University of Ferrara

Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering at HERMES

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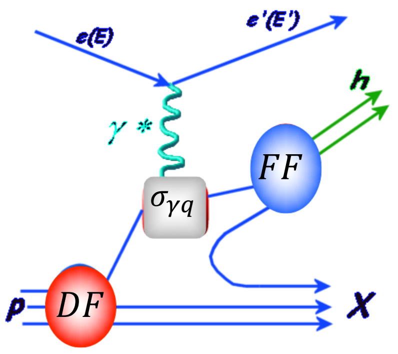
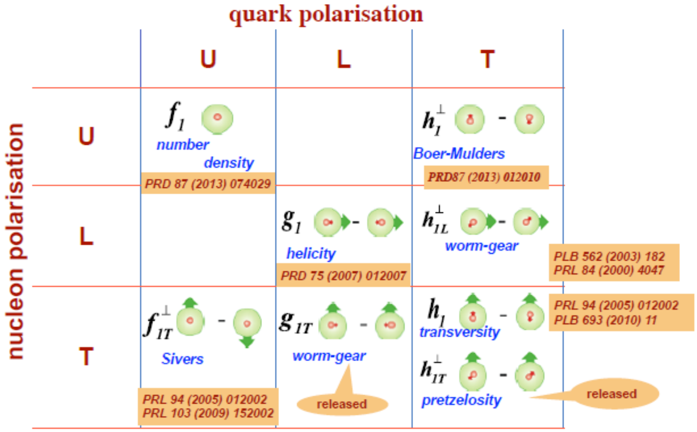
TMDs in SIDIS





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

$$= \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h}$$

$$+ \quad \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h}$$

$$+ \quad S_\parallel \left[\sqrt{2\varepsilon(1+\varepsilon)}\, \sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon \sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h} \right]$$

$$+ \quad S_\parallel \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\, \cos\phi_h\, F_{LL}^{\cos\phi_h} \right]$$

$$+ \quad |S_\perp| \Big[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right)$$

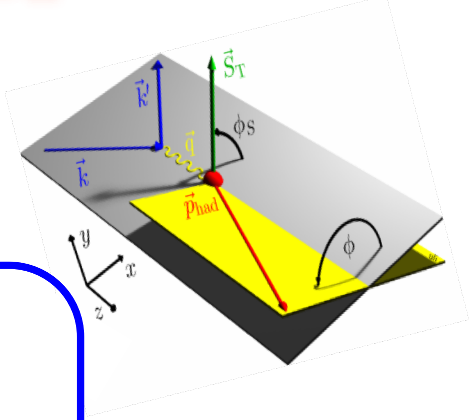
$$+ \quad \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\, \sin(3\phi_h - \phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+ \quad \sqrt{2\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\, \sin(2\phi_h - \phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$

$$+ \quad |S_\perp| \lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h - \phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S}$$

$$+ \quad \sqrt{2\varepsilon(1-\varepsilon)}\, \cos(2\phi_h - \phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

Bacchetta et al JHEP 08



Prepared for submission to JHEP

DESY Report 20-119

hermes

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The HERMES Collaboration

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[a] Deceased.

NEW!!

Published on Dec. 2 2020!!

[JHEP 12 (2020) 010] arXiv:2007.07755v1

The "Hermes TMDs Bible"

- **Compendium of HERMES TMDs results obtained with transv. Pol. H target** (84 pages!)
- 10 azimuthal modulations ($6\ A_{U\perp} + 4\ A_{L\perp}$)
- 1D and 3D projections in $x, z, P_{h\perp}$
- 7 hadron types: $\pi^{\pm}, \pi^{0}, K^{\pm}, p, \bar{p}$
- 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!)** (include correction for ε-dependent kinematic prefactors)
- Supplementary material includes: +140 1D Plots, +300 3D plots, 120 tables of results

- Previously published **Collins/Sivers asymm.** are also included, based on an improved analysis of the same data and now extended to $p/\bar{p}$ and and also provided in 3D binning.

Differences w.r.t previous analyses (besides 3D binning, $p/\bar{p}$ asymm. and extraction of SFAs):

- 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

PREPARED FOR SUBMISSION TO JHEP
DESY REPORT 20-119

hermes

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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)

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

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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

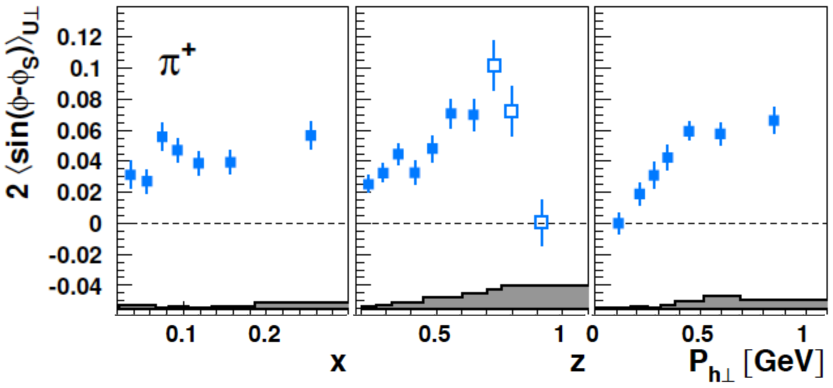
All other 1D SFA results in back-up slides!

✓ : incompatible with NULL hypothesis at 95% CL

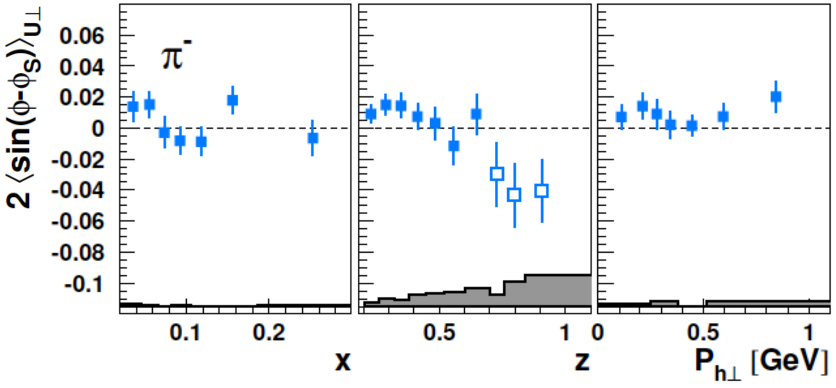
(✓) : incompatible with NULL hypothesis at 90% CL

Selected results

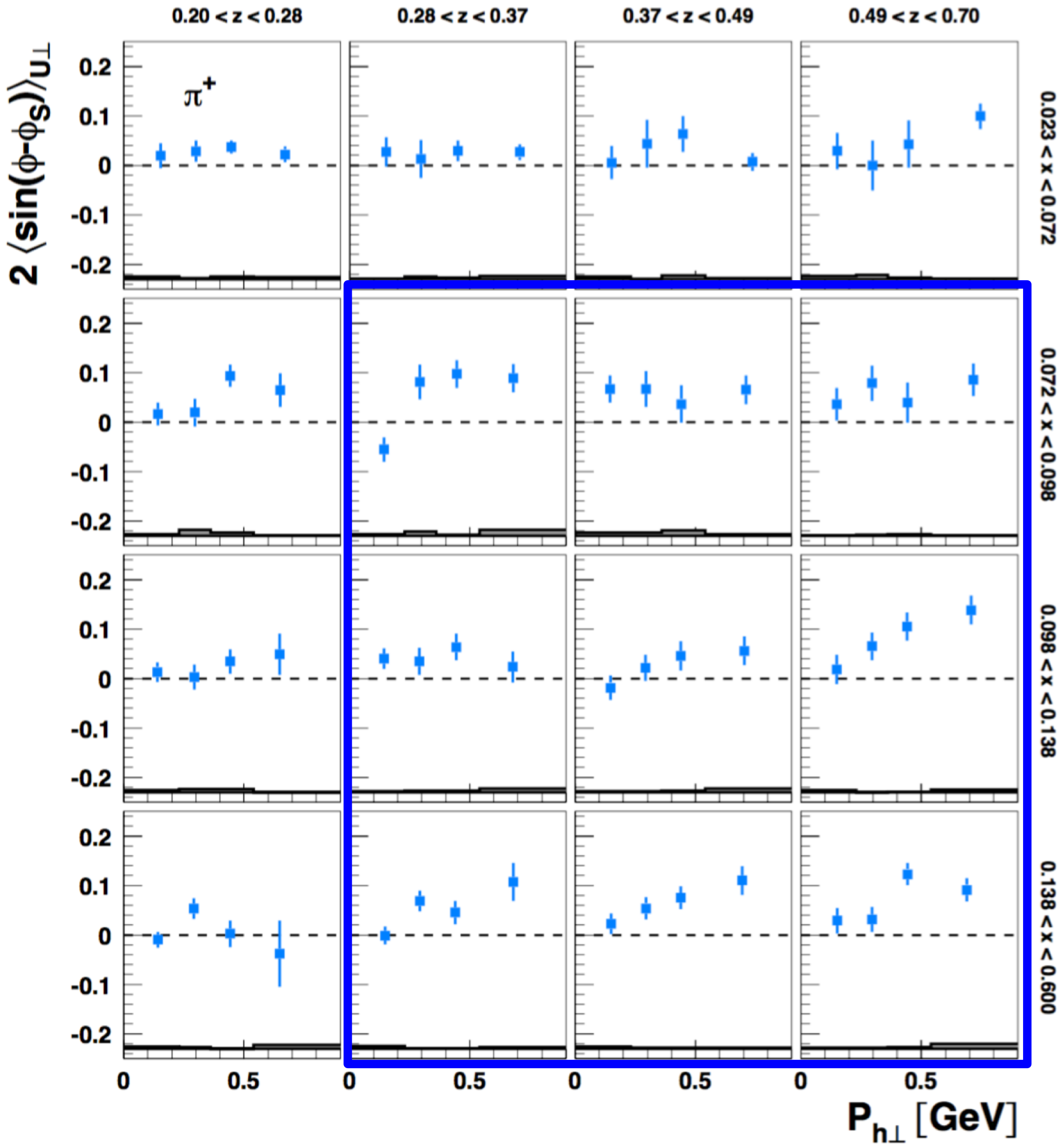
Sivers amplitudes: pions results



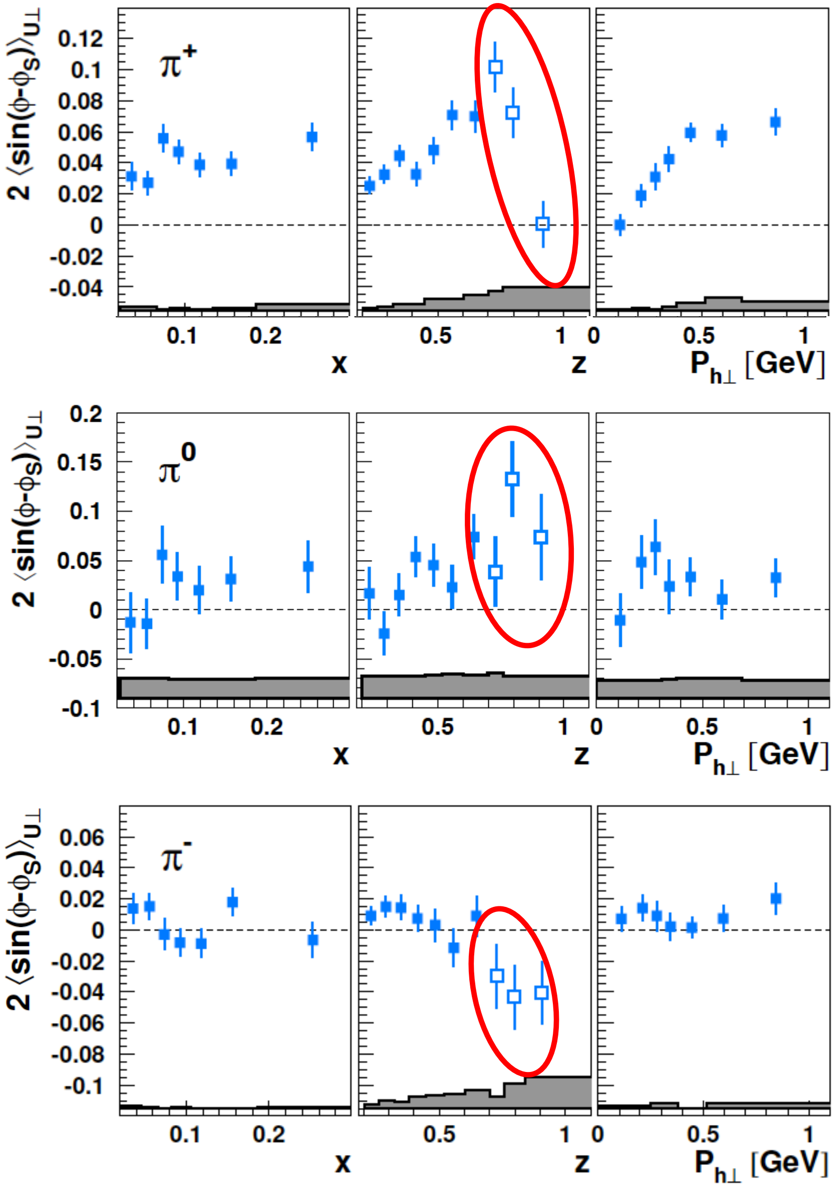
- large positive amplitude → clear evidence of non-zero $f_{1T}^{\perp,u}$
- signal rises with x, z and $P_{h\perp}$ in SIDIS region $(0.2 < z < 0.7)$
- More informative 3D projections confirm and further detail the rise of the amplitude at large x, z and $P_{h\perp}$



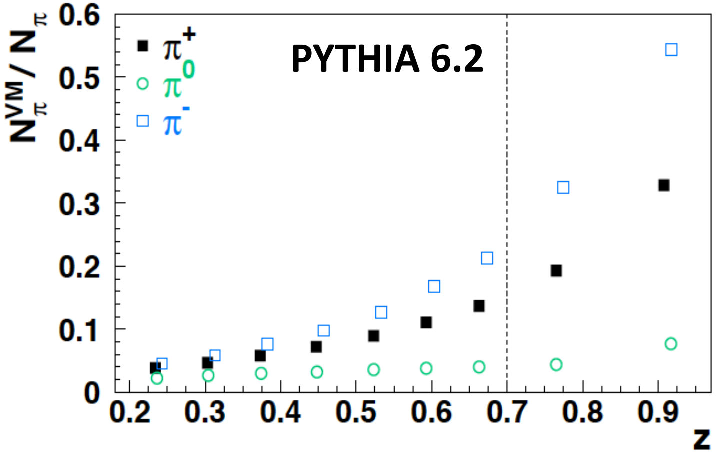
Vanishing due to the cancellation of the opposite Sivers effect for *u* and *d* quarks



Sivers amplitudes: pions results

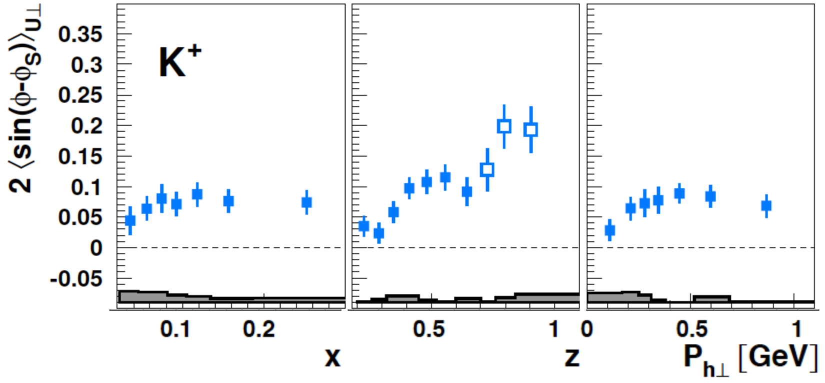


- Sudden drop at large-z (> 0.7) reveals a change of mechanism in this **semi-exclusive region**
- Contributions from decays of exclusively produced ρ^0 into $\pi^+\pi^-$ are large in this region!

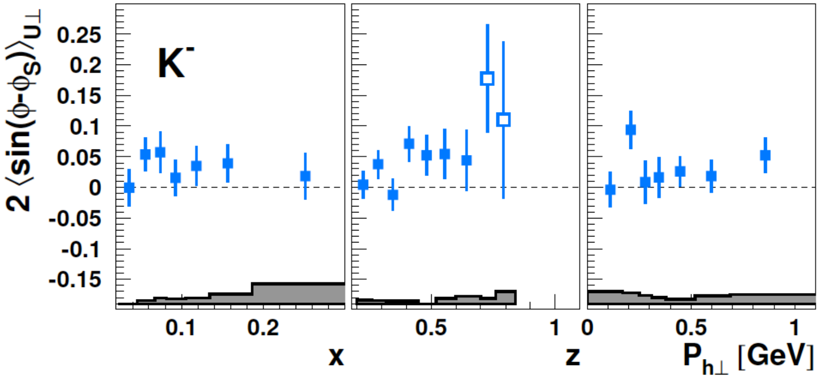


- intermediate size between those of π^+ and π^- reflects isospin symmetry at the amplitude level
- π^0 amplitude is much less susceptible to VM decays and no sudden change is observed at large z → observed positive signal cannot be attributed solely to contributions from VM
- An alternative (concurrent?) 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

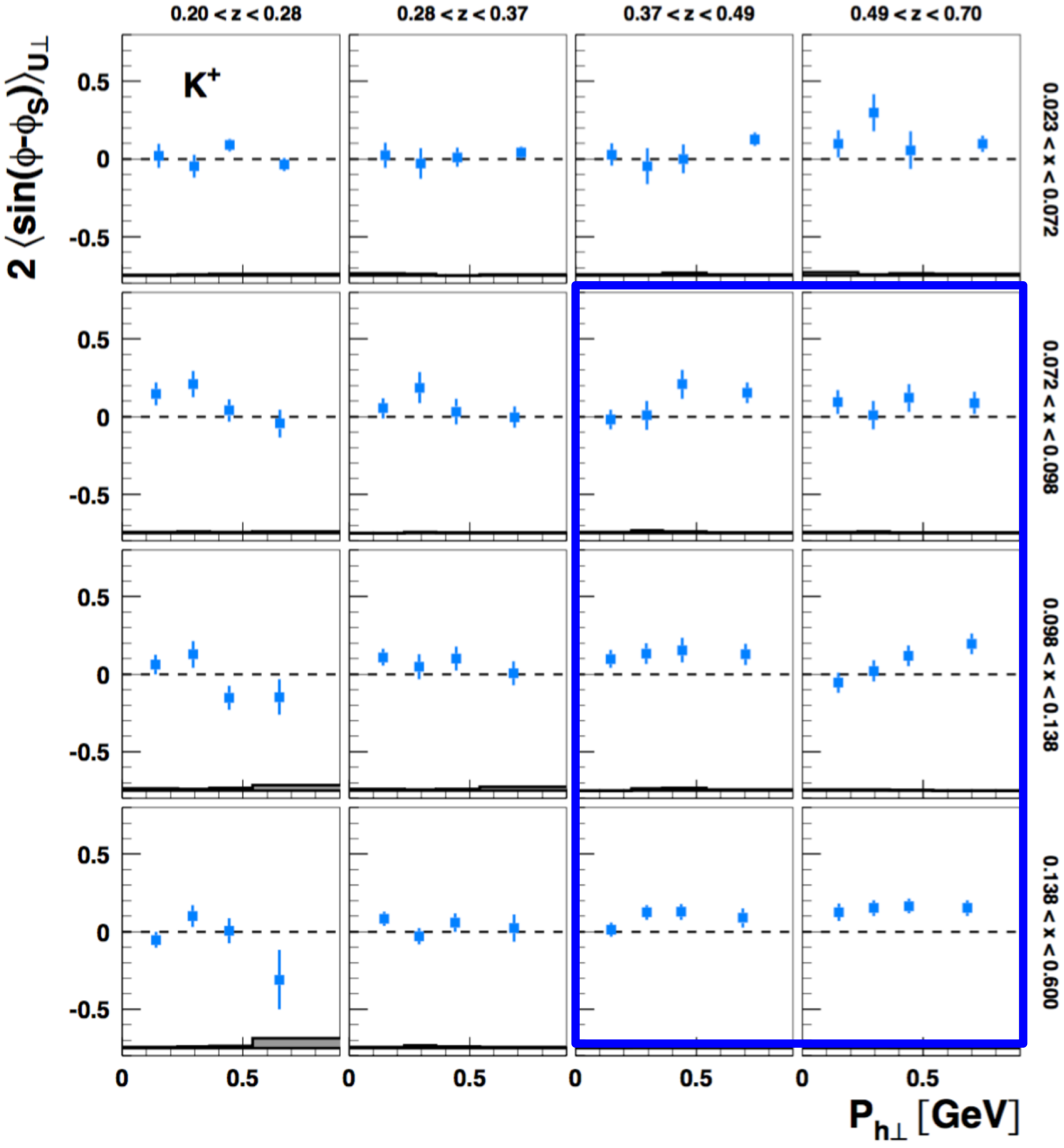


Large positive amplitude, similar kinematic dep. of π^+

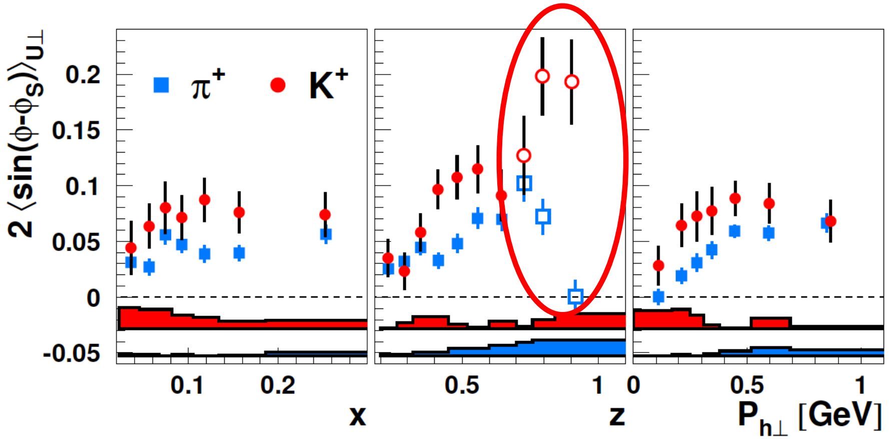


Positive amplitude, different than π^-

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



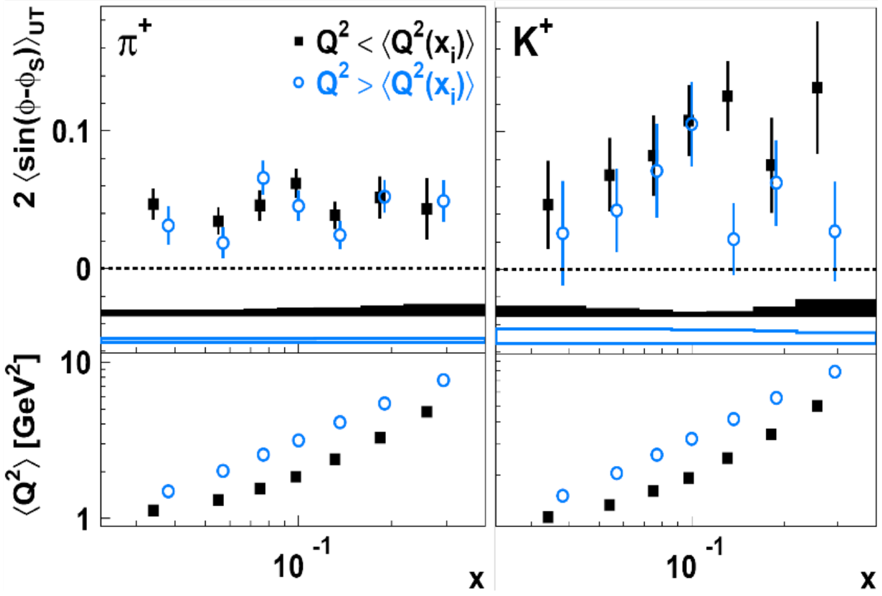
Sivers amplitudes: the K^+ vs. π^+ issue



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

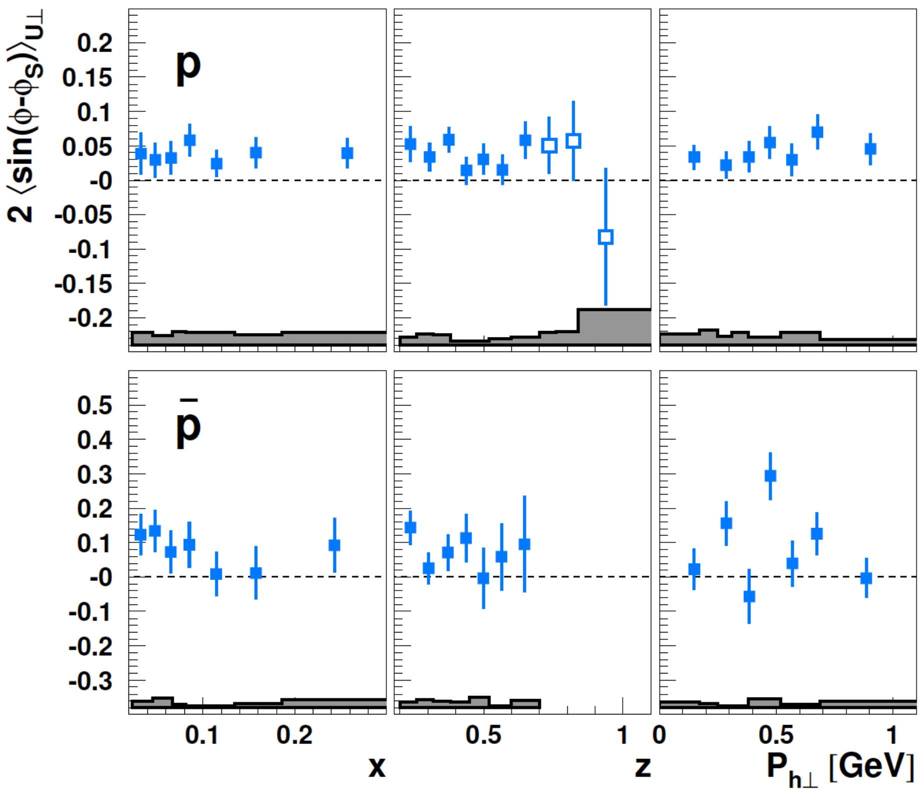
- u-quark dominance, but different sea-quark content
- possible differences in k_T dependence of the fragmentation functions for different quark flavors (entering the convolution integral)?
- different impact of higher-twist effects
- K^+ amplitude keeps rising with z in semi-exclusive region (no sudden change) → Contribution from exclusive VM decays much less pronounced for Kaons than for pions.

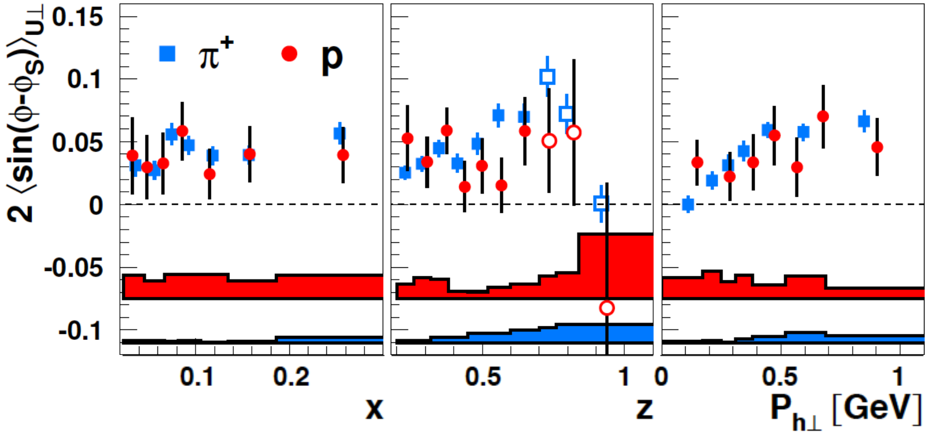
Phys. Rev. Lett. 103 (2009) 152002



- each x-bin divided into two Q^2 bins
- no effect for pions, but hint of suppression at larger Q^2 for kaons

Sivers amplitudes: protons results

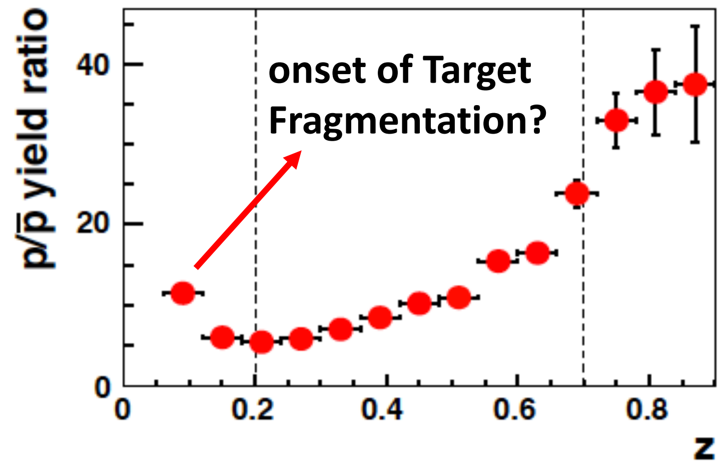


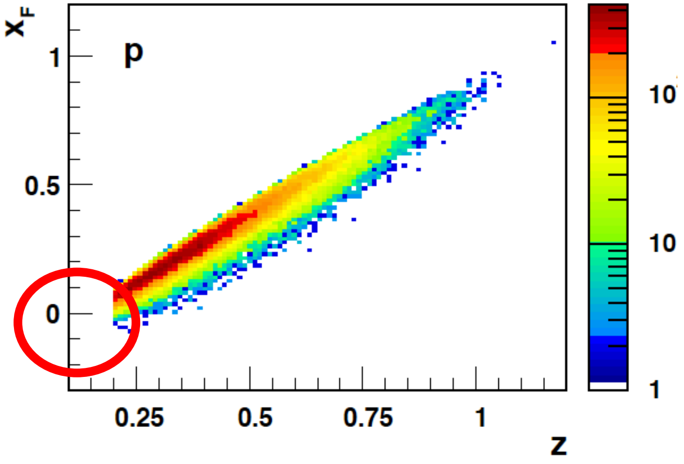


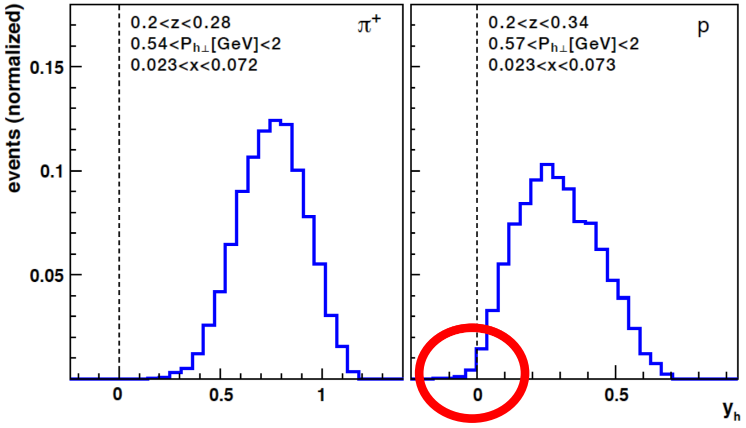
First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive

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

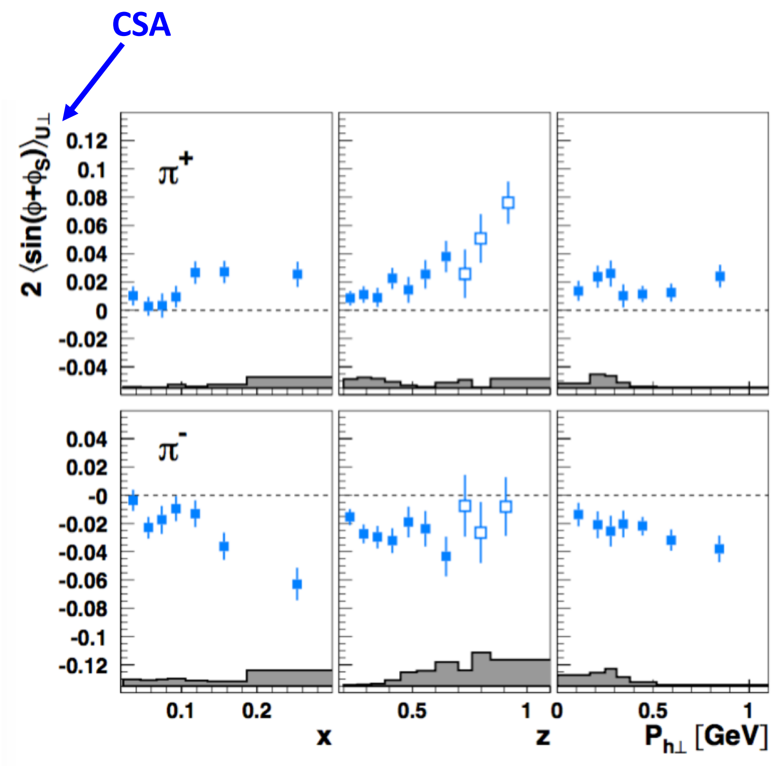


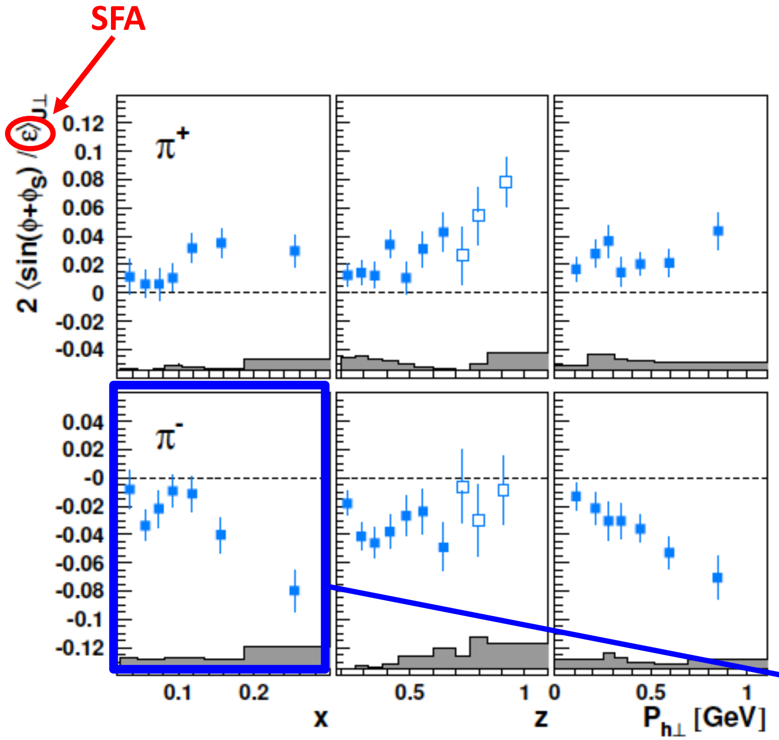


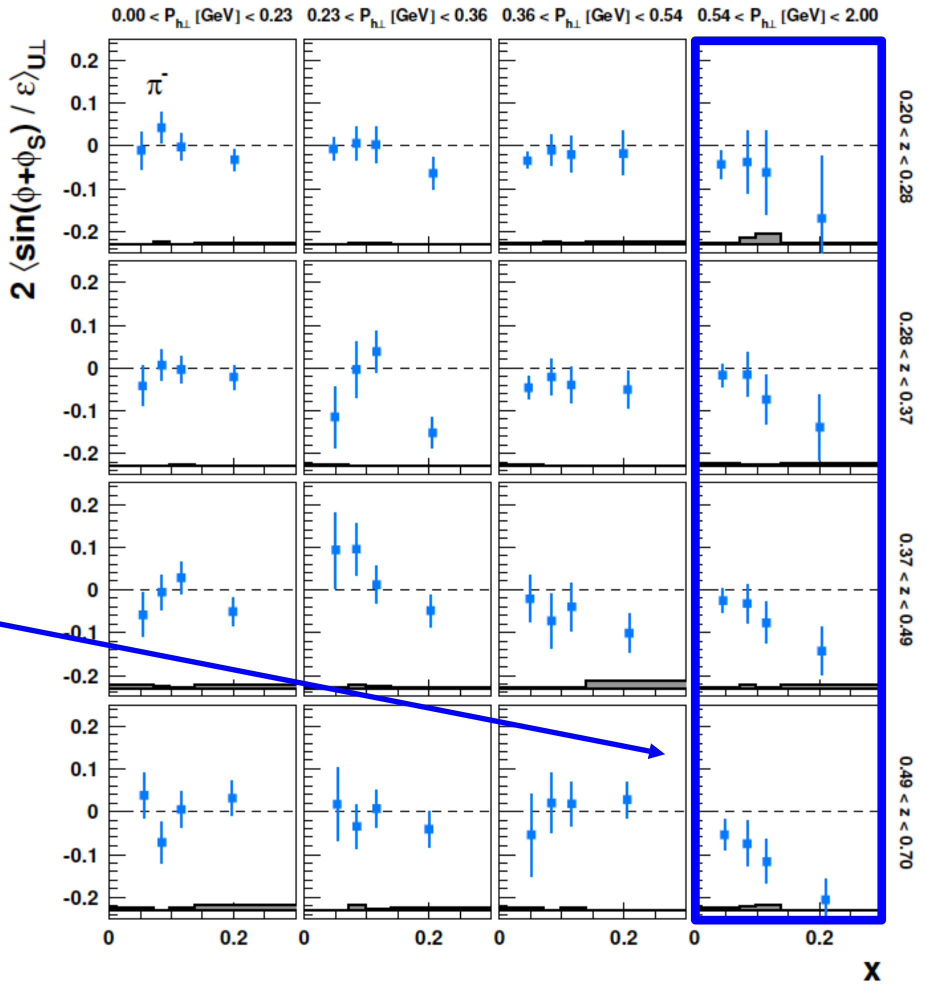


At the selected kinematics the vast majority of protons are compatible with being produced in CFR (find more studies in paper)

Collins amplitudes: pions results





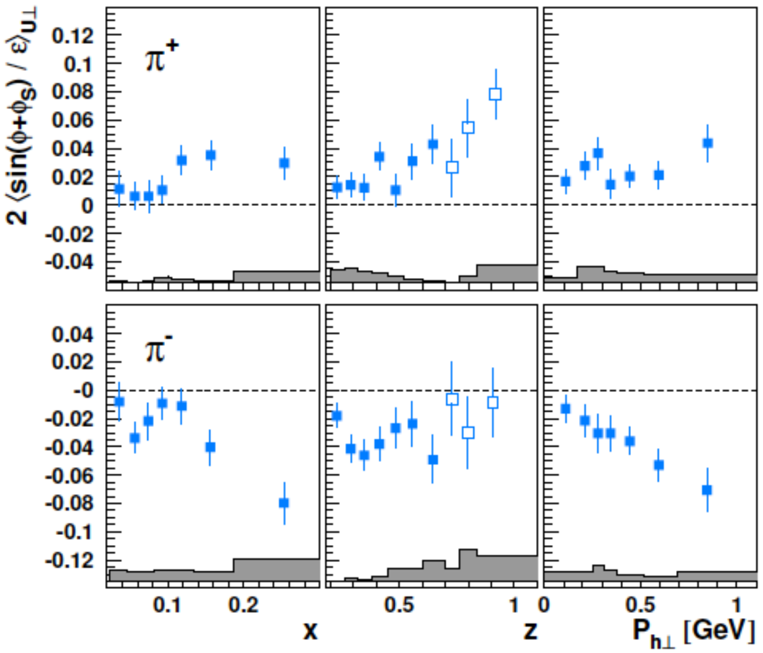


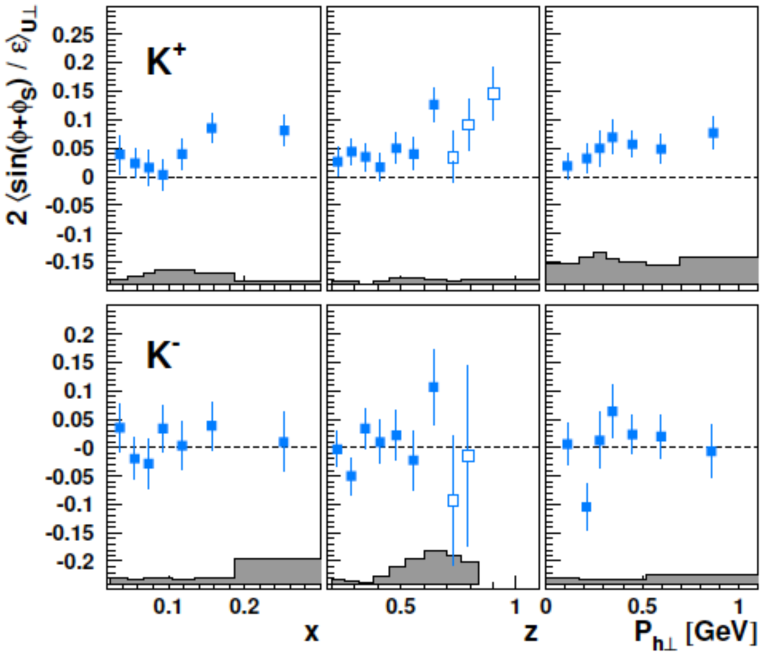
- Large and opposite amplitudes
- Clear evidence of non-zero transversity
- Negative π^- amplitude points to large disfavoured ($u \to \pi^-$) Collins FF opposite to the favoured one ($d \to \pi^-$)

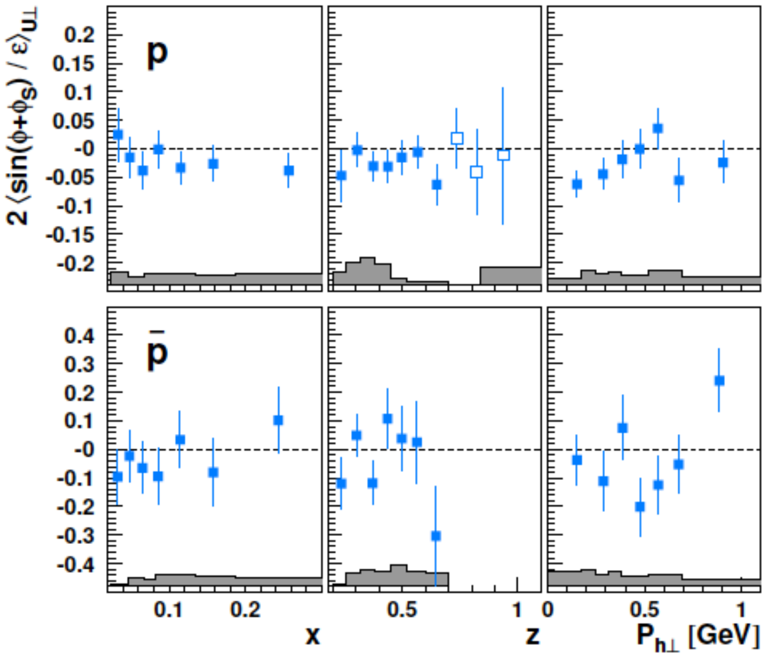
- ε-dependent kinematic prefactor < 1 for Collins case
- Collins SFA amplitudes appear slightly amplified w.r.t. CSA ones

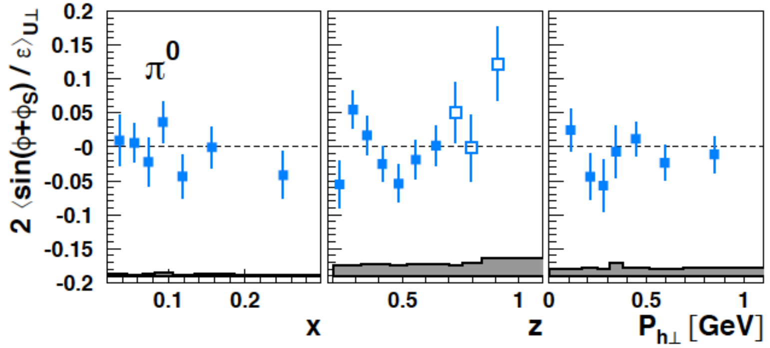
- 3D projections confirm and further detail the rise of the amplitude at large x and $P_{h\perp}$

Collins amplitudes: all SFA 1D results







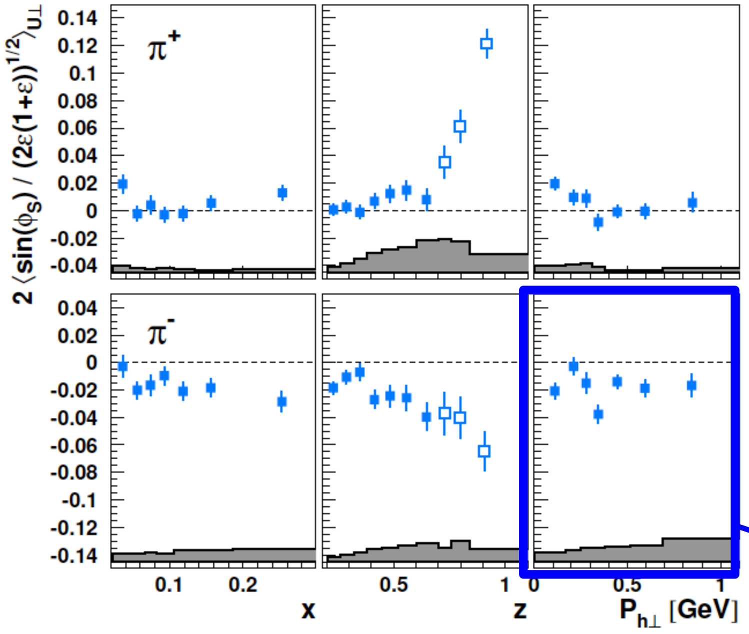


- ≈ 0: intermediate between π^+ and π^-

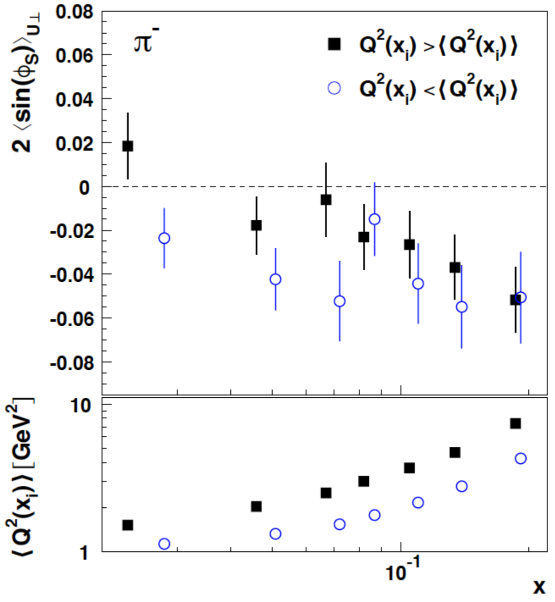
- K^+ exhibits a very similar kinematic dependence as π^+, but amplitude is twice as large!
- $K^- \approx 0$: only disfavored and opposite $(u \rightarrow K^-, d \rightarrow K^-)$ fragmentation mechanisms can contribute

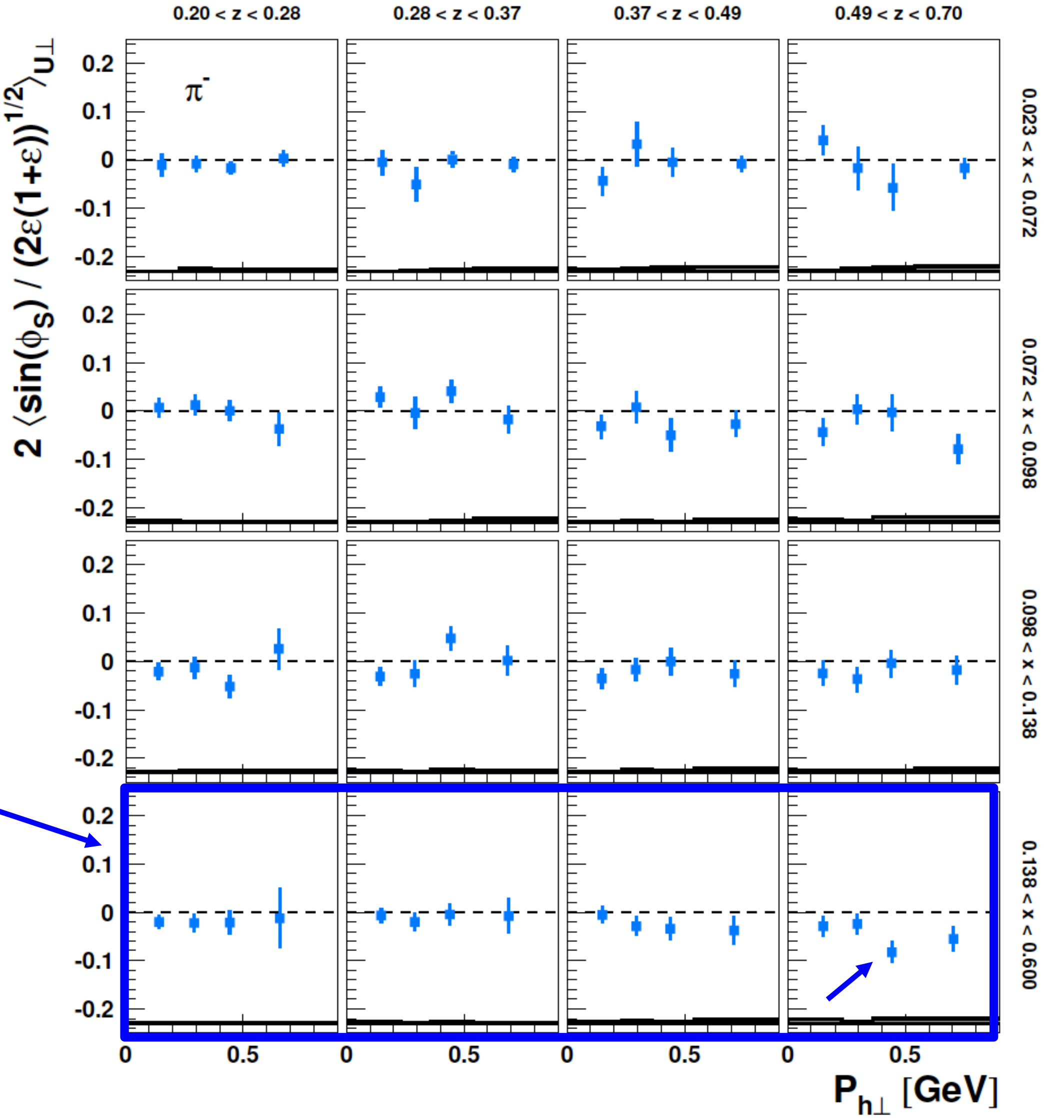
- **First measurement of Collins asymm. for protons/antiprotons!**
- **proton amplitude is non zero (negative)**
- antiproton amplitude ≈ 0
- Collins effect is a fragmentation process, but too little is known about this effect for spin-$\frac{1}{2}$ hadron production

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



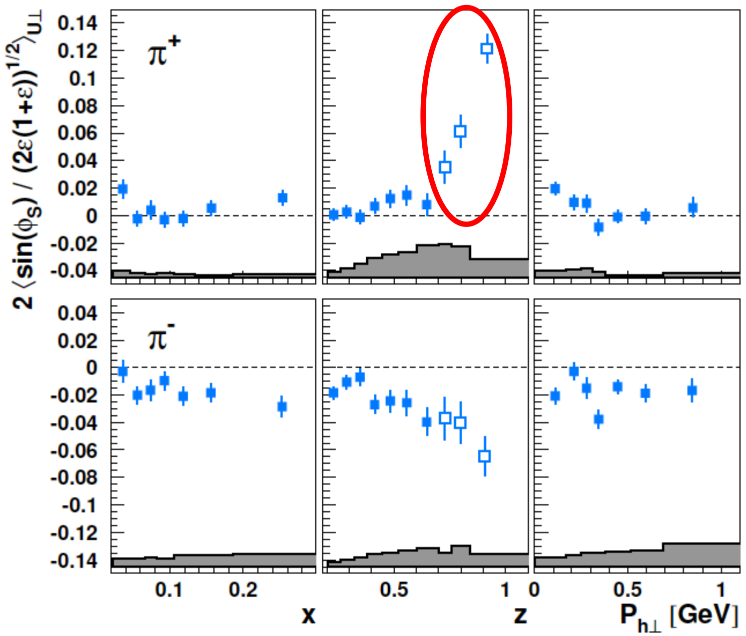
- Charged pions amplitudes non-zero and opposite
- Negative π^- amplitude increases with x and z
- Overall similar behaviour of Collins asymmetries!

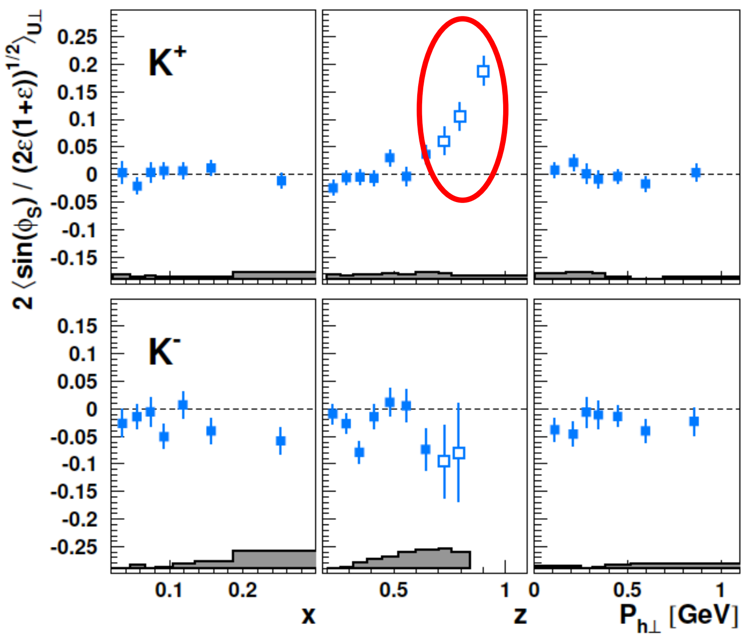


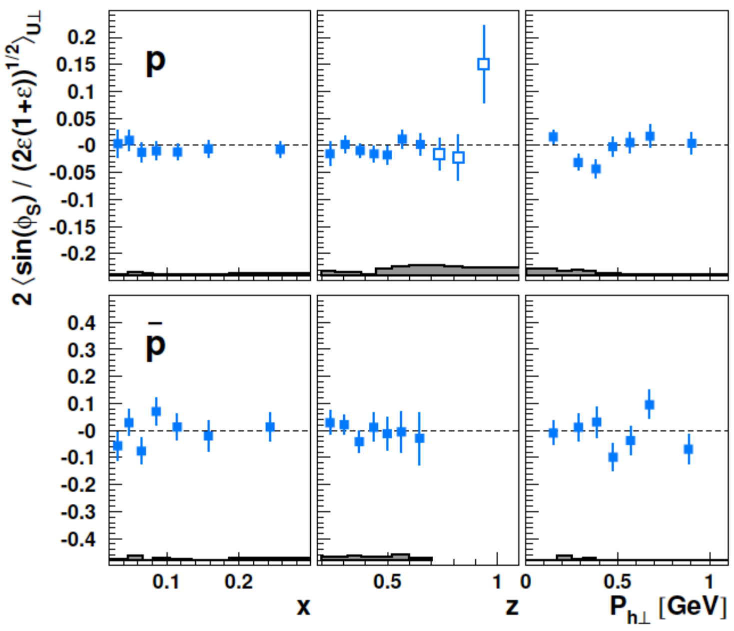


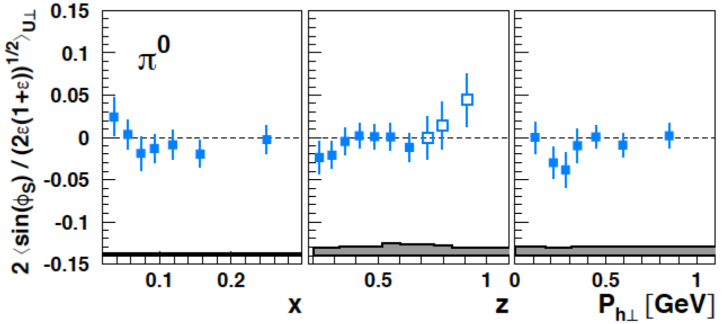
- Subleading-twist term: interesting to study the Q^2 dependence
- x-Q^2 strongly correlated → split each x bin in two Q^2 regions: $\lessgtr \langle Q^2\rangle$ of each x bin
- Hint of suppression at higher Q^2

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









- π^+ 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!

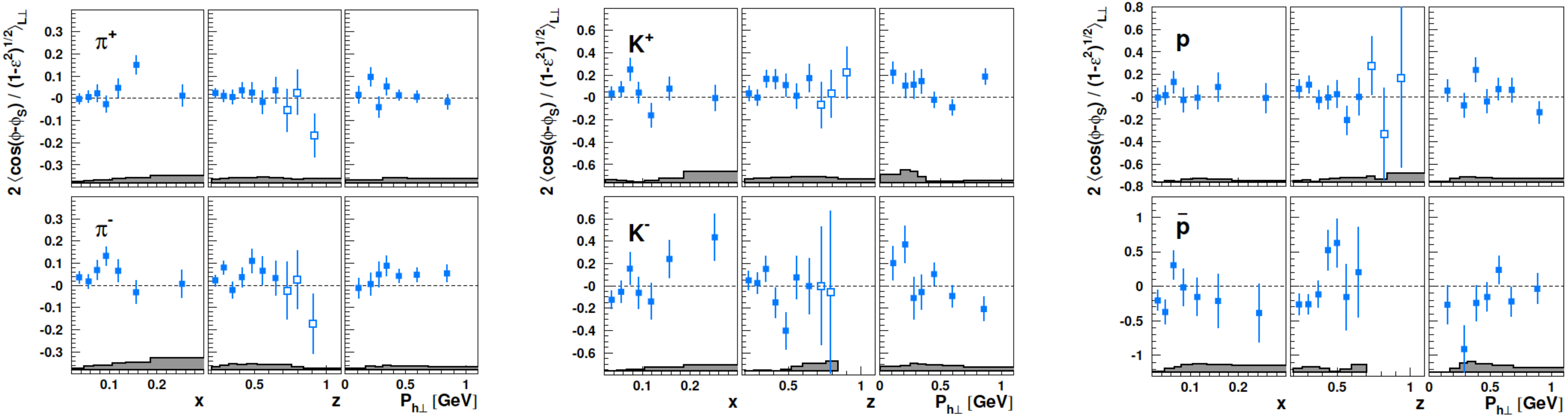
- **Flavor sensitivity** ensured by the excellent hadron ID of the HERMES experiment reveals interesting and unexpected facets of data

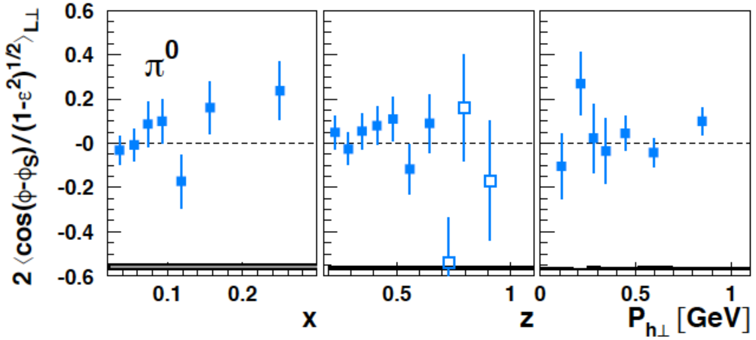
- The **3D imaging of the nucleon** is a fashinating and fast evolving research field. HERMES has been a pioneer experiment in this fiels and continues to play a key role in these studies.

Backup

The other SFA results…

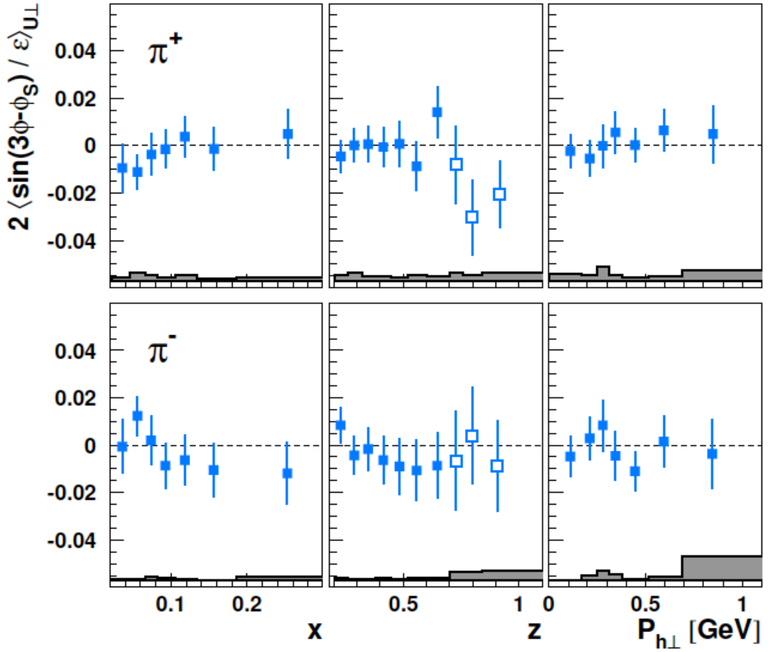
The $\cos(\phi - \phi_S)$ DSA: all SFA 1D results

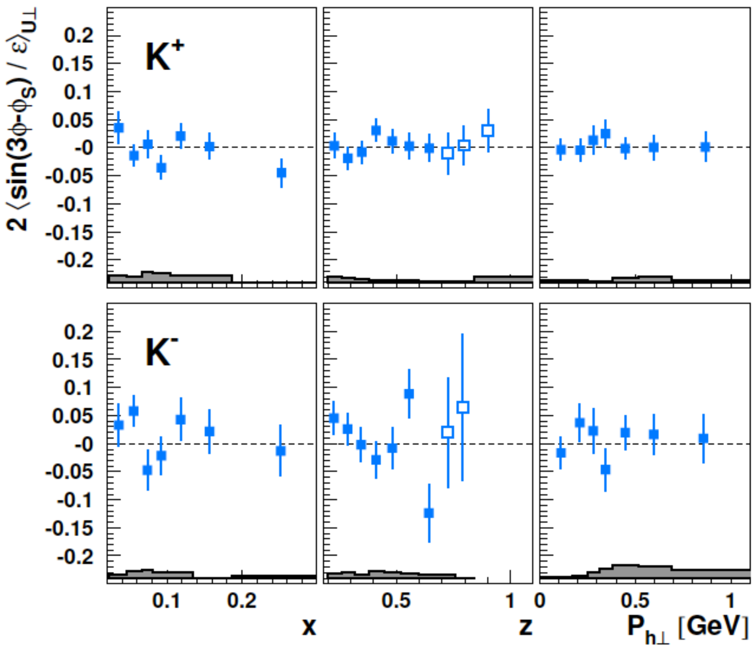


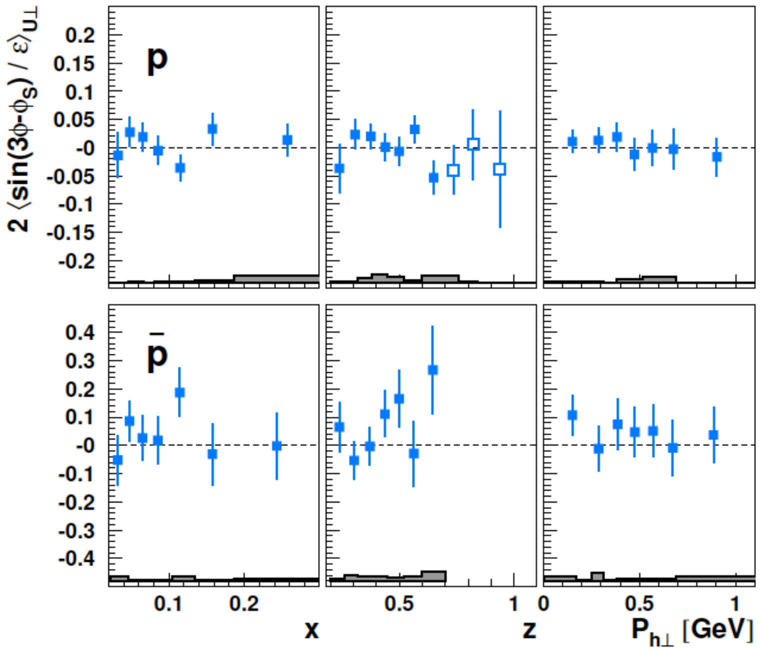


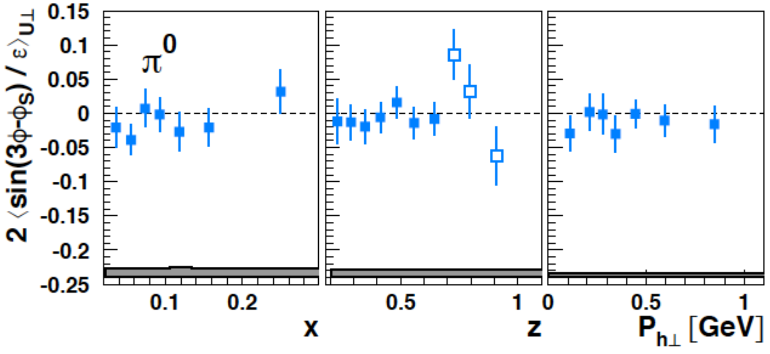
- **π^+, π^- and K^+ amplitudes are non-zero in SIDIS region ($0.2 < z < 0.7$)**
- **indication of a non-zero worm-gear function g_{1T}**
- amplitudes consistent with zero for all other hadron species
- Larger stat. errors (compared to SSAs) due to low beam polarization

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





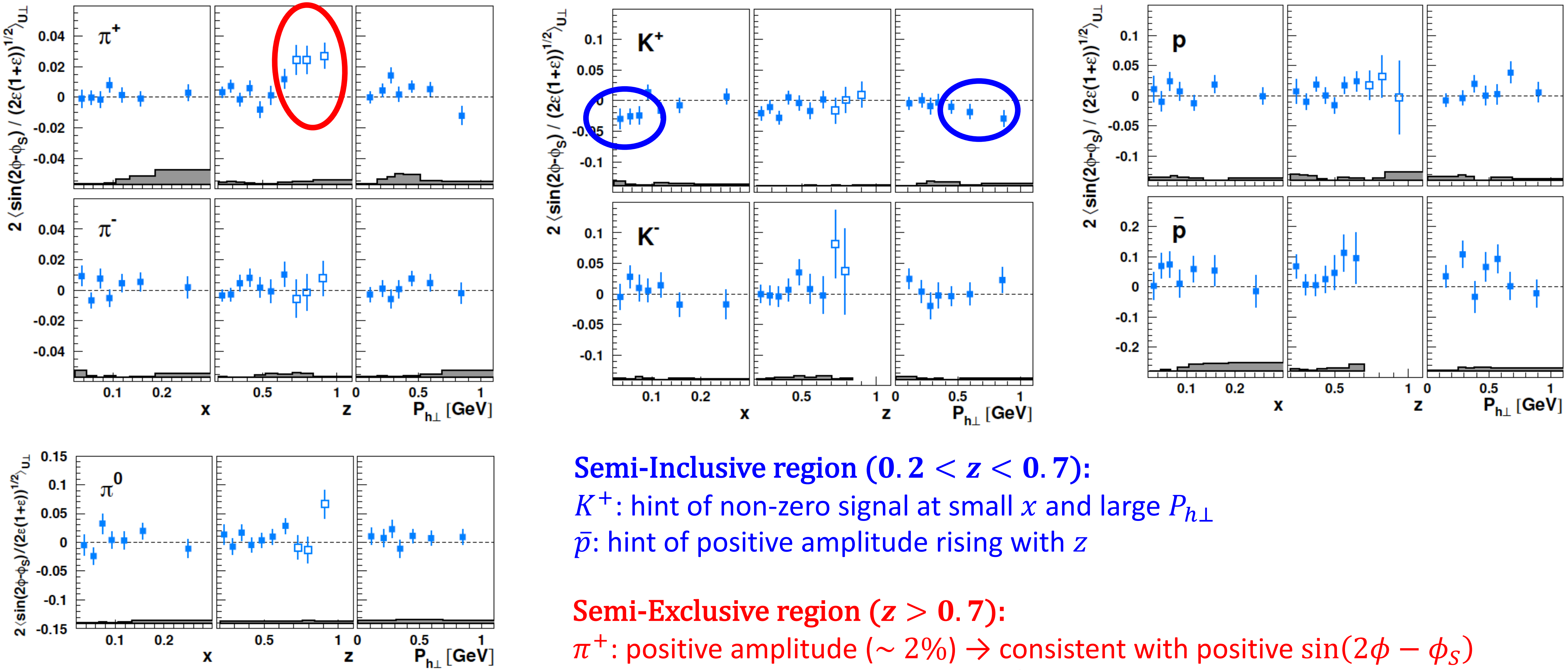




Suppressed by two powers of $P_{h\perp}$ w.r.t. Collins and Sivers amplitudes

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 ($0.2 < z < 0.7$):

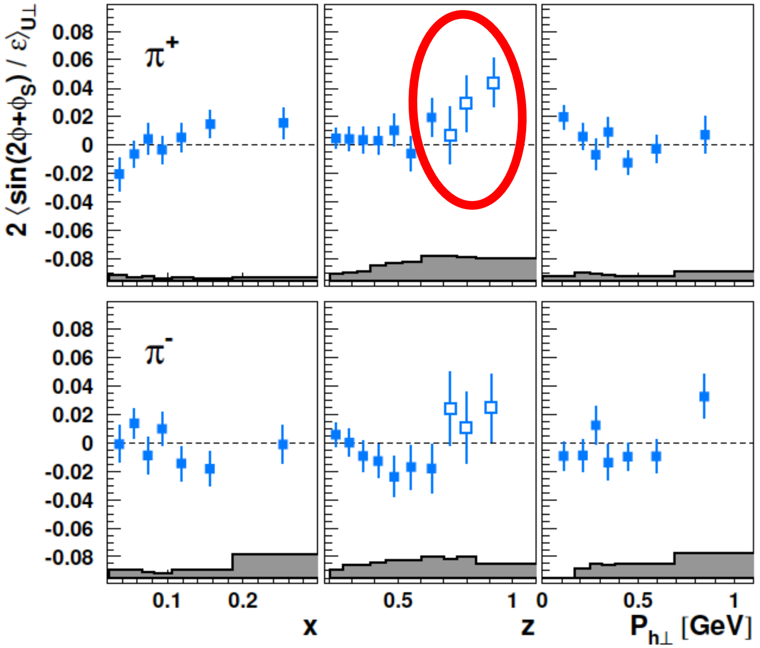
K^+: hint of non-zero signal at small x and large $P_{h\perp}$

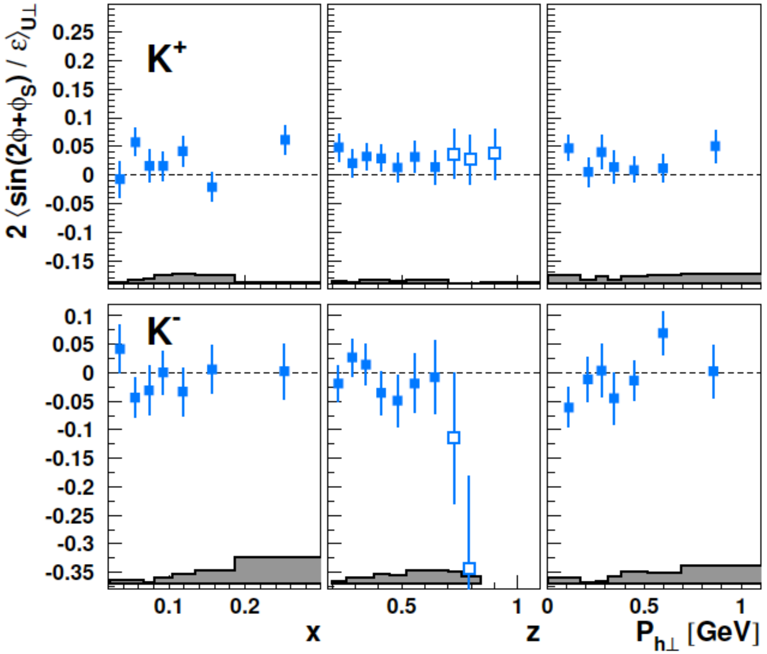
$\bar{p}$: hint of positive amplitude rising with z

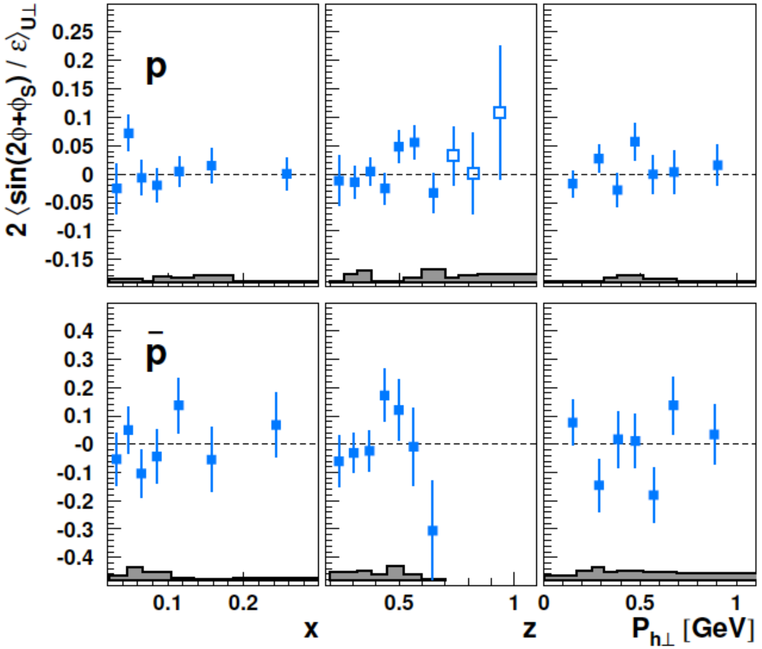
Semi-Exclusive region ($z > 0.7$):

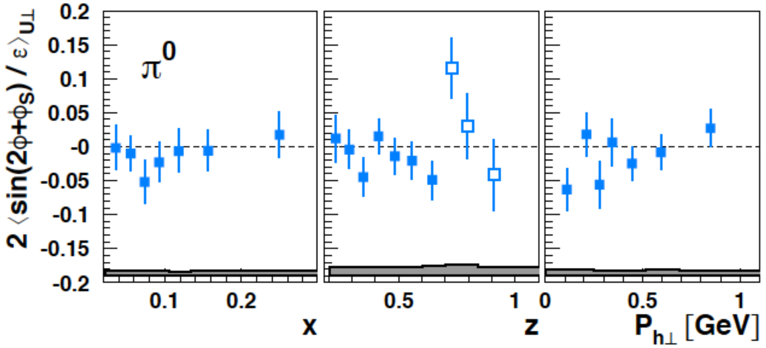
π^+: positive amplitude ($\sim 2\%$) → consistent with positive $\sin(2\phi - \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

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

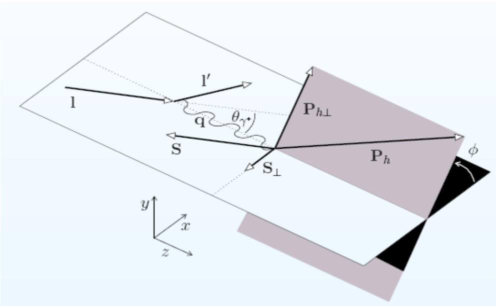








Arises solely from the small longit. target polarization component



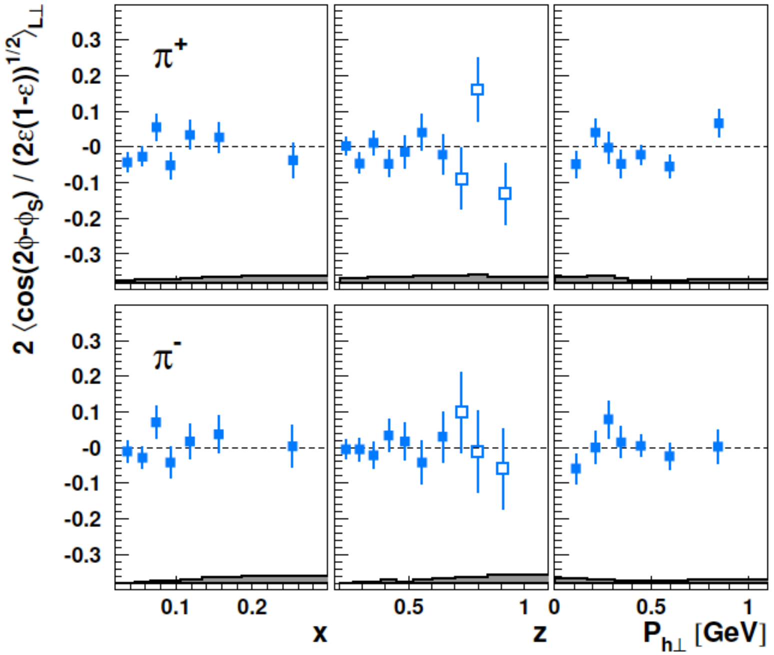
Semi-Inclusive region ($0.2 < z < 0.7$):

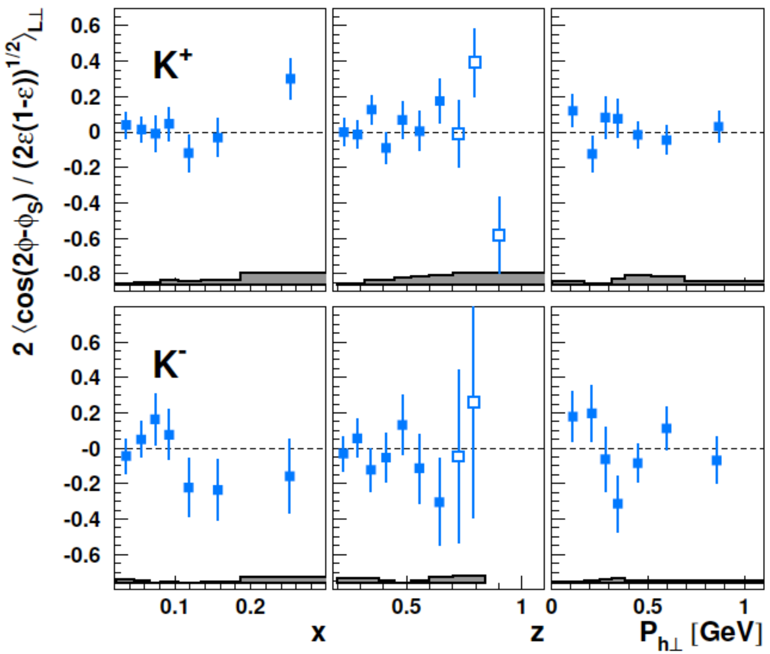
K^+: positive amplitude over full z range

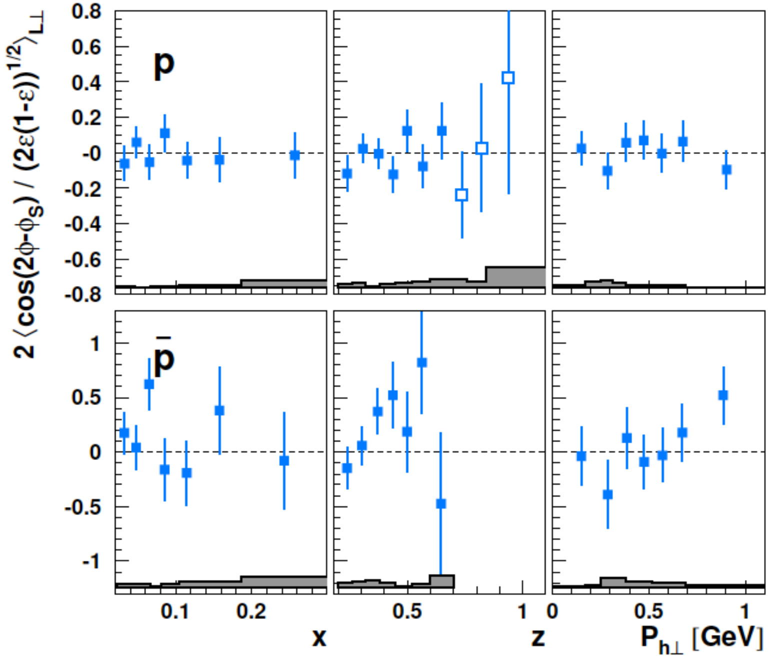
Semi-Exclusive region ($z > 0.7$):

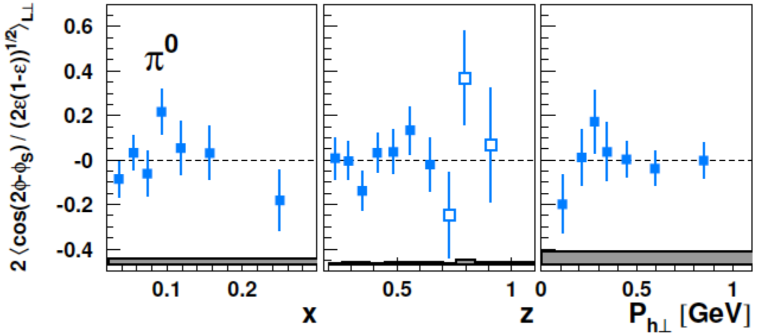
π^+: positive amplitude rising with z → consistent with positive $\sin(2\phi + \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

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



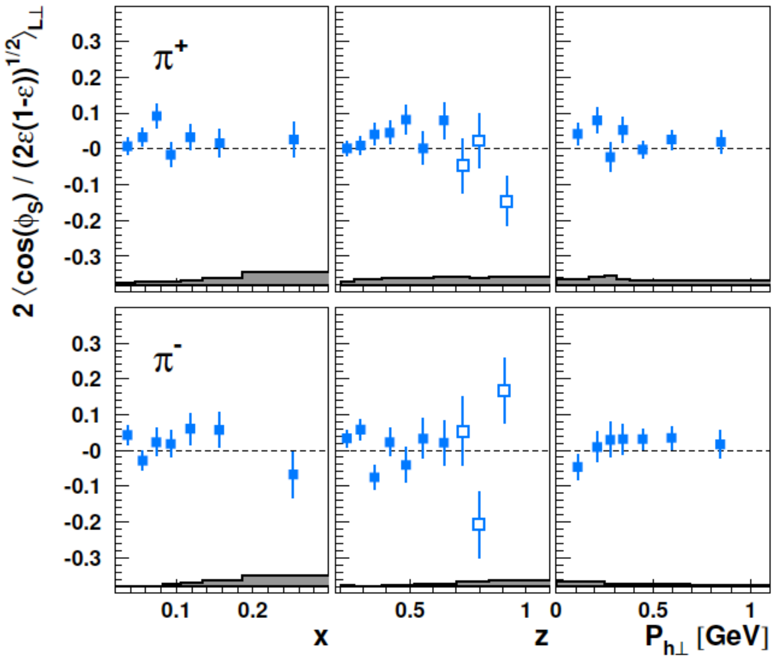


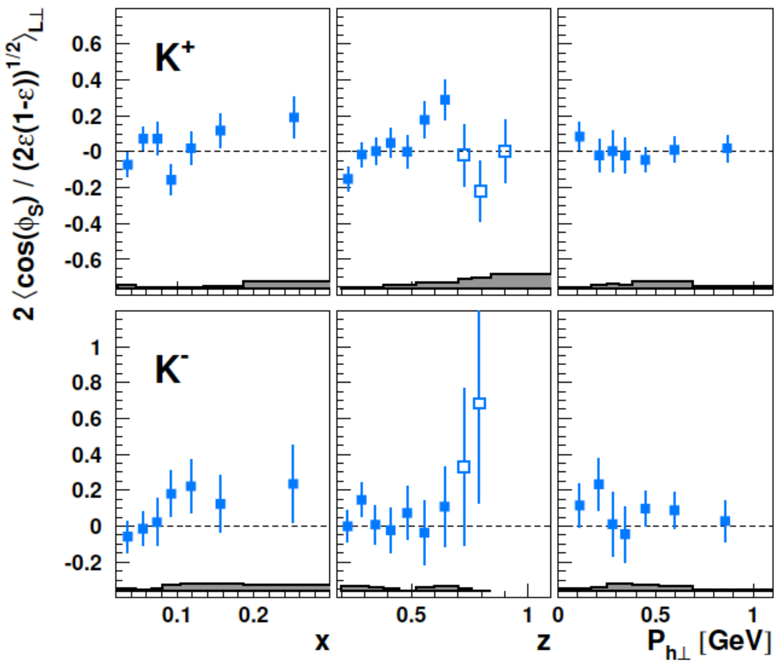


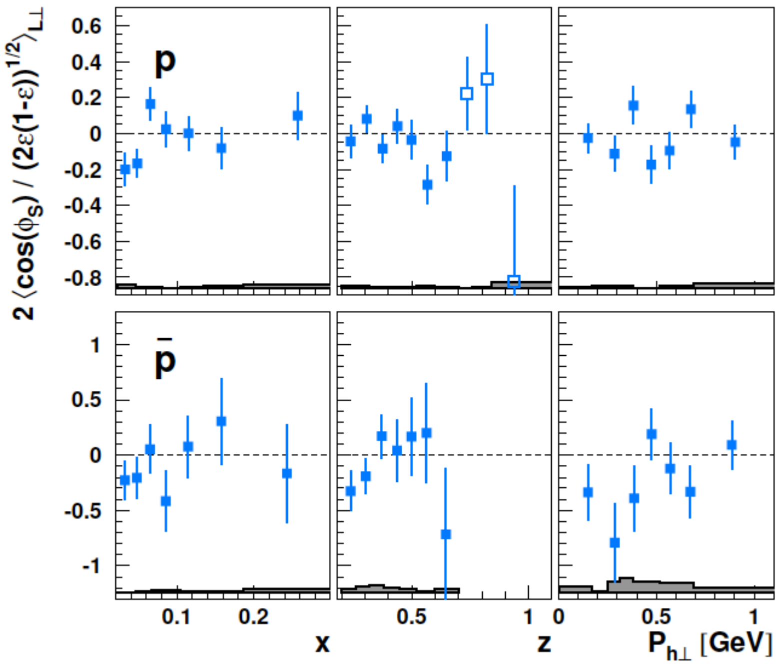


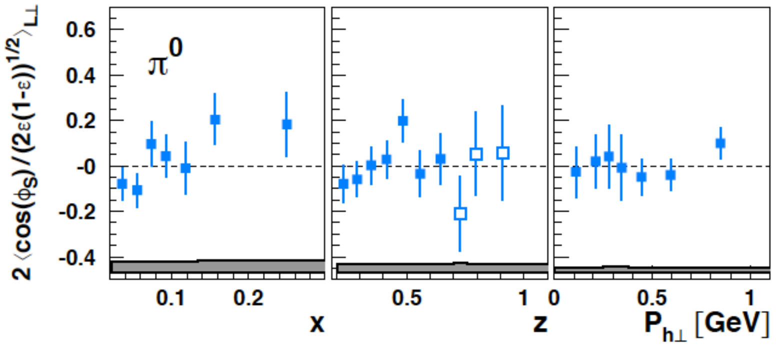
All results are consistent with zero

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





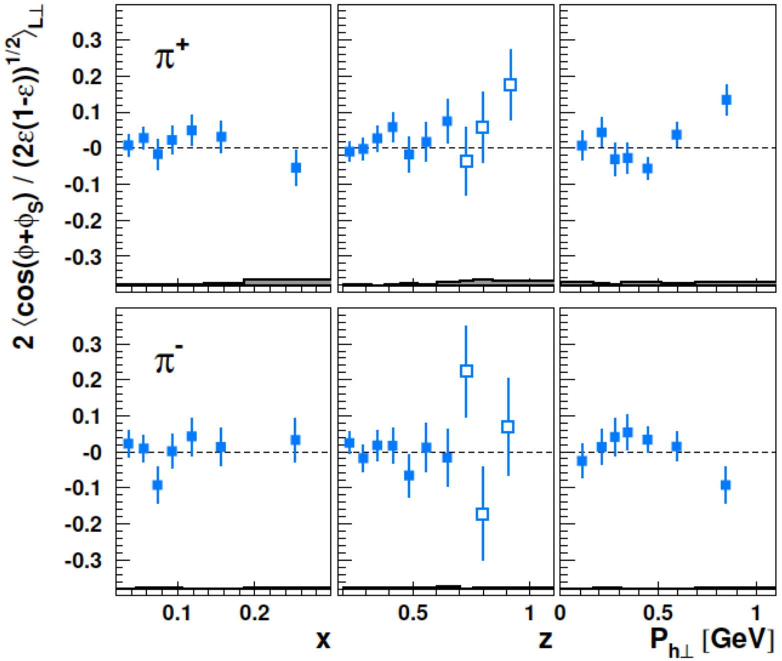


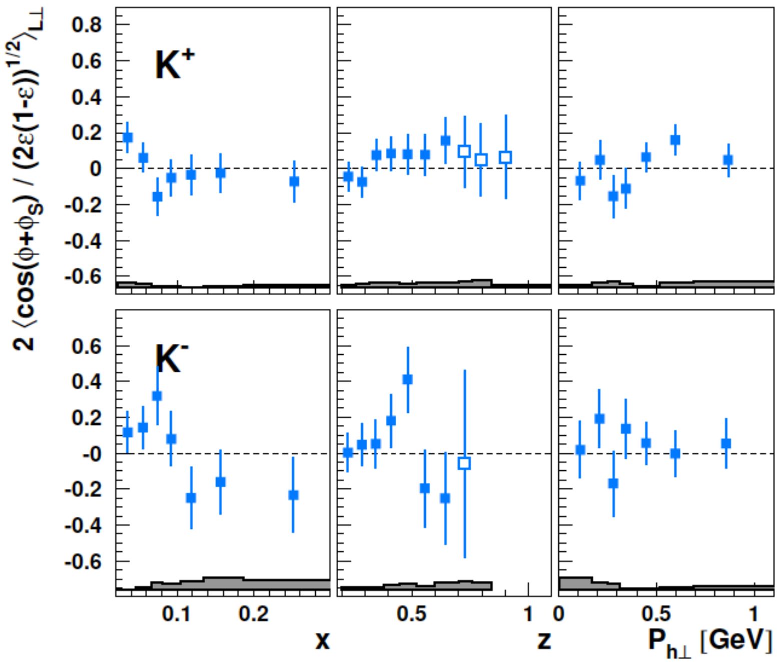


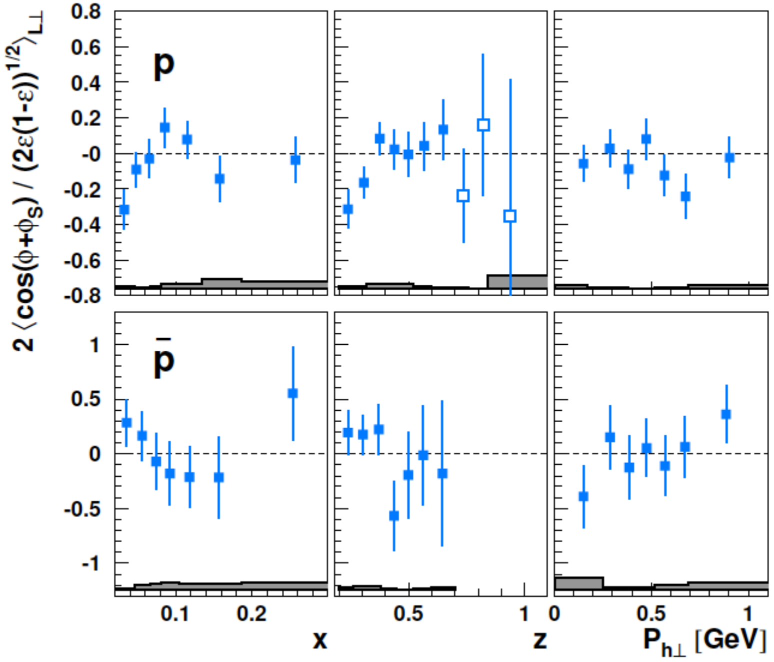
Can receive contributions from the longitudinal target polarization component

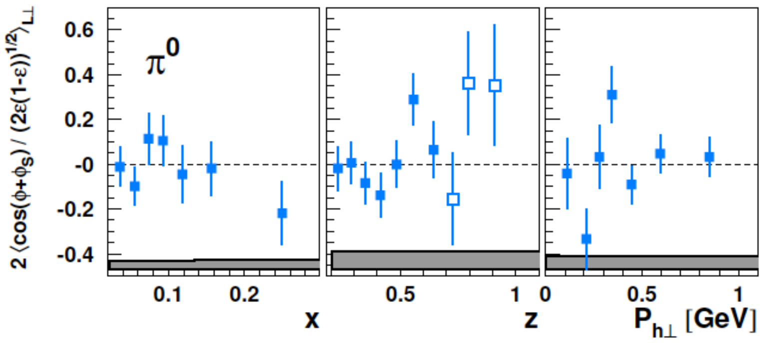
K^-: small positive amplitude

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



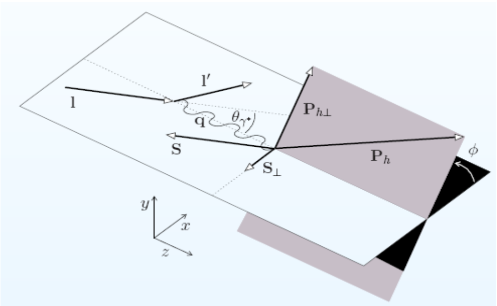






Arises solely from the small longit. target polarization component

All results consistent with zero



Miscellania

The SFA amplitudes (NEW!)

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

$$\mathbb{P}\Big(x, z, \epsilon, P_{h\perp}, \phi, \phi_S, P_l, S_\perp : 2\langle\sin(\phi-\phi_S)\rangle^h_{U\perp}, \ldots 2\langle\cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{L\perp}\Big)$$

$$= \Big[1 + S_\perp\Big(2\langle\sin(\phi-\phi_S)\rangle^h_{U\perp}\sin(\phi-\phi_S) + \epsilon\, 2\langle\sin(\phi+\phi_S)/\epsilon\rangle^h_{U\perp}\sin(\phi+\phi_S) + \epsilon\, 2\langle\sin(3\phi-\phi_S)/\epsilon\rangle^h_{U\perp}\sin(3\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}\, 2\langle\sin(\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\rangle^h_{U\perp}\sin(\phi_S) + \sqrt{2\epsilon(1+\epsilon)}\, 2\langle\sin(2\phi-\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\rangle^h_{U\perp}\sin(2\phi-\phi_S) + \epsilon\, 2\langle\sin(2\phi+\phi_S)/\epsilon\rangle^h_{U\perp}\sin(2\phi+\phi_S)\Big)$$

$$+ P_l S_\perp\Big(\sqrt{1-\epsilon^2}\, 2\langle\cos(\phi-\phi_S)/\sqrt{1-\epsilon^2}\rangle^h_{L\perp}\cos(\phi-\phi_S) + \sqrt{2\epsilon(1-\epsilon)}\, 2\langle\cos(\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{L\perp}\cos(\phi_S) + \sqrt{2\epsilon(1-\epsilon)}\, 2\langle\cos(2\phi-\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{L\perp}\cos(2\phi-\phi_S) + \sqrt{2\epsilon(1-\epsilon)}\, 2\langle\cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{L\perp}\cos(\phi+\phi_S)\Big)\Big]^w$$

$A_{U\perp}$ 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 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 CSA amplitudes

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

$$\mathbb{P}\Big(x, z, P_{h\perp}, \phi, \phi_S, P_l\,, S_\perp : 2\,\langle\sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp}\,, \ldots\; 2\,\langle\cos(\phi+\phi_S)\rangle^h_{\mathrm{L}\perp}\Big)$$

$$\begin{aligned}
= \Big[1 + S_\perp \Big(& 2\,\langle\sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(\phi-\phi_S) + 2\,\langle\sin(\phi+\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(\phi+\phi_S) + \\
& 2\,\langle\sin(3\phi-\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(3\phi-\phi_S) + 2\,\langle\sin(\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(\phi_S) + \\
& 2\,\langle\sin(2\phi-\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(2\phi-\phi_S) + 2\,\langle\sin(2\phi+\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(2\phi+\phi_S)\Big) \\
+ P_l\, S_\perp \Big(& 2\,\langle\cos(\phi-\phi_S)\rangle^h_{\mathrm{L}\perp} \cos(\phi-\phi_S) + 2\,\langle\cos(\phi_S)\rangle^h_{\mathrm{L}\perp} \cos(\phi_S) + \\
& 2\,\langle\cos(2\phi-\phi_S)\rangle^h_{\mathrm{L}\perp} \cos(2\phi-\phi_S) + 2\,\langle\cos(\phi+\phi_S)\rangle^h_{\mathrm{L}\perp} \cos(\phi+\phi_S)\Big)\Big]^w
\end{aligned}$$

$A_{U\perp}$ SSAs

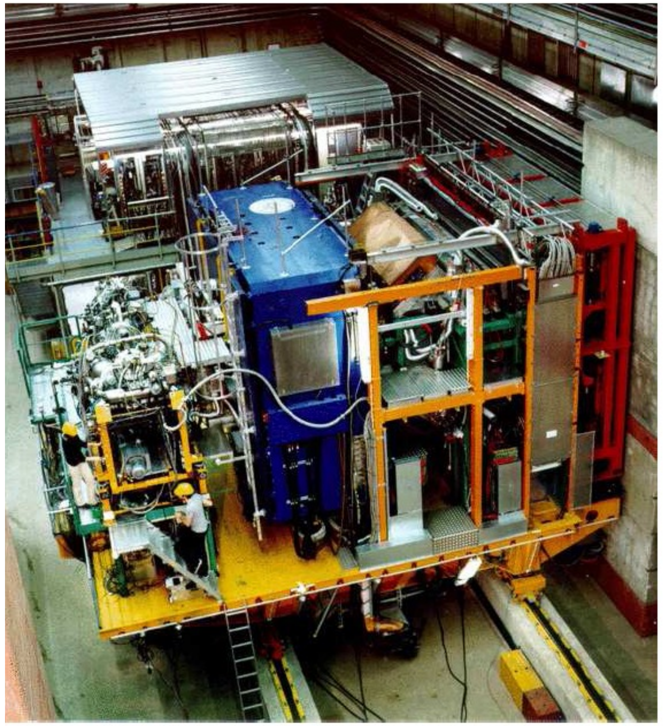
$A_{L\perp}$ DSAs

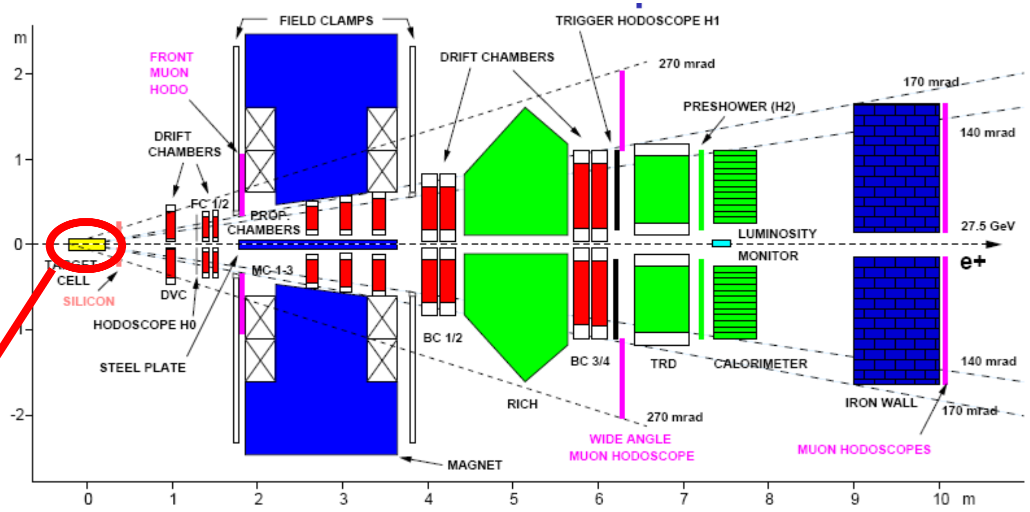
10 Fourier components:

- 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)

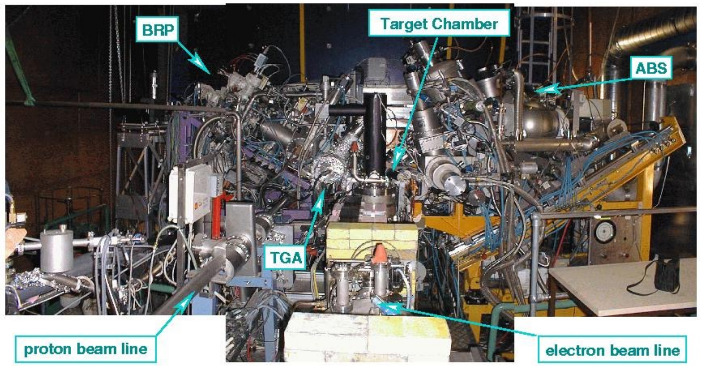
- **The CSA amplitudes include in their definition the ε-dependent kinematic prefactors that enter the various cross section terms**

The HERMES experiment at HERA (1995-2007)



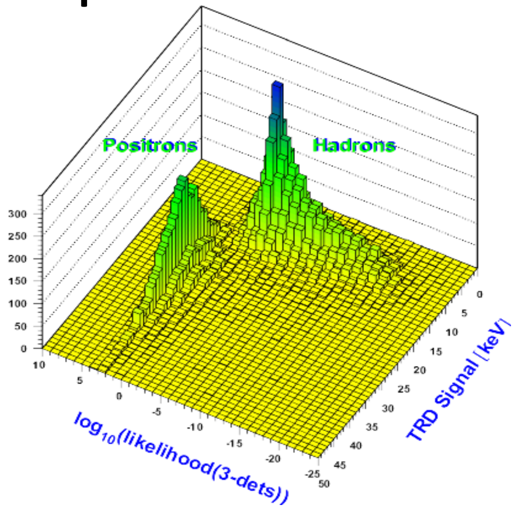


The polarized gas target

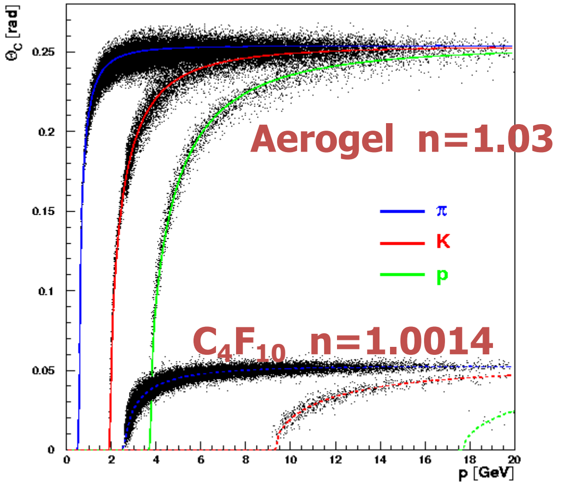


TRD, Calorimeter, preshower, RICH:

lepton-hadron > 98%



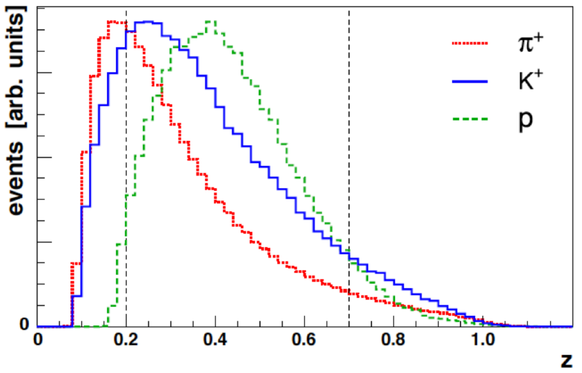
hadron separation

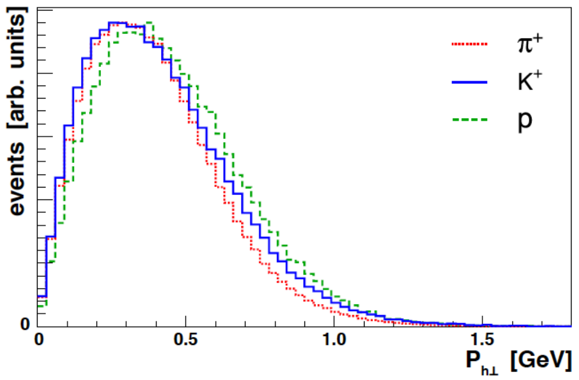


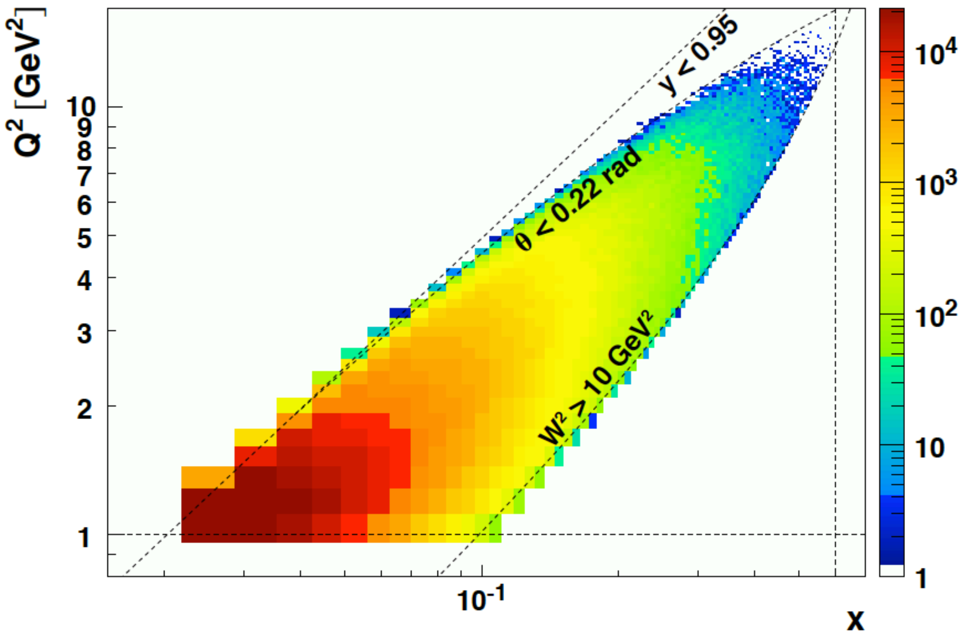
π ~ 98%, K ~ 88% , P ~ 85%

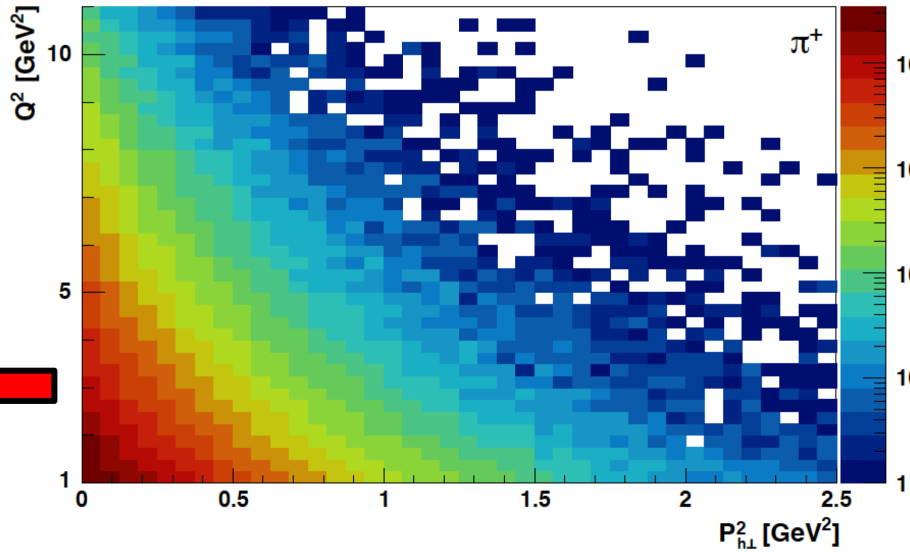
Kinematic coverage

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



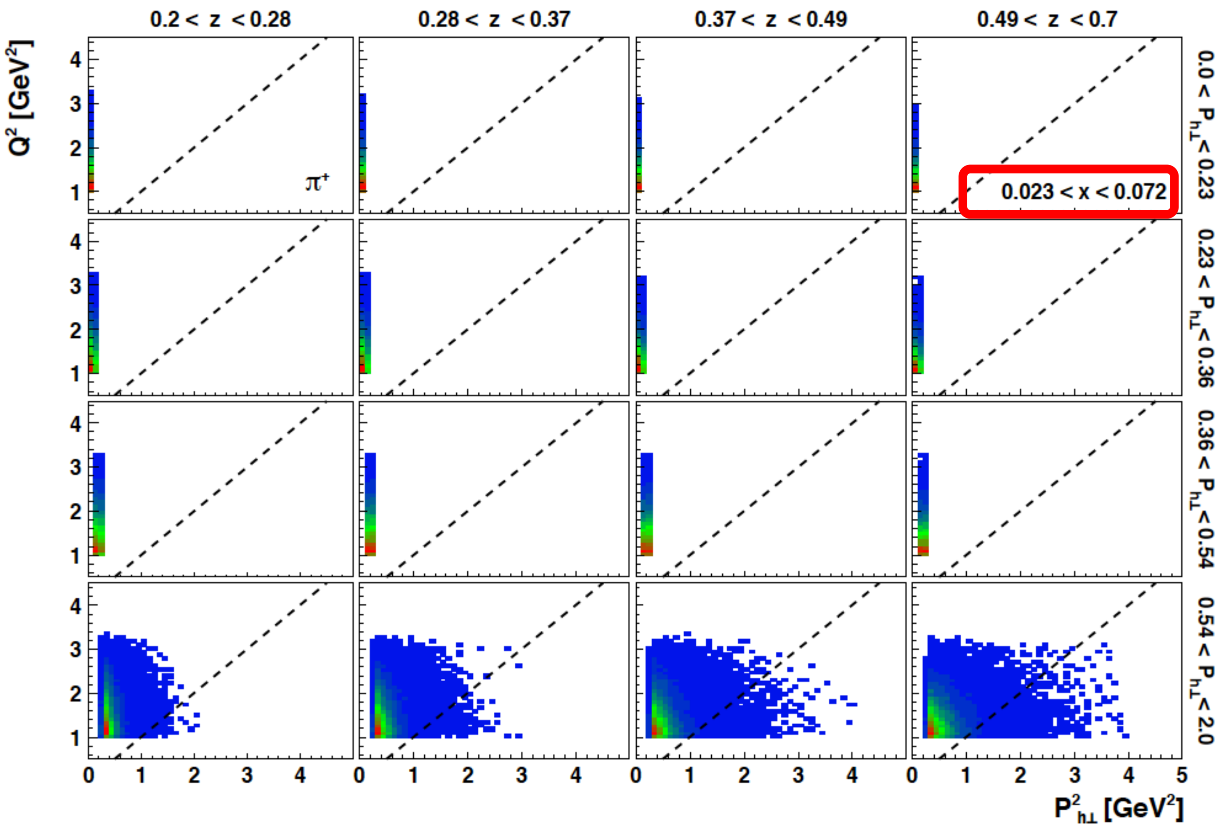


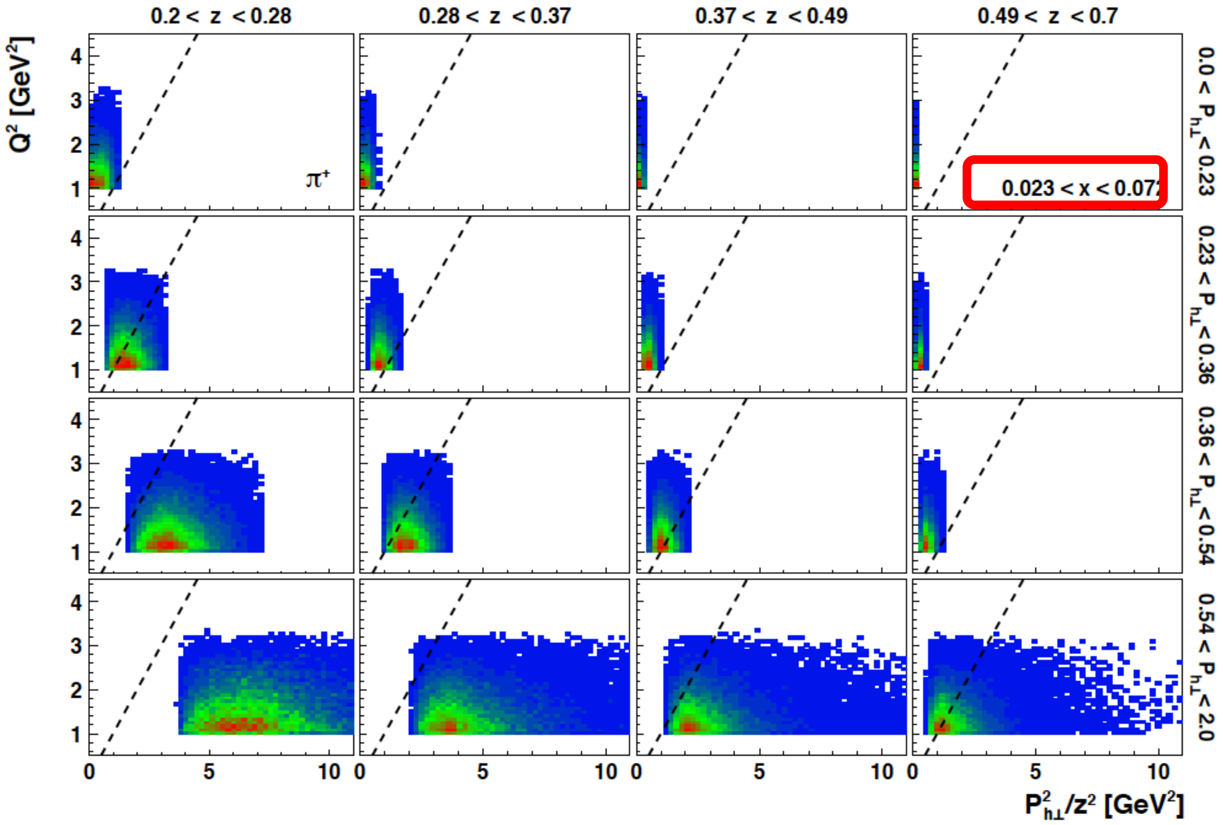




- Factorization requirement $P_{h\perp}^2 \ll Q^2$ fulfilled for most of the selected DIS events
- the stricter constraint $P_{h\perp}^2 \ll z^2 Q^2$ is violated at large $P_{h\perp}$ in the region of small x and small z
- detailed studies in appendix B of the paper (and next slides)

Factorization requirements



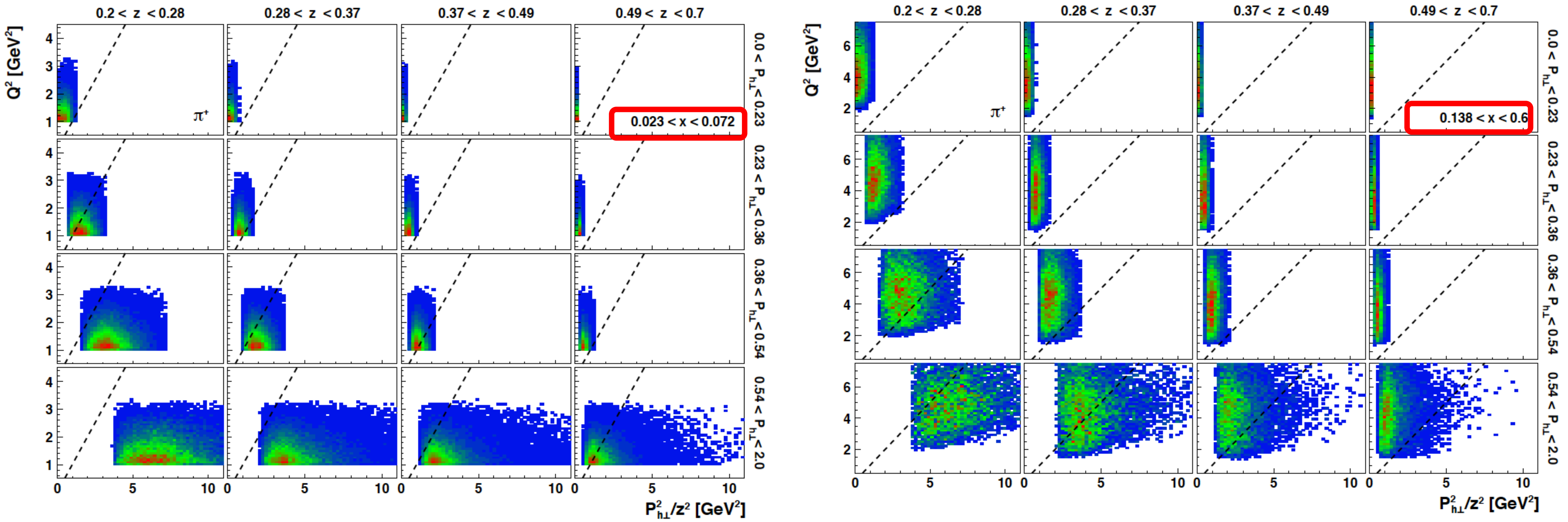


Due to x-Q^2 correlation, the first x bin corresponds to the small Q^2 region, where the requirement $P_{h\perp}^2 \ll Q^2$ is less favorable

The $1/z^2$ scale factor becomes large at small z making the condition $P_{h\perp}^2/z^2 \ll Q^2$ unfulfilled for the majority of the events

[$P_{h\perp}^2/z^2 \approx q_T$ represents the transverse momentum of the virtual photon in the frame where the two hadrons involved (initial and final, for SIDIS) are collinear.]

Factorization requirements



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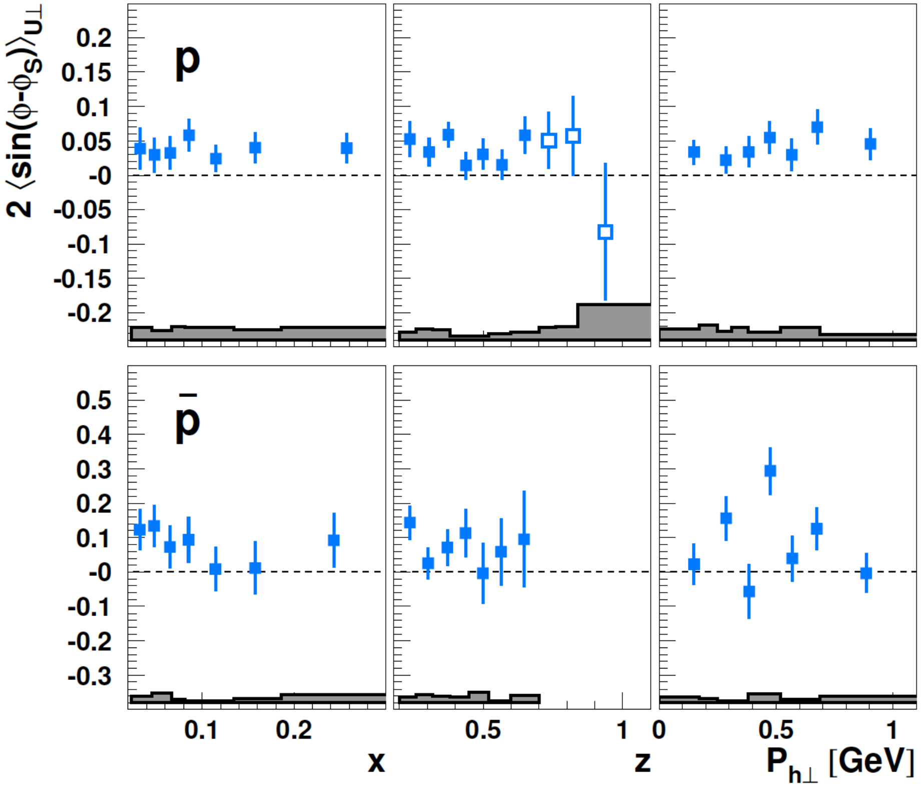
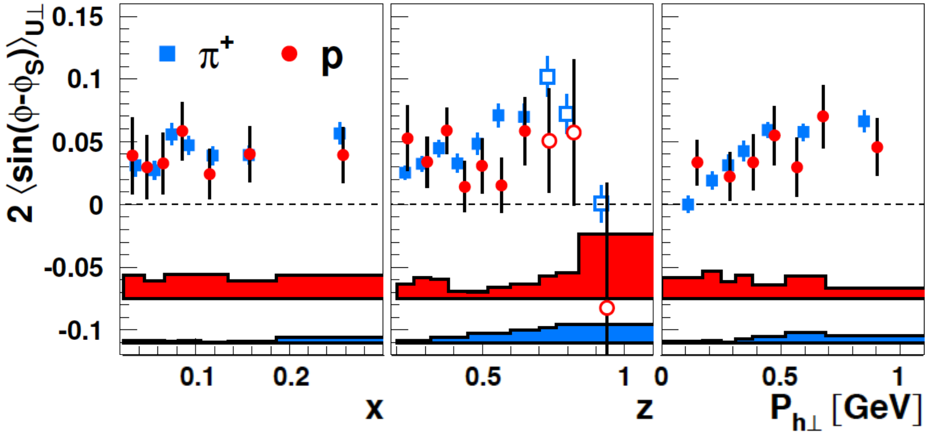
Sivers amplitudes: protons results



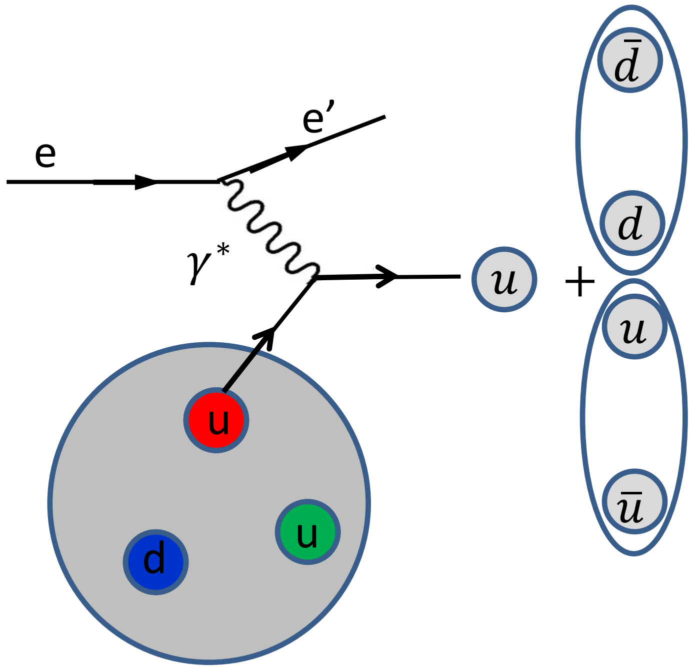
First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive



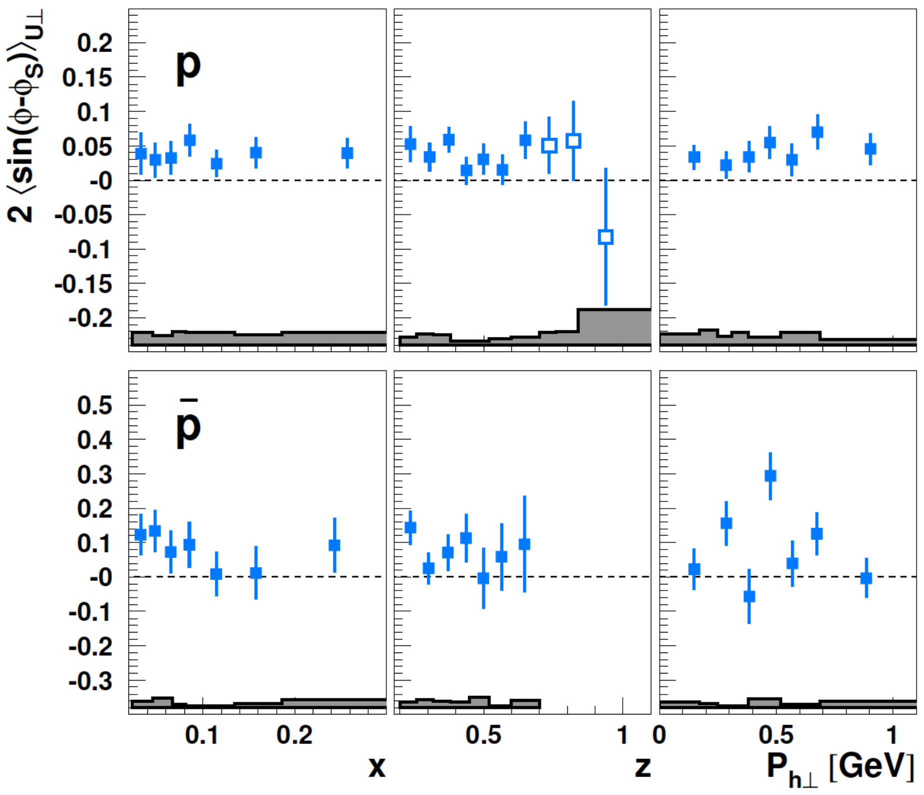
Similar agreement between $\bar{p}$ and π^+ (but with larger statistical errors)

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



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])

Sivers amplitudes: protons results



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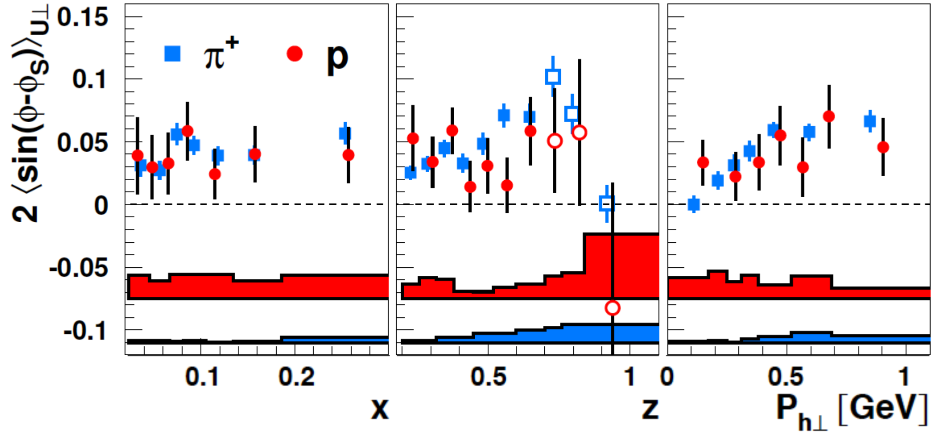

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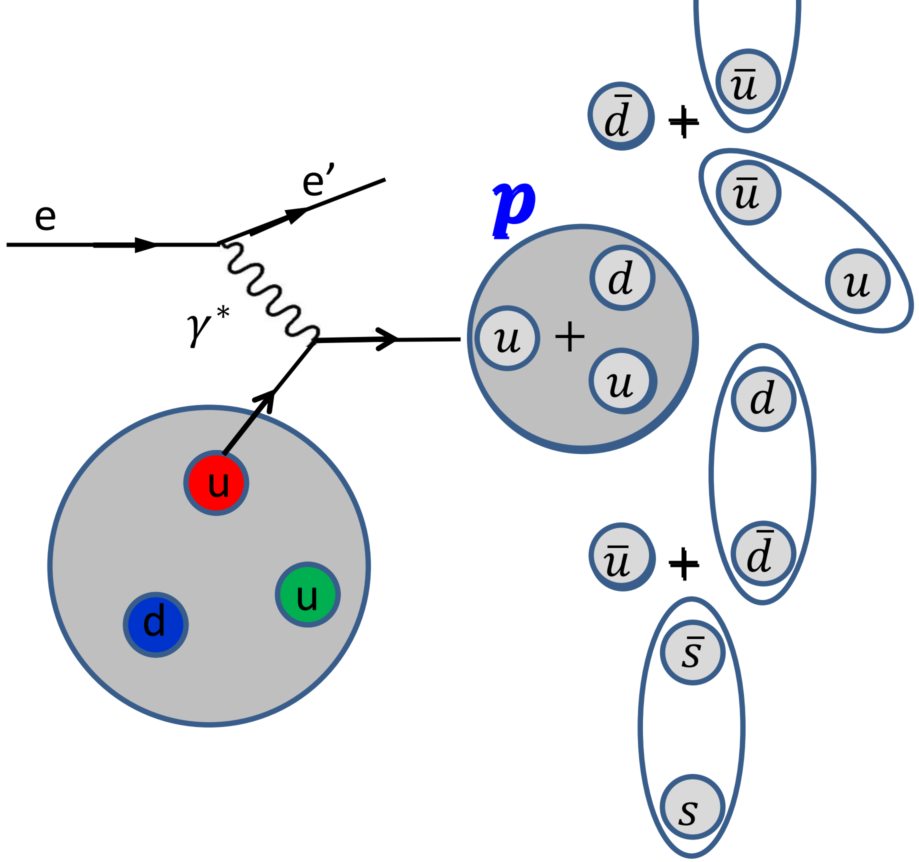

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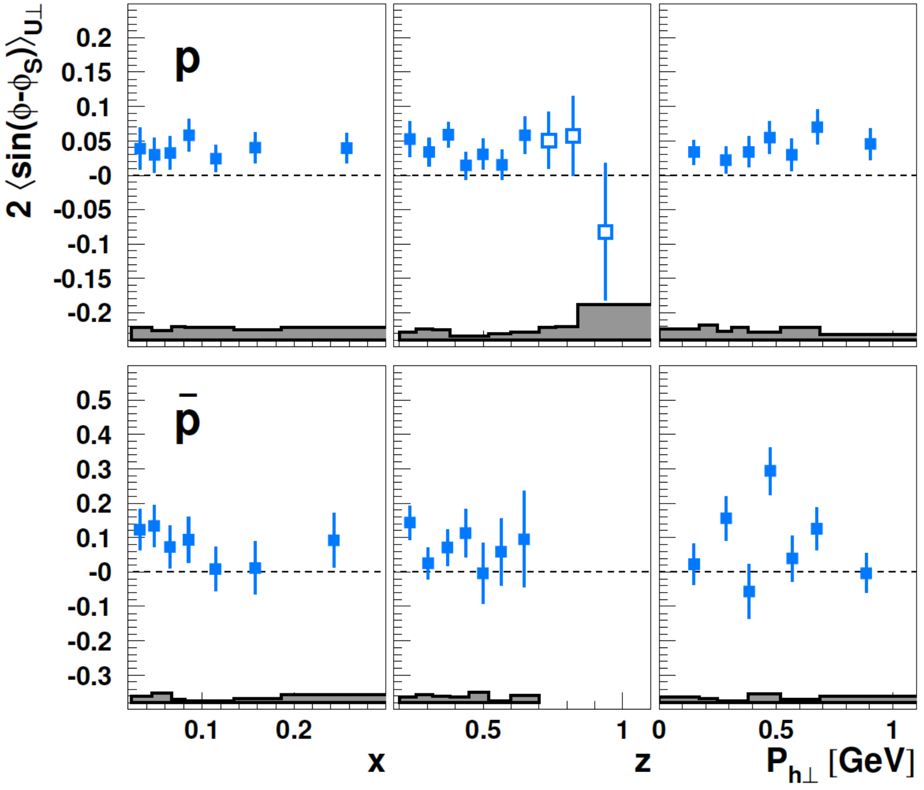
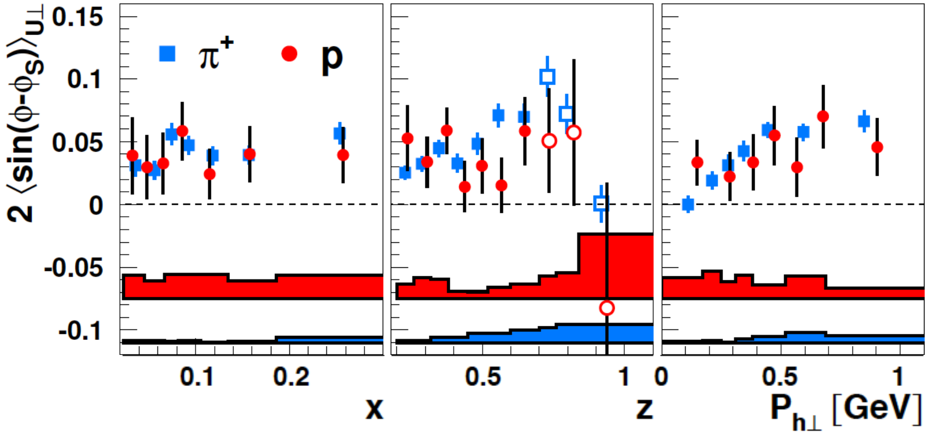
Sivers amplitudes: protons results



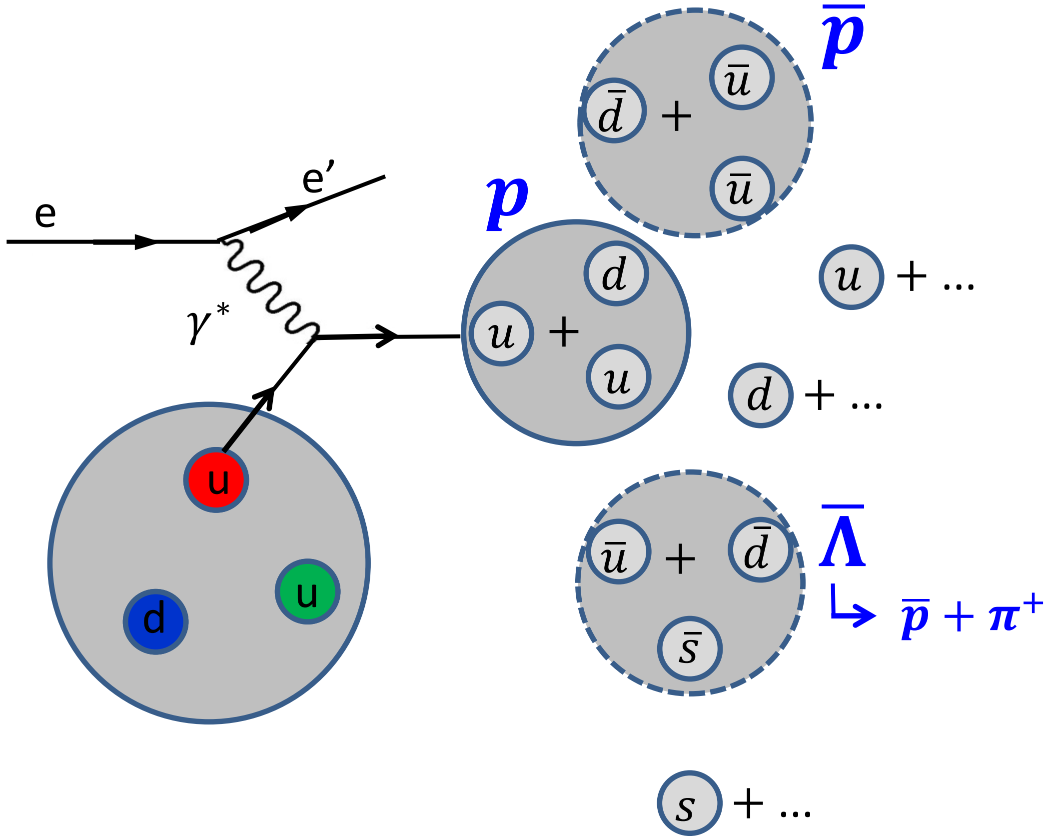
First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive



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

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



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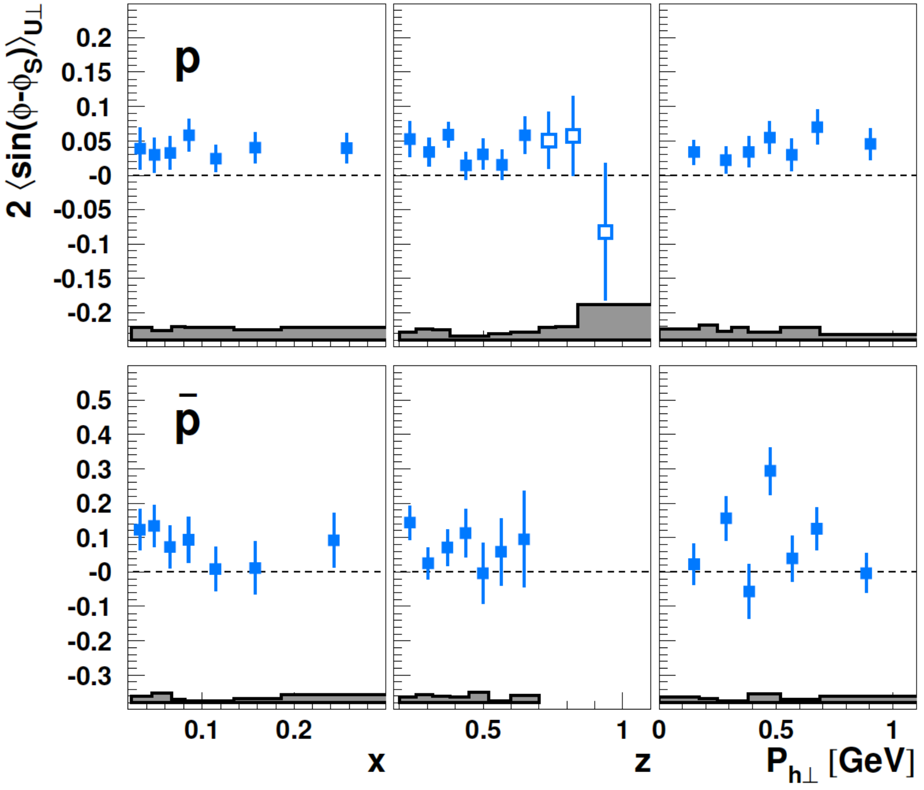

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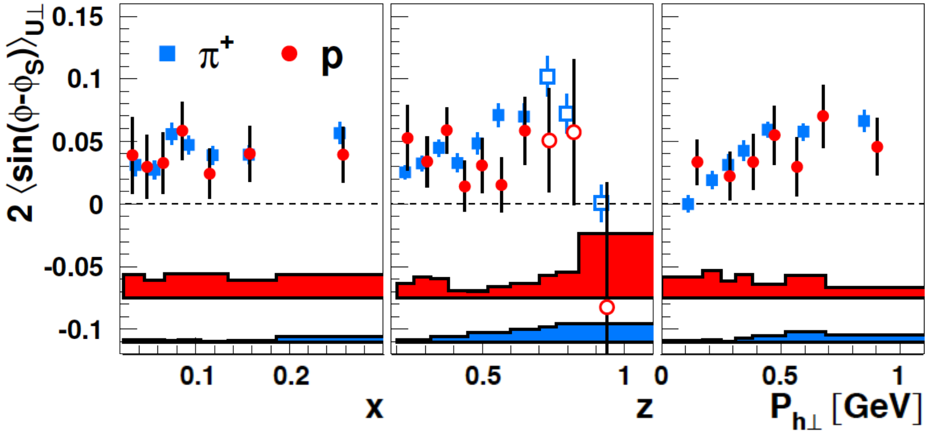

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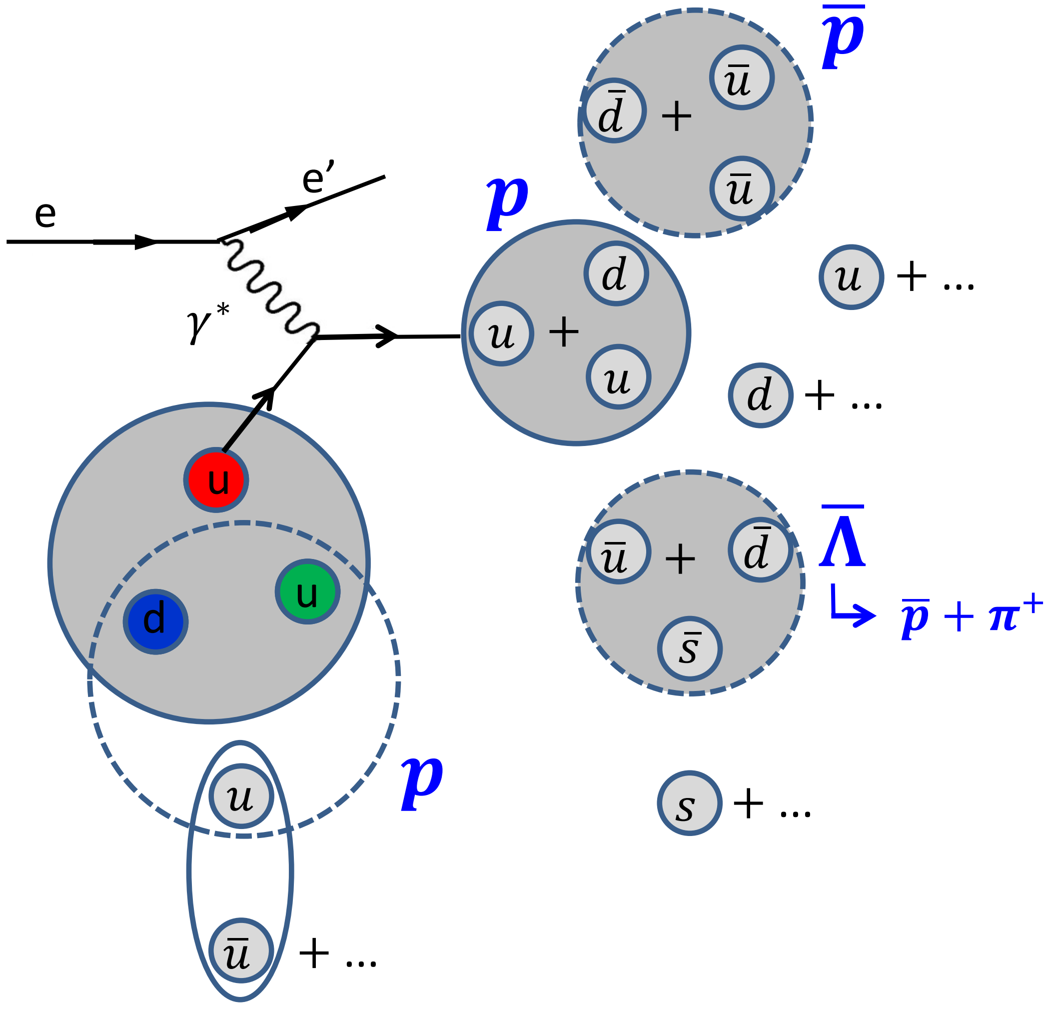
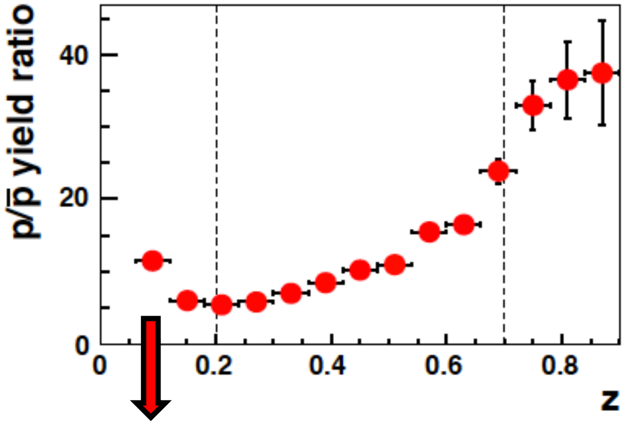
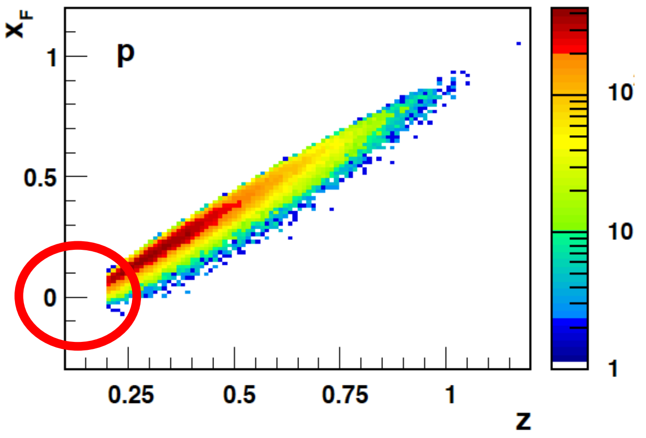


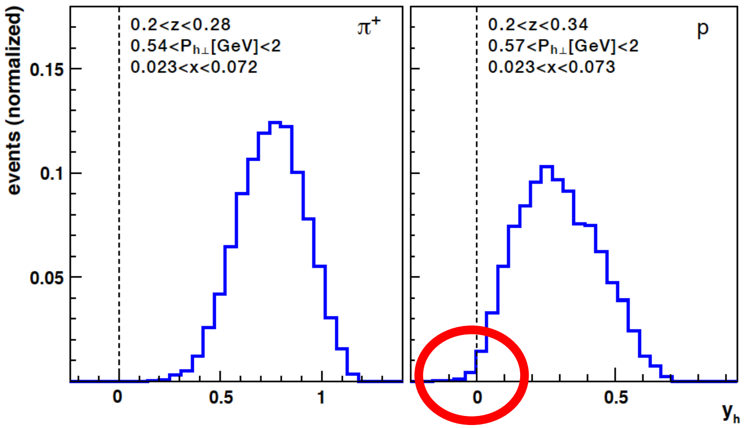
…also from TFR (low z, high $P_{h\perp}$)

Sivers amplitudes: protons results



onset of Target Fragmentation ?





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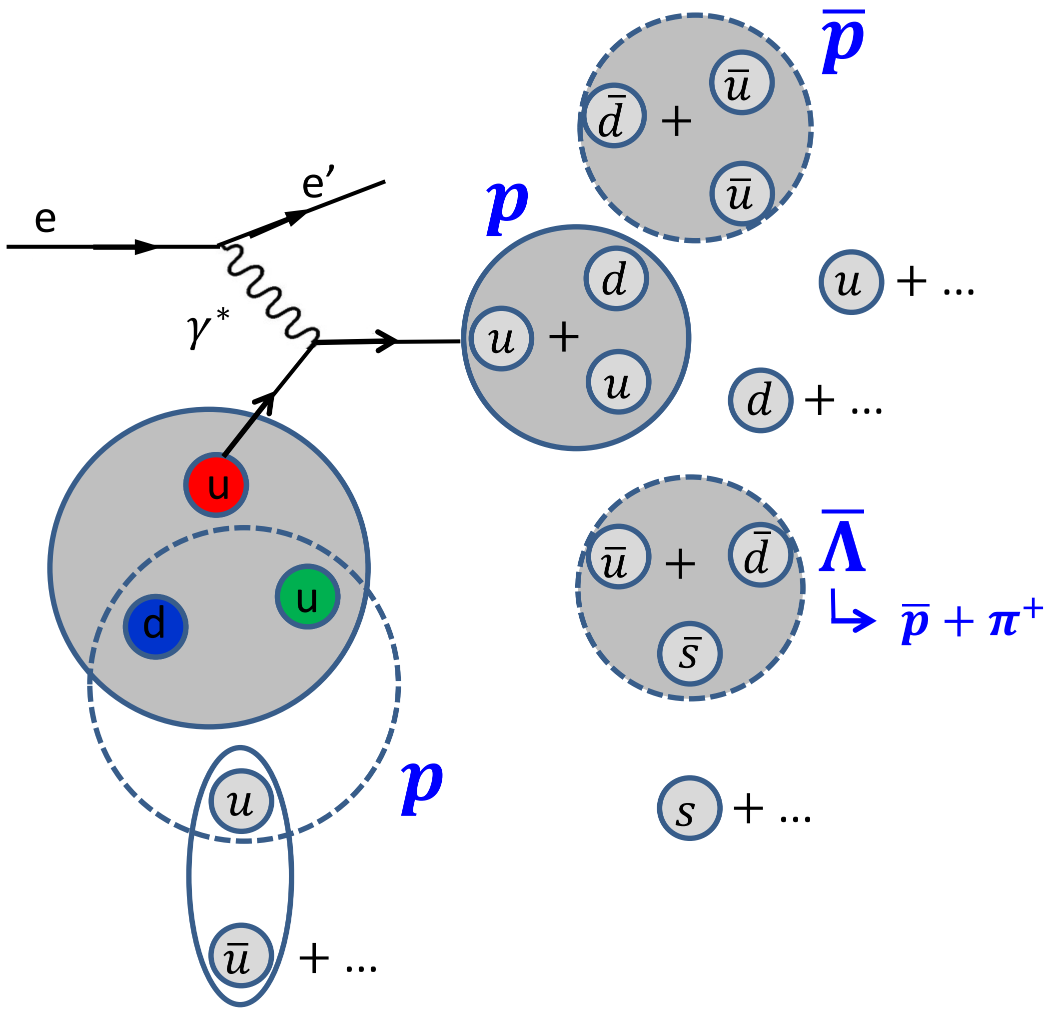
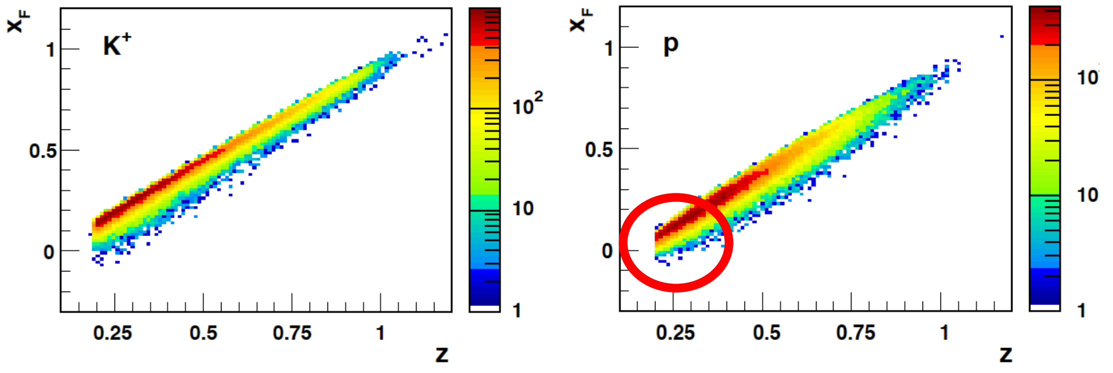


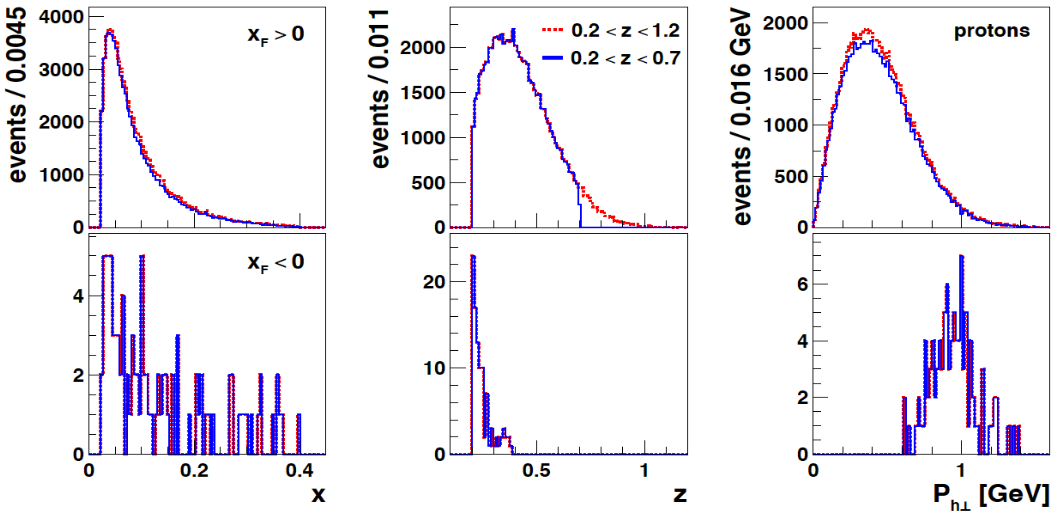
...also from TFR (low z, high $P_{h\perp}$)

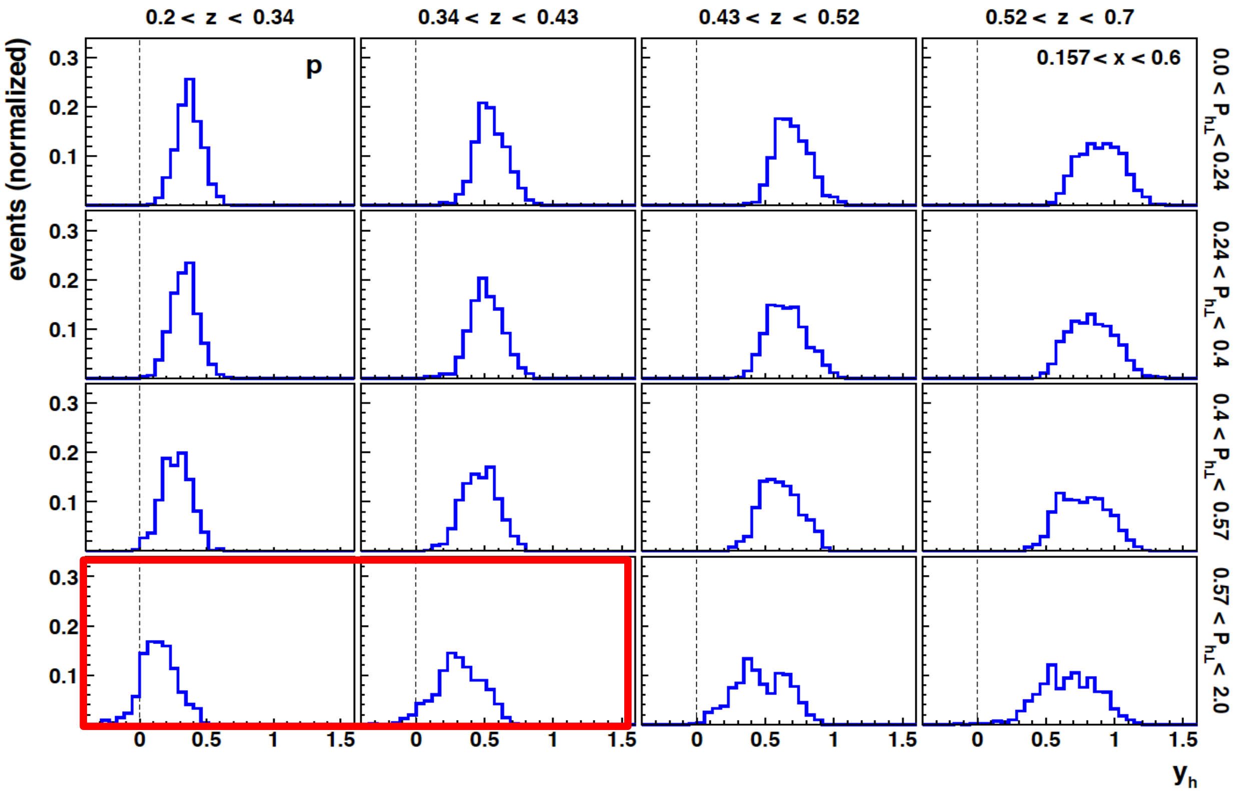
At the selected kinematics the vast majority of protons are compatible with being produced in CFR (find more studies in paper)

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
- negative values point at target fragmentation







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

The Sivers term

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

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

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

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

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

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

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

Describes correlation between quark transverse momentum and nucleon transverse polarization

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

Sivers

Unpol. FF

Sivers CSA and SFA amplitudes coincide (no ε-dep. prefactor)!

The Collins term

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

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

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

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

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

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

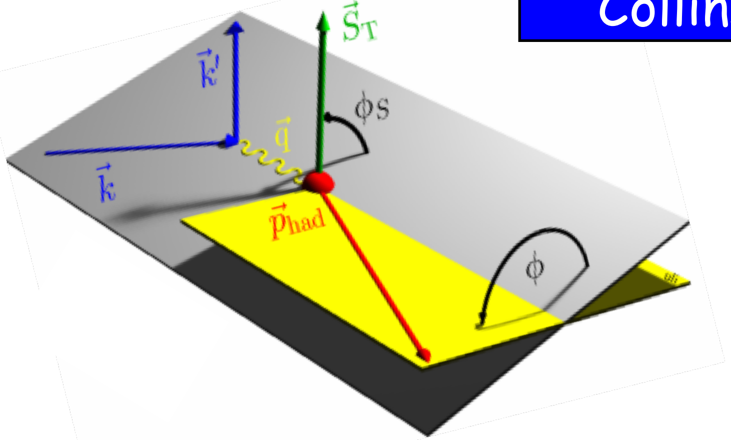
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{\mathrm{LT}}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{\mathrm{LT}}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

Describes probability to find transversely polarized quarks in a transversely polarized nucleon

Transversity

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

Collins FF



The sub-leading twist $\sin\phi_S$ term

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

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

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

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

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

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

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

Sensitive to worm-gear $g_{1T}^{\perp}$, sivers, transversity + higher-twist DF and FF

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Big\{\Big(xf_T D_1 - \frac{M_h}{M}h_1\frac{\tilde{H}}{z}\Big) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\Big[\Big(xh_T H_1^{\perp} + \frac{M_h}{M}g_{1T}\frac{\tilde{G}^{\perp}}{z}\Big) - \Big(xh_T^{\perp}H_1^{\perp} - \frac{M_h}{M}f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\Big)\Big]\Big\}$$

It is the only contribution to the cross section that survives integration over hadron transverse momentum:

$$F_{\rm UT}^{\sin(\phi_S)}(x,Q^2,z) = \int d^2\mathbf{P}_{h\perp}\,F_{\rm UT}^{\sin(\phi_S)}(x,Q^2,z,P_{h\perp}) = -x\frac{2M_h}{Q}\sum_q e_q^2\,h_1^q\frac{\tilde{H}^q(z)}{z}$$

providing sensitivity to transversity w/o involving a convolution over intrinsic transverse momenta.

The essentially unknow $\tilde{H}^q$ interaction-dependent FF has been found to be related to the Collins function. These circumstances may explain the observed **similar qualitative behavior of the $2\langle sin(\phi_S)\rangle_{U\perp}$ and the Collins asymmetries.**

Other HERMES results

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

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

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

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

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

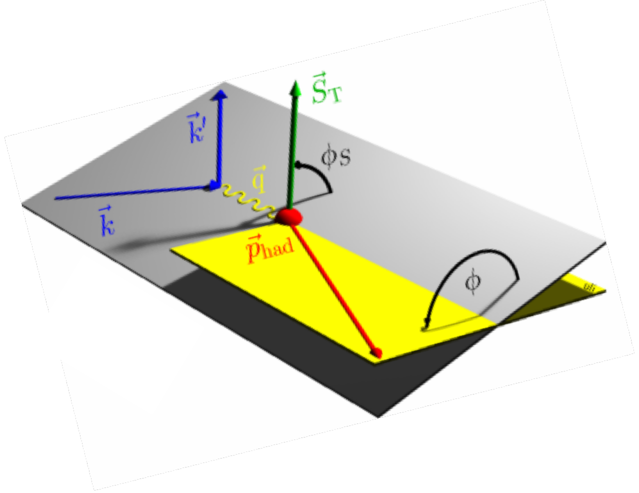
$$+ S_L\,\lambda_l\Big[\sqrt{1-\epsilon^2}F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi)F_{\rm LL}^{\cos(\phi)}\Big]$$

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

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

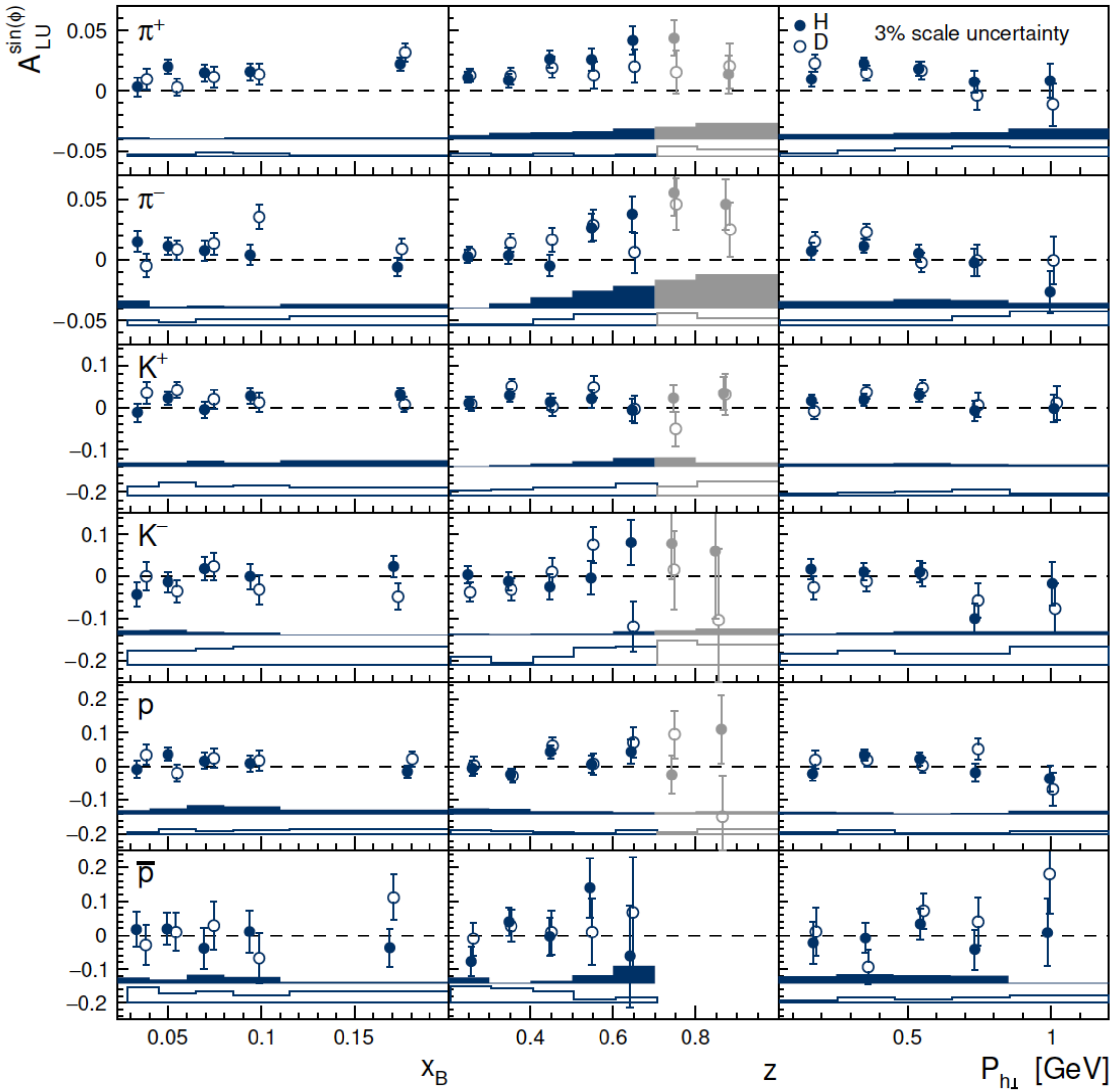
Sensitive to f_1 , Boer-Mulders + higher-twist DF and FF

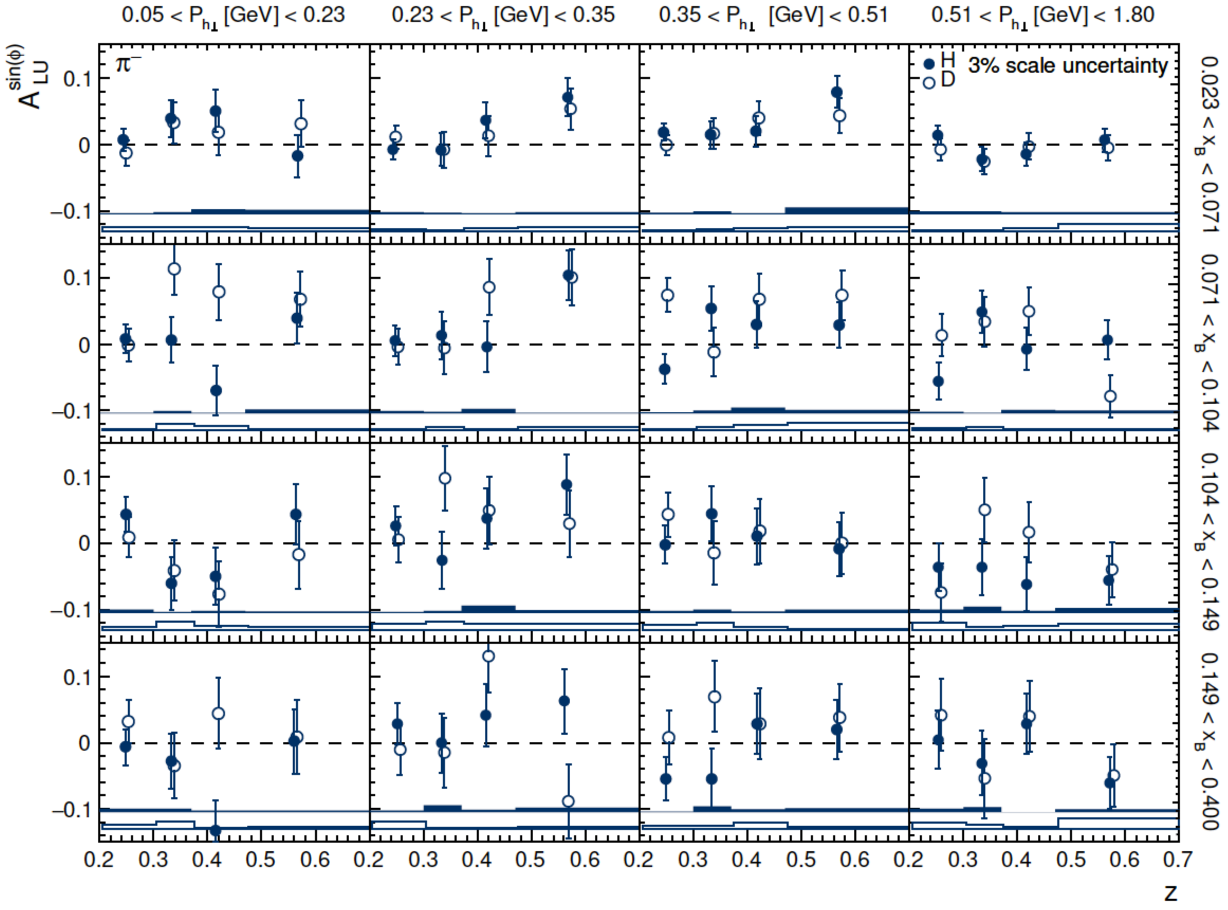
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$



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

Phys. Lett. B 797 (2019) 134886



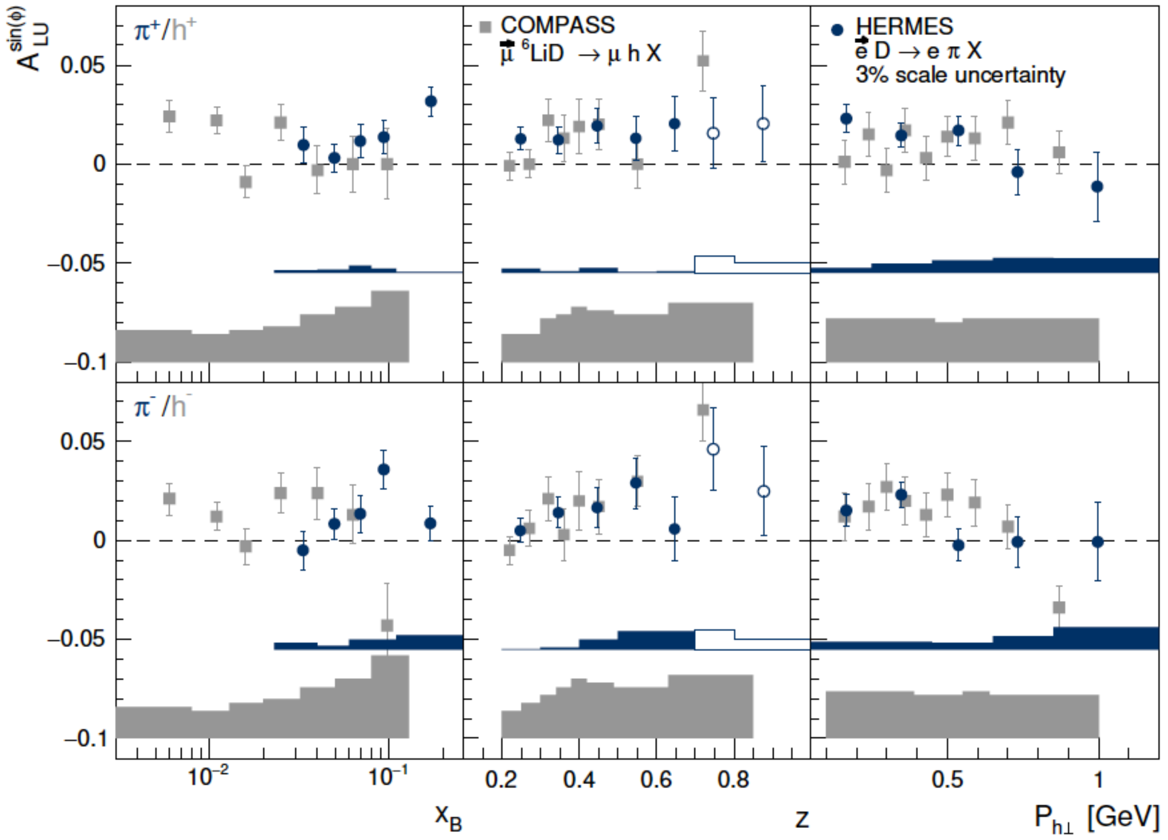


- Large positive amplitudes rising with z for π^+ and π^-
- Small positive amplitude with mild kinematic dep. for K^+
- Results compatible with zero for K^-, p and $\bar{p}$

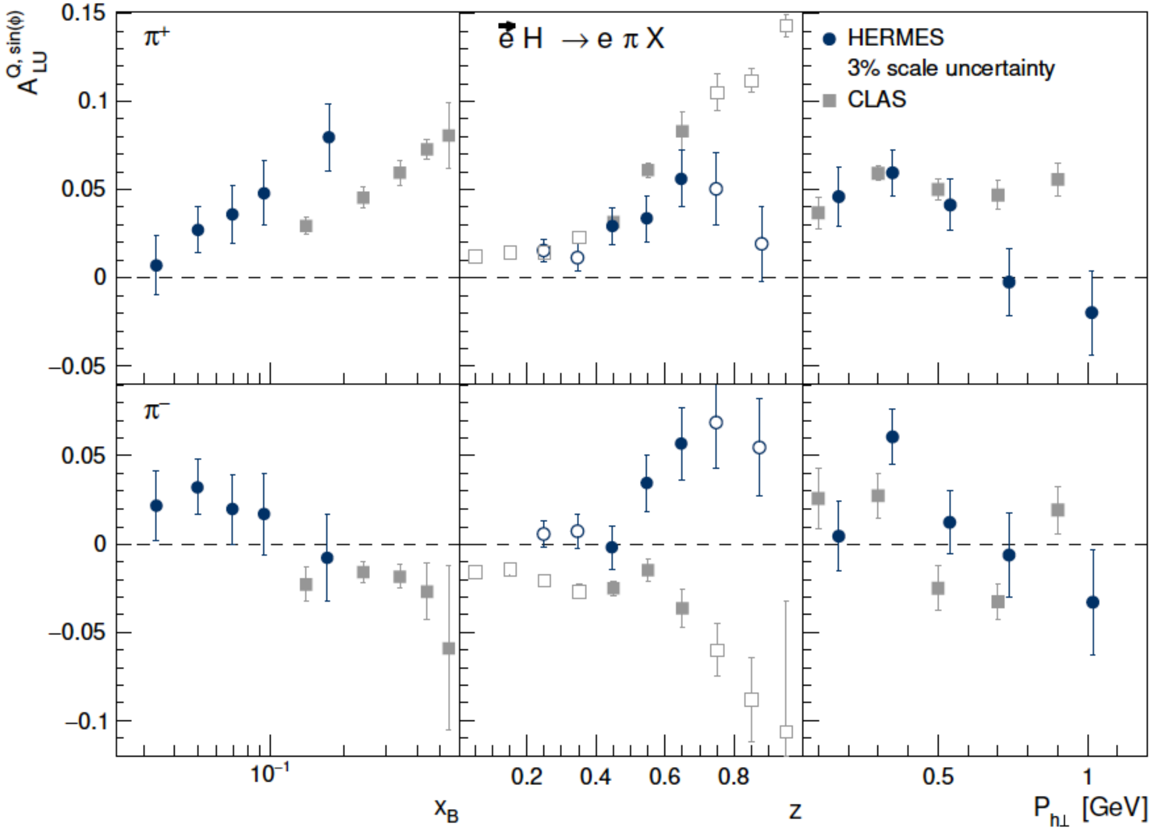
Sub-leading twist $\sin(\phi)$ BSA

Phys. Lett. B 797 (2019) 134886

HERMES vs. COMPASS



HERMES vs. CLAS



Sign change with increasing x?

Boer-Mulders function

Describes correlation between quark transverse momentum and transverse spin in unpolarized nucleon

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

$$F_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2}[f_1 \otimes D_1 + \cdots]$$

Cahn effect

Boer-Mulders

Collins FF

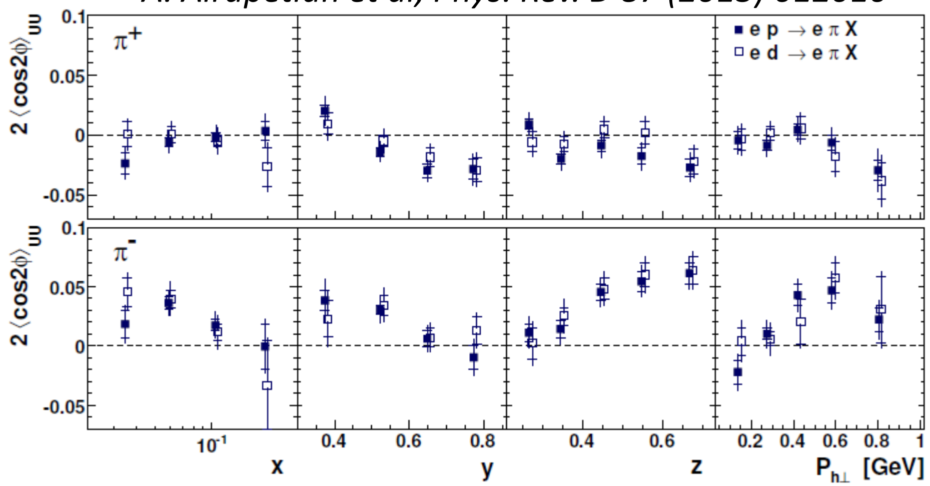
$$F_{UU}^{\cos(\phi)} \propto +\frac{1}{Q}[h_1^\perp \otimes H_1^\perp + f_1 \otimes D_1 \ldots]$$

Cahn effect

Interaction dependent terms

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

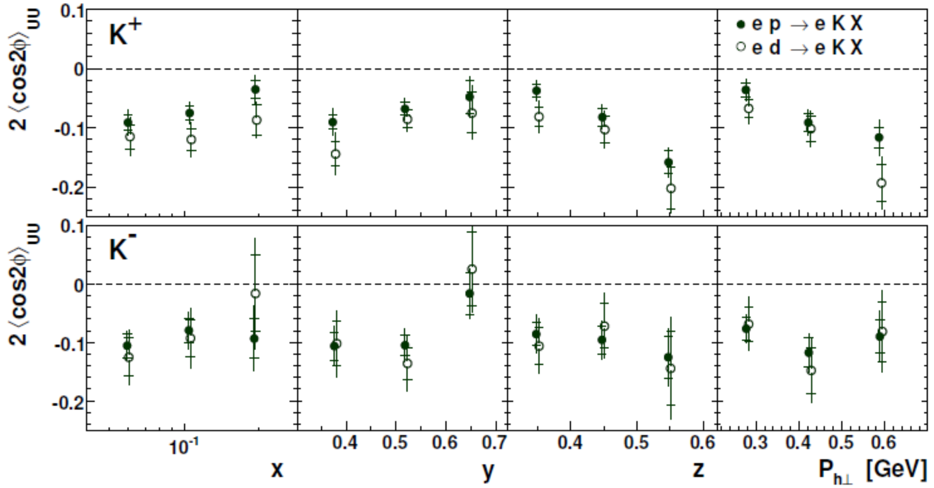
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



negative

positive

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



Large and negative

Large and negative

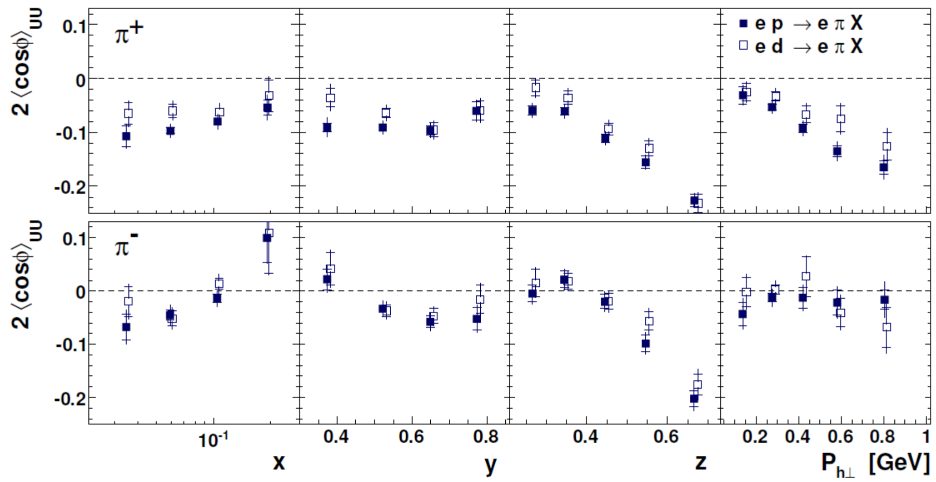
- **K^+/K^- amplitudes larger than for pions , have different kinematic dependencies than pions and have same sign**

→ different role of Collins FF for pions and kaons?

→ 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



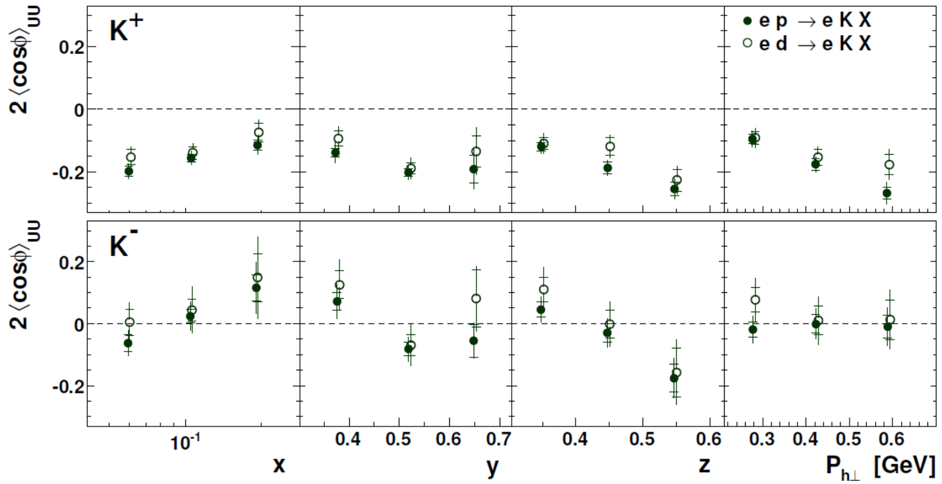
negative

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?

Worm-gear $h_{1L}^{\perp}$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1L}^{\perp}H_1^{\perp}\right]$$

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

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

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

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

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

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

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

Describes the probability to find transversely polarized quarks in a longitudinally polarized nucleon

Distribution Functions

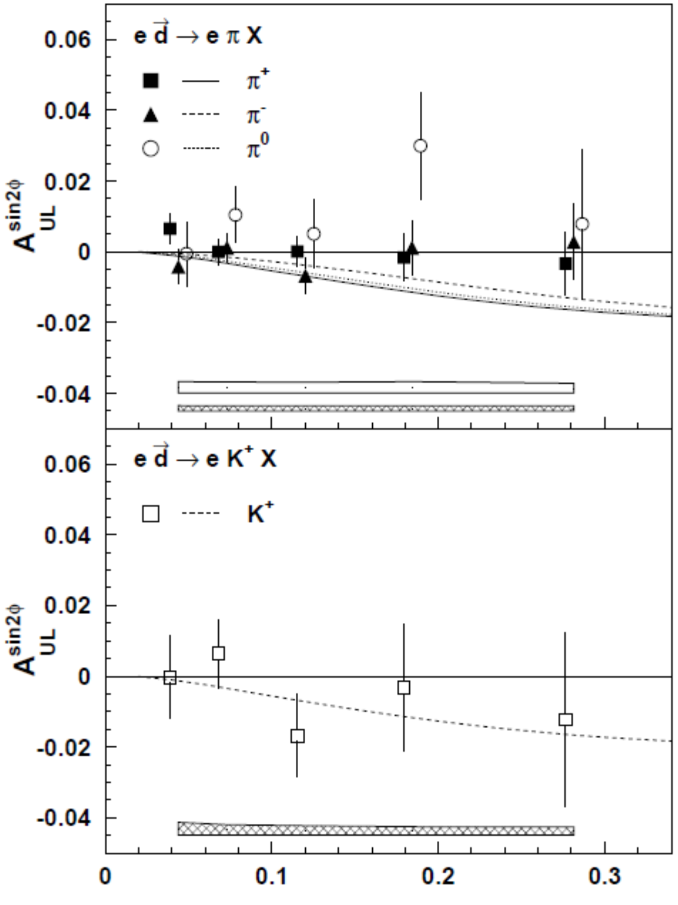
		quark U	quark L	quark T
nucleon	U	f_1		$h_1^{\perp}$
nucleon	L		g_1	$h_{1L}^{\perp}$
nucleon	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1, $h_{1T}^{\perp}$

Fragmentation Functions

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

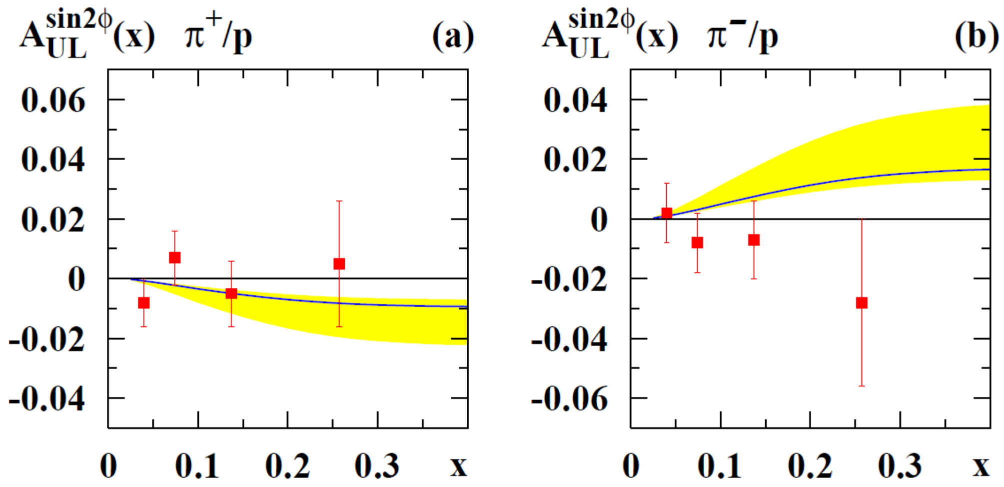
The sin(2ϕ) amplitude $\propto h_{1L}^{\perp}(x,p_T^2)\otimes H_1^{\perp}(z,k_T^2)$

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