Transverse spin effects in SIDIS at 11 GeV with transversely polarized target using the CLAS12 detector

(A CLAS12 experiment proposal for PAC38)

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A CLAS12 Proposal For PAC38

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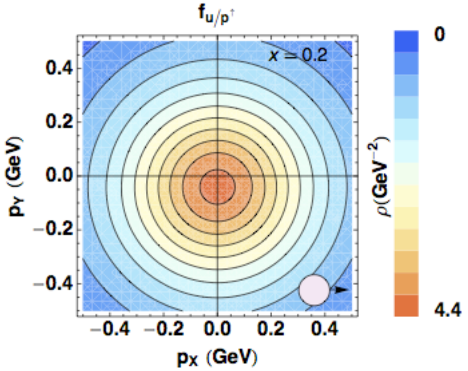
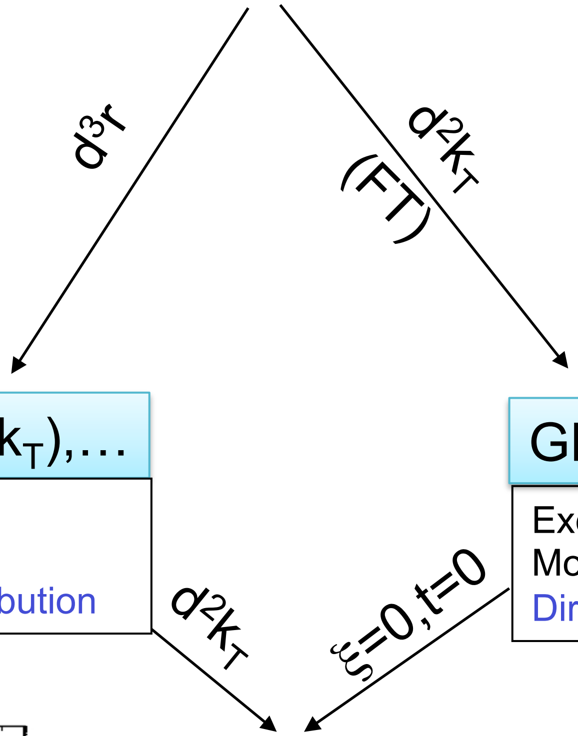
PHYSICS MOTIVATIONS

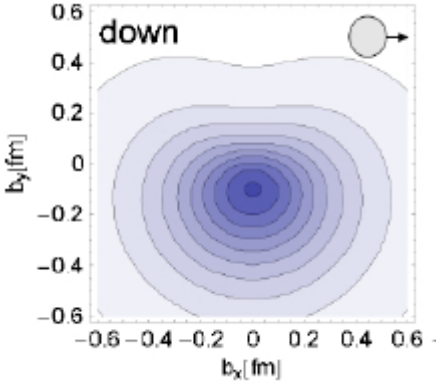
Quantum phase-space distributions of quarks

$W_p^q(x,k_T,r)$ “Mother” Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k







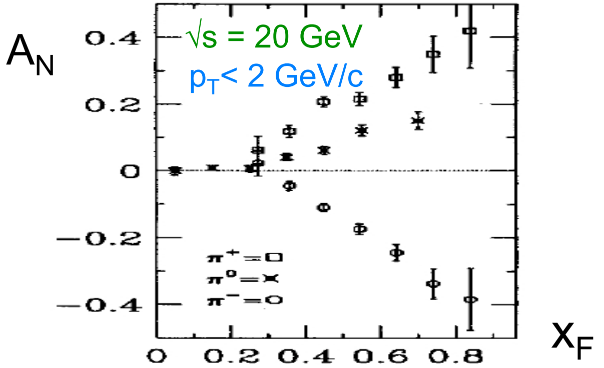
TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

May explain SSA



PDFs $f_p^u(x)$,…

LOI 11-105
Exclusive Physics: DVCS with Transverse Target

May solve proton spin puzzle

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\ \left[H(x,\zeta,t)+E(x,\zeta,t)\right]$$

Leading Twist TMDs

Quark polarisation

Nucleon polarisation

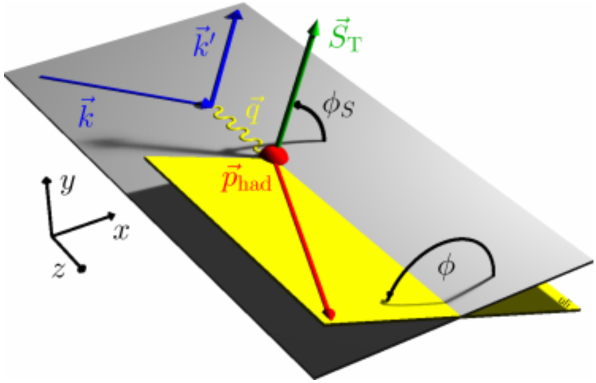
	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ - *Boer Mulders*
L		g_1 - *Helicity*	$h_{1L}^\perp$ - *Worm-gear*
T	$f_{1T}^\perp$ - *Sivers*	$g_{1T}^\perp$ - *Worm-gear*	h_1 - *Transversity* $h_{1T}^\perp$ - *Pretzelosity*

E12-09-007
Quark number and helicities

E12-06-112
E12-09-008
Boer-Mulders for pions and kaons

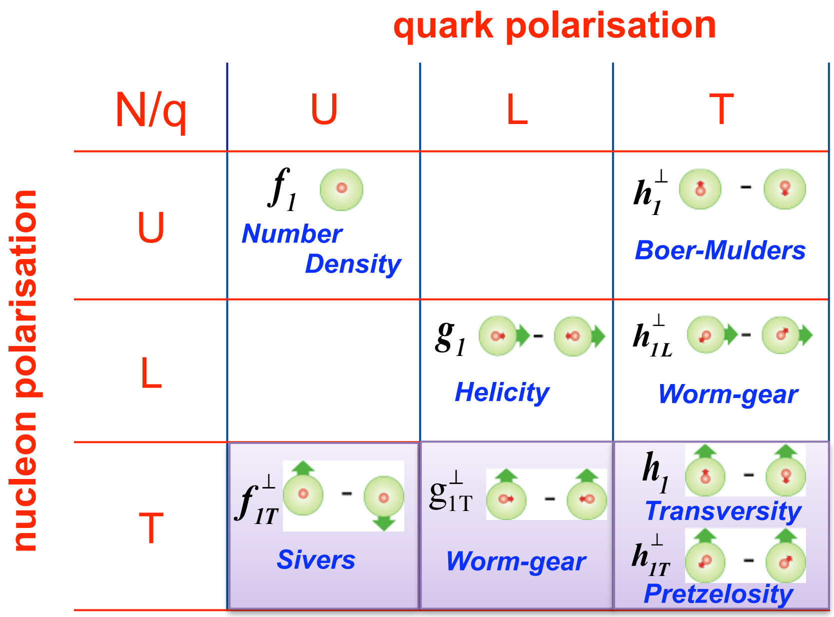
E12-07-107
E12-09-009
Spin-effects for pions and kaons

PR12-11-111
This proposal



CLAS12 has access to all of them through specific azimuthal modulations (ϕ, ϕ_S) of the cross-section thanks to the polarized beam and target

Leading Twist TMDs



quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 **Number Density**		$h_1^\perp$ - **Boer-Mulders**
L		g_1 - **Helicity**	$h_{1L}^\perp$ - **Worm-gear**
T	$f_{1T}^\perp$ - **Sivers**	$g_{1T}^\perp$ - **Worm-gear**	h_1 - **Transversity** $h_{1T}^\perp$ - **Pretzelosity**

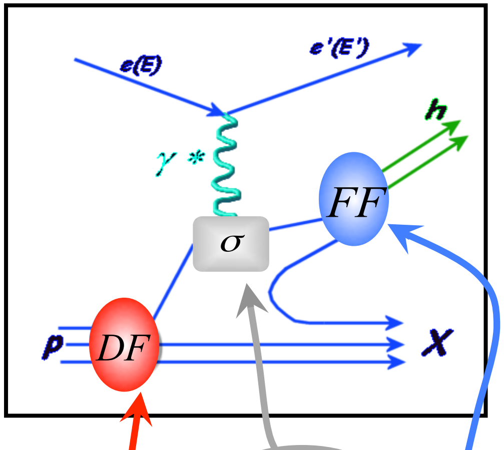
Transversity:

Survives transverse momentum integration (missing leading-twist collinear piece)

Differs from helicity due to relativistic effects and no mix with gluons in the spin-1/2 nucleon

Other elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects



$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

SIDIS cross section:

$h_1 \otimes H_1^\perp$

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \overset{Leading}{\underset{Twist}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$f_{1T}^\perp \otimes D_1$ $\quad$ $h_{1T}^\perp \otimes H_1^\perp$

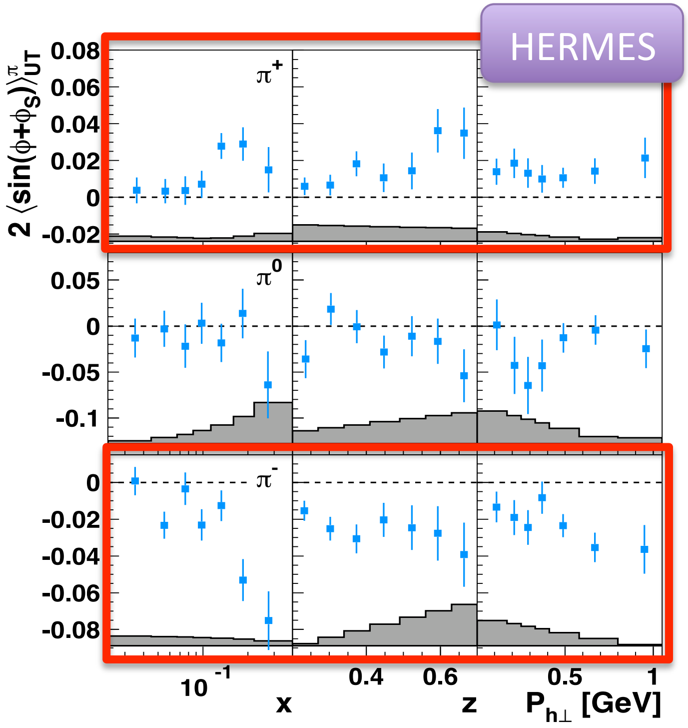
$$+S_T\left\{\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\}$$

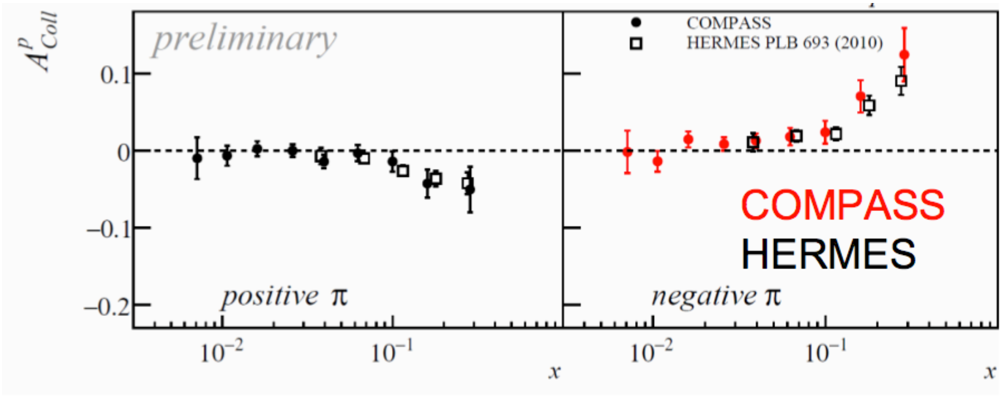
$g_{1T}^\perp \otimes D_1$

$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\dots$$

The Collins amplitude

$h_1 \otimes H_1^\perp$



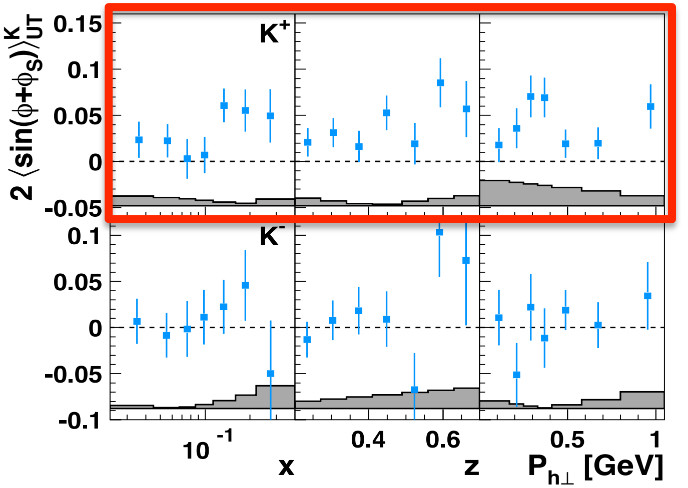


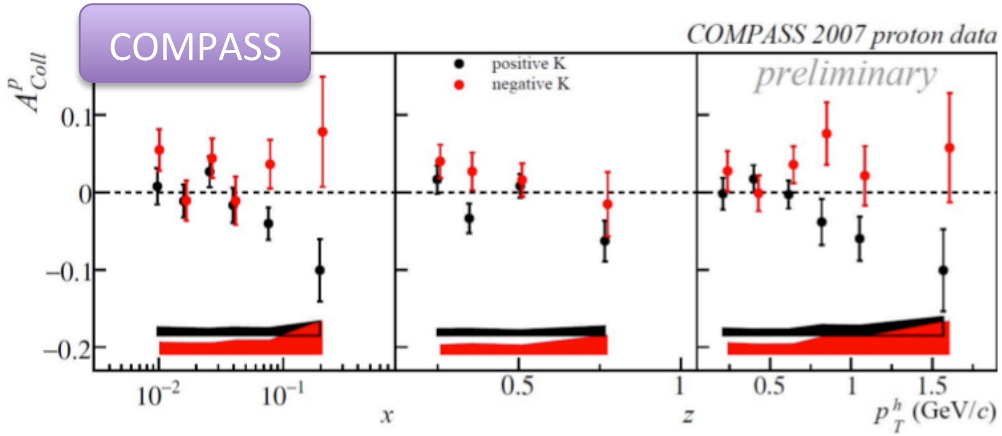
Access to transversity and Collins functions

Consistent non-zero signals for pions

Opposite sign for pions reveals Collins features

Puzzle in (low-statistics) kaon signals:
K^+ amplitudes larger then π^+
K^- amplitudes are not in agreement





Transversity and Tensor Charge

$h_1 \otimes H_1^{\perp}$

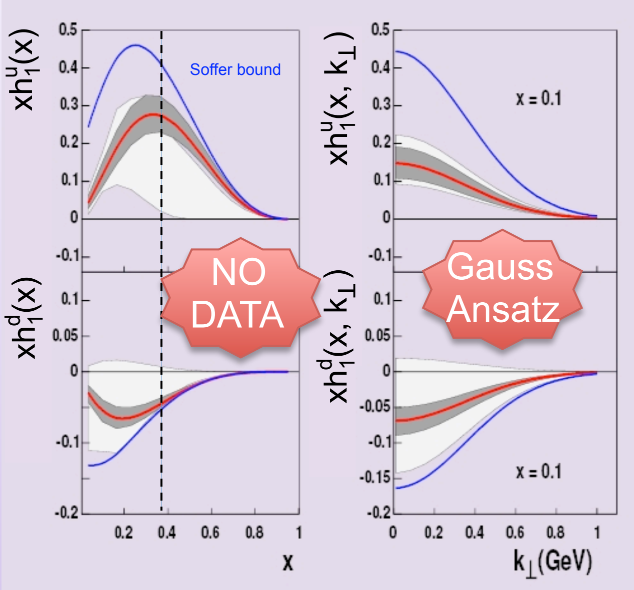
$lp \rightarrow l'hX$

$ld \rightarrow l'hX$

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto h_1(x) \otimes H_1^{\perp q}(z)$$

$e^+e^- \rightarrow h_1 h_2 X$

First extraction of Transversity!



NO DATA

Gauss Ansatz

Anselmino et al. Phys. Rev. D 75 (2007)

- Existing data limited to x < 0.3
- Statistics not enough to adress p_T dependence
  → gaussian ansatz
- Fragmentation extracted from high energy colliders
  → evolution properties assumed

Coverage at high-x to extract the tensor charge ?

$$\int_0^1 dx\left[h_1^q(x) - \bar{h}_1^q(x)\right] = \delta q$$

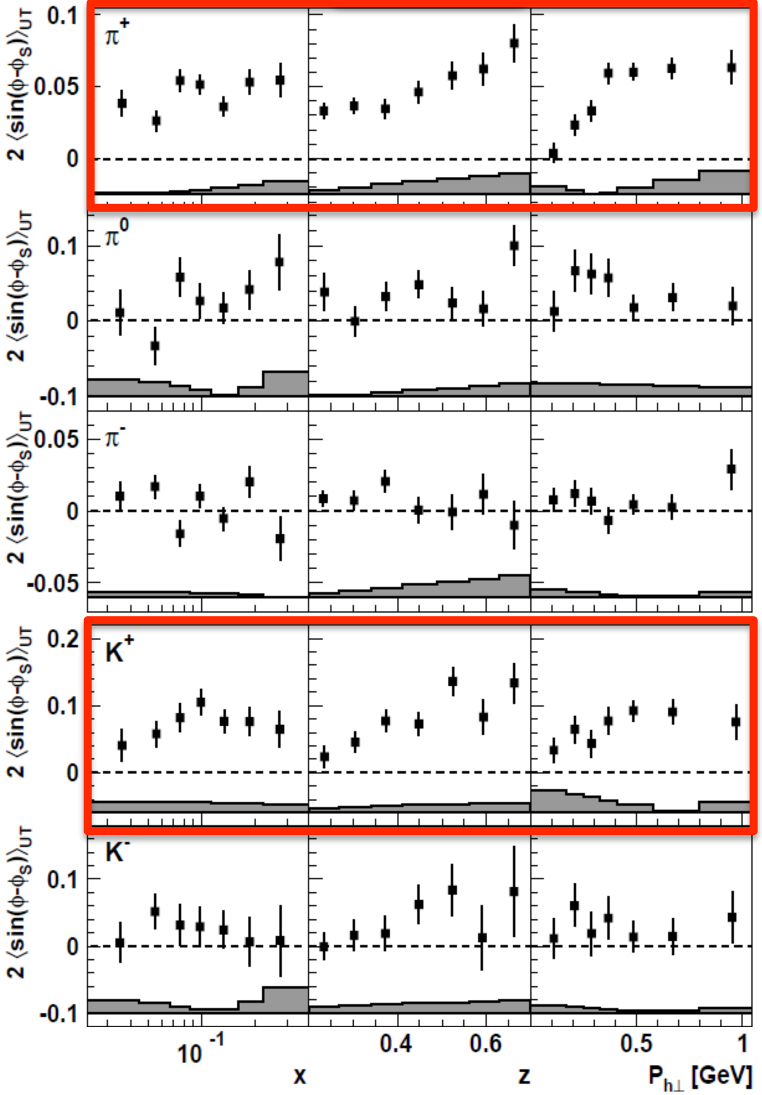
Precise data to resolve convolution and p_T dependence (i.e. Bessel approach) ?

Multi-dimentional analysis to constrain Collins ?

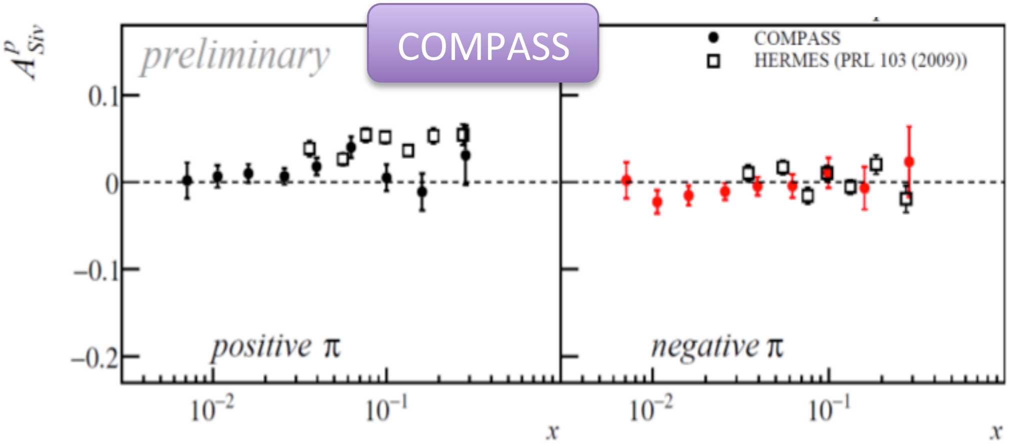
The Sivers effect

$f_{1T}^{\perp} \otimes D_1$

HERMES



COMPASS



Related to quark orbital angular momentum

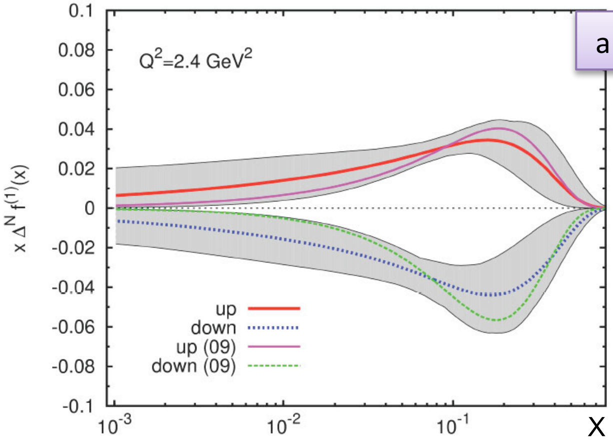
Non zero signals for π^+ and K^+

Not good consistency of results

Flavor tagging

K^+ signals larger than π^+

?

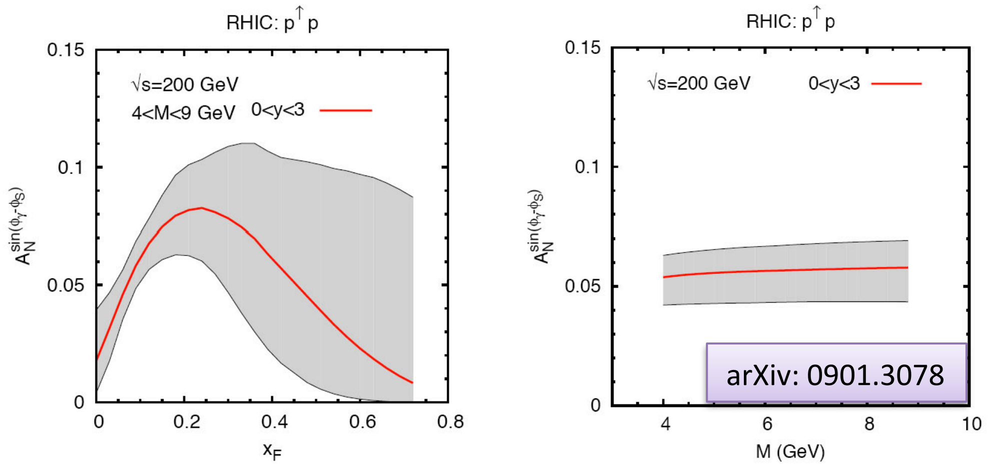


arXiv: 1107.4446

The Sivers effect

$f_{1T}^{\perp} \otimes D_1$

Sivers effect from SIDIS to Drell-Yan



arXiv: 0901.3078

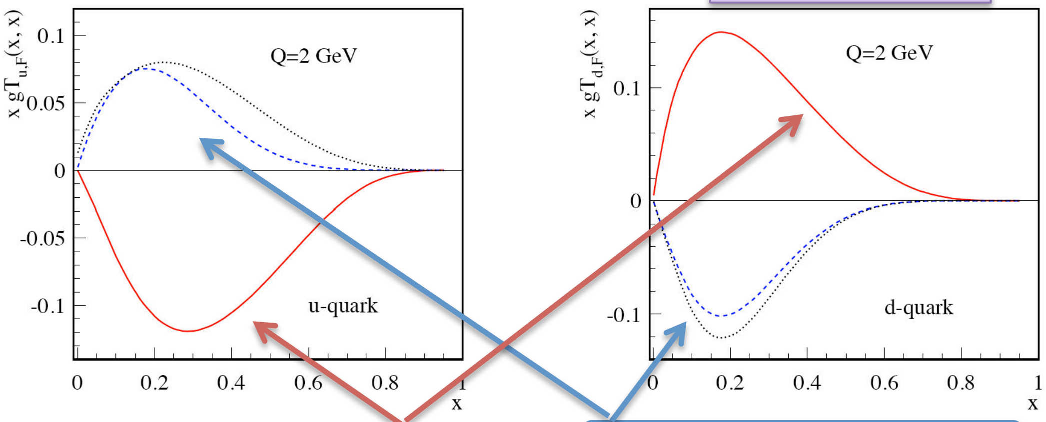
Coverage at large x and relation with Drell-Yan

Sign change as a crucial test of TMDs factorization

?

Sivers effect from SIDIS to pp

arXiv: 1103.1591



T3 correlator from pp

Sivers moment from SIDIS

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

Coverage at large p_T and relation with twist-3 collinear approach

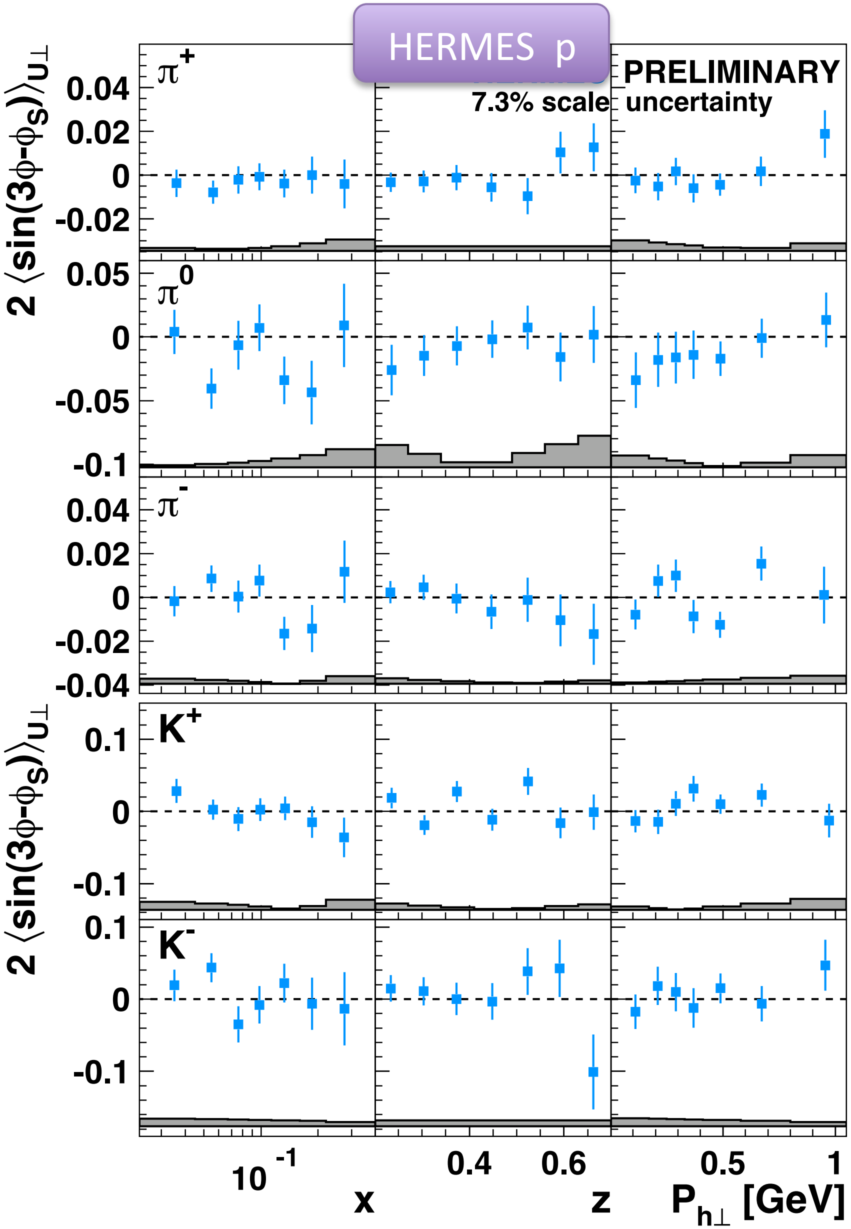
Sign mismatch between SIDIS and pp SSA ?

?

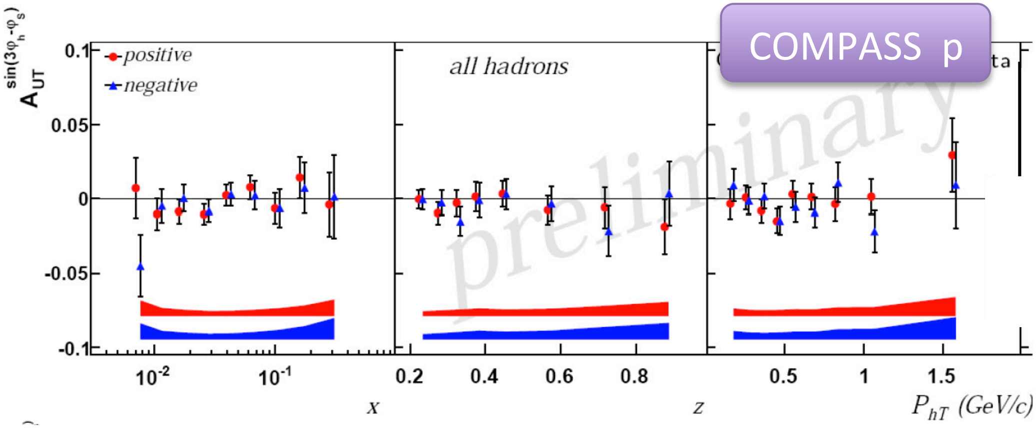
The Pretzelosity

$h_{1T}^{\perp} \otimes H_1^{\perp}$

HERMES p



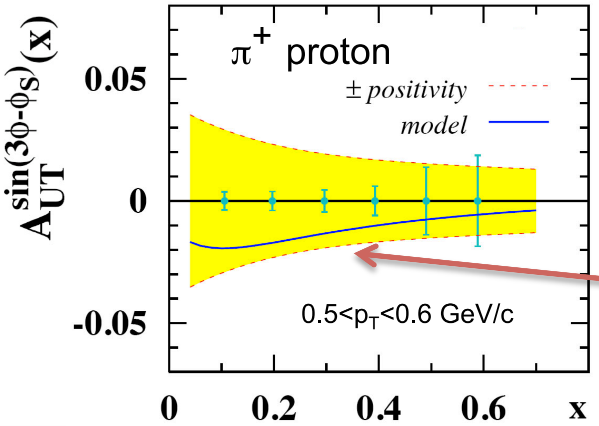
COMPASS p



Sensitive to the D-wave component and the non spherical shape of the nucleon

Statistical power of existing data is not enough to observe significant signals

“pretzelosity” still basically unknown ?



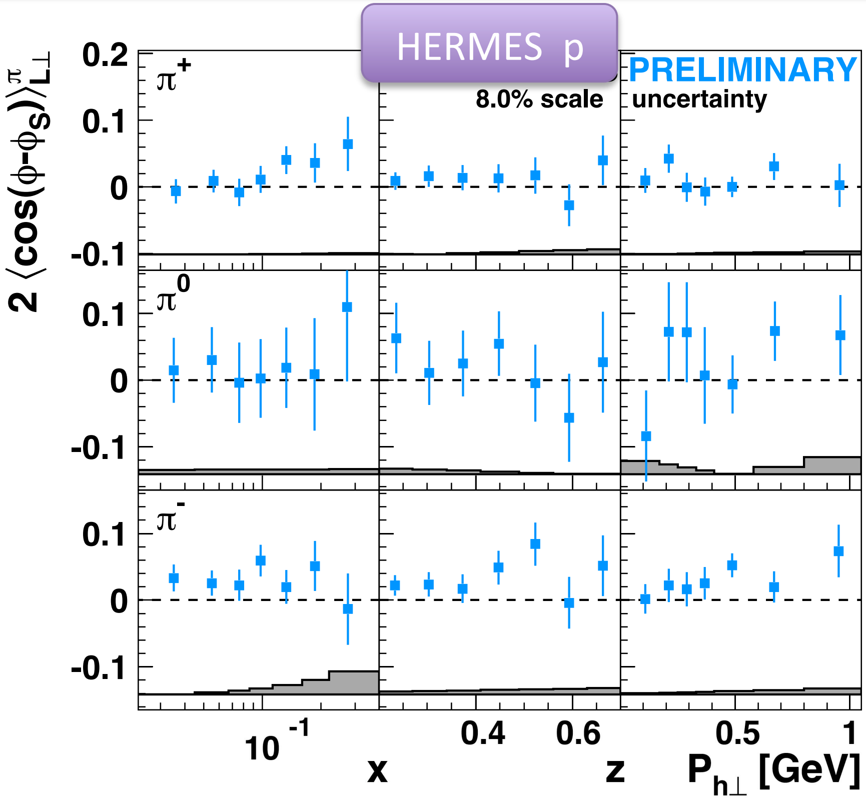
arXiv: 0812.3246

Few % signal expected at Jlab from covariant model

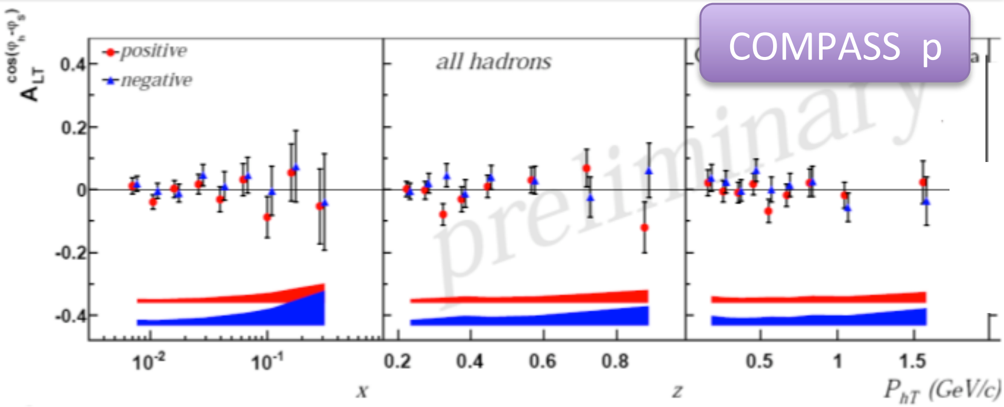
The Worm-gear function

$g_{1T}^{\perp} \otimes D_1$

HERMES p



COMPASS p



Related to quark orbital motion

Statistics not enough to investigate relations supported by many theoretical models:

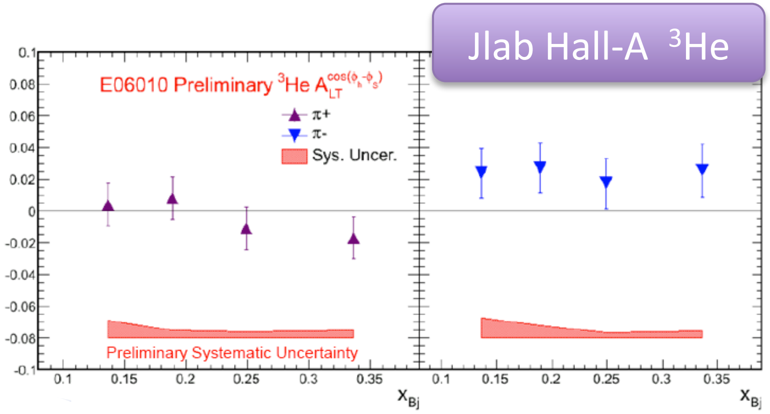
$$g_{1T}^{q} = -h_{1L}^{\perp q}$$

(supported by Lattice QCD and first data)

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x\int_x^1 \frac{dy}{y}\, g_1^q(y)$$

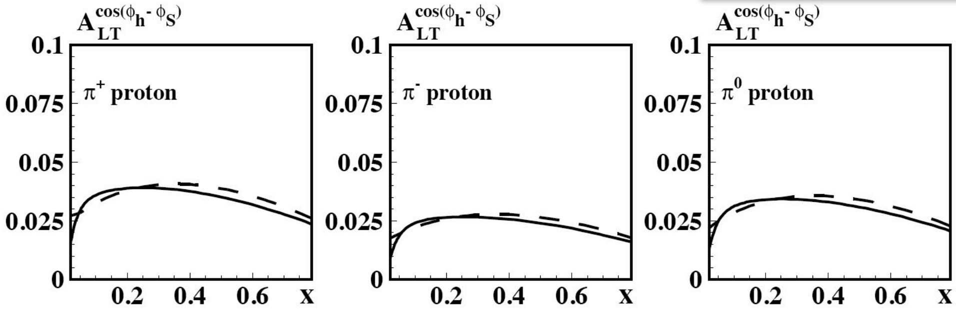
(Wandura-Wilczek type approximation)

Jlab Hall-A ^{3}He



From constituent quark model:

arXiv: 0903.1271



Honour and Duty

TMDs describe a new class of phenomena providing novel insights into the rich nuclear structure

DIS experiments get access to all PDFs and FFs, but in a convoluted way, first generation non-zero results provide promises but also open questions

Full coverage of valence region not achieved

Limited knowledge on transverse momentum dependences

Flavor decomposition often missing

Evolution properties to be defined

Role of the higher twist to be quantified

Universality ⟷ Fundamental test of QCD

Still incomplete phenomenology is asking for new inputs

Crucial: completeness
flavor tagging and four-fold differential extraction in all variables (x,z,Q^2,P_T)
to have all dependencies resolved

EXPERIMENTAL SETUP

The CLAS12 Spectrometer

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

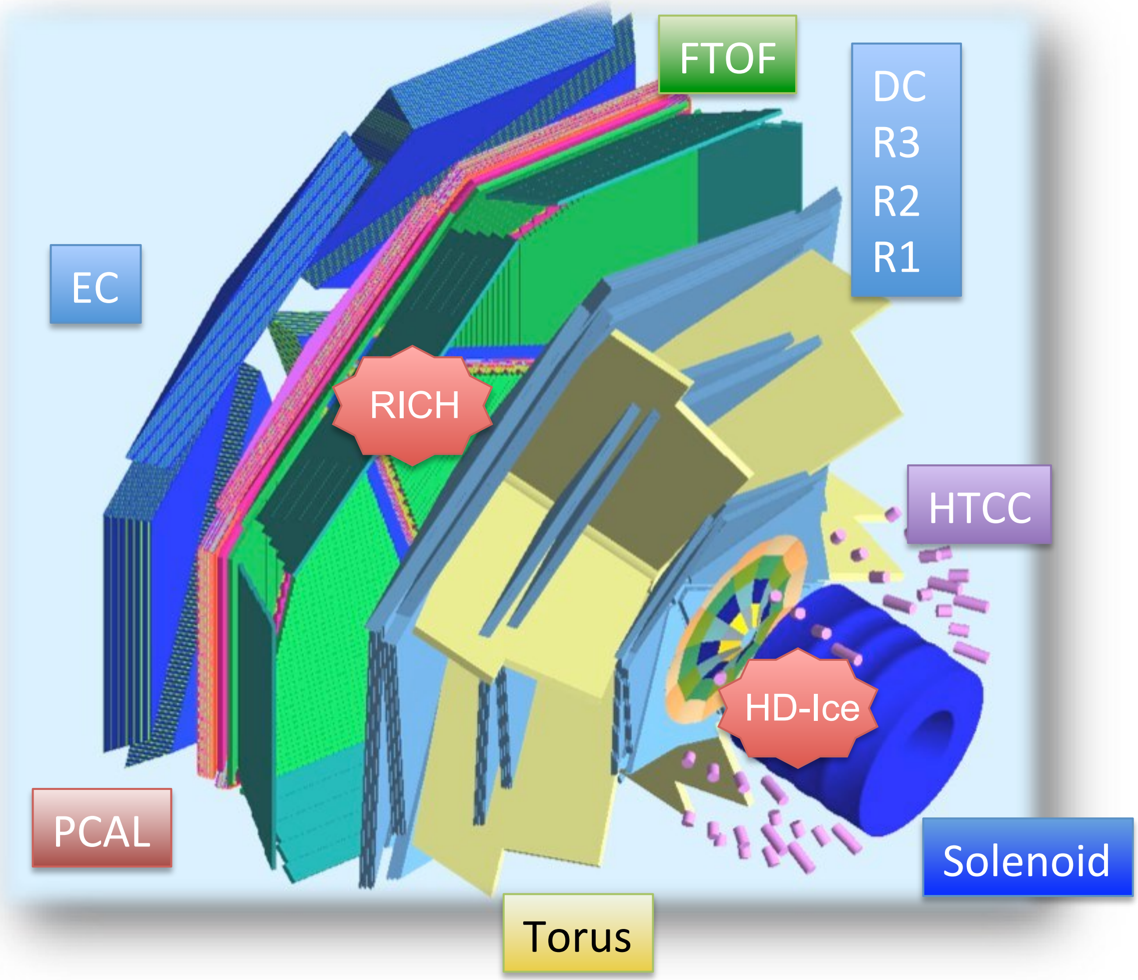
Highly polarized electron beam

H and D polarized targets

Broad kinematic range coverage (current to target fragmentation)

HD-Ice: Transverse Target new concept
(commission with CLAS at 6 GeV common to LOI 11-105)

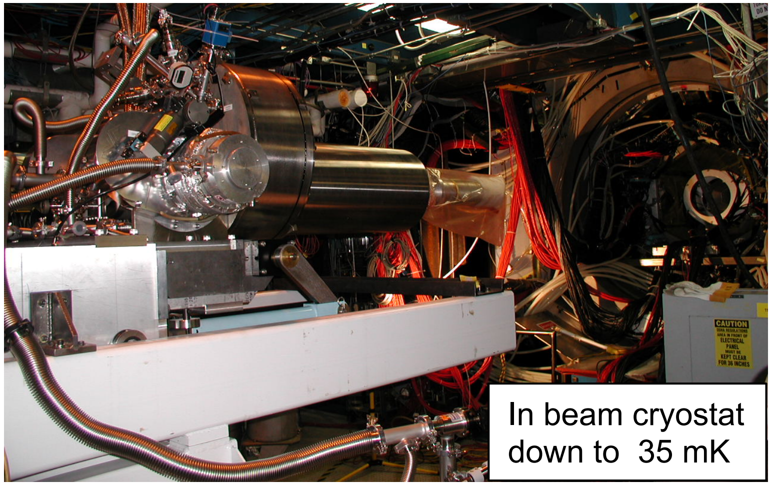
RICH: Hadron ID for flavor separation
(common to SIDIS approved exp.)



PAC30 report (2006): Measuring the kaon asymmetries is likely to be as important as pions …. The present capabilities of the present CLAS12 design are weak in this respect and should be strengthened.

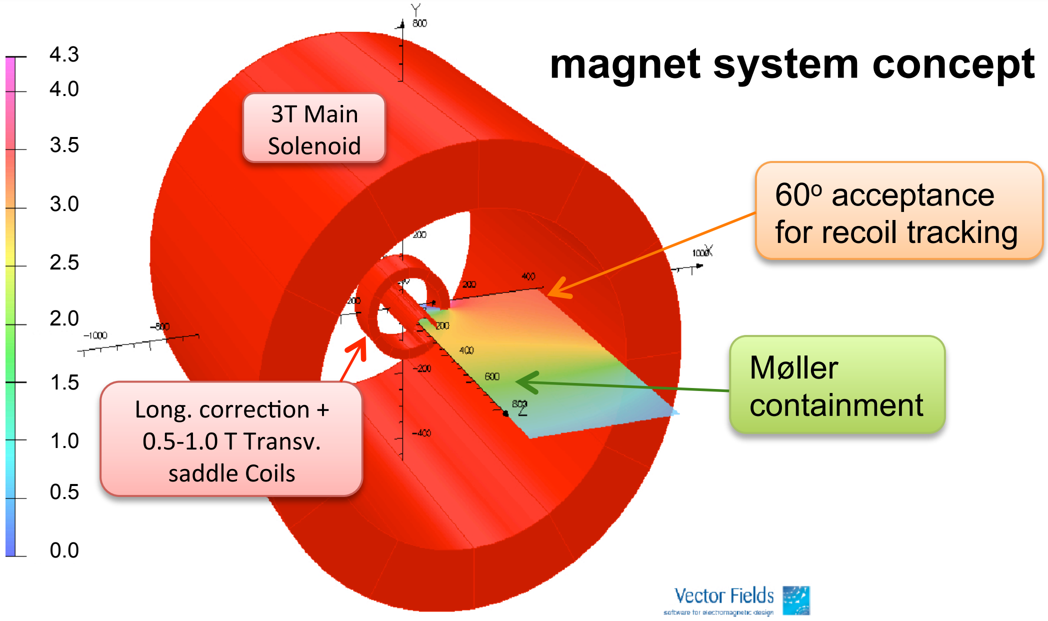
Transversely Polarized HD-Ice Target

Up to 75% H and 40 % D polarization independently controlled



In beam cryostat down to 35 mK

magnet system concept



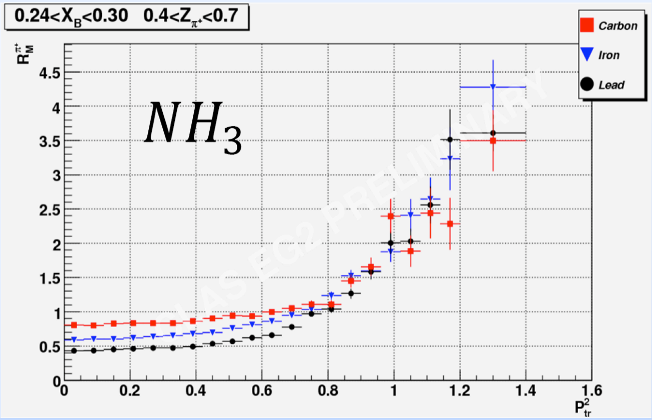
3T Main Solenoid

60° acceptance for recoil tracking

Møller containment

Long. correction + 0.5-1.0 T Transv. saddle Coils

HD-Ice target vs standard nuclear targets



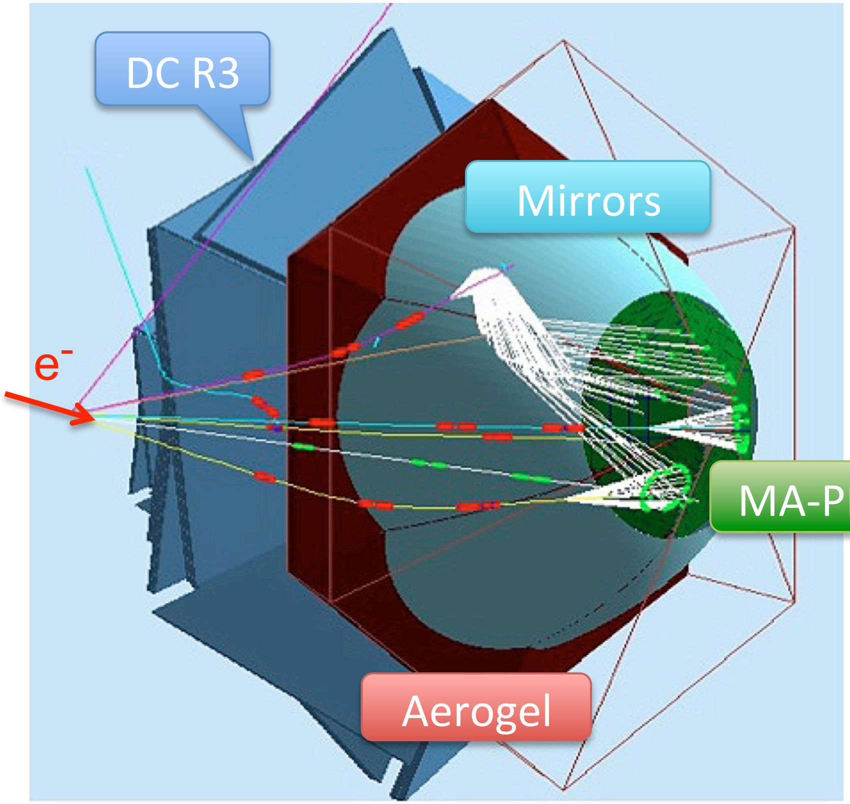
Advantages:

- ➢ Minimize nuclear background
  small dilution and nuclear effets at large p_T
- ➢ Weak holding field (BdL ≤ 0.1 Tm)
  wide acceptance, negligible beam deflection, viable field inversion

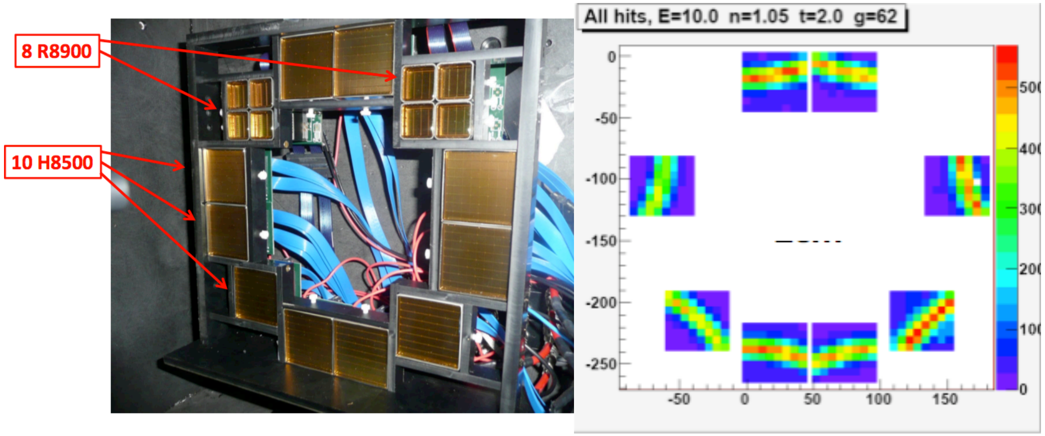
Disadvantages:

- ➢ Very long polarizing times (months)
- ➢ Need to demonstrate that can remain polarized for long periods with an electron beam: as consevative approach we consider 1/10 of full luminosity (compensated by better dilution)

The RICH Detector



Test beam results at CERN, July 2011



Simulation of n=1.05 aerogel + H8500:

≥ 10 p.e. for direct rings

(confirmed by preliminary test-beam results)

≥ 5 p.e. for reflected rings

≥ 500 pion rejection factor @ 99% kaon eff.

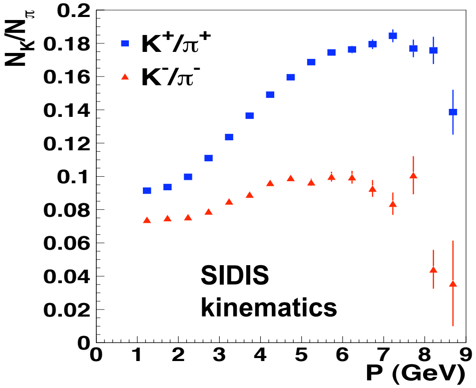
RICH goal:

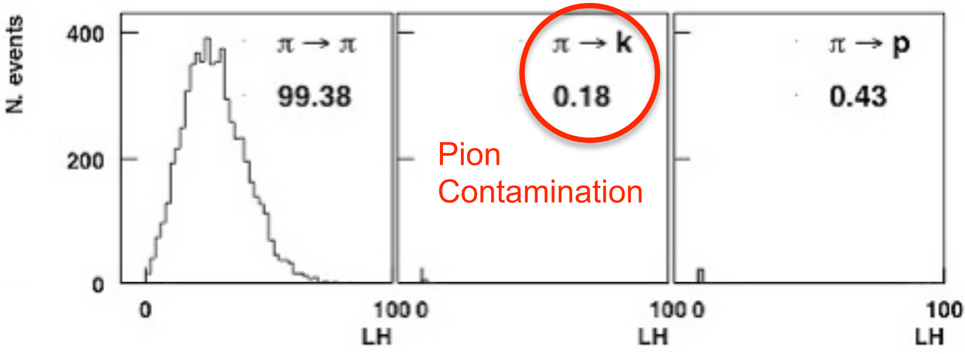
π/K/p separation

of **4-5 σ @ 8 GeV/c**

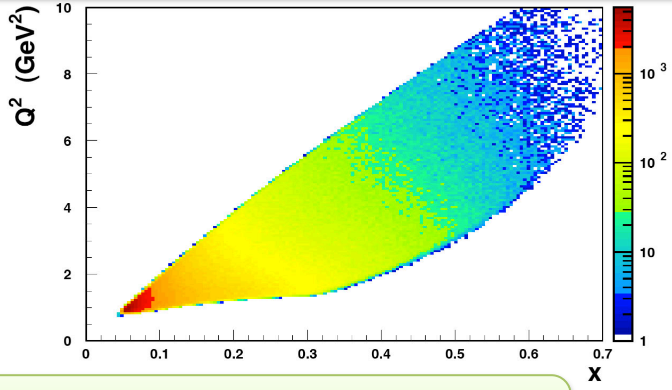
for a pion rejection

factor **1:1000**

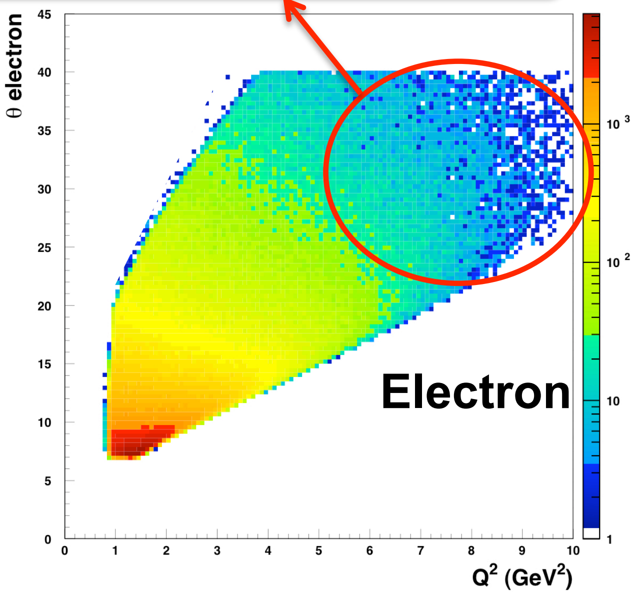


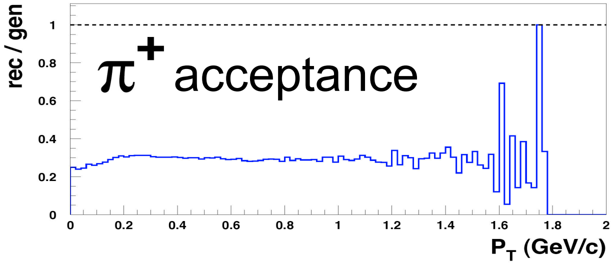


CLAS12 Kinematic Coverage

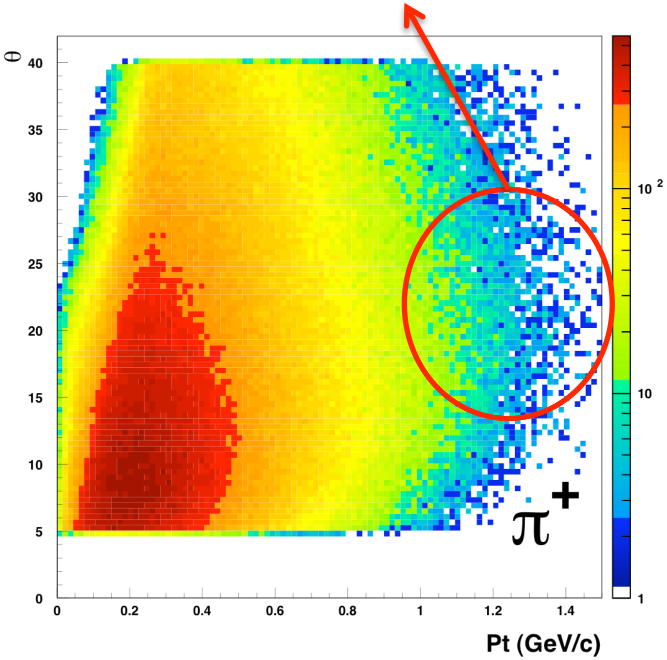


Large electron scattering angles (> 20°) mandatory to reach high Q^2 values





Intermediate angular range (15-30°) mandatory to reach high P_T values



The CLAS12 forward detector is perfectly suitable for high-Q^2 and high-p_T measurements in the valence since designed to cover up to 40 degrees angles

PROJECTIONS

Single- and Double-Spin asymmetries

- **Experiment:** CLAS12 with
  HD-Ice transversely polarized target
  75 % polarization and 1/3 dilution for Hydrogen @ 10^{34} cm^{-2} s^{-1}
  RICH detector for flavor tagging
  pions, kaons and protons ID in the 3-8 GeV/c momentum range

- **Event selection**:

$Q^2 > 1$ GeV^2, $x > 0.05$	select DIS region
$W^2>4$ GeV^2 , $M_X^2>2$ GeV^2	suppress resonances
$0.10 < y < 0.85$	for high detection efficiency and small radiative corrections
$0.3 < z < 0.7$	select current fragmentation and avoid exclusivity corner

- **Analysis**: in each kinematic bin, the relevant Fourier amplitudes (Collins, Sivers, etc) are extracted simultaneously, thanks to their specific azimuthal dependence, by a Maximum-Likelihood fit unbinned in ϕ,ϕ_S of the yields for opposite spin states

$$p.d.f. = \varepsilon(x,y,z,p_T,\phi,\phi_S)\sigma_{UU}(x,y,z,p_T)/\mathrm{N}\times$$

Multiplicative term : irrelevant for balanced spin samples

$$\rho(P)\ \left\{1+\ldots+P\left[A^{Coll}(\lambda_{Coll},x,y,z,p_T)\sin(\phi+\phi_S)+A^{Siv}(\lambda_{Siv},x,y,z,p)\sin(\phi-\phi_S)+\ldots\right]\right\}$$

Unpolarized terms

Other polarized terms

Systematic uncertainty

Error source	Error type	Uncertainty
Acceptance corrections	relative	2÷5 %
ρ^0 contamination	relative	1÷3 %
Radiative corrections	relative	2 %
Target polarization	relative	4 %
Al background (dilution)	relative	1÷3 %
H/D background (dilution)	relative	1÷4 %
Total	relative	5÷9 %

Several 10^{-3} for 0.05-0.1 typical asymmetries

Estimates based on:

- Experience & methods from CLAS/HERMES measurements

Reduces with statistics and bin number (no long range integrations)

Benefits from the large acceptance (edge effects, vector meson decays)

- Current knowledge on HD-Ice target

Dominated by uncertainties in transfer losses between cryostats

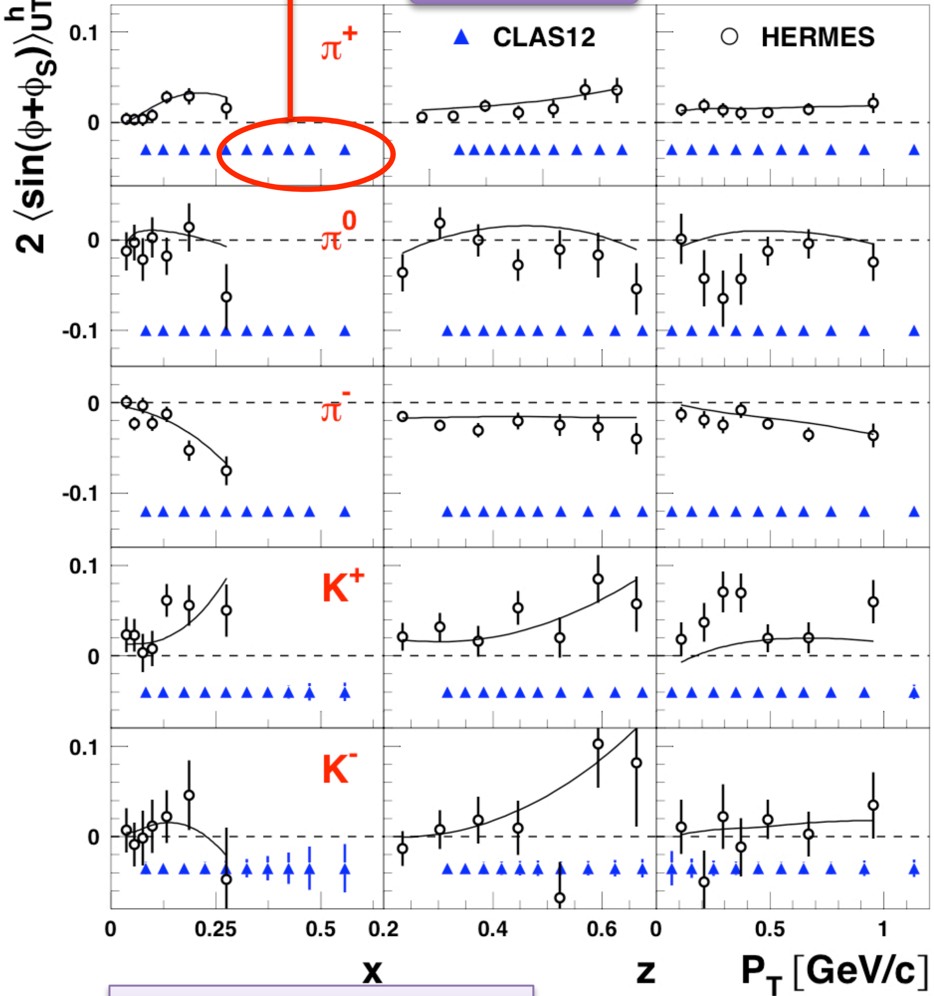
Optimization after tests in 2012 spring

CLAS12 Projections

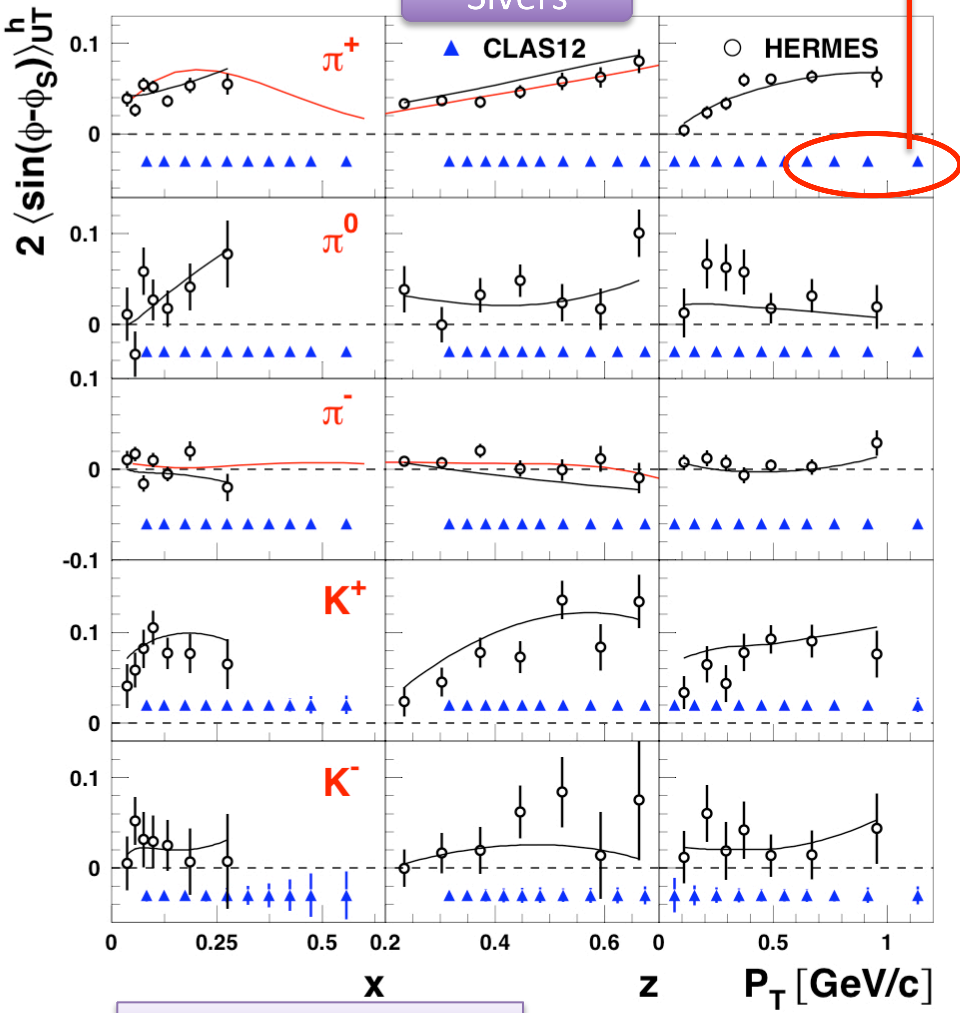
Large x important to constrain the tensor charge

Large p_T important to link to the perturbative regime and for Bessel function analysis

Collins



Sivers

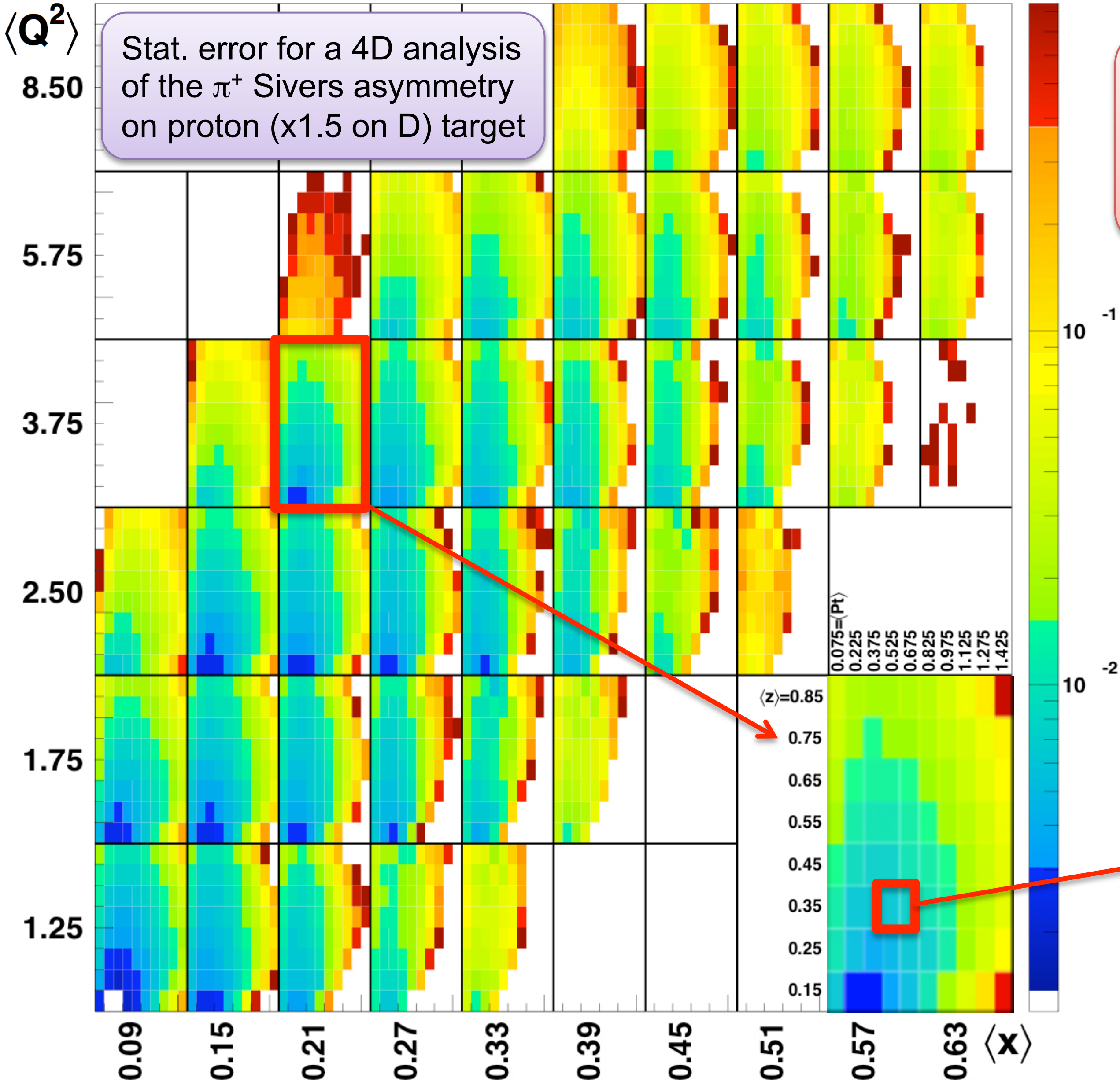


Black curve: arXiv: 0906.3918

Red curve: arXiv: 0911.3677

Statistical precision

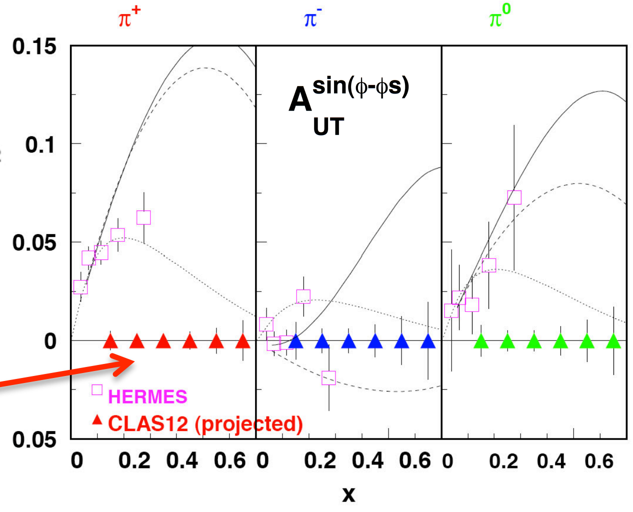
Stat. error for a 4D analysis of the π^+ Sivers asymmetry on proton (x1.5 on D) target



4D analysis is possible

Beam-time request is defined to achieve few % absolute error at the wanted high-Q^2 high-p_T

x projection in a z-p_T bin of the π^+ Sivers asymmetry



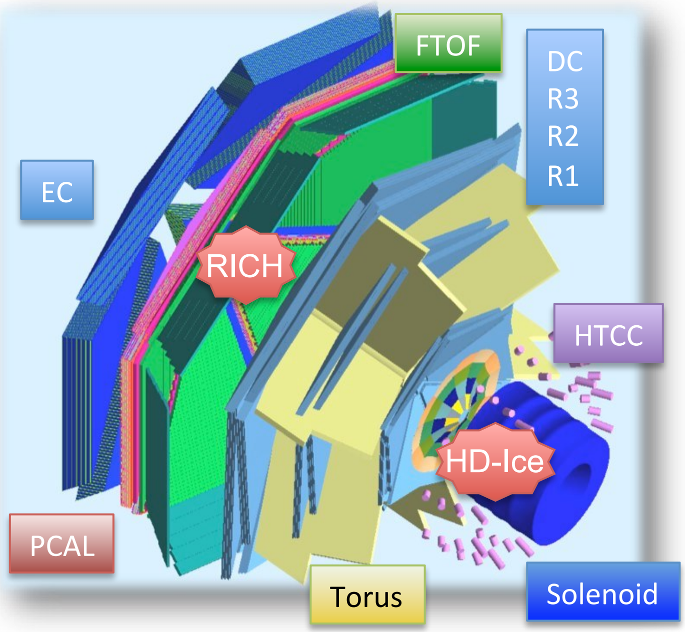
Curves from hep-ph/0507266 and hep-ph/0507181

The main goals

Transverse spin effects in SIDIS at 11 GeV with transversely polarized target using the CLAS12 detector

- Access to leading-twist poorly known or unmeasured TMDs which provide 3-dimensional picture of the nucleon in momentum space (nucleon tomography);
  - * SSA: ***Transversity, Sivers, Pretzelosity function***s;
  - * DSA: ***g_{1T} worm-gear function***;
- Multi dimensional analysis in x, Q^2, z, p_T thanks to large-acceptance and high-luminosity;
  - * ***precise mapping of the valence*** (tensor charge);
  - * ***disentangle parton distribution from fragmentation functions*** (x vs z);
  - * ***isolate sub-leading-twist effects*** from 1/Q dependence (side product: g2) ;
  - * ***flavor decomposition of pT dependence***;
  - * ***investigate perturbative to non-perturbative QCD transient*** from p_T dependence;
- Together with already approved experiments with unpolarized and longitudinally polarized targets, ***complete the mapping of the TMD table at CLAS12***.

Beam time request



The proposed experiment requires:

- 11 GeV (highly polarized) electron beam
- CLAS12 detector equipped with:
  - HD-Ice transversely polarized target
  - Suitable magnetic system (compensation + saddle coil)
  - RICH (pion/kaon separation within 3-8 GeV/c)

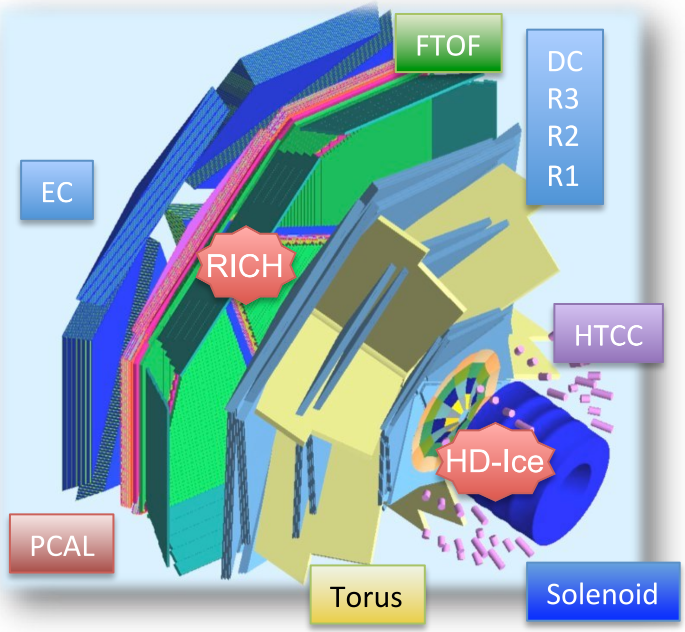
In order to reach the desired statistical precision at high-Q^2 and high-p_T (perturbative limit) for both pions and kaons, and to allow a fully differentyal analysis in x,Q^2,z,p_T

we ask the PAC to award 100 days of beam time

(including 20 days for calibrations, empty target runs, supportive tests, etc.)

Back Up Slides

Requirements



The proposed experiment requires:

- Control over background contributions:
  - nuclear background
  - vector meson decays
  - target fragmentation

- Full kinematical coverage:
  - large pT (link to perturbative regime + Bessel extraction)
  - large Q2 (control on higher-twists)

- Particle ID:
  - kaons versus pions
  - π^0 versus charged pions
  - di-hadrons

Potential for transverse HD with e^-

eg. 4 nA of e^- on 5 cm of HD ➔ *Luminosity* = 10^{34} cm^{-2} s^{-1}

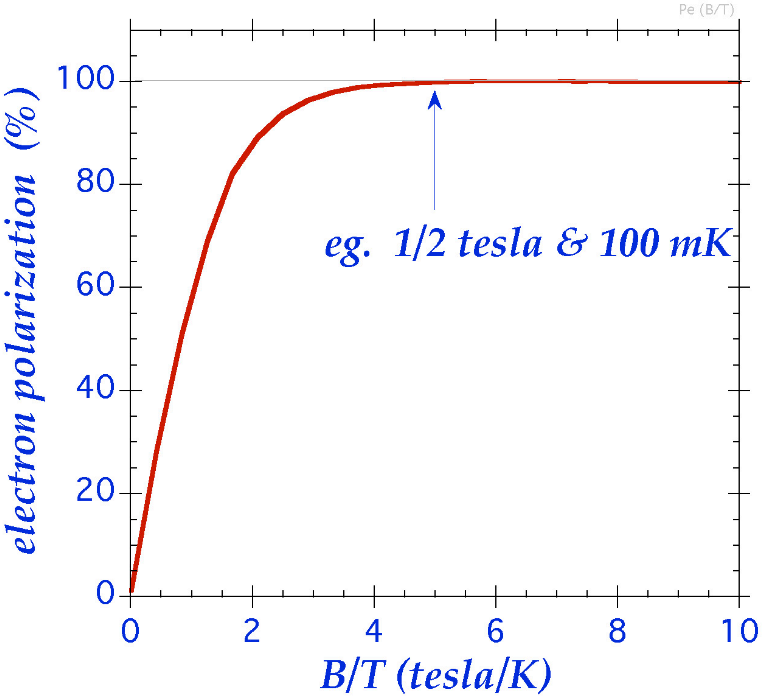
➔ 10 mW of beam heating

- low temperatures not required to hold HD spins (polarization mechanism very different from DNP)

- paramagnetic centers / ionized electrons will have no effect if they are polarized

➔ requires only *short* ~1/2 tesla fields
  - field uniformity not important for HD
  - *BdL* ~ 0.1 *Tm* ➔ no beam deflection

➔ requires sufficient cooling to maintain a few hundred mK
  - tests with Roots circulation in May/12



Transversely Polarized HD-Ice Target

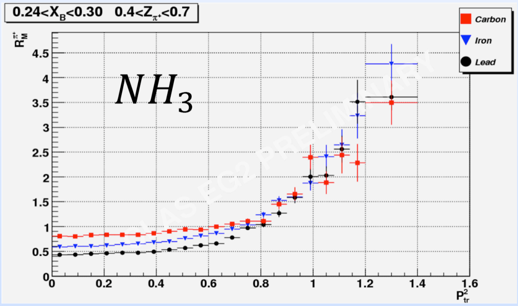
Composition for a 10cm, 1.5cm OD solid HD-Ice target

Material	gm/cm^2	mass fraction (%)
HD	0.735	82%
Al	0.155	14%
CTFF	0.065	4%

Heat extraction is accomplished with thin aluminum wires running through the target

The target polarization (75% H and 40 % D) will be measured with a NMR system

HD-Ice target vs standard nuclear targets



Advantages:

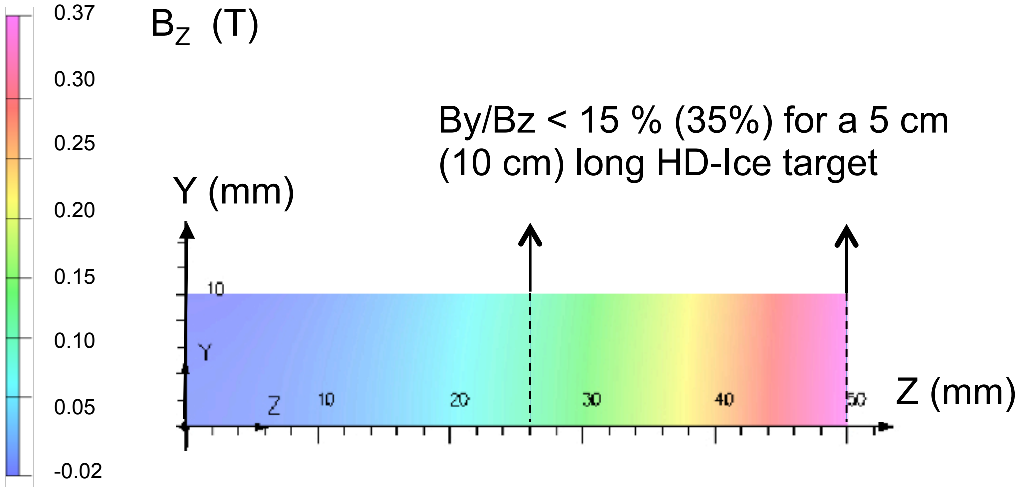
1. Small dilution (fraction of events from polarized material)
2. Less nuclear background (no nuclear attenuation)
3. Wider acceptance (small field)
4. H and D polarizations independently controlled
5. Small field (*∫Bdl~0.005-0.05 Tm*) → beam deflection negligible
6. Less radiation length (small Z) → reduced background from Bremsstrahlung photons

Disadvantages:

1. HD target is highly a complex device with very long polarizing times (months).
2. Need to demonstrate that can remain polarized for long periods with an electron beam

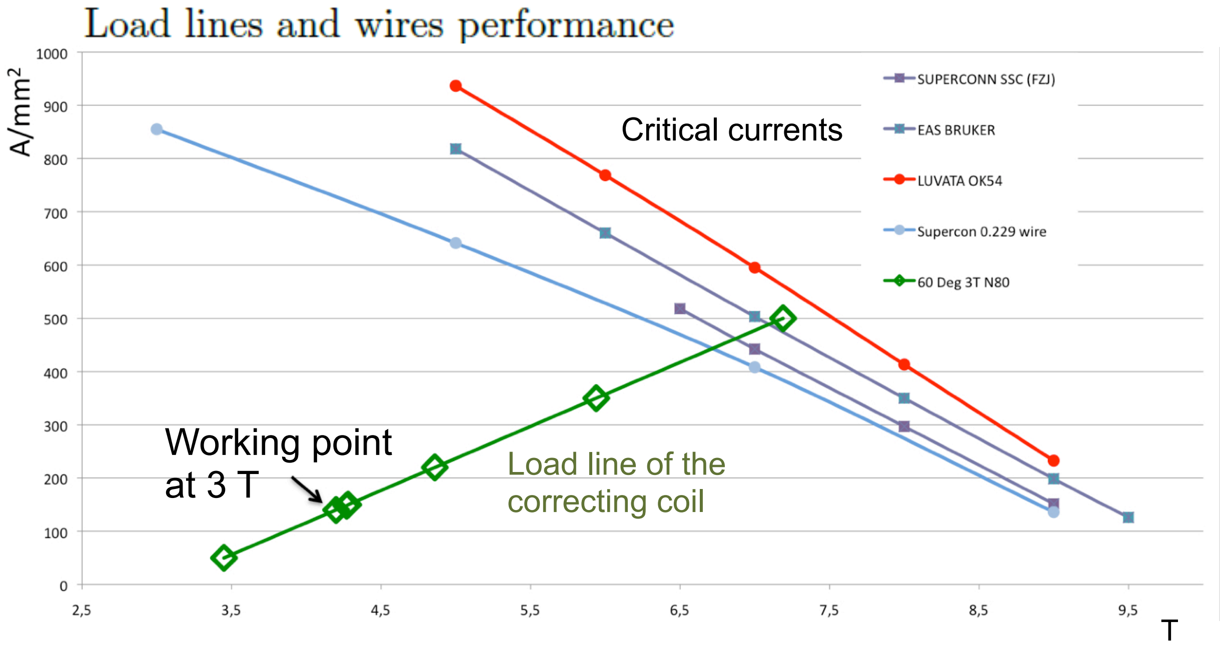
TT magnet Working Point

- Comparable with mixing due to polarization transverse to beam
- Can be improved with reduction of large-angle acceptance
- Final design depending on target dimensions



By/Bz < 15 % (35%) for a 5 cm (10 cm) long HD-Ice target

- Large safety margin
- Feasible with standard SC wires
- Enough freedom for performance optimization



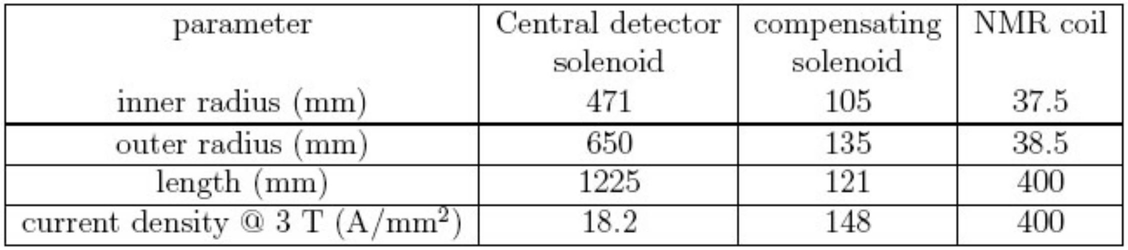
Critical currents

Working point at 3 T

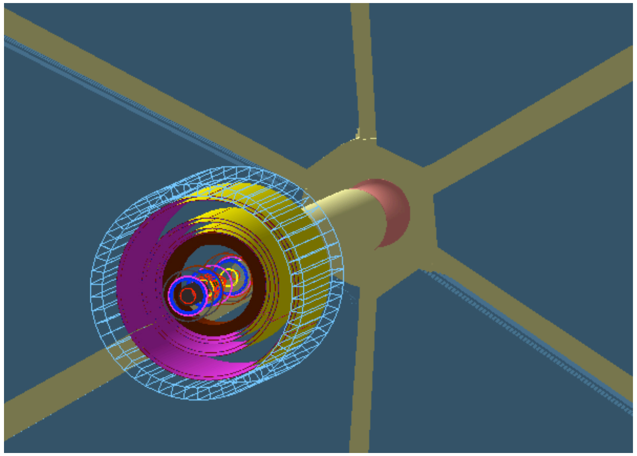
Load line of the correcting coil

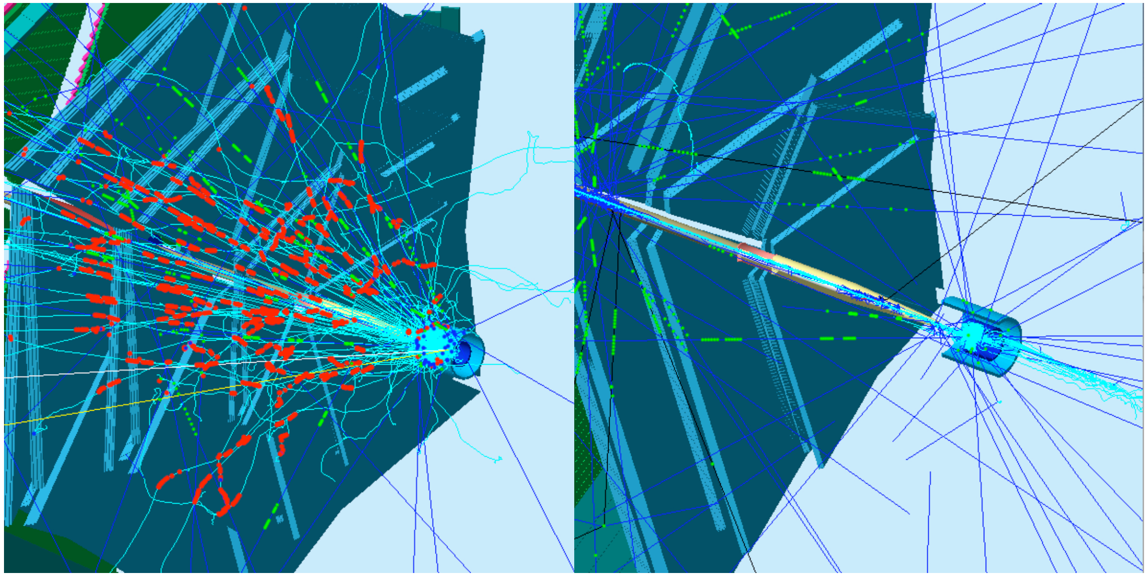
TT Magnet Configuration

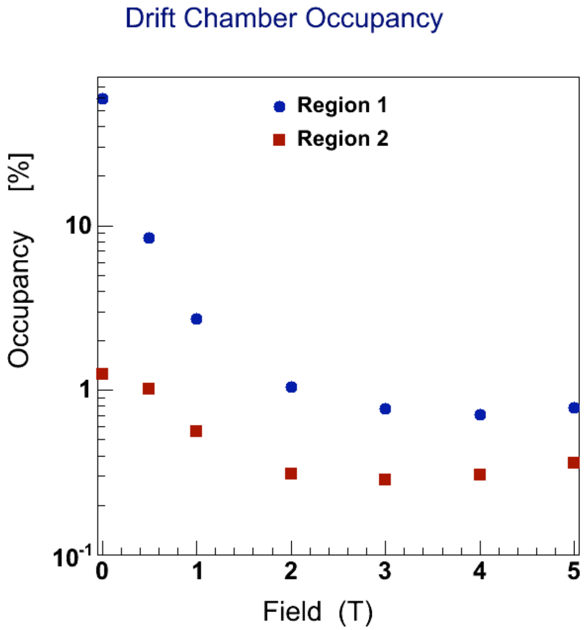
- The HD-Ice target transverse polarization is mantained with a transverse magnet (saddle coil, 0.5 – 1 T)
- Operation with a transversely polarized target requires shielding from the longitudinal magnetic field provided by the main solenoid



parameter	Central detector solenoid	compensating solenoid	NMR coil
inner radius (mm)	471	105	37.5
outer radius (mm)	650	135	38.5
length (mm)	1225	121	400
current density @ 3 T (A/mm^2)	18.2	148	400



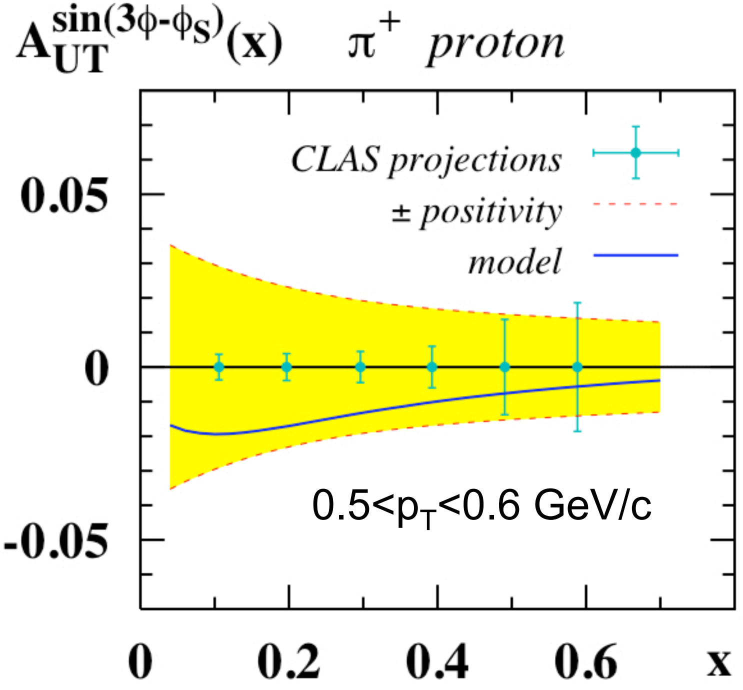


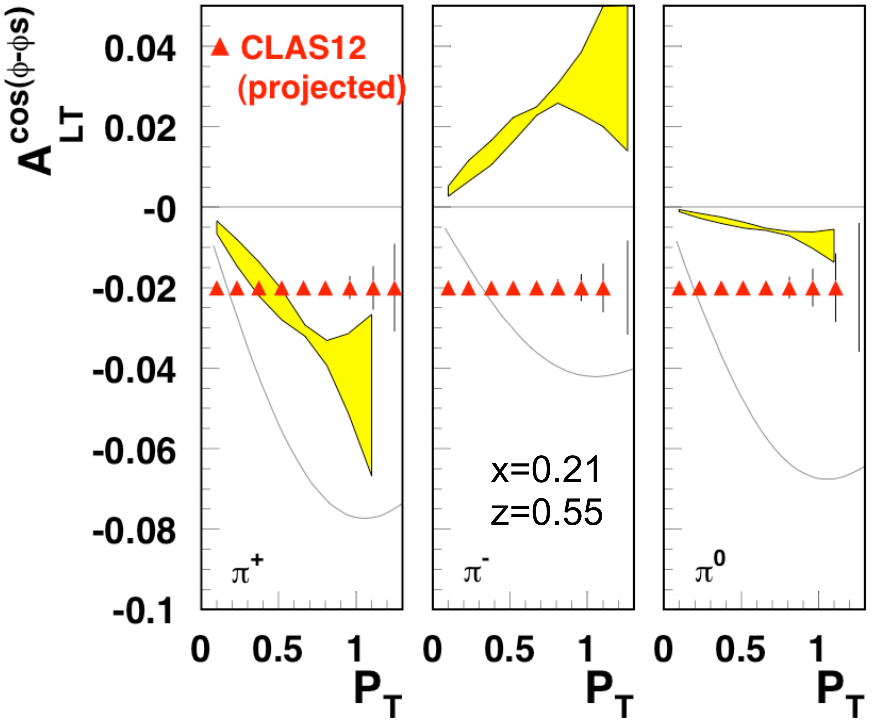


Statistical precision

Projections for a 2D analysis (x-p_T) of the Ptretzelosity asymmetry

Statistical error for double spin asymmetry

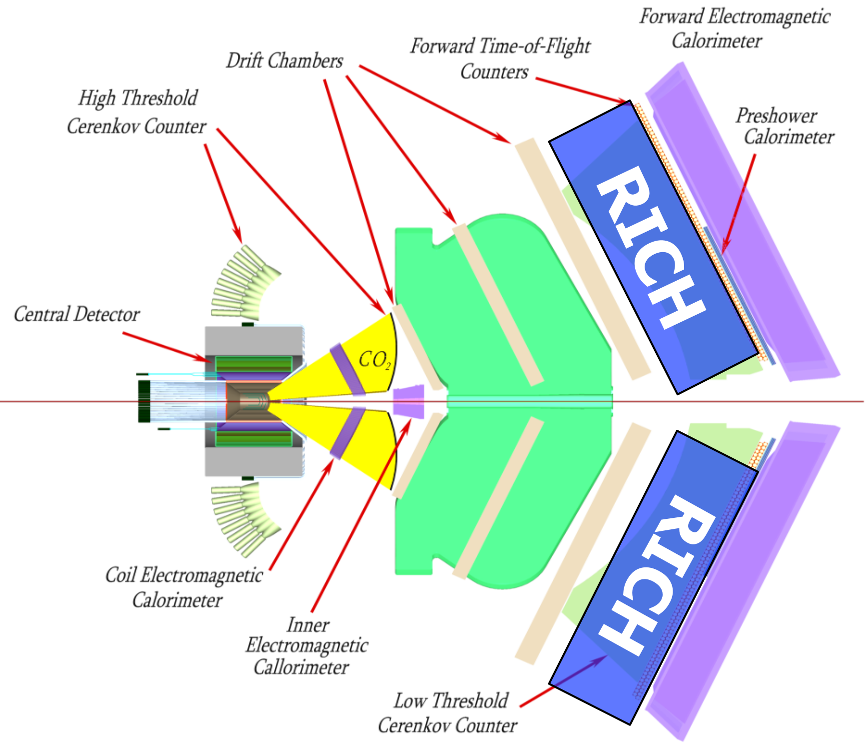


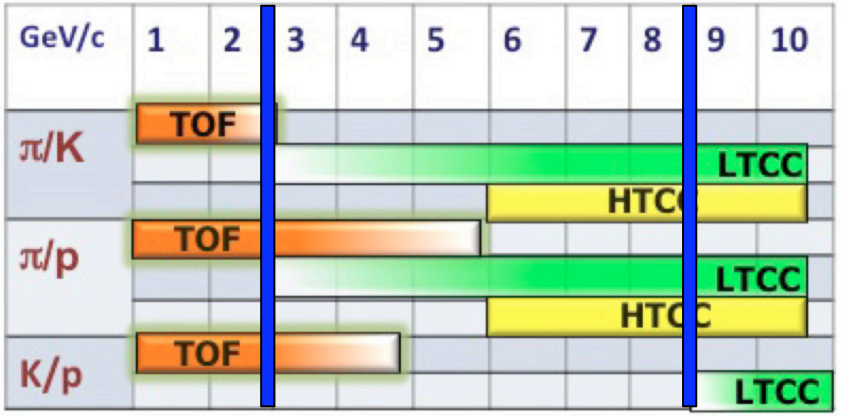


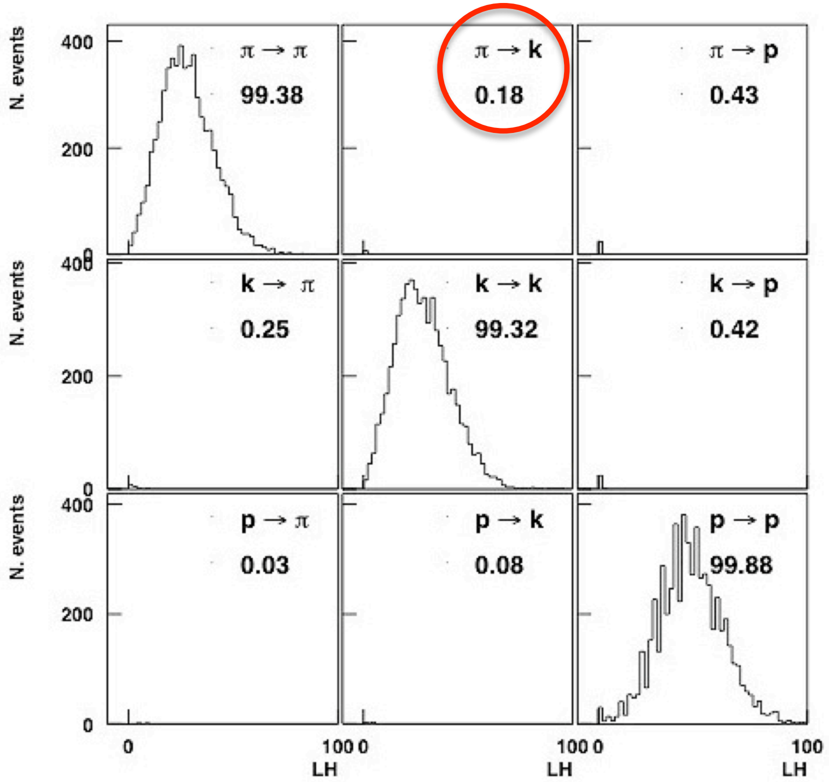
Curve: relativistic covariant model
arXiv: 0812.3246

Curve: light-cone constituent quark model
Phys. Rev. D79 (2009)
Band: 2 transverse gaussian width
Phys Rev D73 (2006)

The RICH Detector







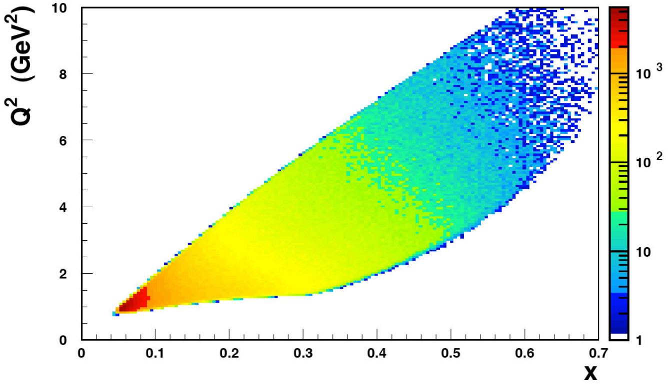
full pion / kaon / proton separation over whole accessible momentum range of 2 – 8 GeV for SIDIS exp.

π/K separation of **4-5 σ @ 8 GeV/c** for a rejection factor **1:1000**
Ratio K/π ~ 0.1-0.15 for SIDIS experiments

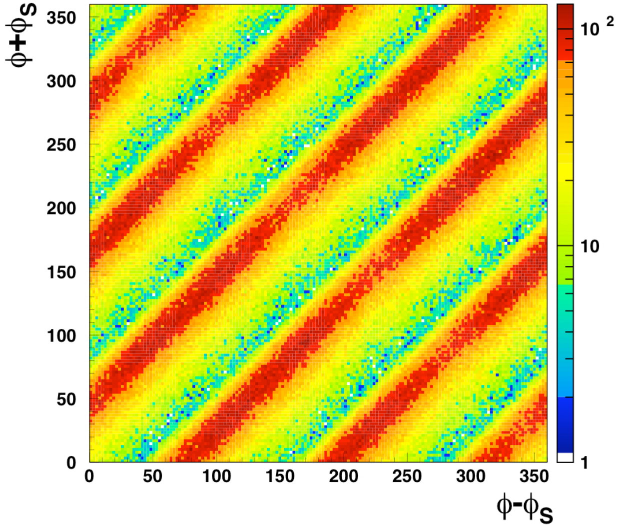
CLAS12 Kinematic Coverage

$0.05 < x < 0.6$ for $Q^2 > 1$ GeV^2

Cover valence region at several GeV Q^2

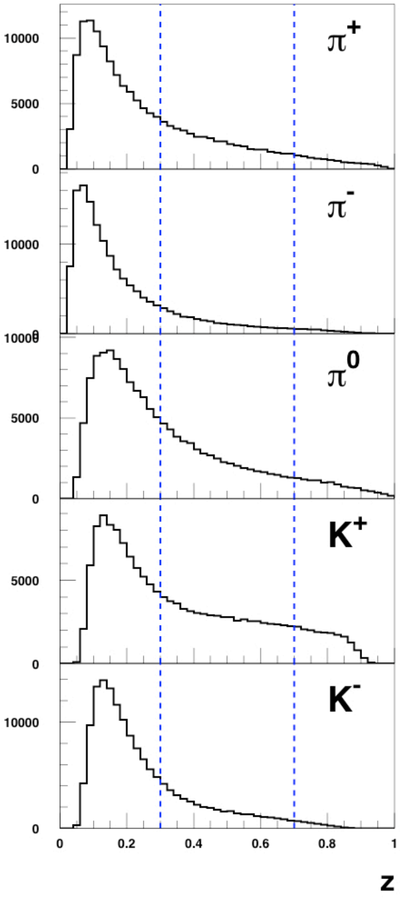


Azimuthal angular coverage



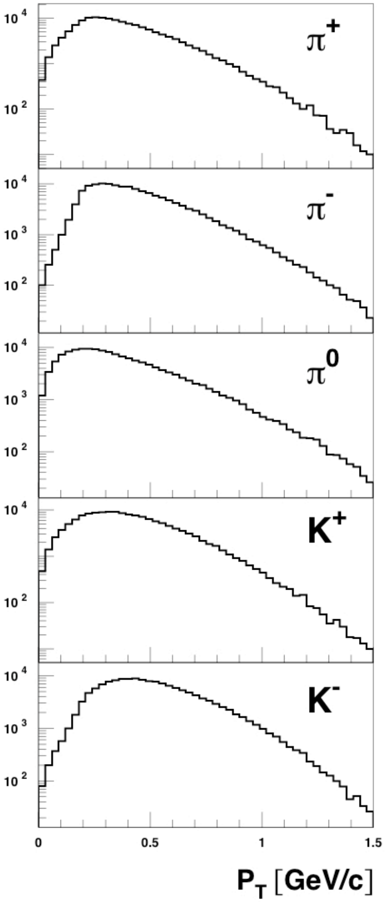
$0.3 < z < 0.7$

Current fragmentation
No exclusivity corner

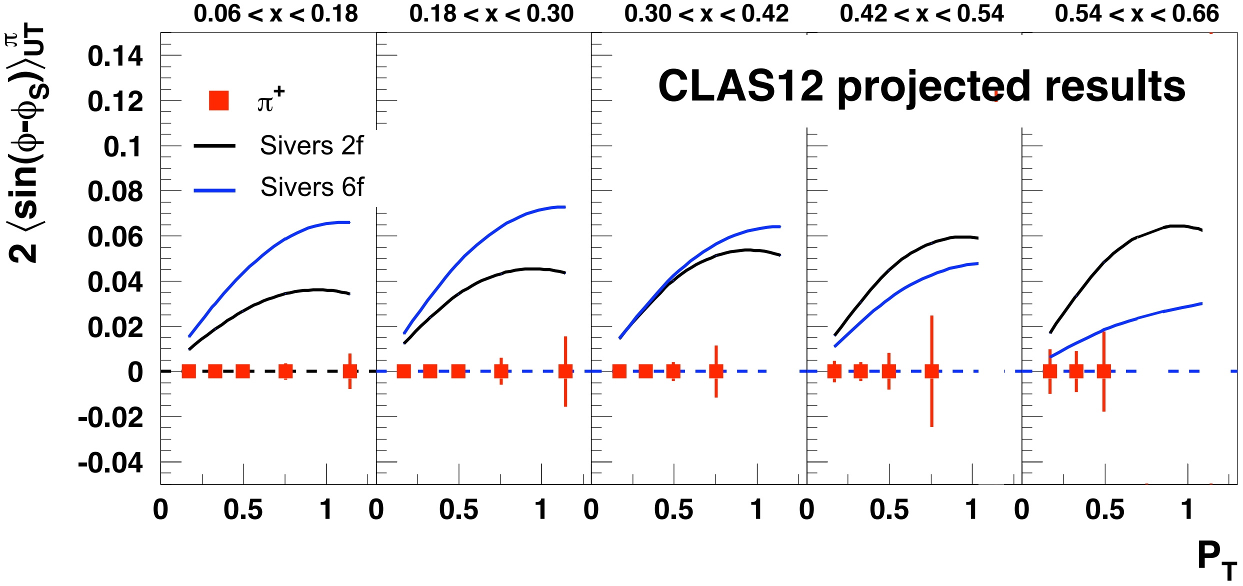


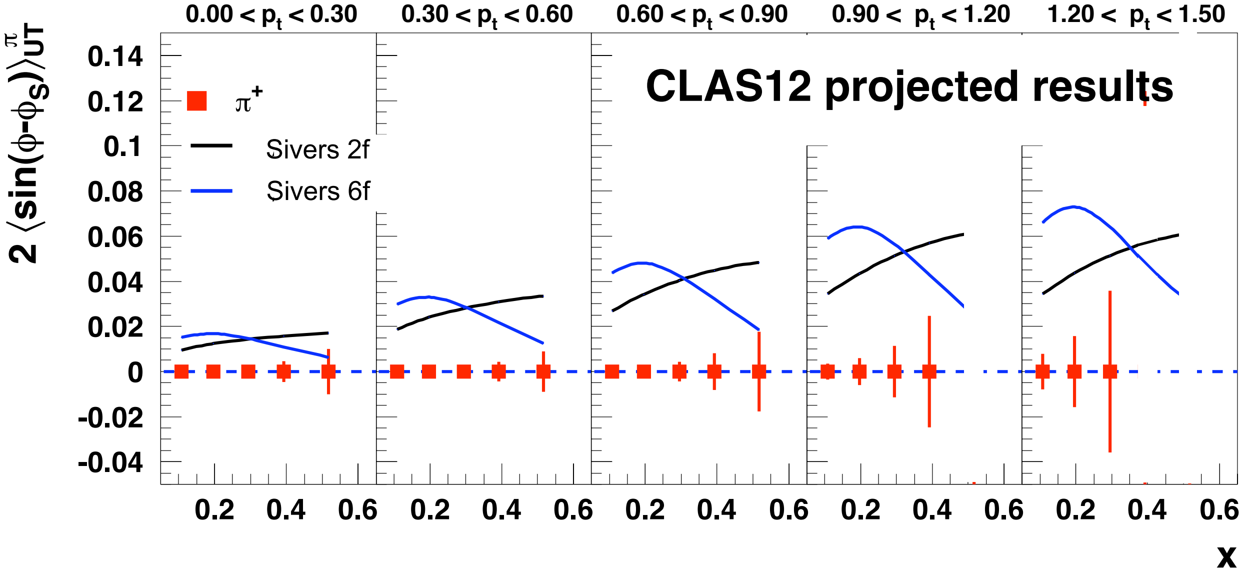
$P_T > 1$ GeV/c

Limit given by
cross-section



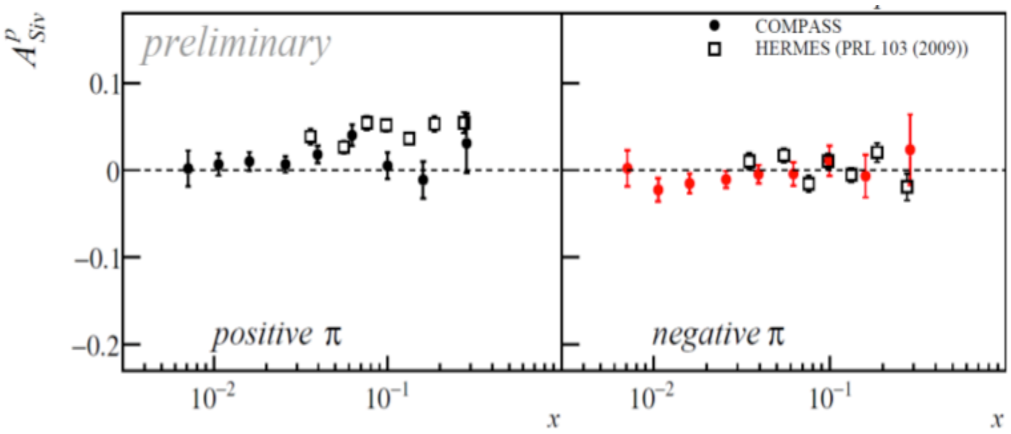
CLAS12 Kinematic Coverage





The Sivers effect

$f_{1T}^{\perp} \otimes D_1$



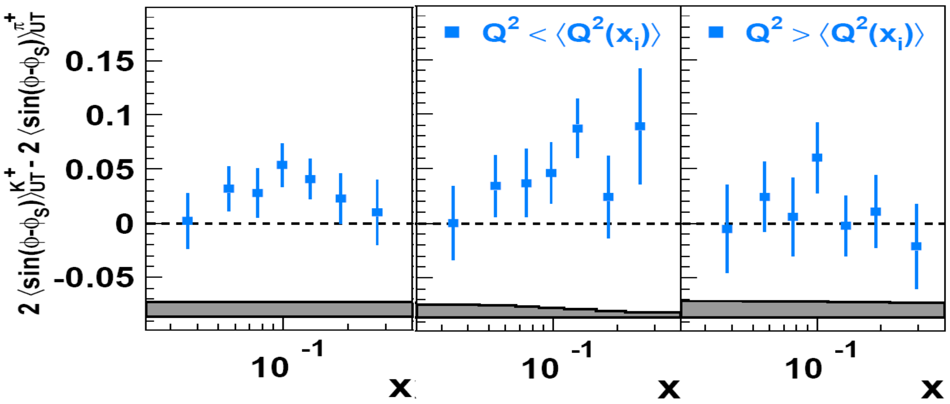
Disagreement for pions !?

Q^2 evolution ?

Higher-twist contributions ?

Sudakov suppression ?

π^+/K^+ production dominated by u-quarks, but HERMES observes a difference at low-Q^2



Kaon signal larger than pion

Non trivial role of sea quarks ?

$$\pi^+ \equiv |u\bar{d}\rangle,\ K^+ \equiv |u\bar{s}\rangle$$

Impact of different k_T dependence of FFs in the convolution integral ?

Higher-twist contrib. for Kaons ?

P_T-dependence Extraction

The **product** of TMDs and fragmentation function in **Fourier space** is related to the weighted integral of the cross section : arXiv:1107.5294

$$2\pi \int_0^{\frac{\pi}{2}} d\phi_h \int_0^{\infty} d|\mathbf{P}_{h\perp}||\mathbf{P}_{h\perp}| J_0(|\mathbf{P}_{h\perp}||\mathbf{b}_T|) \left[\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h} |\mathbf{P}_{\perp} d|\mathbf{P}_{h\perp}|\right]$$

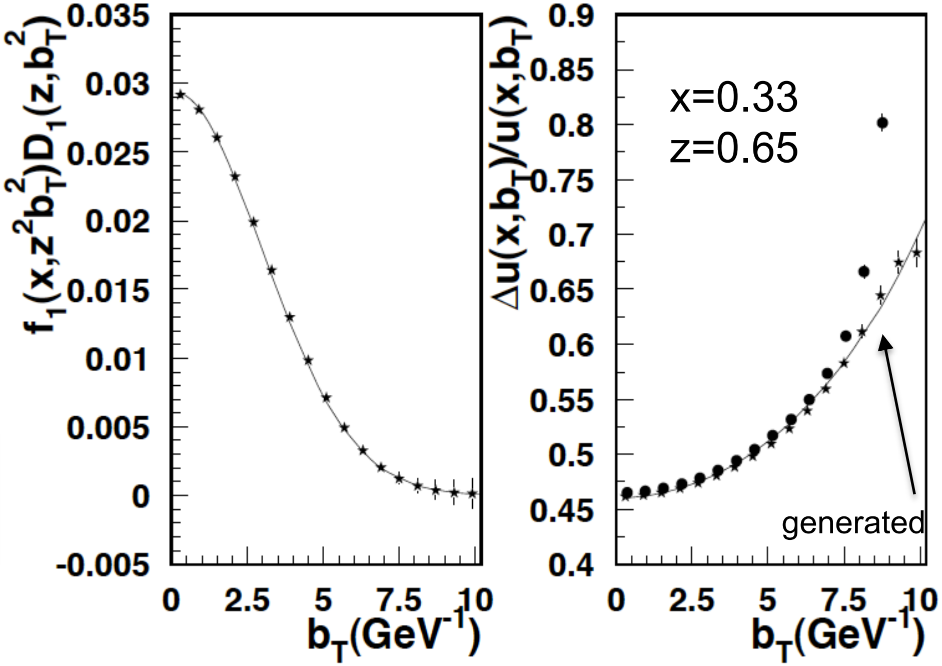
J_0 = Bessel function

$\tilde{f}_1, \tilde{D}_1 =$ TMDs Fourier transf.

$$= \frac{\alpha^2}{yQ^2}\frac{y^2}{(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\sum_{\alpha} e_{\alpha}^2 \left\{\tilde{f}_1^a(x, z^2\mathbf{b}_T^2) + S_{\parallel}\lambda_e\sqrt{1-\epsilon^2}\,\tilde{g}_1^a(x, z^2\mathbf{b}_T^2)\right\} \tilde{D}_1^a(z\mathbf{b}_T^2)$$

- The formalism in **b_T-space** avoids convolutions → easier to **perform a model independent analysis**
- The transformation depends on the parameter **$|b_T|$**
- P_T range of CLAS12 allows extraction of b_T dependences for all relevant range of b_T (up to 2 fm)

After acceptance correction (stars) the b_T-dependence of the $\Delta u/u$ ratio has been recovered in a wide range of b_T



The Bessel sums

$$\Delta u(x,b_T)/u(x,b_T) = \frac{S_\pi^{pol+} - S_\pi^{pol-}}{S_\pi^{unp+} + S_\pi^{unp-}}$$

$$S_\pi^{unp\pm}(x_i, z_i, b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/A(x_i, y_i)$$

$$S_\pi^{pol\pm}(x_i, z_i, b_T j) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/A(x_i, y_i)/\sqrt{1-\epsilon}$$

$$A(x,y) = \frac{\alpha^2}{x_{_B} y Q^2} \frac{y^2}{(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_{_B}}\right)$$

The Unbinned ML method

The event distribution and probability density distribution for target polarization distribution $\rho(P)$

$$
\begin{aligned}
C\,N(P,x,y,z,P_t,\phi,\phi_S) \;=\;& \rho(P)\;\varepsilon(x,y,z,P_t,\phi,\phi_S)\;\underline{\sigma}_{UU}(x,y,z,P_t)\times \\
& \Big\{ 1 + A_{UU}^{\cos\phi}(x,y,z,P_t)\cos\phi + A_{UU}^{\cos 2\phi}(x,y,z,P_t)\cos(2\phi) \\
& \quad + P\,[A_C(\lambda_1,x,y,z,P_t)\sin(\phi+\phi_S) + A_S(\lambda_2,x,y,z,P_t)\sin(\phi-\phi_S)] \Big\} \\
\equiv\;& F(\lambda_1,\lambda_2,P,x,y,z,P_t,\phi,\phi_S)
\end{aligned}
$$

All terms

the parameter-independent factor $\varepsilon\underline{\sigma}_{UU}$ can be omitted in the numerator of the Likelihood:

$$
\mathcal{L}(\lambda_1,\lambda_2) \;=\; \prod_{i=1}^{N} \frac{F(\lambda_1,\lambda_2,P_i,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si})^{W_i}}{\mathcal{N}(\lambda_1,\lambda_2)^{W_i}}
$$

W_i are event weights (from e.g. RICH PId)

In a binned analysis residual acceptance dependence because of integrated quantities (acceptance/efficiency does not factorize) ⟶ systematics

The Unbinned ML method

In the PDF normalization integral

$$\mathcal{N}(\lambda_1,\lambda_2) = \int \mathrm{d}P\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_t\,\mathrm{d}\phi\,\mathrm{d}\phi_S\;\rho(P)\;\varepsilon(x,y,z,P_t,\phi,\phi_S)\;\underline{\sigma}_{UU}(x,y,z,P_t)\times$$

$$\Big\{1 + A_{UU}^{\cos\phi}(x,y,z,P_t)\cos\phi + A_{UU}^{\cos2\phi}(x,y,z,P_t)\cos(2\phi)$$

$$+ P\left[A_C(\lambda_1,x,y,z,P_t)\sin(\phi+\phi_S) + A_S(\lambda_2,x,y,z,P_t)\sin(\phi-\phi_S)\right]\Big\}$$

All terms

the denominator is independent of λ_1 and λ_2 and can be ignored in the likelihood maximization, if the whole data set has no net polarization:

$$\int \mathrm{d}P\,P\,\rho(P) = 0$$

Rapid cycling of the target spin states is crucial !