Workshop on "Drell-Yan Opportunities at RHIC"
May 11th-13th, 2011 - BNL

What semi-inclusive DIS has taught us about TMDs

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eman ta zabal zazu
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Euskal Herriko Unibertsitatea

TMDs*)

*) transverse-momentum-dependent (TMD) -- aka unintegrated -- PDFs and FFs

- go beyond the approximation of collinear moving partons
- importance realized, e.g., in
  - late 70s [Cahn]: transverse momentum or partons lead to cosine modulations in unplarized semi-inclusive DIS
  - 90s [Sivers]: transverse motion of unpolarized partons in transversely polarized nucleons lead to transverse single-spin asymmetries
- complimentary to generalized parton distribution that probe transverse spatial d.o.f.

Spin-Momentum Structure of the Nucleon

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

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Bigg[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^i S^i h_1$$

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

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

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

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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

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Twist-2 TMDs

Boer-Mulders

Sivers

worm-gear

transversity

Mulders-Tangerman*

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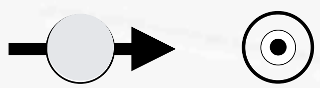
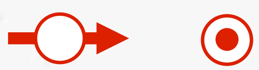
*aka Pretzelosity

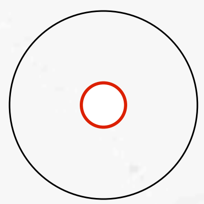
TMDs - Probabilistic interpretation

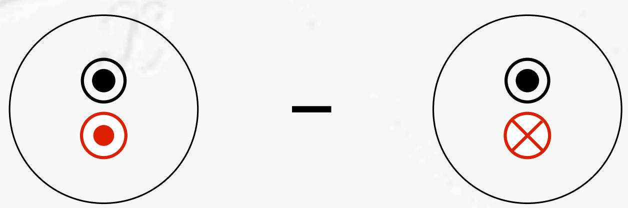
Proton goes out of the screen/ photon goes into the screen

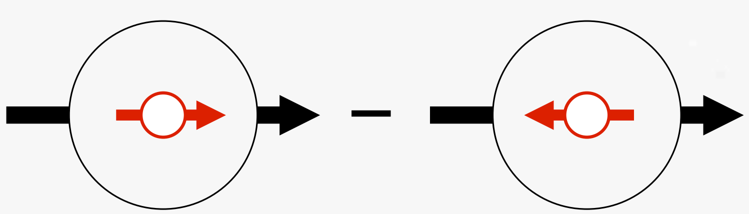
 nucleon with transverse or longitudinal spin

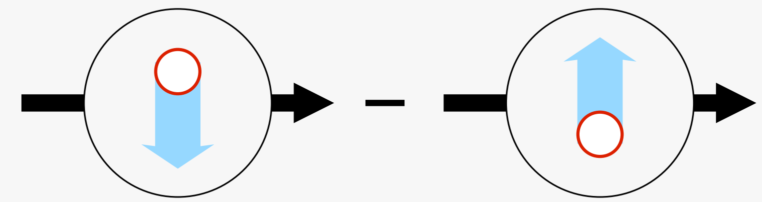
 parton with transverse or longitudinal spin

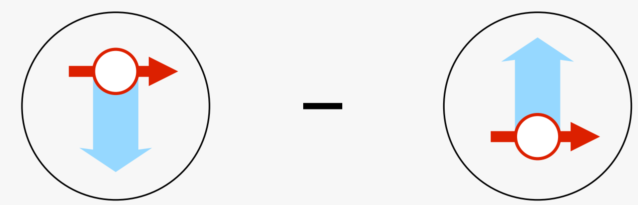
 parton transverse momentum

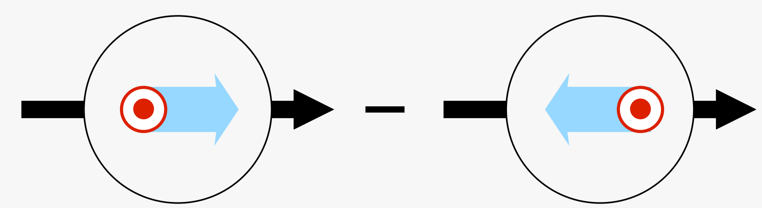
$f_1 =$ 

$g_1 =$ 

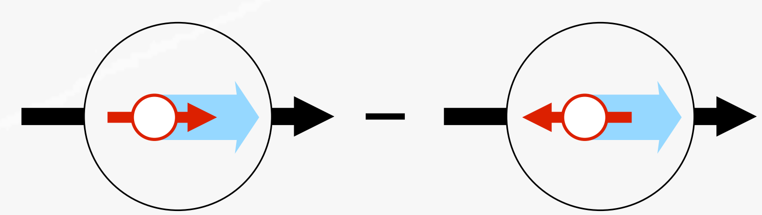
$h_1 =$ 

$f_{1T}^{\perp} =$ 

$h_1^{\perp} =$ 

$g_{1T} =$ 

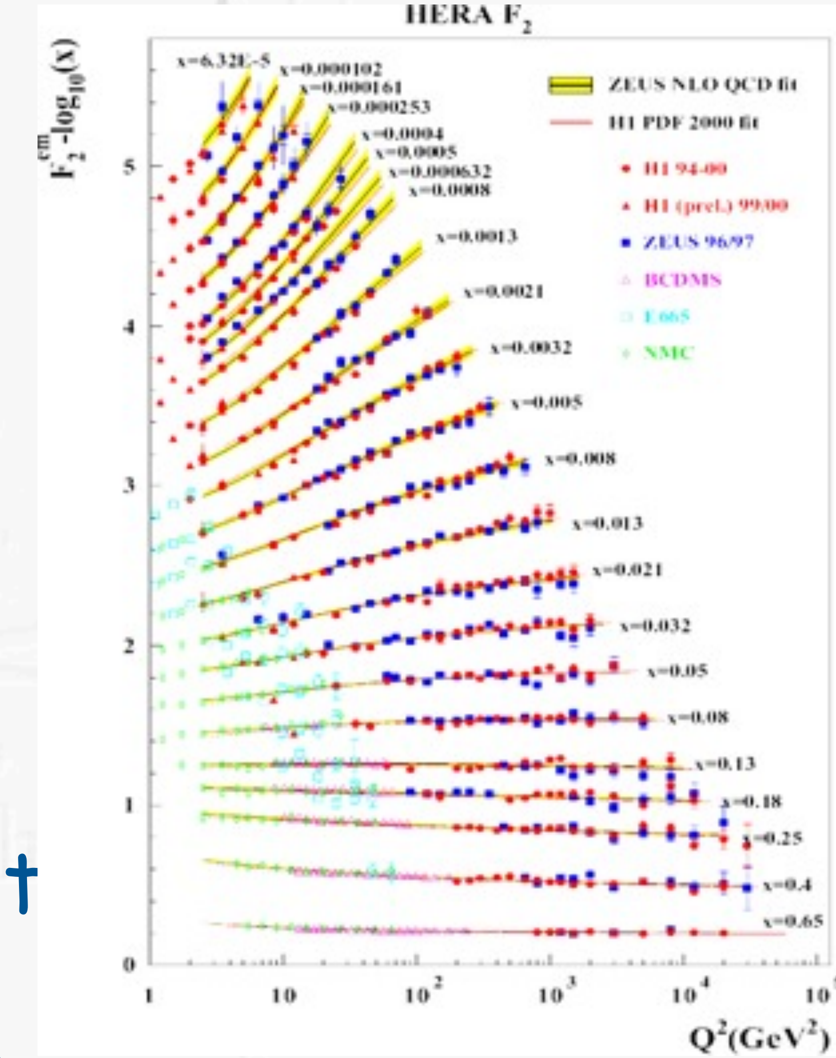
$h_{1L}^{\perp} =$ 

$h_{1T}^{\perp} =$ 

[courtesy of A. Bacchetta]

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

Momentum density



- plenty of data available
- but only for integrated version of f_1
- some efforts to get unintegrated gluon densit
- spin asymmetries involve unintegrated f_1 in denominator
- need multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$

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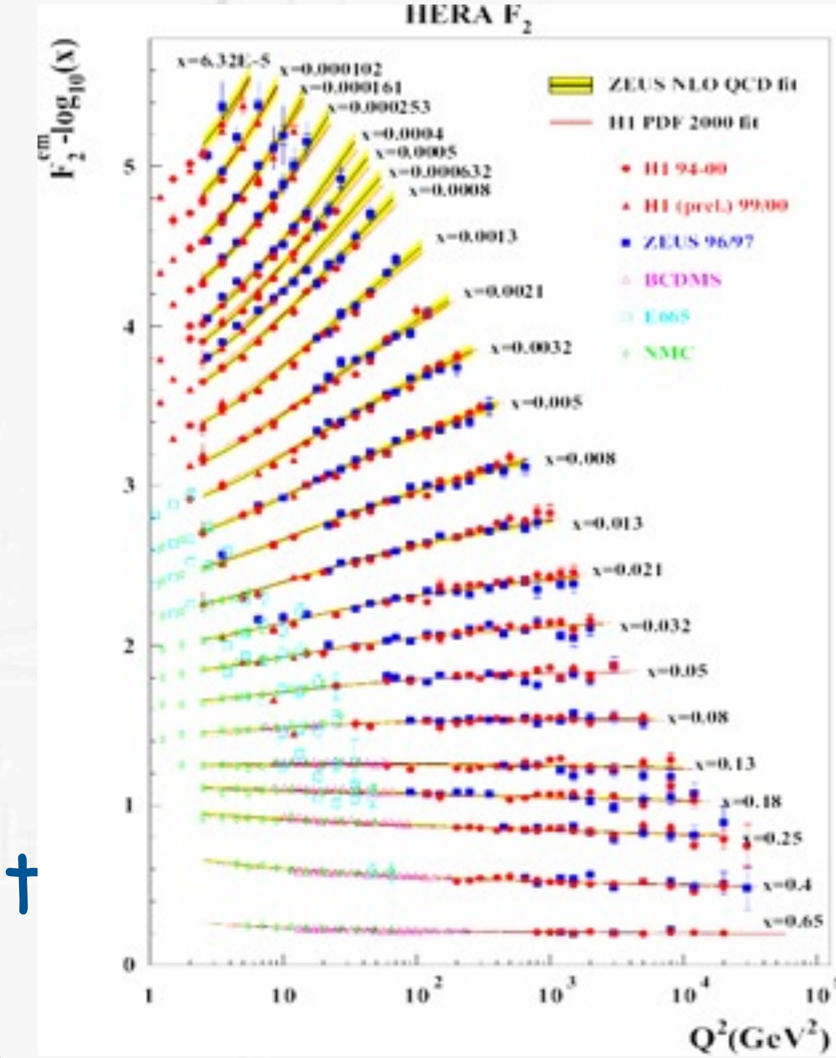

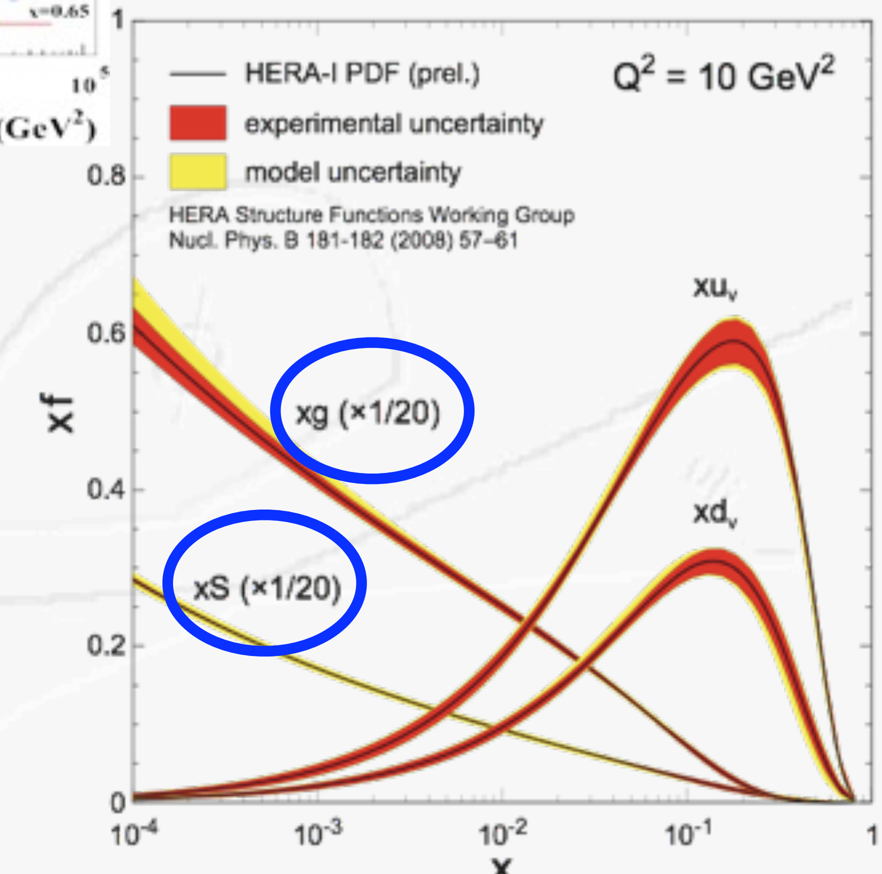

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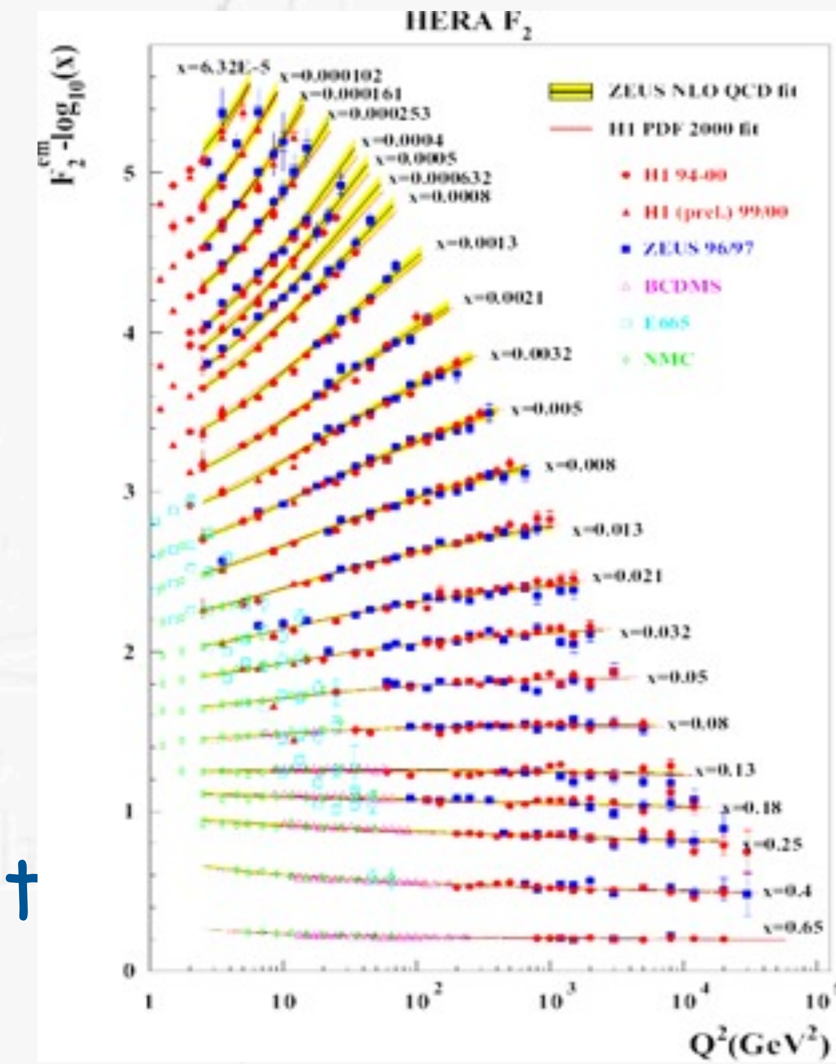

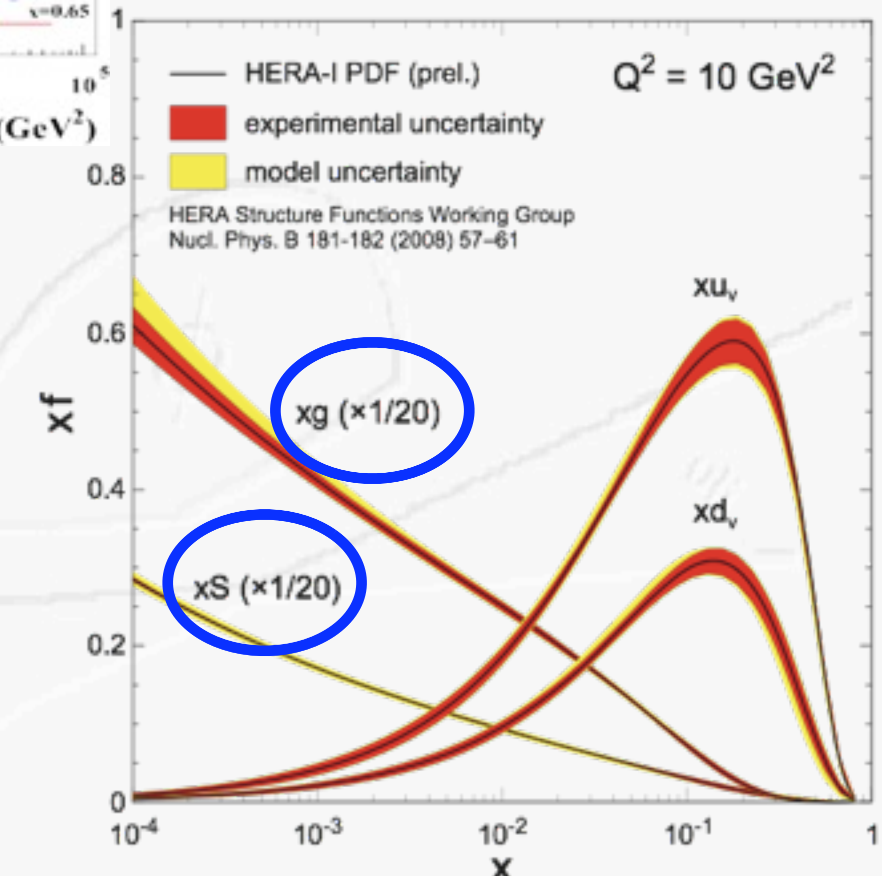

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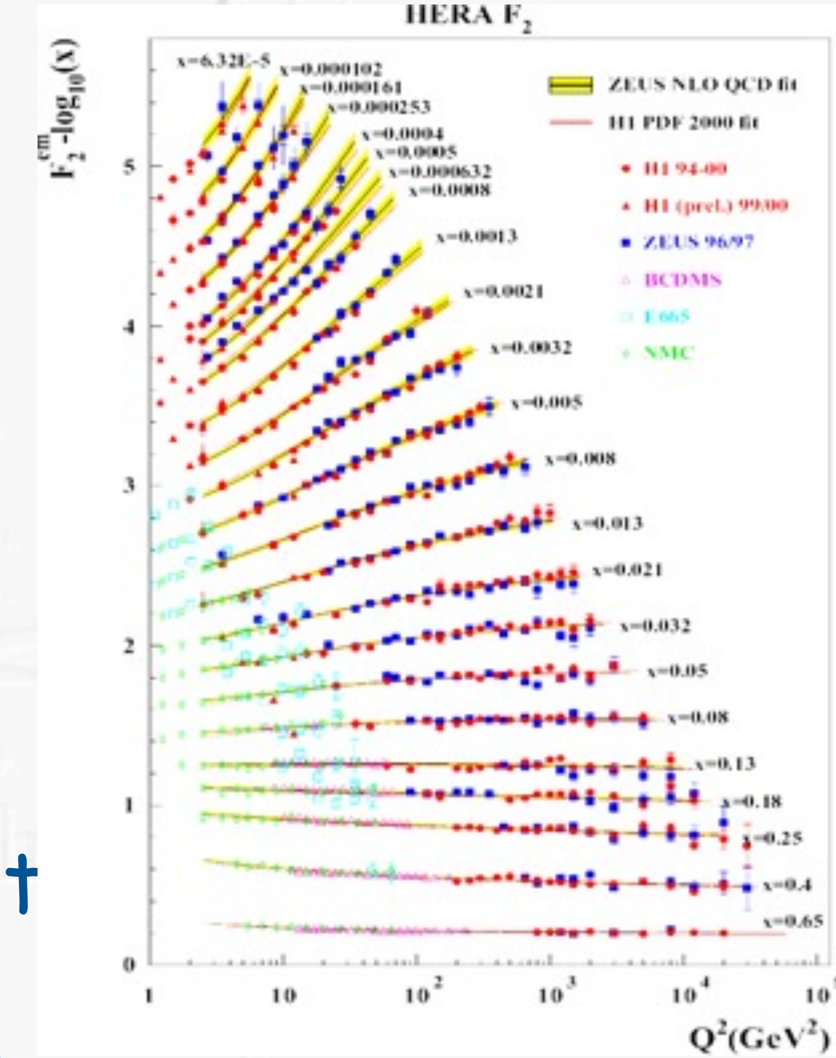

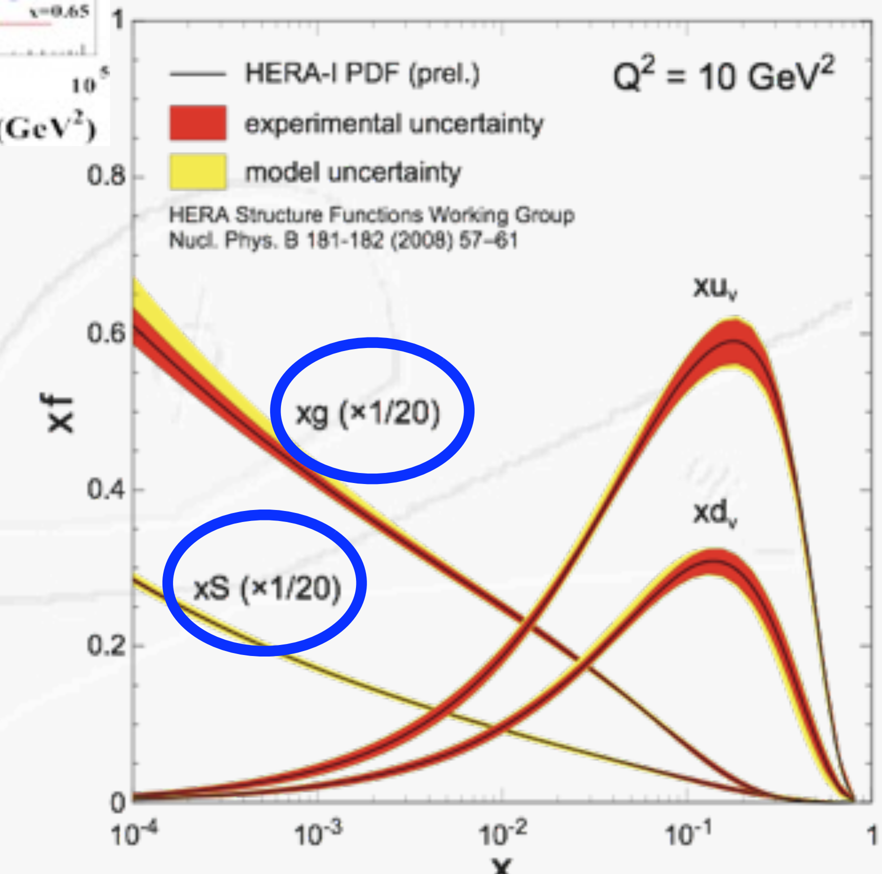

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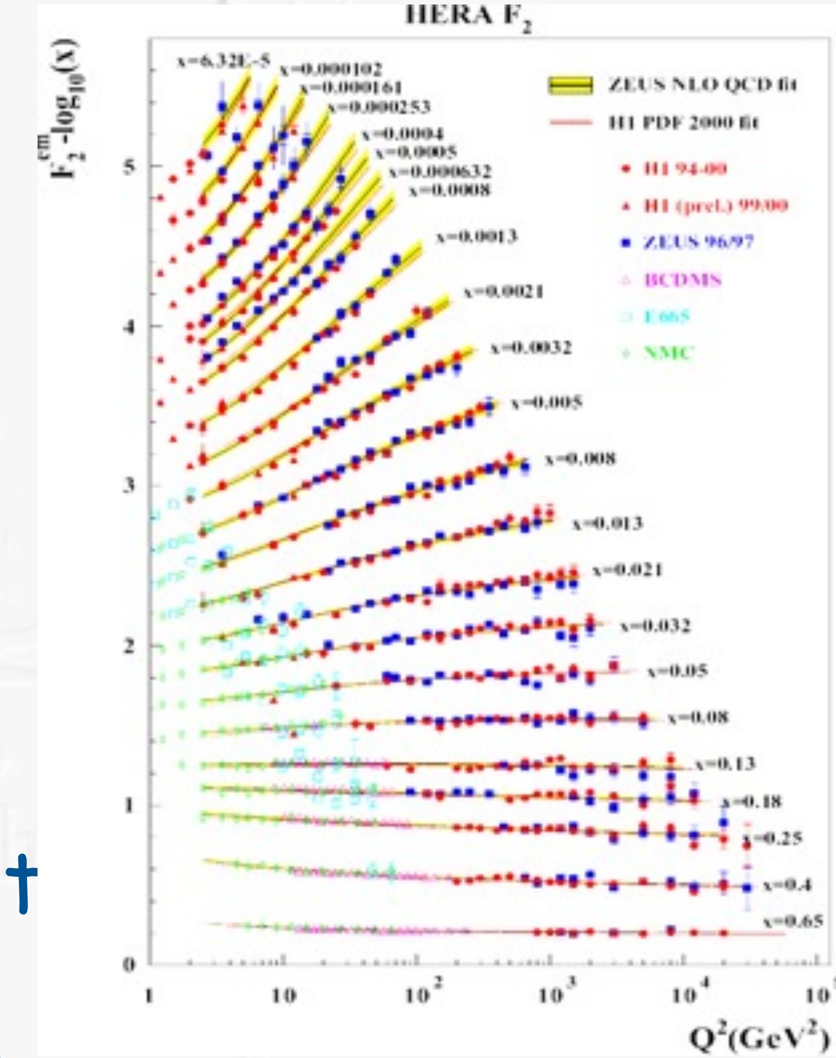

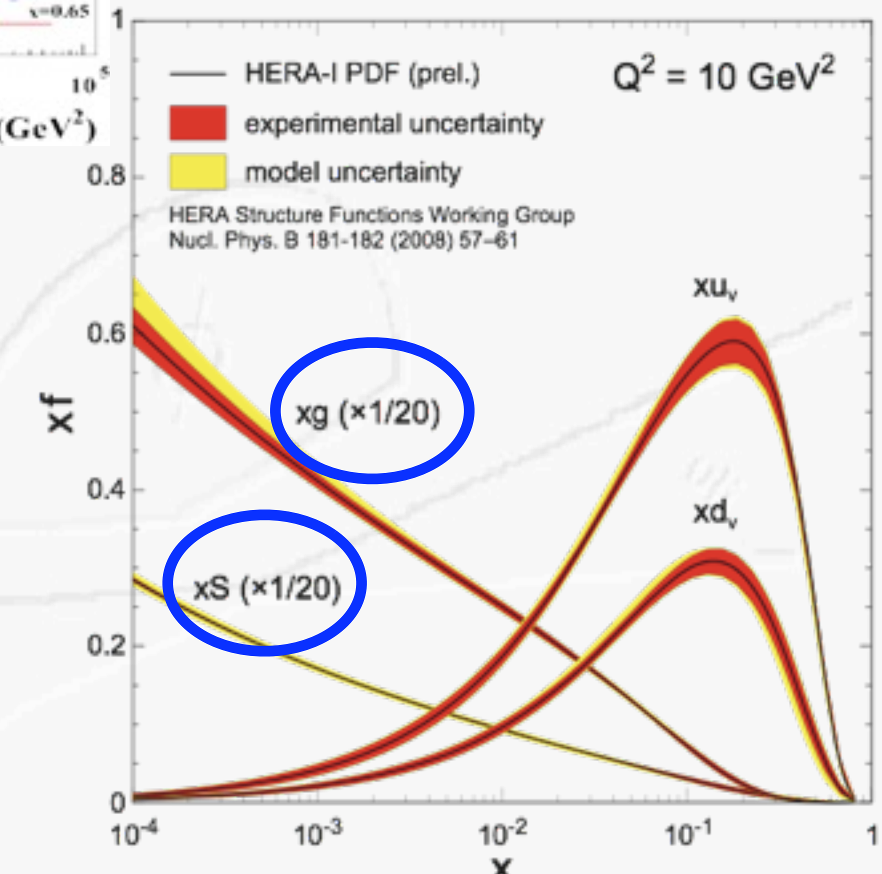

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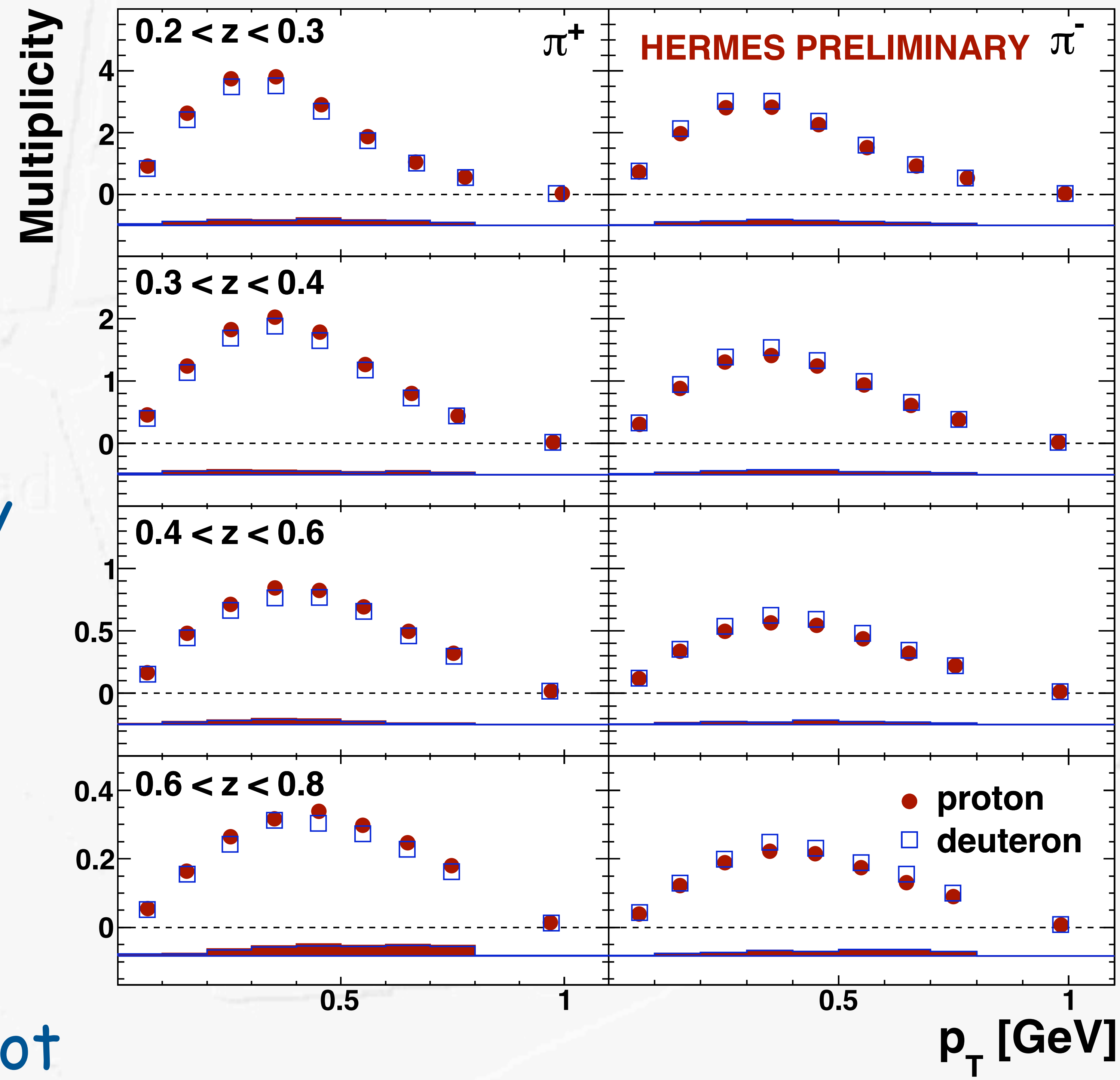

also available for kaons

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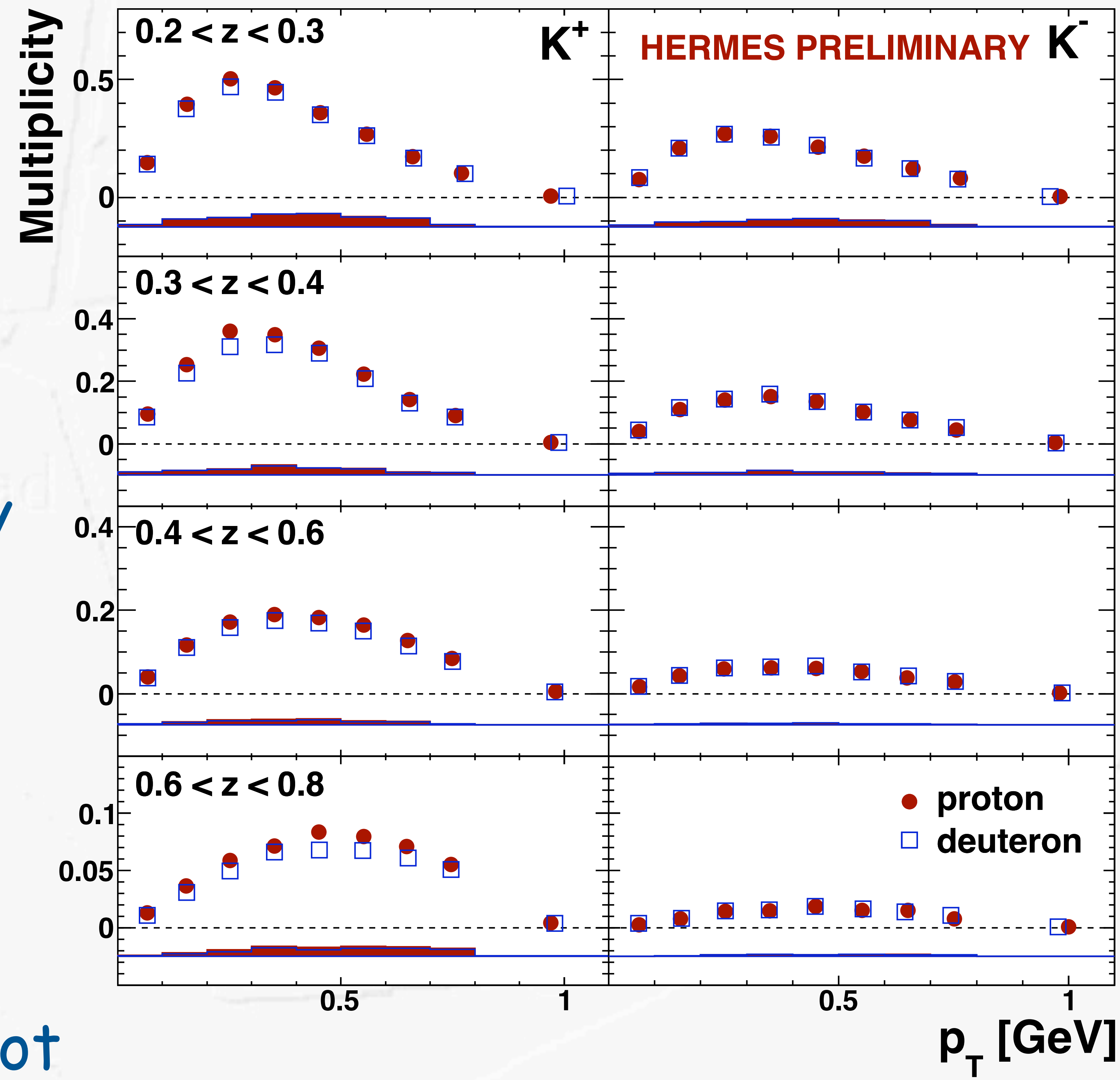

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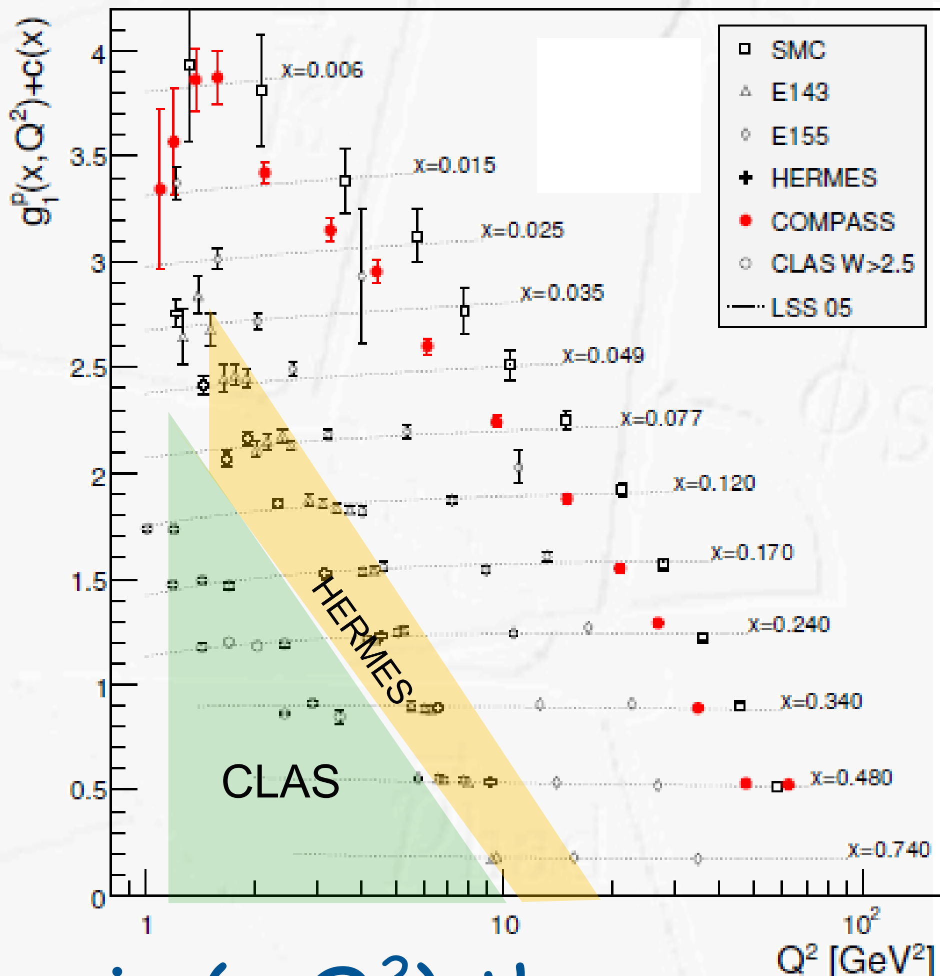
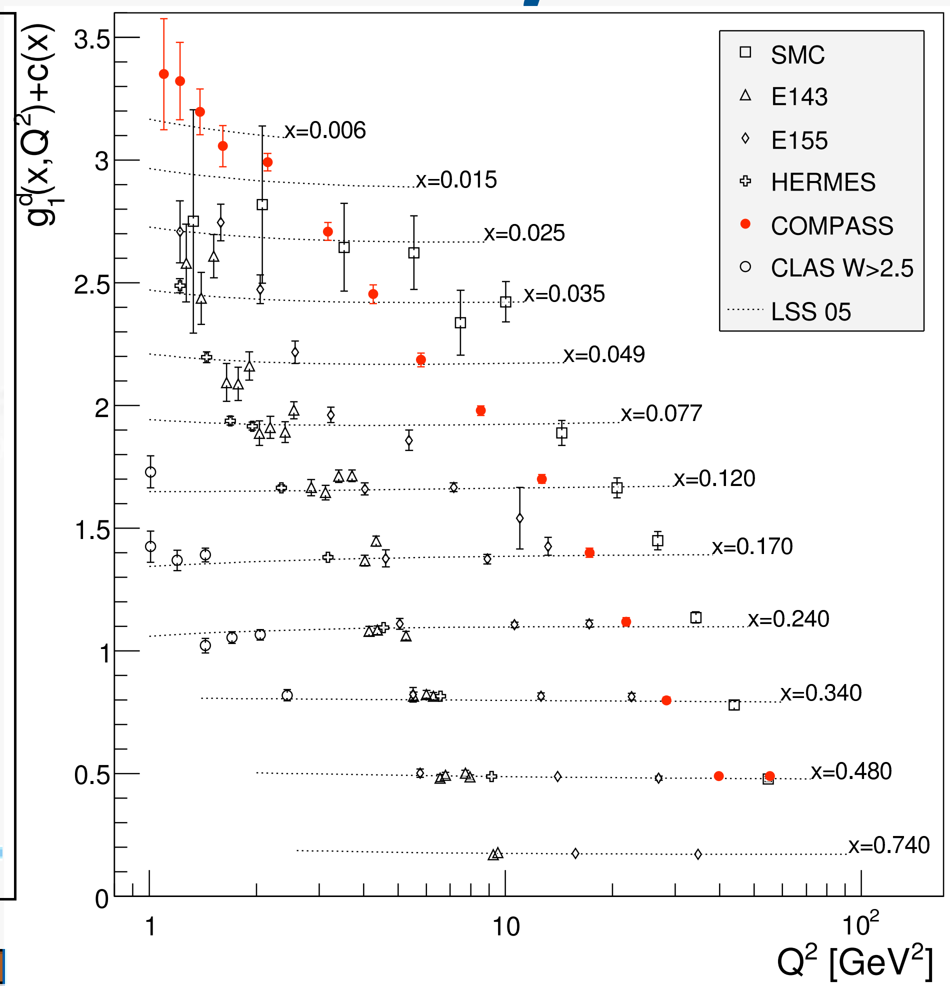
Helicity density





- smaller range in (x,Q^2) than for f_1
- data mainly for integrated version of g_{1L}
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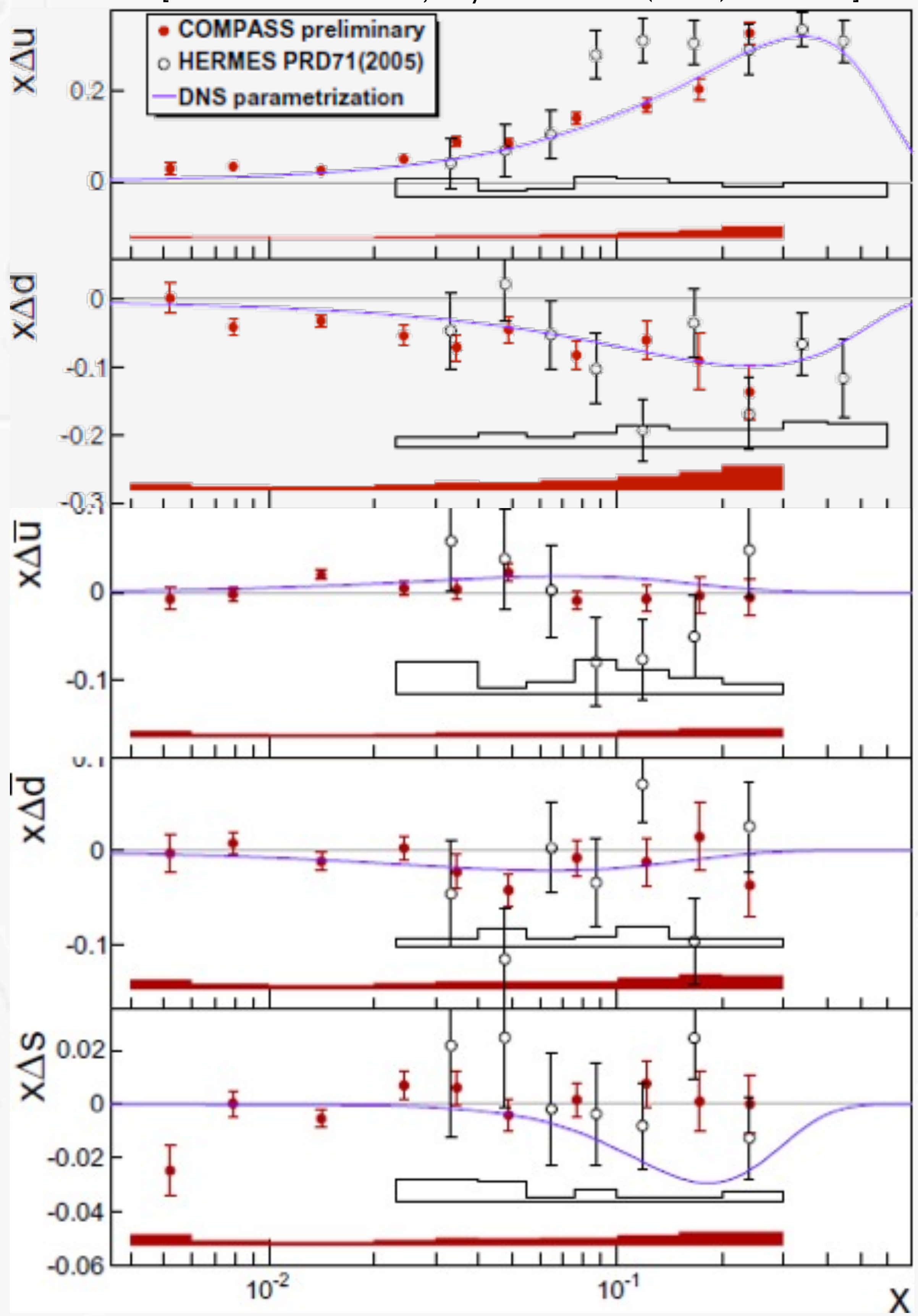
Helicity density

[M.G. Alekseev et al., Phys.Lett. B693 (2010) 227-235]



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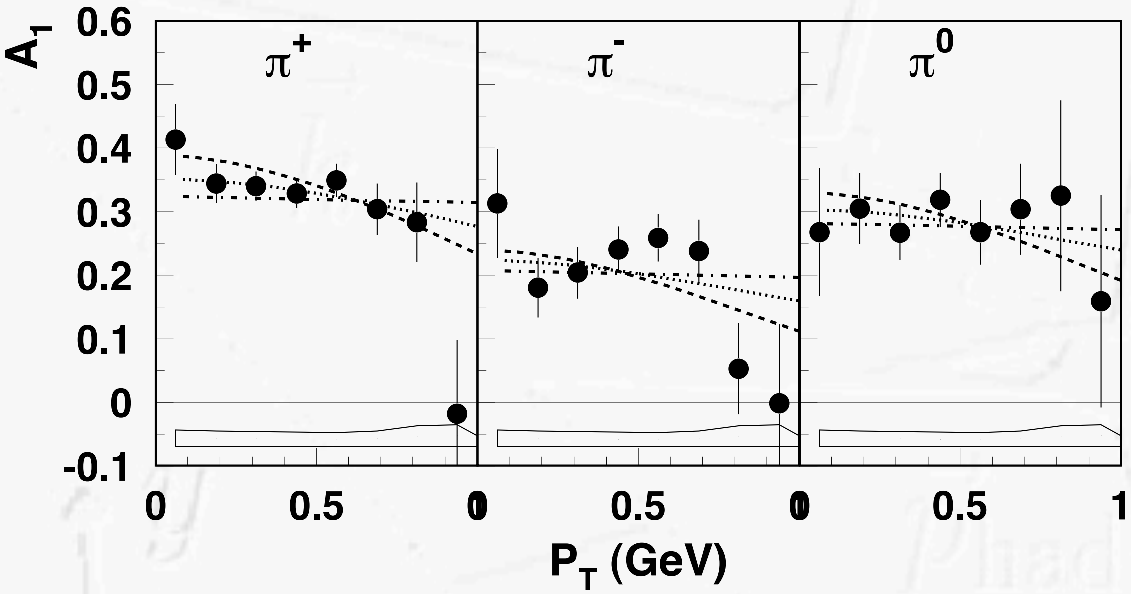
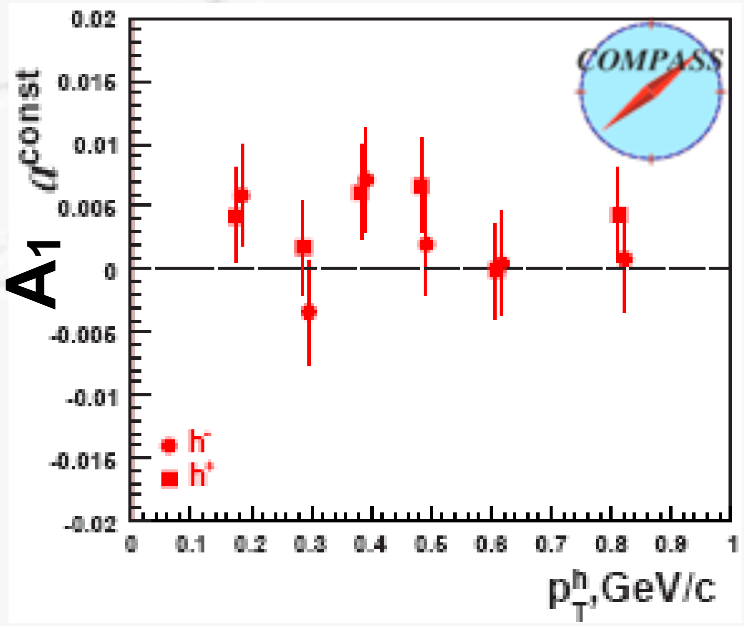
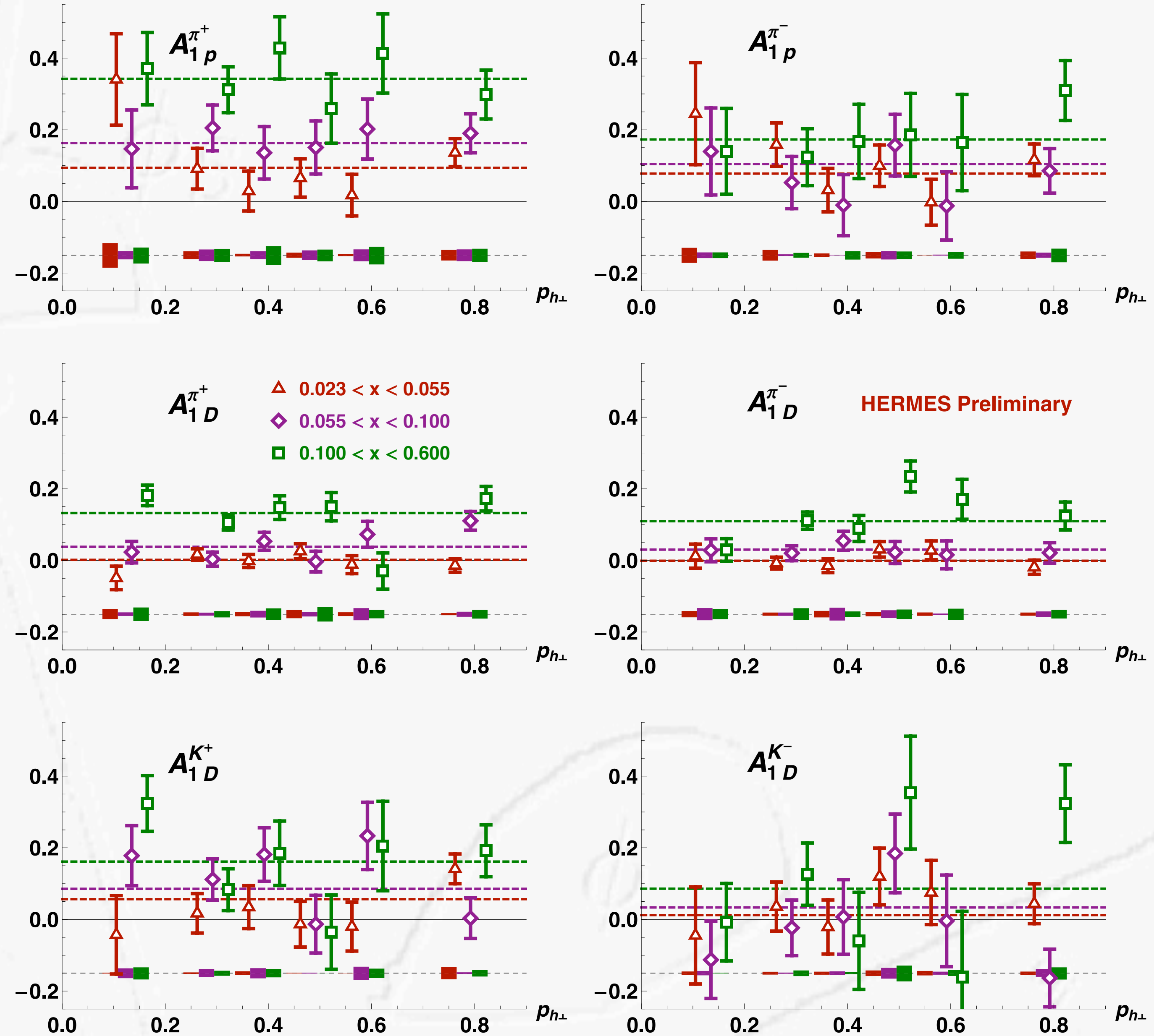
Helicity density (unintegrated)

Avakian et al. [CLAS], PRL 105 (2010) 262002







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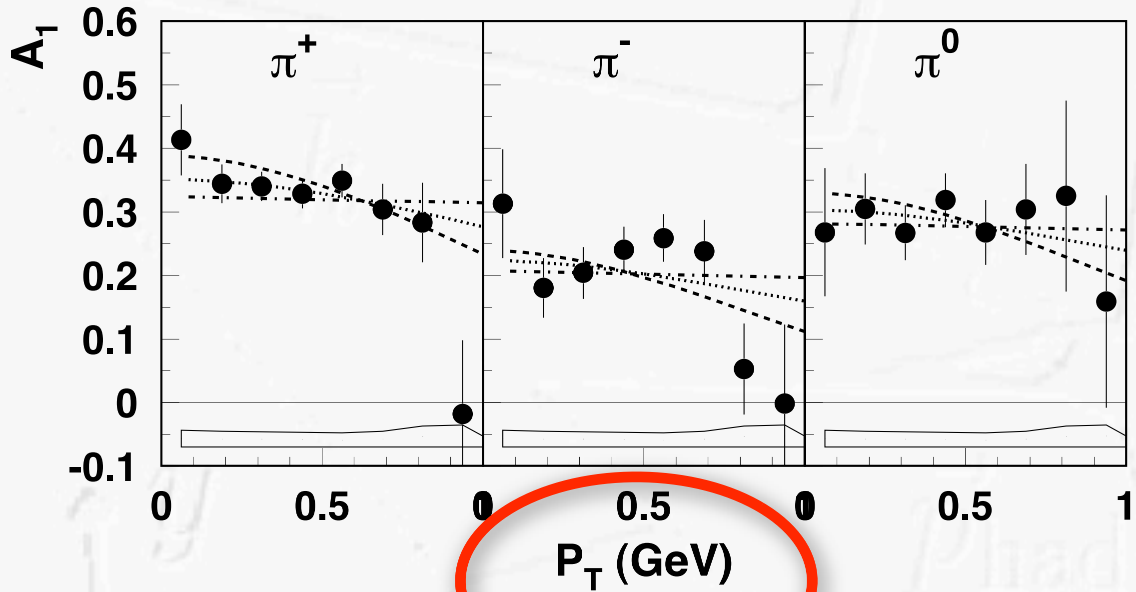

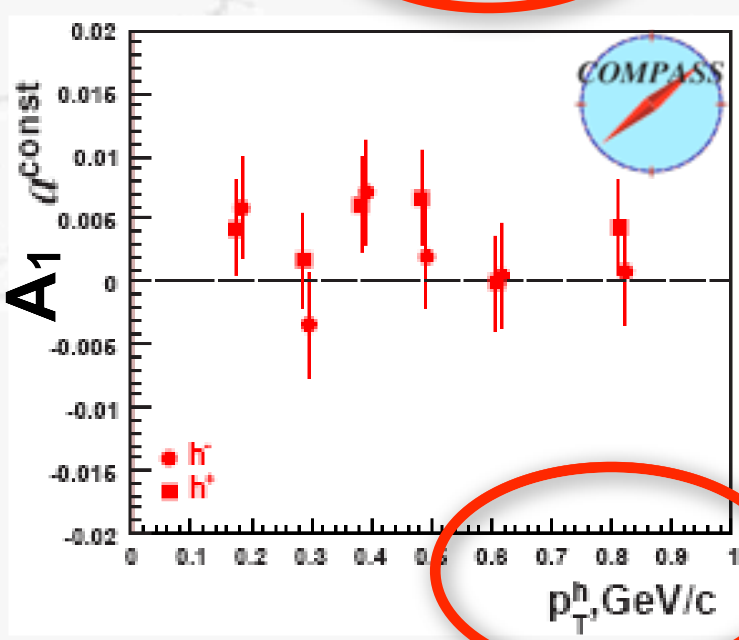

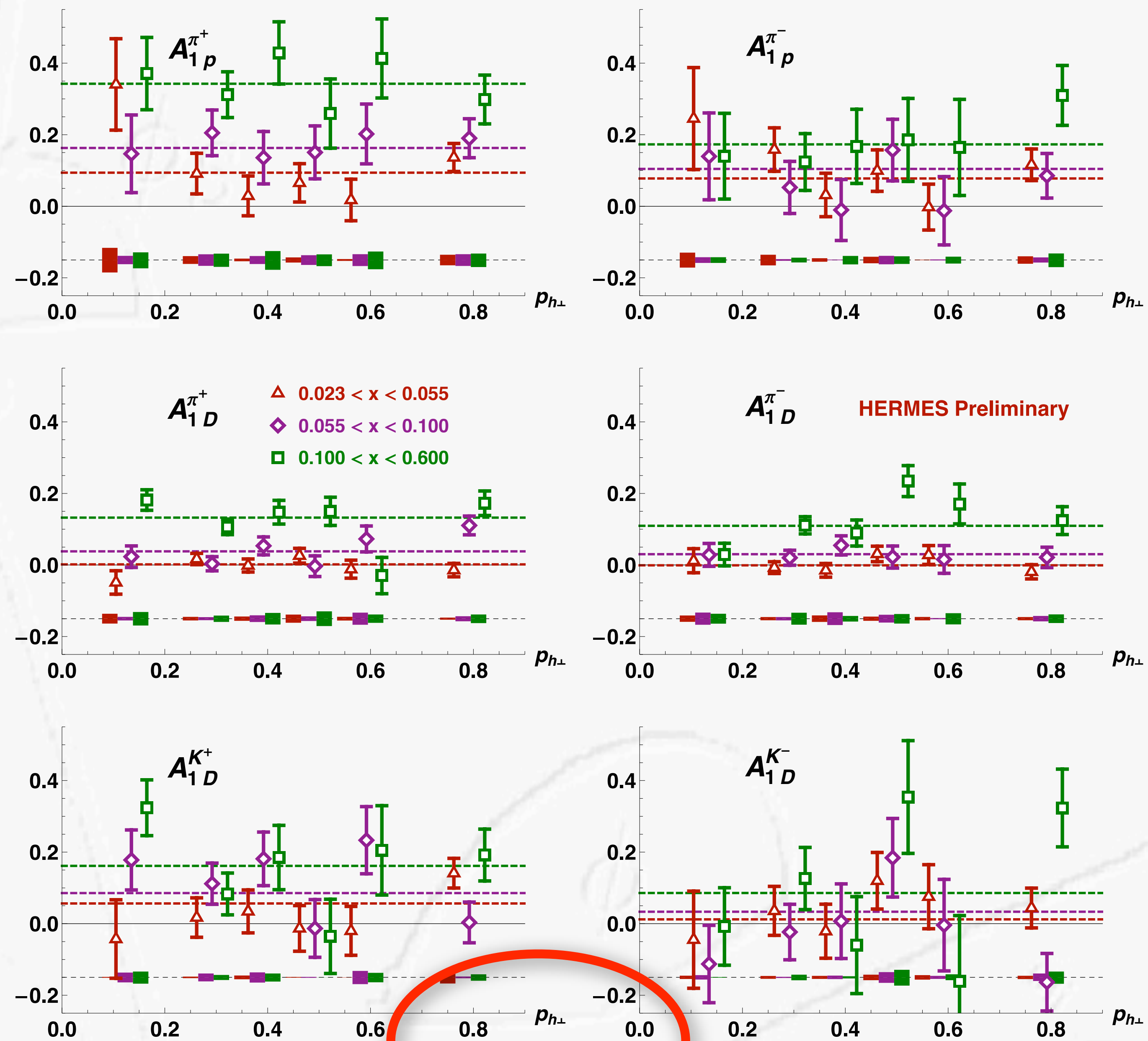

only weak if any dependence on $P_{h\perp}$ seen

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Helicity density (unintegrated)

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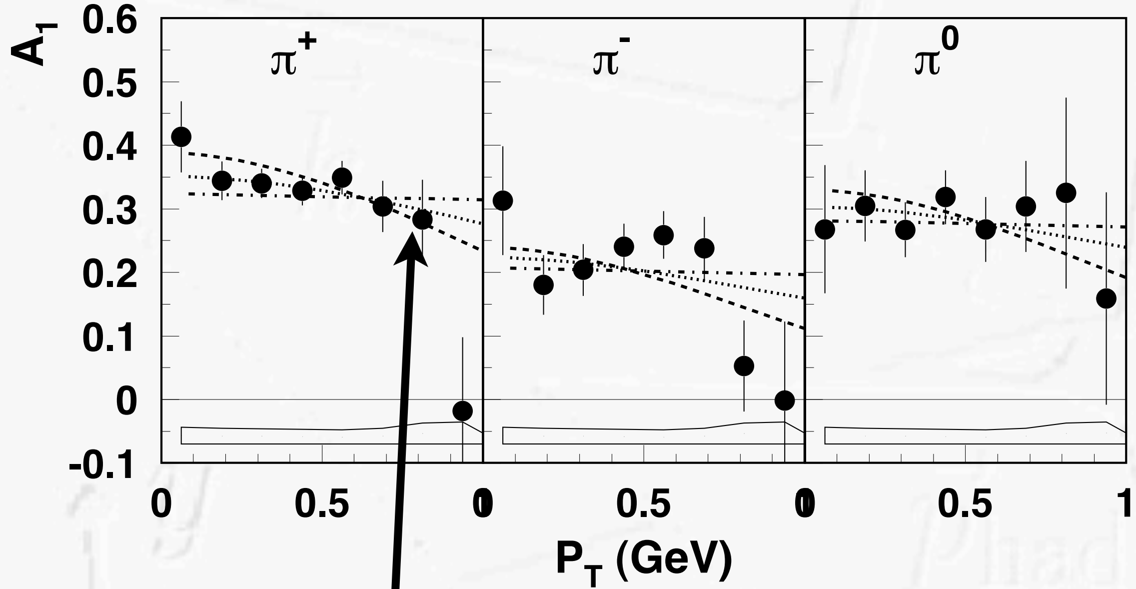

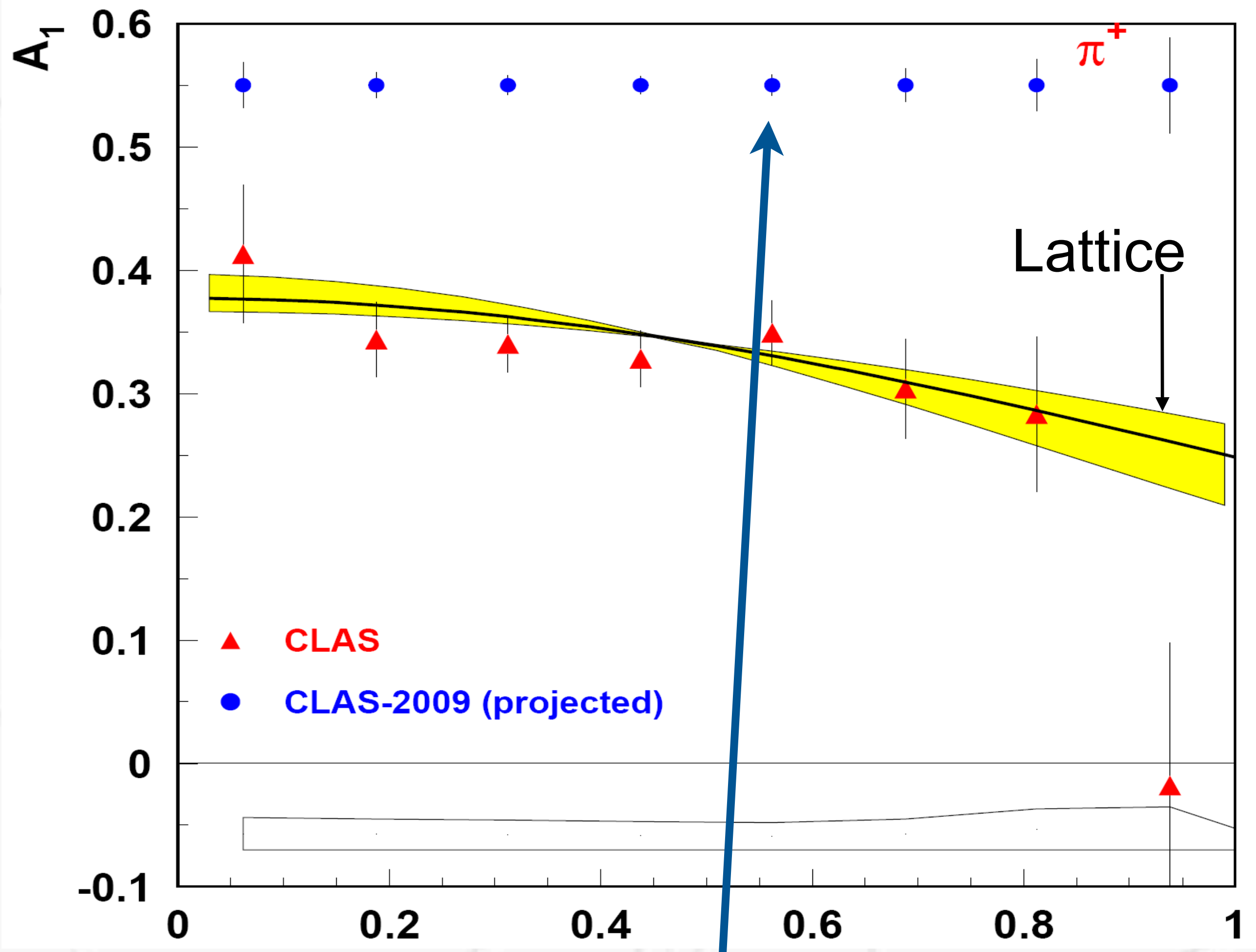

CLAS data hints at width μ_2 of g_1 that is less than the width μ_0 of f_1

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

New CLAS data will allow multi-D binning to study $P_{h\perp}$ dependence for fixed x

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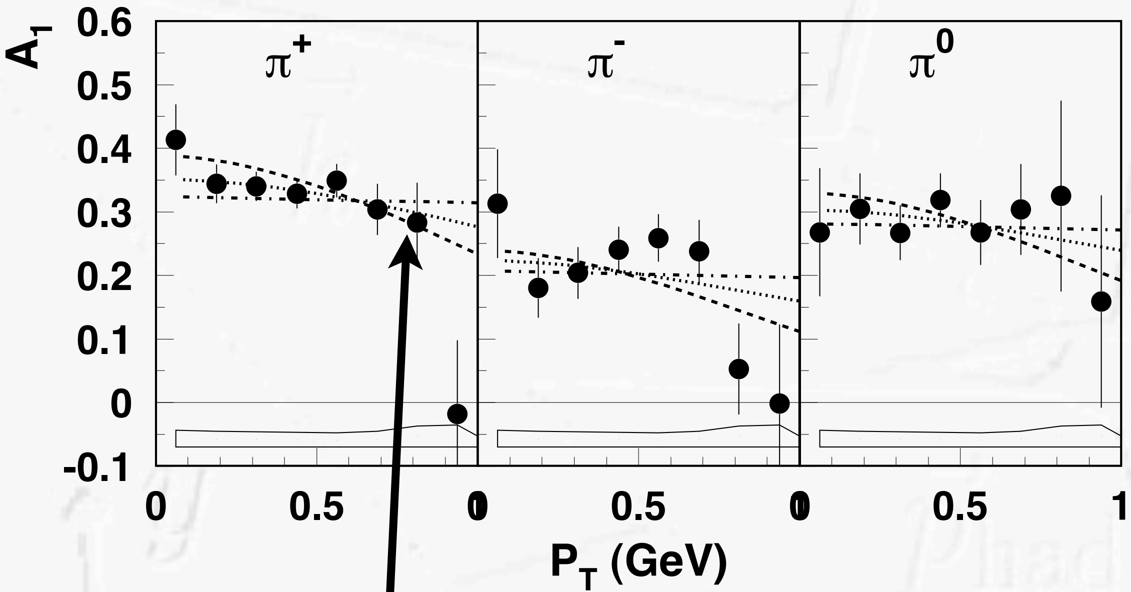

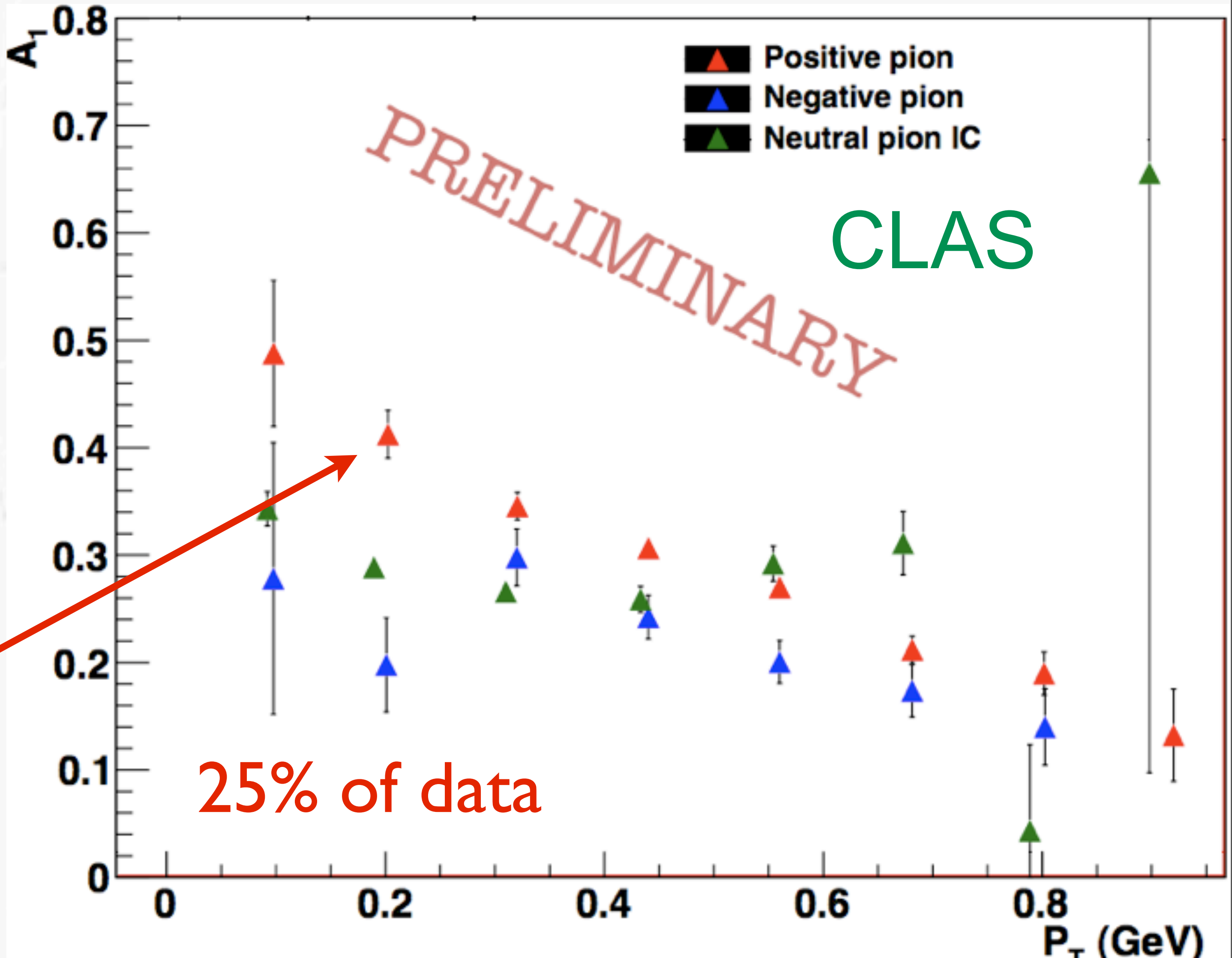

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The quest for transversity

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Transversity distribution

chiral-odd transversity involves quark helicity flip

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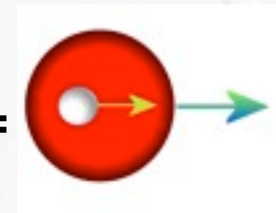
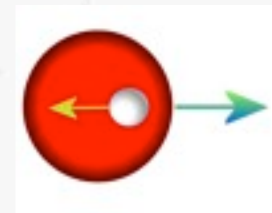
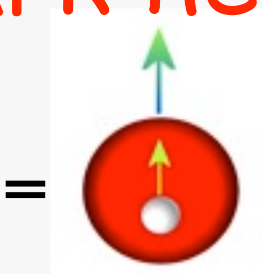
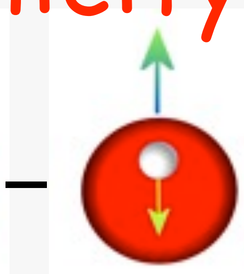
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 

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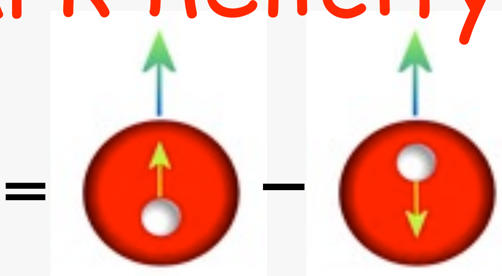
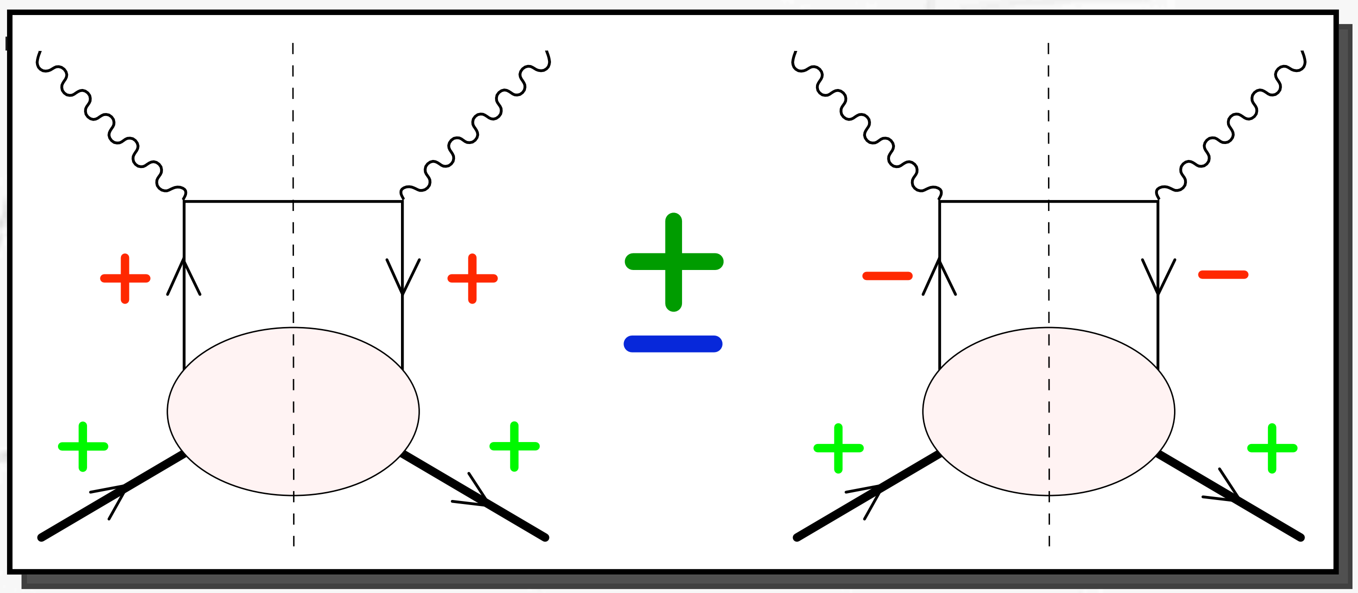
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



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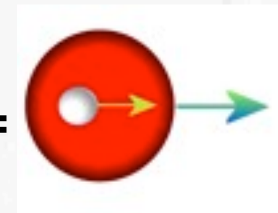
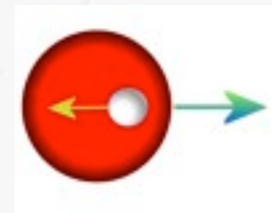
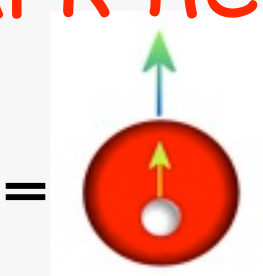
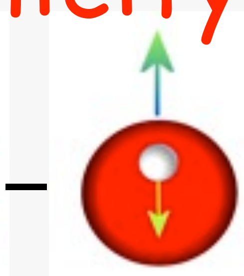
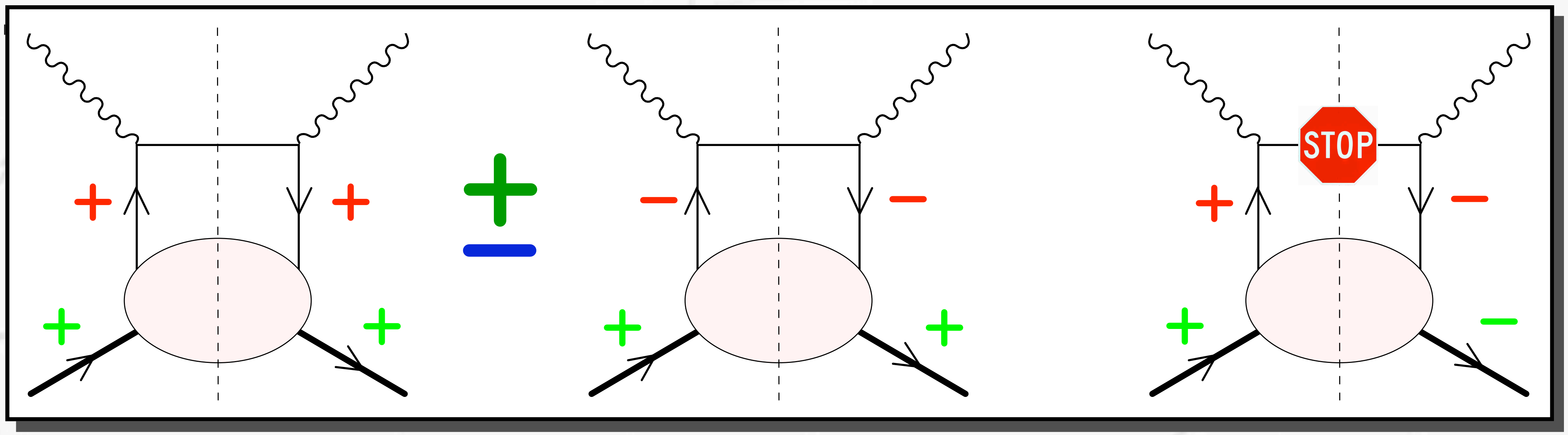
$g_1^q =$  $-$ 

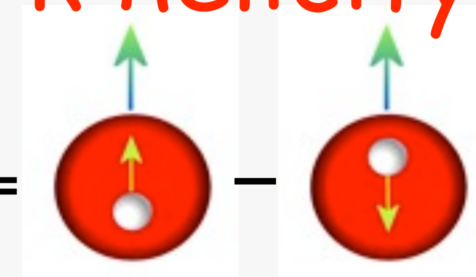
$h_1^q =$  $-$ 

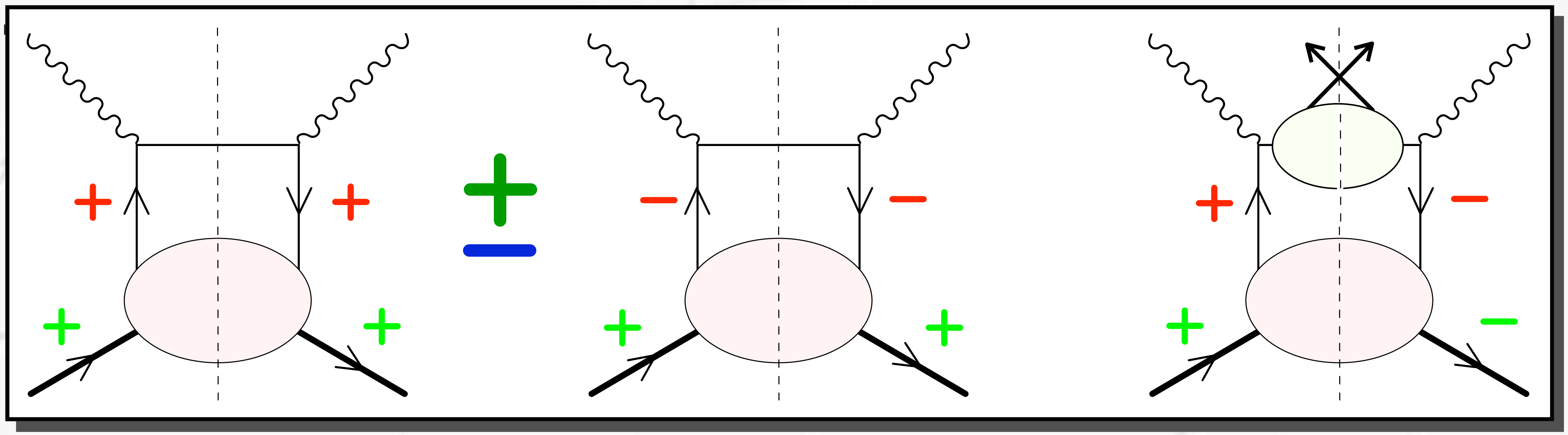


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution

chiral-odd transversity involves quark helicity flip

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

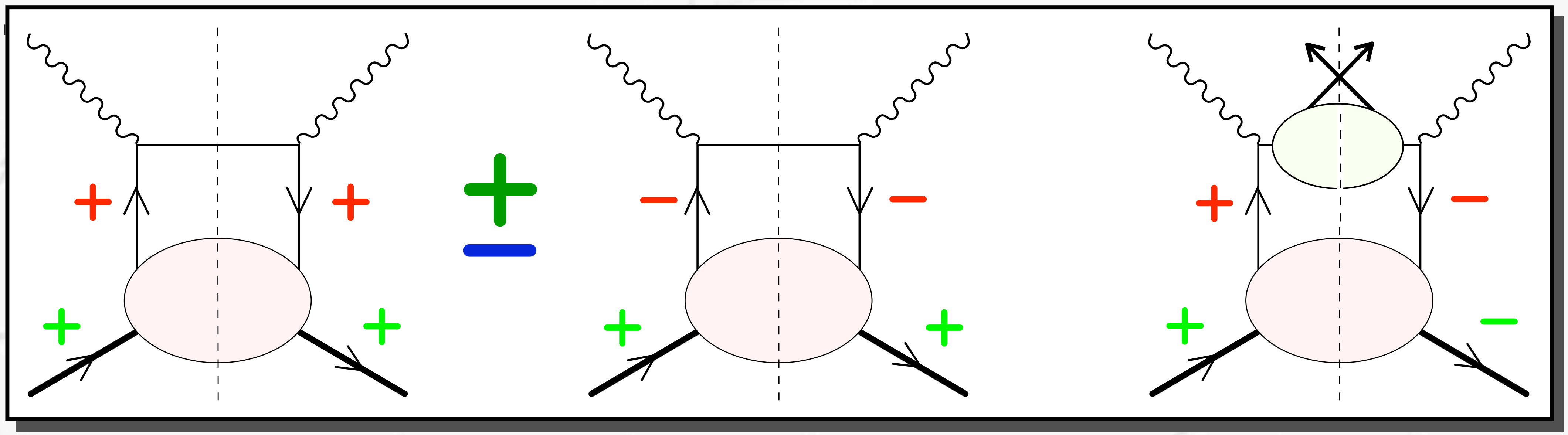


need to couple to chiral-odd fragmentation function:

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

Transversity distribution

chiral-odd transversity involves quark helicity flip



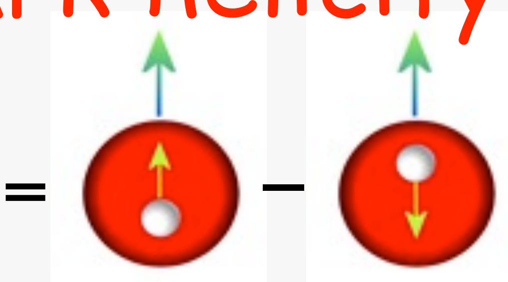
need to couple to chiral-odd fragmentation function:

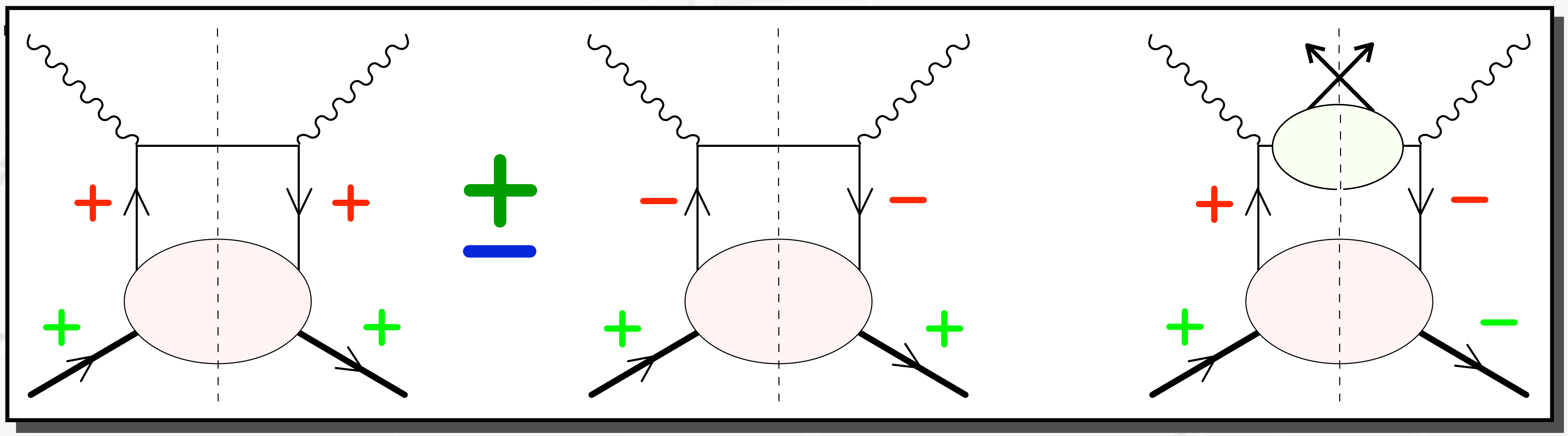
- **transverse spin transfer** (polarized final-state hadron)

	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

chiral-odd transversity involves quark helicity flip

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



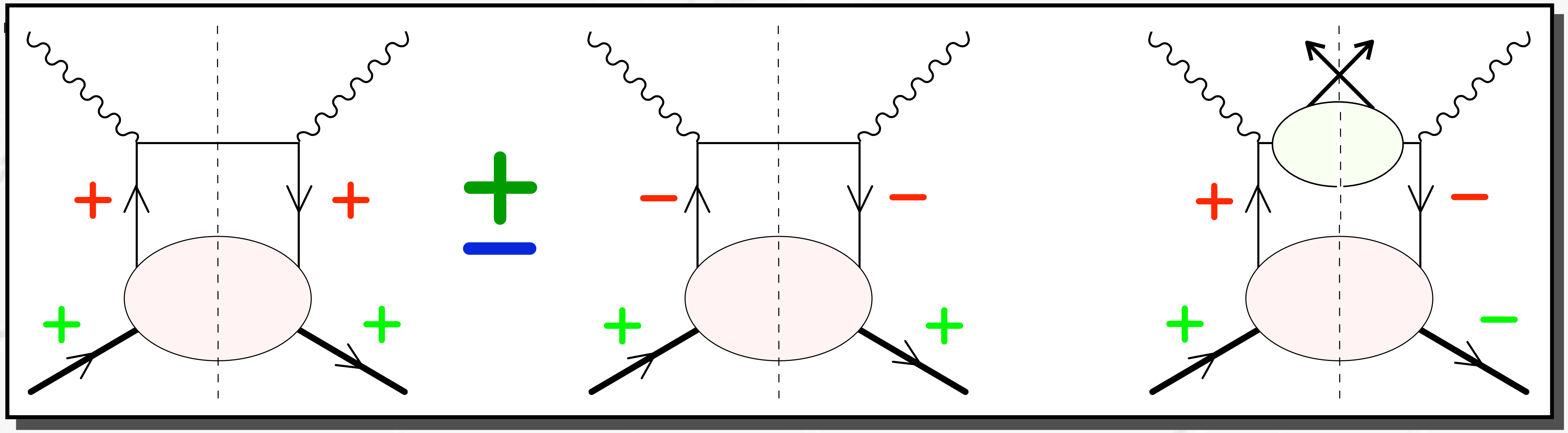
need to couple to chiral-odd fragmentation function:

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

	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

chiral-odd transversity involves quark helicity flip



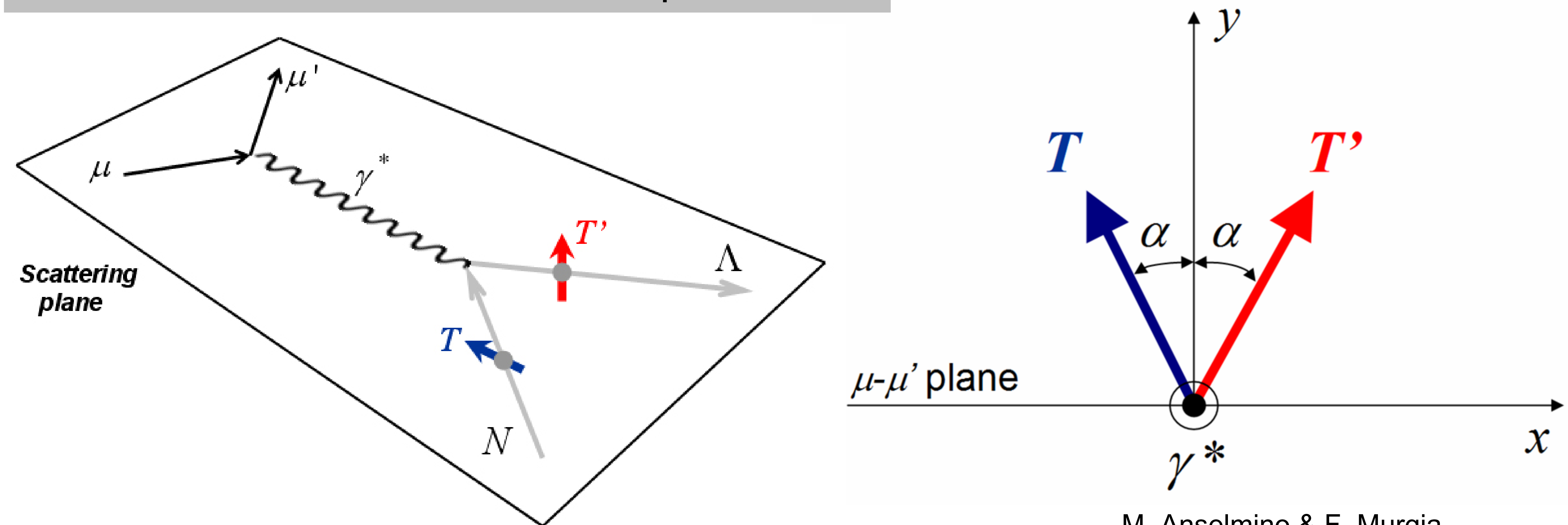
need to couple to chiral-odd fragmentation function:

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

	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

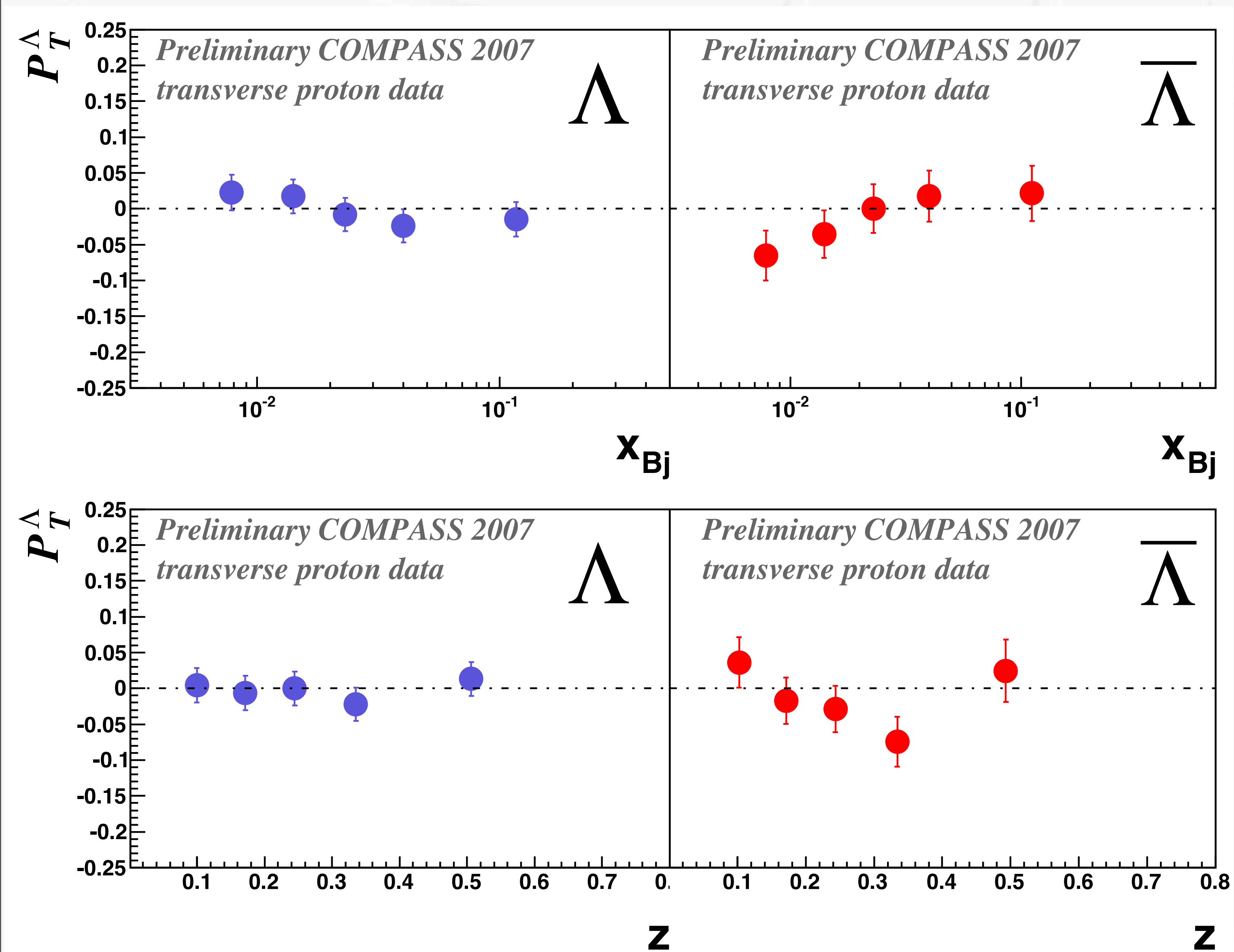


M. Anselmino & F. Murgia,
Physics Letters B 483 (2000) 74-86

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

	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)



- 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
Ξ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04

Quark polarizations in hyperons

	Δu		Δd		Δs	
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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
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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

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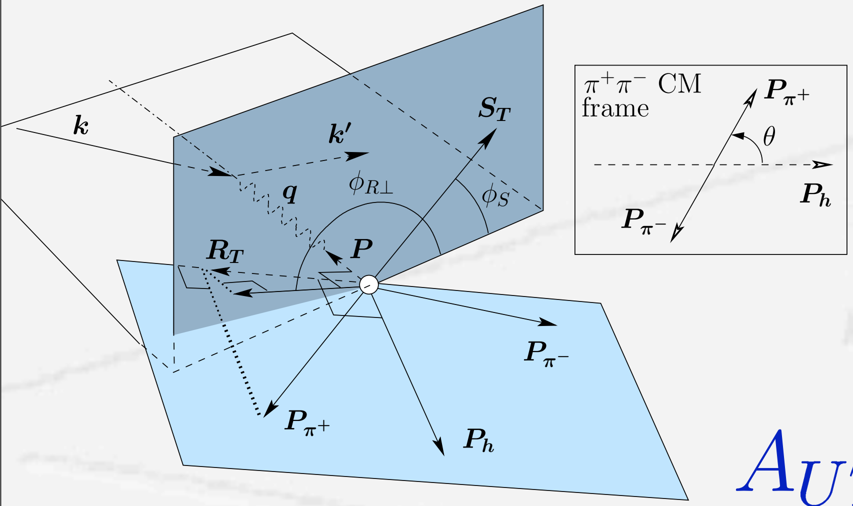
- better sensitivity to u and d quarks via charged Sigma's
- large analyzing power of the parity-violating decay $\Sigma^+ \to p\pi^0$
  - good probe of u-quark polarization
  - need good acceptance and neutral pion reconstruction



2-Hadron Fragmentation

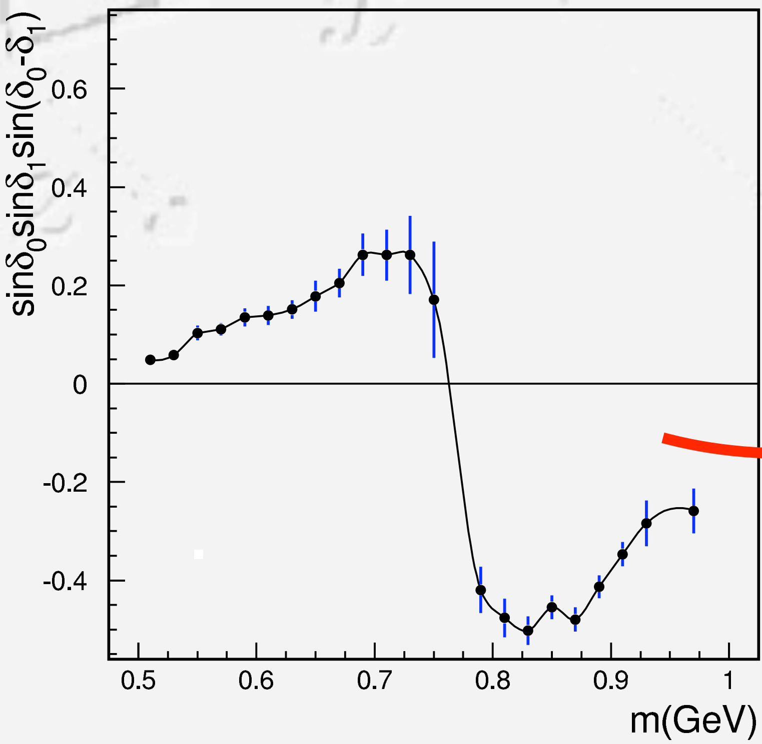
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

Expansion of $H_1^{\sphericalangle}$ in Legendre moments:

$$H_1^{\sphericalangle}(z, \cos\theta, M_{\pi\pi}^2) = H_1{}^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\theta H_1{}^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$

describe interference between 2 pion pairs coming from different production channels.

about $H_1^{\sphericalangle,sp}$:



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

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

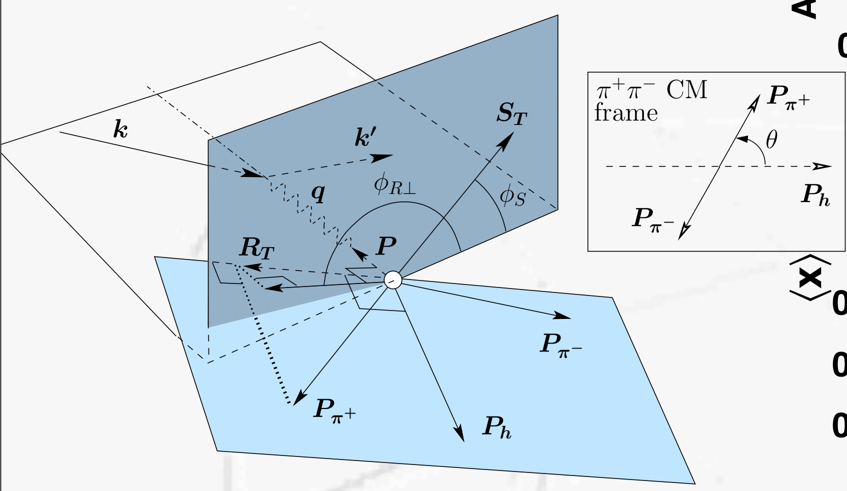
δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

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

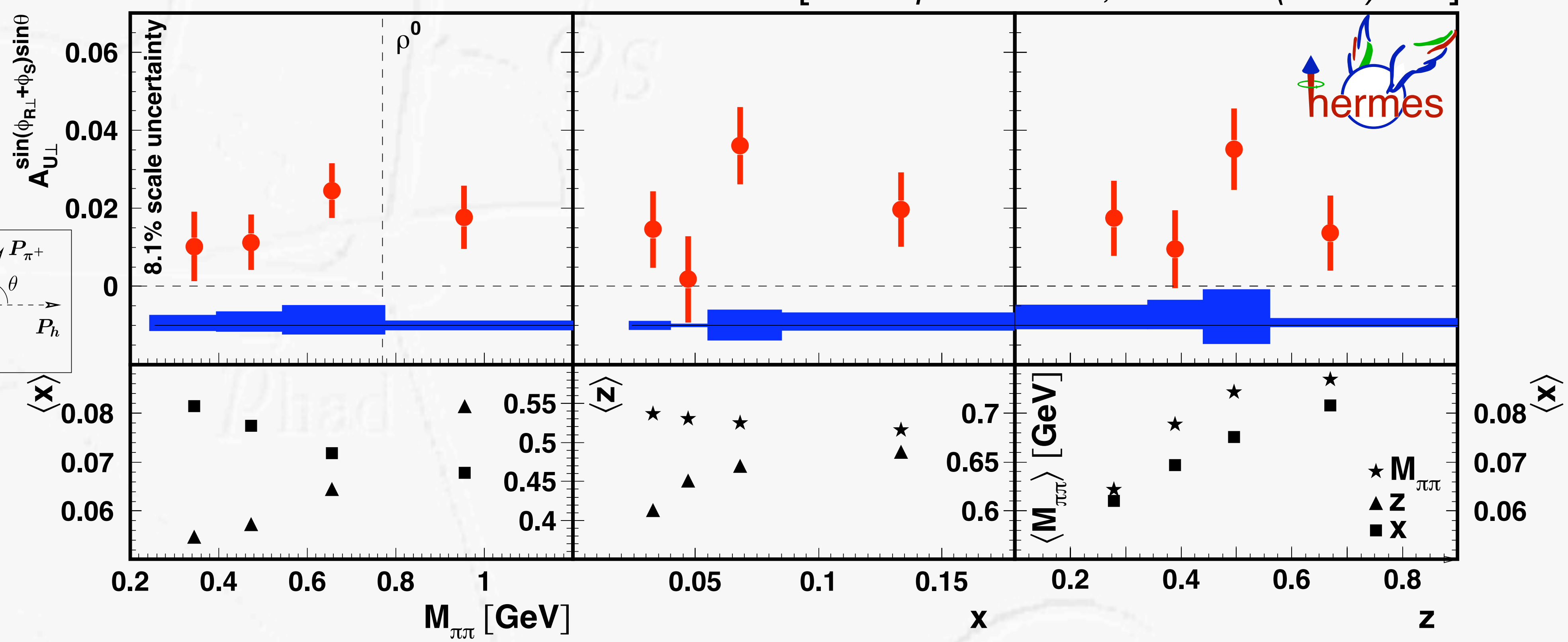
$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

	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 (2-hadron fragmentation)



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



	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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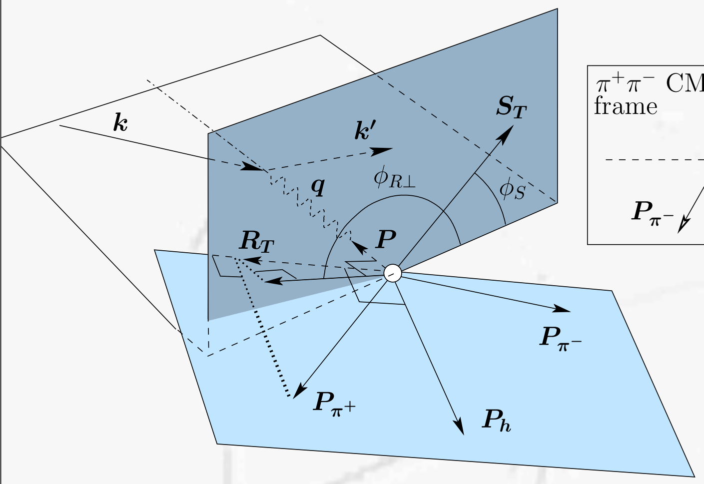
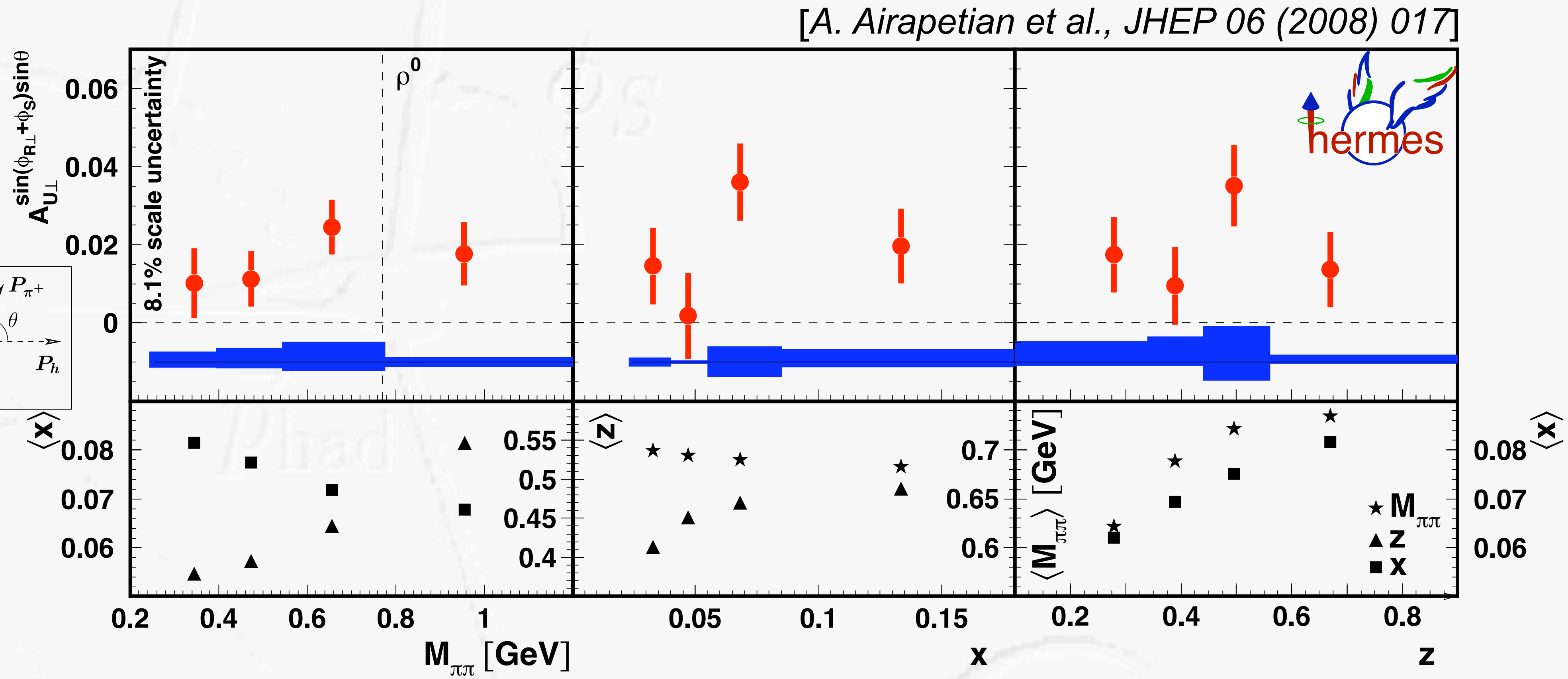
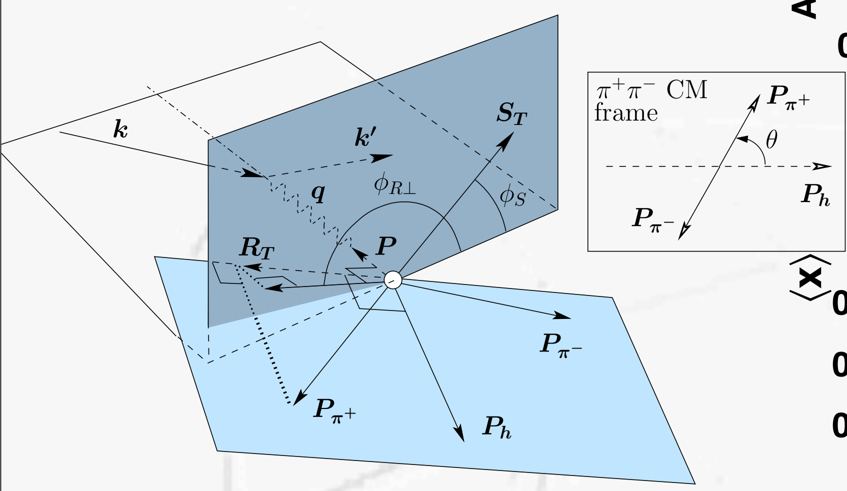




☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

	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 (2-hadron fragmentation)



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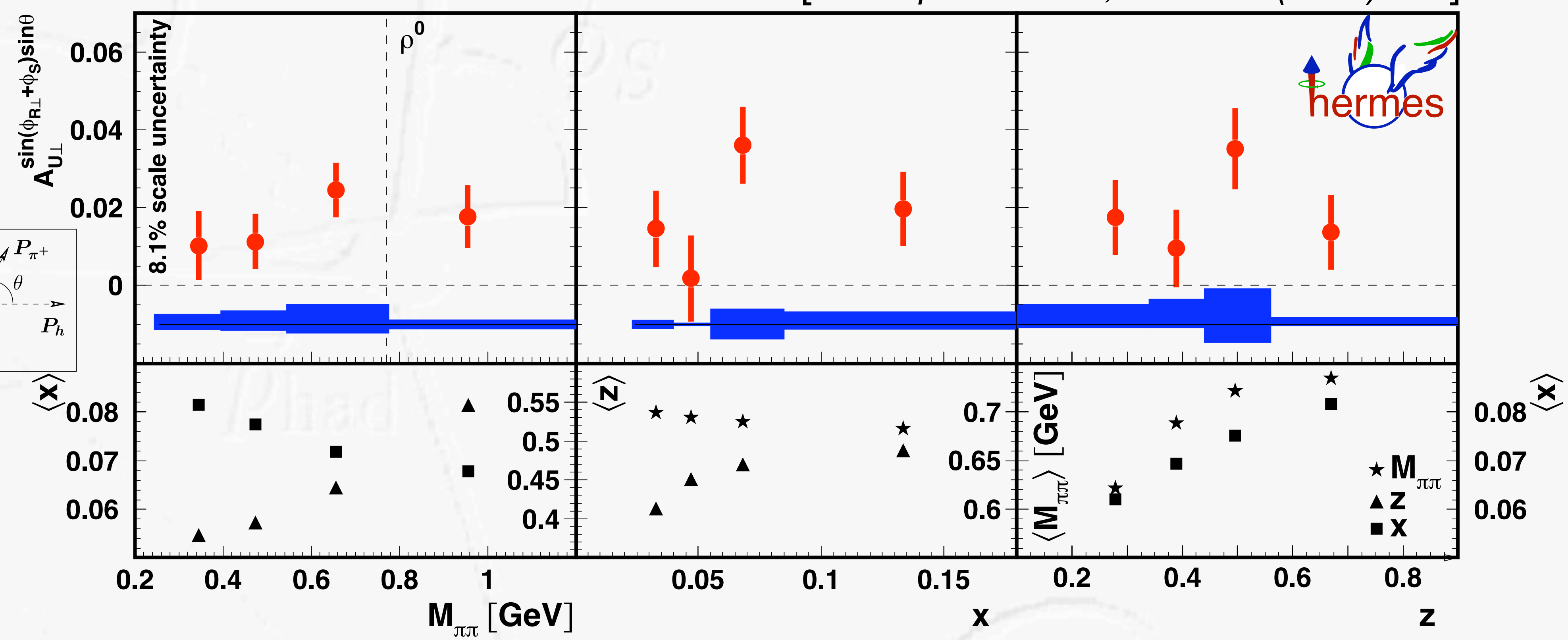


☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

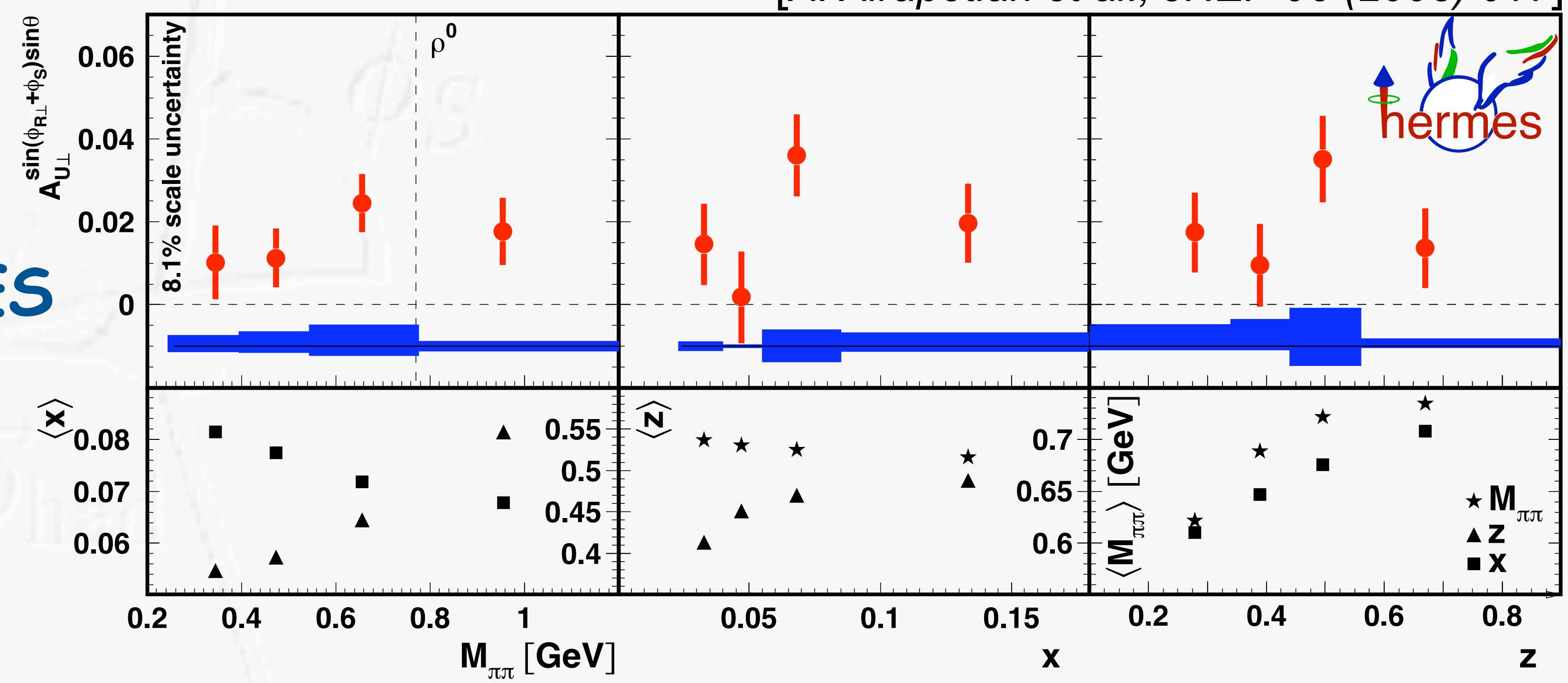
☑ invariant-mass dependence rules out Jaffe model predicting a sign change to rho mass

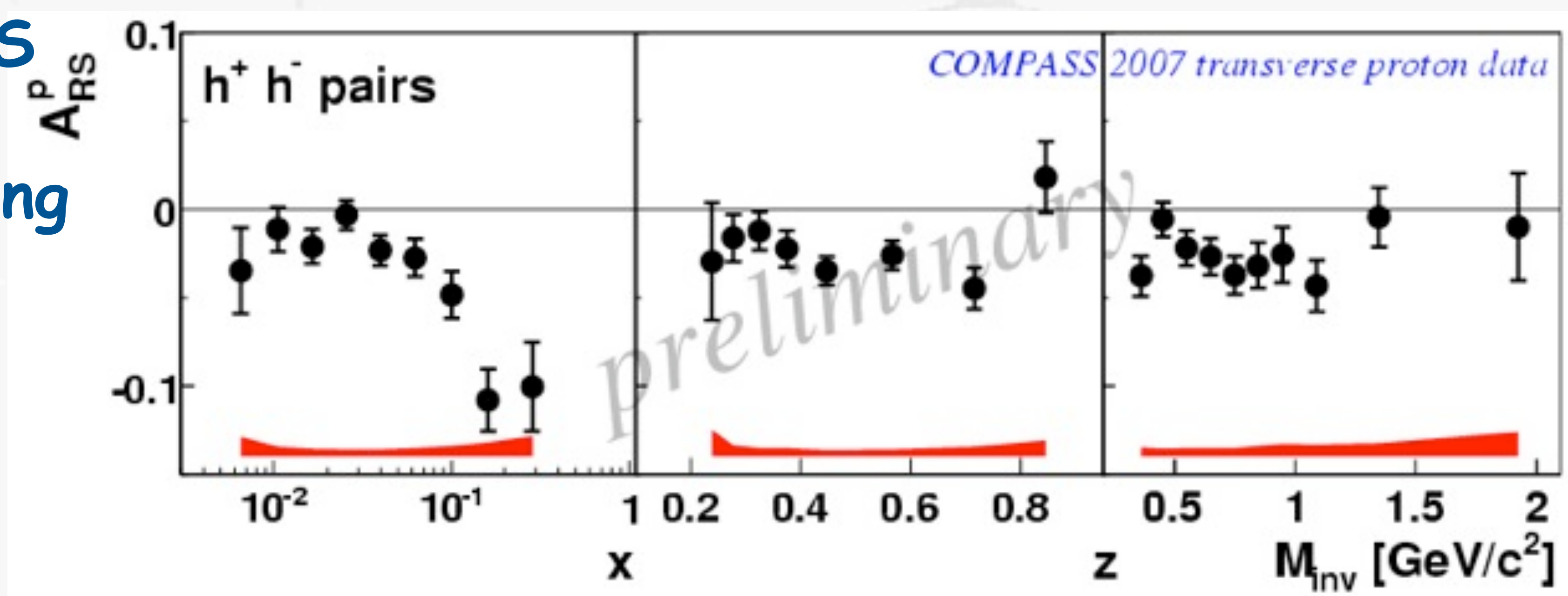
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

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

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





	U	L	T
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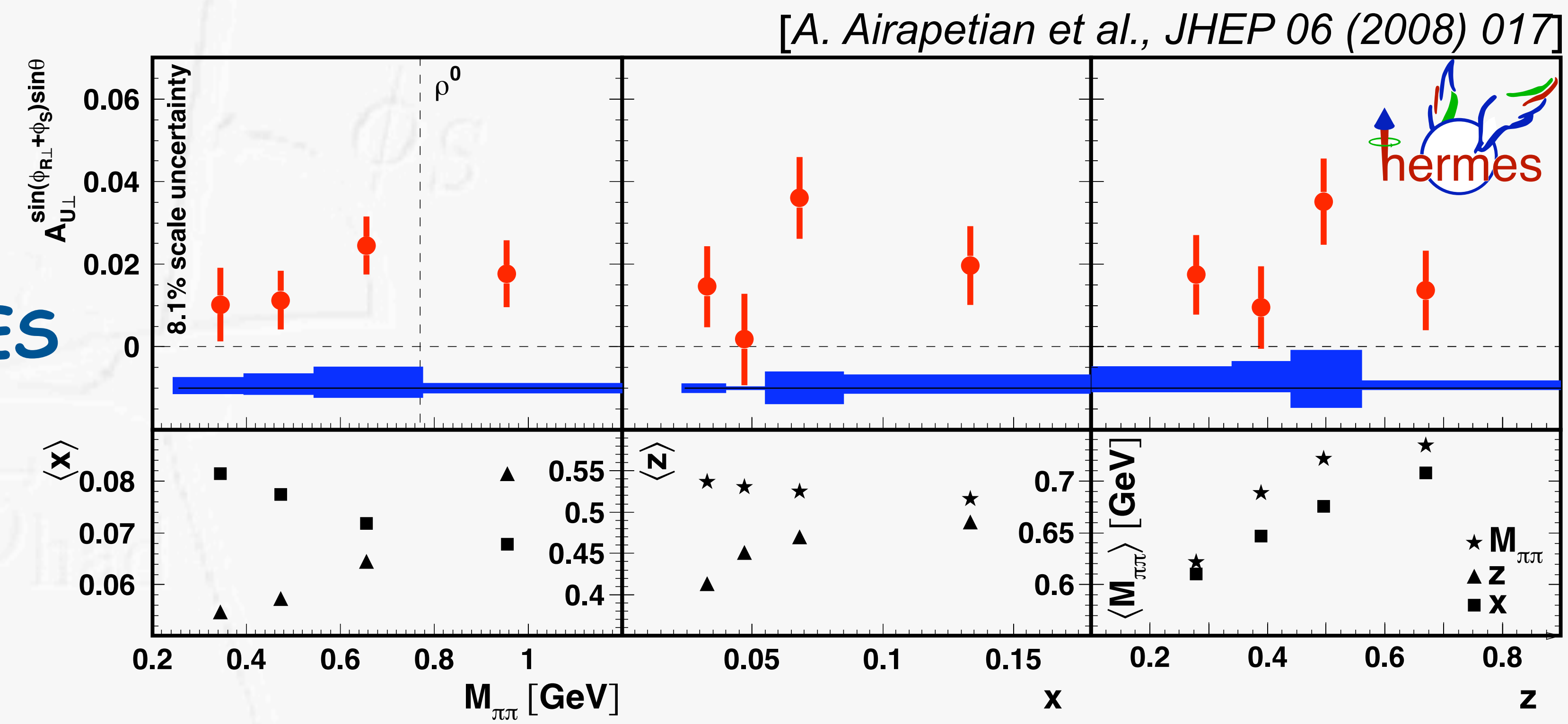

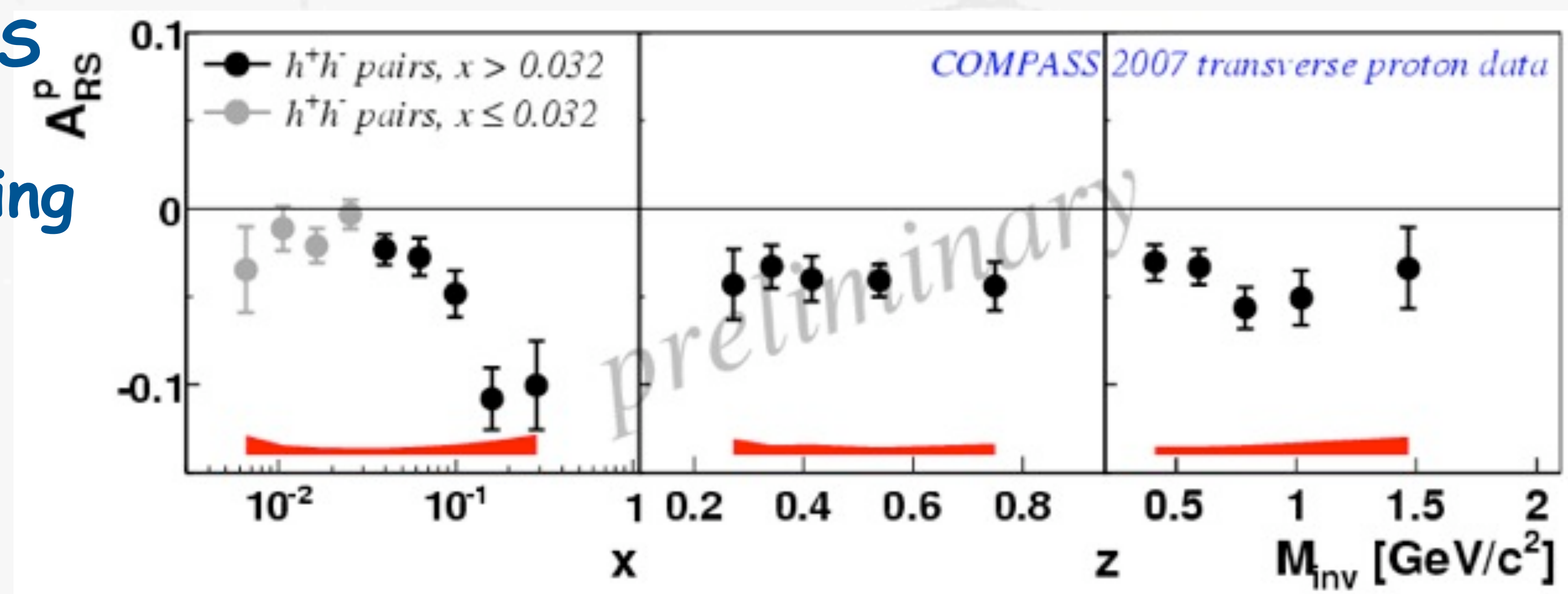

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L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

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

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- COMPASS: hadron pairs HERMES: pion pairs
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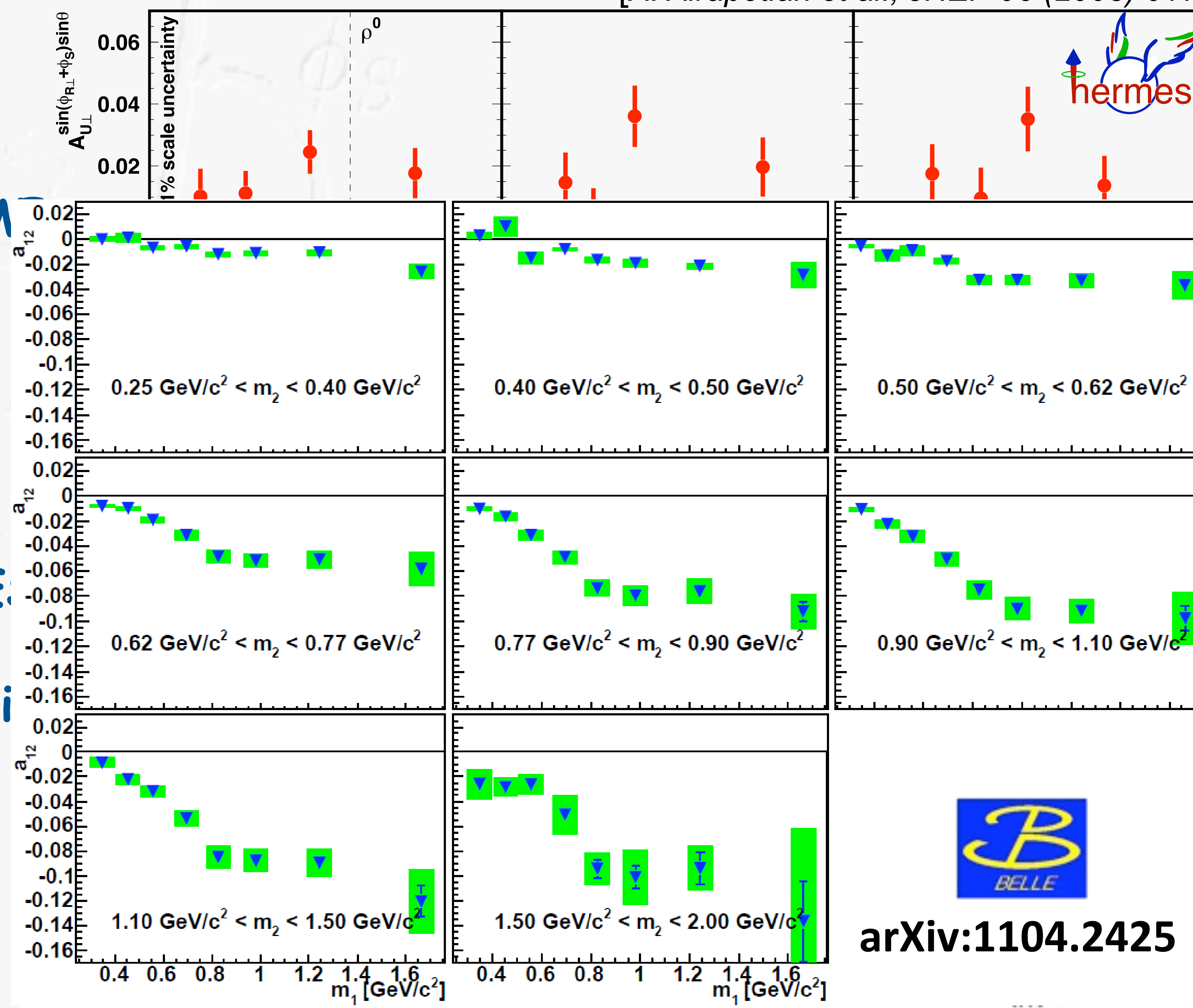


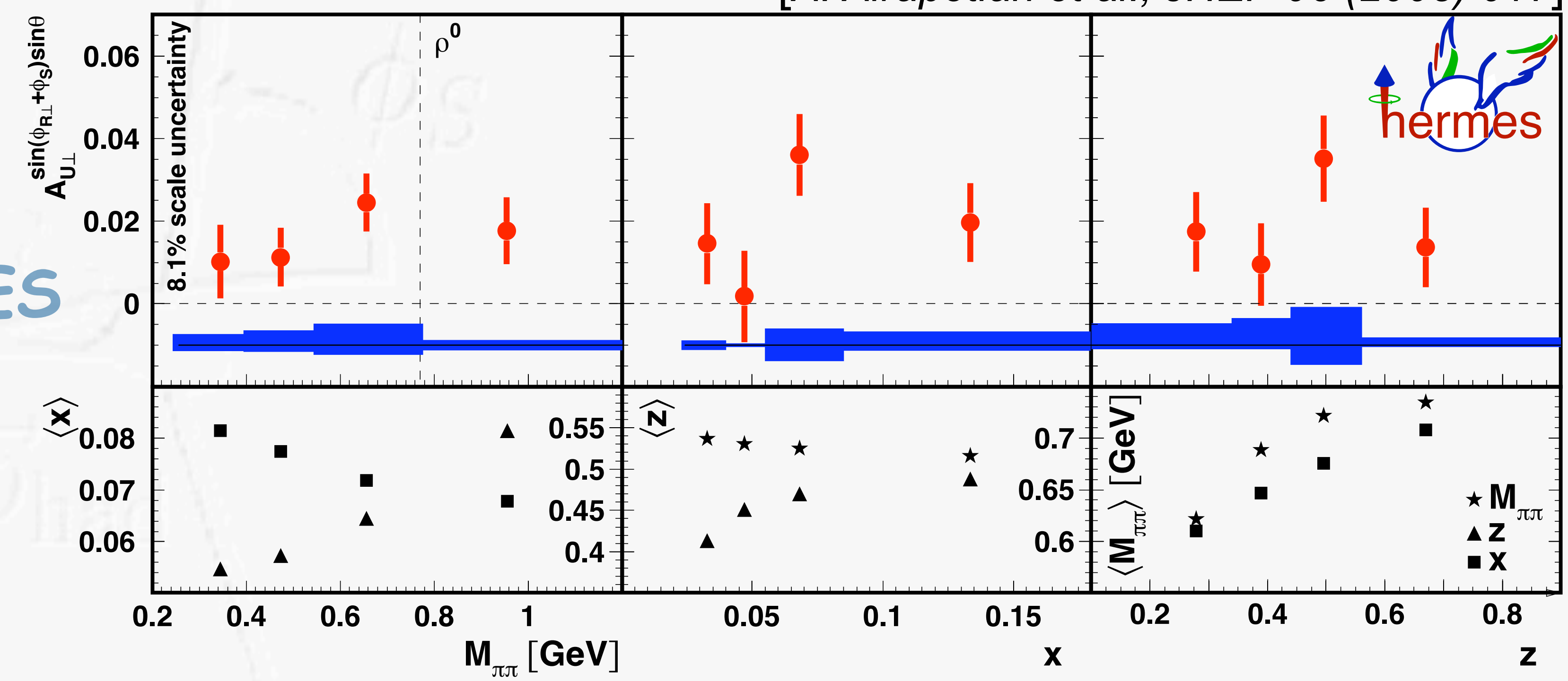
arXiv:1104.2425

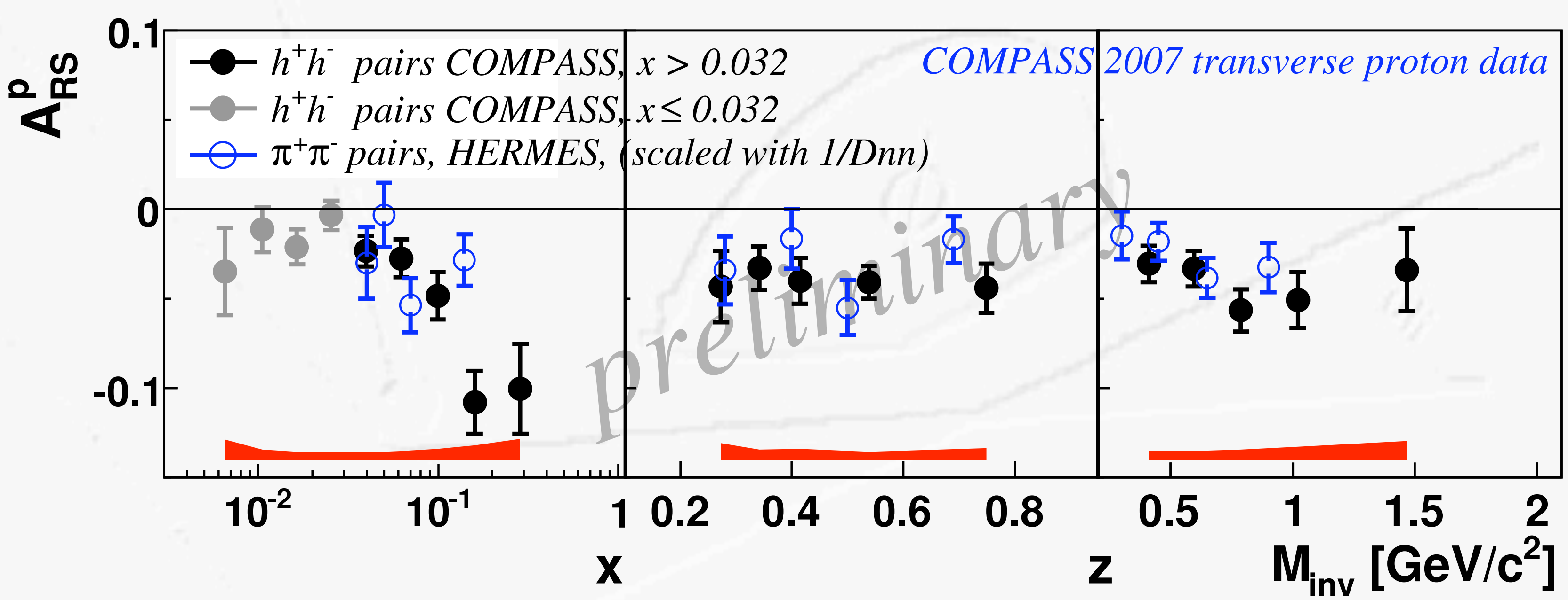
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

- non-zero amplitudes both from COMPASS and HERMES
- COMPASS: hadron pairs HERMES: pion pairs
- COMPASS divides out depolarization factor D_{nn}
- comparable when also done for HERMES data

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





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L		g_{1L}	$h_{1L}^{\perp}$
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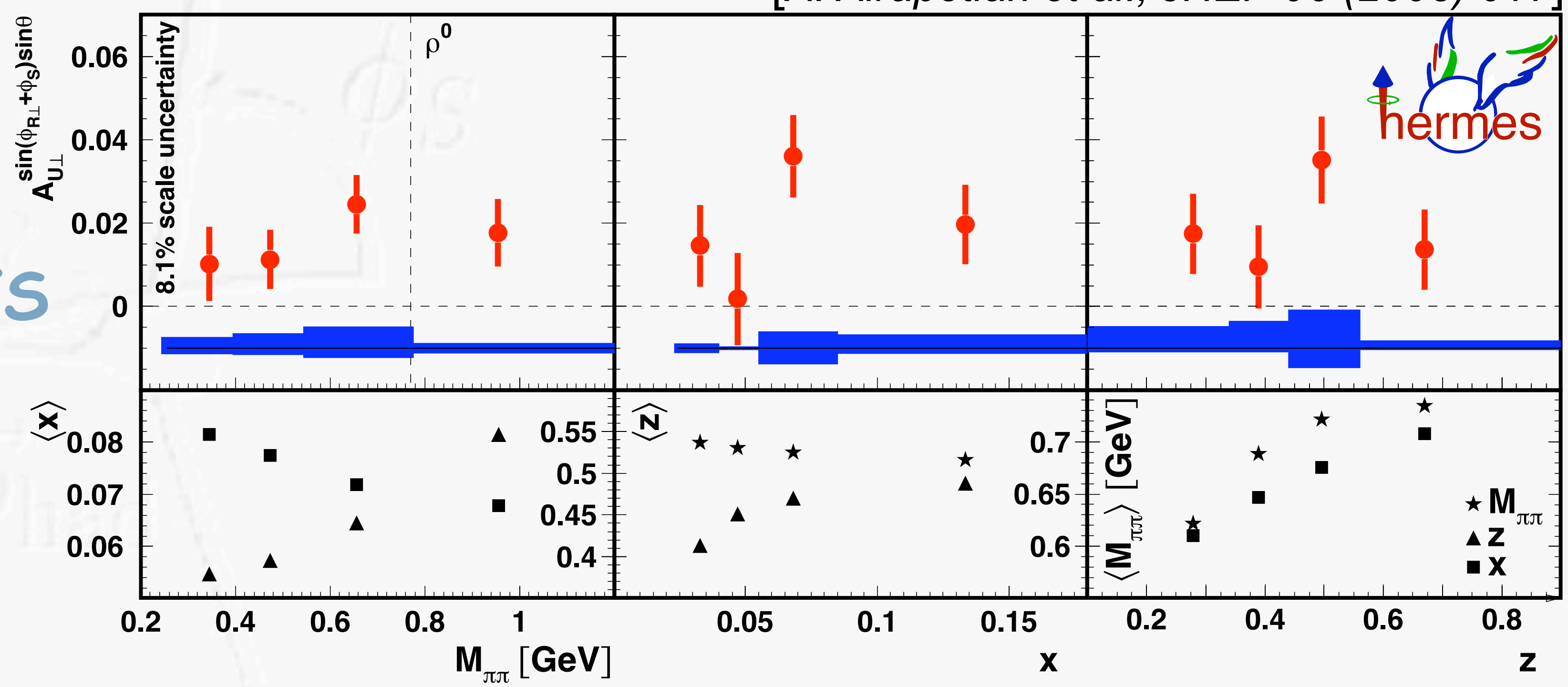
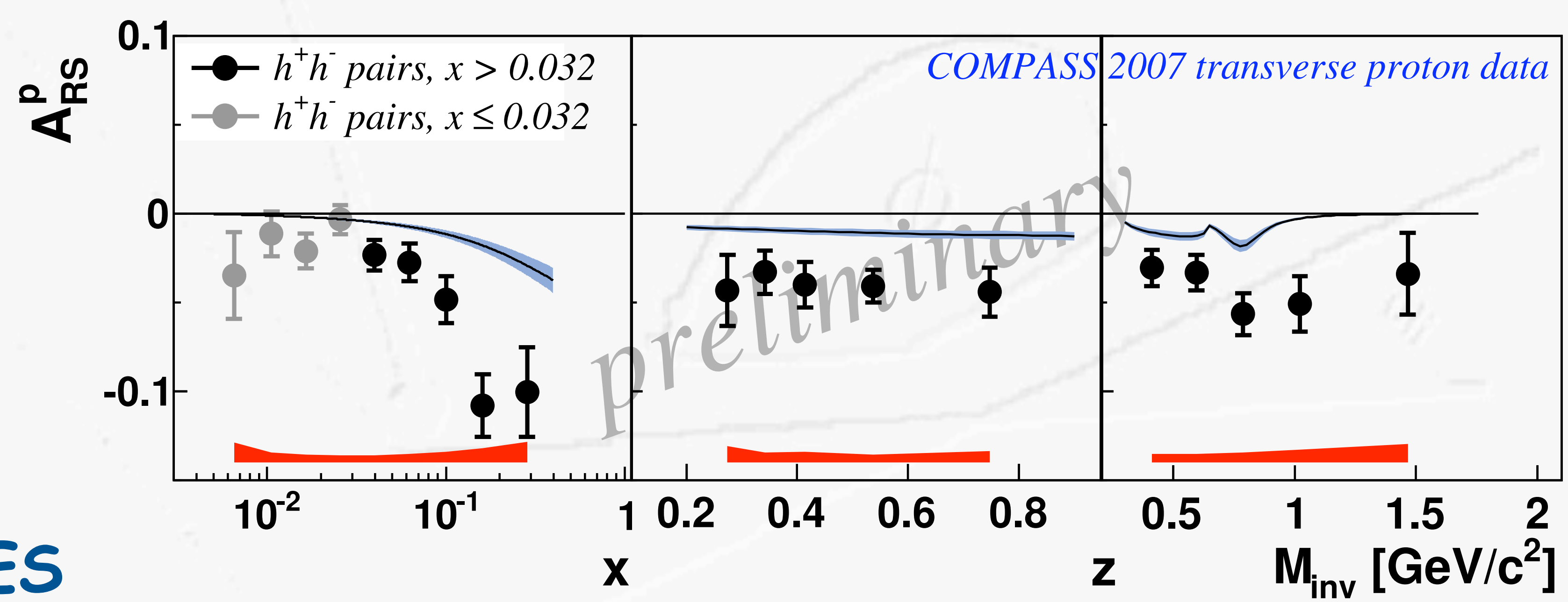
Transversity distribution (2-hadron fragmentation)

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



- non-zero amplitudes both from COMPASS and HERMES
- COMPASS: hadron pairs
  HERMES: pion pairs
- COMPASS divides out depolarization factor D_{nn}
- comparable when also done for HERMES data
- bad comparison w/ model prediction based on HERMES



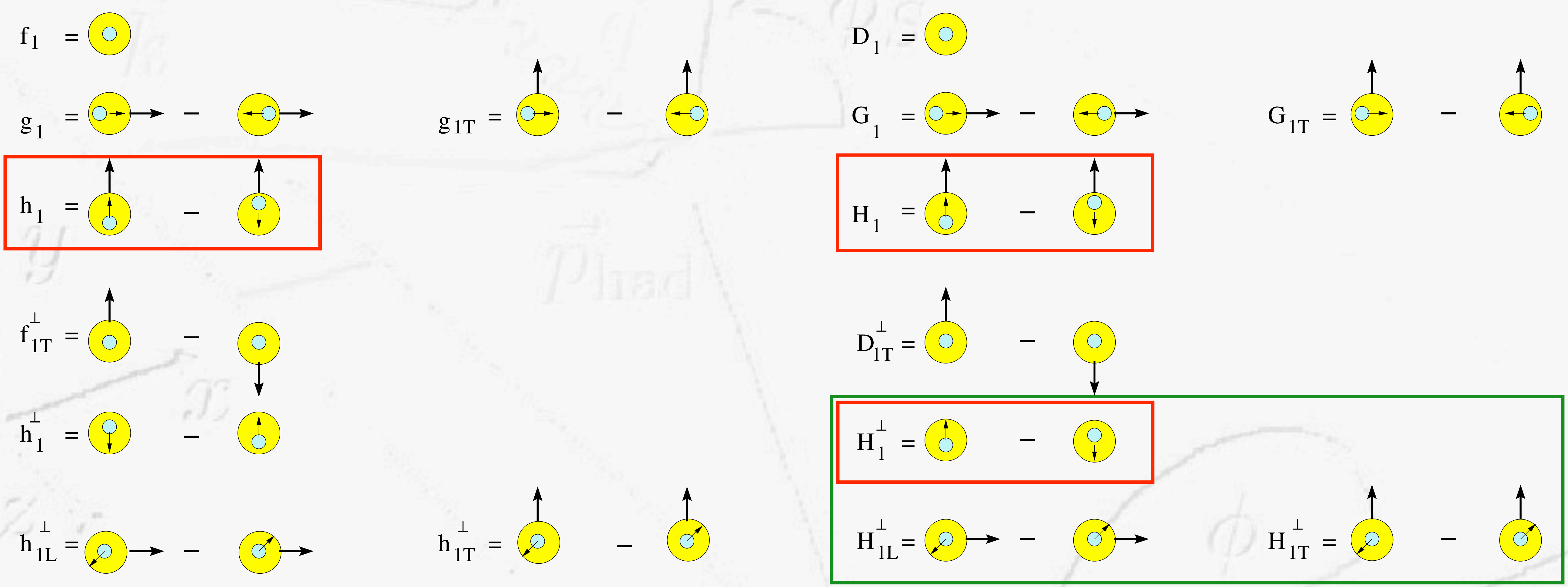
Transversity with TMD FFs

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 $\Rightarrow$ T-odd Collins FF

$\Rightarrow$ leads to Single-Spin Asymmetrie (SSA)

Ex.: Appearance of TMDs in SIDIS

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

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

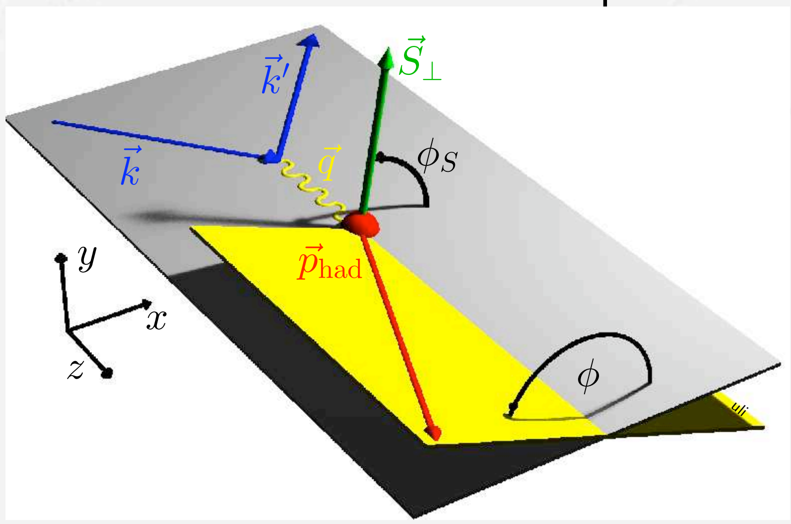
$$+S_T \left\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \right.$$

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

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

σ_{XY}

Beam **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

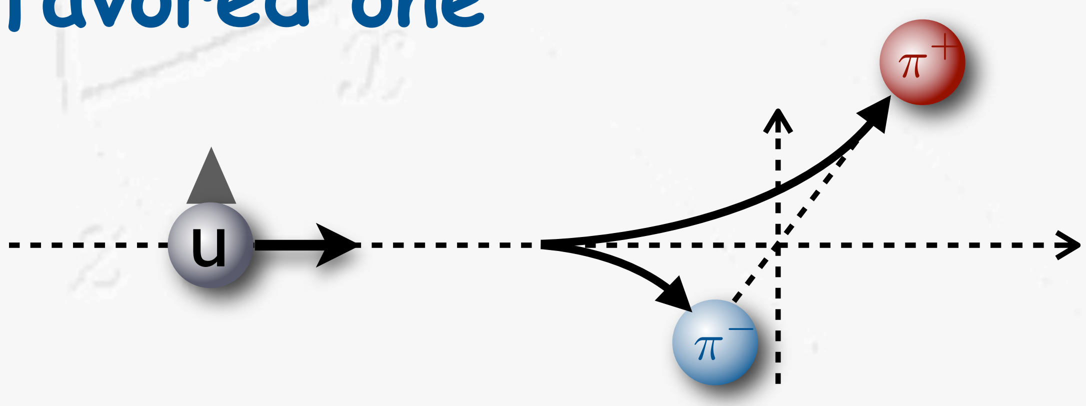
Bacchetta et al., JHEP 0702 (2007) 093

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

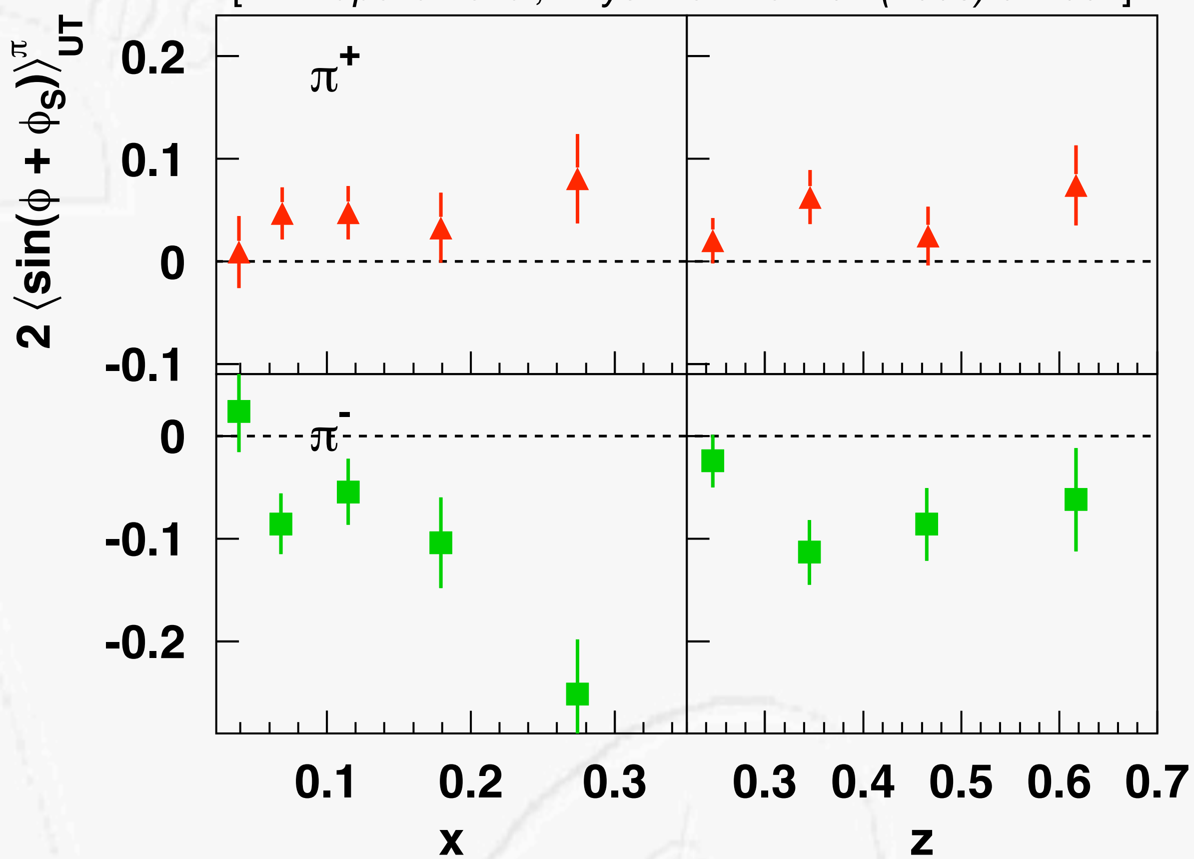
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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



[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

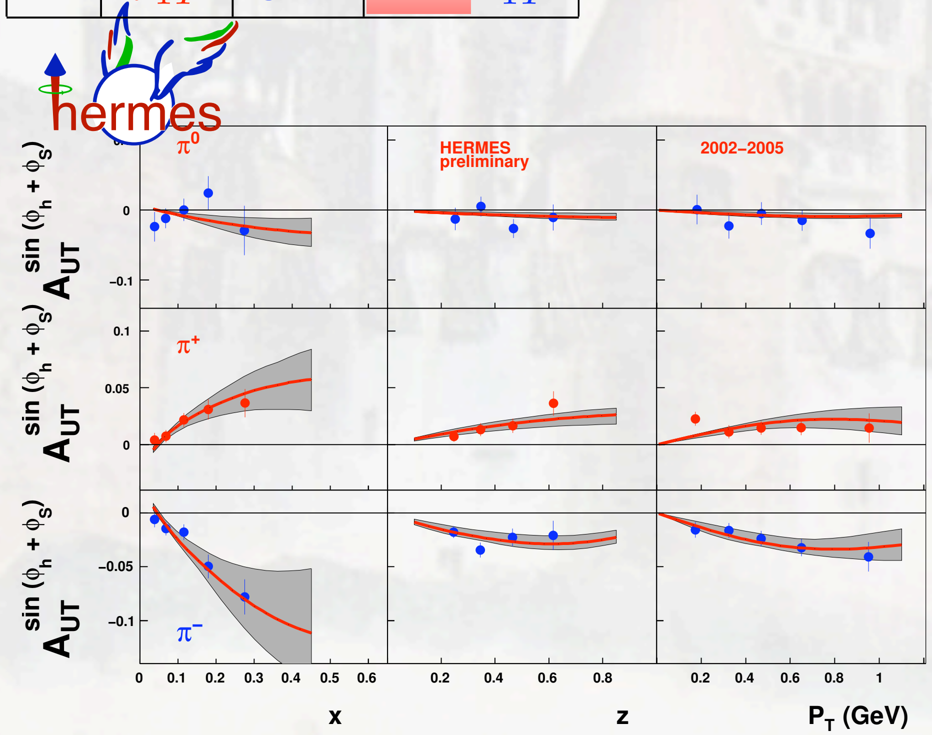
Non-zero transversity
Non-zero Collins function

- leads to various cancellations in SSA observables

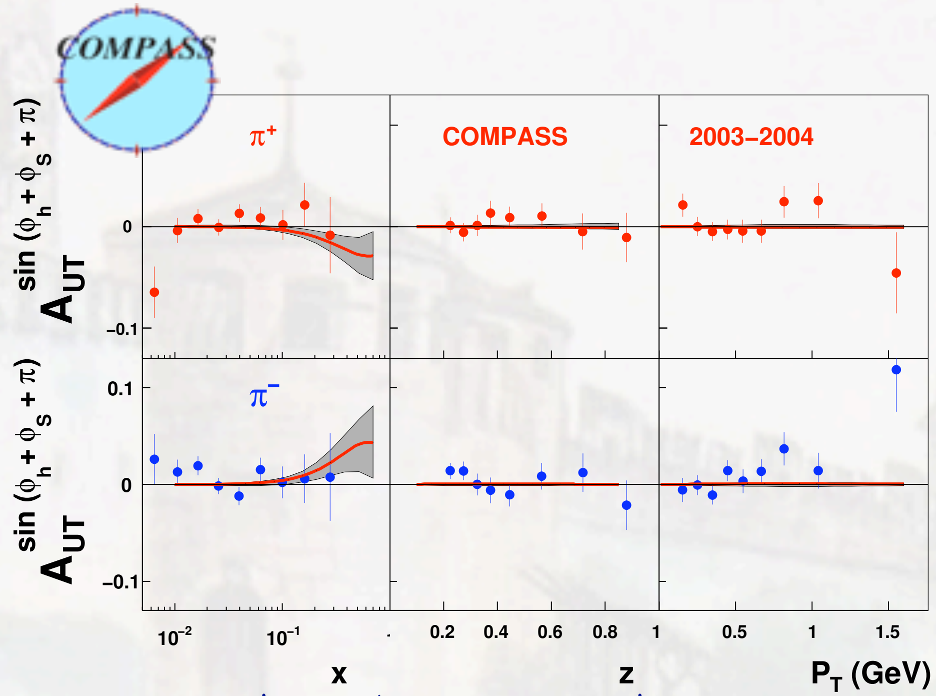
Wednesday, May 11, 2011

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

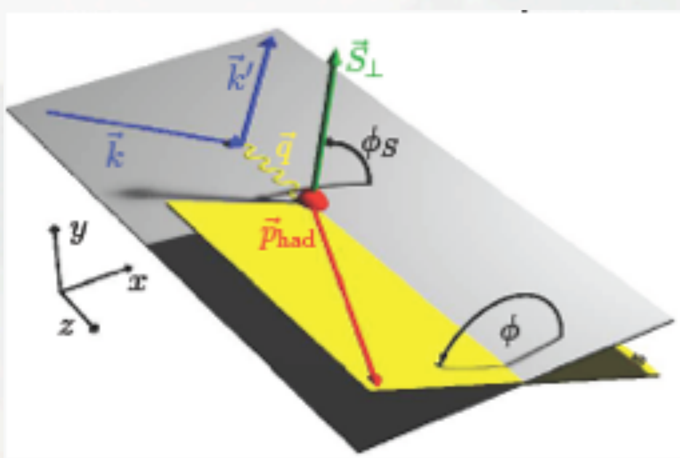
Fit of Collins amplitudes



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



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



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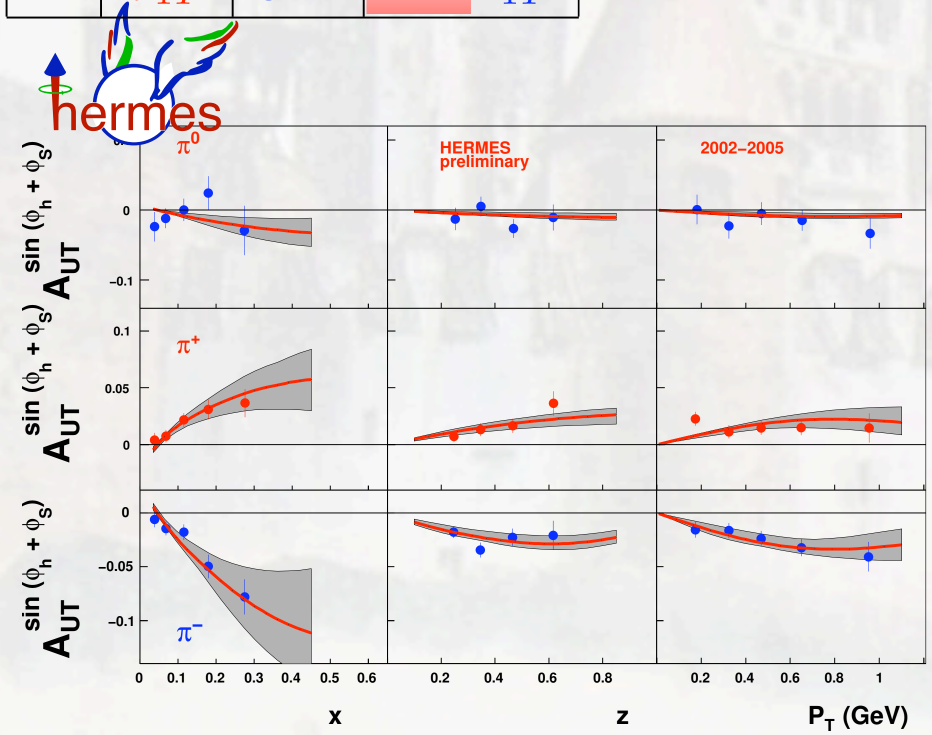
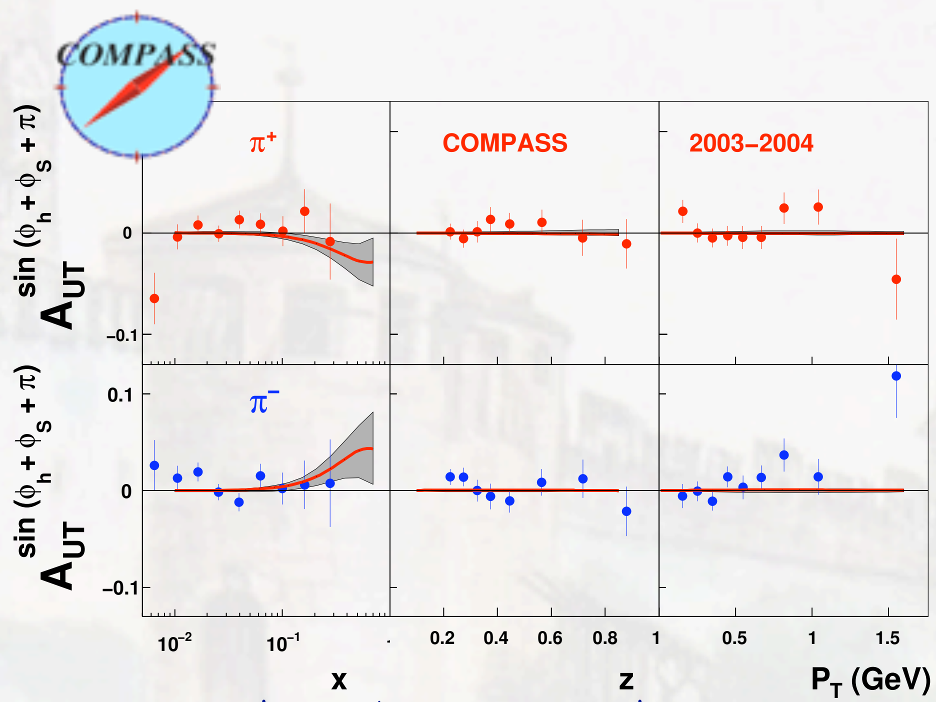
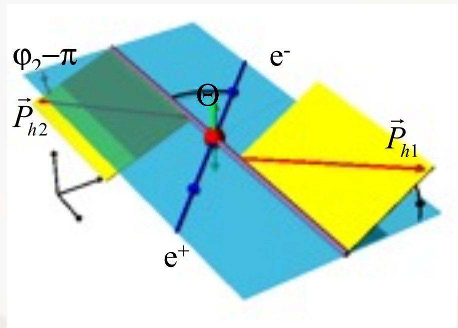
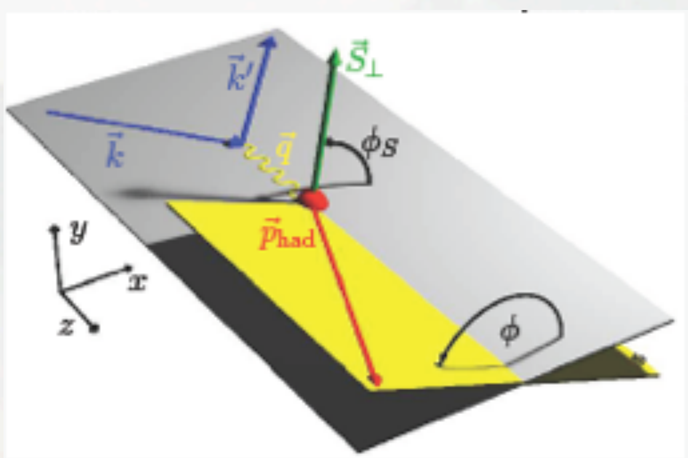
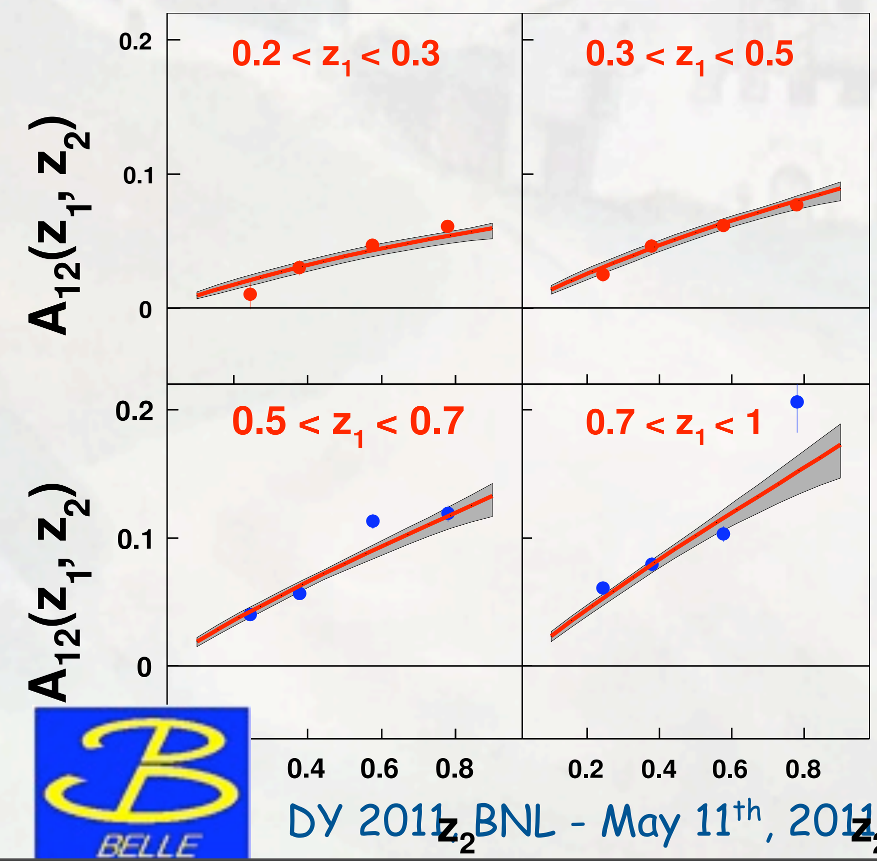






$$e^\pm p^\uparrow \rightarrow e^\pm \pi X \qquad \mu^\pm d^\uparrow \rightarrow \mu^\pm \pi X \qquad e^+e^- \rightarrow \pi\pi X$$





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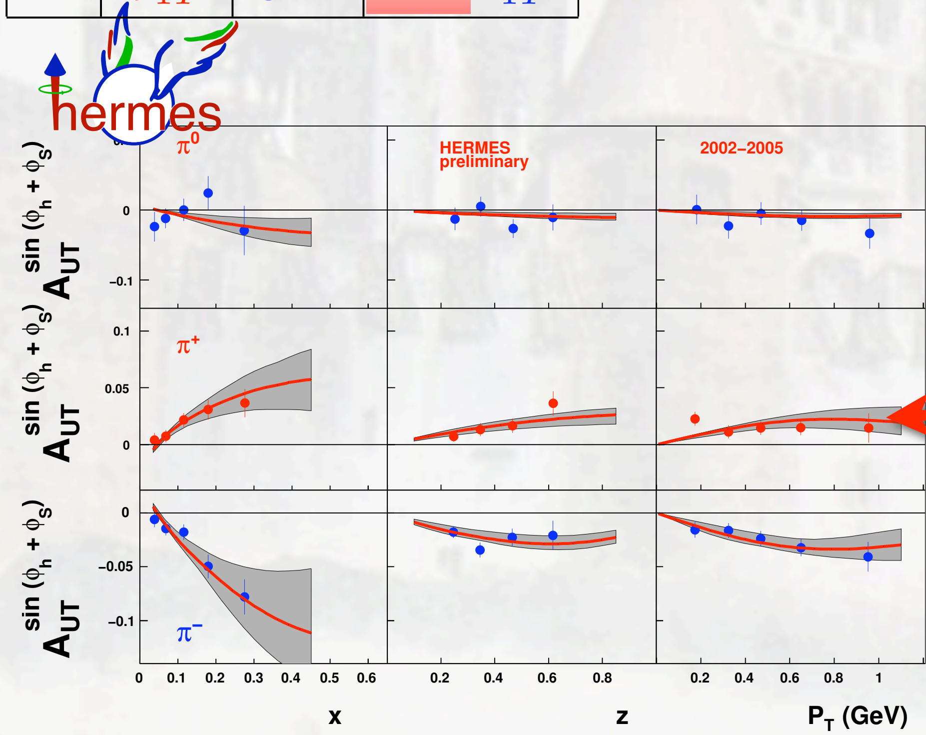

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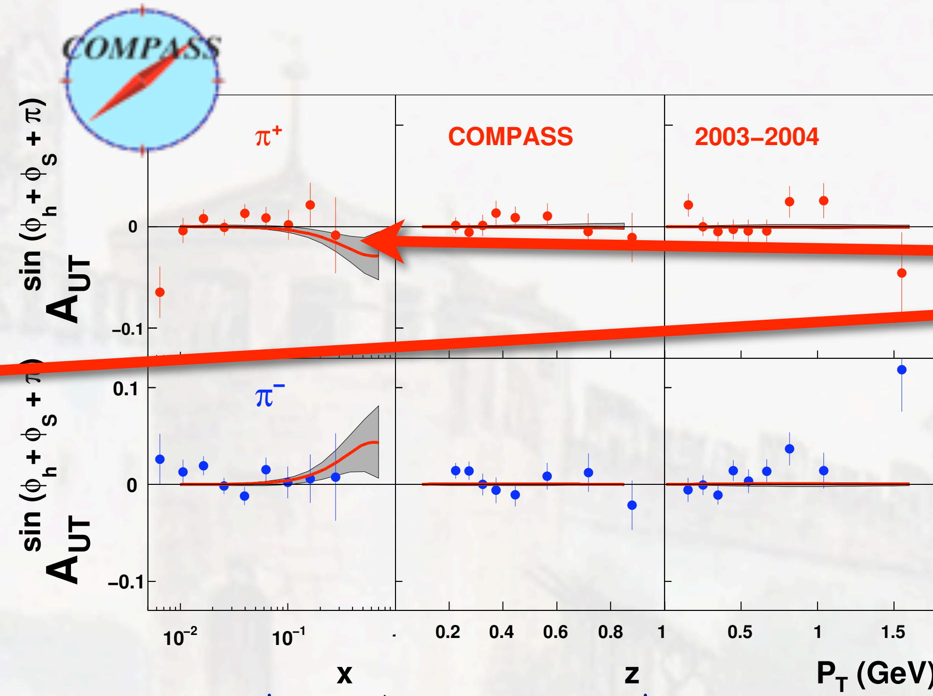
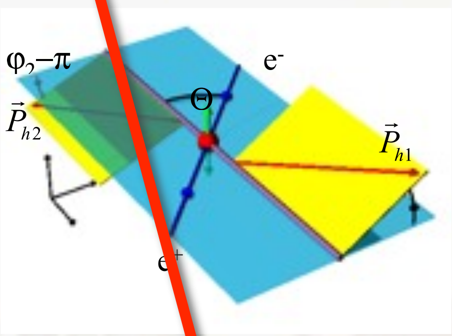


$$\mu^\pm \mathbf{d}^\uparrow \to \mu^\pm \pi \mathbf{X}$$

fit to data



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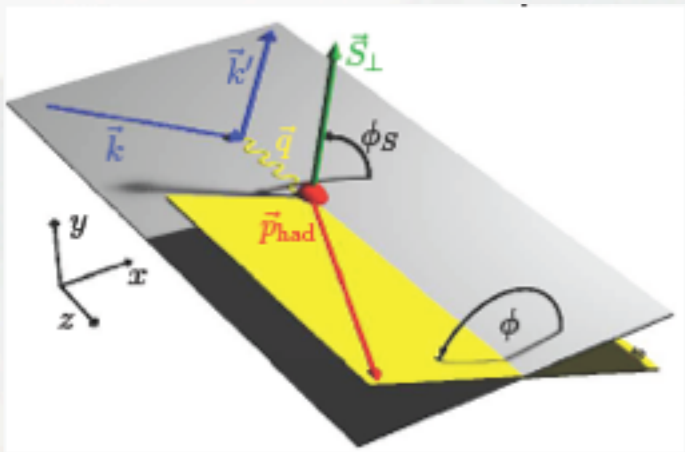

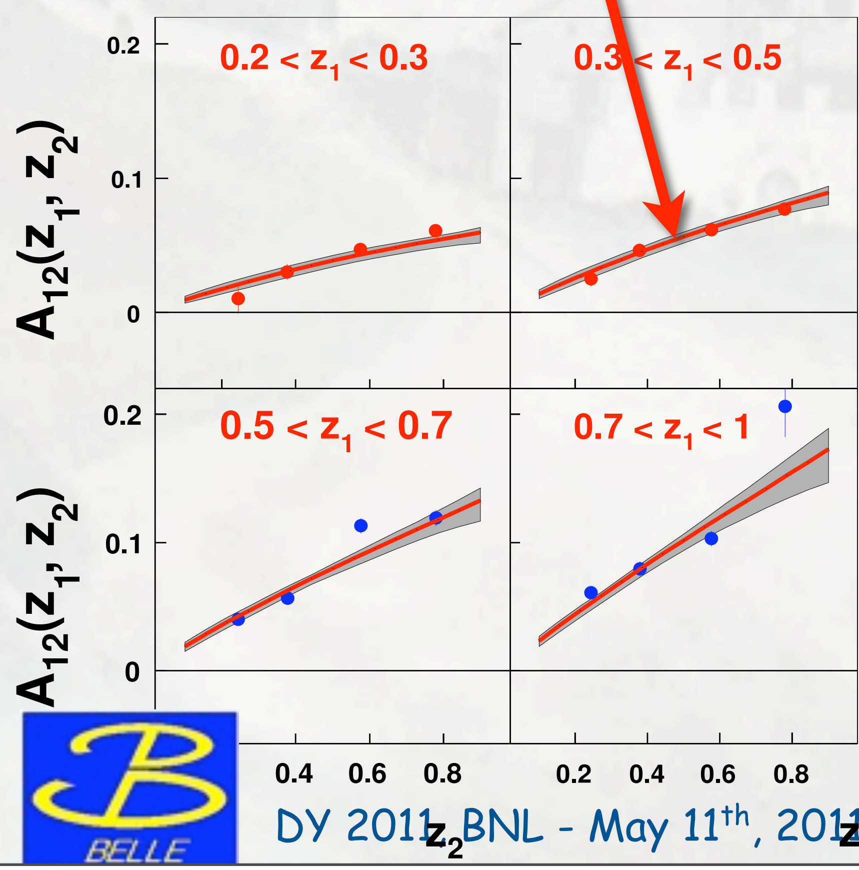

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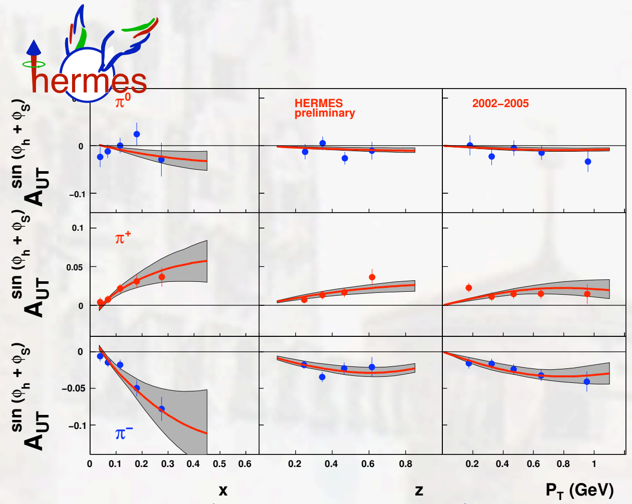

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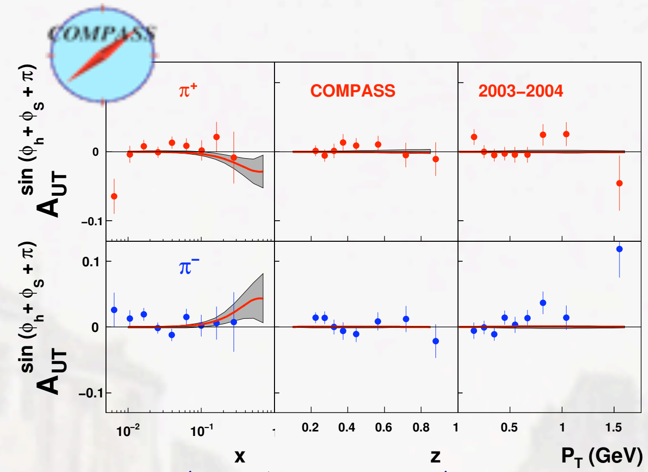

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fit to data

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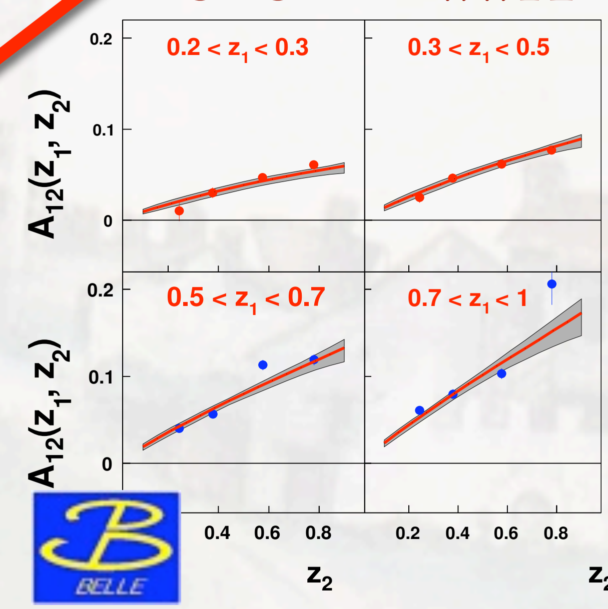
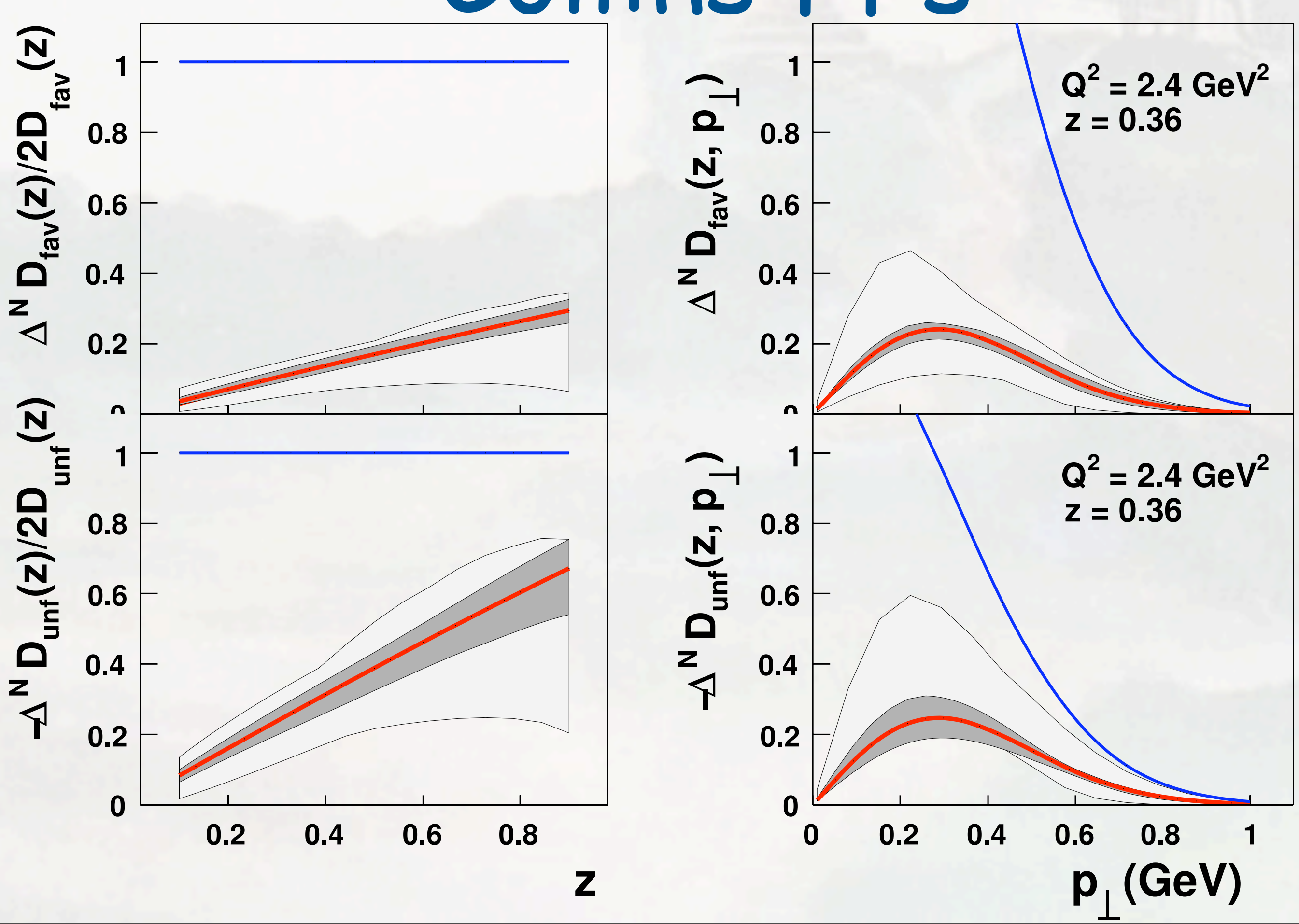


Collins FFs



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

Fit of Collins amplitudes

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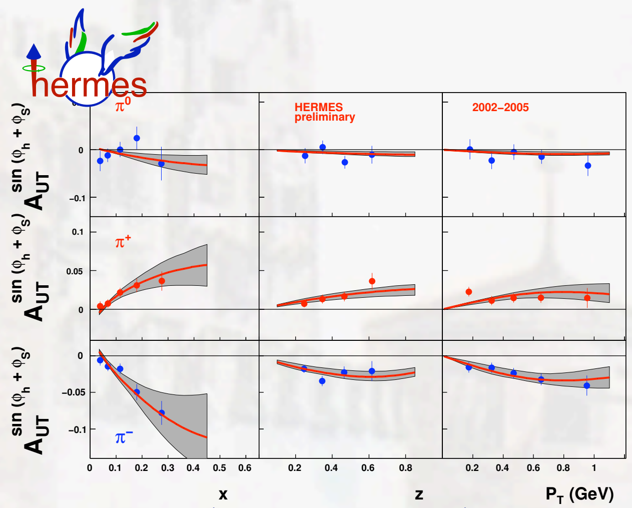
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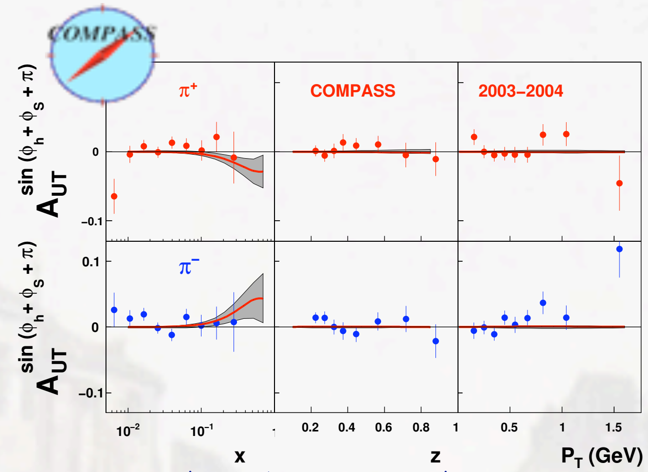
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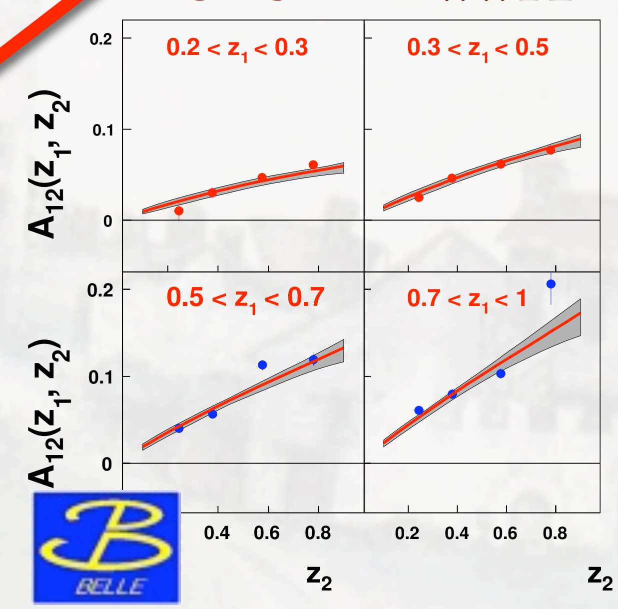
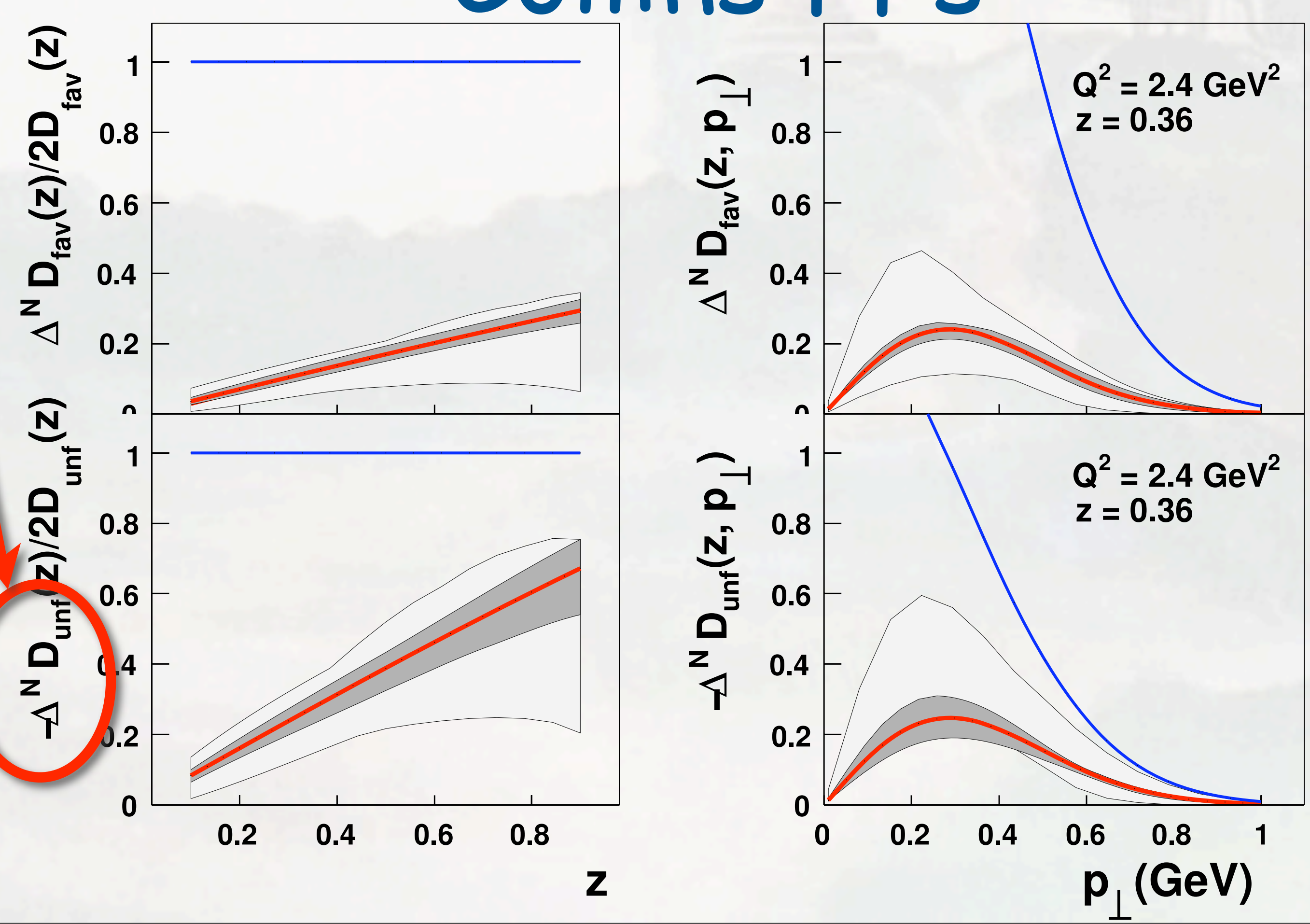
fit to data


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

opposite sign

Collins FFs



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

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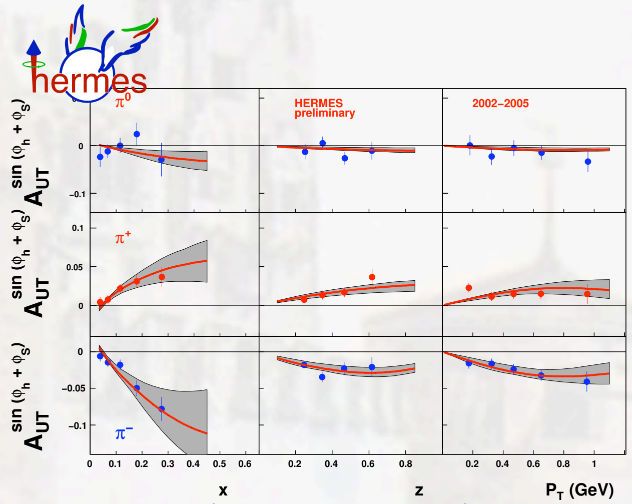
Fit of Collins amplitudes



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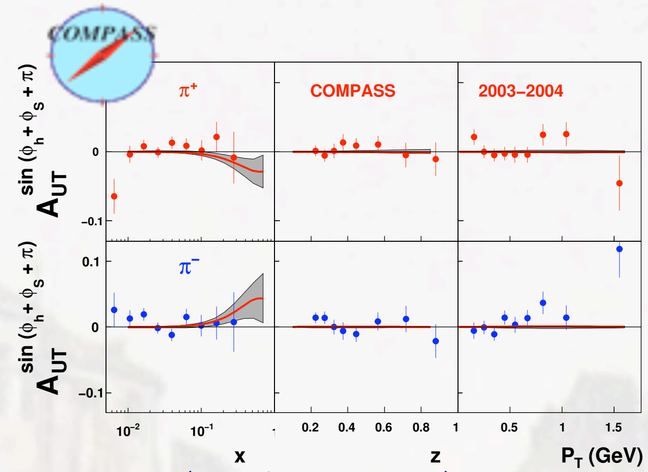

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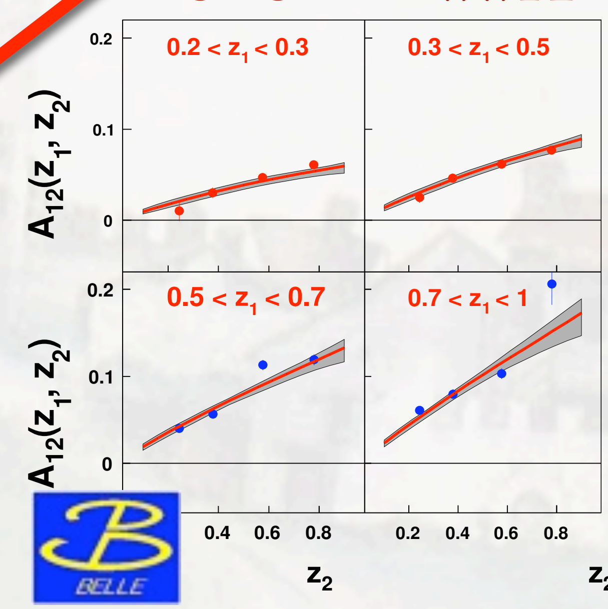

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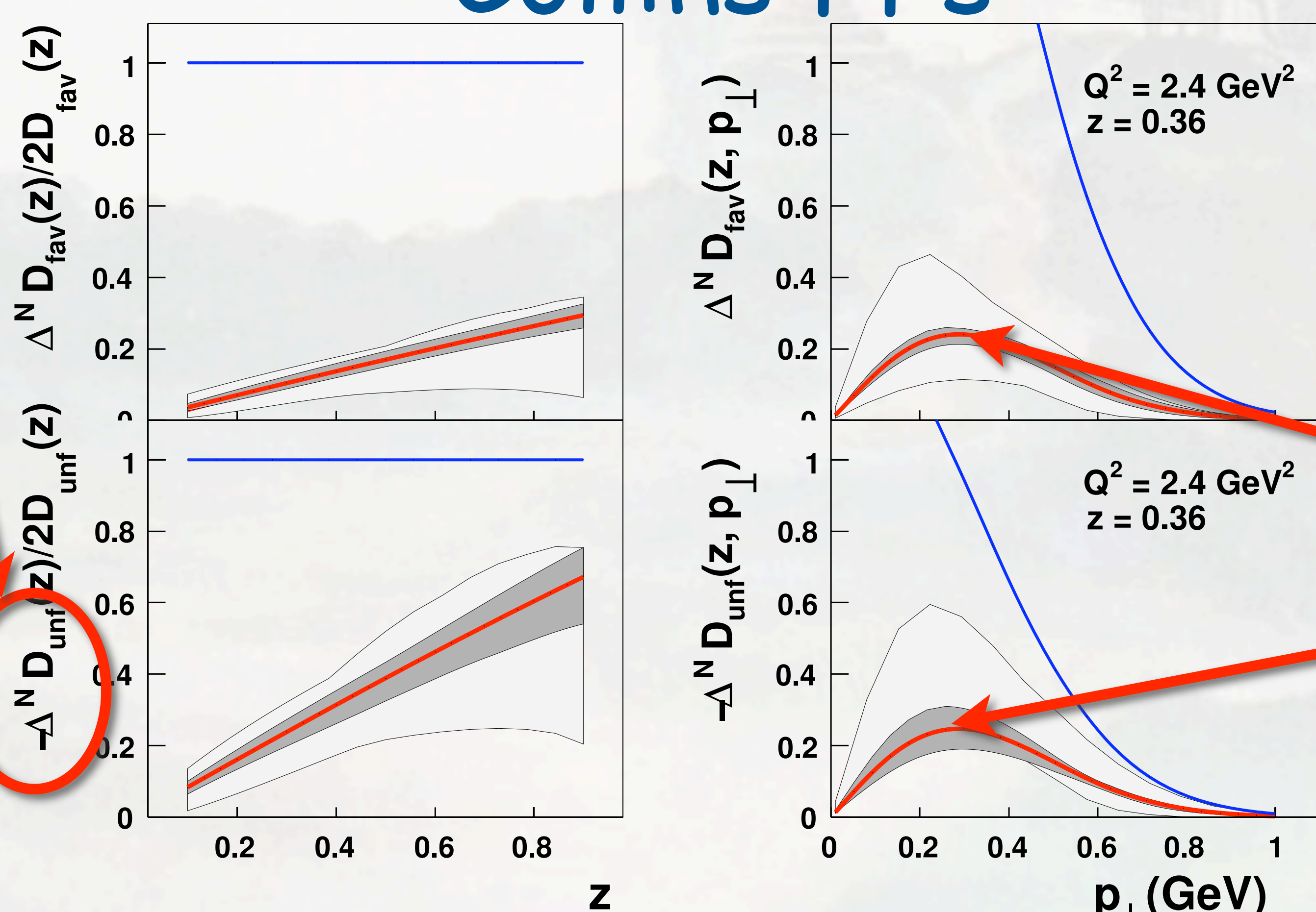

similar magnitude

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

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L		g_{1L}	$h_{1L}^\perp$
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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)
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[7] Anselmino et al., PRD 75 (07)
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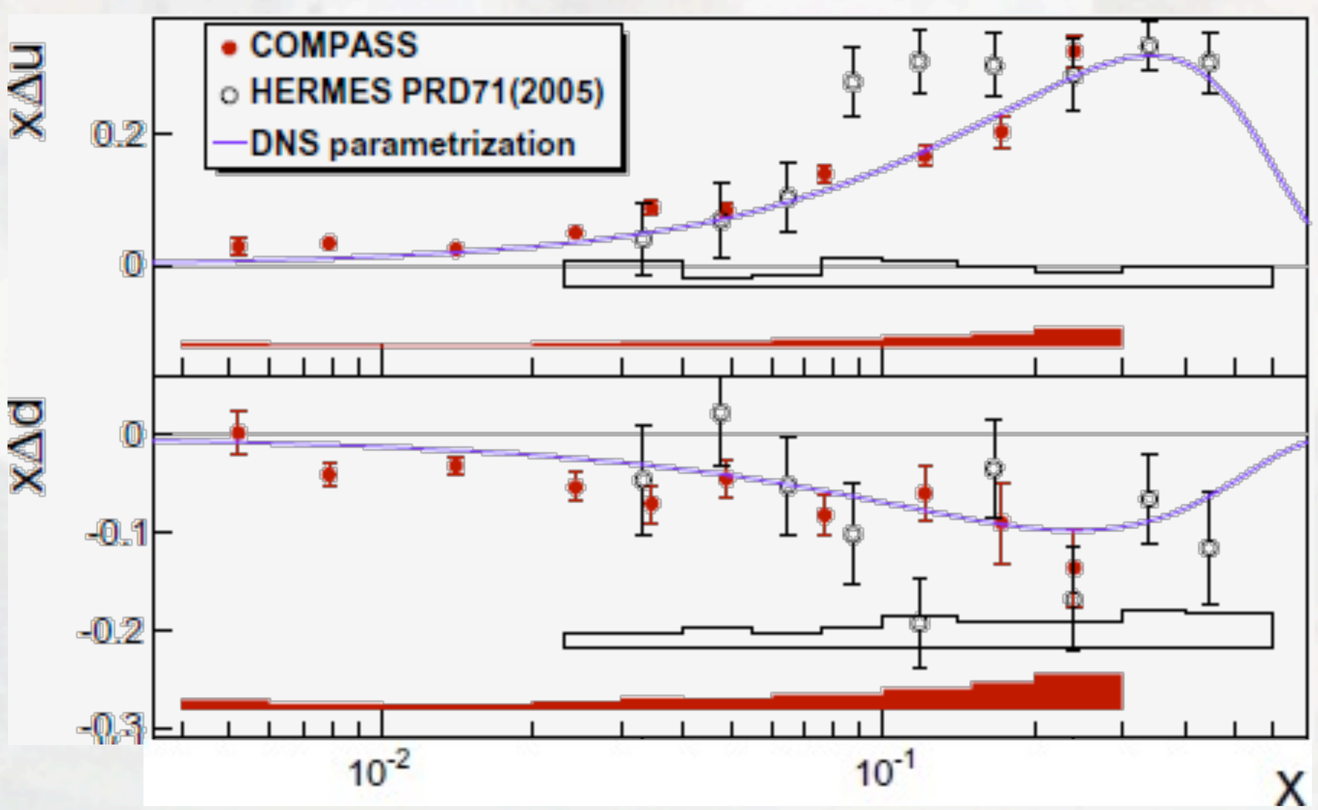

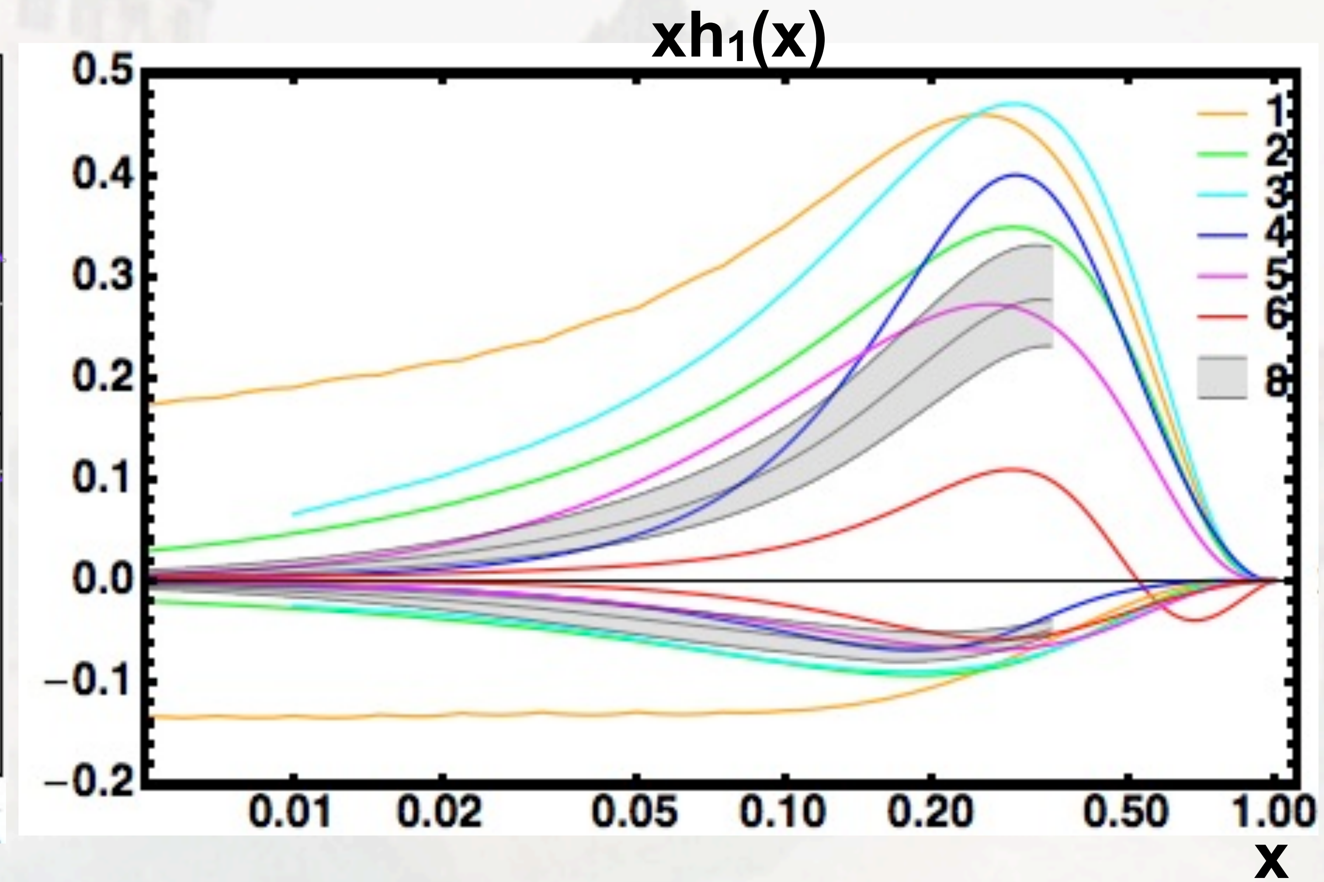

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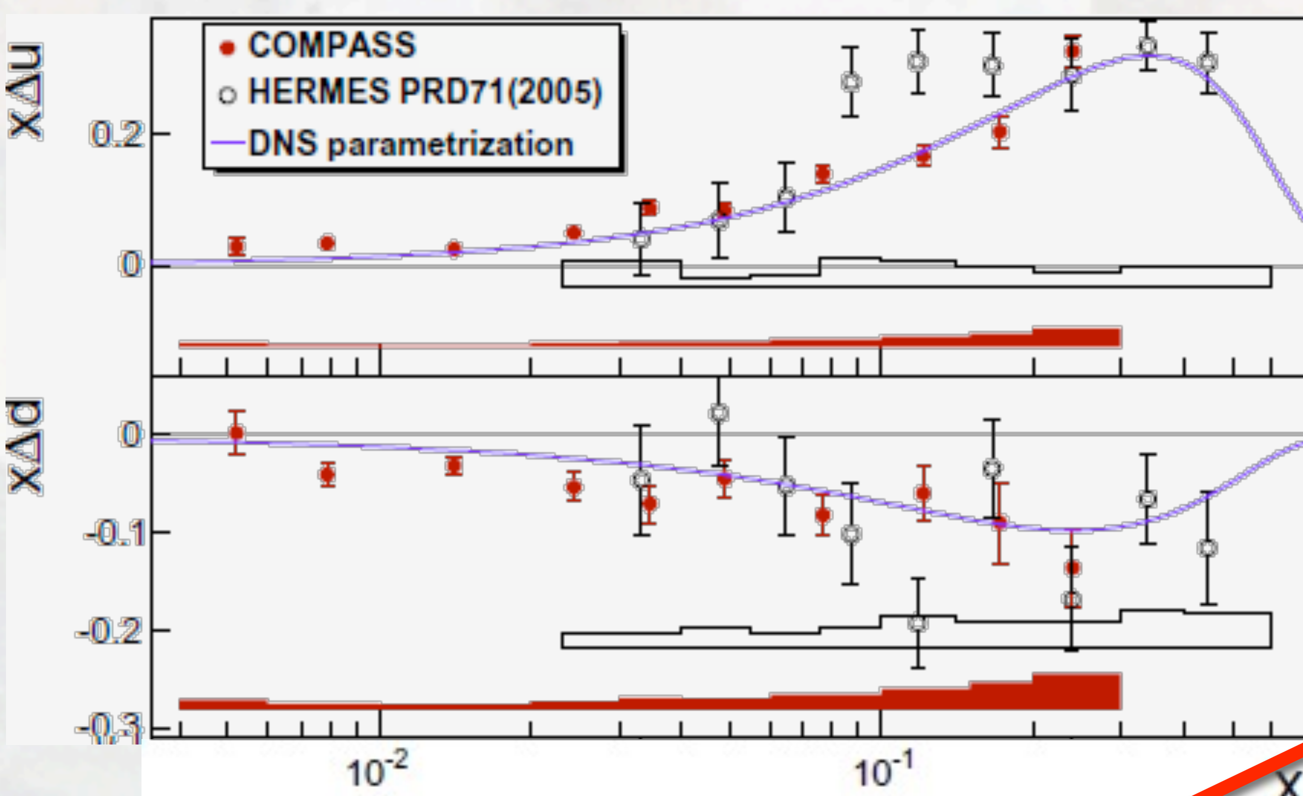

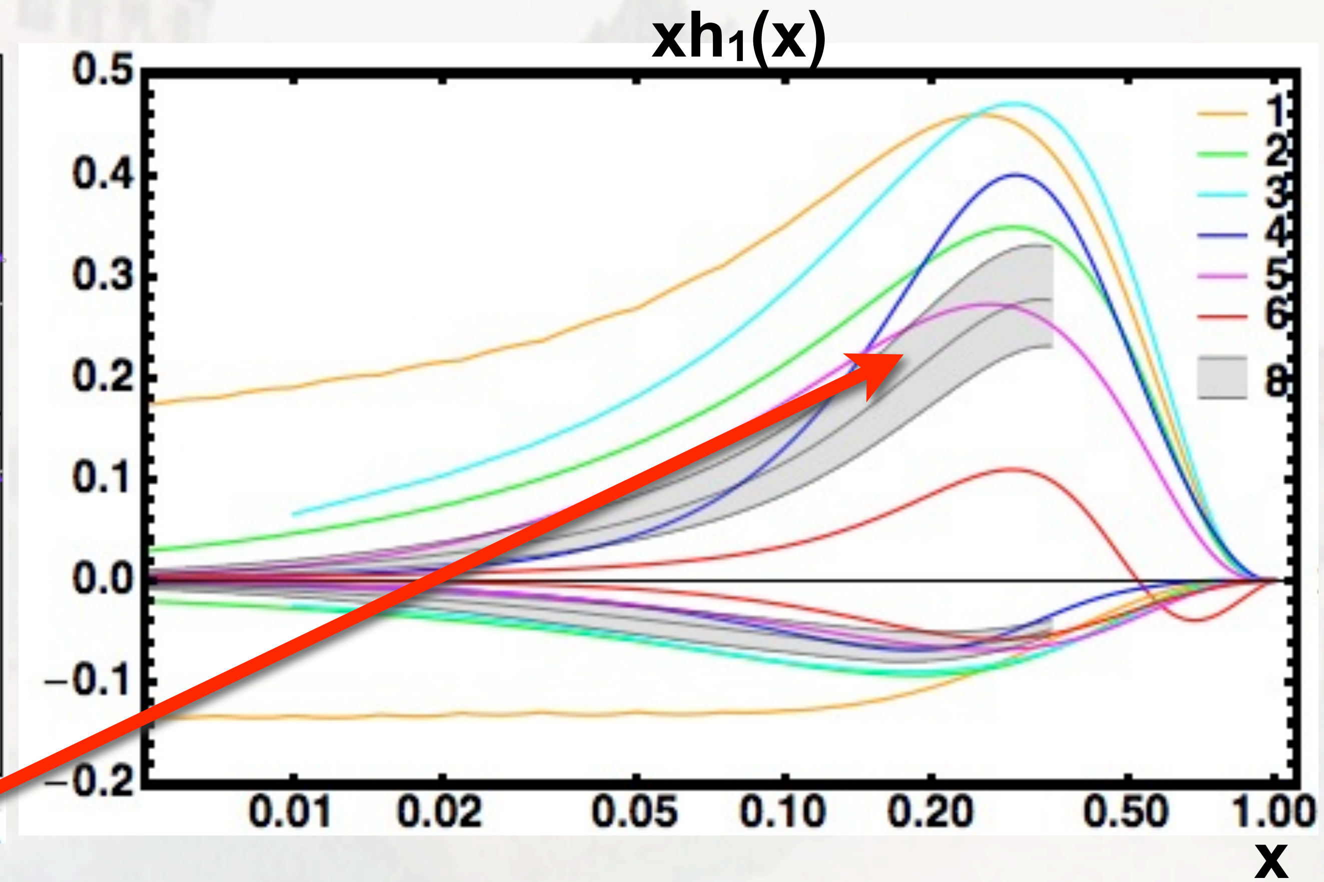

☑ u quark transversity along nucleon spin

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

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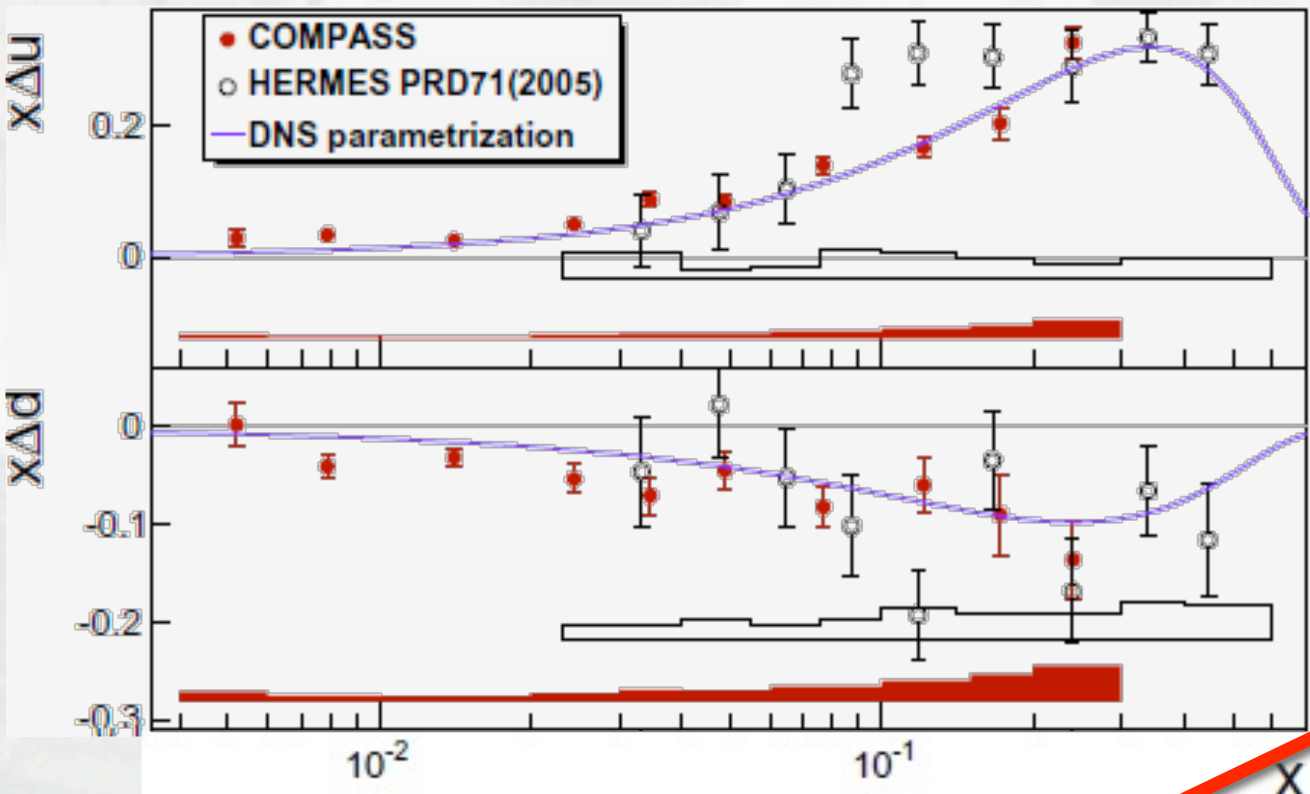

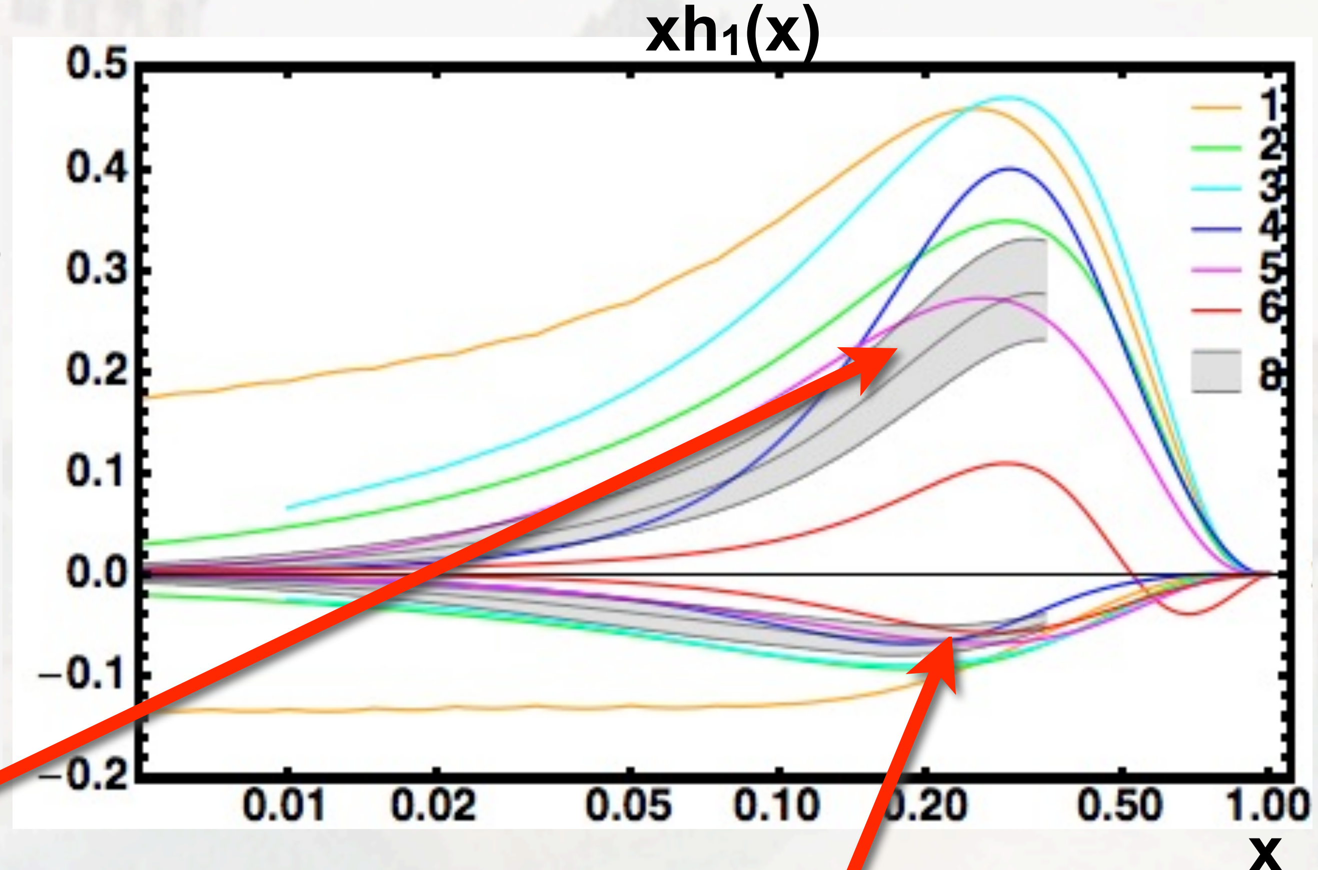

☑ u quark transversity along nucleon spin

☑ 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, $h_{1T}^\perp$

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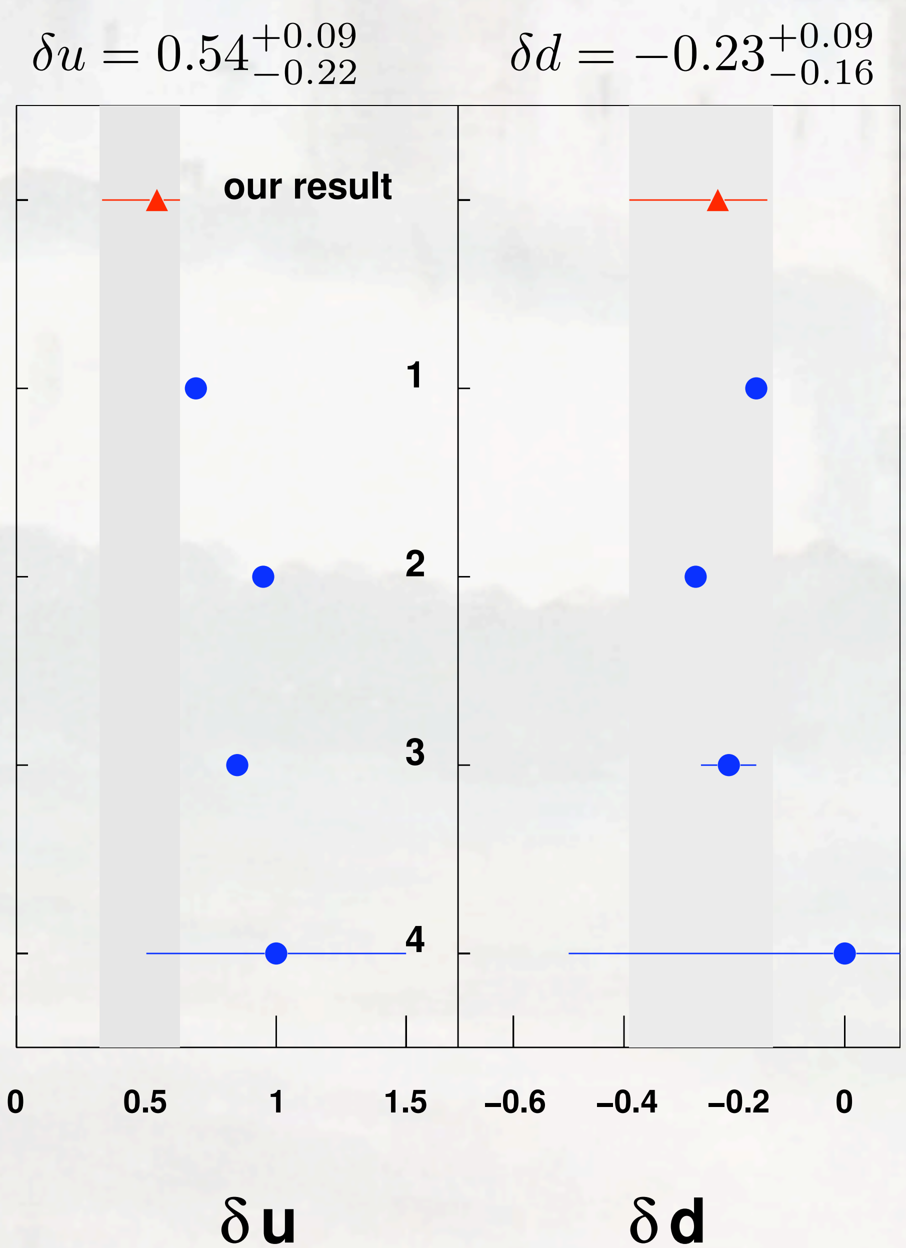

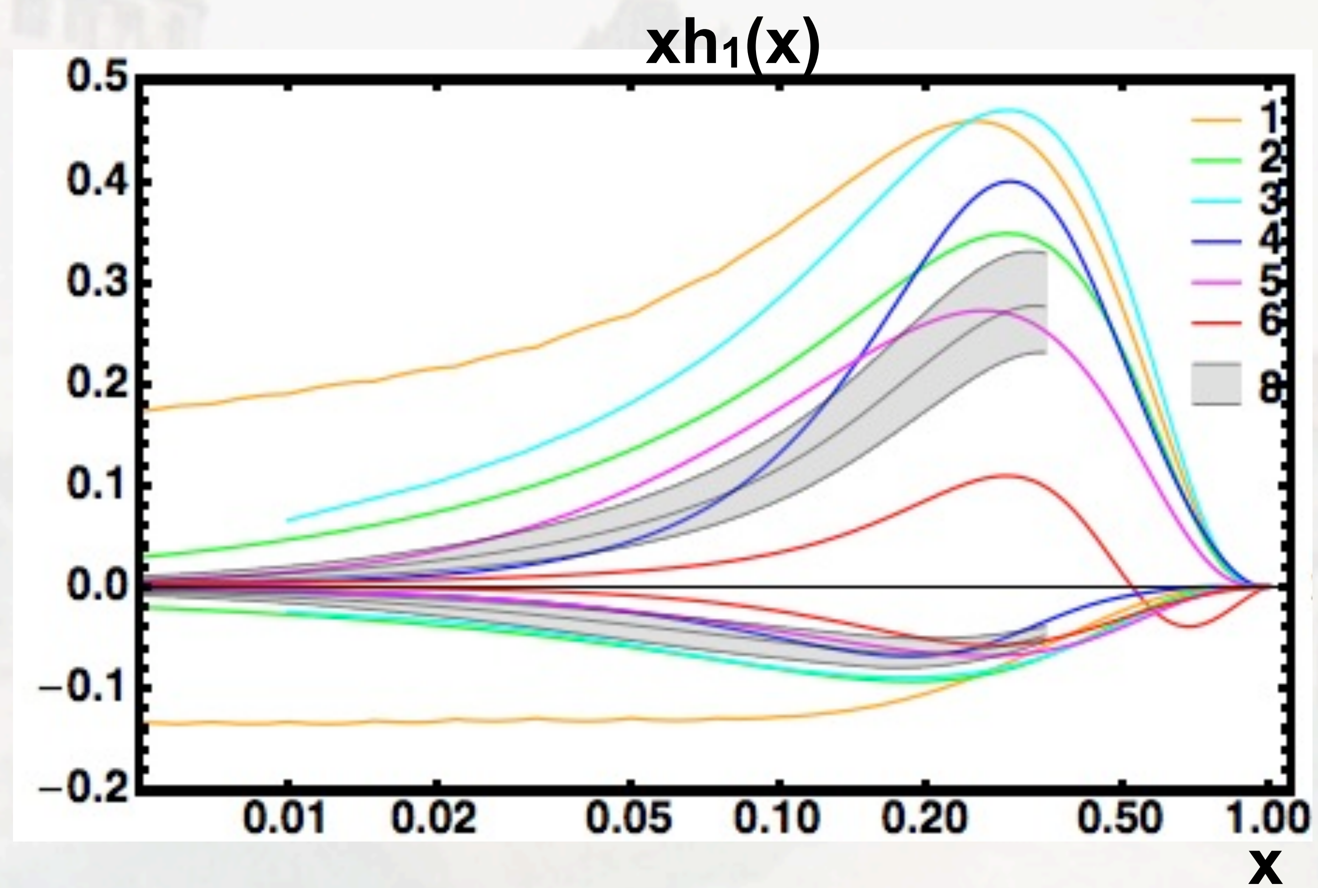

tensor charge:

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

	U	L	T
U	f_1		$h_1^\perp$
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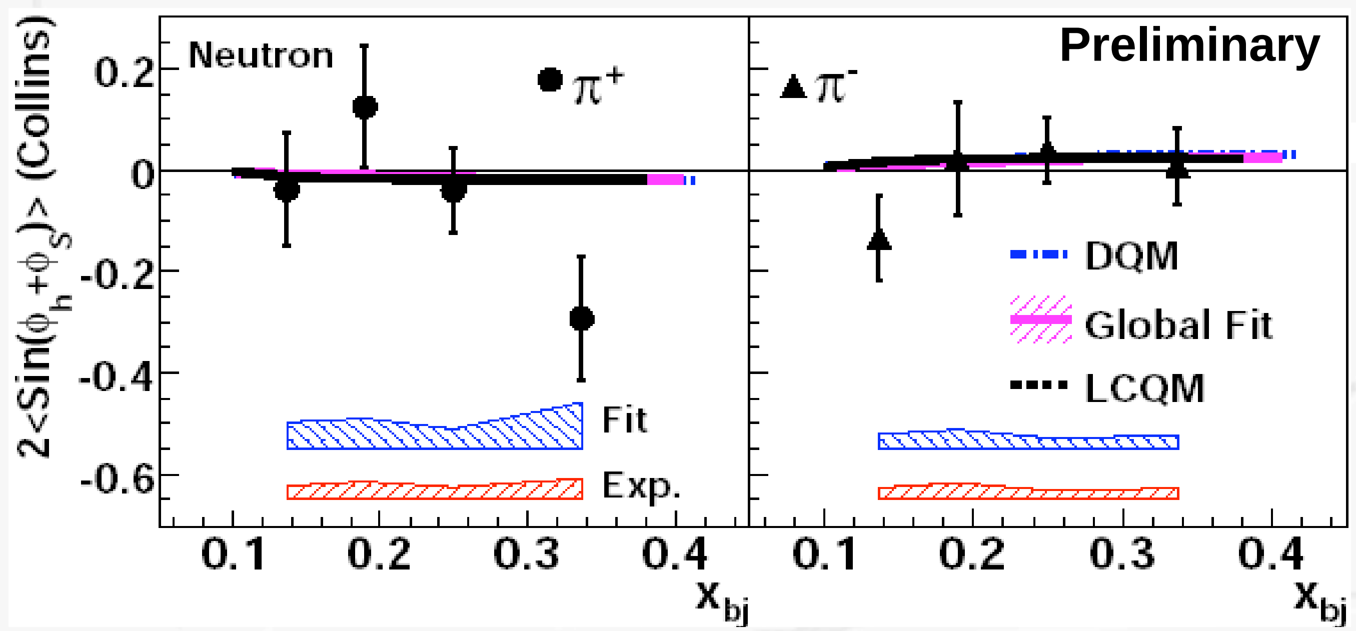
Transversity distribution (Collins fragmentation)

- wealth of new results available and/or analyses ongoing
  - JLab
  - COMPASS
  - HERMES
  - BELLE
  - BaBar

^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010



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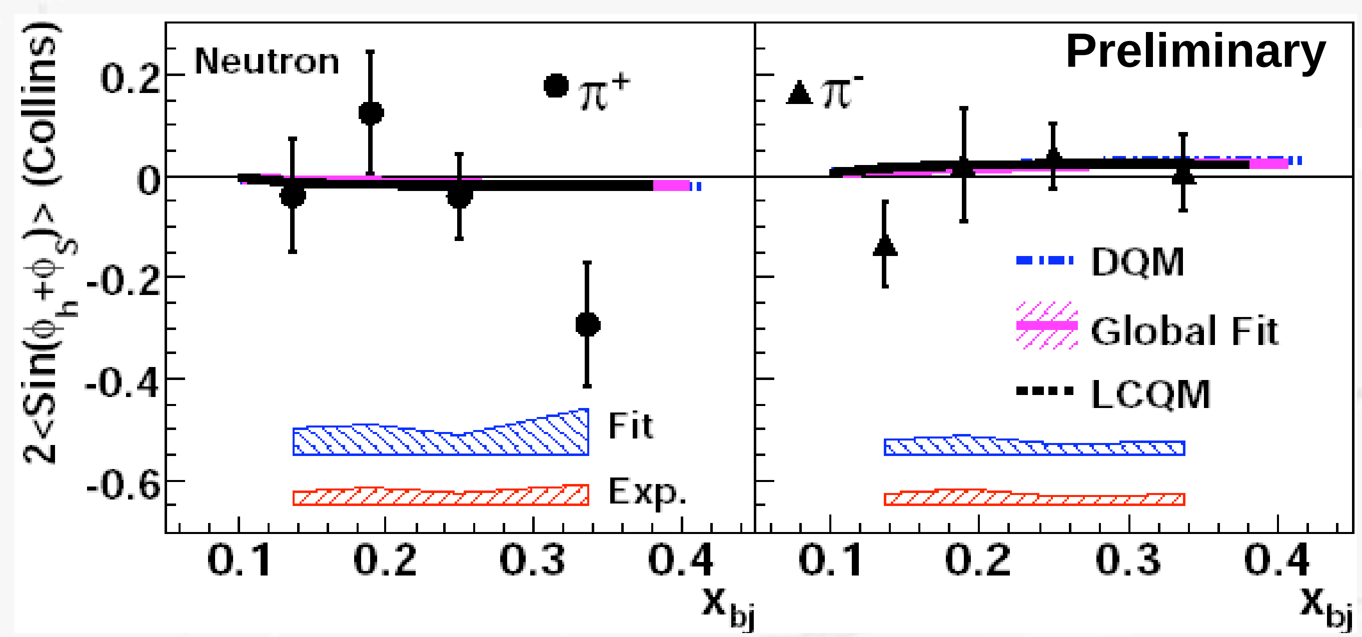

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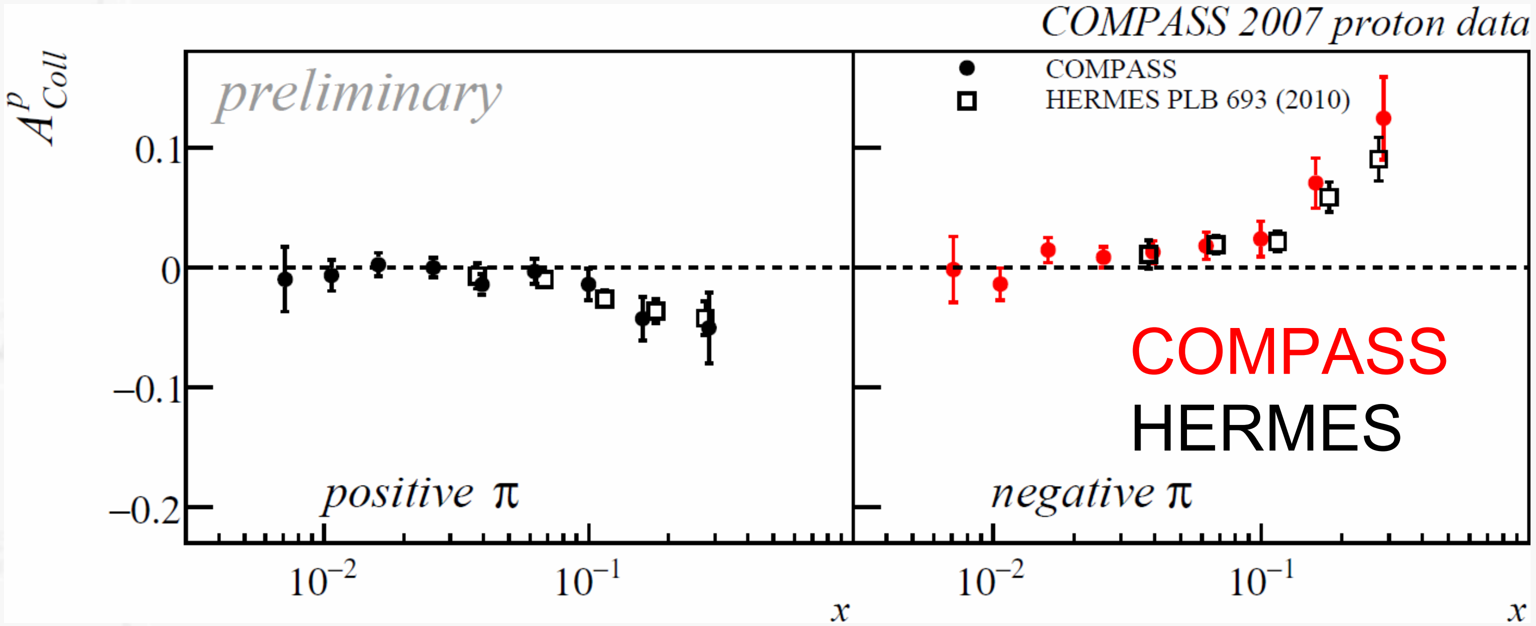
Collins amplitudes COMPASS & HERMES



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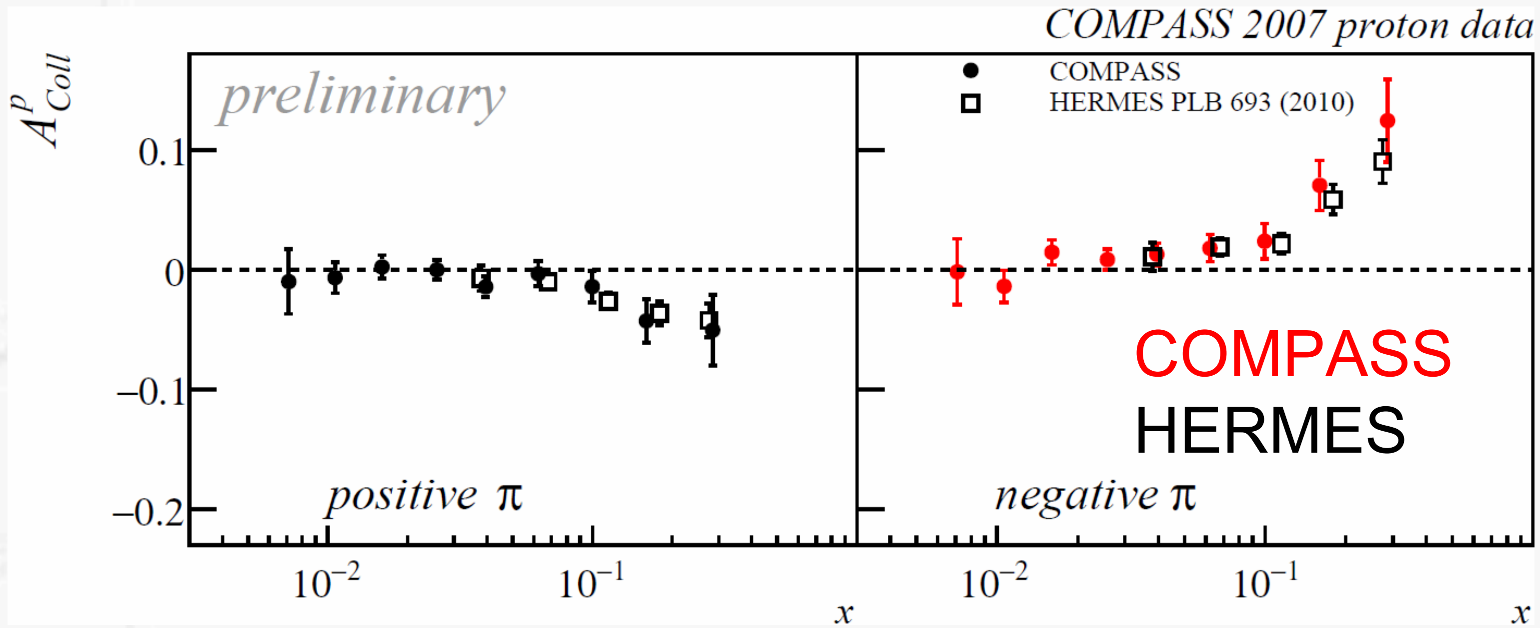
Collins amplitudes COMPASS & HERMES

- similar behavior for pions



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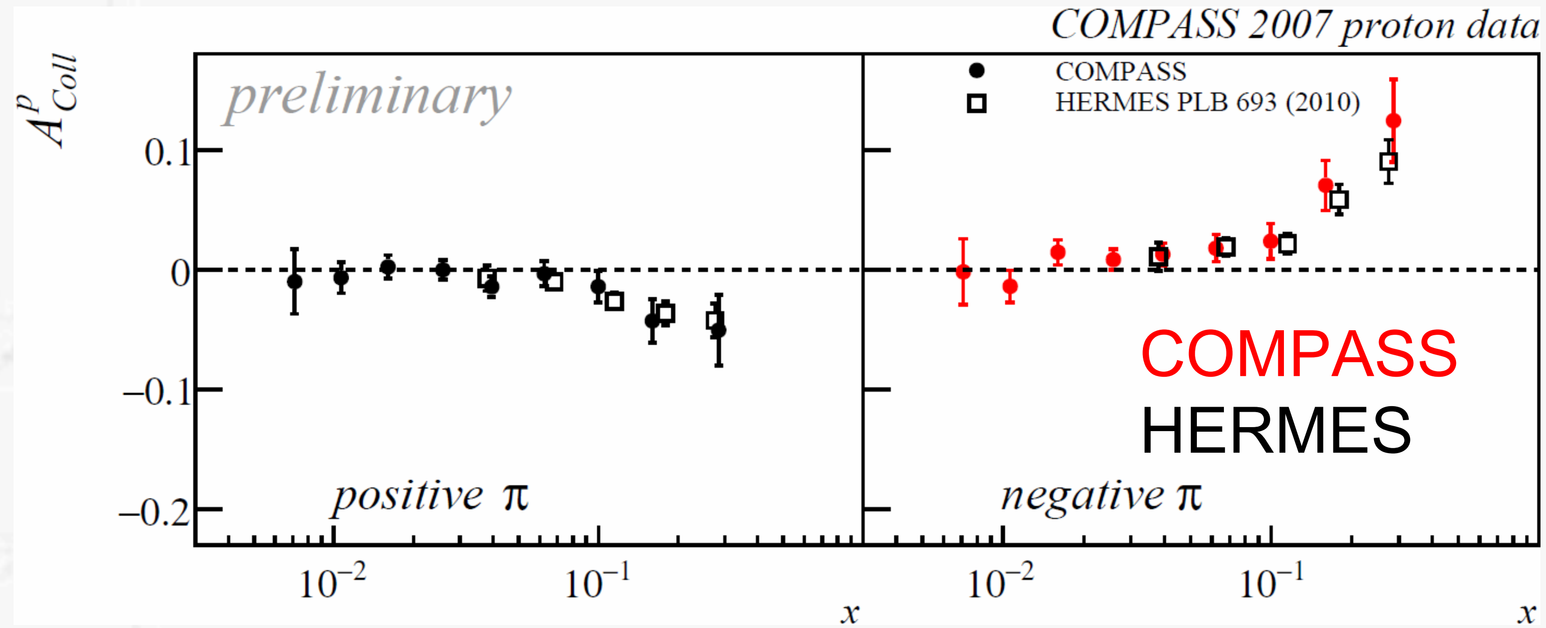
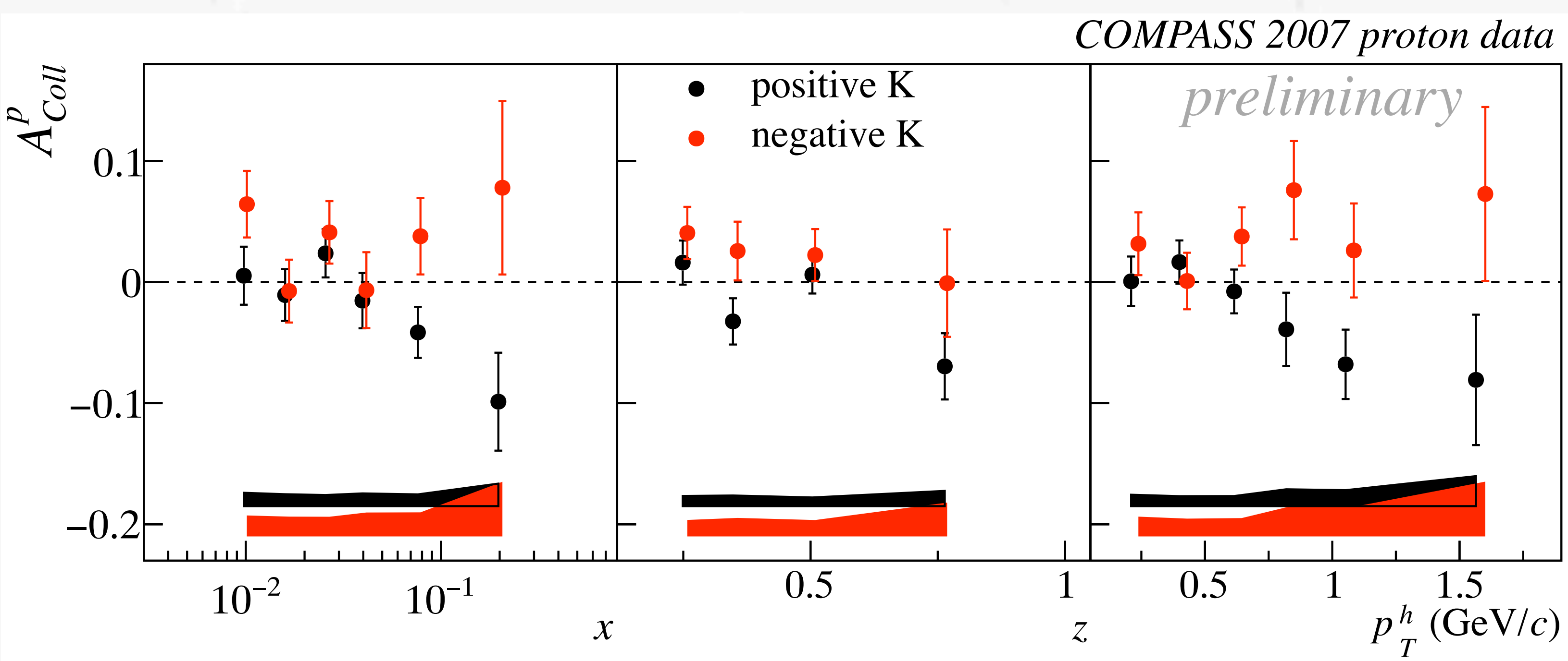
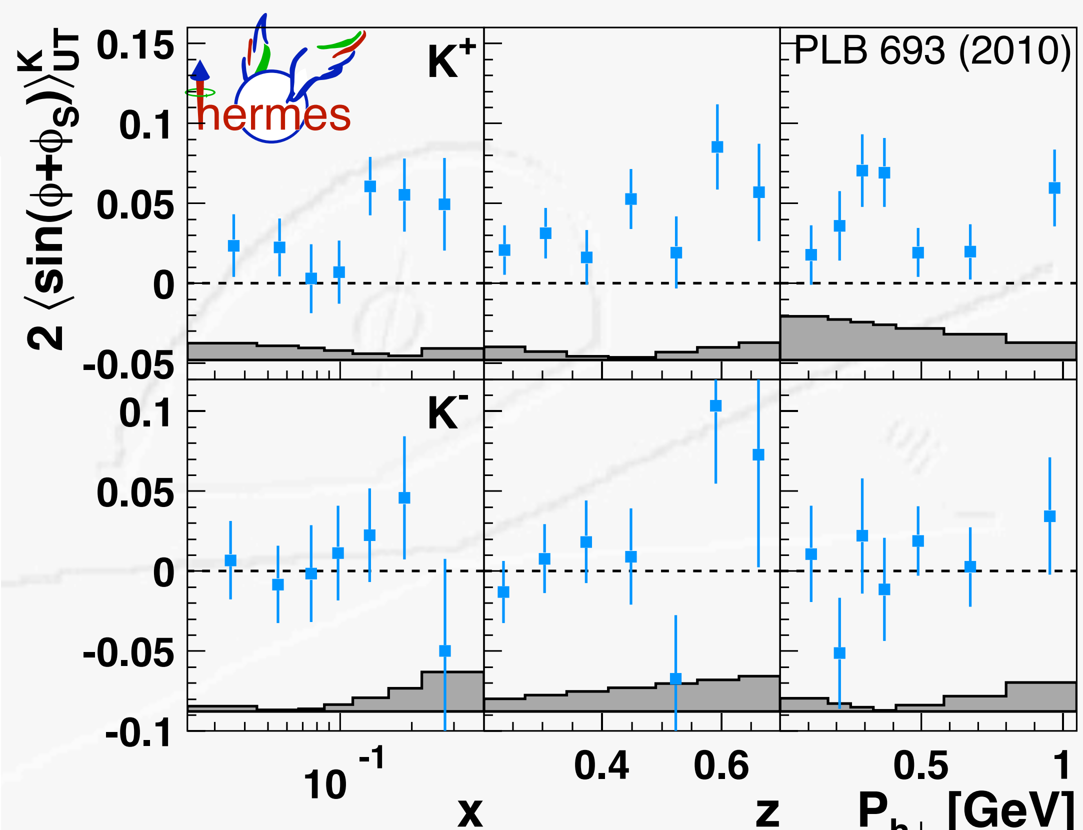
Collins amplitudes COMPASS & HERMES

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







Transversity's friends

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Pretzelosity

- 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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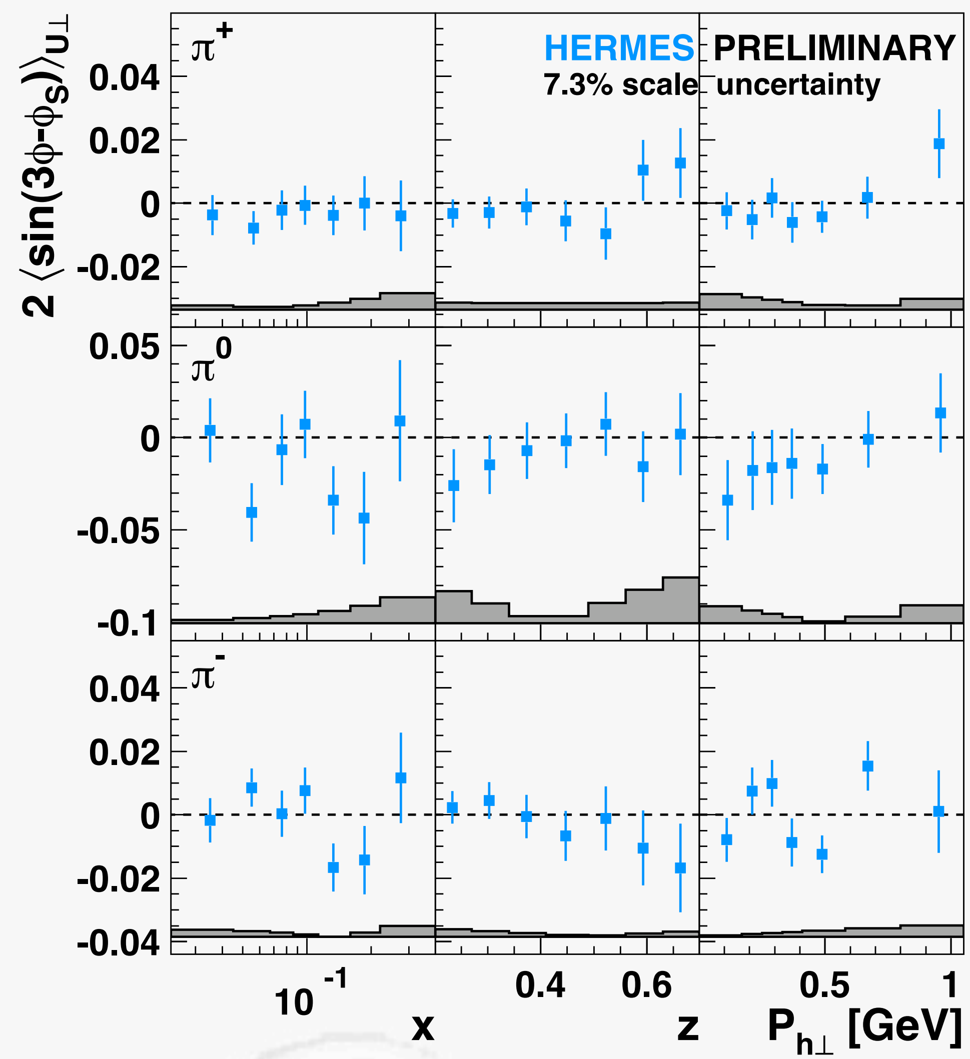

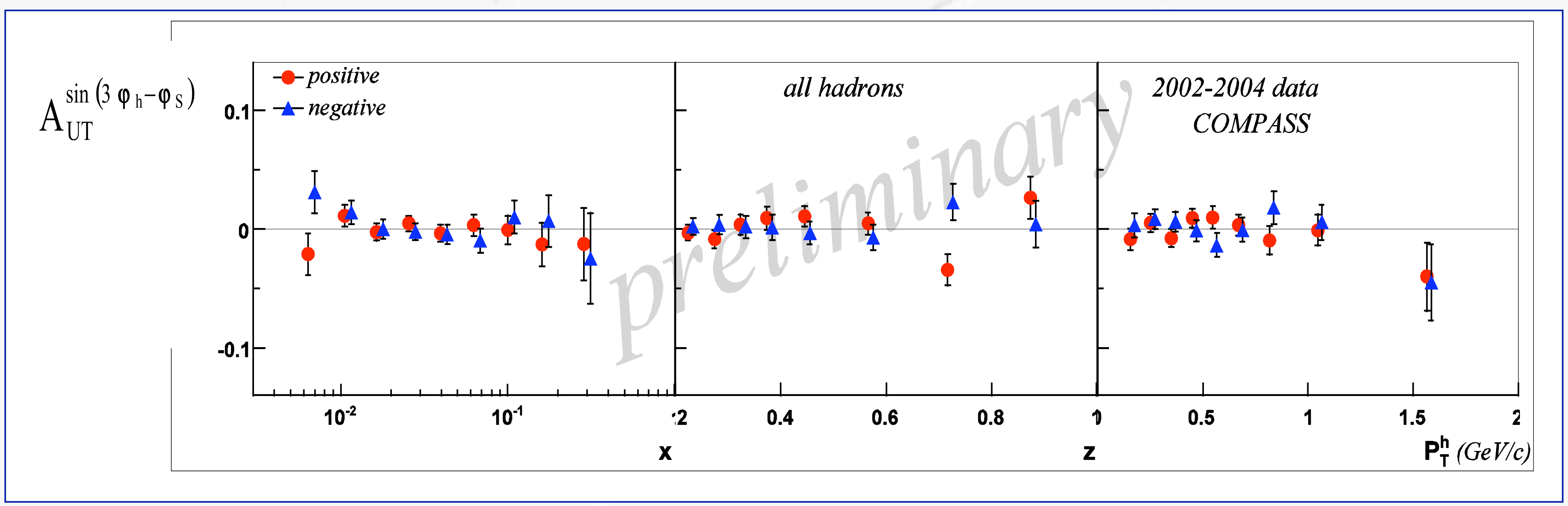

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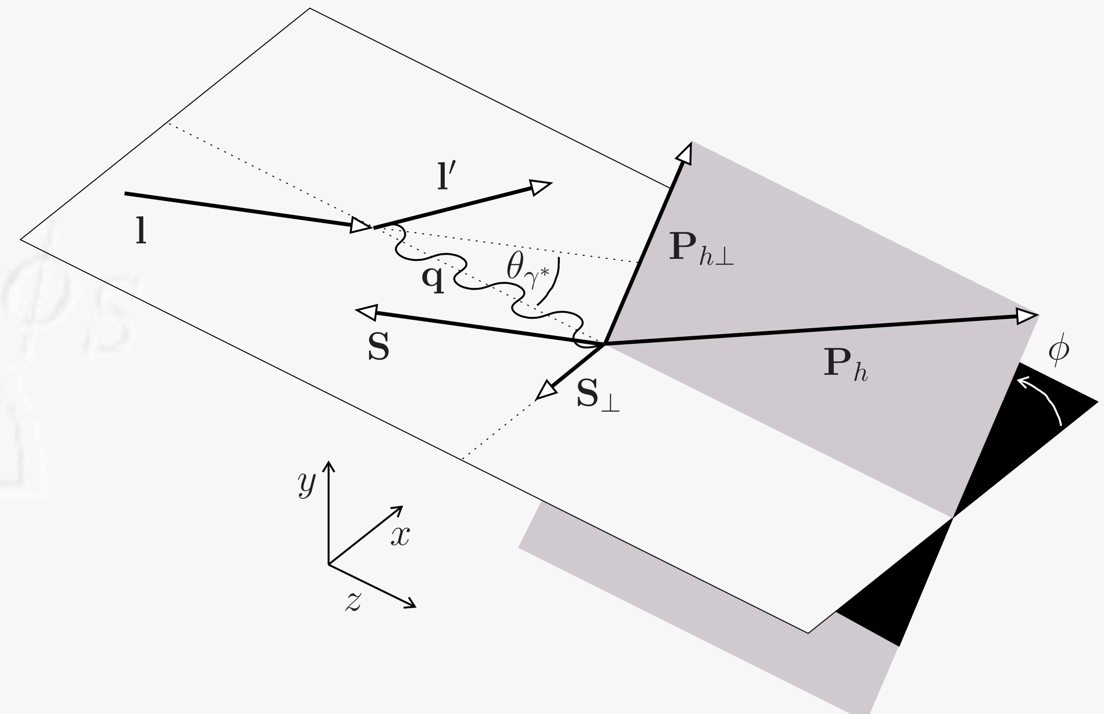
Pretzelosity



- could also use longitudinally polarized targets:

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

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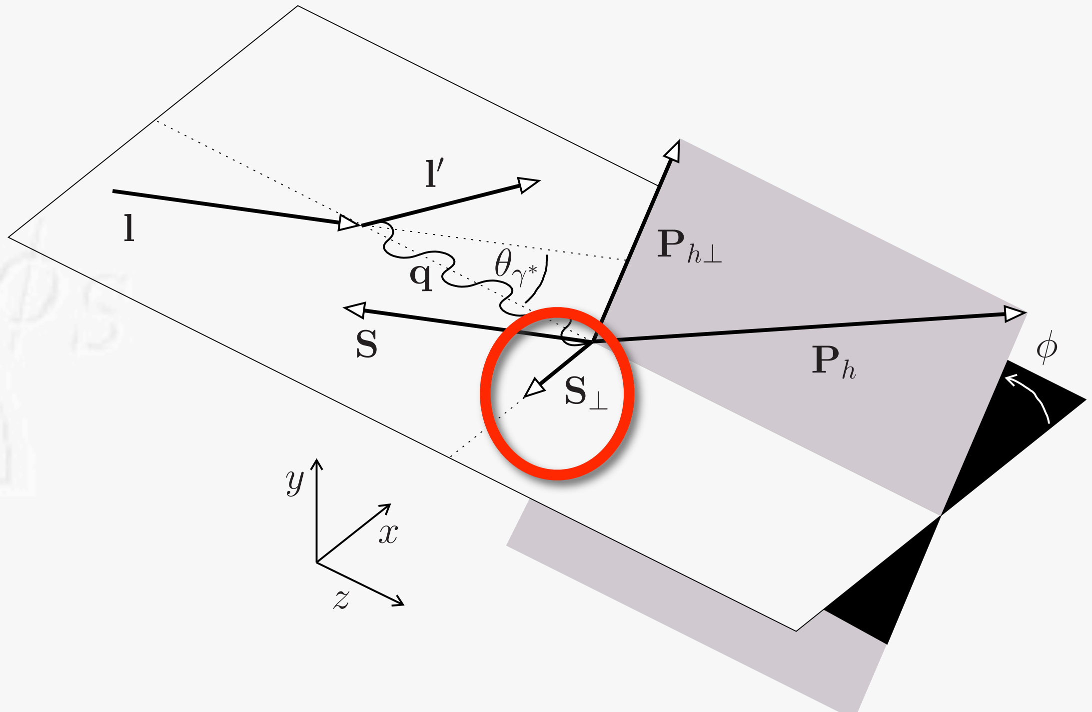
$$\sin(\mathbf{3}\phi - \phi_S) \rightsquigarrow -\sin(\mathbf{3}\phi)$$



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

Pretzelosity

- could also use longitudinally polarized targets:

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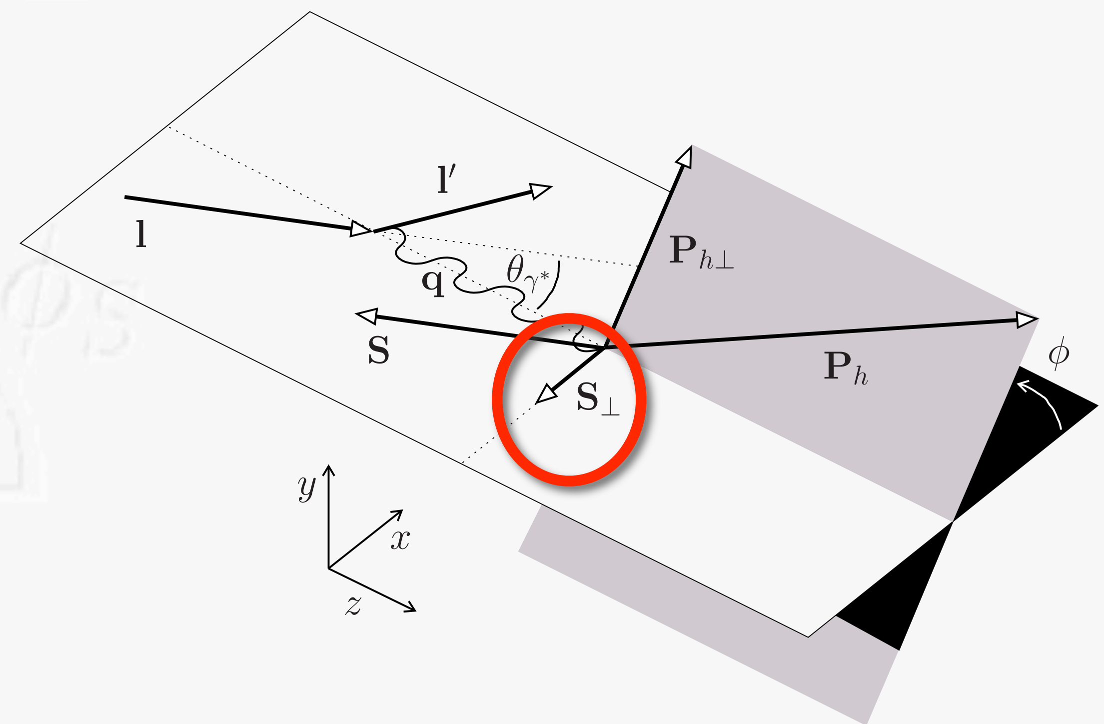
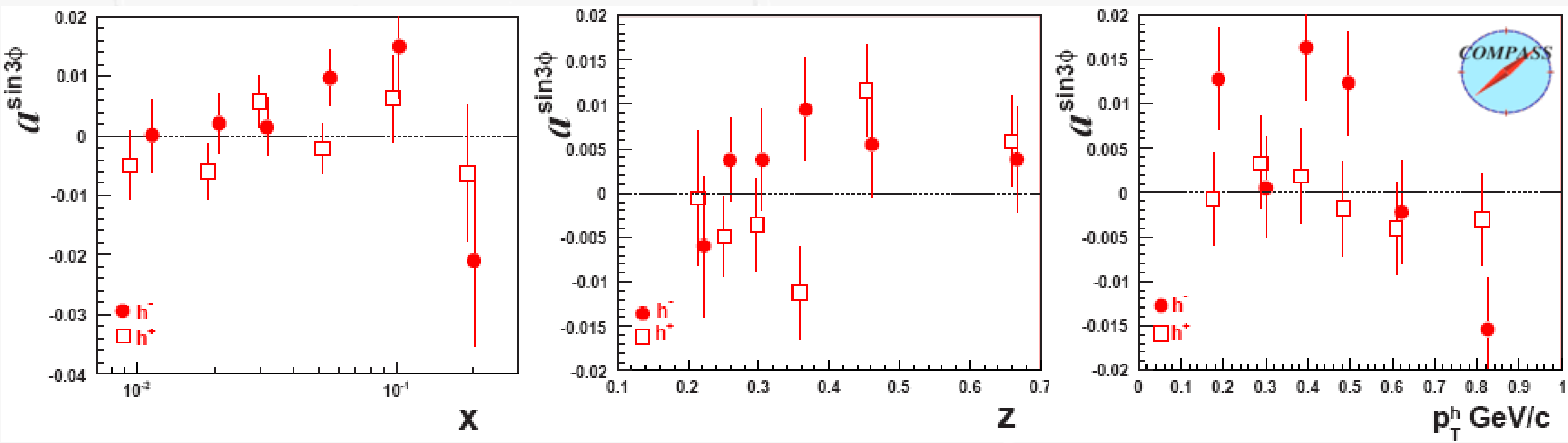
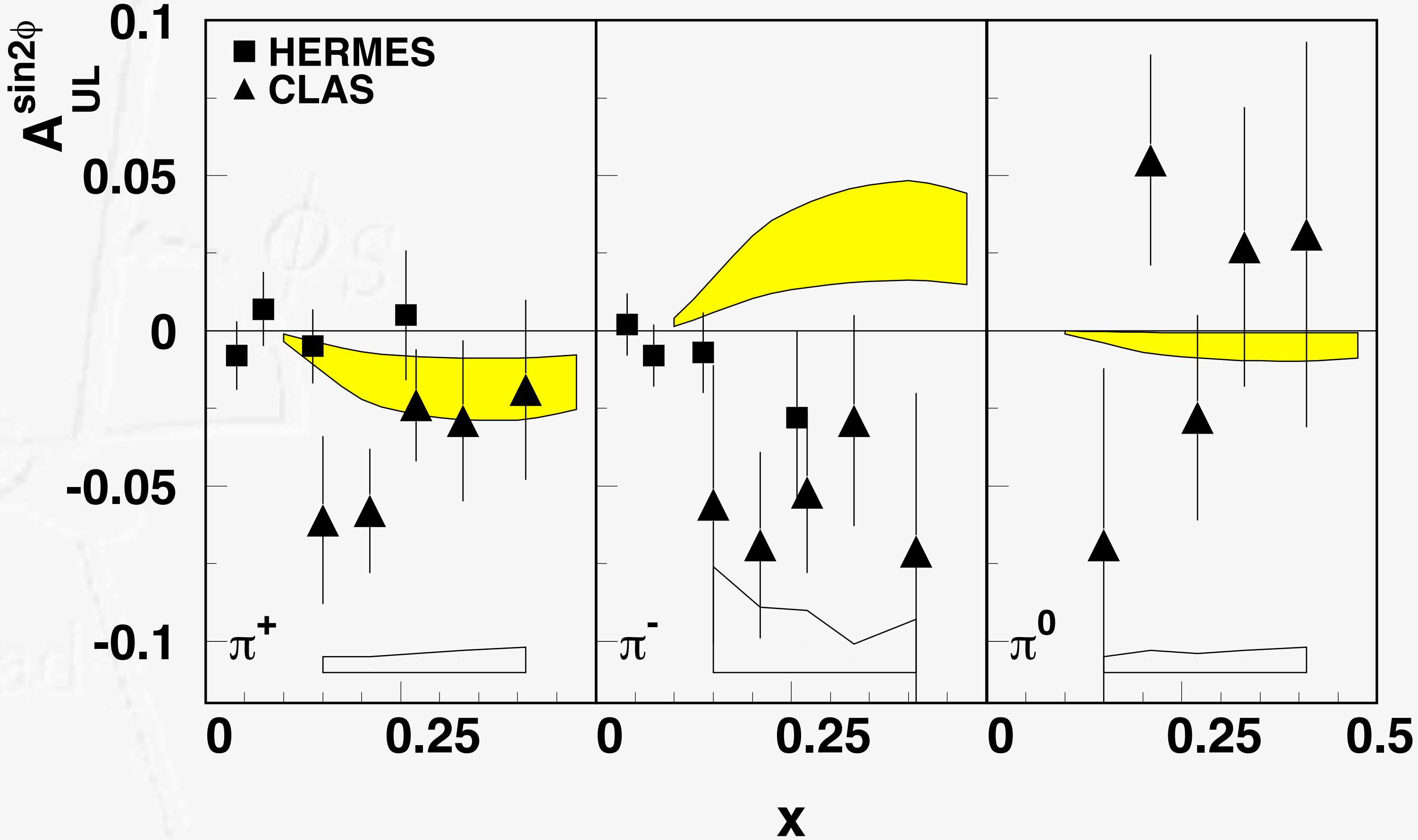


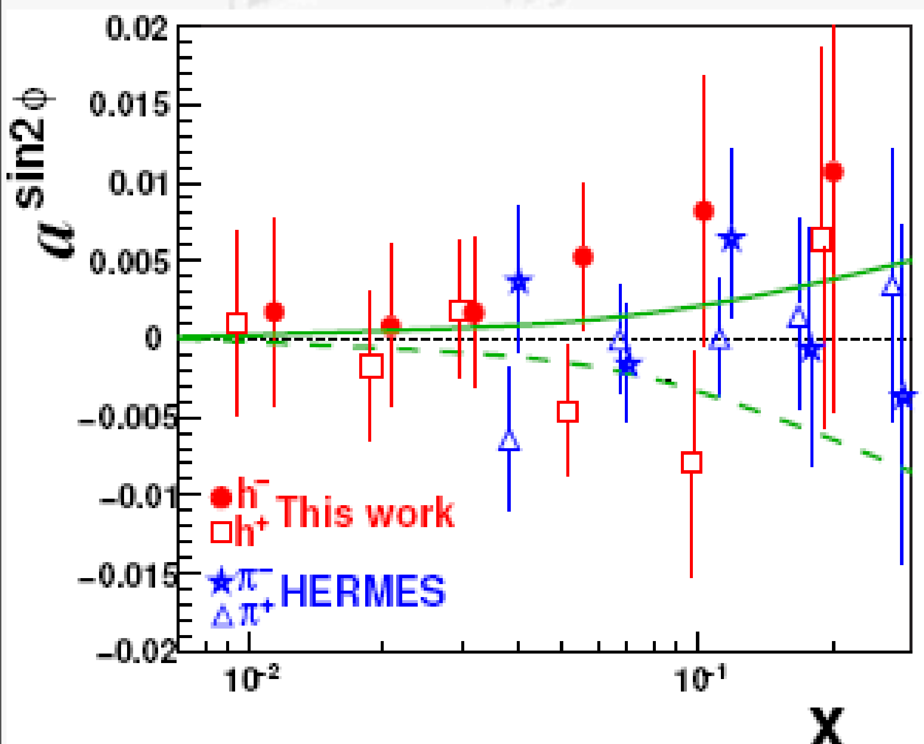


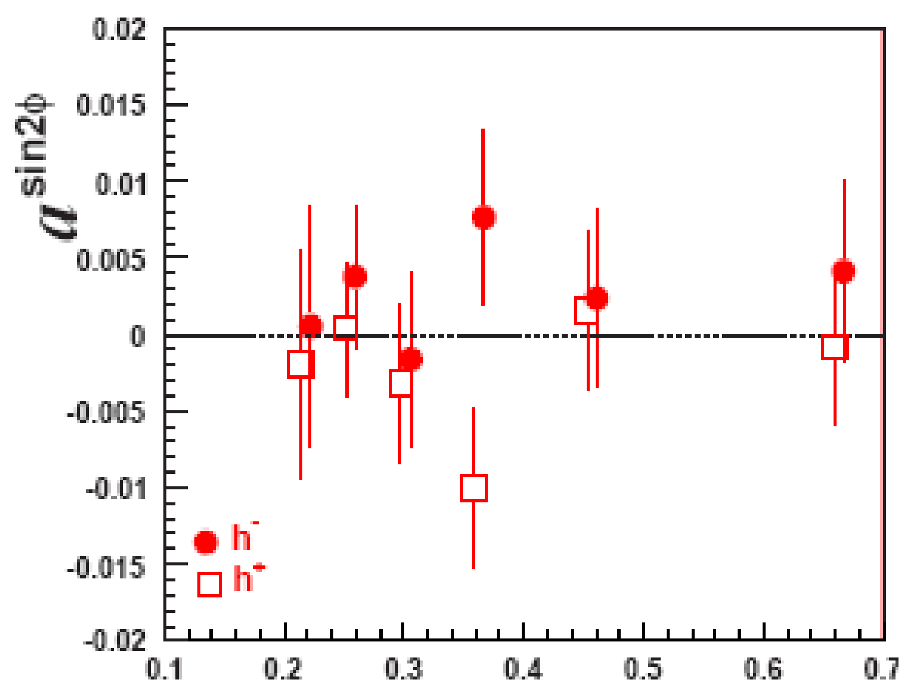
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

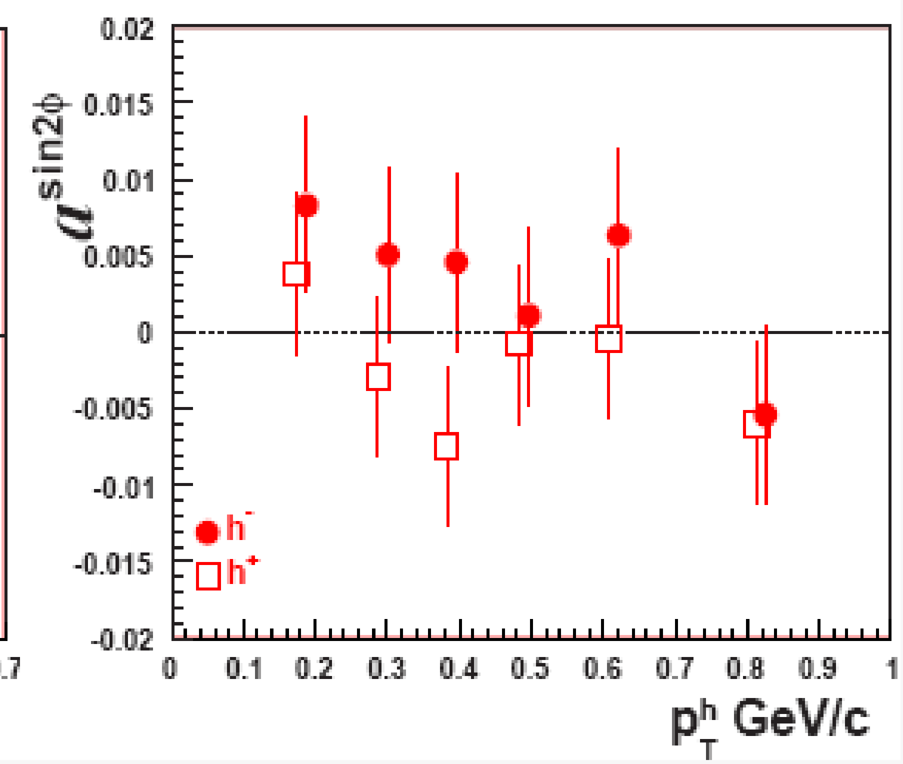
Worm-Gear I

- again chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES





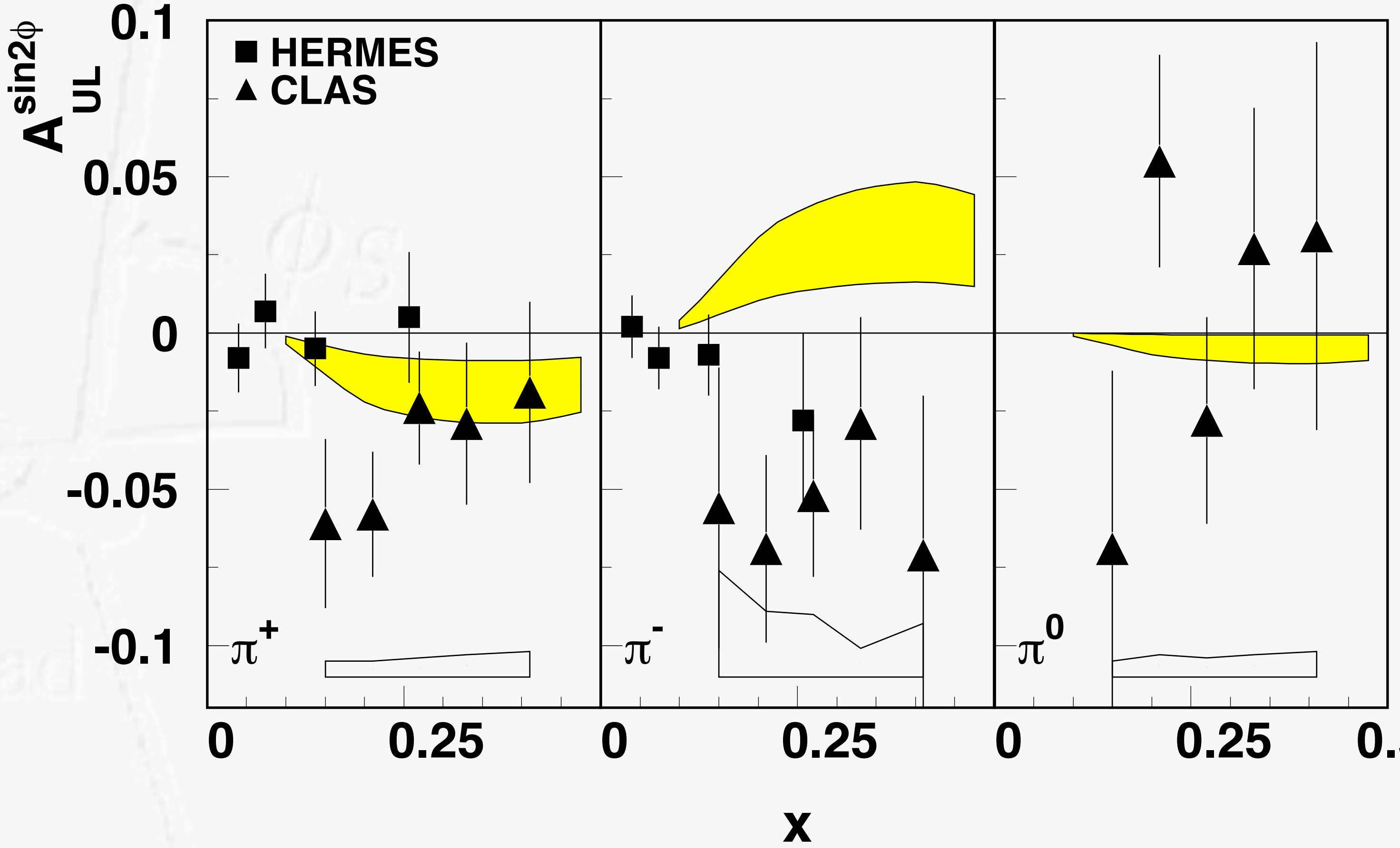




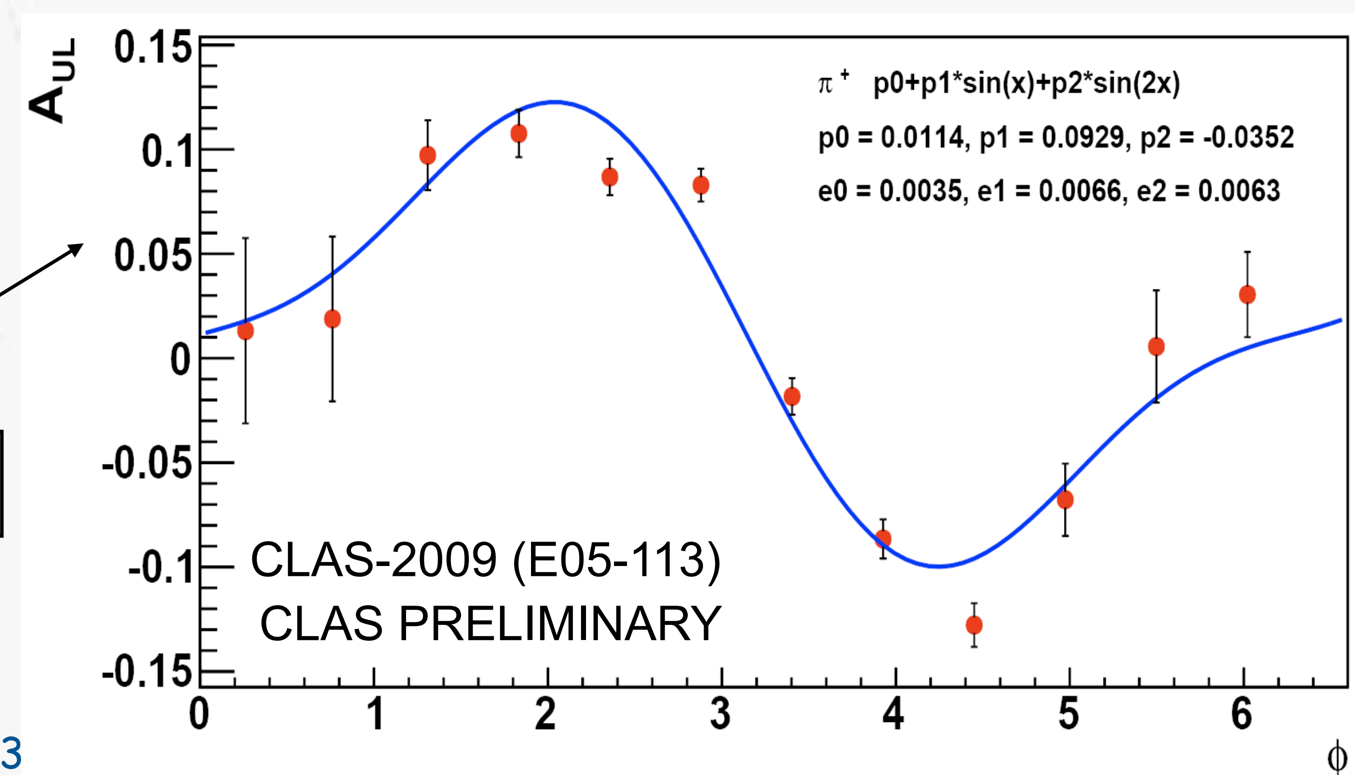
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Worm-Gear I

- again chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES
- new data from CLAS



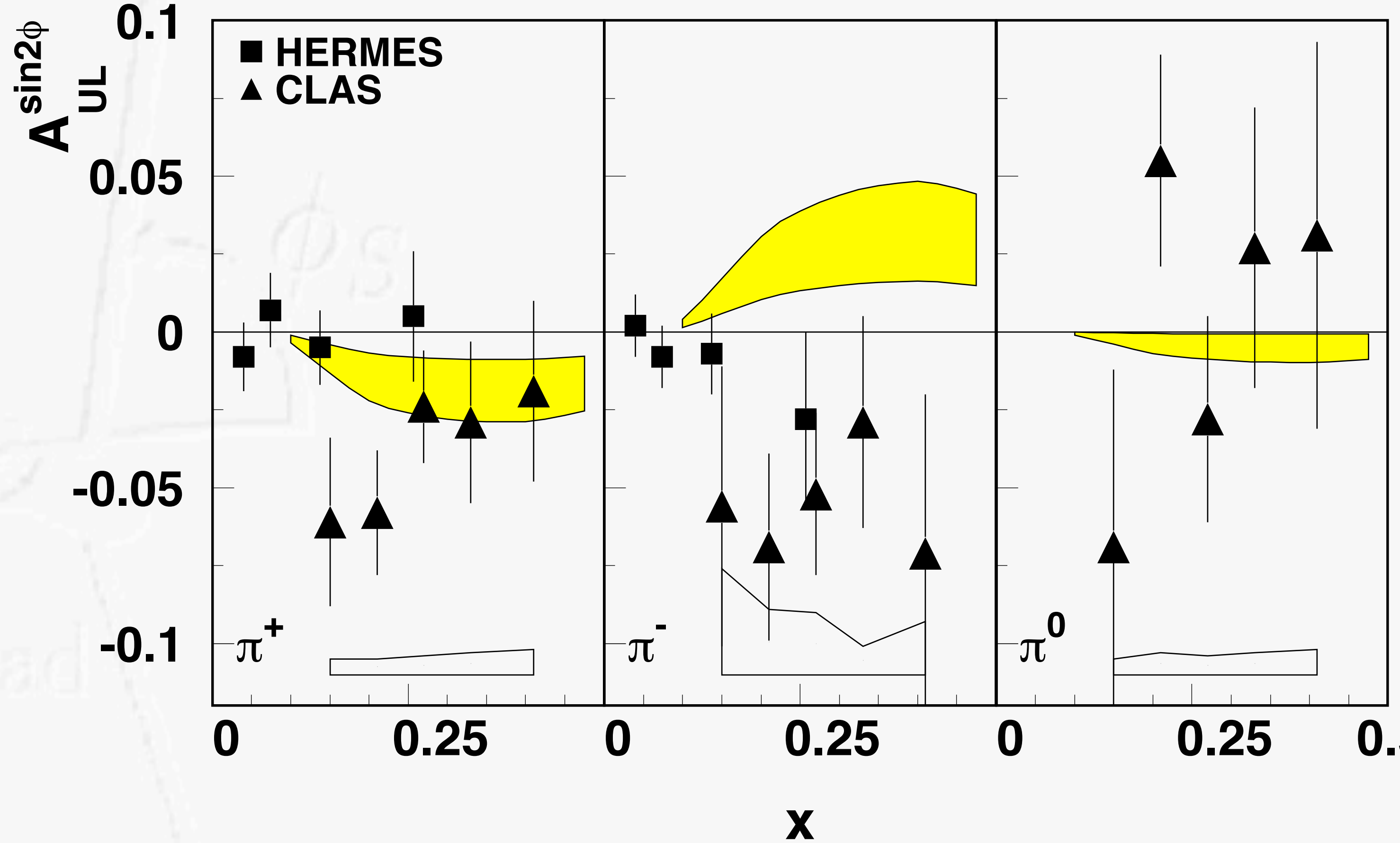
~10% of E05-113 data



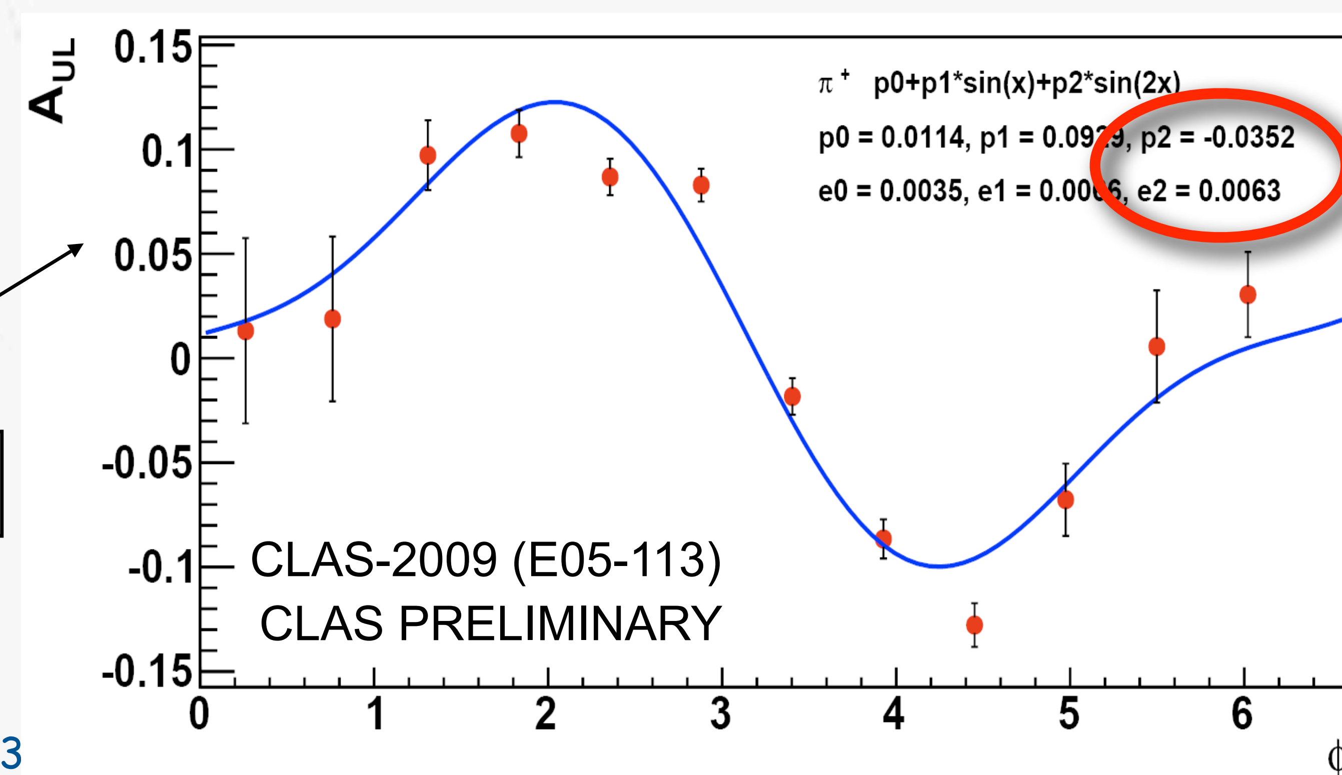
Worm-Gear I

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

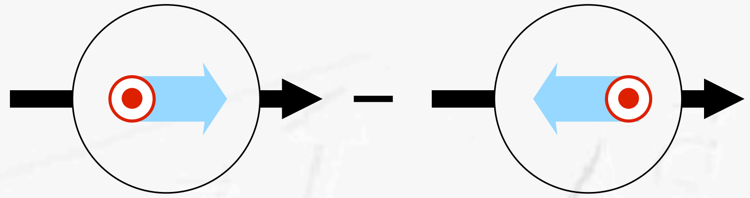
- again chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES
- new data from CLAS



~10% of E05-113 data

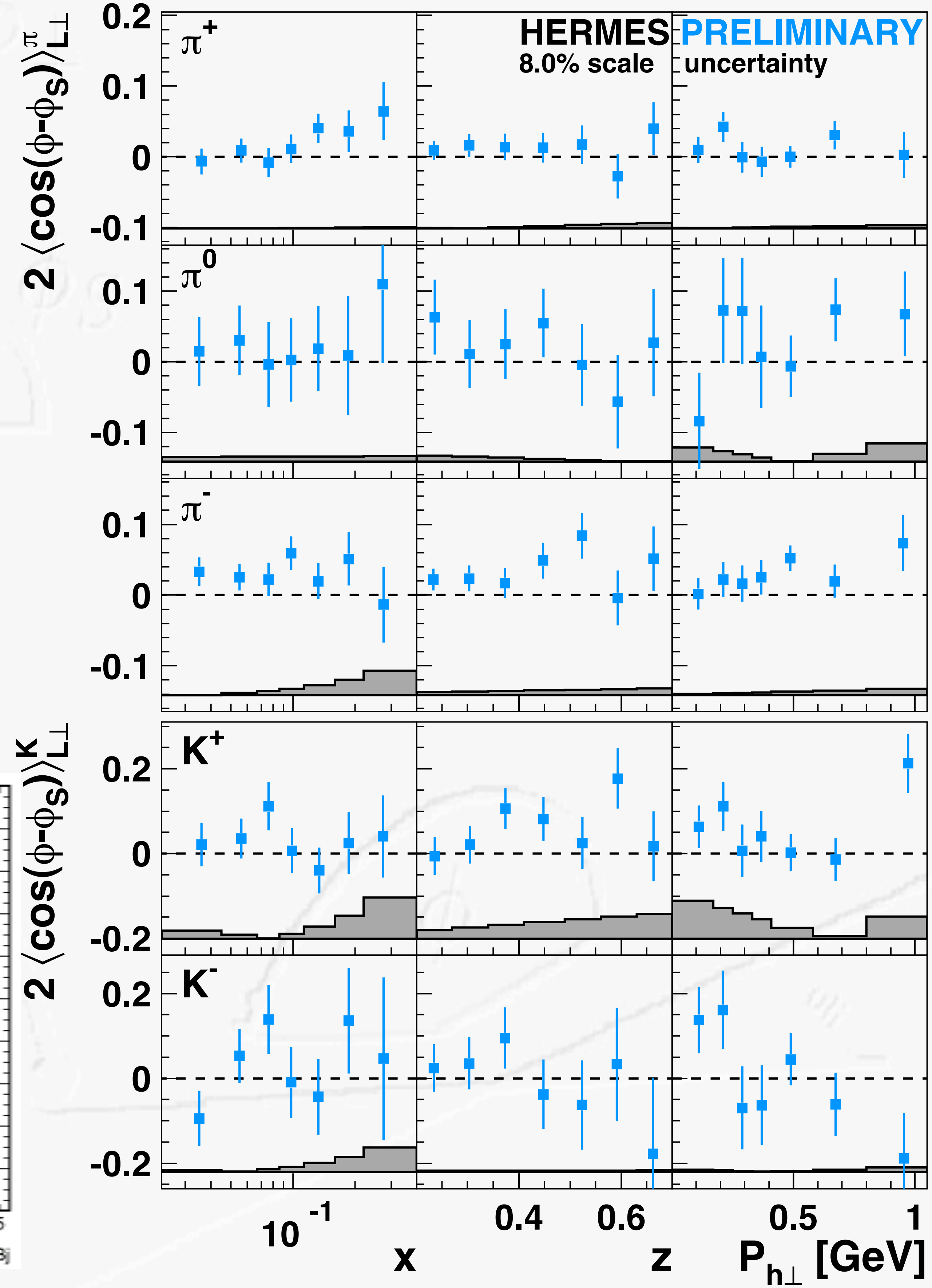


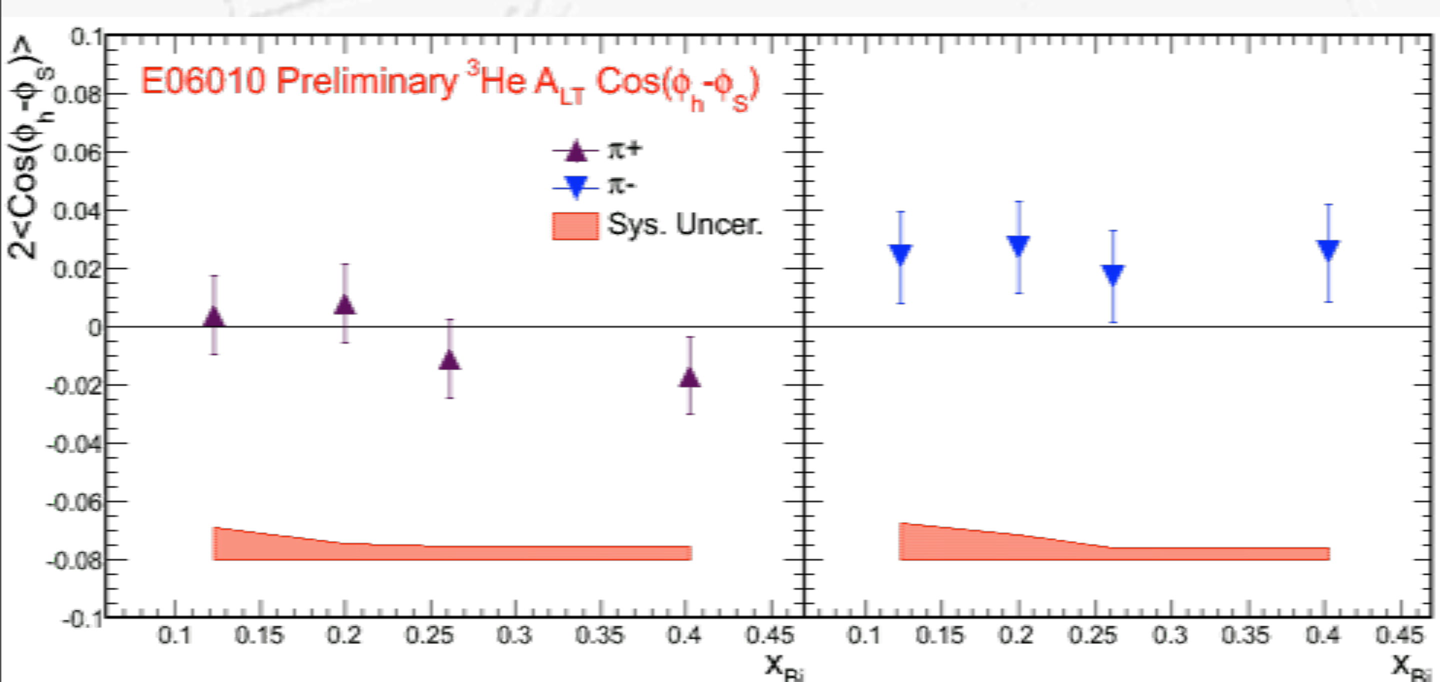
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

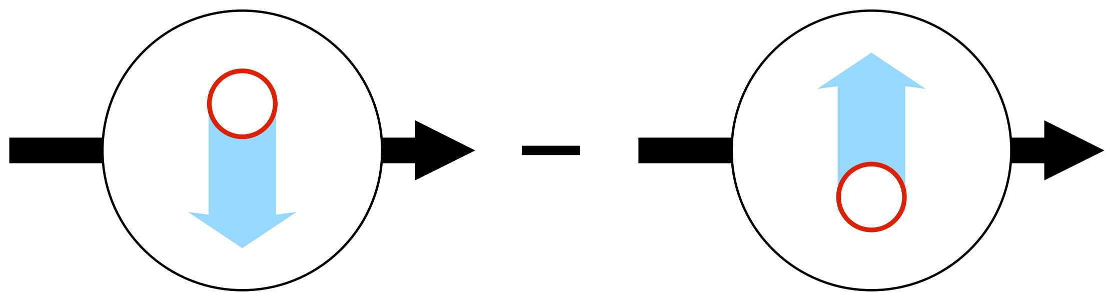


Worm-Gear II

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

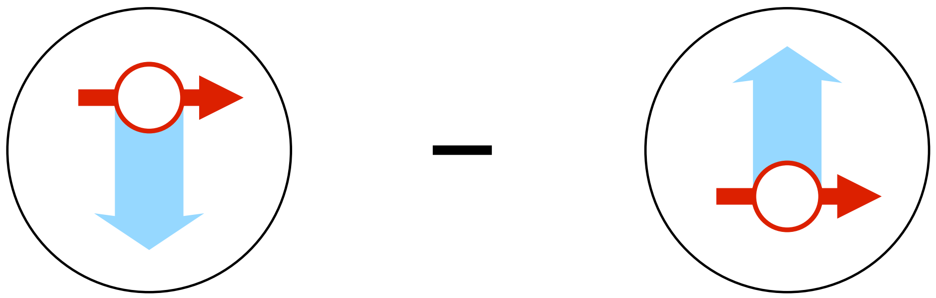




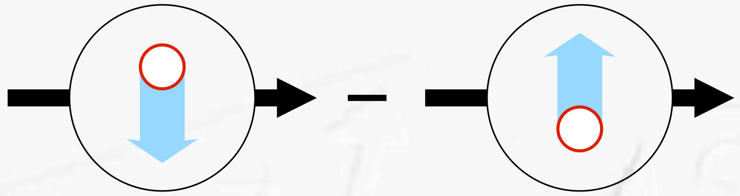


“gauge-link physics”

naively T-odd distributions

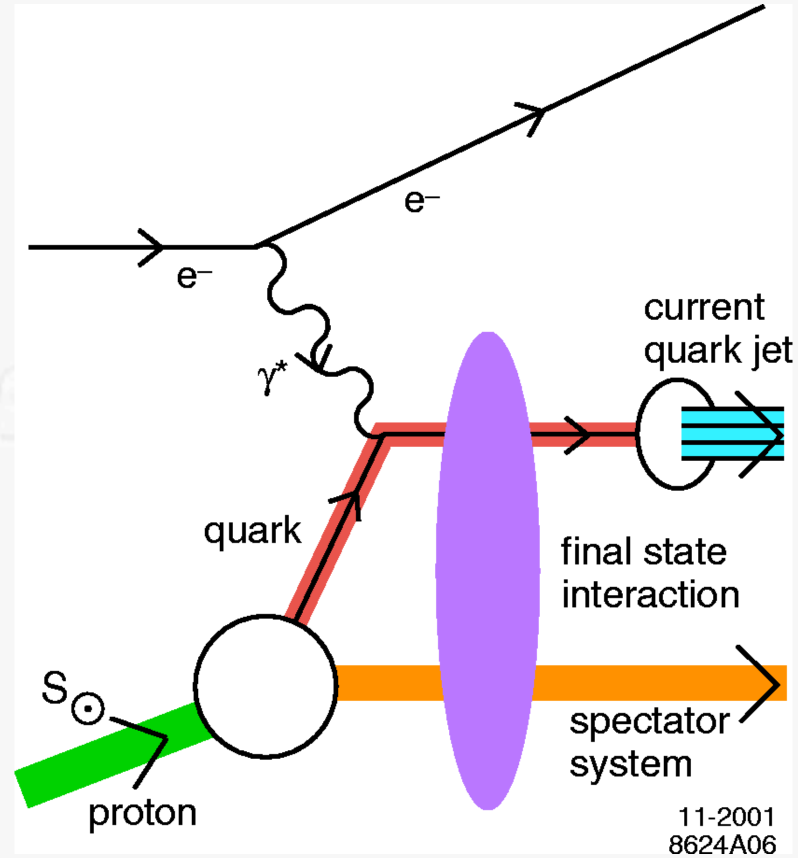


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



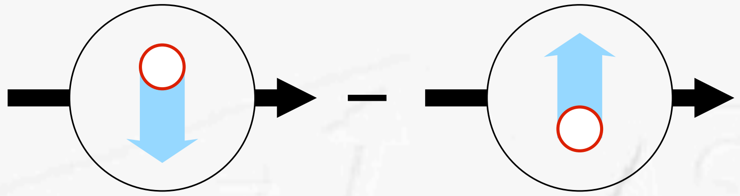
Sivers function

- naive T-odd
- requires FSI via non-perturbative gluon (gauge link) exchange(s)
- leads to opposite sign in DIS and DY (firm QCD prediction!)
- relation to GPD E + FSI yields opposite signs of Sivers fct. for up and down quarks



[S. Brodsky et al., Phys. Lett. B530, 99 (2002)]

	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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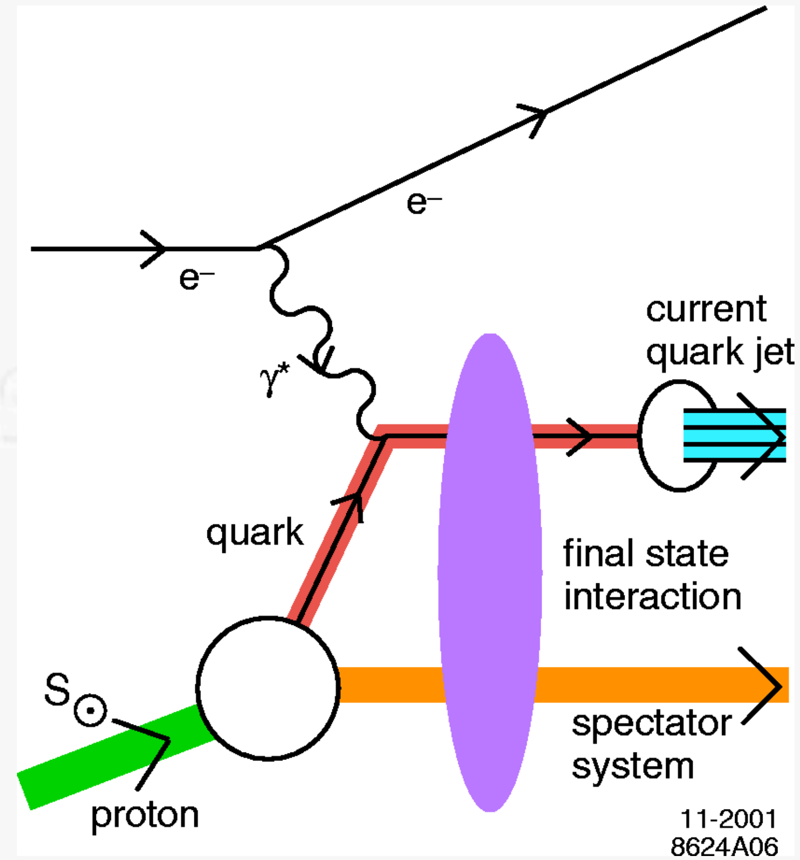

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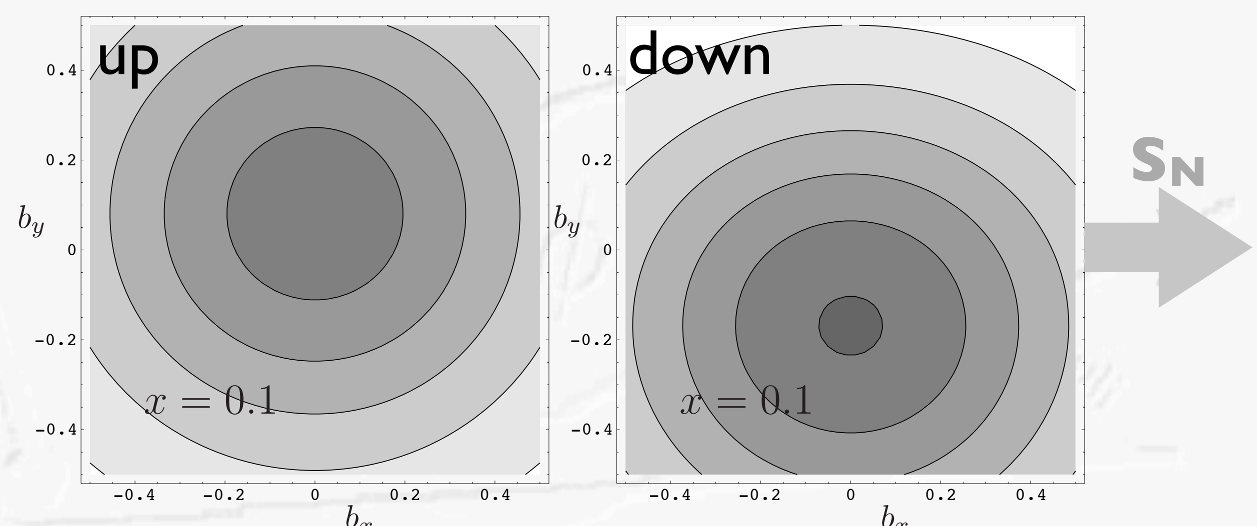
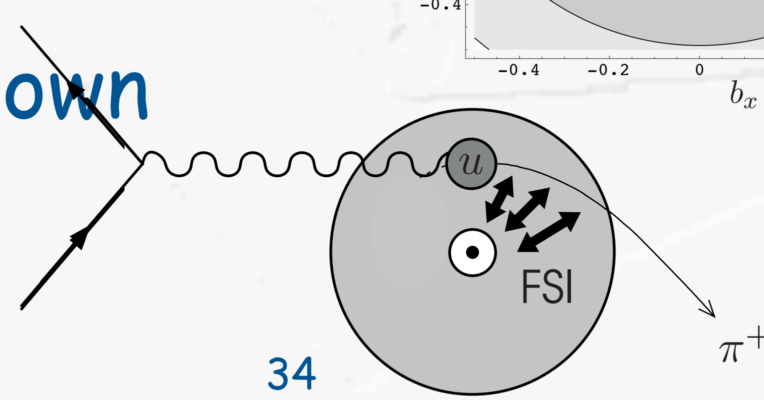


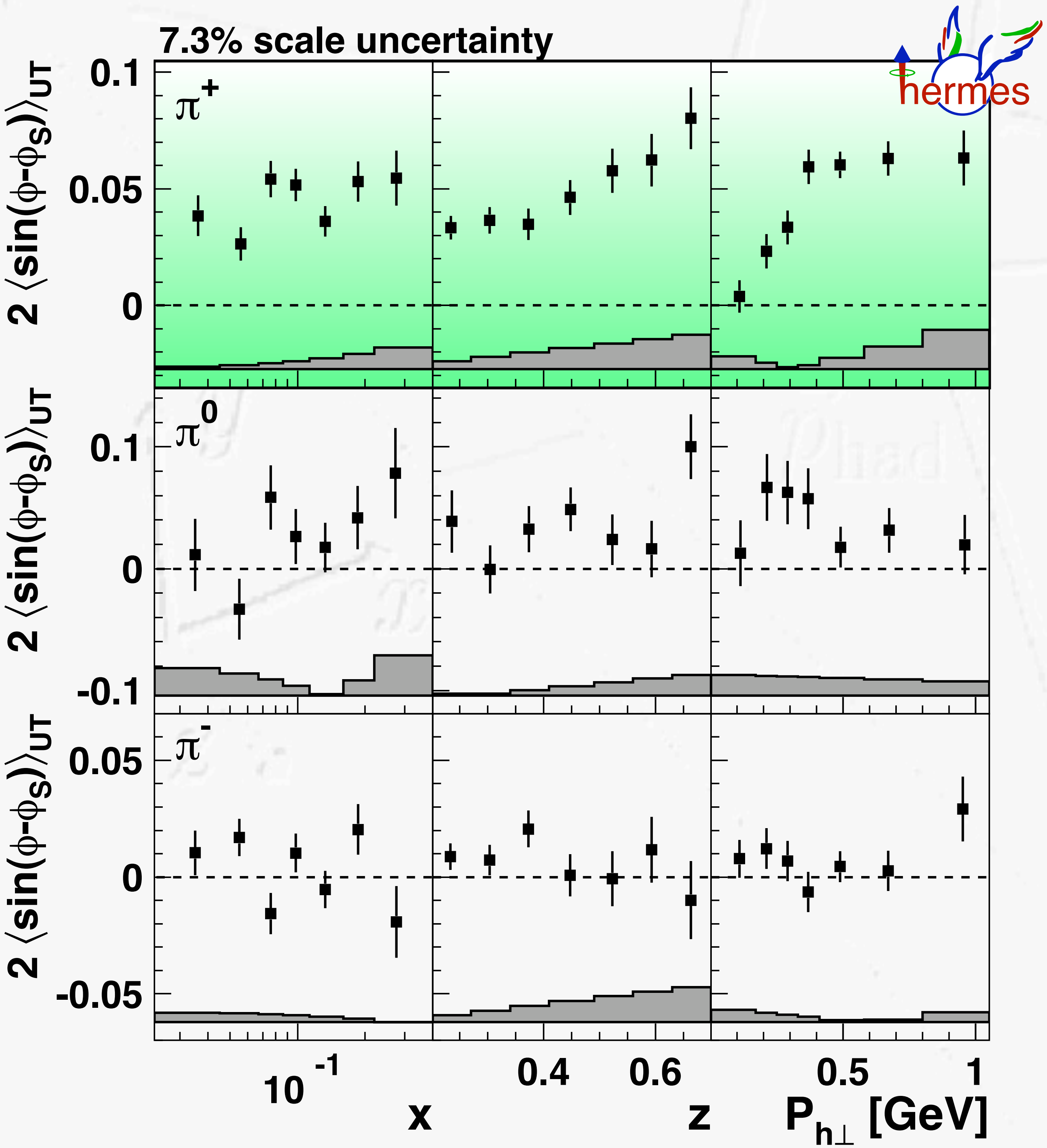
[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]



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

Sivers amplitudes for pions

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



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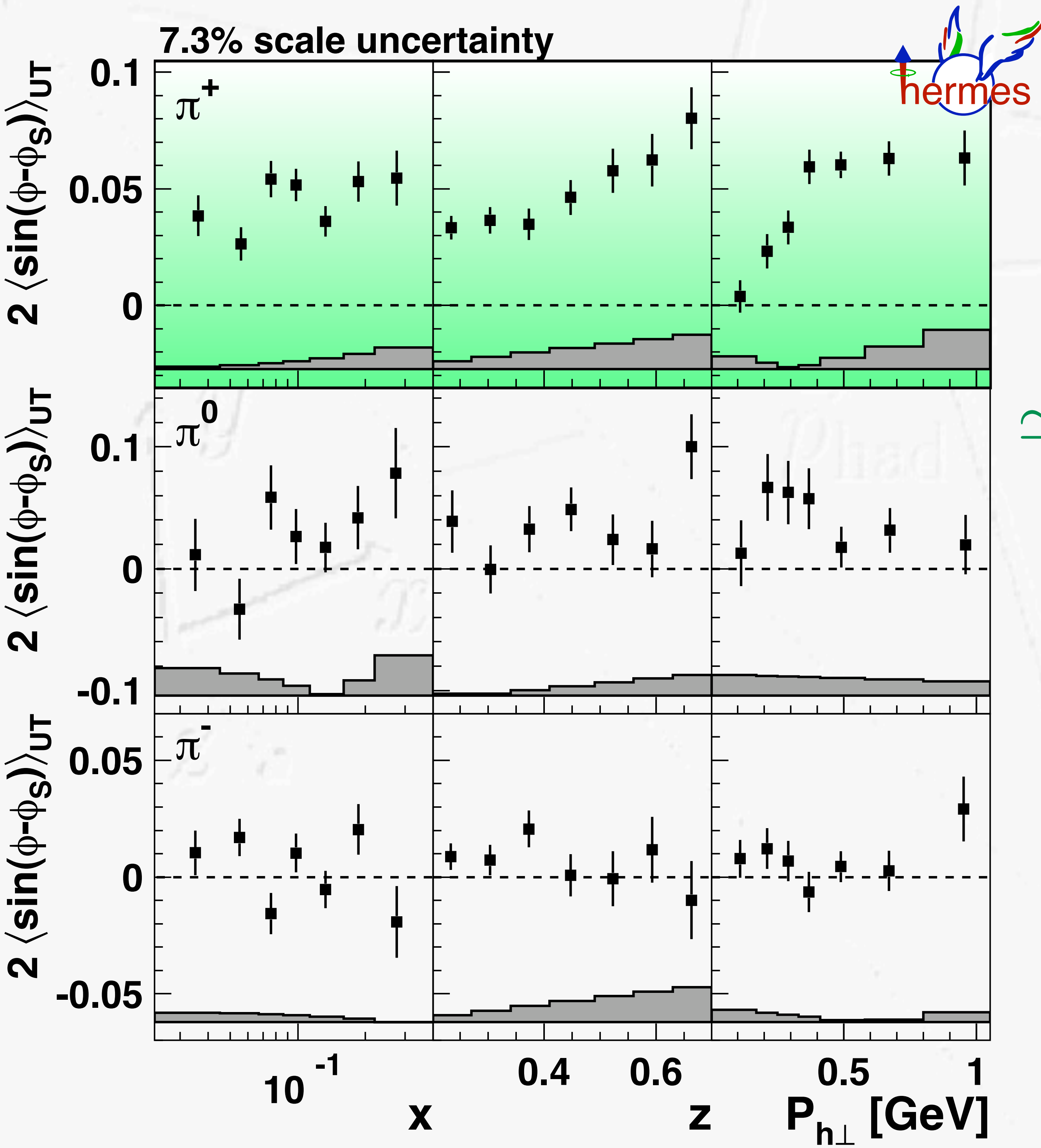

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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

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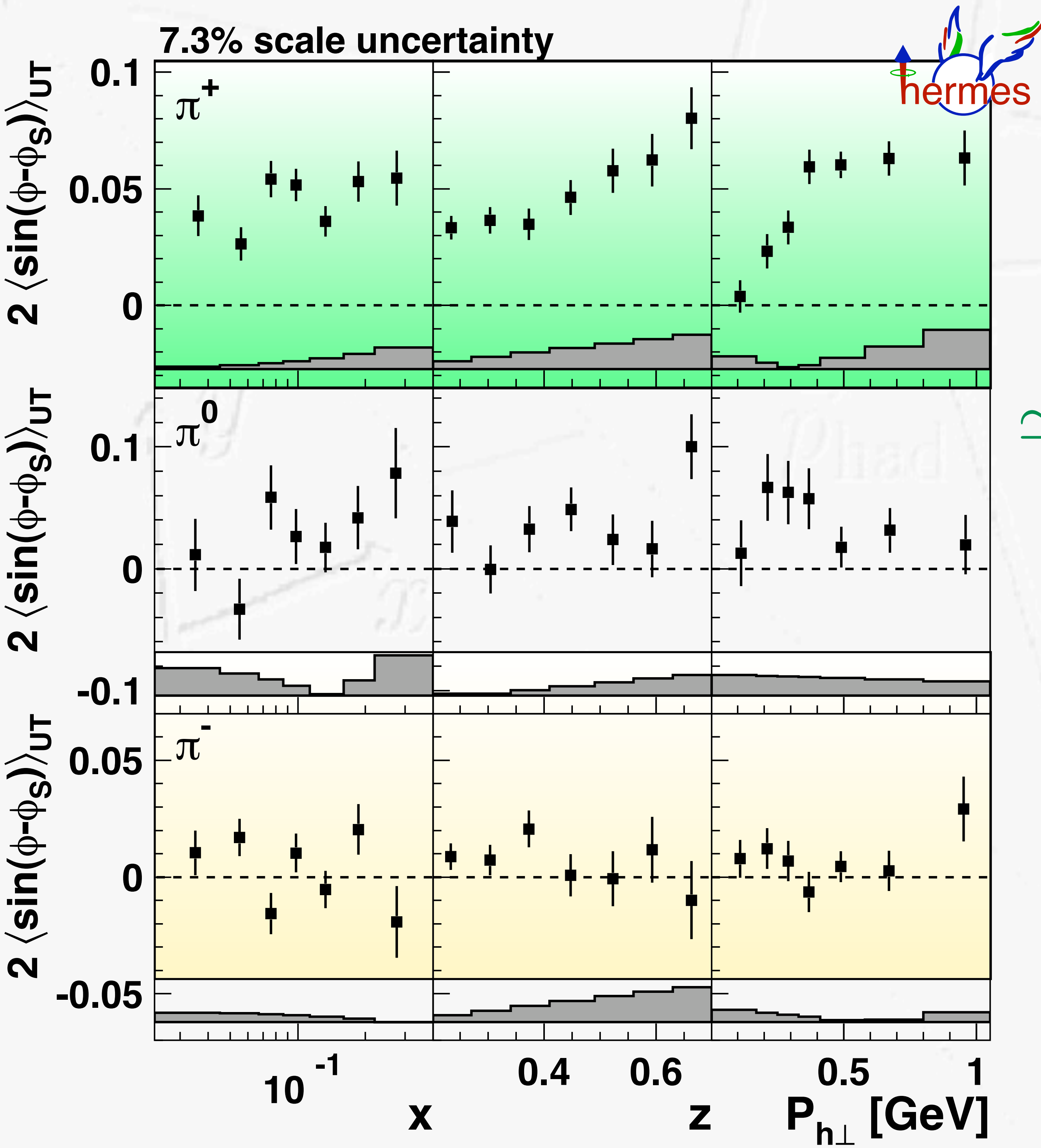

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☛ u-quark Sivers DF < 0

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

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

Sivers amplitudes for pions

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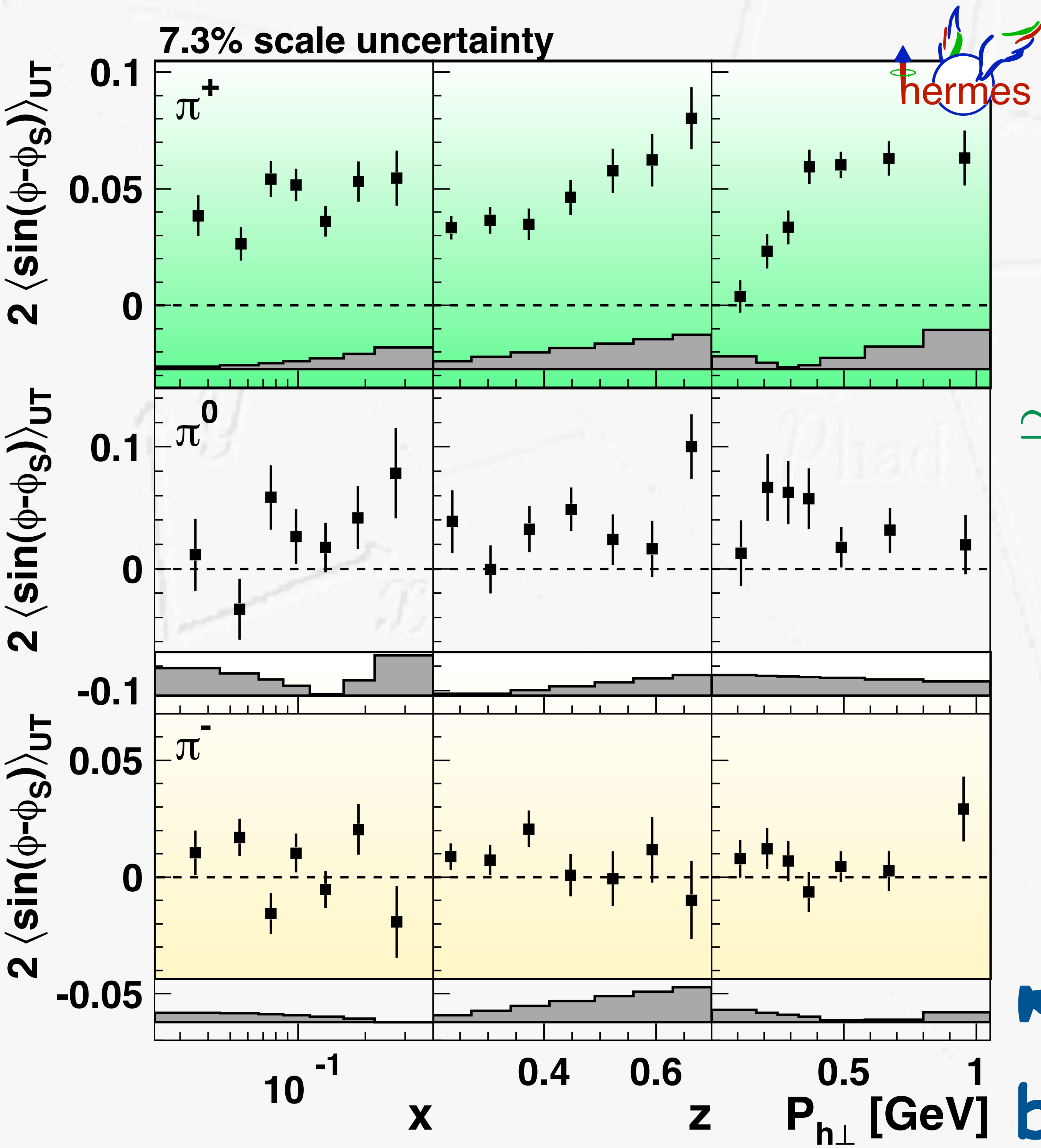

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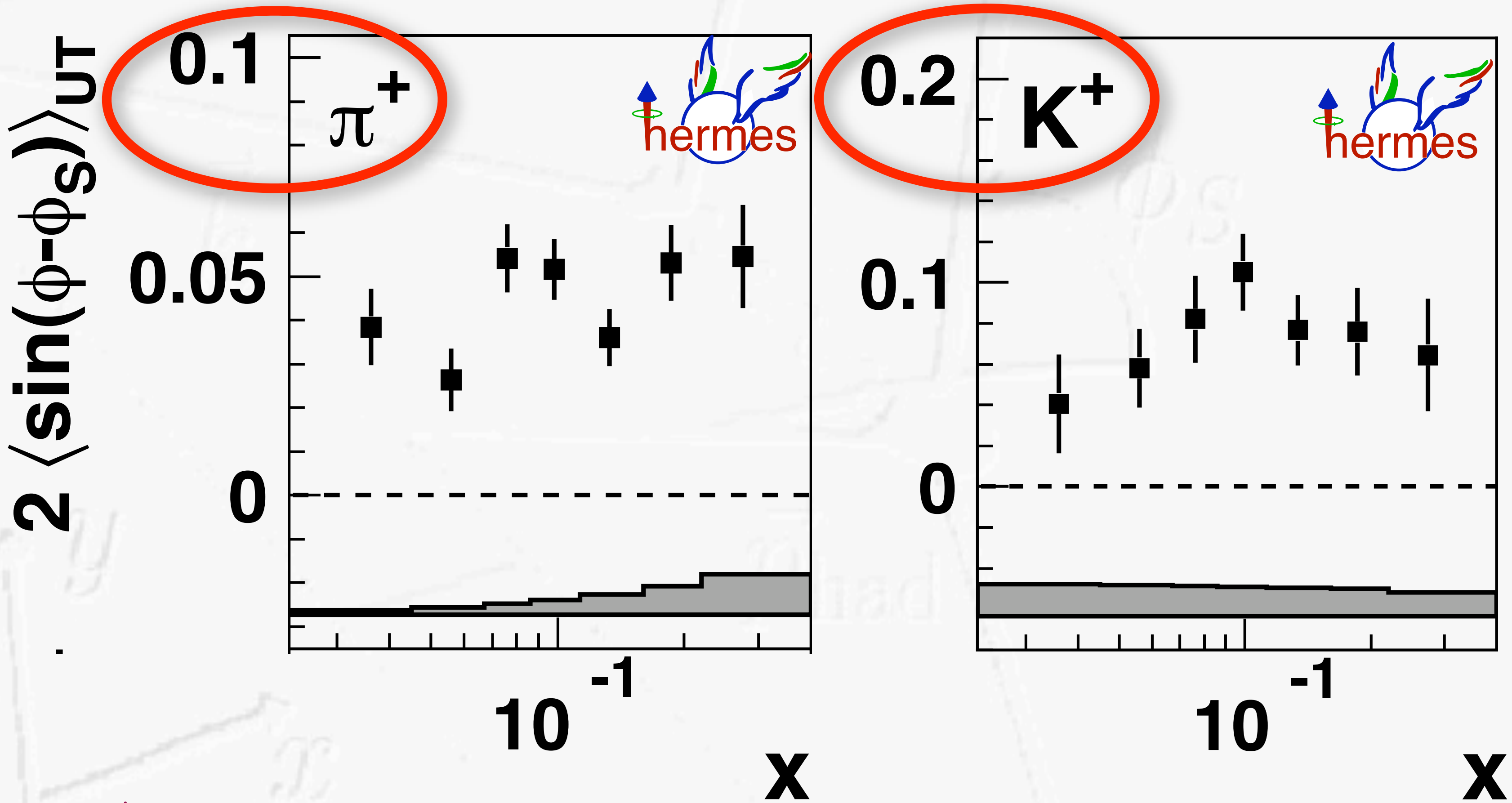
- ☛ u-quark Sivers DF < 0
- ☛ d-quark Sivers DF > 0 (cancelation for π^-)
- ☛ u-d cancelation supported by COMPASS D data

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

Sivers amplitudes pions vs. kaons



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	U	L	T
U	f_1		$h_1^\perp$
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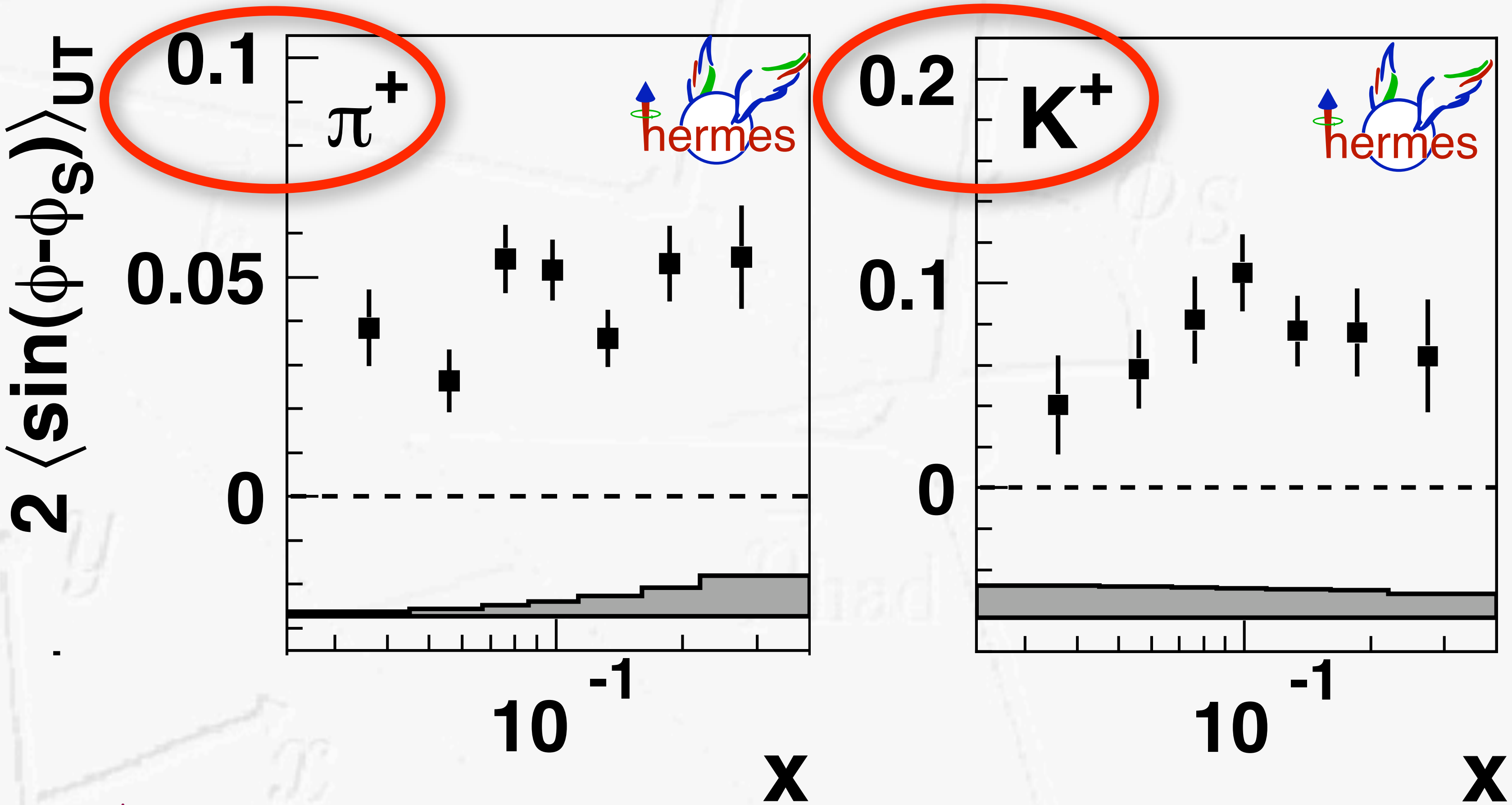

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

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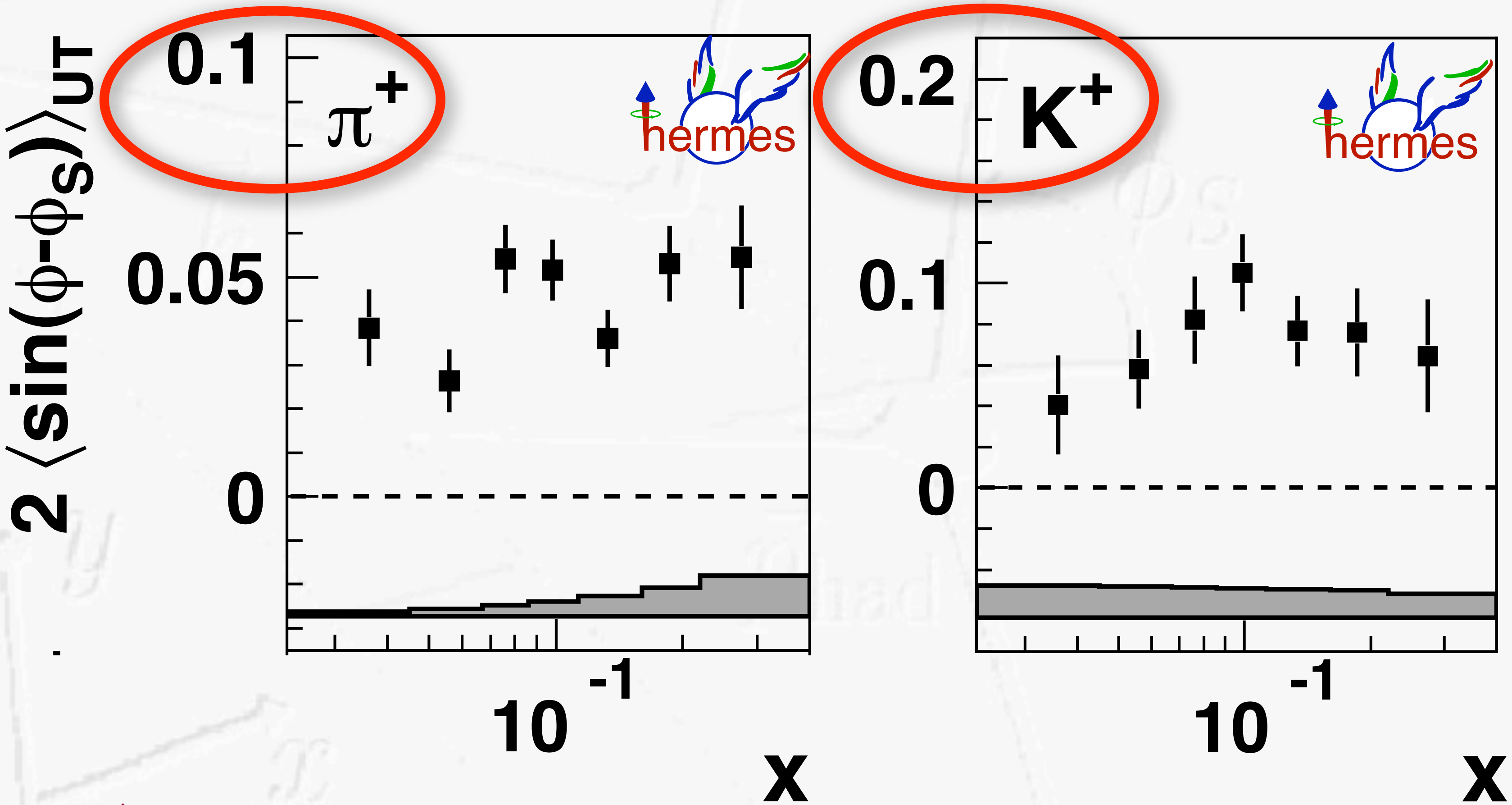

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on k_T dependence of fragmentation functions

	U	L	T
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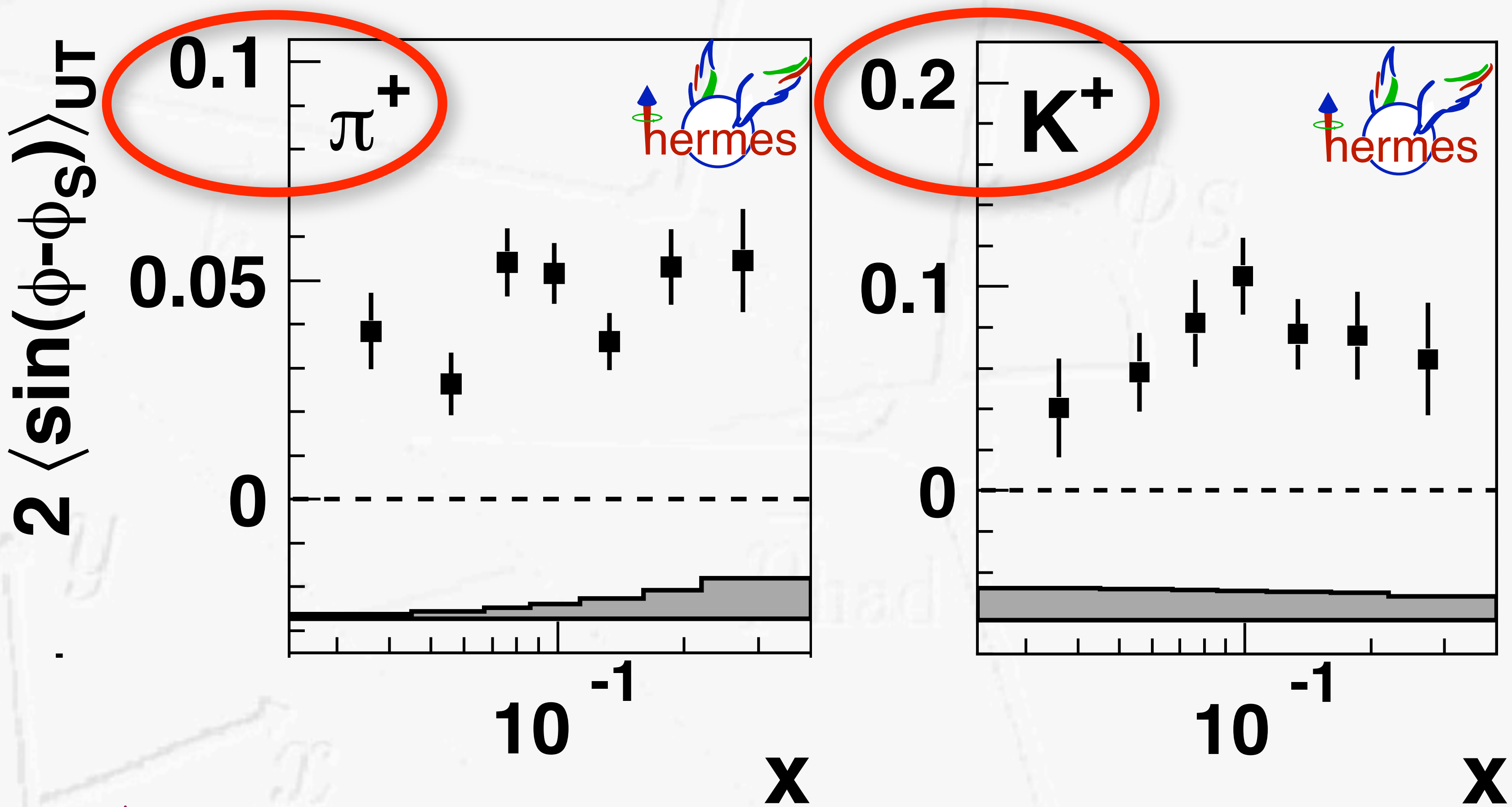
Sivers amplitudes pions vs. kaons



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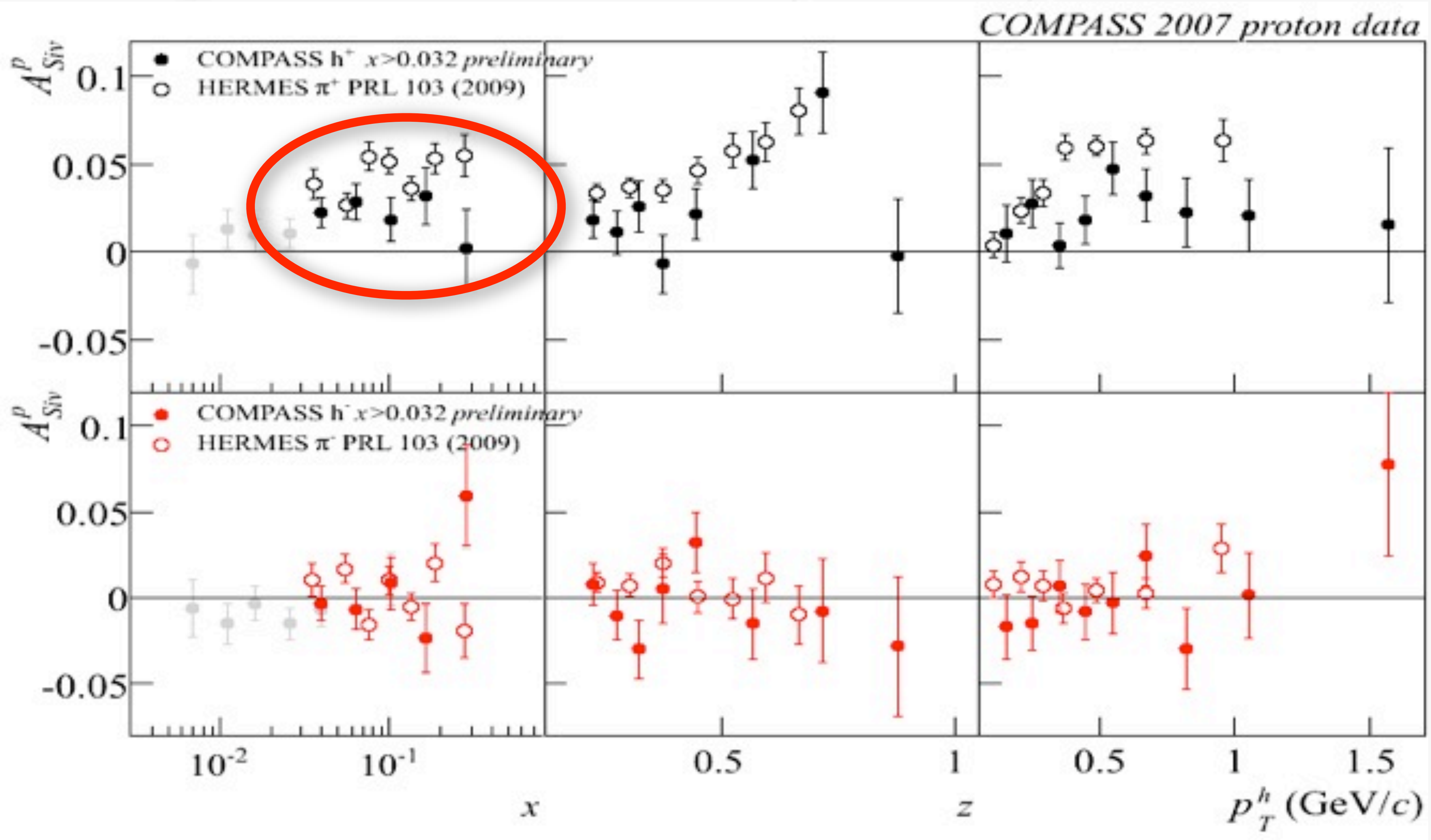
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on k_T dependence of fragmentation functions
- possible difference in dependences on the kinematics integrated over

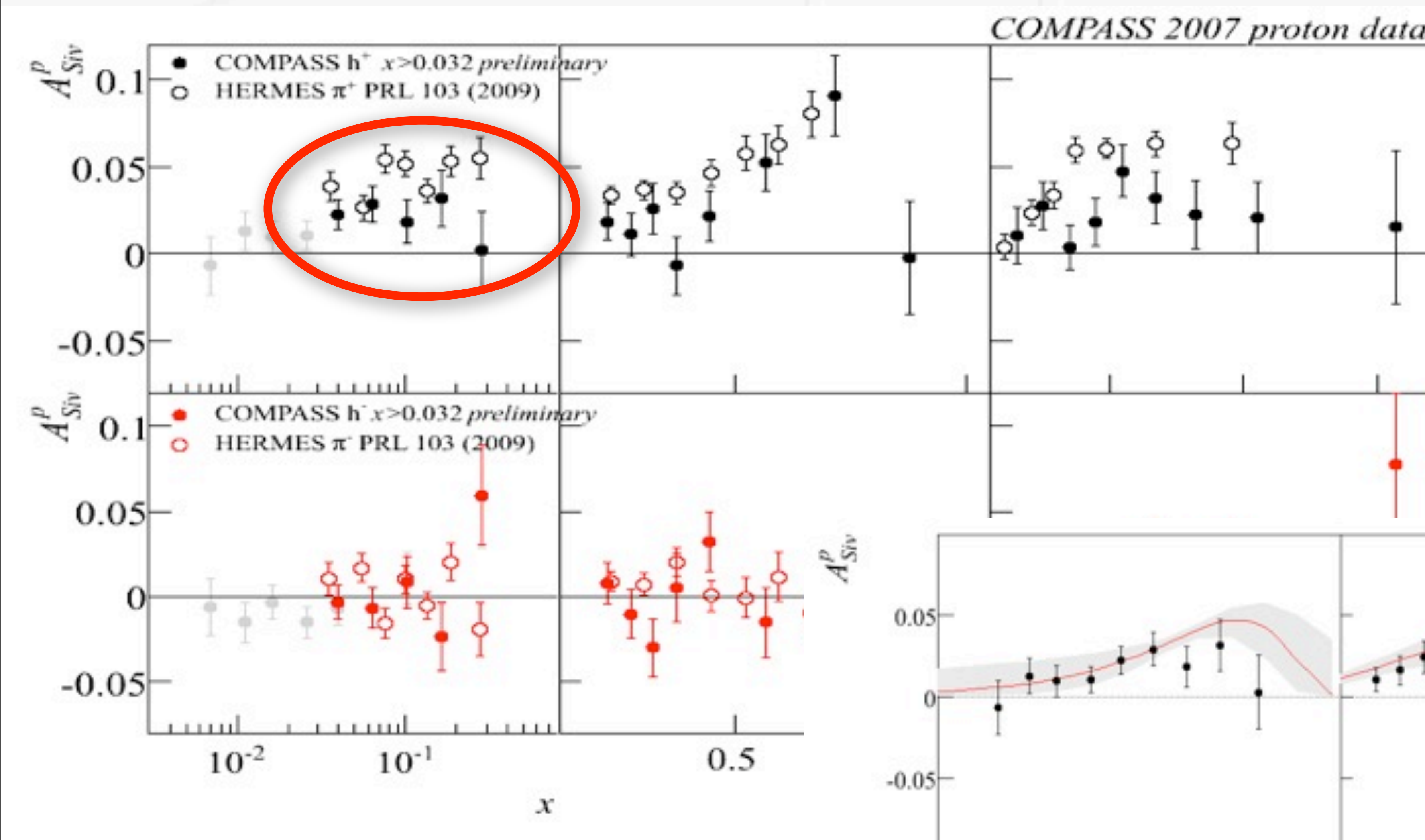
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

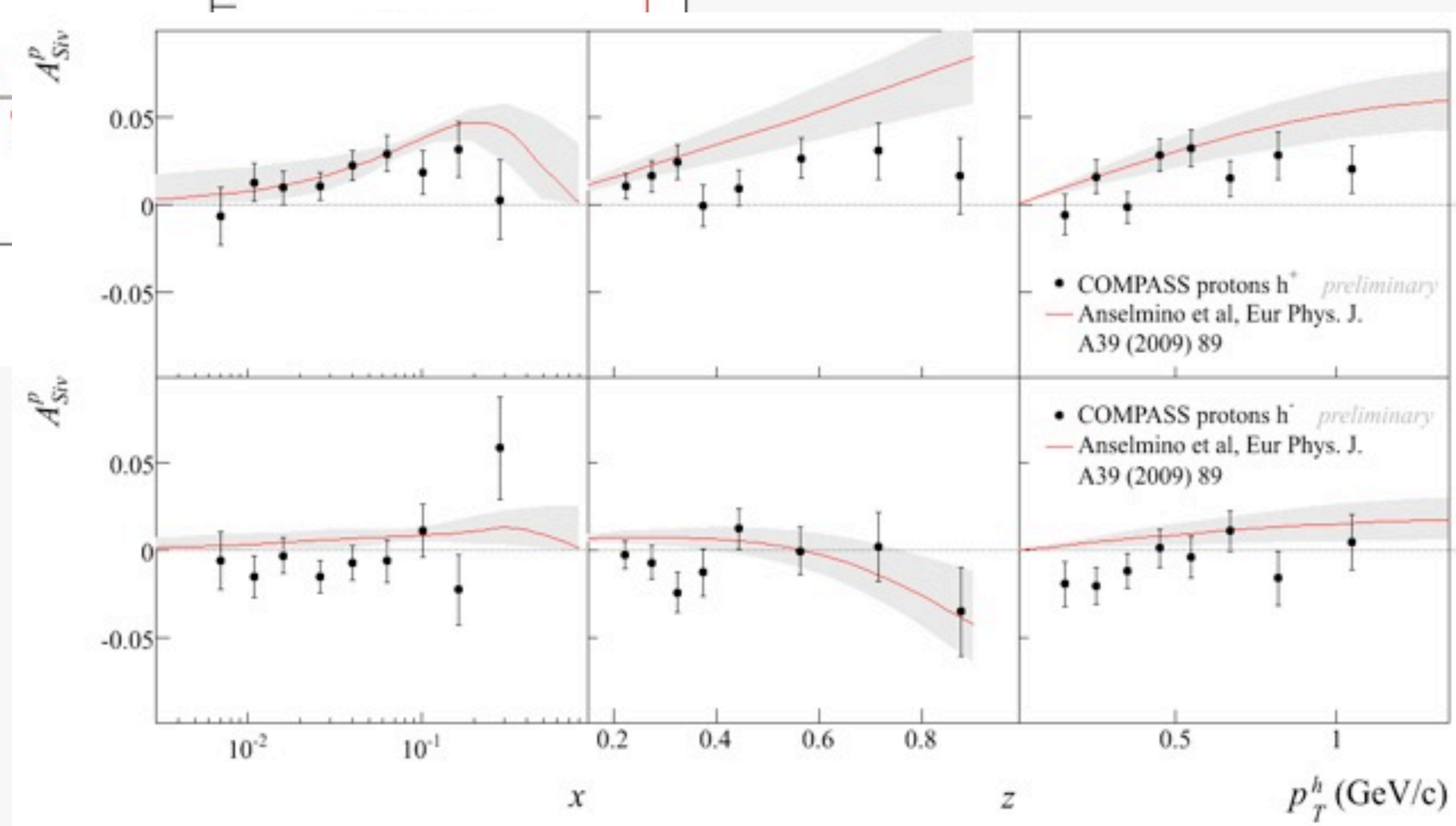
Sivers amplitudes COMPASS & HERMES



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

Sivers amplitudes COMPASS & HERMES

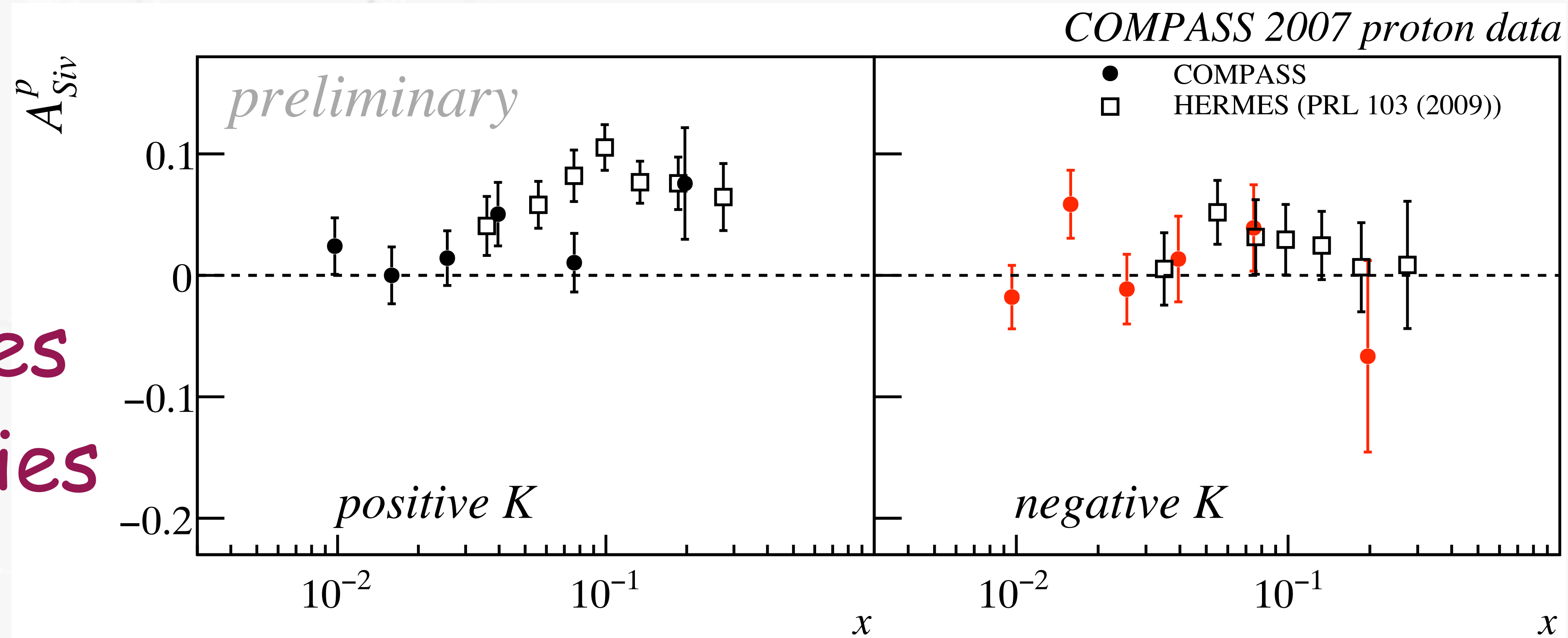




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes

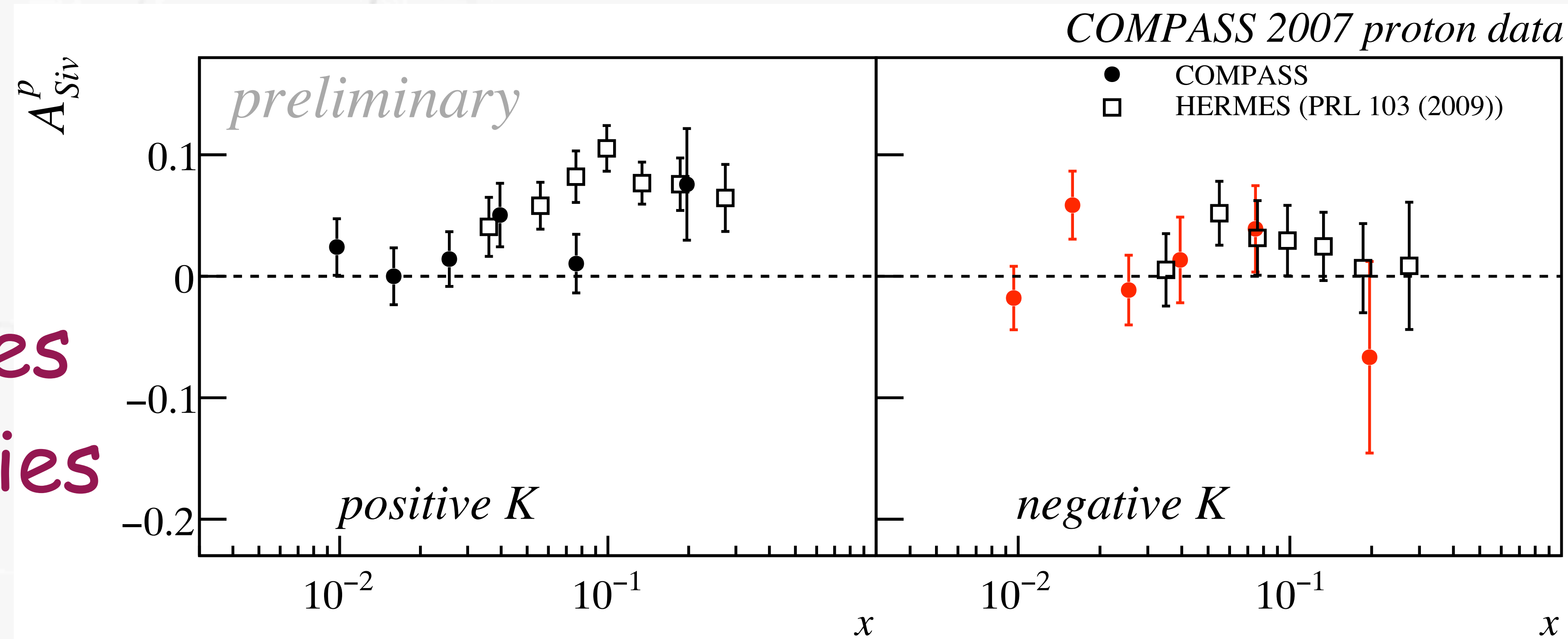
also COMPASS sees large K⁺ asymmetries



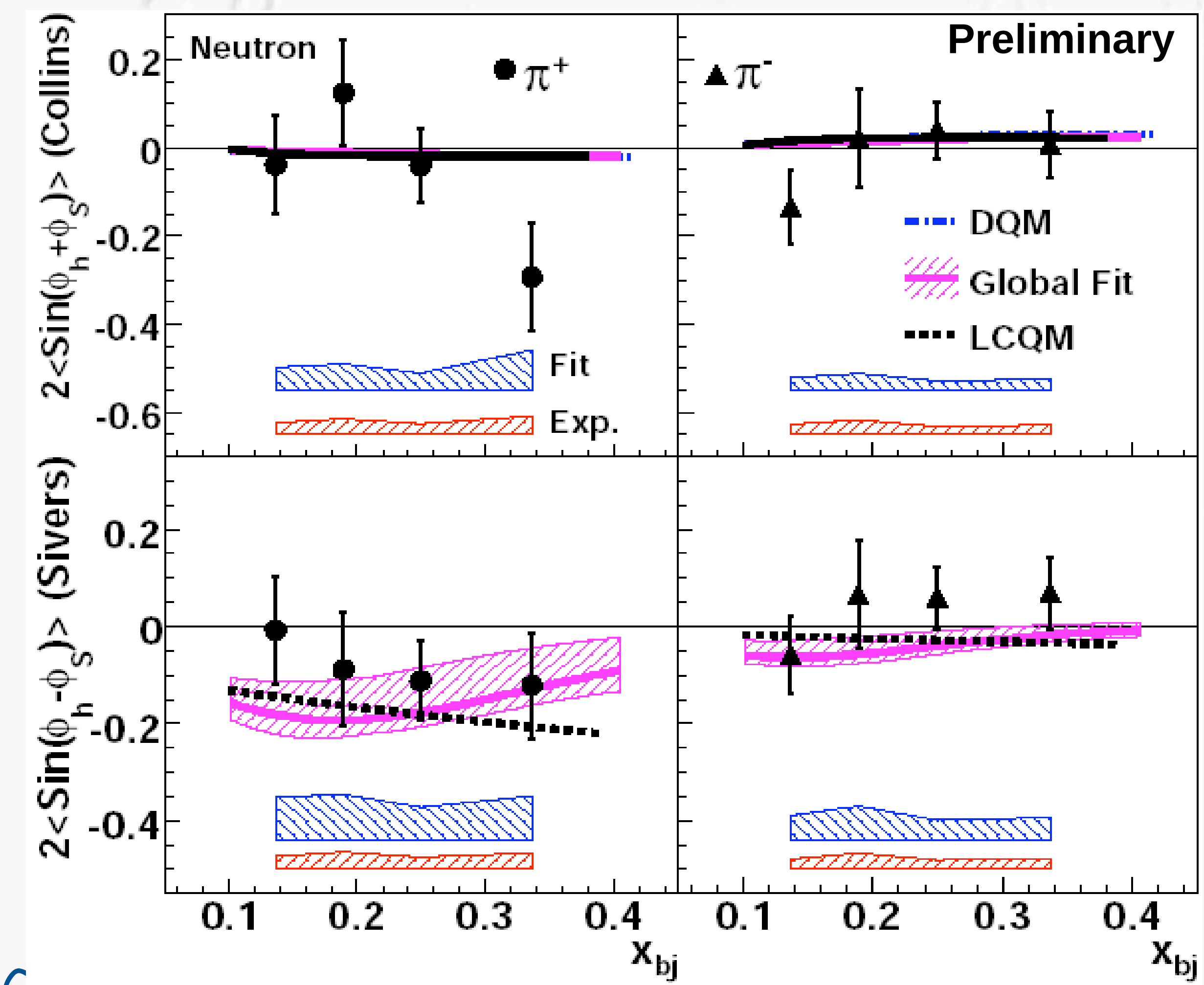
Wednesday, May 11, 2011

Sivers amplitudes

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



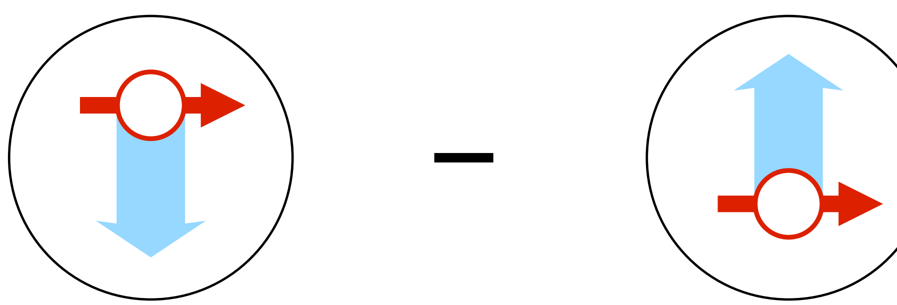
also COMPASS sees large K+ asymmetries



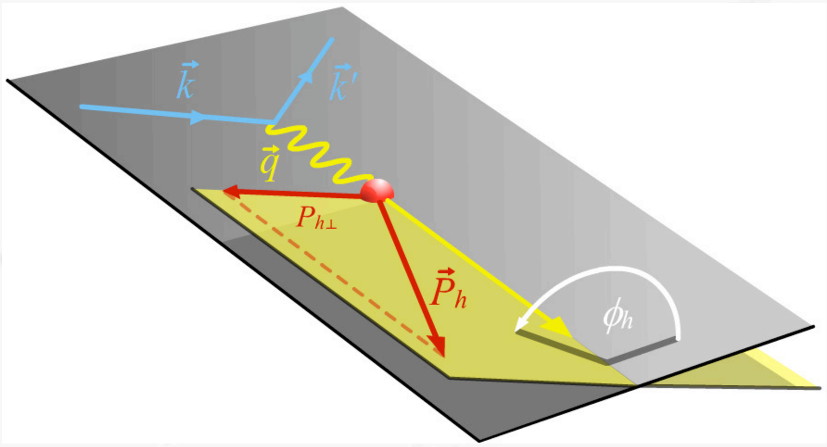
data on ^{3}He target from JLab available for pions

Boer-Mulders

the other naively T-odd distribution



Modulations in spin-independent SIDIS cross section



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

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

BOER-MULDERS EFFECT

leading twist

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

CAHN EFFECT

next to leading twist

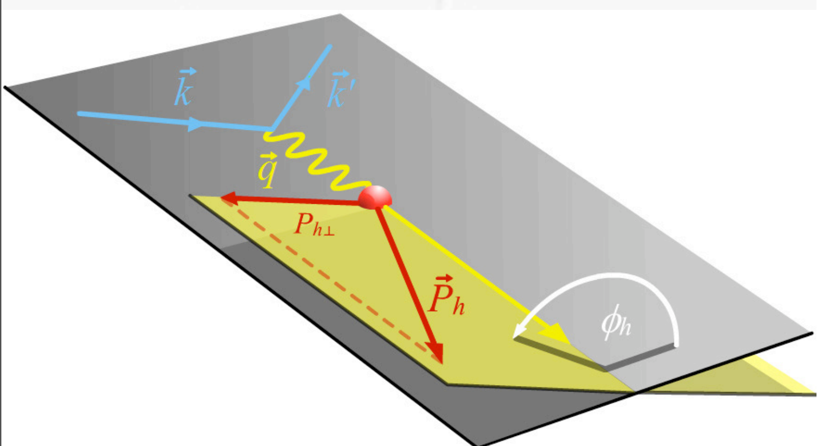
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\;h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\;f_1 D_1 + \ldots\right]$$

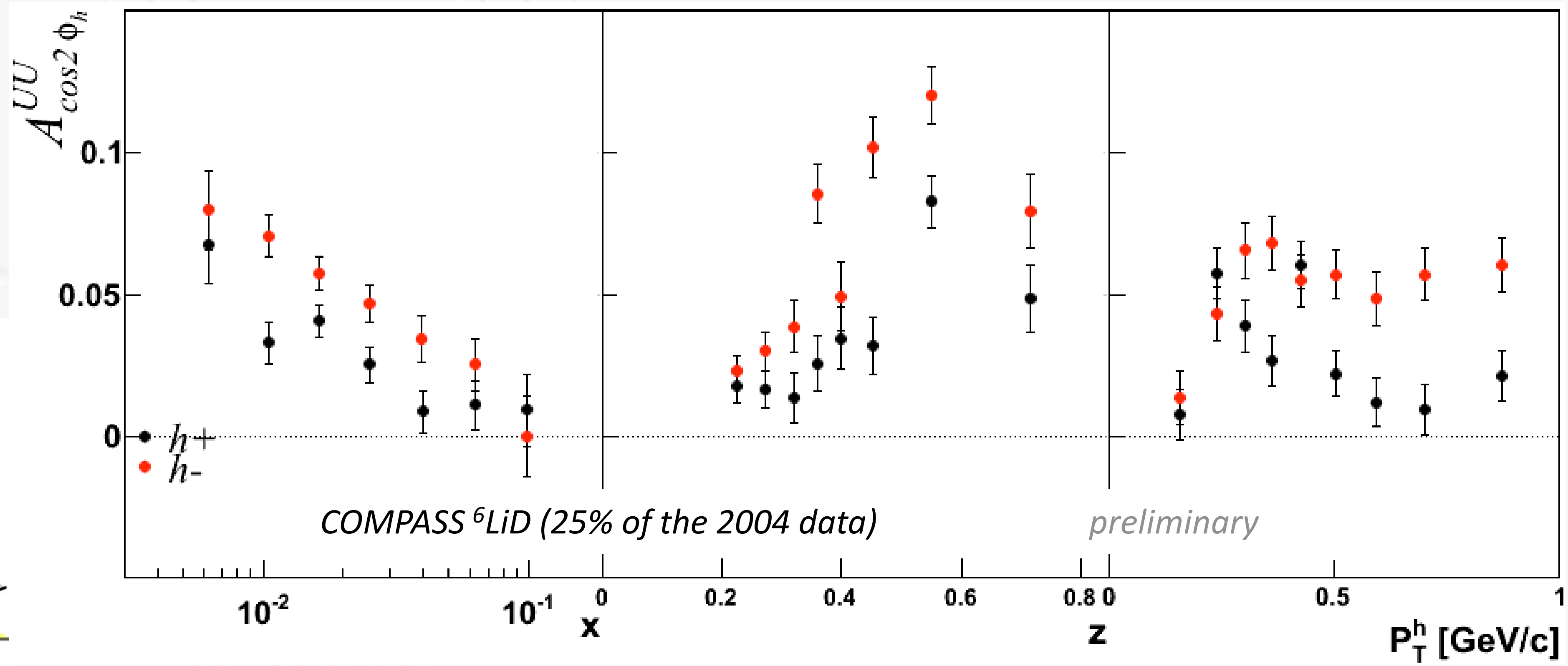
Interaction dependent terms neglected

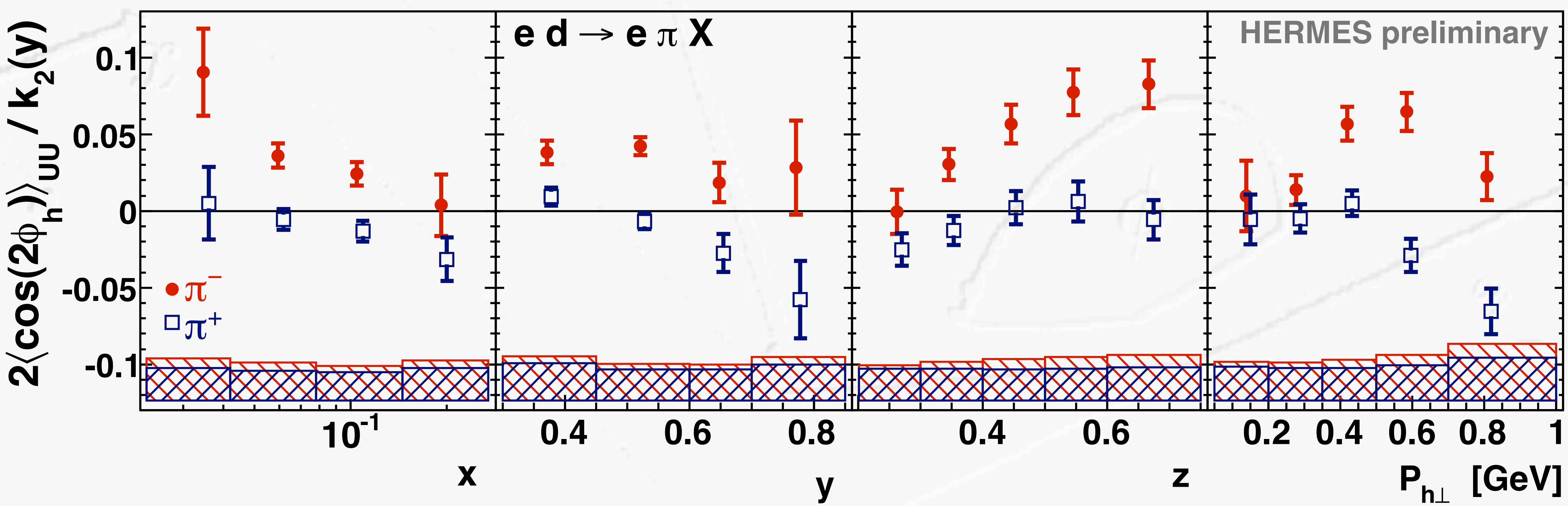
(Implicit sum over quark flavours)

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

Signs of Boer-Mulders

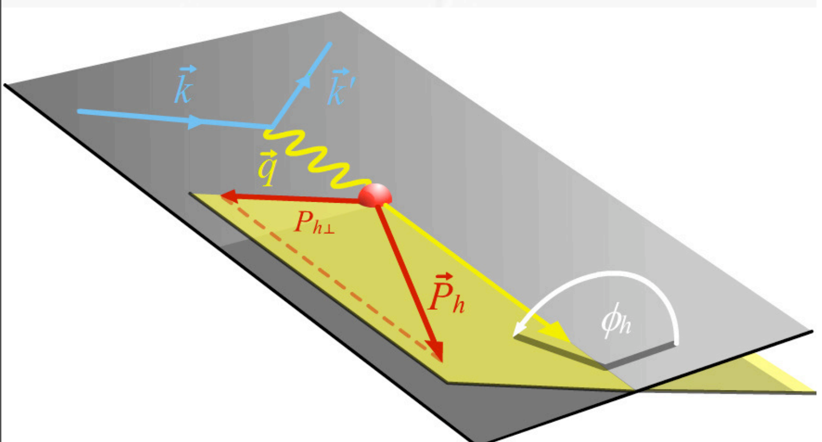


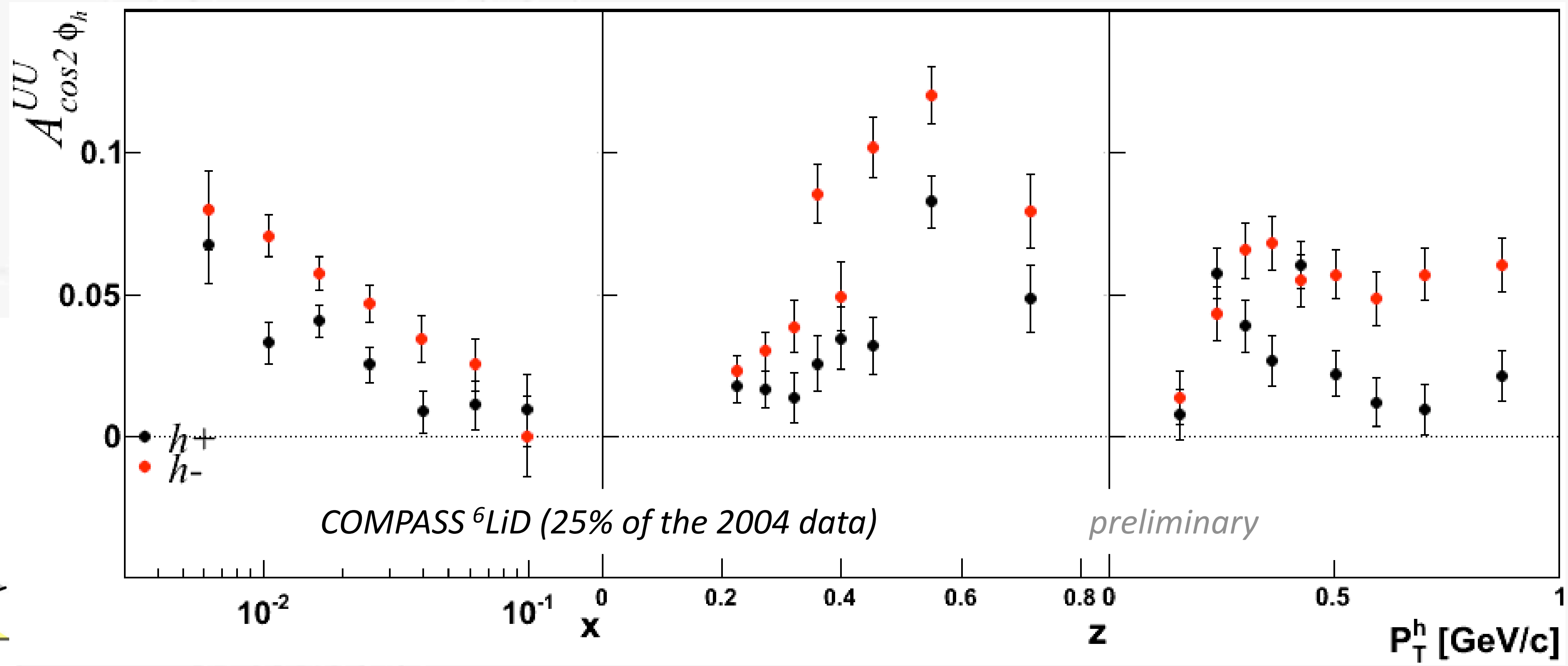


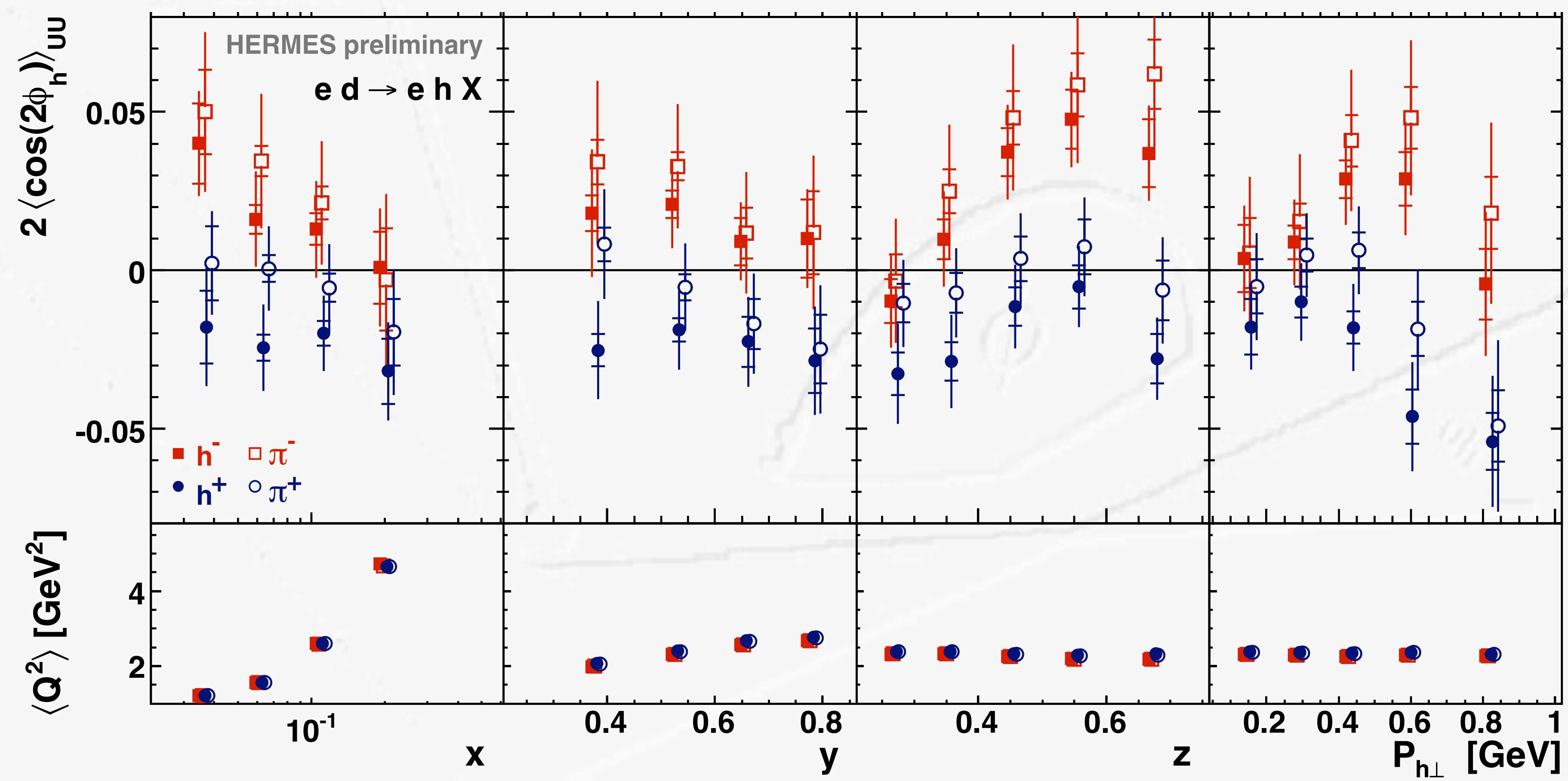


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Signs of Boer-Mulders







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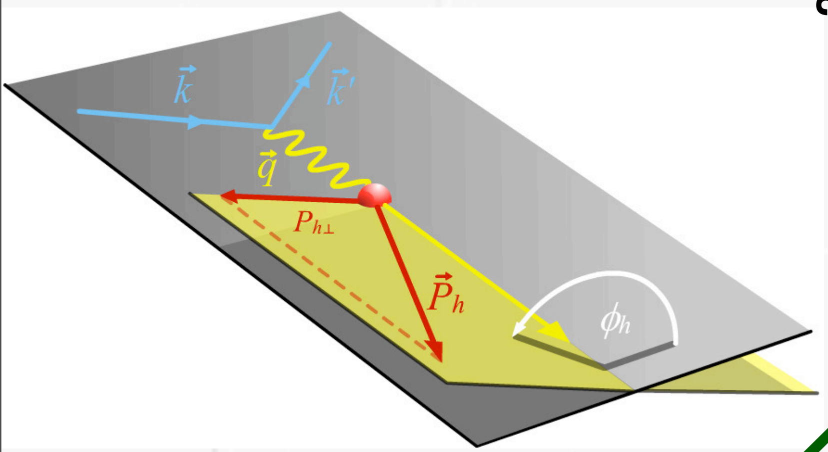
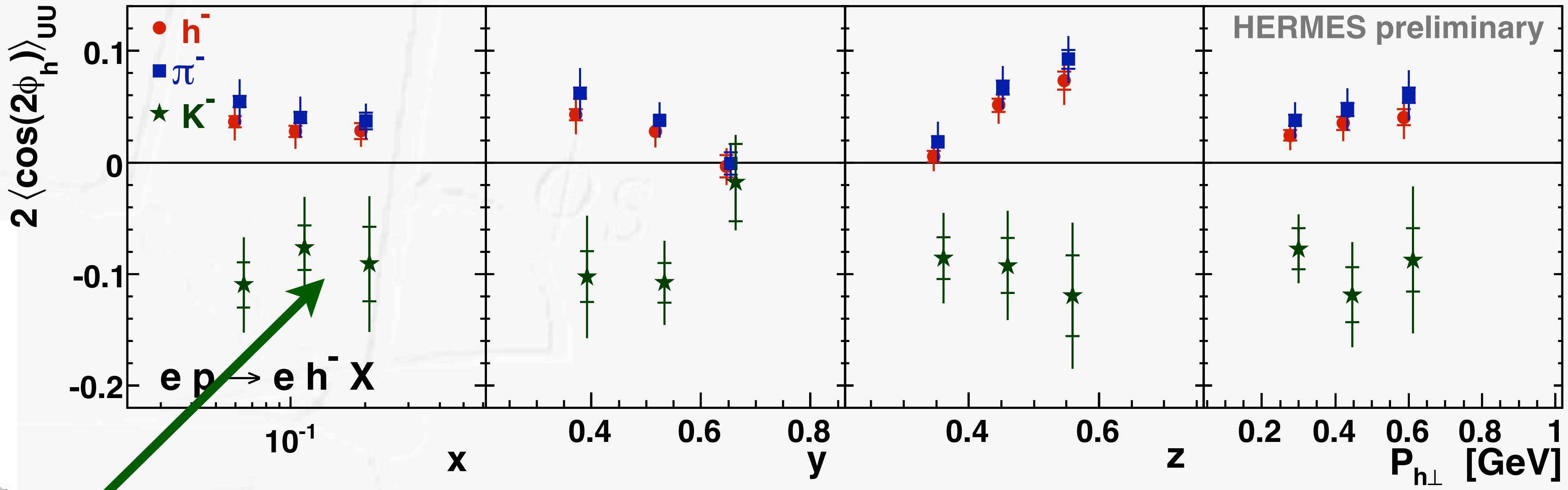
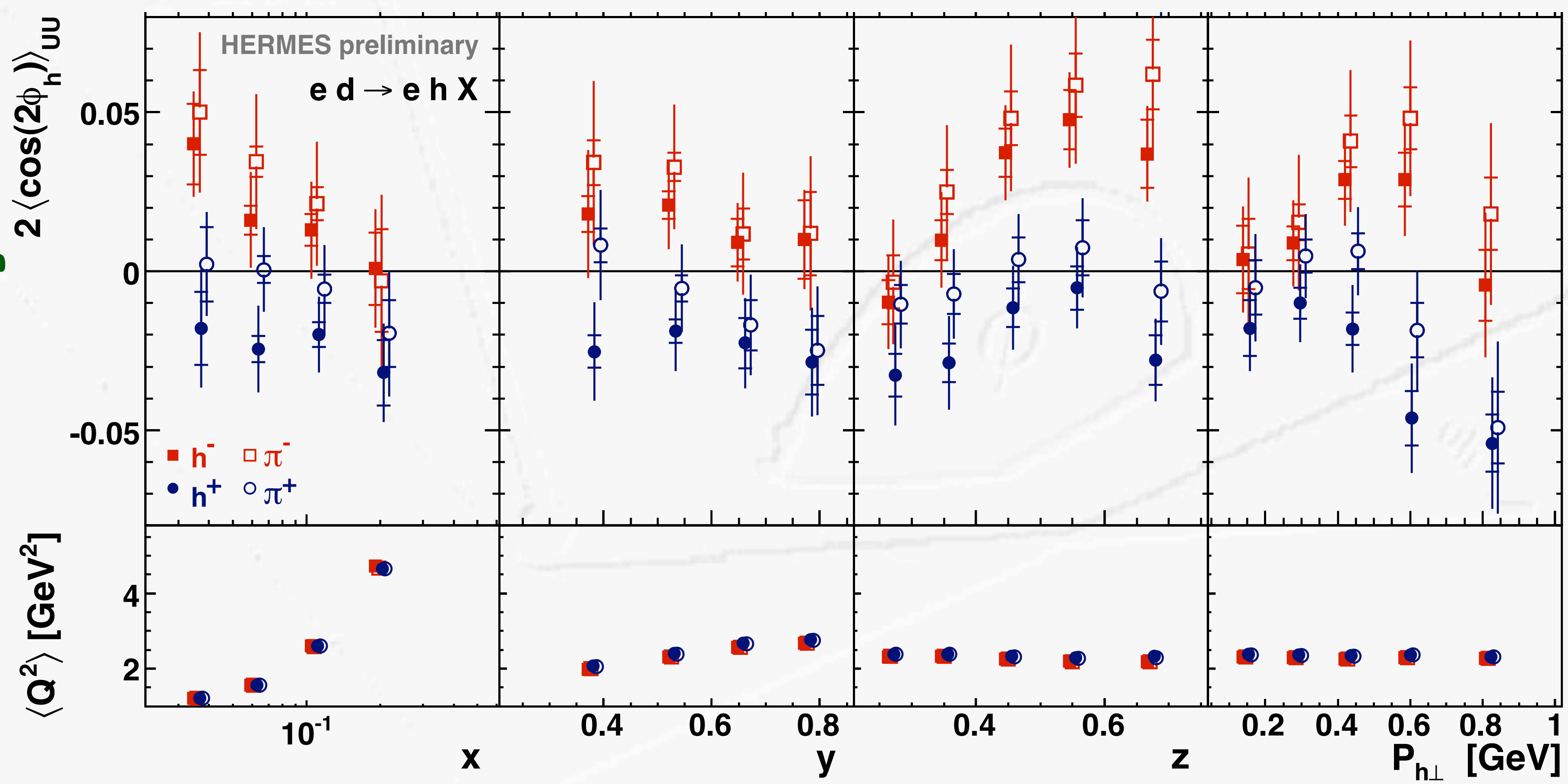




intriguing behavior for kaons



Cahn effect?

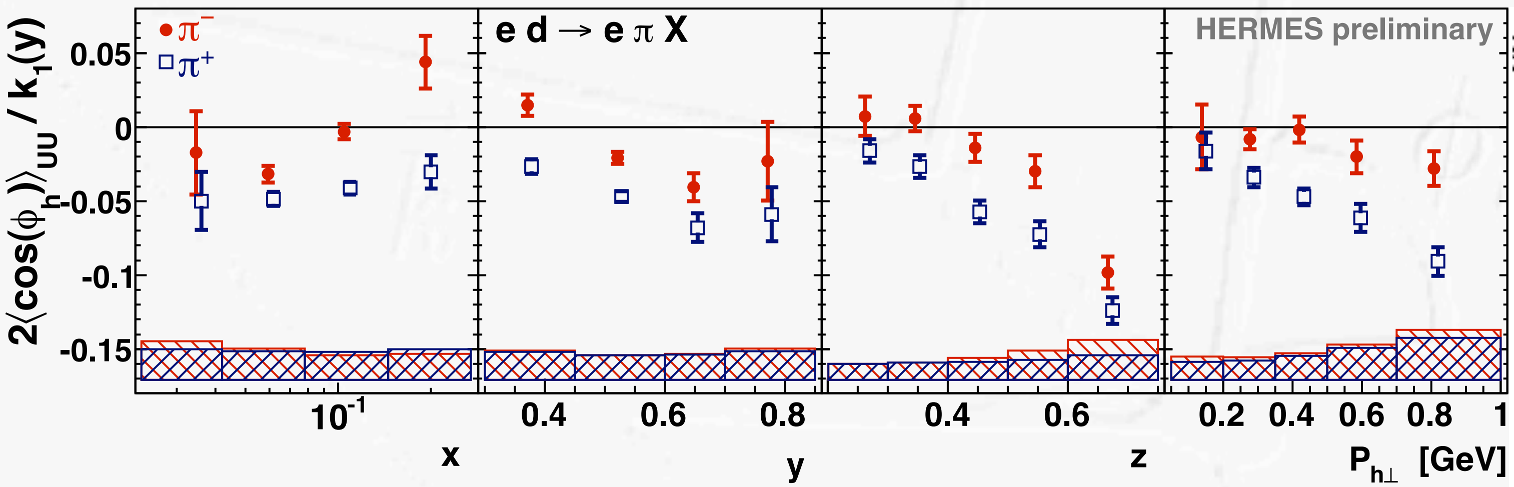
BOER-MULDERS EFFECT

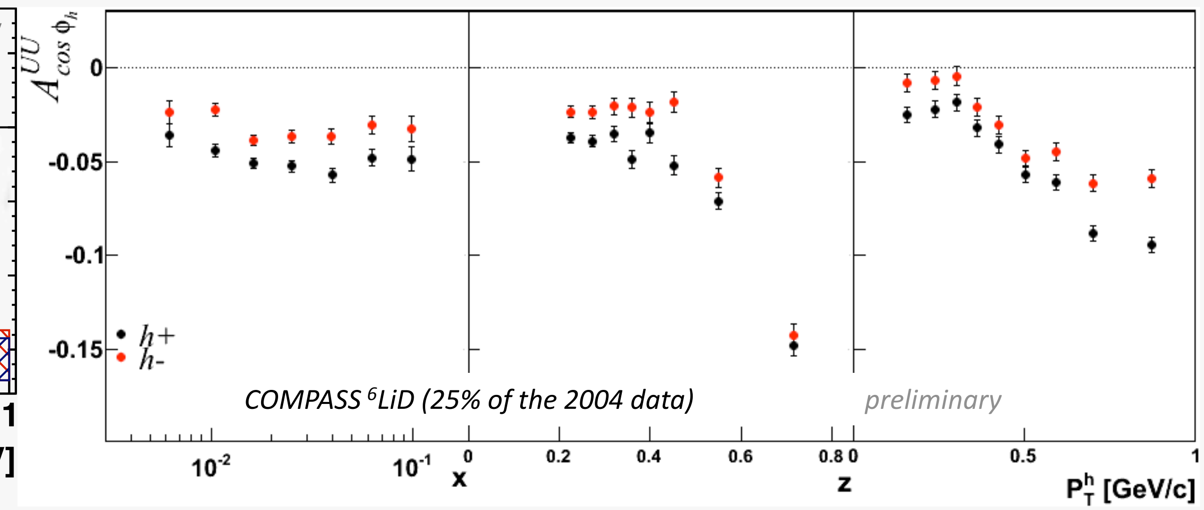
CAHN EFFECT

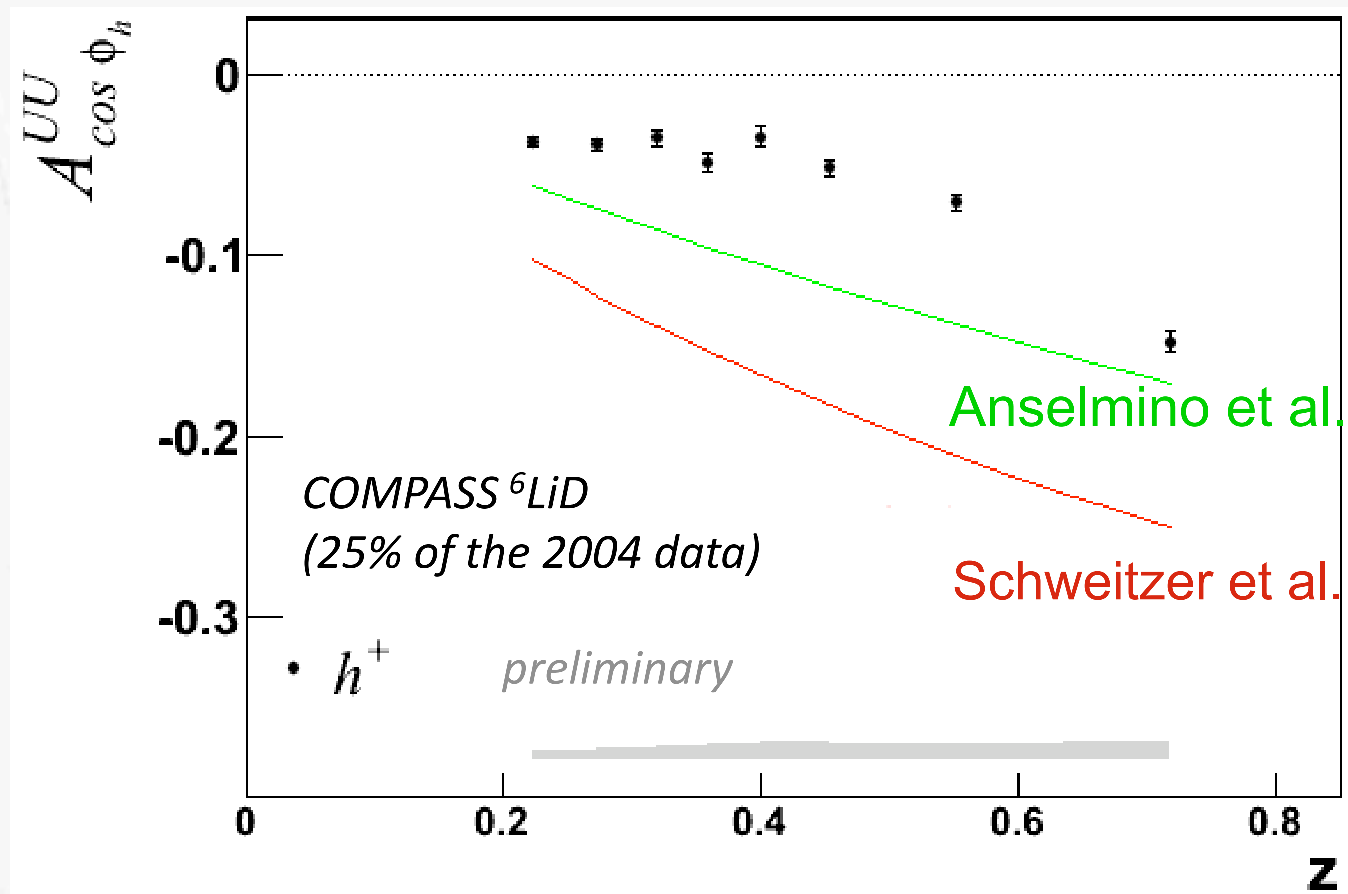
Interaction dependent terms neglected

next to leading twist

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







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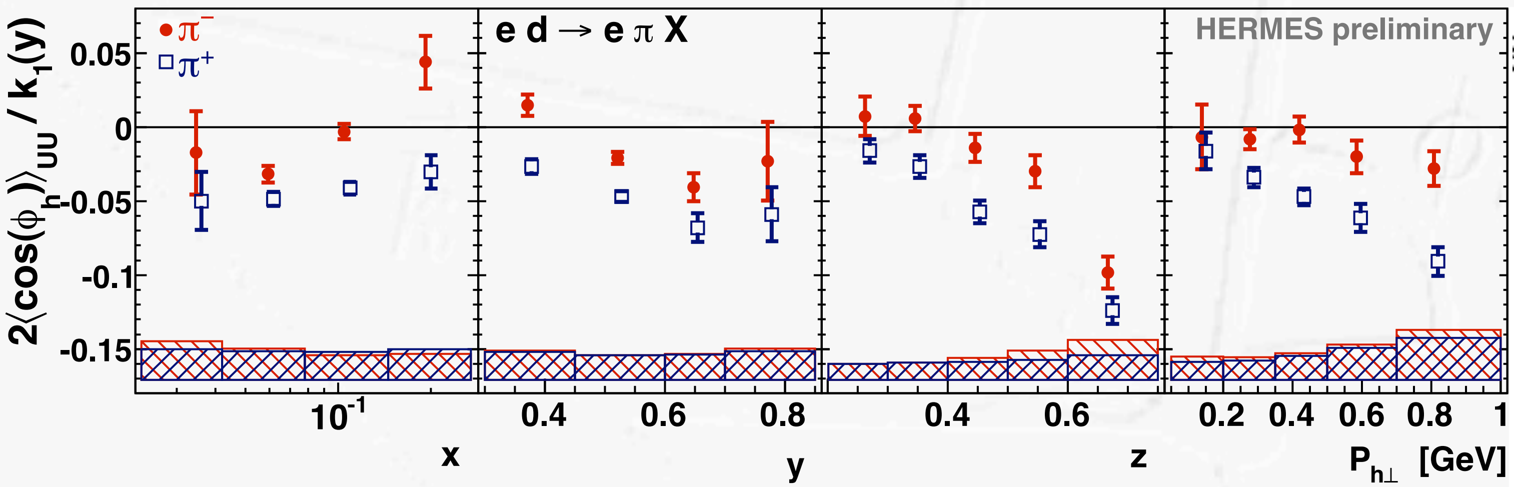

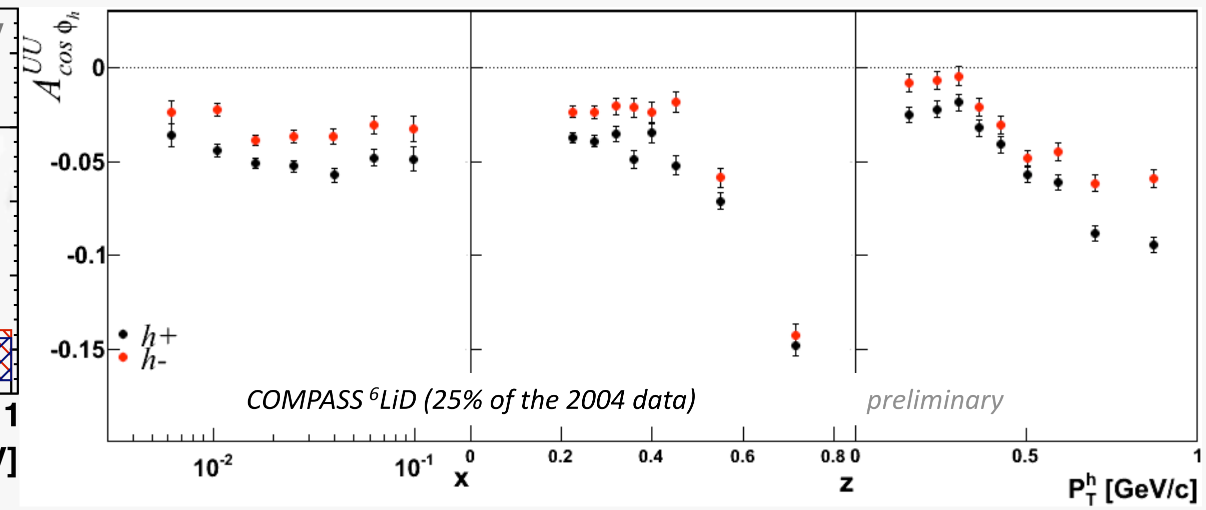

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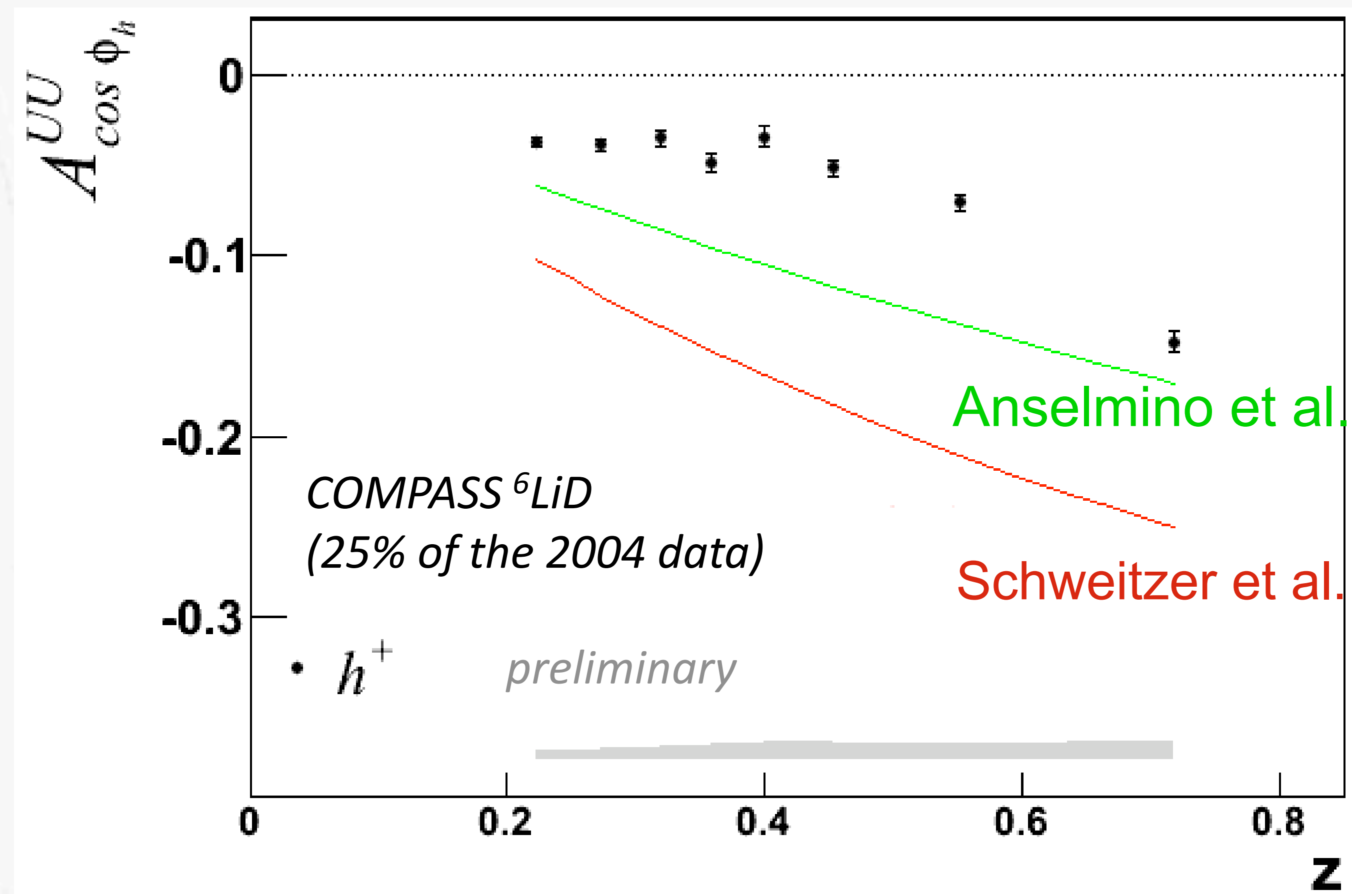
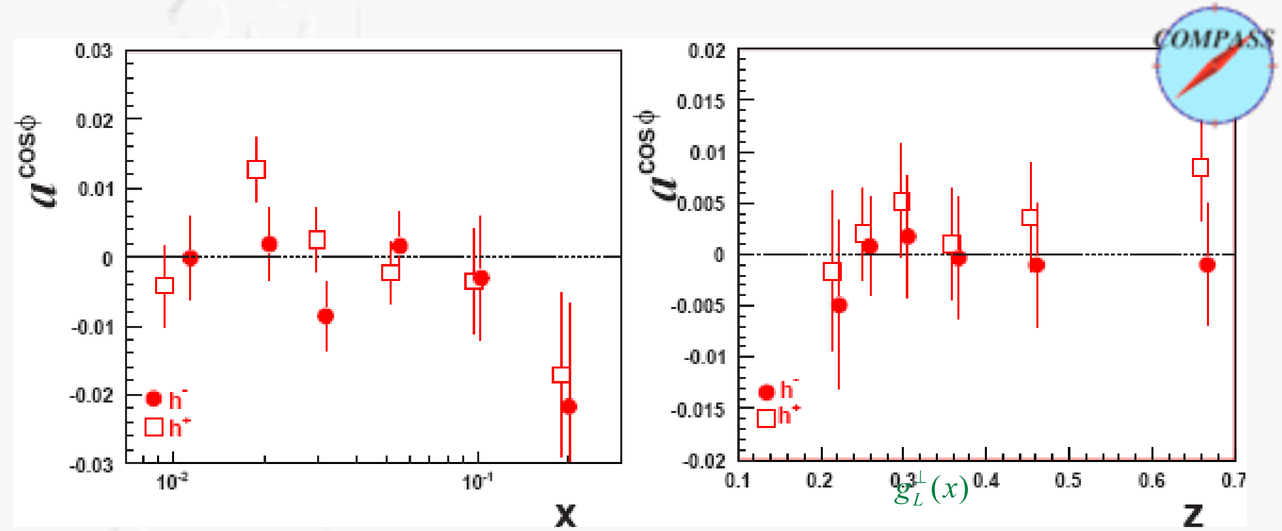
➡ sign of Boer-Mulders in $\cos\phi$ modulation or "real" twist-3?



Other twist-3 effects



$$A_{\rm LL}^{\cos\phi} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^{\perp} D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Other twist-3 effects

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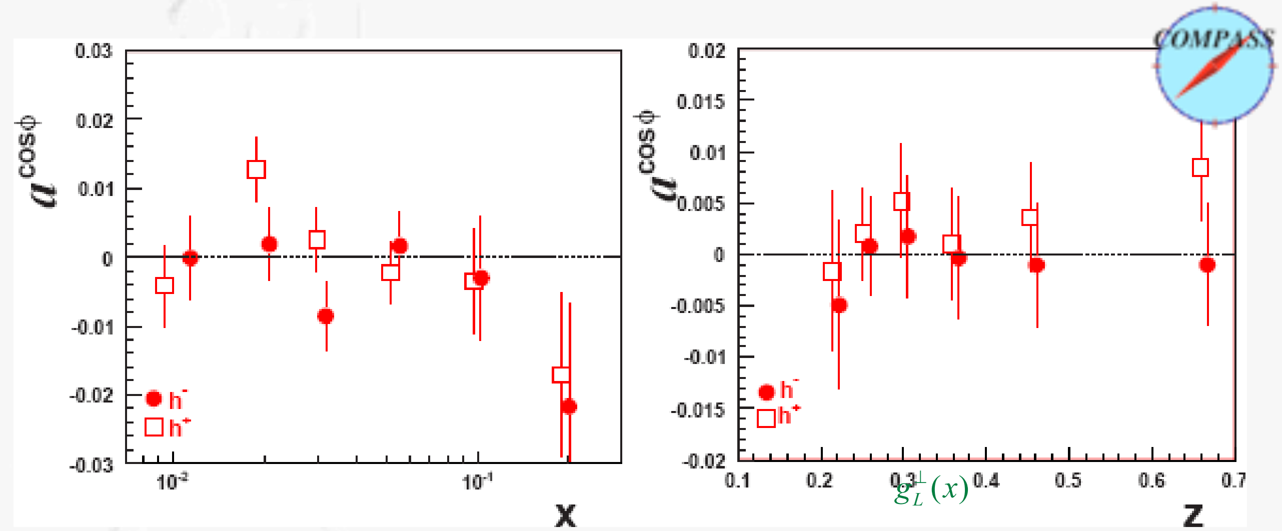
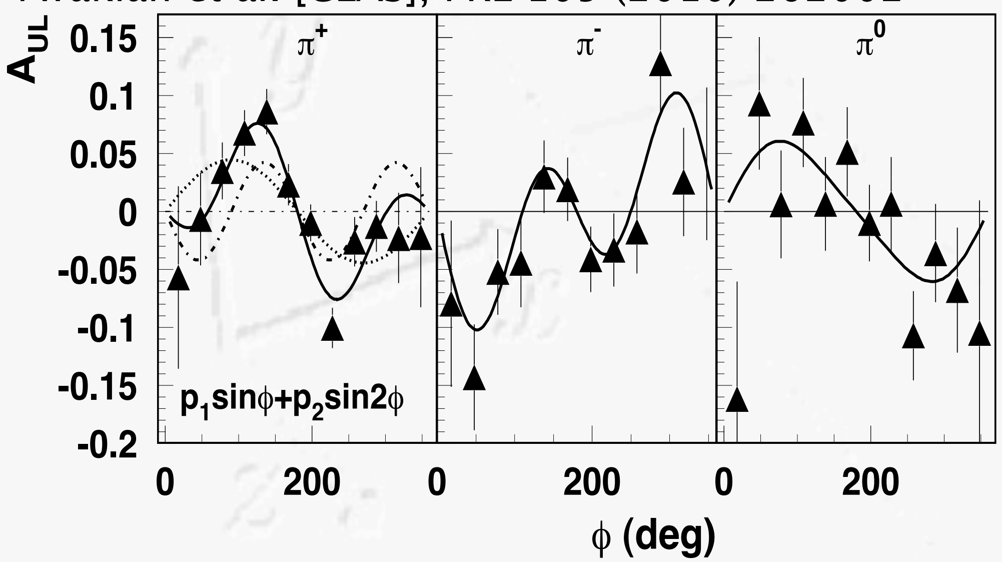


$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^\perp - \frac{M_h}{M}\, g_{1L}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^\perp D_1 + \frac{M_h}{M}\, h_{1L}^\perp\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], PRL 105 (2010) 262002



$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^\perp + \frac{M_h}{M}\, g_{1L}\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^\perp D_1 - \frac{M_h}{M}\, h_{1L}^\perp\frac{\tilde{H}}{z}\right)\right]$$

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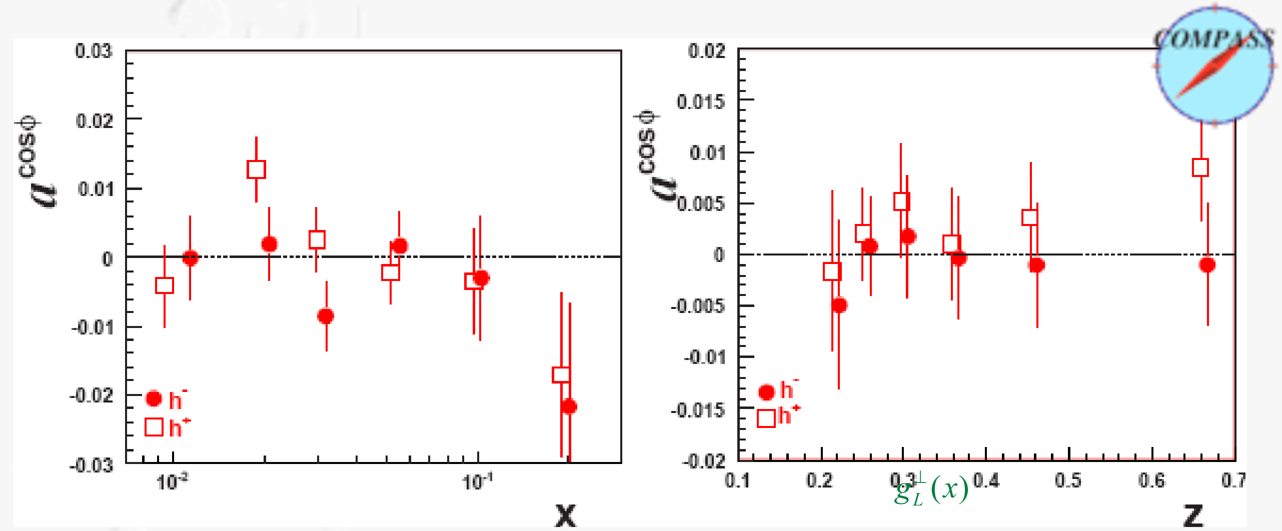

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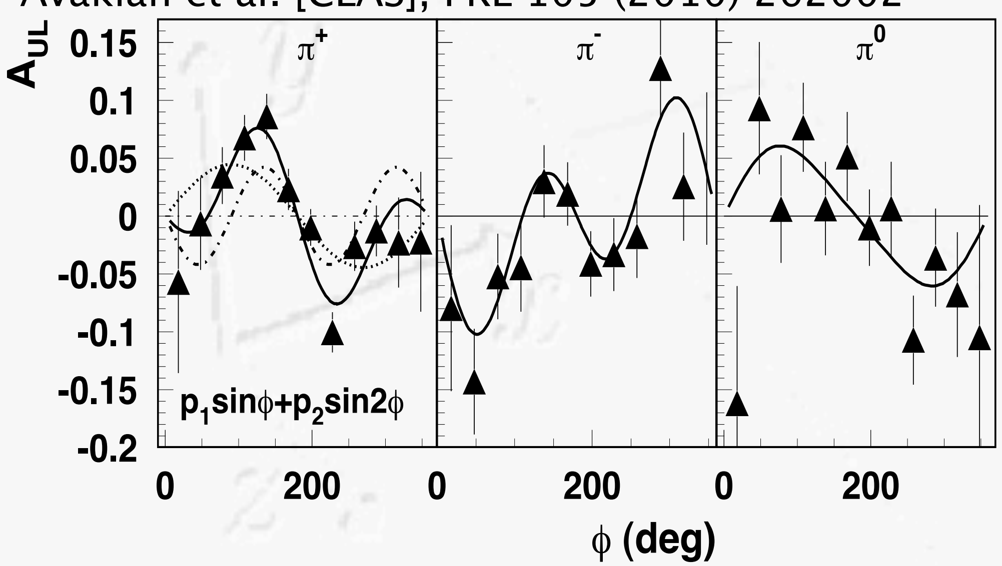

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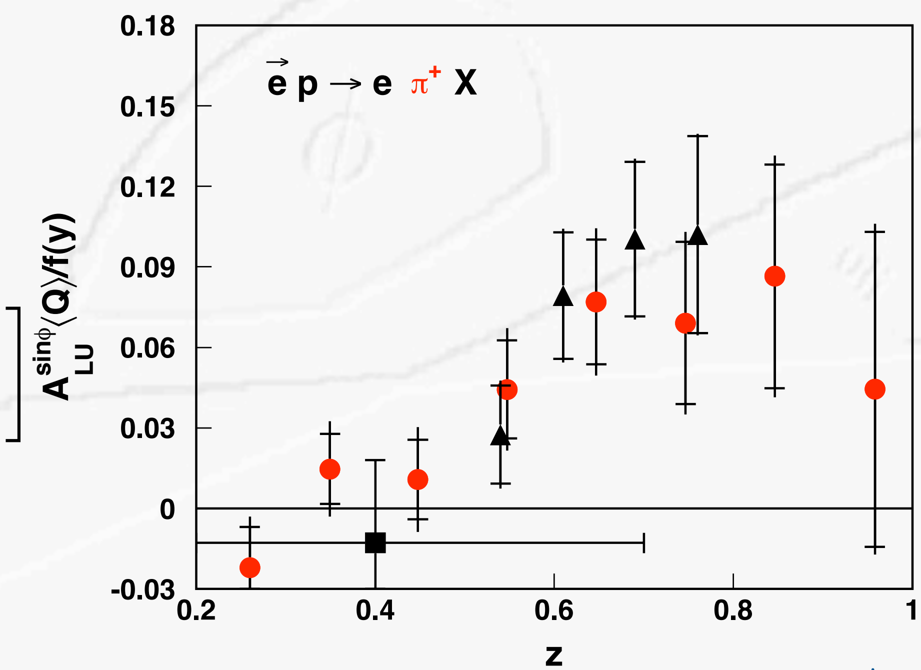

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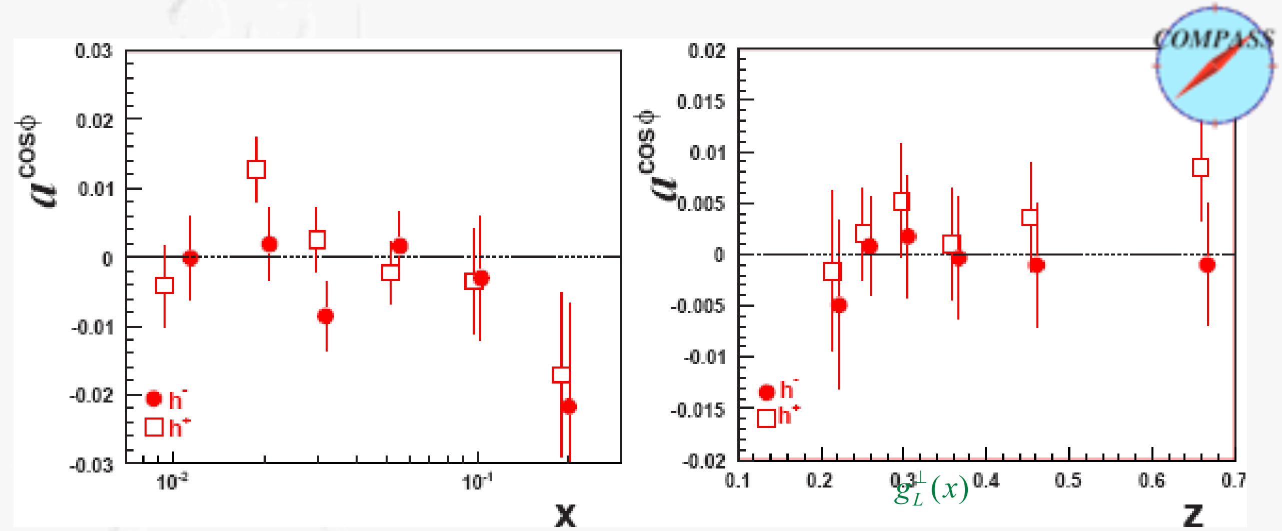

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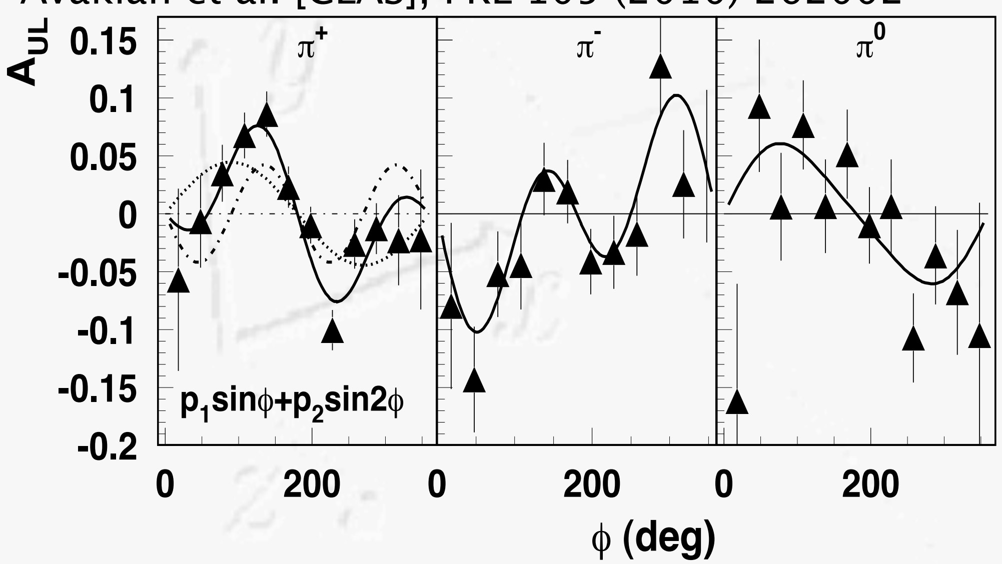

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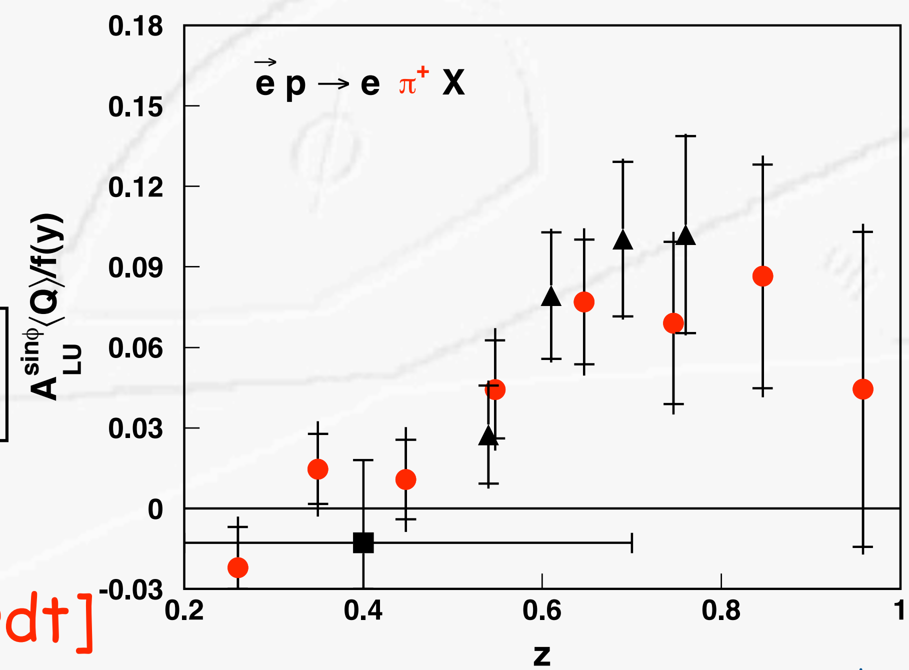

$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e\, H_1^\perp + \frac{M_h}{M}\, f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^\perp D_1 + \frac{M_h}{M}\, h_1^\perp \frac{\tilde{E}}{z}\right)\right]$$

transverse force on transversely pol. quarks [M. Burkardt]

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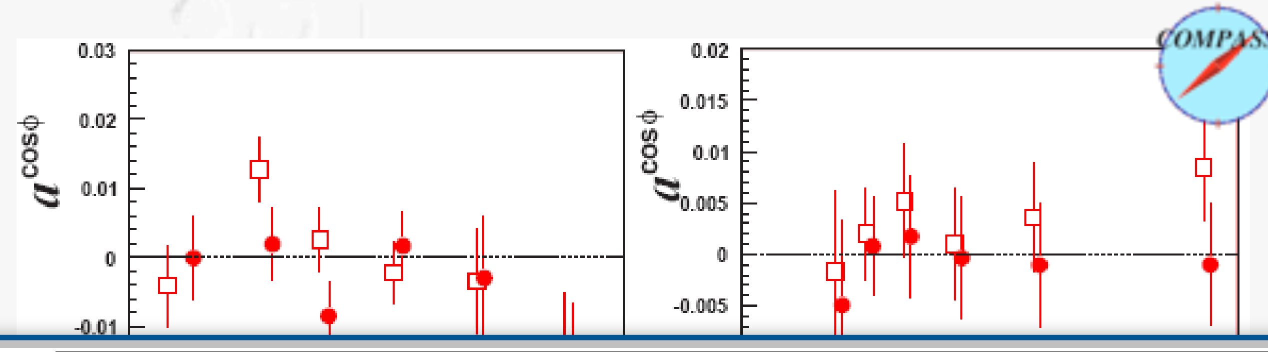

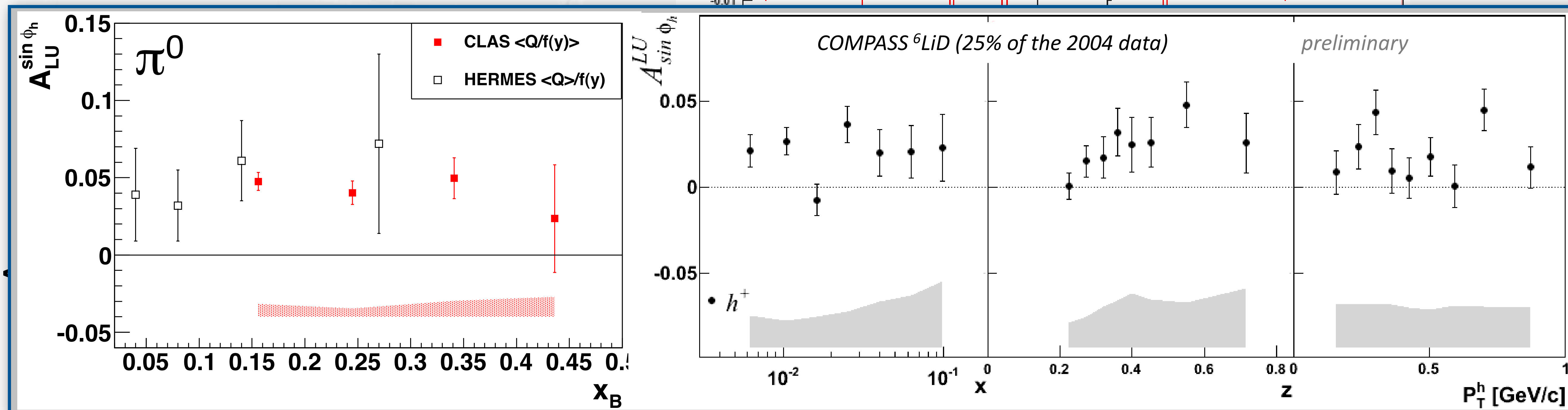

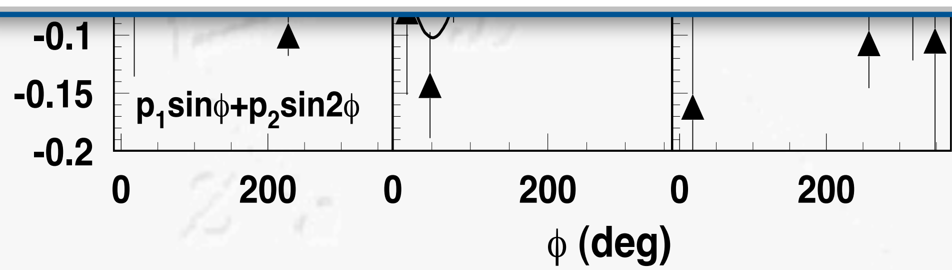

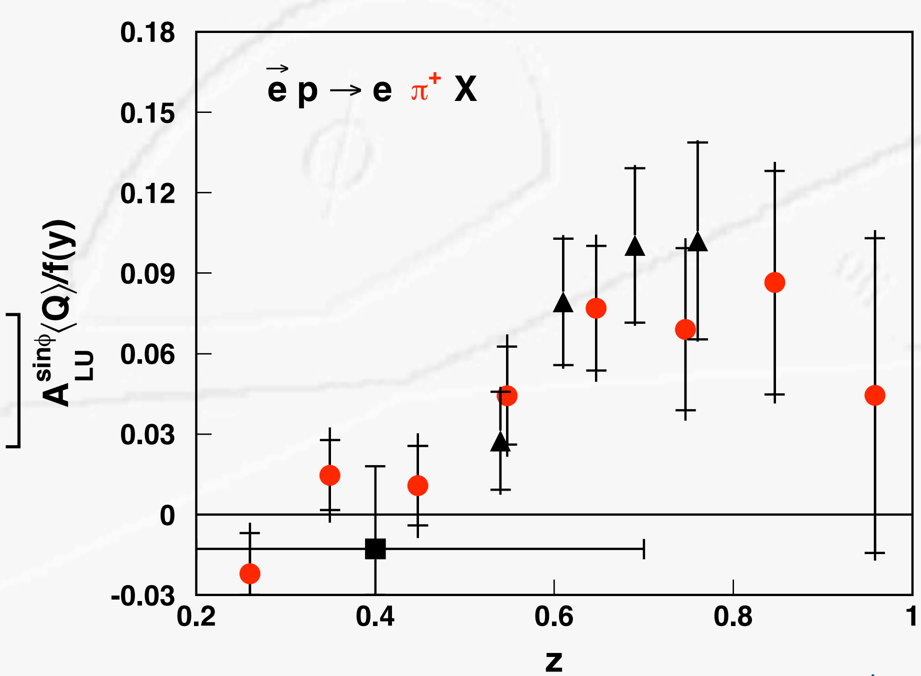

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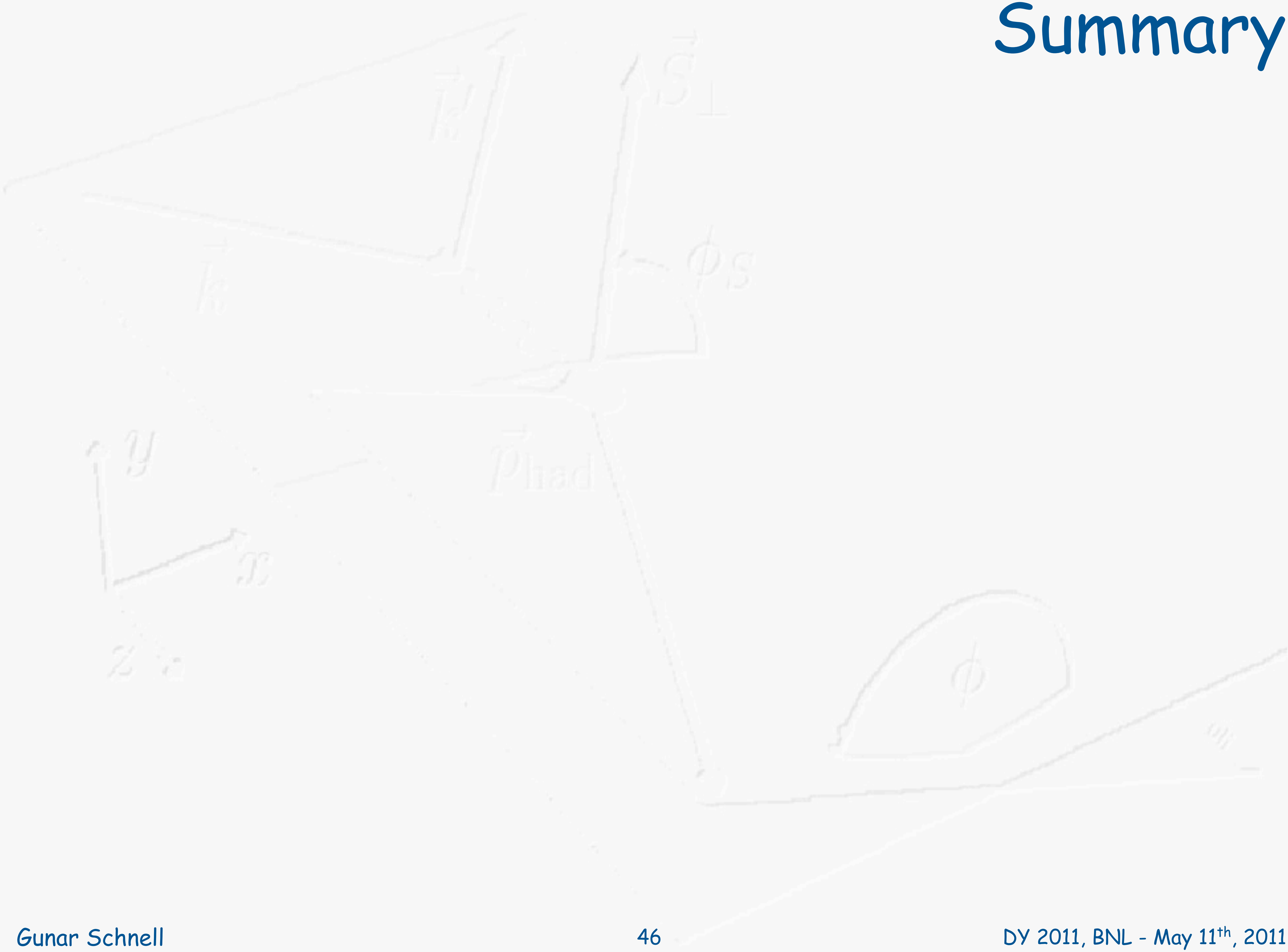
$$\sigma_{LU}\propto\sin\phi_{R\perp}\left[xe(x)H_1^{\sphericalangle}(z,\zeta,M_h^2)+\frac{1}{z}f_1(x)\tilde{G}^{\sphericalangle}(z,\zeta,M_h^2)\right]$$

Summary



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