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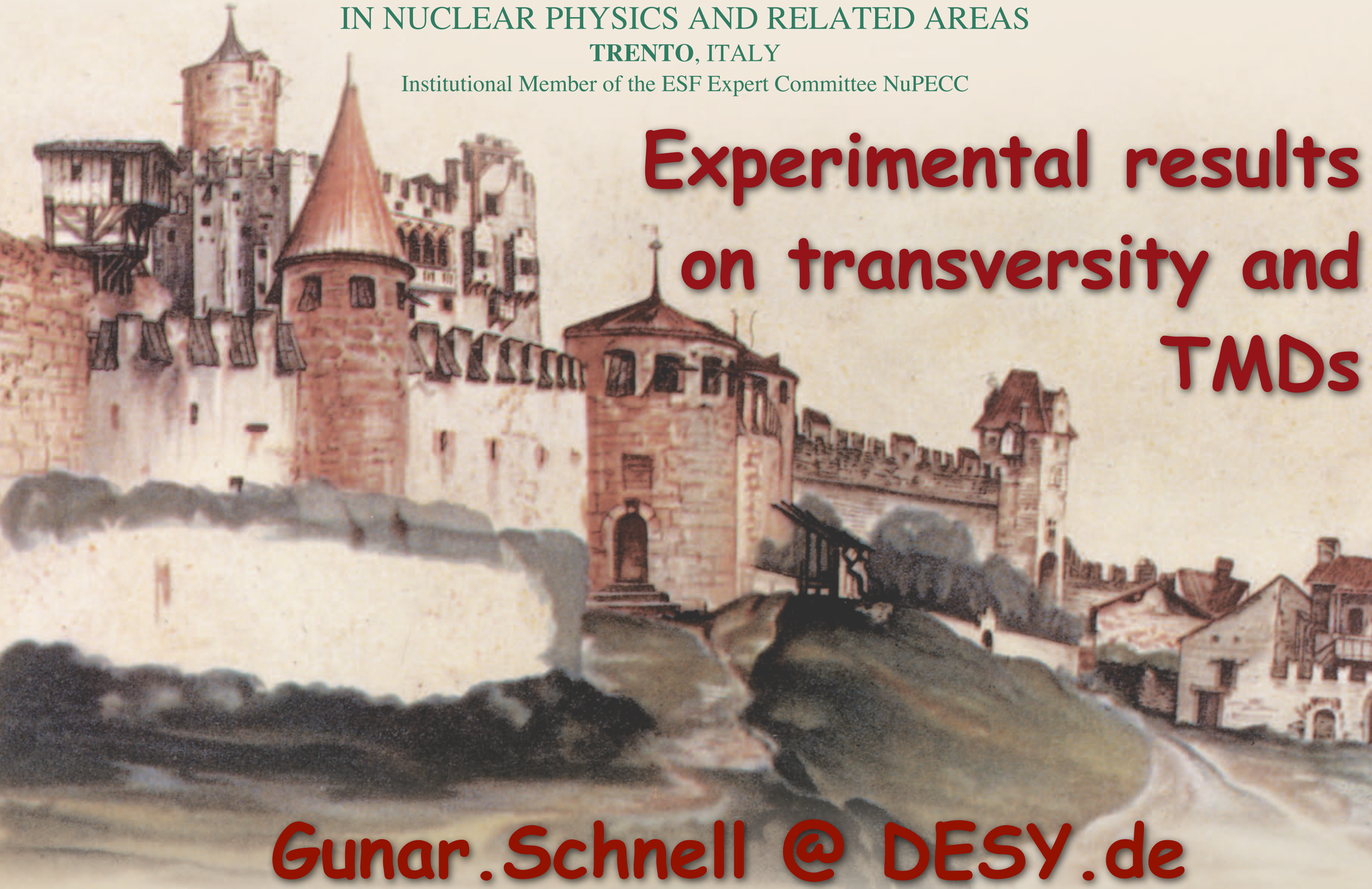
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the ESF Expert Committee NuPECC



Experimental results on transversity and TMDs

Gunar.Schnell @ DESY.de

Spin-Momentum Structure of the Nucleon

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

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

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

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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helicity

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Twist-2 TMDs

Boer-Mulders

Sivers

transversity

Mulders-Tangerman*

worm-gear

- functions in black survive integration ... momentum
- functions in green box are chirally odd
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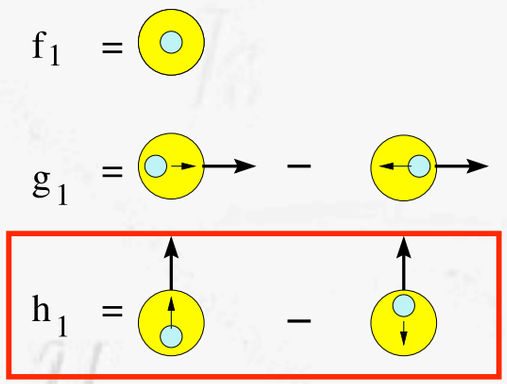
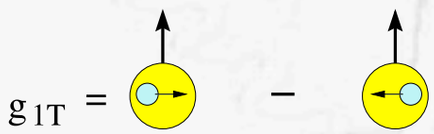
*aka Pretzelosity

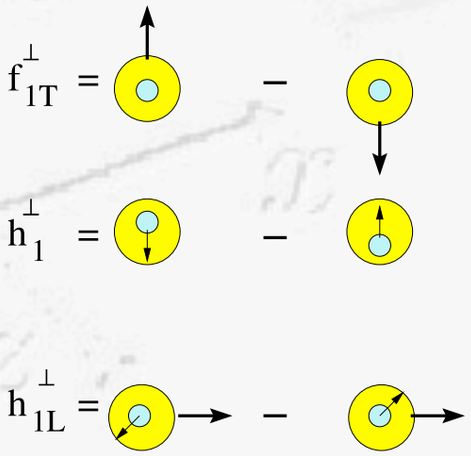
Ex.: Appearance of TMDs in SIDIS

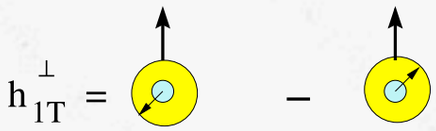
Leading-Twist

Distribution Functions

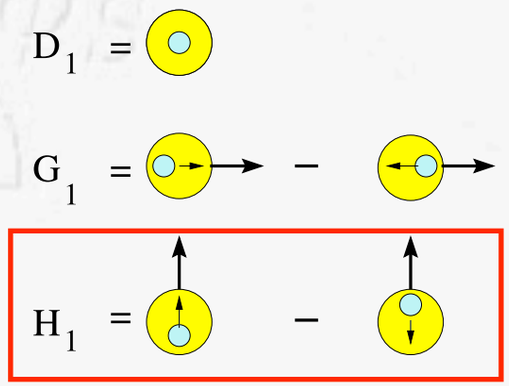


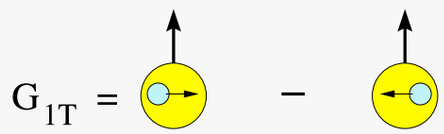


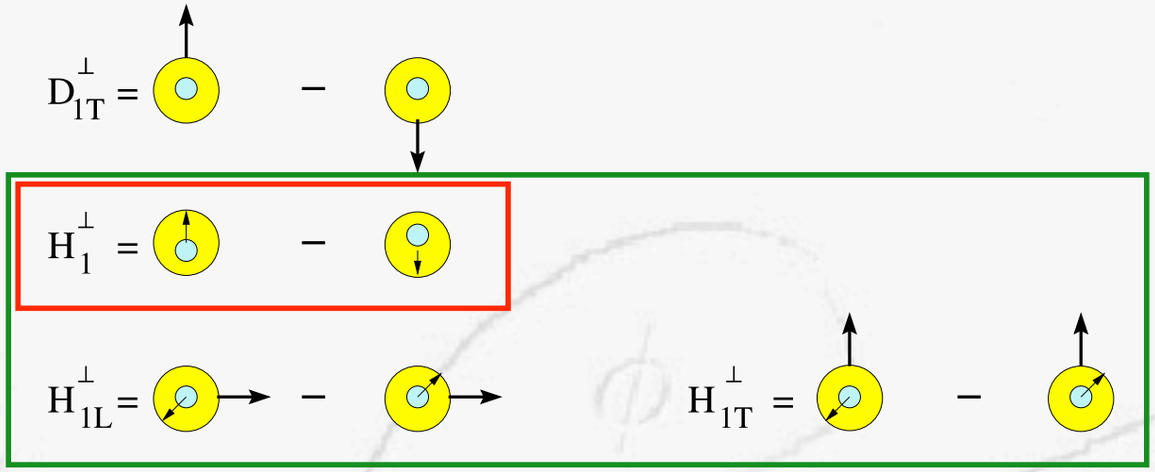




Fragmentation Functions







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

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

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

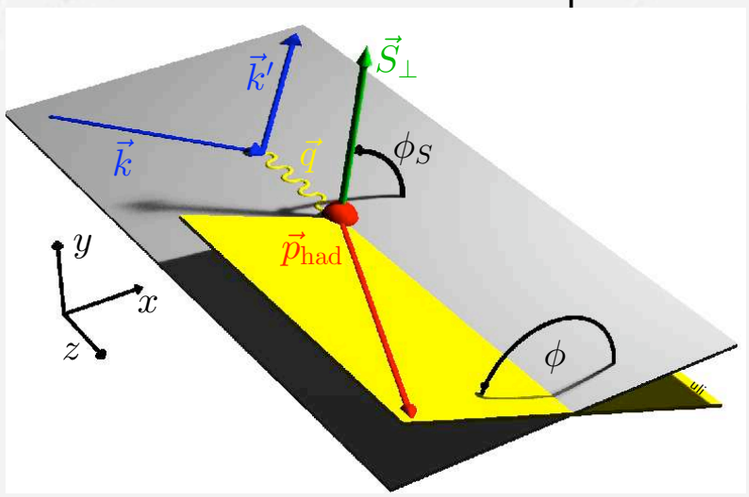
$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

σ_{XY}

Beam Target Polarization

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



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

Momentum density

	U	L	T
U	f_1		$h_1^\perp$
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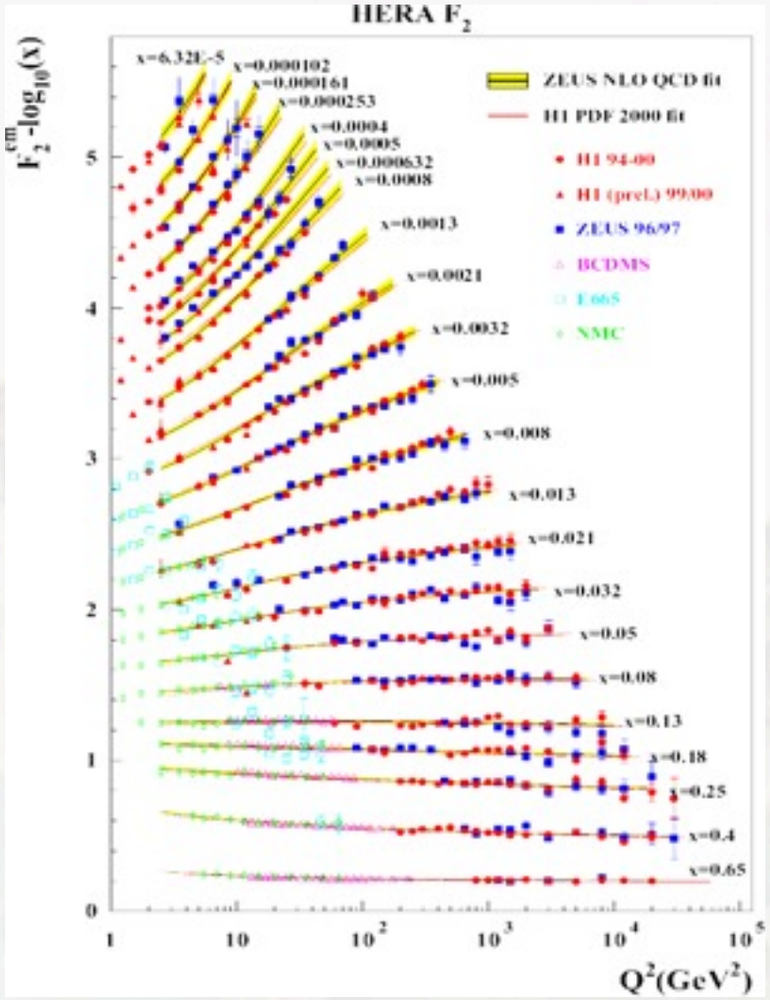

- plenty of data available
- but only for integrated version of f_1
- spin asymmetries involve unintegrated f_1 in denominator
- need multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$
- some efforts to get unintegrated gluon density

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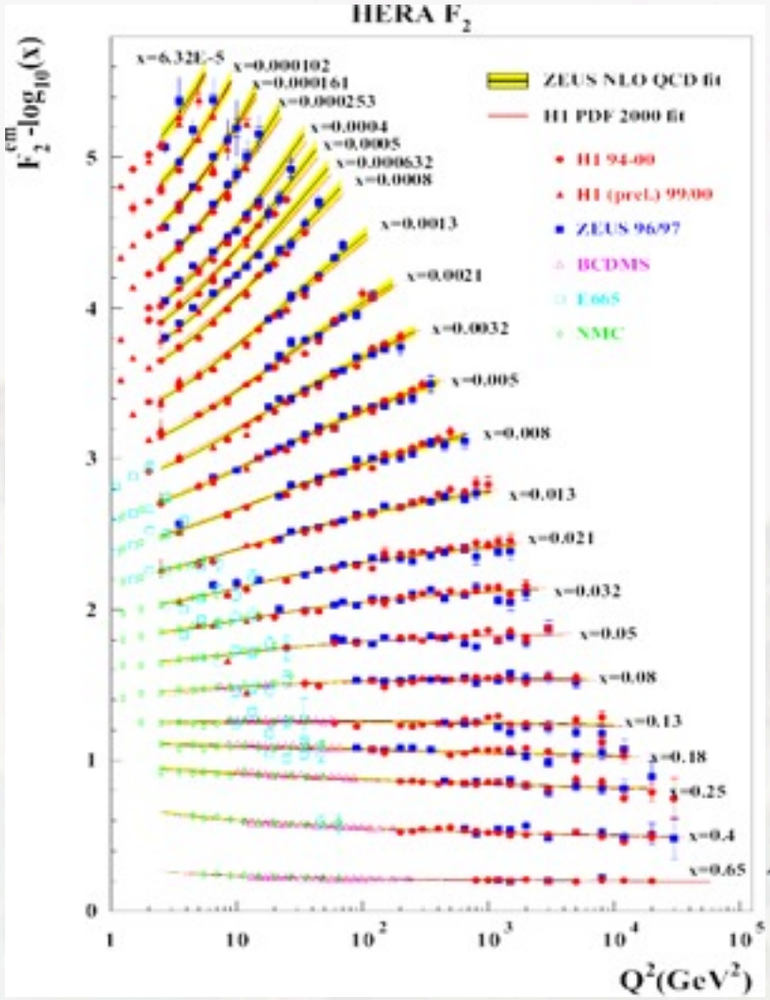

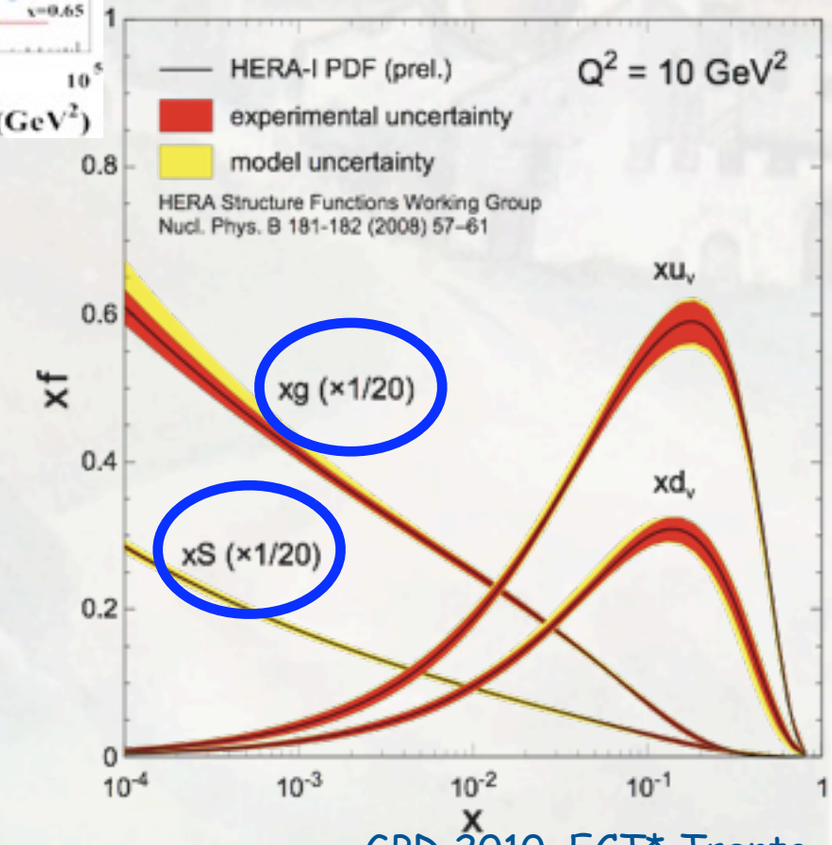

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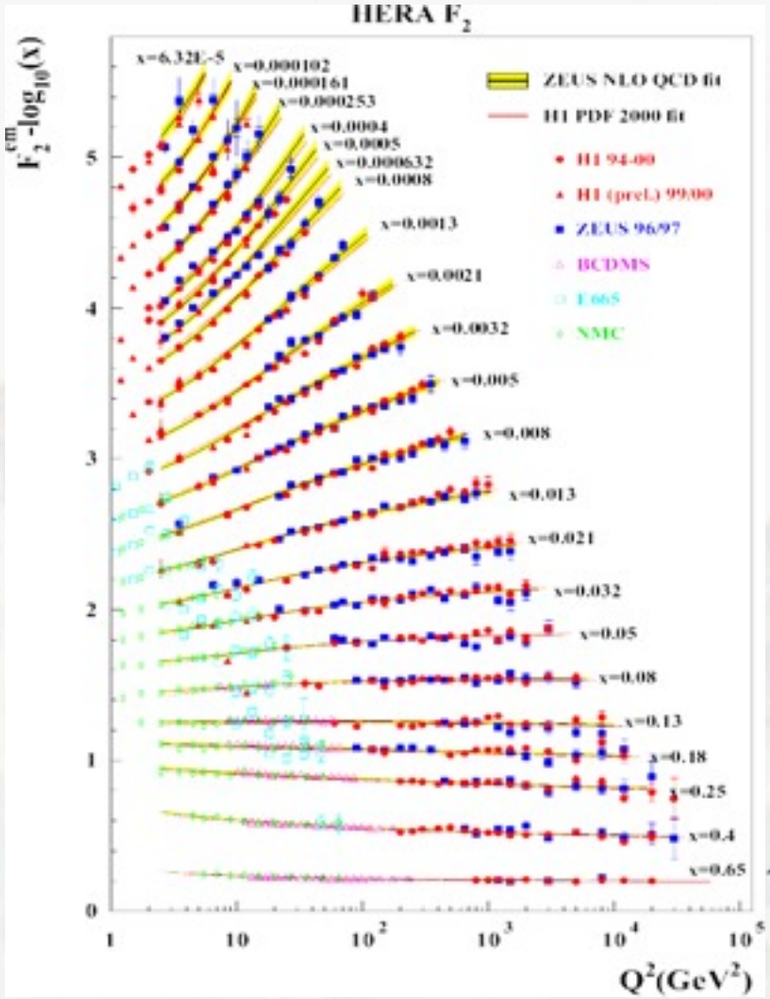

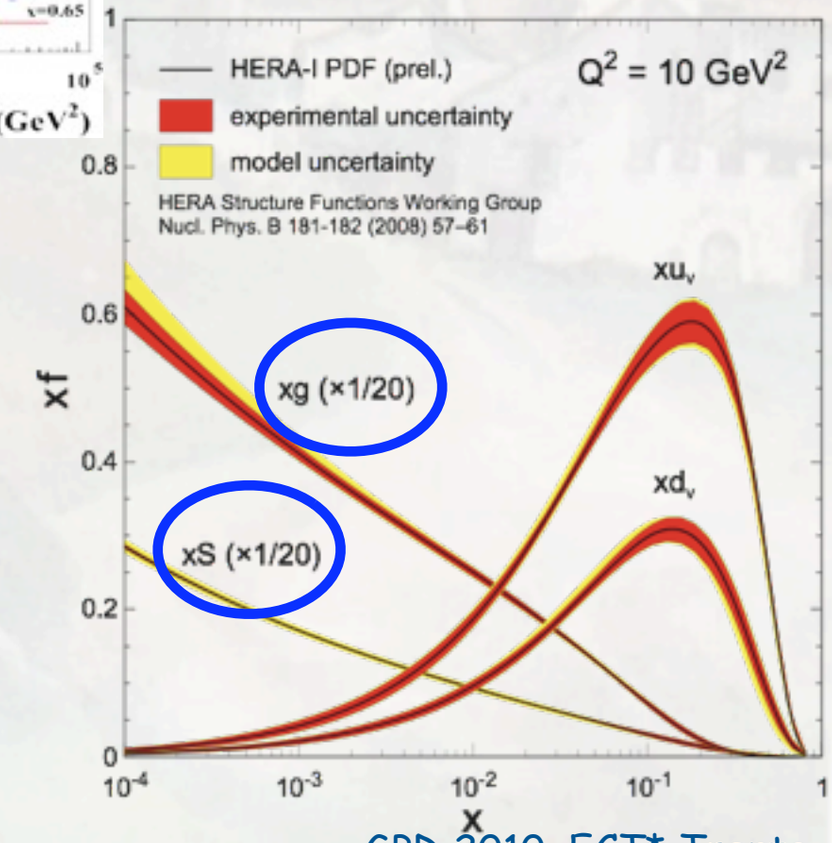

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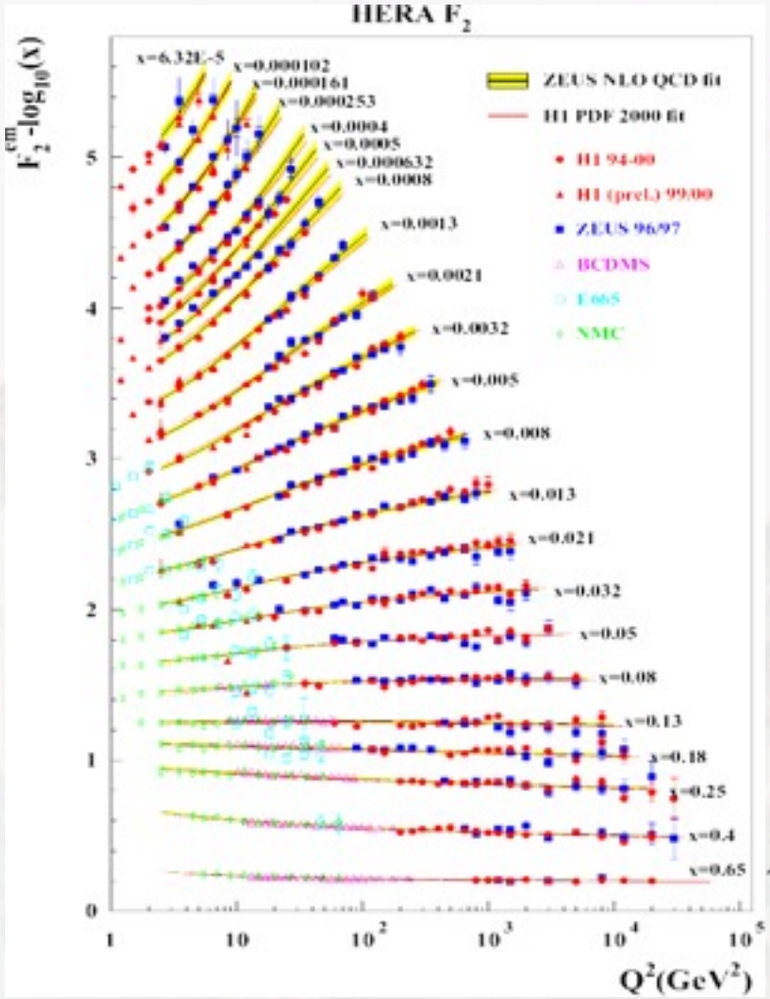

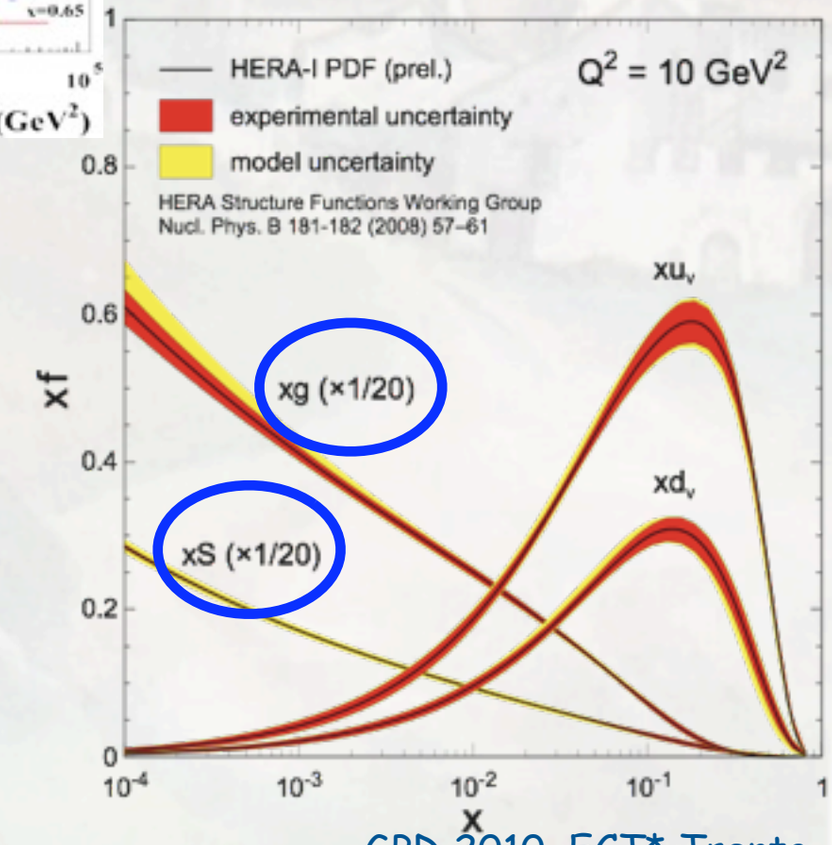

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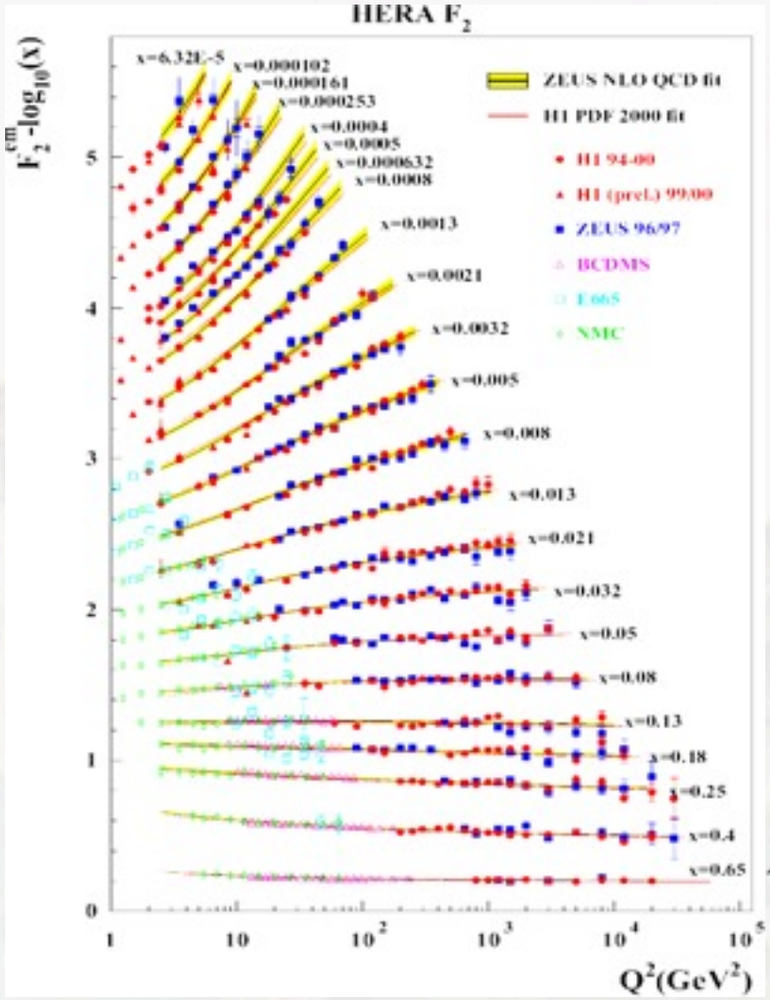

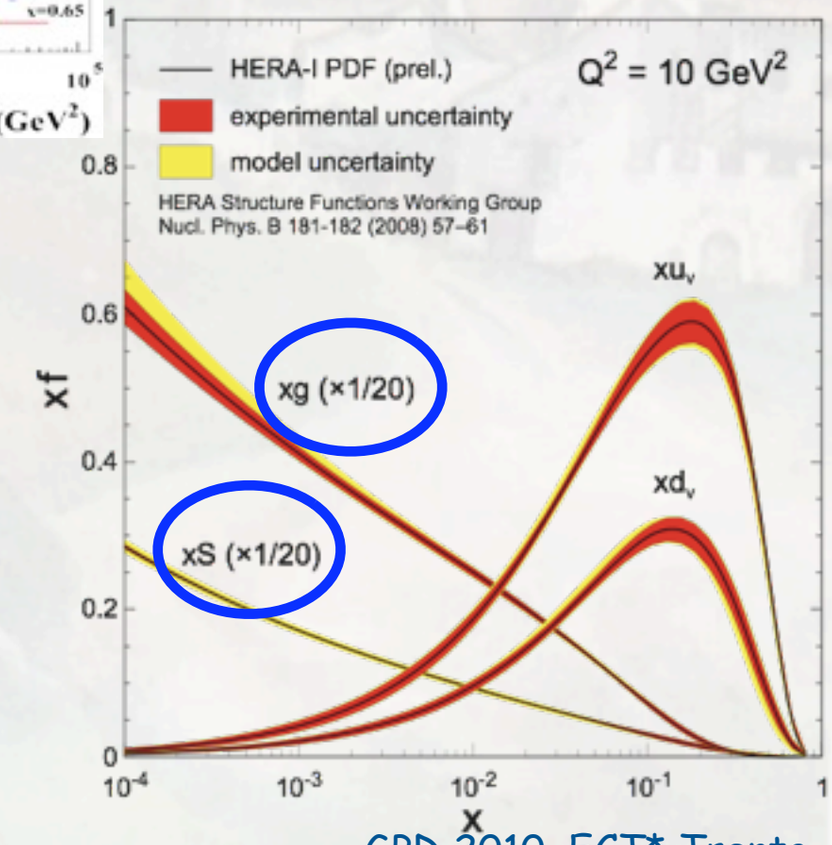

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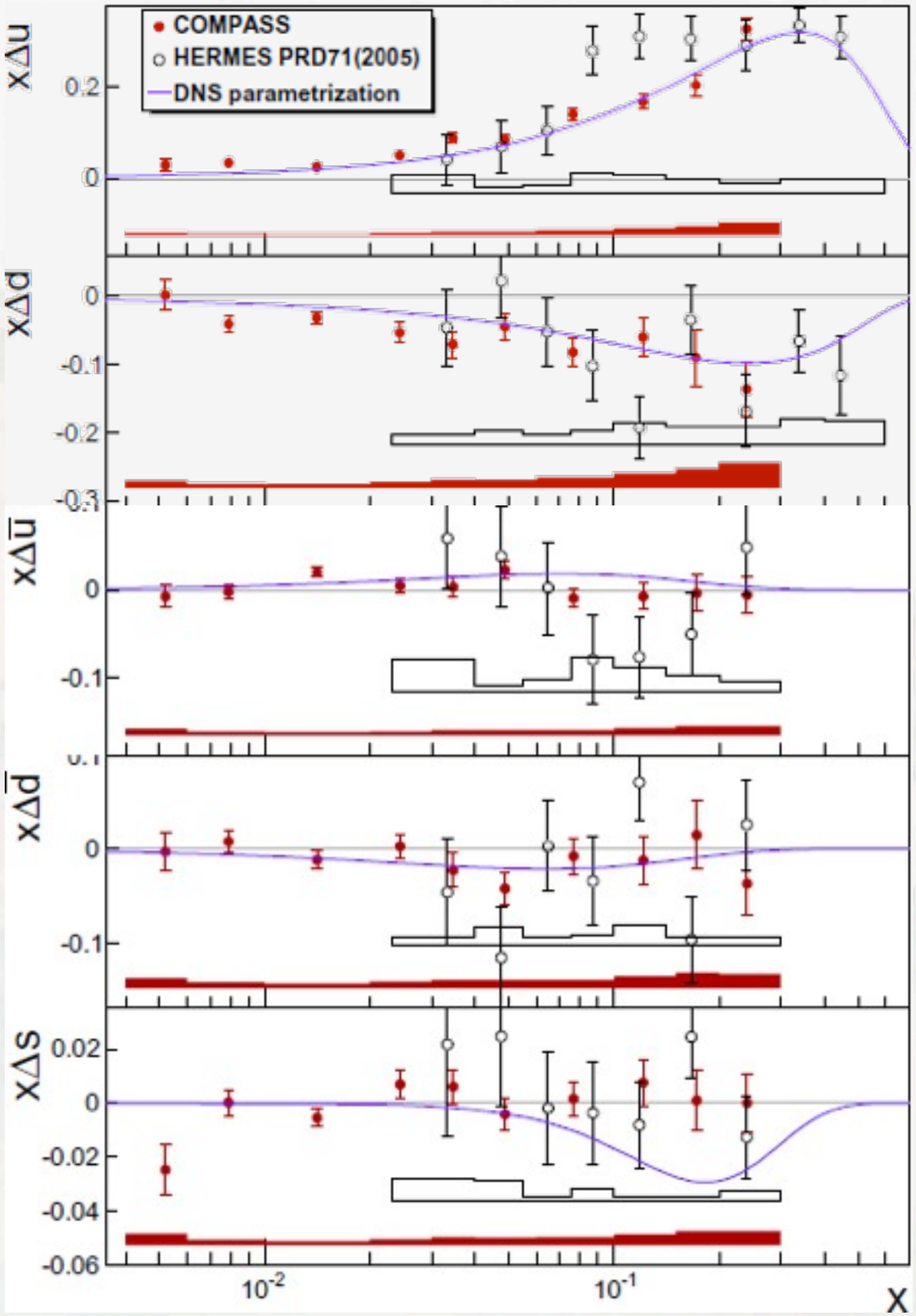
Helicity density

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



- smaller range in (x,Q^2) than for f_1
- data mainly for integrated version of g_{1L}
- need asymmetries not only binned in x but also in $P_{h\perp}$

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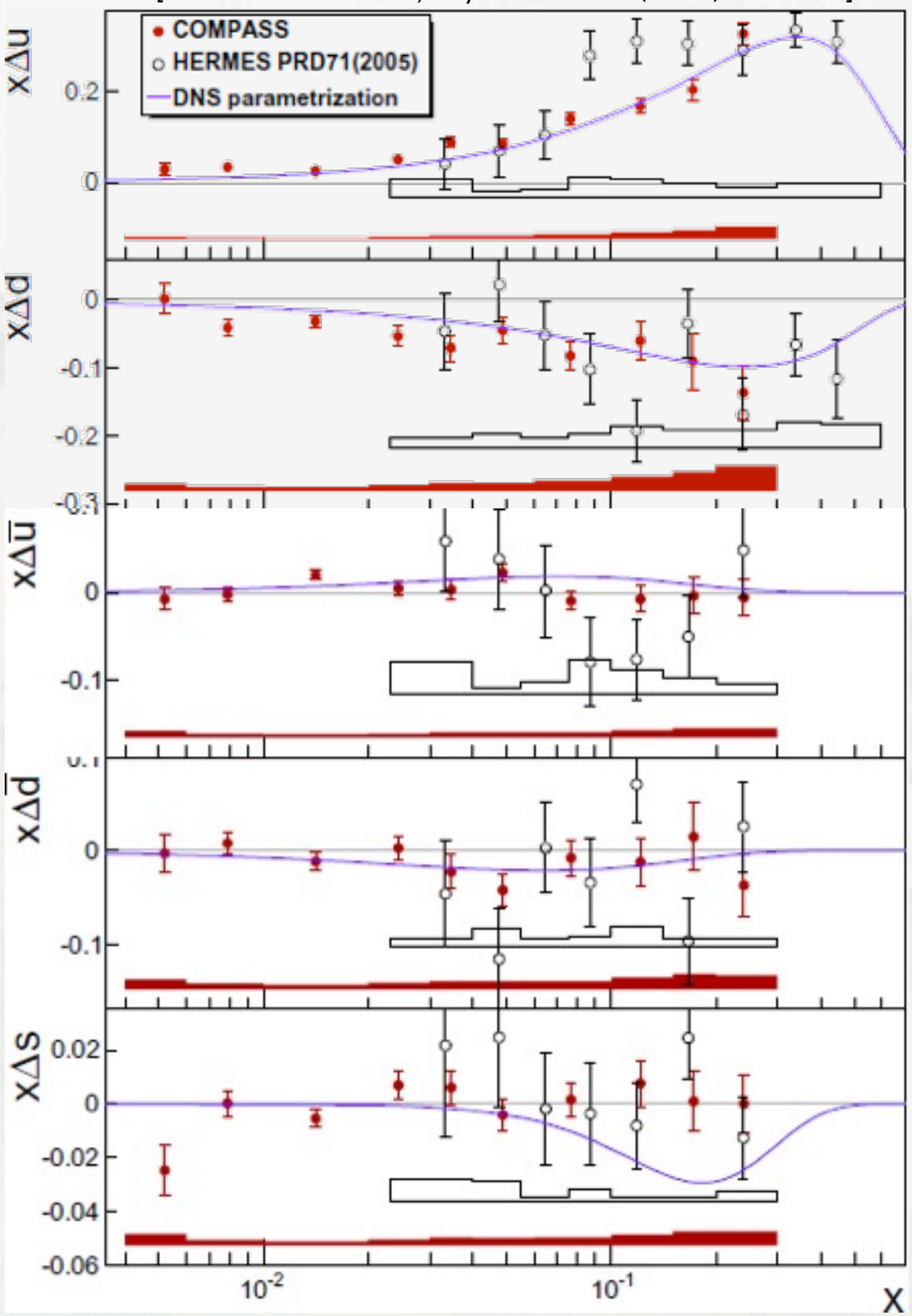

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☛ E.-M. Kabuss, W. Vogelsang

Helicity density (unintegrated)

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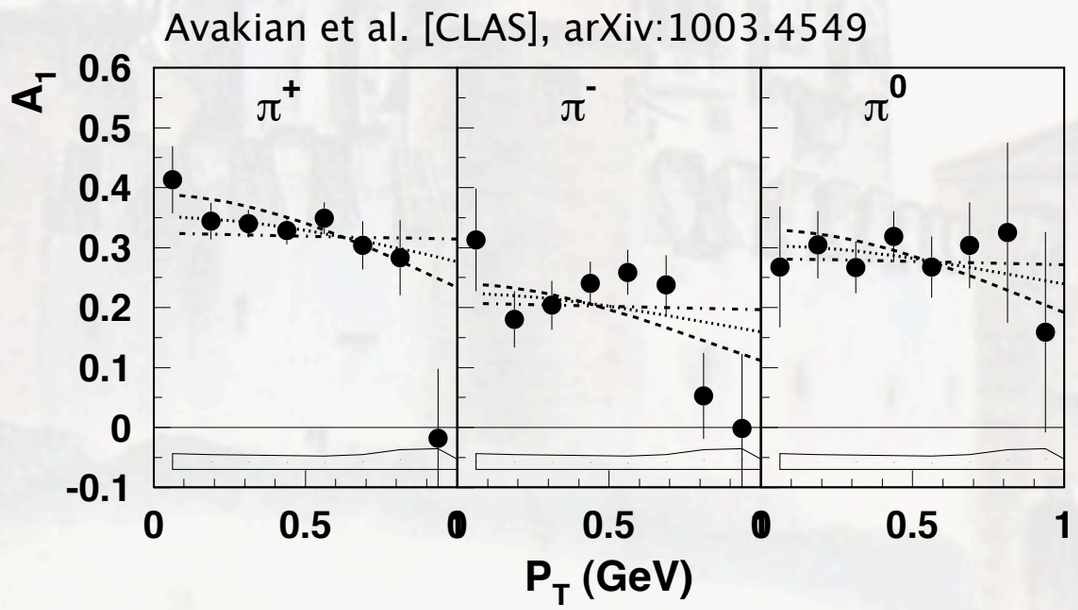

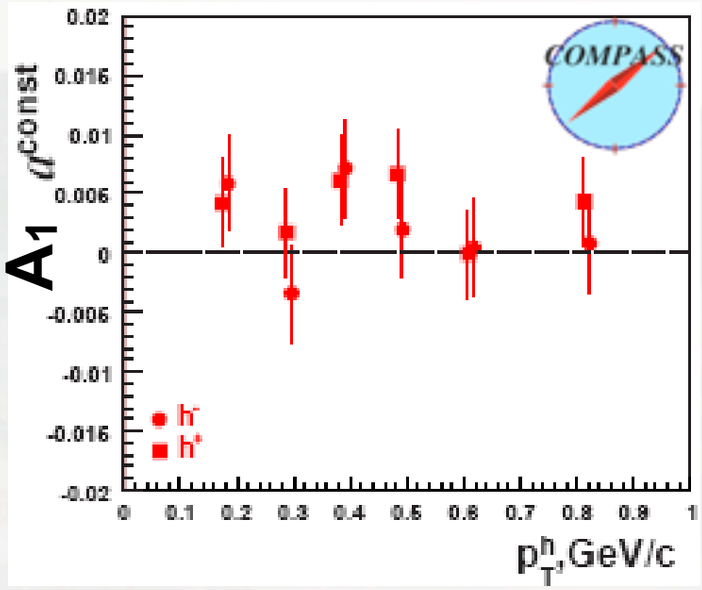

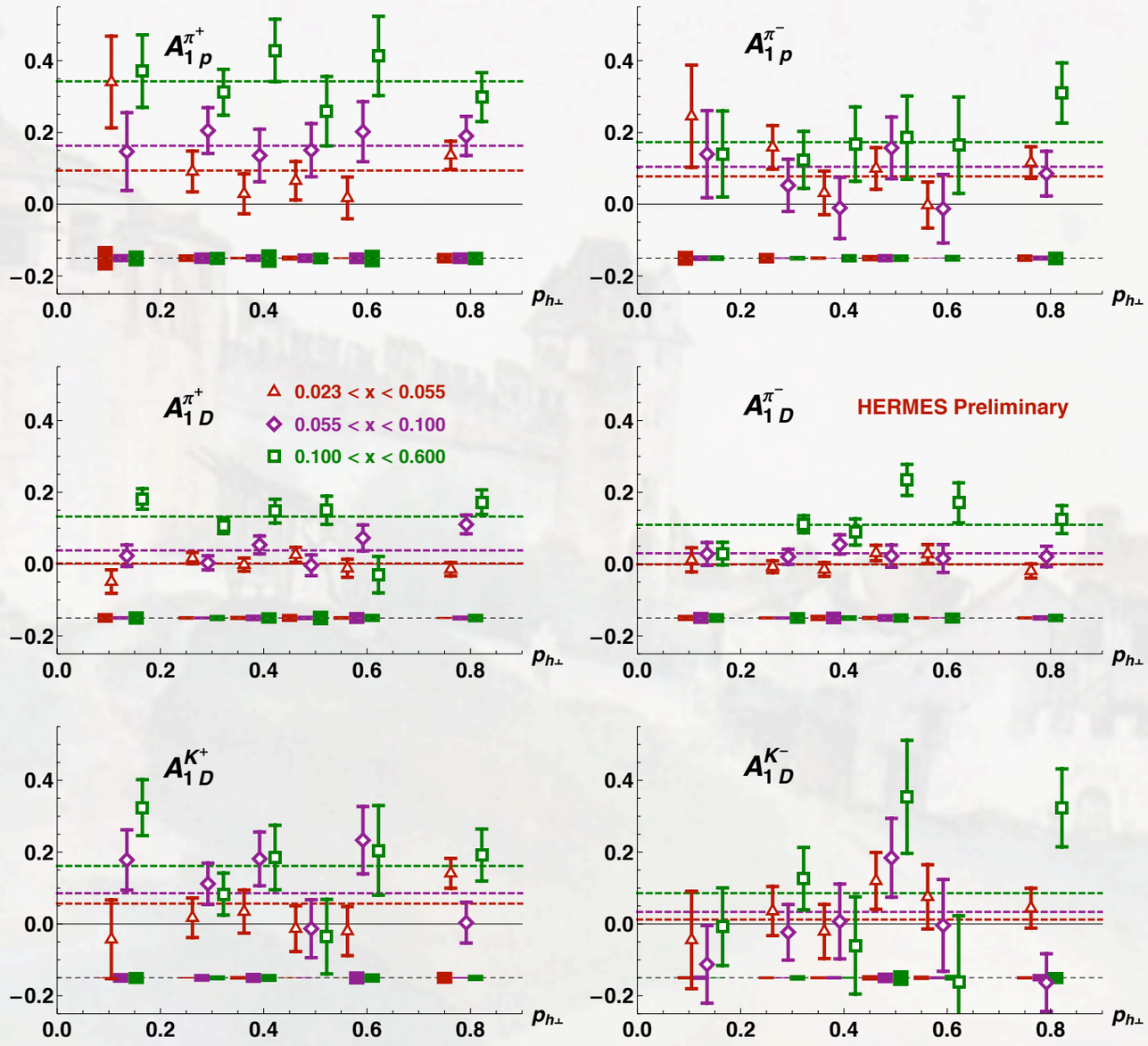

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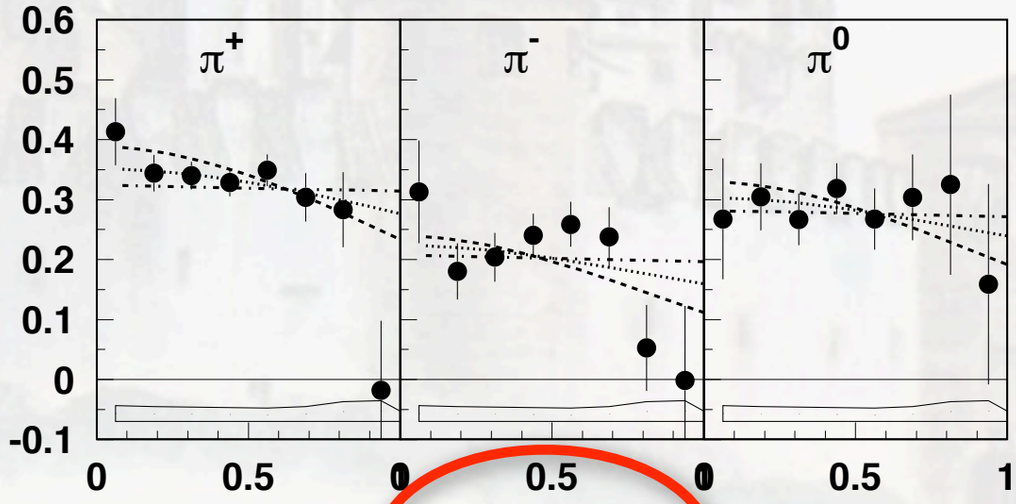
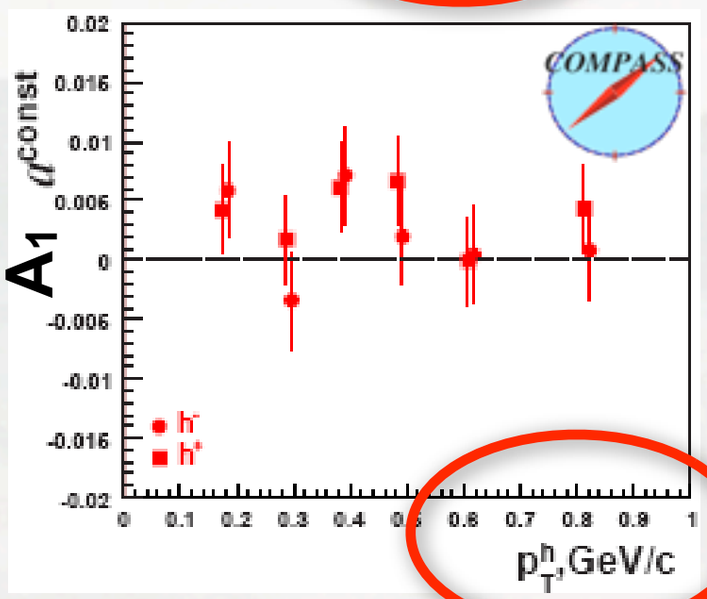
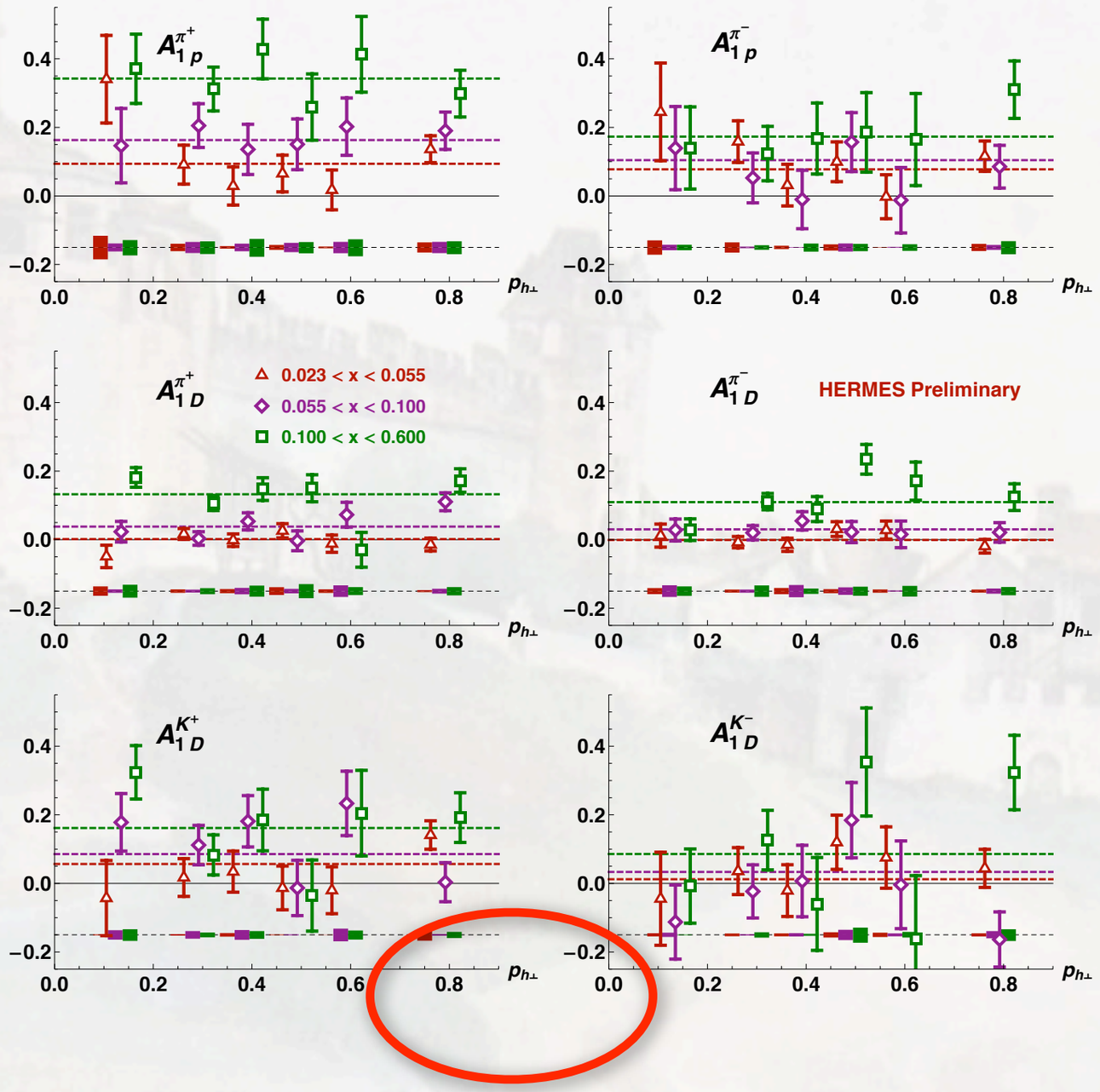
Helicity density (unintegrated)

Avakian et al. [CLAS], arXiv:1003.4549







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

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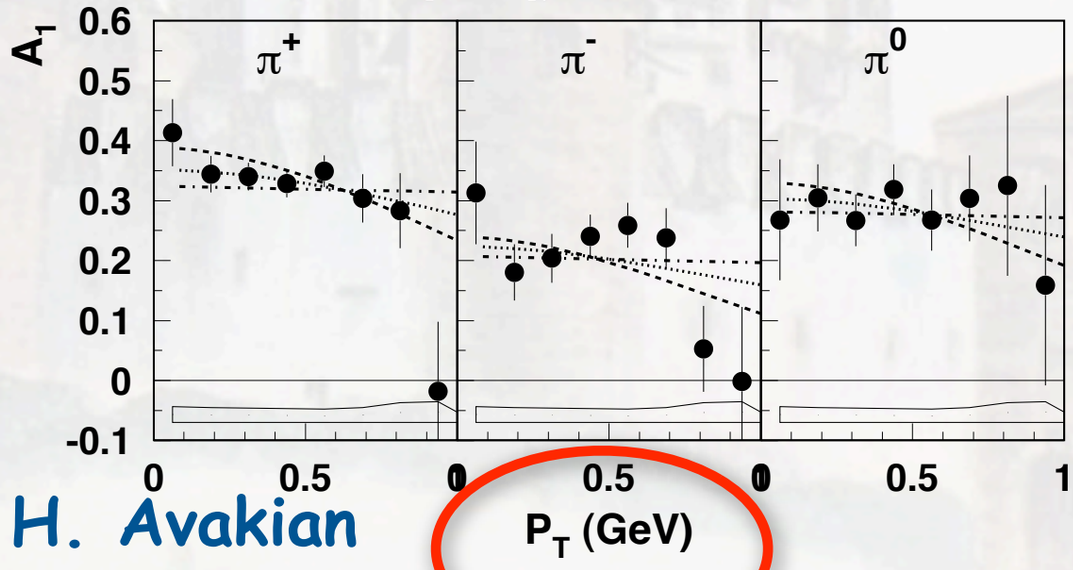
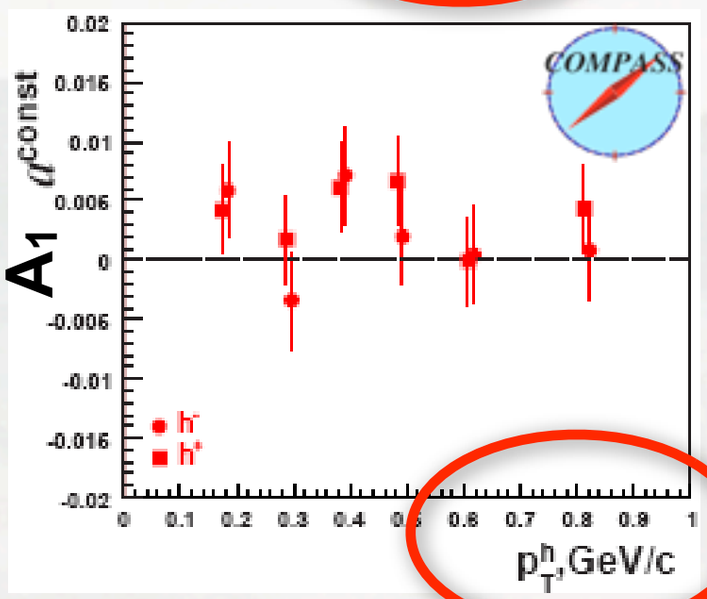
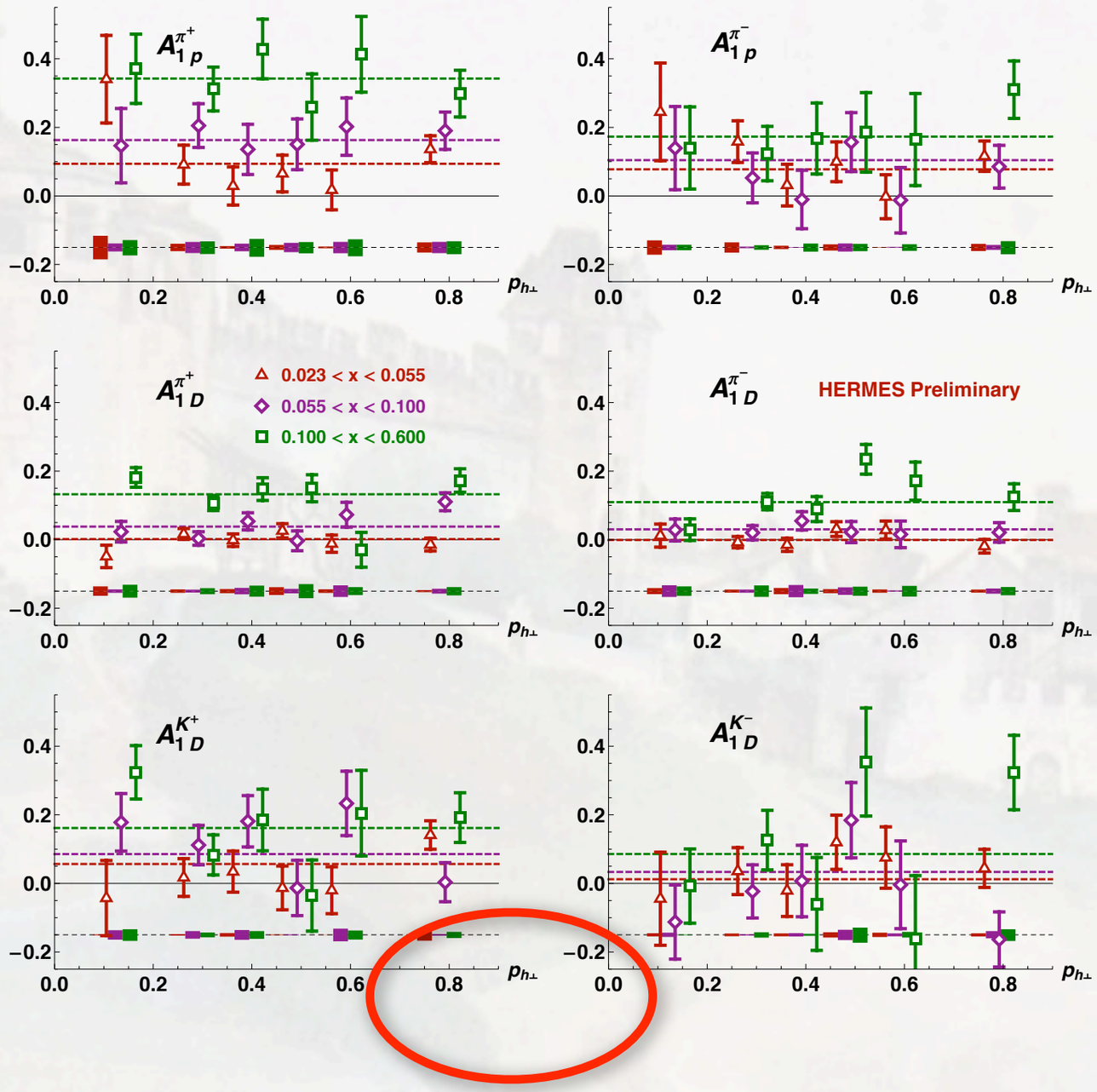


☛ H. Avakian





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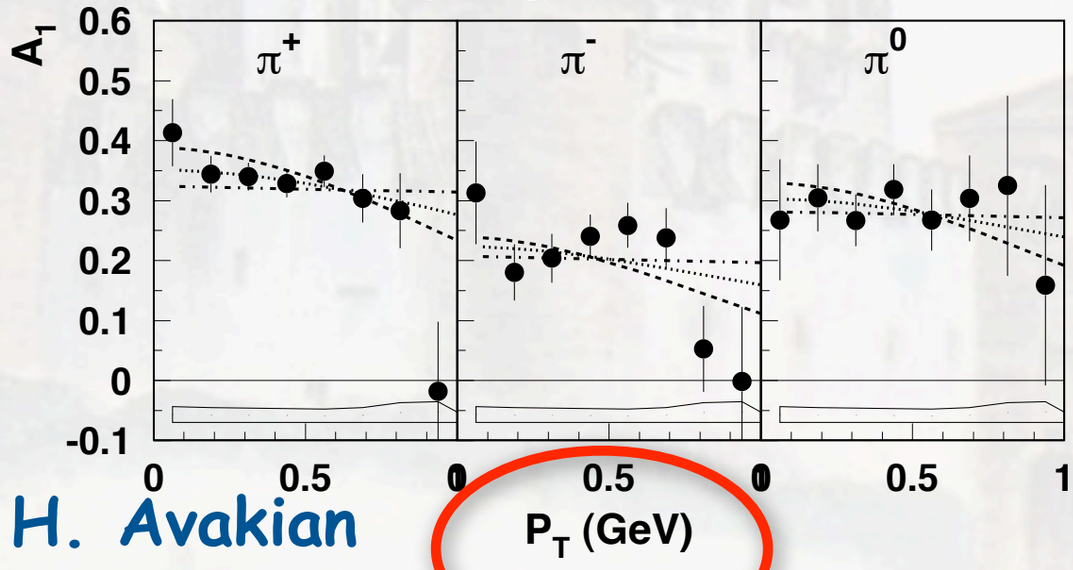

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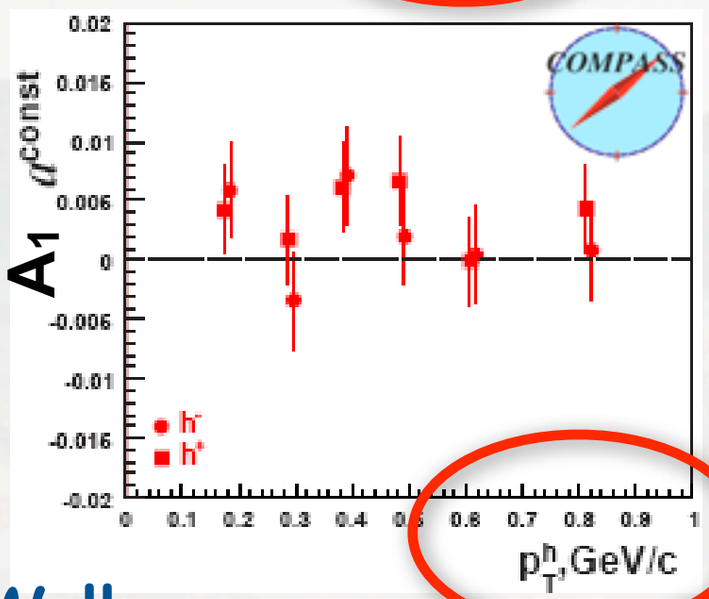
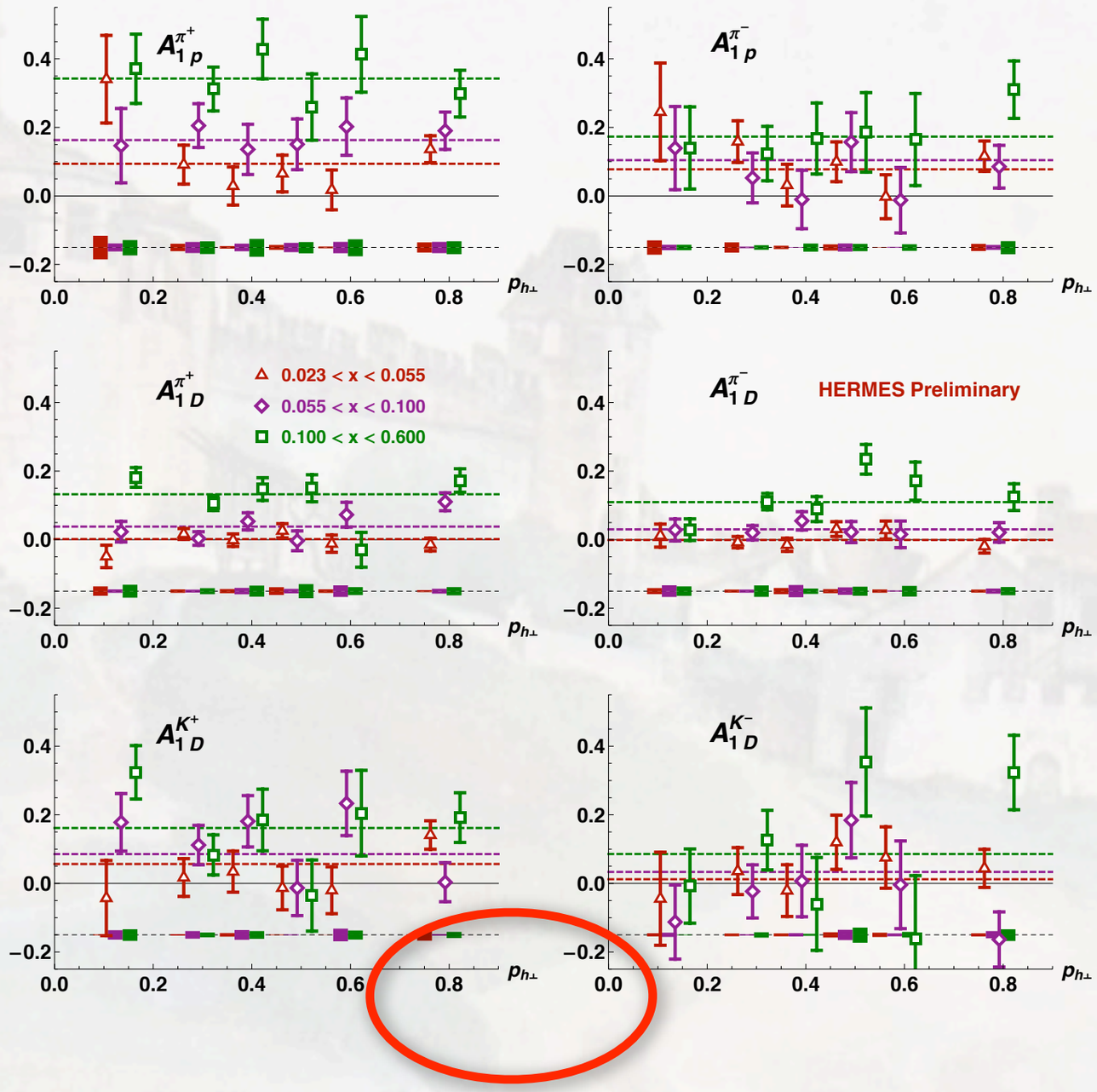


☛ H. Wollny



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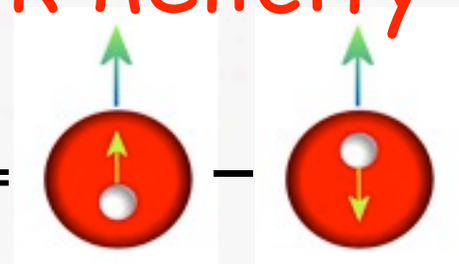
Transversity distribution

chiral-odd transversity involves quark helicity flip

$f_1^q =$ 

$g_1^q =$ 

$h_1^q =$ 

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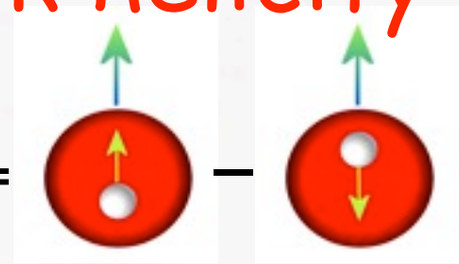
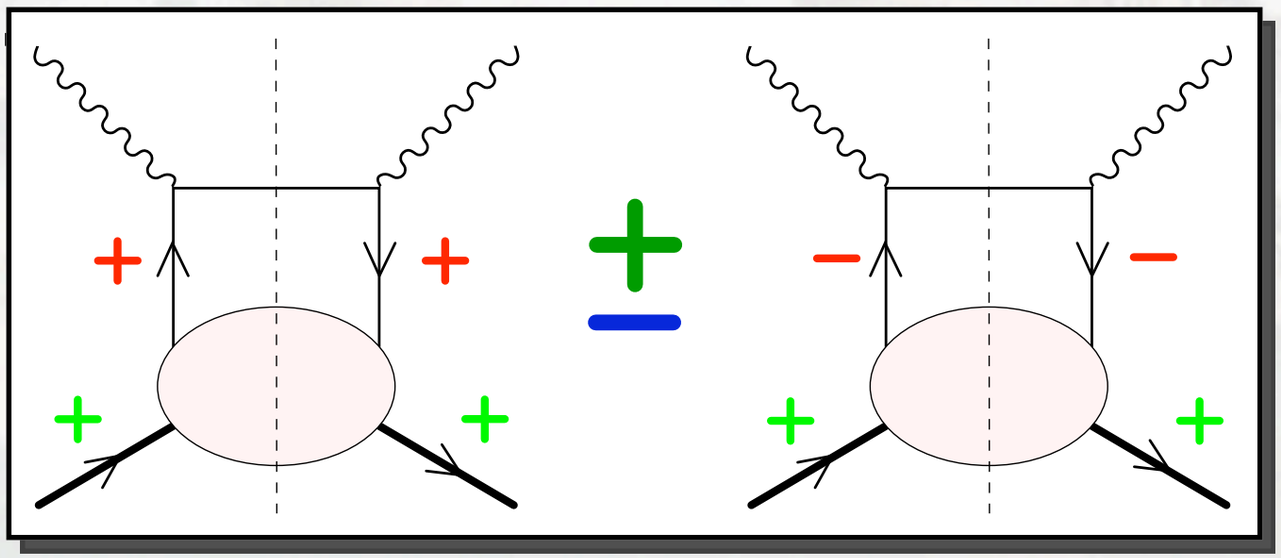
$h_1^q =$ 



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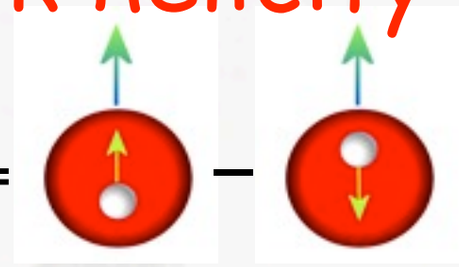
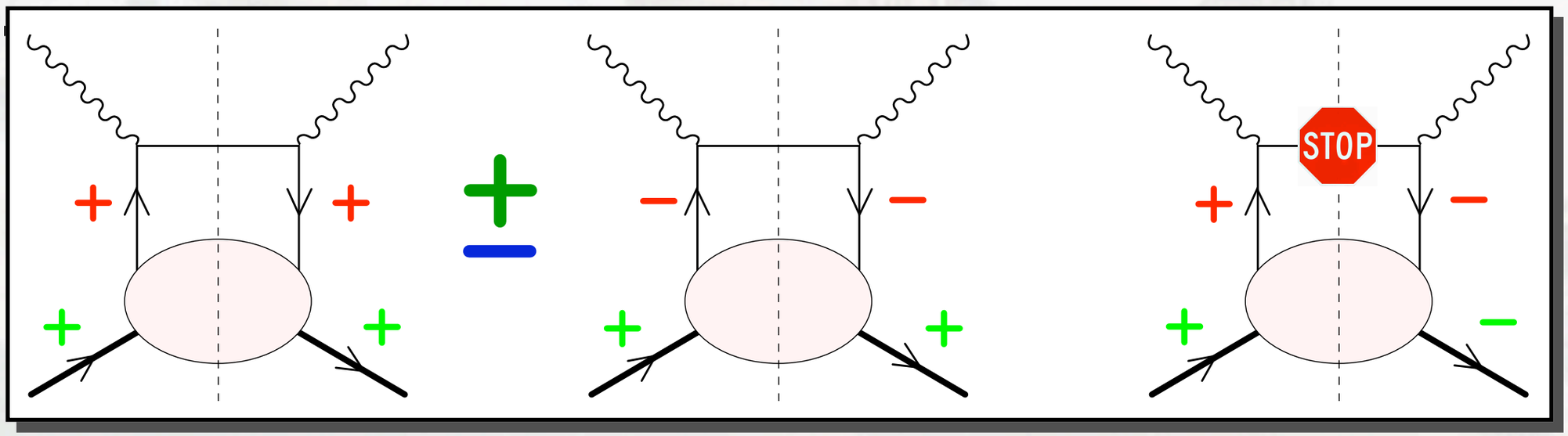
$h_1^q =$ 



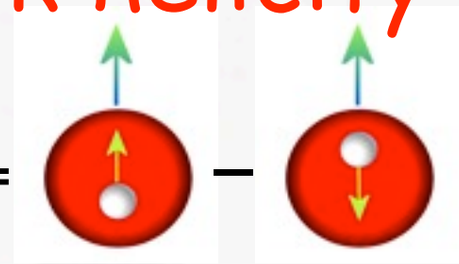
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

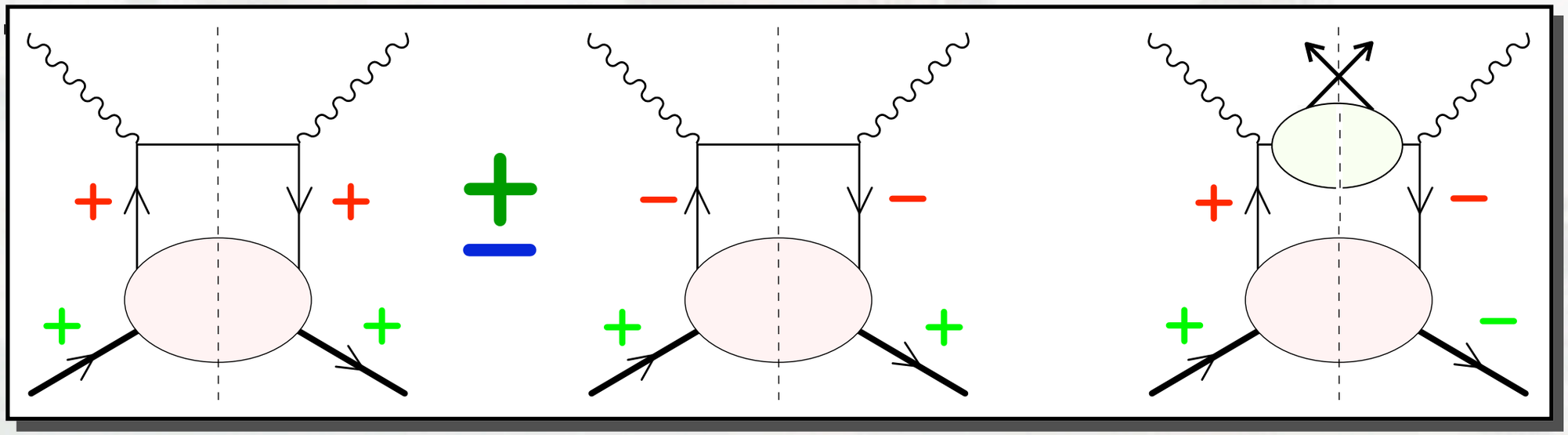
Transversity distribution

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, $h_{1T}^\perp$

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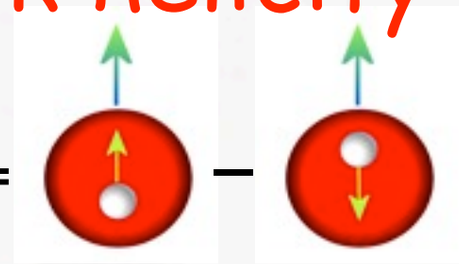
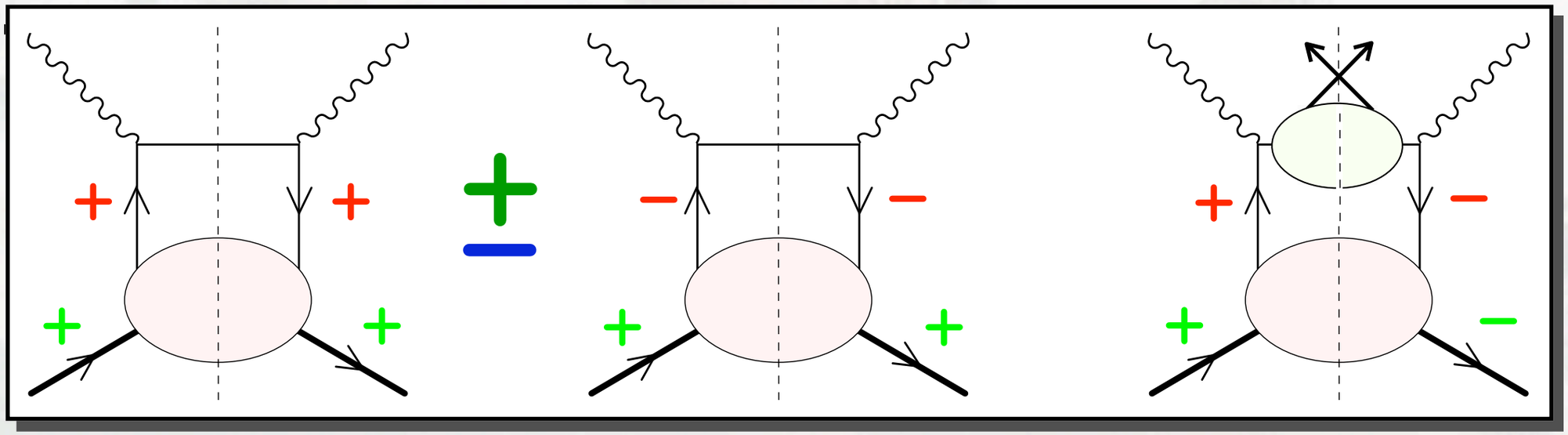
$h_1^q =$ 



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

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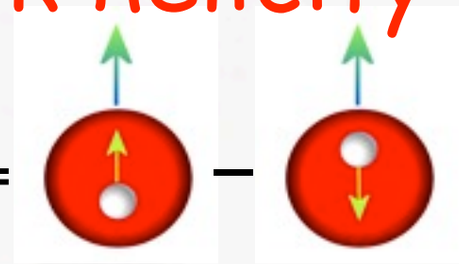
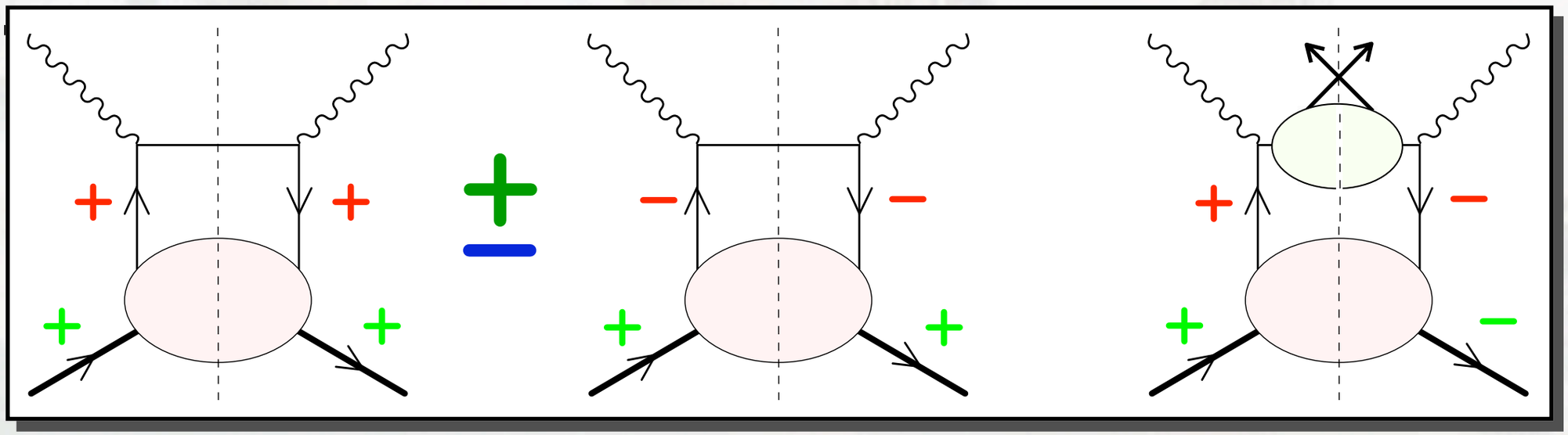
$h_1^q =$ 



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, $h_{1T}^\perp$

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chiral-odd transversity involves quark helicity flip

$f_1^q =$ 

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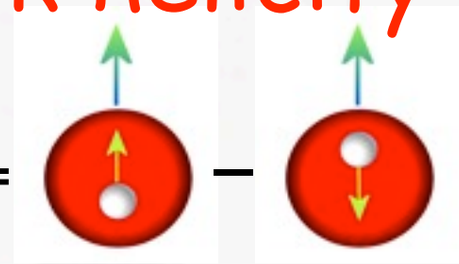
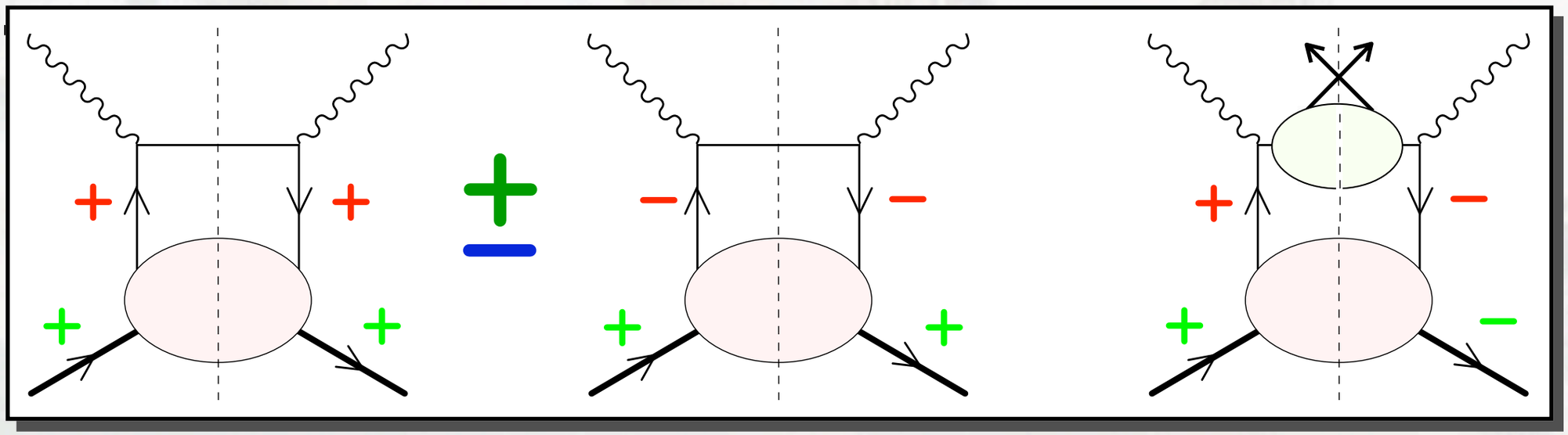
$h_1^q =$ 



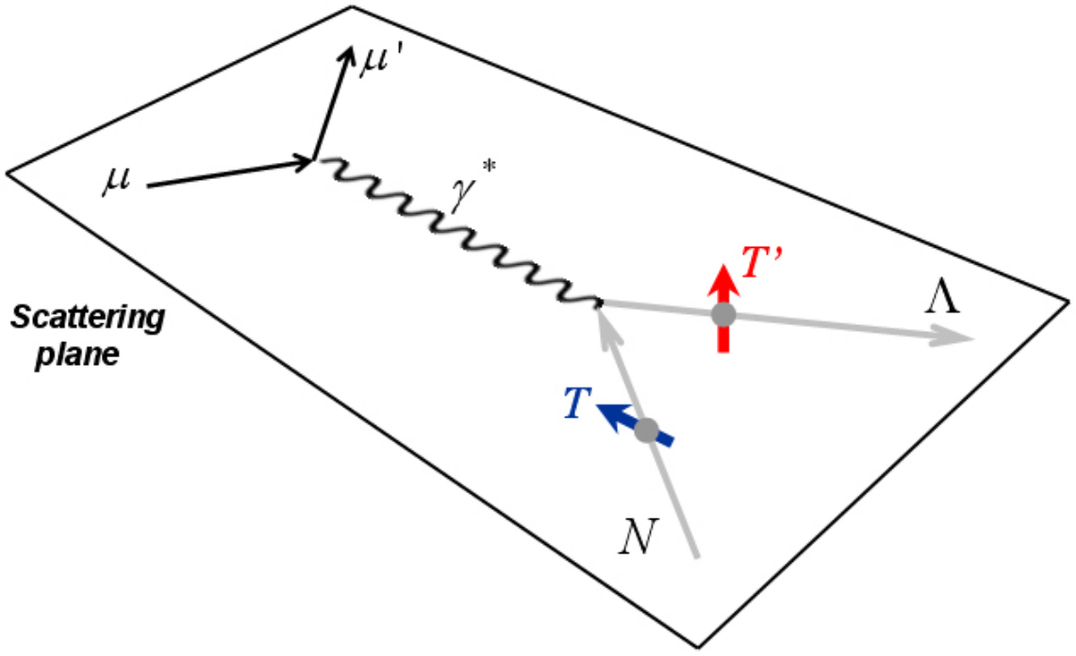
need to couple to chiral-odd fragmentation function:

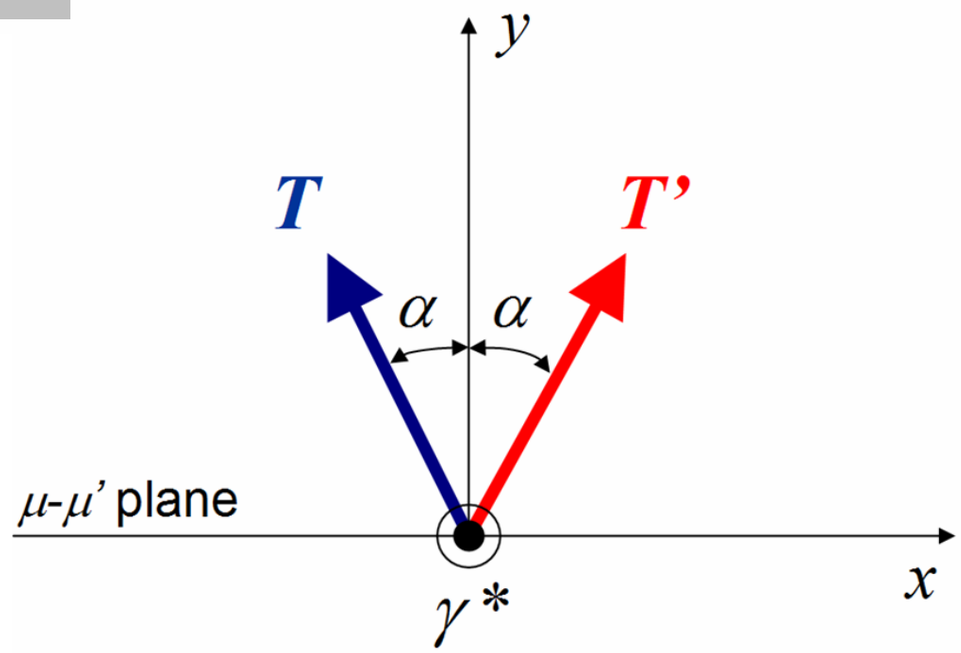
- **transverse spin transfer** (polarized final-state hadron)
- **2-hadron fragmentation**
- **Collins fragmentation**

	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



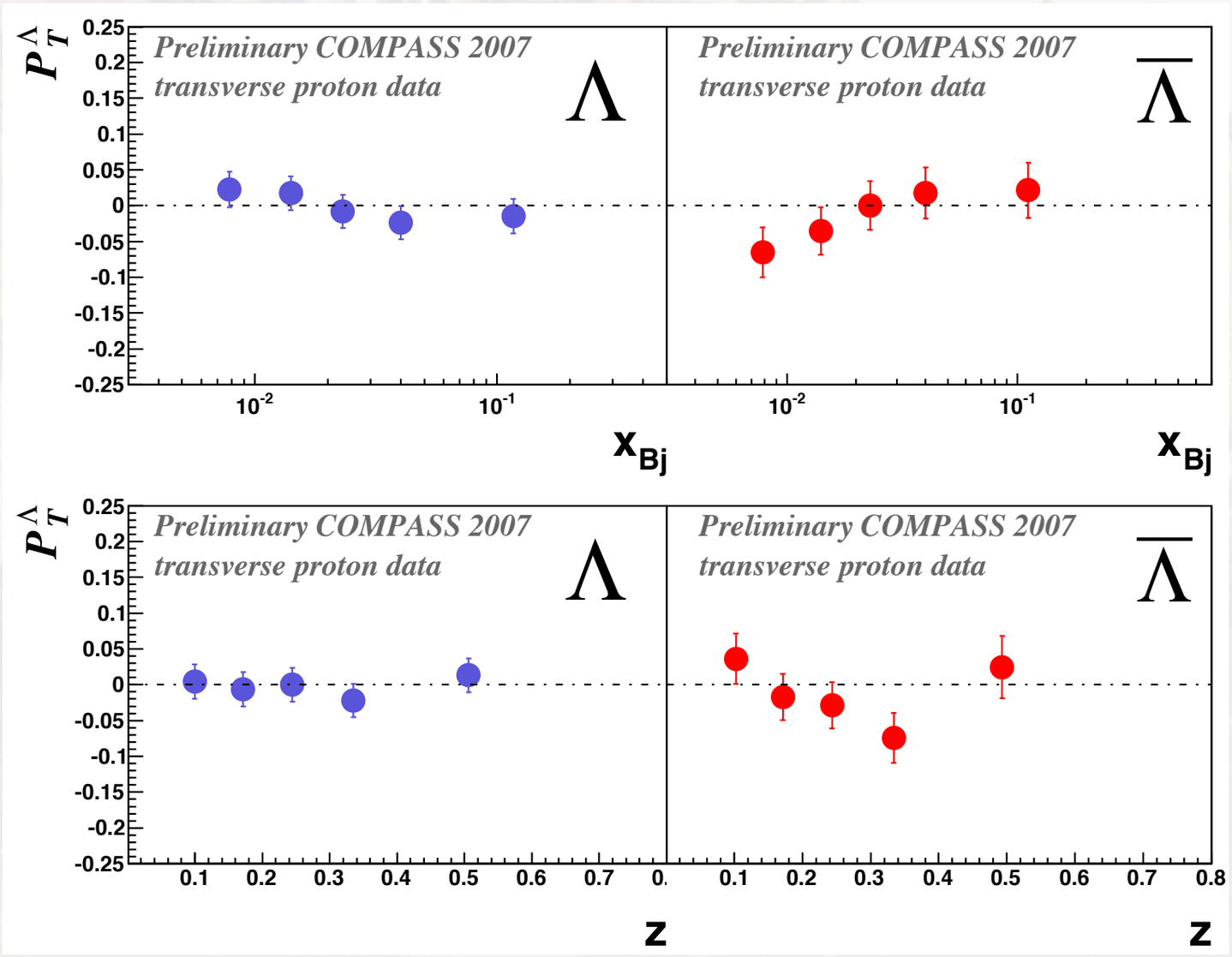


M. Anselmino & F. Murgia,
Physics Letters B 483 (2000) 74-86

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

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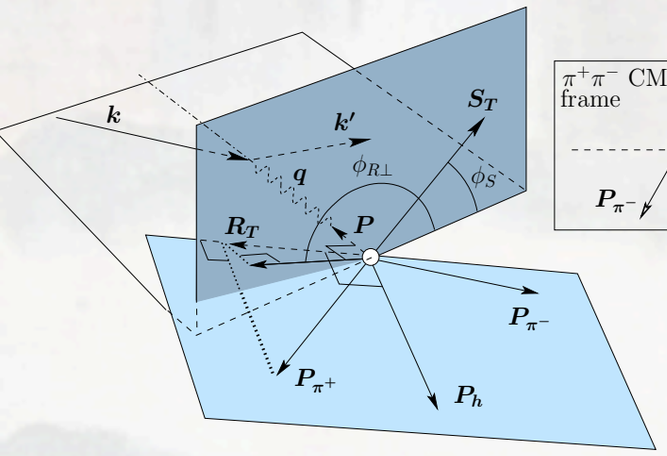
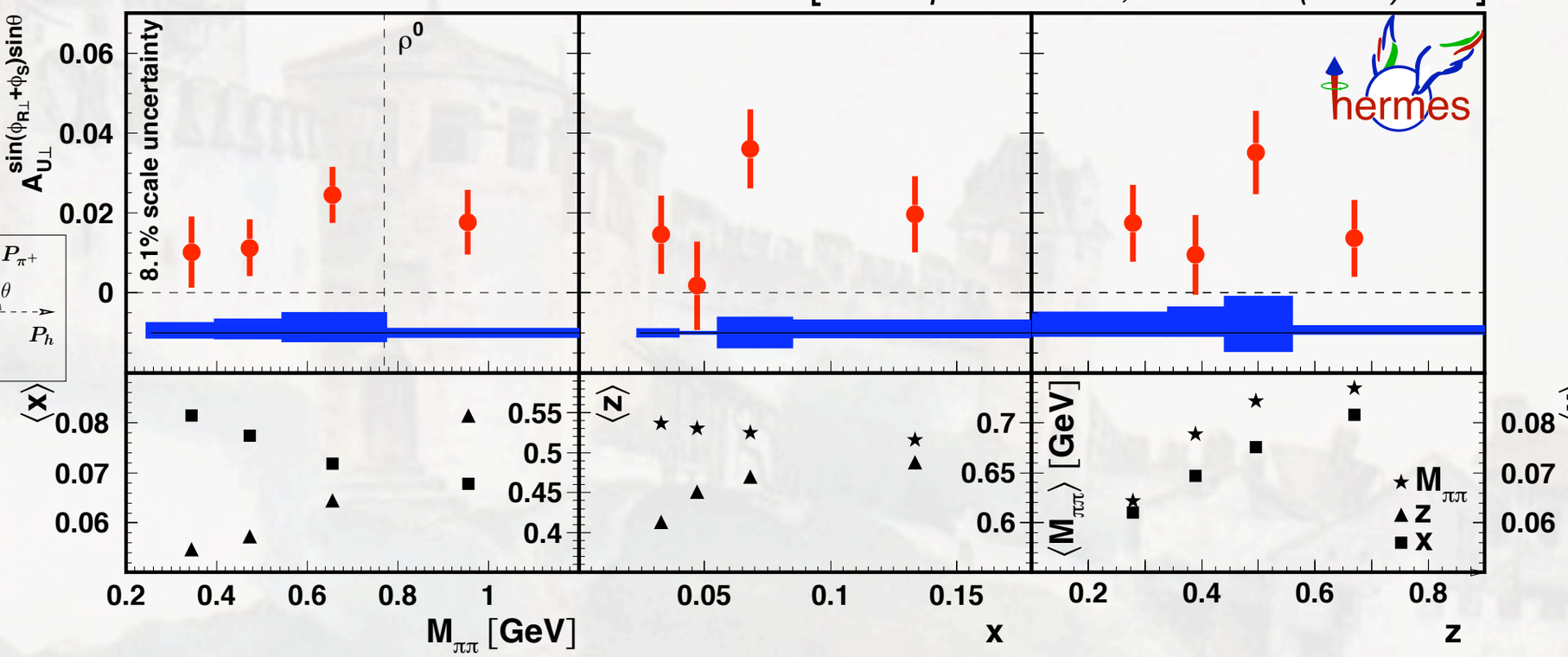
- **better sensitivity to u and d quarks via charged Sigma's**

	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
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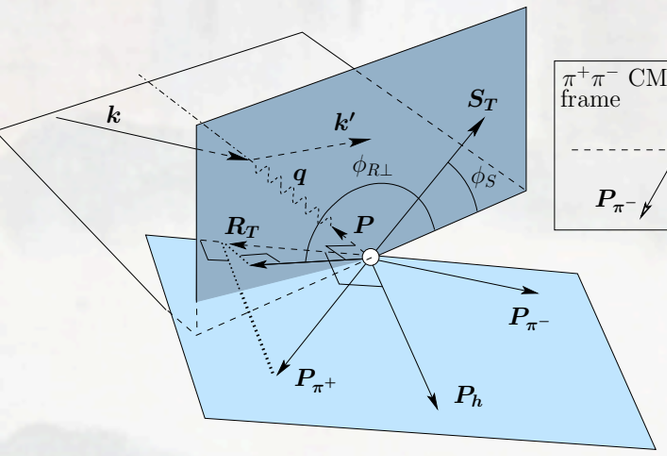

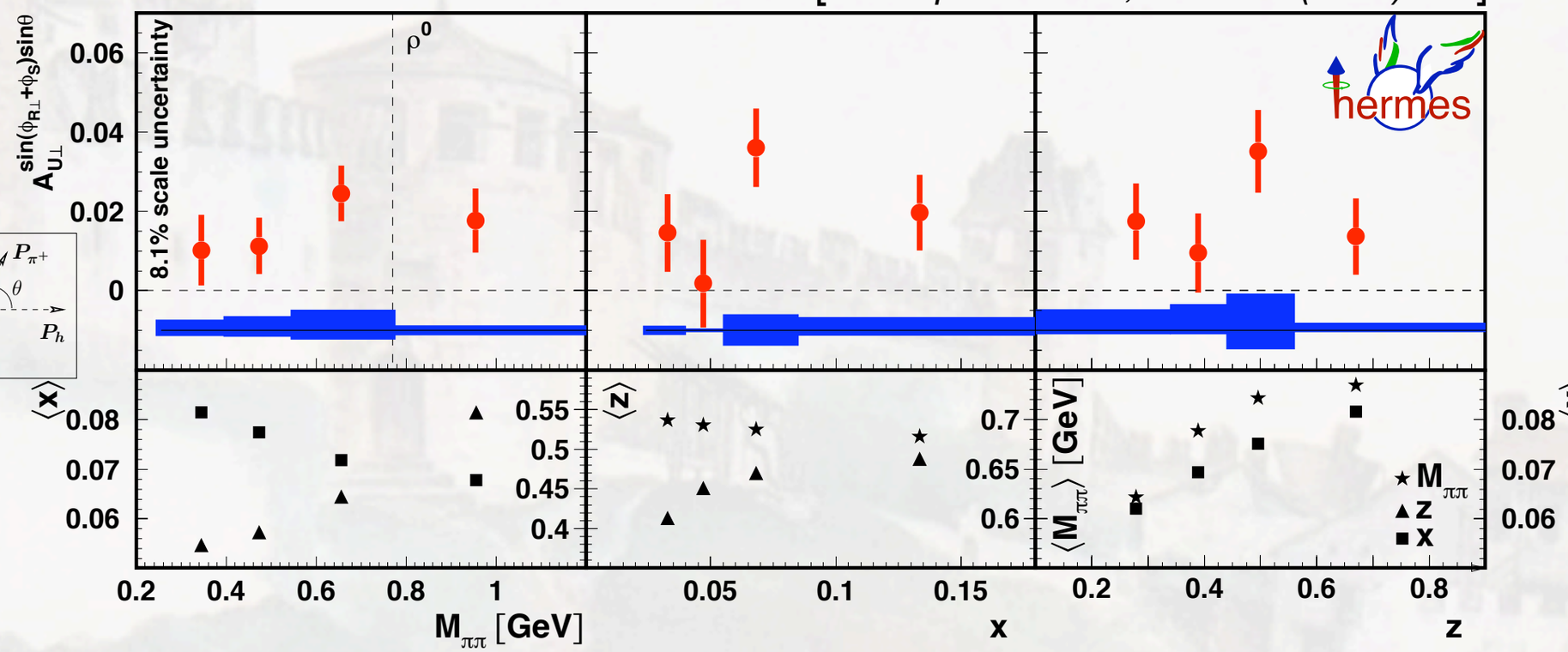

☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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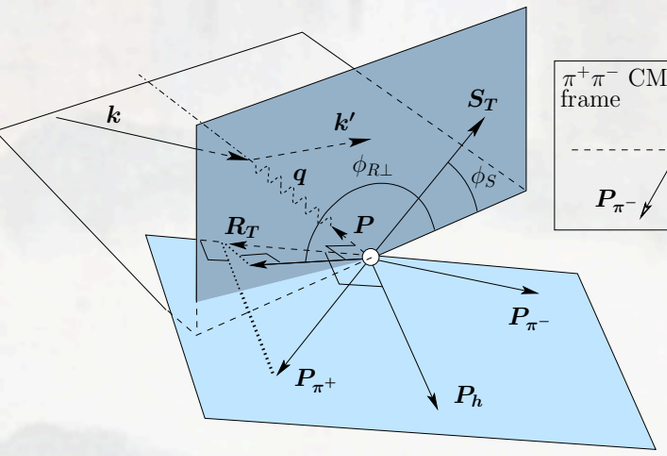

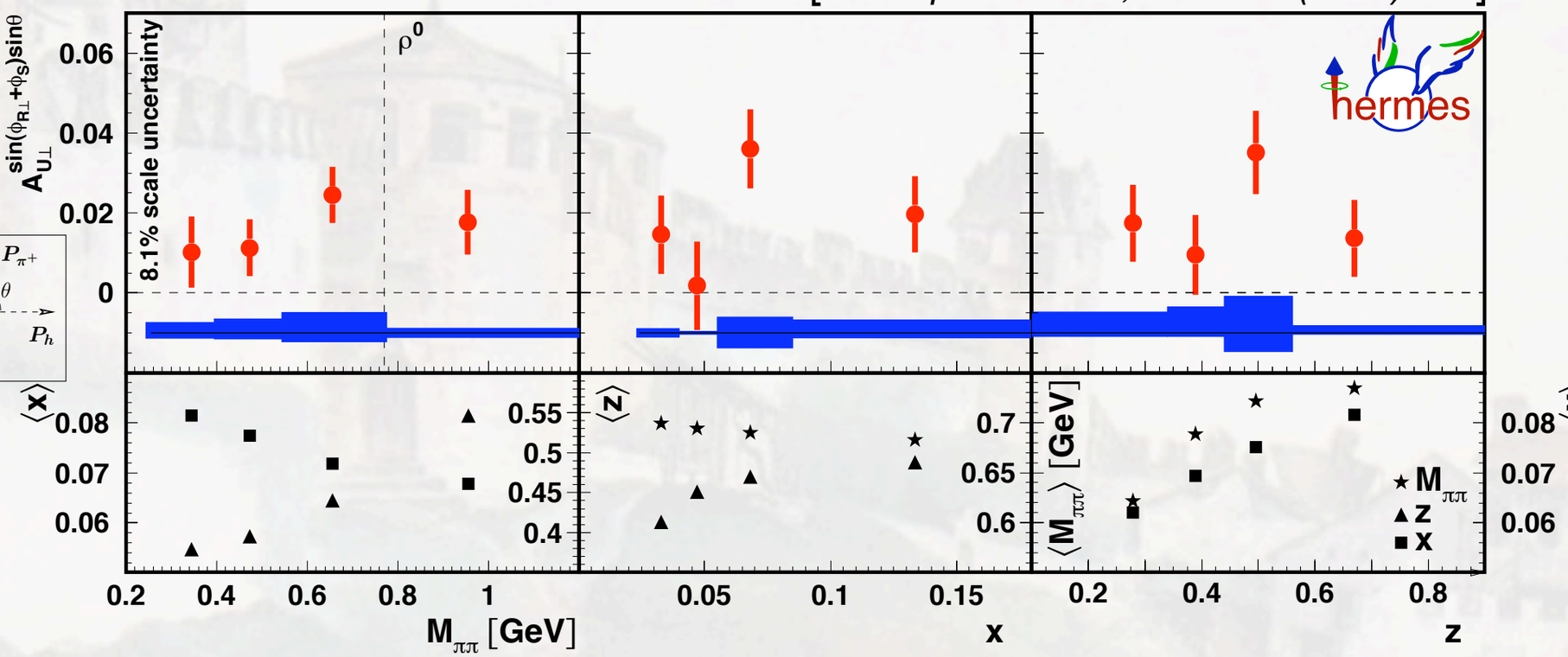

- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- ☑ invariant-mass dependence rules out Jaffe model predicting a sign change to rho mass

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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
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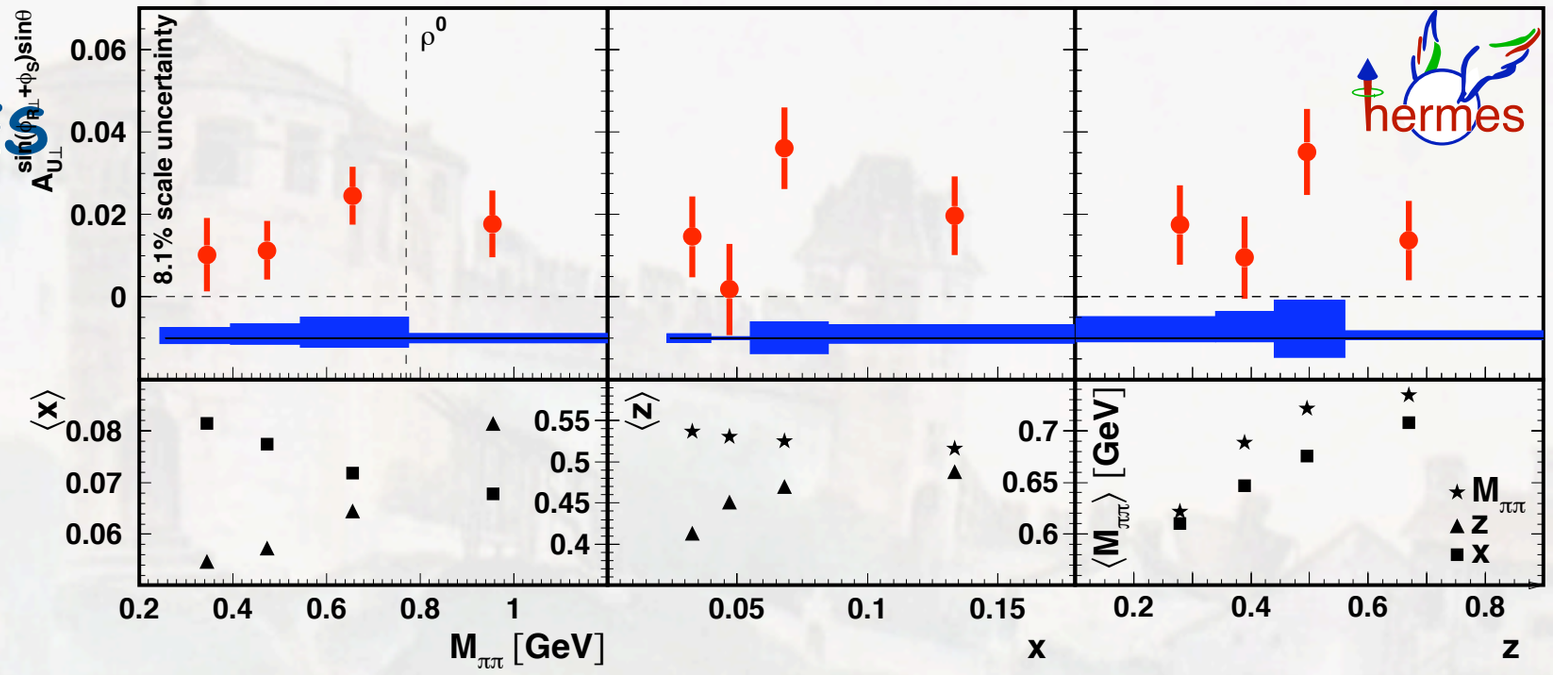

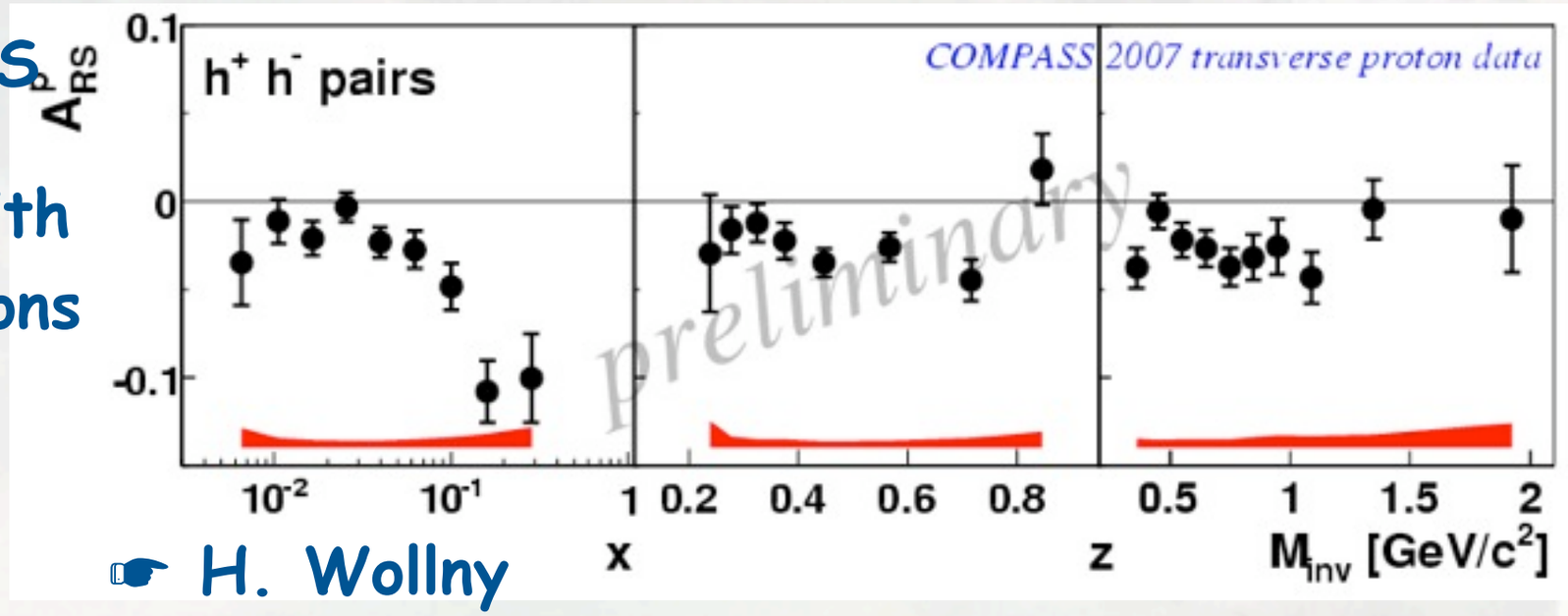

☛ H. Wollny

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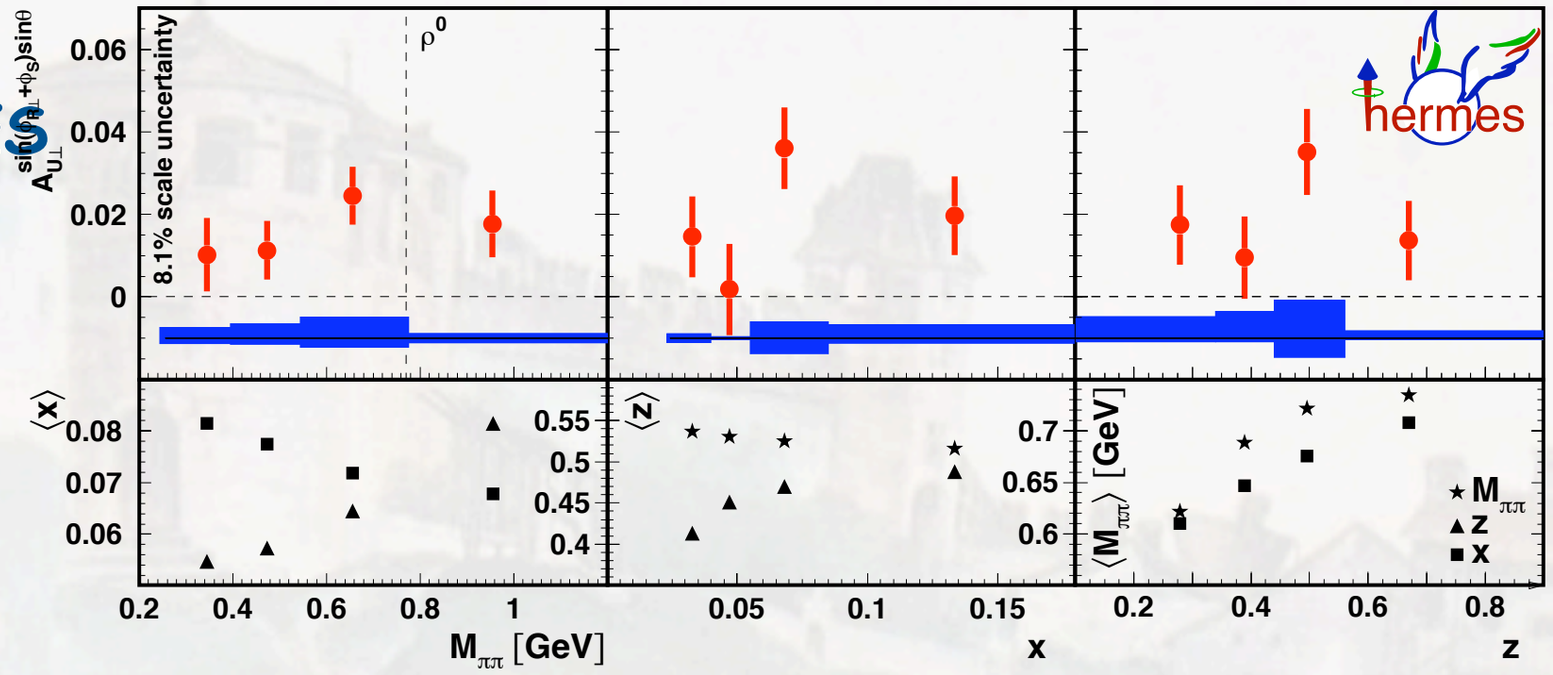

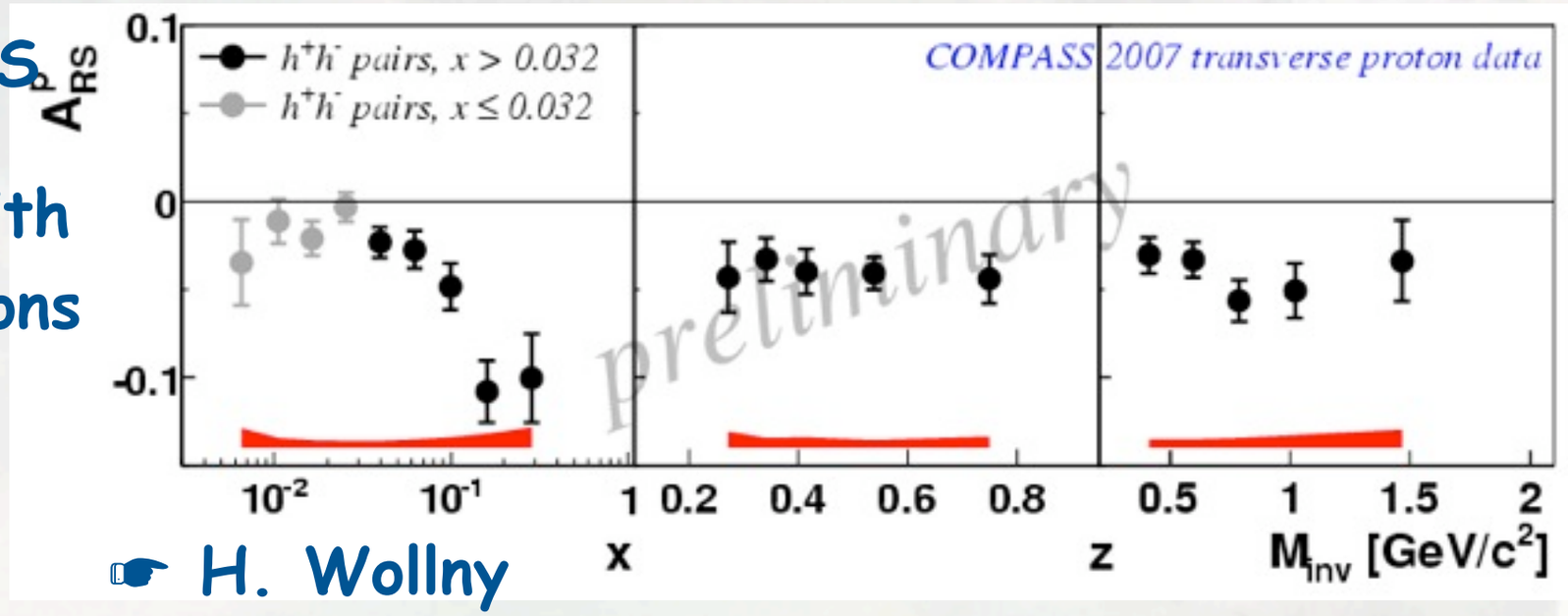

☛ H. Wollny

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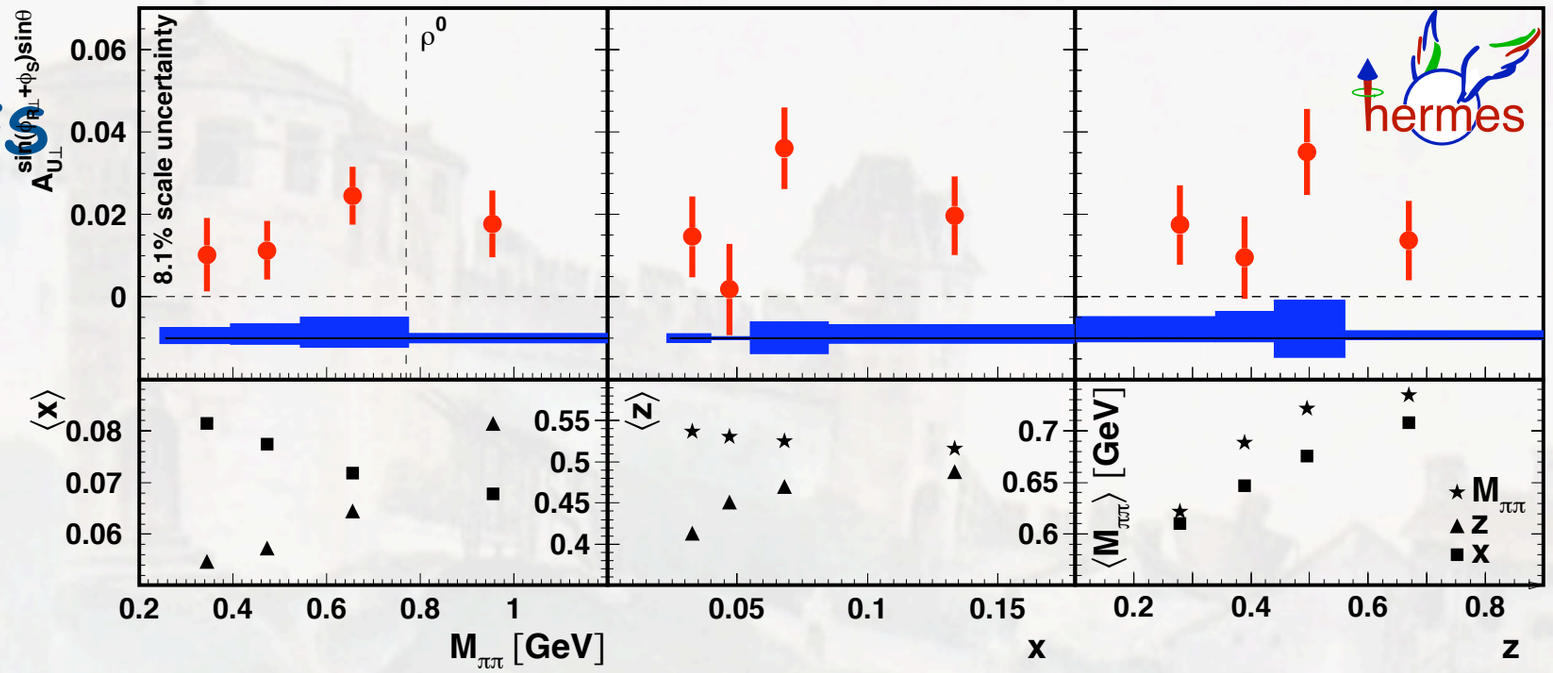

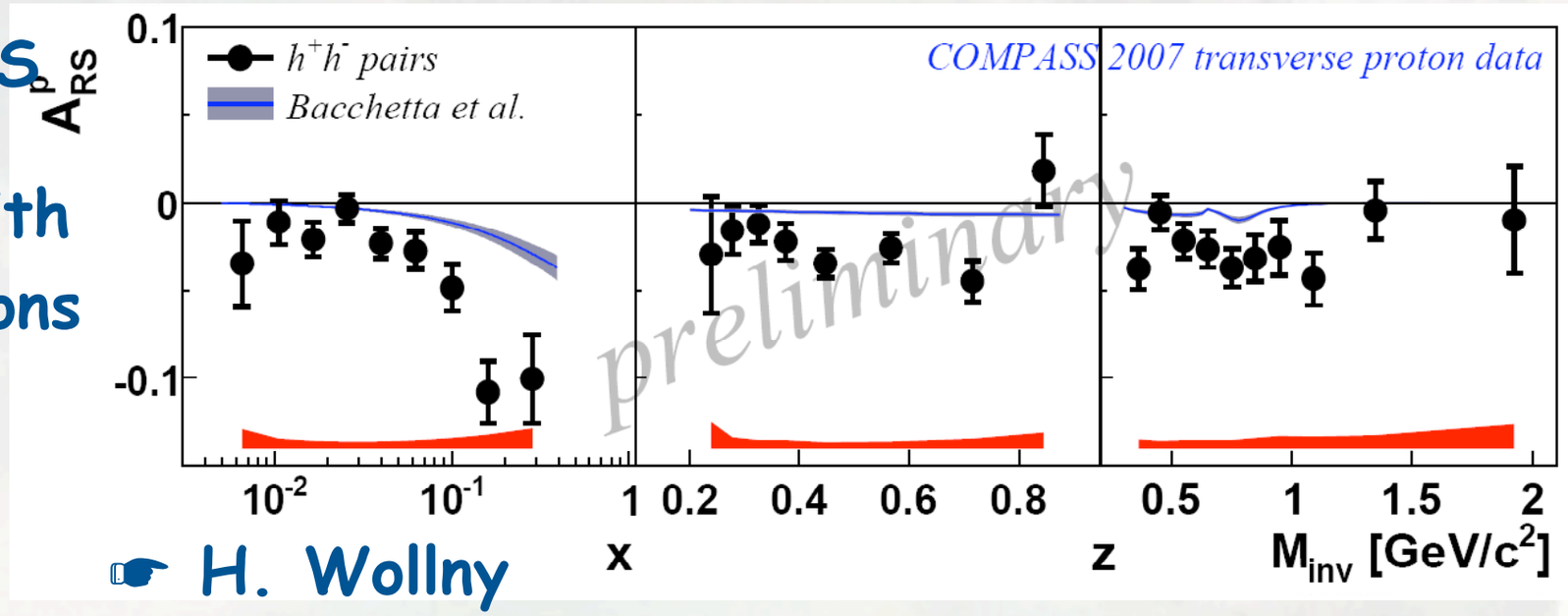

☛ H. Wollny

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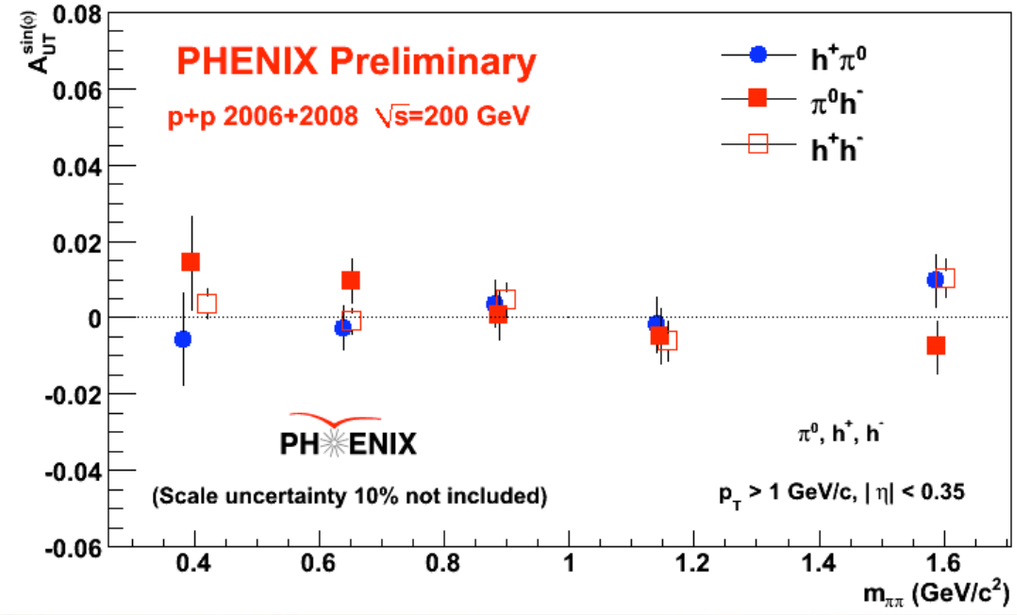

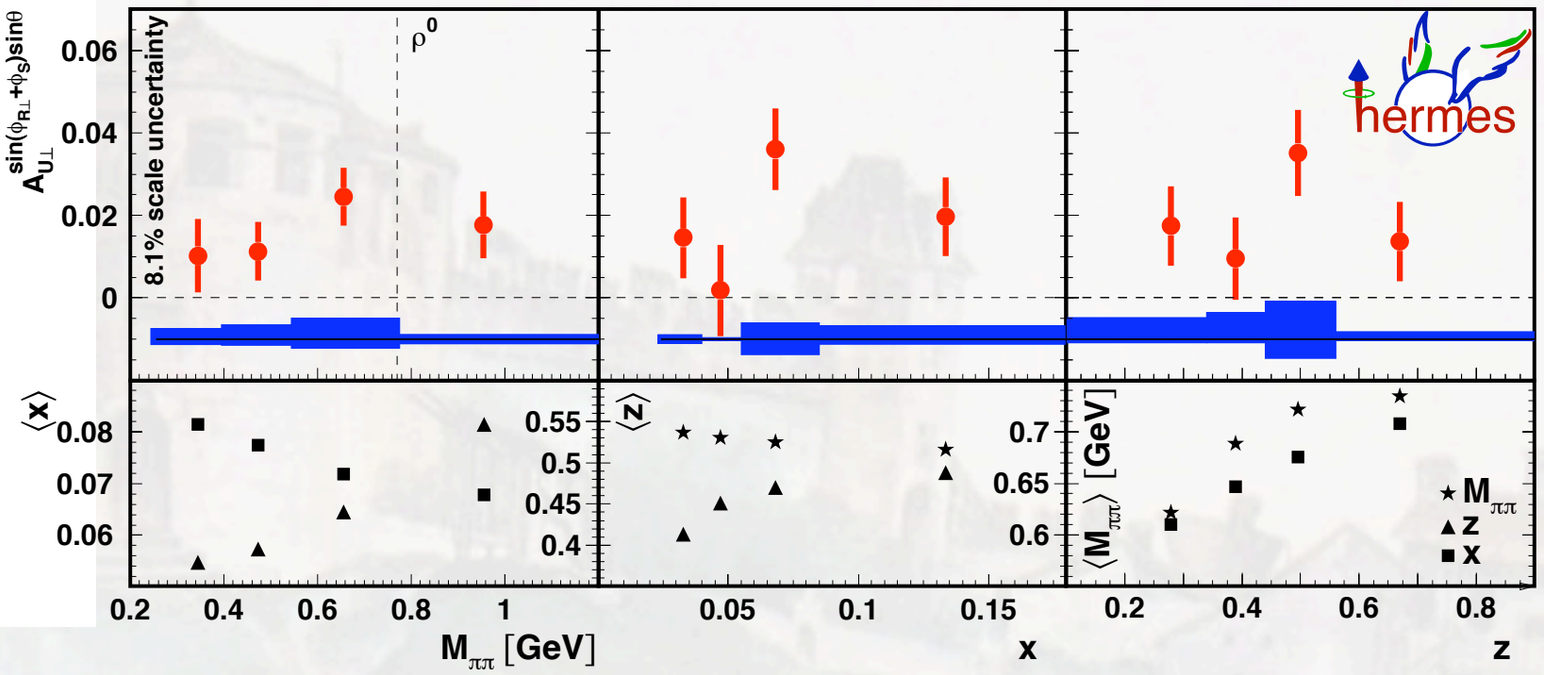

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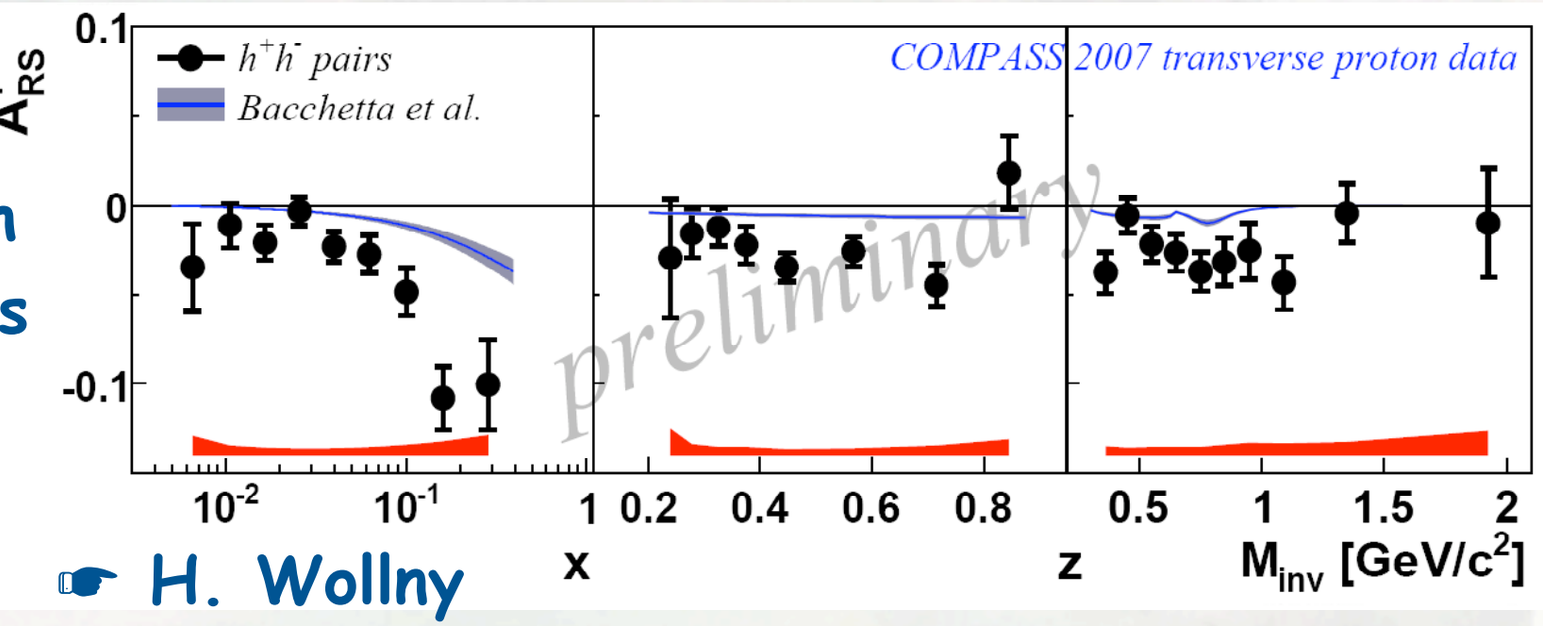

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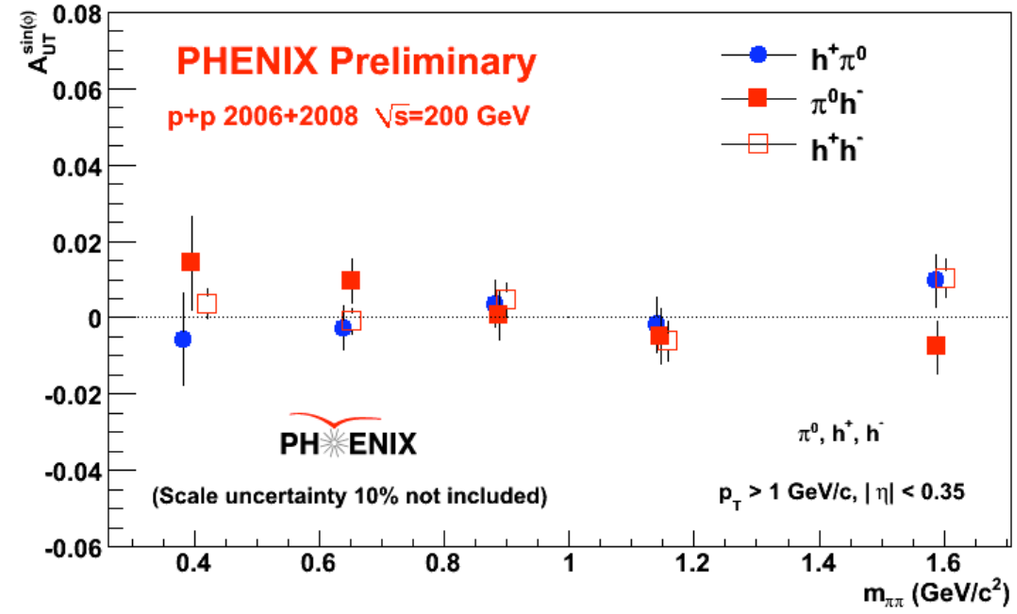
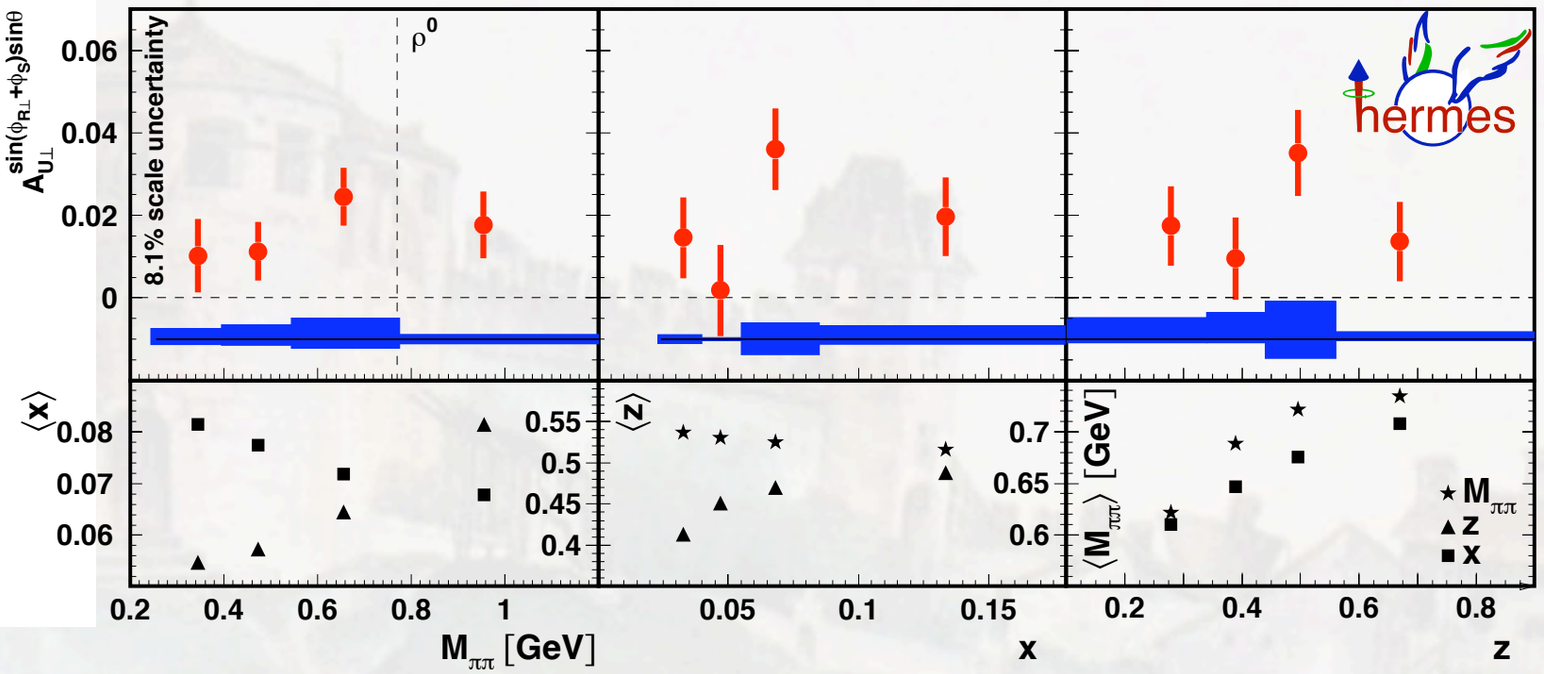
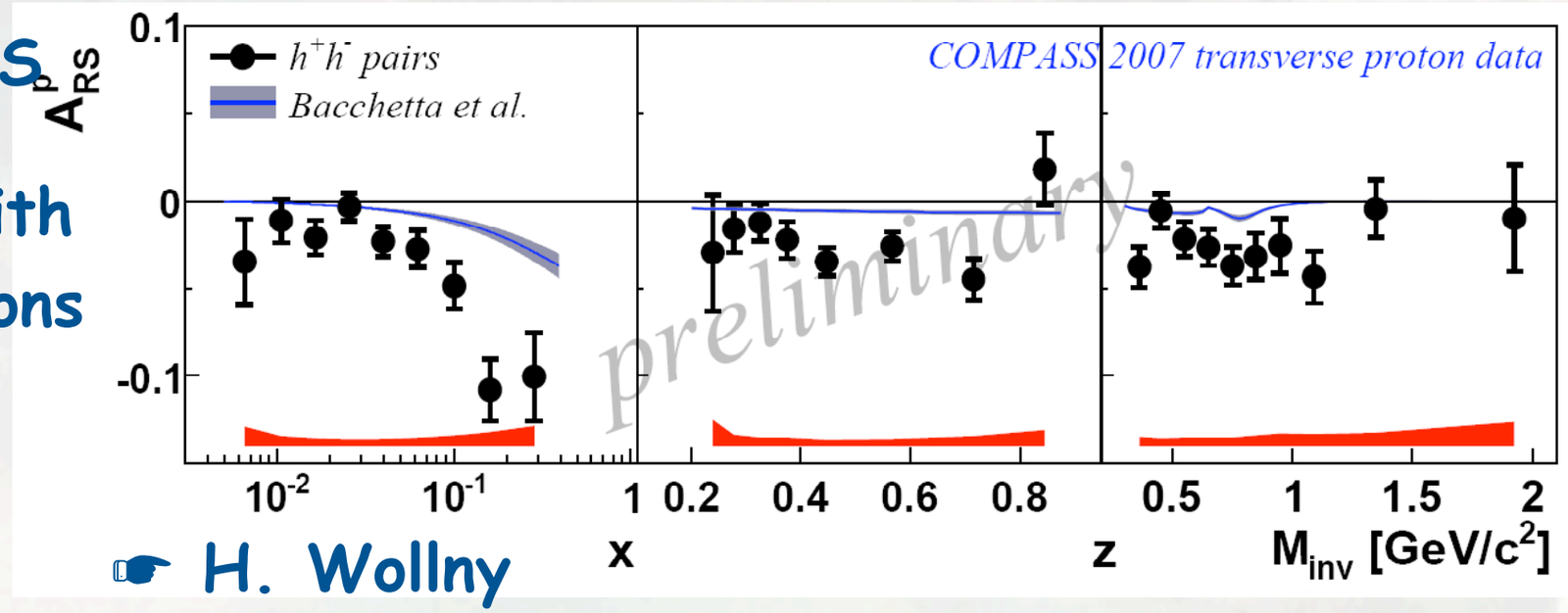




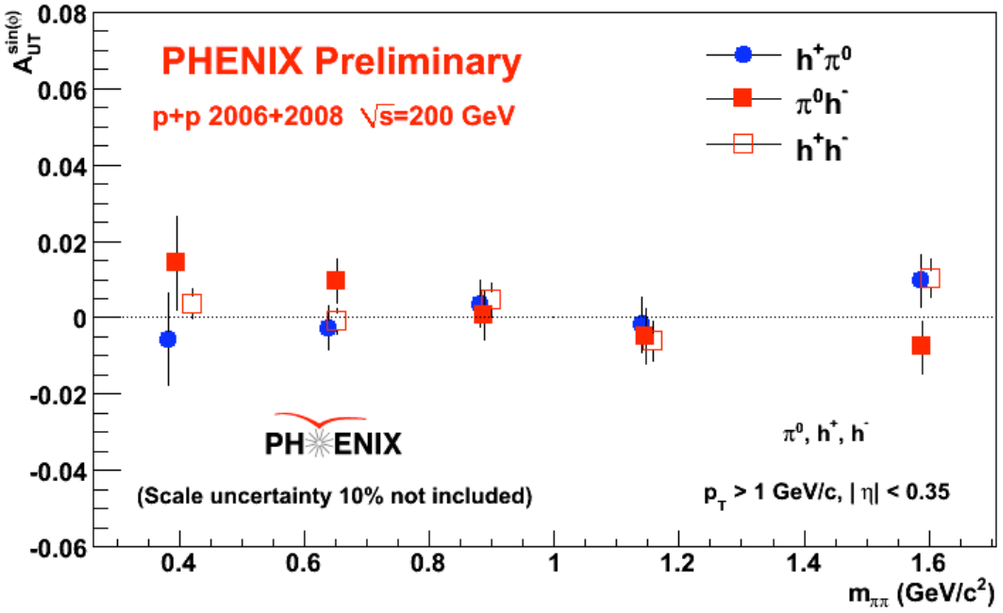
- larger amplitudes at COMPASS than at HERMES
- data from pp consistent with zero but dominated by gluons

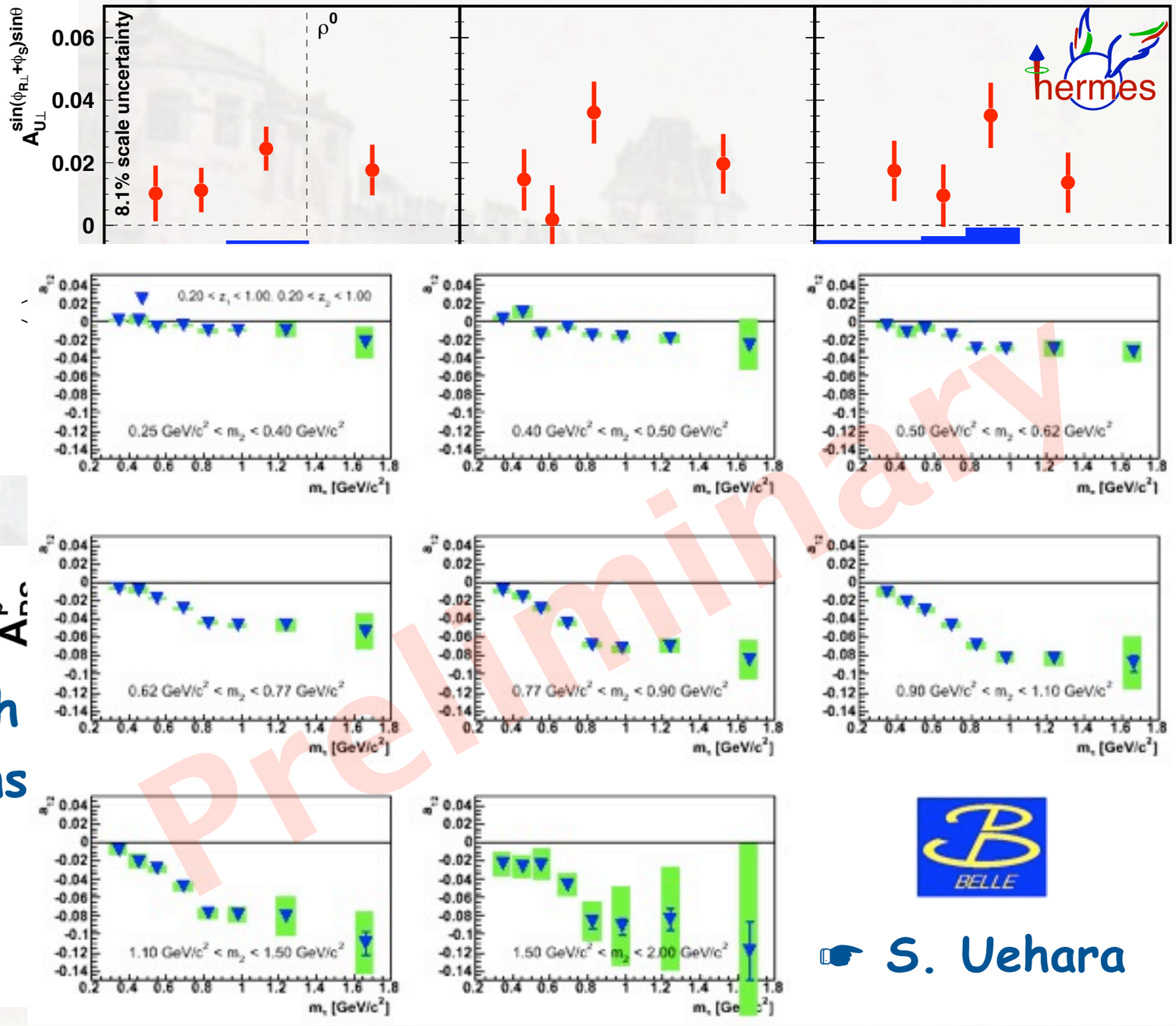


☛ H. Wollny

	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)





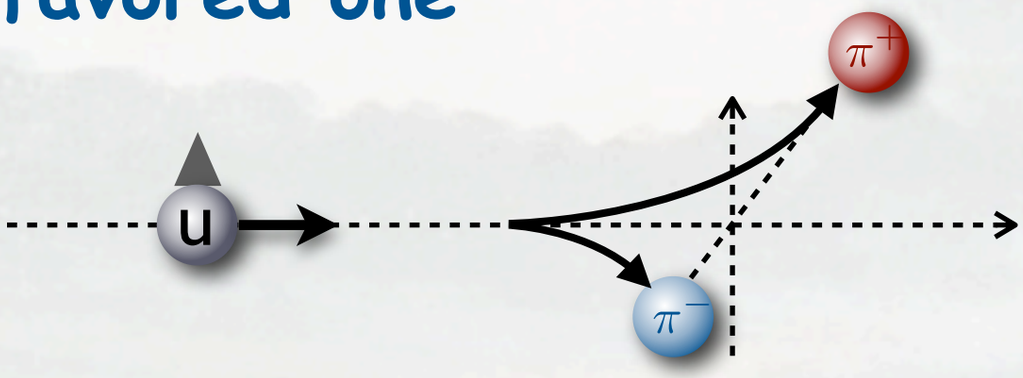
- larger amplitudes at COMPASS than at HERMES
- data from pp consistent with zero but dominated by gluons
- first results from e^+e^- by BELLE

☛ S. Uehara

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

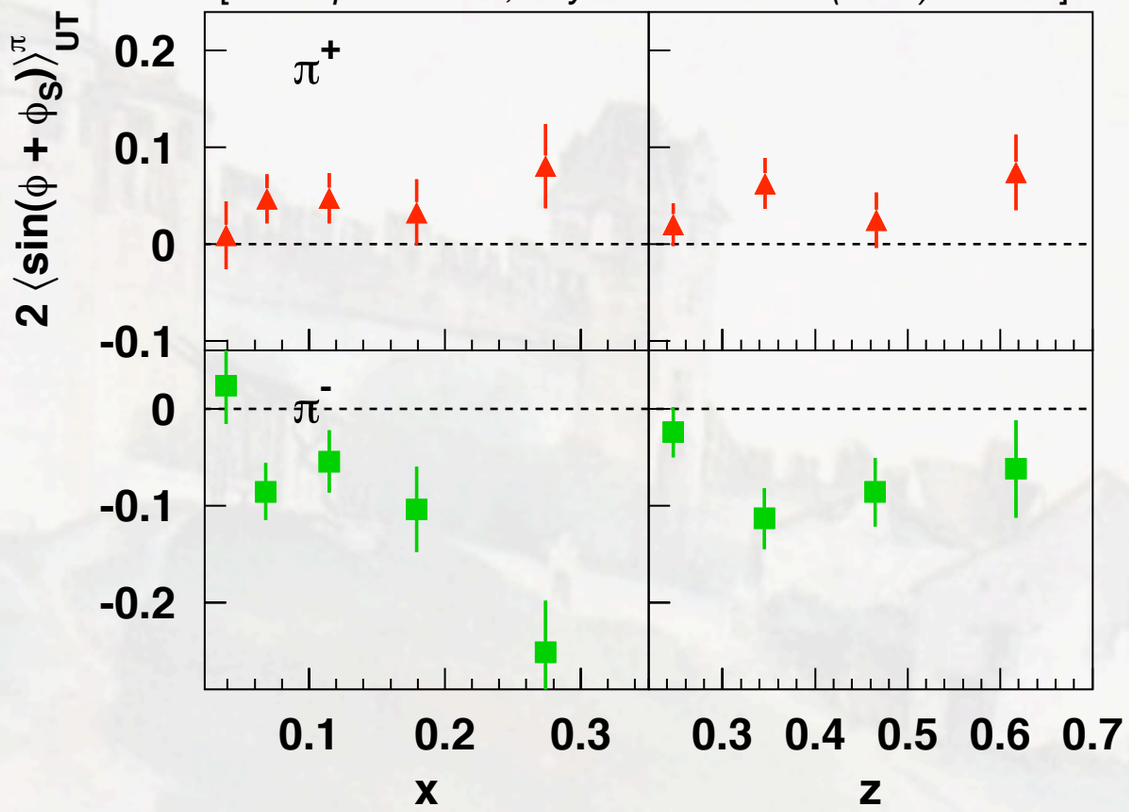
Transversity distribution (Collins fragmentation)

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



- leads to various cancellations in SSA observables

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

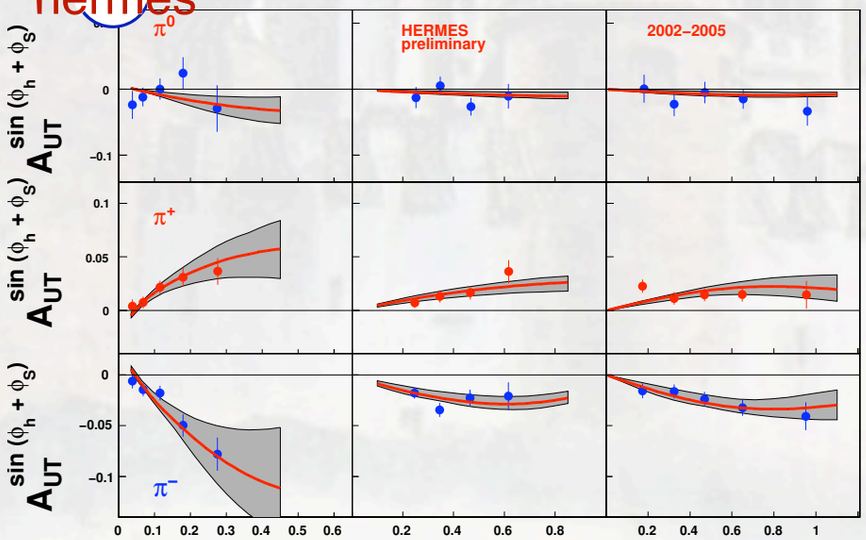


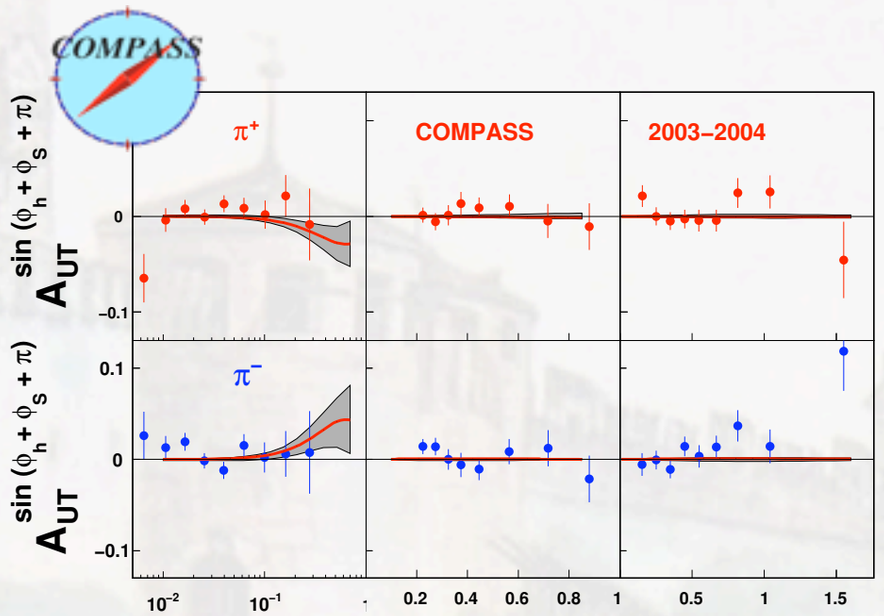
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

Fit of Collins amplitudes

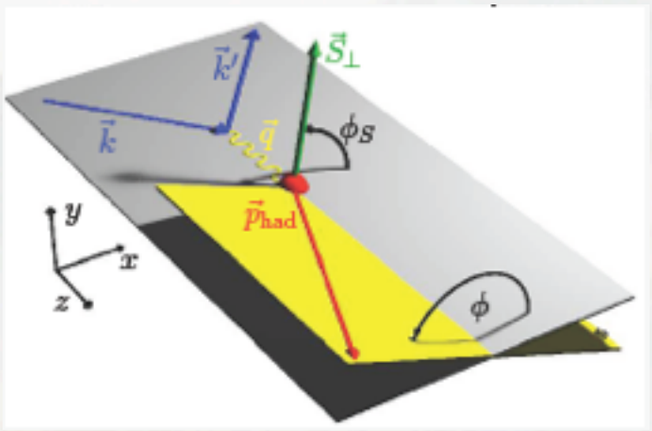
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$





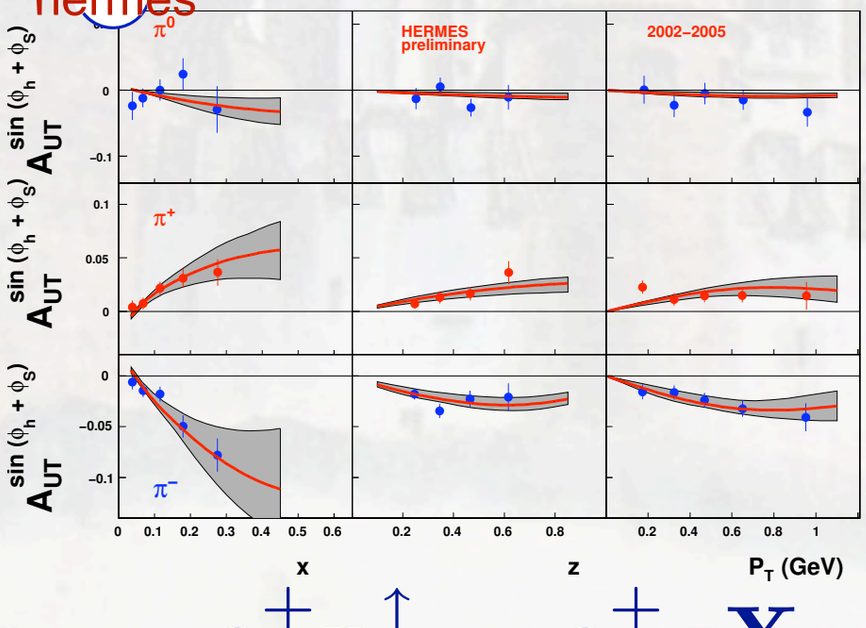
$$e^{\pm}p^{\uparrow} \rightarrow e^{\pm}\pi X \qquad \mu^{\pm}d^{\uparrow} \rightarrow \mu^{\pm}\pi X$$

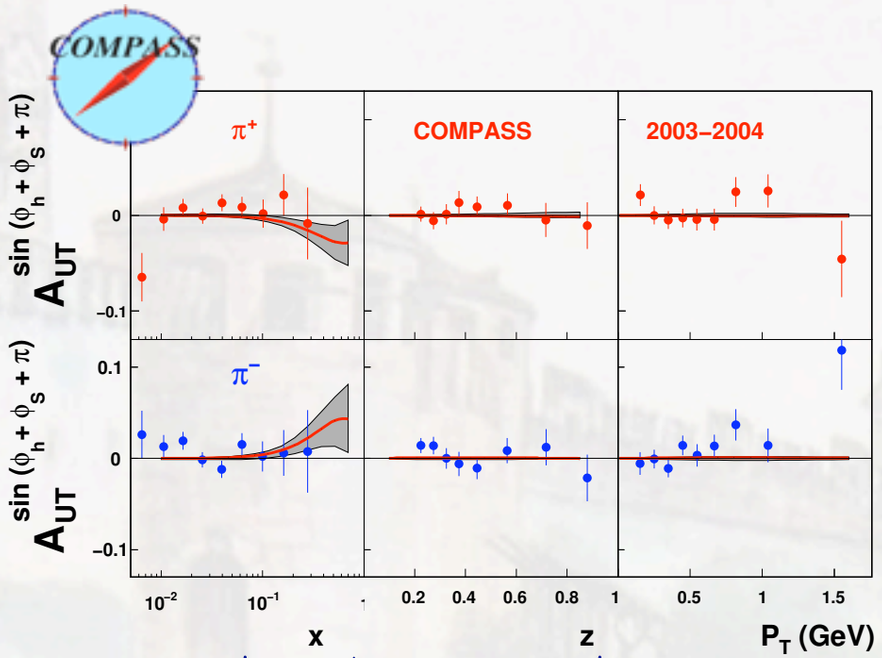
x z P_T (GeV) x z P_T (GeV)

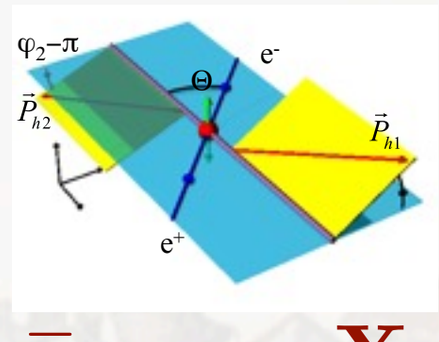


Fit of Collins amplitudes

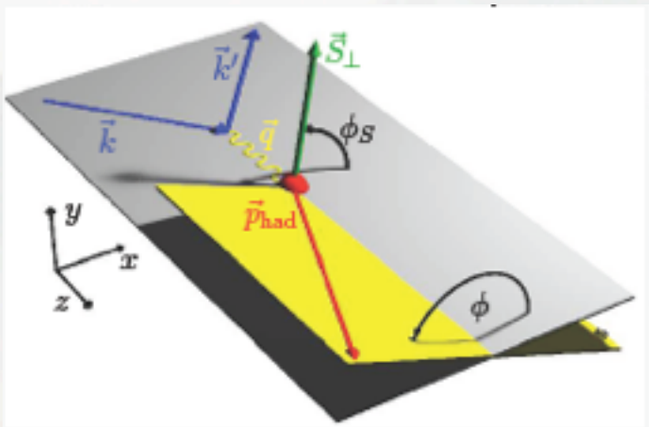
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

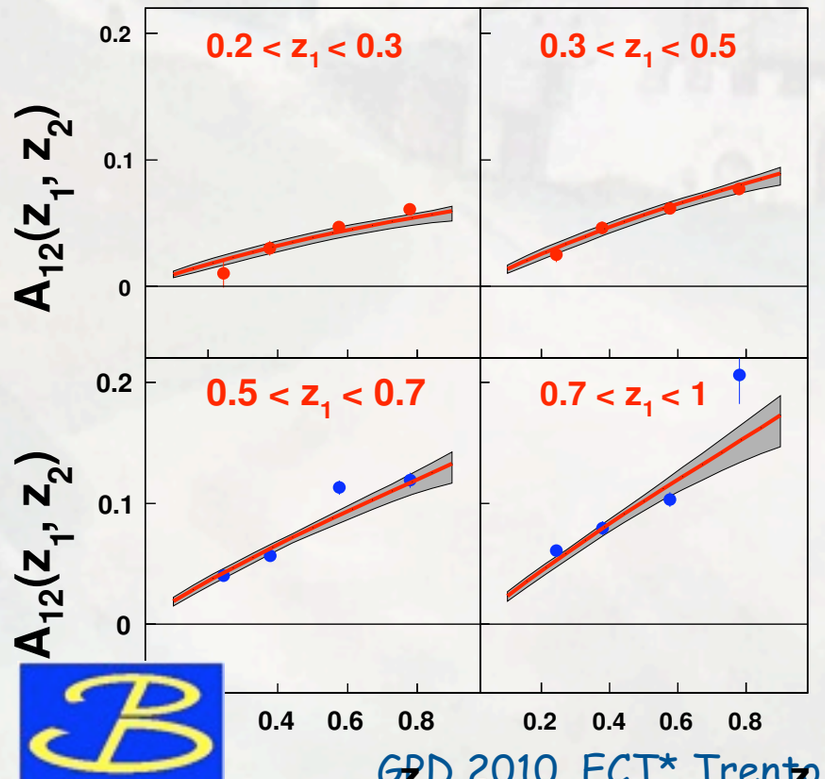






$\mathbf{e^{\pm}p^{\uparrow} \rightarrow e^{\pm}\pi X}$ $\mu^{\pm}\mathbf{d}^{\uparrow} \rightarrow \mu^{\pm}\pi\mathbf{X}$ $\mathbf{e^+e^- \rightarrow \pi\pi X}$





Fit of Collins amplitudes

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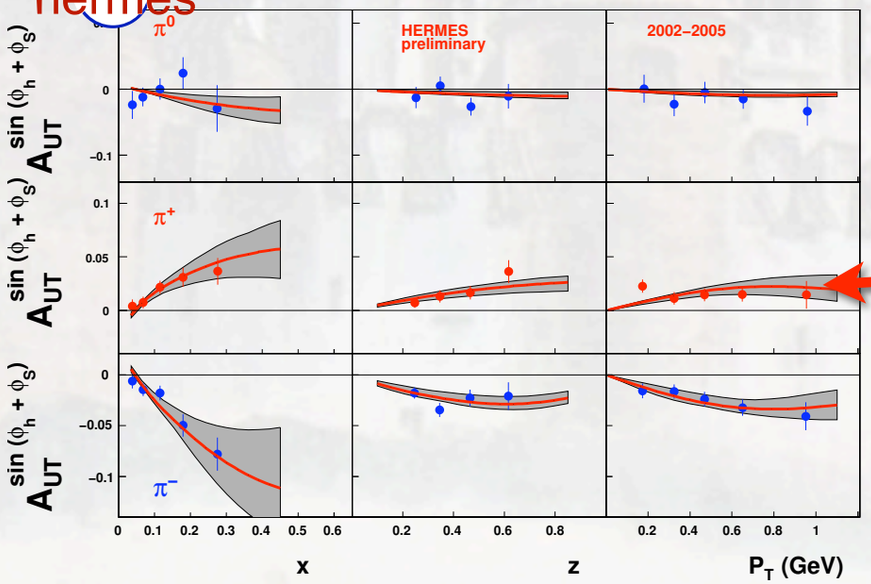
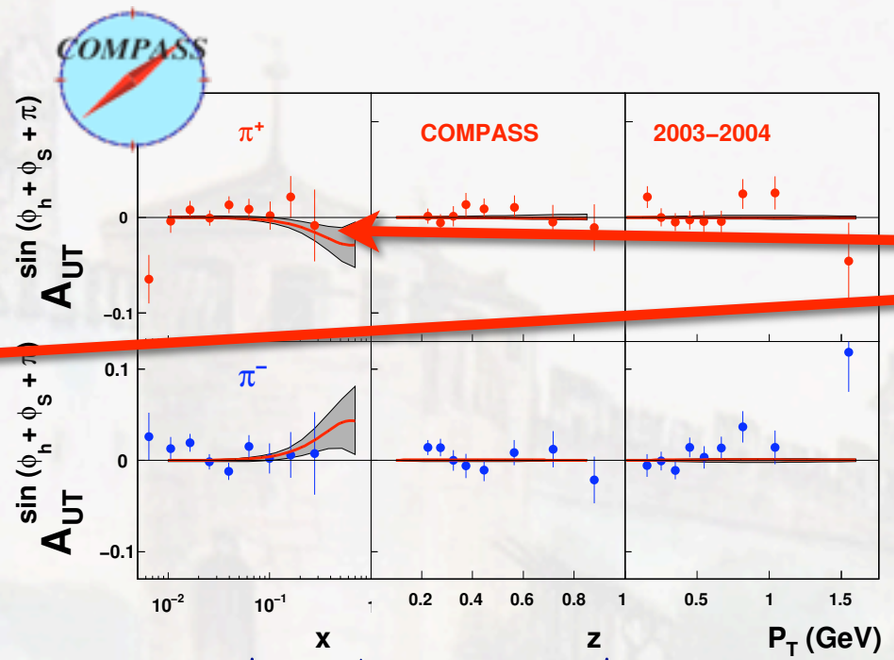
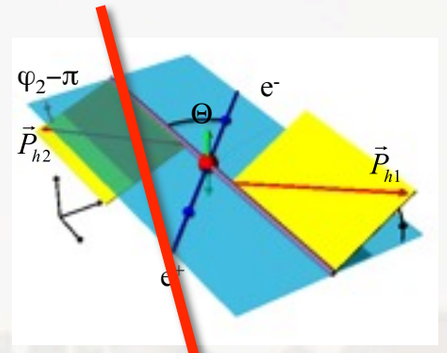


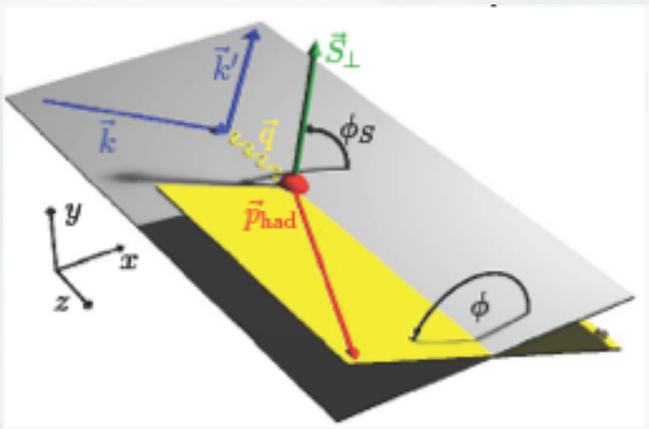


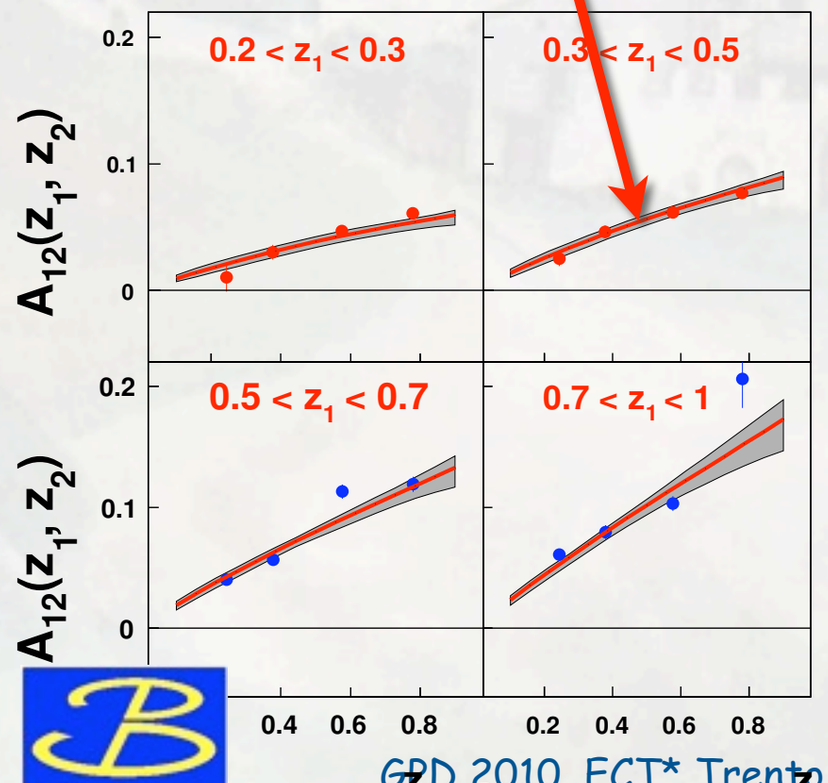
☛ M. Anselmino

fit to data



$e^\pm p^\uparrow \to e^\pm \pi X$ $\quad$ $\mu^\pm d^\uparrow \to \mu^\pm \pi X$ $\quad$ $e^+e^- \to \pi\pi X$





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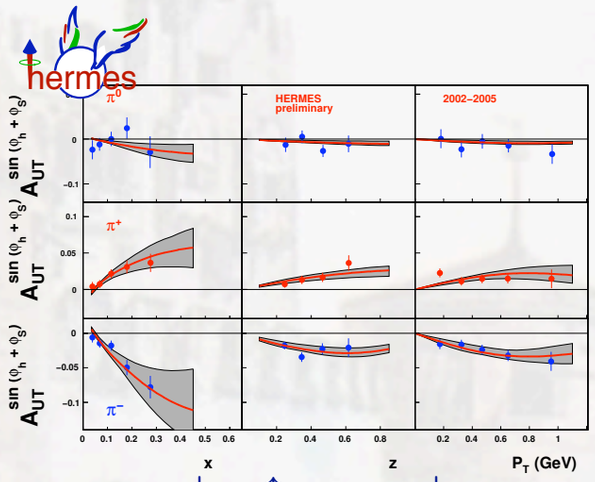
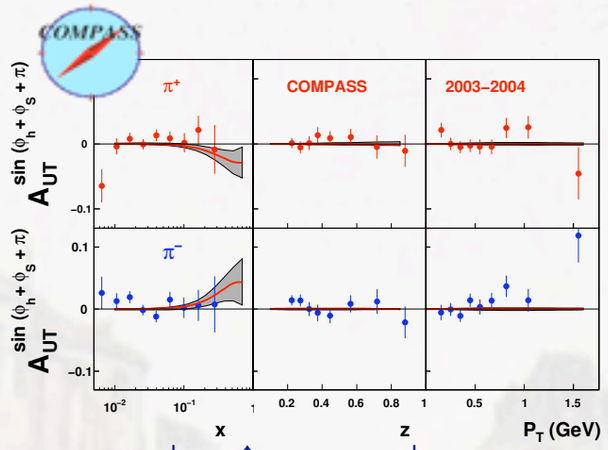
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Fit of Collins amplitudes



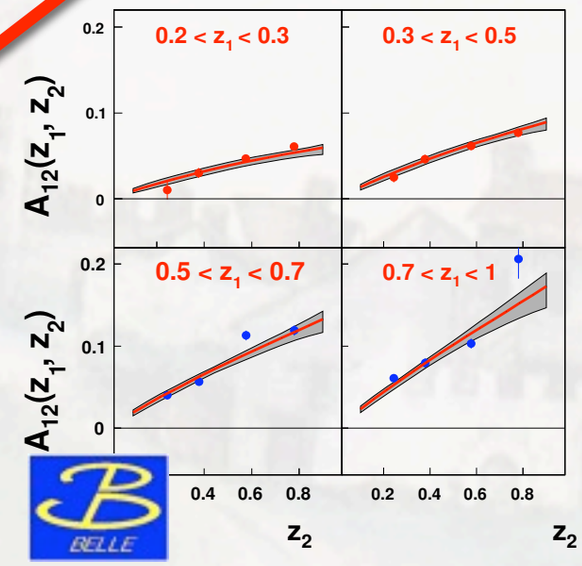
$e^\pm p^\uparrow \to e^\pm \pi X$



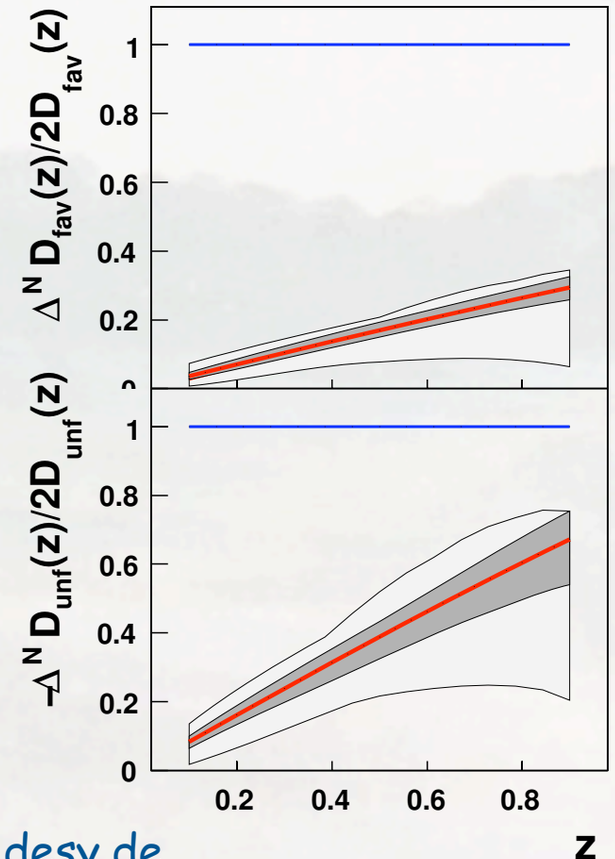
$\mu^\pm d^\uparrow \to \mu^\pm \pi X$

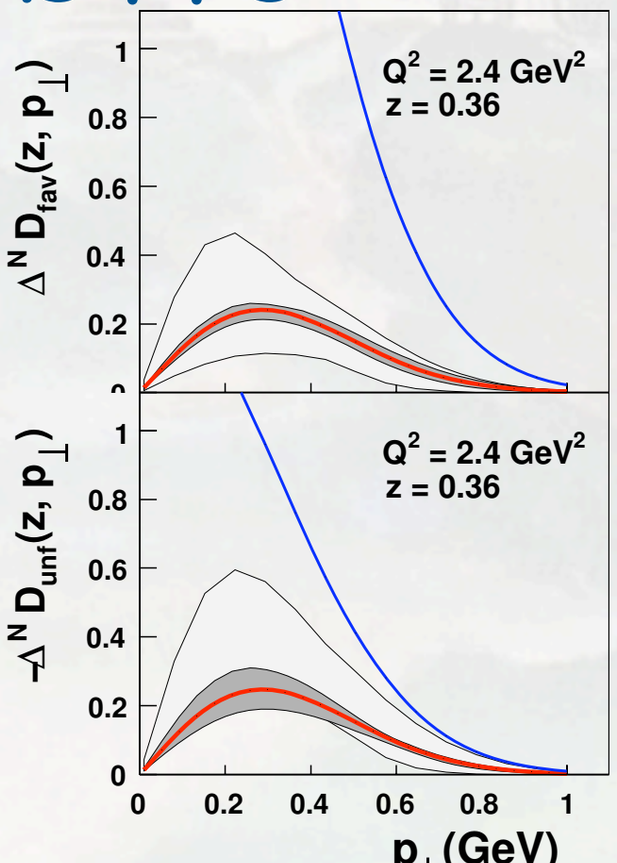
☛ M. Anselmino
fit to data

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



Collins FFs





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

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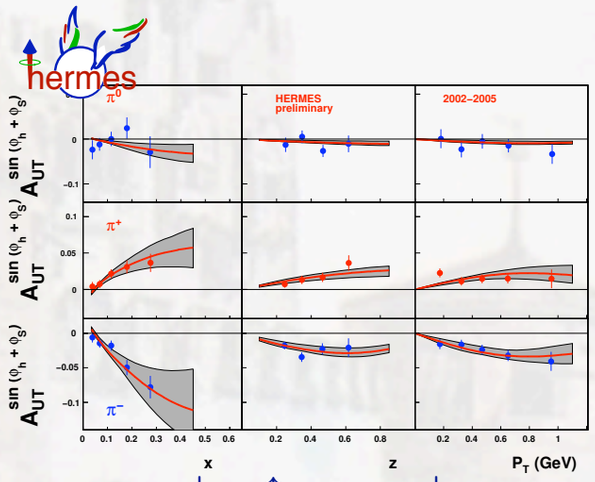
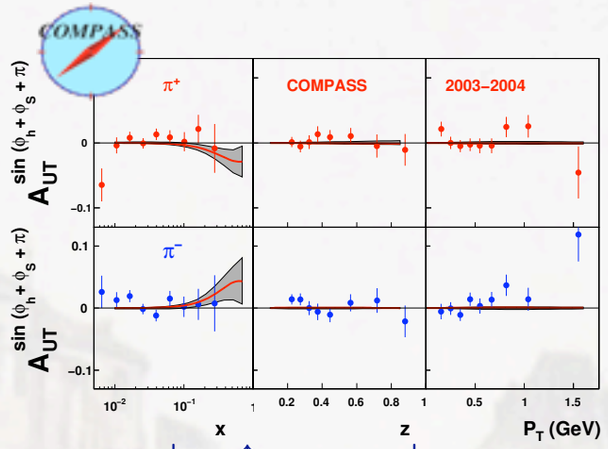
Fit of Collins amplitudes



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



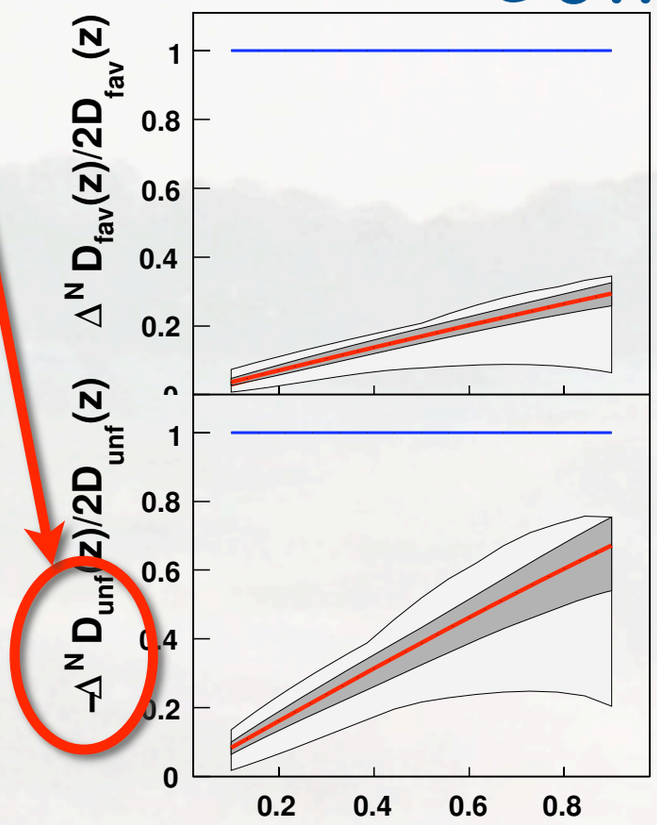
$\mu^\pm d^\uparrow \to \mu^\pm \pi X$

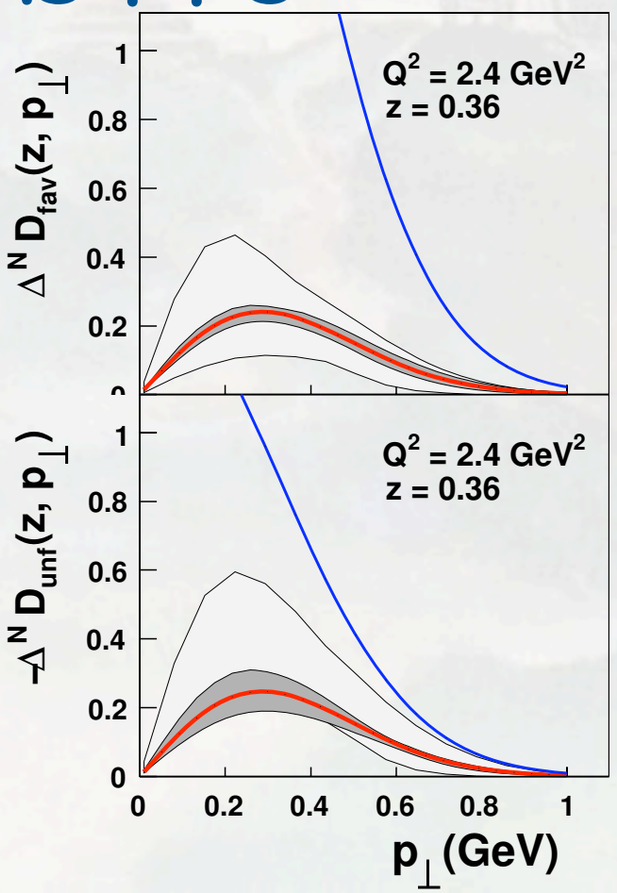
☛ M. Anselmino

fit to data

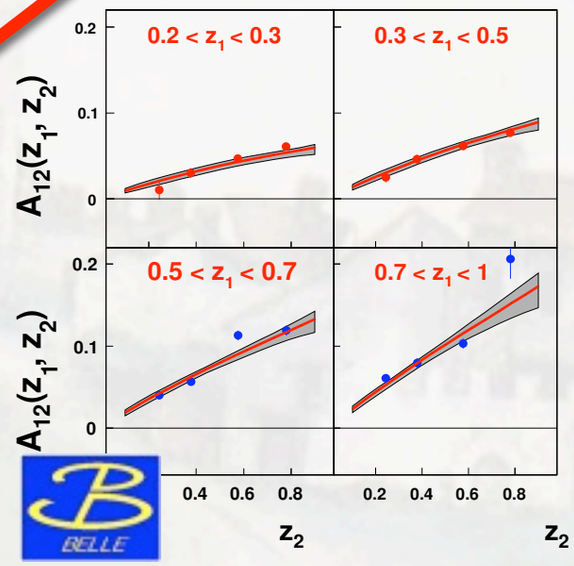
opposite sign

Collins FFs





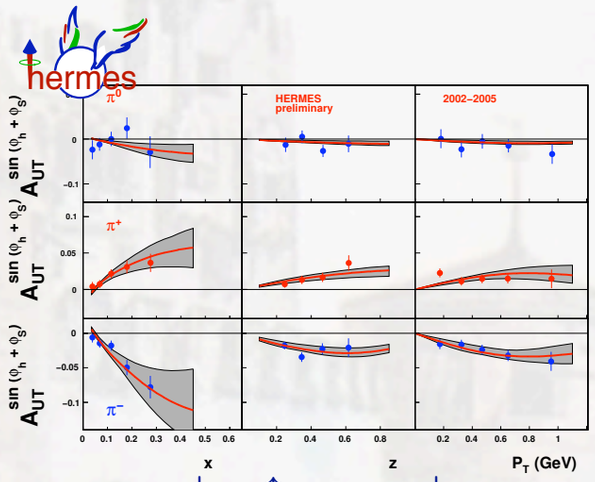
$e^+e^- \to \pi\pi X$



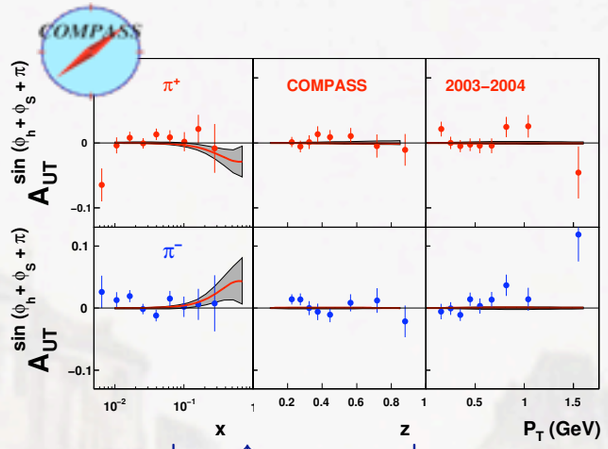
[Anselmino et al., *Nucl.Phys.Proc.Suppl.191 (2009) 98*]

Fit of Collins amplitudes

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



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



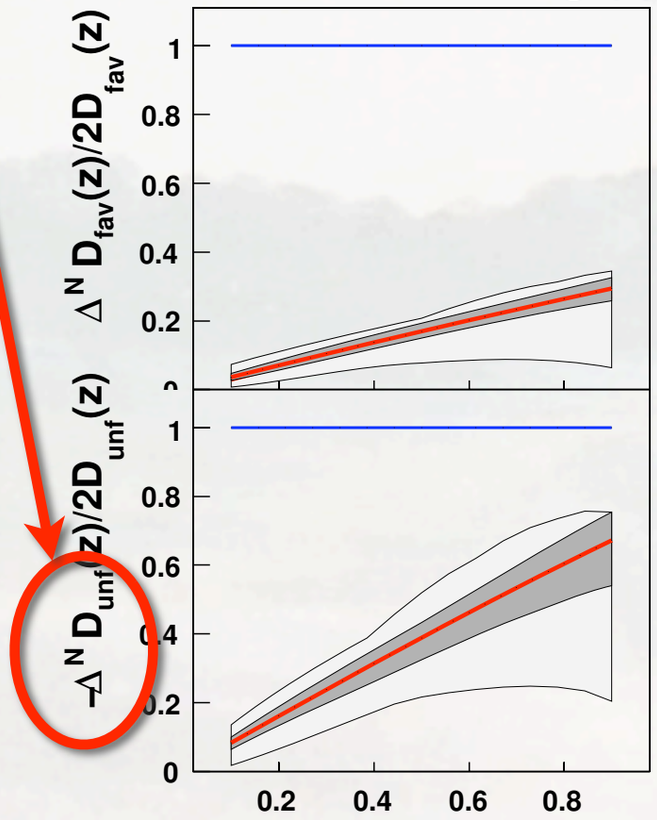
$\mu^\pm d^\uparrow \to \mu^\pm \pi X$

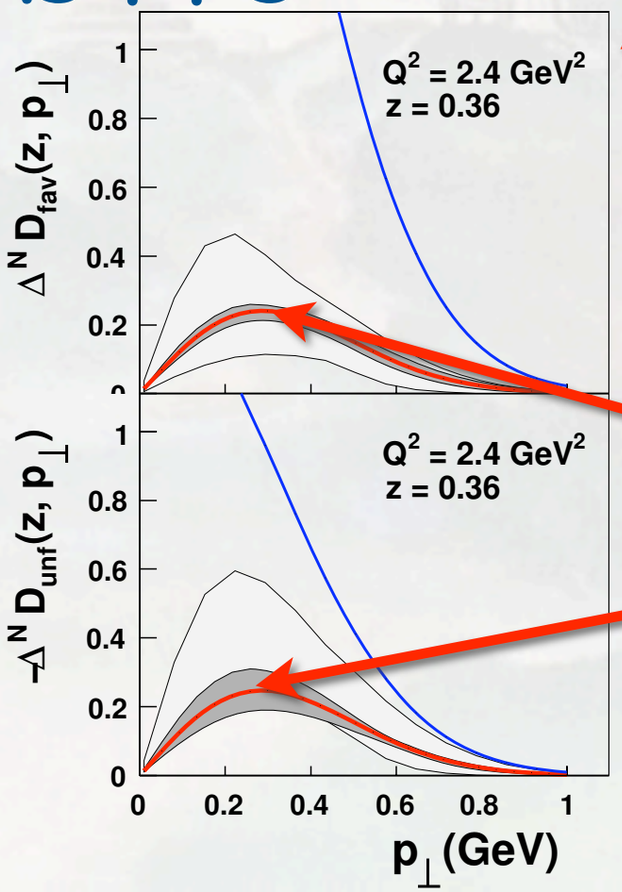
☛ M. Anselmino

fit to data

opposite sign

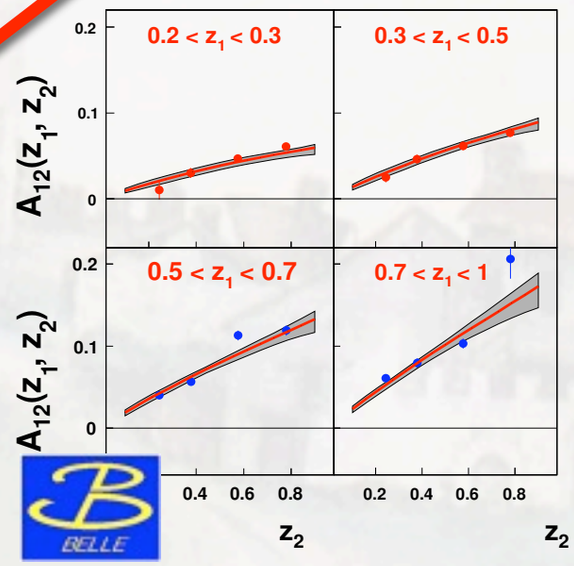
Collins FFs





similar magnitude

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



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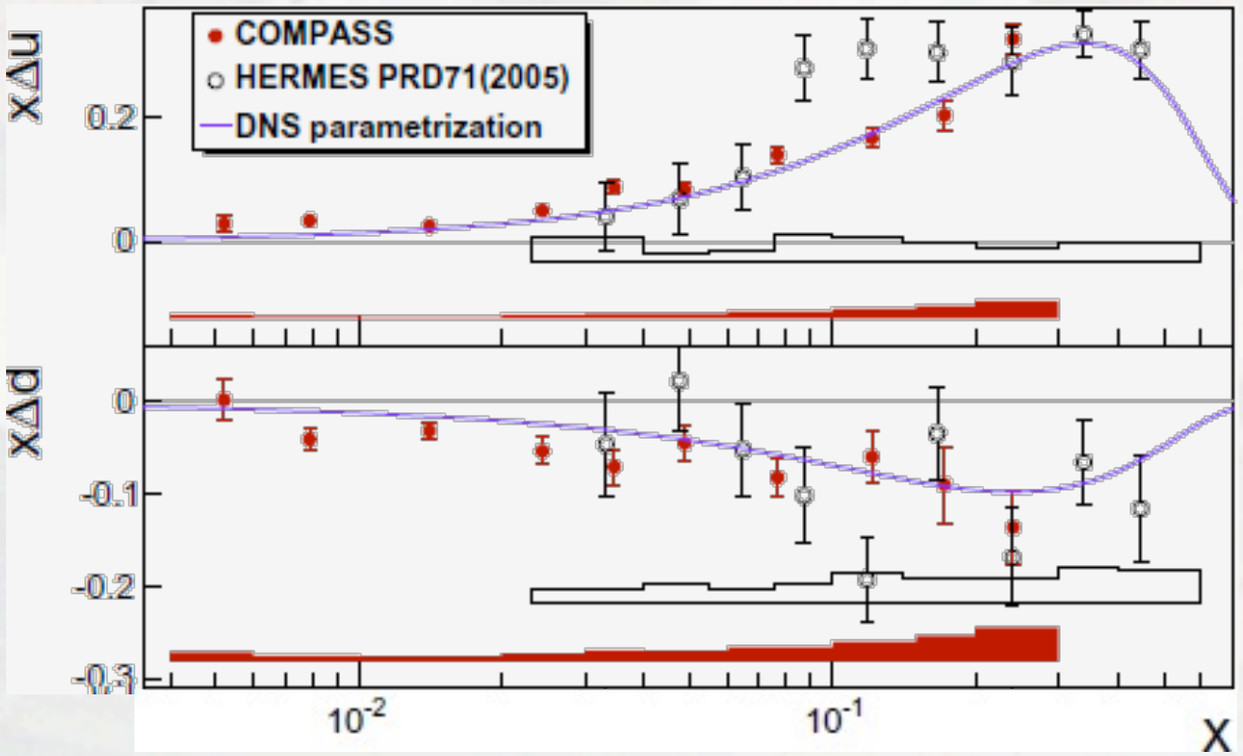
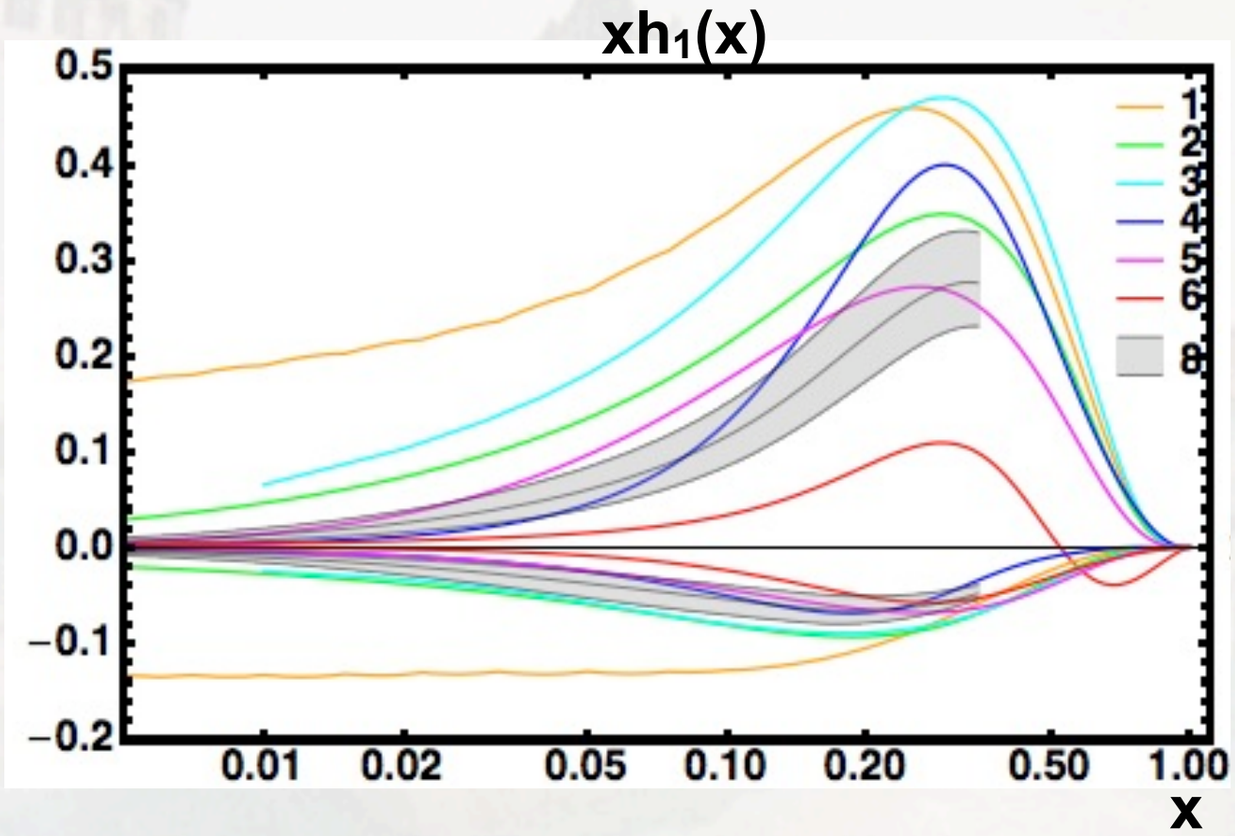
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity: models and fits

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





	U	L	T
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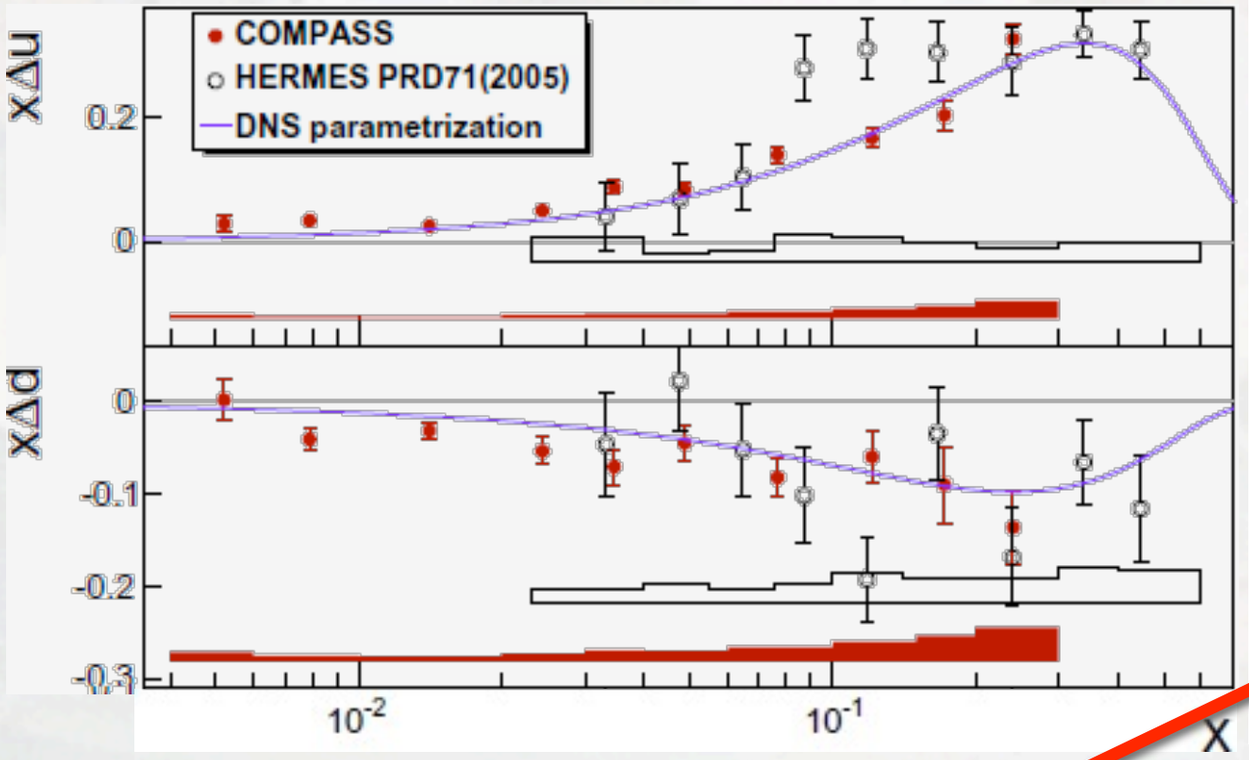

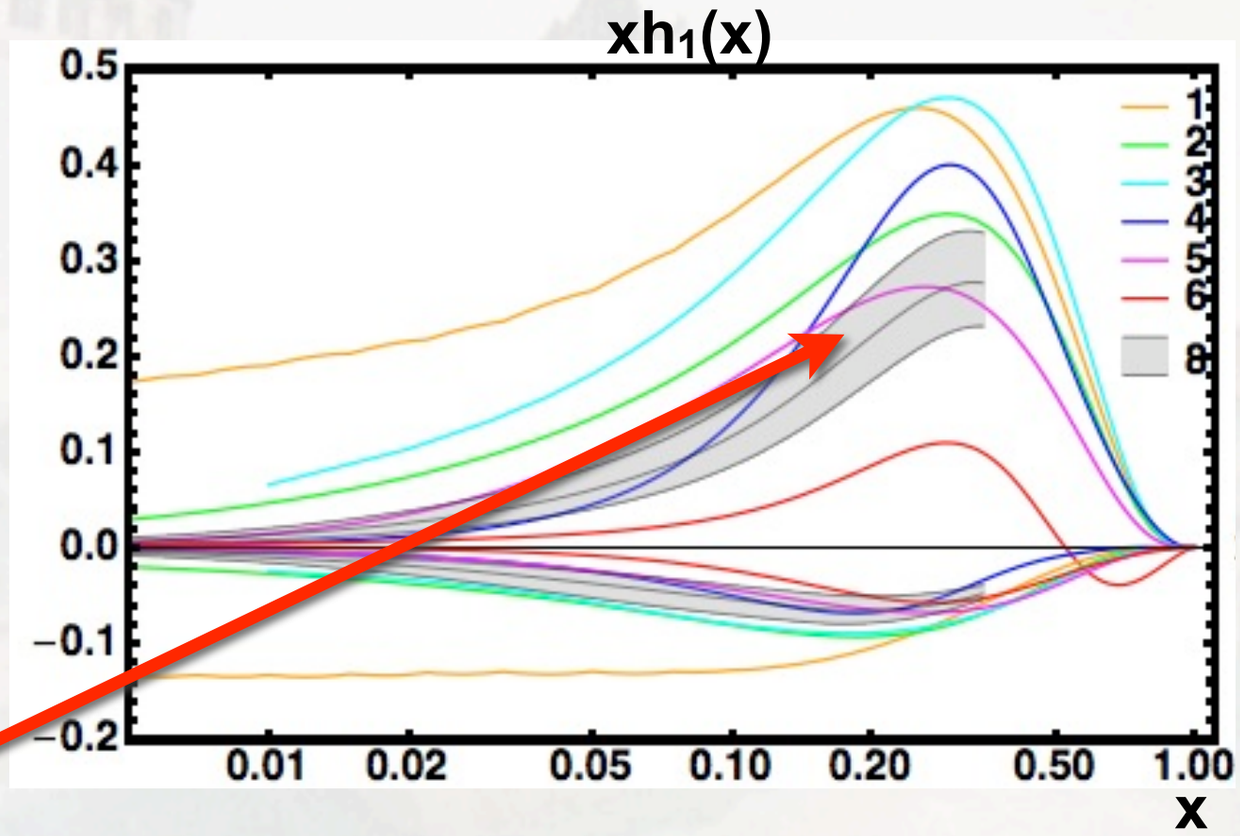

☑ u quark transversity along nucleon spin

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

Transversity: models and fits

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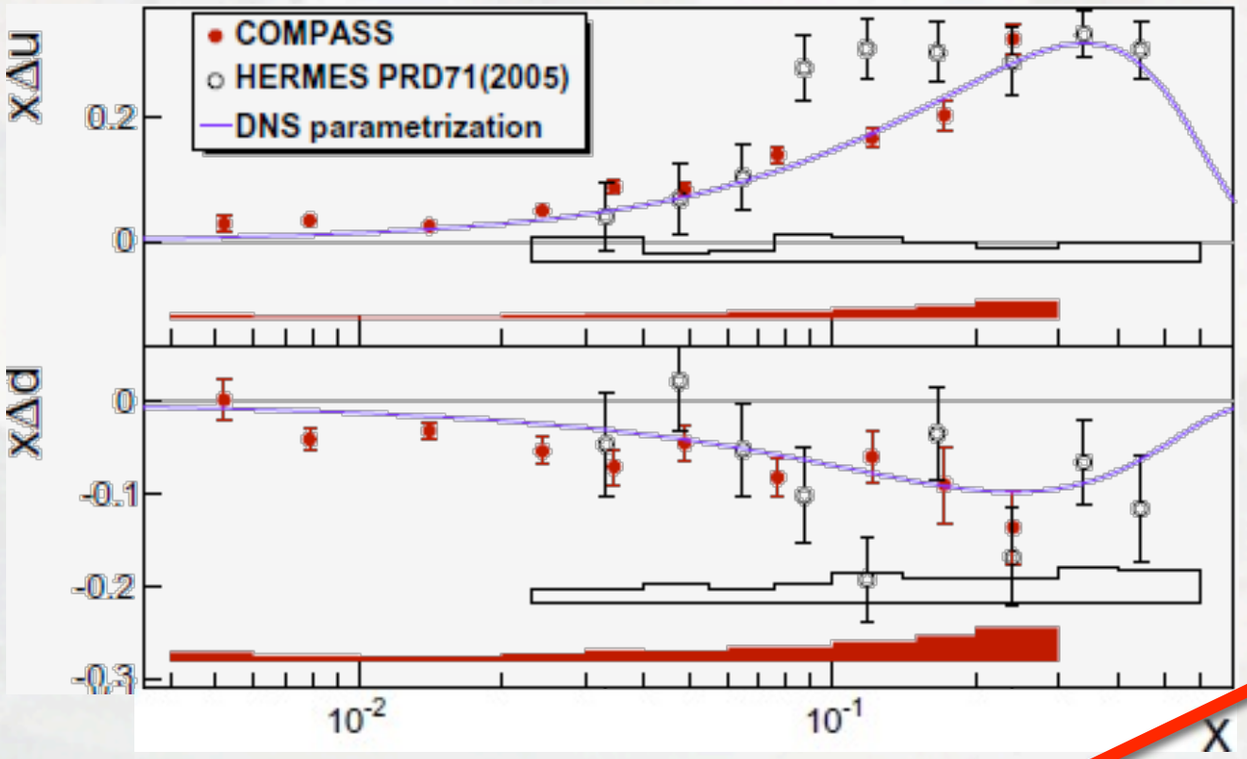

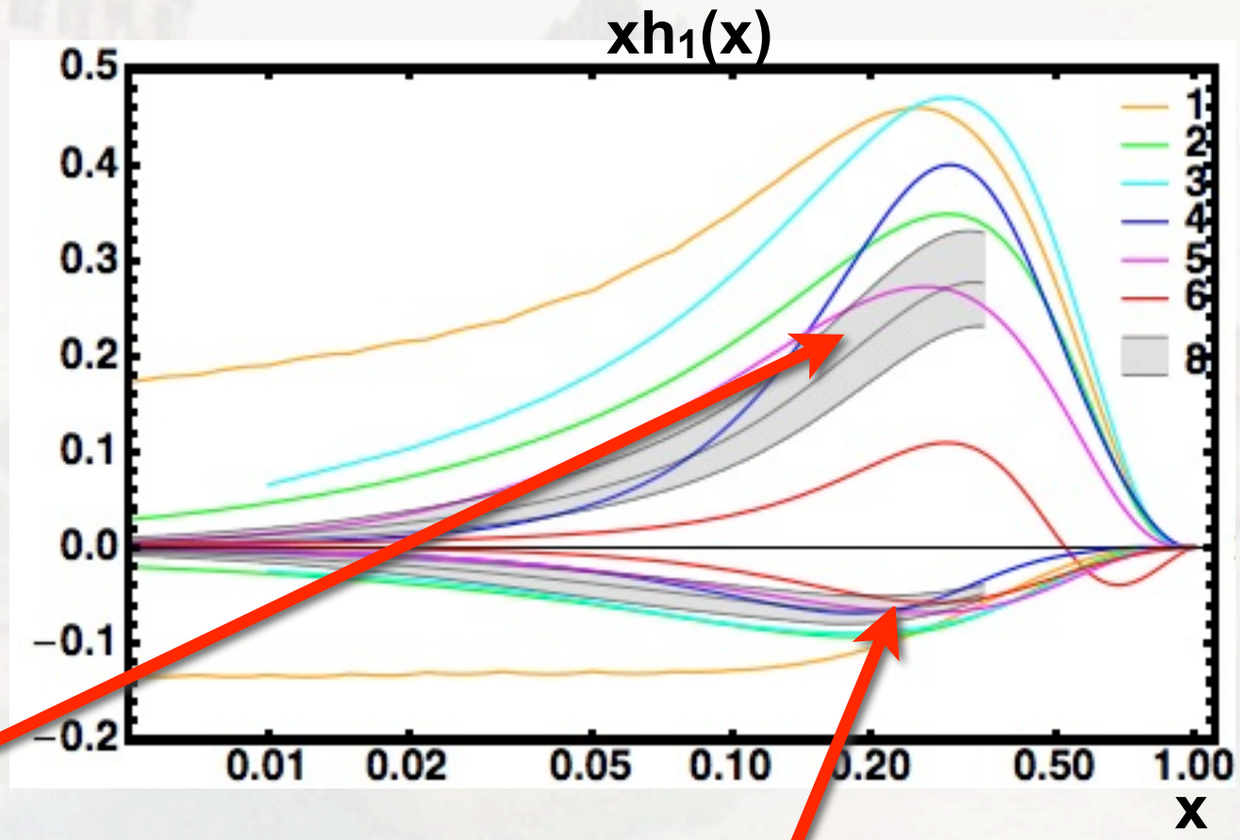

☑ u quark transversity along nucleon spin

☑ d quark transversity anti-parallel to nucleon spin

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, $h_{1T}^\perp$

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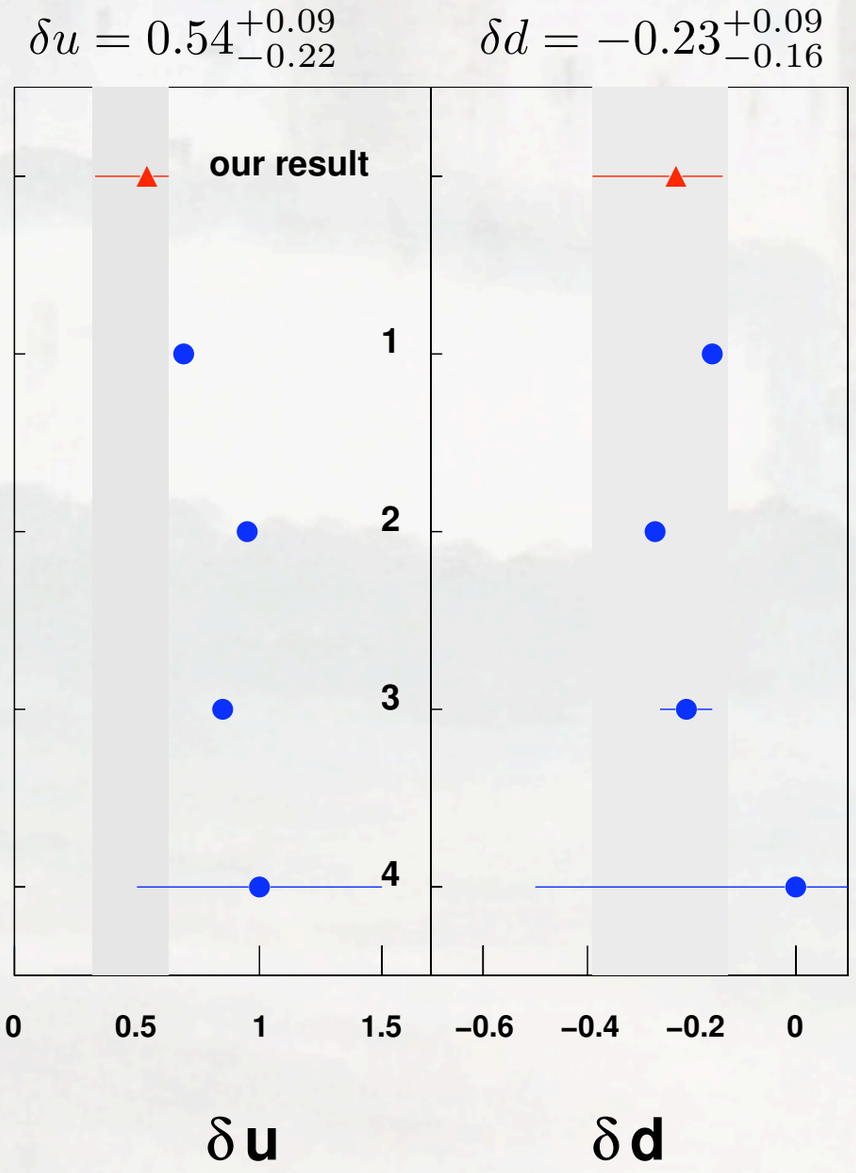
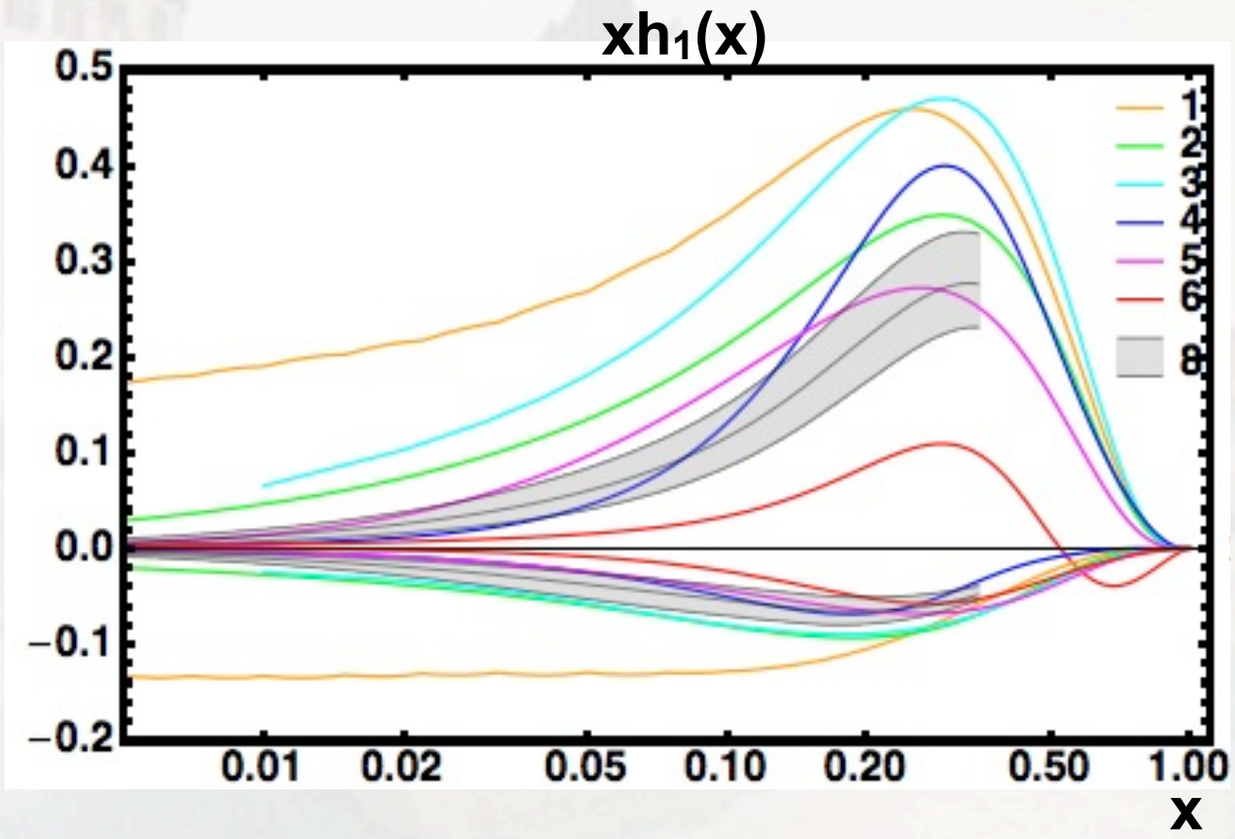




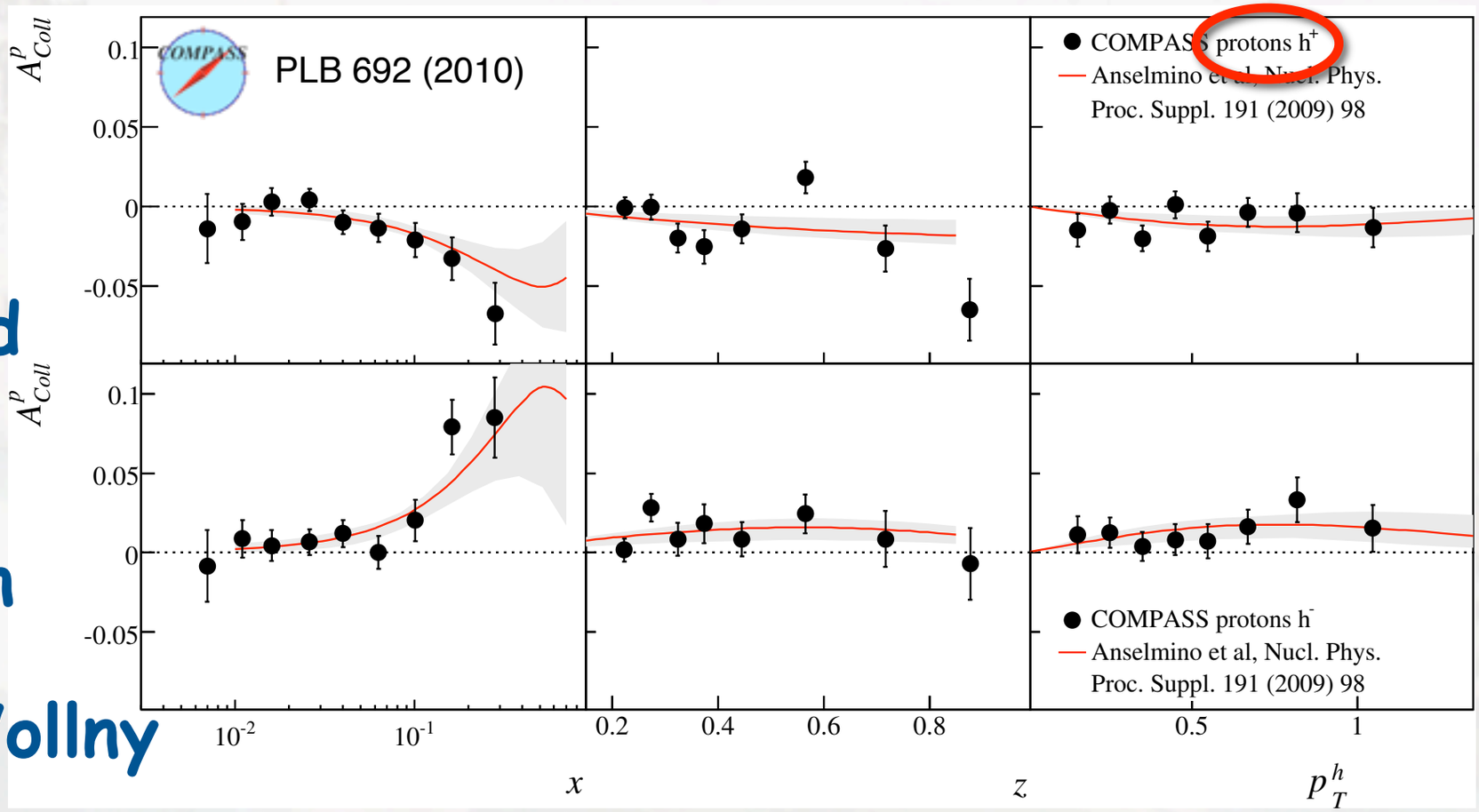
tensor charge:

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

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

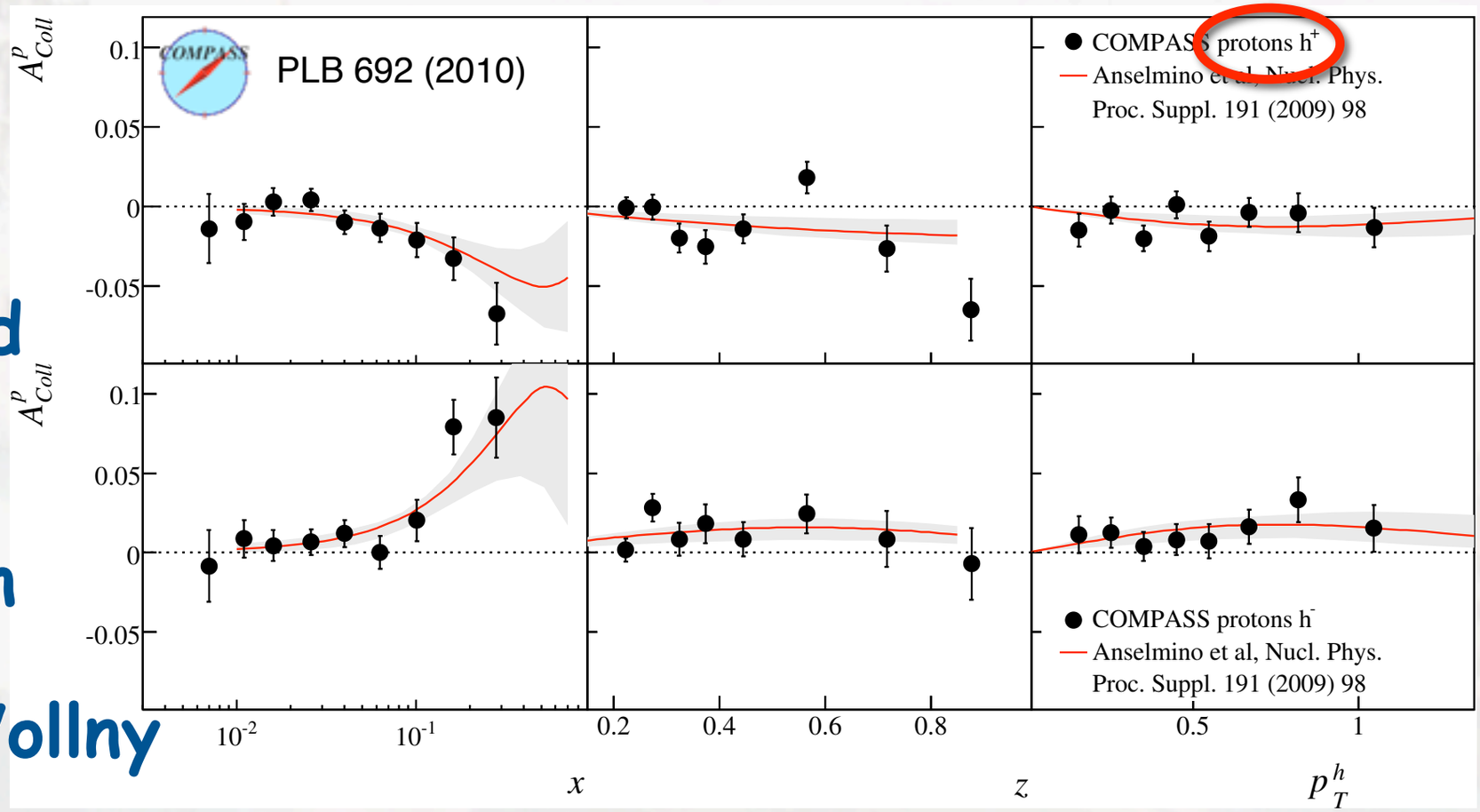
Transversity distribution (Collins fragmentation)

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



	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

	U	L	T
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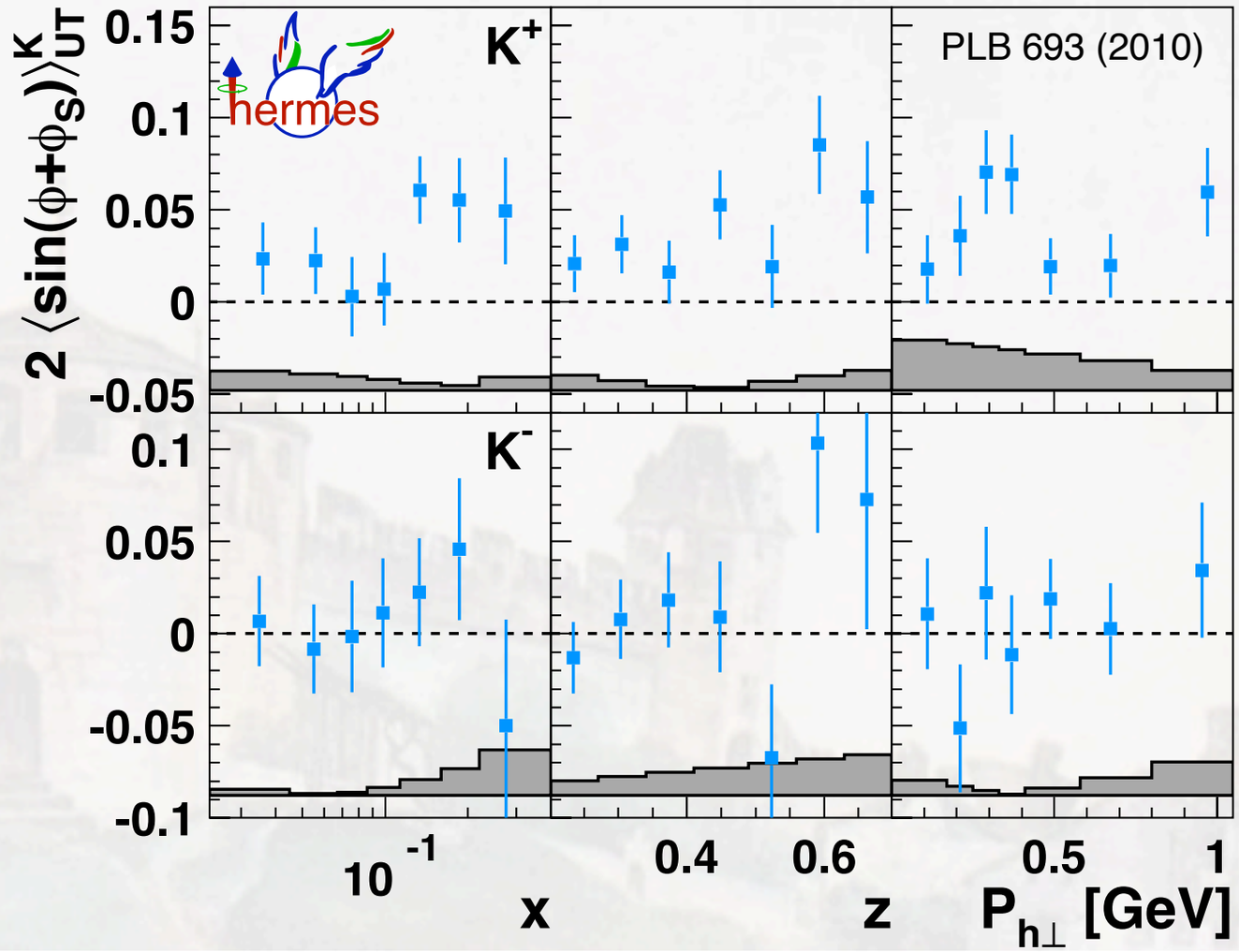
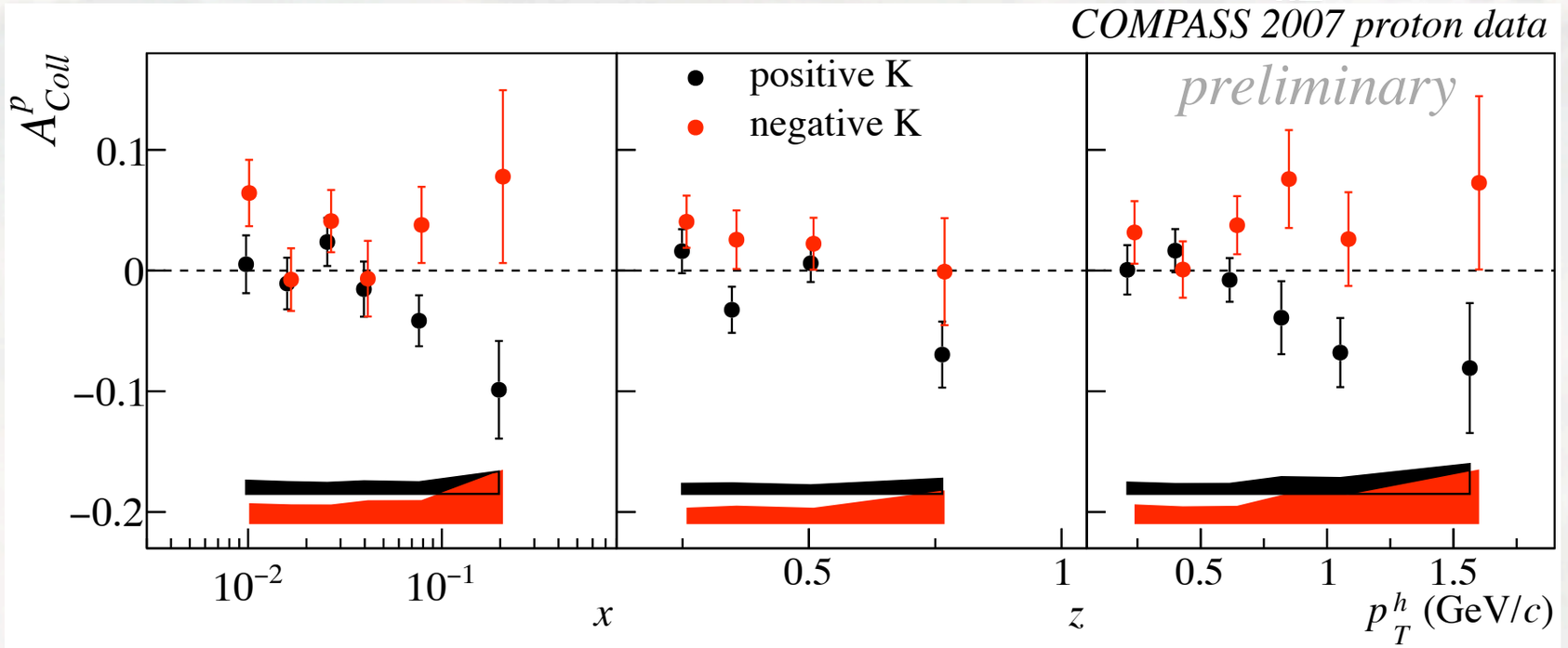
Collins amplitudes for kaons



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



gunar.schnell @ desy.de

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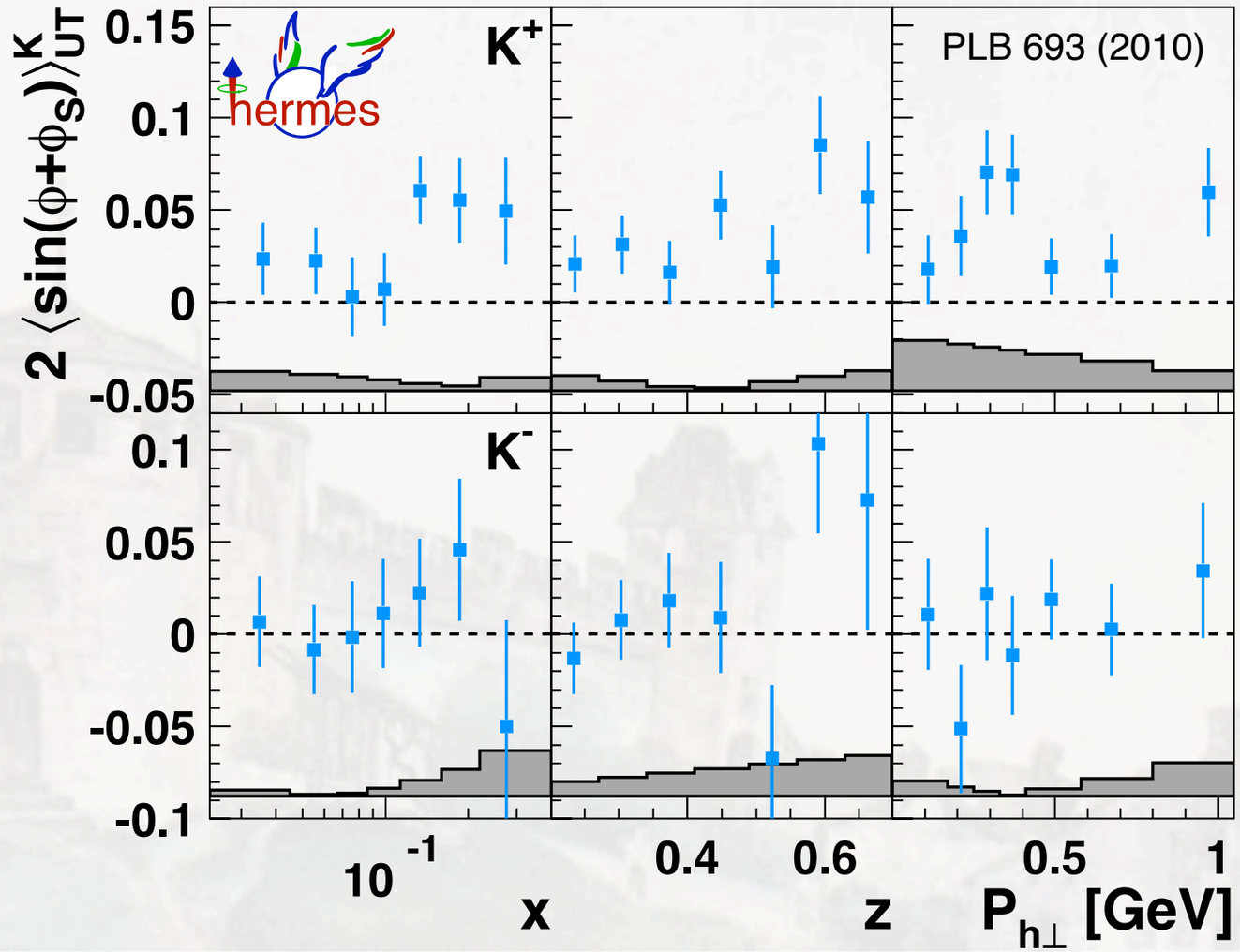

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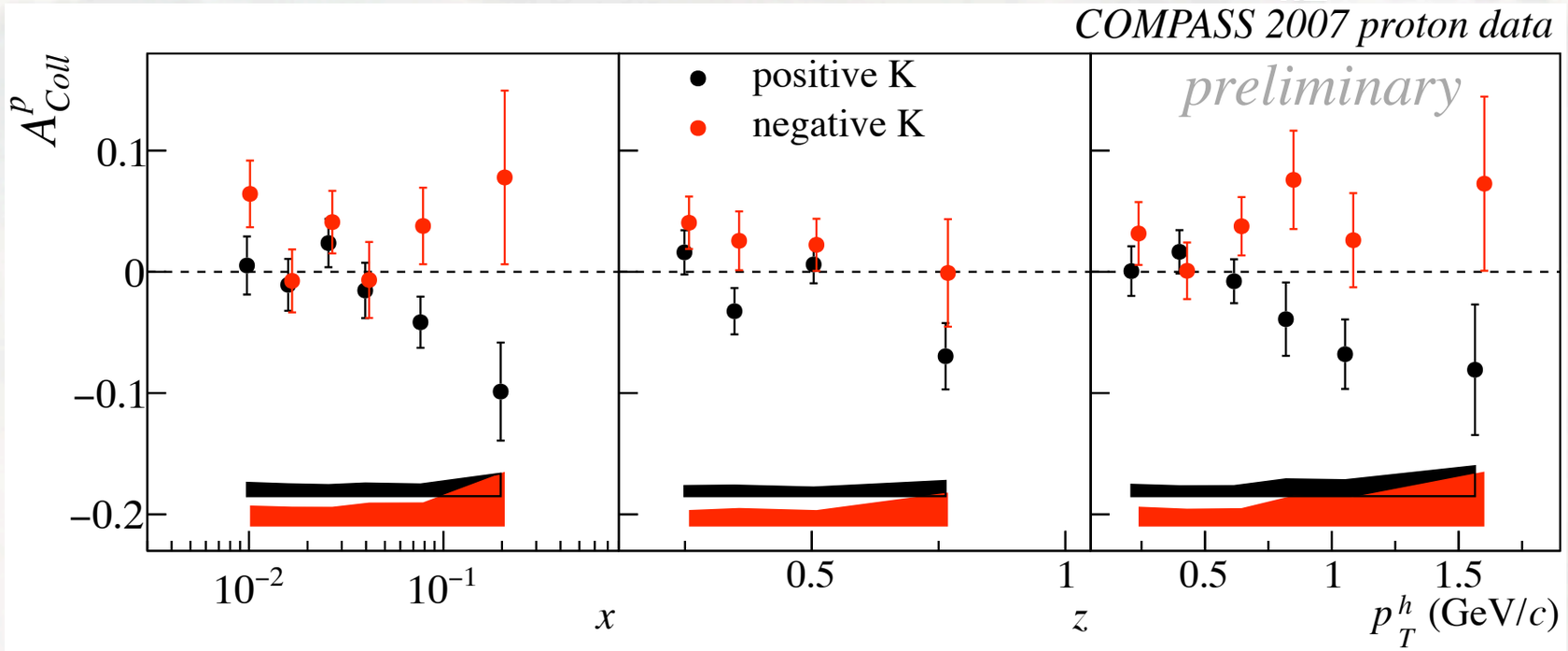
☛ H.Wollny, L.Pappalardo



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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

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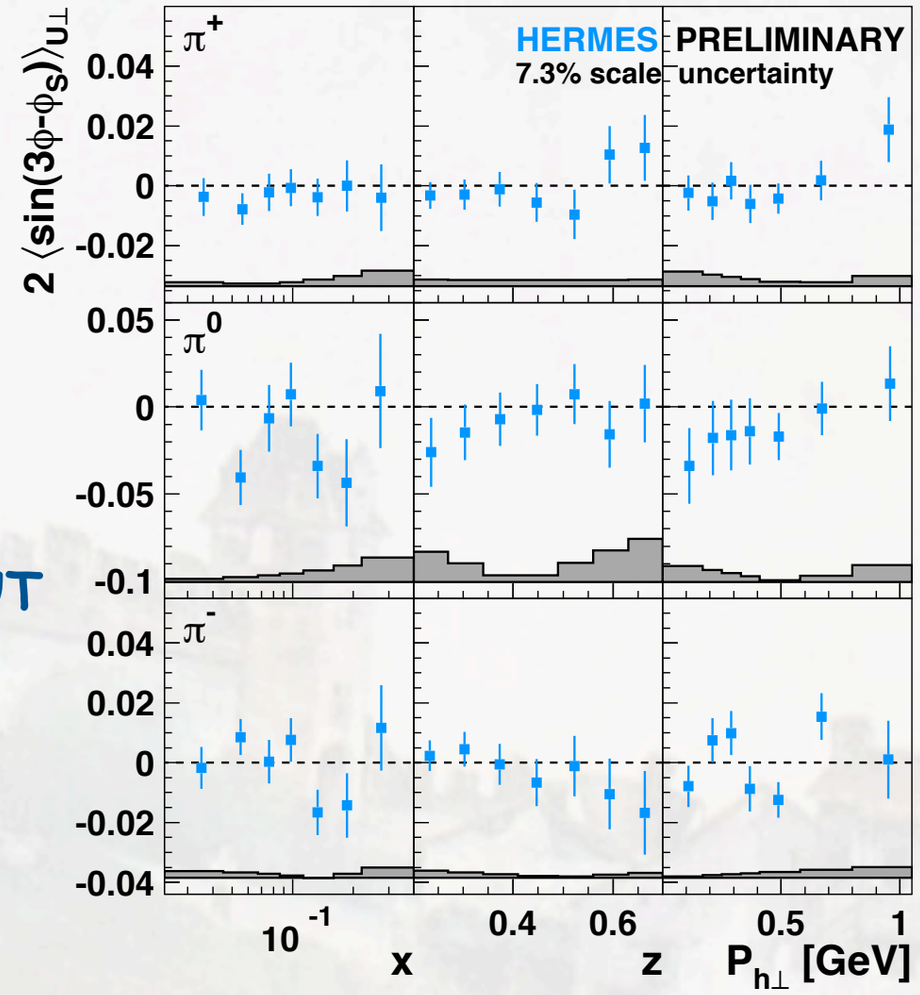

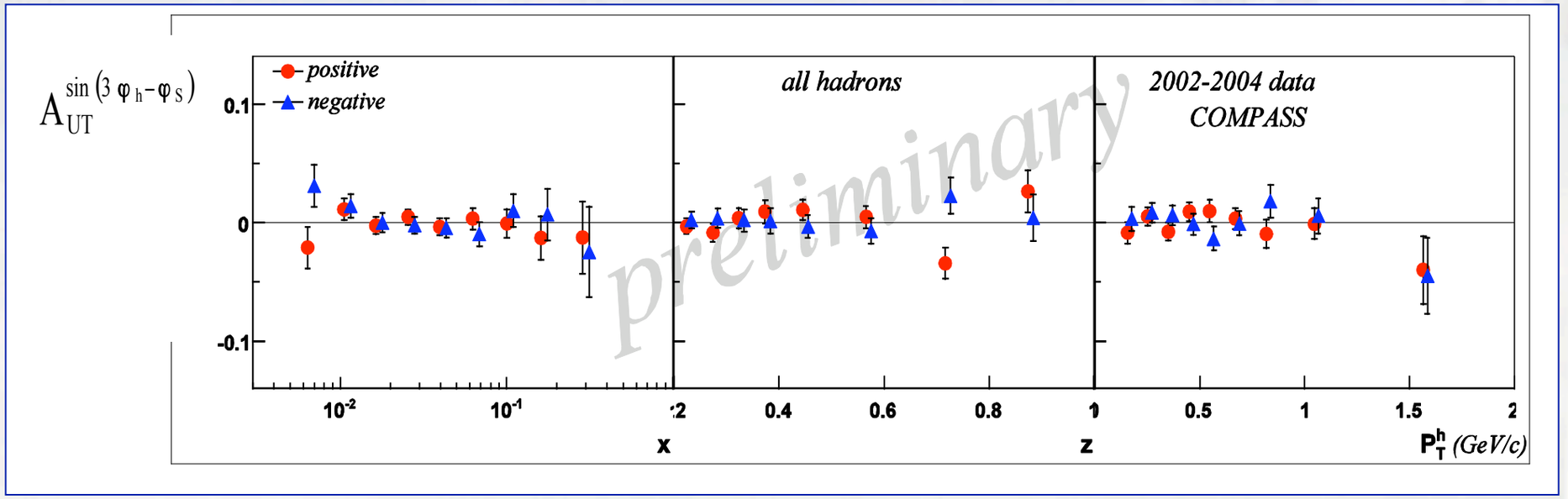

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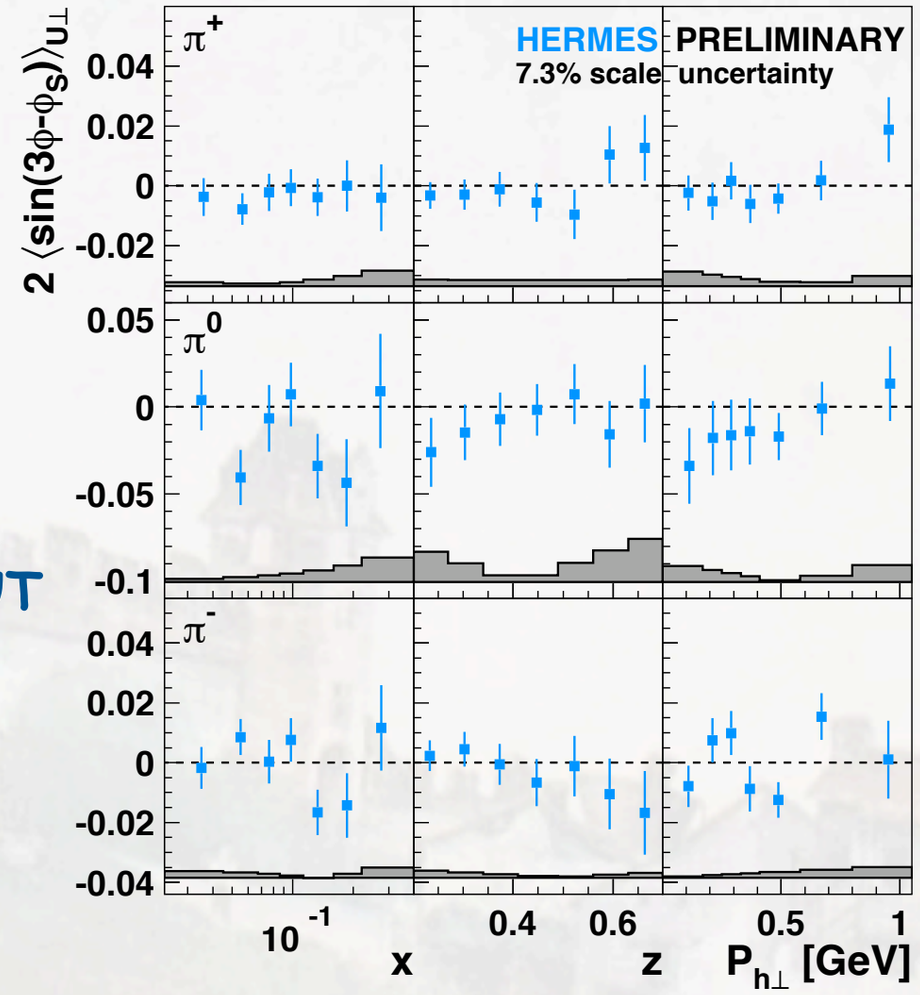

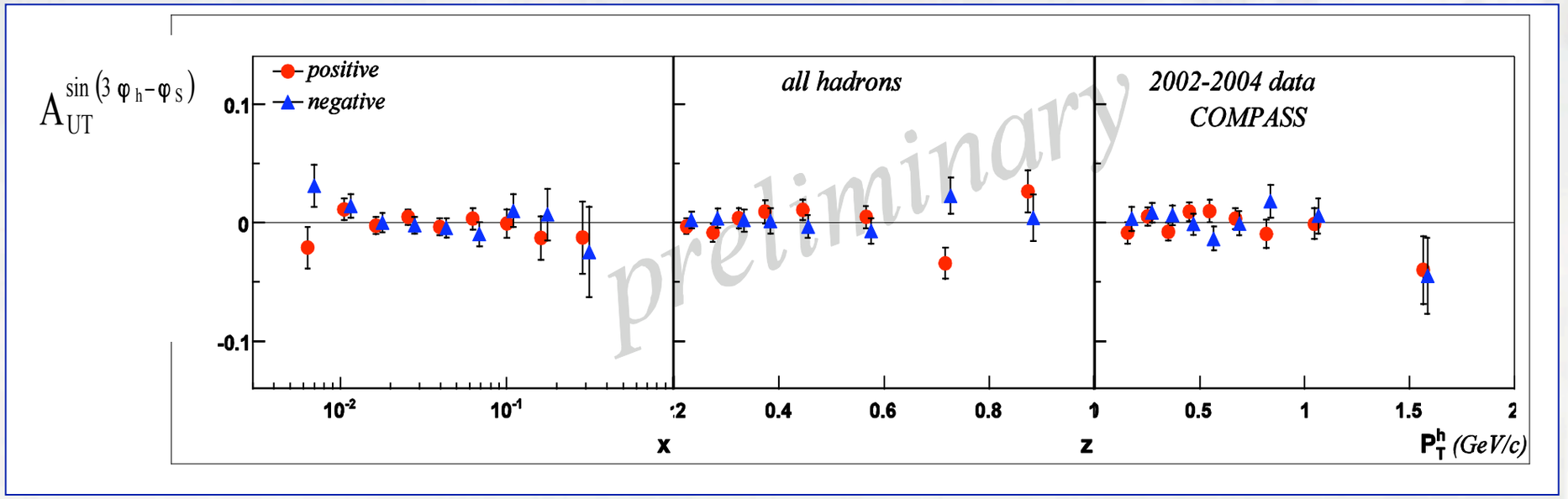

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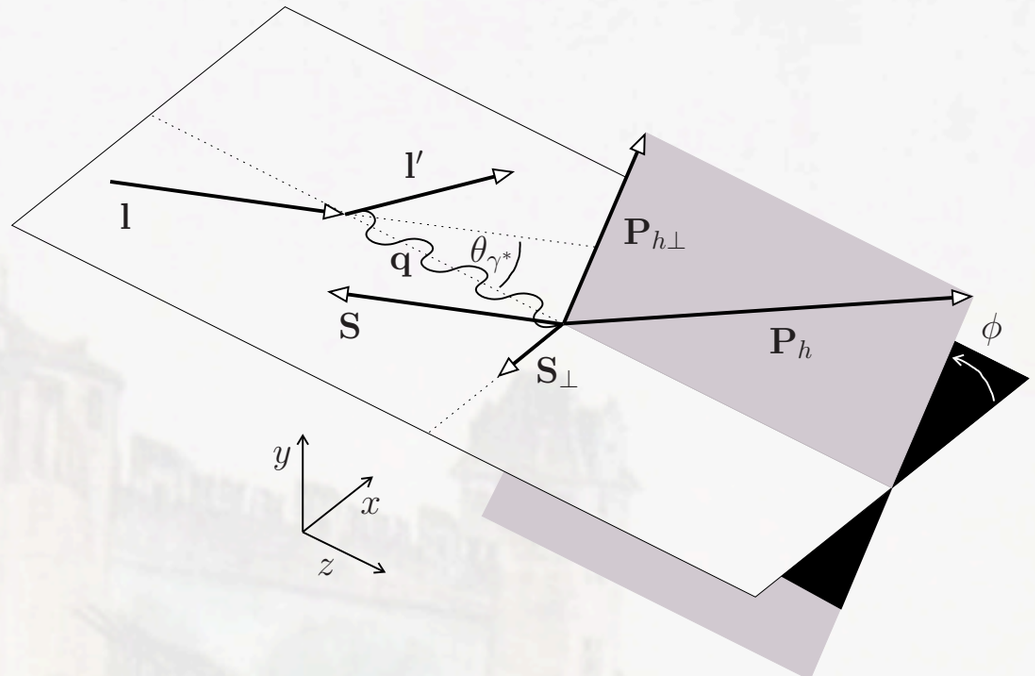
$$\sin(3\phi - \phi_S) \rightsquigarrow -\sin(3\phi)$$



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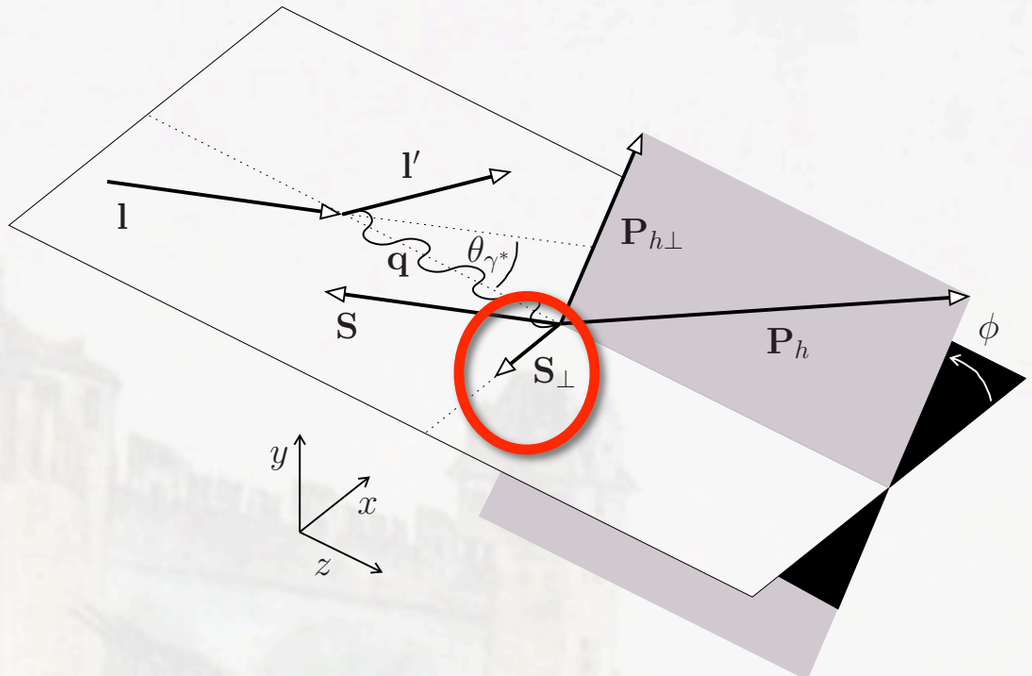

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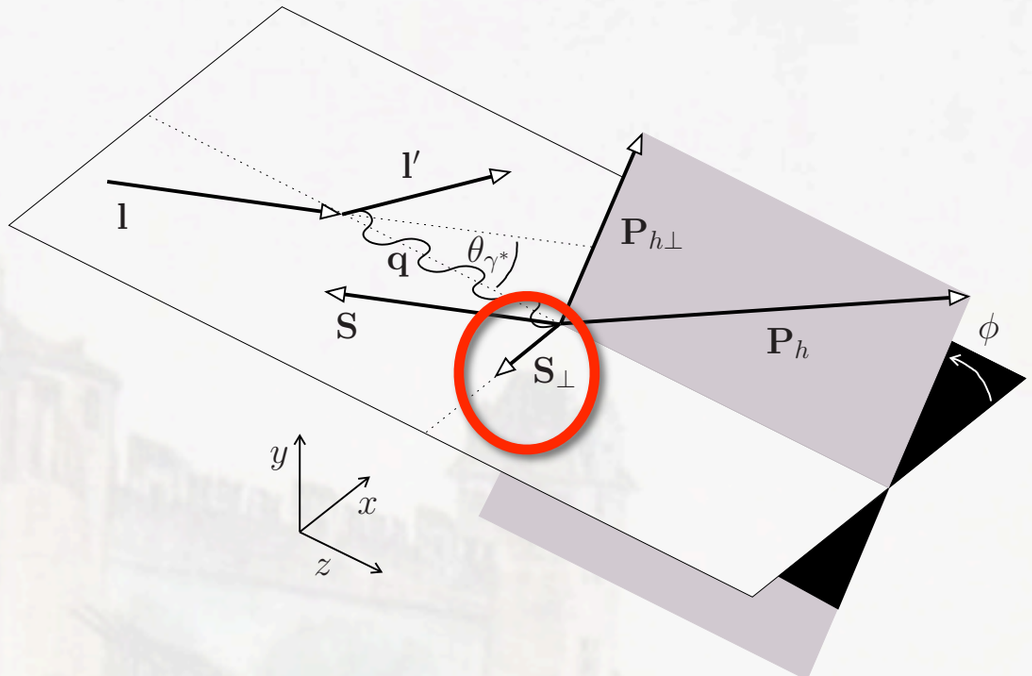

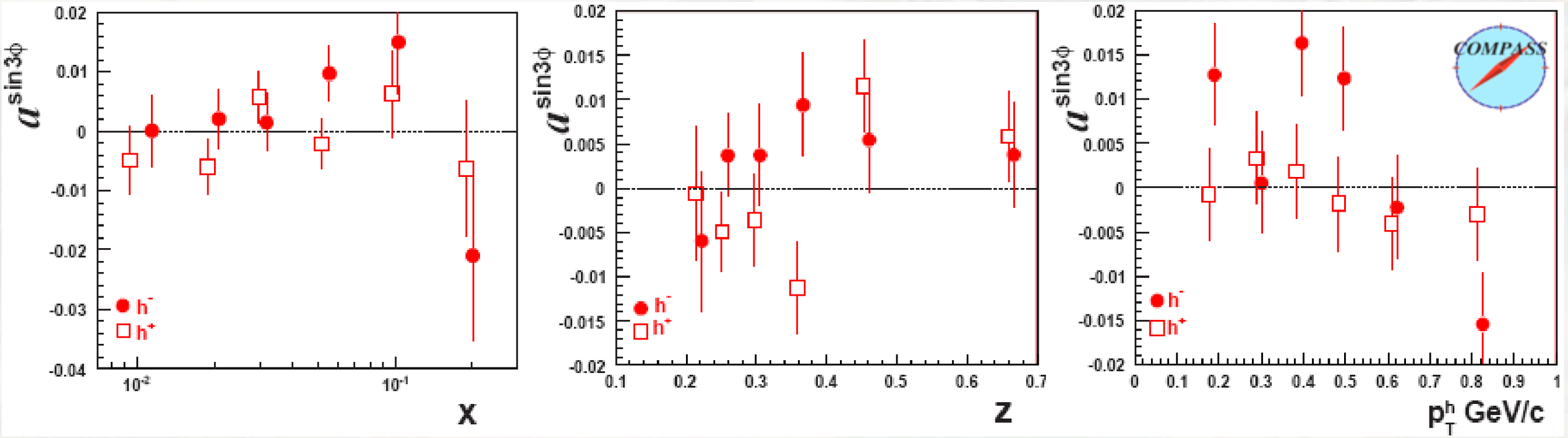

Worm-Gear I

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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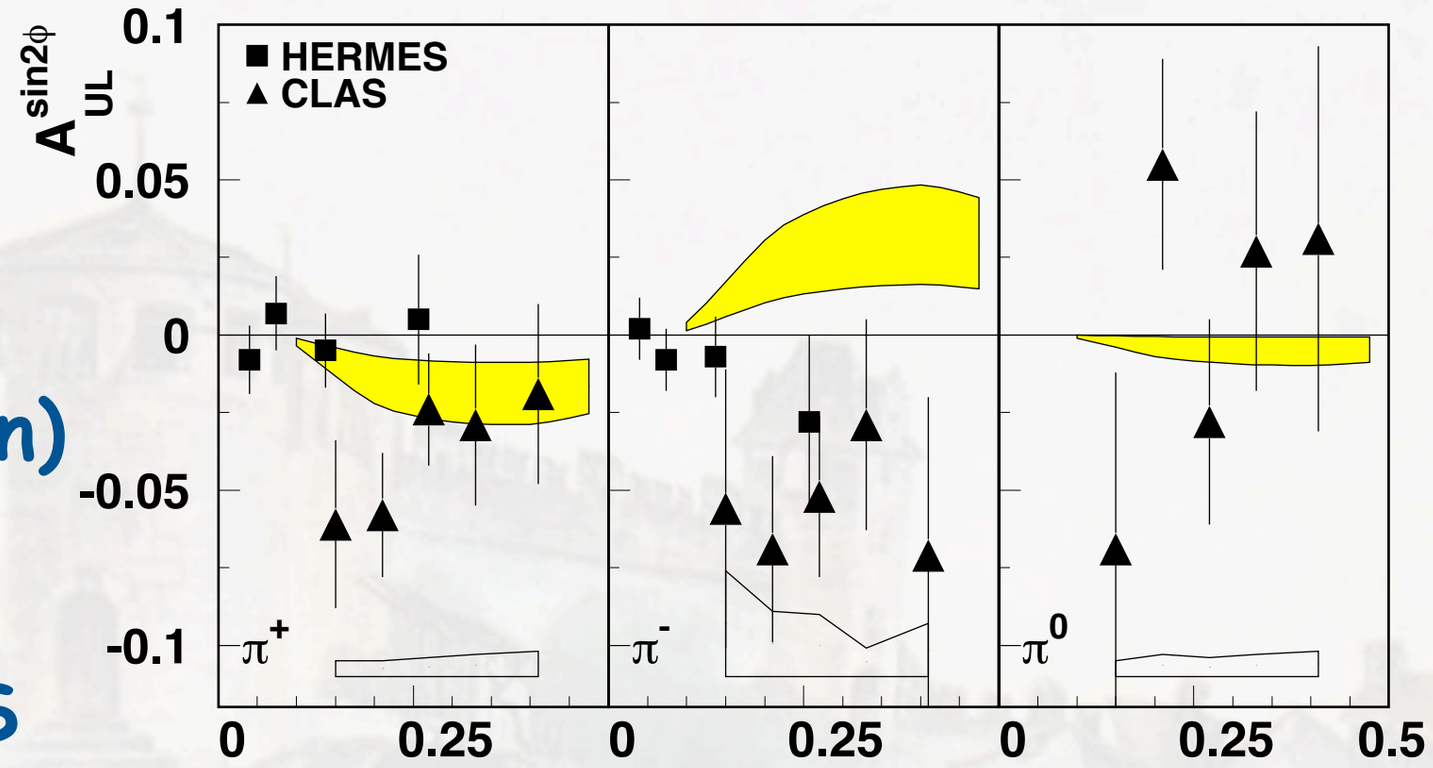
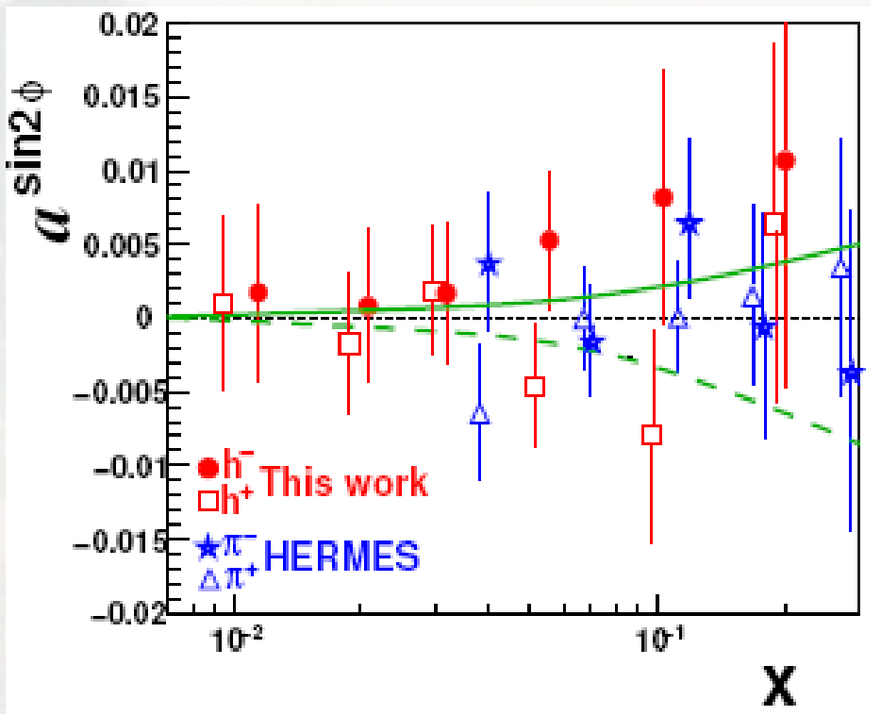
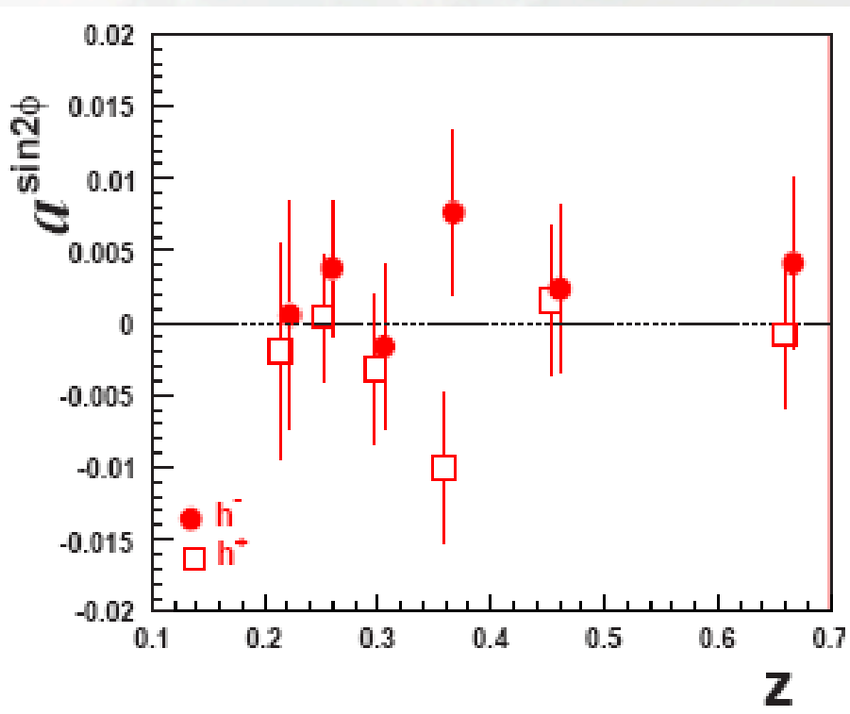
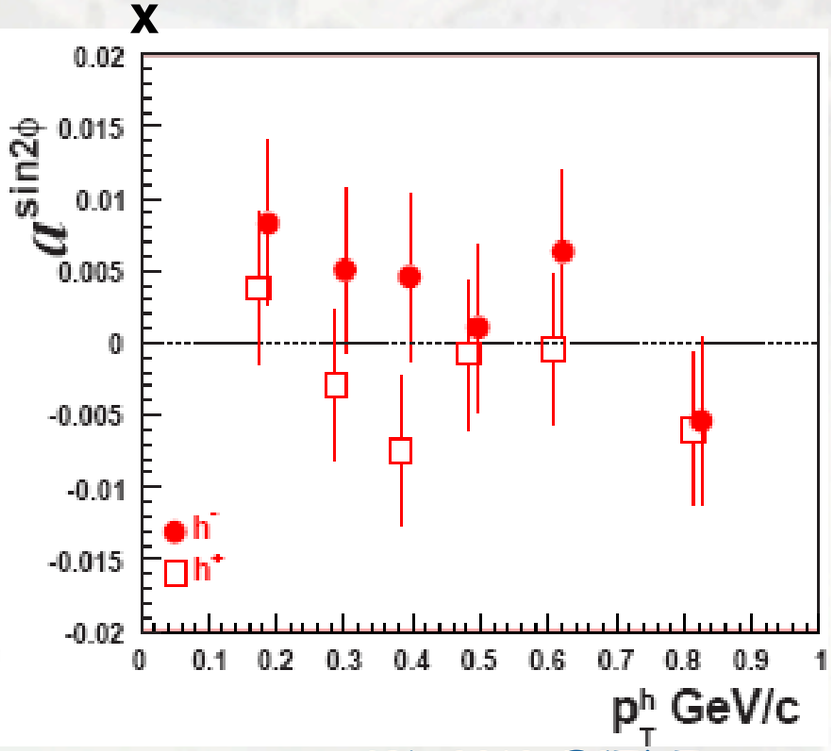
- chiral-odd
- evidence from CLAS (new results coming soon)
- consistent with zero at COMPASS and HERMES









Worm-Gear I

	U	L	T
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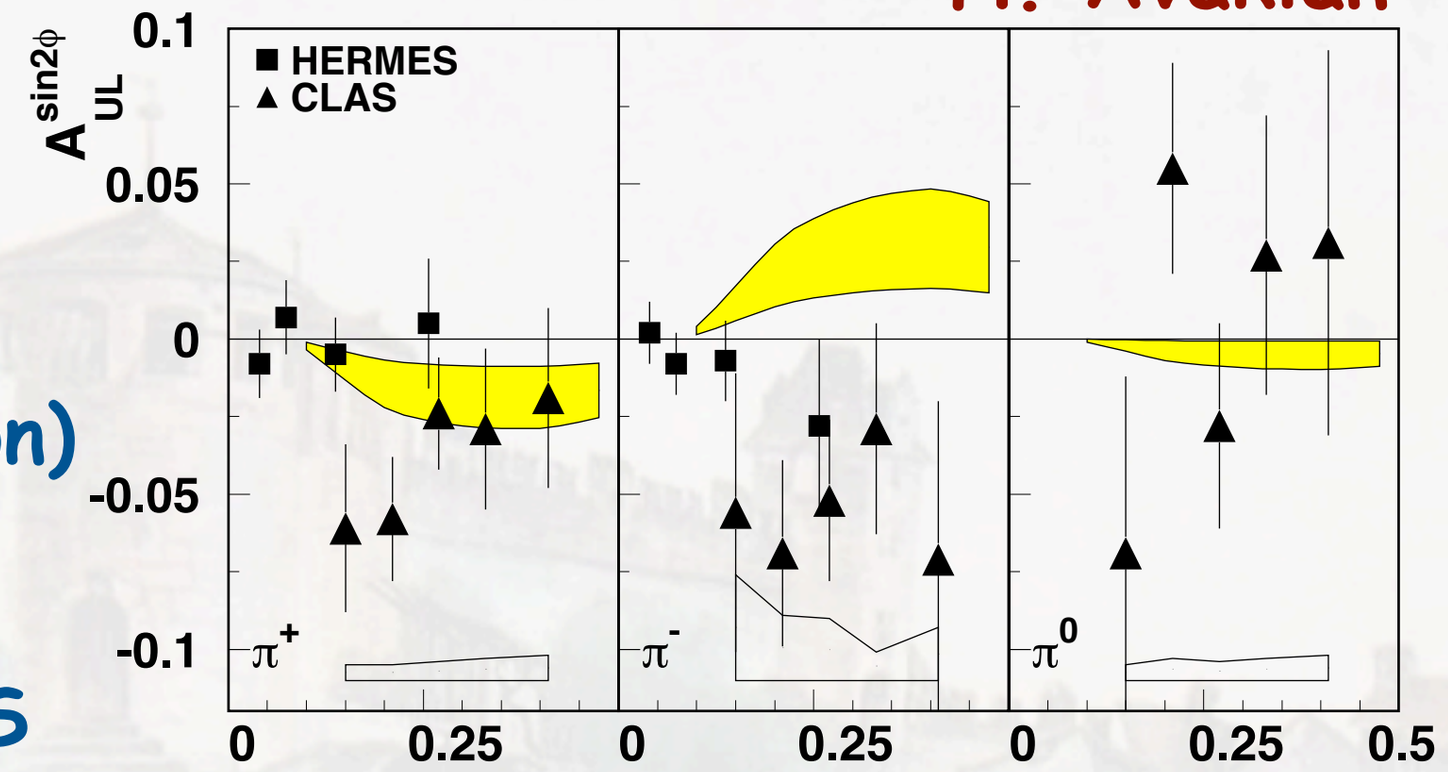
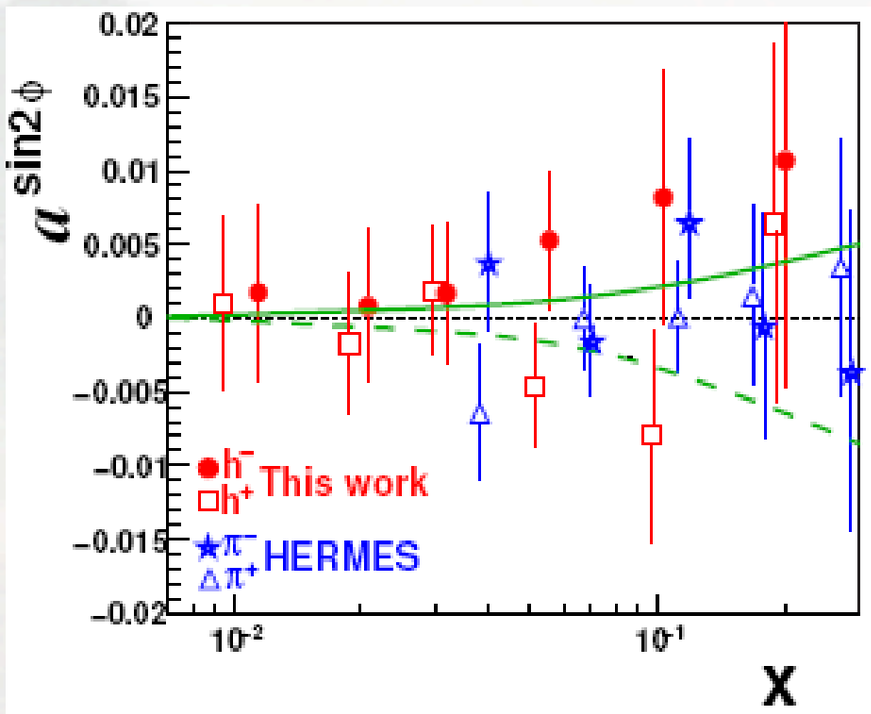
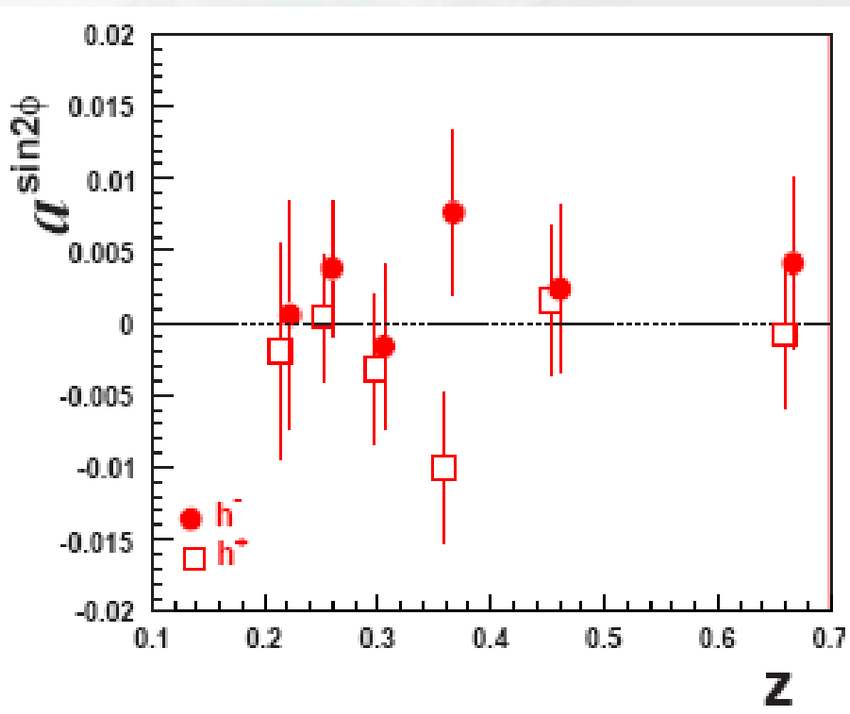
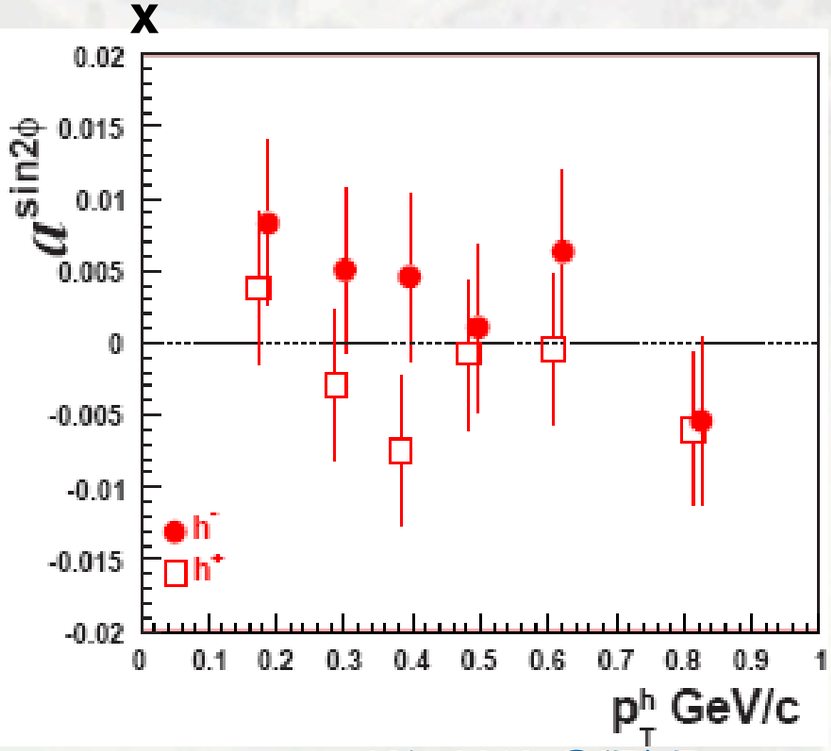
☛ H. Avakian





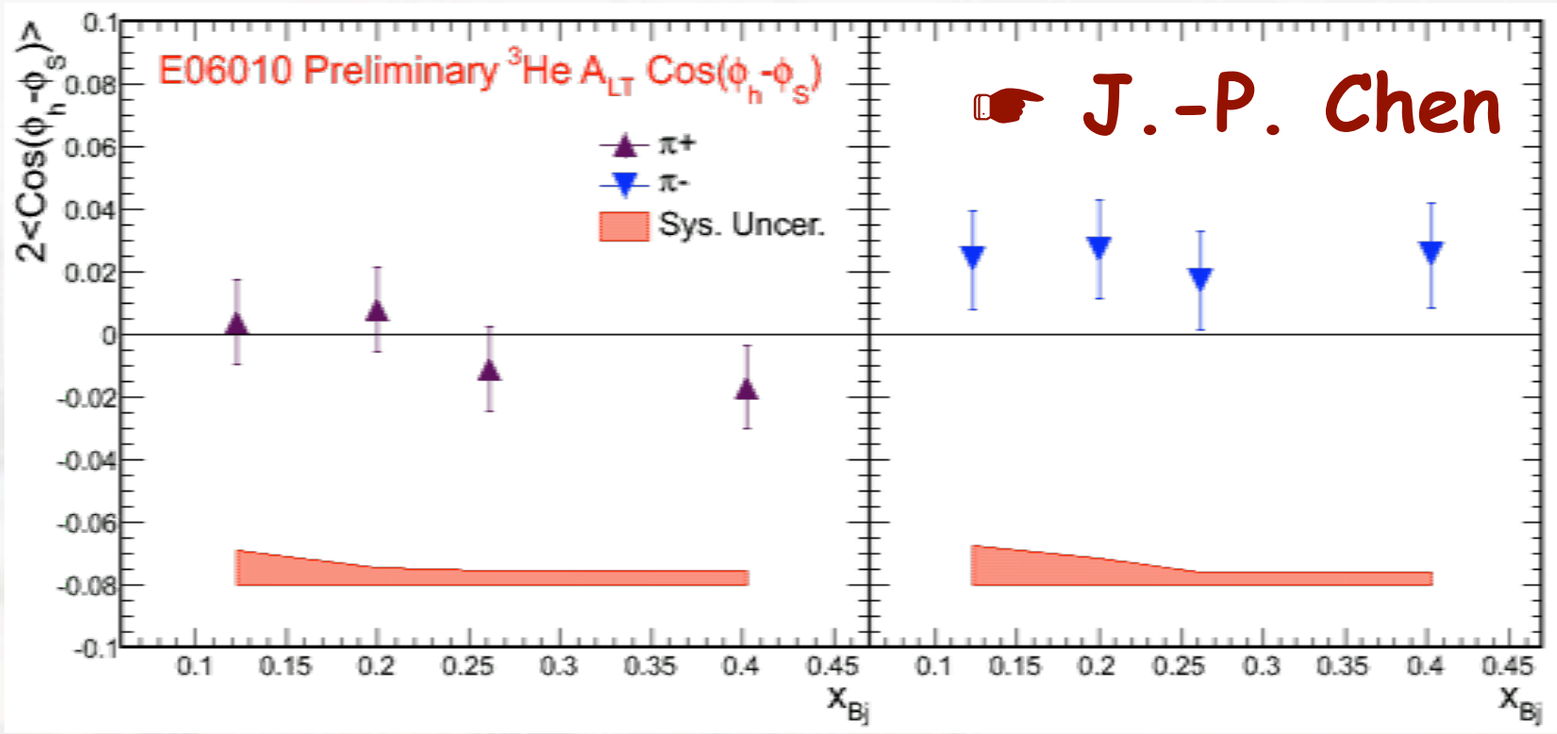




Worm-Gear II

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

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



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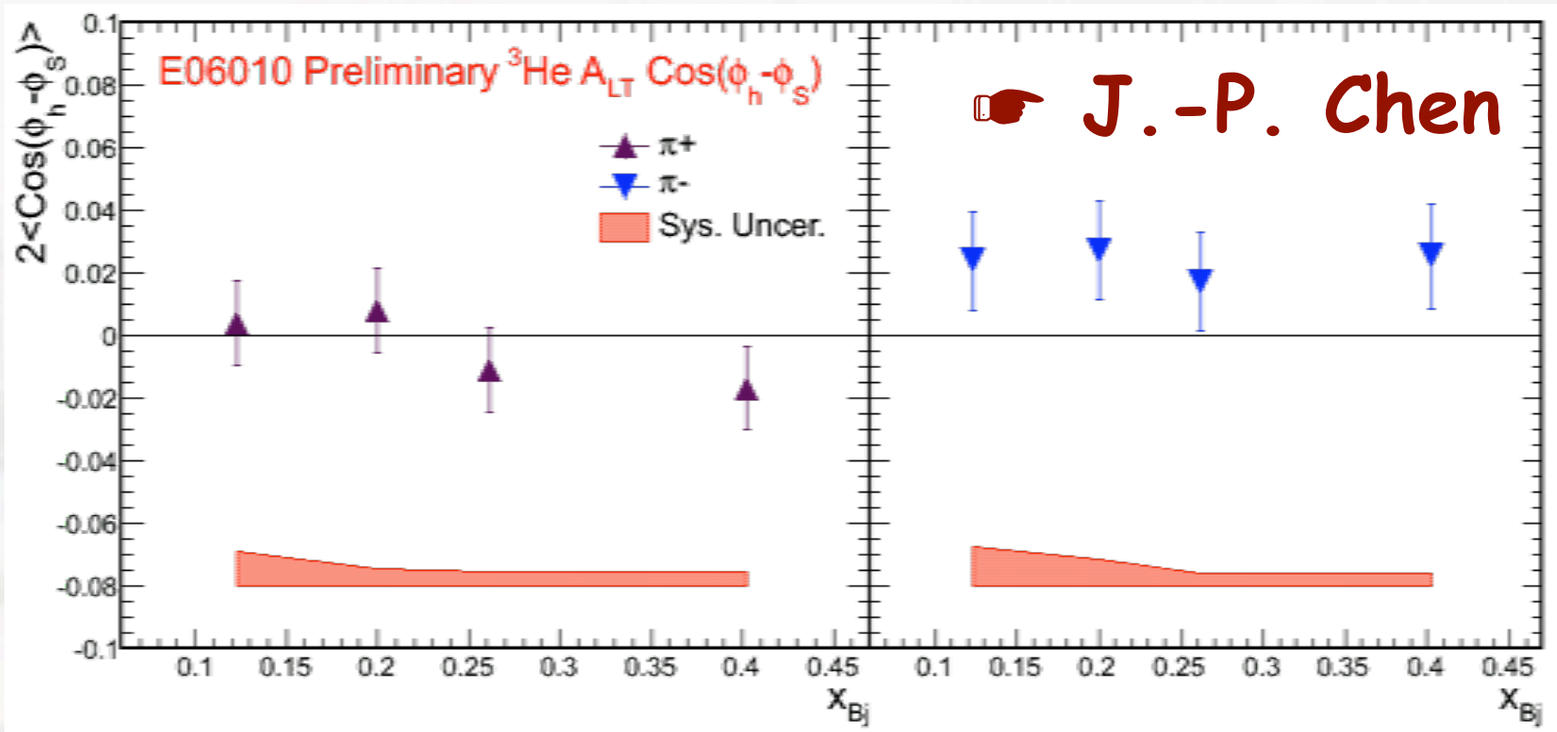

- only indirect hints from proton data via A_{UT}

$$\propto \left(\mathbf{x f_T^\perp D_1} - \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{h_1}\frac{\tilde{\mathbf{H}}}{\mathbf{z}}\right) - \mathcal{W}(\mathbf{p_T}, \mathbf{k_T}, \mathbf{P_{h\perp}})\left[\left(\mathbf{x h_T H_1^\perp} + \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{g_{1T}}\frac{\tilde{\mathbf{G}}^\perp}{\mathbf{z}}\right) - \left(\mathbf{x h_T^\perp H_1^\perp} - \frac{\mathbf{M_h}}{\mathbf{M}}\mathbf{f_{1T}^\perp}\frac{\tilde{\mathbf{D}}^\perp}{\mathbf{z}}\right)\right]$$

Worm-Gear II

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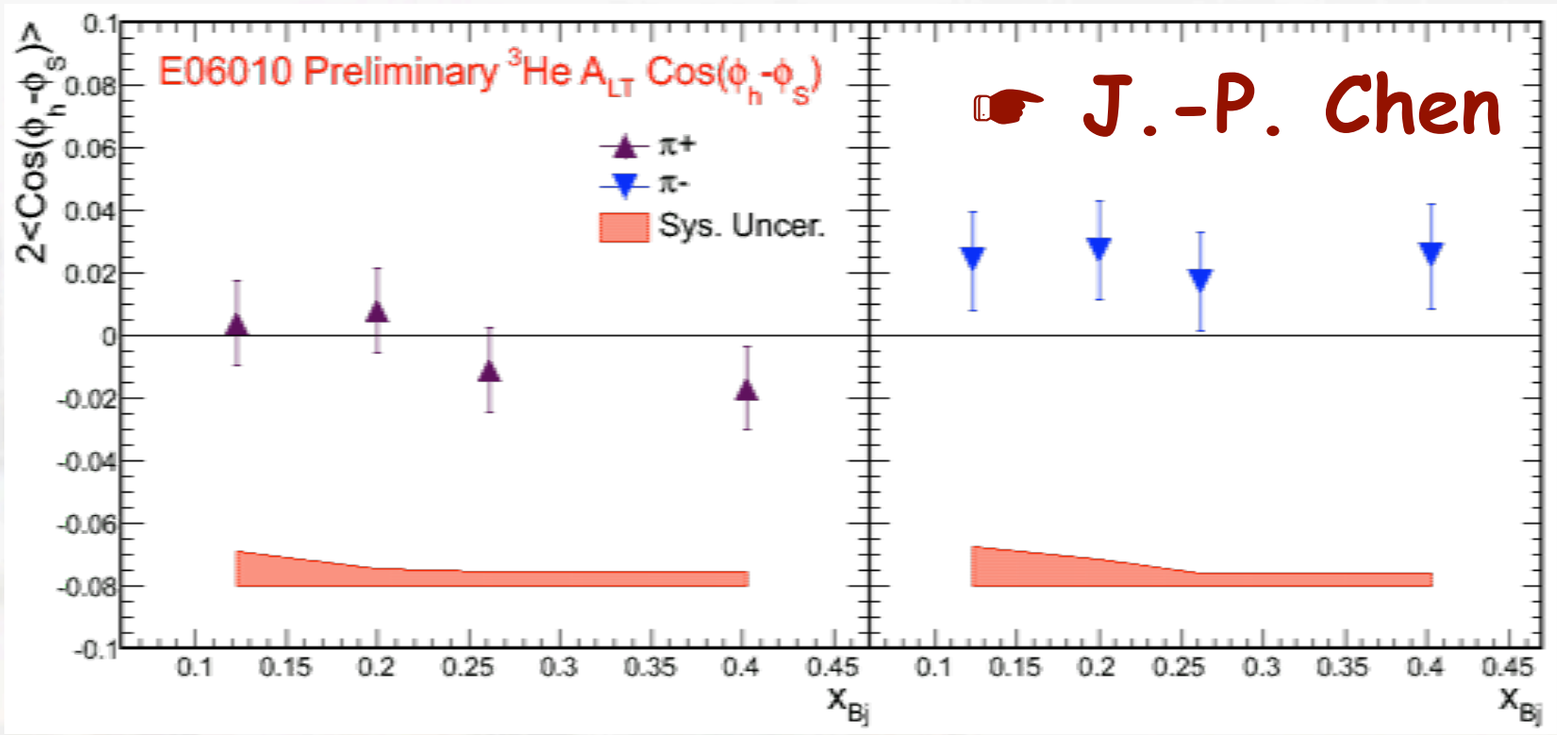
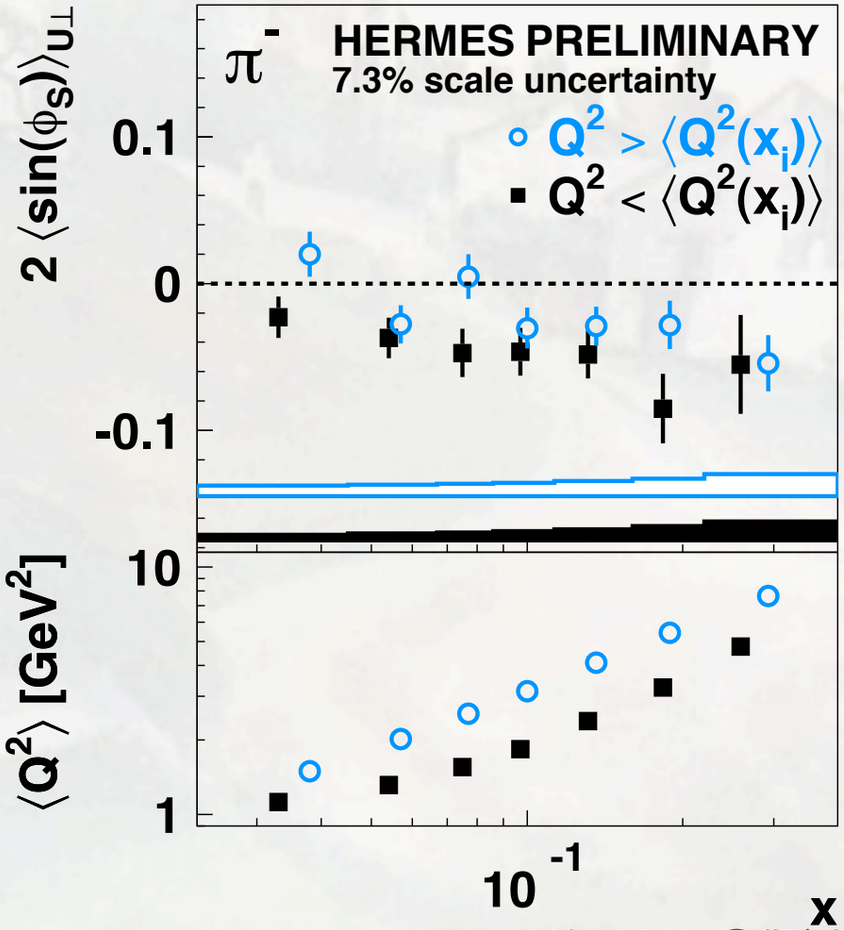
$$\propto \left(x f_T^\perp D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right) - \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z} \right) - \left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z} \right) \right]$$



☛ J.-P. Chen



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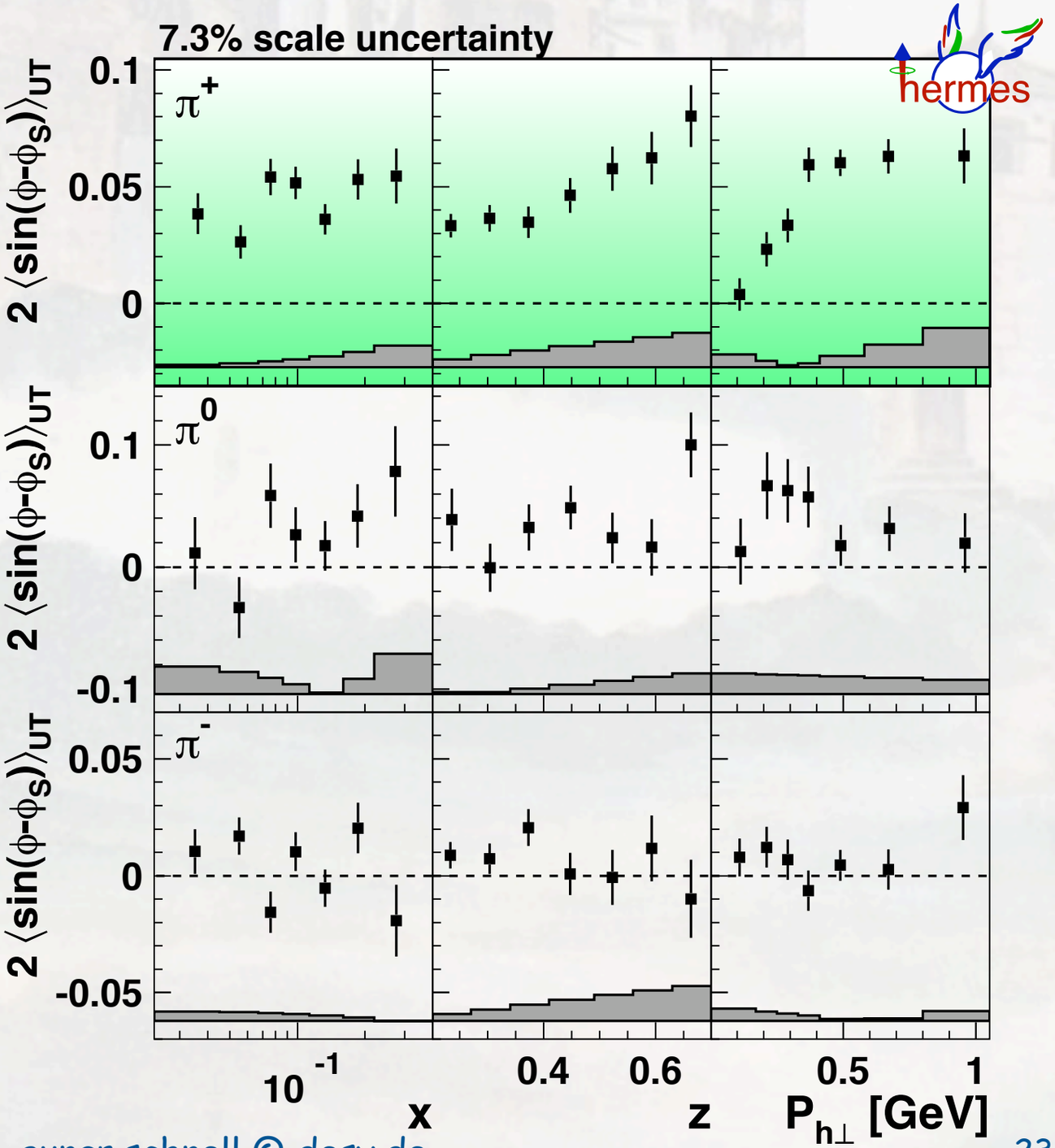
Sivers amplitudes for pions

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



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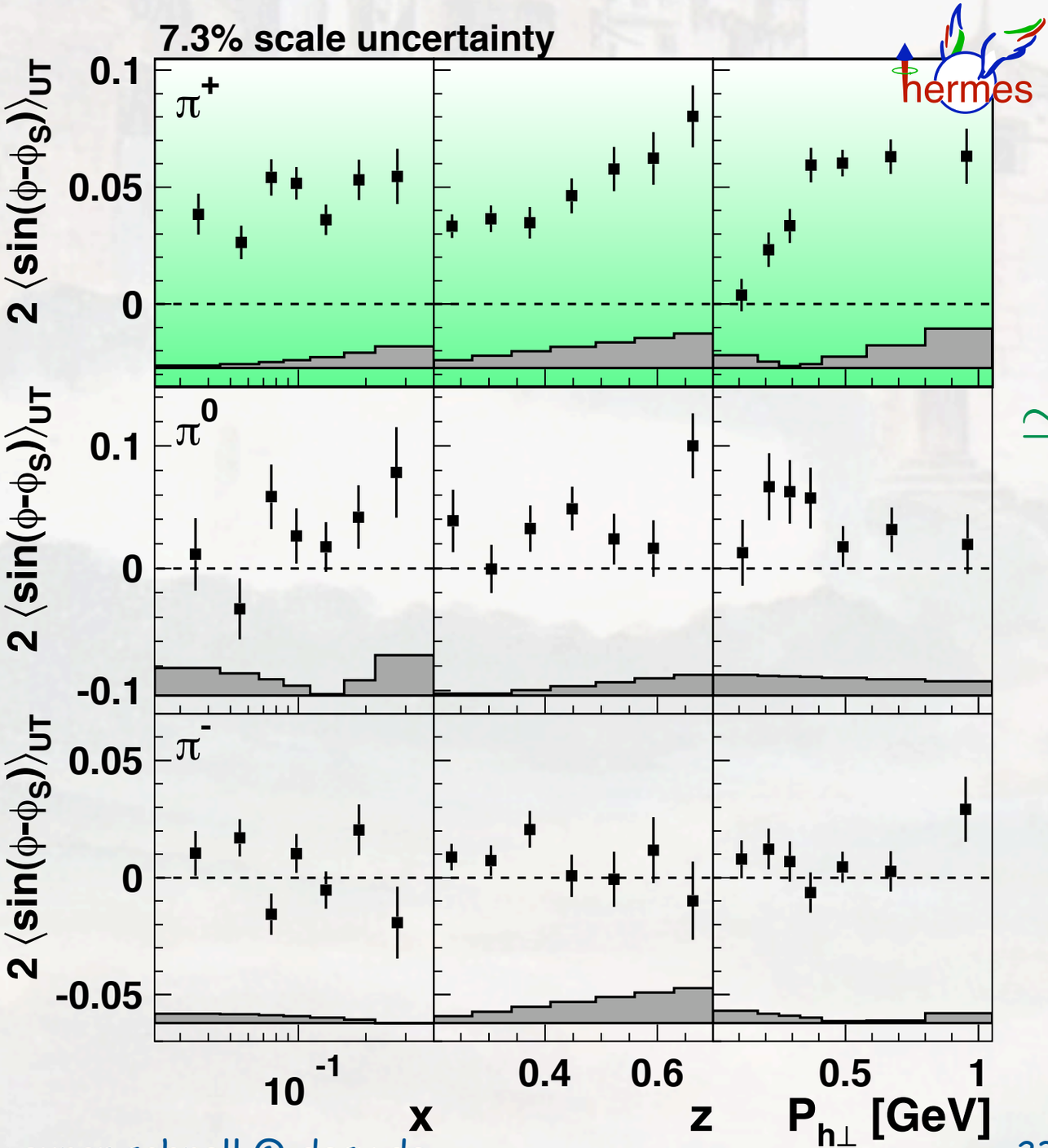

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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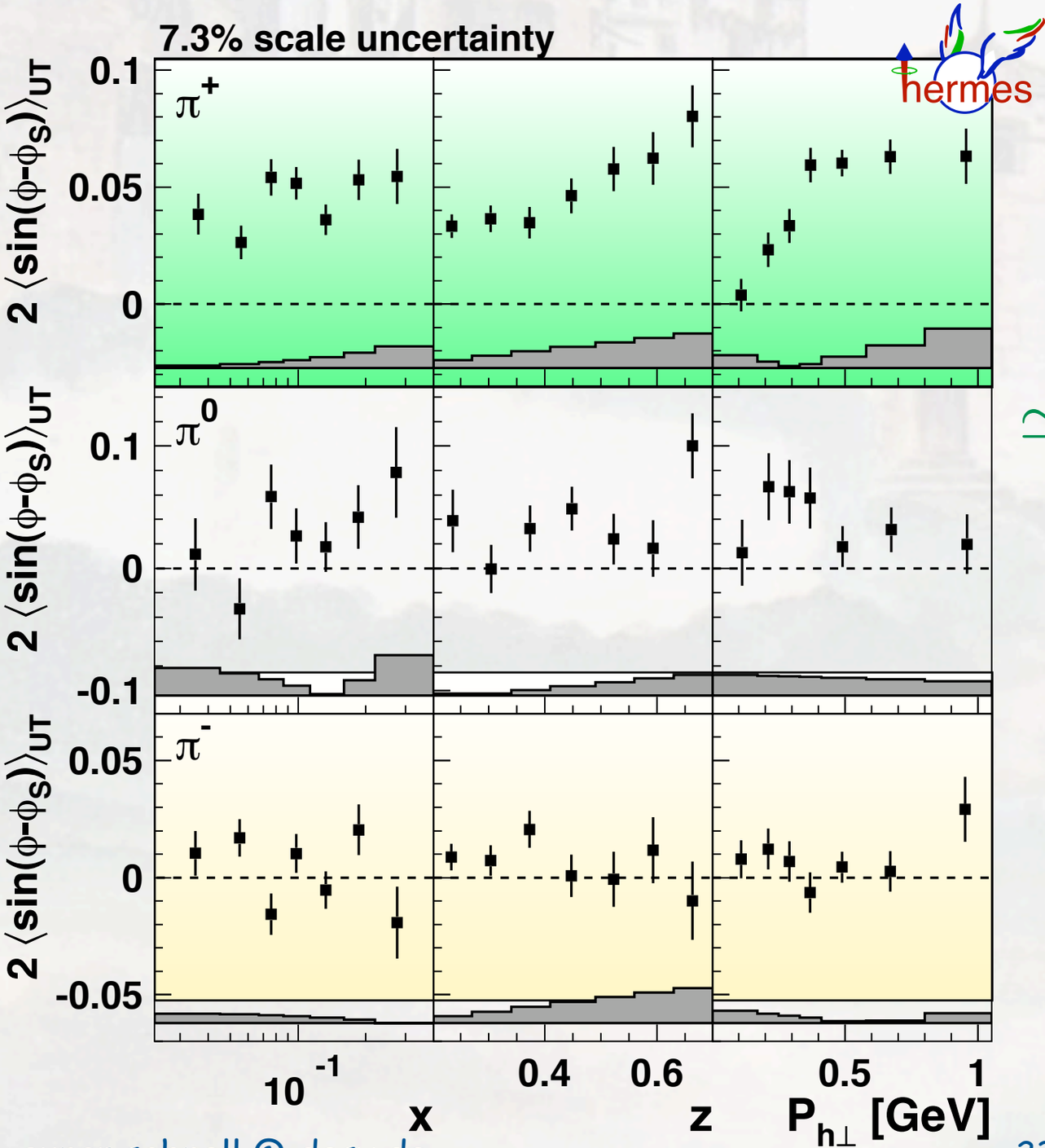

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- ☛ d-quark Sivers DF > 0 (cancelation for π^-)

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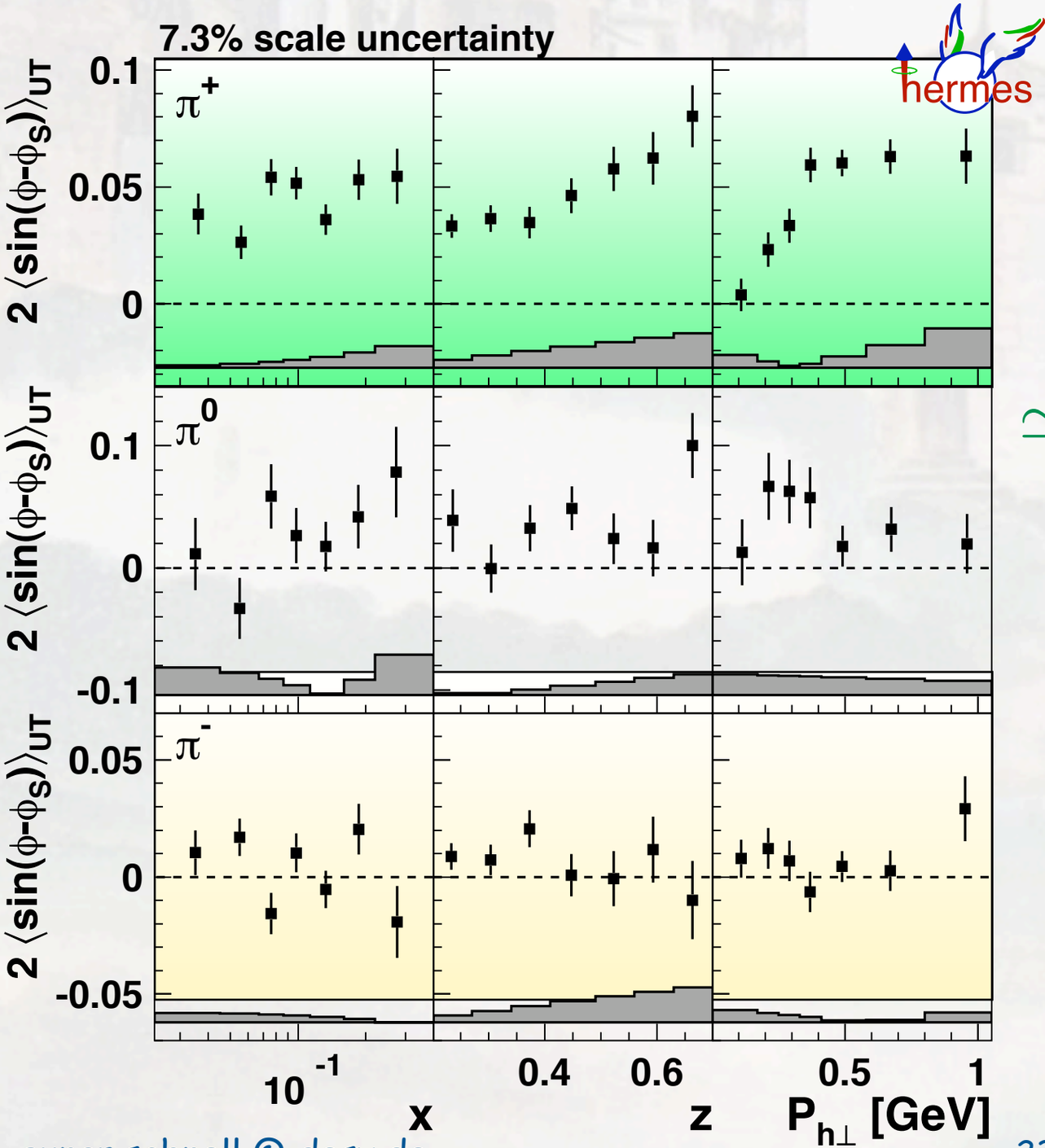

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- L.Pappalardo

Sivers function

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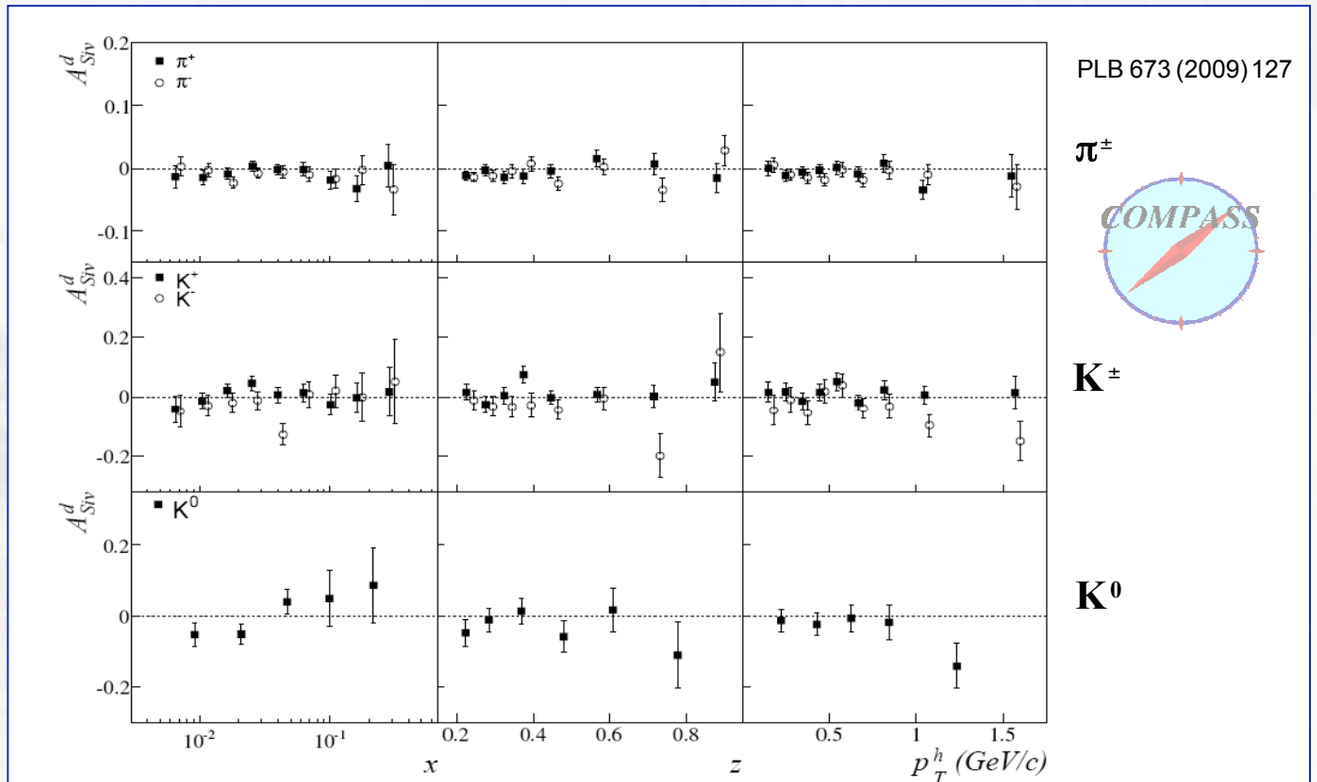
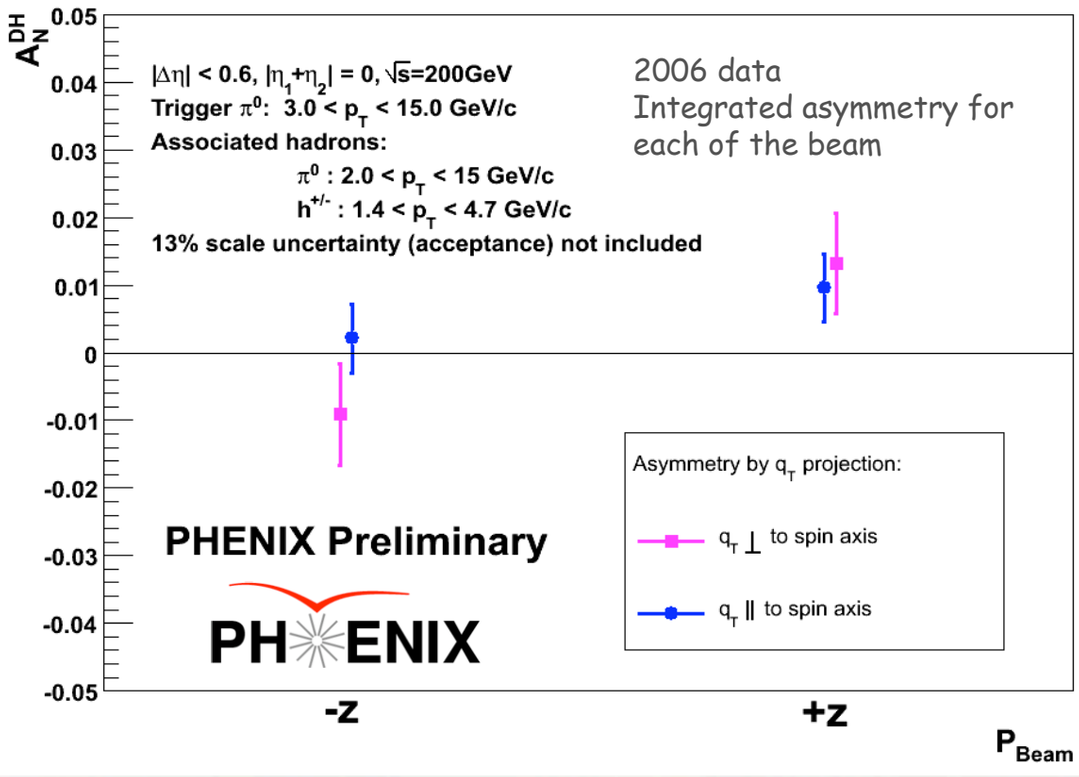
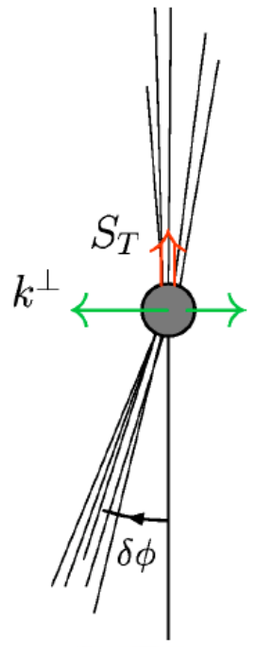
- cancelation for D target supports opposite signs of u and d Sivers
- small gluon Sivers suggested by PHENIX
- new results from JLab using ^{3}He target and from COMPASS for proton target
  - ☛ **J.-P.Chen, H.Wollny**
- check sign change of Sivers function in upcoming DY experiments







pp collisions

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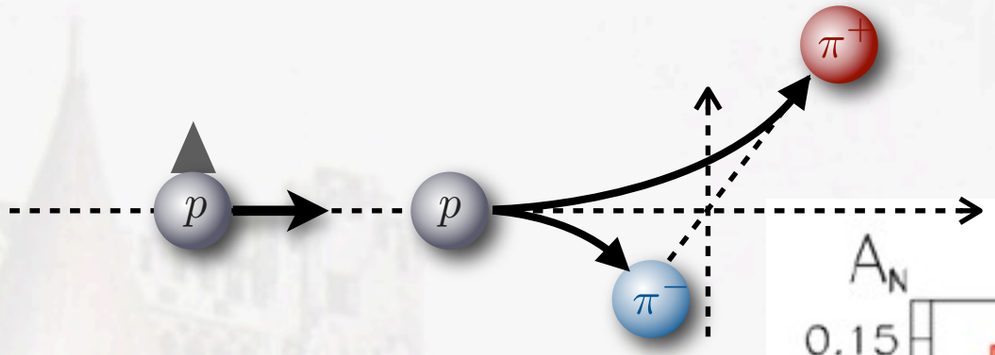
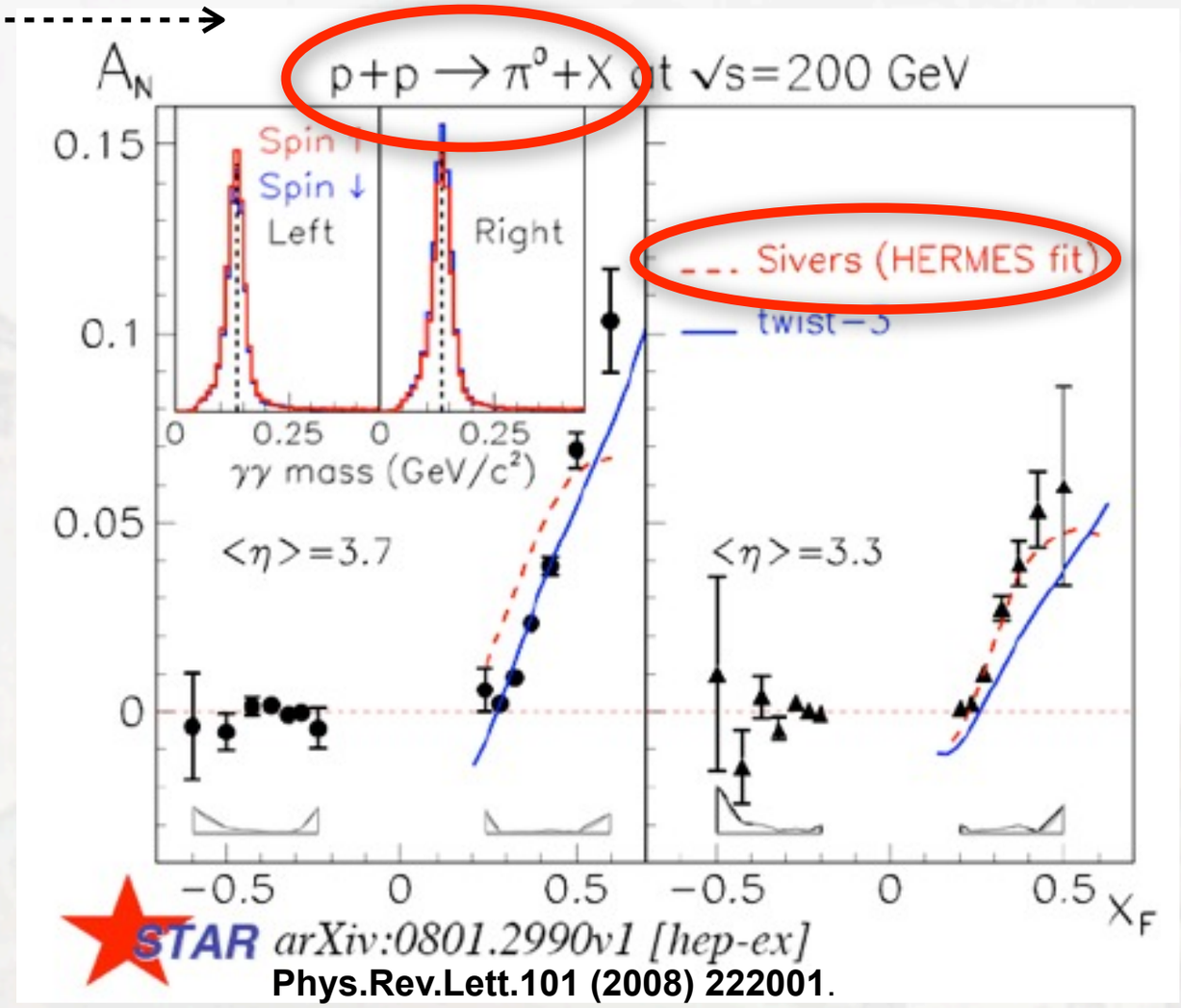


- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect



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

pp collisions

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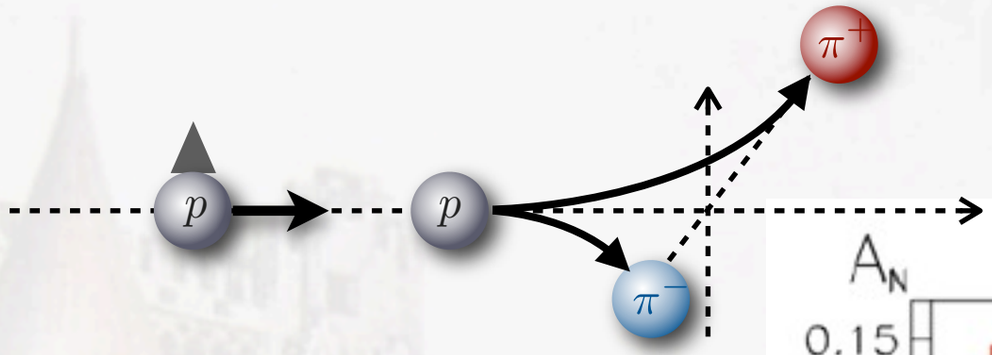

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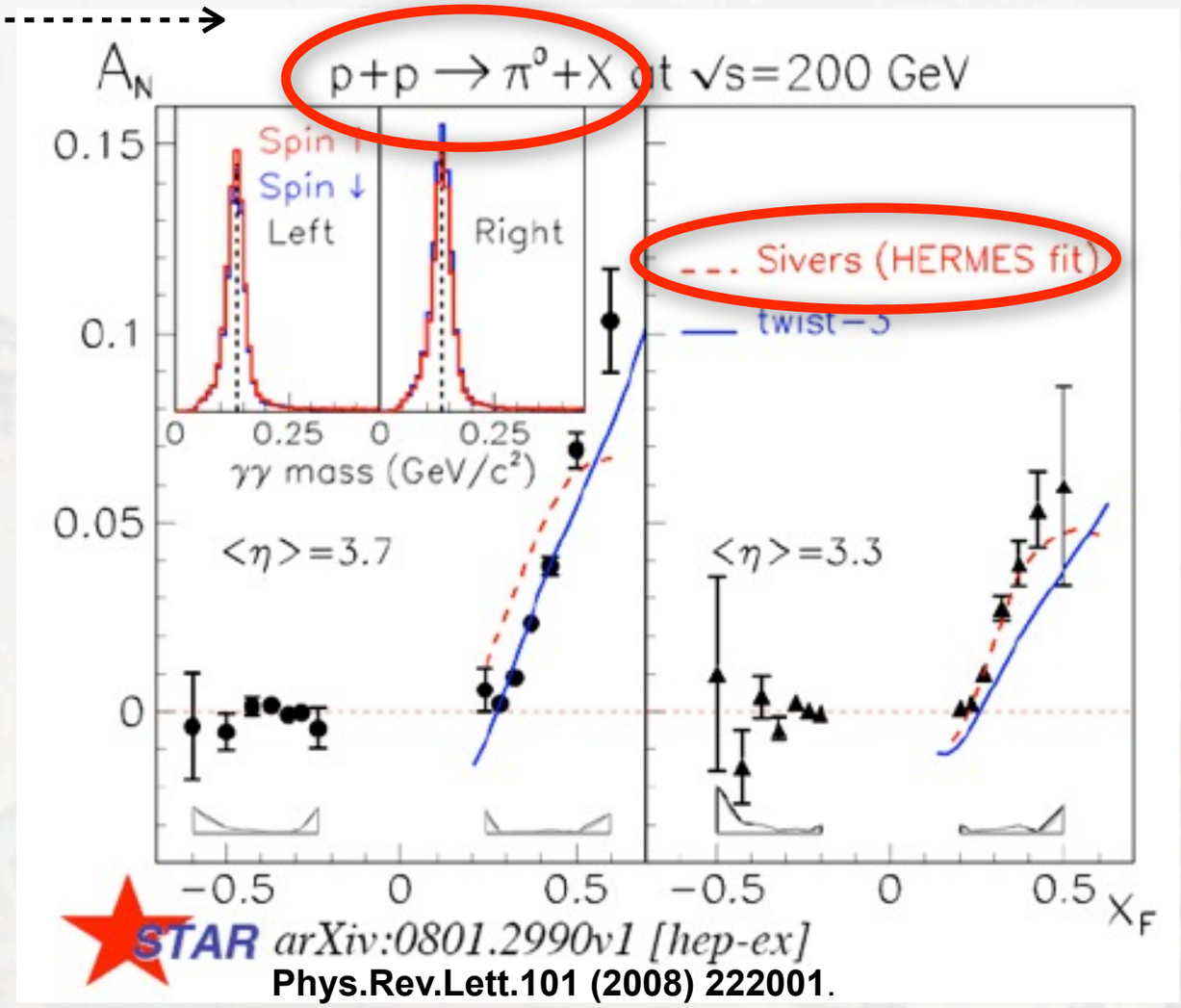
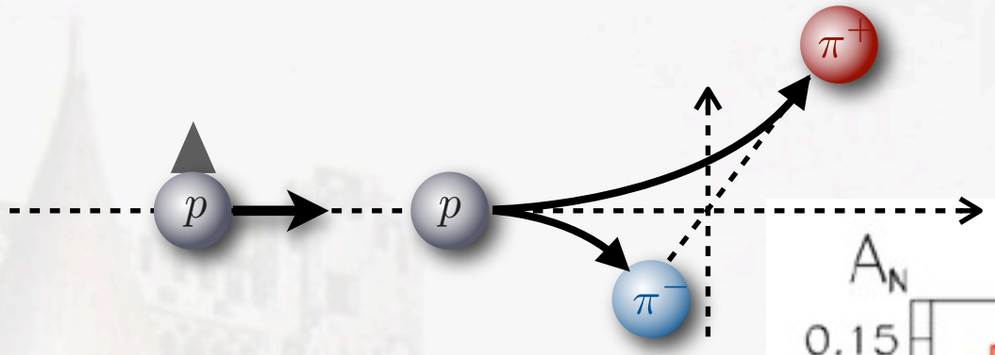
- only sizable in forward direction

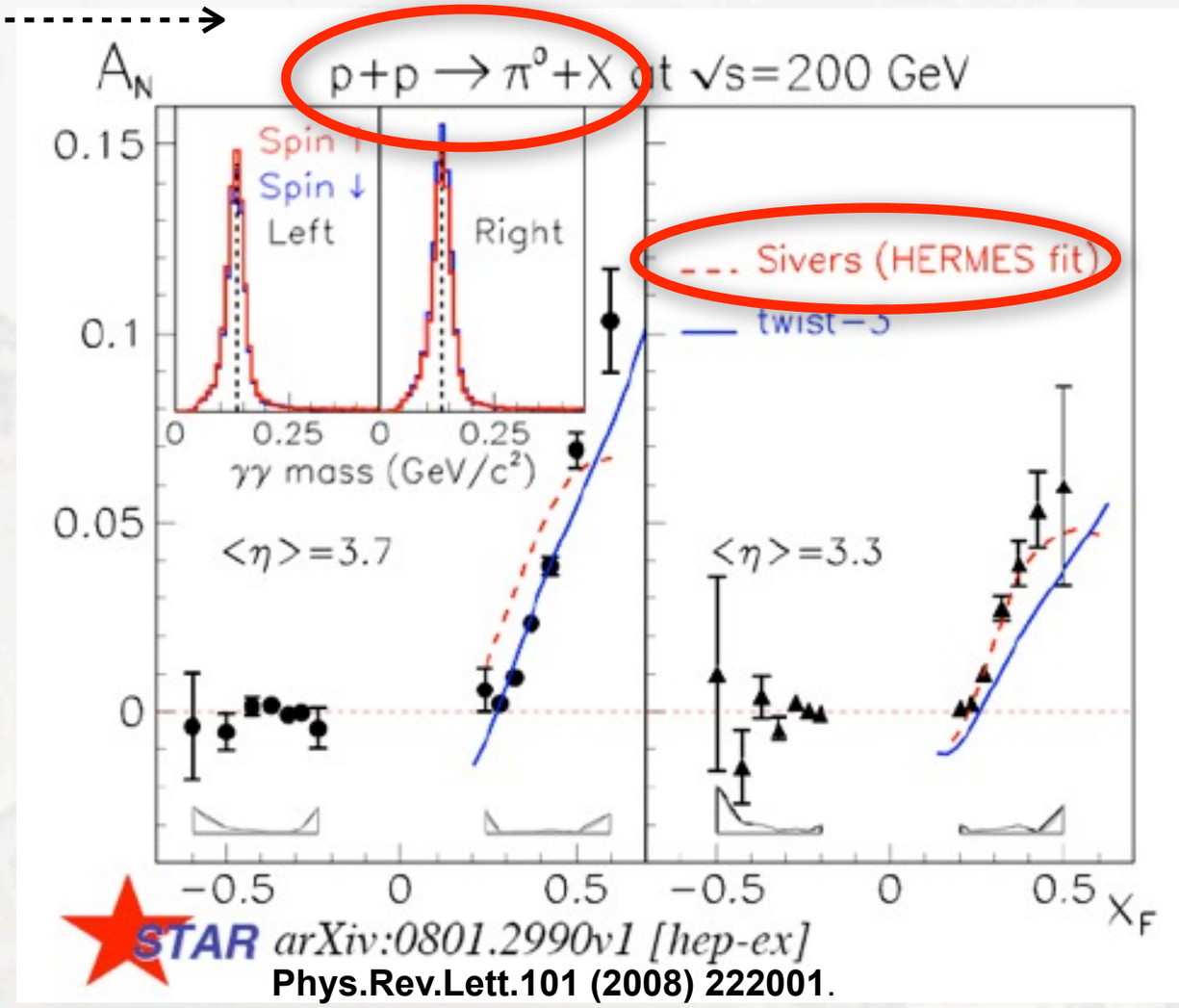


pp collisions

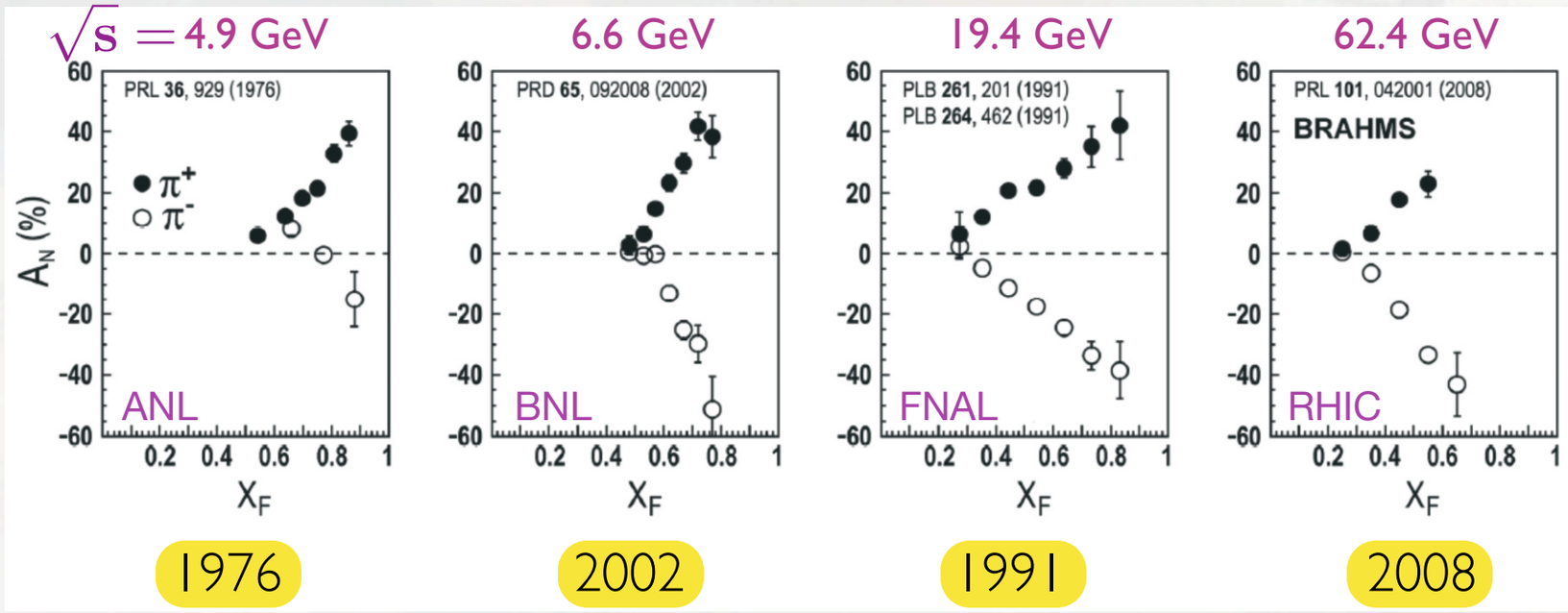
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



- Sivers 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:



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



	U	L	T
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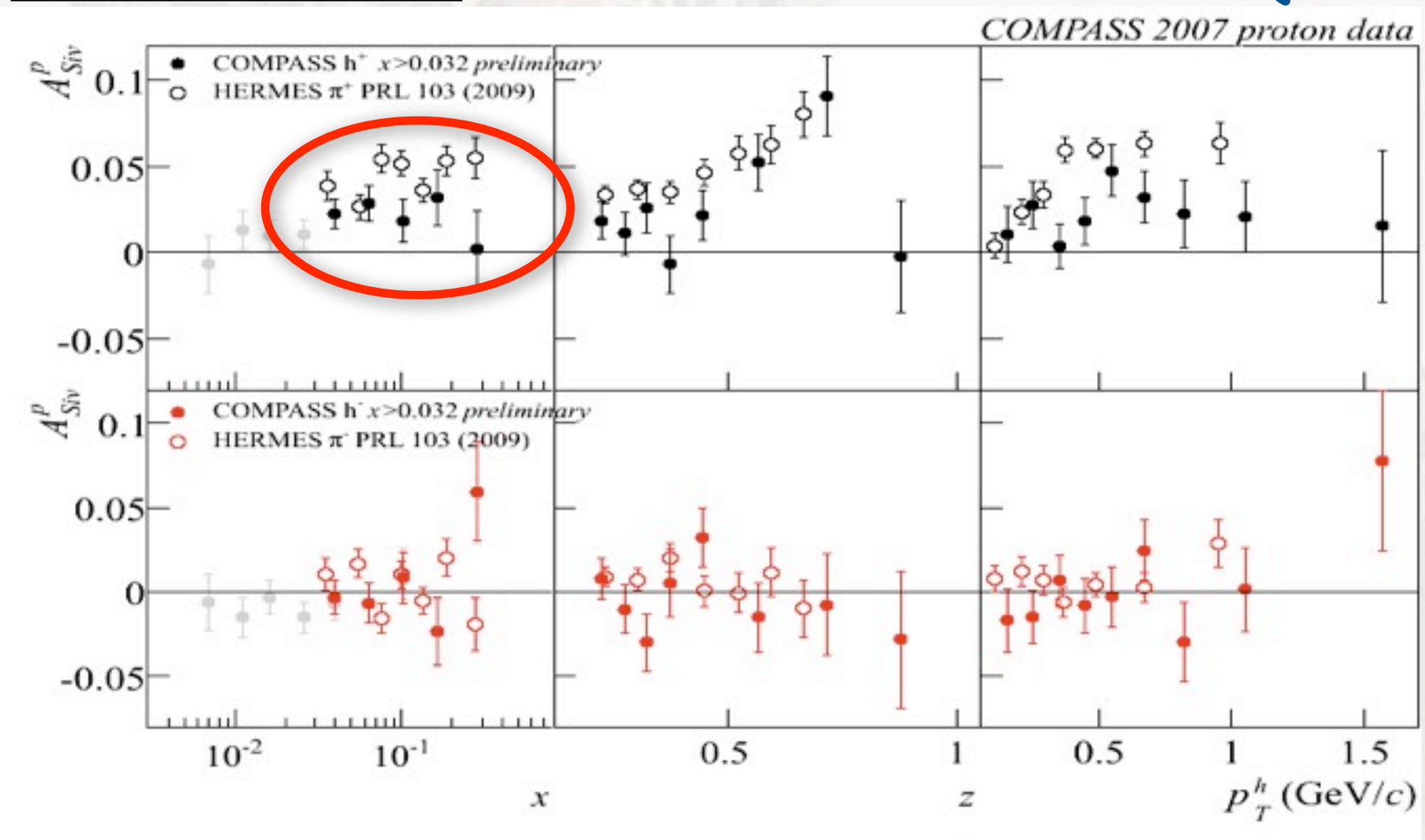
Sivers function (some surprises)



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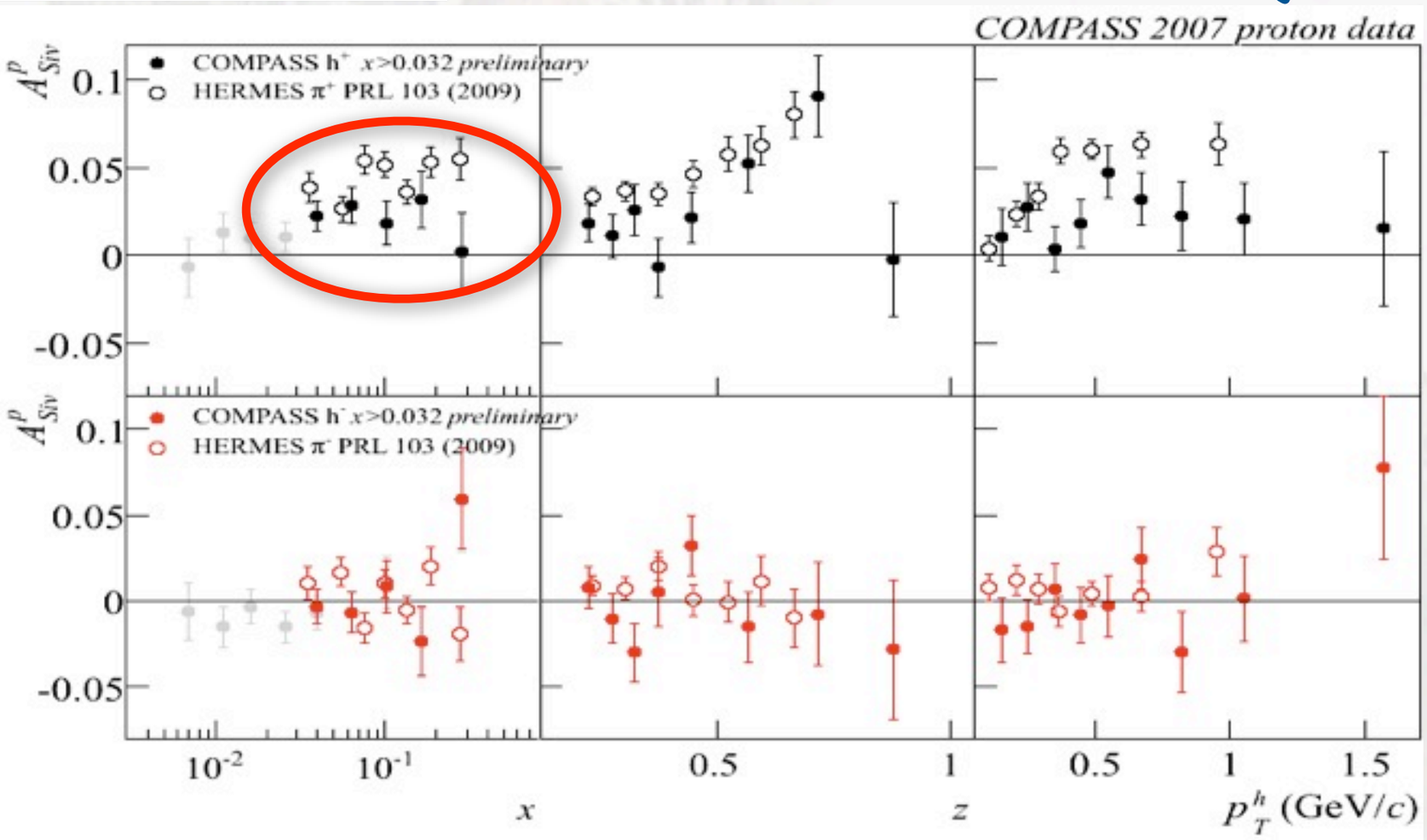

☛ H. Wollny

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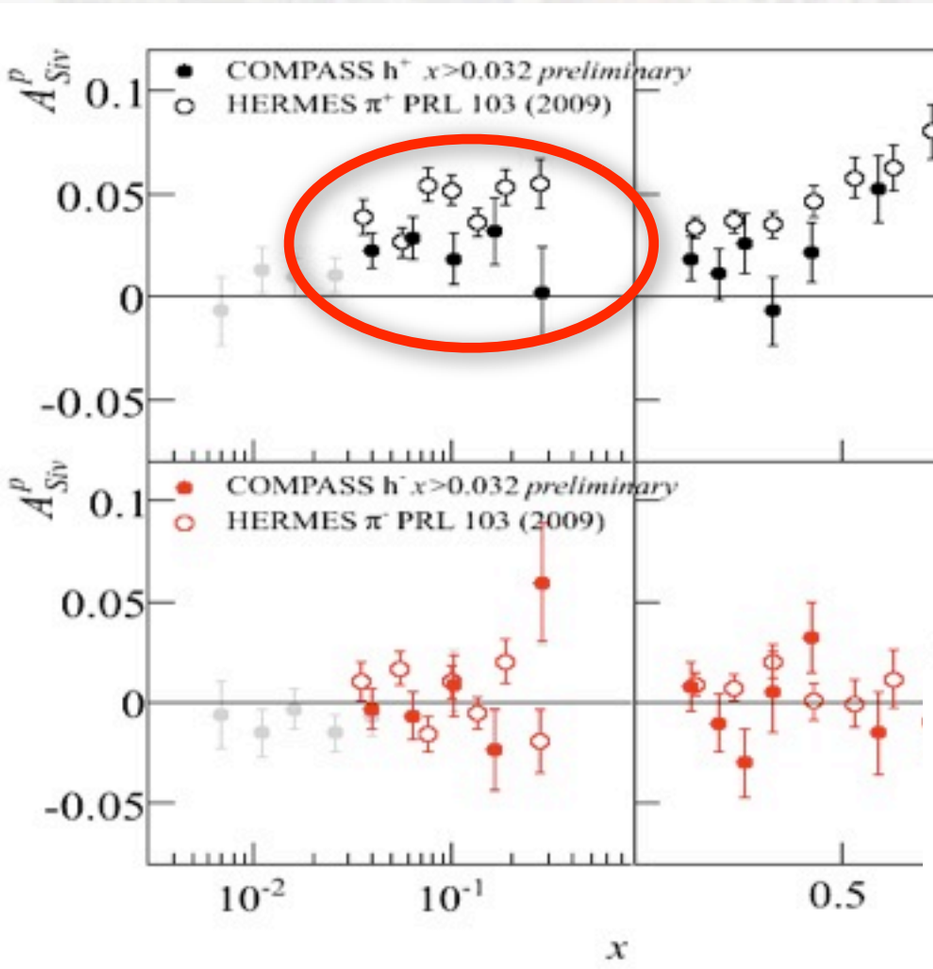

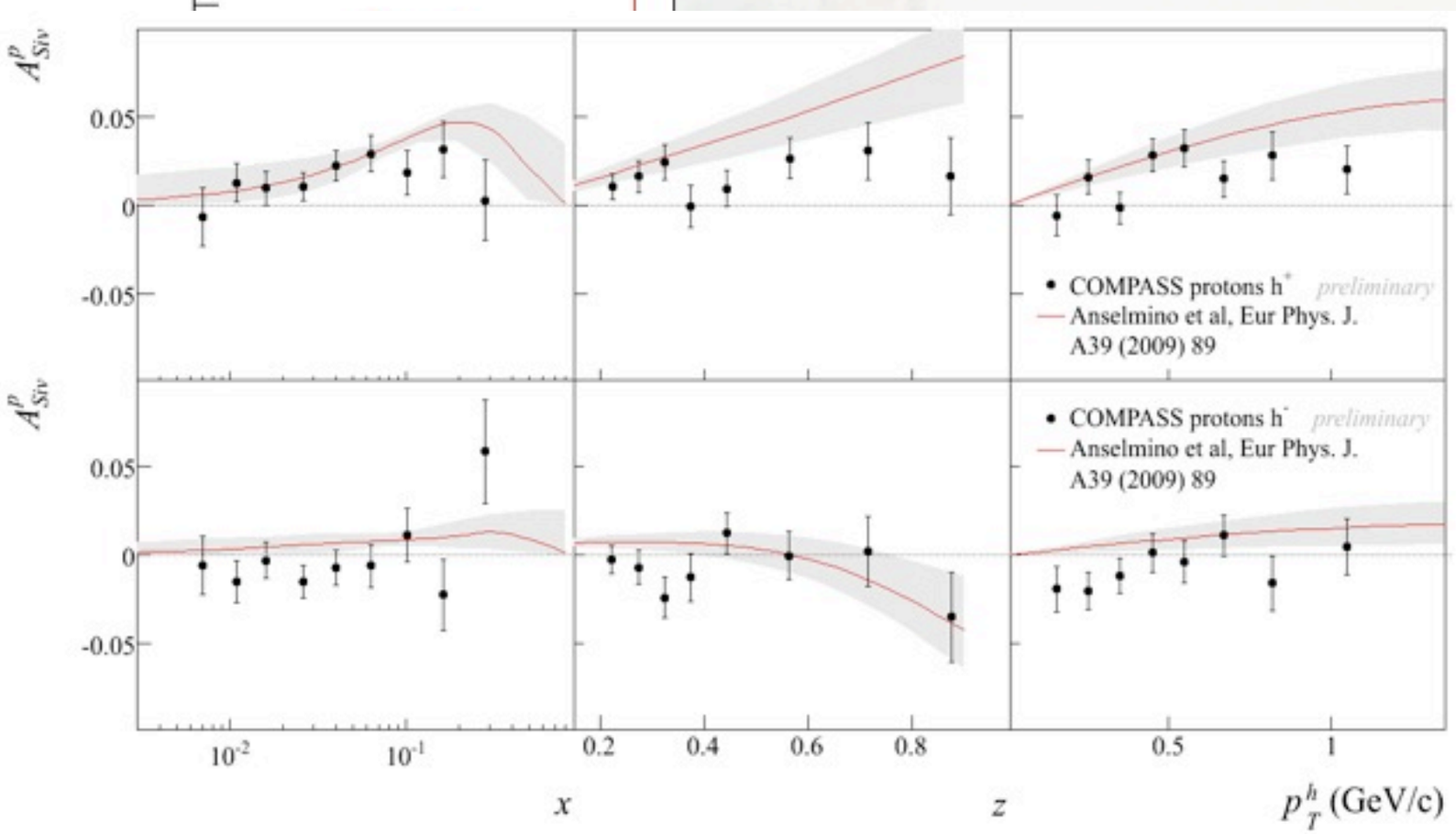

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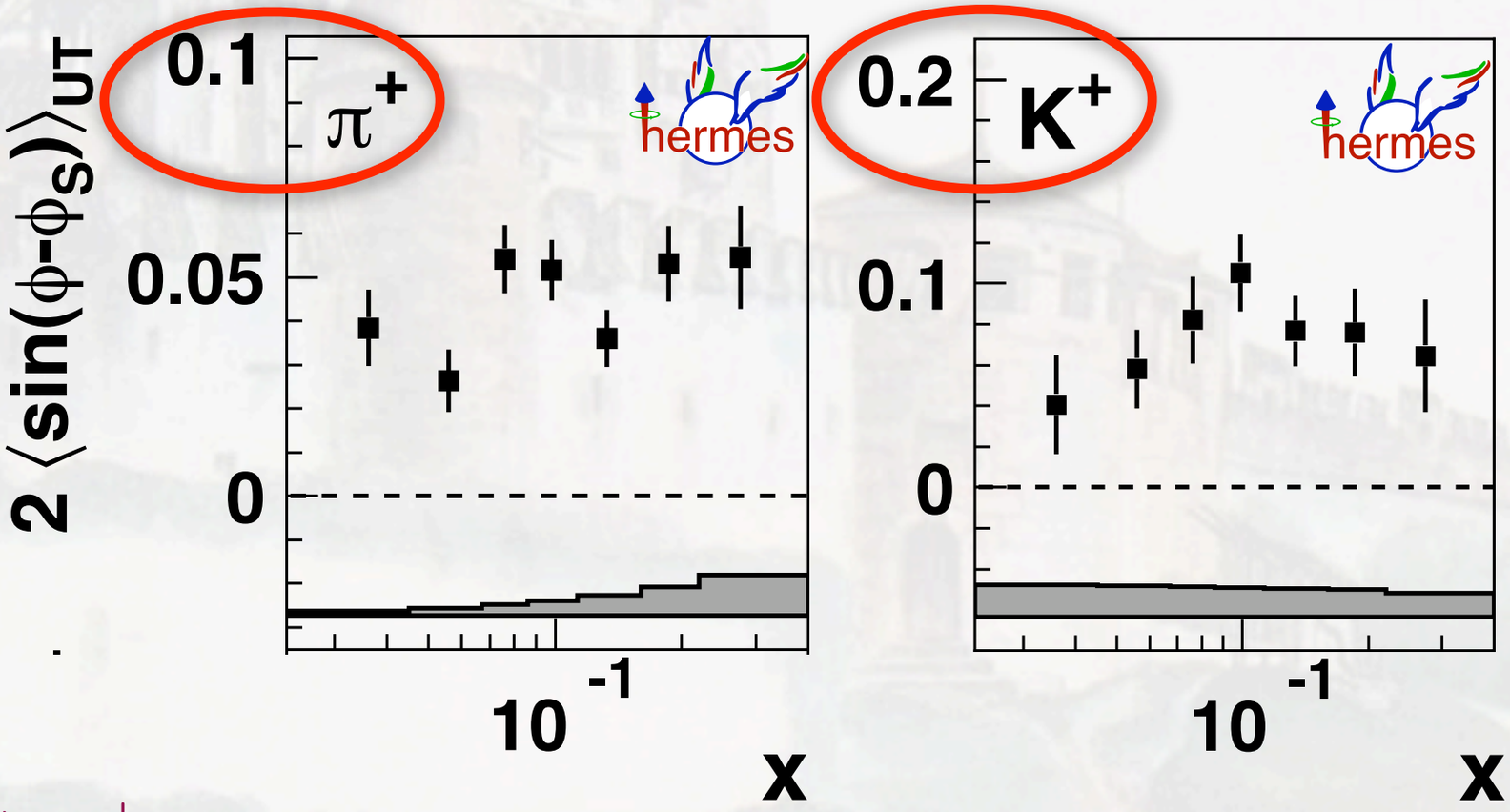

π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{\mathbf{f_{1T}^{\perp,u}(x,p_T^2)} \otimes_{\mathcal{W}} \mathbf{D_1^{u\to\pi^+/K^+}(z,k_T^2)}}{\mathbf{f_1^u(x,p_T^2)} \otimes \mathbf{D_1^{u\to\pi^+/K^+}(z,k_T^2)})}$

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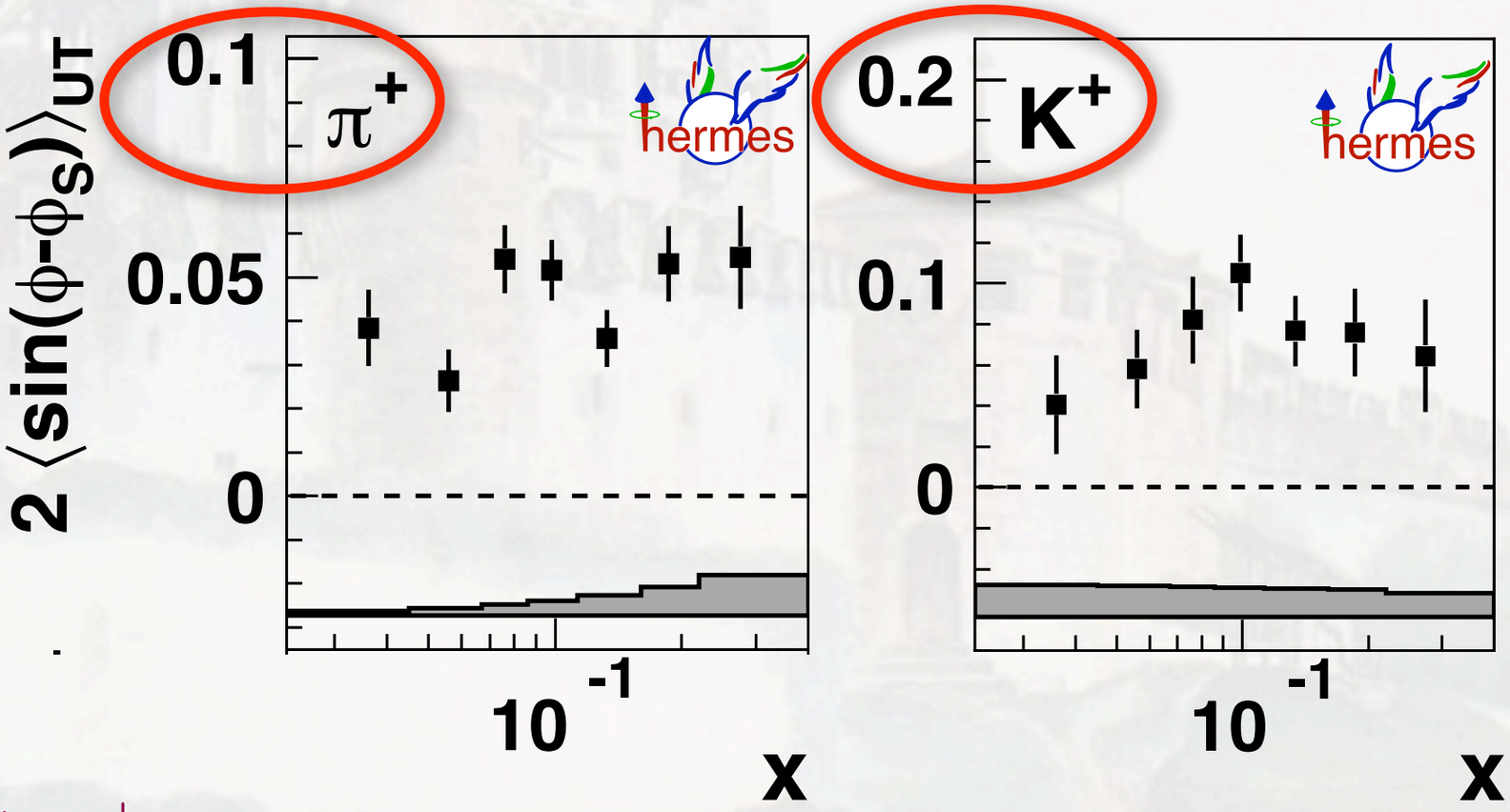

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks?**

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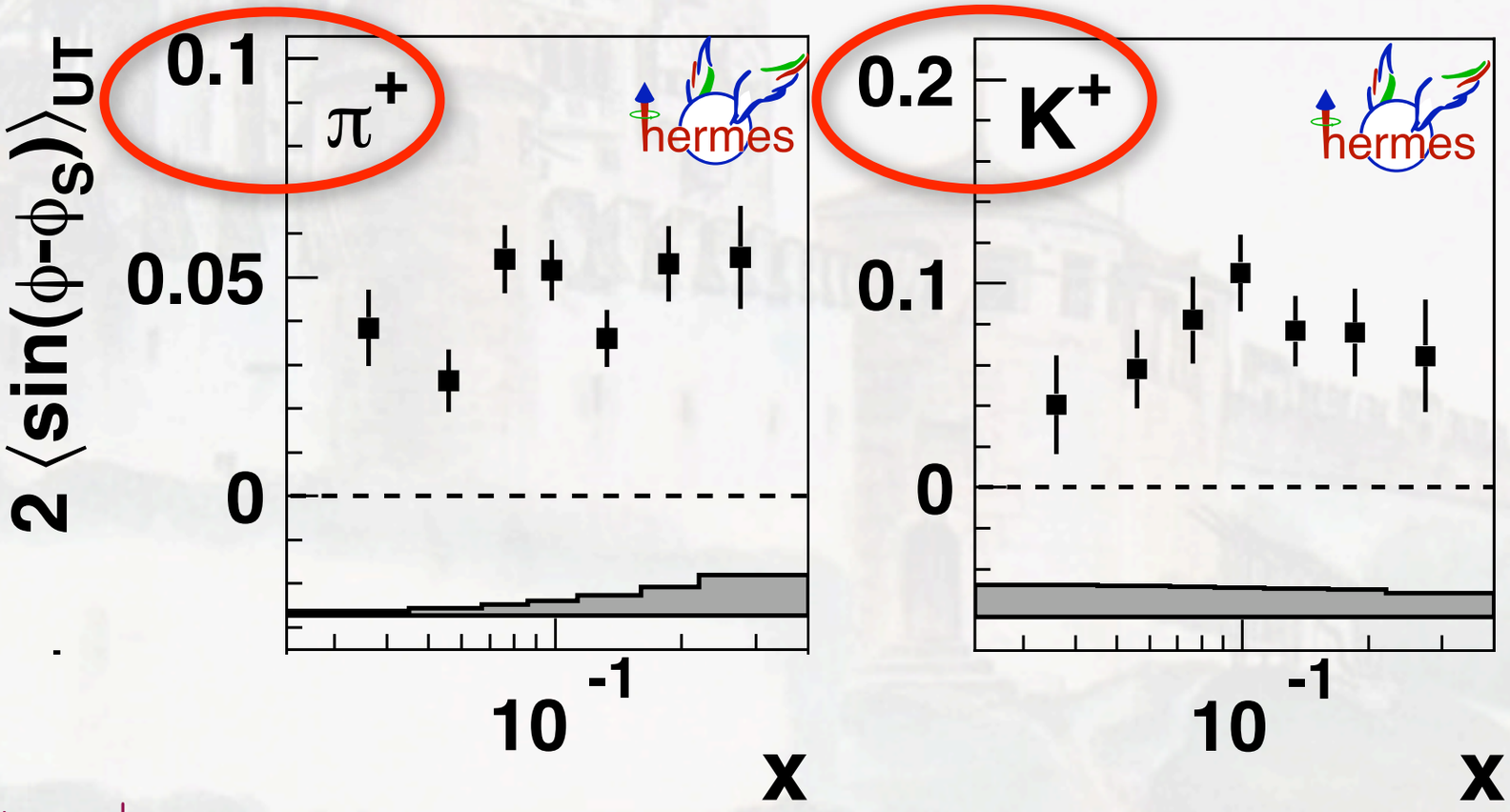

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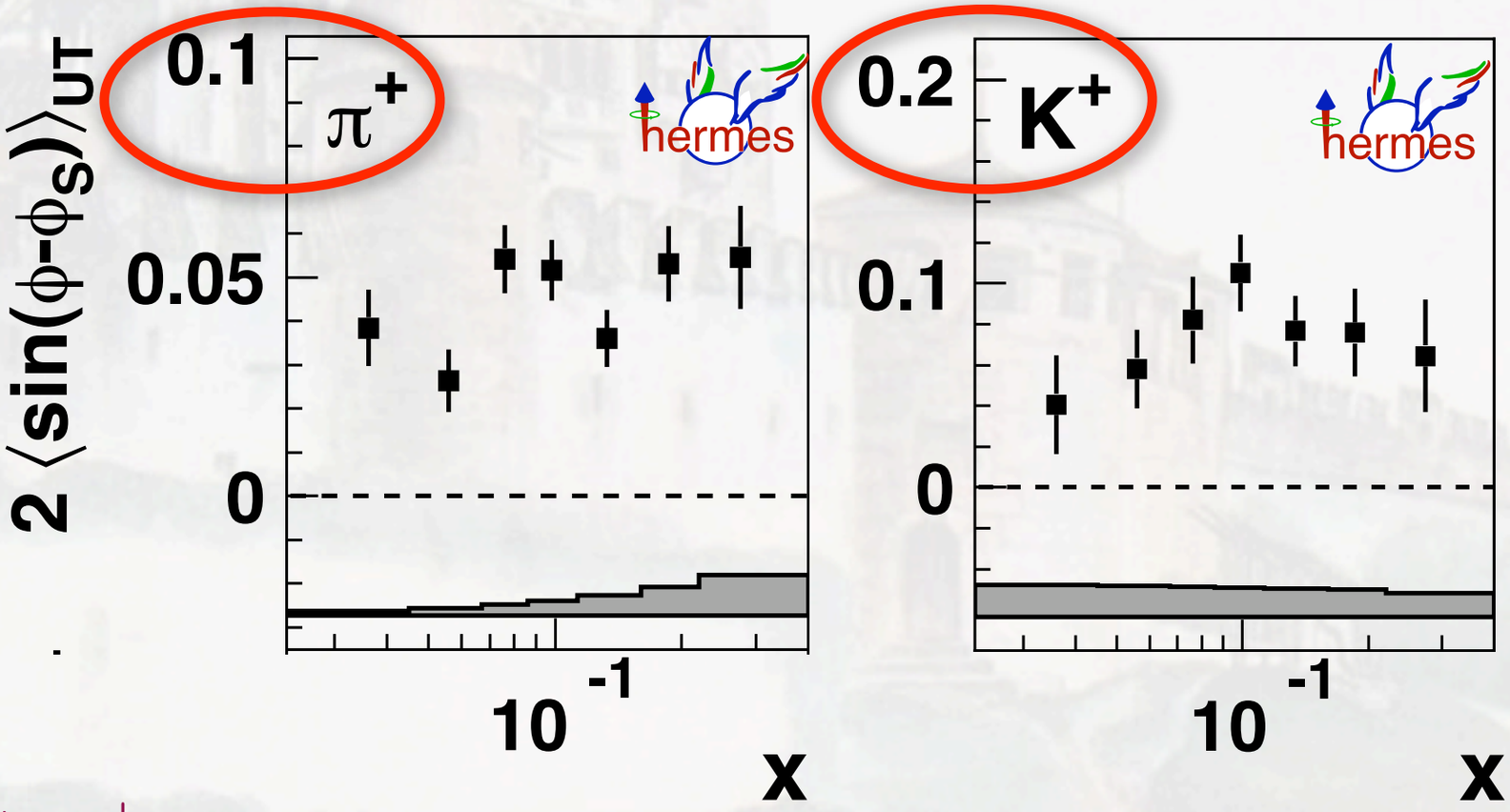

☛ H. Wollny, L. Pappalardo

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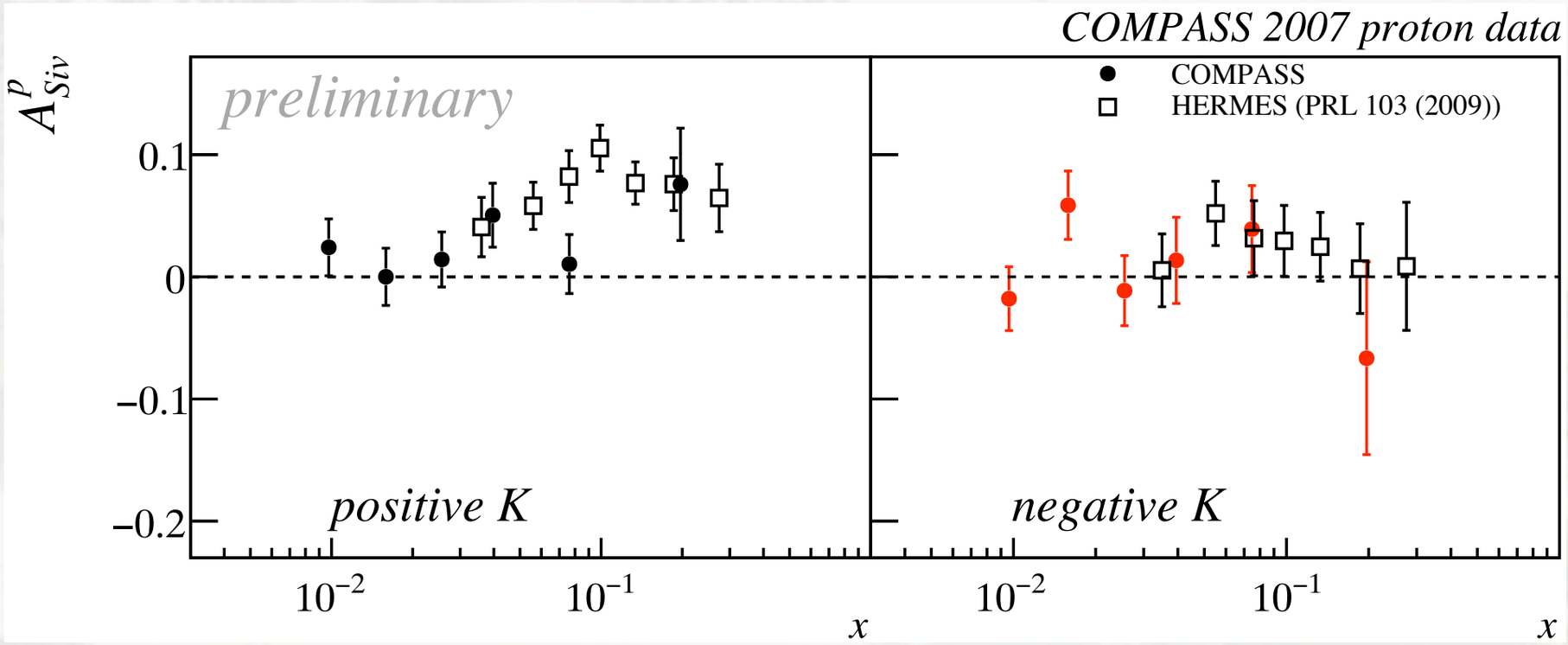

☛ H. Wollny, L. Pappalardo

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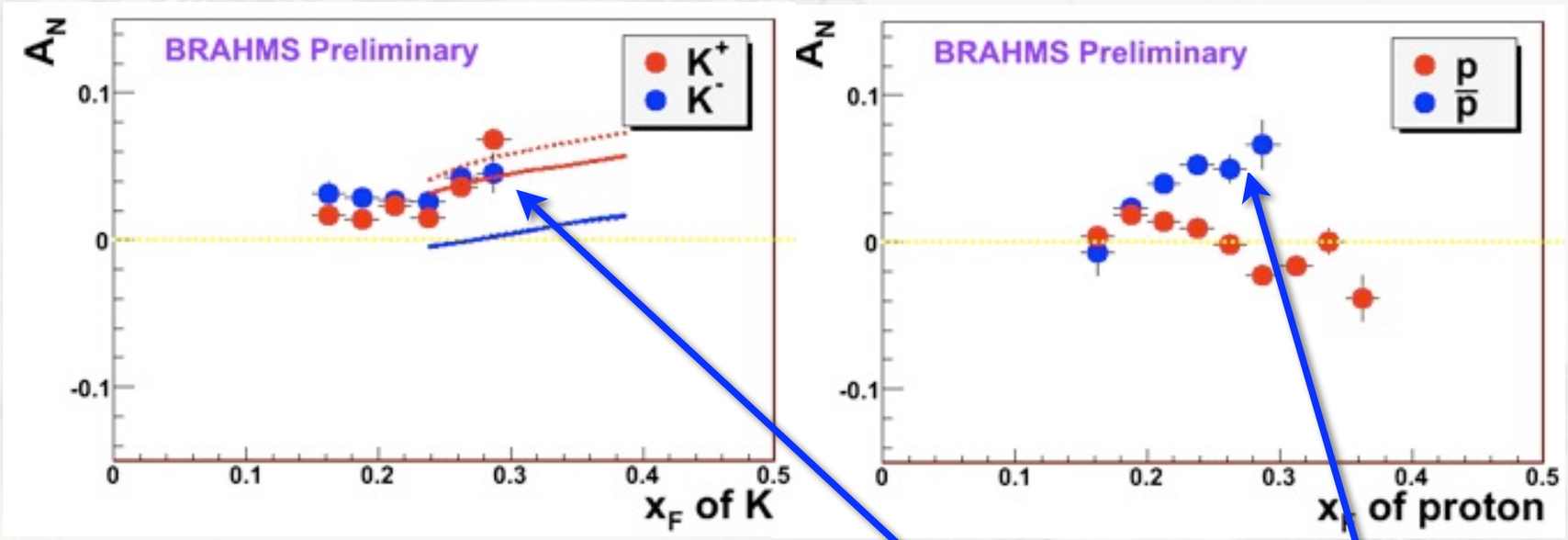

large K^- and anti-proton asymmetries

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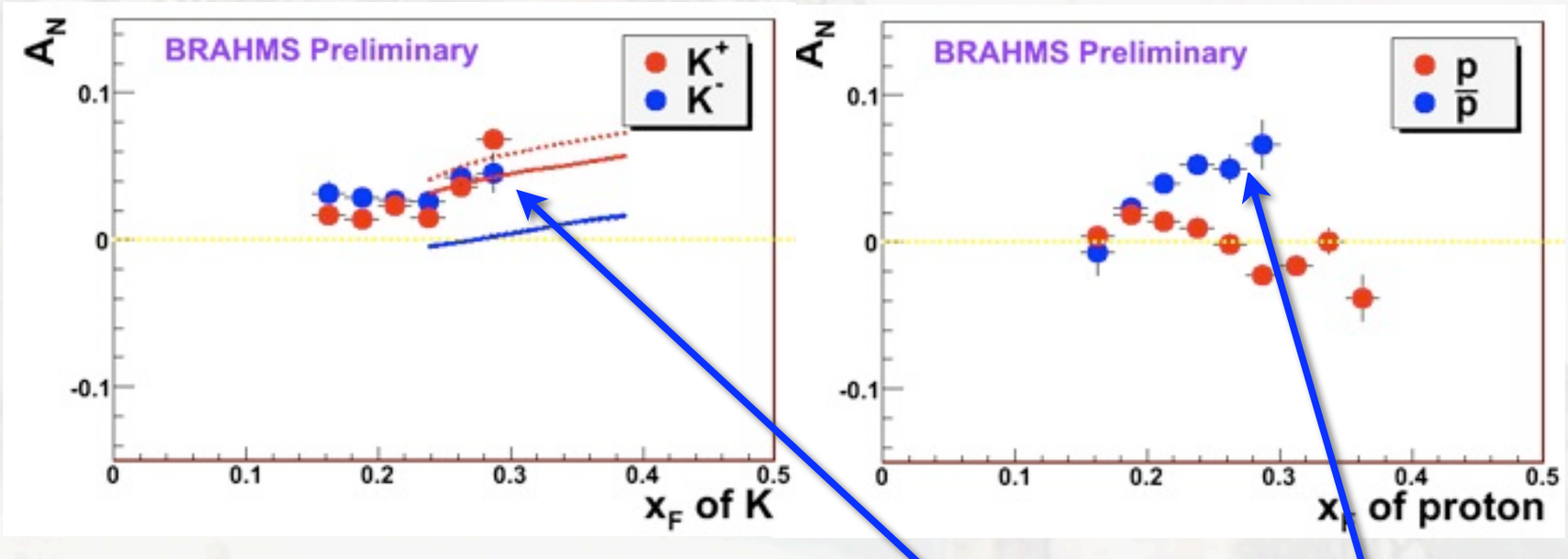

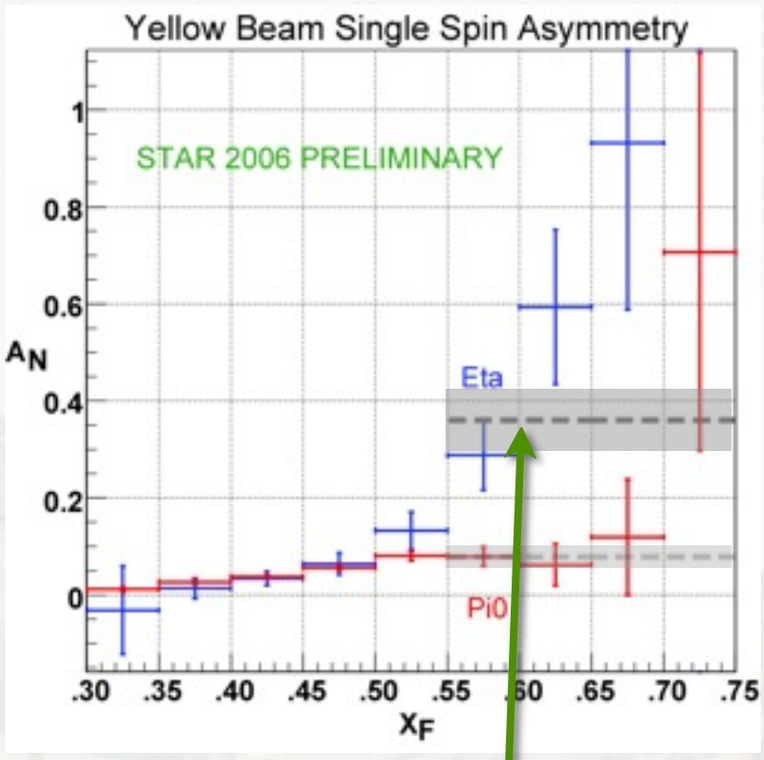

large K^- and anti-proton asymmetries

large eta asymmetries

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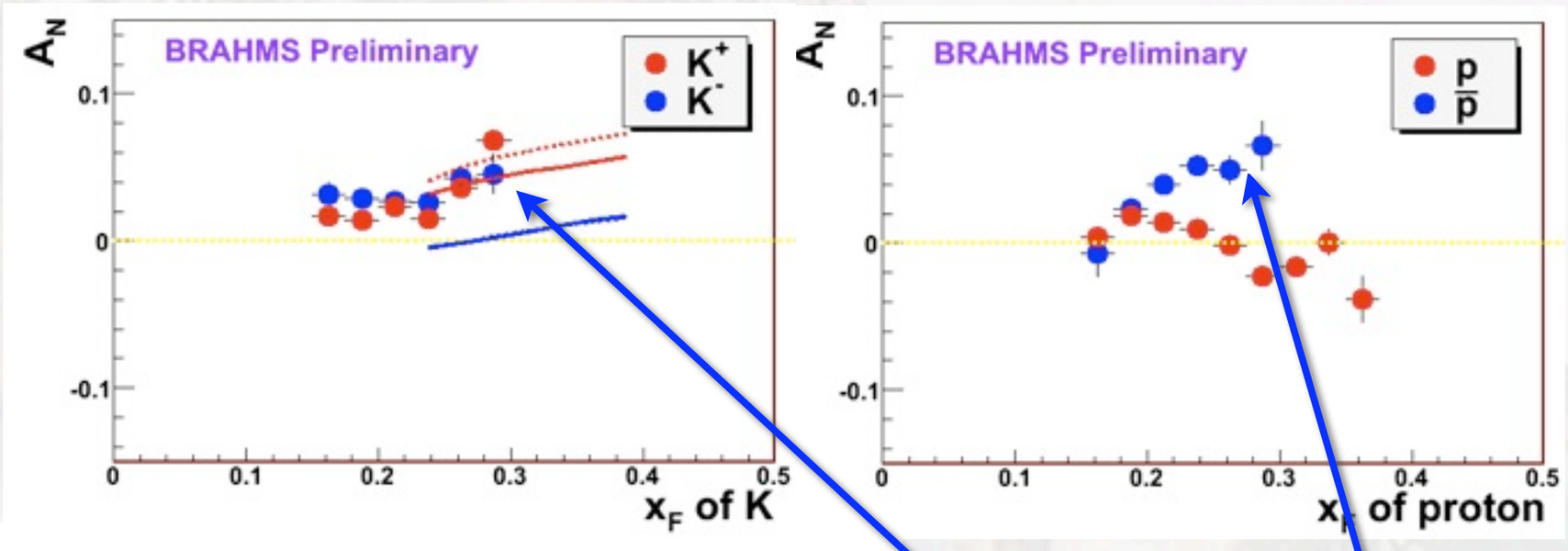
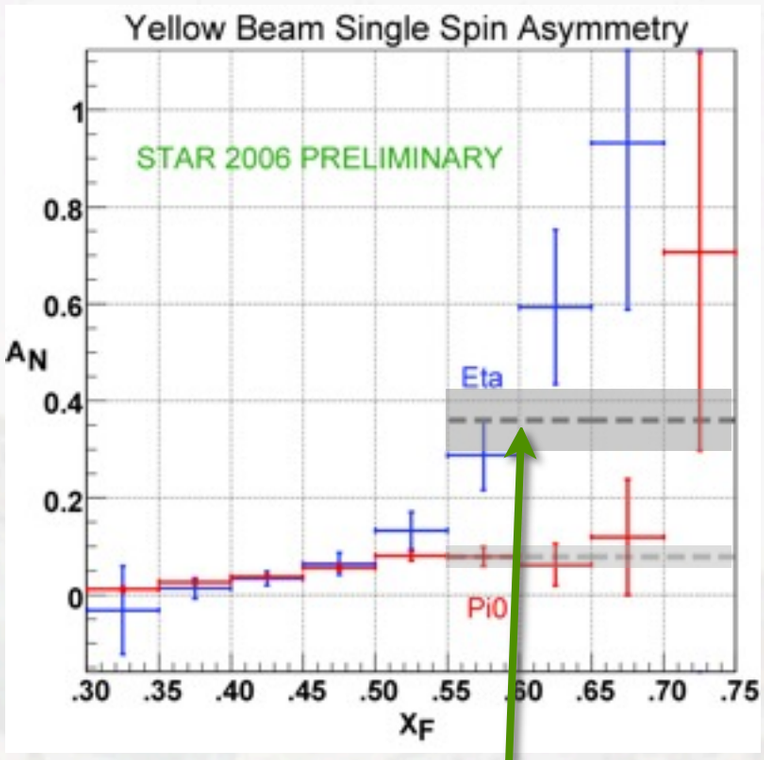
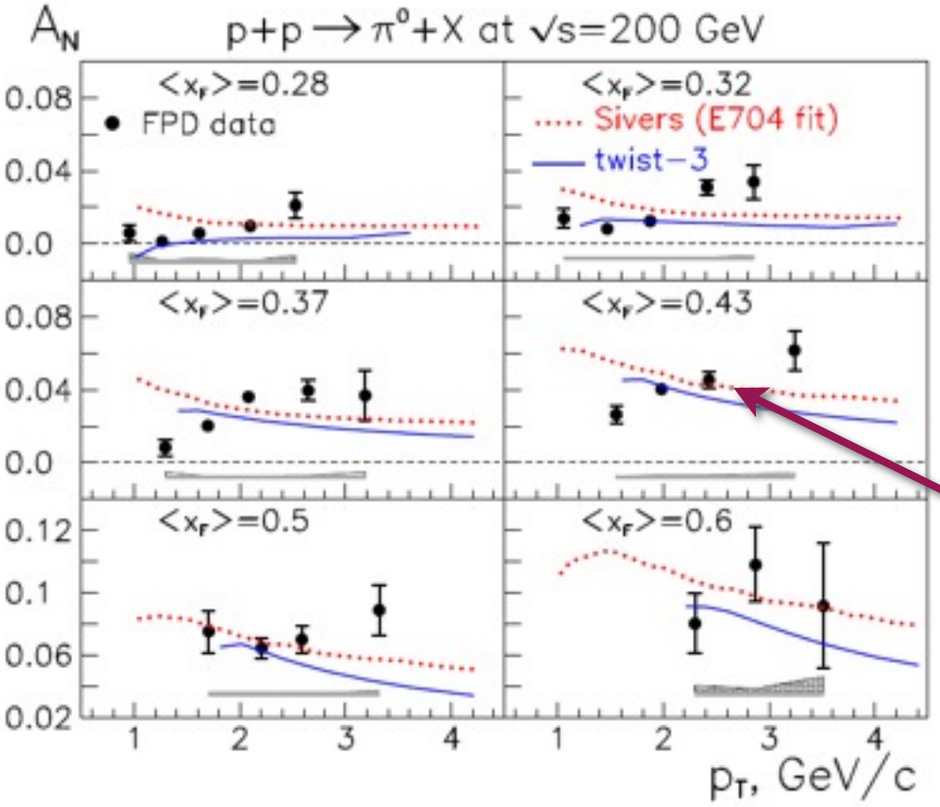
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

(even more surprises)





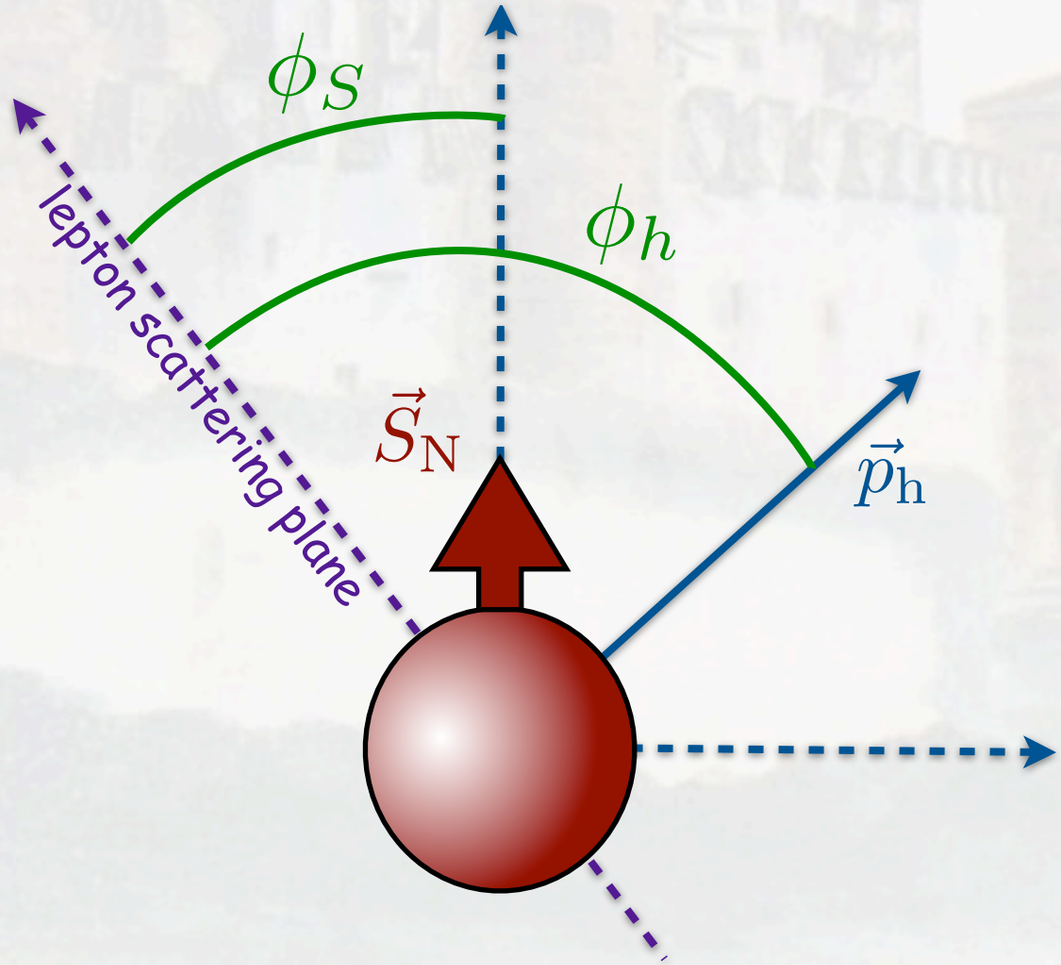


large K^- and anti-proton asymmetries at fixed x_F don't follow expected (perturbative) behavior

large eta asymmetries

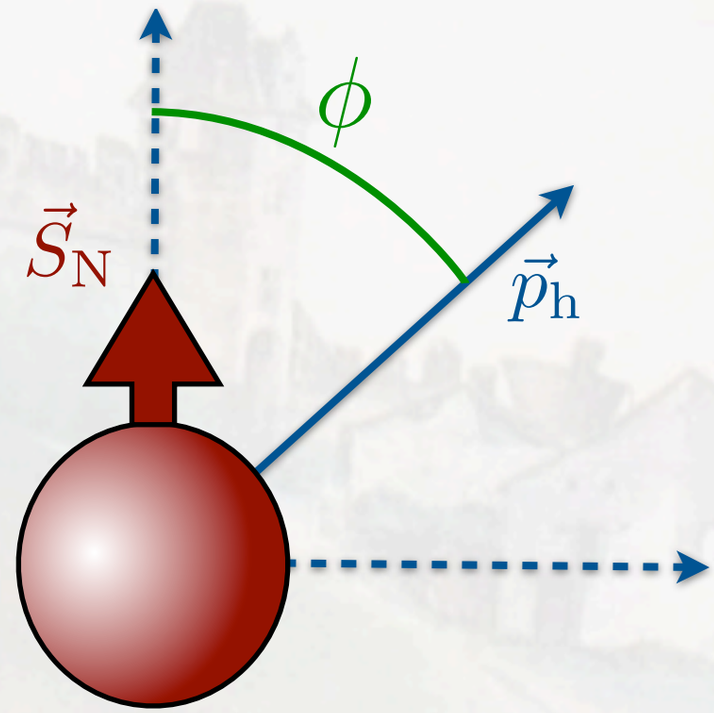
Inclusive hadron electro-production

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



virtual photon going into the page

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



lepton beam going into the page

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

➠ "Sivers angle"

Inclusive hadron electro-production

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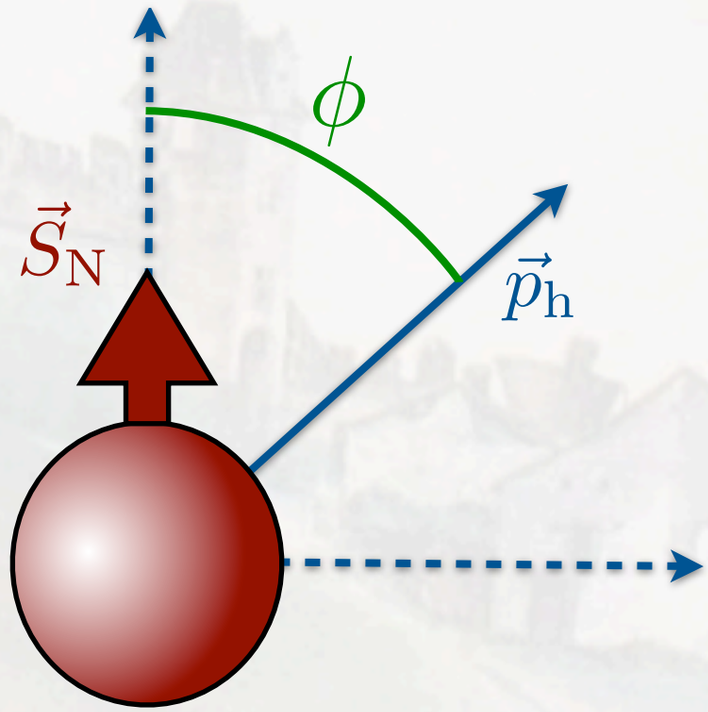

Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

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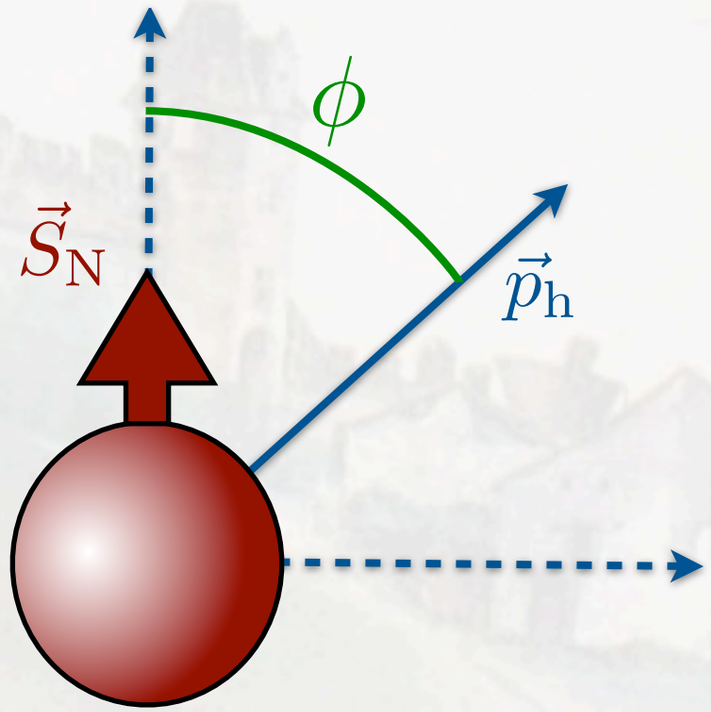

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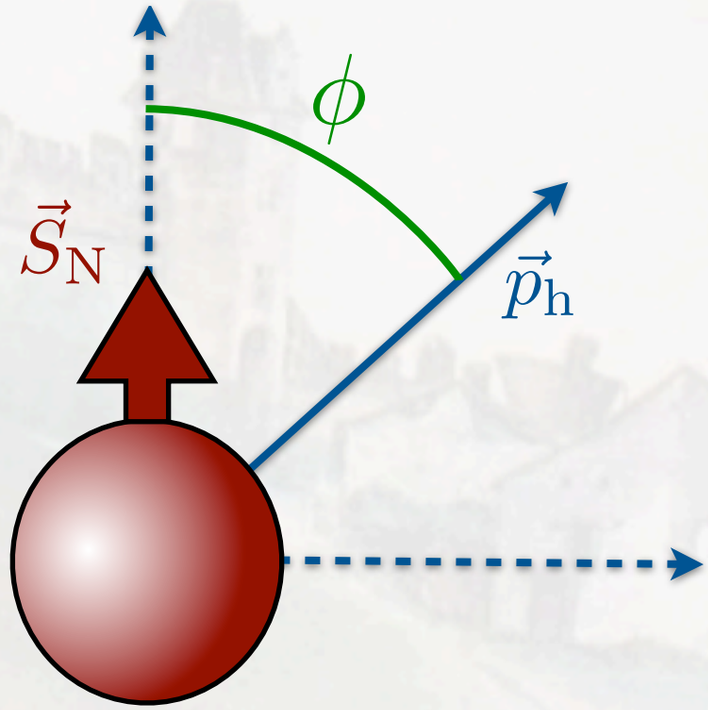
  ➥ hadronic component of photon relevant?



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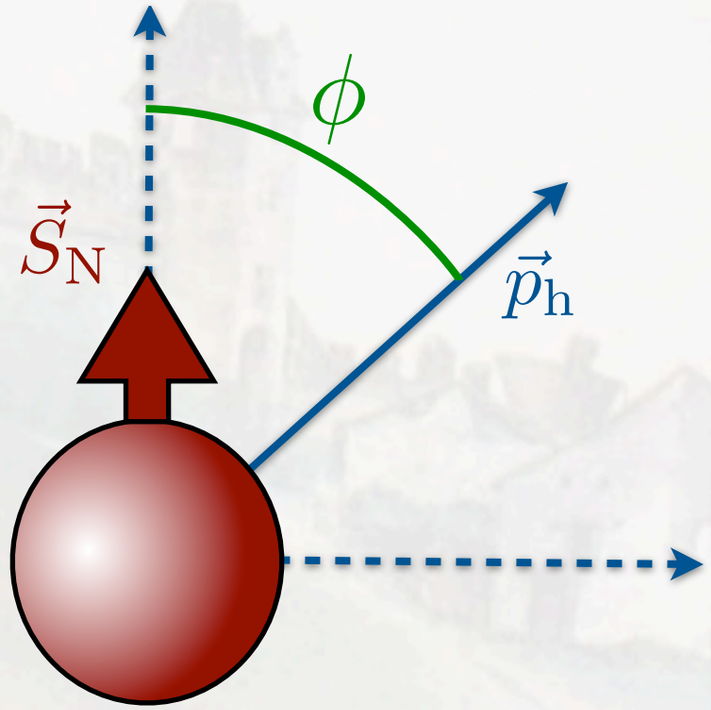

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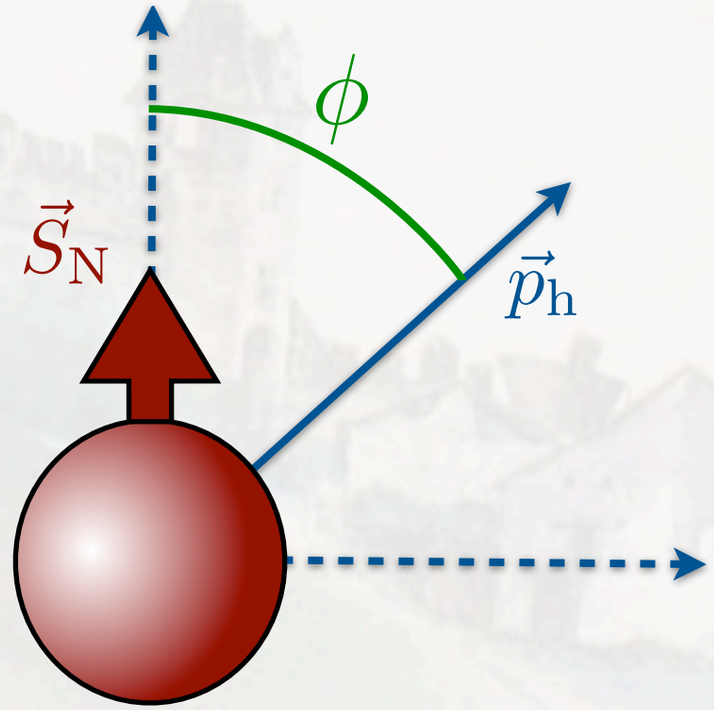
$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$



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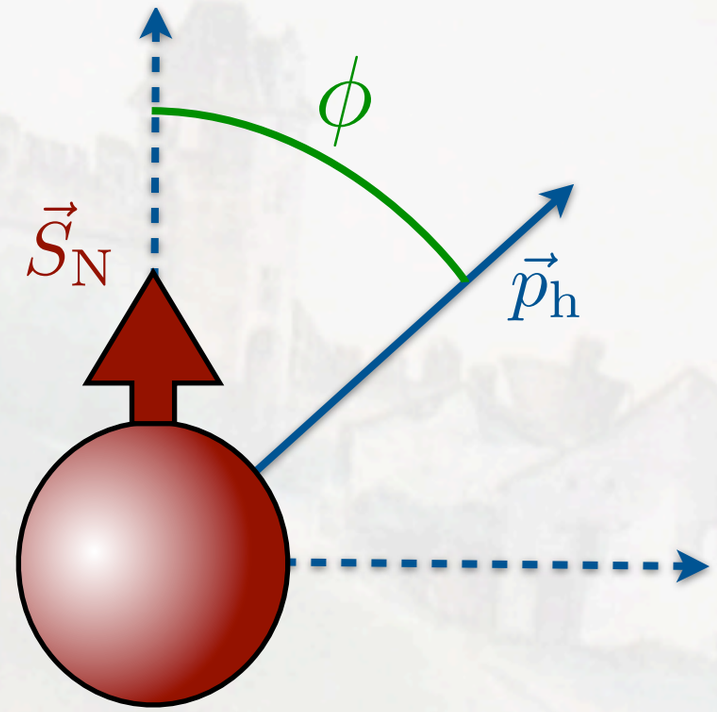

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F)\sin\phi$$

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

	U	L	T
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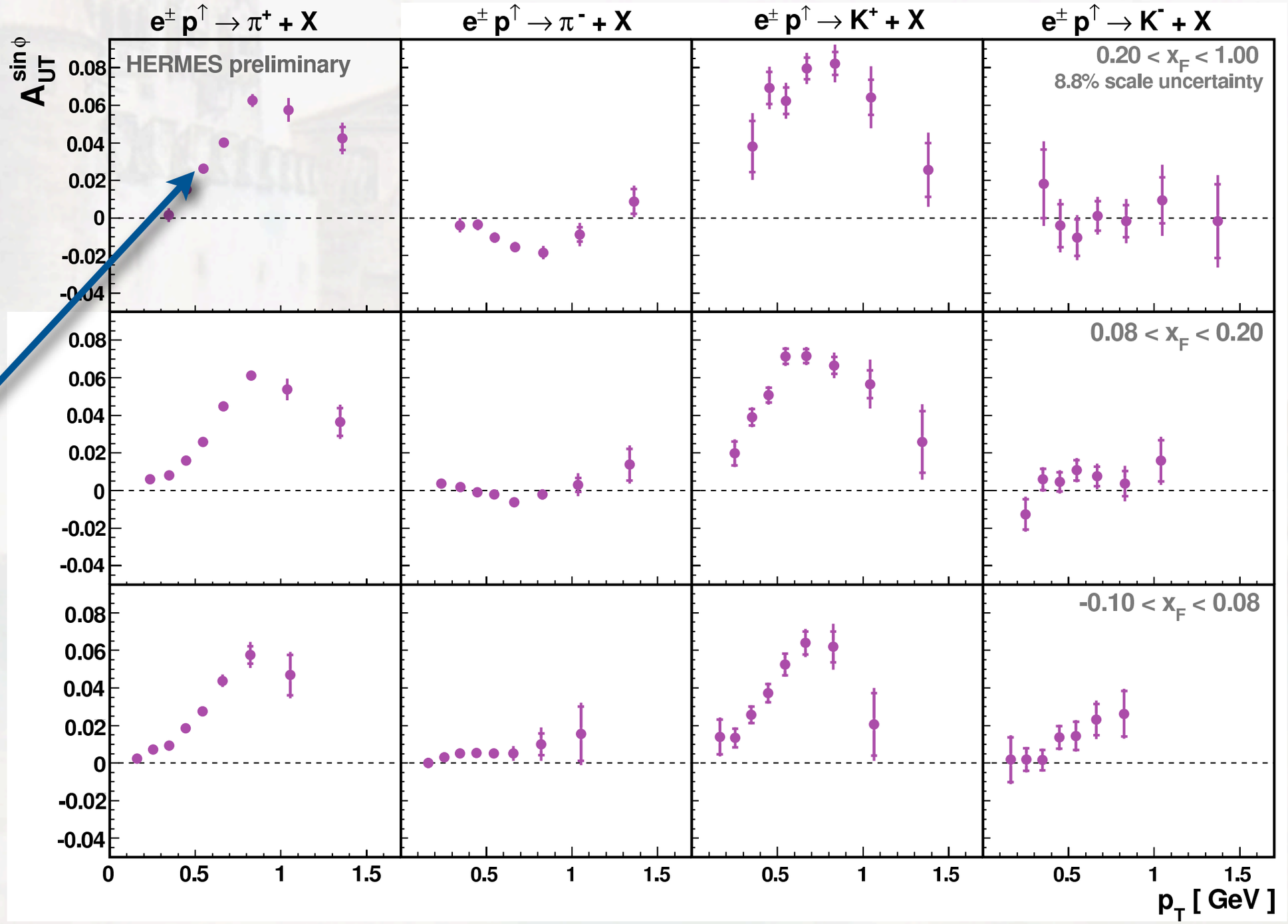
Inclusive hadrons in ep

increasing amplitudes with turnover



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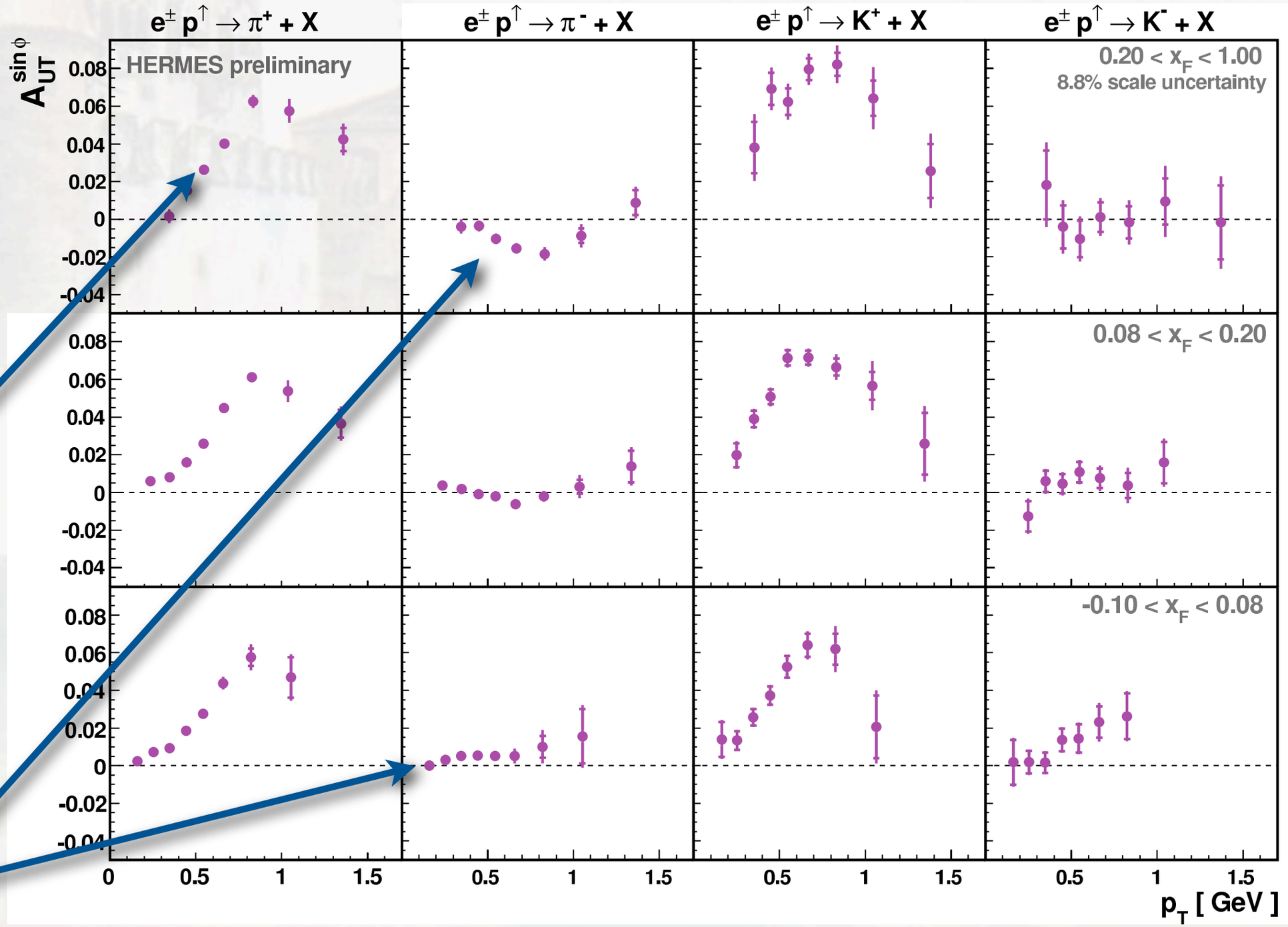

increasing amplitudes with turnover

sign change

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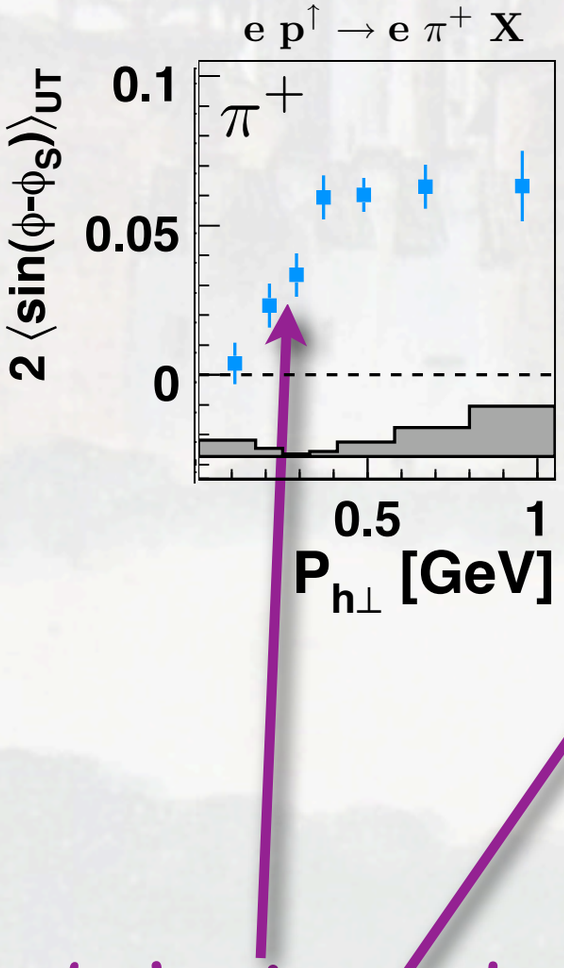
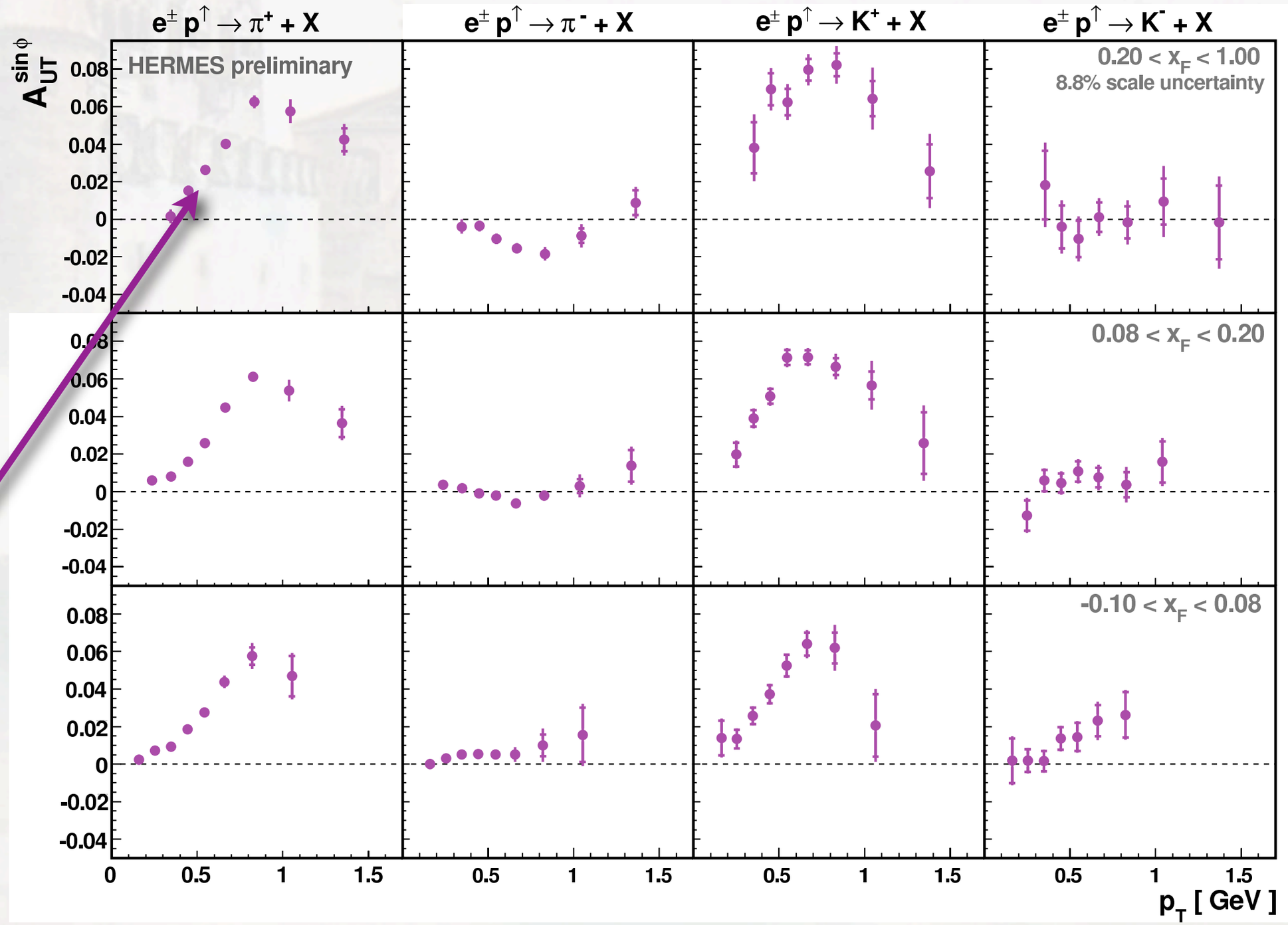


behavior and size similar to SIDIS Sivers



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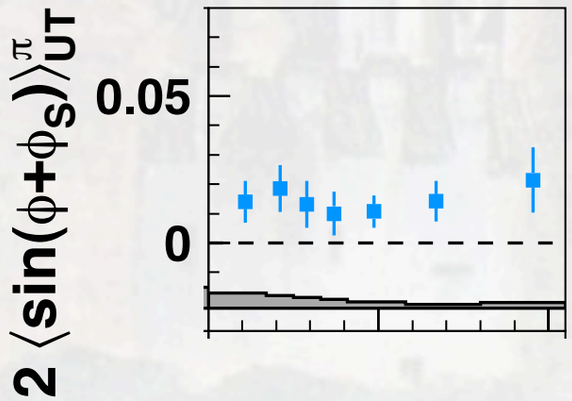

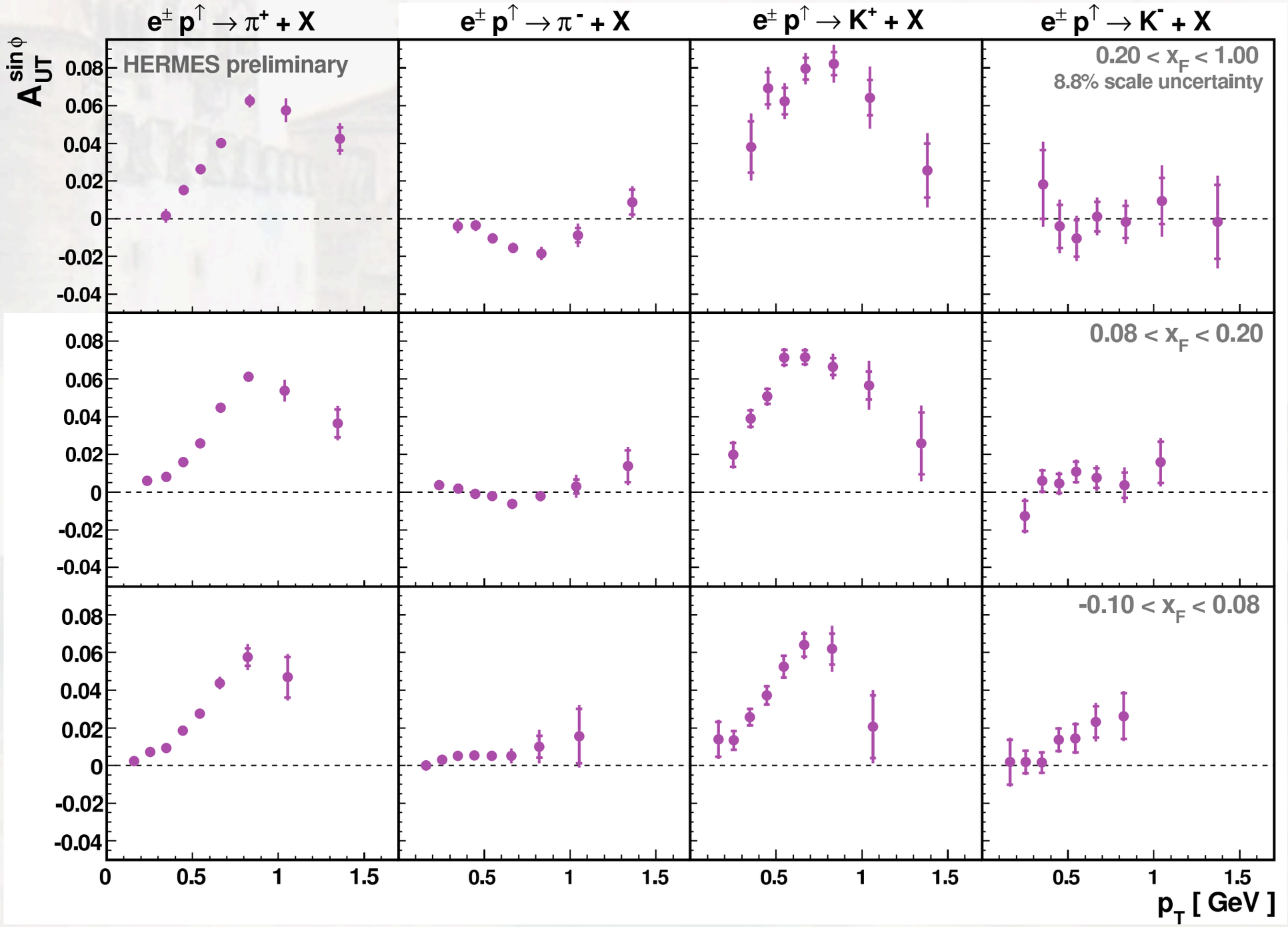

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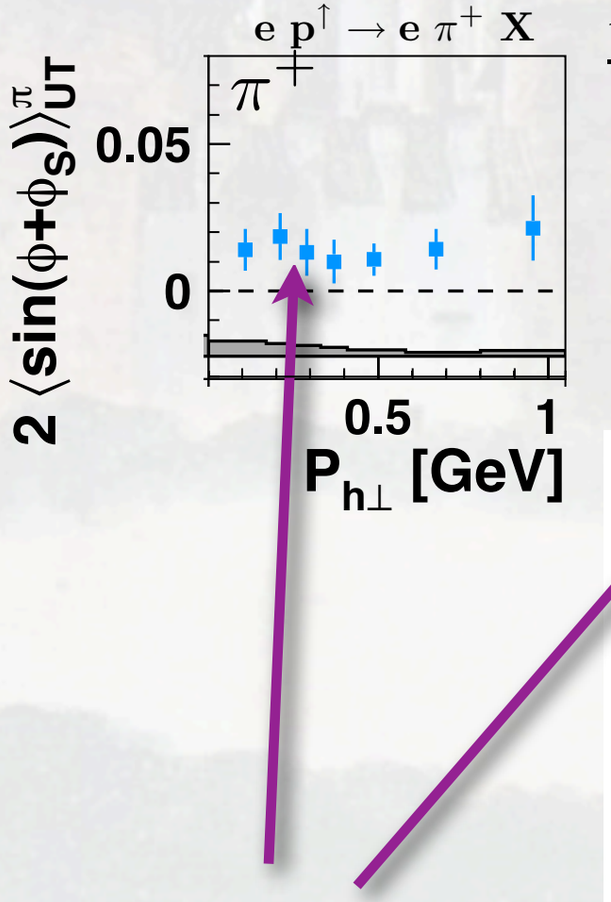
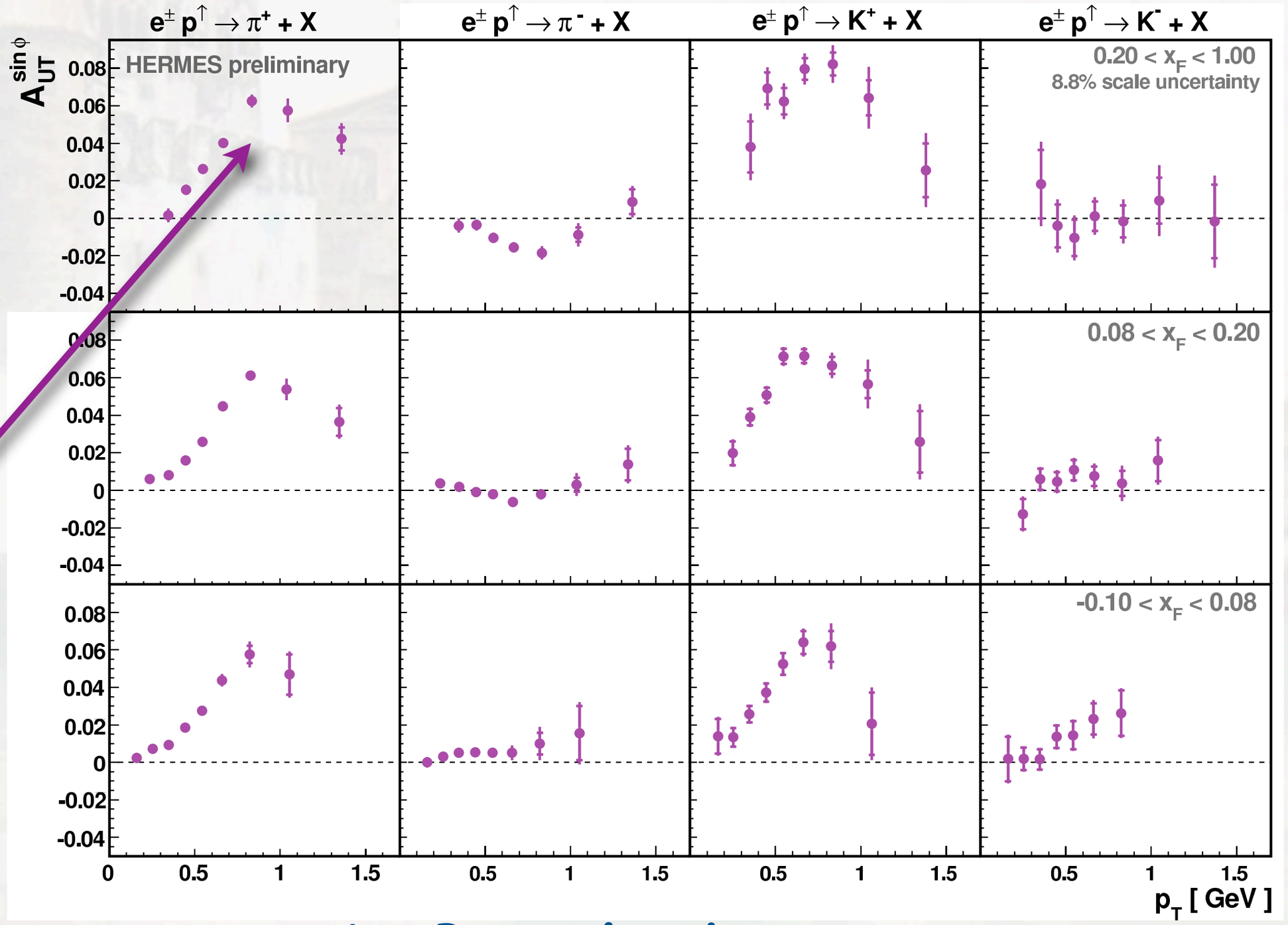


but not to
SIDIS Collins



☛ L. Pappalardo

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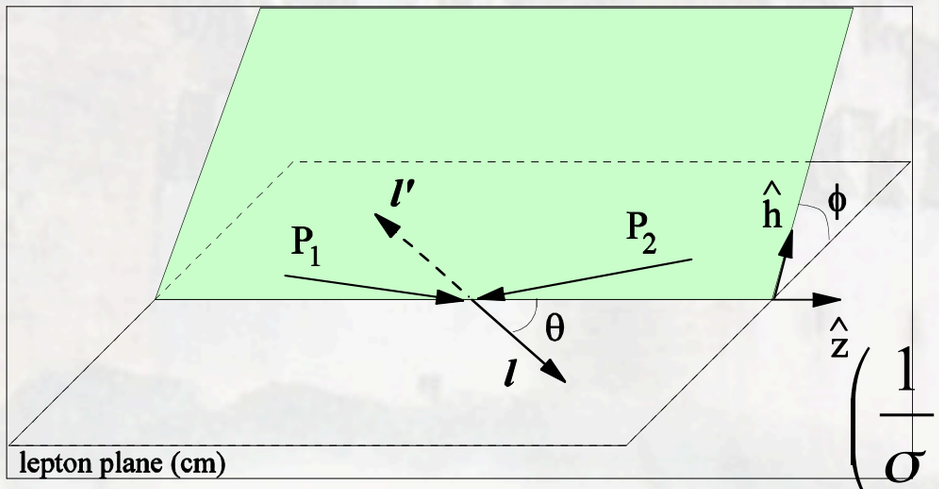
Boer-Mulders function (Drell-Yan)



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

- Lam-Tung relation: $1-\lambda = 2\,\nu$
  - insensitive to QCD corrections
  - clear sign for Boer-Mulders effect ($\sim \nu$)
  - violated in pion-induced Drell-Yan

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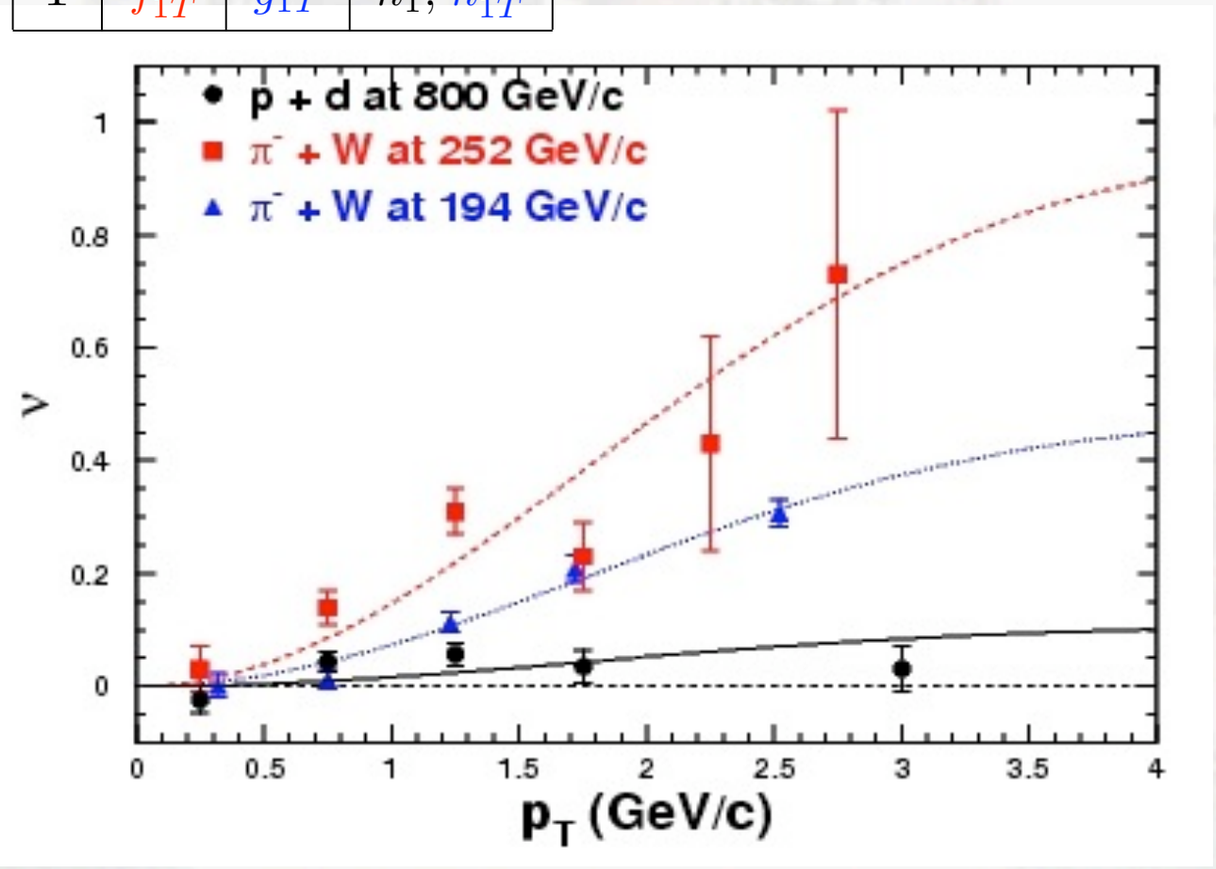
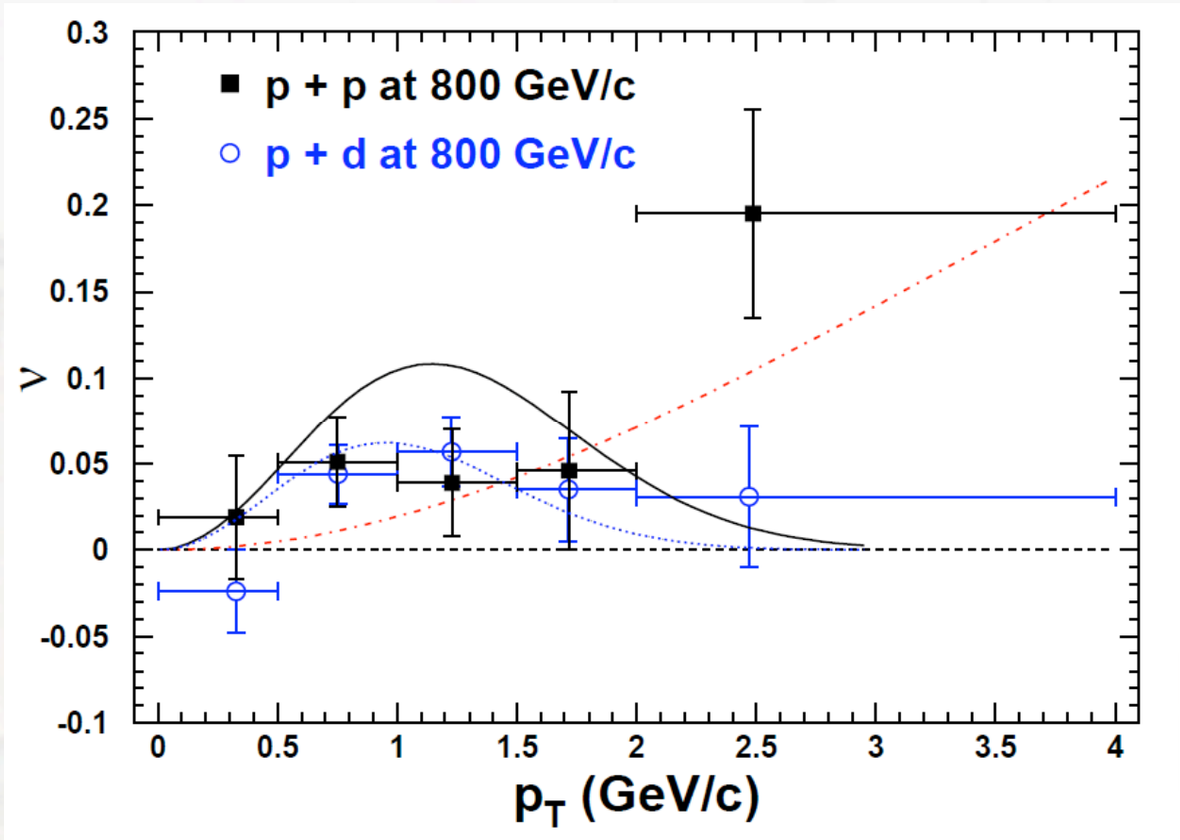
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

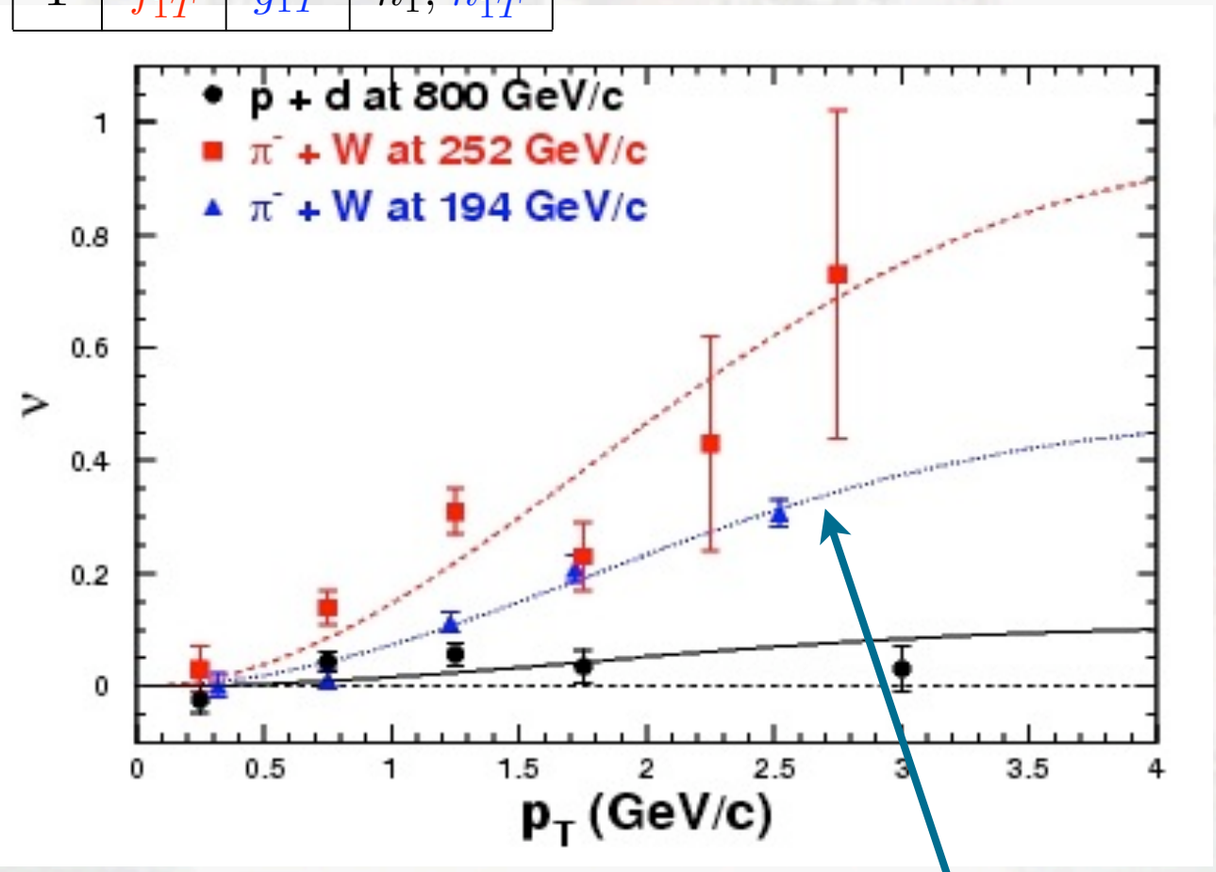
Signs of Boer-Mulders

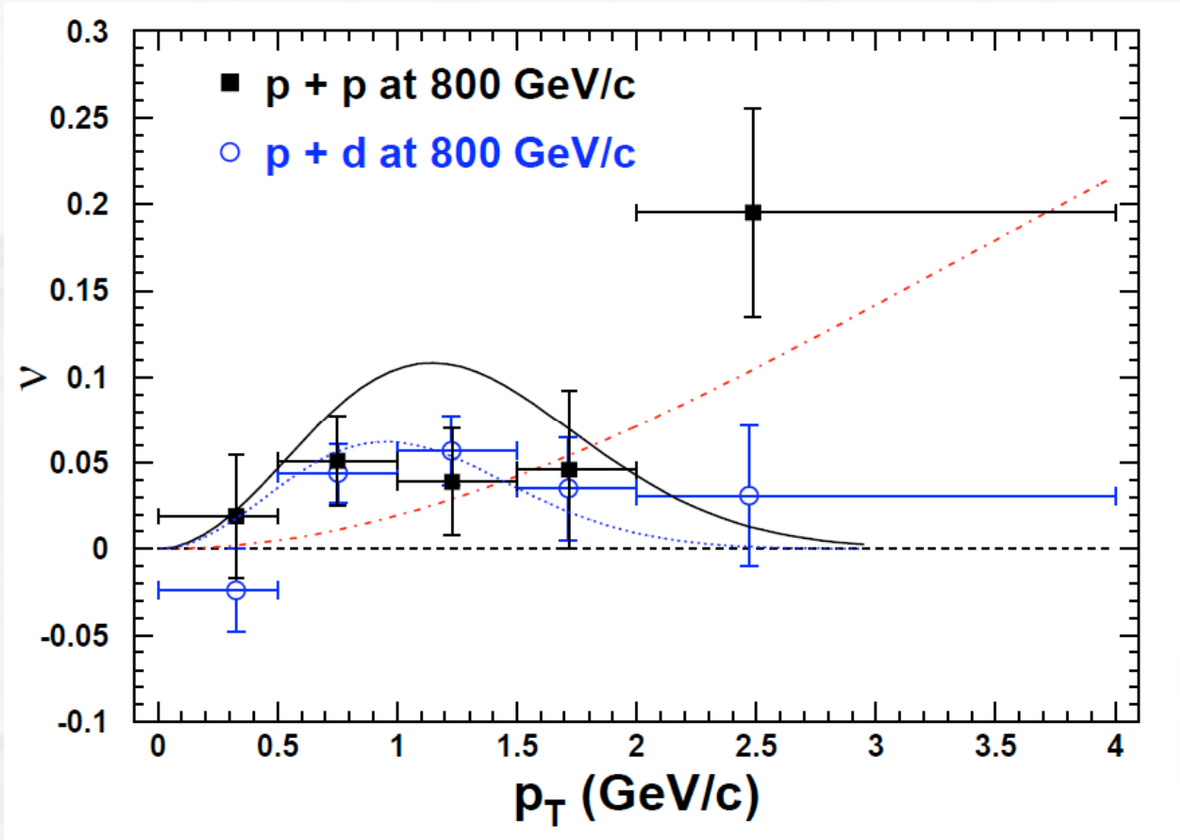




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Signs of Boer-Mulders

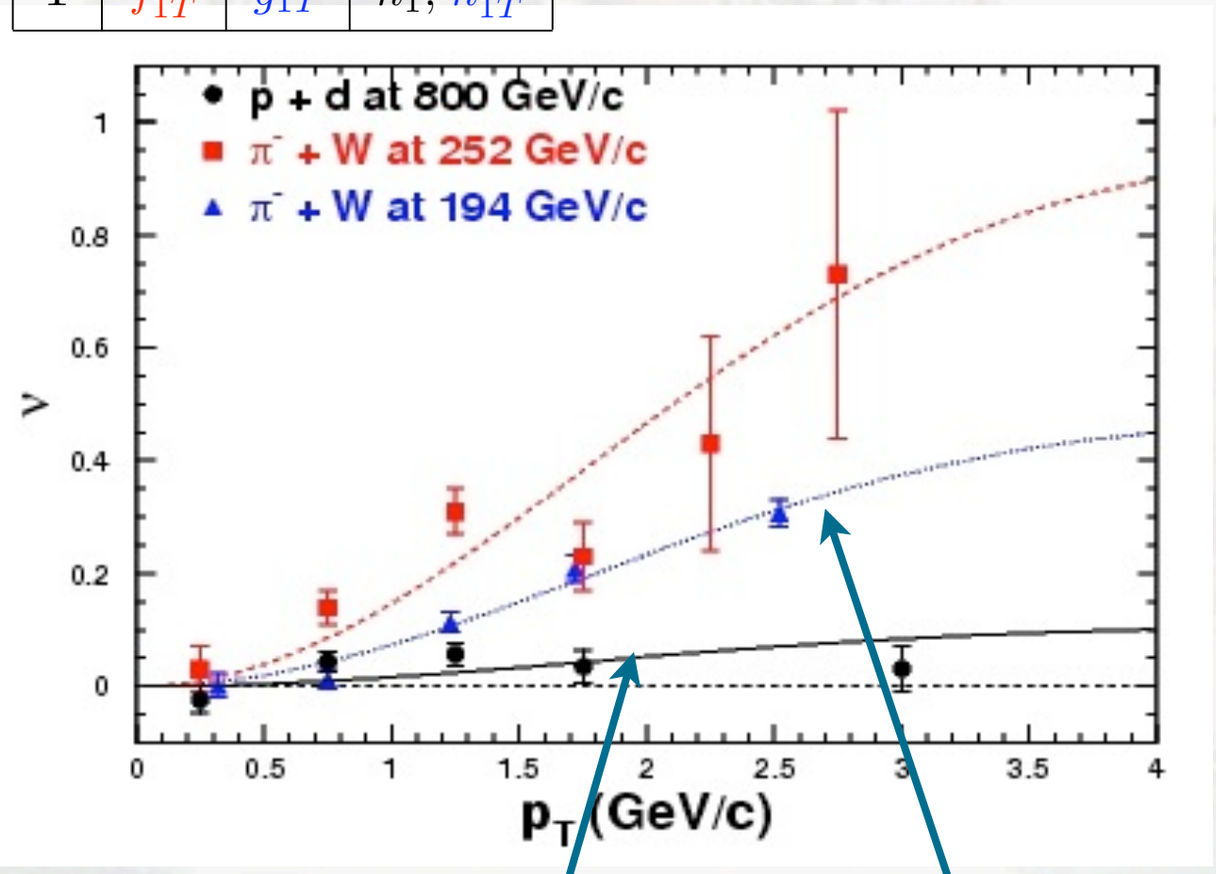


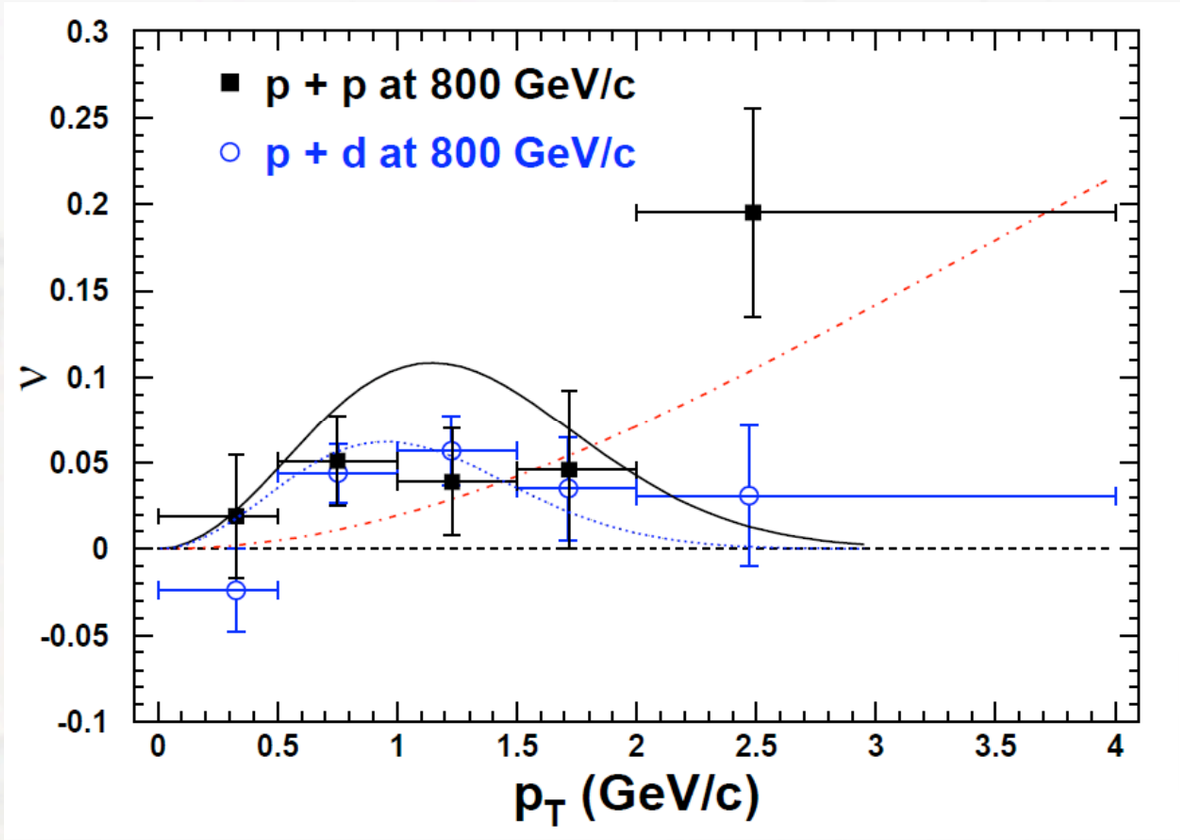


valence BM fctn

	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



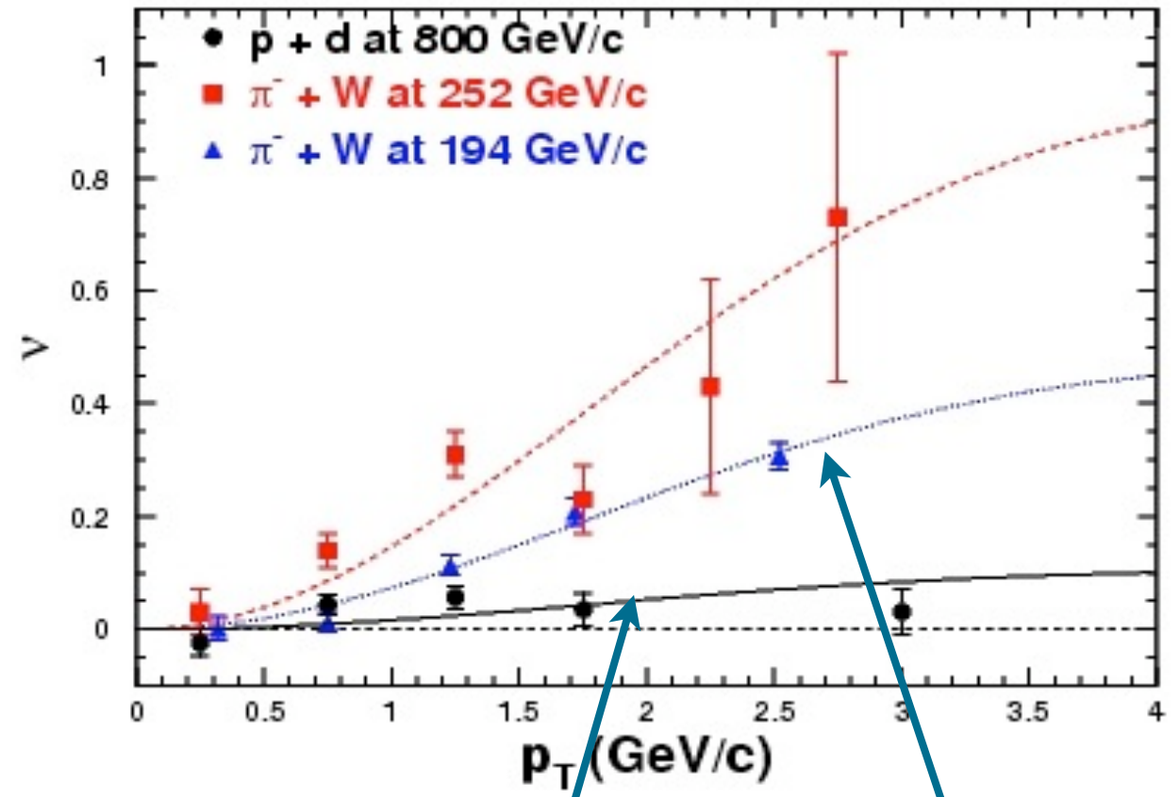


valence and sea BM fctn

valence BM fctn

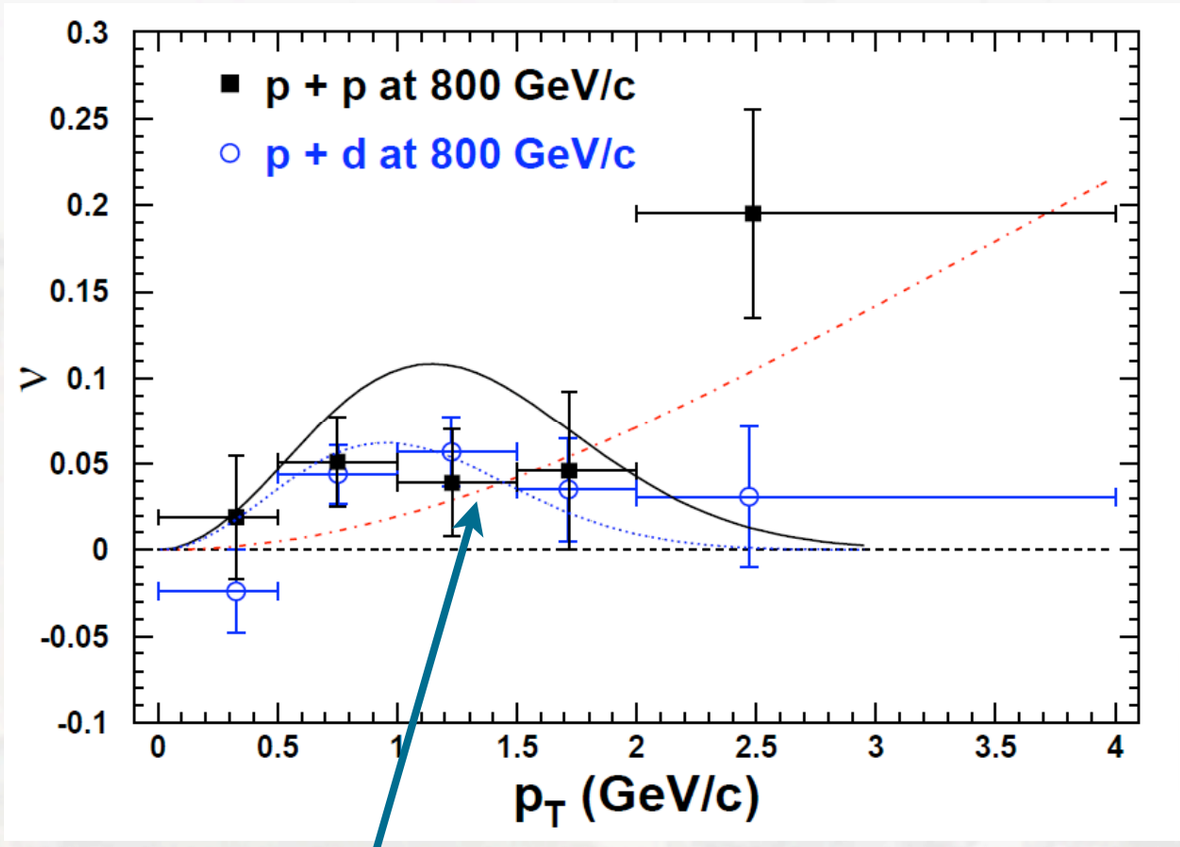
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Signs of Boer-Mulders



valence and sea BM fctn

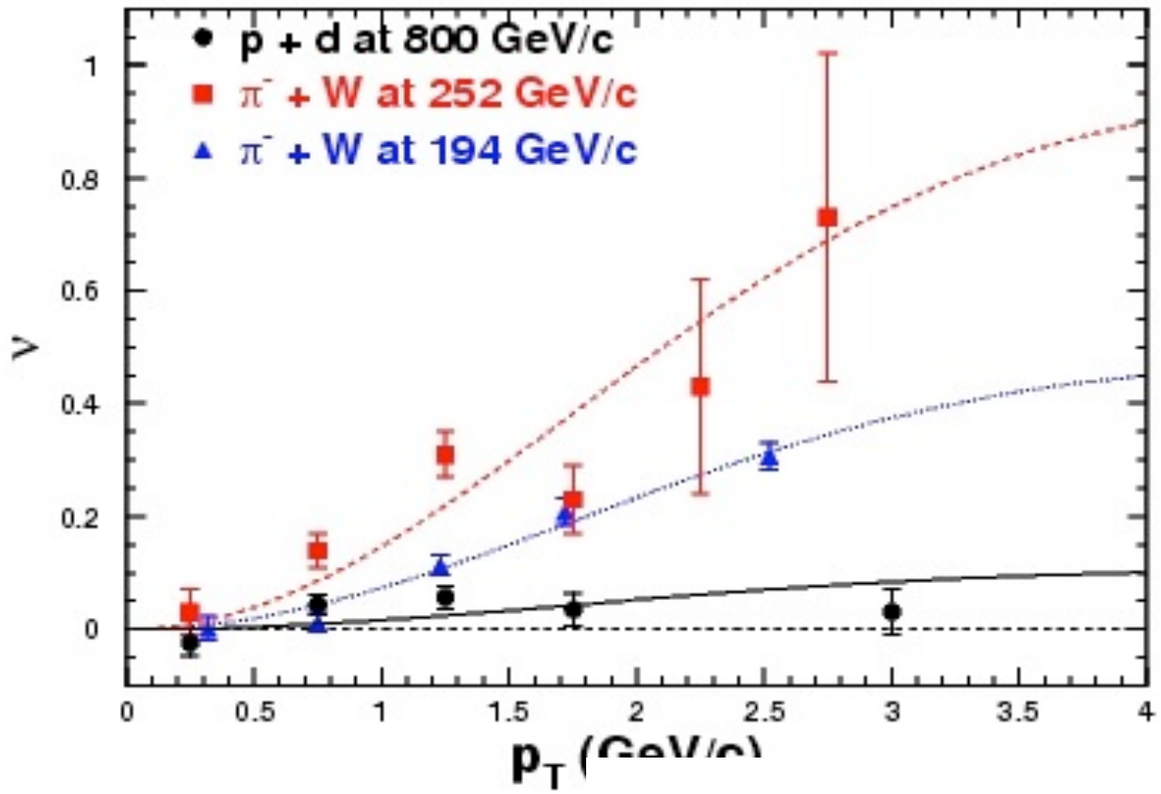
valence BM fctn

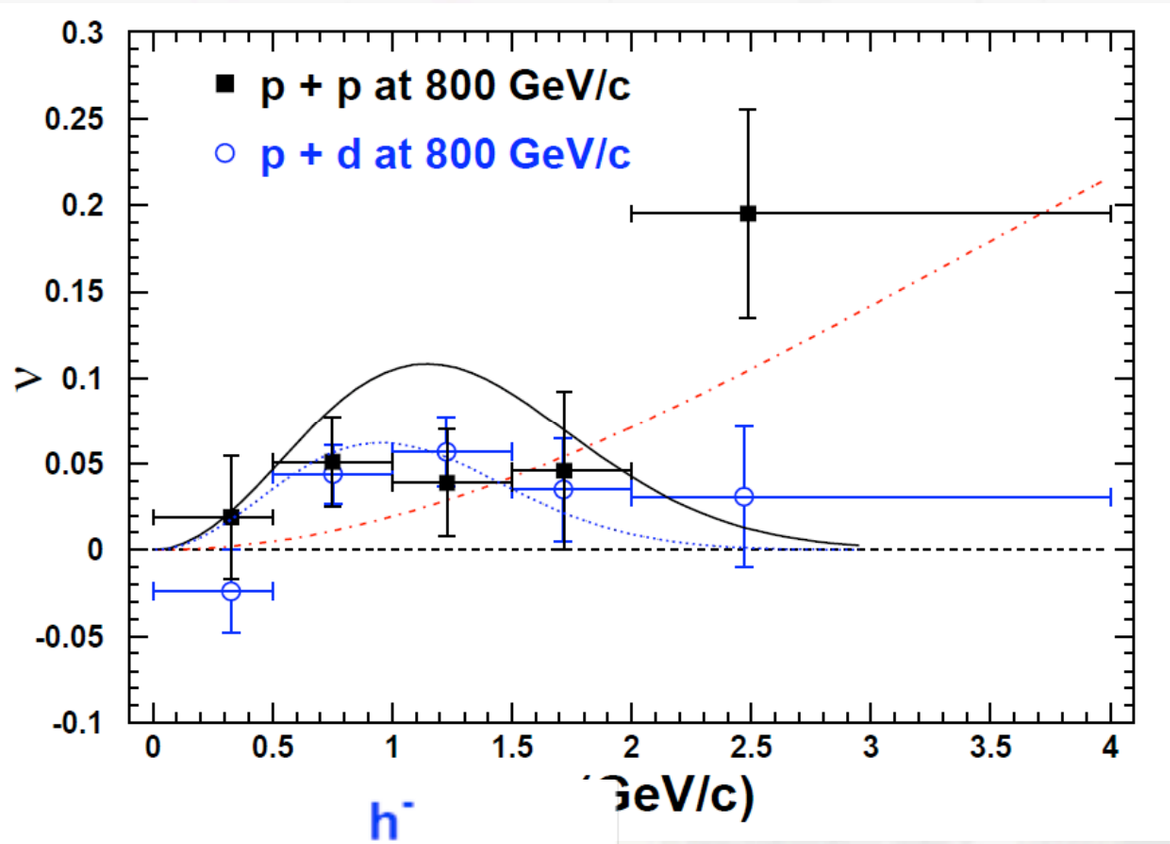


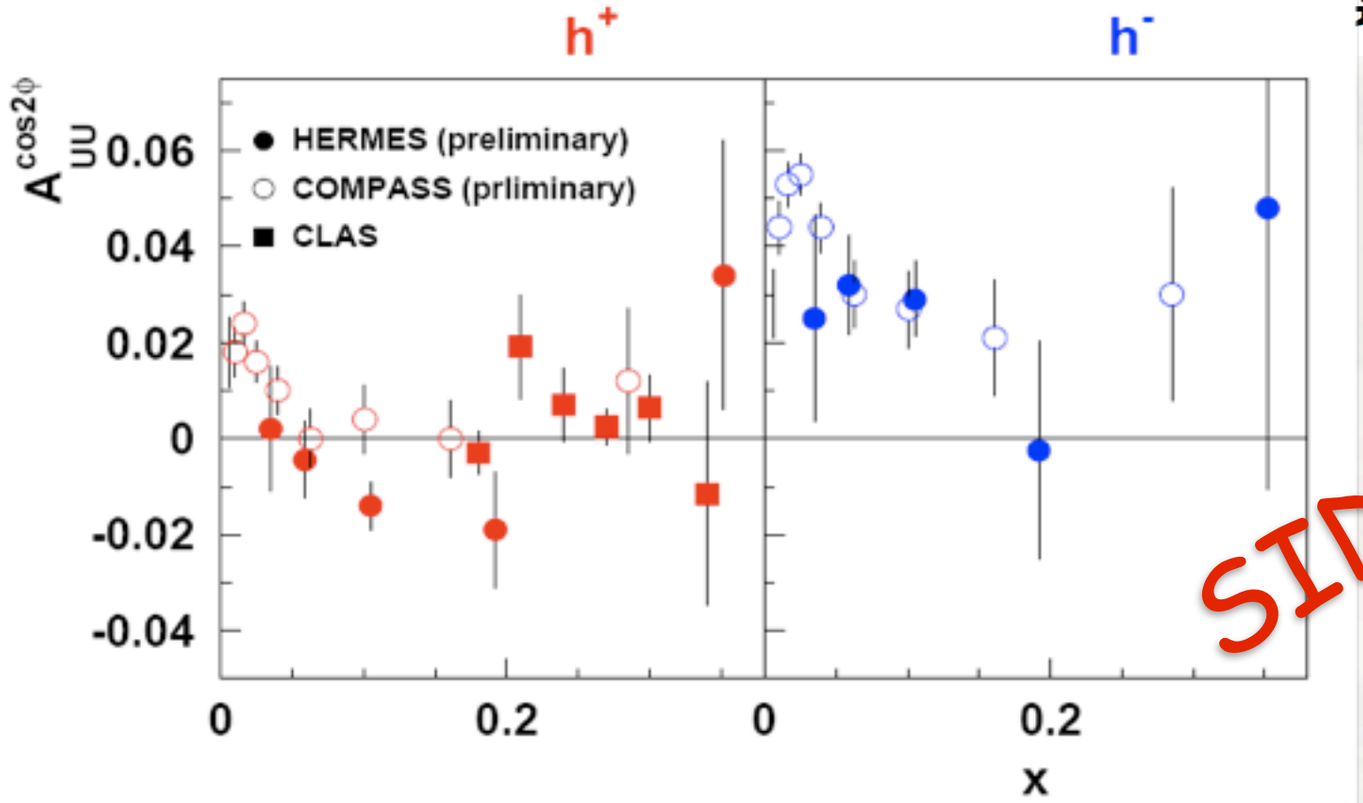
similar BM fctn for up and down quarks?

	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

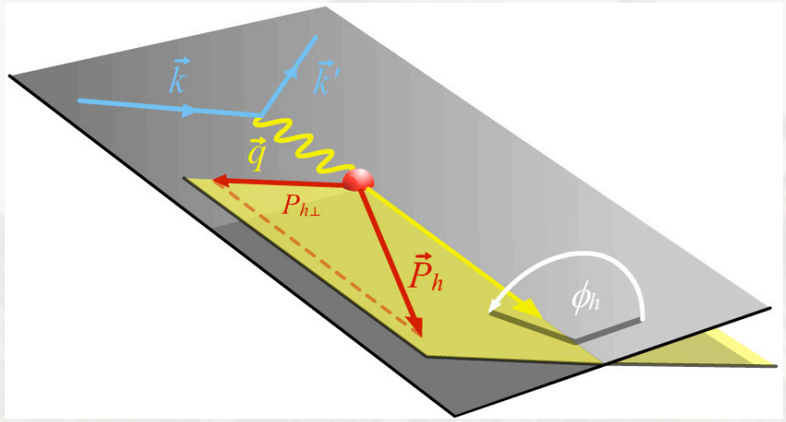






SIDIS

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

CAHN EFFECT

leading twist

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

next to leading twist

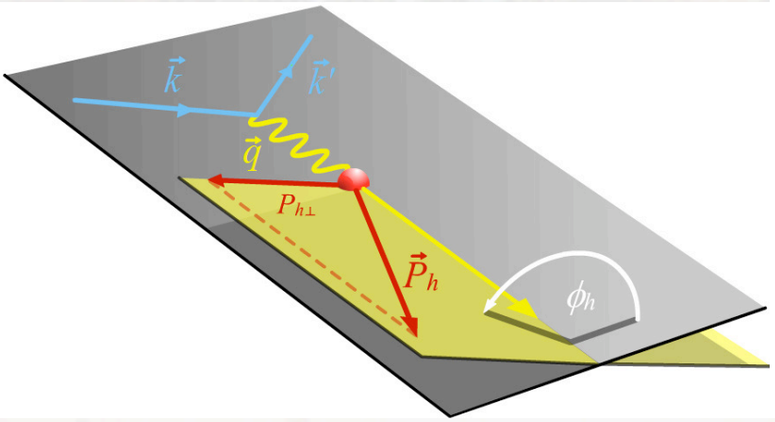
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\,x\;h_1^{\perp}H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\,x\;f_1D_1 + \ldots\right]$$

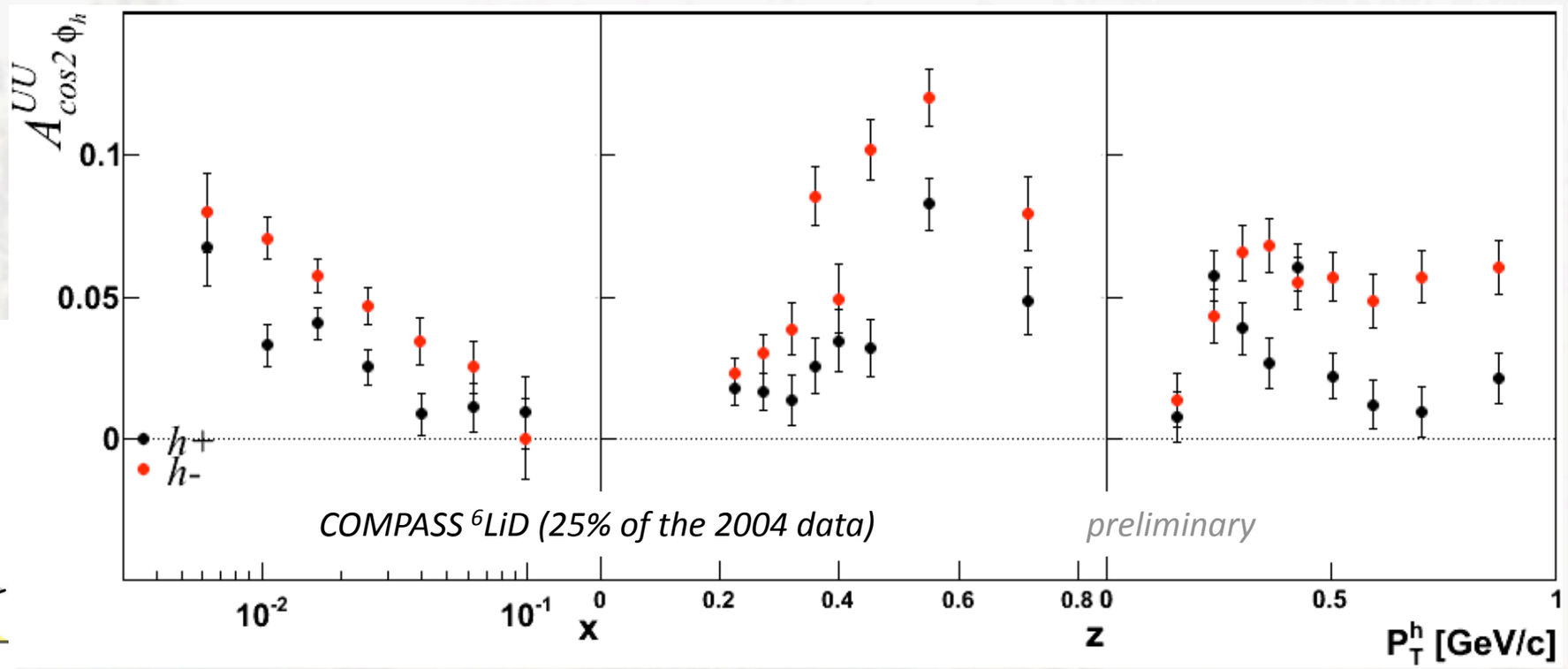
Interaction dependent terms neglected

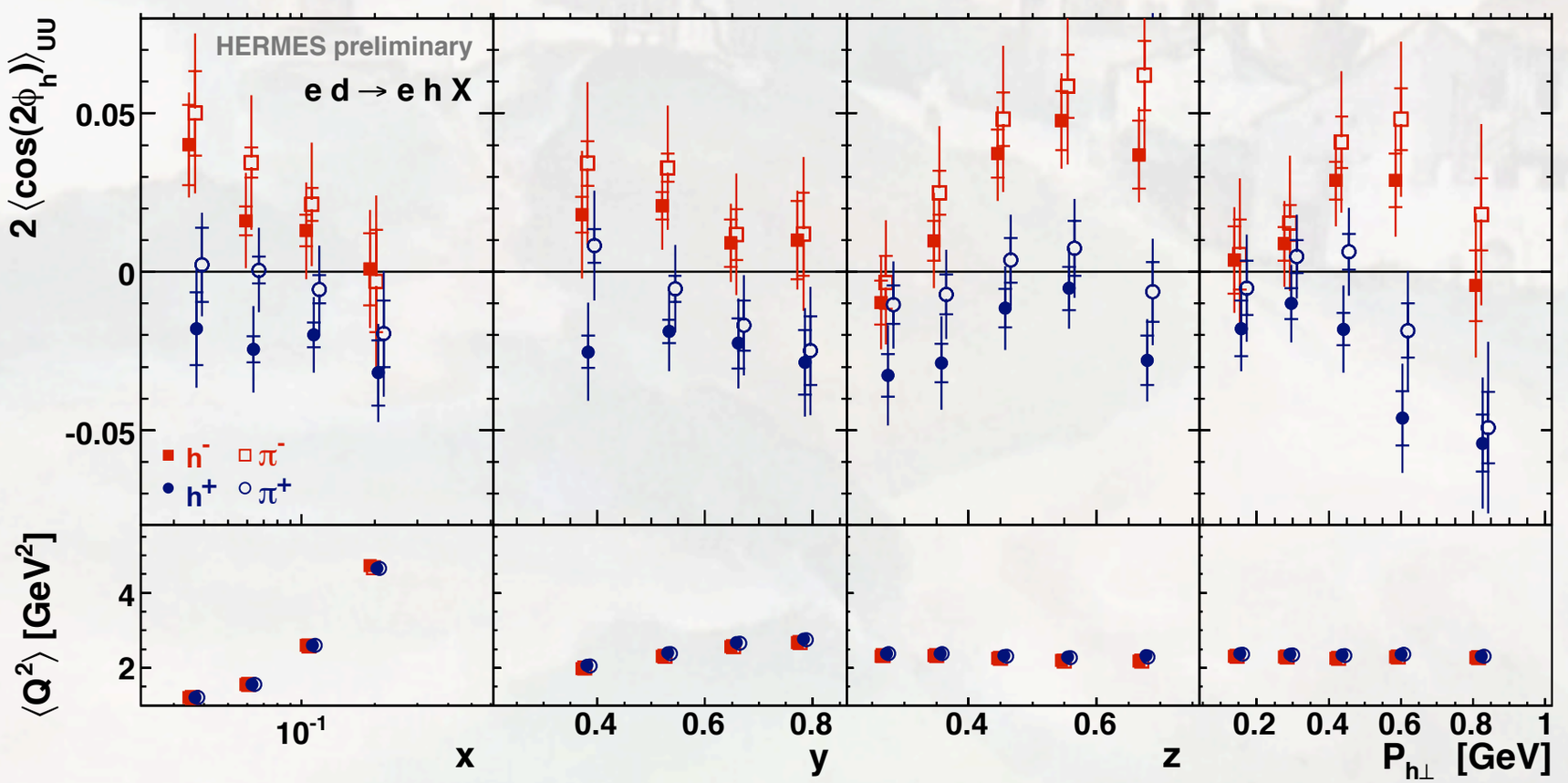
(Implicit sum over quark flavours)

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, $h_{1T}^\perp$



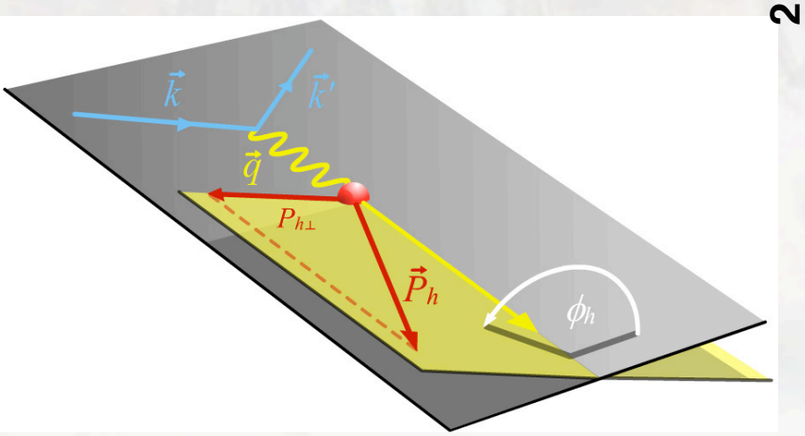


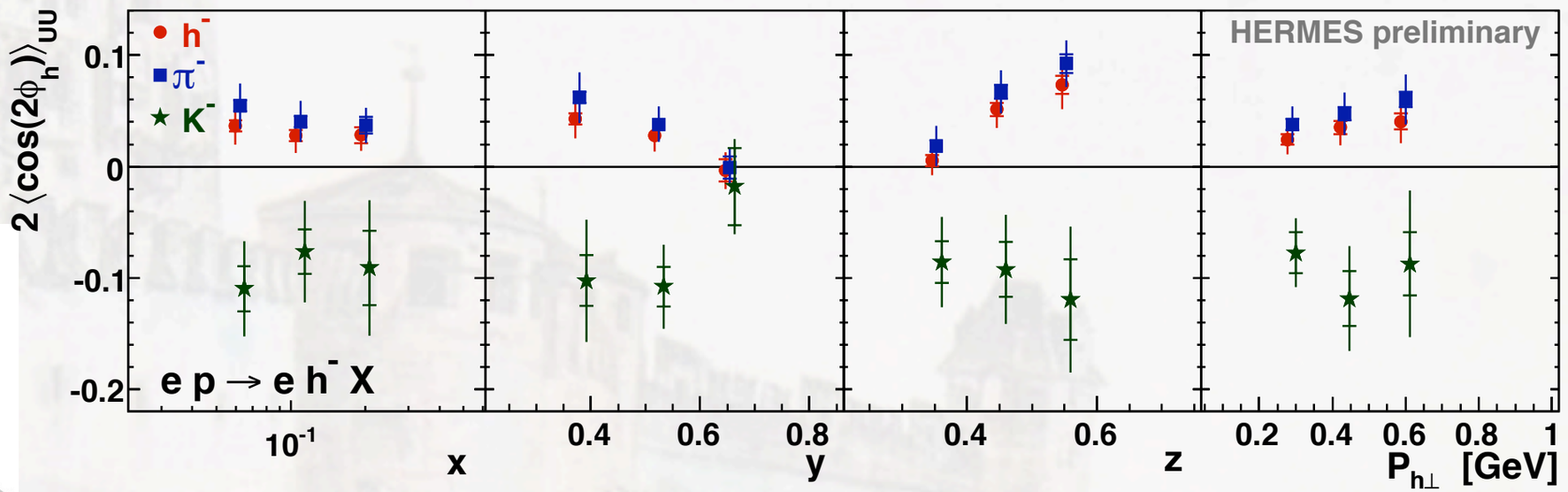


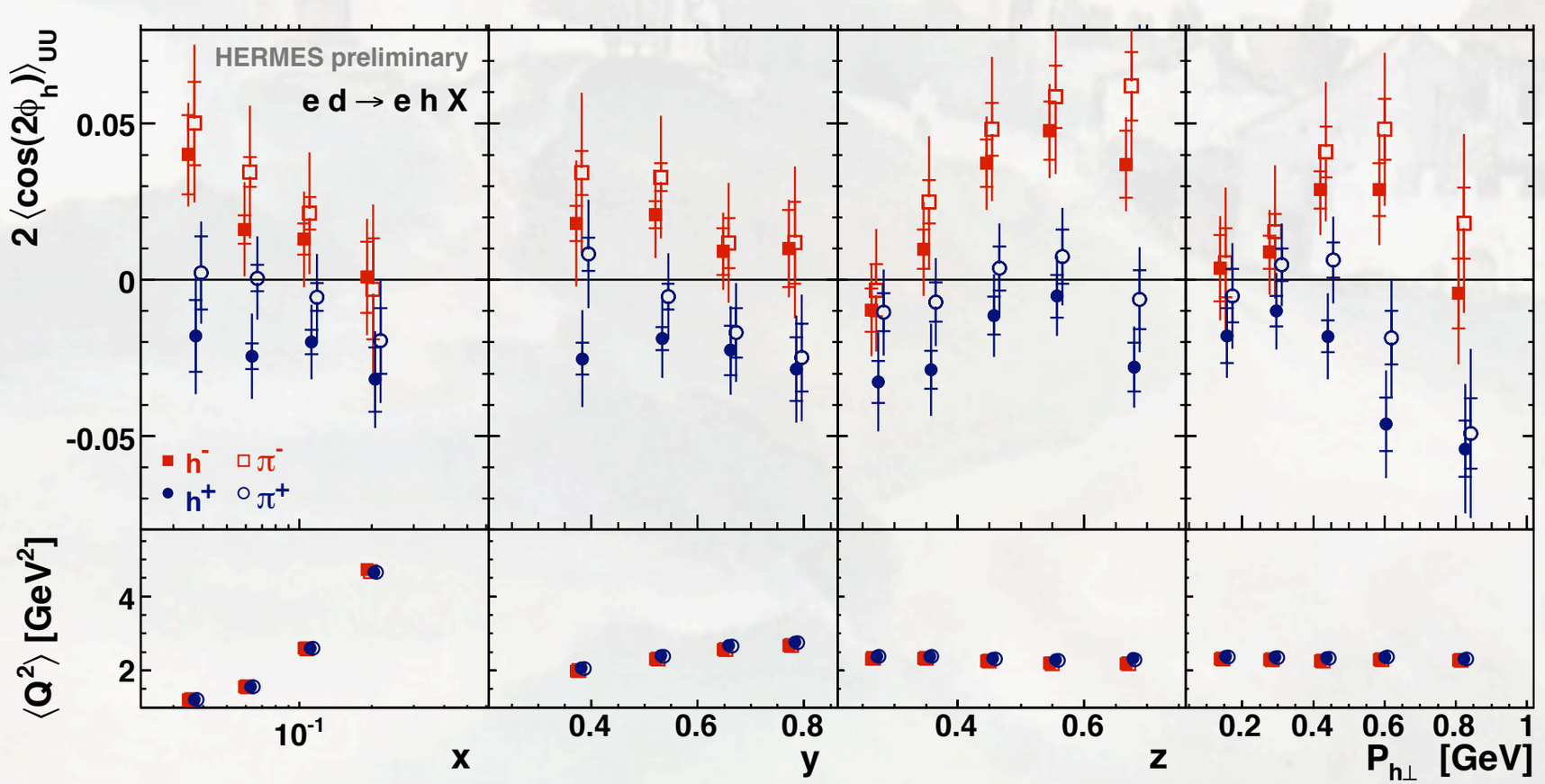
☛ H. Wollny,
L. Pappalardo

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, $h_{1T}^\perp$







☛ H. Wollny,
L. Pappalardo

Cahn effect?

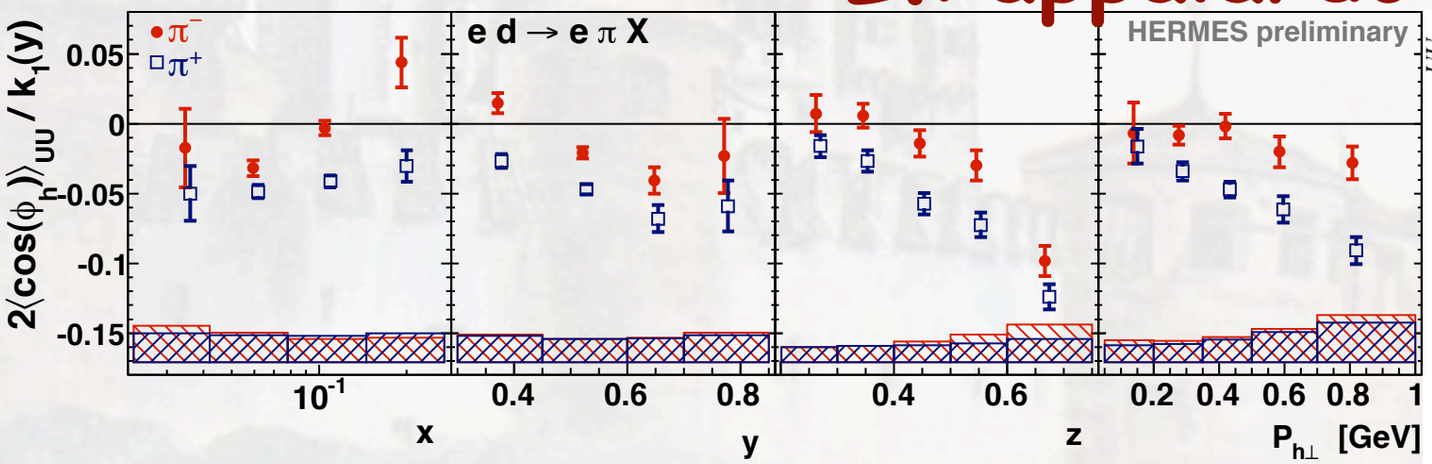
BOER-MULDERS EFFECT

CAHN EFFECT

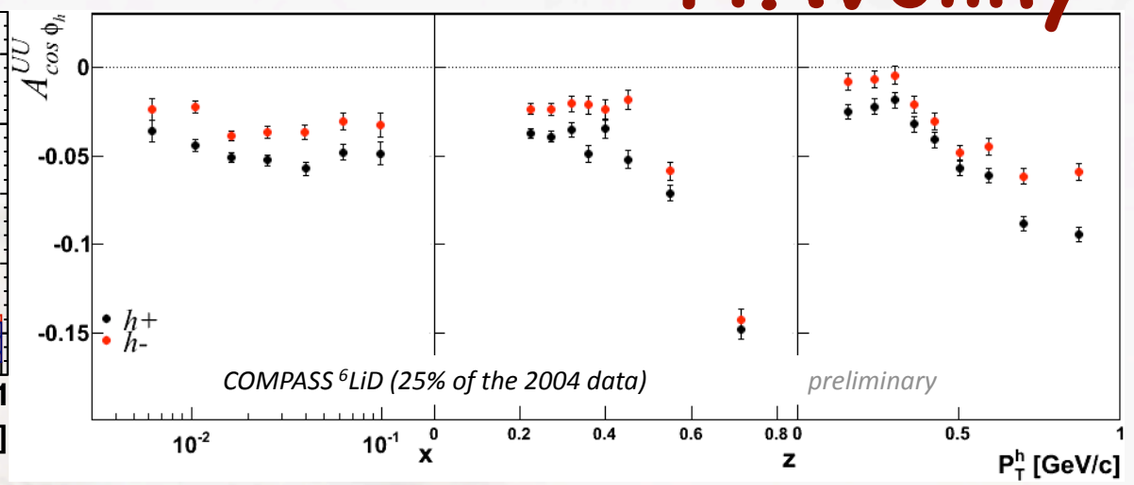
$$\text{next to leading twist}\quad F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\, x\, h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\, x\, f_1 D_1 + \dots\right]$$

Interaction dependent terms neglected

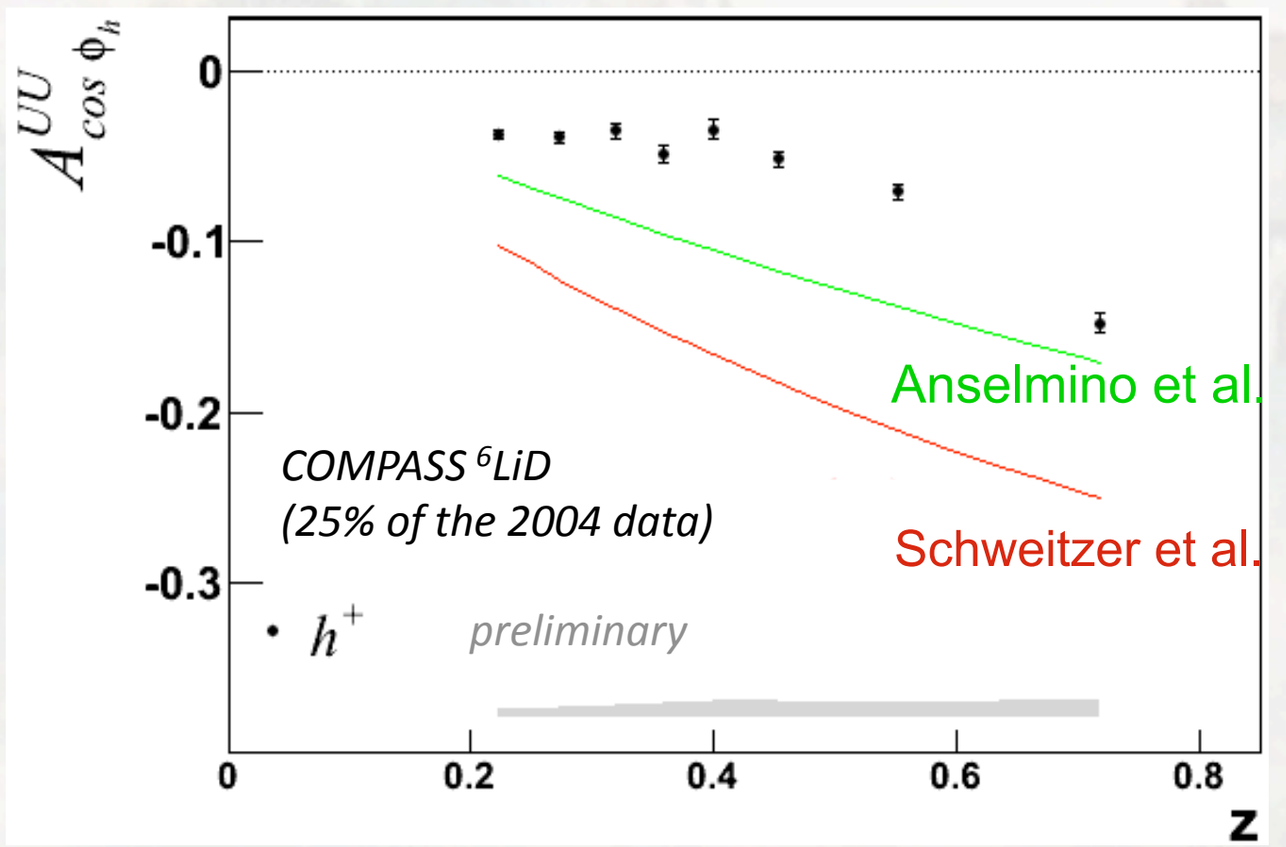
☛ L.Pappalardo



☛ H.Wollny



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



Cahn effect?

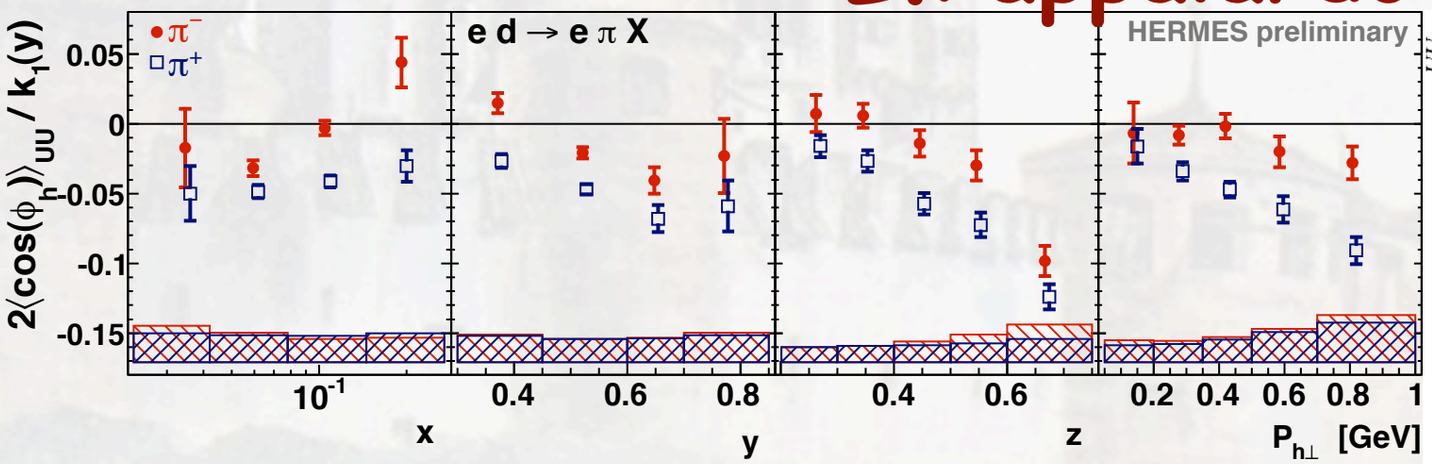
BOER-MULDERS EFFECT

CAHN EFFECT

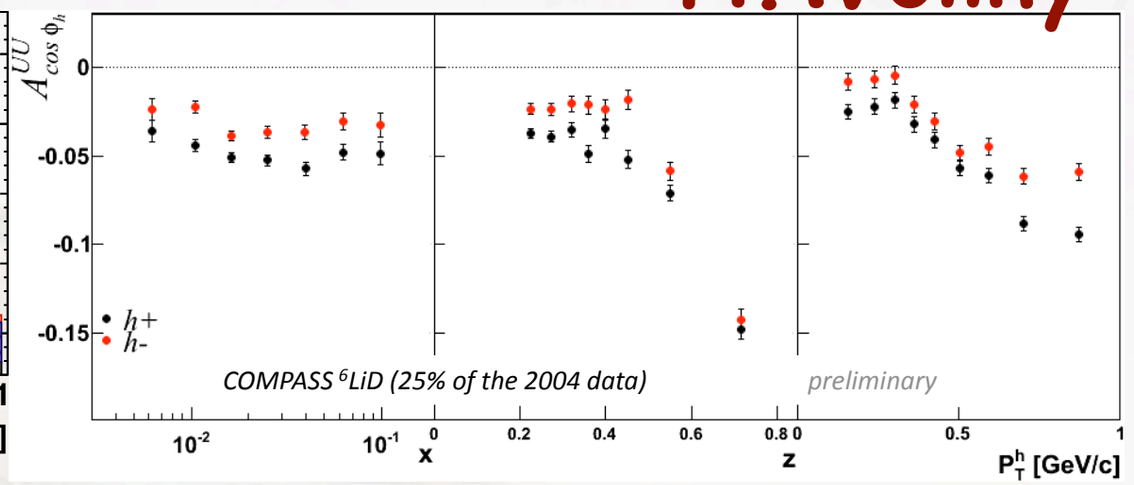
$$\text{next to leading twist}\quad F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\, x\, h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\, x\, f_1 D_1 + \dots\right]$$

Interaction dependent terms neglected

☛ L.Pappalardo

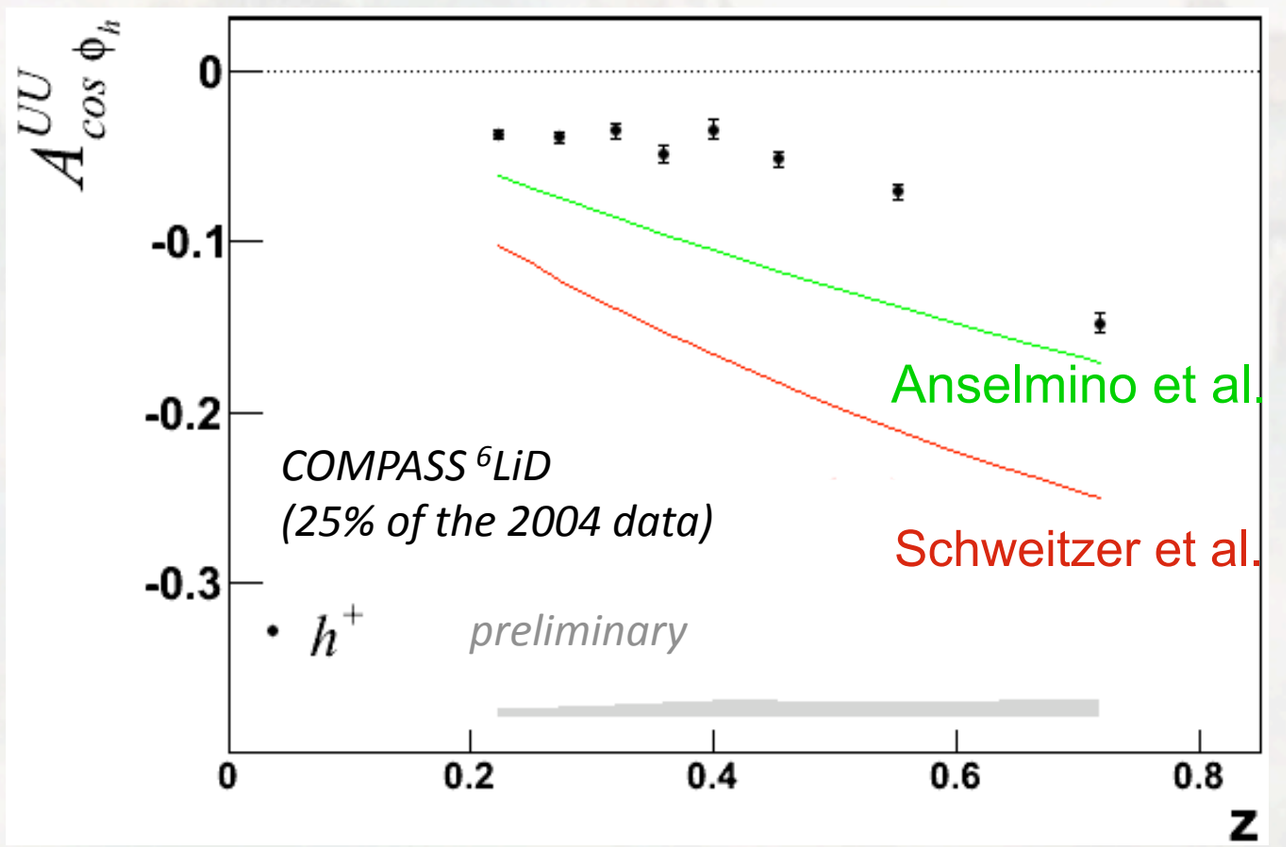


☛ H.Wollny



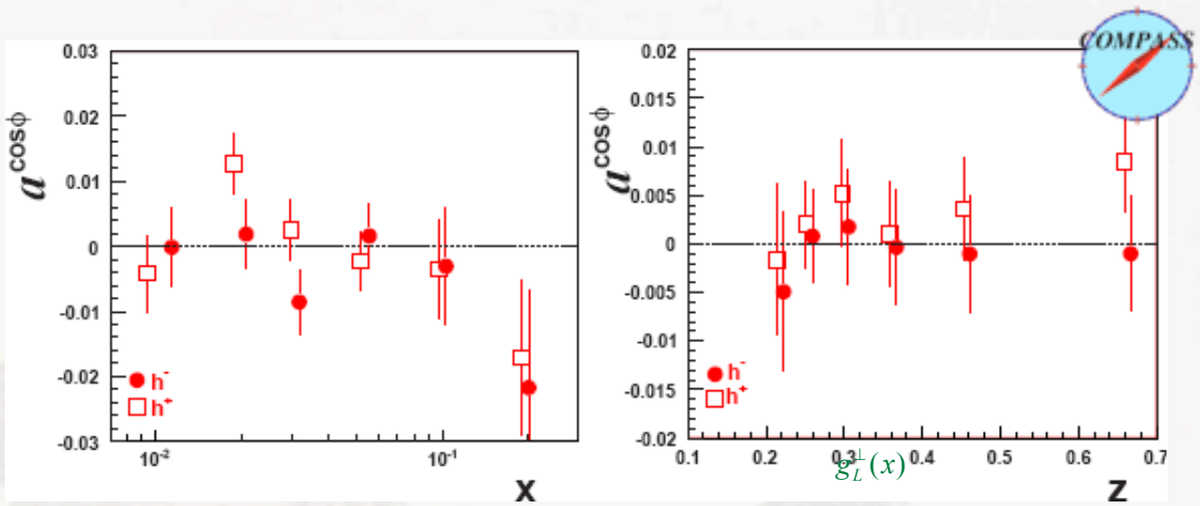
- no dependence on hadron charge expected
- prediction off from data

➡ sign of Boer-Mulders in cosϕ modulation or "real" twist-3?



Other (twist-3) TMDs

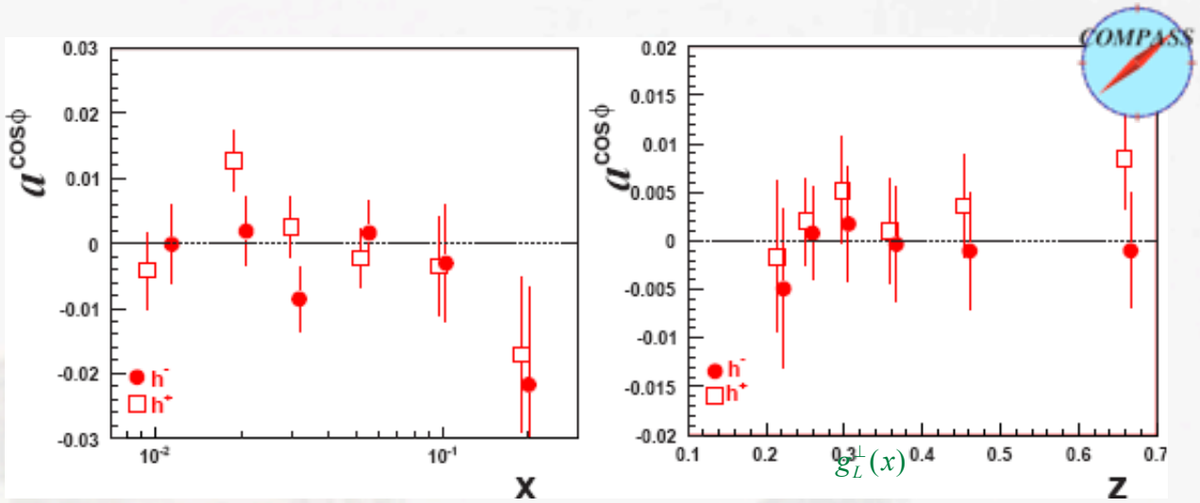
$$A_{\mathrm{LL}}^{\cos\phi}$$



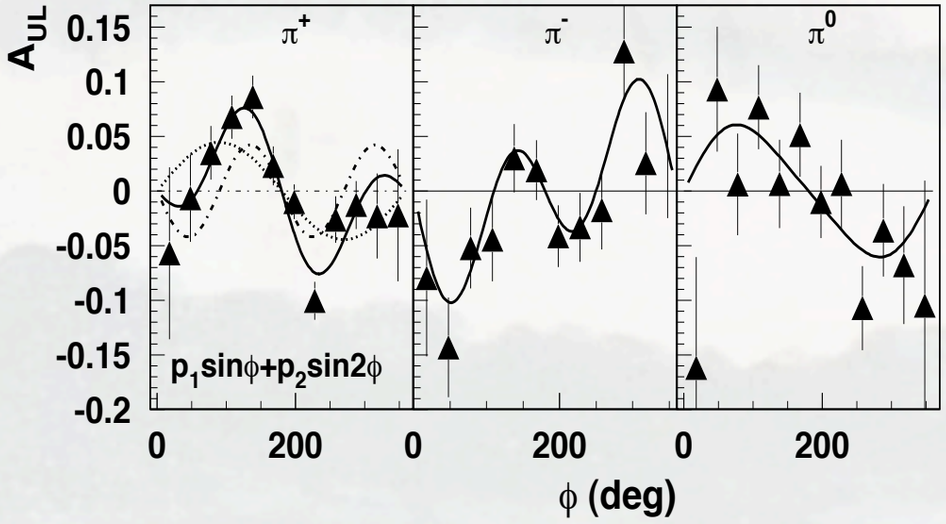
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^{\perp} - \frac{M_h}{M}\, g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^{\perp} D_1 + \frac{M_h}{M}\, h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Other (twist-3) TMDs

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



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

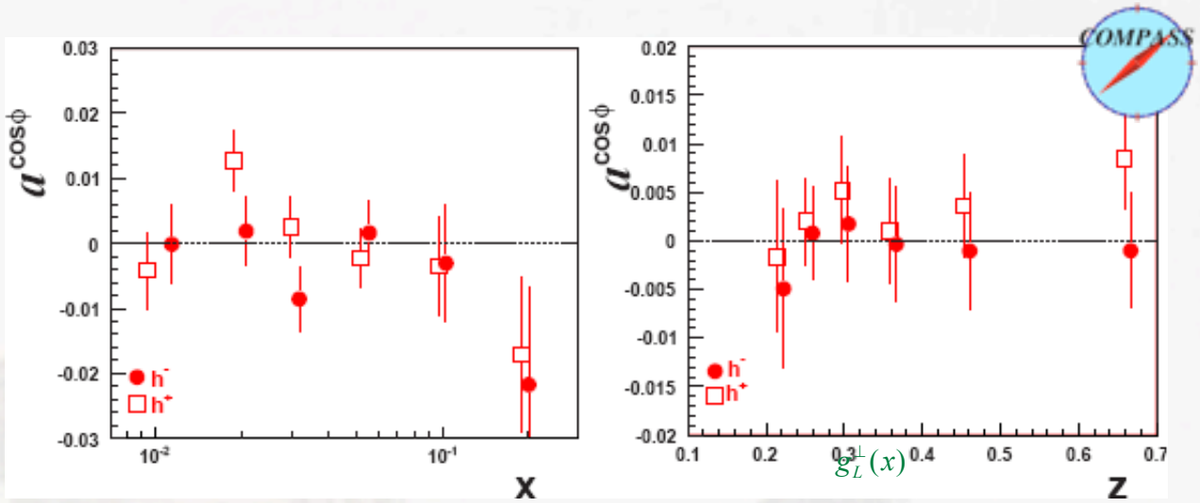


$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^{\perp} + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^{\perp} D_1 - \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549

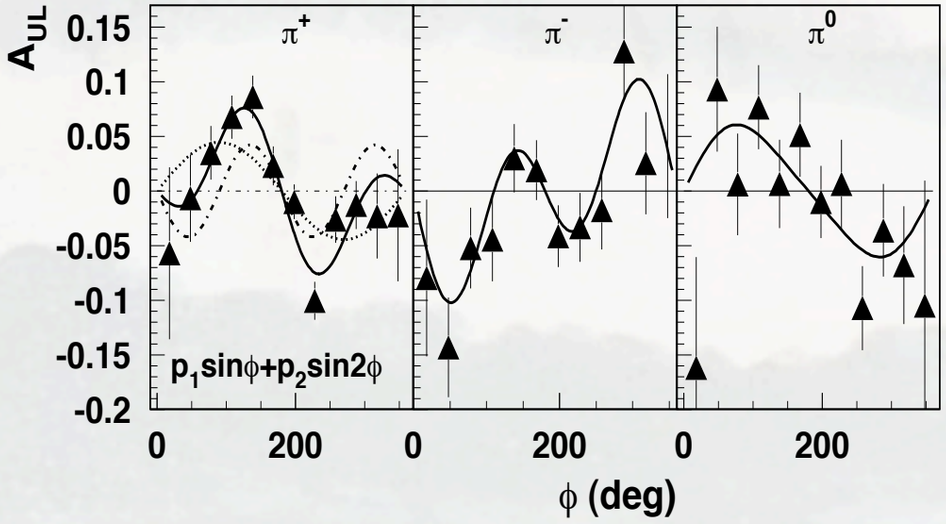
Other (twist-3) TMDs

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



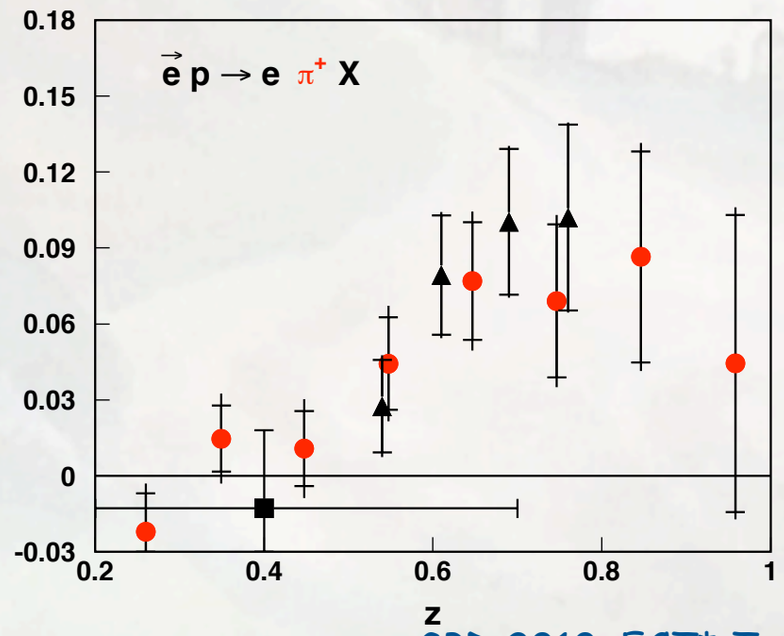
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^{\perp} - \frac{M_h}{M}\, g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^{\perp} D_1 + \frac{M_h}{M}\, h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



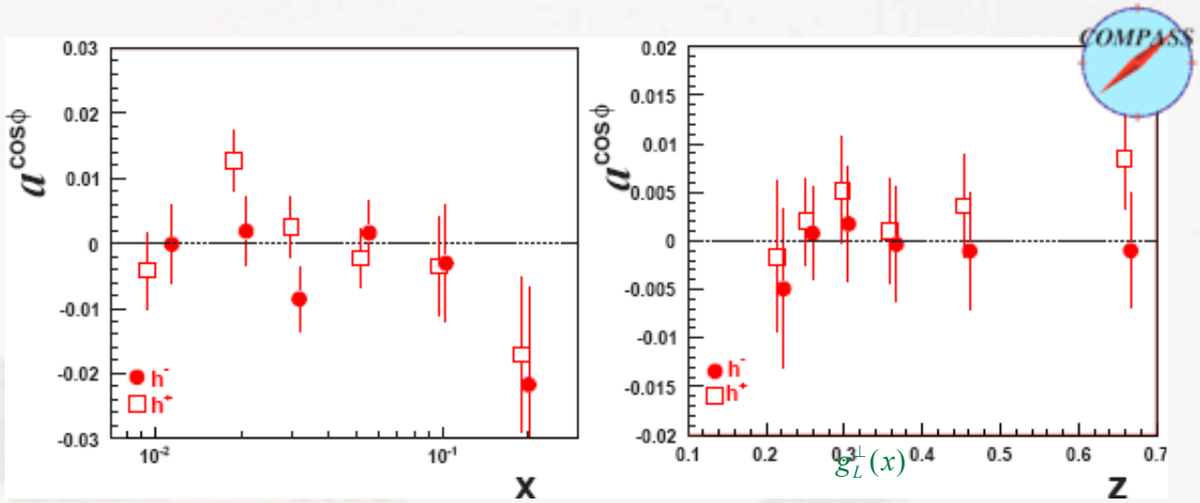
$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^{\perp} + \frac{M_h}{M}\, g_{1L}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^{\perp} D_1 - \frac{M_h}{M}\, h_{1L}^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

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



Other (twist-3) TMDs

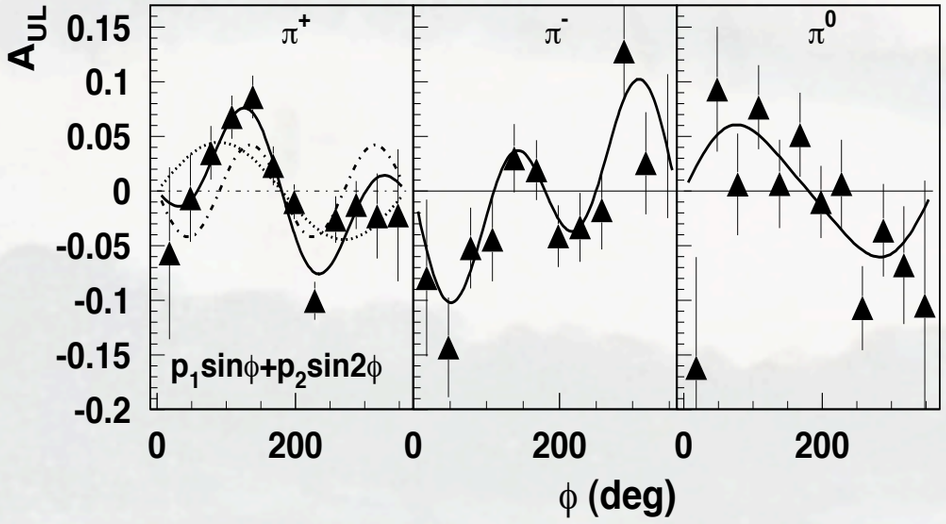
$$A_{\mathrm{LL}}^{\cos\phi}$$



$g_L^{\perp}(x)$

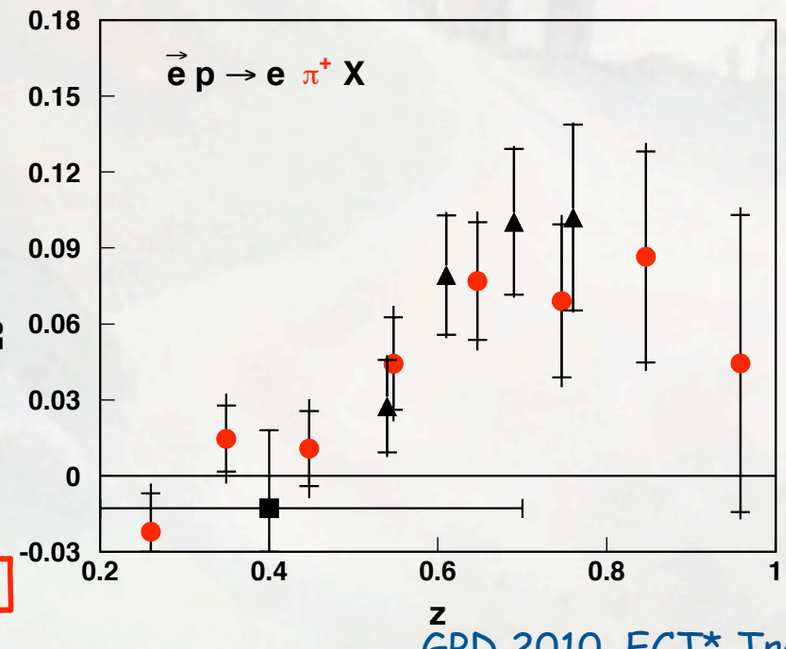
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^{\perp} D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



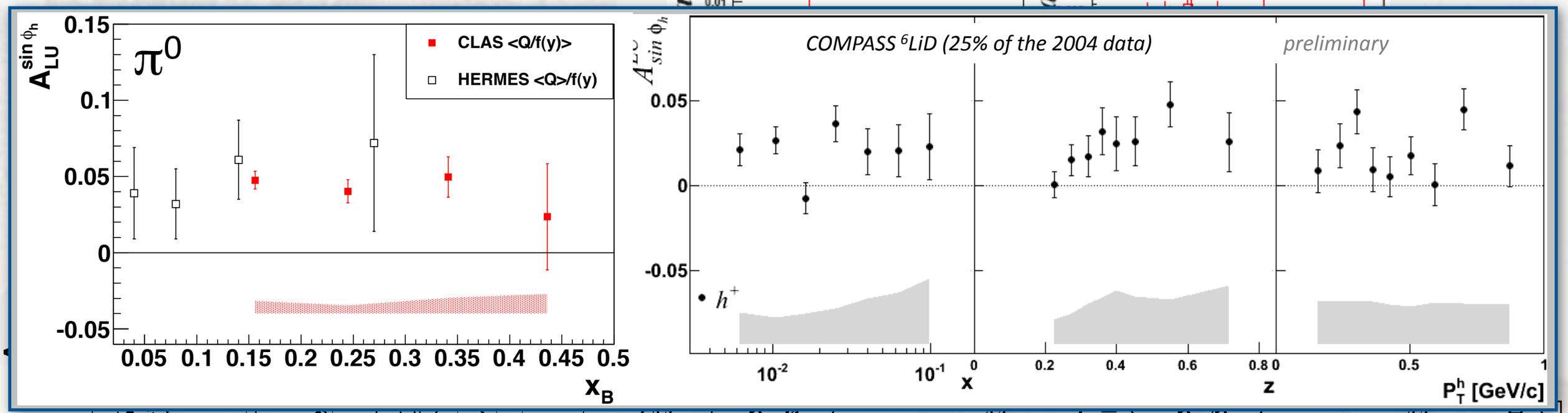
$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^{\perp} + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^{\perp} D_1 - \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

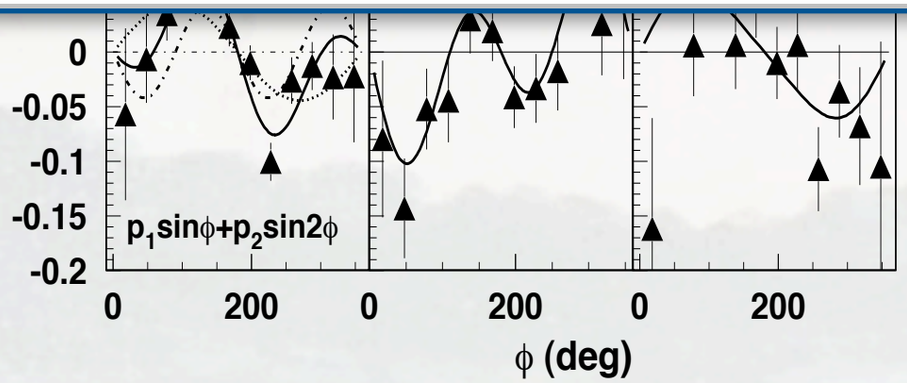
$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



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

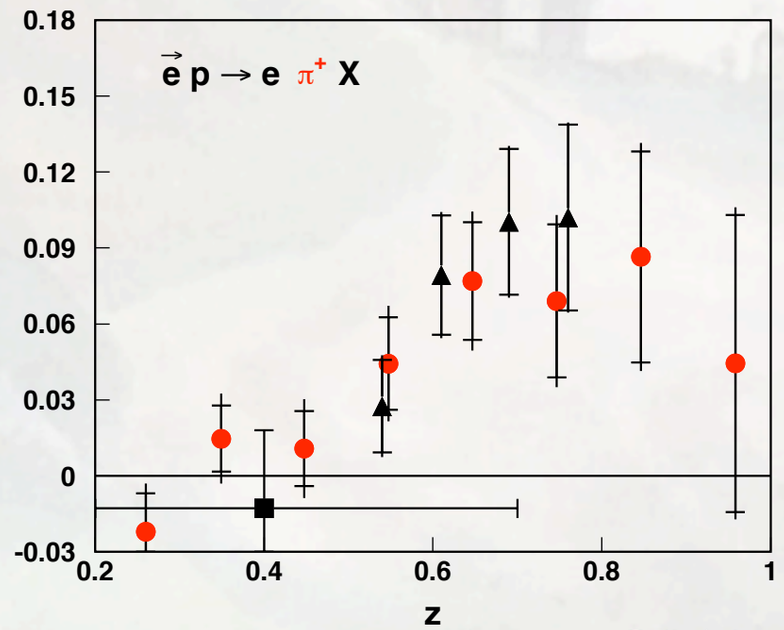
Other (twist-3) TMDs





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

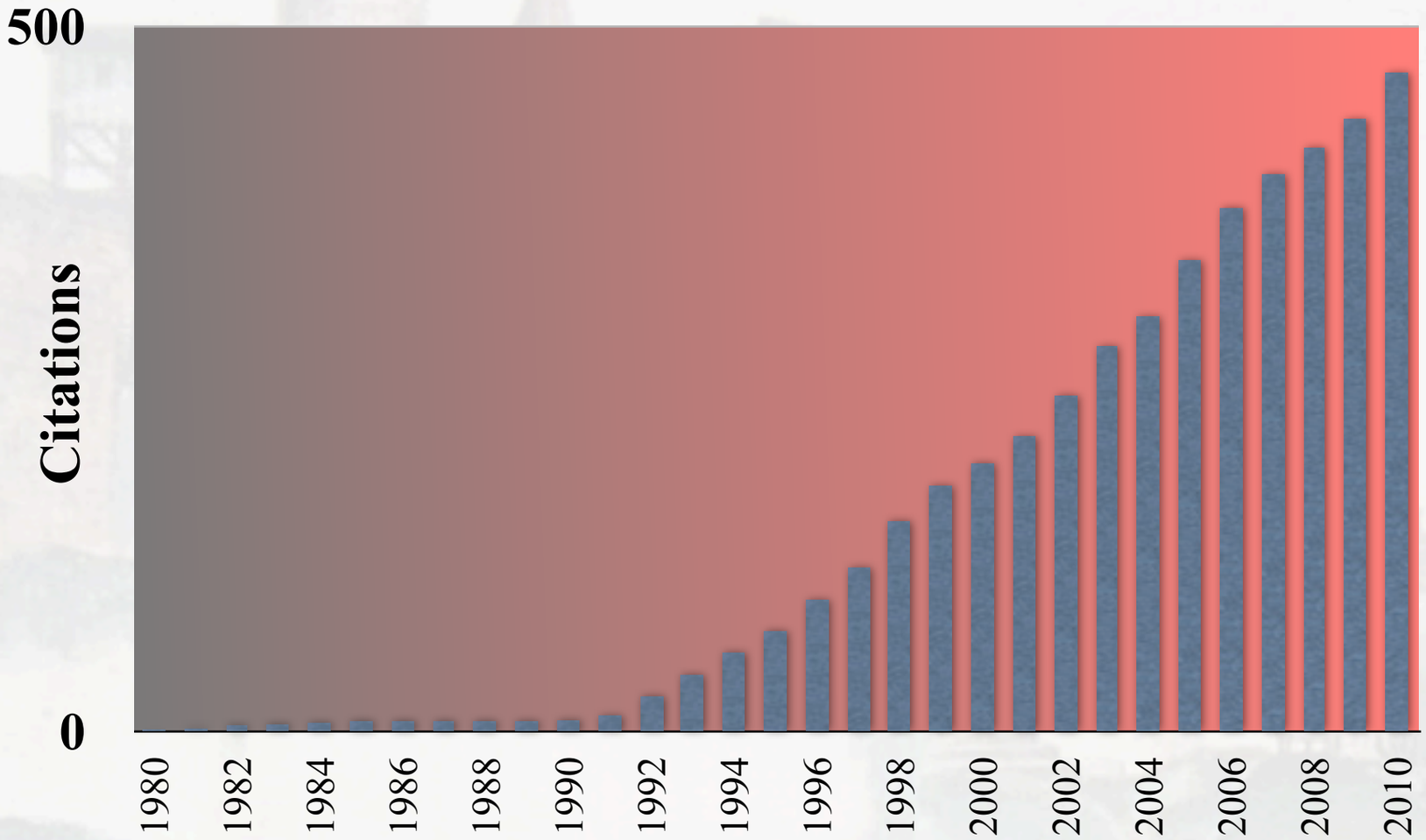
$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$



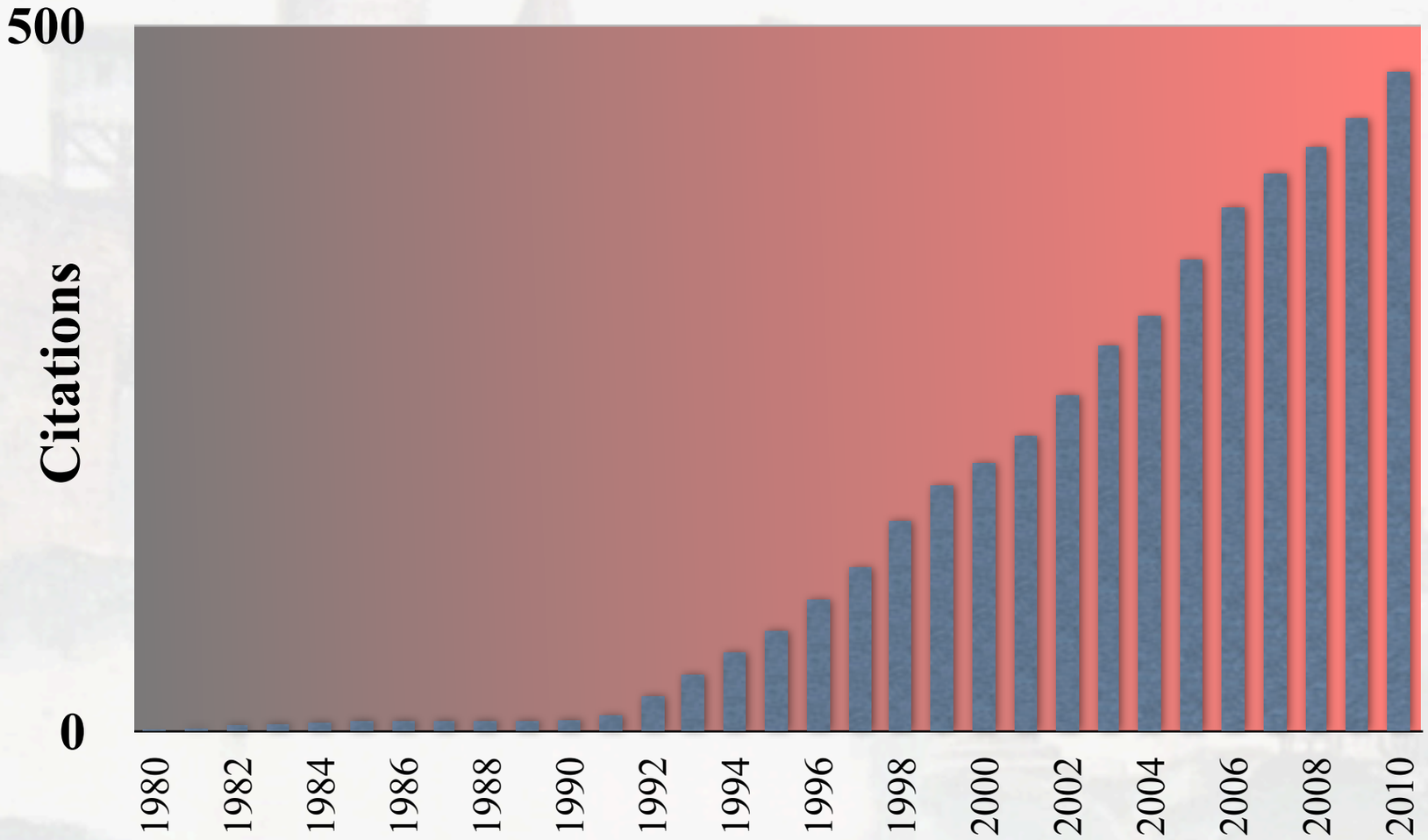
☛ H. Avakian, H. Wollny

Instead of a summary …

Instead of a summary …

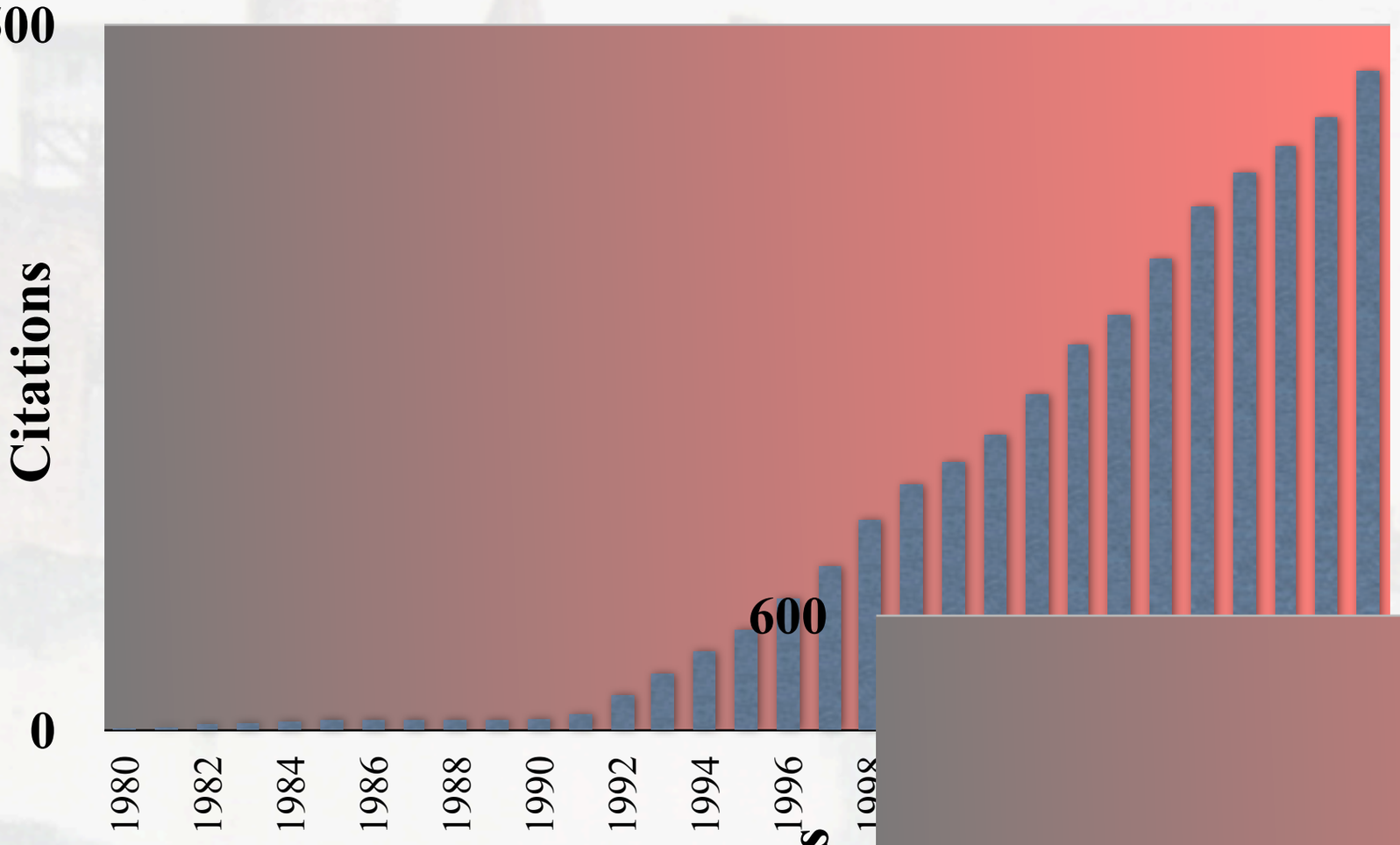


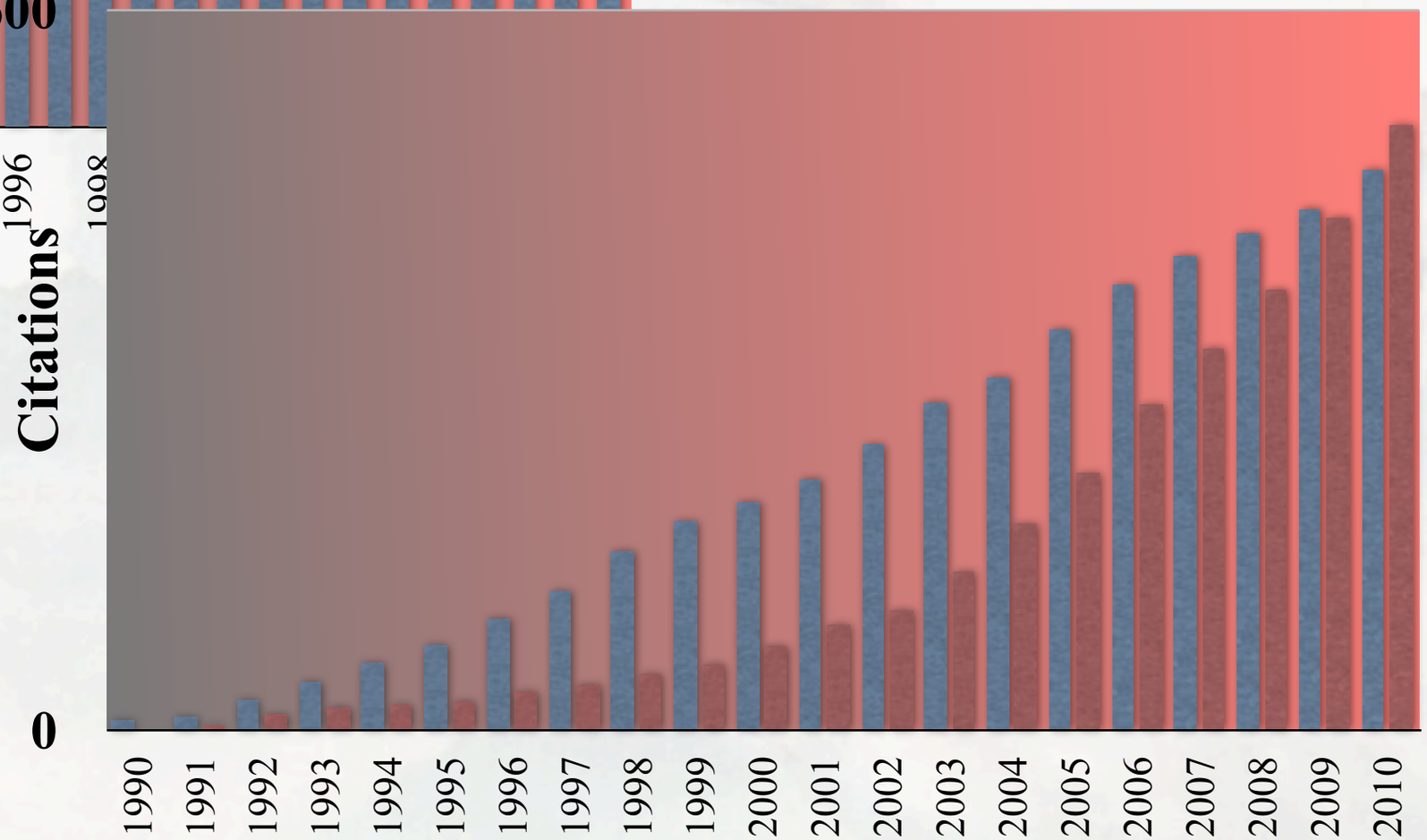
Instead of a summary …



☚ transversity '79
Ralston & Soper

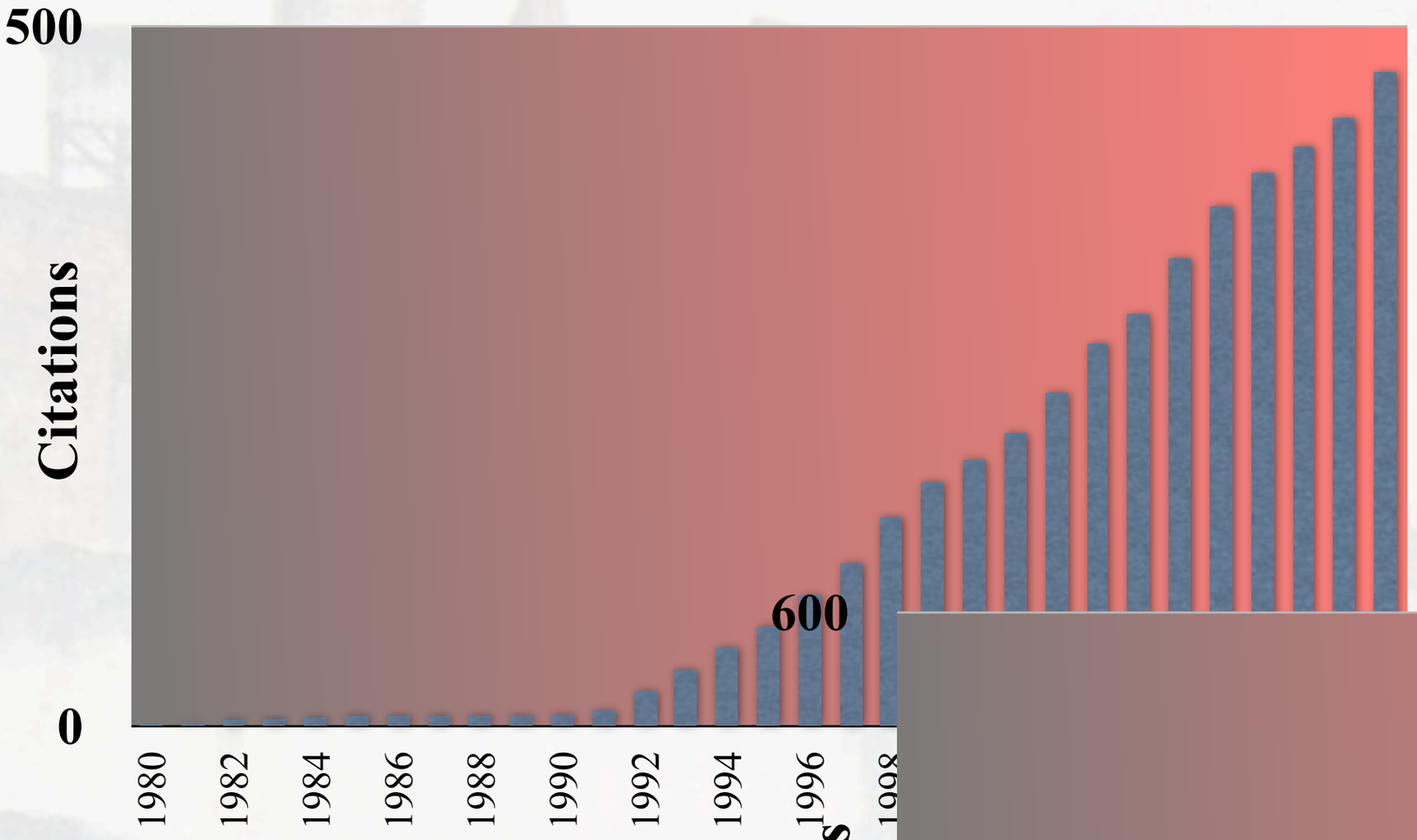
Instead of a summary …





☚ transversity '79
Ralston & Soper

Instead of a summary …



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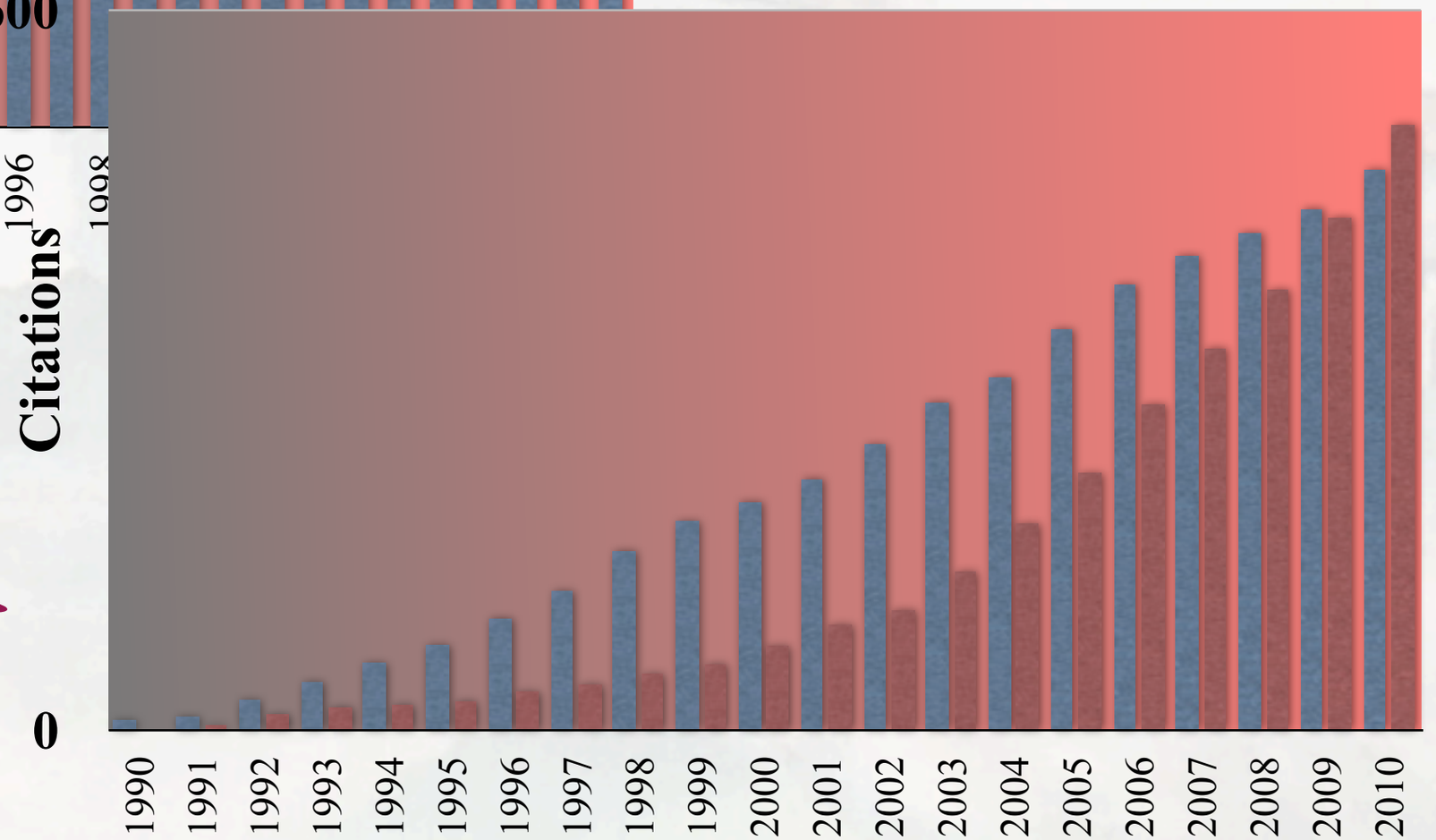
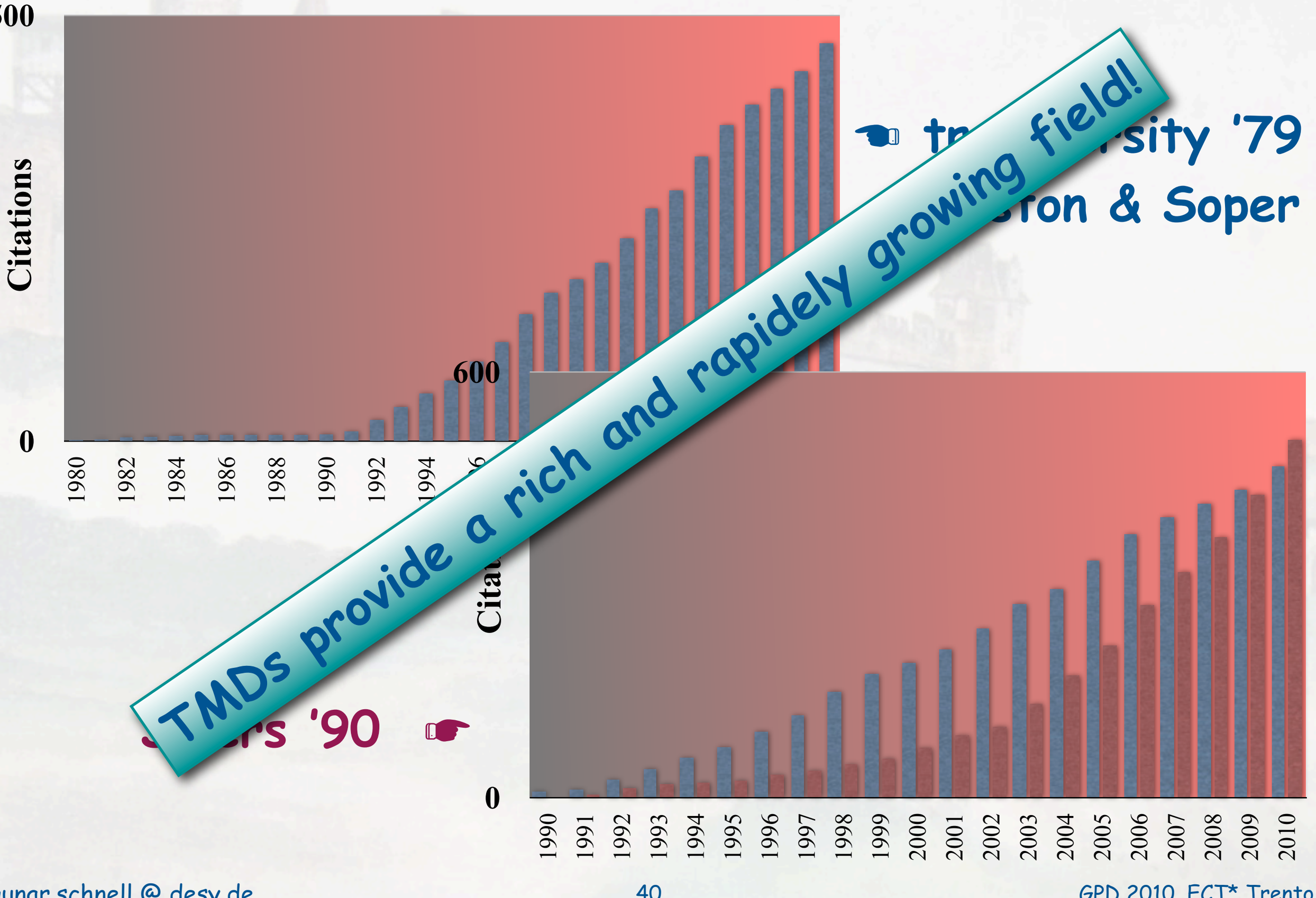


Sivers '90 ☚

Instead of a summary …



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…r's '90 ☛

TMDs provide a rich and rapidely growing field!