EUNPC2012

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Analyzing nucleon spin structure through SIDIS at Jefferson Lab

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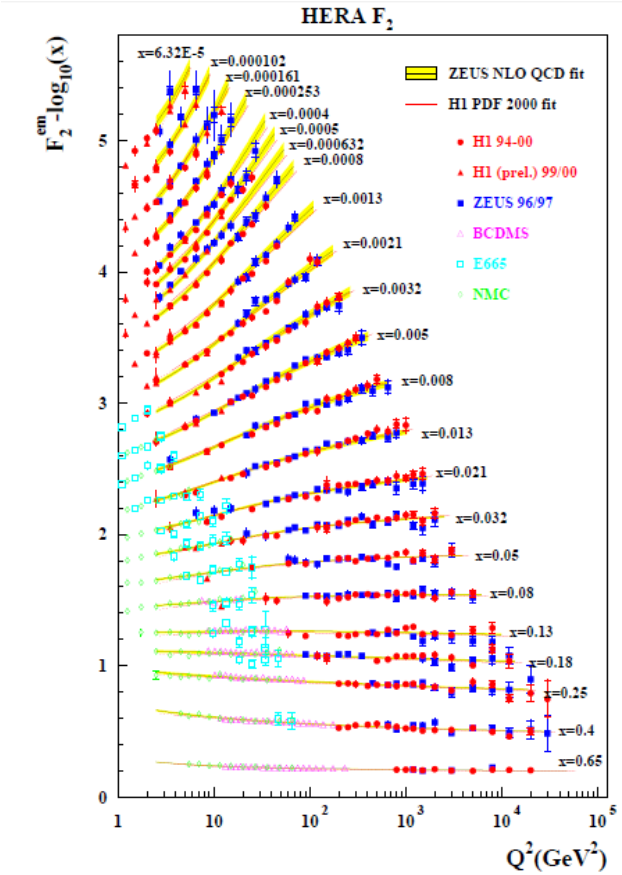
The proton from a longitudinal perspective

In the last decades, Deep Inelastic Scattering (DIS) greatly contributed to depict a longitudinal rapresentation of the nucleon



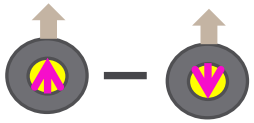
At the leading order (twist)[1], three Parton Distribution Functions (PDF) exhaust the description of quarks inside the nucleon:

- $f_1^q(x)$: number density of an unpolarized quark in an unpolarized nucleon
  - *known with high accuracy*

- $g_1^q(x)$: number density of longitudinally polarized quark in a longitudinally polarized nucleon
  - *less well known (but there are measurements: see, e.g., Hermes data for 5 different quark flavours*)*

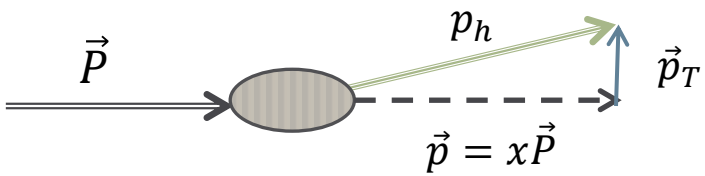
- $h_1^q(x)$: number density of transversely polarized quarks in a transversely polarized nucleon
  - *the transversity is the only missing ingredient to complete the leading-twist picture of the nucleon.*

[1]*Twist refers to the order in M/Q at which the distribution function contributes to the cross-section. See Jaffe, hep-ph/9602236.*
**A. Airapetian et al. PRD 71, 012003 (2005)*



...and from a tranverse one.

The proton has also a **non-collinear structure**

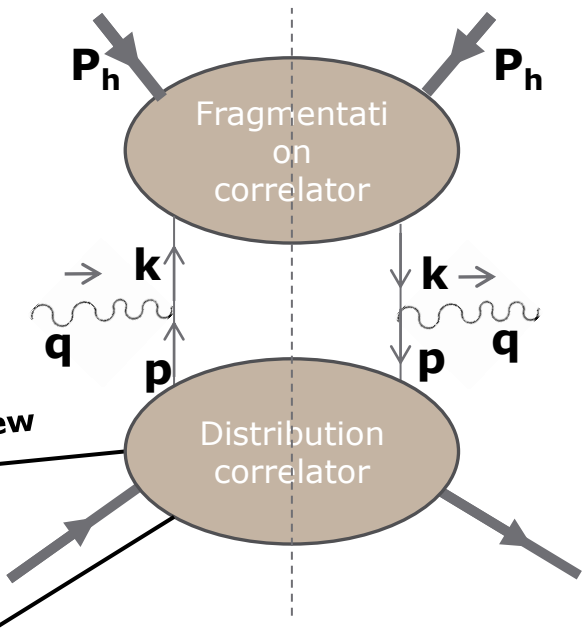


and its theoretical description is enriched.
In the collinear approximation the proton is described as

$$\Phi(x) = \frac{1}{2}\left\{ f_1 \not{n}_+ + S_L\, g_1 \gamma_5 \not{n}_+ + h_1 \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} \right\}$$

while, once a tranverse component for the quark momentum is considered, we got

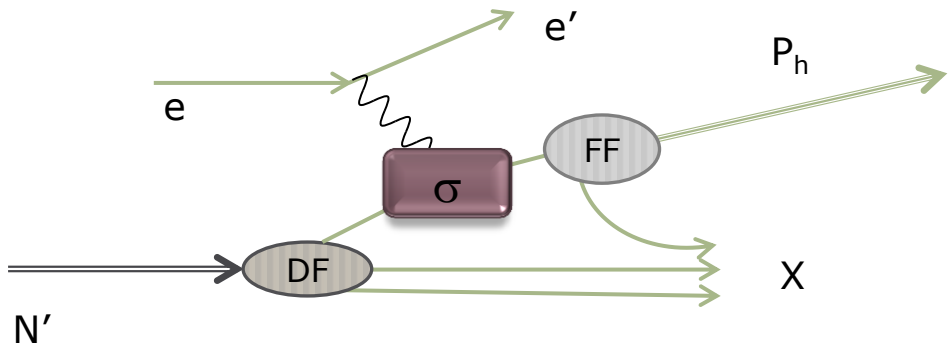
$$\Phi(x, p_T) = \frac{1}{2}\left\{ f_1 \not{n}_+ - f_{1T}^{\perp} \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} \not{n}_+ + S_L\, g_{1L} \gamma_5 \not{n}_+ - g_{1T} \frac{p_T \cdot S_T}{M} \gamma_5 \not{n}_+ \right.$$
$$+ h_{1T} \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} + S_L\, h_{1L}^{\perp} \frac{[\not{p}_T, \not{n}_+]\gamma_5}{2M}$$
$$\left. - h_{1T}^{\perp} \frac{p_T \cdot S_T}{M} \frac{[\not{p}_T, \not{n}_+]\gamma_5}{2M} + i h_1^{\perp} \frac{[\not{p}_T, \not{n}_+]}{2M} \right\}$$



1. TMDs depend on x and p_T
2. Describe correlations between p_T and quark or nucleon spin (**spin-orbit correlations**)
3. Provide **a 3-D picture** of the nucleon in momentum space (**nucleon tomography**)

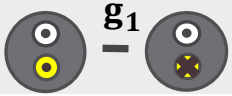
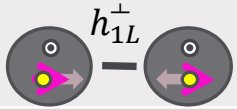
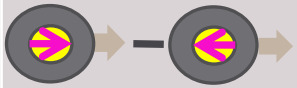
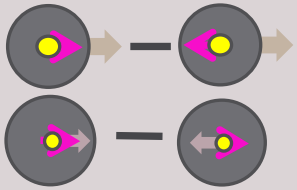
Accessing the Tranverse Momentum Distributions (TMDs)

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



together with the outgoind electron a final hadron is detected, that gives access to p_T

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		$\boldsymbol{G_{1L}}$	$H_{1L}^\perp$
T	$H_1^\perp$	G_{1T}	$\boldsymbol{H_1}, H_{1T}^\perp$

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

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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

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

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

Longitudinally pol. target

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

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

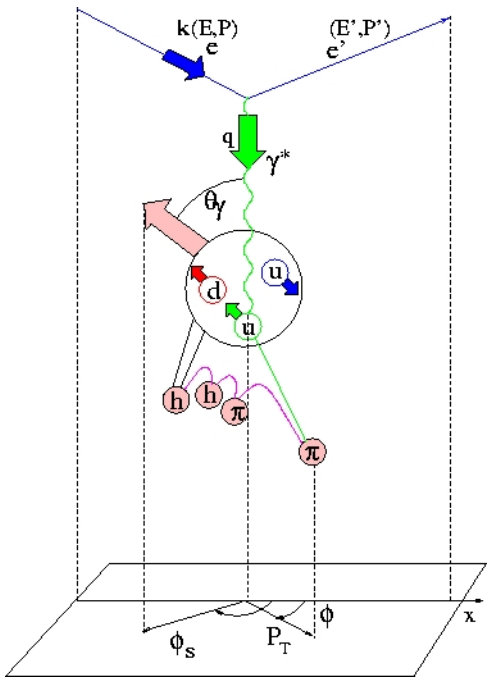
Tranversely pol. target

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

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

18 structure functions appear in the cross-section

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



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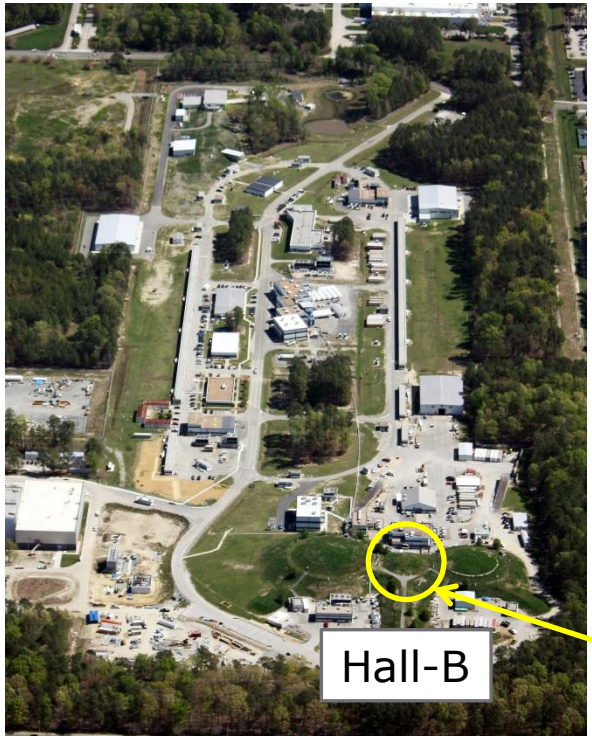
Bacchetta *et al.*, JHEP 0702:093 (2007)

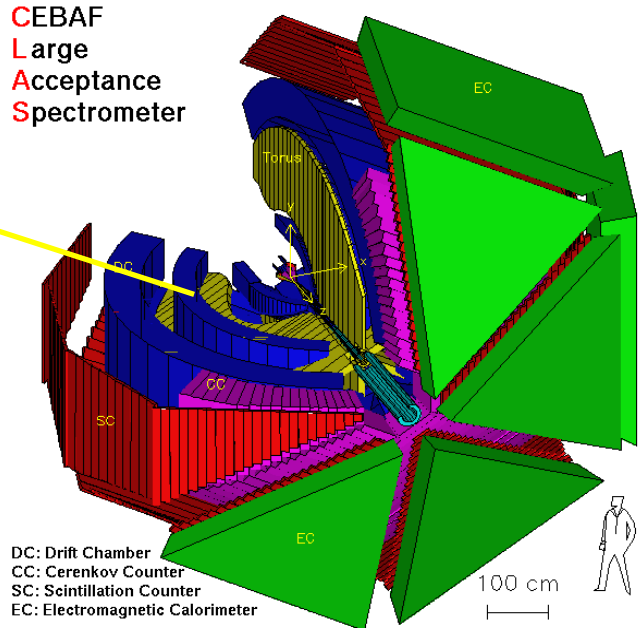
CEBAF & CLAS (Cebaf Large Acceptance Spectrometer)



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

Presently upgrading to 12 GeV!

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SIDIS@CLAS in the 6 GeV era

During the 6 GeV era, CLAS accessed the **unpolarized** and **longitudinally polarized** parts of the cross-section

$$
\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)
&\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} \\
&+ \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big] \\
&+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big] \\
&+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big] \\
&+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big] \\
&+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
&\quad + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \\
&\quad + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} \\
&\quad + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big] \\
&+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} \\
&\quad + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} \\
&\quad + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big] \Big\}
\end{aligned}
$$

Unpolarized targets

- Liquid H target, 60 days data taking – **2001-2002**

  σ_{UU} **PRD 80, 032004 (2009)**

- Liquid H target, 60 days data taking – **2005**

  π^0 **BSA Phys. Lett. B 704, 397 (2011)**

Longitudinally polarized targets

- NH3, ND3 targets, 5 days data taking **2001**

  A_{UL}, A_{LL} **PRD 80, 032004 (2009)**

- NH3, ND3 targets (E05-113), 60 days data taking **2009**

  Experiment E05-113, analyses ongoing

Longitudinally-polarized contribution

By using a 5.7 GeV polarized electron beam impinging on a LONGITUDINALLY polarized target CLAS extracted

- **Single Spin Asymmetry** (SSA)

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

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

$$\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)
&\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} \\
&+ \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\Big] \\
&+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\Big] \\
&+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\Big] \\
&+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\Big] \\
&+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
&+ \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} \\
&+ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} \\
&+ \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big] \\
&+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} \\
&+ \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} \\
&+ \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

A. Airapetian et al. (HERMES Collaboration), Phys. Rev. Lett. 84, 4047 (2000).

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

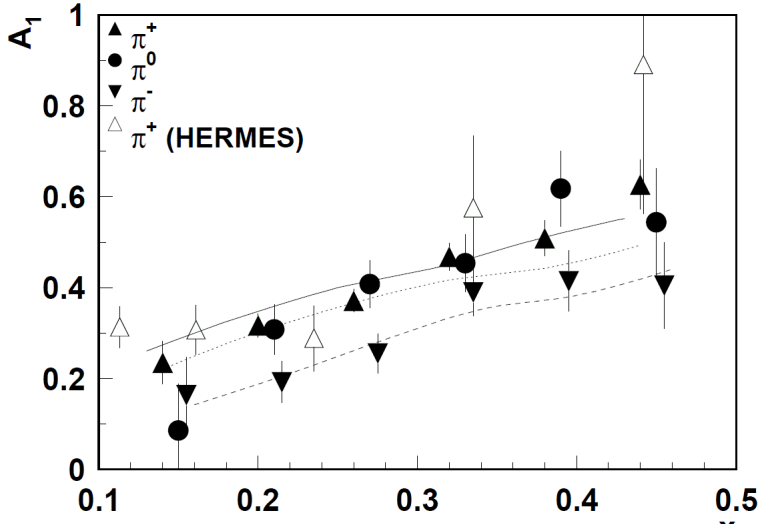
q/H	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_1^{\perp}$	G_{1T}	$H_1, H_{1T}^{\perp}$

Longitudinally-polarized contribution → A_1 *x*-dependence

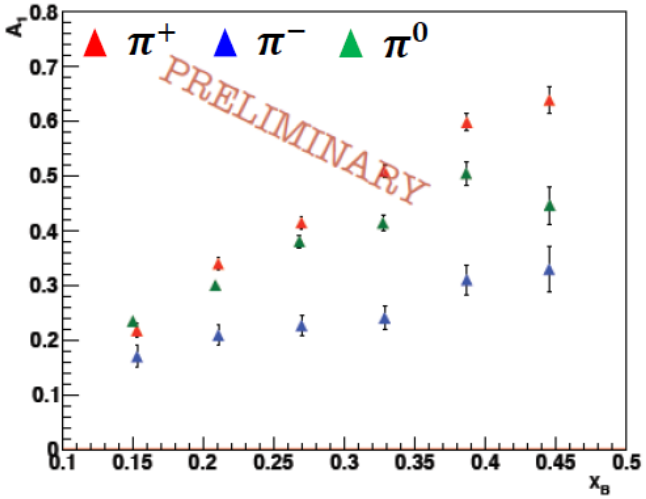
$$A_{LL} = \frac{1}{fD'(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

- $f = 0.14$ is the dilution factor
- $D'(y)$ is a depolarization factor
- $P_B \sim 70\%$ is the beam polarization
- $P_T \sim 75\%$ is the target polarization
- $N^{\pm}$ the luminosity integrated yields

x-dependence from 2001 data set



NEW DATA (2009): analysis in progress



- 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.**

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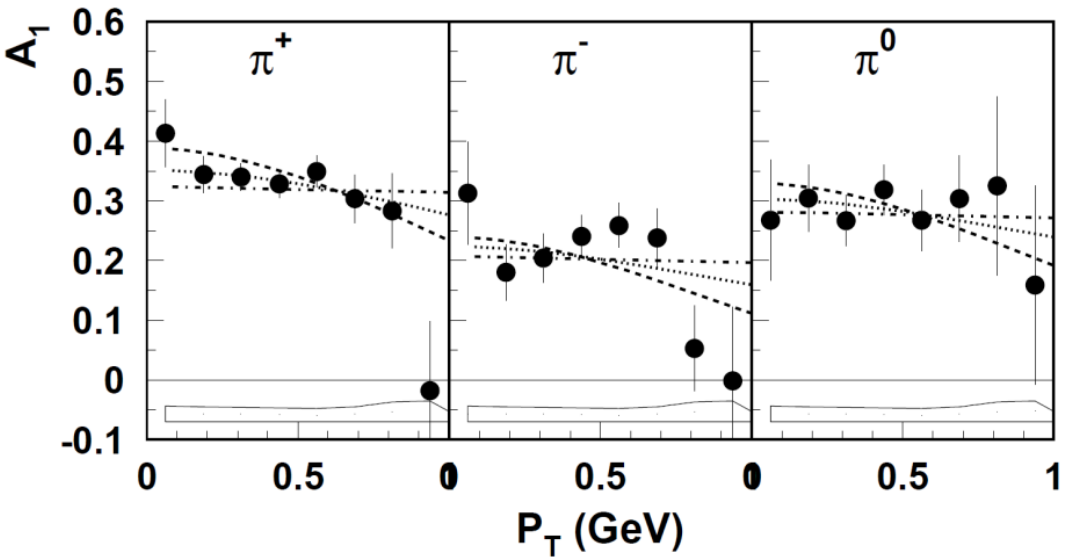
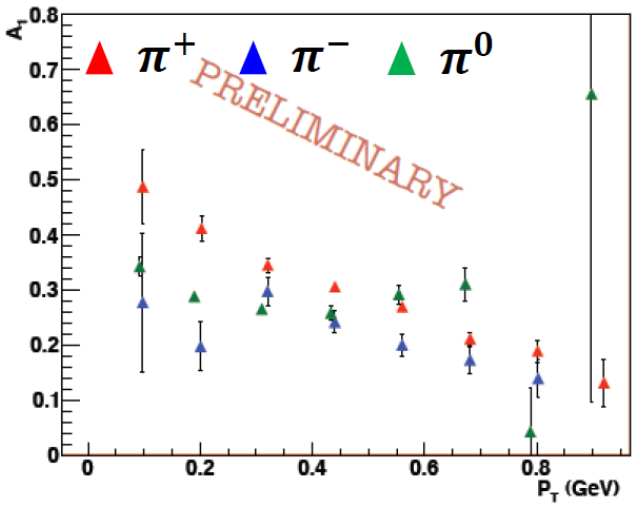
Longitudinally-polarized contribution → A_1 p_T-dependence

p_T-dependence from 2001 data set



NEW DATA (2009): analysis in progress



- 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**

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

- - - - - $R = 0.40$
- - - - - - - - $R = 0.68$
— · — · $R = 1.0$

With these new data set – 10 times more statistics – a 2-D analysis (x, p_T) will be performed

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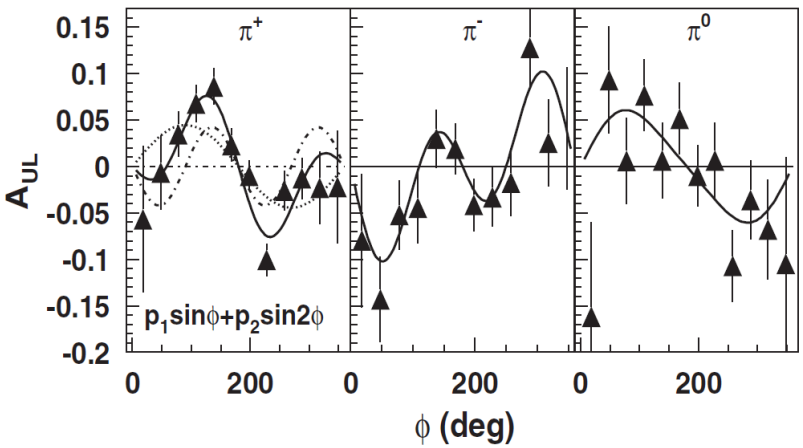
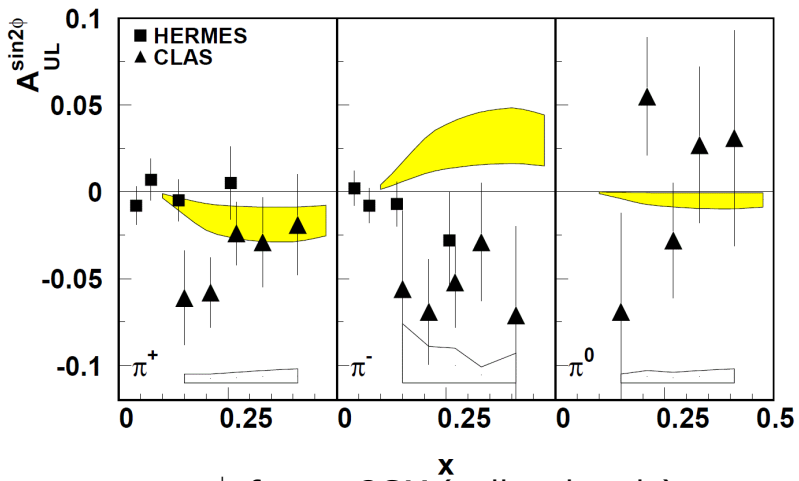
#M. Anselmino et al., Phys. Rev. D 74, 074015 (2006).

Longitudinally-polarized contribution → SSA

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-} \propto A_{UL}^{\sin\varphi}\sin\varphi + A_{UL}^{\sin 2\varphi}\sin 2\varphi \rightarrow h_{1L}^{\perp}\otimes \mathrm{H}_1^{\perp}$$

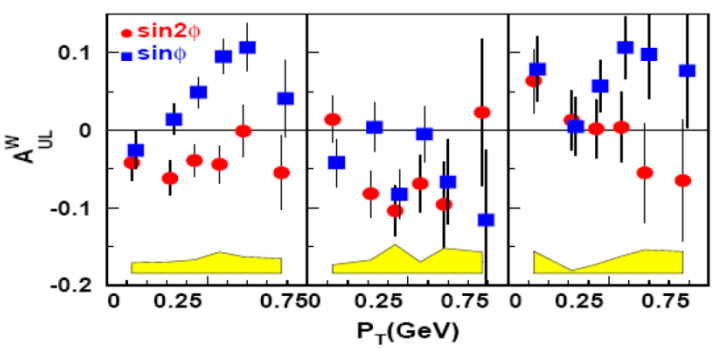


Kotzinian-Mulders Asymmetries



- 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. $\mathrm{H}_1^{\perp}$ Collins from HERMES & Belle data
3. Good agreement for π^+
4. Opposite sign for π^-



NEW DATA (2009): analysis in progress

- Large $\sin\varphi$ component → HIGHER TWIST contribution important @CLAS kinematics
- 2-D extraction $A_{UL}^{\sin\varphi}(x, p_T)$ & $A_{UL}^{\sin 2\varphi}(x, p_T)$ ongoing

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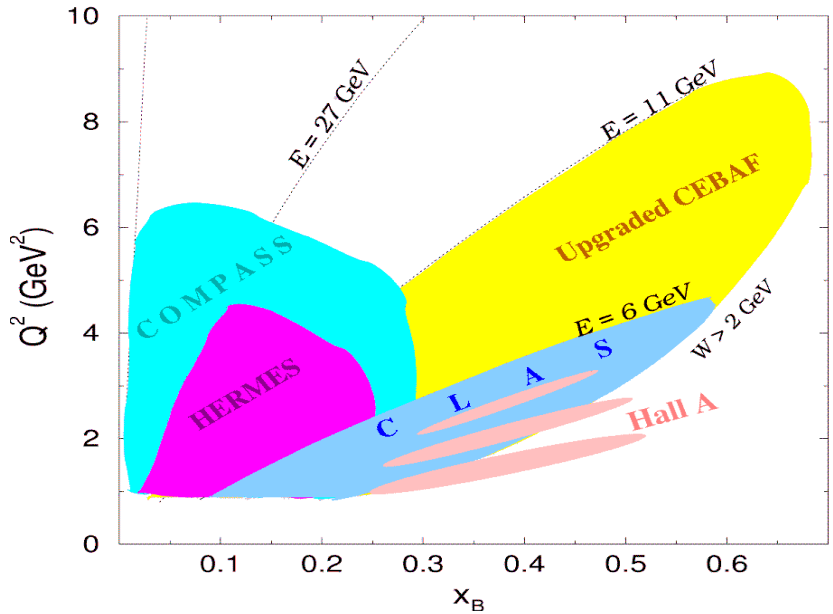
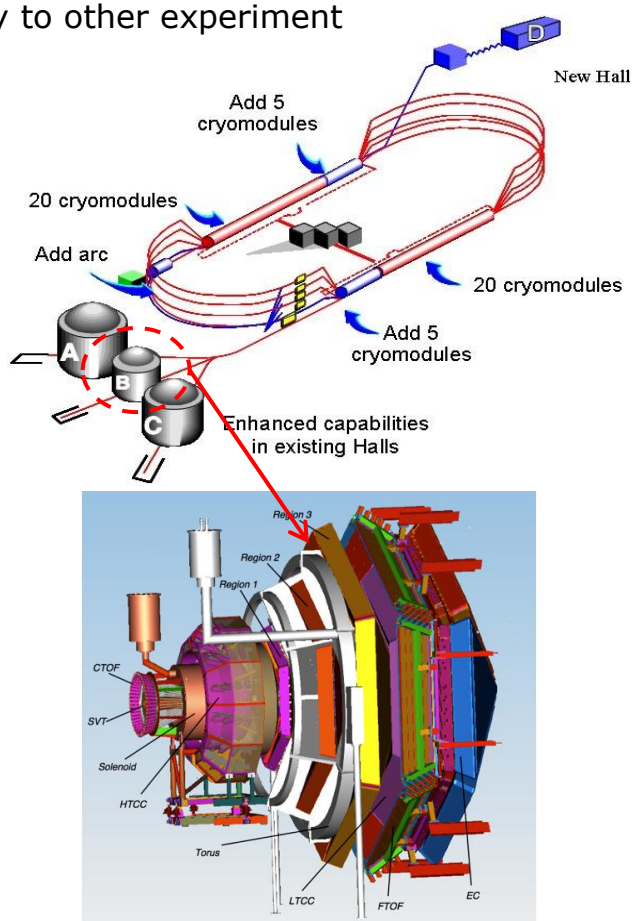
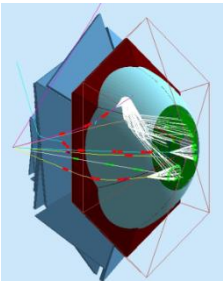
TMD in the CLAS12 era

12 GeV CEBAF will explore a kinematical region complementary to other experiment



Valence region will be highly explored @CLAS





CLAS12 detector with

1. RICH for π/k separation in the 3-8 GeV momentum range
2. HD-ice target

In the future: transversely polarized term

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

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

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

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

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

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

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

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

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 $\rightarrow A_{LT}^{cos(\varphi-\varphi_S)} \propto g_{1T} \otimes D_1$

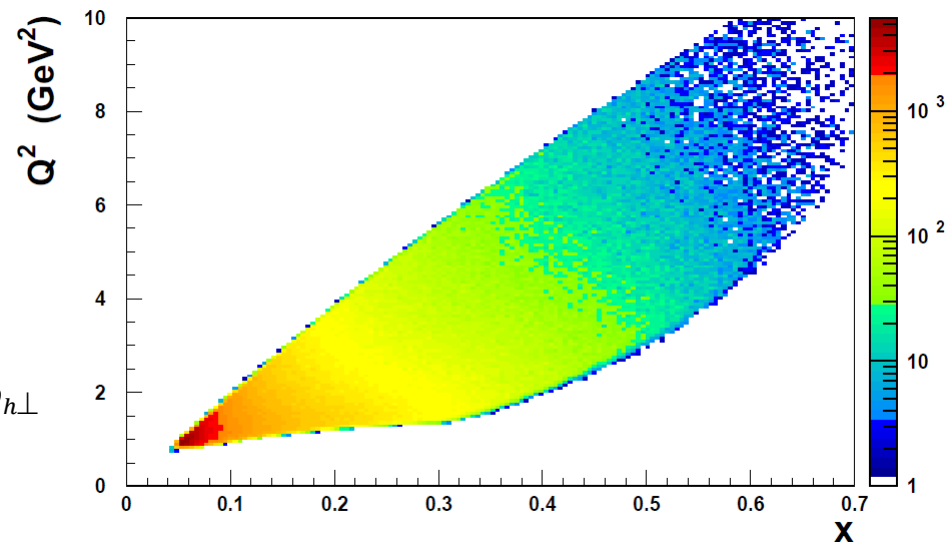
TMD in the CLAS12 era - 2

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**.

Phase-space explored by CLAS12



The RICH subdetector will allow measurements involving kaons

- ✓ 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.

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

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Collins@CLAS12

Collins effect: it is due to the correlation among quark tranverse polarization and the tranverse momentum of the final hadron

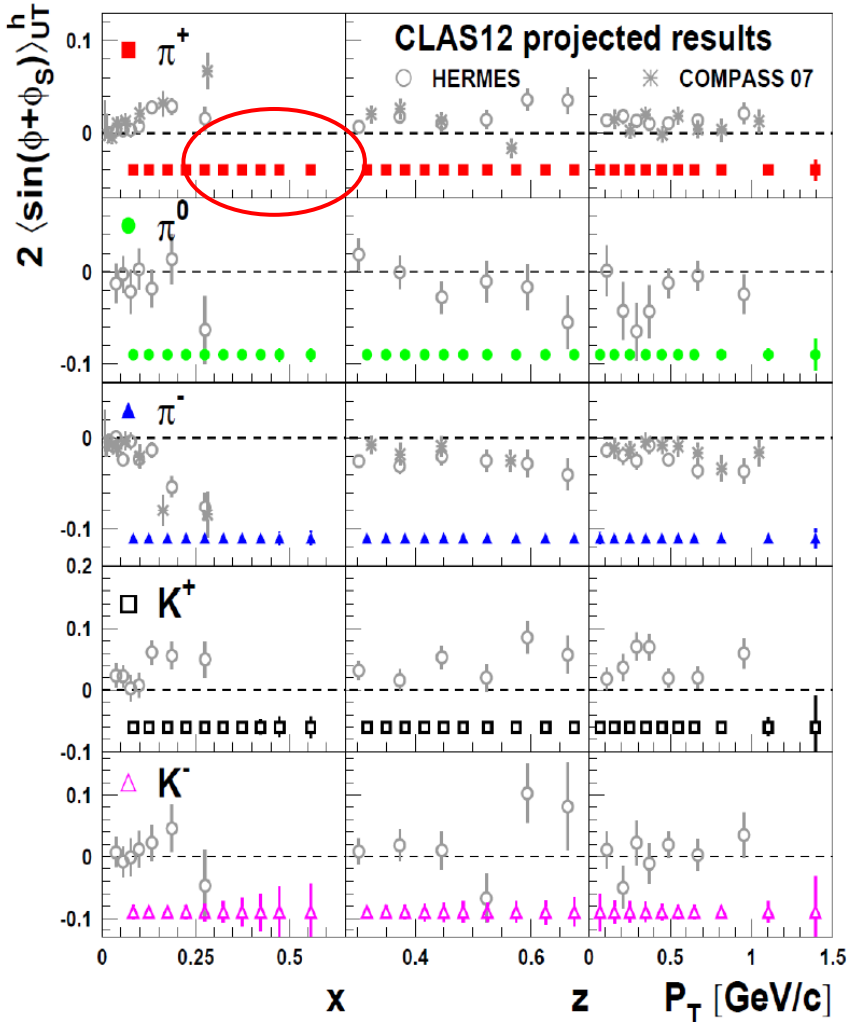
- It appears as an azimuthal asymmetry in the direction of the final hadron
- Effects already observed @HERMES & COMPASS
- Gives access to transversity

$$A_{UT}^{\sin(\varphi+\varphi_S)} \propto h_1 \otimes H_{1T}$$

With CLAS12:

- large statistics on the high-x region, important to constraint the tensor charge
- high resolution and broad range in p_t to test the transition from perturbative to non-perturbative regime

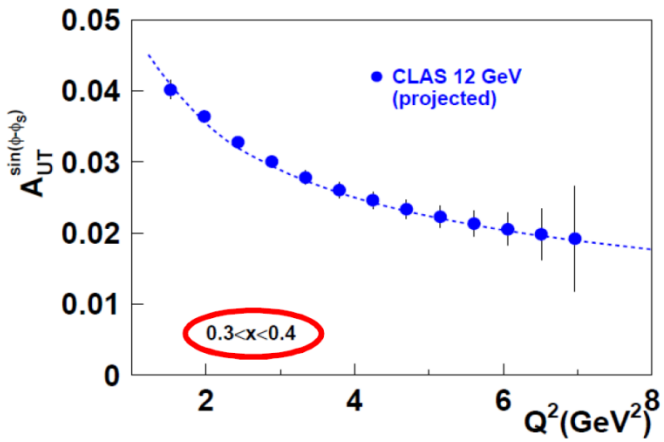
Projections for L = 5 · 10^{33} cm^{-2} s^{-1}, HD-ice target with a H polarization ~ 60%, f~1/3, RICH detector



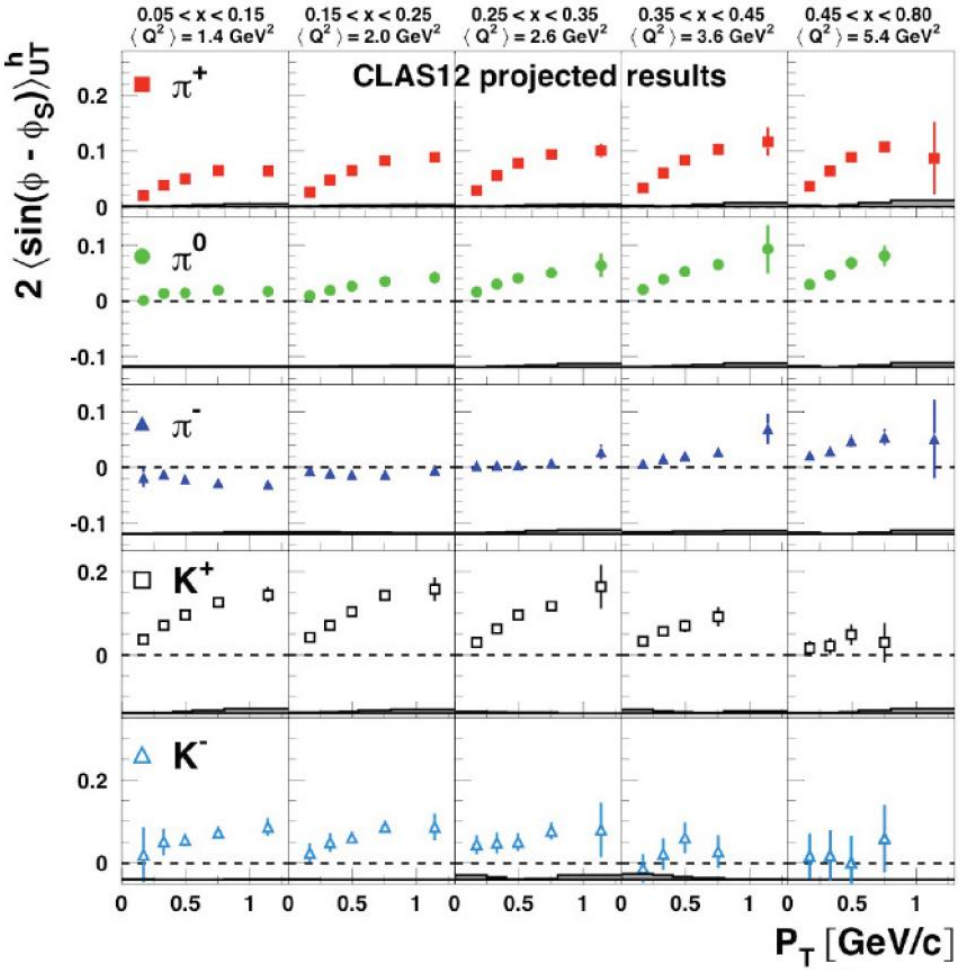
Sivers@CLAS12

Sivers effect: it is due to the correlation among quark tranverse momentum and nucleon tranverse polarization

- It appears as an azimuthal asymmetry in the direction of the final hadron
- It implies the presence of an **angular momentum**
- Gives access to the Sivers function $f_{1T}^{\perp} \rightarrow A_{UT}^{\sin(\varphi-\varphi_S)} \propto f_{1T}^{\perp} \otimes D_1$



Q^2-dependence of Sivers asymmetry → test of the TMD evolution



Projections for L = 5 · 10^{33} cm^{-2} s^{-1}, HD-ice target with a H polarization ~ 60%, f~1/3, RICH detector

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	11	80			
		L/T separation	8.8	20	20		
			6.6	20	20		
E12-06-119b	Sabatie	DVCS pol. target	11	120	120	175	Assume polarized experiments run 50% of time w/ reversed field
E12-06-109	Kuhn	Long. Spin Str.	11	82	50		
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	82	007/008 need 26d reversed field
PR-09-007(a)	Hafidi	Partonic SIDIS	11	56	26		
PR-09-008	Contalbrigo	Boer-Mulders w/ Kaons	11	56			
Total				**1139**		**517**	

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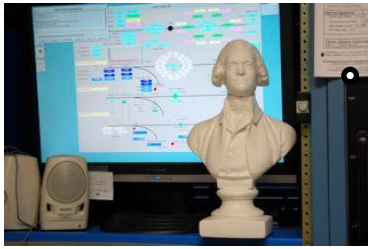
Conclusions

- 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, CLAS@Hall-B performed important measurements related to the **unpolarized** and to the **longitudinal** part of the cross-section, providing information for the structure function behaviour in the **valence region**
- In the 12 GeV era, the upgraded CLAS12 will wide the explored kinematical range for the **understanding of the nucleon spin structure**
- 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** (transition between perturbative and non-perturbative regime)



(President Thomas Jefferson in the Hall-B Counting Room)

A lot of hadrons ahead!

backup

Unpolarized contribution

In the unpolarized term of the cross-section, two structure functions appear:

- $F_{UU}^{\cos(2\varphi)}$ leading twist

$$d\sigma_{UU}^{Cos2\phi} \propto \cos 2\phi \cdot \sum_q e_q^2 I\left[\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}\boxed{h_1^{\perp}H_1^{\perp q}}\right]$$

Boer-Mulders

- $F_{UU}^{\cos(\varphi)}$ sub-leading twist

Cahn effect

$$d\sigma_{UU}^{Cos\phi} \propto \cos\phi \cdot \sum_q e_q^2 \frac{2M}{Q} I\left[-\frac{(\hat{P}_{h\perp}\cdot\vec{p}_T)}{M_h}x\boxed{h_1^{\perp}H_1^{\perp q}}-\frac{(\hat{P}_{h\perp}\cdot\vec{k}_T)}{M}x\boxed{f_1D_1+\ldots}\right]$$

$$\begin{aligned}
\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ & \boxed{\begin{aligned}&\left[F_{UU,T}+\epsilon F_{UU,L}\right.\\ &\left.+\sqrt{2\epsilon(1+\epsilon)}\cos(\phi)F_{UU}^{\cos(\phi)}+\epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right]\end{aligned}}\\
+\ \lambda_l & \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{LU}^{\sin(\phi)}\right]\\
+\ S_L & \left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi)F_{UL}^{\sin(\phi)}+\epsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]\\
+\ S_L\ \lambda_l & \left[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\right]\\
+\ S_T & \left[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right)\right.\\
& +\epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)}+\epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\\
& +\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)}\\
& \left.+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\right]\\
+\ S_T\ \lambda_l & \left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right.\\
& +\sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)}\\
& \left.+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\}
\end{aligned}$$

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

q/H	U	L	T
U	D_1		$H_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$H_1^{\perp}$	G_{1T}	$H_1, H_{1T}^{\perp}$

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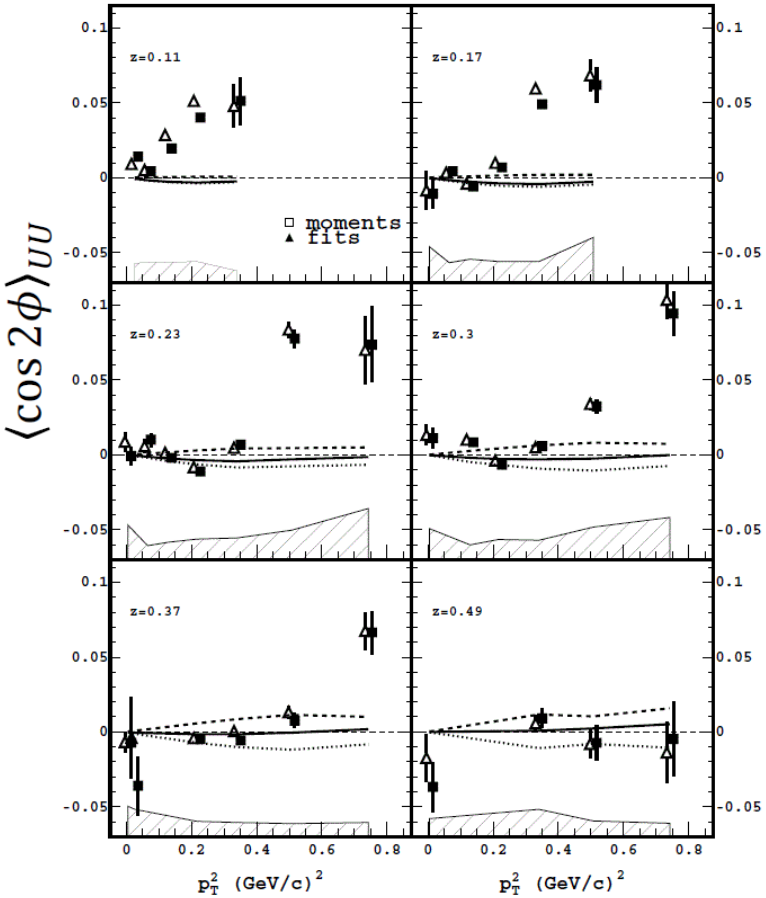
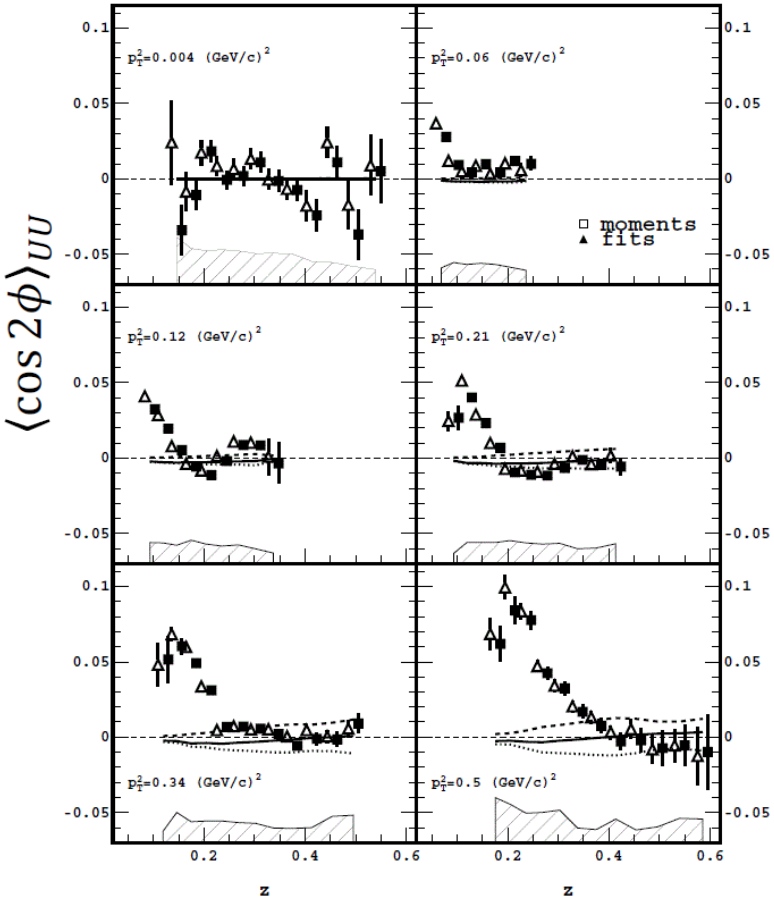
Boer-Mulders effect

$$\langle \cos 2\phi \rangle_{UU} \propto h_1^{\perp} \otimes H_1^{\perp q}$$

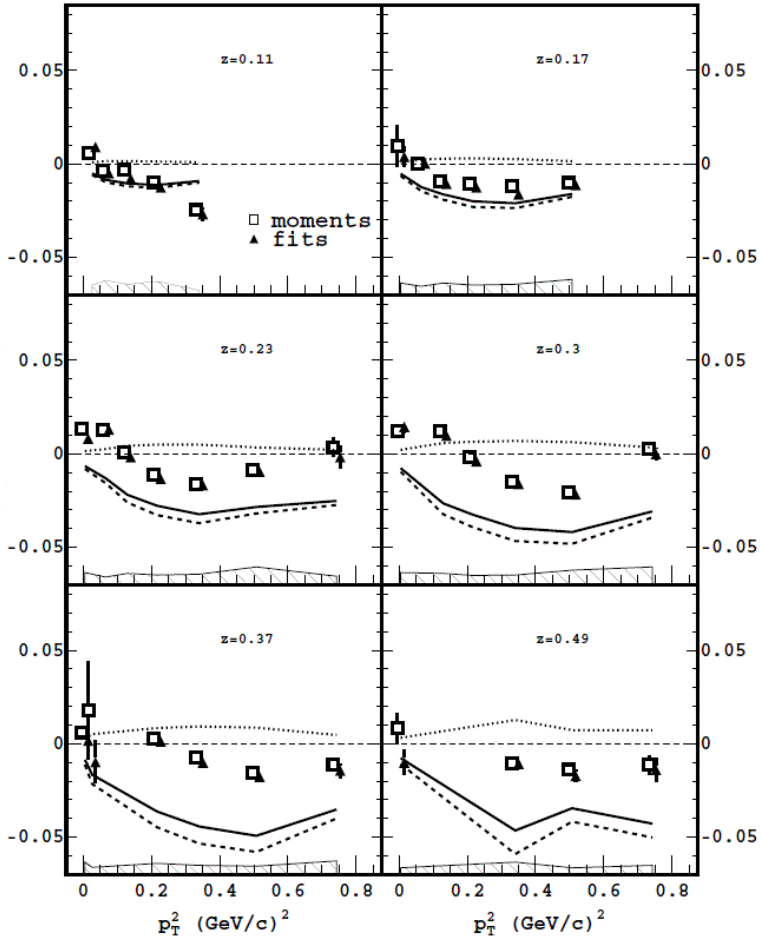


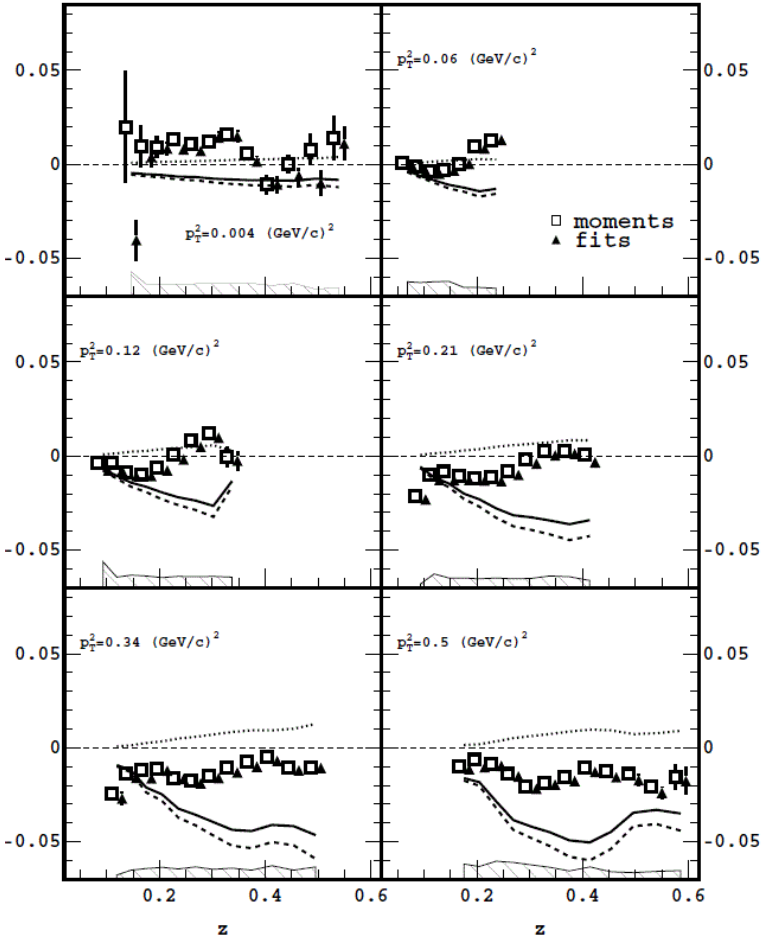


1. Positive amplitudes in the *low-z, high-p_T regions*, zero elsewhere
2. Theoretical predictions expect zero amplitudes → consistent with data but for *low-z, high-p_T regions*

Boer-Mulders + Cahn effect

$$\langle \cos\phi \rangle_{UU} \propto h_1^{\perp} \otimes H_1^{\perp q} + f_1 \otimes D_1$$





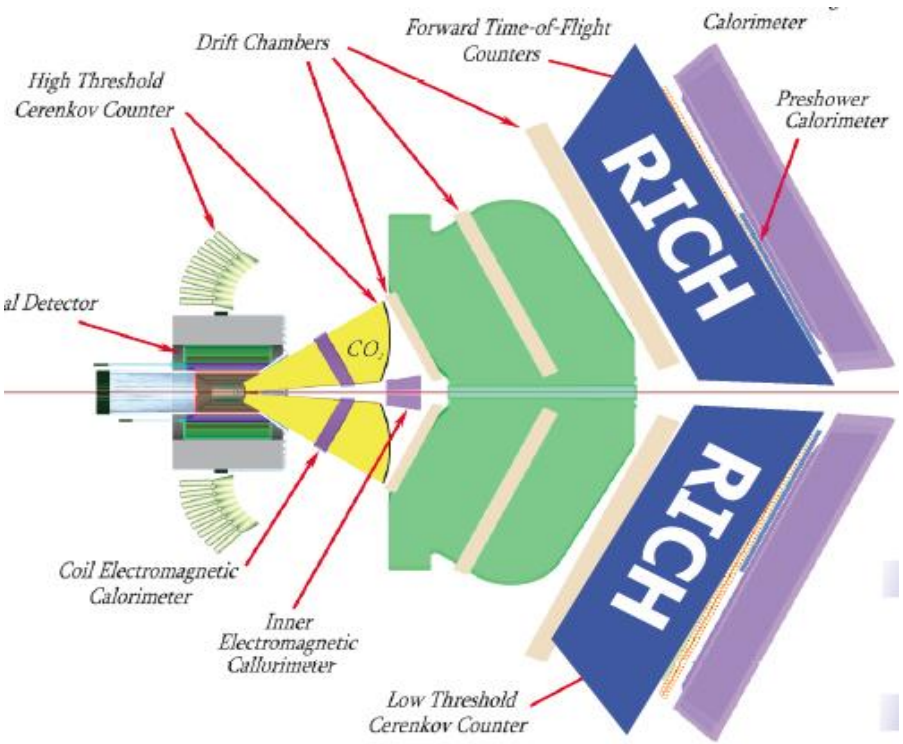
1. Non-zero amplitudes
2. Sign change in the *high-p_T regions*
3. Theoretical predictions show same behaviours but larger amplitudes

clas12

CLAS12 is an ideal environment to study dihadron processes. Its large acceptance will allows the simultaneous detection of the scattered electrons and of the hadrons from the hadronization of the struck quarks.

PID in the forward region relies in the

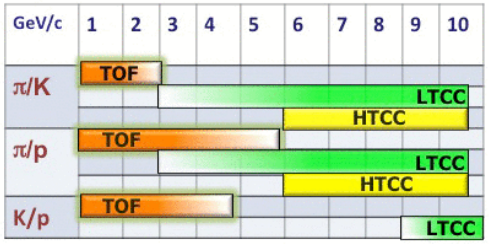
- High-Threshold Cherenkov Counter
- Low-Threshold Cherenkov Counter
- Forward Time-Of-Flight system



BUT

- For momenta in the range 2.5−5 GeV/c the π/K separation relies only on the LTCC performance.
- In the 4.7−8 GeV/c momentum region it is not possible to separate protons from kaons.

A RICH detector is under development for CLAS12 to take the place of LTCC in SIDIS analysis.

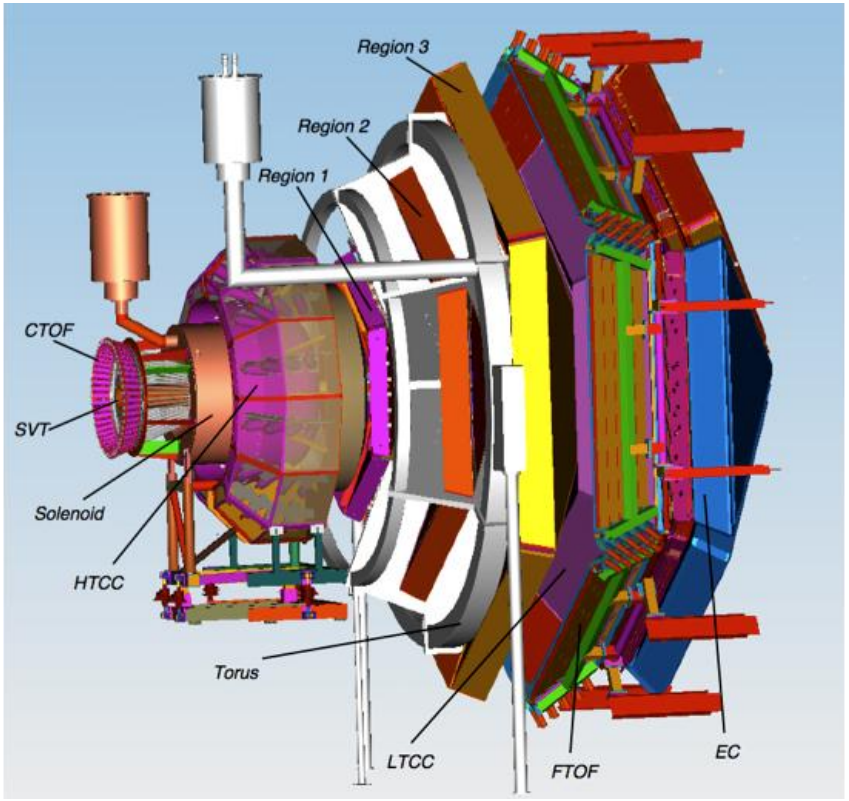


clas12

CLAS12 will be composed of a **forward detector** and a **central detector**

Forward Detector

- Torus Magnet
- Forward Tracker
- High-Threshold Cherenkov Counter
- Low-Threshold Cherenkov Counter
- Forward Time-Of-Flight system
- Preshower Calorimeter
- Electromagnetic Calorimeter
- Inner e.m. Calorimeter



Central Detector

- SOLENOID Magnet
- Barrel Silicon Tracker
- Central TOF

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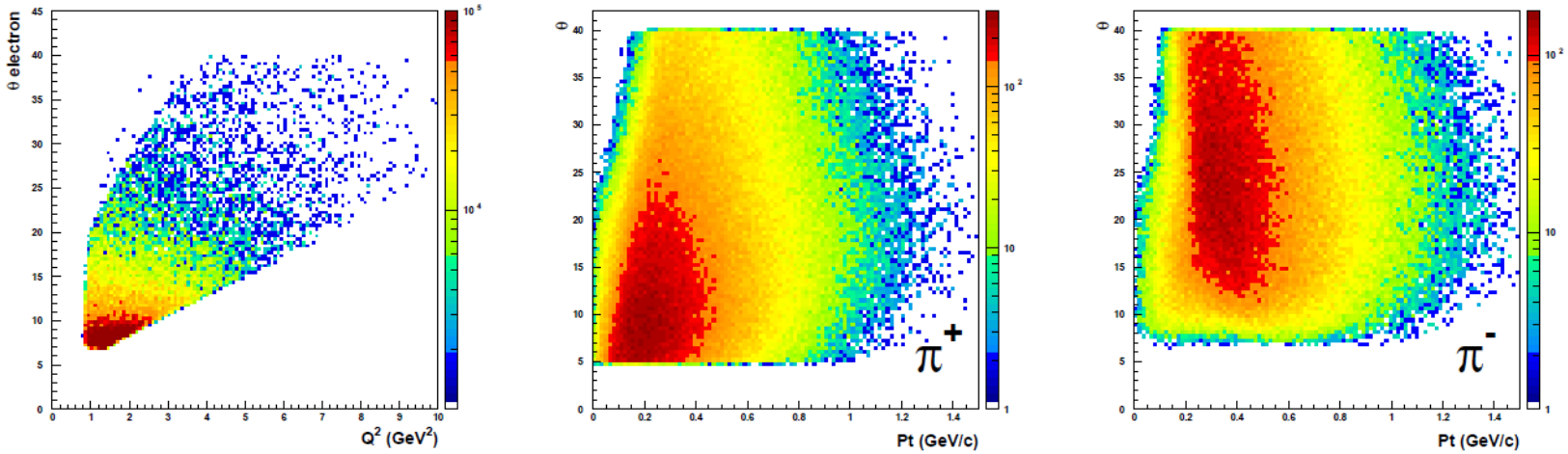
clas12 kinematics & sistematics



Error source	Systematic error (%)
H/D background	4
Target polarization P_T	5
acceptance corrections	4
Al background contribution	3
ρ^0 contamination	3
Radiative corrections	2
Total	~ 9

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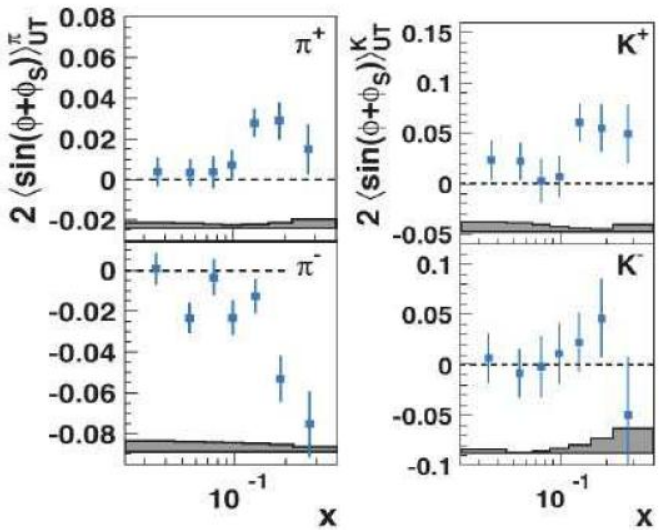
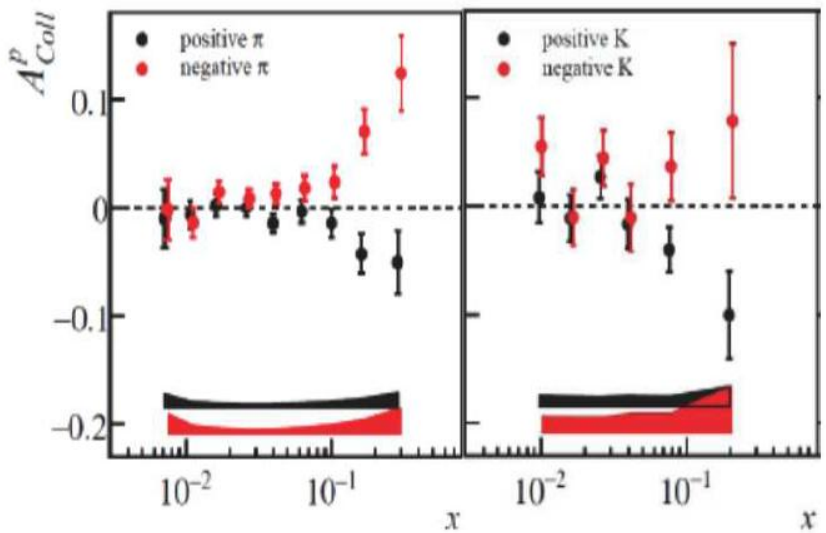
Collins@HERMES & COMPASS

HERMES data



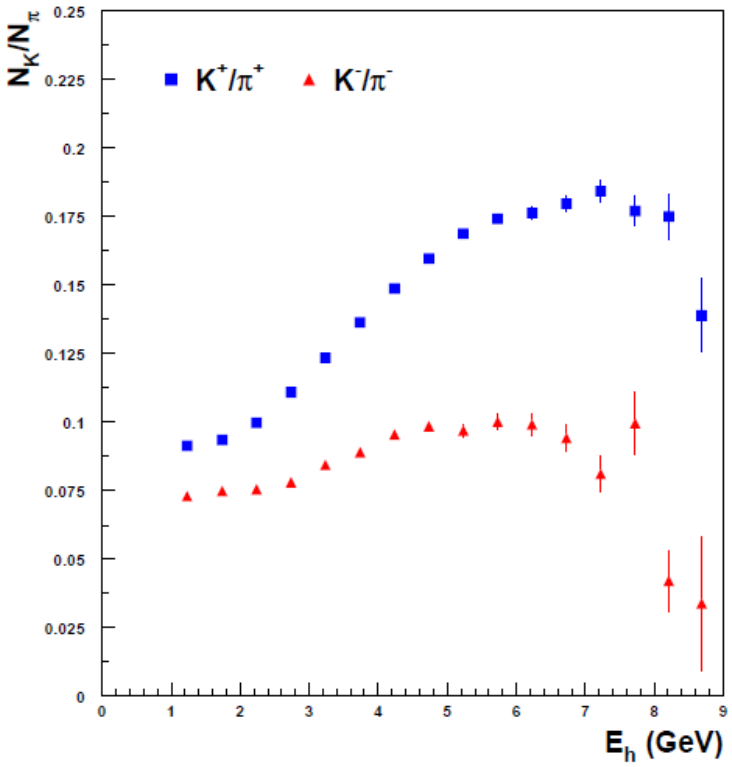
A. Airapetian et al., Phys. Lett. B 693, 11 (2010).

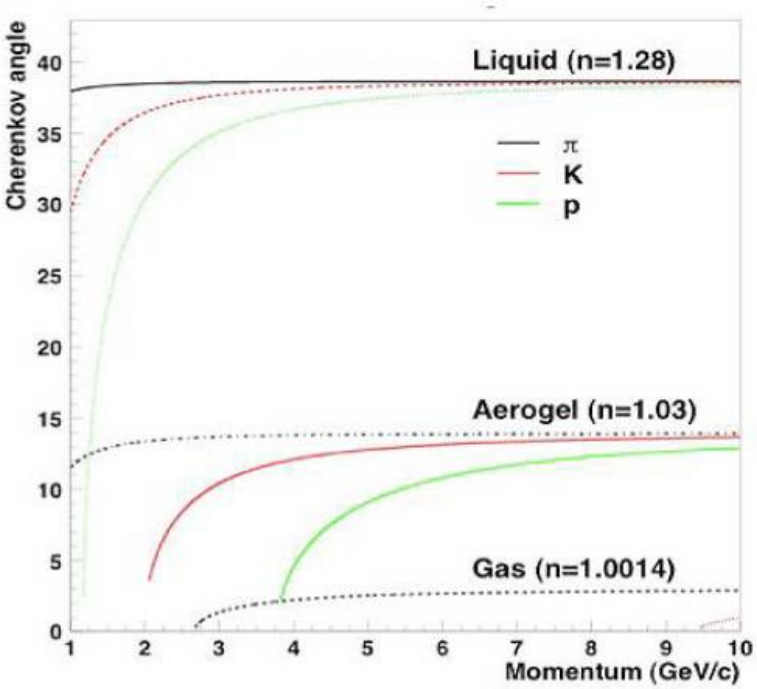
COMPASS data



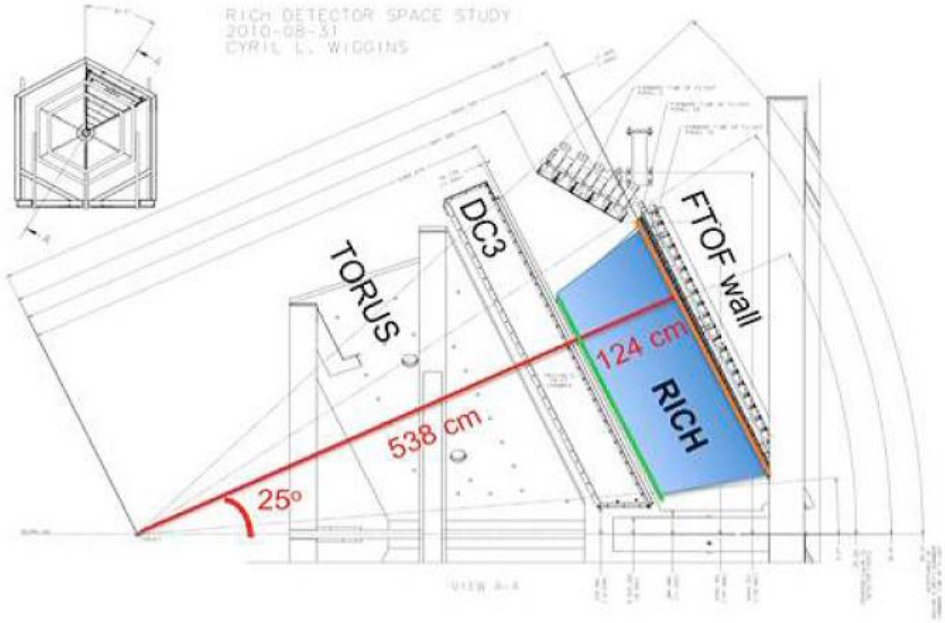
C.f.C. Schill (2011), DIS 2011 Conference.

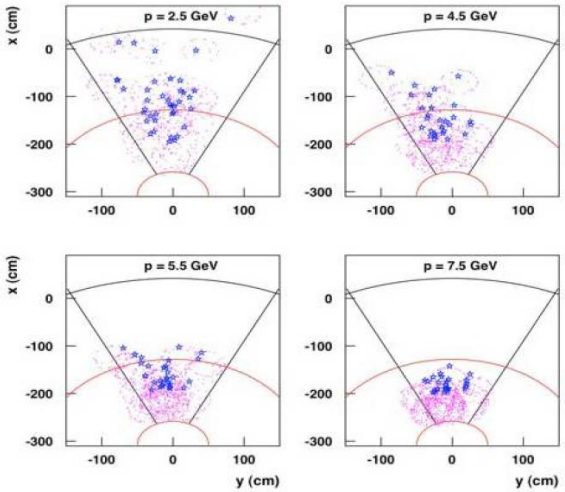
RICH – π/k ratio and aerogel

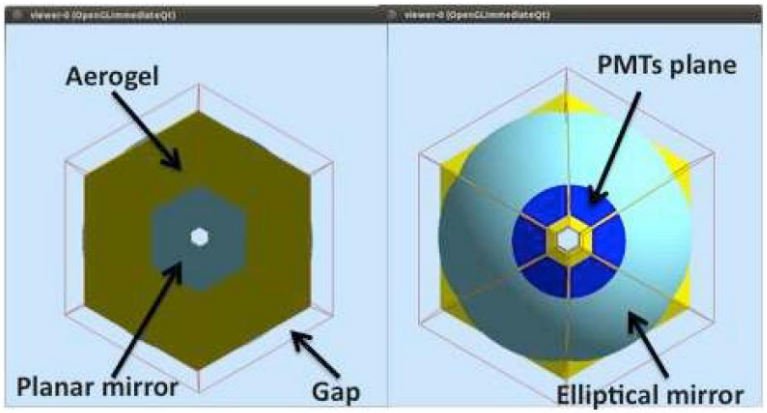




RICH – positioning& angular distributions







CLAS12 initial science program

Physics Focus	Approved Experiments	Letters Of Intent Supported
GPD & Exclusive Processes	3	1
SIDIS & TMD	4	4
PDF & DIS	2	1
Elastic & Resonances FF	2	
Hadronization & Color Transparency	2	
Baryon Spectroscopy		1
Total	13	7

CLAS12 represents the ideal environment to study the structure of the nucleon at high x_B.

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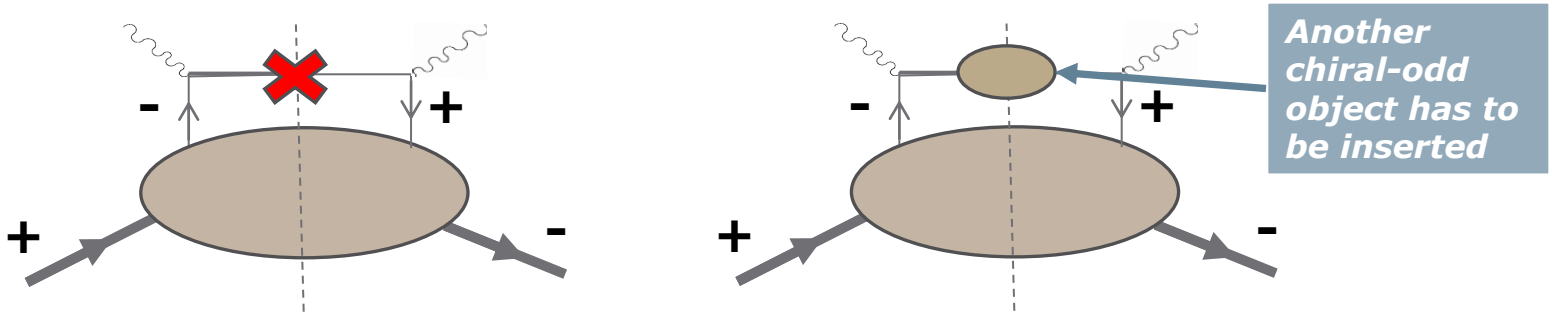
chirality

As a chiral-odd object, transverse polarization of quarks cannot be probed through the cleanest hard process, the DIS.



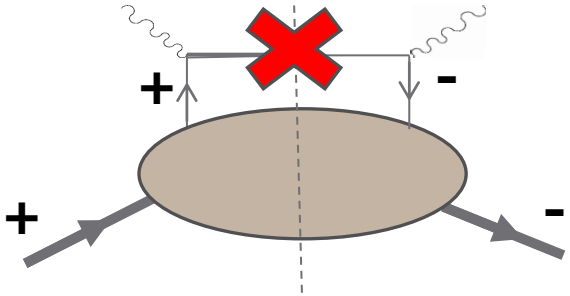
Odd-chiral nature of transversity

Helicity basis $|+\rangle, |-\rangle$

Transverse Spin basis $|\uparrow\rangle, |\downarrow\rangle$

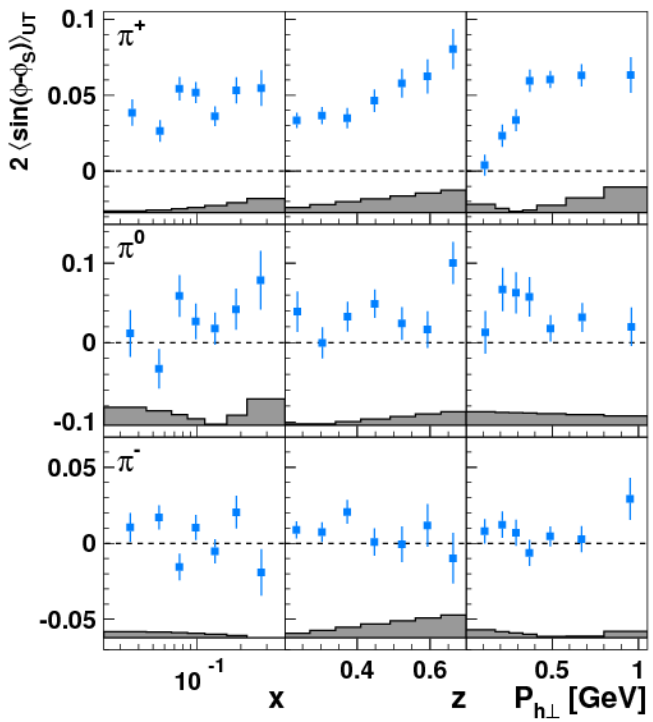
Tranversity in Helicity basis

$$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm i\,|-\rangle)$$



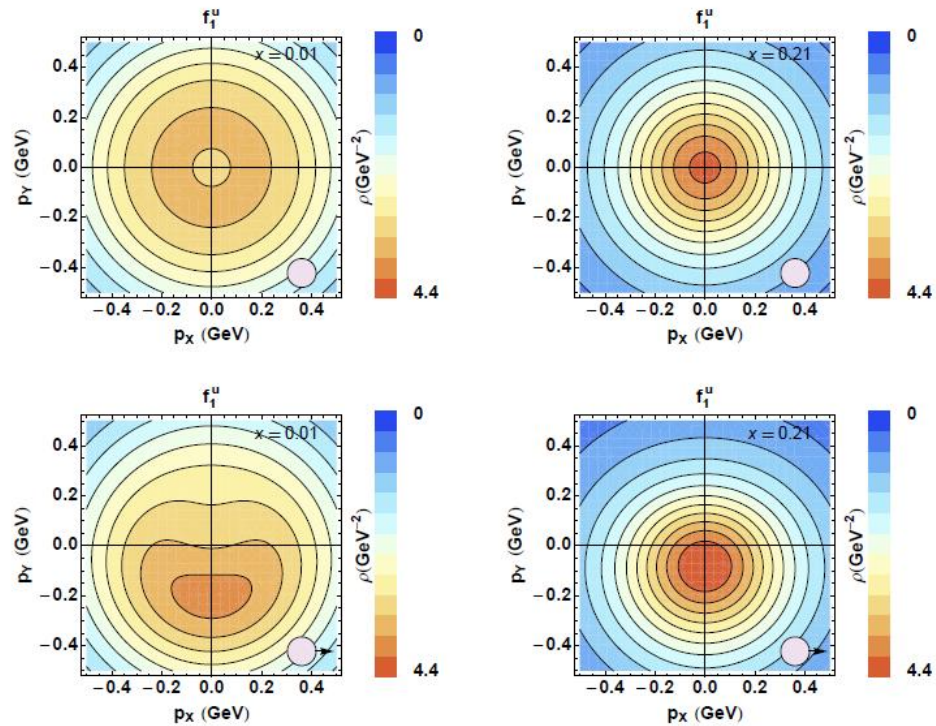
Sivers-like distorsion

HERMES data on the Sivers asymmetries°



°A. Airapetian, et al., *Phys. Rev. Lett.* 103, 152002 (2009)

a non-zero Sivers function means that the distribution of quarks in transverse momentum is affected by the direction of the nucleon's spin



A. Bacchetta, Conti, Guagnelli, Radici, arXiv:1003:1328

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