Hall-B Run Group H
CLAS12 Experiments with a Transversely Polarized Target

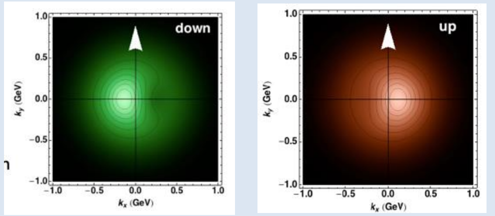
Contalbrigo Marco - INFN Ferrara

JLab PAC53 Meeting, 23th July 2025

3D Nucleon Structure by DIS

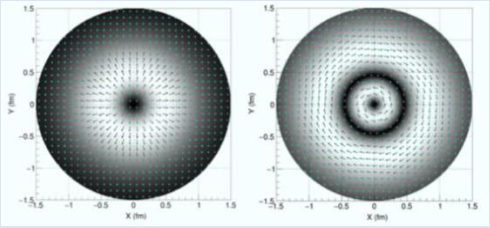
TMD (x, k_T) quark polarisation

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

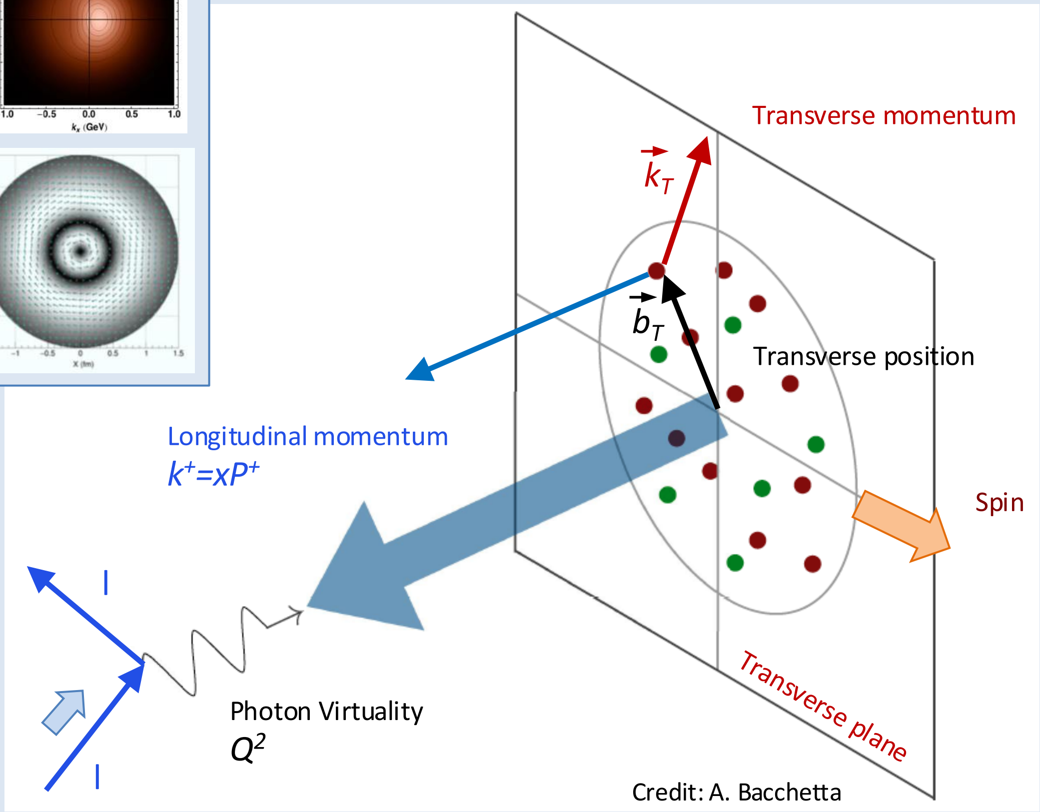


GPD (x, b_T) quark polarisation

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



Confinement Scale



High Energy Probe
Hard Scale

PAC39 2012

Experiment	Contact	Title	Rating	PAC days
C12-11-111	M. Contalbrigo	Transverse spin effect in SIDIS at 11 GeV with a transversely polarized target using CLAS12	A	110
C12-12-009	H. Avakian	Measurement of transversity with di-hadron production in SIDIS with a transversely polarized target	A	110
C12-12-010	L. Elouadrhiri	Deeply Virtual Compton scattering at 11 GeV with transversely polarized target using the CLAS12 detector	A	110

Access to unique observables in

- SIDIS hadron
- SIDIS Di-hadron
- DVCS

All RGH experiments selected among the high impact JLab measurements PAC42 [2014]

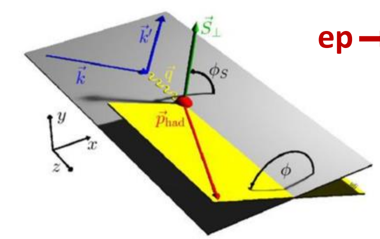
RGH experiment status (with HDice) confirmed at PAC48 in 2020 (during jeopardy process) with C1 condition on target performance

RGH status modified to C2 in 2024 (during jeopardy process) to properly evaluate the target change

✓ GEANT simulations ✓ Impact study ✓ Systematics

Gather unprecedented information on

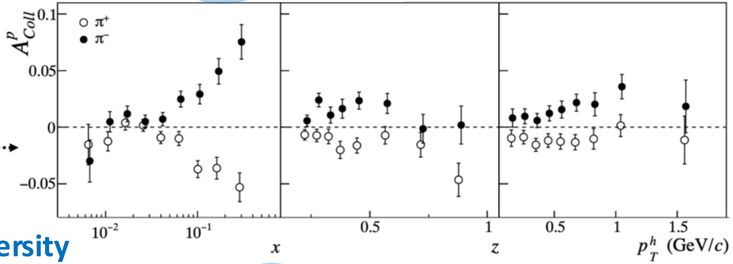
- Transversity
- Tensor charge
- Sivers, $h_{1T}^{\perp}$, $g_{1T}^{\perp}$, $H_1^{\perp}$
- GPD E
- quark OAM



ep → e'hX, e'hhX

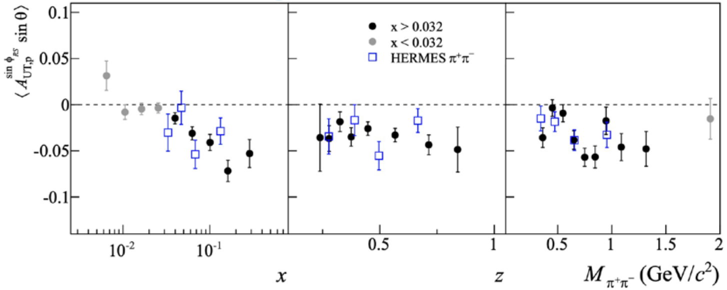
$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}\,d\phi\,d\phi_S} \propto \left[F_{UU} + \epsilon\cos(\phi)F_{LU}^{\cos(2\phi)}\right] + S_L\left[\sin(2\phi)F_{LU}^{\sin(2\phi)}\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL}\right]$$
$$+\, S_T\left[\sin(\phi-\phi_S)\,F_{UT}^{\sin(\phi-\phi_S)} + \epsilon\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)}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

$\sigma_{UT}^{Collins} \propto S_T\,\sin(\phi+\phi_S)\,C[h_1(x,k_T) \times H_1^\perp(z,p_T)]$ C. Adolph, PLB 744 (2015) 250



Transversity

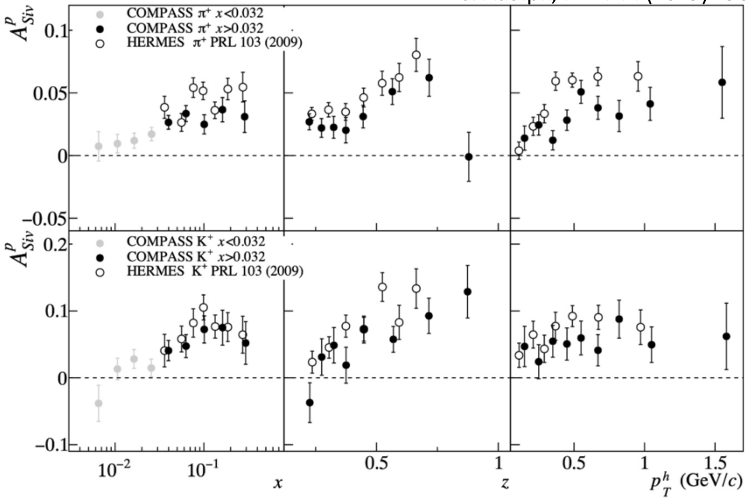
$\sigma_{UT}^{IFF} \propto S_T\,\sin(\phi_{R\perp}+\phi_S)\sin(\theta)\,h_1(x)H_1^{\sphericalangle}(z,M_{hh})]$ G.D. Alexeev, PLB 845 (2023) 138155

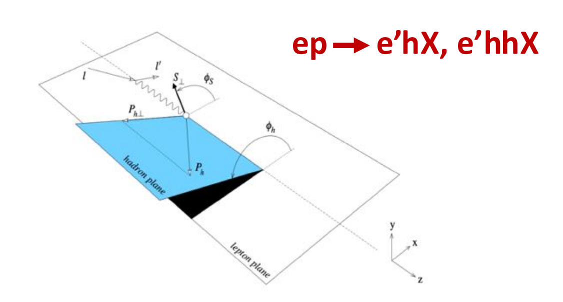


Sivers

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

C. Adolph, PLB 744 (2015) 250

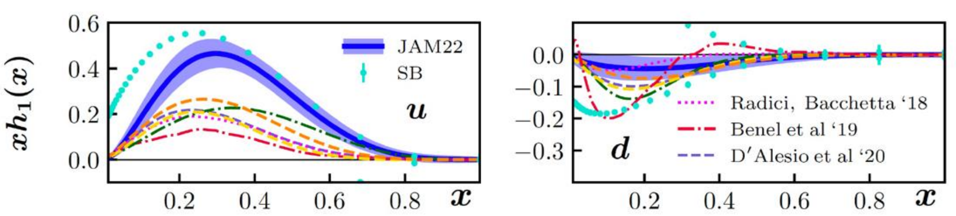




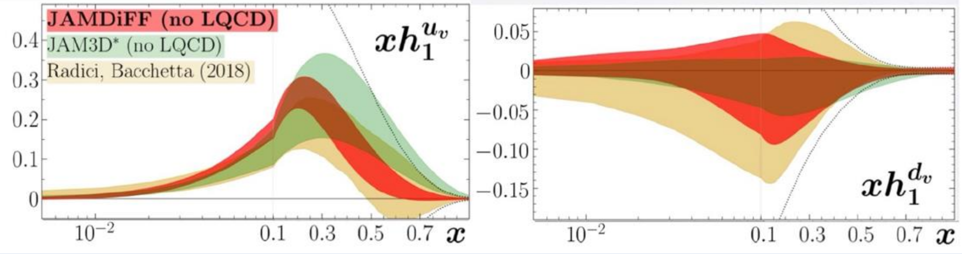
Large sensitivity expected in the valence region
Lack of data above x = 0.3 and no fully differential (4D) analysis available so far

CLAS12 can be the first experiment to achieve a 4D analysis in the valence region

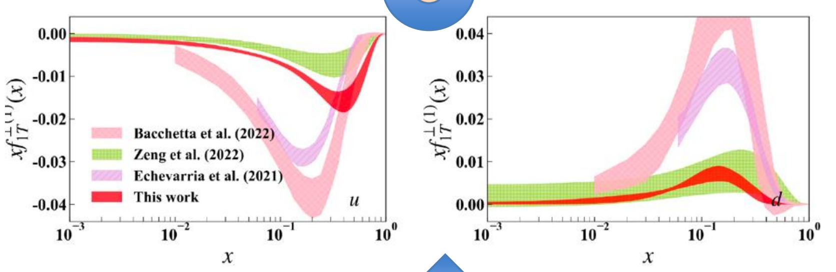
Transversity from single hadron SIDIS



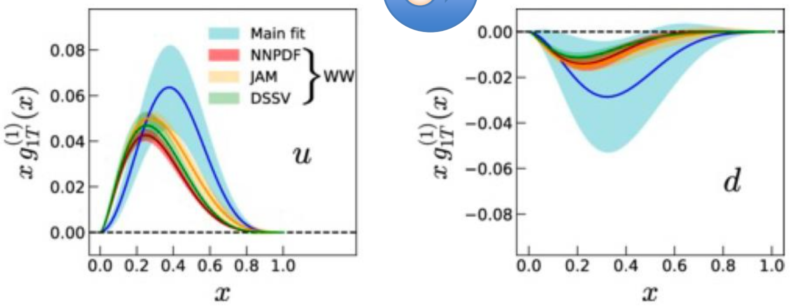
Transversity from di-hadron SIDIS



Sivers



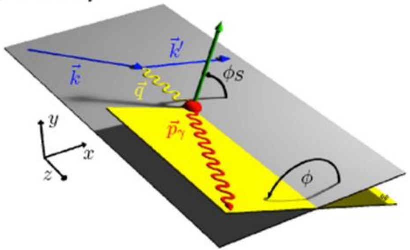
Kotzinian-Mulders

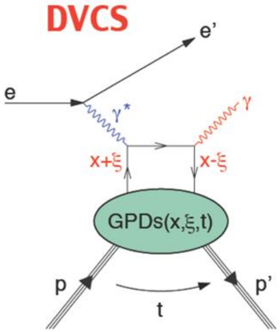


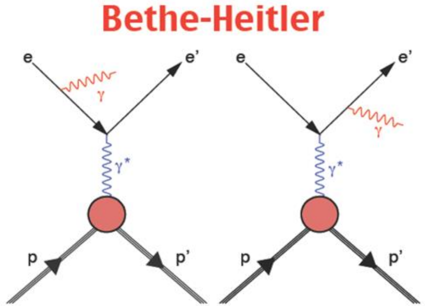
Deep Virtual Compton Scattering

$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$

ep → e' p' γ





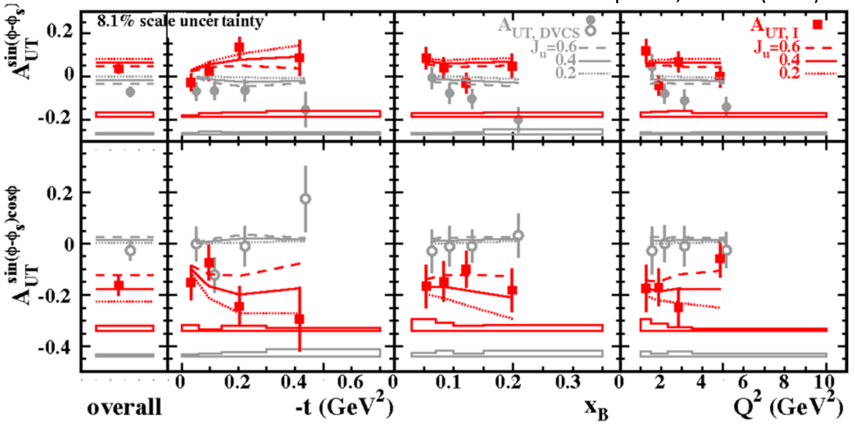


Rare access to Im$\mathcal{E}$ CFF with no kinematic suppression

$$d\sigma^{I}_{UT} = \frac{-K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{\sum_{n=0}^{3} c^{I}_{n,TP-}\sin(\phi-\phi_S)\cos(n\phi) + \sum_{n=1}^{3} s^{I}_{n,TP+}\cos(\phi-\phi_S)\sin(n\phi)\right\}$$

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

A. Airapetian, PLB 74 (2011) 15

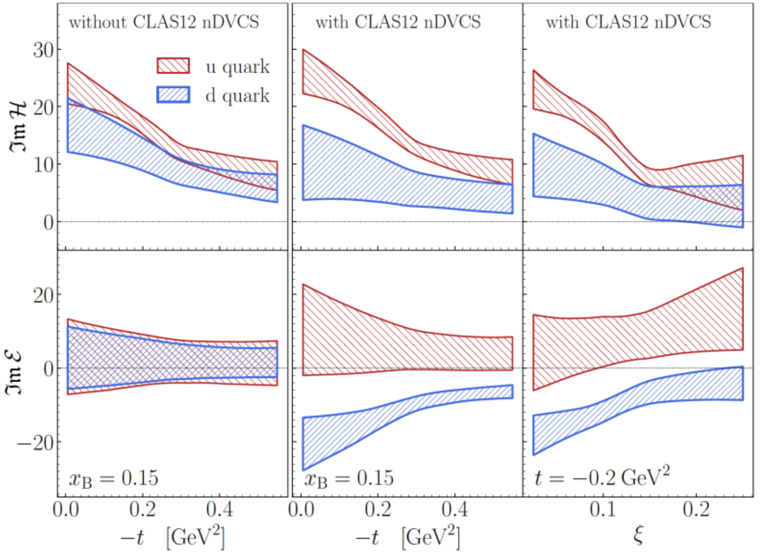


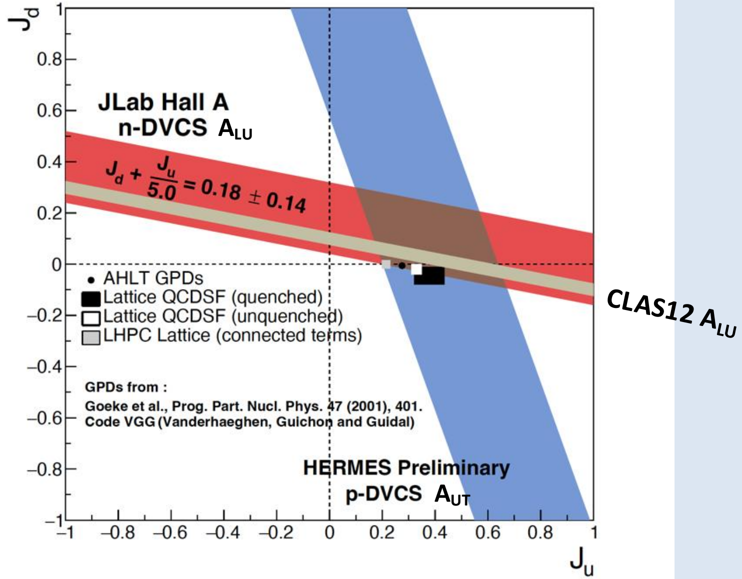
GPD E is essential to pin down the quark dynamics (OAM)
It is poorly known expecially for the u-quark flavor

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

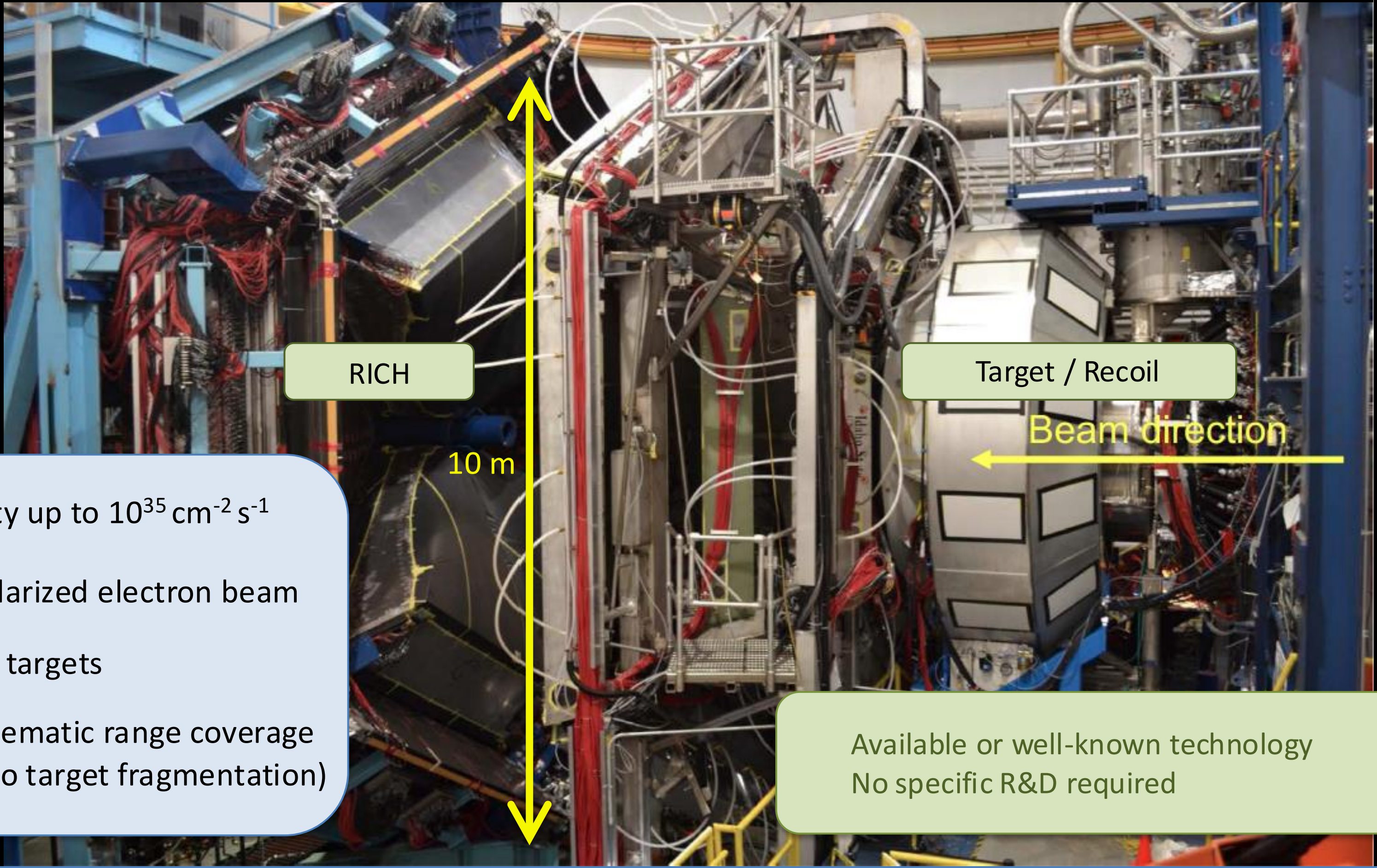
CLAS12 can be the first experiment in exploiting both
A_{LU} measurement on neutron with
A_{UT} measurement on proton

CLAS12 RGB measurement of A_{LU} on neutron, Phys.Rev.Lett. 133 (2024) 21, 211903





Large acceptance spectrometer. Operational since 02/18



Luminosity up to 10^{35} cm^{-2} s^{-1}

Highly polarized electron beam

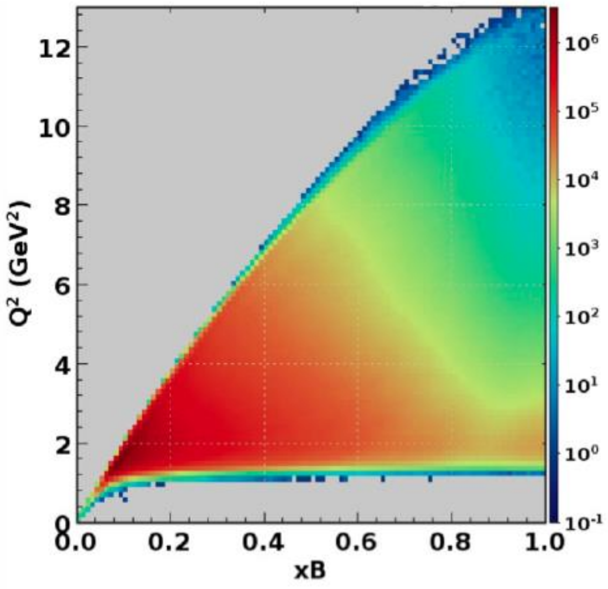
Polarized targets

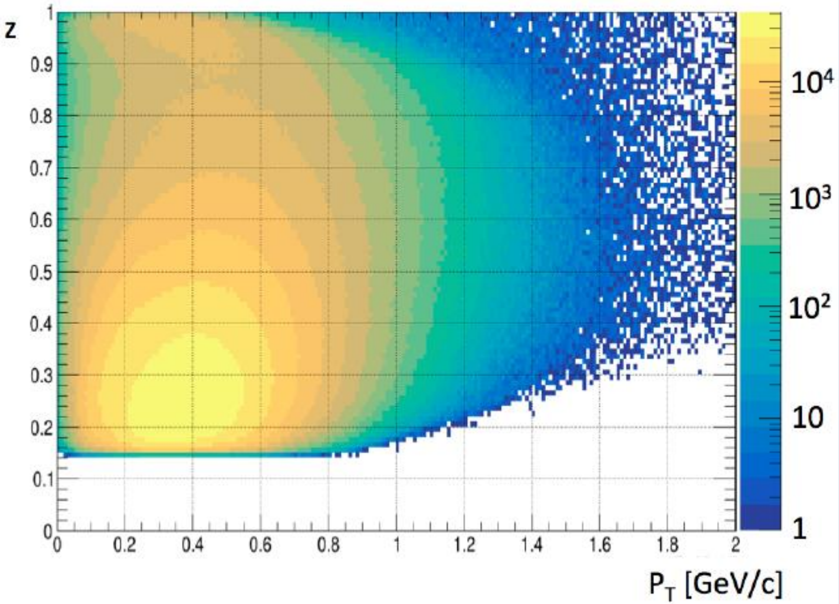
Broad kinematic range coverage (current to target fragmentation)

Available or well-known technology
No specific R&D required

Features: wide phase space cover, excellent PID and statistics optimized for a multi-D analysis

- disentangle kinematical correlations
- verify expected dependences (e.g. in Q^2) and isolate peculiar regimes (e.g. in z)
- study transition regions (e.g. in P_T)



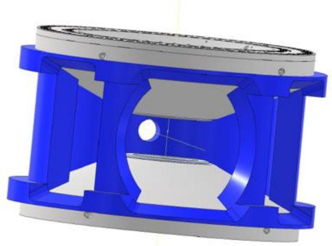


Most viable solution to prioritize physics

Consolidated dynamically polarized NH_3 technology

Designed based on already successful realizations

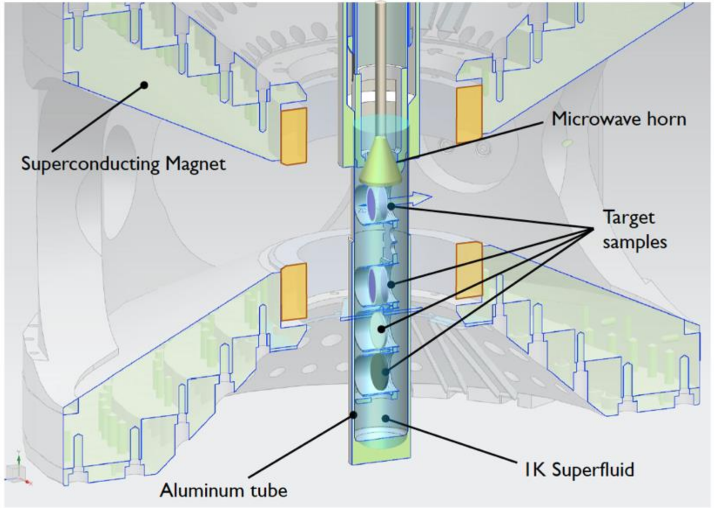
Hall-A G2p-Gep target (replica optimized for HTCC)
Hall-C E12-15-005 magnet (replica optimized for recoil detection)

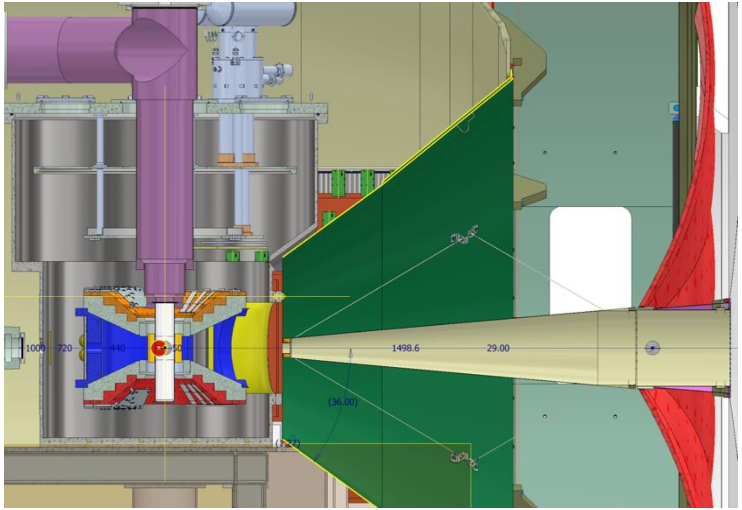


5T dipole acceptance:

$\pm$ 25° vertical

$\pm$ 65° horizontal





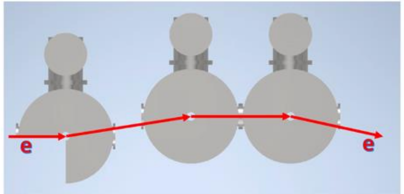
Based on

existing 0.7 cm raster

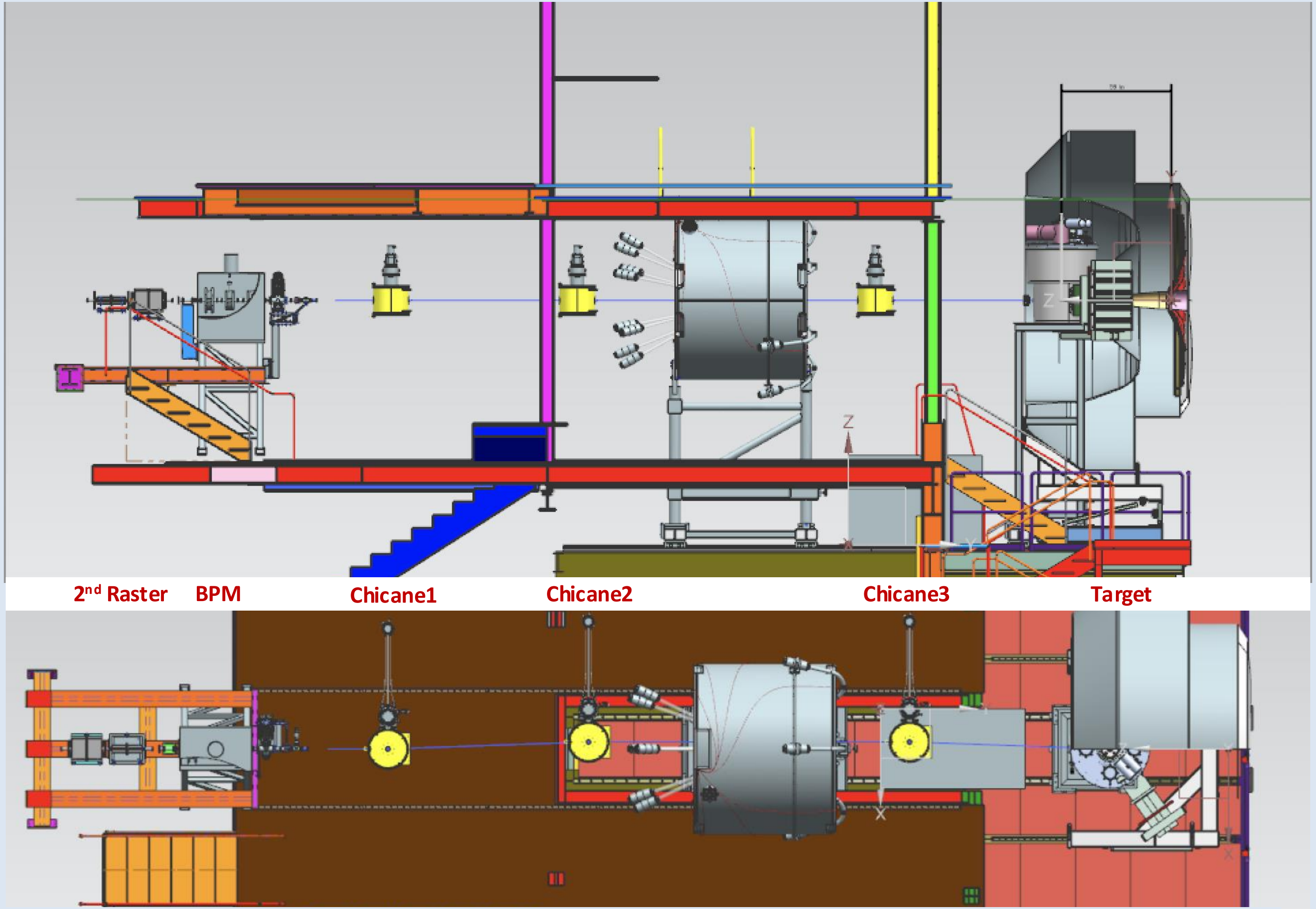
commercial 7.5T magnets

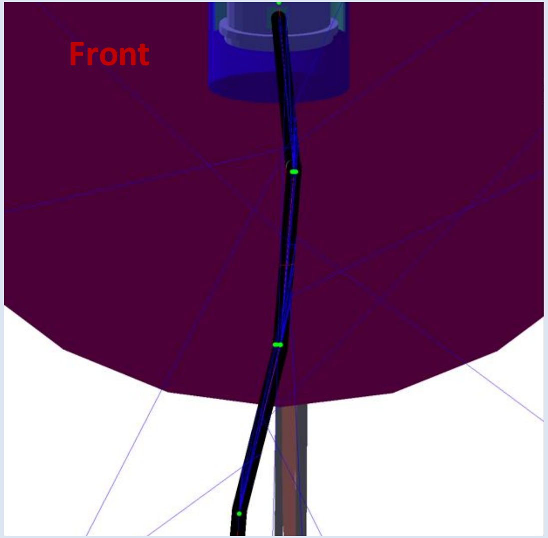
gnets Inc.

CryoMagnets Inc.

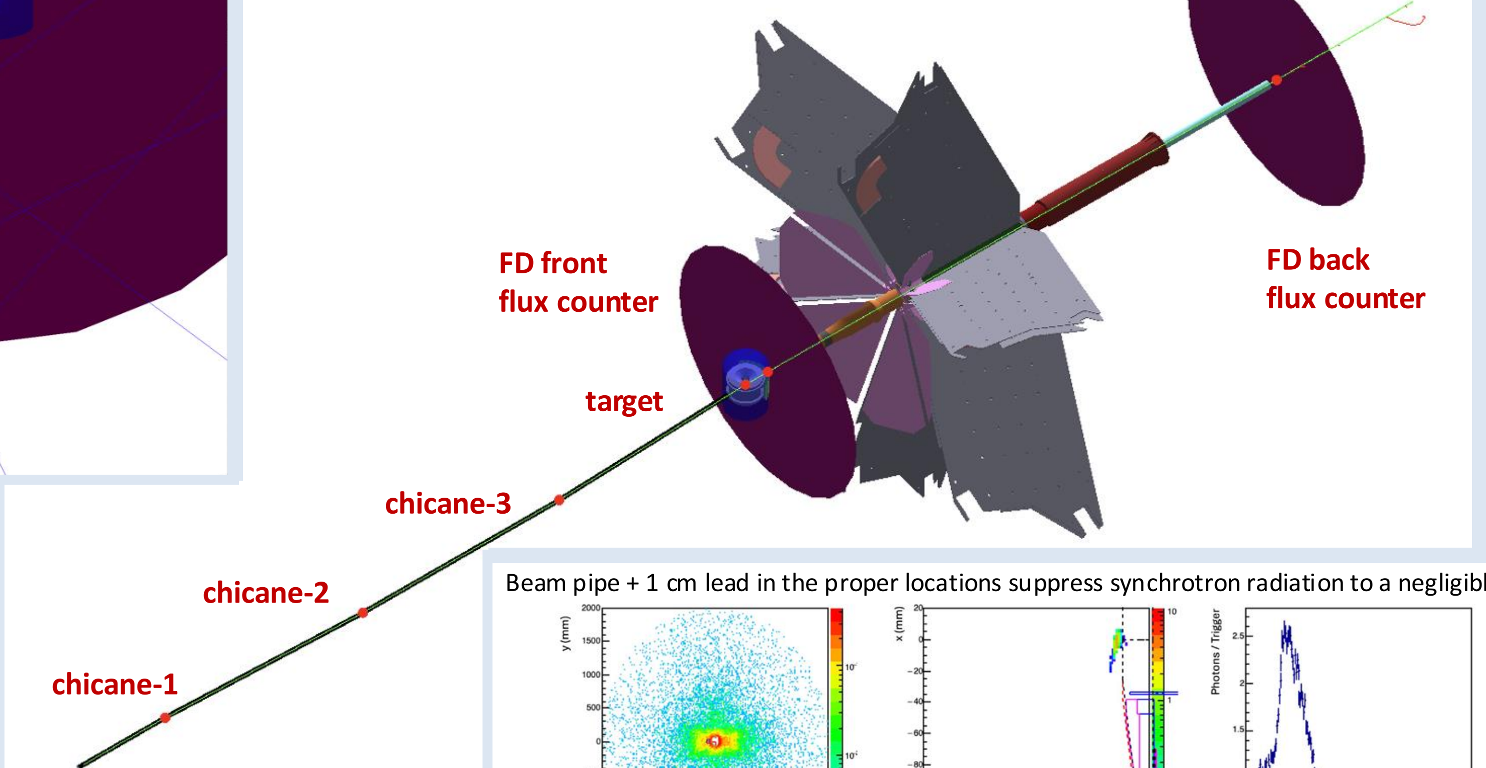


- ✓ space
- ✓ synchrotron radiation
- ✓ beam rastering

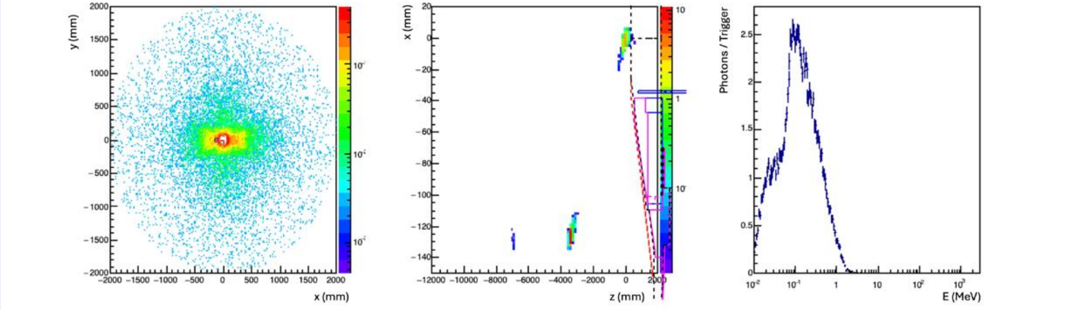




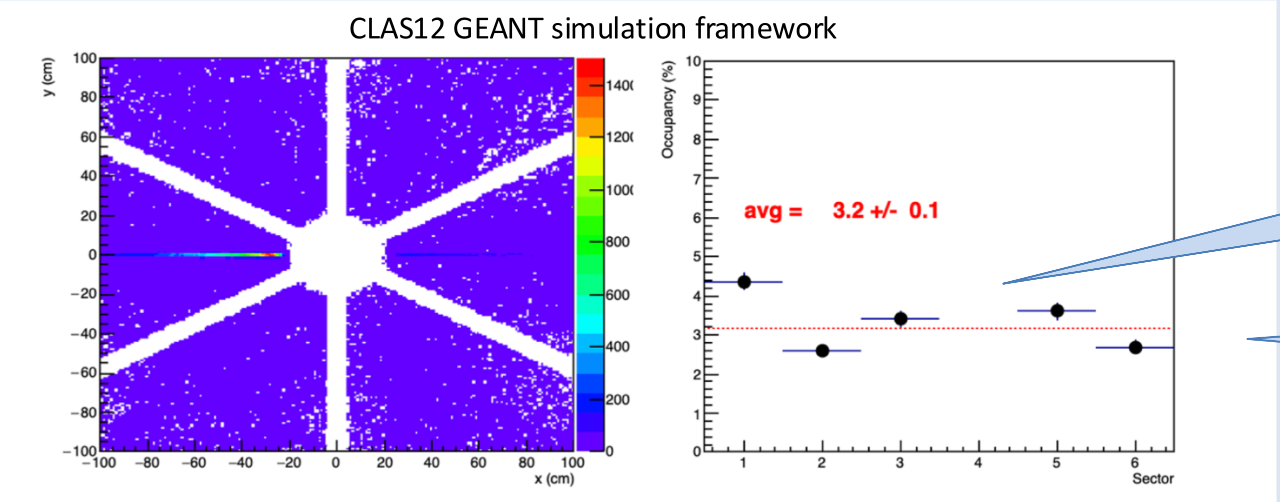
CLAS12 GEANT simulation framework



Beam pipe + 1 cm lead in the proper locations suppress synchrotron radiation to a negligible level



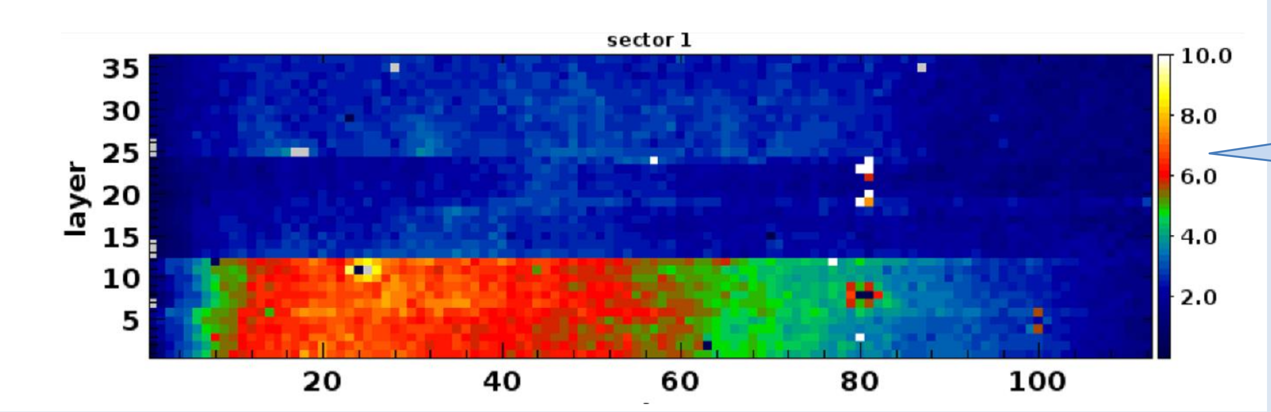
Geant Simulation: DC Occupancy



RGH MC (NH_3)

Assume to switch OFF DC in sector 4 and move RICH in sector 3

x2 with CLAS12 gate



RGC DATA (NH_3)

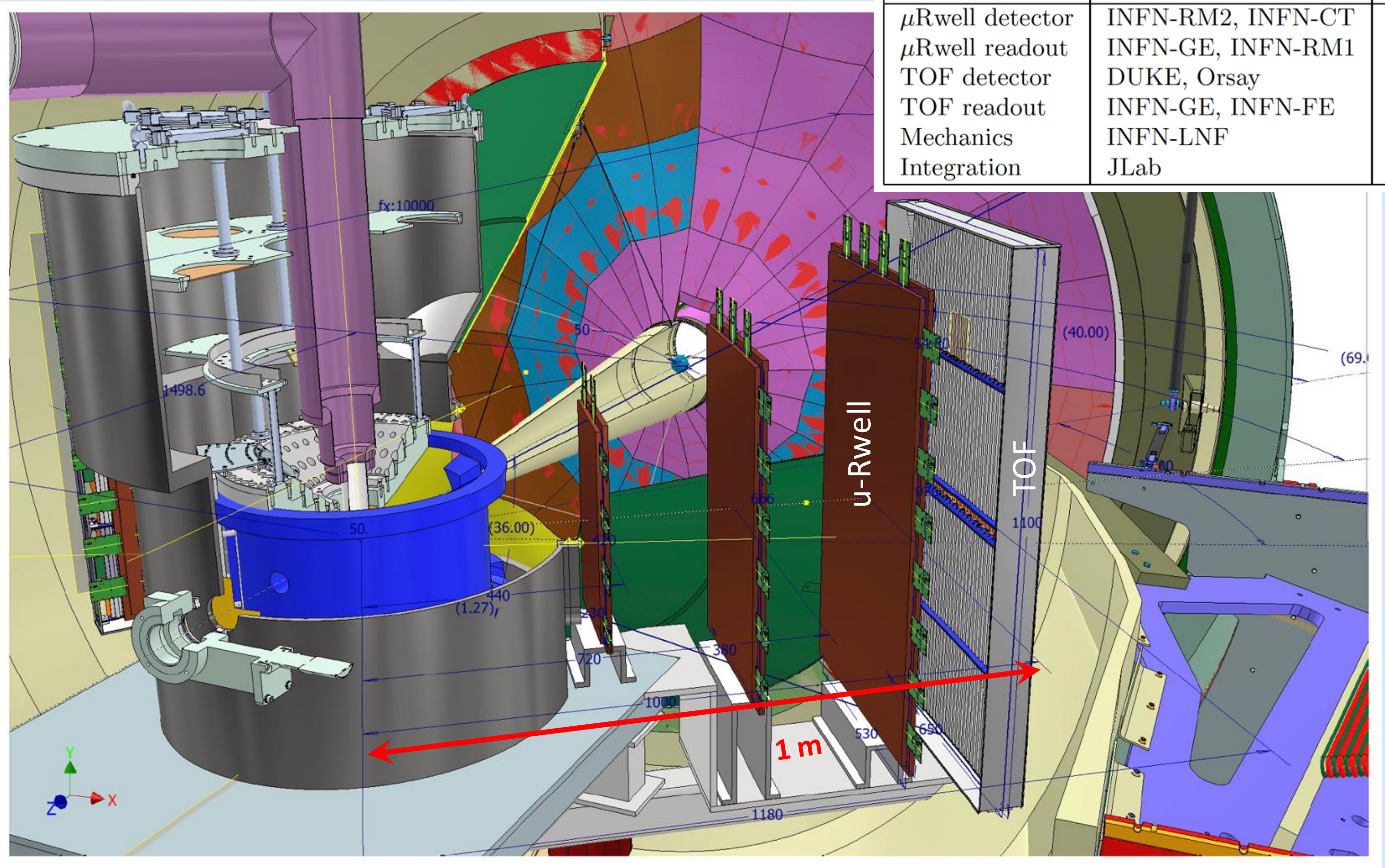
Present performance*

Typical DC occupancy measured at CLAS12

*No high-lumi

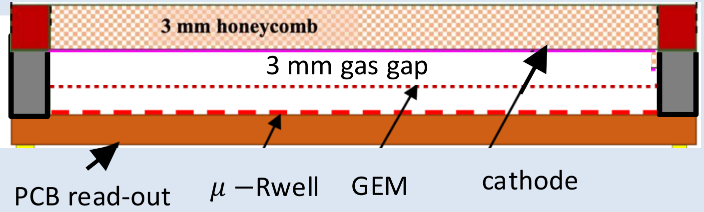
Target & Recoil Detector

Task	Leading Institution	Expertise
μRwell detector	INFN-RM2, INFN-CT	CLAS12 upgrade, ePIC tracking
μRwell 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



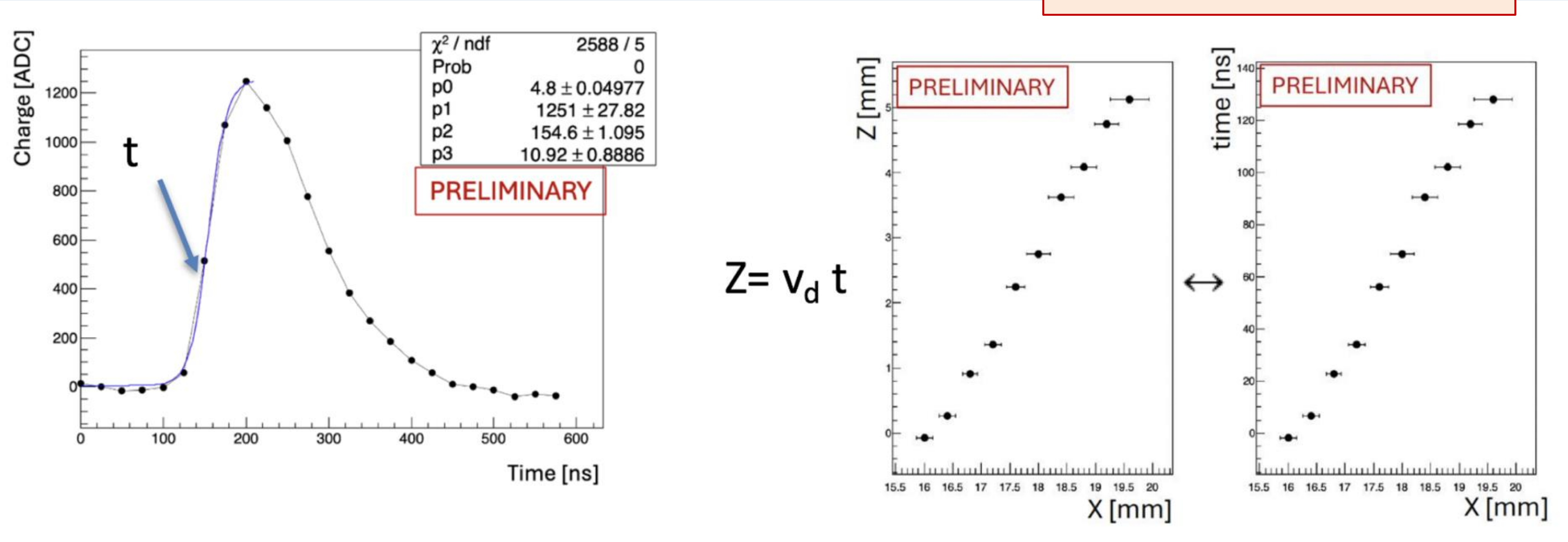
GEM-μRwell to provide 2D information with 100 μm resolution

- ✓ Wanted gain/efficiency is preserved below 600 V safe bias
- ✓ 5 ns time resolution can be achieved from signal shape fit
- ✓ TPC-like readout to correct the impinging angle has been proven
- ✓ Suitable APV25 readout available



μRwell as spin off of the high-lumi project (various prototypes up to 40 x 46 cm² exist)

Test-beam at CERN in Oct '24



Recoil TOF

T. Rostomyan, NIMA 986 (2021) 164801 – MUSE experiment

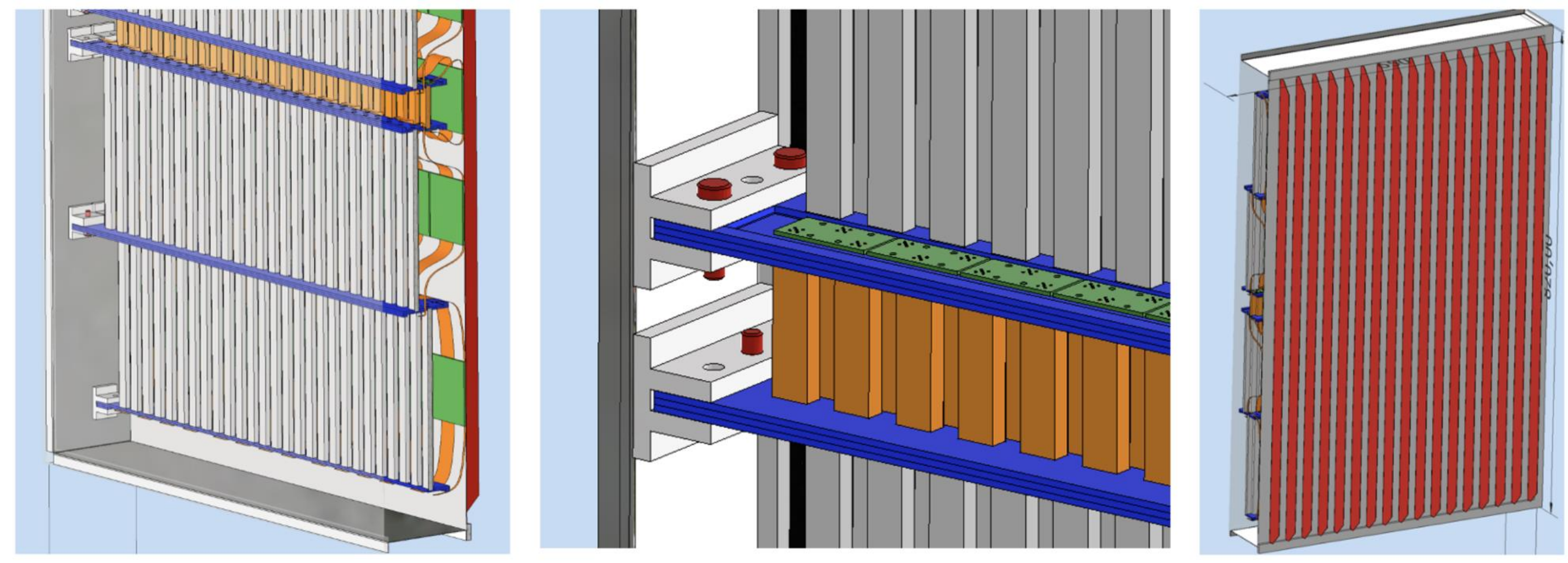
Table A.2: Time resolutions and efficiencies for 3 mm thick, 300 mm long and 12 mm wide BC-404 BM paddles. All results are better than the experimental requirements.

Scintillator	SiPM	σ_T (ps)	ϵ (%)
BC-404	S13360-3075PE	59	≥ 99.9
BC-404	S13360-3050PE	60	≥ 99.7
BC-404	ASD-NUV3S-P-40	65	≥ 99.0

Scintillating bars + SiPM to tag particles with 100 ps resolution

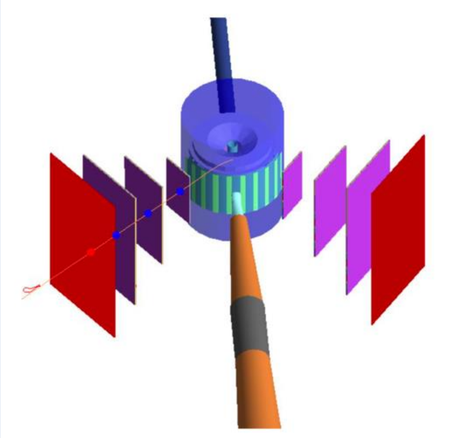
- ✓ Flexible geometry to provide spatial matching and control of accidentals
- ✓ Compact layout
- ✓ Suitable readout exist (MAROC or PETIROC chip)

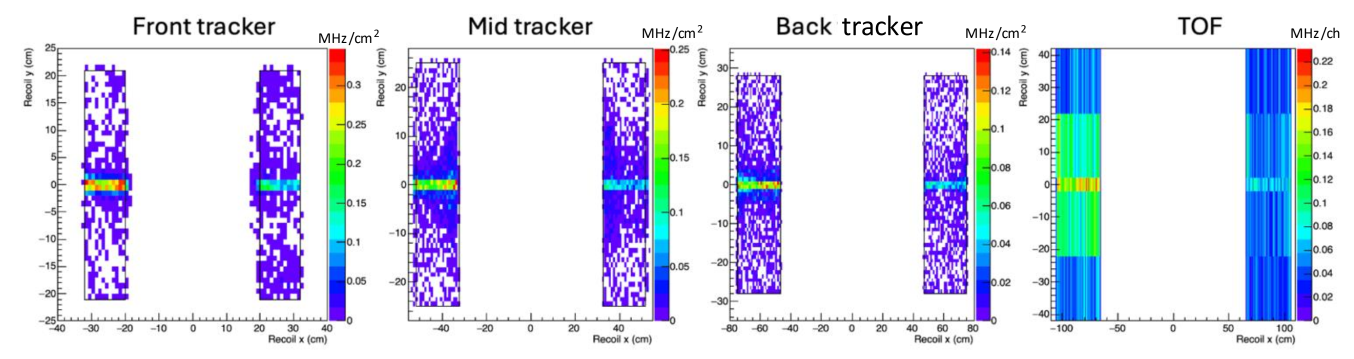
Proven to match 100 ps by PANDA and MUSE R&D



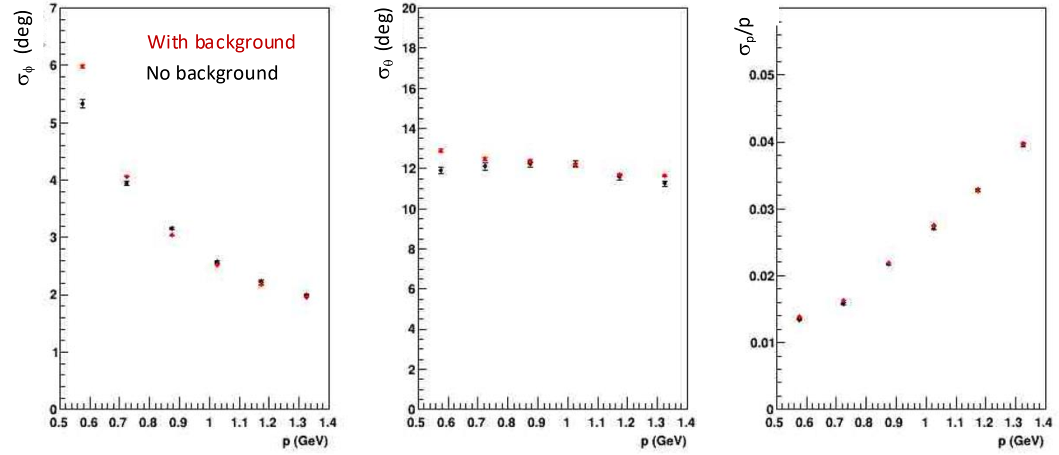
Geant Simulation: Recoil Performance

Recoil technology can cope with the background rates





Background has a minimal impact: similar recoil resolution, few percent effiicency loss

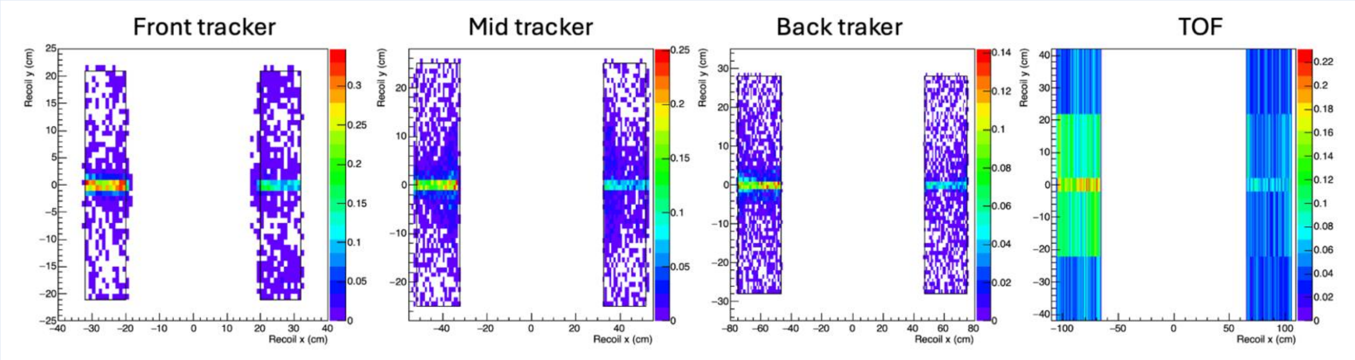


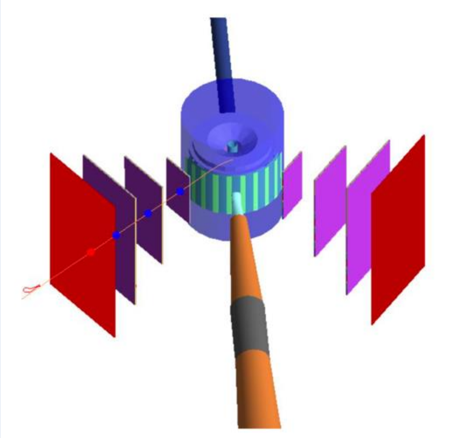
Still basic reconstruction algorithm provides a conservative estimate

Recoil reconstruction is adequate even in the presence of background

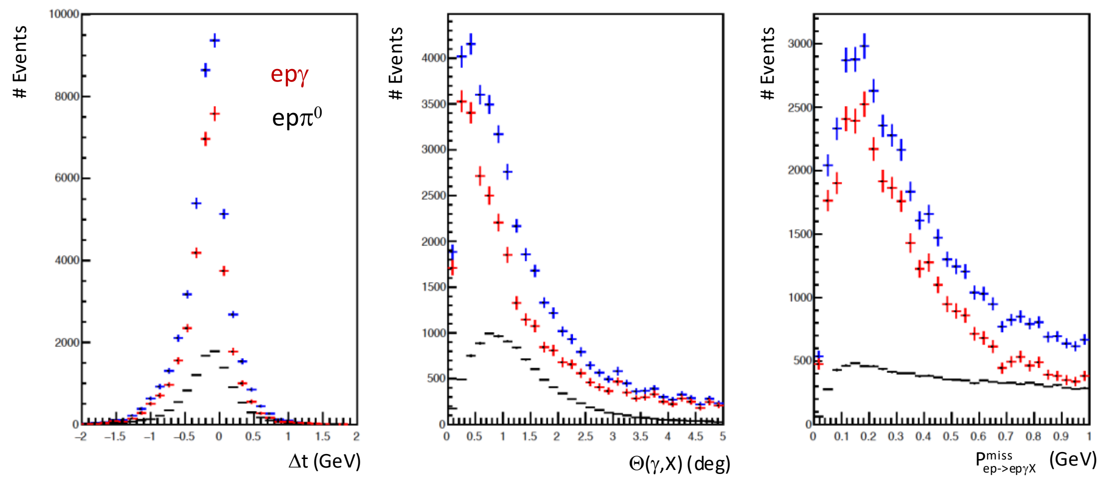
Geant Simulation: Recoil Performance

Recoil technology can cope with the background rates





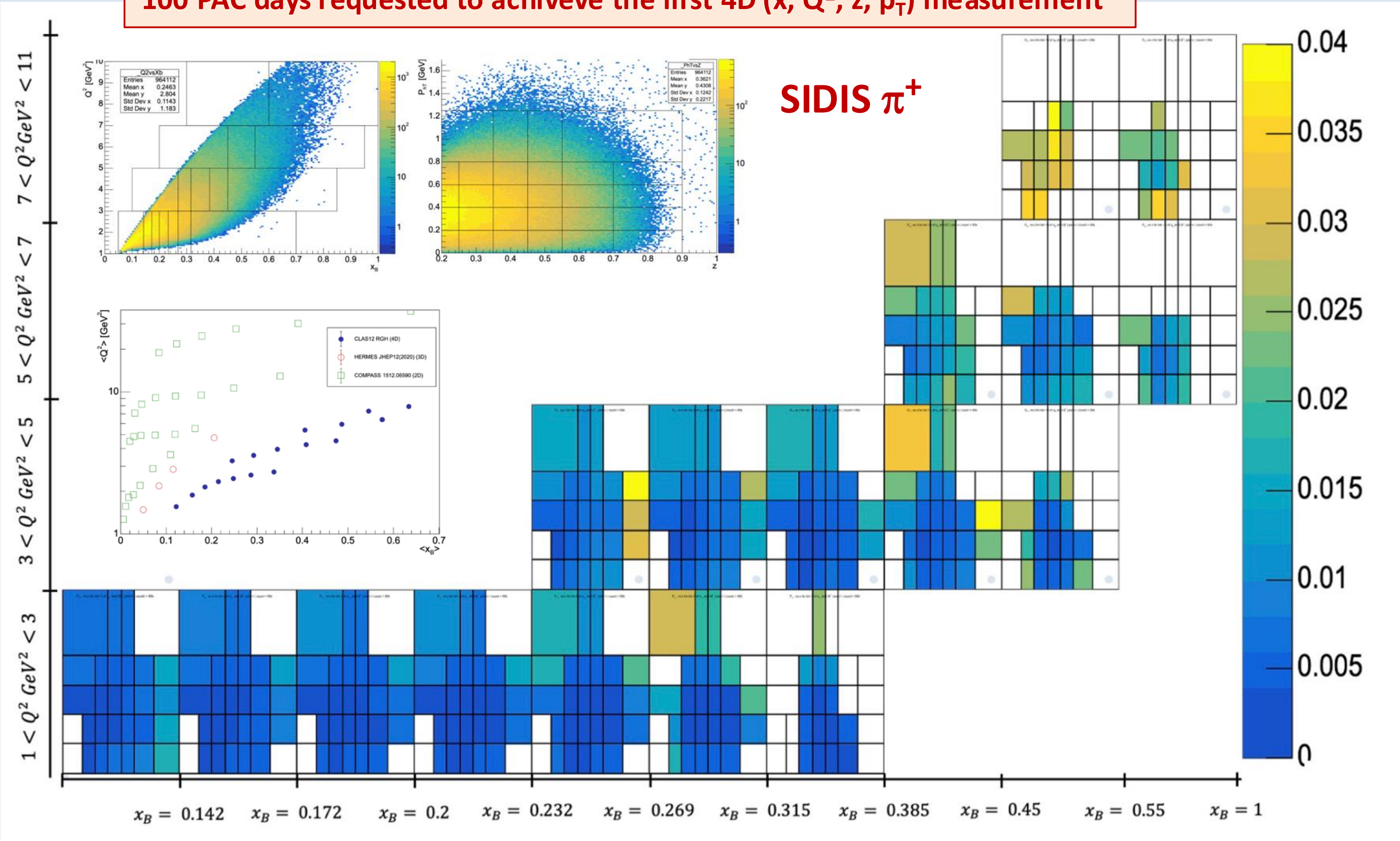
π^0 contamination is at the level of RGC (~ 30%)



Still basic reconstruction algorithm provides a conservative estimate

Recoil reconstruction is adequate even in the presence of background

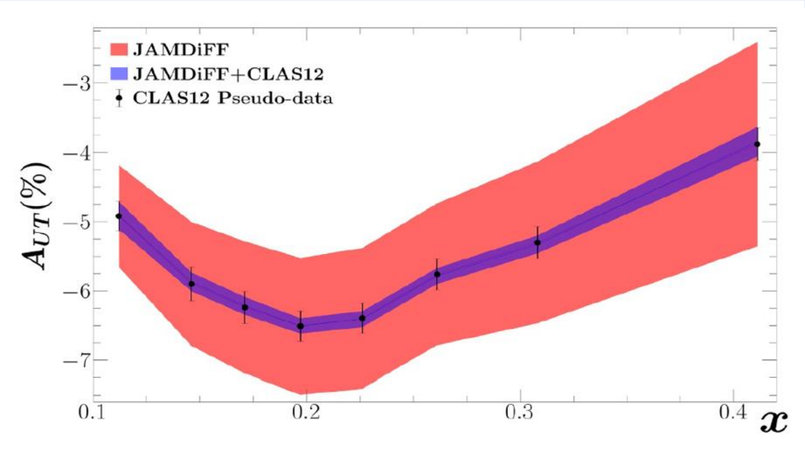
100 PAC days requested to achiveve the first 4D (x, Q^2, z, p_T) measurement

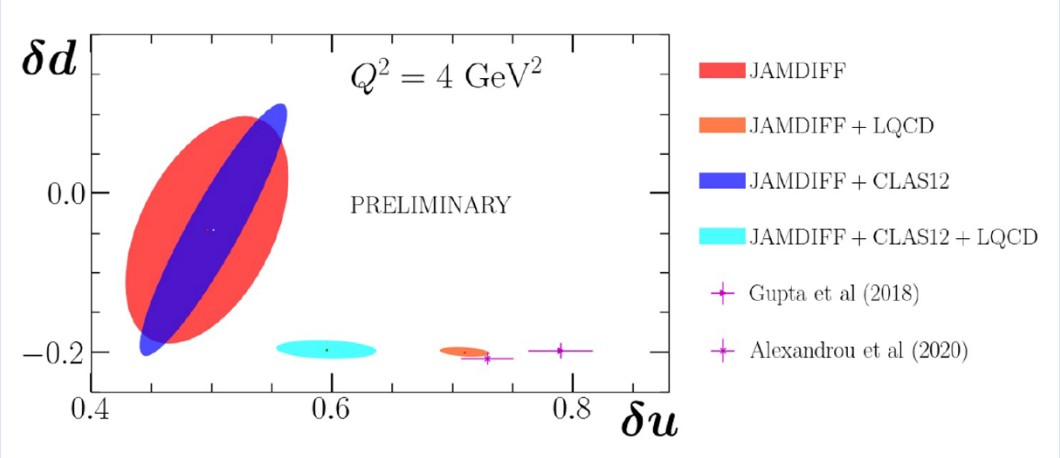


Fundamental quantity related to BSM physics: EDM and tensor coupling

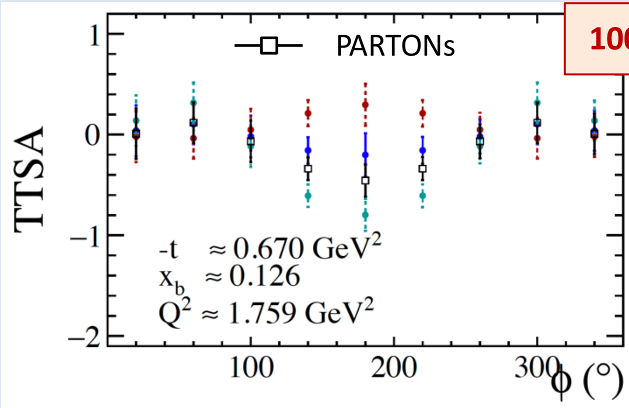
Projections with and without CLAS12 di-hadron pseudo-data (with lattice inputs)

100 PAC days requested to be competitive in precision to lattice for δu



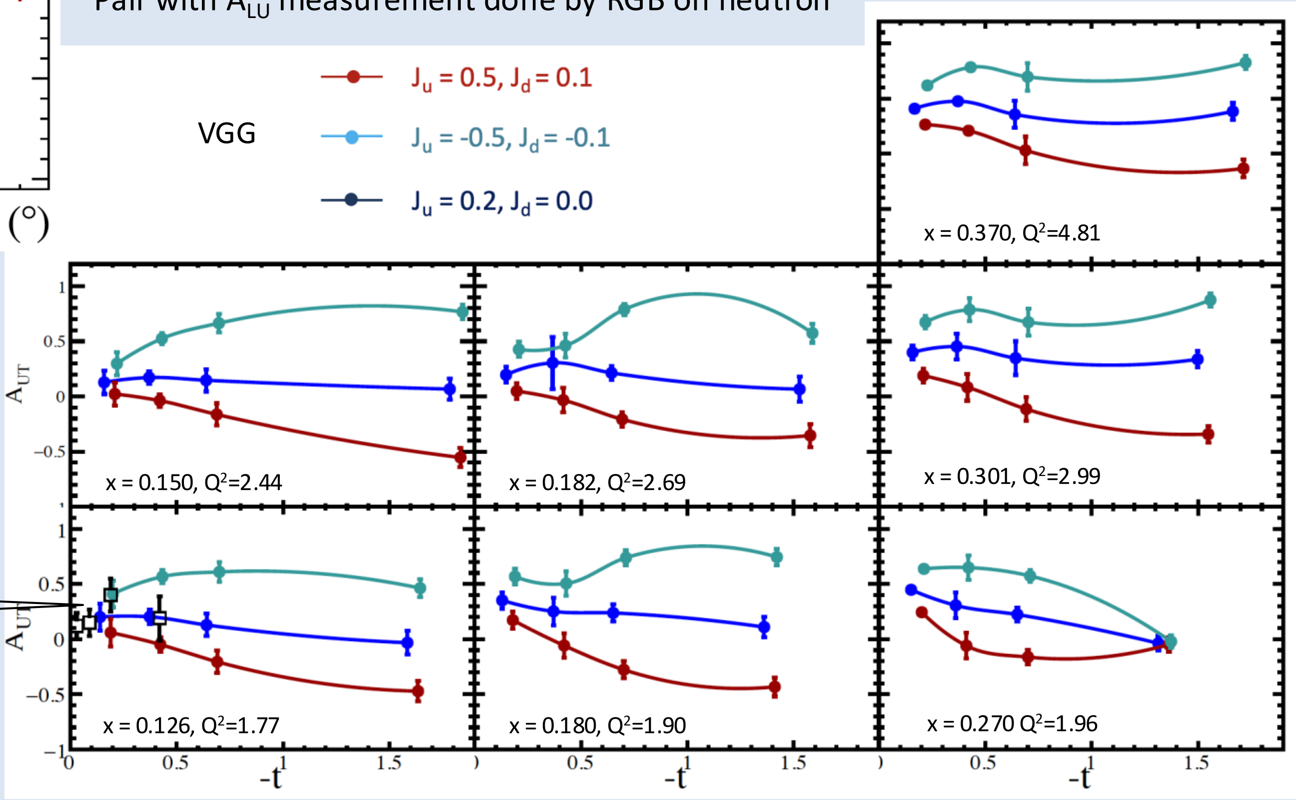


$$\delta u = \int_0^1 dx\,(h_1^u(x) - h_1^{\bar{u}}(x))\,, \quad \delta d = \int_0^1 dx\,(h_1^d(x) - h_1^{\bar{d}}(x))$$



100 PAC days requested to get unprecedented access to elusive quark angular momenta

Supersede the only other A_{UT} measurement
Pair with A_{LU} measurement done by RGB on neutron

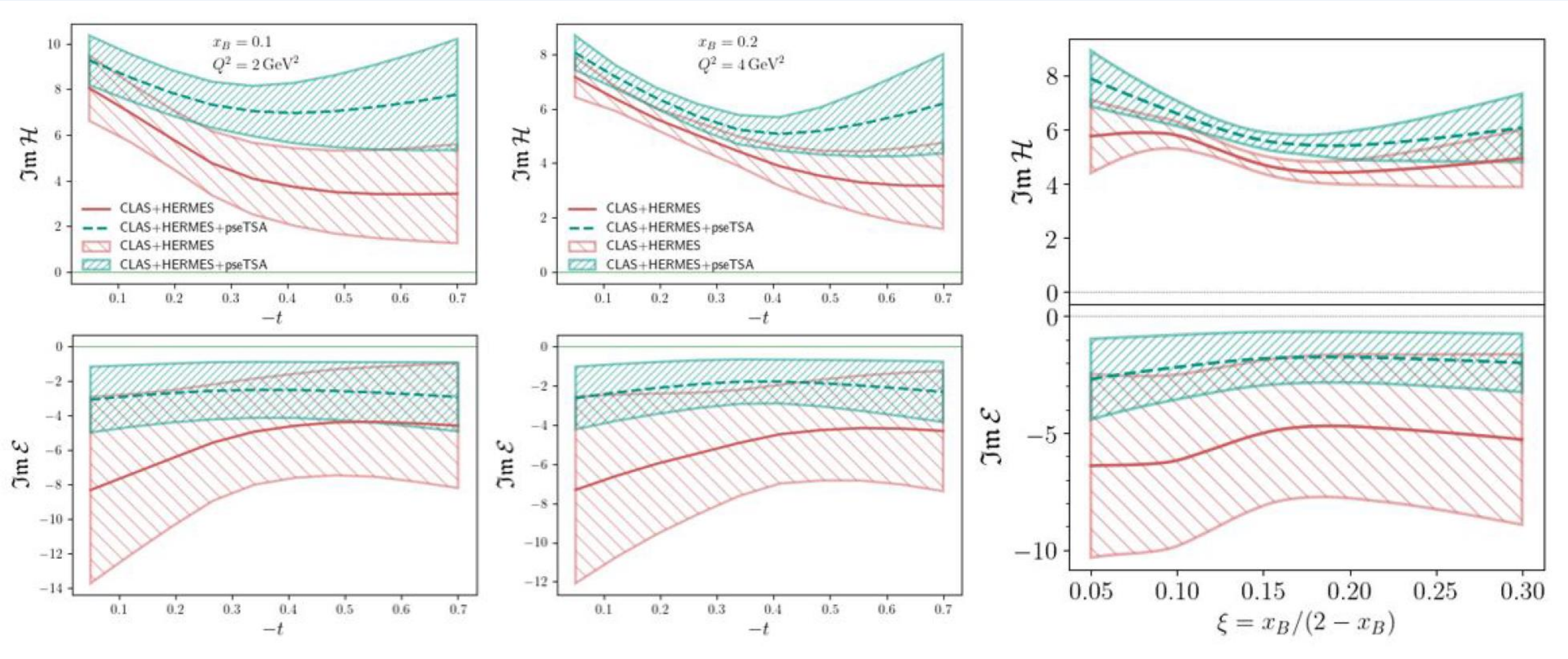


Superior discrimination power between various OAM model hypotheses

HERMES

Analysis of Melany Higuera Angulo using GEPARD framework (LDRD project) and relevant data + RGH pseudo-data

100 PAC days requested to reduce by 2/3 the uncertainty on Im $\mathcal{E}$



Systematics

RGH measurements are expected to be dominated by the statistical uncertainty

Target spin state can be regularly rotated by microwave-induced swap preserving acceptance
RGH luminosity 5 x 10^{33} cm^{2} s^{-1} is 1/20 of the nominal CLAS12 luminosity
Consolidated methods based on previous experience
Inputs from previous CLAS12 experiments will reduce assumptions in systematics

To be noted: previous high-luminosity CLAS12 experiments provide a solid benchmark e.g.,
unpolarized cross section terms will be constrained by RGA/RGB and target dilutions by RGC

Conservative systematics are derived from previous relevant realizations and analyses,
with a cross-check for RGH acceptance peculiarities.

SIDIS single hadron

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

SIDIS di- 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%

DVCS

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

Beam Request

RGH implements the target configuration which is most sensitive to the 3D nucleon structure study and capitalizes on CLAS12 with a complete set of target polarizations

100 (physics) + 25 (ancillary) PAC days requested to achieve unprecedent precision in the valence region

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

100 days of physics run to achieve the RGH goals

5 days for commissioning and alignment

8+2 days for background studies (target dilutions)

10 days for target annealing and target replacements

PAC Review

Theory Report

RGH measurements are critical for the studies of transverse spin phenomena in QCD with high impact physics such as the elusive nucleon tensor charge that is relevant for a broad community including LQCD and BSM physics.

TAC Report

No major technical hurdle.

In the replies, proponents clarified details on: chicane, beam monitor, and beam polarization uncertainty.

PAC Readers

Scientific goals are well aligned with the 2023 NSAC Long Range Plan, preceding and complementing the EIC program.

Awareness of current literature, competing efforts, and theoretical frameworks.

Rare opportunity to get unprecedented access to the parton dynamics in the valence region with a multi-D framework

Acknowledgment of CLAS12 demonstrated capability, established target technology, full GEANT simulation.

In the replies, proponents clarified details on:

Instrumentation (vibrations, field mapping, precision in target re-position, chicane geometry, target spin swap,..)

Systematics (background subtraction, unpolarized terms, longitudinal photon component, acceptance effects, radiative effects, …)

Thank you very much to you and your colleagues for the detailed answers and additional plots.

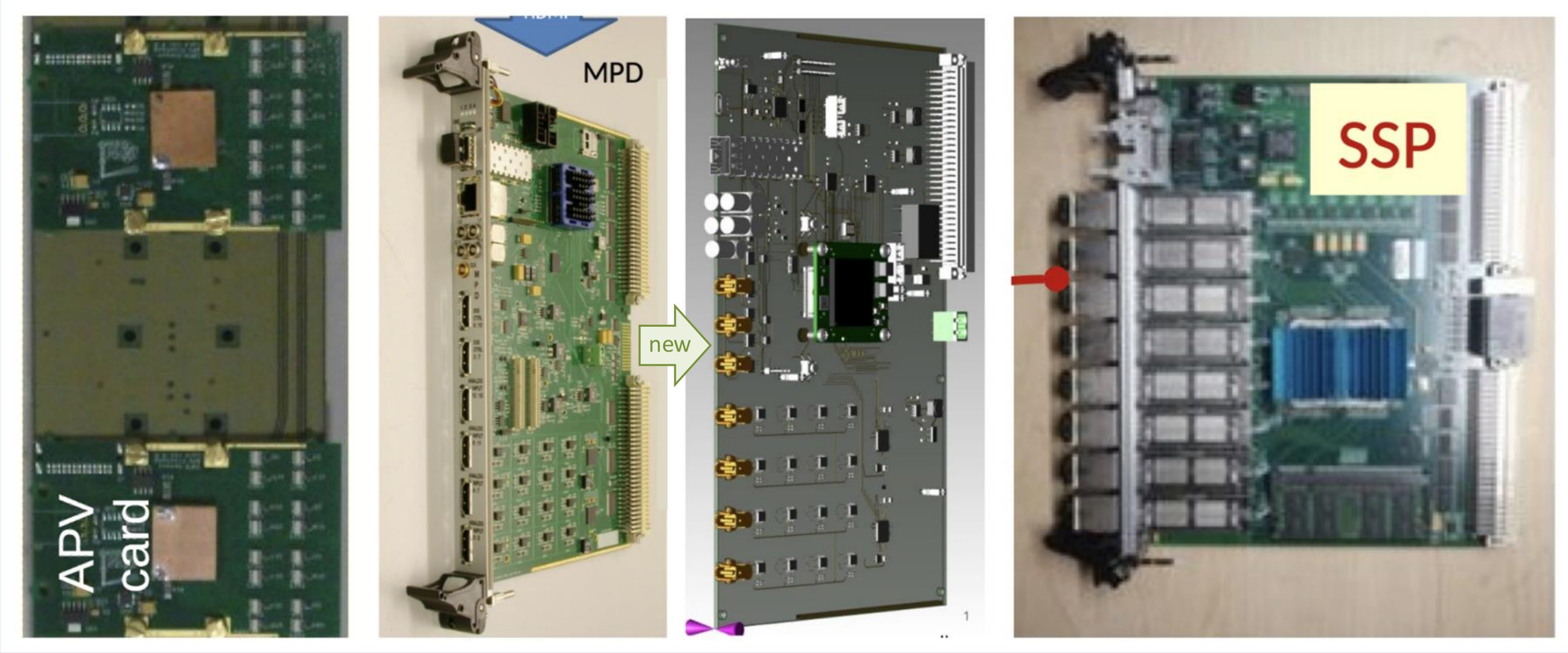
In addition, we would be happy to understand how the acceptance stability will be ensured and whether the MC will be used to simulate the impact of possible acceptance variations. We can discuss about that point during the PAC next week.

Fiducial cuts will be implemented at the analysis level to select the detector regions of suitable stability. During the calibration procedure of the various CLAS12 subsystems, dead or inefficient channels are flagged, on a run-by-run basis, in the calibration database, and this is done also for the Monte Carlo. These dead/inefficient channels are then eliminated in the reconstruction, for both data and MC. Run-dependent simulations are then produced, which include the run-dependent dead or inefficient detector channels. We don't foresee major differences in the way the acceptance will vary during RGH with respect to previously run CLAS12 experiments. CLAS12 is a quite stable setup overall.

Enough (> 10 k) spare channels exist from INFN GEM project for SBS in Hall-A

Based on the well-known APV25 chip + SSP DAQ (upgraded version of MPD under study)

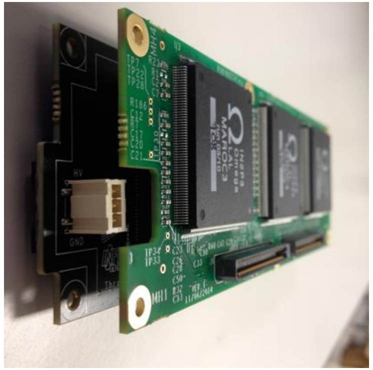
- ✓ Able to cope with 500 kHz/cm^2 and 60% occupancy
- ✓ Same system used with the μRwell prototypes



Enough (> 1 k) spare channels from RICH readout to be updated to ALERT firmware to get < 100 ps readout jitter

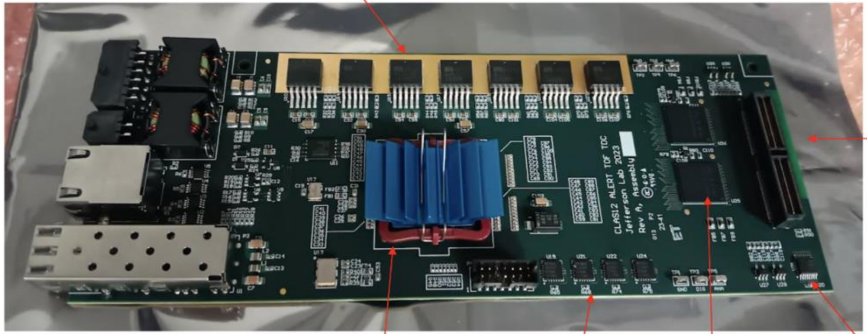
RICH readout

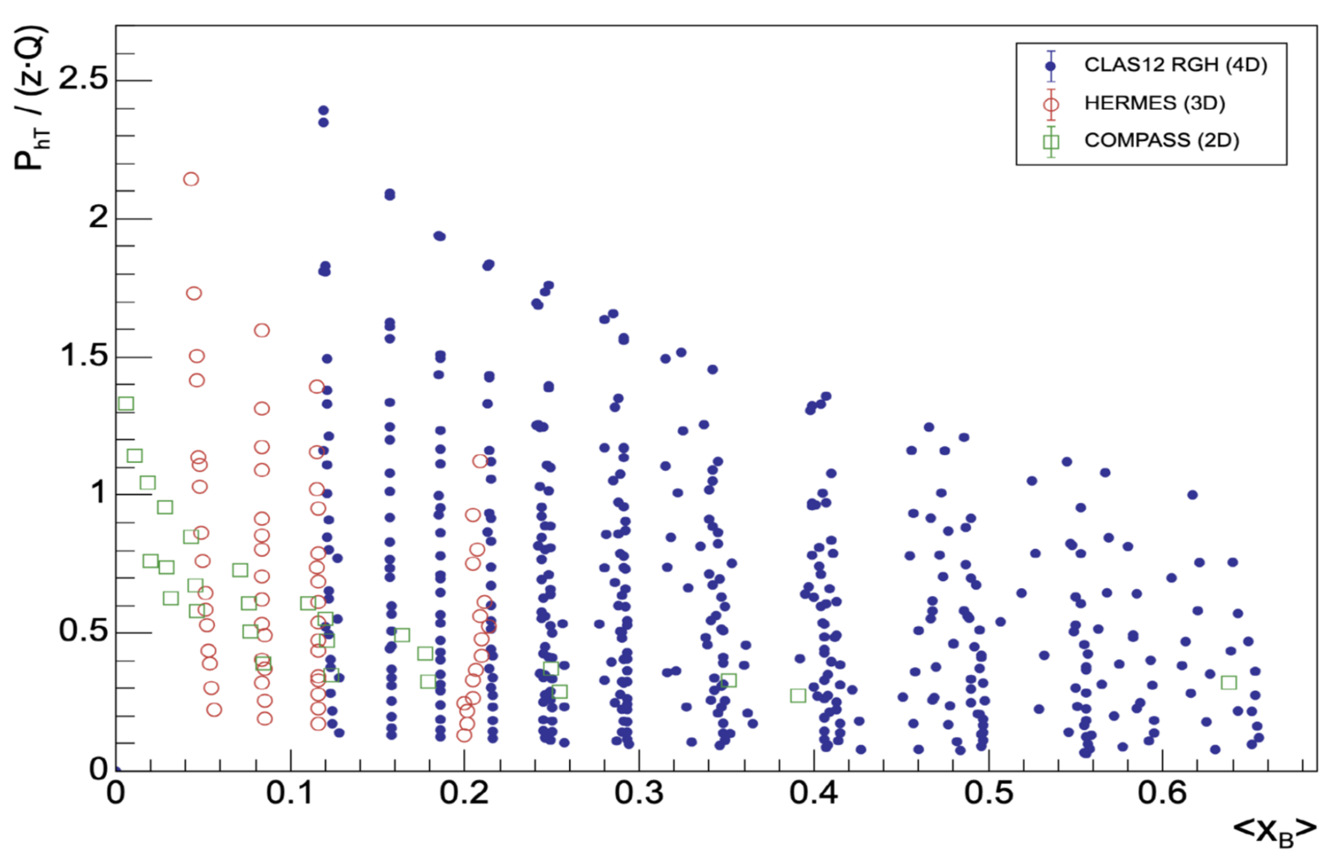
- ✓ MAROC dynamic range can cope with multi-photon signals
- ✓ Clock distribution supports 100 ps readout precision



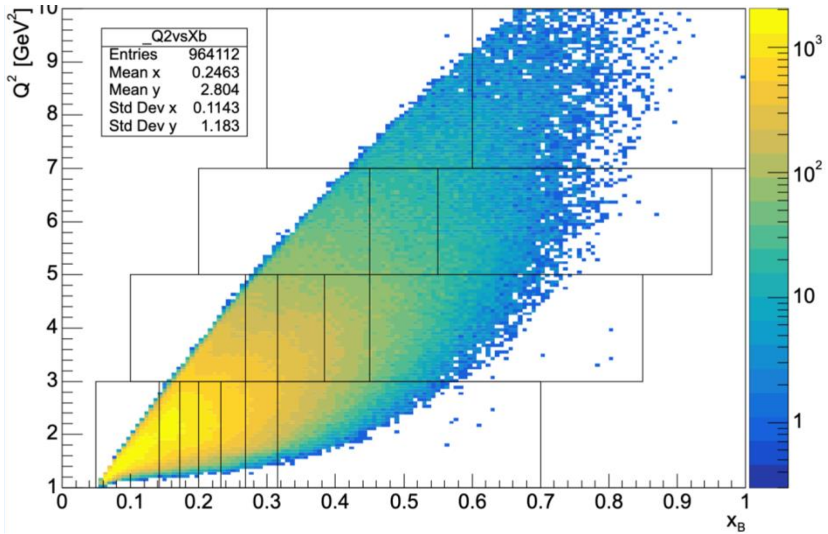
Option to adopt CLAS12-ALERT readout

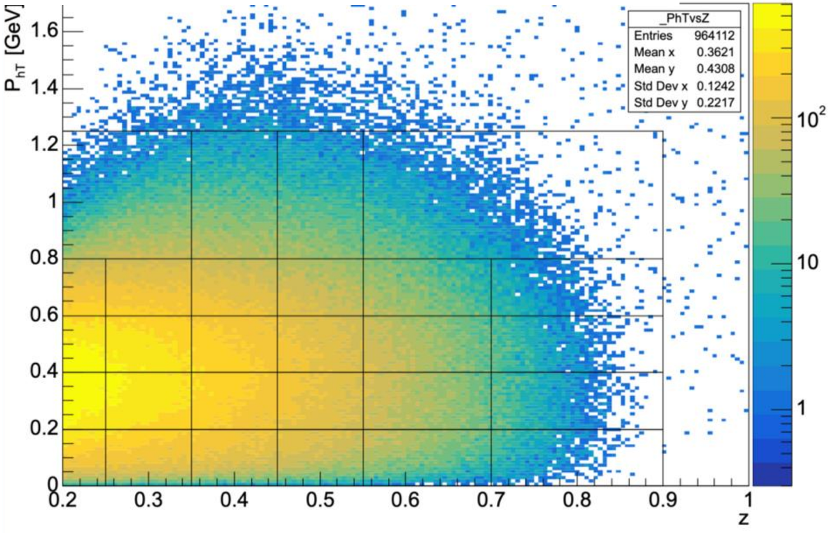
- ✓ PETIROC has a better dynamic range (multi-photons)
- ✓ Clock distribution supports 50 ps readout precision



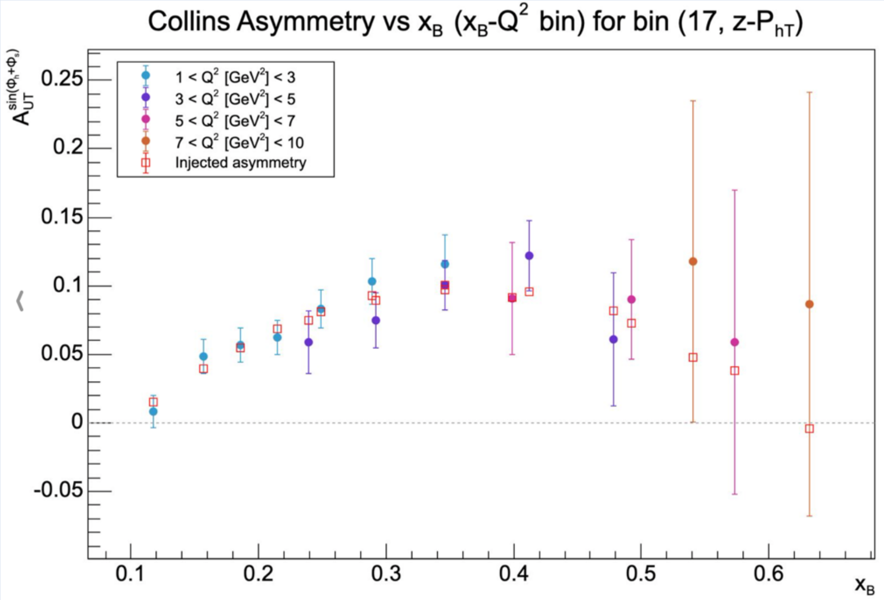


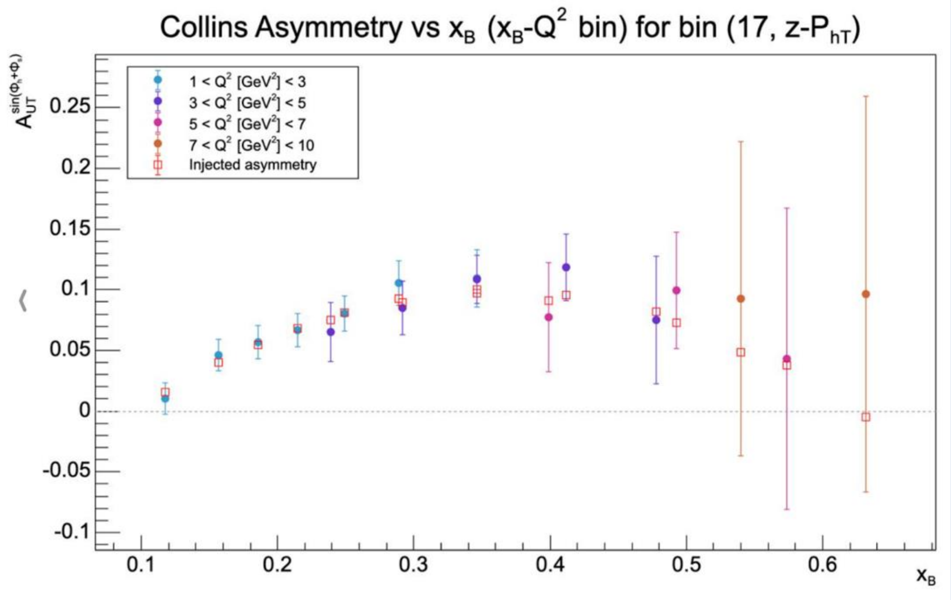
CLAS12 RGH (4D)
HERMES (3D)
COMPASS (2D)
$P_{hT} / (z \cdot Q)$
0
0.5
1
1.5
2
2.5
0.1
0.2
0.3
0.4
0.5
0.6
$<x_B>$


_Q2vsXb
Entries 964112
Mean x 0.2463
Mean y 2.804
Std Dev x 0.1143
Std Dev y 1.183
Q^2 [GeV^2]
x_B

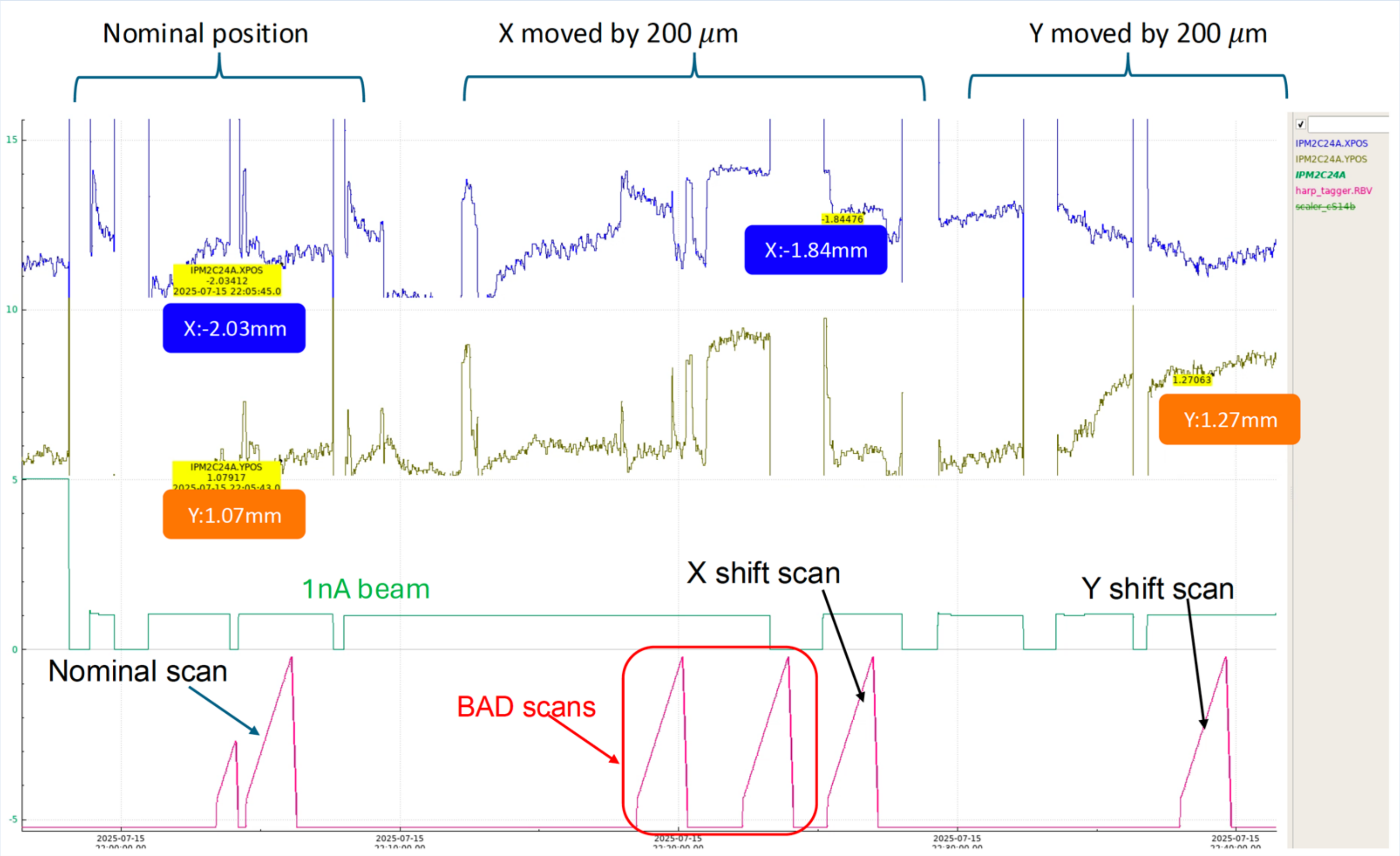

_PhTvsZ
Entries 964112
Mean x 0.3621
Mean y 0.4308
Std Dev x 0.1242
Std Dev y 0.2217
P_hT [GeV]
z

Simulation Check

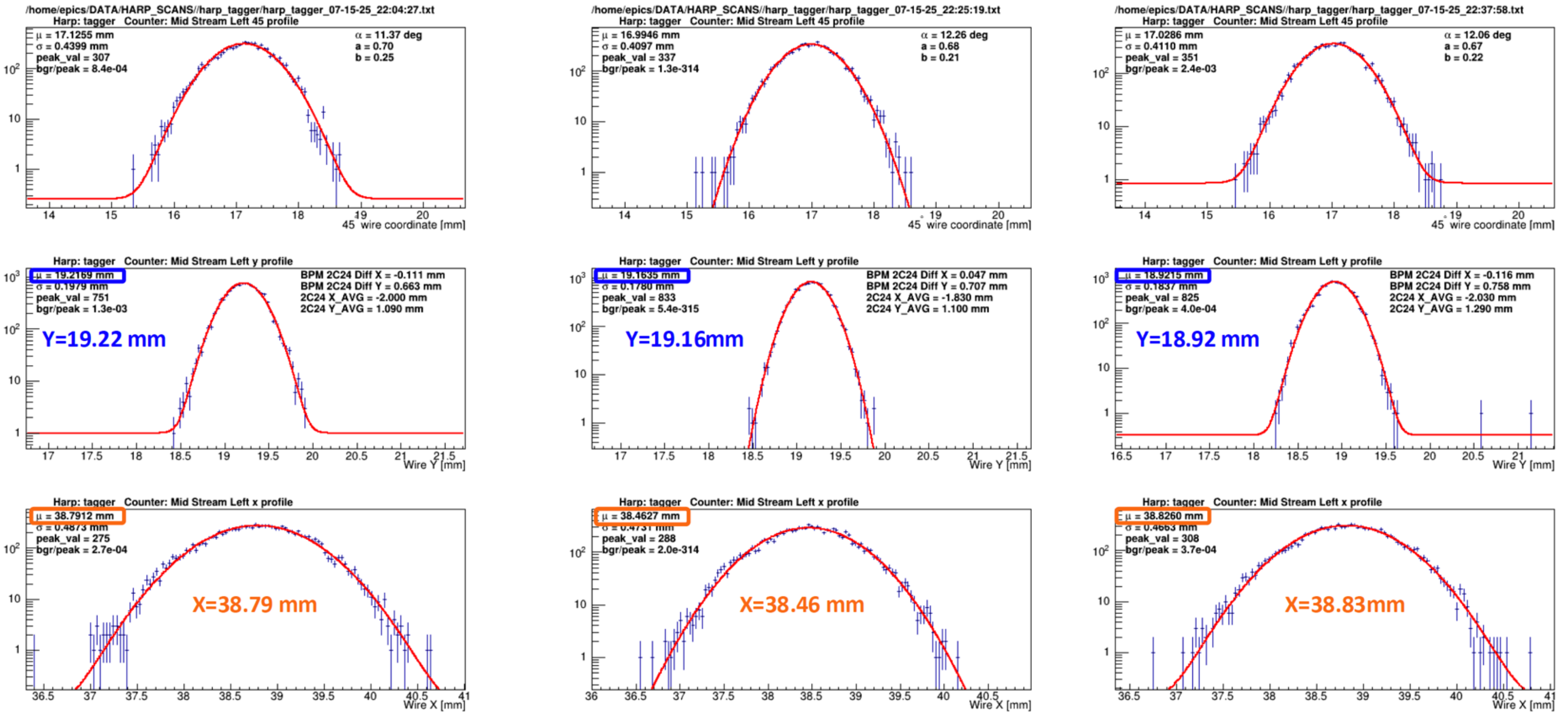




Beam Line Test at 1 nA



Nominal positions	X Is moved by 200 μm	Y Is moved by 200 μm
2C24 BPM locked at X -2, Y +1.1	2C24 BPM locks at X -1.8, Y +1.1	2C24 BPM locks at X -2, Y +1.3



Magnet Configuration

Minimal forces generated by mutual interaction of magnets

Target vs chicane

Table 3: Coil forces at 5T central field:

Coil number	Fx (N)	Fy (N)	Fz(N)
1	0	644876	0
2	0	22573	0
3	0	-109371	0
4	0	-64090	0
5	0	-644876	0
6	0	-22573	0
7	0	109371	0
8	0	64090	0
Total	0	0	0

Table 4: Coil forces in presence of 3 chicane magnet

Coil number	Fx (N)	Fy (N)	Fz(N)
31	0	644942	358
32	0	22600	178
33	0	-109362	76
34	0	-64087	25
35	0	-644942	358
36	0	-22600	178
37	0	109362	76
38	0	64087	25
Total	0	0	1275

Target vs torus

Table 5: Target coil force with and without Torus

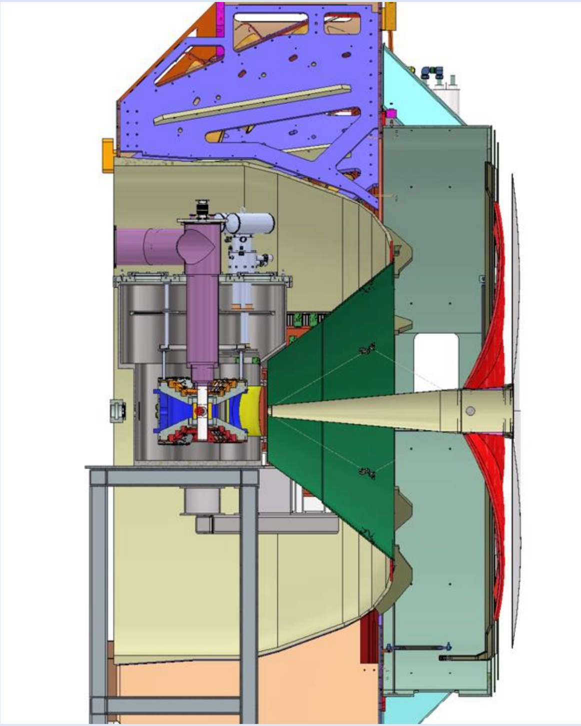
Target Magnet Coil #	Without Torus			With Torus		
	Fx (N)	Fy (N)	Fz (N)	Fx (N)	Fy (N)	Fz (N)
1	0	-644876	0	0	-644876	0
2	0	-22573	0	0	-22573	0
3	0	109371	0	0	109371	0
4	0	64090	0	0	64090	0
5	0	644876	0	0	644876	0
6	0	22573	0	0	22573	0
7	0	-109371	0	0	-109371	0
8	0	-64090	0	0	-64090	0
Total Force	0	0	0	0	0	0

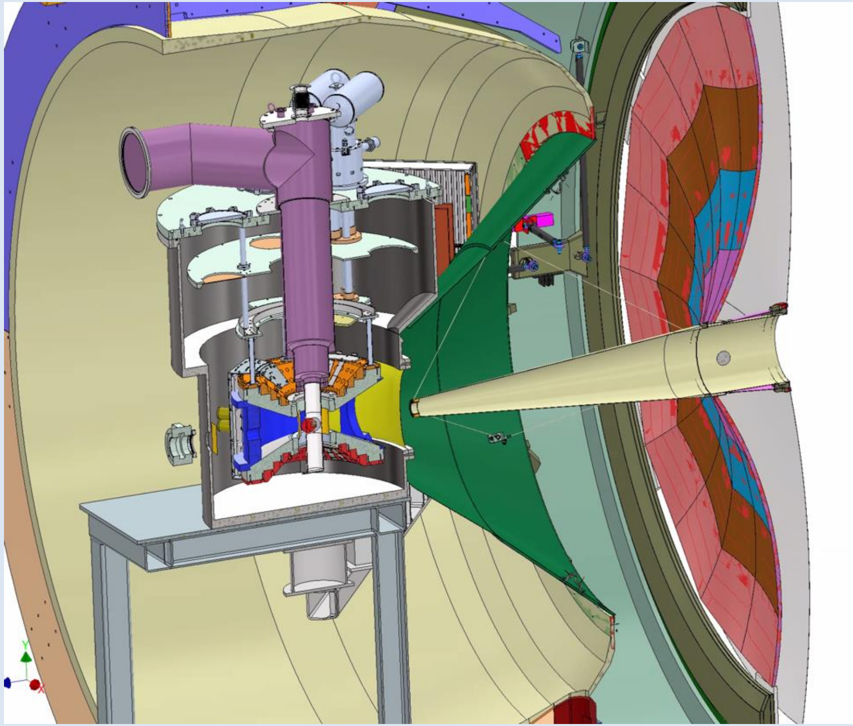
Torus vs target

Table 7: Comparison of Torus coil force with and without Target magnet

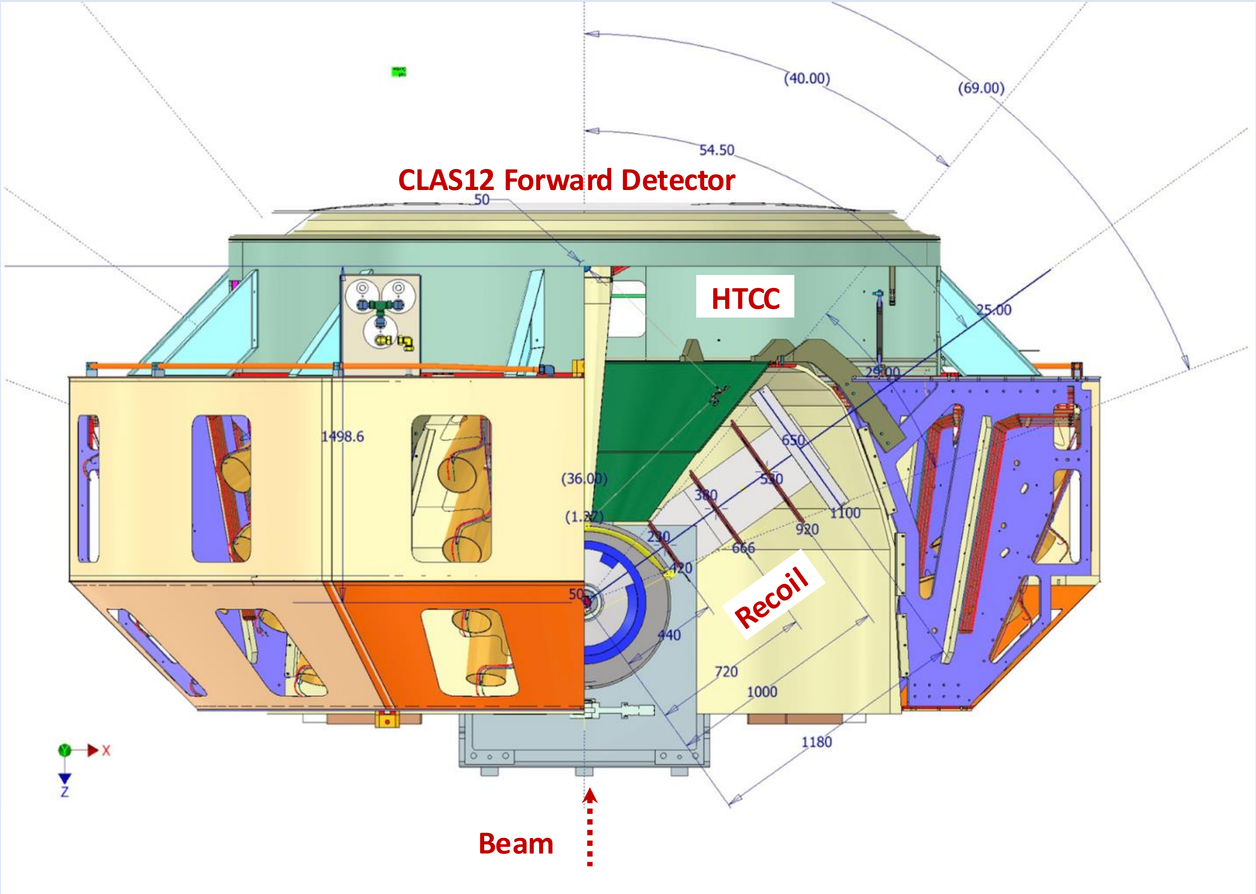
Torus Magnet Coil #		Without Target Magnet			With Target Magnet			Effect of Target Magnet		
Coil	SubCoil	Fx (N)	Fy (N)	Fz (N)	Fx (N)	Fy (N)	Fz (N)	Fx (N)	Fy (N)	Fz (N)
1	1	0	1220649	0	300	1220649	0	300	0	0
	2	0	361535	411162	95	361535	411162	95	0	0
	3	0	-294544	729023	338	-294544	729023	338	0	0
	4	0	-177228	75215	71	-177228	75215	71	0	0
	5	0	-246391	-99549	-19	-246391	-99549	-19	0	0
	6	0	-76474	-181546	-258	-76474	-181546	-258	0	0
	7	0	291655	-721872	-1139	291655	-721872	-1139	0	0
	8	0	350962	-212458	125	350962	-212458	125	0	0
2	9	-1057113	610325	0	-1056808	610322	0	305	-3	0
	10	-313099	180768	411162	-313025	180780	411086	74	12	-77
	11	255083	-147272	729023	255048	-147057	728682	-35	215	-341
	12	153484	-88614	75215	153441	-88548	75187	-43	66	-28
	13	213381	-123196	-99549	213218	-123112	-99475	-163	83	74
	14	66228	-38237	-181546	66109	-38317	-181366	-119	-80	179
	15	-252581	145828	-721872	-252522	145137	-720893	58	-690	979
	16	-303942	175481	-212458	-303776	175457	-212346	166	-24	112
3	17	-1057113	-610325	0	-1056808	-610322	0	305	3	0
	18	-313099	-180768	411162	-313025	-180780	411086	74	-12	-77
	19	255083	147272	729023	255048	147057	728682	-35	-215	-341
	20	153484	88614	75215	153441	88548	75187	-43	-66	-28
	21	213381	123196	-99549	213218	123112	-99475	-163	-83	74
	22	66228	38237	-181546	66109	38317	-181366	-119	80	179
	23	-252581	-145828	-721872	-252522	-145137	-720893	58	690	979
	24	-303942	-175481	-212458	-303776	-175457	-212346	166	24	112
4	25	0	-1220649	0	300	-1220649	0	300	0	0
	26	0	-361535	411162	95	-361535	411162	95	0	0
	27	0	294544	729023	338	294544	729023	338	0	0
	28	0	177228	75215	71	177228	75215	71	0	0
	29	0	246391	-99549	-19	246391	-99549	-19	0	0
	30	0	76474	-181546	-258	76474	-181546	-258	0	0
	31	0	-291655	-721872	-1139	-291655	-721872	-1139	0	0
	32	0	-350962	-212458	125	-350962	-212458	125	0	0
5	33	1057113	-610325	0	1057418	-610327	0	305	-3	0
	34	313099	-180768	411162	313172	-180755	411239	74	12	77
	35	-255083	147272	729023	-255118	147487	729364	-35	215	341
	36	-153484	88614	75215	-153527	88680	75243	-43	66	28
	37	-213381	123196	-99549	-213544	123279	-99622	-163	83	-74
	38	-66228	38237	-181546	-66347	38157	-181725	-119	-80	-179
	39	252581	-145828	-721872	252639	-146518	-722851	58	-690	-979
	40	303942	-175481	-212458	304108	-175504	-212570	166	-24	-112
6	41	1057113	610325	0	1057418	610327	0	305	3	0
	42	313099	180768	411162	313172	180755	411239	74	-12	77
	43	-255083	-147272	729023	-255118	-147487	729364	-35	-215	341
	44	-153484	-88614	75215	-153527	-88680	75243	-43	-66	28
	45	-213381	-123196	-99549	-213544	-123279	-99622	-163	-83	-74
	46	-66228	-38237	-181546	-66347	-38157	-181725	-119	80	-179
	47	252581	145828	-721872	252639	146518	-722851	58	690	-979
	48	303942	175481	-212458	304108	175504	-212570	166	24	-112
	All coils	0	0	-141	0	0	-141	0	0	0

3D Model



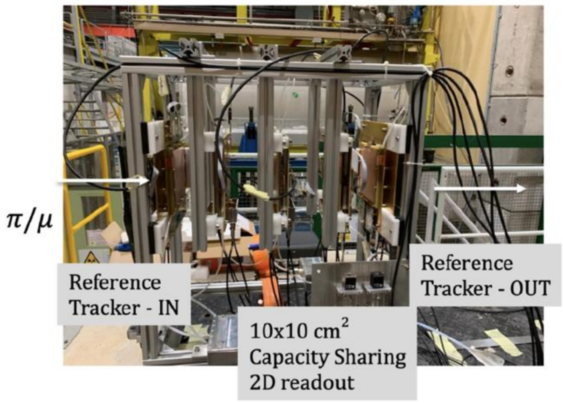


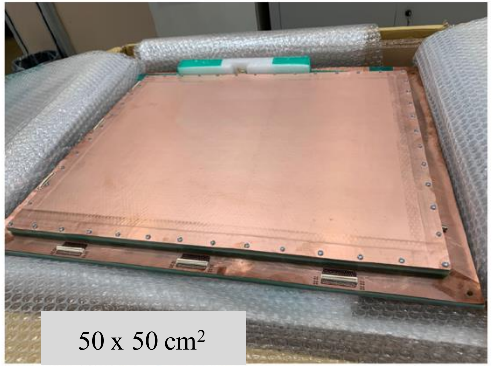
Recoil Dimensions

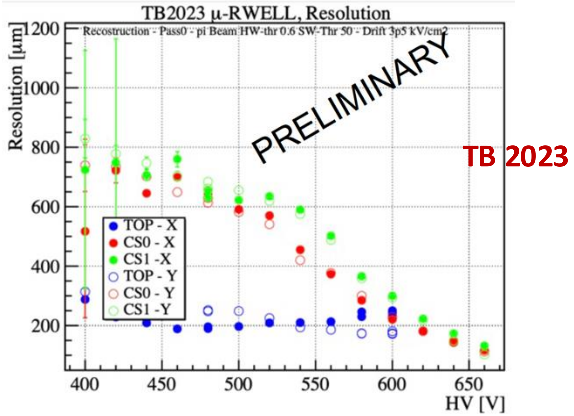


RGH Recoil Detector

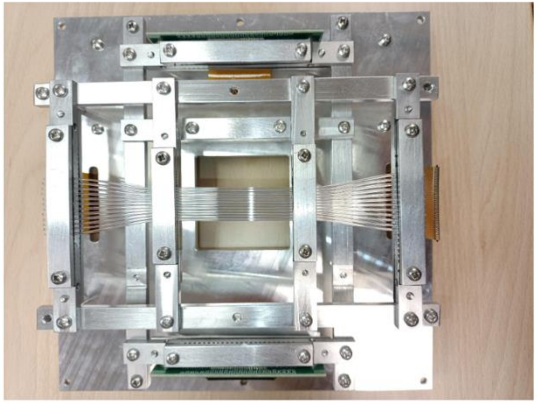
Spatial resolution O(100 μm) with μ-Rwell tecnology under development for the CLAS12 high-lumi project

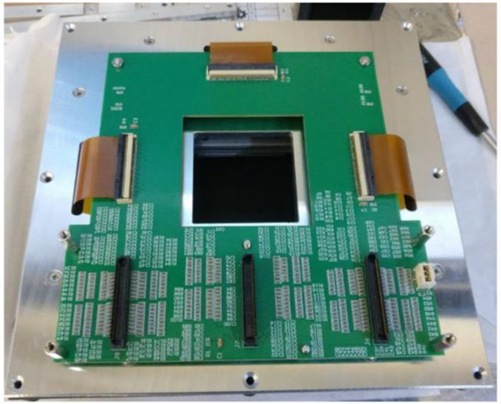


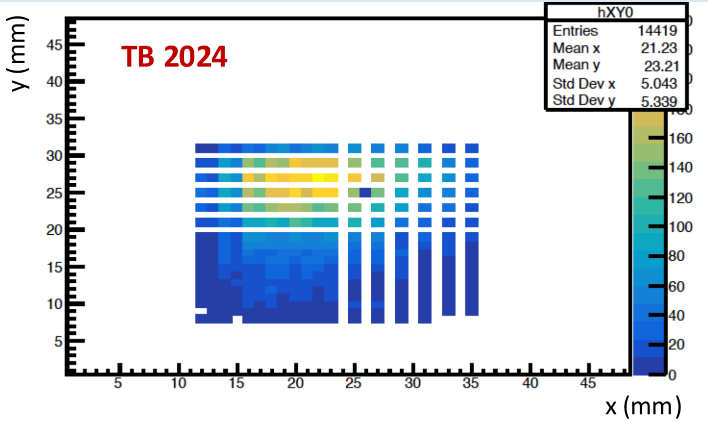




Time resolution O(100 ps) with scintillating technology (CLAS12 TOF) or in synergy with other projects (e.g. INFN fast tracker)

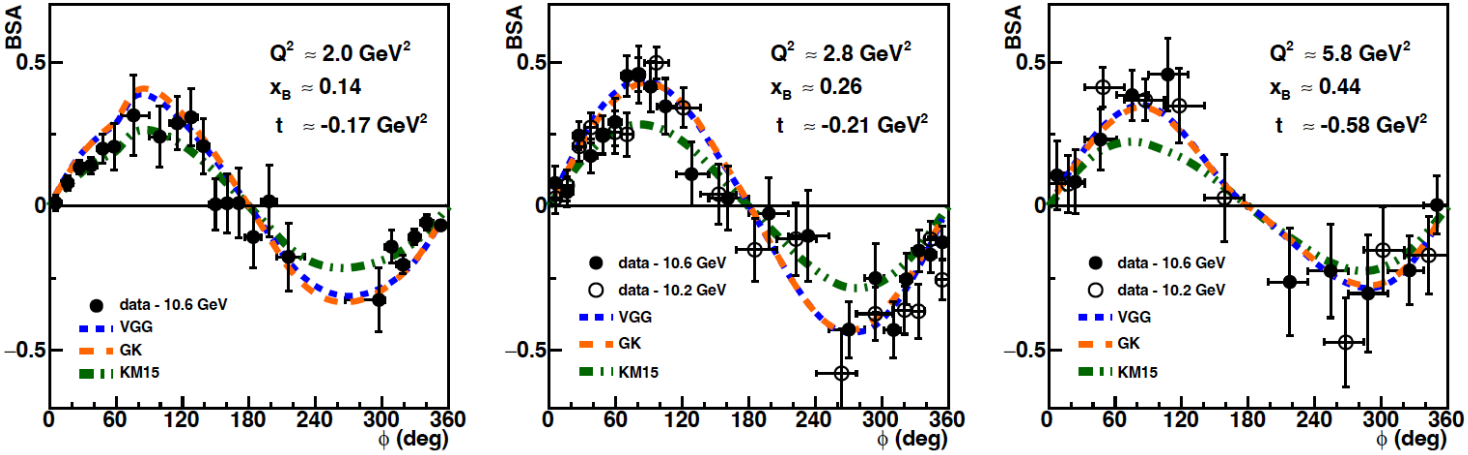






First CLAS12 measurement of DVCS beam-spin asymmetries in the extended valence region

G. Christiaens at al., Phys.Rev.Lett. 130 (2023) 21, 211902

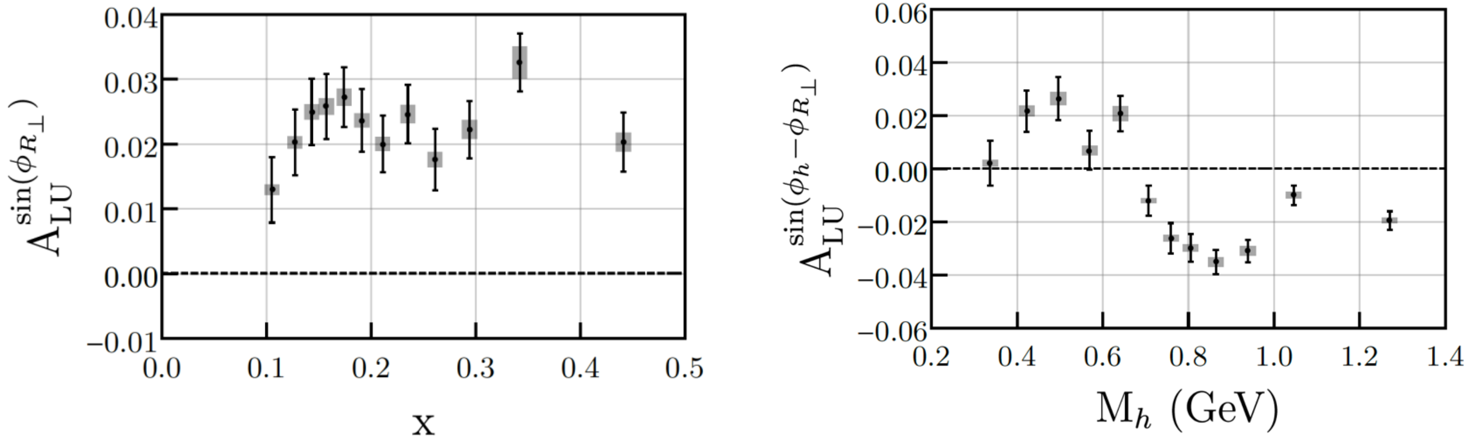


Sensitive to GPDs and the 3D structure of the nucleon

With respect the past:
- extended range in the valence region well inside the DIS regime
- superior statistics instrumental for multidimensional study & model assessment

Observation of Beam Spin Asymmetries in the Process $ep \to e'\pi^+\pi^- X$ with CLAS12

T.B. Hayward at al., Phys.Rev.Lett. 126 (2021) 152501



Sensitive to TMDs and the strong-force correlations in hadron formation

With respect the past:
- extended range in the valence region well inside the DIS regime
- superior statistics instrumental for multidimensional study
- large acceptance for elusive correlations

NH_3 target

L = 10^{35} cm^{-2} s^{-1}

Sheet-of-flame bakground

Forward Angle Detector
covers 8°-15° in polar angle

Large Angle Detector
Covers 15°-24° in polar angle