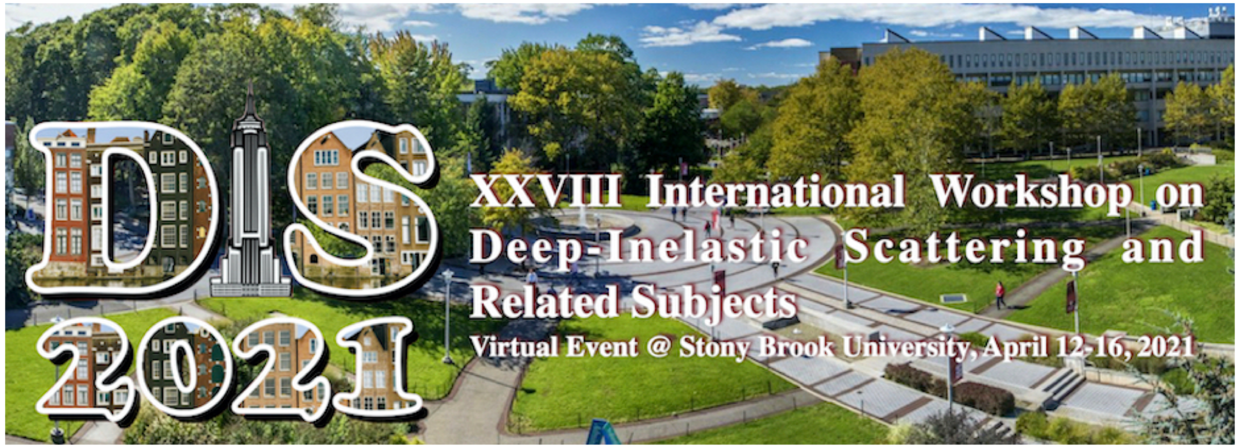
University of Ferrara



Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

Luciano L. Pappalardo (for the HERMES Collaboration)

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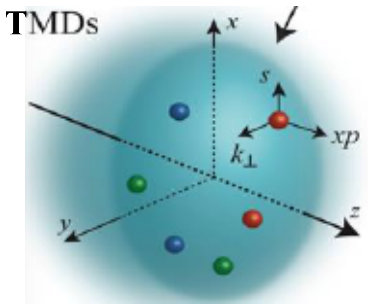
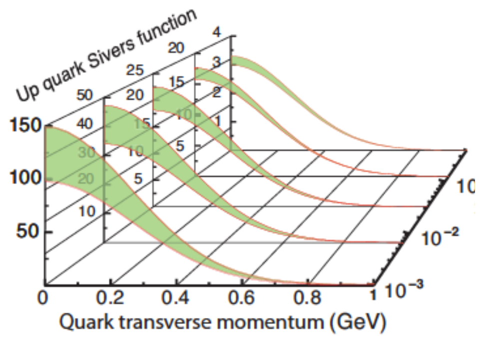
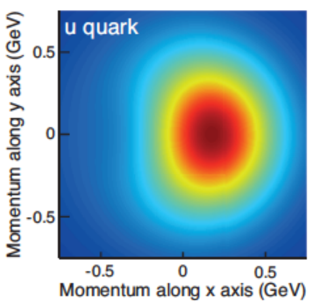
TMDs in SIDIS





arXiv:1212.1701



- encode flavour-dependent correlations between p_T and the spin orientation of the parent hadron or of the quark itself
- 3D description of nucleon structure in momentum space (→ **nucleon tomography**)

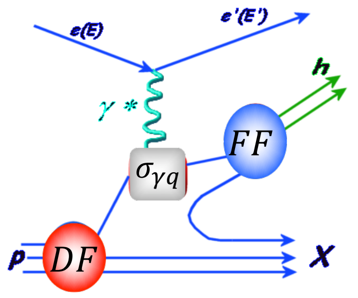
quark polarisation

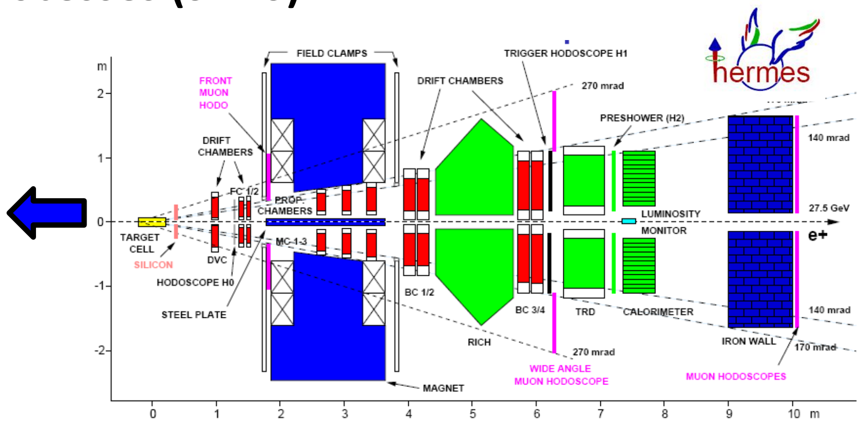
nucleon polarisation	U	L	T
U	f_1 number density (PRD 87 (2013) 074029)		$h_1^\perp$ Boer-Mulders (PRD87 (2013) 012010)
L		g_1 helicity (PRD 75 (2007) 012007)	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers (PRL 94 (2005) 012002, PRL 103 (2009) 152002)	g_{1T} worm-gear (released)	h_1 transversity; $h_{1T}^\perp$ pretzelosity (released)

PLB 562 (2003) 182
PRL 84 (2000) 4047

PRL 94 (2005) 012002
PLB 693 (2010) 11

Semi-inclusive DIS processes (SIDIS)





$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz_h\, d\phi_h\, dP_{h\perp}^2}$$

$$\begin{aligned}
&= \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h}\\
&+ \quad \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h}\\
&+ \quad S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right]\\
&+ \quad S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\, F_{LL}^{\cos\phi_h}\right]\\
&+ \quad |S_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\\
&+ \quad \varepsilon\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}\\
&+ \quad \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]\\
&+ \quad |S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S}\\
&+ \quad \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}$$

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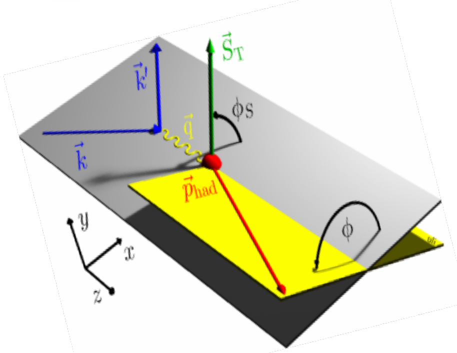

The "Hermes TMDs Bible"


Prepared for submission to JHEP
DESY Report 20-119

Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

The HERMES Collaboration

A. Airapetian[13,16] N. Akopov[26] Z. Akopov[6] E.C. Aschenauer[7] W. Augustyniak[25] R. Avakian[26,a] A. Bacchetta[21] S. Belostotski[19,a] V. Bryzgalov[20] G.P. Capitani[11] E. Cisbani[22] G. Ciullo[10] M. Contalbrigo[10] W. Deconinck[6] R. De Leo[2] E. De Sanctis[11] M. Diefenthaler[9] P. Di Nezza[11] M. Düren[13] G. Elbakian[26] F. Ellinghaus[5] A. Fantoni[11] L. Felawka[23] G. Gavrilov[6,19,23] V. Gharibyan[26] Y. Holler[6] A. Ivanilov[20] H.E. Jackson[1,a] S. Joosten[12] R. Kaiser[14] G. Karyan[6,26] E. Kinney[5] A. Kisselev[19] V. Kozlov[17] P. Kravchenko[9,19] L. Lagamba[2] L. Lapikás[18] P. Lenisa[10] W. Lorenzon[16] S.I. Manaenkov[19] B. Marianski[25,a] H. Marukyan[26] Y. Miyachi[24] A. Movsisyan[10,26] V. Muccifora[11] Y. Naryshkin[19] A. Nass[9] G. Nazaryan[26] W.-D. Nowak[7] L.L. Pappalardo[10] P.E. Reimer[1] A.R. Reolon[11] C. Riedl[7,15] K. Rith[9] G. Rosner[14] A. Rostomyan[6] J. Rubin[15] D. Ryckbosch[12] A. Schäfer[21] G. Schnell[3,4,12] B. Seitz[14] T.-A. Shibata[24] V. Shutov[8] M. Statera[10] A. Terkulov[17] M. Tytgat[12] Y. Van Haarlem[12] C. Van Hulse[12] D. Veretennikov[3,19] I. Vilardi[2] S. Yaschenko[9] D. Zeiler[9] B. Zihlmann[6] P. Zupranski[25]

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[a] Deceased.

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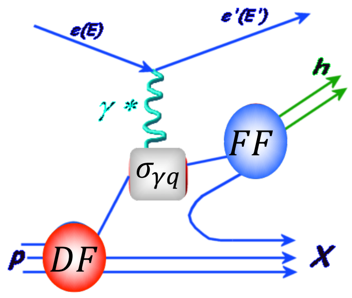
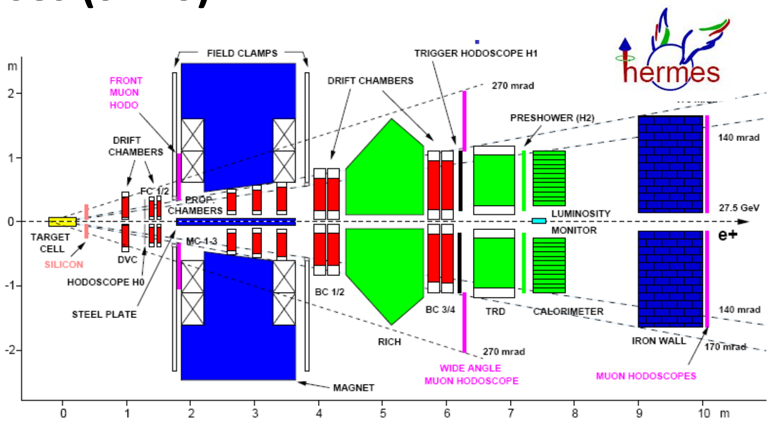
Semi-inclusive DIS processes (SIDIS)





$$
\begin{aligned}
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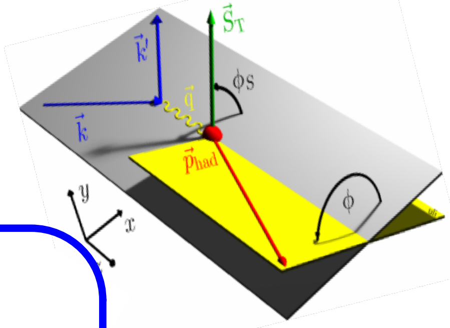
&= \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}\\
&+\ \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\\
&+\ S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]\\
&+\ S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]\\
&+\ |S_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\\
&+\ \varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\\
&+\ \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]\\
&+\ |S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}\\
&+\ \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

Bacchetta et al JHEP 08



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- **Compendium of HERMES TMDs results obtained with transv. Pol. H target** (84 pages!)
- 10 azimuthal modulations ($6\ A_{U\perp} + 4\ A_{L\perp}$)
- 7 hadron types
- 2 types of asymmetries:
  - ***Cross-Section Asymmetries (CSA):*** entire Fourier amplitude of each cross-section term
  - ***Structure-Function Asymmetries (SFA):*** pure ratios of structure functions **(NEW!)** (corrected for ε-dependent kinematic prefactors)

Advances w.r.t previous analyses:

- **3D binning in $x, z, P_{h\perp}$** (before only 1D)
- **$p/\bar{p}$ asymmetries** (in addition to $\pi^{\pm}, \pi^0, K^{\pm}$)
- **Use of a later data production**, which includes updated tracking and alignment info
- **Extraction of π^0 asymmetries is improved** in various aspects, including background subtr.
- **1D binning optimized and extended to the high-z** ("semi-exclusive") region ($0.7 < z < 1.2$)
- **The x range is extended up to 0.6** (before was up to 0.4)

SSA and DSA amplitudes

The relevant asymmetry amplitudes are extracted in an unbinned ML fit of the Fourier decomposition of the cross section in the azimuthal angles ϕ and ϕ_S (separately for CSA and SFA amplitudes)

$$-\ln \mathbb{L} = -\sum_{i=1}^{N_h} w_i \ln \mathbb{P}\left(x_i, z_i, P_{h\perp,i}, \phi_i, \phi_{S,i}, P_{l,i}, S_{\perp,i} : 2\left\langle \sin\left(\phi - \phi_S\right)\right\rangle_{\mathrm{U}\perp}^{h}, \ldots\right)$$

Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[Sivers]	✓		✓	✓	✓	(✓)	✓
$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

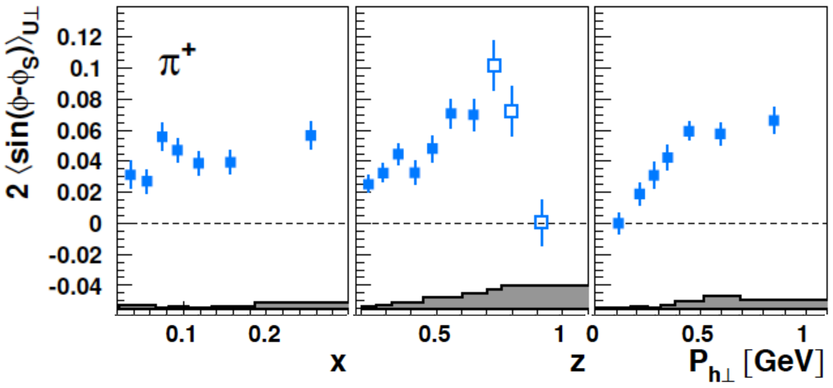
All other 1D SFA results in back-up slides!

✓ : incompatible with NULL hypothesis at 95% CL

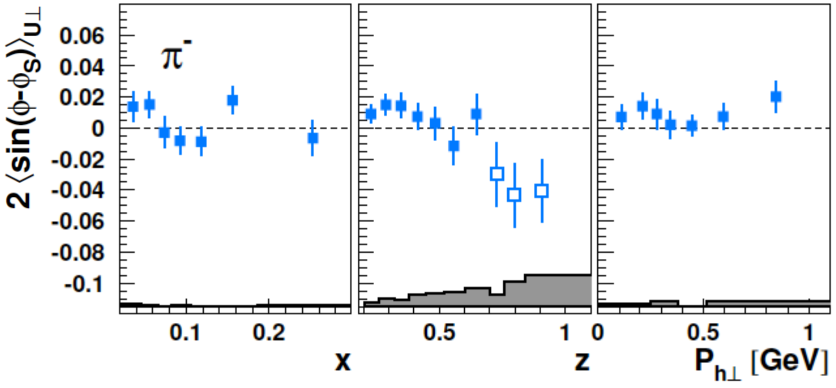
(✓) : incompatible with NULL hypothesis at 90% CL

Selected results

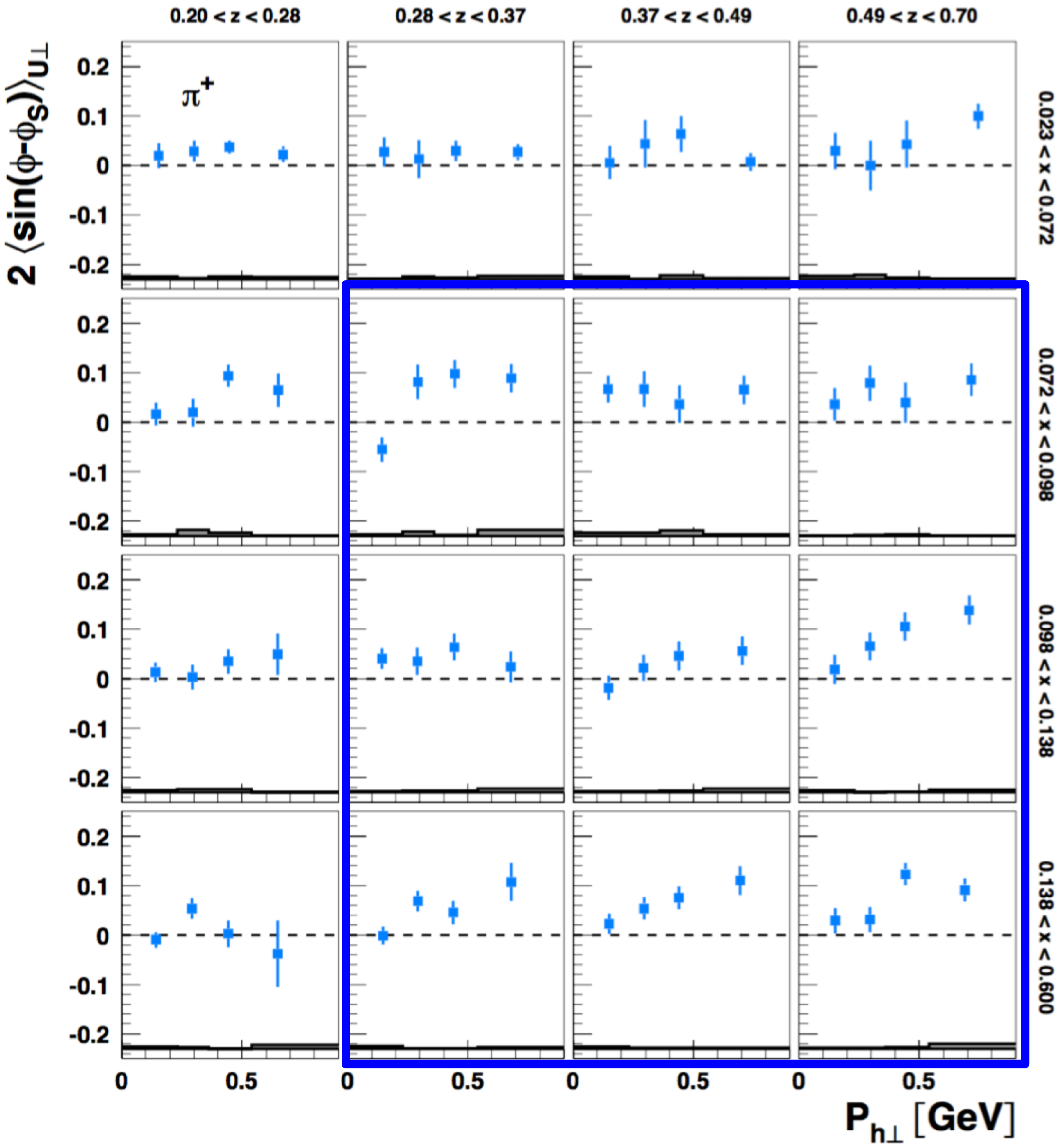
Sivers amplitudes: pions results



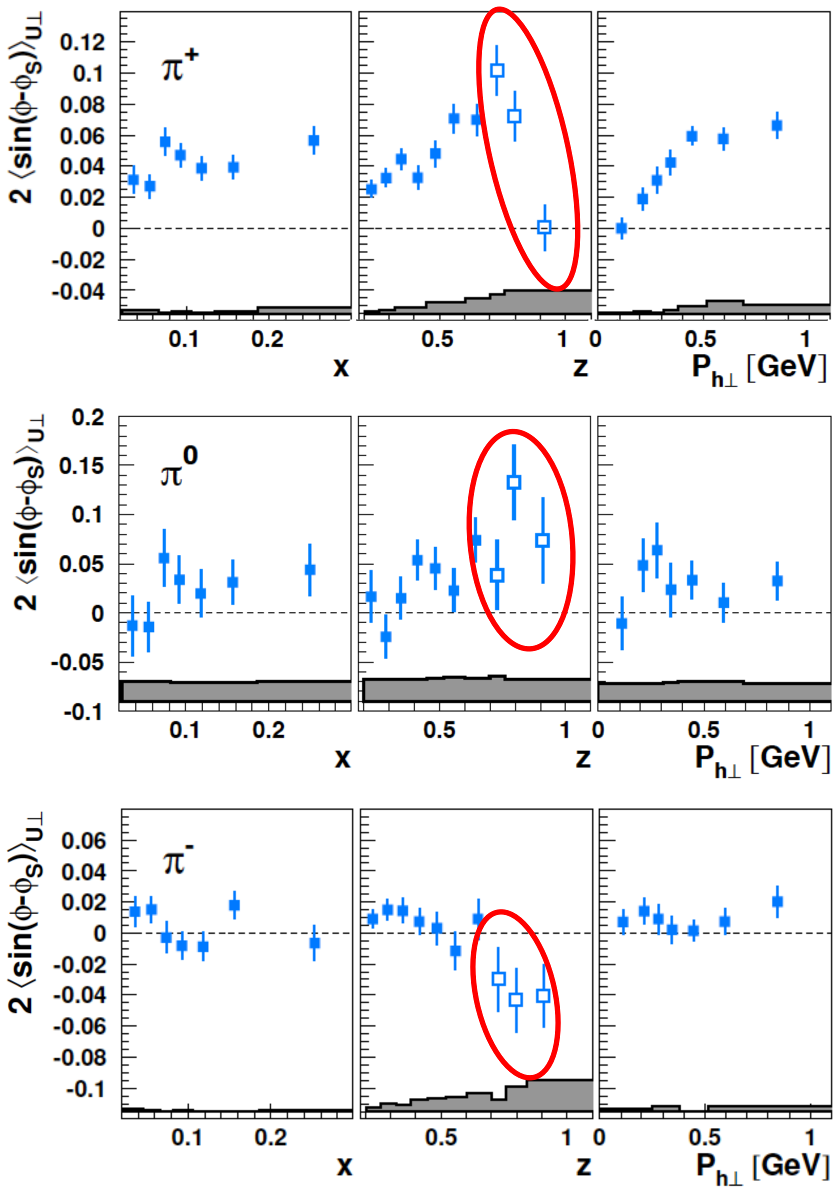
- large positive amplitude → clear evidence of non-zero $f_{1T}^{\perp,u}$
- signal rises with x, z and $P_{h\perp}$ in SIDIS region ($0.2 < z < 0.7$)
- More informative 3D projections confirm and further detail the rise of the amplitude at large x, z and $P_{h\perp}$

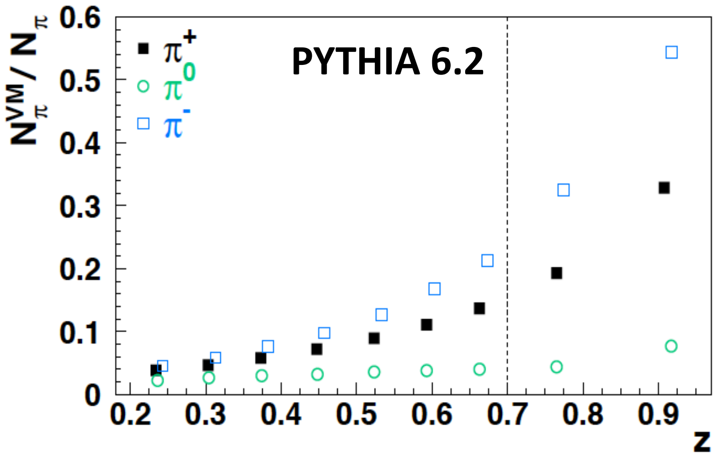


Vanishing due to the cancellation of the opposite Sivers effect for *u* and *d* quarks



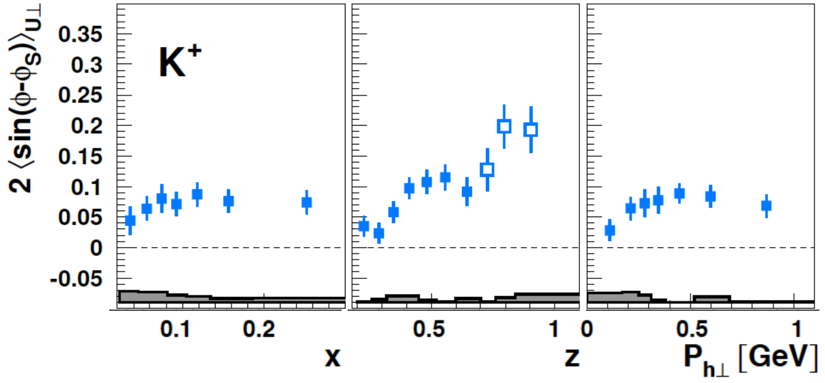
Sivers amplitudes: pions results



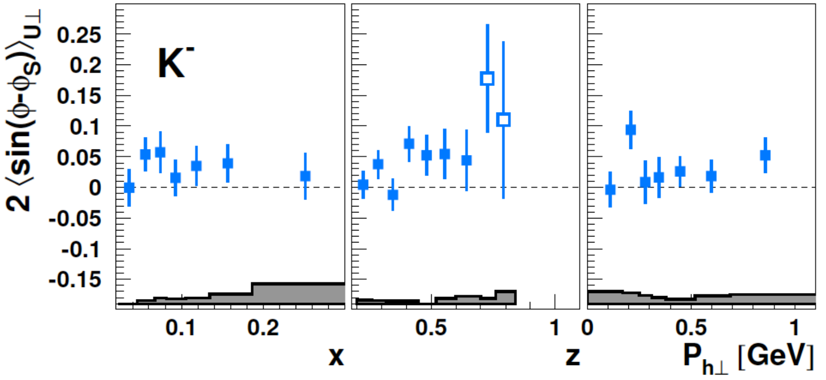


- Sudden drop at large-z (> 0.7) reveals a change of mechanism in this **semi-exclusive region**
- Contributions from decays of exclusively produced ρ^0 into $\pi^+\pi^-$ are large in this region!
- intermediate size between those of π^+ and π^- reflects isospin symmetry at the amplitude level
- π^0 amplitude is much less susceptible to VM decays and no sudden change is observed at large z → observed positive signal cannot be attributed solely to contributions from VM
- An alternative (concurrent?) explanation: at large z, favored fragmentation ($d \rightarrow \pi^-$) prevails over the disfavored one ($u \rightarrow \pi^-$) → no cancellation and a non-zero amplitude opposite to that of π^+ is observed.

Sivers amplitudes: Kaons results

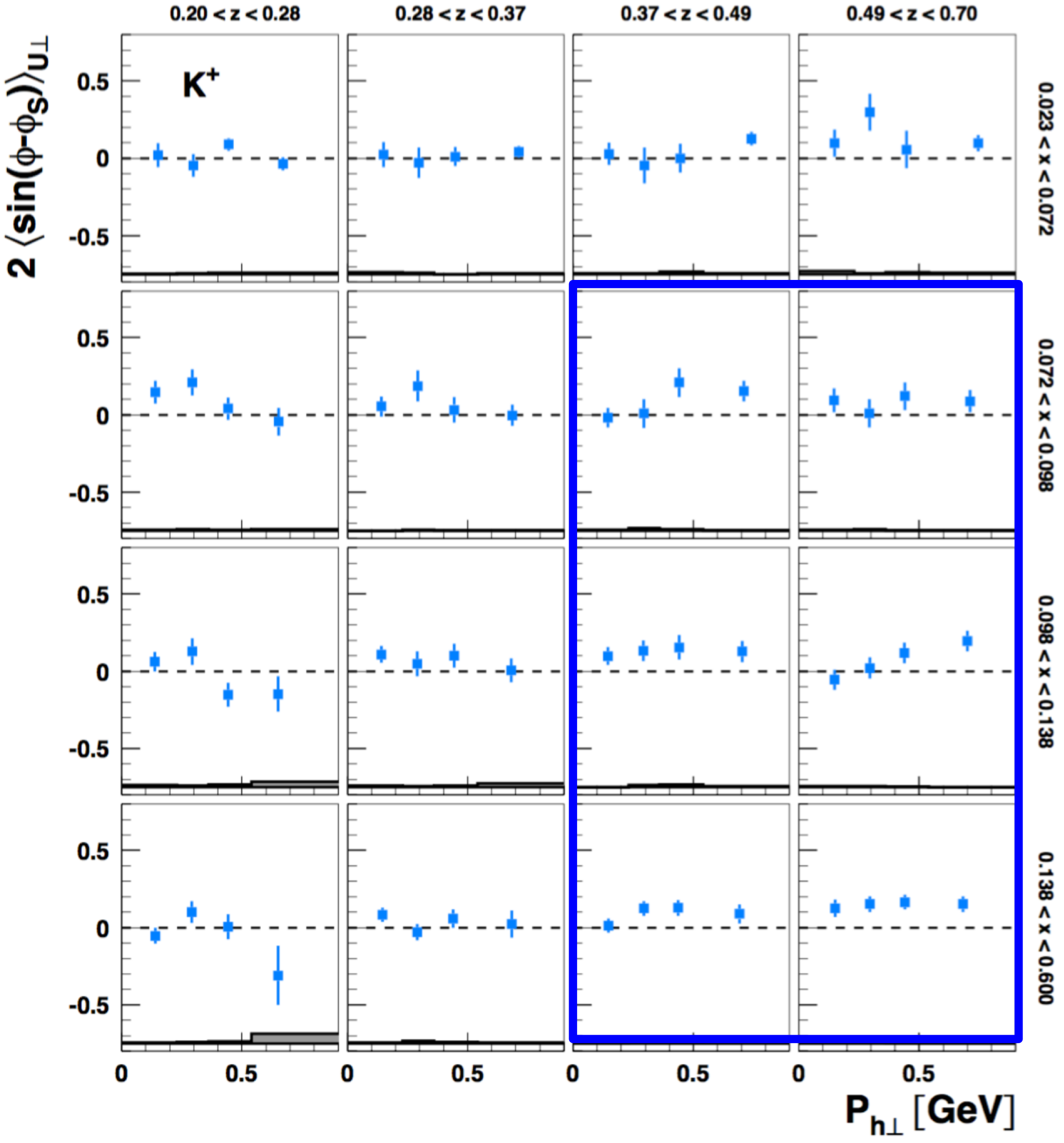


Large positive amplitude, similar kinematic dep. of π^+

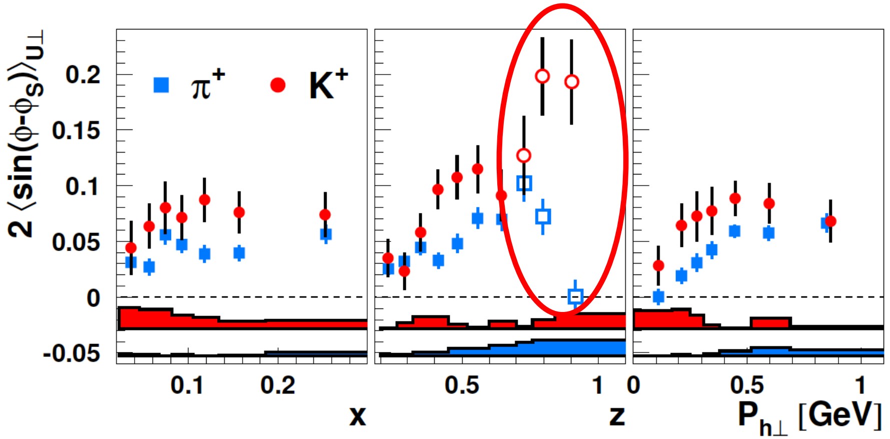


Positive amplitude, different than π^-

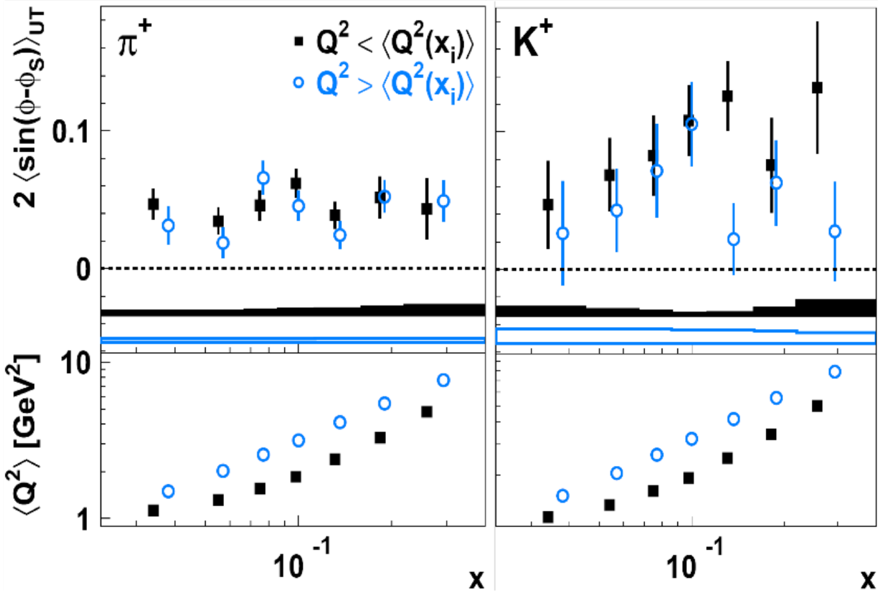
K^- is a pure sea object with no valence quarks in common with target proton



Sivers amplitudes: the K^+ vs. π^+ issue



Phys. Rev. Lett. 103 (2009) 152002



Similar kinematic dependence in SIDIS region but K^+ is substantially larger!

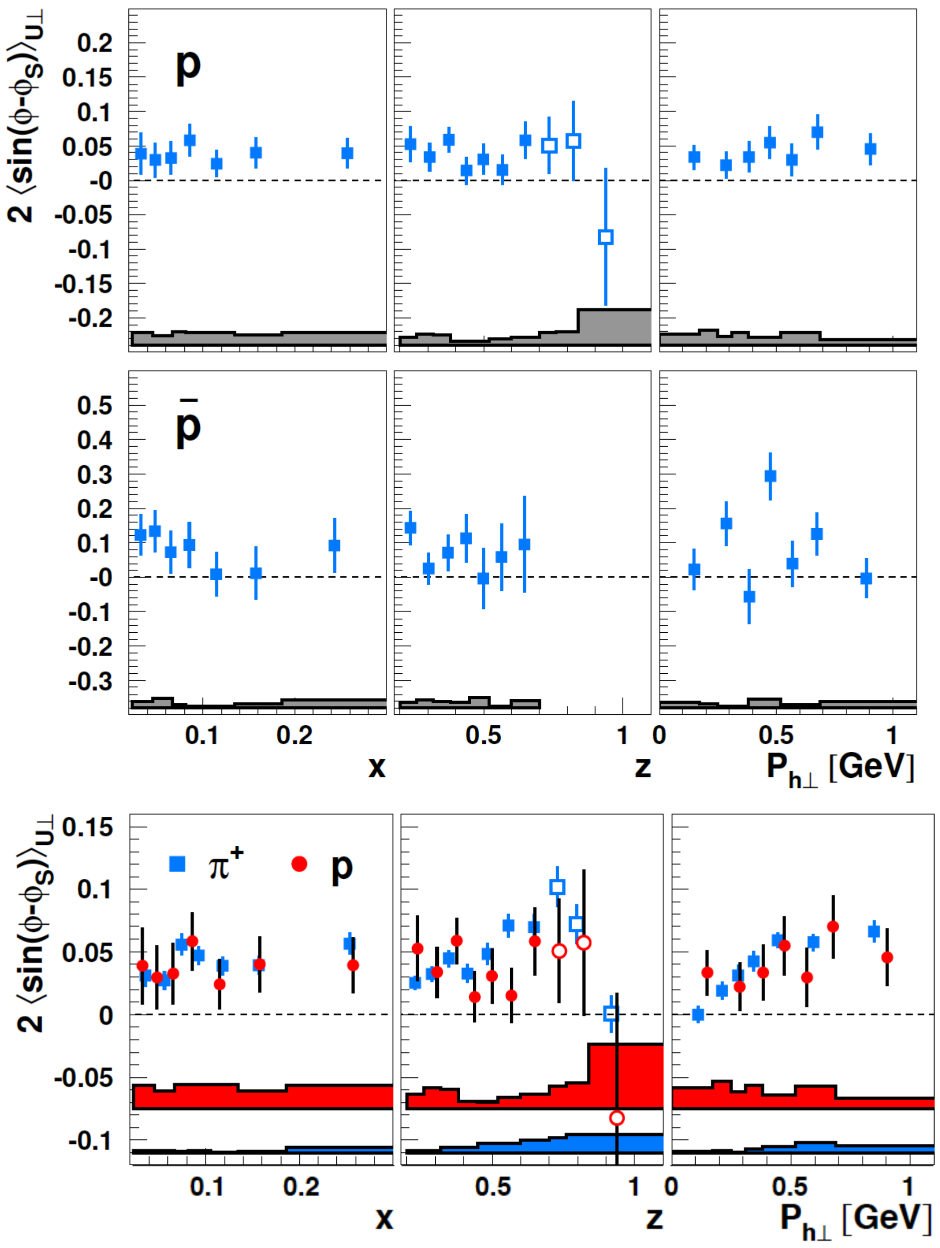
- both expected to be mainly produced from scattering off u-quarks
- but **different sea-quark content**
- there could be a different k_T dependence of the fragmentation functions for different (sea) quarks flavours (entering the convolution integral)?
- different impact of higher-twist effects ?

- K^+ amplitude keeps rising with z in semi-exclusive region (no sudden change) → Contribution from exclusive VM decays much less pronounced for Kaons than for pions.

- x-Q^2 strongly correlated → split each x bin in two Q^2 regions: $\lessgtr \langle Q^2\rangle$ of each x bin

- no effect for pions, but hint of suppression at larger Q^2 for kaons

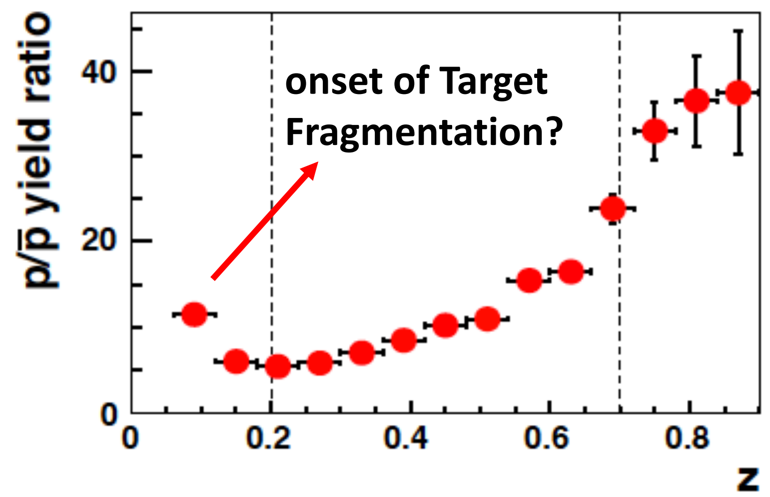
Sivers amplitudes: protons results

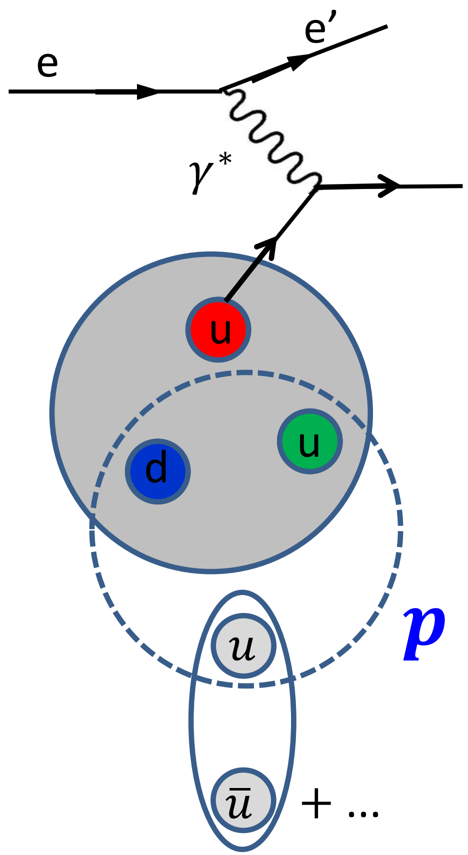


First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive

Proton production is particularly susceptible to receive contributions from **Target Fragmentation**

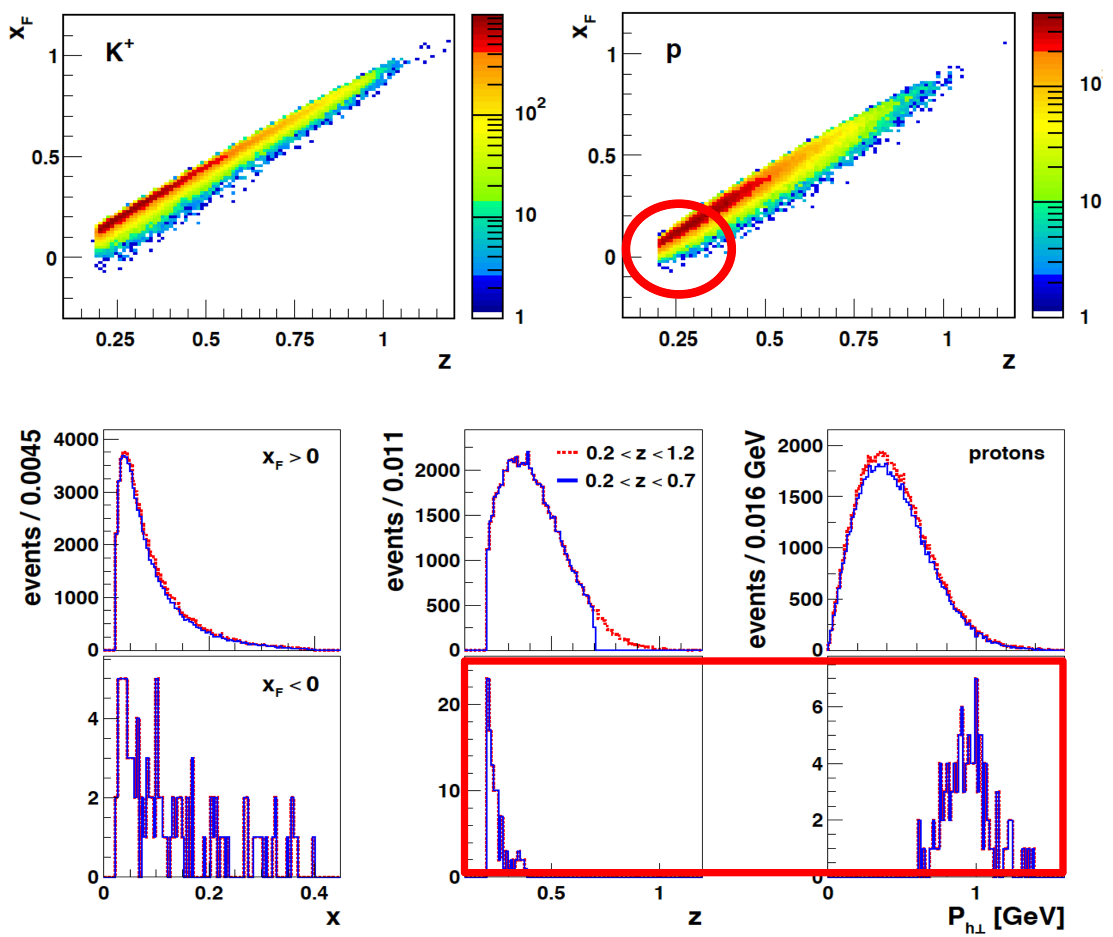


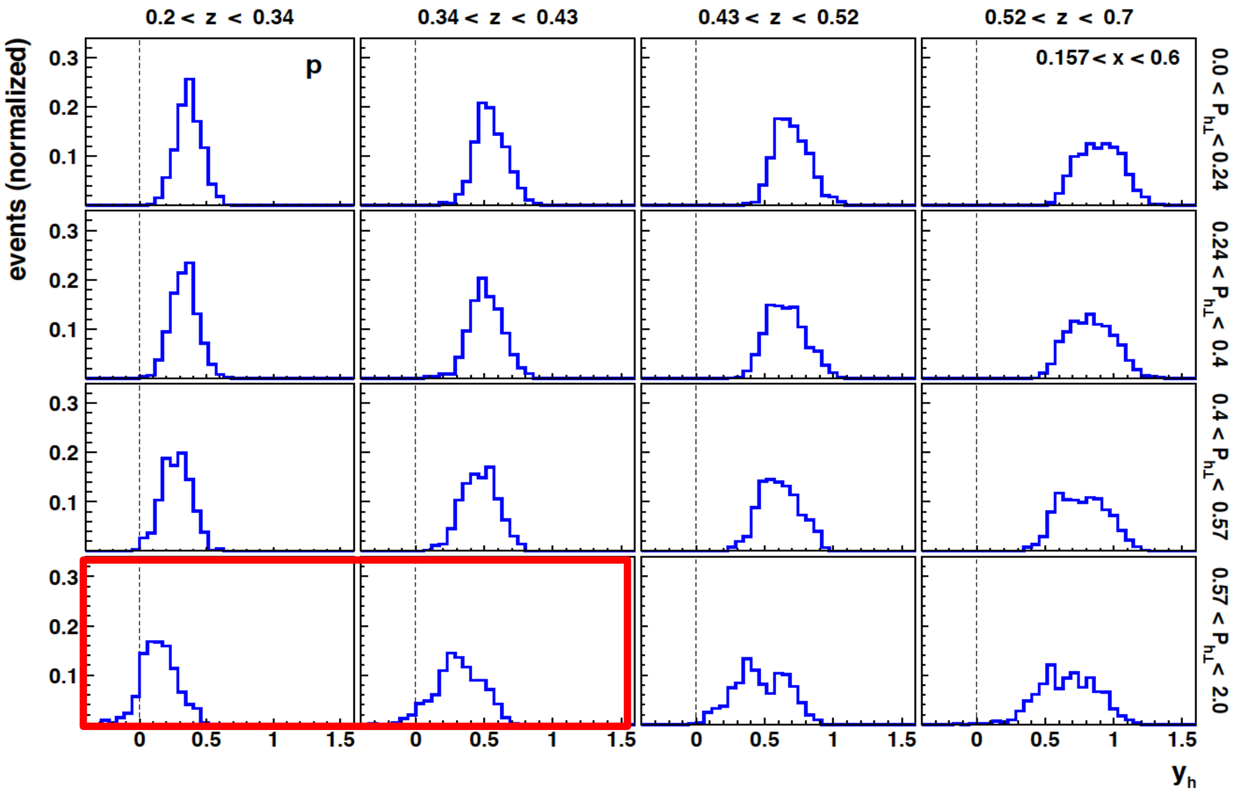


(low z, high $P_{h\perp}$)

Sivers amplitudes: protons results (CFR vs. TFR)

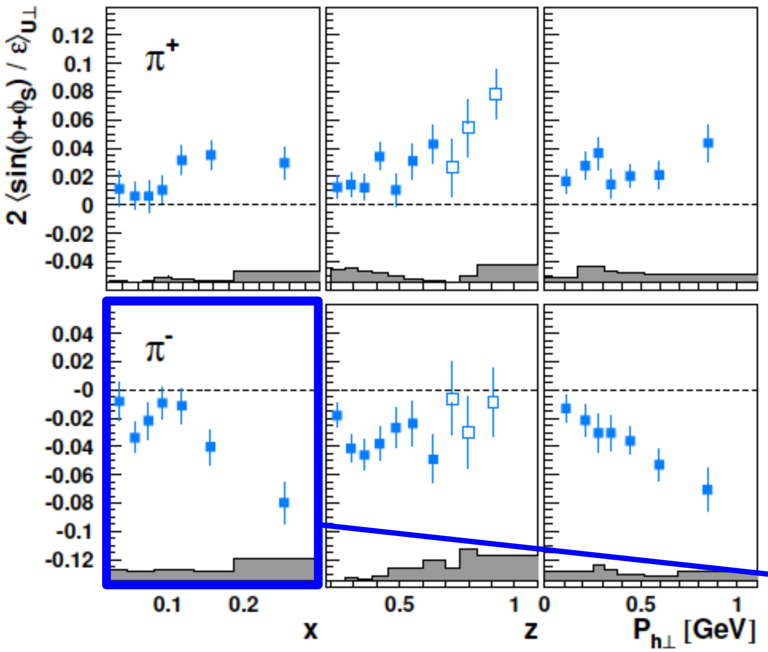
- No generally-accepted recipe exists
- positive values of x_F and rapidity (y_h) are typically associated with hadrons produced from the struck quark (CFR)
- negative values point at target fragmentation (TFR)



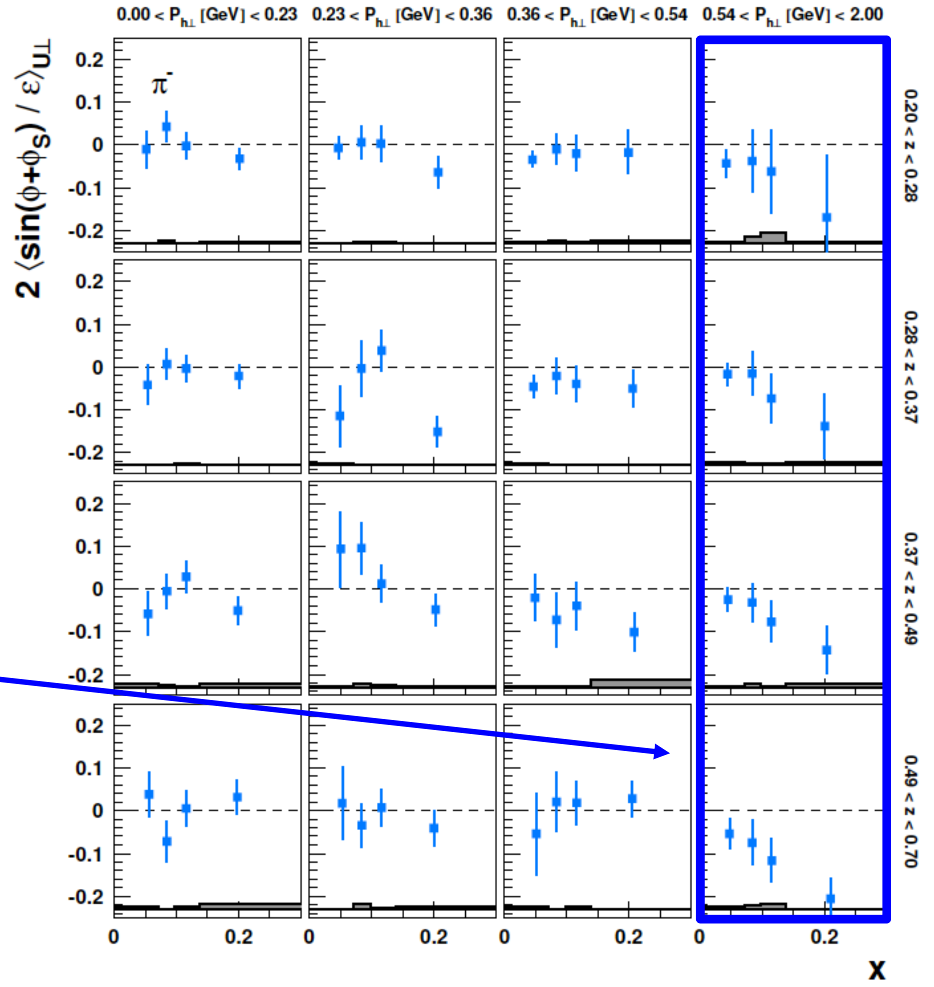


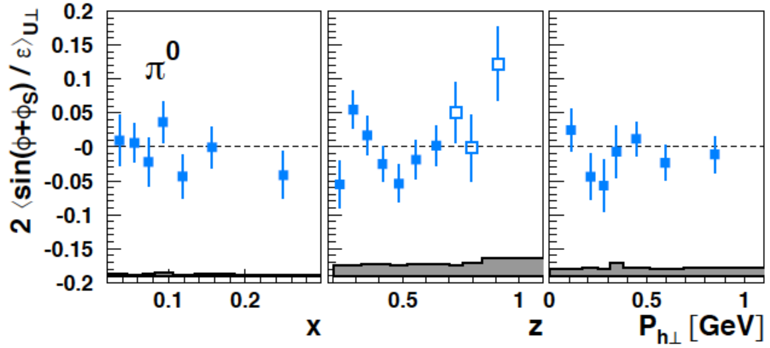
At the selected kinematics the vast majority of protons are compatible with being produced in CFR

Collins amplitudes: SFA pion results



- Large and opposite amplitudes
- Clear evidence of non-zero transversity
- Negative π^- amplitude points to large disfavoured ($u \to \pi^-$) Collins FF opposite to the favoured one ($d \to \pi^-$)

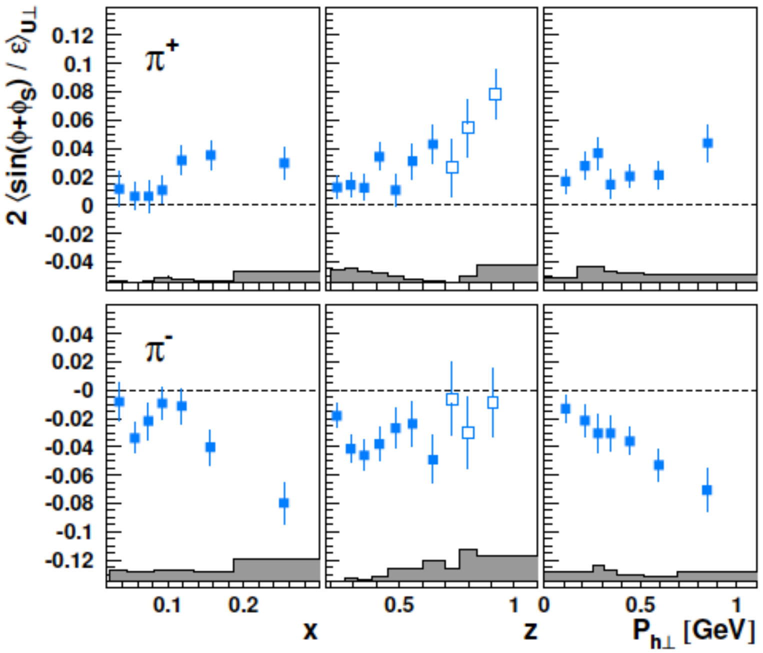


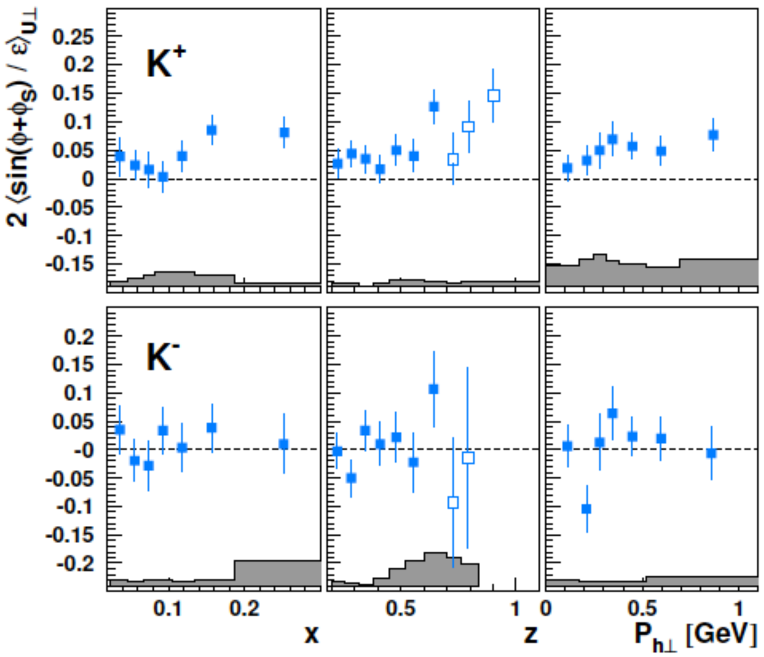


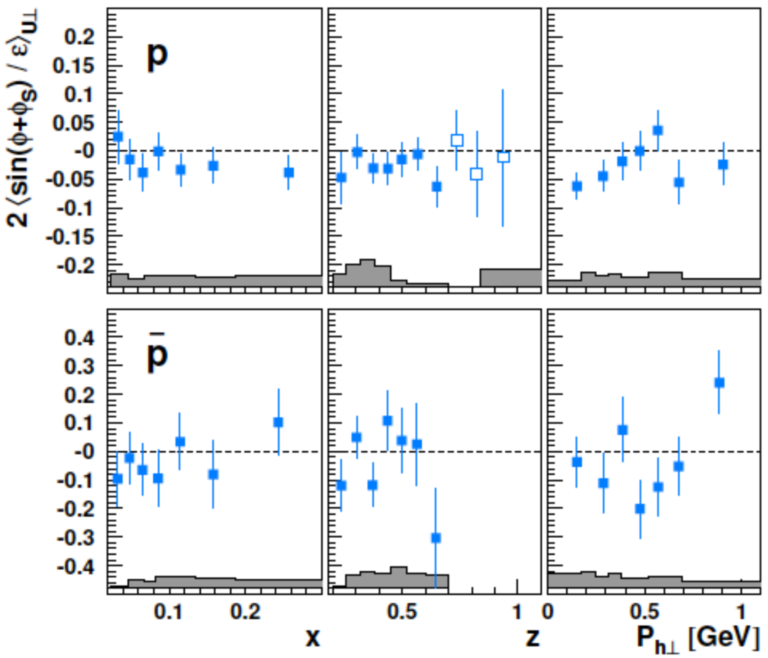
- ≈ 0: intermediate between π^+ and π^-

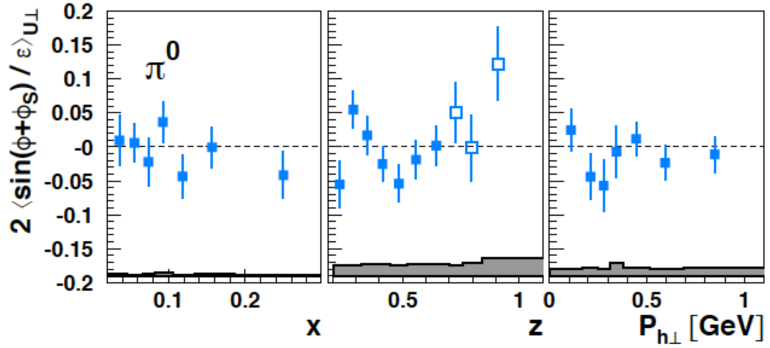
- 3D projections confirm and further detail the rise of the amplitude at large x and $P_{h\perp}$

Collins amplitudes: all SFA 1D results





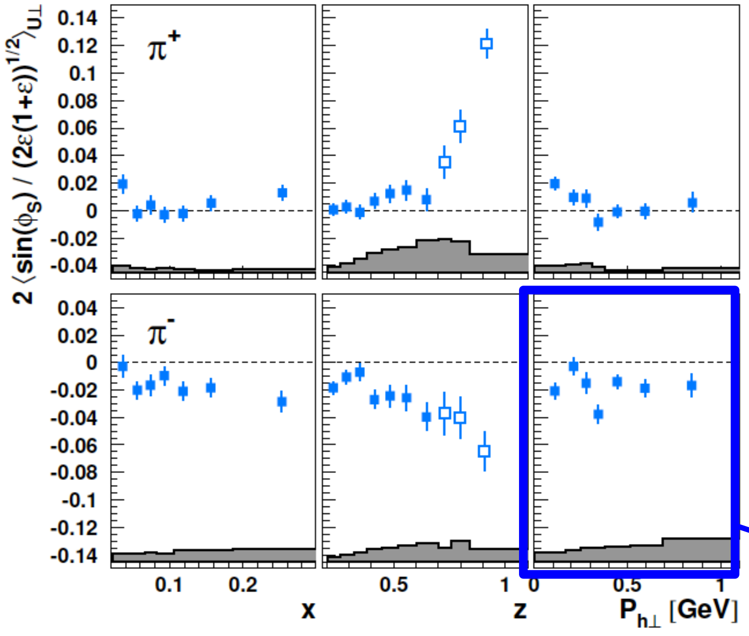




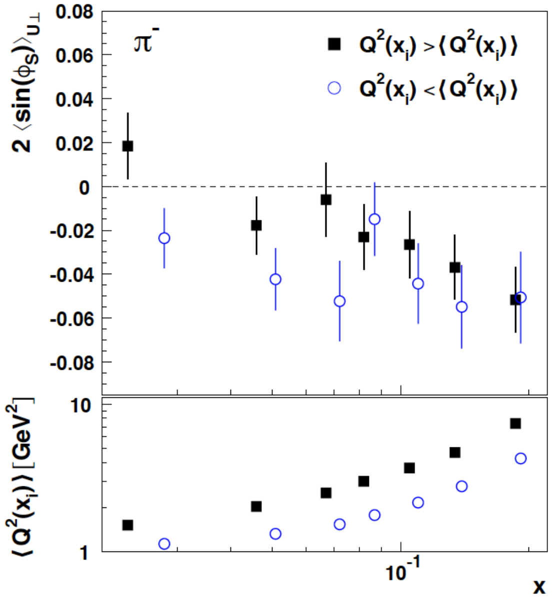
- K^+ exhibits a very similar kinematic dependence as π^+, but amplitude is twice as large!
- $K^- \approx 0$: only disfavored and opposite ($u \to K^-, d \to K^-$) fragmentation mechanisms can contribute

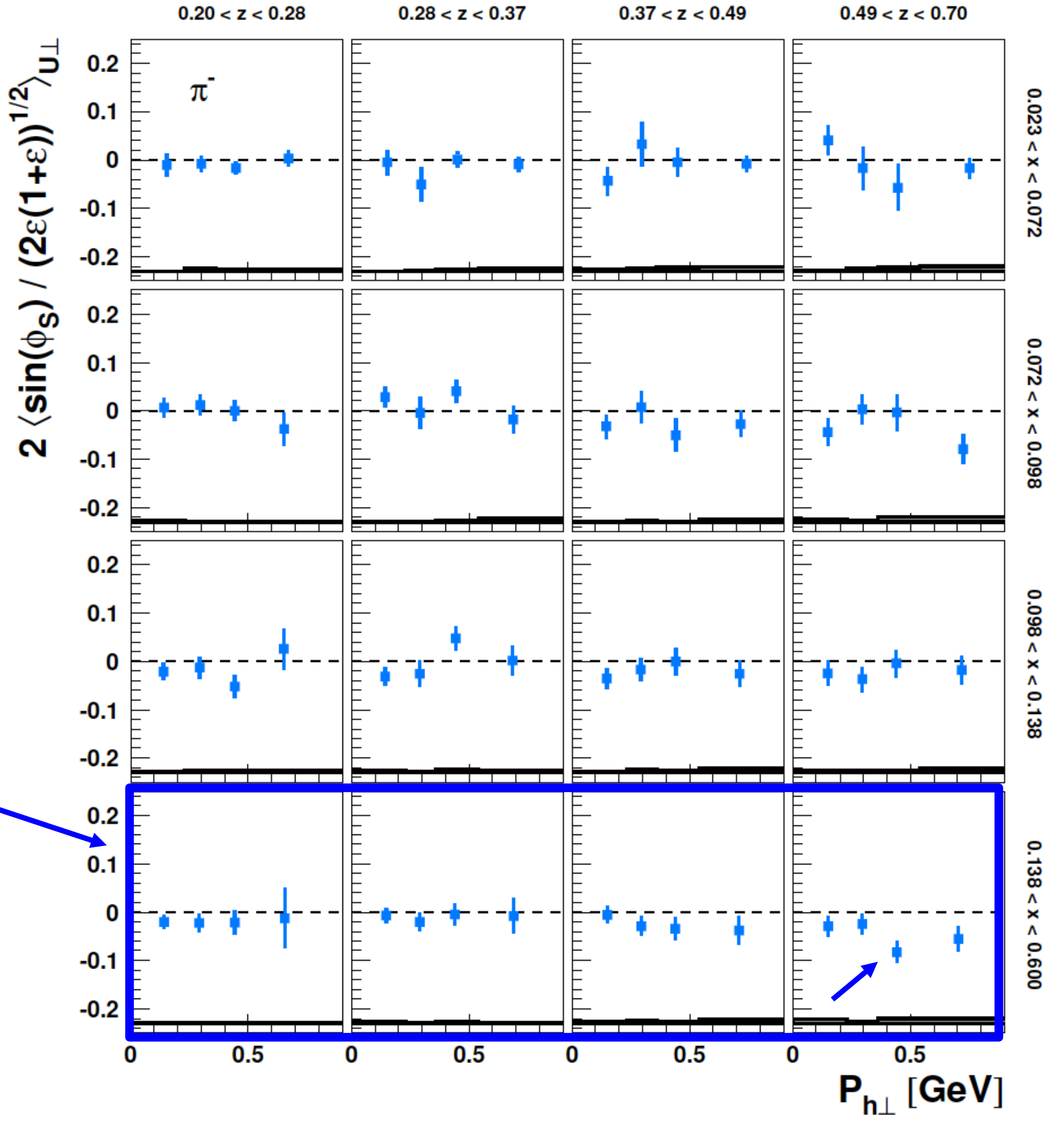
- **First measurement of Collins asymm. for protons/antiprotons!**
- **proton amplitude is non zero (negative)**
- antiproton amplitude ≈ 0
- Collins effect is a fragmentation process, but too little is known about this effect for spin-$\frac{1}{2}$ hadron production

The sub-leading twist $\sin\phi_S$ term: pions SFA results



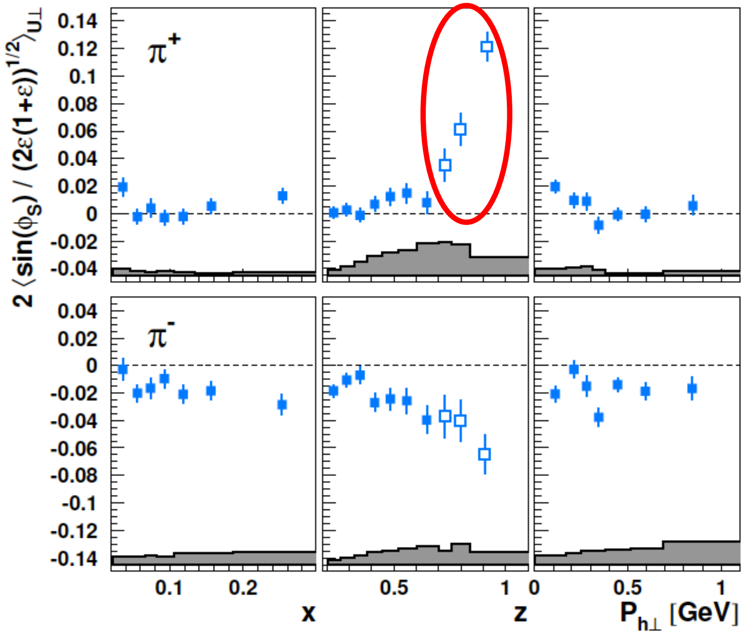
- Charged pions amplitudes non-zero and opposite
- Negative π^- amplitude increases with x and z
- Overall similar behaviour of Collins asymmetries!

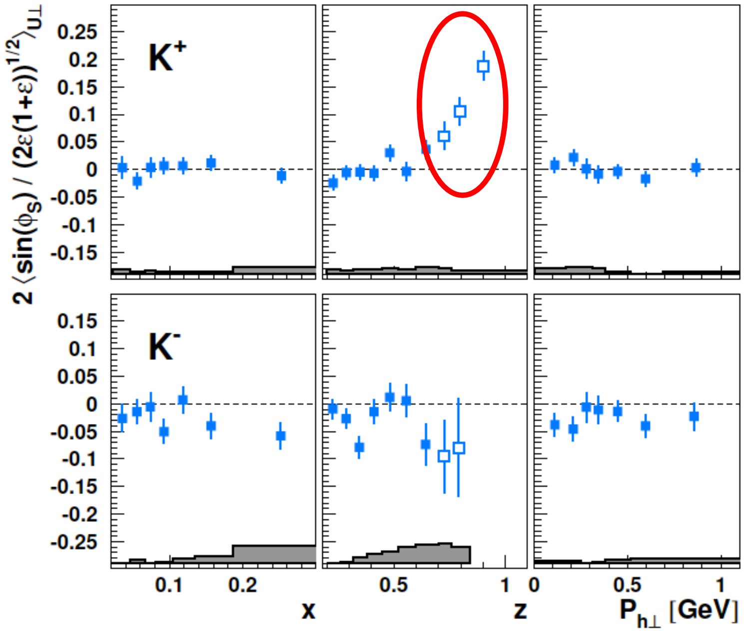


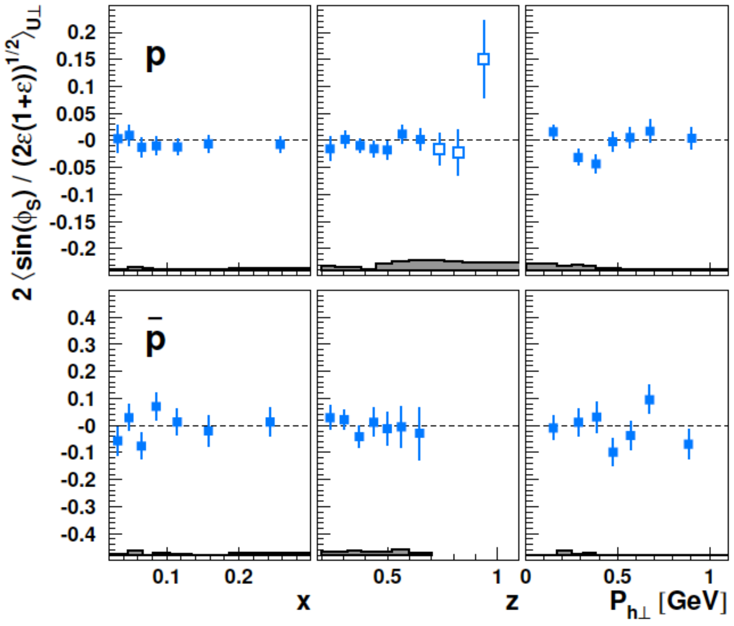


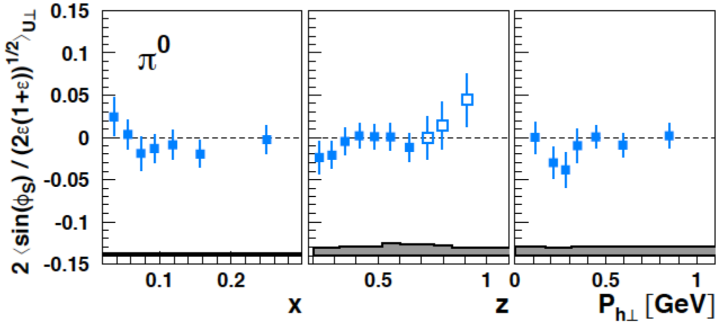
- Subleading-twist term: interesting to study the Q^2 dependence
- Split each x-bin in two Q^2 regions
- Hint of suppression at higher Q^2

The sub-leading twist $\sin\phi_S$ term: all SFA 1D results









- $\pi^+$and K^+amplitudes in SIDIS region $(0.2 < z < 0.7)$ are similar: small and positive
- K^- negative and similar to π^-
- $\pi^0, p, \bar{p}$ results vanishing
- striking z-dependence in "semi-exclusive region" for π^+/K^+ consistent with large $\sin(\phi_S)$ amplitude observed in exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

Conclusions

- The full collection of leading- and subleading-twist SSAs and DSAs with a transversely polarized H target has now been published, based on an improved analysis including proton/antiproton results, as well as results in a 3D binning and extended to the large-z ("semi-exclusive region") region.

- A **rich phenomenology** and surprising effects arise when intrinsic transverse degrees of freedom (spin, momentum) are not integrated out!

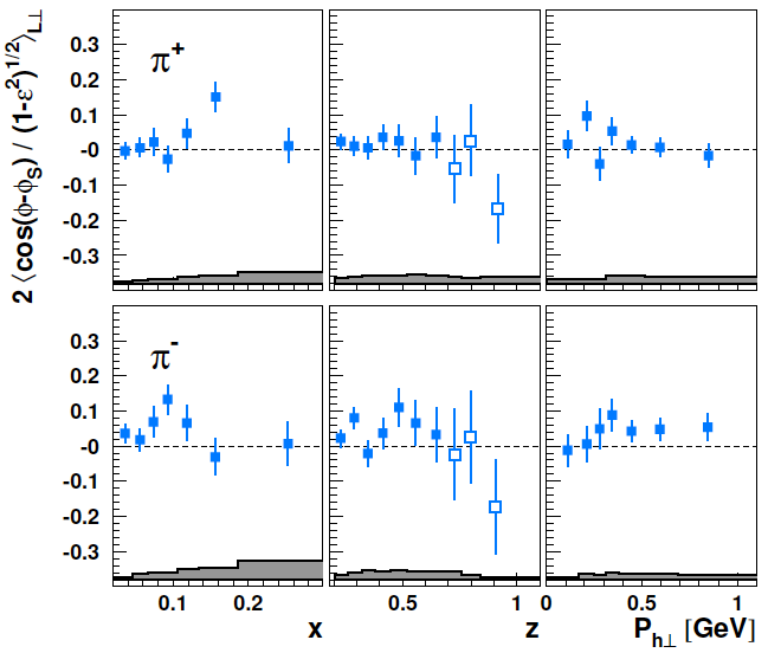
- **Flavor sensitivity** ensured by the excellent hadron ID of the HERMES experiment reveals interesting and unexpected facets of data (e.g. $\pi \leftrightarrow K$)

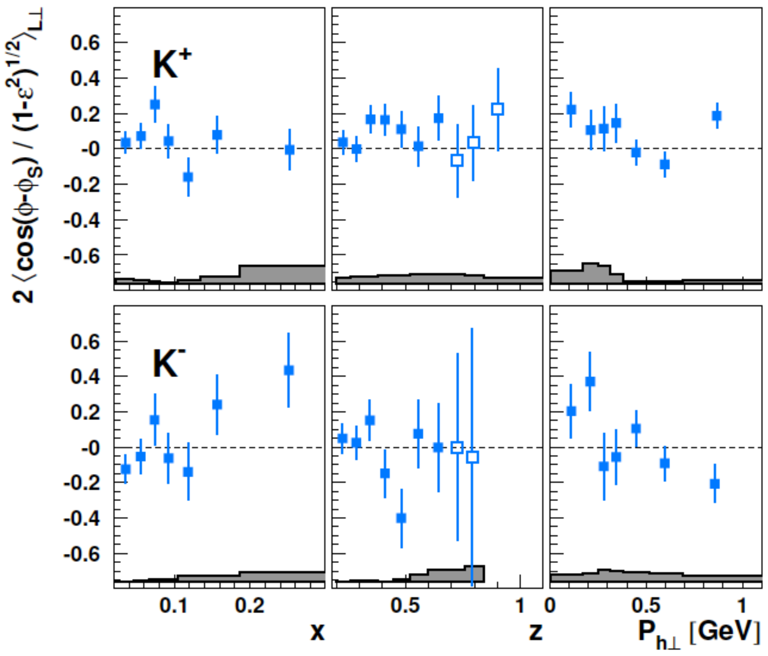
- The **3D imaging of the nucleon** is a fashinating and fast evolving research field. HERMES has been a pioneer experiment in this fiels and continues to play a key role in these studies.

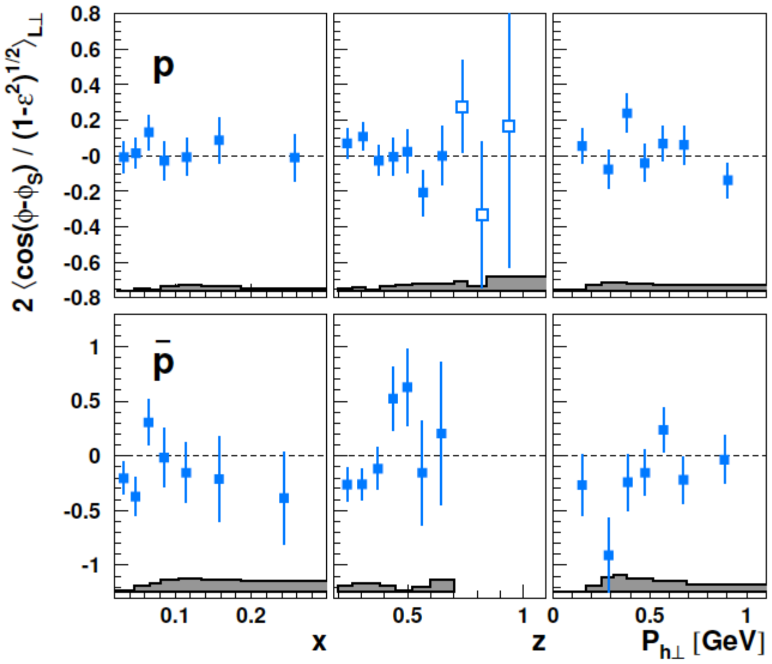
Backup

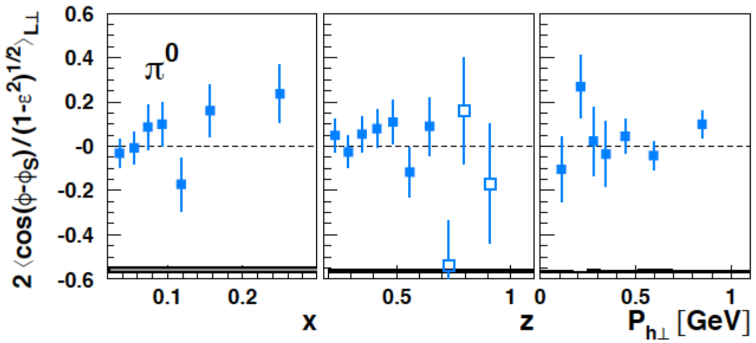
The other SFA results…

The $\cos(\phi - \phi_S)$ DSA: all SFA 1D results



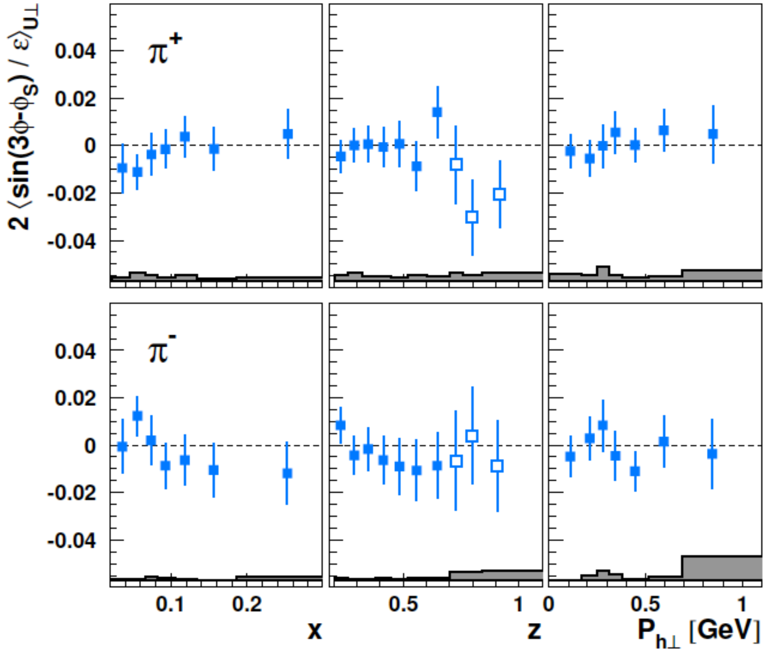


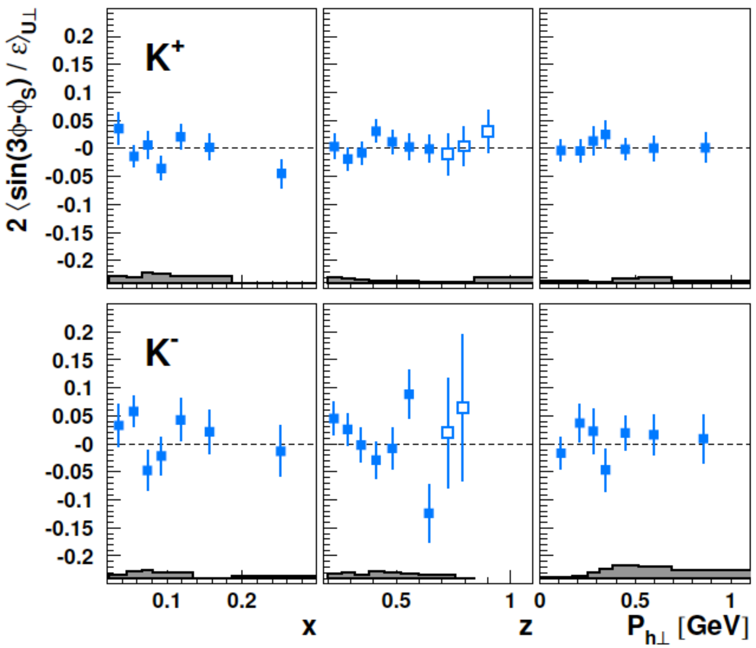


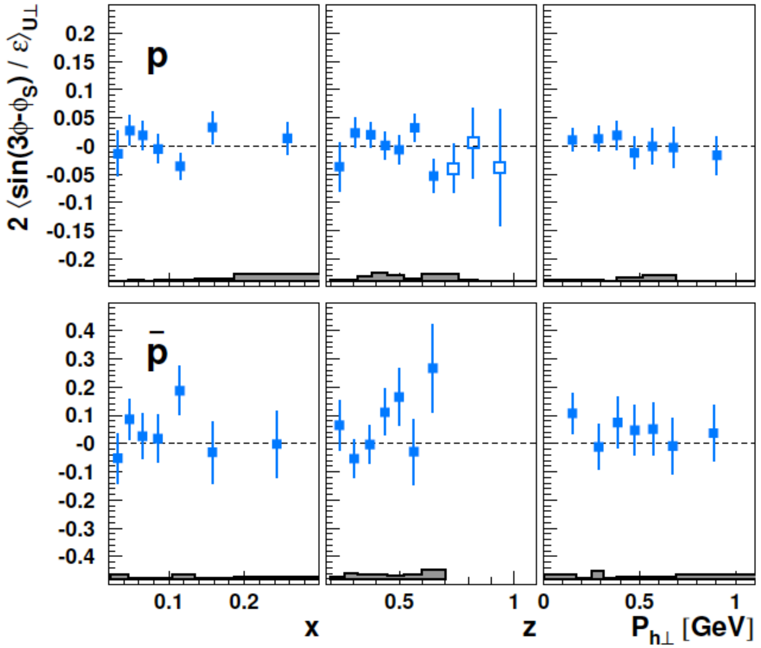


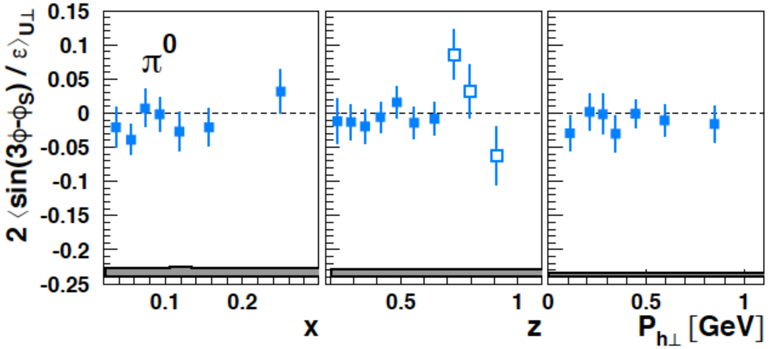
- **π^+, π^- and K^+ amplitudes are non-zero in SIDIS region ($0.2 < z < 0.7$)**
- **indication of a non-zero worm-gear function g_{1T}**
- amplitudes consistent with zero for all other hadron species
- Larger stat. errors (compared to SSAs) due to low beam polarization

$\langle \sin(3\phi - \phi_S)\,/\varepsilon \rangle_{U\perp}$ (Pretzelosity): all 1D results





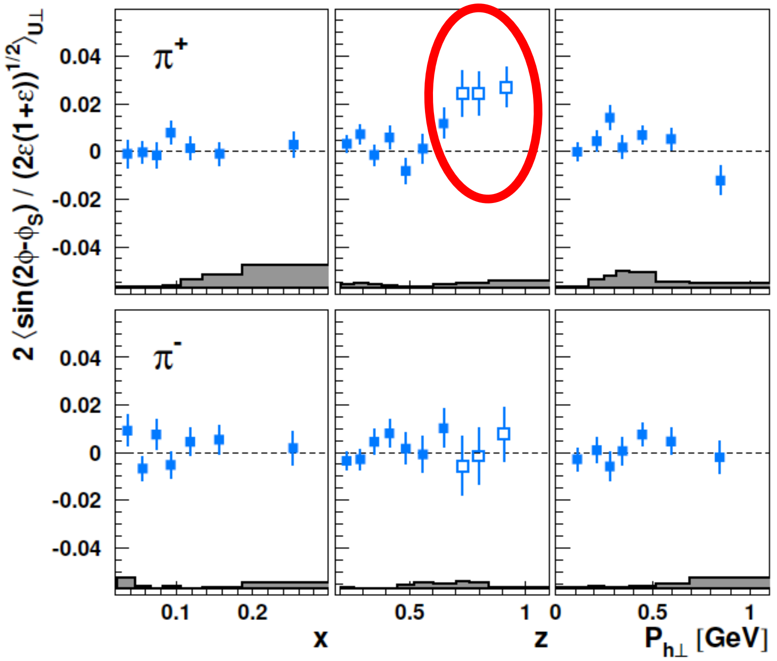


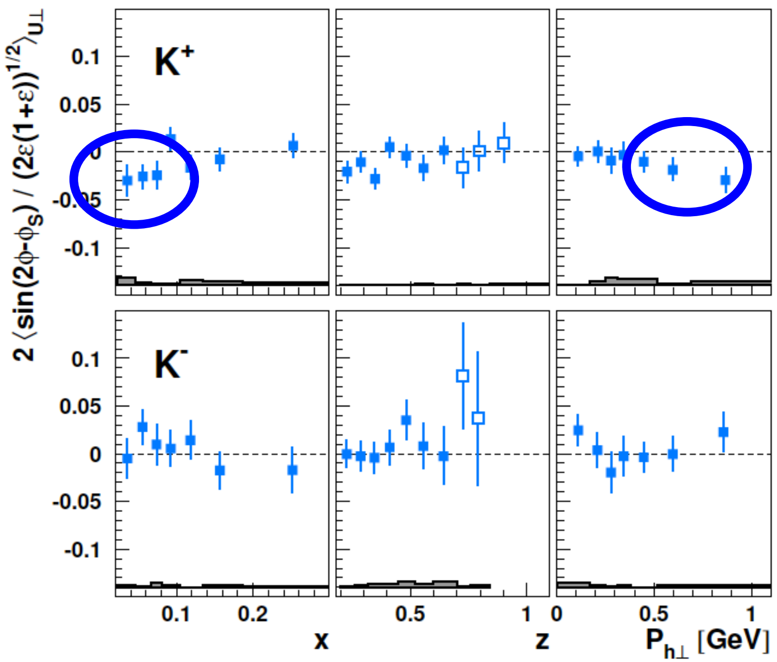


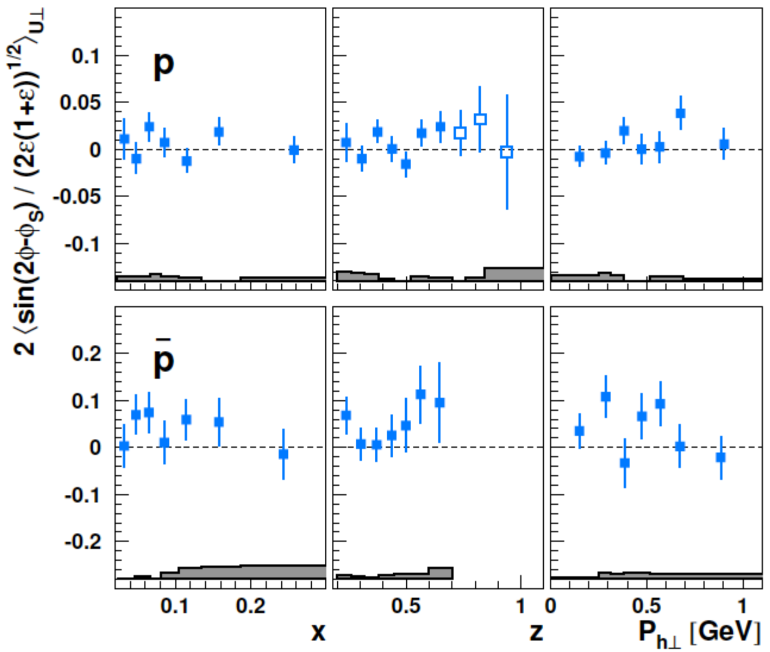
Suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

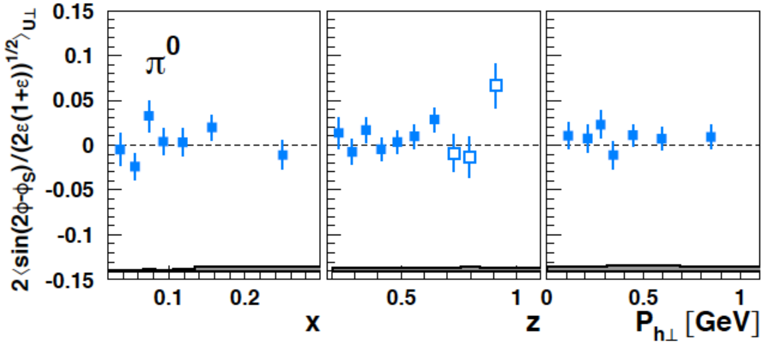
All results are consistent with zero

$\left\langle \sin(2\phi - \phi_S)\,/\sqrt{2\varepsilon(1+\epsilon)} \right\rangle_{U\perp}$: all 1D results









Semi-Inclusive region ($0.2 < z < 0.7$):

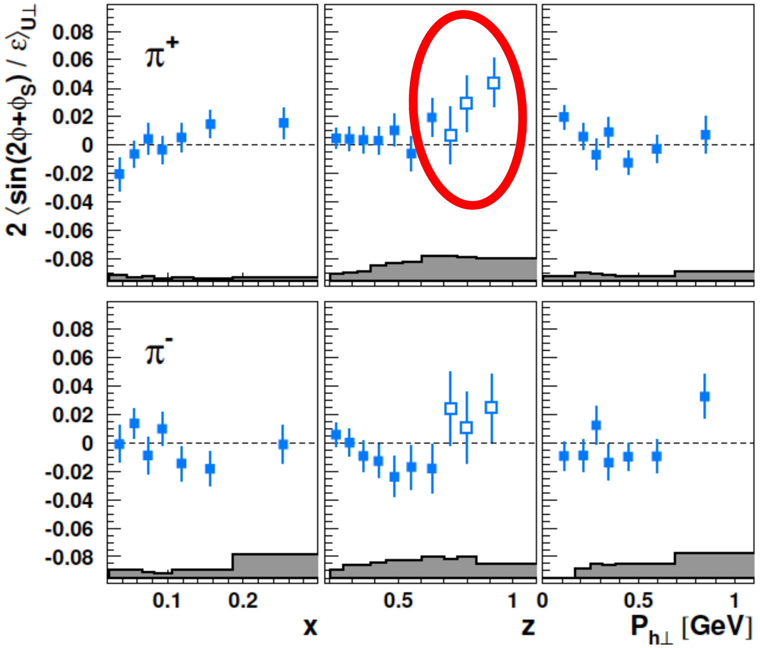
K^+: hint of non-zero signal at small x and large $P_{h\perp}$

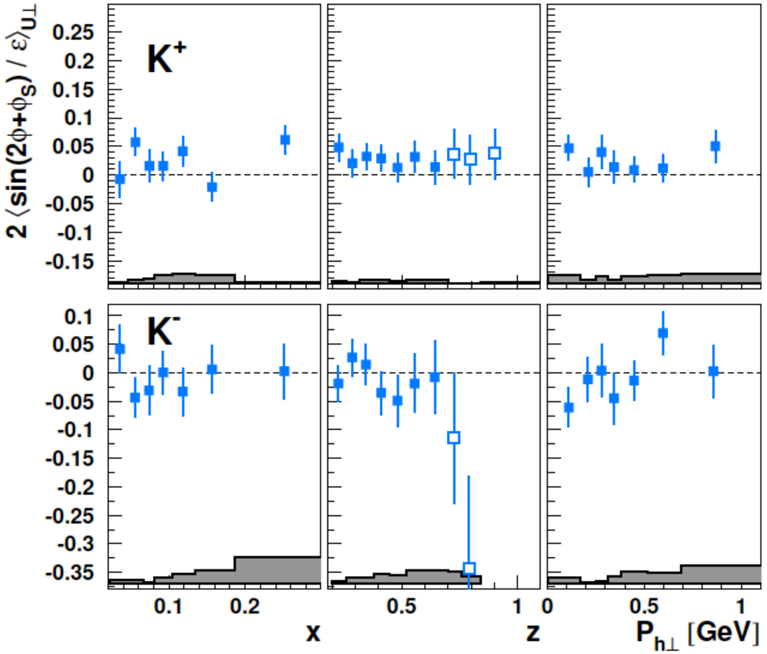
$\bar{p}$: hint of positive amplitude rising with z

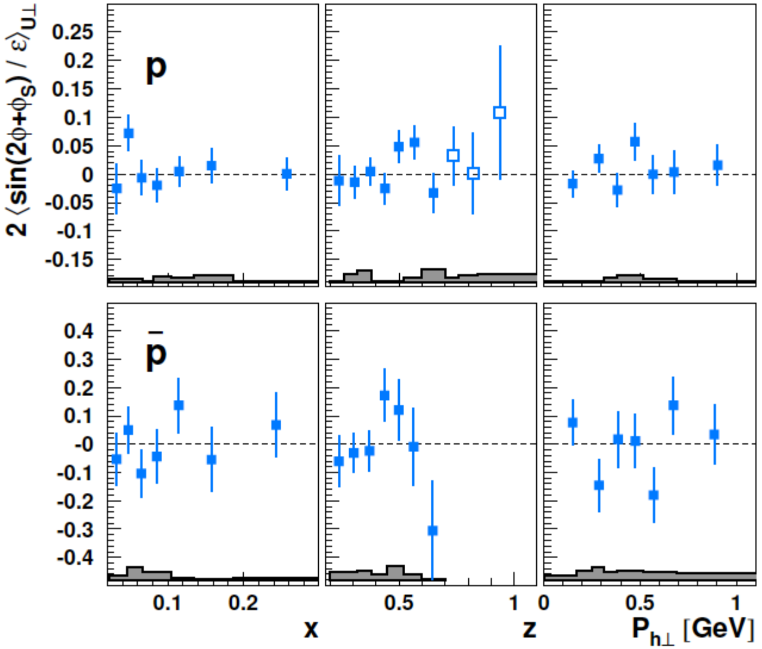
Semi-Exclusive region ($z > 0.7$):

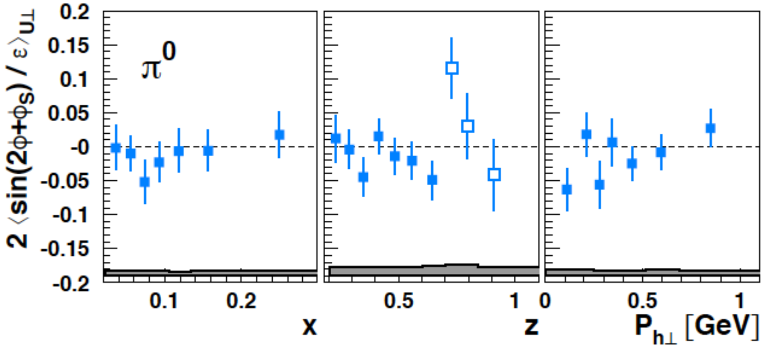
π^+: positive amplitude ($\sim 2\%$) → consistent with positive $\sin(2\phi - \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

$\langle \sin(2\phi + \phi_S)\,/\varepsilon \rangle_{U\perp}$: all 1D results

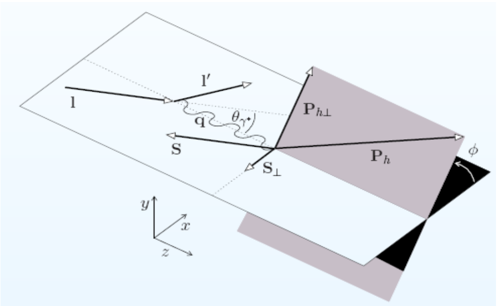








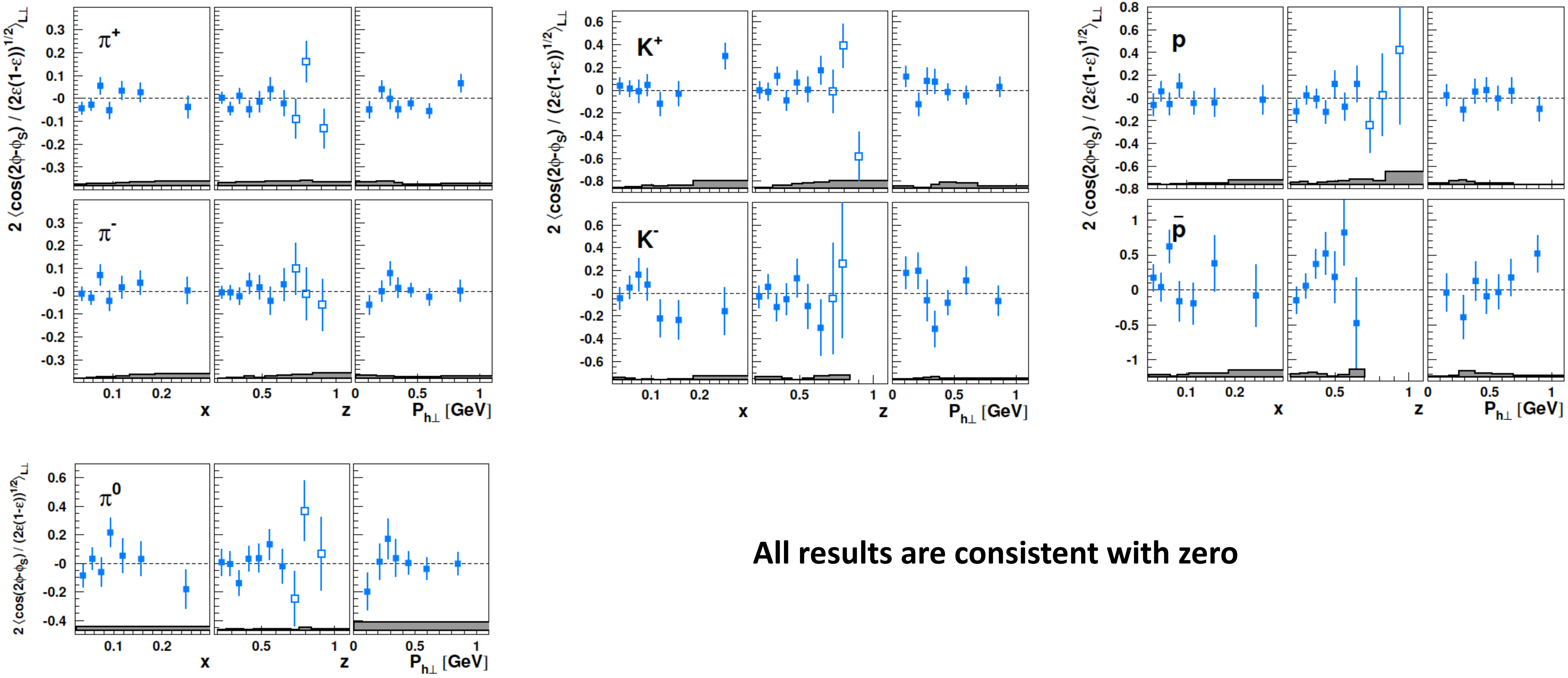
Arises solely from the small longit. target polarization component



Semi-Inclusive region ($0.2 < z < 0.7$):
K^+: positive amplitude over full z range

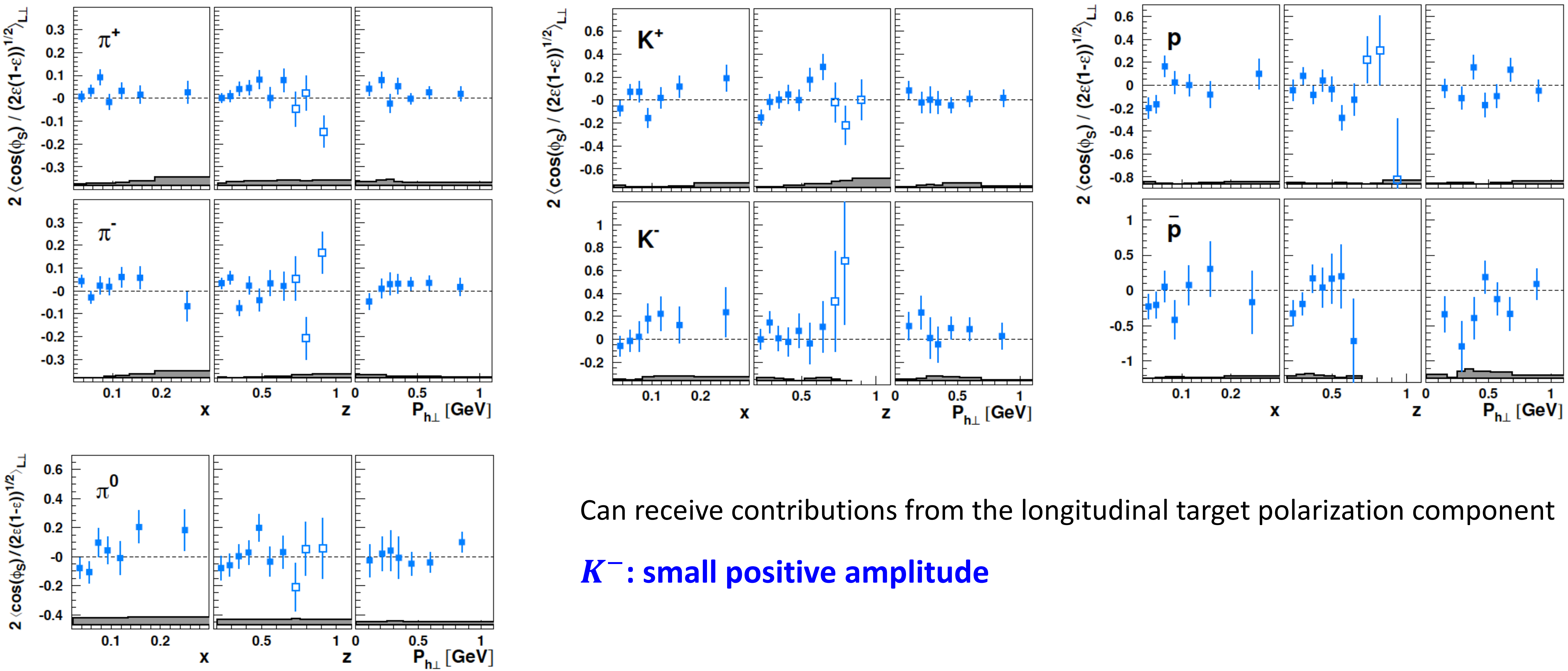
Semi-Exclusive region ($z > 0.7$):
π^+: positive amplitude rising with z → consistent with positive $\sin(2\phi + \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

$\left\langle \cos(2\phi - \phi_S) / \sqrt{2\varepsilon(1-\epsilon)} \right\rangle_{L\perp}$: all 1D results



All results are consistent with zero

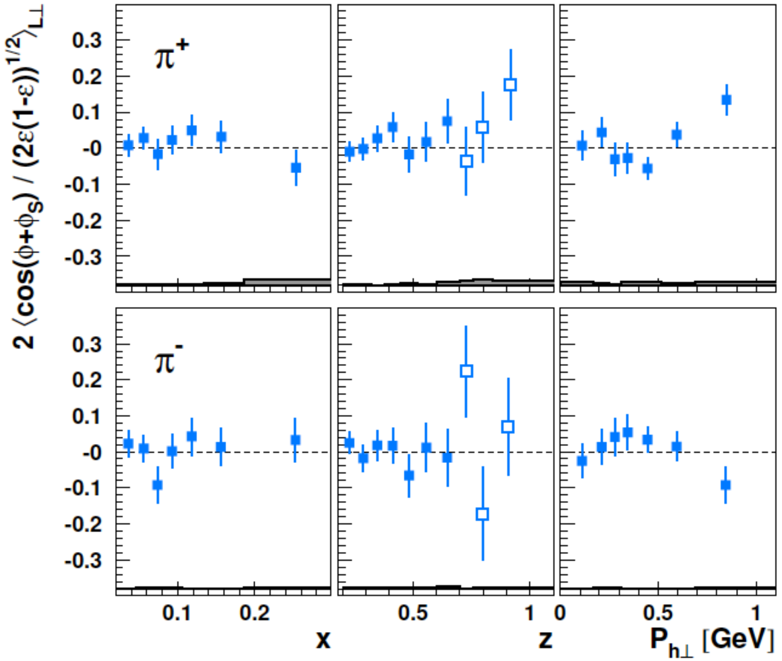
$\left\langle \cos(\phi_S) / \sqrt{2\varepsilon(1-\epsilon)} \right\rangle_{L\perp}$: all 1D results

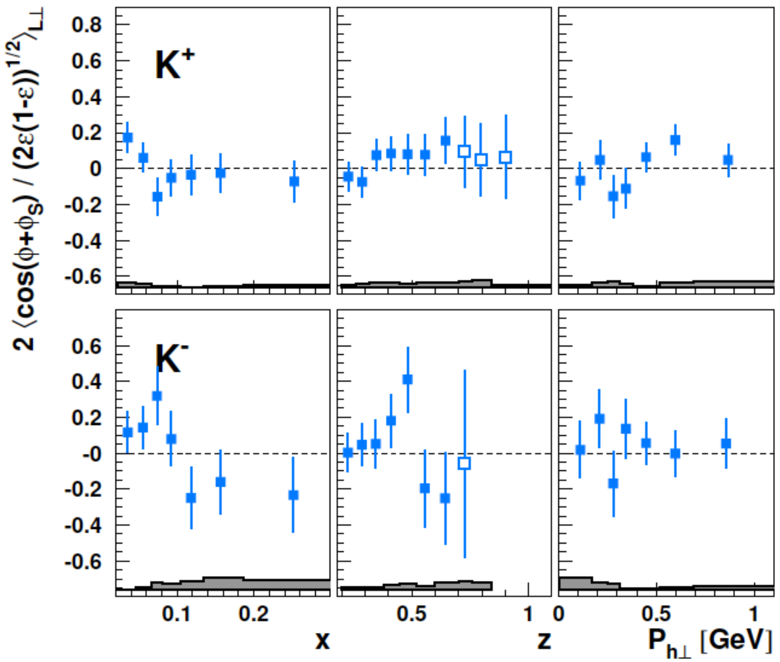


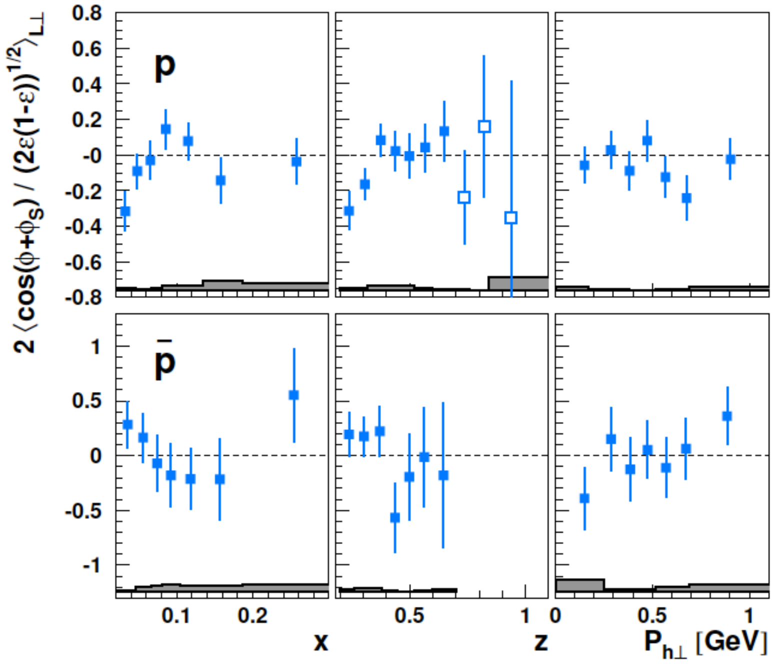
Can receive contributions from the longitudinal target polarization component

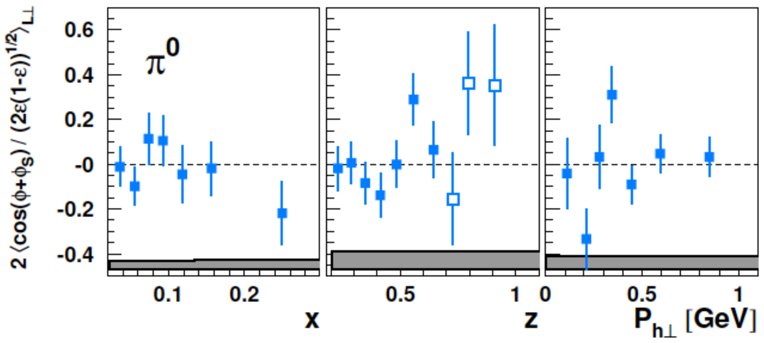
K^-: small positive amplitude

$\left\langle \cos(\phi + \phi_S) \,/\sqrt{2\varepsilon(1-\epsilon)} \right\rangle_{L\perp}$: all 1D results



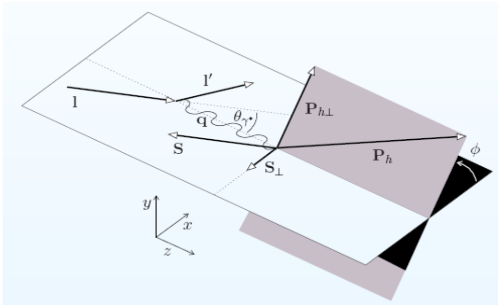






Arises solely from the small longit. target polarization component

All results consistent with zero



Miscellania

The CSA amplitudes

The probability-density function used for the **CSA decomposition** of the cross section

$$
\begin{aligned}
&\mathbb{P}\Big(x, z, P_{h\perp}, \phi, \phi_S, P_l\,, S_\perp : 2\left\langle \sin(\phi-\phi_S)\right\rangle^h_{\mathrm{U}\perp}, \ldots\ 2\left\langle \cos(\phi+\phi_S)\right\rangle^h_{\mathrm{L}\perp}\Big) \\
&= \Big[1 + S_\perp\Big(2\left\langle \sin(\phi-\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(\phi-\phi_S) + 2\left\langle \sin(\phi+\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(\phi+\phi_S) + \\
&\qquad 2\left\langle \sin(3\phi-\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(3\phi-\phi_S) + 2\left\langle \sin(\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(\phi_S) + \\
&\qquad 2\left\langle \sin(2\phi-\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(2\phi-\phi_S) + 2\left\langle \sin(2\phi+\phi_S)\right\rangle^h_{\mathrm{U}\perp} \sin(2\phi+\phi_S)\Big) \\
&\quad + P_l\, S_\perp\Big(2\left\langle \cos(\phi-\phi_S)\right\rangle^h_{\mathrm{L}\perp} \cos(\phi-\phi_S) + 2\left\langle \cos(\phi_S)\right\rangle^h_{\mathrm{L}\perp} \cos(\phi_S) + \\
&\qquad 2\left\langle \cos(2\phi-\phi_S)\right\rangle^h_{\mathrm{L}\perp} \cos(2\phi-\phi_S) + 2\left\langle \cos(\phi+\phi_S)\right\rangle^h_{\mathrm{L}\perp} \cos(\phi+\phi_S)\Big)\Big]^w
\end{aligned}
$$

$A_{U\perp}$ SSAs

$A_{L\perp}$ DSAs

10 Fourier components:

- 6 $A_{U\perp}$ SSAs (4 leading-twist + 2 subleading twist)
- 4 $A_{L\perp}$ DSAs (2 leading-twist + 2 subleading twist)
- $\sin(2\phi + \phi_S)$ and $\cos(\phi + \phi_S)$ terms arise purely from the small but non-vanisning longitudinal target-polarization component (target polarization states are referred to the lepton beam direction)

- **The CSA amplitudes include in their definition the ε-dependent kinematic prefactors that enter the various cross section terms**

The SFA amplitudes (NEW!)

The probability-density function used for the **SFA decomposition** of the cross section

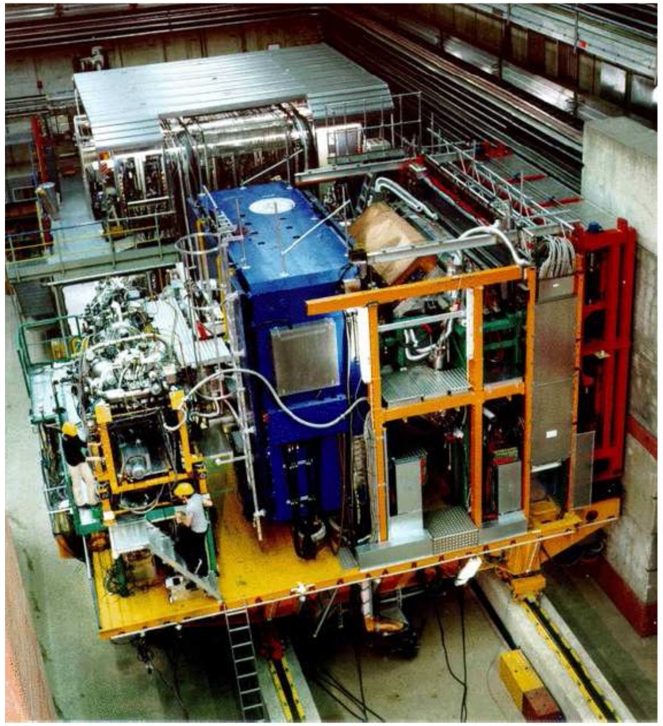
$$
\begin{aligned}
&\mathbb{P}\Big(x, z, \epsilon, P_{h\perp}, \phi, \phi_S, P_l\,, S_\perp : 2\langle \sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp}, \dots 2\langle \cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\,\rangle^h_{\mathrm{L}\perp}\Big) \\
&= \Big[1 + \left.\begin{aligned} &S_\perp\Big(2\langle \sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(\phi-\phi_S) + \boxed{\epsilon}\, 2\langle \sin(\phi+\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(\phi+\phi_S) + \\
&\quad \boxed{\epsilon}\, 2\langle \sin(3\phi-\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(3\phi-\phi_S) + \boxed{\sqrt{2\epsilon(1+\epsilon)}}\, 2\langle \sin(\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\,\rangle^h_{\mathrm{U}\perp} \sin(\phi_S) + \\
&\quad \boxed{\sqrt{2\epsilon(1+\epsilon)}}\, 2\langle \sin(2\phi-\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\,\rangle^h_{\mathrm{U}\perp} \sin(2\phi-\phi_S) + \boxed{\epsilon}\, 2\langle \sin(2\phi+\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(2\phi+\phi_S)\Big)\end{aligned}\right\} A_{U\perp}\ \text{SSAs} \\
&\quad \left.\begin{aligned} &+P_l\, S_\perp\Big(\boxed{\sqrt{1-\epsilon^2}}\, 2\langle \cos(\phi-\phi_S)/\sqrt{1-\epsilon^2}\,\rangle^h_{\mathrm{L}\perp} \cos(\phi-\phi_S) + \boxed{\sqrt{2\epsilon(1-\epsilon)}}\, 2\langle \cos(\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\,\rangle^h_{\mathrm{L}\perp} \cos(\phi_S) + \\
&\quad \boxed{\sqrt{2\epsilon(1-\epsilon)}}\, 2\langle \cos(2\phi-\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\,\rangle^h_{\mathrm{L}\perp} \cos(2\phi-\phi_S) + \boxed{\sqrt{2\epsilon(1-\epsilon)}}\, 2\langle \cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\,\rangle^h_{\mathrm{L}\perp} \cos(\phi+\phi_S)\Big)\Big]^w\end{aligned}\right\} A_{L\perp}\ \text{DSAs}
\end{aligned}
$$

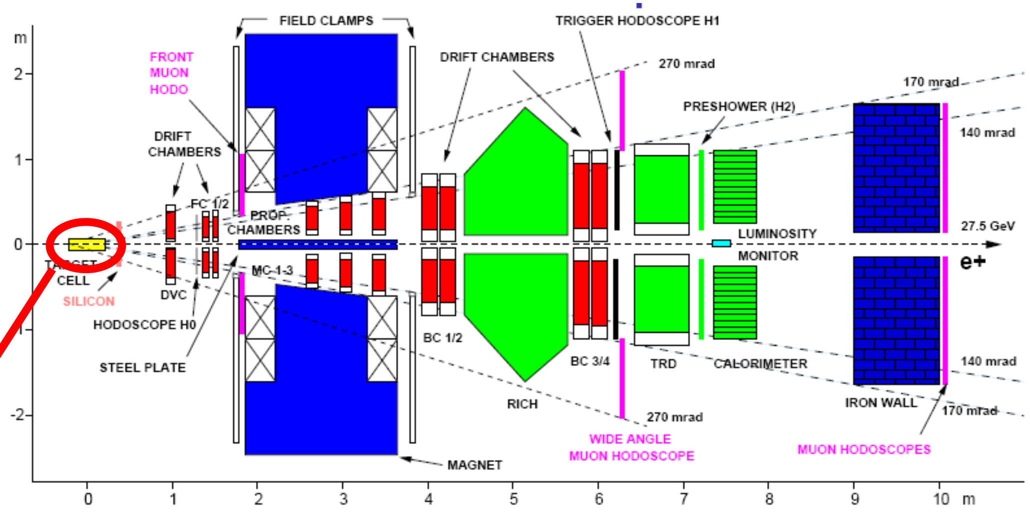
10 Fourier components:

- 6 $A_{U\perp}$ SSAs (4 leading-twist + 2 subleading twist)
- 4 $A_{L\perp}$ DSAs (2 leading-twist + 2 subleading twist)
- $\sin(2\phi+\phi_S)$ and $\cos(\phi+\phi_S)$ terms arise purely from the small but non-vanisning longitudinal target-polarization component (target polarization states are referred to the lepton beam direction)

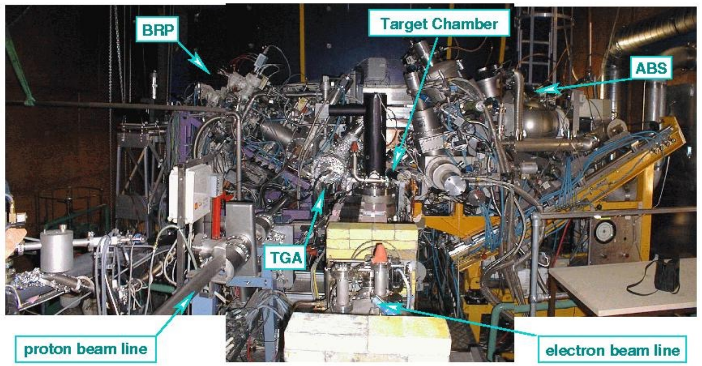
- **The SFA amplitudes do not include the ε-dependent kinematic prefactors of the various cross section terms.**
- They are obtained by including explicitly the ε-dependent kinematic prefactors in the probability-density function separated from the fit parameters.

The HERMES experiment at HERA (1995-2007)

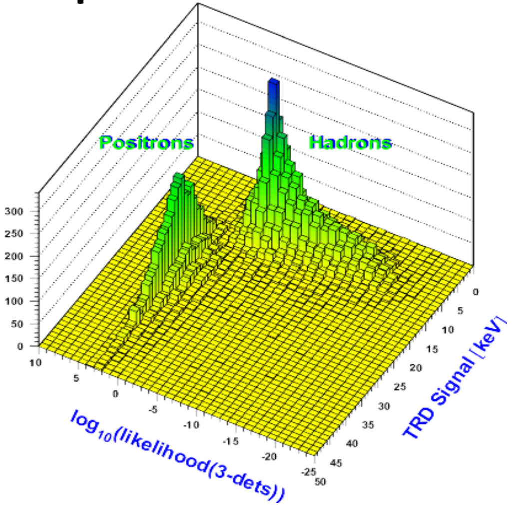




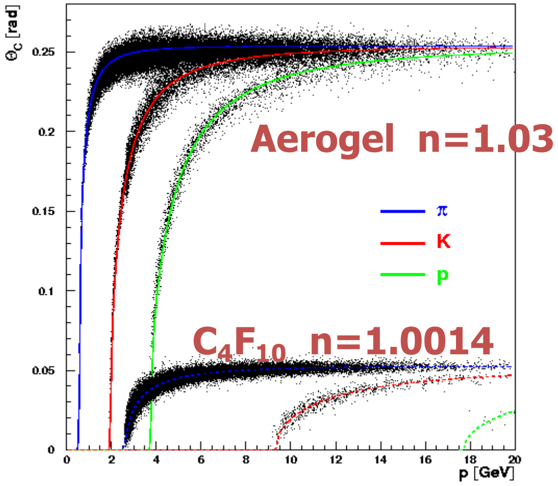
The polarized gas target



TRD, Calorimeter, preshower, RICH:
lepton-hadron > 98%



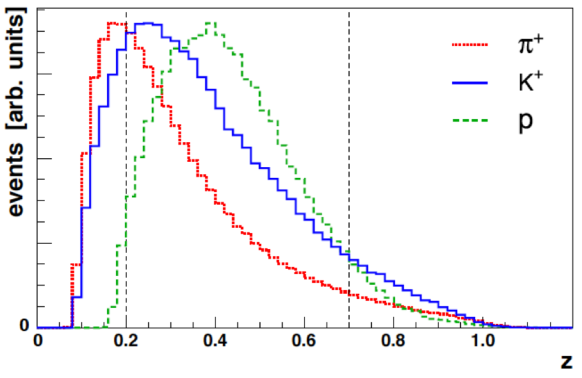
hadron separation

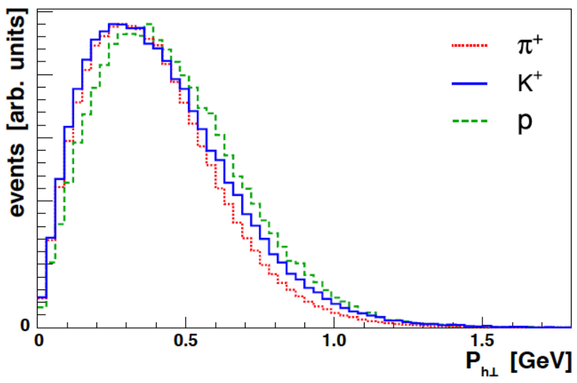


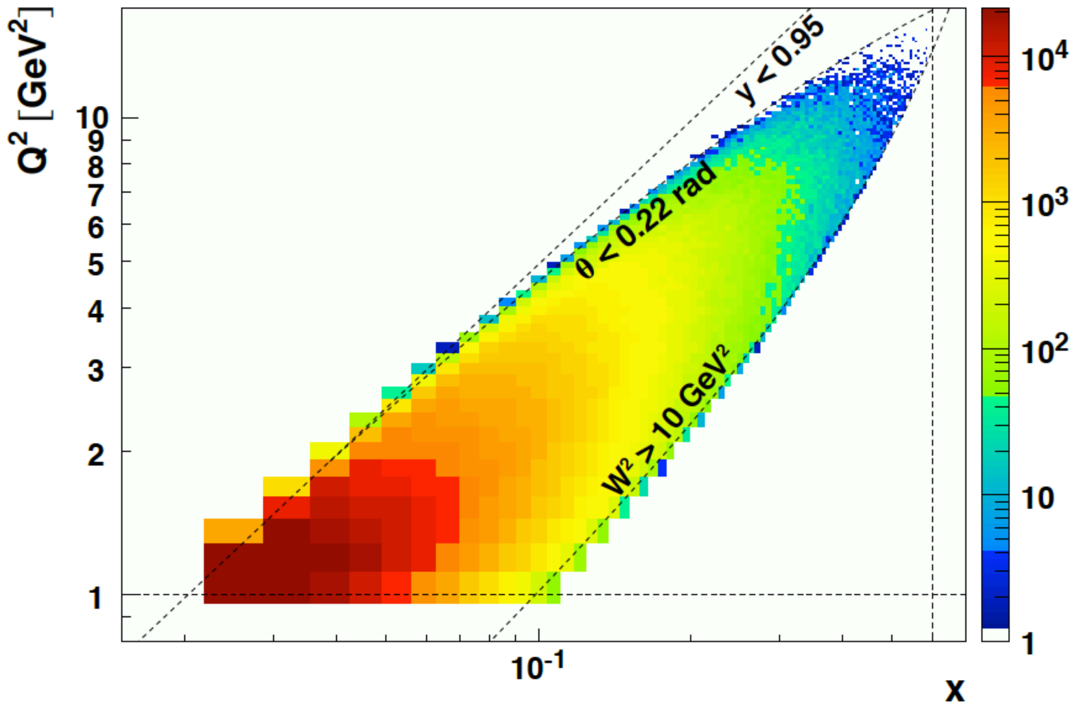
π ~ 98%, K ~ 88% , P ~ 85%

Kinematic coverage

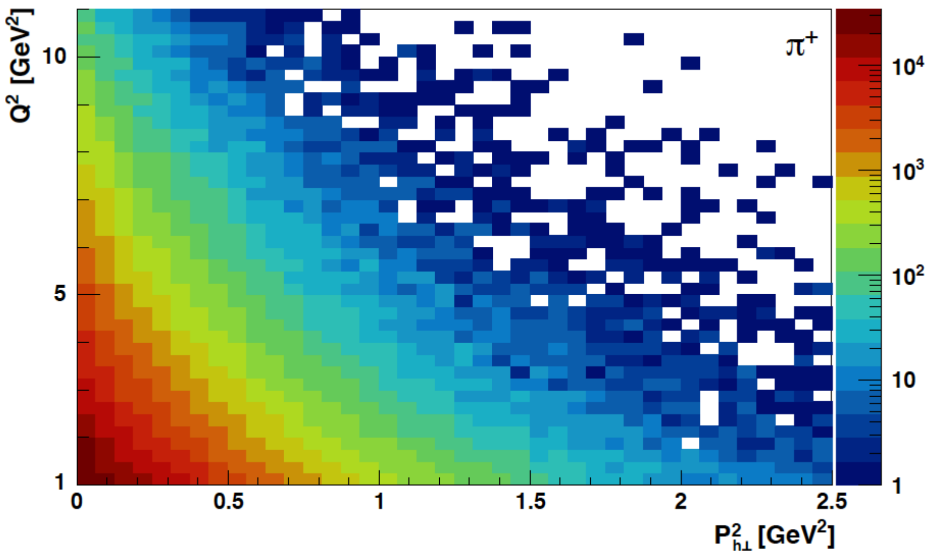
Scattered lepton:		Q^2	$> 1\,\mathtt{GeV}^2$	
		W^2	$> 10\,\mathtt{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\mathtt{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathtt{GeV}$	charged mesons
	$4\,\mathtt{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathtt{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\mathtt{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\mathtt{GeV}$	
	$0.2 <$	z	< 0.7 (1.2 for the "semi-exclusive" region)	







Kinematic coverage and factorization requirements

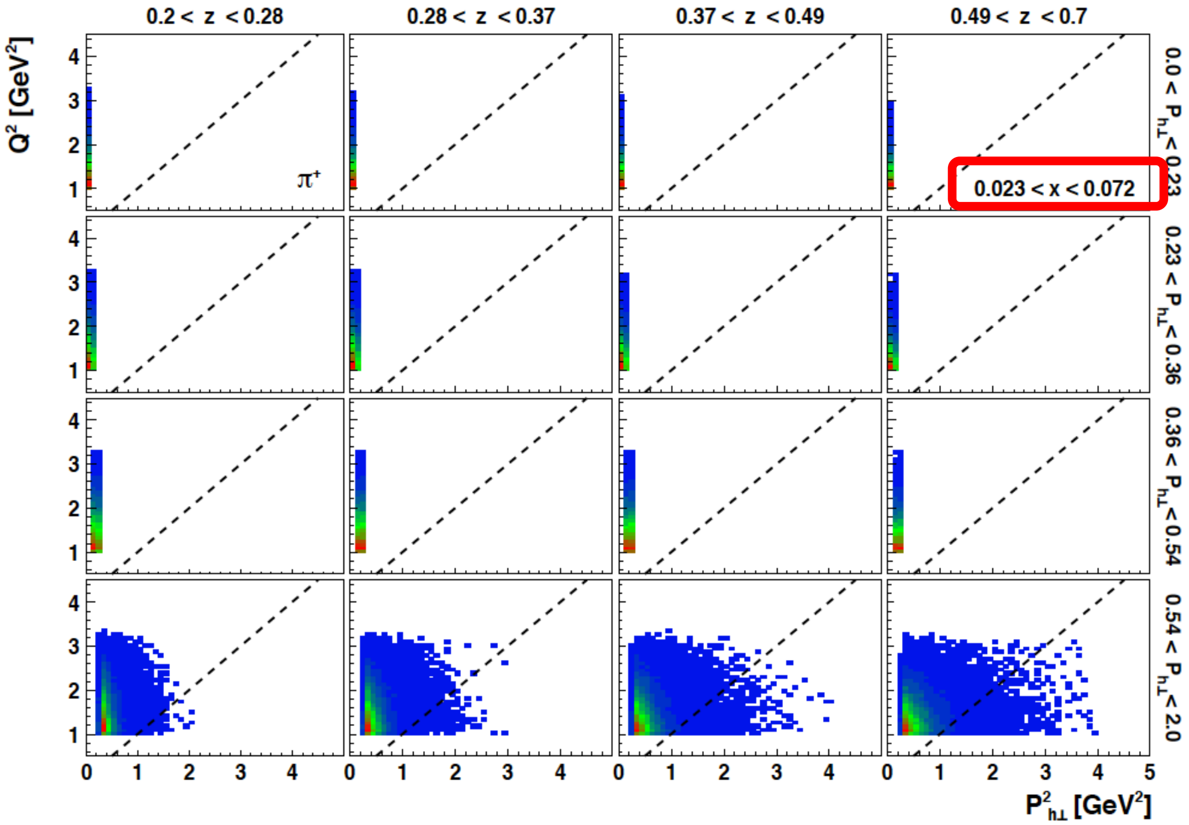


- Factorization requirement $P_{h\perp}^2 \ll Q^2$ fulfilled for most of the selected DIS events

- the stricter constraint $P_{h\perp}^2 \ll z^2Q^2$ is violated at large $P_{h\perp}$ in the region of small x and small z

- detailed studies in appendix B of the paper (and next slides)

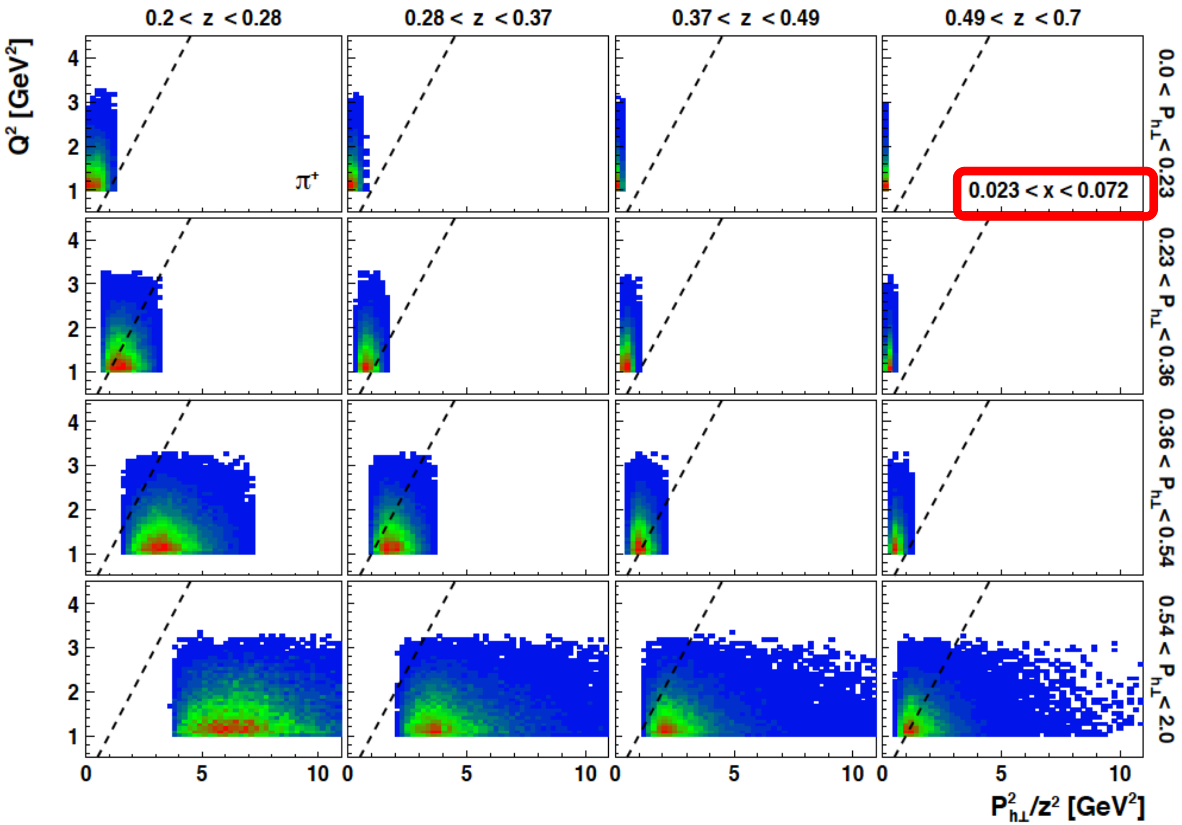
Due to x-Q^2 correlation, the **first x bin** corresponds to the **small Q^2 region**, where the **TMD-factorization requirement $P_{h\perp}^2 \ll Q^2$** is less favourable.



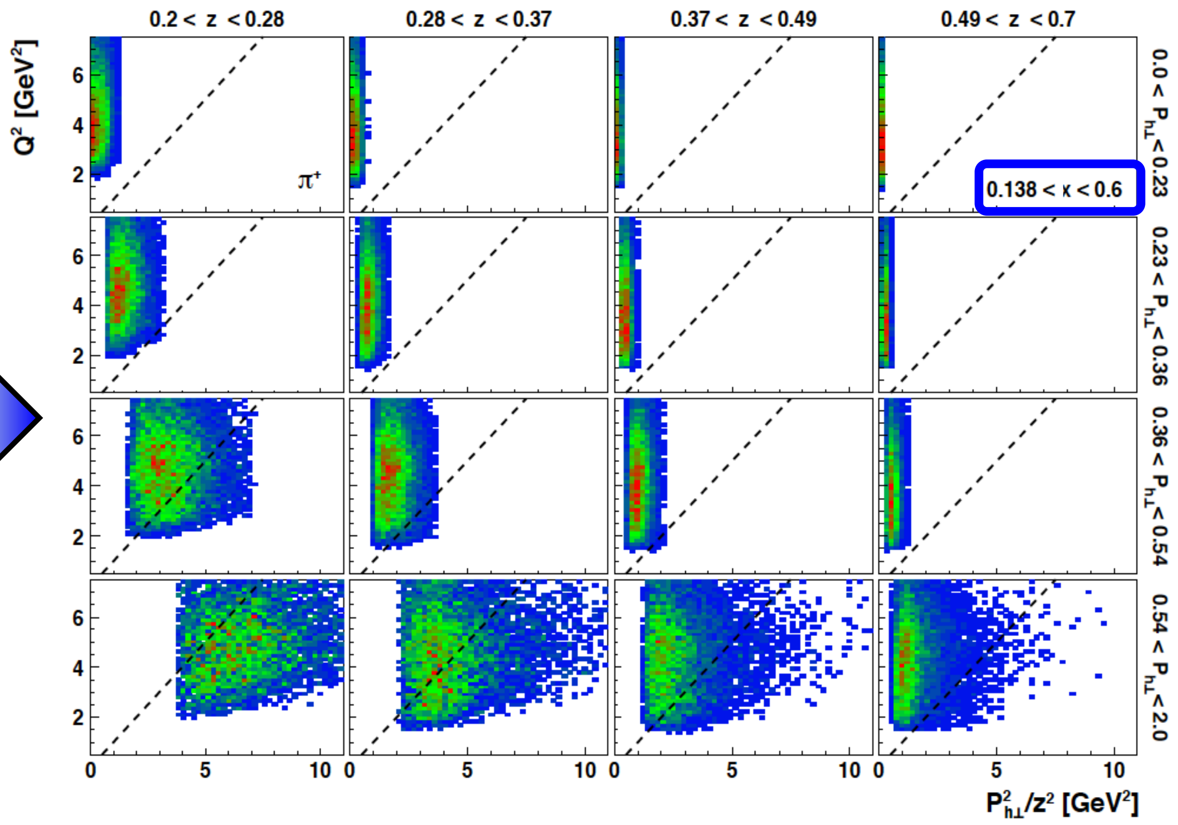
TMD-factorization requirement $P_{h\perp}^2 \ll Q^2$ fulfilled for most of the selected DIS events!

Factorization requirements

Due to the $1/z^2$ factor, which becomes large at small z, the **stricter condition $P_{h\perp}^2/z^2 \ll Q^2$** is unfulfilled for the majority of the events:

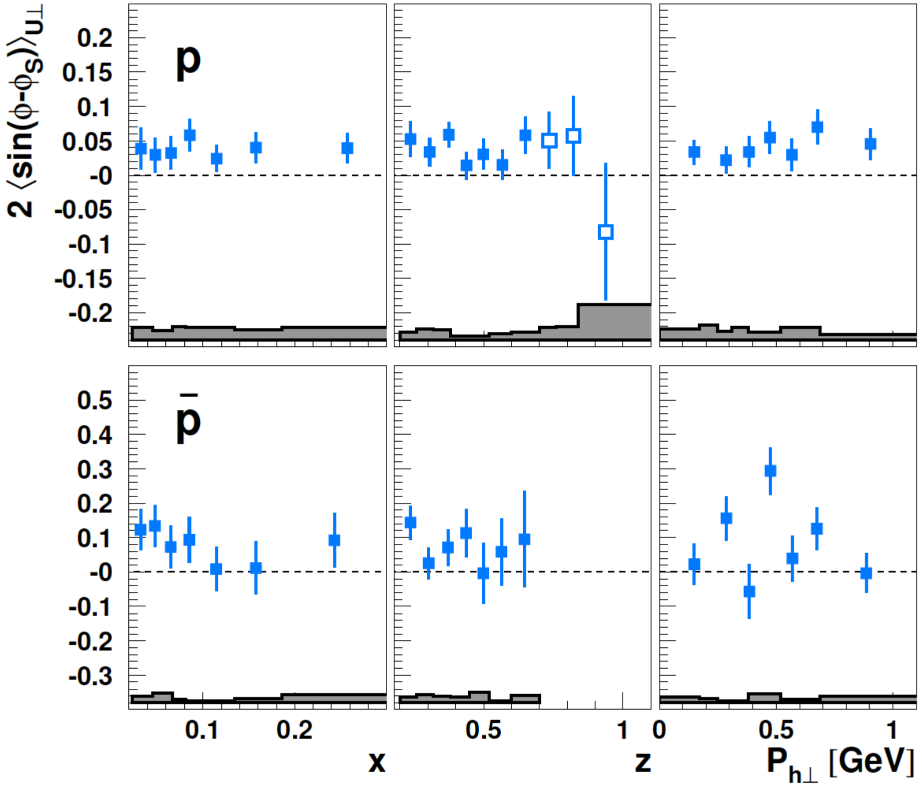


First x-bin → smaller Q^2



Last x-bin → larger Q^2

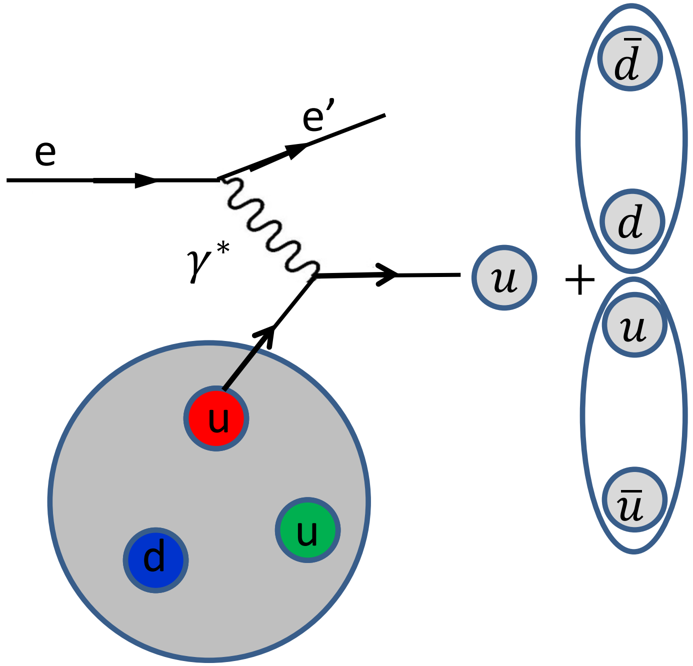
Sivers amplitudes: protons results

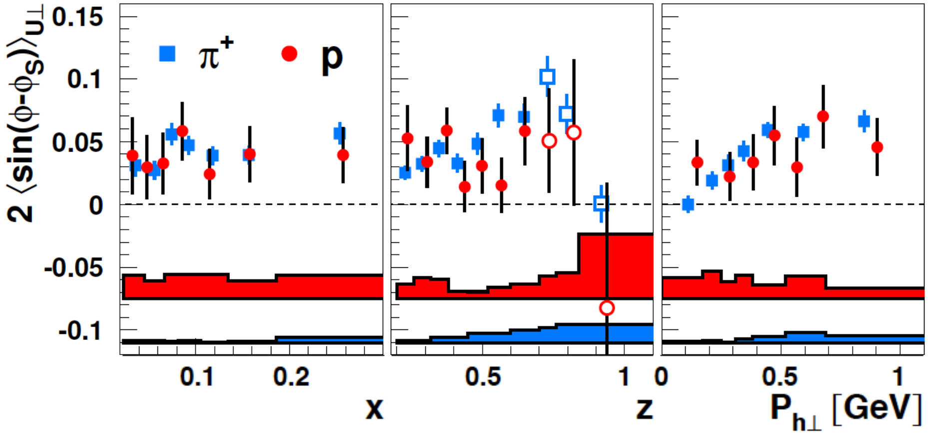


First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive

A naive fragmentation process that can lead to $p/\bar{p}$:





Similar agreement between $\bar{p}$ and π^+ (but with larger statistical errors)

Let's assume scattering off the up quark (dominance of u-quarks in $p/\bar{p}$ production supported by global fits of FF [Phys.Rev.D76:074033,2007])

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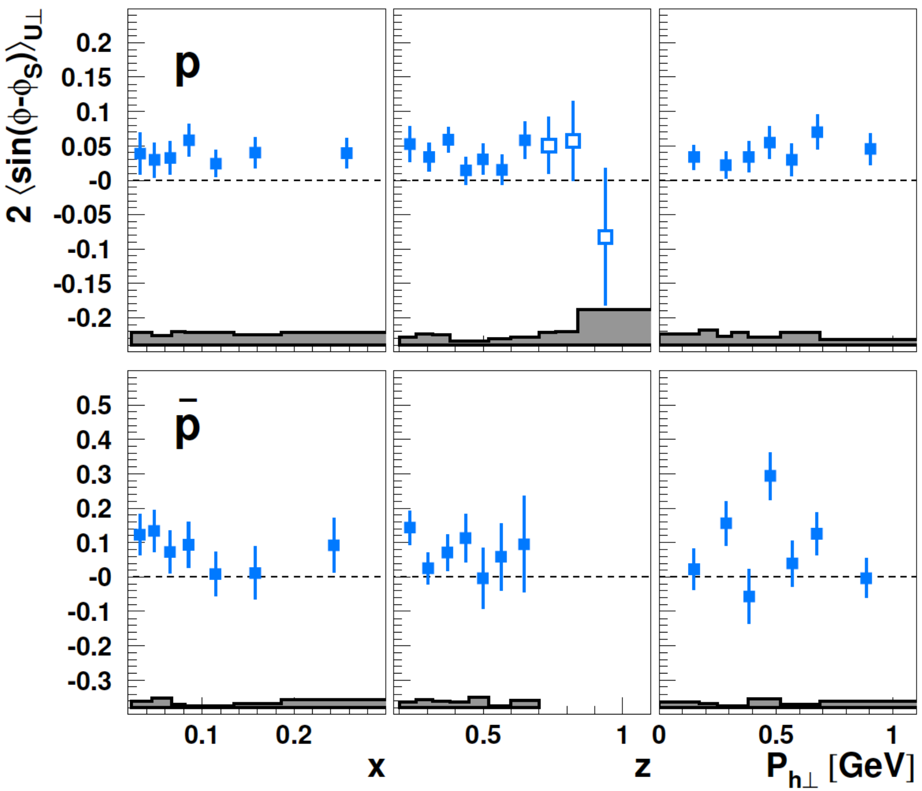

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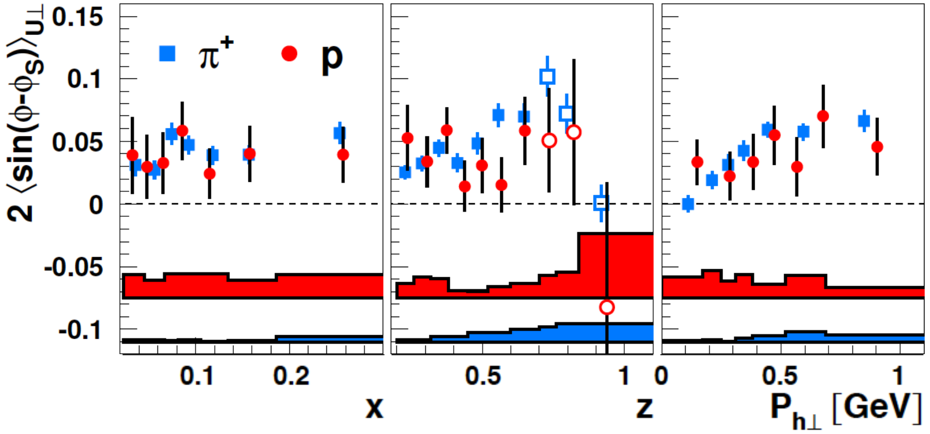

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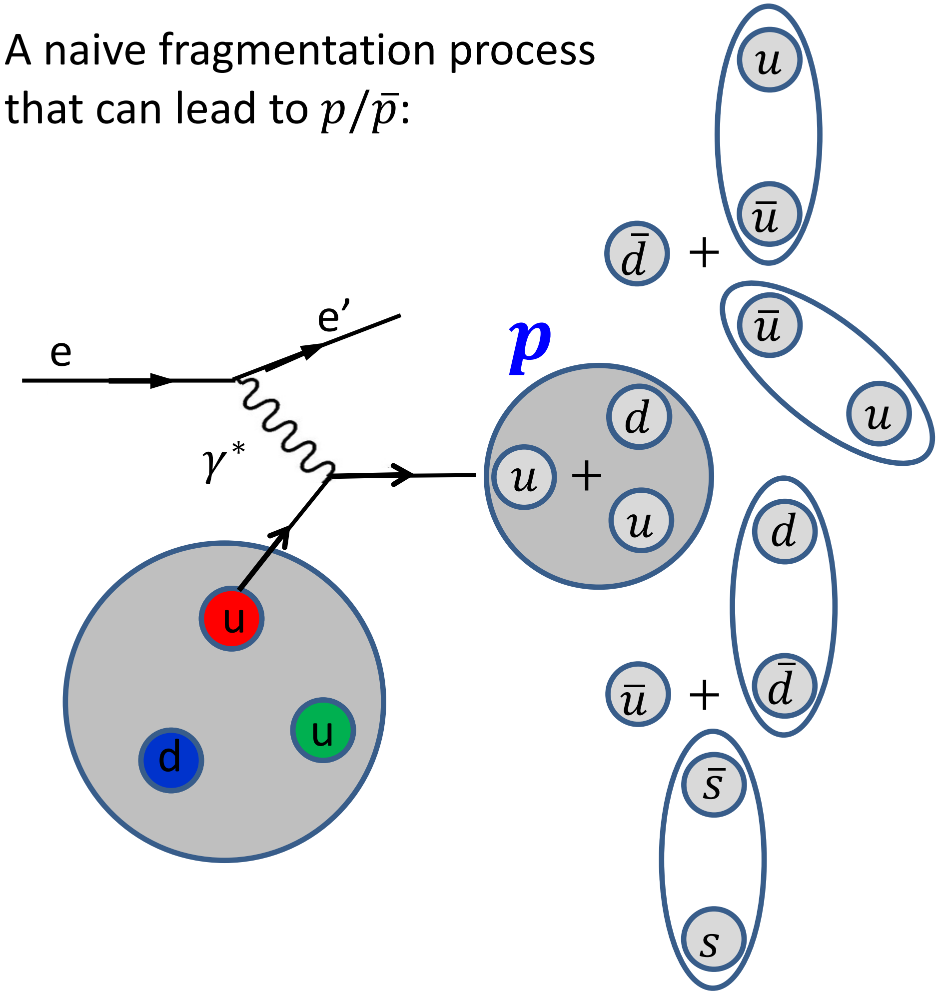

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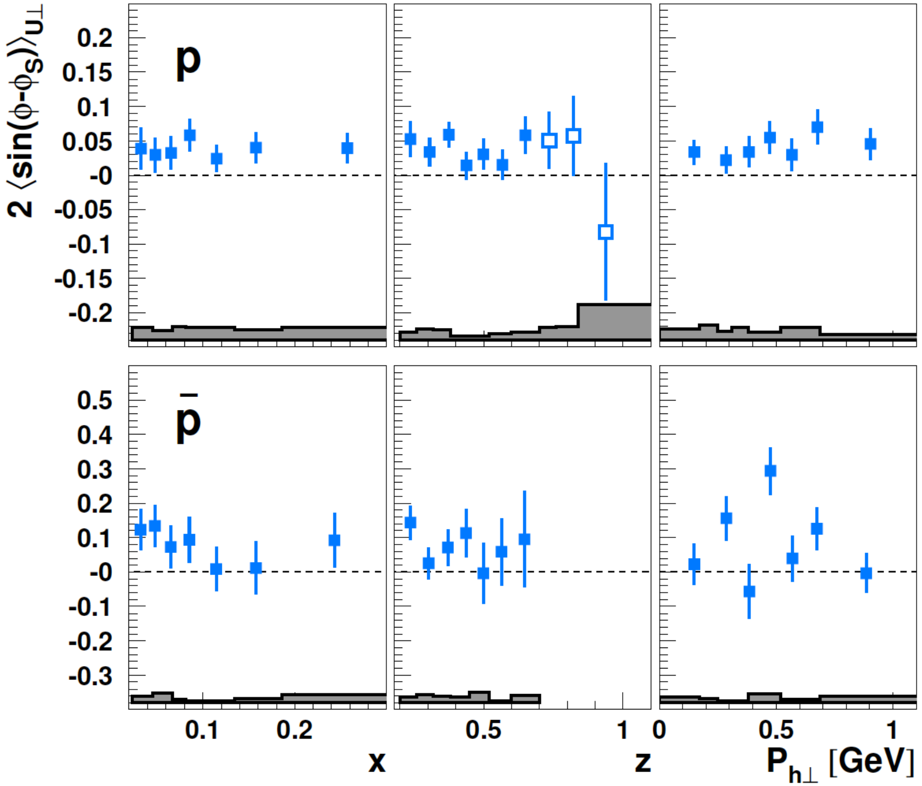

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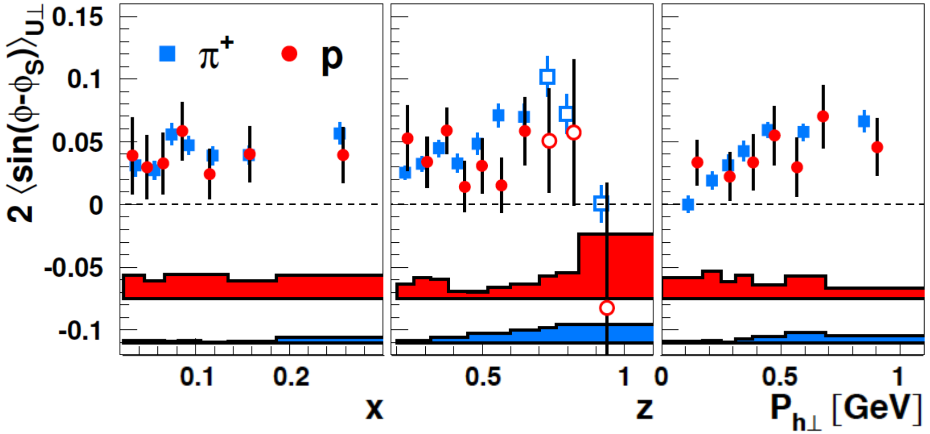

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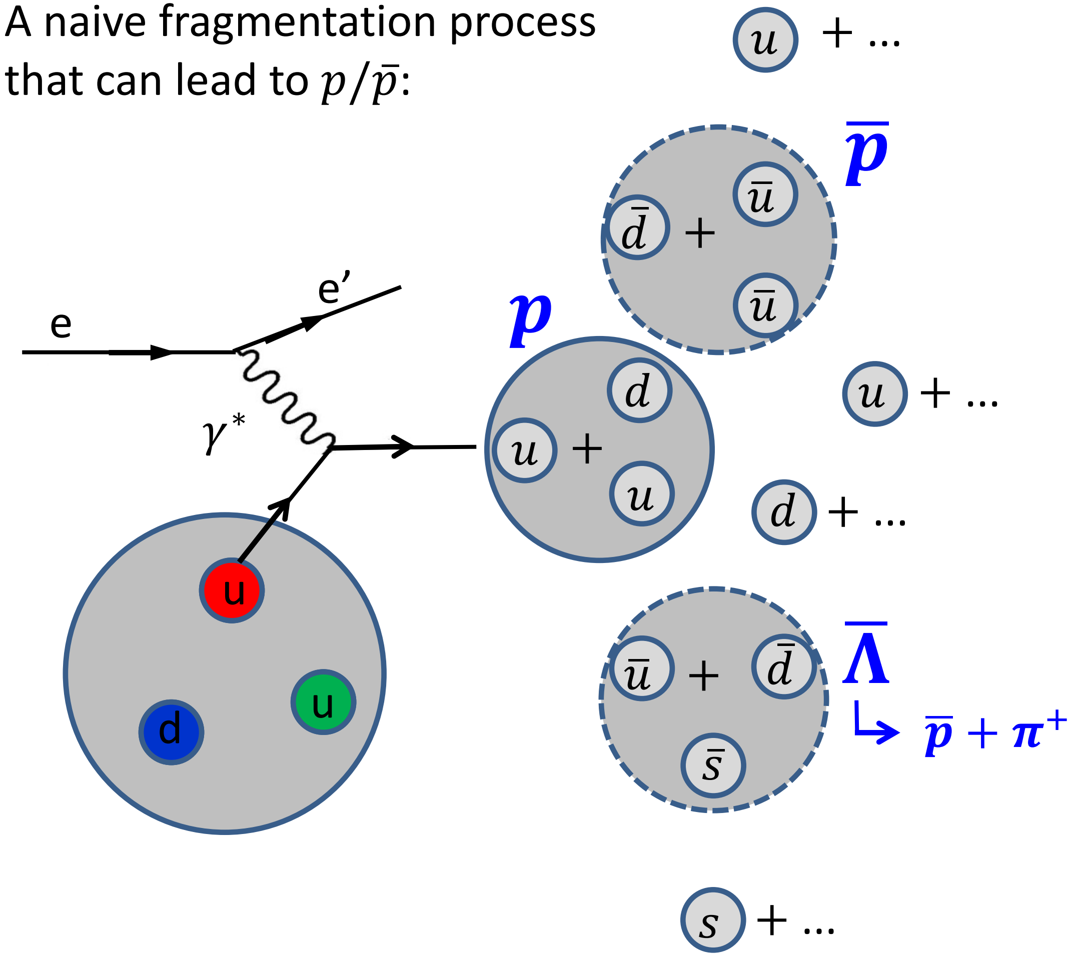

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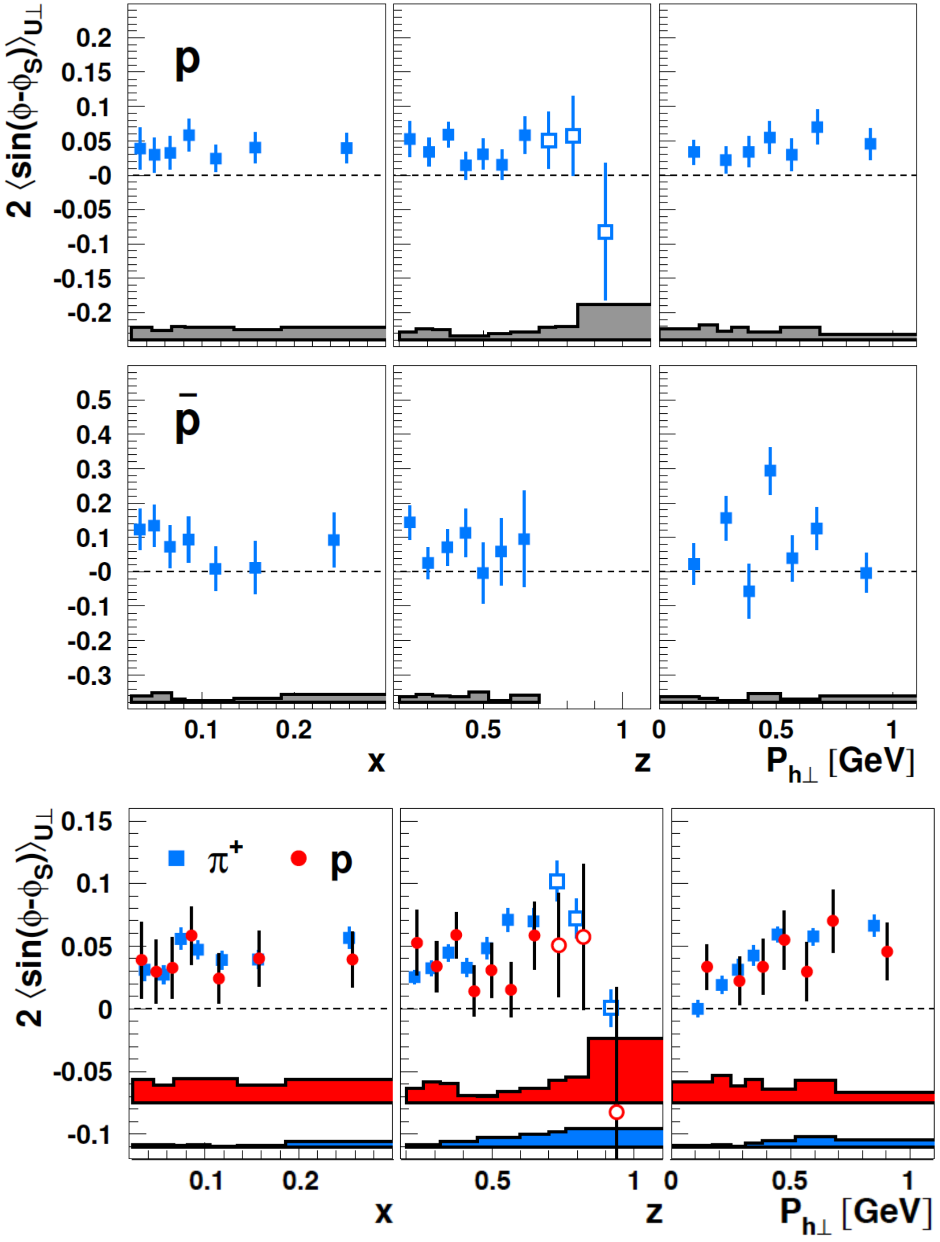
Sivers amplitudes: protons results



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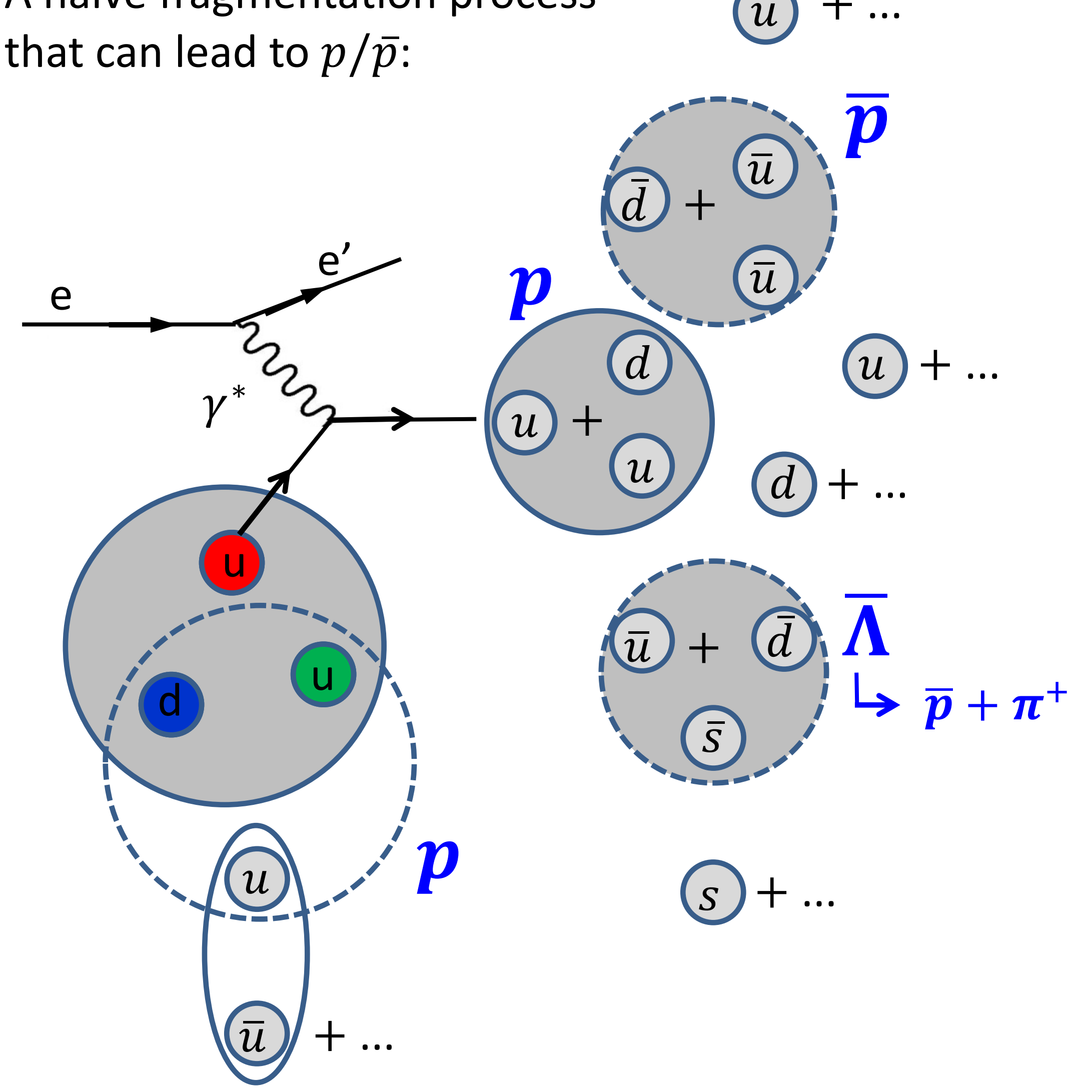
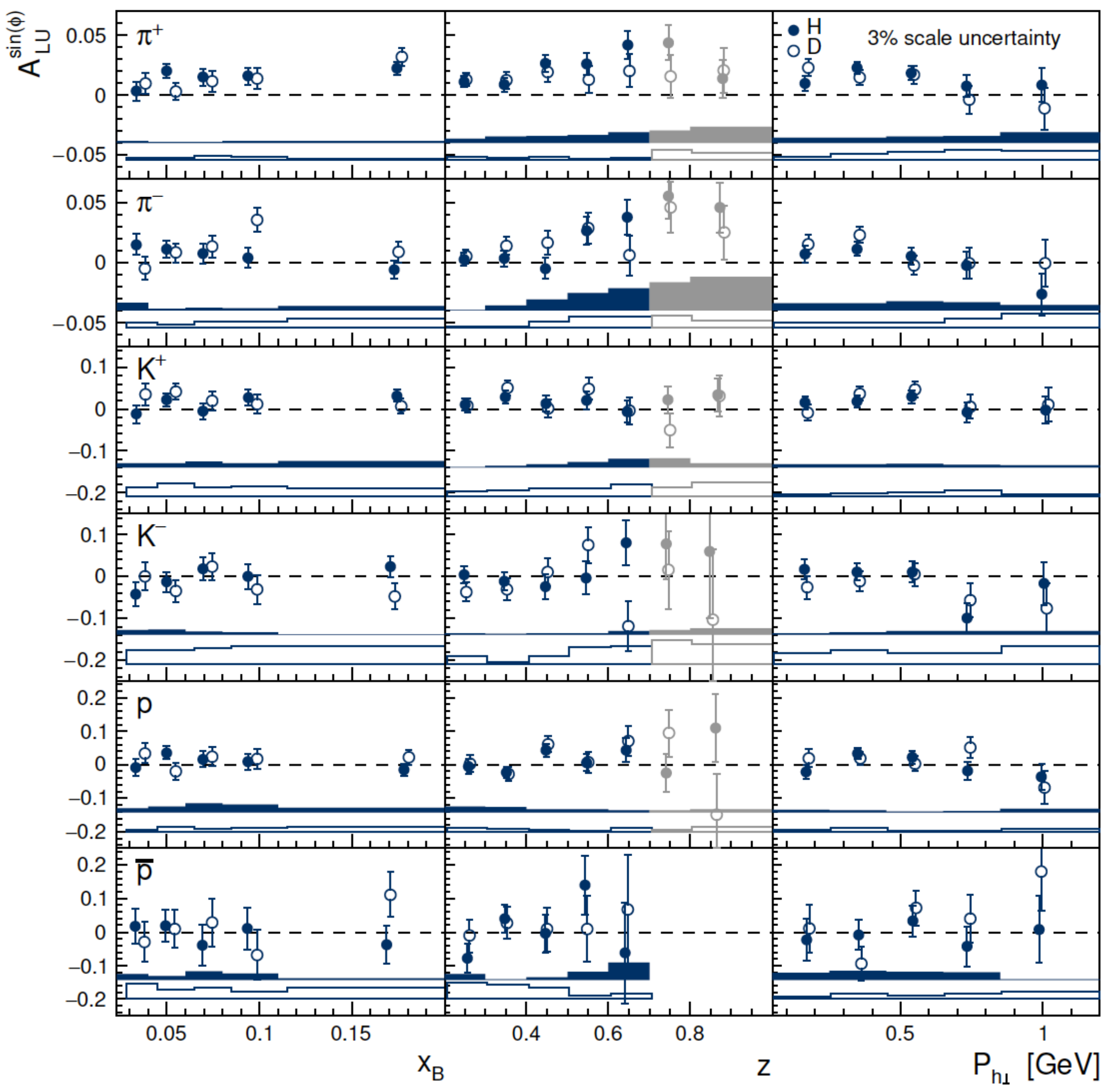


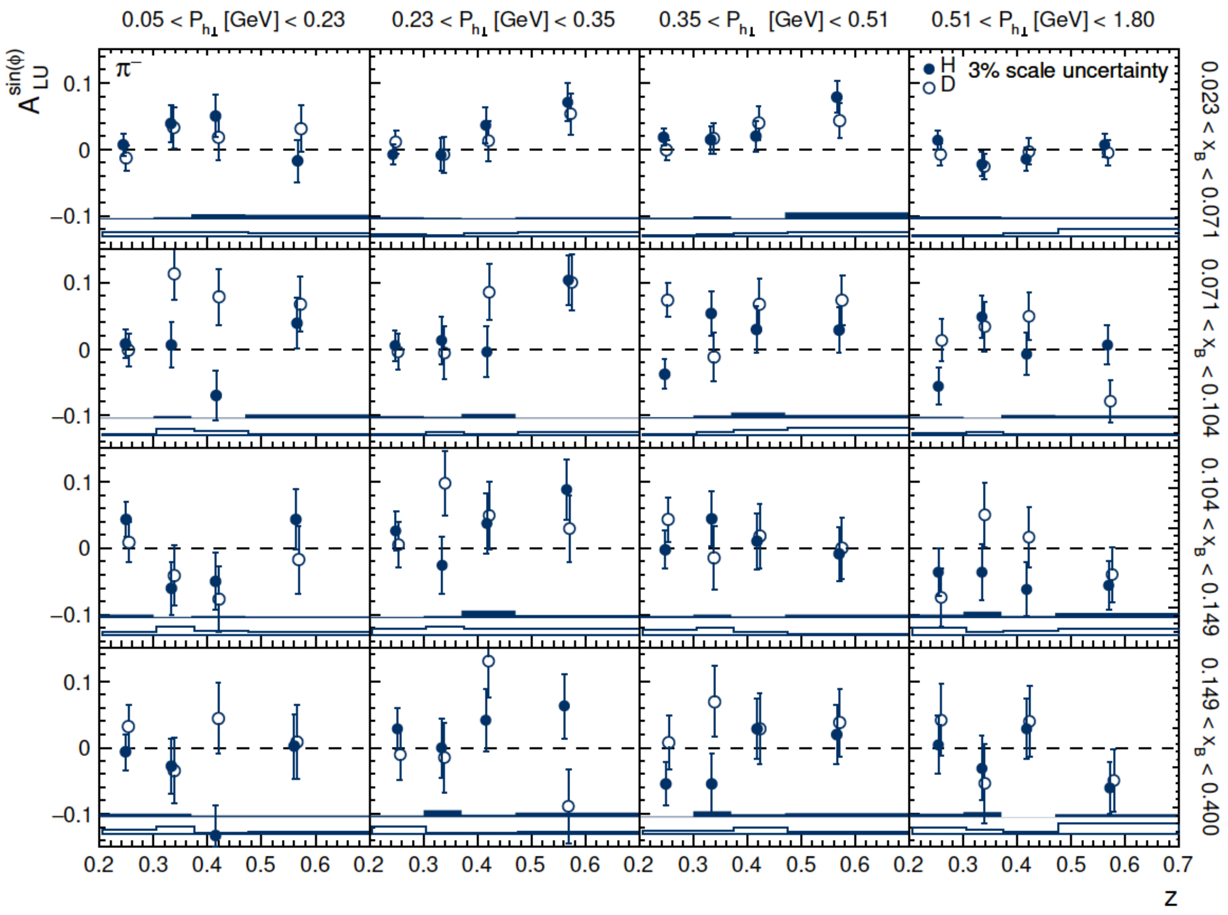
...also from TFR (low z, high $P_{h\perp}$)

Other HERMES results

Sub-leading twist $\sin(\phi)$ BSA

Phys. Lett. B 797 (2019) 134886



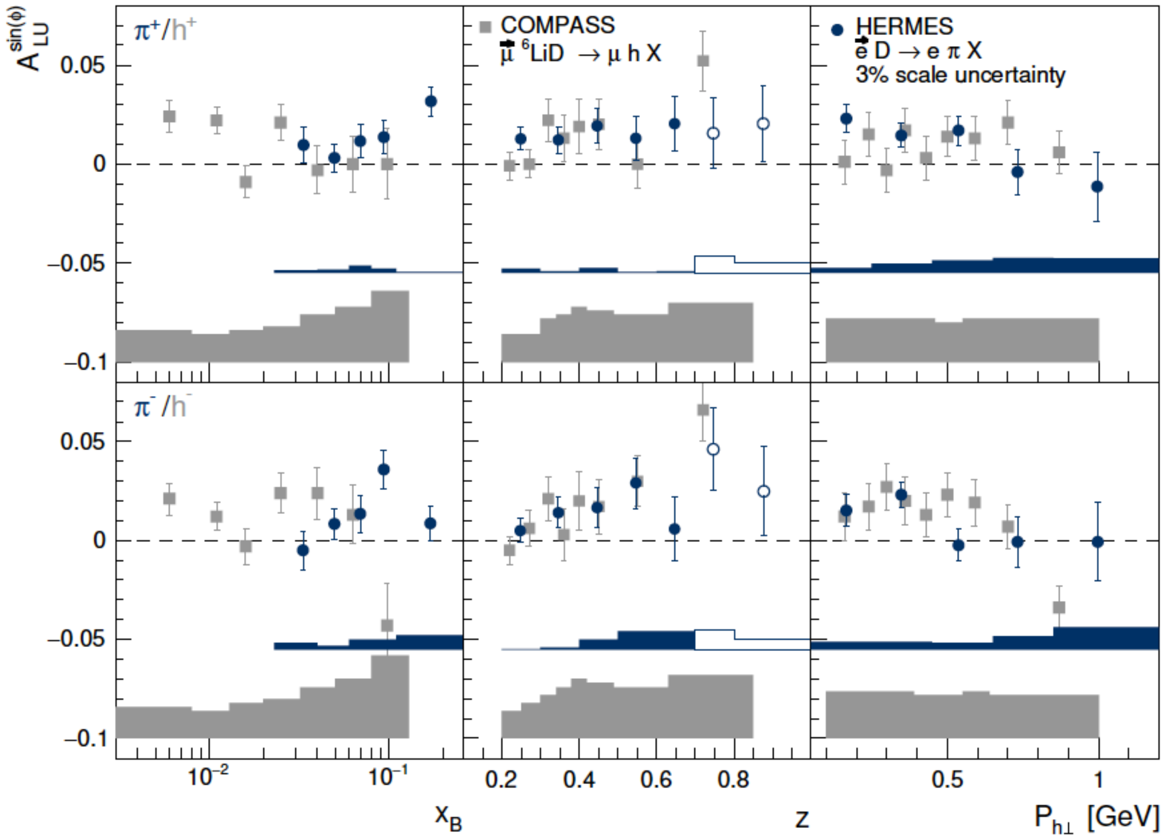


- Large positive amplitudes rising with z for π^+ and π^-
- Small positive amplitude with mild kinematic dep. for K^+
- Results compatible with zero for K^-, p and $\bar{p}$

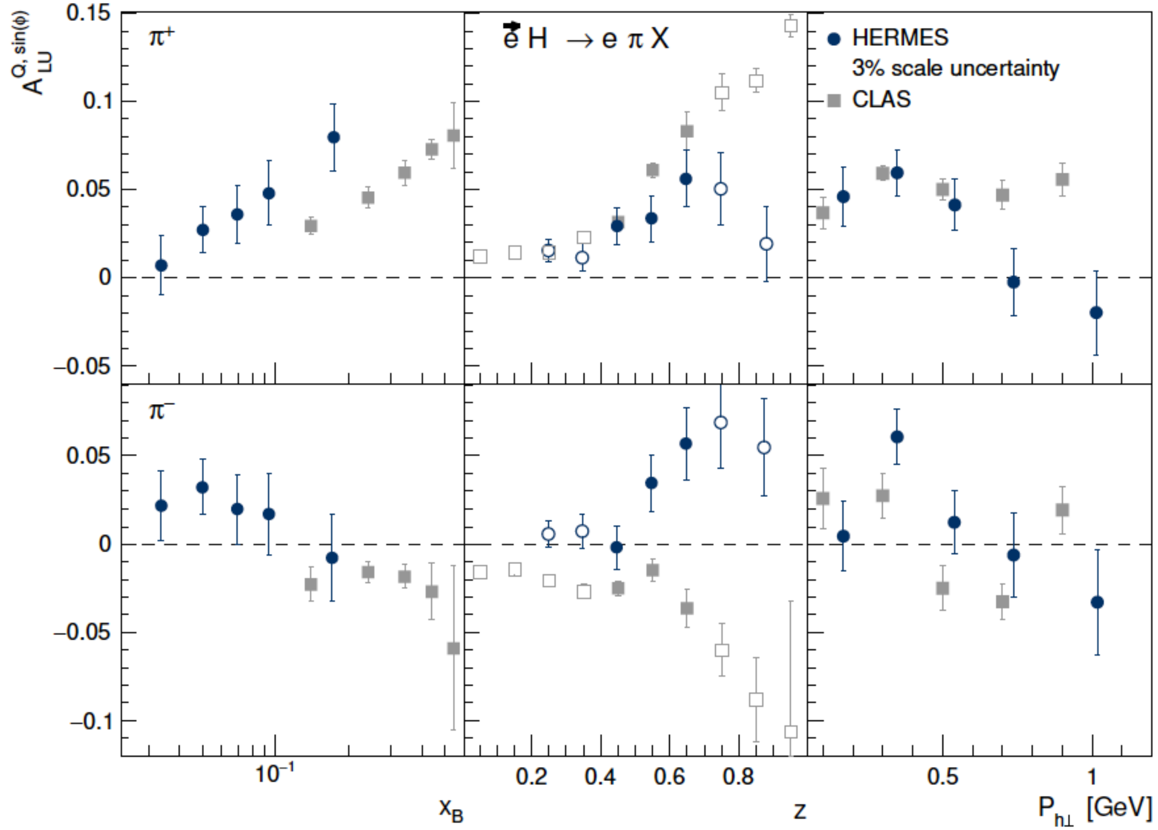
Sub-leading twist $\sin(\phi)$ BSA

Phys. Lett. B 797 (2019) 134886

HERMES vs. COMPASS



HERMES vs. CLAS

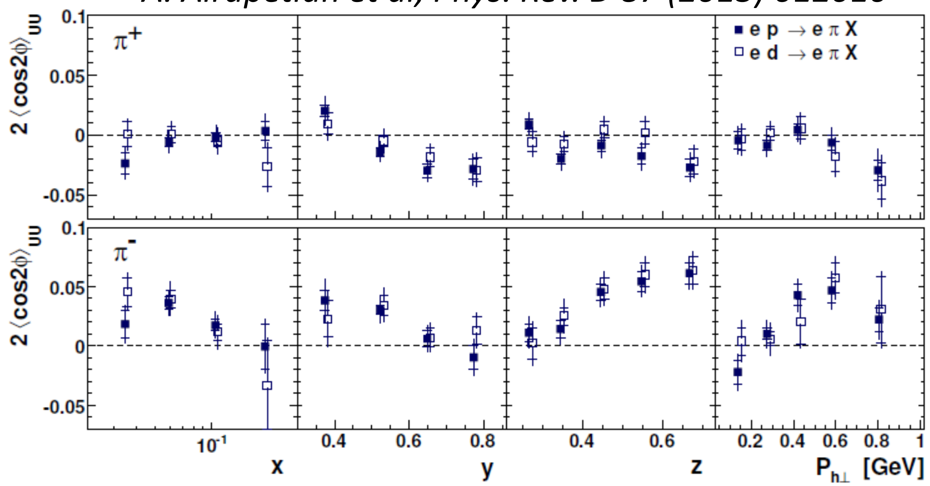


$$\underbrace{\hspace{4cm}}$$

Sign change with increasing x?

The cos2ϕ amplitudes $\propto h_1^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

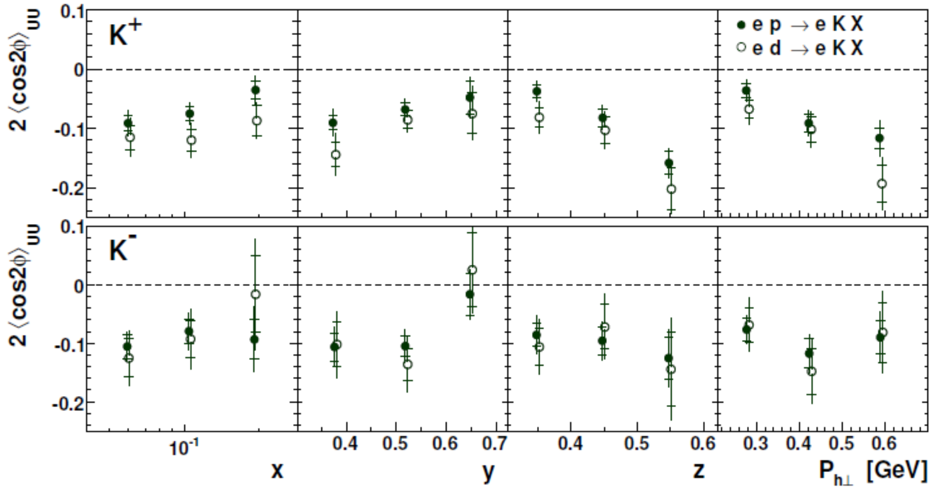
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

positive

- **Amplitudes are significant**
  $\rightarrow$ evidence of BM effect
- **similar results for H & D**
  $\rightarrow h_1^{\perp,u} \approx h_1^{\perp,d}$
- **Opposite sign for π^+/π^-**
  $\rightarrow$ opposite signs of fav/unfav Collins FF



Large and negative

Large and negative

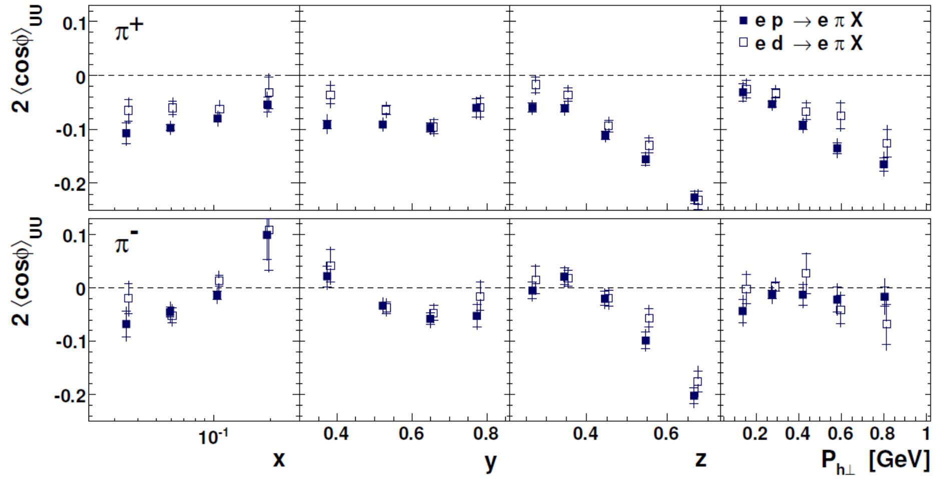
- **K^+/K^- amplitudes larger than for pions, have different kinematic dependencies than pions and are both negative**

$\rightarrow$ different role of Collins FF for pions and kaons?

$\rightarrow$ significant contribution from scattering off strange quarks**?**

The cosϕ amplitudes $\propto +\frac{1}{Q}[h_1^{\perp} \otimes H_1^{\perp} + f_1 \otimes D_1 \ldots]$

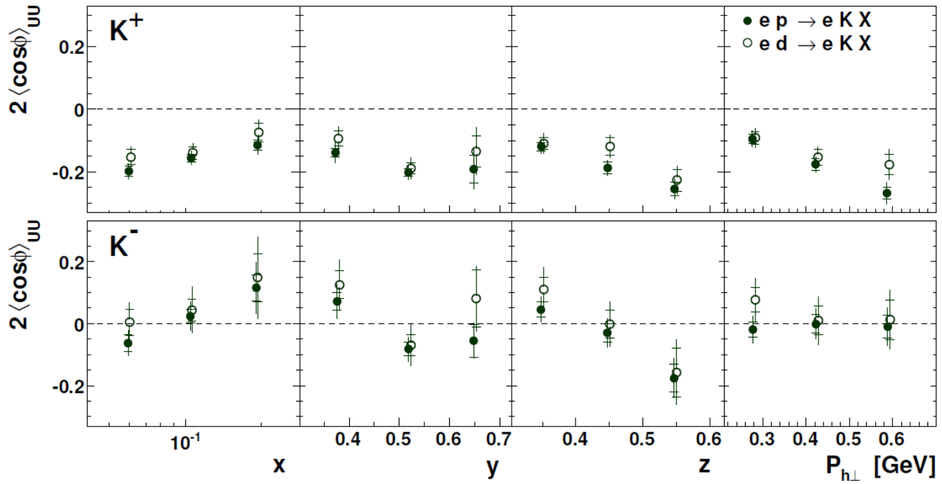
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

negative

- **Significant and of same sign** → Chan effect weekly flavor dependent?
- **Clear rise with z for π^+& π^- and $P_{h\perp}$ for π^+**
- **Different $P_{h\perp}$ dependence** → contrib. of flavor dependent effects (e.g. BM) for π^-?



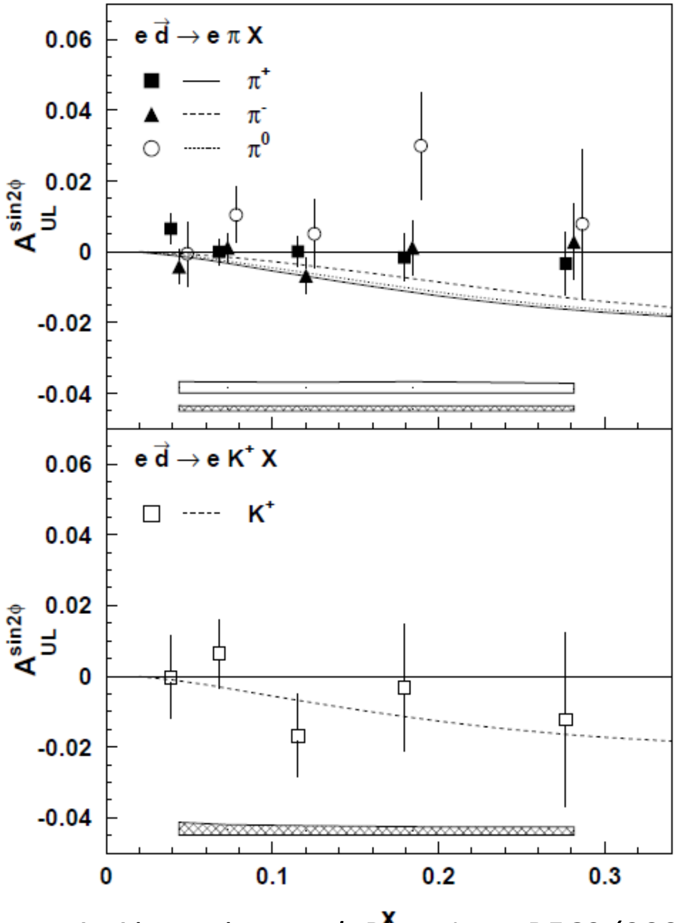
Large and negative

Consist. with 0

- **K^+ amplitudes larger than π^+** → different Collins FF for π & K
- **$K^- \approx 0$ different than K^+ (in contrast to $\cos 2\phi$)**
- Significant contrib from interaction dependent terms?

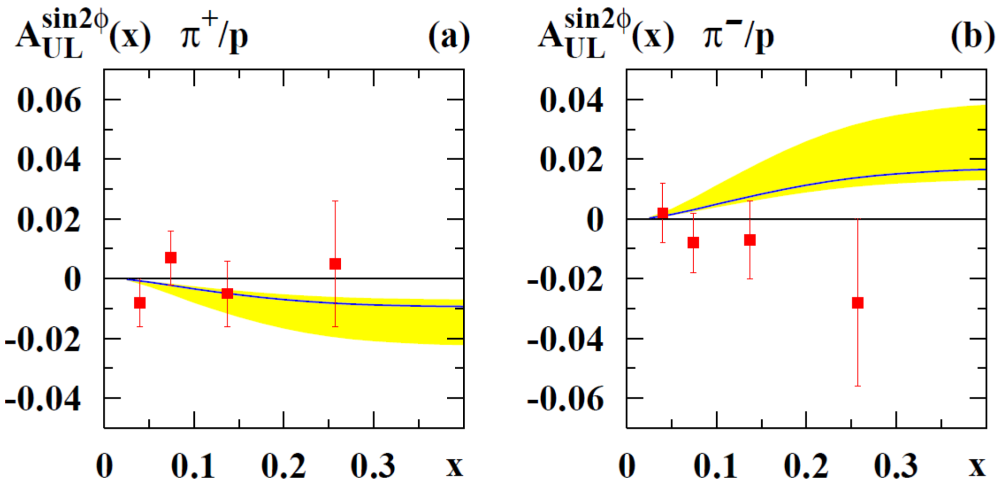
The sin(2ϕ) amplitude $\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

Deuterium target



A. Airapetian et al, Phys. Lett. B562 (2003)

Hydrogen target



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

Amplitudes consistent with zero for all mesons and for both H and D targets