JLab news on TMD observables

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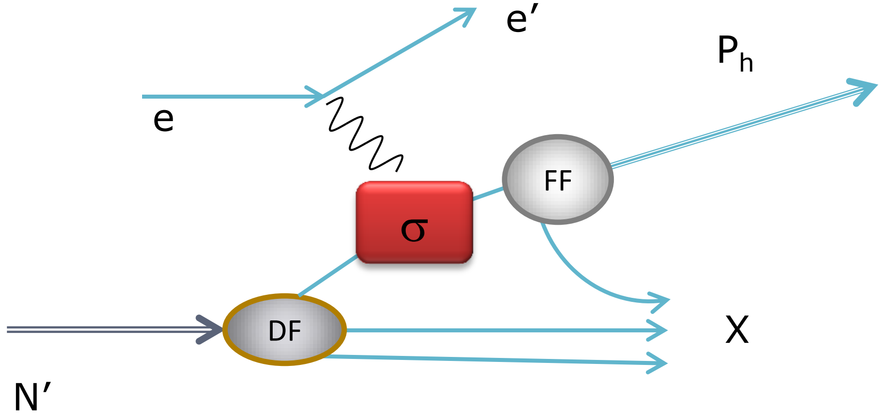
Bound state internal dynamics and hadronization mechanism

To access tranverse structure of the nucleon we rely on Semi-Inclusive DIS (SIDIS):



Through ***Factorization***
$\rightarrow \sigma^{ep\rightarrow ehX} = \sum_q DF \otimes \sigma^{eq\rightarrow eq} \otimes FF$

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

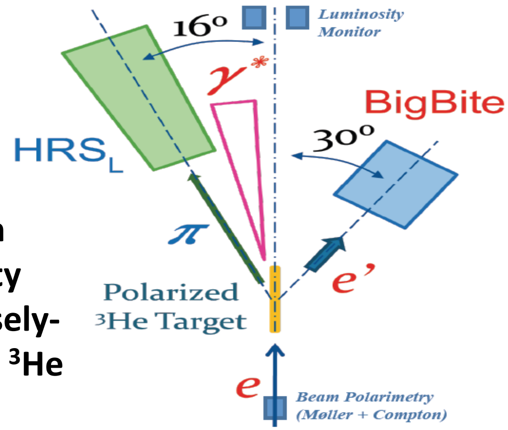
Fragmentation Functions

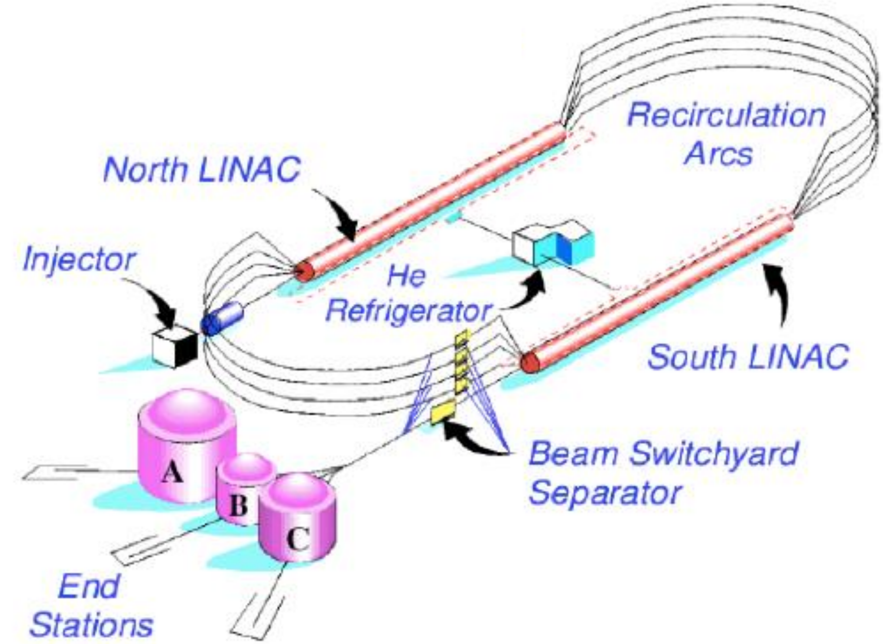
q/H	U	L	T
U	$\boldsymbol{D_1}$		$H_1^{\perp}$
L		$\boldsymbol{G_{1L}}$	$\mathrm{H}_{1L}^{\perp}$
T	$\mathrm{H}_1^{\perp}$	G_{1T}	$\boldsymbol{H_1}, \mathrm{H}_{1T}^{\perp}$

FF describe the transition from the partonic to the hadronic d.o.f.

The three experimental Halls@JLab

The CEBAF provides longitudinally-polarized electrons to 3 experimental Halls, characterized by different and complementary characteristics.



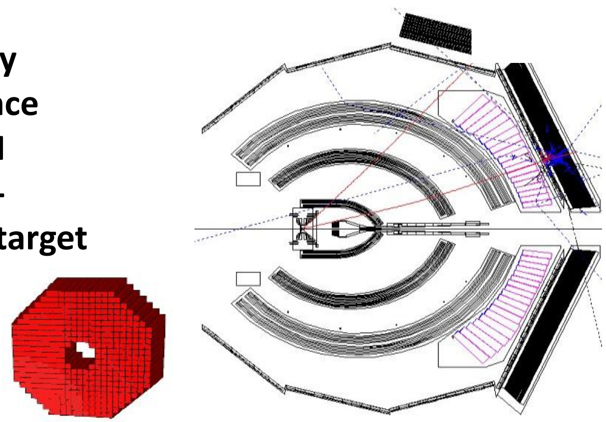


Hall-A

1. Very-high luminosity
2. Transversely-polarized ^3He target

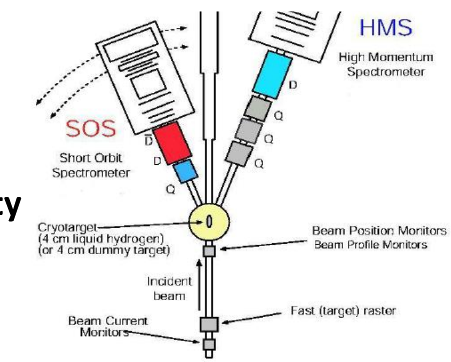
Hall-B

1. High luminosity
2. Large acceptance
3. Unpolarized ^2H Longitudinally-polarized ^3NH target



Hall-C

1. Very-high luminosity
2. Precision measurements



Single-hadron SIDIS cross-section

Depending on the degrees of freedom active in the process, various TMD&&FF can be accessed:

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

Unpolarized target

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big] + \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big]$$

Longitudinally pol. target

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big] + S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big]$$

Tranversely pol. target

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

18 structure functions appear in the cross-section

$$F_{ij,K} \propto DF \otimes FF$$

JLab TMD program explored the different terms:

1. Unpolarized contributions (Hall-B, Hall-C)
2. Longitudinally-polarized contributions (Hall-B)
3. Transversely-polarized contributions (Hall-A)

SIDIS measurements@Hall A

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

Hall-A accessed the **transversely-polarized part** of the single-hadron SIDIS cross-section.

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

1. ***X. Qian at al., PRL 107:072003(2011)***, extraction of Collins and Sivers moments on a **tranversely-polarized ^{3}He target** - $\pi^{\pm}$ **SIDIS** $\rightarrow F_{UT}^{\sin\varphi-\varphi_S}, F_{UT}^{\sin\varphi+\varphi_S}$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]$$

1. ***Huang at al., PRL 108:052001(2012),*** First "direct measurement" on **effective n target** at Jlab - $\pi^{\pm}$ **SIDIS** $\rightarrow F_{LT}^{\cos\varphi-\varphi_S}$

SIDIS measurements@Hall A: Single-Spin Asymmetries

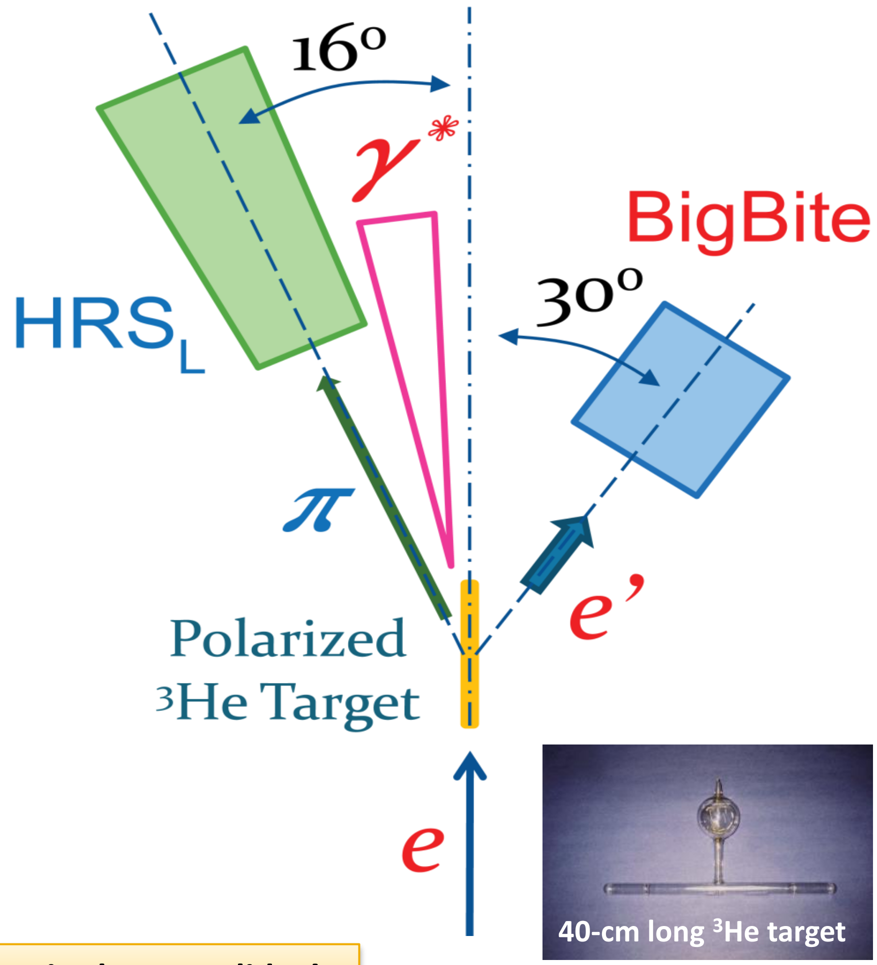
The reaction $^3\boldsymbol{He}^{\uparrow}(\vec{\boldsymbol{e}}, \boldsymbol{e}'\boldsymbol{\pi}^{\pm})\boldsymbol{X}$ was studied.

The final state particles were detected through the following equipment:

- BigBite@30° as **electron arm**
  - $0.6\ GeV^2 < P_e < 2.5\ GeV^2$
- HRS_L@16° as **hadron arm**
  - $P_h = 2.35\ GeV$

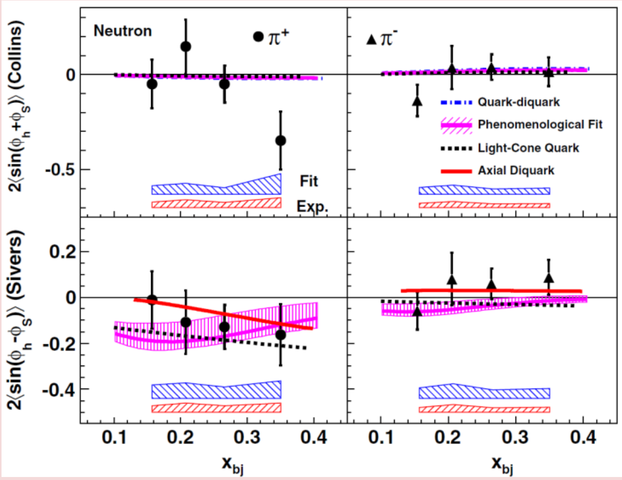
The kinematic explored in this measurement covers the region $\boldsymbol{Q^2 > 1\ GeV^2, W > 2.3\ GeV, m_X > 1.6\ GeV}$.

The final set of data was divided in 4 x_B bins.



Thanks to E. Cisbani and J.P. Chen for the material shown in the next slides!

Hall A Single-Spin Asymmetries - results



X. Qian at al., PRL 107:072003(2011)

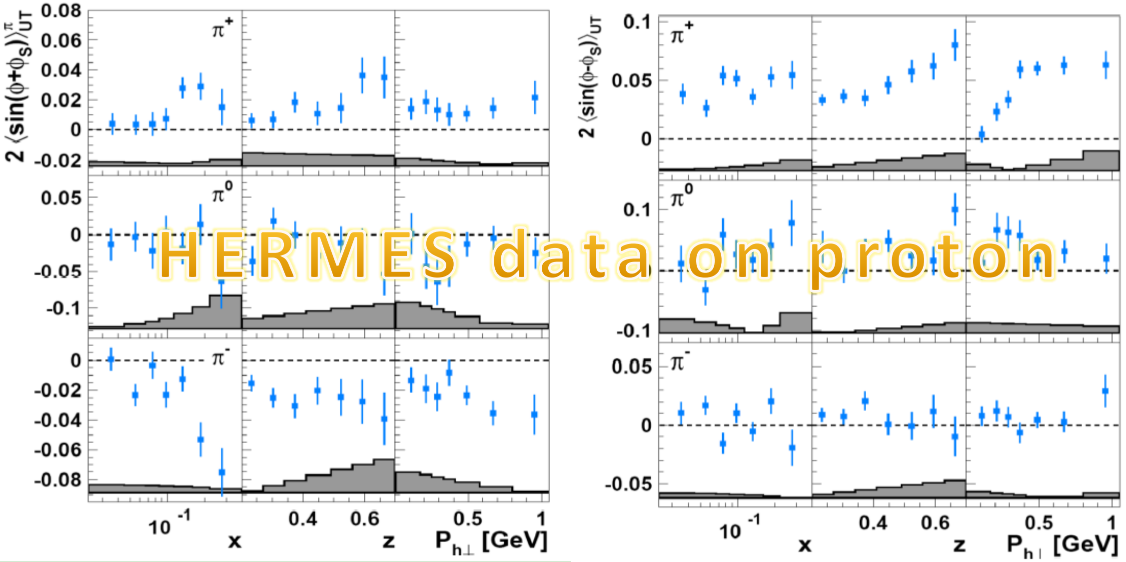
Collins effect: $F_{UT}{}^{\sin\varphi+\varphi_S} \propto h_1 \otimes H_1{}^{\perp}$

Sivers effect: $F_{UT}{}^{\sin\varphi-\varphi_S} \propto f_{1T}{}^{\perp} \otimes D_1$

Neutron: $A_{^3He}{}^{C/S} = P_n(1-f_p)A_n{}^{C/S} + P_p f_p A_p{}^{C/S}$

Neutron Collins moments are small → non zero for the π^+ @ $x = 0.34$.

Data favor negative Sivers moments for π^+, while for the π^- they are close to zero → it supports negative d-quark Sivers function

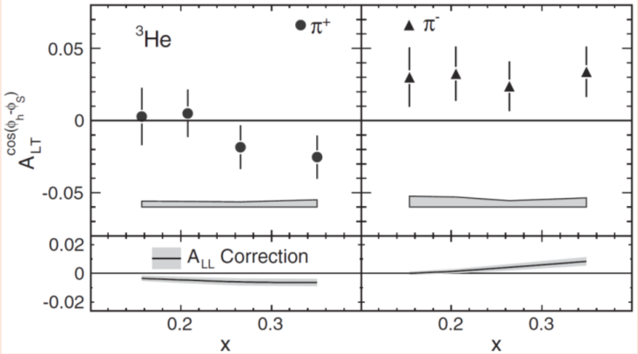


With respect to the neutron results, on the proton it has been observed:

- non-zero Collins signal for π^+, π^-
- Opposit behaviour for Sivers: both HERMES and COMPASS data show a significantly positive Sivers moment for π^+
- Data on neutron → negative d-quark Sivers function?

SIDIS measurements@Hall A: Double-Spin Asymmetry A_{LT}

The reaction $^{3}\boldsymbol{He}^{\uparrow}(\vec{\boldsymbol{e}},\boldsymbol{e}'\boldsymbol{\pi}^{\pm})\boldsymbol{X}$ was studied: $A_{LT} \approx A_{LT}^{\cos(\varphi_h-\varphi_S)} \cos(\varphi_h-\varphi_S) \approx C[g_{1T}{}^{q} D_1]$.

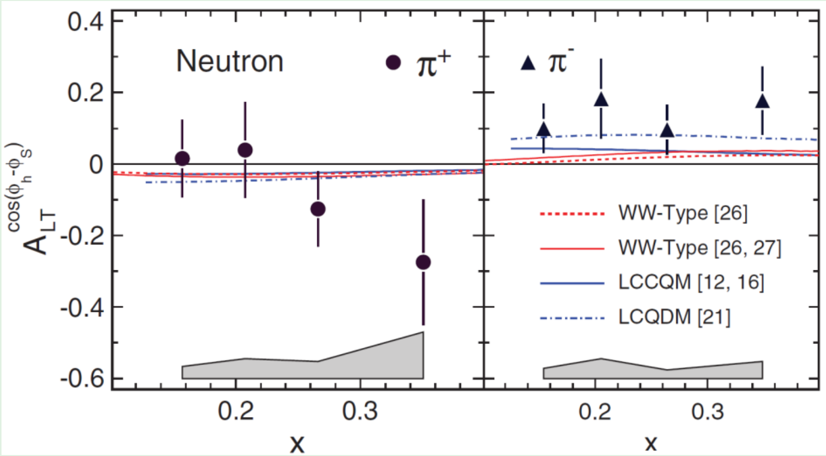


π^+asymmetries are consistent with zero.

π^-asymmetries are positive with a 2.8σ significance.

Huang at al., PRL 108:052001(2012)

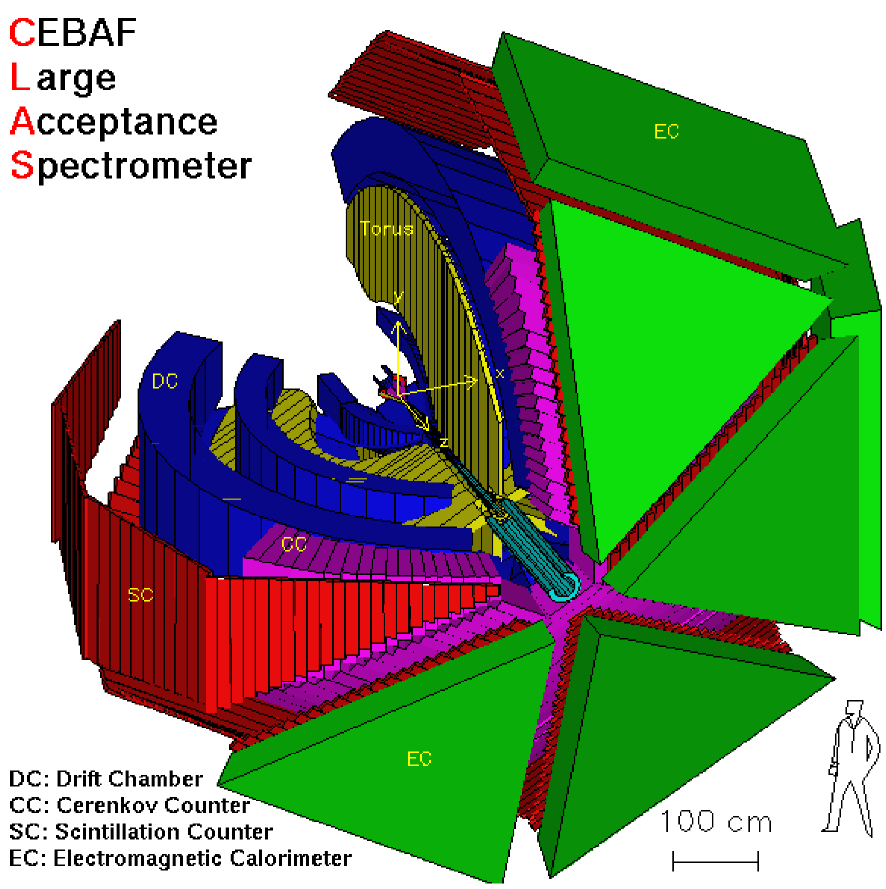
Neutron: $A_{LT}{}^{n} = \frac{\left(A_{LT}{}^{^3He} - f_p A_{LT}{}^{p} P_p\right)}{(1-f_p)P_n}$



π^+asymmetries are consistent with zero.

π^-asymmetries are consistent in sign with model predictions but favor a larger magnitude
→ Different $P_{h\perp}$ dependence? Higher-twist effects?

The CLAS detector@Hall-B



The CLAS detector is provided with:

- Toroidal magnetic field (6 supercondicting coils)
- Drift chambers (argon/CO2 Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters (e/π separation)

It is provided with different targets, allowing it to access various observables:

1. Unpolarized liquid-hydrogen target
2. Longitudinally-polarized ^{3}NH target

SIDIS measurements@Hall B: overview

CLAS accessed both the unpolarized and longitudinally-polarized term of the SIDIS cross-section.

$$\frac{d\sigma^h}{dx\, dy\, d\phi_S\, dz\, d\phi\, d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] + \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big]$$

1. M. Osipenko *et al.*, **PRD 80, 032004 (2009)** , π^+ SIDIS → $F_{UU}{}^{\cos(\varphi)}$, $F_{UU}{}^{\cos(2\varphi)}$
2. M. Aghasyan *et al.*, **Phys. Lett. B 704, 397 (2011)**, π^0 SIDIS →$F_{LU}{}^{\sin\varphi}$
3. W. Gohn *et al.*, **paper in progress**, $\pi^{0,\pm}$ SIDIS →$F_{LU}{}^{\sin\varphi}$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon \sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big]$$

$$+ S_L\, \lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big]$$

1. H. Avakian *et al.*, **PRD 80, 032004 (2009)**, $\pi^{0,\pm}$ SIDIS →$F_{UL}{}^{\sin 2\varphi}$, $A_{LL}{}^{?}$
2. Experiment E05-113, analyses ongoing: $\pi^{0,\pm}$ SIDIS →F_{LU}, F_{UL}, F_{LL}

SIDIS@Hall-B: Beam-Spin Asymmetry on unpolarized ^2H

A_{LU} is proportional to the structure function

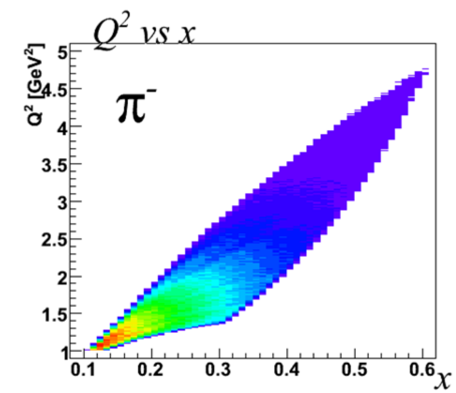
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

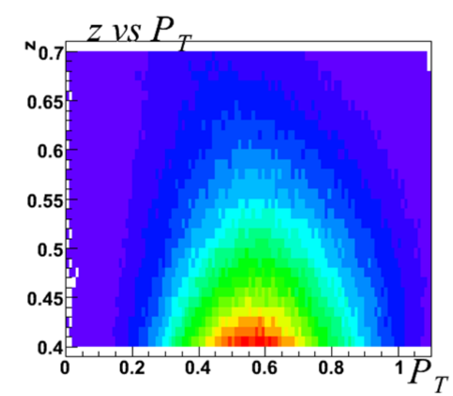
1. $e(x)$ is the *chiral-odd*, **twist-3** PDF Jaffe and Ji, Nucl.Phys.B357, 527 (1992)
2. $h_1{}^{\perp}$ is the **leading-order** Boer-Mulders TMD D. Boer, P.J. Mulders, Phys. Rev. D57 (1998) 5780, hep-ph/9711485
3. $g^{\perp}$ is the **twist-3**, *T-odd* PDF A. Bacchetta, P.J. Mulders, and F. Pijlman, Phys.Lett.B595, 309 (2004), hep-ph/0405154
4. $H_1{}^{\perp}$ is the naive *T-odd* Collins fragmentation function J.C. Collins, Nucl.Phys.B396, 161 (1993), hep-ph/9208213
5. $\tilde{E}$ and $\tilde{G}^{\perp}$ are **twist-3** fragmentation functions.

It is extracted by impinging a longitudinally-polarized electron beam on a unpolarized liquid-hydrogen target (P_e~75%).

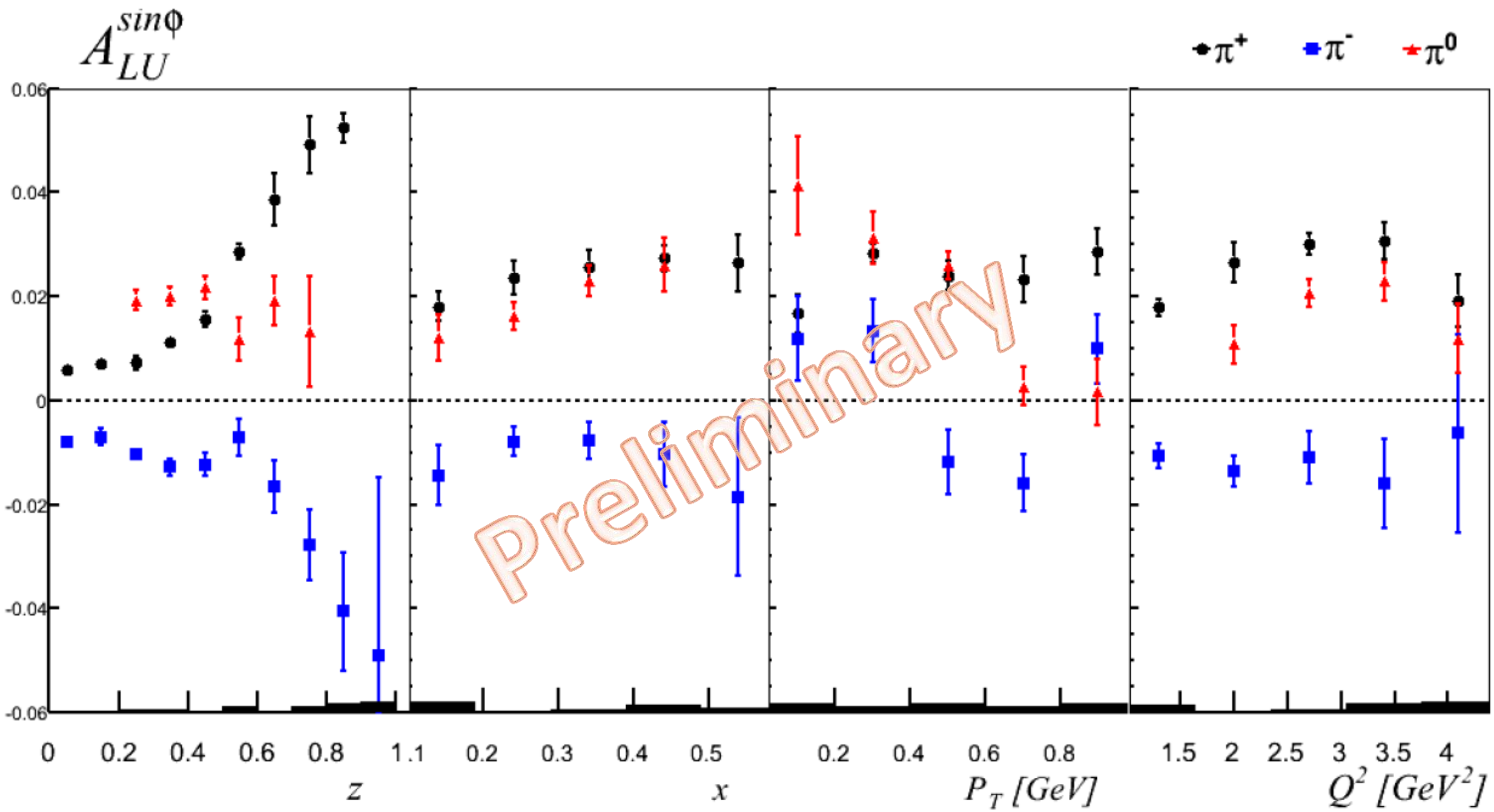
→ Entire structure function is twist-3, so in commonly used Wandzura-Wilczek approximation entire asymmetry = 0!

Unpolarized liquid ^2H
Liquid-hydrogen target H_2
Beam energy: 5.5 GeV
Luminosity: 21 fb^{-1}



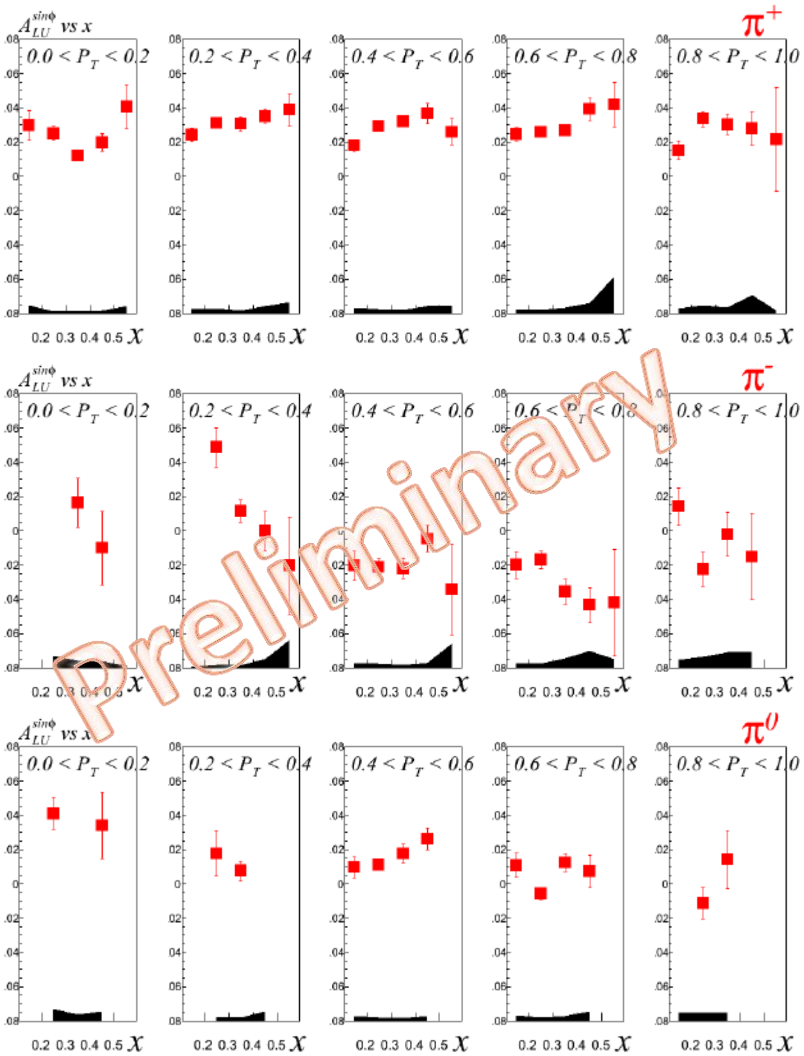


Beam-Spin Asymmetry: 1-D dependence



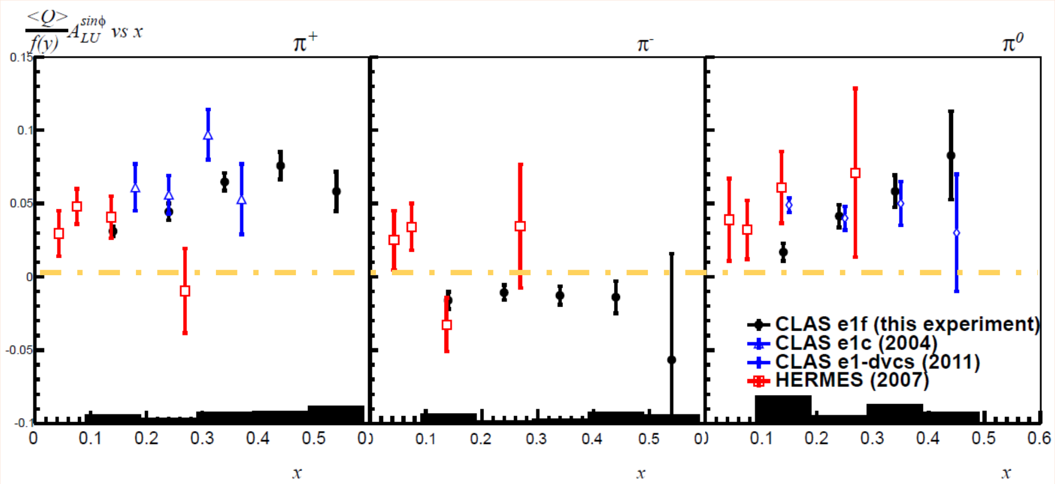
Analysis by W. Gohn. Thanks to him for the material in the next slides!

Beam-Spin Asymmetry: $A_{LU}^{\sin\varphi}$ 2-D dependence



- $A_{LU}^{\sin\varphi}$ in 2-dimensional binning vs x_B and P_T (5 bins each)
- Integrated over $Q^2 > 1\ GeV^2$ and $0.4 < z < 0.7$
- Error bars represent statistical errors.
- Shaded region denotes systematic error.

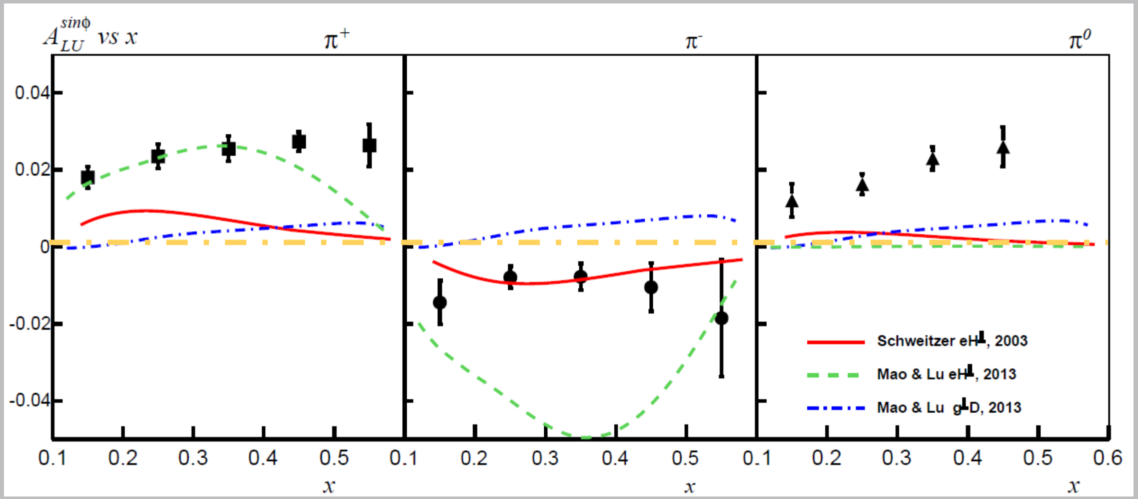
Comparison to models & previous experiment



HERMES, A. Airapatian et al., Phys. Lett. B648, 164 (2007), hep-ex/0612059

Comparison with previous measurements (evolution-weighted).

1. It is the first $\pi^- A_{LU}$ measured by CLAS.
2. First measurement with sufficient precision to determine the sign of $A_{LU}{}^{\sin\varphi}$



Each model curve shows the convolution of one TMD with one fragmentation function. The curves shown display $e(x) \otimes H_1{}^{\perp}$or $g_1(x) \otimes D_1$

SIDIS@Hall-B: Asymmetries on longitudinally-polarized ^{3}NH

New experiment in 2009 with a **longitudinally-polarized** ^{3}NH target & the CEBAF **longitudinally-polarized** electron beam
→ single (A_{LU}, A_{UL}) and double-spin asymmetries (A_{LL}) can be extracted

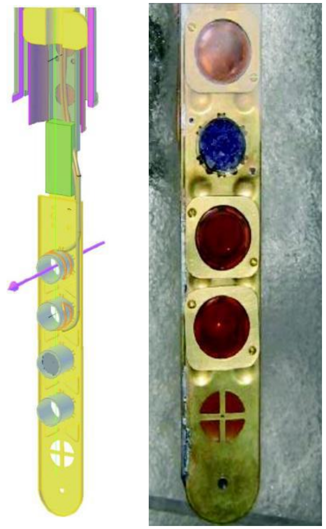
Longitudinally-polarized ^{3}NH
Hydrogen target NH_3
Beam energy: 5.967
Luminosity: 50.7 fb^{-1}
$\boldsymbol{P^{\uparrow} = 82\%,\ P^{\downarrow} = 75\%}$

- **Single Spin Asymmetry** (SSA)

Analysis by S. Koirala & S. Jawalkar

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-} \propto A_{UL}^{\sin\varphi}\sin\varphi + A_{UL}^{\sin 2\varphi}\sin 2\varphi$$

1. $A_{UL}^{\sin 2\varphi}$: it is the only term arising at LEADING ORDER, and it involves the coupling $h_{1L}^{\perp}\otimes \mathrm{H}_1^{\perp}$ .The only available measurements by Hermes* is consistent with zero.
2. $A_{UL}^{\sin\varphi}$: expected to be dominated from higher-twist contributions



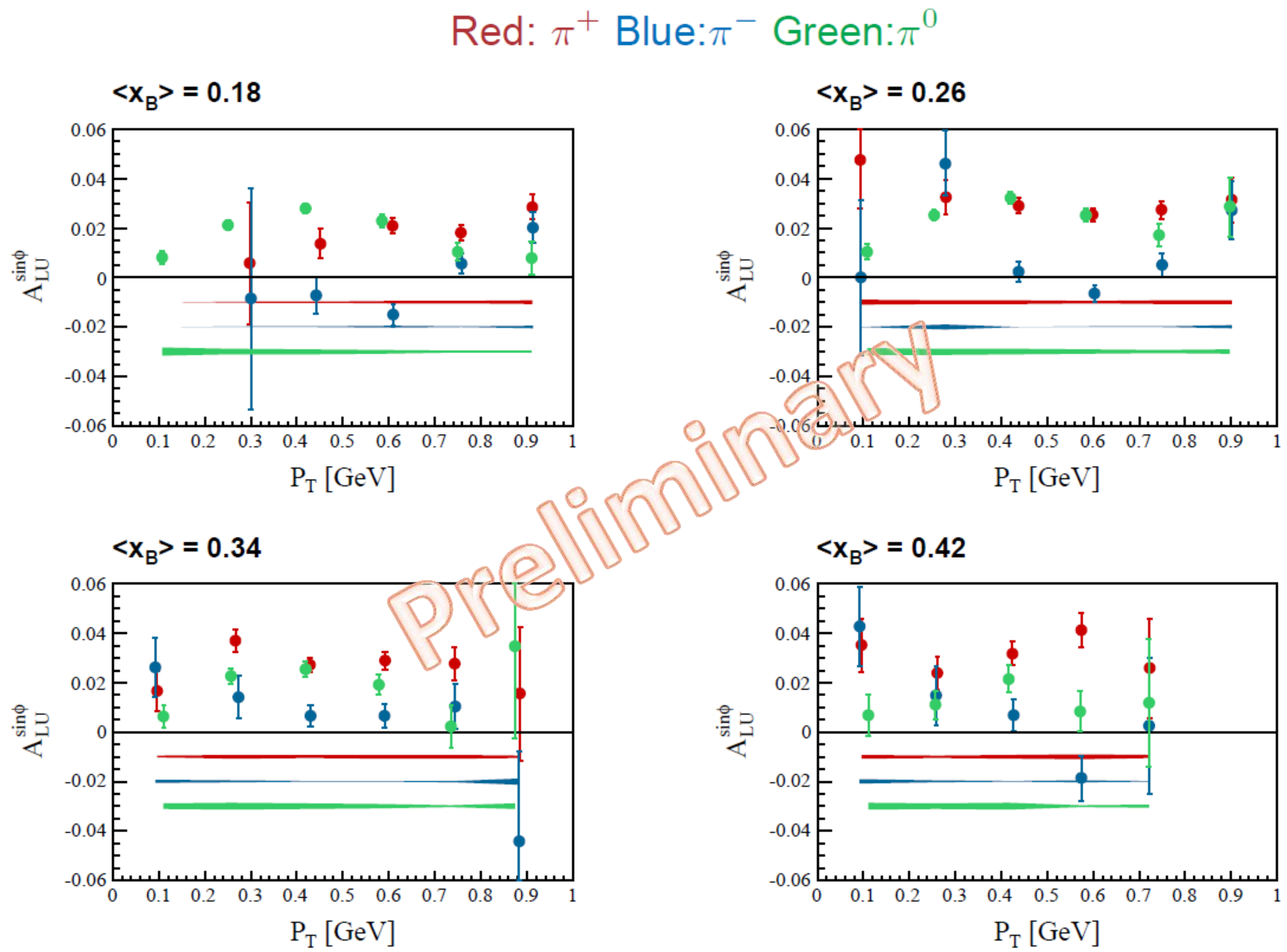
- **Double-Spin Asymmetry** (DSA)

$$A_{LL} = \frac{1}{fD'(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

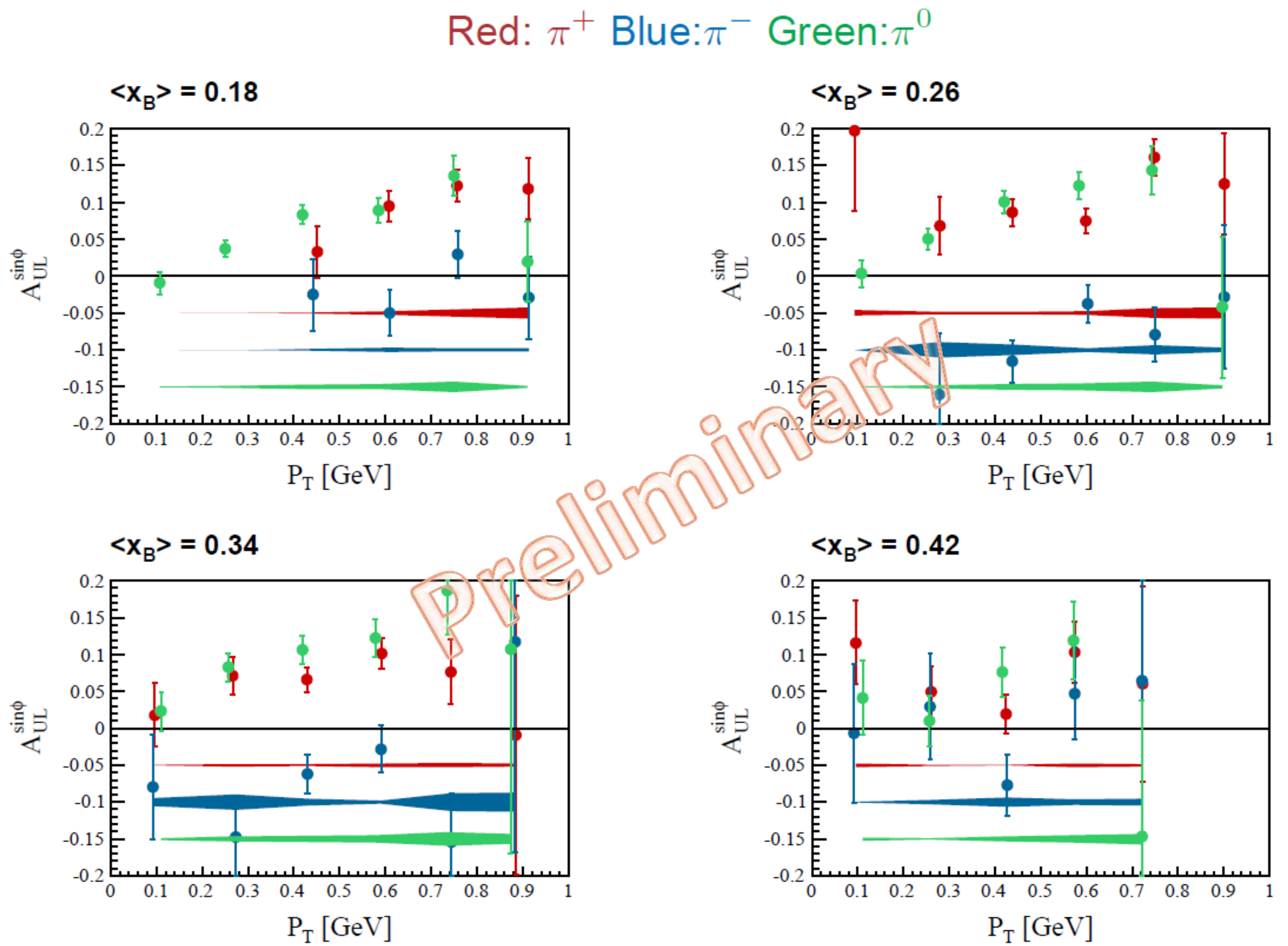
g_1 is well known in the collinear case → its p_T dependence only recently explored

Thanks to S. Koirala for the material in the next slides!

Beam-Spin Asymmetry on longitudinally-polarized ^3NH

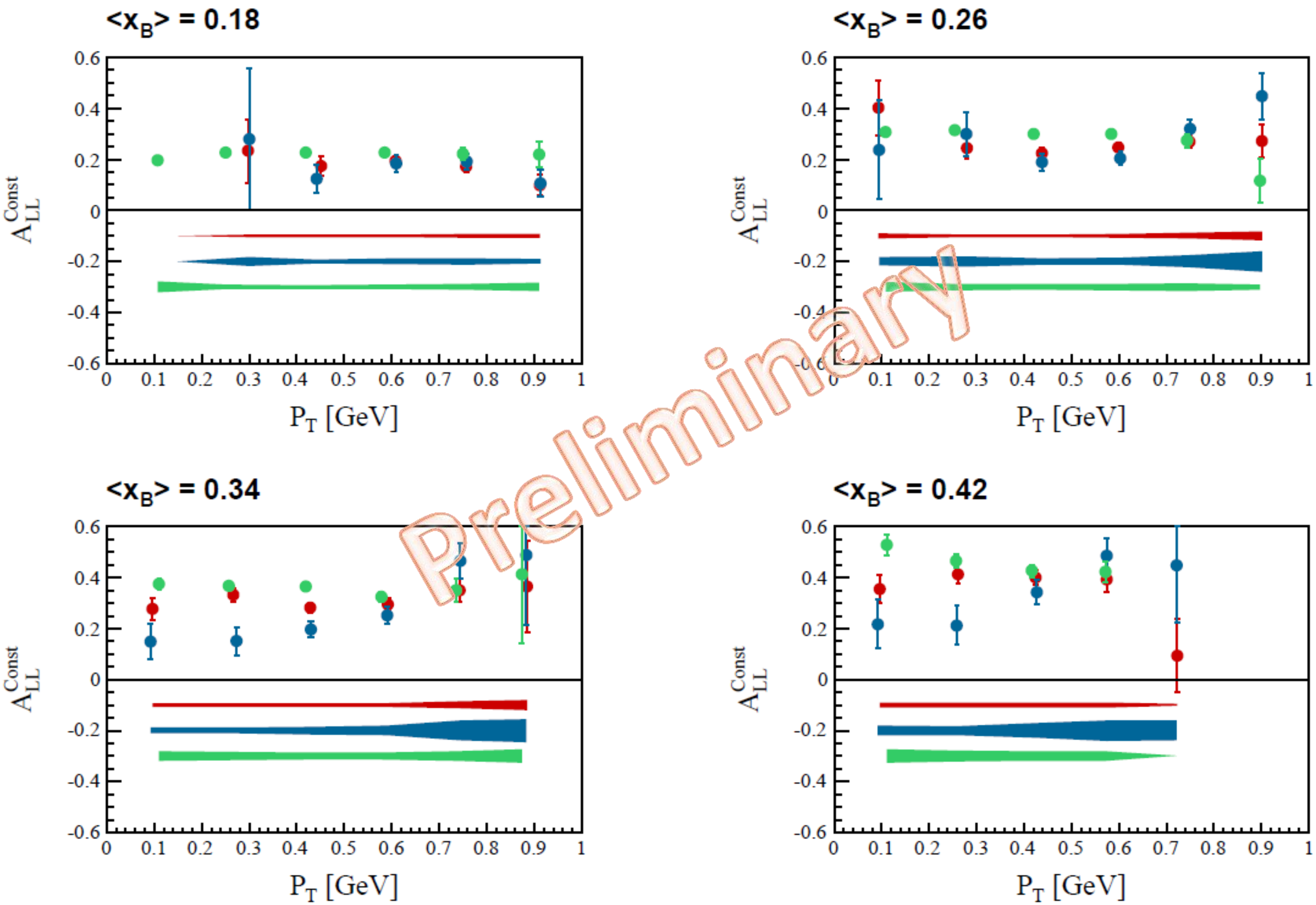


Target-Spin Asymmetry on longitudinally-polarized ^3NH



Double-Spin Asymmetry on longitudinally-polarized ^{3}NH

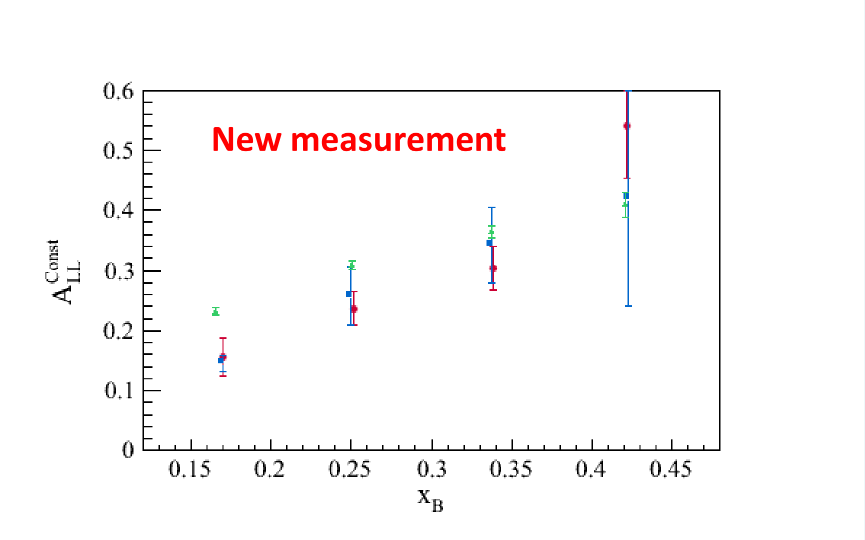
Red: π^+ Blue: π^- Green: π^0



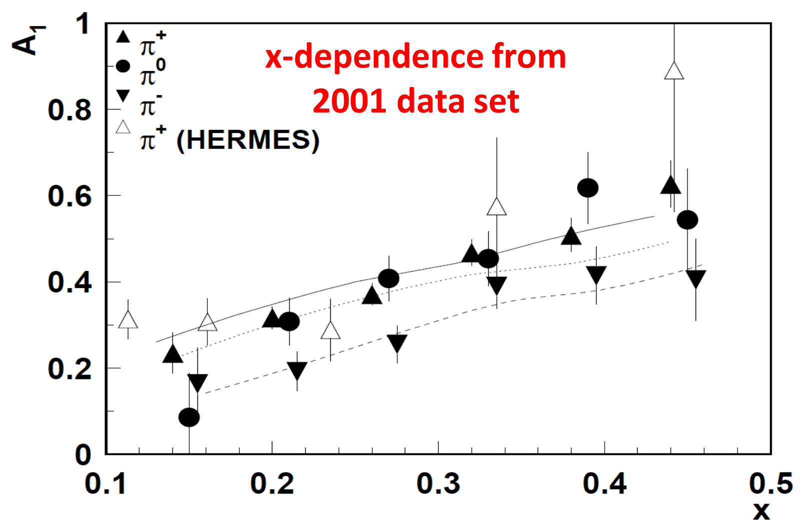
Longitudinally-polarized contribution → A_1 x-dependence

$$A_{LL} = \frac{1}{fD'(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

- f is the dilution factor
- $D'(y)$ is a depolarization factor
- P_B is the beam polarization
- P_T is the target polarization
- $N^{\pm}$ the luminosity integrated yields



- Very precise data in the **high-x region**
- Consistent with HERMES data in the **low-x region** → weak Q^2 dependence of A_1
- Data consistent with calculation using leading-order GRSV* PDFs



***M. Gluck, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. D 53(1996) 4775.**

Conclusions

- Correlations among parton tranverse momentum & spin is essential to **relate the nucleon structure to its elementary degrees of freedom.**

- Azimuthal asymmetries extracted so far suggest that such correlations may be important.

- In the 6 GeV era, Hall-A & Hall-B experiments performed important measurements related to the **unpolarized** and to the **longitudinal/transverse** part of the cross-section, providing information for the structure function behaviour in the **valence region.**

- The relatively-low Q^2 region explored at JLab will allow to explore higher-twist effects, expected to play an appreciable role in the JLab kinematics.

- In the 12 GeV era, the high-luminosity and high precision of the measurements will allow multidimensional analysis of the moments, especially in the **high-x (valence) region and high p_T region** (*i.e.* at the transition between perturbative and non-perturbative regime)

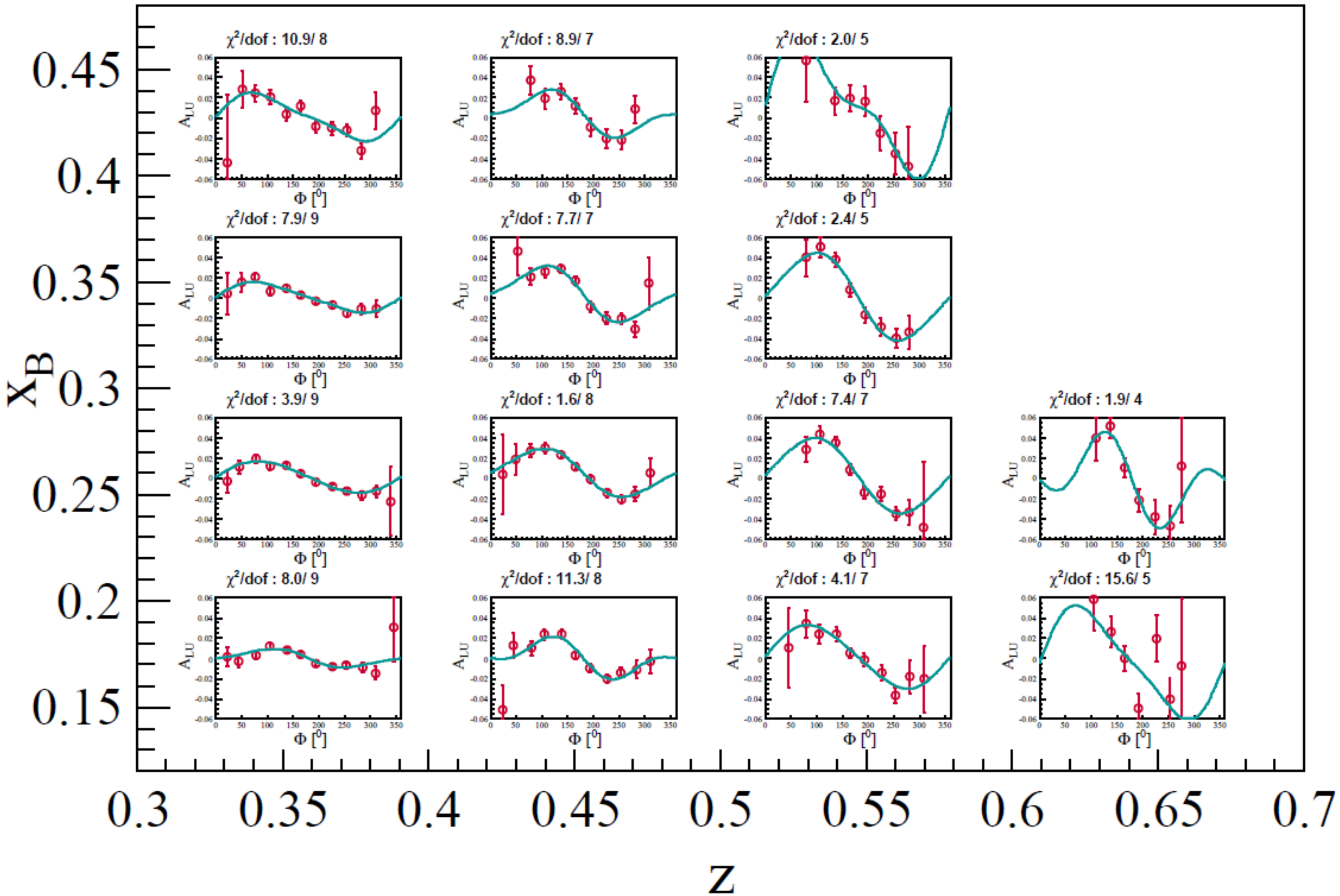
backup

Single-hadron SIDIS cross section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

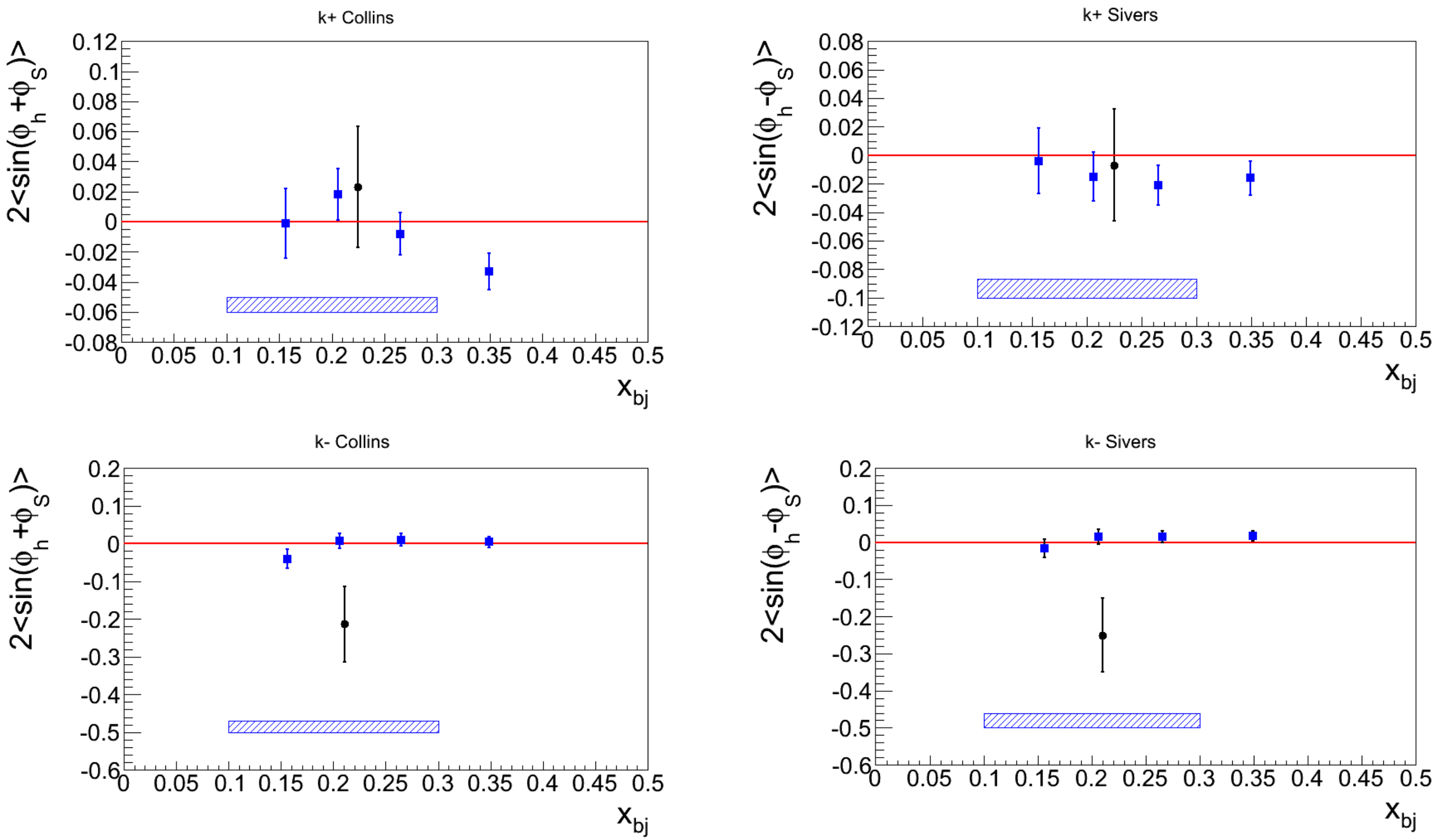
$$\begin{aligned}
\Big\{ & \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}} \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\mathrm{UU}}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\mathrm{UU}}^{\cos(2\phi)}\Big] \\
+ \; & \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\mathrm{LU}}^{\sin(\phi)}\Big] \\
+ \; & S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\mathrm{UL}}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\mathrm{UL}}^{\sin(2\phi)}\Big] \\
+ \; & S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\mathrm{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\mathrm{LL}}^{\cos(\phi)}\Big] \\
+ \; & S_T \Big[\sin(\phi-\phi_S)\left(F_{\mathrm{UT,T}}^{\sin(\phi-\phi_S)} + \epsilon F_{\mathrm{UT,L}}^{\sin(\phi-\phi_S)}\right) \\
& + \epsilon\sin(\phi+\phi_S) F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ \; & S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

Example of fit on the ^{3}NH data



Hall A Single-Spin Asymmetries - kaons

An extraction for SSAs in the kaon case has been performed → 1 x_B bin



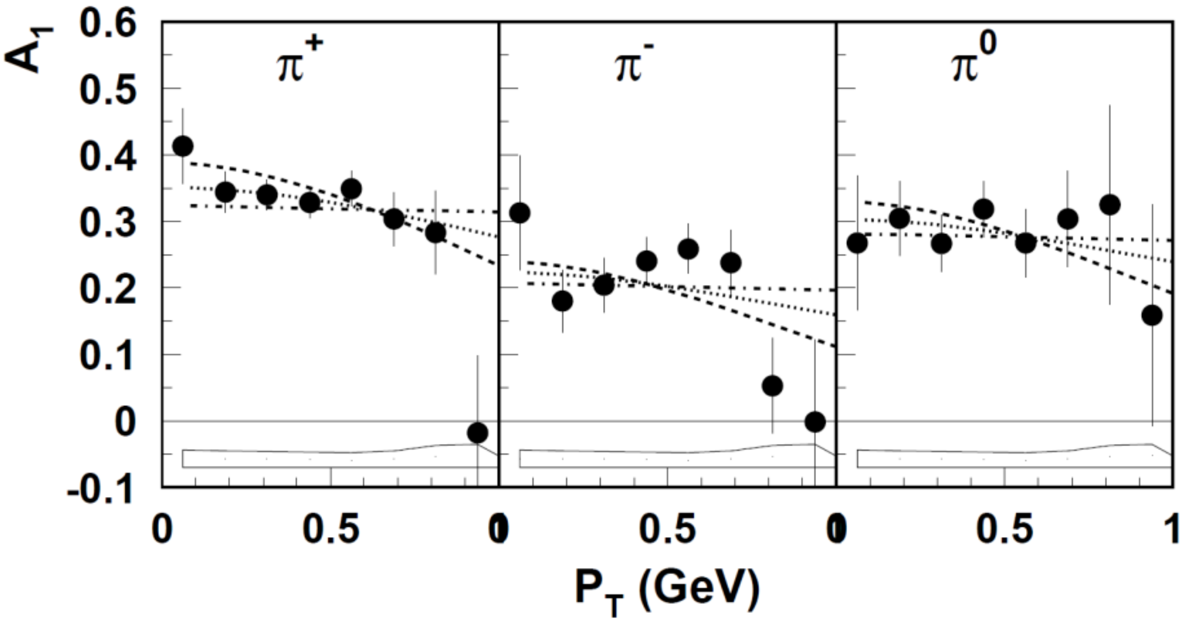
Blue points: pion PRL 107 (2011) 072003

Black points: kaon **PRELIMINARY** (**Y. Zhao/DNP2013**)

Asymmetries:

- K+ consistent with 0
- K- large and negative

Longitudinally-polarized contribution → A_1 p_T-dependence



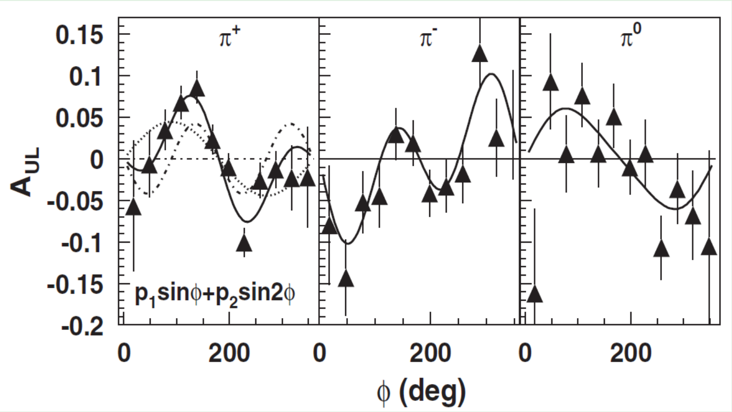
- Dependence could be related to different widths for TMD for different quark flavours & polarizations, resulting from different orbital motion of quarks polarized || or anti-|| to the proton spin

- Compared with predictions from **Torino group# → different values for the ratio**

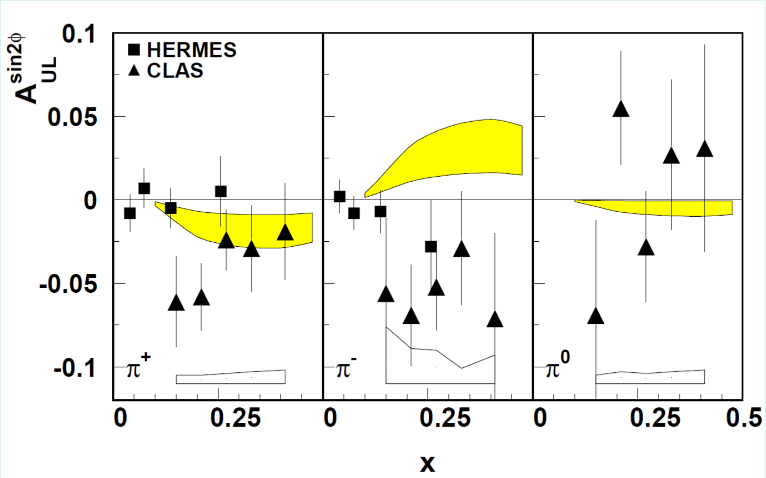
$$R = \frac{k_\perp \, width \, of \, g_1}{k_\perp \, width \, of \, f_1}$$

Longitudinally-polarized contribution → SSA

$$A_{UL} = \frac{1}{f P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto A_{UL}^{\sin\varphi} \sin\varphi + A_{UL}^{\sin 2\varphi} \sin 2\varphi \rightarrow h_{1L}^{\perp} \otimes H_1^{\perp}$$

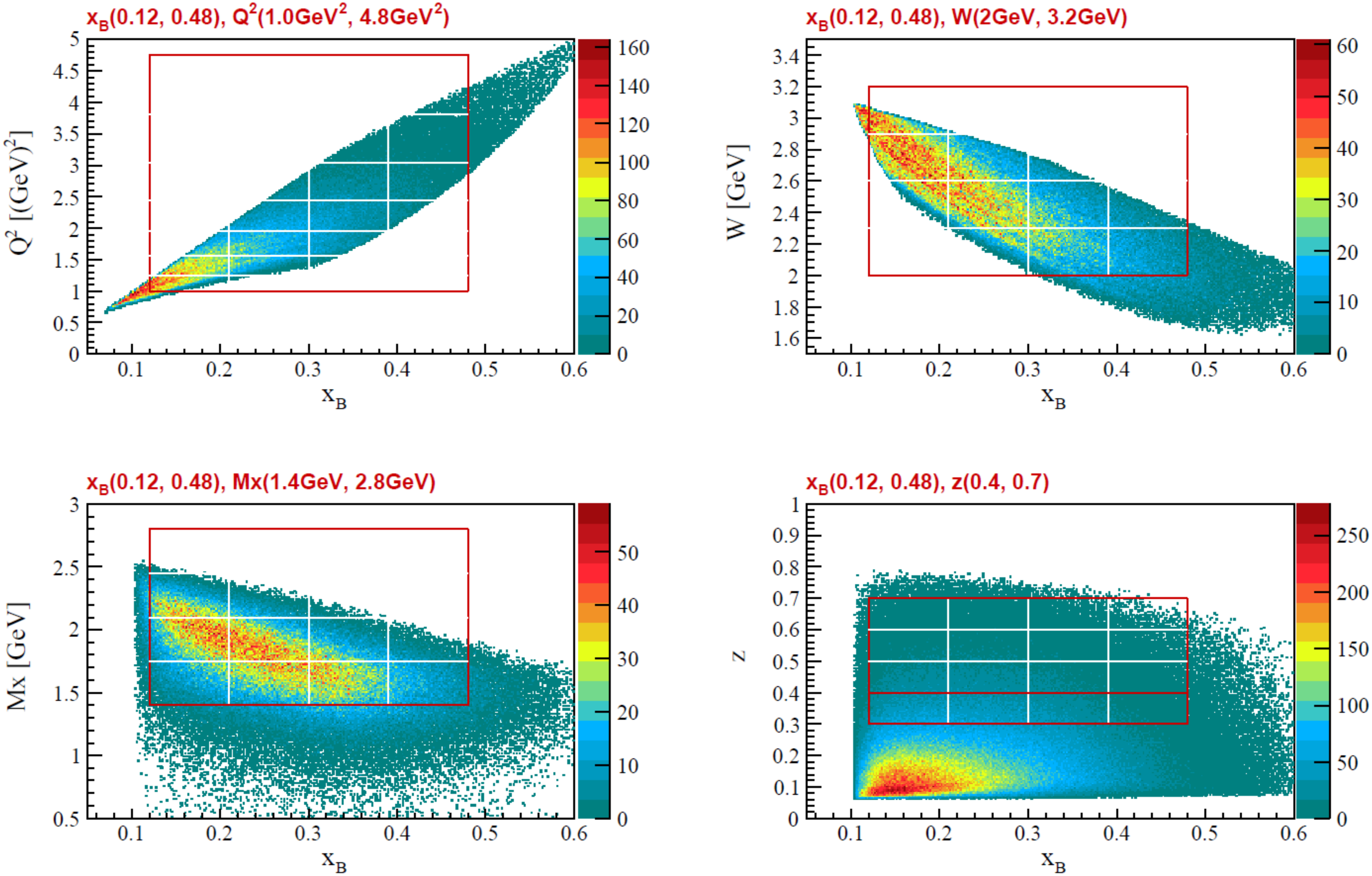


- Clear $\sin 2\varphi$ modulation for $\pi^{\pm}$
- Collins function suppressed for π^0?
- Small modulation in agreement with HERMES results → cancellation among favored and unfavored Collins observed by HERMES & Belle



1. $h_{1L}^{\perp}$ from χQSM (yellow bands)
2. $H_1^{\perp}$ Collins from HERMES & Belle data
3. Good agreement for π^+
4. Opposite sign for π^-

eg1-dvcs kinematics



CLAS@Jefferson Lab

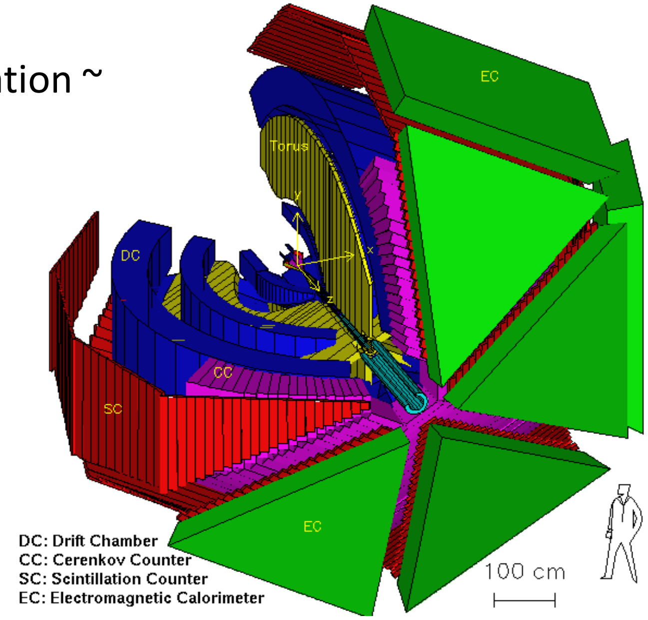
The ***Cebaf Large-Acceptance Spectrometer* (CLAS)** is installed in the Hall-B of the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA).

The CEBAF:

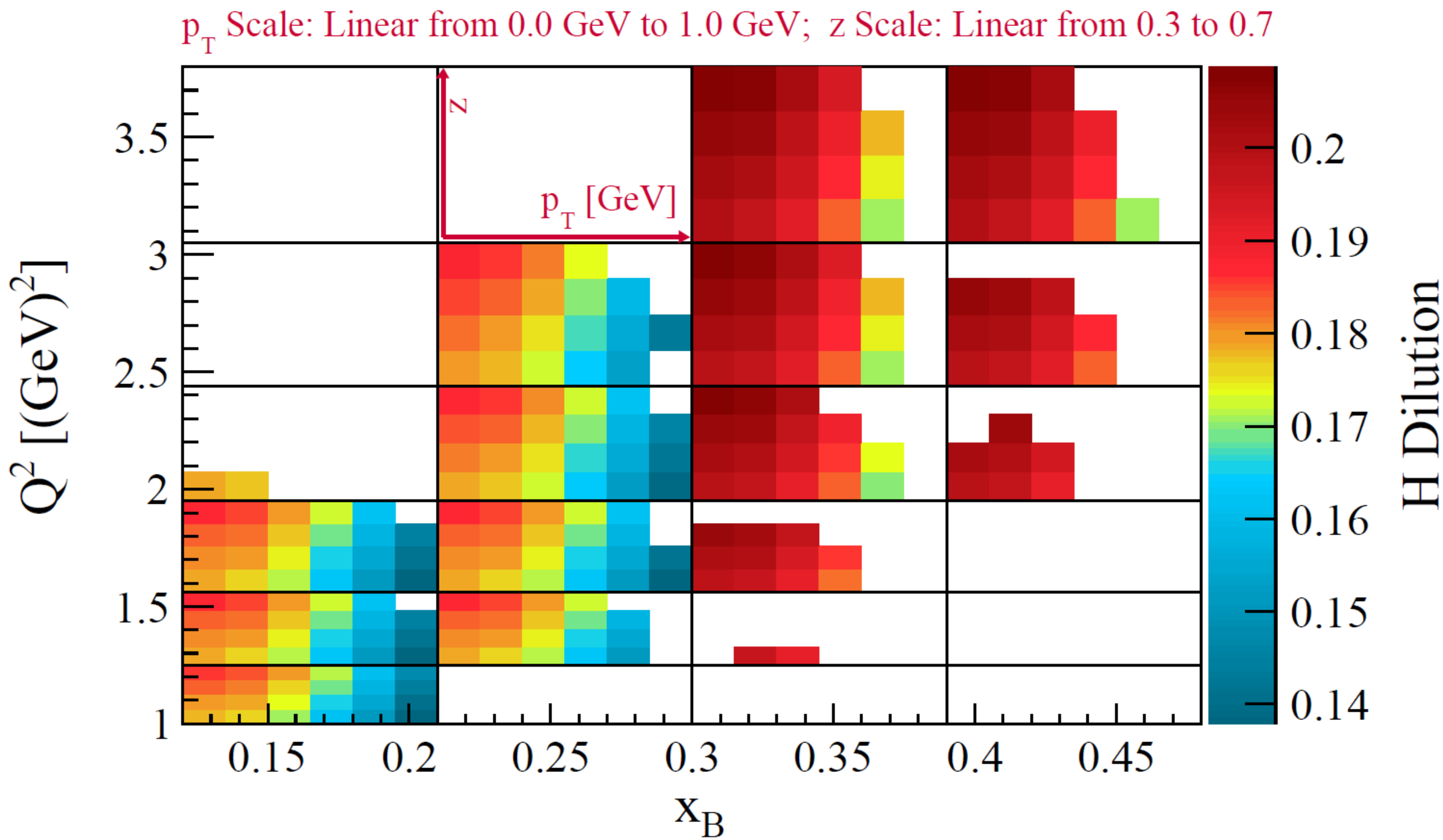
- provides a continous electron beam with a duty factor ~ 100%;
- with a beam energy up to 6 GeV;
- has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- and the beam has a polarization ~ 85%

The CLAS detector is provided with:

- Toroidal magnetic field (6 superconducting coils)
- Drift chambers (argon/CO_2 Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters (e/π separation)



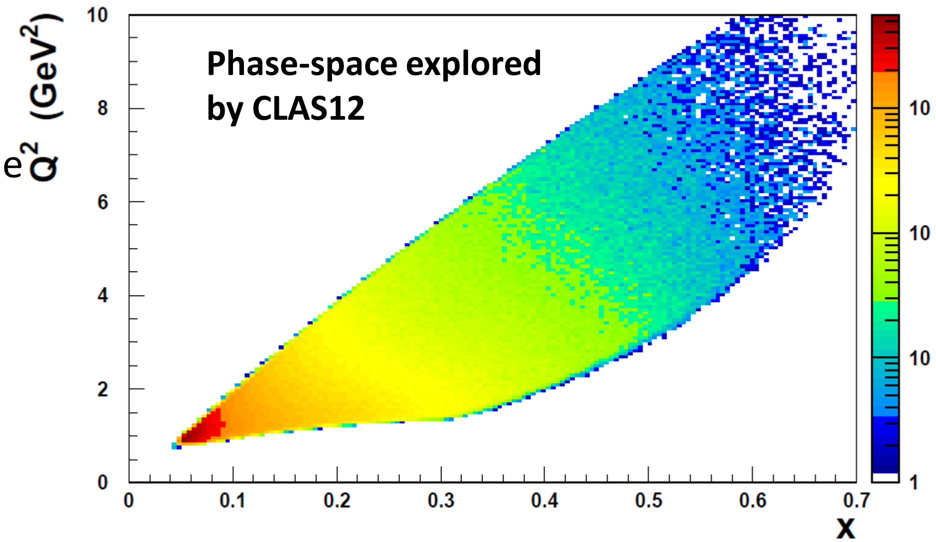
SIDIS dilution factor



TMDs in the CLAS12 era

In the 12 GeV era, CLAS12 will be able – combining measurements with unpolarized, tranversely- and longitudinally-polarized targets - to put important constraints on all chiral-odd, leading-twist TMDs in the range

- $1 < Q^2 < 8\ GeV^2$
- $0.05 < x < 0.6$
- $P_{h\perp} < 1.5\ GeV$



The Q-dependence will allow to **isolate higher-twist effects**, while the extended $p_{h\perp}$ range will open the exploration of the **transition from non-perturbative to perturbative region**.

The RICH subdetector will allow measurements involving kaons

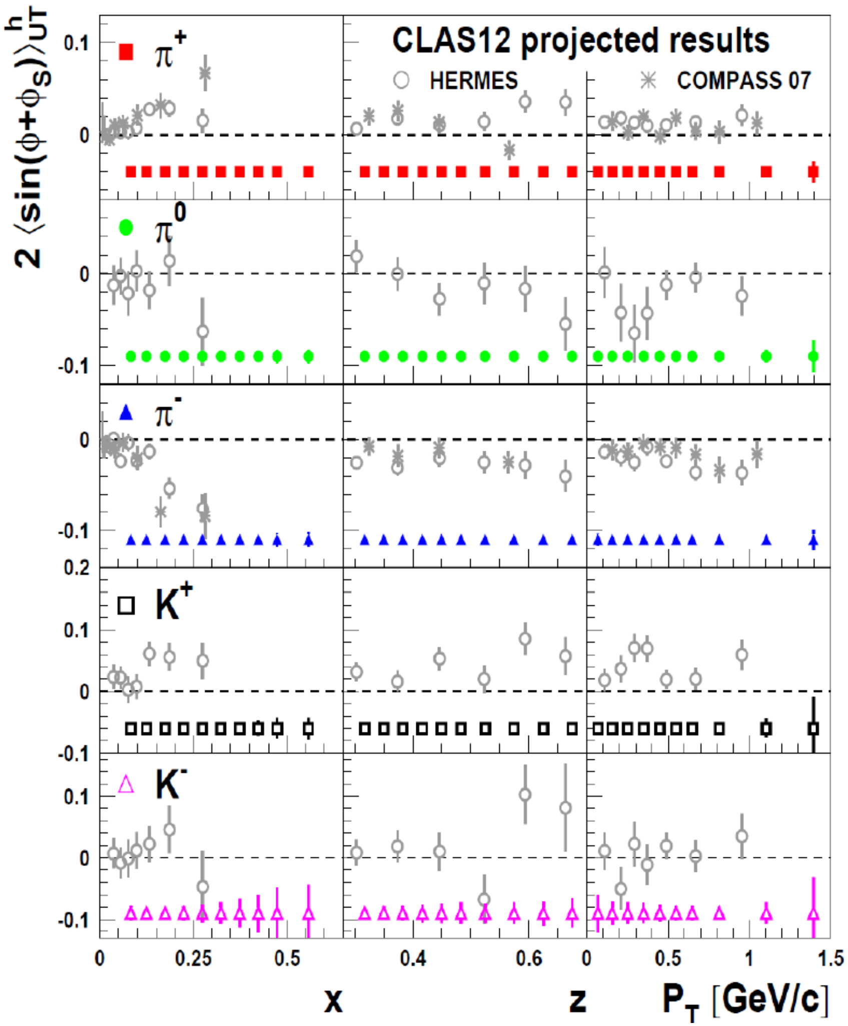
A high-luminosity, large-acceptance experiment, also provided with an efficient hadron identification, will be able to explore the relevant kinematical dependence essential to interprete the results

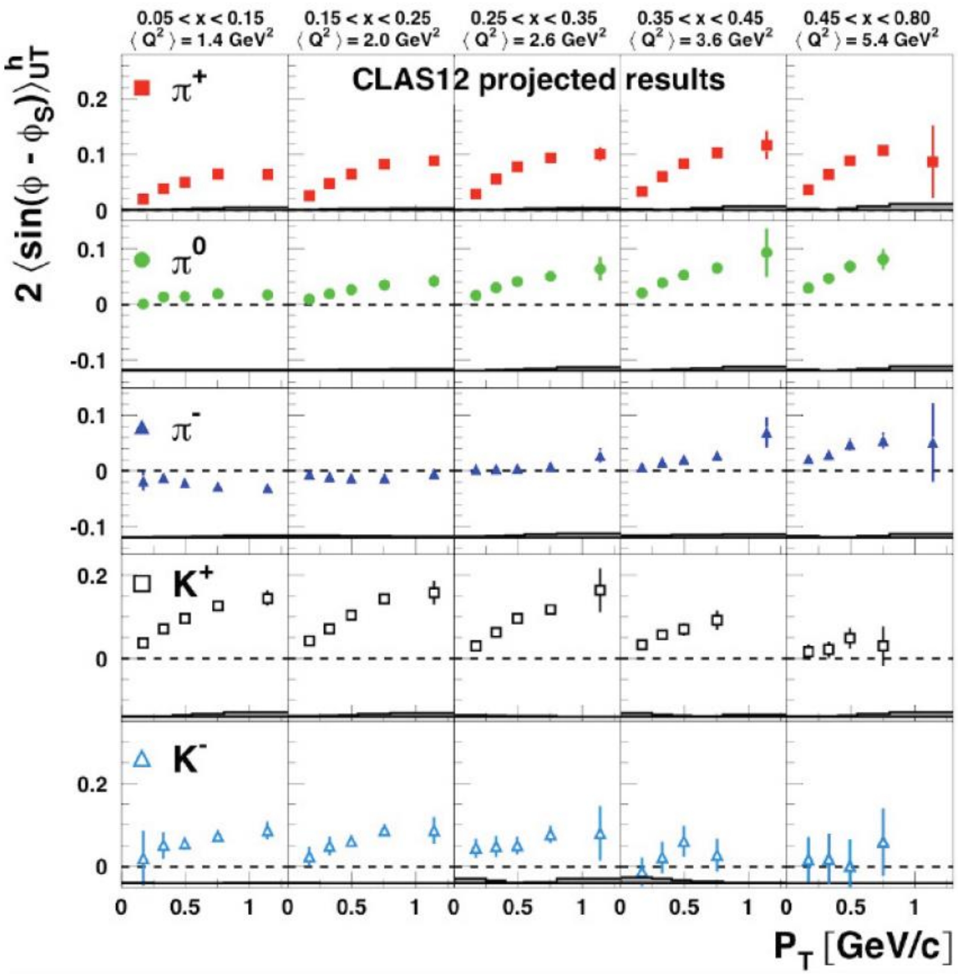
- ✓ Their measurement is challenged by the almost one order of magnitude larger pion flux
- ✓ Very little is known about the spin-orbit correlations related to the **strange quark**
- ✓ Indication of non-trivial role of the sea quarks in the nucleon, and of the fragmetation mechanism in the presence of a strange quark
- ✓ Kaons my provide enhanced sensitivity to **higher-twist** effects.

CLAS12 physics program

Proposal	Contact Person	Physics	Energy (GeV)	PAC days	Parallel Running	Run Group	Comment
PR-09-103	Gothe, Mokeev	N^* at high Q^2	11	60			
E12-06-119a	Sabatie	DVCS pol. beam	11	80	80	120	
E12-06-112	Avakian	$ep \rightarrow e\pi^{+/-/0}X$	11	60			
E12-06-108	Stoler	DVMP in π^0,η prod L/T separation	11	80			
			8.8	20	20		
			6.6	20	20		
E12-06-119b	Sabatie	DVCS pol. target	11	120	120		Assume polarized experiments run 50% of time w/ reversed field
E12-06-109	Kuhn	Long. Spin Str.	11	82	50	175	
E12-07-107	Avakian	TMD SSA	11	103	5		
PR-09-007(b)	Hafidi	Partonic SIDIS	11	103			
PR-09-009	Avakian	Spin-Orbit Corr.	11	103			
E12-06-106	Hafidi	Color Trans. ρ^0	11	40	40	40	
E12-06-117	Brooks	Quark Hadronizat.	11	60	60	60	
E12-06-113	Bültman	Neutron Str. Fn.	11	40	40	40	cond. appr.
E12-07-104	Gilfoyle	Neutron mag. FF	11	56	56		007/008 need 26d reversed field
PR-09-007(a)	Hafidi	Partonic SIDIS	11	56		82	
PR-09-008	Contalbrigo	Boer-Mulders w/ Kaons	11	56	26		
Total				**1139**		**517**	

Collins&Sivers@CLAS12





Transverse terms@CLAS12

In the CLAS12 era, the presence of a tranversely polarized target will give access to the tranverse part of the cross-section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{\rm UU,T} + \epsilon F_{\rm UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{\rm UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{\rm UU}^{\cos(2\phi)}\Big]$$

$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{\rm LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{\rm UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{\rm UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\rm LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\Big(F_{\rm UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{\rm UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\sin(\phi+\phi_S) F_{\rm UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{\rm UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\rm UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\rm UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\rm LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\rm LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\rm LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

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

E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

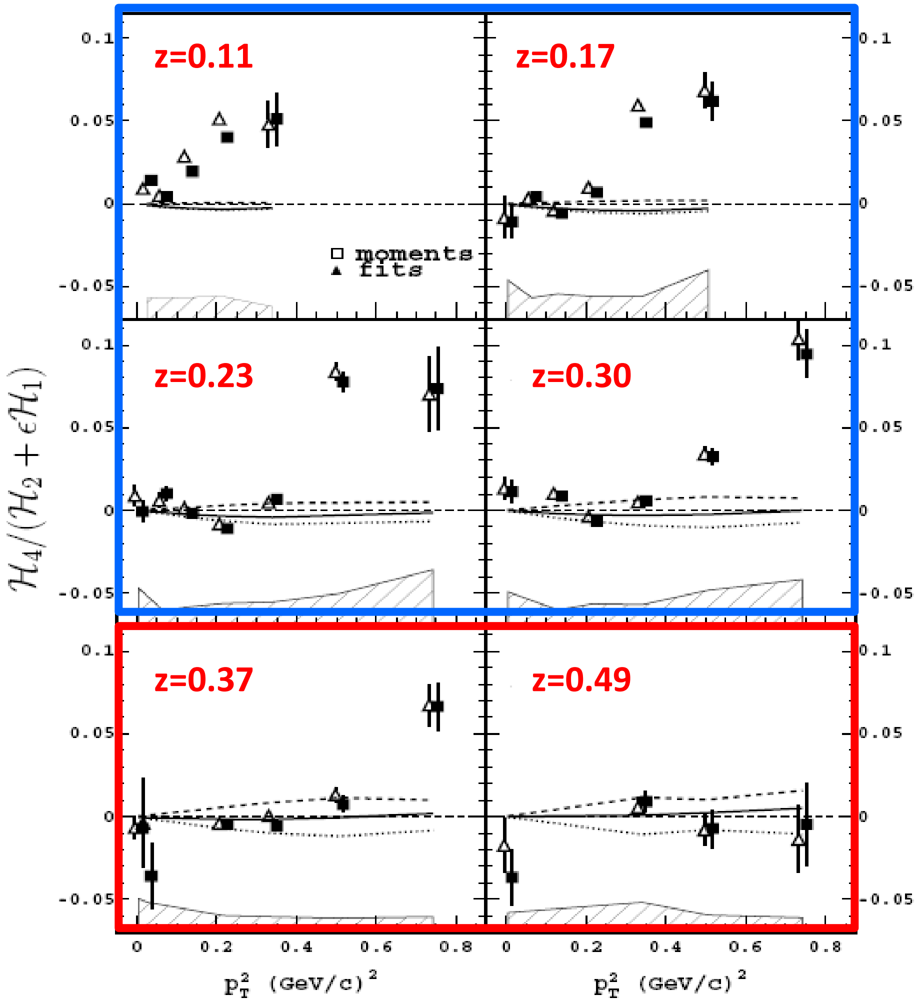
E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

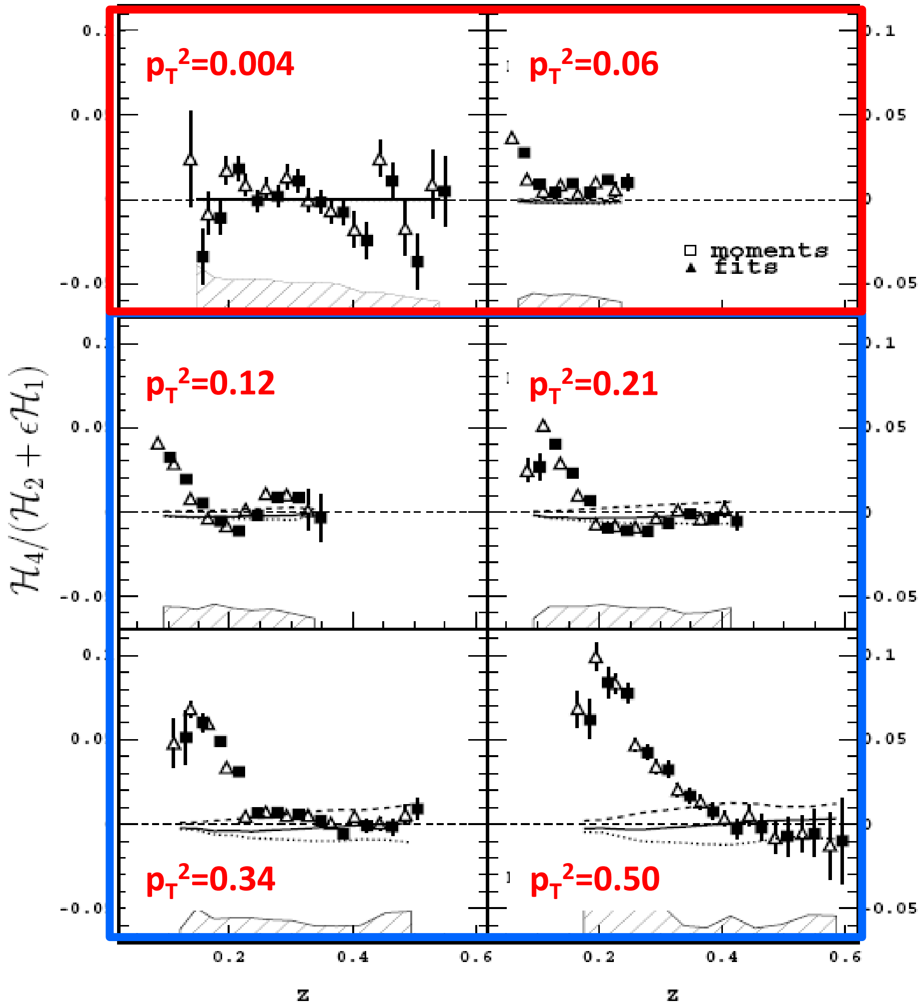
Tranversely polarized targets

- PR12-11-111: **Pion/Kaon** SIDIS
- PR12-12-009: **Pion/Kaon** SIDIS

- **Tranversity** $\rightarrow A_{UT}^{\sin(\varphi+\varphi_S)} \propto h_1 \otimes H_{1T}$
- **Sivers function** $\rightarrow A_{UT}^{\sin(\varphi-\varphi_S)} \propto f_{1T} \otimes D_1$
- **Pretzelosity** $\rightarrow A_{UT}^{\sin(3\varphi-\varphi_S)} \propto h_{1T} \otimes H_{1T}$
- **Worm-gear** $\rightarrow A_{LT}^{\cos(\varphi-\varphi_S)} \propto g_{1T} \otimes D_1$

Boer-Mulders effect



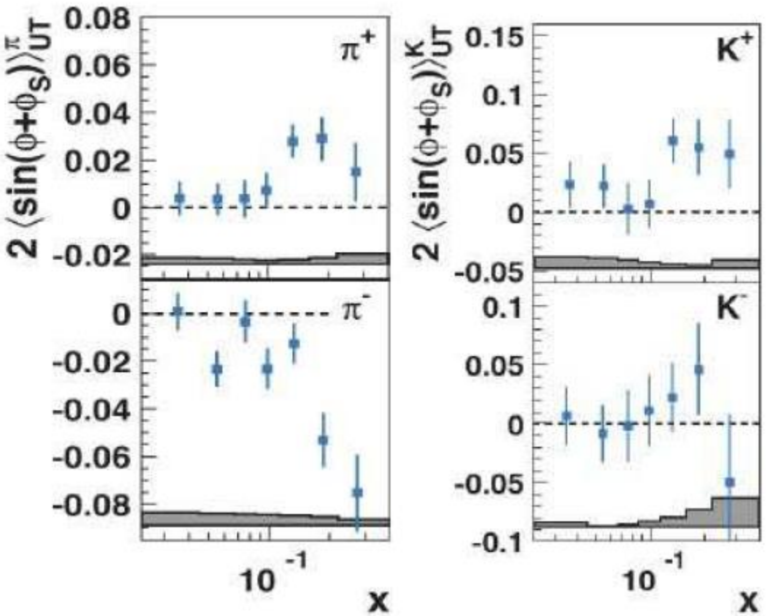


amplitudes are positive in low-z and high p_T^2 regions and show a strong kinematic dependence

predicted amplitudes are very small and agree with data only in high-z and low p_T^2 regions

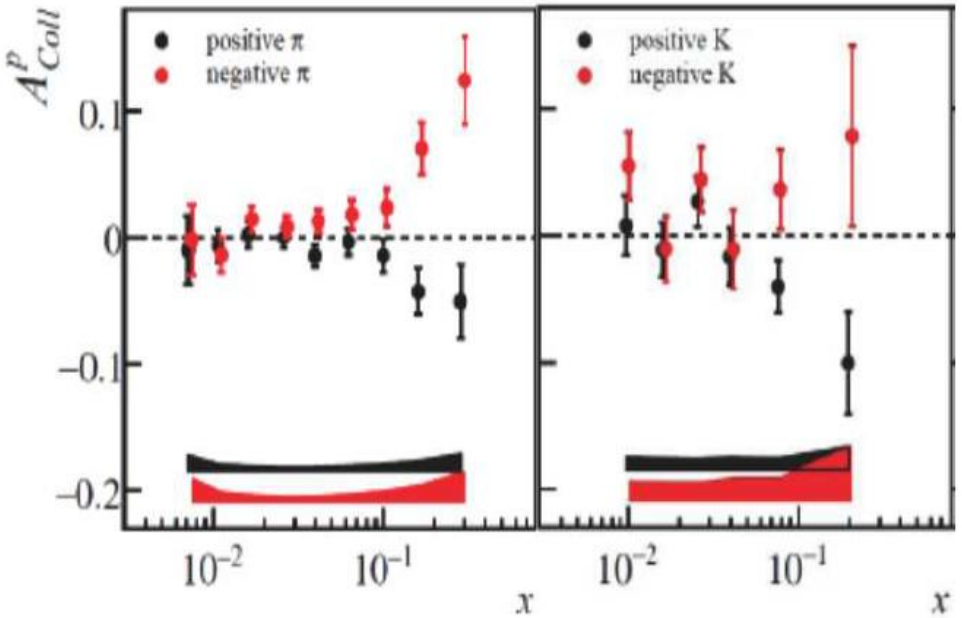
Collins@HERMES & COMPASS

HERMES data



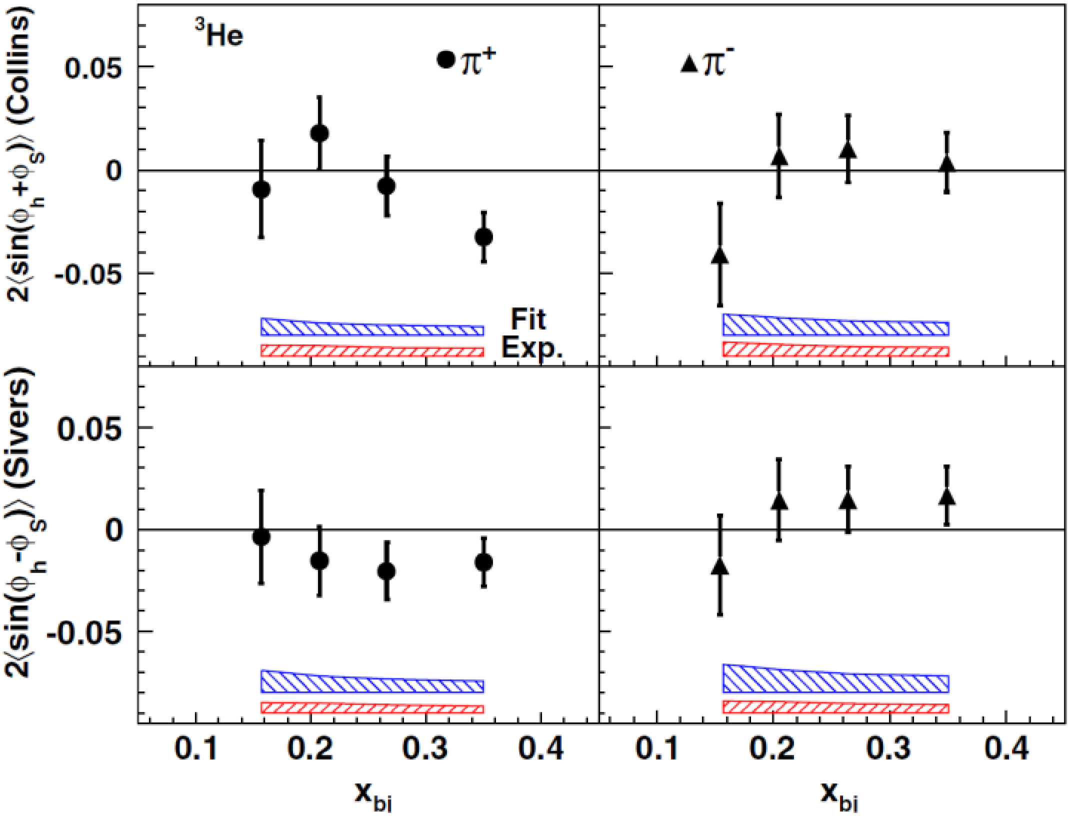
A. Airapetian et al., Phys. Lett. B 693, 11 (2010).

COMPASS data



C.f.C. Schill (2011), DIS 2011 Conference.

Sivers&Collins on ^3He@Hall-A



Both Collins and Sivers moments are below 5%.

The Collins moments are mostly consistent with zero, except for the π^+ Collins moment at $x = 0.35$ (2.3 σ deviation).

π^+ Sivers moments favor negative values, while π^- ones are consistent with zero.

title