Recent HERMES results on the 3D imaging of the nucleon

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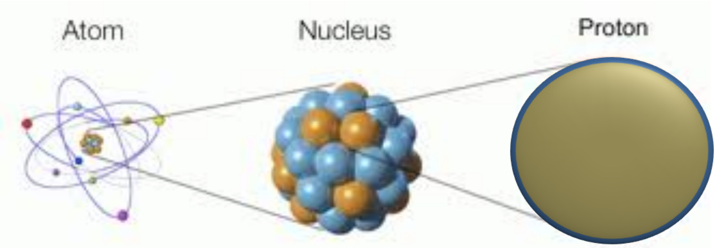
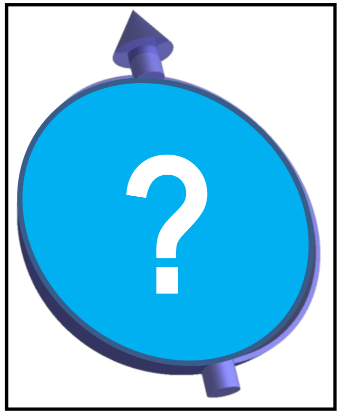
Looking deeply into the proton

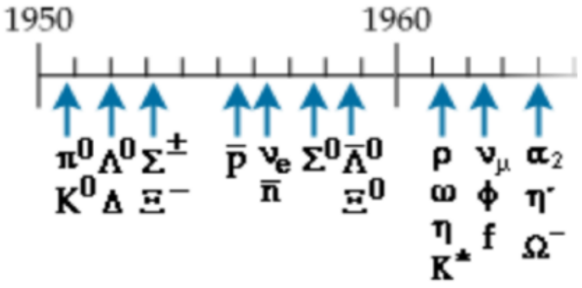


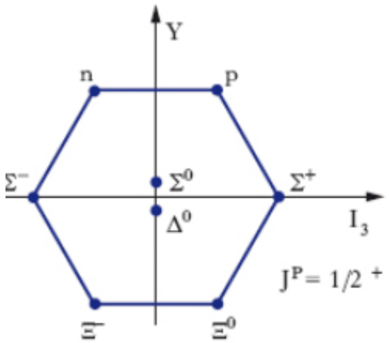
size $\approx 10^{-15}$ **m**

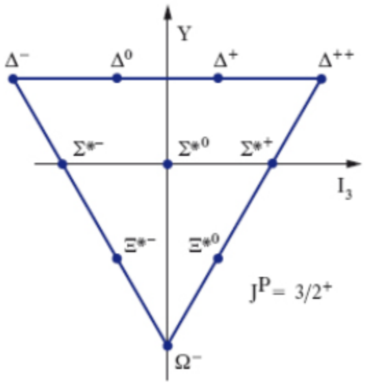
< 1960



- **Elementary particle?**

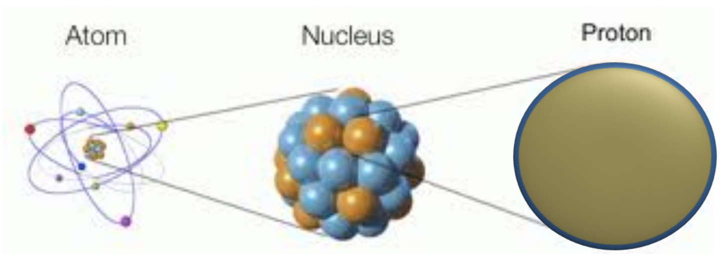




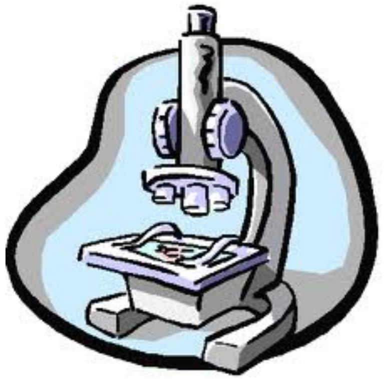


- Hadrons having the same J^P quantum numbers form **multiplets** in the Y-I_3 plane.
- These regularities were suspected to be the manifestation of **some internal degree of freedom, i.e. hadrons must have an internal structure!**

Looking deeply into the proton



Internal structure
$\mathbf{10^{-15} \leftrightarrow 10^{-18}\ m}$



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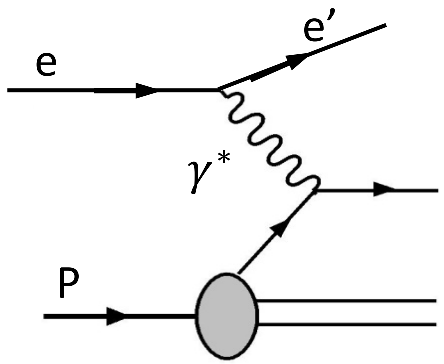
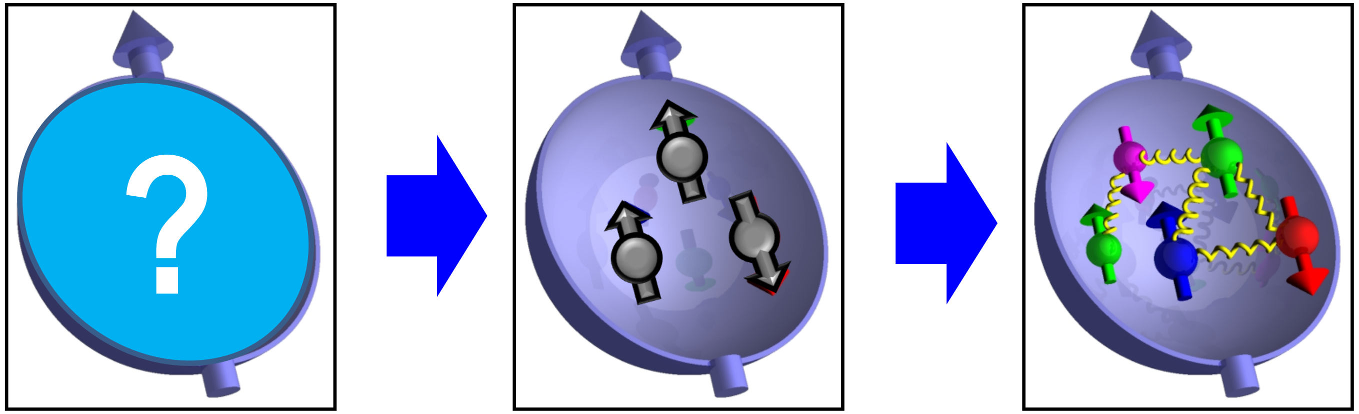


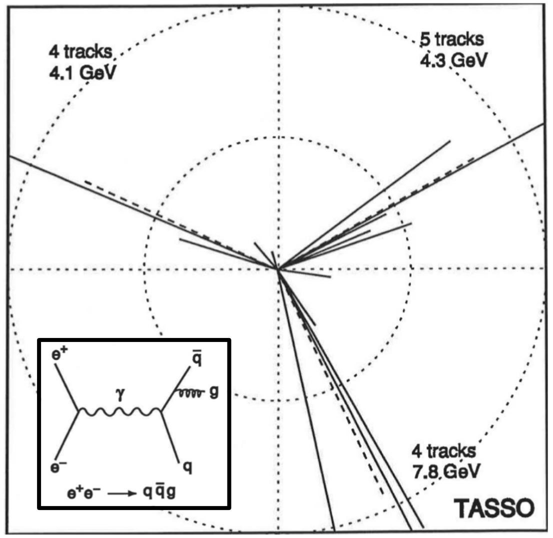
< 1960 | 1964-1969 | 1972-1979



- **Elementary particle?**

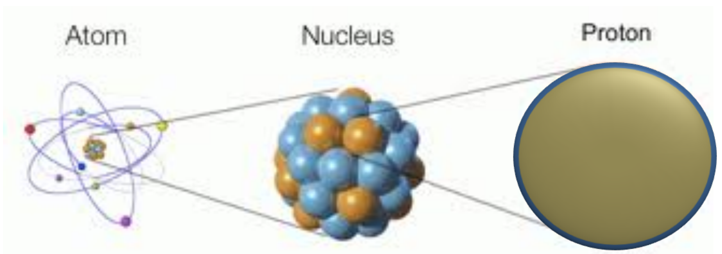
- **Quark hypothesis** (Gell-Mann - Zweig)
- **Scaling at SLAC** ('69)
- **Parton Model** (Faynman, Bjorken)

- **QCD** lagrangian
- **colors**, sea quarks, gluons
- **discovery of gluons** (PETRA '73)



First 3-jet event from PETRA observed through the TASSO detector in 1979

Looking deeply into the proton



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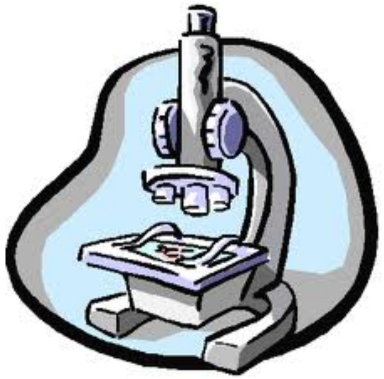

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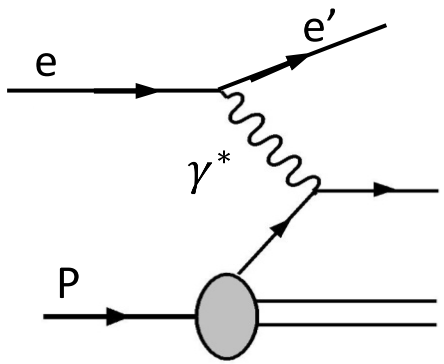

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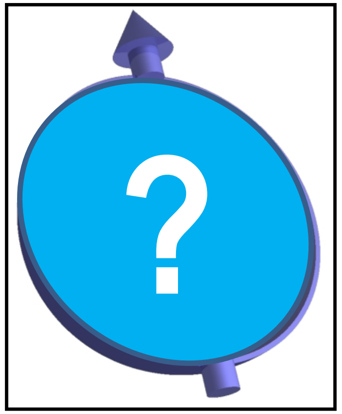
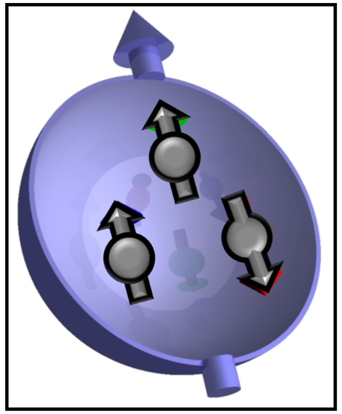


- **Elementary particle?**

1964-1969



- **Quark hypothesis** (Gell-Mann - Zweig)
- **Scaling at SLAC** ('69)
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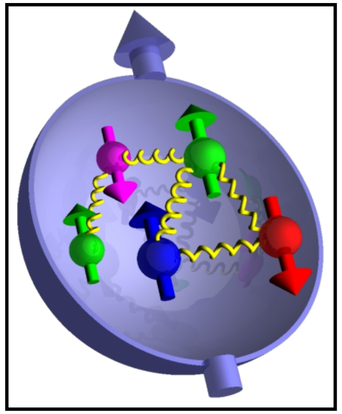
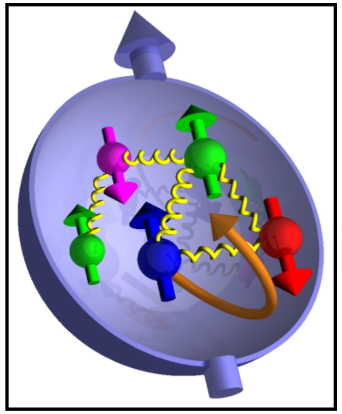
1972-1979



- **QCD** lagrangian
- **colors**, sea quarks, gluons
- **discovery of gluons** (PETRA '73)

> 1988

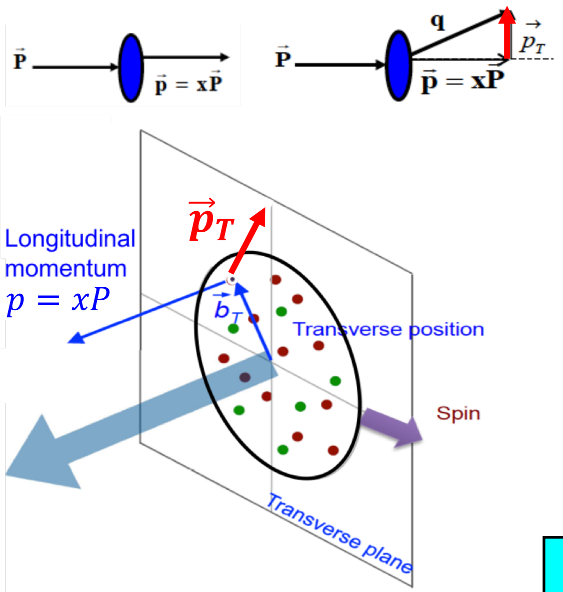


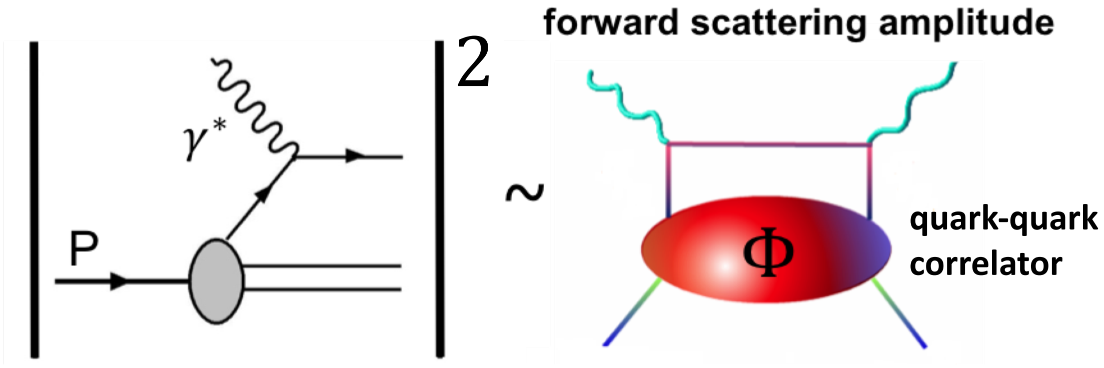
- EMC experiment: the **spin crisis**

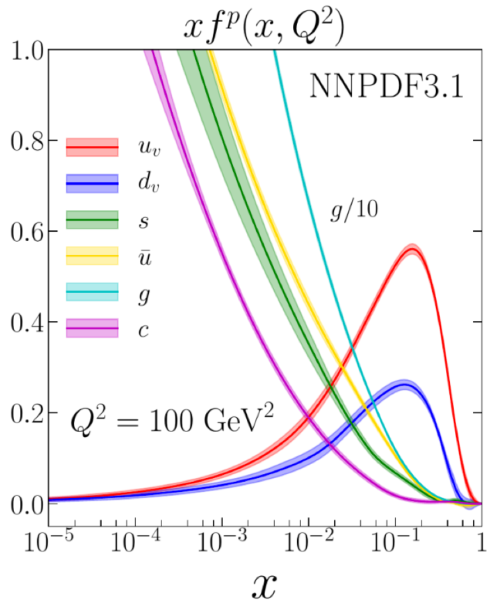
$$\frac{1}{2} = \underbrace{\frac{1}{2}(\Delta u_V + \Delta u_V + \Delta q_S)}_{\sim 30\%} + \underbrace{\Delta G + L_q + L_g}_{\sim 70\%}$$

...today

The nucleon **collinear** structure



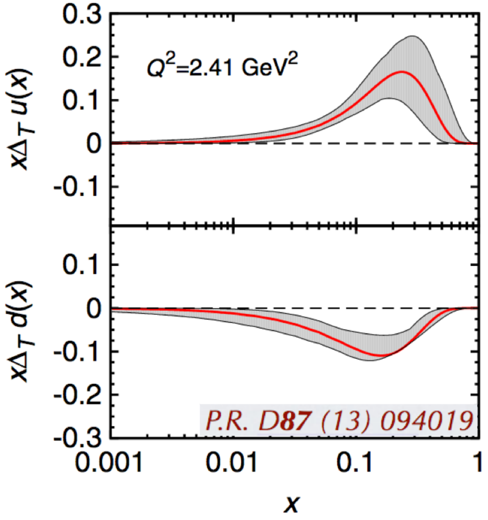


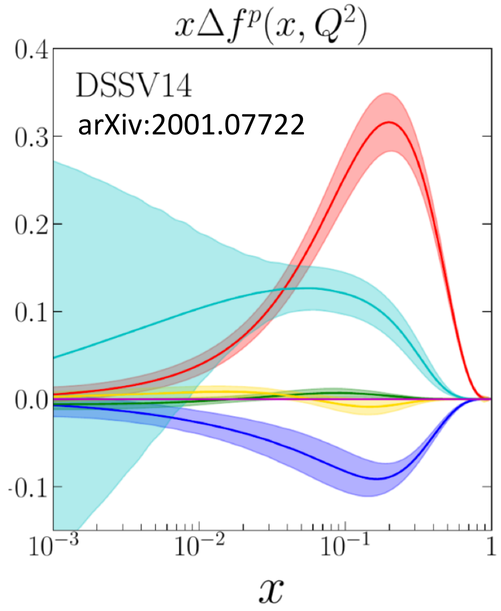


$$\Phi = \frac{1}{2}[f_1(x)\not{P} + \lambda_N g_1(x)\gamma_5\not{P} + h_1(x)\not{P}\gamma_5\not{S}_T]$$

momentum — helicity — transversity

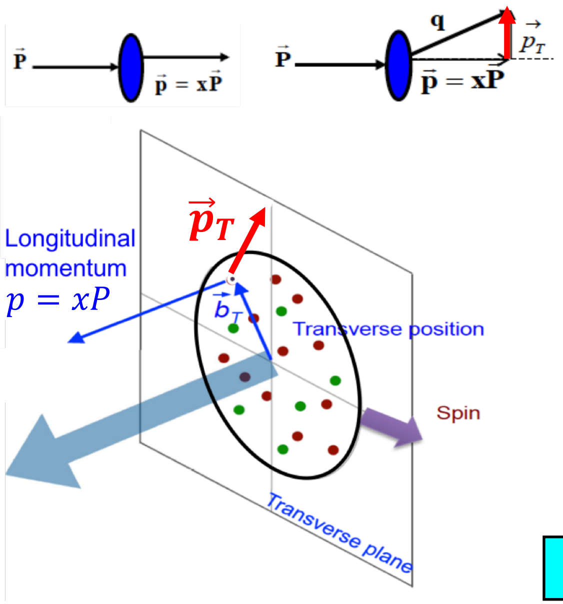
nucleon \ quark	U	L	T
U	f_1		
L		g_1	
T			h_1



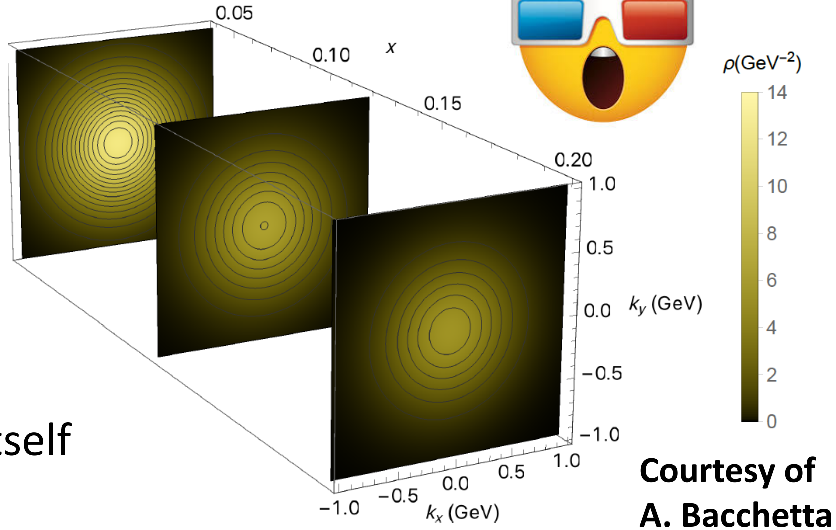


- ➢ **Complete description of the collinear structure of the nucleon at leading-twist**
- ➢ **Only PDFs that survive integration over quark transverse momentum p_T.**

The nucleon non-collinear structure

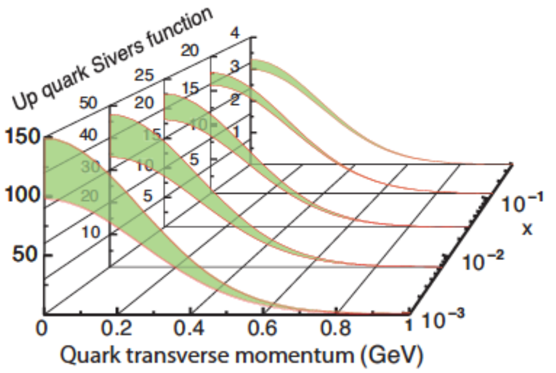


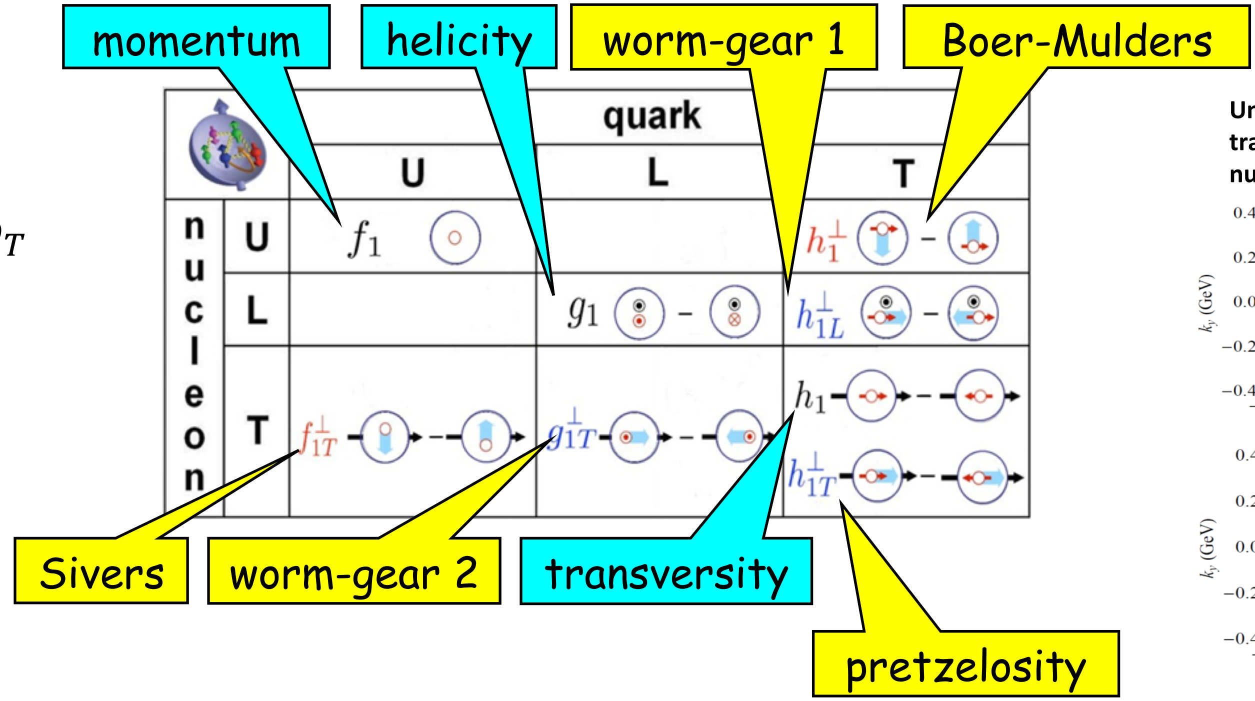
- Provide **a 3-dim picture** of the nucleon in momentum space (**nucleon tomography**)
- Describe correlations between p_T
  - and the spin orientation of the parent hadron
  - and the spin orientation of the parton itself
  - and are flavor dependent



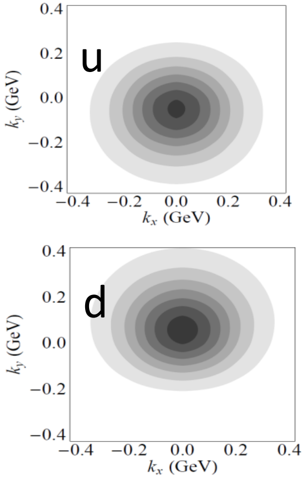
Courtesy of A. Bacchetta

- **8 leading-twist TMDs**
- TMDs depend on x and p_T

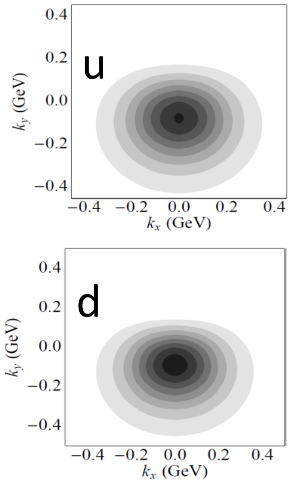




Unpolarized quarks in a transversely polarized nucleon (Sivers effect)

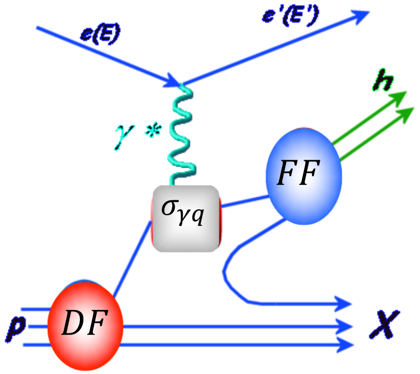


transv. pol. quarks in unpol. nucleon (B-M)



Phys.Rev.D81:114013,2010

Semi-Inclusive Deep-Inelastic scattering (SIDIS)



Unpol FF

Collins FF

target polarization

$F_{XY,Z} \propto$ **DF** $\otimes$ **FF**

beam polarization

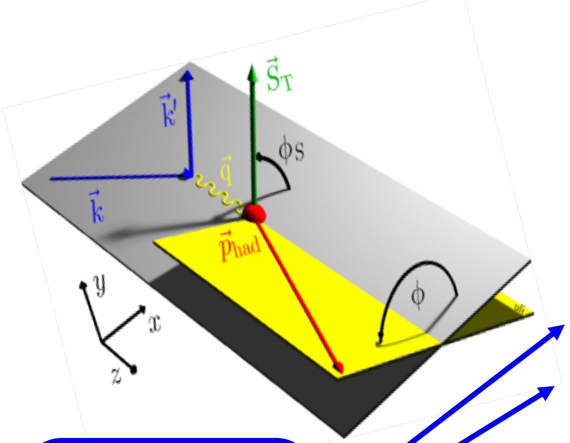
virtual photon polarization

Fragmentation Functions (FF)

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

TMD factorization: $\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$

(requires $P_{h\perp}^2 \ll Q^2$)



Parton Distributions Functions (DF)

		quark		
		U	L	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 - ; $h_{1T}^\perp$ -

hermes

Sivers

W-G 2

transversity

Pretzelosity

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

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

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

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

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

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

$$
+ \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]
$$

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

The HERMES TMD bible

PREPARED FOR SUBMISSION TO JHEP
DESY REPORT 20-119

hermes

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

The HERMES Collaboration

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[a] Deceased.

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NEW!!

Published Dec. 2 2020 on: JHEP 12 (2020) 010

target polarization

$F_{XY,Z} \propto$ ***DF*** $\otimes$ ***FF***

beam polarization

virtual photon polarization

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

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NEW!!

arXiv:2007.07755v1 [hep-ex] 15 Jul 2020

Published Dec. 2 2020 on: JHEP 12 (2020) 010

- **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)

Advances w.r.t previous analyses:

- **3D binning** (before only 1D)
- $\boldsymbol{p/\bar{p}}$ **asymmetries** (in addition to $\pi^{\pm}, \pi^0, K^{\pm}$)
- **Extraction of SFAs** (in addition to CSAs)
- **Use of a later data production**, which includes updated tracking and alignment info
- **Extraction of $\boldsymbol{\pi^0}$ 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)

The SFA amplitudes (NEW!)

The relevant asymmetry amplitudes are extracted in an unbinned ML fit of the Fourier decomposition of the cross section

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

$$\mathbb{P}\Big(x, z, \epsilon, P_{h\perp}, \phi, \phi_S, P_l, S_\perp : 2\langle \sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp}, \ldots 2\langle \cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{\mathrm{L}\perp}\Big)$$
$$= \Big[1 + S_\perp\Big(2\langle \sin(\phi-\phi_S)\rangle^h_{\mathrm{U}\perp} \sin(\phi-\phi_S) + \epsilon\, 2\langle \sin(\phi+\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(\phi+\phi_S) +$$
$$\epsilon\, 2\langle \sin(3\phi-\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(3\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}\, 2\langle \sin(\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\rangle^h_{\mathrm{U}\perp} \sin(\phi_S) +$$
$$\sqrt{2\epsilon(1+\epsilon)}\, 2\langle \sin(2\phi-\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\rangle^h_{\mathrm{U}\perp} \sin(2\phi-\phi_S) + \epsilon\, 2\langle \sin(2\phi+\phi_S)/\epsilon\rangle^h_{\mathrm{U}\perp} \sin(2\phi+\phi_S)\Big)$$
$$+ P_l S_\perp\Big(\sqrt{1-\epsilon^2}\, 2\langle \cos(\phi-\phi_S)/\sqrt{1-\epsilon^2}\rangle^h_{\mathrm{L}\perp} \cos(\phi-\phi_S) + \sqrt{2\epsilon(1-\epsilon)}\, 2\langle \cos(\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{\mathrm{L}\perp} \cos(\phi_S) +$$
$$\sqrt{2\epsilon(1-\epsilon)}\, 2\langle \cos(2\phi-\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{\mathrm{L}\perp} \cos(2\phi-\phi_S) + \sqrt{2\epsilon(1-\epsilon)}\, 2\langle \cos(\phi+\phi_S)/\sqrt{2\epsilon(1-\epsilon)}\rangle^h_{\mathrm{L}\perp} \cos(\phi+\phi_S)\Big)\Big]^w$$

$A_{U\perp}$ 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-vanishing longit. target-polarization component

- **The SFA amplitudes do not include the ε-dependent kinematic prefactors**
- Are extracted by including explicitly the ε-dependent kinematic prefactors in the probability-density function, separated from the fit parameters.

SSA and DSA amplitudes

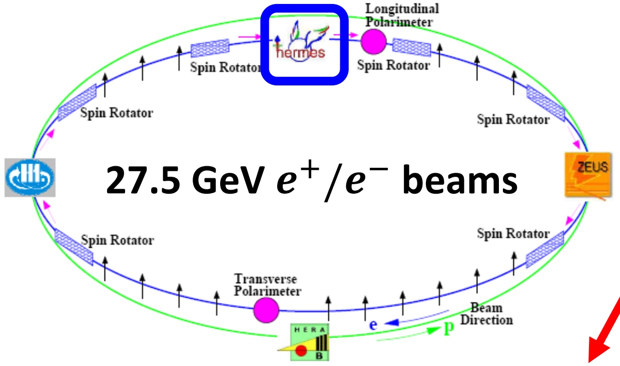
Azimuthal modulation		Significant non-vanishing Fourier amplitude						
		π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[Sivers]	✓		✓	✓	✓	(✓)	✓
$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$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

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

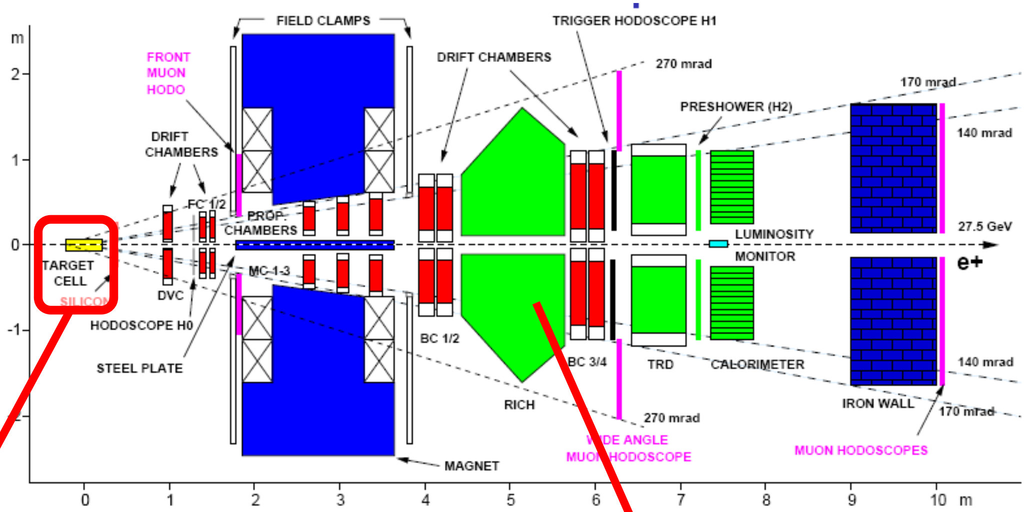
✓ : incompatible with NULL hypothesis at 95% CL

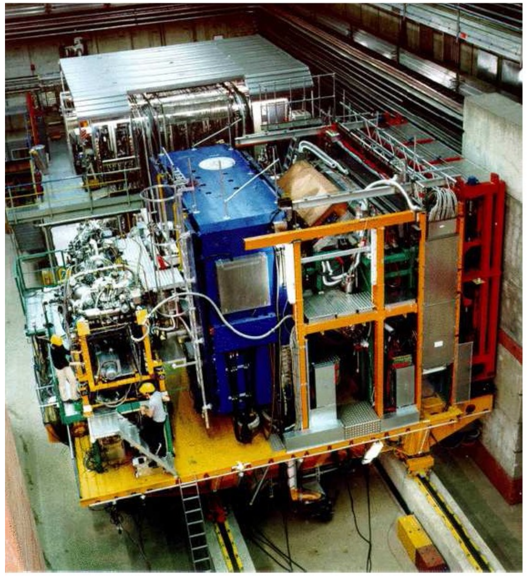
(✓) : incompatible with NULL hypothesis at 90% CL

The HERMES experiment at HERA (1995-2007)

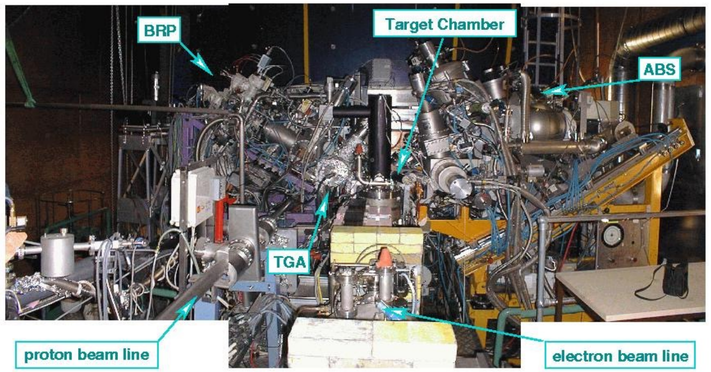


27.5 GeV e^+/e^- beams

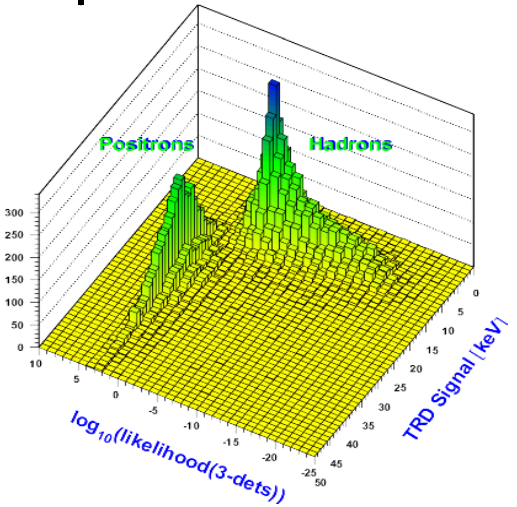


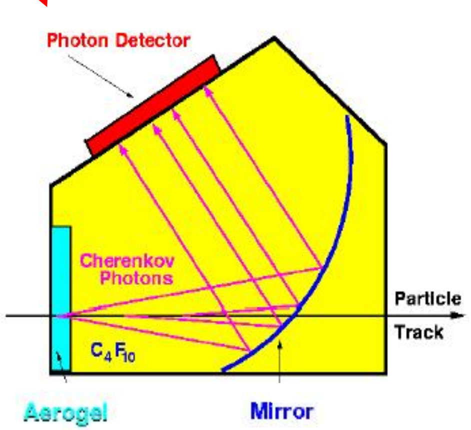


The polarized gas target

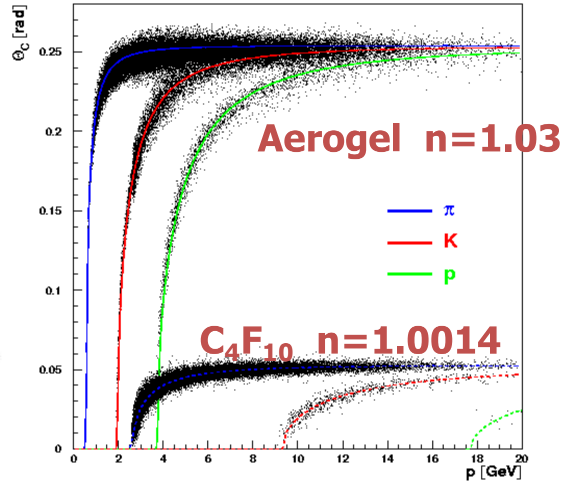


TRD, Calorimeter, preshower, RICH:
lepton-hadron > 98%





hadron separation



π ~ 98%, K ~ 88% , P ~ 85%

Selected results

The Sivers term

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

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

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

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

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

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

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

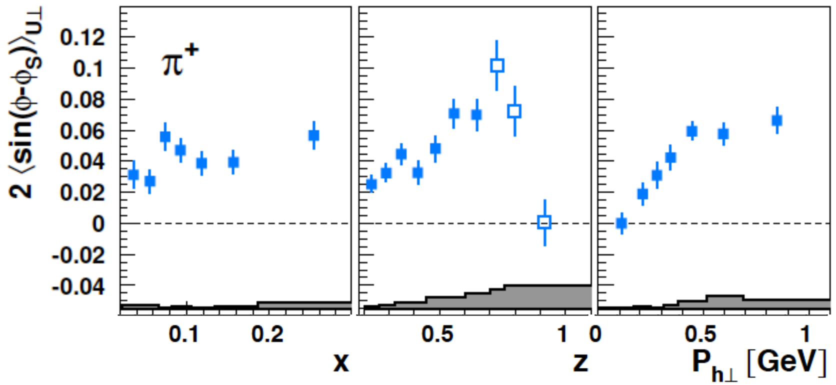
Describes correlation between quark transverse momentum and nucleon transverse polarization

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

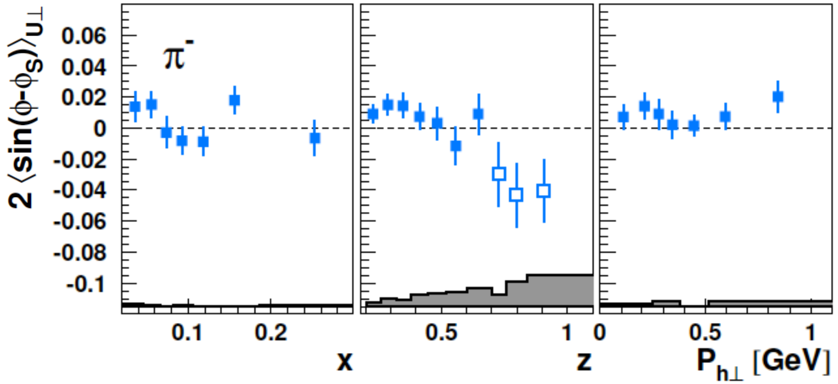
Sivers

Unpol. FF

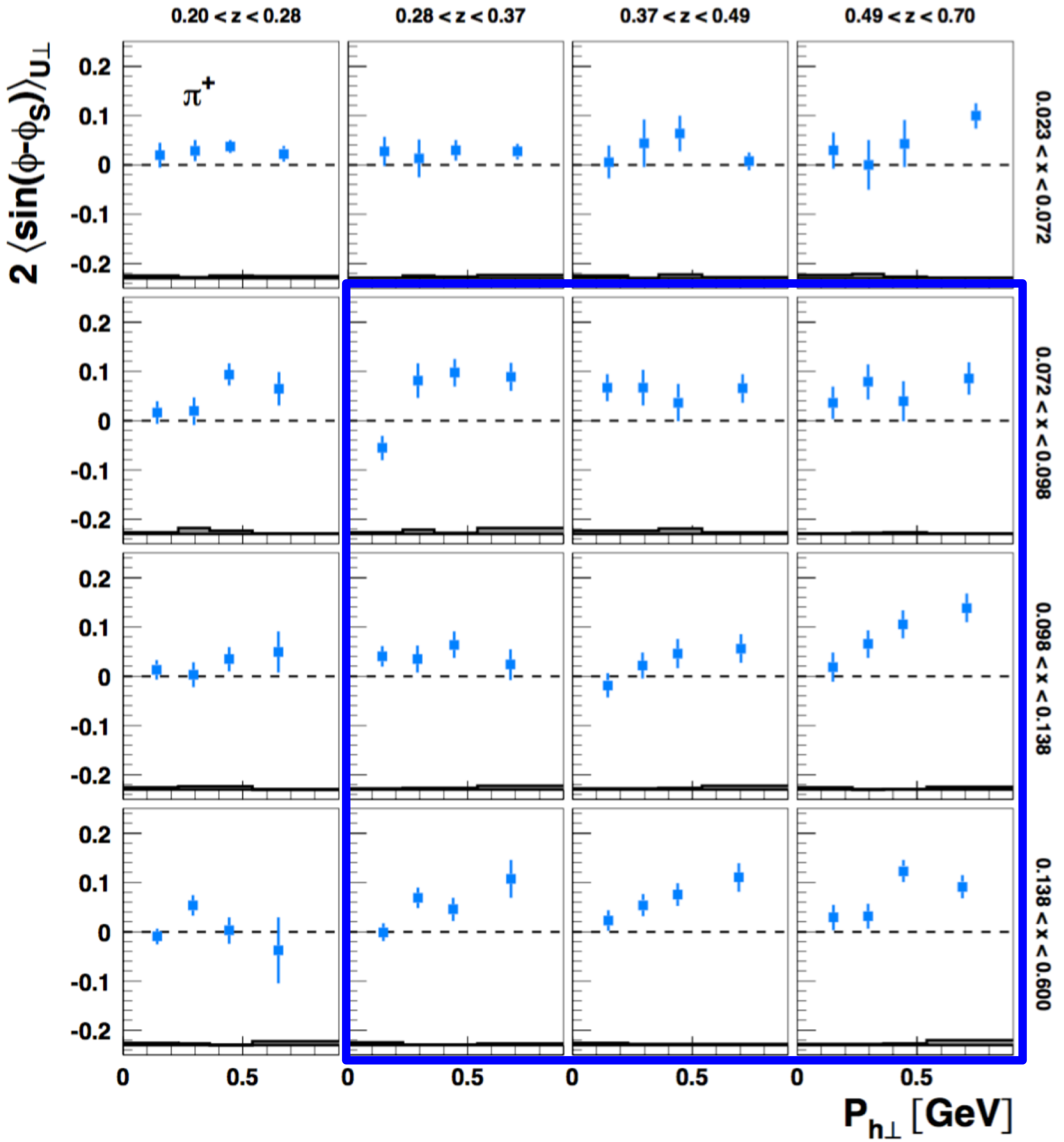
Sivers amplitudes: pions results



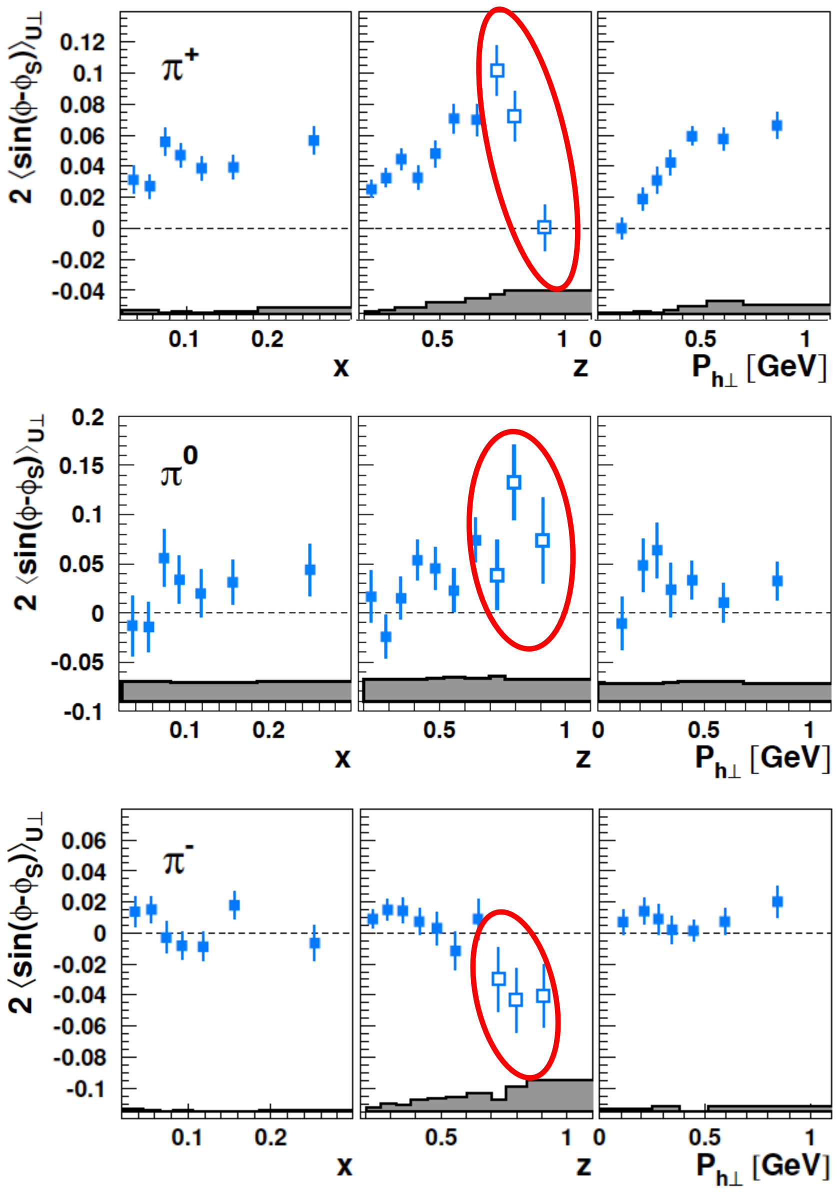
- large positive amplitude → clear evidence of non-zero $f_{1T}^{\perp,u}$
- signal rises with x, z and $P_{h\perp}$ in SIDIS region ($0.2 < z < 0.7$)
- More informative 3D projections confirm and further detail the rise of the amplitude at large x, z and $P_{h\perp}$

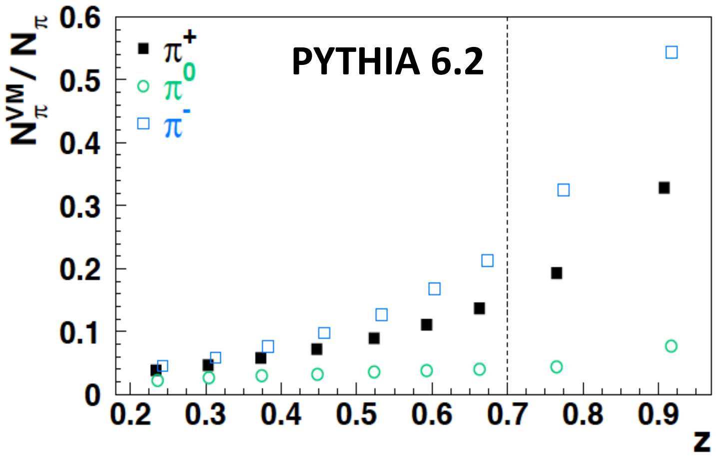


Vanishing due to the cancellation of the opposite Sivers effect for *u* and *d* quarks



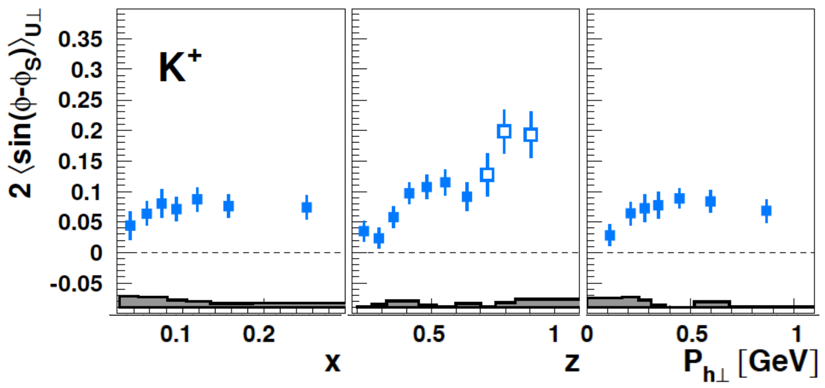
Sivers amplitudes: pions results



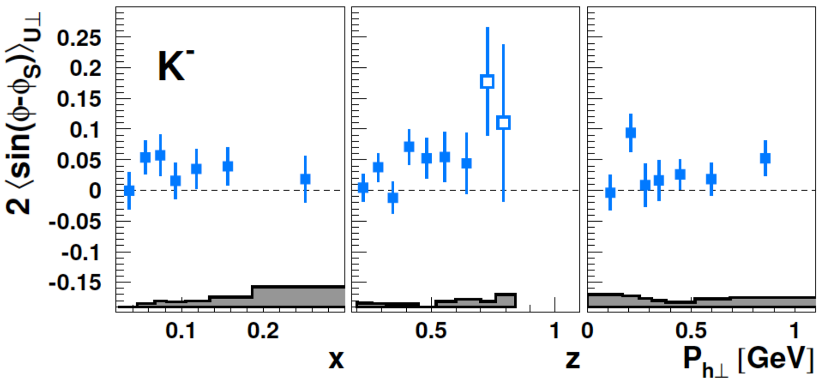


- Sudden drop at large-z (> 0.7) reveals a change of mechanism in this **semi-exclusive region**
- Contributions from decays of exclusively produced ρ^0 into $\pi^+\pi^-$ are large in this region!
- intermediate size between those of π^+ and π^- reflects isospin symmetry at the amplitude level
- π^0 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

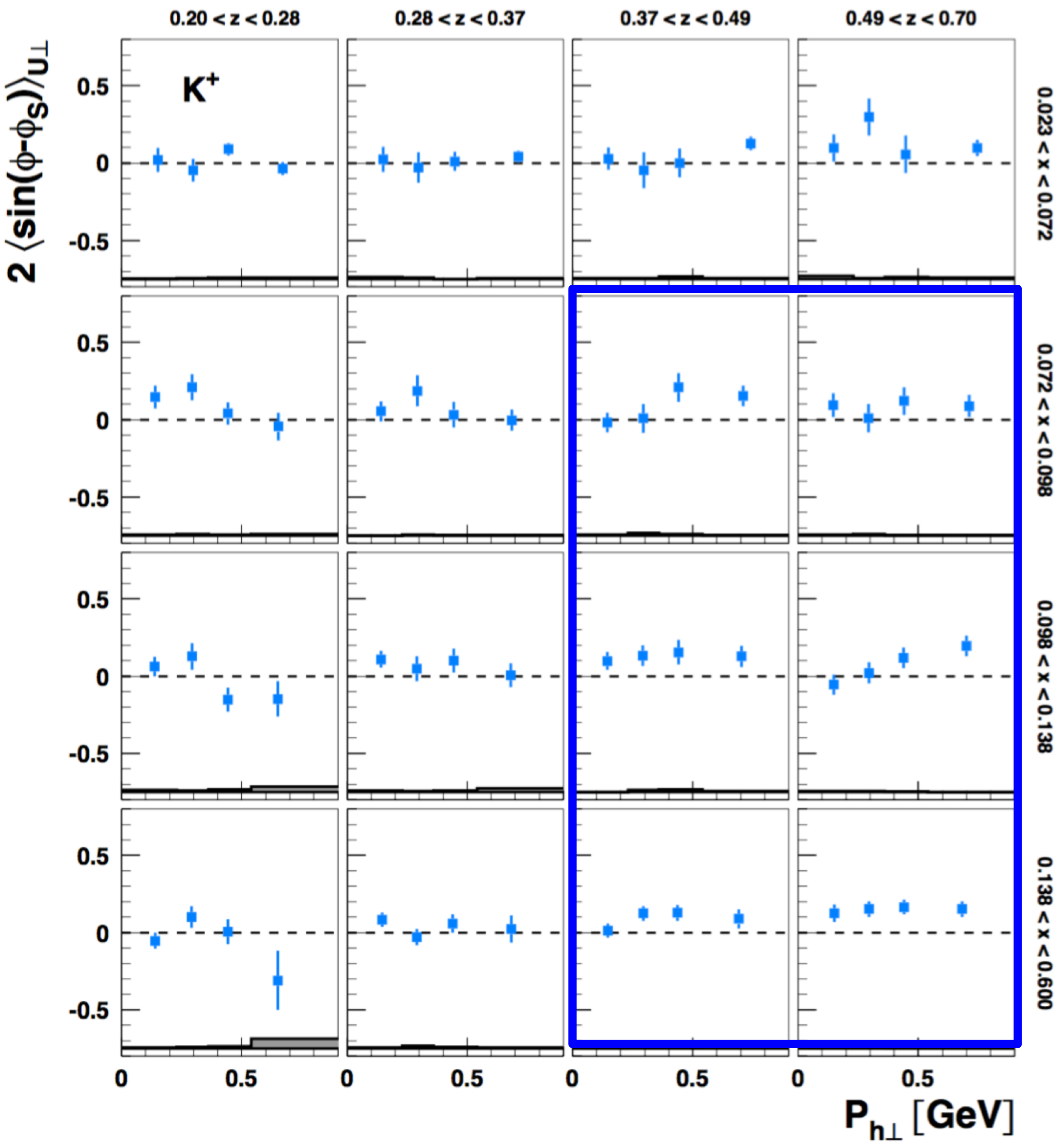


Large positive amplitude, similar kinematic dep. of π^+

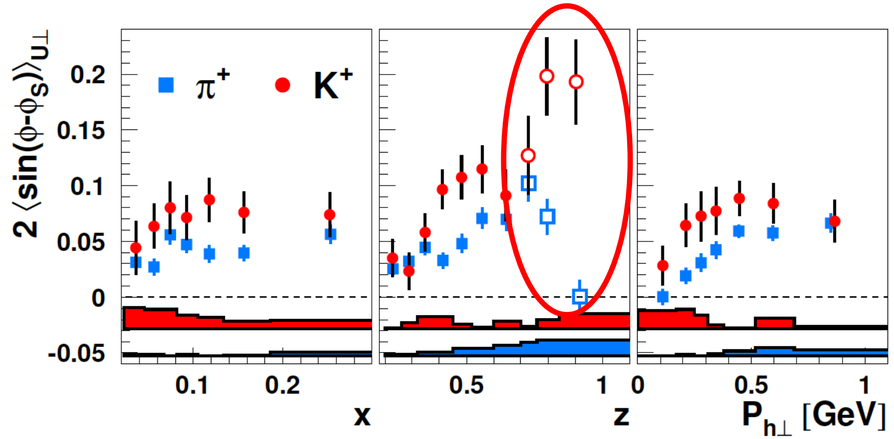


Positive amplitude, different than π^-

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.

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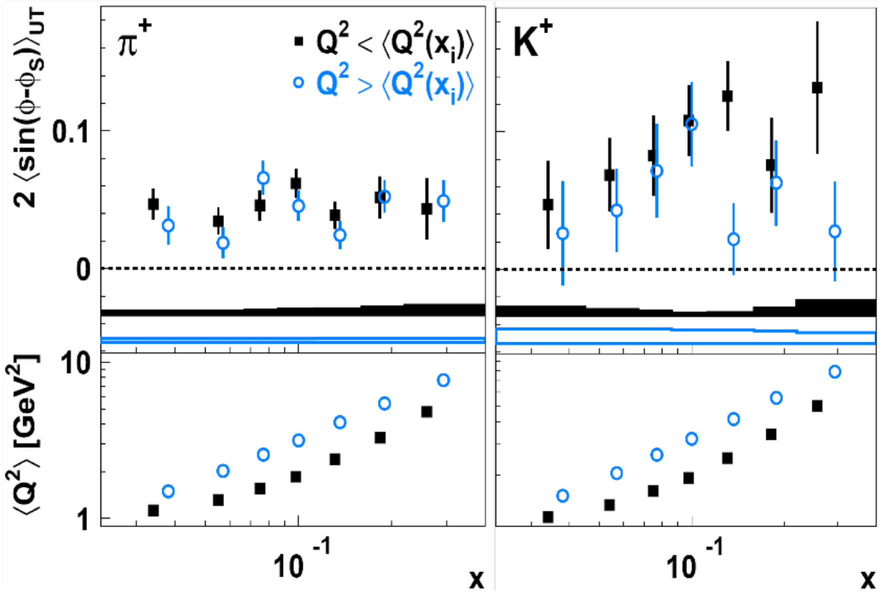
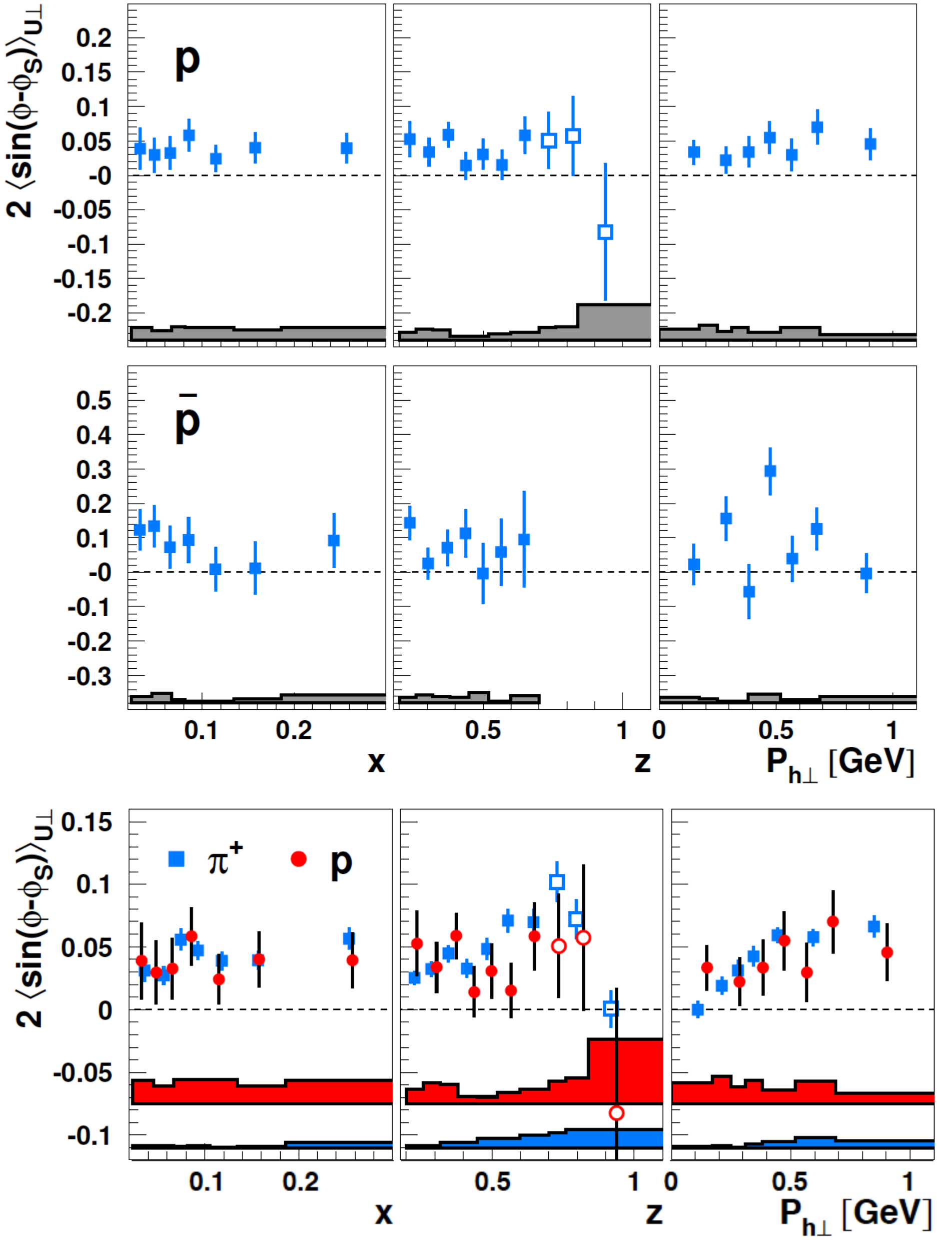


- each x-bin divided into two Q^2 bins
- no effect for pions, but hint of suppression at larger Q^2 for kaons

Sivers amplitudes: protons results

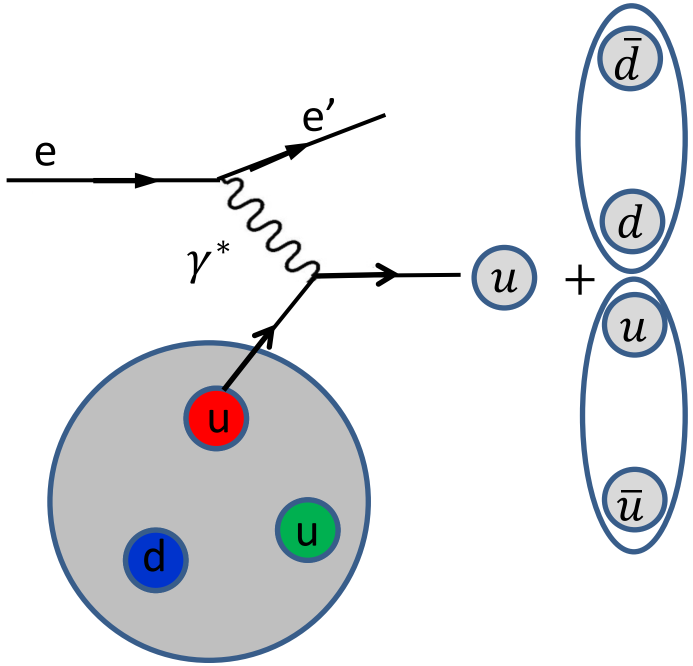


First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive

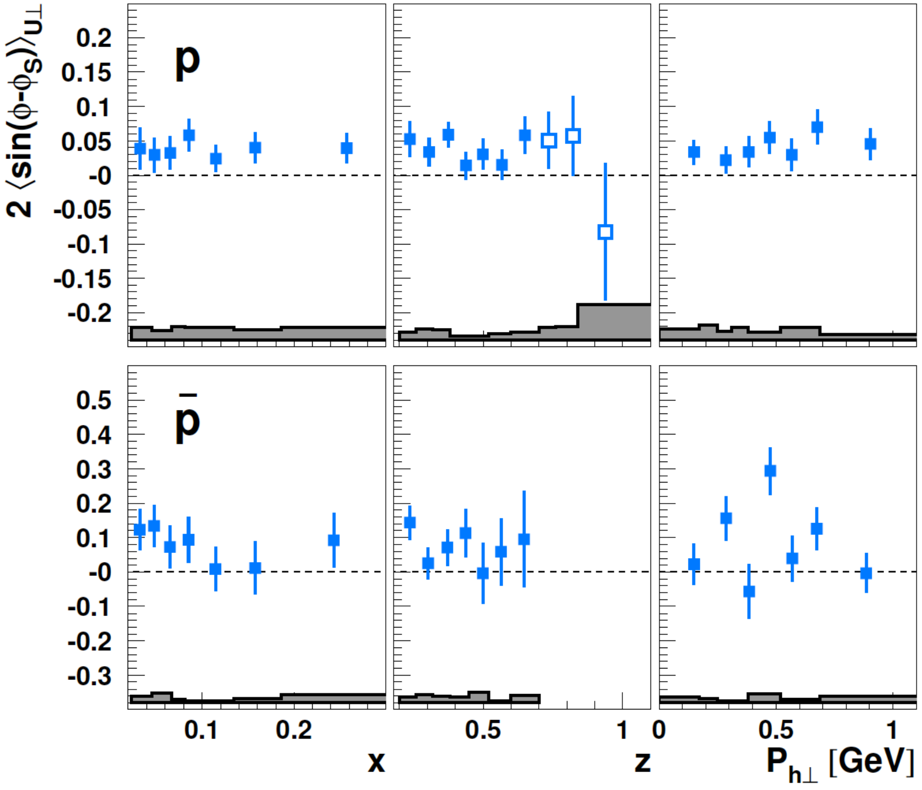
Similar agreement between $\bar{p}$ and π^+ (but with larger statistical errors)

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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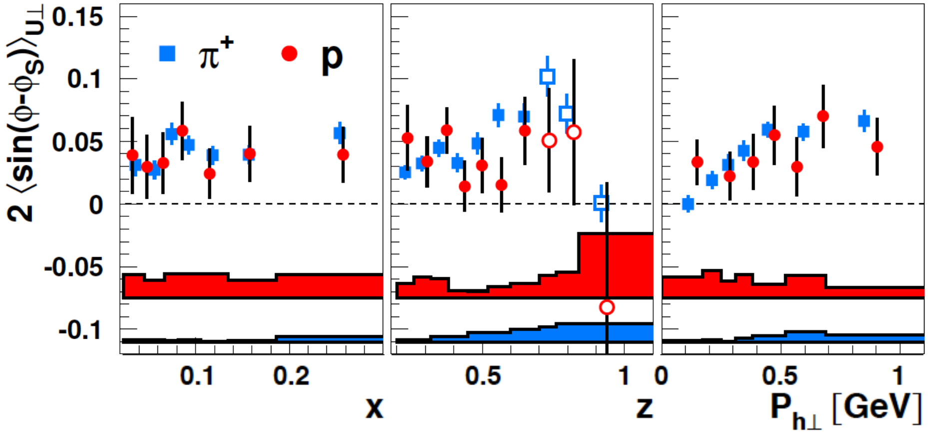

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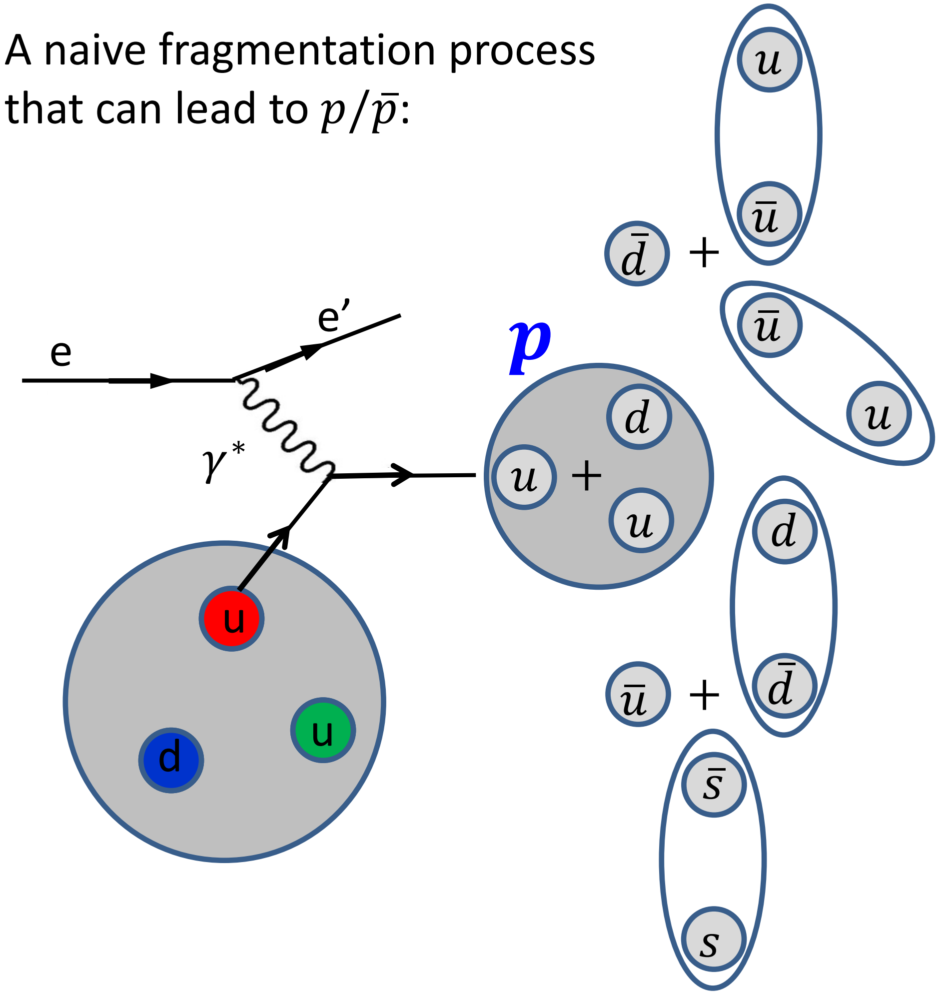

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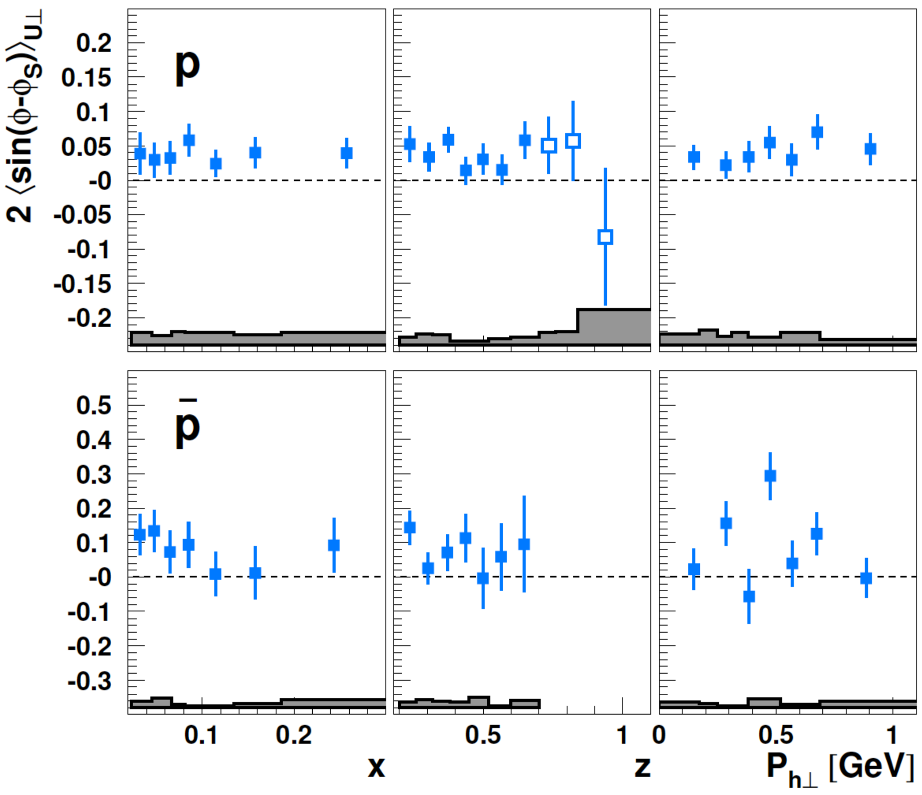
Sivers amplitudes: protons results



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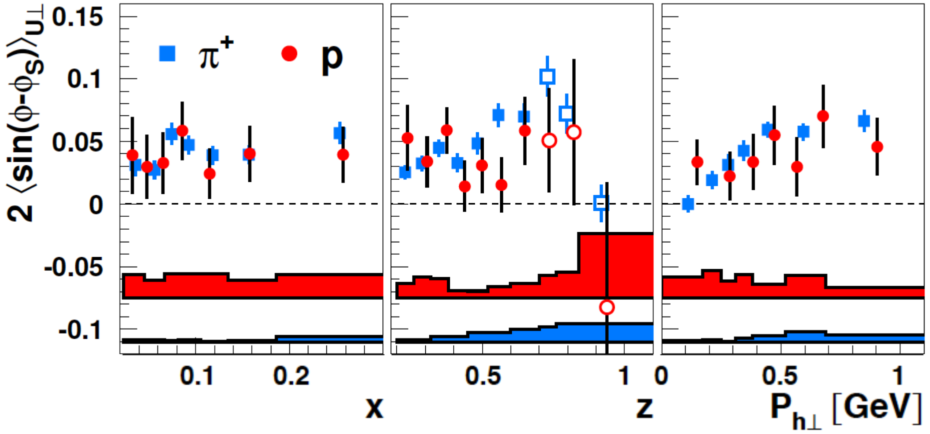
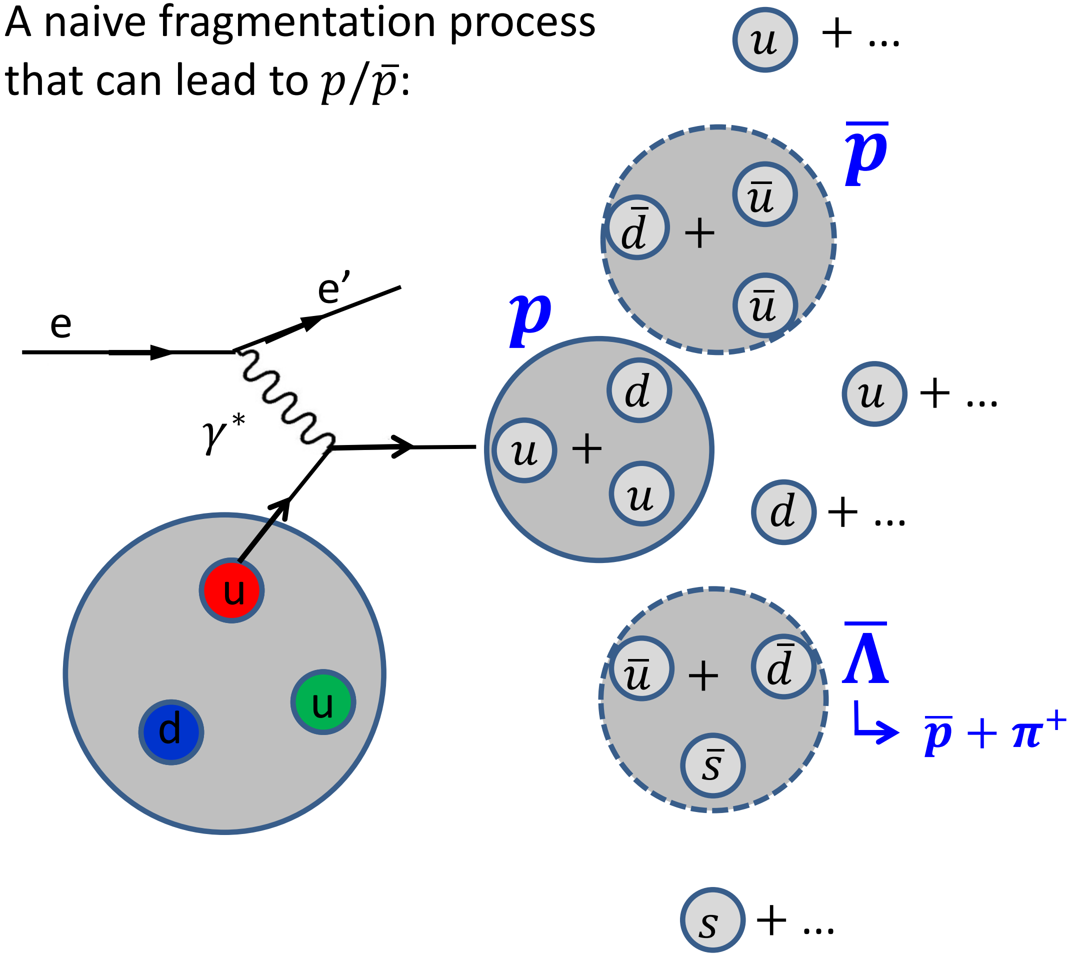


Similar agreement between $\bar{p}$ and π^+ (but with larger statistical errors)

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



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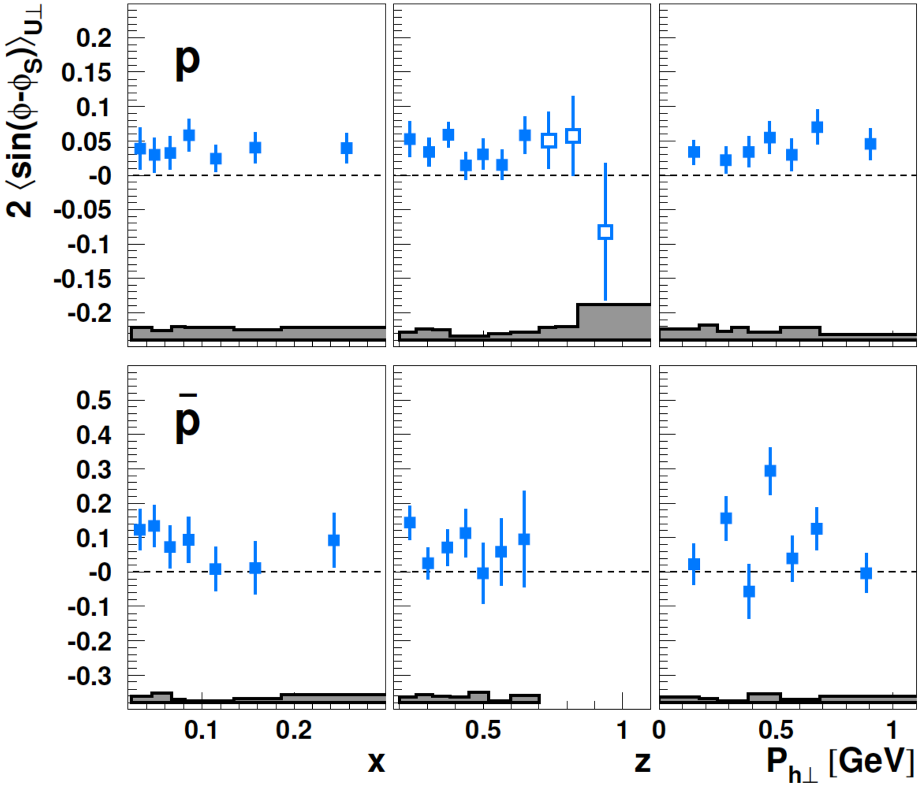
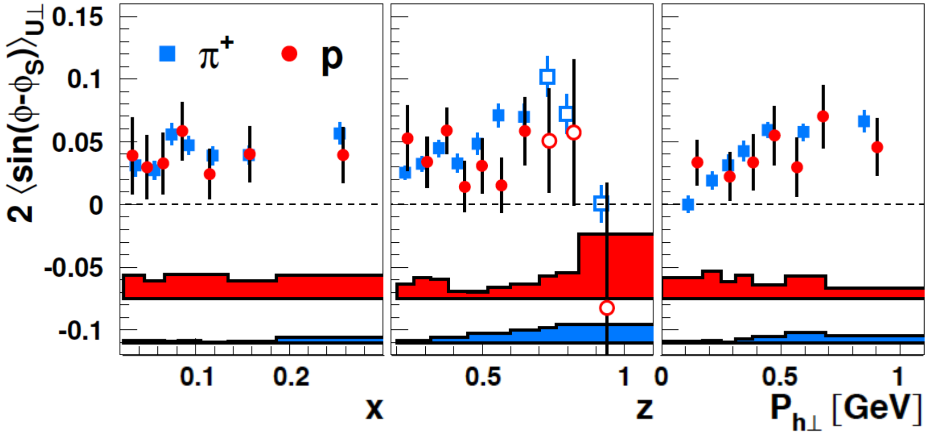
Sivers amplitudes: protons results



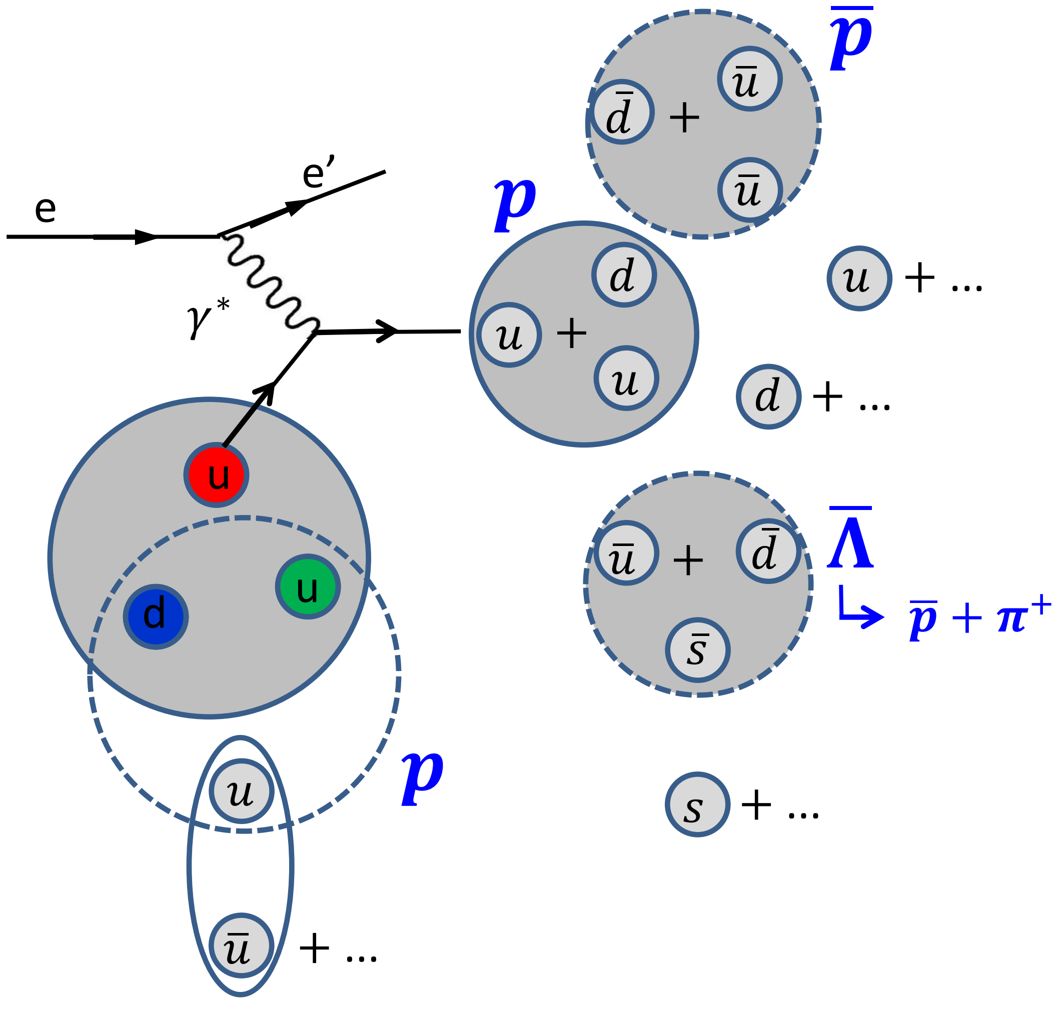
First measurement of Sivers asymmetries for $p, \bar{p}$ in SIDIS

Both amplitudes are non-zero and positive



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

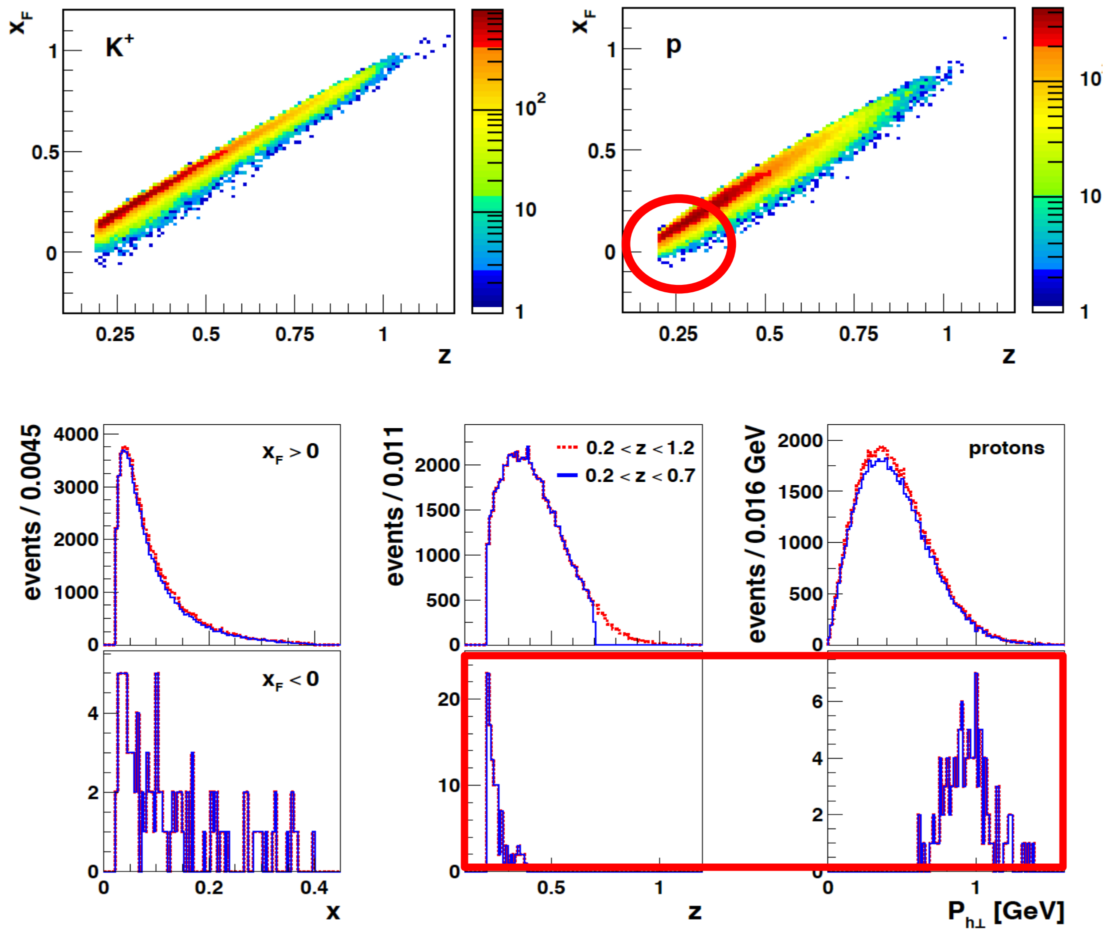
A naive fragmentation process that can lead to $p/\bar{p}$:

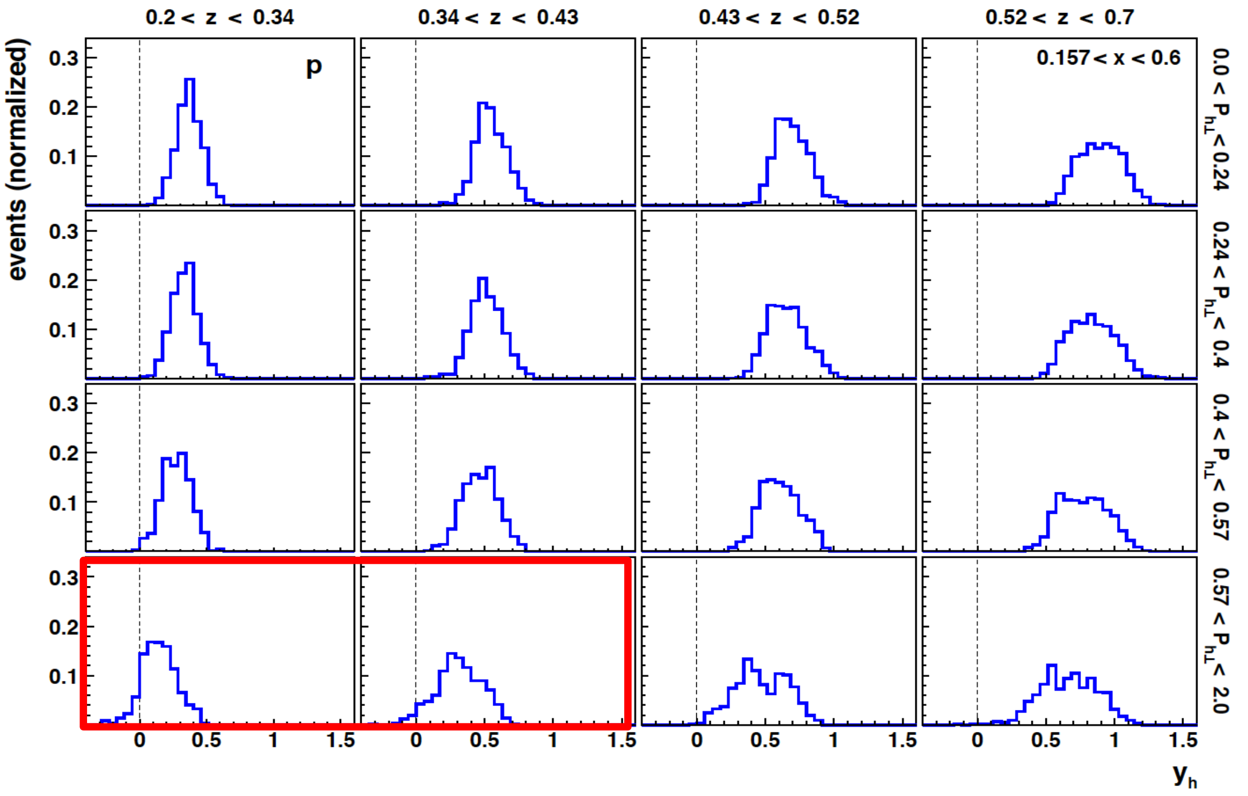


…also from TFR (low z, high $P_{h\perp}$)

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

The Collins term

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

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

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

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

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

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

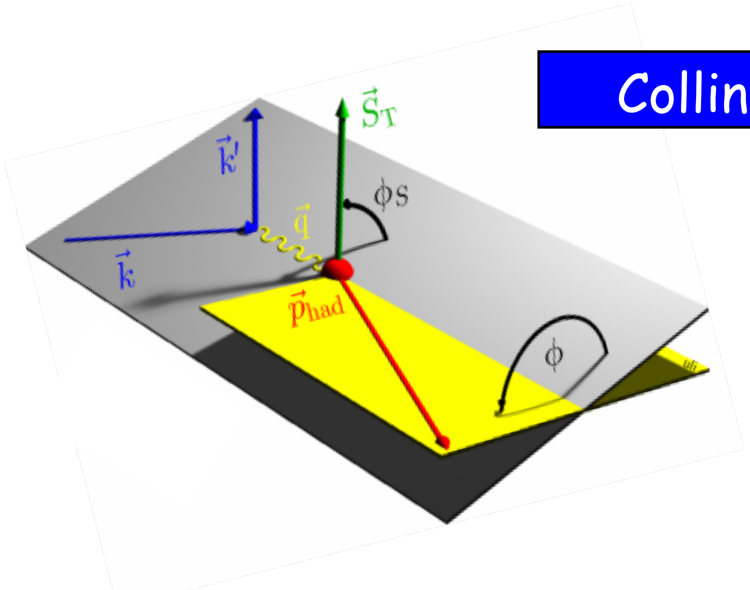
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F^{\cos(\phi-\phi_S)}_{\mathrm{LT}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F^{\cos(\phi_S)}_{\mathrm{LT}} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F^{\cos(2\phi-\phi_S)}_{\mathrm{LT}}\Big] \Big\}$$

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

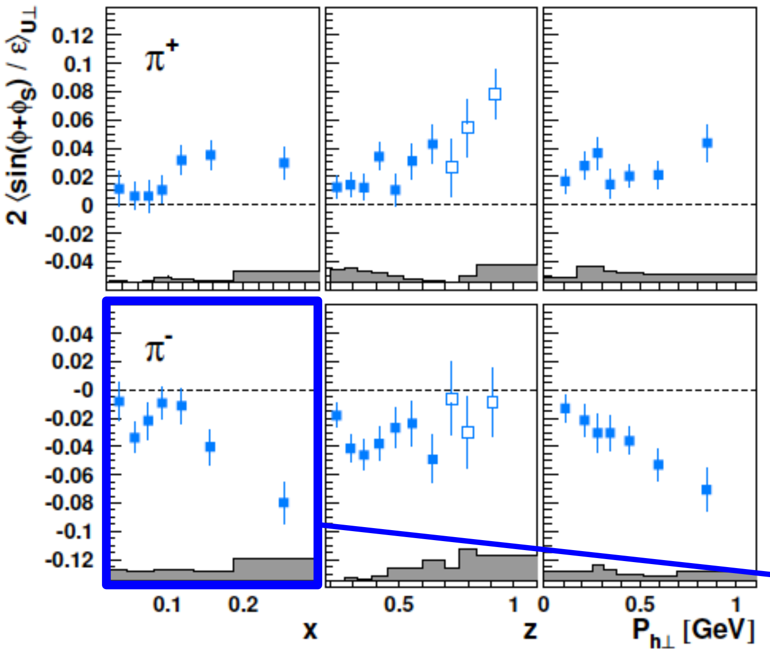
Transversity

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

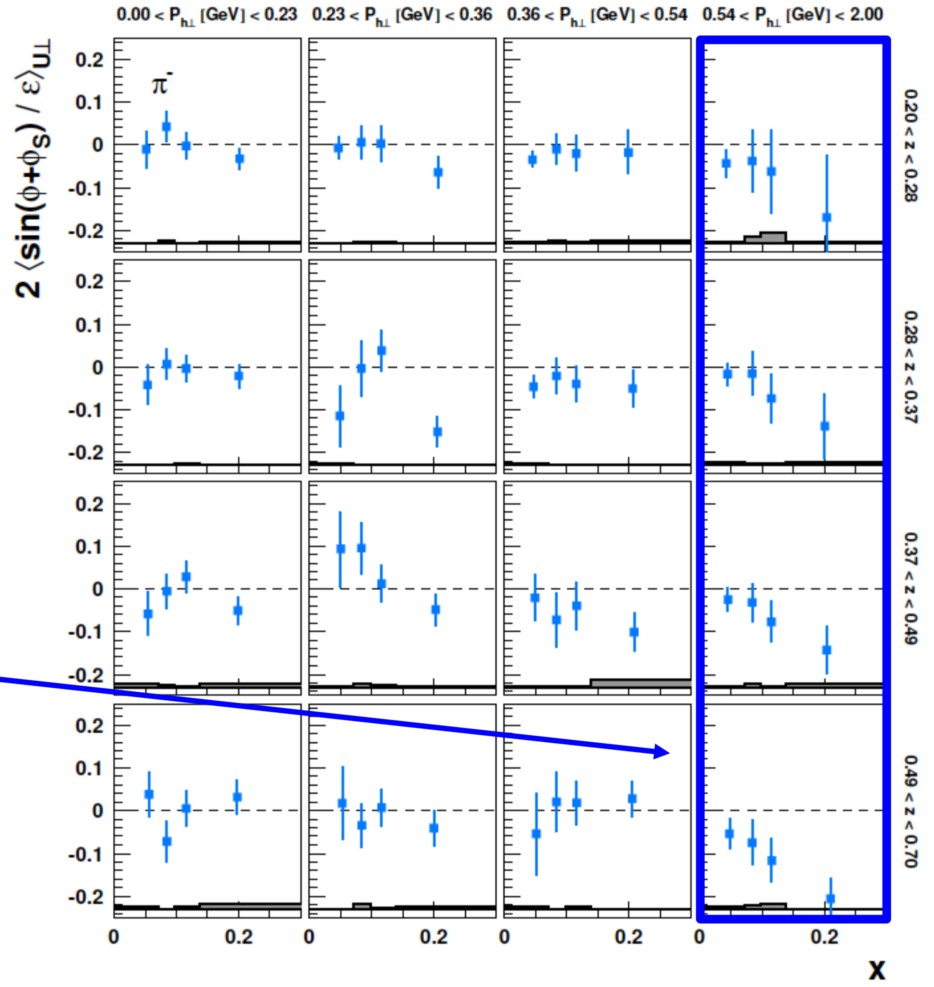
Collins FF

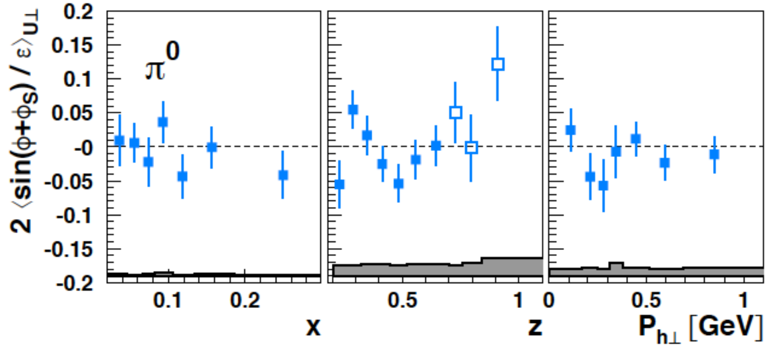


Collins amplitudes: SFA pion results



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

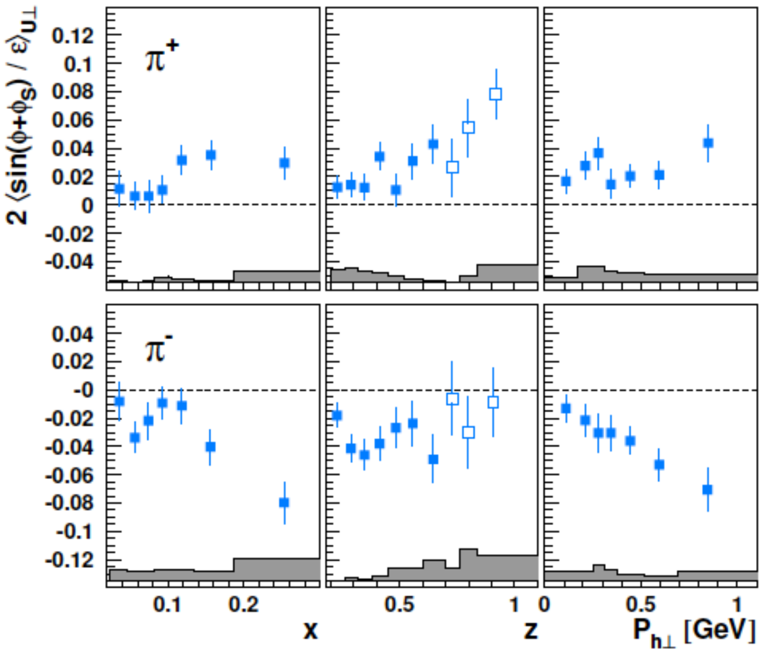


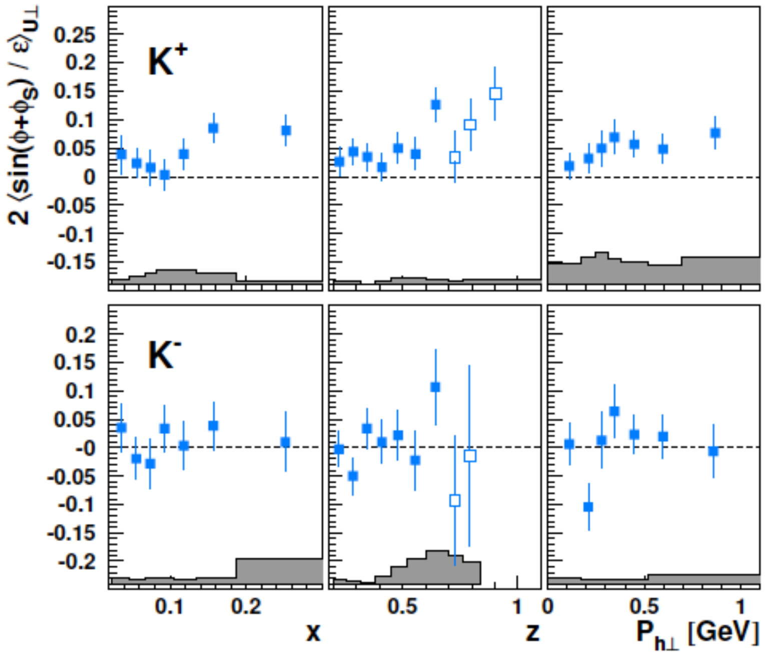


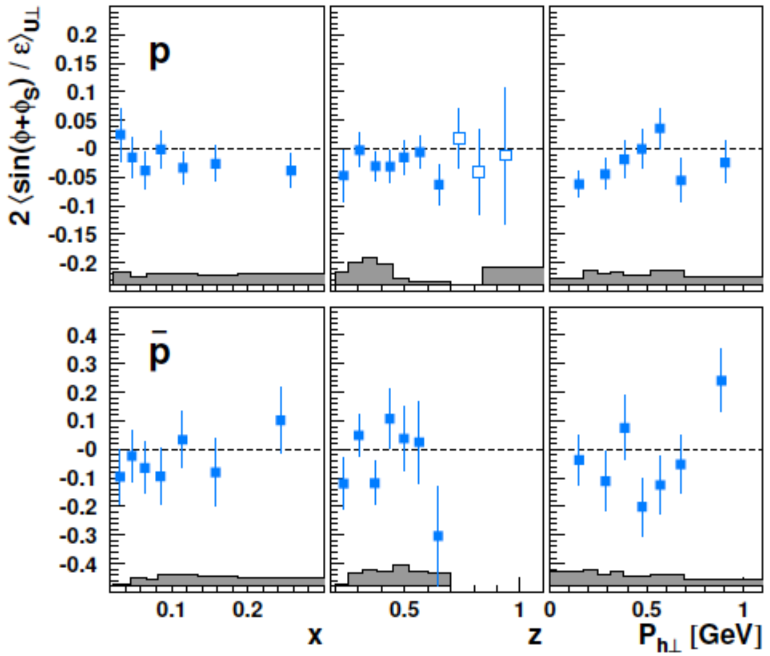
- ≈ 0: intermediate between π^+ and π^-

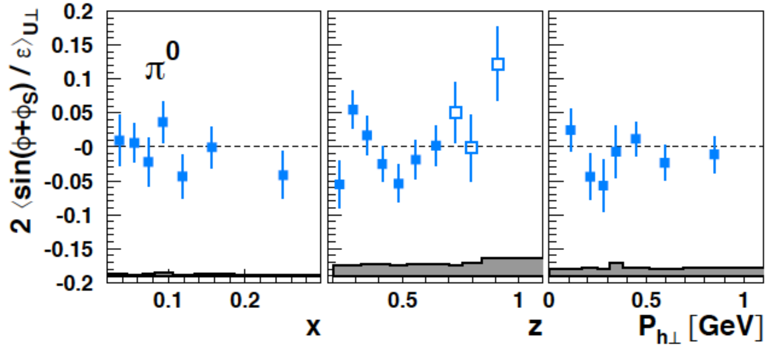
- 3D projections confirm and further detail the rise of the amplitude at large x and $P_{h\perp}$

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 $(u \rightarrow K^-, d \rightarrow K^-)$ 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 Pretzelosity term

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

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

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

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

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

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

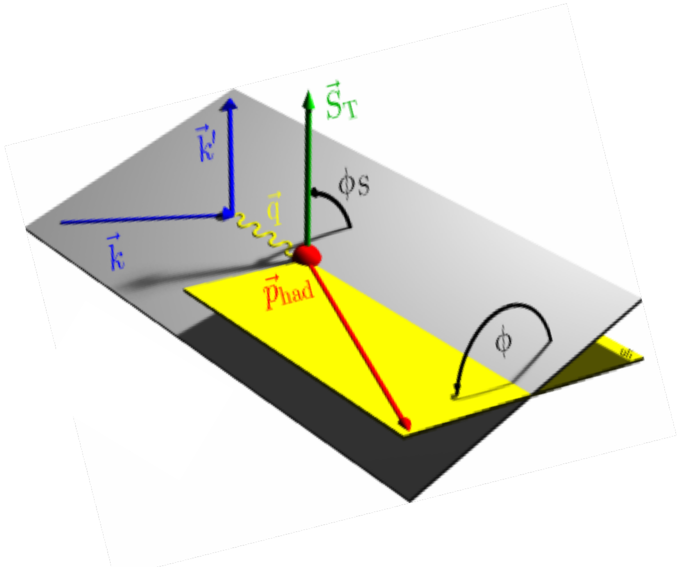
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big] \Big\}$$

Describes correlation between the quark transverse momentum and transverse spin in a transversely polarized nucleon

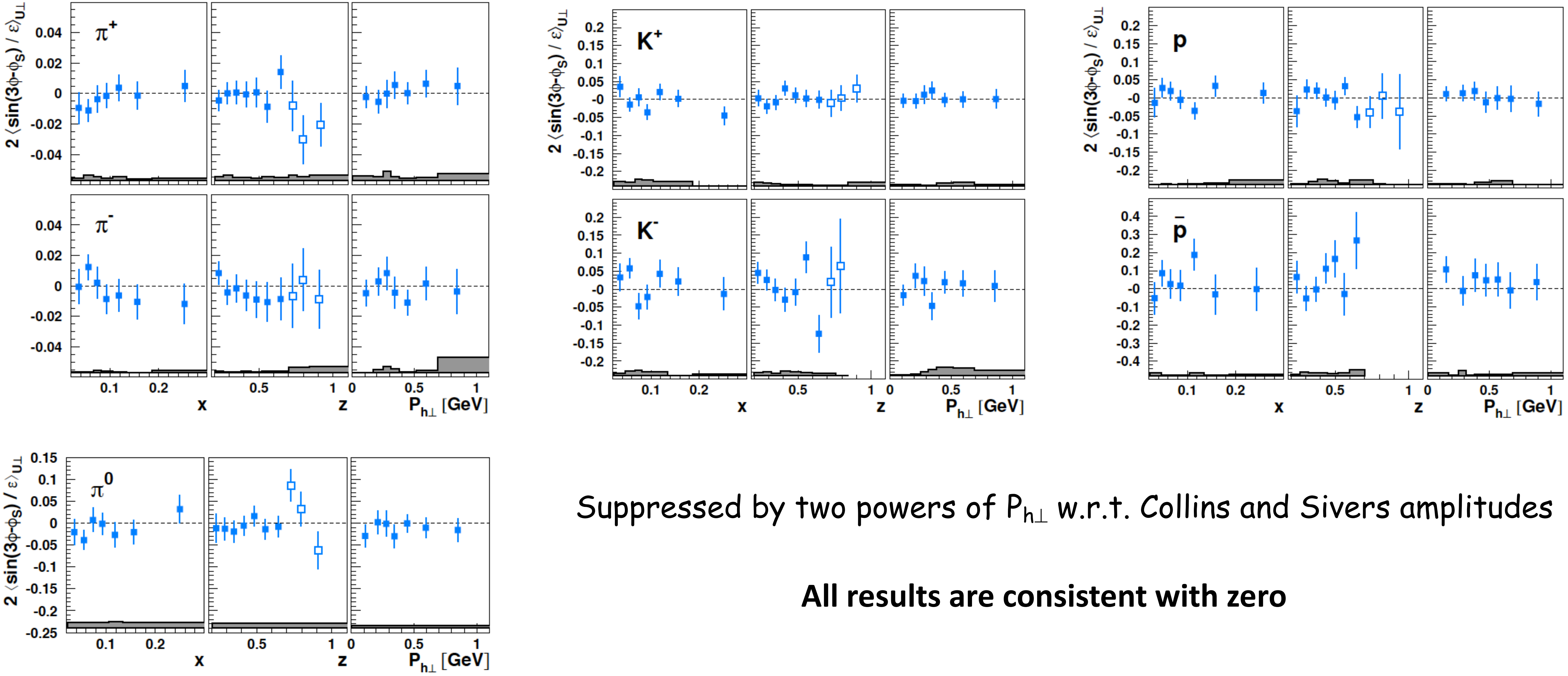
Prtetzelosity

$$F_{UT}^{\sin(3\phi-\phi_S)}(x,z,P_{h\perp},Q^2) = \mathcal{C}\left[\frac{2(\hat{\mathbf{h}}\cdot\mathbf{p}_T)(\mathbf{p}_T\cdot\mathbf{k}_T) + \mathbf{p}_T^2(\hat{\mathbf{h}}\cdot\mathbf{k}_T) - 4(\hat{\mathbf{h}}\cdot\mathbf{p}_T)^2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)}{2M^2M_h} h_{1T}^{\perp,q} H_1^{\perp,q\to h}\right]$$

Collins FF



$\langle \sin(3\phi - \phi_S)\, /\varepsilon \rangle_{U\perp}$ (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

The $\cos(\phi - \phi_S)$ DSA

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

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

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

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

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

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

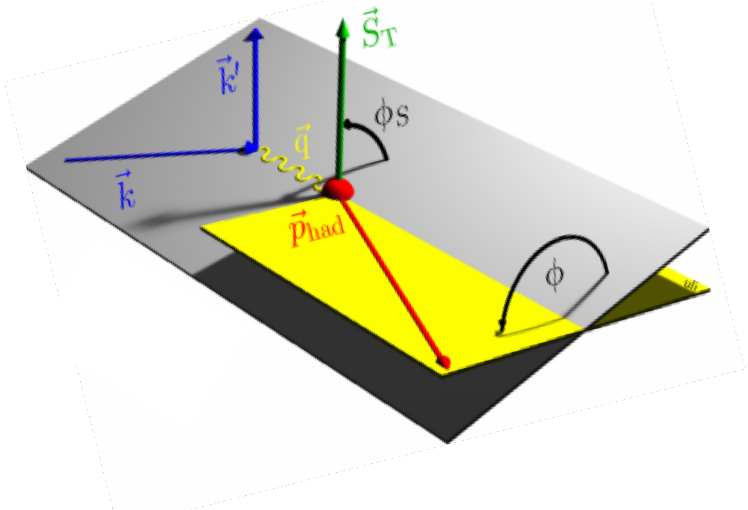
$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big] \Big\}$$

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

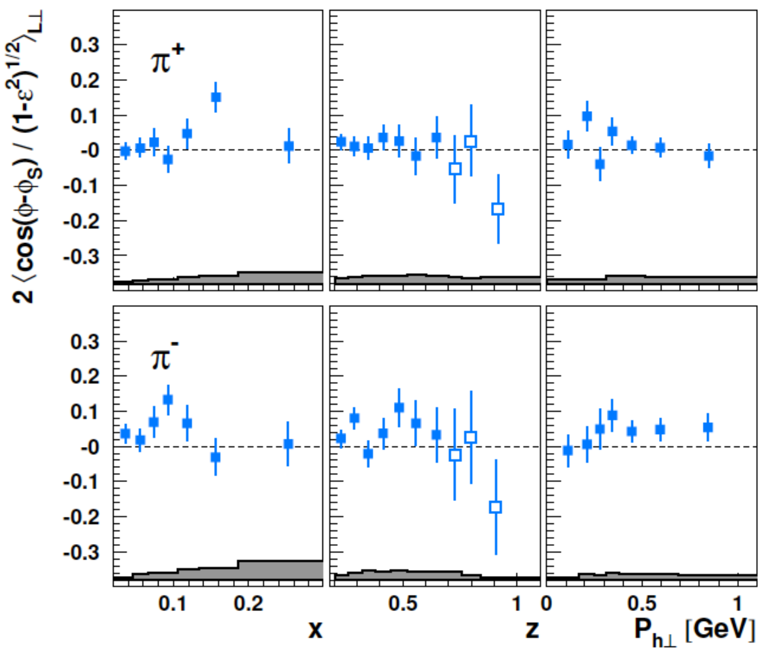
worm-gear (II)

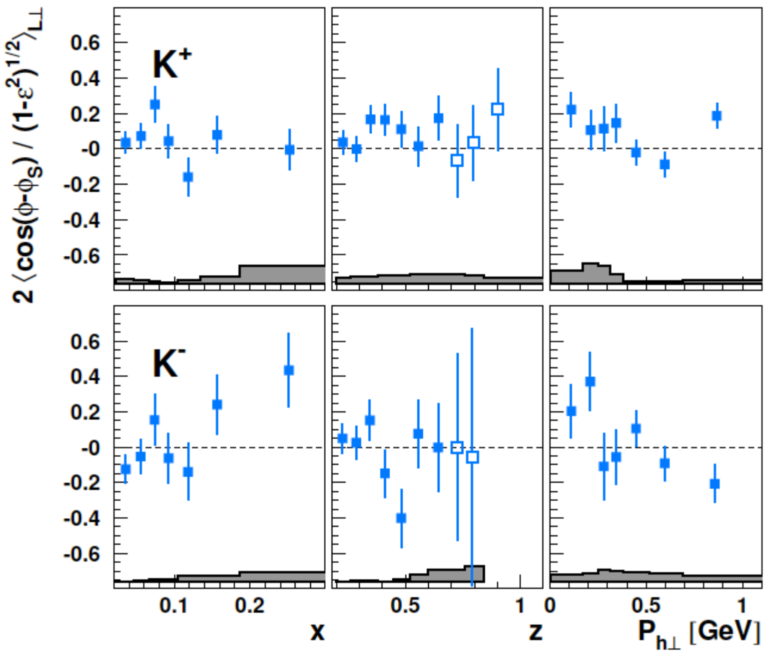
$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} D_1\right]$$

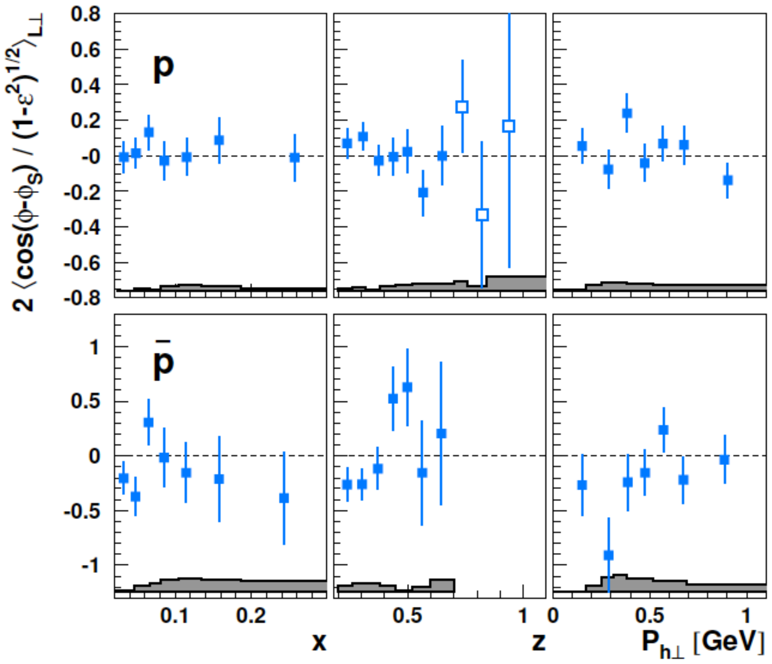
Unpol FF

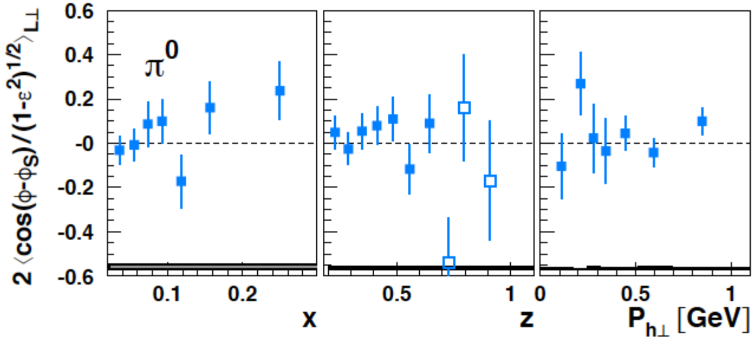


The $\cos(\phi - \phi_S)$ DSA: all SFA 1D results









- **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

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

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

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

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

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

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

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

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

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

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

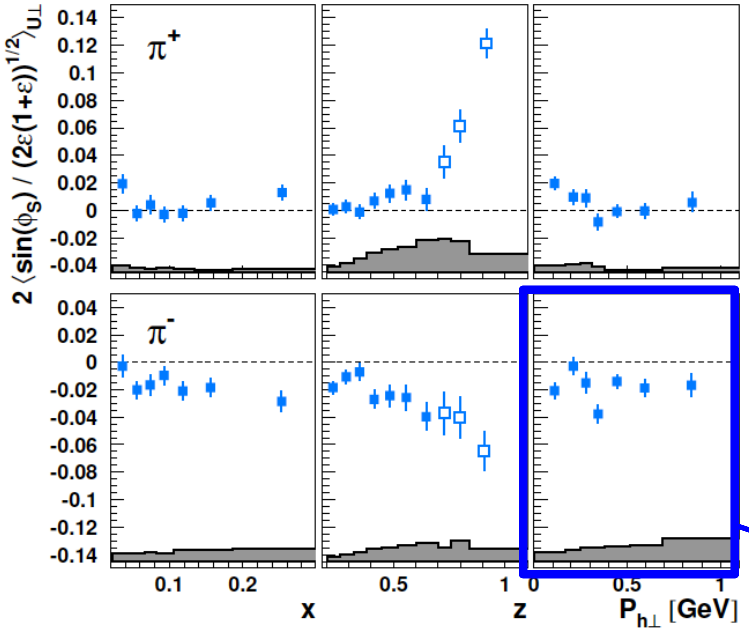
It is the only contribution to the cross section that survives integration over hadron transverse momentum:

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

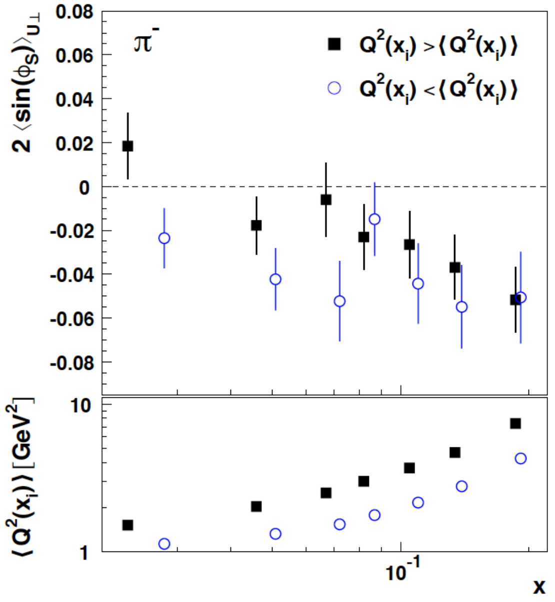
providing sensitivity to transversity w/o involving a convolution over intrinsic transverse momenta.

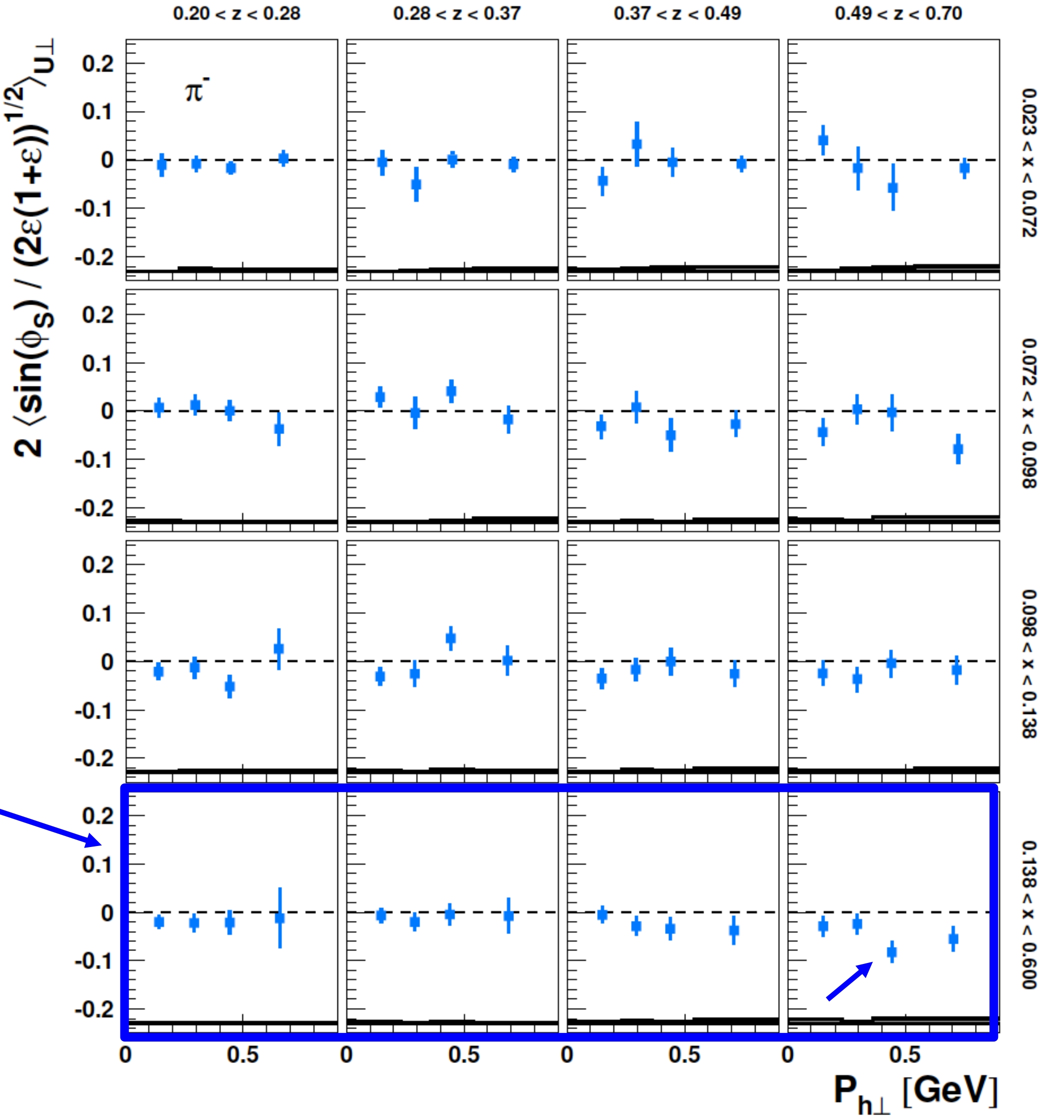
The essentially unknow $\tilde{H}^q$ interaction-dependent FF has been found to be related to the Collins function. These circumstances may explain the observed **similar qualitative behavior of the $2\langle sin(\phi_S)\rangle_{U\perp}$ and the Collins asymmetries**.

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



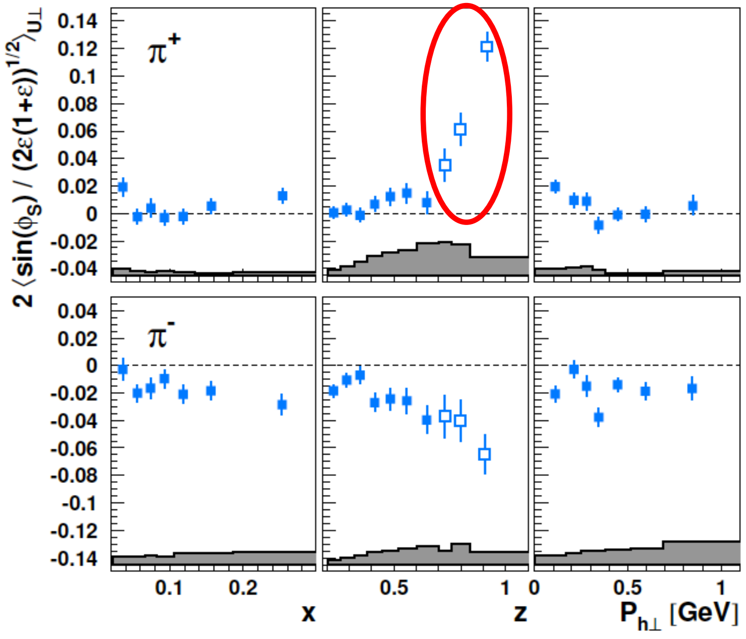
- Charged pions amplitudes non-zero and opposite
- Negative π^- amplitude increases with x and z
- Overall similar behaviour of Collins asymmetries!

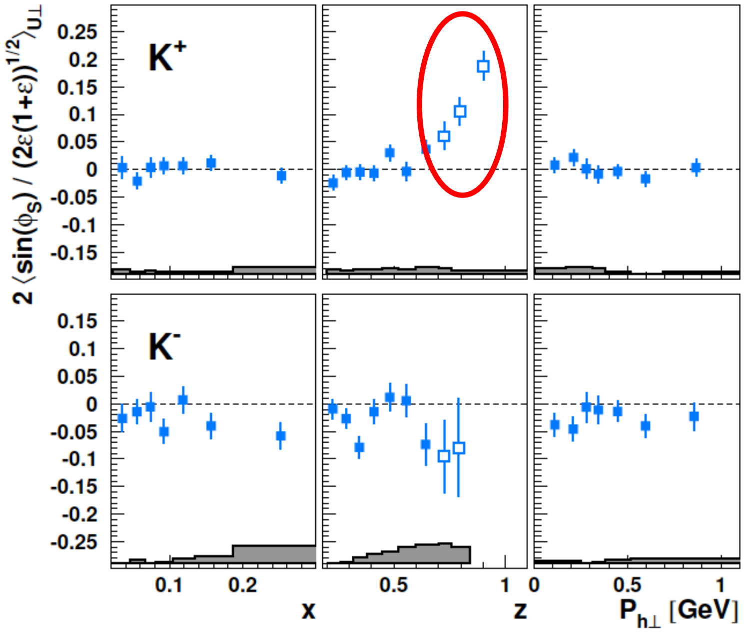


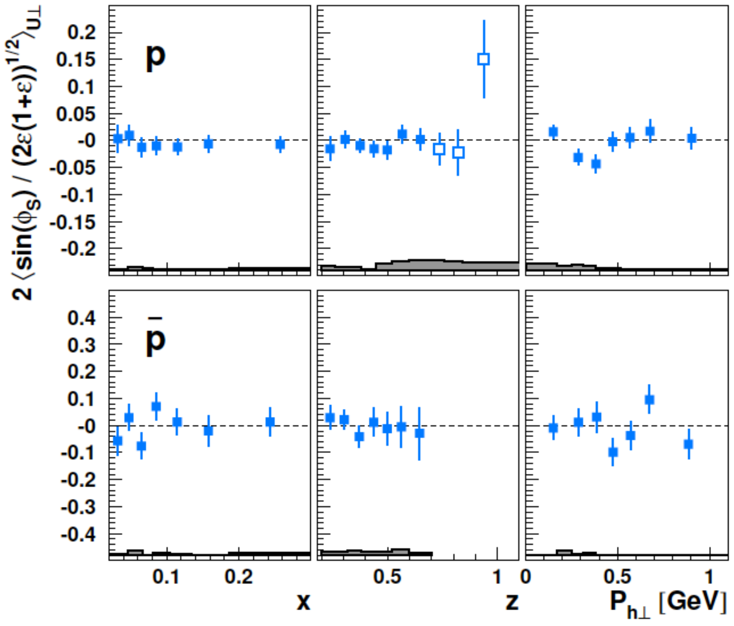


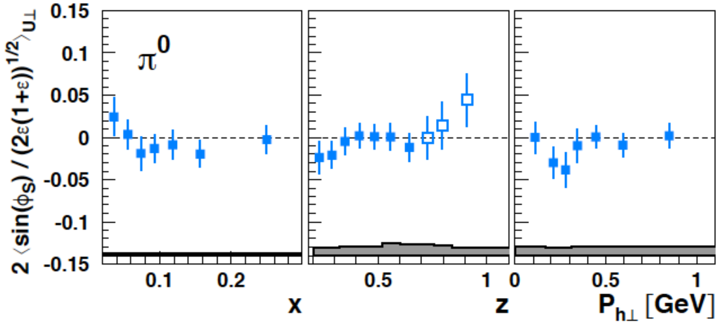
- Subleading-twist term: interesting to study the Q^2 dependence
- x-Q^2 strongly correlated → split each x bin in two Q^2 regions: $\lessgtr \langle Q^2 \rangle$ of each x bin
- Hint of suppression at higher Q^2

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









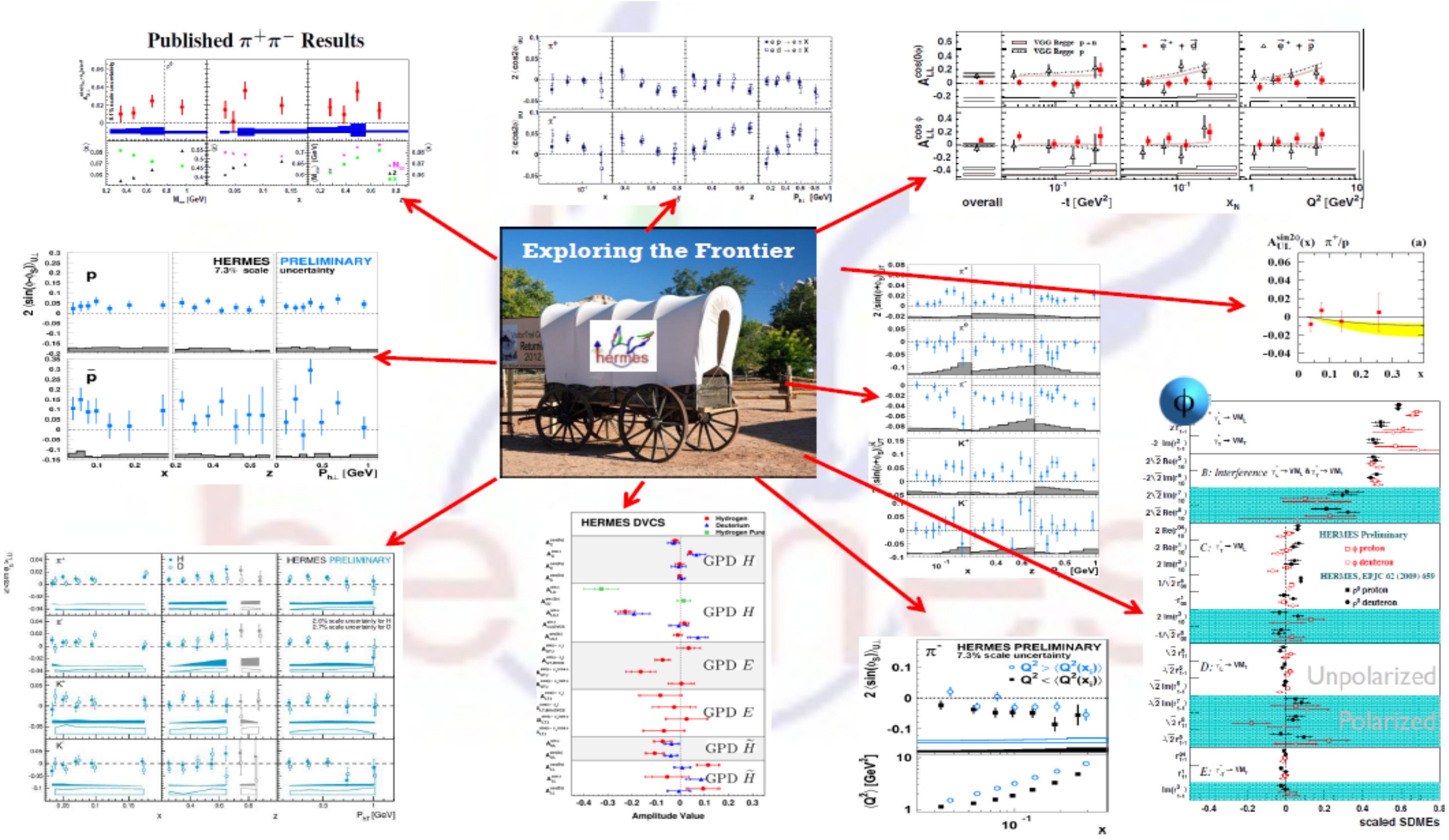
- $\pi^+$and K^+amplitudes in SIDIS region $(0.2 < z < 0.7)$ are similar: small and positive
- K^- negative and similar to π^-
- $\pi^0, p, \bar{p}$ results vanishing
- striking z-dependence in "semi-exclusive region" for π^+/K^+ consistent with large $\sin(\phi_S)$ amplitude observed in exclusive π^+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

Conclusions

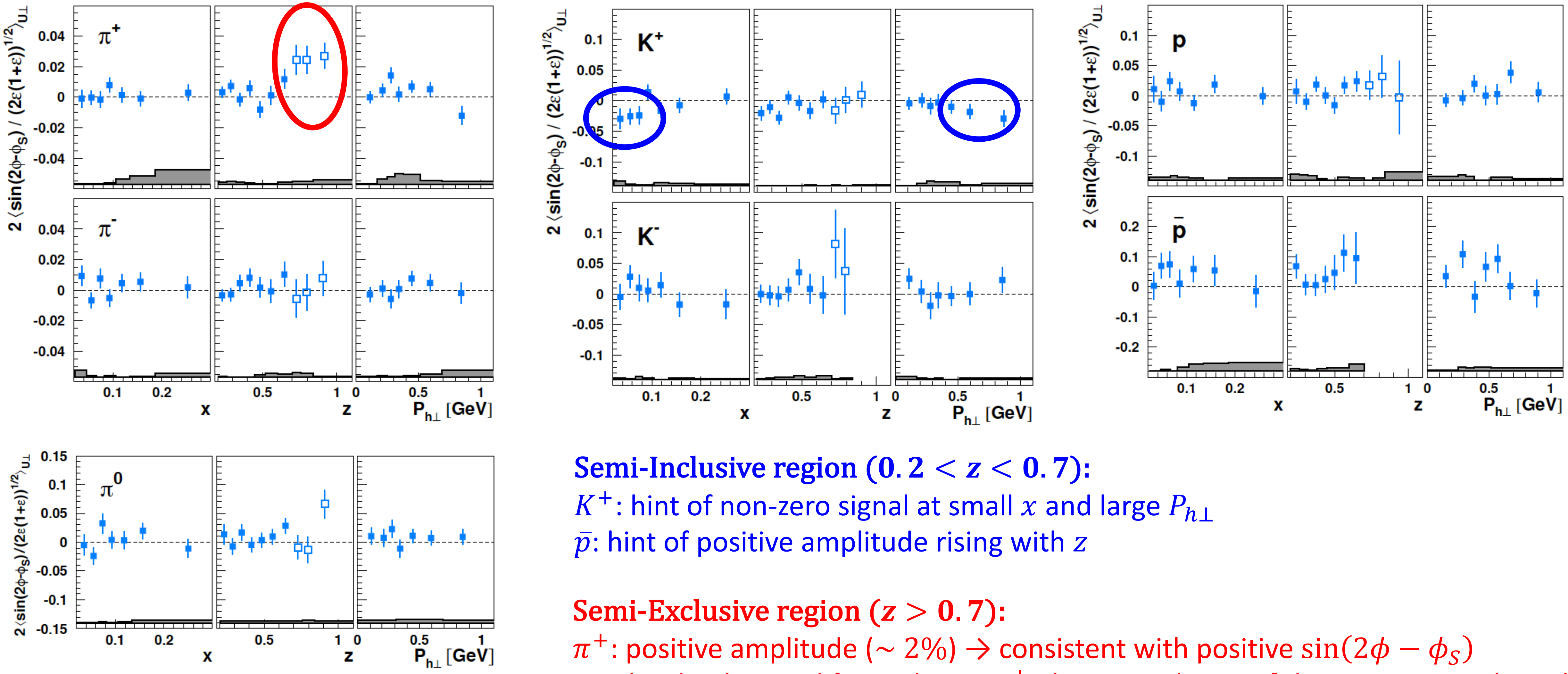
The **3D imaging of the nucleon** is a fashinating and fast evolving research field. HERMES has been a pioneer experiment in this fiels and continues to play a key role in these studies!



Backup

The other SFA results…

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



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

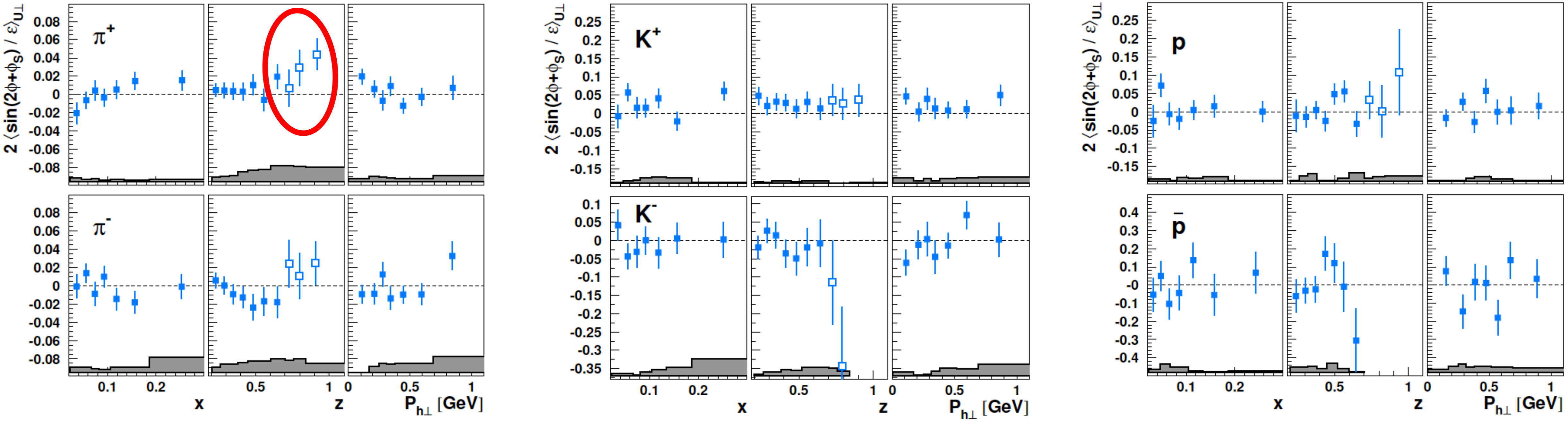
K^+: hint of non-zero signal at small x and large $P_{h\perp}$

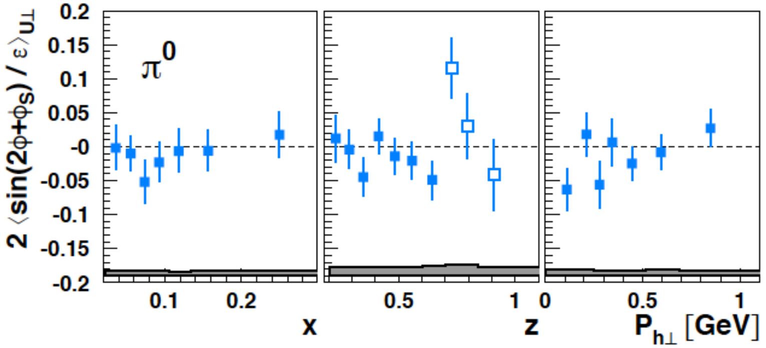
$\bar{p}$: hint of positive amplitude rising with z

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

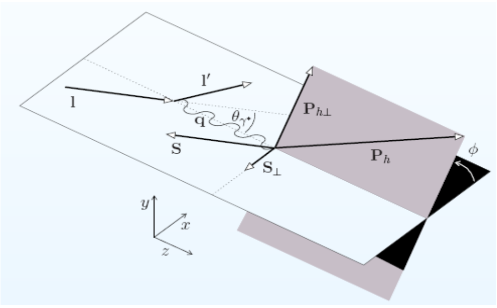
π^+: positive amplitude ($\sim 2\%$) → consistent with positive $\sin(2\phi - \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

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





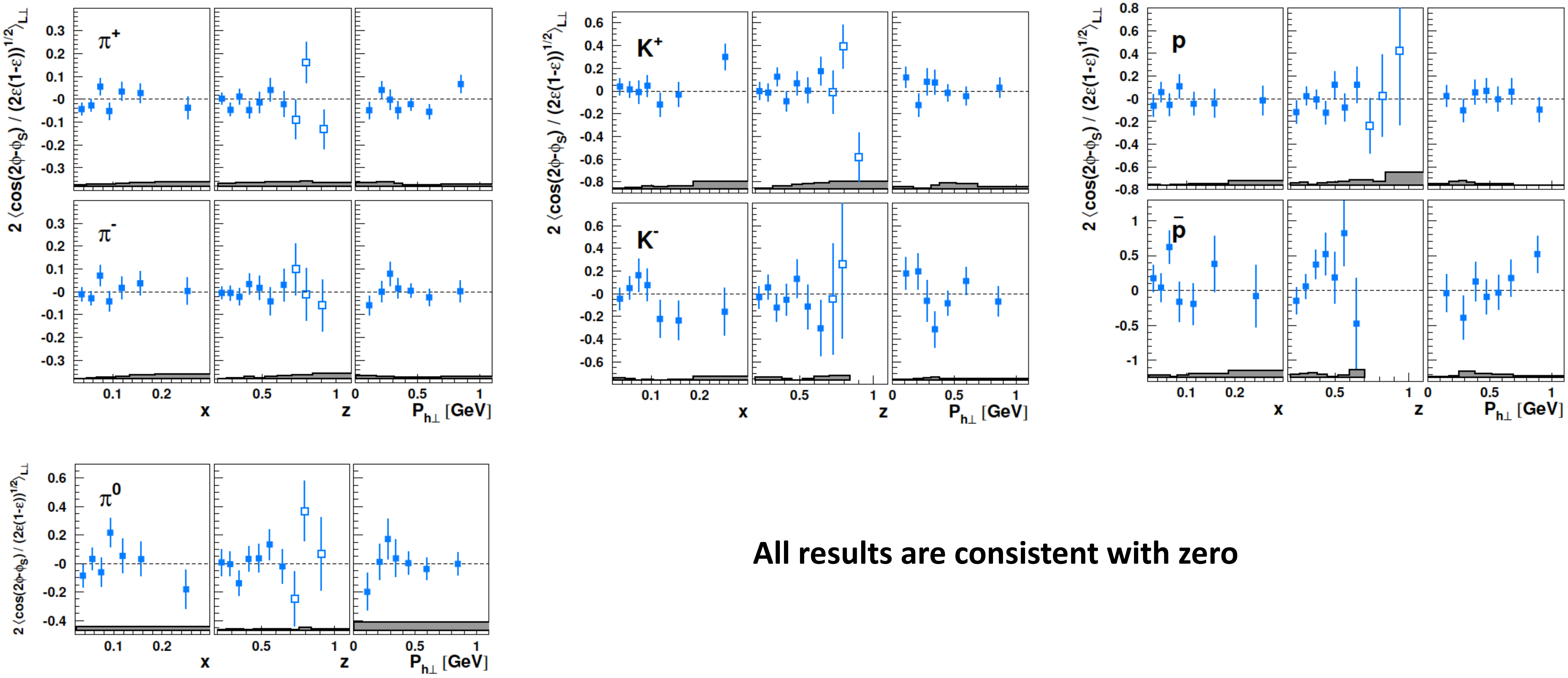
Arises solely from the small longit. target polarization component



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

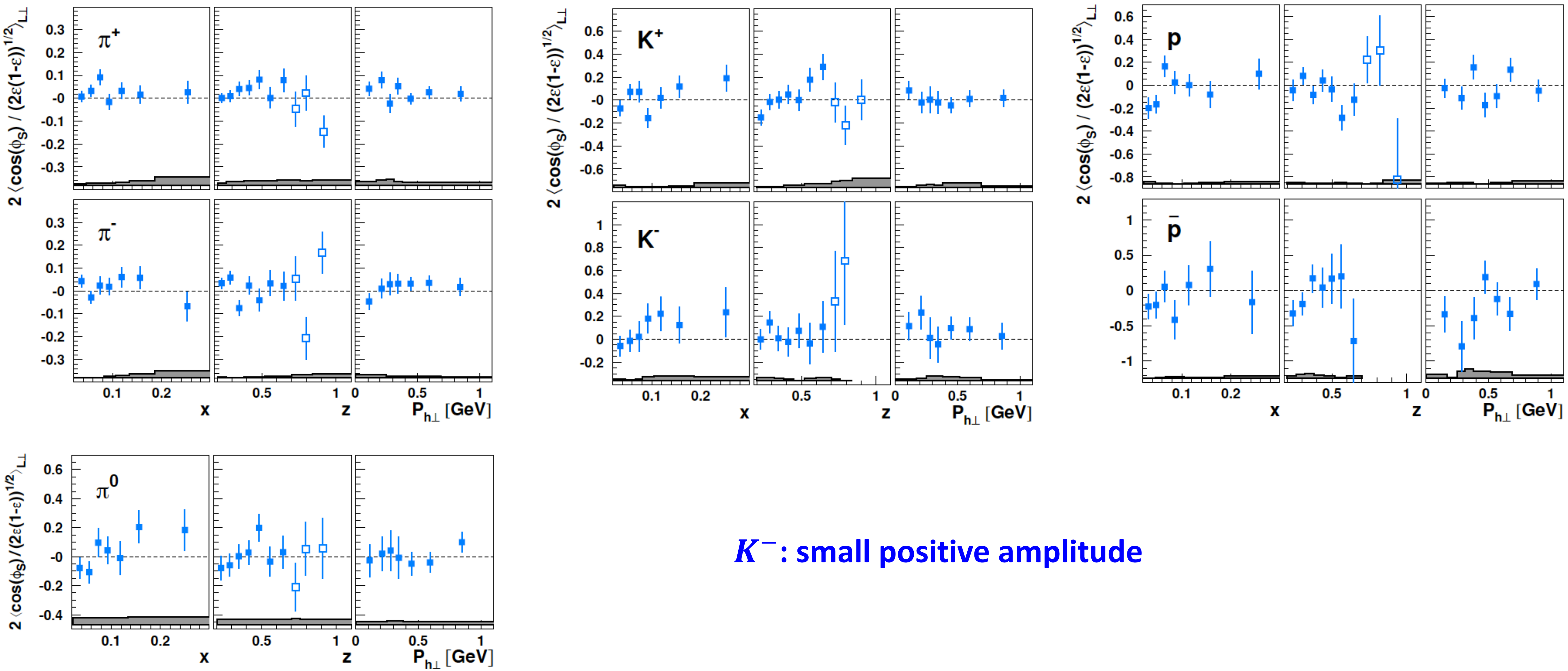
Semi-Exclusive region ($z > 0.7$):
π^+: positive amplitude rising with z → consistent with positive $\sin(2\phi + \phi_S)$ amplitude observed for exclusive π^+ electroproduction [Phys. Lett. B 682 (2010)]

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



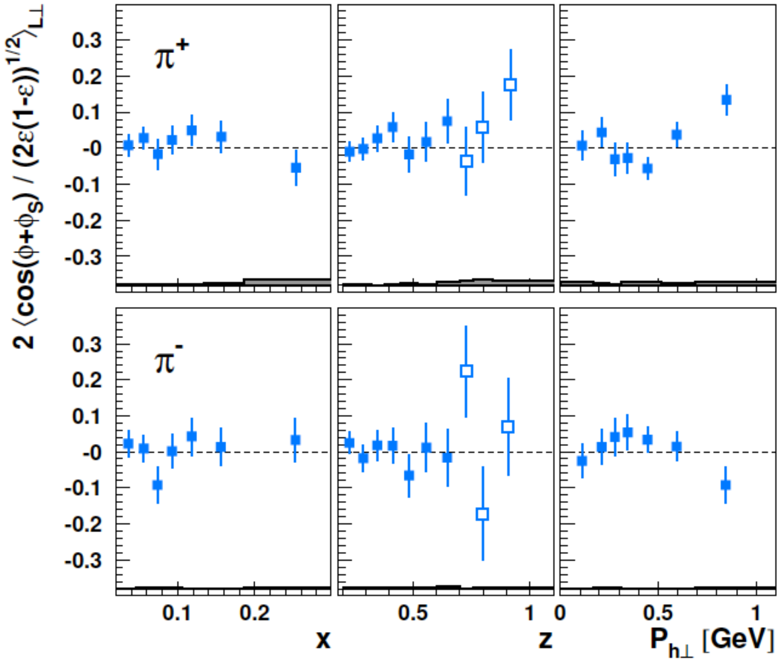
All results are consistent with zero

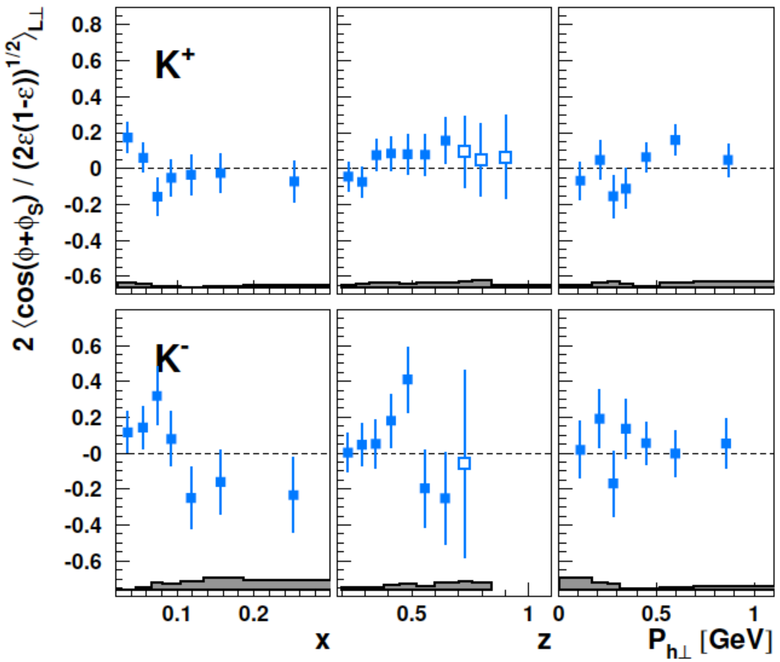
$\left\langle \cos(\phi_S) / \sqrt{2\varepsilon(1-\epsilon)} \right\rangle_{L\perp}$: all 1D results

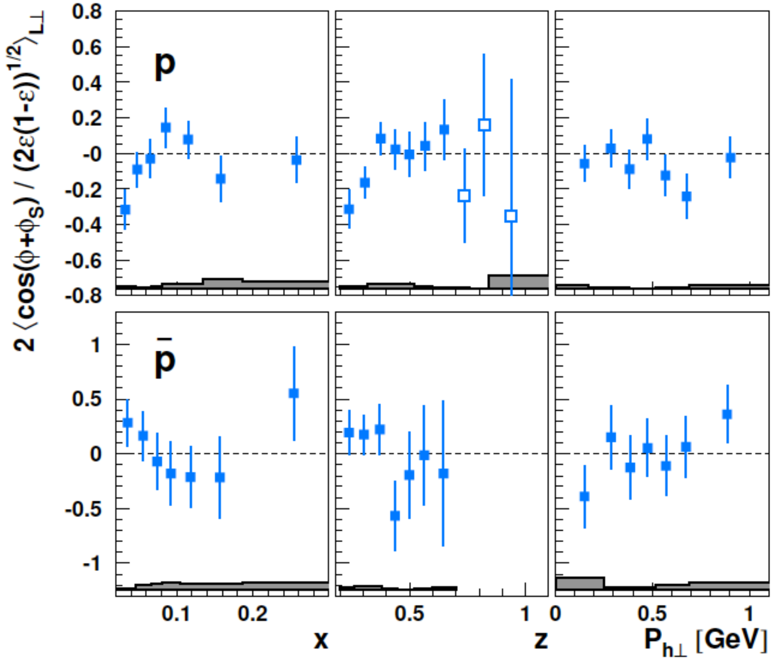


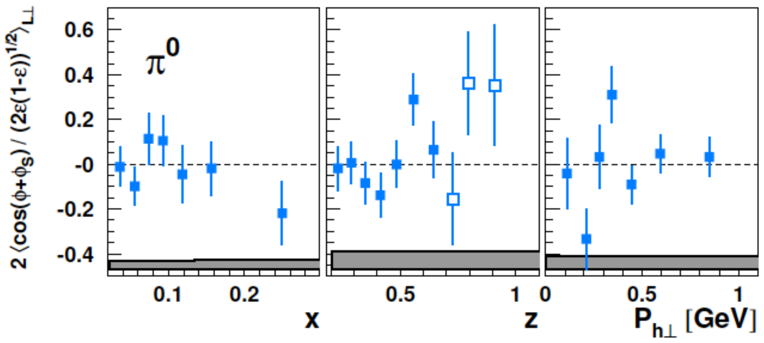
K^{-}: small positive amplitude

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



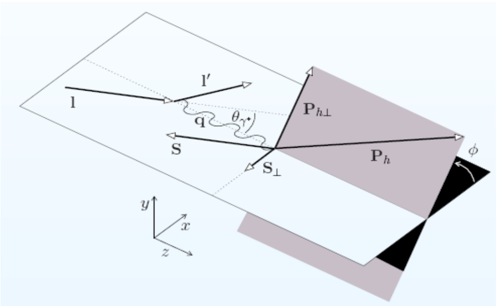






Arises solely from the small longit. target polarization component

All results consistent with zero



Other HERMES results

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

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

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

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

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

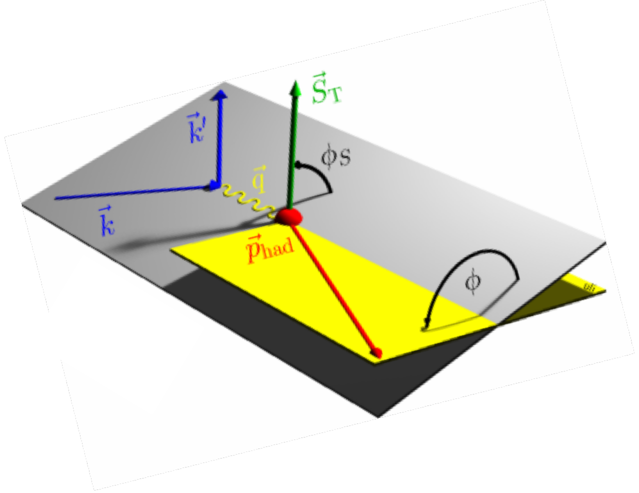
$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{\rm LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{\rm LL}^{\cos(\phi)}\Big]$$

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

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

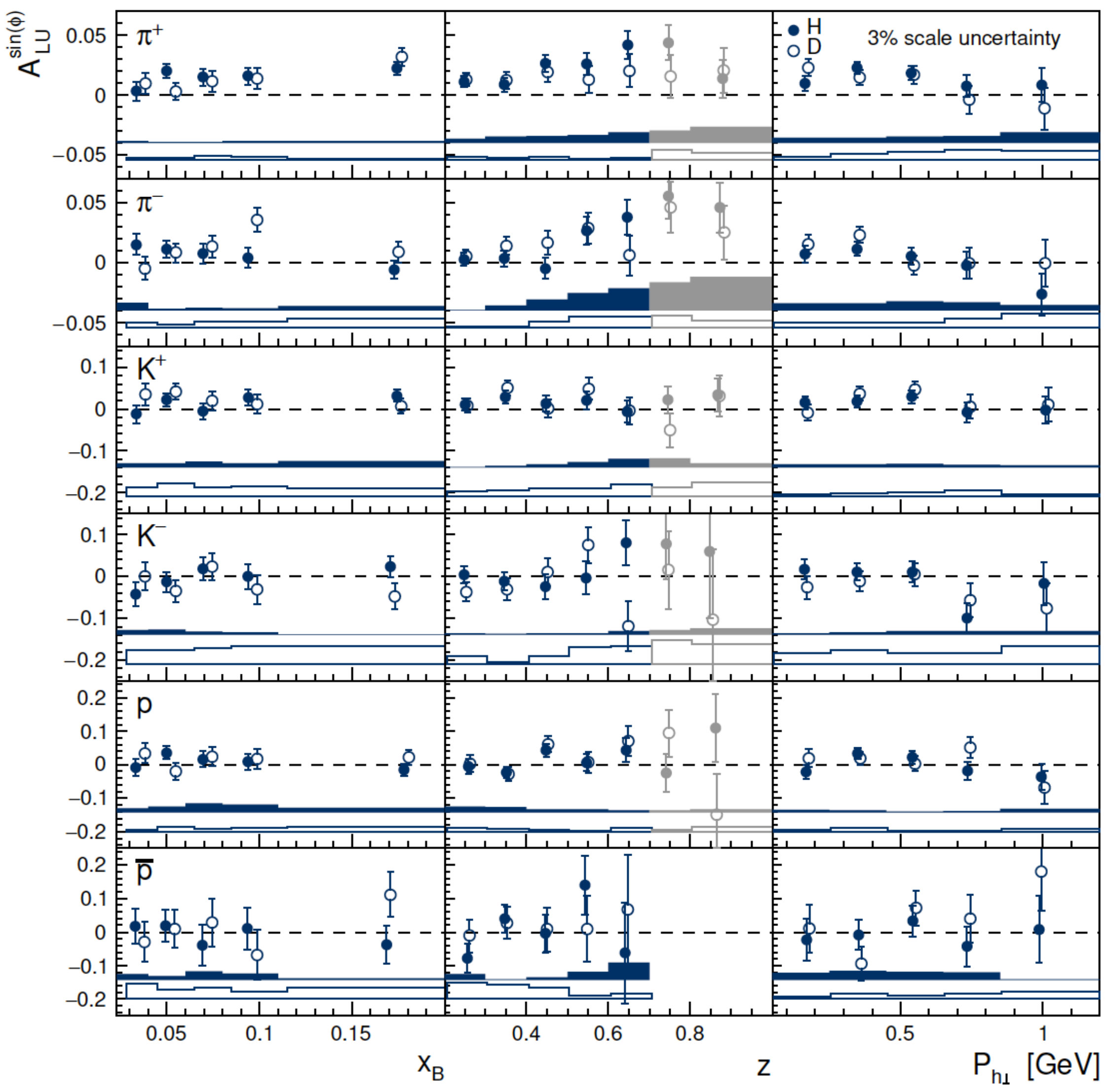
Sensitive to f_1 , Boer-Mulders + higher-twist DF and FF

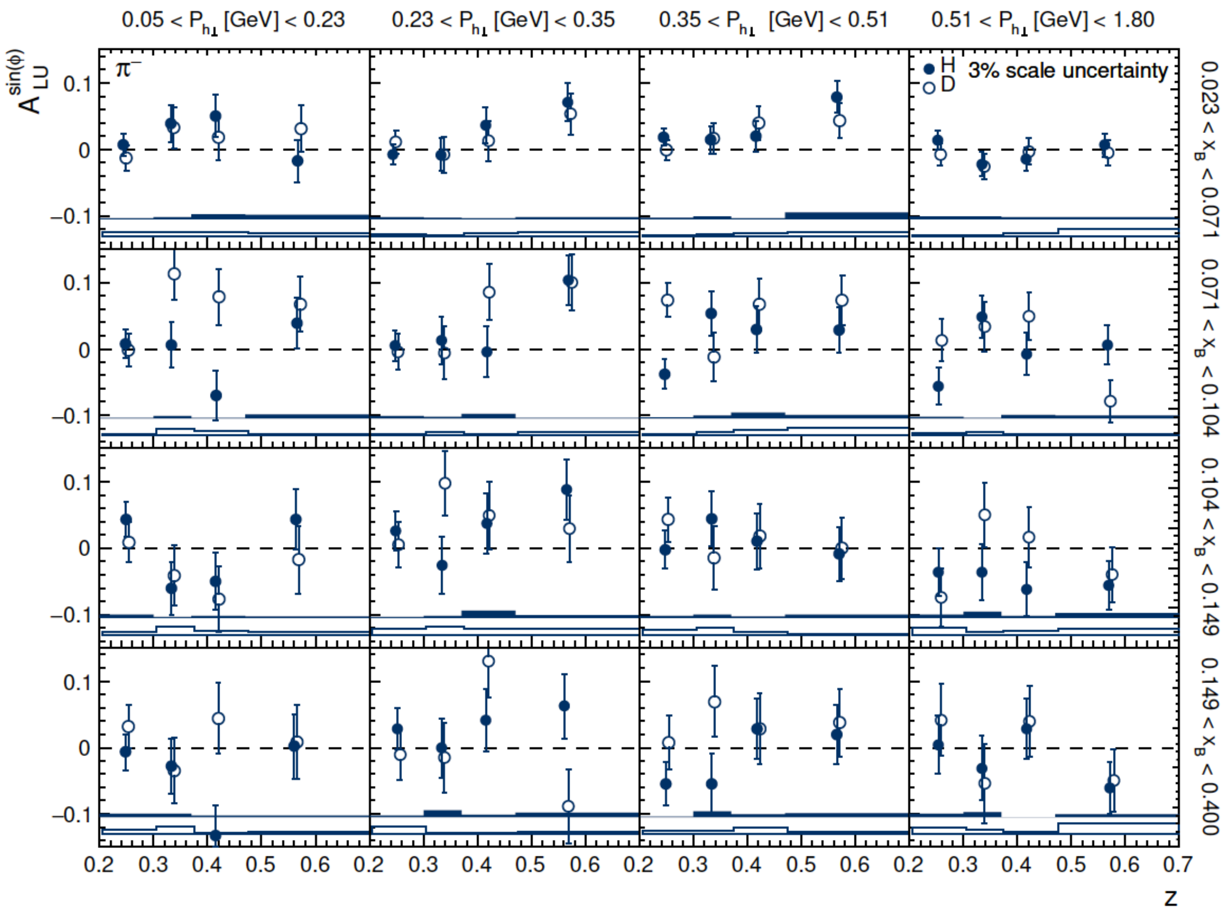
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right]$$



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

Phys. Lett. B 797 (2019) 134886



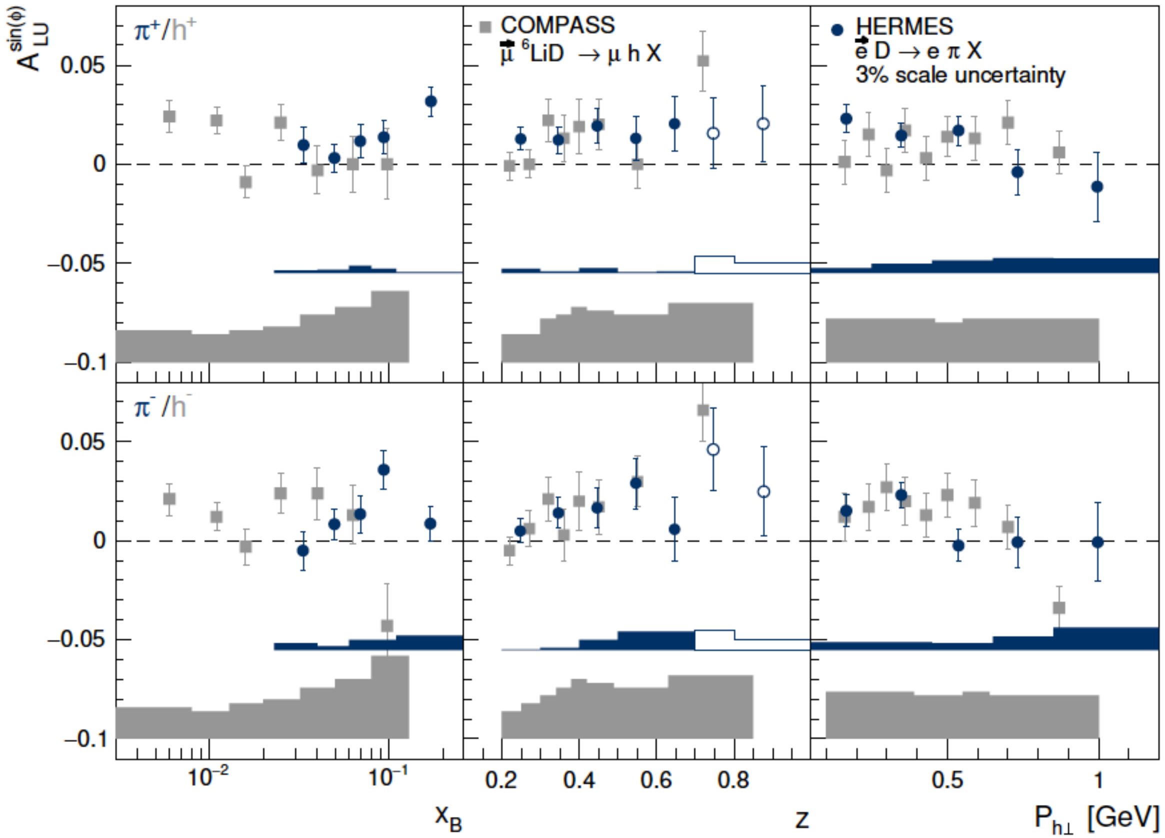


- Positive amplitudes rising with z for π^+ and π^-
- Small positive amplitude with mild kinematic dep. for K^+
- Results compatible with zero for K^-, p and $\bar{p}$

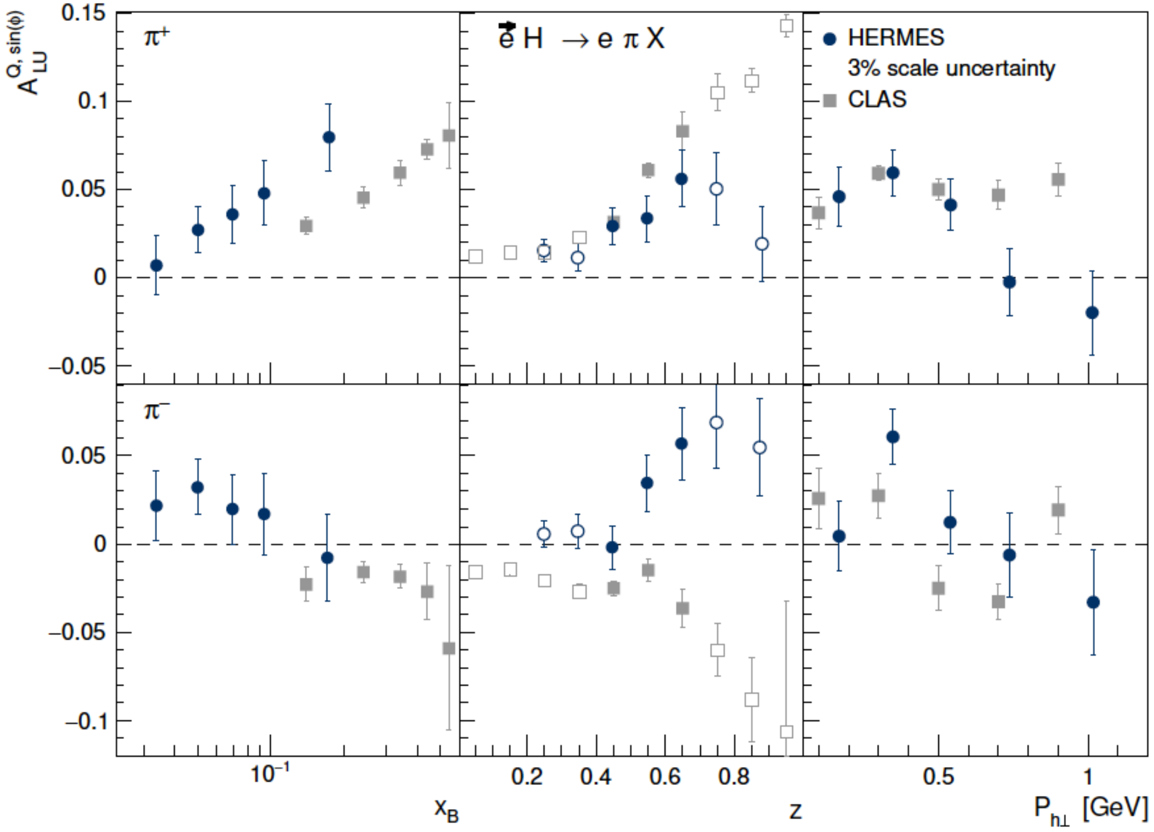
Sub-leading twist $\sin(\phi)$ BSA

Phys. Lett. B 797 (2019) 134886

HERMES vs. COMPASS



HERMES vs. CLAS



Sign change with increasing x?

Boer-Mulders function

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

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

Cahn effect

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

Boer-Mulders

Collins FF

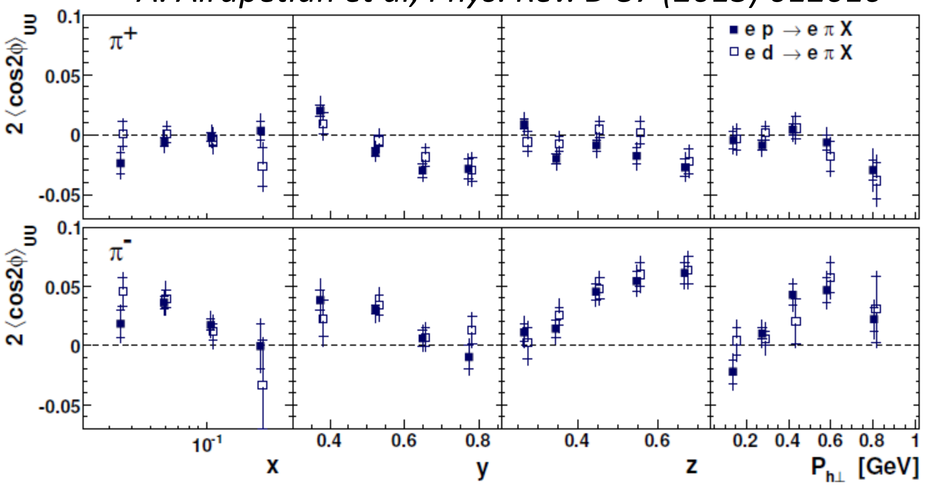
$$F_{UU}^{\cos(\phi)} \propto +\frac{1}{Q}[h_1^\perp \otimes H_1^\perp + f_1 \otimes D_1 \ldots]$$

Cahn effect

Interaction dependent terms

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

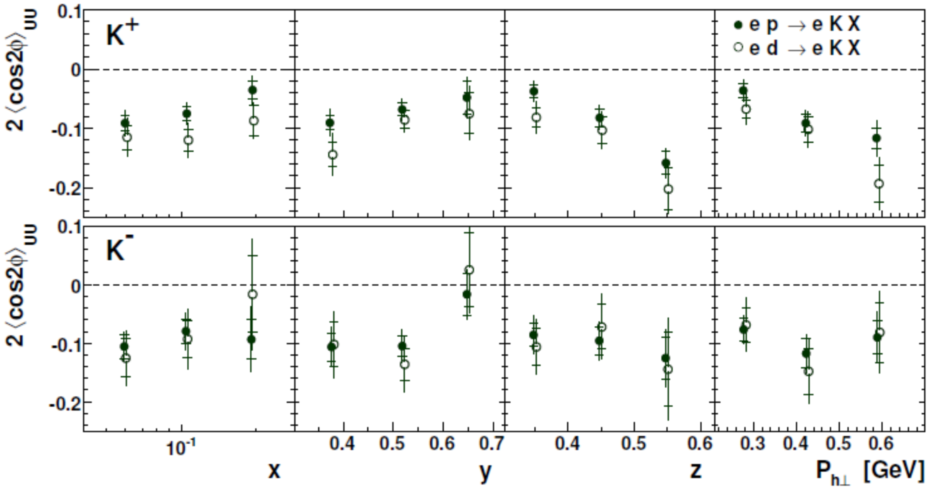
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



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

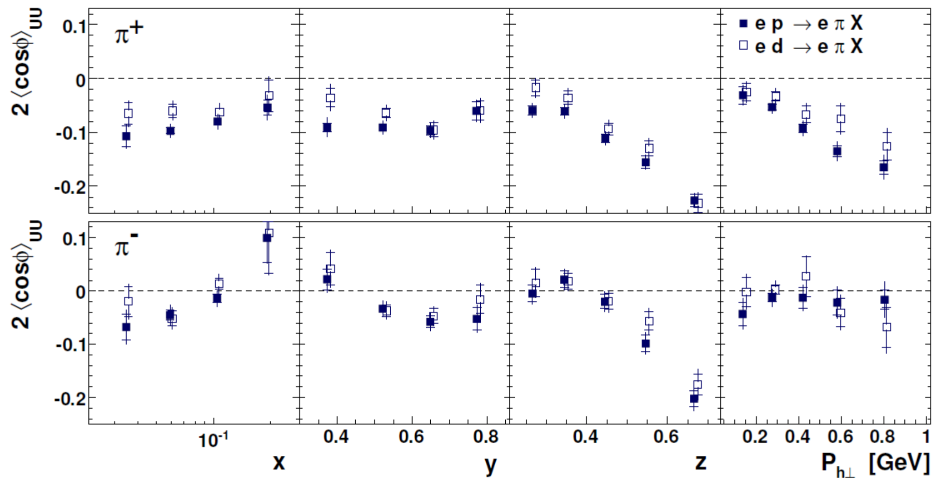
- **K^+/K^- amplitudes larger than for pions , have different kinematic dependencies than pions and have same sign**

→ different role of Collins FF for pions and kaons?

→ significant contribution from scattering off strange quarks**?**

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

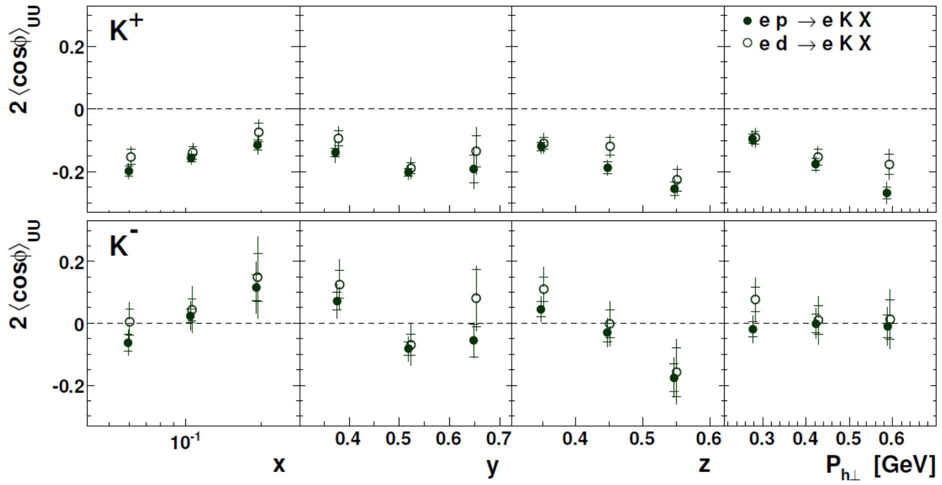
A. Airapetian et al, Phys. Rev. D 87 (2013) 012010



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 $h_{1L}^{\perp}$

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

$$\Big\{ \Big[F_{\mathrm{UU,T}} + \epsilon F_{\mathrm{UU,L}}$$

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

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

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

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

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

$$+\epsilon\sin(\phi+\phi_S)F_{\mathrm{UT}}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{\mathrm{UT}}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{\mathrm{UT}}^{\sin(\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)F_{\mathrm{UT}}^{\sin(2\phi-\phi_S)}\Big]$$

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

$$+\sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{\mathrm{LT}}^{\cos(\phi_S)}$$

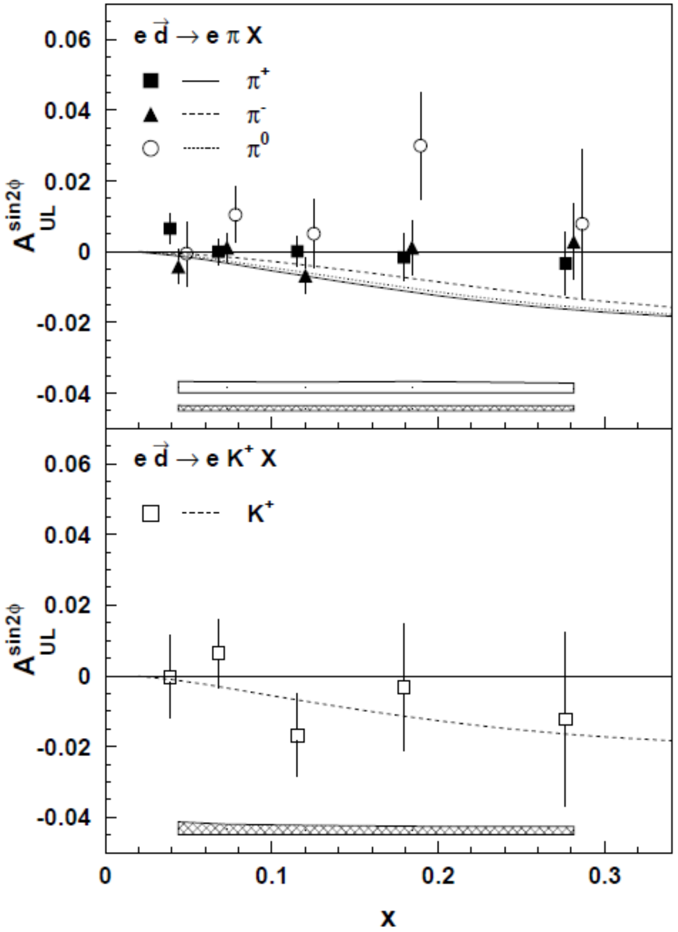
$$+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{\mathrm{LT}}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$

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

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

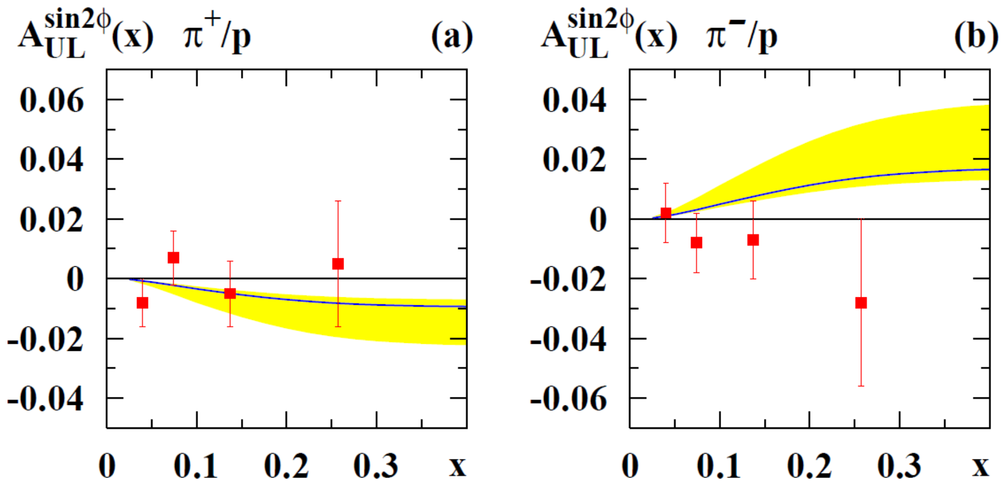
The sin(2ϕ) amplitude $\propto h_{1L}^{\perp}(x, p_T^2) \otimes H_1^{\perp}(z, k_T^2)$

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

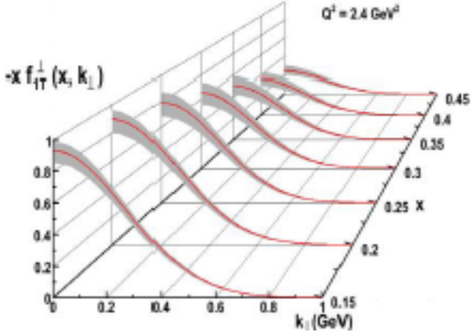
Miscellanea

Mapping the phase-space of the nucleon

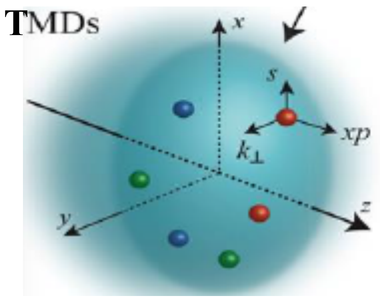
$W(x, k_\perp, b_\perp)$

$\int d^2 b_\perp$ → $f(x, k_\perp)$

$\int d^2 k_\perp$ → $f(x, b_\perp)$ $\xrightarrow{FT}$ $H(x, \xi, t)$

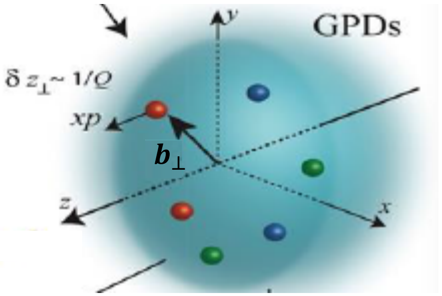


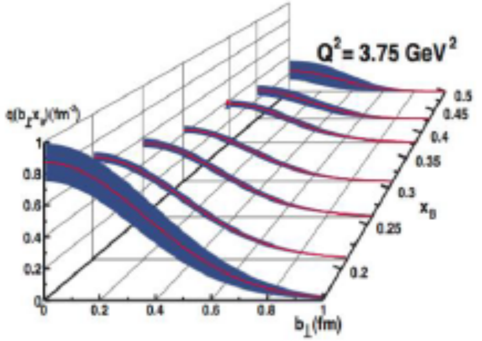
TMDs: **3D description in longitudinal (x) and transverse ($k_\perp$) mom.**



3D

1D

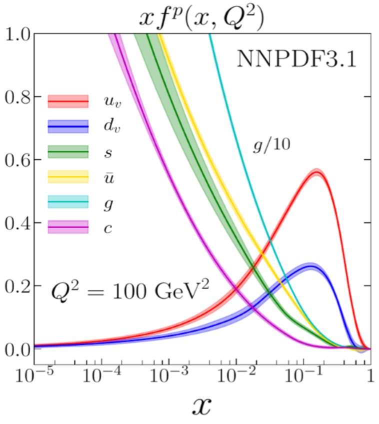


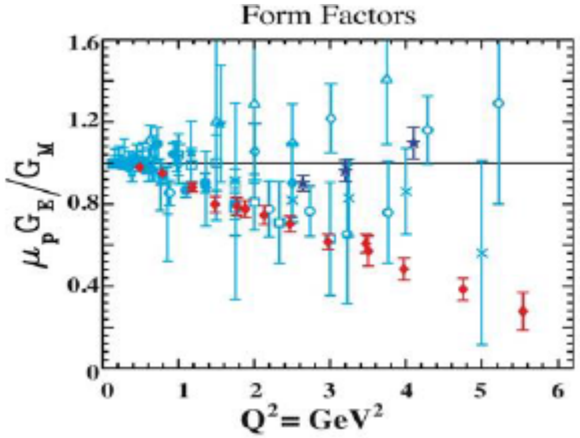


GPDs: **3D description in longit. momentum (x) and transverse location ($b_\perp$)**

$\int d^2 p_T$ → $f(x)$

$\int dx$ → $F(Q^2)$





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 (first four lines)

$A_{L\perp}$ DSAs (last two lines)

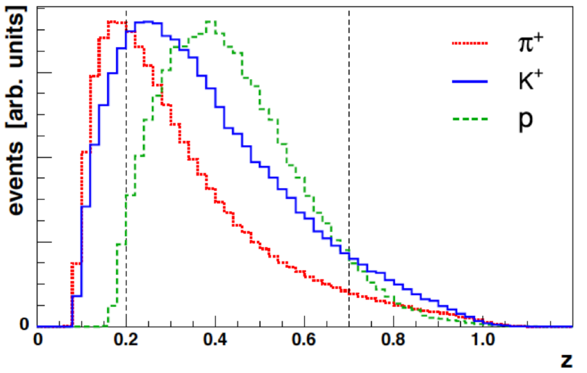
10 Fourier components:

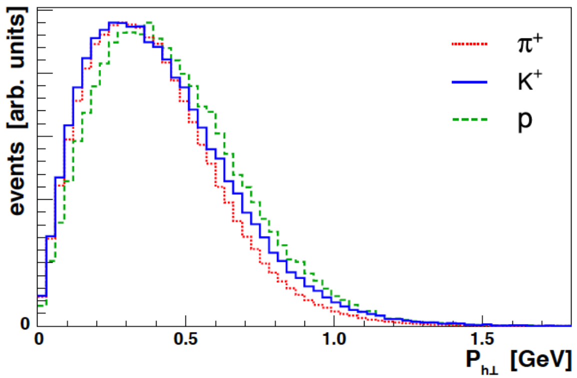
- 6 $A_{U\perp}$ SSAs (4 leading-twist + 2 subleading twist)
- 4 $A_{L\perp}$ DSAs (2 leading-twist + 2 subleading twist)
- $\sin(2\phi+\phi_S)$ and $\cos(\phi+\phi_S)$ terms arise purely from the small but non-vanishing longitudinal target-polarization component along the virtual photon direction (target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

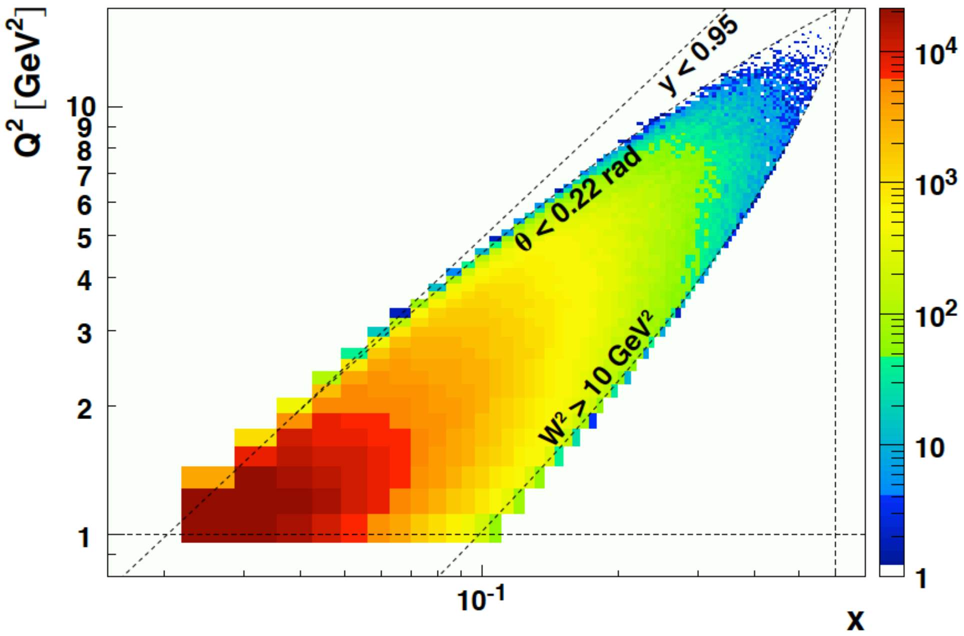
- **The CSA amplitudes include in their definition the ε-dependent kinematic prefactors**

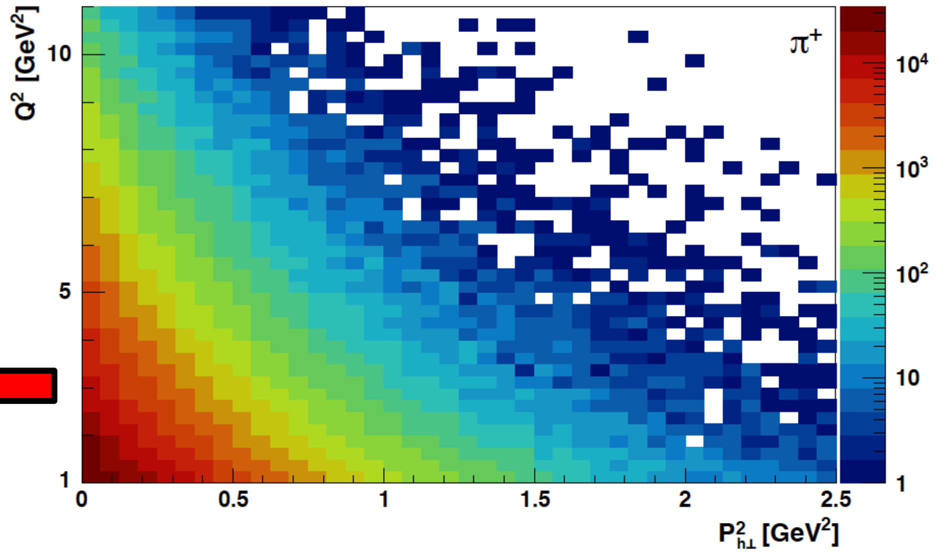
Kinematic coverage

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)	



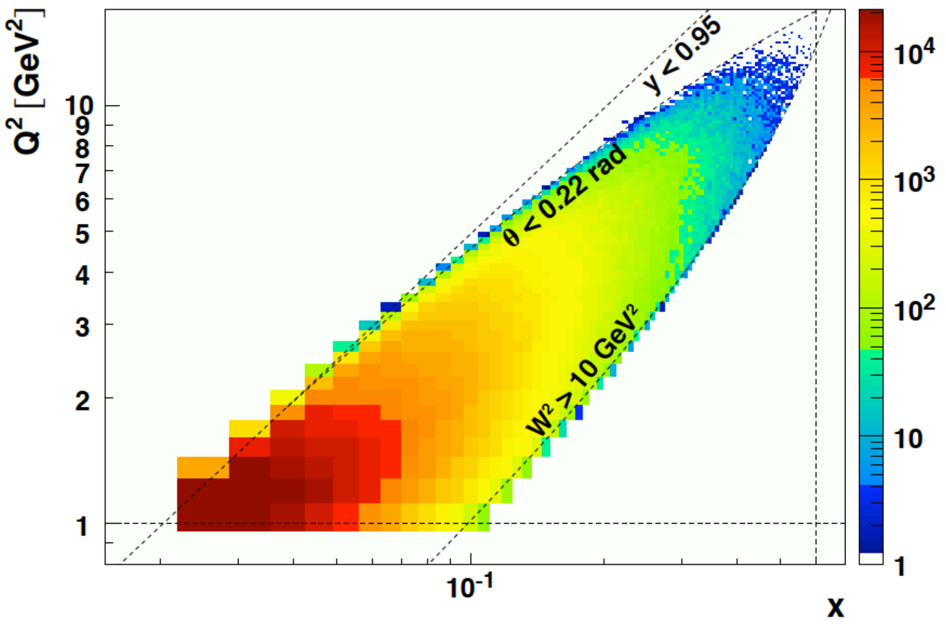






- Factorization requirement $P_{h\perp}^2 \ll Q^2$ fulfilled for most of the selected DIS events
- the stricter constraint $P_{h\perp}^2 \ll z^2 Q^2$ is violated at large $P_{h\perp}$ in the region of small x and small z
- detailed studies in appendix B of the paper (and next slides)

Kinematic coverage and factorization requirements



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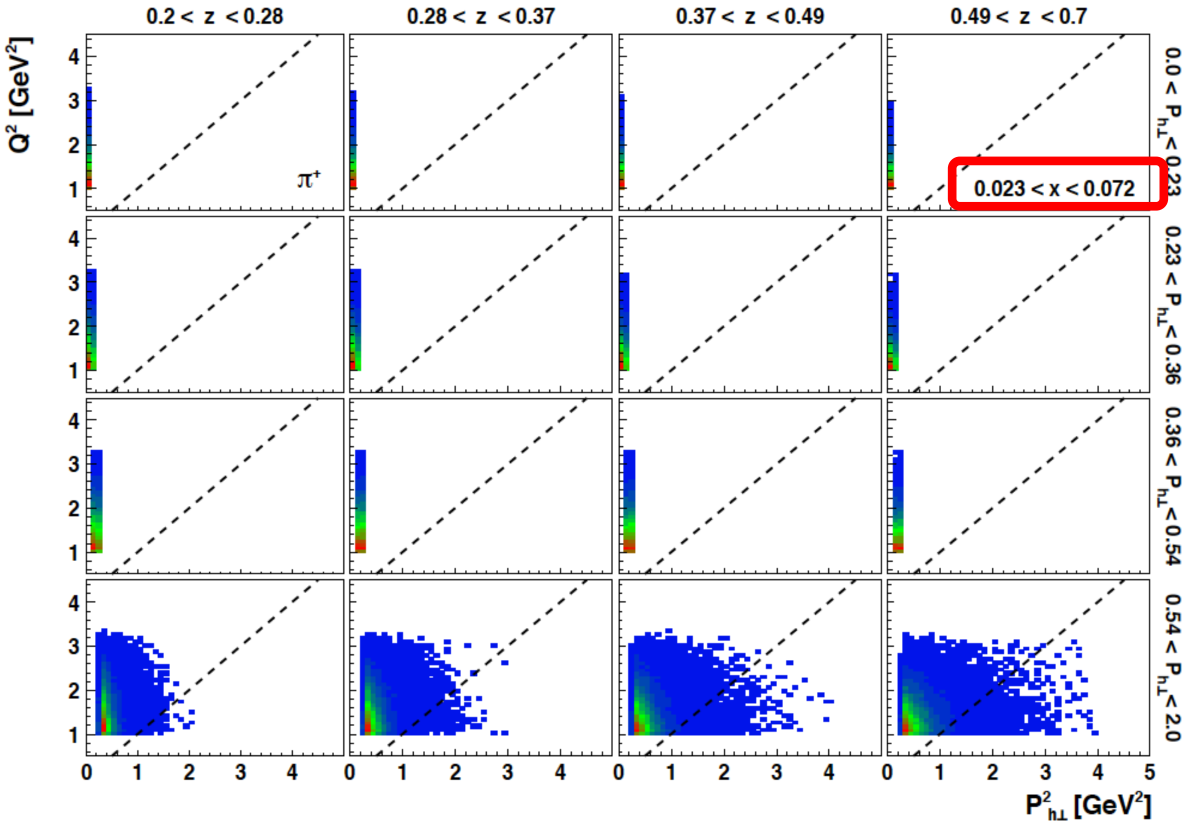
	$4\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\mathrm{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\mathrm{GeV}$	
	$0.2 <$	z	< 0.7 (1.2 for the "semi-exclusive" region)	

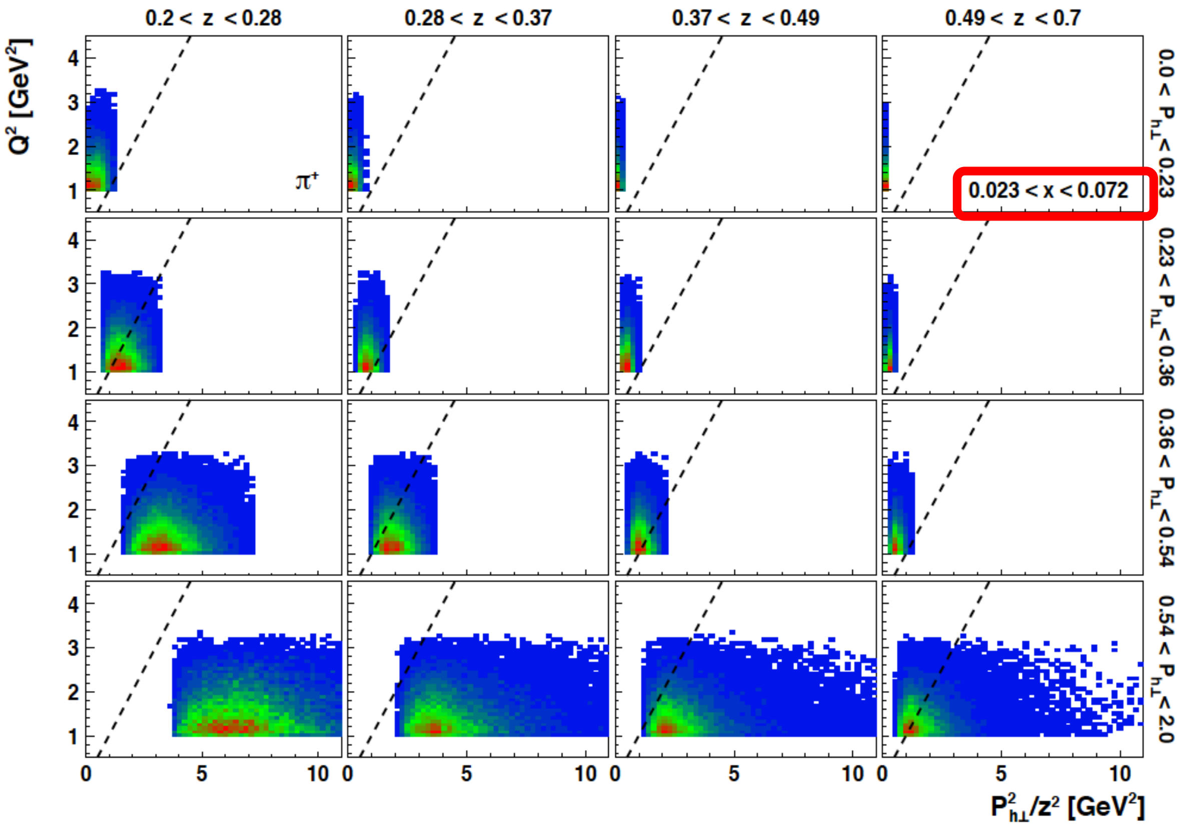
Due to x-Q^2 correlation, the **first x bin** corresponds to the **small Q^2 region**, where the **TMD-factorization requirement $P_{h\perp}^2 \ll Q^2$** is less favourable.



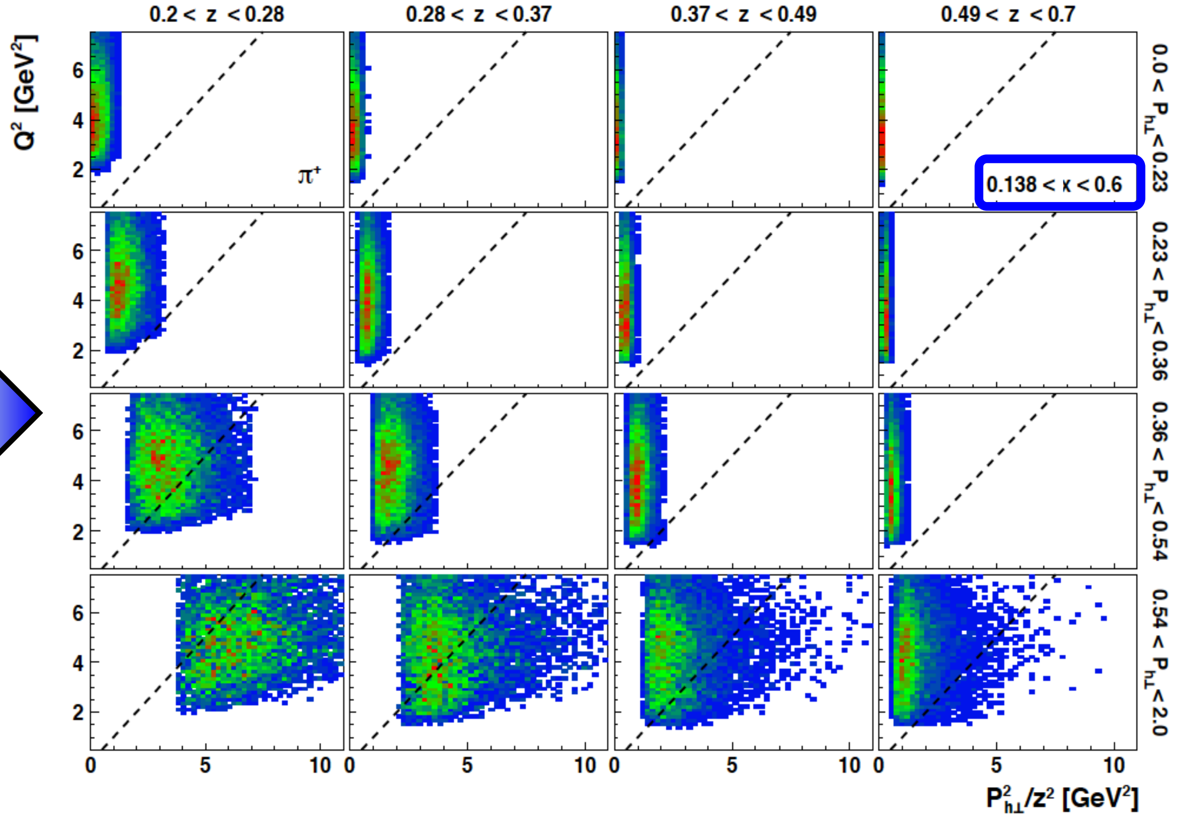
TMD-factorization requirement $P_{h\perp}^2 \ll Q^2$ fulfilled for most of the selected DIS events!

Factorization requirements

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

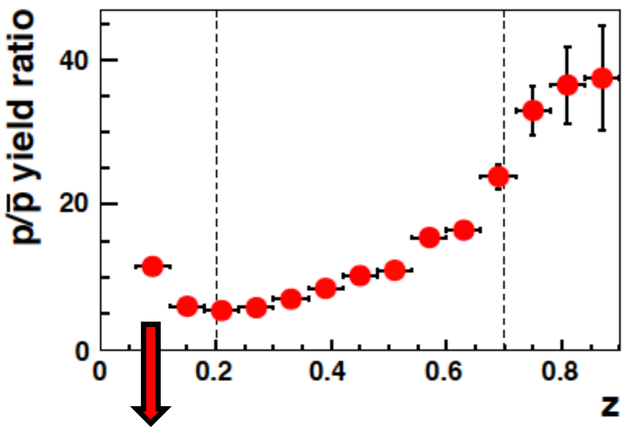


First x-bin → smaller Q^2

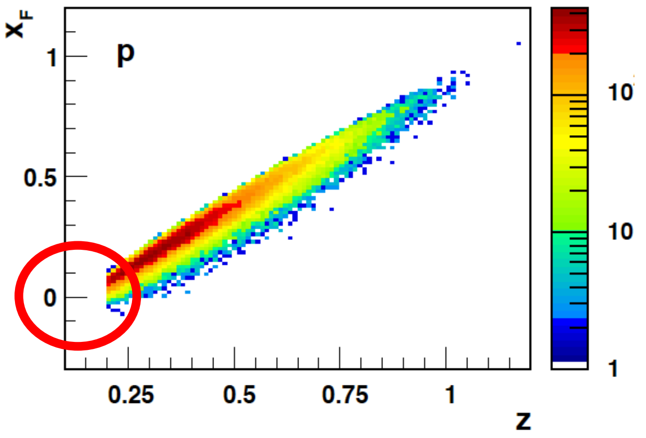


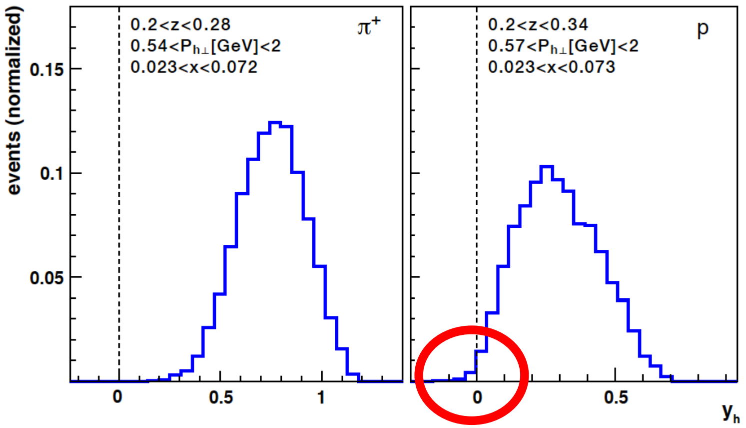
Last x-bin → larger Q^2

Sivers amplitudes: protons results

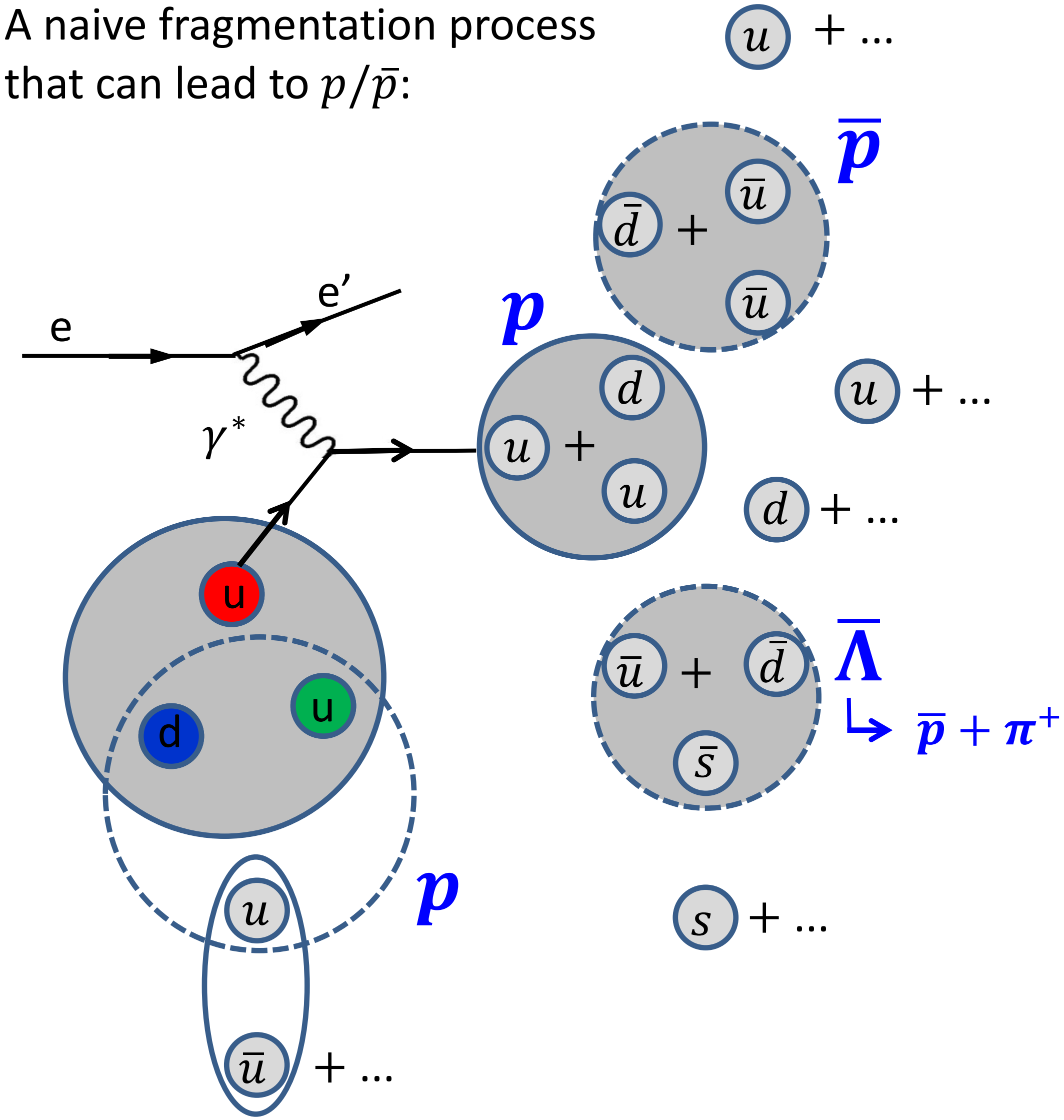


onset of Target Fragmentation ?





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



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

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