Overview of HERMES results on longitudinal spin asymmetries

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(on behalf of the HERMES Collaboration)

24th International Spin Symposium
SPIIN2021
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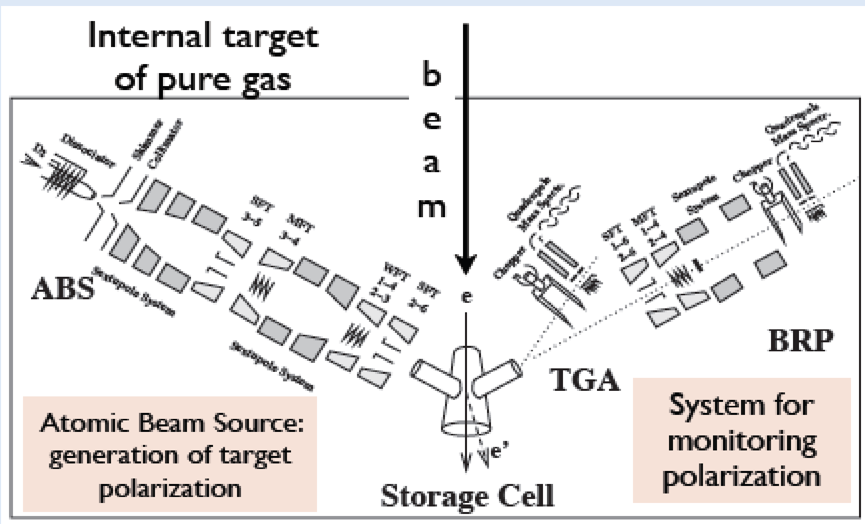
- The HERMES experiment.
- 3D picture of the nucleon:
  - A_{LL} asymmetry in semi-inclusive DIS,
  - A_{LU} asymmetry in semi-inclusive DIS.
- Summary

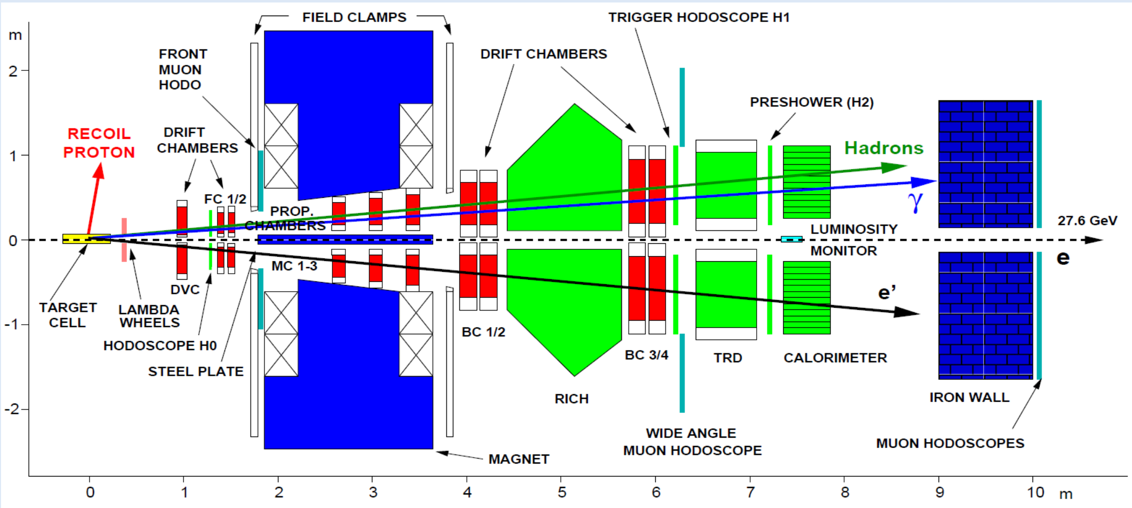
HERMES at DESY

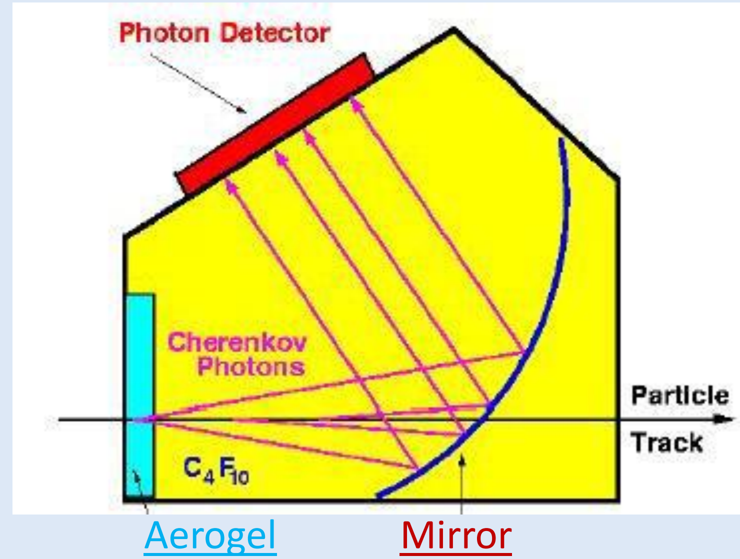
Self-polarized e^+ and e^- beams
27.6 GeV
Helicity switched every few months

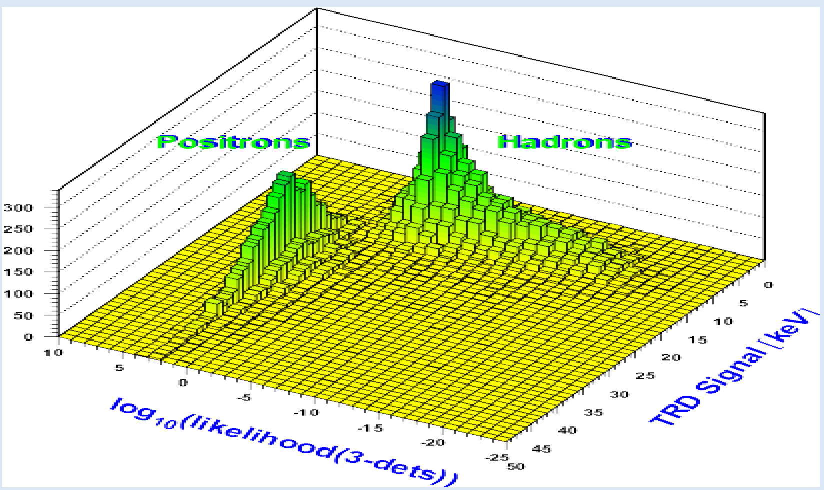


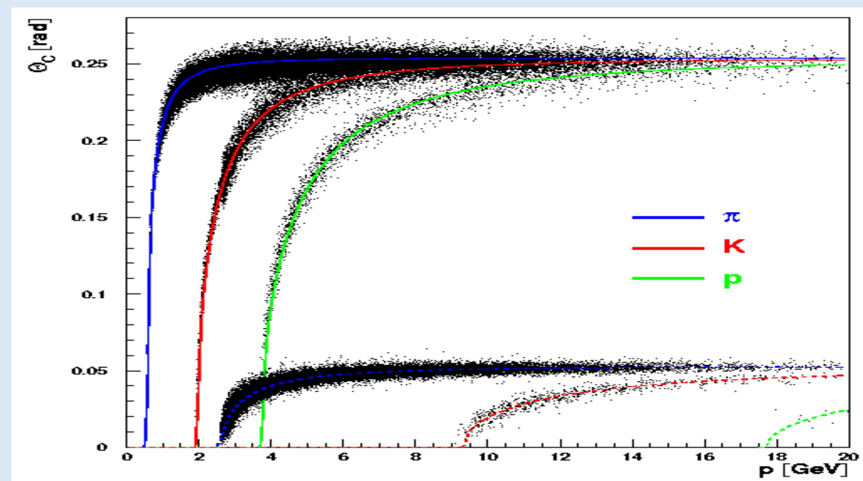
Polarized hydrogen (Long.,Trans.), deuterium (Long.)
Polarization flipped at 60-180 s time interval
Unpolarized *H,D,He,N,Ne,Kr,Xe*

The HERMES Spectrometer





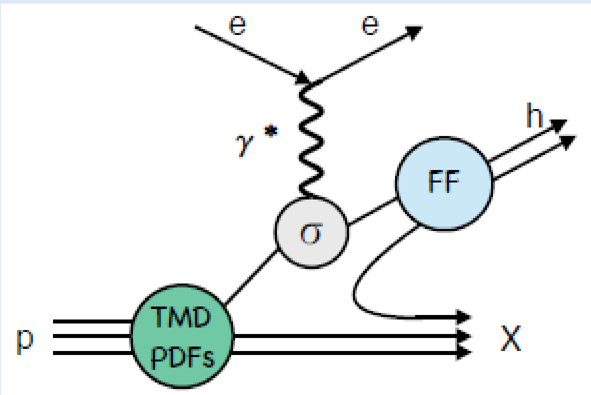


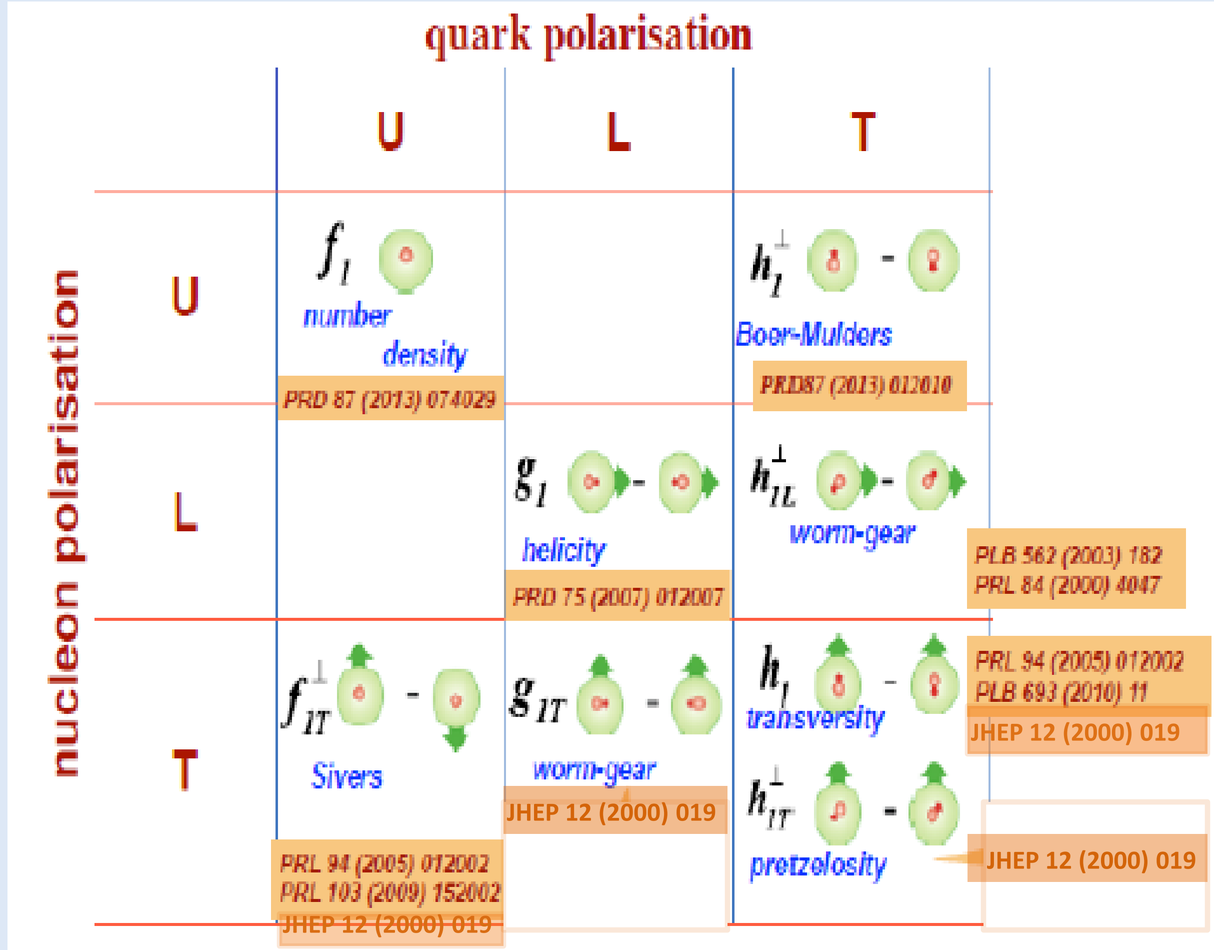


- PID: RICH, TRD, Preshower and Calorimeter; lepton-hadron > 98%
- Momentum resolution of charged particles: $\delta P/P \simeq 1.5\%$

Hrachya Marukyan, 18.10.2021, SPIN2021, Matsue, Japan

Semi-inclusive DIS processes (SIDIS)



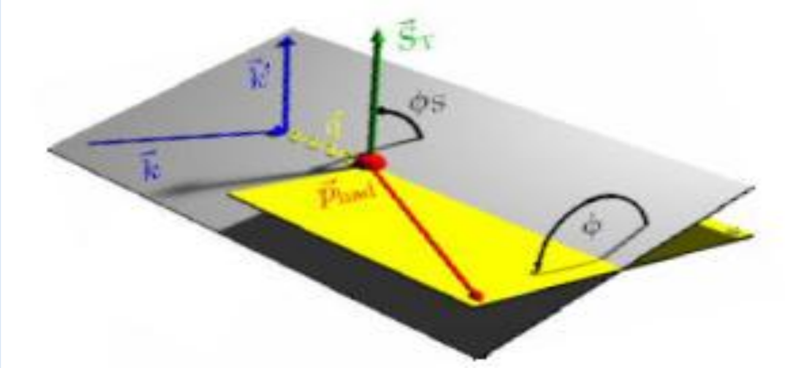


<u>SIDIS processes</u>:

- Describe spin-orbit correlation: correlations between the hadron transverse momentum and quark or nucleon spin
- Sensitive to quark orbital angular momentum

The SIDIS cross-section

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



$F_{XY,Z} \propto \mathrm{PDF} \otimes \mathrm{FF}$

X=beam, Y=target,

Z=γ^*polarization

TMD PDFs

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

FFs

		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$

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$$\begin{aligned}
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& + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{\mathrm{UT}}^{\sin(\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big] \\
+ S_T\,\lambda_l \; & \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} \\
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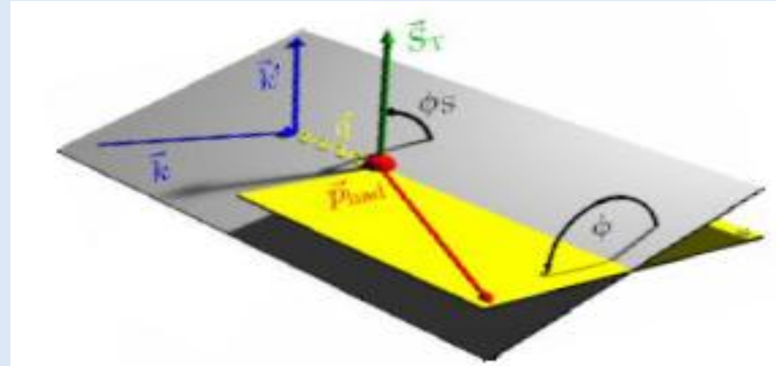
\end{aligned}$$



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nucleon	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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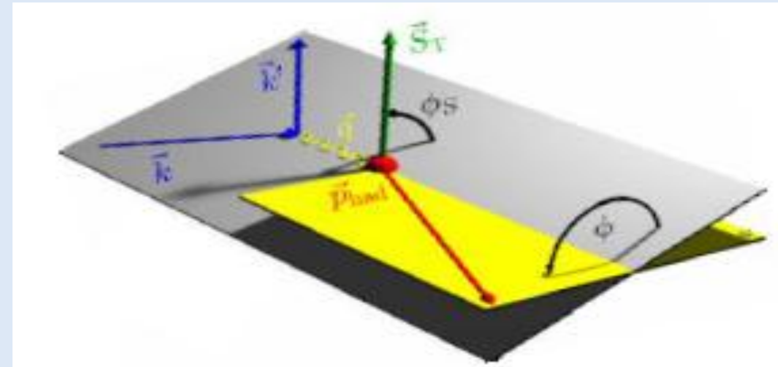
$$+ \lambda_l \left[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi)F_{\mathrm{LU}}^{\sin(\phi)}\right]$$

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

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

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

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



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nucleon	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

FFs

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A_{LL} in semi-inclusive DIS

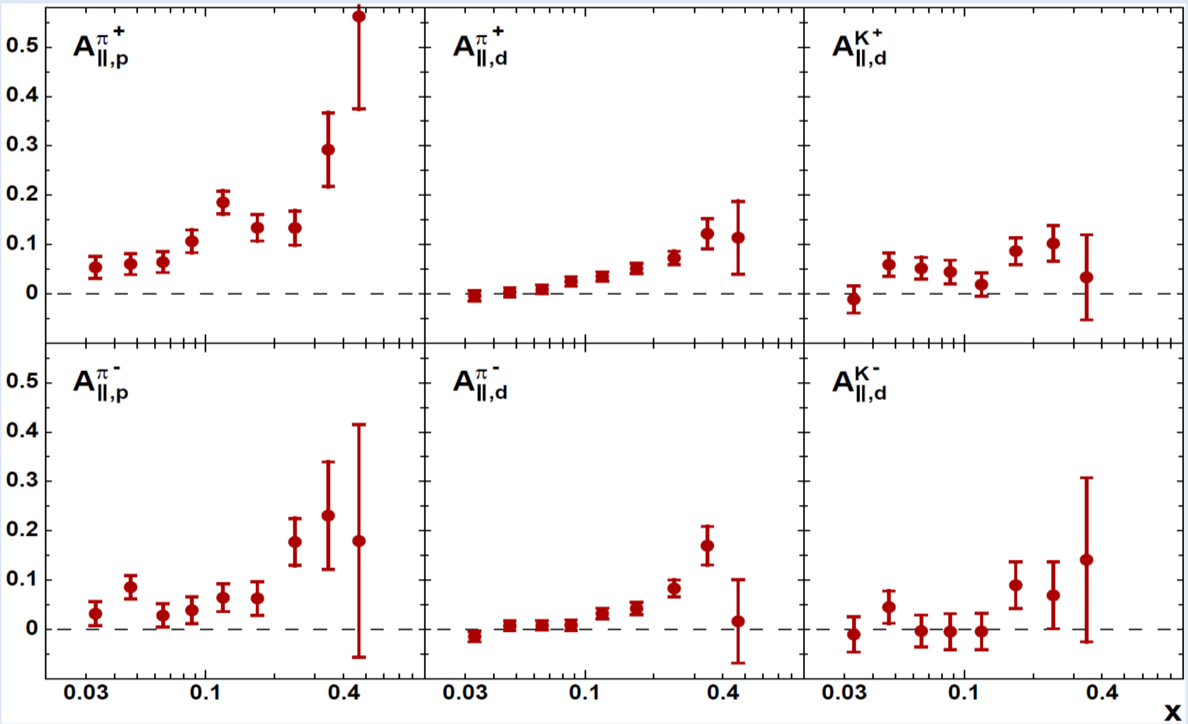
- Longitudinally polarized e^+/e^- beam
- Longitudinally polarized H & D targets

The longitudinal double-spin asymmetries $A^{h}_{\|,N}$

Refined studies $\Longrightarrow$ extend the results published in PRD 71 (2005) 012003

$$A_{\|}^{h} \equiv \frac{C_{\varphi}^{h}}{f_D}\left[\frac{L_{\substack{\rightarrow\\ \rightarrow}} N^{h}_{\substack{\rightarrow\\ \leftarrow}} - L_{\substack{\rightarrow\\ \leftarrow}} N^{h}_{\substack{\rightarrow\\ \rightarrow}}}{L_{\substack{\rightarrow\\ \rightarrow}} N^{h}_{\substack{\rightarrow\\ \leftarrow}} + L_{\substack{\rightarrow\\ \leftarrow}} N^{h}_{\substack{\rightarrow\\ \rightarrow}}}\right]_{B}$$

Phys. Rev. D99 (2019) no.11, 112001



$$\sigma_{LL} \propto g_{1L}{}^{q} \otimes D_1{}^{q\to h}$$

- The x dependence of the asymmetries were found to be essentially identical to those in prior HERMES analyses (A. Airapetian et al. Phys.Rev.D71 012003 (2005))
- A low-Q^2 bin was added, spanning 0.5 to 1 GeV^2 , to allow for a better control of migration of events in the unfolding procedure

The longitudinal double-spin asymmetries $A^{h}_{\parallel,N}$

$$A^{h}_{\parallel} \equiv \frac{C^{h}_{\varphi}}{f_D}\left[\frac{L_{\substack{\rightarrow\\ \rightarrow}} N^{h}_{\substack{\rightarrow\\ \leftarrow}} - L_{\substack{\rightarrow\\ \leftarrow}} N^{h}_{\substack{\rightarrow\\ \rightarrow}}}{L_{\substack{\rightarrow\\ \rightarrow}} N^{h}_{\substack{\rightarrow\\ \leftarrow}} + L_{\substack{\rightarrow\\ \leftarrow}} N^{h}_{\substack{\rightarrow\\ \rightarrow}}}\right]_B$$

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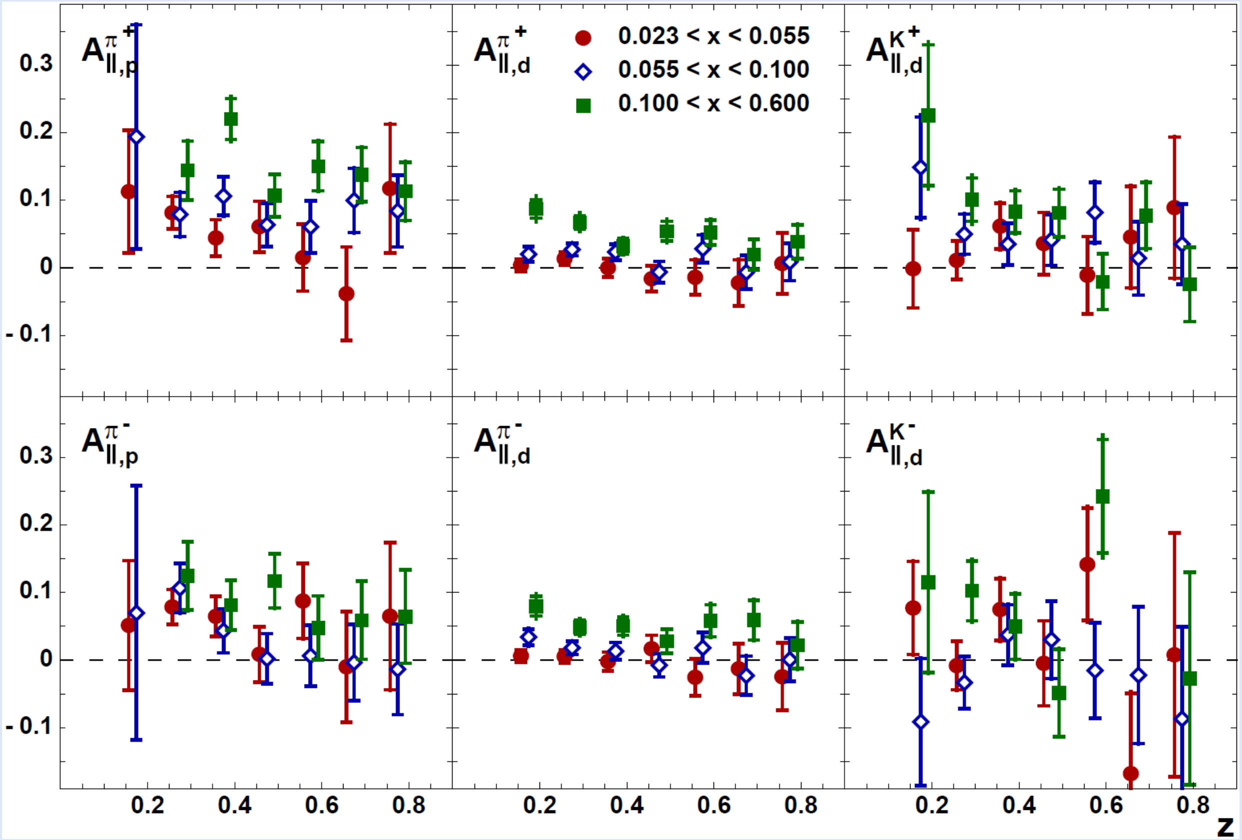
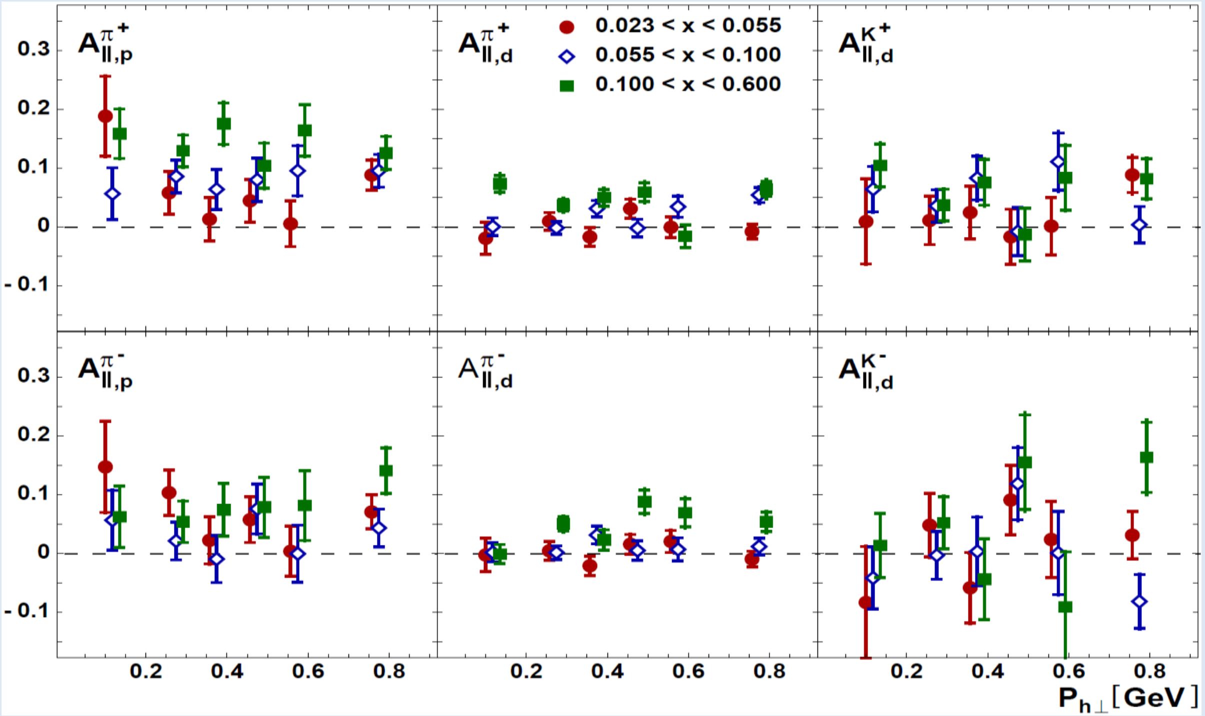


- No strong dependence on z is visible
- Agreement with COMPASS results for $h^{\pm}$ production from longitudinally polarized deuterons

The longitudinal double-spin asymmetries $A^{h}_{\parallel,N}$

$$A^{h}_{\parallel} \equiv \frac{C^{h}_{\varphi}}{f_D}\left[\frac{L_{\underset{\rightarrow}{\rightarrow}} N^{h}_{\underset{\leftarrow}{\rightarrow}} - L_{\underset{\leftarrow}{\rightarrow}} N^{h}_{\underset{\rightarrow}{\rightarrow}}}{L_{\underset{\rightarrow}{\rightarrow}} N^{h}_{\underset{\leftarrow}{\rightarrow}} + L_{\underset{\leftarrow}{\rightarrow}} N^{h}_{\underset{\rightarrow}{\rightarrow}}}\right]_B$$

Phys. Rev. D99 (2019) no.11, 112001

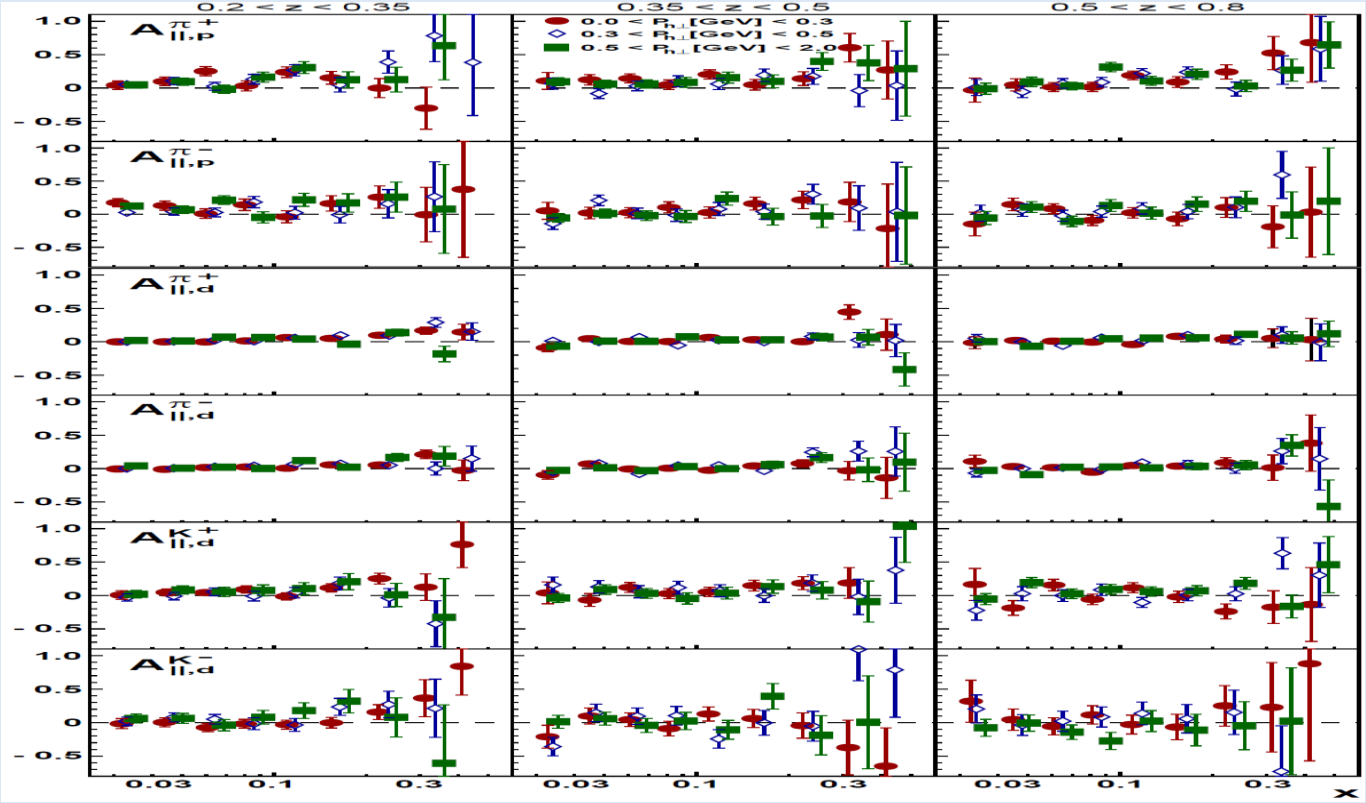


- No strong dependence on $P_{h\perp}$ is visible
- Consistent with weak dependence reported by CLAS (H. Avakian et al. Phys. Rev. Lett. 105 62002 (2010)) and COMPASS (Alekseev et al. Eur. Phys. J. C70, 39 (2010), C. Adolph et al. (2016), ArXiv: 1609.06062[hep-ex])

Hadron-tagged longitudinal double-spin asymmetry

Phys. Rev. D99 (2019) no.11, 112001

asymmetry binned simultaneously in x, z, and $P_{h\perp}$



- The asymmetry is binned in a grid with nine bins in x, three bins in $P_{h\perp}$, and three bins in z
- There is possibly an indication that the non-vanishing asymmetry for π^- from protons observed in the one-dimensional binning in x is caused to a large extent by low-z pions
- Three-dimensionally binned asymmetries are the most complete, unintegrated, longitudinally polarized double-spin dataset to date

Azimuthal moments of asymmetries

Azimuthal moments of asymmetries are potentially sensitive to unique combinations of distribution and fragmentation functions.

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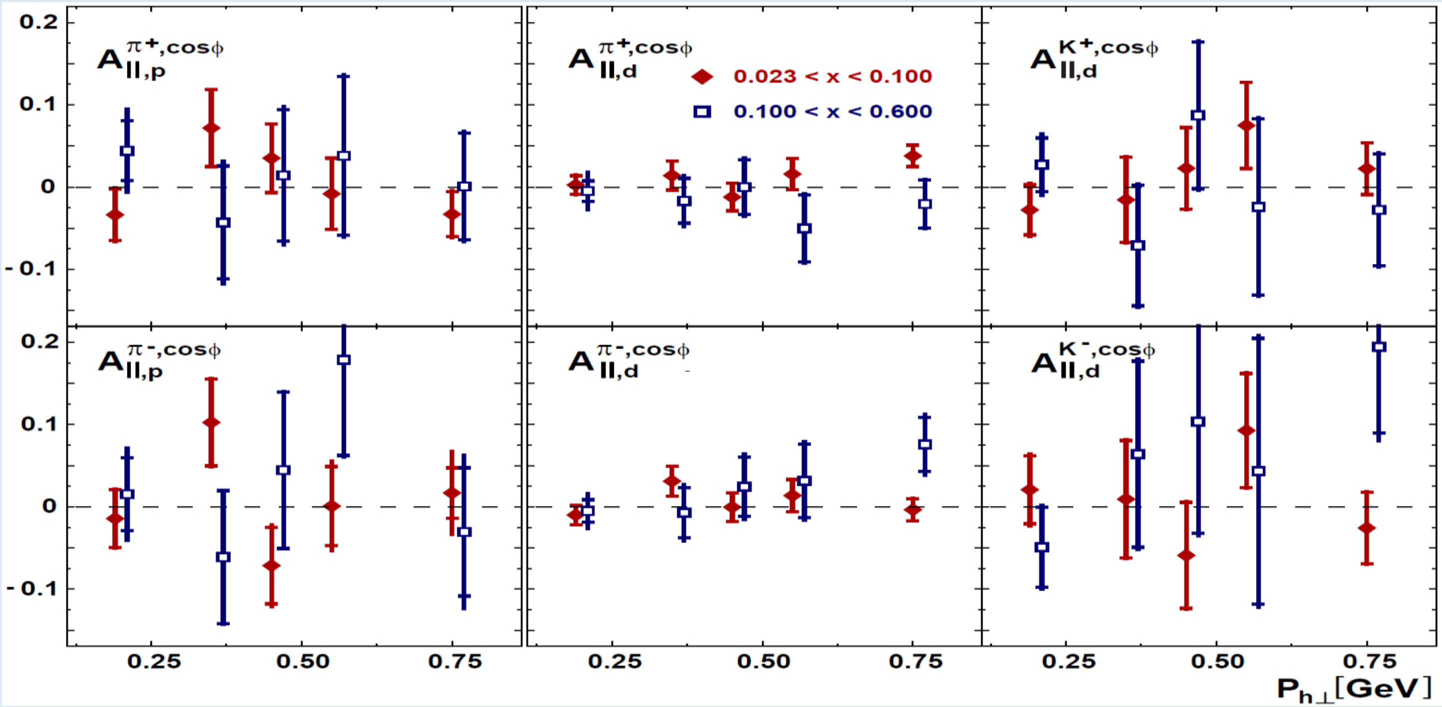
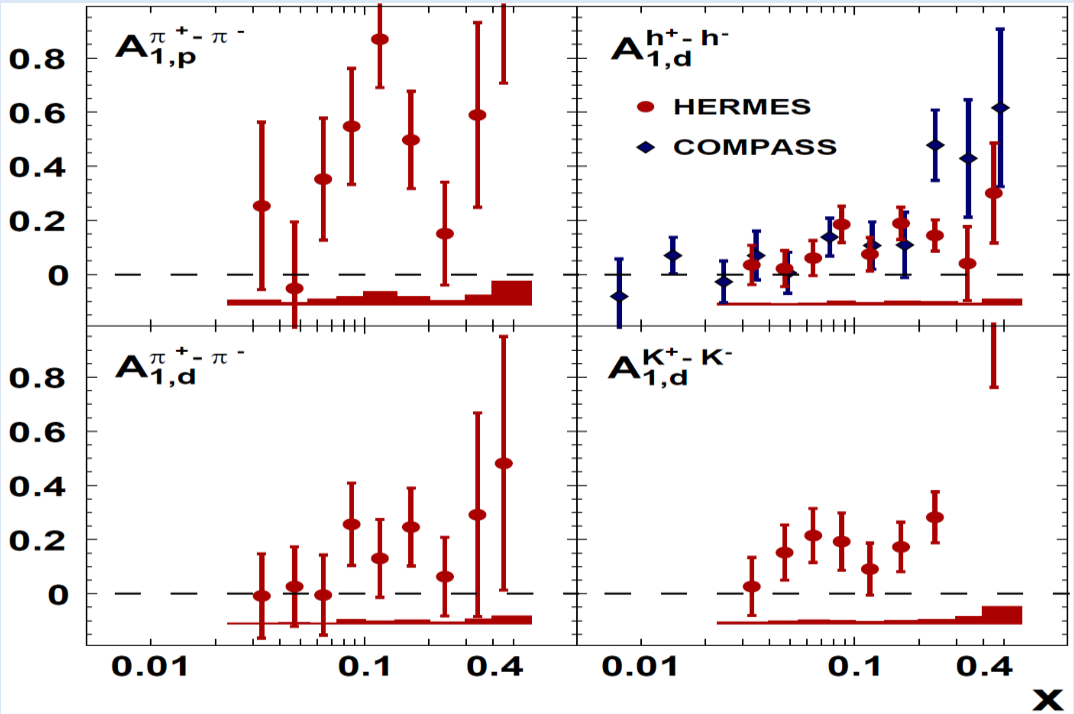


- The functional form used included constant, cos ϕ, and cos 2ϕ terms
- Each of these cosine moments is found to be consistent with zero. (A similar result was obtained for unidentified hadrons for deuteron data from the COMPASS experiment
- A vanishing cos 2ϕ asymmetry as found here can be expected: in the one-photon-exchange approximation there is no $A^{h,\cos 2\phi}_{LL}$ contribution to the cross section

Hadron charge-difference asymmetries

$$A_1^{h^+-h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$

Phys. Rev. D99 (2019) no.11, 112001



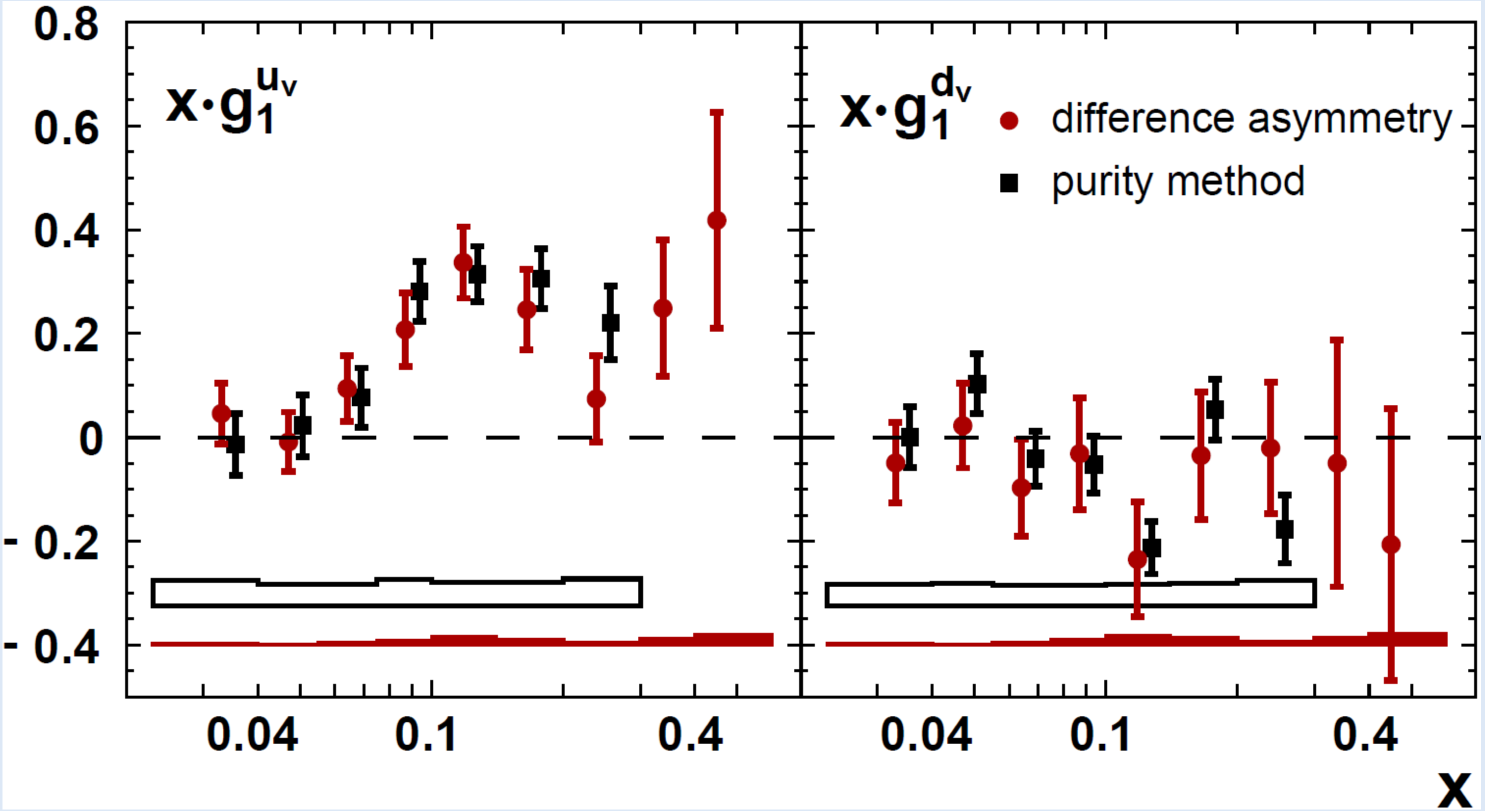
- Perhaps surprising feature: the uncertainties for the kaon asymmetry are considerably smaller than those on the pion asymmetry despite the smaller sample size
- This is a result of the larger difference between yields of charged kaons compared to that of the charged pions (as K⁻ shares no valence quarks with the target), which causes a significantly larger denominator in the asymmetry

Helicity distributions for valence quarks

$$D_1^{q\to h^+} = D_1^{\bar{q}\to h^-}$$

$$A_{1,d}^{h^+-h^-} \overset{LO,LT}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}$$

Phys. Rev. D99 (2019) no.11, 112001



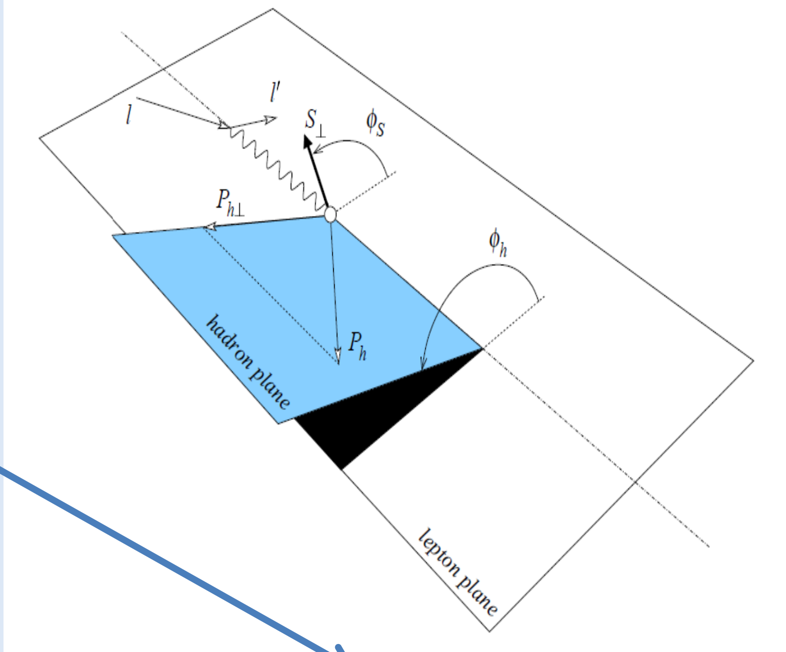
- Consistent results using two methods that have very different and quite complementary model assumptions: no significant deviation from the factorization hypothesis

A_{LU} in semi-inclusive DIS

- Longitudinally polarized e^+/e^- beam
- Unpolarized H & D targets

The SIDIS cross-section: A_{LU} amplitudes

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,\boxed{F_{LU}^{\sin\phi_h}} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad+|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$



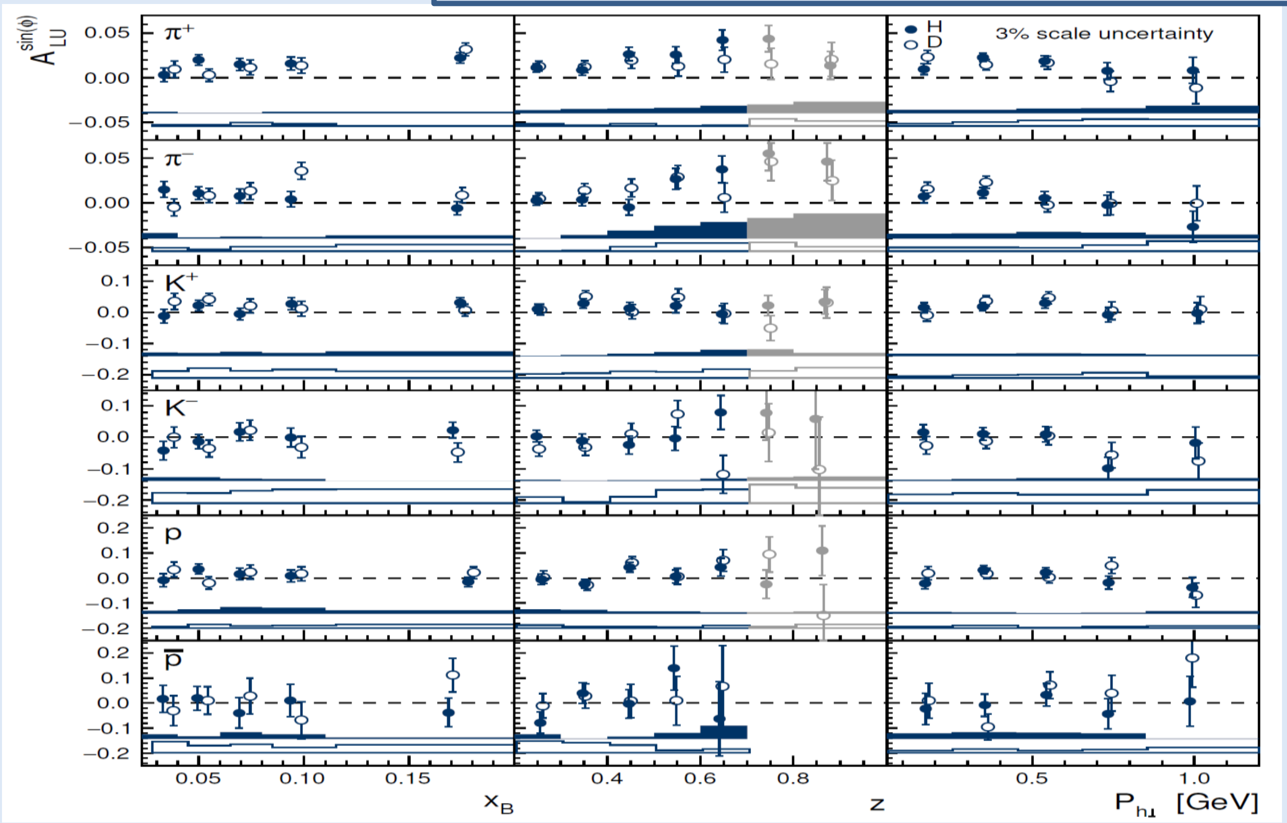
In case of longitudinal beam (L)
and unpolarized target (U)
only subleading-twist terms
can contribute to the asymmetry.
The structure function of interest :

$$F_{LU}^{\sin\phi_h}$$

A_{LU} amplitudes: Subleading twist

Phys. Lett. B 797(2019) 134886

$$F_{LU}^{\sin(\phi_h)} \propto xeH_1^{\perp} \oplus \frac{M_h}{M_z} f_1\tilde{G}^{\perp} \oplus xg^{\perp}D_1 \oplus \frac{M_h}{M_z} h_1^{\perp}\tilde{E}$$

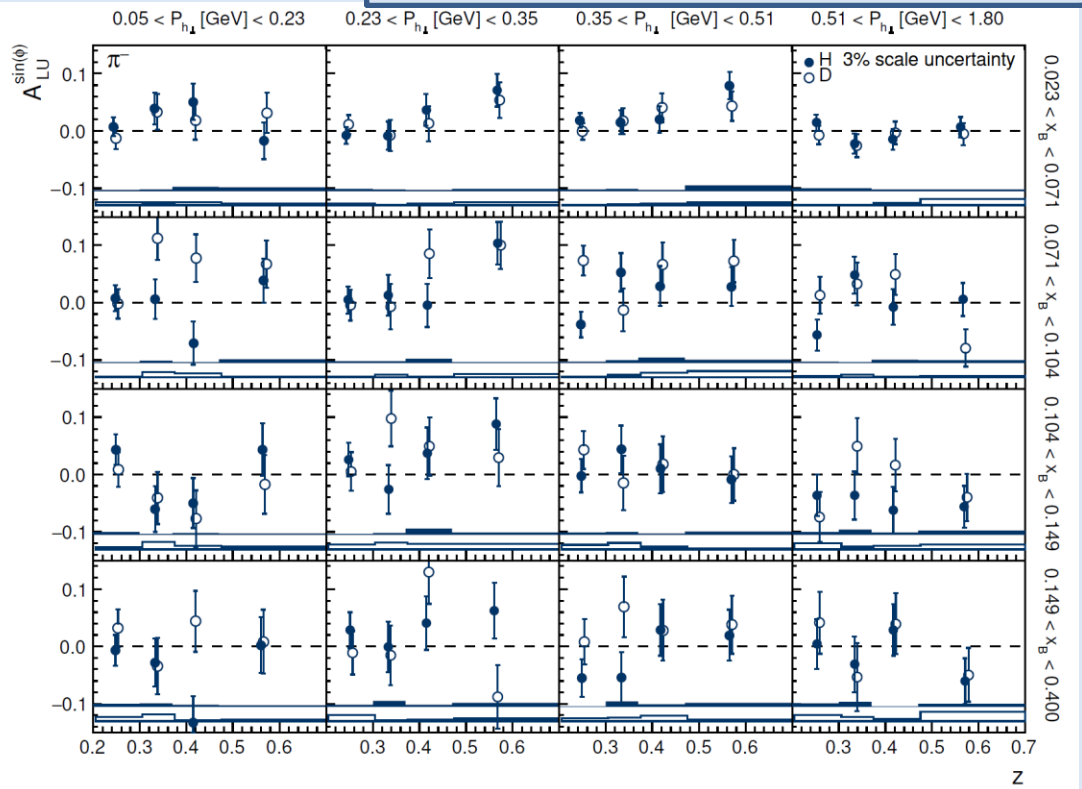


- Significant positive amplitudes for (in particular positive) pions, rising as a function of z
- Possible increase of the amplitude vs. $P_{h\perp}$ for low values of $P_{h\perp}$, decrease at high $P_{h\perp}$ for $\pi^{\pm}$
- For K^+ a small, positive amplitude is seen, for K^-, proton and anti-proton compatible with 0

A_{LU} amplitudes: Subleading twist; 3D extraction

Phys. Lett. B 797(2019) 134886

$$F_{LU}^{\sin(\phi_h)} \propto xeH_1^{\perp} \oplus \frac{M_h}{M_z} f_1\tilde{G}^{\perp} \oplus xg^{\perp}D_1 \oplus \frac{M_h}{M_z} h_1^{\perp}\tilde{E}$$

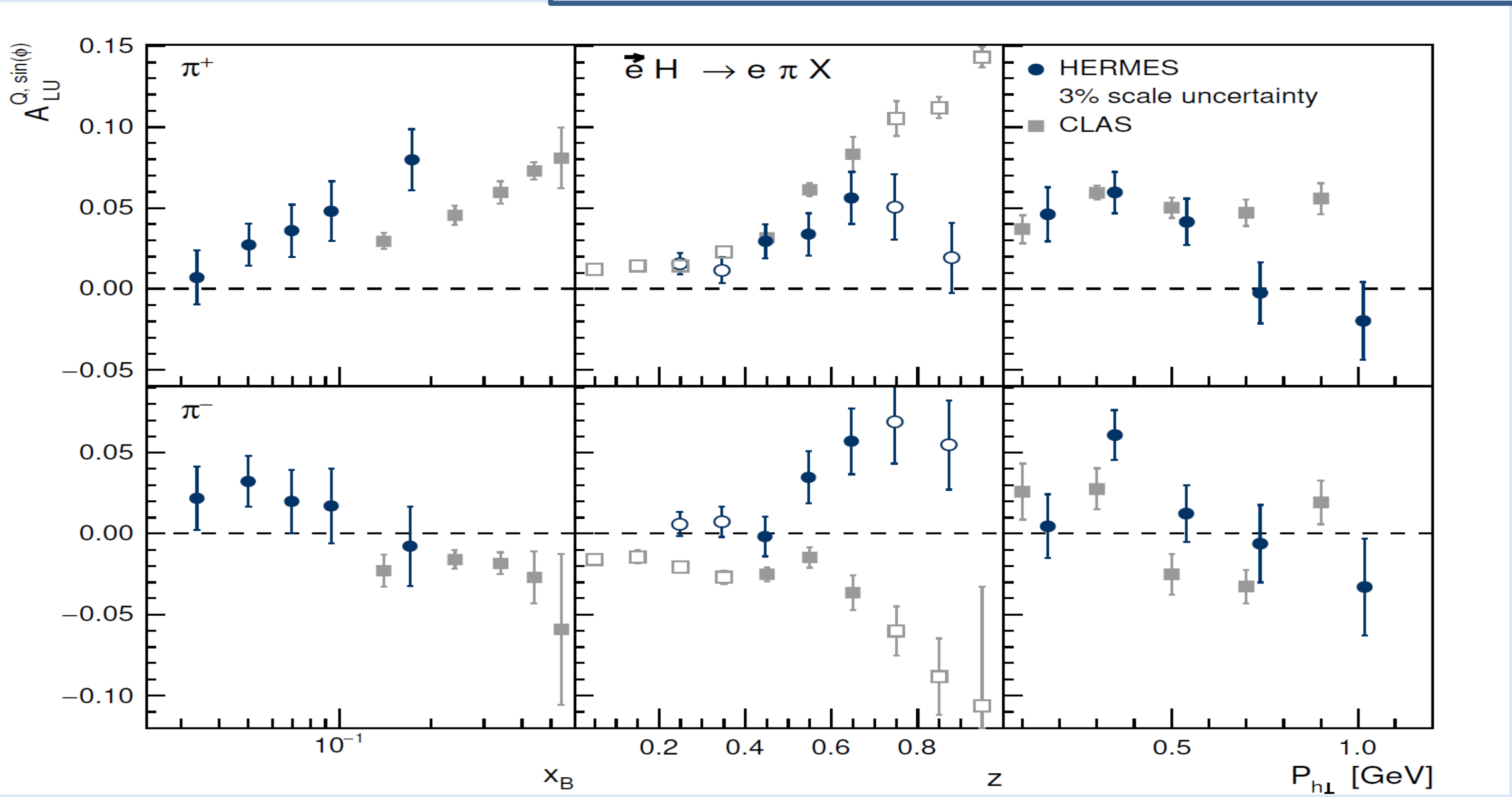


- The rise of the asymmetry amplitude as a function of z seen in the one-dimensional extraction is observed here for certain regions in x_B and $P_{h\perp}$
- Other hadrons: no distinctive kinematic dependence is visible
- 3D projections allow to constrain global fits in a more profound way

A_{LU} amplitudes: Subleading twist

Phys. Lett. B 797(2019) 134886

$$F_{LU}^{\sin(\phi_h)} \propto xeH_1^{\perp} \oplus \frac{M_h}{M_z} f_1\tilde{G}^{\perp} \oplus xg^{\perp}D_1 \oplus \frac{M_h}{M_z} h_1^{\perp}\tilde{E}$$

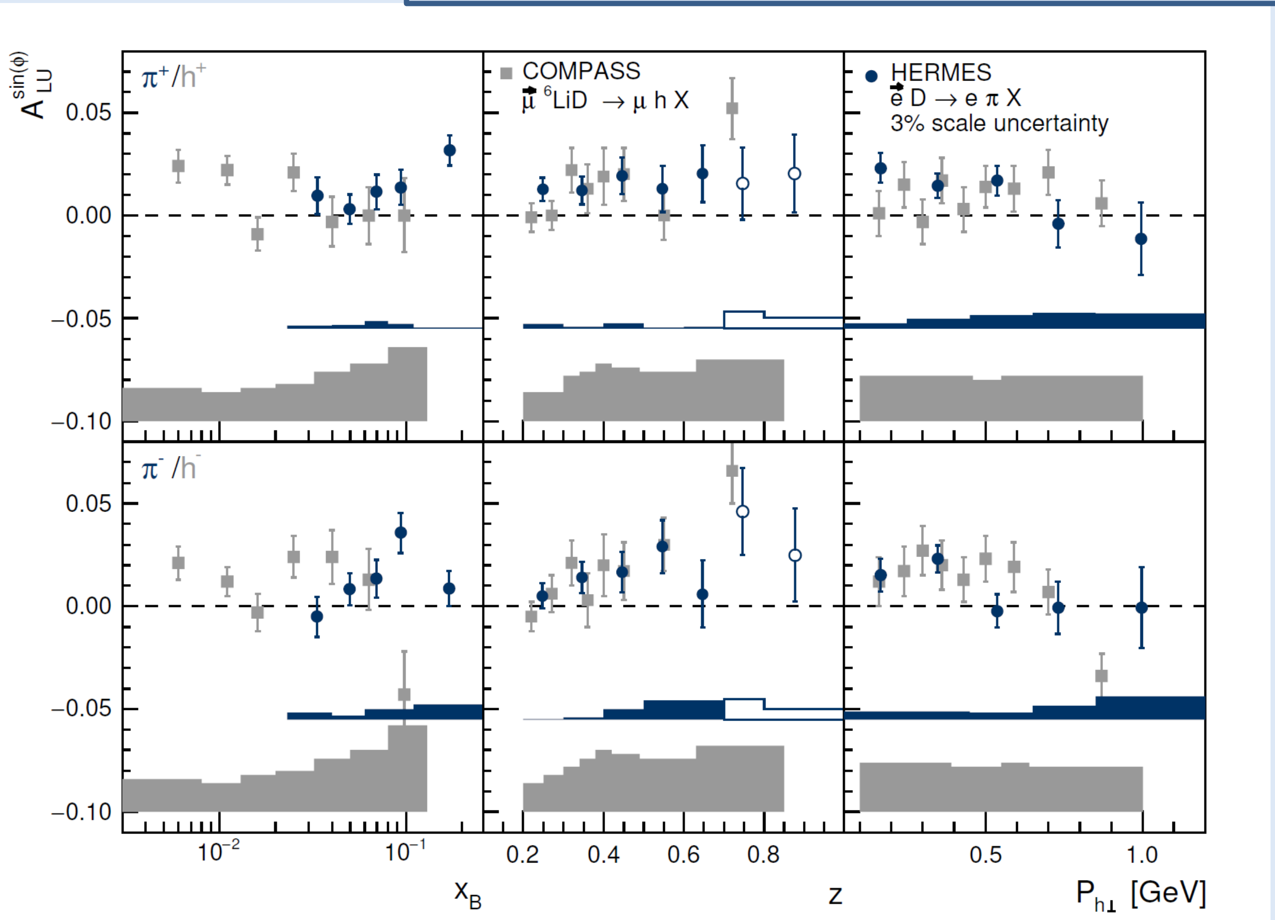


- Opposite behavior at HERMES/CLAS negative pions in z projection due to different x-ranges probed in different experiments
- Hint at the dominance of contributions from different pairs of PDFs and FFs

A_{LU} amplitudes: Subleading twist

Phys. Lett. B 797(2019) 134886

$$F_{LU}^{\sin(\phi_h)} \propto xeH_1^\perp \oplus \frac{M_h}{M_z} f_1\tilde{G}^\perp \oplus xg^\perp D_1 \oplus \frac{M_h}{M_z} h_1^\perp \tilde{E}$$



- Consistent behavior for charged pions (hadrons) at HERMES/COMPASS for isoscalar targets

Summary

- 3D picture of the nucleon:

  - A_{LL} in semi-inclusive DIS: Phys. Rev. D99 (2019) no.11, 112001
    - Refined studies ⟹ Extend the results of double-spin asymmetries published earlier by HERMES;
    - One-dimensional binning in x ⟹ Extended to 3D extraction;
    - Three-dimensionally binned asymmetries are the most complete, unintegrated, longitudinally polarized double-spin dataset to date;
    - Hadron charge-difference asymmetries ⟹ Helicity distributions for valence quarks.

  - A_{LU} in semi-inclusive DIS: Phys. Lett. B 797(2019) 134886
    - Subleading twist;
    - 3D extraction;
    - Hint at the dominance of contributions from different pairs of PDFs and FFs in different region of x.

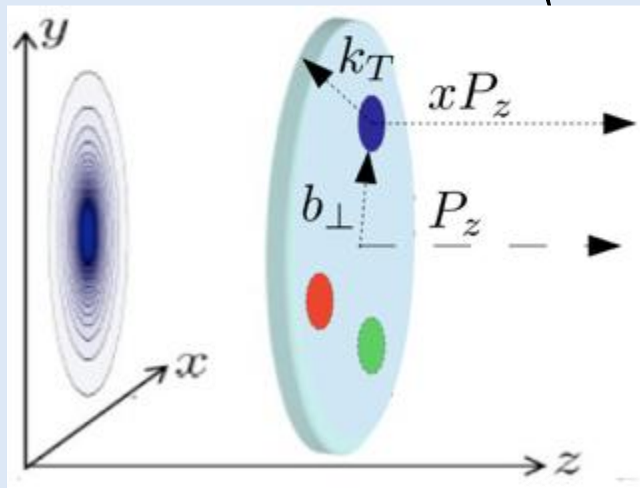
Thank You

Backup Slides

3D picture of the nucleon

Wigner distributions $W\left(x,\vec{k}_T,\vec{b}_\perp\right)$

$\int d^2\vec{b}_\perp$



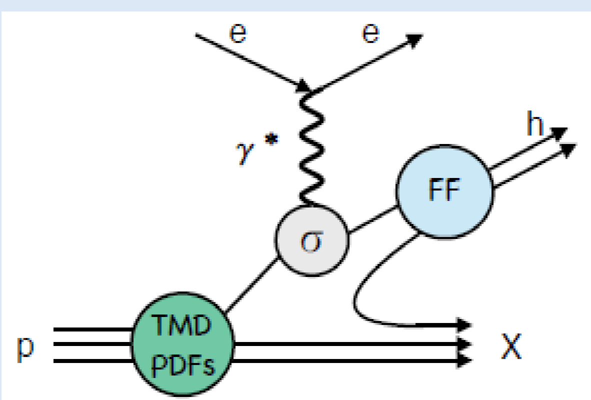
$\int d^2\vec{k}_T$

TMD PDFs: $f_p^q(x,k_T)$,…

GPDs: $H_p^q(x,\xi,t)$, …

Semi-inclusive measurements
Direct info about momentum distribution

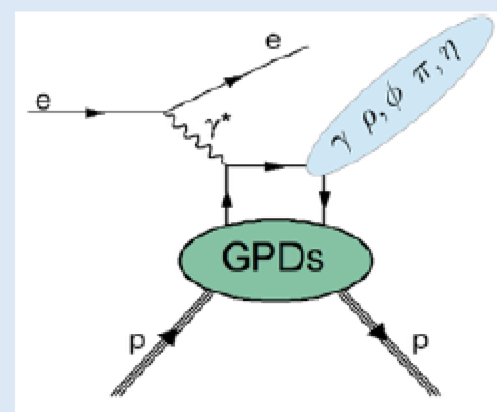
Exclusive Measurements
Direct info about spatial distribution



$\int d^2\vec{k}_T$

ξ=0, t=0

PDFs $f_p^q(x)$,…



Virtual-photon–nucleon asymmetry A_1^h

$$A_1^h \equiv \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} = \frac{1}{D(1+\eta\gamma)} A_{\parallel}^h$$

- The asymmetries $A_{\parallel,N}^h$ was transformed into a corresponding A^h_1 asymmetry, fit with a set of polynomial functions: one linear in x only, one linear in both x and $P_{h\perp}$, and second order in both variables

- No clear preference for any of the functional forms

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