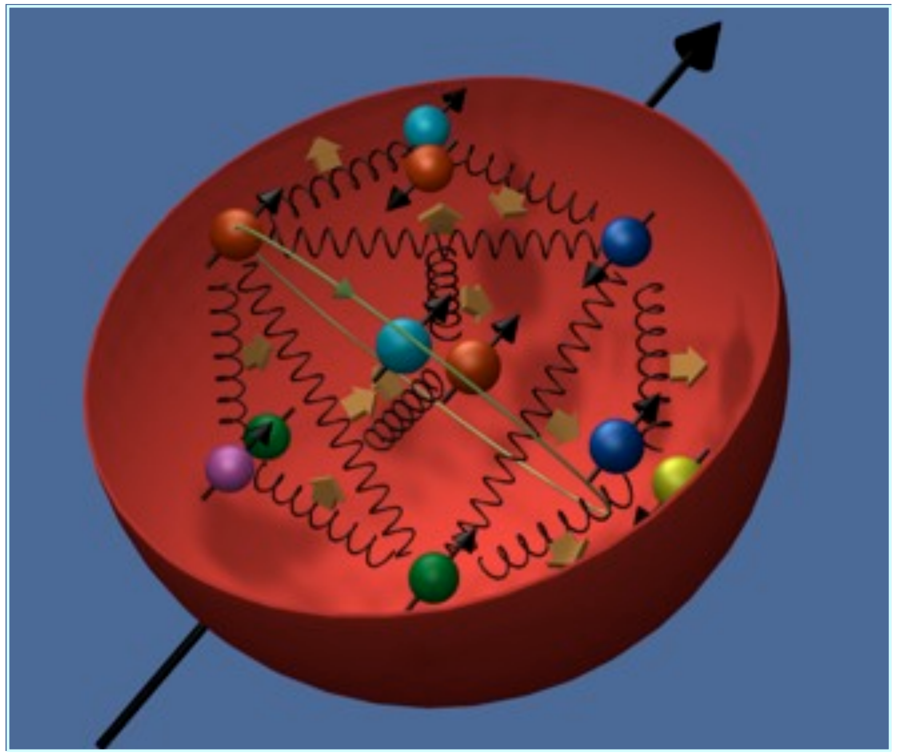
A Workshop in Honor of Gary Goldstein's 70th Birthday

Transversity and its chiral-odd/-even friends

gunar.schnell @ desy.de

The proton spin "puzzle"



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- $\frac{1}{2}\Delta\Sigma$ ← quark spin
- ΔG ← gluon spin
- $L_q + L_g$ ← orbital angular momentum

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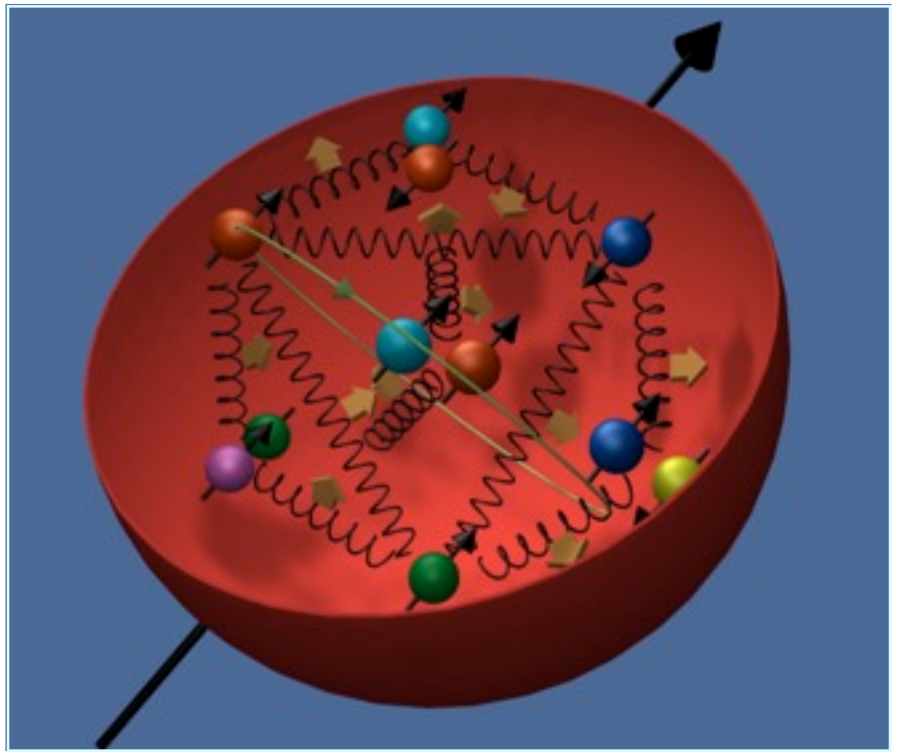

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$$+ \Delta G \quad \leftarrow \text{gluon spin}$$

$$+ L_q + L_g \quad \leftarrow \text{orbital angular momentum}$$

- Inclusive DIS from longitudinally polarized Deuterium target:

$\Delta\Sigma = 0{,}330 \pm 0{,}025^{\text{(exp.)}} \pm 0{,}011^{\text{(theory)}} \pm 0{,}028^{\text{(evol.)}}$

PRD 75 (2007) 012007

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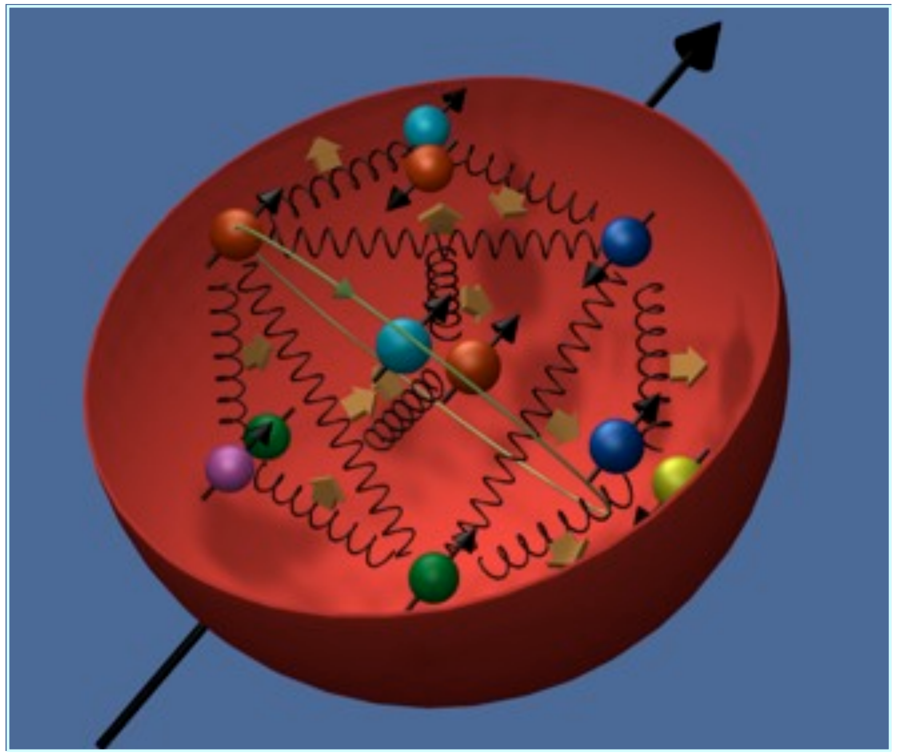

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- High-p_T hadrons at HERMES:

JHEP 1008 (2010) 130

$$\Delta G/G = 0.071 \pm 0.034^{(stat)} \pm 0.010\ ^{(sys\text{-}exp)}\ {}^{+0.127}_{-0.105}\ ^{(sys\text{-}model)}$$

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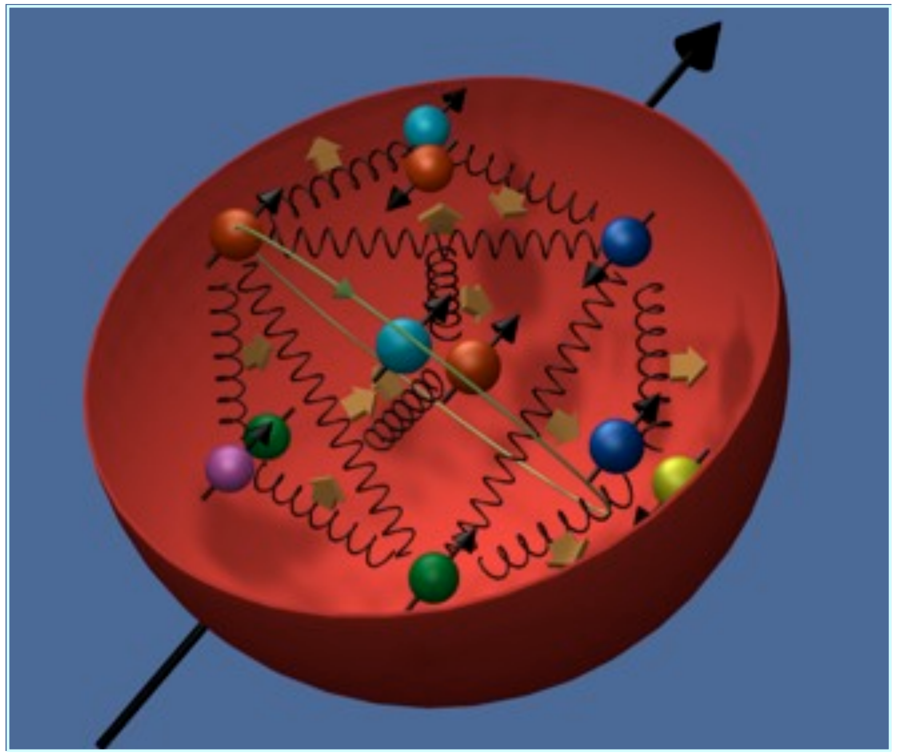

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- spin-orbit correlations
- hard exclusive reactions

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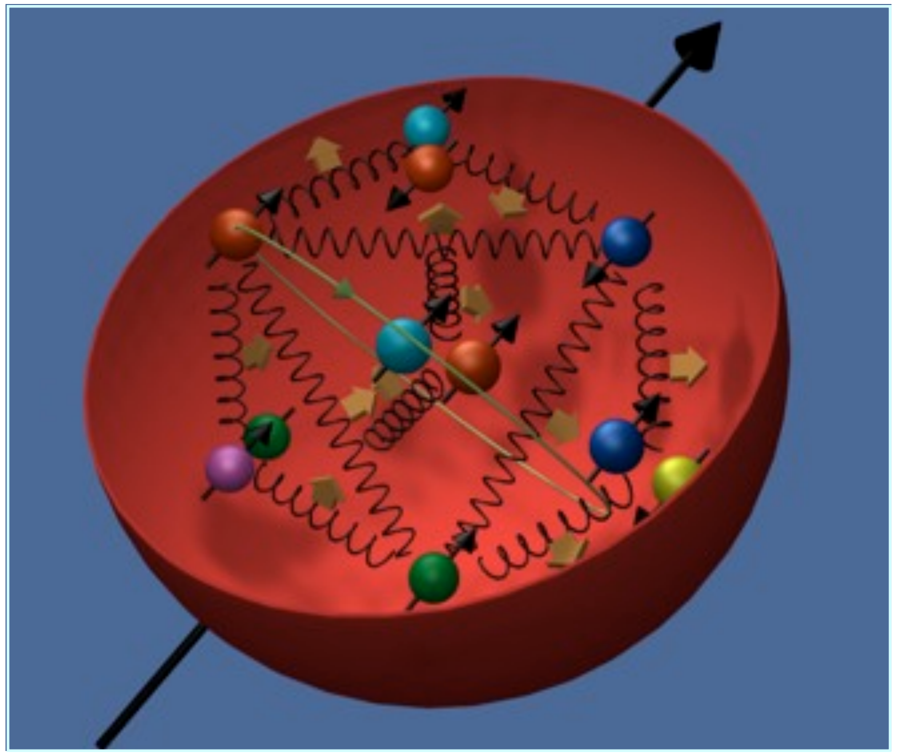

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- spin-orbit correlations
- hard exclusive reactions

Need to add transverse degrees of freedom - 3D structure

- Inclusive DIS on longitudinally polarized Deuterium target:

$\Delta\Sigma = 0 \ldots 0{,}025^{(exp.)} \pm 0{,}011^{(theory)} \pm 0{,}028^{(evol.)}$

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- … p_T hadrons at HERMES:

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Spin-Momentum Structure of the Nucleon

$$\frac{1}{2}\mathrm{Tr}\left[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\right] = \frac{1}{2}\left[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + \lambda\Lambda\,g_1 + \lambda\,S^i k^i\frac{1}{m}\,g_{1T}\right]$$

$$\frac{1}{2}\mathrm{Tr}\left[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\right] = \frac{1}{2}\left[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\frac{1}{m}\,h_1^\perp + s^i S^i h_1 + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\frac{1}{m}\,h_{1L}^\perp\right]$$

quark pol. (columns) / nucleon pol. (rows)

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

Twist-2 TMDs

- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

Spin-Momentum Structure of the Nucleon

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$$+ s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Big]$$

helicity

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$…_1$, $h_{1T}^\perp$

Twist-… …MDs

Boer-Mulders

Sivers

worm-gear

transversity

Mulders-Tangerman*

- functions in black survive integration … …se momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

*aka Pretzelosity

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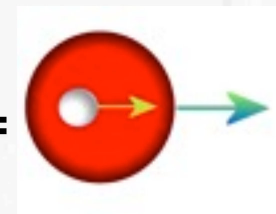
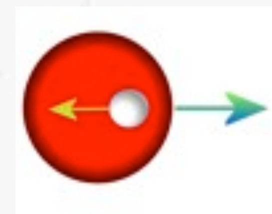
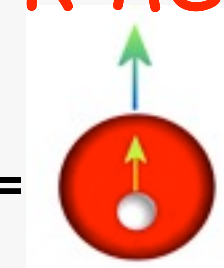
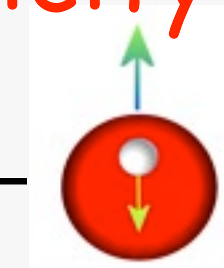
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

Transversity distribution

chiral-odd transversity involves quark helicity flip

$f_1^q =$ 

$g_1^q =$  $-$ 

$h_1^q =$  $-$ 

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U	f_1		$h_1^\perp$
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T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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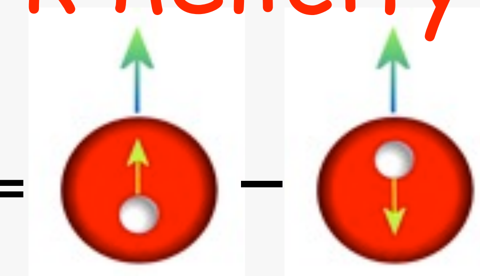
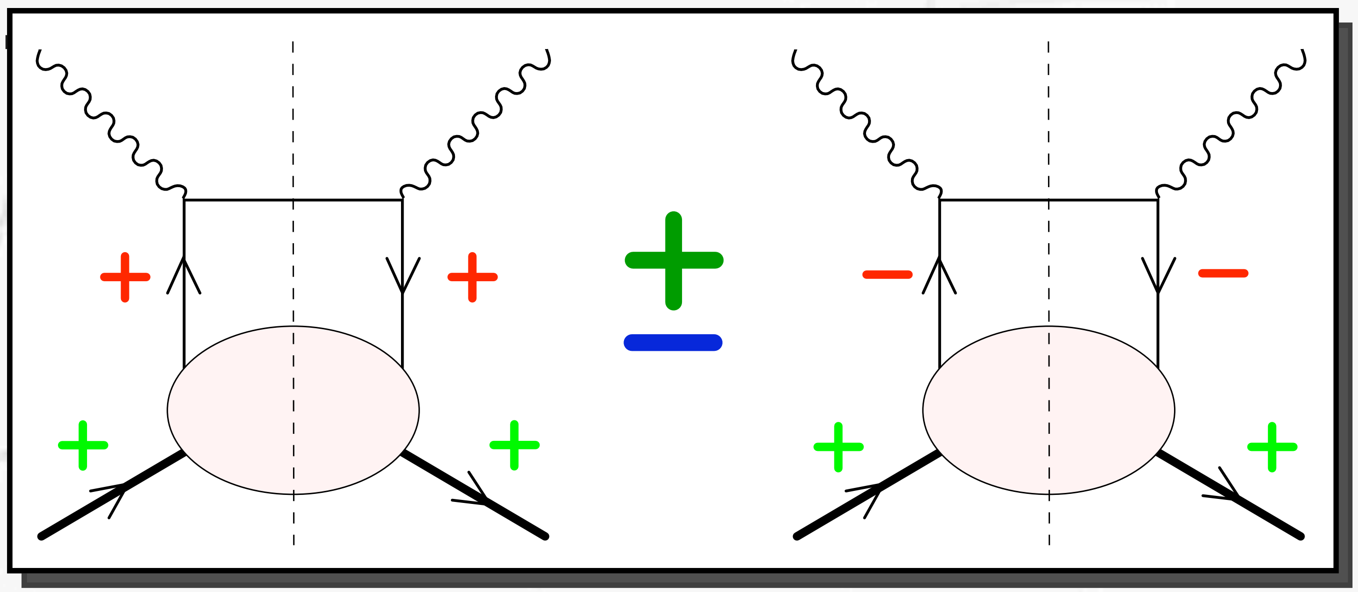
$h_1^q =$ 



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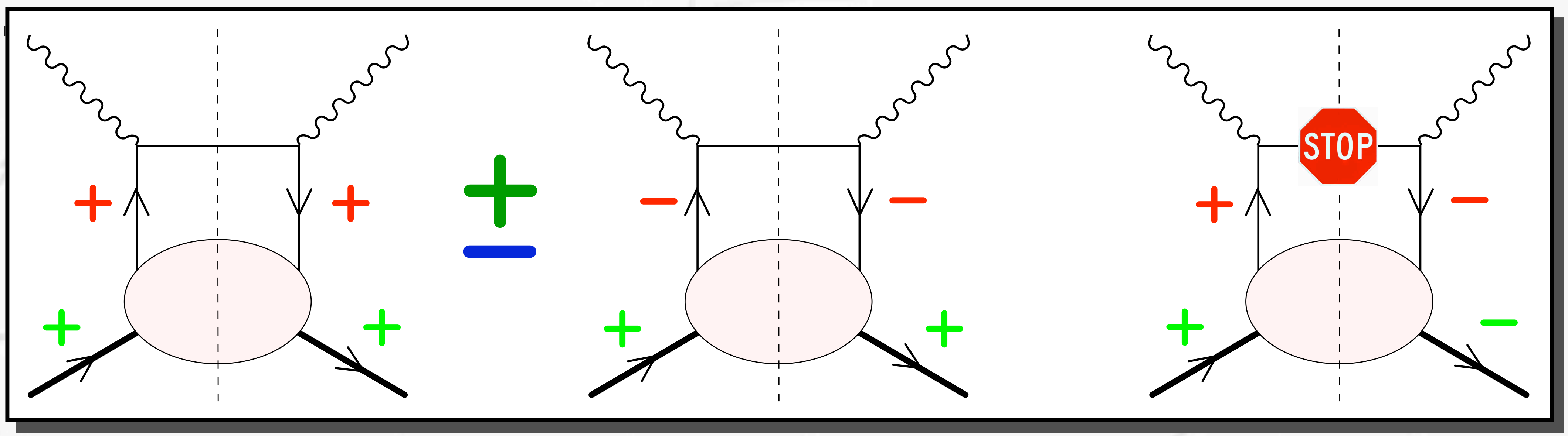

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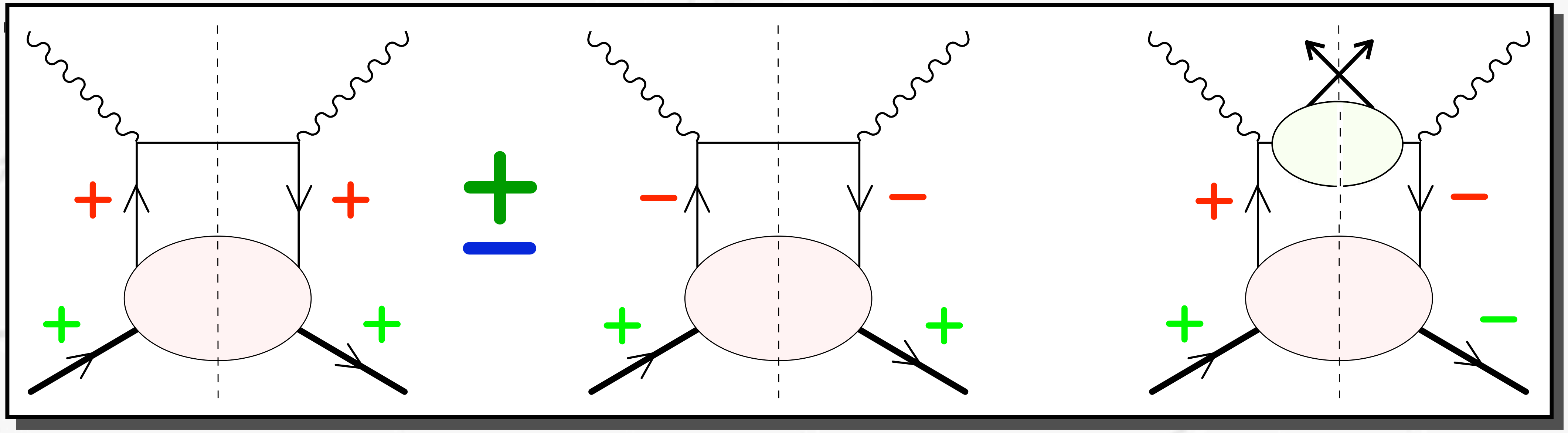

need to couple to chiral-odd fragmentation function:

	U	L	T
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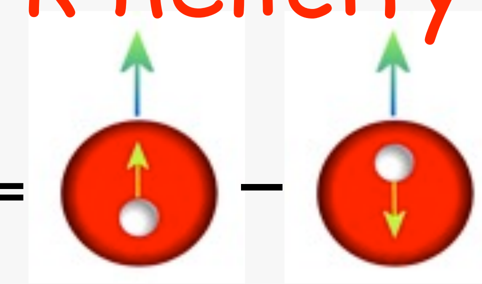
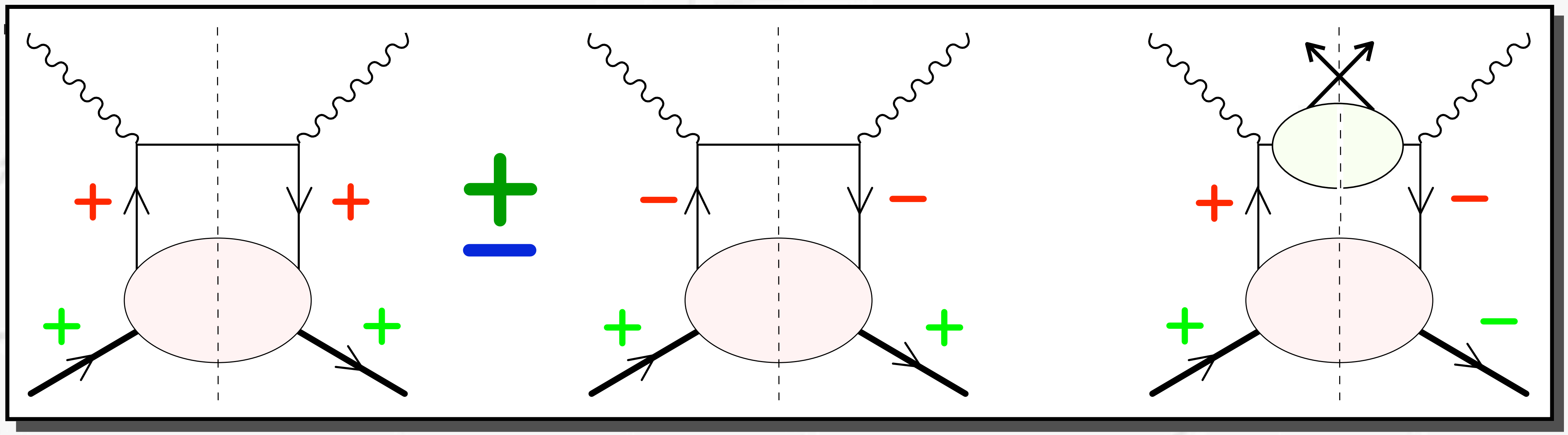
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



need to couple to chiral-odd fragmentation function:

- **transverse spin transfer** (polarized final-state hadron)

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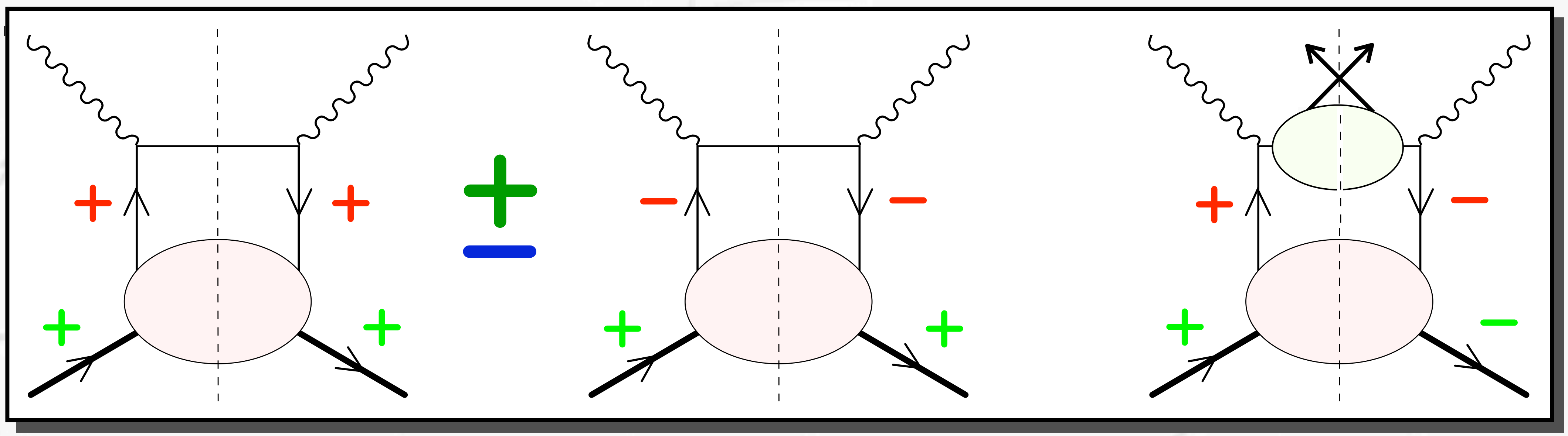

need to couple to chiral-odd fragmentation function:

- **transverse spin transfer** (polarized final-state hadron)
- **2-hadron fragmentation**

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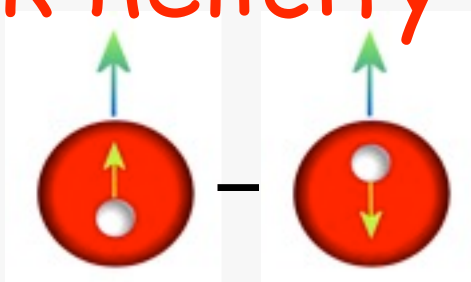
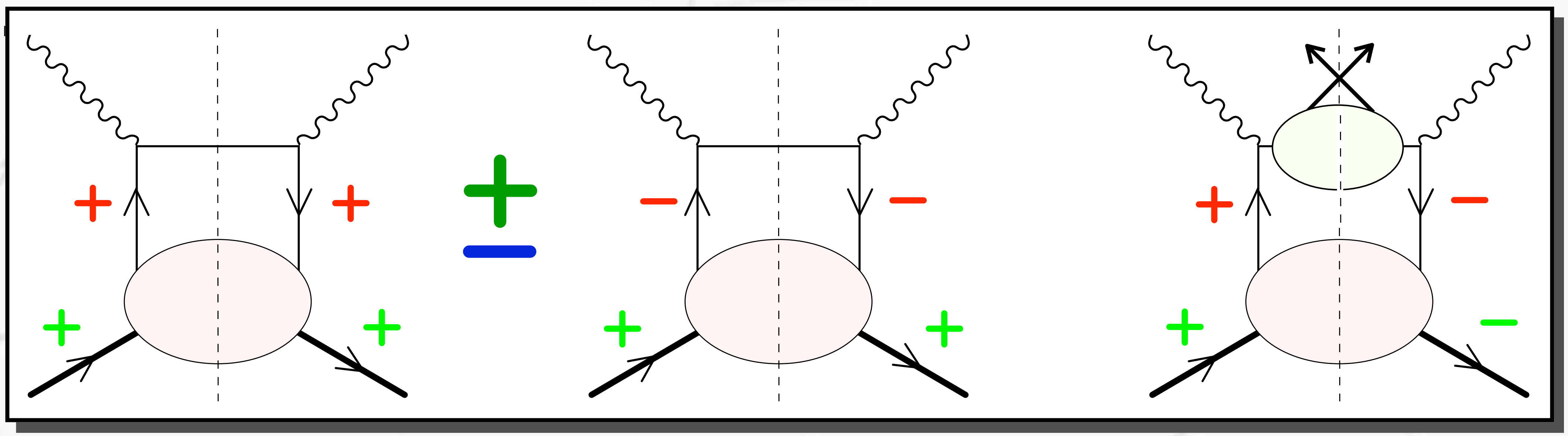
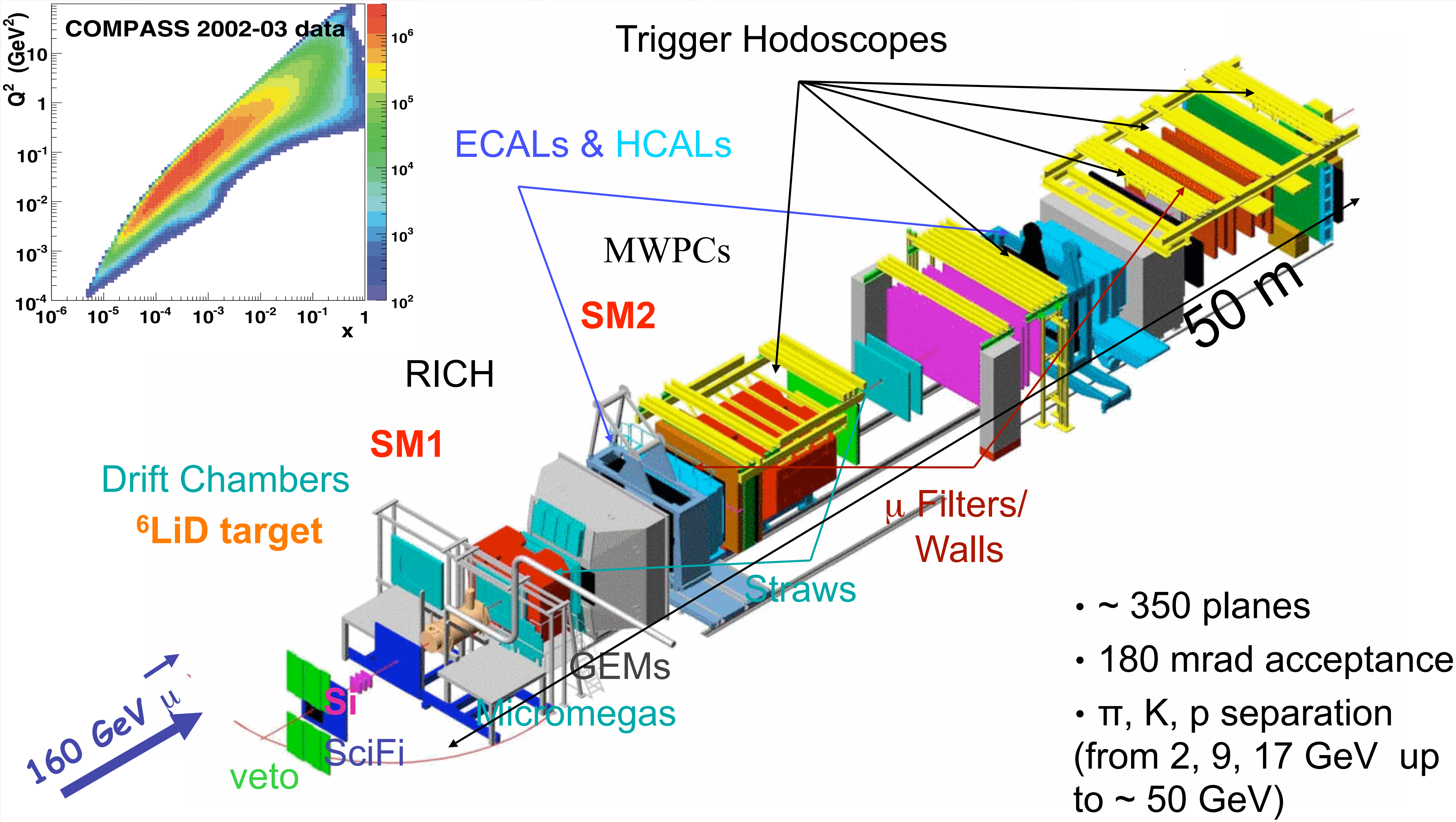
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



need to couple to chiral-odd fragmentation function:

- **transverse spin transfer** (polarized final-state hadron)
- **2-hadron fragmentation**
- **Collins fragmentation**

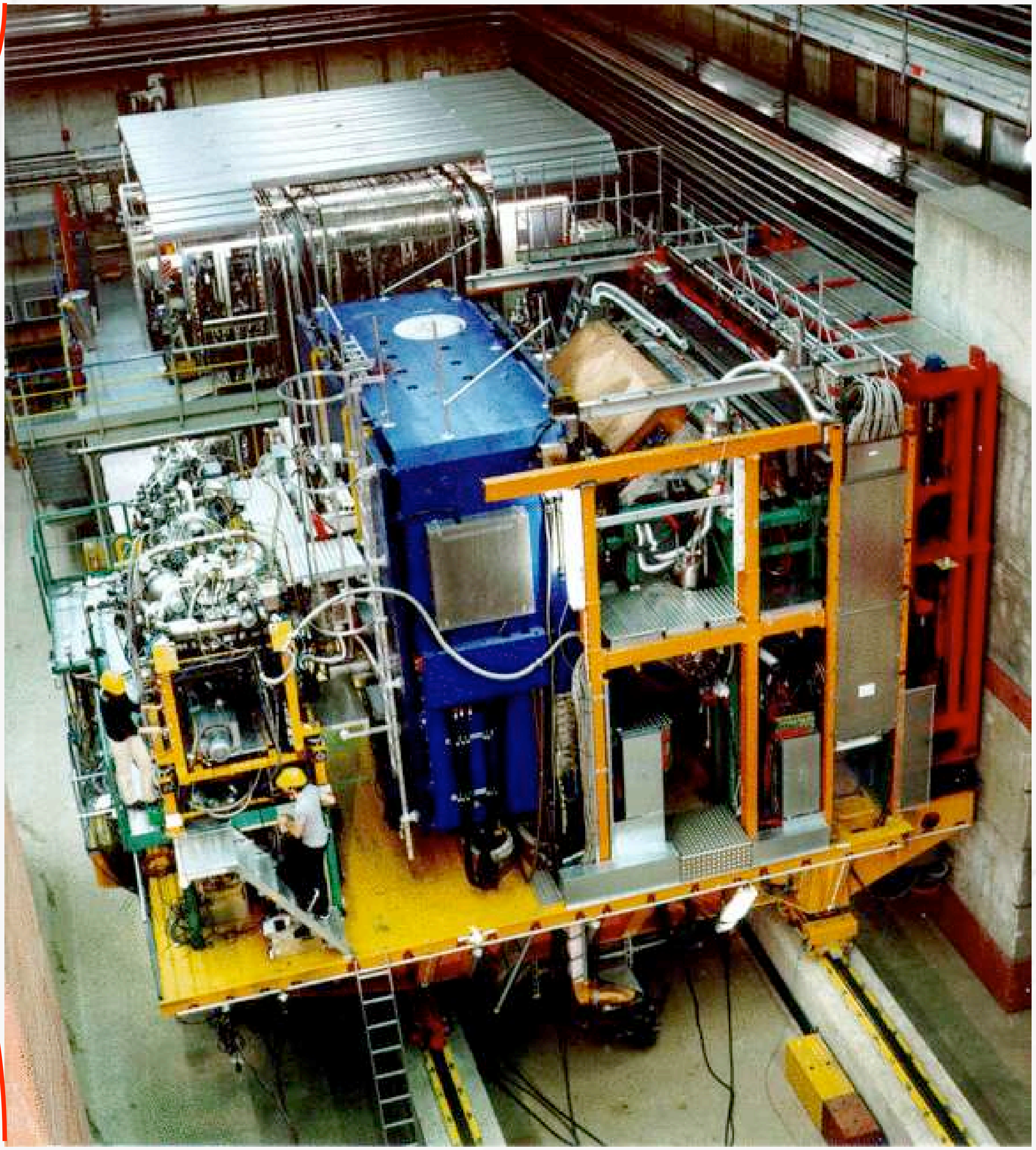
The COMPASS experiment @ CERN



- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

HERMES Experiment (†2007) @ DESY

27.6 GeV polarized e^+/e^- beam scattered off ...



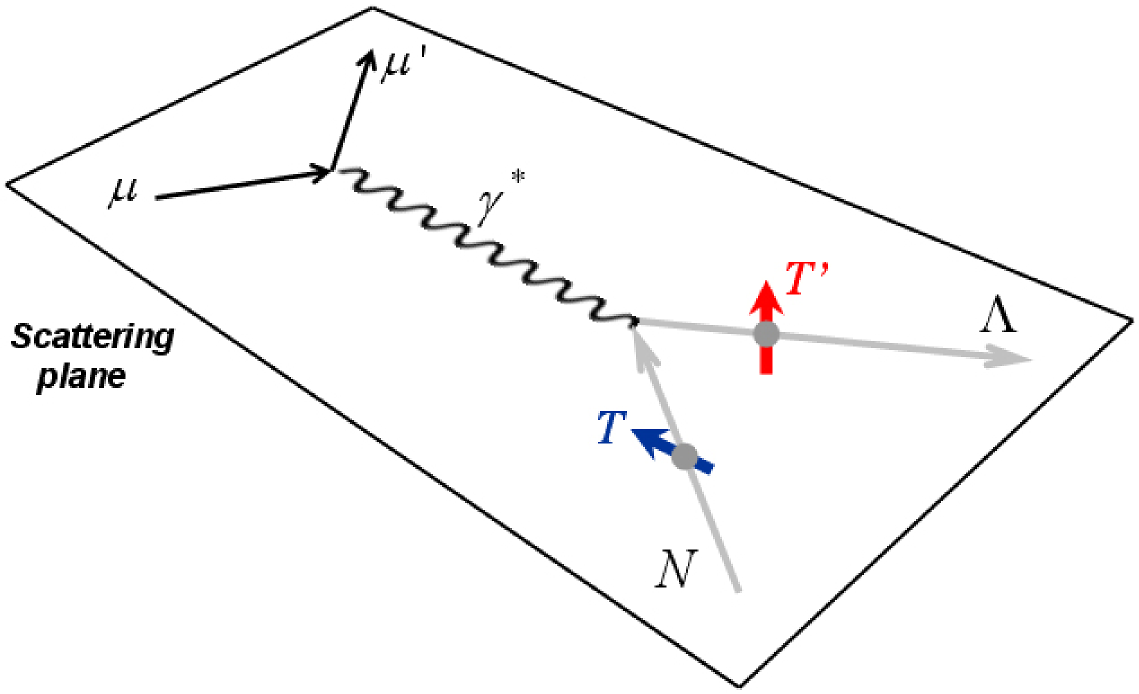
unpolarized (H, D, He,..., Xe) as well as **transversely (H)** and longitudinally (H, D) polarized (pure) gas targets

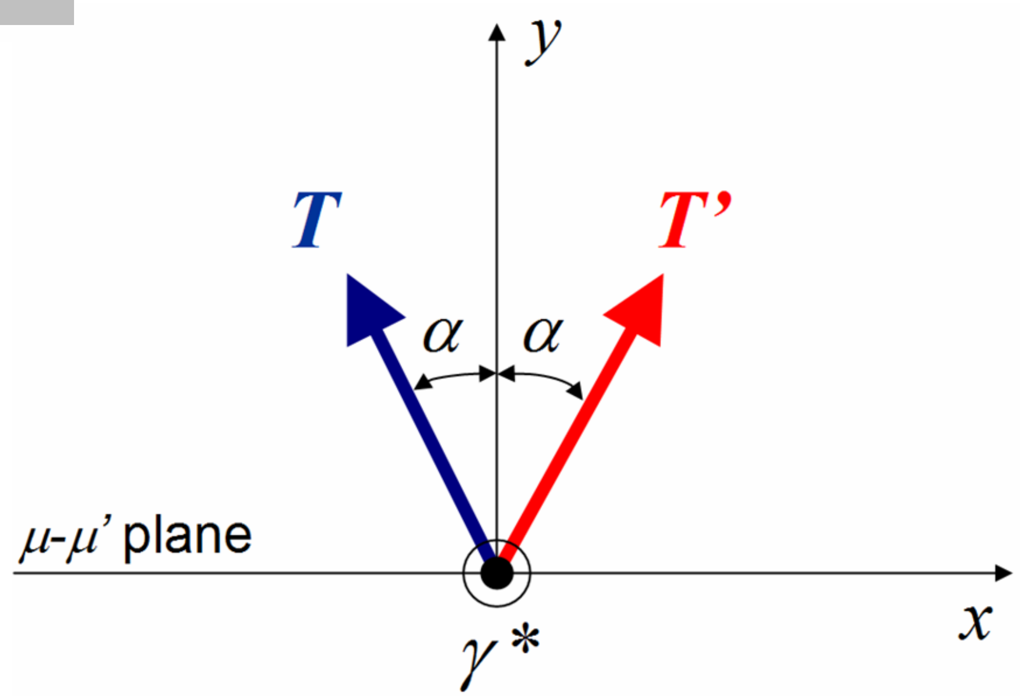
The quest for transversity

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

Transversity distribution (transverse-spin transfer)

Quantization axis for transverse Λ polarization





M. Anselmino & F. Murgia, Physics Letters B 483 (2000) 74-86

T (initial quak spin) : component of target spin perpendicular to γ*
T' (final quark spin) : symmetric of the ***T*** w.r.t. the normal to the scattering plane

Transversity distribution (transverse-spin transfer)

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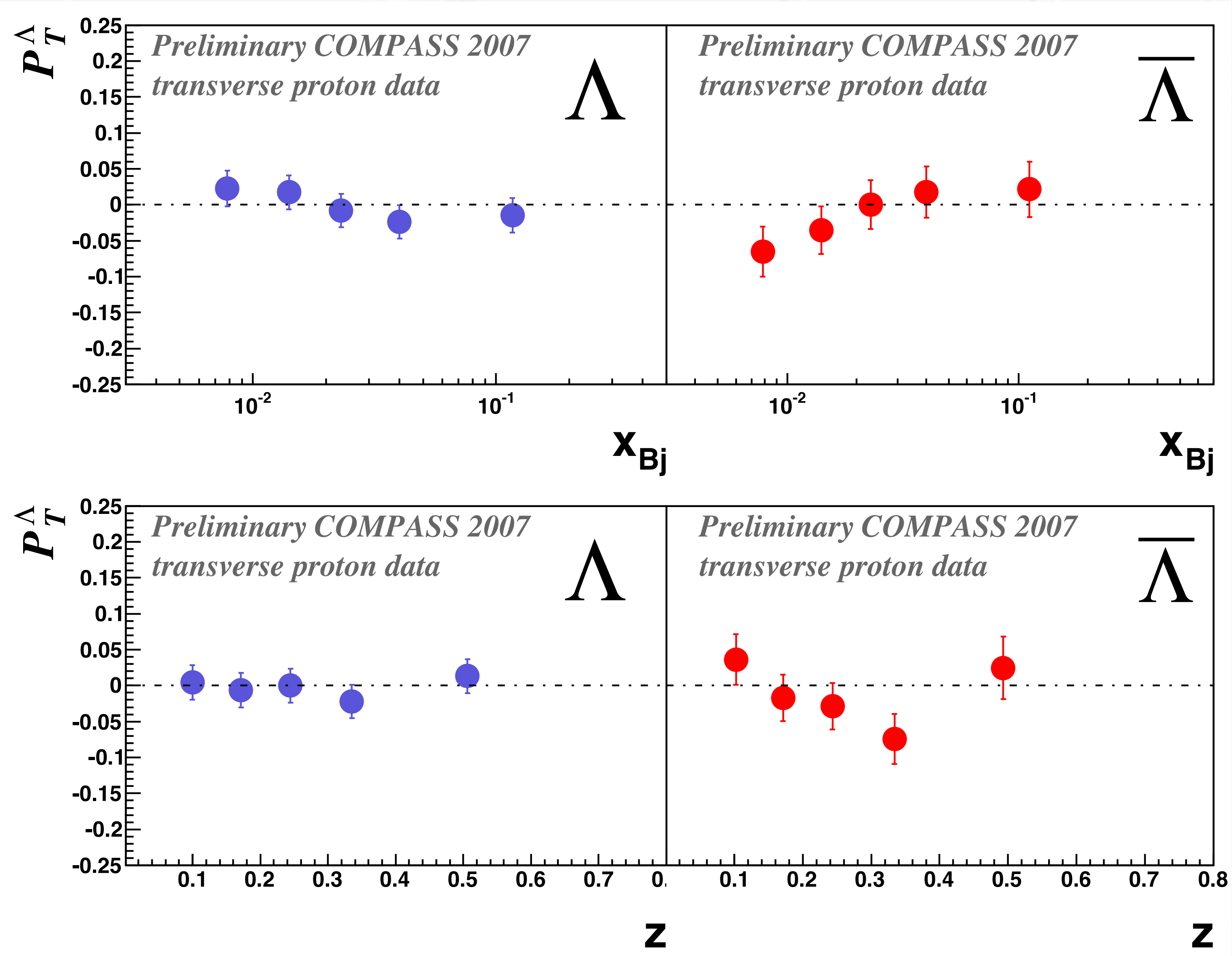

- compatible with zero
- low sensitivity to u & d quark polarization?
- measured at lower x where transversity is expected not to be large
- 2010 data will reduce statistical uncertainty by factor 2
- need to look at other hyperons?

Quark polarizations in hyperons

	Δu		Δd		Δs	
p	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05
n	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05
Σ^+	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^0	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Λ	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma + 2D)$	0.58 ± 0.04
Ξ^0	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04
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Quark polarizations in hyperons

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- better sensitivity to u and d quarks via charged Sigma's
- large analyzing power of the parity-violating decay $\Sigma^+ \to p\pi^0$
  - good probe of u-quark polarization

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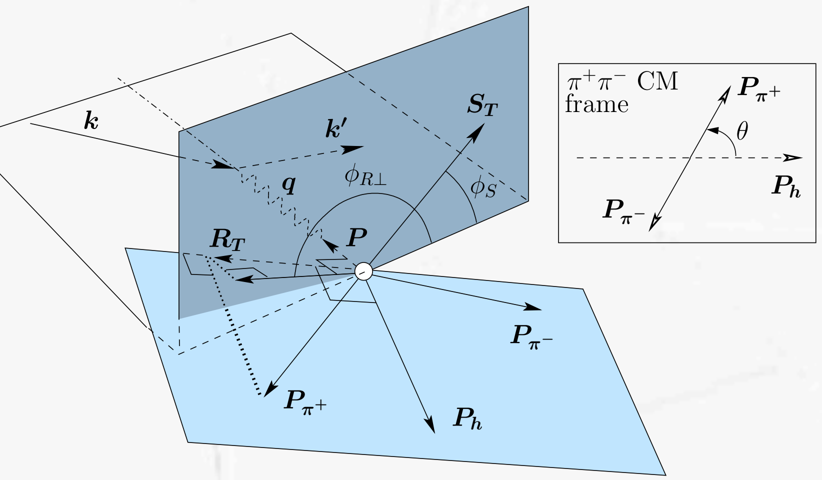
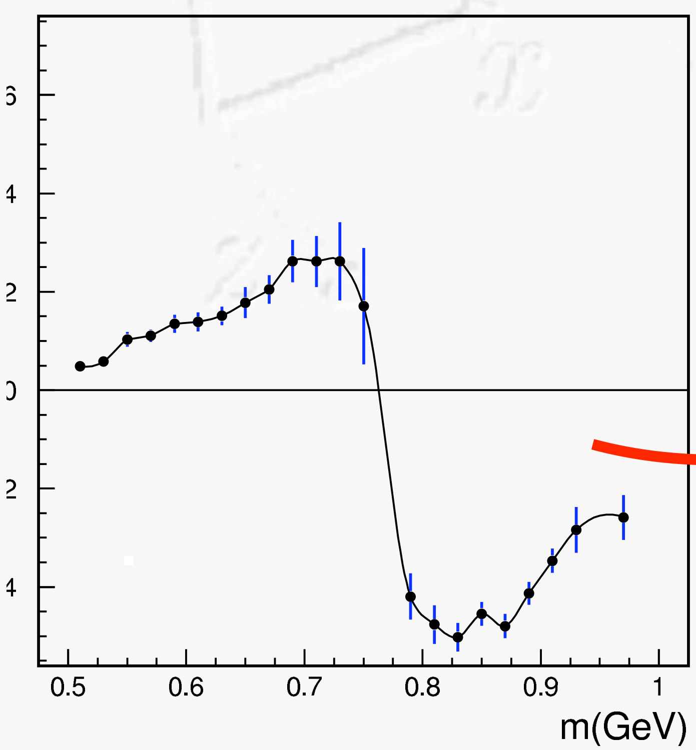
Transversity distribution (2-hadron fragmentation)



$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$



Jaffe et al. [**hep-ph/9709322**]:

$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) H_1^{\sphericalangle,sp'}(z)$$

δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

$$= \mathcal{P}(M_{\pi\pi}^2) H_1^{\sphericalangle,sp'}(z)$$

$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

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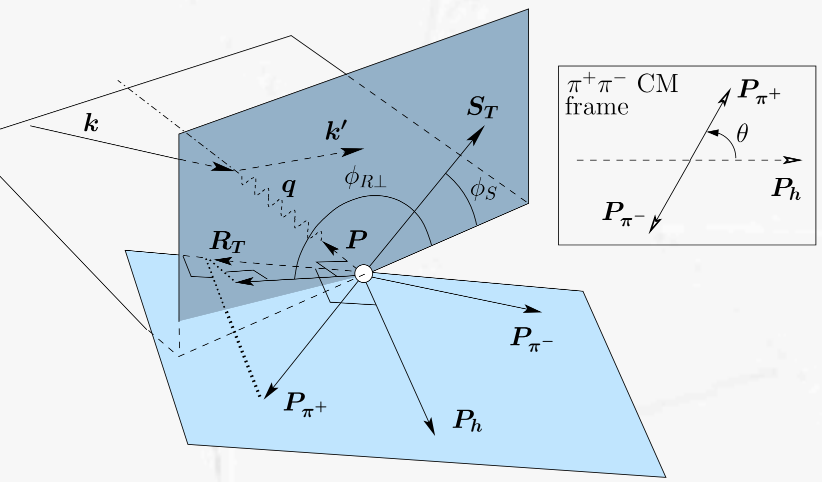
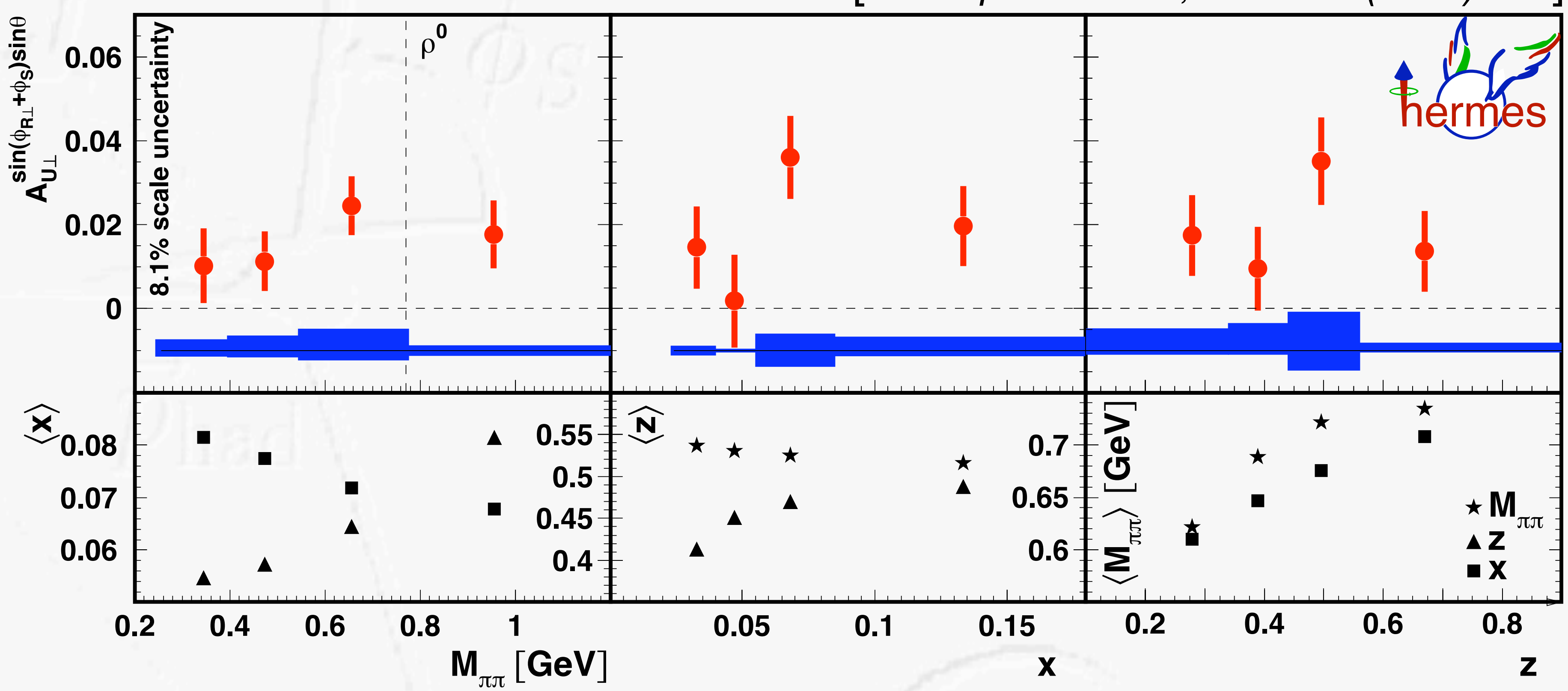
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)



[A. Airapetian et al., JHEP 06 (2008) 017]



☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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

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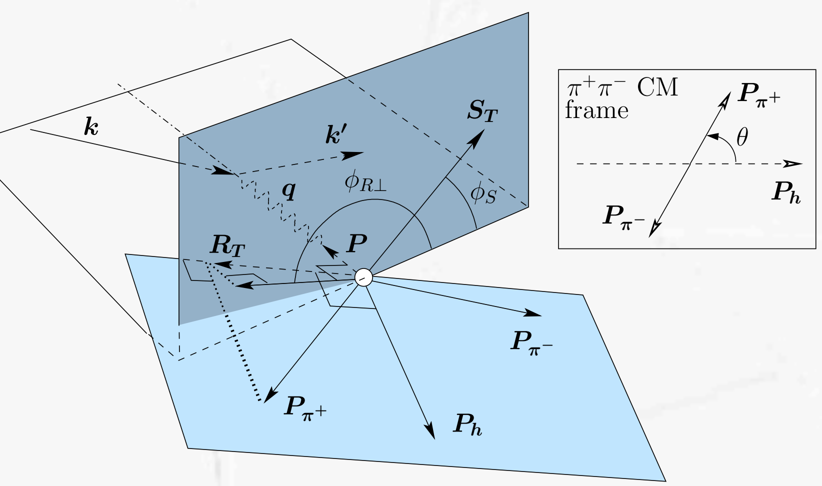

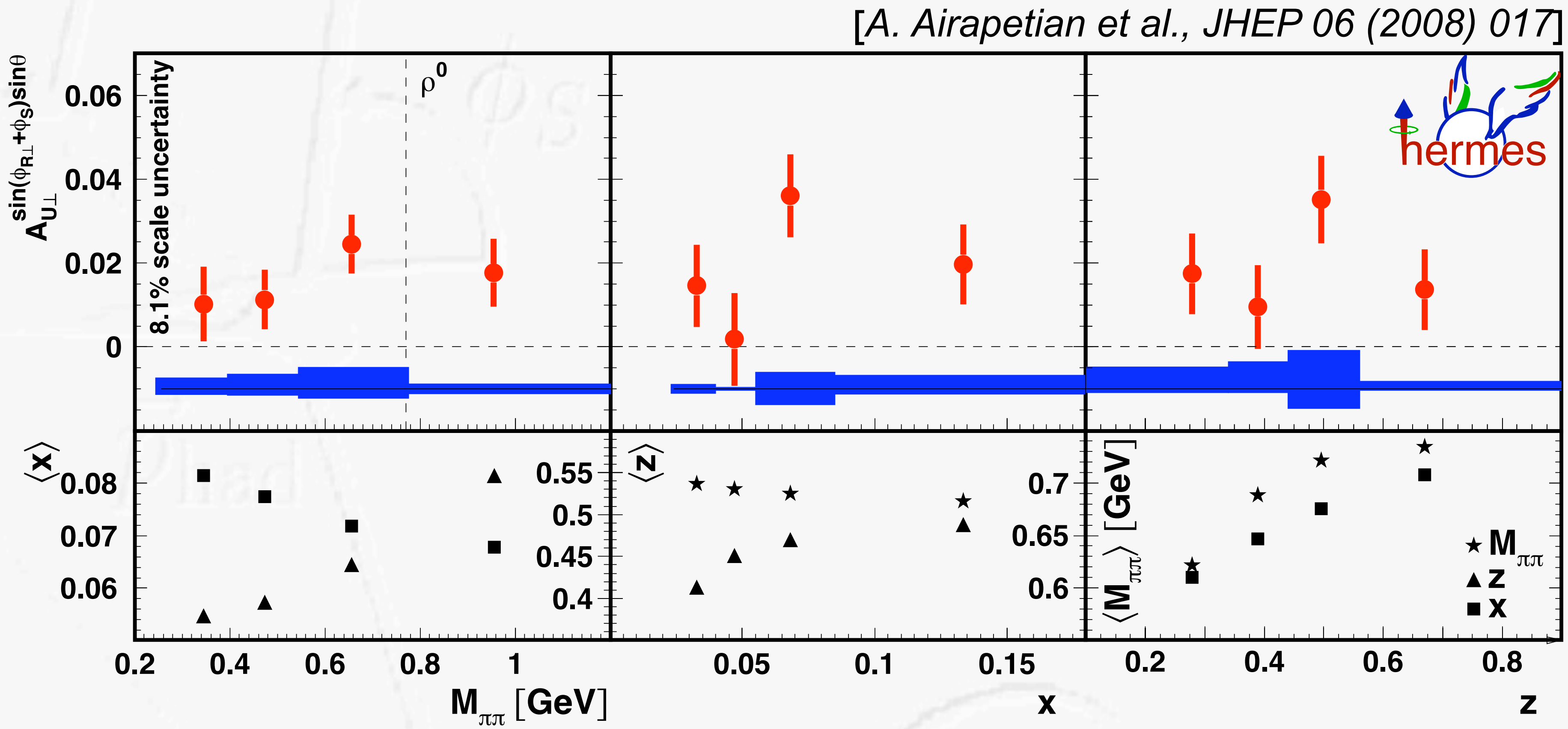

- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- ☑ invariant-mass dependence rules out Jaffe model predicting a sign change to rho mass

	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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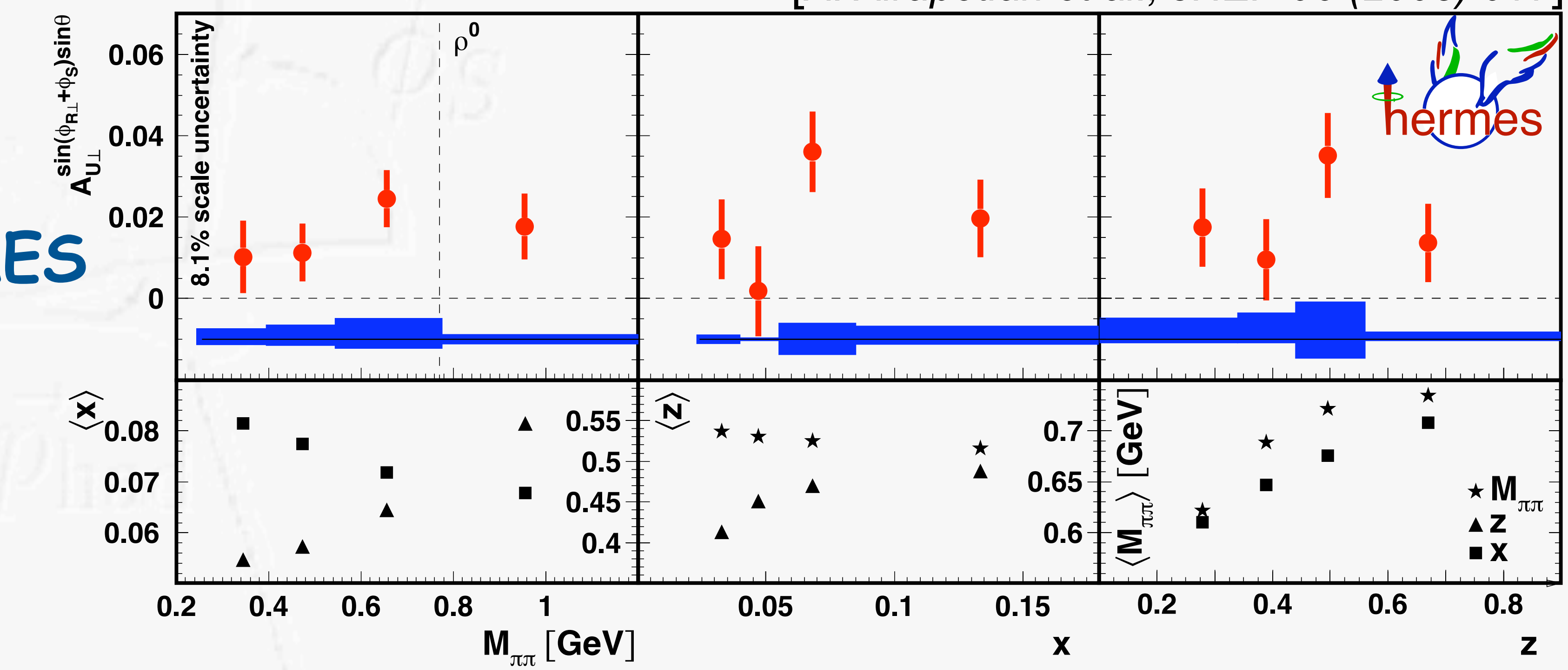
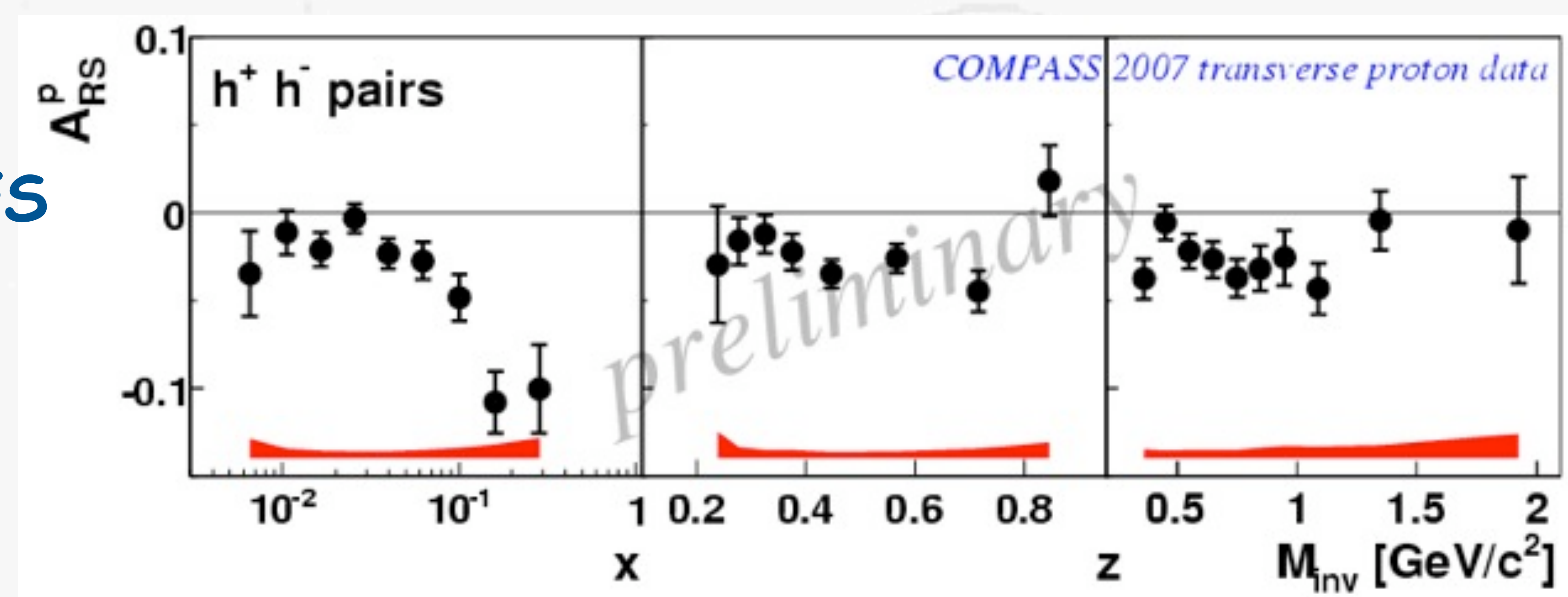


- non-zero amplitudes both from COMPASS and HERMES
- similar $M_{\pi\pi}$ dependence
- COMPASS: hadron pairs HERMES: pion pairs
- larger amplitudes at COMPASS than at HERMES
- first results from e^+e^- by BELLE



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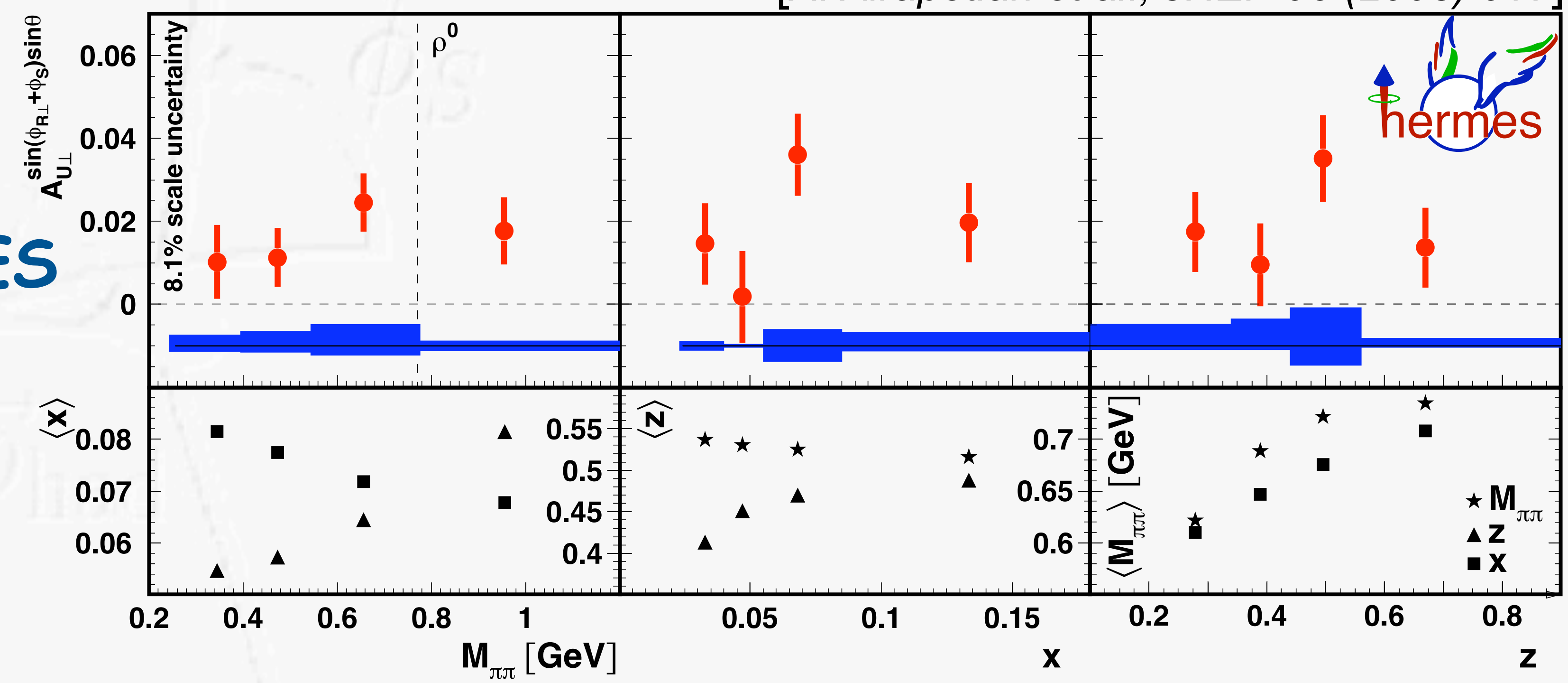

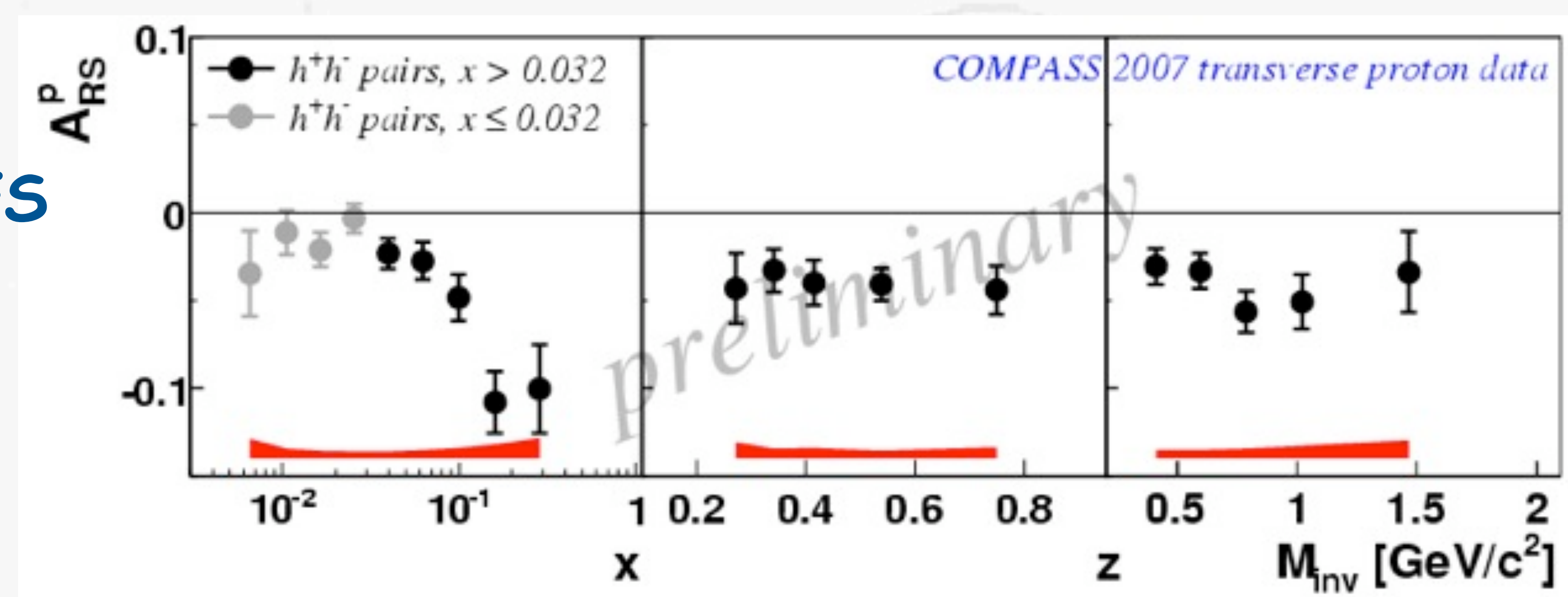

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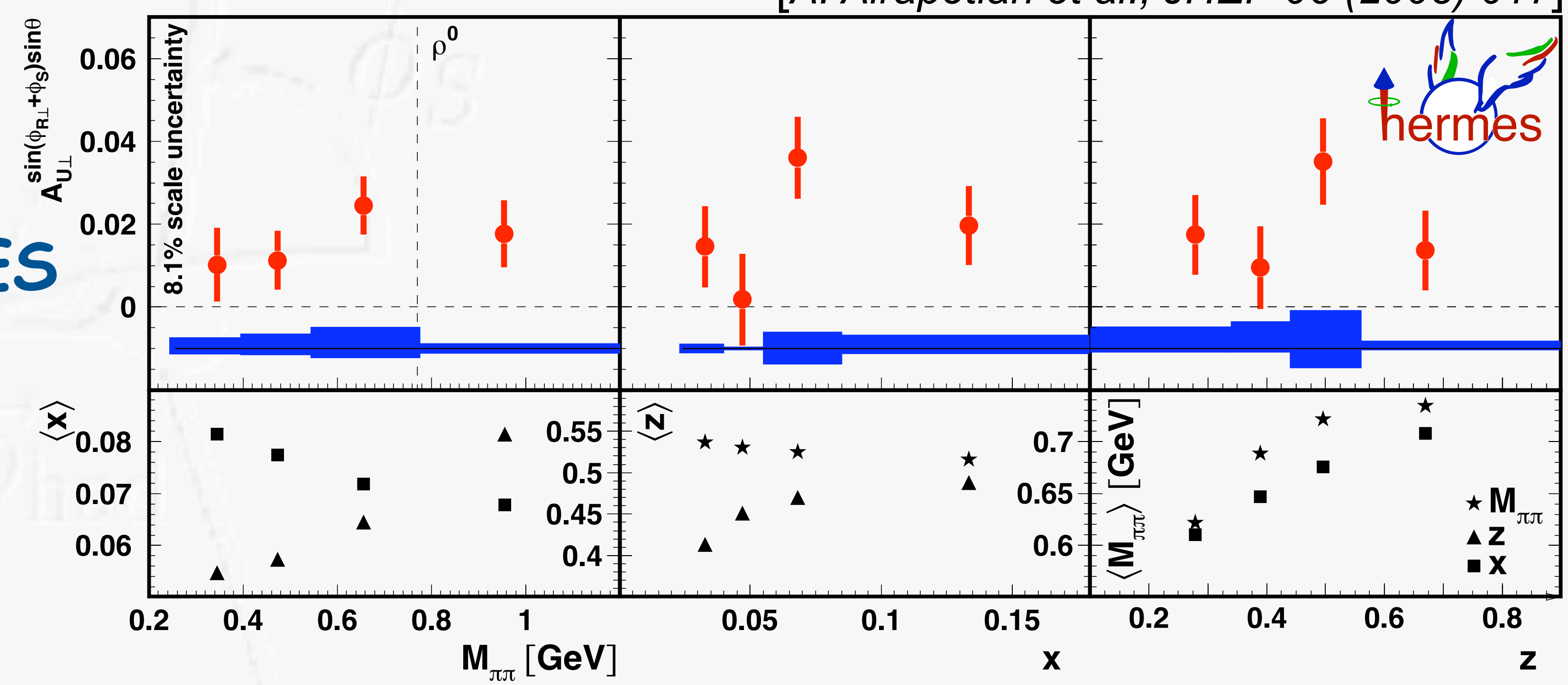

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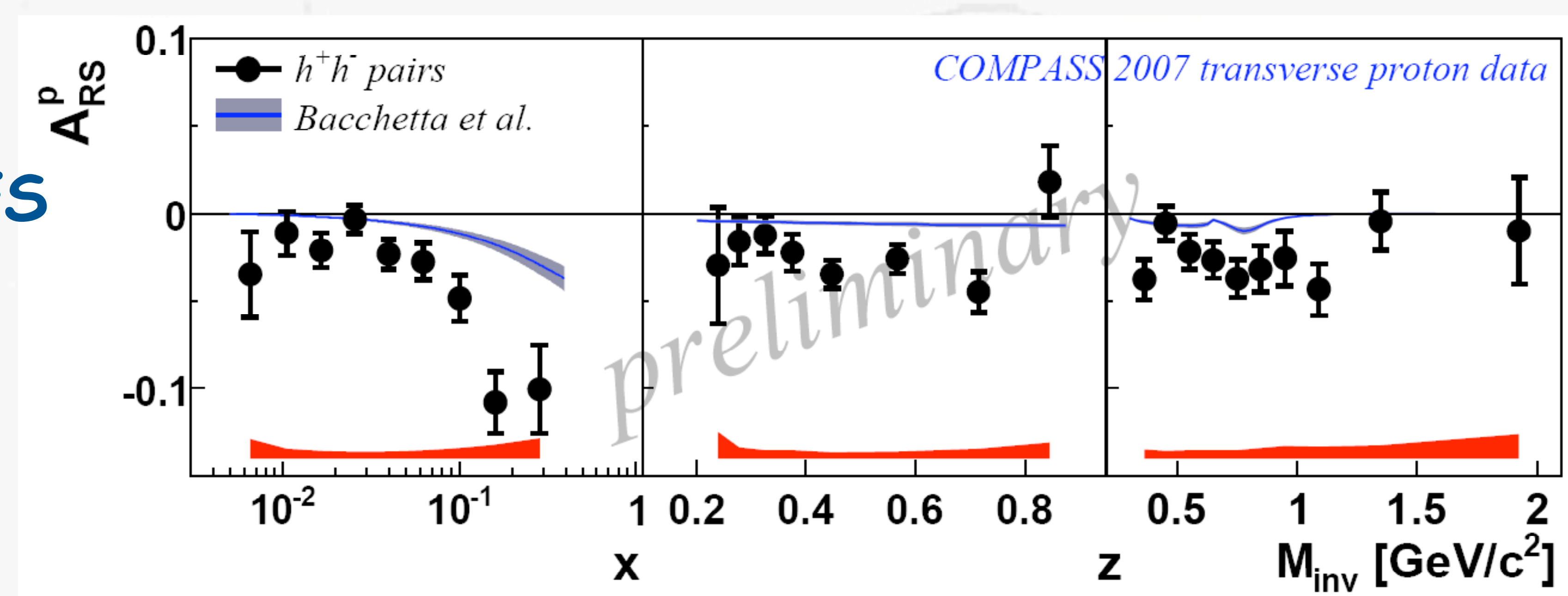

	U	L	T
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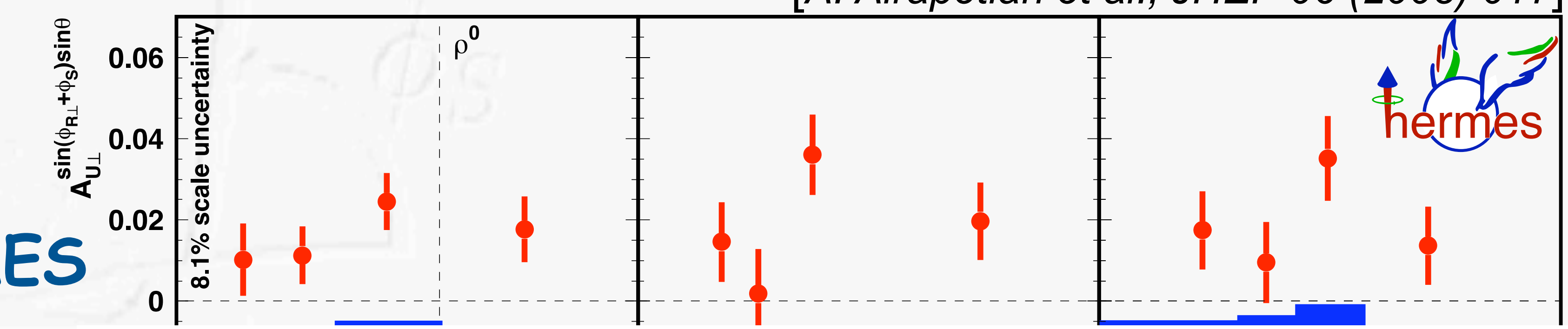
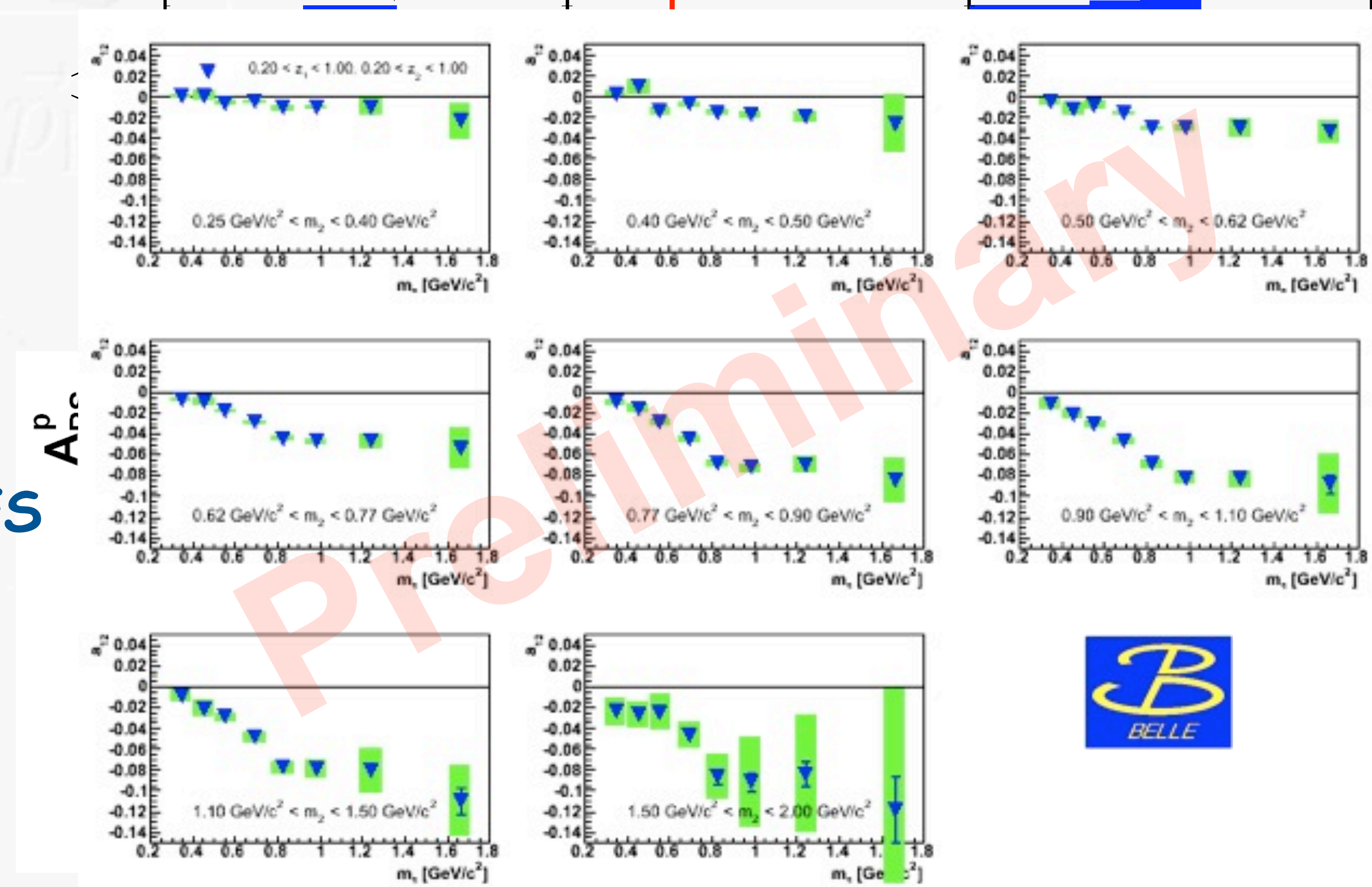
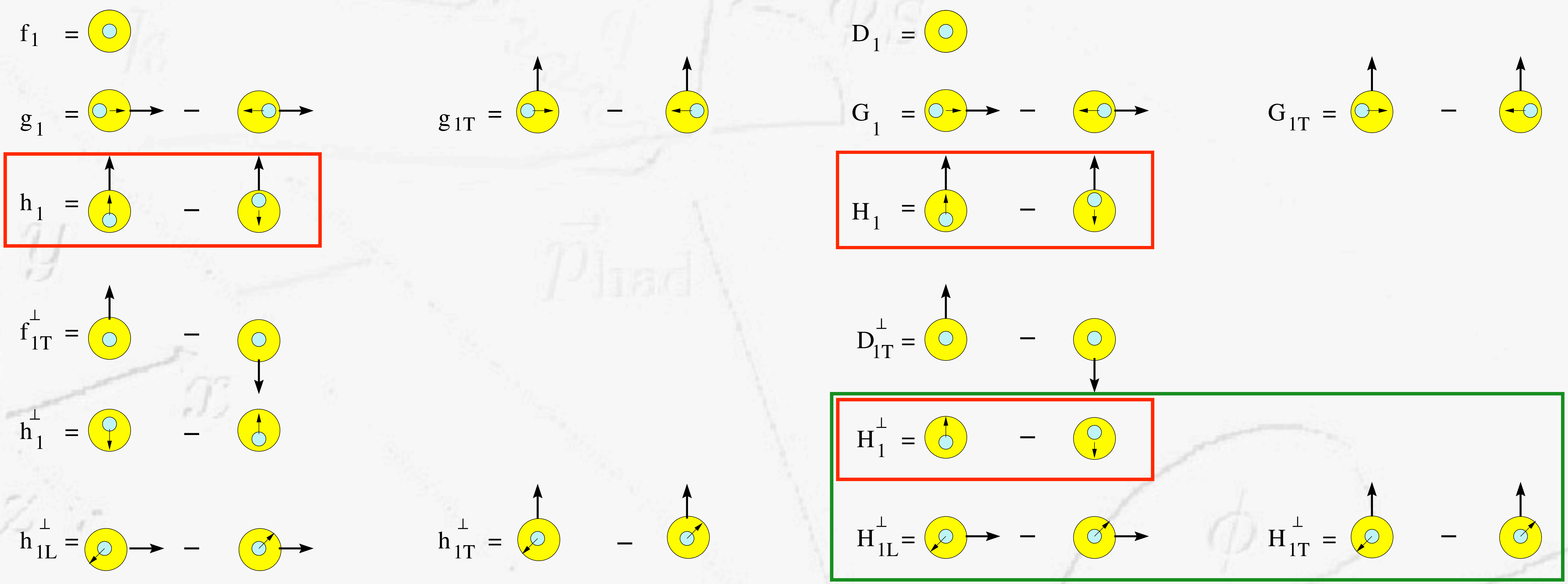




Ex.: Appearance of TMDs in SIDIS

Leading-Twist

Distribution Functions | Fragmentation Functions



Chiral-odd transversity h_1 must couple to chiral-odd FF

can use k_T-unintegrated chiral-odd FF ⇒ T-odd Collins FF

⇒ leads to Single-Spin Asymmetrie (SSA)

Ex.: Appearance of TMDs in SIDIS

$$d\sigma = d\sigma^{0}_{UU} + \cos 2\phi \, d\sigma^{1}_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^{3}_{LU}$$

$$+S_L \left\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^{7}_{LL} \right] \right\}$$

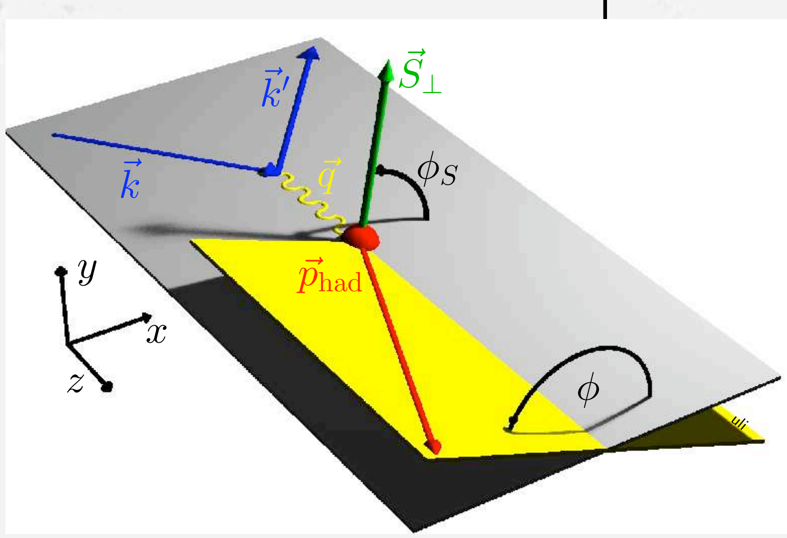
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

$$+ \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right)$$

$$\left. +\lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}$$

σ_{XY}: X → **Beam**, Y → **Target**

Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

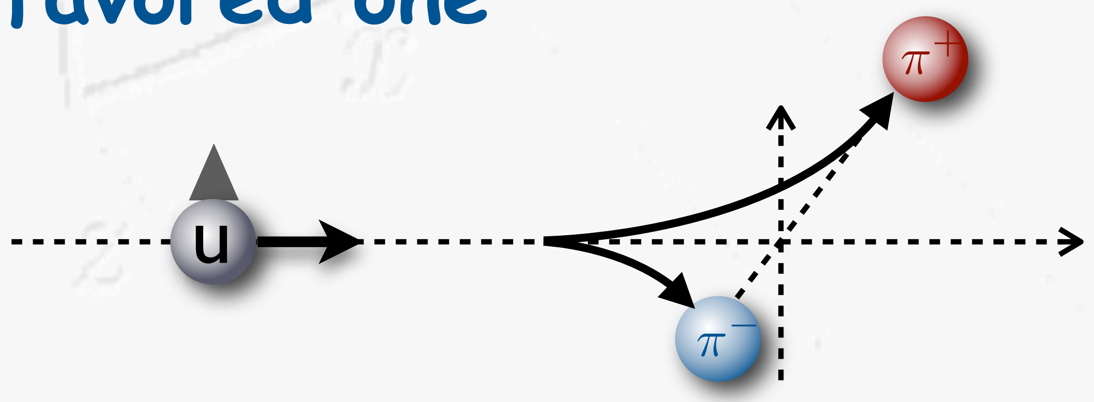
Bacchetta et al., JHEP 0702 (2007) 093

“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

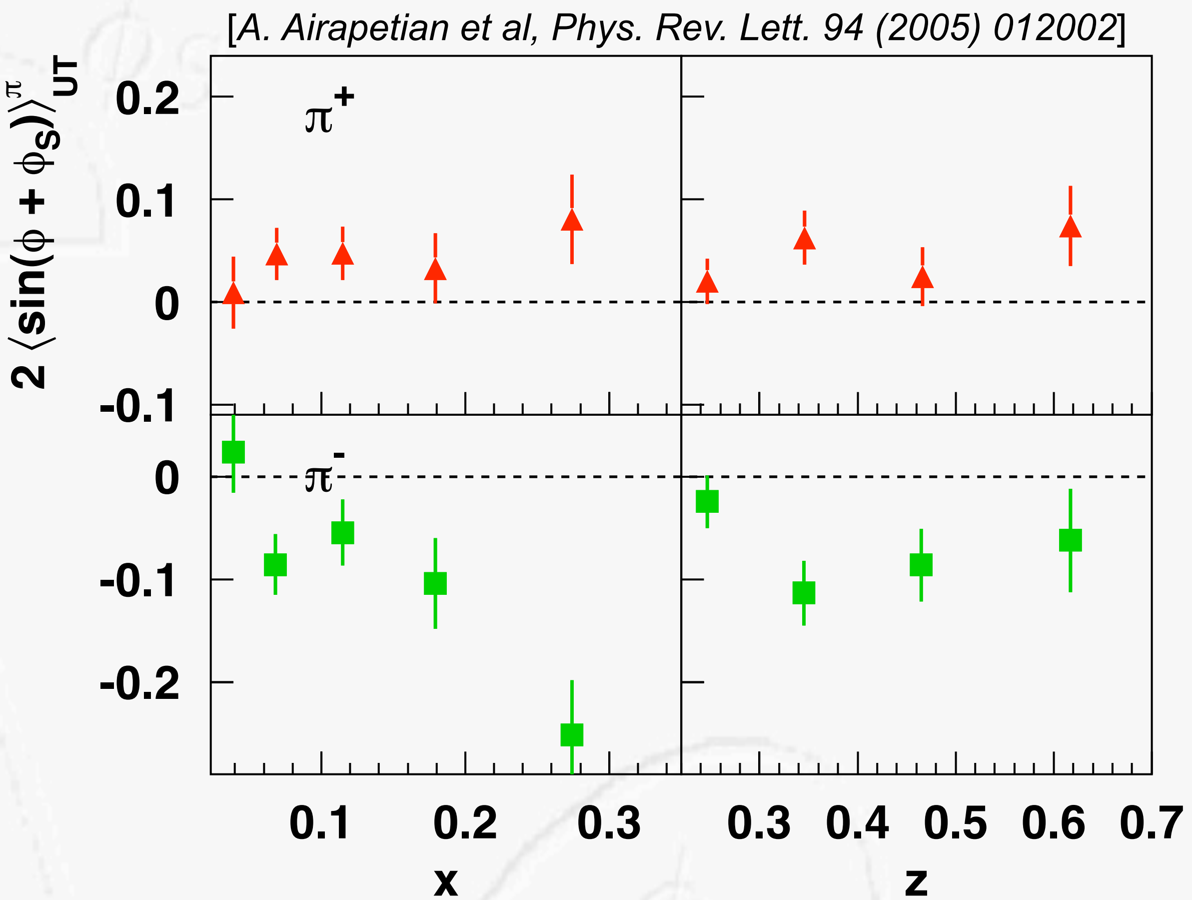
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (Collins fragmentation)

- significant in size and opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one



- leads to various cancellations in SSA observables

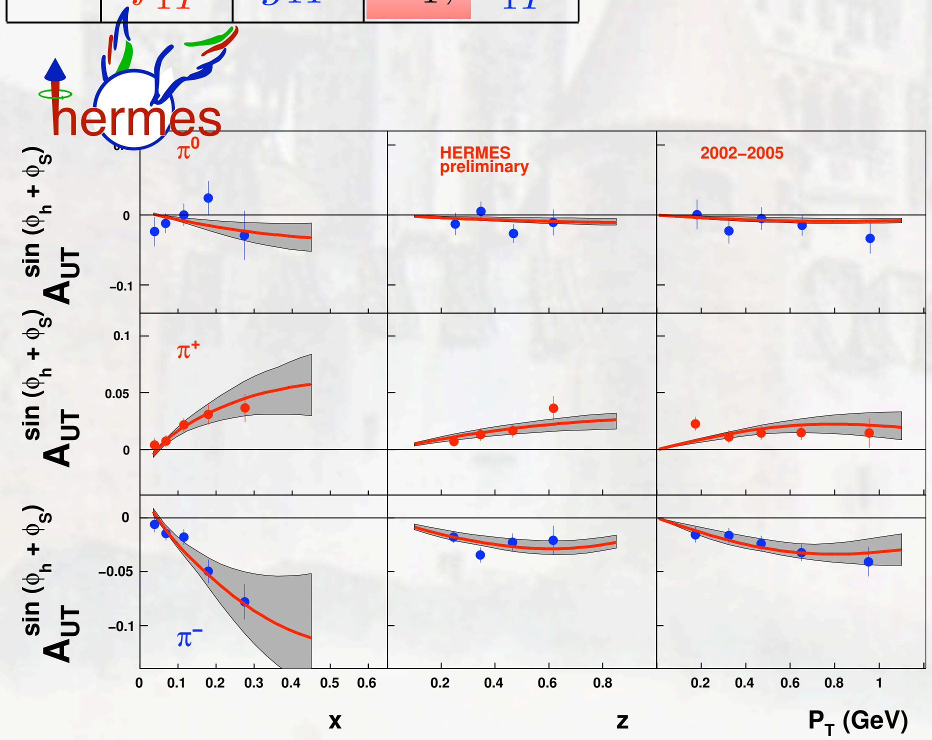


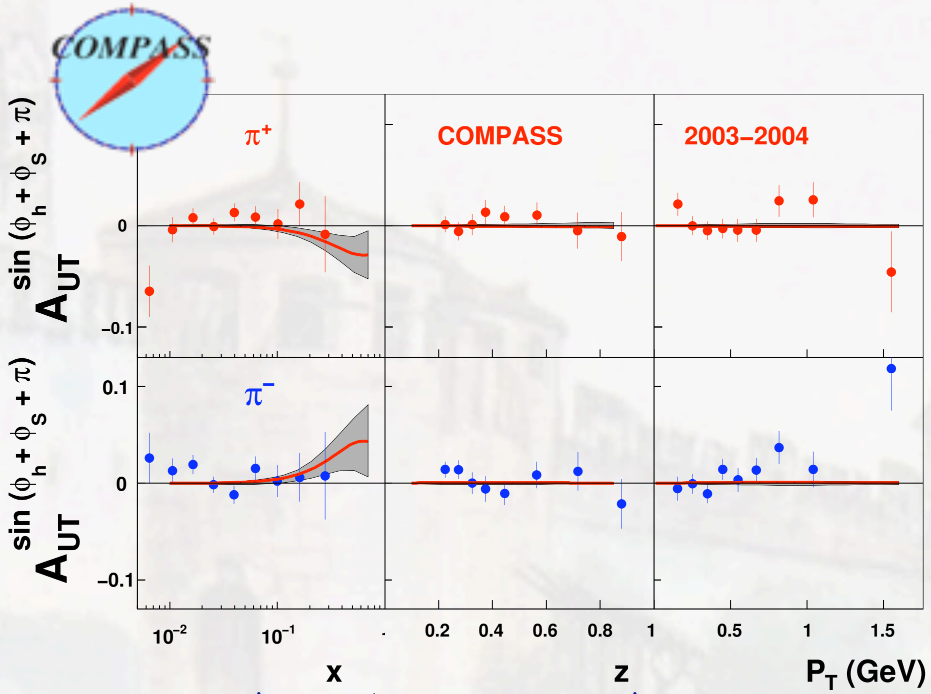
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

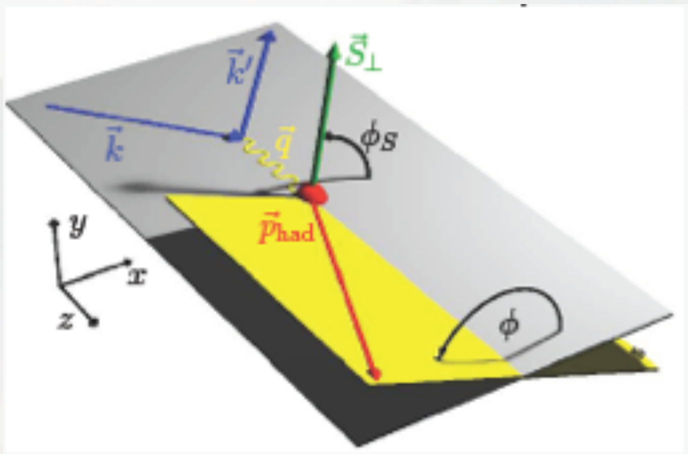
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Fit of Collins amplitudes





$$e^{\pm}p^{\uparrow} \rightarrow e^{\pm}\pi X \qquad \mu^{\pm}d^{\uparrow} \rightarrow \mu^{\pm}\pi X$$



Fit of Collins amplitudes

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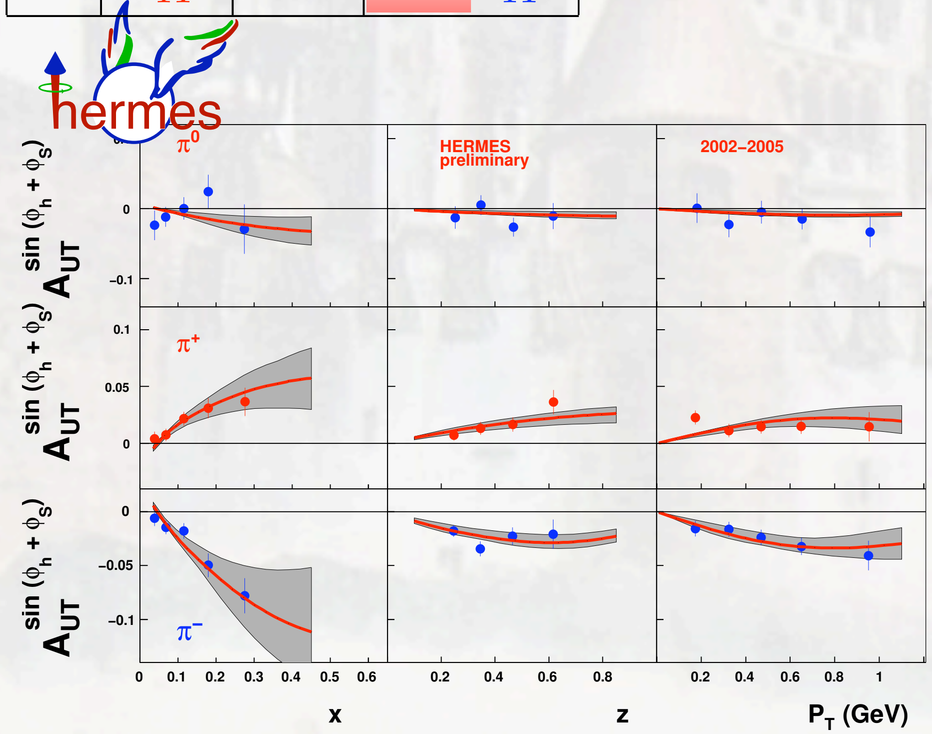
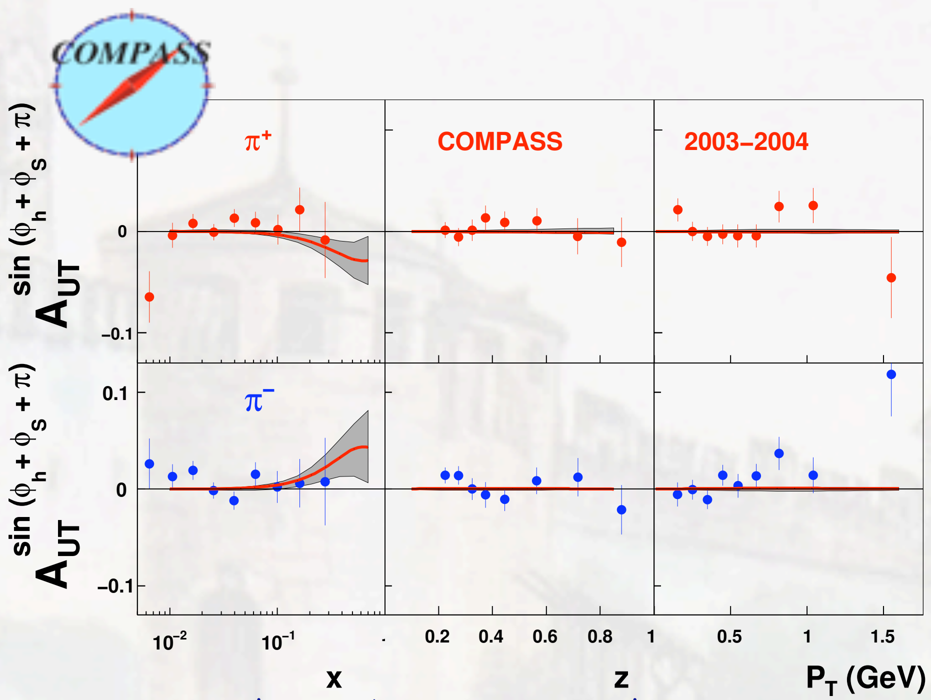


$$e^\pm p^\uparrow \to e^\pm \pi X$$



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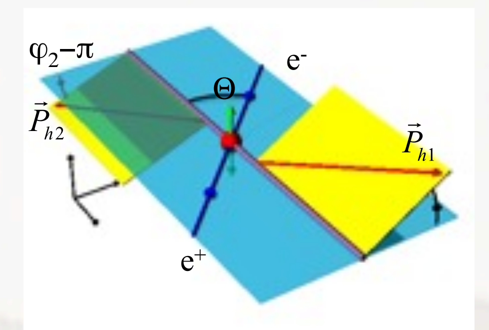
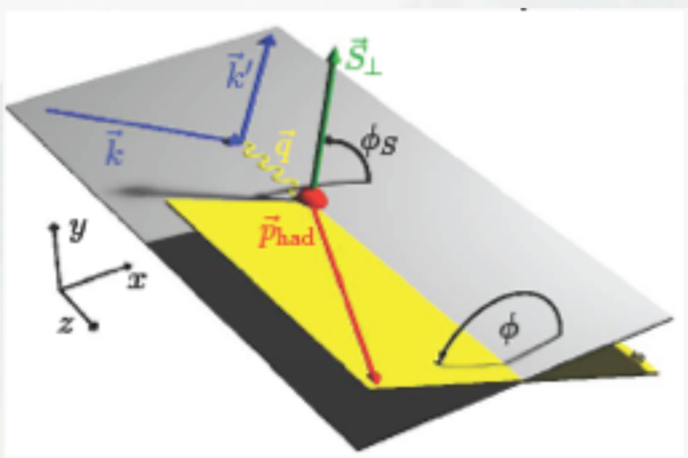
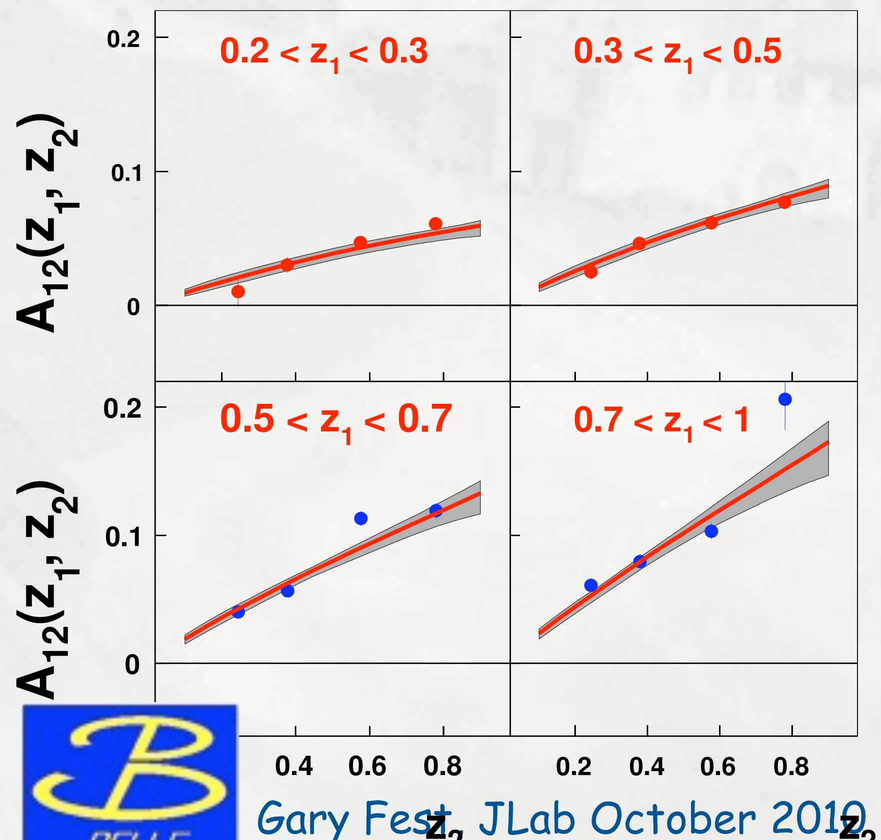


$$e^+e^- \to \pi\pi X$$





Fit of Collins amplitudes

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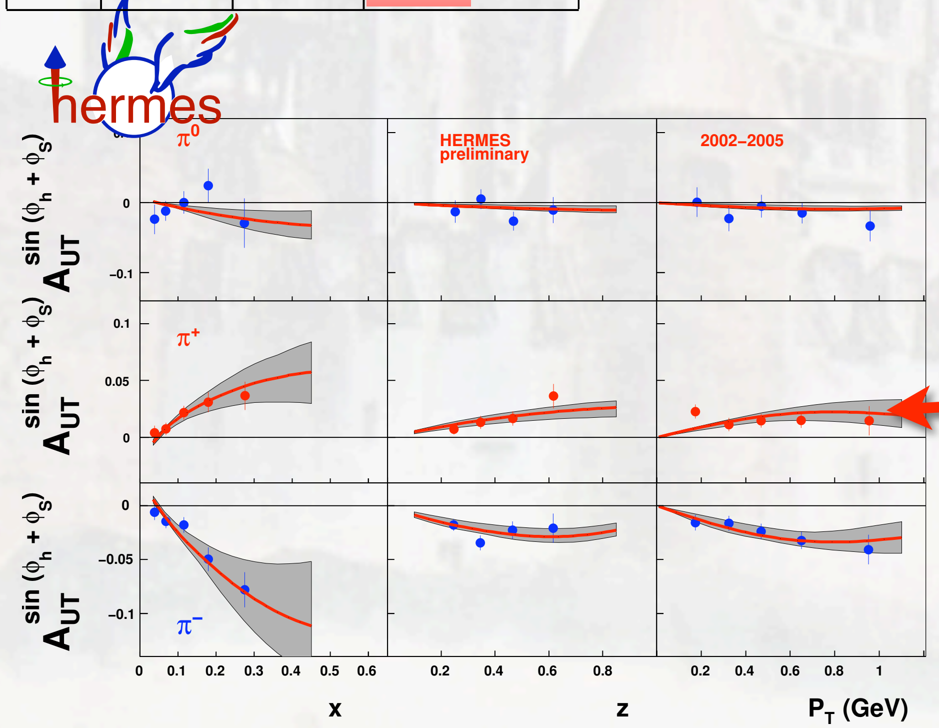
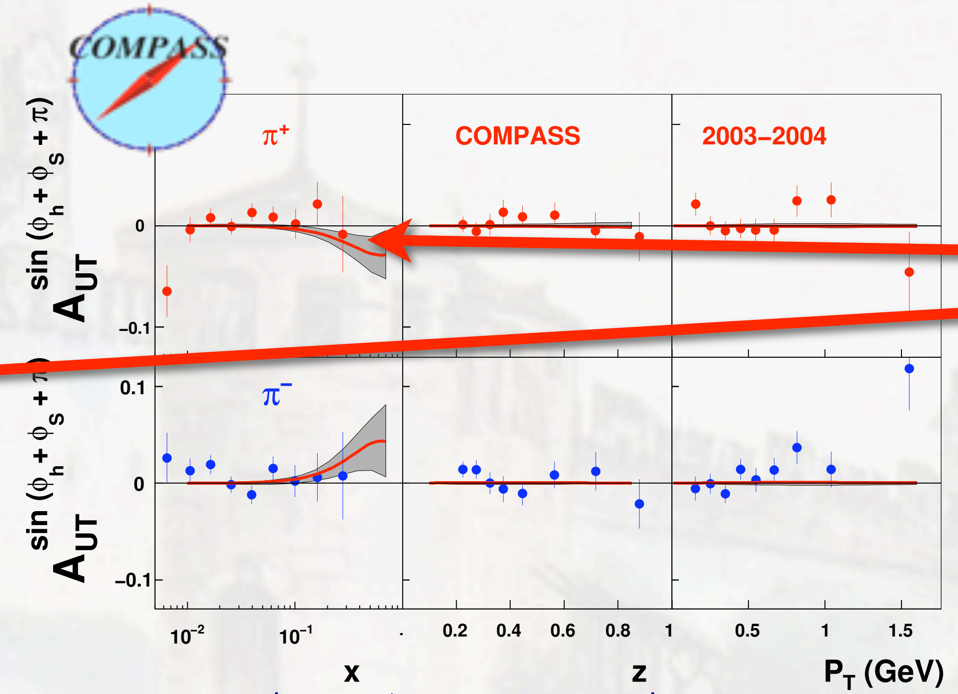
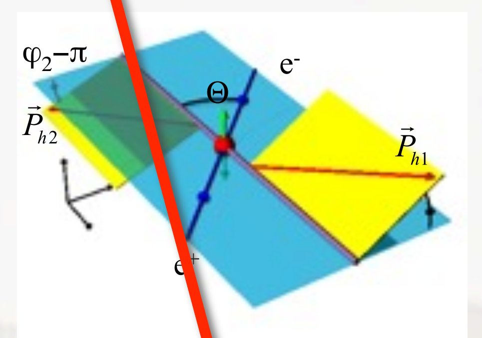




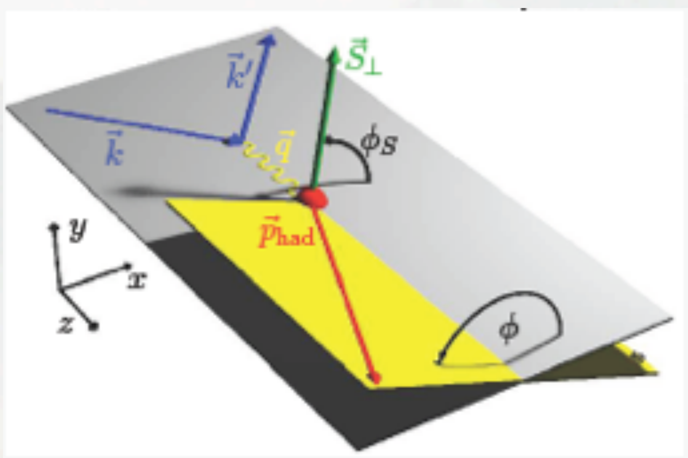
fit to data

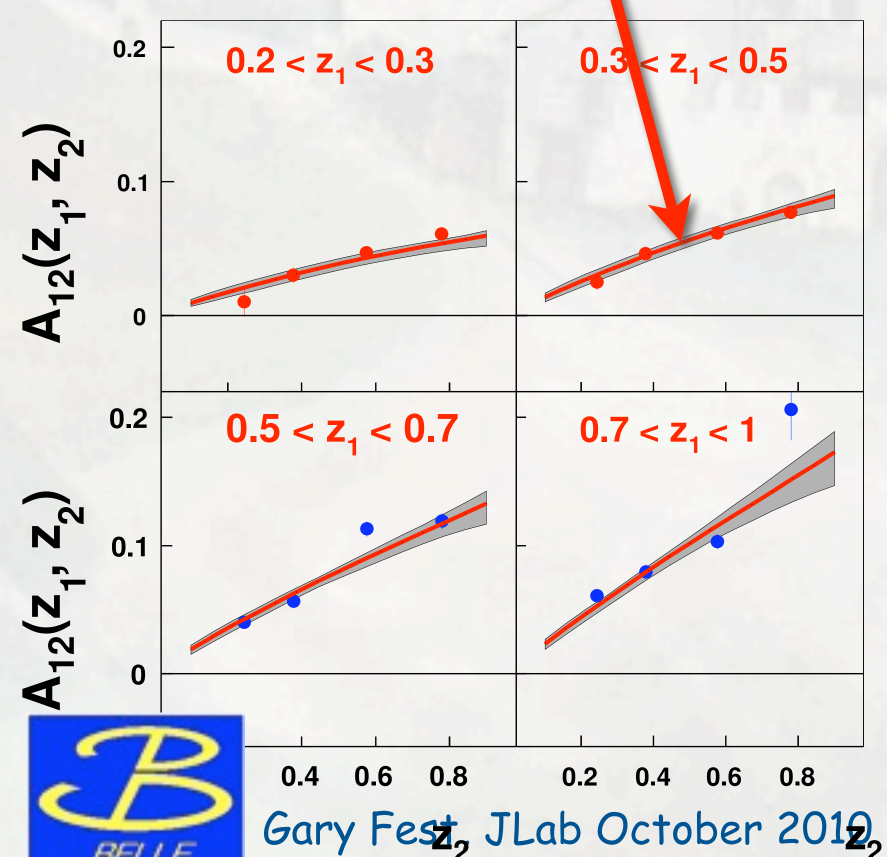


$$\mathbf{e^\pm p^\uparrow \to e^\pm \pi X}$$

$$\mathbf{\mu^\pm d^\uparrow \to \mu^\pm \pi X}$$

$$\mathbf{e^+ e^- \to \pi\pi X}$$





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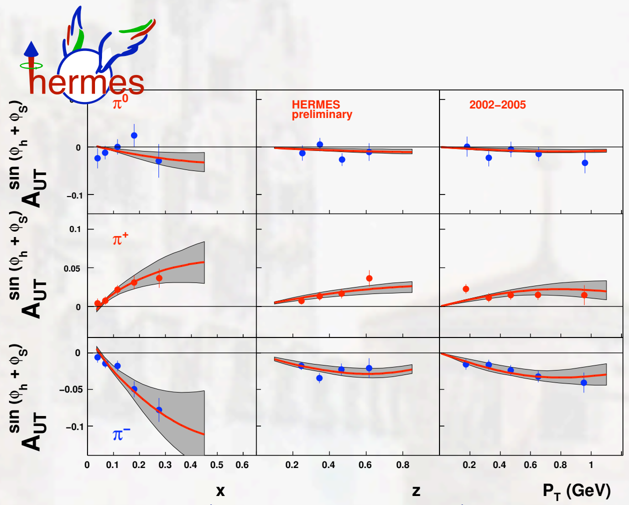
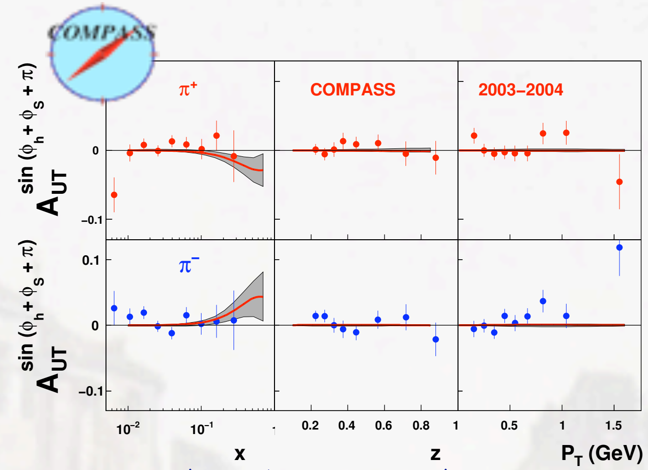
Fit of Collins amplitudes



$\mathbf{e^\pm p^\uparrow \rightarrow e^\pm \pi X}$



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fit to data

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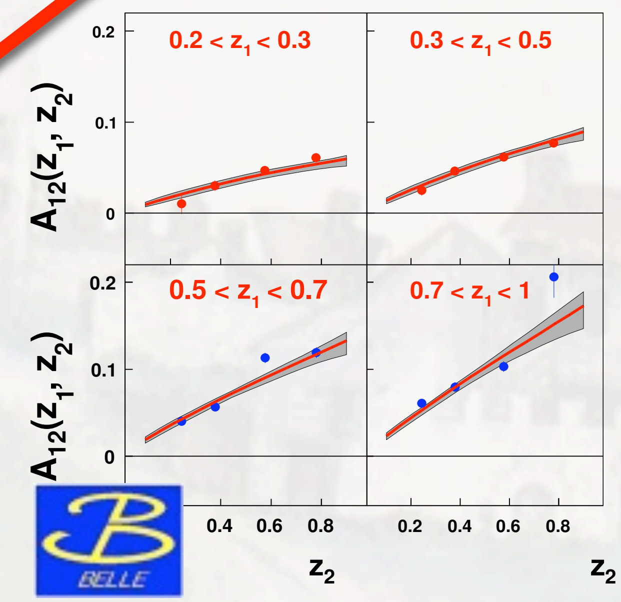
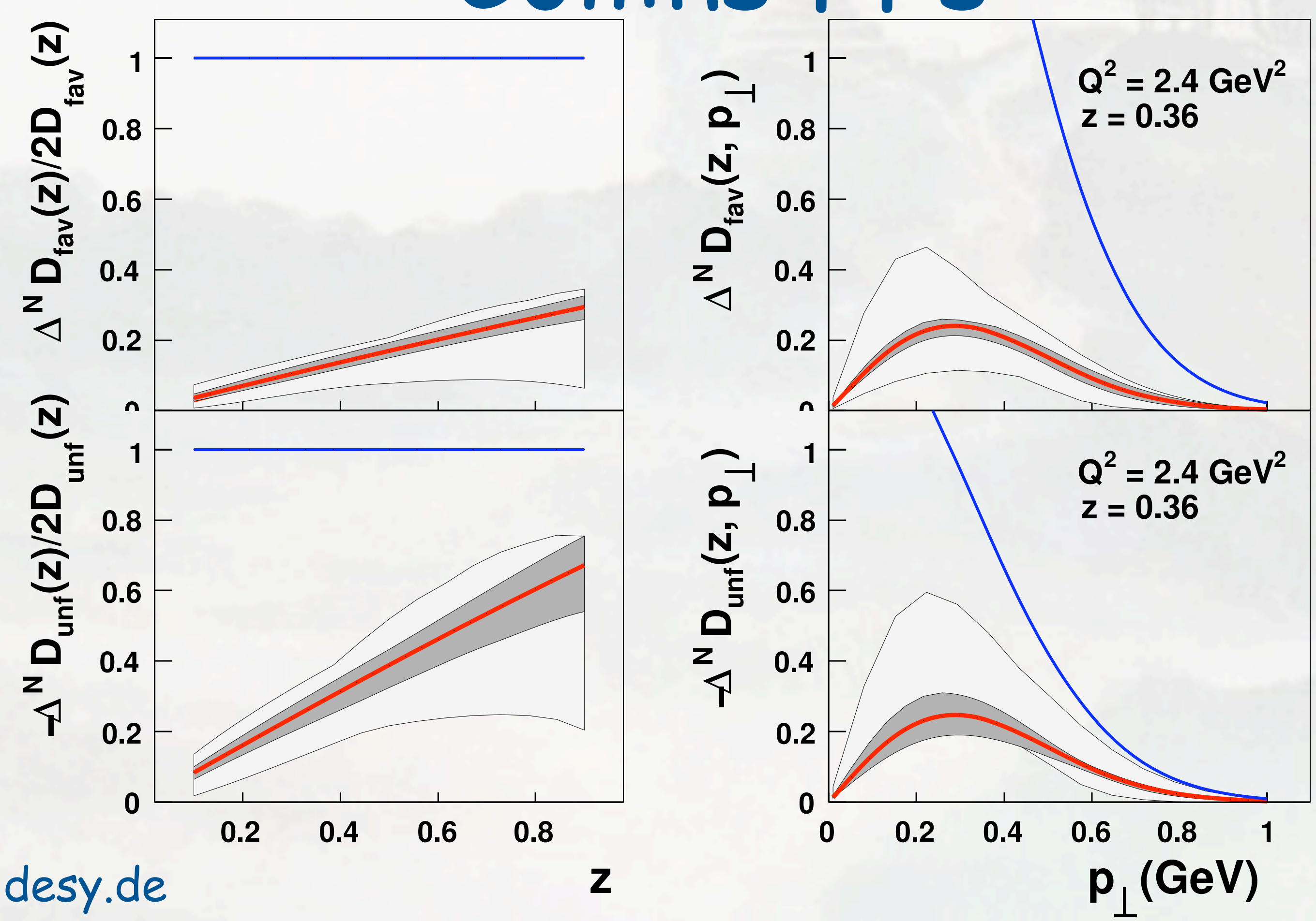


Collins FFs



[Anselmino et al., *Nucl.Phys.Proc.Suppl.191 (2009) 98*]

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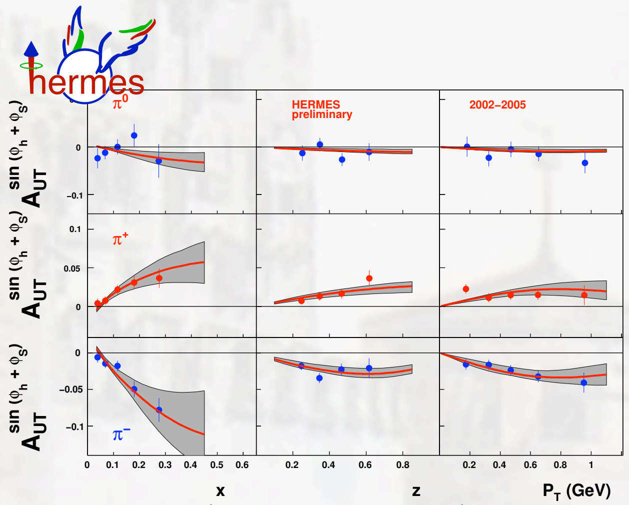

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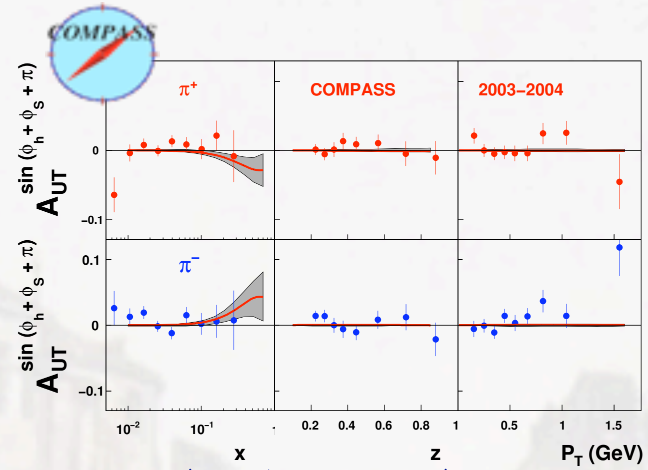

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fit to data

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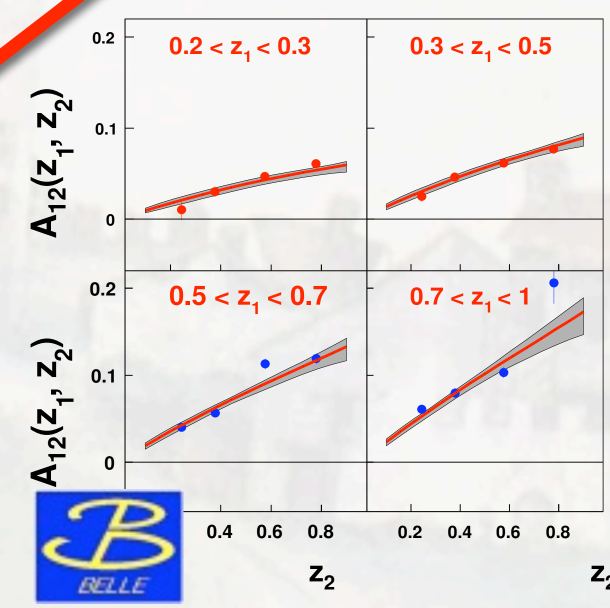
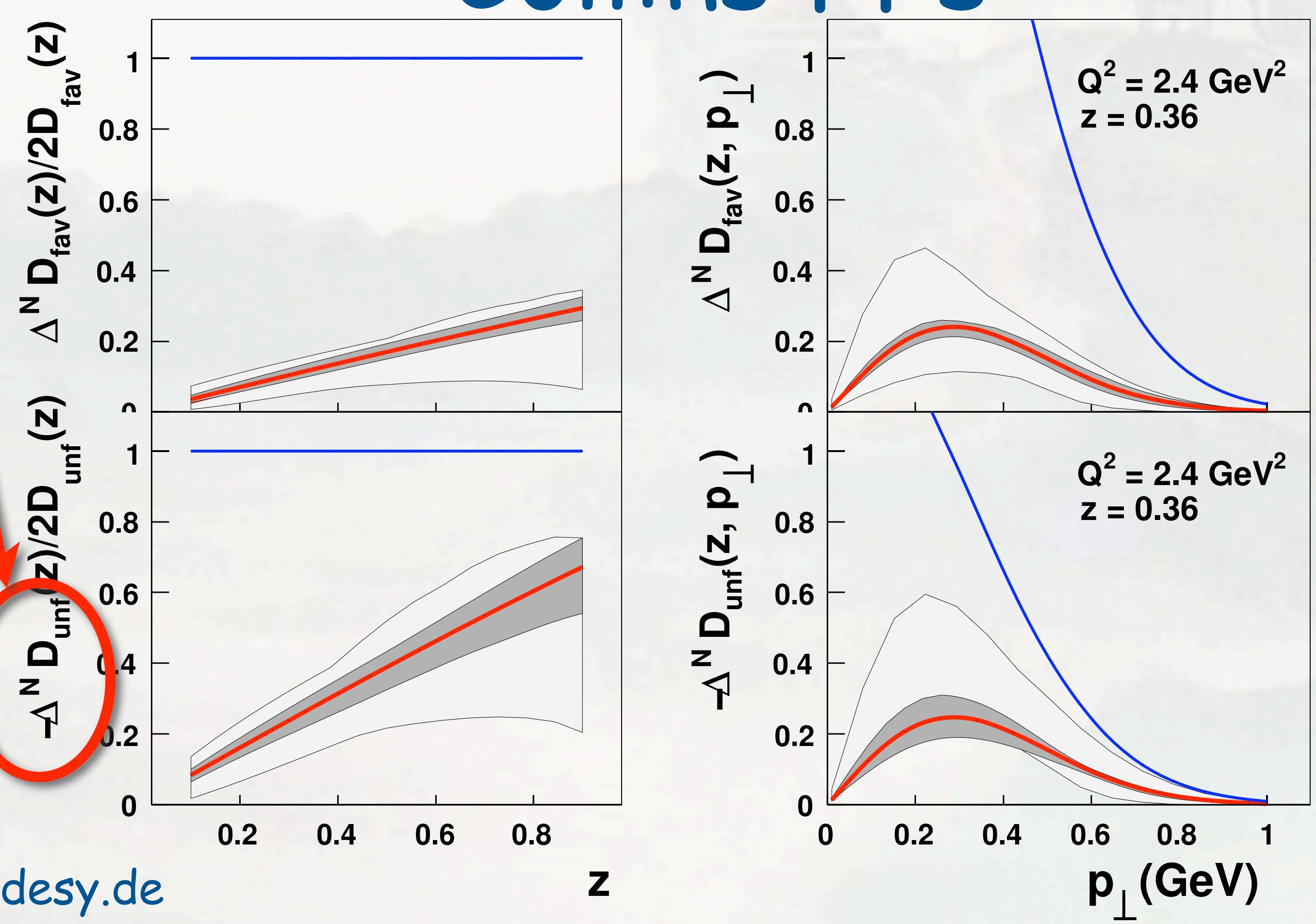


opposite sign

Collins FFs



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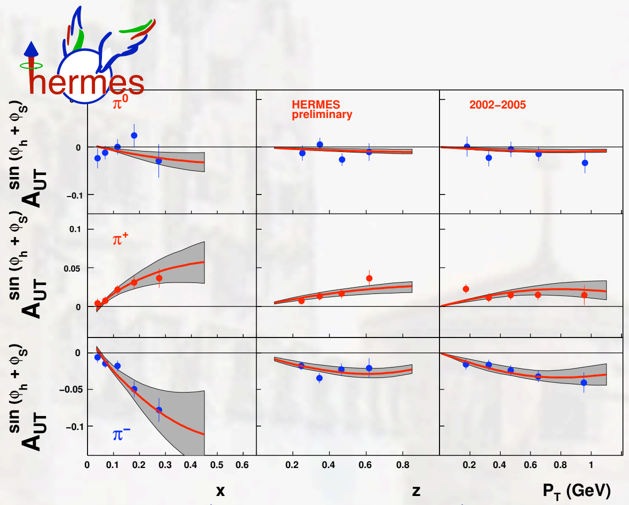

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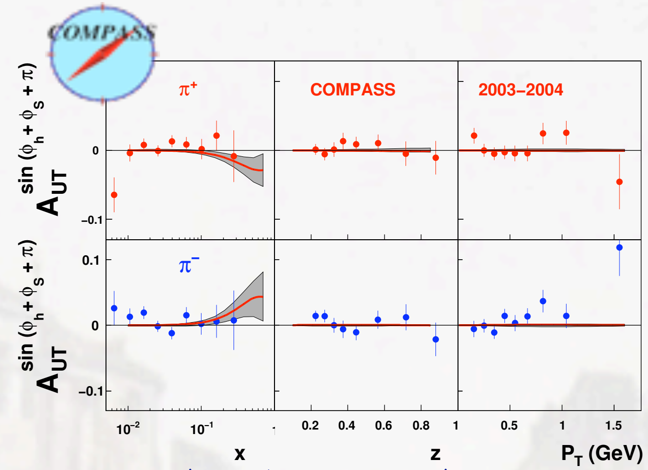
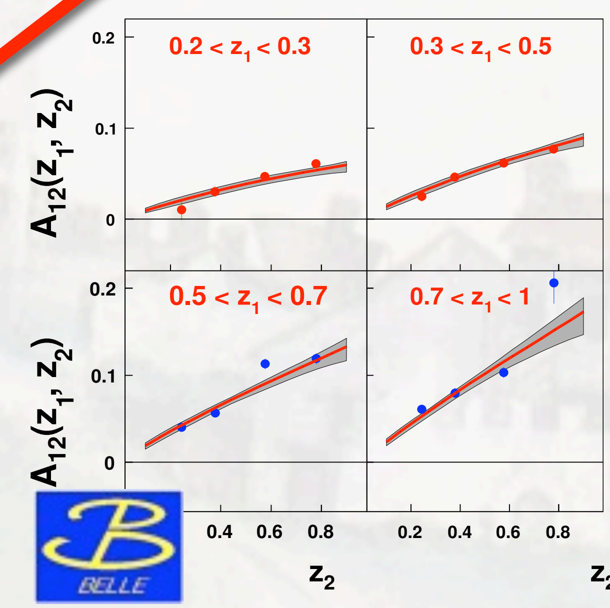


$\mu^\pm \mathbf{d}^\uparrow \to \mu^\pm \pi \mathbf{X}$

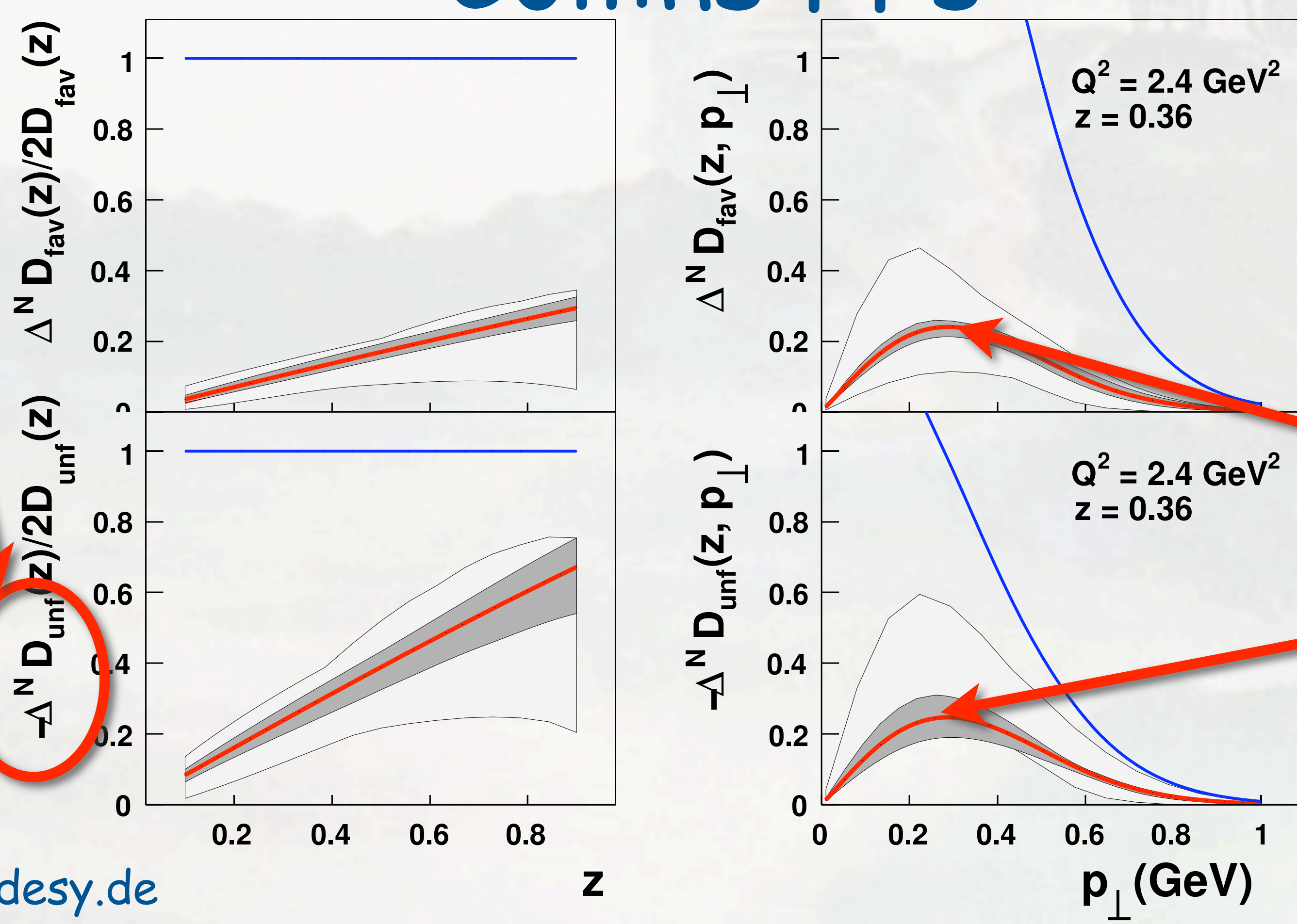
fit to data

$\mathbf{e^+e^- \to \pi\pi X}$



opposite sign

Collins FFs



similar magnitude

[Anselmino et al., *Nucl.Phys.Proc.Suppl.191 (2009) 98*]

Transversity: models and fits

	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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[1] Soffer et al. PRD 65 (02)
[2] Korotkov et al. EPJC 18 (01)
[3] Schweitzer et al., PRD 64 (01)
[4] Wakamatsu, PLB 509 (01)
[5] Pasquini et al., PRD 72 (05)
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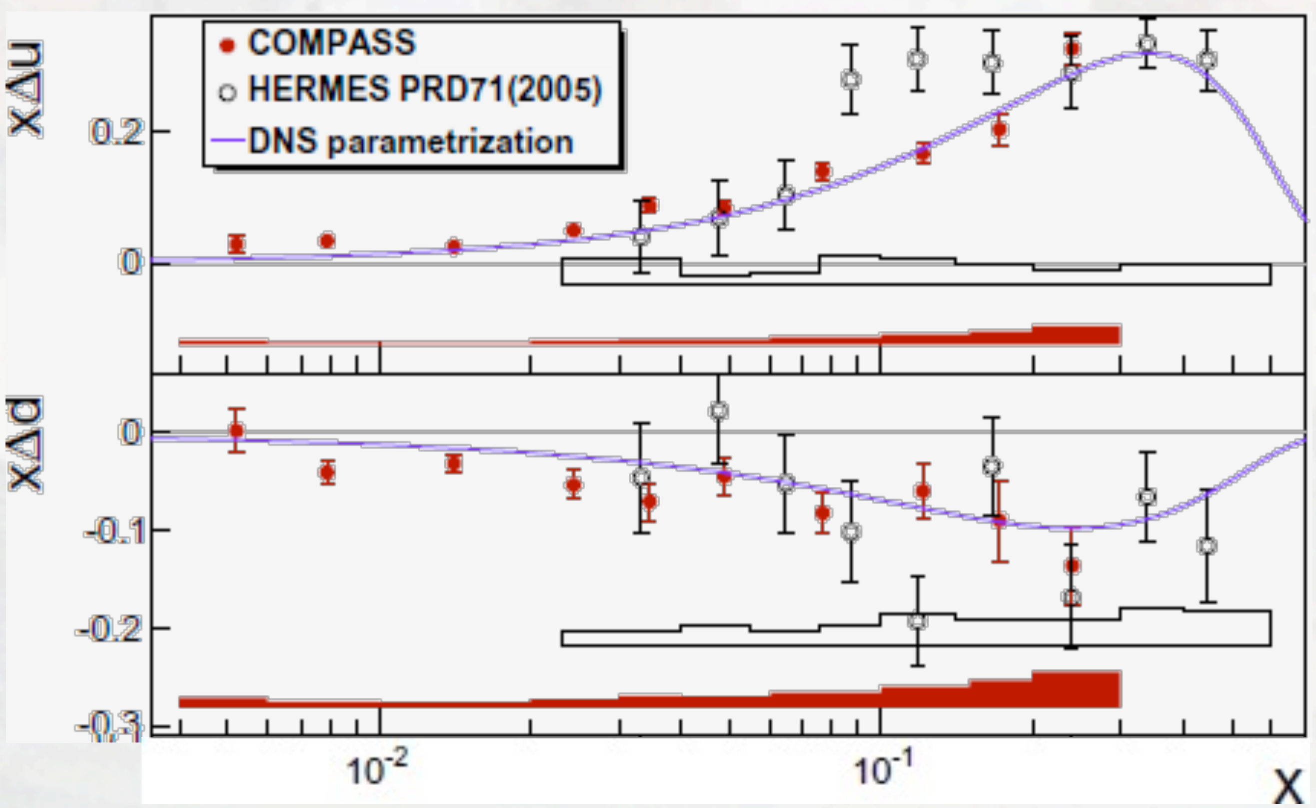
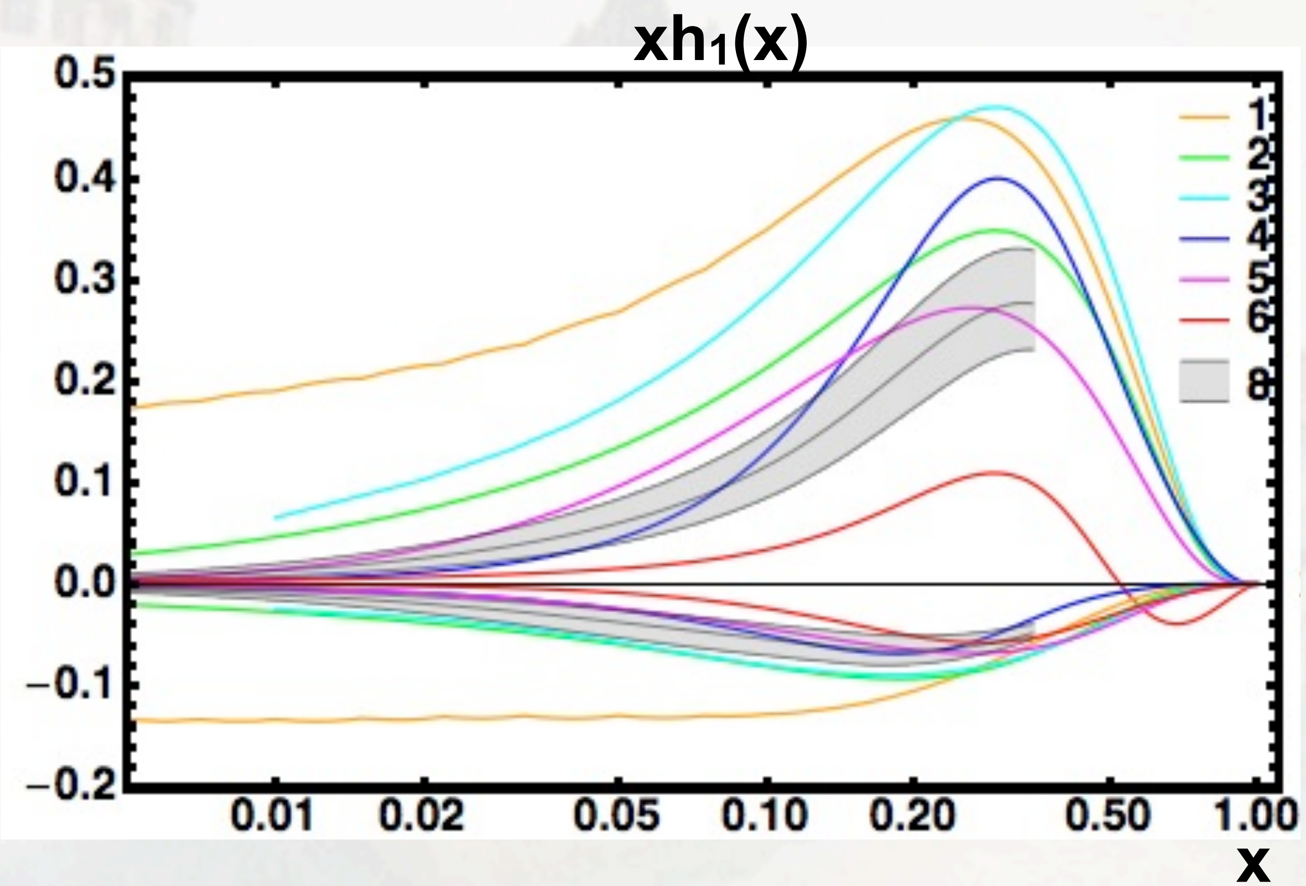
[7] Anselmino et al., PRD 75 (07)
[8] Anselmino et al., arXiv:0807.0173





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Transversity: models and fits

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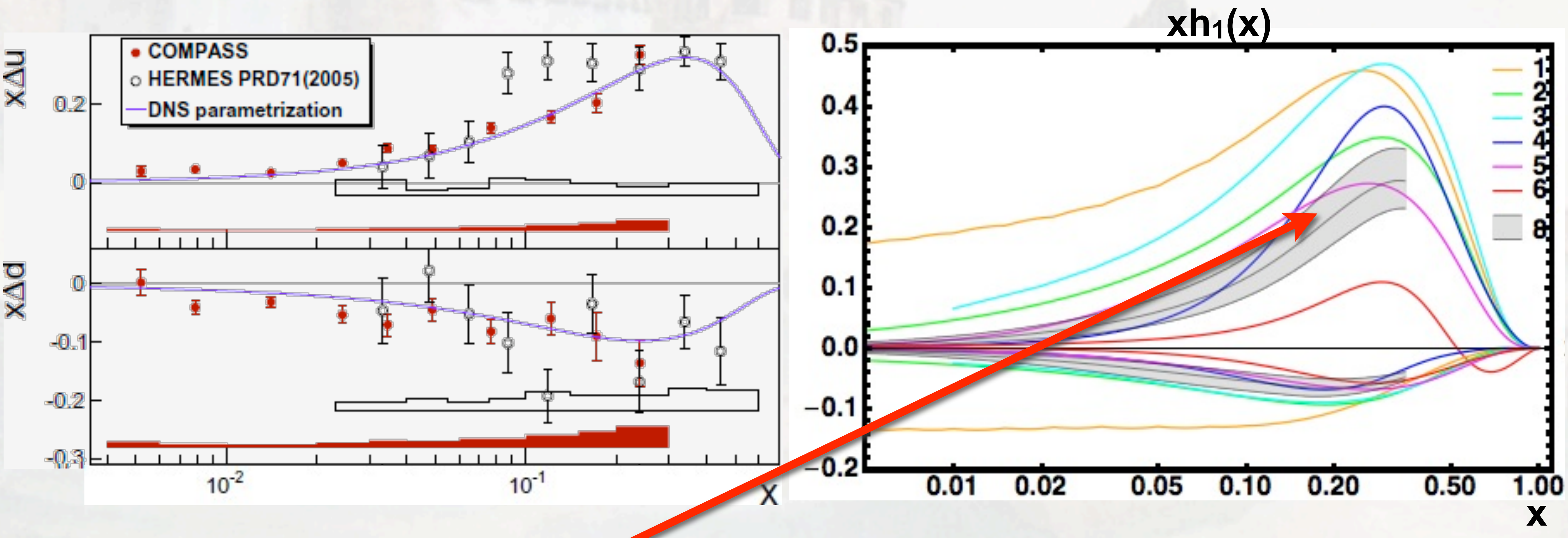

☑ u quark transversity along nucleon spin

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

Transversity: models and fits

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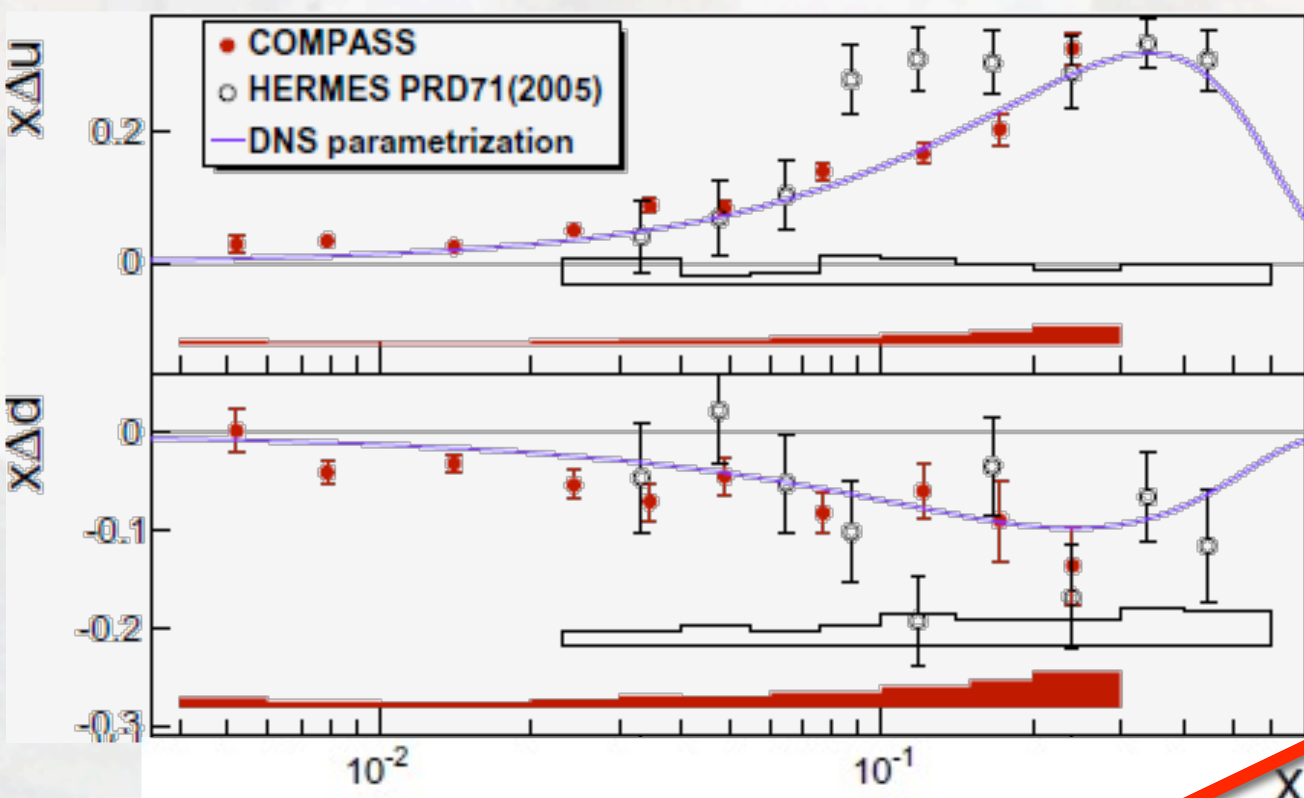
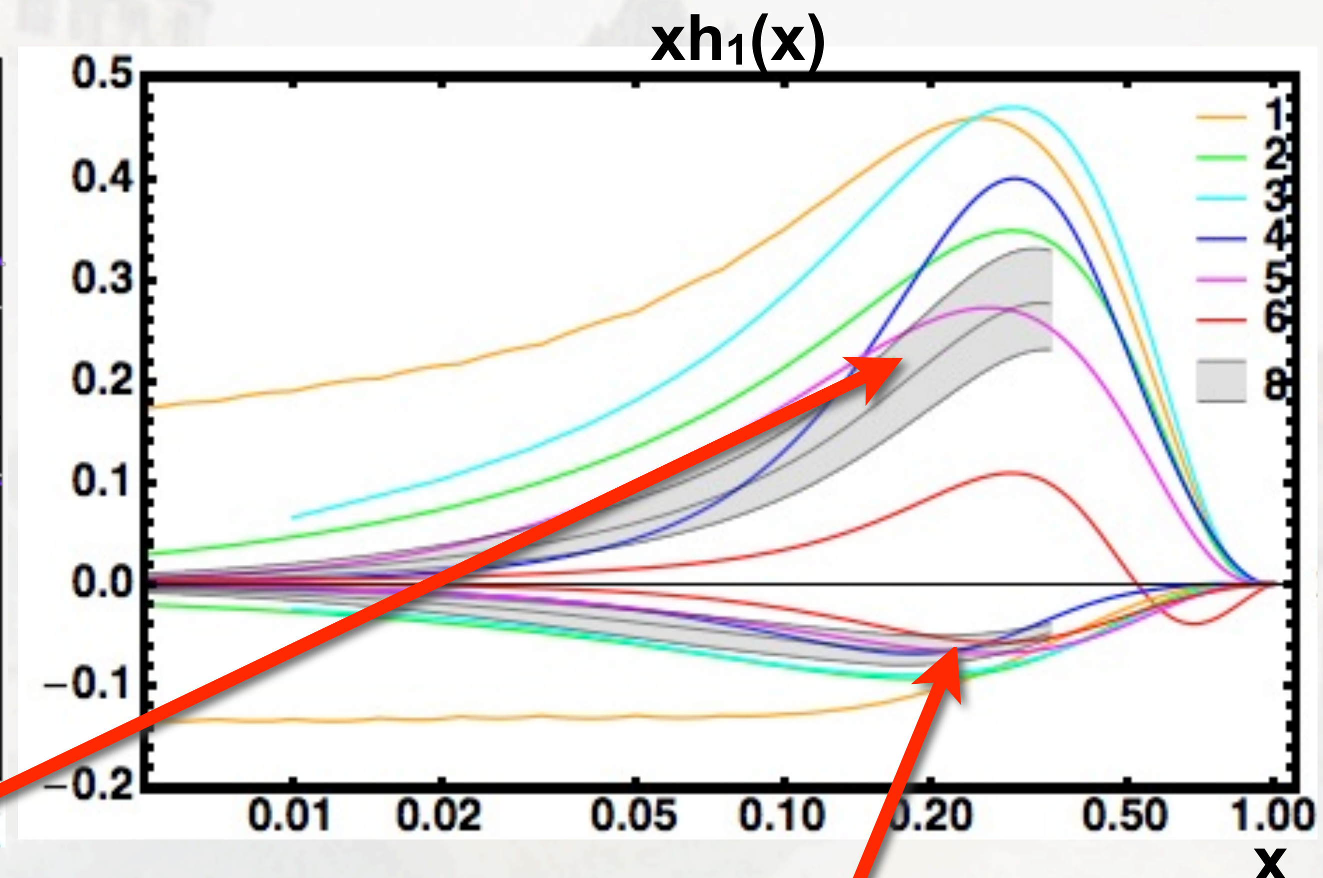




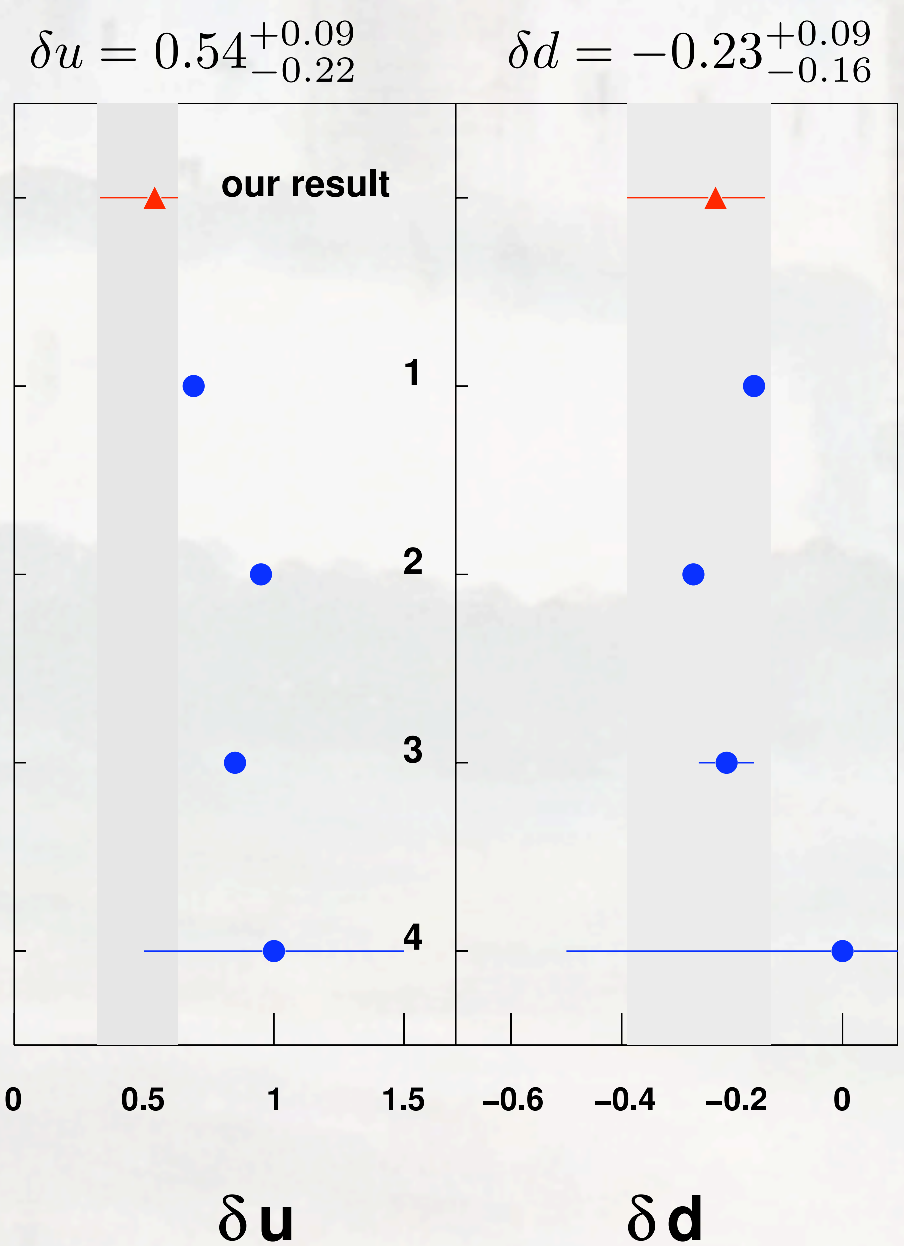
☑ u quark transversity along nucleon spin

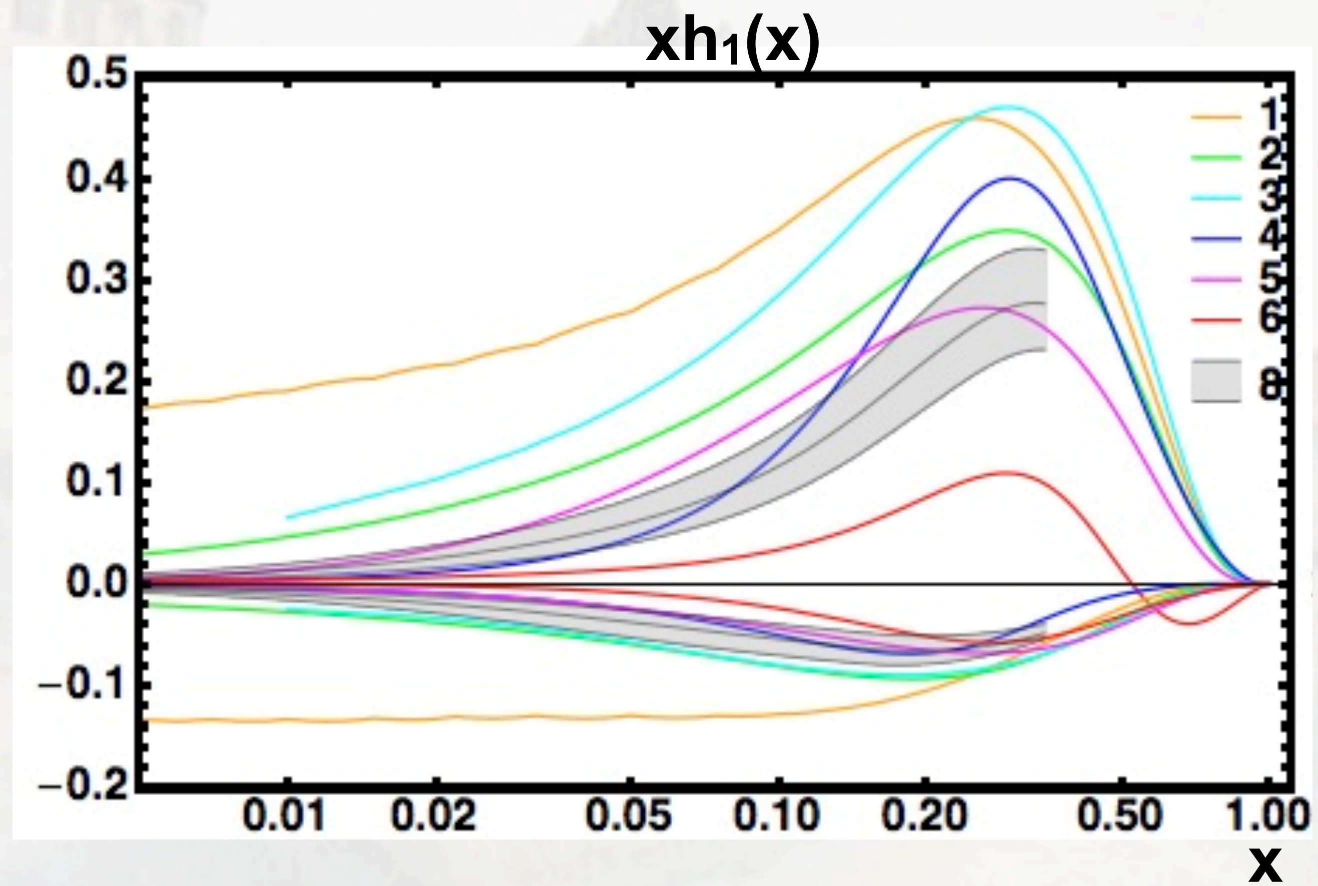
☑ d quark transversity anti-parallel to nucleon spin

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

Transversity: models and fits

[1] Soffer et al. PRD 65 (02)
[2] Korotkov et al. EPJC 18 (01)
[3] Schweitzer et al., PRD 64 (01)
[4] Wakamatsu, PLB 509 (01)
[5] Pasquini et al., PRD 72 (05)
[6] Bacchetta, Conti, Radici, PRD 78 (08)
[7] Anselmino et al., PRD 75 (07)
[8] Anselmino et al., arXiv:0807.0173





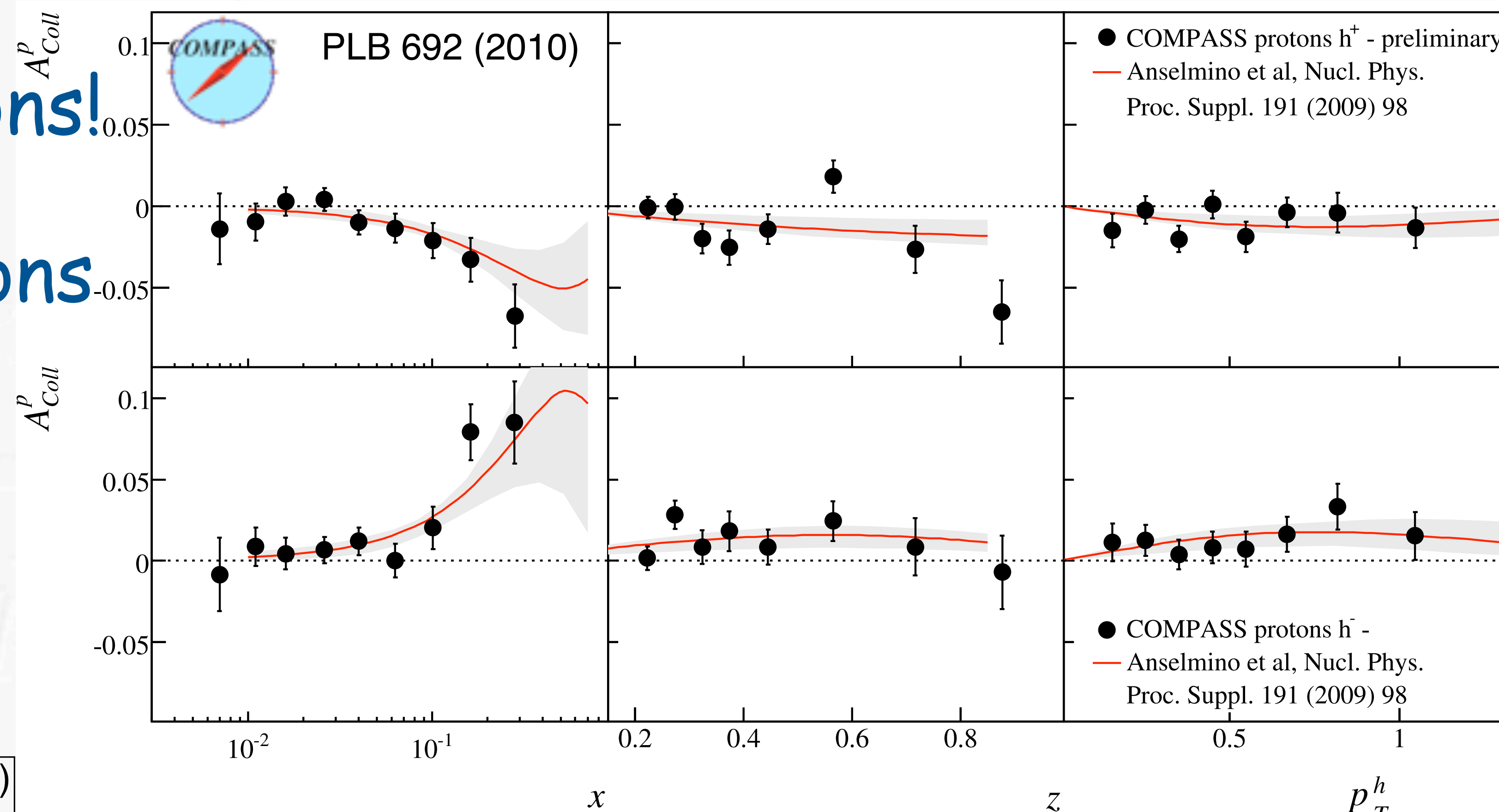
tensor charge:

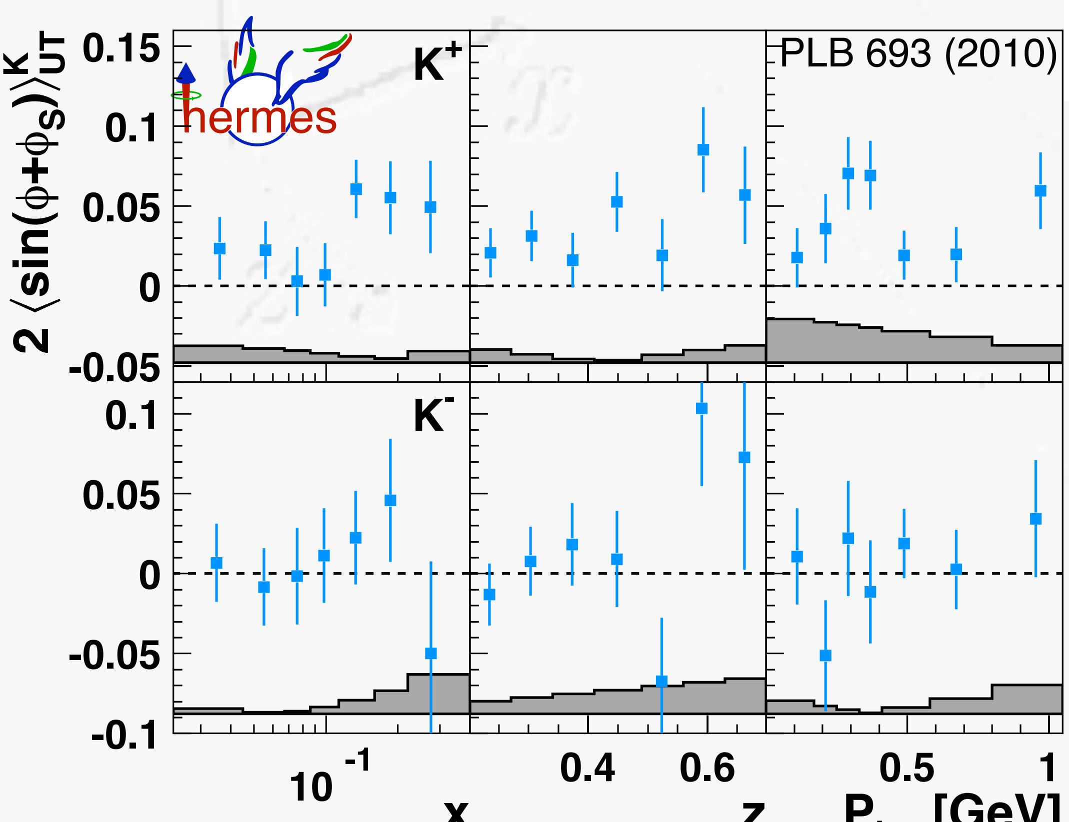
$$\delta q \equiv \int_0^1 dx \left[h_1^q(x) - h_1^{\bar{q}}(x)\right]$$

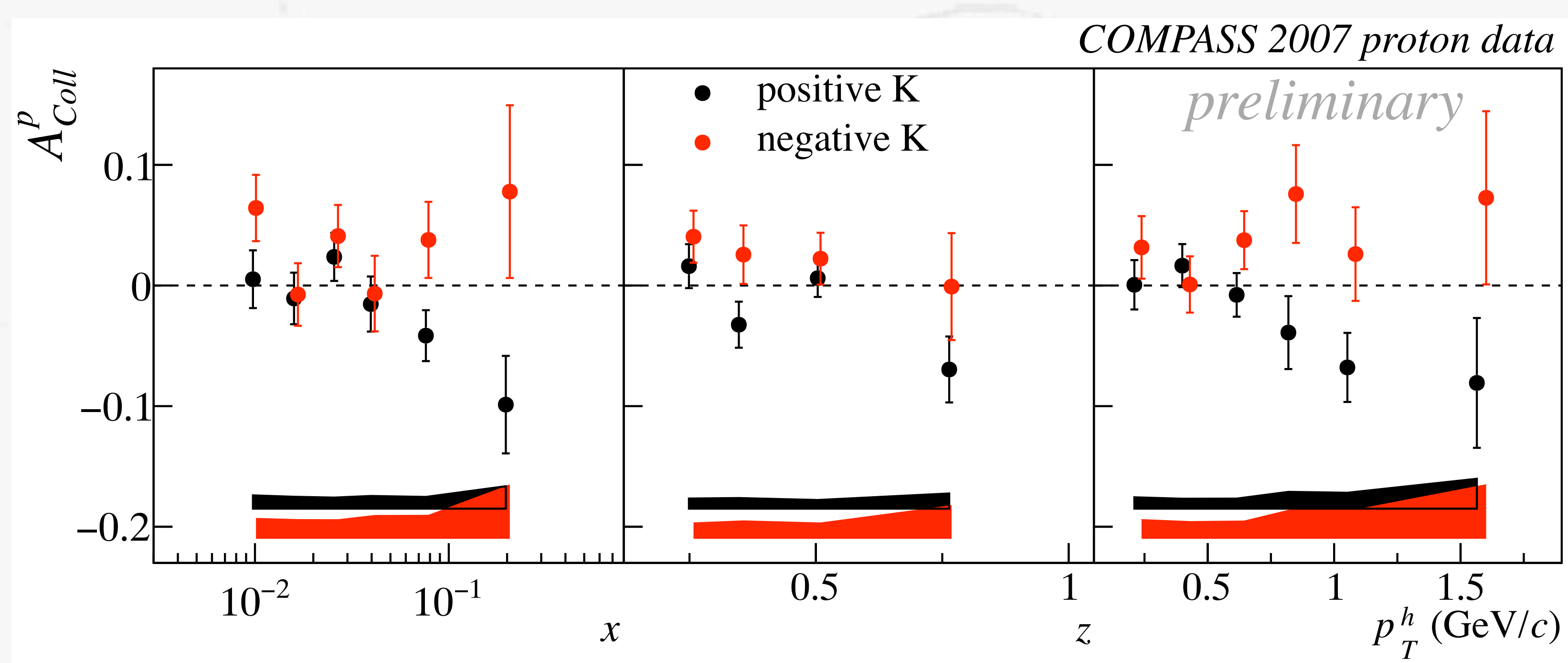
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

New DIS data on Collins

- opposite sign conventions!
- similar behavior for pions
- similar behavior for K^+
- different trend for K^-







Transversity's friends

Pretzelosity

	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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- chiral-odd ➥ needs Collins FF (or similar)
- leads to $\sin(3\phi - \phi_s)$ modulation in A_{UT}
- proton and deuteron data consistent with zero
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$

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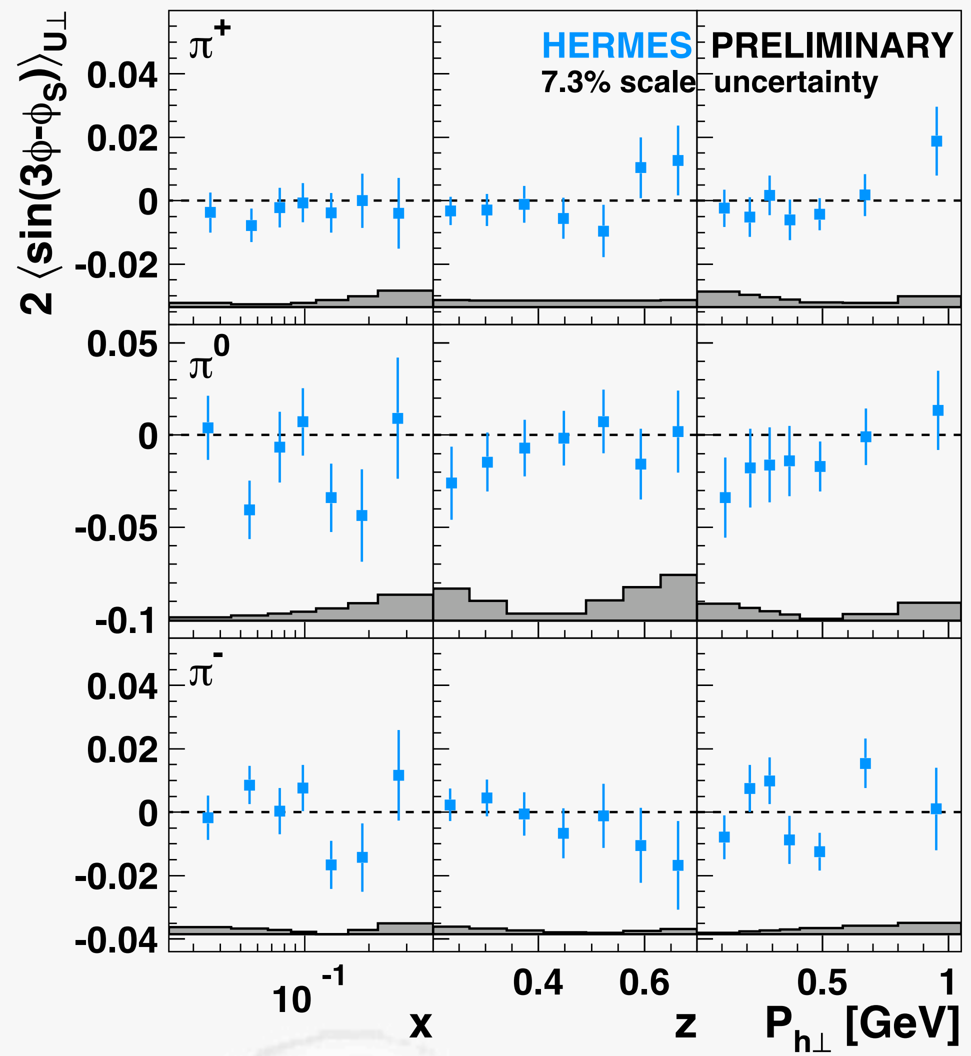

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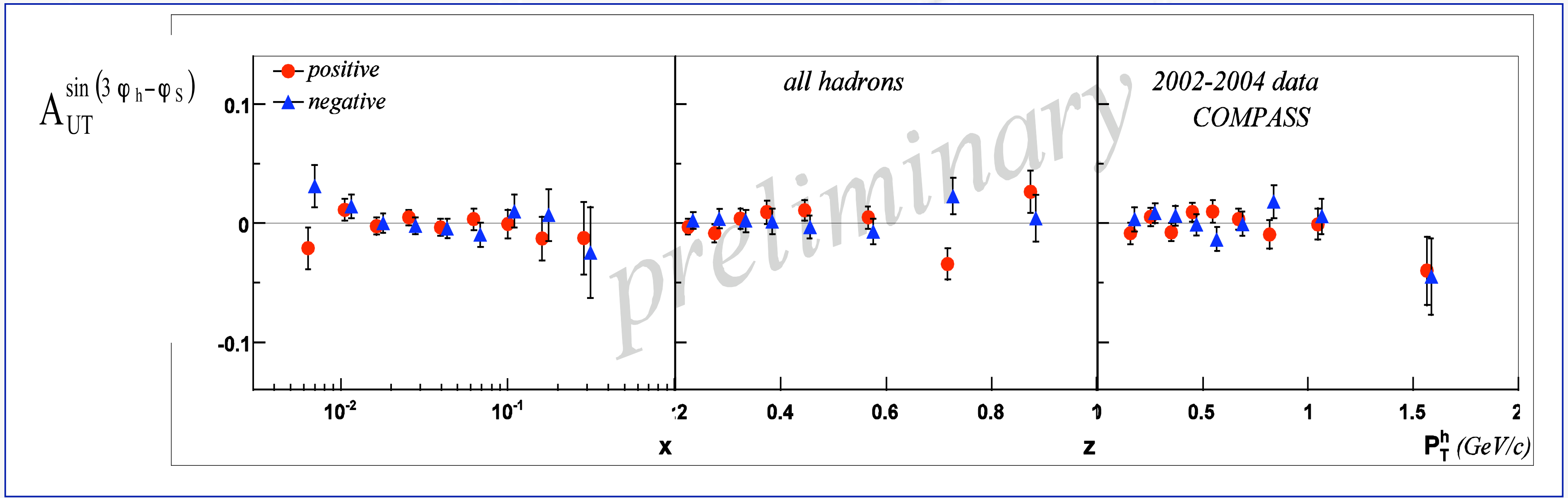

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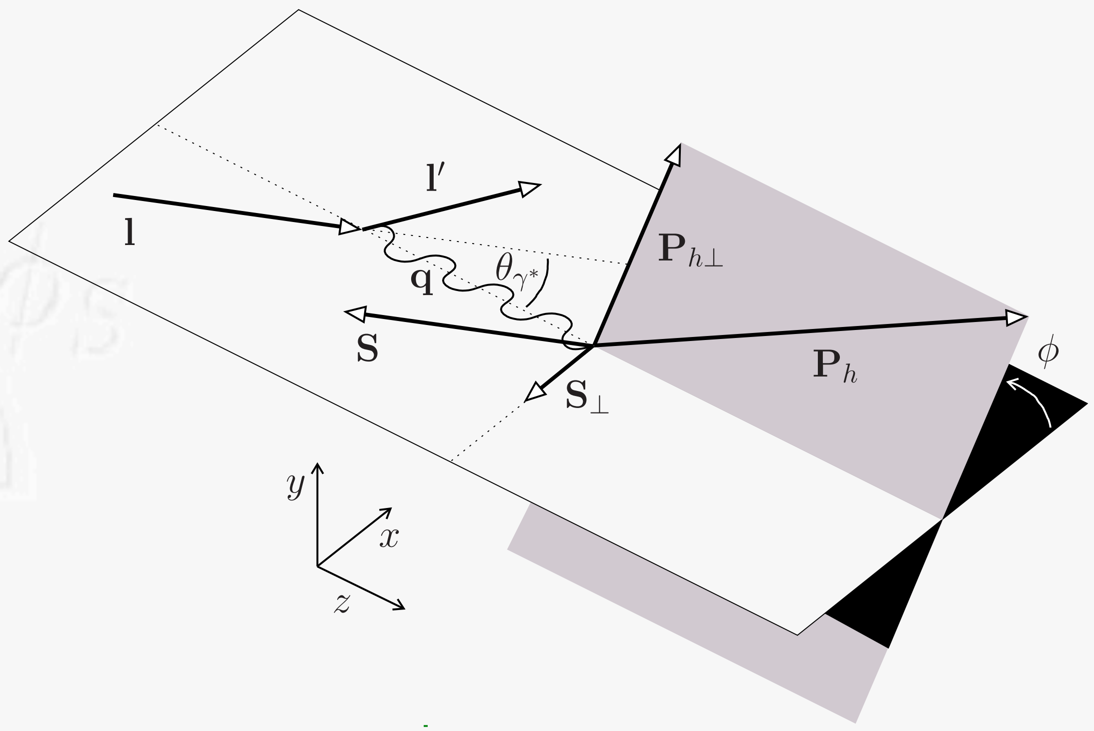

- could also use longitudinally polarized targets:

$$\sin(\mathbf{3}\phi - \phi_S) \rightsquigarrow -\sin(\mathbf{3}\phi)$$

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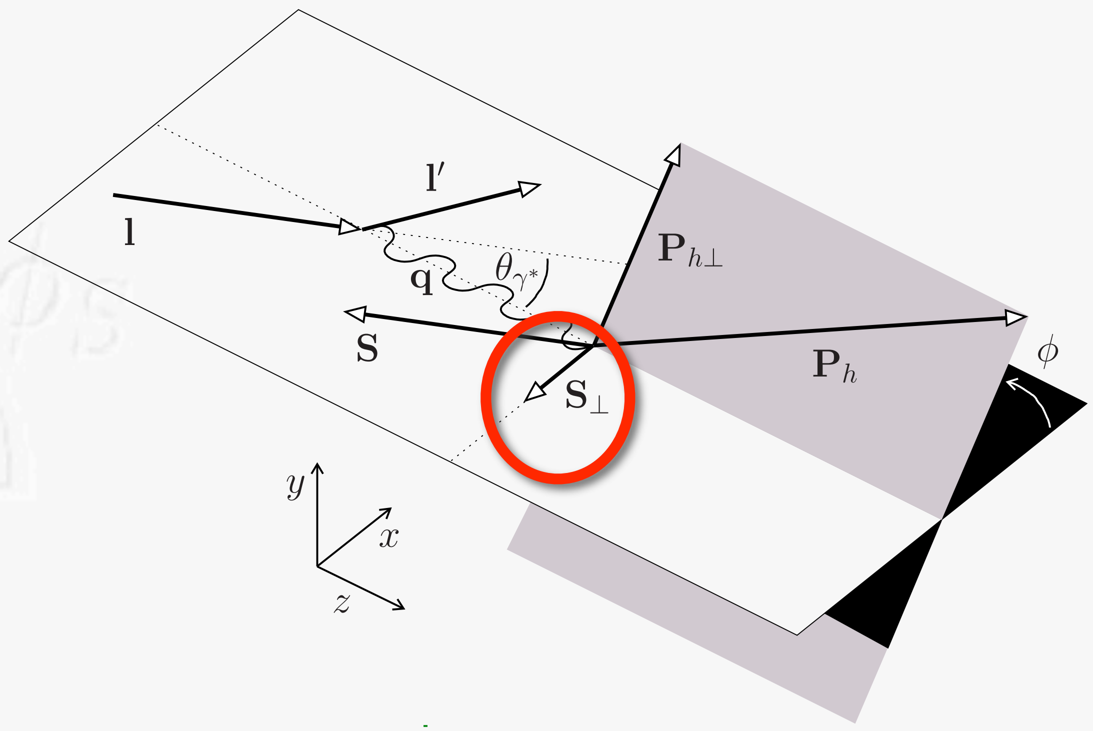

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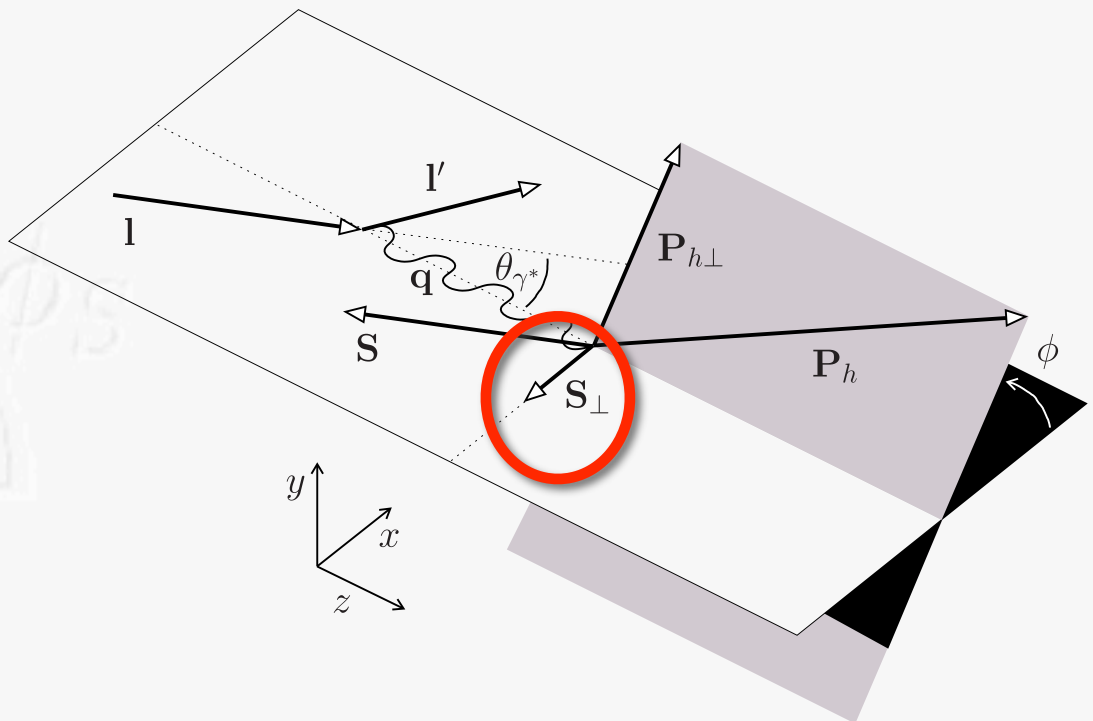

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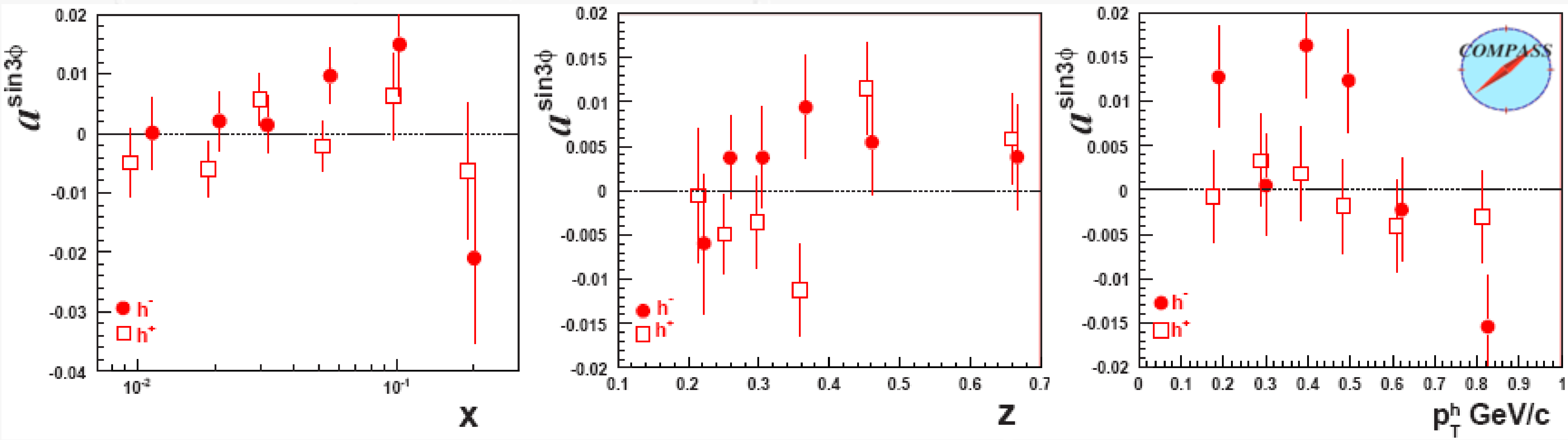

Worm-Gear I

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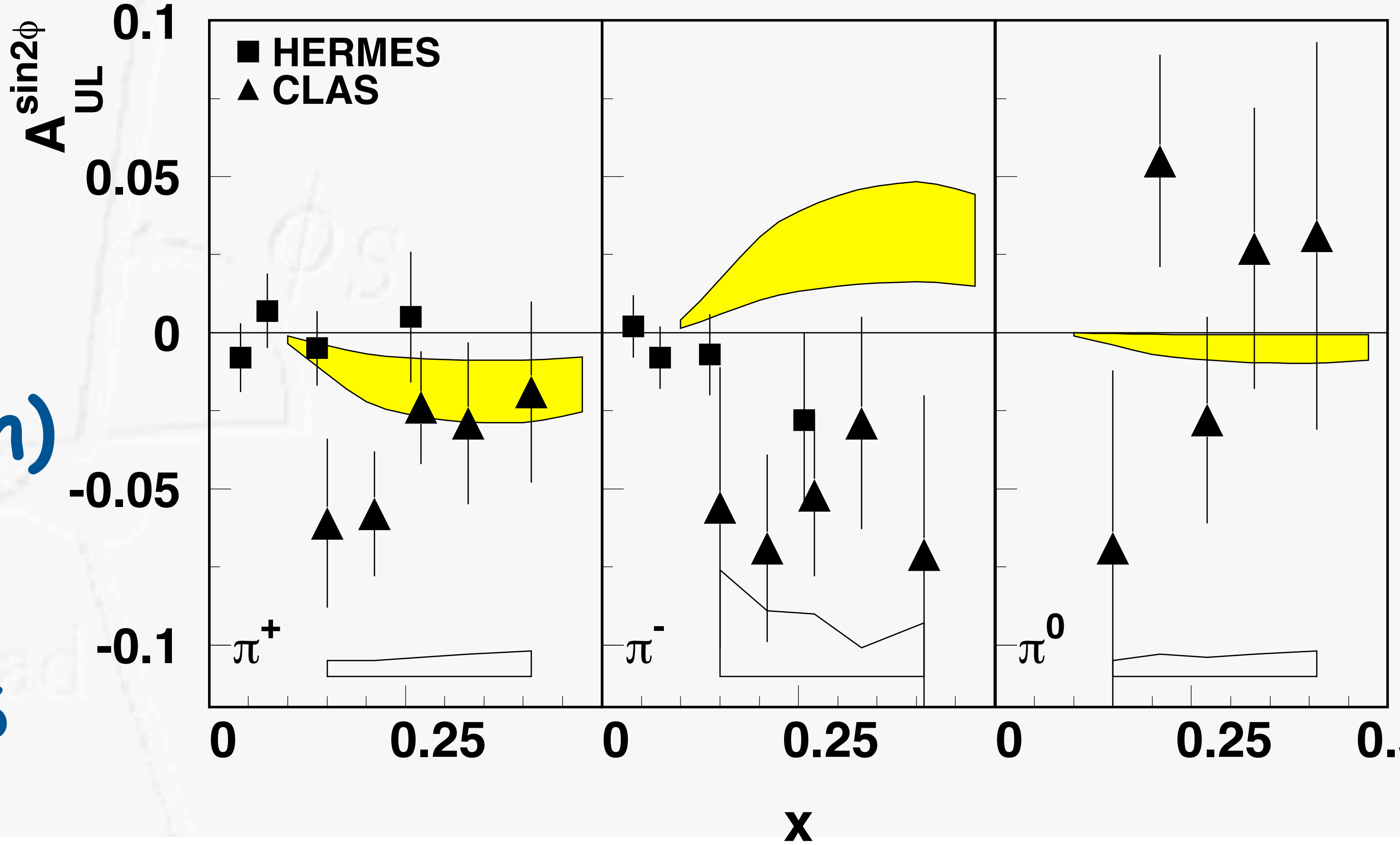
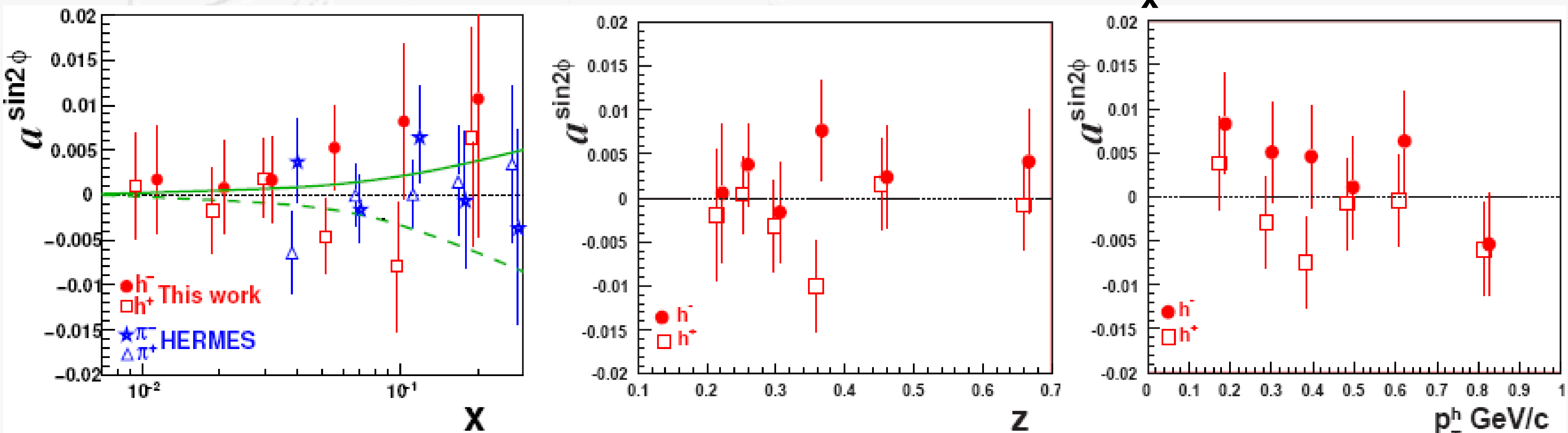
- again chiral-odd
- evidence from CLAS (new results coming soon)
- consistent with zero at COMPASS and HERMES





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☛ H. Avakian

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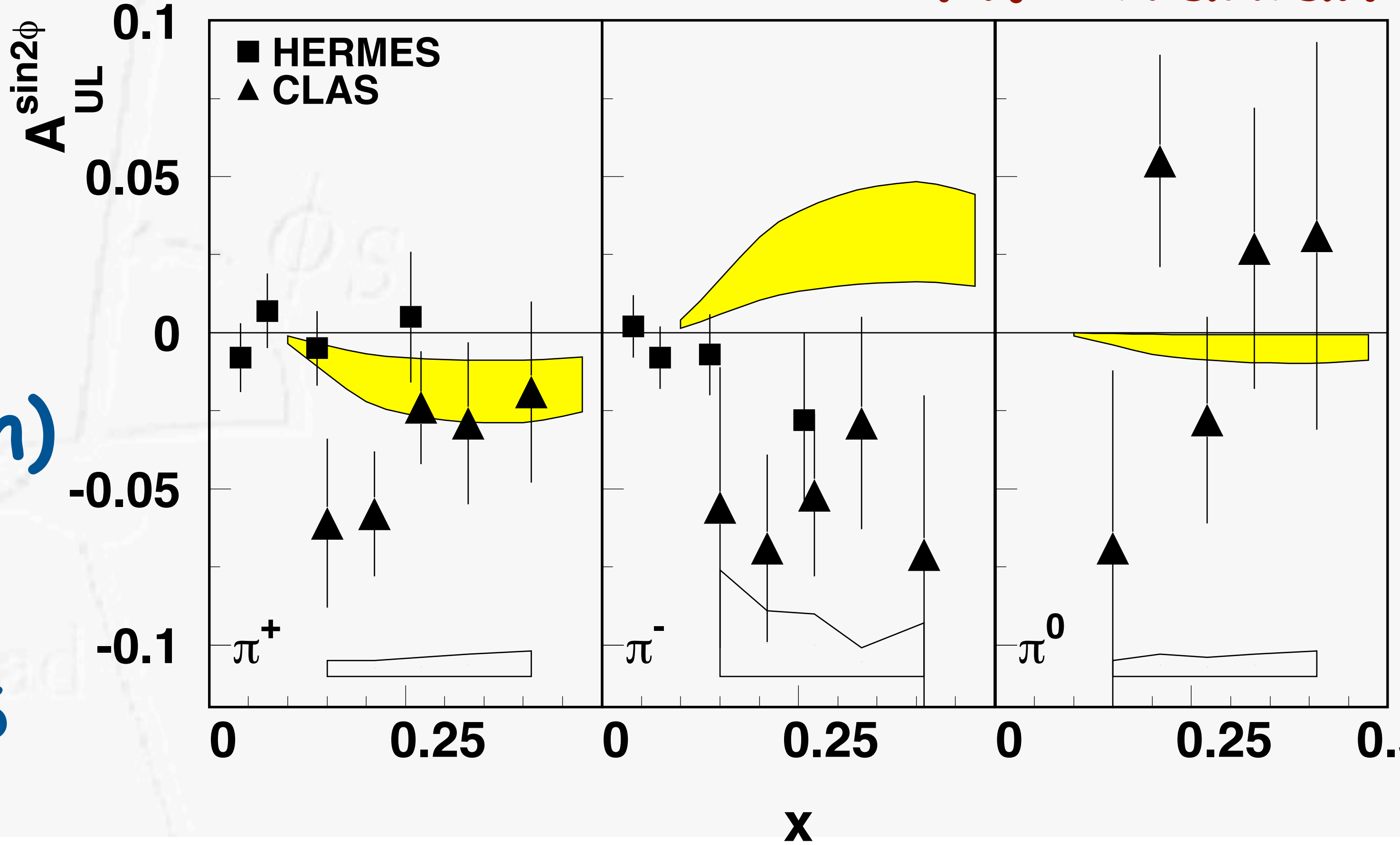

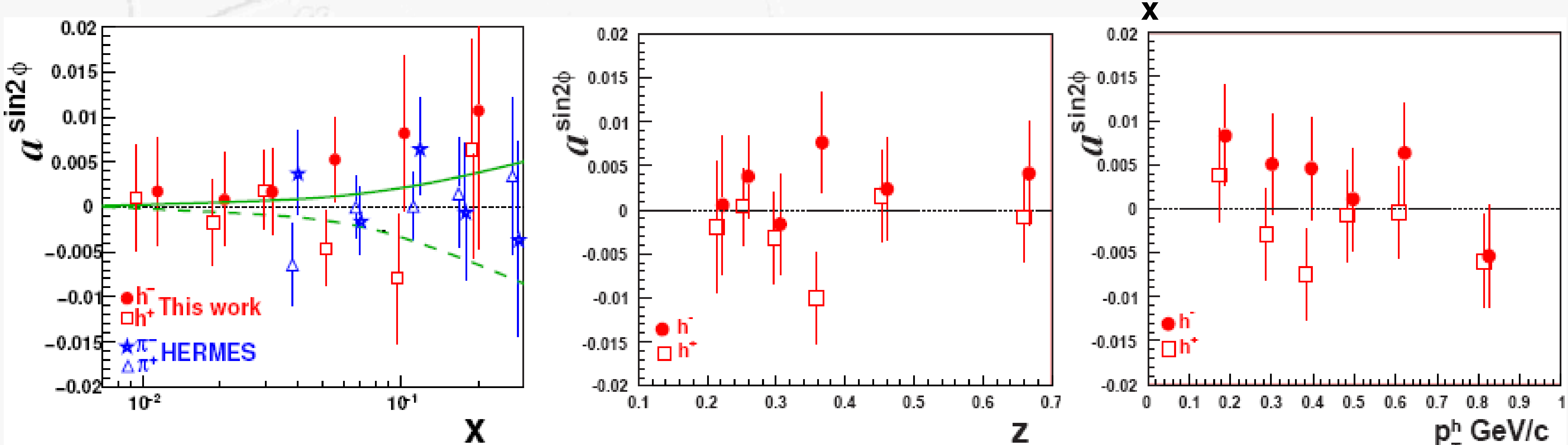

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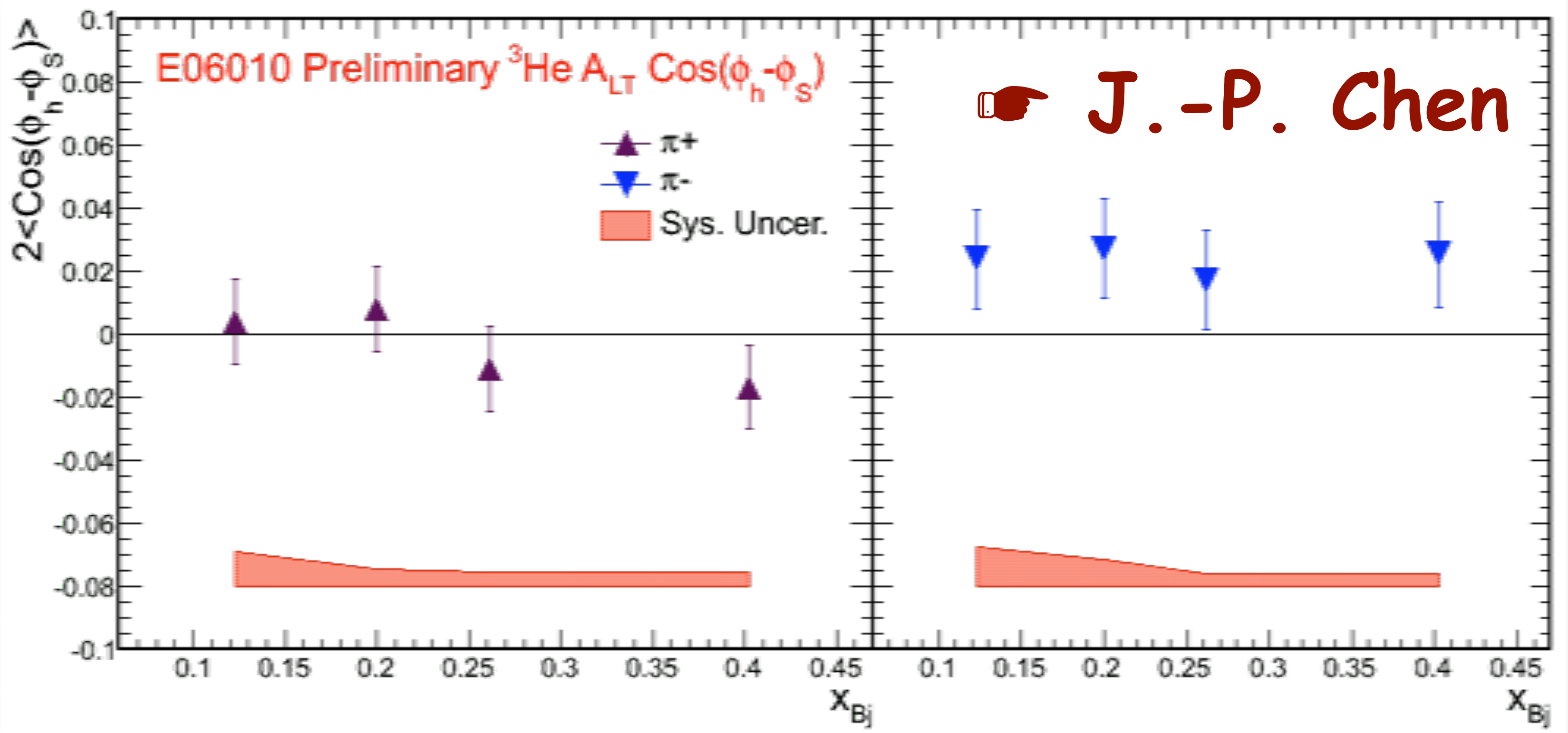
Worm-Gear II

- chiral even
- first direct evidence for worm-gear g_{1T} on ^3He target



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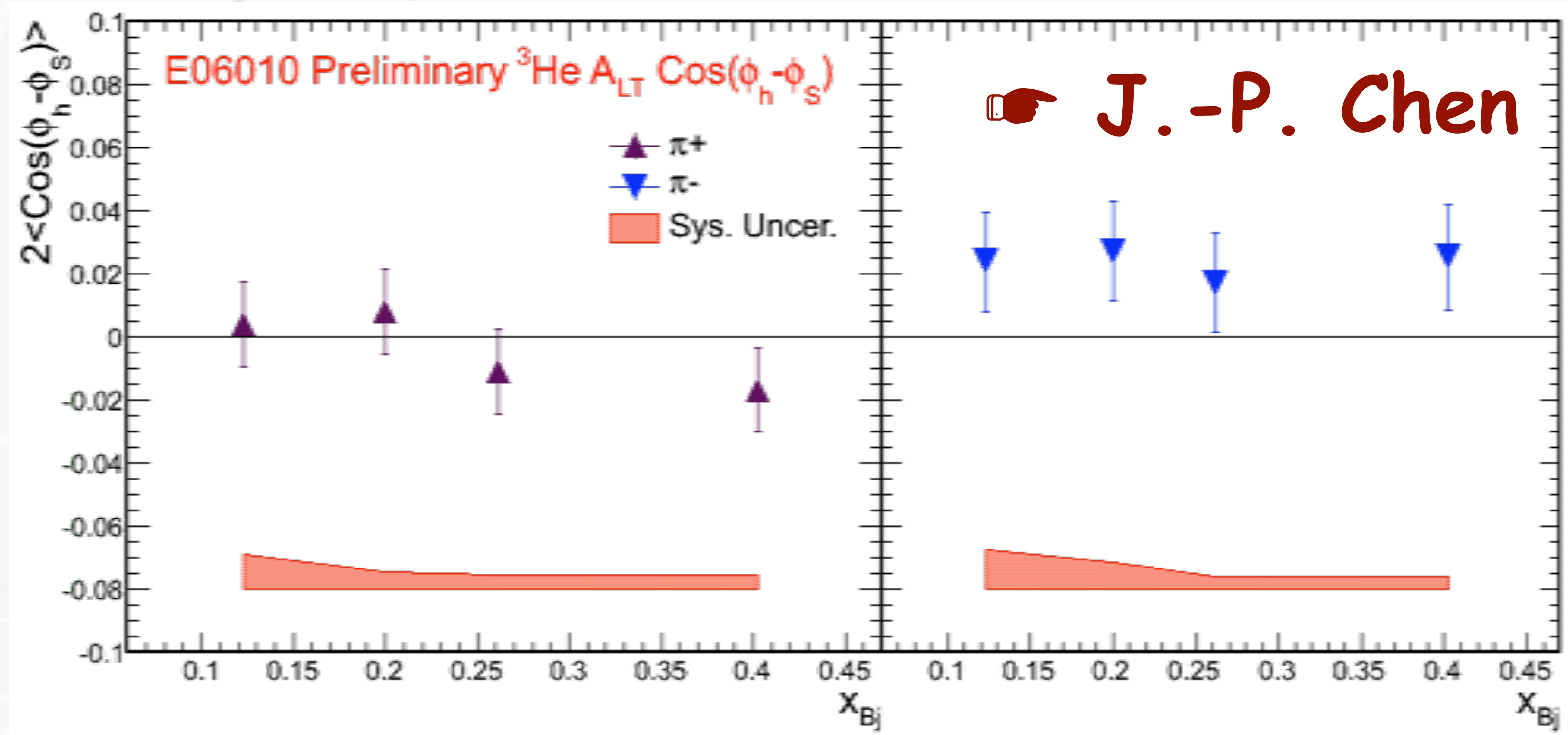

- chiral even
- first direct evidence for worm-gear g_{1T} on ^{3}He target
- only indirect hints from proton data via A_{UT}

$$\propto \left(x f_T^\perp D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right)$$

$$- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z} \right) - \left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z} \right) \right]$$

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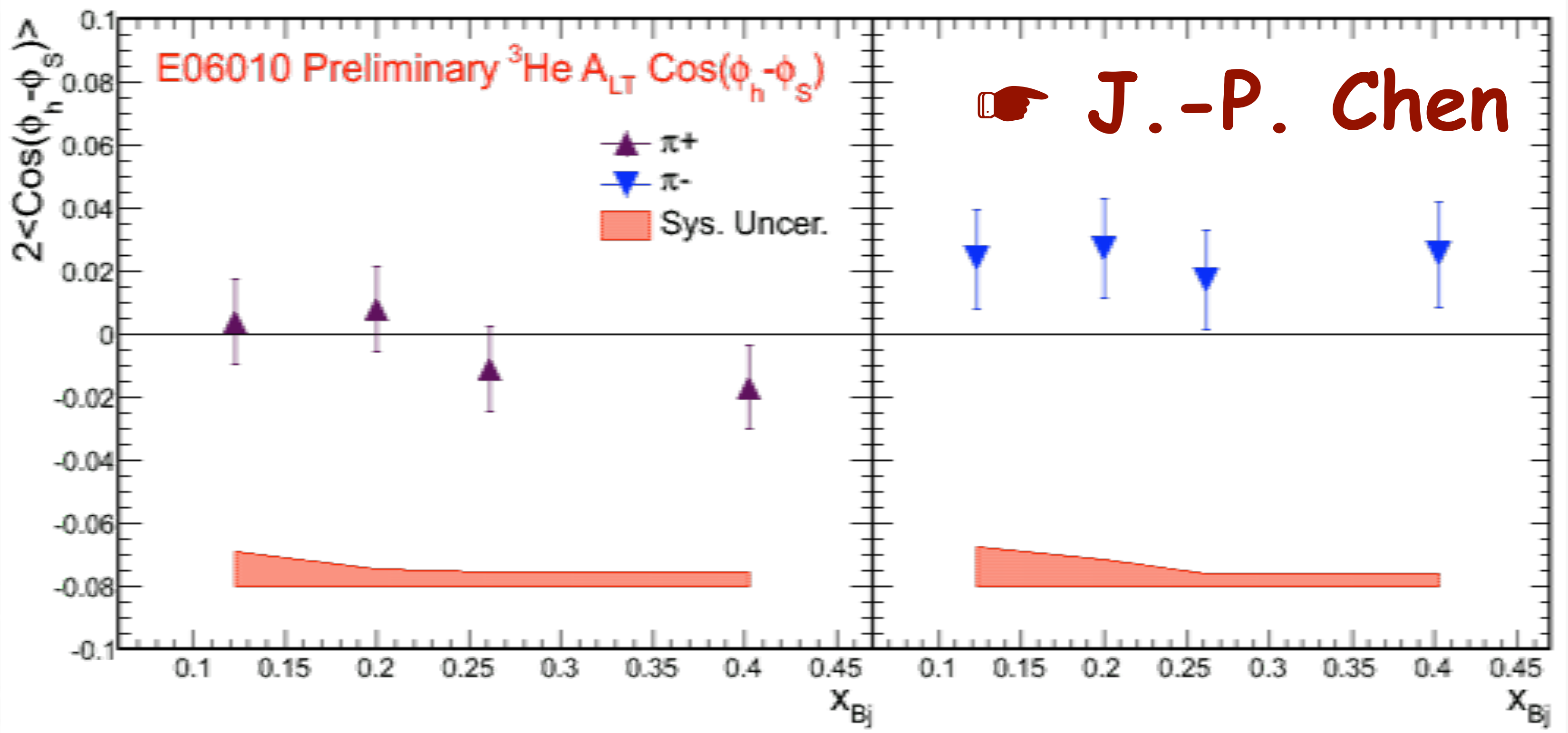

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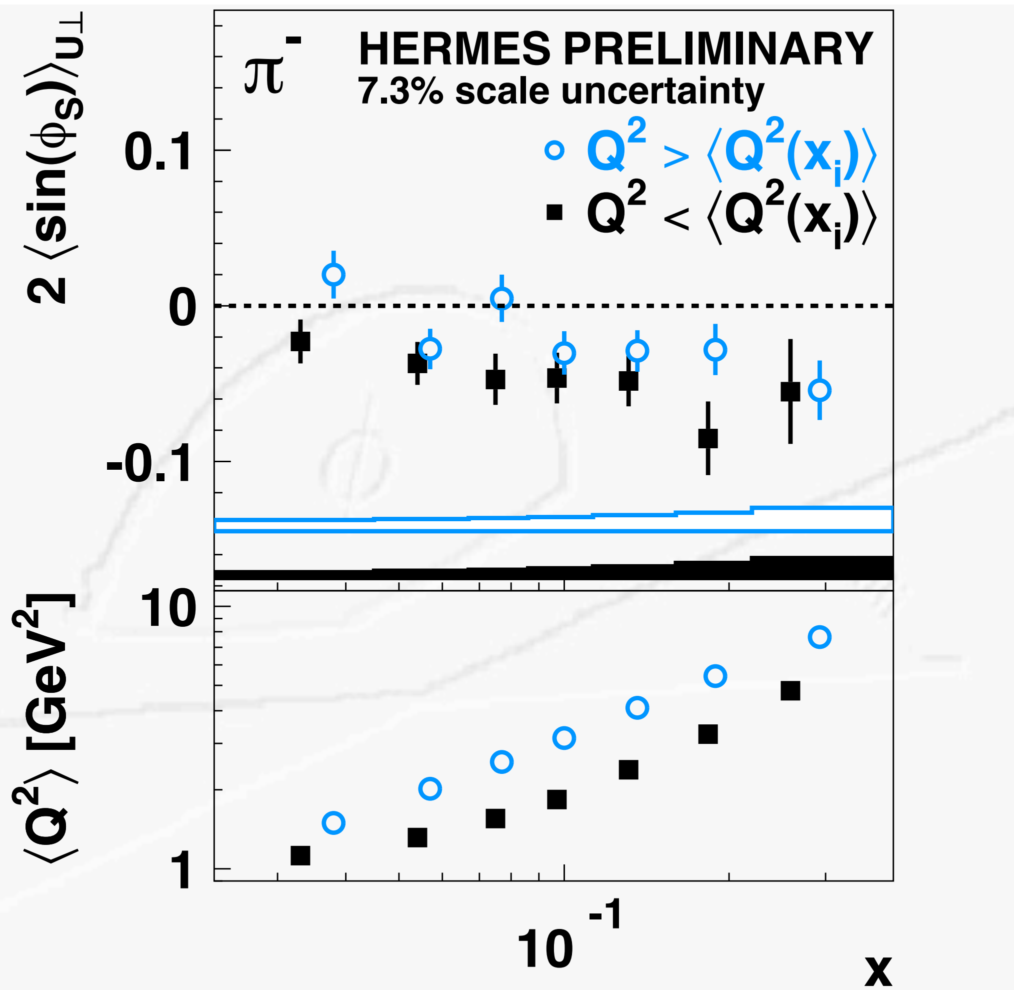
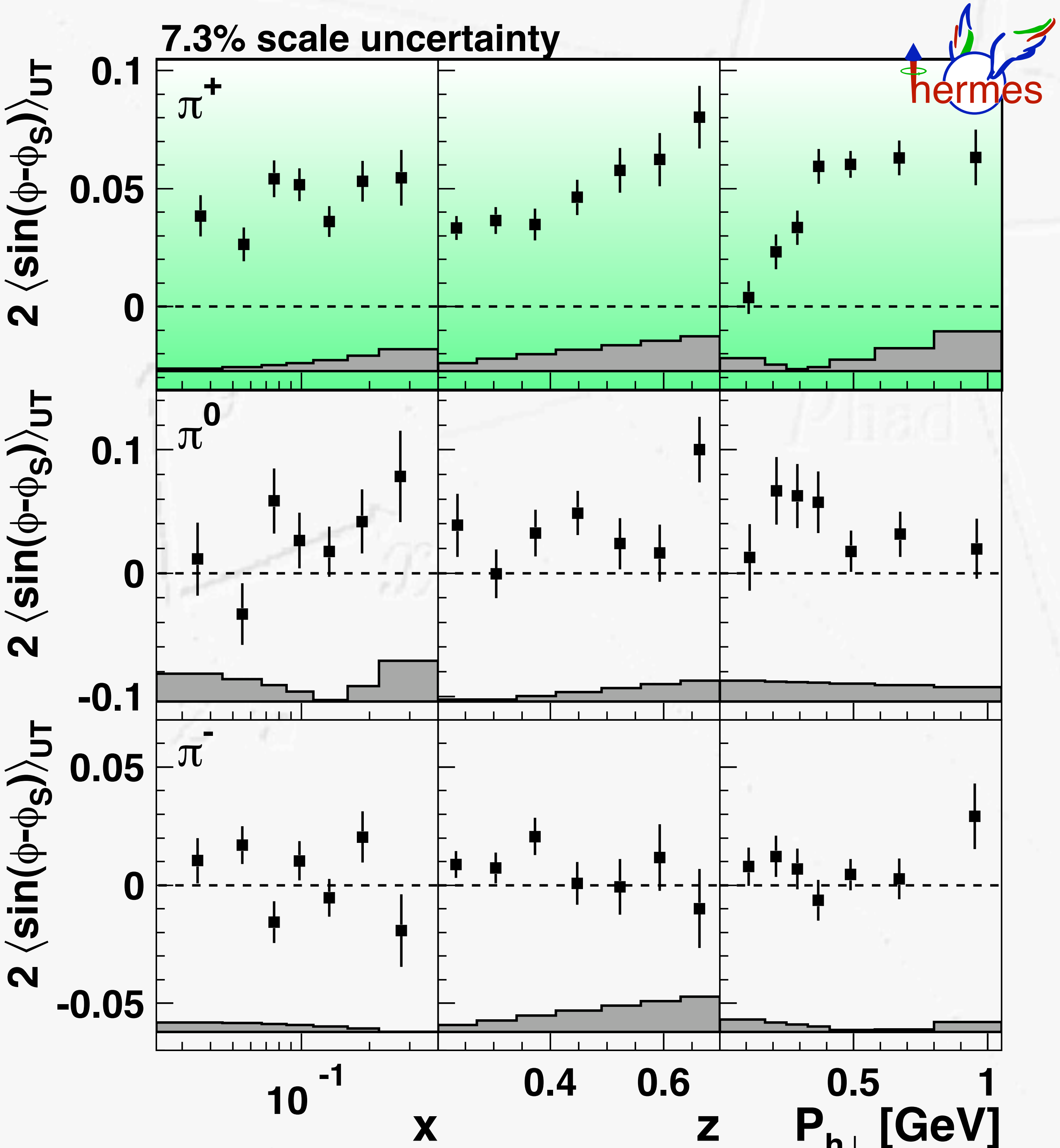


Sivers amplitudes for pions

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

$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2)\otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



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Sivers amplitudes for pions

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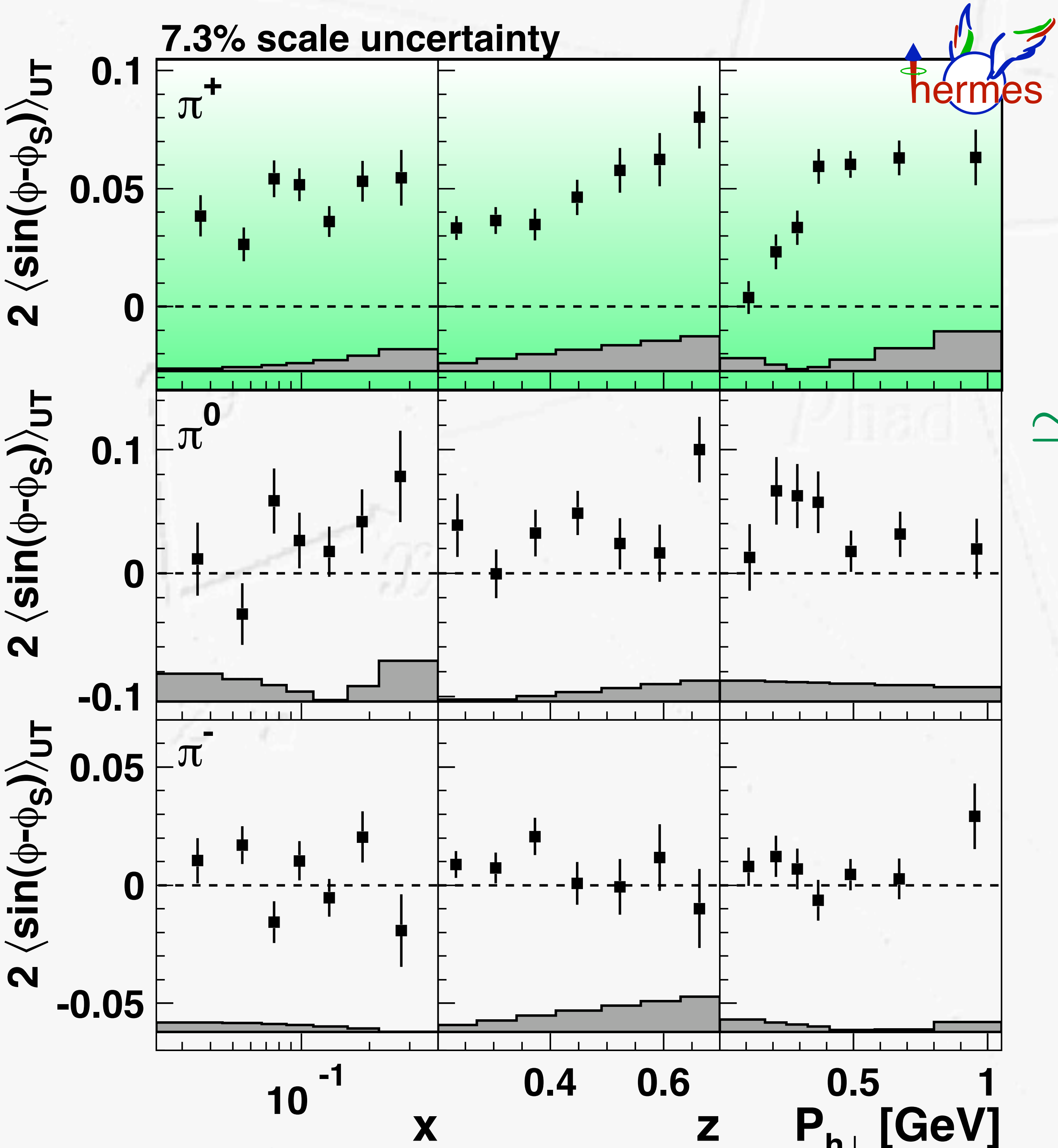

π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ **u-quark Sivers DF < 0**

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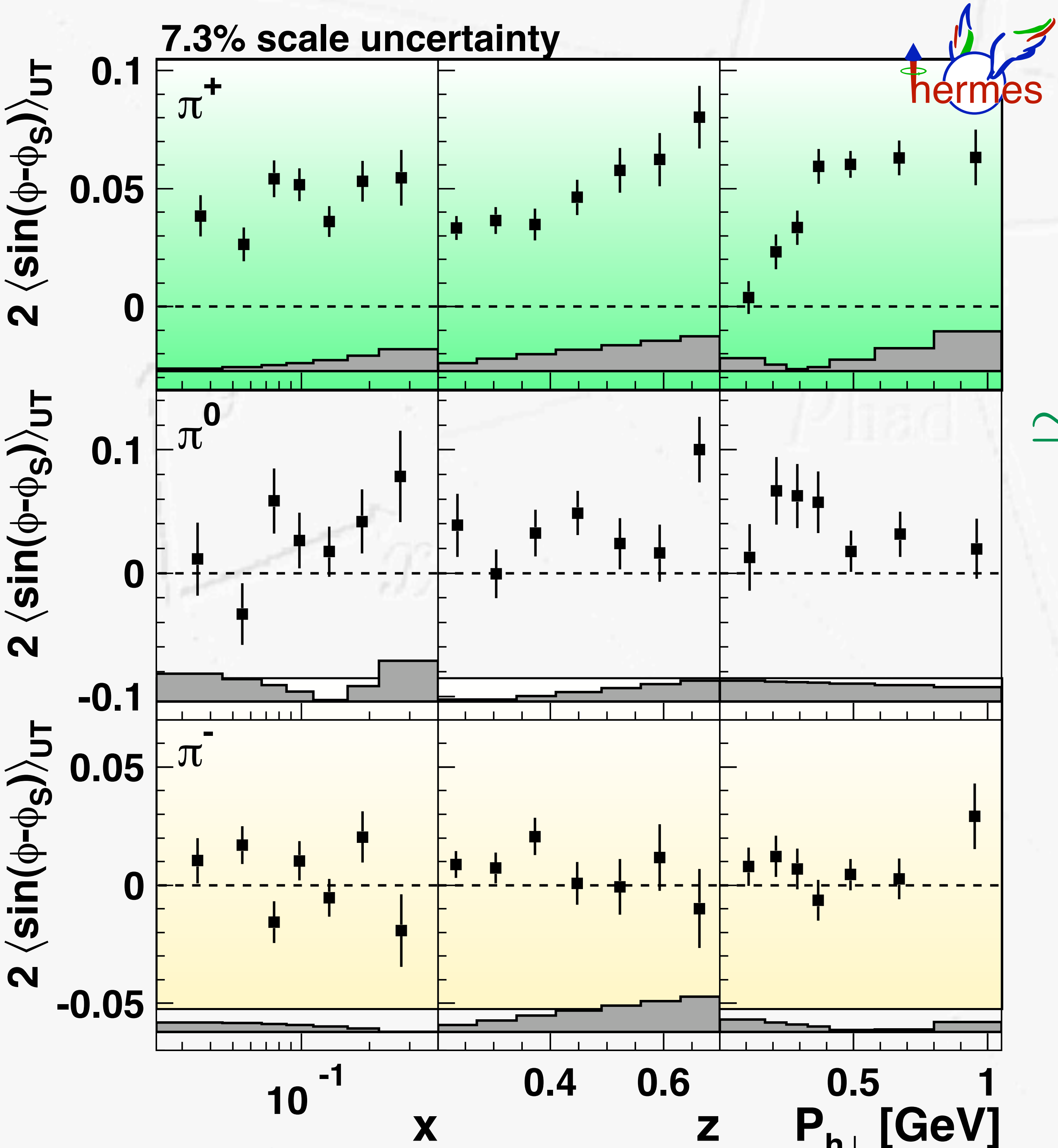

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☛ **u-quark Sivers DF < 0**

☛ **d-quark Sivers DF > 0 (cancelation for π^-)**

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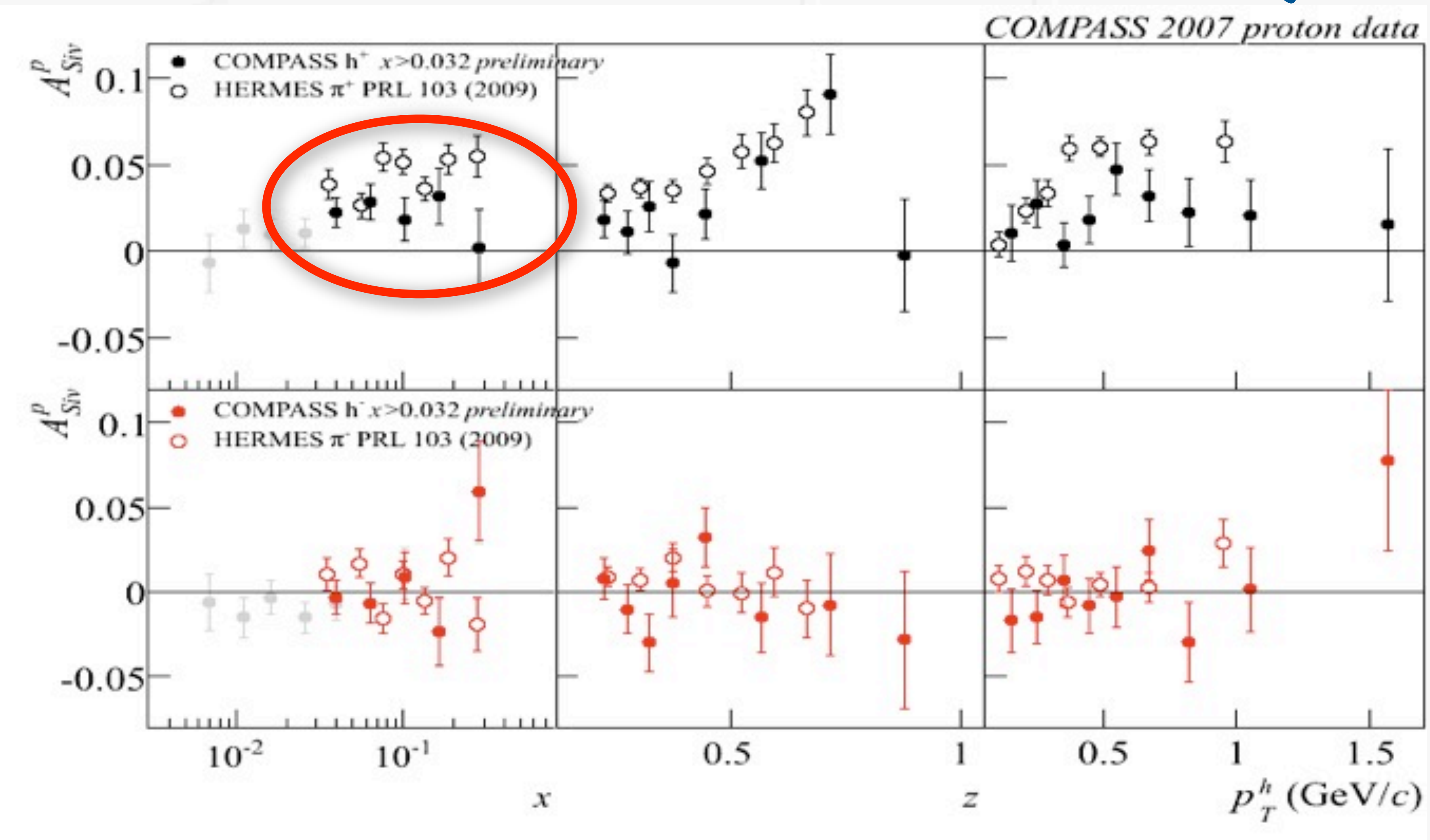
Sivers function (some surprises)



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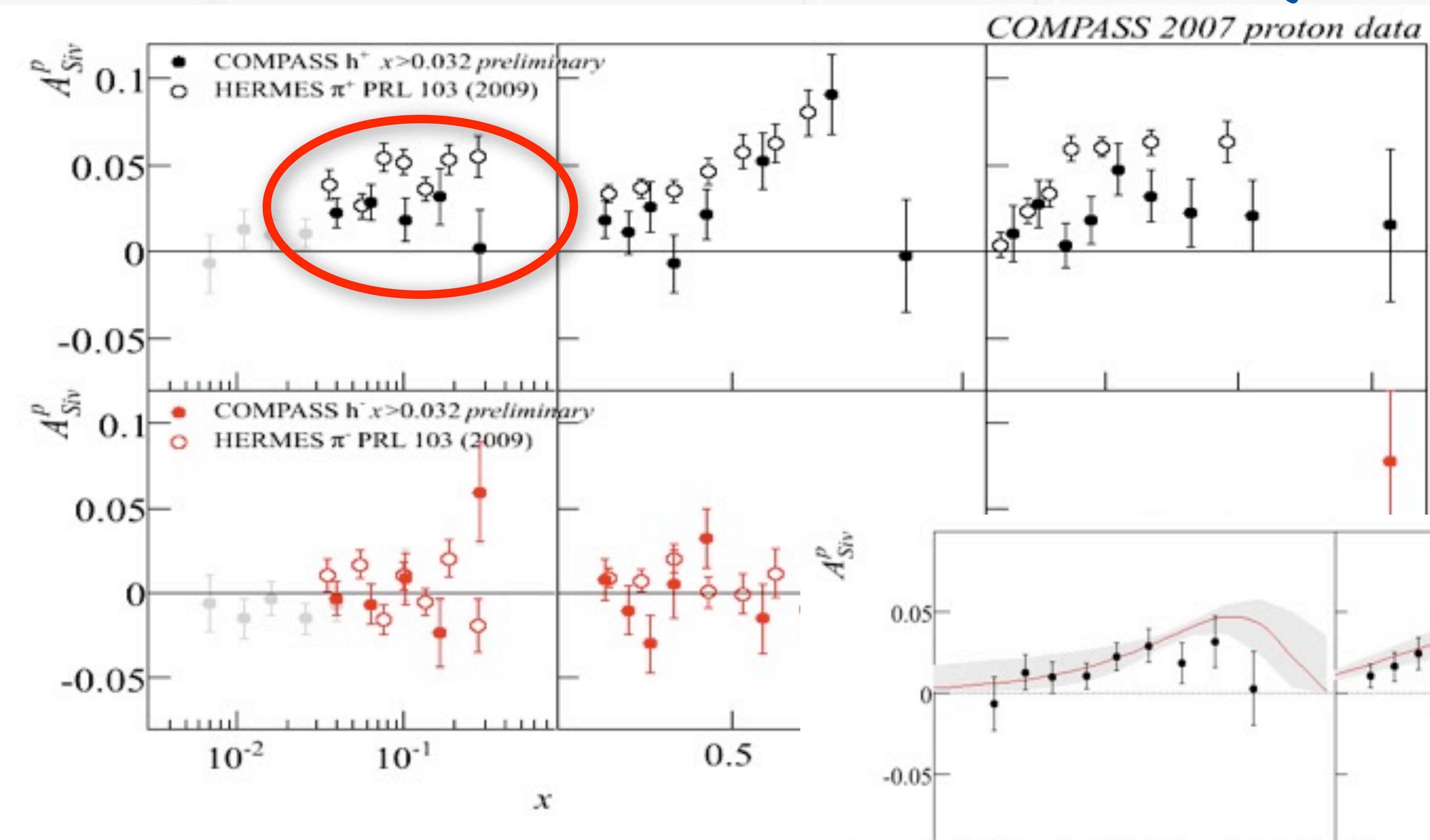

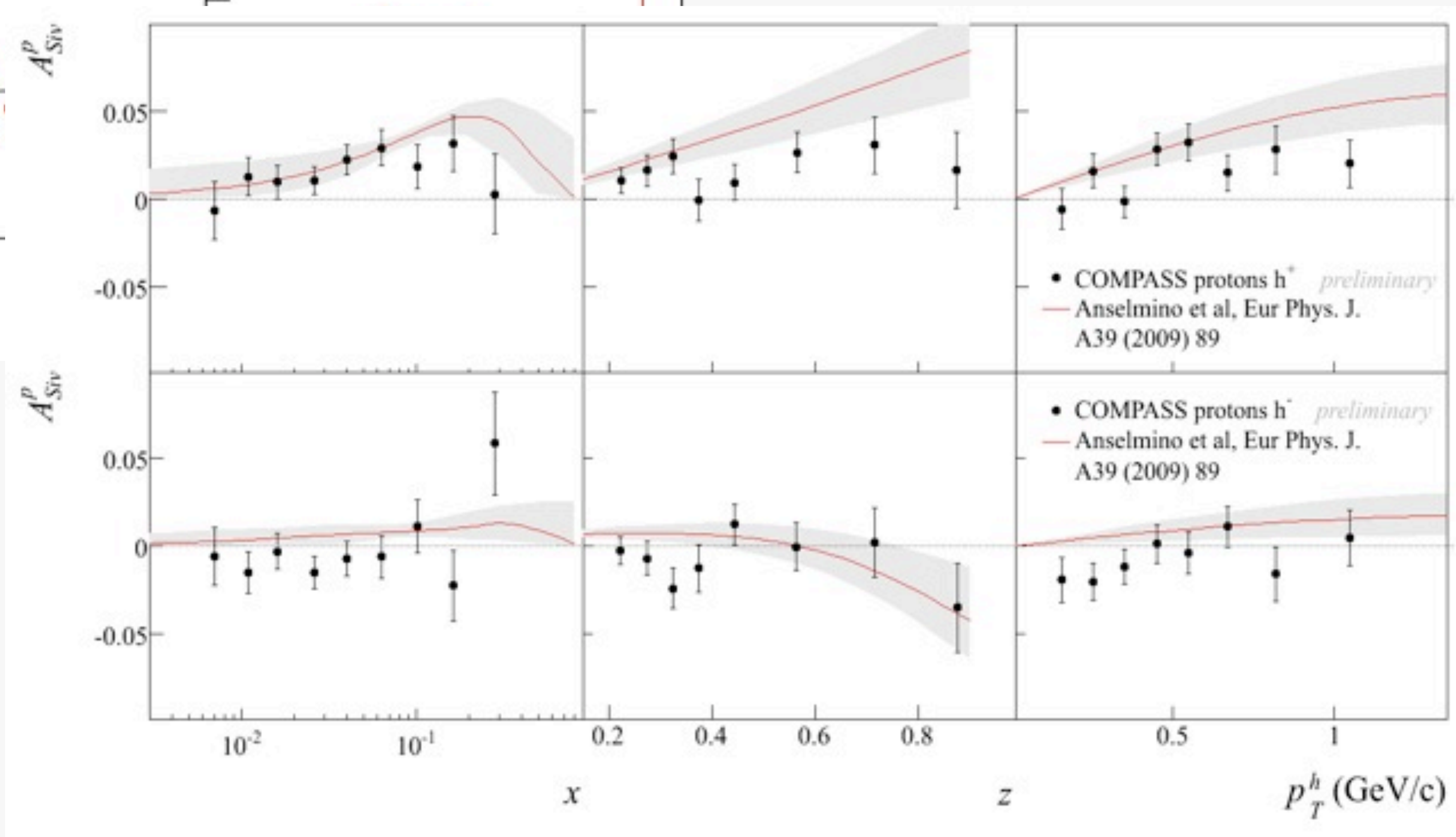

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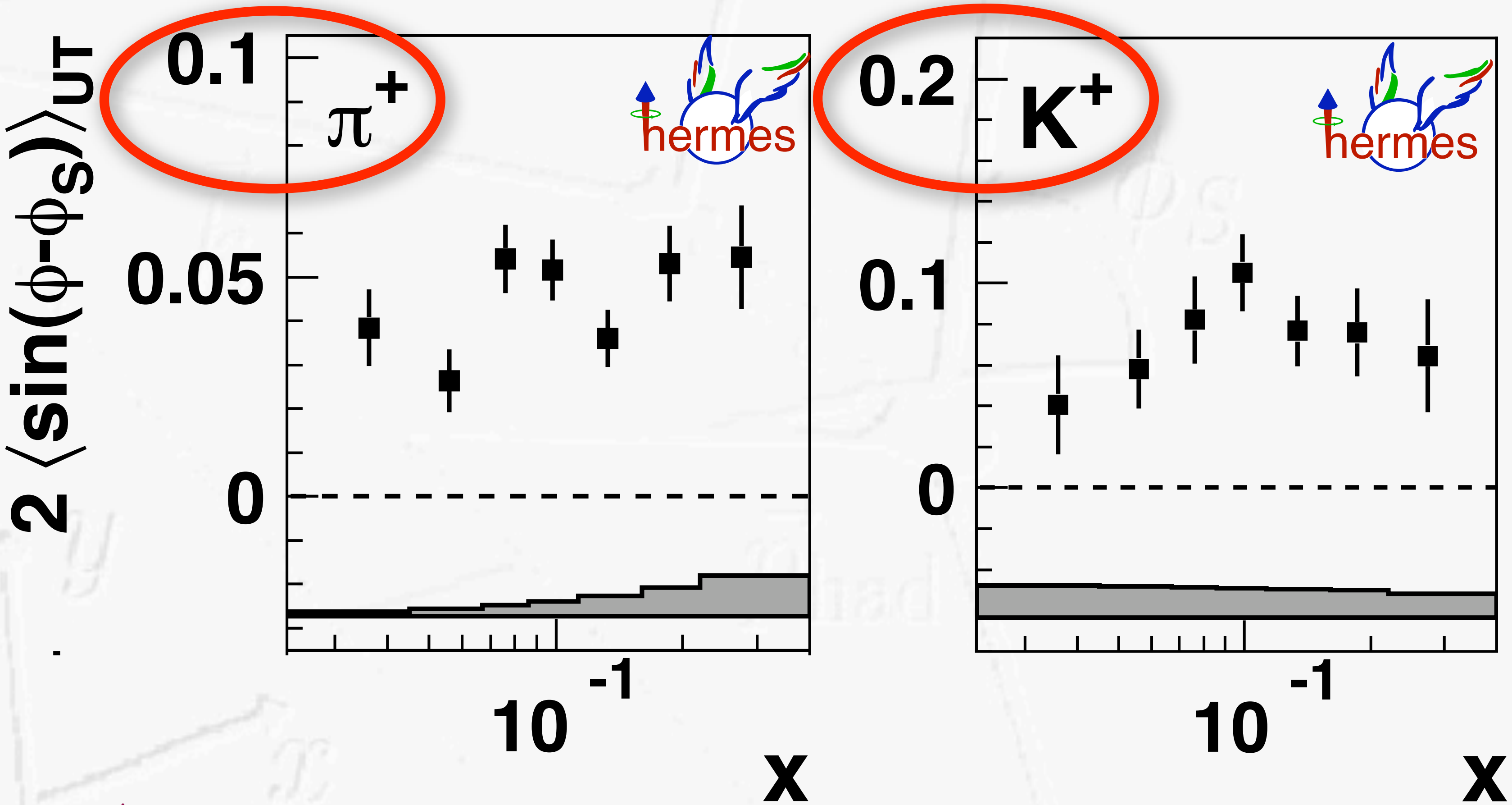

π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$

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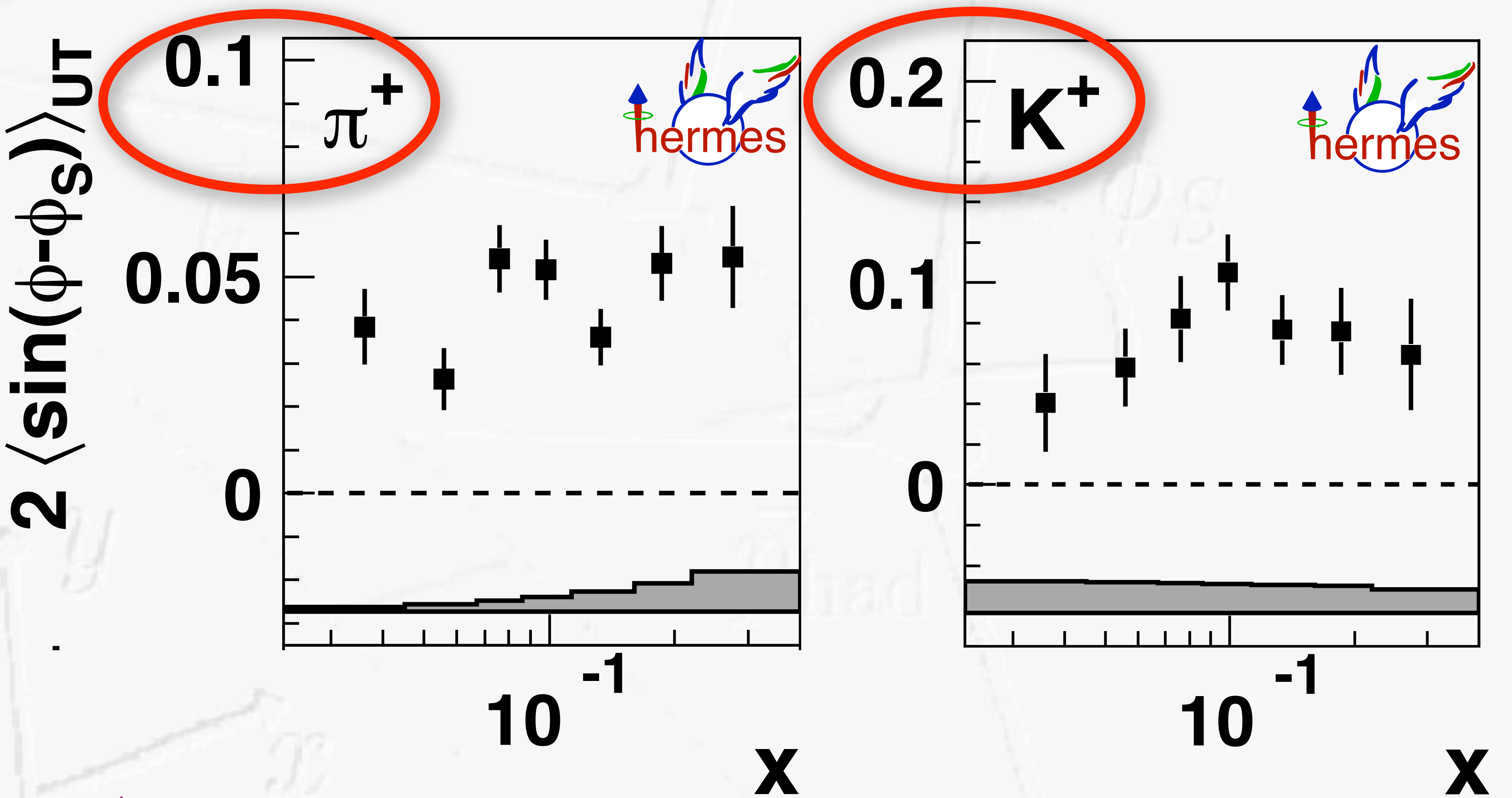

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- $K^+ = |u\bar{s}\rangle\ \&\ \pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

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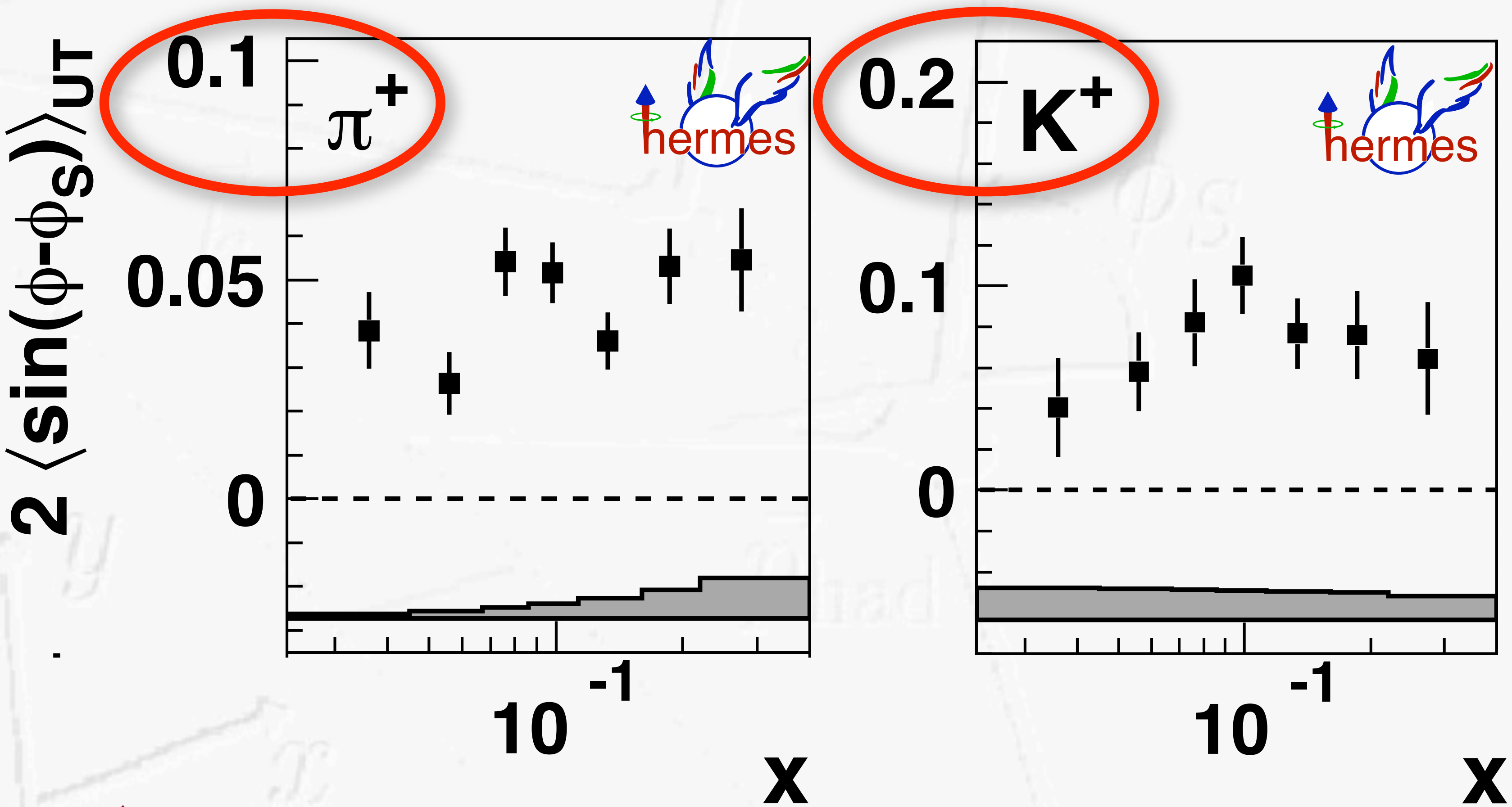

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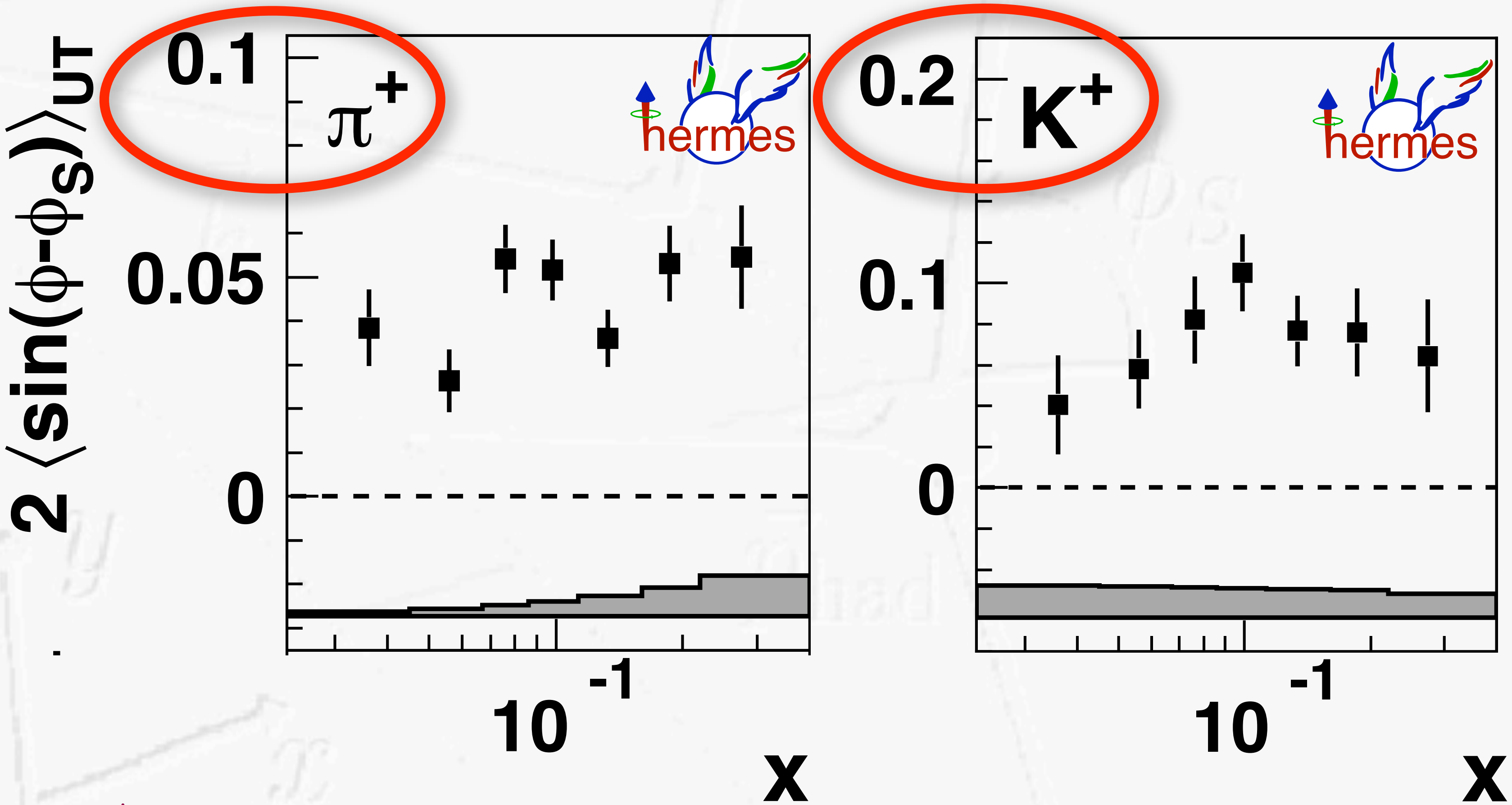

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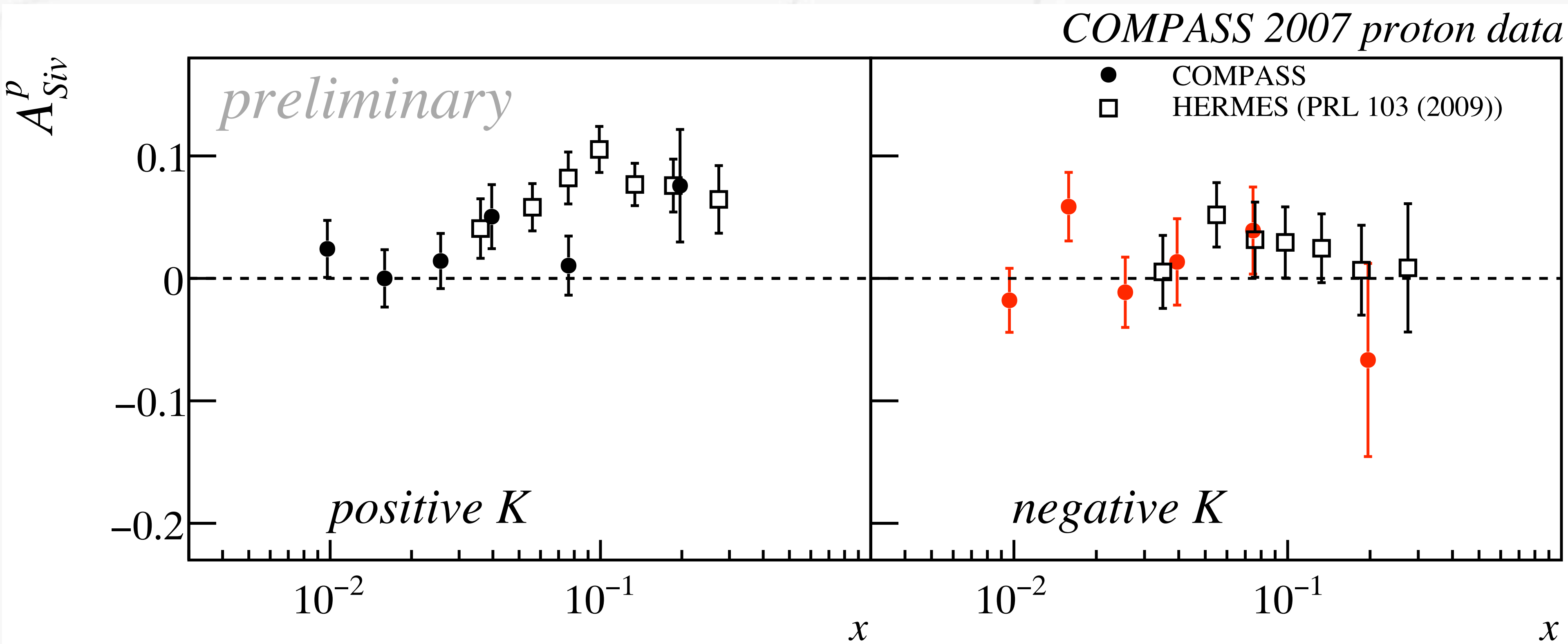

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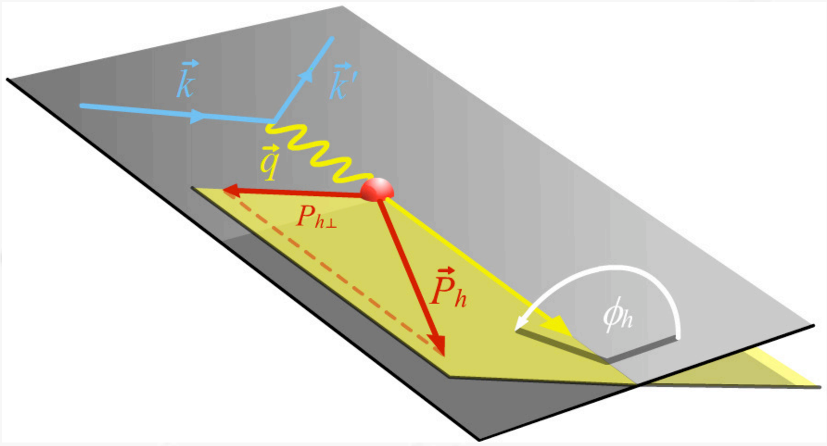
Modulations in spin-independent SIDIS cross section



$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)\,F_{UU,T} + B(y)F_{UU,L}$$

$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp\right]$$

BOER-MULDERS EFFECT

CAHN EFFECT

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\,h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\,f_1 D_1 + \dots\right]$$

Interaction dependent terms neglected

(Implicit sum over quark flavours)

Signs of Boer-Mulders

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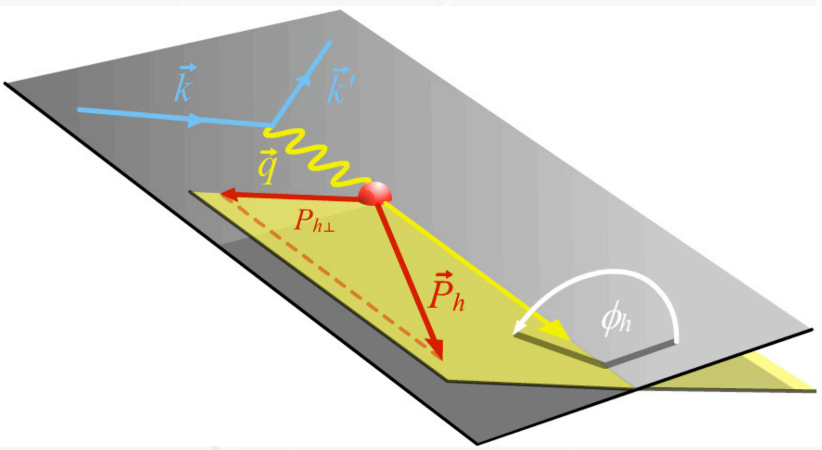

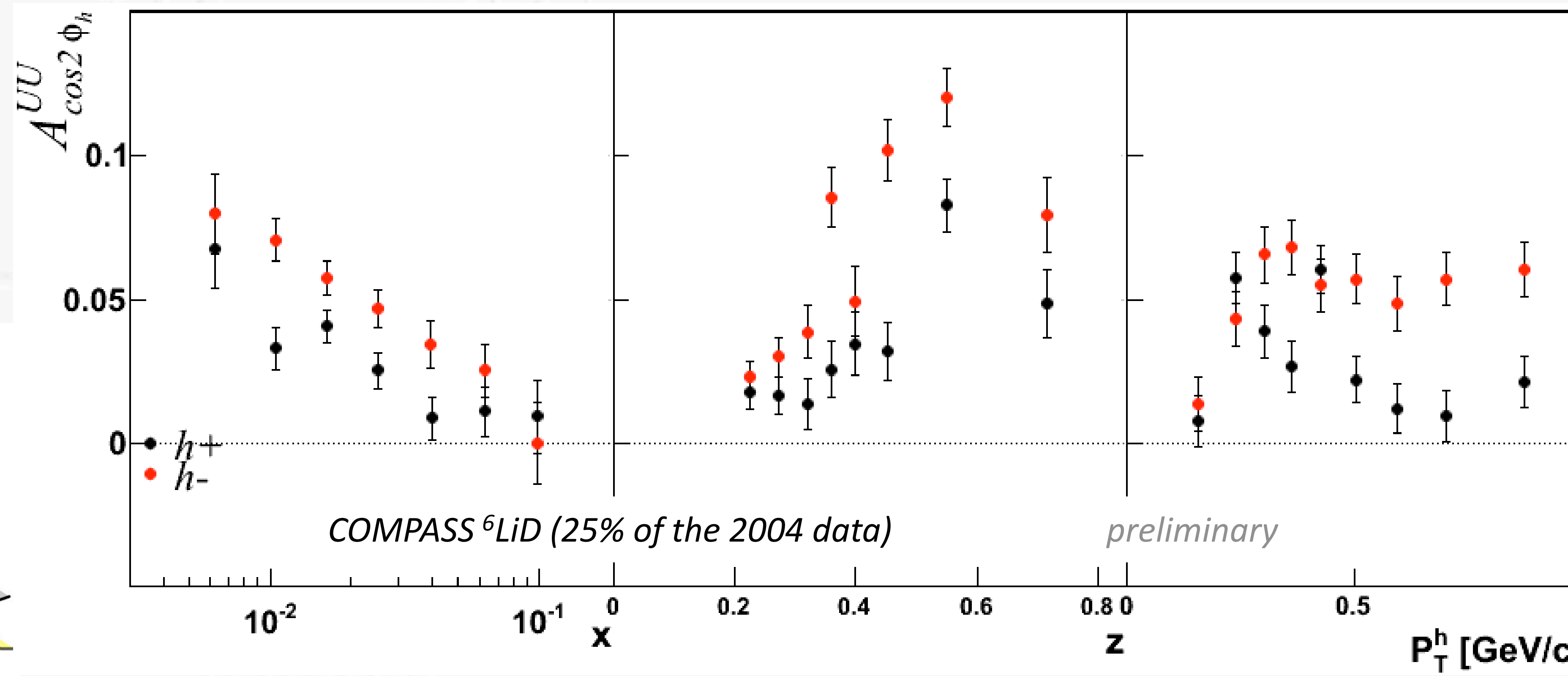

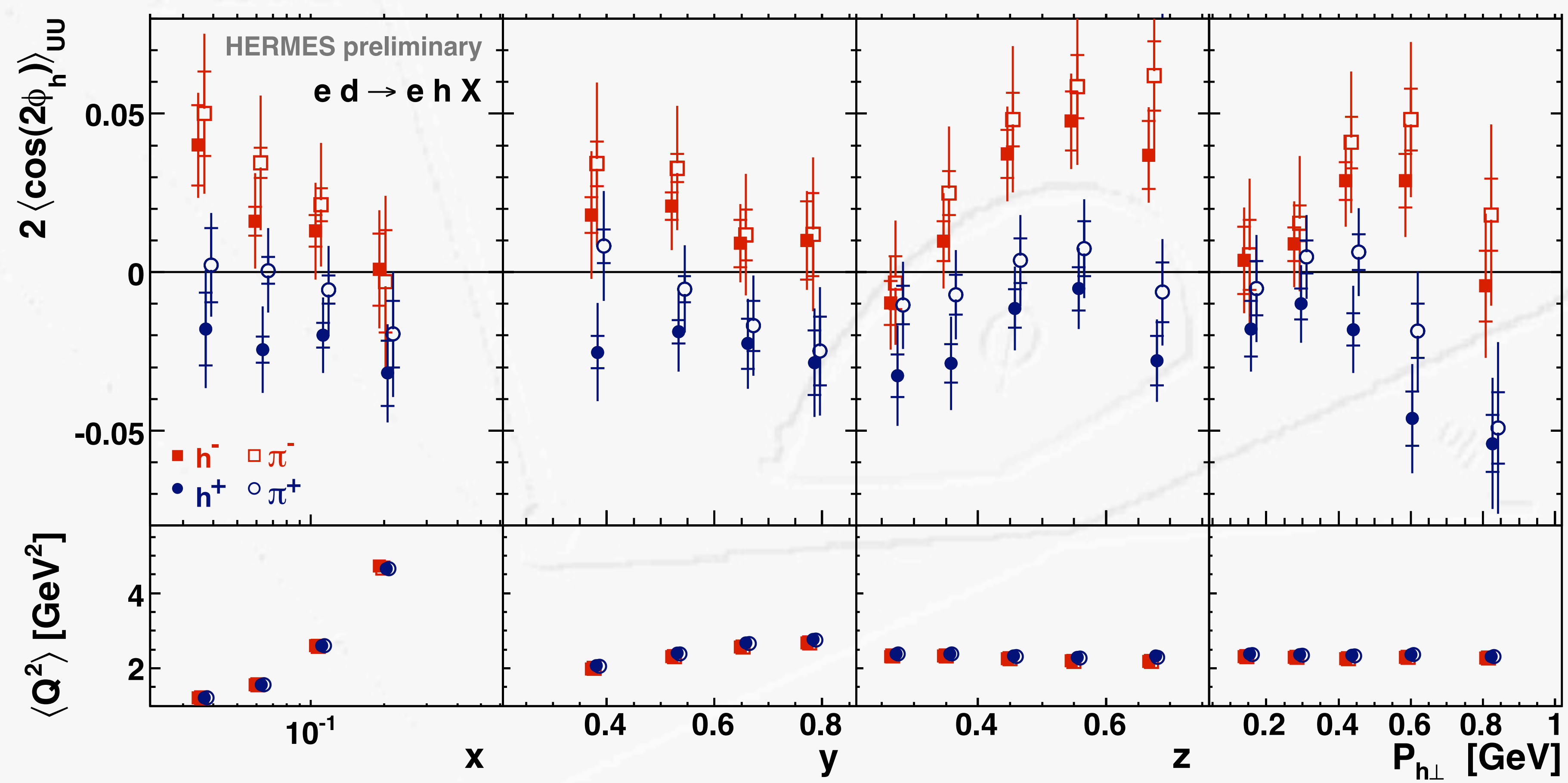

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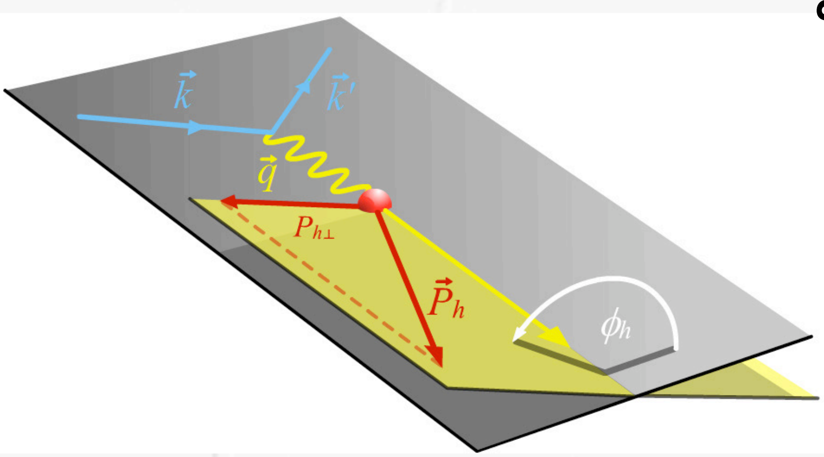
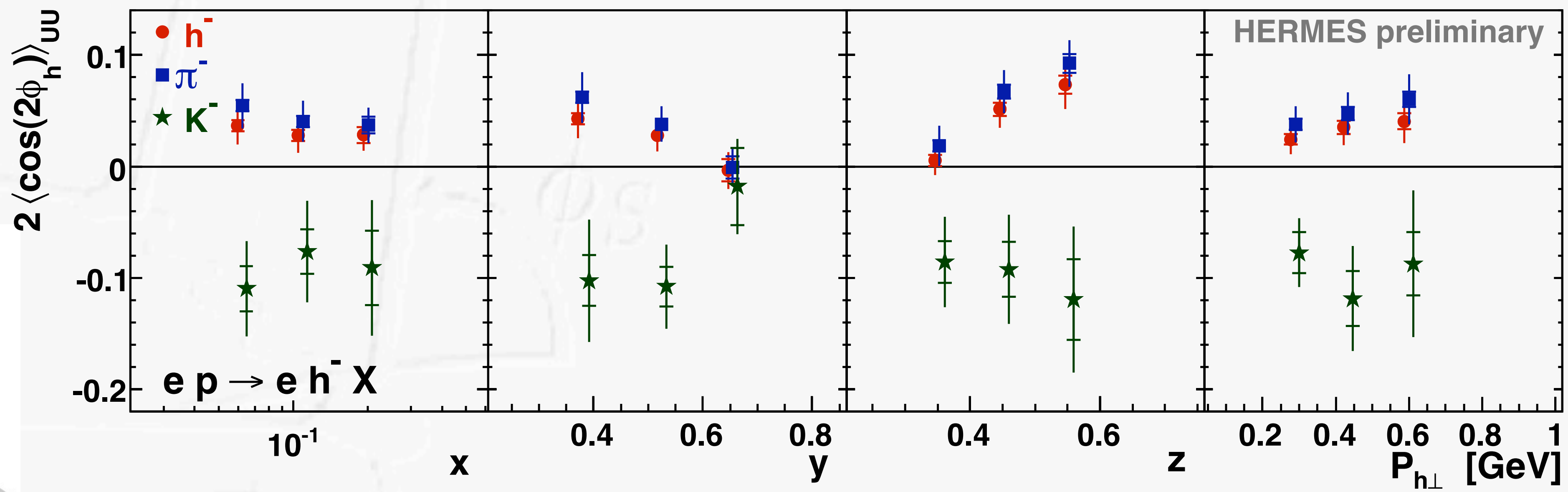
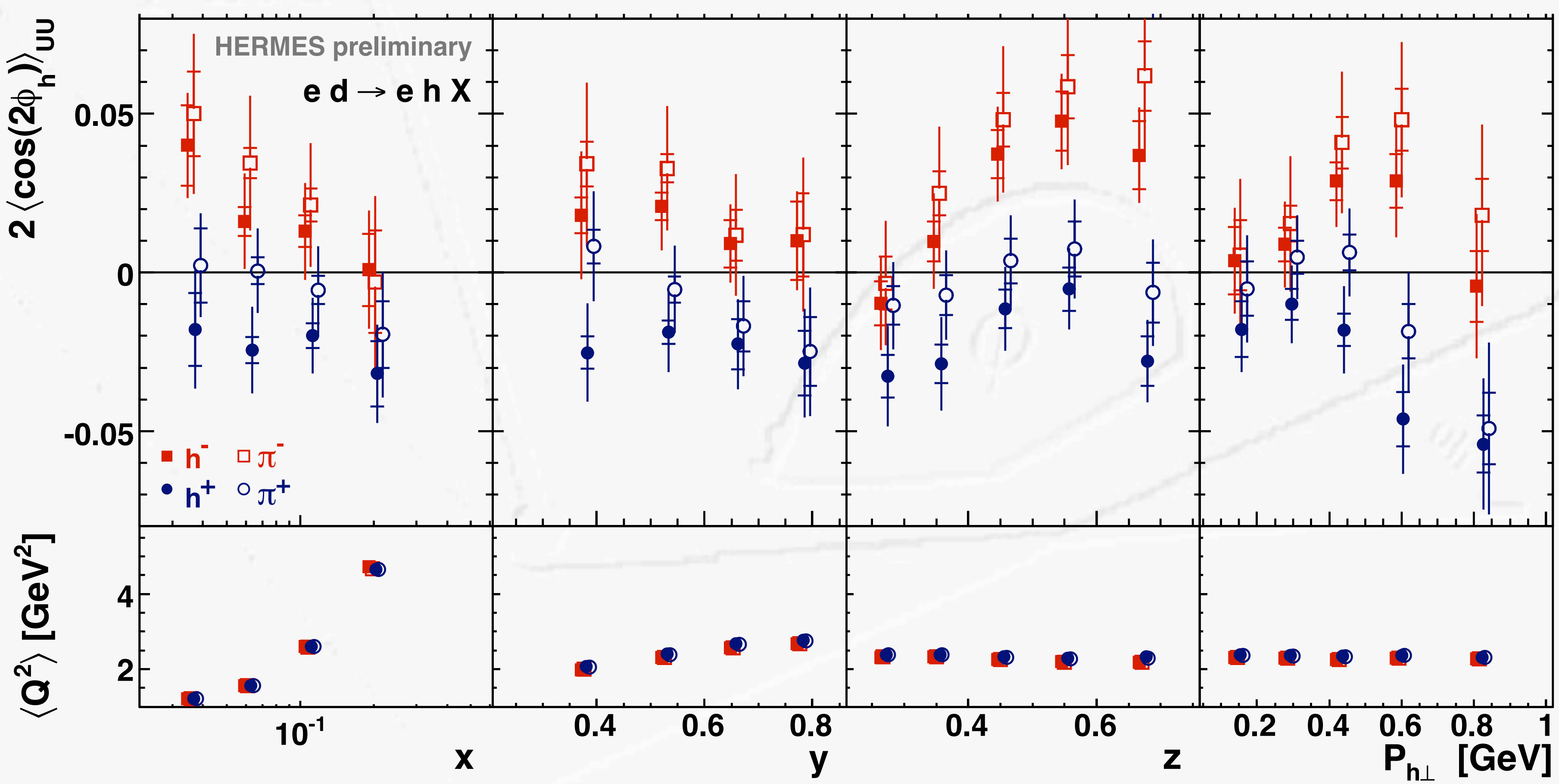
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Signs of Boer-Mulders







Cahn effect?

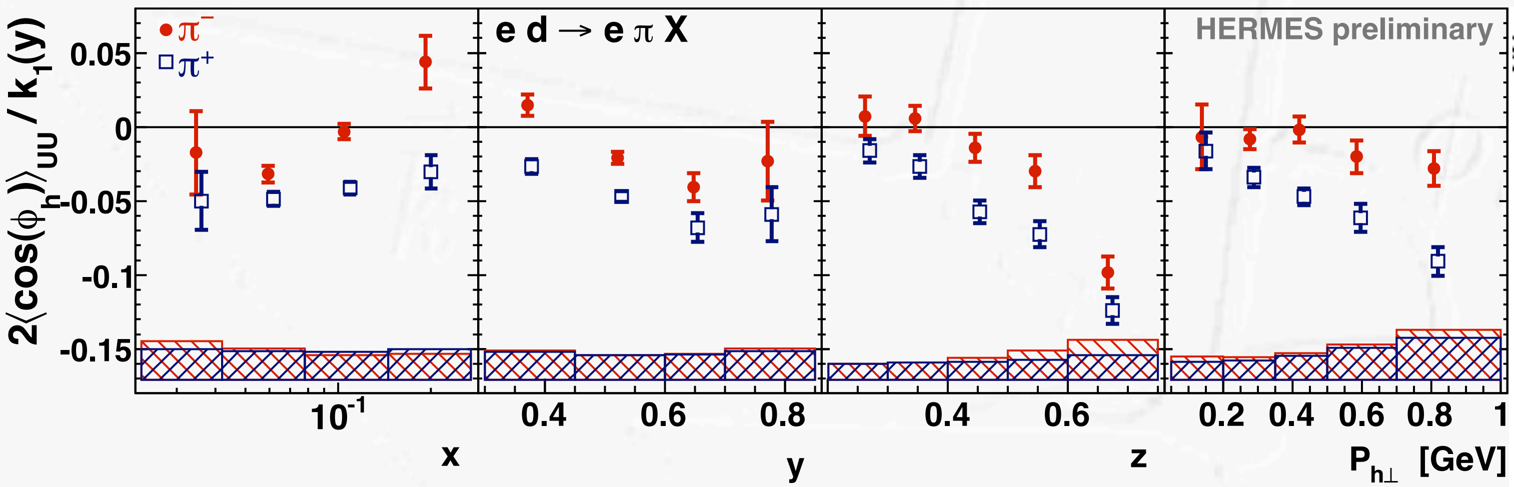
next to leading twist

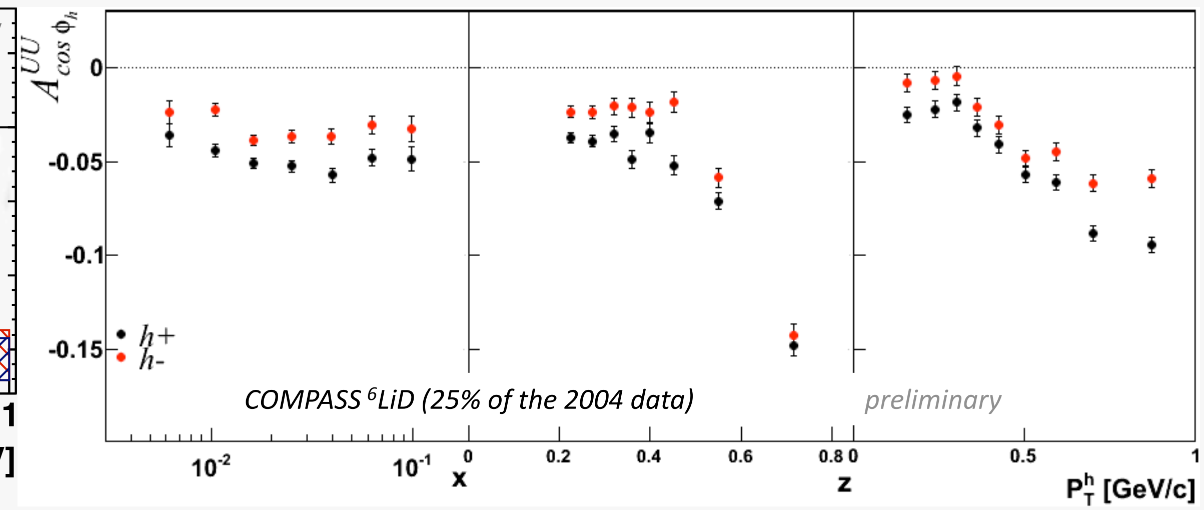
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

BOER-MULDERS EFFECT

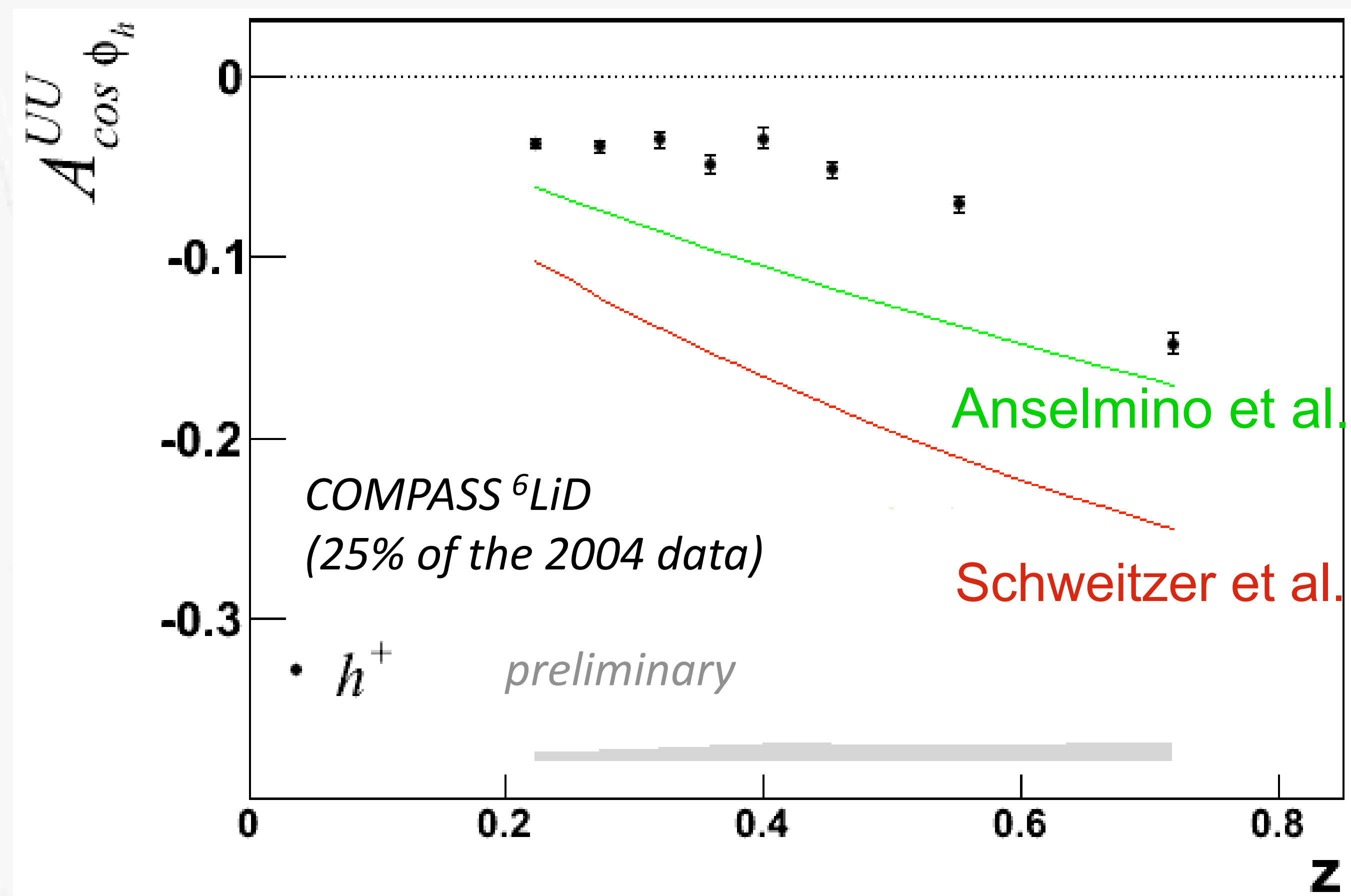
CAHN EFFECT

Interaction dependent terms neglected





- no dependence on hadron charge expected
- prediction off from data



Cahn effect?

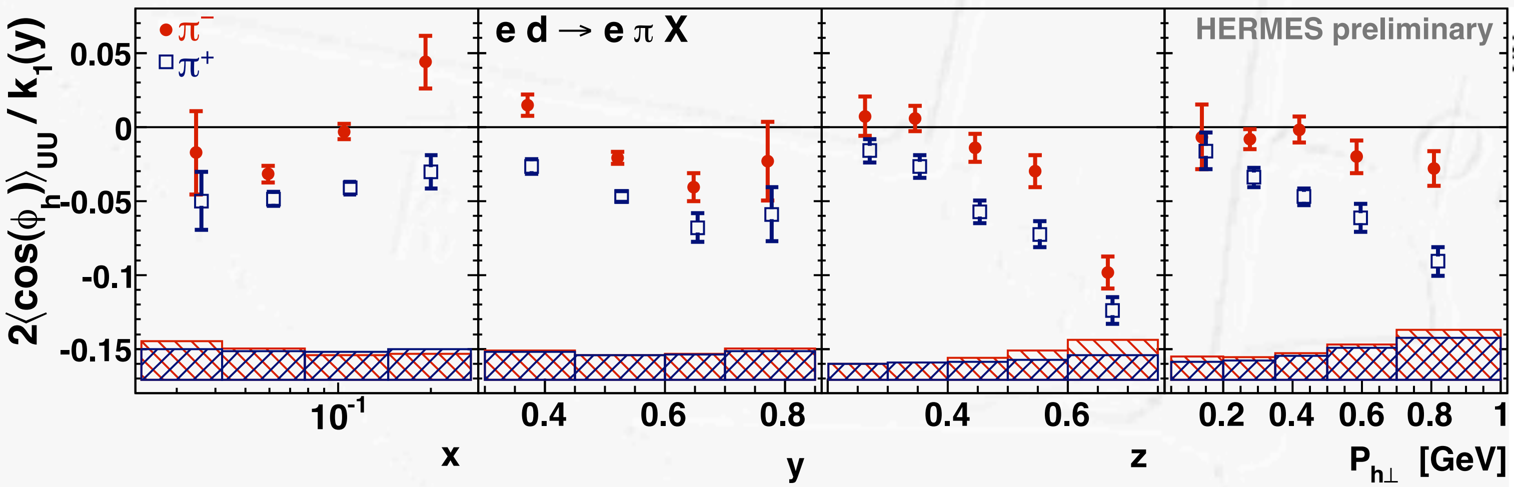
BOER-MULDERS EFFECT

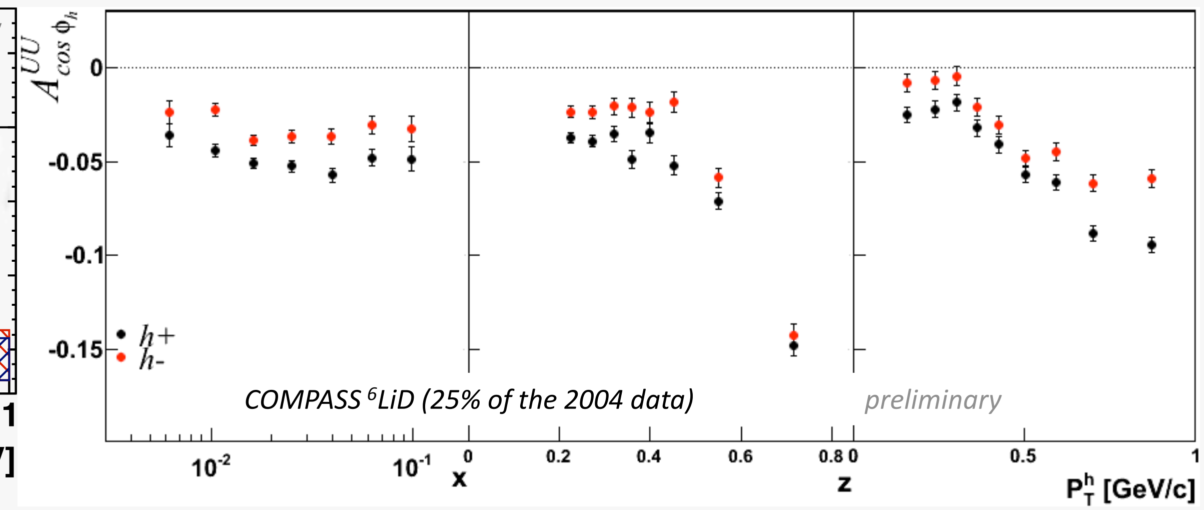
CAHN EFFECT

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

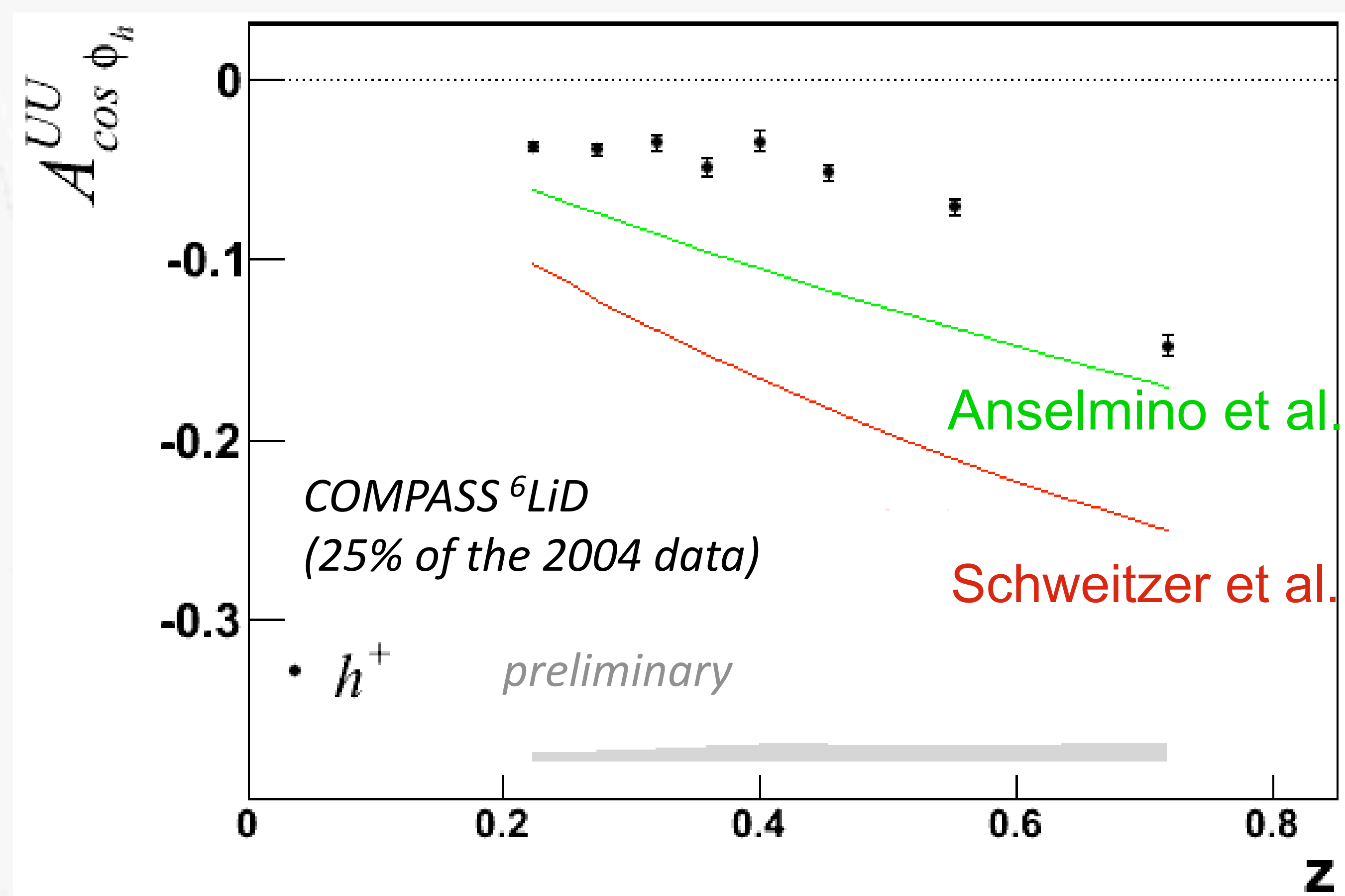
Interaction dependent terms neglected





- no dependence on hadron charge expected
- prediction off from data

➡ sign of Boer-Mulders in $\cos\phi$ modulation or "real" twist-3?



Summary

- transversity is non-zero and quite sizable
  - can be measured, e.g., via Collins effect or s-p interference in 2-hadron fragmentation
- Sivers and Boer-Mulders effects are also non-zero
  - direct probe of "physics of the QCD gauge links"
- so far no sign of a non-zero Mulders-Tangerman distribution
- but first evidence for non-vanishing worm-gear functions