

CLAS12 Run-group H Experiments with a Transversely Polarized Target

H. Avakian^{1,2+,3}, N. Baltzell, J. Brock, V. Burkert³, D. Carman, R. De Vita,
C. Dilks, L. Elouadrhiri³⁺, F.-X. Girod, Y. Gotra, I.M. Higuera Angulo,
T. Kageya, C. Keith^{1,2,3}, V. Kubarovsky, J.D. Maxwell, R. Parendyan, E.
Pasyuk, B. Singh, S. Stepanyan, R. Tyson, X. Wei¹, V. Ziegler
Jefferson Lab, Newport News, VA 23606, USA

T. Hellstern, G. Matousek, M. McEaney, A. Liu, C. Pecar, A. Vossen²,
N. Wickramaarachchi, Z. Zhao
Duke University, Durham, NC 27708, USA

J.S. Alvarado, C. Munoz Camacho, R. Dupré, M. Hoballah, D. Marchand,
S. Niccolai³, F. Touchte-Codjo, E. Voutier, L. Xu
IJCLAB, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France

L. Barion, G. Ciullo, M. Contalbrigo^{1+*}, L. Del Bianco, P. Lenisa,
L.L. Pappalardo², S. Plavully, L. Polizzi, F. Spizzo
INFN Sezione di Ferrara and University of Ferrara, 44122 Ferrara FE, Italy

M. Mirazita^{1,2}, S. Tomassini
INFN Sezione di Frascati, 00044 Frascati RM, Italy

A. Courtoy²
Universidad Nacional Autónoma de México, 04510 Mexico City, Mexico

S. Diehl, K. Joo¹, A. Kim, A. Kripko, D. Terrero Cepeda
University of Connecticut, Storrs, CT 06269, USA

M. Bondi, N. Randazzo
INFN Sezione di Catania and Catania University, 95125 Catania CT, Italy

M. Battaglieri, F. Bzeih, R. De Vita, P. Musico, T. Nagorna, M. Osipenko,
M. Ripani, M. Spreafico, S. Vallarino, T. Vittorini
INFN Sezione di Genova, 16146 Genova GE, Italy

E. Cisbani, G.M. Urciuoli
INFN Sezione di Roma, 00185 Roma RM, Italy

C. Ammendola, A. D'Angelo, A. Fantini, S. Gramigna, L. Lanza, A. Rizzo,
E. Sidoretti, L. Torlai
*INFN Sezione di Roma Tor Vergata and Tor Vergata University, 00133 Roma
RM, Italy*

R. Perrino
INFN Sezione di Bari, 70126 Bari BA, Italy

A. Bianconi, V. Mascagna, L. Venturelli
University of Brescia and INFN Sezione di Pavia, 25121 Brescia BS, Italy

G. Arcadi, G. Foti, A. Fulci, A. Pilloni, A. Riggio
University of Messina and INFN Sezione di Catania, 98122 Messina ME, Italy

A. Bacchetta, B. Pasquini
INFN Sezione di Pavia and University of Pavia, 27100 Pavia PV, Italy

M.E. Boglione, A. Filippi, A. Signori
INFN Sezione di Torino and University of Torino, 10125 Torino TO, Italy

F. Bossù, P. Chatagnon, S. Polcher Rafael
IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

B. McKinnon
University of Glasgow, Glasgow G12 8QQ, UK

F. Benmokhtar
Duquesne University, Pittsburgh, PA 15282, USA

S. Lee, M. Zurek
Argonne National Laboratory, Lemont, IL 60439, USA

A. Schmidt
George Washington University, Washington, DC 20052, USA

T. Hayward
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

V. Baturin, T. Rogers
Old Dominion University, Norfolk, VA 23529, USA

P. Nadel-Turonski
South Carolina University, Columbia, SC 29208, USA

M. Carpinelli
INFN Laboratori del Sud and Milano Bicocca University, 20126 Milano, Italy

The CLAS Collaboration

* Contact Person for the Run-Group: Marco Contalbrigo, contalbrigo@fe.infn.it

+ Contact Person for the Experiment

¹ C12-11-111 Spokesperson

² C12-12-009 Spokesperson

³ C12-12-010 Spokesperson

Executive Summary

The CLAS12 run-group H (RGH) comprises 3 experiments, requiring a transversely polarized target, originally approved with rating A by PAC39 [1] and selected among the high-impact JLab measurements by PAC41 [2]:

- **C12-11-111** *Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using CLAS12*: a multi-dimensional analysis of the semi-inclusive deep-inelastic scattering (SIDIS) reactions to access transversity and tensor charge, and the Sivers and Collins functions connected with the spin-orbit phenomena of the strong-force dynamics [3];
- **C12-12-009** *Measurement of transversity with dihadron production in SIDIS with transversely polarized target*: a multi-dimensional analysis of the SIDIS reactions at 11 GeV exploiting the dynamics of the dihadron final state to access transversity in the benchmark collinear limit and investigate novel parton correlations inaccessible on the single hadron case [4];
- **C12-12-010** *Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector*: a first-time multi-dimensional extraction of the transverse target spin asymmetry for the DVCS reaction to access E , the most elusive Generalized Parton Distribution entering Ji's angular momentum sum rule [5].

The RGH experiments pursue a science case of utmost interest as highlighted in the current 2023 NSAC Long Range Plan. They will have a strong sensitivity to several crucial observables whose current knowledge is severely limited by the sparse data available. The RGH experiments are precursors and complementary to one of the pillars of the EIC science programs [6, 7] and will cover the valence phase space with unprecedented precision. The RGH program completes a comprehensive study of all possible target and beam polarization observables with the existing CLAS12 large-acceptance spectrometer. Distinctive features, common to all three RGH experiments, are the precise measurement of parton distributions and phenomena in the poorly explored valence region (large Bjorken- x) where current models project their magnitude to be peaking, a luminosity at least one order of magnitude higher than the previous experiments, a large acceptance detector for the disentanglement of the various correlations and kinematic regimes, and an excellent particle identification capability to access flavor sensitivity.

All three experiments received a C1 condition to address technical issues related to target performance. The eventually adopted solution foresees a dynamically polarized NH_3 target with a dedicated recoil detector that replaces the CLAS12 solenoid and Central Detector. Such a solution favors consolidated polarized-target technologies and relies on previous successful realizations at JLab. During the jeopardy process at PAC52, the status of RGH changed to a C2 condition to assess in more details the revised experimental configuration, in particular regarding the achievable physics impact in conjunction with the required beamtime [8]. The specific requests of PAC52 have been addressed here:

- a full GEANT simulation of the beamline is discussed in Section 3.2;

-
- a full GEANT simulation of the different physics measurement is discussed in Section 3.3.3;
 - the systematic uncertainties for the different measurements are discussed in Section 5.3;
 - impact studies of the proposed measurements on the physics of TMDs and GPDs are presented in Sections 5.1 and 5.2.3.

The achievable luminosity is defined by the background level in the detector and the nominal $\mathcal{L} = 5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ RGH value corresponds to the most realistic (based on real data) and conservative (based on present CLAS12 capability without ongoing upgrades) estimate and requires a modest beam current of $\approx 1 \text{ nA}$. In order to allow a multidimensional analysis to disentangle the relevant kinematic correlations in an unexplored region of valence, be competitive with lattice calculations on the u-flavor tensor charge, and provide relevant constraints to the GPD E , a total of 125 PAC days are requested, including 25 PAC days of commissioning, calibration, and target operations, and 100 PAC days of production data taking.

Contents

1	Physics Motivation	7
1.1	SIDIS off Transversely Polarized Proton	8
1.1.1	Transversity	10
1.1.2	Sivers	12
1.1.3	Collins and Interference Fragmentation	14
1.1.4	Additional Correlators	14
1.2	DVCS on Transversely Polarized Protons	17
1.2.1	GPD E	18
1.3	Status and Main Competitors	22
2	Experimental Details	26
2.1	CLAS12 Spectrometer	26
2.1.1	Forward Detector	26
2.2	Beamline Elements	28
3	Required Equipment	28
3.1	Transverse Target	28
3.2	Beam Chicane	32
3.3	Recoil Detector	37
3.3.1	μ Rwell Tracking	39
3.3.2	Scintillation Timing	42
3.3.3	Recoil Simulation and Reconstruction	44
3.3.4	Physics Background	48
3.3.5	Mechanical Model	53
3.3.6	Available Resources	56
3.4	Luminosity	58
4	Kinematics	60
4.1	DVCS	60
4.2	SIDIS	62
5	Projections	67
5.1	Semi-inclusive Physics	67
5.1.1	Impact study: Sivers	69
5.1.2	Impact study: Tensor charge	70
5.2	DVCS	75
5.2.1	π^0 Background	77
5.2.2	DVCS on Polarized NH_3 : the RGC Example	78
5.2.3	Impact study: extraction of the CFF $\Im m \mathcal{E}$	80
5.3	Systematic Uncertainties	81
6	Beam Time Request	83
7	Summary	84
A	Resources	85

Abstract

We propose an optimized experimental configuration to meet the goals of three C2 conditionally approved deep-inelastic scattering (DIS) experiments with CLAS12 and a transversely polarized target, identified as run-group H (RGH). The usage of a transversely polarized Hydrogen target in conjunction with the CLAS12 spectrometer and an 11 GeV polarized electron beam will provide access to unique aspects of nucleon structure at the scale of confinement. In particular, the experiments of RGH will measure transverse target single- and double-spin asymmetries in semi-inclusive and hard-exclusive reactions to chase some of the most elusive and peculiar parton distributions and correlation functions among the Transverse Momentum Dependent (TMDs) and Generalized Parton Distributions (GPDs).

C12-11-111 will study the semi-inclusive reaction $ep^\uparrow \rightarrow ehX$, (with h an identified hadron and X the undetected final state), to access leading-twist parton distribution functions in a transversely polarized nucleon. The transversity, the Sivers function, and the so-called “pretzelosity” function describe the correlation between the transverse nucleon polarization and, respectively, the transverse polarization of partons, the transverse momentum of unpolarized partons, and the transverse momentum of transversely polarized partons. Furthermore, double-spin asymmetries based on both the target transverse and the beam longitudinal polarizations will provide access to the so-called “worm-gear” function, sensitive to the correlation between the transverse momentum of longitudinally polarized partons and the nucleon transverse polarization. RGH data will also provide constraints to the transverse-momentum dependent Collins fragmentation function.

C12-12-009 will study the semi-inclusive reaction $ep^\uparrow \rightarrow eh_1h_2X$ (with h_1 and h_2 two identified final-state hadrons) to access the transversity distribution and its first moment, the tensor charge, in a reaction that can be described by a standard collinear formalism and provides a benchmark for the alternative transverse-momentum dependent (TMD) extraction.

C12-12-010 will measure the deeply virtual Compton scattering (DVCS) on the proton, $ep^\uparrow \rightarrow ep\gamma$, whose azimuthal spin asymmetries depend on combinations of Generalized Parton Distributions (GPDs), to provide access to the elusive and poorly constrained GPD E . E is the missing ingredient to quantify the quarks’ orbital momentum contribution to the proton spin. Only the transverse-target spin asymmetry of DVCS has a strong sensitivity to the E GPD of the proton, and so far it has been measured only by HERMES, on a limited kinematic coverage and with very poor statistics. RGH will measure also double-spin asymmetries for proton DVCS, giving access to the real part of the target-spin dependent DVCS amplitude.

This set of experiments will contribute to a comprehensive investigation of nucleon structure in the CEBAF energy domain performed with the same spectrometer. The x , Q^2 , z , $P_{h\perp}$ dependencies will be studied in a wide kinematic range thanks to the large acceptance of CLAS12. Flavor sensitivity will be ensured by the available excellent particle identification systems.

In order to allow a multi-dimensional analysis to disentangle the relevant kinematic correlations in an unexplored region of valence, be competitive with lattice calculations on the u-flavor tensor charge, and provide relevant constraints to the GPD E , a total of 125 PAC days are requested, including 25 PAC days of commissioning, calibration and target operations, and 100 PAC days of production data taking.

1 Physics Motivation

In recent years, the study of nucleon structure received a renovated impulse thanks to a new investigation paradigm. New parton distributions (PDFs) and fragmentation functions (FFs) have been introduced to describe the rich complexity of hadron structure, focusing on the parton transverse degrees of freedom at the scale of confinement and moving toward the achievement of a 3D description of parton dynamics. Relevant examples are transverse momentum dependent (TMD) and generalized (GPD) parton distributions, that correlate the longitudinal momentum fraction (referred to the direction of the hard probe) with the intrinsic partonic transverse momentum or position, respectively. These novel distribution functions can be classified depending on the spin orientation of the target nucleon and the quark, as these dictate the type of underlying correlation, see Figure 1.

TMDs		quark polarisation		
nucleon polarisation	N/q	U	L	T
	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$

GPDs		quark polarisation		
nucleon polarisation	N/q	U	L	T
	U	H		$\mathcal{E}_T$
	L		$\tilde{H}$	$\tilde{\mathcal{E}}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Fig. 1: TMD and GPD classification based on the relevant spin (target nucleon or quark) orientation.

Since TMDs and GPDs are derived by integrations of distinctive components of 5-dimensional Wigner functions [9], the most general parton distribution functions, they are formally independent. Nevertheless, intriguing model-dependent relations can be found among them. An interesting example is the possible relationship between the Sivers TMD function $f_{1T}^\perp$ and the GPD E. The Sivers function is related to the distortion in the momentum distribution of an unpolarized parton when the parent nucleon is transversely polarized. The GPD E enters the Ji sum rule [10] for the longitudinal angular momentum and describes an imbalance in the impact parameter space of the quarks in reactions with nucleon helicity flip, but unaffected quark helicity. The two can be related by the so-called lensing mechanism, inspired by results of spectator models and described by a flavor-independent function, representing the effect of the QCD interaction of the outgoing quark with the rest of the nucleon [11]. This relationship has been used to infer constraints on the quark angular momenta [12].

Exploring parton correlations at the confined scale is a formidable challenge. The peculiar nature of the strong force, which favors multi-body interactions, is reflected in a complex variety of possible correlations and requires the capability to explore large portions of the phase space and disentangle various kinematic dependencies. This can be ultimately achieved only by collecting observables from all the possible reactions, typically deep-inelastic scattering, Drell-Yan, e^+e^- annihilation, and hadron-hadron interactions, investigated in

various facilities over the world.

Deep-inelastic scattering (DIS) experiments play a special role, thanks to clean control of the probe kinematics and rich phenomenology, which convolutes parton distributions and fragmentation functions. A novel level of sophistication is required to the DIS experiments as they should conjugate precision, in discriminating semi-inclusive and exclusive reaction details and hadron species, and power, in collecting large amounts of data to allow multidimensional analyses. The investigation of the non-perturbative parton dynamics typically requires two scales: a hard scale defining the DIS regime and a soft scale accessing the confined dynamics. The first scale is associated with the virtual photon 4-momentum Q . The second is associated with the intrinsic momentum $k_\perp$ of the partons (in the case of TMDs) or with the 4-momentum transferred t to the unbroken target nucleon (in the case of GPDs). Note that the hard scale should be larger than the soft scale to allow proper factorization, but not too large to avoid an overwhelming dilution via perturbative radiation effects (in the case of semi-inclusive reactions) or unnecessary cross-section suppression (in the case of exclusive reactions).

Fixed-target DIS experiments have played an essential role despite the limited statistics accumulated so far. The CLAS12 Run Group H program aims to collect several fundamental measurements that provide access to elusive quantities and are only possible with the use of a transversely polarized target in conjunction with a high-precision spectrometer of large acceptance and unprecedented luminosity.

Note that, in order to suppress unwanted experimental effects, the experiments typically measure asymmetries defined as

$$A_{UT} = \frac{\Delta\sigma_{UT}}{2\sigma_{UU}} = \frac{\sigma_{UT}^\uparrow - \sigma_{UT}^\downarrow}{\sigma_{UT}^\uparrow + \sigma_{UT}^\downarrow}$$

where the subscripts indicate the beam and target polarization states. In such asymmetries, also some theoretical contributions like gluon radiation and evolution effects tend to cancel out. Due to these reasons, the asymmetry observable is typically less sensitive to second-order corrections and to transitions between different kinematical regimes. At the same time, asymmetries require knowledge of σ_{UU} to provide constraints onto the parton distributions. The CLAS12 program will start with asymmetry measurements, but may be eventually extended to cross-section measurements as done by the precursor CLAS.

1.1 SIDIS off Transversely Polarized Proton

TMDs can be measured in polarized semi-inclusive DIS (SIDIS) reactions, where the leading hadron is measured in conjunction with the scattered lepton. The SIDIS cross sections can be Fourier decomposed into terms that depend on beam (λ_e) and target ($S_{L,T}$) polarizations:

$$\begin{aligned}
\frac{d\sigma_{UT}}{dx dQ^2 dz dP_{h\perp} d\phi d\phi_S} &\propto \left[F_{UU} + \epsilon \cos(\phi) F_{LU}^{\cos(2\phi)} \right] \\
&+ S_L \left[\sin(2\phi) F_{LU}^{\sin(2\phi)} \right] + S_T \left[\sin(\phi - \phi_S) F_{UT}^{\sin(\phi - \phi_S)} \right. \\
&+ \left. \epsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \epsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \right] \quad (1) \\
&+ \lambda_e S_L \left[\sqrt{1 - \epsilon^2} F_{LL} \right] \\
&+ \lambda_e S_T \left[\sqrt{1 - \epsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} \right] + O\left(\frac{1}{Q^2}\right)
\end{aligned}$$

where the cross section depends on the Bjorken x , the photon virtuality Q^2 , the hadron energy fraction z , the hadron transverse momentum $P_{h\perp}$, the azimuthal angles ϕ and ϕ_S of the produced hadron and target spin with respect to the lepton scattering plane, respectively, see Figure 2. Polarization pre-factors depend on the ratio ϵ of the longitudinal and transverse photon fluxes. Each term has a distinctive modulation in the azimuthal angles and contains a structure function F_{XY} with subscripts XY indicating the beam and target polarization.

Within TMD factorization, each structure function can be interpreted as a convolution of a parton distribution and a fragmentation function, e.g.:

$$F_{UU} = C [f_1(x, k_T) \times D_1(z, p_T)] \quad (2)$$

where the convolution

$$C = x \sum_q e_q^2 \int d^2 p_T d^2 k_T \delta(P_{h\perp} - z k_T - p_T) w(k_T, p_T) f_1^q(x, k_T) D_1^q(z, p_T) \quad (3)$$

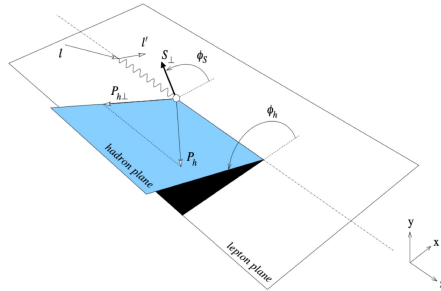


Fig. 2: Scheme illustrating the definition of the angles ϕ of the hadron production plane and ϕ_S , the component of the target polarization vector that is orthogonal to $\vec{q}$, with respect to the lepton scattering plane and $S_\perp$.

runs over the intrinsic transverse momentum k_T of the parton and the transverse momentum p_T generated during fragmentation. The delta function δ ensures the conservation of momentum for the observed transverse momentum $P_{h\perp}$, and the weight function w is a calculable kinematic factor.

The theory tools to extract TMD parton distributions are still an area of active research. Current frameworks work best with a significant separation between the large scale, Q^2 , and the small scale, the intrinsic transverse momentum. For kinematics where these conditions are not fulfilled, corrections can be important. This is of course not intrinsic to the underlying theory of QCD. Interestingly enough, current TMD fits, like Nanga Parbat, are able to describe the unpolarized TMD cross section over a wide kinematic range even outside the "safe" region. To evaluate the potential impact of the expected RGH data, we organized a mini-workshop with various theory groups from Italy and the US. The conclusion was that the di-hadron extraction of transversity, since it relies on a collinear framework, is unproblematic. As mentioned above, the existing TMD frameworks describe current data quite well. Therefore, the high-precision RGH data were deemed absolutely crucial to test those frameworks and provide input for further refinement.

1.1.1 Transversity

The *transversity* PDF h_1 describes the parton transverse polarization inside a transversely polarized nucleon, reflects the relativistic nature of parton confinement, and exhibits peculiar evolution properties. It is the least known leading PDF that does not vanish when integrated in the parton transverse momentum $k_\perp$, and can thus be studied in the collinear limit. Because it is chirally-odd, being associated to a flip of the parton helicity, it requires a peculiar fragmentation, also chirally-odd, to be observed in DIS reactions, see Section 1.1.3.

The interpretation of single-hadron production

$$\sigma_{UT}^{Collins} \propto S_T \sin(\phi + \phi_S) C[h_1(x, k_T) \times H_1^\perp(z, p_T)] \quad (4)$$

requires the Collins fragmentation function $H_1^\perp$ and the TMD formalism to describe its genuine transverse-momentum dependence. Among the most recent extractions, some utilize only DIS data [13], some exploit DIS and e^+e^- data [14, 15, 16], some consider in addition inclusive single-spin asymmetries in proton-proton collisions [17, 18, 19]. Most of them impose the Soffer bound and some introduce constraints from Lattice calculations [13, 18].

The interpretation of di-hadron production

$$\sigma_{UT}^{IFF} \propto S_T \sin(\phi_{R\perp} + \phi_S) \sin(\theta) h_1(x) H_1^\triangleleft(z, M_{hh}) \quad (5)$$

requires the interference fragmentation function $H_1^\triangleleft$, and can be performed within the collinear formalism as it survives the $P_{h\perp}$ integration allowing to clear the convolution in transverse momentum. Here θ is the polar angle of the hadron production, $\phi_{R\perp}$ is the azimuthal angle of the *relative* momentum

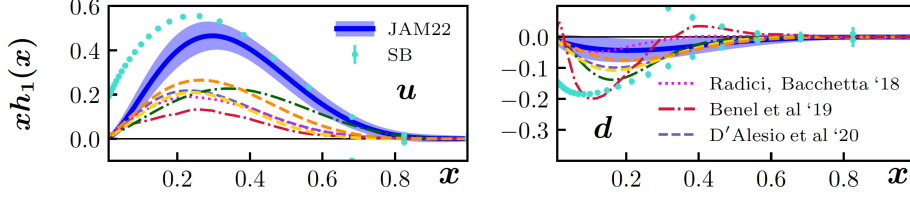


Fig. 3: Transversity PDF $xh_1^{u_v}$ (left) and $xh_1^{d_v}$ (right) plotted as a function of x at the scale $\mu^2 = 4 \text{ GeV}^2$. The plot is from the JAM3D-22 global analysis [18] (blue solid line with $1\text{-}\sigma$ error bars) and compares the results with alternative extractions from single hadron [14] (green dash-dotted line), [20] (yellow dashed line), [15] (orange dashed line), [16] (blue dashed line) and di-hadron [21] (magenta dotted line), [22] (red dash-dotted line) observables. The generated Soffer bound (SB) is also displayed (cyan points).

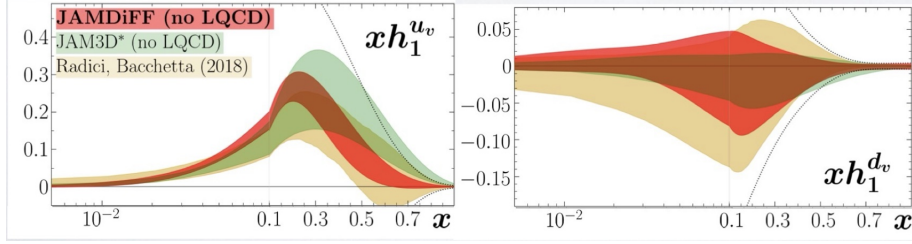


Fig. 4: Transversity PDF $xh_1^{u_v}$ (left) and $xh_1^{d_v}$ (right) plotted as a function of x at the scale $\mu^2 = 4 \text{ GeV}^2$. The plot is from the JAMDiFF analysis of di-hadron asymmetries [23] (red band) and compares the results with the alternate analysis [21] (yellow band) and the JAM3D single-hadron extraction [18] (green band). The Soffer bound is indicated by the dotted curve. A logarithmic scale is used below Bjorken $x = 0.1$.

of the produced pair with mass M_{hh} . Among the most recent extractions, some utilize only SIDIS and e^+e^- data [22], some also exploit proton-proton collisions [21, 23, 24]. All analyses impose the Soffer bound and some introduce lattice constraints [23, 24].

Although essential for the description of nucleon structure, due to its chirally-odd nature, transversity has only recently been accessed in a limited kinematic range and with large uncertainties [25]. A compendium of results is shown in Figure 3 and Figure 4. Recent phenomenological extractions typically peak in the region of $x \gtrsim 0.3$ where world data are very sparse. The dispersion of the extracted distributions manifests the uncertainty derived from the severe lack of data and the consequent model-dependent assumptions introduced as compensation.

The transversity first moment in Bjorken x , the tensor charge, is a fundamental quantity in quantum chromodynamics (QCD) connected to searches of beyond-the-Standard-Model phenomena such as the Electric Dipole Moment

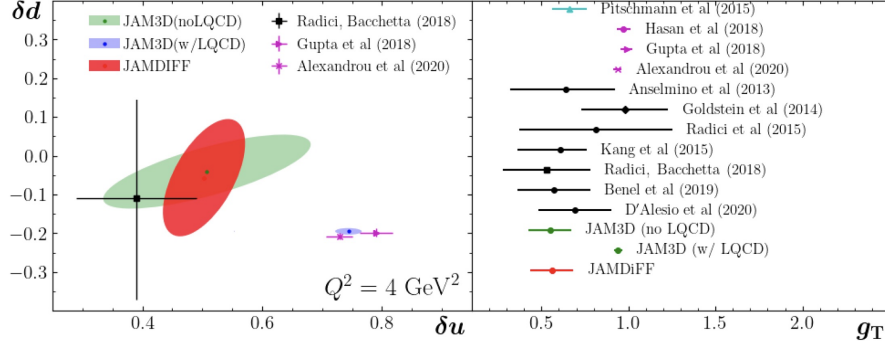


Fig. 5: The tensor charge δu , δd (left) and g_T (right) from [24]. Phenomenological extractions based on single-hadron observables [18] with (cyan) and without (green) inputs from lattice, and double-hadron observables [23] (red), are compared to previous extractions [14, 16, 20, 21, 22, 26], (black), and to lattice calculations [27, 28, 29] (magenta).

(EDM) of particles [30] and the tensor interaction [31]. From the above phenomenological analyses of the transversity function, constraints on the global g_T and flavor-separated δu , δd tensor charges can be inferred. Despite the large uncertainty, there is an apparent tension with the estimates derived from lattice calculations, see Fig. 5. Currently, the lattice constraints have a superior precision and, whenever introduced in the phenomenology extractions, as done in [17, 24, 23], completely dominate the result. This signals a lack of competitive experimental datasets.

The CLAS12 data from RGH will cover an unexplored kinematic regime at high Bjorken- x (valence region) and will allow multidimensional analyses over all relevant kinematical dependencies. The tensor charge receives substantial contributions in the valence-quark region at $x \gtrsim 0.3$. While this is true for many polarization-dependent PDFs, this feature is even stronger for transversity as the contribution from (spin-1) gluons is vanishing due to its chirally-odd nature. New data in the uncharted valence-quark region can clarify the current tensions between extractions from phenomenology and lattice QCD. The proposed run group will provide unprecedented constraints to the tensor charge and allow a precise comparison with lattice QCD, see Section 5.1.

1.1.2 Sivers

The Sivers PDF $f_{1T}^\perp$ is a genuine TMD function which vanishes with $k_\perp$ integration. Among the most intriguing parton distributions, it requires a non-zero parton orbital angular momentum and a correlation with the nucleon spin. As a consequence of its non-trivial gauge-invariant definition, the Sivers function probes QCD at the amplitude level: it is naively T-odd (does not violate T-invariance due to the interaction phase) and exhibits a peculiar process dependence. A sign change is expected when moving from SIDIS to Drell-Yan processes, and its verification is one of the most urgent goals of the present

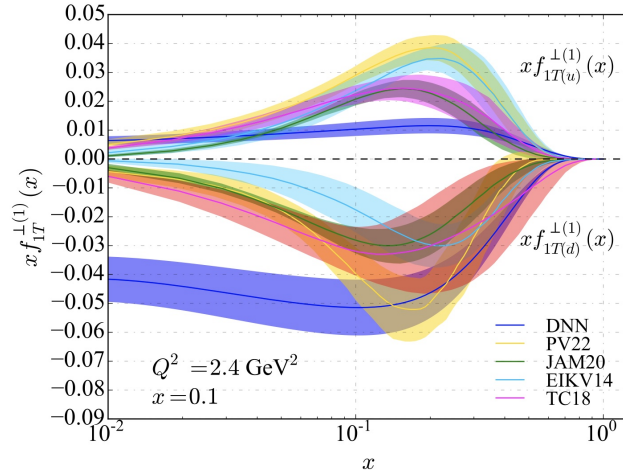


Fig. 6: First moment of the Siverts PDF $xf_{1T}^{\perp(1)}$ plotted as a function of x for u (d) flavor in the upper (lower) panel of the figure. The plot is based on a deep neural network analysis of single-hadron asymmetries [32] (magenta band) and compares the results with the alternate analyses [17] (green band), [33] (cyan band), [34] (yellow band) and [35] (pink band).

experimental activity [25]. It is among the few TMDs that, while describing the non-perturbative nature when $k_{\perp} \ll Q^2$, should in principle match the perturbative regime with increasing transverse momentum, providing a formal bridge between the two QCD descriptions [36]. It can be studied in single-hadron production, as transversity, but with a different azimuthal modulation and in conjunction with the ordinary unpolarized fragmentation function:

$$\sigma_{UT}^{Sivers} \propto S_T \sin(\phi - \phi_S) C[f_{1T}^{\perp}(x, k_T) \times D_1(z, p_T)] \quad (6)$$

Despite the presence of the better known unpolarized FF D_1 , the explicit dependence and convolution in transverse momentum complicate the interpretation of the results. In the absence of new data, the situation is similar to that of the transversity function, with a variety of diverse results peaking in the valence, see Figure 6. A global analysis, encompassing the latest data from SIDIS, Drell-Yan, and $W^{\pm}/Z$ -boson production processes, indicates that new data from COMPASS allow a significant reduction of the uncertainty on the d flavor, see Figure 7. However, no fully differential measurement (in all relevant variables) is available so far. Note that a significant Siverts effect was recently predicted for dihadrons [37].

The CLAS12 data will allow an extended coverage in the valence region and a disentanglement of the kinematic dependencies, a crucial information for the study of Siverts and related phenomena, and the connections among different QCD regimes.

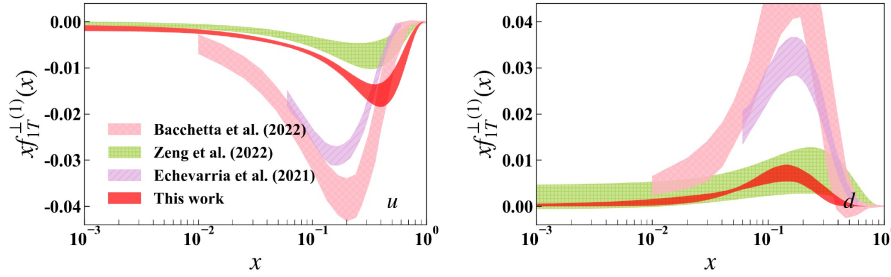


Fig. 7: First moment of the Siverts PDF $xf_{1,T}^{\perp(1)}$ for u (left) and d (right) flavor, plotted as a function of x at the scale $Q = 2$ GeV. The plot is from a global analysis [38] (red band) with the inclusion of the latest deuteron A_{UT} data from COMPASS, and compares the results with the alternate analyses [39] (green band), [40] (magenta band) and [34] (pink band).

1.1.3 Collins and Interference Fragmentation

The *Collins* and *Di-hadron* FFs originate from spin-orbit effects connecting the spin orientation of a fragmenting quark with the final observed hadron or di-hadron transverse momentum, respectively. Convincing evidences were found for the existence of these mechanisms [25]. These peculiar FFs act as a quark polarimeter and allow one to access the elusive chirally-odd distribution functions in SIDIS reactions. In particular, the Collins FF features a real dependence on transverse momentum (does not survive a p_T integration) and requires a genuine TMD formalism [18, 20, 15, 14]. In contrast, the Interference FF sensitive to the hadron pair *relative* transverse momentum can be studied in the collinear limit, providing a complementary access to transversity that does not depend on the TMD formalism [22, 26], and can be reliably extended to the hadron-hadron scattering case [21, 23, 24].

Independent information on these FFs can be extracted at the e^+e^- colliding machines [41], when the leptons annihilate in a light quark-antiquark pair. Indeed, due to angular momentum conservation, a correlation of the mutual spin orientation is inherited by the quark-antiquark pair, that manifests as a little anisotropy in the relative distribution of the final-state particles. The analysis of these FFs is complicated by the convolution in transverse momentum for pure TMD functions like Collins, or the involved final state for the dihadron fragmentation, resulting in a spread of results, see e.g. Figure 8. It is interesting to note that new data will be instrumental to validate the proper field-theoretical definition and interpretation of dihadron fragmentation functions from factorization theorems [42, 43].

High-precision data from CLAS12 can complement present and future information gathered at the much higher center-of-mass energy of experiments at the e^+e^- colliders, like BELLE-II, and at hadron-hadron colliders, like RHIC.

1.1.4 Additional Correlators

It is worth mentioning that, aside from the selected fundamental measurements discussed above, many other important observables can be measured simulta-

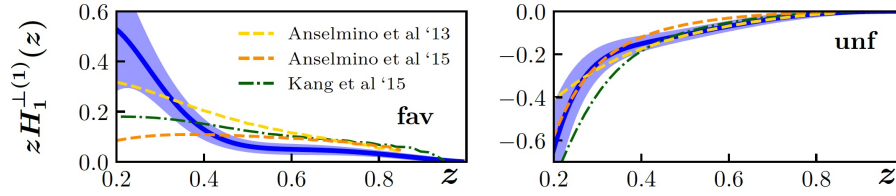


Fig. 8: First moment of the Collins FF $zH_1^{\perp(1)}$ for the favored and the unfavored case, plotted as a function of z at the scale $Q^2 = 4 \text{ GeV}^2$. The plot is from a global analysis [18] (magenta band) and compares the results with the alternate analyses [20] (yellow dotted curve), [15] (orange dotted band) and [14] (green dash-dotted curve).

neously with a transversely polarized target. In practice, in fact, azimuthal amplitudes sensitive to the poorly known leading-twist “pretzelosity” $h_{1T}^{\perp}$ and “worm-gear” g_{1T} TMDs, as well as to several sub-leading-twist transverse-momentum-dependent PDFs and FFs [25, 44] can be extracted simultaneously in the analysis of the same data.

The naive-T-even chiral-odd pretzelosity TMD $h_{1T}^{\perp}$, related to a quadrupolar distortion of the quark density, describes the dependence of the number density of quarks on the relative orientation of p_T and the transverse polarizations of both the quark and the parent nucleon. Angular momentum conservation requires that the struck quark absorbs two units of orbital angular momentum, implying either the presence of $S - D$ interference in the nucleon wave function or matrix elements that are quadratic in a P wave component [45, 46, 47, 48, 49, 50]. In various models the pretzelosity distribution appears as the difference between the helicity and the transversity distributions, and therefore incorporates genuine relativistic effects in the nucleon structure. Experimentally, it is accessible through a $\sin(3\phi - \phi_S)$ modulation of the SIDIS cross section. Measurements of this asymmetry amplitude have been reported by the JLab Hall-A Collaboration [51], using a transversely polarized ^3He target (an effectively neutron target), as well as by the COMPASS [52] and HERMES [53] Collaborations, based on the use of transversely polarized NH_3 and H targets, respectively. In particular, HERMES reported the first 3D extraction of this asymmetry amplitude in the x , z and $P_{h\perp}$ variables for pions, charged kaons, and protons/antiprotons. All present results are consistent with zero within the experimental uncertainties. However, one has to consider that, at the relatively low transverse momenta of these measurements ($P_{h\perp} \lesssim 1 \text{ GeV}$), the amplitude of the $\sin(3\phi - \phi_S)$ modulation is expected to be suppressed with respect to, e.g., the Collins amplitude, by a factor of $P_{h\perp}^2$. The significantly higher statistical precision achievable with the proposed experiment is a key requirement for a first potential observation of a non-vanishing signal.

The chiral-even and naive-T-even $g_{1T}^{\perp}$ TMD [45] describes the number density of longitudinally polarized quarks in a transversely polarized nucleon. The name “worm gear” refers to the orthogonal orientation of the spins of quarks and nucleons. In the Wandzura-Wilczek-type approximation (see, e.g., [54]) it can be related to the helicity PDF g_1 . The convolution of the $g_{1T}^{\perp}$ TMD with the unpolarized fragmentation function D_1 can be accessed through measurements

of the $\cos(\phi - \phi_S)$ modulation of the SIDIS cross section using a transversely polarized target in combination with a longitudinally polarized beam. The first measurement of the corresponding asymmetry amplitude has been reported by the JLab Hall-A Collaboration using a transversely polarized ^3He target [55]. While the results for positive pions are consistent with zero, the ones for negative pions provide the first evidence of a non-vanishing $g_{1T}^\perp$. Non-zero amplitudes have also been reported by the COMPASS and HERMES Collaborations, for unidentified charged hadrons [52] and positive pions [53] respectively. Recently, a first global extraction of the worm-gear TMD $g_{1T}^\perp$ became available [56] based on the above mentioned SIDIS data.

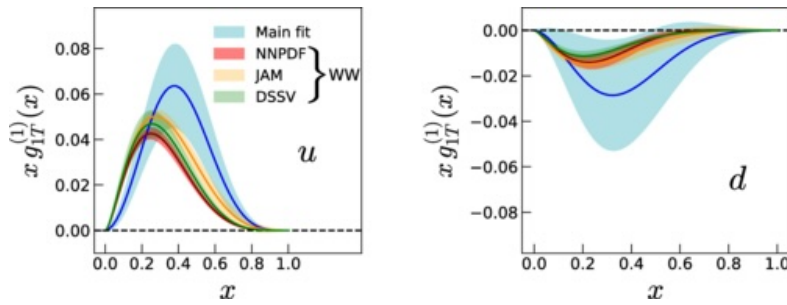


Fig. 9: Comparison of the $xg_{1T}^{(1)}$ extraction at $Q^2 = 4 \text{ GeV}^2$ for up quarks (left) and down quarks (right) from Ref. [56] with calculations based on the Wandzura-Wilczek (WW) approximation taken from NNPDF [57], JAM [58], and DSSV [59].

However, all presently published results are affected by large uncertainties. The relatively higher luminosity and beam polarization degree represent promising prerequisites for precision measurements of $g_{1T}^\perp$ with the proposed experiment, with the additional advantage of ensuring a coverage in the essentially uncharted high- x region.

One of the most unexpected recent HERMES results is the observation of large subleading twist $\sin(\phi_S)_{\text{UT}}$ Fourier amplitudes [53], showing a clear kinematic dependence for charged mesons. In particular, the 3D binning reveals that those non-vanishing asymmetries arise predominantly from the large- x and large- z region. The underlying structure function is given by a sum of several terms, each of which contains a twist-3 TMD convoluted with a twist-2 TMD. The twist-3 objects have no probabilistic interpretation and contain interaction-dependent terms, i.e., they involve quark-gluon correlations in the nucleon wave function. All these terms are suppressed by the factor (M/Q) . Being related to subleading-twist cross-section contributions, it is interesting to explore the Q^2 dependence of this Fourier amplitude. Due to the limited statistics and the strong x - Q^2 correlation, the HERMES results are typically not binned in Q^2 . In order to observe a possible genuine Q^2 dependence, each 1D x bin has been split into the two regions of Q^2 , revealing a hint of enhancement of the amplitude for the regions of lower Q^2 , though not very pronounced, due to the relatively small lever arm in Q^2 . The large statistics expected for the proposed

experiment will allow to study this effect with a finer x - Q^2 2D binning, and in a kinematic region (large- x) where the amplitude is expected to rise even further.

1.2 DVCS on Transversely Polarized Protons

The formalism of GPDs [60, 10, 61, 62, 63, 64, 65] provides a universal description of the partonic structure of the nucleon, providing the spatial distributions in the transverse plane of partons carrying a given longitudinal momentum fraction. The simultaneous knowledge of longitudinal momentum and transverse position gives access to the angular momentum of quarks and gluons. Therefore, the determination of GPDs can clarify the so-called “spin crisis”, which ensued from the measurements showing that the spins of the quarks contribute to only 20-30% of the nucleon’s spin. GPDs are most easily accessed in the measurement of the exclusive leptonproduction of a photon (DVCS, which stands for Deeply Virtual Compton Scattering) on the nucleon, at sufficiently large Q^2 , which is the virtuality of the photon emitted by the initial lepton ($Q^2 = -(k - k')^2$, where k and k' are the momenta of the initial and final state leptons, respectively). Figure 10 illustrates the leading-order diagram for DVCS, where QCD factorization is applied, splitting the process into the hard quark-photon scattering part, calculable in perturbative QED, and the soft nucleon-structure part. Considering only helicity-conserving processes and the quark sector, the soft structure of the nucleon is parametrized by four GPDs for each quark flavor: $H, \tilde{H}, E, \tilde{E}$ (the tilde denotes polarized GPDs), which depend, in leading-order and leading-twist QCD, upon three variables: x, ξ , and t . x , the average parton momentum fraction, is not accessible experimentally in the DVCS process. $x + \xi$ and $x - \xi$ are the longitudinal momentum fractions of the quarks, respectively, coming out from and going back into the nucleon. t is the squared four-momentum transfer between the final- and initial-state nucleons.

DVCS shares the same final state with the Bethe-Heitler (BH) process, where a real photon is emitted by either the incoming or the scattered electron. At the cross-section level BH is typically larger than DVCS, but information on the latter can be obtained by extracting the DVCS/BH interference term, and exploiting the fact that the amplitude from BH can be computed. Spin-dependent asymmetries, which at leading-twist depend mainly on the interference term, can then be connected to linear combinations of real and imaginary parts of Compton Form Factors (CFFs, $\mathcal{F} = \{\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}\}$), defined for a generic GPD F ($F = \{H, E, \tilde{H}, \tilde{E}\}$) as

$$\Re \mathcal{F} = \mathcal{P} \int_0^1 dx \left[\frac{1}{x - \xi} \pm \frac{1}{x + \xi} \right] [F(x, \xi, t) \mp F(-x, \xi, t)] \quad (7)$$

$$\Im \mathcal{F} = F(\xi, \xi, t) \mp F(-\xi, \xi, t), \quad (8)$$

where $\mathcal{P}$ is the principal value of the integral, and the top and bottom signs apply, respectively, to the unpolarized GPDs (H, E) and to the polarized GPDs ($\tilde{H}, \tilde{E}$).

Measuring GPDs is a complex task, calling for a long-term experimental program comprising the measurement of different observables. Refs. [66, 65] describe the sensitivity of the DVCS observables to the 4 GPDs. Such a dedicated experimental program, mainly focused on a proton target, has been carried out worldwide, in particular at JLab, with CLAS/CLAS12 and Hall A [67, 68, 69,

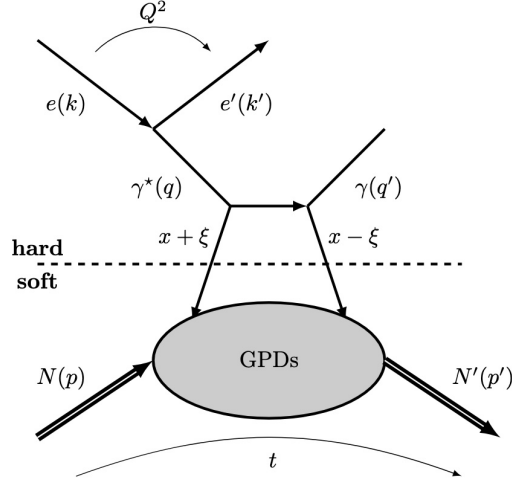


Fig. 10: The “handbag” diagram for the DVCS process on the nucleon $eN \rightarrow e'N'\gamma$. The four-vectors of the incoming/outgoing electrons, photons, and nucleons are denoted by k/k' , q/q' , and p/p' , respectively. $t = (p - p')^2$ and ξ is proportional to the Bjorken variable x_B ($\xi \simeq \frac{x_B}{2-x_B}$, where $x_B = \frac{Q^2}{2M\nu}$, M is the nucleon mass, and $\nu = E_e - E_{e'}$).

70, 71, 72, 73, 74, 75], at HERA with HERMES [76, 77, 78, 79, 80, 81, 82], H1 [83, 84, 85], and Zeus [86, 87], and at CERN with COMPASS [88], bringing strong constraints to the GPD H and some initial indications on the size and kinematic dependence of $\tilde{H}$.

1.2.1 GPD E

Measuring DVCS on transversely polarized protons is essential to quantify the quarks' angular momentum contribution to the proton's spin. Indeed, the transverse-target spin asymmetry (TTSA, hereafter also denoted by A_{UT} where T indicates the transversely polarized target and U the unpolarized beam) for DVCS on the proton is strongly sensitive to the GPD E , which is poorly known and constrained. E is of particular interest as it enters, along with H , in Ji's sum rule [10]

$$\sum_q \int_{-1}^{+1} dx x [H^q(x, \xi, t=0) + E^q(x, \xi, t=0)] = 2 J_q, \quad (9)$$

which links the total angular momentum J_q carried by each quark q to the sum of the second moments over x of the GPDs H and E .

All terms contributing to the exclusive photon leptonproduction cross section have been expanded by Belitsky, Mueller, and Kirchner [89] up to twist-3 in Fourier series in ϕ . In the case of a transversely polarized target the expansion is done also as a function of $\phi - \phi_S$, where ϕ_S , the angle between the lepton scattering plane and $S_\perp$, the component of the target polarization vector that is orthogonal to $\vec{q}$, see Figure 11.

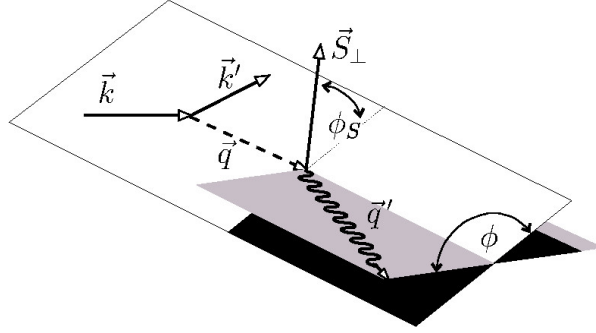


Fig. 11: Scheme illustrating the definition of the angles ϕ , formed by the leptonic and photon production planes, and ϕ_S formed by the lepton scattering plane and $S_\perp$, the component of the target polarization vector that is orthogonal to $\vec{q}$.

The contribution to the total cross section coming from the BH-DVCS interference is given, in the case of a transversely polarized target, by:

$$d\sigma_{UT}^I = \frac{-K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^3 c_{n,TP-}^I \sin(\phi - \phi_S) \cos(n\phi) + \sum_{n=1}^3 s_{n,TP+}^I \cos(\phi - \phi_S) \sin(n\phi) \right\}, \quad (10)$$

The extraction of A_{UT}^I gives access to the leading Fourier coefficient in Equation 11, which, in turn, relates to the CFF as

$$c_{1,TP-}^I \propto -\frac{M}{Q} \Im \left\{ \frac{t}{4M^2} \left[(2 - x_B) F_1 \mathcal{E} - 4 \frac{1 - x_B}{2 - x_B} F_2 \mathcal{H} \right] + x_B \xi \left[F_1 (\mathcal{H} + \mathcal{E}) - (F_1 + F_2) (\tilde{\mathcal{H}} + \frac{t}{4M^2} \tilde{\mathcal{E}}) \right] \right\}, \quad (11)$$

where F_1 and F_2 are the Dirac and Pauli form factors. Therefore, the measurement of A_{UT} with a proton target provides a rare access to the CFF $\Im \mathcal{E}$ with no kinematic suppression of its contribution relative to those of the other CFFs.

The current knowledge of the GPD E comes mainly from the combination of the results from HERMES for proton-DVCS on a transversely polarized target [78], described in Sec. 1.3, and the recent CLAS12 results for the beam-spin asymmetry for DVCS on the neutron [90]. Figure 12 shows the impact of the CLAS12 nDVCS data on the quark-flavor separation of the CFFs $\Im \mathcal{H}$ and $\Im \mathcal{E}$. It is evident how the inclusion of the nDVCS beam-spin asymmetries, which are strongly sensitive to the $\Im \mathcal{E}$ for the neutron, is vital for the separation of the u and d CFFs.

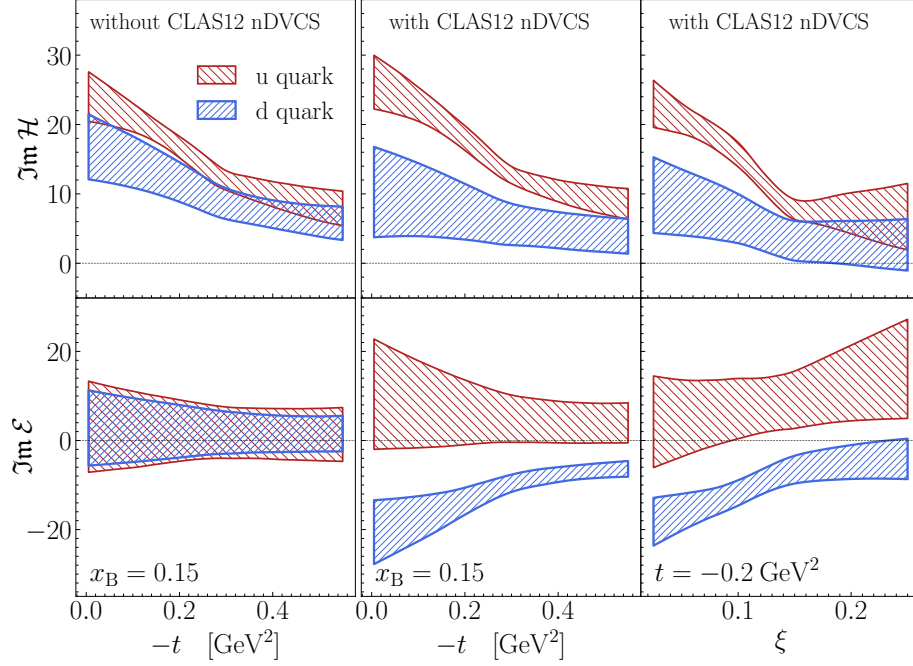


Fig. 12: Extraction of up (u , coarser shading, red) and down (d , finer shading, blue) quark contributions to $\Im\mathcal{H}$ (top) and $\Im\mathcal{E}$ (bottom) as a function of $-t$ (left and middle) and ξ (right). The leftmost column shows the extraction of the two CFFs without the CLAS12 nDVCS data, which are instead included in the other two columns.

The HERMES pDVCS and CLAS12 nDVCS data were also combined in a preliminary, model-dependent extraction of J_u and J_d , the quarks' angular-momentum contributions to the nucleon spin, shown in Fig.13. The blue, red, and beige bands are obtained from the comparison of the VGG model, in which the GPD E is parametrized directly by J_u and J_d , with, respectively, the HERMES data, the Hall-A nDVCS cross section differences, and the CLAS12 nDVCS beam-spin asymmetries. The CLAS12 results, albeit of limited statistical precision, provide a strong constraint on J_d . The RGH data can bring a comparable constraint on J_u .

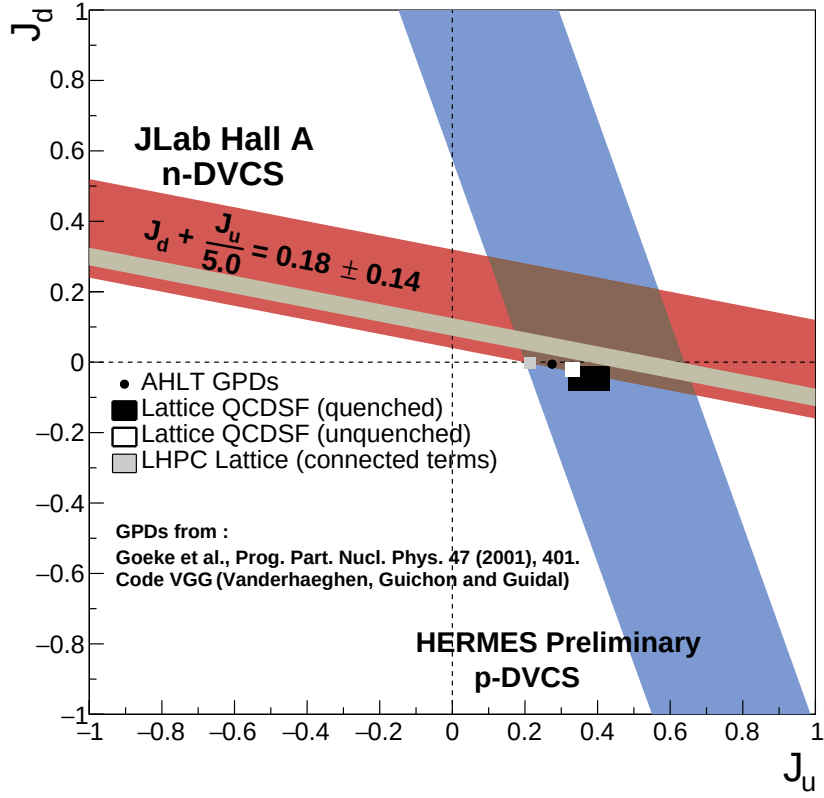


Fig. 13: Model-dependent extraction of J_u and J_d using the HERMES (blue band), nDVCS Hall A (red band) and nDVCS CLAS12 (beige band), results, compared to the predictions of the VGG model (original plot presented in [91], updated with CLAS12 results by M. Hoballah (A. Hobart))

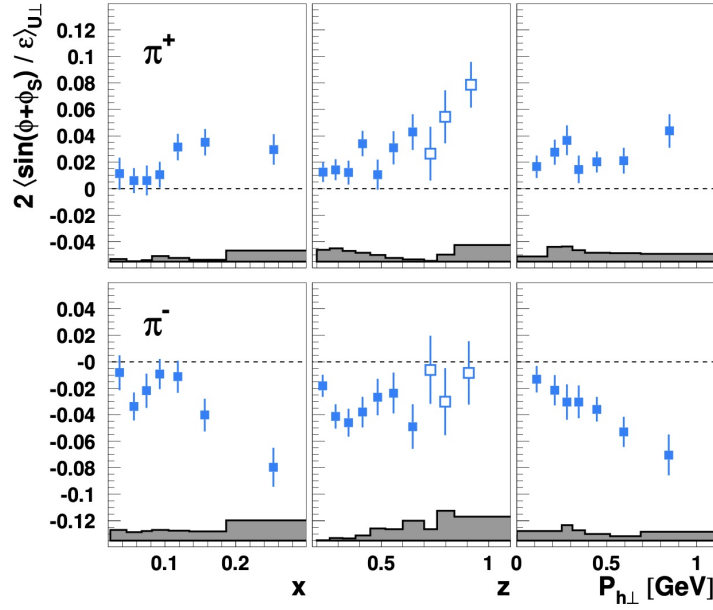


Fig. 14: Collins asymmetries for charged pions measured by HERMES either in bins of x , z , or $P_{h\perp}$. Data at large values of z , marked by open points in the z projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination. The plot is from [53].

1.3 Status and Main Competitors

There is evidence of the existence of compelling correlations between the parton degrees of freedom at the scale of confinement. These manifest in final-state particle correlations (typically azimuthal asymmetries with respect to a reference interaction plane) in high-energy scattering reactions. Such kind of phenomena have been confirmed in SIDIS, Drell-Yan, e^+e^- annihilation, and hadron-hadron collisions. Theory has made enormous progress in recent years in developing the proper interpretation framework based on novel parton distribution and fragmentation functions that account for the parton transverse degrees of freedom in space, momentum, and spin. Lattice calculations are steadily advancing [92, 93, 94, 95] and can offer benchmark quantities or complementary constraints to phenomenological models. Lepton scattering off a transversely polarized nuclear target provides the most sensitive configuration to a series of elusive parton distributions. However, such a measurement represents one of the most complicated challenges for an experiment, resulting in a general lack of precise data. New fully differential measurements, especially in the uncharted valence region, are instrumental in supporting such advances and moving toward a rigorous treatment that could lead to real predictive power.

The lepton-production of mesons off a transversely polarized target has been

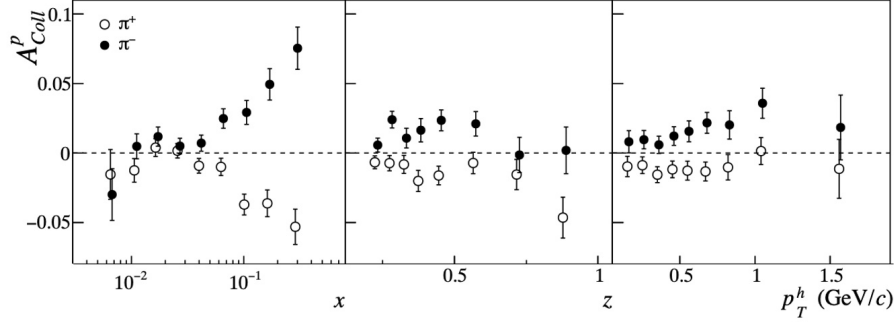


Fig. 15: The Collins asymmetries for charged pions measured by COMPASS on proton as a function of either x , z and P_{hT} . The figure is from Ref. [96].

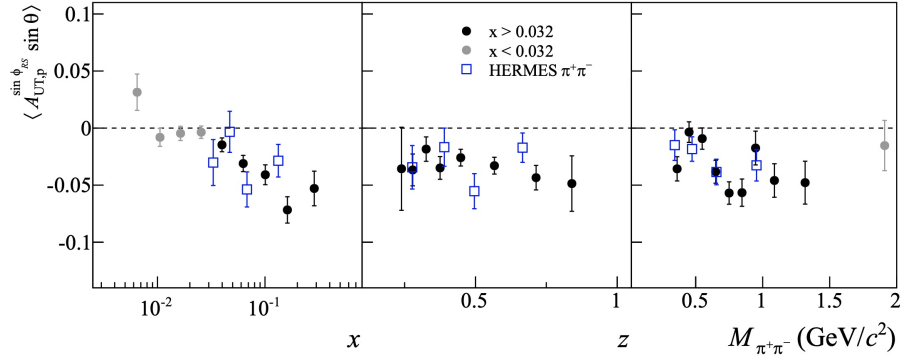


Fig. 16: Comparison of pair asymmetries measured by the HERMES [101] (blue open squares) with the results of COMPASS re-evaluated in the $x > 0.032$ region (black dots). The figure is from Ref. [97].

studied with seminal works at HERMES and COMPASS. These studies typically analyze one kinematical dependence at a time, integrating over all the others. Some reference examples are shown in Figures 14, 15, 16, and 17. Few new results have become available in recent times. COMPASS published the study on dihadron transverse-spin-dependent asymmetry on proton and deuterium targets [97], and the results on deuteron data from the 2022 run [98]. HERMES completed a 3D multidimensional extraction [53] and COMPASS a P_T -weighted analysis [99] of already published data. COMPASS presented a preliminary 3D multi-dimensional extraction [100] but the data have not been published.

It should be noted that all these results are limited to Bjorken x below 0.3. These results have been complemented by measurements on a transversely polarized ^3He target at Jefferson Lab [103, 55, 51, 104], extending into the valence region, but with a limited beam energy (6 GeV) and statistics, preventing a multidimensional analysis. No result achieves a fully differential analysis (4D) in all the relevant variables. COMPASS explored an extended range in (x, Q^2)

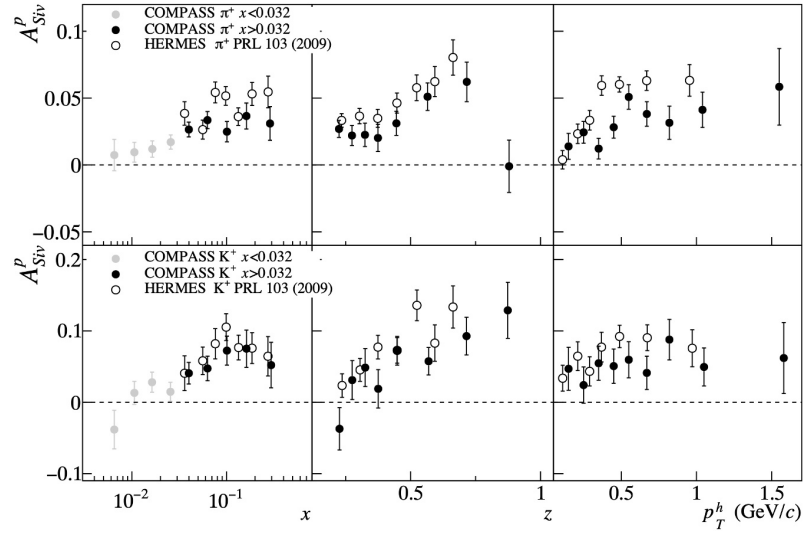


Fig. 17: Comparison of Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of x , z and $P_{h\perp}$ measured by HERMES [102], with the results of COMPASS requiring $x > 0.032$. The figure is from Ref. [96].

but integrating out the hadron variables ($z, P_{h\perp}$) [52]. Results involving kaons suggest intriguing distinctive features with respect to the pions, but the even more limited data set prevents a conclusive analysis [53].

The interest in data on transversely polarized targets is manifest from the steady flow of phenomenological analyses of the sparse SIDIS data collected in the past couple of decades, in conjunction with proton-proton, e^+e^- and Drell-Yan data, see Sections 1.1.1 - 1.1.3. These studies use data from BELLE [105, 106, 107], Babar [108, 109] and BESIII [110] to constrain fragmentation functions. Data on di-hadron production in hadron-hadron collision with one transversely polarized beam particle [111, 112] can be reliably used in the collinear framework. Data on inclusive asymmetries A_N in hadron production [113, 114, 115, 116] are sometimes used assuming a generalized factorization. Experimental data exist on Collins hadron-in-jet [117, 118] and A_N in jets [119, 118]. COMPASS published preliminary Drell-Yan data consistent with the fundamental QCD prediction of a sign change of naive time-reversal-odd TMD PDFs (i.e. Sivers) when comparing the Drell-Yan process with SIDIS [120]. A similar indication came from $W^\pm/Z$ vector boson production at STAR [121].

The multi-dimensional data from RGH precede the future measurements at the EIC [6, 7, 122] in a complementary kinematic regime, and are instrumental for supporting the progress of the theory framework in preparation of the EIC. The precise data of RGH will complement the information gathered from independent observables in hadron-hadron collision that are sensitive on valence x at higher Q^2 values. This is a part of the physics program at the upgraded STAR and sPHENIX [123], now running at RHIC, and at LHCspin [124, 125, 126], a project for a future polarized target internal to LHCb. At JLab, the SoLID

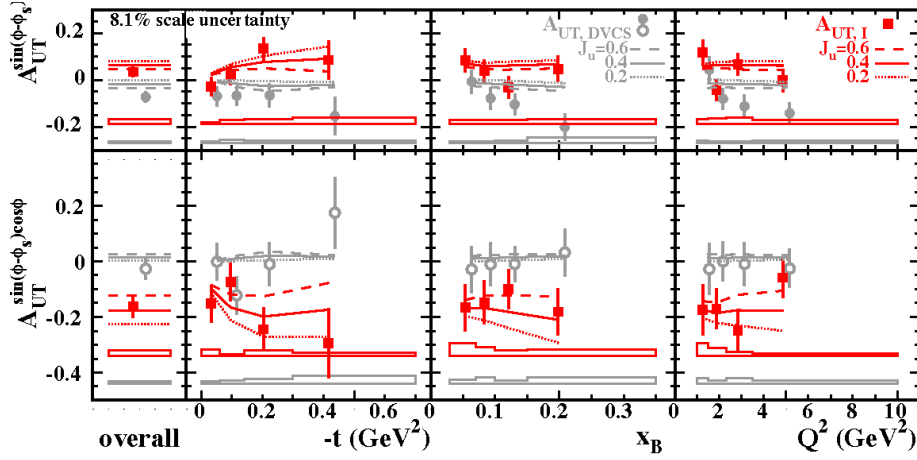


Fig. 18: Asymmetry amplitudes of the squared DVCS amplitude $A_{UT,DVCS}$ (circles) and the interference term $A_{UT,I}$ (squares). The error bars (bands) represent the statistical (systematic) uncertainties, excluding the 8.1% scale uncertainty due to the target polarization measurement uncertainty. The curves are predictions of the VGG model [129, 63, 130, 131], with three different values for the u -quark total angular momentum J_u and fixed d -quark total angular momentum $J_d = 0$ [132]. The figure is from Ref. [81].

experiment [127, 128] has been mentioned as a strategic opportunity in the 2023 Long Range Plan for Nuclear Science and is awaiting CD0. The high-luminosity experiment E12-09-018 on a transversely polarized ^3He target is awaiting a re-scheduling (and possible re-location) of the SBS experiment.

No new DVCS results on transversely polarized targets became available after the low-statistics, limited-coverage HERMES data were released, and the RGH experiment provides the only opportunity to overcome this lack of information. The DVCS results from HERMES [78] are presented in Figure 18, in the entire kinematics range ($\langle -t \rangle = 0.12 \text{ GeV}^2$, $x_B = 0.09$, $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$). The amplitudes $A_{UT,DVCS}$ and $A_{UT,I}$ for the same azimuthal dependence are shown together in each panel. The filled symbols represent the asymmetry amplitudes related to different coefficients of the BMK expansion. The amplitudes represented by the unfilled symbols are expected to be suppressed, and are indeed found to be typically small. The amplitudes $A_{UT,I}^{\sin(\phi-\phi_S)\cos(n\phi)}$, $n = 0, 1$ were found to have substantial magnitudes with opposite signs but with little kinematic dependence. The overall result of the amplitude $A_{UT,DVCS}^{\sin(\phi-\phi_S)}$, shown in the top row of Figure 18, is non-zero by 2.8 times the total uncertainty. The amplitude $A_{UT,DVCS}^{\sin(\phi-\phi_S)\cos\phi}$, expected to be suppressed, was indeed found to be small. Therefore, the HERMES data present kinematic dependencies of moments of A_{UT} on one variable at a time, integrating on the others. The RGH data will instead allow a first-time extraction of the full ϕ dependence of the DVCS TTSA in 4-dimensional bins (Q^2 , x_B , $-t$, ϕ), and will cover a much wider phase space than the one spanned by HERMES. This will be presented in detail in Section 5.

2 Experimental Details

The RGH experiment exploits the CEBAF high-quality beam [133] in conjunction with the large acceptance CLAS12 spectrometer [134] in Hall B, complemented by a transversely polarized target (see Sec. 3.1) and a dedicated recoil detector (see Sec. 3.3).

2.1 CLAS12 Spectrometer

The CLAS12 spectrometer has been designed to run at high luminosity, up to about 3 orders of magnitude higher than the precursor experiments like HERMES and COMPASS, and bring the 3D nucleon structure studies into the precision phase. CLAS12 started taking data with unpolarized hydrogen targets in spring 2018 and has been running successfully since, with different targets and detector configurations. In particular, CLAS12 successfully ran with longitudinally polarized NH_3 and ND_3 targets in 2022-2023. Detailed calibration procedures and event reconstruction algorithms have been developed to reach performances close to, or in some cases superior of, the design specifications.

2.1.1 Forward Detector

With respect to the goals of Run-Group H, the CLAS12 spectrometer has specifically demonstrated to be able to achieve the following performances:

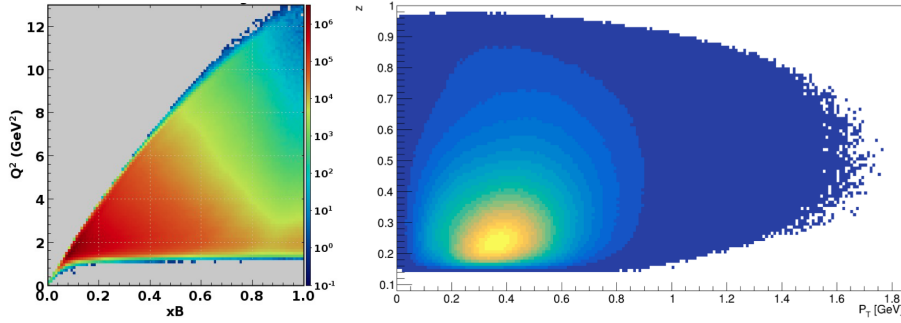


Fig. 19: The CLAS12 reach in the relevant kinematic variables at a beam energy of 10.6 GeV. (Left) Inclusive electron coverage in the hard scale Q^2 versus Bjorken x . (Right) Charged hadrons coverage in the transverse momentum P_T versus the fractional energy z .

Tracking The single-track forward reconstruction efficiency has been improved with the implementation of Machine-Learning algorithms to support effective denoising and track segment finding, to a level better than 90% at the design luminosity of $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, with a dependence on the beam current of $98 - 0.1 \times I(\text{nA})$ percent. The typical measured resolutions in the relevant kinematic quantities are $\sigma_p/p = (0.5 - 1.5)\%$ and $\sigma_\theta = 1 - 2 \text{ mrad}$ [134].

Scattered Electron The efficiency of the CLAS12 trigger for DIS events, with the electron scattered inside the acceptance at an energy above 1.5 GeV,

is greater than 99% [135]. Electrons are identified by a combination of signals in the Cherenkov counters and calorimeters. Thanks to the large acceptance of CLAS12, scattered electrons are detected in a wide kinematic range from elastic events to DIS, with an extended reach at large values of Q^2 , Bjorken x , and forward hadron kinematics (see Fig. 19).

Exclusive events Event selection and background suppression have been successfully achieved in the CLAS12 environment. The large amount and variety of collected data and the gained experience provide a solid ground for any new development. The DVCS final state in the $ep\gamma$ topology has been successfully extracted from the NH_3 and ND_3 data of Run Group C, taken with the longitudinally polarized target (two analyses are in the final stages). An interesting study is ongoing to exploit Machine-Learning techniques for the identification of exclusive DVCS events based on the electron and photon information provided by the CLAS12 Forward Detector with no (or partial) recoil proton information: promising results have been obtained on RGA data, with increased statistics and comparable physics observable with respect to the traditional analysis based on a complete recoil reconstruction. In the case of RGH, such a technique can provide a systematic check for the standard DVCS analysis in the $ep\gamma$ topology, and extend its kinematical coverage beyond the acceptance of the recoil detector.

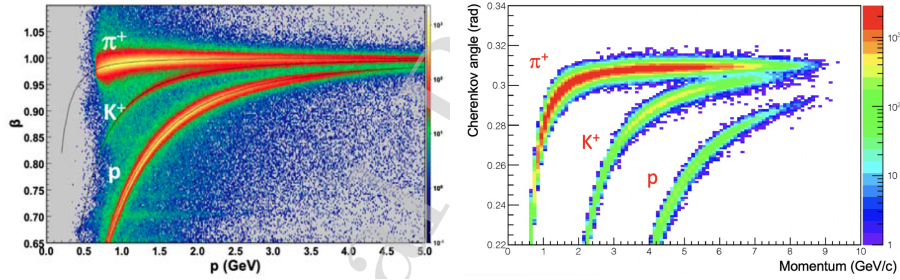


Fig. 20: (Left) The hadron separation provided by the Forward Time-Of-Flight system. (Right) The hadron separation obtained by the RICH detector.

Hadron PID Identification of hadrons is essential to gather flavor information in SIDIS observables. The CLAS12 Forward Time-Of-Flight system (FTOF) provides excellent pion separation from kaons and protons at momenta up to about 2 GeV/c and 5 GeV/c [136], respectively, see left panel of Fig. 20. To complement the CLAS12 baseline configuration and provide hadron separation in the whole range of interest for SIDIS physics, up to momenta of 8 GeV/c, a ring-imaging Cherenkov detector (RICH) has been realized. The first module was installed in 2018 before the start of CLAS12 data taking and the second module completed in 2022 before the start of the RGC polarized target run [137]. Data analysis shows that the CLAS12 RICH is able to achieve a time resolution of ≈ 0.7 ns and a Cherenkov angle resolution of ≈ 1.5 mrad [138], matching specifications, and provide hadron separation in the wanted momentum range, see right panel of Fig. 20.

2.2 Beamline Elements

The standard beamline equipment in Hall B comprises position, current, and halo monitors, connected to the interlock system. Among the Beam Position Monitors (BPMs), three nA BPMs, (2C21 at the beginning of the tunnel, 2C24 at the end of the tunnel before the hall proper, and 2H01 on the space frame), measure beam transfer (x,y) position relative to their center as well as the beam current. The stripline BPMs (2H00 close to the target and other on the upstream tunnel) measure the beam position but are reliable only for beam currents above 25 nA and will not be used by RGH. The position monitor 2H01 (together with 2H00 if the current is high enough) close to the interaction region is the most important one to keep the beam position steady on the target. A feedback system (the orbit locks) uses (x,y) positions on this BPM, and the Horizontal and Vertical correctors on 2C22/2C23/2H00 girders to keep the beam position stable.

The Hall-B Faraday cup provides an instantaneous beam current reading. It is not cooled and cannot operate at high currents but works fine at 1 nA, with an integrated rate of 906.2 counts/sec. The Synchrotron Light Monitor (SLM) measures the amount of synchrotron light generated by the electron beam in the magnetic field of the last dipole right before the Hall-B upstream tunnel. The main use of this current monitor is to measure the helicity-related beam intensity (charge) asymmetry, but can be used for beam-charge accounting if needed.

The beam-halo counters consist of photomultiplier tubes with plastic attached to their photocathodes strapped to the beam pipes along the beamline. The rates in halo counters are good indicators of the beam transport quality. In addition to the halo counters, there is a beam offset monitor (BOM) just upstream of the target.

The CLAS12 beamline has already operated at a beam current of 1 nA. Some specific monitors cannot work at such a low beam current, but there is enough redundancy in current and position monitors to ensure normal operation and safe control. The same beam raster utilized for the RG-C operation will be used (note that the target material is the same), with a radius envelope of 6.5 mm and a frequency of 1 Hz.

3 Required Equipment

3.1 Transverse Target

The experiments described here will utilize a new, dynamic nuclear polarized (DNP) target of solid ammonia (NH_3), specifically designed to operate inside the CLAS12 High Threshold Cherenkov Counters (HTCC). The ammonia samples will be continuously polarized using microwave-induced spin-flip transitions at a temperature of 1 K and in a 5 T magnetic field. Similar target systems have been used with success at JLab in experimental halls A, B, and C [139, 140, 141] and with electron beam currents up to 140 nA. Most recently, a longitudinally polarized target of NH_3 and ND_3 was used for the Run Group C experiments with CLAS12 [142]. In this system, the 5 T polarizing field was provided by the CLAS12 solenoid, which will be removed for Run Group H in order to install a 5 T split-coil magnet with a vertical field orientation. While the magnetic field

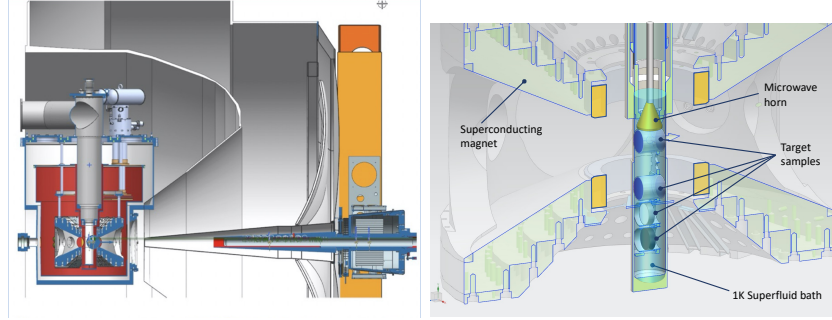


Fig. 21: Left: Conceptual design showing the dynamically polarized target at the center of the CLAS12 HTCC. Right: Closeup of target samples suspended in superfluid helium.

requirements for frozen-spin polarized targets are less stringent, beam heating and radiation damage exclude their use in the CEBAF electron beam [143]. One advantage of DNP is that the target's polarization direction can be made parallel or anti-parallel to the applied field by a slight adjustment of the microwave frequency. Reversing the polarization typically requires less than four hours.

The target considered here will resemble a compact version of the system used in Hall C and Hall A and most recently described by Pierce *et al.* [139]. A vertical ladder suspends multiple target cells into a pumped bath of superfluid helium at 1 K (Fig. 21). For the RGH experiments, the ladder will have two cells ($\varnothing 1.5 \times 2.0$) cm³ filled with 1–2 mm granules of frozen ammonia (0.87 g/cm³), an empty cell, as well as carbon and polyethylene (CH₂) samples for background and dilution studies. As has been the case for the Hall A and C polarized targets, small NMR coils will be located inside the ammonia cells to measure the proton polarization with a relative accuracy of about 4%. The coils are fabricated from 1 mm capillary surrounded by a teflon sleeve, and reduce the filling factor of the cells by a few percent. The cells are machined from PCTFE, a fluorinated plastic that is transparent to the 140 GHz microwaves for polarizing the ammonia but does not produce a background proton NMR signal. Thin aluminum windows are glued to their upstream and downstream faces. The superfluid bath is constrained by a thin-walled aluminum tube. The superfluid and aluminum windows contribute to the overall scattering at the level of about 25% (Table 1).

Liquid helium to the target will be supplied by the Hall B buffer dewar and pumped to a vapor pressure of approximately 0.1 torr by a set of high-capacity Roots pumps. Each target cell will contain about 2 g of solid ammonia and will require less than 0.5 W of microwave power for optimum polarization. Heat from the 1 nA beam will deposit less than 10 mW.

The 5 T superconducting magnet will be similar in design to the split-coil magnet intended for transversely polarized target experiments in Hall C. Unfortunately, this magnet was designed for a horizontal field orientation and cannot provide the 60° aperture for scattered protons that is needed for the DVCS portion of this proposal. The superconducting windings of the new magnet will be identical to those of the existing magnet but will be separated by an aluminum frame with a more favorable geometry for RGH. The magnet and 1 K refriger-

Item	Number	Material	Density g/cm ³	Length cm	Thickness g/cm ²
Bath windows	2	AL7075	2.81	0.01	0.056
Superfluid	2	He-II	0.14	0.2	0.058
Cell Windows	2	AL6061	2.70	0.003	0.016
Ammonia	1	NH ₃	0.52	2.00	1.04
Superfluid	1	He-II	0.06	2.00	0.12

Tab. 1: Materials in the beam around the polarized target. The first superfluid entry corresponds to liquid helium outside the target cell, and the second to liquid inside the cell. The density of materials inside the cell have been adjusted for an ammonia packing fraction of 0.6.

ator will be housed in a vacuum chamber with a thin aluminum exit window matching the aperture of the magnet (Fig. 48).

Based on previous experience at JLab, proton polarizations of 90% or higher can be expected. Radiation damage from the electron beam slowly destroys the polarization, and so the beam will be rastered over the face the target to reduce this effect. After a dose of about $2.5 \times 10^{15} \text{ e}^{-1} \text{ cm}^{-2}$, the damage can be partially repaired by annealing the sample to about 90 K for several minutes (Fig. 23). Assuming a beam current of 1 nA and a raster diameter of 1.3 cm, an ammonia sample can last approximately six days before annealing is necessary. With two ammonia samples on the ladder, anneals will take place after about 14 days of beam. This process can be performed *in situ* and remotely, using heaters inside the target cryostat, and will require about 4 h with polarization recovery.

However, the annealing procedure becomes progressively less successful, and the ammonia must be replaced after about five or six anneals. With two ammonia samples on the ladder, this corresponds to about 70–80 days of beam before the ladder must be replaced.

Due to a lack of overhead space, the target cryostat must be removed from the HTCC in order to remove and replace the target ladder. For this purpose, it will be attached to a cart mounted on the Hall B rail system, as has been the case with nearly all target systems utilized with both CLAS and CLAS12, including polarized targets. The cryostat only needs to be retracted about 60 cm in order to access and remove the sample ladder, but this could require significant disassembly of some beamline components. We make the conservative estimate that up to 48 h will be needed to perform this operation, and it will be performed twice.

The target polarization will be measured using the standard method of continuous-wave NMR, in which the polarization is proportional to the area under the NMR absorption signal (Fig. 24). The constant of proportionality is determined by measuring the signal using a sample of known polarization. This is achieved by allowing the sample spins to come into thermodynamic equilibrium with the superfluid bath, in which case the polarization is given by Maxwell-Boltzmann statistics as $\tanh(\mu_p B/kT)$, where μ_p , B , k , and T are the proton magnetic dipole moment, the field strength, Boltzmann constant, and bath temperature, respectively. These “thermal equilibrium” (TE) calibrations should be performed routinely to reduce the systematic error on target polar-

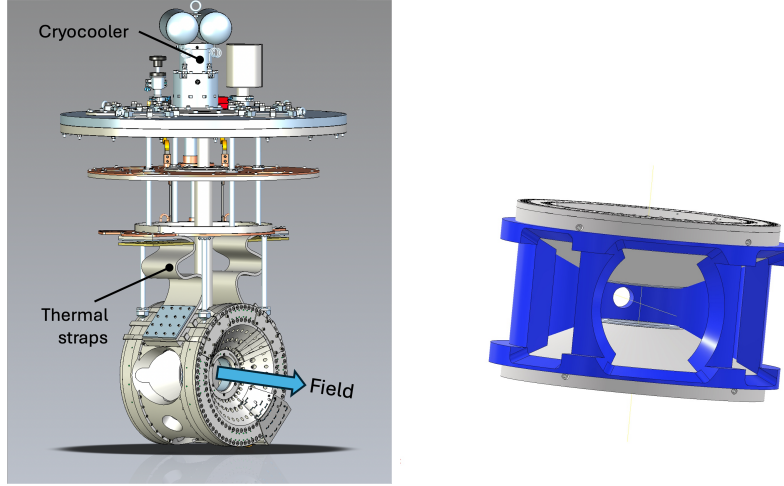


Fig. 22: Left: Superconducting magnet for polarized target experiments in Hall C. The magnet has been successfully tested to 5 T at Jefferson Lab. Right: Conceptual redesign of the magnet coils with a different intercoil support (green) for RGH. The opening in the forward directions for scattered particles spans $\pm 60^\circ$ in the horizontal plane and $\pm 25^\circ$ in the vertical. The magnet is rotated to produce a vertical field.

ization. Because the proton's TE polarization is quite small (0.5% at 5 T and 1 K), significant signal averaging is needed for an accurate measurement. We envision making the calibrations once per week, requiring eight hours.

We calculate the overhead associated with these target operations over the course of a 120 day (17 week) experiment with the assumptions listed below and find a total of about nine days. We anticipate that the overhead can be reduced by coordinating these operations with scheduled CEBAF beam study and maintenance periods.

- TE calibrations (with polarization recovery) will be performed every week, requiring eight hours. Total number: 17. Total time: 136 h
- Anneals (with polarization recovery) will be performed once every two weeks, requiring four hours. Total number: 8. Total time: 32 h.
- The target ladder will be replaced two times, requiring 24 hours. Total time: 48 h.
- Total overhead: 216 h (9 days)

An idealized two-week (42 shift) operational sequence that is based on these estimates is given below. In this scenario, background measurements constitute about 15% of the beam time. Polarization loss due to radiation damage is partly compensated by spending less time with the initial target polarity and reversing the order of the polarity for the second ammonia target.

- 8 shifts, + polarity with Ammonia target #1;
- 9 shifts, - polarity with Ammonia target #1;

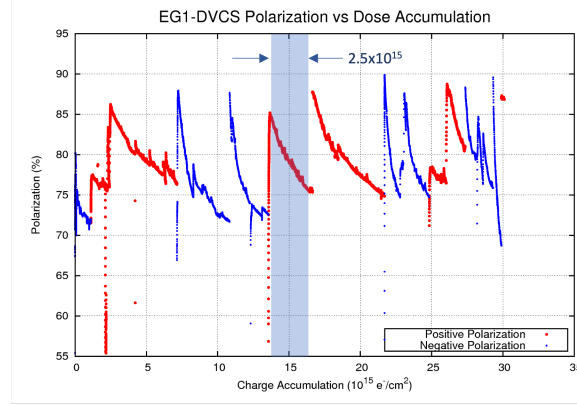


Fig. 23: Performance of the 6 GeV CLAS polarized target during the EG1-DVCS experiment. The shaded band indicates a depolarizing dose of $2.5 \times 10^{15} \text{ e}^{-1} \text{ cm}^{-2}$.

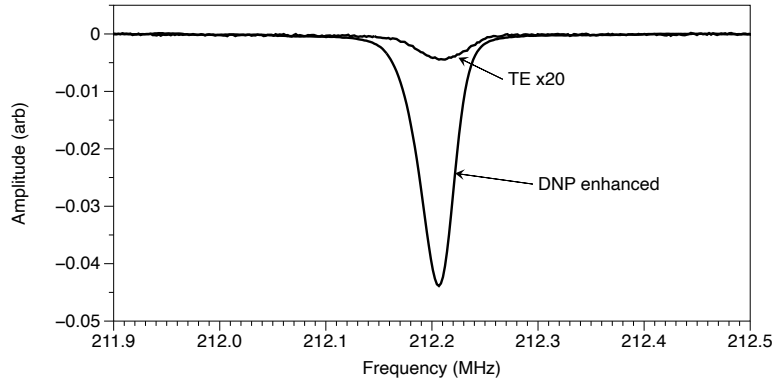


Fig. 24: NMR signals for protons in thermal equilibrium (TE) at 1 K and enhanced by DNP to approximately 90%. The TE signal is multiplied by twenty for clarity.

- 3 shifts, background studies (C, CH₂ or empty);
- 1 shifts, TE calibration;
- 8 shifts, - polarity with Ammonia target #2;
- 9 shifts, + polarity with Ammonia target #2;
- 2.5 shifts, background studies (C, CH₂ or empty);
- 1.5 shifts, Anneal + TE calibration;

3.2 Beam Chicane

The 5 T polarizing field of the target is transverse to the beam. Its integral of 1.64 Tm implies a deflection of 2.15 degree for 10.6 GeV beam particles. A

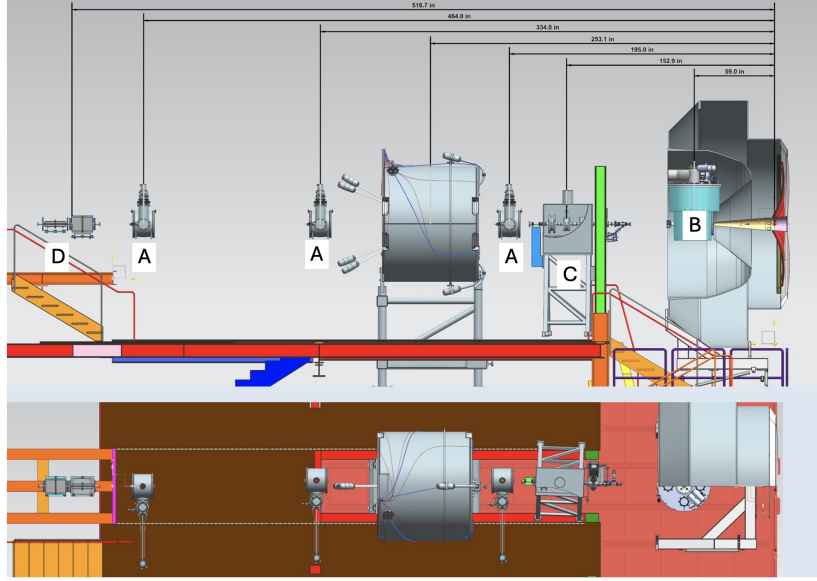


Fig. 25: Preliminary layout of the chicane (A) used to compensate the beam bending of the target holding magnet (B). The second raster pair (D) will be moved upstream to save space for the 2H01 BPM (C).

magnet chicane has been designed in order to compensate such a bending and ensure that the non-interacting particles pass by the experiment, and reach the Hall-B dump within the downstream vacuum pipe, without further interactions.

The chicane needs to be compact to fit within the constrained space of the Hall-B beamline. A workable solution has been outlined that is compatible with the other beam elements and the CLAS12 solenoid, when the latter is moved into a park position, see Figure 25. It can be realized with commercially available superconducting 7.5 T split-pair magnets, e.g from CryoMagnets Inc. [144]. With respect to items in stock, minor modifications are required: a change of orientation of the cooling head and a widening of the cryostat bore in the bending plane. The field uniformity is sufficient to avoid beam orbit perturbations even accounting for a rastered beam with a radius envelope of 7 mm, see Section 2.2.

The beam chicane generates synchrotron radiation upstream of the detector. According to analytic estimates and past experience, no real issue was anticipated. Nevertheless, a dedicated study has been carried out with GEANT simulation. The chicane model has been implemented in the GEMC framework used by CLAS12, see Figure 26. The field of the chicane magnets has been rescaled (down) to match the same field integral of the target magnet. The central magnets have been moved off axis by 13 cm to align with the bended beam. Simulations show that beam particles are transported through the chicane along the expected trajectory, impinge on the target at the desired angle, and align downstream to the axis of the CLAS12 vacuum pipe, see Figure 27. The photons are generated in the bending sections of the line (where a significant magnetic field is present) and span a horizontal flare that could extend

into CLAS12 in the absence of any material. The beam pipe itself, plus 15 mm lead shield in the relevant positions, are enough to effectively suppress the synchrotron photons generated upstream. The vast majority of the synchrotron radiation generated close to the interaction region is trapped inside the downstream CLAS12 vacuum pipe. The 1% surviving fraction escapes the vacuum pipe due to rescattering. This amounts to an $O(1 \text{ GHz})$ photon flux distributed over the entire multi squared-meter surface of the CLAS12 Forward Detector, see Figure 28. Simulations show that this flux does not generate any significant background in the experiment, as expected by its low-energy spectrum peaked at 0.1 MeV.

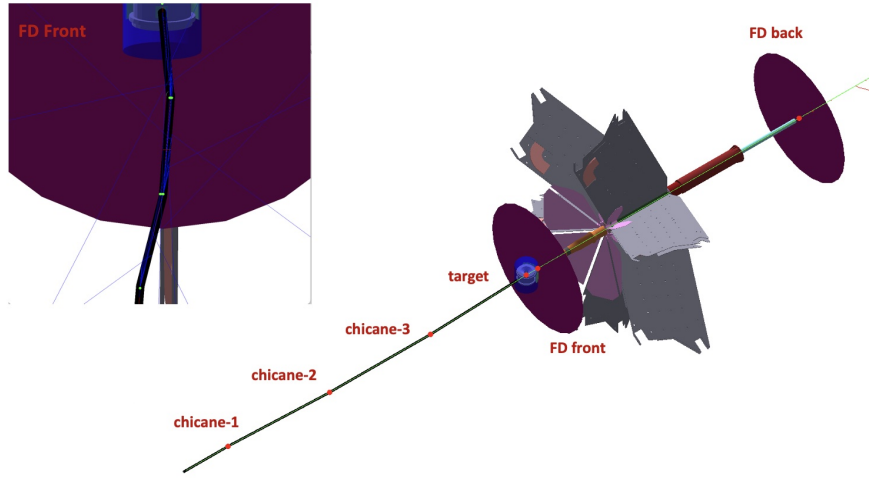


Fig. 26: The magnet chicane implemented in the CLAS12 GEMC simulation framework. The passing particles are recorded by flux planes at the magnet locations, and on the front and back faces of the CLAS12 Forward Detector (only the torus magnet structure is visible for simplicity). The insert shows a section of the beam pipe, with the synchrotron photon trajectories shown in blue.

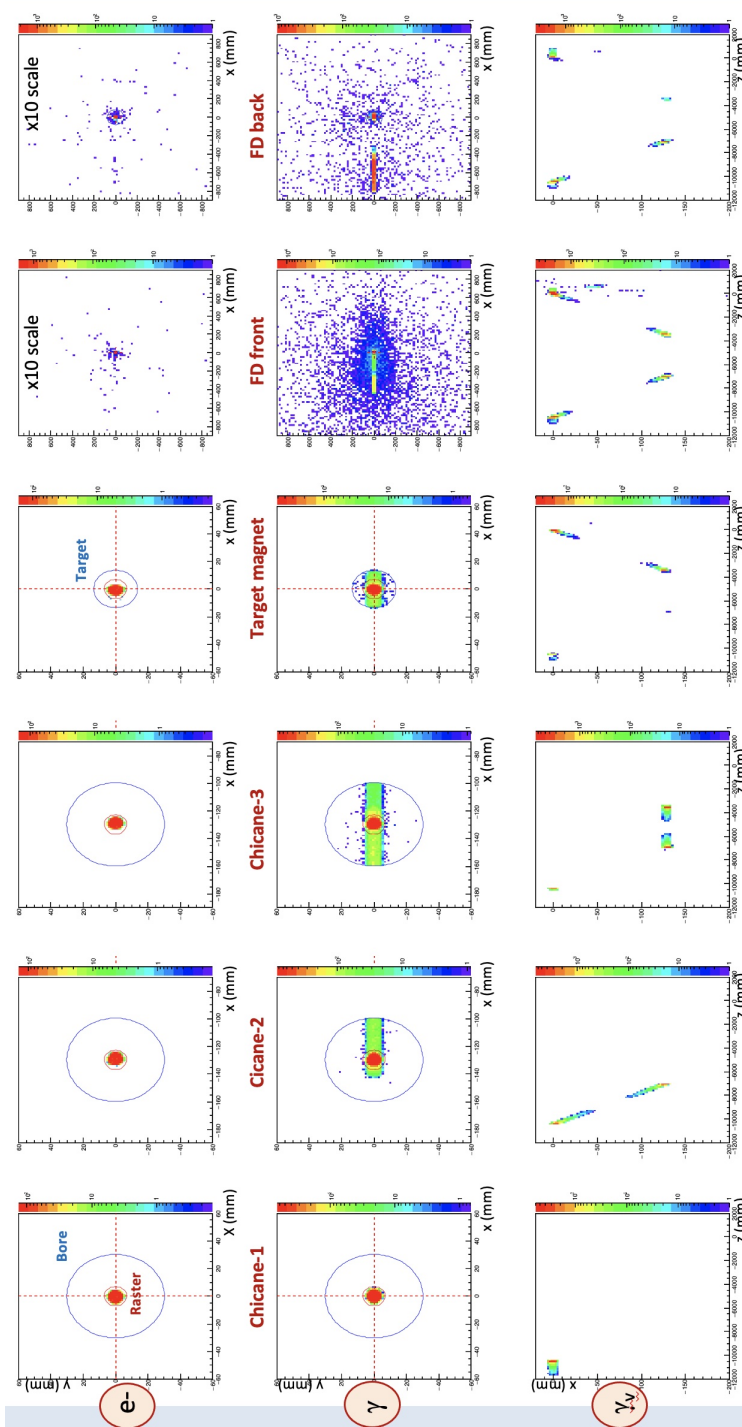


Fig. 27: First and second row: spatial distribution of the beam particles on relevant planes along the CLAS12 beamline. Along the row: center of the first, second and third chicane magnets, center of the target magnet, front and back face of the CLAS12 Forward Detector. Third row: emission point of the synchrotron photons impinging on the same planes above. The electron beam particles are transported through the chicane along the expected trajectory (first row). The synchrotron photons create a horizontal flare (second row) because emitted (at a varying angle) in the bending sections of the beam line (third row). The beam pipe and shielding have been removed to allow free flight of particles.

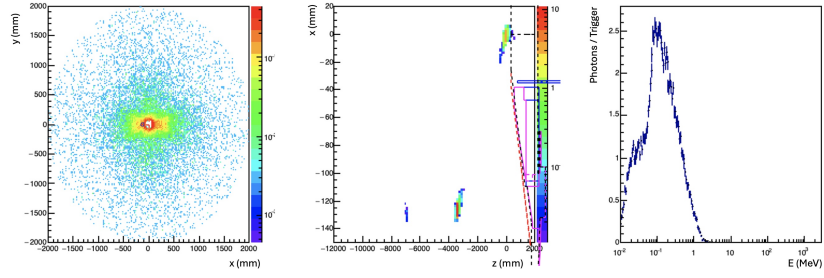


Fig. 28: Spatial distribution at the front of the CLAS12 Forward Detector (left), emission vertex position (center) and energy spectrum (right) of the synchrotron photons escaping the beam pipe and a 15-mm lead shielding. The last panel is normalized to the number of triggers, i.e. data acquisitions with a gate of 252 ns at the RGH luminosity.

3.3 Recoil Detector

The chosen target magnet structure provides open acceptance in the angular region favored for recoil detection, up to 70 degrees (and beyond, thanks to the magnet bending). Protons below 30 degrees are detected in the CLAS12 Forward Detector. In order to detect protons at larger angles, a dedicated recoil detector will be implemented exploiting the left and right openings in the magnet structure. In each side, a simple geometry based on four detection planes (three tracking planes and one time-of-flight (TOF) plane) is anticipated. The solid-angle coverage should match the magnet apertures and span ± 25 degrees vertically and 29 degrees horizontally, leaving a blind central region of ± 40 degrees. The distance from the center of the target is chosen to optimize acceptance within the clearance of the CLAS12 HTCC (see Table 2).

Plane	Name	Distance from IP (mm)	Width (mm)	Height (mm)
1	Tracker Region 1	440	230	420
2	Tracker Region 2	720	380	670
3	Tracker Region 3	1000	530	920
4	Time-of-flight	1180	650	1100

Tab. 2: Dimensions of the RGH recoil detector planes covering the magnet apertures on the left and right side of the target.

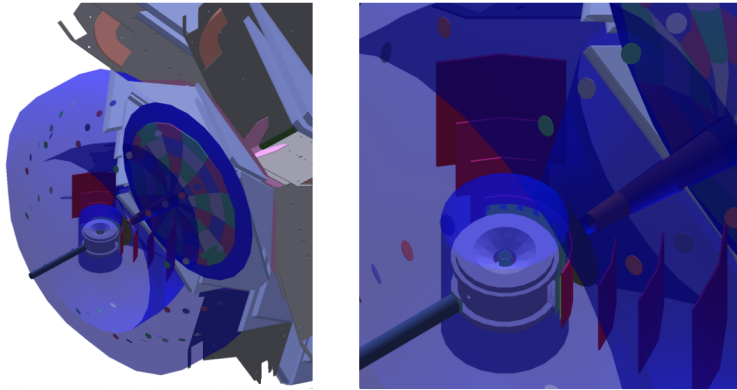


Fig. 29: Concept of the RGH recoil detector in front of CLAS12 HTCC detector.

Such a detector does not pose a specific technological challenge. It can be derived from developments with comparable spatial and time resolution that are already underway for the CLAS12 upgrade in luminosity and for the ePIC detector at EIC. The area to cover is limited, resulting in a manageable number of readout channels, of the order of 10k for tracking and 1k for TOF, see Sec. 3.3.3. The development effort and construction costs can be minimized by borrowing part of the readout electronics.

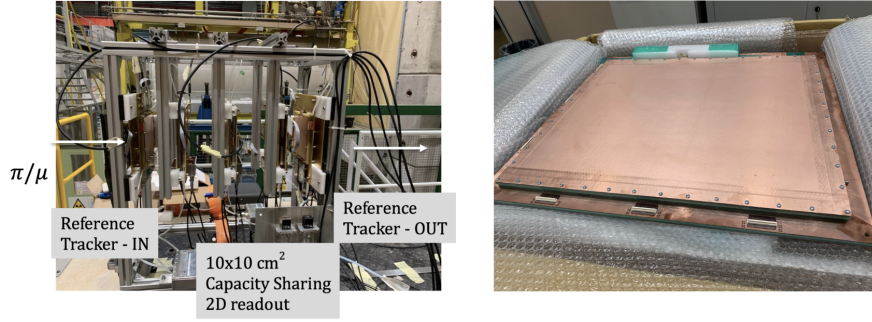


Fig. 30: Setup used for testing the μ Rwell performance during a test-beam at the SPS North Area H8C at CERN in June 2023 (left). Large area $40 \times 46 \text{ cm}^2$ μ Rwell prototype with a 2D anode readout.

The tracking detector can be derived from the ongoing CLAS12 high-luminosity and ePIC tracking projects based on the μ Rwell technology (Sec. 3.3.1). Several $10 \times 10 \text{ cm}^2$ prototypes have been produced at INFN with 2D reading layout of $\approx 0.5 \text{ mm}$ strip pitch, approaching a spatial resolution close to $100 \text{ }\mu\text{m}$ and a time resolution better than 10 ns , see Fig. 30 (left). The maximum width of the current μ Rwell foils is 620 mm and therefore compatible with the RGH dimensions. A large area $40 \times 46 \text{ cm}^2$ prototype with a 2D capacity sharing readout has already been realized and is now being tested (Fig. 30 right). The readout can be largely borrowed from the readout of the GEM chambers produced at INFN for SBS in Hall A, that are currently stored as spares but will become available after the SBS run. This readout is based on the APV25 chip, the chip used for the ongoing μ Rwell prototype tests. As a backup solution, the readout under study for the high-luminosity project, based on the VMM3 chip, can be adopted.

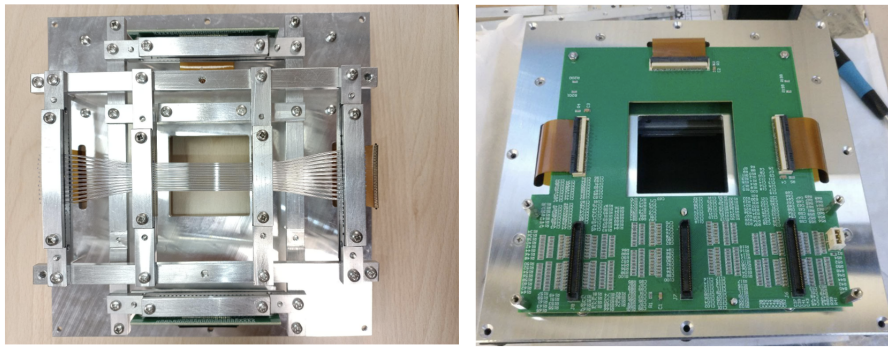


Fig. 31: The scintillating fiber tracking prototype under construction.

To improve the time resolution to a sub-ns level, a plane of scintillating bars readout by SiPMs can be used. Scintillating technology is already well in use at CLAS12 for the Forward and Central Time-Of-Flight systems (FTOF and

CTOF) and the Central Neutron Detector (CND). The SiPM sensors offer a compact and cost-effective solution that is insensitive to magnetic fringe fields. Resolutions better than 100 ps have been obtained with fast scintillating rods a few millimeters thick, 10 mm wide, and of variable length [145, 146]. Prototypes based on fibers and rods are being realized at INFN, see e.g. Fig. 31 (left). The readout can be derived (and largely borrowed) from the one of the CLAS12 RICH detectors, based on the MAROC3 chip, see Fig. 31 (right). This readout has already been successfully used with SiPM matrices for detecting signals down to a few photo-electrons, achieving a single-photon time resolution of 0.5 ns, largely driven by the FPGA settings. A new firmware is available to push the time resolution to better than 100 ps, provided that a proper clock distribution is implemented, as achieved by the ALERT readout. As an alternative, minimal front-end electronics can be designed to match the ADC/TDC readout modules of the CLAS12 timing detectors that are not in use during RGH (CND, CTOF), although this may limit the total channel number.

3.3.1 μ Rwell Tracking

The modern photolithographic technology on flexible and standard PCB supports has allowed the invention of novel and robust micro-pattern gas detectors (MPGDs), such as GEM [147], THGEM [148, 149] and Micromegas [150]. These detectors exhibit good spatial and time resolution, high rate capability, large sensitive area, flexible geometry, good operational stability and radiation hardness. However, due to the fine structure and the typical micrometric distance of their electrodes, MPGDs generally suffer from spark occurrence that can eventually damage the detector. The micro-Resistive WELL (μ Rwell) is a compact, simple and robust MPGD developed for large area applications requiring the operation in harsh environment [151]. The detector amplification stage, similar to a GEM foil, is realized with a polyimide structure micro-patterned with a blind-hole matrix, embedded through a thin Diamond-Like-Carbon (DLC) resistive layer with the readout circuit board (PCB). The introduction of a resistive layer mitigates the transition from streamer to spark and gives the possibility to achieve large gains ($> 10^4$) in the presence of high particle rates (up to 10 MHz/cm²) [152].

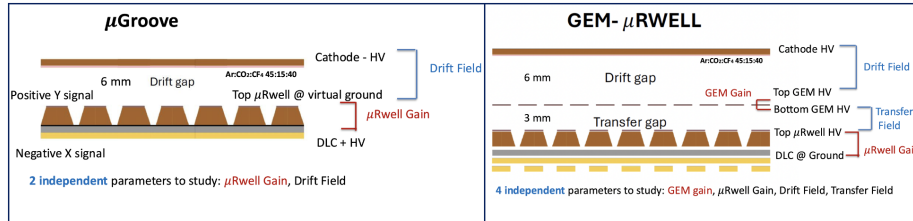


Fig. 32: Alternative architecture under test for obtaining a 2D readout within the same μ Rwell chamber: Split cathode with a micro-groove plate (left) and GEM- μ Rwell COMPASS-like stack (right).

The μ Rwell technology aims to provide micro-pattern gas detectors with performance similar to GEMs but more robust architecture against sparks thanks

to the resistive cathode layer. It was originally developed at INFN and is currently under study for the high-luminosity upgrade of CLAS12 and for the inner tracking of ePIC at EIC. The ongoing R&D at INFN has goals that are consistent with the RGH requirements. These are time resolution better than 10 ns, space resolution better than 150 μm , efficiency greater than 95%, low material budget (of the order of 1% χ_0). Different solutions are being studied to obtain an optimized 2D (x, y) strip readout within the same chamber with a discrete pitch dimension (of the order of 0.5 mm to contain the number of channels) and sufficient gain. Prototypes have been realized to test the realistic performance in lab and with beam tests. Prototypes of $10 \times 10 \text{ cm}^2$ have been tested in pairs to compare the relative performance. Large prototypes of $40 \times 46 \text{ cm}^2$ area, comparable with the RGH needs, were also successfully produced. Among the tested options, there is a capacitive sharing readout, a top-segmented readout with a segmentation of just the copper layer of the multiplication stage, or the μGroove readout with a fully grooved multiplication stage, see Fig. 32 (left). They typically meet the specifications only at voltages above 600 V, when the chamber becomes unstable. Promising results have been obtained with a GEM- μRwell COMPASS-like readout, see Fig. 32 (right). In the latter case, a gain of $5 \cdot 10^4$ and an efficiency of 97% was obtained at safe voltages around 550 V. The efficiency was measured to be pretty uniform throughout the detector surface.

The μRwell readout has been studied with the reference APV25 chip that has been a standard for several years [153]. The APV25 is a 128-channel analog pipeline chip that provides signal sampling with a typical time bin of 25 ns. The basic time information is provided by the sample with the maximum signal amplitude. In order to improve the time resolution, an analysis of the signal shape of all the recorded samples is required. In this case, a time resolution comparable or better than 5 ns can be obtained. In the basic charge-centroid method, the centroid of the cathode signals is used to estimate the position of the impinging particle. It is typically accurate only for trajectories close to 90 degrees with respect to the tracking plane. The μTPC method attempts a more sophisticated analysis to infer the particle angle from the distribution in time and space of the distributed anode signals. It requires adequate time and space resolutions to properly correlate the information. This was demonstrated with the GEM- μRwell prototypes readout by APV25 at the CERN test beam, see Fig. 33.

The RGH baseline solution is an architecture based on the well-known APV25 chip and derived from the existing GEM tracker development for Hall-A SBS. The front-end APV card mounting the chip features 128 analog channels, 40 MHz (25 ns) signal sampling, up to 130 analog sample pipeline per channel, up to 3.4 μs trigger latency, and 100 kHz rate multiplexed readout, see Fig. 34. Up to 16 APV cards (2048 channels) can be connected via HDMI cables to a single MPD VME board. The MPD mounts an Arriga GX FPGA with 128 MB DDR2-RAM and provides FIR filter, common mode and pedestal subtraction, zero suppression, remote configuration, and 2 ns trigger resolution, see Fig. 35. Up to 32 MPDs can be connected to a single SSP module via optical fiber links. The SSP module has been developed by the JLab fast-electronics group and is already in use in CLAS12 for the RICH readout.

The SBS readout electronics and firmware have been developed by INFN in collaboration with JLab. INFN has available at JLab more than 270 APV cards (35000 channels) and 24 MPD boards that can be re-allocated after the end of

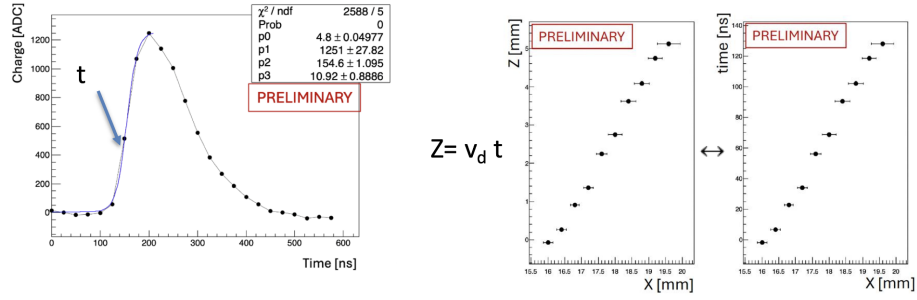


Fig. 33: Example of fit of the μ Rwell sampled signal to maximize the time resolution (left) and correlation in time and space obtained with the μ TPC method (right).

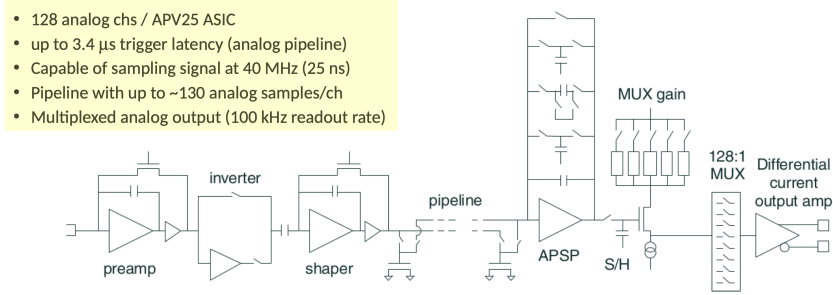


Fig. 34: The APV25 chip logic diagram and main features.

the SBS run. INFN also has available one VME/VSX crate and a SSP module. The main INFN groups and experts involved in the SBS tracker readout, INFN-RM1 with Evaristo Cisbani and INFN-GE with Paolo Musico, are part of the RGH recoil project and will support its development. An example is the work in progress to develop a new version of the MPD module. Beyond an upgrade to more modern and powerful FPGAs, the new module aims to move from VME to 1 GB/s baseline Ethernet connection (with the possibility to push up to 10 GB/s), support a trigger rate up to 30 kHz with an increased number of samples, and provide new cabling options to the existing APV25 front-end cards.

The VMM3 chip foreseen for the CLAS12 high-lumi upgrade offers a backup solution for the readout. INFN personnel at INFN-GE involved in the development of a readout chain based on this chip is part of RGH.

The SBS front-tracker has an expected rate up to 500 kHz/cm² and an estimated strip occupancy of 60%. With 3 samples per event and a trigger rate of 5 kHz, the MPD-SSP chain has to be able to handle a 100 Mb/s transfer rate. To this goal, no more than 15 APV cards have been connected to the same MPD. The RGH specifications are less stringent. At the foreseen $5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity, the expected rate in the RGH recoil detector planes approaches a value close to 300 kHz/cm² only in the sheet-of-flame region along the bending plane of the magnet, see Fig. 36 and Sec. 3.3.4. In the rest of the detector, the

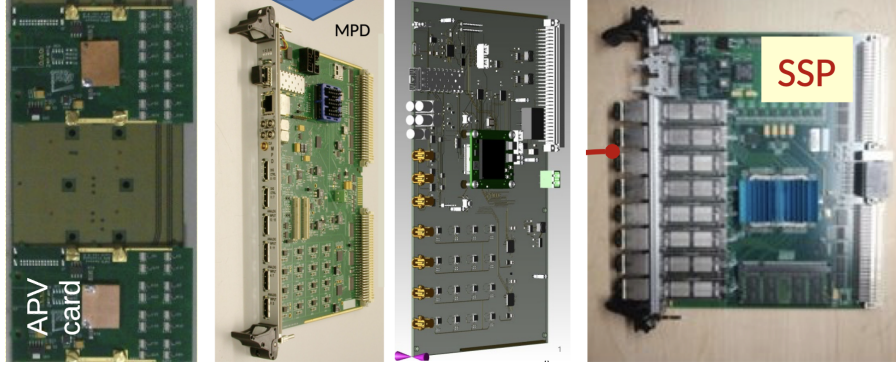


Fig. 35: The essential elements of the SBS tracker APV25 readout chain: the APV front-end card (left), the MPD FPGA board in the existing version and in the upgraded version under development (center) and the SSP data-acquisition module (right).

rate is one order of magnitude lower.

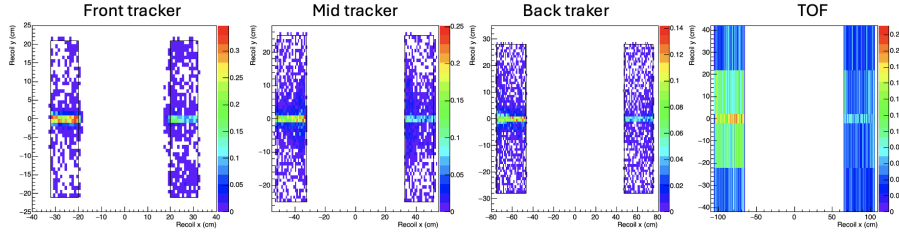


Fig. 36: Expected background rate on the RGH recoil detection planes expressed in MHz/cm² for tracking (first three panels) and MHz/ch for TOF (last panel).

3.3.2 Scintillation Timing

The main requirements for the RGH recoil timing detector are, in addition to O(100 ps) time resolution, a compact layout to fit into the HTCC envelope while maximizing acceptance, and a flexible tessellation to provide matching with μ Rwell tracks and control of background accidentals.

The baseline solution is a plane of scintillating bars readout by SiPM sensors. This technology is well known thanks to studies connected to Medical Imaging [154], and does not require innovative developments to achieve the desired time resolution once coupled to the right readout electronics [155].

Contained scintillator dimensions naturally mitigate the dependence of the time resolution on the bar geometry and particle impact point. The scintillation light yield is driven by the thickness of the bar, but the usable light fraction is ultimately dictated by the active area coverage of the bar rim. Being compact, SiPM does not require large thicknesses. Time resolutions better than 100 ps were reported with bars of 5 mm thickness and variable length up to 20 cm [145]

and more recently even with bars of 3 mm thickness and 30 cm length [146]. This performance has also been reproduced with full simulations including optical photons for the geometry utilized here. In case of need, more than one SiPM can be connected in series to cover a large rim area while containing the number of readout channels.

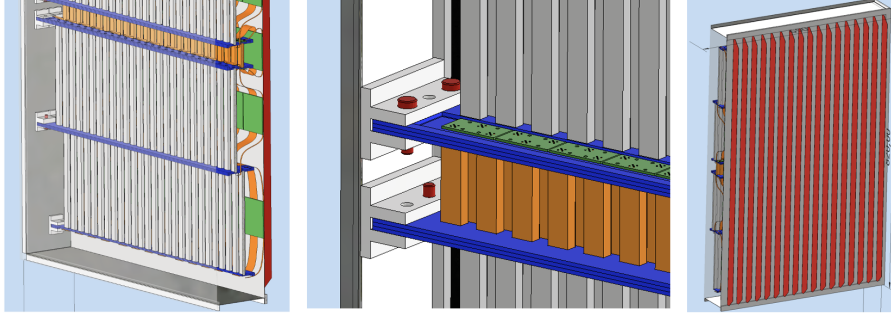


Fig. 37: Concept for the RGH recoil TOF. The timing wall is composed by arrays of vertical scintillating bars readout by SiPMs with the front-end electronics mounted on the downstream support structure (left). Detail of the frame fixing the bars and mounting the sensors (center). The support structure provides cooling and services (right).

Because just a coarse space information is required to match the recoil track, the bar dimensions can be chosen to mitigate the rate of background accidentals. The current design assumes vertical bars with a width of 12 mm and two lengths: 40 mm across the bending plane where background concentrates, and 200 mm outside it. In this way, the accidental rate is limited to be below 200 kHz per readout channel, see Fig. 36. The recoil TOF concept is depicted in Fig. 37. The scintillating bars are staggered into arrays and readout on both ends by SiPMs. The bars are vertical to provide best space segmentation in the target magnet bending plane. The timing wall is composed by five arrays of bars whose height is optimized to cope with the expected background levels. The readout electronics are mounted on the downstream supporting structure that provides heat dissipation and services. The front window is minimized in material budget but conductive to provide a Faraday cage. The bars are staggered in order to avoid any dead areas due to wrapping or in the region close to the readout electronics.

The readout of the RGH timing SiPMs can be adopted from existing realizations at CLAS12. The easiest solution is to use the spare RICH electronics based on the MAROC3 chip, which is designed for small signals and has been successfully coupled to SiPM in the R&D phase. This chip was successfully run for years at CLAS12, for a Cherenkov application that requires single-photon sensitivity. In the RICH readout, the discriminated signals are fed into a FPGA with an implemented digital TDC with a time bin of 1 ns. A better time resolution was not required for RICH but it can be improved with an existing firmware upgrade (developed for ALERT, see below). However, the clock distribution architecture, based on optical fiber links and the SSP module, would limit the resolution to something around 100 ps, with a contribution comparable to the

sensor.

A better solution is the reuse of the ALERT board design done at JLab and based on the PETIROC chip. PETIROC2 has 32 analog input channels that are independently managed and a dynamic range more suited to a multi-photon regime than MAROC. Each channel is divided into two signals, one for time stamping using a TDC and one for charge measurement. The time branch of each channel is preamplified before it is fed into the TDC developed using a leading edge in addition to a Time-to-Amplitude converter. The time bin is 25 ps resulting in a resolution better than 40 ps, with a latency greater than 10 μ s. The charge of the pulse is obtained storing the shaped signal values at its peaking time using a switch capacitor array (SCA). The peaking time is defined with respect to a delayed trigger signal produced by the time branch. The ALERT board, see Fig. 38, mounts two PETIROC chips and drives 48 channel SiPM inputs with an individual bias ≈ 1 V trimming. It mounts the same FPGA utilized in the CLAS12 RICH readout with an upgraded TDC firmware of 16 ps bin ensuring an intrinsic time resolution better than 35 ps. In the low-noise time-over-threshold readout mode, it can record a measurement proportional to the input charge. The low noise amplification and discrimination chain allow low thresholds (≈ 40 fC) well matched to the expected signal. The clock distribution is done via an ethernet link that preserves a global readout time resolution of about 50 ps, adding a marginal contribution to the one of the sensor.

The development of the recoil ToF detector is synergistic with the R&D activities for a KLM-like detector at the EIC [156] and is pursued by the Duke group. This detector would also use scintillator bars with a direct SiPM readout optimized for timing resolutions better than 100 ps. Currently, simulations for this detector are well advanced and were adapted for RGH. Similarly, a front-end board holding the SiPMs and its amplifier circuit developed within KLM can serve as a benchmark and backup solution for the RGH recoil. Planned cosmic ray test stands for the KLM can also be used for the development of the proposed TOF detector.

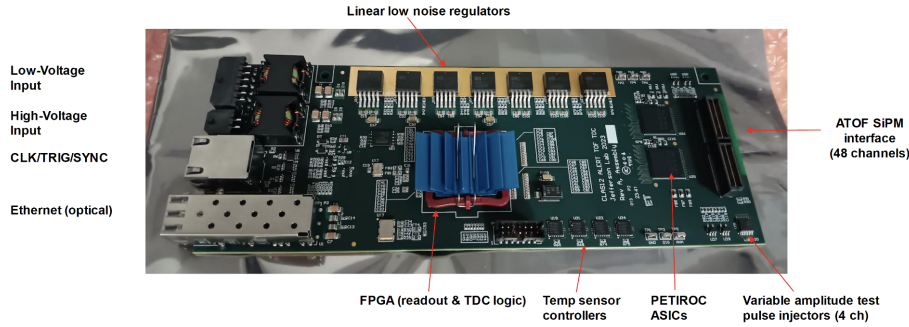


Fig. 38: The ALERT readout board designed by the fast-electronics group at JLab.

3.3.3 Recoil Simulation and Reconstruction

A full simulation of the RGH recoil detector was implemented in GEMC, the GEANT4-based simulation package of CLAS12. Consistently with the other

subdetectors of CLAS12, the geometry of the tracker and of the TOF was defined in the "common-tools" section of Coatjava (the CLAS12 reconstruction software). This ensures automatically that both the simulation and the reconstruction refer to the same geometry. The materials were defined in GEMC. For the tracker, the example of the CLAS12 high-luminosity μ Rwell chambers was followed (Fig. 39), and a two-dimensional readout with perpendicular strips in x and y was adopted.

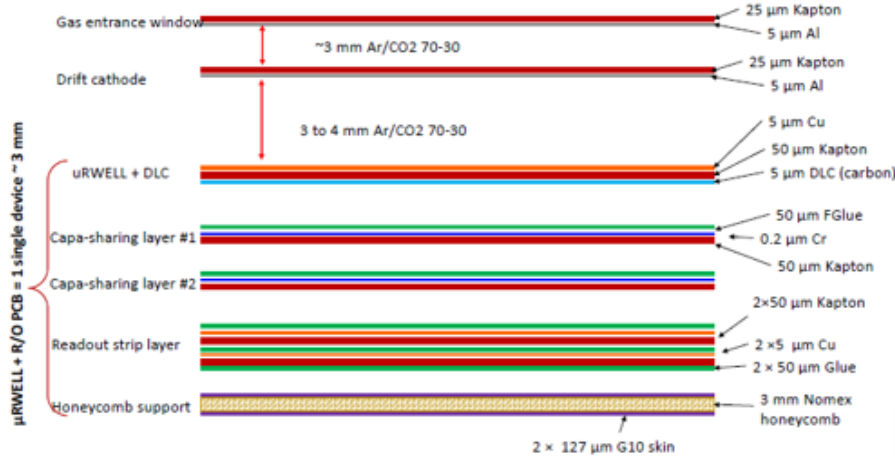


Fig. 39: The layers of material implemented in GEMC for the μ Rwell tracker.

Figure 40 shows the recoil detector as portrayed by interactive GEMC, with the tracker in purple and the TOF in red.

The GEMC digitization of the tracker adopted the same parameters (gain, drift velocity, time resolutions) that were established for the high-luminosity upgrade μ Rwell chambers. For the TOF, the digitization parameters were derived from detailed simulation studies carried out by the Duke group for the development of the EIC KLM-like detector. In each of the two sectors, the tracking planes are 3 μ Rwell chambers with 2D readout and 1-mm strip pitch to optimize space resolution. The two TOF planes consist of vertical scintillator rods with 10 mm width and 5 mm thickness to achieve 100 ps of time resolution. To contain accidentals hits and some basic spatial correlation, the rods are organized in 5 rows of two lengths (40 mm in the bending plane, and 260 mm outside). Each rod is readout by two 3×3 mm² SiPMs attached at the center of opposite rims. The rods are staggered to preserve acceptance over the sensor location, see Fig. 37. This geometry results in the number of channels outlined in Table 3.

The reconstruction was implemented in Coatjava. For the TOF, hits were created combining ADC and TDC information, and then were grouped into clusters using their positions and timing. Similarly, for the tracker hits were created using the strip IDs and their timing information. They were then grouped into clusters, separately for the x and y strips, and then the x and y clusters were associated into crosses.

For the sake of time and to minimize code complexity, an approximated tracking/reconstruction algorithm was developed. First of all, it was observed

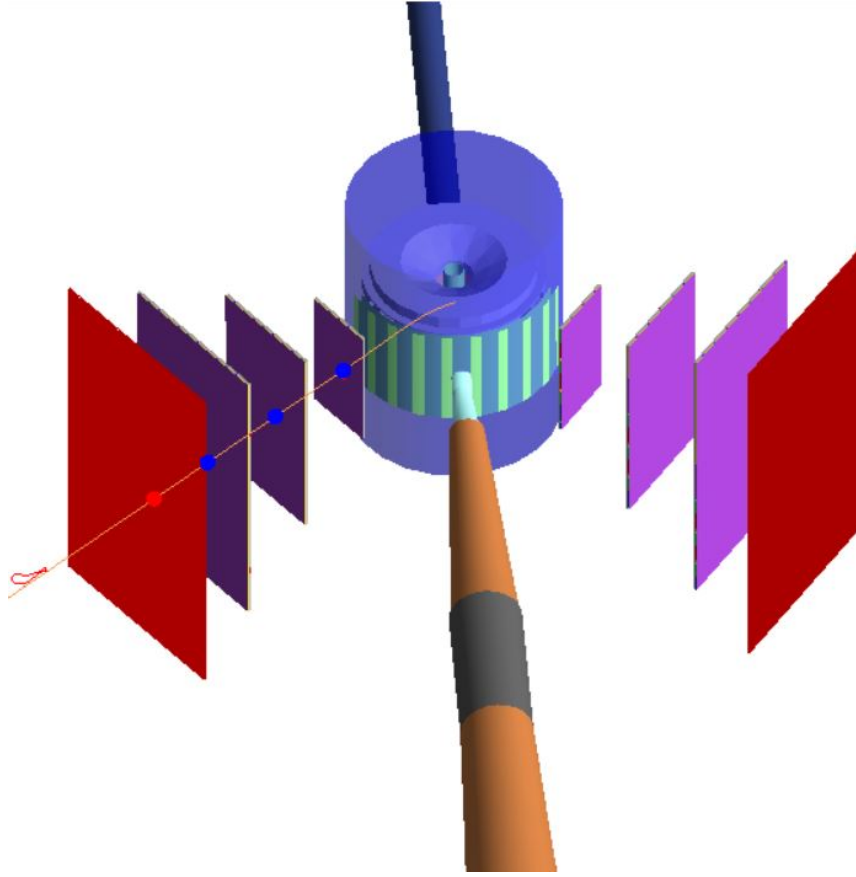


Fig. 40: The recoil detector as shown by interactive GEMC. The tracker layers are presented in purple, and the time-of-flight panels in red. A proton track is visible on the left.

that the magnetic field in the region of the recoil detector is so weak that a linear tracking can be implemented among the 3 layers of the tracker and the TOF. This was achieved by looping over all the crosses of each layer, fitting a straight line through each combination of 3 crosses, and choosing the fitted line that gave the best χ^2 and was closest to the interaction vertex (obtained from the forward tracking). The intersection "T" of the fitted line with the TOF panel was determined, the closest TOF cluster to the intersection was found, and its timing was taken to compute β . For the path-length calculation, the intersection "P" of the fitted line with a cylinder, coaxial with the target magnet, of radius 30 cm was determined (this radius corresponds to where the target magnetic field starts to become non-negligible). The last piece of trajectory was approximated with the segment VP, connecting the interaction vertex "V" and the point P. This approximation, which avoided a lengthy and cumbersome implementation of track swimming in the magnetic field, is of course worse for the lower momenta (stronger bending). The path length was then defined as the sum of the two segments, TP and VP, and β was computed combining the path

Plane	Name	x Strip (mm)	y Strip (mm)	Channel N.
1	Front tracker	1	1	1300
2	Mid tracker	1	1	2100
3	Back tracker	1	1	2900
4	Time-of-flight	10	40 and 260	1260

Tab. 3: Granularity and number of readout channels of the RGH recoil detector planes.

length and the measured time of flight. The absolute value of the momentum was deduced from β assuming that the track belonged to a proton. In order to determine the momentum components, and thus the angles θ and ϕ at the vertex, the following procedure was adopted:

- We observed that the track does not bend in the xy plane, and therefore the angle ϕ can be obtained from the xy position of the Region-1 cross.
- We found that there is a one-to-one correspondence between the yz components of the momentum and the angle between the fitted track and the line joining the interaction vertex to the cross in Region 1 (Fig. 41). This dependence was parametrized with a polynomial fit and used to deduce the momentum yz component.
- Knowing ϕ , p_{yz} , and p , the other momentum components and the angle θ are computed.

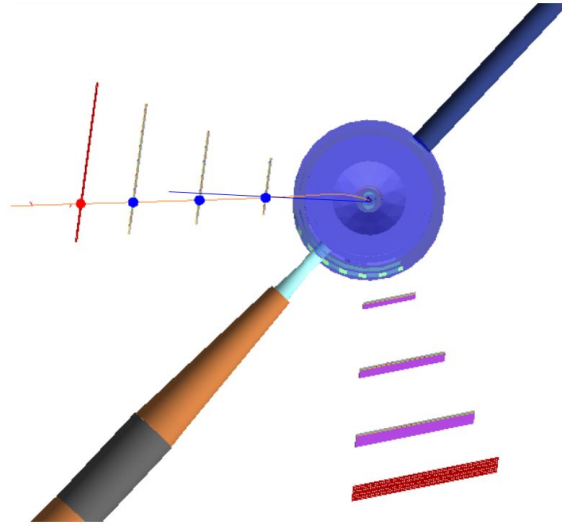


Fig. 41: The angle between the orange line (the fitted track) and the blue line (joining the vertex with the first cross in Region 1) is used to parametrize the momentum component in the yz plane. Figure made with interactive GEMC.

Figure 42 shows the resolutions, defined as the differences of generated and

reconstructed variables, for momentum and angles obtained by the recoil detector for simulated protons in DVCS kinematics.

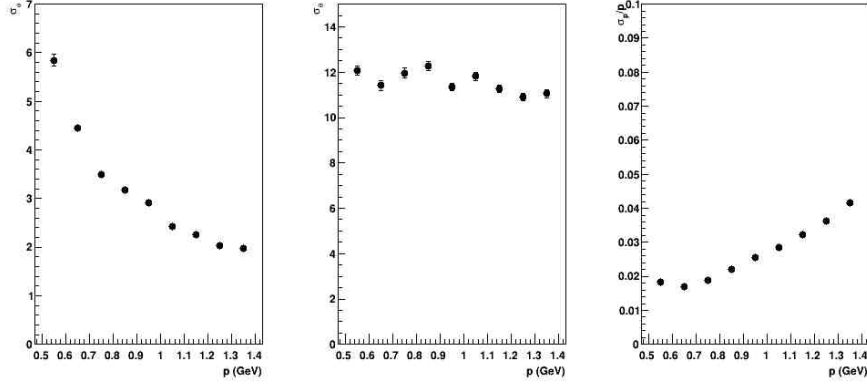


Fig. 42: Angular (left for ϕ and middle for θ) and momentum (right) resolutions, as a function of momentum, obtained with the recoil detector for simulated protons in DVCS kinematics.

3.3.4 Physics Background

A detailed study of background sources was performed via GEMC simulation, using a standardized 252 ns acquisition window around the triggered event, indicating three main components. The first component comes from beam particles losing energy in the target material and bending outside the beam orbit into the detector acceptance, see Fig. 43. They are concentrated in the bending plane of the target magnet and illuminate only one side of the recoil detector, being negatively charged. In most cases the background particle transverses all the recoil projective layers and therefore provides 4 space hits (three from tracking and one from TOF). The second background component comes from shower particles generated in the target region (Fig. 44). These are almost symmetric in charge and therefore illuminate both sides of the detector, but are still concentrated in the bending plane of the target magnet. More than one background particle could be generated in the event, with a recorded hit number which is typically a multiple of 4 (the recoil detector layers). The third background component comes from secondary interactions in the material downstream the target region, especially in the shielding material surrounding the CLAS12 beam pipe (Fig. 45). These low-energy particles have an erratic path with an associated random number of hits on the whole surface of the recoil detection planes.

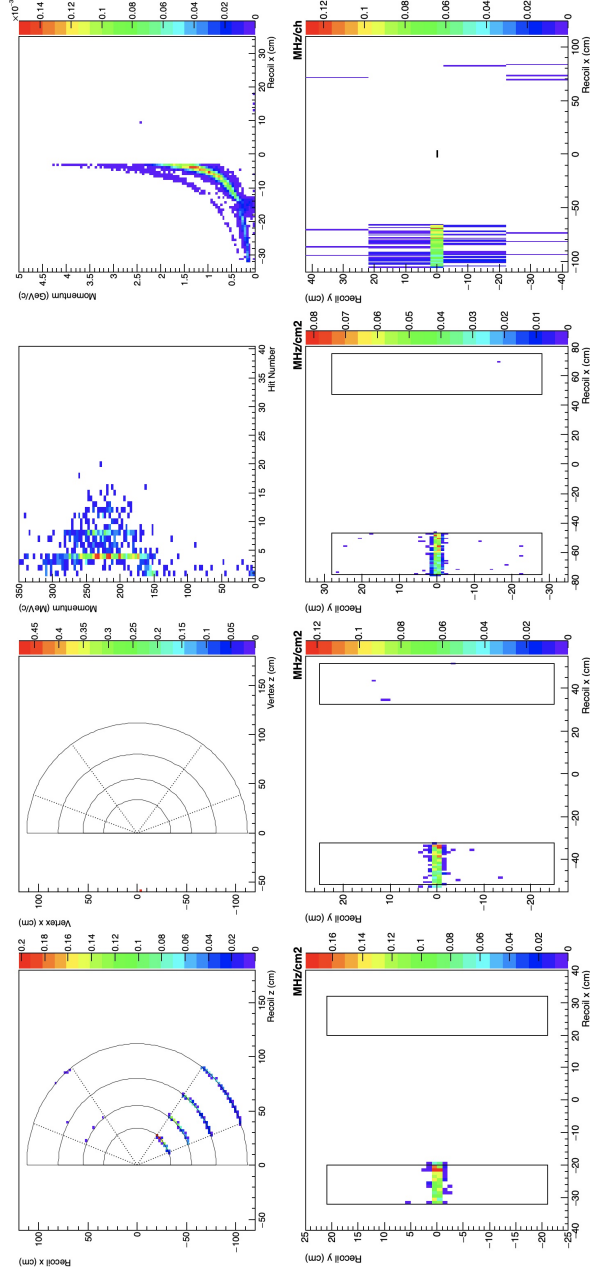


Fig. 43: Expected background on the RGH recoil detection planes (three tracking plus one TOF plane) from beam particles losing energy into the target material. The top row shows the projection on the bending plane of the recorded hits (left), the location of the originating vertex (center-left), the distribution in momentum and hit multiplicity per particle (center-right) and the correlation between momentum and detected x position on the bending plane (right). The vertex is not visible as far upstream along the beam line. The bottom row shows the background rate (in MHz/cm² for tracking and MHz/ch for TOF) for the four detector layers.

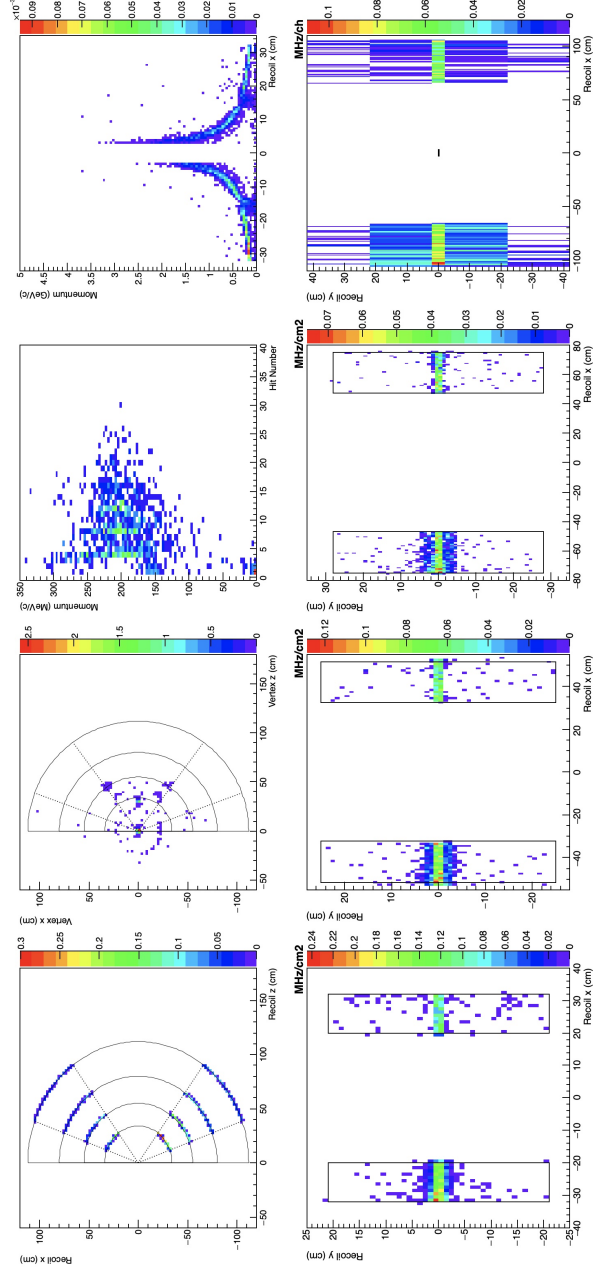


Fig. 44: Expected background on the RGH recoil detection planes (three tracking plus one TOF plane) from shower particles generated into the target region. Panels are organized as in Fig.16.

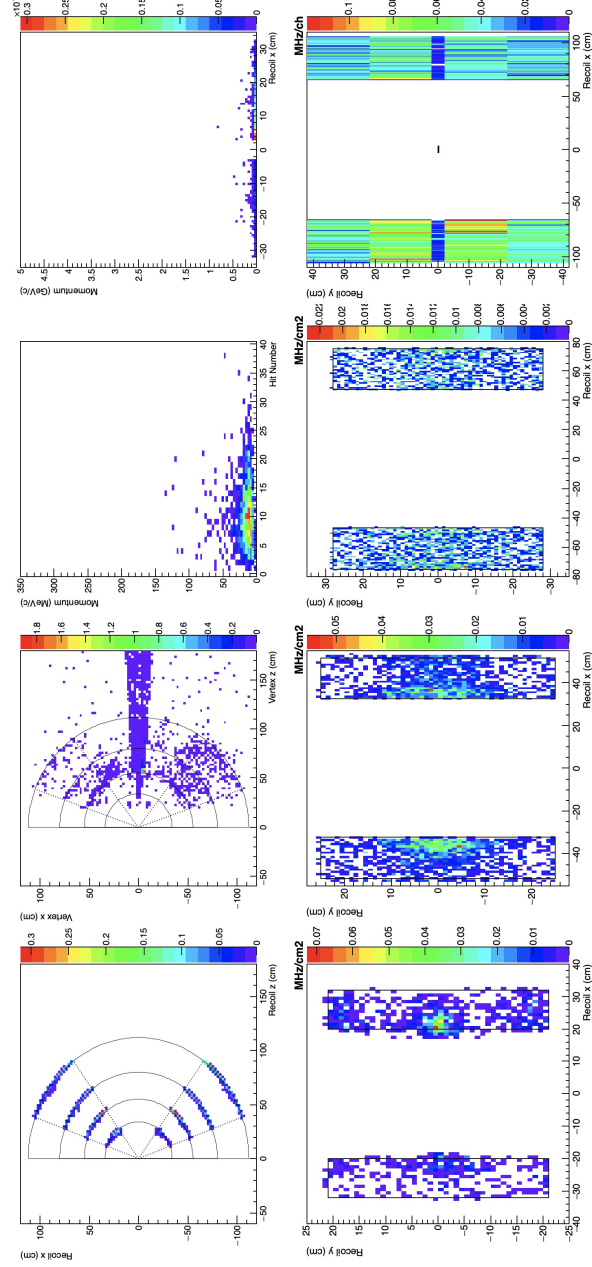


Fig. 45: Expected background on the RGH recoil detection planes (three tracking plus one TOF plane) from secondary interactions downstream the target region. Panels are organized as in Fig.16.

A preliminary, low-statistics study of the effects of the background on the tracking performances of the recoil detector was carried out. Background events were produced with GEMC, using the nominal luminosity for RGH and the full detector setup, and their recoil ADC hipo banks were merged, using the CLAS12 bg-merger software, to the ones of the proton-DVCS simulation. In order to handle the presence of the background, the reconstruction algorithm previously described was modified including a cut on the relative time differences between the three regions of the tracker, and the TOF hit position was added to constrain the track fitting procedure. Figure 46 shows the resolutions obtained including the background. With respect to the no-background case (Figure 42), the momentum resolution gets worse, as expected, but not excessively, while the angular resolutions remain comparable. A reduction in overall efficiency of less than 20% is observed in the presence of background. As mentioned above, a simple and approximated reconstruction algorithm has been adopted at this stage, in particular, for the reconstruction of the path length and for the time matching. Therefore, the performances of the recoil detector in the presence of background, which are already reassuring, will improve when a more accurate reconstruction, keeping into account the magnetic field map and the curved trajectory of the particles, and using optimized time matching cuts, will be implemented.

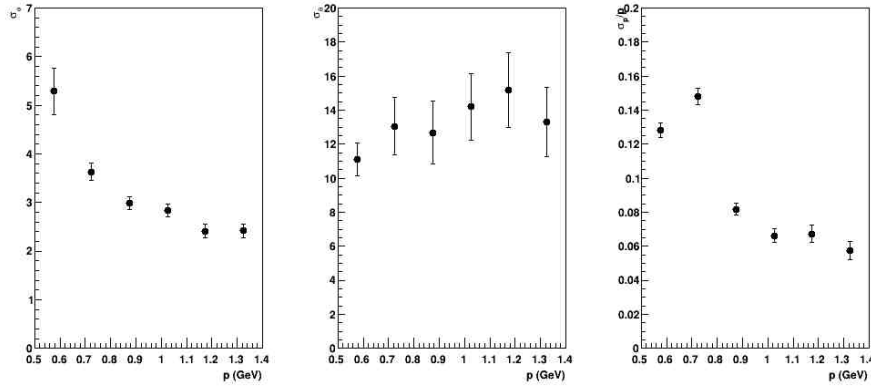


Fig. 46: Angular (left for ϕ and middle for θ) and momentum (right) resolutions, as a function of momentum, obtained with the recoil detector for simulated protons in DVCS kinematics plus merged background in the tracker.

The cryostat of the RGH target and holding magnet is an adaptation of previous realizations in Hall A and Hall C. It should fit into the clearance of the HTCC detector together with the newly designed recoil detector, see Figure 47. The RGH target position is assumed to remain the same as the current center of the CLAS12 solenoid. The cryostat allows for the exchange of the target and annealing of the irradiated targets in situ. It houses thin aluminum windows for the beam and scattered particles to minimize secondary interactions (Fig. 48). The rectangular exit window is similar to the one realized for the hydrogen target in Hall C.

Fig. 47: Overview of the RGH target and recoil system inside the HTCC clearance. The target magnet structure (blue), the μ Rwell chambers (brown) and the scintillation wall (gray) are visible. The μ Rwell are readout from two sides: see the front-end electronics board (green).

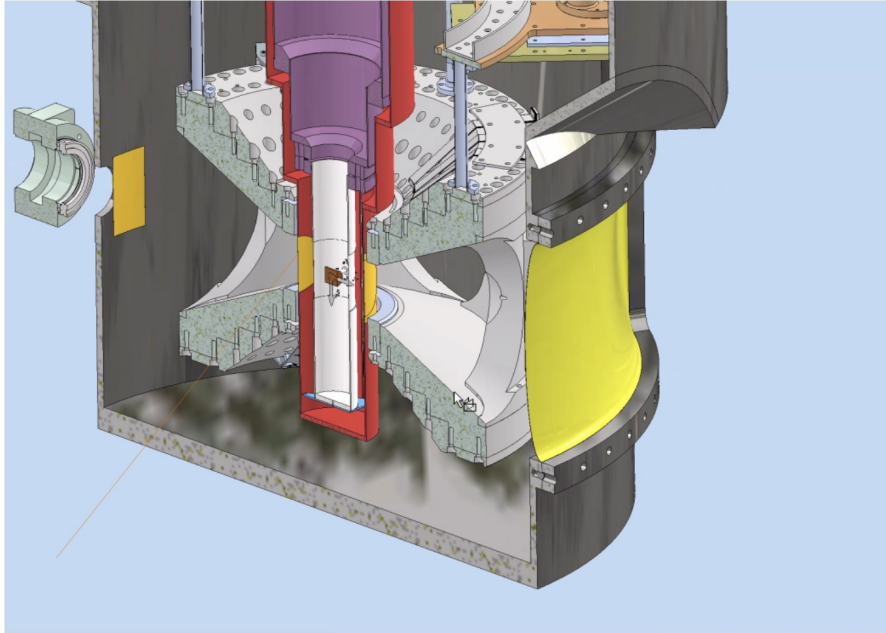


Fig. 48: The entrance and exit windows of the RGH target cryostat.

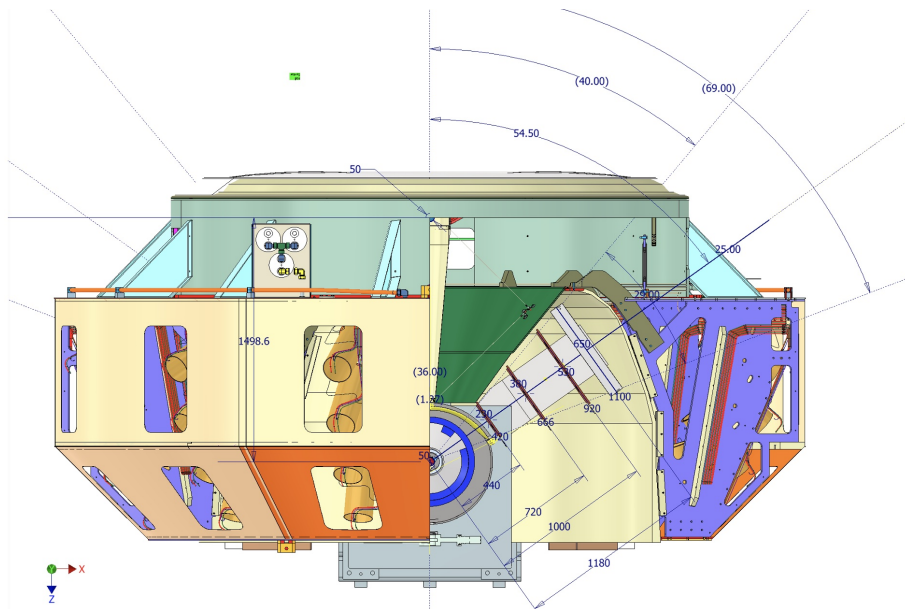


Fig. 49: Top view of the RGH target cryostat and recoil detector showing the clearance and the relevant acceptance angles.

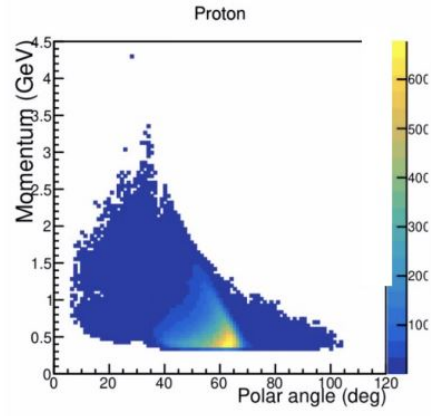


Fig. 50: Momentum versus polar angle distribution of the protons from DVCS events.

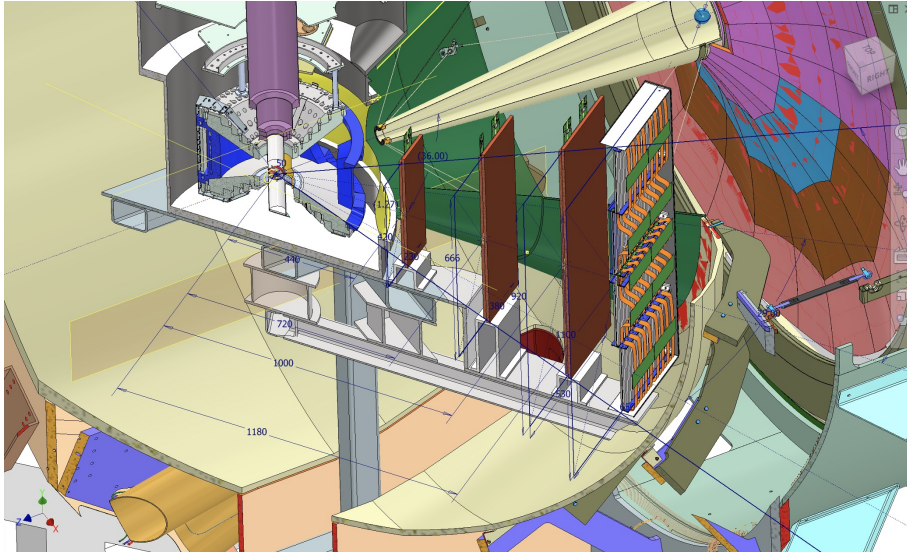


Fig. 51: The support of the RGH recoil detector is a cart able to roll in and out of the HTCC, and can be realized without interference with the HTCC.

3.3.6 Available Resources

The RGH recoil detector construction is expected to take roughly 3 years and will occur in parallel to the target development as a mainly in-kind user contribution. The time estimate accounts for the detector realization and commissioning, and it assumes that no major electronics development is required thanks to the already existing readout systems and the limited amount of readout channels. Groups already involved in the essential technology R&D are part of the RGH recoil project, see Table 4.

Task	Leading Institution	Expertise
μ Rwell detector	INFN-RM2, INFN-CT	CLAS12 upgrade, ePIC tracking
μ Rwell readout	INFN-GE, INFN-RM1	SBS GEM tracking readout
TOF detector	DUKE, Orsay	EIC KLM, CLAS12 CND
TOF readout	INFN-GE, INFN-FE	CLAS12 FT and RICH readout
Mechanics	INFN-LNF	CLAS12 RICH mechanics
Integration	JLab	Hall-B infrastructure and beam

Tab. 4: Main elements of the RGH recoil detector with associated leading Institutions.

INFN-RM2 and INFN-CT work in close contact with the group of Gianni Bencivenni, the inventor of μ Rwell technology, for the CLAS12 upgrade and the ePIC tracking system. A strong expertise has been developed in optimizing the detector performances for 2D readout and optimized detector operations. Several $10 \times 10 \text{ cm}^2$ prototypes with different 2D readout schemes have been tested at CERN within the CLAS12 high-luminosity upgrade project and the ePIC endcap tracker detector development. A very promising hybrid solution, with a 2D COMPASS-like readout and a GEM charge pre-amplification stage, called G-Rwell, has been identified as the version able to achieve the required position and time resolution performances, also obtaining the highest gas gain at relatively low applied voltages. Large area G-Rwell detectors are presently being designed and constructed, and will be tested at CERN by the end of 2025. A valuable experience on the integration of MPGD trackers within a large experiment has been developed by a new member of the group, who has worked on the installation of a cylindrical GEM detector in the BES III experiment. INFN-GE and INFN-RM1 have introduced the GEM technology in the SBS program of Hall A and developed the GEM readout based on the APV25 currently running in the SBS experiments. The estimated effort accounts for 6 chambers plus 2 spares, the APV25 readout adaptation to CLAS12 and the possible MPD board upgrade, quantified assuming to connect 15 APV cards to a single MPD as done in SBS, resulting in five new boards plus a spare. Duke is studying a scintillator+SiPM system for the EIC KLM project, while IJCLab Orsay, that built the CLAS12 Central Neutron Detector, will provide expertise, support for software (simulation and reconstruction) and possibly for mechanical integration. INFN-GE and INFN-FE has experience in SiPM readout for calorimetry and Cherenkov detectors. The effort estimate accounts for two planes of 700 small scintillating bars instrumented by SiPM, the production of 30 PETIROC front-end boards plus spares, and the adaptation of existing electronics to RGH needs. INFN-LNF has been responsible for the design of the CLAS12 RICH

detector - of its assembly, installation, and initial commissioning; it will be responsible for the design of the recoil detector and will contribute to the design of the cryostat. The mechanics and integration account for the installation tools and the required services (power supply and cabling, gas system, slow control, interlock).

The involved groups ensure adequate expertise and workforce to cover both hardware and software needs.

3.4 Luminosity

The CLAS collaboration has completed experimental runs with liquid hydrogen and deuterium targets, and has reached the design luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ with a deuterium target and 45 nA electron beam current. This is much higher than the nominal luminosity $\mathcal{L} = 5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ assumed for the RGH experiments. The ongoing high-luminosity project aims to complement the CLAS12 tracking with a front layer of μ -Rwell detectors, able to improve the spatial resolution and rate capability of CLAS12 tracking in the most critical region close to the interaction point, and support a factor two increase in luminosity.

With a dynamically polarized ammonia target, the luminosity is no longer limited by the target polarization lifetime, but by the background induced on the open-acceptance spectrometer. CLAS12 has measured hit occupancy levels in the Drift Chambers (DC), the most sensitive detectors, as a function of the beam intensity and solenoid current. The typical occupancy is driven by Moeller scatterings in the target and secondary interactions in the shielding around the downstream beam pipe, in the detector structure and in the air filling the experimental hall. The CLAS12 simulations reproduce the data within an acceptable 30% level.

For the RGH experiments, where the CLAS12 solenoid is replaced by the target 5T transverse polarizing field, the Moeller background is no longer contained inside the beam pipe, but is mainly trapped inside the target region. The baseline of the RGH experiments is to run without the Forward Tagger (FT-OFF) and with additional shielding elements installed to minimize the secondary interactions.

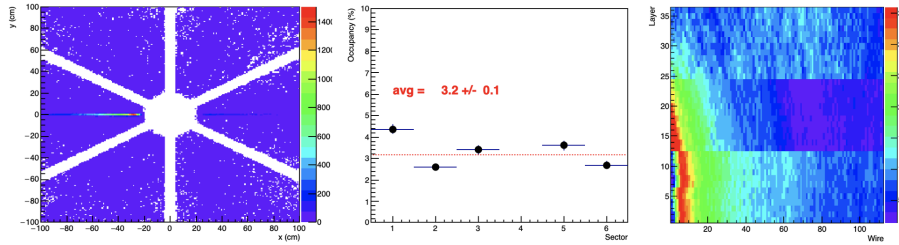


Fig. 52: Simulation results at the nominal RGH luminosity. Background hit distribution on the first DC tracking layer with the so-call sheet-of-flame in sector 4 clearly visible (left). Mean hit occupancy for all DC layers but 4 (center). Hit occupancy per single layer and wire on sector 4 (right).

The RGH background has an additional peculiar component, due to the energy loss of the beam particles passing without interaction through the target. If the loss is big enough, the particle is bent outside the pipe and into the detector acceptance. This background is concentrated in the bending plane of the 5T target magnet, creating the so-called *sheet-of-flame*, see Fig. 52 (left). With a vertical magnetic field, the sheet-of-flame will illuminate sector 4 to a level that could be hardly sustainable with the present DC readout, able to record just a single hit in the extended readout gate (between $0.5 \mu\text{s}$ and $1.5 \mu\text{s}$ depending on the drift cell size). As a conservative approach, this proposal assumes to switch off the critical DC layers in sector 4 (no tracking), and operate

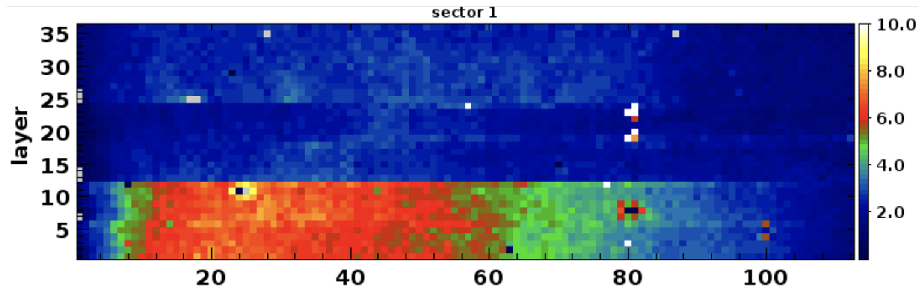


Fig. 53: Typical RGC occupancies as measured by the CLAS12 online monitor during the RGC run with a NH_3 target.

the other sectors up to a maximum tolerable occupancy rate of 6-8% as already achieved (even with higher occupancy hot-spots) during the RGC data-taking on longitudinally polarized NH_3 and ND_3 targets, see Fig. 53. This corresponds to the design RGH luminosity of $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, once a conservative factor of 2 is used to account for the different DC readout gates in simulations, see Fig. 52 (center), and real data.

There are concrete possibilities to exceed the conservative luminosity estimate above. RGH will benefit from the ongoing tracking improvements based on Machine-Learning techniques [157, 158]. With the addition of the μ -Rwell tracking layer under development for the CLAS12 high-lumi project, a significant improvement in luminosity is expected (up to a factor of two). Optimization studies are ongoing to adapt the CLAS12 background shielding to RGH. Possible mitigation measures can be introduced to partially operate the critical DC layers in sector 4. They include switching off just the DC wires close to the beam where the background particles concentrate and compensate with the high-lumi tracking layer, see Fig. 52 (right), veto the events with multiple particles as resolved by the high-lumi tracking layer, upgrade the DC readout to process multiple hits in the readout gate. An interesting option is to rotate the target by 90 degrees in order to align the sheet-of-flame with the torus coil shadow. It should also be reminded that upgrades to the software reconstruction of CLAS12 are ongoing, and an AI-assisted tracking which does not rely on hits in all DC superlayers has already been implemented. All these developments are being pursued to maximize the physics output of RGH experiments, with the possibility of improving what has been projected at the time of this proposal.

4 Kinematics

RGH will run with the torus at a nominal current of 3770 A. The solenoid will be off and in parking position. The Central Detector will be replaced by the RGH recoil detector.

4.1 DVCS

In RGH, the acceptance for recoil proton is limited in azimuthal angle (± 25 degrees) by the target magnet structure. However, the RGH recoil detector has been designed to intercept the most populated interval of polar angles, that is between 40 and 80 degrees (Fig. 54), similarly to the Central Detector of CLAS12. Therefore, aside from the different kick induced by the transverse magnetic field, the phase-space coverage will be similar to that of other run groups of CLAS12, such as RGA and RGC (the experiment that used a longitudinal dynamically polarized target). Figures 55, 56, and 57 show the kinematic coverage in the RGH setup including the proton recoil detector, for the azimuthal versus polar angle of the three final-state particles, for the momentum versus θ , and for the relevant proton-DVCS variables, respectively. Note that Sector 4 is removed from the analysis to produce the DVCS projections, see Section 5.2.

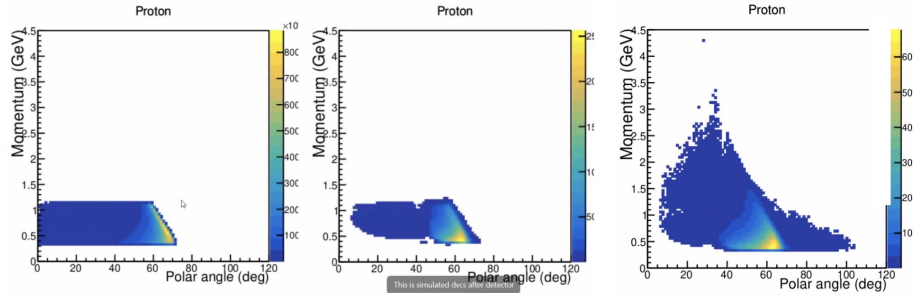


Fig. 54: Proton kinematics in DVCS reaction at 10.6 GeV beam energy. Generated protons (left), protons inside the RGH acceptance (center), and protons detected in CLAS12 during the RGA run (right).

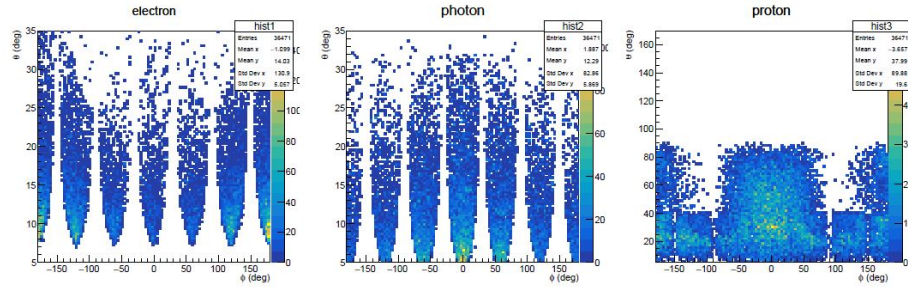


Fig. 55: ϕ versus θ distributions for electrons (left), photons (middle), and proton (right), for proton-DVCS events simulated in RGH conditions.

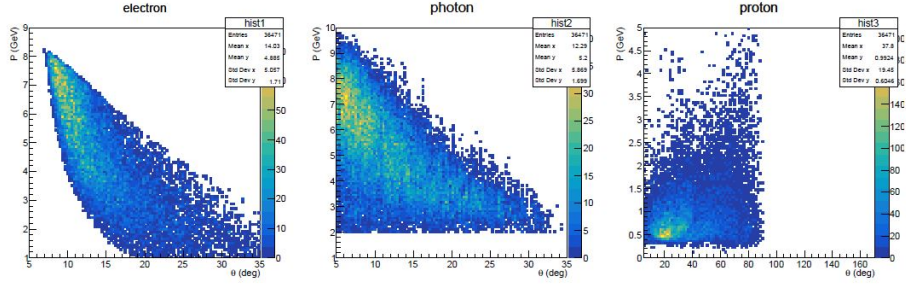


Fig. 56: From left to right: momentum versus θ for electrons (left), photons (middle), and protons (right), for proton DVCS events simulated in RGH conditions.

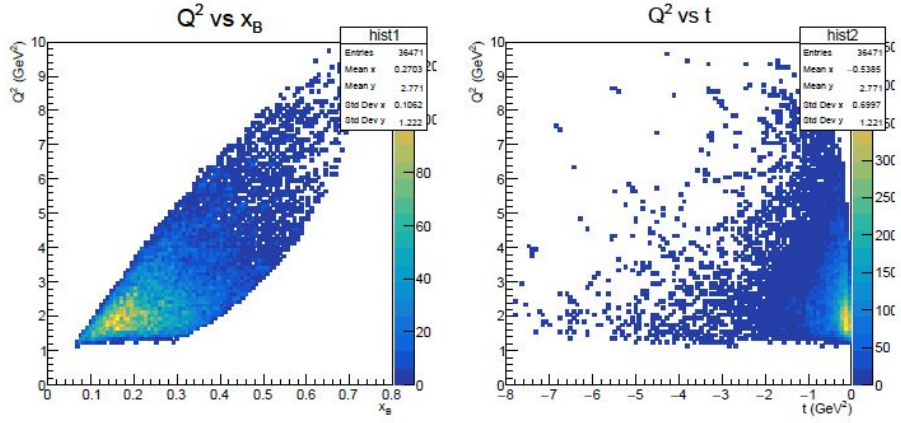


Fig. 57: Q^2 vs x_B (left) and Q^2 vs t (right) for proton DVCS events simulated in RGH conditions.

4.2 SIDIS

The support structure of the RGH target magnet is designed to essentially preserve the forward acceptance and, thus, the SIDIS phase space, see Figure 58. The missing sector (sector 4) does not limit the phase space due to the rotational symmetry of the reaction mechanism, which is defined with respect to the lepton scattering plane. A multi-dimensional binning is possible, covering an extended range in x and Q^2 , see Figure 59. In all of the (x, Q^2) bins, there is coverage for the relevant values of the hadron fractional energy z (from 0.2 to 0.8) and the transverse momentum $P_{h\perp}$ (up to 1 GeV/c), see Figures from 60 to 63.

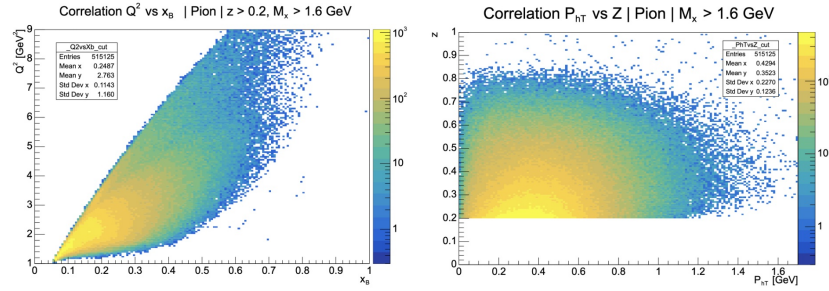


Fig. 58: Q^2 vs x_B (left) and z vs $P_{h\perp}$ (right) for SIDIS events simulated in RGH conditions.

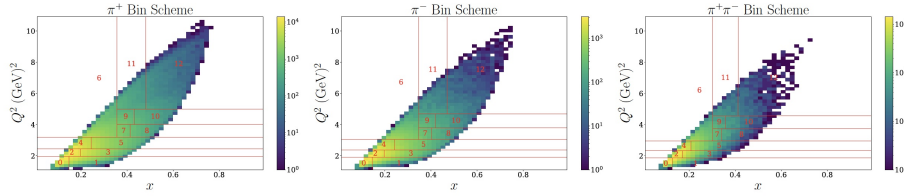


Fig. 59: Possible binning scheme in x and Q^2 for SIDIS events with a leading positive pion (left), negative pion (center) and pion pair (right).

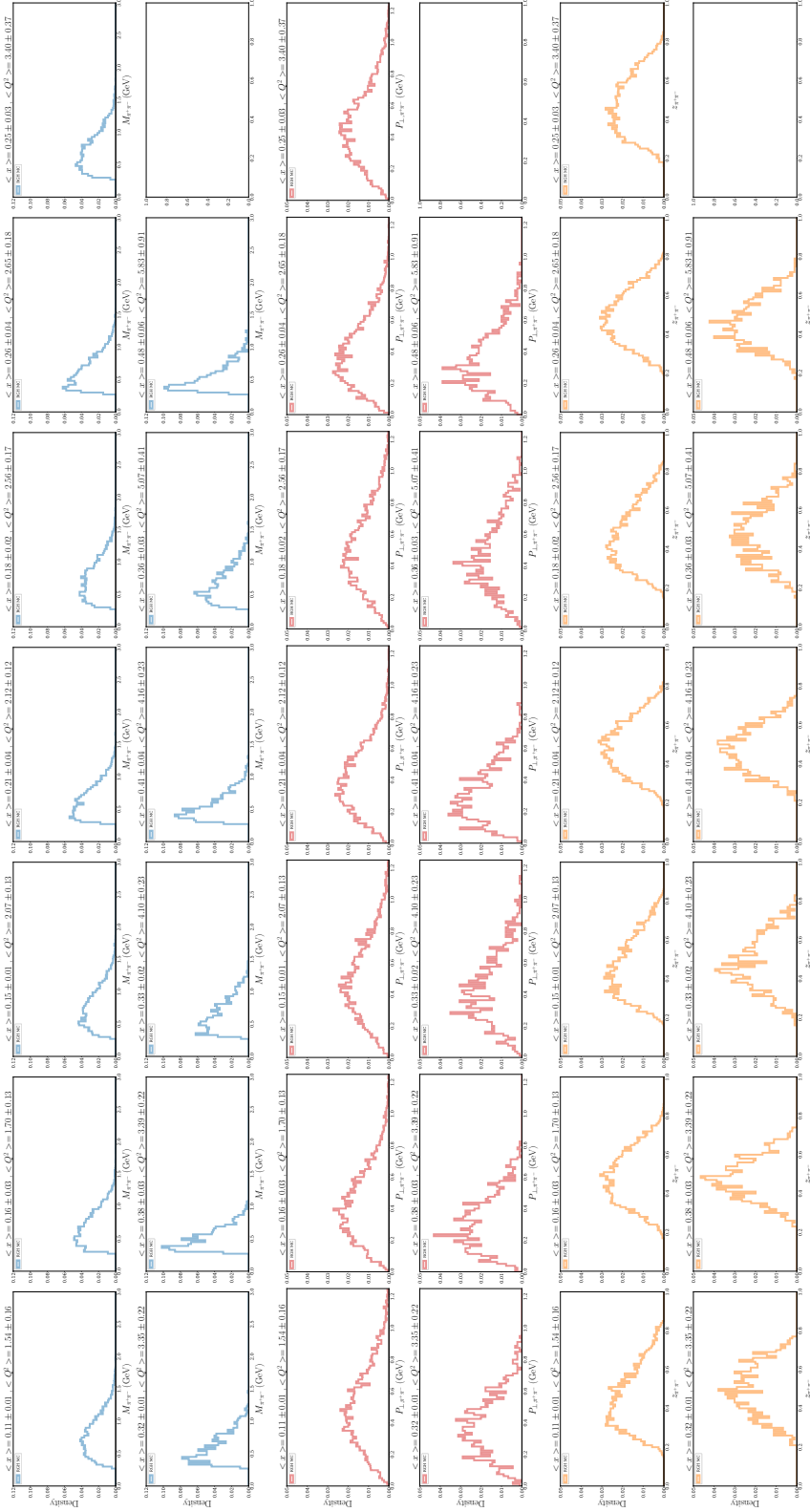
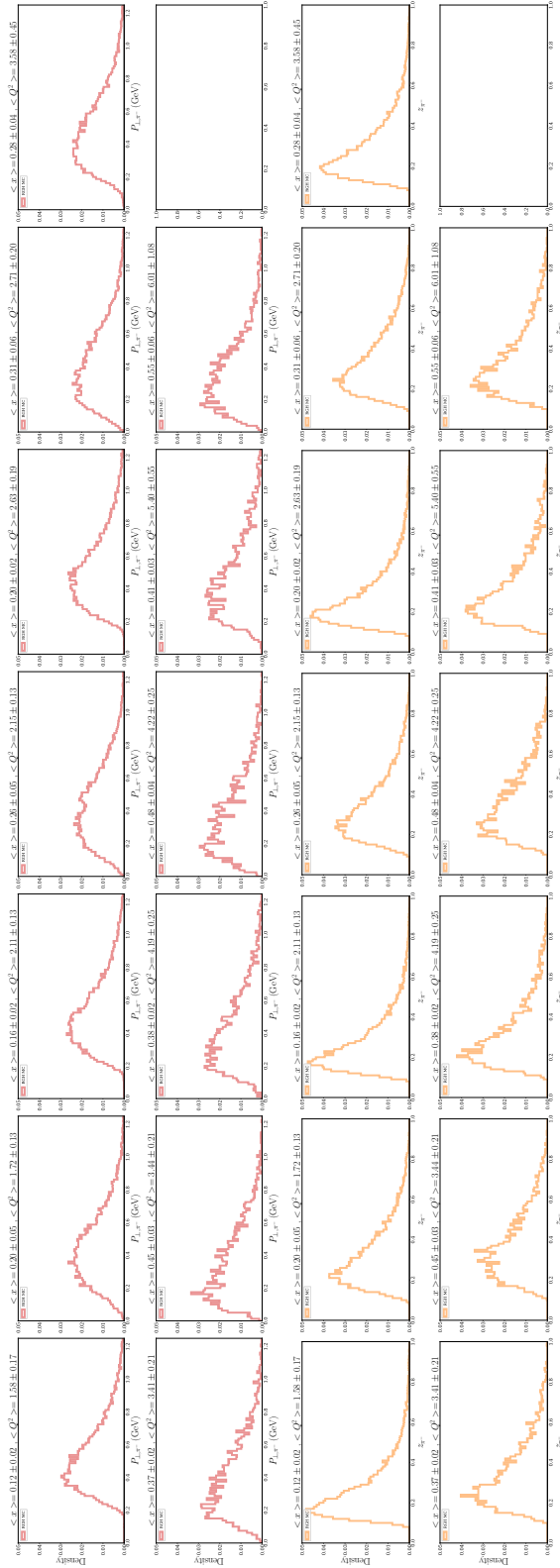


Fig. 60: Distribution of the invariant mass (top row), transverse momentum (middle row) and fractional energy z (bottom row) of SIDIS pion pairs in various (x, Q^2) bins.

Fig. 61: Distribution of transverse momentum (top row) and fractional energy z (bottom row) of SIDIS negative pions in various (x, Q^2) bins.

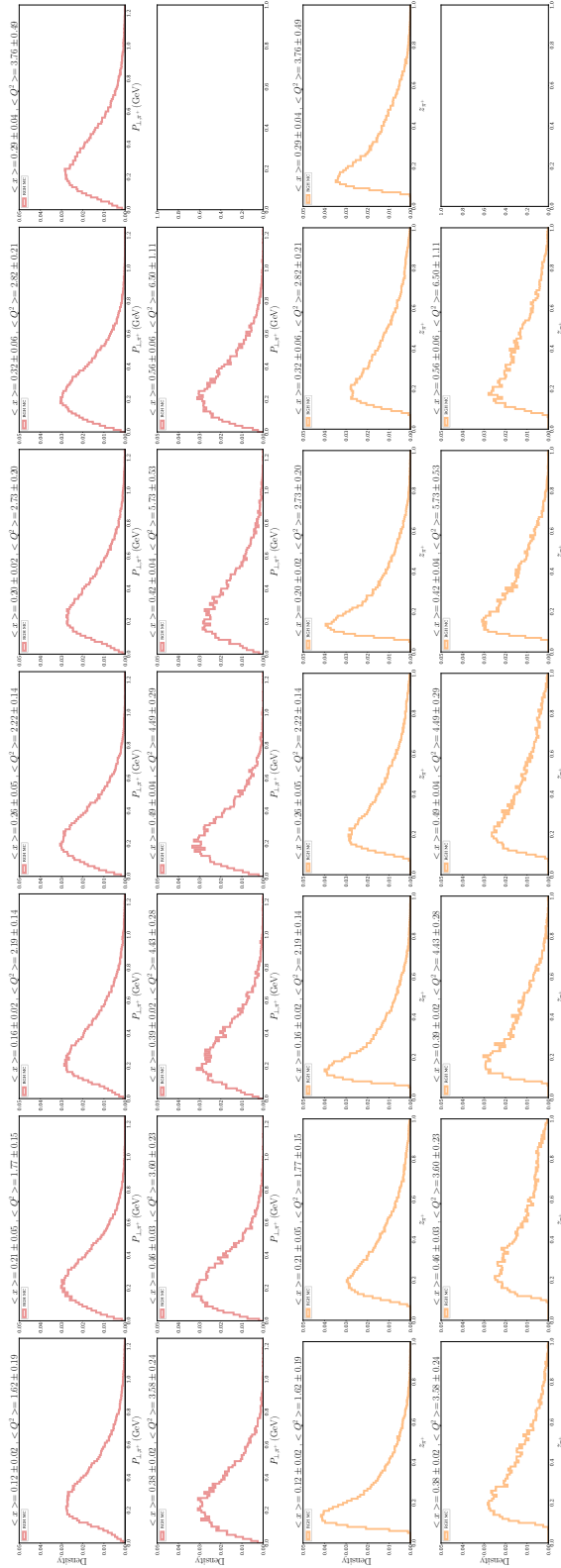


Fig. 62: Distribution of transverse momentum (top row) and fractional energy z (bottom row) of SIDIS positive pions in various (x, Q^2) bins.

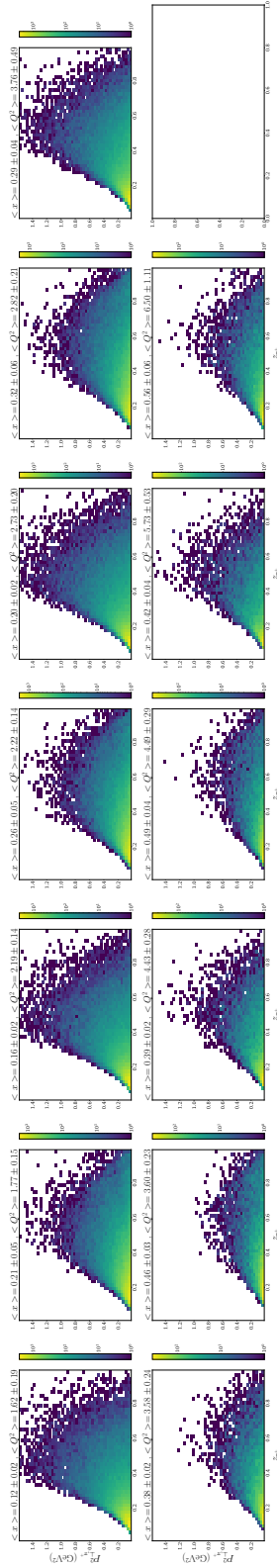


Fig. 63: Correlation between transverse momentum squared and fractional energy z of SIDIS positive pions in various (x, Q^2) bins.

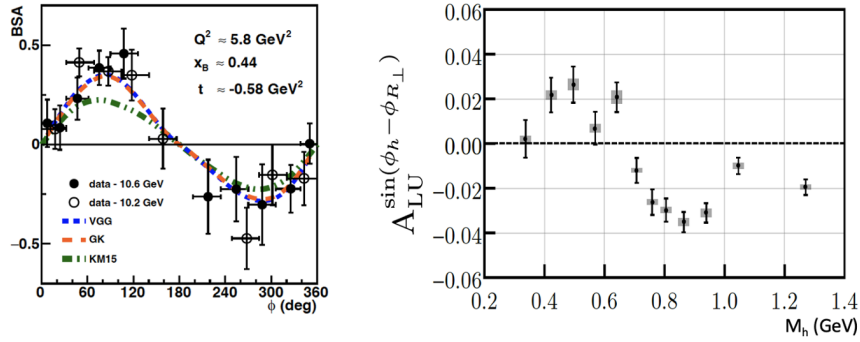


Fig. 64: Examples of CLAS12 published results on beam-spin asymmetries. Left: DVCS asymmetry as a function of the azimuthal angle ϕ compared to phenomenological models [159]. Right: SIDIS dihadron asymmetry found to be not-zero for the first time [160].

5 Projections

The RGH projections are based on solid ground, as they refer to a running experiment (CLAS12) and a consolidated polarized target technology. The luminosity is not defined by any target irreducible limits, but by the capability in containing the background levels in the experiment, something that is manageable and for which there are many concrete prospects of improvement.

Physics analyses are in progress using the 10.6 GeV data and provide a realistic benchmark for RGH performance. CLAS12 results for the SIDIS and exclusive channels have been published by the CLAS Collaboration and presented at conferences. As examples, published beam-spin asymmetries of DVCS events, dihadron and π^+ SIDIS events, based on a fraction of the recorded statistics, are shown in Fig. 64 and Fig. 65 (left), respectively. The data confirm that CLAS12 allows for a much extended reach within the DIS regime (large Q^2) with respect to CLAS and the valence region (large x) with respect to previous experiments, with an unprecedented statistical precision. Thanks to improved knowledge of instrumental effects and the refinement of calibration procedures and reconstruction algorithms, further progress is expected toward the best CLAS12 performances before the start of RGH experiments.

A selection of physics channels is presented in the following, in order to discuss the impact of RGH data in few benchmark cases. As anticipated in Section 1, beam polarization, large acceptance, and particle identification in the final state open the possibility to explore a variety of observables with comparable performances.

5.1 Semi-inclusive Physics

Due to the definition of an orthogonal direction, transverse single-spin asymmetries (TTSAs) are key observables for the access of transverse momentum dependent parton distribution functions (TMDs) [162]. The extraction of TMDs is

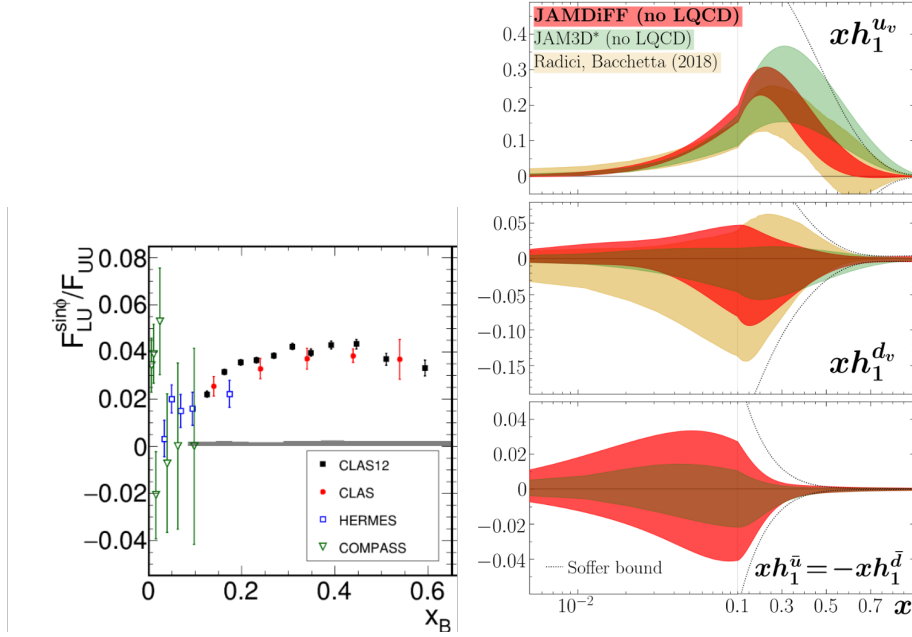


Fig. 65: Left: SIDIS π^+ beam-spin asymmetries measured by CLAS12 as a function of Bjorken x compared with world data. Figure from [161]. Right: Current extractions of transversity from SIDIS, pp and e^+e^- data. Figure from [23]. Legacy data are mainly limited to $x < 0.3$. This lack of data in the valence region explains the large uncertainty and difference between the transversity extractions.

a focus of the nuclear physics community to access the 3D momentum structure of the proton.

Examples of different global extractions of transversity are shown in Fig. 65 (right). The precision of the extractions and their compatibility become worse in the valence-quark region. This is due to the lack of data for $x > \approx 0.3$. Since the magnitude of transversity peaks in the same region, this leads to significant uncertainties in the tensor charge, which is the integral of the transversity function over x . The tensor charge can be compared with lattice calculations and is also needed to calculate Beyond Standard-Model phenomena in certain scenarios of new physics with tensor coupling or particle electric dipole moment. World data on longitudinal beam-spin asymmetries (BSAs) compared to the CLAS12 RGA results are shown in Fig. 65 (left). We expect a similar x coverage for RGH, reaching up to $x \approx 0.6$. This would cover the whole peak structure in the current transversity extractions.

Data-driven projections for SIDIS observables have been derived following the method explained in Section 5.2, and benefit from the fact that the forward acceptance of pions, and π^0 in particular, is largely preserved. The full simulation for the RGH setup was used. The number of events was determined from RGC simulations correcting for the ratio of the delivered RGC luminosity to the expected integrated luminosity of RGH as well as the ratio of the acceptances of

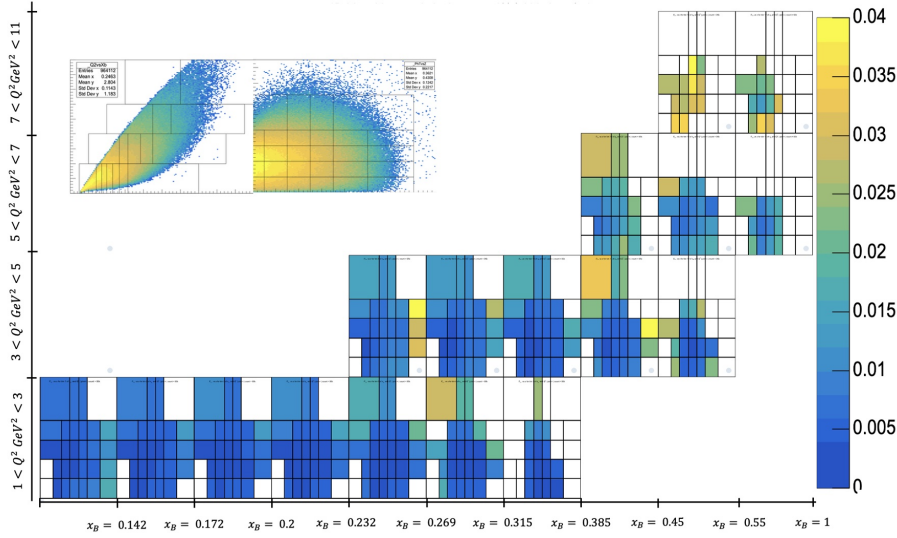


Fig. 66: Expected statistical error on A_{UT} of SIDIS π^+ , after 100 PAC days of RGH data-taking, as visualized on a 4D $(x, Q^2, z, P_{h\perp})$ bin map. A fully differential analysis will be possible up to $x = 0.6$.

RGC to RGH. Note that in the SIDIS case, where nuclear interactions (on nitrogen) cannot be kinematically suppressed, the target dilution factor $f = 3/17$ should be treated as polarization and multiply the error instead of the yield.

5.1.1 Impact study: Sivers

The expected statistical error on A_{UT} of SIDIS π^+ , after 100 PAC days of RGH data taking, is visualized on a 4D $(x, Q^2, z, P_{h\perp})$ bin map in Figure 66. A fully differential analysis will be possible, extending into the uncovered valence region up to $x = 0.6$. This brings a major improvement with respect to previous experiments, see Fig. 67, that published only mono-dimensional analyses at $x \leq 0.3$, except a 3D analysis by HERMES limited at $x \leq 0.2$ [53] and a 2D study extended in x and Q^2 but integrating the relevant hadron variables z and $P_{h\perp}$ [52].

Similarly to other polarization-sensitive TMDs, the Sivers function appears to have maximum amplitude in the valence region, see Sec. 1.1.1, 1.1.2 and 1.1.4. This is the region where a multidimensional analysis could become possible for the first time with RGH data. This unprecedented set of data will be instrumental to disentangle the various dependencies and cover the kinematic regimes of interest.

Recent measurements of BSAs indicate possible strong contributions to inclusive pion spin asymmetries from vector-meson (VM) decays. In addition, several JLab proposals have been approved to study longitudinal photon contributions in inclusive pion multiplicities. The Sivers effects also receive a contribution from longitudinal photons, which was never measured or quantified, suggesting that the systematics on the Sivers effect measurements may be cur-

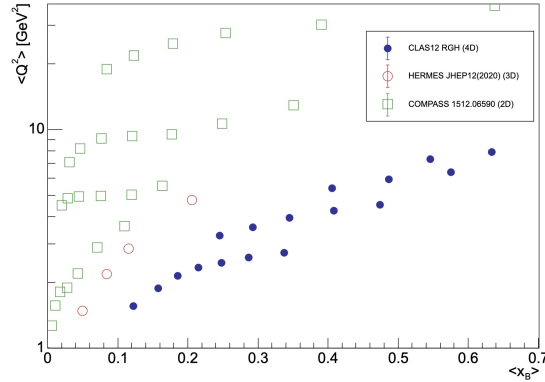


Fig. 67: Coverage of the (x, Q^2) phase space in SIDIS A_{UT} of CLAS12, with respect to HERMES and COMPASS. Note the CLAS12 is the only experiments expected to be able to perform a 4D analysis (blue dot). HERMES published a 3D analysis up to $x \approx 0.2$ [53] (open red dot). COMPASS published a 2D study extended in x and Q^2 but at the price to integrate the relevant hadronic variables z and $P_{h\perp}$ [52] (open green square). All other results are mono-dimensional and not extending above $x = 0.3$

rently underestimated. This makes the measurements of all observables in semi-inclusive π^0 production, and the Sivers effect in particular, critical: the neutral pion is known to receive a minor contribution from exclusive vector-meson decays, and, even in the exclusive limit, minor contributions from longitudinal photons. The high statistics of CLAS12 at large x , where the effects are significant, would allow detailed measurements of TTSA's, in particular as a function of the transverse momentum of hadrons.

An example of the projected Sivers asymmetry measurement with CLAS12-RGH as a function of the transverse momentum of neutral pions in a small bin in x is shown in Fig. 68. Due to correlations of x and P_T of hadrons, measurement over several bins in x , Q^2 and P_T would allow to constrain the k_T -dependence of the Sivers function.

5.1.2 Impact study: Tensor charge

Understanding the transverse momentum dependencies of all kinds of observables in polarized SIDIS, including multiplicities and Sivers asymmetry, has always been a challenging task for theory, but it is instrumental in providing important information for phenomenological studies and a validation of the underlying dynamics description. The contributions from VM, and the strong correlations between hadrons produced in SIDIS, make the measurements with dihadrons critical for the interpretation of complex observables, such as single-spin asymmetries and transverse single-spin asymmetries in particular.

RGH pseudo-data have been used to estimate the impact on our present knowledge of the flavor-separated tensor charge in the JAM framework using di-hadron asymmetries following the setup described in Ref. [23]. The JAM fit

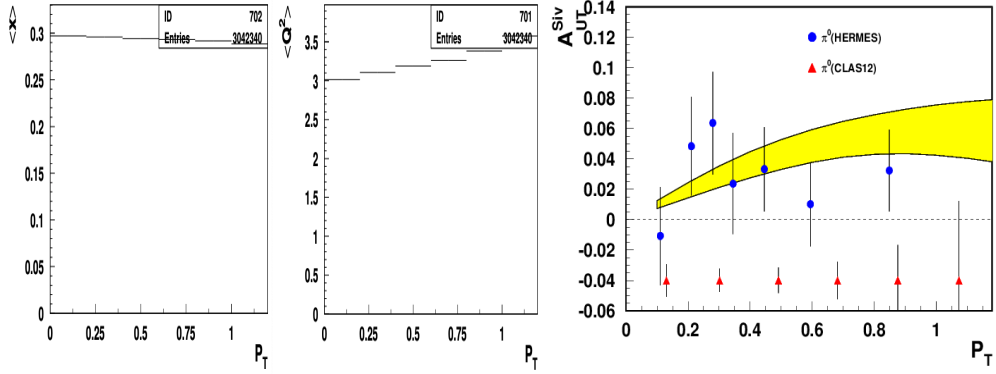


Fig. 68: Kinematical averages of x and Q^2 in bins of P_T used to project the Sivers SSA for π^0 s and the projections for the Sivers SSA versus P_T , for a given small bin in x ($0.25 < x < 0.35$) and z -bin $0.3 < z < 0.8$. The yellow band shows the calculation from JAM3D-22 [18] with the relative uncertainty band calculated in the kinematical point $x = 0.3$, $Q^2 = 3 \text{ GeV}^2$, and $z = 0.4$. The HERMES points are the only existing TTSA measurement for SIDIS π^0 up to now [53]. The red points show the projected statistical error bars for RGH.

uses a parametrized functional form. To our knowledge, there is currently no pure unparametrized (neural network) fit for transversity. A consequence of this is that JAM may underestimate uncertainties on the transversity distribution and thus on the tensor charge in kinematic regions where there are no data. Therefore, it may underestimate the impact of the CLAS12 data. However, as shown below, even with the current setup, the CLAS12 data have a significant impact on the extraction of transversity and tensor charge and may be able, for the first time, to differentiate between the tensor charge value preferred by current extractions from data and from the lattice. The pseudo-data were derived from existing CLAS12 data accounting for the different acceptance and luminosity of RGH. The expected data will significantly reduce the present uncertainty of the di-hadron asymmetry as shown in Figure 69. Specifically, uncertainties in the valence quark region that dominates the value of the tensor charge will be reduced. Current phenomenological extractions from single and di-hadrons favor different values of the tensor charge from those obtained from the lattice. However, due to the restricted kinematical reach of current datasets, no strong conclusion on the compatibility of data and lattice can be drawn: without inclusion of the lattice data, the phenomenological fit prefers a value for the tensor charge that is inconsistent with the lattice value. However, including the lattice value as an overall constraint still yields a good description of the data while producing a value of the tensor charge that is consistent with the lattice result. This behavior is interpreted as evidence that the current data cannot make a strong statement if there is agreement with lattice or not. This is likely due to kinematical areas that are not covered by the data. This behavior has been seen both in the single and di-hadron extractions. As shown in Fig. 70, the situation changes when the projected RGH data is included with the assumption that it follows the current best phenomenological extraction from data only.

Now the fit including the data prefers a different value of the tensor charge than lattice, even when including the lattice point as an overall constraint. The interpretation of this behavior is that the fit now cannot accommodate the tensor charge value preferred by the data and by lattice at the same time. Thus RGH data will be able to differentiate between the tensor charge value preferred by the current data and the lattice [163].

This demonstrates the impact that the projected data will have on the extraction of the tensor charge and the solution of this longstanding issue.

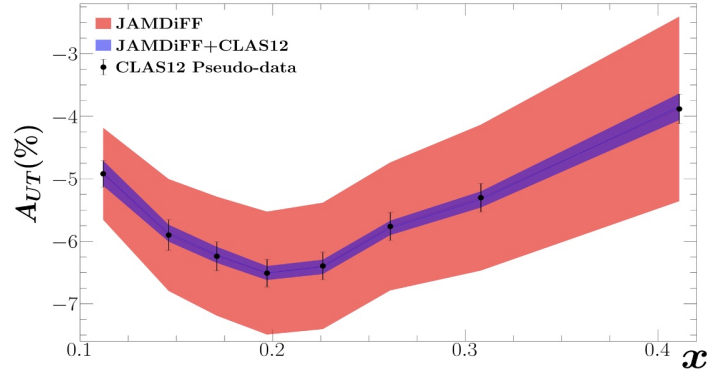


Fig. 69: Impact of the RGH pseudo-data on the JAMDiFF phenomenological fit, from [163].

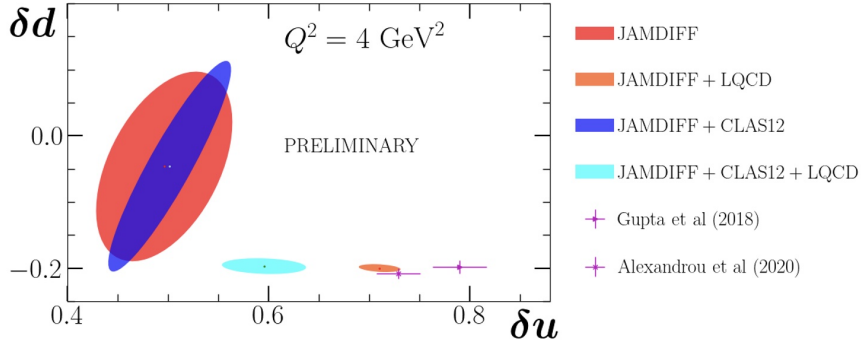


Fig. 70: Impact of the RGH pseudo-data on the tensor charge δu of the u quark flavor, from [163]. The RGH dataset will be competitive with lattice calculations and provide for the first time an effective benchmark.

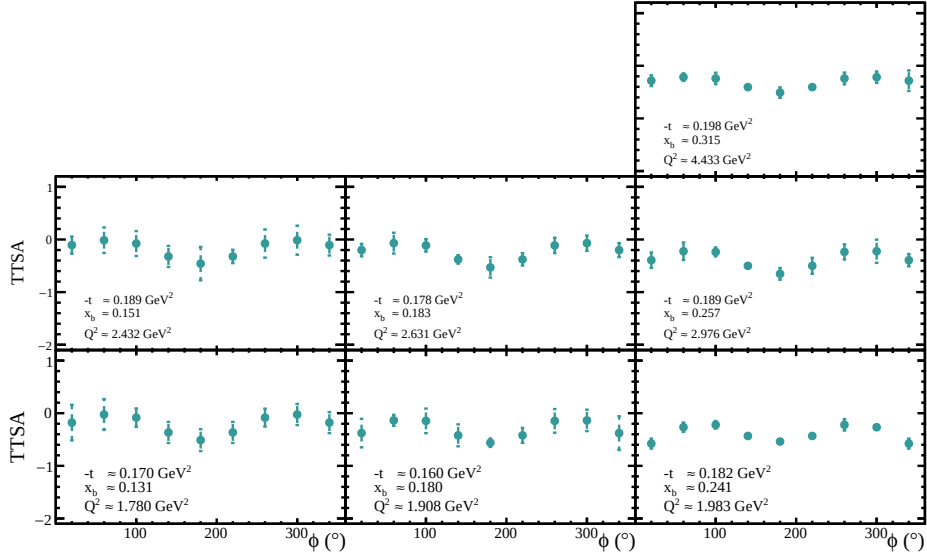


Fig. 71: Projections for the transverse target-spin asymmetry versus ϕ which will be obtained by RGH for the proton-DVCS reaction, for the lowest bin in $-t$, for 3 bins in x_B (along the horizontal axis), and 3 bins in Q^2 (along the vertical axis). The average kinematics is indicated on each plot.

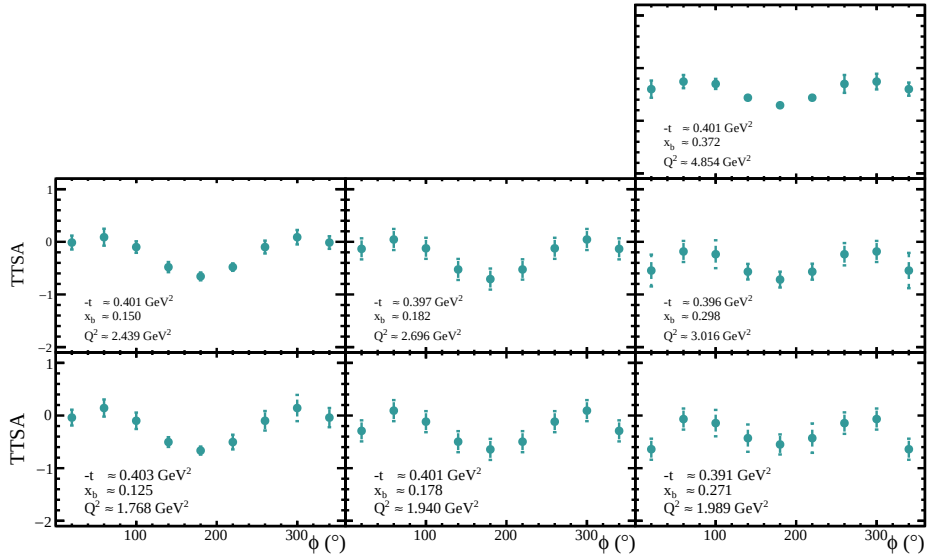


Fig. 72: Projections for the transverse target-spin asymmetry versus ϕ which will be obtained by RGH for the proton-DVCS reaction, for the second bin in $-t$, for 3 bins in x_B (along the horizontal axis), and 3 bins in Q^2 (along the vertical axis). The average kinematics is indicated on each plot.

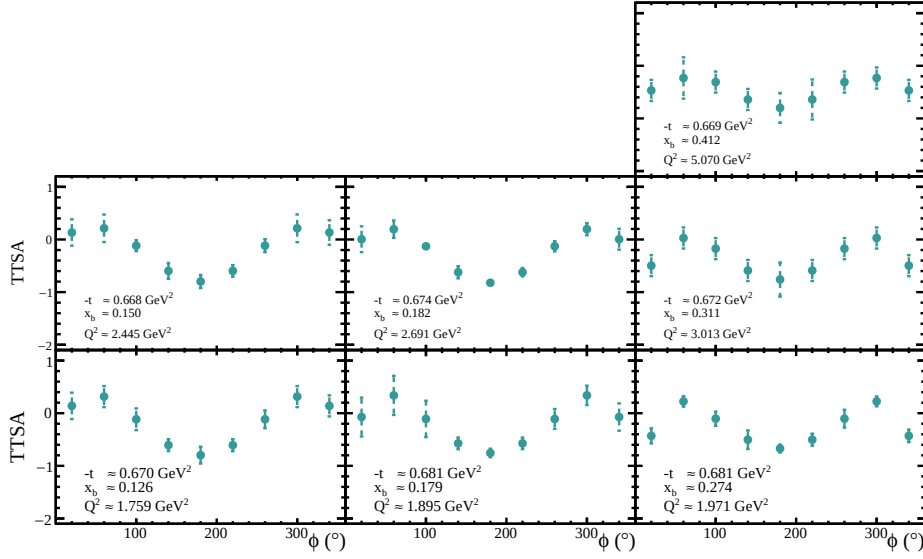


Fig. 73: Projections for the transverse target-spin asymmetry versus ϕ which will be obtained by RGH for the proton-DVCS reaction, for the third bin in $-t$, for 3 bins in x_B (along the horizontal axis), and 3 bins in Q^2 (along the vertical axis). The average kinematics is indicated on each plot.

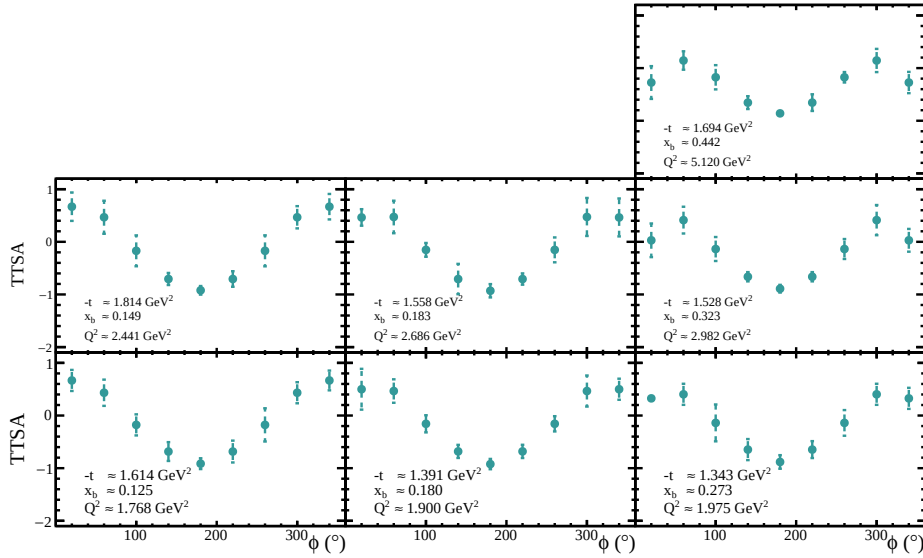


Fig. 74: Projections for the transverse target-spin asymmetry versus ϕ which will be obtained by RGH for the proton-DVCS reaction, for the fourth bin in $-t$, for 3 bins in x_B (along the horizontal axis), and 3 bins in Q^2 (along the vertical axis). The average kinematics is indicated on each plot.

5.2 DVCS

Measuring DVCS on a transversely polarized proton target is crucial, as the transverse target-spin asymmetry (TTSA) is the DVCS observable with the strongest sensitivity to the GPD E of the proton. Knowing E is paramount to extract the contribution of the quarks' angular momentum to the proton spin via the Ji sum rule [10].

Projections for the DVCS TTSA that will be obtained by RGH were computed using a data-driven method to estimate the yields. Proton-DVCS yields (Y) were extracted using data from the RGA Fall 2018 period. The acceptances were computed for the RGH and the RGA configurations using an event generator for DVCS in NH_3 , the CLAS12 GEANT4-based simulation software, GEMC, and the CLAS12 reconstruction. The simulation for RGH included the full realistic description of the recoil tracker and Time-of-Flight detector described in Sec. 3.3. The RGA pDVCS yields were multiplied, for each kinematic bin in $(Q^2, x_B, -t, \phi)$, by the ratio of the RGH and RGA acceptance for pDVCS. Then this product was multiplied by the ratio of the integrated luminosities of RGH and RGA. In this way, the projected yields were estimated in a fully data-driven, model-independent way, and properly accounting for acceptance, efficiency, and luminosity. This is summarized in Eq. 12:

$$Y_{RGH}(i) = Y_{RGA}(i) \cdot \frac{Acc_{RGH}(i)}{Acc_{RGA}(i)} \cdot \frac{L_{RGH}}{L_{RGA}} \cdot \frac{3}{17}, \quad (12)$$

where i labels the 4-dimensional bin in $Q^2, x_B, -t, \phi$, $L_{RGH} = 100 \text{ days} \cdot 5 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $L_{RGA} = 16 \text{ days} \cdot 0.8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, and the factor $3/17$ accounts for the fraction of protons from hydrogen in NH_3 .

The grid of four-dimensional bins was established according to the statistics obtained with Eq. 12. Then, the amplitude of the TTSA was computed, as a function of ϕ , at the average kinematics of each $(Q^2, x_B, -t)$ bin, using the VGG model [130, 131, 66]. The yields obtained via Eq. 12 for RGH were used to deduce the statistical error bars for the TTSA, according to the formula:

$$\sigma_A(i) = \frac{1}{P} \cdot \sqrt{\frac{1 - (P \cdot A)^2}{Y_{RGH}(i)}}, \quad (13)$$

where A is the value of the TTSA at the given $(Q^2, x_B, -t\phi)$ point (represented by i), and P is the target polarization, assumed to be 85%, a value consistent with the typical target performances obtained during the Run Group C run. Note that the selection of the exclusive kinematics via exclusivity cuts largely suppress the nuclear interactions (on nitrogen) and therefore the target dilution $f = 3/17$ reduces the yields, but does not suppress the asymmetry as in the case of SIDIS.

In order to test the sensitivity of the projected data on the GPD E , various sets of quark's angular momenta J_u and J_d were used to compute the TTSA with the VGG model. In this model, indeed, J_u and J_d parametrize directly the GPD E , and can be chosen as input parameters.

The projections for the TTSA are shown in Figs. 71 to 74, plotted as a function of ϕ for each bin in $(Q^2, x_B, -t)$ for the case $J_u = -0.5$, $J_d = -0.1$. Figure 75 shows the transverse target-spin asymmetry versus ϕ for one of the $(Q^2, x_B, -t)$ bins shown in Fig. 73, and for three sets of values of J_u and J_d

(brown: $J_u = 0.5$, $J_d = 0.1$; cyan: $J_u = -0.5$, $J_d = -0.1$; blue: $J_u = 0.2$, $J_d = 0$). The size of the projected error bars allows us to distinguish between the three hypotheses. For comparison, the asymmetry computed with the PARTONS code [164] is also shown (in black), as a cross check of the model used to produce the projections.

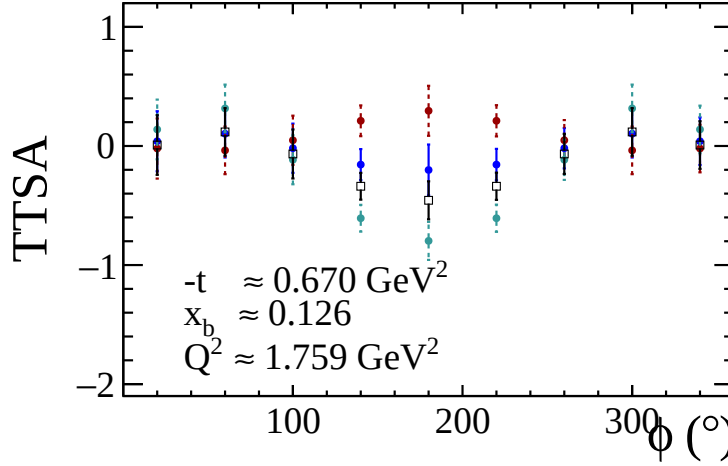


Fig. 75: Projections for the transverse target-spin asymmetry versus ϕ which will be obtained by RGH for the proton-DVCS reaction, for one $(Q^2, x_B, -t)$ bin, and for 3 sets of values of the quark's angular momenta J_u and J_d , as computed by the VGG model. Brown: $J_u = 0.5$, $J_d = 0.1$; cyan: $J_u = -0.5$, $J_d = -0.1$; blue: $J_u = 0.2$, $J_d = 0$. For comparison, the open black squares show the values computed with PARTONS [164]. The error bars reflect the expected statistics of RGH.

This is even more evident in Fig. 76, which shows the A_{UT} moments, extracted by fitting the TTSA with the function $A_{UT} \sin(\phi - \phi_S) \cos \phi$. The colors indicate the three sets of values given to VGG for J_u and J_d . Aside from some kinematics for which the expected statistical precision will be poorer, the precision of the data will be enough to discriminate between the various model hypotheses. Moreover, this will be the first time that the TTSA of pDVCS will be extracted in 4 dimensions and on such a vast kinematic coverage. The only existing published data for this observable, measured by HERMES [165], are included in Fig. 76, represented by the 4 black points in the bottom-left plot. The RGH experiment will not only improve on the statistical precision of those particular kinematics but also extend the measurement of the TTSA over a much larger phase-space region. The inclusion of the RGH pDVCS data in global fits for the extraction of GPDs will strongly constrain the poorly known GPD E of the proton, as will be detailed in Sec. 5.2.3. This will allow us, in particular, to map the t -dependence of the imaginary part of the GPD E , and thus to make an important step toward the extraction of the contribution of the quarks' angular momentum to the proton spin via the Ji sum rule.

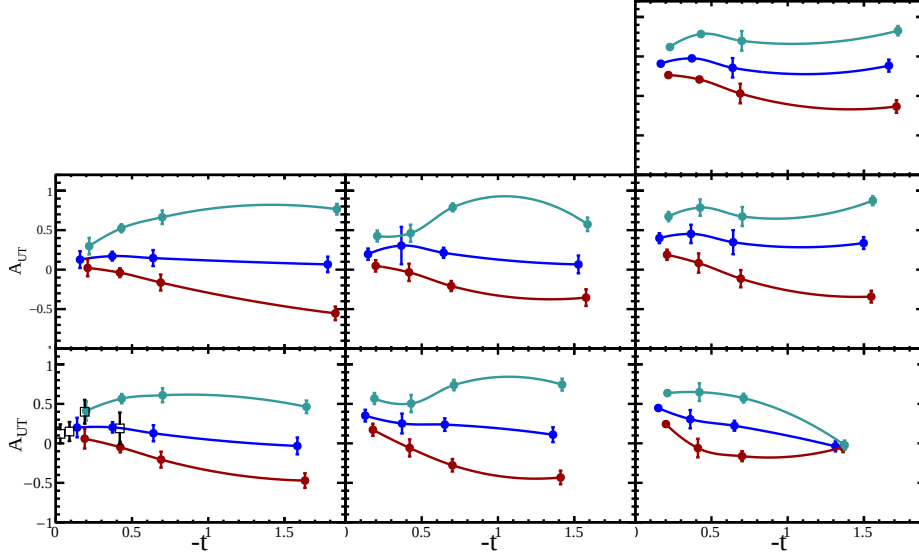


Fig. 76: Projections for the A_{UT} moments which will be obtained by RGH for the proton-DVCS reaction, for the full grid of $(Q^2, x_B, -t)$ bins, and for 3 sets of values of the quark's angular momenta J_u and J_d , as computed by the VGG model. The error bars reflect the expected statistics of RGH. The color code is the same as in the caption of Fig. 75. The 4 black points in the bottom-left plot are the HERMES data [165].

5.2.1 π^0 Background

Once the events containing one electron, one proton, and one photon are selected, the pDVCS/BH final state can be isolated by cutting on the missing masses and other exclusivity variables. However, due to the finite resolutions of the detectors, the final event sample will still be contaminated by events coming from the $ep\pi^0$, where one photon from the π^0 decay is detected in the forward calorimeters while the other escapes detection. This contamination will be evaluated and subtracted as was done in previous DVCS CLAS analyses [69, 72, 71, 73], by extracting exclusive $ep\pi^0$ events — detecting both decay photons — from the data, and using Monte-Carlo simulations to evaluate the ratio of acceptances of π^0 events with 1 and 2 photons detected. The final number of pDVCS/BH events, in each 4-dimensional bin, will be obtained as:

$$N_{DVCS}(Q^2, x_B, -t, \phi) = N_{ep\gamma}(Q^2, x_B, -t, \phi) - N_{\pi^0 1\gamma}(Q^2, x_B, -t, \phi) \quad (14)$$

where

$$N_{\pi^0 1\gamma}(Q^2, x_B, -t, \phi) = N_{\pi^0}^{data}(Q^2, x_B, -t, \phi) \cdot \frac{N_{\pi^0 1\gamma}^{MC}(Q^2, x_B, -t, \phi)}{N_{\pi^0 2\gamma}^{MC}(Q^2, x_B, -t, \phi)}. \quad (15)$$

Here $N_{ep\gamma}$ is the number of events, in a given 4-dimensional bin, passing the DVCS exclusivity cuts, $N_{\pi^0}^{data}$ is the number of events passing the $ep\pi^0$

exclusivity cuts, $N_{\pi^0 1\gamma}^{MC}$ is the number of reconstructed simulated π^0 's passing the DVCS exclusivity cuts, and $N_{\pi^0 2\gamma}^{MC}$ is the number of reconstructed simulated π^0 's passing the $ep\pi^0$ exclusivity cuts. An alternative π^0 background subtraction method was adopted in [75], and will be used as a systematic check in the RGH DVCS analysis.

The level of π^0 background in the RGH setup was evaluated as follows: Monte-Carlo exclusive $ep\pi^0$ events produced on an NH_3 target were generated and passed through the full GEMC simulation and reconstruction chain, for both the RGH and the RGA configurations. Then the π^0 yield was obtained using the same strategy as in Eq. 12, thus scaling the RGA $ep\pi^0$ experimental yields by the ratio of acceptances of RGH and RGA times the luminosity ratio. Figure 77 shows the obtained projected yields in RGH conditions for DVCS (red), $ep\pi^0$ (black), and the sum of DVCS+ π^0 (blue), as a function of three exclusivity variables, after applying the following DVCS selection cuts (on all variables except the plotted one): $E_\gamma > 2$, $Q^2 > 1.0 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $p_p > 0.3 \text{ GeV}$, $p_e > 1.0 \text{ GeV}$, $\Delta\phi < 1.5^\circ$, $\Delta t < 2 \text{ GeV}^2$, $p_X(ep \rightarrow ep\gamma X) < 1 \text{ GeV}$, $\theta_{\gamma X} < 5^\circ$. By comparing the black and blue histograms of Fig. 77 within the regions of the DVCS selection cuts, the π^0 contamination appears to be roughly 30%. This is consistent with what was typically found in other CLAS12 experiments for the DVCS detection topology with photons in the ECAL, as is shown in Sec. 5.2.2 for the RGC case.

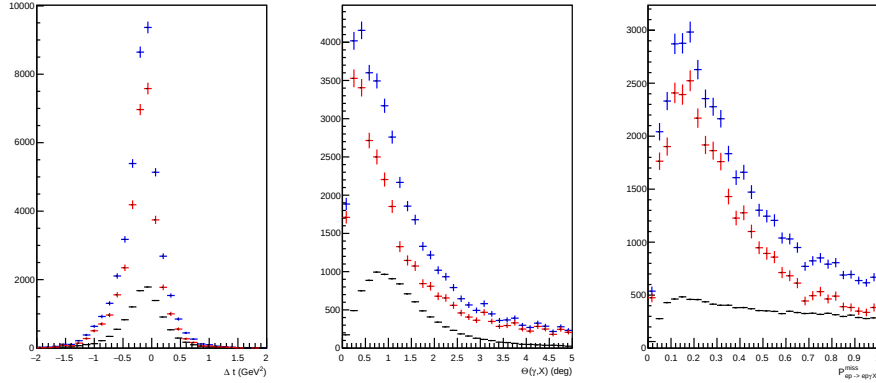


Fig. 77: Projections of yields for DVCS (red), $ep\pi^0$ (black), and DVCS+ π^0 (blue), for three exclusivity variables: the difference between two ways of computing the t variable (left), the cone angle between detected and missing γ (middle), and the missing momentum from $ep \rightarrow ep\gamma X$ (right). For each plot, the DVCS exclusivity cuts are applied on all variables except the plotted one.

5.2.2 DVCS on Polarized NH_3 : the RGC Example

As mentioned previously, data were recently taken by CLAS12 with a longitudinally polarized target during the Run Group C (RGC) experiment, and a

DVCS analysis on protons in NH_3 is ongoing [166]. One of the three run periods composing RGC ("Fall2022") had no Forward Tagger to detect photons, as will be the case for RGH. Here below we show some plots from the ongoing preliminary DVCS analysis to support our simulation-based studies and corroborate the feasibility of the extraction of the DVCS events as well as the assumptions we made in our estimate of the systematic uncertainties (Sec. 5.3).

Figure 78 shows the variables used to ensure the exclusivity of the DVCS final state, and the effects of the applied cuts. In particular, the reduction of the carbon data after cuts shows how effective the exclusivity cuts are in removing the nitrogen background. This is also evident from Fig. 79, where the dilution factor for DVCS is plotted as a function of each of the 4 kinematic variables: its value is around 95%. The dilution factor was computed with two different methods yielding very similar results. This motivates our choice of systematic uncertainty in Sec. 5.3.

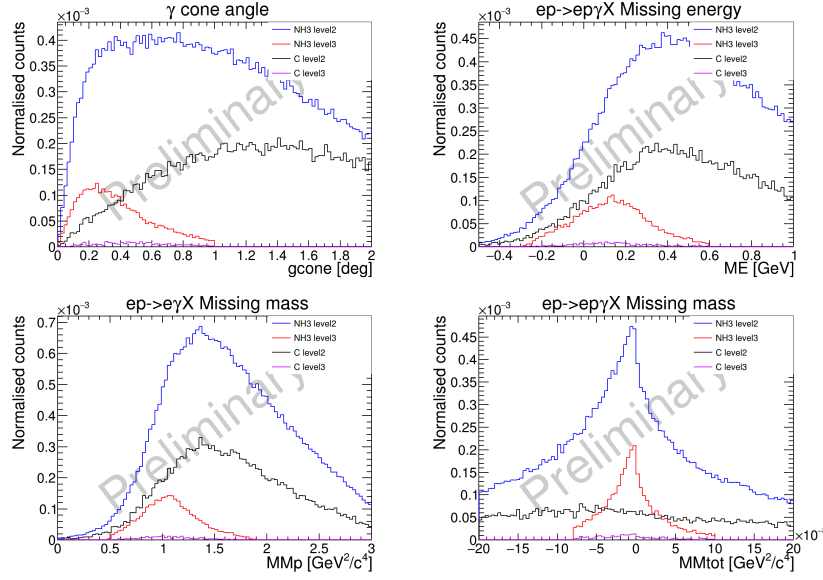


Fig. 78: Preliminary proton-DVCS analysis on CLAS12-RGC data (Fall2022), courtesy of Samy Polcher (CEA Saclay). Exclusivity variables for the selection of the DVCS final state: cone angle between the measured and the missing photon (top left), missing energy of the $e\gamma$ system (top right), missing mass of the $e\gamma$ system (bottom left), missing mass of the $e\gamma$ system (bottom right). The colored lines represent the NH_3 data with no cuts (blue), the carbon data with no cuts (black), the NH_3 data after exclusivity cuts (red), and the carbon data after exclusivity cuts (purple).

The π^0 background subtraction for the Fall2022 dataset DVCS analysis has not yet been completed. Instead, it was carried out for the FTON periods of RGC, and the value of the contamination as a function of ϕ as well as its impact on the target-spin asymmetry (TSA) is shown in Fig. 80. In the central ϕ region, which is dominated by EC photons (same situation as RGH), the π^0

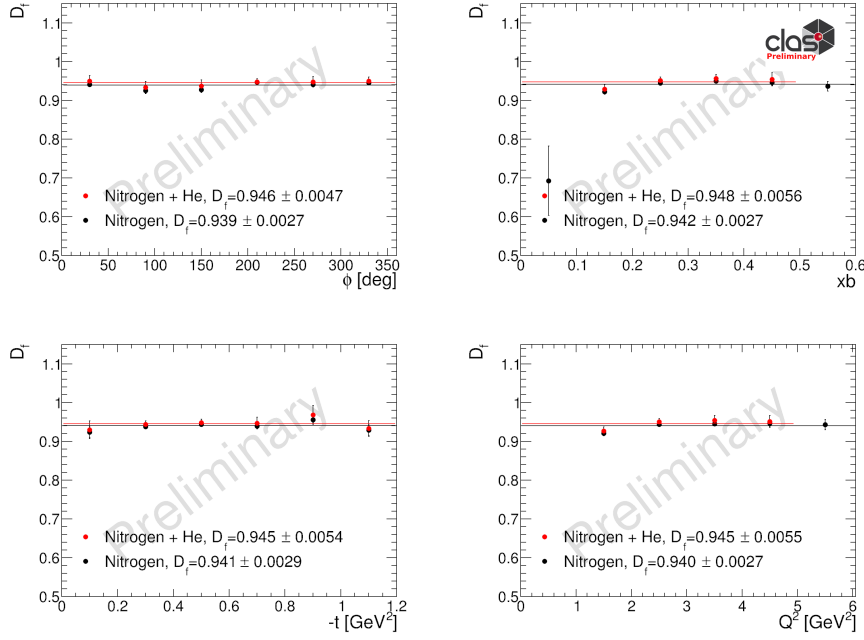


Fig. 79: Preliminary dilution factor for DVCS events, RGC Fall2022 data, as a function of ϕ (top left), x_B (top right), $-t$ (bottom left), Q^2 (bottom right). The black and red points correspond to two different methods to compute the dilution factor, and yield very similar results.

cross section is high and the DVCS one is low, and the π^0 background reaches 30%. However, its impact on the TSA appears minimal, due to the small size of the TSA for exclusive π^0 production compared to the DVCS.

5.2.3 Impact study: extraction of the CFF $\Im\mathcal{E}$

The sensitivity of the RGH pDVCS TTSA to CFFs, in particular to $\Im\mathcal{E}$, was tested by including it in a fit of CFFs by the output of neural networks as an effective parameterization, serving as unbiased interpolation function [167]. Here, the values at the network input represent the kinematical variables x_B , Q^2 , and t , and the values at output represent the imaginary and real parts of the CFFs. Preliminary CFF extractions are presented in Fig. 81: it shows the $\Im\mathcal{H}$ and $\Im\mathcal{E}$ CFFs, extracted by fits to old CLAS, HERMES proton data, and recent CLAS12 data (red bands), and including also the projected TTSA from RGH (green bands). There is an evident reduction, by more than a factor of 3, of the vertical width of the bands for $\Im\mathcal{E}$, after the inclusion of the RGH projected data. Note that the vertical shift of the green band with respect to the red one is merely a reflection of the values of the projected TTSA, which are taken from the VGG model and do not necessarily correspond to reality. What matters is that the precision on the knowledge of $\Im\mathcal{E}$ will increase considerably, and become roughly compatible with the precision on

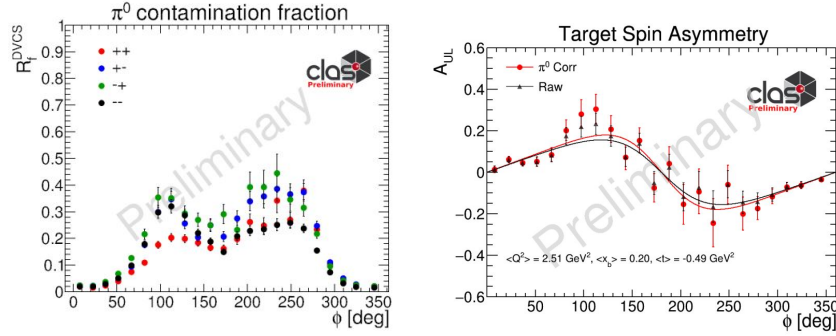


Fig. 80: Left: π^0 contamination on proton DVCS events, as a function of ϕ and for all combinations of spin of beam and target. Right: preliminary longitudinal target-spin asymmetry for proton DVCS (RGC Summer2022 dataset), with and without π^0 subtraction.

$\Im m\mathcal{H}$, thanks to the RGH proton DVCS measurement. This result, combined with the recently obtained results [90] for the beam-spin asymmetry of DVCS on the neutron (the other observable strongly sensitive to E , but mainly for the d quark), will allow an accurate flavor separation of the $\Im m\mathcal{H}$ and $\Im m\mathcal{E}$ CFFs. Therefore, the RGH experiment will bring us closer to the extraction of the contribution of the angular momentum of the u and d quarks to the total spin of the nucleons.

Although this proposal is focused on the TTSA as the main DVCS observable that will be measured, it must be reminded that the double (beam-target) spin asymmetry (DTSA) will also be measurable, without any change of conditions for the experiment, as the CEBAF beam is always polarized. The DTSA is sensitive to a combination of the real CFFs of the GPDs E and H . Therefore, RGH will also bring new constraints on the real parts of the two GPDs entering the Ji's sum rule.

5.3 Systematic Uncertainties

Note that RGH presently assumes to run at a luminosity that is 20 times lower than the nominal CLAS12 value. As a consequence, the precision of the RGH results is expected to be statistically dominated, especially for DVCS.

At JLab, there is a consolidated knowledge of the NH_3 target polarization, which increased with the recent CLAS12 RGC run. When using NMR to measure the polarization of the NH_3 target, the typical uncertainty is 4-5%. The SANE experiment in Hall C (similar target geometry) quotes an uncertainty in the dilution factor of 2% [141].

The published analyses from CLAS/CLAS12 of SIDIS and DVCS observables present systematic uncertainties on acceptance and radiative corrections that are good references for RGH. Possible effects of the missing sector will be mitigated by the microwave-induced swap of the target polarization and are expected to not significantly increase the acceptance uncertainty because the CLAS12 acceptance is already not azimuthally uniform. The RGH recoil is based on technologies (MGPD tracking and scintillating materials) that are al-

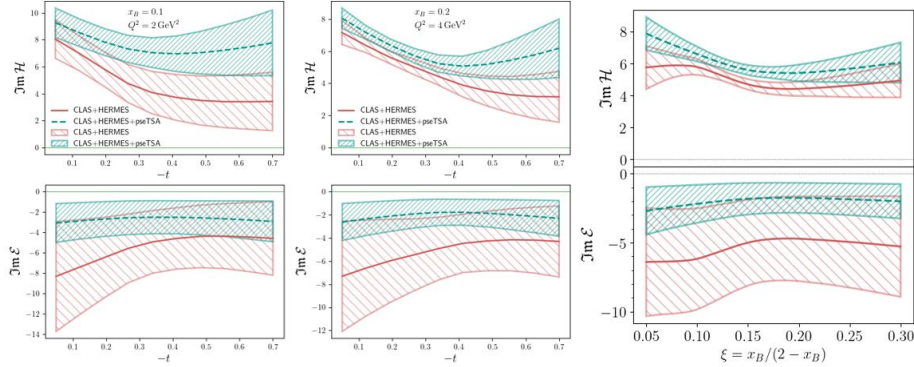


Fig. 81: Impact of the projected transverse target spin asymmetries from RGH on the extraction of the imaginary CFFs of the GPDs H (top) and E (bottom). In the first and second columns the CFFs are plotted as a function of $-t$ for two different Q^2 - x_B kinematics (indicated on the top figures), while the third one is plotted as a function of ξ and computed at $-t = 0.2 \text{ GeV}^2$ and a $Q^2 = 4 \text{ GeV}^2$. The red shaded areas represent the CFF extraction using all the published CLAS and CLAS12 proton-DVCS data plus the HERMES ones, while the green areas show the extraction with those same data plus the projected TTSA from RGH. (Preliminary analysis by Melany Higuera Angulo using the GEPARD framework <https://gepard.phy.hr/>)

ready in use at CLAS12. The effect of the recoil detector performance was studied varying resolution and kinematic range, and typical variations were found to be within 5%. Particle identification, accidental coincidences, and the photo-production of electrons that are misidentified as the scattered electron are typically found to be negligible. The main contributions to systematic uncertainties are listed, for the different reactions of interest, in Tables 5 to 7.

For DVCS, it is anticipated that the main source of systematic uncertainty will come from the choice of the exclusivity cuts. This has been observed in several previous DVCS analyses in CLAS and CLAS12. In the case of the polarized-target analysis, the exclusivity cuts serve the dual purpose of minimizing π^0 contamination as well as reducing the nuclear background from nitrogen. Following the results obtained in the published NH_3 CLAS DVCS analysis [72], we assume around 10% of systematic uncertainty associated to the choice of the exclusivity cuts. The π^0 subtraction will contribute to a few percent of systematic uncertainty, as was established in several previous DVCS analyses by changing the background-subtraction method. The 5% of uncertainty due to the performances of the recoil detector was estimated, as mentioned above, by studying the variation of the DVCS yields with varying detector resolutions.

Source	Systematic Uncertainty
Target polarization	5 %
Target dilution	2 %
Radiative effects	3 %
Acceptance and bin-migration	3 %

Tab. 5: Estimated main contributions to the systematic uncertainty for SIDIS single hadron.

Source	Systematic Uncertainty
Target polarization	5 %
Target dilution	2 %
Baryonic contribution from target fragmentation	1-6%
Bin migration close to ρ mass	1-10%

Tab. 6: Estimated main contributions to the systematic uncertainty for SIDIS di-hadron.

Source	Systematic Uncertainty
Target polarization	5 %
Target dilution	1 %
Recoil performances	5 %
π^0 background	3 %
Exclusivity cuts	10 %

Tab. 7: Estimated main contributions to the systematic uncertainty for DVCS.

6 Beam Time Request

The requested PAC days of data taking for the RGH physics and calibration runs are listed in Table 8. The days listed here are calculated assuming that the accelerator is available at all times with 100% of duty cycle.

To achieve the physics goals of the RGH experiments (according to the projections presented in Sec. 5), 100 PAC days of physics data taking are requested.

The run time with ancillary targets (^{12}C , CH_2 and Empty) accounts for 5 days of commissioning of the new elements (beam line, target, detector), and detector alignment runs. In addition, 8+2 days are required for background-targets running, to correct for the dilution due to the target's nuclear content.

The overhead for target operations is described in Sec. 3.1 and summarized here. Assuming 1 nA and raster diameter of 1.3 cm, each ammonia sample will last about 6 days of beam before annealing is necessary. With two interchangeable ammonia cells on the ladder and some days of background running, one would only need to anneal every 14 days and replace the samples after about 70–80 days (we assume twice). Annealing and polarization recovery will require about 4 h. Thermal equilibrium (TE) calibrations of the NMR instrumentation will be performed weekly and require 8 hours. The target replacement could take UP TO 24 h, depending on the final layout of the beam line. This amounts to 9 days of target overhead, plus 1 day dedicated to Moller runs to measure

the beam polarization.

Beam Energy (GeV)	Beam Current (nA)	Beam Requirements	Target	Material Thickness (mg/cm ²)	Beamtime (PAC days)
10.6	1	Polarized	NH ₃	1040	100
10.6	1	Polarized	¹² C, CH ₂	1040, 1040	5+8
10.6	1	Polarized	Empty	na	2
Operations					10
Total					125

Tab. 8: Data-taking time required to achieve the proposed physics goals assuming the accelerator is available at all times (100% duty cycle).

7 Summary

The RGH experiments at CLAS12 offer a compelling physics program that has the potential to provide unprecedented information on the peculiar parton dynamics within the nucleon and during fragmentation. It will complement the information gathered with unpolarized and longitudinally polarized targets by the same experiment. Since the approval in 2012, the interest in this field of research has grown worldwide and culminated with the start of the EIC Project. The theoretical understanding and lattice calculations have made important progresses, which consolidate the interest in new experimental results. At the same time, a comprehensive program has been pursued at JLab to understand and overcome the technical challenges connected with running a transversely polarized target inside CLAS12. The adopted solution is based on extended validation tests of target alternatives with electron beam, real data and concrete experience acquired so far running the experiment, and the choice of consolidated technologies to favor physics over development. CLAS12 is a running facility with the desired resolution, acceptance and particle identification capabilities validated, and with further potential upgrades being pursued that could boost the RGH reach. We request the PAC to approve the RGH beam time request of 125 PAC days.

A Resources

JCLab Orsay

IJCLab is one of the most active groups in the field of Generalized Parton Distributions within the JLab user community. Its members serve as co-spokespersons for multiple GPD-related experiments and are recognized as leading scientists in the field of nucleon tomography. They have authored numerous high-impact publications on the structure of protons and neutrons through Deeply Virtual Compton Scattering studies, utilizing the GPD framework. Beyond their scientific leadership, the IJCLab group has made substantial contributions to the Hall B physics program, significantly enhancing its instrumentation (calorimeters, scintillation counters, gaseous detectors). Silvia Niccolai is a spokesperson of the DVCS proposal and will lead the IJCLab team, currently composed of 6 staff scientists and several students and post-docs, in the construction, installation, the running of the experiment and the analysis of the data. Currently the group is in charge of the RGH recoil-tracker full GEMC simulation and of its reconstruction and tracking software. A possible technical contribution in the recoil project is envisaged, but it is conditional to the future availability of funding.

Duke

The Duke group has a long-standing interest in transverse spin physics. The group led several CLAS analyses in di-hadron, polarized hyperon, exclusive vector meson and single hadron SIDIS analyses and plans to focus its effort on RGH analyses once data are available. Duke plans to commit significant resources to the R&D, construction and commissioning of the RGH instrumentation. A focus of the group will be the ToF system, which profits from the experience that the Duke group gathered with R&D for similar technology for the EIC. The Duke group led the simulation effort for the ToF scintillator and plans to continue the development for the full detector for RGH. The construction, commissioning, and software development for the RGH recoil detector, specifically the ToF detector, will be a priority of the Duke group in the future and Duke plans to take a leading role. The exact contributions will be contingent on the success of dedicated funding proposals.

INFN-RM2

The INFN-RM2 and INFN-CT groups work closely with the group led by Gianni Bencivenni, the inventor of the μ Rwell technology, contributing to both the CLAS12 upgrade and the ePIC tracking system. They have developed a strong expertise in this technology, participating in R&D efforts on several μ Rwell configurations. One focus of their work is the TOP-readout layout, enabling operation at lower gas gains compared to the traditional “COMPASS” readout (which features decoupled X-Y readout). The X-coordinate readout on the TOP of the amplification stage can introduce dead zones in the active area, therefore a novel design of the wells, aligned on equally spaced grooves has been tested; a so-called μ -Groove prototype has been tested, proving to reach 97% intrinsic efficiency. Hybrid configurations are also under investigation to obtain higher charge gains and more stable detector operation. An important development in this context is the G-Rwell, a hybrid MPGD technology that combines features of GEM and μ Rwell detectors. It employs a GEM foil for

pre-amplification, placed above the μ Rwell layer, which provides a compact and discharge-protected readout structure. Given the experience gained in the development, simulation, and analysis of μ Rwell -based tracking systems, we are strongly interested in contributing to the construction and development of the recoil detectors that will be used in the RGH measurements.

INFN-CT

The INFN-CT group works in close collaboration with the INFN-RM2 group on the development of innovative μ Rwell layouts. The group has a particular expertise in the simulation and analysis of μ Rwell tracking detectors, developed during its work on the CLAS12 upgrade. The group is responsible for the Monte-Carlo simulation of μ Rwell tracking, developing both the geometry description and the digitization for CLAS12. INFN-CT has also contributed to the development of dedicated software for μ Rwell data analysis, especially in implementing the μ TPC (micro Time Projection Chamber) technique. This readout method leverages the time of arrival of ionization clusters and the signal amplitude of the strips to reconstruct hit positions. The μ TPC approach provides an almost flat spatial resolution of approximately 150 μ m across a wide range of incident angles. Given the experience gained in the development, simulation, and analysis of μ Rwell -based tracking systems, we are strongly interested in contributing to the construction and development of the recoil detectors that will be used in the RGH measurements.

INFN-FE

The INFN-FE group has a long-standing interest in parton distributions and contributed significantly to the success of the precursor HERMES experiment. The group has coordinated the analyses with inclusive and transversely polarized data, and was responsible for the HERMES polarized target during the data taking. The group has experience in magnet, cryogenic, and vacuum technologies and is interested in supporting the development of the RGH target system. The group promoted the investigation of 3D nucleon structure studies at JLab and EIC. It coordinated the construction of the CLAS12 RICH detector and developed the readout electronics in collaboration with JLab. INFN-FE is interested in supporting the development of the RGH recoil detector, in particular on the readout of the TOF system, with the possibility to use the spare electronics of the RICH. INFN-FE has technical staff and local mechanical and electronic workshops that can support the preparation of RGH.

INFN-LNF

The INFN-LNF physicists have been among the proponents of several CLAS12 experiments aiming at the study of the nucleon partonic distribution functions and are spokespersons of two of the original experiments composing RGH. The group also has experience in the analysis of the data to extract observables relevant for nucleon structure studies. The group has been responsible for the mechanical design of the CLAS12 RICH detector, of its assembly, installation and initial commissioning and for the development of several software components for its calibration and monitoring. INFN-LNF will be responsible for the design of the RGH recoil detector and will contribute to the design of the target cryostat. INFN-LNF has technical staff and a mechanical workshop that could support the construction of the recoil detector.

INFN-RM1

The INFN-RM1 group is involved in the experimental study of the nucleon structure and internal dynamics by DIS since the HERMES experiment. At JLab the group has contributed and is active in the investigation of the TMDs on the neutron, through the polarized ^3He target in HallA. Rome1 has directly contributed to the definition of the proposal for the measurement of the Single Spin Asymmetry of the SIDIS process on polarized ^3He target at high luminosity using the SBS equipment (approved experiment E12-09-018) including the GEM trackers and the refurbished HERMES RICH. The RGH DIS physics program represents an excellent opportunity to deepen our understanding in the field, and the C12-11-111 experiment, in particular, will provide rather complementary data respect to the SIDIS SBS E12-09-018 approved experiment where the Rome1 group member is co-spokesperson. Moreover, the Rome1 team is interested in supporting the implementation of the experimental apparatus, with particular focus on the tracking system where the group can share its ~ 15 years experience on the development of the MPGD and related acquisition system based on the APV25 chip. The latter has been carried out together with the colleagues of INFN-GE for the SBS GEM trackers; its back-end board is undergoing an upgrade and is proposed as the baseline readout for the RGH μRwell tracking under development, with the possibility to reuse the APV25 front-end electronics of the SBS GEMs.

UConn

The UConn group has been actively involved in the CLAS12 physics program. We led efforts that included data quality assurance, calibration, software development for RICH, momentum corrections, and the development of data unfolding procedures, which resulted in several of the first-round publications of CLAS12. These publications addressed beam spin asymmetries and absolute cross sections of inclusive scattering, hard exclusive channels, and pion/kaon SIDIS processes. The group extracted inclusive cross sections, marking the first absolute cross section measurements with CLAS12 (arXiv:2501.14996). The group is currently working on extracting azimuthal modulations of unpolarized SIDIS cross sections, which are sensitive to the Boer-Mulders function and Cahn effects. The group will lead the efforts to measure A_{UT} to study the Sivers function from RGH. Furthermore, the group will contribute to the preparation of the experiment, data collection, simulations, and data analysis for the successful RGH run and publications.

INFN-GE

The INFN-GE group has extensive expertise in scintillation-based detectors and readout systems. It led the design, deployment, and operation of the CLAS12 Forward Tagger calorimeter, coordinating a multi-institutional project that included a plastic scintillator hodoscope (developed by the University of Edinburgh) and a MicroMegas-based tracker (developed by CEA-Saclay). In recent years, the group has further refined techniques involving scintillating fibers coupled to SiPMs within the BDX project. INFN-GE, in close collaboration with Hall B and JLab DAQ experts, is also leading the development of a new streaming readout DAQ system for CLAS12. In addition to detector development and readout expertise, the group has strong capabilities in detector commissioning and calibration, data reconstruction and particle matching algorithms, innova-

tive AI-assisted data analysis, and simulation software development (GEMC, GEANT4, FLUKA). The group operates a fully equipped laboratory in Genova for assembling and testing detector prototypes prior to installation. This facility is supported by INFN-GE's Electronics Service, Machine Shop, Mechanical Design Service, and Computing Center. The INFN-GE group is committed to designing and deploying the TOF SiPM readout system, implementing the detector geometry and response in the GEMC simulation framework, and contributing to its commissioning, calibration, and operation.

CEA Saclay

The CEA Saclay group is supporting this proposal. The Saclay group is actively involved in CLAS12 analyses on DVCS, in particular, it has led the first publication on DVCS and TCS beam spin asymmetries using RGA data. Currently, the group is strongly involved in the analyses of DVCS asymmetries using the longitudinal polarized target data of RGC. Saclay's experience and support will be beneficial for the success of this proposal.

UNAM

The UNAM group contributed to projections, preliminary studies as well as writing of the original C12-12-009 proposal. In recent years, the UNAM group has worked towards improving the extraction of the collinear transversity PDF, through alternative statistical methods [22]. UNAM group now focuses on Uncertainty Quantification for inverse problems, such as PDF extraction, which ensures the proper account of various sources of uncertainties in the determination of non-perturbative functions through innovative methodologies. They have been actively involved in the analyses of the BSA for di-hadron that is related to the twist-3 PDF $e(x)$ [168], and as such have acquired experience in processing JLab's analyses. Also, A. Courtoy has co-authored recent articles about the field-theoretical definition and interpretation of dihadron fragmentation functions from factorization theorems [42, 43]. In the future, her group would be interested in getting involved in preliminary studies of the transversity PDF with an emphasis on uncertainty quantification, aiming to provide comprehensive interpretation to present puzzles and issues [169], such as the disagreement between the lattice-determined and phenomenological tensor charge. In particular, precision on such quantities are important to test non-standard fundamental interactions, BSM [31]. Also, studies of multiplicities would be of interest for tests of sum rules, related to the definition of DiFF and factorization [43]

South Carolina

The nuclear physics group at the University of South Carolina (USC) has extensive experience in the construction of scintillator-based time-of-flight detectors for (including, e.g., CLAS and MUSE). The scintillator lab has is also used for R&D supported by the EIC detector R&D program. This R&D is carried out in collaboration with Duke and Indiana University and aims to develop a highly segmented hadronic calorimeter also providing excellent muon identification based on the KLM detector used in Belle. The test stand at USC uses a stack of scintillator bars read out by SiPMs. The USC group also has an interest in the physics opportunities with a transversely polarized target. The group is currently involved in exclusive dilepton measurements (E12-12-001, E12-11-003B) with unpolarized targets. While rates with a transversely polarized target

may be too low for TCS and J/psi production, there would be opportunities to study other exclusive meson channels providing complementary information.

References

- [1] JLab PAC. PAC39 Report, 2012. https://www.jlab.org/exp_prog/PACpage/PAC399/PAC39_Final_Report.pdf.
- [2] JLab PAC. PAC41 High-Impact Selection, 2014. https://www.jlab.org/exp_prog/PACpage/PAC41/PAC41_Report.pdf.
- [3] H Avakian et al. Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using the CLAS12 Detector, 2012. https://www.jlab.org/exp_prog/proposals/12/C12-11-111.pdf.
- [4] H. Avakian et al. Measurement of transversity with dihadron production in SIDIS with transversely polarized target, 2012. https://www.jlab.org/exp_prog/proposals/12/PR12-12-009.pdf.
- [5] H. Avakian et al. Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector, 2012. https://www.jlab.org/exp_prog/proposals/12/PR12-12-010_rv.pdf.
- [6] A. Accardi et al. Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all. *Eur. Phys. J. A*, 52(9):268, 2016.
- [7] R. Abdul Khalek et al. Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report. *Nucl. Phys. A*, 1026:122447, 2022.
- [8] JLab PAC. PAC52 Report, 2024. https://www.jlab.org/sites/default/files/PAC/PAC52/PAC52_REPORT_2024.pdf.
- [9] C. Lorce and B. Pasquini. Quark Wigner Distributions and Orbital Angular Momentum. *Phys. Rev. D*, 84:014015, 2011.
- [10] X.-D. Ji. Gauge-Invariant Decomposition of Nucleon Spin. *Phys. Rev. Lett.*, 78:610–613, 1997.
- [11] Matthias Burkardt. Chromodynamic lensing and transverse single spin asymmetries. *Nucl. Phys. A*, 735:185–199, 2004.
- [12] Alessandro Bacchetta and Marco Radici. Constraining quark angular momentum through semi-inclusive measurements. *Phys. Rev. Lett.*, 107:212001, 2011.
- [13] Huey-Wen Lin, W. Melnitchouk, Alexei Prokudin, N. Sato, and H. Shows. First Monte Carlo Global Analysis of Nucleon Transversity with Lattice QCD Constraints. *Phys. Rev. Lett.*, 120(15):152502, 2018.
- [14] Zhong-Bo Kang, Alexei Prokudin, Peng Sun, and Feng Yuan. Extraction of Quark Transversity Distribution and Collins Fragmentation Functions with QCD Evolution. *Phys. Rev. D*, 93(1):014009, 2016.
- [15] M. Anselmino, M. Boglione, U. D’Alesio, J. O. Gonzalez Hernandez, S. Melis, F. Murgia, and A. Prokudin. Collins functions for pions from SIDIS and new e^+e^- data: a first glance at their transverse momentum dependence. *Phys. Rev. D*, 92(11):114023, 2015.

- [16] Umberto D'Alesio, Carlo Flore, and Alexei Prokudin. Role of the Soffer bound in determination of transversity and the tensor charge. *Phys. Lett. B*, 803:135347, 2020.
- [17] Justin Cammarota, Leonard Gamberg, Zhong-Bo Kang, Joshua A. Miller, Daniel Pitonyak, Alexei Prokudin, Ted C. Rogers, and Nobuo Sato. Origin of single transverse-spin asymmetries in high-energy collisions. *Phys. Rev. D*, 102(5):054002, 2020.
- [18] L. Gamberg, M. Malda, J.A. Miller, D. Pitonyak, A. Prokudin, and N. Sato. Updated QCD global analysis of single transverse-spin asymmetries: Extracting $\bar{H}$, and the role of the Soffer bound and lattice QCD. *Phys. Rev. D*, 106(3):034014, 2022.
- [19] M. Boglione, U. D'Alesio, C. Flore, J.O. Gonzalez-Hernandez, F. Murgia, and A. Prokudin. Simultaneous reweighting of Transverse Momentum Dependent distributions. *Phys. Lett. B*, 854:138712, 2024.
- [20] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, and A. Prokudin. Simultaneous extraction of transversity and Collins functions from new SIDIS and e+e- data. *Phys. Rev. D*, 87:094019, 2013.
- [21] Marco Radici and Alessandro Bacchetta. First Extraction of Transversity from a Global Analysis of Electron-Proton and Proton-Proton Data. *Phys. Rev. Lett.*, 120(19):192001, 2018.
- [22] J. Benel, A. Courtoy, and R. Ferro-Hernandez. A constrained fit of the valence transversity distributions from dihadron production. *Eur. Phys. J. C*, 80(5):465, 2020.
- [23] C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, and R. Seidl. First simultaneous global QCD analysis of dihadron fragmentation functions and transversity parton distribution functions. *Phys. Rev. D*, 109(3):034024, 2024.
- [24] C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, and R. Seidl. Transversity Distributions and Tensor Charges of the Nucleon: Extraction from Dihadron Production and Their Universal Nature. *Phys. Rev. Lett.*, 132(9):091901, 2024.
- [25] H. Avakian, A. Bressan, and M. Contalbrigo. Experimental results on TMDs. *Eur. Phys. J. A*, 52(6):150, 2016. [Erratum: *Eur.Phys.J.A* 52, 165 (2016)].
- [26] Marco Radici, A. Courtoy, Alessandro Bacchetta, and Marco Guagnelli. Improved extraction of valence transversity distributions from inclusive dihadron production. *JHEP*, 05:123, 2015.
- [27] Rajan Gupta, Yong-Chull Jang, Boram Yoon, Huey-Wen Lin, Vincenzo Cirigliano, and Tanmoy Bhattacharya. Isovector Charges of the Nucleon from 2+1+1-flavor Lattice QCD. *Phys. Rev. D*, 98:034503, 2018.

- [28] Rajan Gupta, Boram Yoon, Tanmoy Bhattacharya, Vincenzo Cirigliano, Yong-Chull Jang, and Huey-Wen Lin. Flavor diagonal tensor charges of the nucleon from (2+1+1)-flavor lattice QCD. *Phys. Rev. D*, 98(9):091501, 2018.
- [29] C. Alexandrou, S. Bacchio, M. Constantinou, J. Finkenrath, K. Hadjiyianakou, K. Jansen, G. Koutsou, and A. Vaquero Aviles-Casco. Nucleon axial, tensor, and scalar charges and σ -terms in lattice QCD. *Phys. Rev. D*, 102(5):054517, 2020.
- [30] M. Pitschmann, C.-Y. Seng, C.D. Roberts, and S.M. Schmidt. Nucleon tensor charges and electric dipole moments. *Phys. Rev. D*, 91:074004, 2015.
- [31] A. Courtoy, S. Baeßler, M. González-Alonso, and S. Liuti. Beyond-Standard-Model Tensor Interaction and Hadron Phenomenology. *Phys. Rev. Lett.*, 115:162001, 2015.
- [32] I. P. Fernando and D. Keller. Extraction of the Sivers function with deep neural networks. *Phys. Rev. D*, 108(5):054007, 2023.
- [33] Miguel G. Echevarria, Ahmad Idilbi, Zhong-Bo Kang, and Ivan Vitev. QCD Evolution of the Sivers Asymmetry. *Phys. Rev. D*, 89:074013, 2014.
- [34] Alessandro Bacchetta, Filippo Delcarro, Cristian Pisano, and Marco Radici. The 3-dimensional distribution of quarks in momentum space. *Phys. Lett. B*, 827:136961, 2022.
- [35] M. Boglione, U. D'Alesio, C. Flore, and J. O. Gonzalez-Hernandez. Assessing signals of TMD physics in SIDIS azimuthal asymmetries and in the extraction of the Sivers function. *JHEP*, 07:148, 2018.
- [36] A. Bacchetta, D. Boer, M. Diehl, and P.J. Mulders. Matches and mismatches in the descriptions of semi-inclusive processes at low and high transverse momentum. *JHEP*, 08:023, 2008.
- [37] H.H. Matevosyan, A. Kotzinian, E.-C. Aschenauer, H. Avakian, and A.W. Thomas. Predictions for Sivers single spin asymmetries in one- and two-hadron electroproduction at CLAS12 and EIC. *Phys. Rev. D*, 92(5):054028, 2015.
- [38] Chunhua Zeng, Hongxin Dong, Tianbo Liue, Peng Sun, and Yuxiang Zhao. Global analysis of Sivers and Collins asymmetries within the TMD factorization, 12 2024. 2412.18324 hep-ex.
- [39] Chunhua Zeng, Tianbo Liu, Peng Sun, and Yuxiang Zhao. Toward three-dimensional nucleon structures at the Electron-Ion Collider in China: A study of the Sivers function. *Phys. Rev. D*, 106(9):094039, 2022.
- [40] Miguel G. Echevarria, Zhong-Bo Kang, and John Terry. Global analysis of the Sivers functions at NLO+NNLL in QCD. *JHEP*, 01:126, 2021.
- [41] I. Garzia and F. Giordano. Transverse-momentum-dependent fragmentation functions in e^+e^- annihilation. *Eur. Phys. J. A*, 52(6):152, 2016.

- [42] T. C. Rogers, M. Radici, A. Courtoy, and T. Rainaldi. QCD factorization with multihadron fragmentation functions. *Phys. Rev. D*, 111(5):056001, 2025.
- [43] T. Rogers and A. Courtoy. Avenues for a number density interpretation of dihadron fragmentation functions, 4 2024. 2404.02281 hep-ph.
- [44] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P.J. Mulders, and M. Schlegel. Semi-inclusive deep inelastic scattering at small transverse momentum. *JHEP*, 02:093, 2007.
- [45] R.D. Tangerman and P.J. Mulders. Probing transverse quark polarization in deep-inelastic leptonproduction. *Physics Letters B*, 352(1):129–133, 1995.
- [46] Daniel Gutiérrez-Reyes, Ignazio Scimemi, and Alexey A. Vladimirov. Twist-2 matching of transverse momentum dependent distributions. *Phys. Lett. B*, 769:84–89, 2017.
- [47] Daniel Gutierrez-Reyes, Ignazio Scimemi, and Alexey Vladimirov. Transverse momentum dependent transversely polarized distributions at next-to-next-to-leading-order. *JHEP*, 07:172, 2018.
- [48] H. Avakian, A. V. Efremov, P. Schweitzer, and F. Yuan. Transverse momentum dependent distribution function $h_{1T}^\perp$ and the single spin asymmetry $A_{UT}^{\sin(3\phi-\phi_S)}$. *Phys. Rev. D*, 78:114024, 2008.
- [49] Gerald A. Miller. Densities, Parton Distributions, and Measuring the Non-Spherical Shape of the Nucleon. *Phys. Rev. C*, 76:065209, 2007.
- [50] Matthias Burkardt. Spin-orbit correlations and single-spin asymmetries, 9 2007. 0709.2966 hep-ph.
- [51] Y. Zhang et al. Measurement of pretzelosity asymmetry of charged pion production in Semi-Inclusive Deep Inelastic Scattering on a polarized ^3He target. *Phys. Rev. C*, 90(5):055209, 2014.
- [52] C Adolph et al. Sivers asymmetry extracted in SIDIS at the hard scales of the Drell–Yan process at COMPASS. *Phys. Lett. B*, 770:138–145, 2017.
- [53] A. Airapetian et al. Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons. *JHEP*, 12:010, 2020.
- [54] H. Avakian, A. V. Efremov, K. Goeke, A. Metz, P. Schweitzer, and T. Teckentrup. Are there approximate relations among transverse momentum dependent distribution functions? *Phys. Rev. D*, 77:014023, 2008.
- [55] J. Huang et al. Beam-Target Double Spin Asymmetry A_{LT} in Charged Pion Production from Deep Inelastic Scattering on a Transversely Polarized ^3He Target at $1.4 < Q^2 < 2.7 \text{ GeV}^2$. *Phys. Rev. Lett.*, 108:052001, 2012.

- [56] Shohini Bhattacharya, Zhong-Bo Kang, Andreas Metz, Gregory Penn, and Daniel Pitonyak. First global qcd analysis of the tmd g_{1T} from semi-inclusive dis data. *Phys. Rev. D*, 105:034007, Feb 2022.
- [57] Emanuele R. Nocera, Richard D. Ball, Stefano Forte, Giovanni Ridolfi, and Juan Rojo. A first unbiased global determination of polarized pdfs and their uncertainties. *Nuclear Physics B*, 887:276–308, 2014.
- [58] J. J. Ethier, N. Sato, and W. Melnitchouk. First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global qcd analysis. *Phys. Rev. Lett.*, 119:132001, Sep 2017.
- [59] Daniel de Florian, Gonzalo Agustín Lucero, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang. Monte carlo sampling variant of the dssv14 set of helicity parton densities. *Phys. Rev. D*, 100:114027, Dec 2019.
- [60] D. Müller, D. Robaschik, B. Geyer, F.-M. Dittes, and J. Hořejši. Wave functions, evolution equations and evolution kernels from light-ray operators of qcd. *Fortschritte der Physik/Progress of Physics*, 42(2):101–141, 1994.
- [61] A. V. Radyushkin. Nonforward parton distributions. *Phys. Rev. D*, 56:5524–5557, Nov 1997.
- [62] John C. Collins, Leonid Frankfurt, and Mark Strikman. Factorization for hard exclusive electroproduction of mesons in qcd. *Phys. Rev. D*, 56:2982–3006, Sep 1997.
- [63] K. Goeke, M.V. Polyakov, and M. Vanderhaeghen. Hard exclusive reactions and the structure of hadrons. *Progress in Particle and Nuclear Physics*, 47(2):401–515, 2001.
- [64] M. Diehl. Generalized parton distributions. *Physics Reports*, 388(2):41–277, 2003.
- [65] A.V. Belitsky and A.V. Radyushkin. Unraveling hadron structure with generalized parton distributions. *Physics Reports*, 418(1):1–387, 2005.
- [66] M. Guidal. A fitter code for deep virtual compton scattering and generalized parton distributions. *The European Physical Journal A*, 37(3):319–332, September 2008.
- [67] S. Stepanyan et al. Observation of exclusive deeply virtual compton scattering in polarized electron beam asymmetry measurements. *Phys. Rev. Lett.*, 87:182002, Oct 2001.
- [68] C. Munoz Camacho et al. Scaling tests of the cross section for deeply virtual compton scattering. *Phys. Rev. Lett.*, 97:262002, Dec 2006.
- [69] F. X. Girod et al. Measurement of deeply virtual compton scattering beam-spin asymmetries. *Phys. Rev. Lett.*, 100:162002, Apr 2008.
- [70] S. Chen et al. Measurement of deeply virtual compton scattering with a polarized-proton target. *Phys. Rev. Lett.*, 97:072002, Aug 2006.

- [71] E. Seder et al. Longitudinal target-spin asymmetries for deeply virtual compton scattering. *Phys. Rev. Lett.*, 114:032001, Jan 2015.
- [72] S. Pisano et al. Single and double spin asymmetries for deeply virtual compton scattering measured with clas and a longitudinally polarized proton target. *Phys. Rev. D*, 91:052014, Mar 2015.
- [73] H. S. Jo et al. Cross sections for the exclusive photon electroproduction on the proton and generalized parton distributions. *Phys. Rev. Lett.*, 115:212003, Nov 2015.
- [74] M. Defurne et al. E00-110 experiment at jefferson lab hall a: Deeply virtual compton scattering off the proton at 6 gev. *Phys. Rev. C*, 92:055202, Nov 2015.
- [75] G. Christiaens et al. First clas12 measurement of deeply virtual compton scattering beam-spin asymmetries in the extended valence region. *Phys. Rev. Lett.*, 130:211902, May 2023.
- [76] A. Airapetian et al. Measurement of the beam-spin azimuthal asymmetry associated with deeply-virtual compton scattering. *Phys. Rev. Lett.*, 87:182001, Oct 2001.
- [77] A. Airapetian et al. Beam-charge azimuthal asymmetry and deeply virtual compton scattering. *Phys. Rev. D*, 75:011103, Jan 2007.
- [78] A. Airapetian et al. Measurement of Azimuthal Asymmetries With Respect To Both Beam Charge and Transverse Target Polarization in Exclusive Electroproduction of Real Photons. *JHEP*, 06:066, 2008.
- [79] A. Airapetian et al. Separation of contributions from deeply virtual Compton scattering and its interference with the Bethe-Heitler process in measurements on a hydrogen target. *JHEP*, 11:083, 2009.
- [80] A. Airapetian et al. Exclusive Leptoproduction of Real Photons on a Longitudinally Polarised Hydrogen Target. *JHEP*, 06:019, 2010.
- [81] A. Airapetian et al. Measurement of double-spin asymmetries associated with deeply virtual Compton scattering on a transversely polarized hydrogen target. *Phys. Lett.*, B704:15–23, 2011.
- [82] A. Airapetian et al. Beam-helicity and beam-charge asymmetries associated with deeply virtual Compton scattering on the unpolarised proton. *JHEP*, 07:032, 2012.
- [83] F. D. Aaron et al. Measurement of Diffractive Scattering of Photons with Large Momentum Transfer at HERA. *Phys. Lett. B*, 672:219–226, 2009.
- [84] A. Aktas et al. Measurement of deeply virtual compton scattering at HERA. *Eur. Phys. J.*, C44:1–11, 2005.
- [85] C. Adloff et al. Measurement of deeply virtual Compton scattering at HERA. *Phys. Lett.*, B517:47–58, 2001.

- [86] S. Chekanov et al. A Measurement of the Q^{*2} , W and t dependences of deeply virtual Compton scattering at HERA. *JHEP*, 05:108, 2009.
- [87] S. Chekanov et al. Measurement of deeply virtual Compton scattering at HERA. *Phys. Lett.*, B573:46–62, 2003.
- [88] R. Akhunzyanov et al. Transverse extension of partons in the proton probed in the sea-quark range by measuring the dvcs cross section. *Physics Letters B*, 793:188–194, 2019.
- [89] Andrei V. Belitsky, Dieter Mueller, and A. Kirchner. Theory of deeply virtual Compton scattering on the nucleon. *Nucl. Phys.*, B629:323–392, 2002.
- [90] A. Hobart et al. First Measurement of Deeply Virtual Compton Scattering on the Neutron with Detection of the Active Neutron. *Phys. Rev. Lett.*, 133(21):211903, 2024.
- [91] Wolf-Dieter Nowak and HERMES collaboration. Model-dependent constraint on quark total angular momentum based on the transverse target-spin asymmetry measured in deeply virtual compton scattering at hermes. *AIP Conference Proceedings*, 915(1):603–606, 06 2007.
- [92] Huey-Wen Lin et al. Parton distributions and lattice QCD calculations: a community white paper. *Prog. Part. Nucl. Phys.*, 100:107–160, 2018.
- [93] C. Alexandrou et al. Moments of the nucleon transverse quark spin densities using lattice QCD. *Phys. Rev. D*, 107(5):054504, 2023.
- [94] A. Scapellato, C. Alexandrou, K. Cichy, M. Constantinou, K. Hadjiyianakou, K. Jansen, and F. Steffens. Proton generalized parton distributions from lattice QCD. *Rev. Mex. Fis. Suppl.*, 3(3):0308104, 2022.
- [95] Shohini Bhattacharya, Krzysztof Cichy, Martha Constantinou, Andreas Metz, Niilo Nurminen, and Fernanda Steffens. Generalized parton distributions from the pseudodistribution approach on the lattice. *Phys. Rev. D*, 110(5):054502, 2024.
- [96] C. Adolph et al. Collins and Sivers asymmetries in muonproduction of pions and kaons off transversely polarised protons. *Phys. Lett. B*, 744:250–259, 2015.
- [97] G.D. Alexeev et al. Transverse-spin-dependent azimuthal asymmetries of pion and kaon pairs produced in muon-proton and muon-deuteron semi-inclusive deep inelastic scattering. *Phys. Lett. B*, 845:138155, 2023.
- [98] G.D. Alexeev et al. High-Statistics Measurement of Collins and Sivers Asymmetries for Transversely Polarized Deuterons. *Phys. Rev. Lett.*, 133(10):101903, 2024.
- [99] M.G. Alexeev et al. Measurement of P_T -weighted Sivers asymmetries in leptonproduction of hadrons. *Nucl. Phys. B*, 940:34–53, 2019.
- [100] Bakur Parsamyan. SIDIS transverse spin azimuthal asymmetries at COMPASS: Multidimensional analysis. *PoS, QCDEV2015:007*, 2015.

- [101] A. Airapetian et al. Evidence for a Transverse Single-Spin Asymmetry in Leptoproduction of $\pi^+\pi^-$ Pairs. *JHEP*, 06:017, 2008.
- [102] A. Airapetian et al. Observation of the Naive-T-odd Sivers Effect in Deep-Inelastic Scattering. *Phys. Rev. Lett.*, 103:152002, 2009.
- [103] X. Qian et al. Single Spin Asymmetries in Charged Pion Production from Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized ^3He Target. *Phys. Rev. Lett.*, 107:072003, 2011.
- [104] Y. X. Zhao et al. Single spin asymmetries in charged kaon production from semi-inclusive deep inelastic scattering on a transversely polarized ^3He target. *Phys. Rev. C*, 90(5):055201, 2014.
- [105] R. Seidl et al. Measurement of Azimuthal Asymmetries in Inclusive Production of Hadron Pairs in e^+e^- Annihilation at $s^{*(1/2)} = 10.58\text{-GeV}$. *Phys. Rev. D*, 78:032011, 2008. [Erratum: *Phys.Rev.D* 86, 039905 (2012)].
- [106] R. Seidl et al. Invariant-mass and fractional-energy dependence of inclusive production of di-hadrons in e^+e^- annihilation at $\sqrt{s} = 10.58\text{ GeV}$. *Phys. Rev. D*, 96(3):032005, 2017.
- [107] A. Vossen et al. Observation of transverse polarization asymmetries of charged pion pairs in e^+e^- annihilation near $\sqrt{s} = 10.58\text{ GeV}$. *Phys. Rev. Lett.*, 107:072004, 2011.
- [108] J. P. Lees et al. Measurement of Collins asymmetries in inclusive production of charged pion pairs in e^+e^- annihilation at BABAR. *Phys. Rev. D*, 90(5):052003, 2014.
- [109] J. P. Lees et al. Collins asymmetries in inclusive charged KK and $K\pi$ pairs produced in e^+e^- annihilation. *Phys. Rev. D*, 92(11):111101, 2015.
- [110] M. Ablikim et al. Measurement of azimuthal asymmetries in inclusive charged dipion production in e^+e^- annihilations at $\sqrt{s} = 3.65\text{ GeV}$. *Phys. Rev. Lett.*, 116(4):042001, 2016.
- [111] L. Adamczyk et al. Observation of Transverse Spin-Dependent Azimuthal Correlations of Charged Pion Pairs in $p^\uparrow + p$ at $\sqrt{s} = 200\text{ GeV}$. *Phys. Rev. Lett.*, 115:242501, 2015.
- [112] L. Adamczyk et al. Transverse spin-dependent azimuthal correlations of charged pion pairs measured in $p^\uparrow + p$ collisions at $\sqrt{s} = 500\text{ GeV}$. *Phys. Lett. B*, 780:332–339, 2018.
- [113] J. Adams et al. Cross-sections and transverse single spin asymmetries in forward neutral pion production from proton collisions at $s^{*(1/2)} = 200\text{-GeV}$. *Phys. Rev. Lett.*, 92:171801, 2004.
- [114] J. H. Lee and F. Videbaek. Single spin asymmetries of identified hadrons in polarized $p + p$ at $s^{*(1/2)} = 62.4$ and 200-GeV . *AIP Conf. Proc.*, 915(1):533–538, 2007.

- [115] B. I. Abelev et al. Forward Neutral Pion Transverse Single Spin Asymmetries in p+p Collisions at $s^{*}(1/2) = 200$ -GeV. *Phys. Rev. Lett.*, 101:222001, 2008.
- [116] L. Adamczyk et al. Transverse Single-Spin Asymmetry and Cross-Section for π^0 and η Mesons at Large Feynman- x in Polarized $p + p$ Collisions at $\sqrt{s} = 200$ GeV. *Phys. Rev. D*, 86:051101, 2012.
- [117] Leszek Adamczyk et al. Azimuthal transverse single-spin asymmetries of inclusive jets and charged pions within jets from polarized-proton collisions at $\sqrt{s} = 500$ GeV. *Phys. Rev. D*, 97(3):032004, 2018.
- [118] Jaroslav Adam et al. Measurement of transverse single-spin asymmetries of π^0 and electromagnetic jets at forward rapidity in 200 and 500 GeV transversely polarized proton-proton collisions. *Phys. Rev. D*, 103(9):092009, 2021.
- [119] L. C. Bland et al. Cross Sections and Transverse Single-Spin Asymmetries in Forward Jet Production from Proton Collisions at $\sqrt{s} = 500$ GeV. *Phys. Lett. B*, 750:660–665, 2015.
- [120] G.D. Alexeev et al. Final COMPASS Results on the Transverse-Spin-Dependent Azimuthal Asymmetries in the Pion-Induced Drell-Yan Process. *Phys. Rev. Lett.*, 133(7):071902, 2024.
- [121] L. Adamczyk et al. Measurement of the transverse single-spin asymmetry in $p^\uparrow + p \rightarrow W^\pm/Z^0$ at RHIC. *Phys. Rev. Lett.*, 116(13):132301, 2016.
- [122] V. D. Burkert et al. Precision studies of QCD in the low energy domain of the EIC. *Prog. Part. Nucl. Phys.*, 131:104032, 2023.
- [123] David Kapukchyan. Spin and Forward Physics with the STAR detector: Measurements and Future Plans. In *Workshop of QCD and Forward Physics at the the LHC, the future Electron Ion Collider and Cosmic Ray Physics*, pages 113–122, Lawrence, 2020. University of Kansas Libraries.
- [124] M. Santimaria, V. Carassiti, G. Ciullo, P. Di Nezza, P. Lenisa, S. Mariani, L. L. Pappalardo, and E. Steffens. The LHCspin project, 11 2021. 2111.04515 hep-ex.
- [125] A. Accardi et al. LHCspin: a Polarized Gas Target for LHC, 4 2025. 2504.16034 hep-ex.
- [126] Elke-Caroline Aschenauer et al. The RHIC Cold QCD Program, 2 2023. 2302.00605, nucl-ex.
- [127] H. Gao et al. Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic ($e, e'^\pm$) Reaction on a Transversely Polarized ^3He Target at 8.8 and 11 GeV - E12-10-006, 2010. https://www.jlab.org/exp_prog/proposals/10/PR12-10-006.pdf.
- [128] H. Gao et al. Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic ($e, e'^\pm$) Reaction on a Transversely Polarized Proton Target - E12-11-108, 2011. https://www.jlab.org/exp_prog/proposals/11/PR12-11-108.pdf.

- [129] M. Guidal, M. V. Polyakov, A. V. Radyushkin, and M. Vanderhaeghen. Nucleon form-factors from generalized parton distributions. *Phys. Rev.*, D72:054013, 2005.
- [130] M. Vanderhaeghen, Pierre A. M. Guichon, and M. Guidal. Hard electroproduction of photons and mesons on the nucleon. *Phys. Rev. Lett.*, 80:5064–5067, 1998.
- [131] M. Vanderhaeghen, Pierre A. M. Guichon, and M. Guidal. Deeply virtual electroproduction of photons and mesons on the nucleon: Leading order amplitudes and power corrections. *Phys. Rev.*, D60:094017, 1999.
- [132] F. Ellinghaus, W. D. Nowak, A. V. Vinnikov, and Z. Ye. Can the total angular momentum of u-quarks in the nucleon be accessed at HERMES? *Eur. Phys. J.*, C46:729–739, 2006.
- [133] P.A. Adderley et al. The Continuous Electron Beam Accelerator Facility at 12 GeV. *Phys. Rev. Accel. Beams*, 27(8):084802, 2024.
- [134] V.D. Burkert et al. The CLAS12 Spectrometer at Jefferson Laboratory. *Nucl. Instrum. Meth. A*, 959:163419, 2020.
- [135] B. Raydo, S. Boyarinov, A. Celentano, C. Cuevas, R. de Vita, V. Kubarovsky, B. Moffit, S. Niccolai, R. Paremuzyan, and C. Smith. The CLAS12 Trigger System. *Nucl. Instrum. Meth. A*, 960:163529, 2020.
- [136] D.S. Carman et al. The CLAS12 Forward Time-of-Flight system. *Nucl. Instrum. Meth. A*, 960:163629, 2020.
- [137] M. Contalbrigo et al. The large-area hybrid-optics CLAS12 RICH: First years of data-taking. *Nucl. Instrum. Meth. A*, 1057:168758, 2023.
- [138] M. Contalbrigo et al. The CLAS12 Ring Imaging Cherenkov detector. *Nucl. Instrum. Meth. A*, 964:163791, 2020.
- [139] J. Pierce, J. Maxwell, and C. Keith. Dynamically polarized target for the g_2^p and G_E^p experiments at Jefferson Lab. *Nucl. Instrum. Meth. A*, 738:54–60, 2014.
- [140] Christopher Keith. A Dynamically Polarized Solid Target for CLAS12. *PoS*, PSTP2017:008, 2018.
- [141] J. D. Maxwell et al. Design and Performance of the Spin Asymmetries of the Nucleon Experiment. *Nucl. Instrum. Meth. A*, 885:145–159, 2018.
- [142] C. D. Keith, J. Brock, C. Carlin, T. Kageya, V. Lagerquist, J. Maxwell, and P. Pandey. First Use of a Longitudinally Polarized Target with CLAS12. *PoS*, PSTP2022:009, 2023.
- [143] Christopher Keith. Design Considerations for a Transversely Polarized Solid Target in Hall B at Jefferson Lab. *PoS*, SPIN2023:214, 2024.
- [144] CryoMagnetics Inc. 7.5 Tesla Split Pair Cryogen-FREE Magnet System Dual RTB, 2025. <https://cryomagnetics.com/7-5-tesla-split-pair-cryogen-free-magnet-system-dual-rtb/>.

- [145] M. Böhm, A. Lehmann, S. Motz, and F. Uhlig. Fast SiPM Readout of the PANDA TOF Detector. *JINST*, 11(05):C05018, 2016.
- [146] T. Rostomyan et al. Timing detectors with SiPM read-out for the MUSE experiment at PSI. *Nucl. Instrum. Meth. A*, 986:164801, 2021.
- [147] F. Sauli. GEM: A new concept for electron amplification in gas detectors. *Nucl. Instrum. Meth. A*, 386:531–534, 1997.
- [148] L. Periale, V. Peskov, P. Carlson, T. Francke, P. Pavlopoulos, P. Picchi, and F. Pietropaolo. Detection of the primary scintillation light from dense Ar, Kr and Xe with novel photosensitive gaseous detectors. *Nucl. Instrum. Meth. A*, 478:377–383, 2002.
- [149] R. Chechik, A. Breskin, and C. Shalem. Thick GEM-like multipliers: A Simple solution for large area UV-RICH detectors. *Nucl. Instrum. Meth. A*, 553:35–40, 2005.
- [150] Y. Giomataris, P. Rebougeard, J. P. Robert, and Georges Charpak. MICROMEGAS: A High granularity position sensitive gaseous detector for high particle flux environments. *Nucl. Instrum. Meth. A*, 376:29–35, 1996.
- [151] G. Bencivenni, R. De Oliveira, G. Morello, and M. Poli Lener. The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD. *JINST*, 10(02):P02008, 2015.
- [152] G. Bencivenni, R. De Oliveira, G. Felici, M. Gatta, M. Giovannetti, G. Morello, and M. Poli Lener. The μ -RWELL for high rate application. *JINST*, 15(09):C09034, 2020.
- [153] M.J. French et al. Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker. *Nucl. Instrum. Meth. A*, 466:359–365, 2001.
- [154] F. Dubinin, N. Boyko, A. Konotop, G. Dolganov, and A. Zhurkina. PET Prototype Based on Scintillation Detectors GAGG-SiPM Coupled to 32-Channel Petiroc2A Chip. *Phys. Part. Nucl. Lett.*, 21(4):715–718, 2024.
- [155] T. Saleem, S. Ahmad, J.-B. Cizel, C. De La Taille, M. Morenas, V. Nadig, F. Perez, V. Schulz, S. Gundacker, and J. Fleury. Study experimental time resolution limits of recent ASICs at Weeroc with different SiPMs and scintillators. *JINST*, 18(10):P10005, 2023.
- [156] R. Kelleher. A MuID and Hadronic Calorimeter for a Second Detector at the EIC - Talk at the 2024 Fall Meeting of the APS Division of Nuclear Physics, 2012. <https://meetings.aps.org/Meeting/DNP24/Session/F12.6>.
- [157] P. Thomadakis, A. Angelopoulos, G. Gavalian, and N. Chrisochoides. Using machine learning for particle track identification in the CLAS12 detector. *Comput. Phys. Commun.*, 276:108360, 2022.
- [158] P. Thomadakis, A. Angelopoulos, G. Gavalian, and N. Chrisochoides. De-noising drift chambers in CLAS12 using convolutional auto encoders. *Comput. Phys. Commun.*, 271:108201, 2022.

-
- [159] G. Christiaens et al. First CLAS12 Measurement of Deeply Virtual Compton Scattering Beam-Spin Asymmetries in the Extended Valence Region. *Phys. Rev. Lett.*, 130(21):211902, 2023.
- [160] T. B. Hayward et al. Observation of Beam Spin Asymmetries in the Process $ep \rightarrow e' \pi^+ \pi^- X$ with CLAS12. *Phys. Rev. Lett.*, 126:152501, 2021.
- [161] S. Diehl et al. Multidimensional, High Precision Measurements of Beam Single Spin Asymmetries in Semi-inclusive π^+ Electroproduction off Protons in the Valence Region. *Phys. Rev. Lett.*, 128(6):062005, 2022.
- [162] M. Anselmino, A. Mukherjee, and A.1 Vossen. Transverse spin effects in hard semi-inclusive collisions. *Prog. Part. Nucl. Phys.*, 114:103806, 2020.
- [163] Y. Sawaya. Phenomenological fits of di-hadron A_{UT} . *poster at POETIC Conference*, 2025.
- [164] B. Berthou et al. Partons: Partonic tomography of nucleon software. *The European Physical Journal C*, 78(478), 2018.
- [165] A. Airapetian et al. Measurement of Azimuthal Asymmetries With Respect To Both Beam Charge and Transverse Target Polarization in Exclusive Electroproduction of Real Photons. *JHEP*, 06:066, 2008.
- [166] S Polcher et al. Release note: Dvcs on longitudinally polarised proton with the rgc experiment at clas12, 2025. https://clas12-docdb.jlab.org/DocDB/0012/001232/004/releaseNote_DIS2025_v3.pdf.
- [167] K. Kumerički, D. Müller, and K. Passek-Kumerički. Towards a fitting procedure for deeply virtual compton scattering at next-to-leading order and beyond. *Nuclear Physics B*, 794(1):244–323, 2008.
- [168] Aurore Courtoy, Angel S. Miramontes, Harut Avakian, Marco Mirazita, and Silvia Pisano. Extraction of the higher-twist parton distribution $e(x)$ from CLAS data. *Phys. Rev. D*, 106(1):014027, 2022.
- [169] Lucas Kotz, Aurore Courtoy, Pavel Nadolsky, Fredrick Olness, and Maximiliano Ponce-Chavez. Analysis of parton distributions in a pion with Bézier parametrizations. *Phys. Rev. D*, 109(7):074027, 2024.