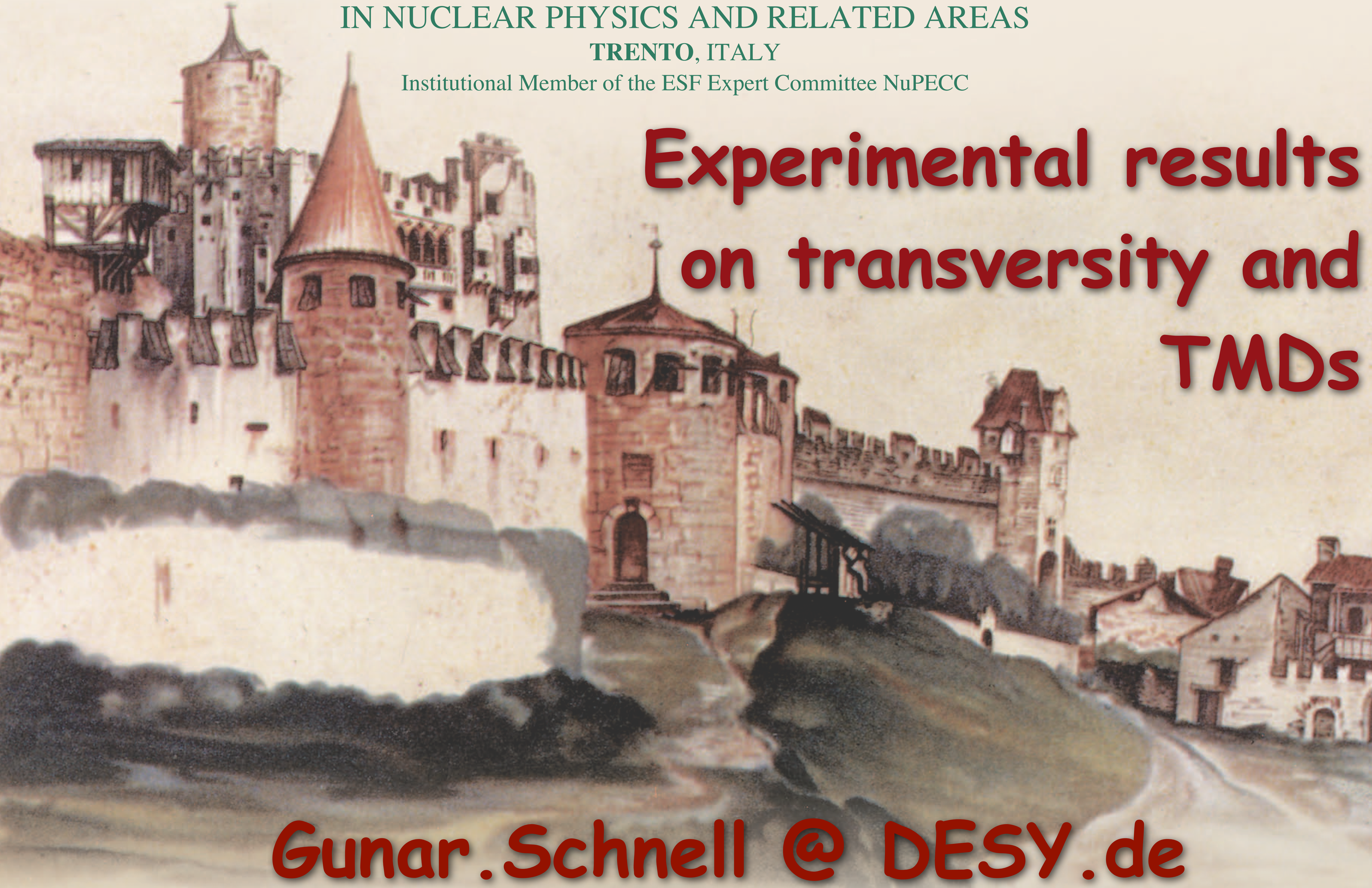
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the ESF Expert Committee NuPECC

Experimental results on transversity and TMDs



Gunar.Schnell @ DESY.de

Spin-Momentum Structure of the Nucleon

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

$$\frac{1}{2}\mathrm{Tr}\left[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\right] = \frac{1}{2}\Bigg[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\frac{1}{m}\,h_1^\perp + s^iS^ih_1$$

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

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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helicity

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Twist-2 TMDs

Boer-Mulders

Sivers

worm-gear

transversity

Mulders-Tangerman*

- functions in black survive integration over transverse momentum
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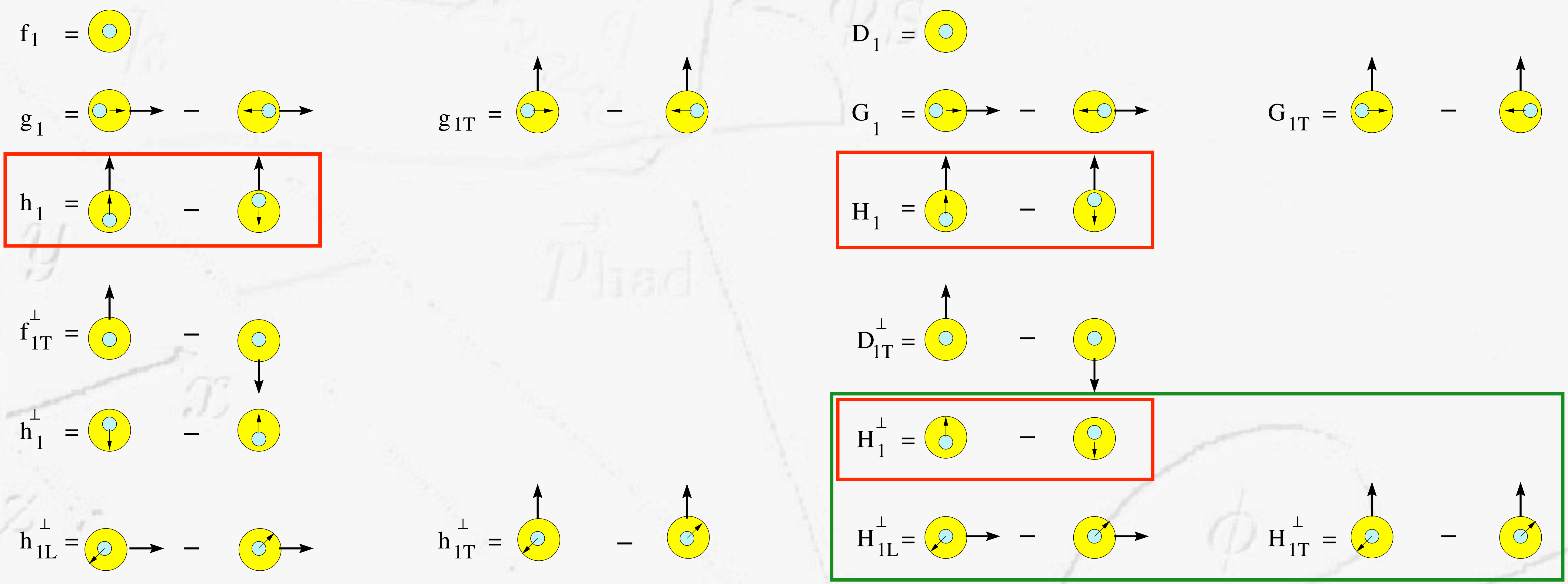
*aka Pretzelosity

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

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

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

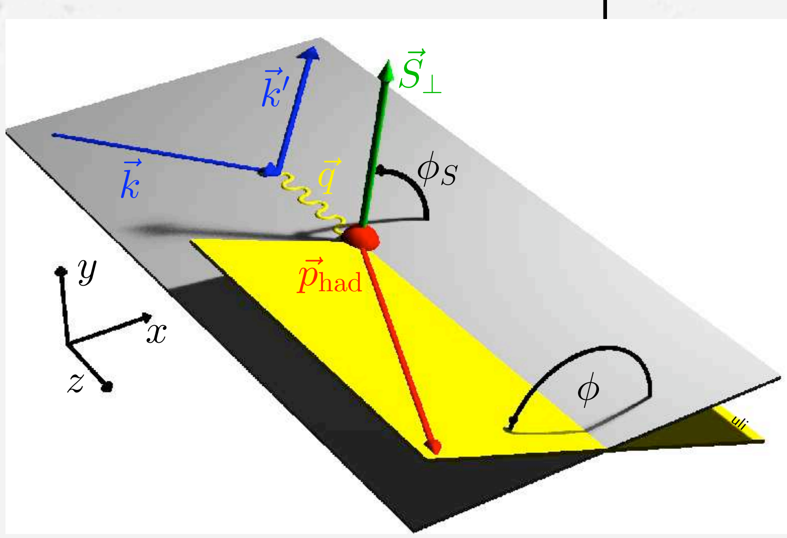
$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

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

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

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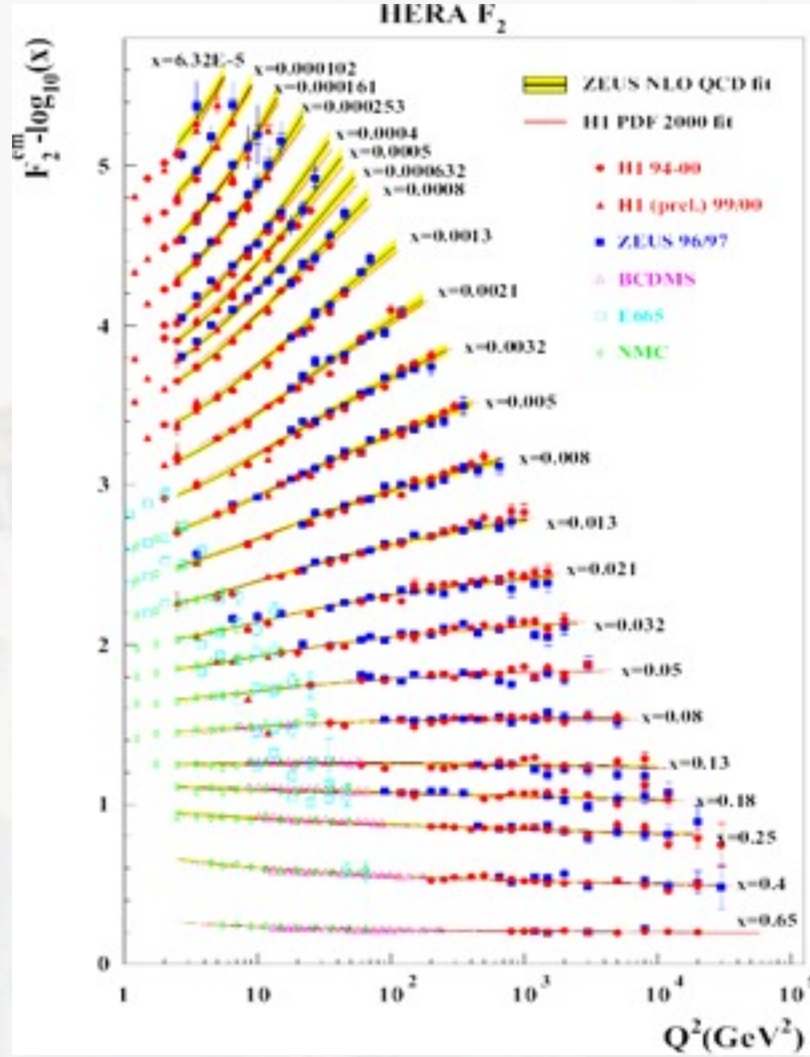
Momentum density



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

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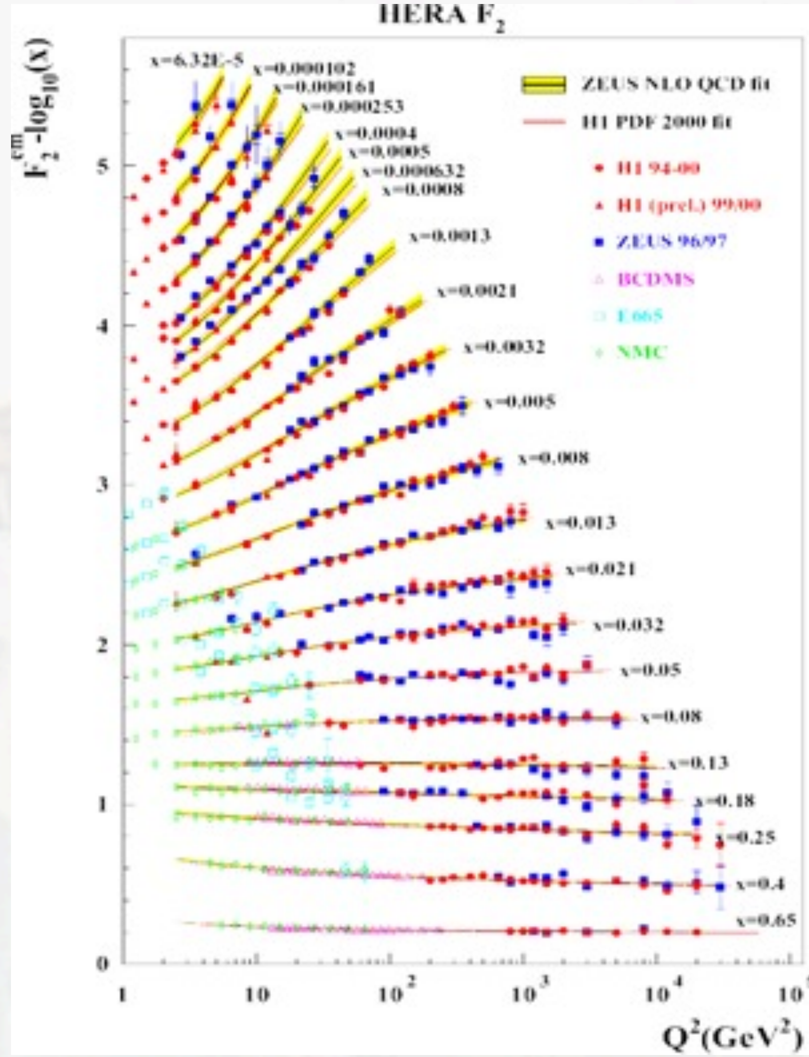

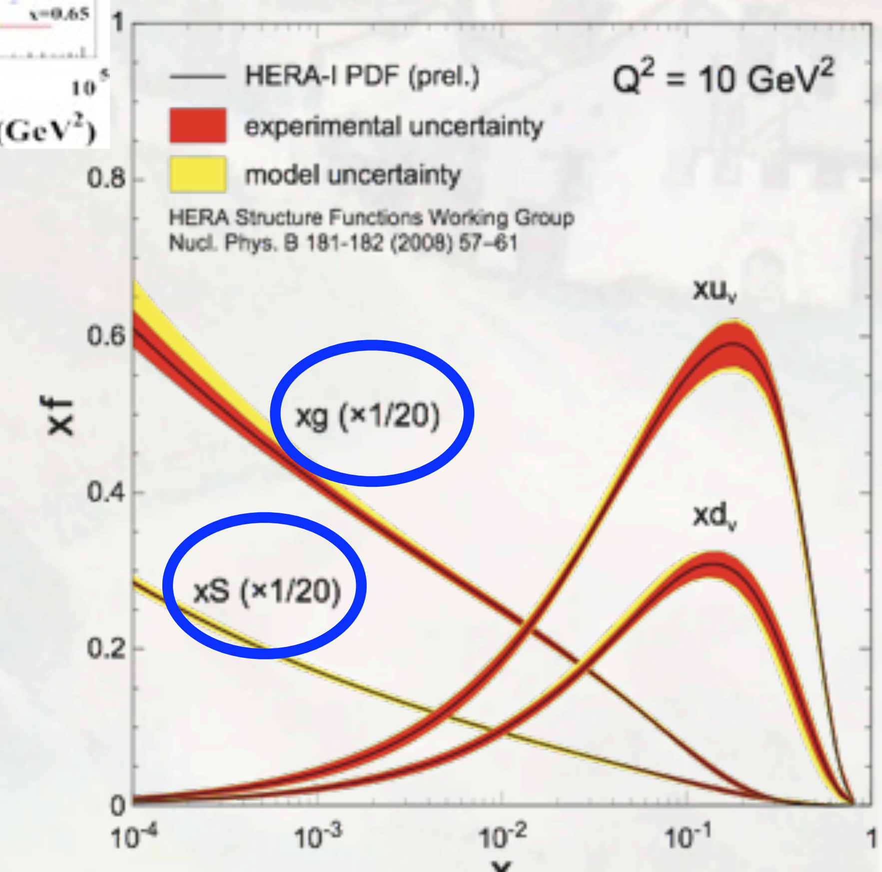

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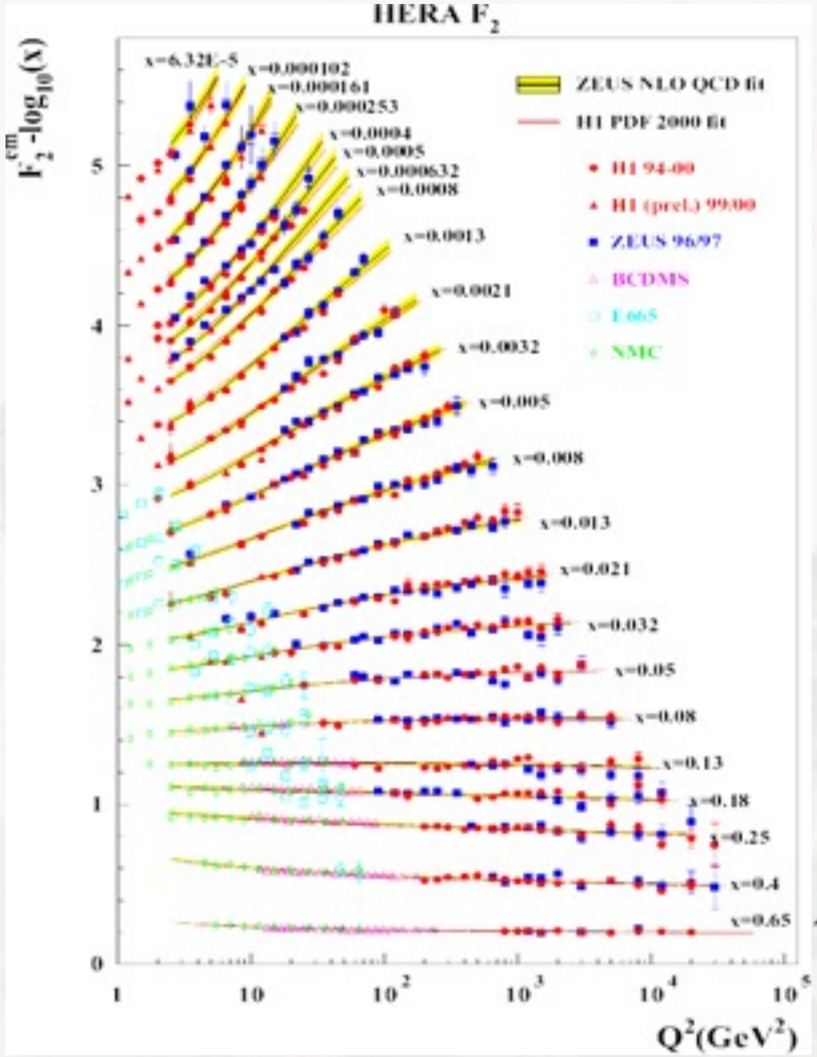

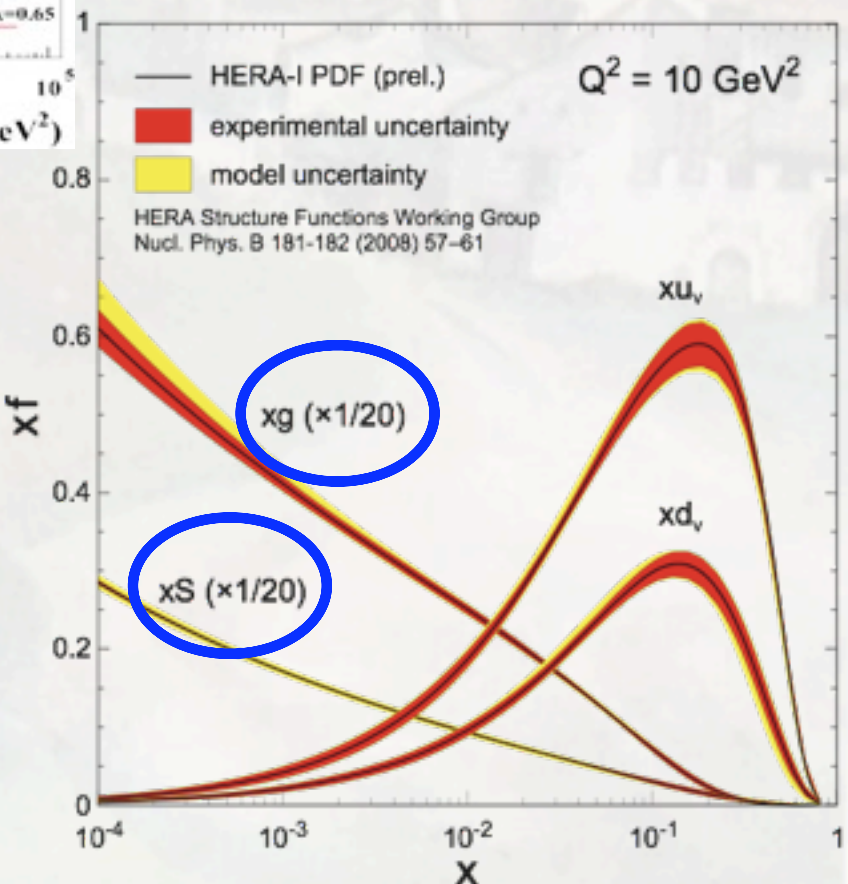

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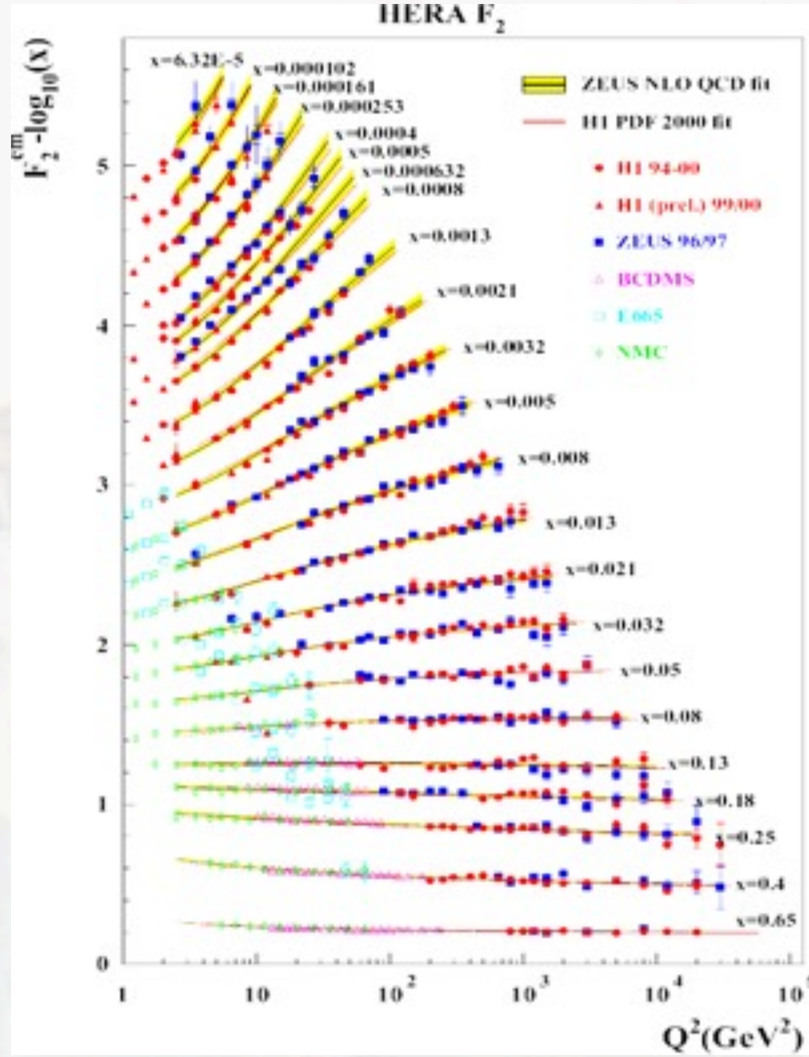

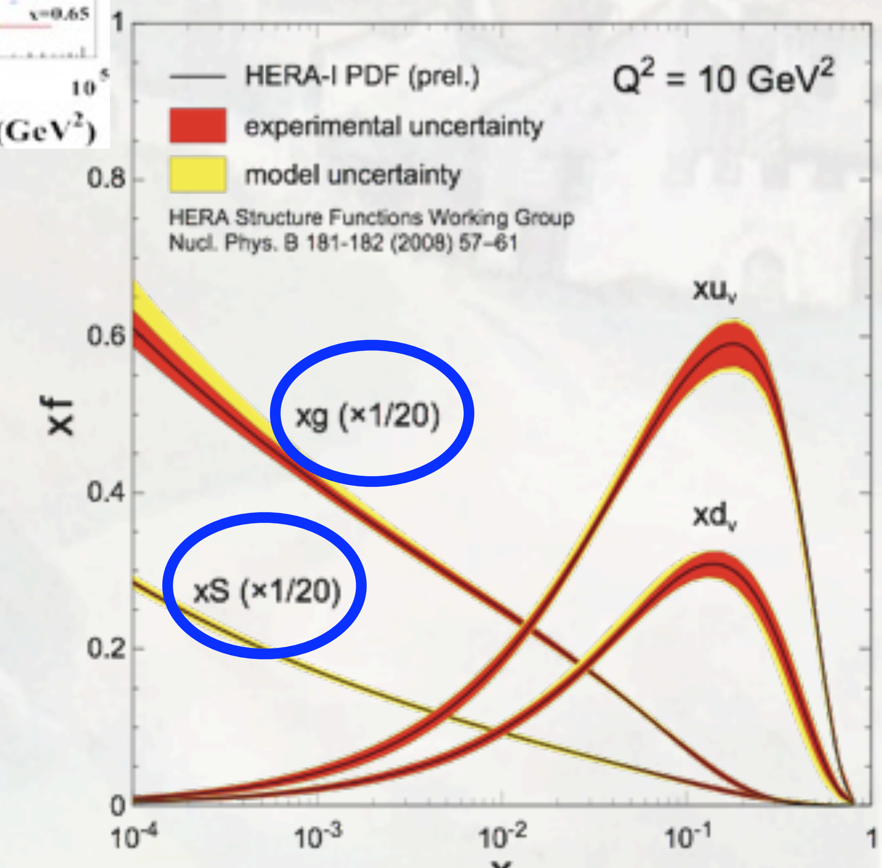

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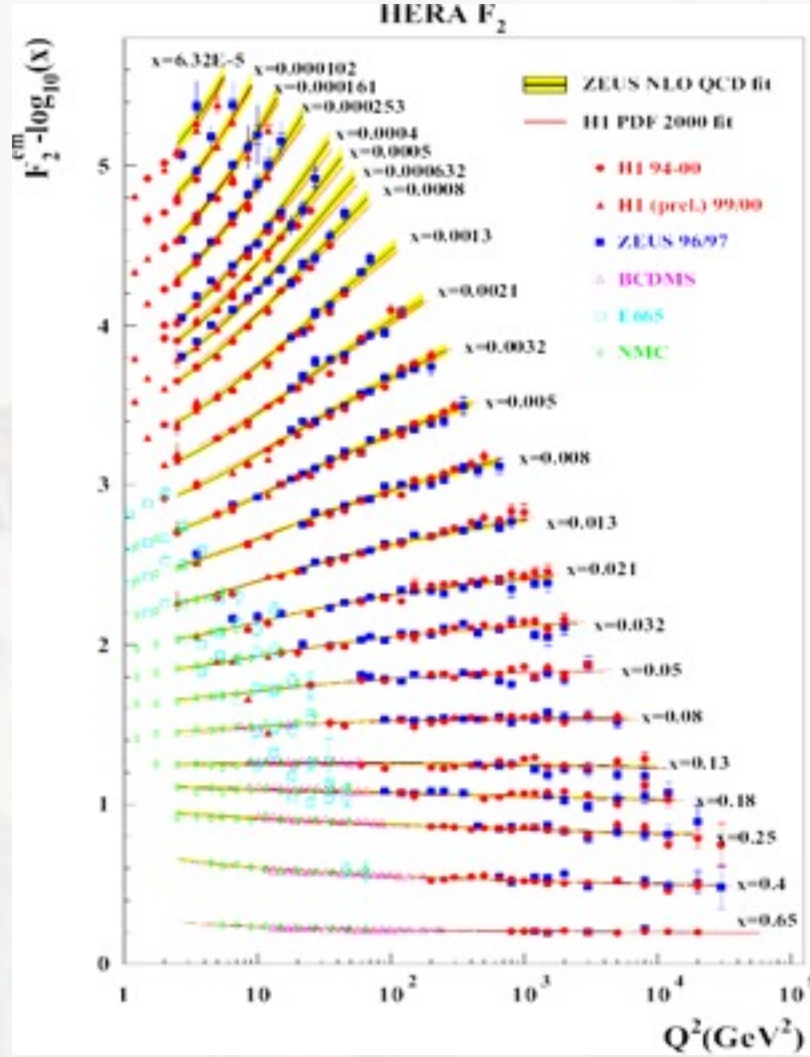

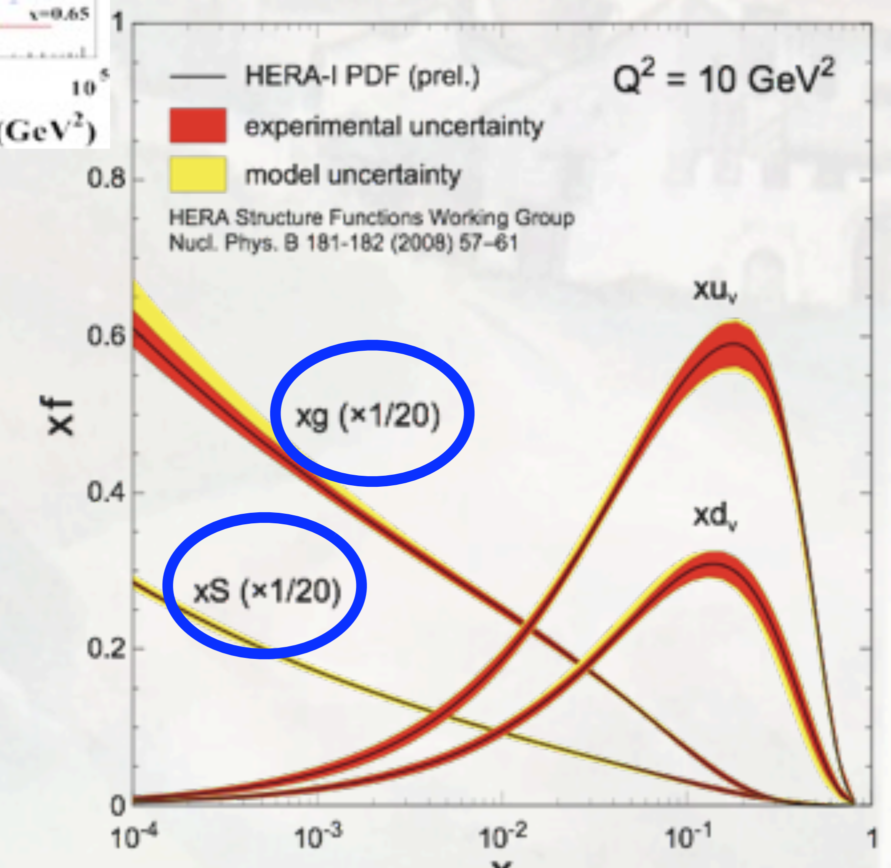

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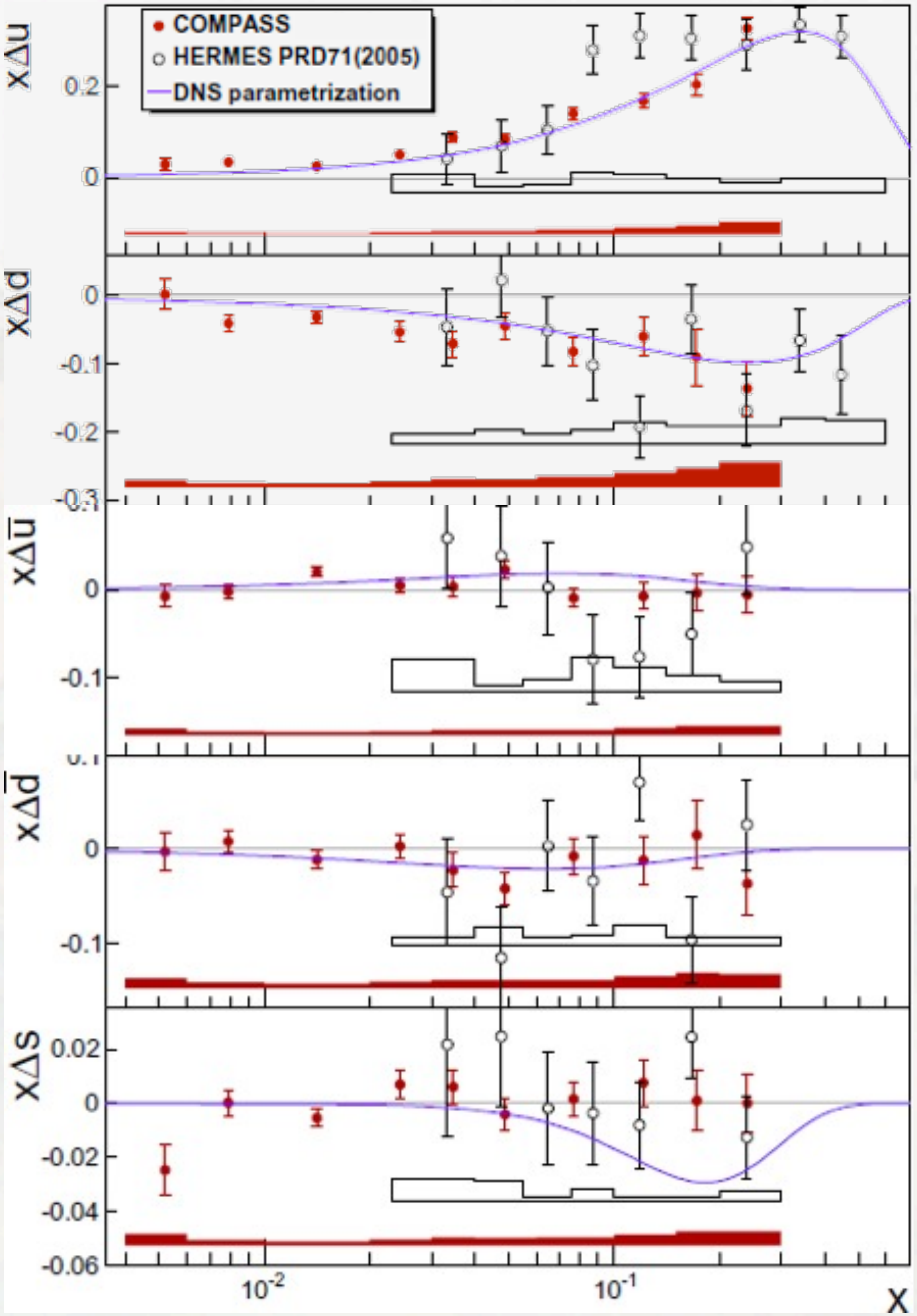
Helicity density

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



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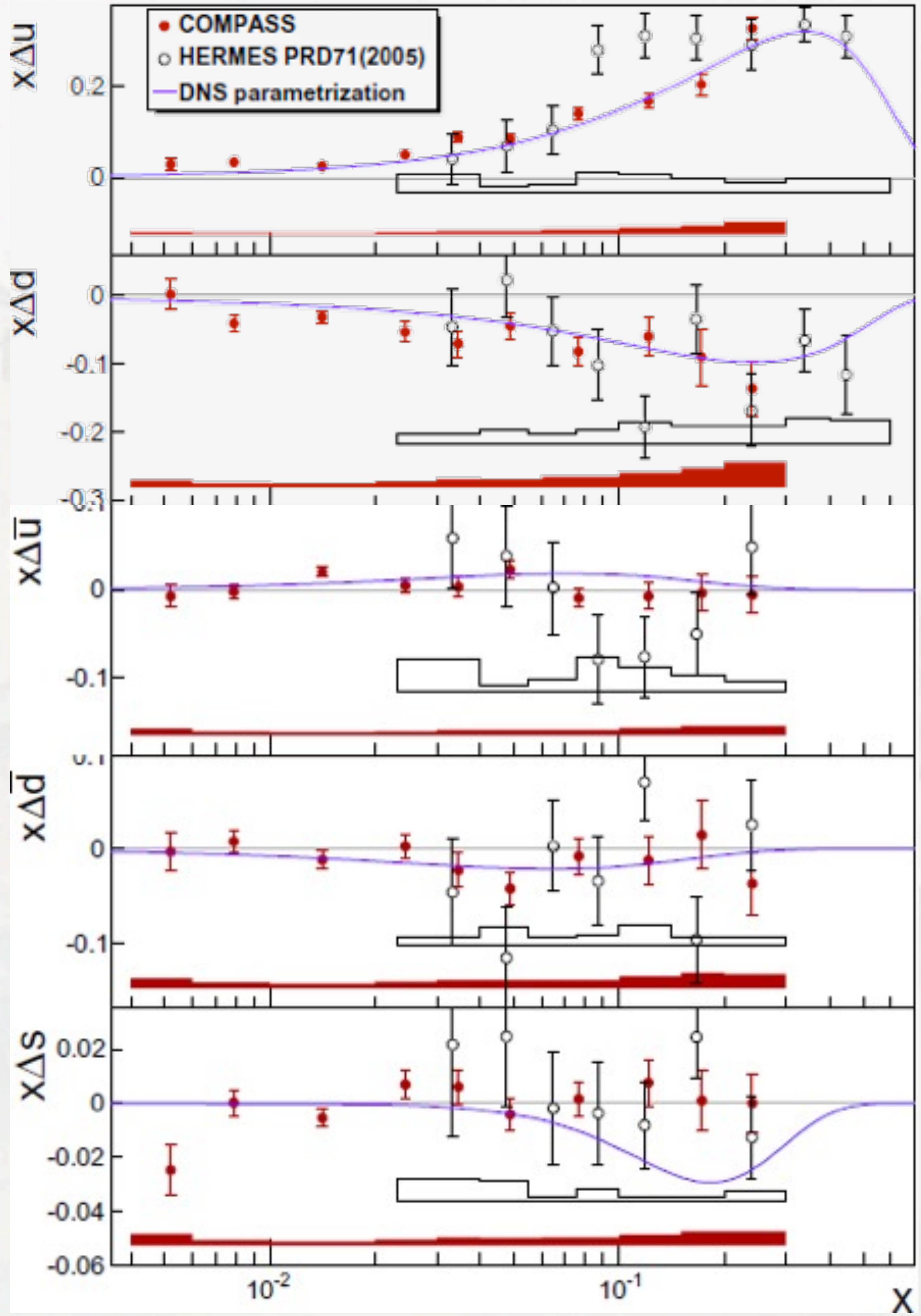

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☛ E.-M. Kabuss, W. Vogelsang

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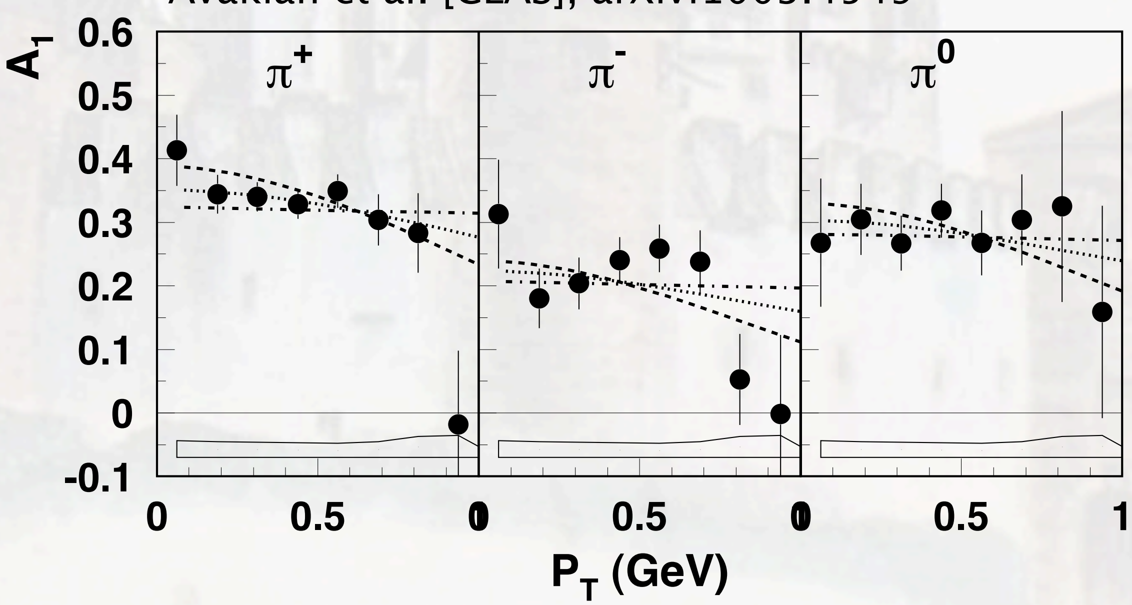
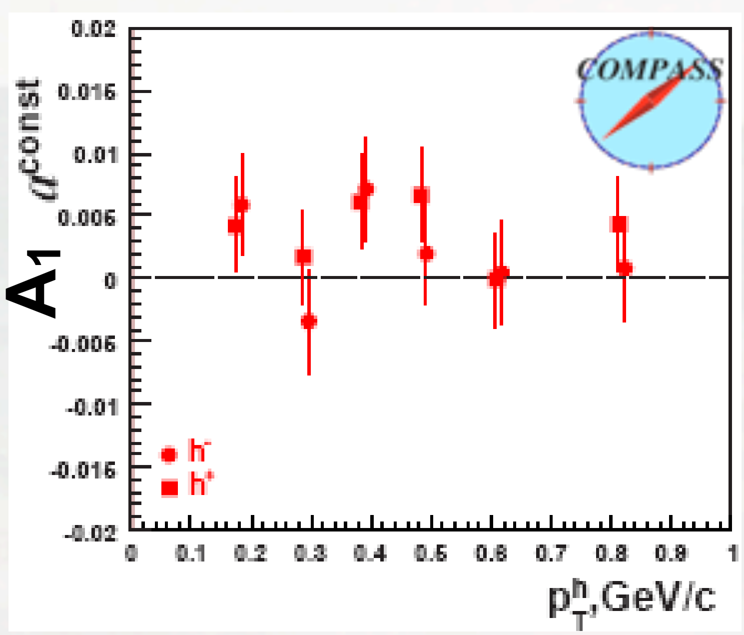
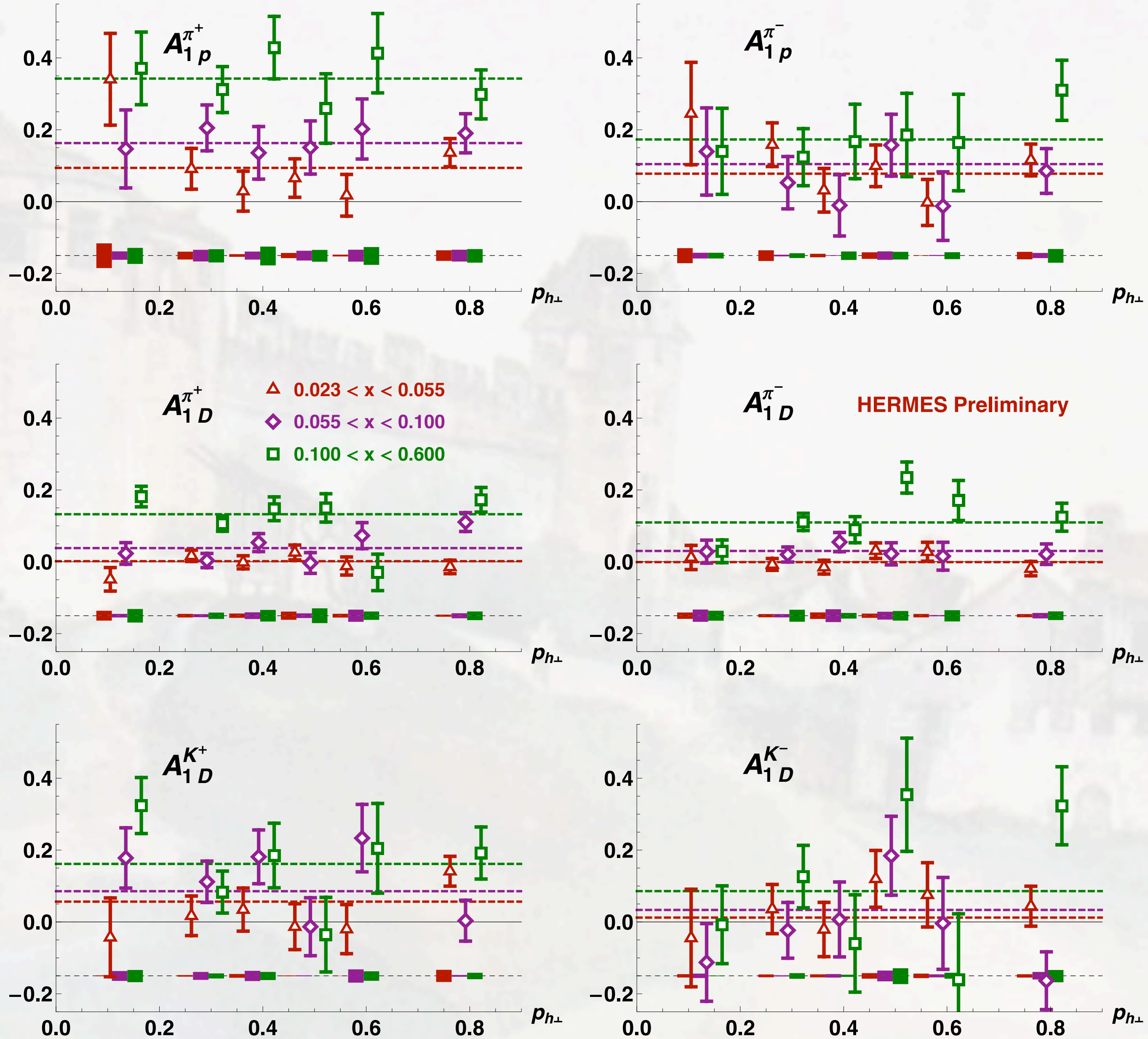
Helicity density (unintegrated)

Avakian et al. [CLAS], arXiv:1003.4549







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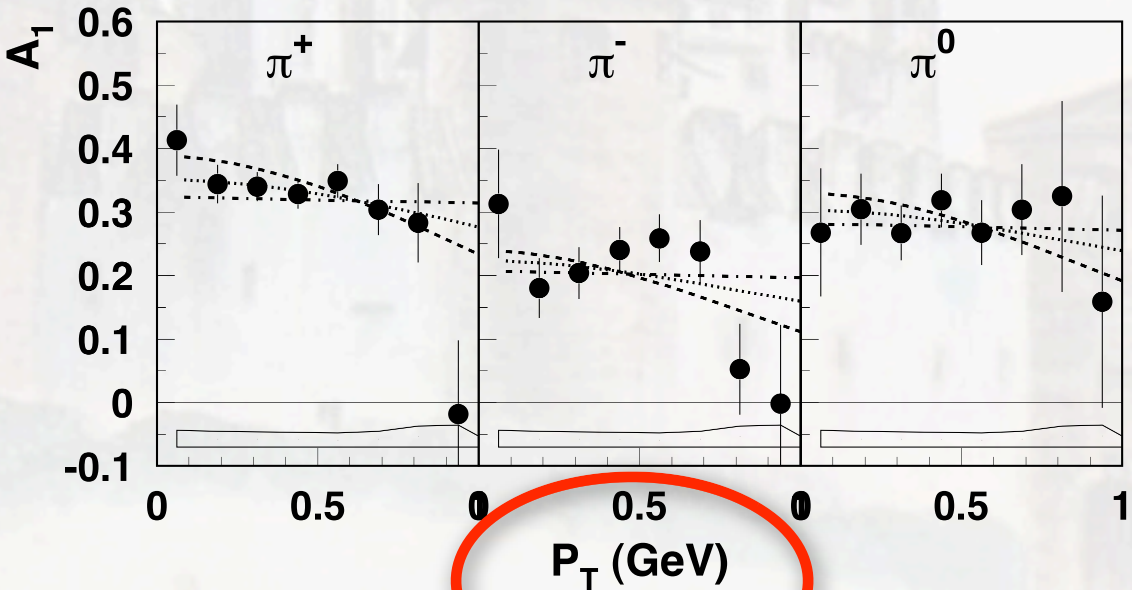

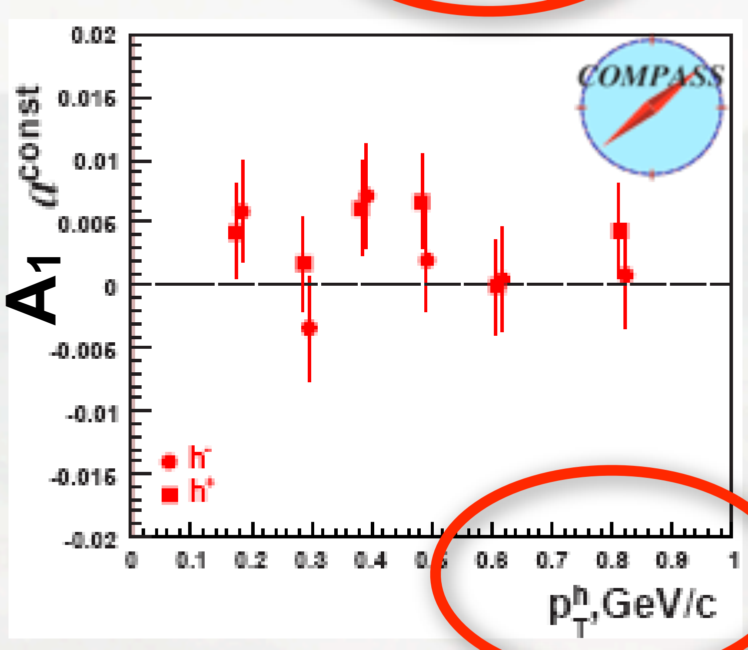

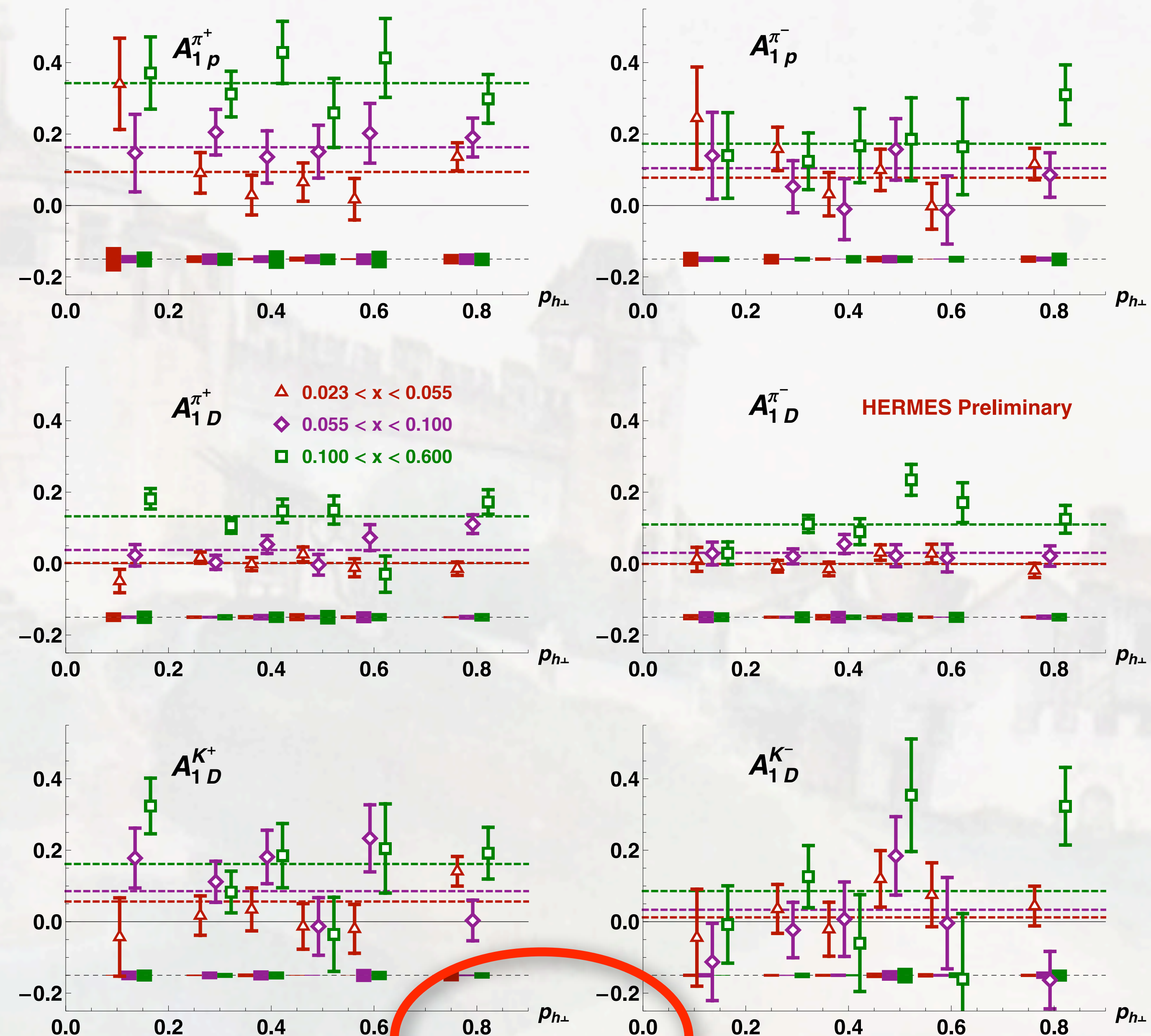

only weak if any dependence on $P_{h\perp}$ seen

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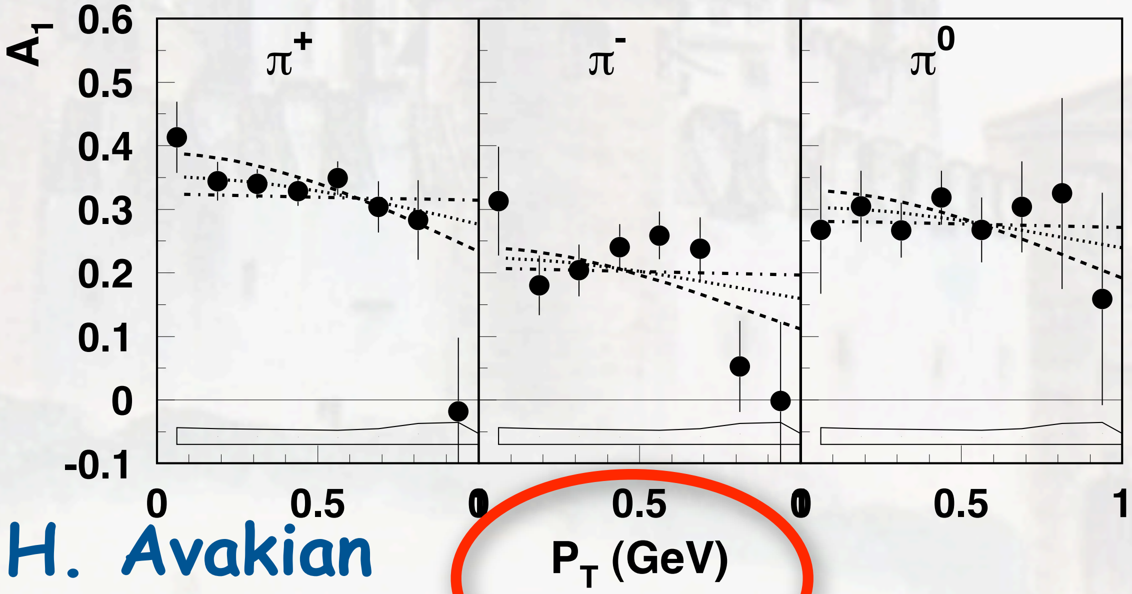
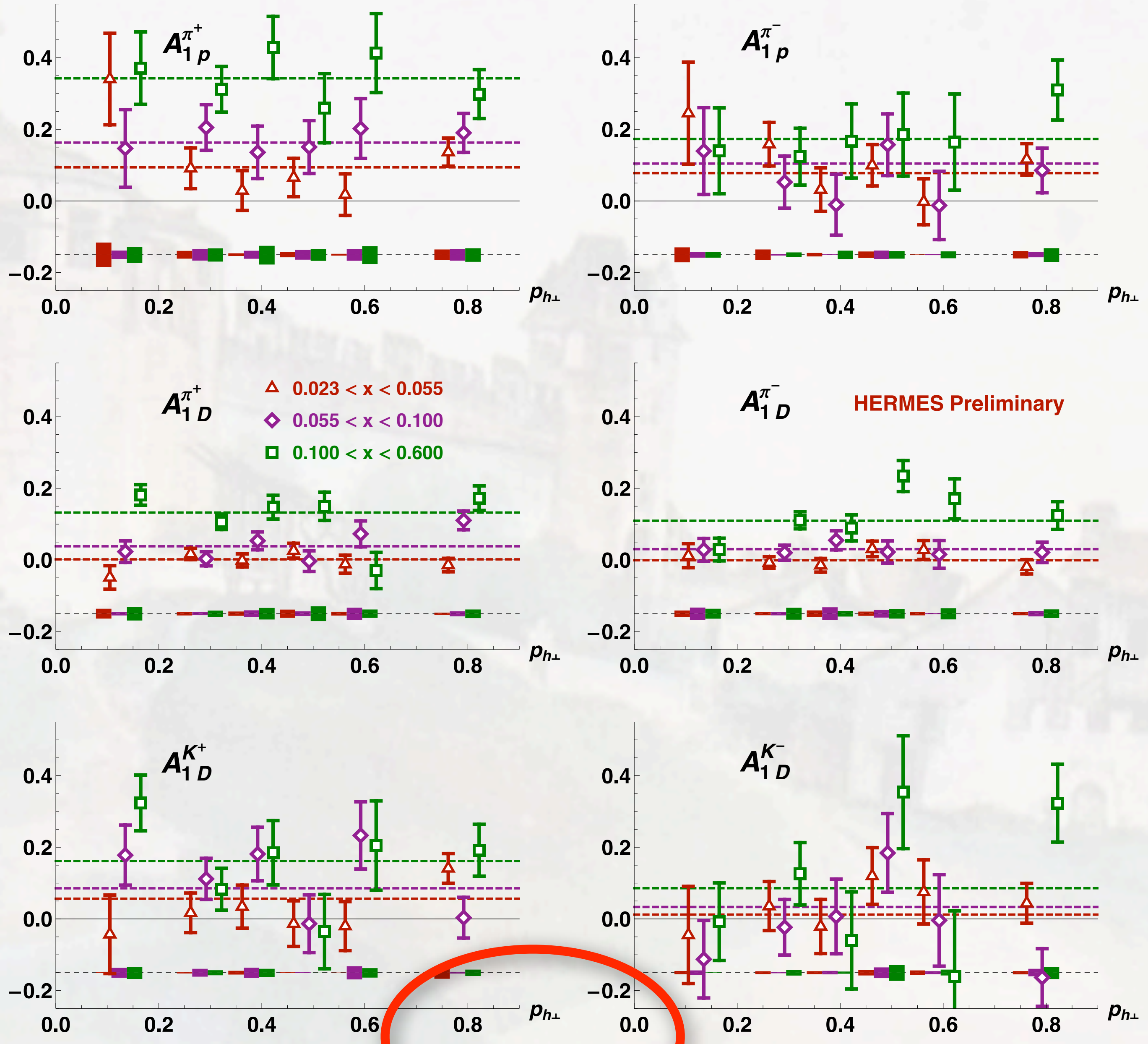
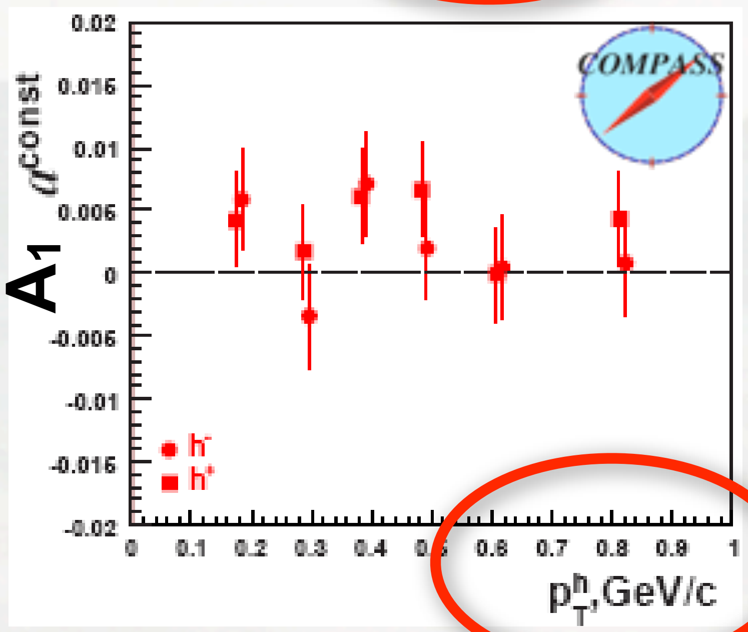


☛ H. Avakian





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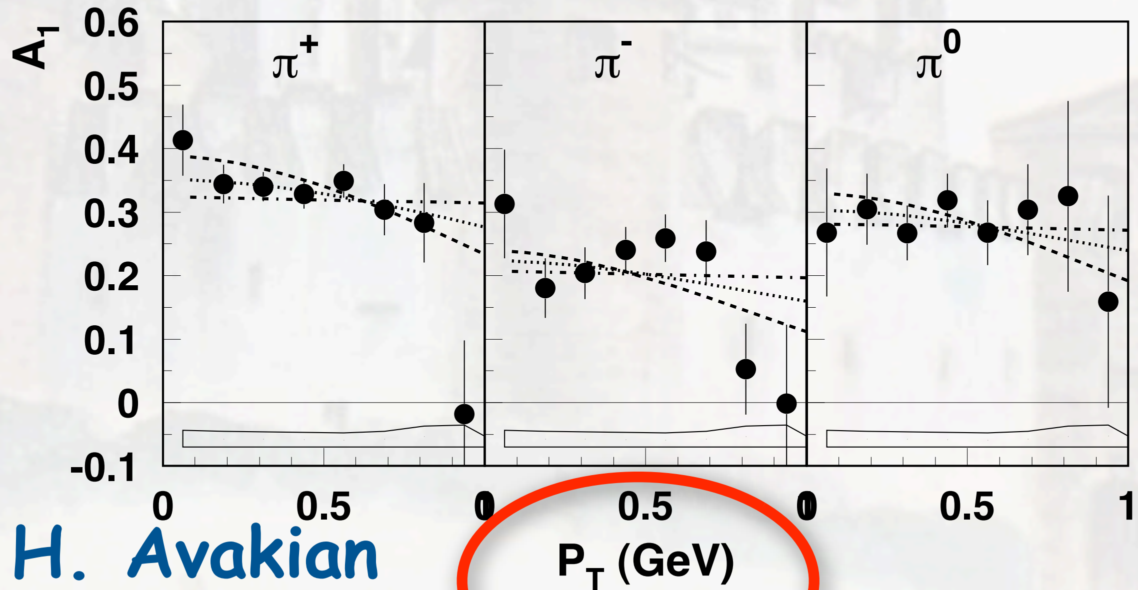

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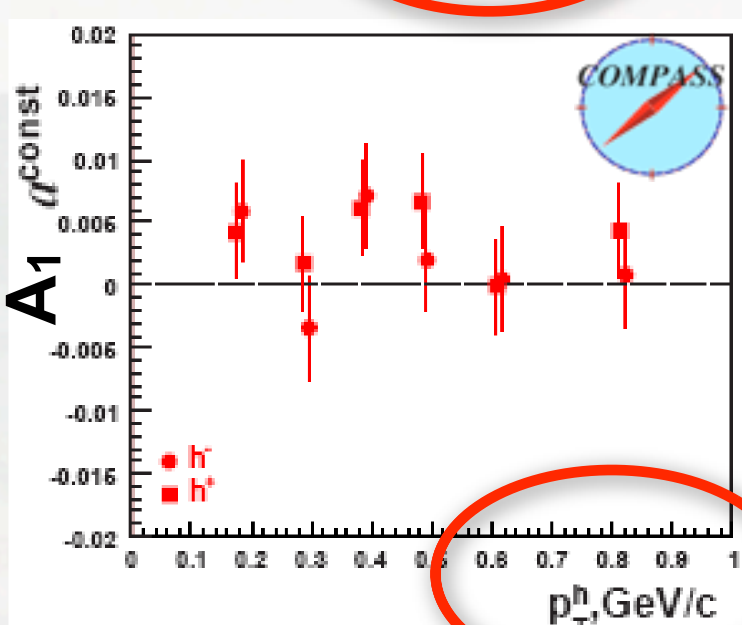
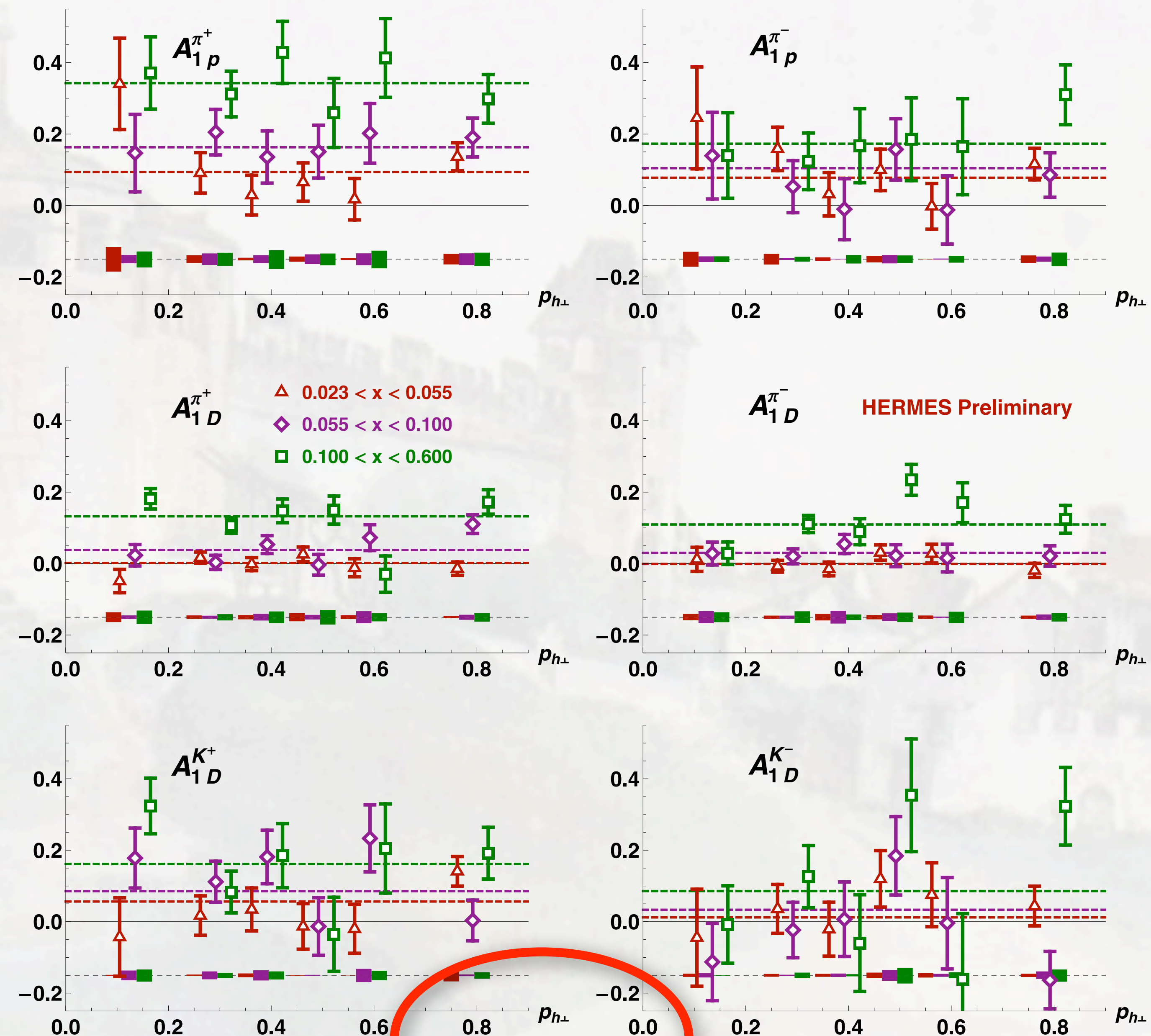


☛ H. Wollny



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Transversity distribution

chiral-odd transversity involves quark helicity flip

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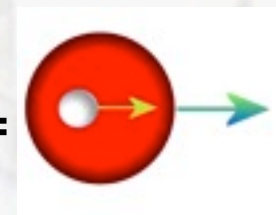
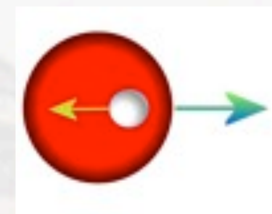
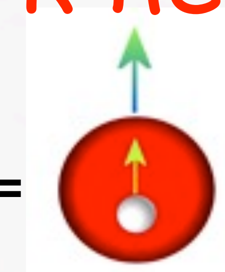
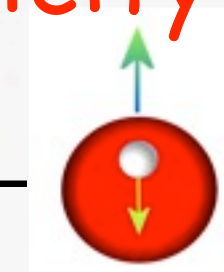
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 

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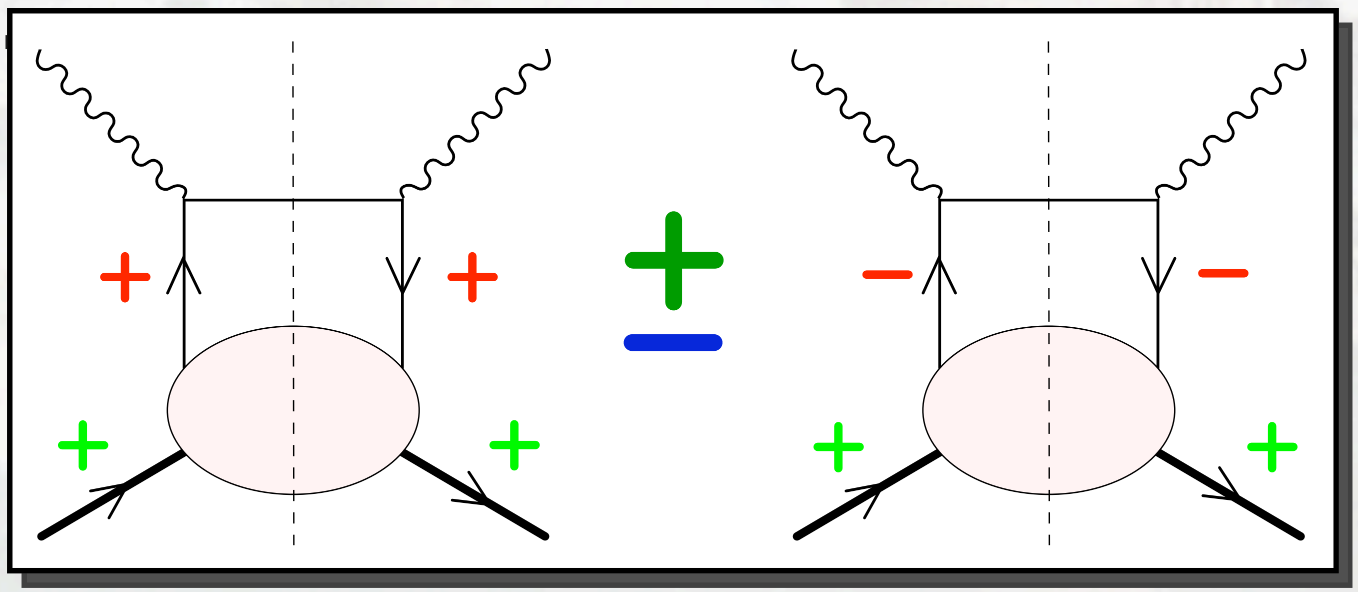

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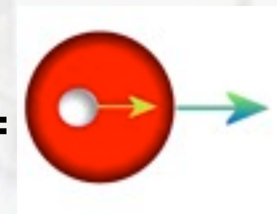
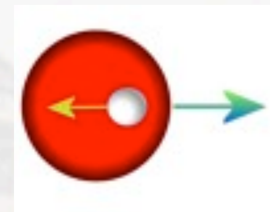
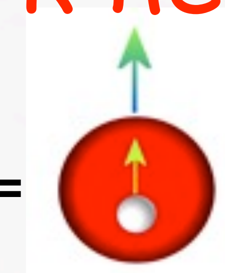
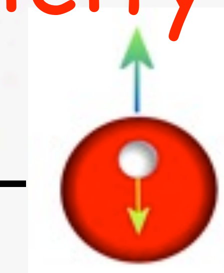
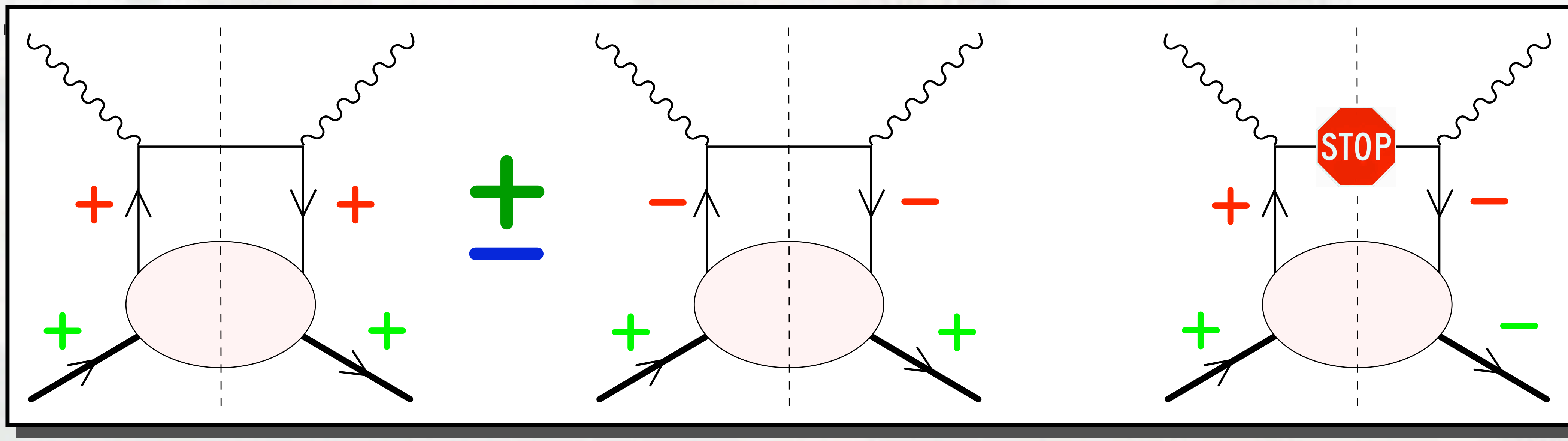
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 



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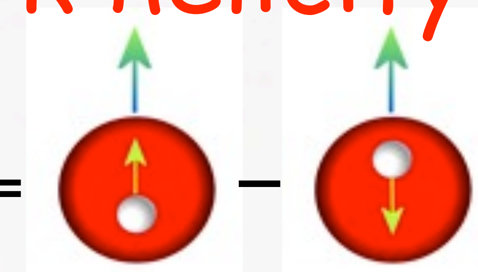
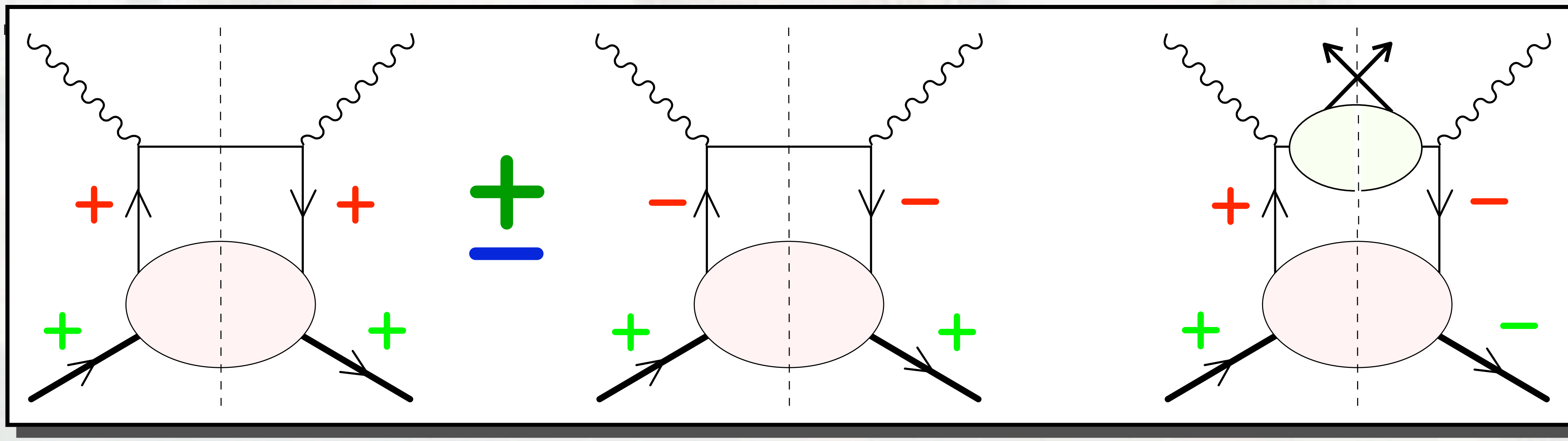
$h_1^q =$ 



need to couple to chiral-odd fragmentation function:

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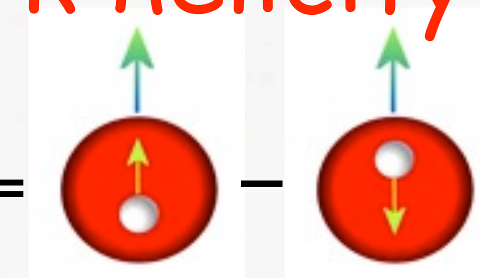
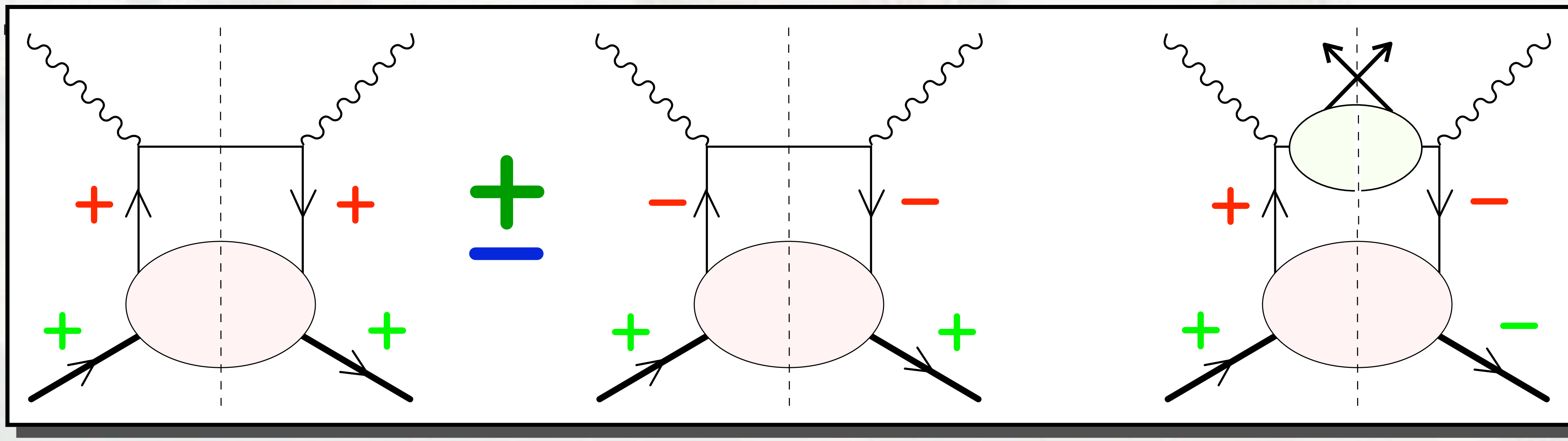
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



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

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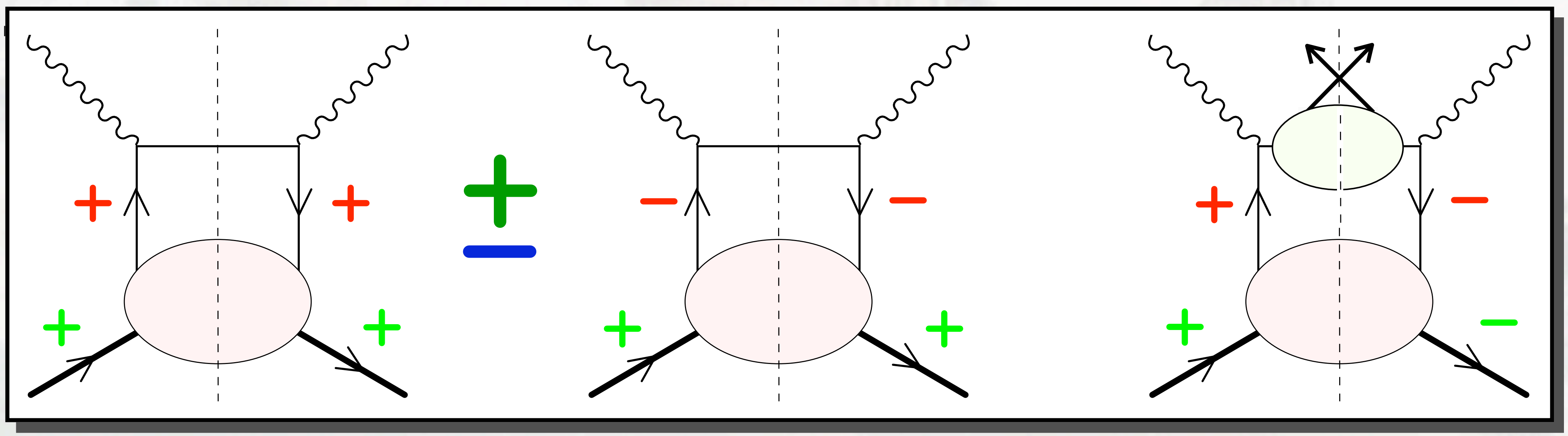

need to couple to chiral-odd fragmentation function:

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

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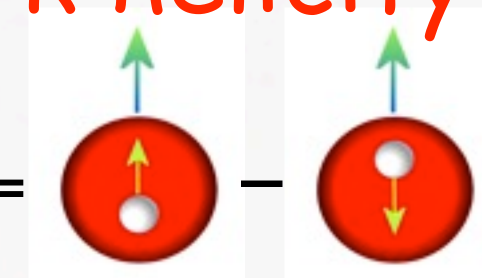
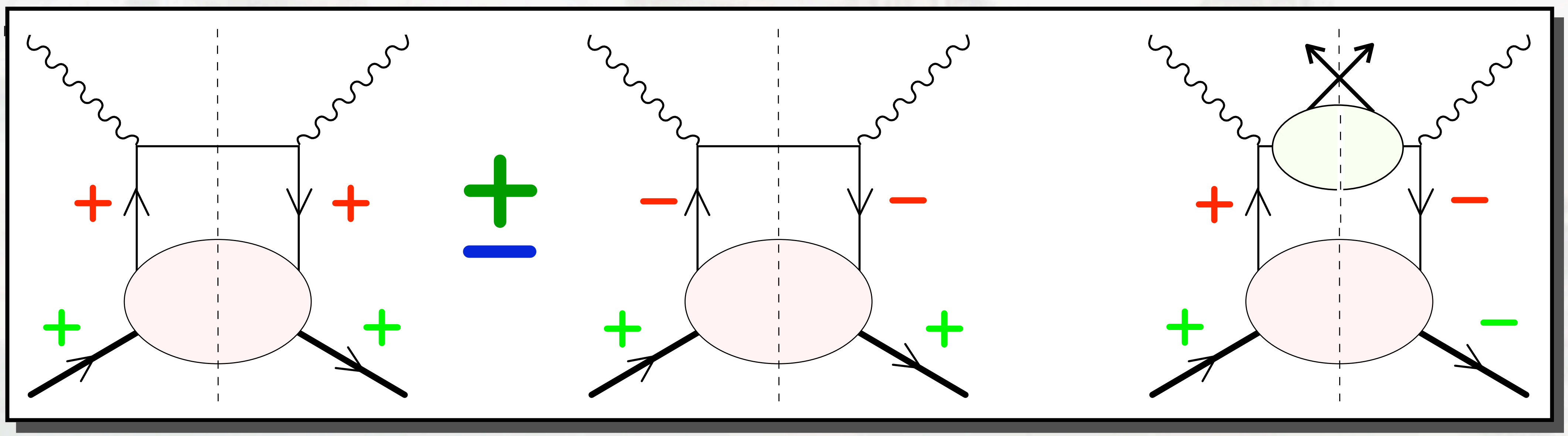
Transversity distribution

chiral-odd transversity involves quark helicity flip

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



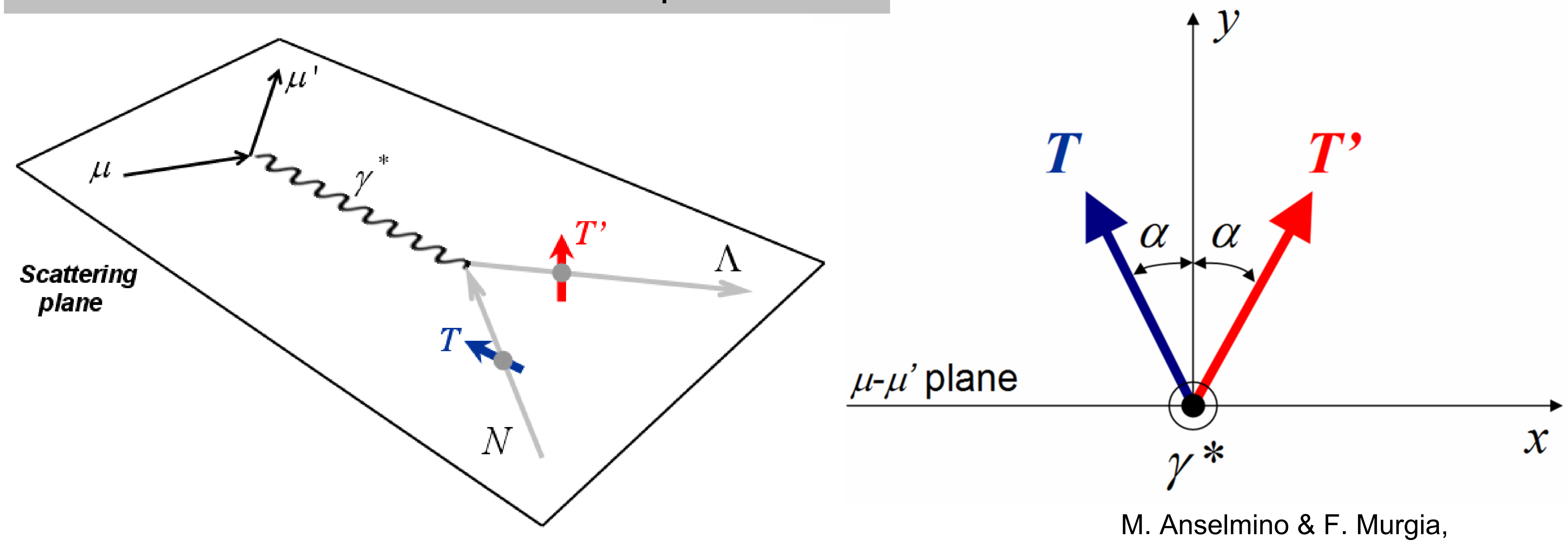
need to couple to chiral-odd fragmentation function:

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

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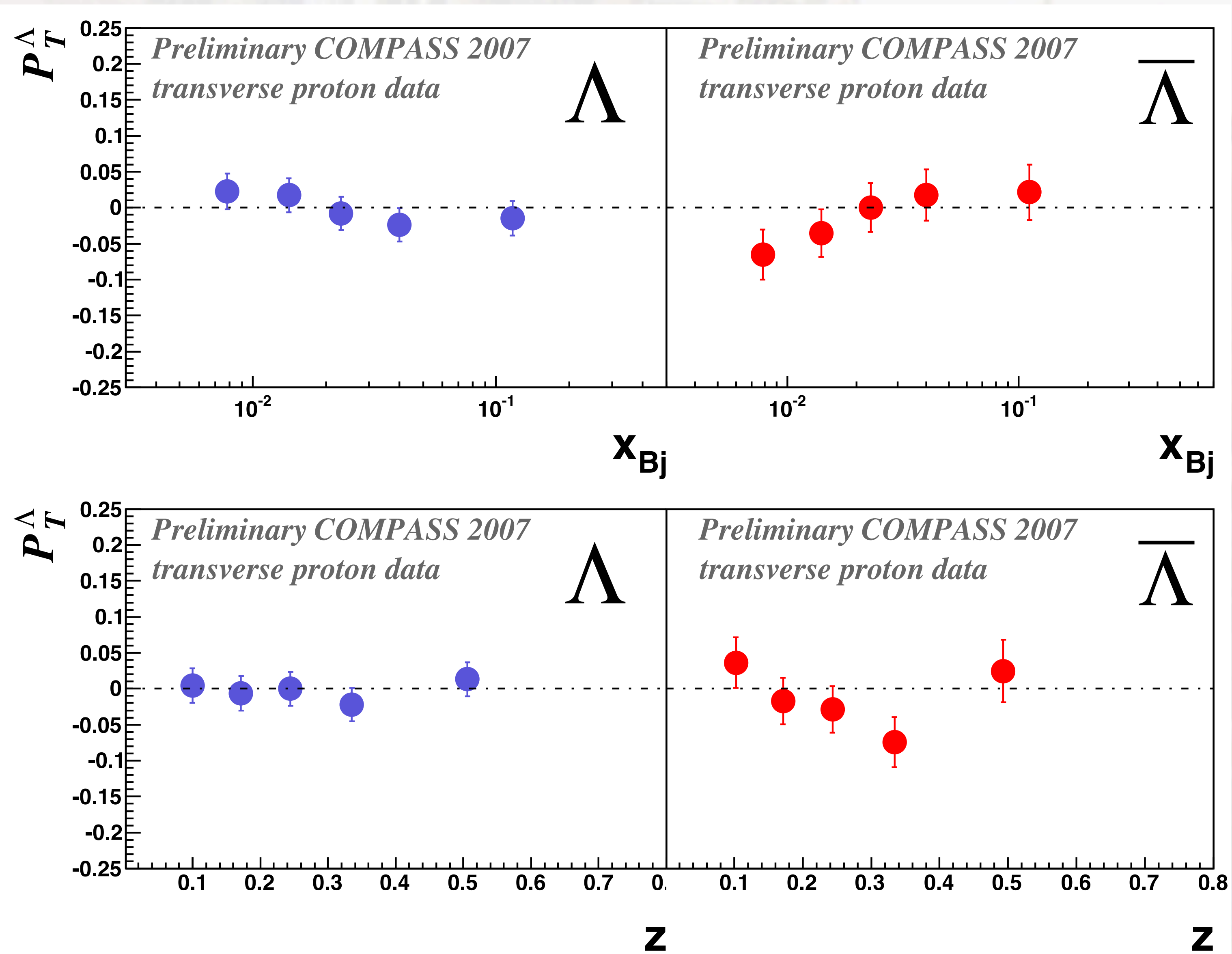
Transversity distribution (transverse-spin transfer)



- 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
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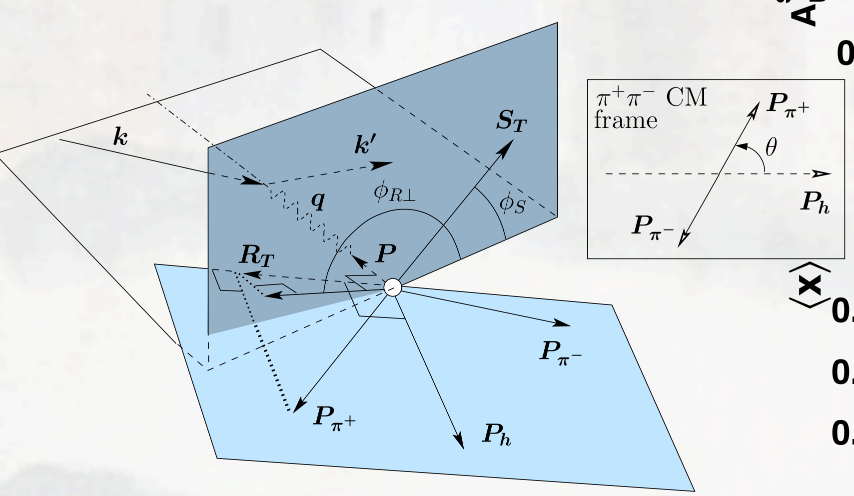
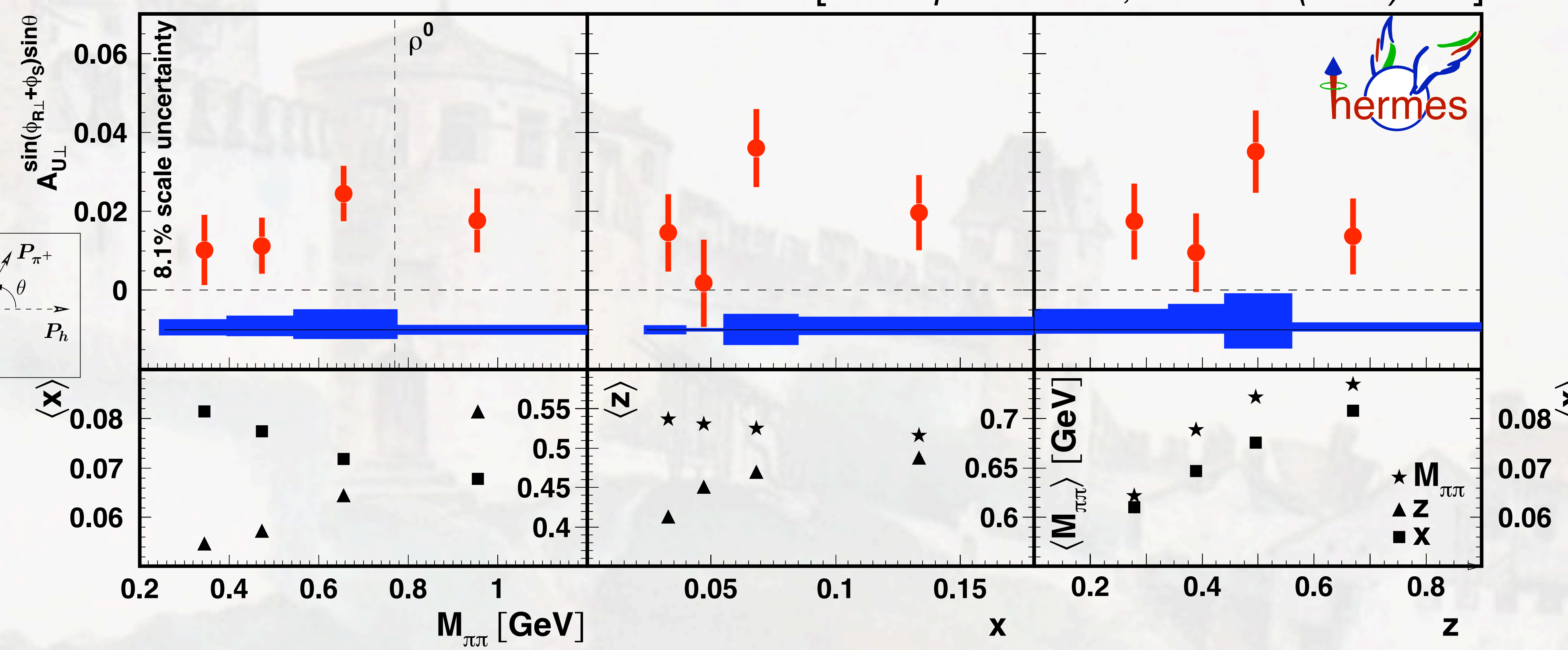
- better sensitivity to u and d quarks via charged Sigma's

	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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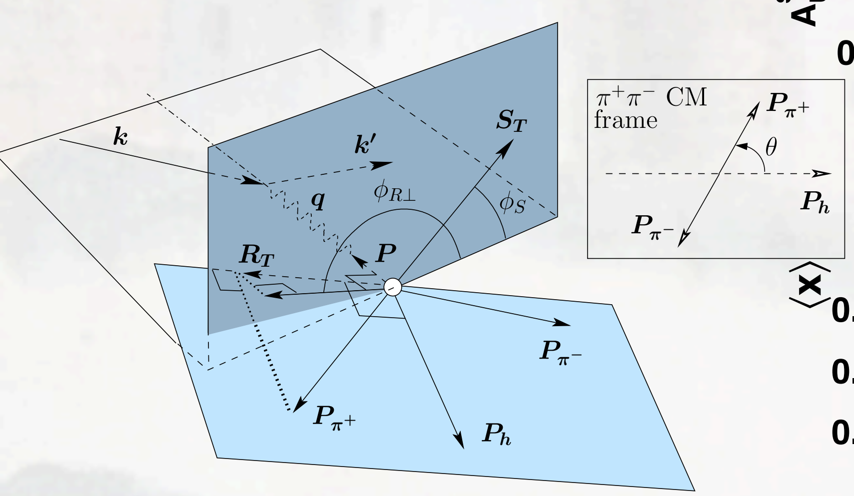
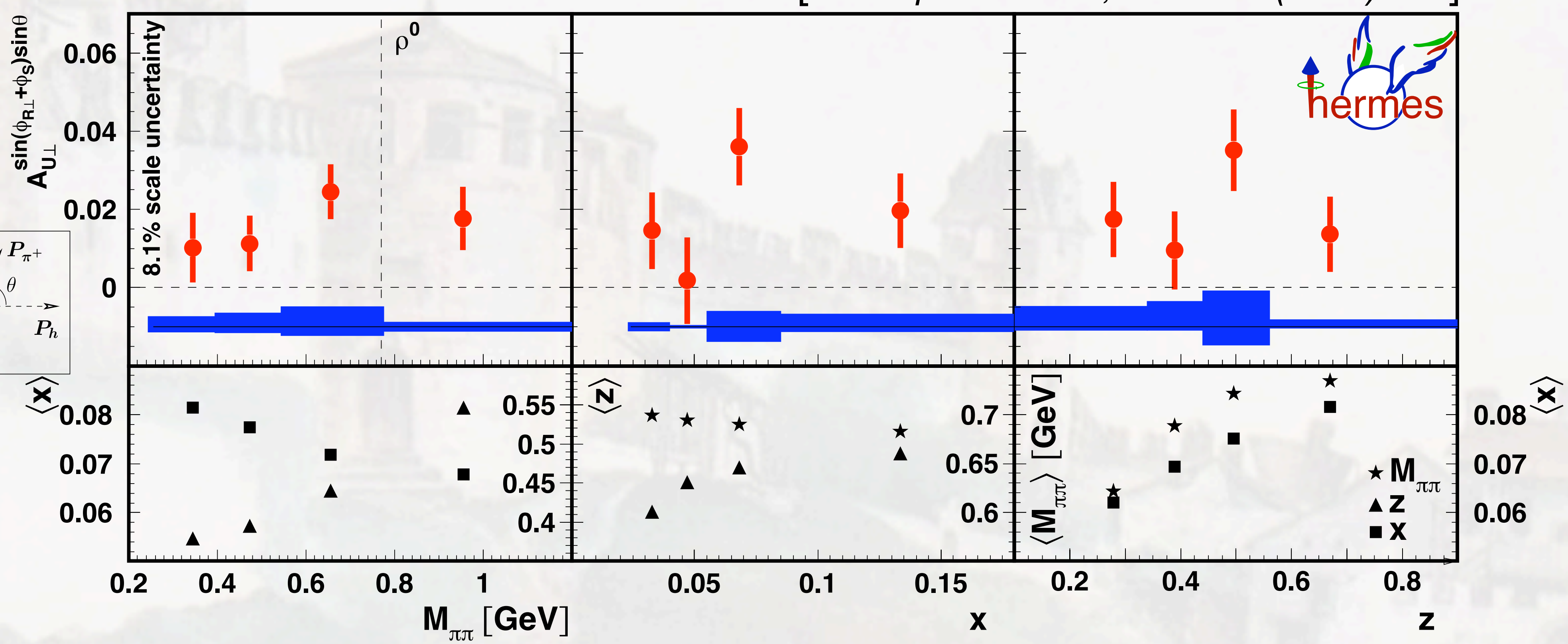


[A. Airapetian et al., JHEP 06 (2008) 017]



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

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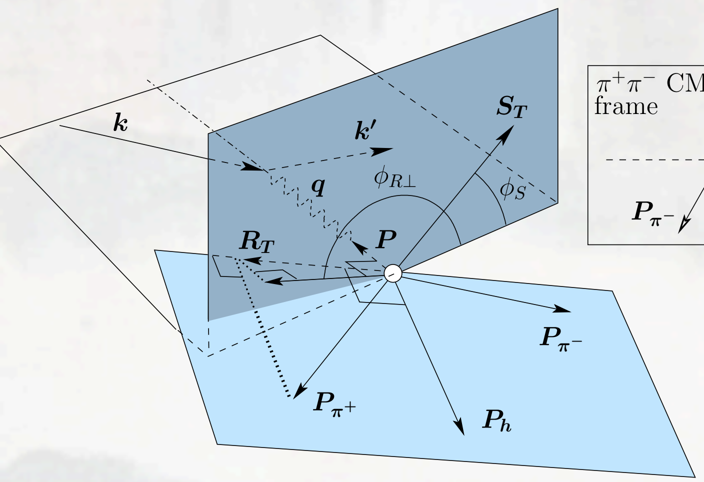

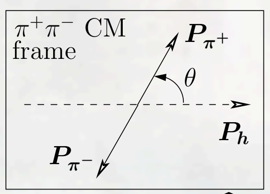

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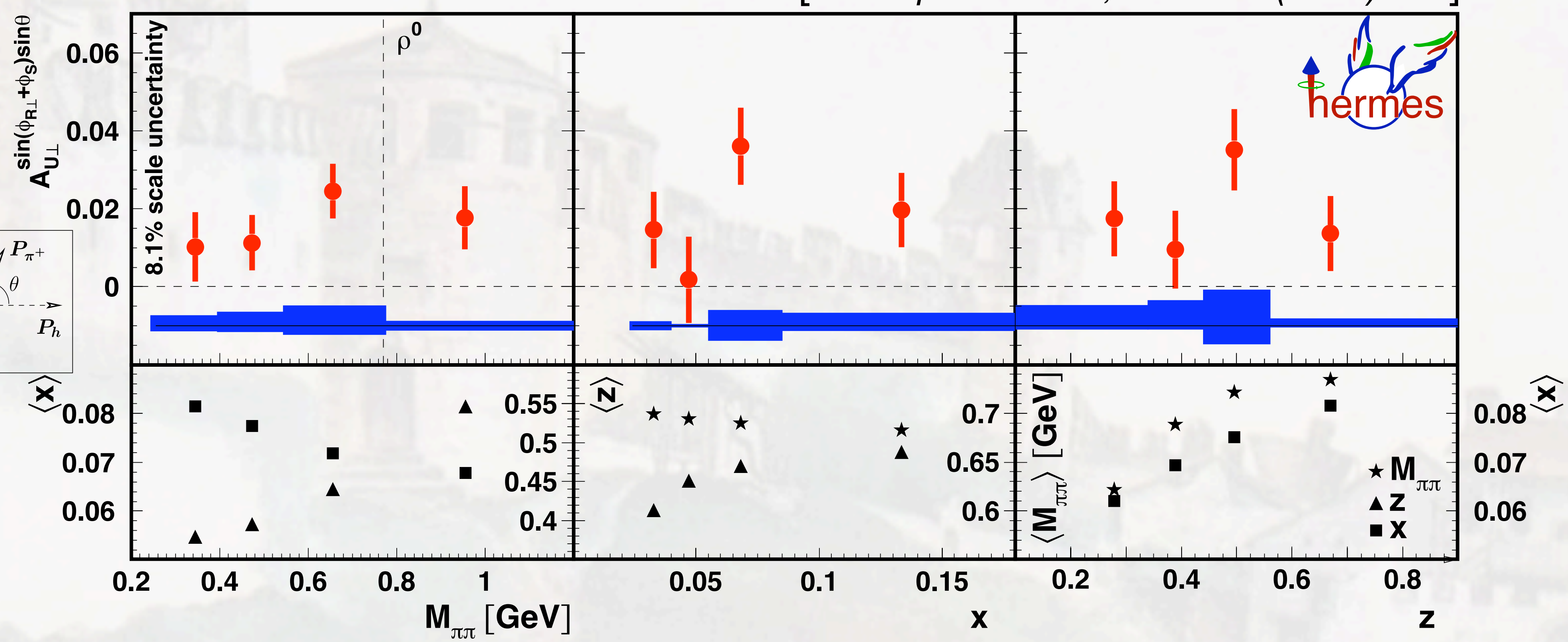

☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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

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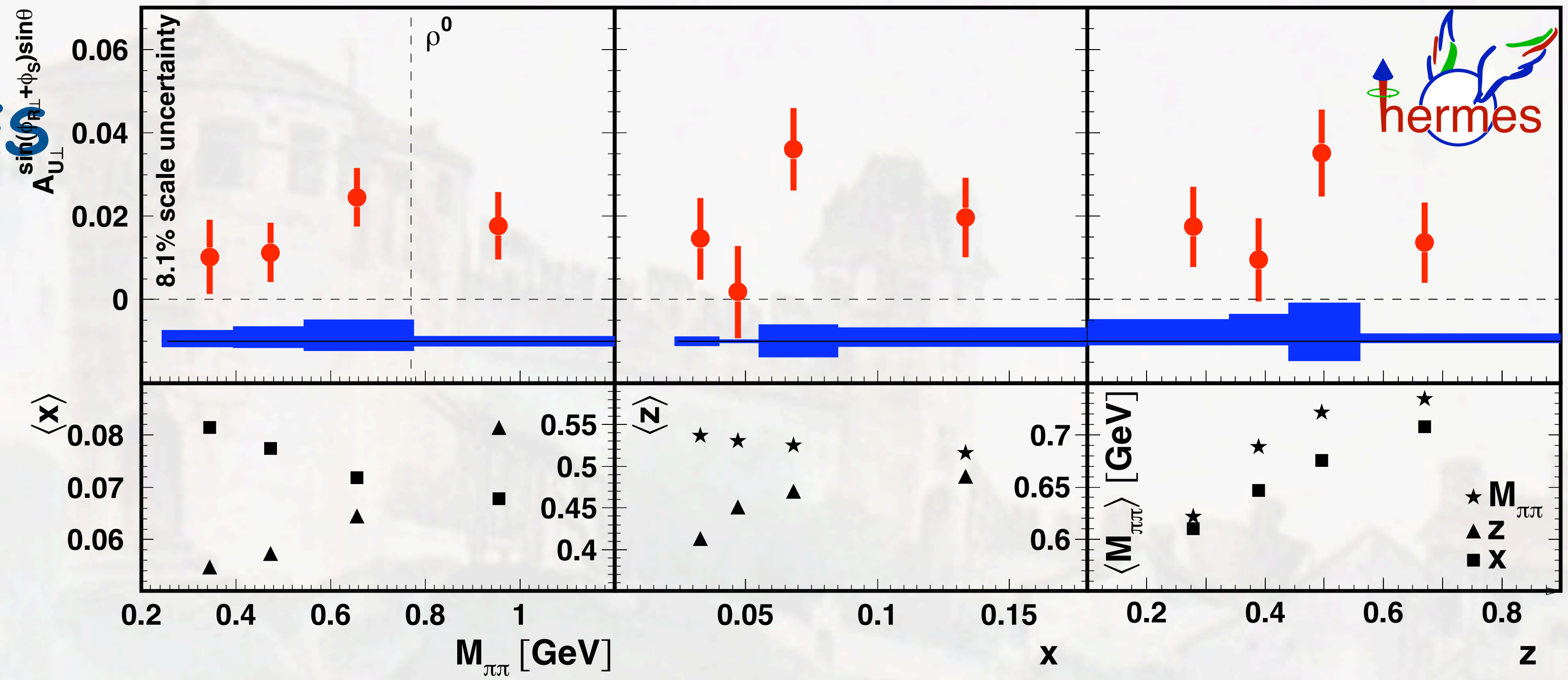
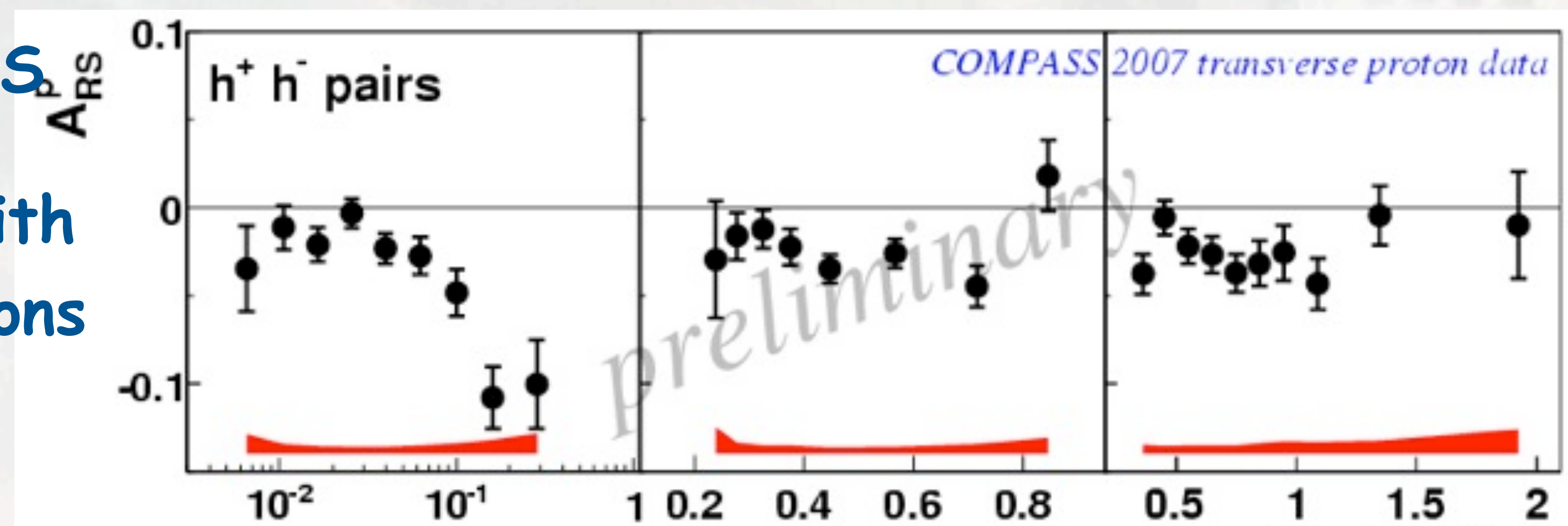
Transversity distribution (2-hadron fragmentation)

- 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
- data from pp consistent with zero but dominated by gluons
- first results from e^+e^- by BELLE





☛ H. Wollny

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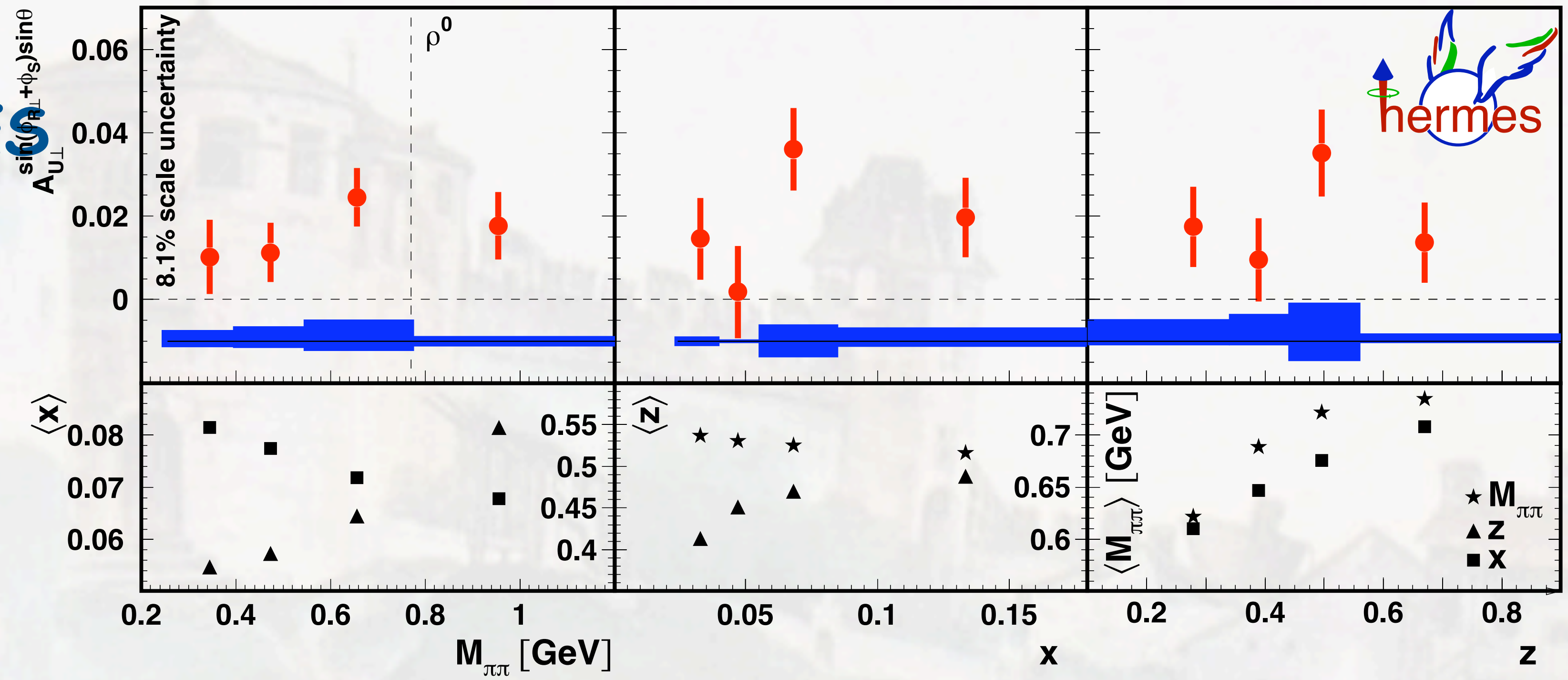

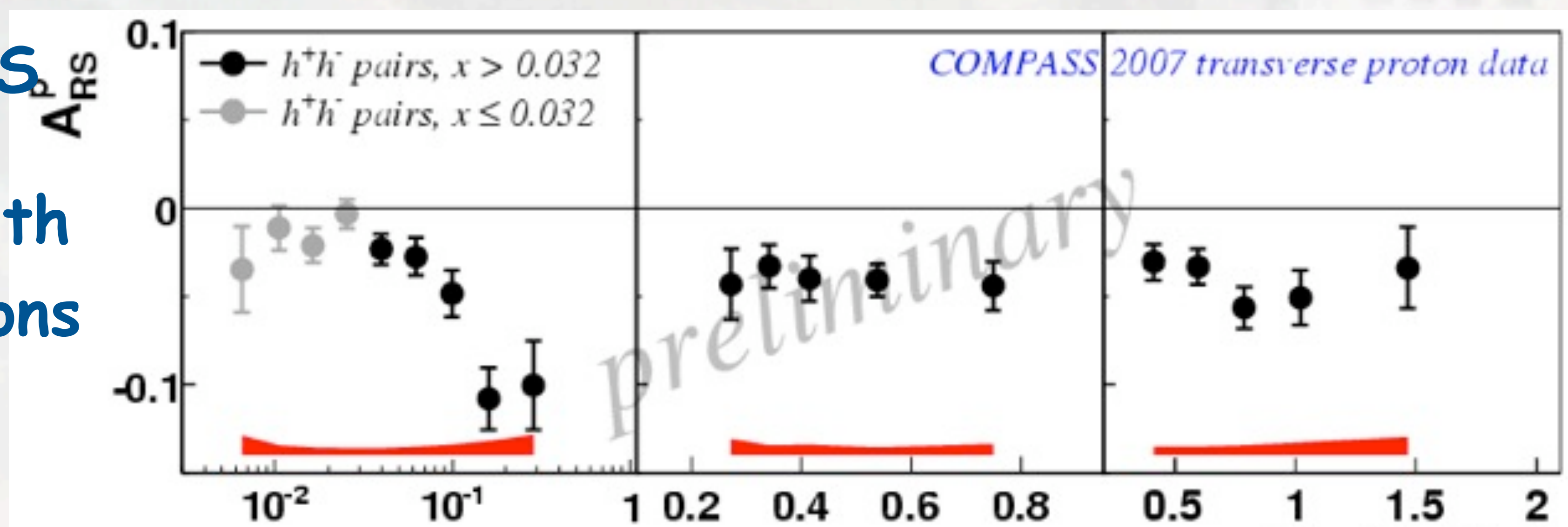

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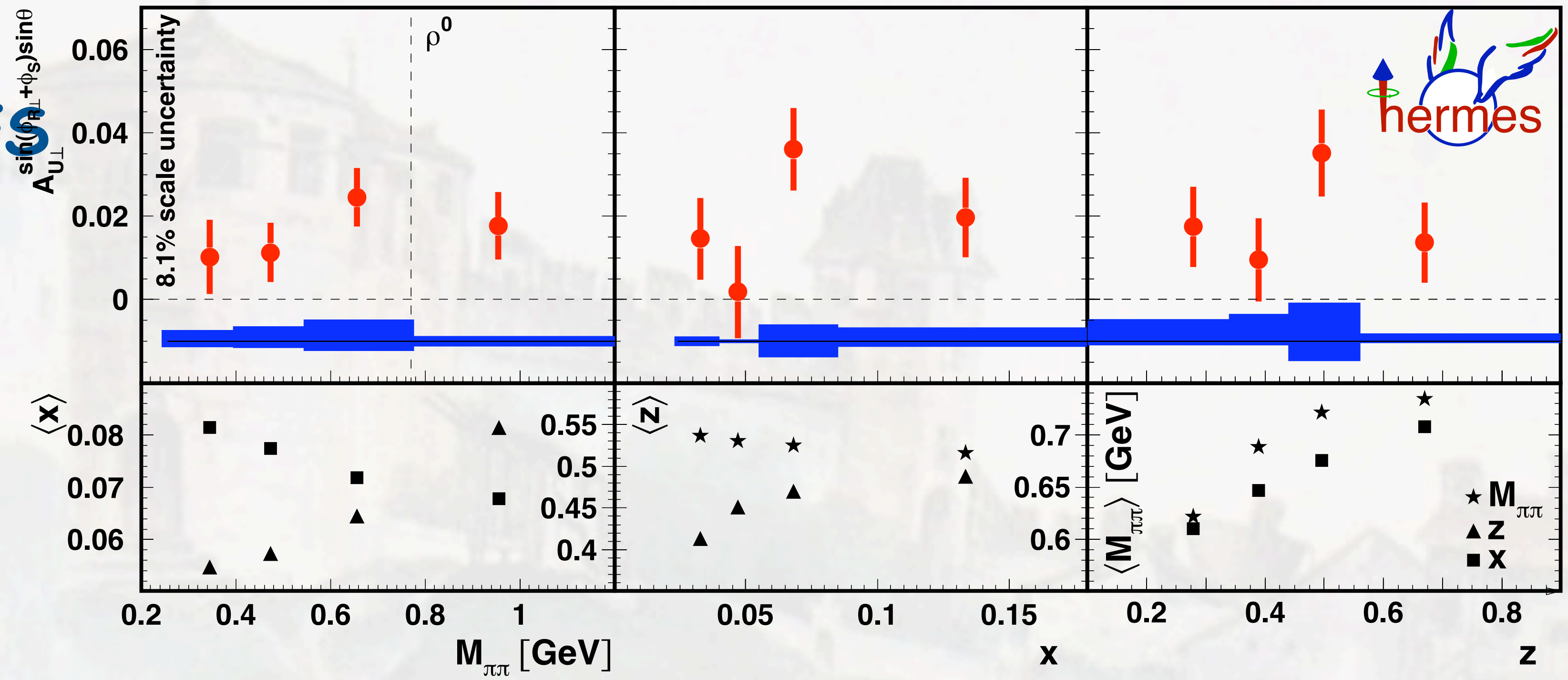

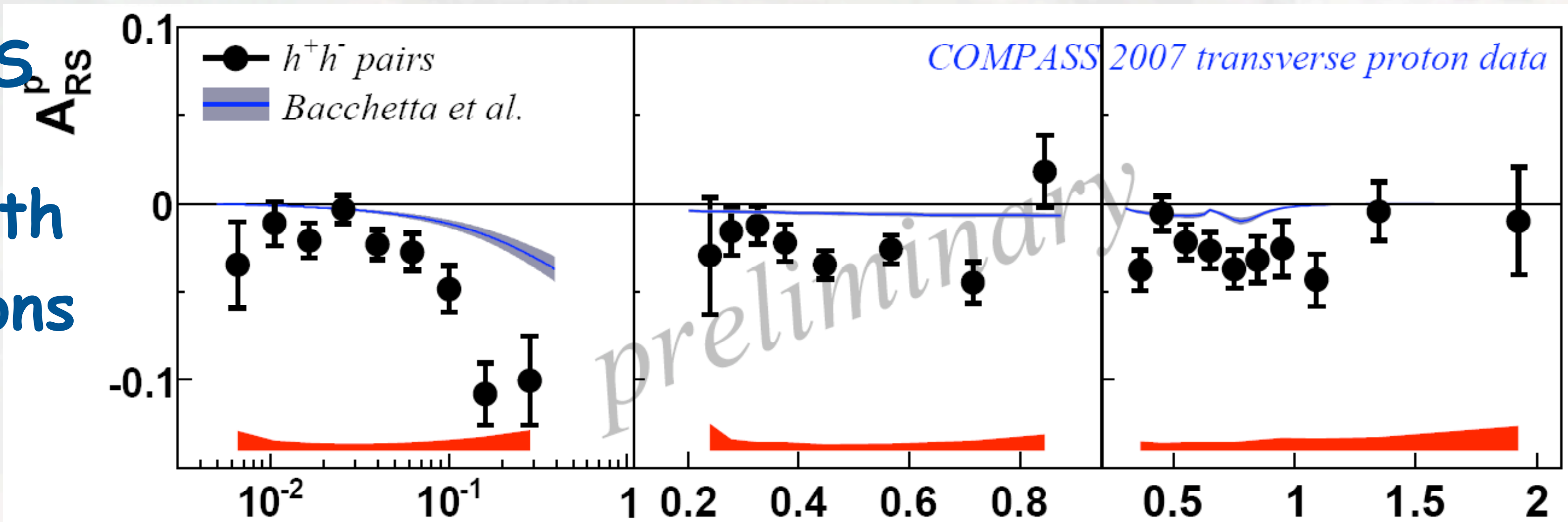

☛ H. Wollny

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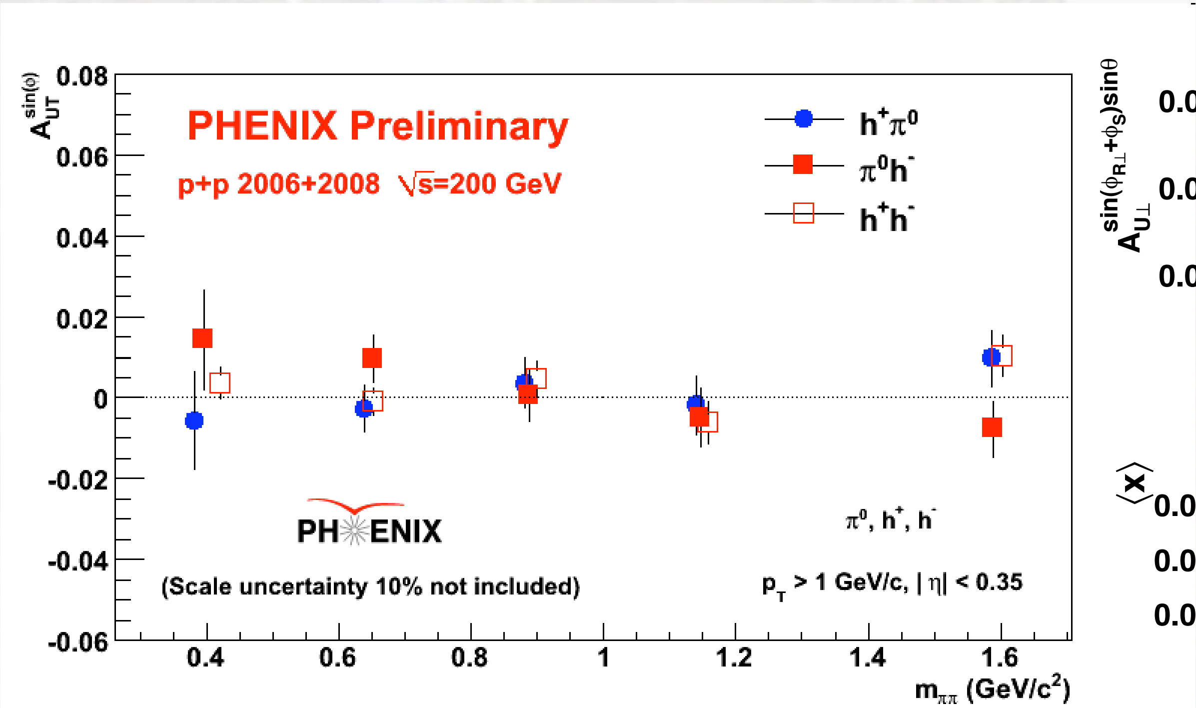

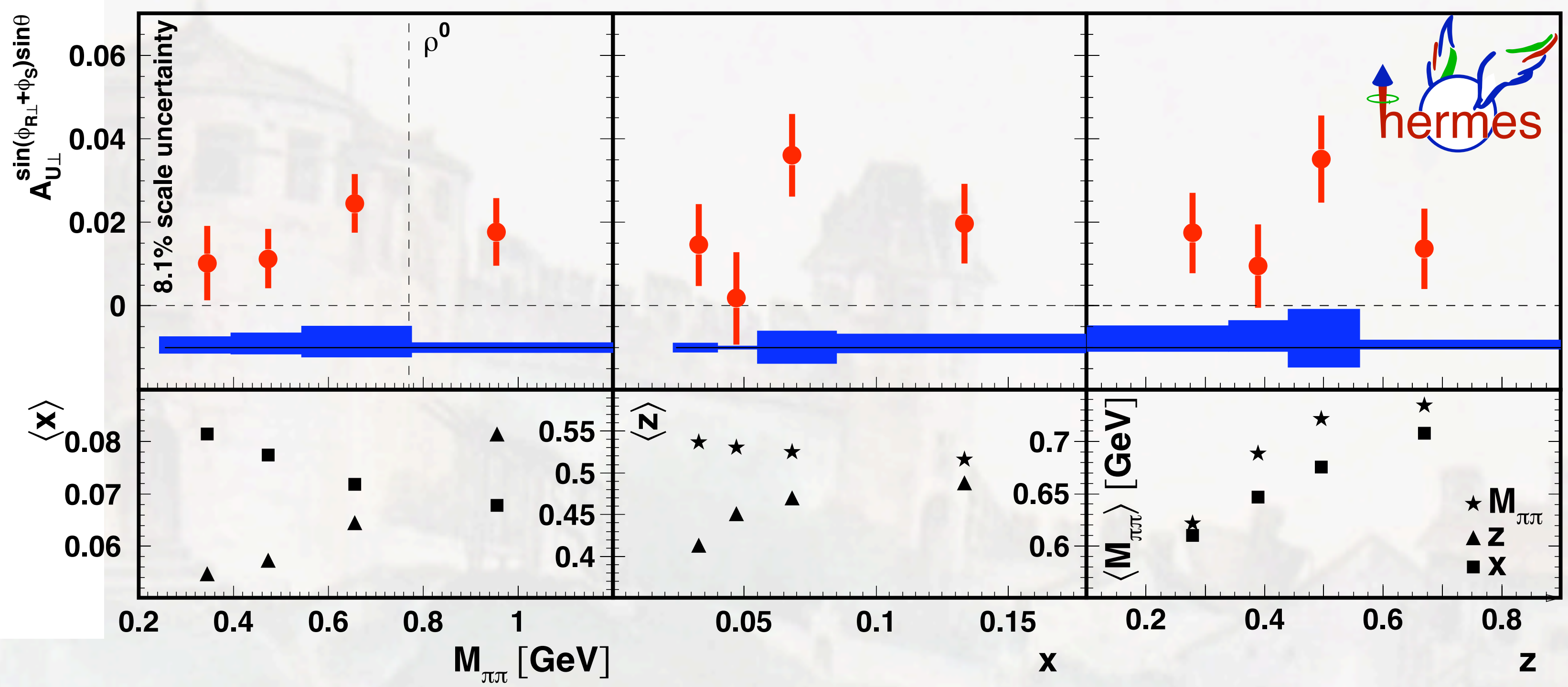

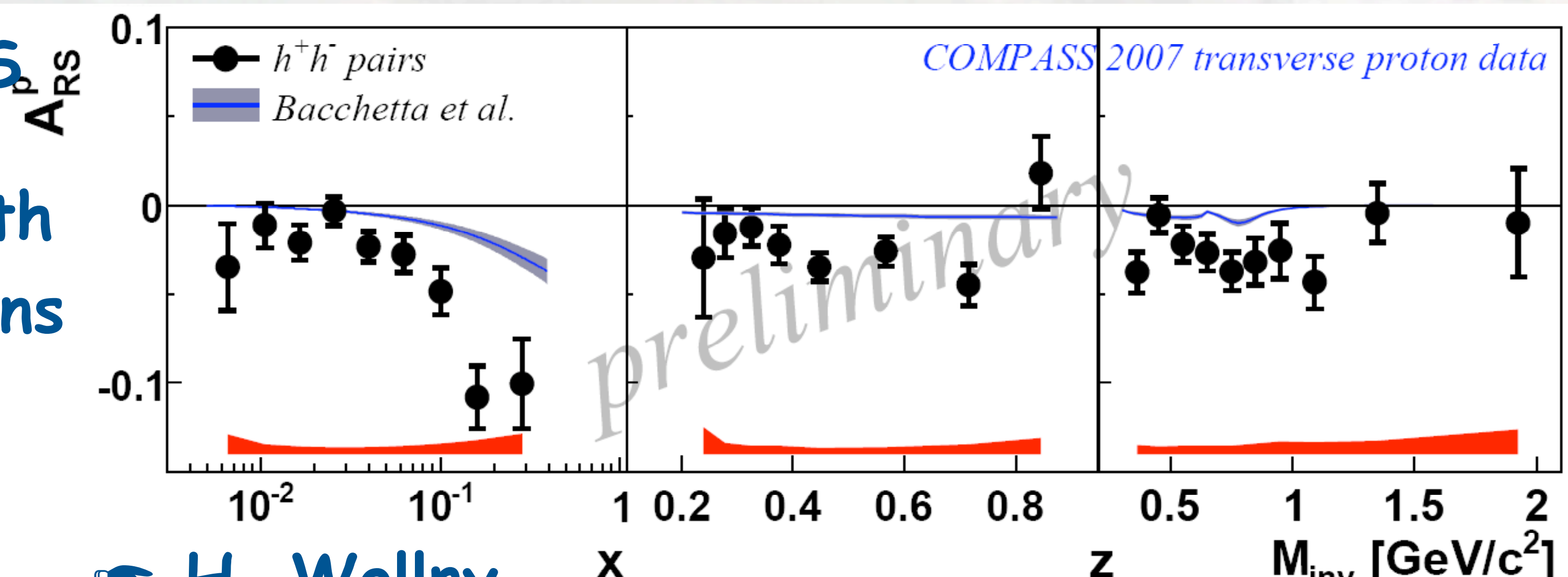

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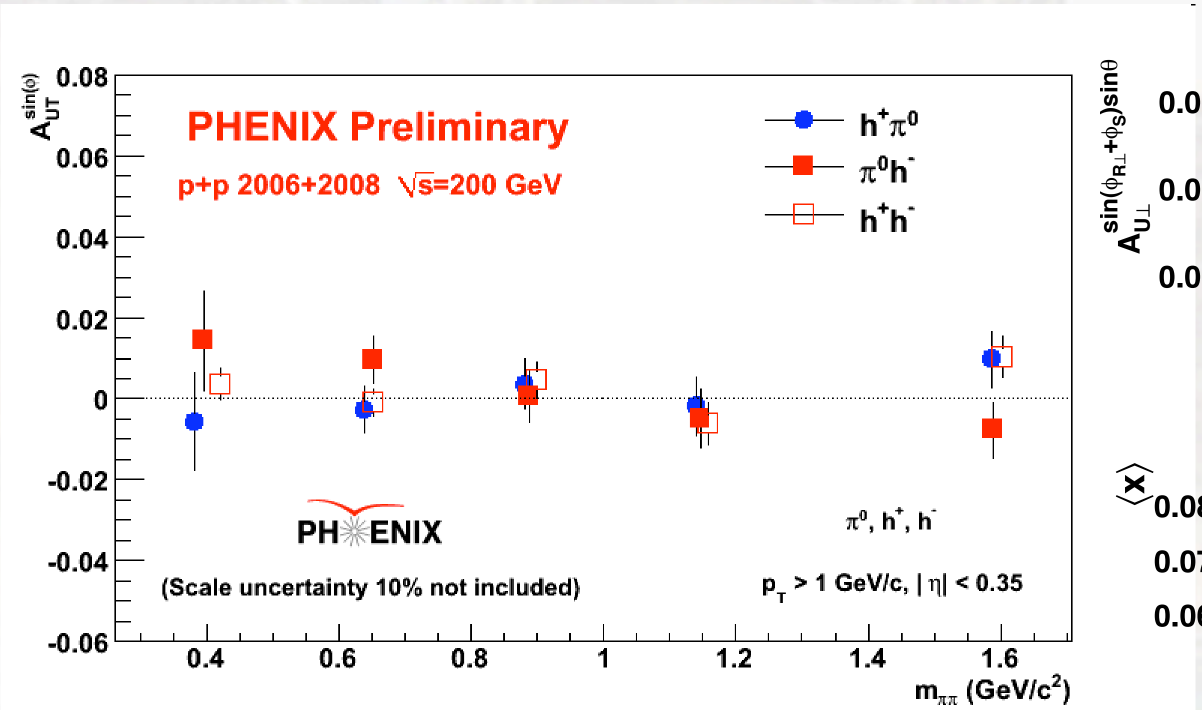
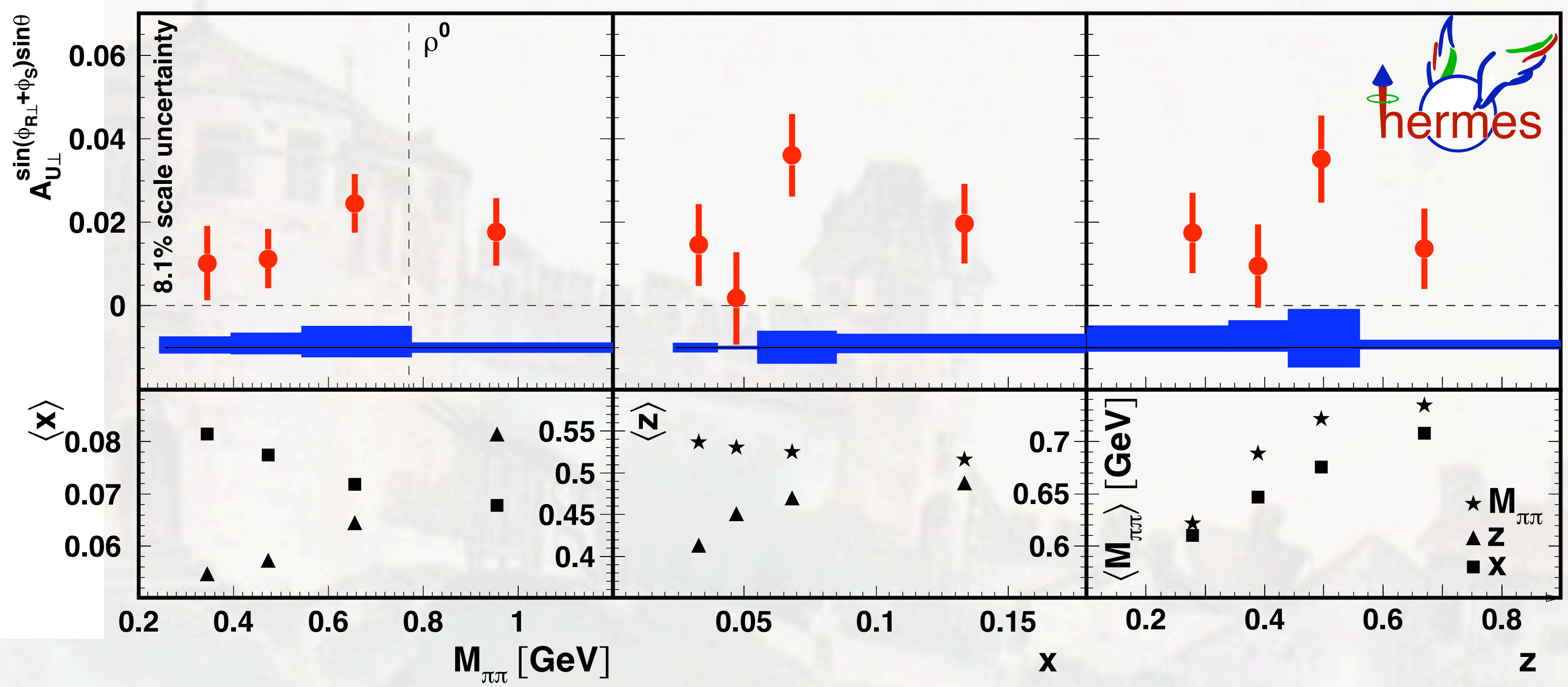
Transversity distribution (2-hadron fragmentation)





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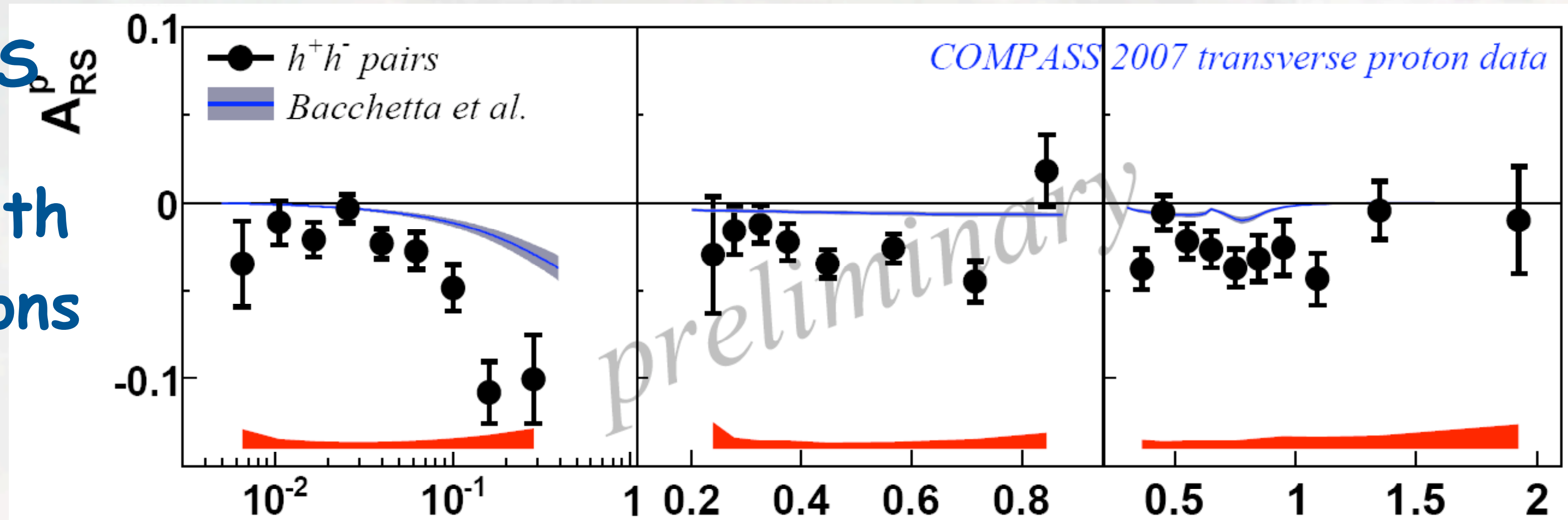

☛ H. Wollny

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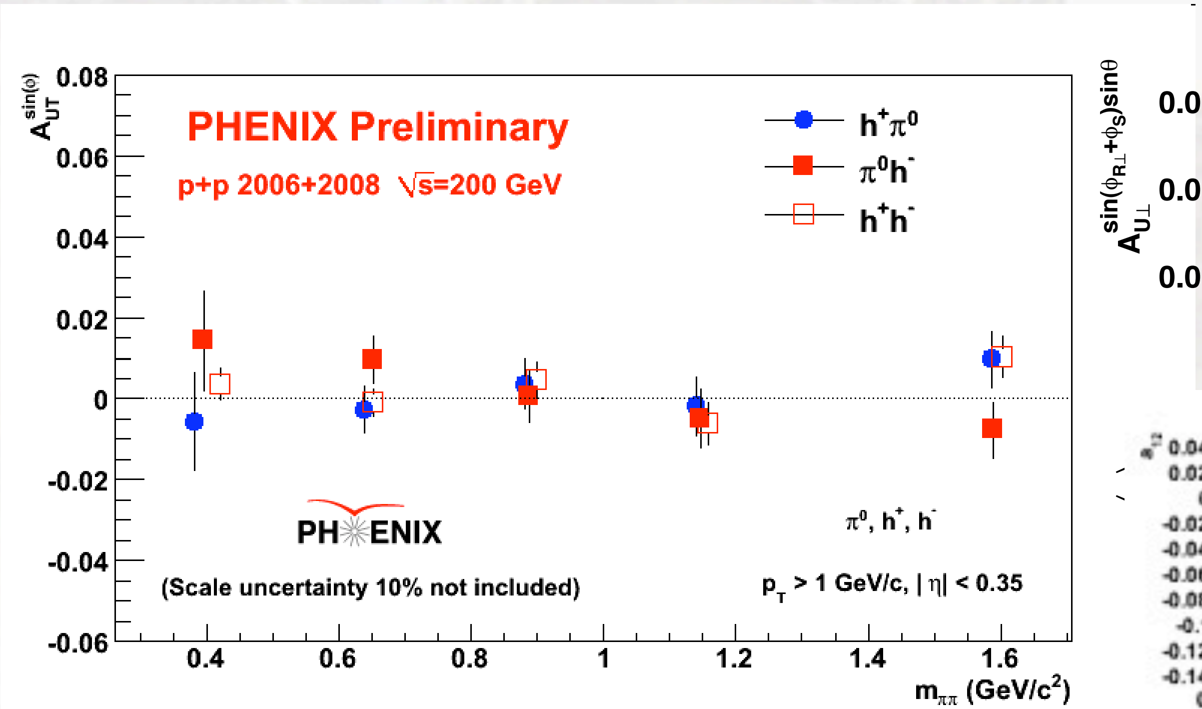
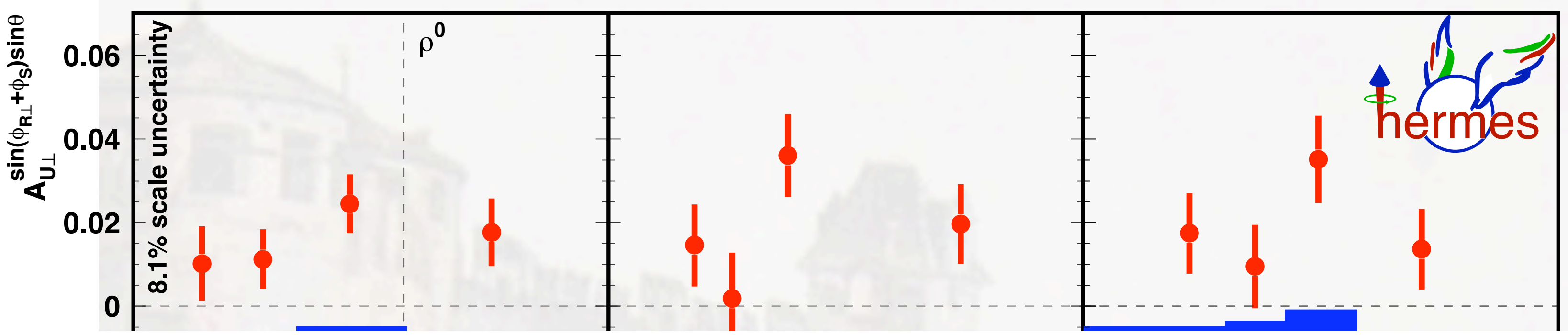
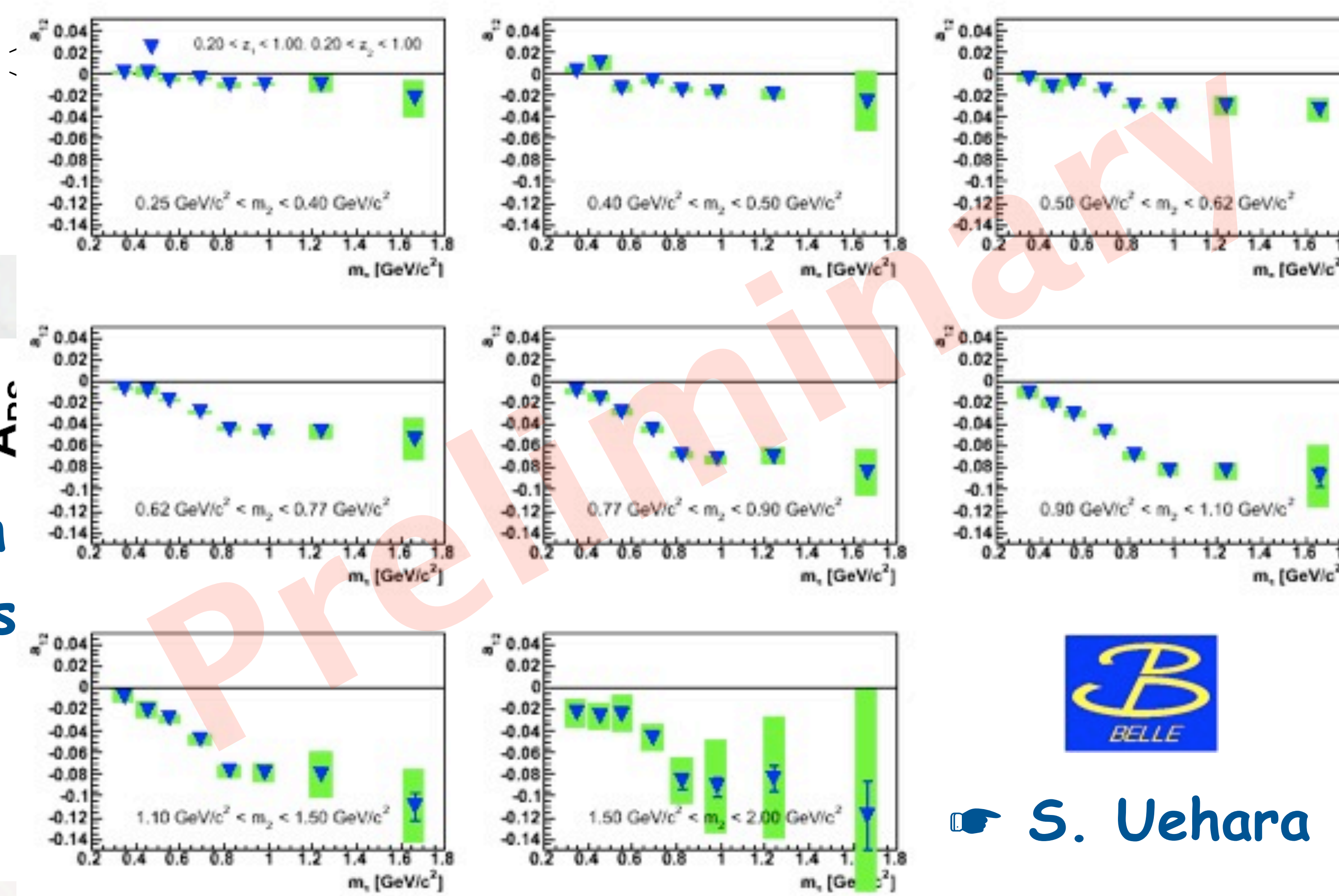
Transversity distribution (2-hadron fragmentation)







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☛ S. Uehara

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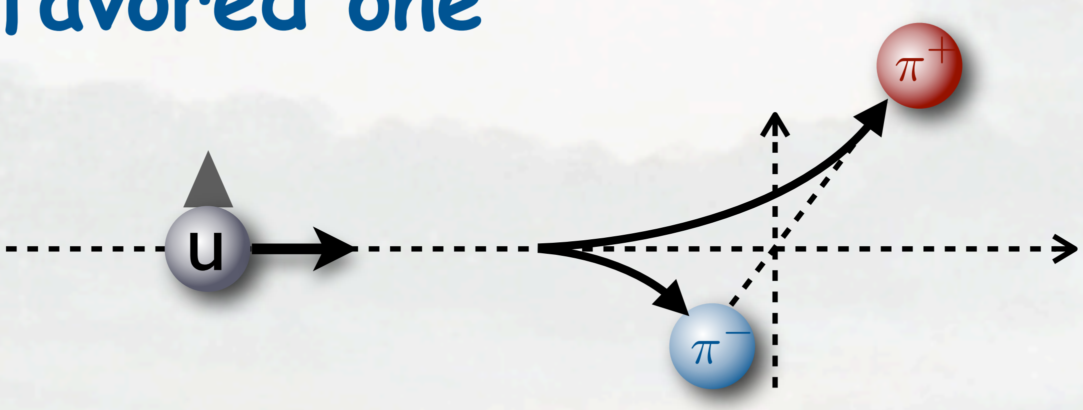
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

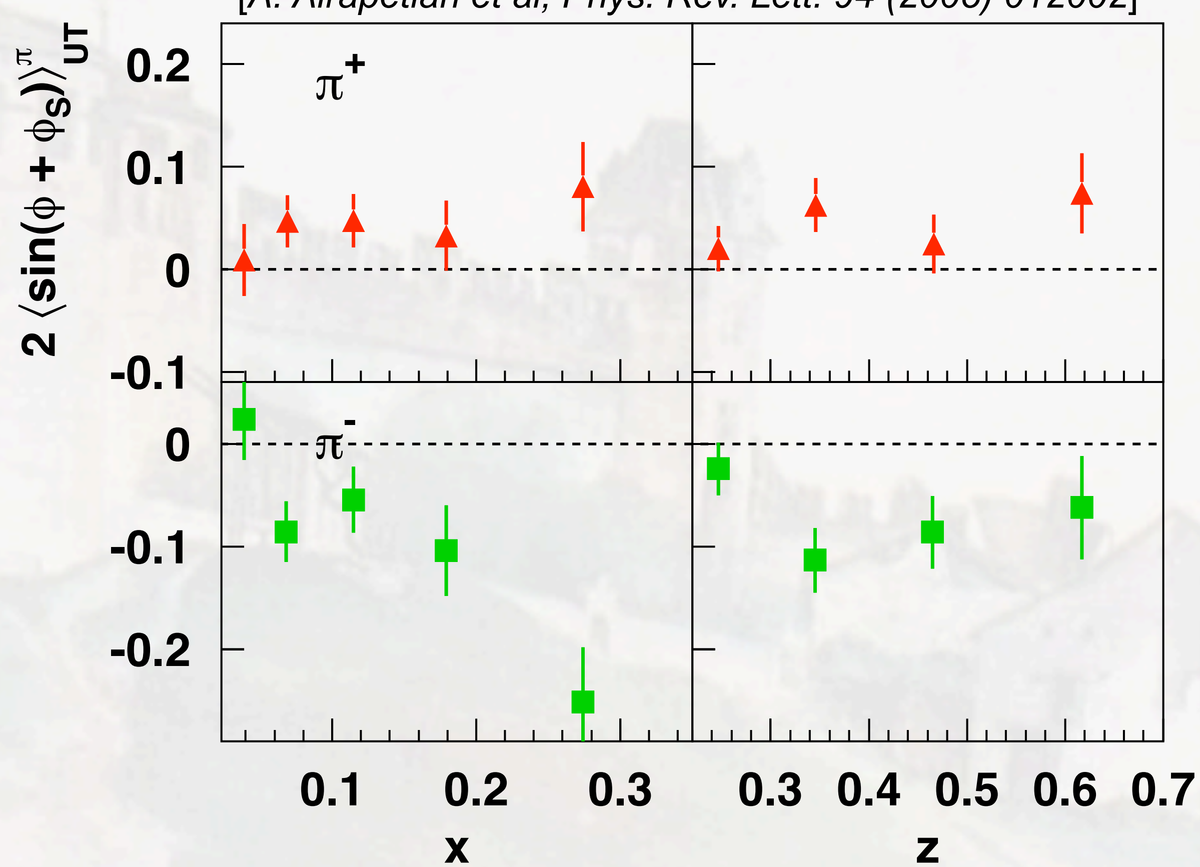
Transversity distribution (Collins fragmentation)

- 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

[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

Fit of Collins amplitudes

	U	L	T
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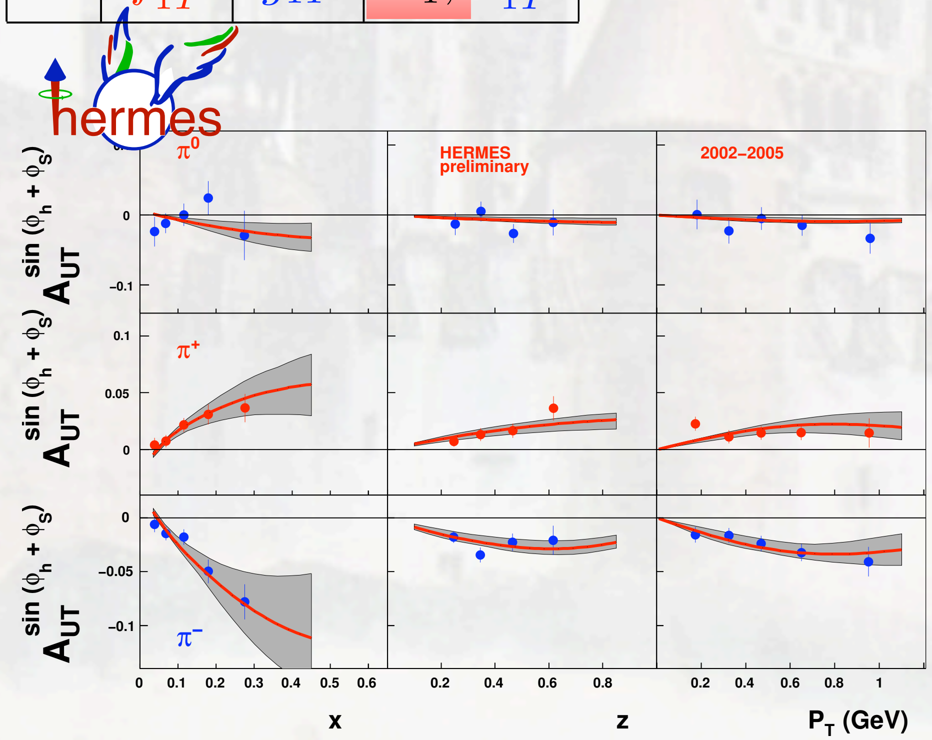
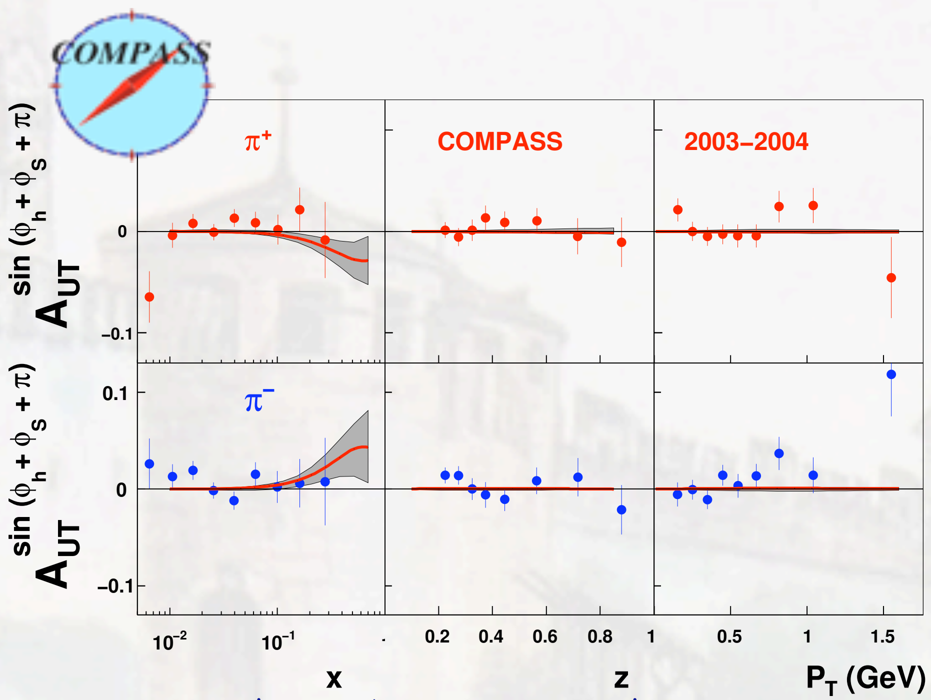
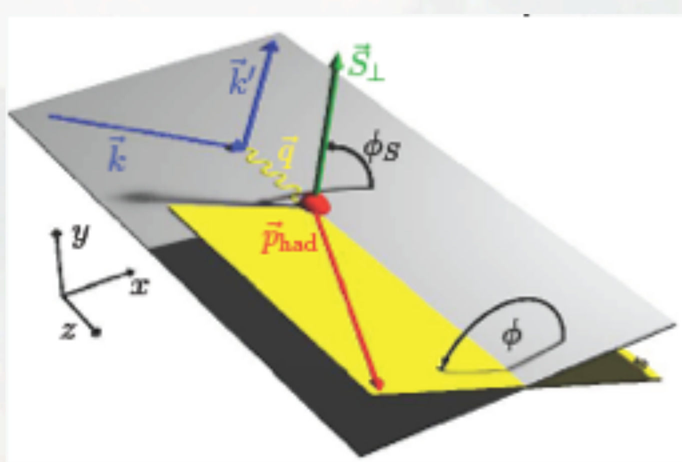


$$e^\pm p^\uparrow \rightarrow e^\pm \pi X$$



$$\mu^\pm d^\uparrow \rightarrow \mu^\pm \pi X$$



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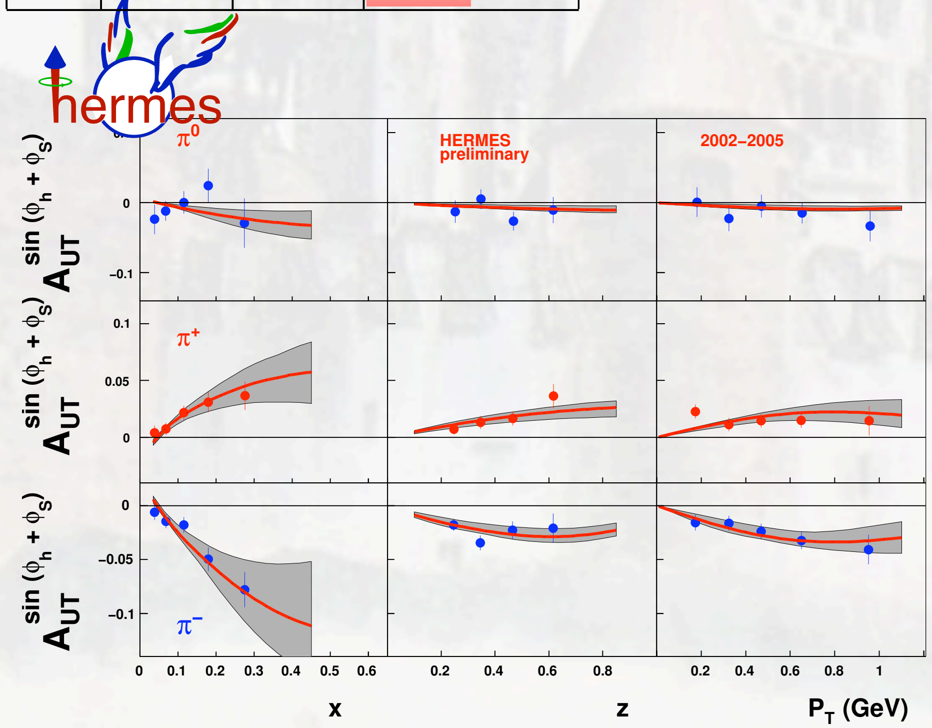
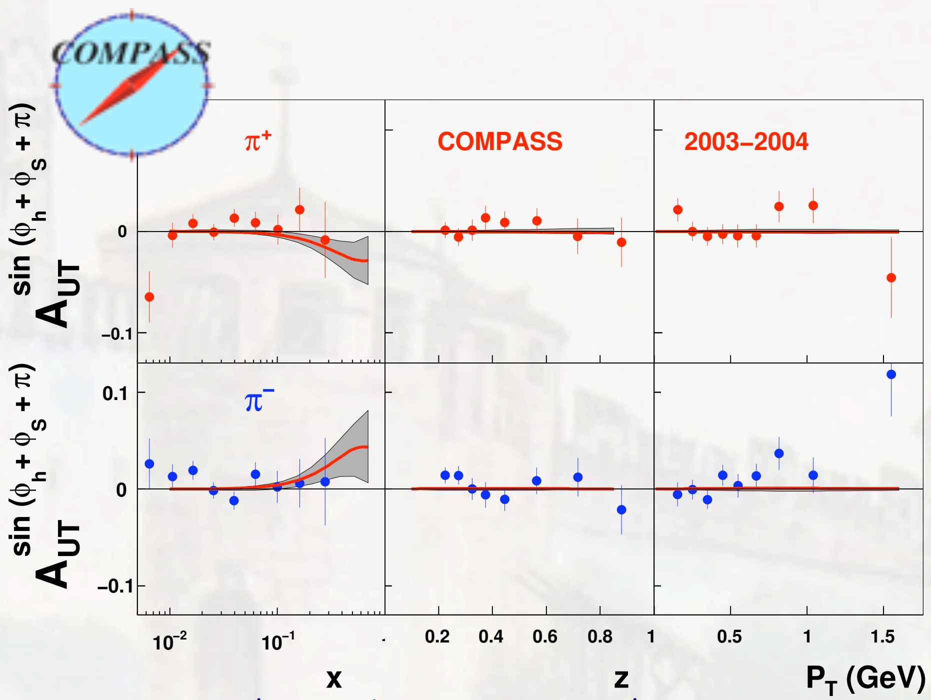
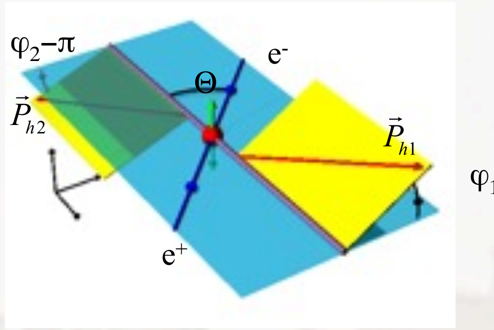
Fit of Collins amplitudes



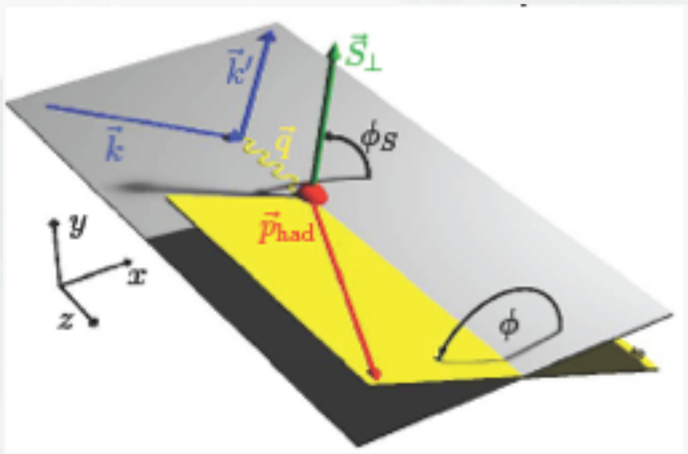


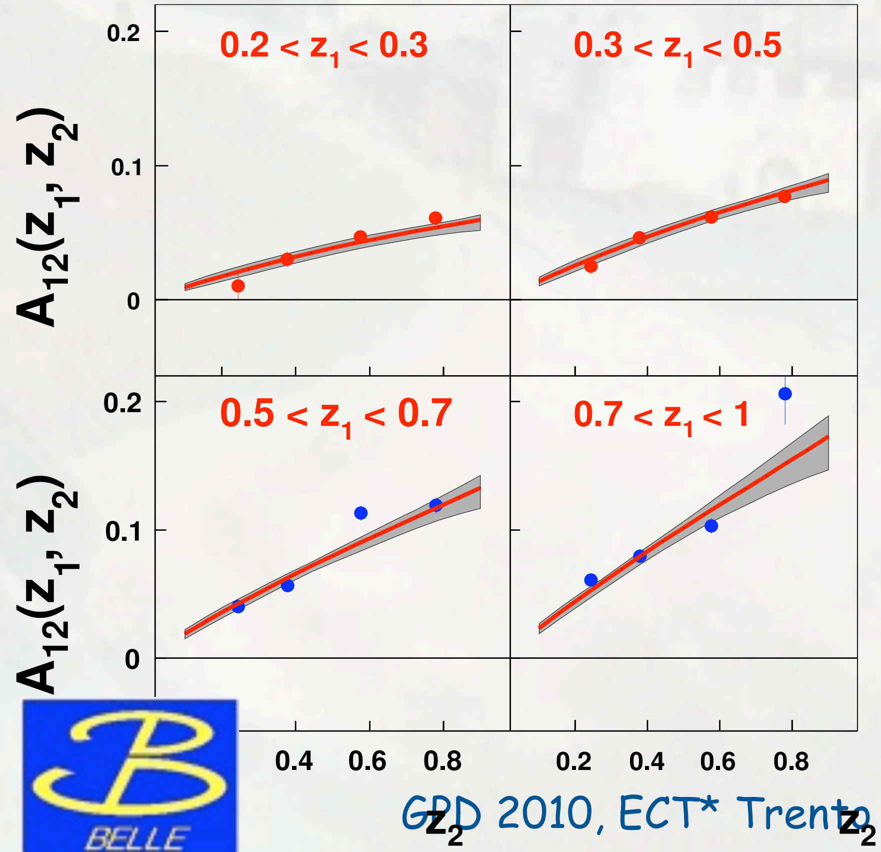


$$\mathbf{e^\pm p^\uparrow \rightarrow e^\pm \pi X}$$

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

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





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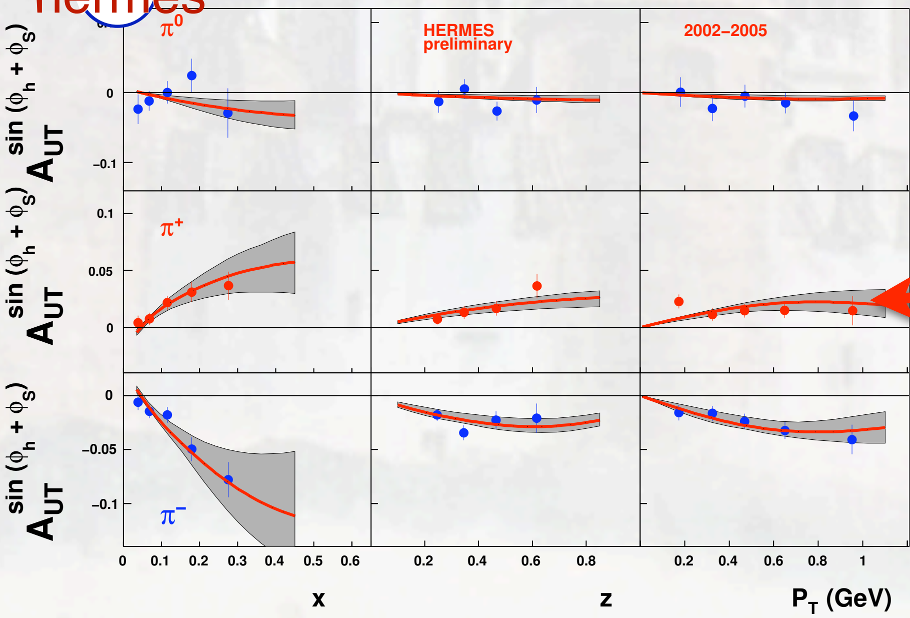
Fit of Collins amplitudes

☛ M. Anselmino

fit to data



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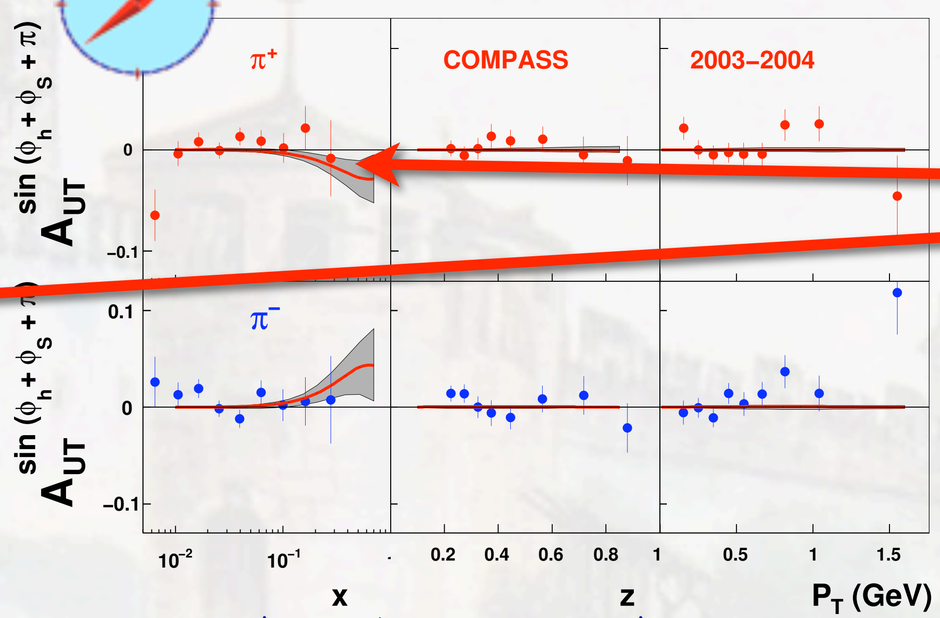
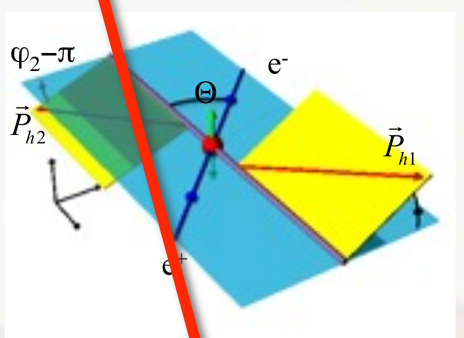
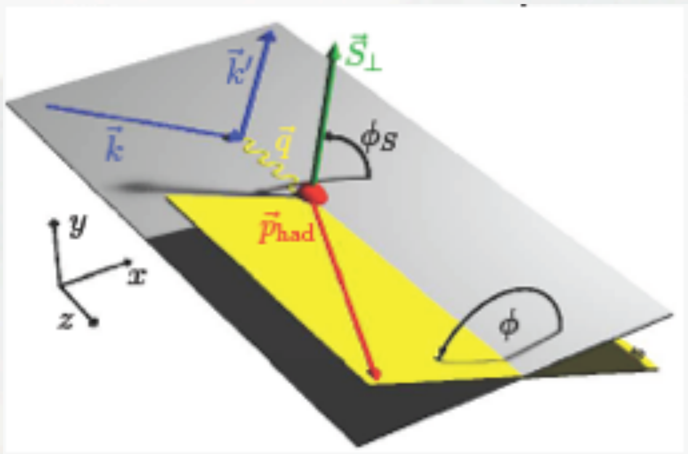
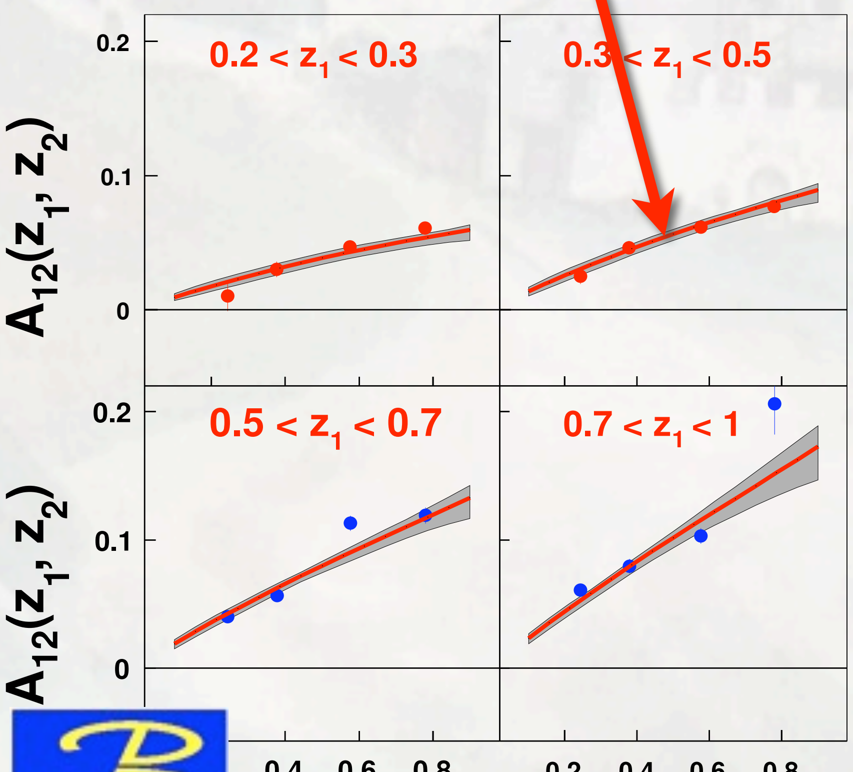


$$\mu^\pm d^\uparrow \rightarrow \mu^\pm \pi X$$



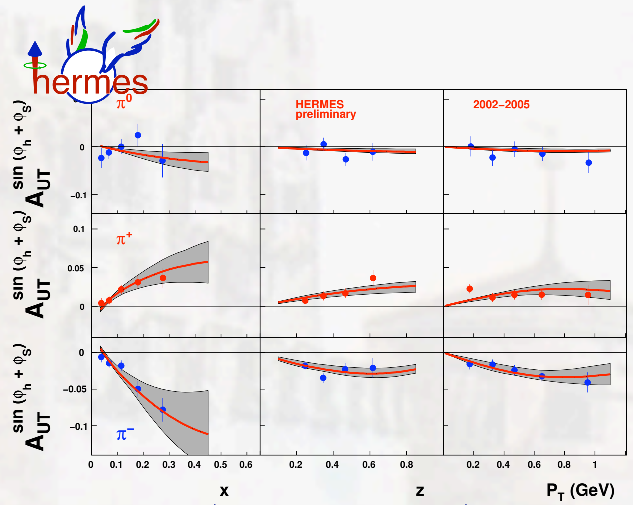
$$e^+e^- \rightarrow \pi\pi X$$



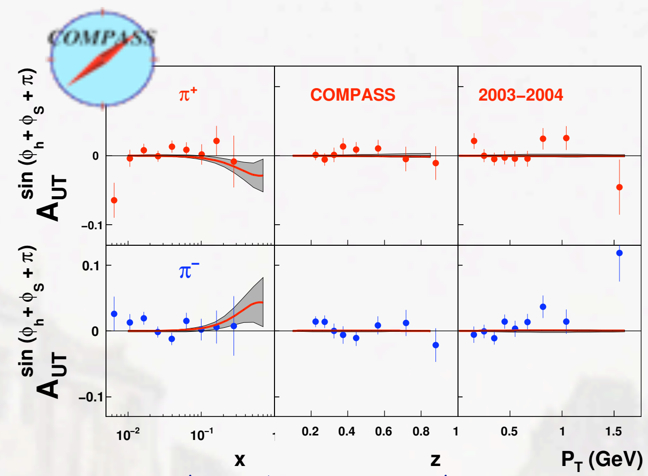


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Fit of Collins amplitudes



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

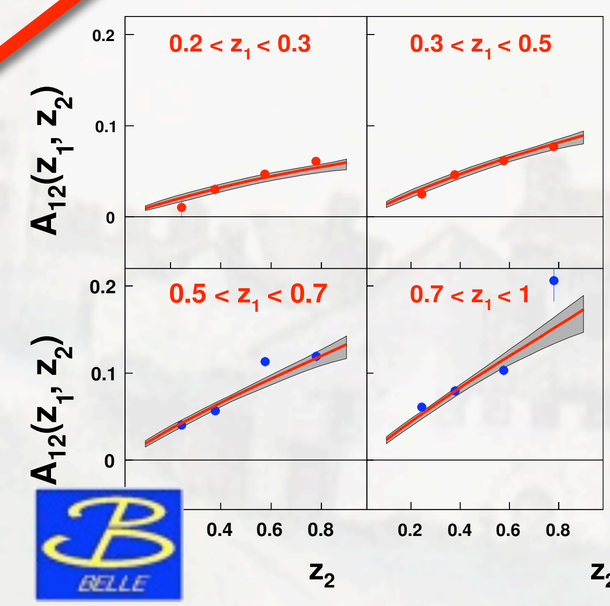


$$\mathbf{\mu^\pm d^\uparrow \to \mu^\pm \pi X}$$

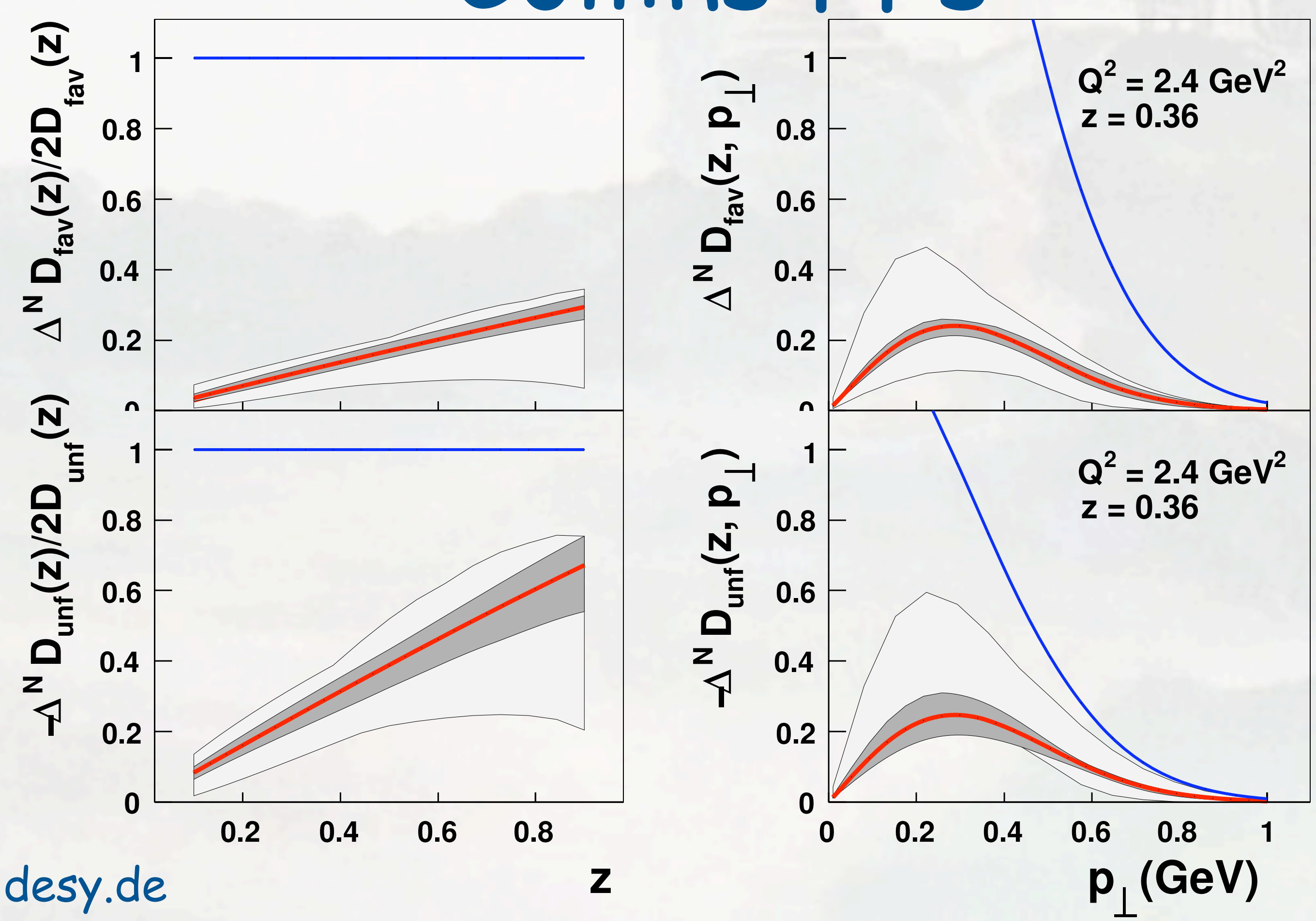
☛ M. Anselmino

fit to data

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



Collins FFs



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

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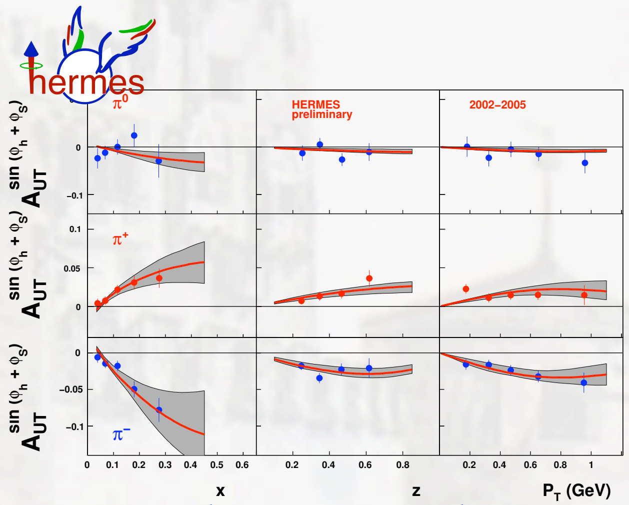
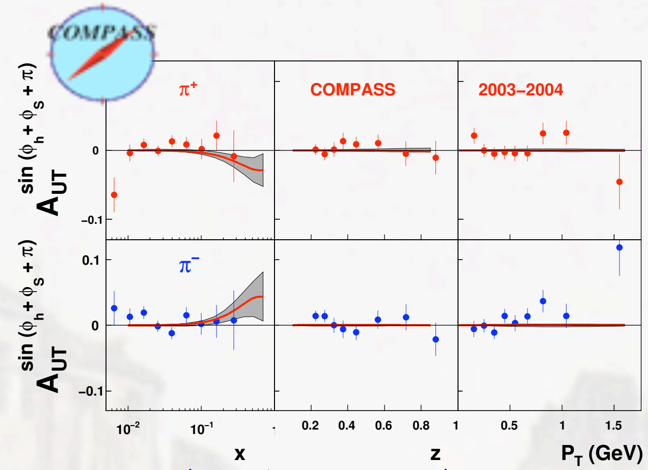


$\mathbf{e^\pm p^\uparrow \rightarrow e^\pm \pi X}$



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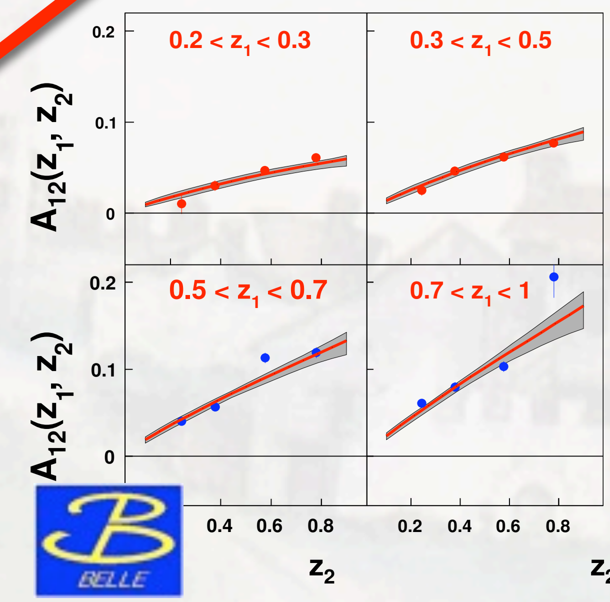
☛ M. Anselmino

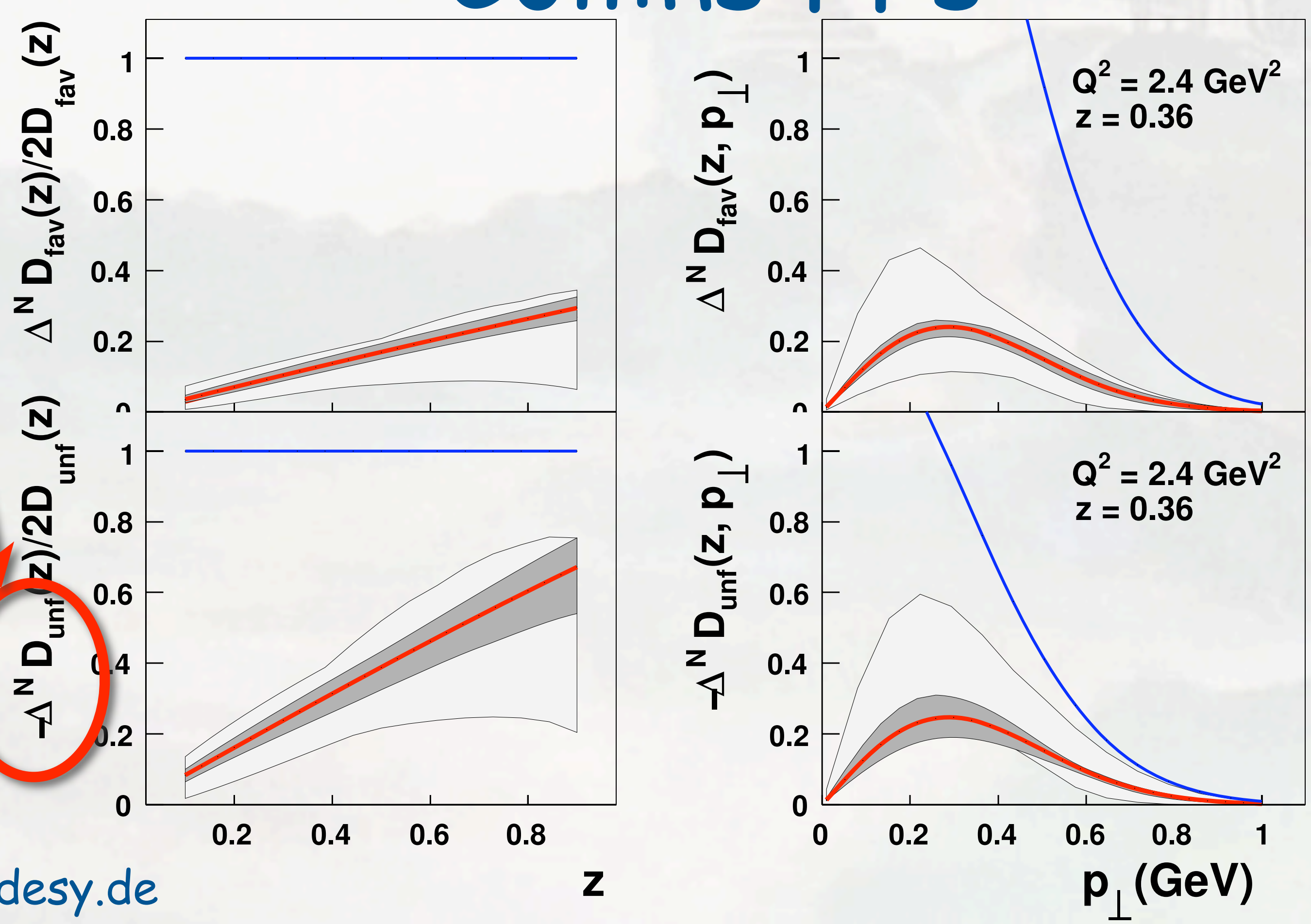
fit to data

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



opposite sign

Collins FFs



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

Fit of Collins amplitudes

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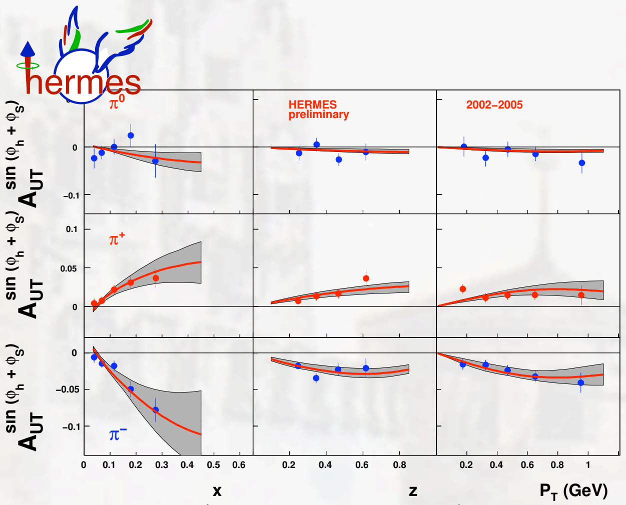
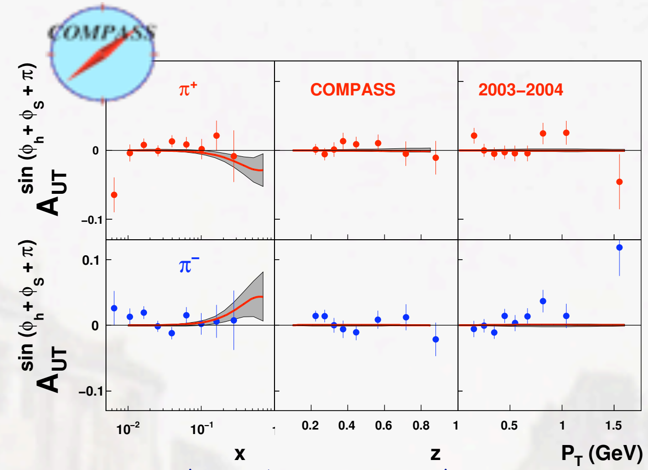


$\mathbf{e^\pm p^\uparrow \to e^\pm \pi X}$

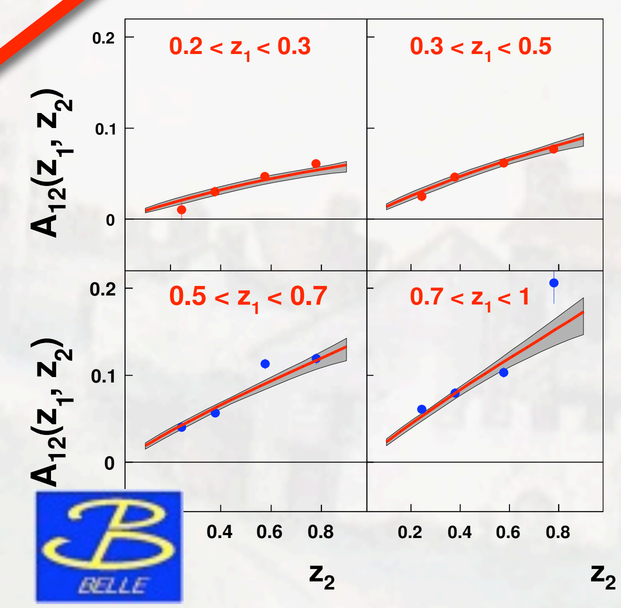


$\mu^\pm \mathbf{d}^\uparrow \to \mu^\pm \pi \mathbf{X}$

☛ M. Anselmino

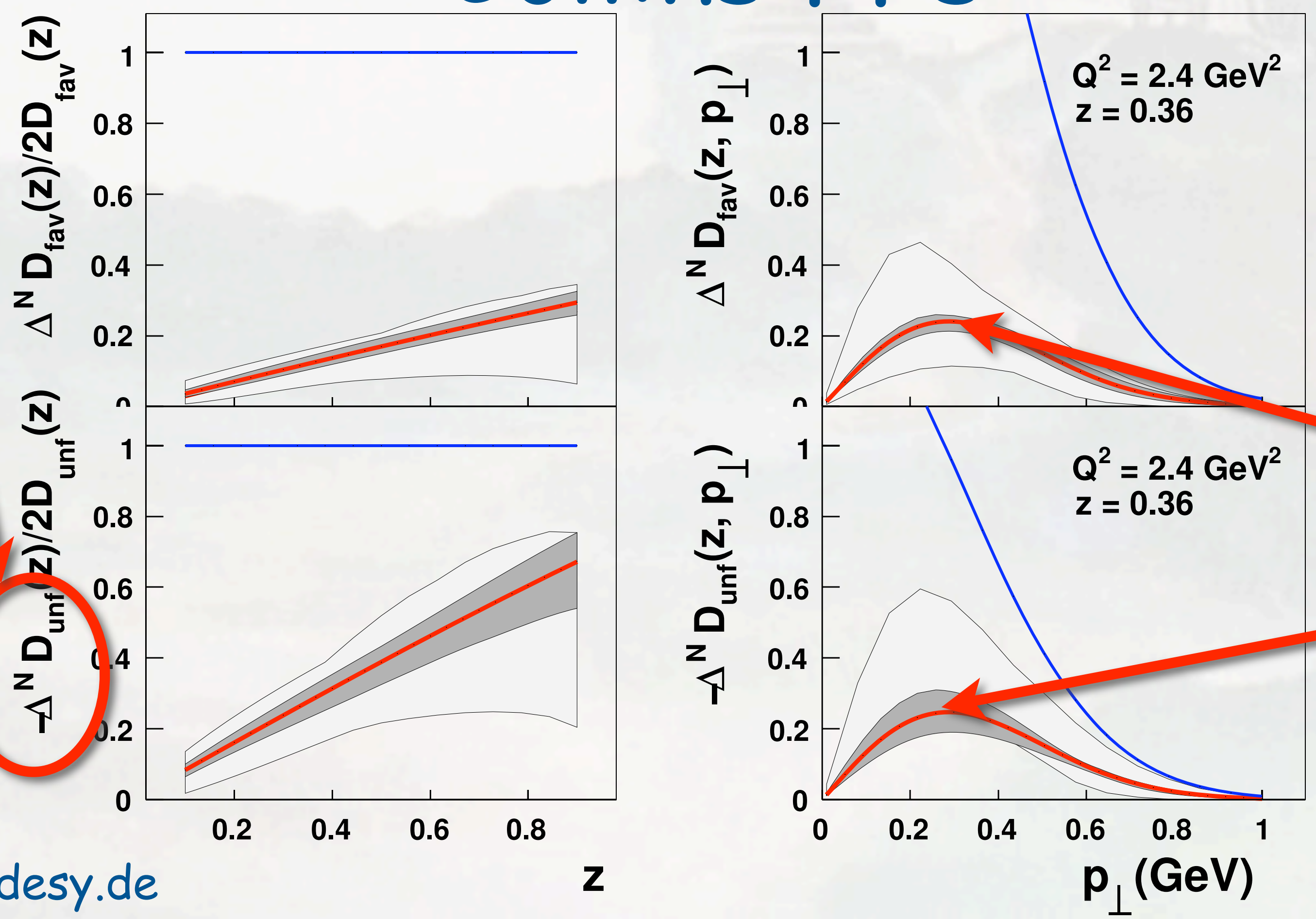
fit to data

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



opposite sign

Collins FFs



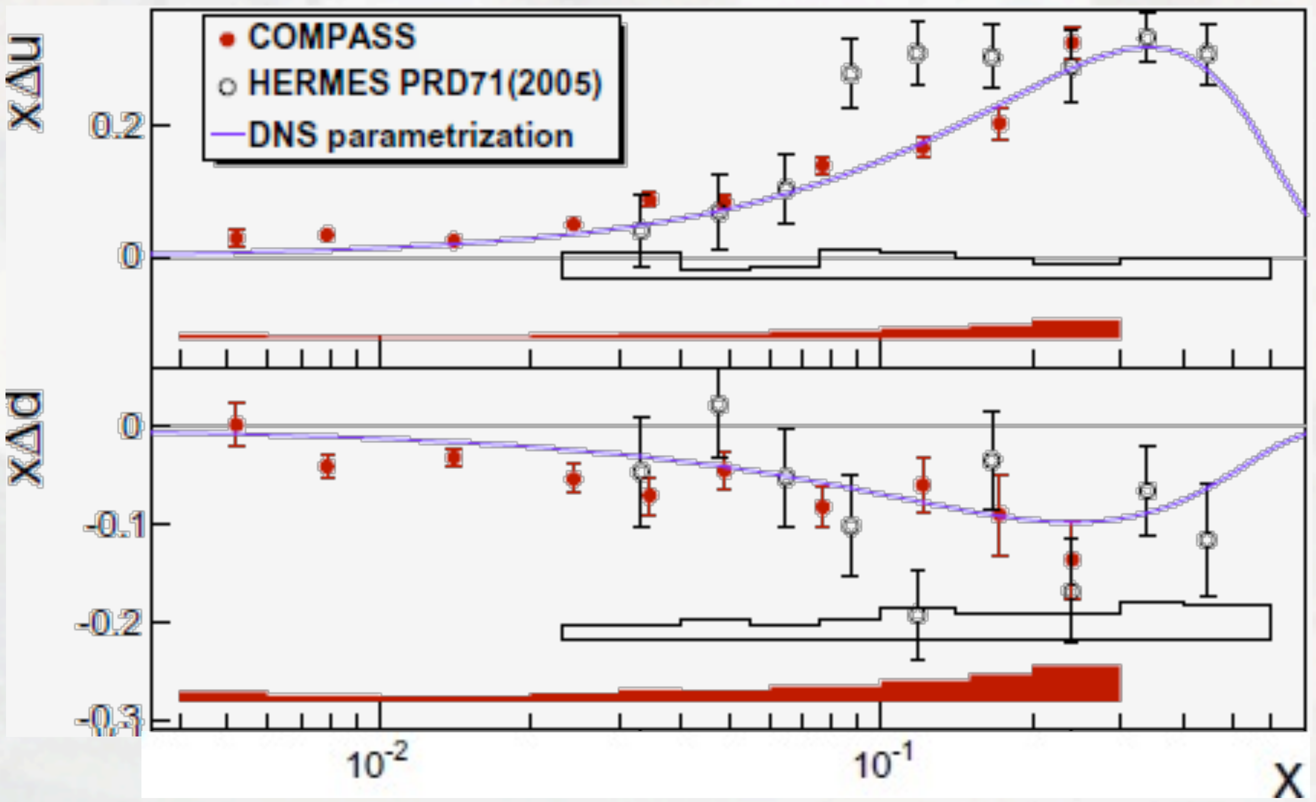
similar magnitude

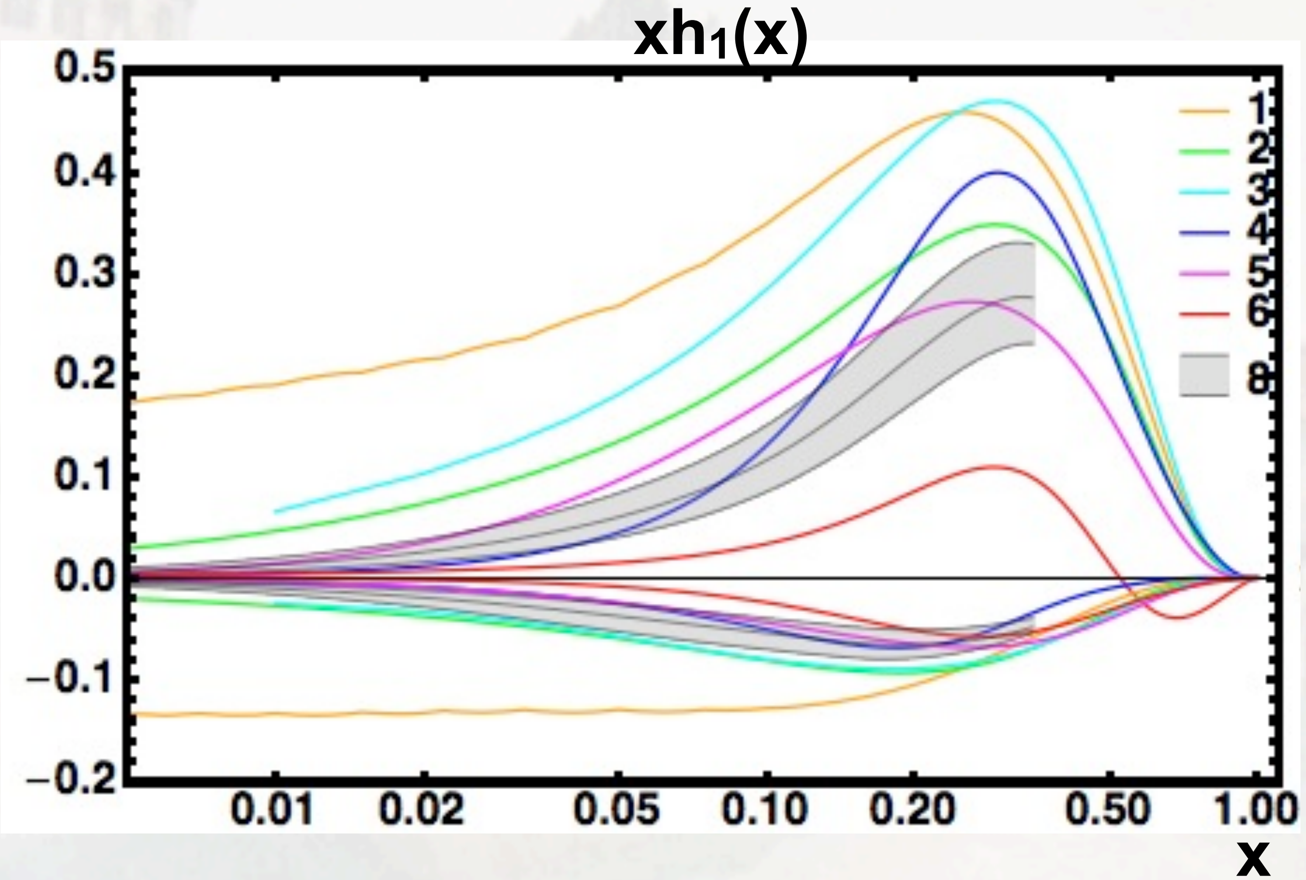
[Anselmino et al., *Nucl.Phys.Proc.Suppl.191 (2009) 98*]

Transversity: models and fits

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

[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





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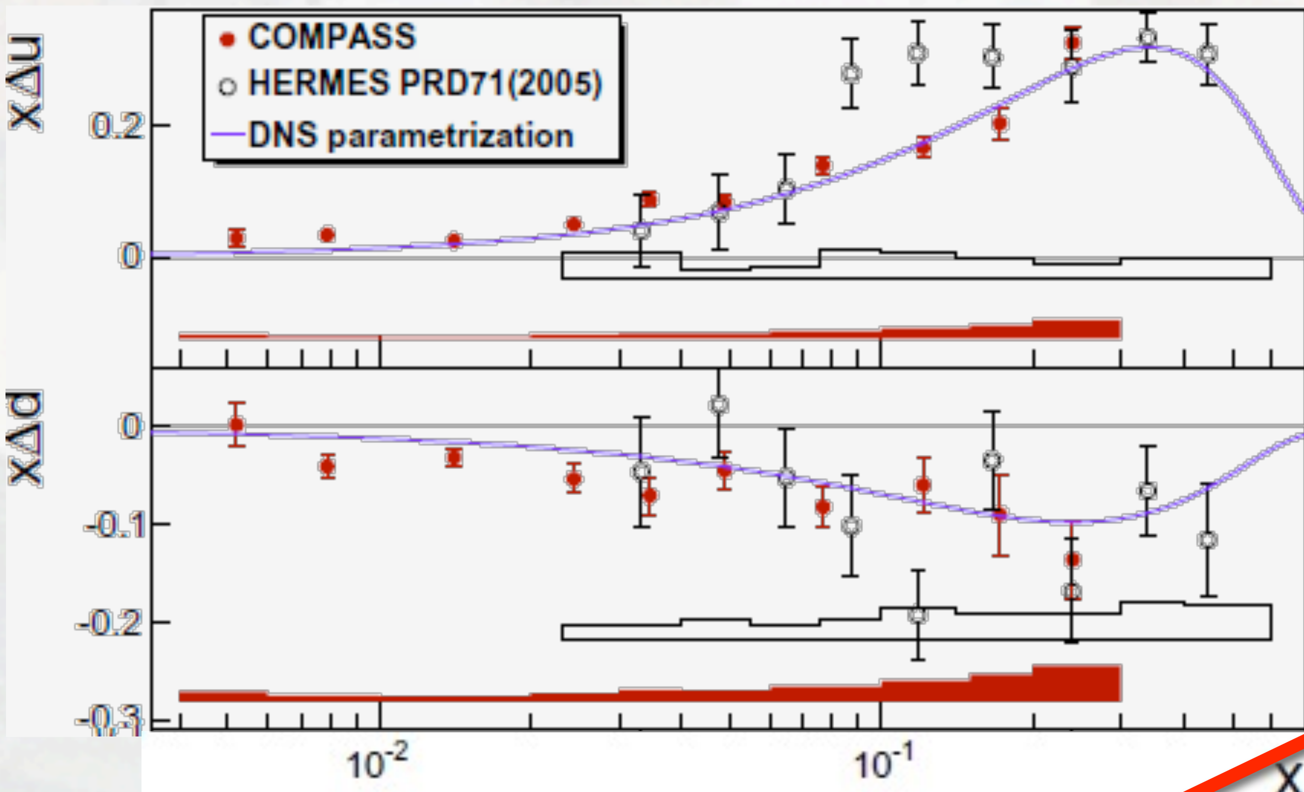

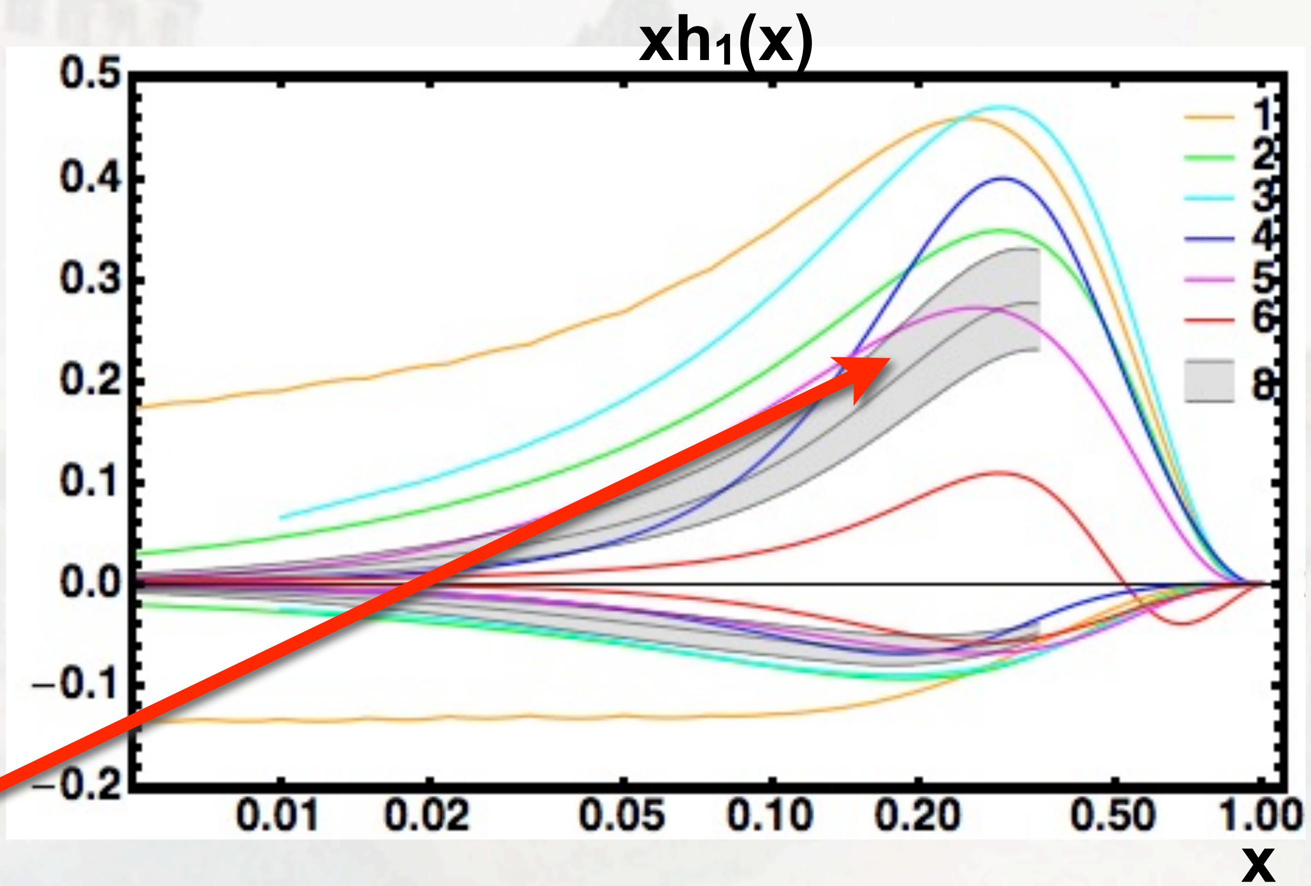

☑ u quark transversity along nucleon spin

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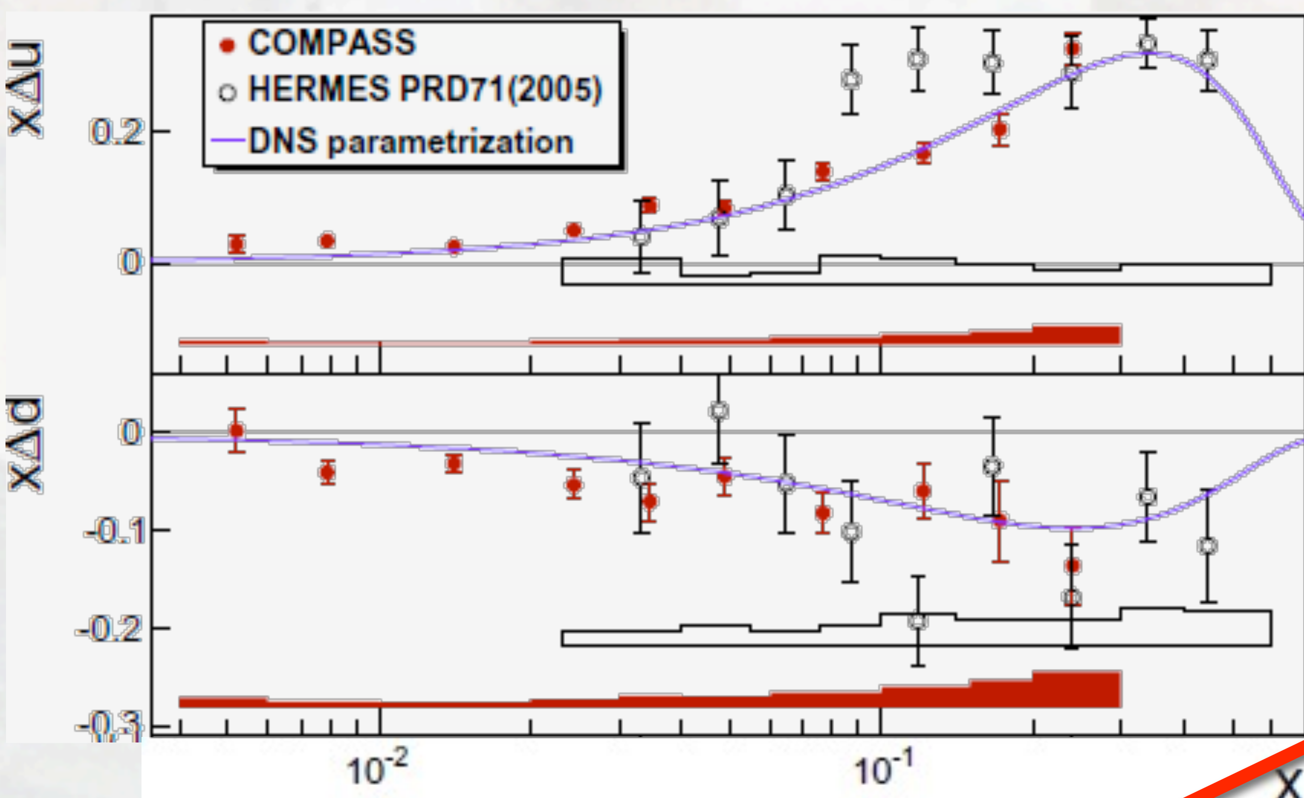

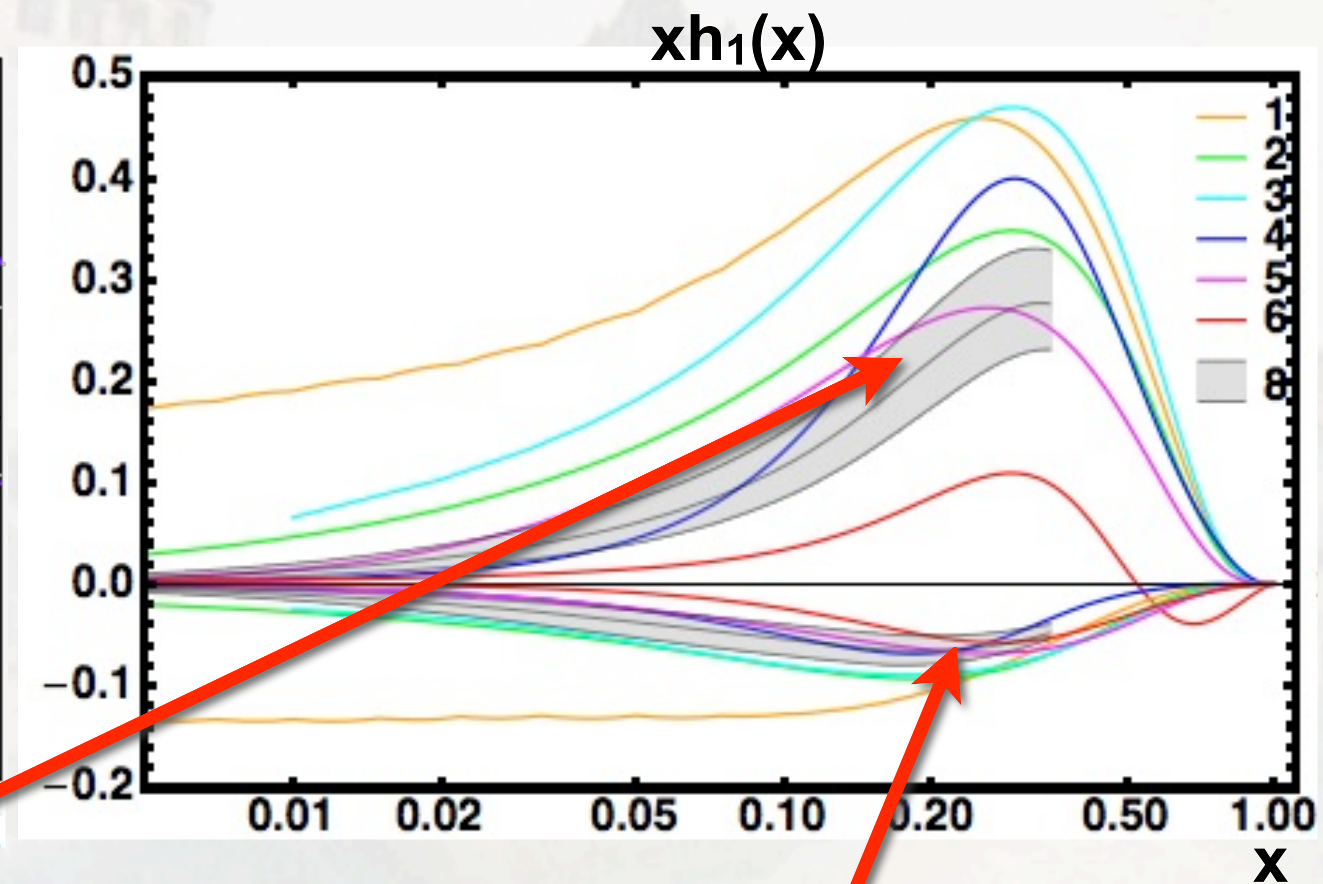

☑ u quark transversity along nucleon spin

☑ 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

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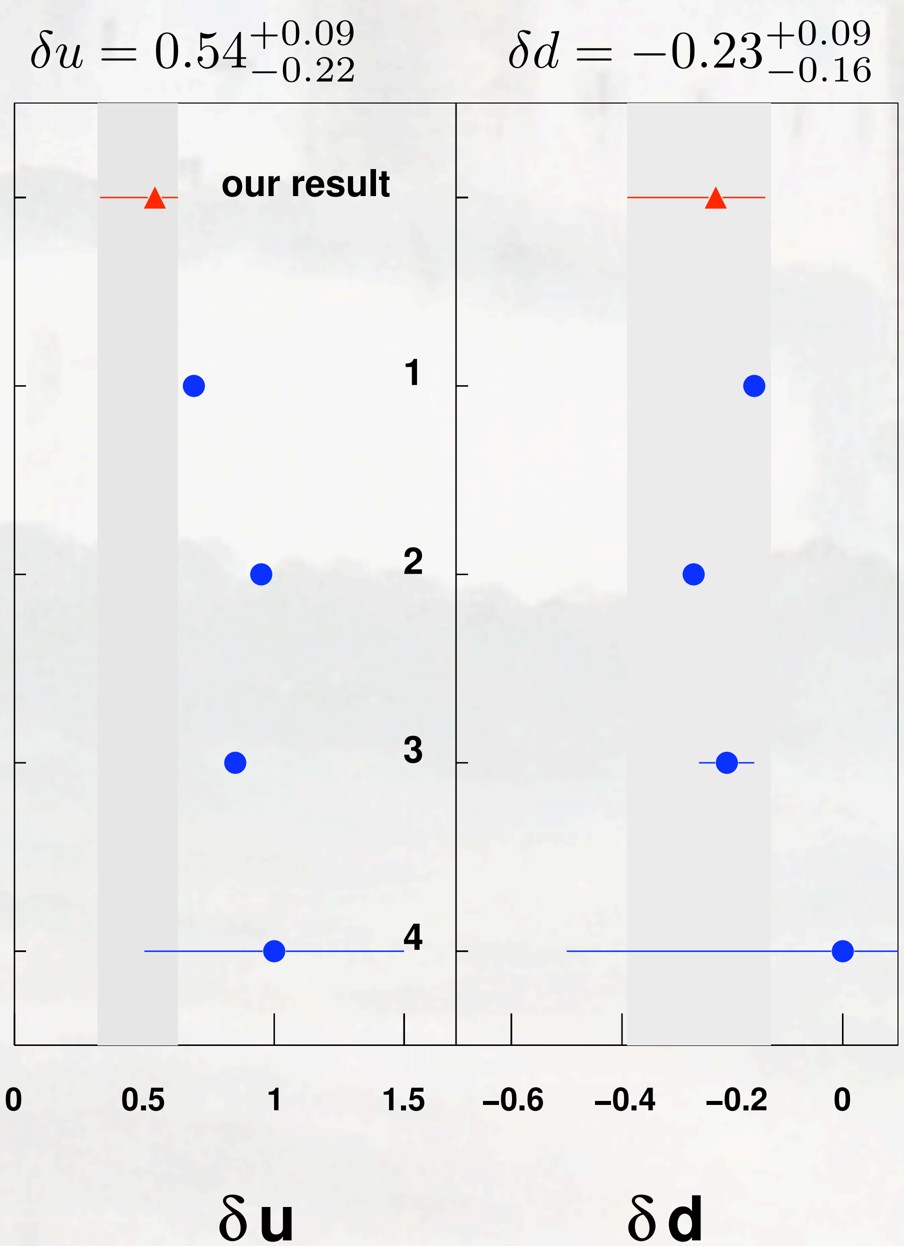
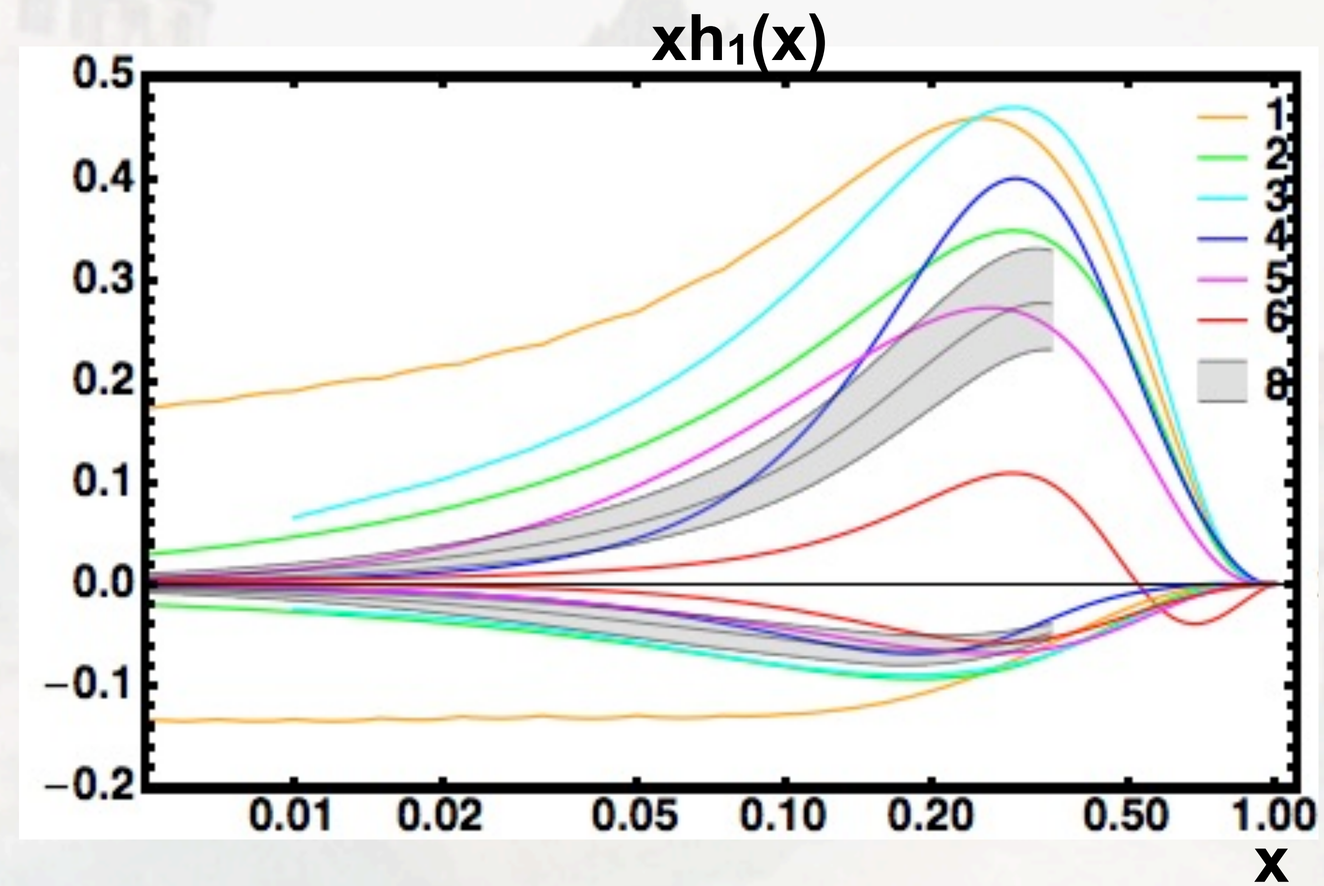




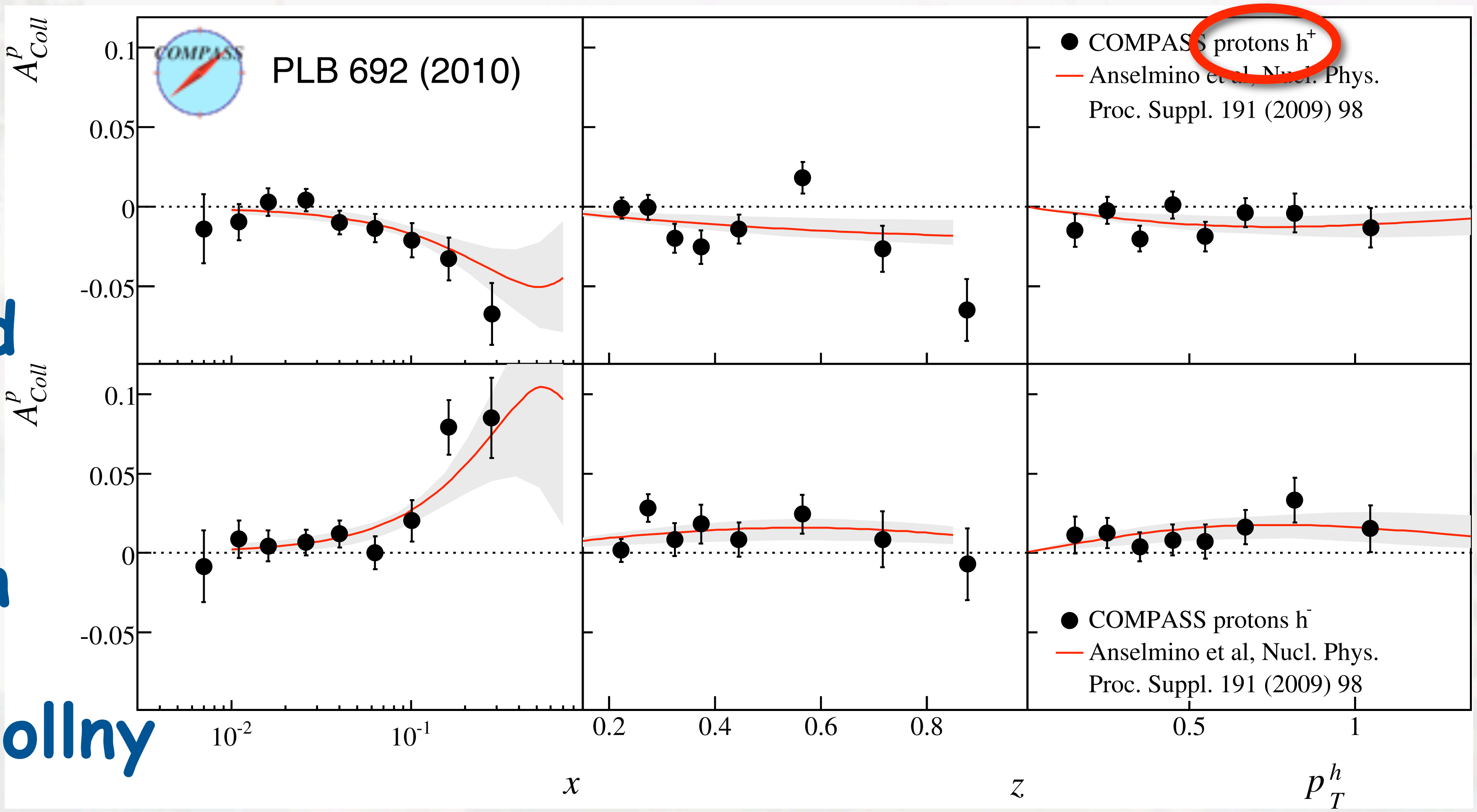
tensor charge:

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

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

Transversity distribution (Collins fragmentation)

- wealth of new results available and analyses ongoing
  - JLab ☛J.-P.Chen
  - COMPASS ☛H.Wollny
  - HERMES ☛L.Pappalardo
  - BELLE ☛S.Uehara
  - BaBar



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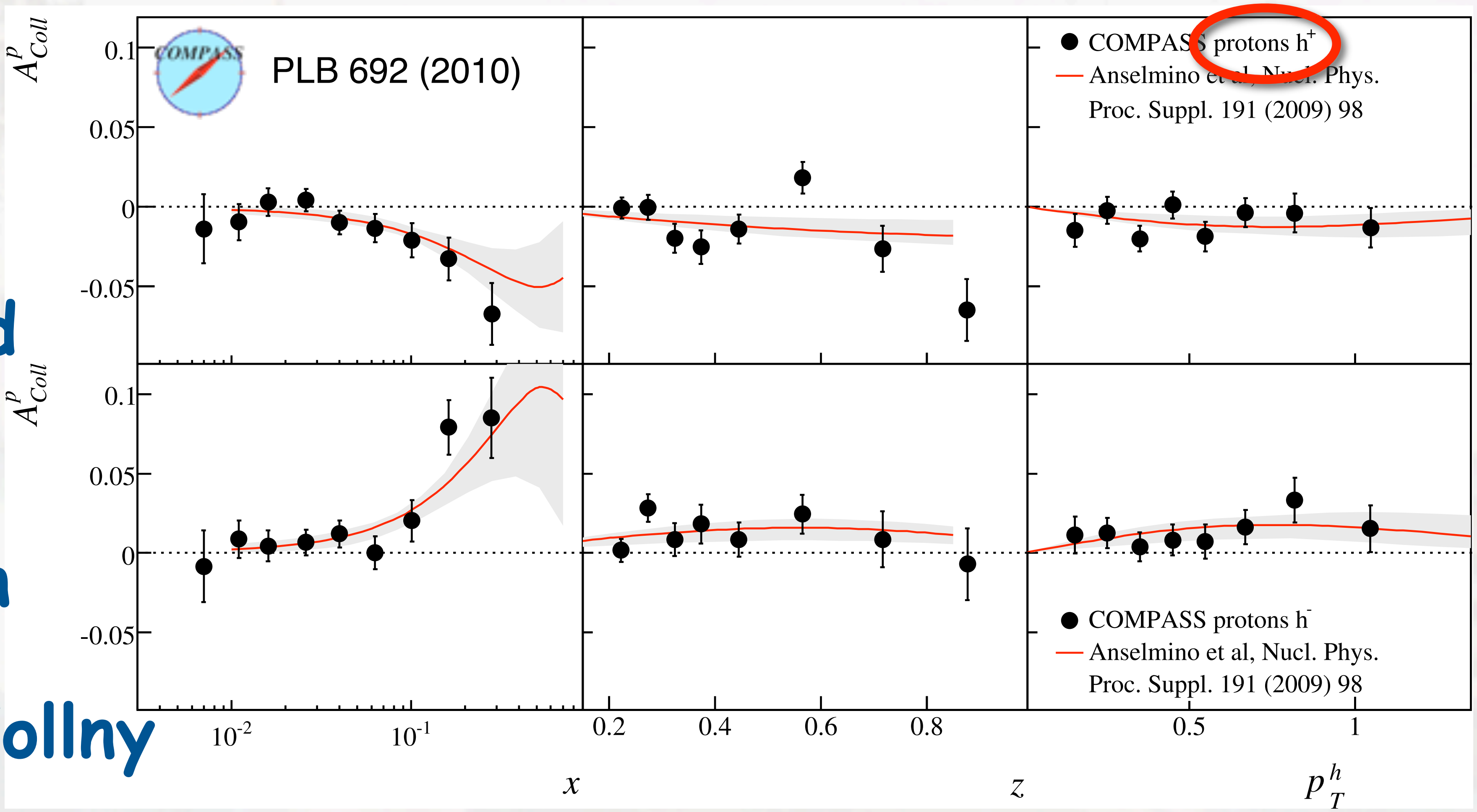

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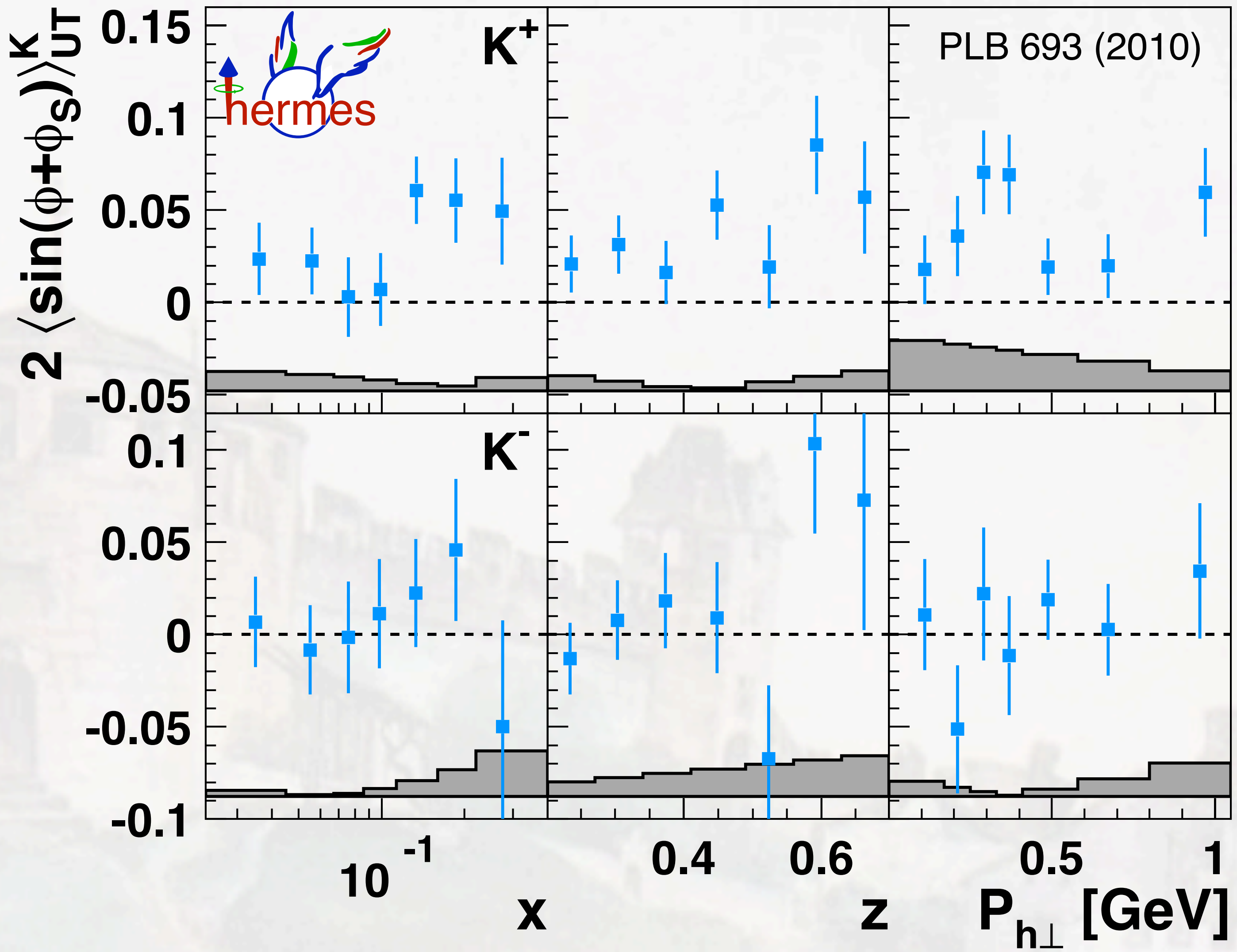
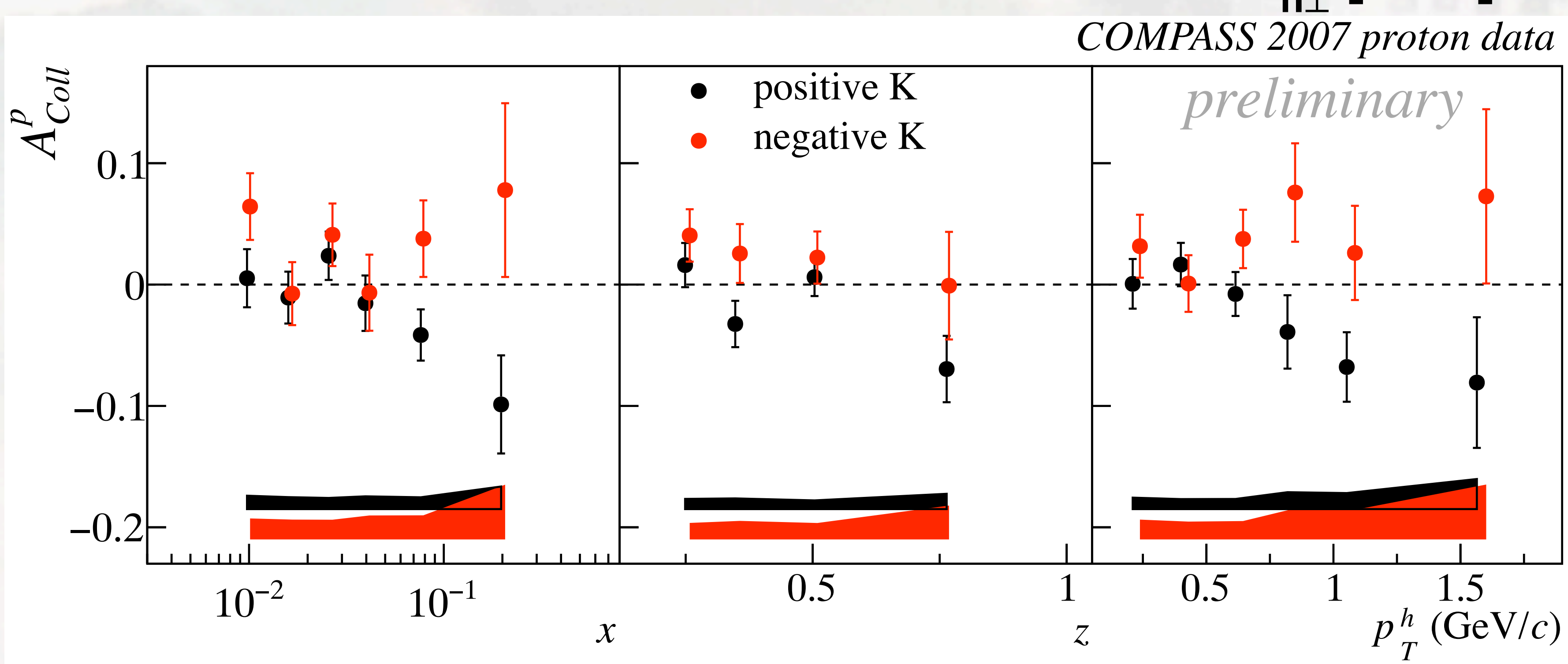
Collins amplitudes for kaons

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





gunar.schnell @ desy.de

	U	L	T
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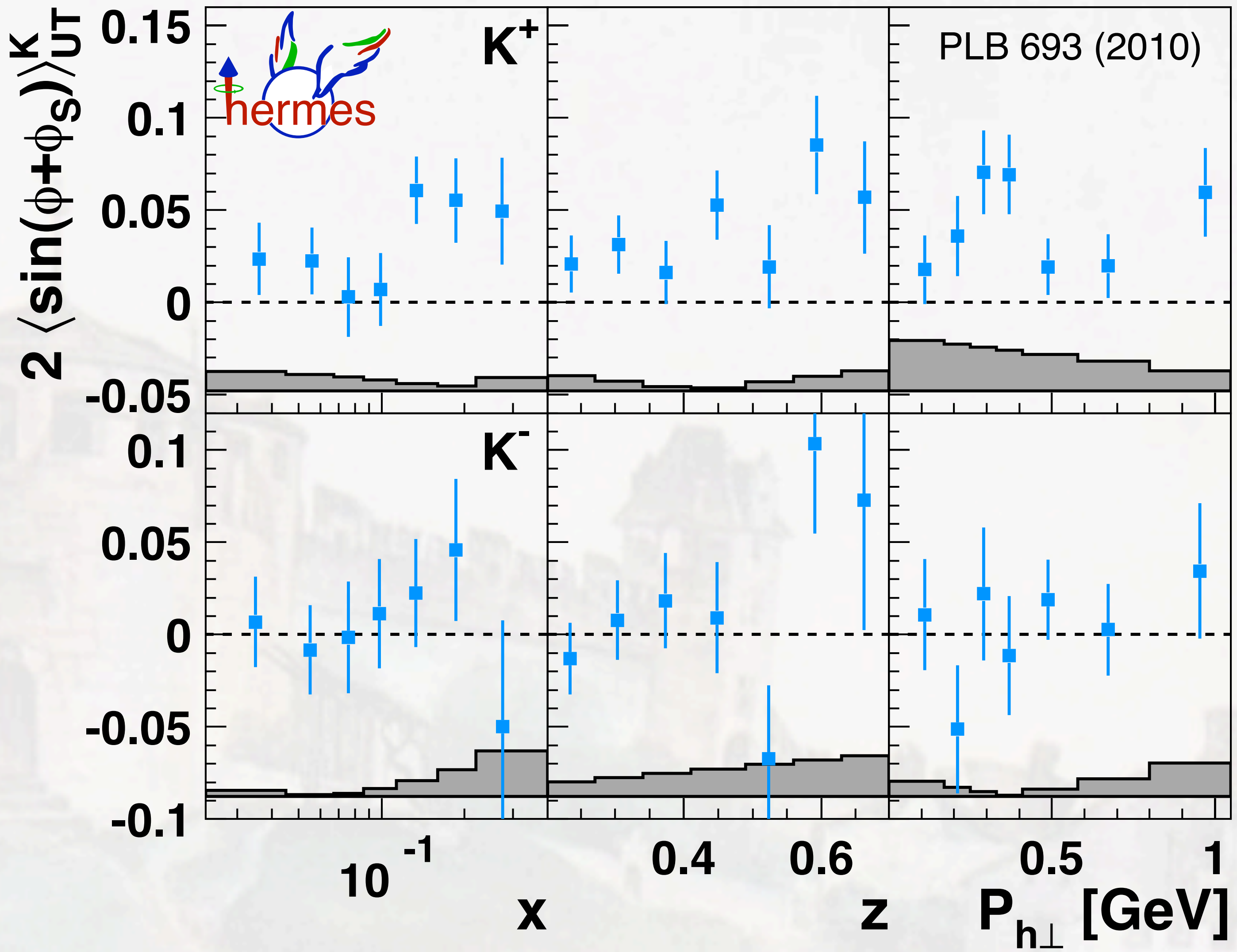
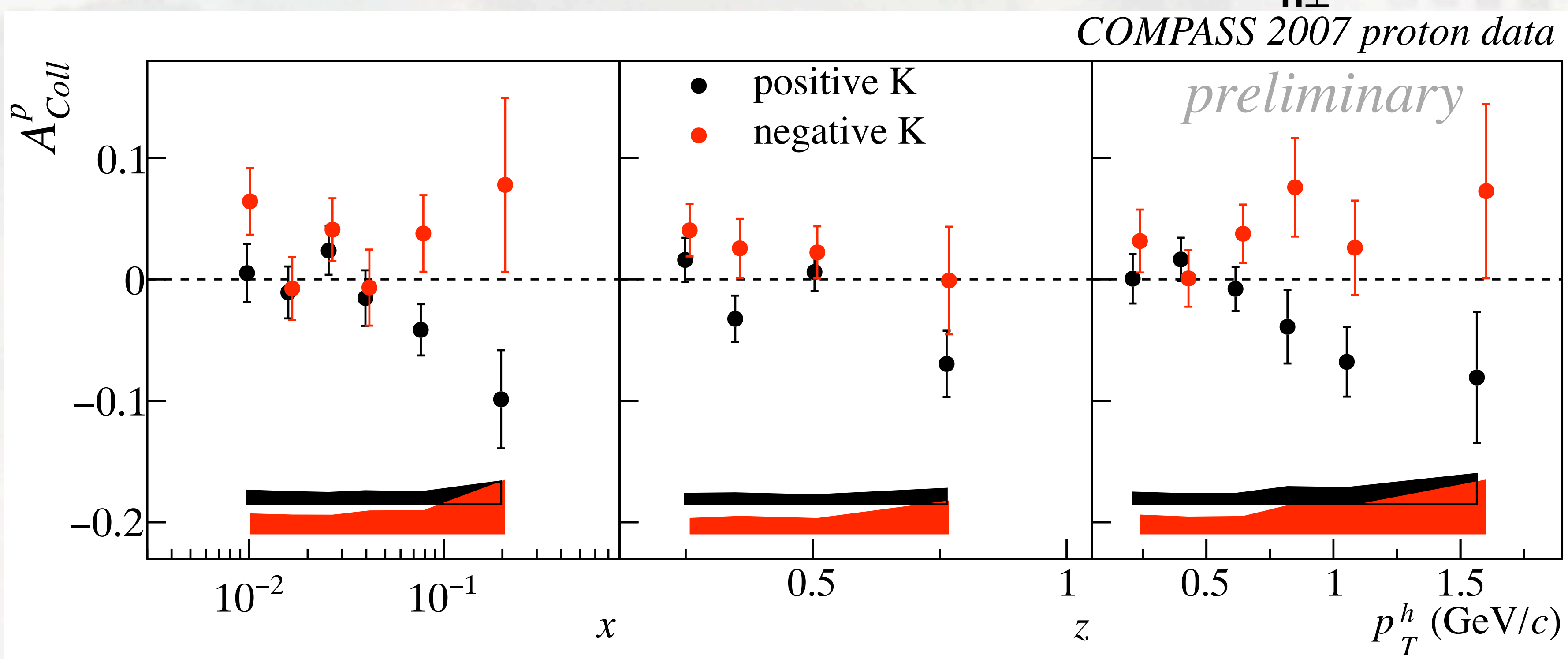
Collins amplitudes for kaons



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

☛ H.Wollny, L.Pappalardo



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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**

	U	L	T
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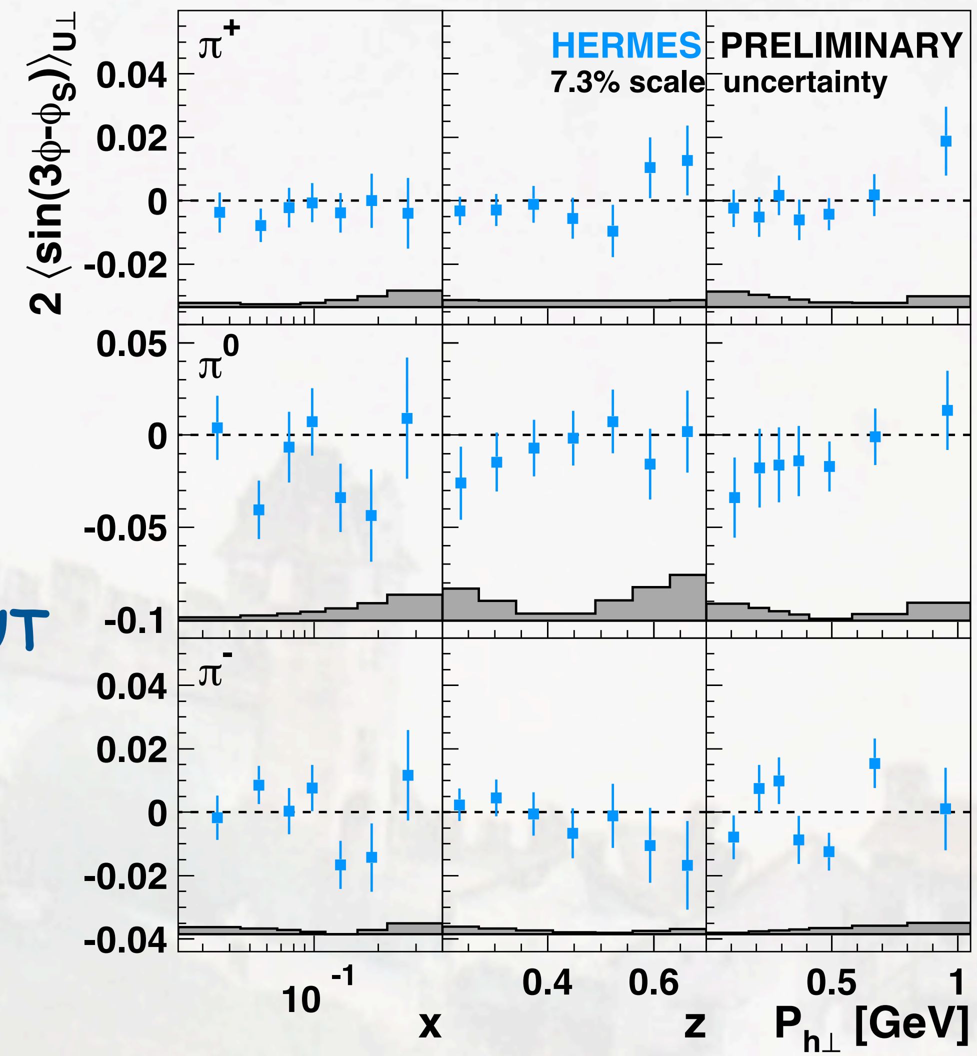
Pretzelosity



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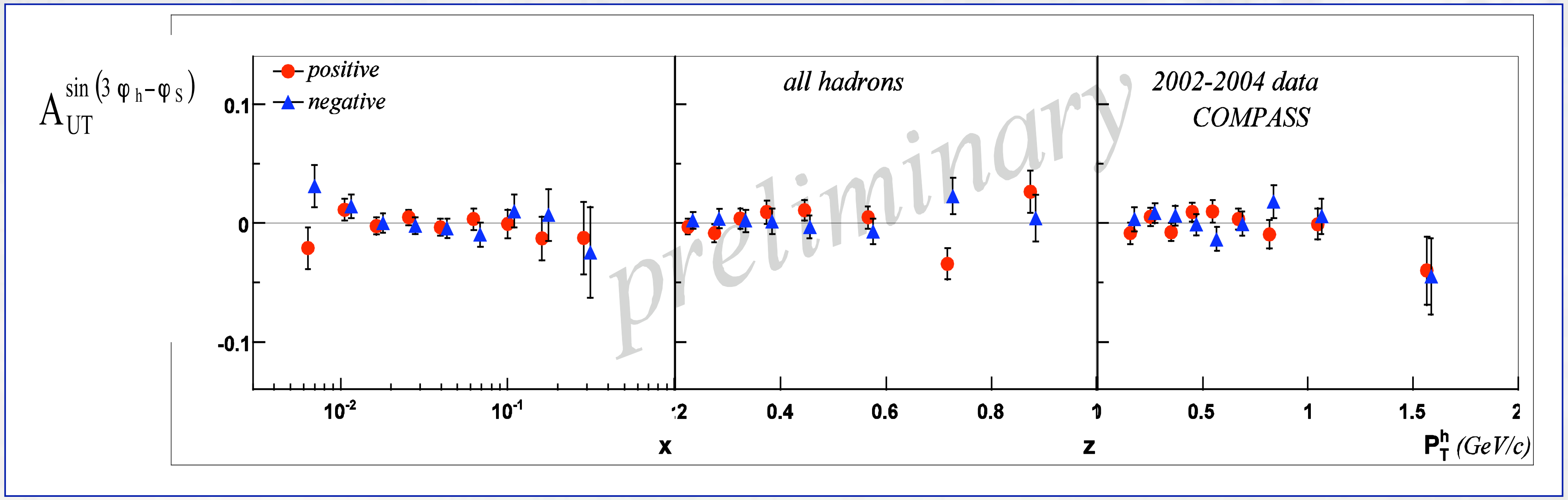

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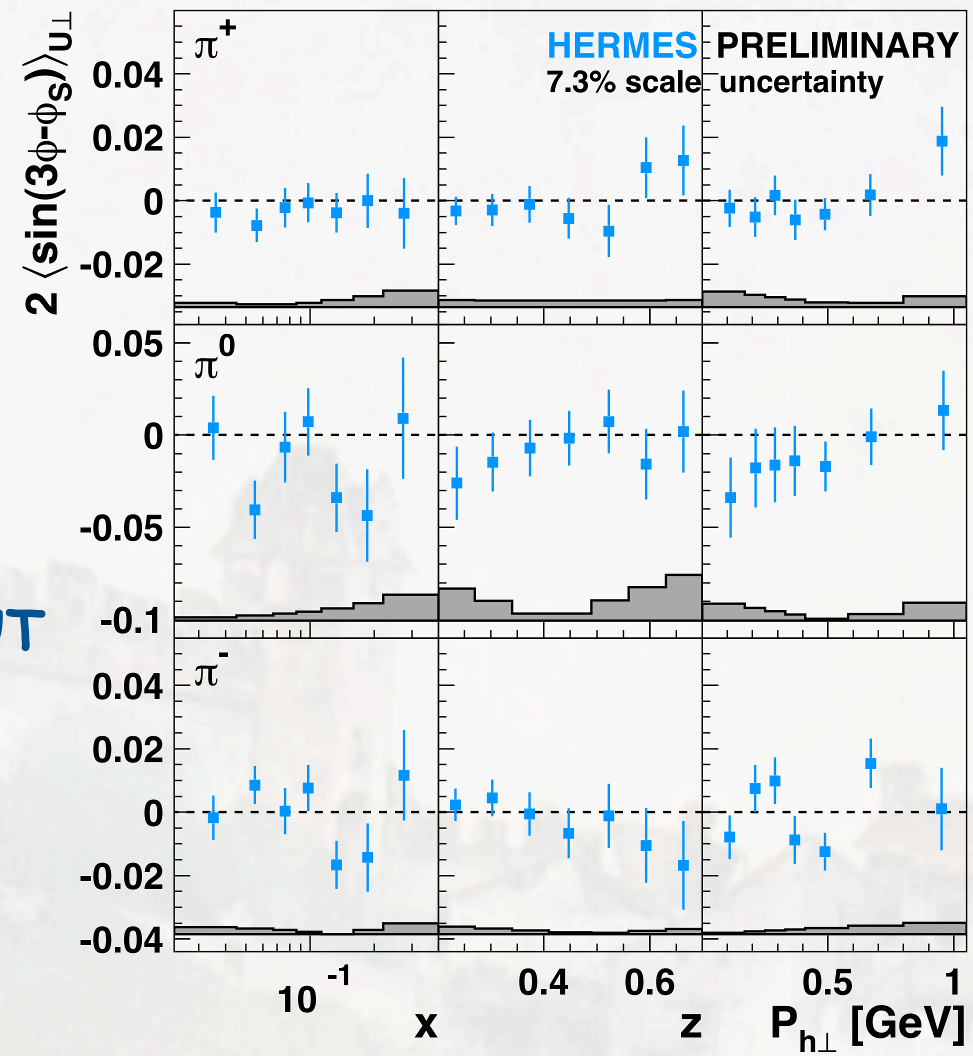

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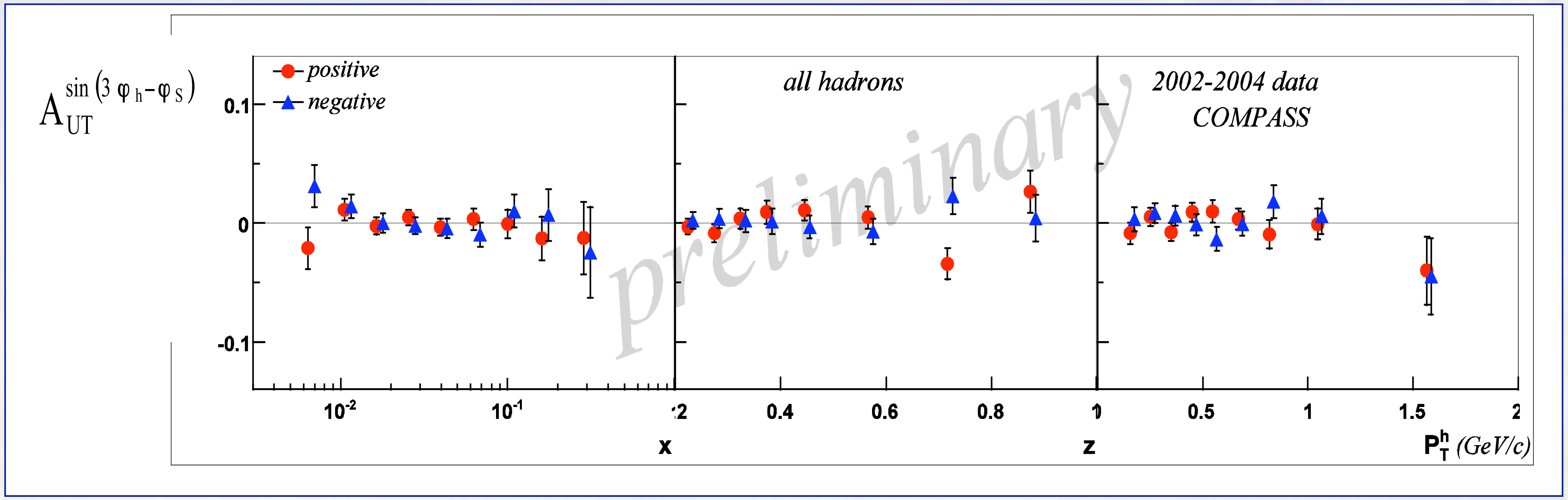

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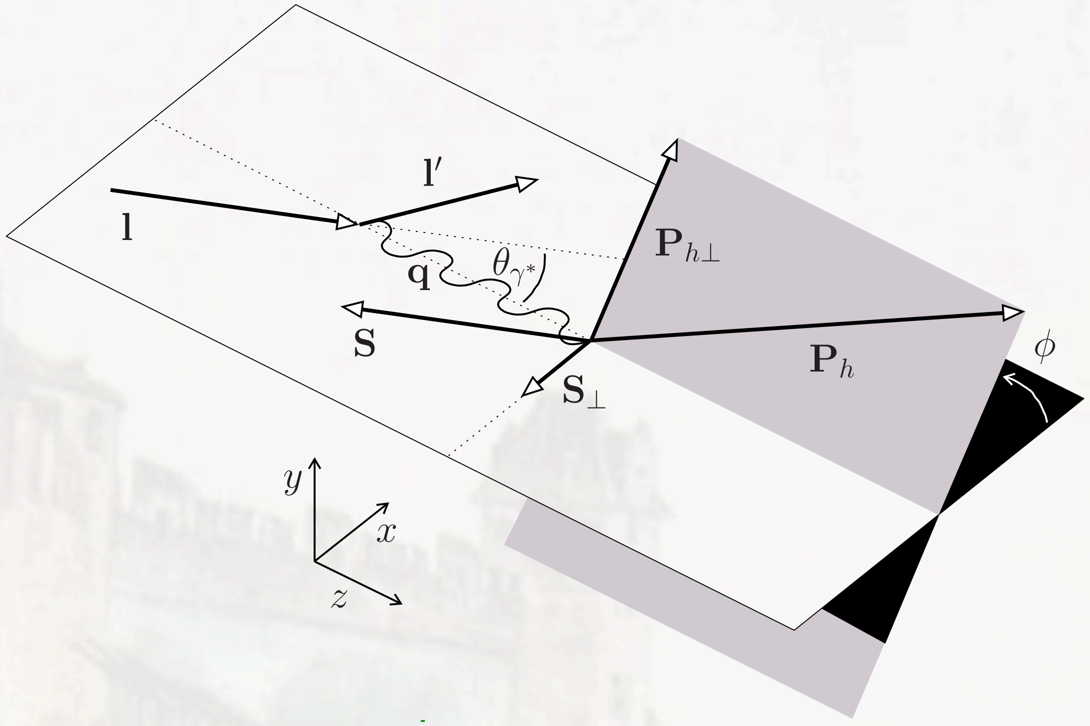
Pretzelosity



- **can also use longitudinally polarized targets:**

$$\sin(3\phi - \phi_S) \rightsquigarrow -\sin(3\phi)$$

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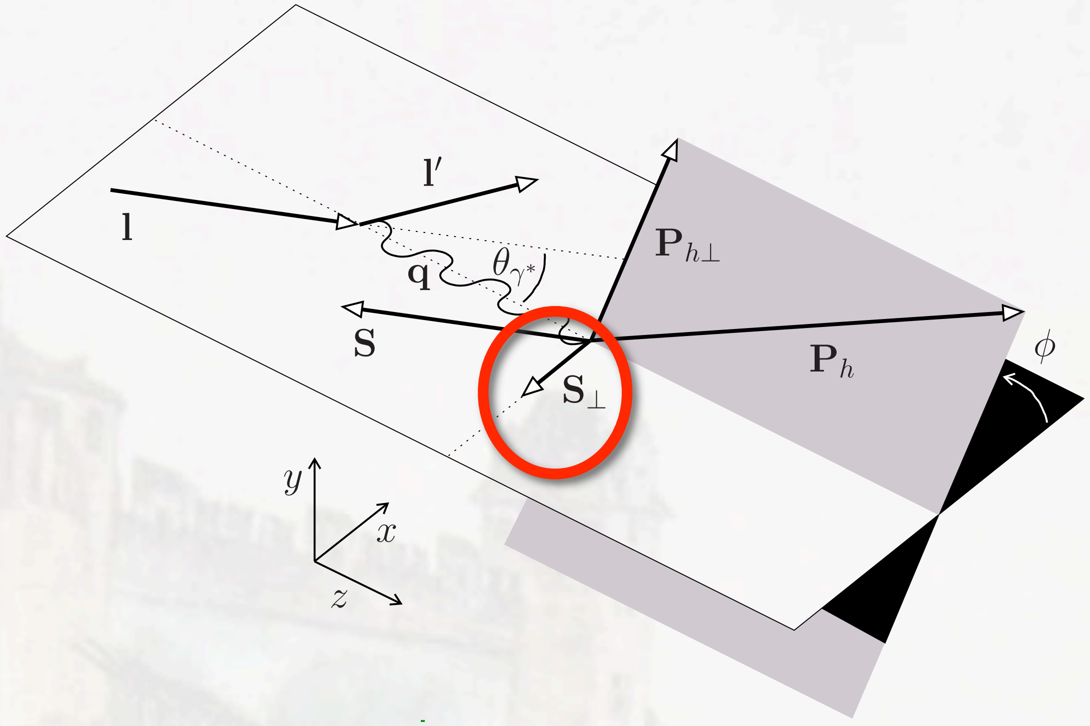

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L		g_{1L}	$h_{1L}^\perp$
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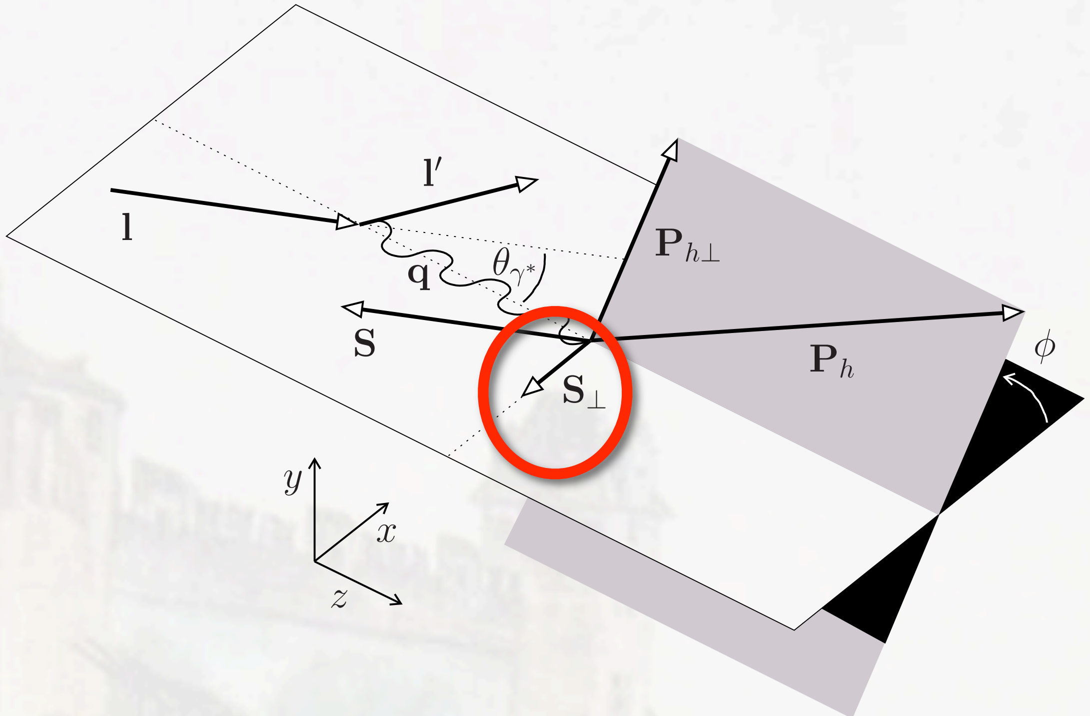
Pretzelosity



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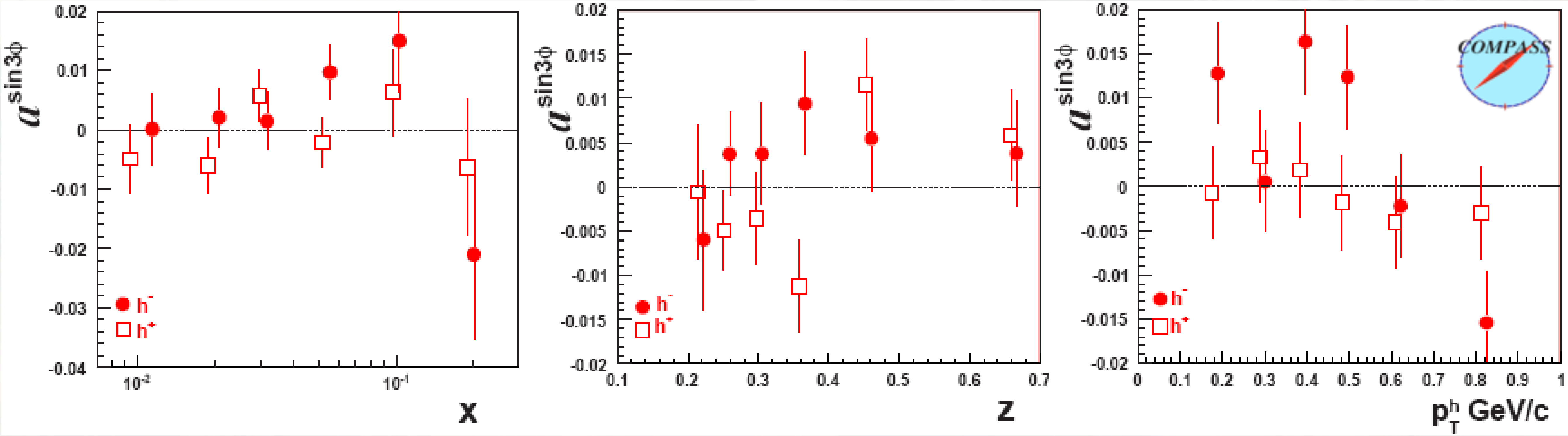
$$\sin(3\phi - \phi_S) \rightsquigarrow -\sin(3\phi)$$



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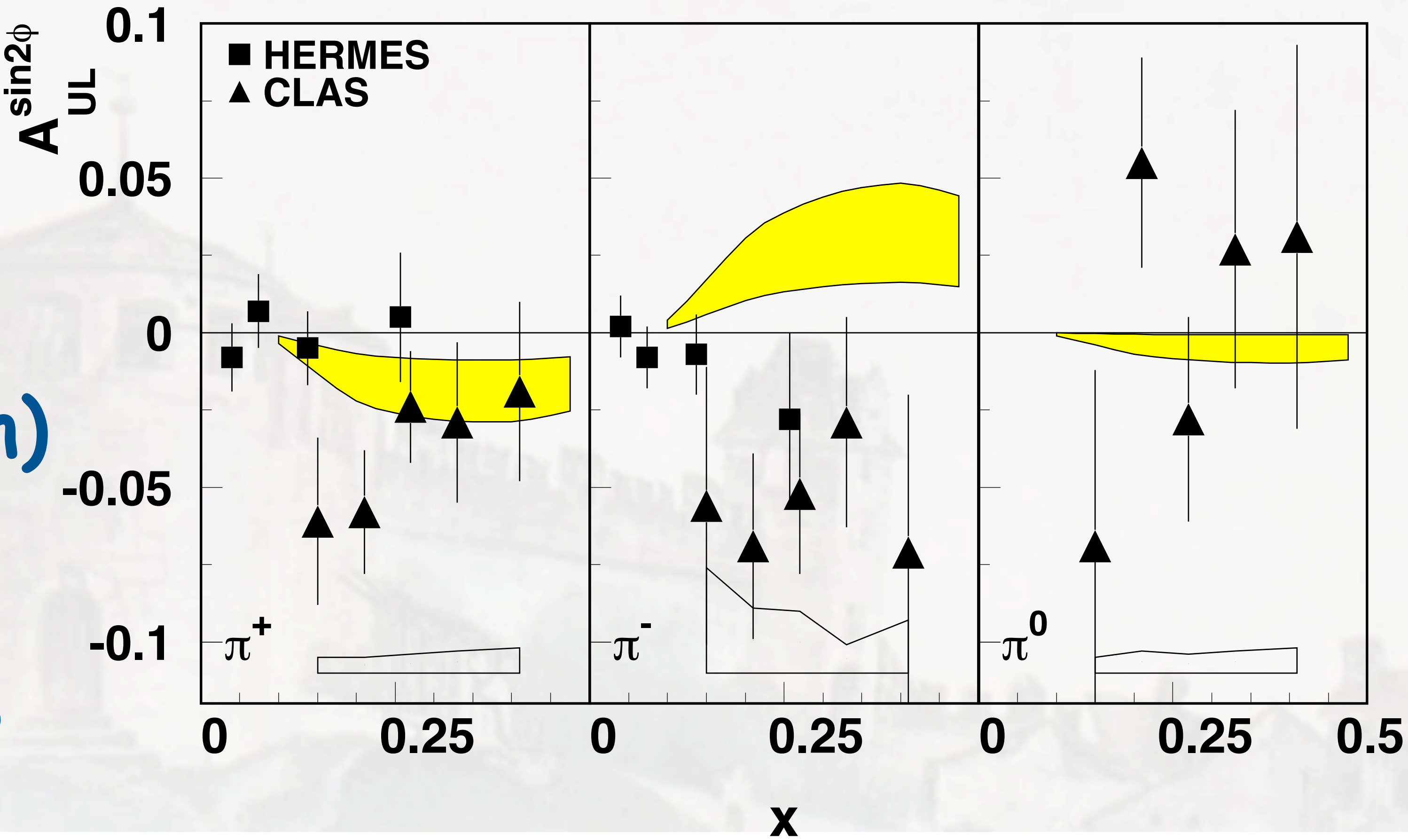
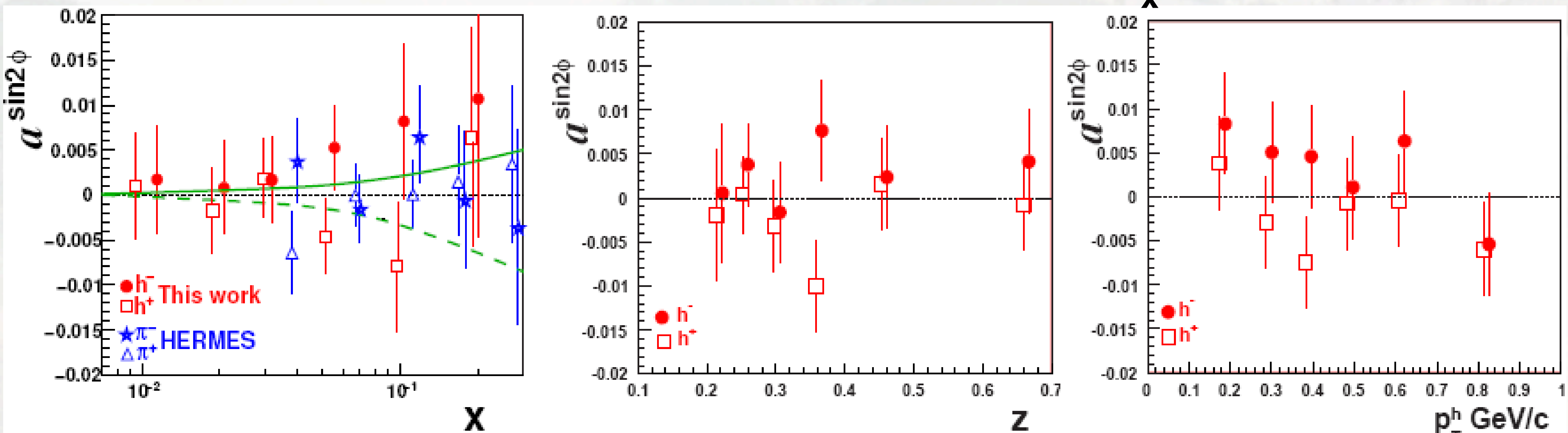
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Worm-Gear I

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





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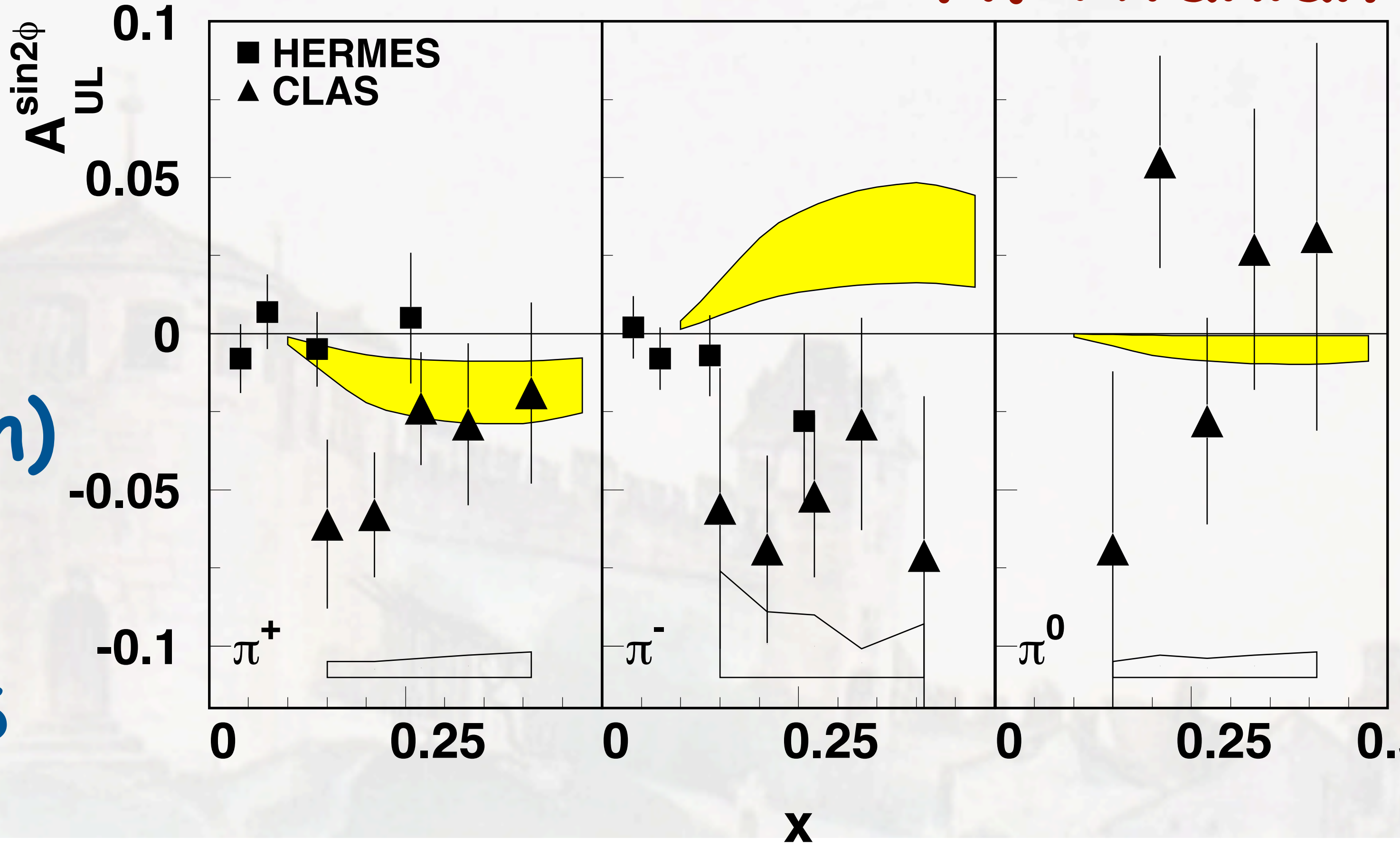
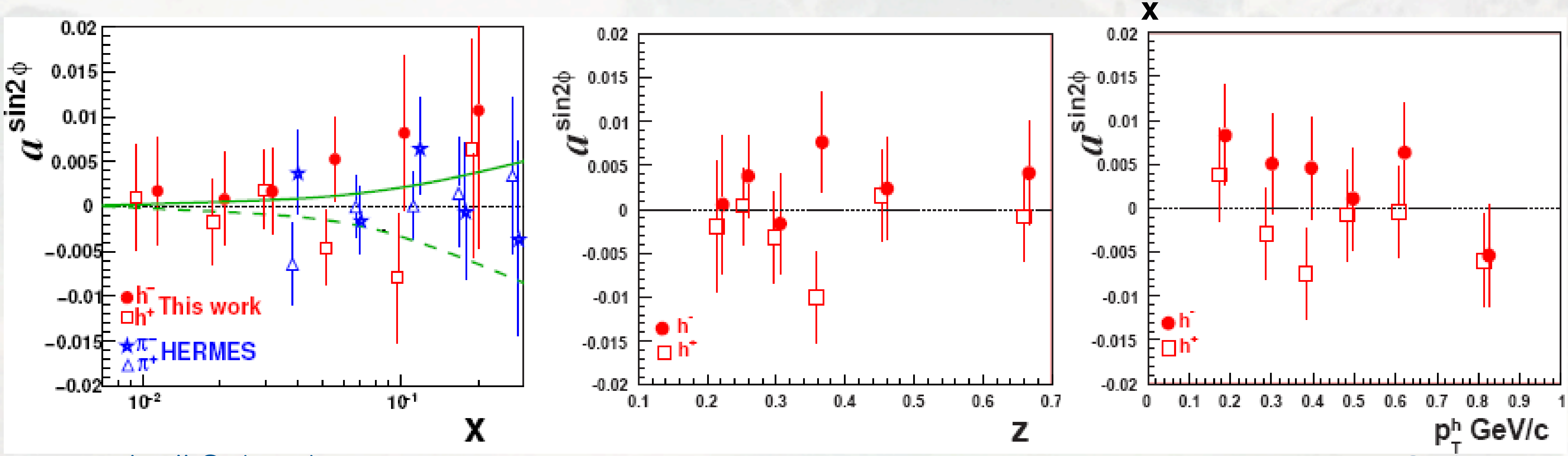
Worm-Gear I

☛ H. Avakian

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





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L		g_{1L}	$h_{1L}^\perp$
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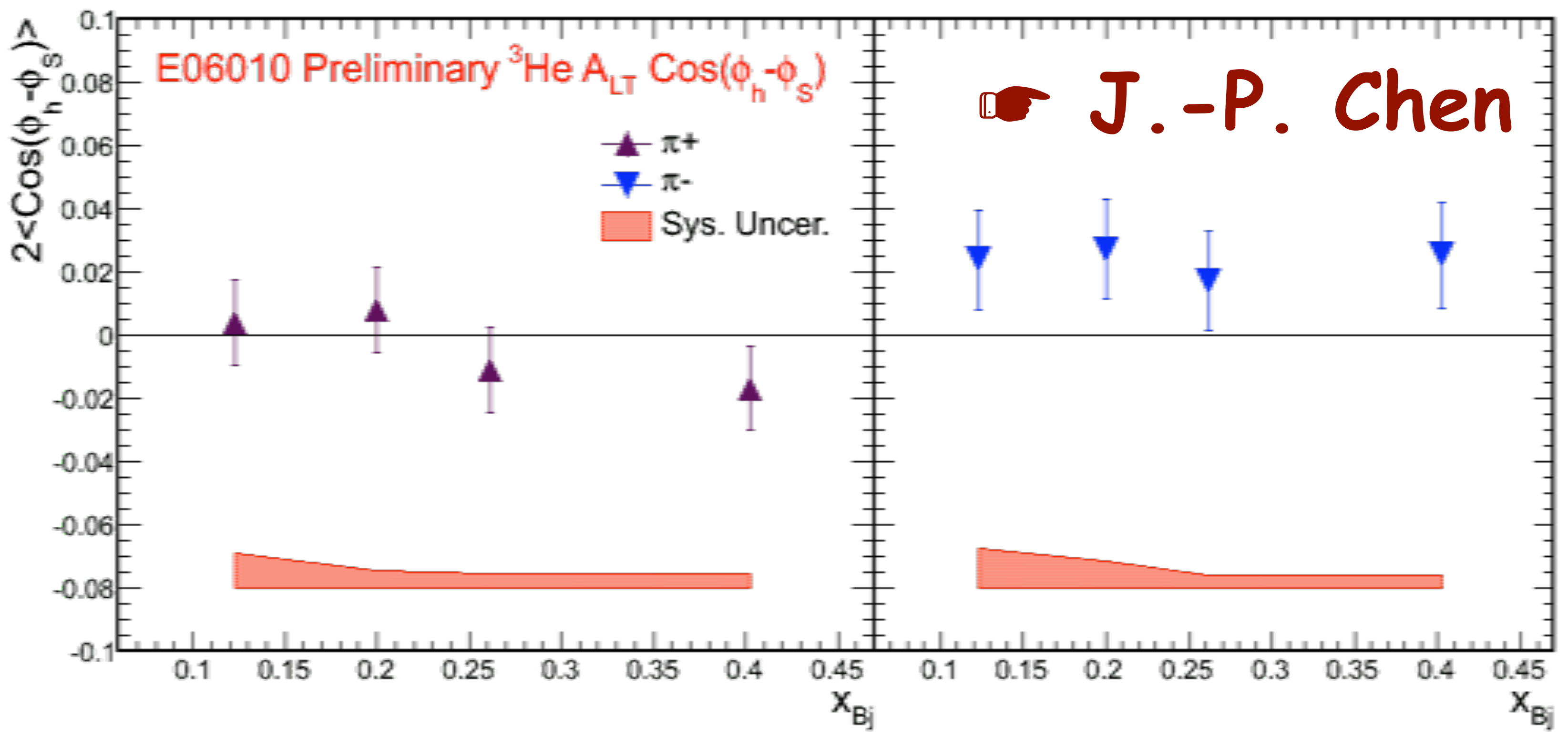
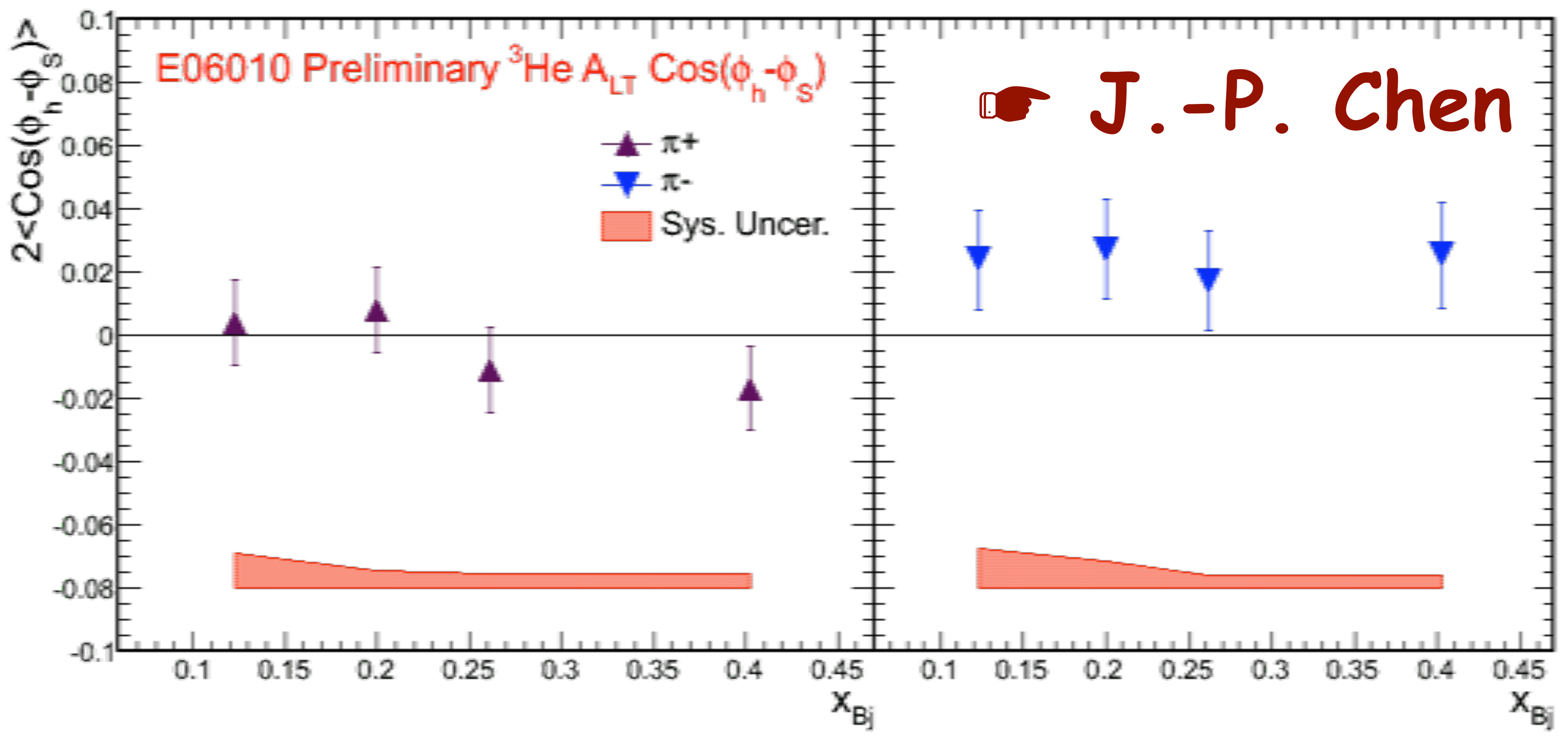
Worm-Gear II

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



	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



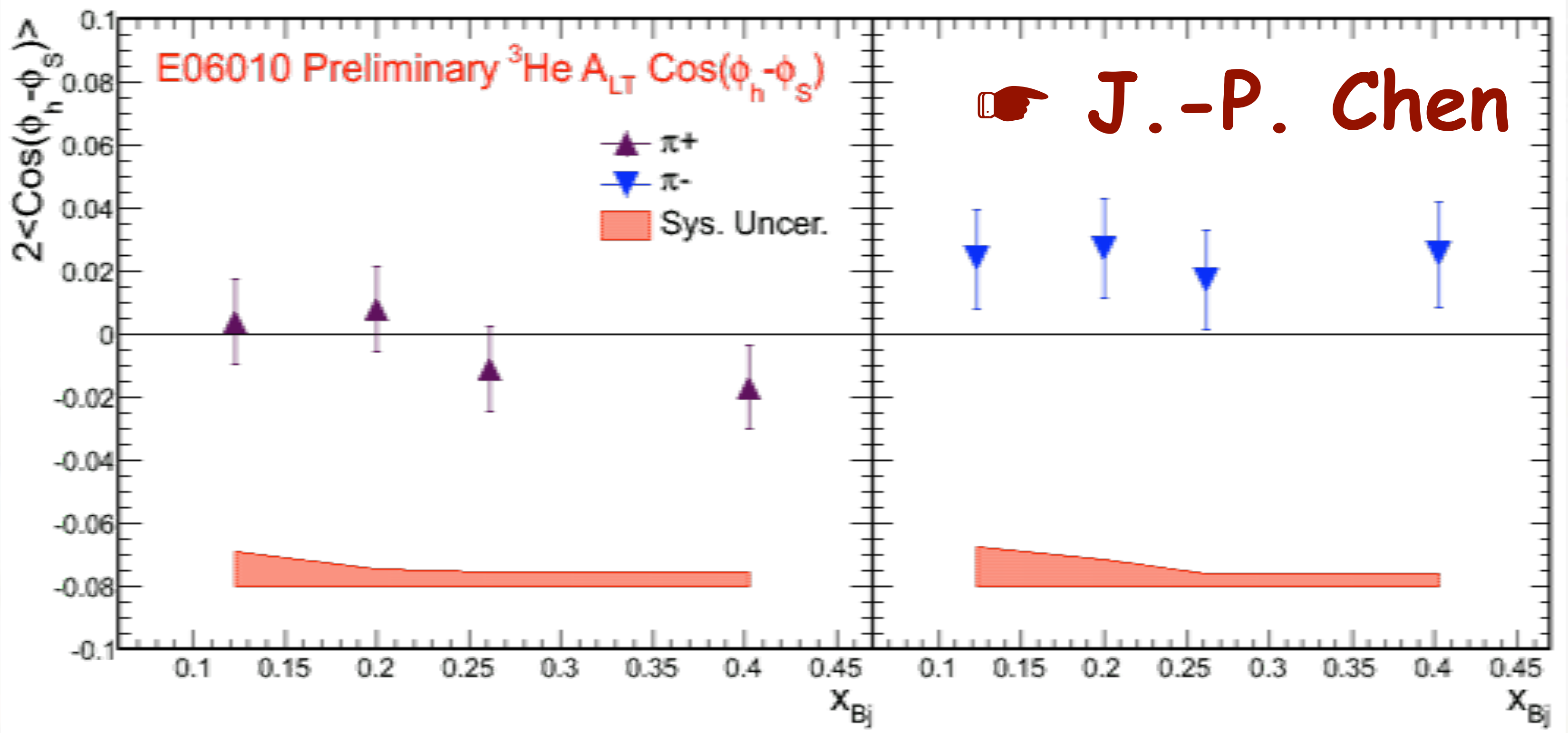
- chiral even
- first direct evidence for worm-gear g_{1T} on ^{3}He target
- only indirect hints from proton data via A_{UT}

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

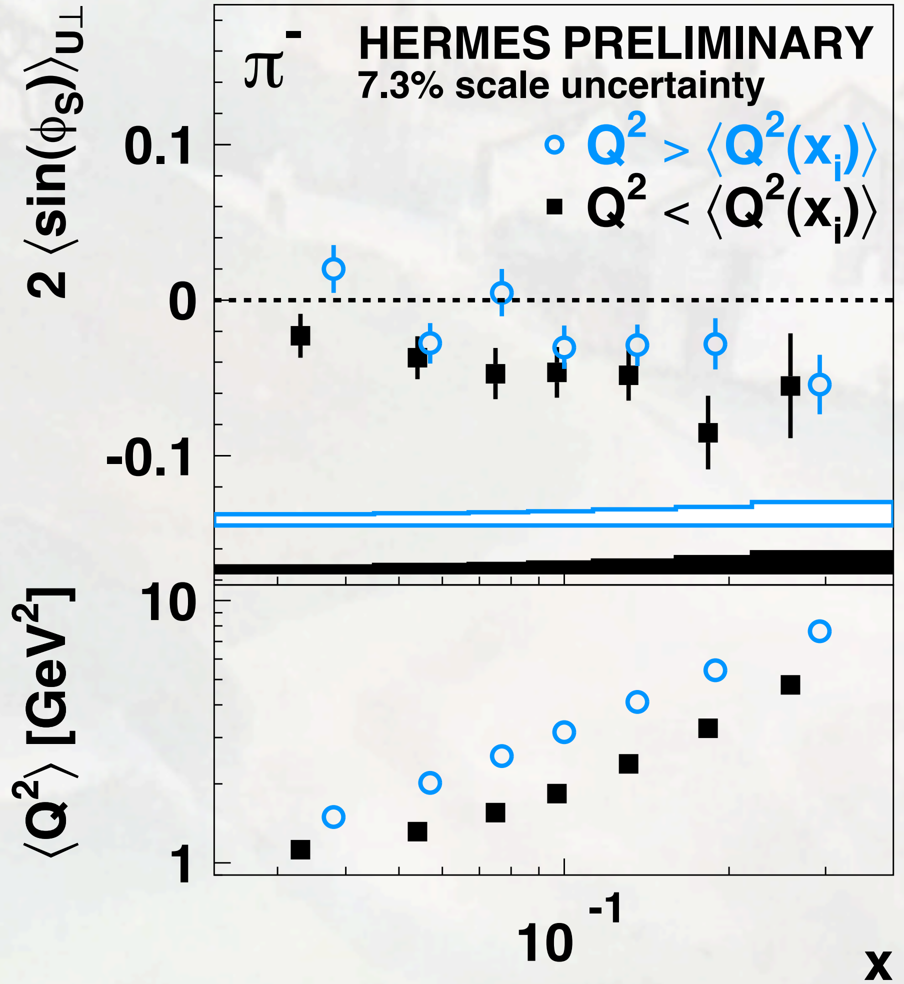
$$- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z} \right) - \left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z} \right) \right]$$

	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
- only indirect hints from proton data via A_{UT} ☛ H. Wollny, L. Pappalardo



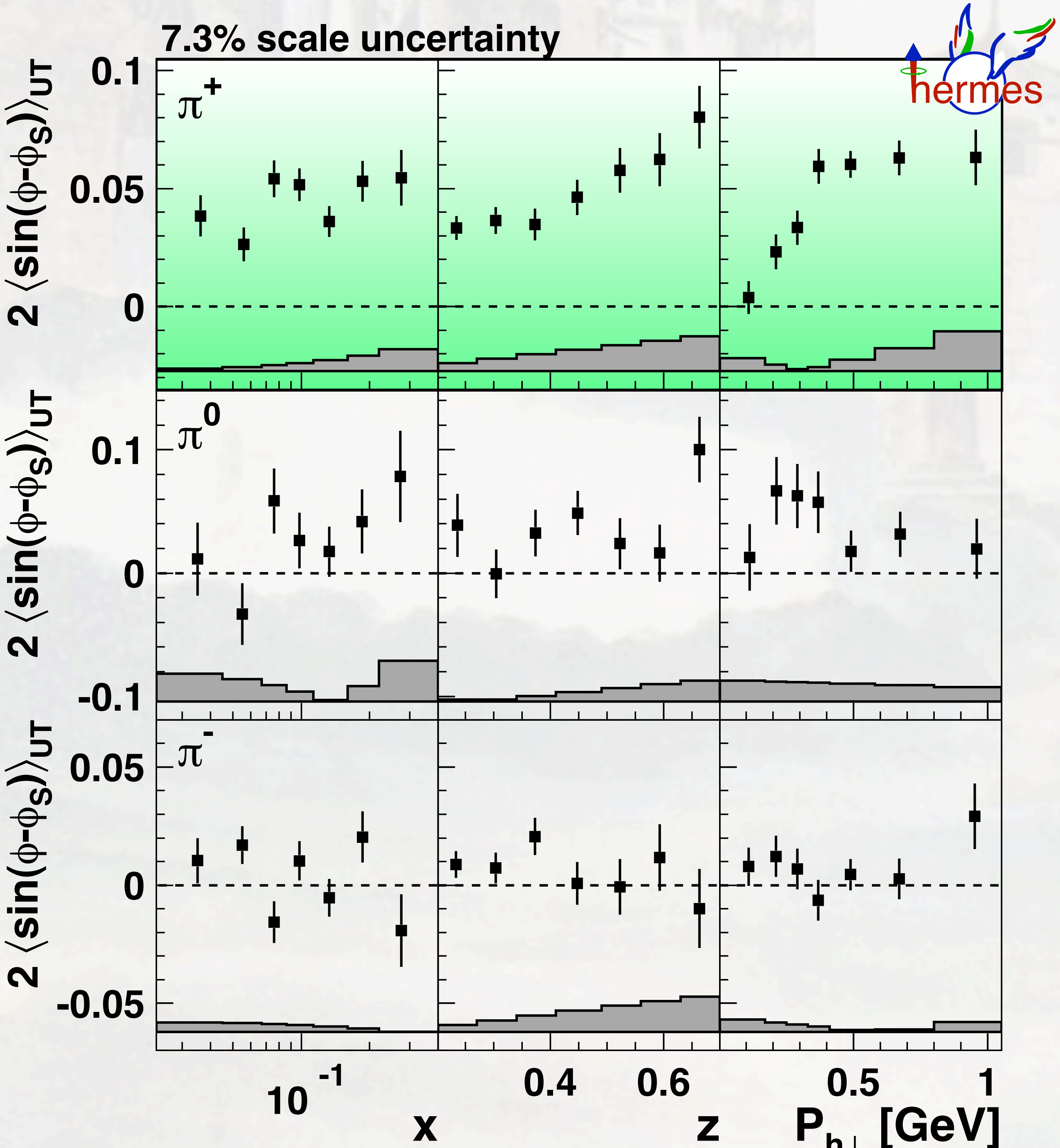
$$\propto \left(x f_T^\perp D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right)$$

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

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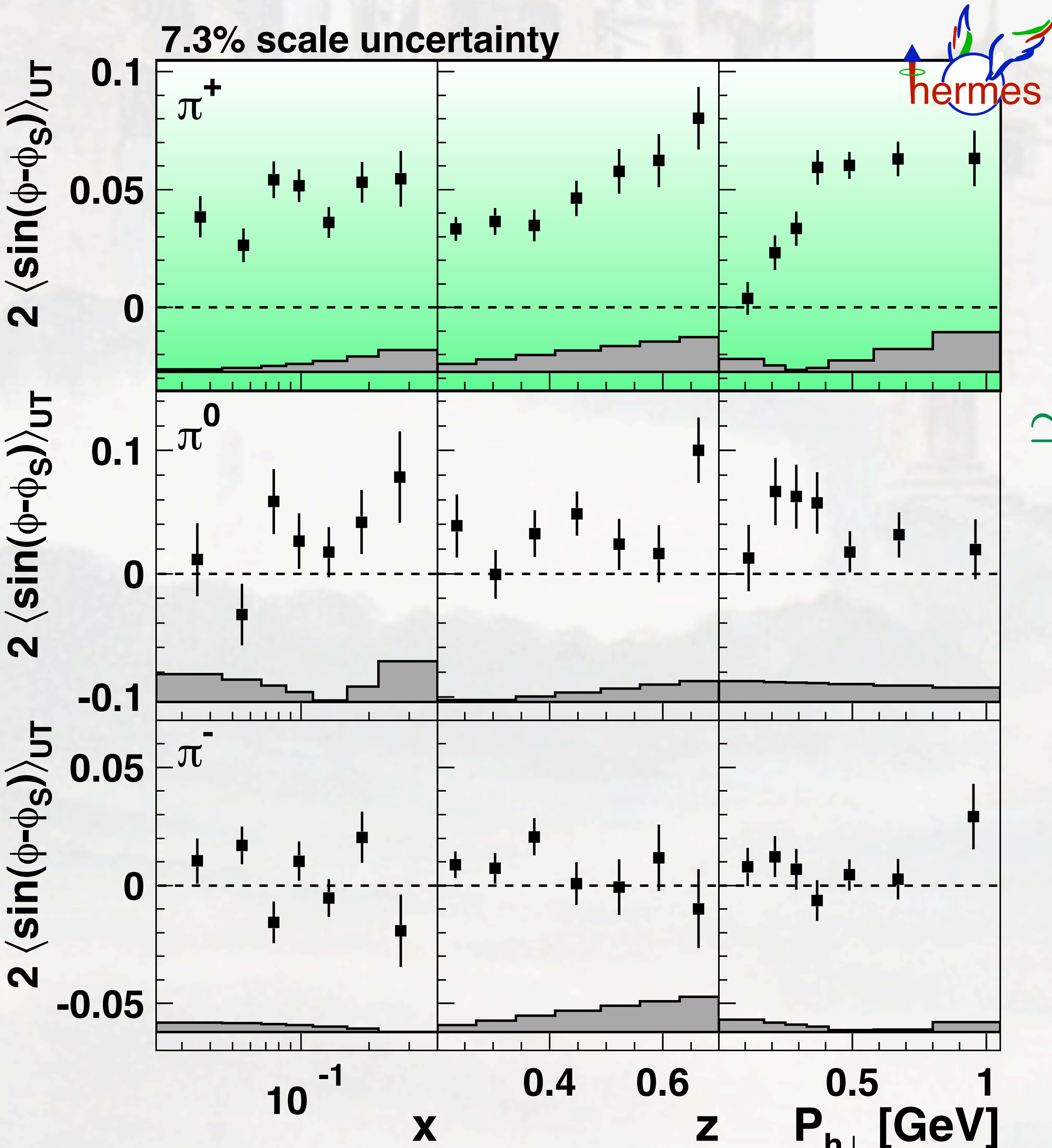

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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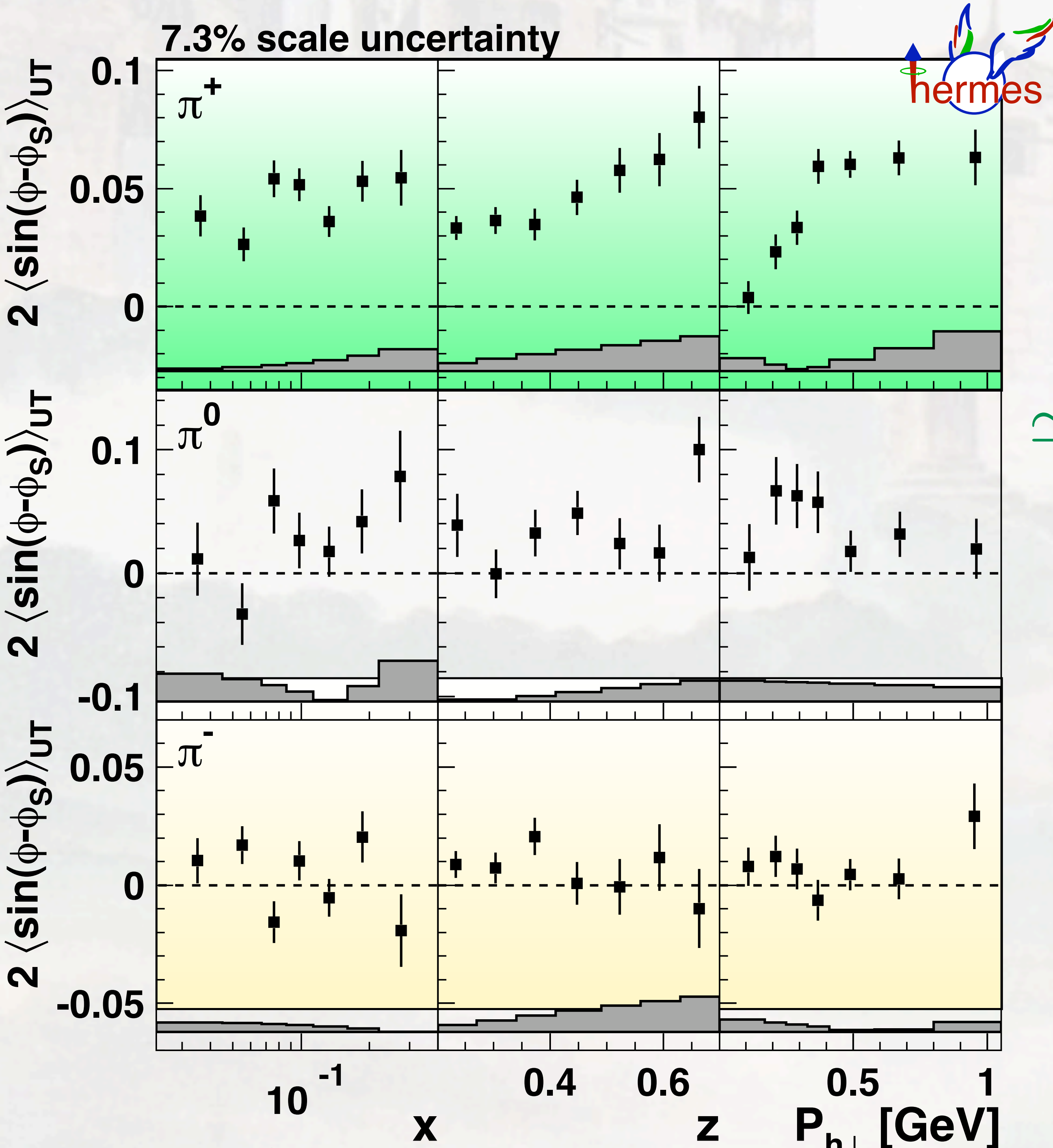

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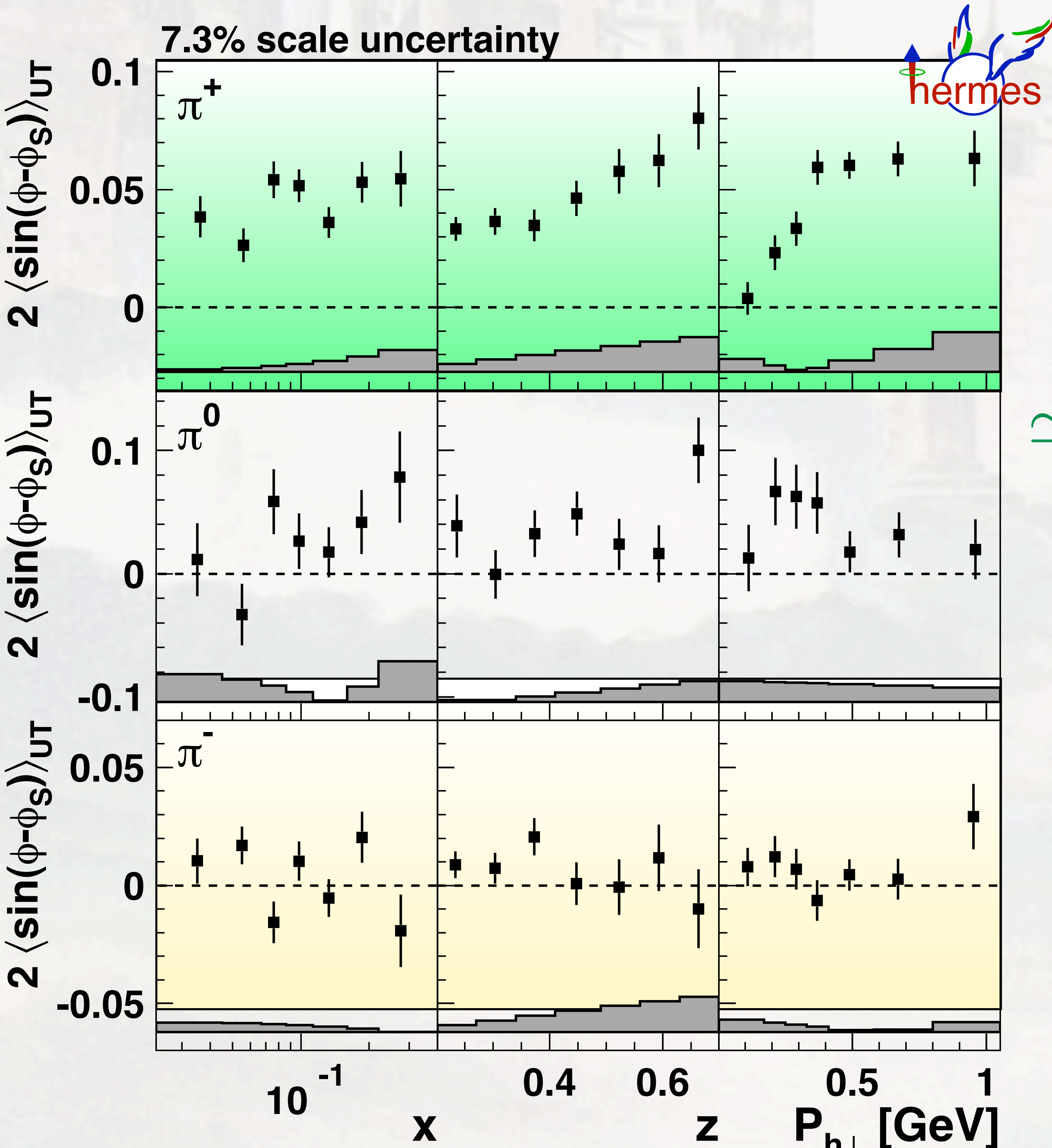
☛ u-quark Sivers DF < 0

☛ 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

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



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☛ L.Pappalardo

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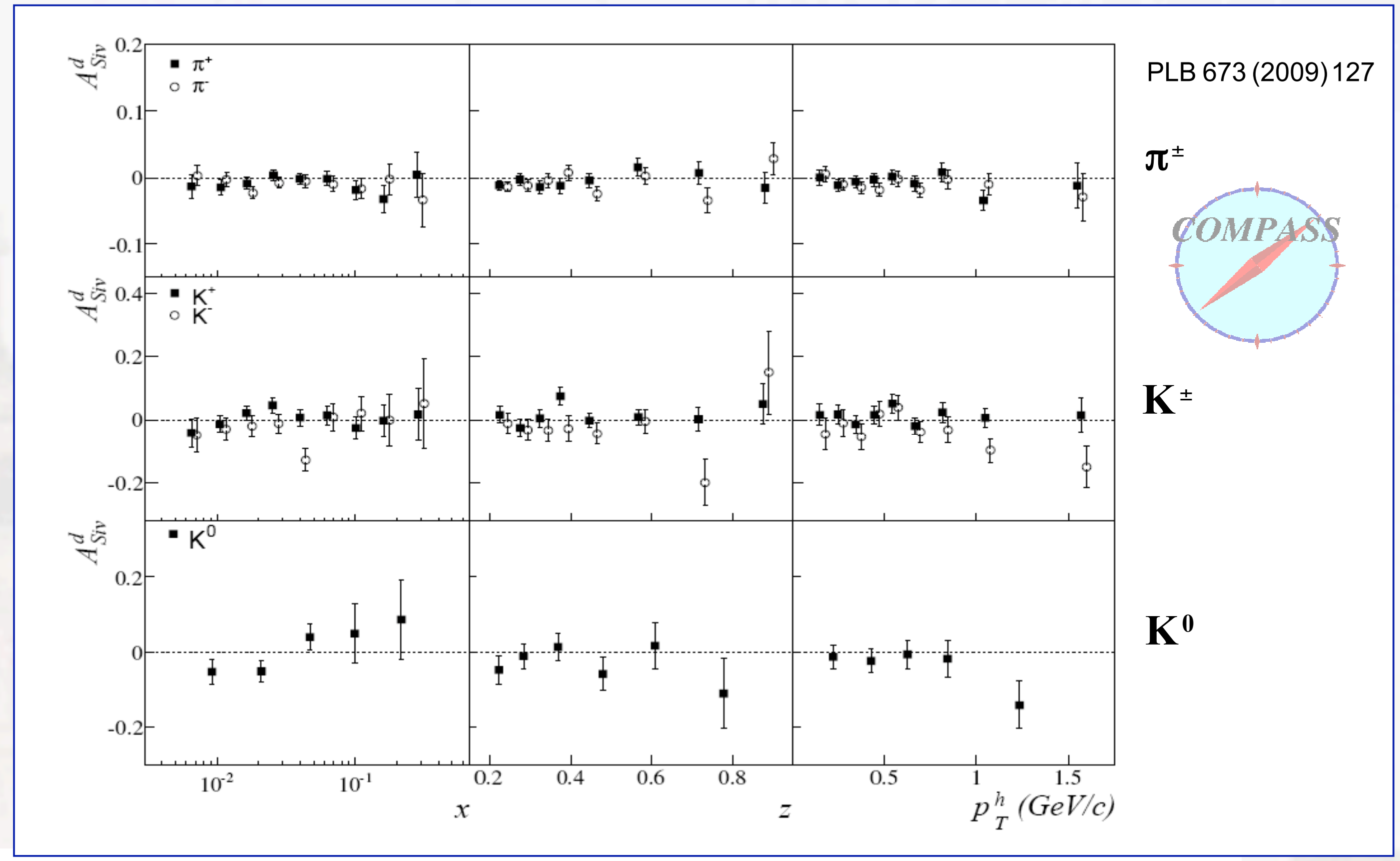
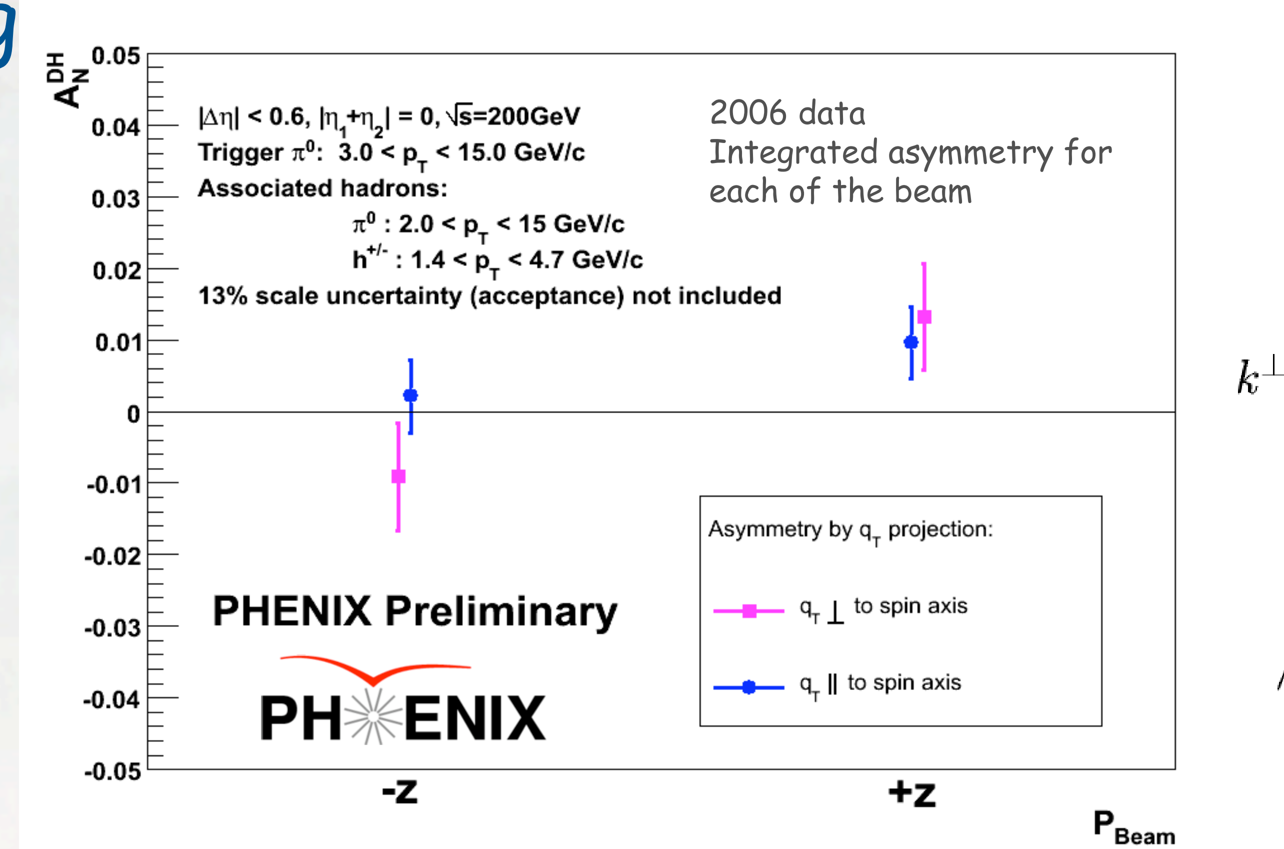
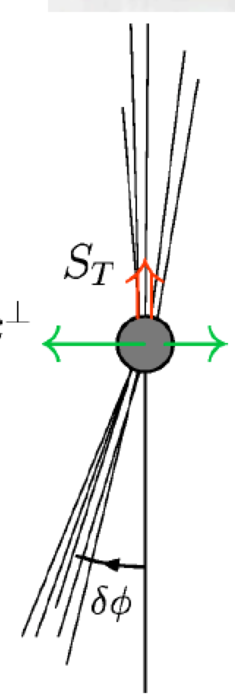
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers function

- cancelation for D target supports opposite signs of u and d Sivers
- small gluon Sivers suggested by PHENIX
- new results from JLab using ^{3}He target and from COMPASS for proton target
  - ☛ **J.-P.Chen, H.Wollny**
- check sign change of Sivers function in upcoming DY experiments







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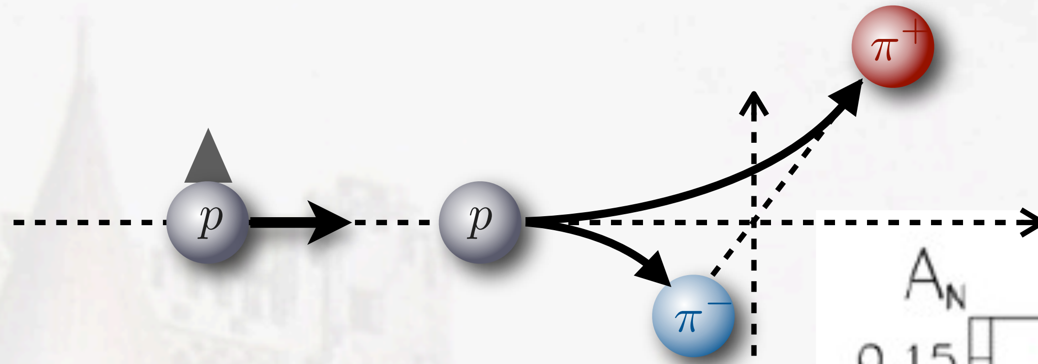
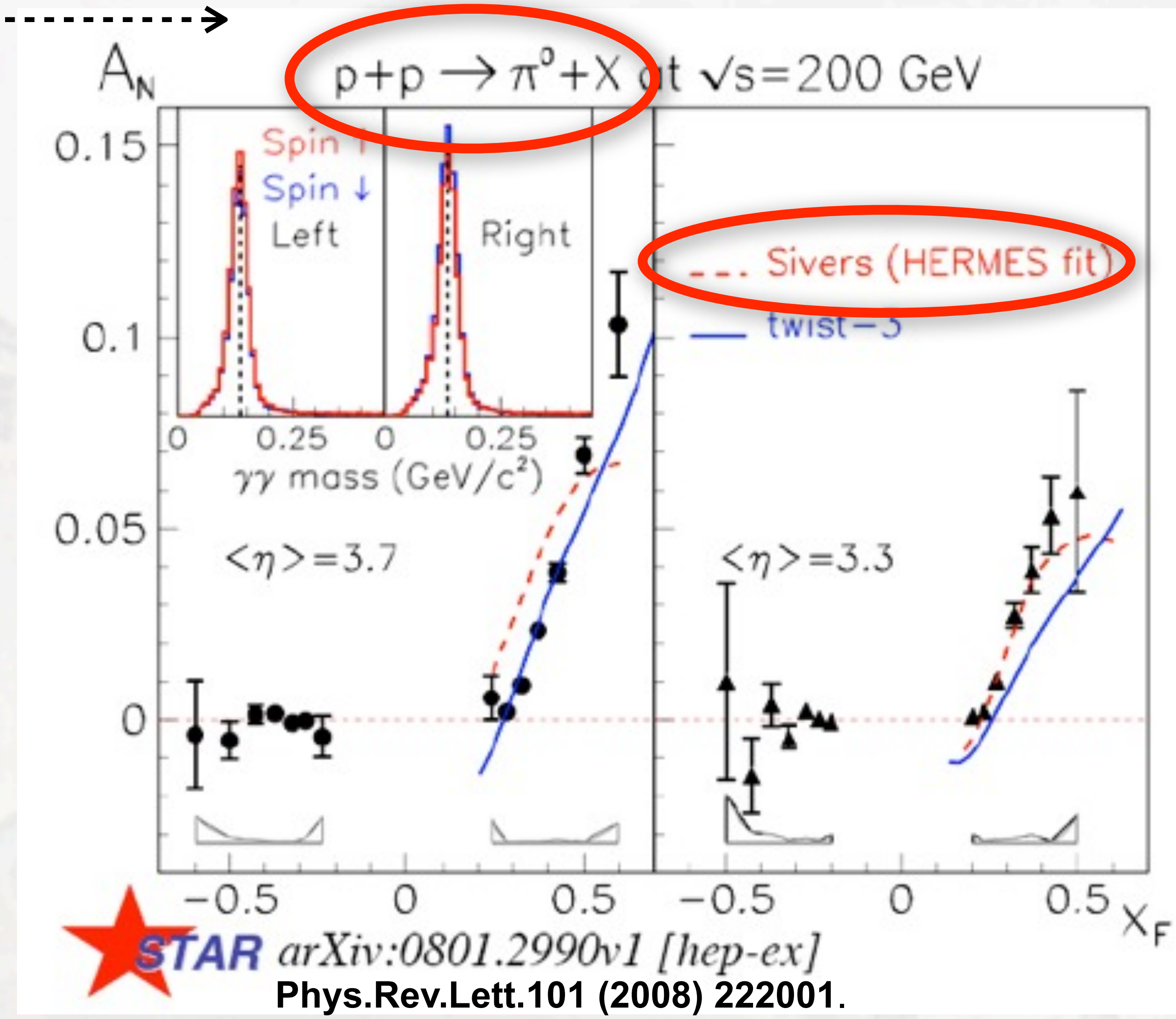


pp collisions

- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect



pp collisions

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U	f_1		$h_1^\perp$
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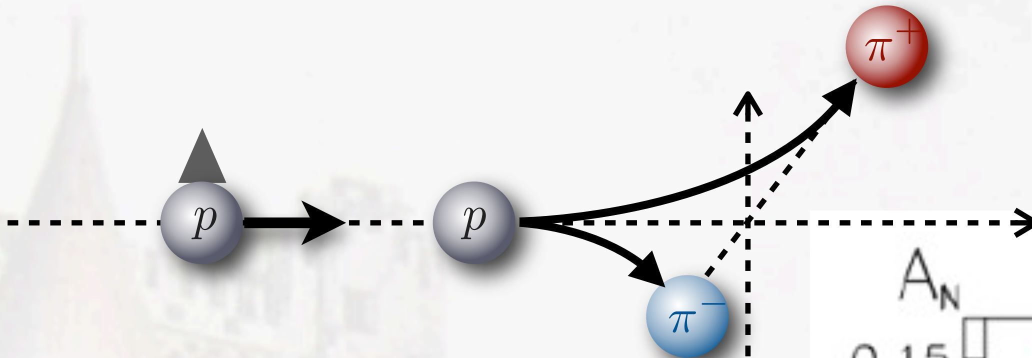

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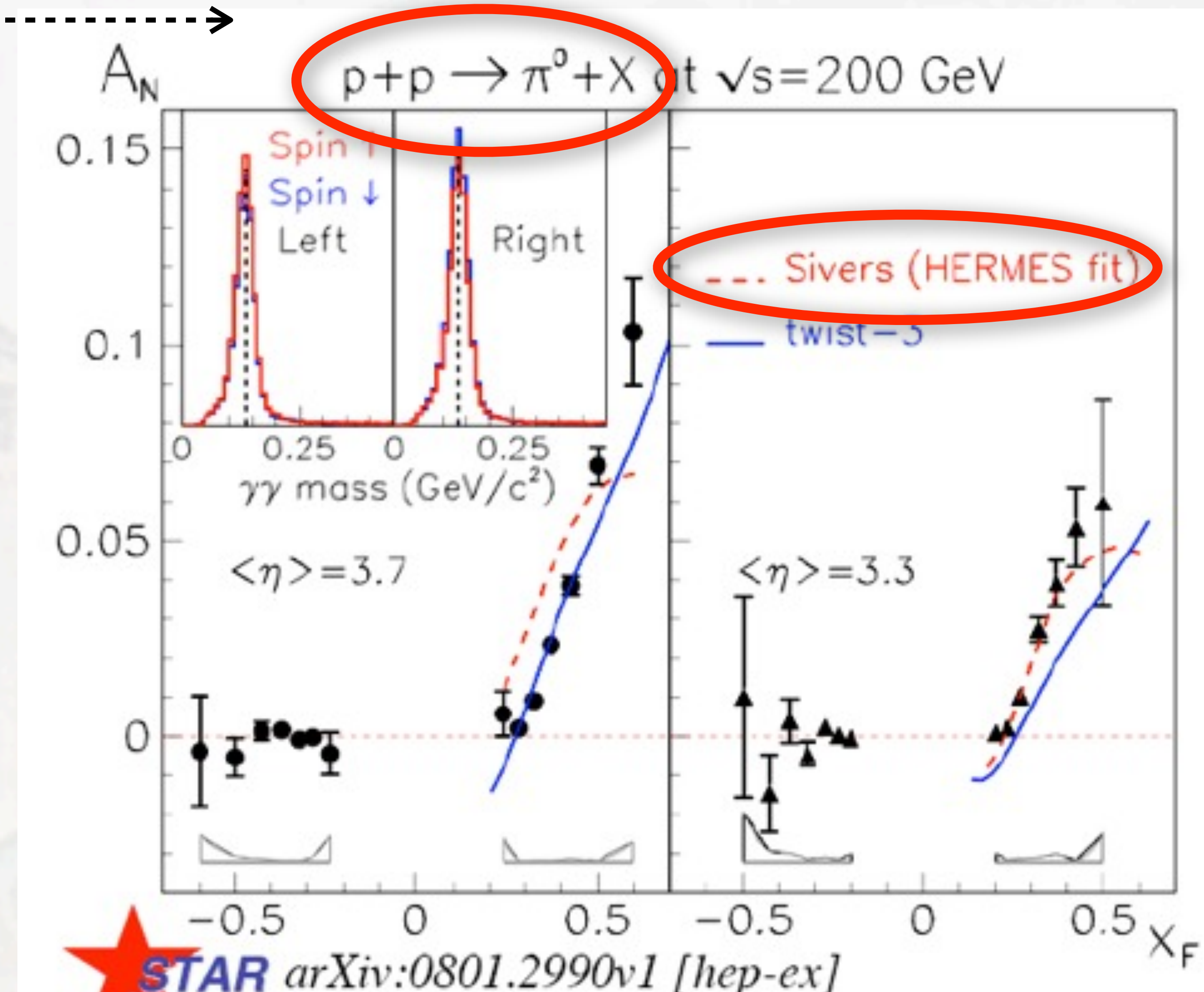

Phys.Rev.Lett.101 (2008) 222001.

pp collisions

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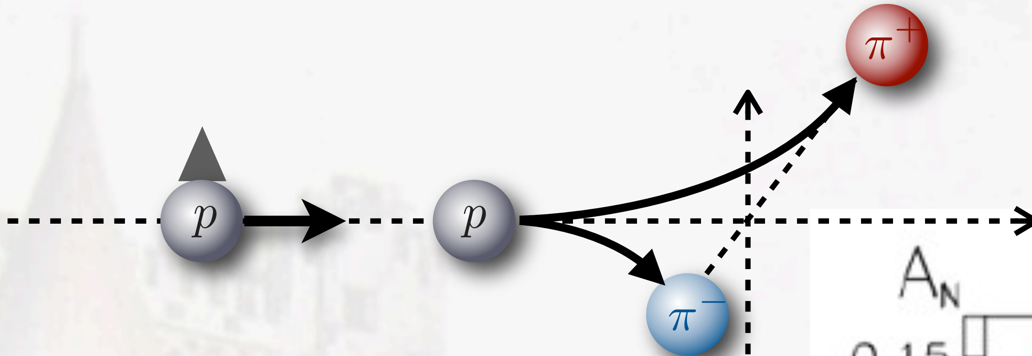
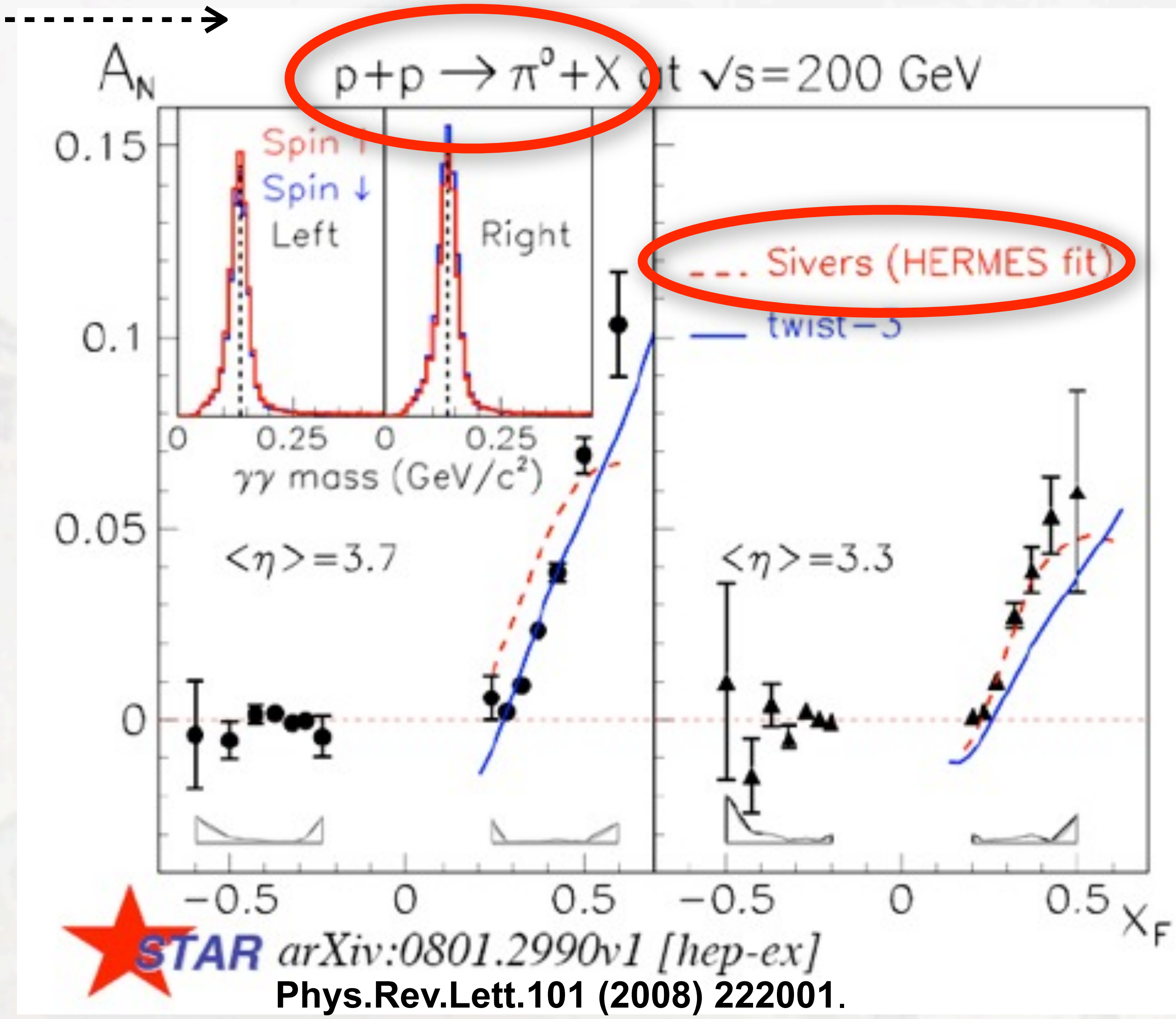
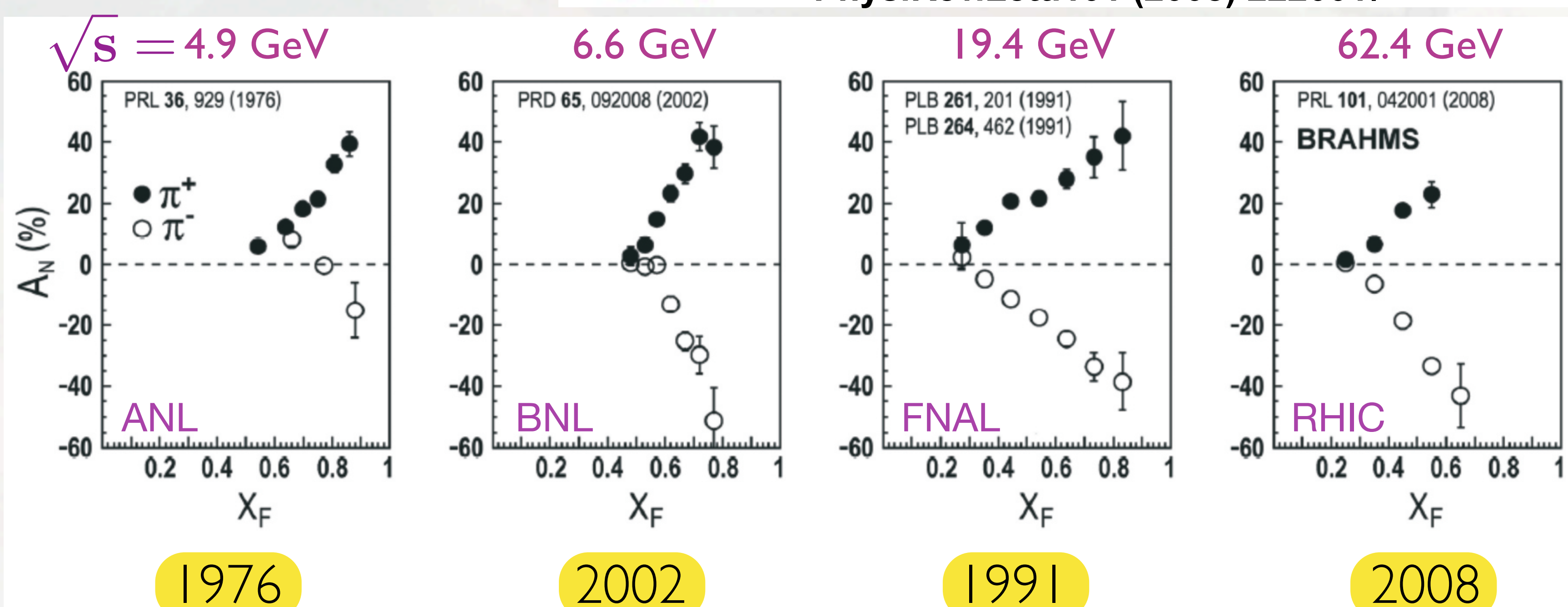


- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect
- only sizable in forward direction
- A_N in pp persist over wide energy range:





	U	L	T
U	f_1		$h_1^\perp$
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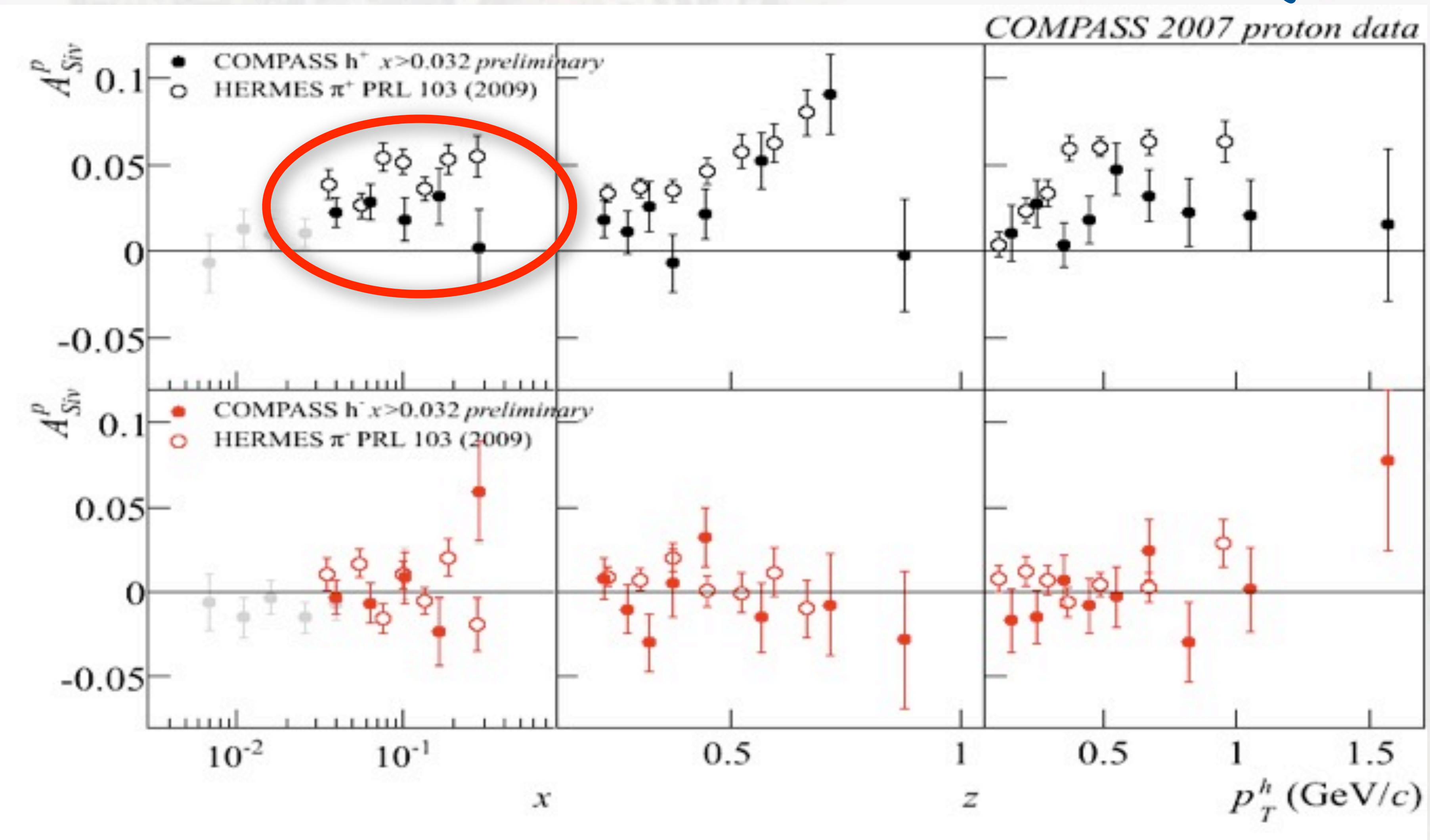
Sivers function (some surprises)



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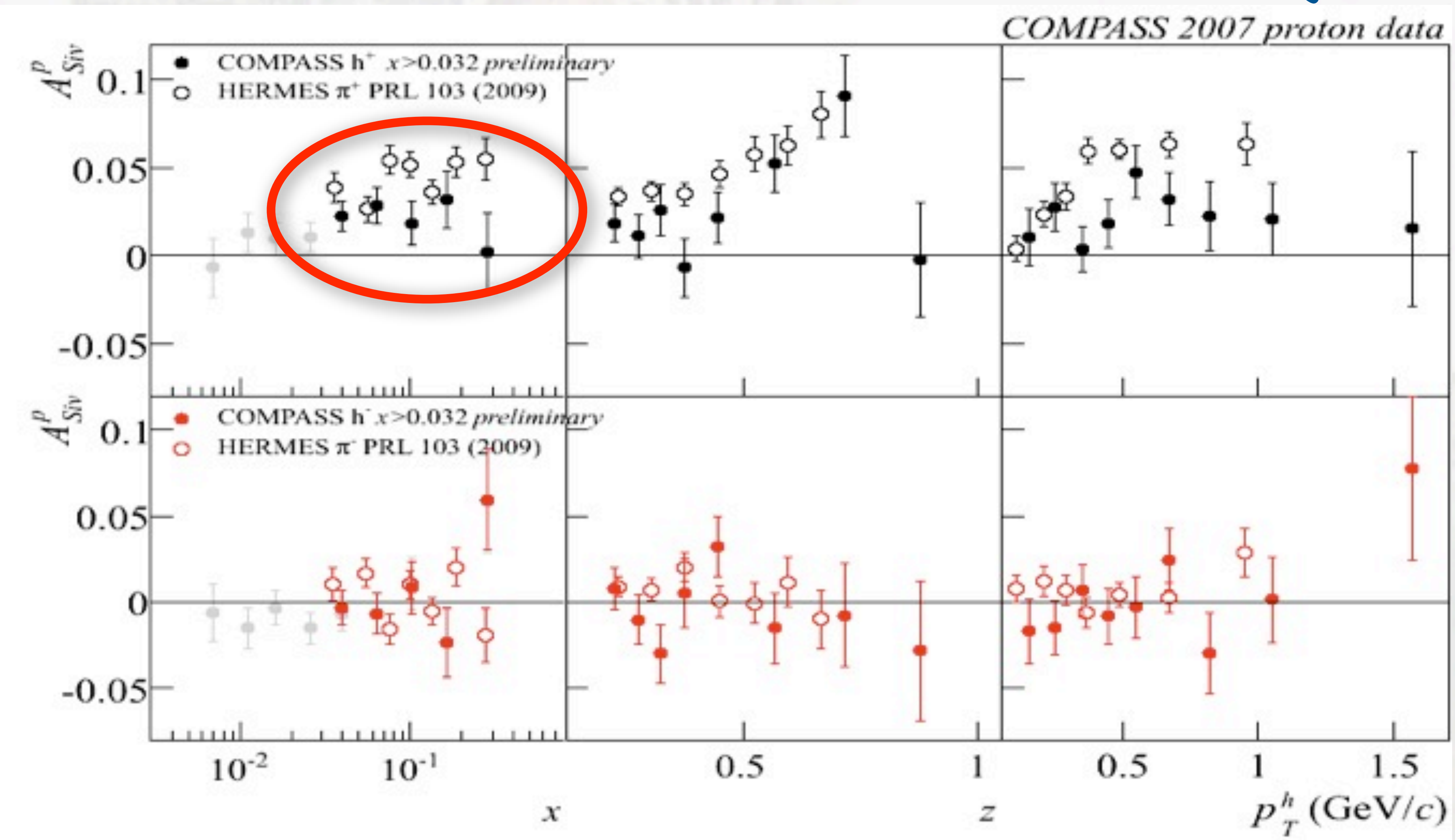

☛ **H. Wollny**

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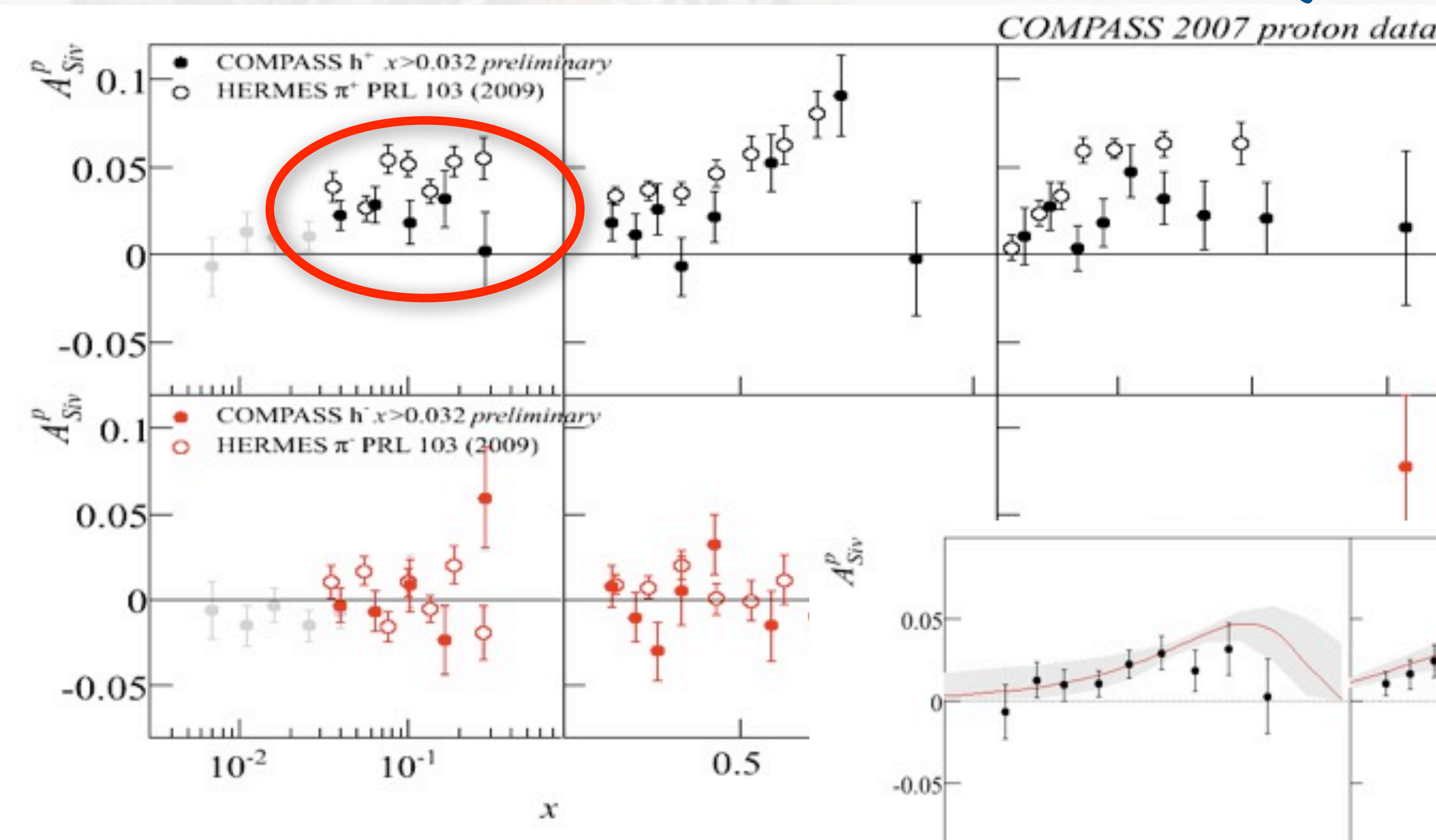

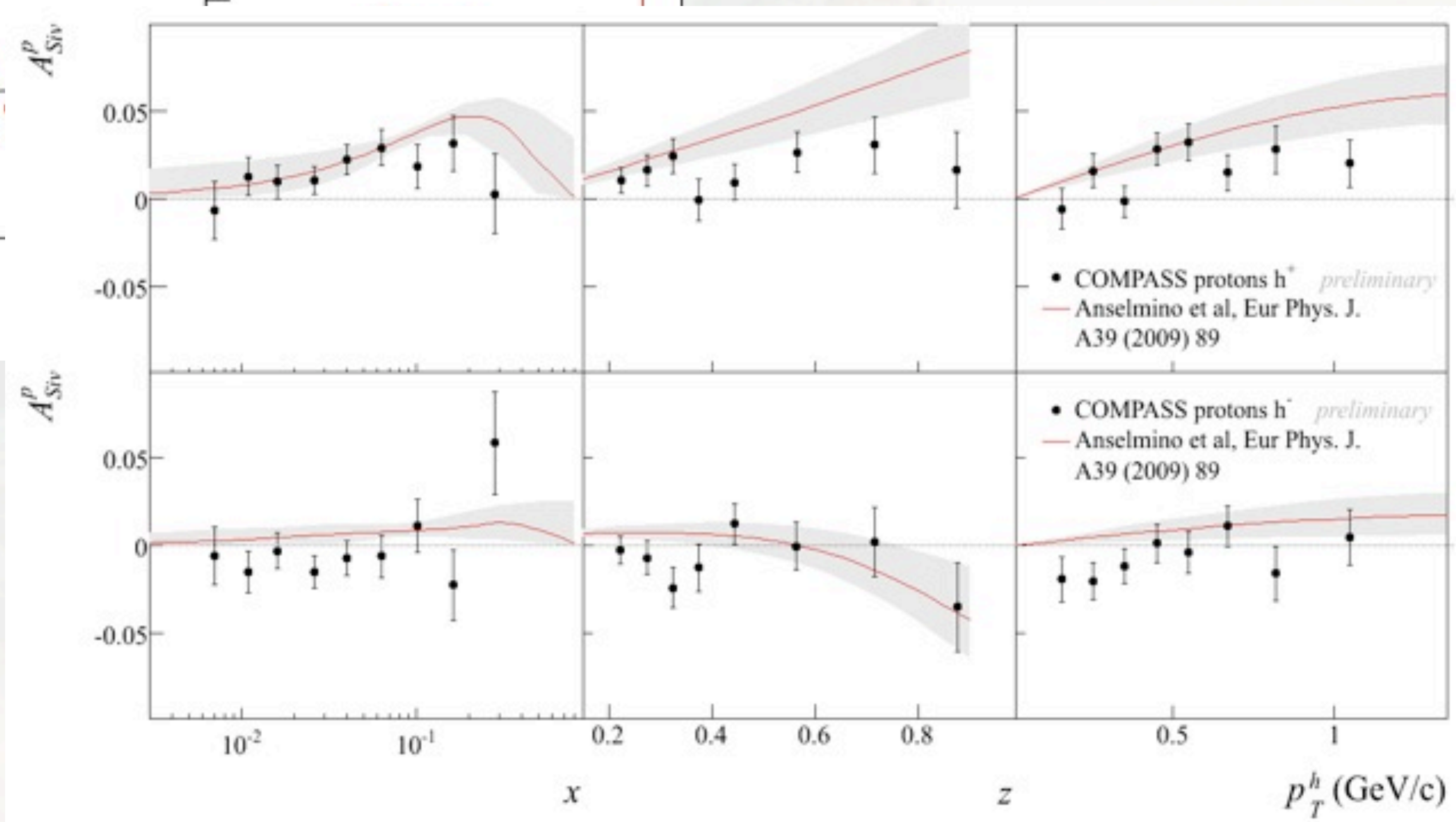

☛ H. Wollny

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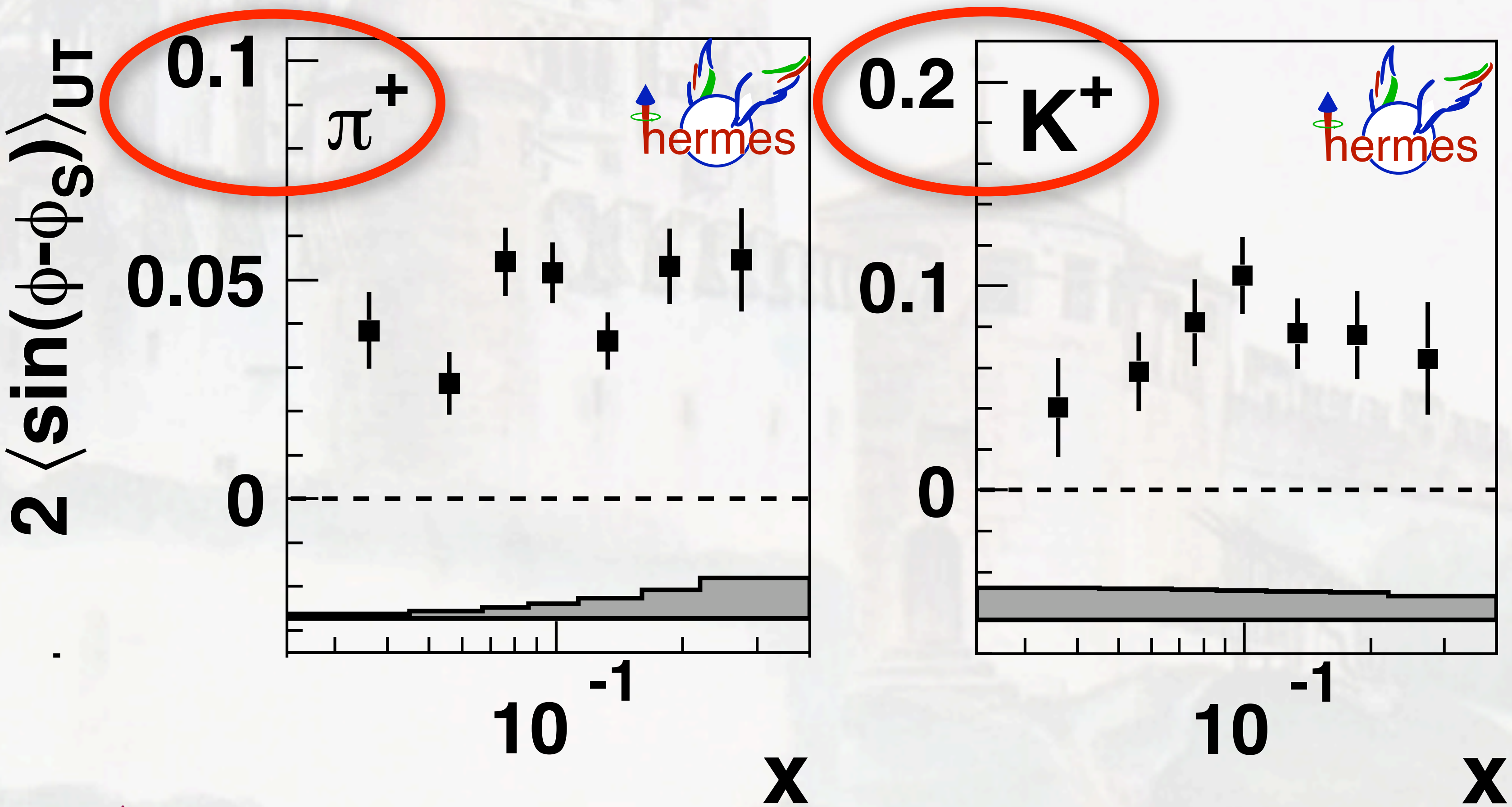

π^+/K^+ production dominated by scattering off u-quarks: $\simeq - \dfrac{\mathbf{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}}{\mathbf{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}}$

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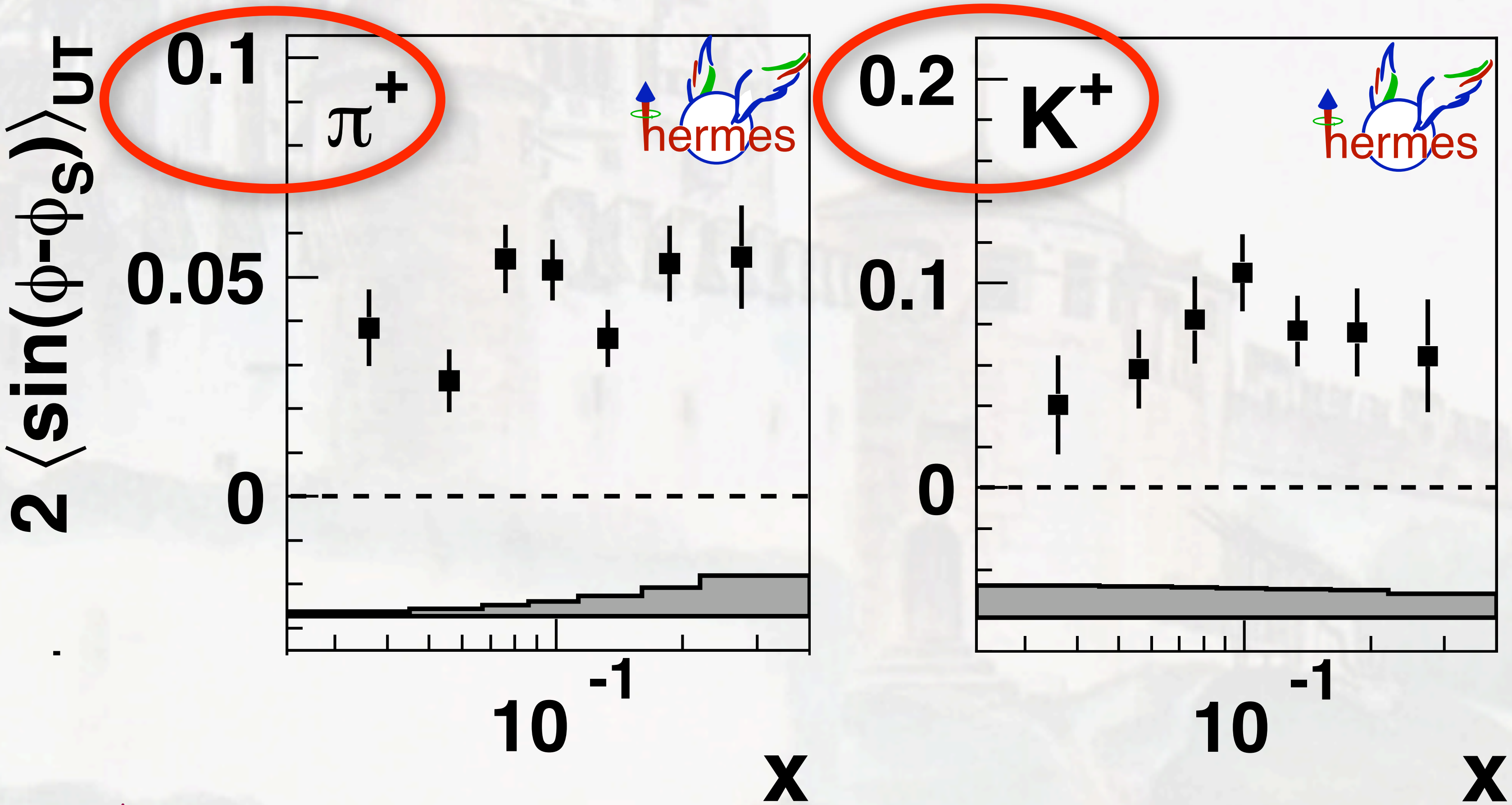

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

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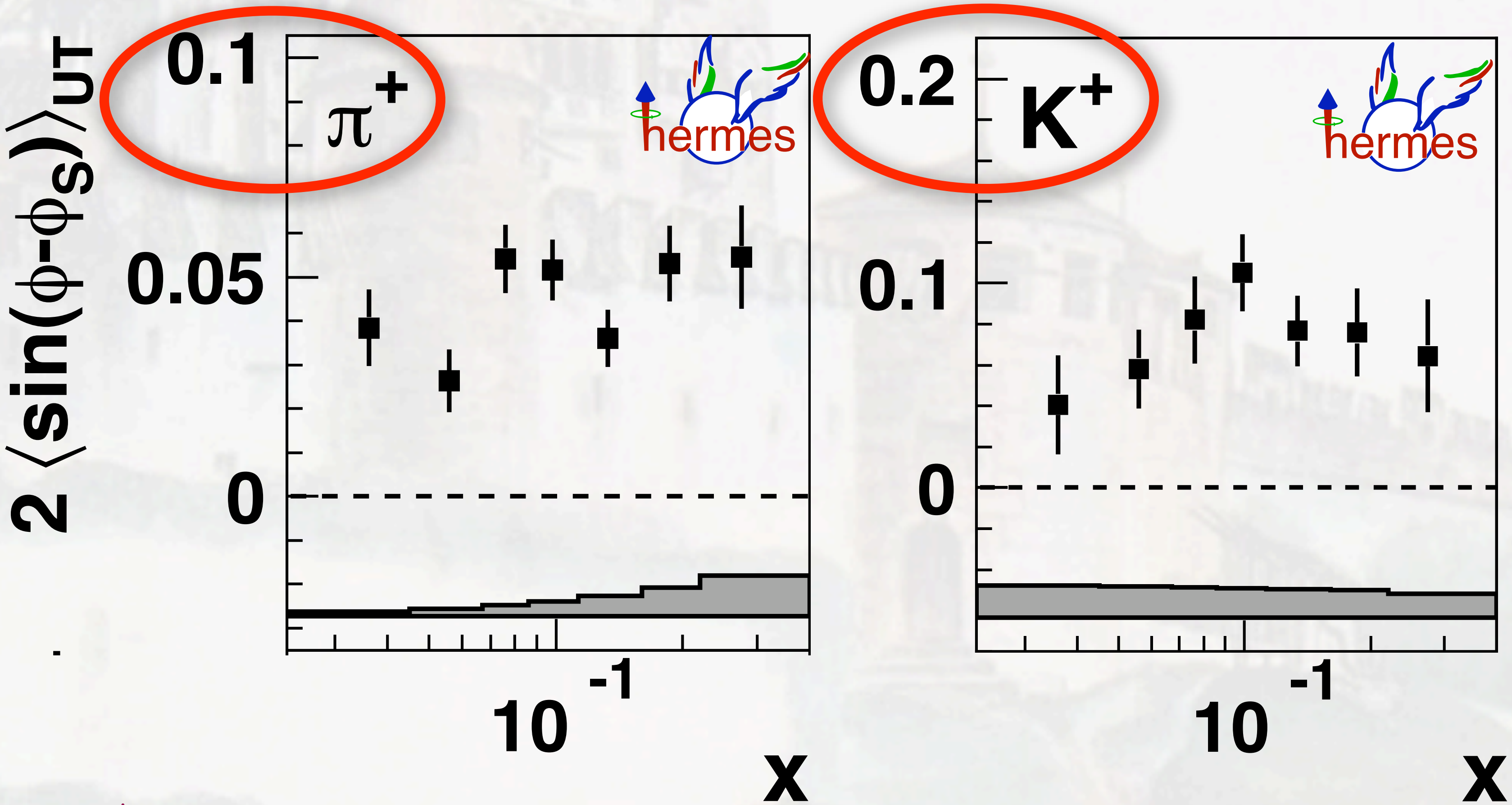

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- convolution integrals depend on k_T dependence of fragmentation functions

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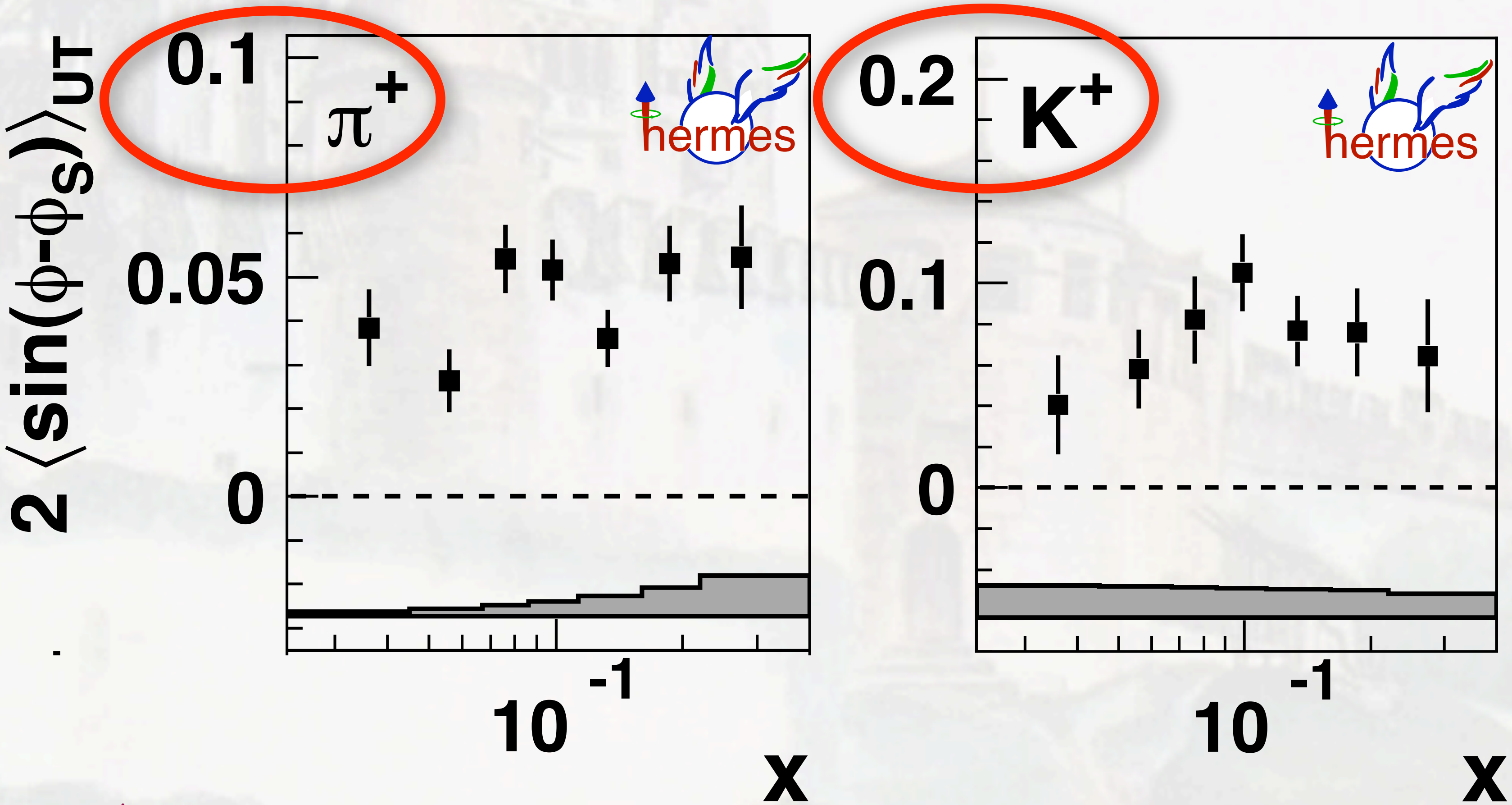

☛ H. Wollny, L. Pappalardo

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

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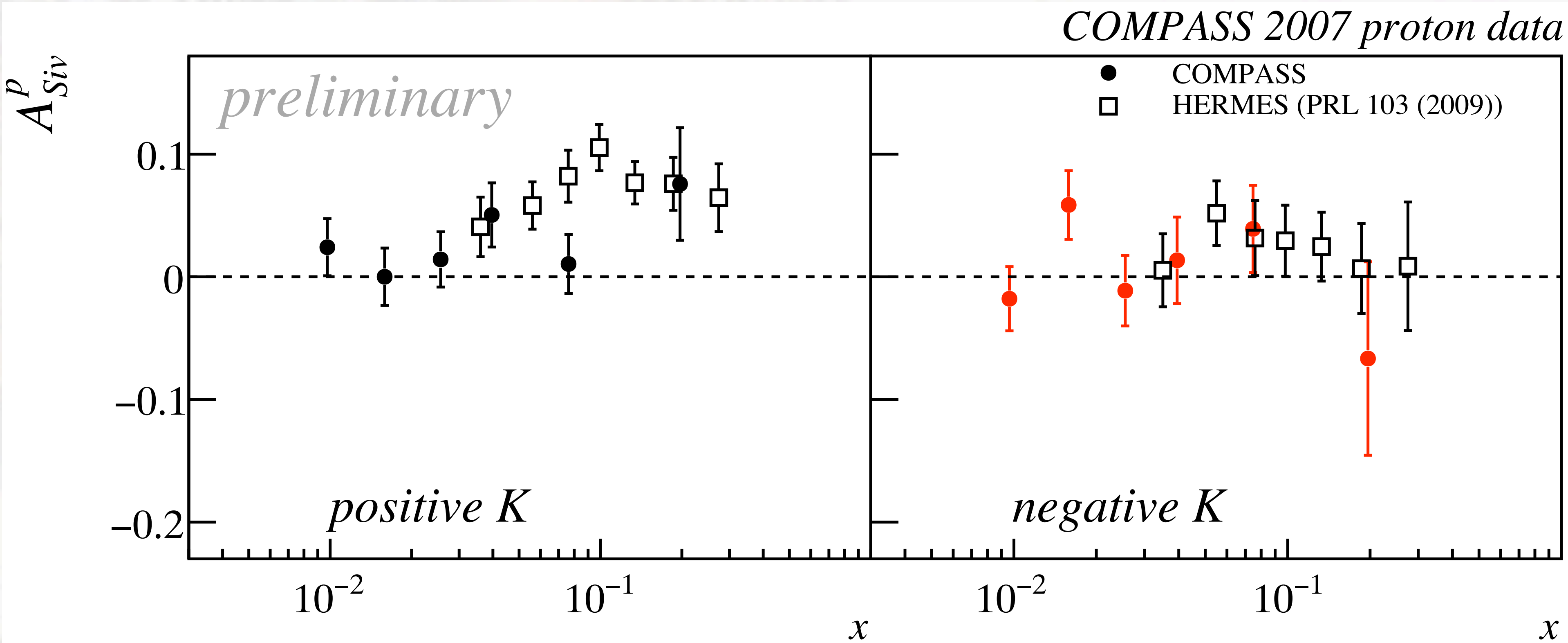
Sivers function (some surprises)



☛ H. Wollny, L. Pappalardo

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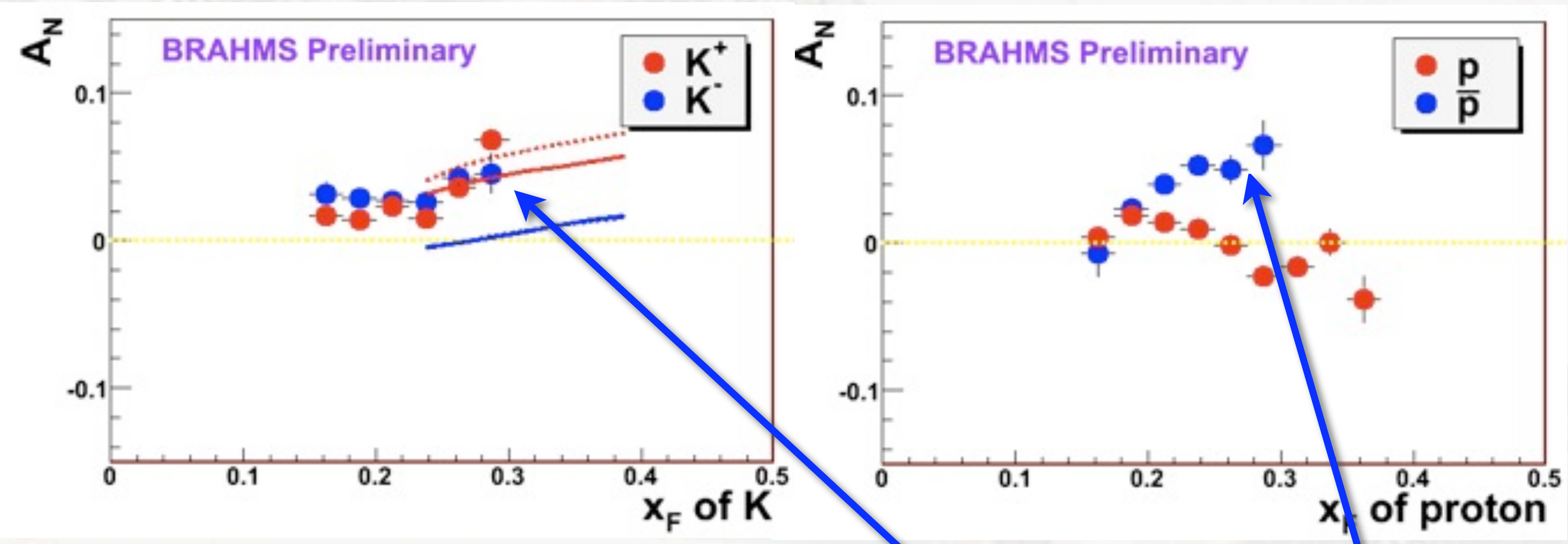
(even more surprises)



large K^- and anti-proton asymmetries

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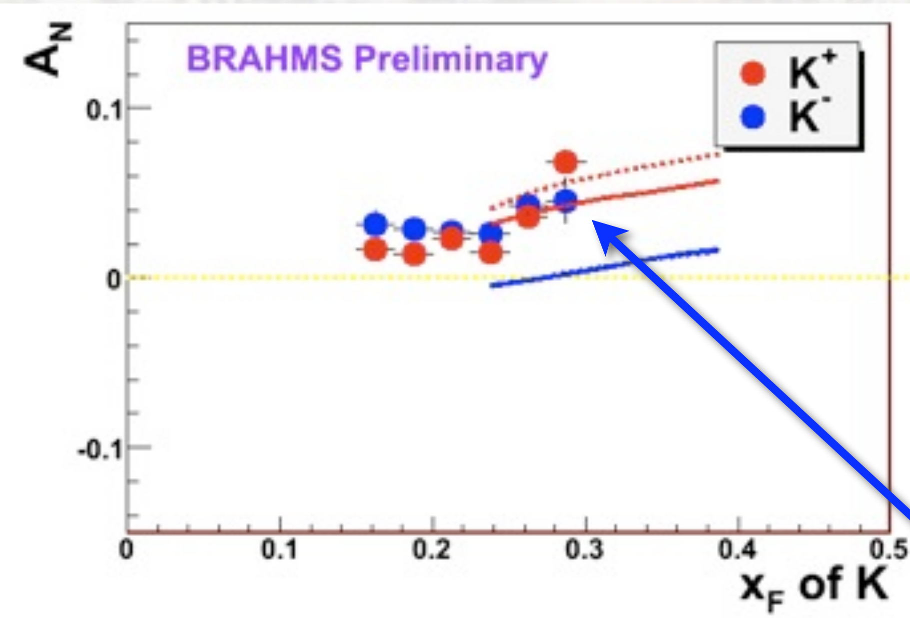
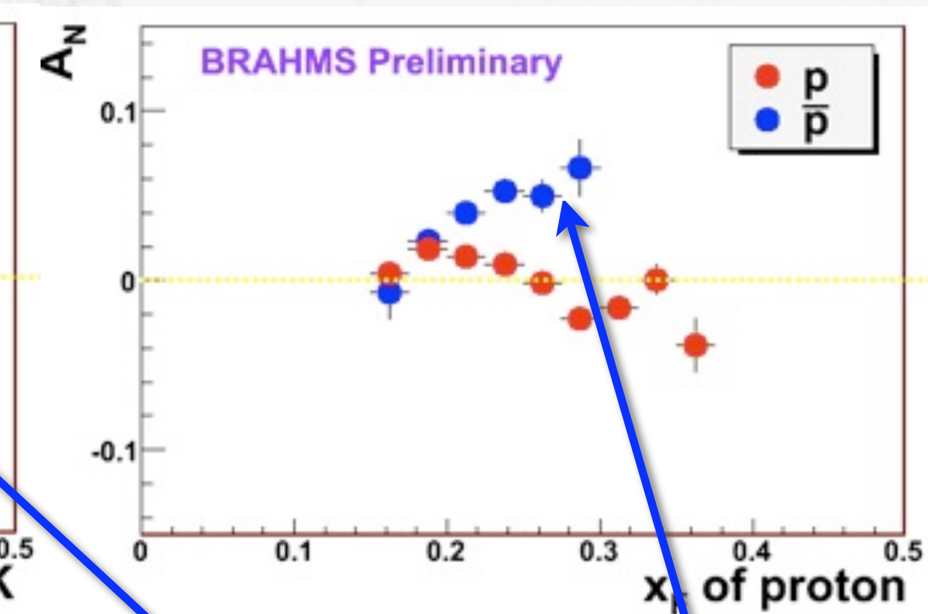
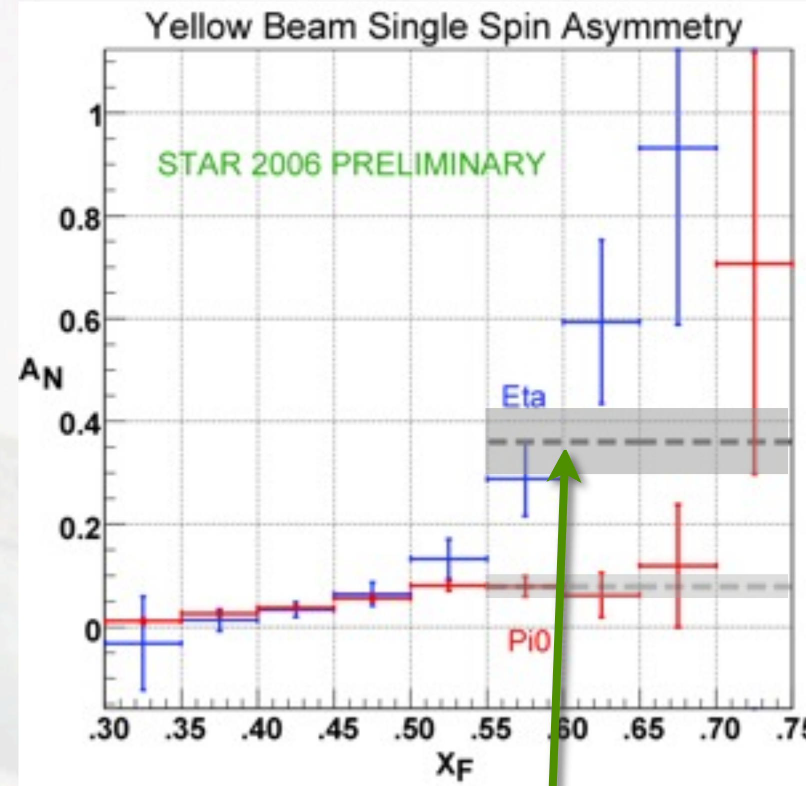
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

(even more surprises)





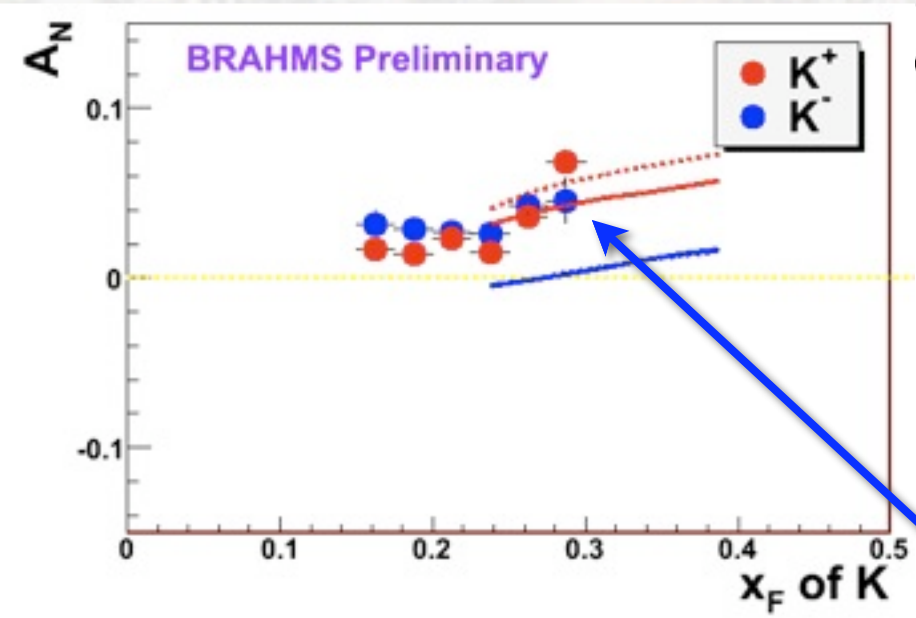


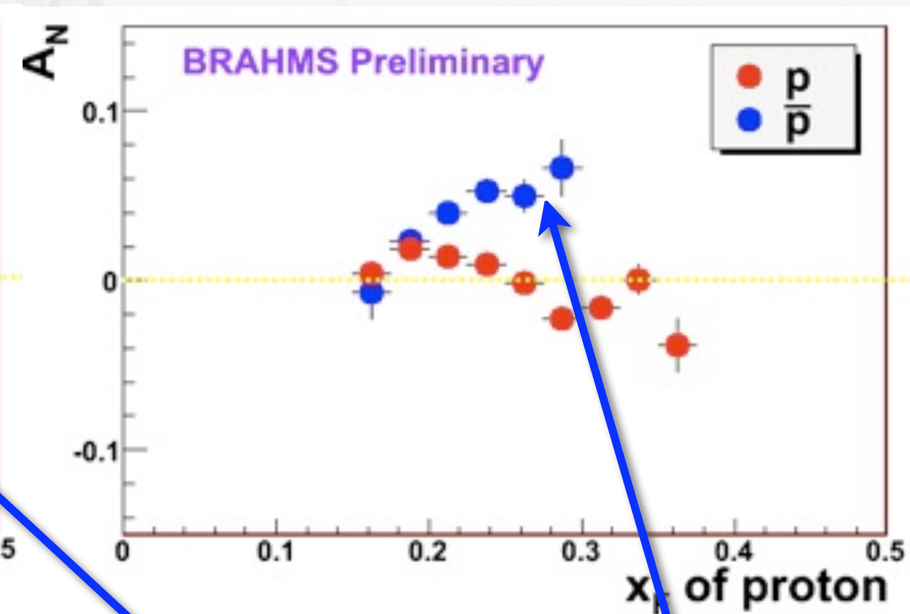
large K$^-$ and anti-proton asymmetries

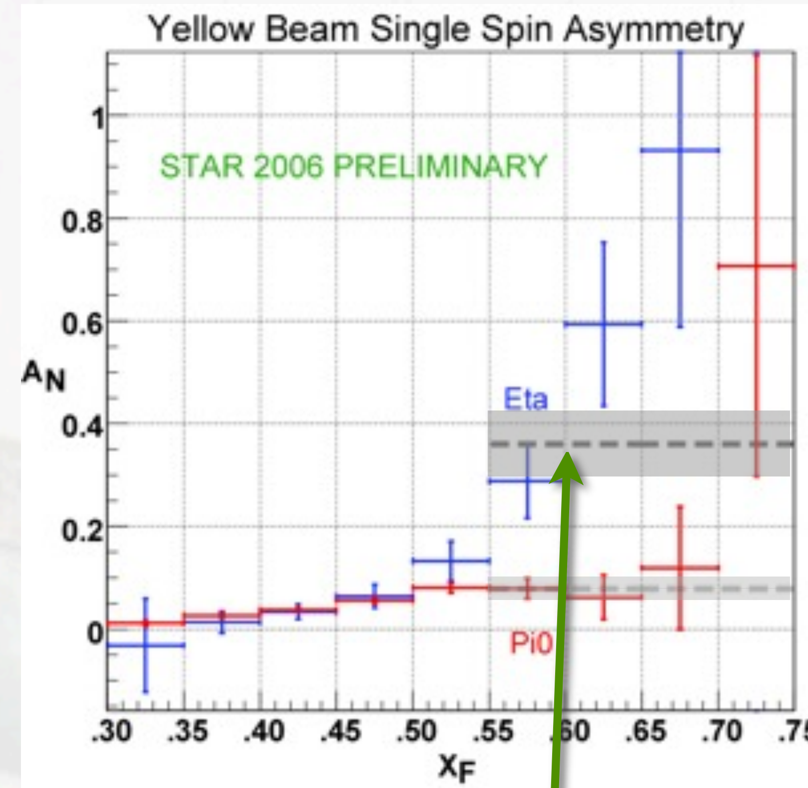
large eta asymmetries

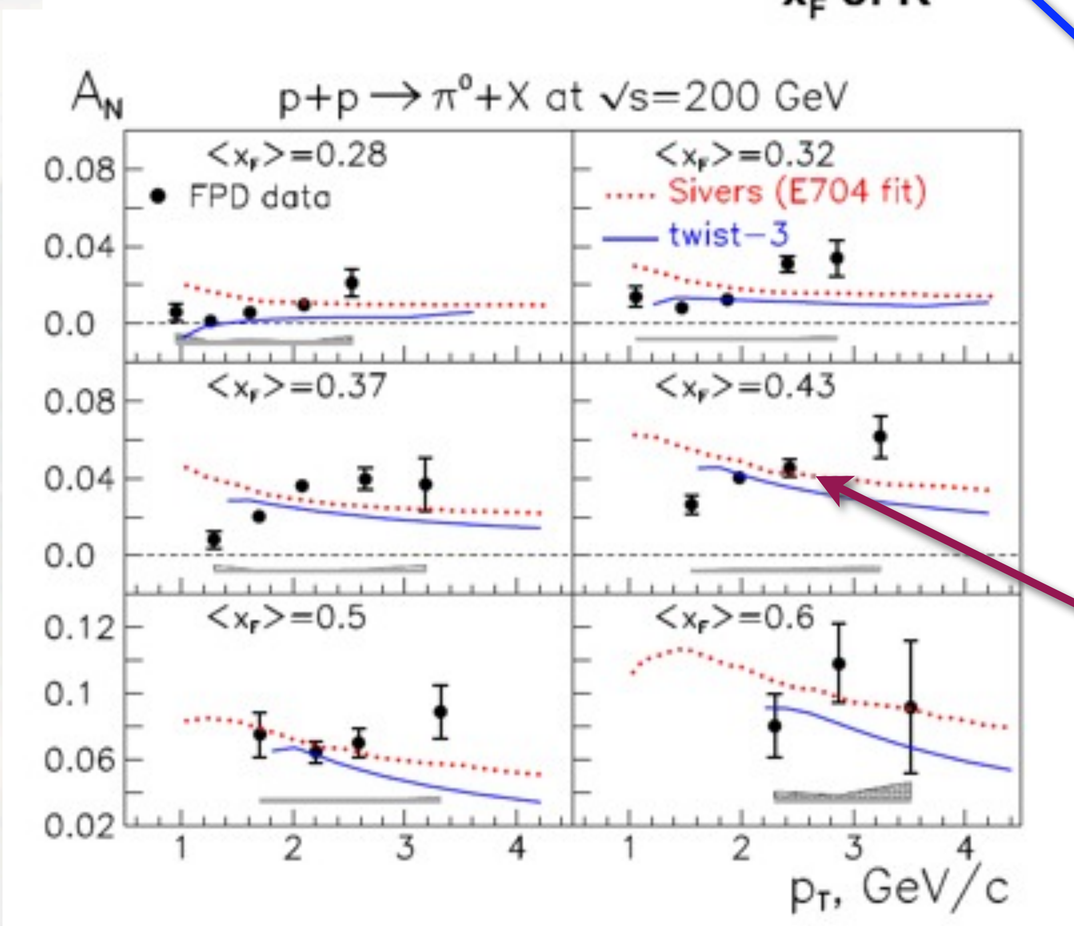
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

(even more surprises)









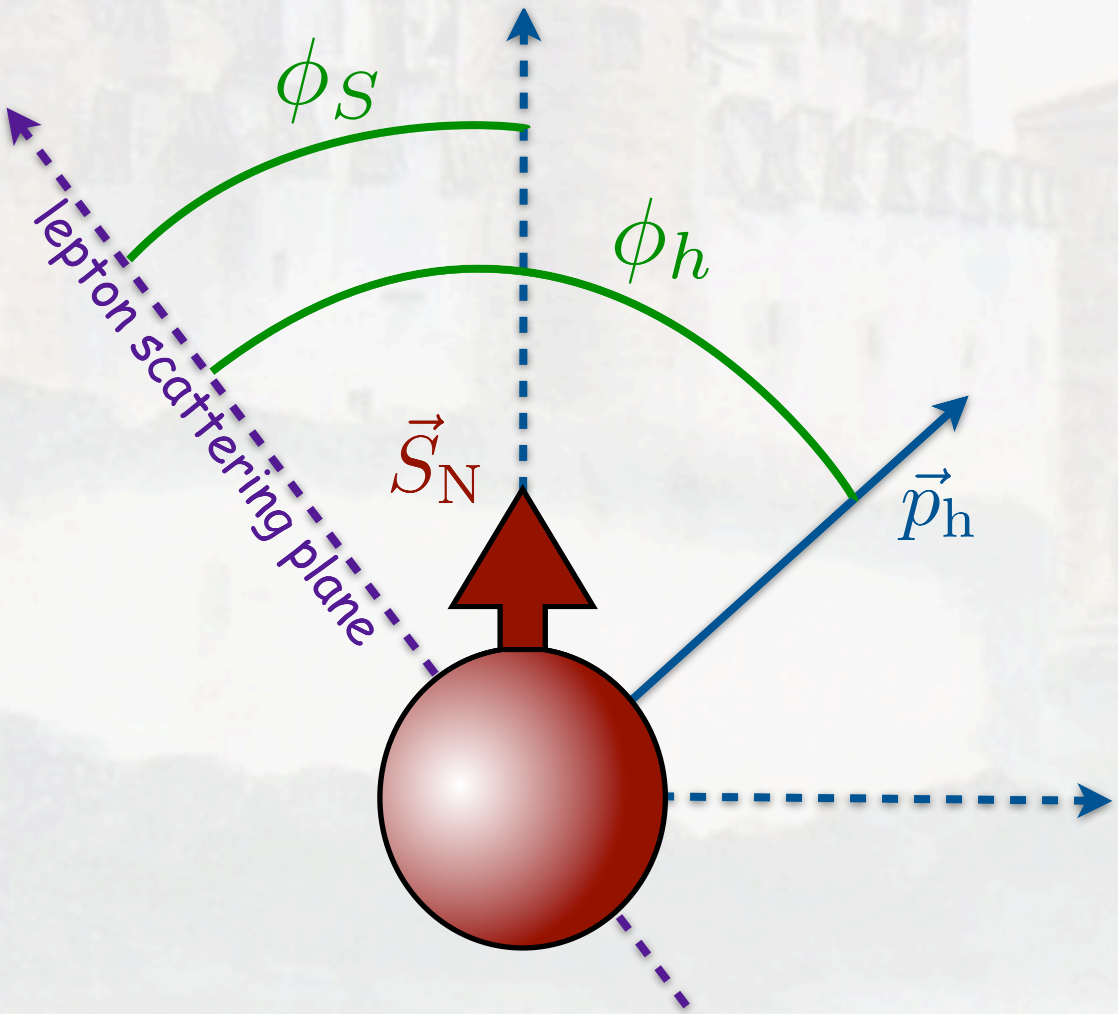
large K^- and anti-proton asymmetries

at fixed x_F don't follow expected (perturbative) behavior

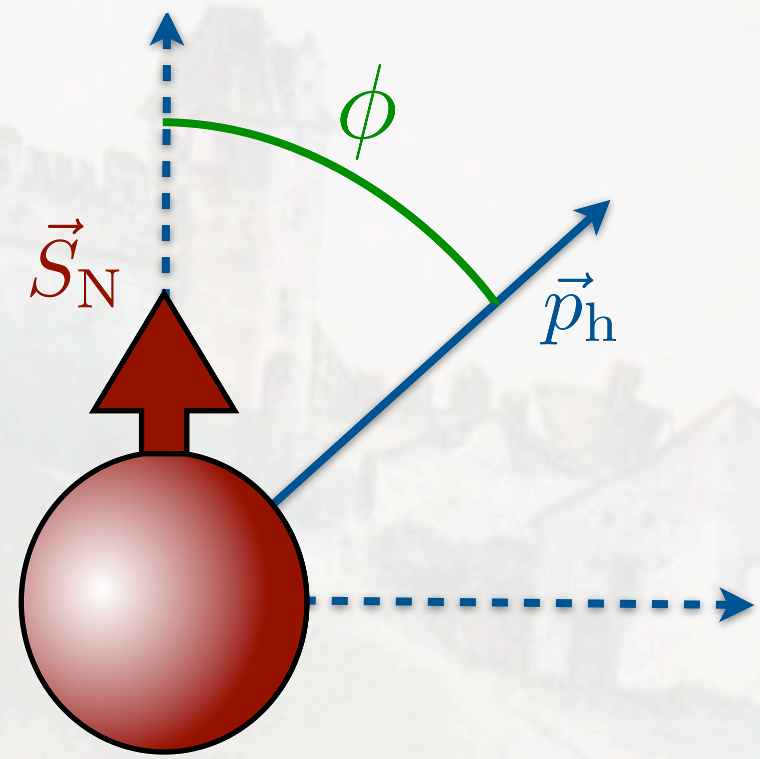
large eta asymmetries

Inclusive hadron electro-production

$$ep^{\uparrow} \to ehX \qquad\qquad ep^{\uparrow} \to hX$$



virtual photon going into the page



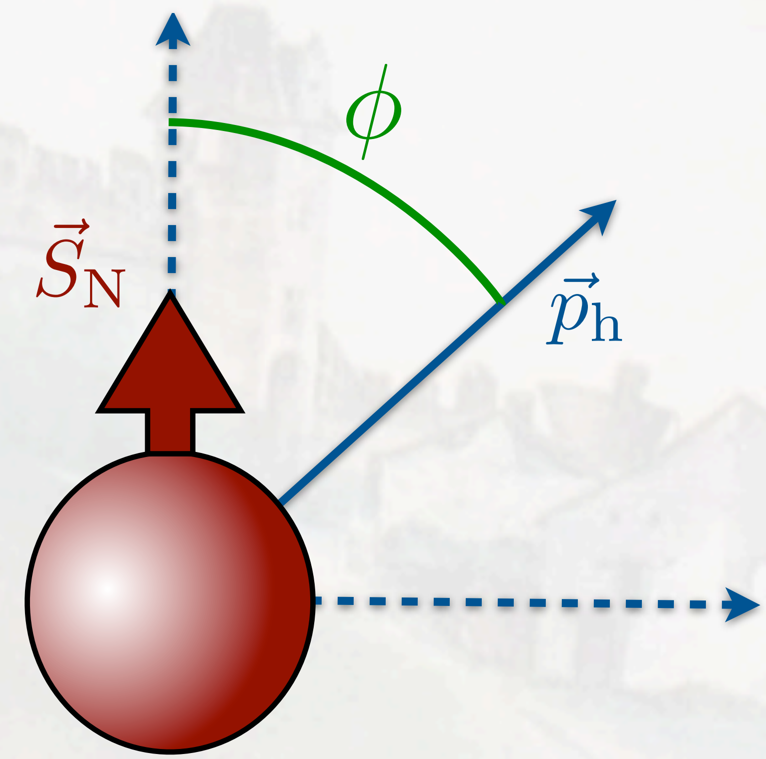
lepton beam going into the page

$$\phi \simeq \phi_h - \phi_S$$

➠ "Sivers angle"

Inclusive hadron electro-production

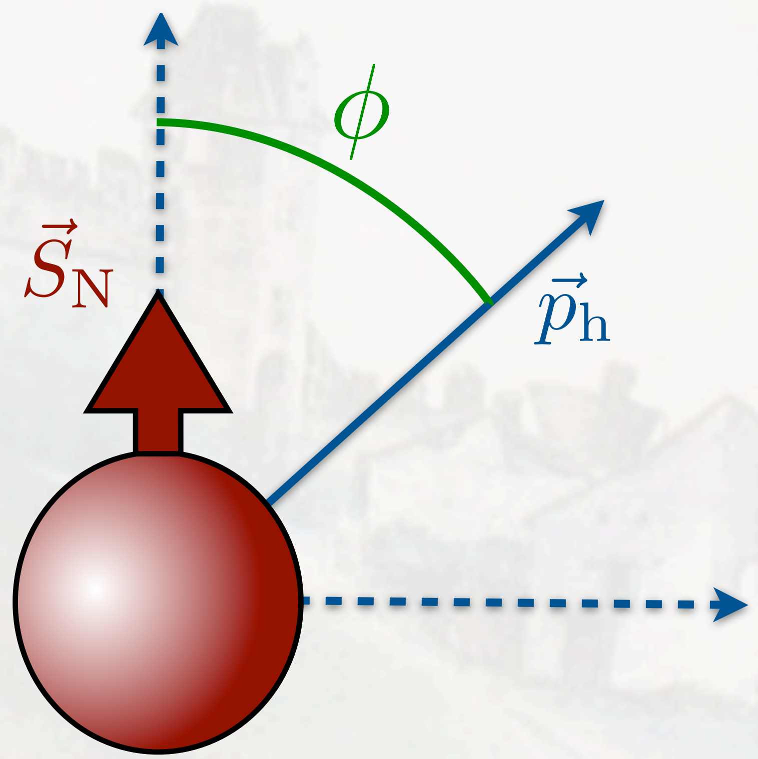
$$ep^{\uparrow} \to hX$$



Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

- scattered lepton undetected
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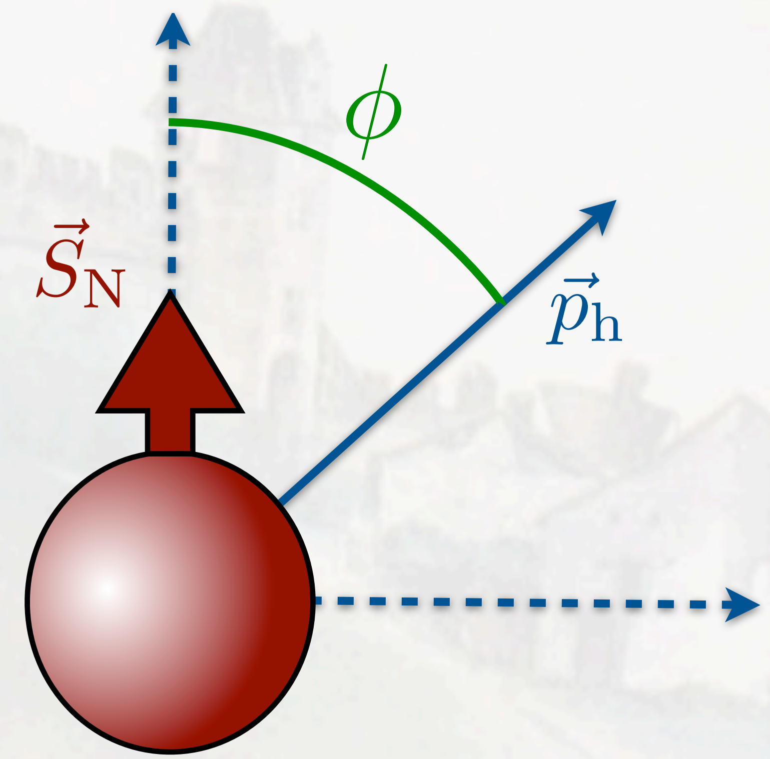
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?

$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

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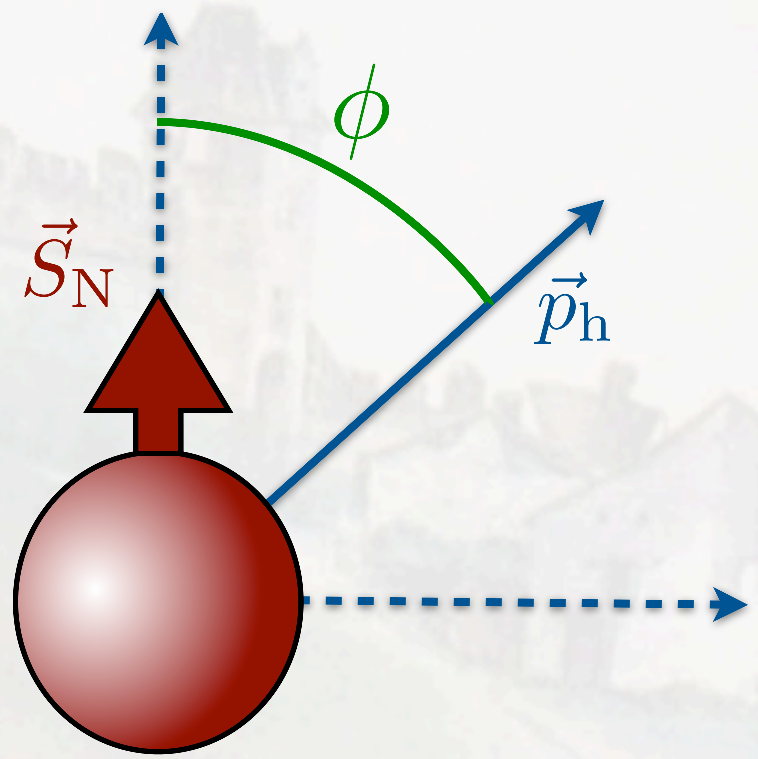
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to S_N ($k \times p_h$) ~ $\sin\phi$

$$ep^{\uparrow} \rightarrow hX$$



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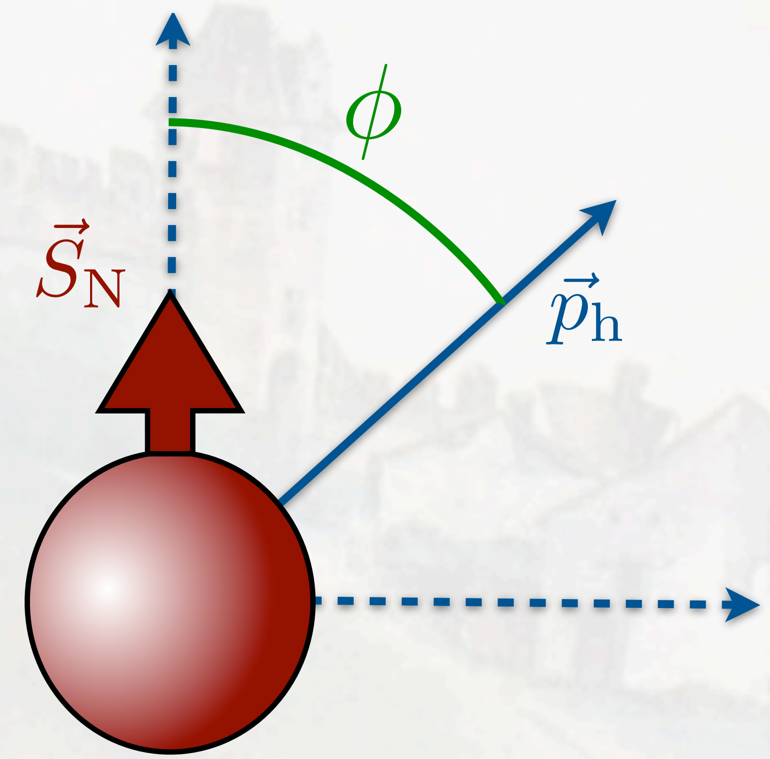
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to S_N ($k \times p_h$) ~ $\sin\phi$

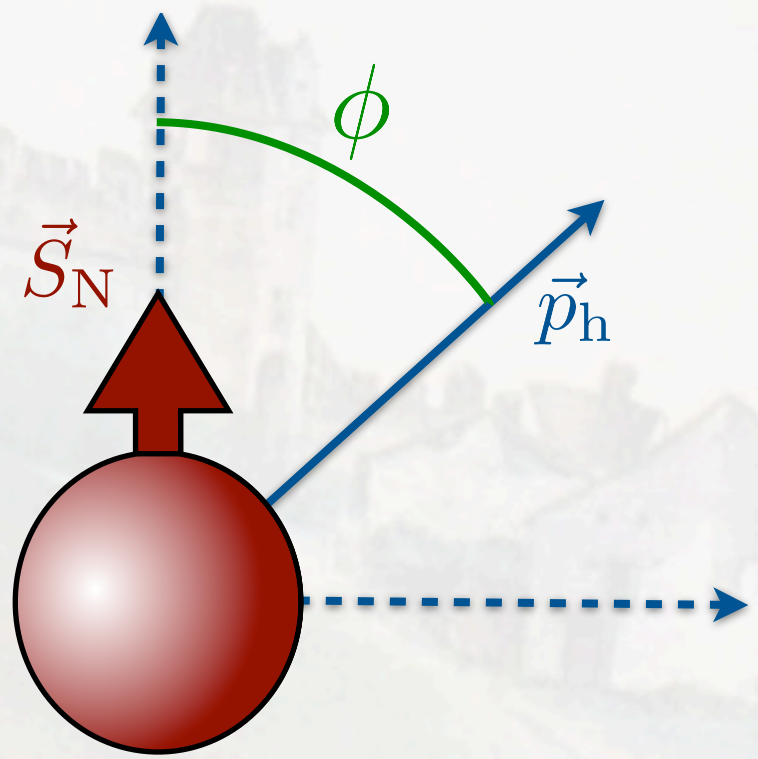


$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

Inclusive hadron electro-production

$$ep^{\uparrow} \rightarrow hX$$

- scattered lepton undetected
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to S_N ($k \times p_h$) ~ $\sin\phi$

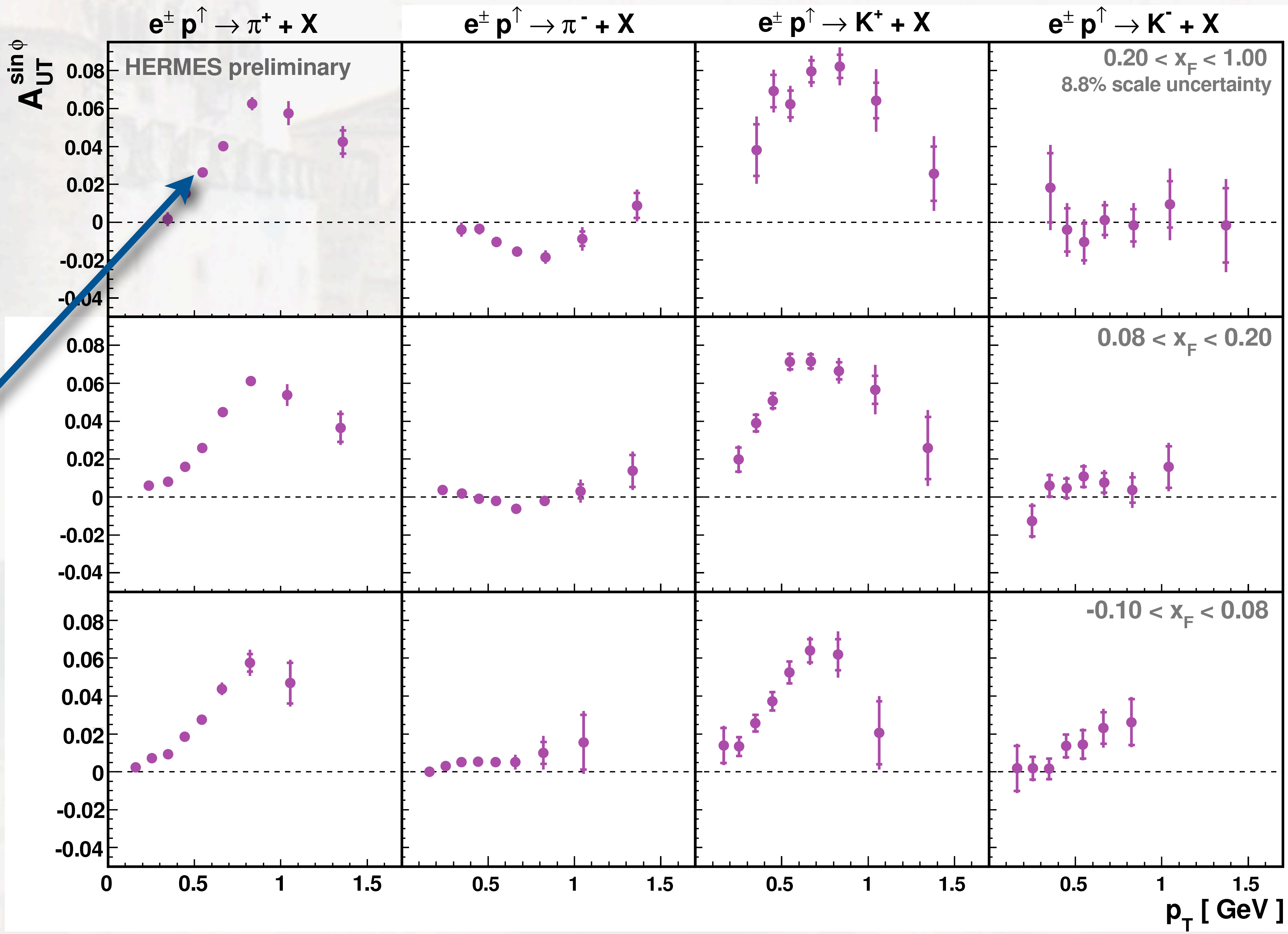


$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

$$A_{\rm N} \equiv \frac{\int_{\pi}^{2\pi} {\rm d}\phi\ \sigma_{\rm UT} \sin\phi - \int_0^{\pi} {\rm d}\phi\ \sigma_{\rm UT} \sin\phi}{\int_0^{2\pi} {\rm d}\phi\ \sigma_{\rm UU}} = -\frac{2}{\pi} A_{\rm UT}^{\sin\phi}$$

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

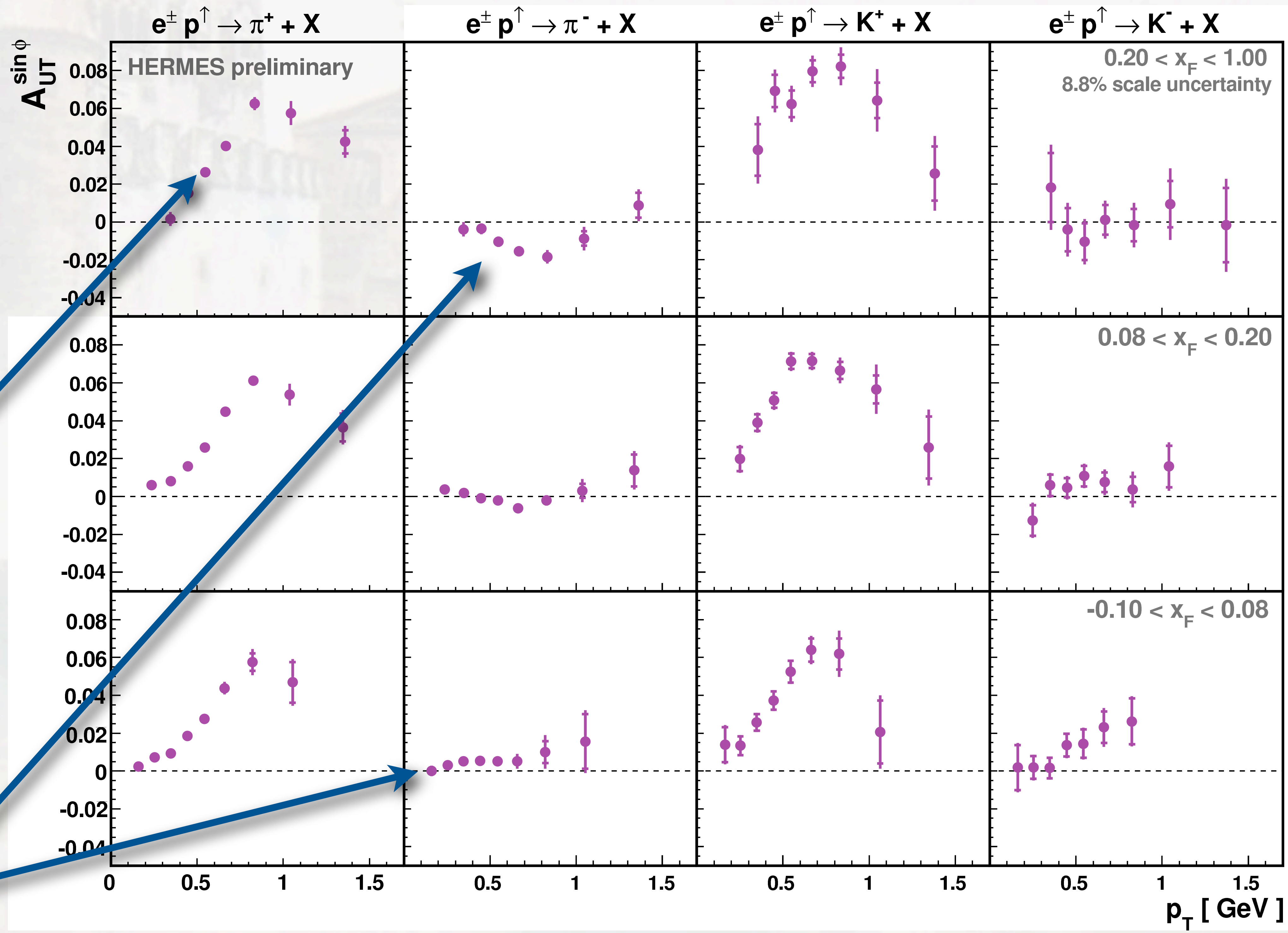
Inclusive hadrons in ep



increasing amplitudes with turnover

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

Inclusive hadrons in ep

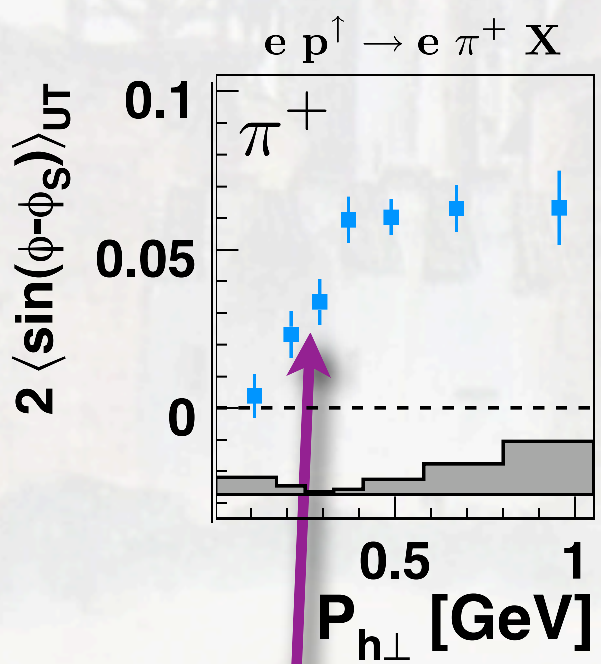


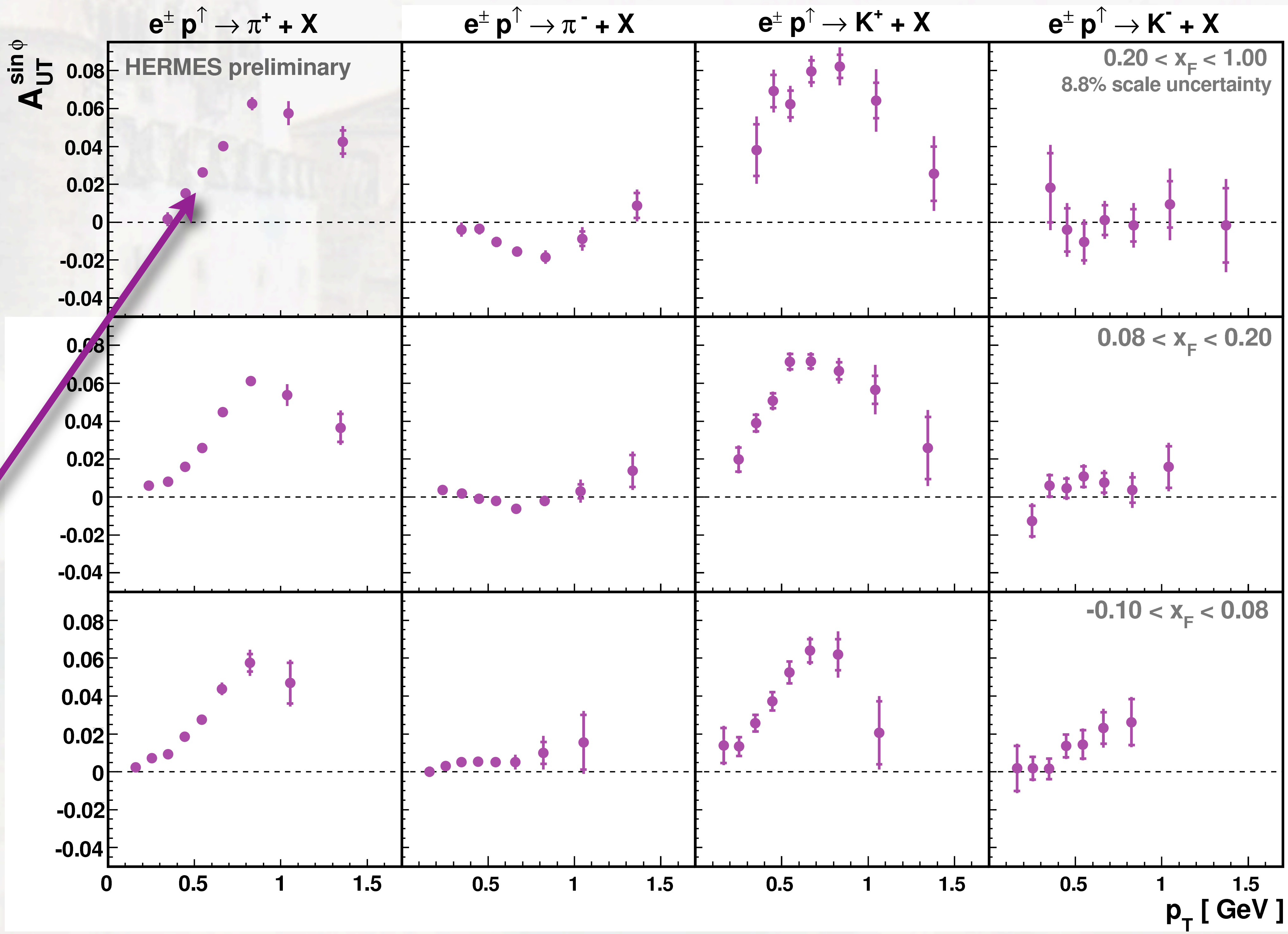
increasing amplitudes with turnover

sign change

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

Inclusive hadrons in ep

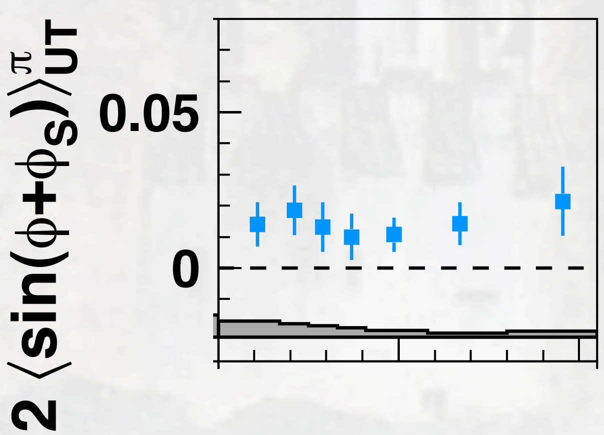


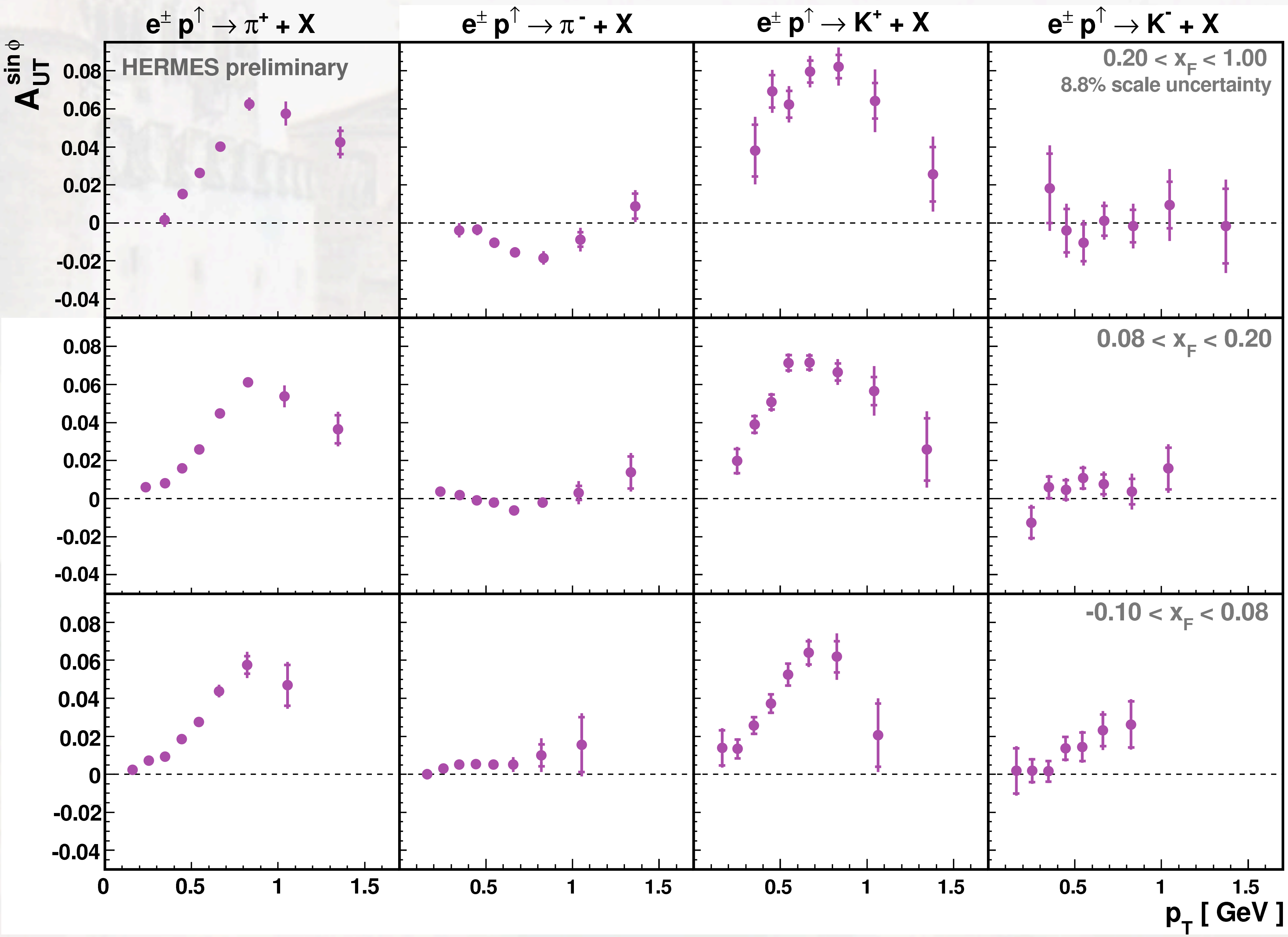


behavior and size similar to SIDIS Sivers

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

Inclusive hadrons in ep

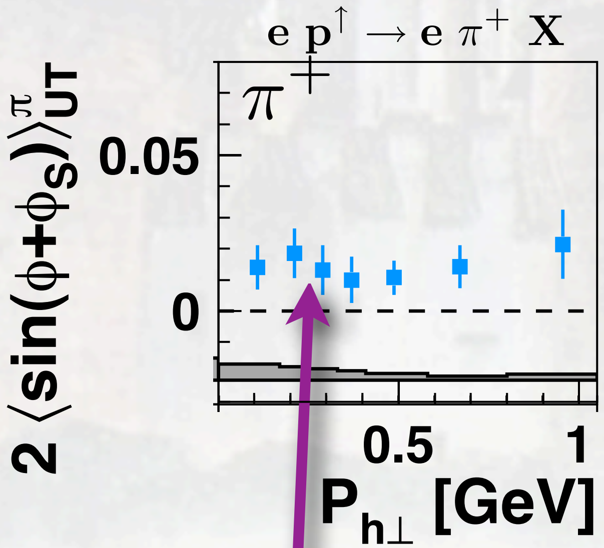


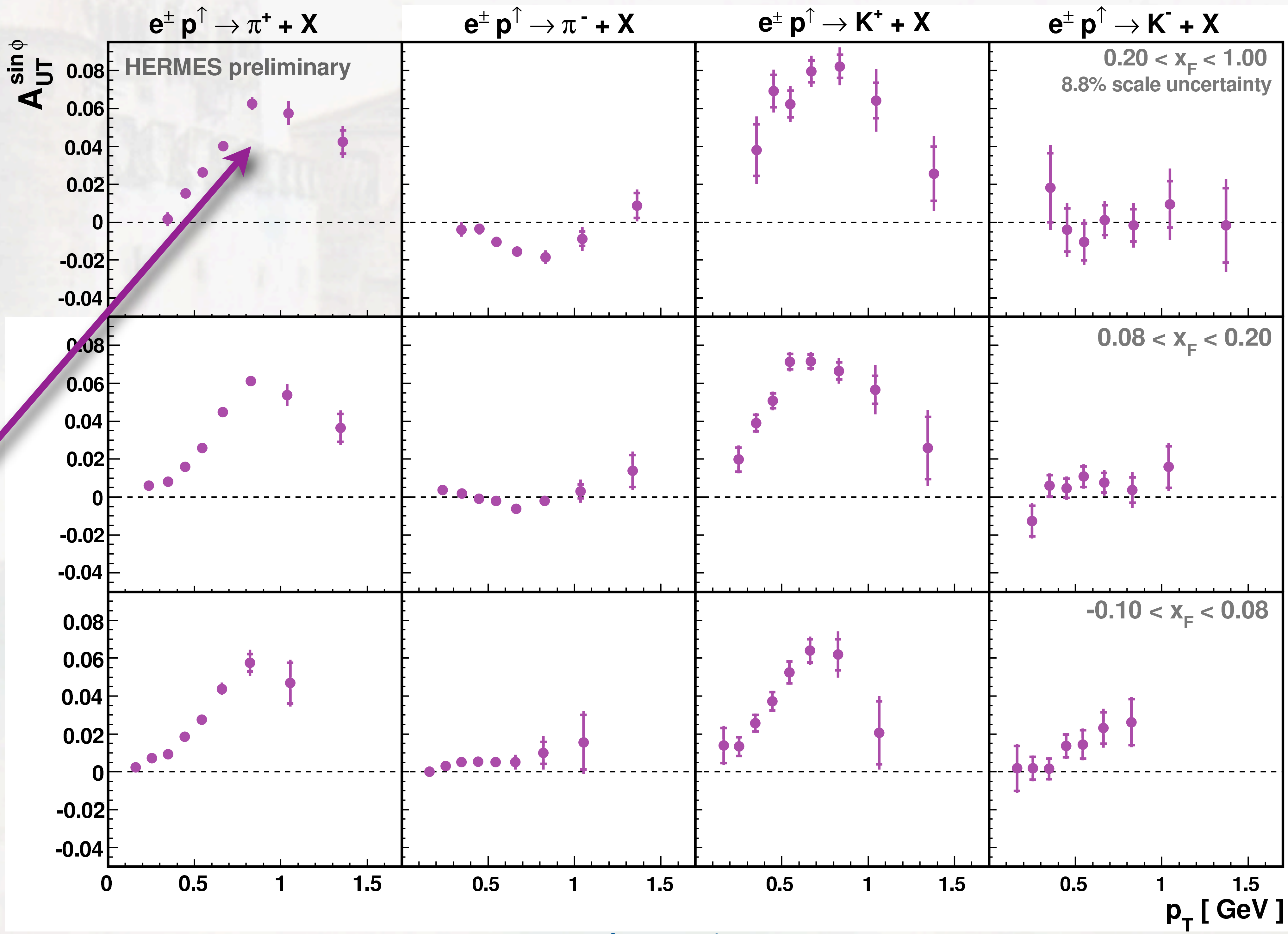


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

hermes

Inclusive hadrons in ep



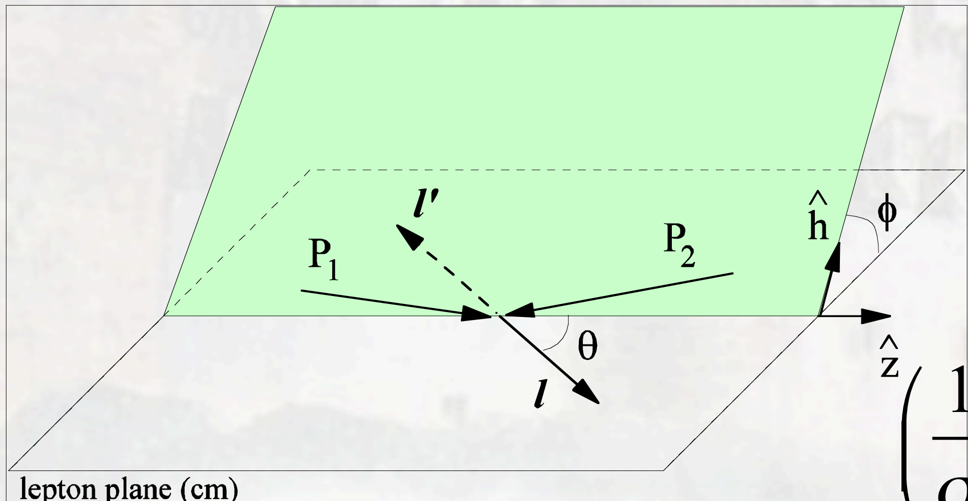


but not to SIDIS Collins

☛ L. Pappalardo

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

Boer-Mulders function (Drell-Yan)

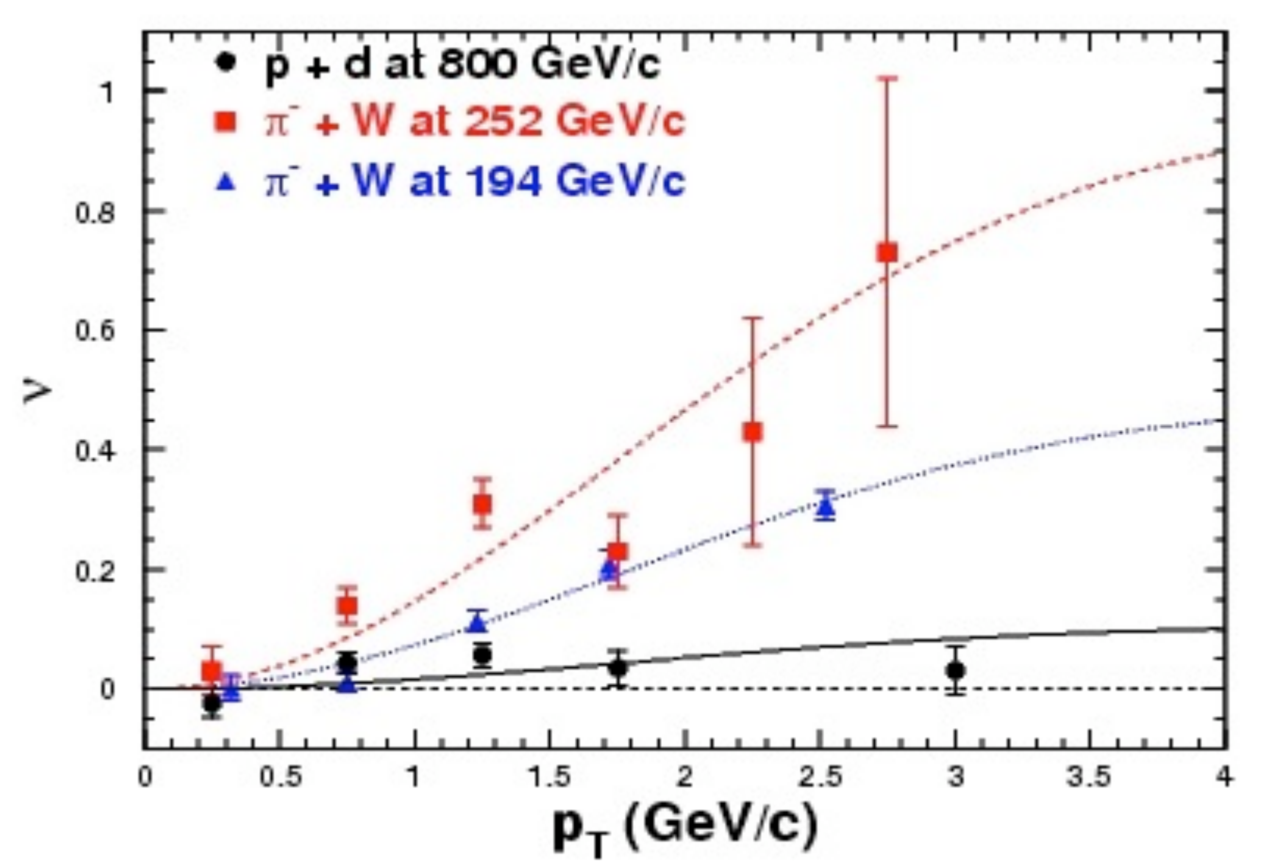


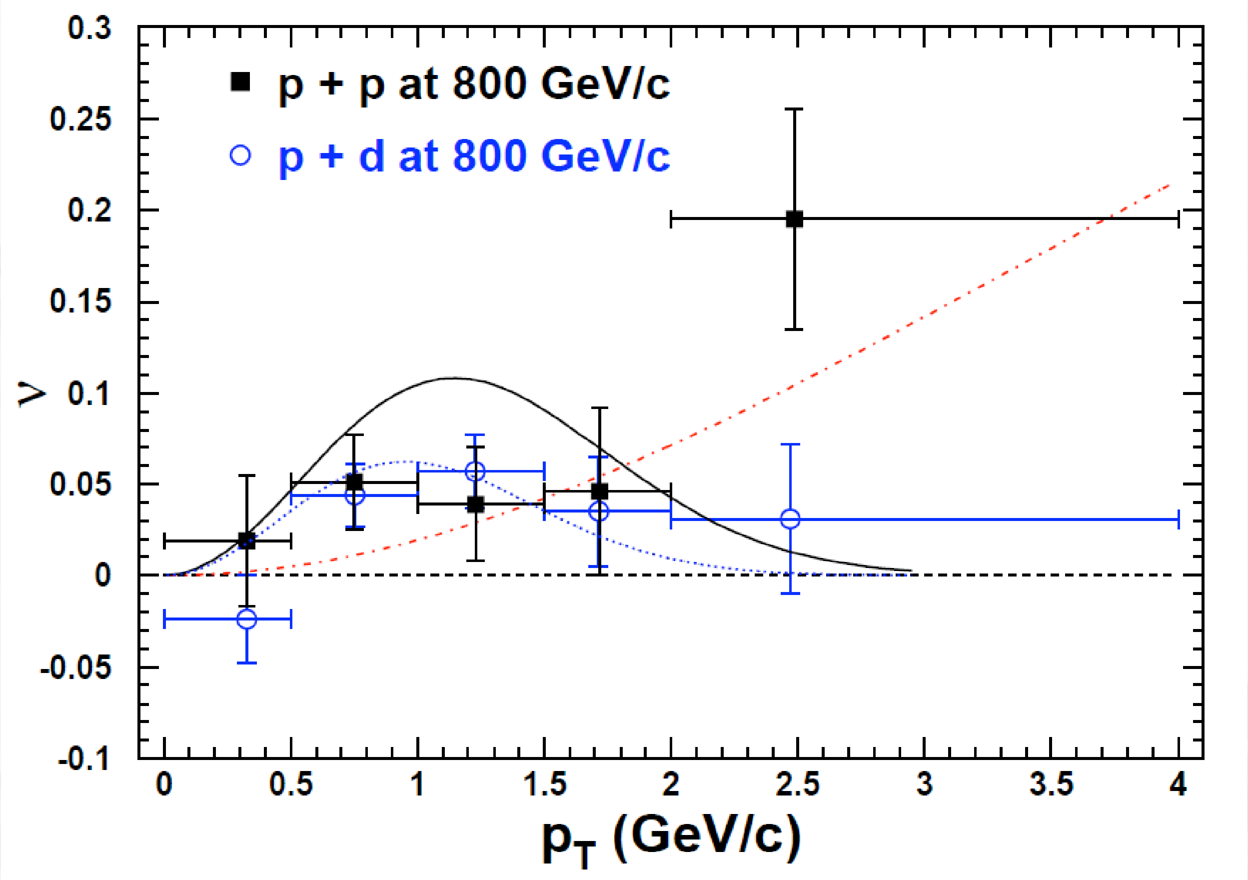
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

- **Lam-Tung relation: 1-λ = 2 ν**
  - **insensitive to QCD corrections**
  - **clear sign for Boer-Mulders effect (~ ν)**
  - **violated in pion-induced Drell-Yan**

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

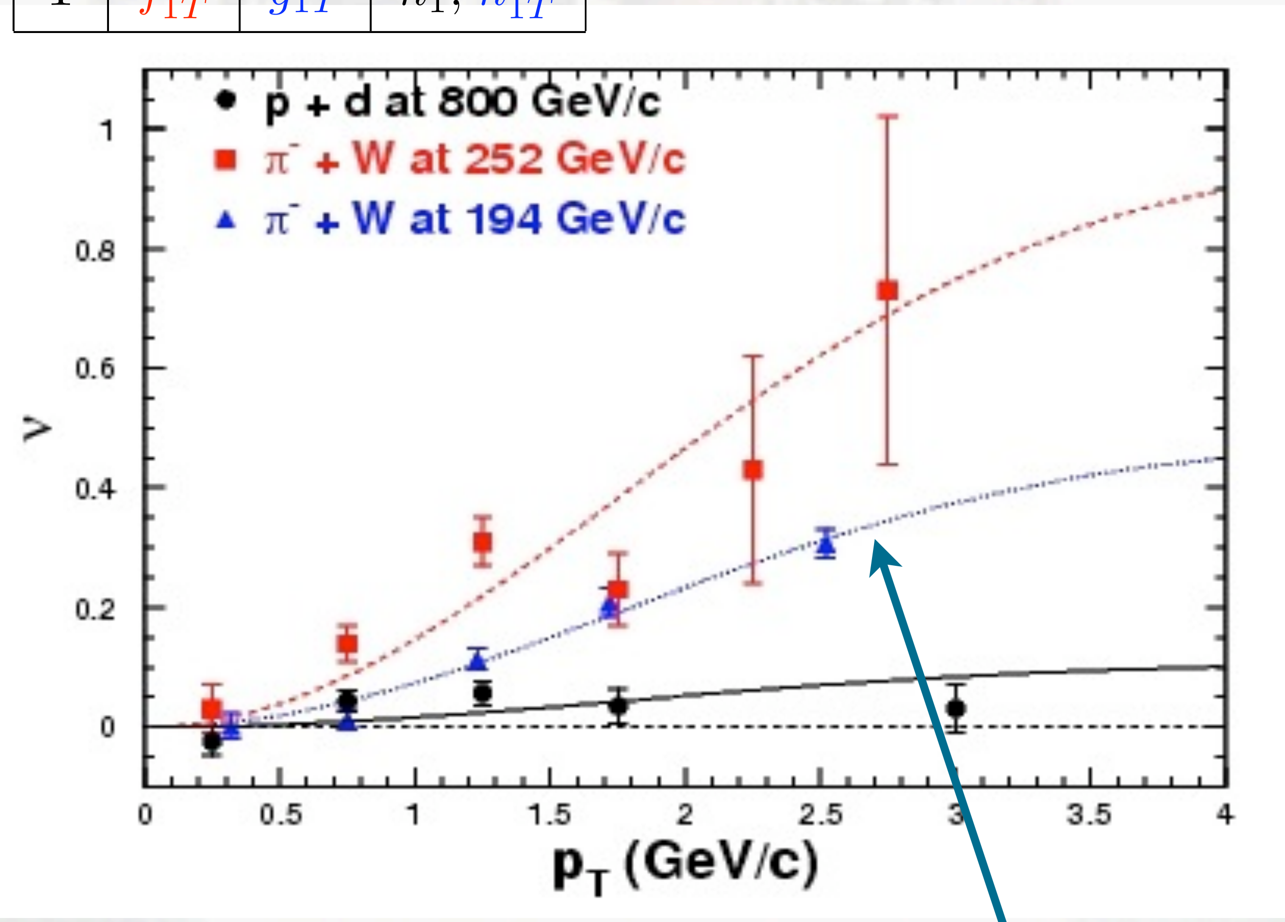
Signs of Boer-Mulders

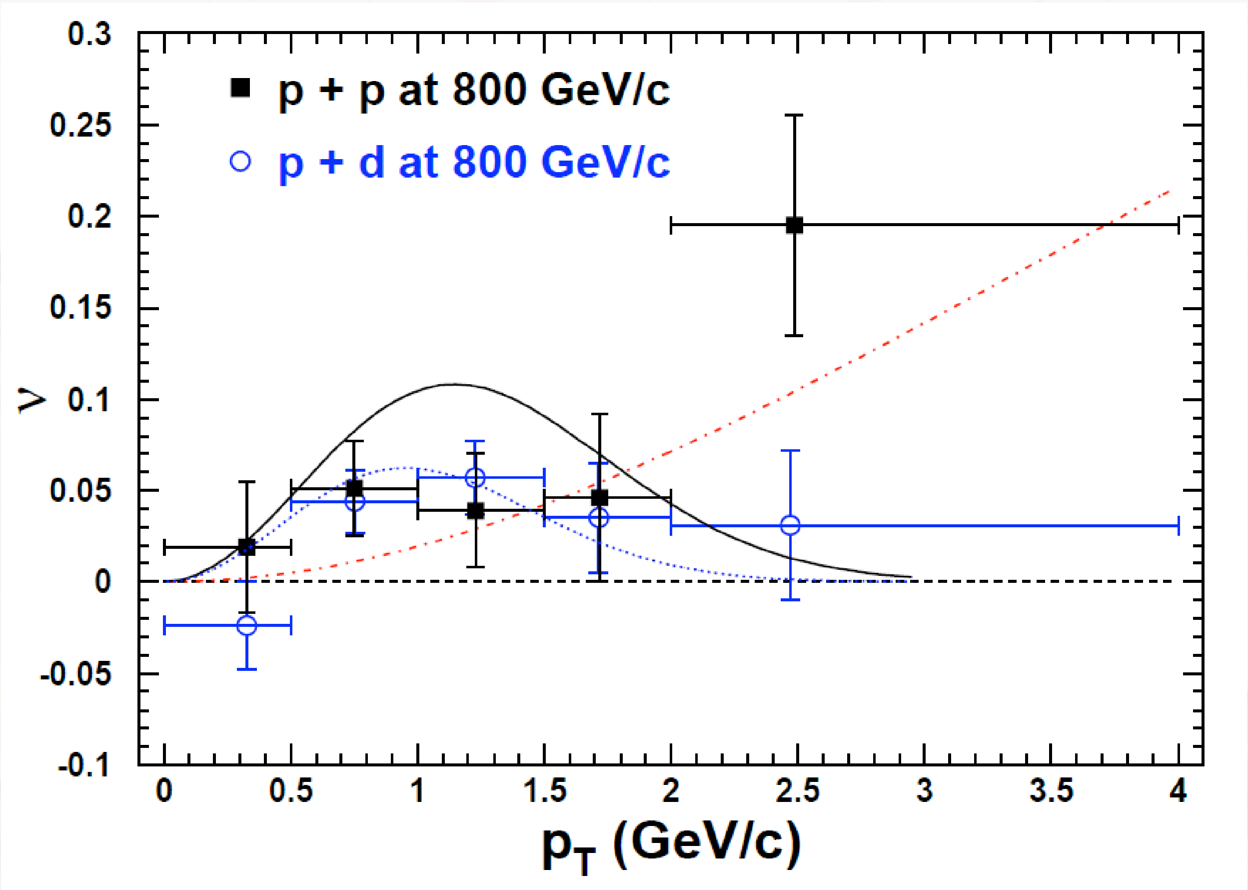




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Signs of Boer-Mulders

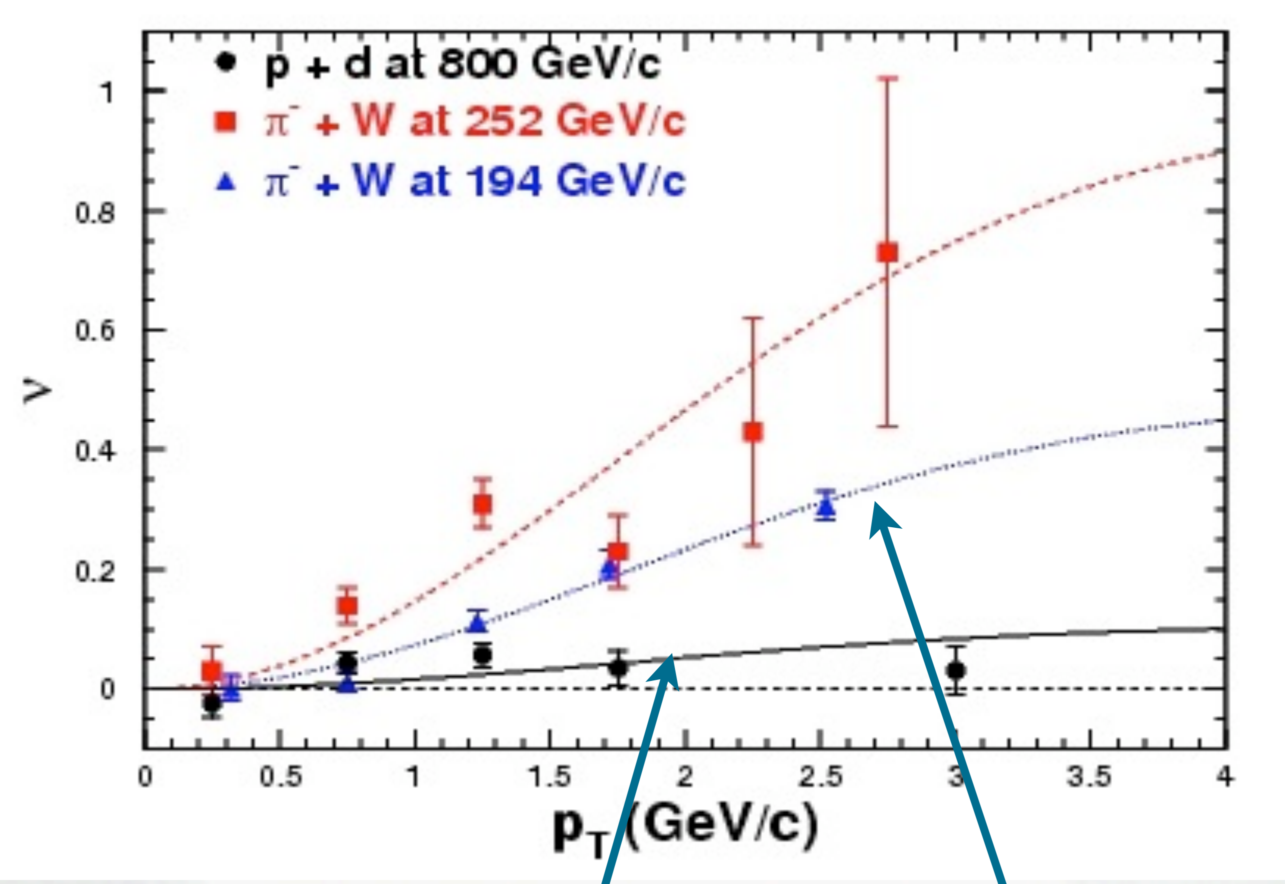


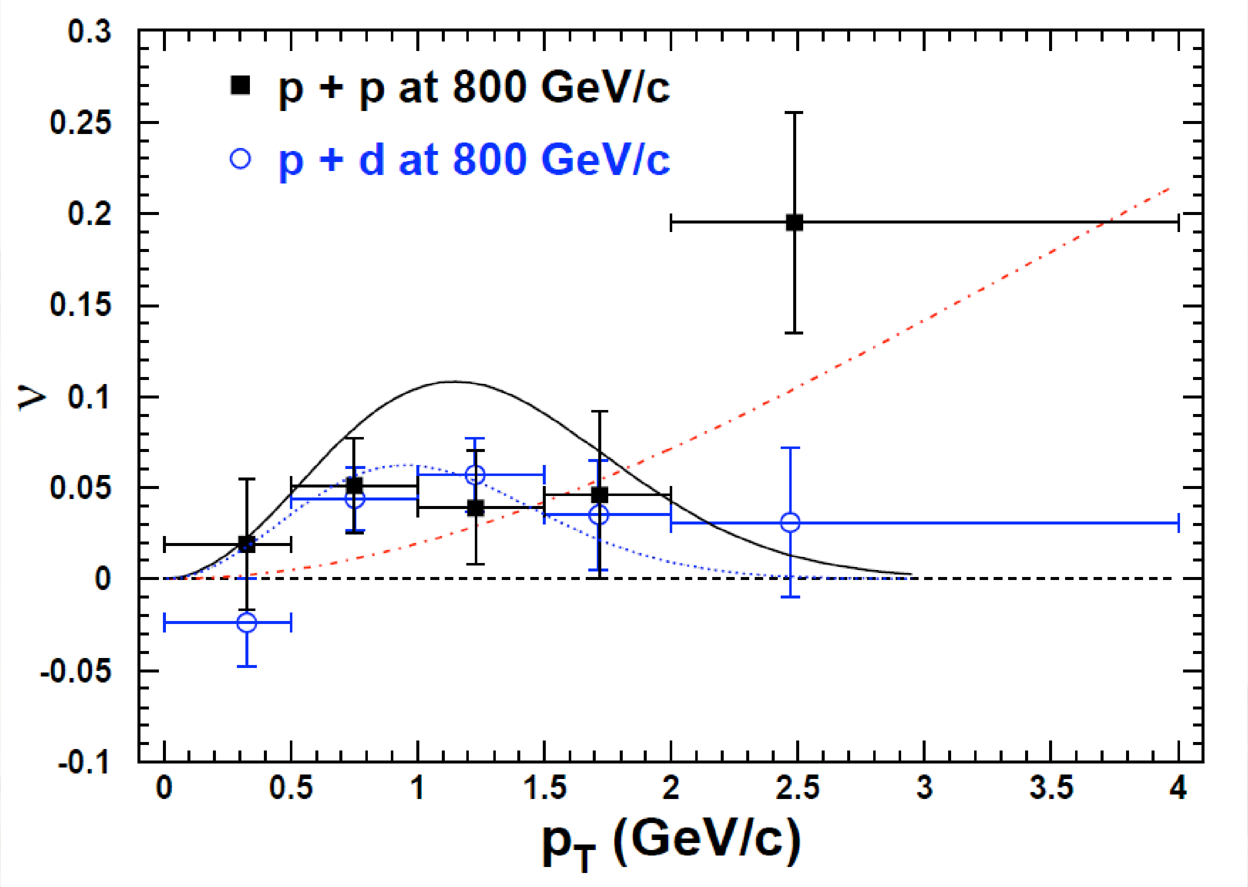


valence BM fctn

	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



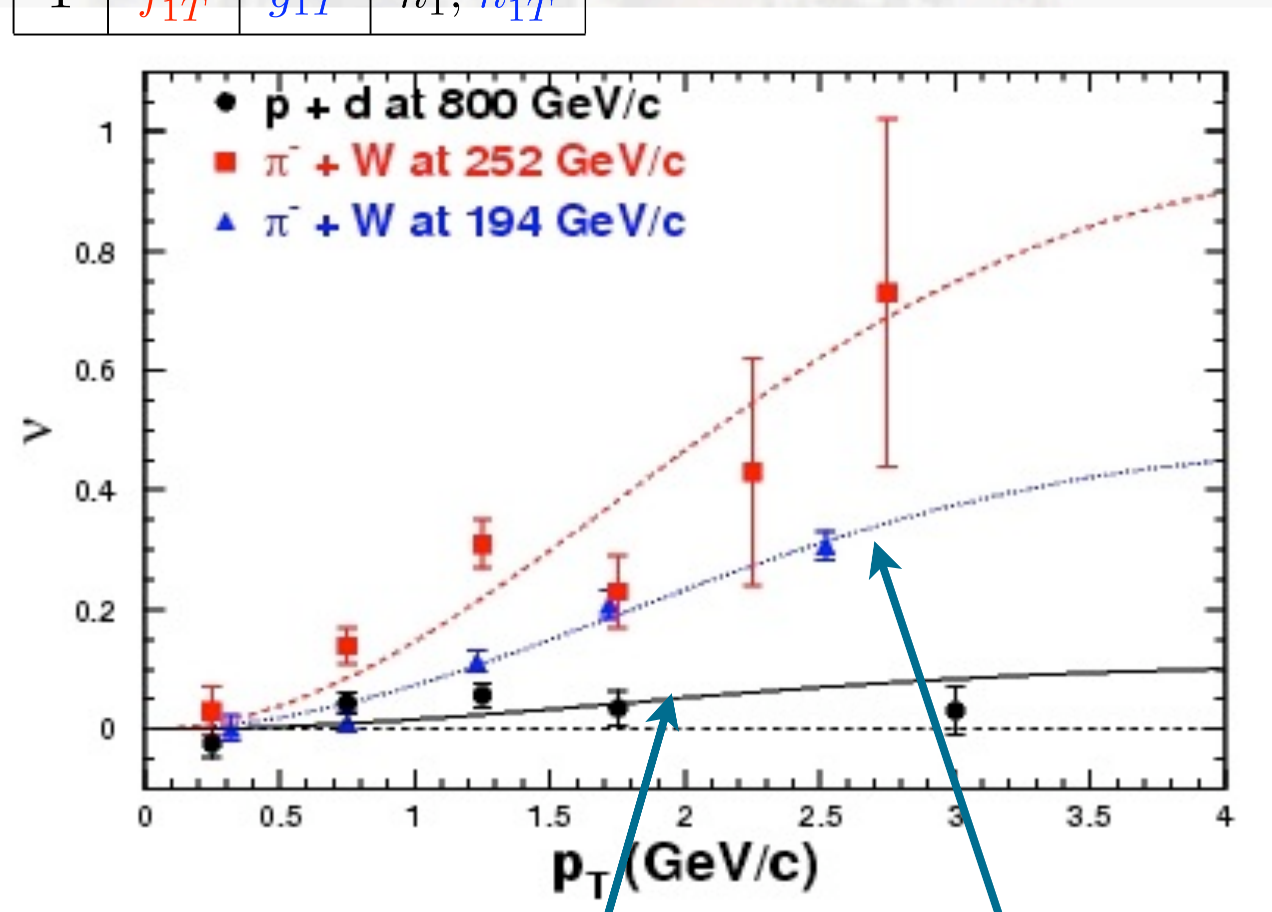


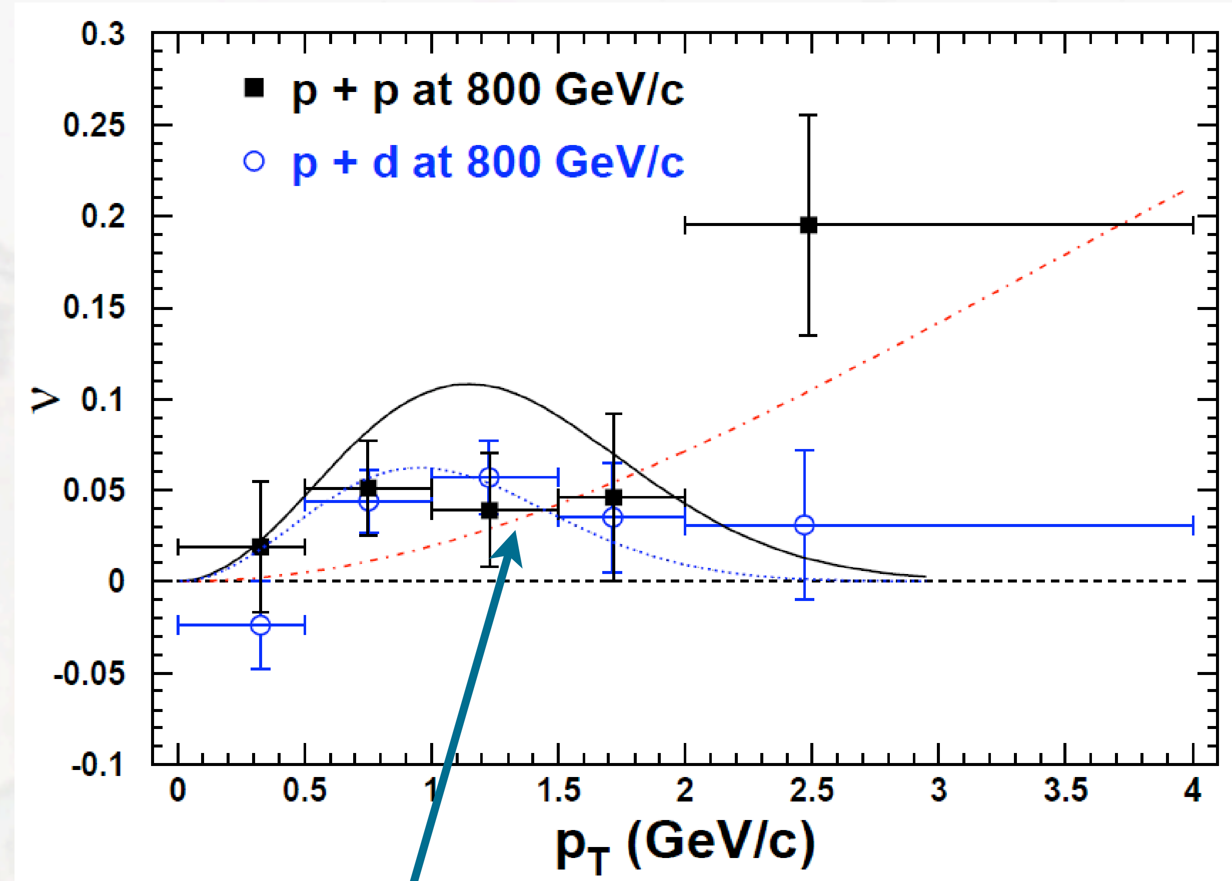
valence and sea BM fctn

valence BM fctn

	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





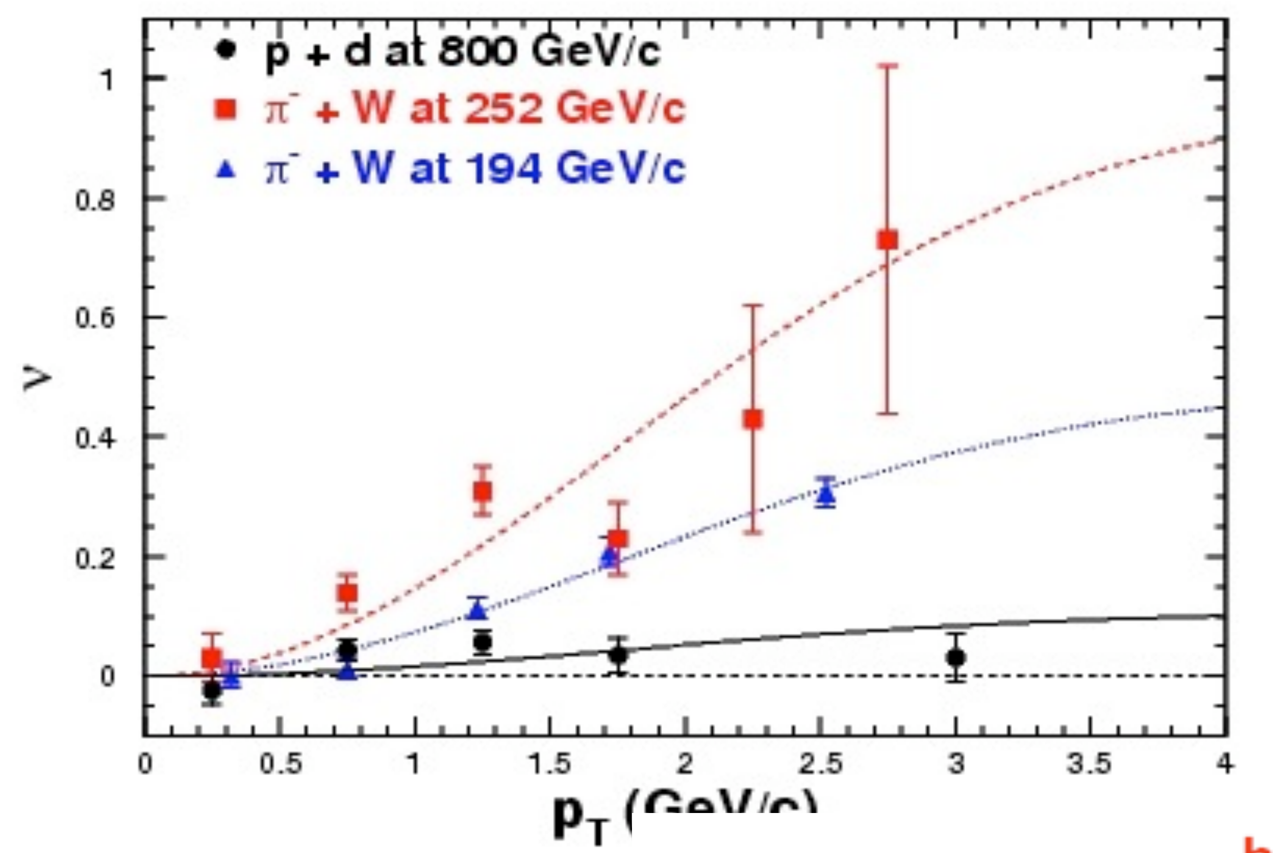
valence and sea BM fctn

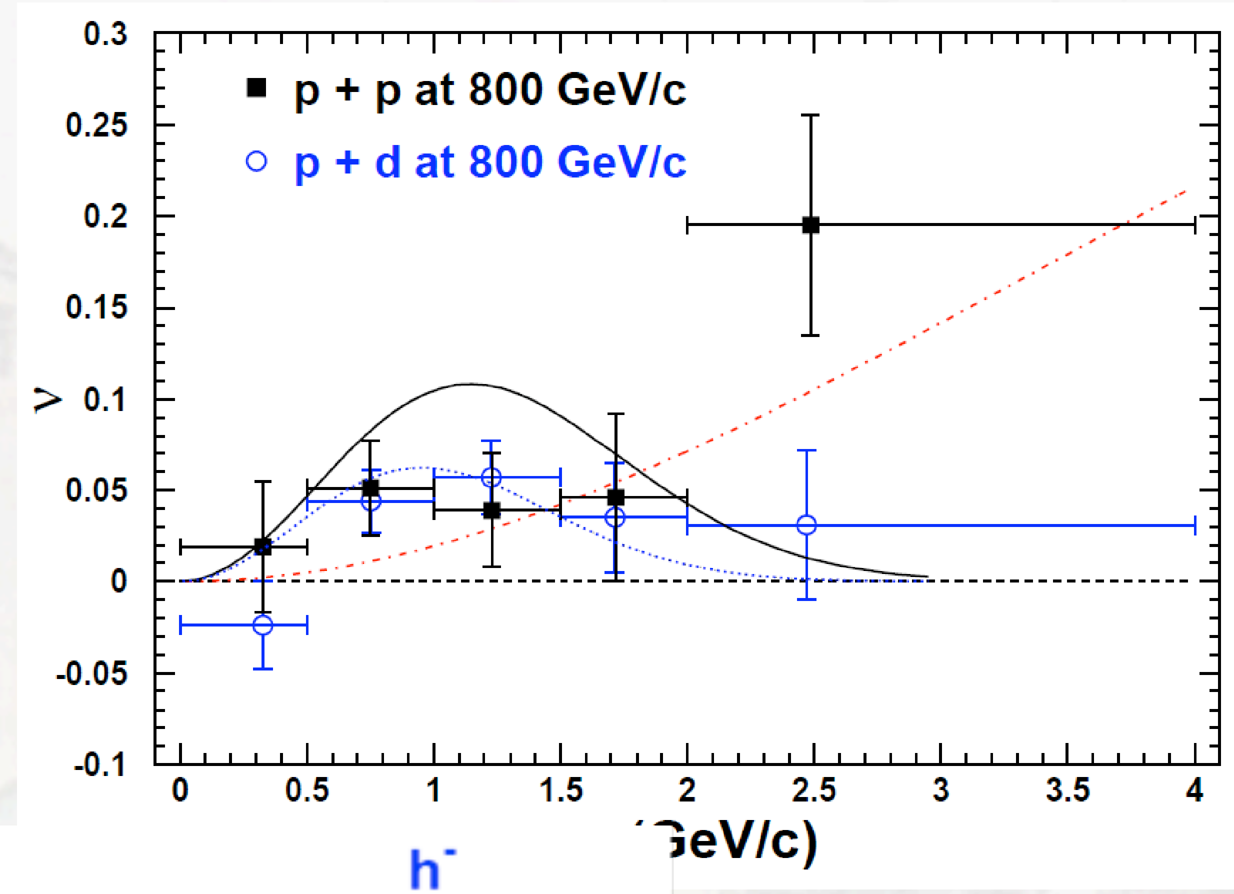
valence BM fctn

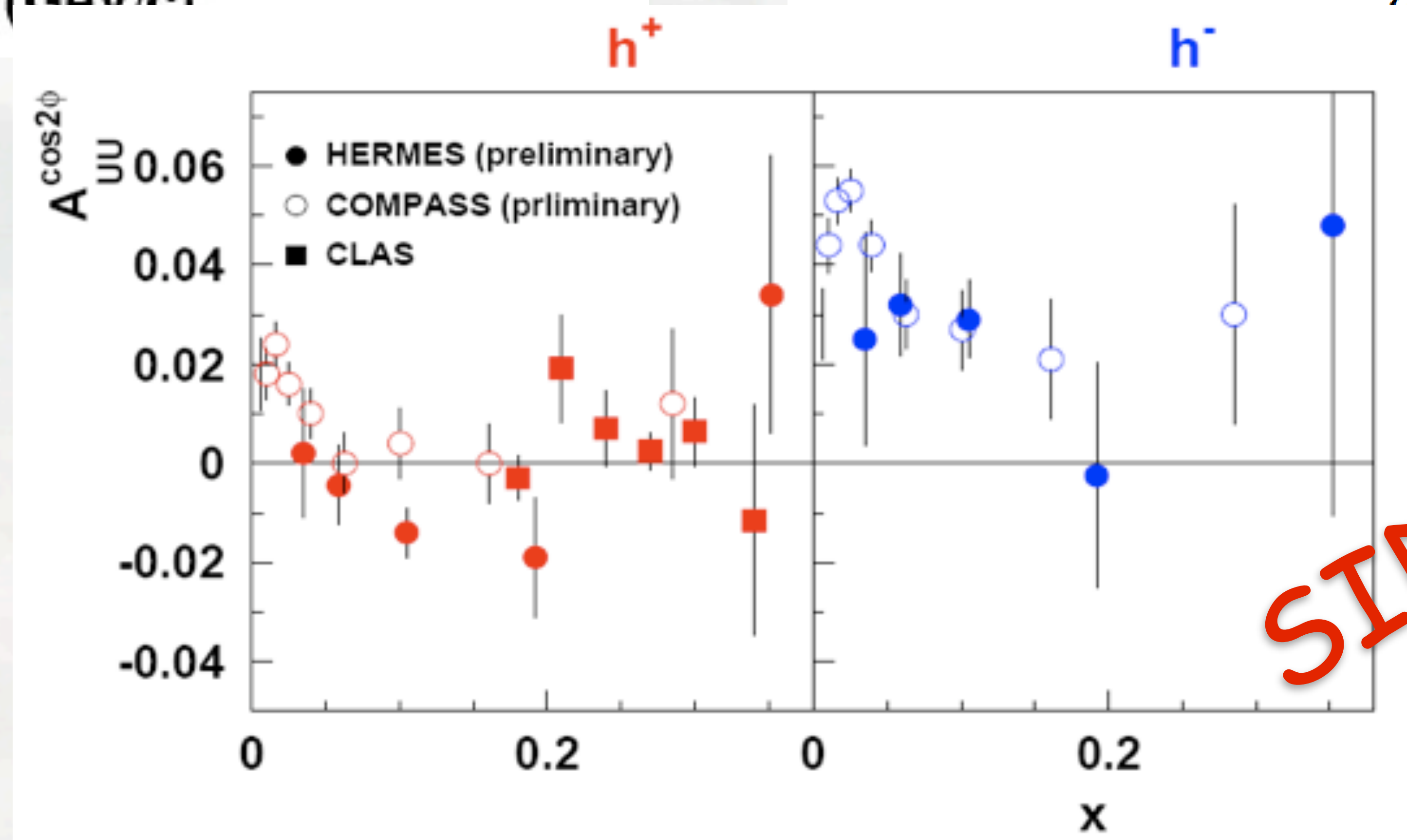
similar BM fctn for up and down quarks?

	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



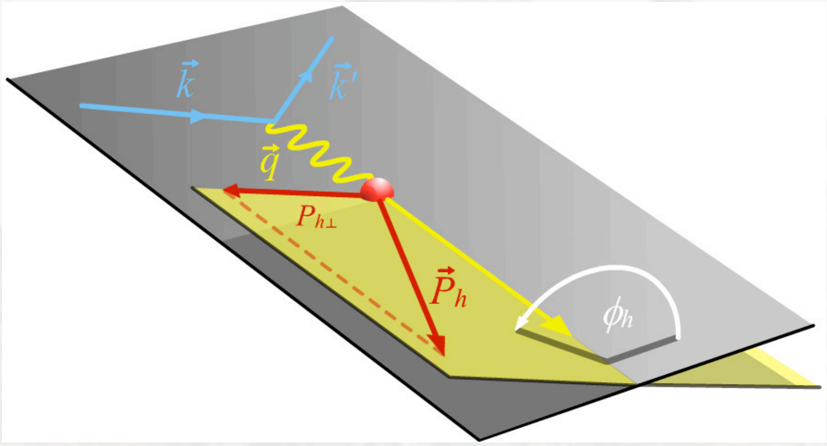




SIDIS

gunar.schnell @ desy.de

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

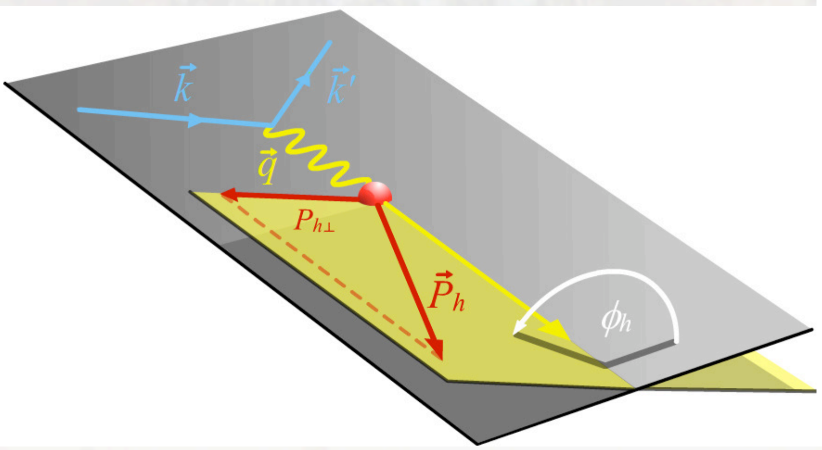
Interaction dependent terms neglected

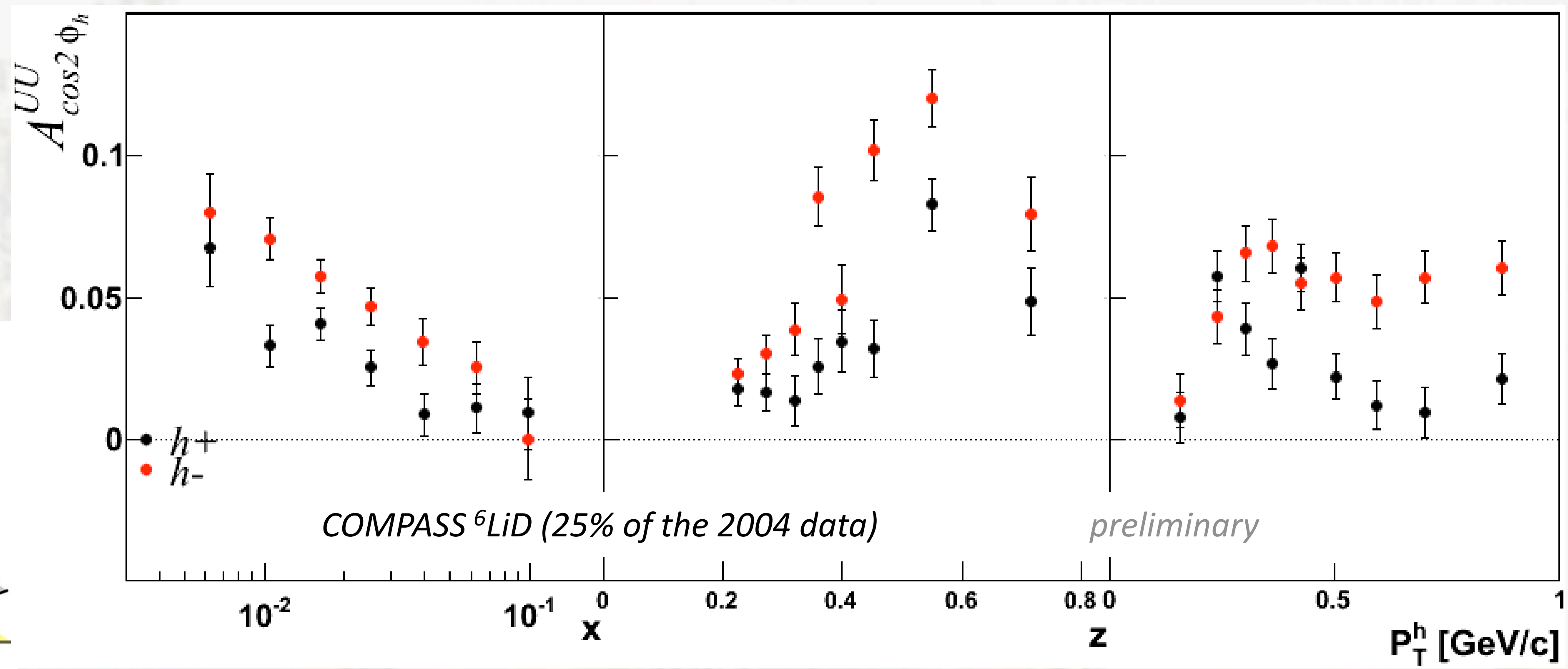
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\,h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\,f_1 D_1 + \ldots\right]$$

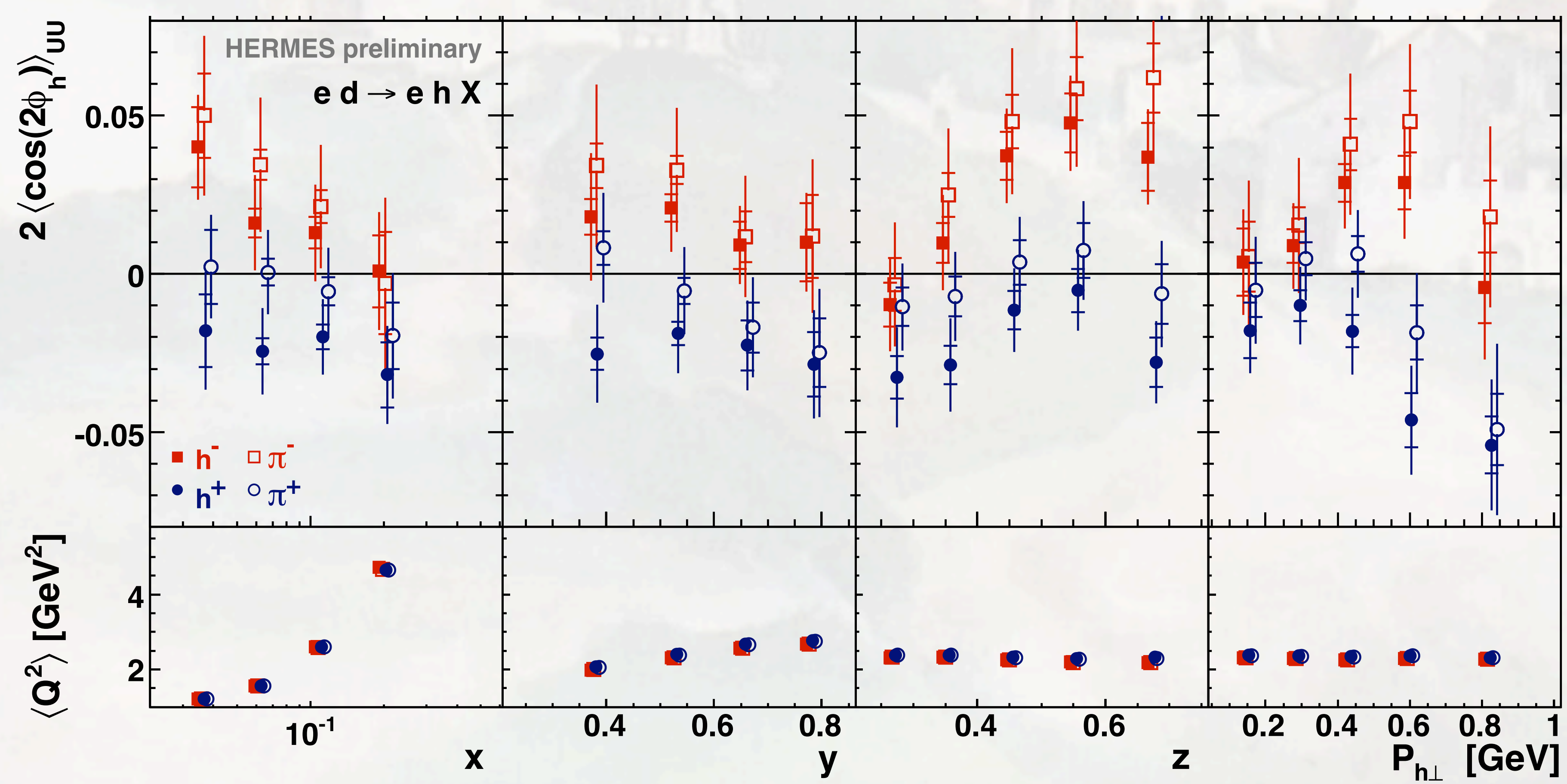
(Implicit sum over quark flavours)

	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



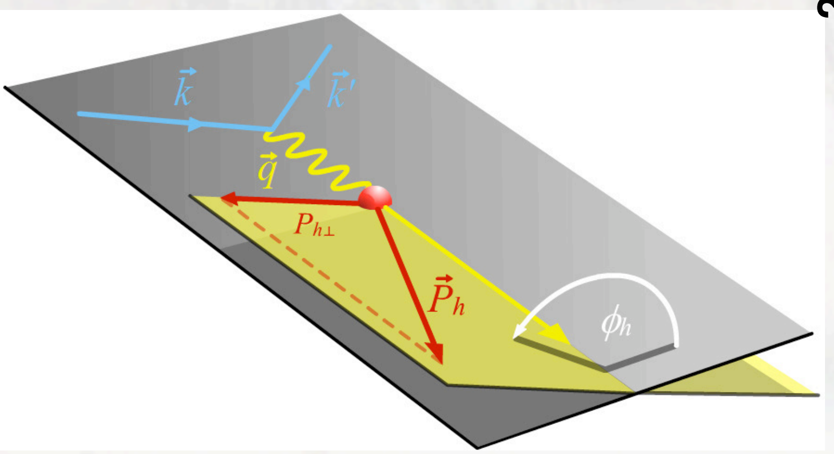


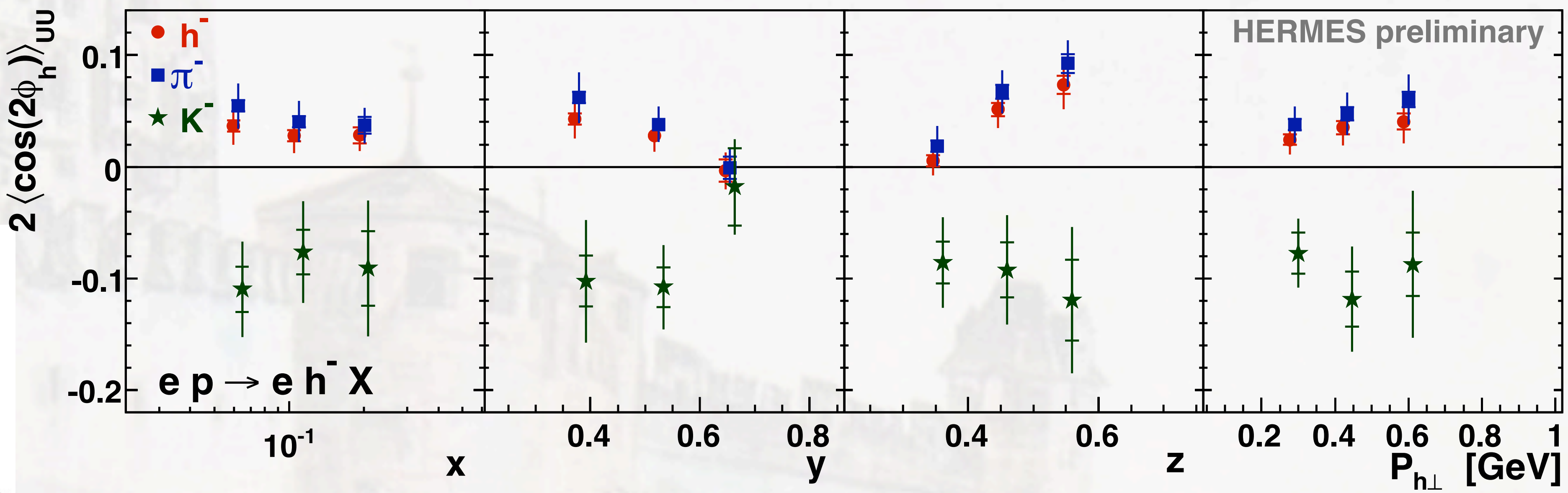


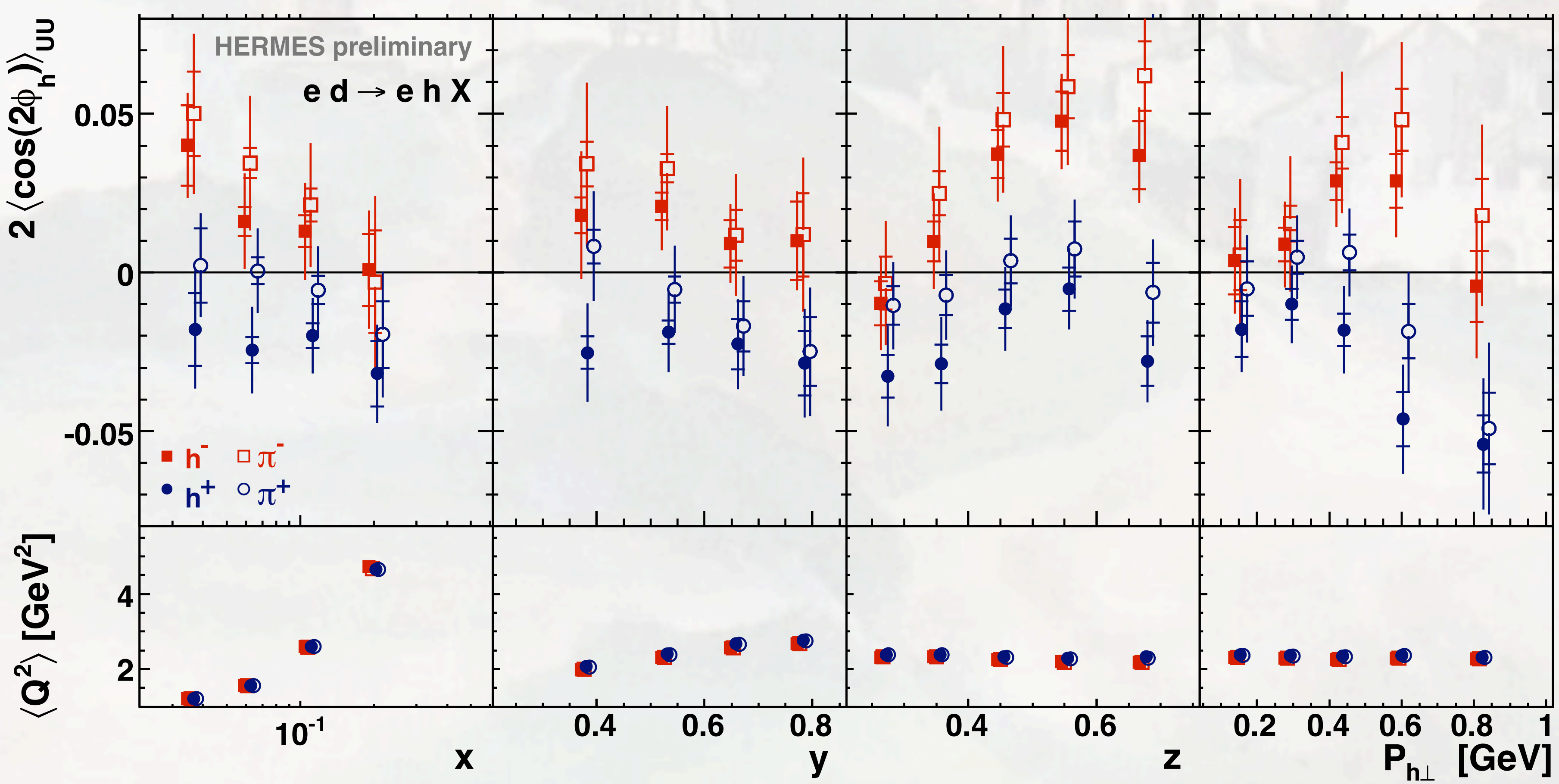
☛ H. Wollny, L. Pappalardo

	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







☛ H. Wollny, L. Pappalardo

Cahn effect?

BOER-MULDERS EFFECT

CAHN EFFECT

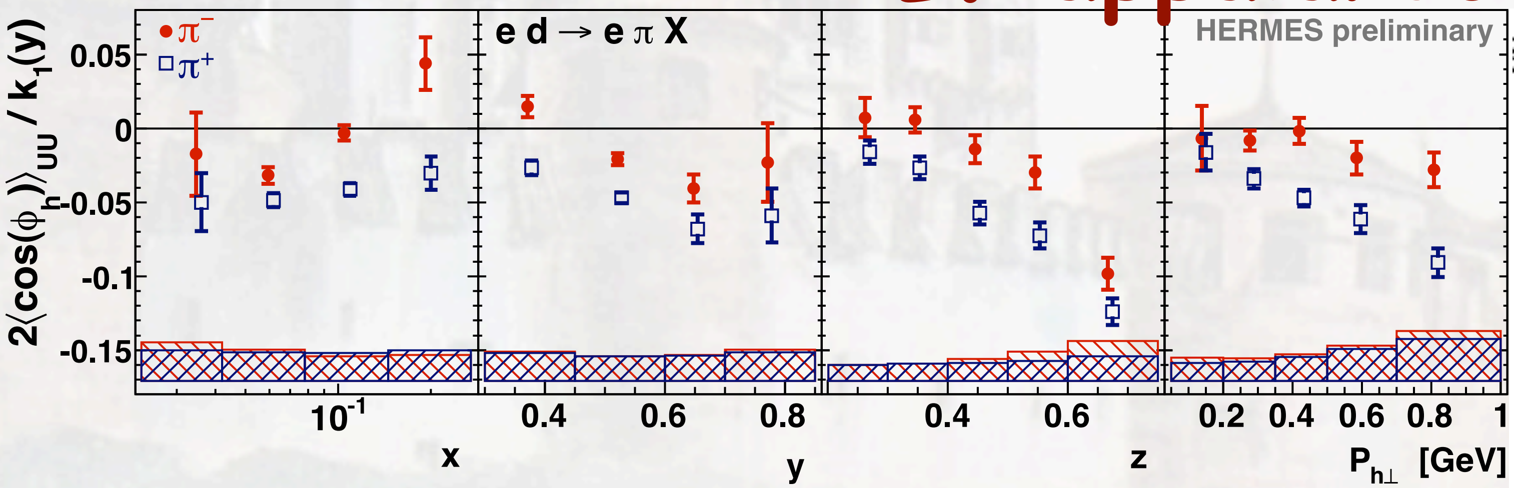
Interaction dependent terms neglected

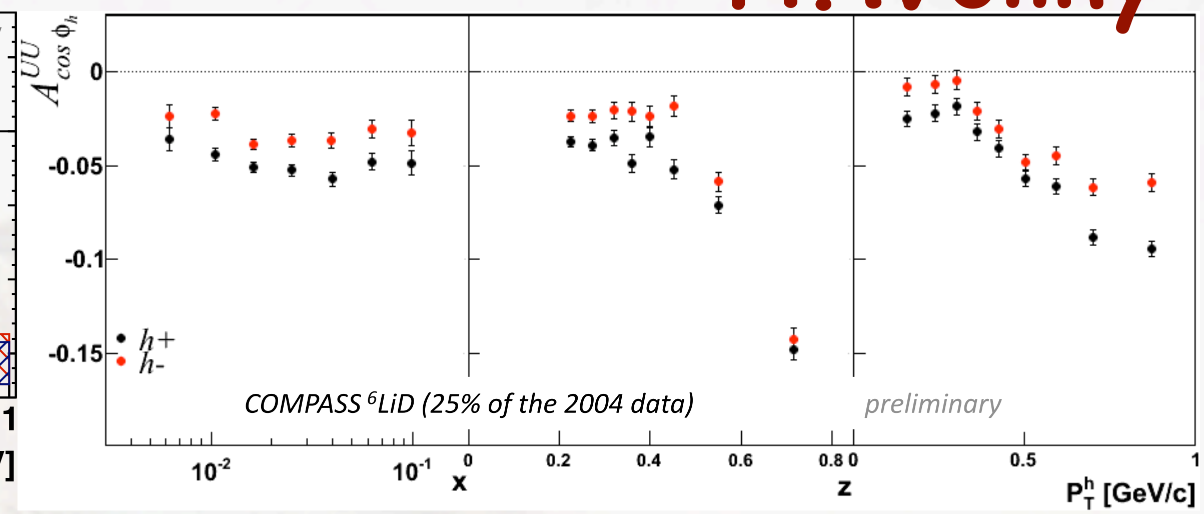
next to leading twist

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

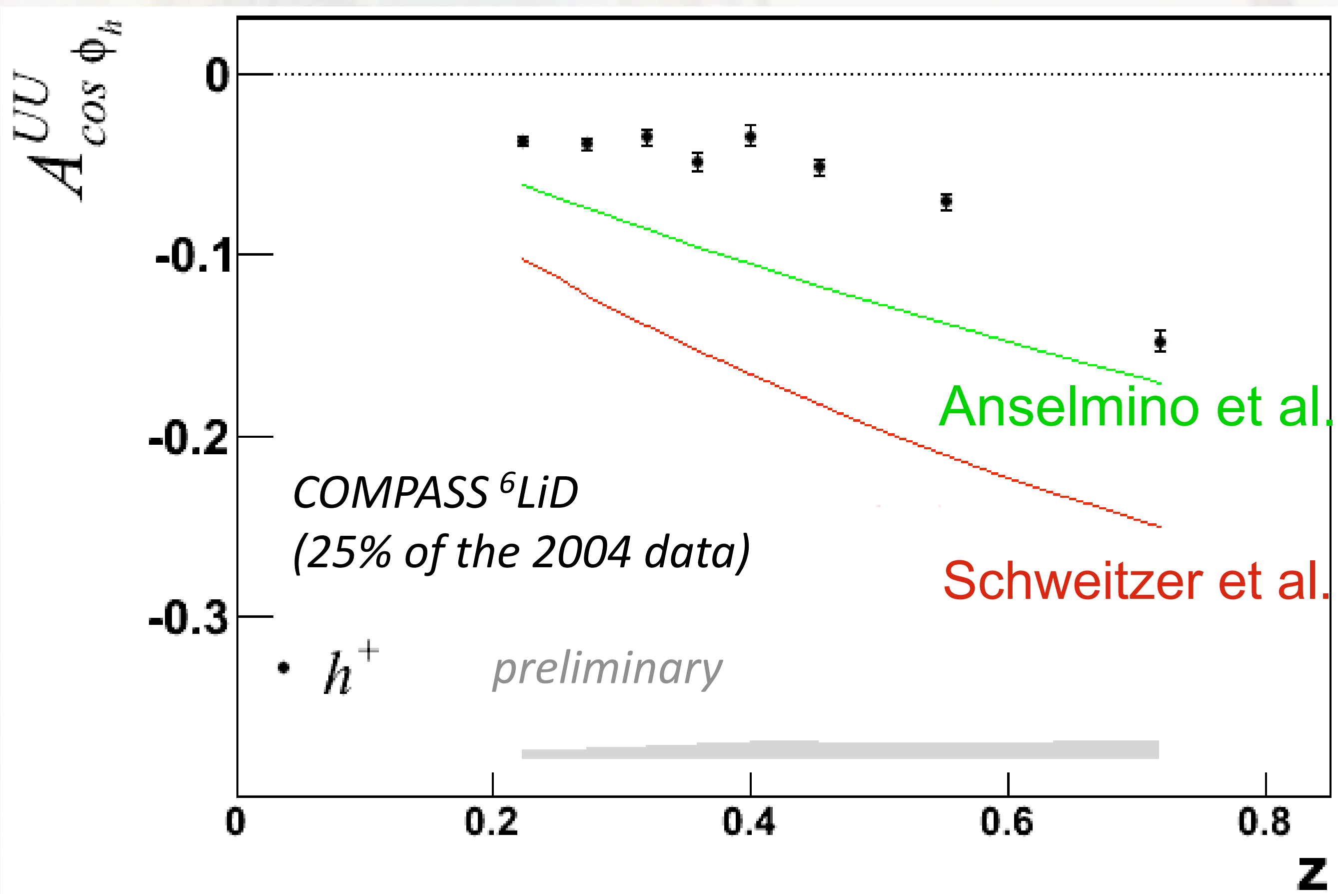
☛ L.Pappalardo

☛ H.Wollny





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



Cahn effect?

BOER-MULDERS EFFECT

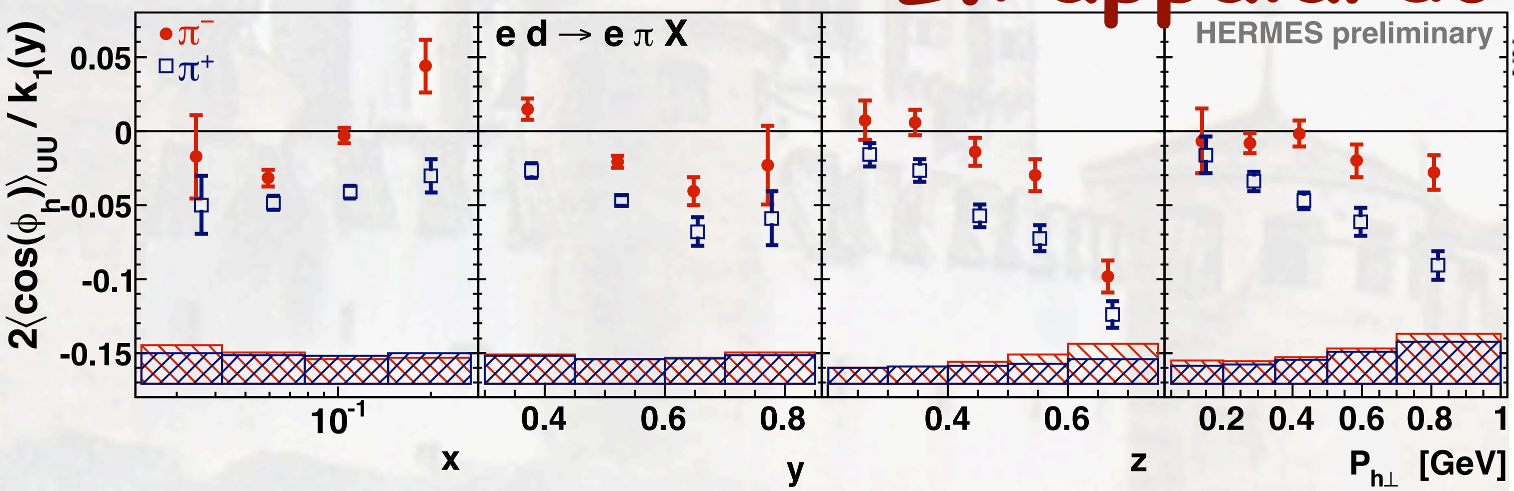
CAHN EFFECT

Interaction dependent terms neglected

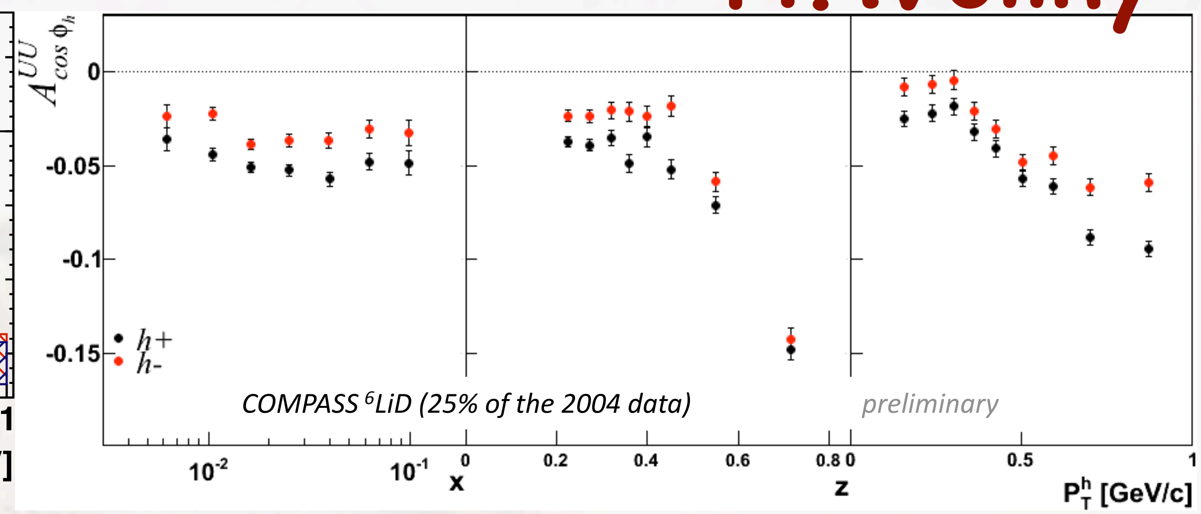
next to leading twist

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

☛ L.Pappalardo

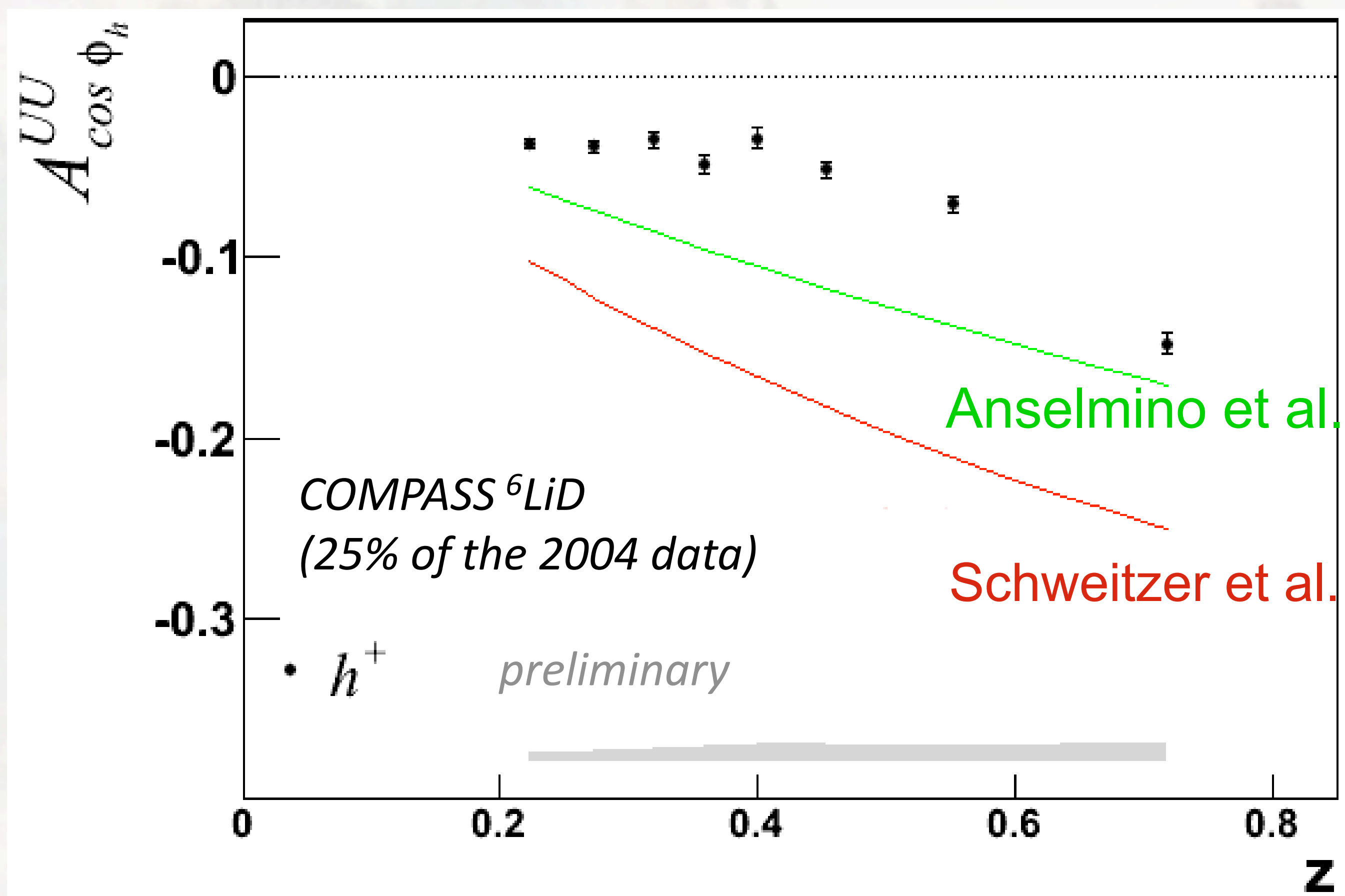


☛ H.Wollny

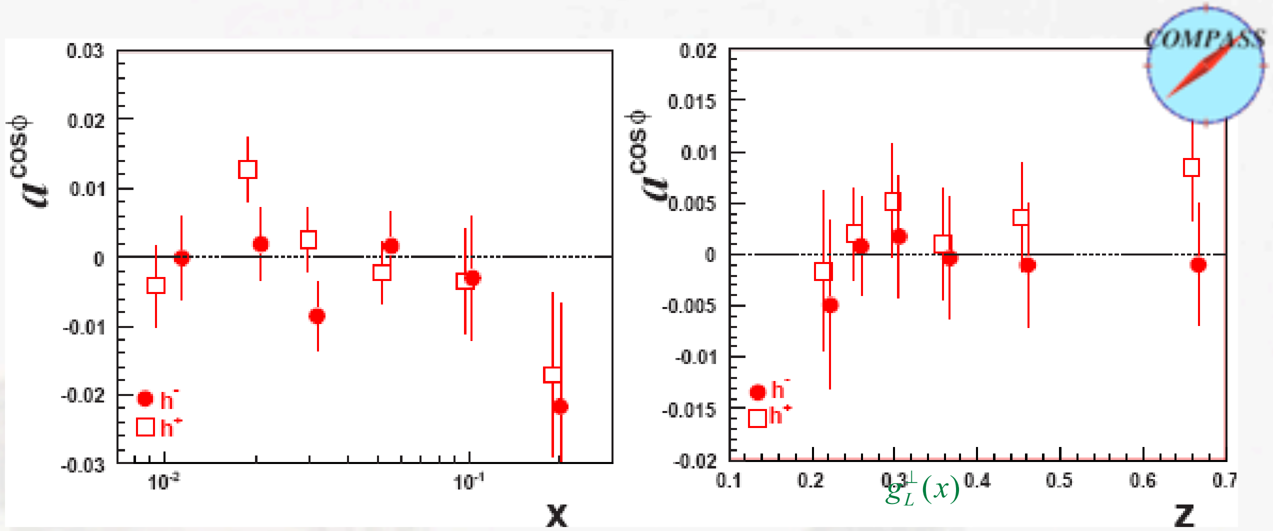


- no dependence on hadron charge expected
- prediction off from data

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

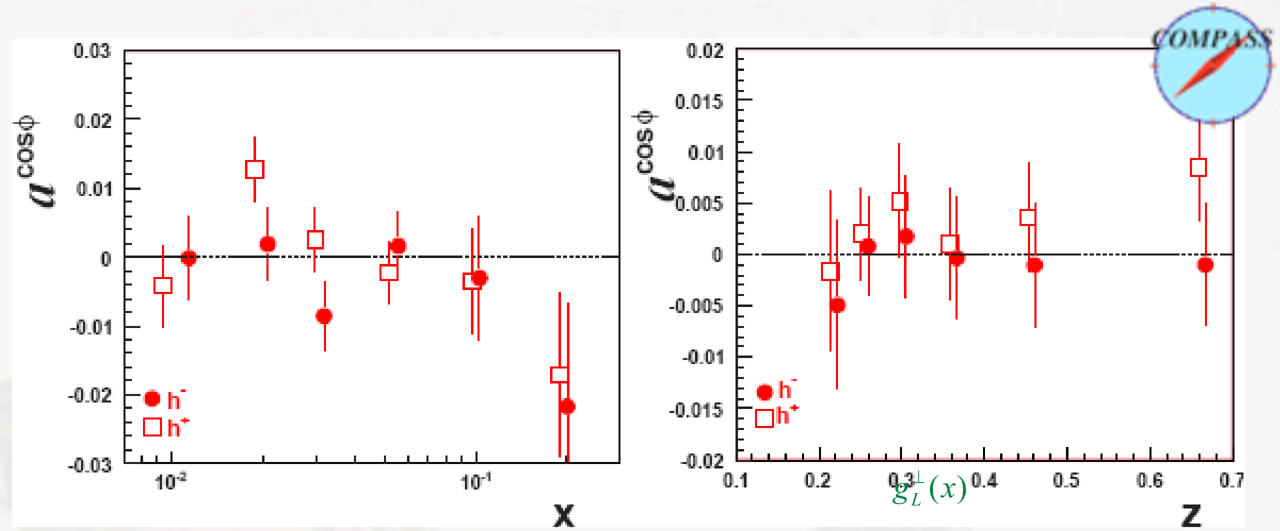


Other (twist-3) TMDs



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

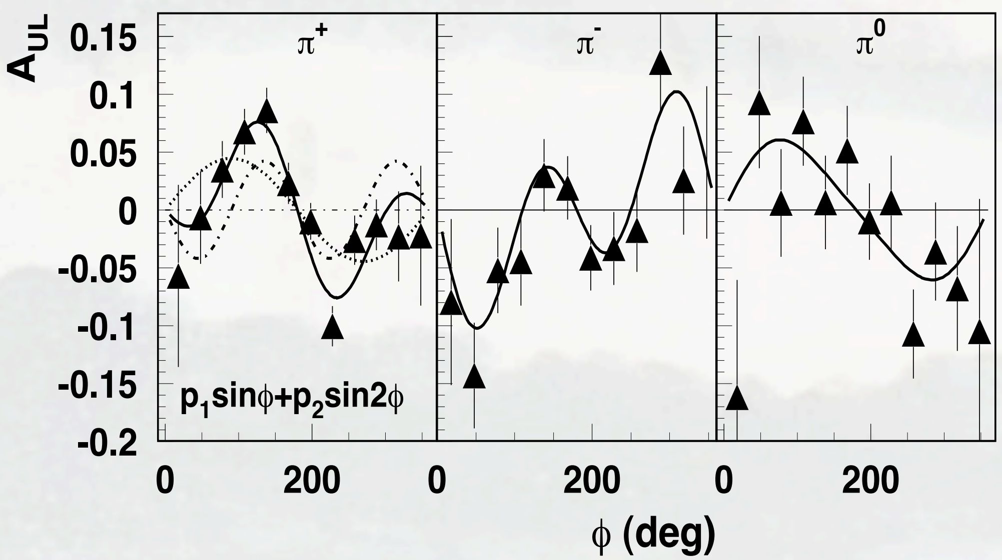
Other (twist-3) TMDs



$A_{LL}^{\cos\phi}$

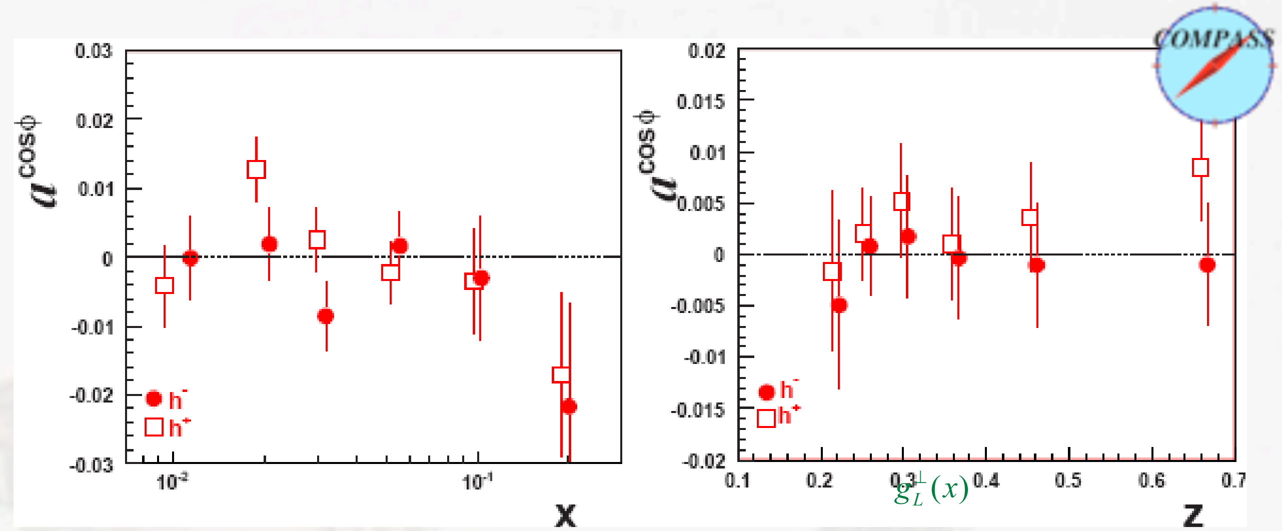
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^\perp - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^\perp D_1 + \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



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

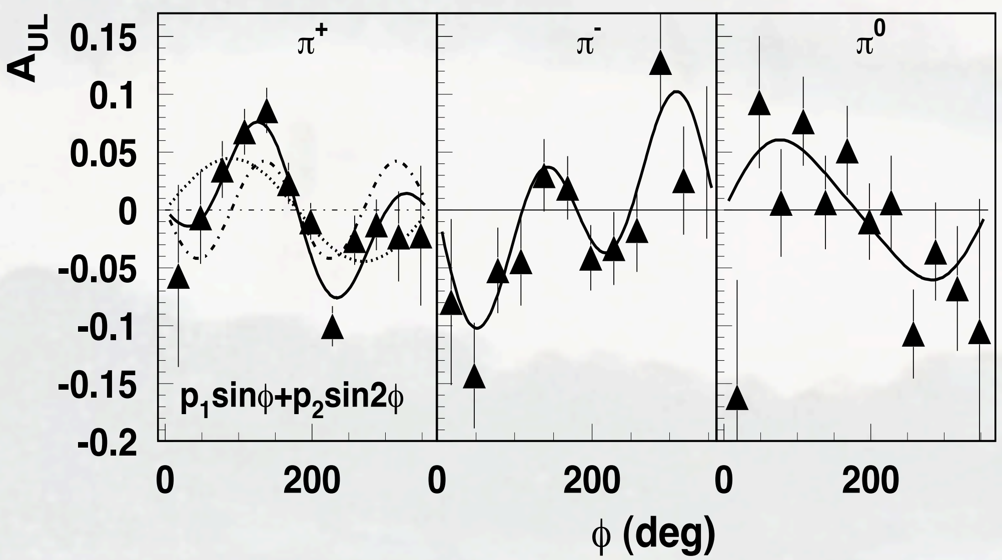
Other (twist-3) TMDs



$A_{\mathrm{LL}}^{\cos\phi}$

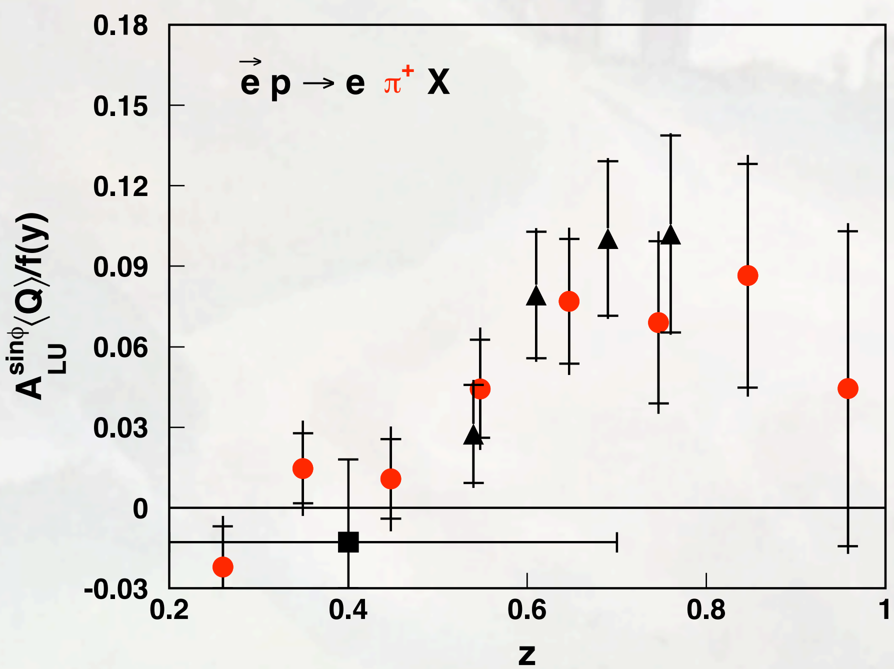
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^\perp - \frac{M_h}{M}\, g_{1L}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^\perp D_1 + \frac{M_h}{M}\, h_{1L}^\perp\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549

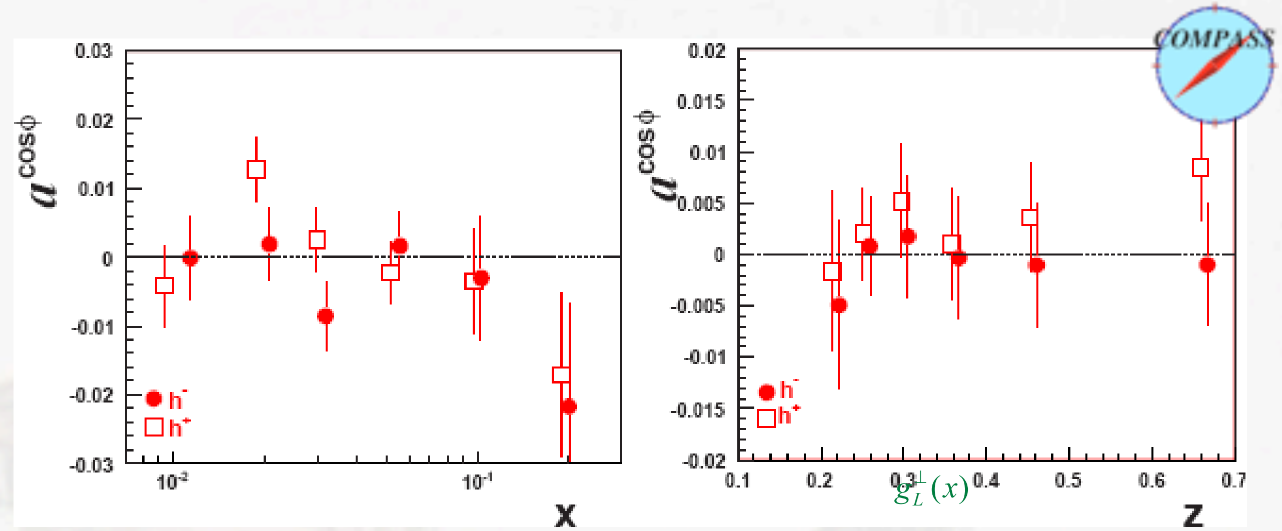


$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^\perp + \frac{M_h}{M}\, g_{1L}\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^\perp D_1 - \frac{M_h}{M}\, h_{1L}^\perp\frac{\tilde{H}}{z}\right)\right]$$

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



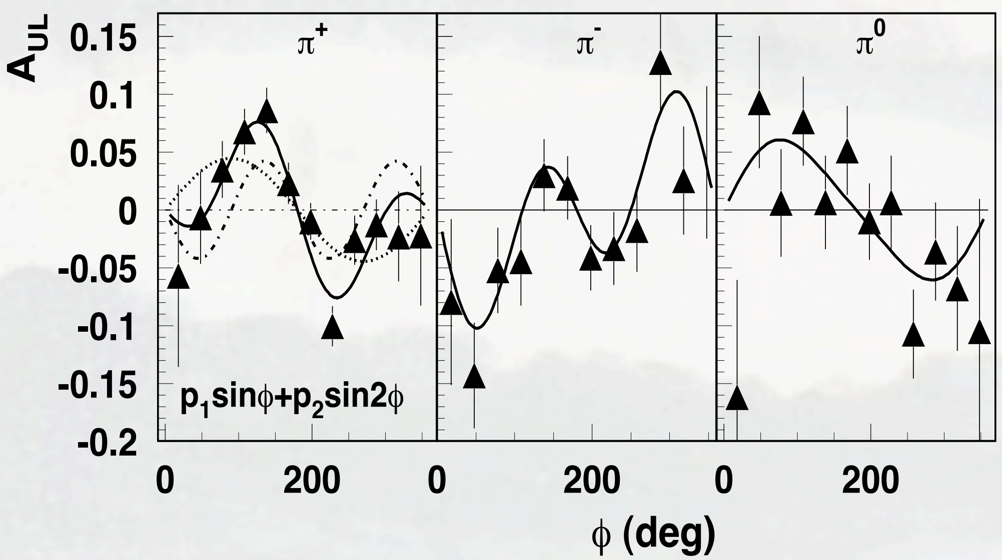
Other (twist-3) TMDs



$$A_{\rm LL}^{\cos\phi}$$

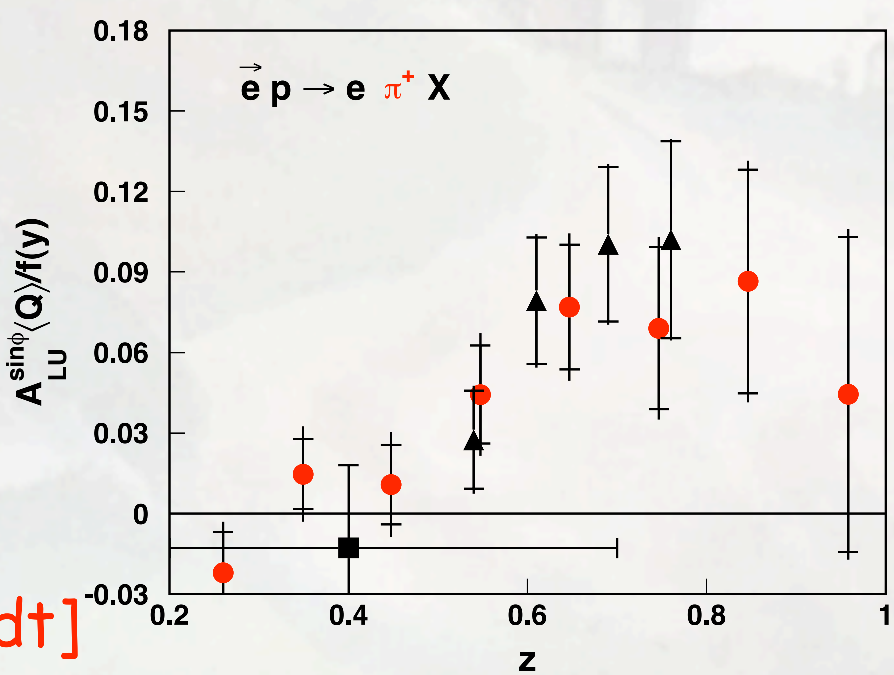
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^\perp - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^\perp D_1 + \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



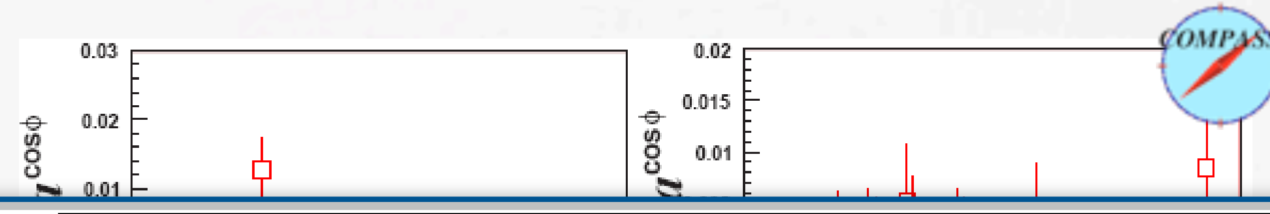
$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L H_1^\perp + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^\perp D_1 - \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{H}}{z}\right)\right]$$

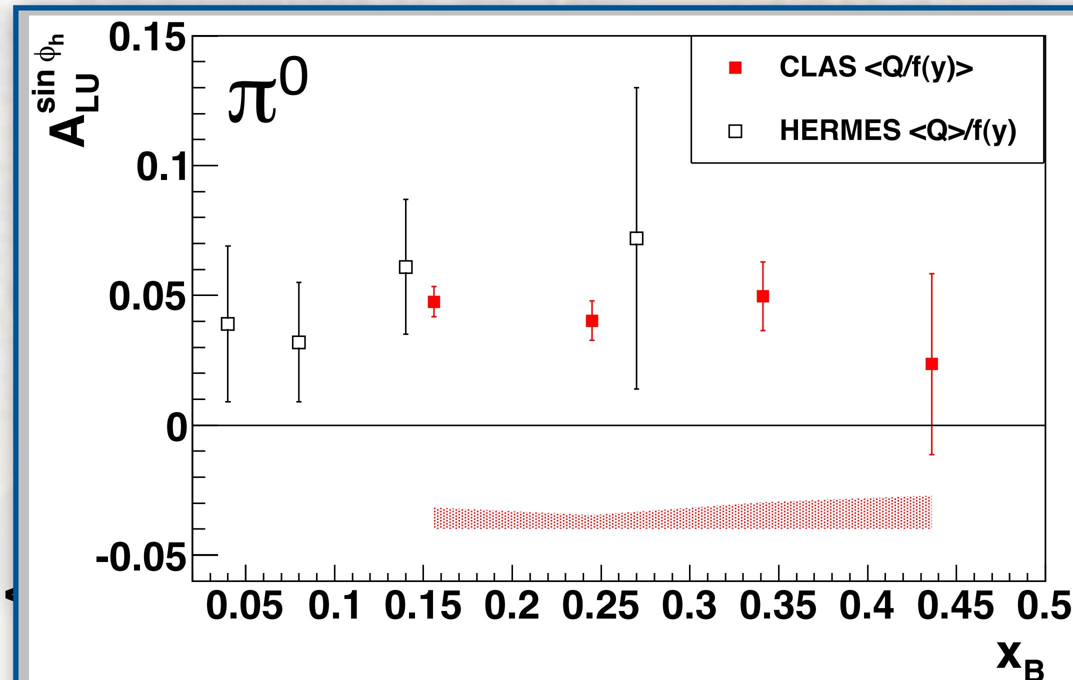
$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

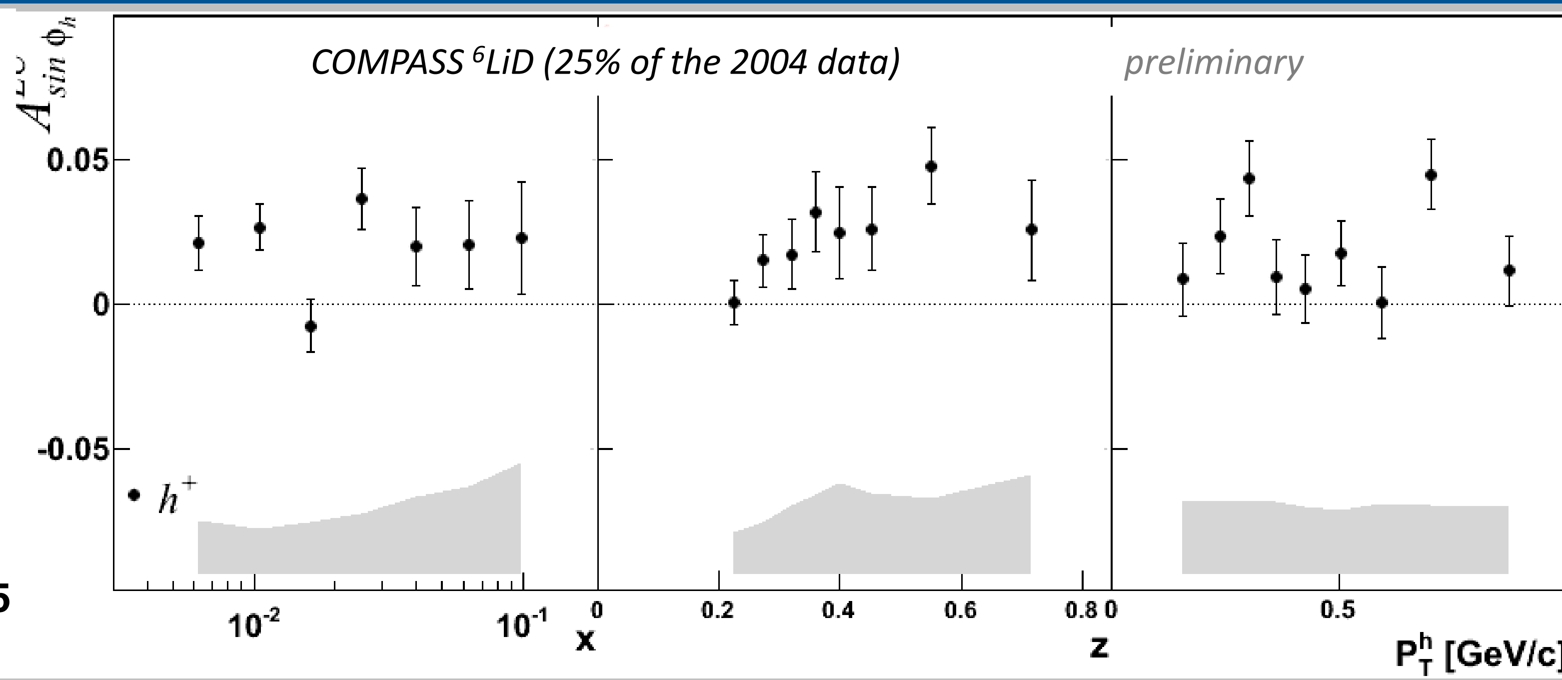


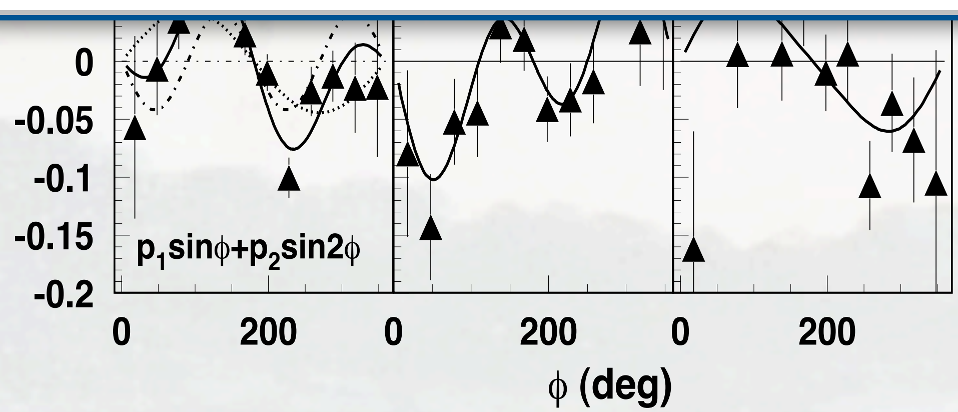
transverse force on transversely pol. quarks [M. Burkardt]

Other (twist-3) TMDs



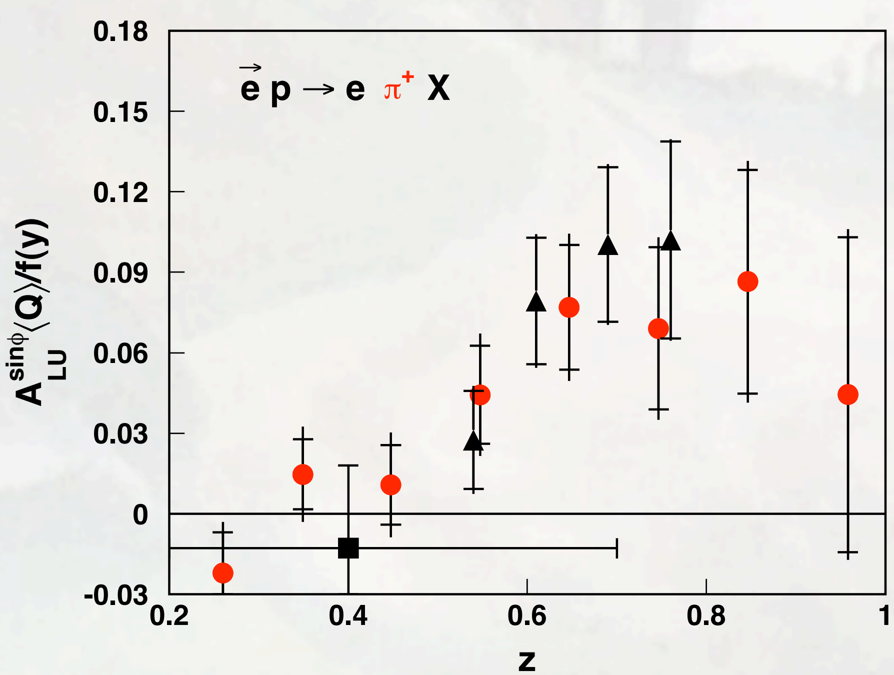






$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L H_1^\perp + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^\perp}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^\perp D_1 - \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{H}}{z}\right)\right]$$

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



☛ **H. Avakian, H. Wollny**

Instead of a summary …

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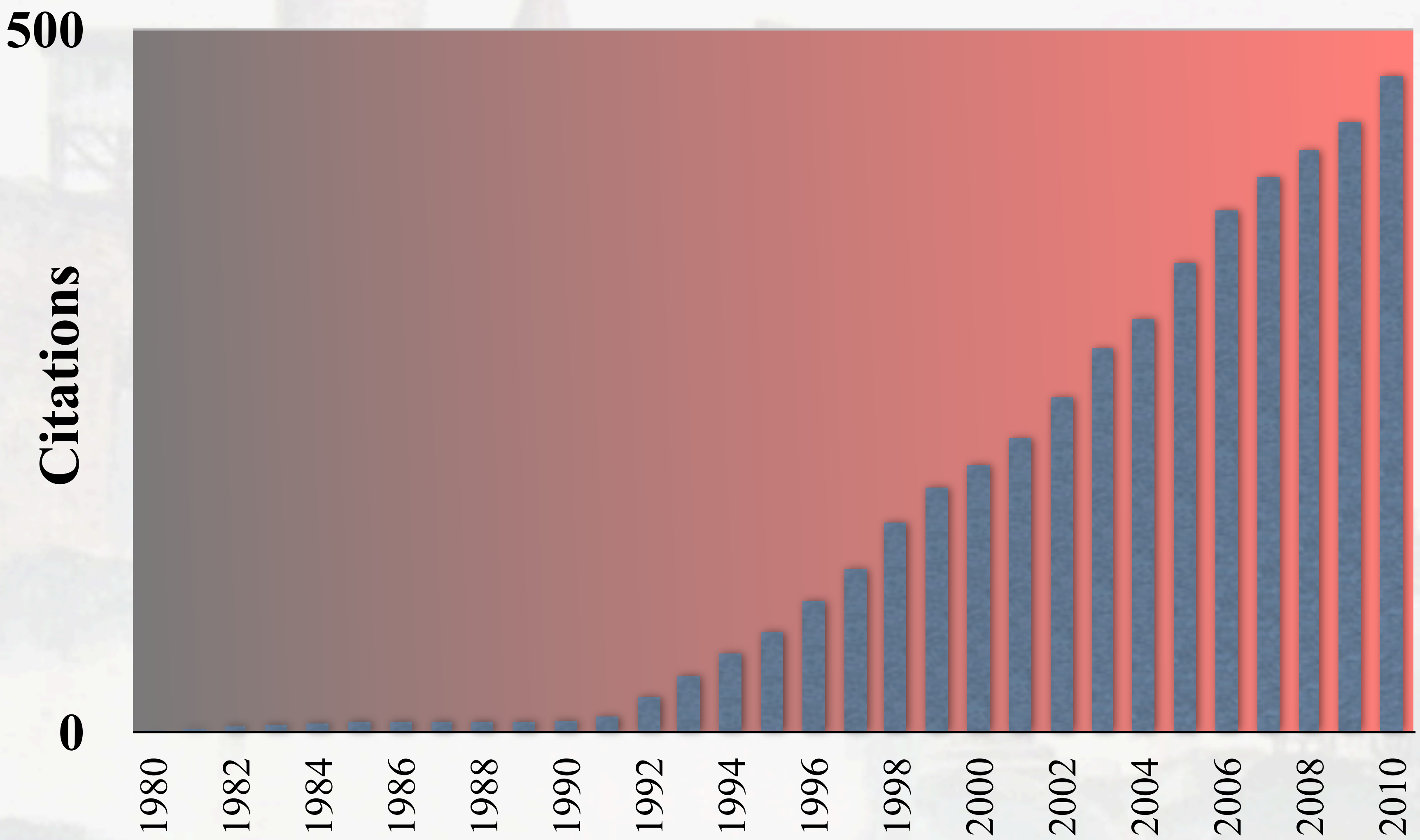
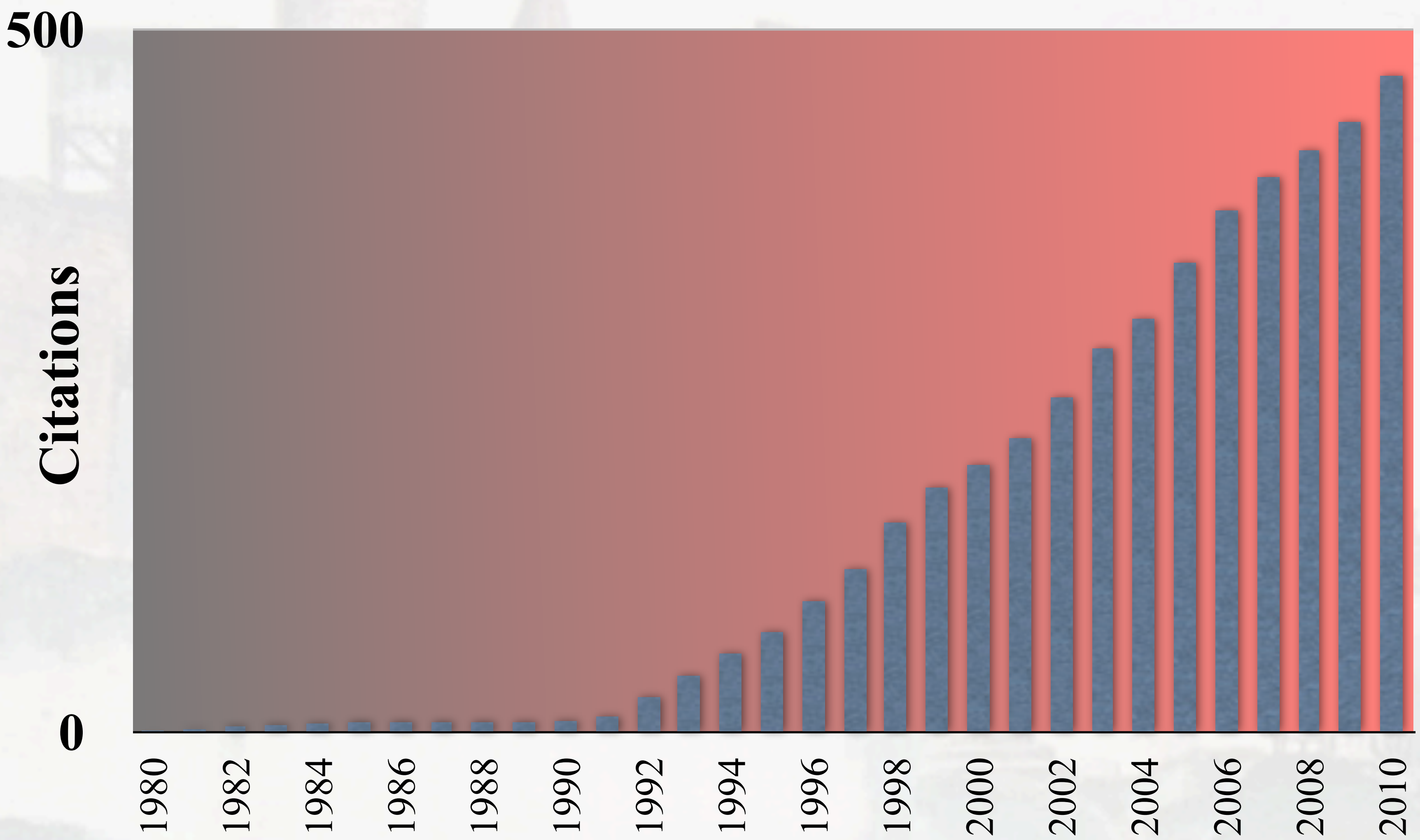
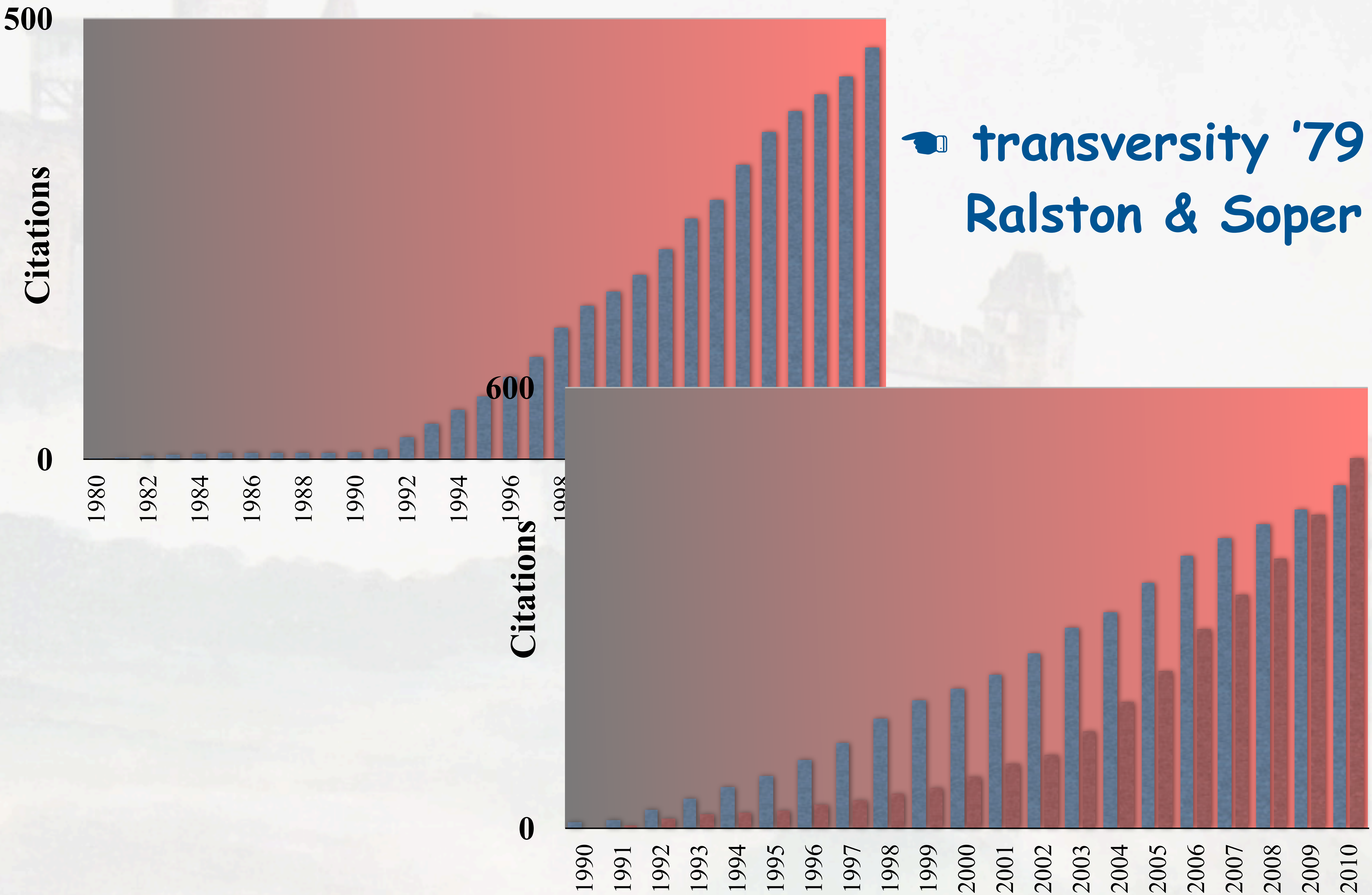


Instead of a summary ...



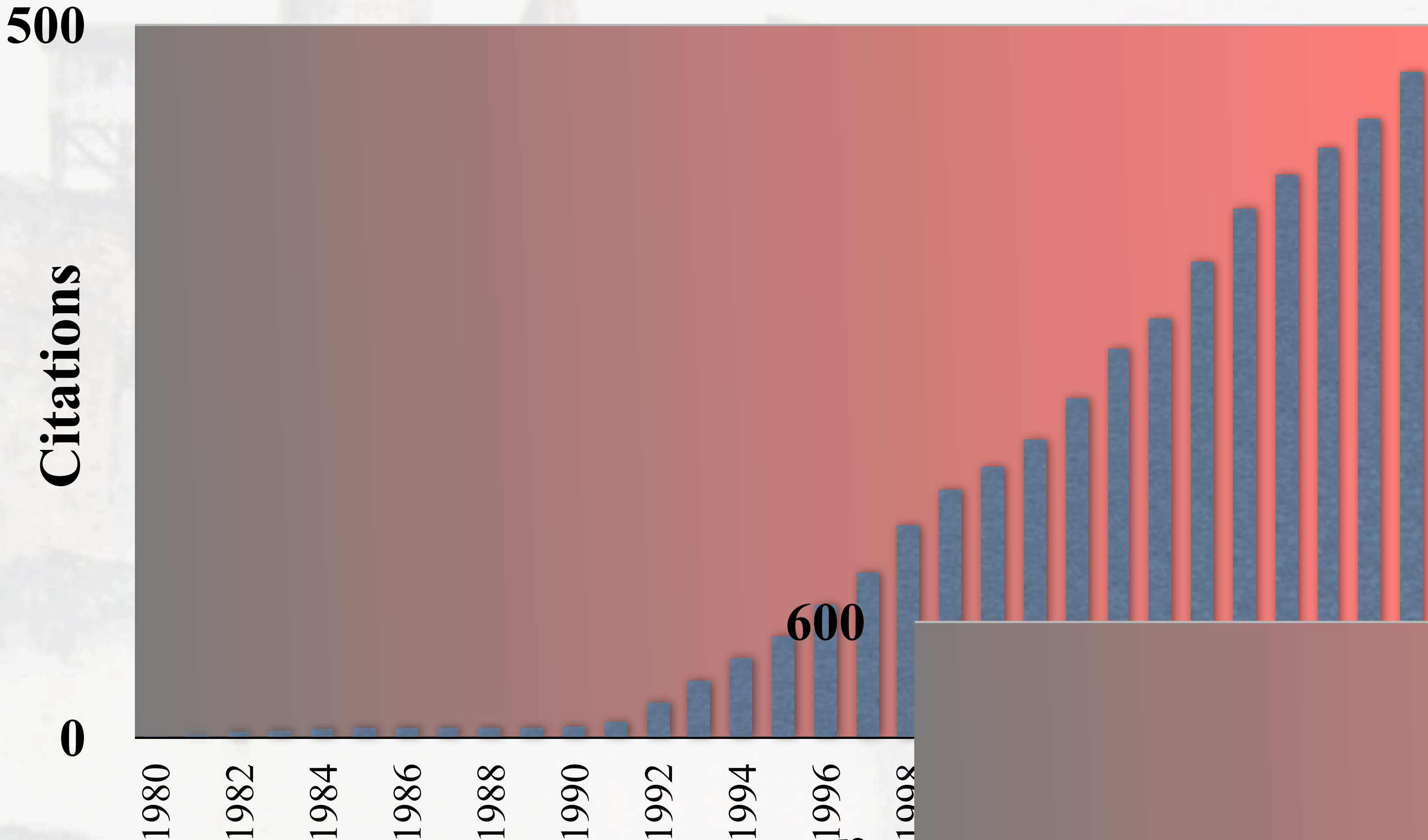
☚ **transversity '79 Ralston & Soper**

Instead of a summary ...

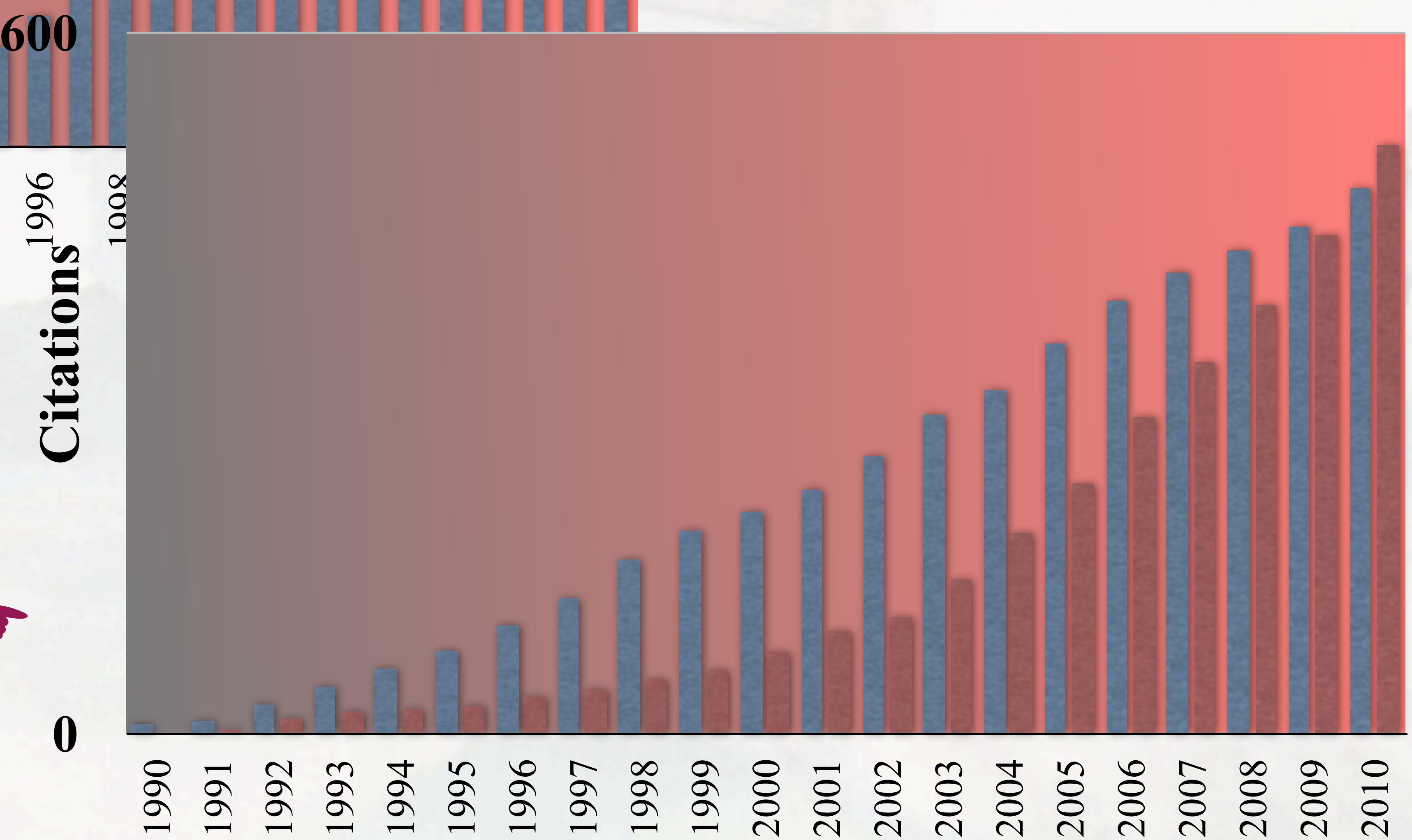


☚ **transversity '79**
Ralston & Soper

Instead of a summary ...

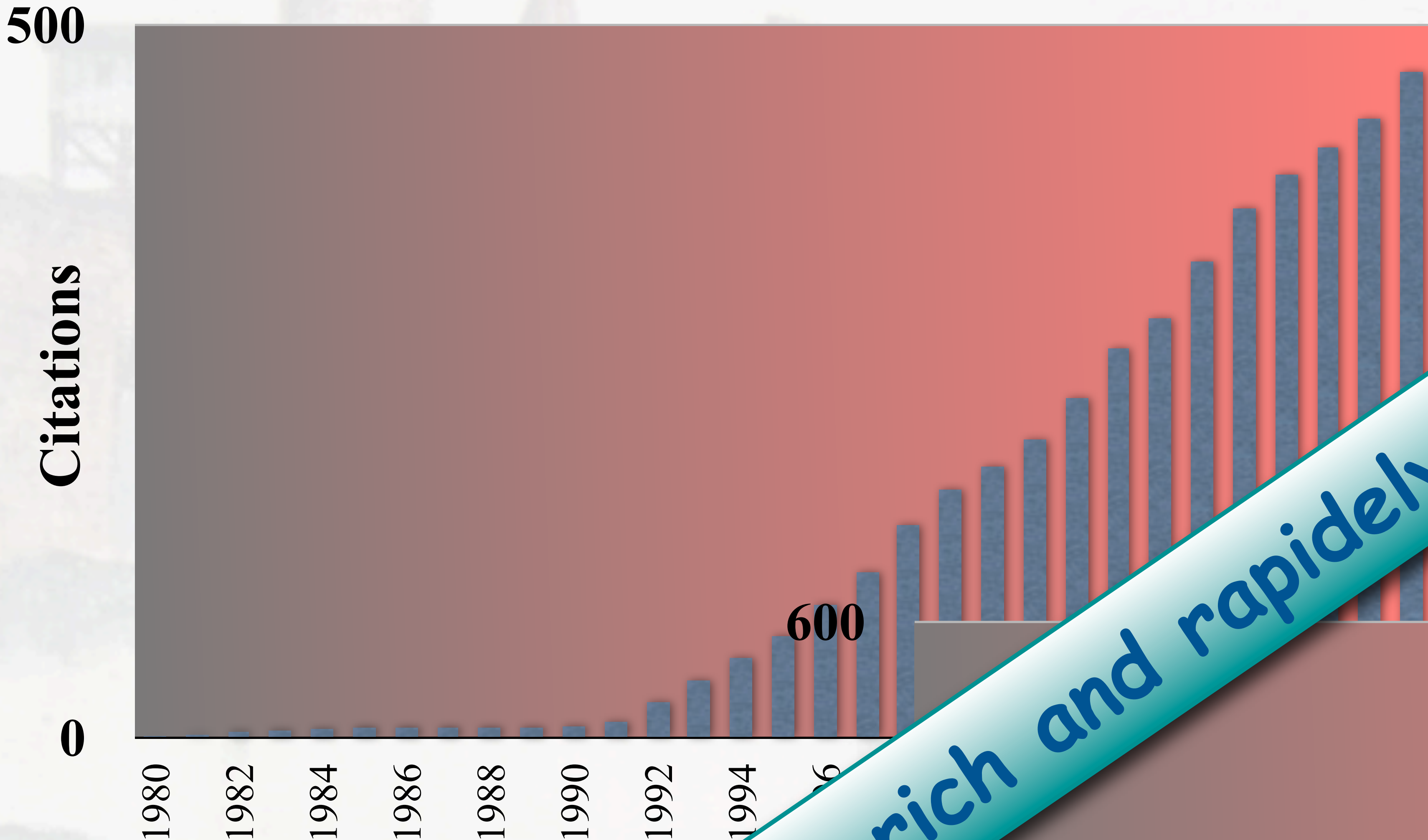


☚ transversity '79
Ralston & Soper



Sivers '90 ☛

Instead of a summary ...



☛ tr… rsity '79

… ston & Soper

TMDs provide a rich and rapidely growing field!

S… ers '90 ☛