INT 12-49W Workshop on "Orbital Angular Momentum in QCD"
February 6th-17th, 2012 - INT

What semi-inclusive DIS has taught us about TMDs

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Euskal Herriko Unibertsitatea

... they exist!

Spin-Momentum Structure of the Nucleon

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

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

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

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, $h_{1T}^\perp$

- each TMD describes a particular spin-momentum correlation
- 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

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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TMD "discovery" status

quark pol.

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- flavor dependence (partially) explored

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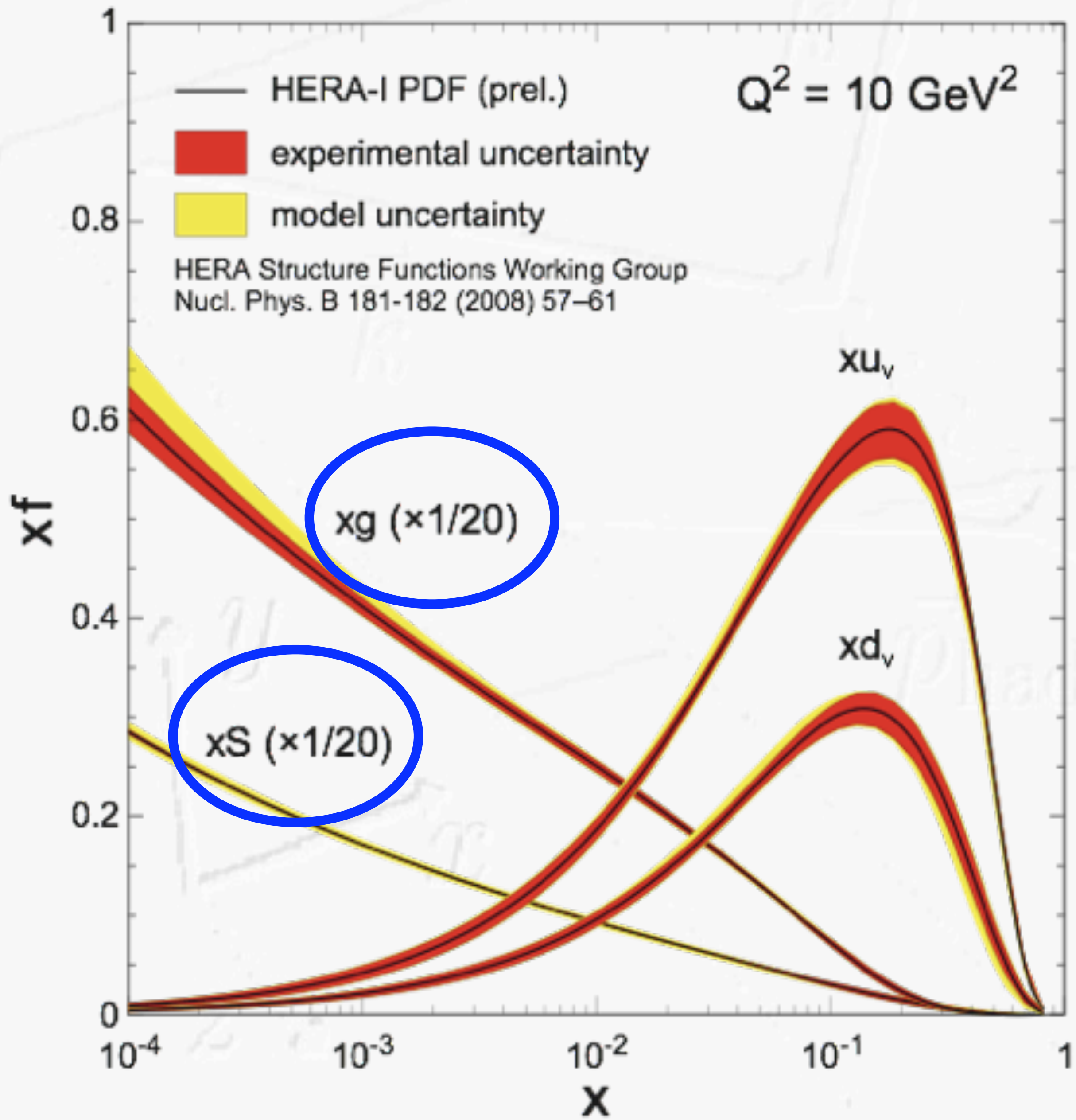
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

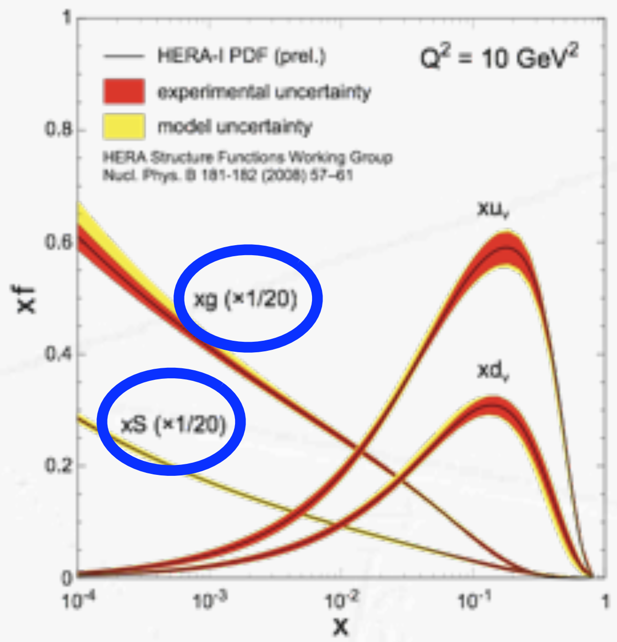
- flavor dependence (partially) explored
- transverse-momentum dependence (largely) unknown

snapshots



HERA-I PDF (prel.)
experimental uncertainty
model uncertainty
HERA Structure Functions Working Group
Nucl. Phys. B 181-182 (2008) 57–61
$Q^2 = 10\ GeV^2$
xu_v
xd_v
xg (×1/20)
xS (×1/20)
xf
x

snapshots

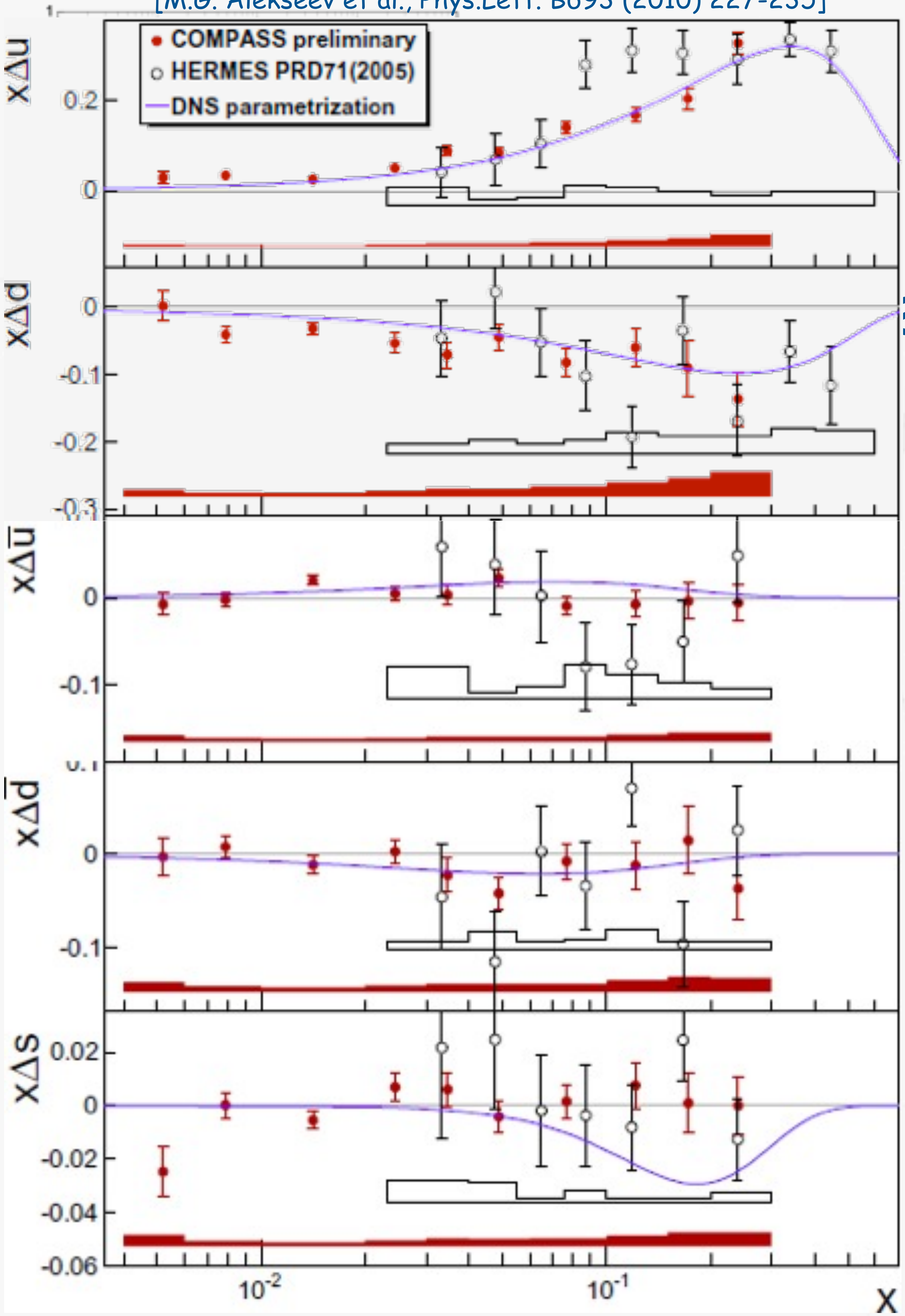


need p_T dependence for f_1 ☛ 6mins*)

*) numbers in A=0 (= no Audience) gauge

snapshots

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



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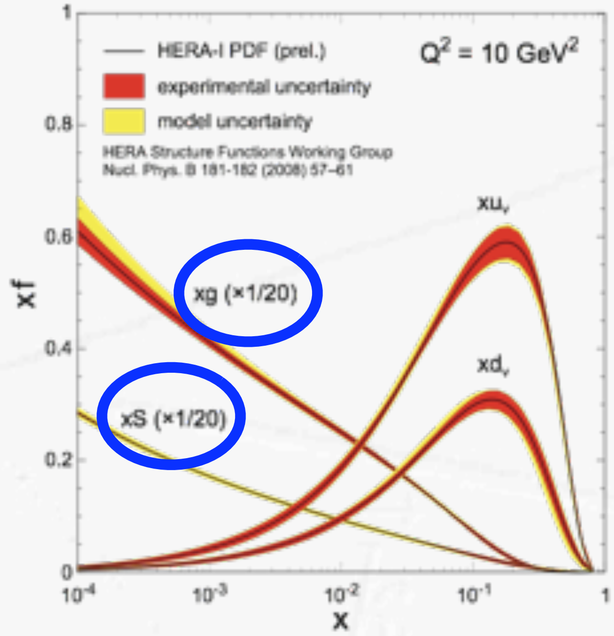

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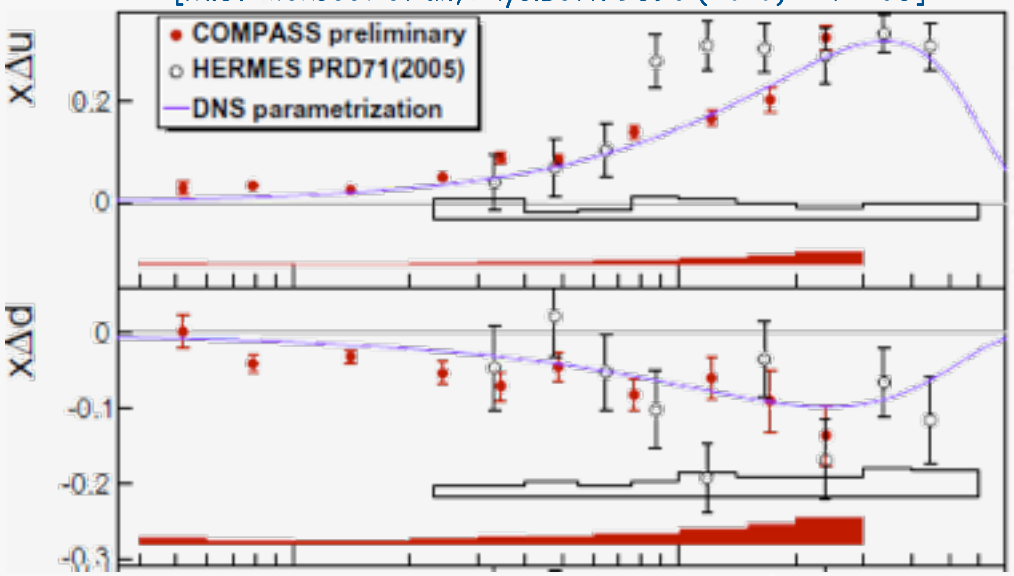
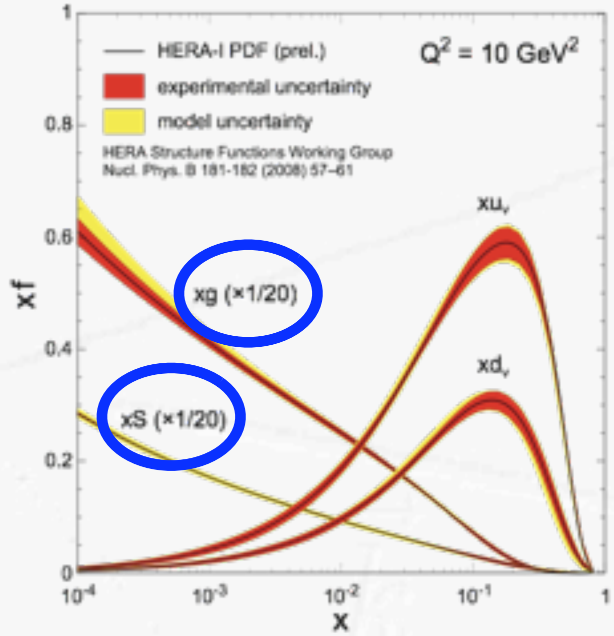


p_T dependence for g_1 ☛ 10mins*)

*) numbers in A=0 (= no Audience) gauge

snapshots



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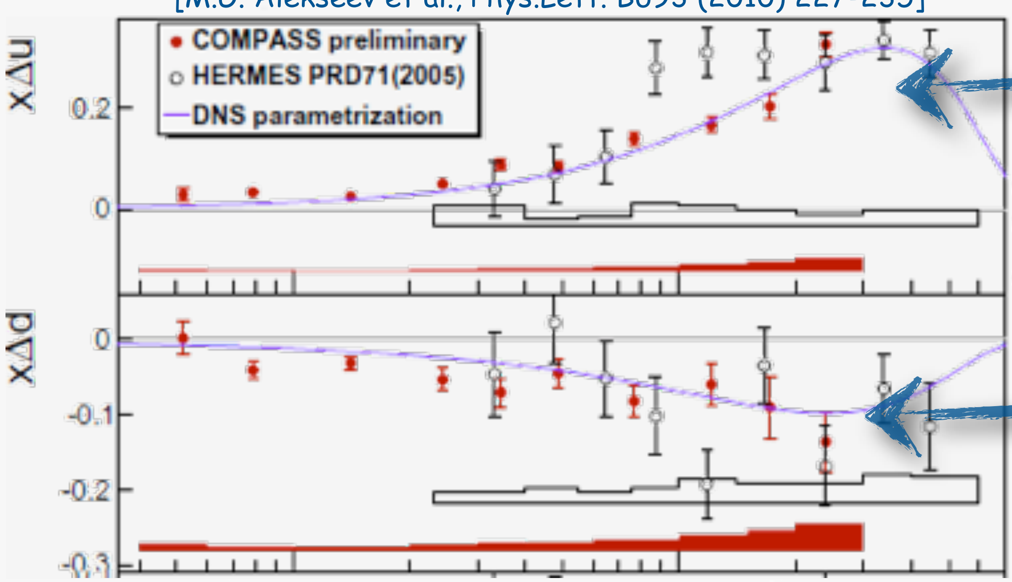
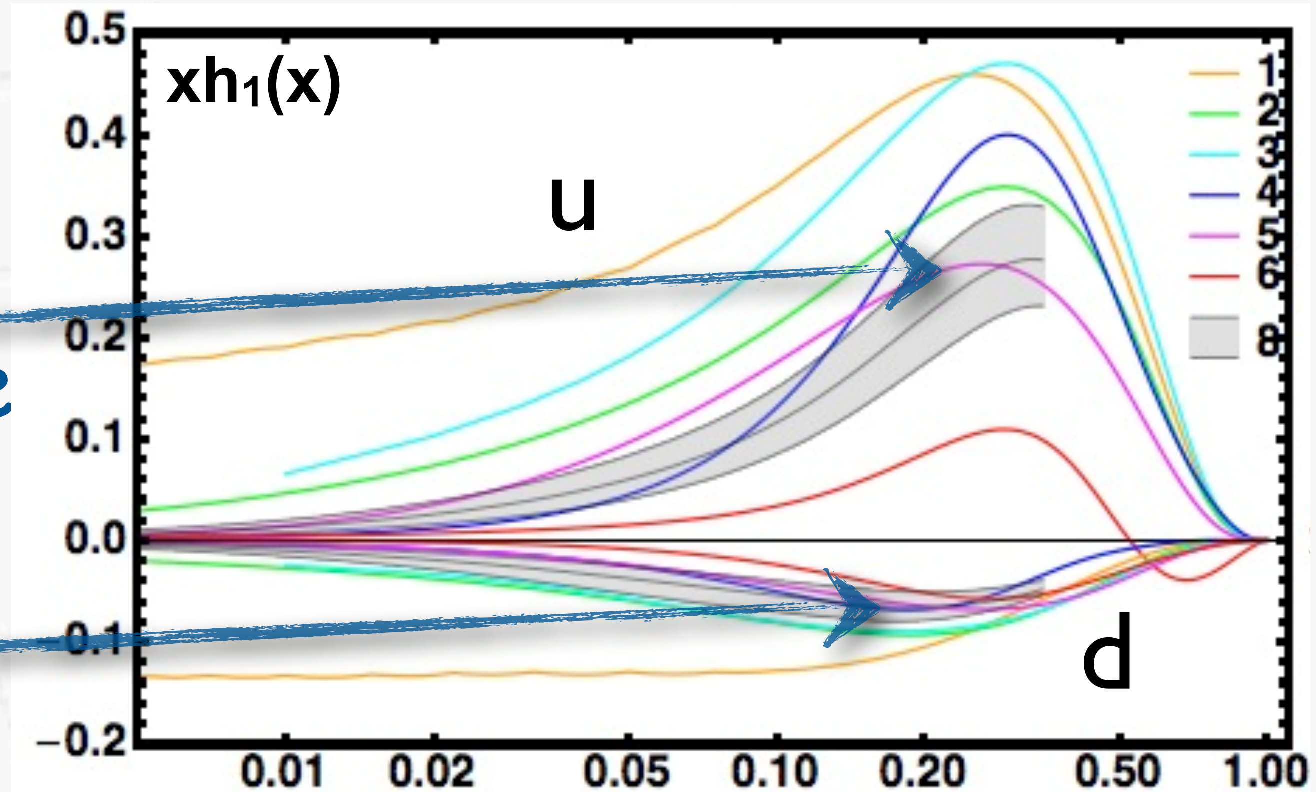
[M.G. Alekseev et al., Phys.Lett. B693 (2010) 227-235]



p_T de



1-6 … various model curves

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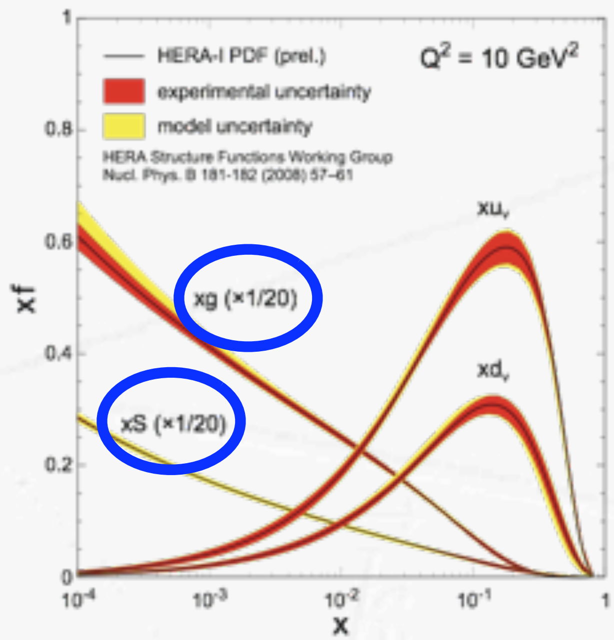
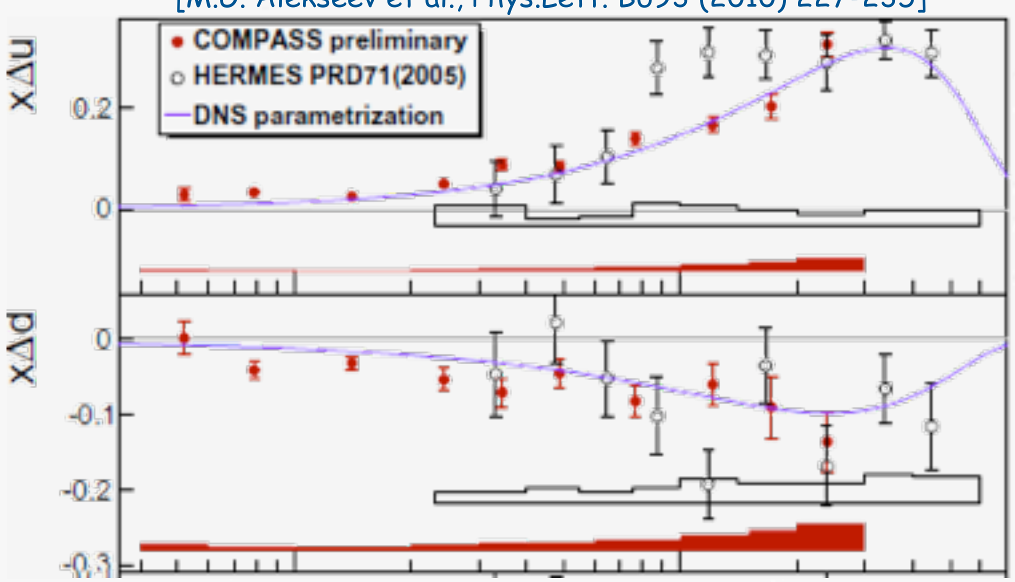
snapshots

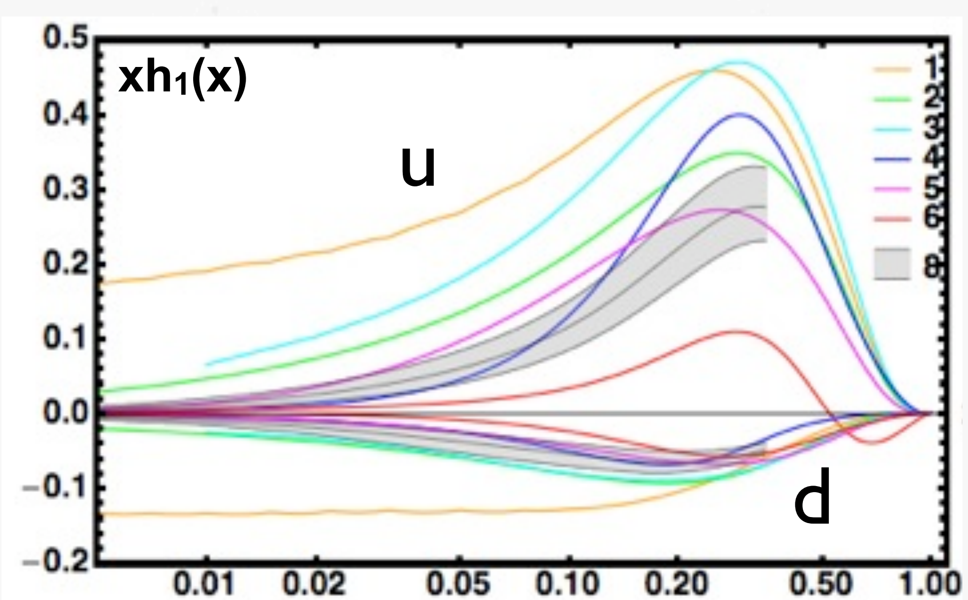


need p_T dependence for f_1 ☛ 6mins*)

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



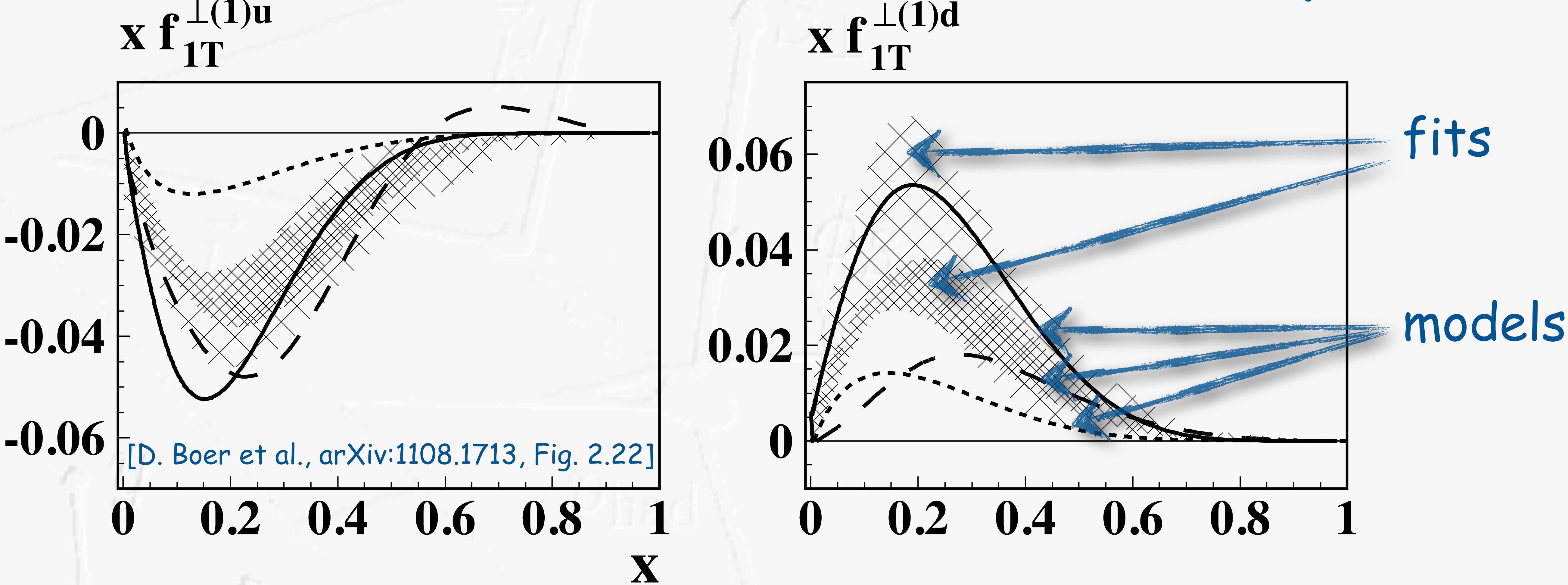
p_T dependence for g_1 ☛ 10mins*)



the data for h_1 ☛ 15mins*)

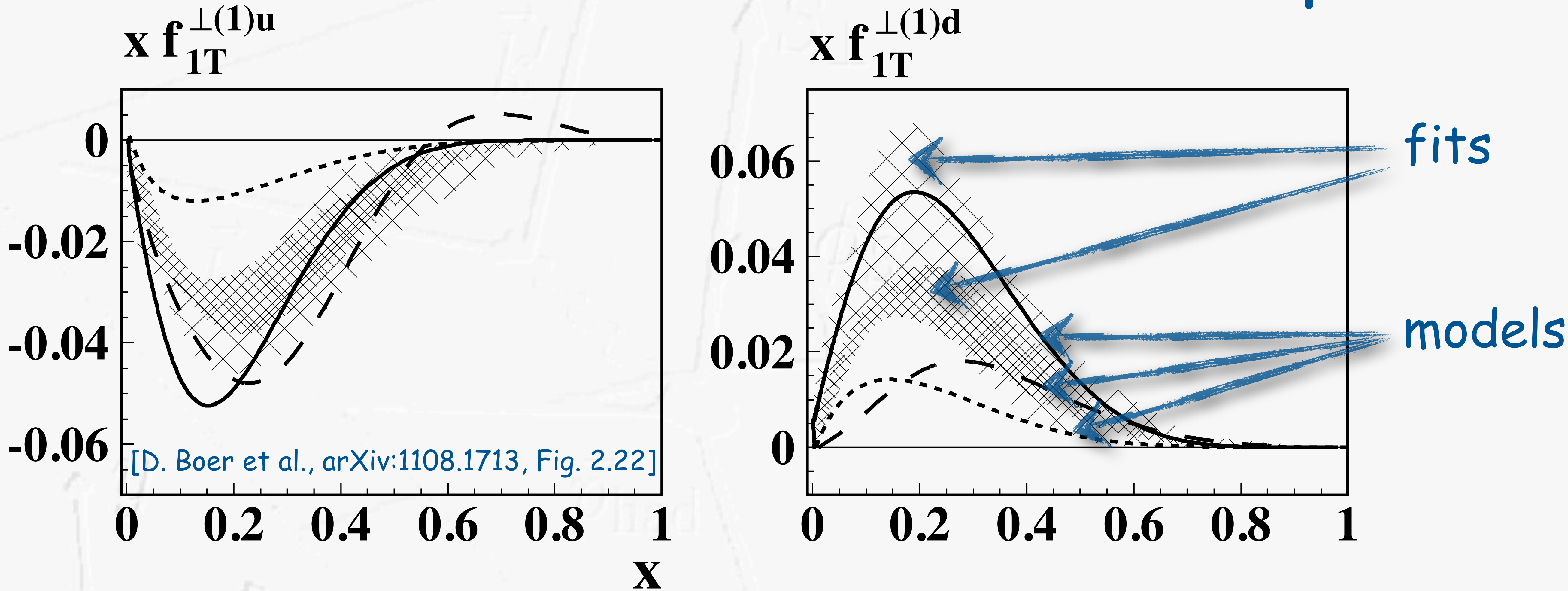
*) numbers in A=0 (= no Audience) gauge

snapshots



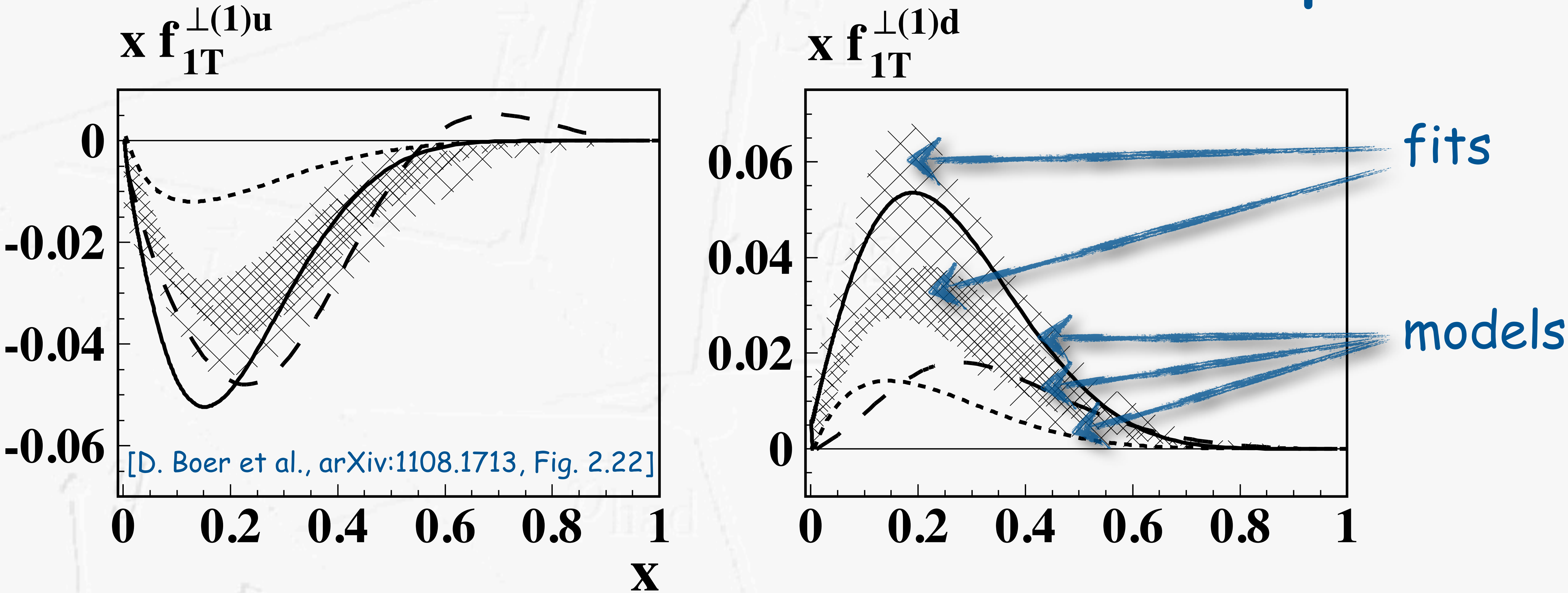
$x\,f_{1T}^{\perp(1)u}$
0
-0.02
-0.04
-0.06
[D. Boer et al., arXiv:1108.1713, Fig. 2.22]
0 0.2 0.4 0.6 0.8 1
x
$x\,f_{1T}^{\perp(1)d}$
0.06
0.04
0.02
0
0 0.2 0.4 0.6 0.8 1
fits
models

snapshots



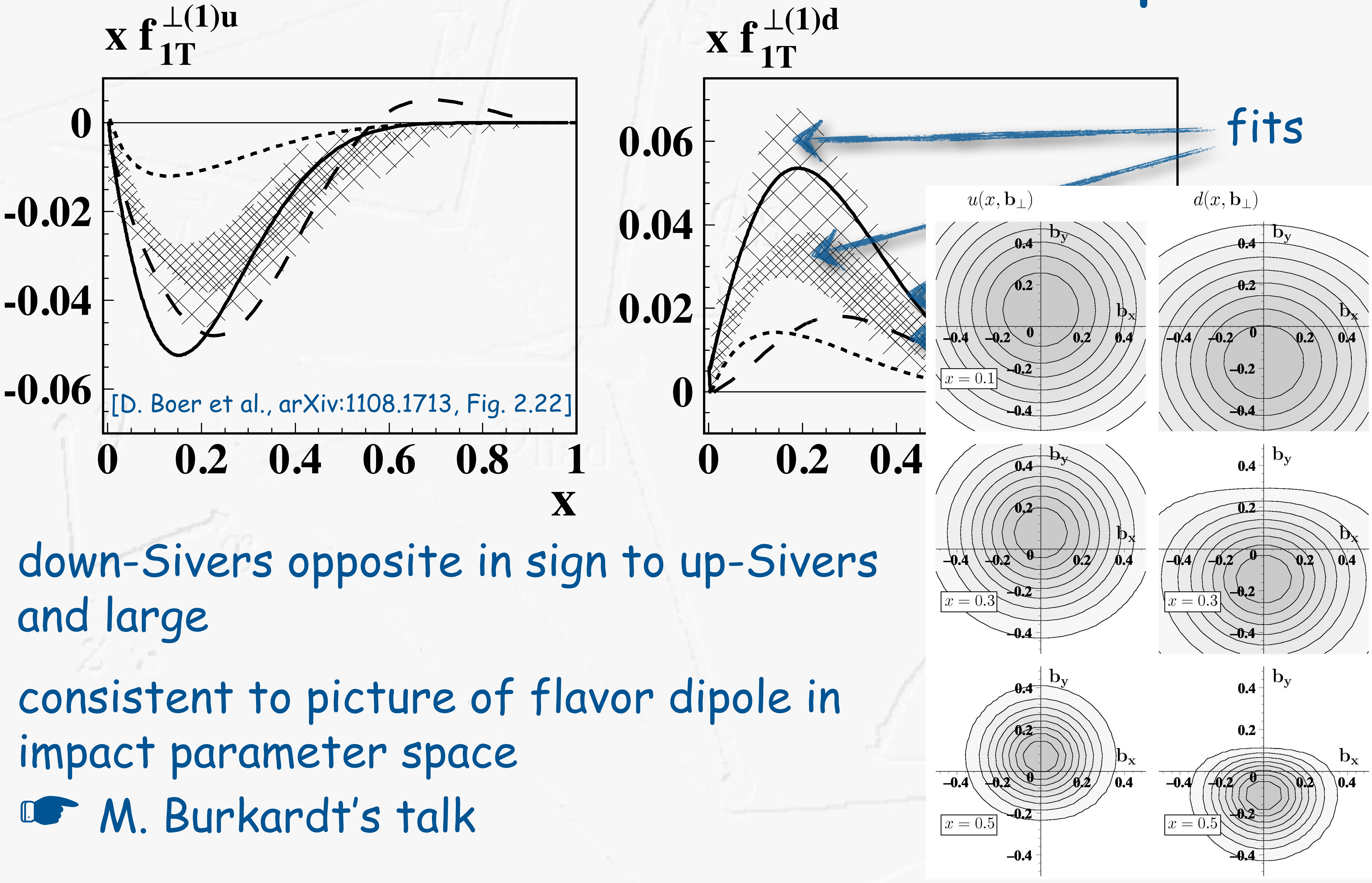
- down-Sivers opposite in sign to up-Sivers and large

snapshots



- down-Sivers opposite in sign to up-Sivers and large
- consistent to picture of flavor dipole in impact parameter space
  ☛ M. Burkardt's talk

snapshots



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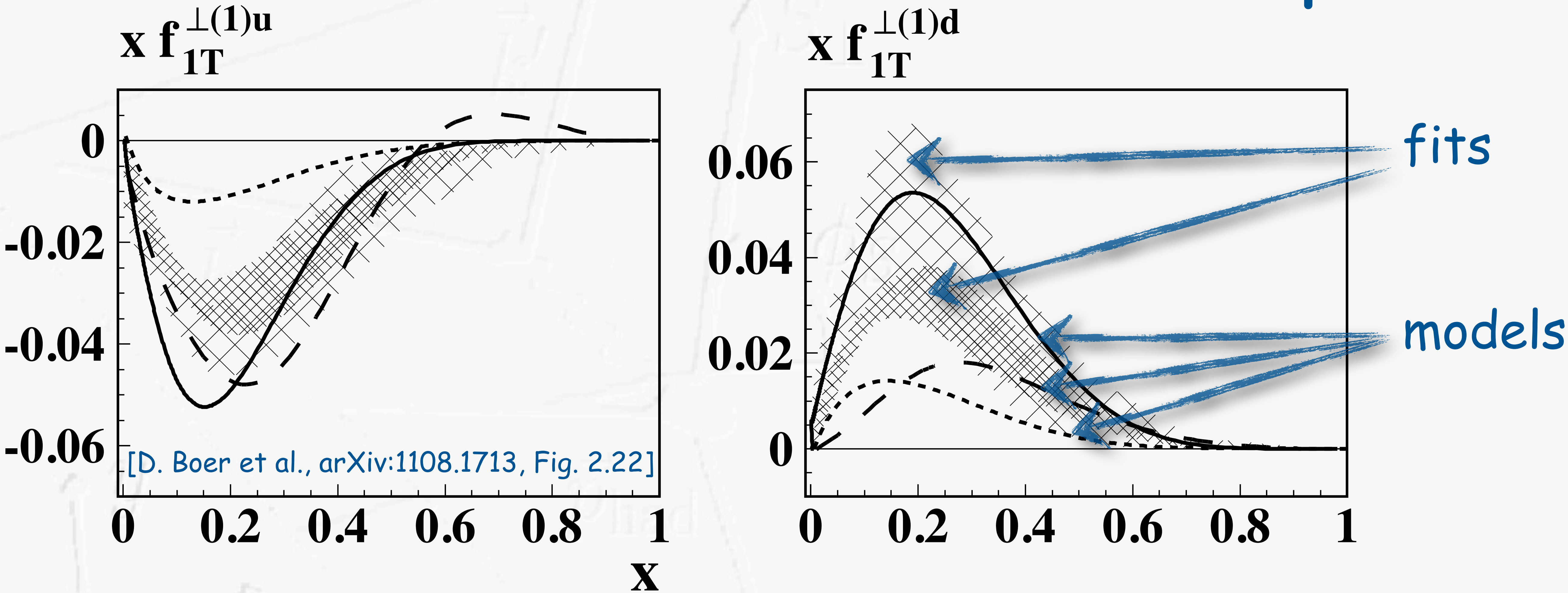

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the data ☛ 25mins*)

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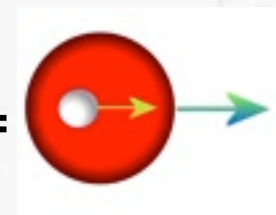
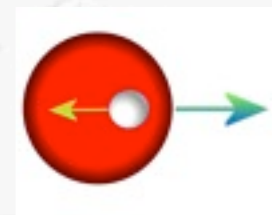
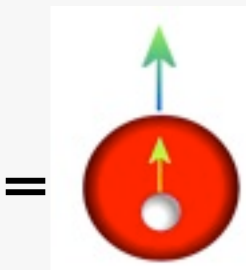
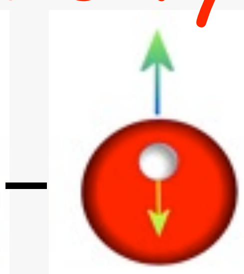
The details

	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-odd distribution

chiral-odd distributions involve quark helicity flip

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

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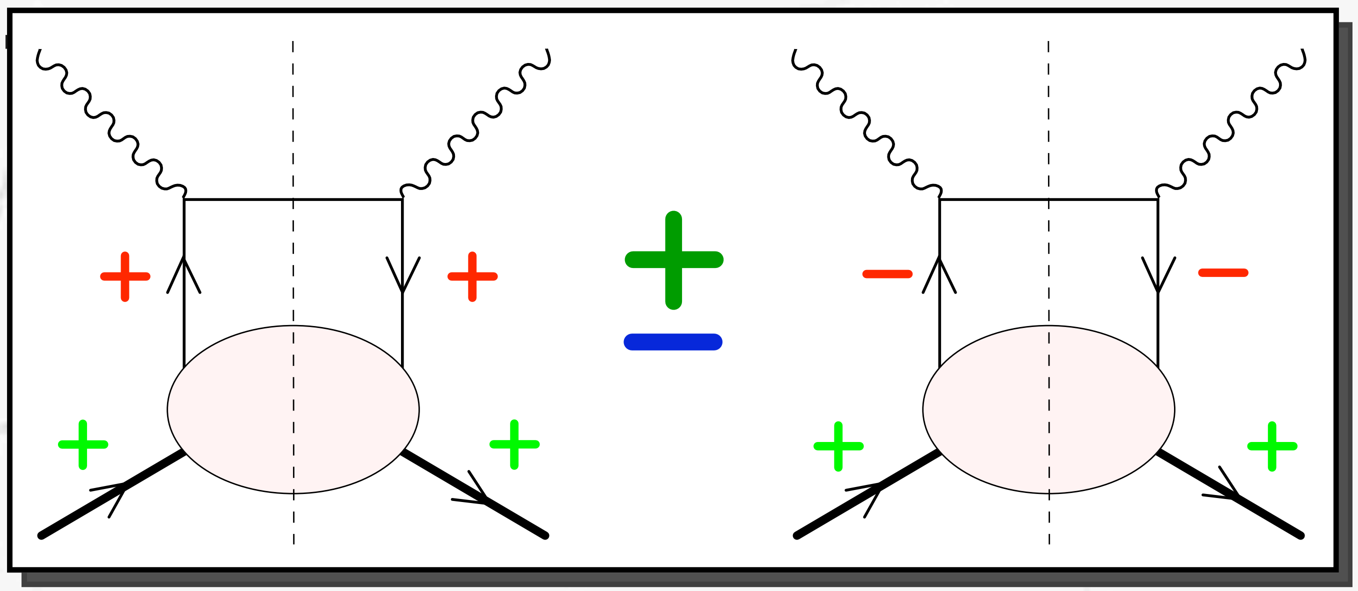

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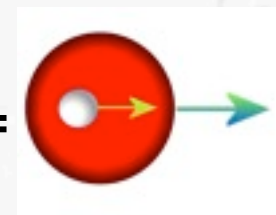
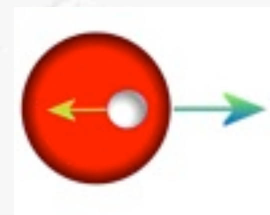
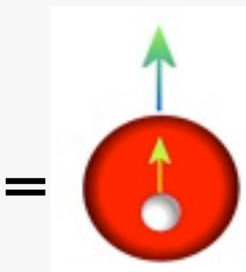
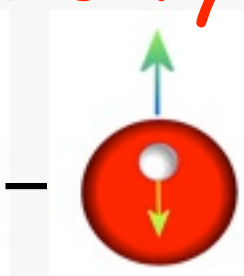
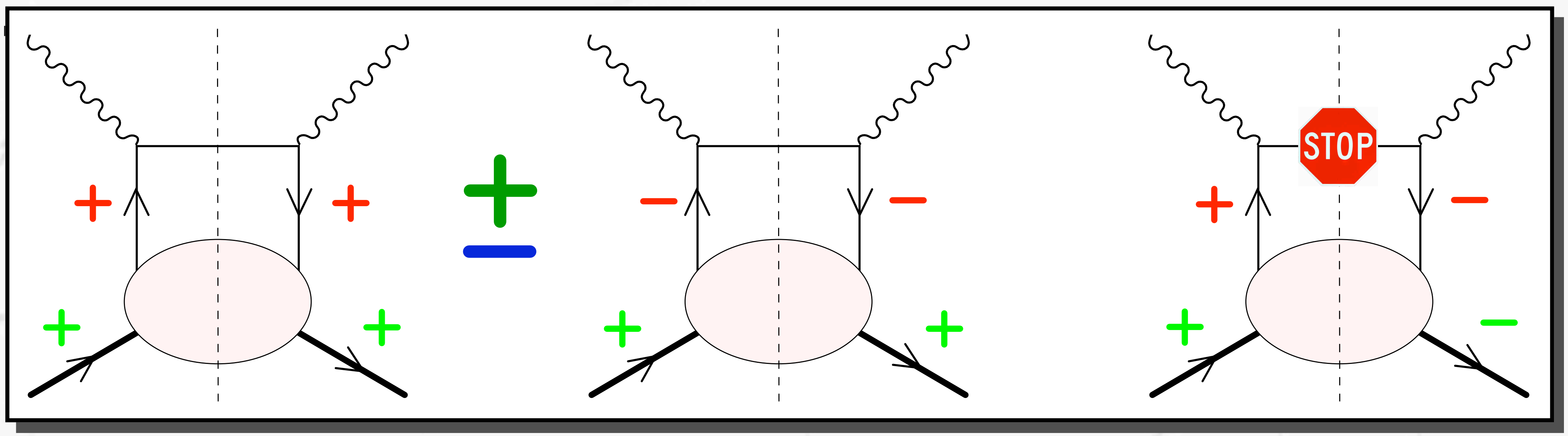
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 



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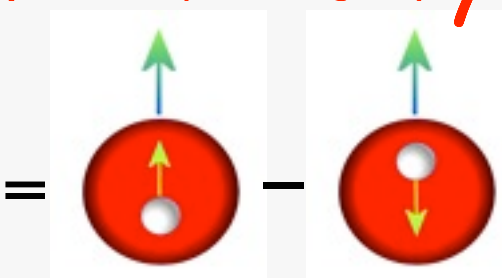
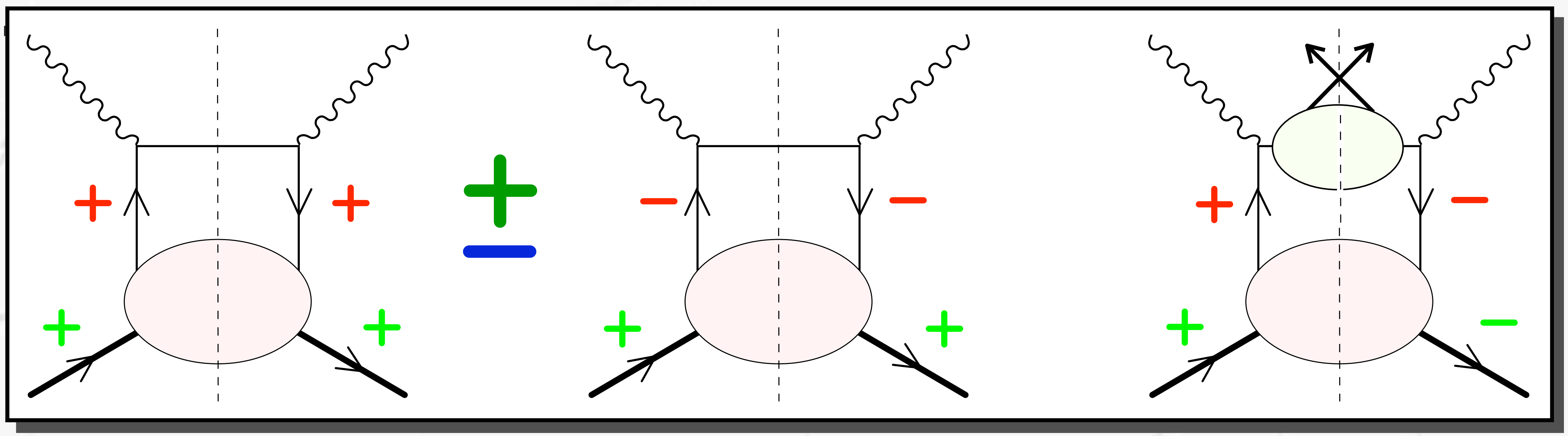
$h_1^q =$ 



need to couple to chiral-odd fragmentation function:

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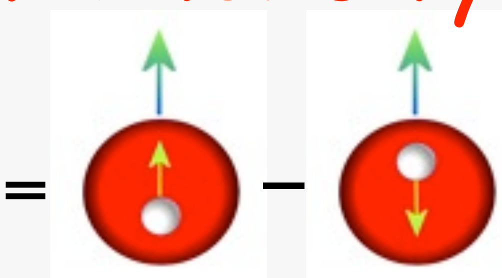
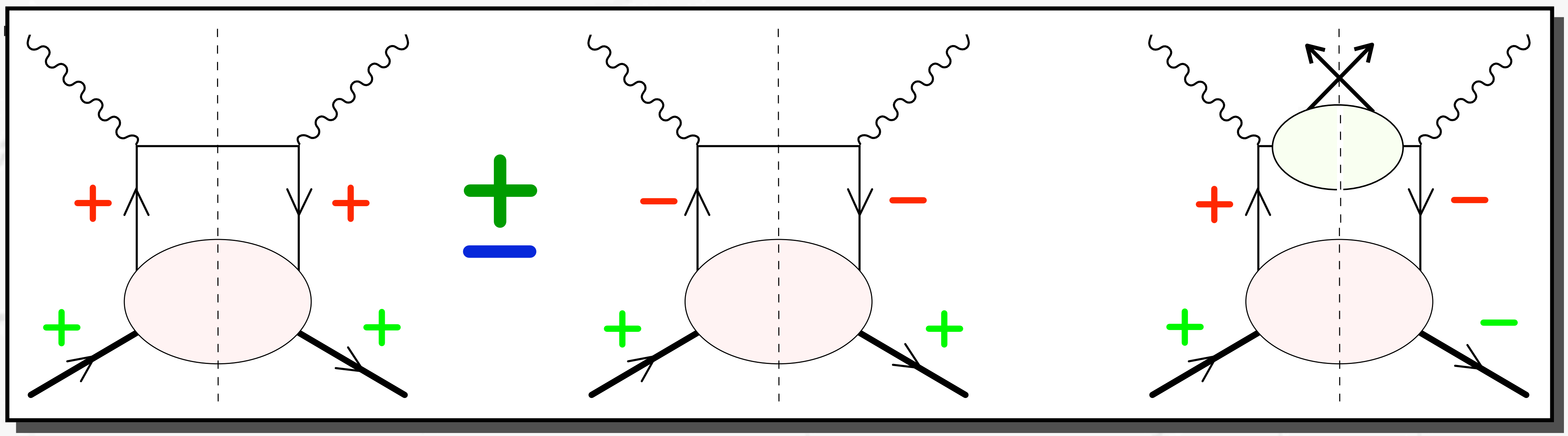
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



need to couple to chiral-odd fragmentation function:

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

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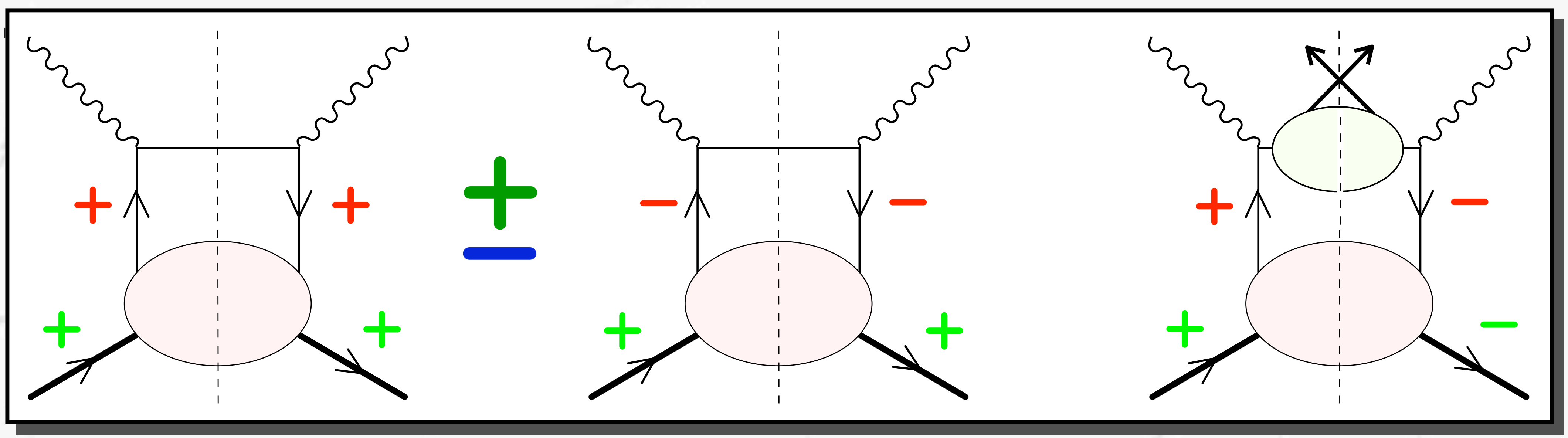

need to couple to chiral-odd fragmentation function:

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

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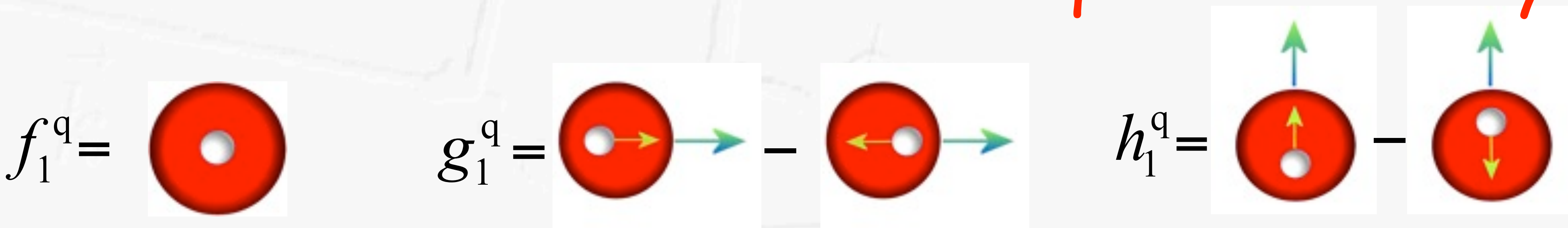

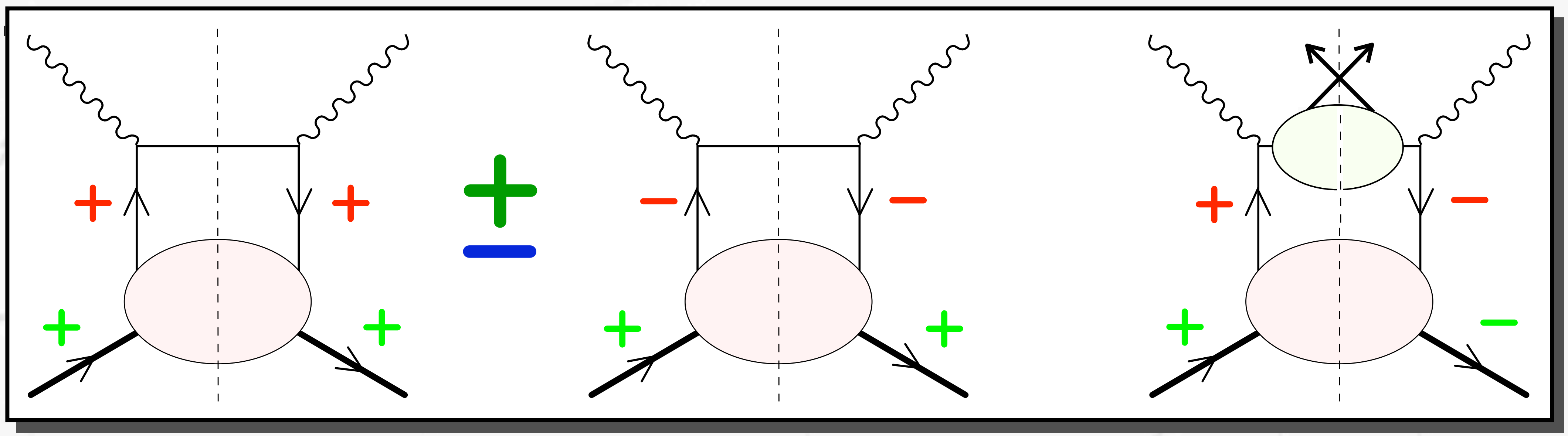

need to couple to chiral-odd fragmentation function:

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

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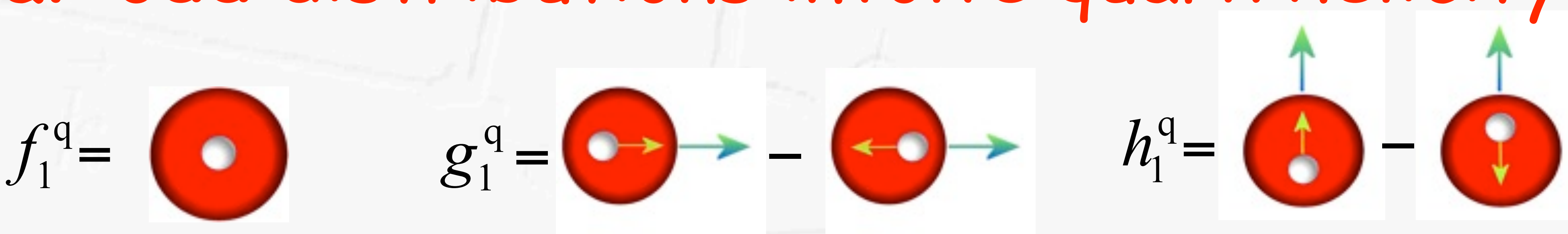

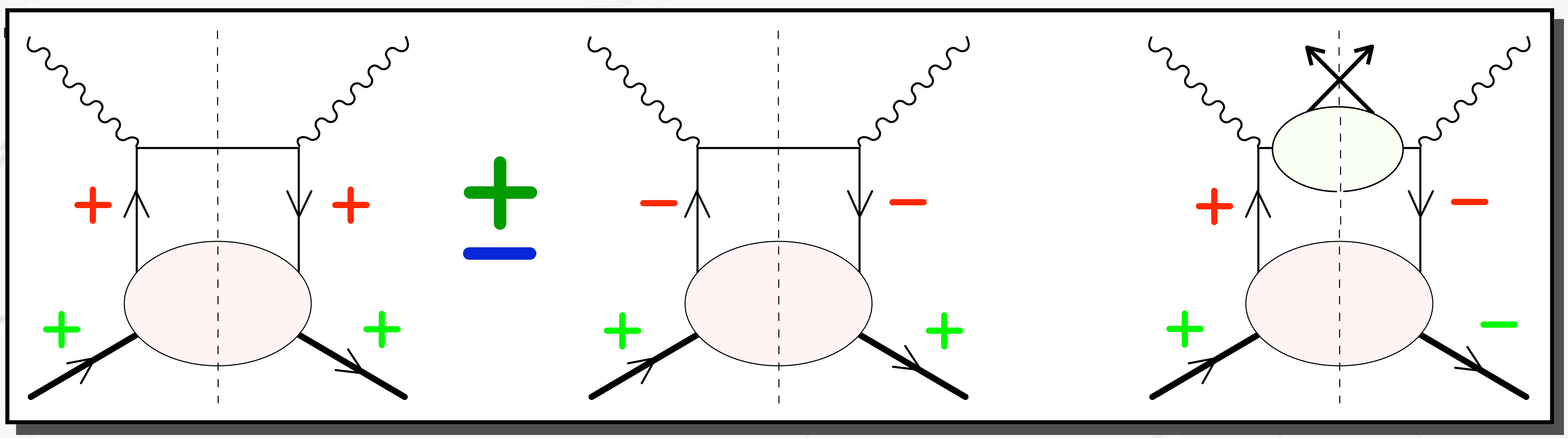

need to couple to chiral-odd fragmentation function:

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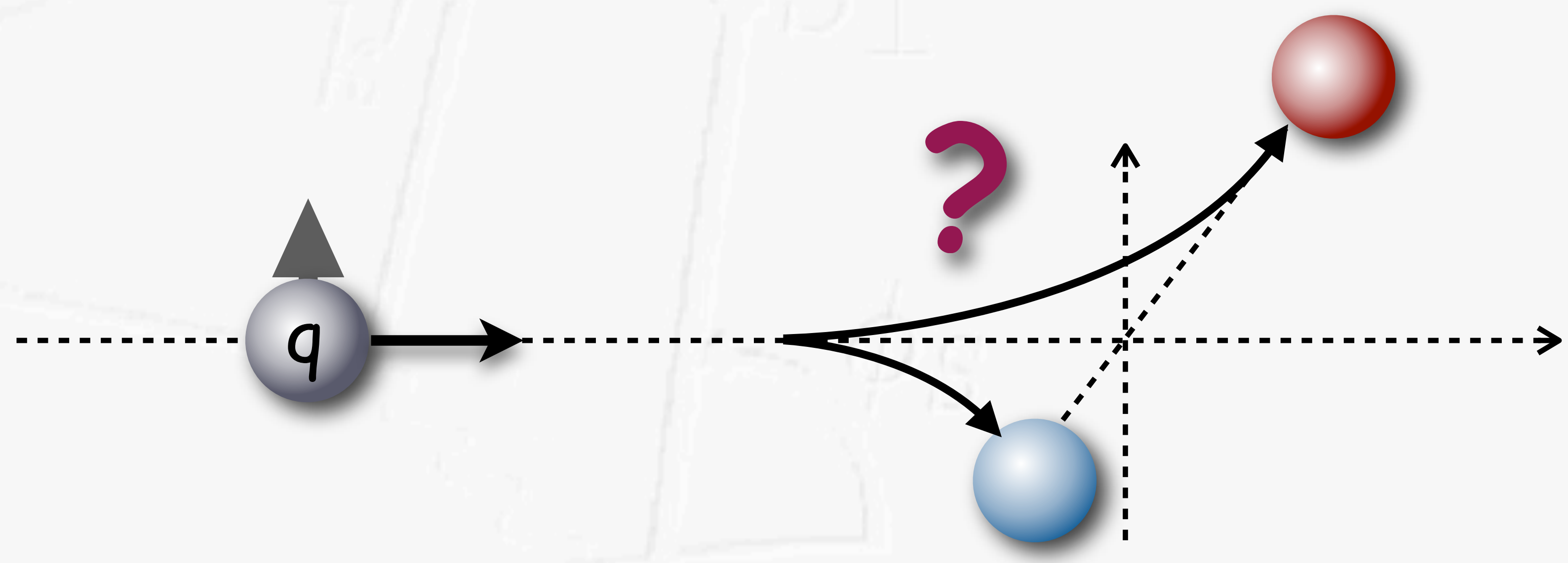
- ☑ **Collins fragmentation**

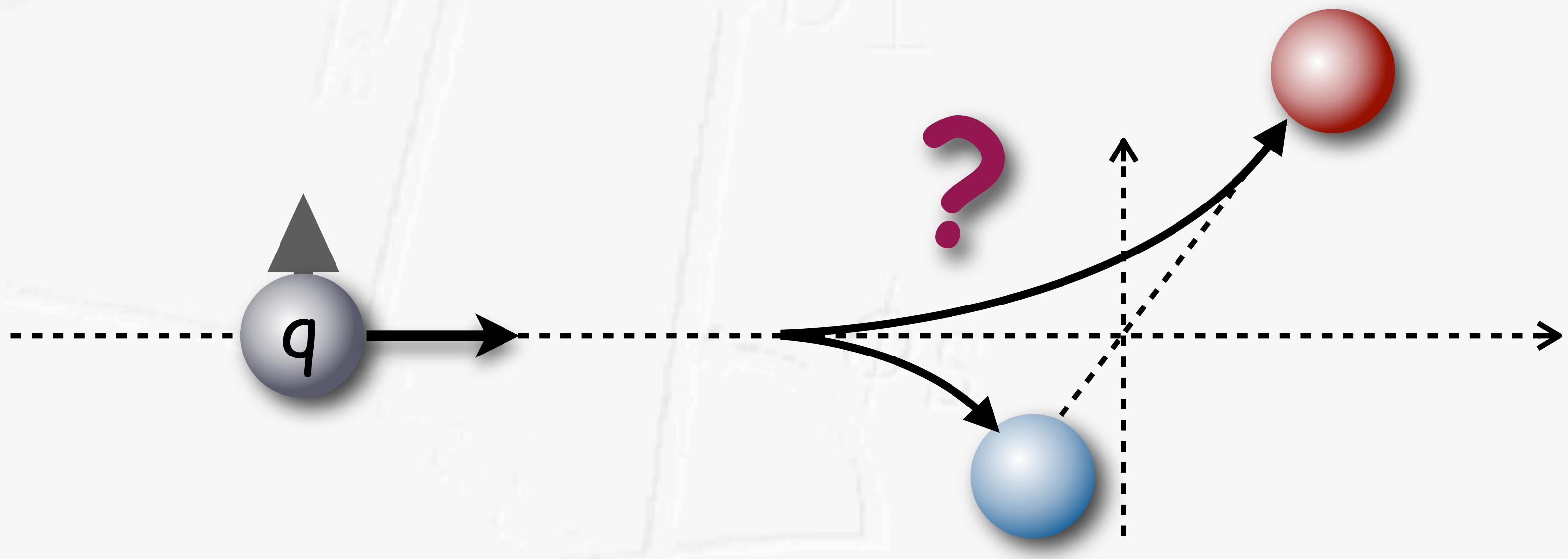
data / details ☛ R. Seidl

Collins fragmentation



- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum

Collins fragmentation



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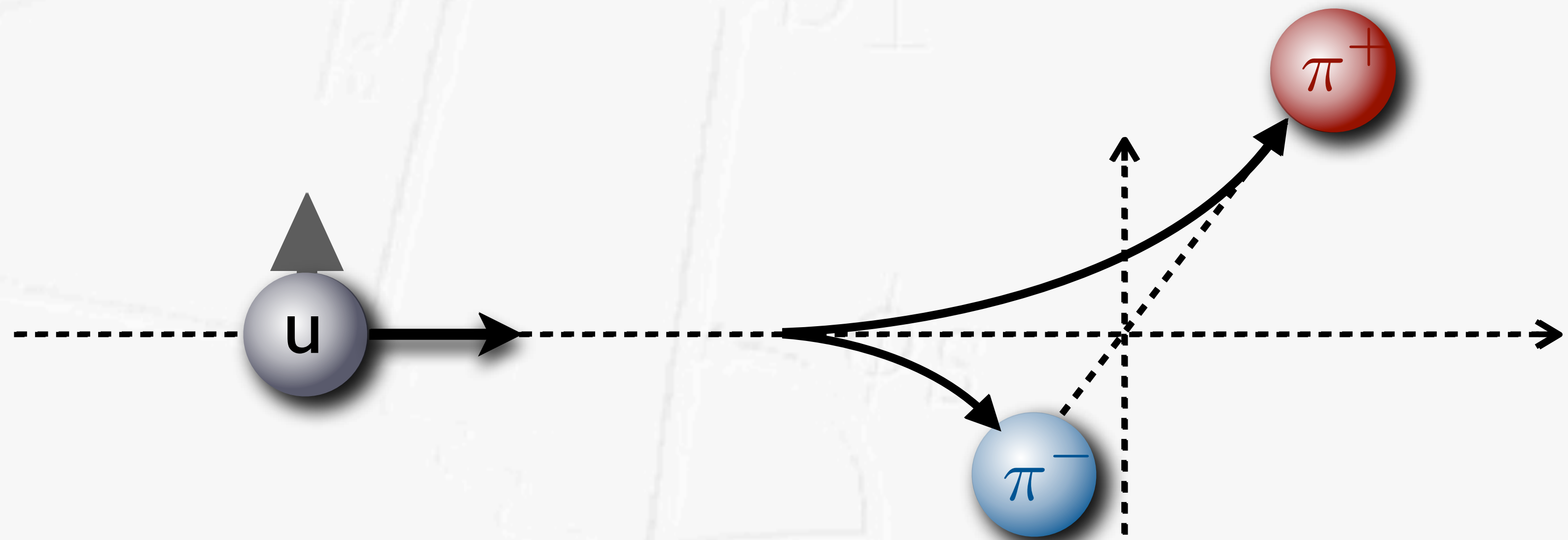
- extracted from SIDIS and e^+e^- annihilation data

Collins fragmentation



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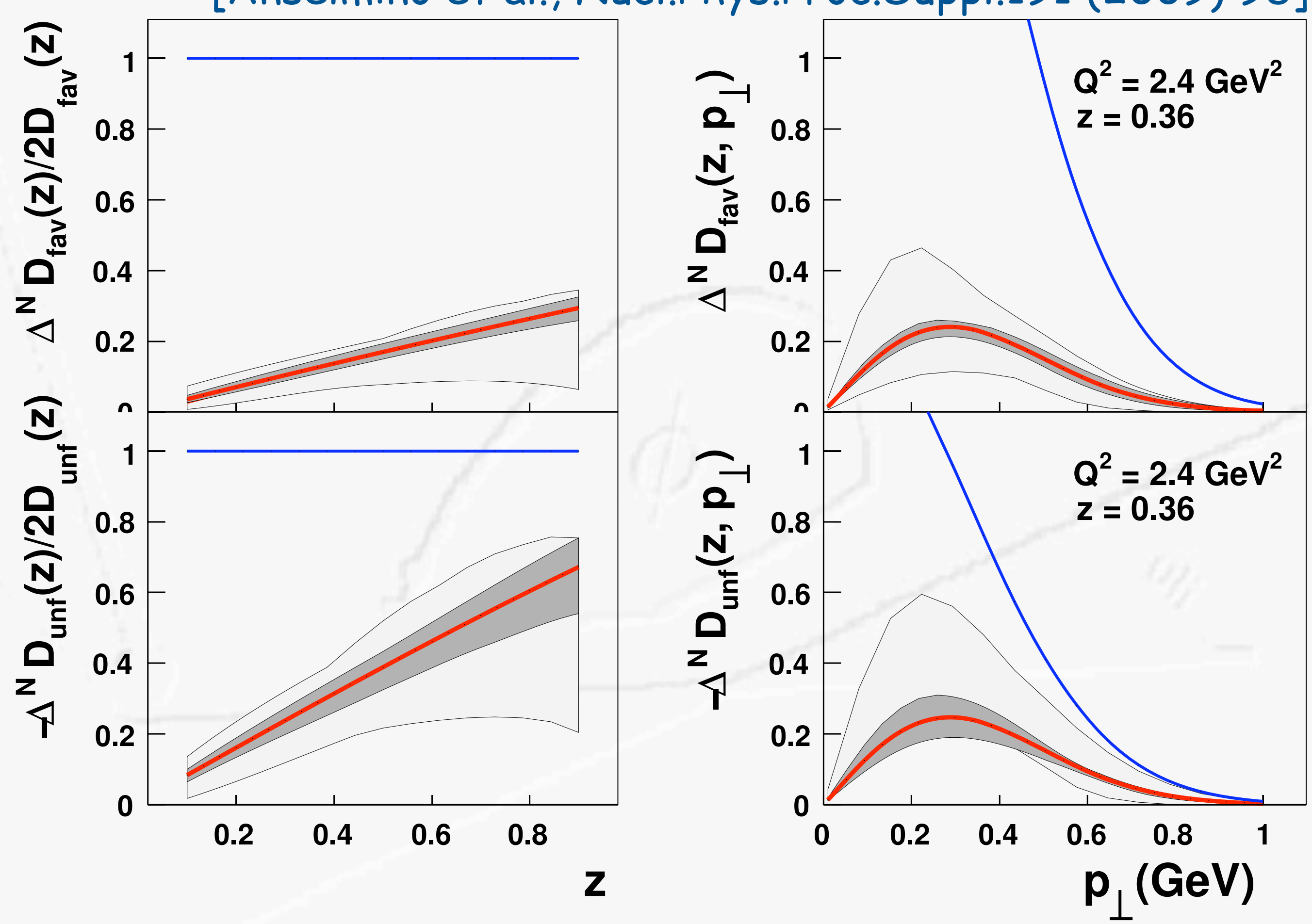
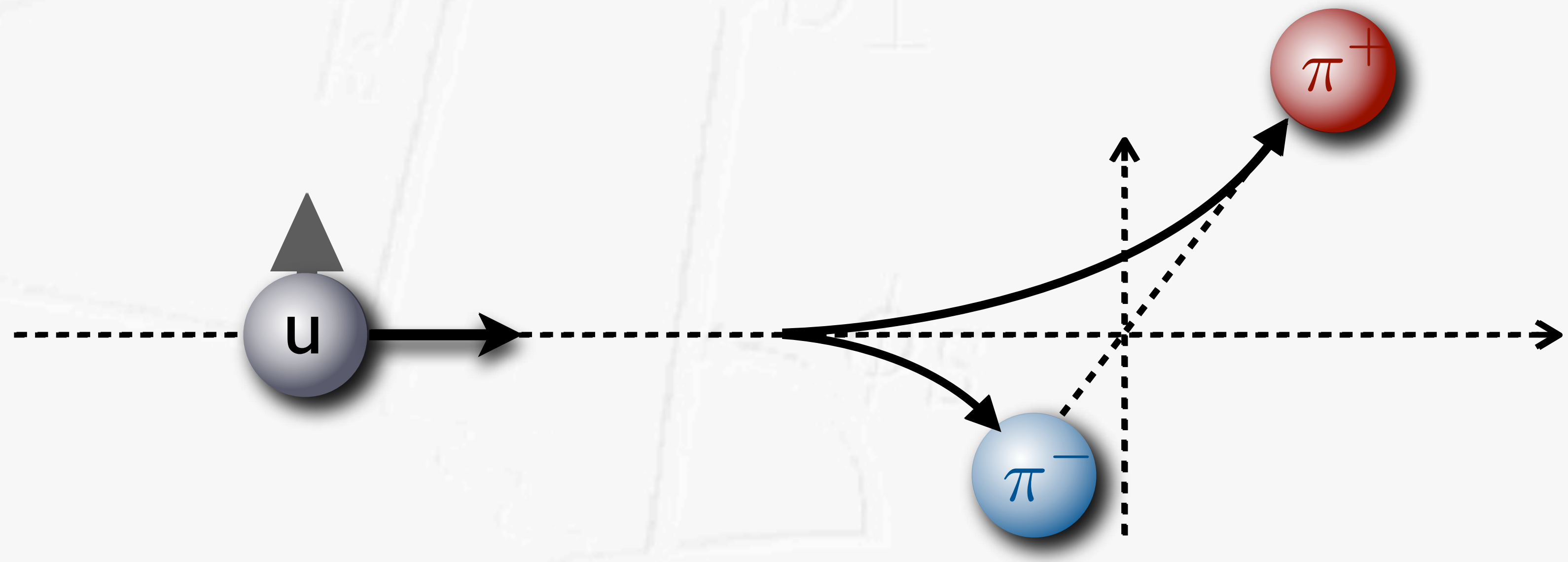
[Anselmino et al., Nucl.Phys.Proc.Suppl.191 (2009) 98]



Collins fragmentation



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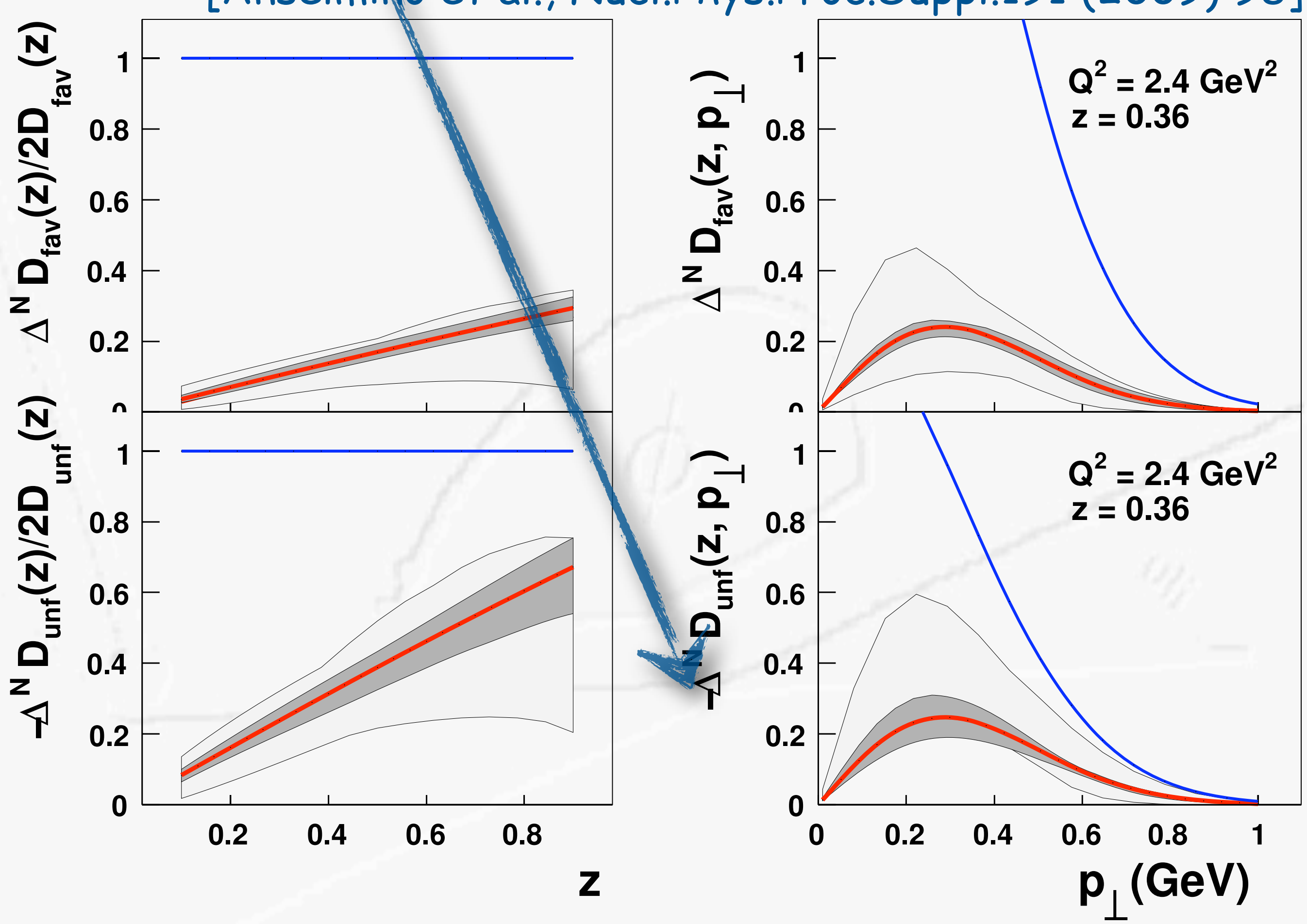

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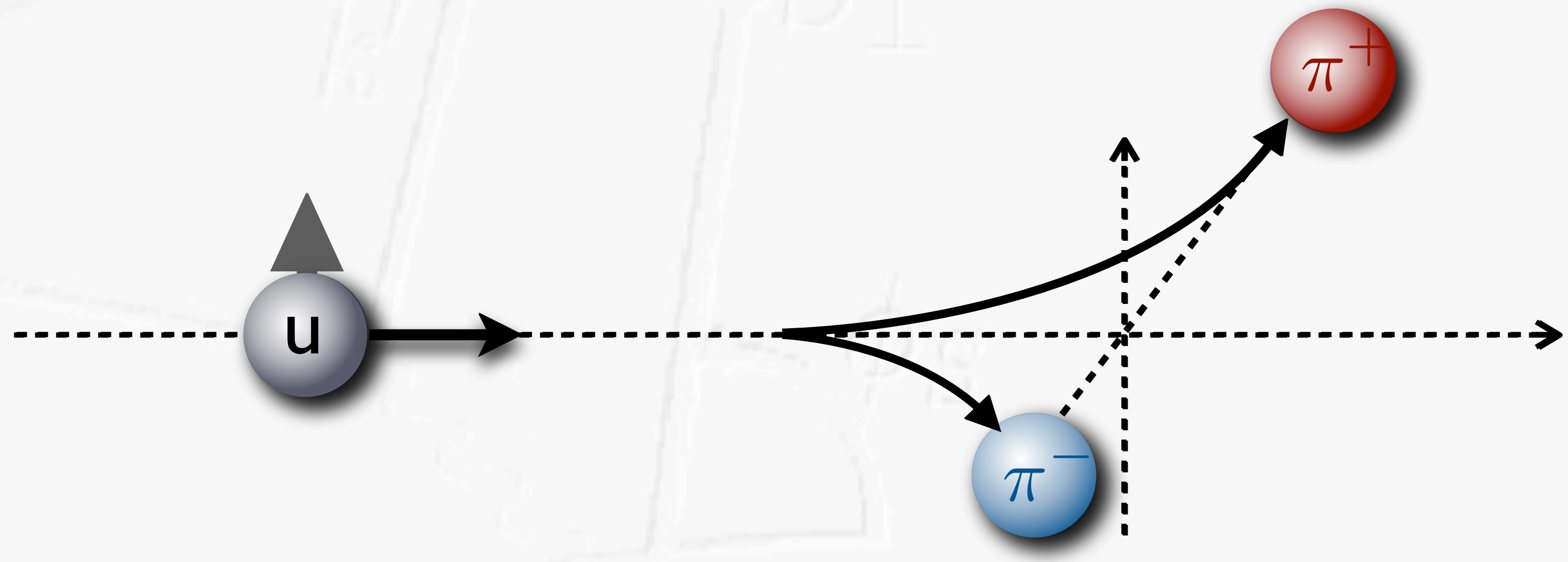

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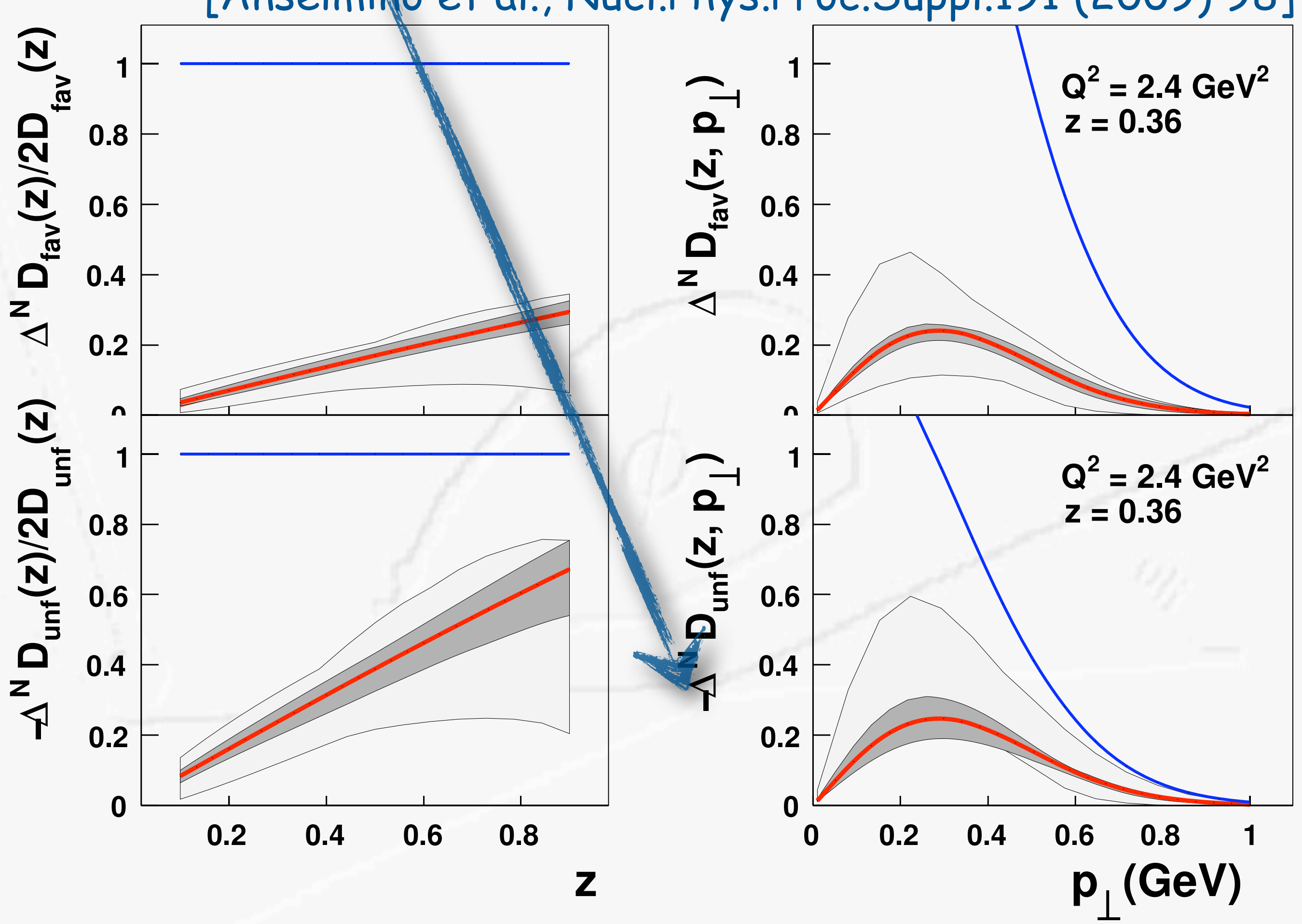
- extracted from SIDIS and e^+e^- annihilation data

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



☛ R. Seidl

1-Hadron Production (ep→ehX)

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

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

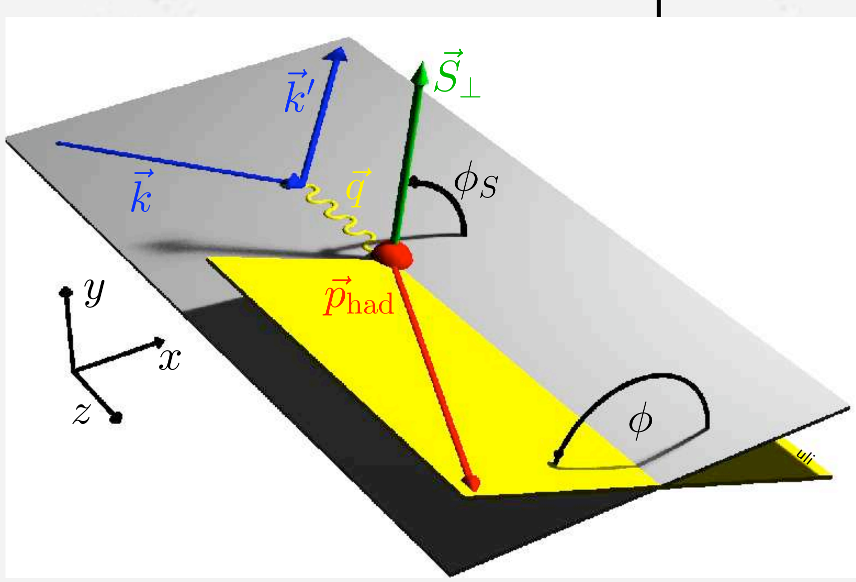
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

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

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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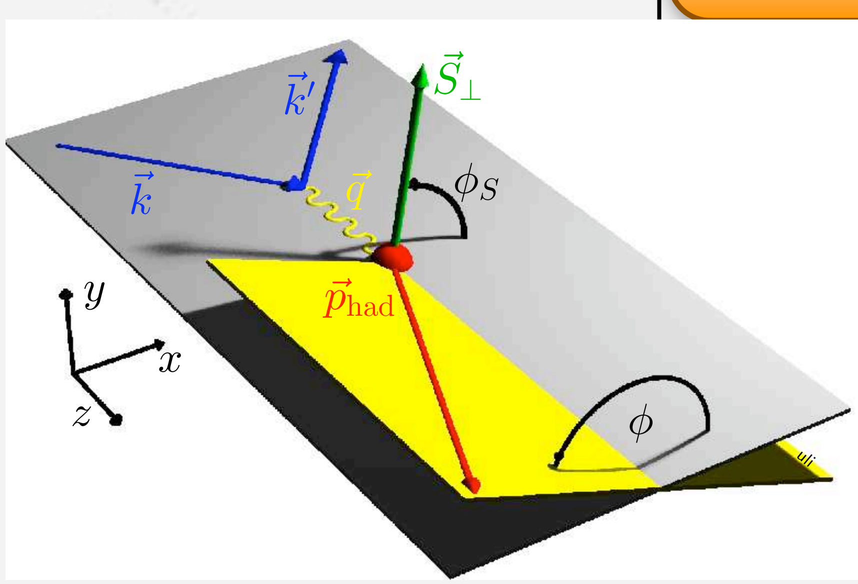
σ_{XY}

Beam **Target**
Polarization



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Cross section without polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

target polarization

beam polarization

virtual-photon polarization

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T}+\epsilon F_{UU,L}}\right\}$$

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093

Cross section without polarization

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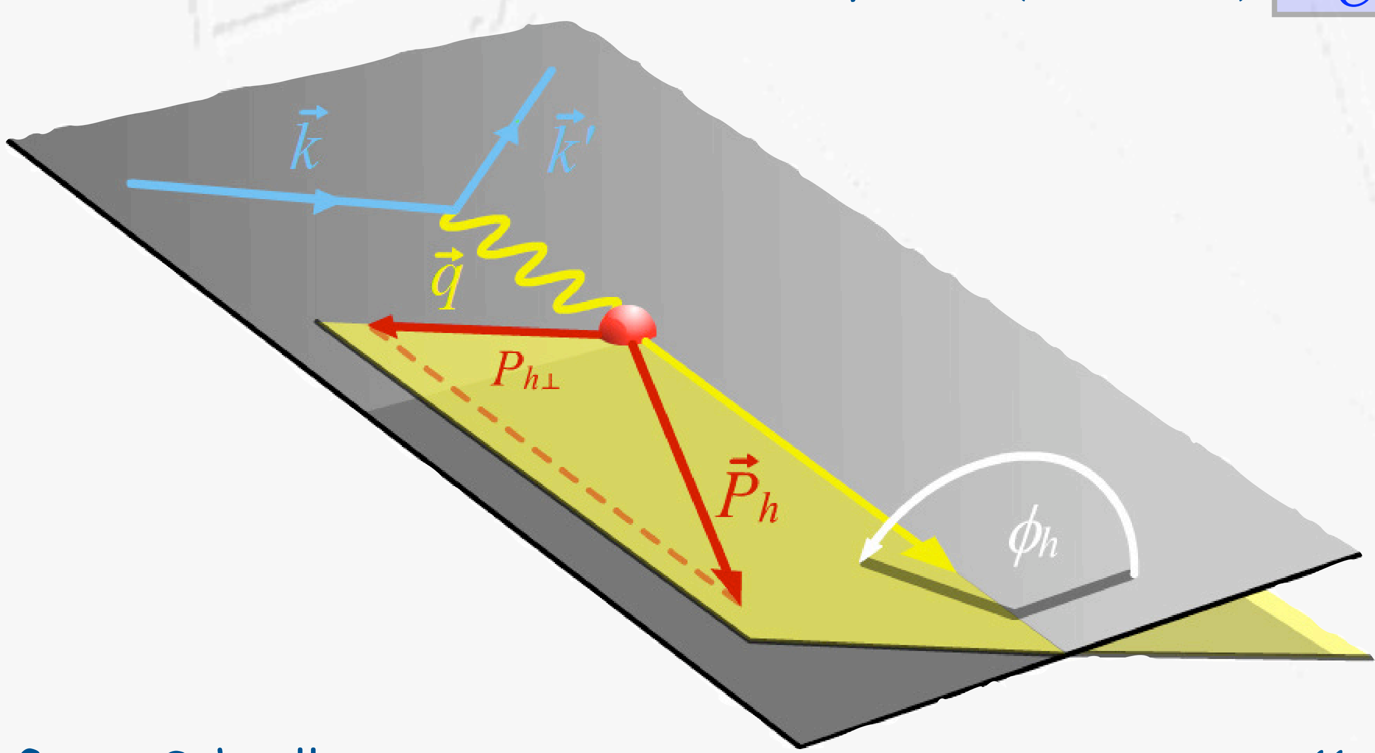
$$\left. + \sqrt{2\epsilon(1-\epsilon)}\,\boxed{F_{UU}^{\cos\phi_h}}\cos\phi_h + \epsilon\boxed{F_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$



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... possible measurements

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

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... possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dxdy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dxdydzdP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon F_{UU,L}}{F_T+\epsilon F_L}$$

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$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

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moments:

normalize to azimuth-independent cross-section

... possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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$$2\langle\cos 2\phi\rangle_{UU} \equiv 2\frac{\int d\phi_h \cos 2\phi\, d\sigma}{\int d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

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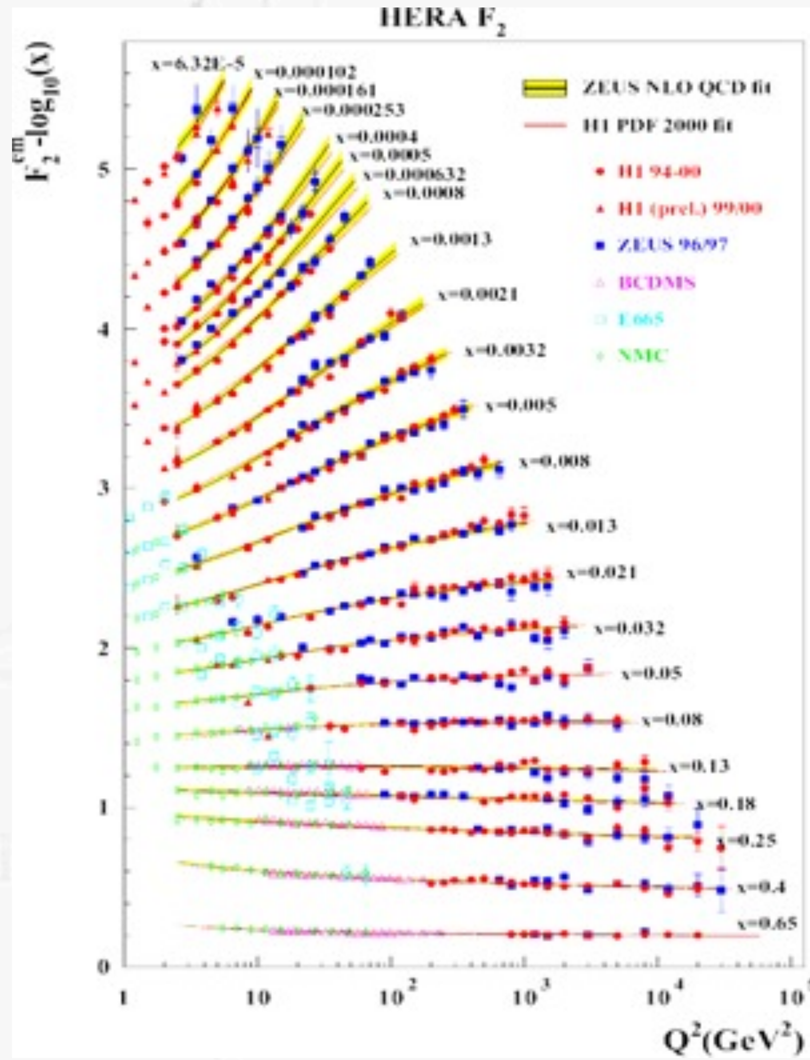
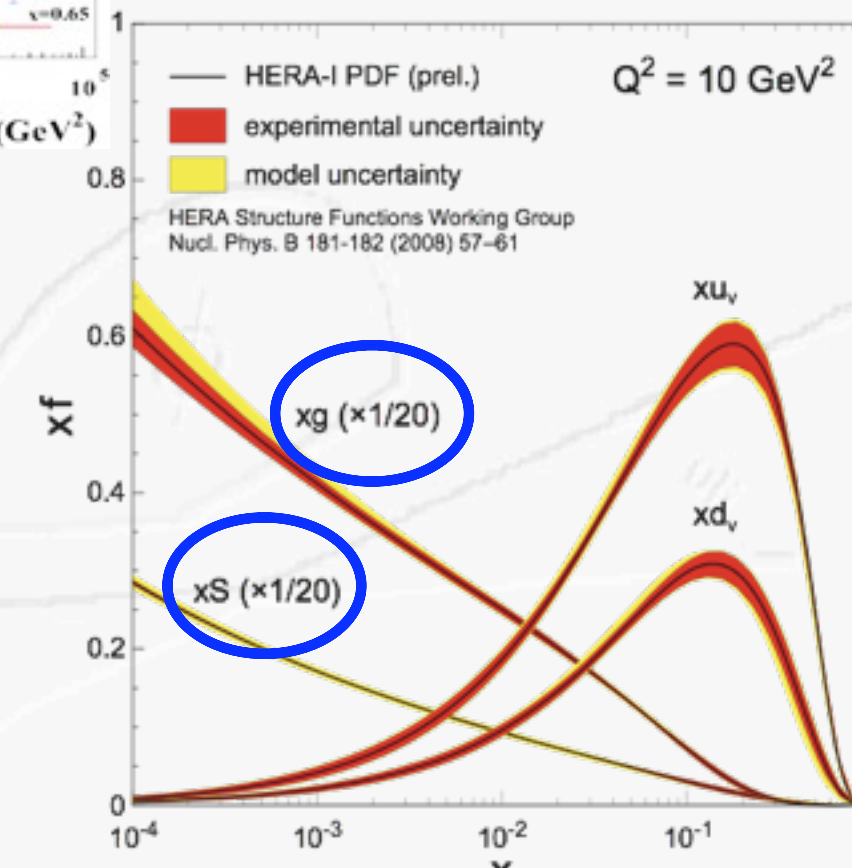
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Momentum density

- plenty of data available
- but only for integrated version of f_1





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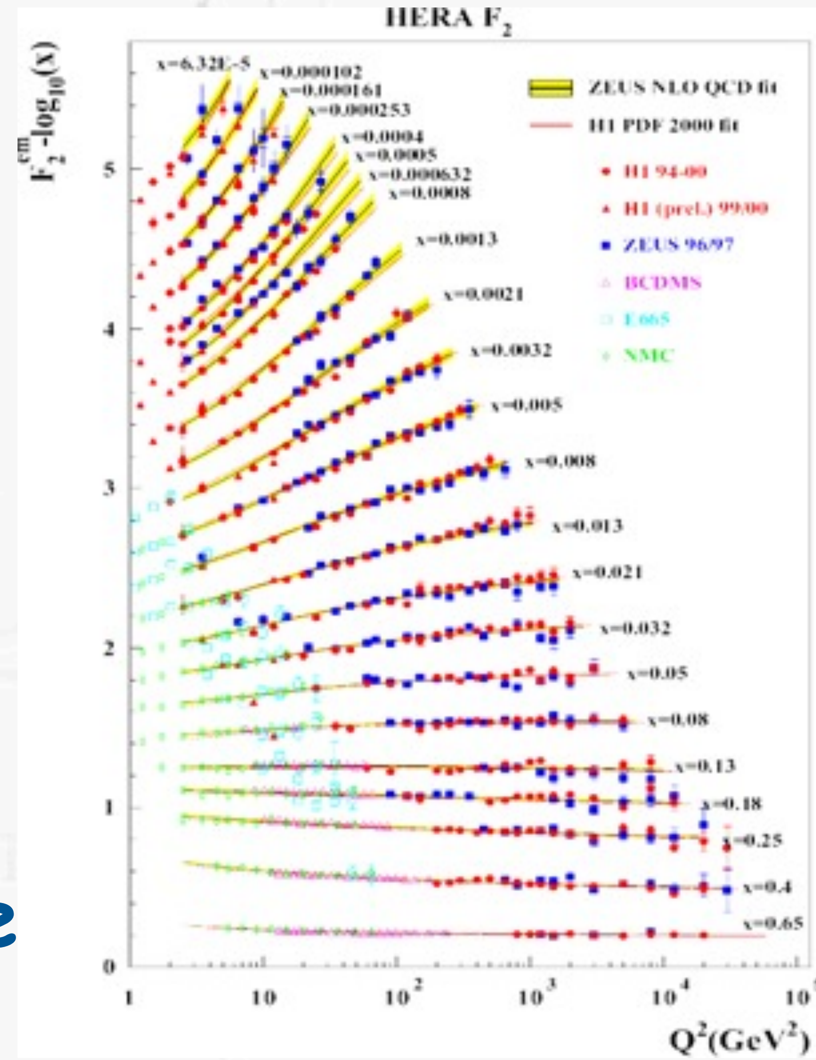
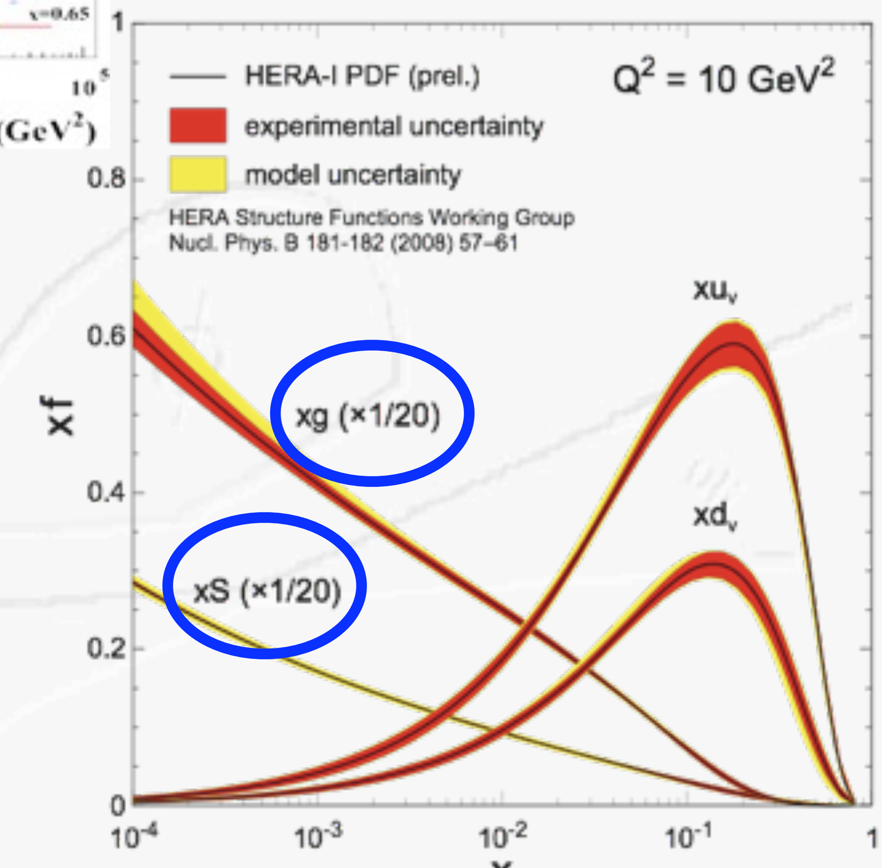
- **spin asymmetries involve unintegrated f_1 in denominator!**





	U	L	T
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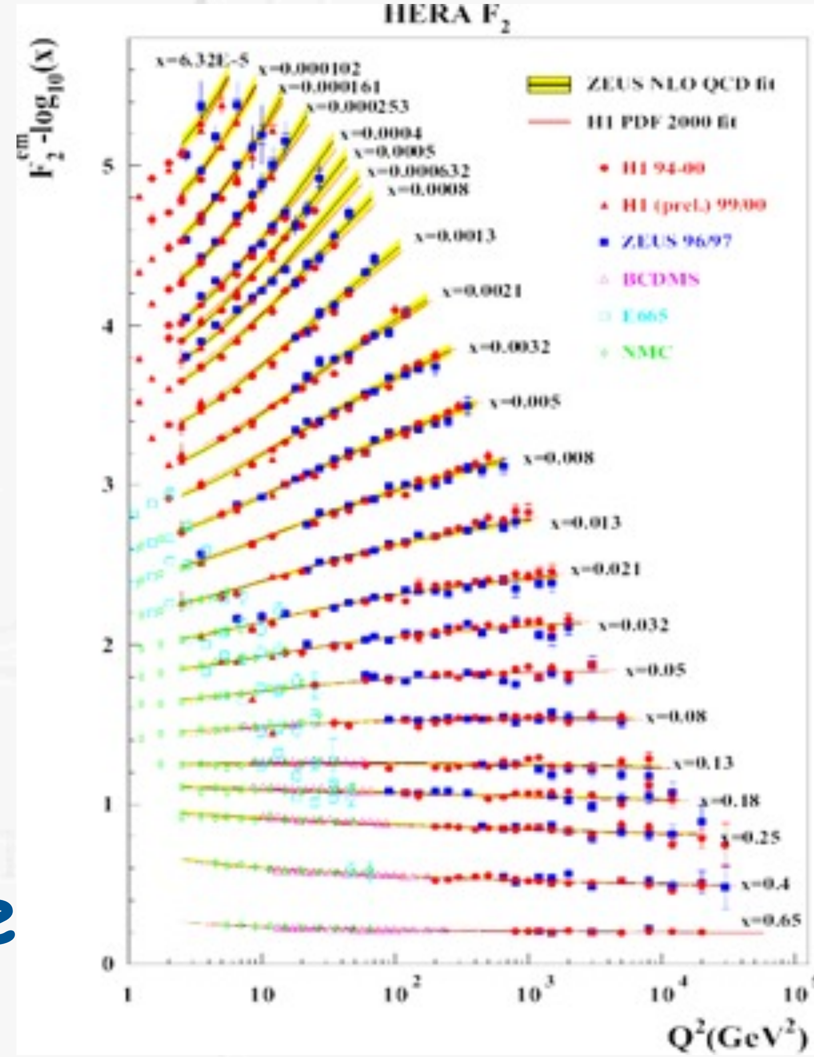
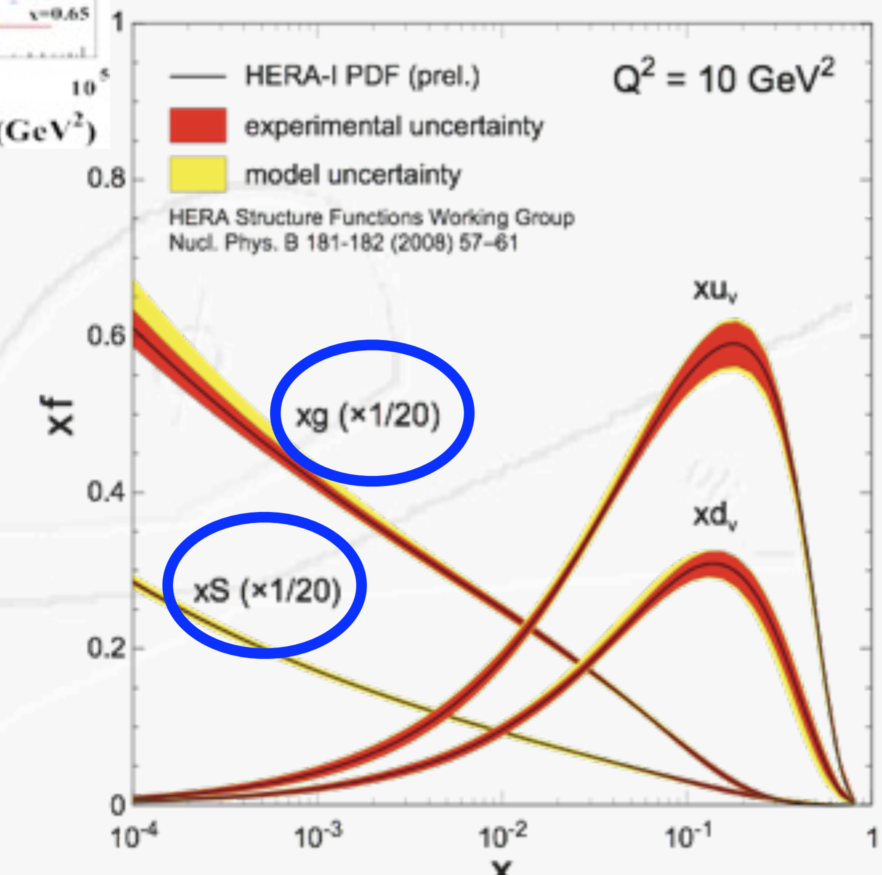
Momentum density

- 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 $P_{h\perp}$**





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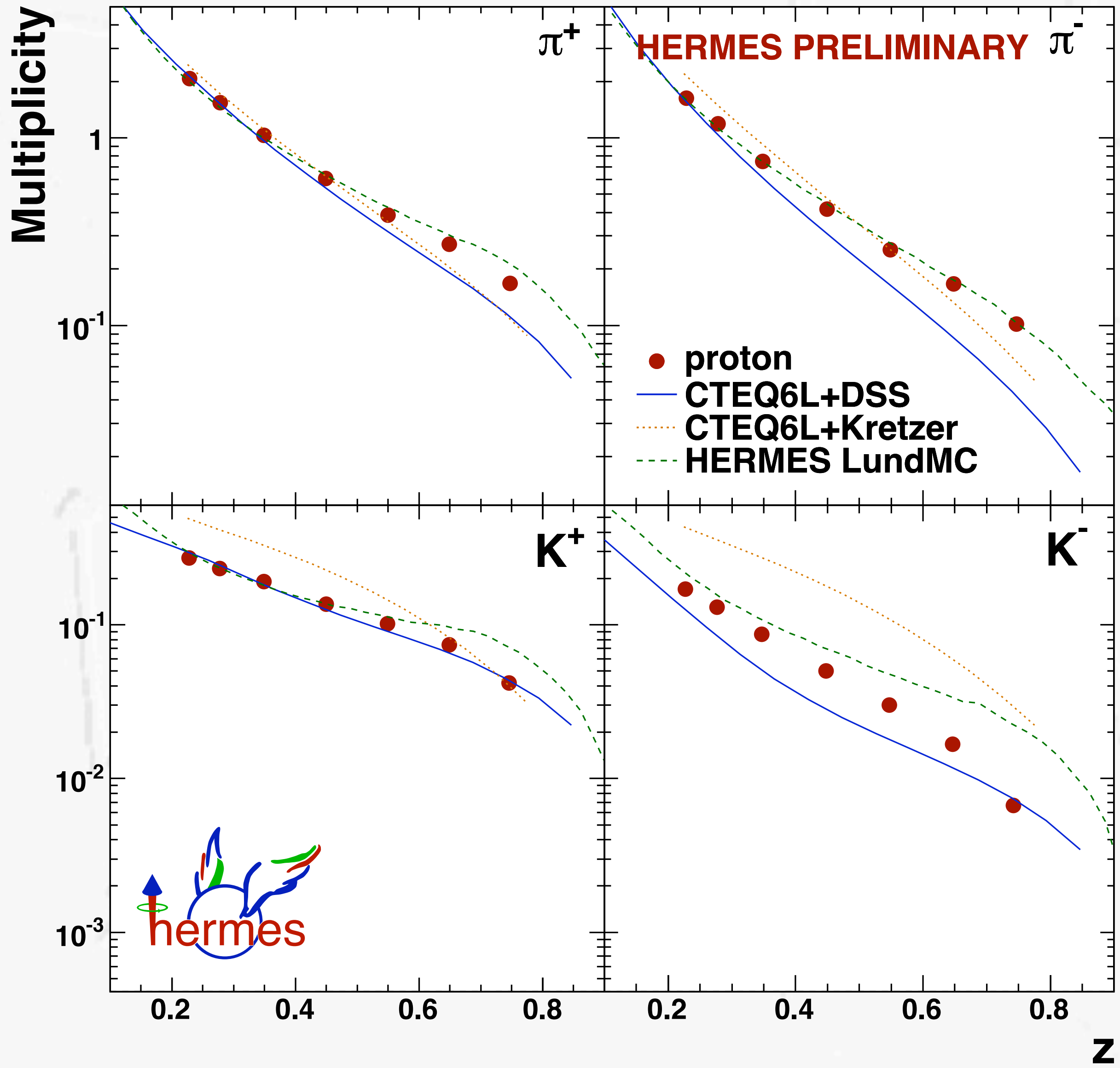
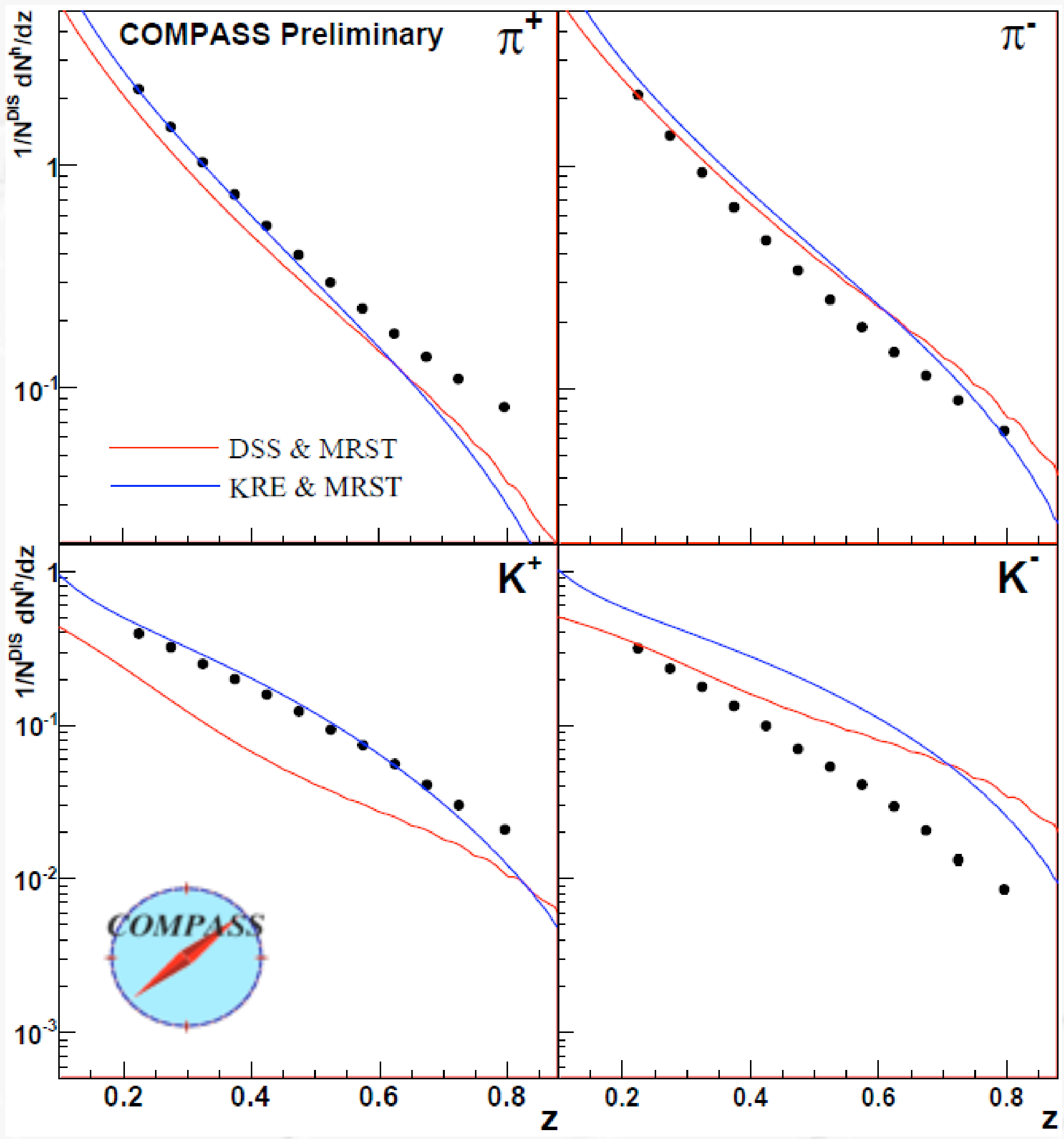
Hadron multiplicities





- $P_{h\perp}$-integrated multiplicities ideal input for FF fits and tests
- kaons difficult to describe

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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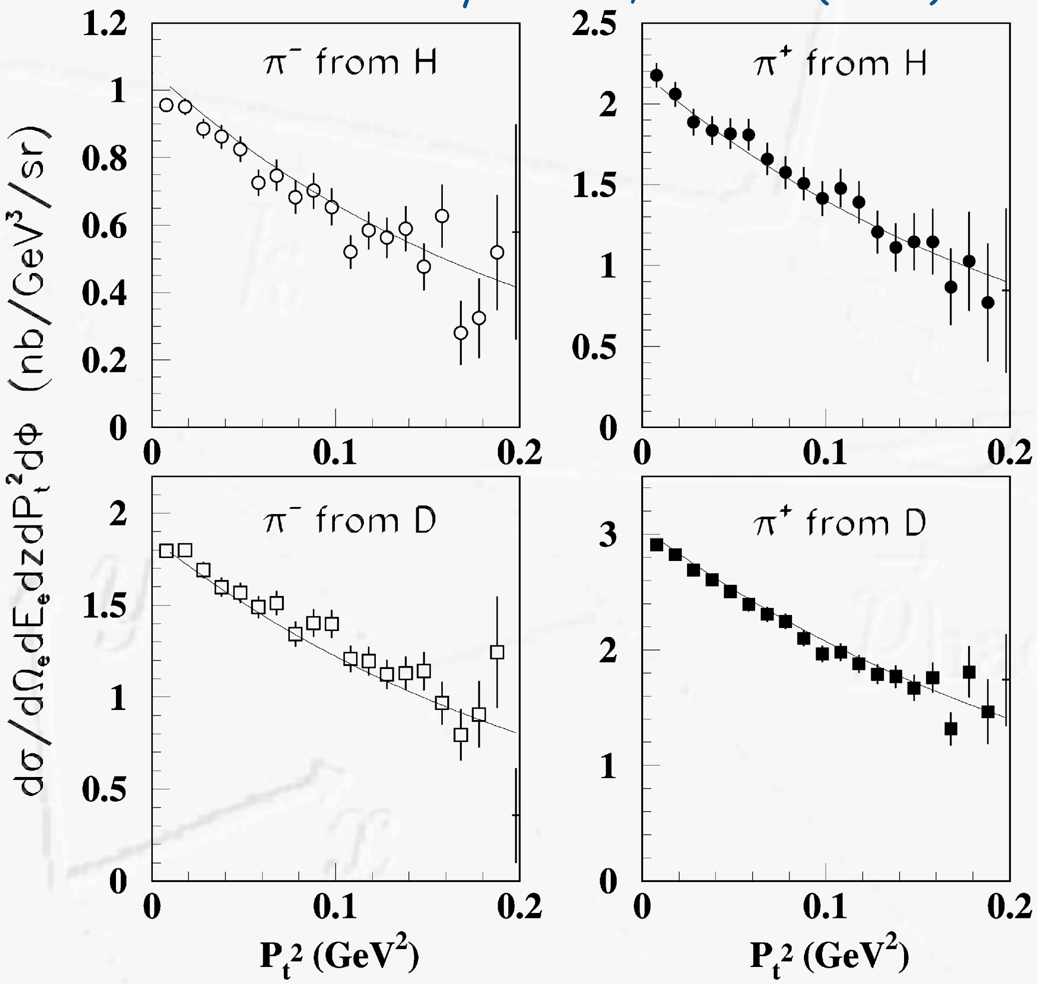
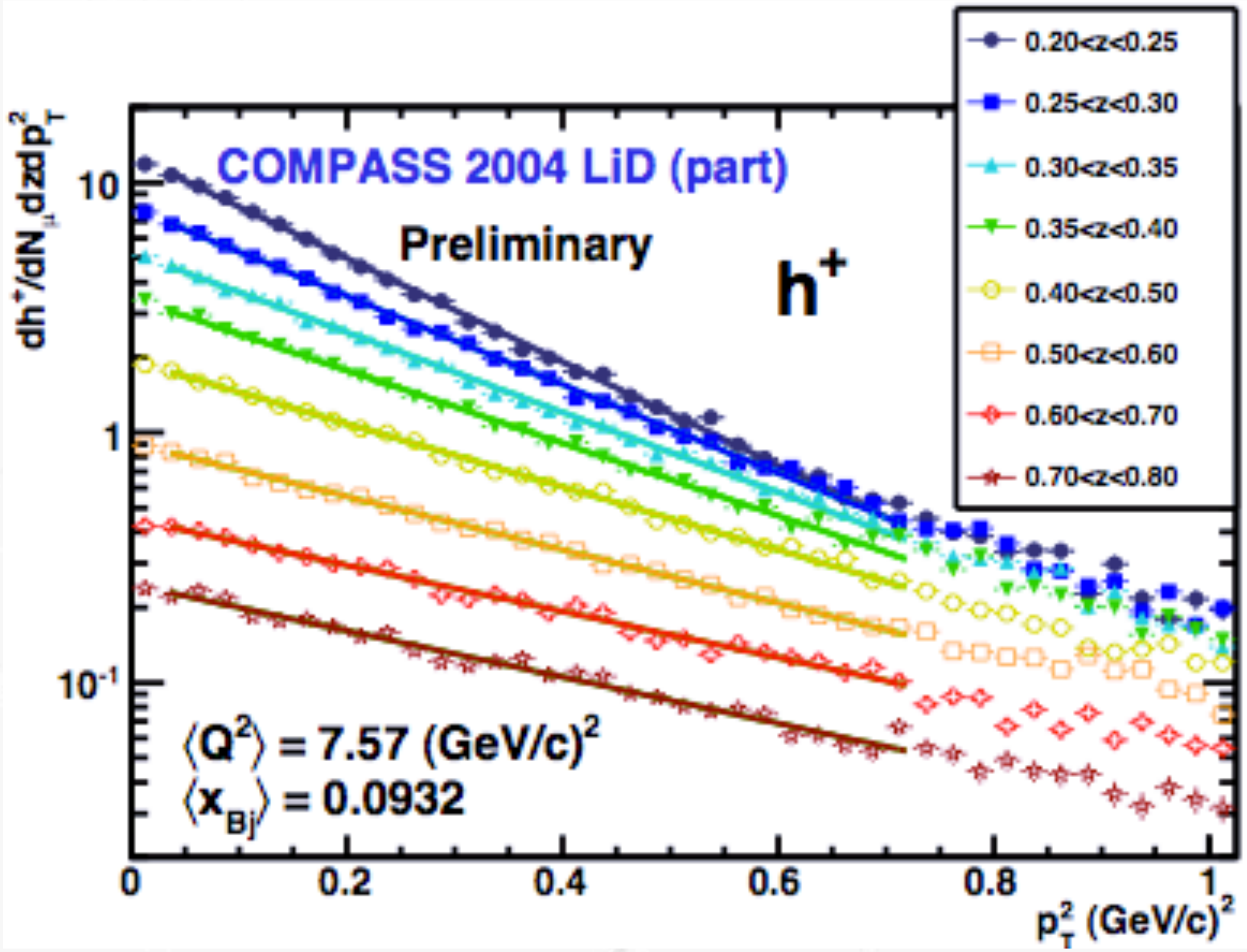
Disentangle z and $P_{h\perp}$-dependence

Mkrtchyan et al., PLB 665 (2008) 20





- study $P_{h\perp}$-dependence -> access to TMDs

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

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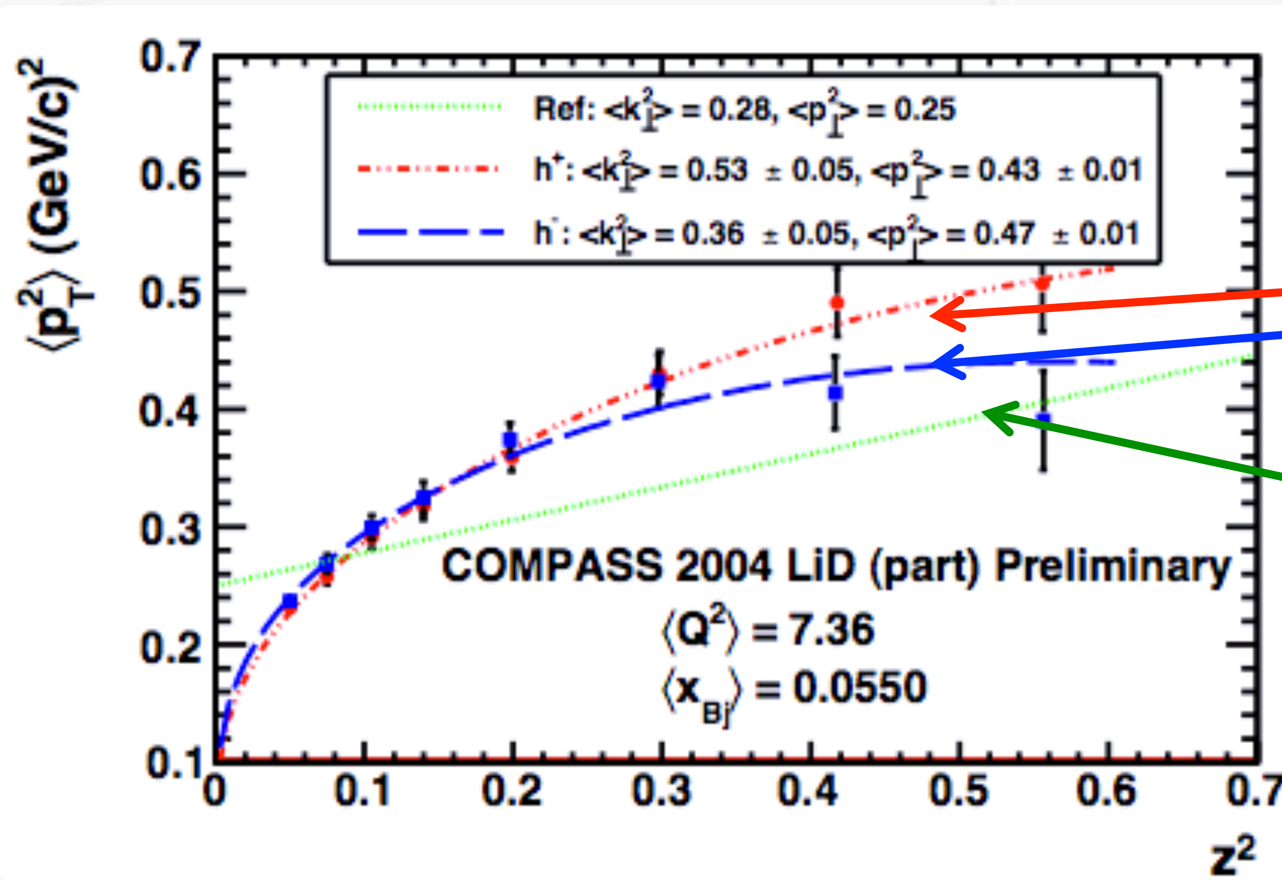

$$\langle p_T^2\rangle = z^\alpha(1-z)^\beta\langle p_\perp^2\rangle + z^2\langle k_\perp^2\rangle$$

α=0.5; β=1.5

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Claude Marchand - DIS 2011

- study $P_{h\perp}$-dependence -> access to TMDs
- constant average (fragmentation) $p_\perp$ excluded

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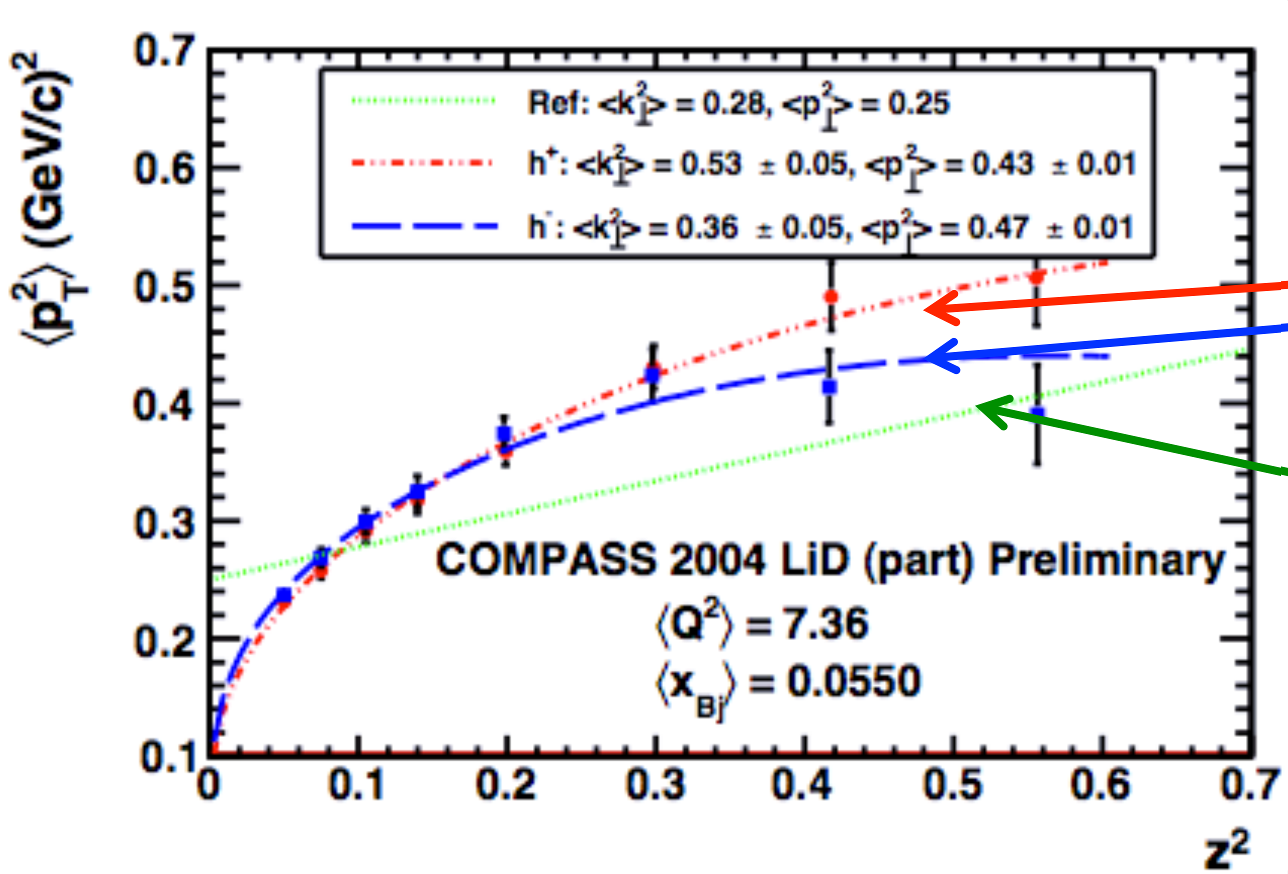

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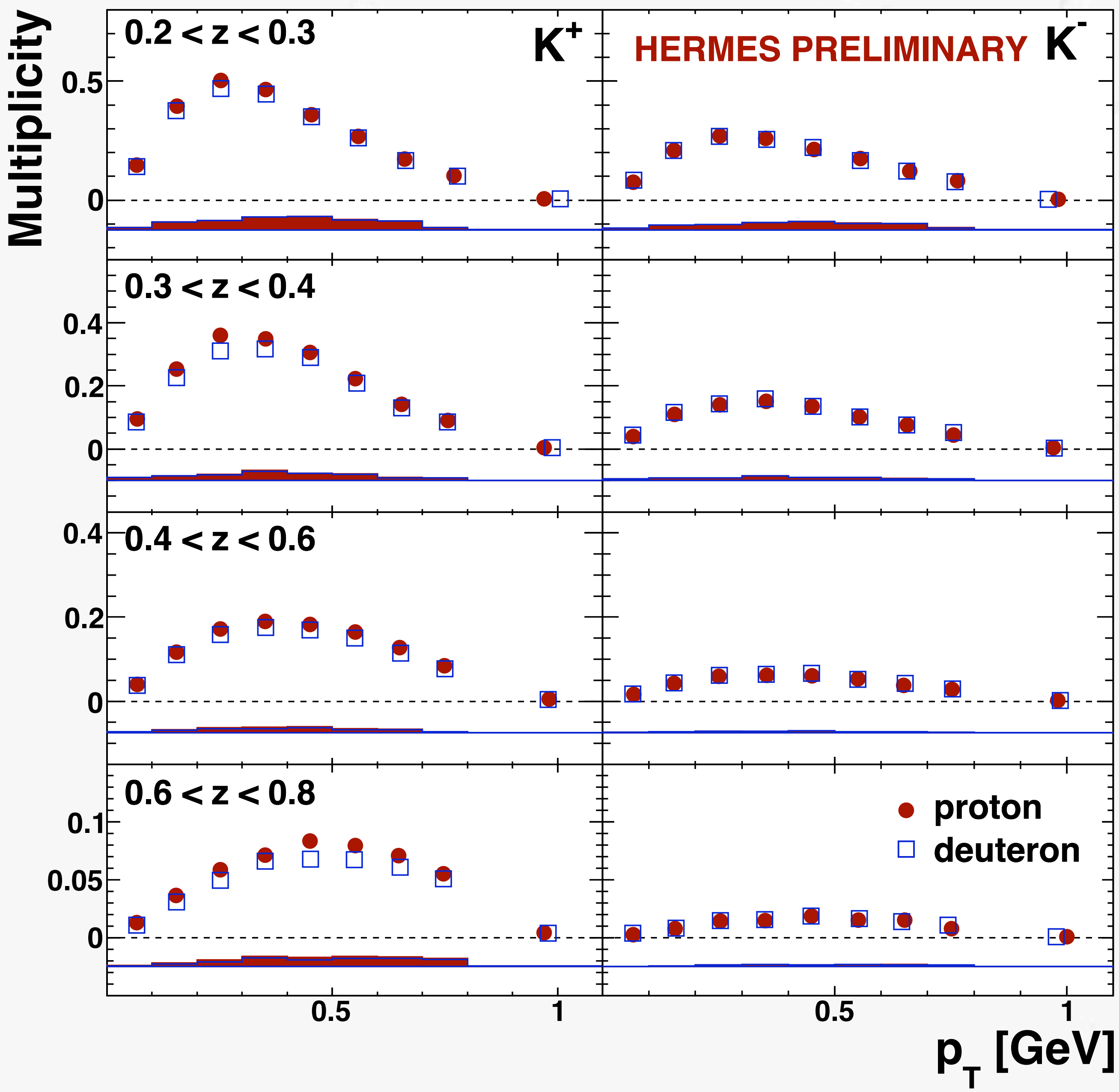
Claude Marchand - DIS 2011

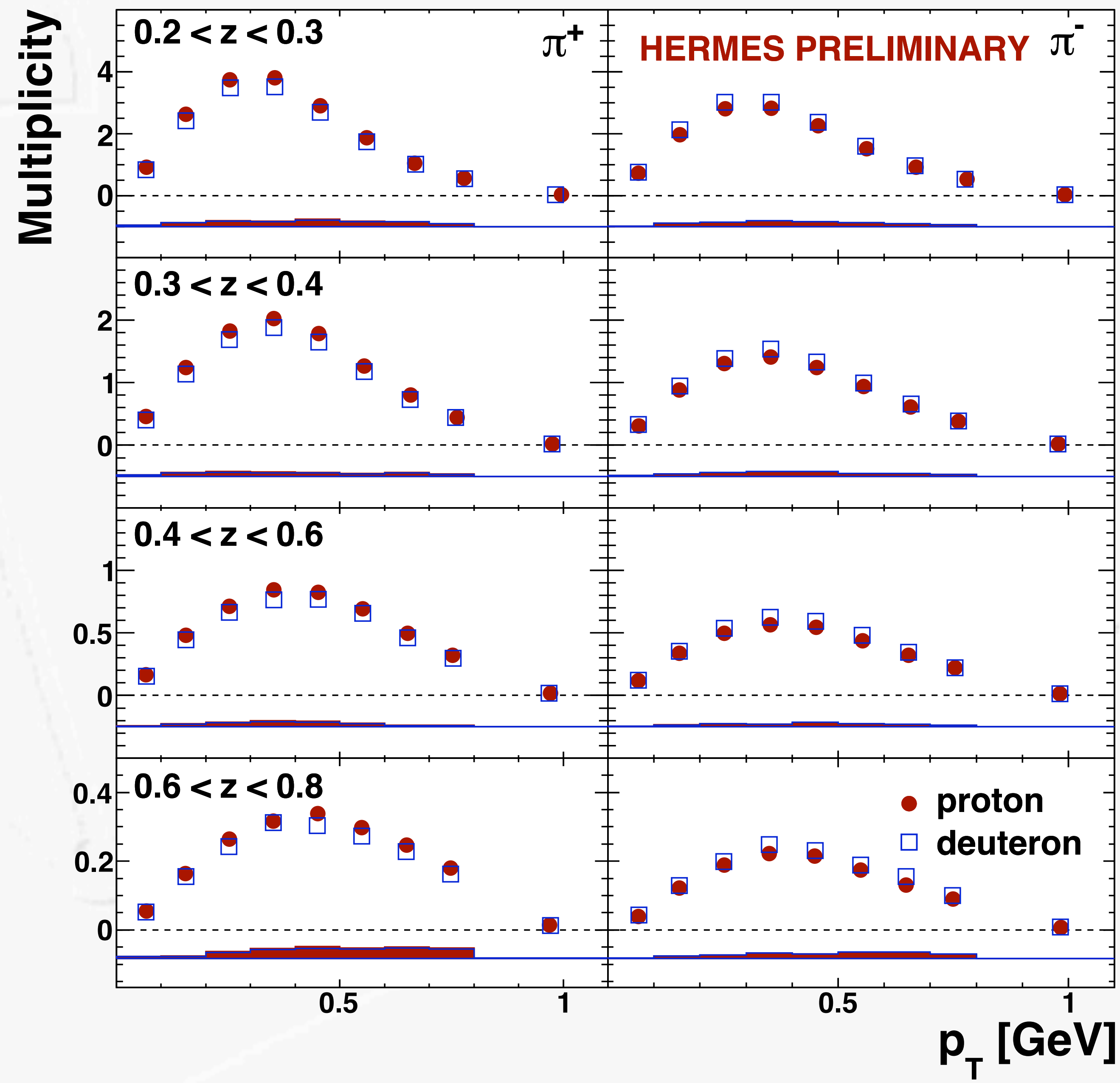
- study $P_{h\perp}$-dependence -> access to TMDs
- constant average (fragmentation) $p_\perp$ excluded
- difference in h^+ and h^- behavior ☛ flavor dependence

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

Disentangle z and $P_{h\perp}$-dependence

- flavor info via target variation and hadron ID





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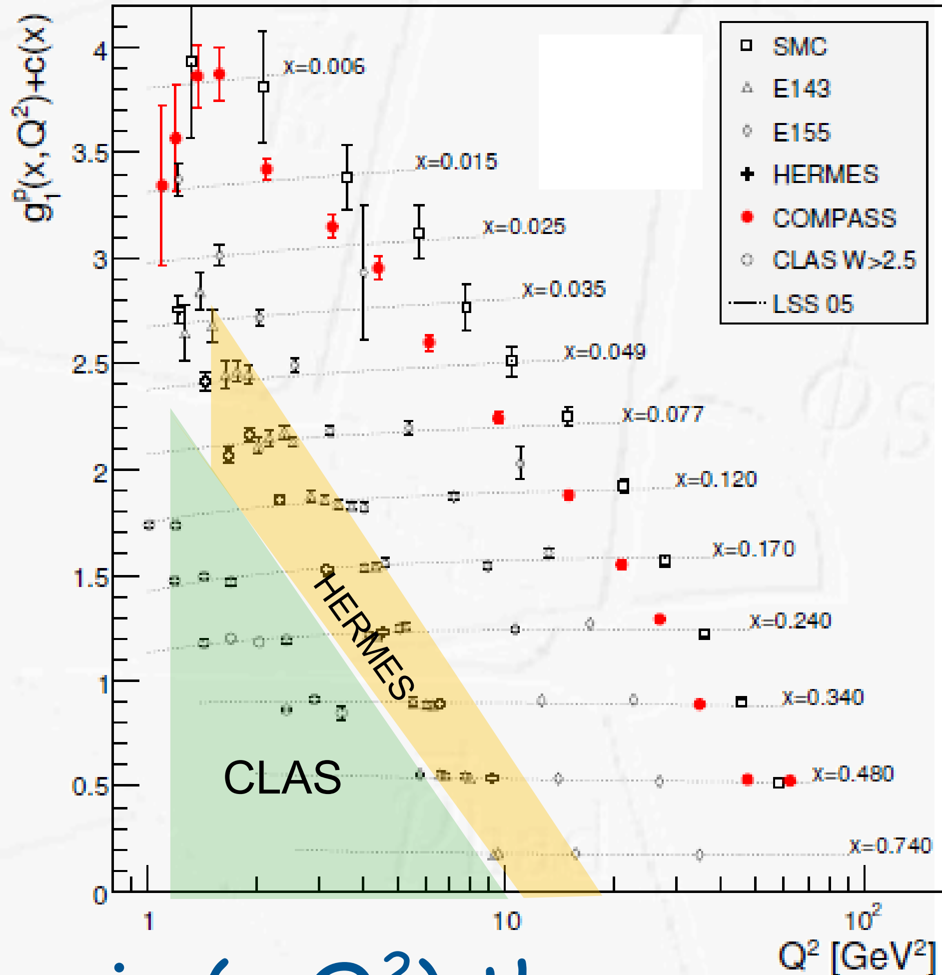
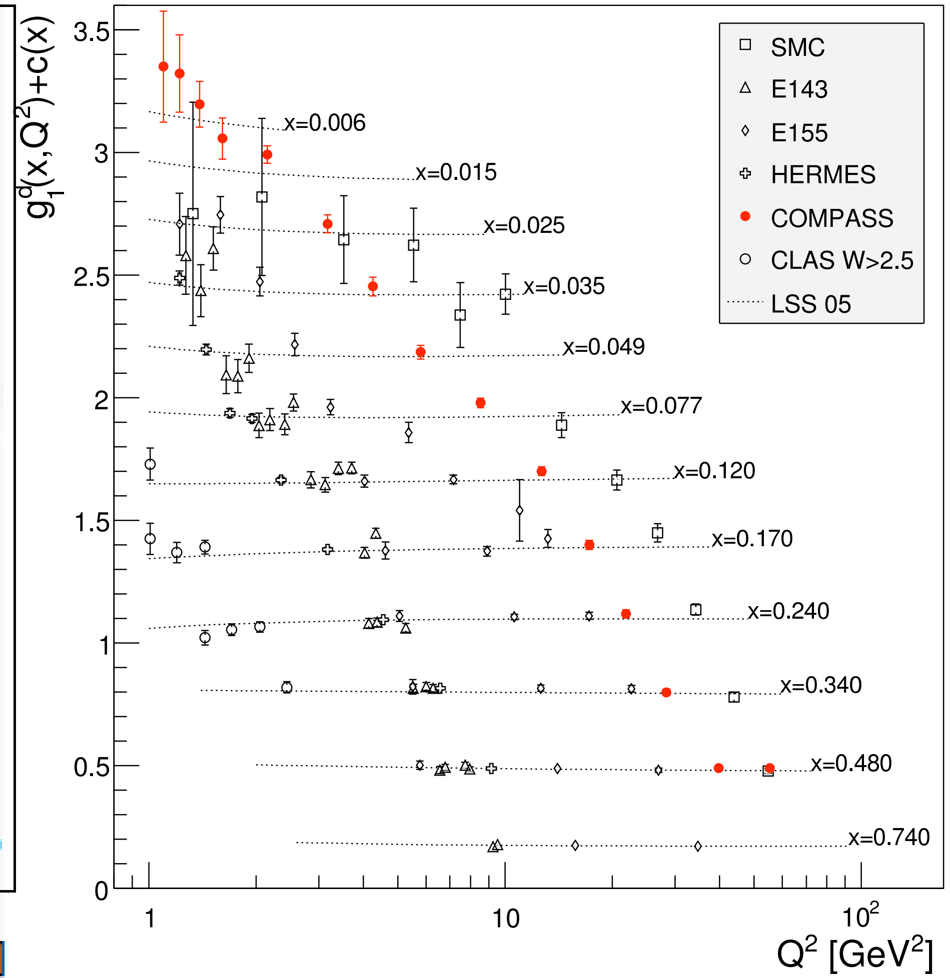
Helicity density





- 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 $P_{h\perp}$**

	U	L	T
U	f_1		$h_1^\perp$
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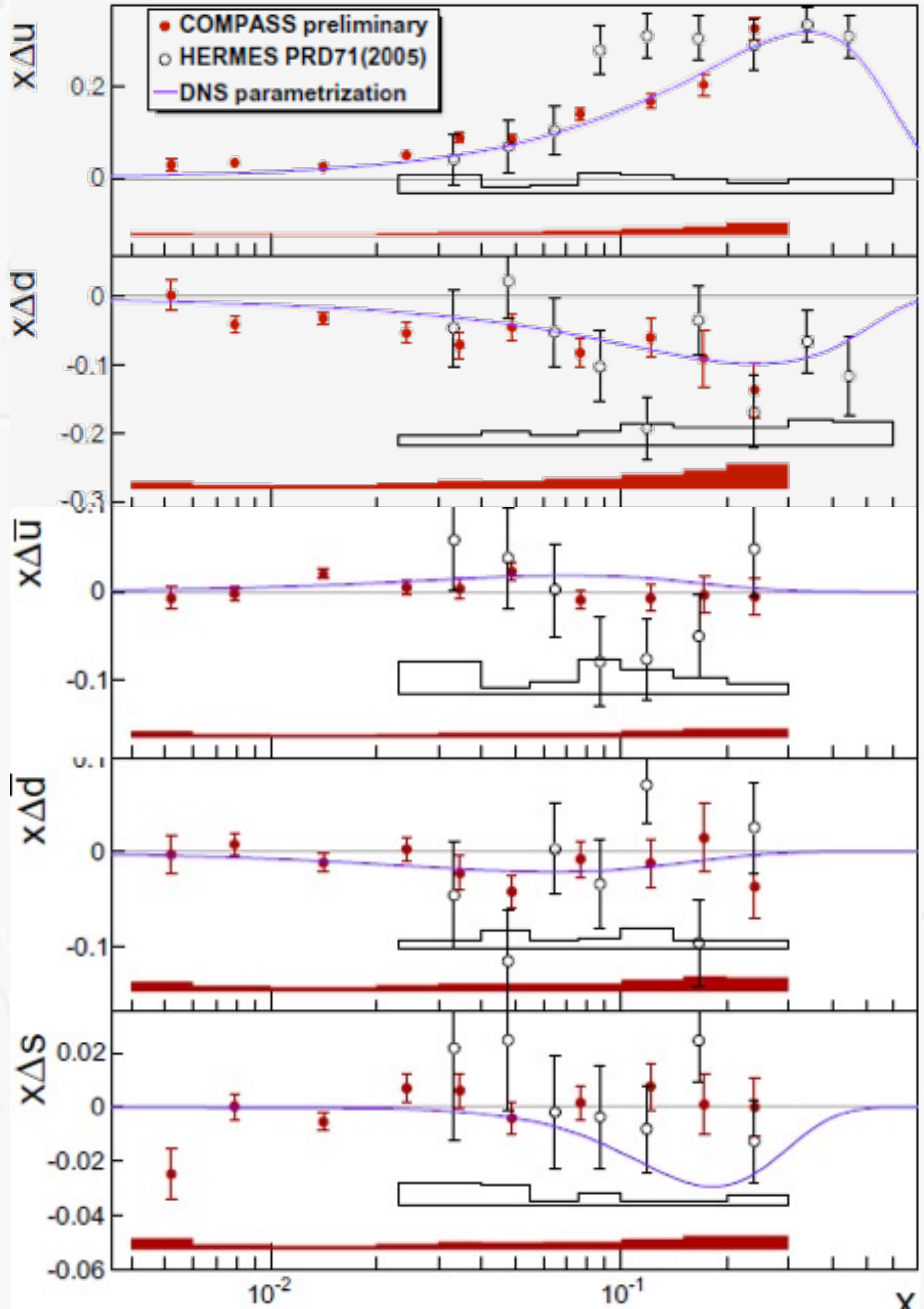
Helicity density

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



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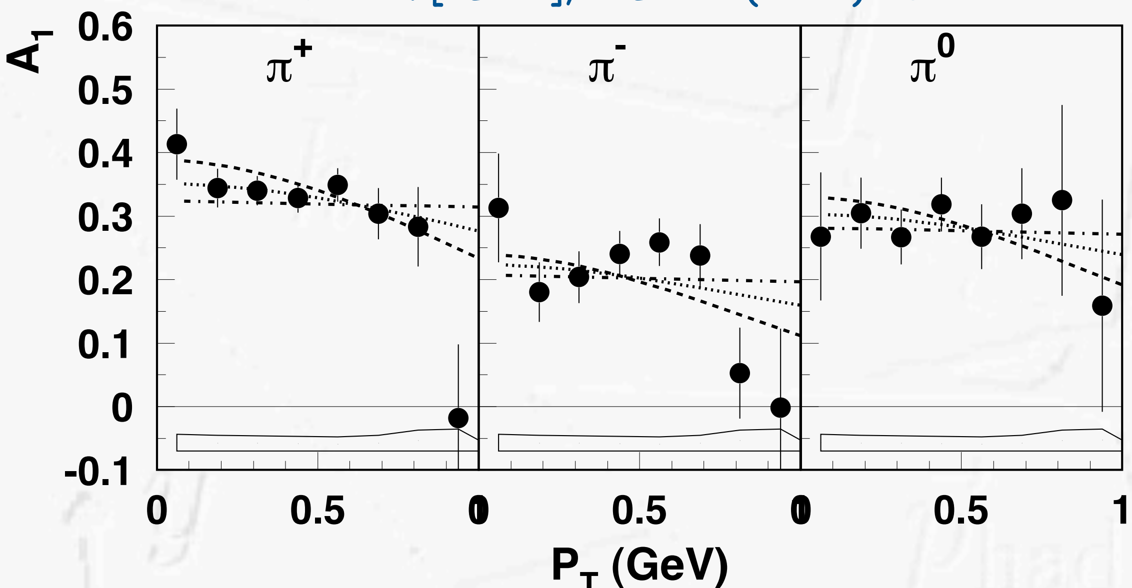
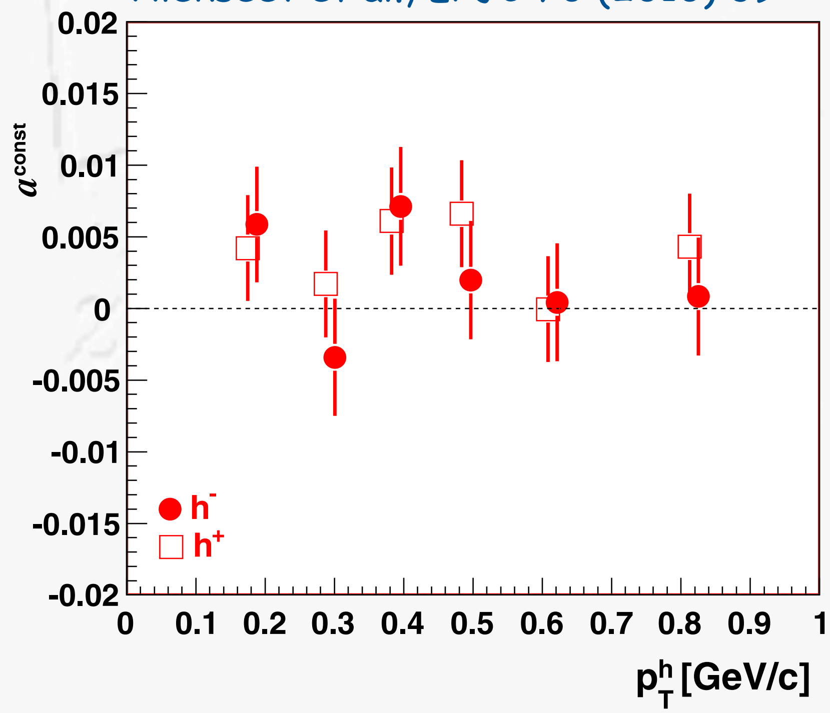
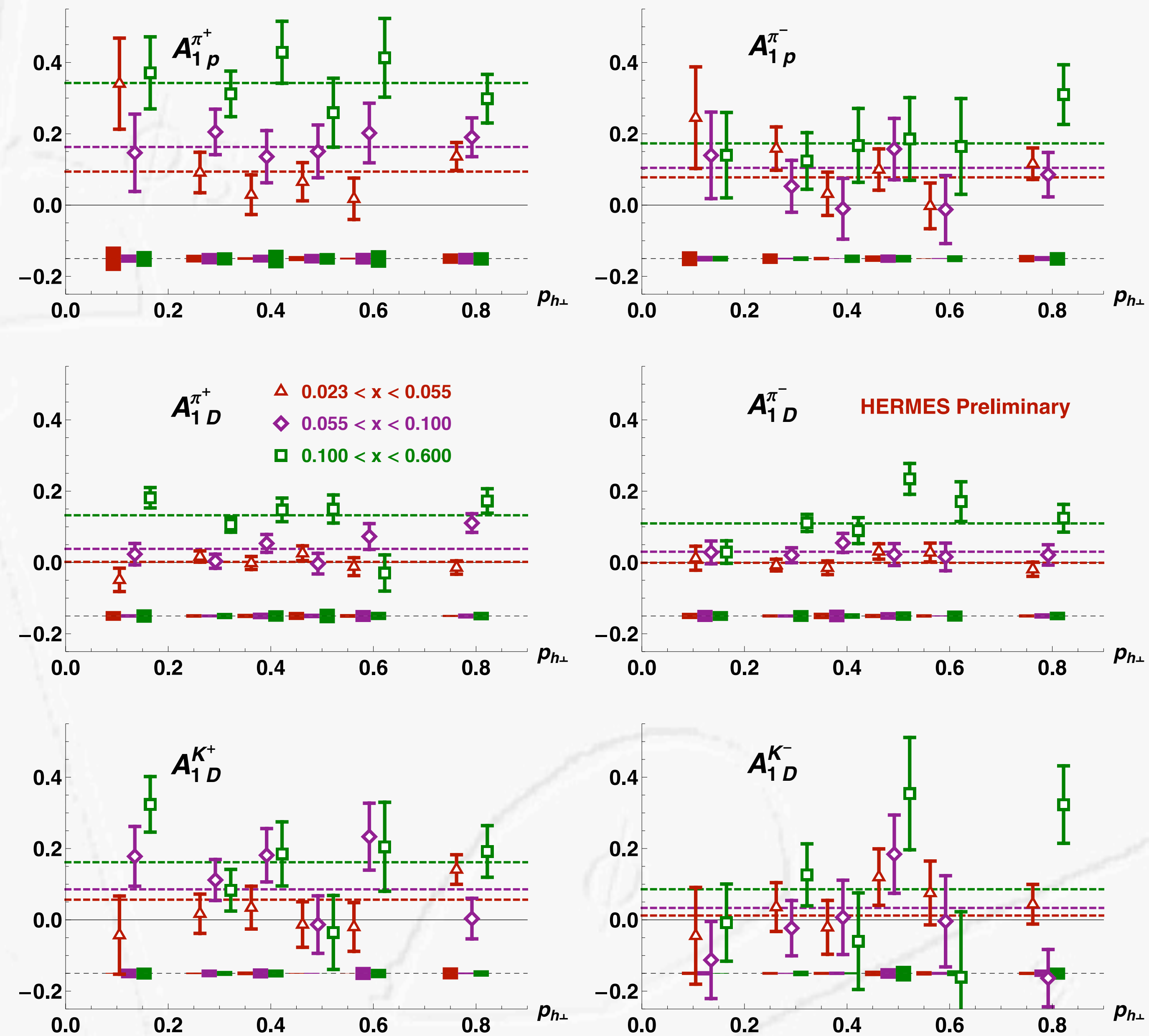
Helicity density (unintegrated)

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



Alekseev et al., EPJC 70 (2010) 39

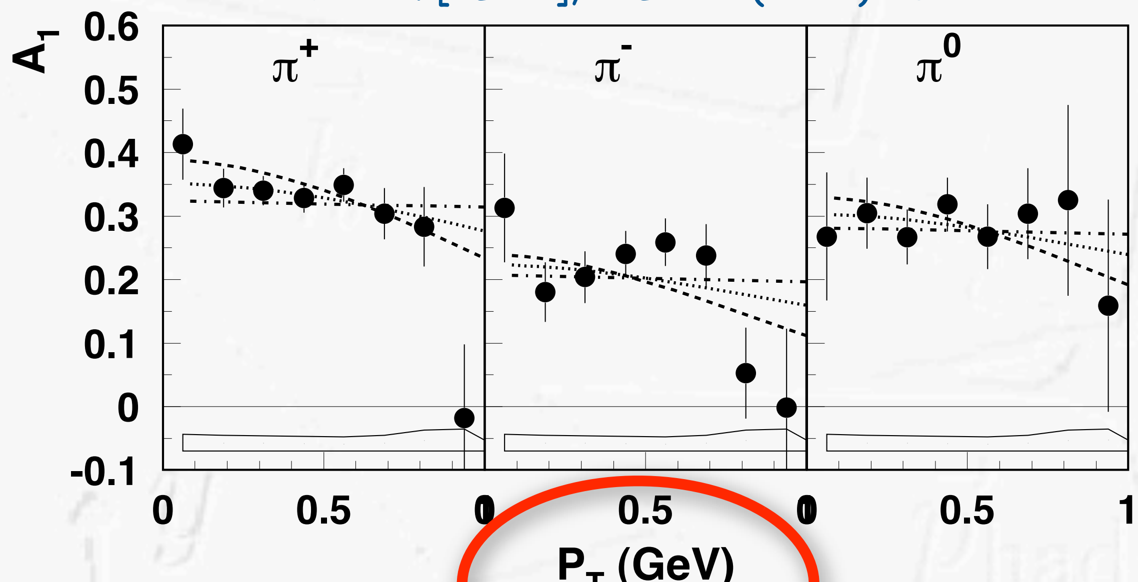




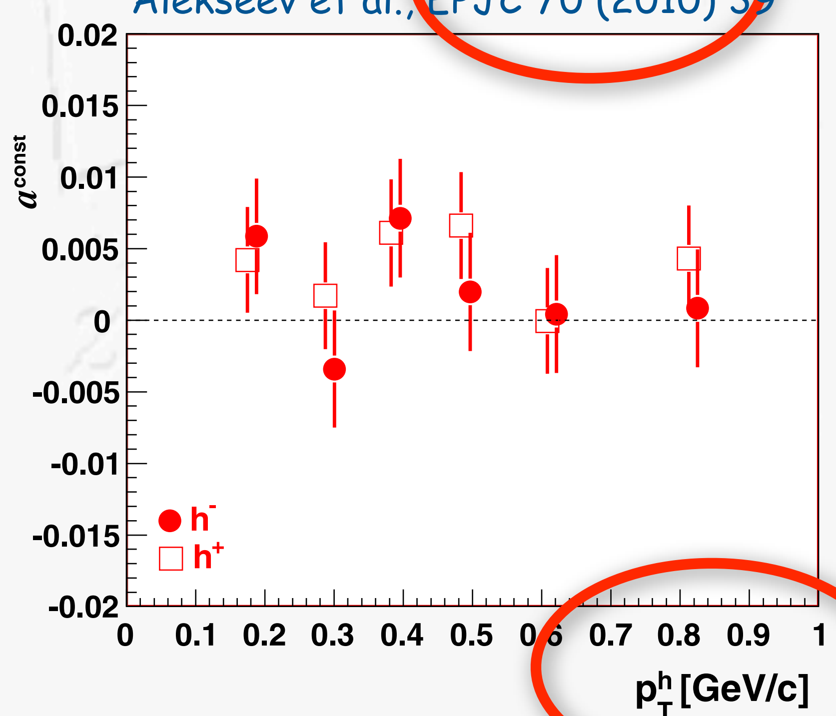
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

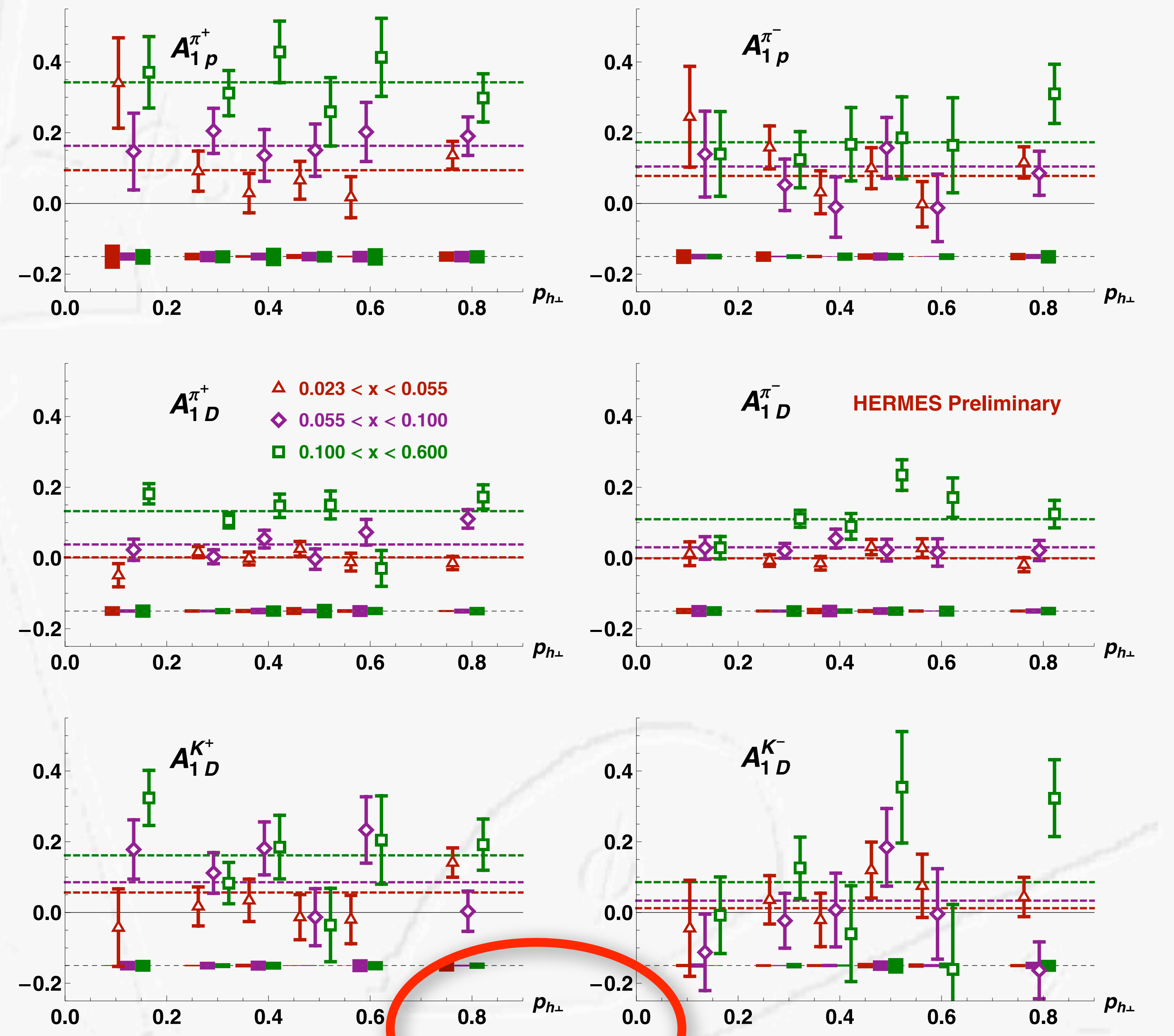
Helicity density (unintegrated)

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



Alekseev et al., EPJC 70 (2010) 39



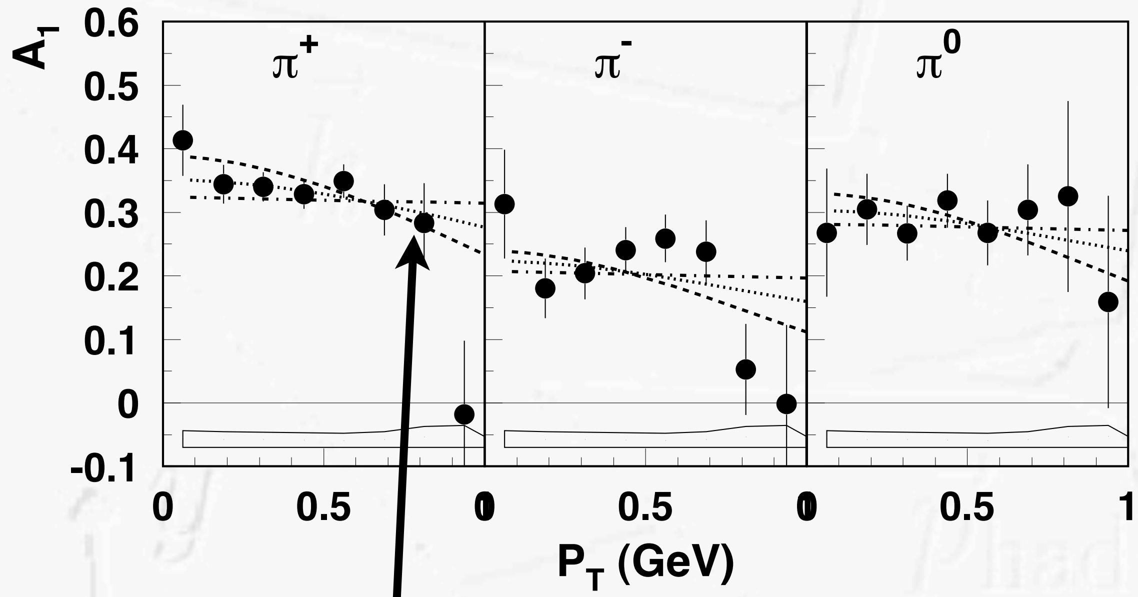


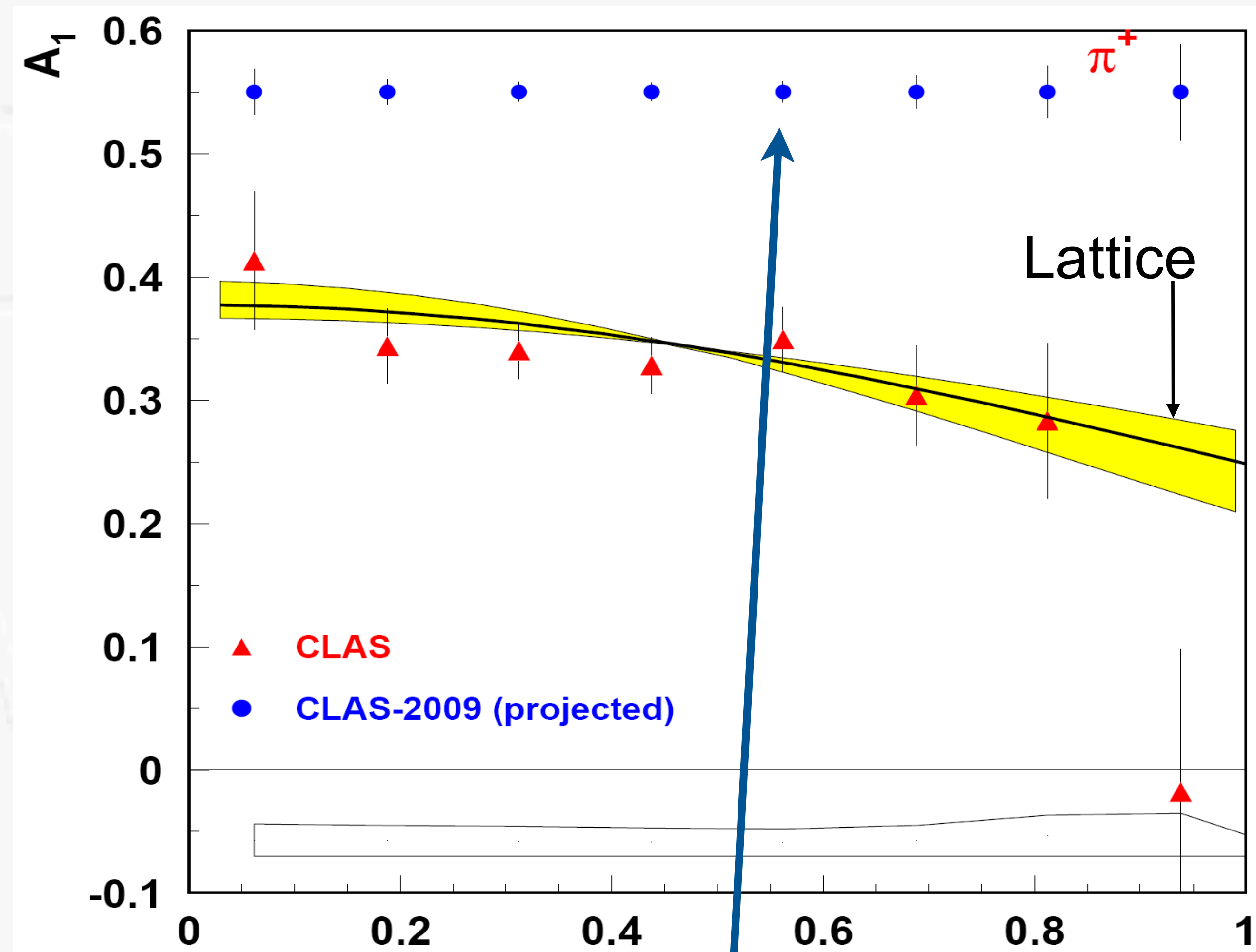
only weak if any dependence on $P_{h\perp}$ seen

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

Helicity density (unintegrated)

Avakian et al. [CLAS], arXiv:1003.4549





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

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

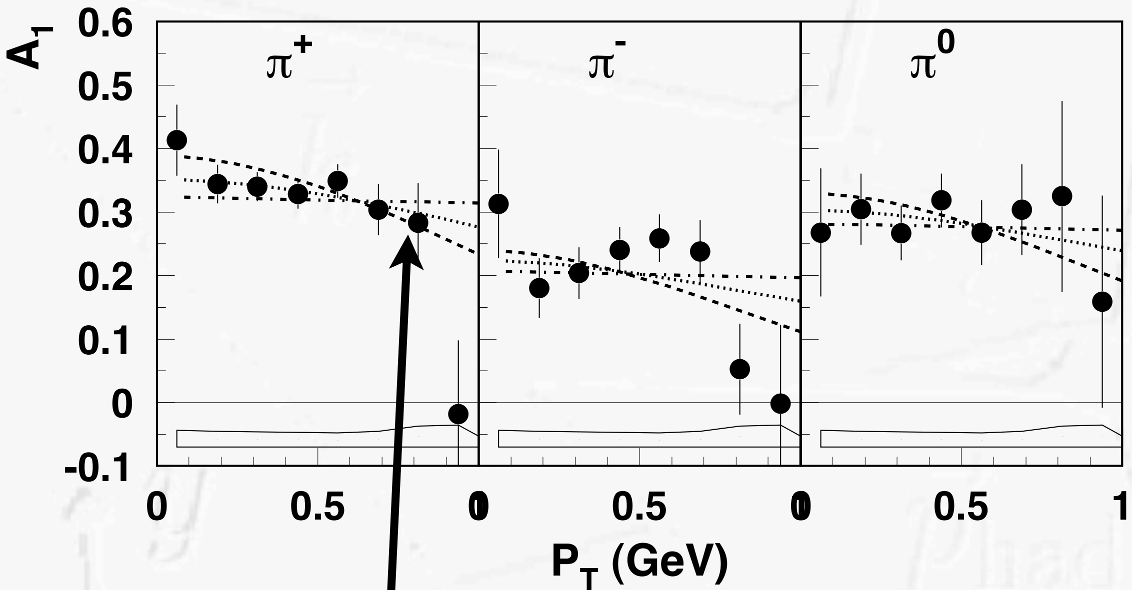
$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

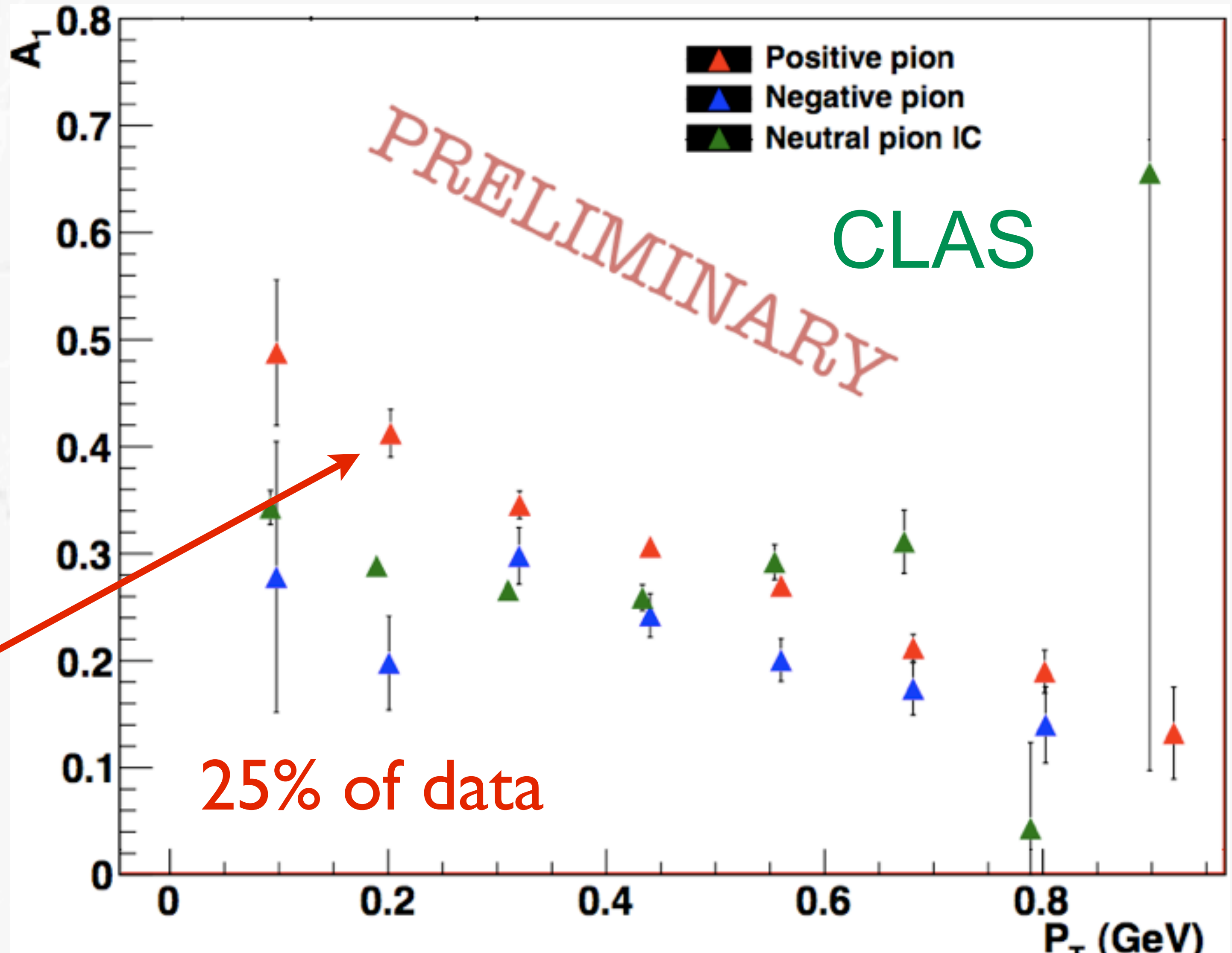
New CLAS data will allow multi-D binning to study $P_{h\perp}$ dependence for fixed x

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

Helicity density (unintegrated)

Avakian et al. [CLAS], arXiv:1003.4549





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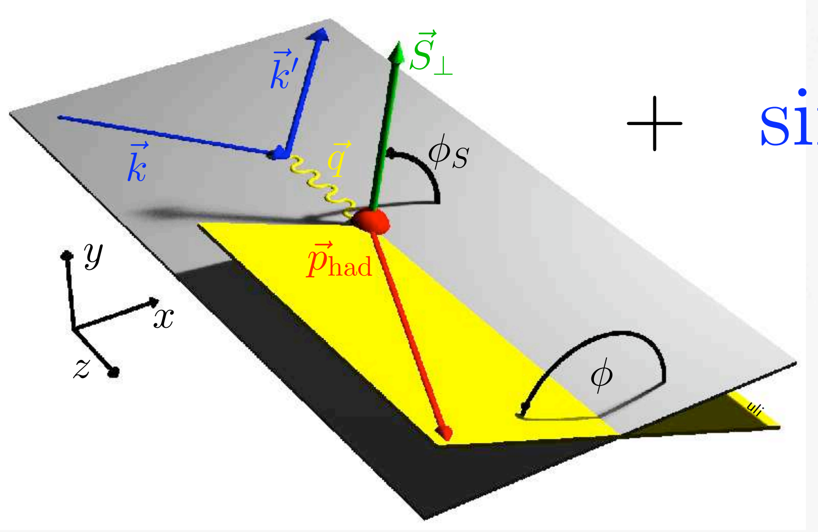
New CLAS data will allow multi-D binning to study $P_{h\perp}$ dependence for fixed x

The quest for transversity

Measuring azimuthal spin asymmetries

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^\uparrow(\phi,\phi_S)-N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S)+N_h^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M_h}h_1^q(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$



$$+ \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{p_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M}f_{1T}^{\perp,q}(x,p_T^2)D_1^q(z,k_T^2)\right]$$

$$+ \quad \cdots$$

$\mathcal{I}[\ldots]$: **convolution integral over initial (p_T) and final (k_T) quark transverse momenta**

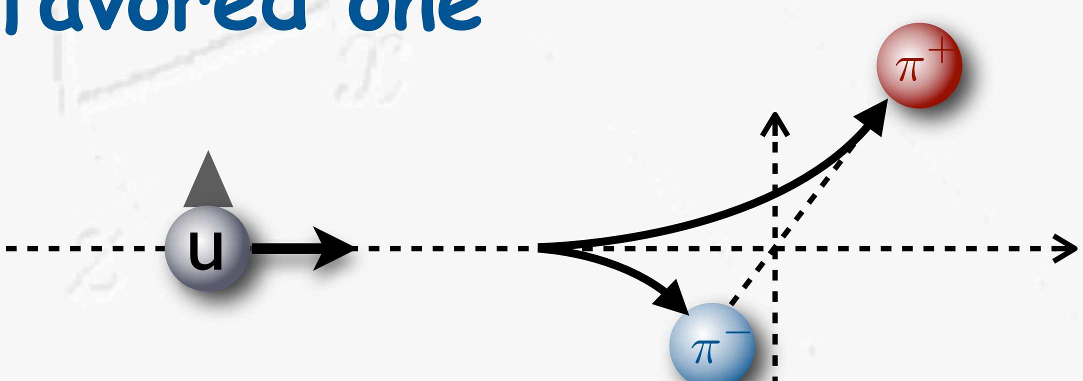
$\Rightarrow$ 2D Max.Likelihd. fit of to get Collins and Sivers amplitudes:

$$\boxed{PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\,\sin(\phi\pm\phi_s)+\ldots)\}}$$

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

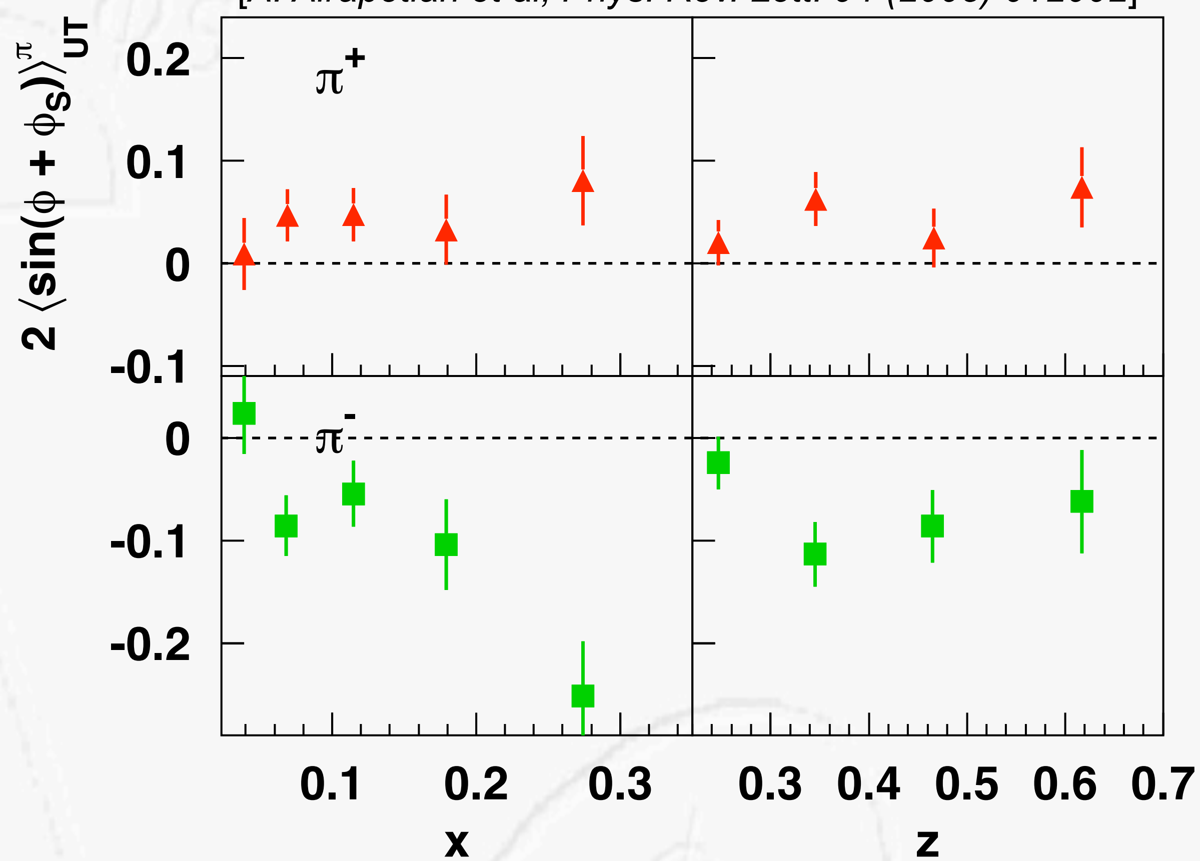
Transversity distribution (Collins fragmentation)

- 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]

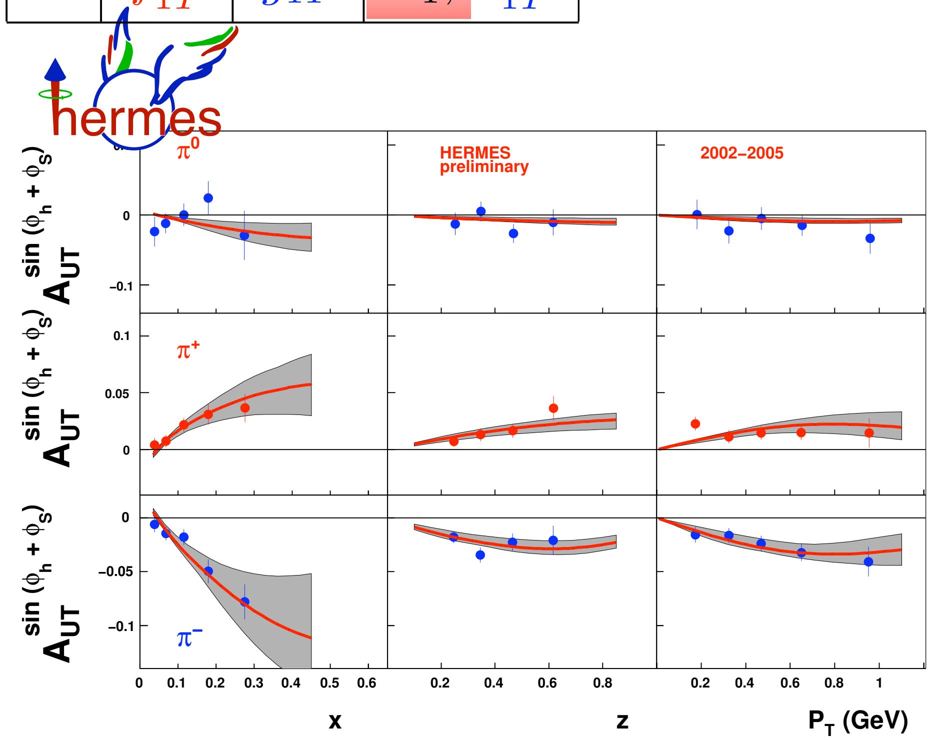


2005: First evidence from HERMES SIDIS on proton

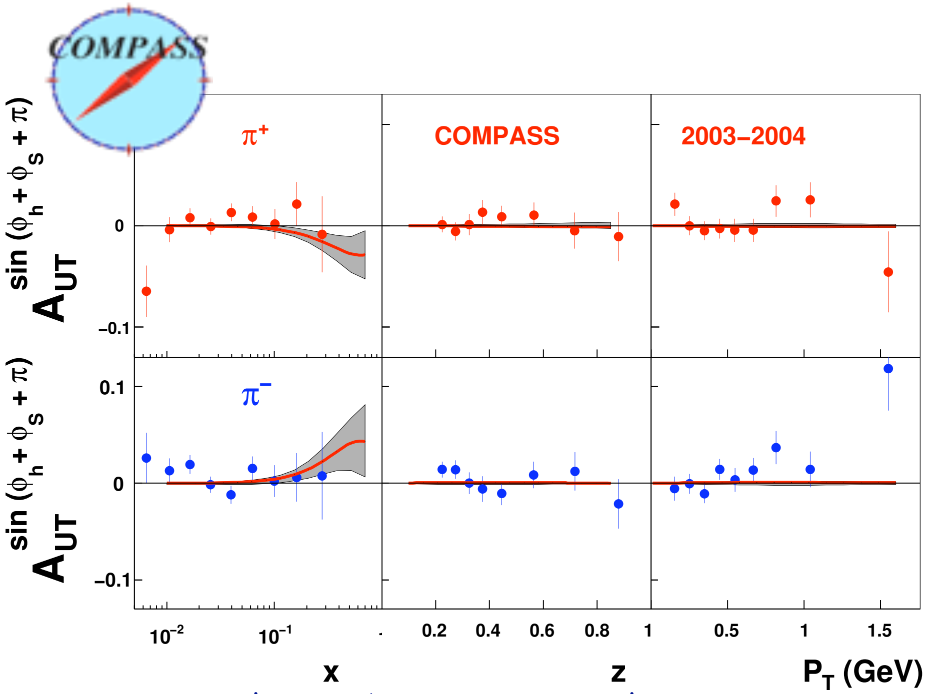
Non-zero transversity
Non-zero Collins function

Fit of Collins amplitudes

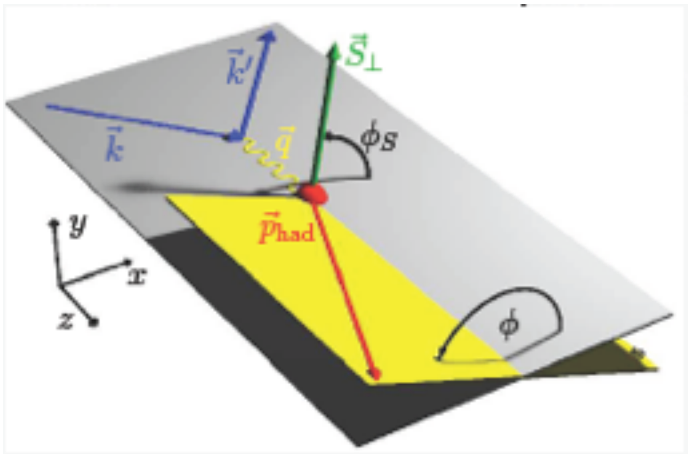
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



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

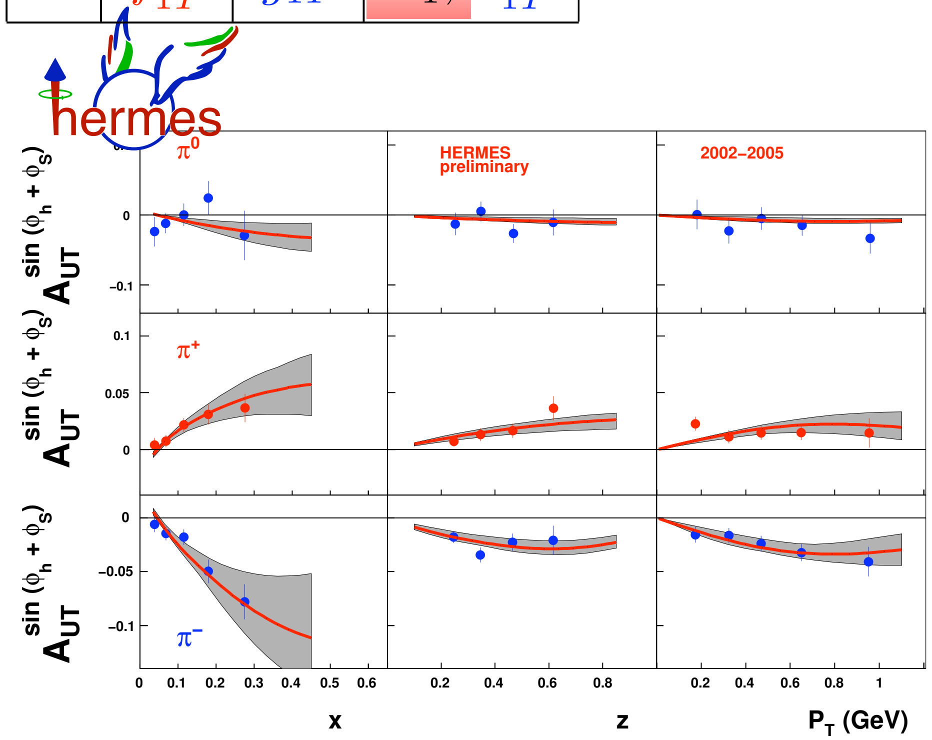


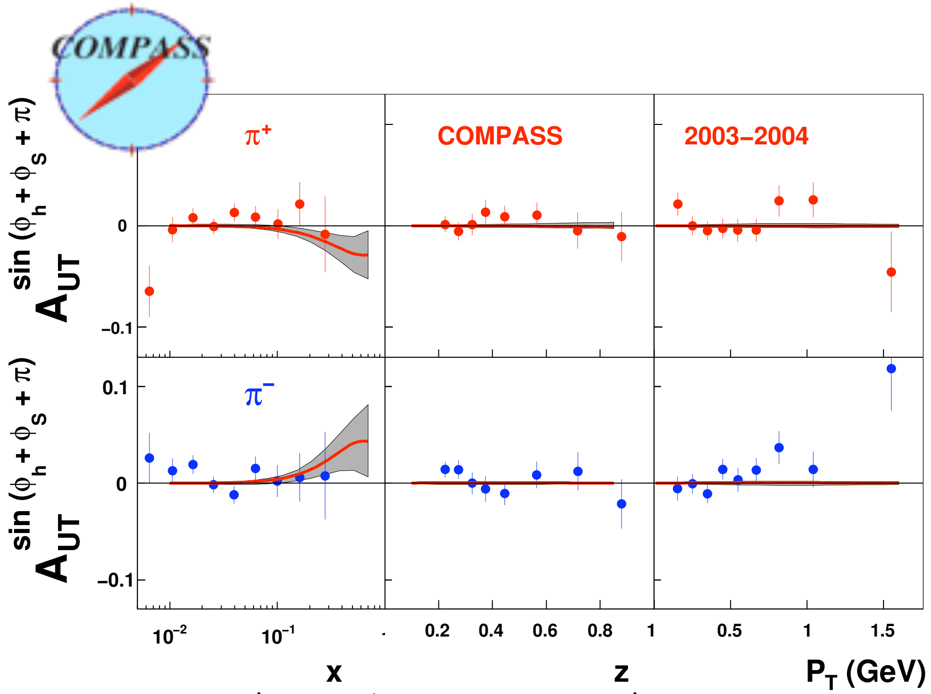
$$\mu^\pm \mathbf{d}^\uparrow \rightarrow \mu^\pm \pi \mathbf{X}$$

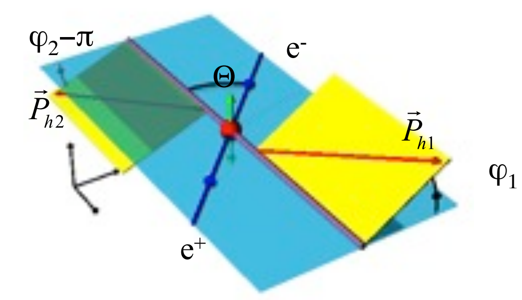


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Fit of Collins amplitudes



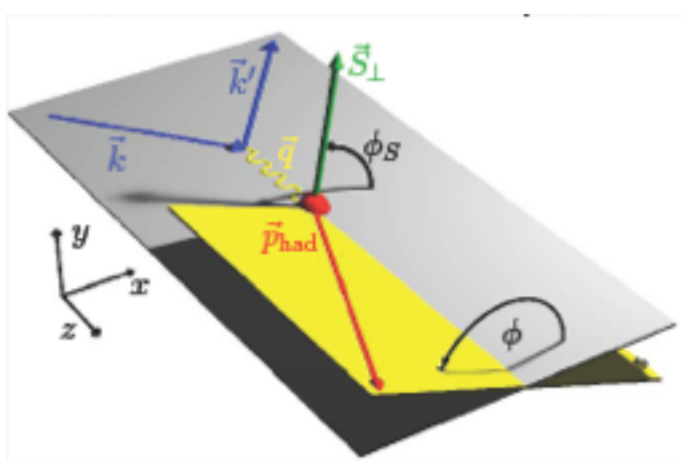


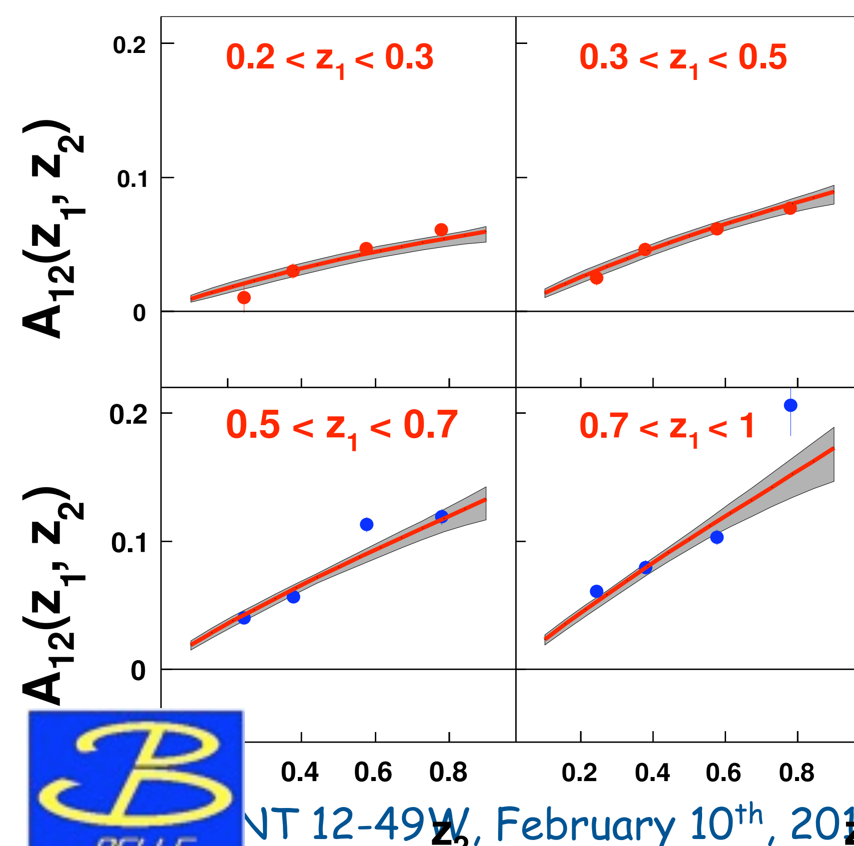


$$\mathbf{e^\pm p^\uparrow \rightarrow e^\pm \pi X}$$

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

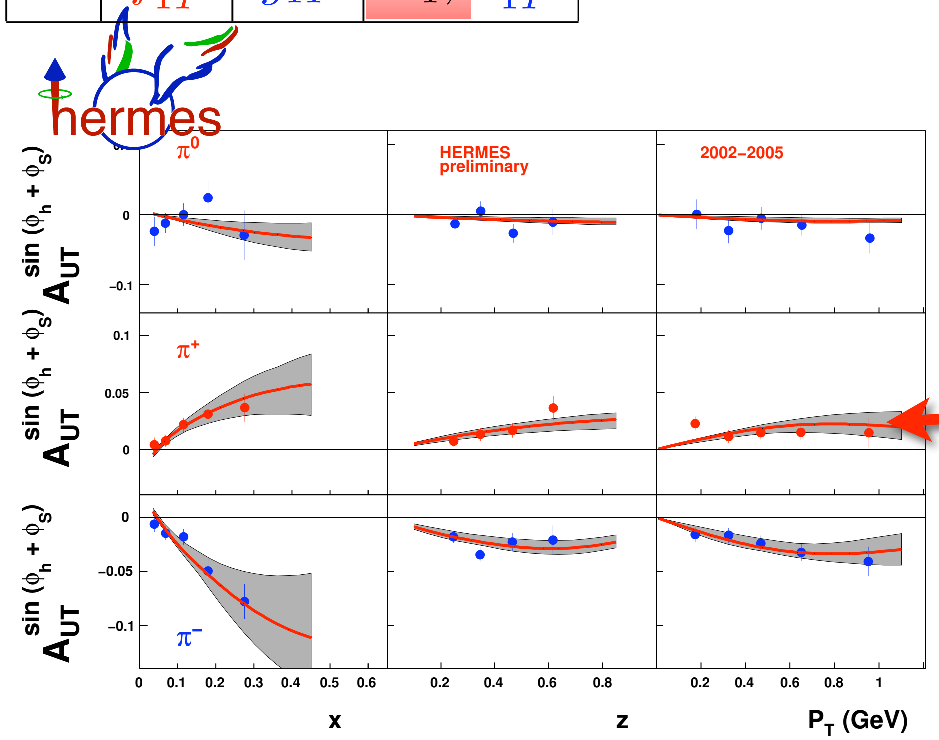
$$\mathbf{e^+ e^- \rightarrow \pi\pi X}$$



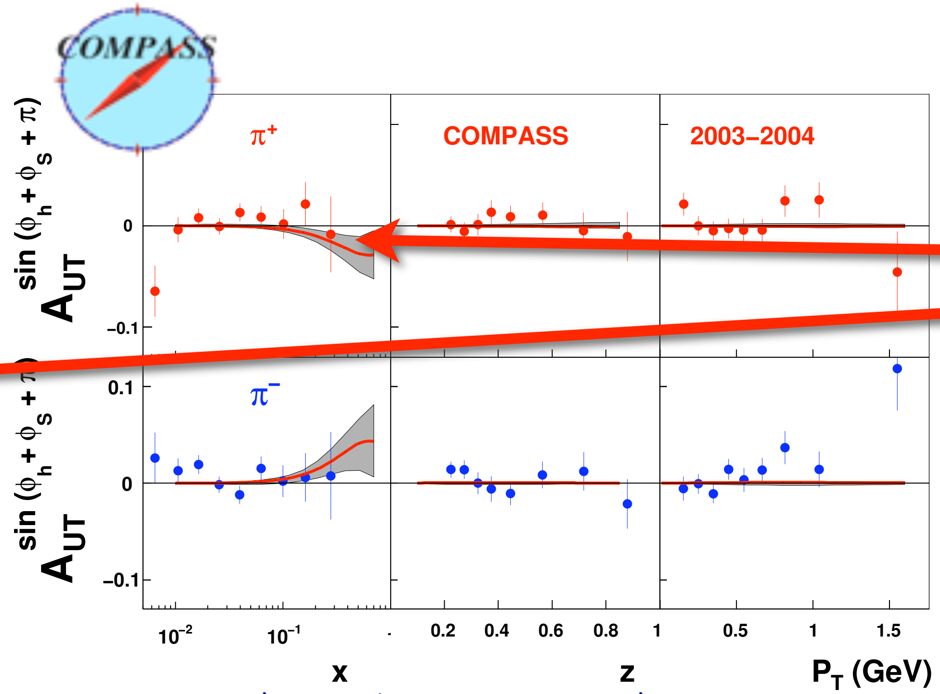


Fit of Collins amplitudes

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

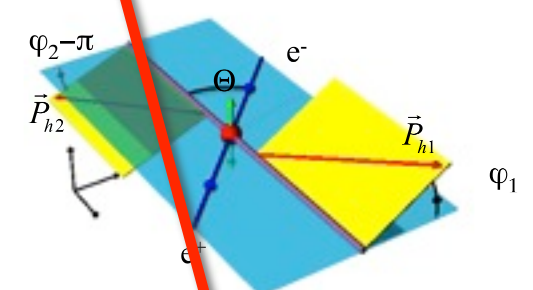


$$e^{\pm}p^{\uparrow} \rightarrow e^{\pm}\pi X$$

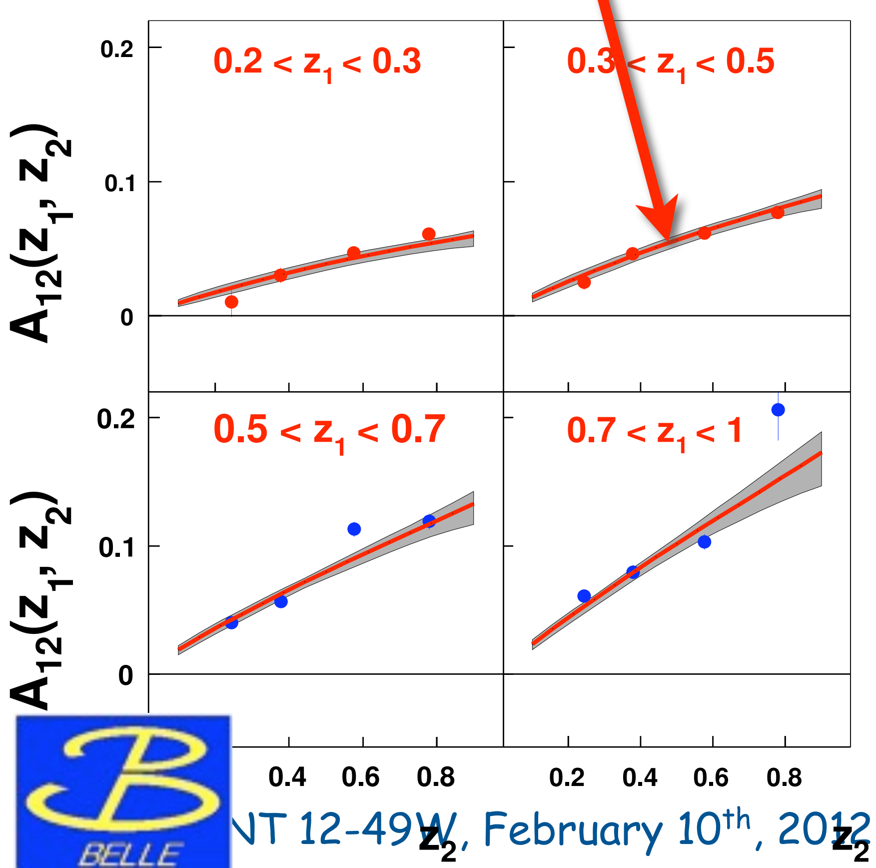


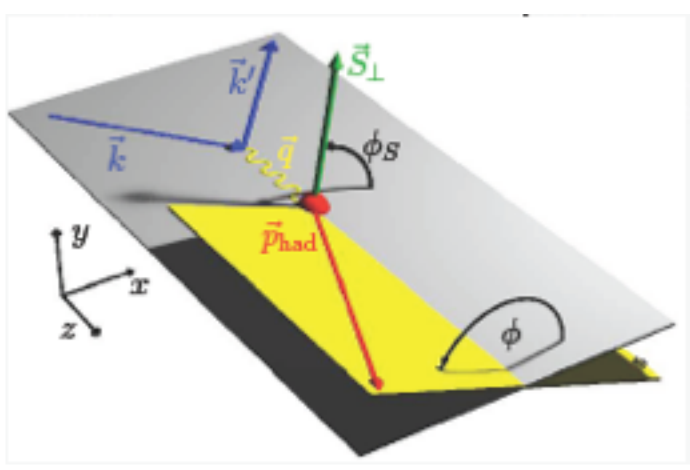
$$\mu^{\pm}d^{\uparrow} \rightarrow \mu^{\pm}\pi X$$

fit to data



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

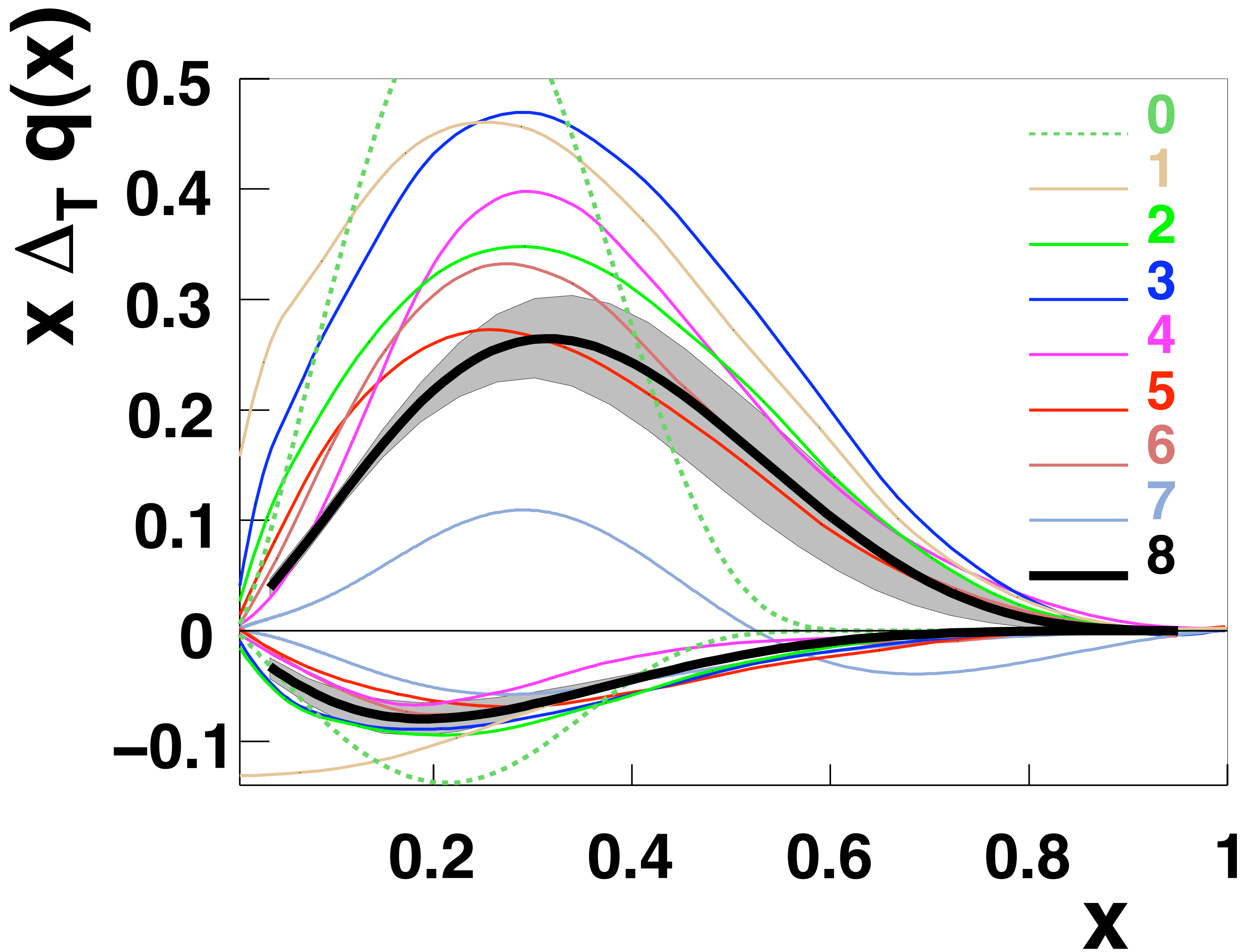




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity: models and fits

[0] Barone et al. PLB 390 (97)
[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] Cloet, Bentz, Thomas, PLB 659 (08)
[7] Bacchetta, Conti, Radici, PRD 78 (08)
[8] Anselmino et al., arXiv:0807.0173



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

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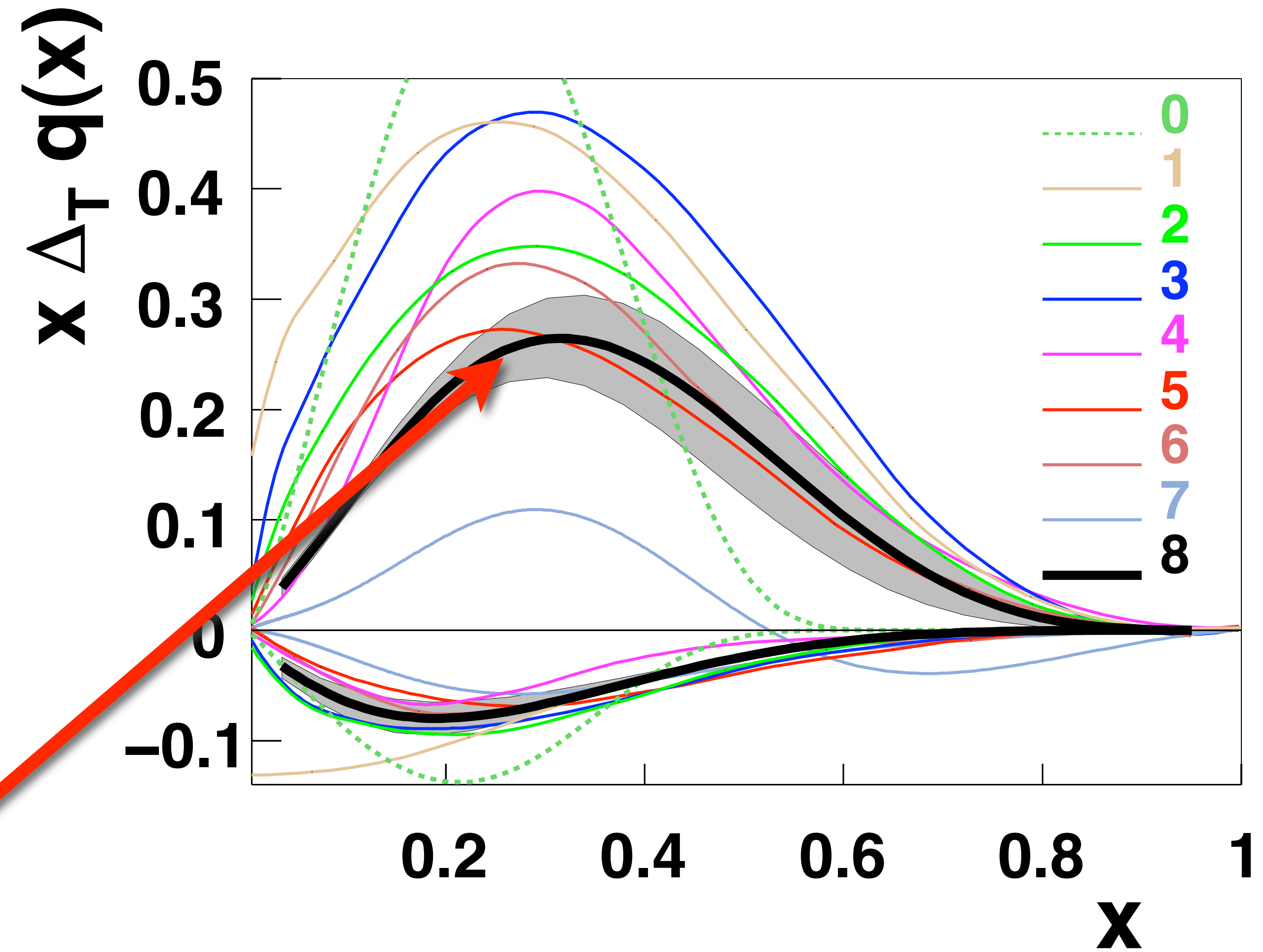

☑ u quark transversity along nucleon spin

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

Transversity: models and fits

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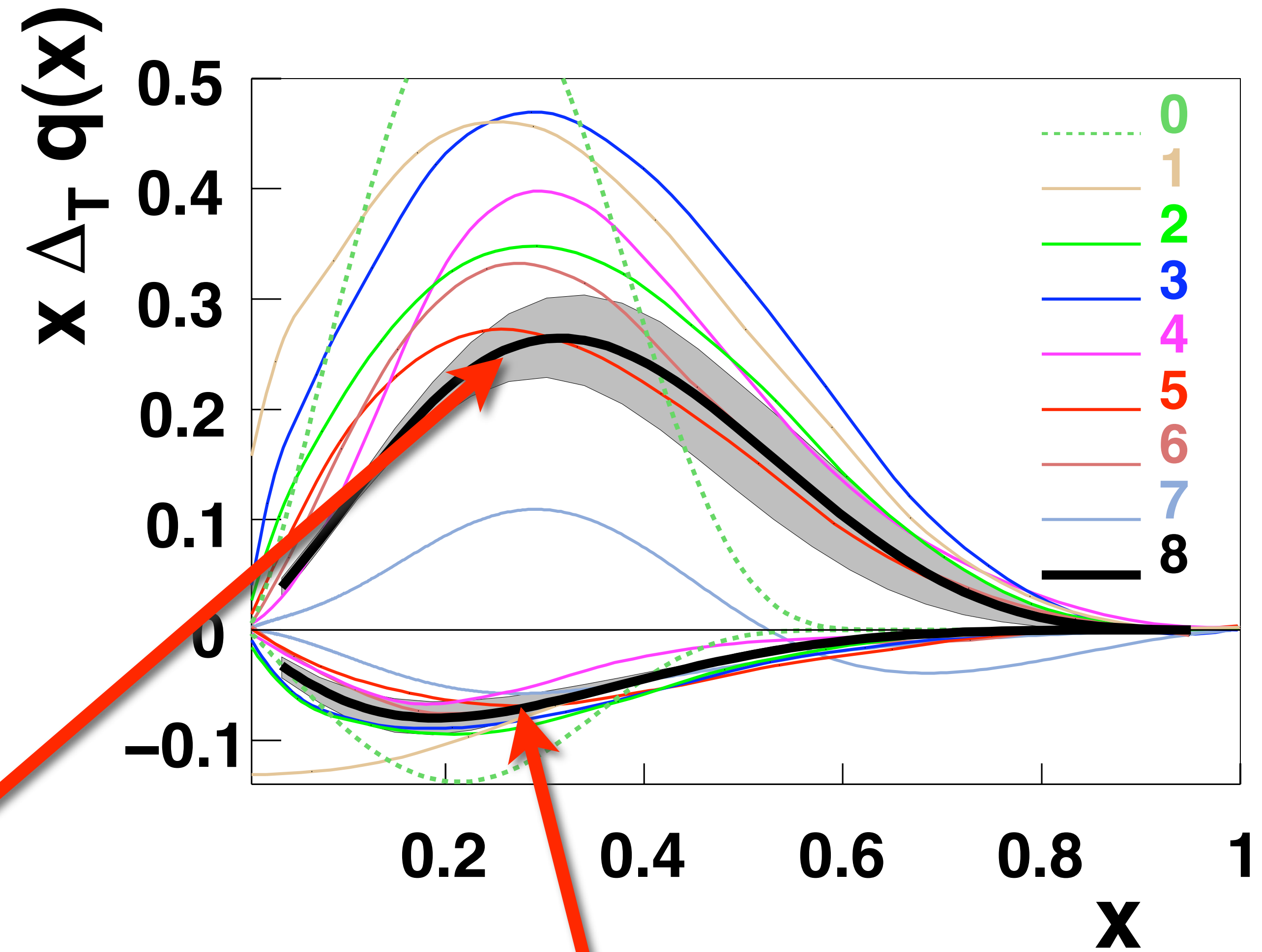

☑ u quark transversity along nucleon spin

☑ d quark transversity anti-parallel to nucleon spin

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

Transversity: models and fits

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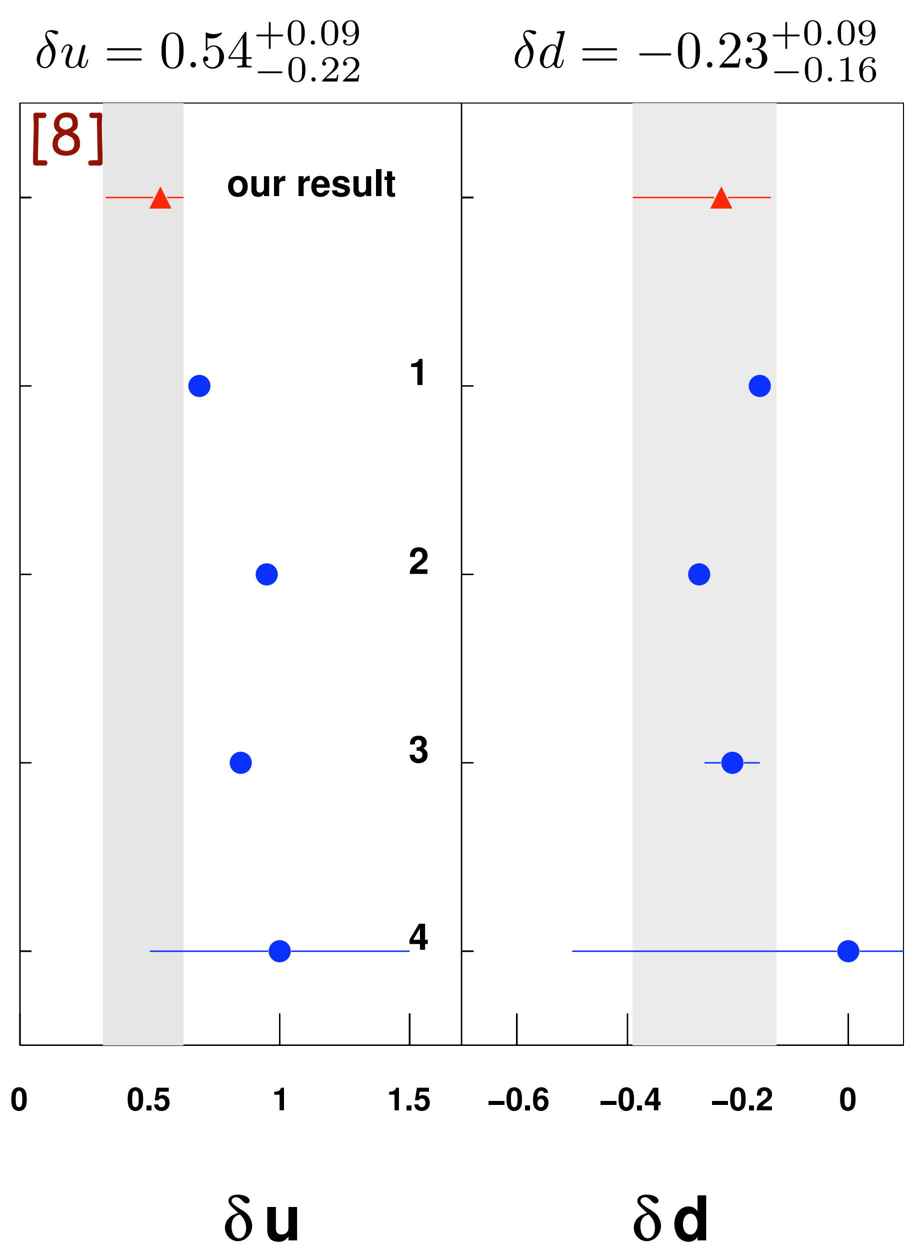

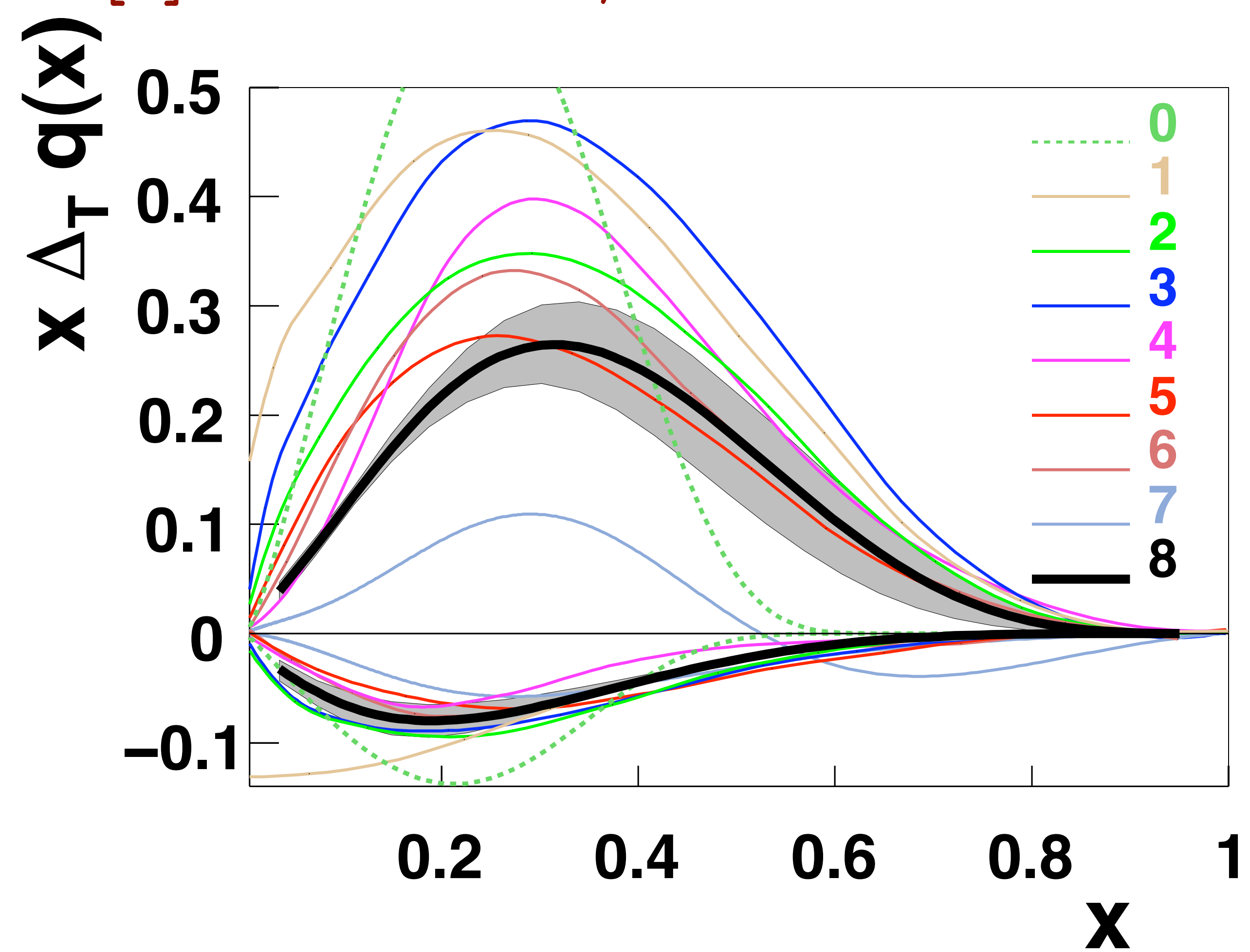

tensor charge:

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

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

Collins amplitudes

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

	U	L	T
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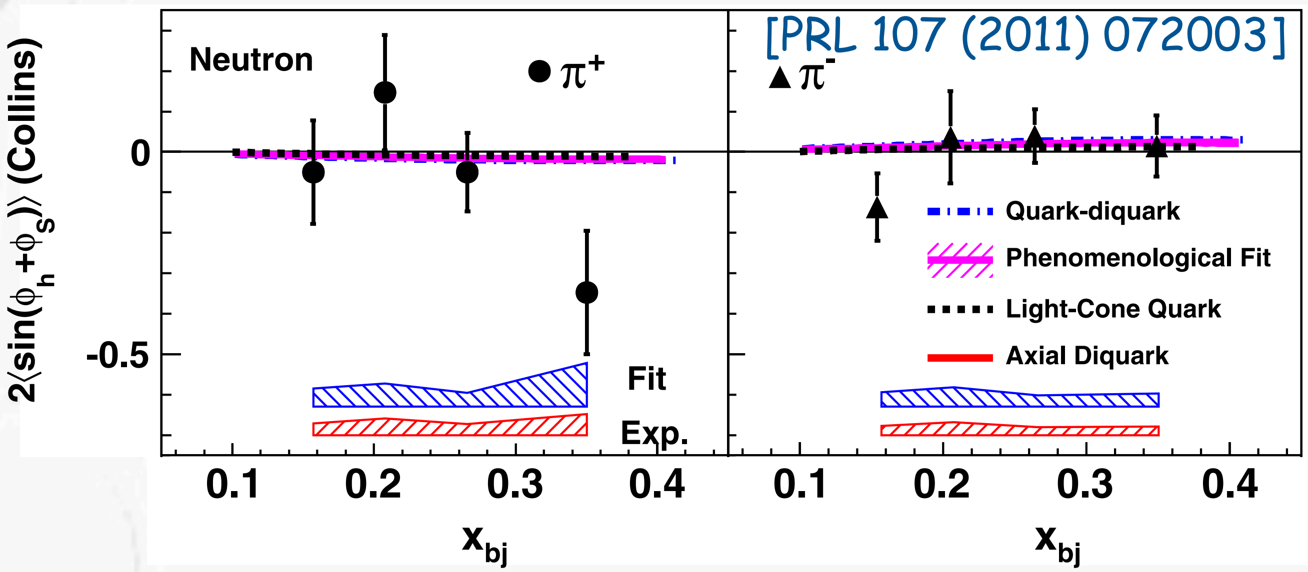
Collins amplitudes



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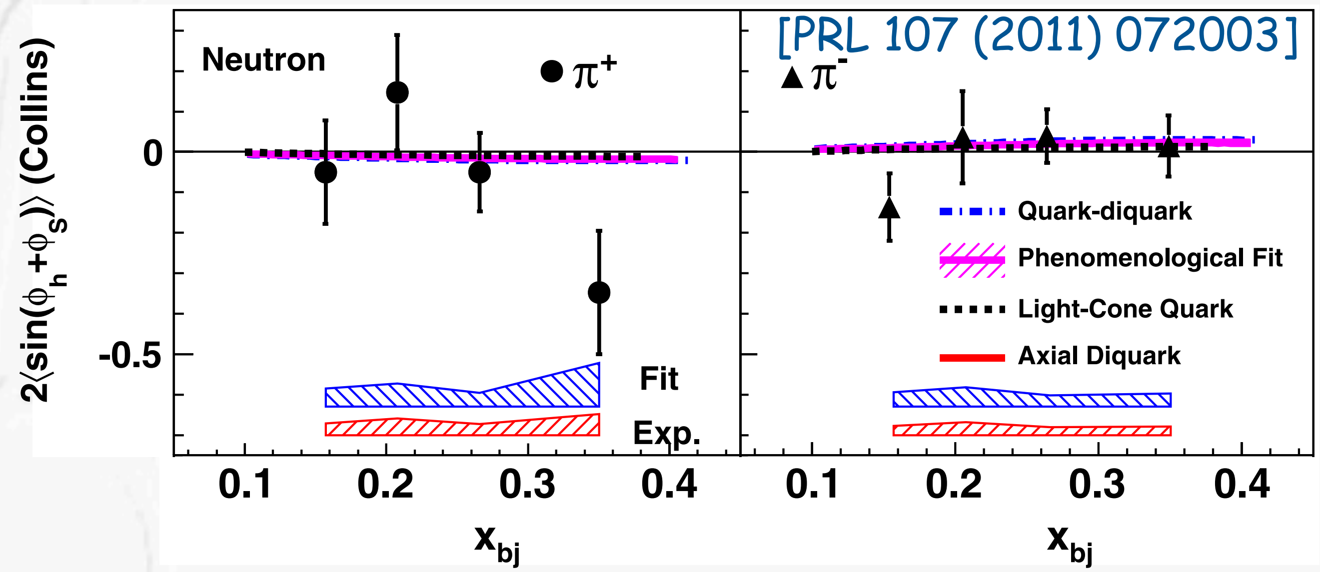
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes



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    - BELLE
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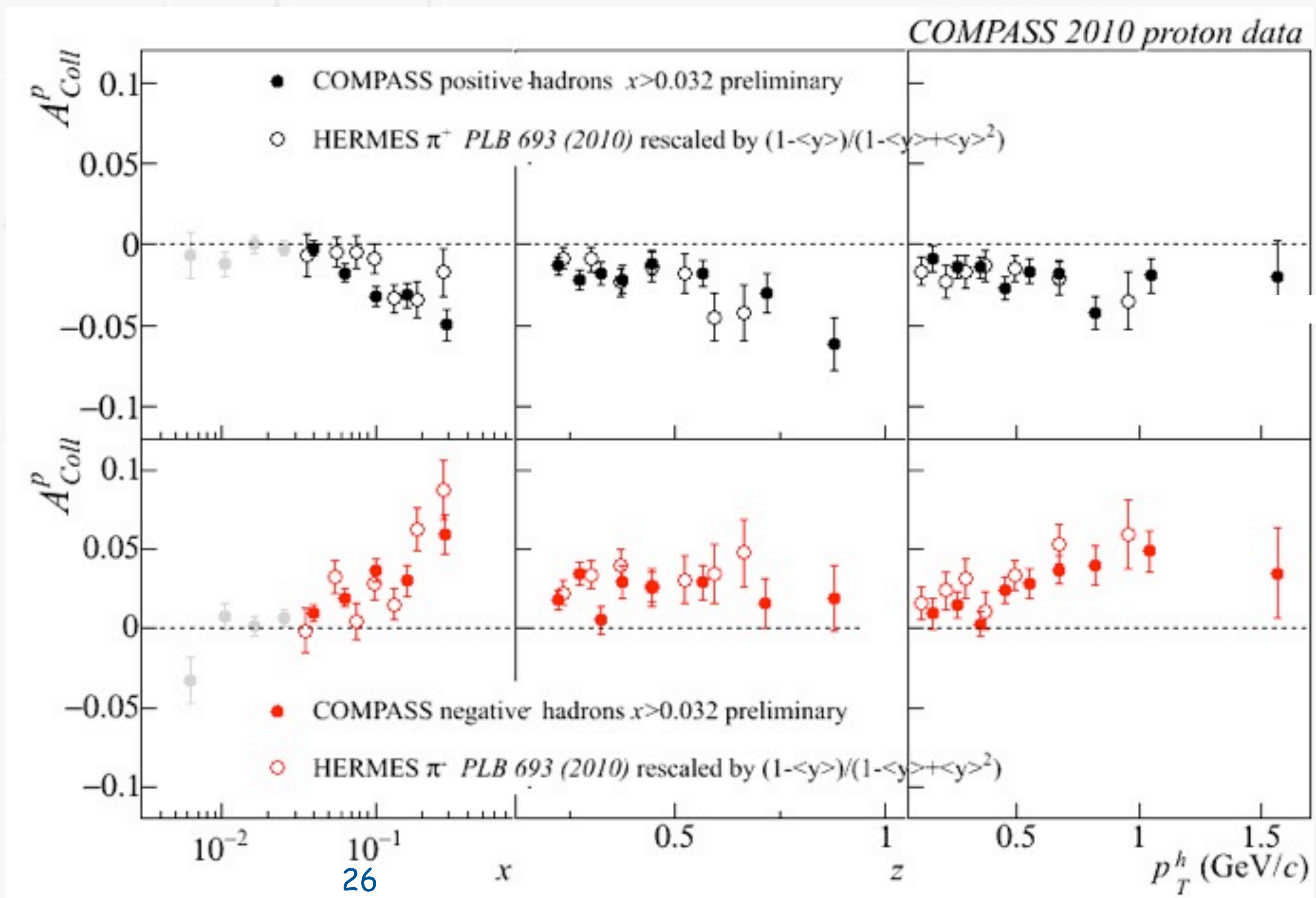
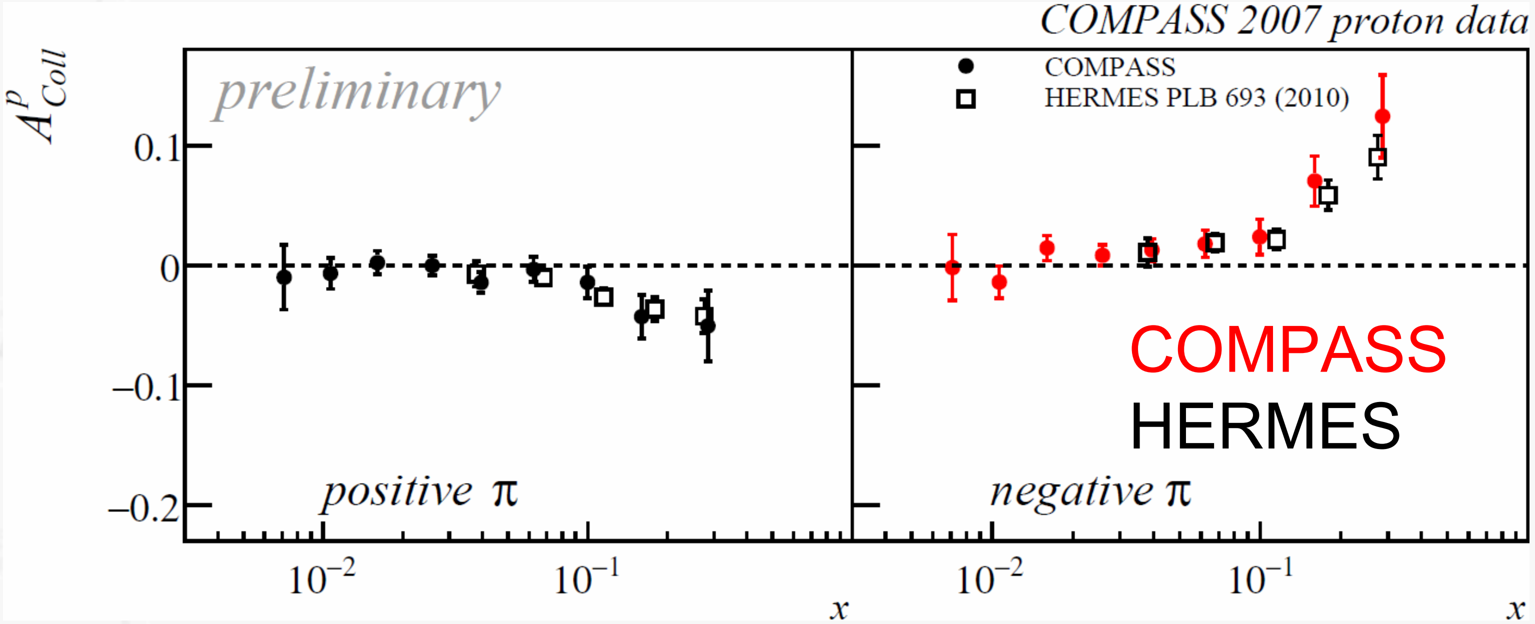


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

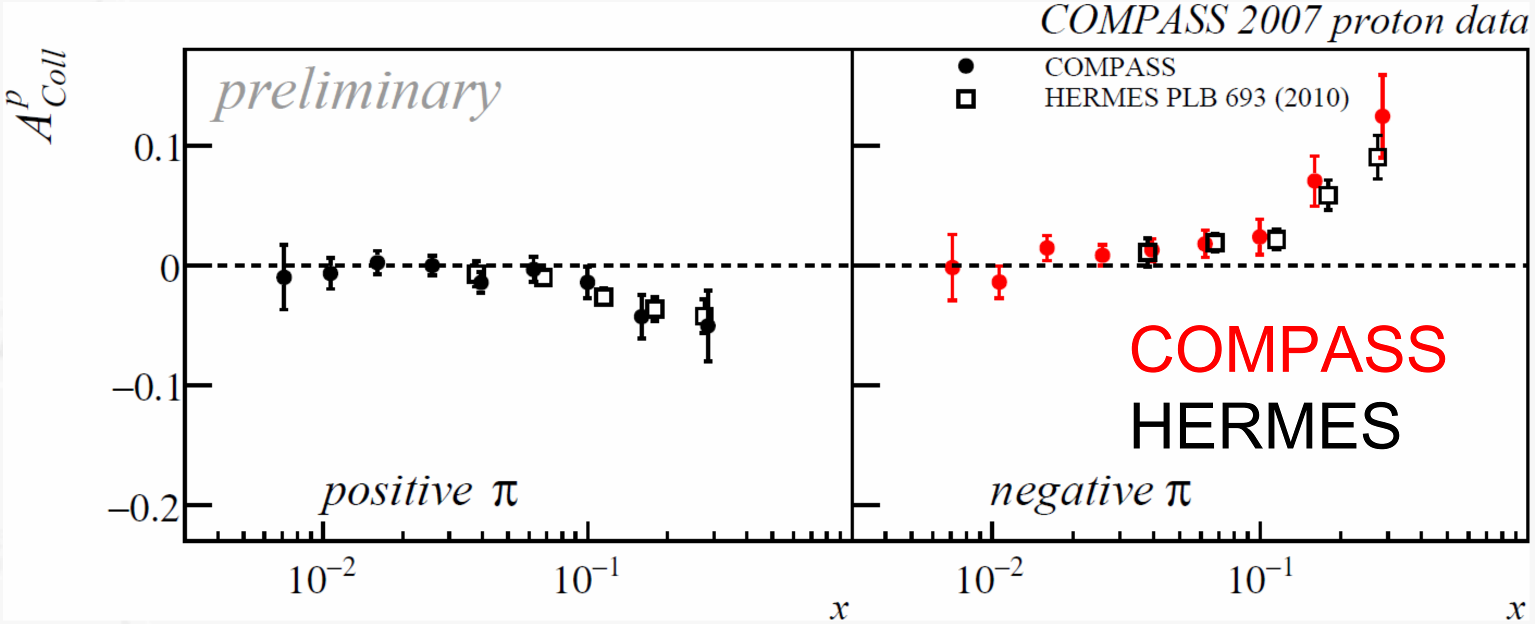


PLB 693 (2010)

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, $h_{1T}^\perp$

- similar behavior for pions

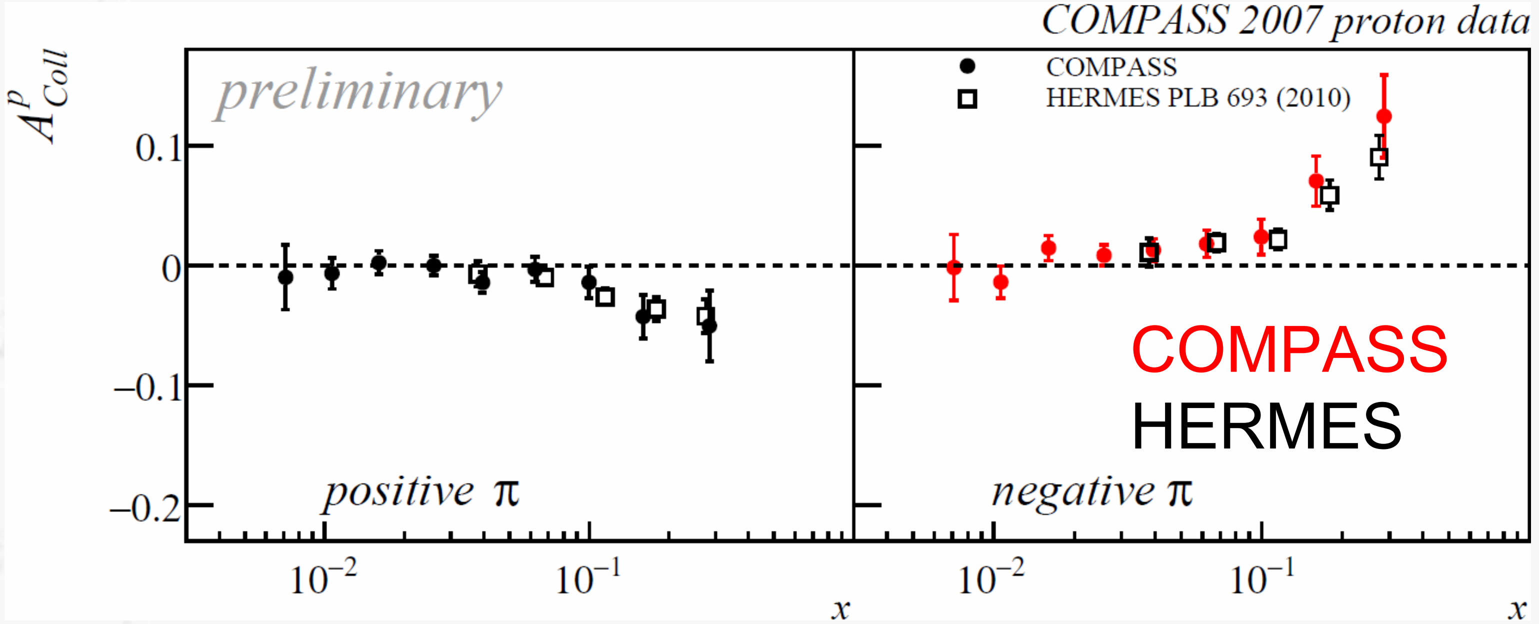


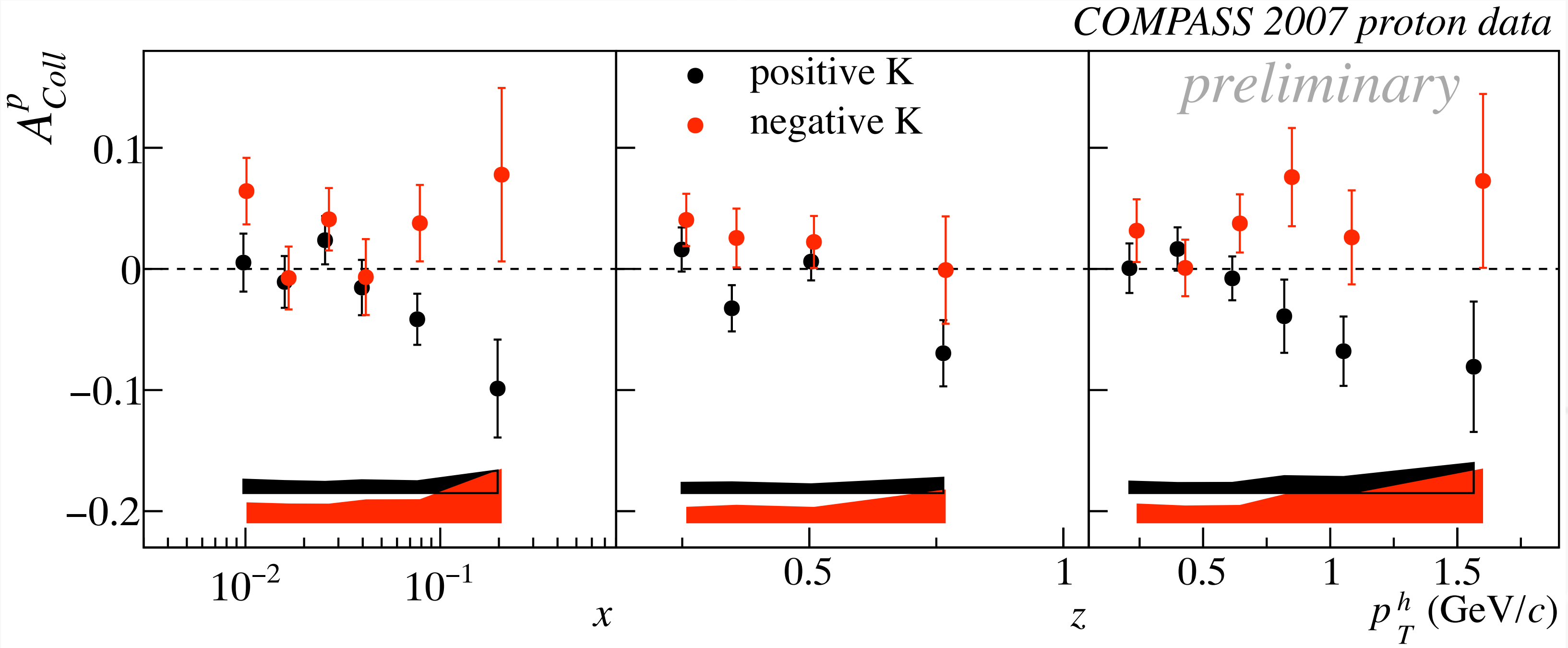
PLB 693 (2010)

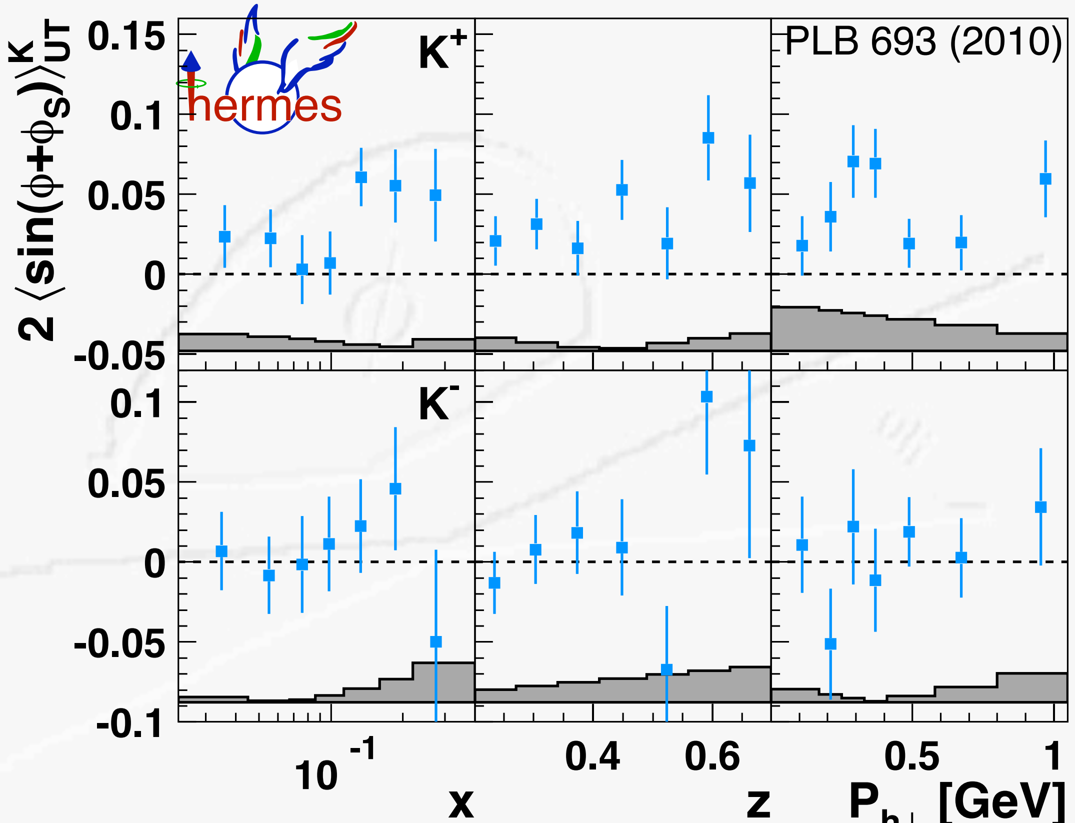
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

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

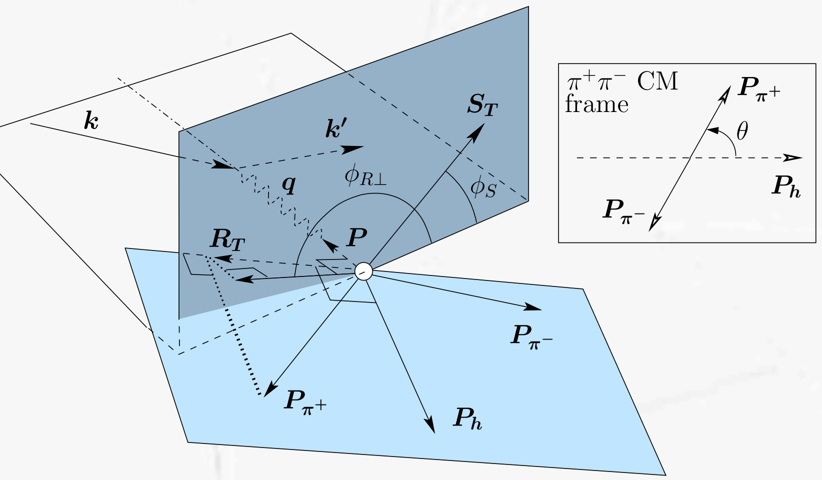




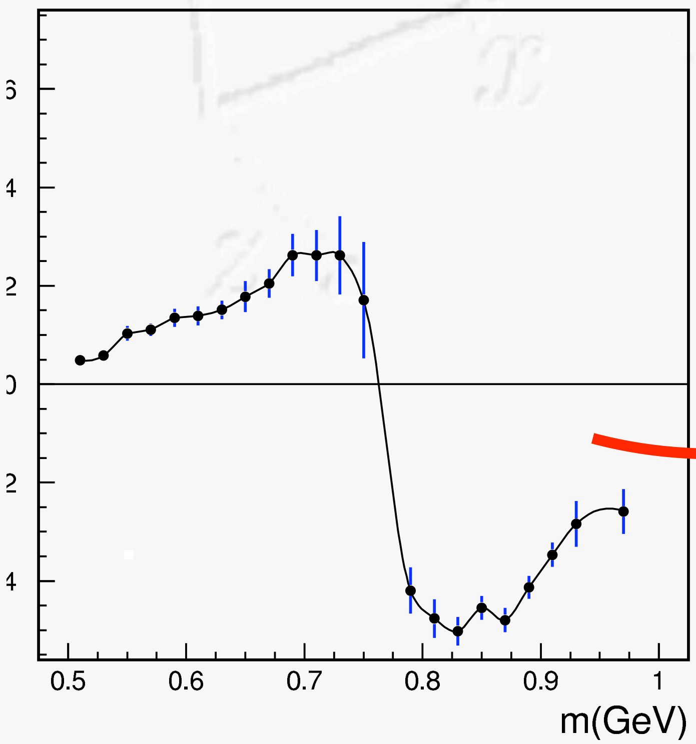


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)



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



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

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

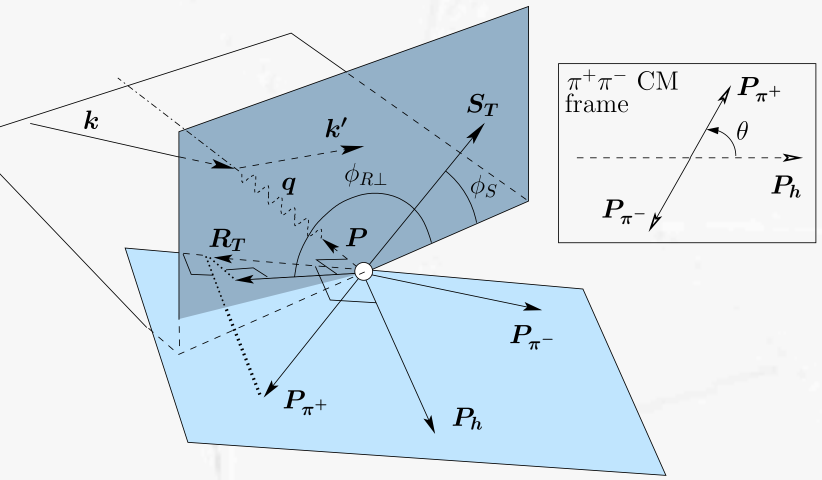
δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

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

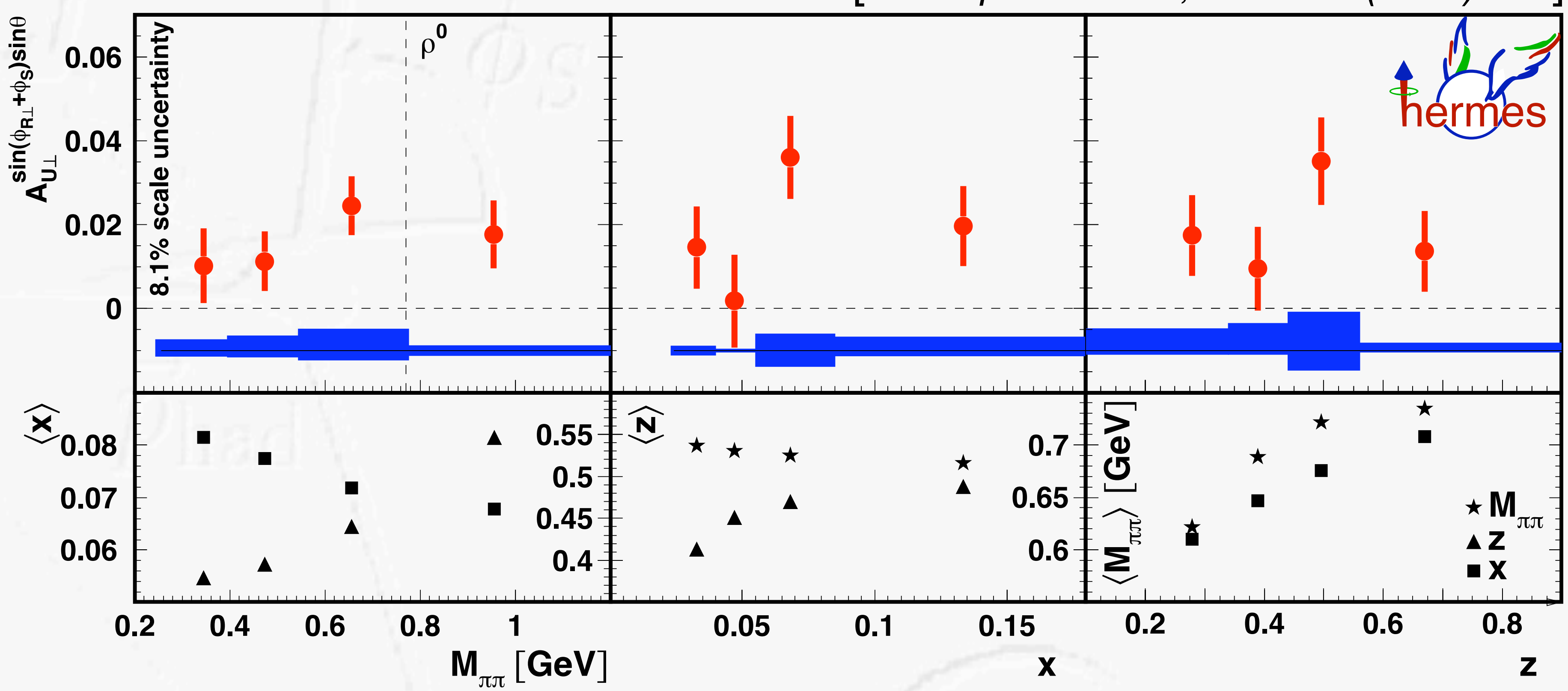
$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

	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)



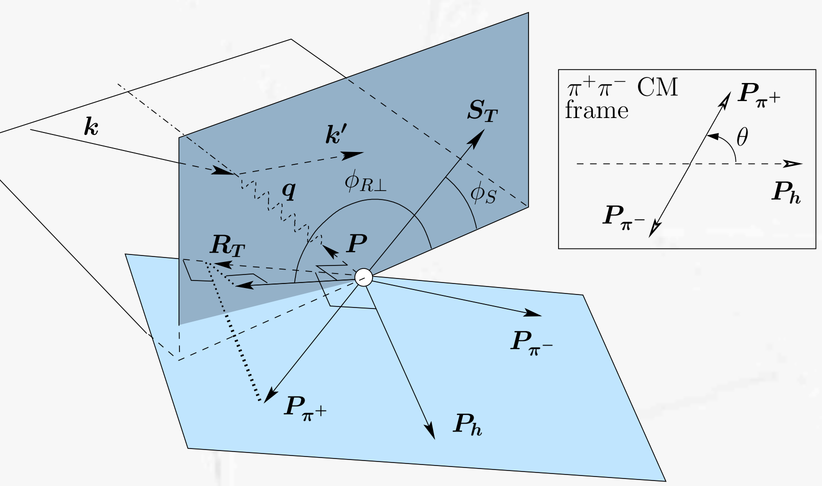
[A. Airapetian et al., JHEP 06 (2008) 017]



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

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

Transversity distribution (2-hadron fragmentation)



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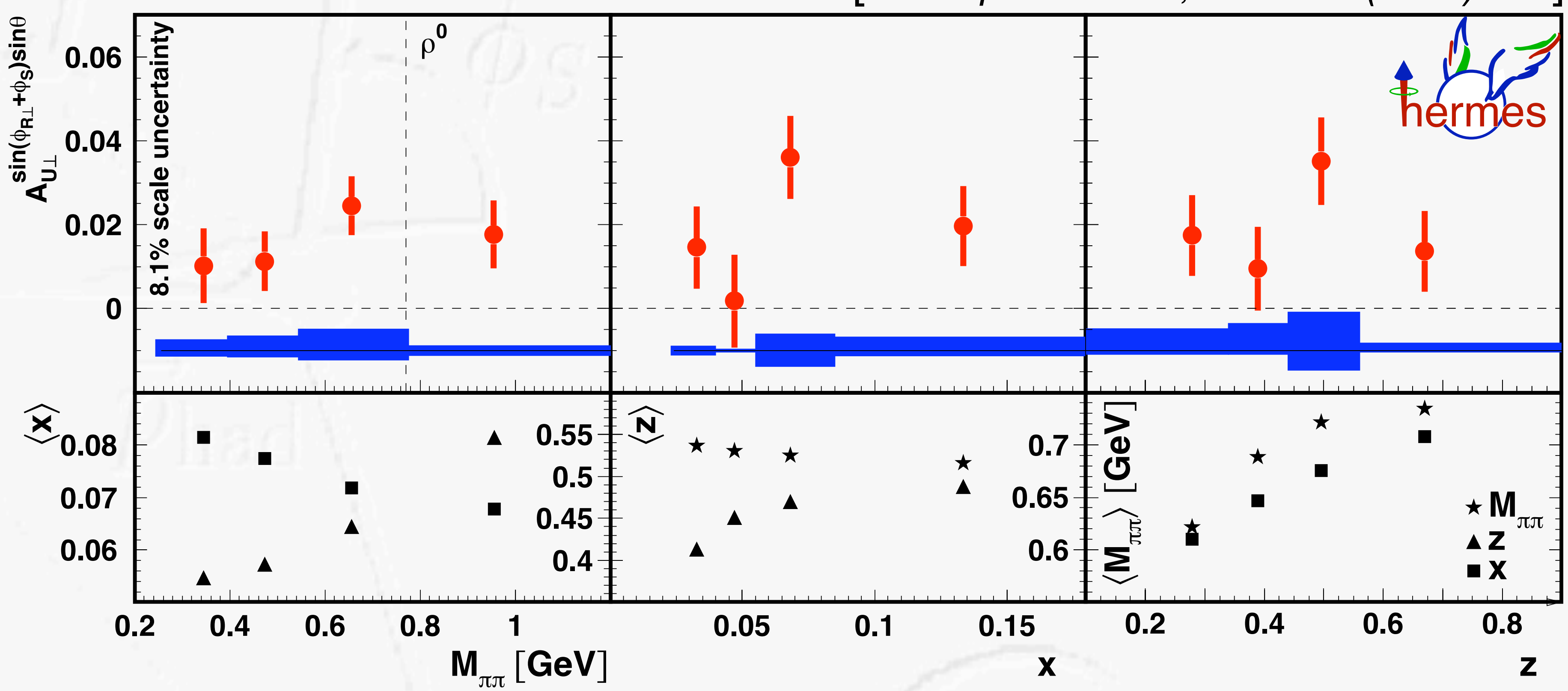

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☑ invariant-mass dependence rules out Jaffe model predicting a sign change to rho mass

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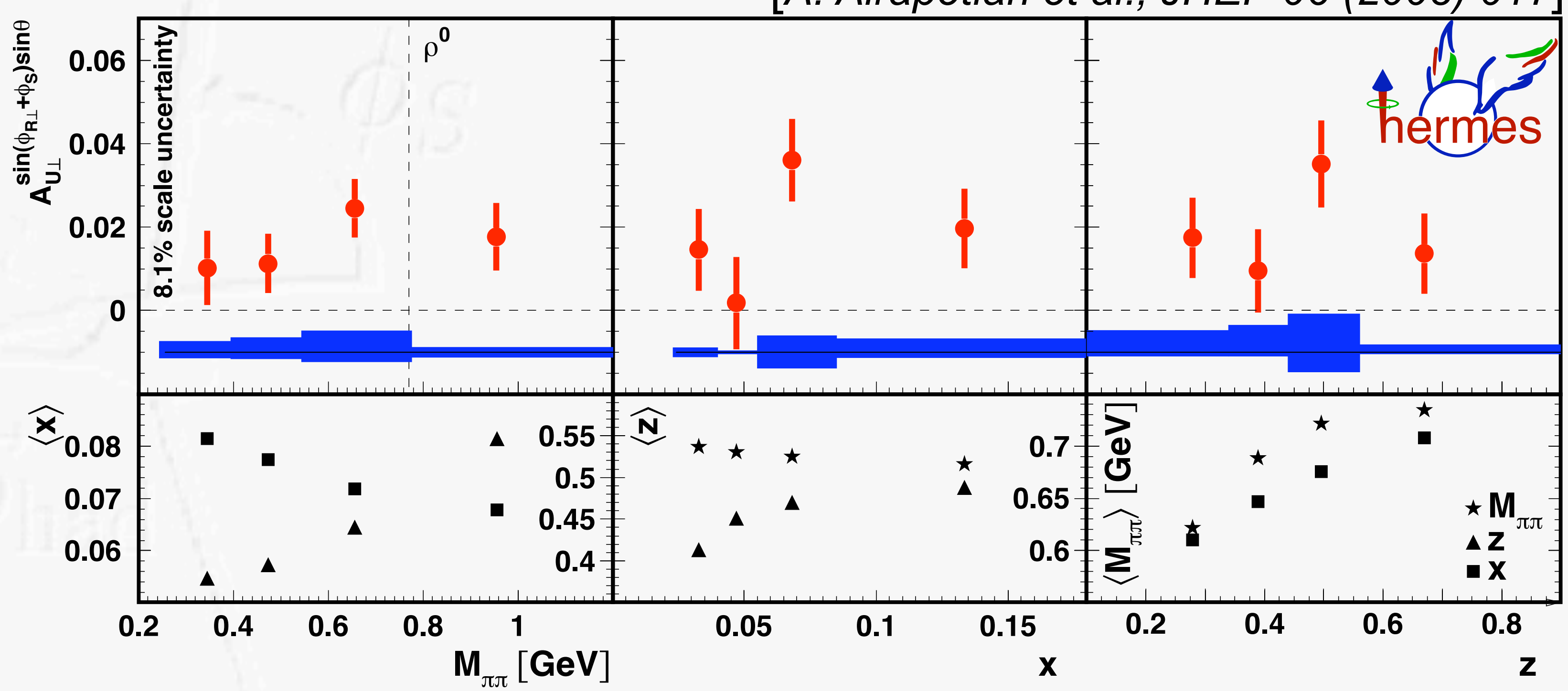

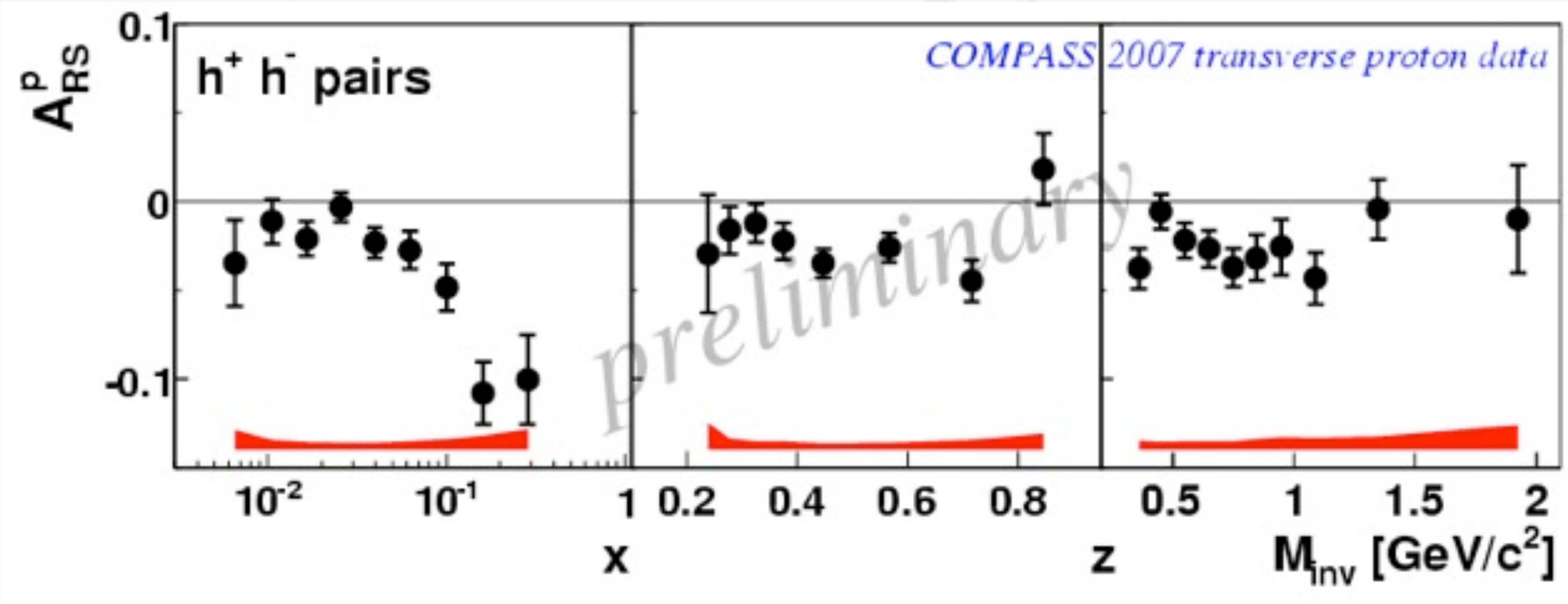

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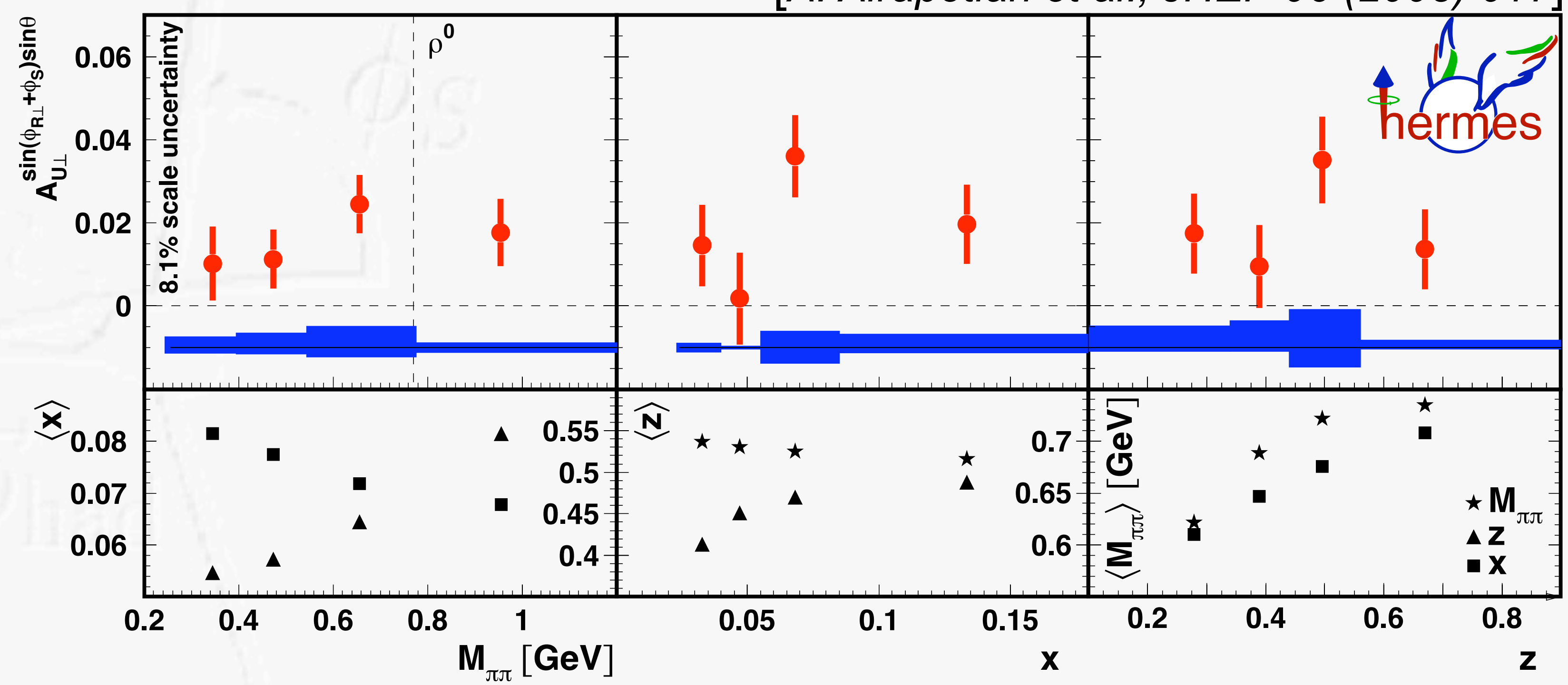
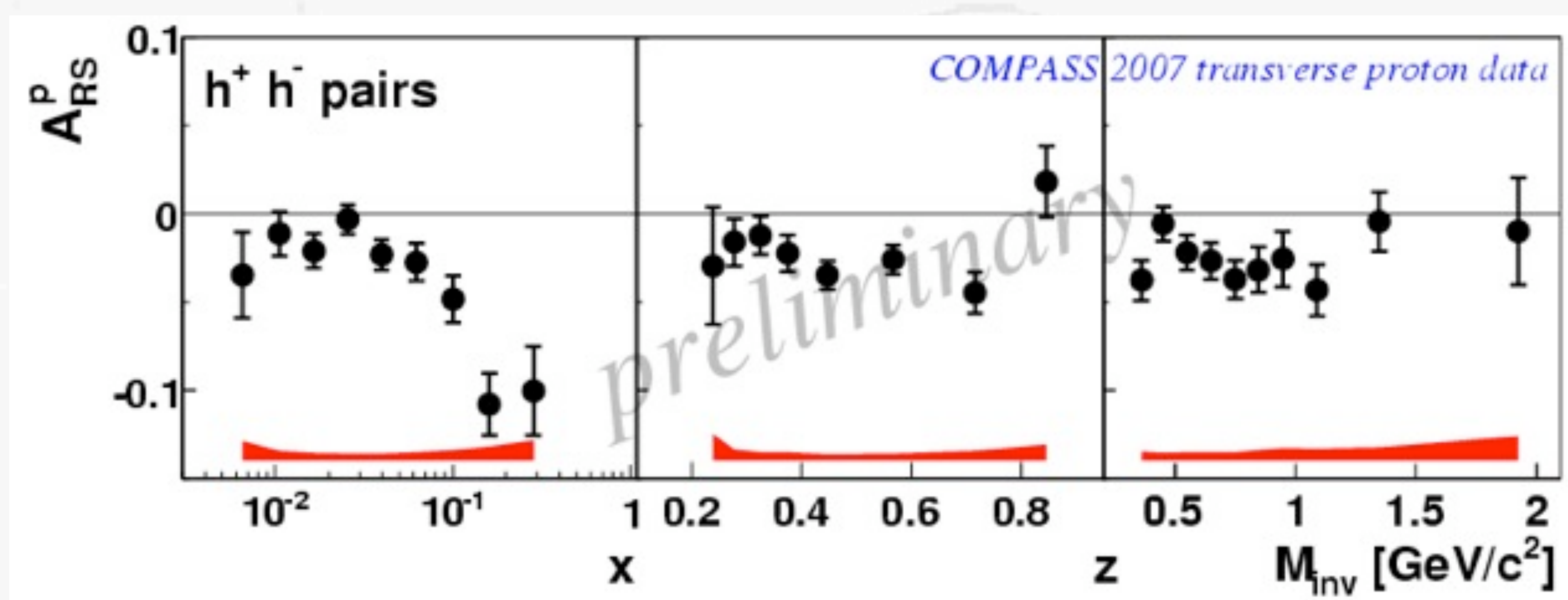
- COMPASS: hadron pairs
  HERMES: pion pairs

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





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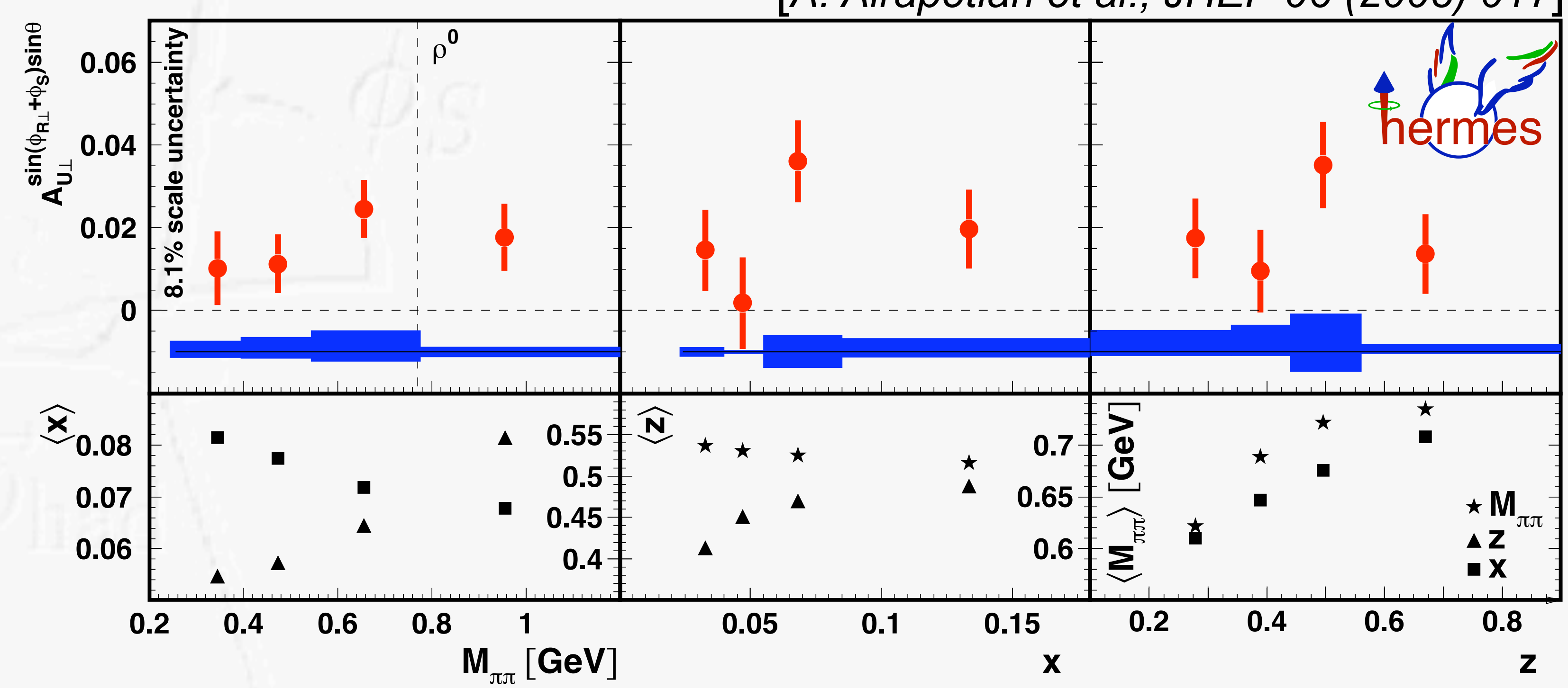

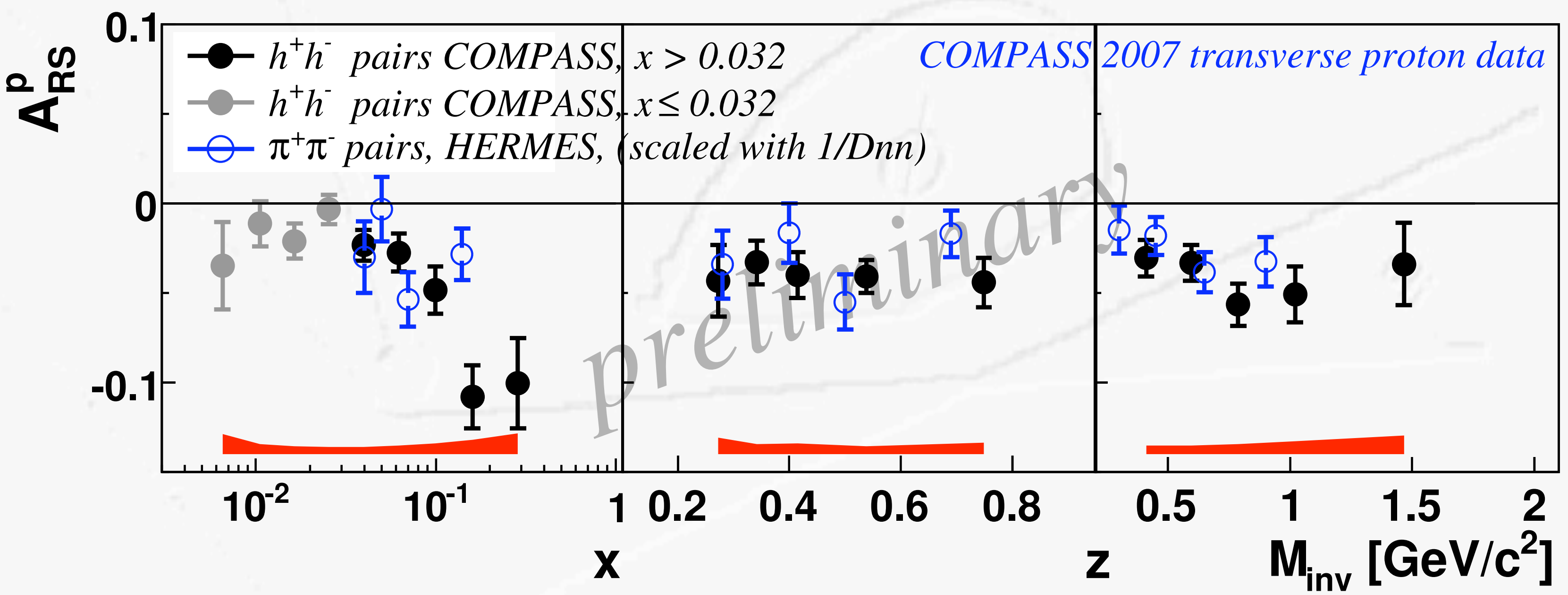

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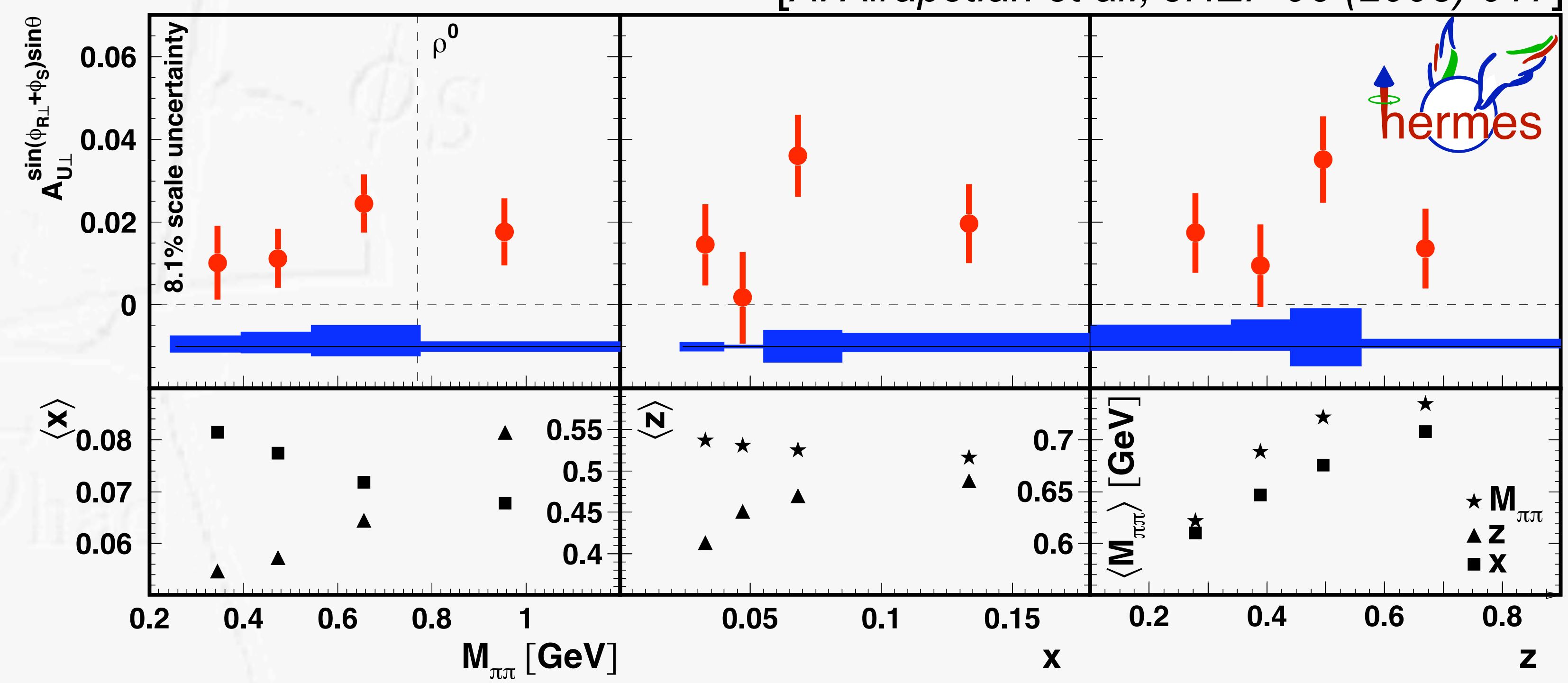

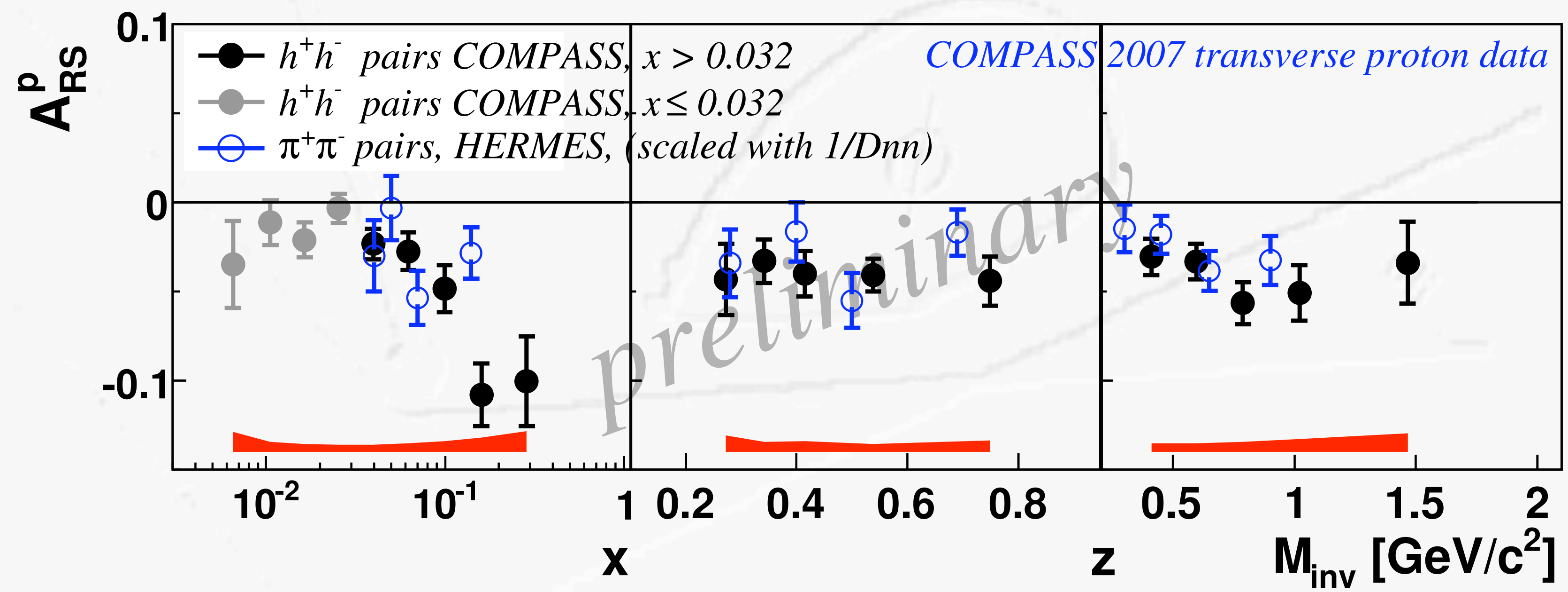

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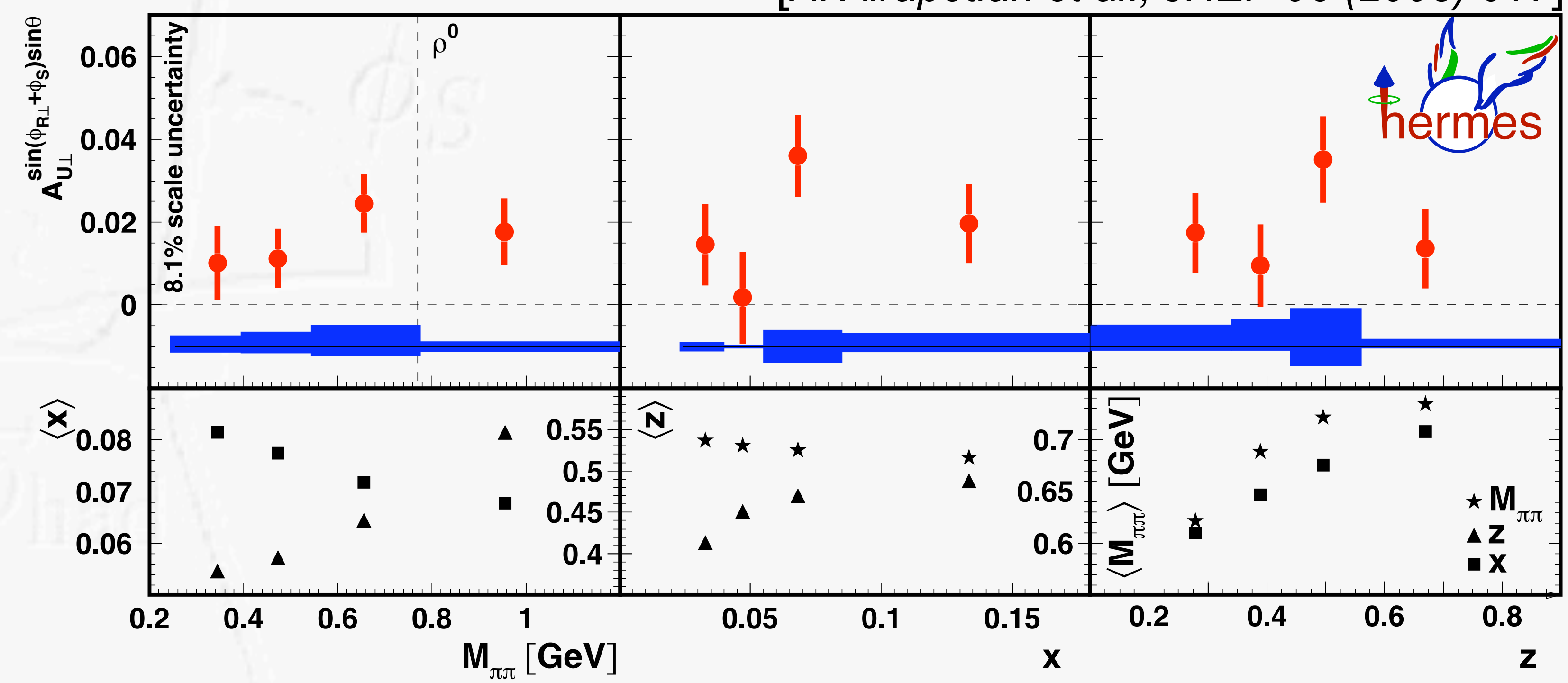

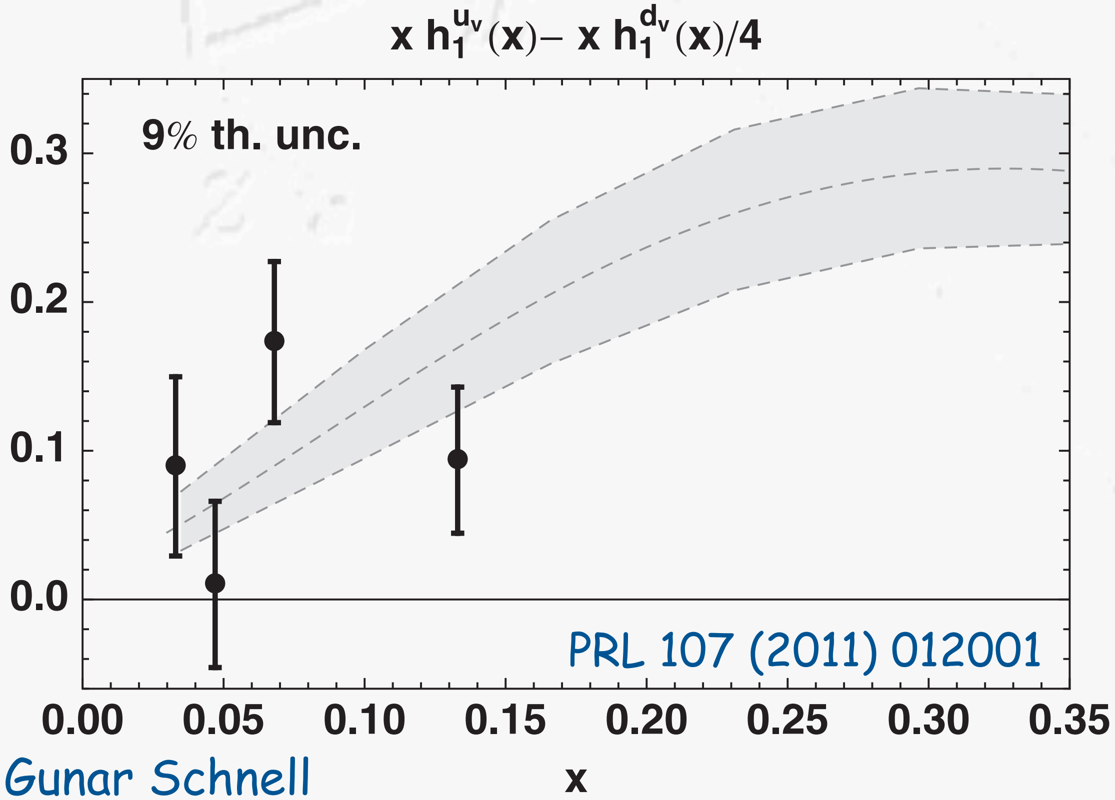

- first (collinear) extraction of transversity (compared to Anselmino et al.)

Transversity's friends

	U	L	T
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Pretzelosity

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

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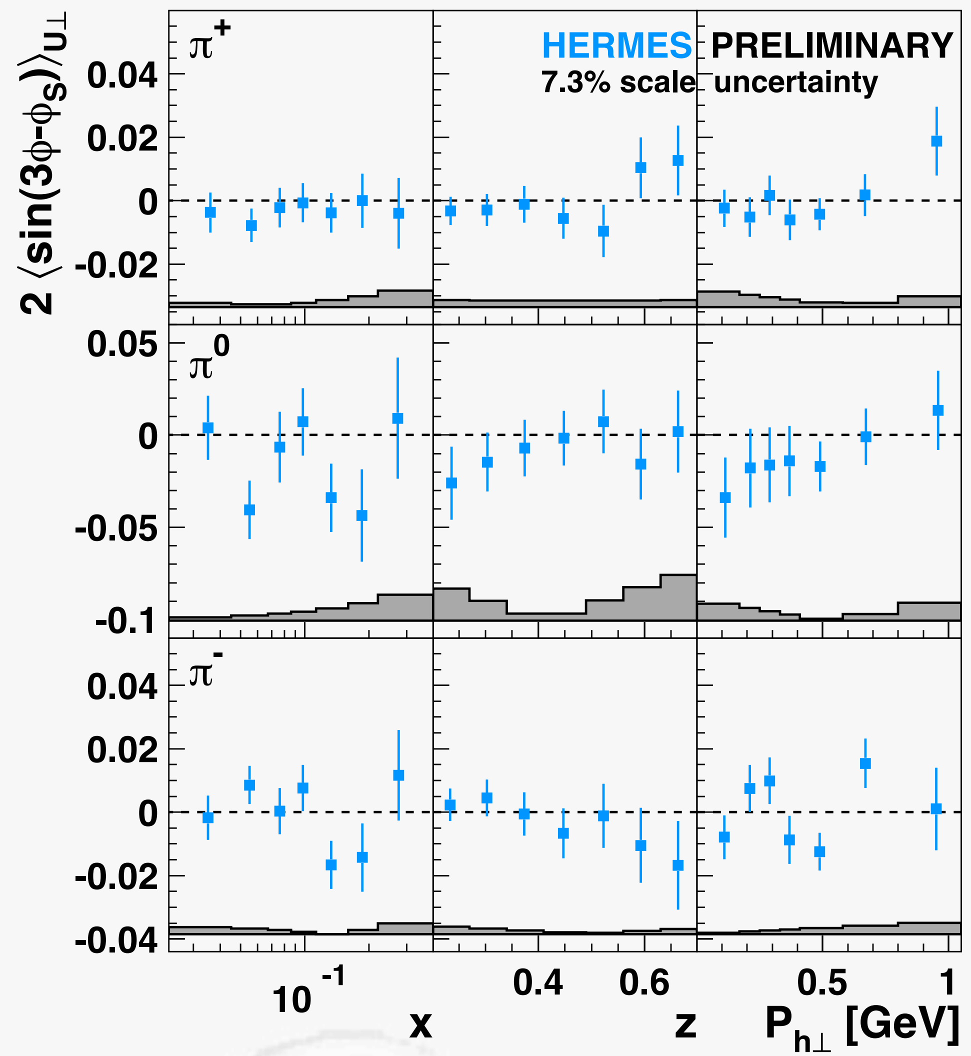

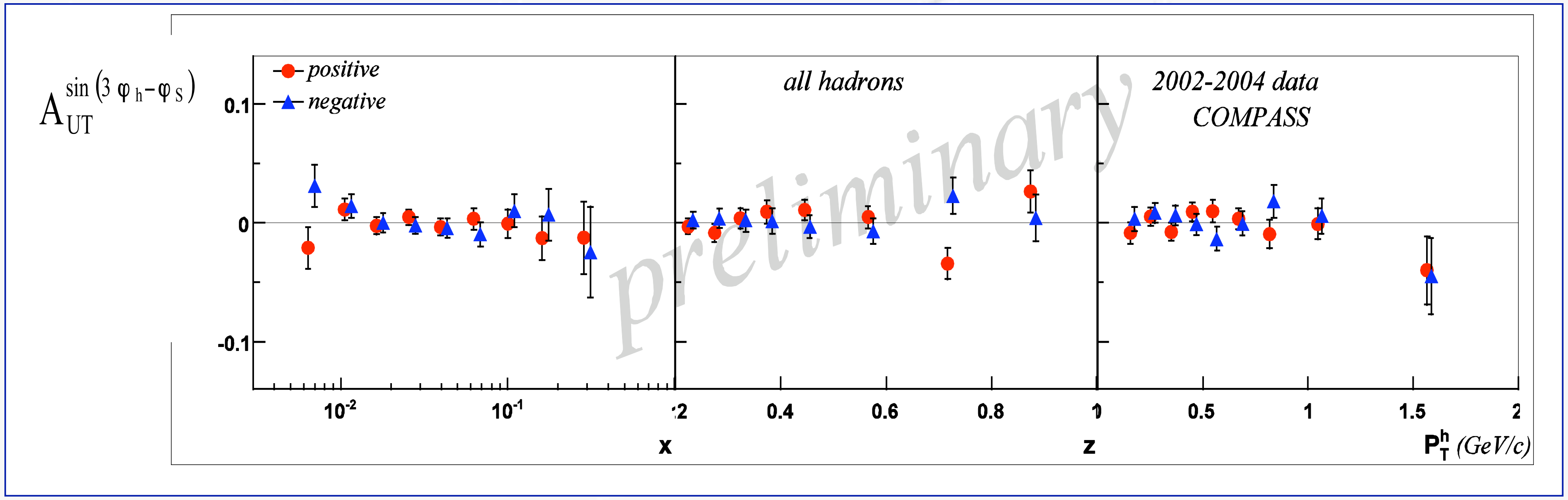

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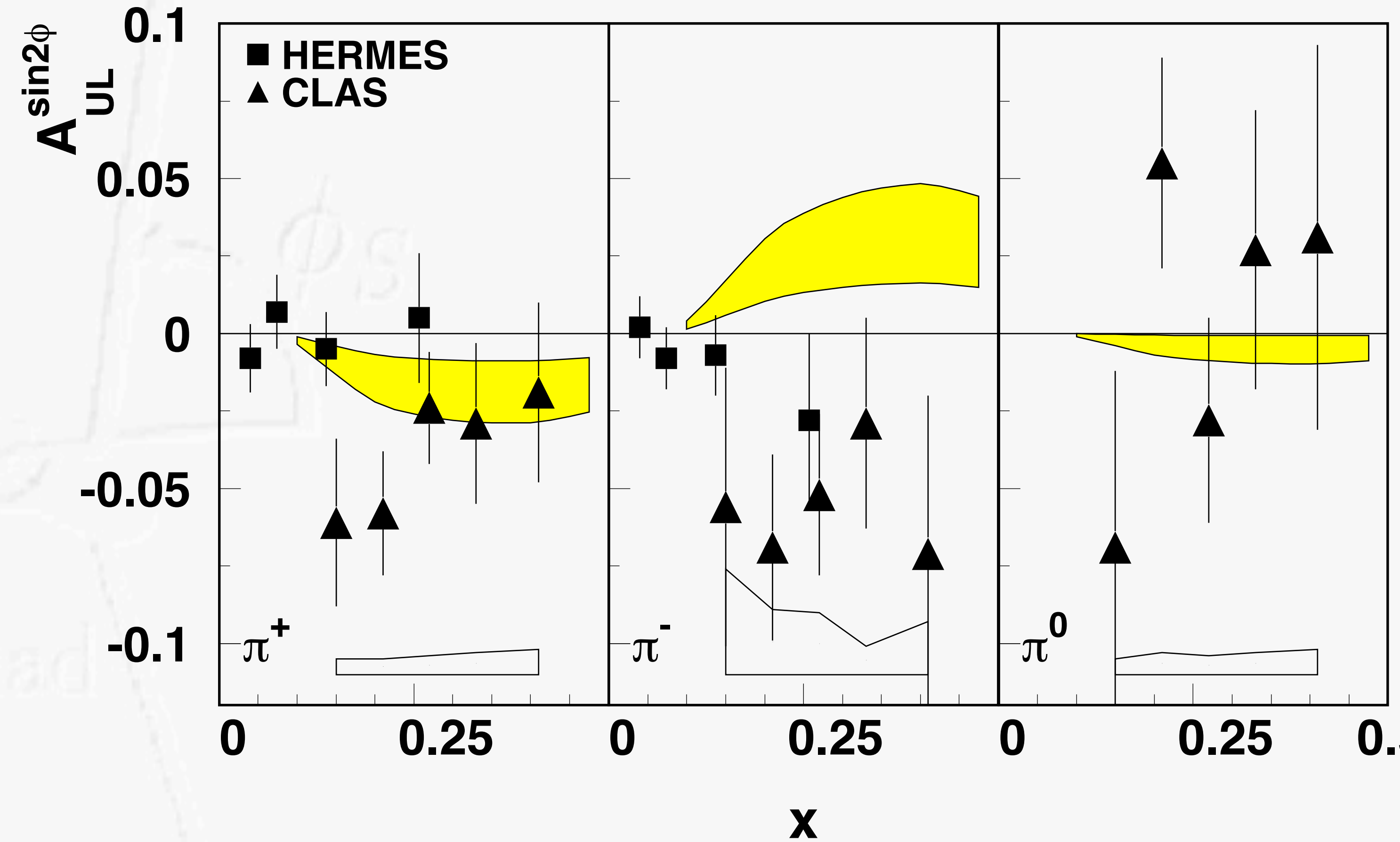
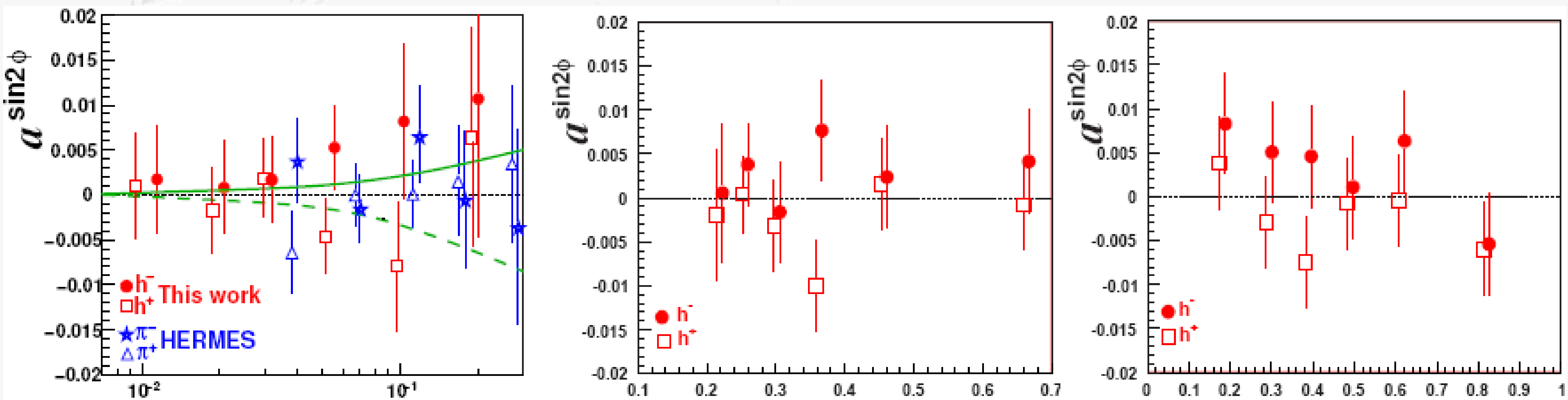
Worm-Gear I

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





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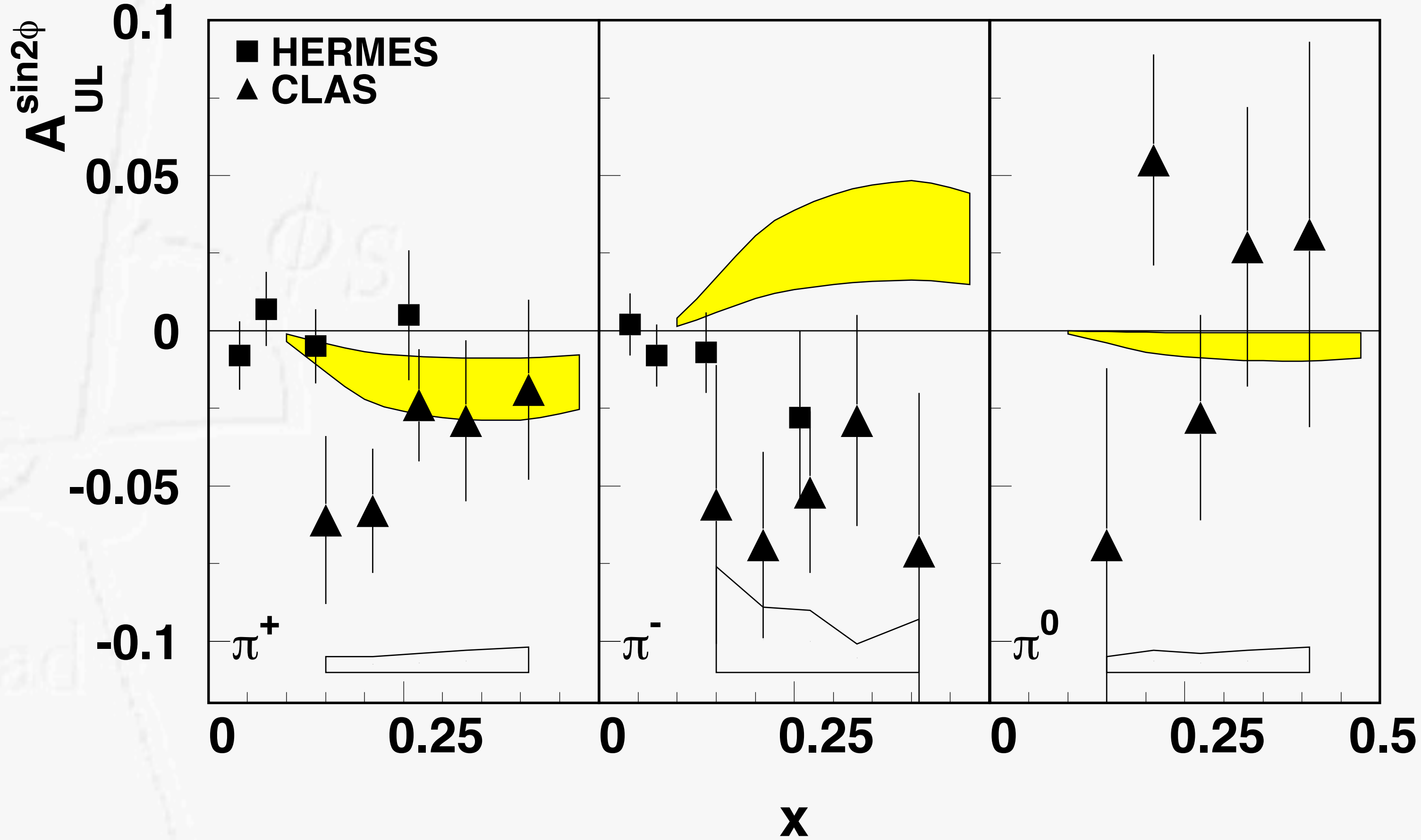
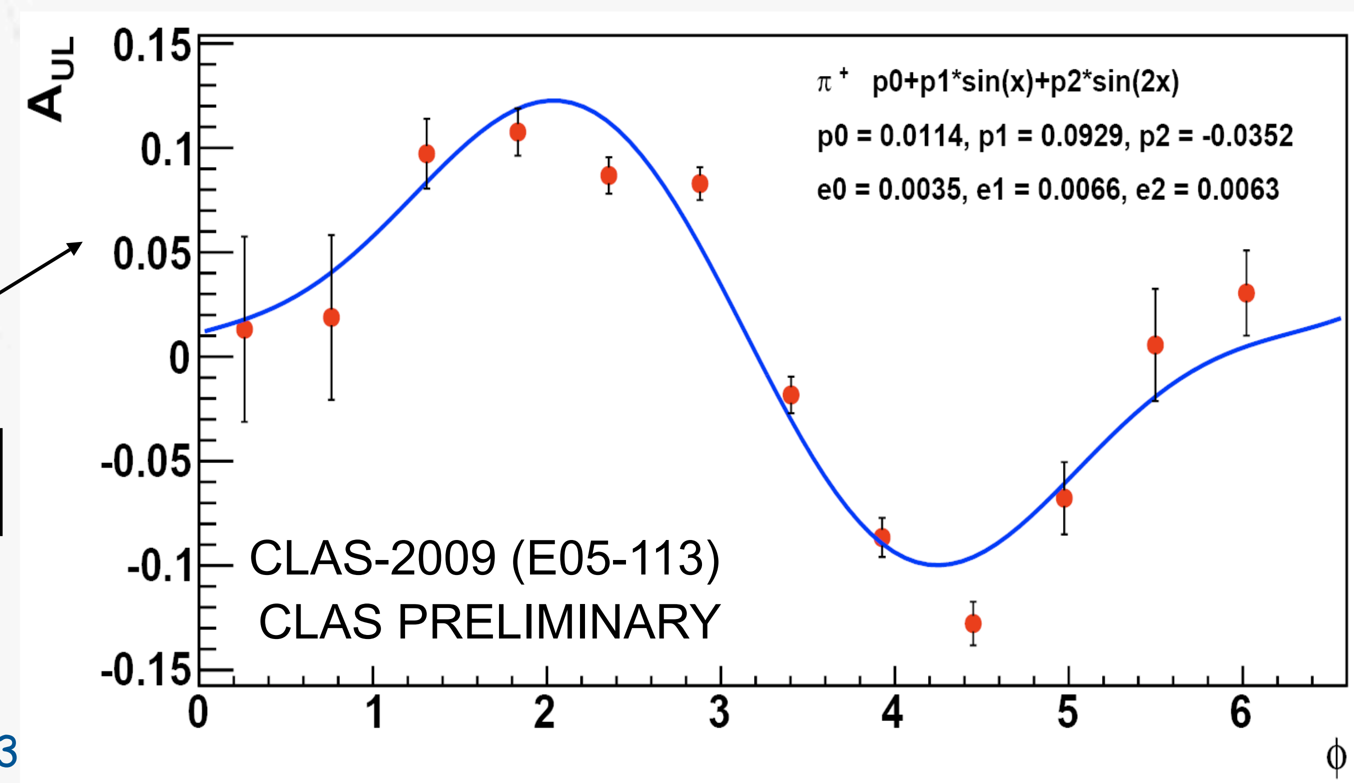


~10% of E05-113 data



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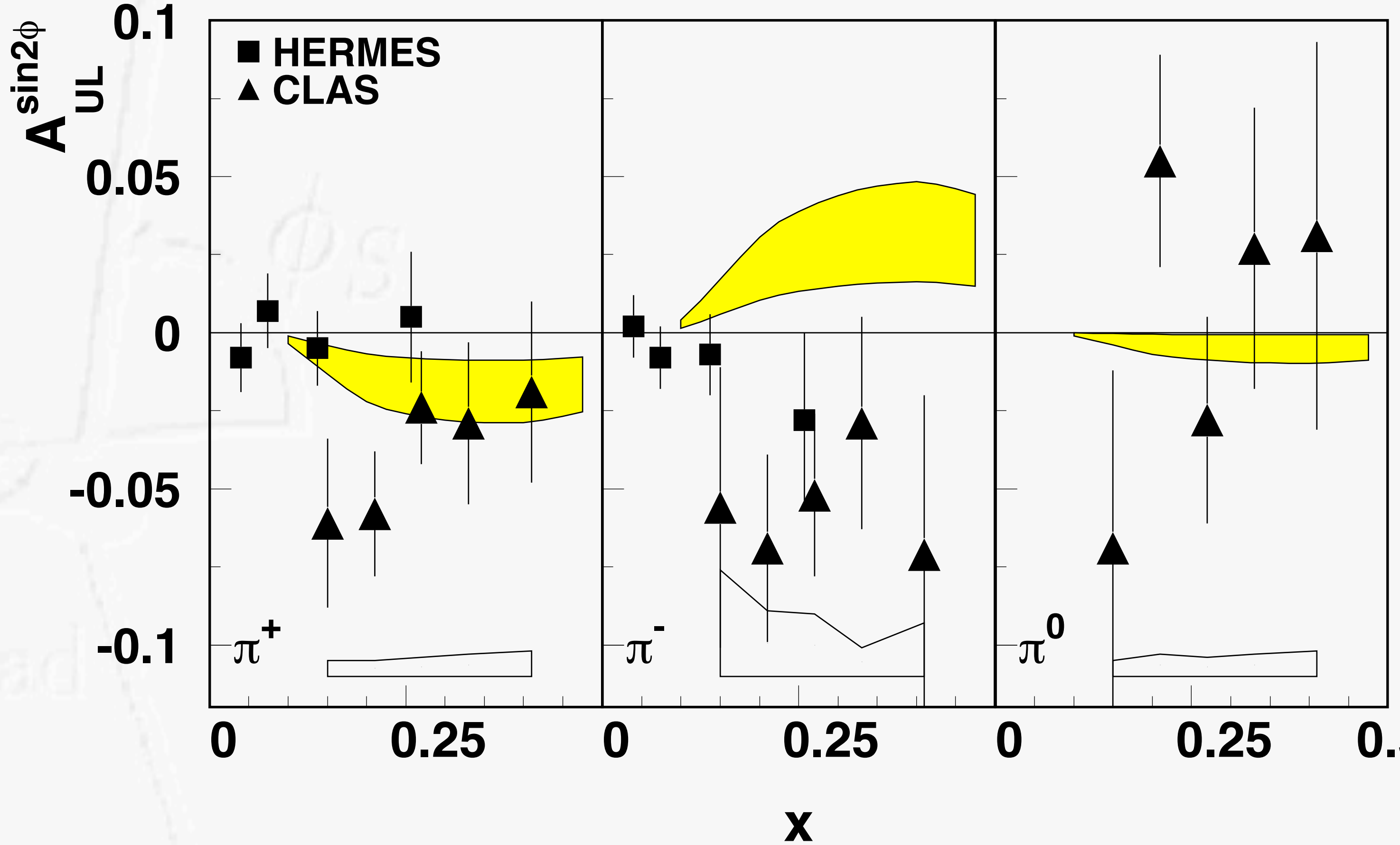

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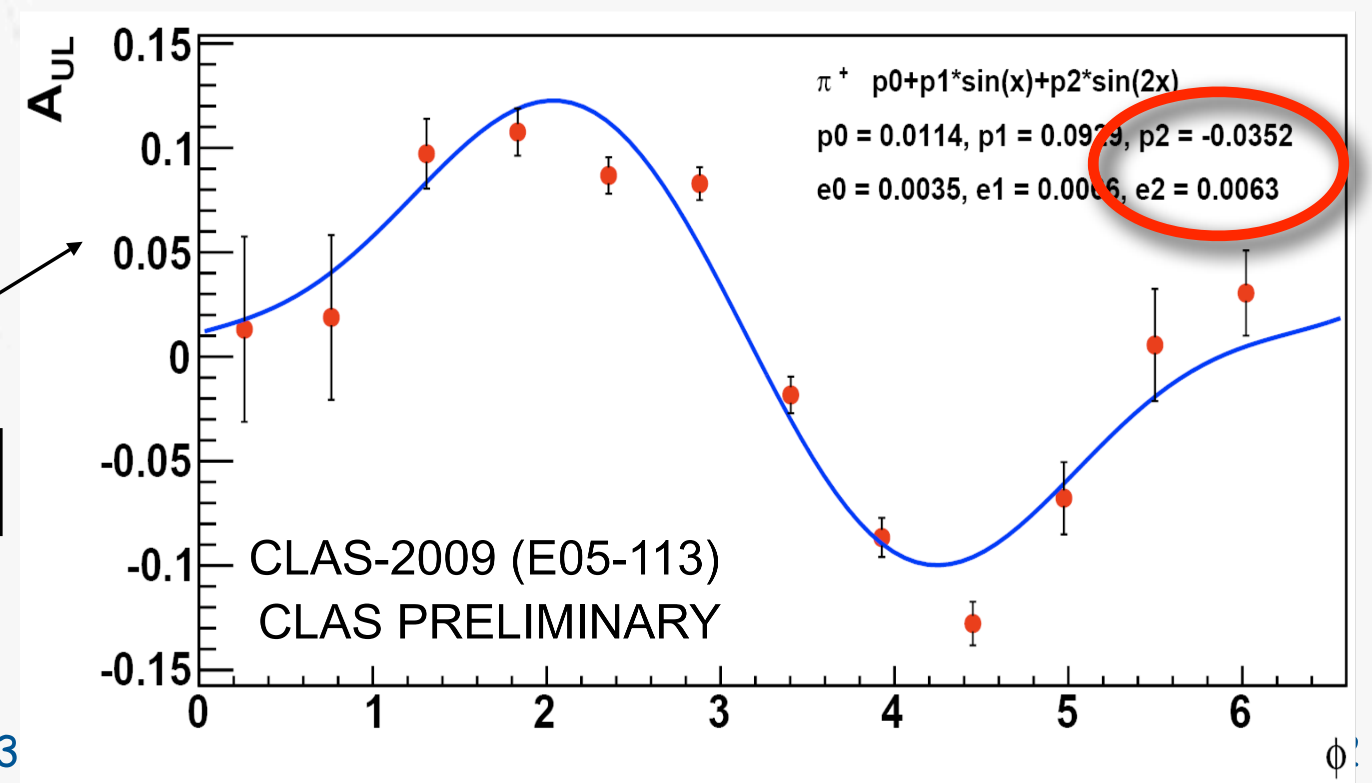
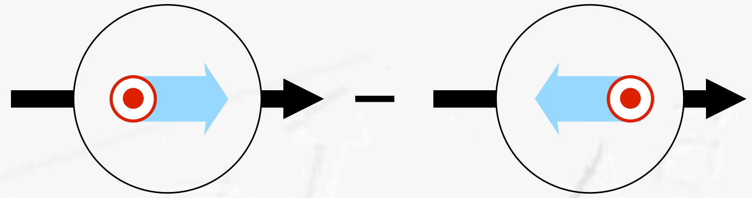


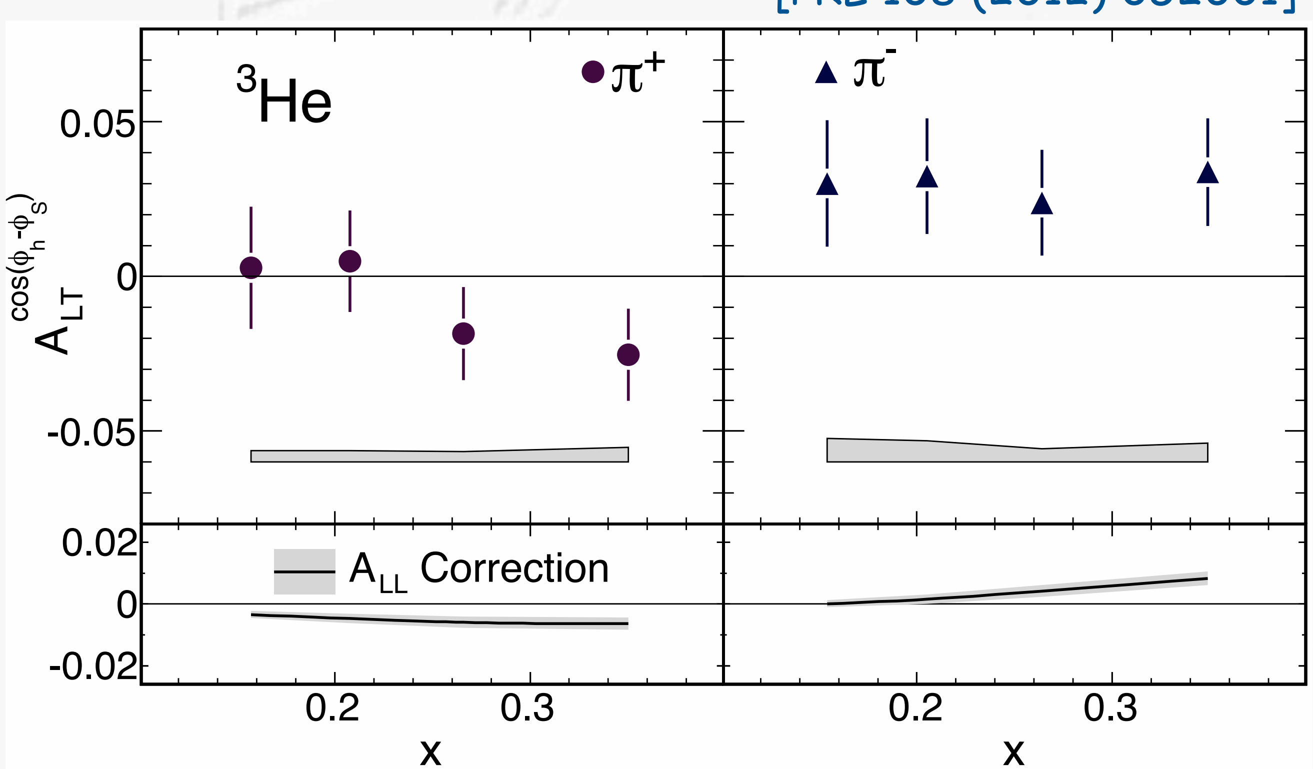
Worm-Gear II

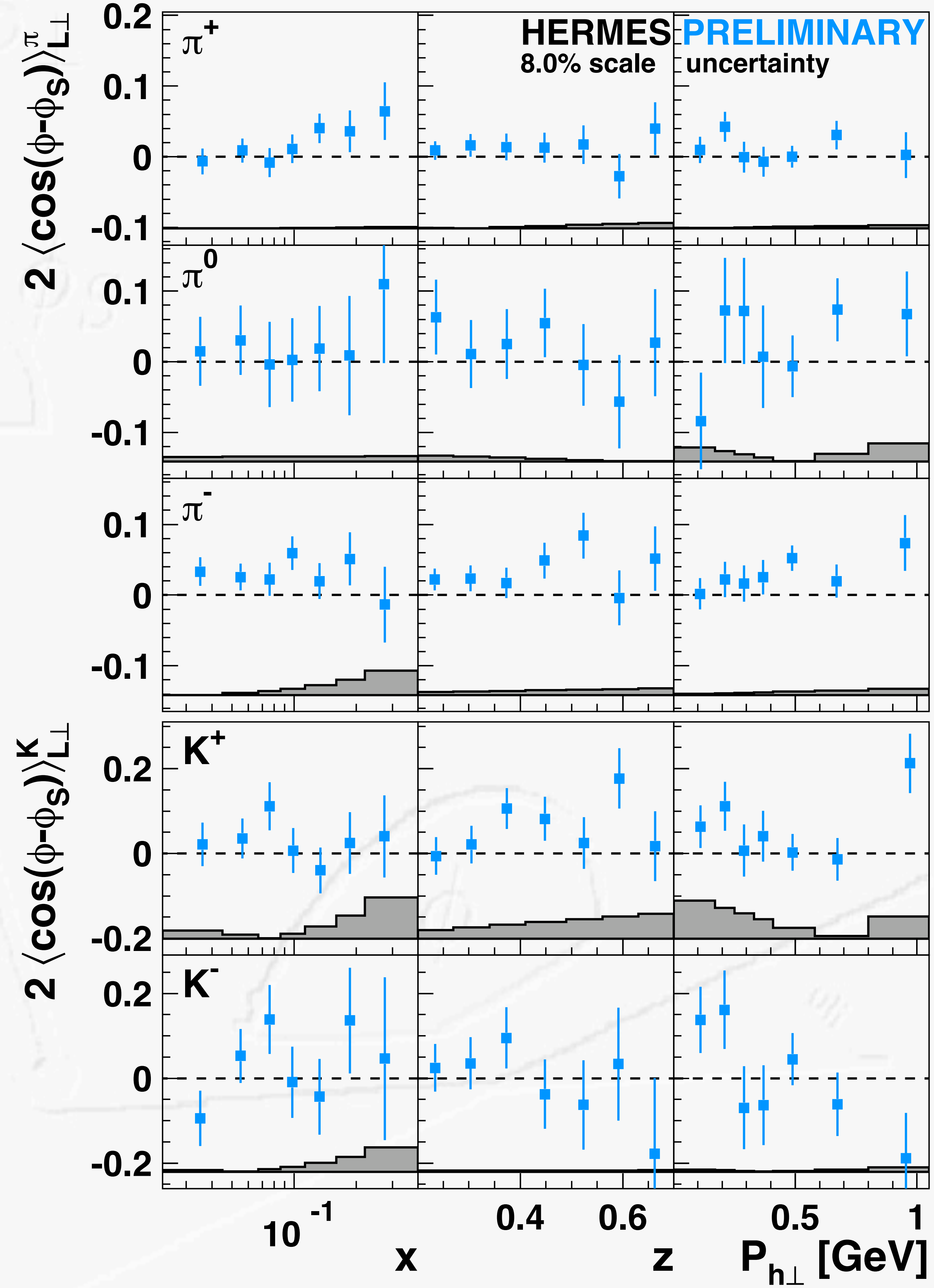
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



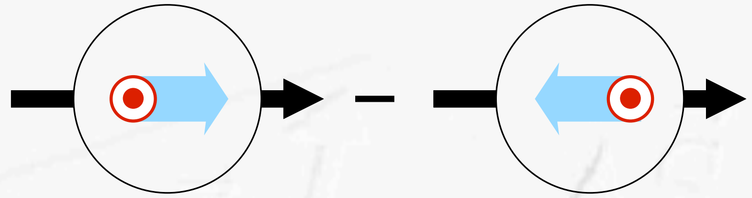
- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES

[PRL 108 (2012) 052001]





	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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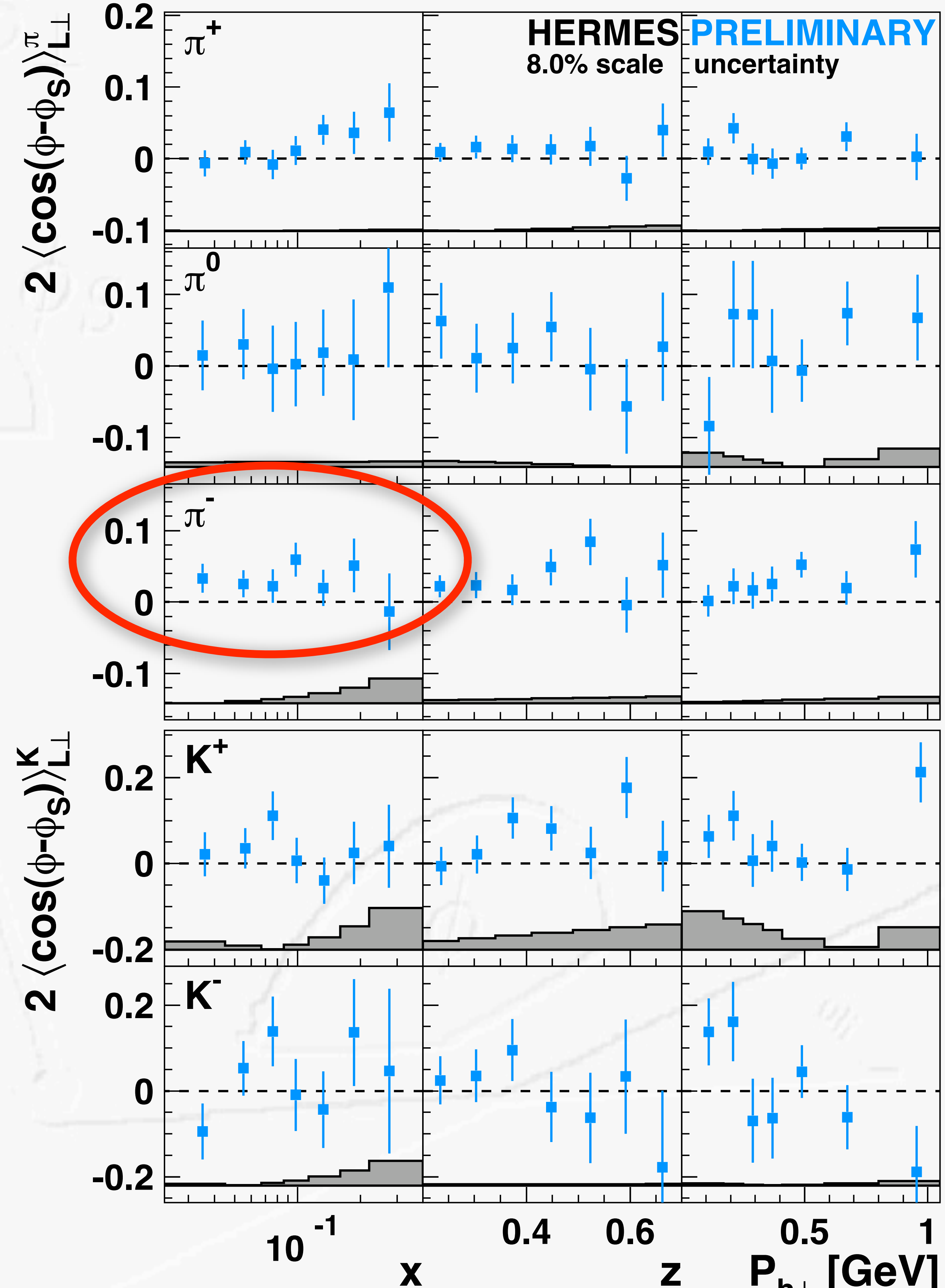
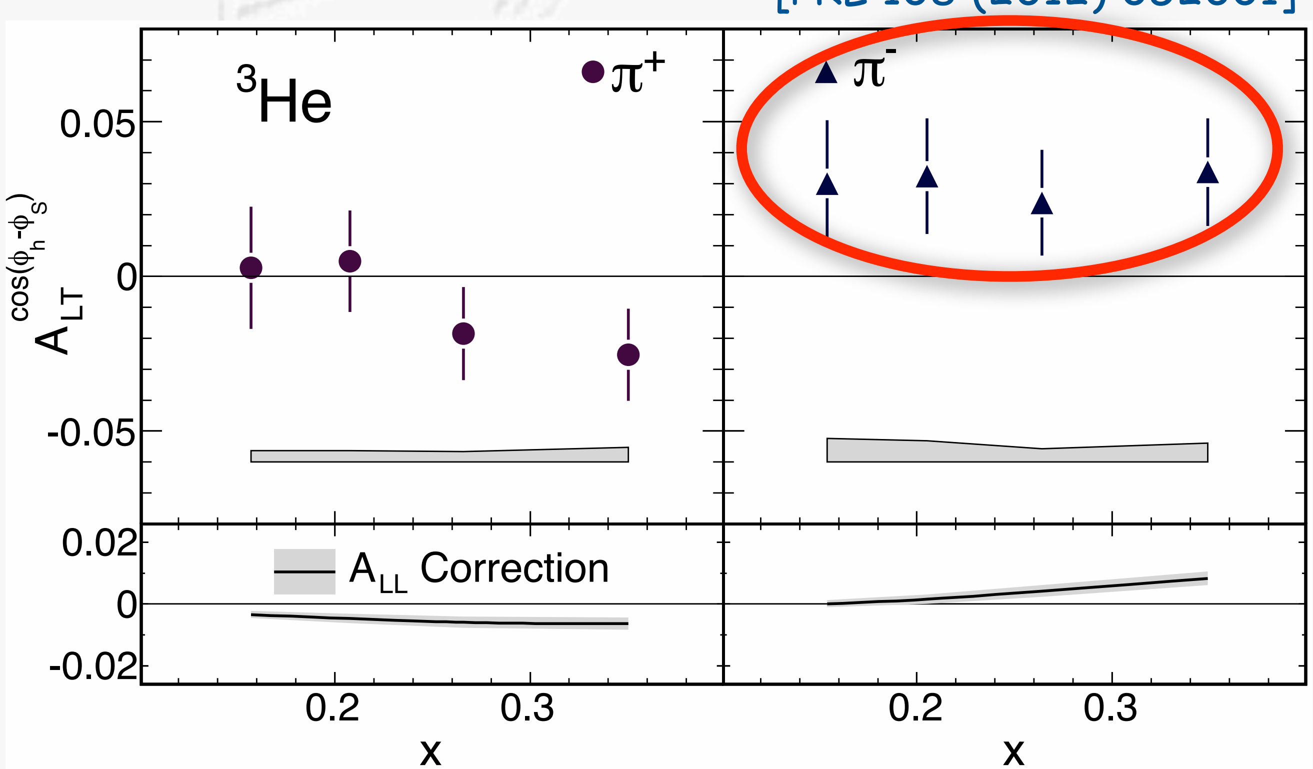
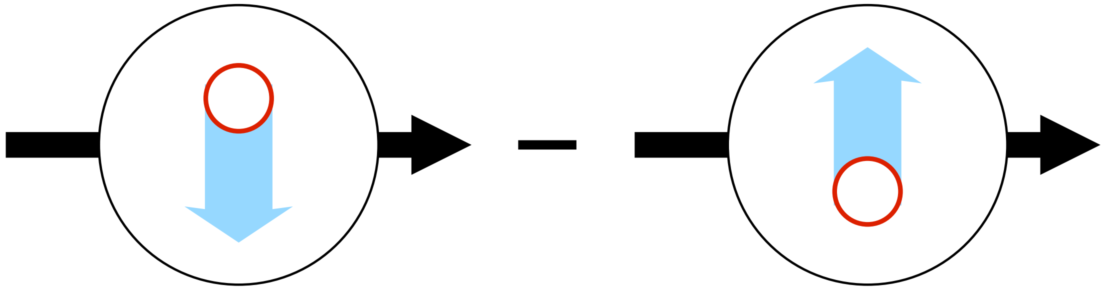


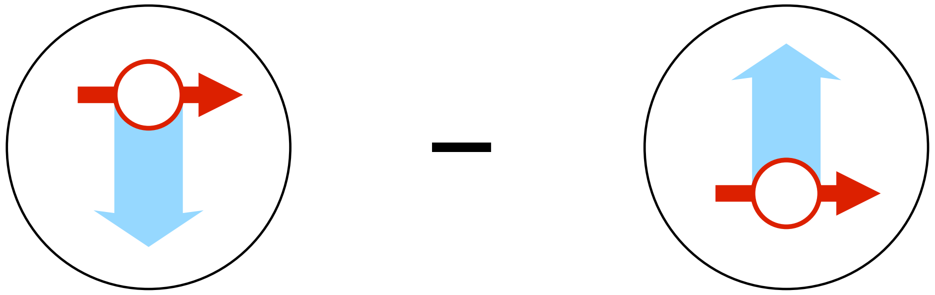
[PRL 108 (2012) 052001]





“gauge-link physics”

naively T-odd distributions



	U	L	T
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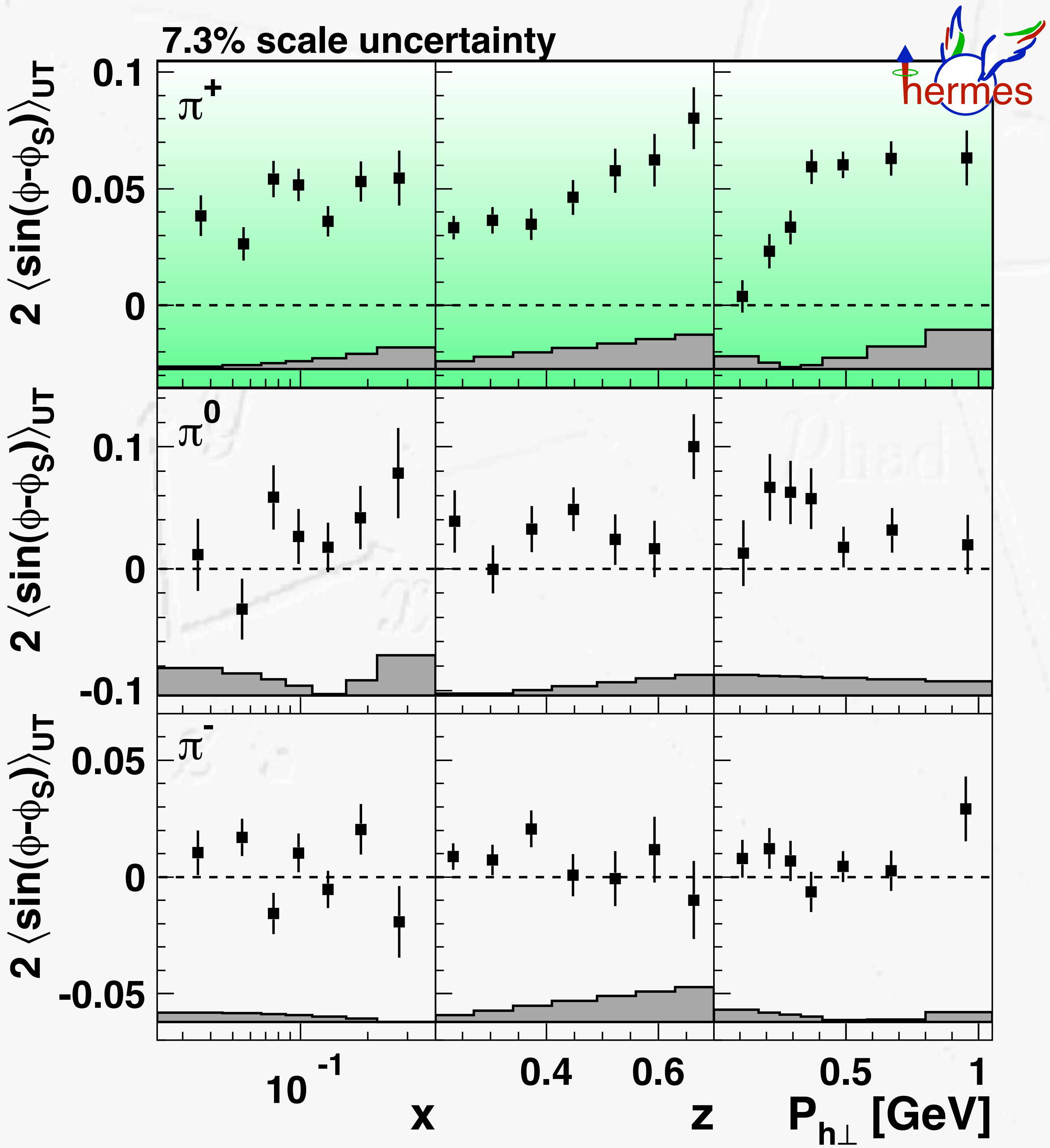
Sivers amplitudes for pions

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



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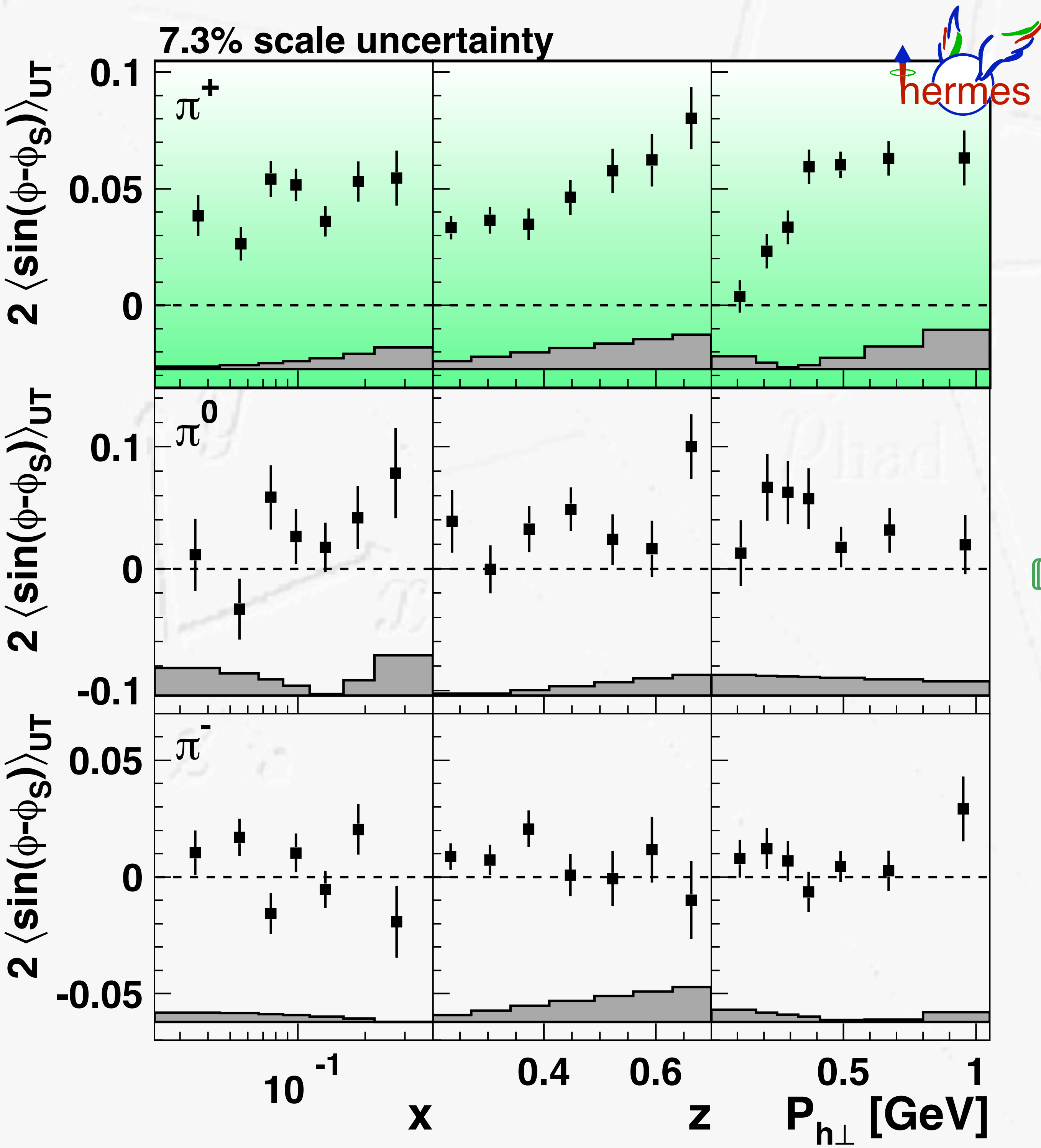

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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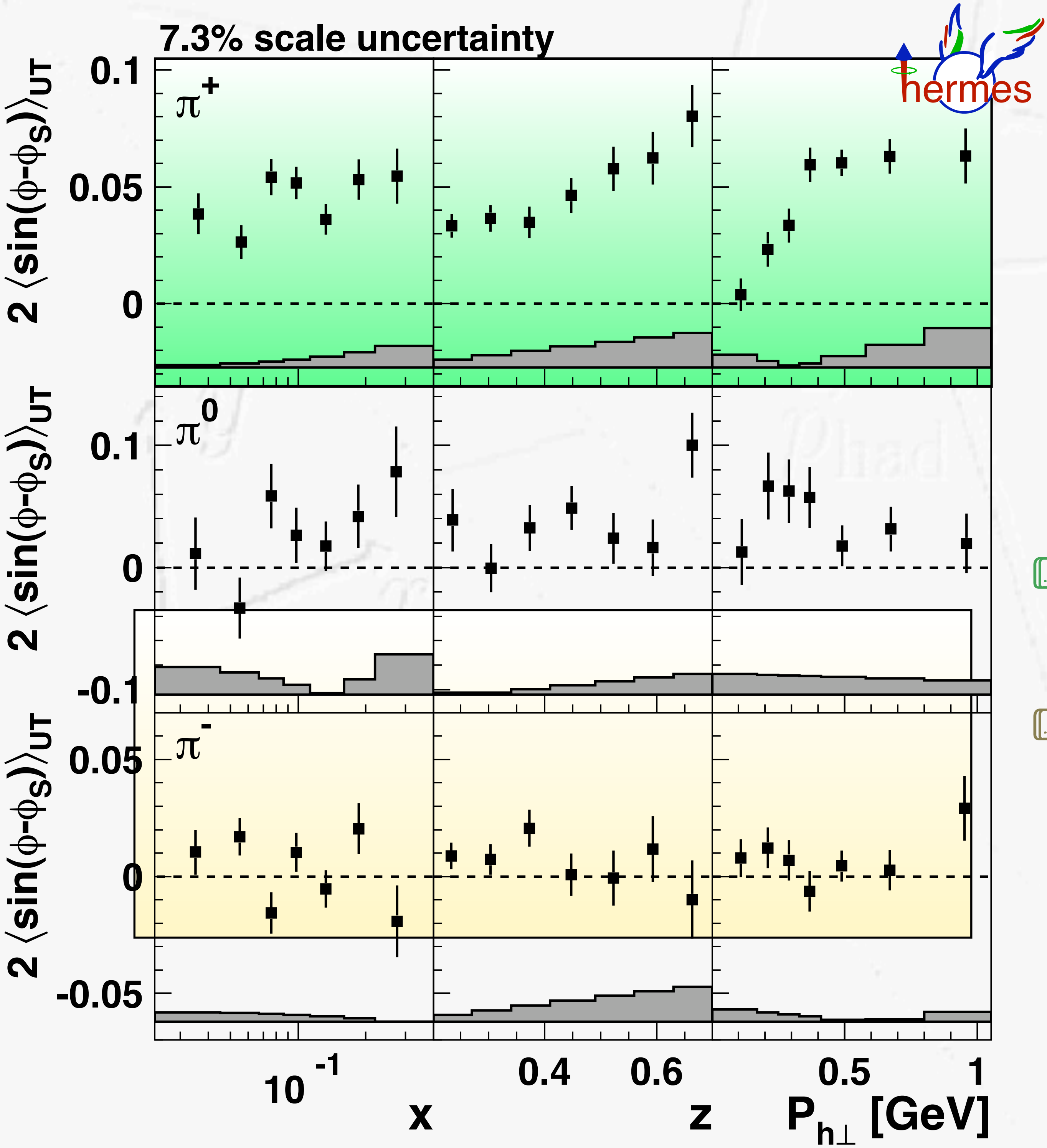

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☛ u-quark Sivers DF < 0

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

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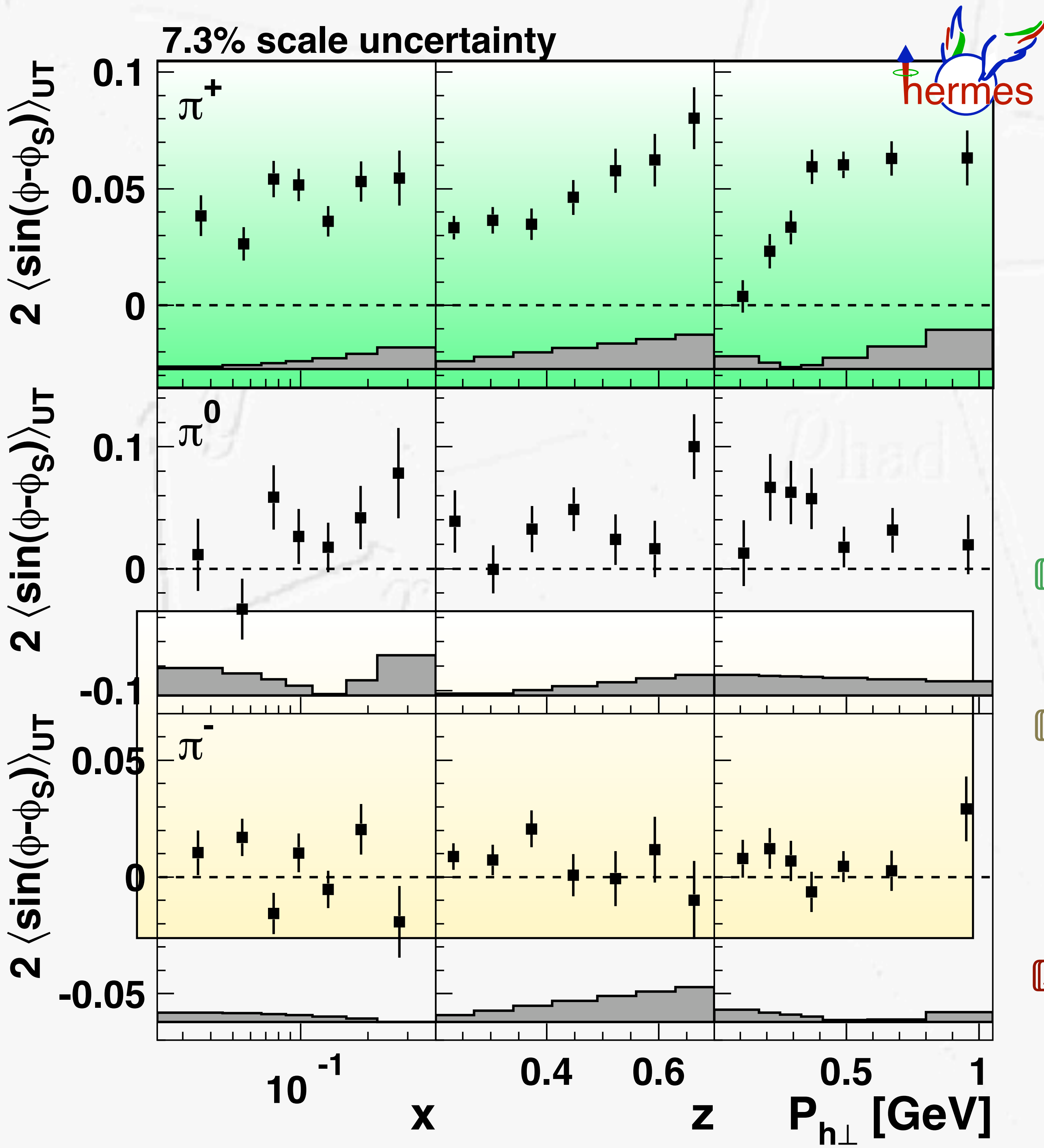

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- u-quark Sivers DF < 0
- d-quark Sivers DF > 0 (cancelation for π^-)
- u-d cancelation supported by COMPASS D data

	U	L	T
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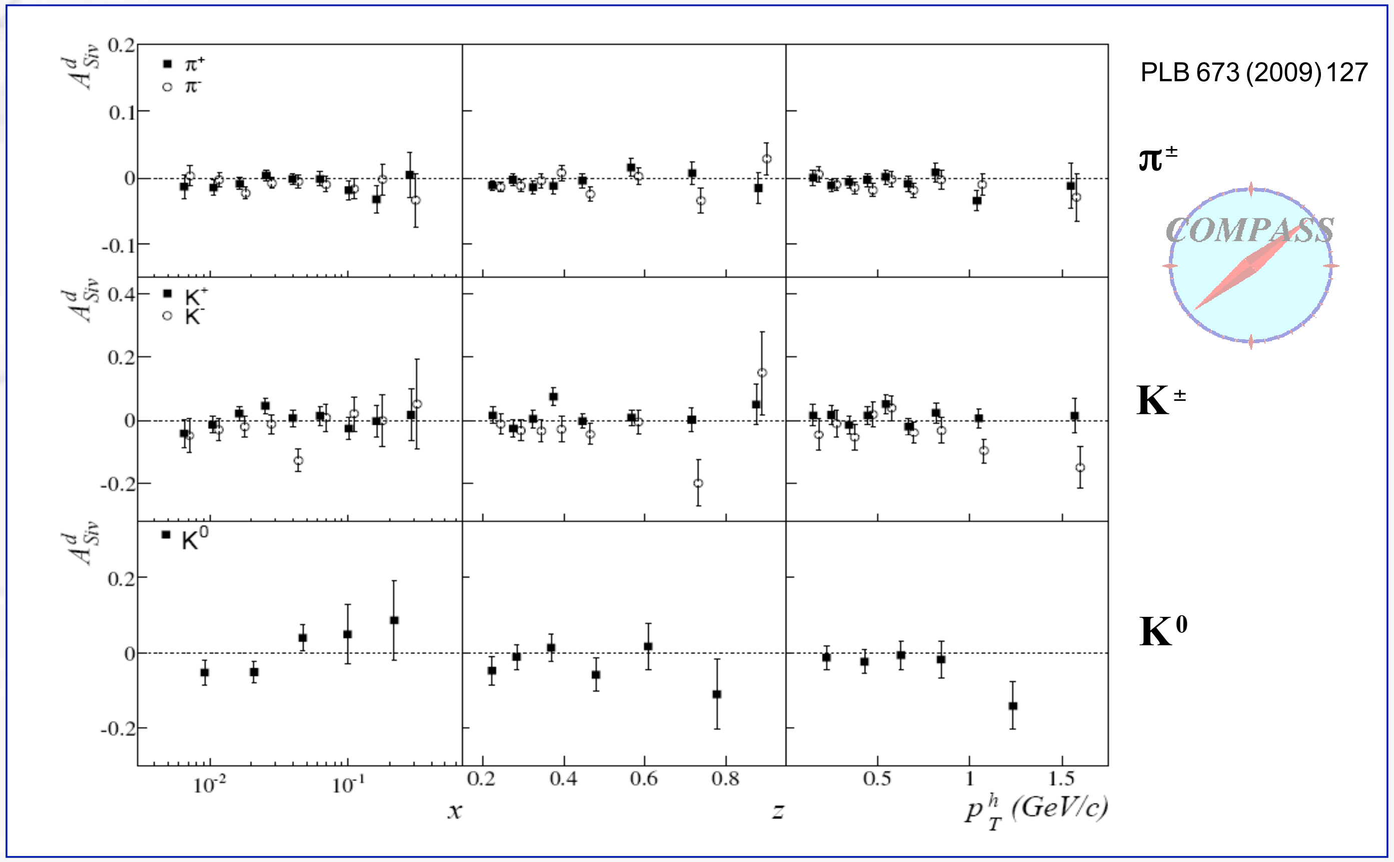
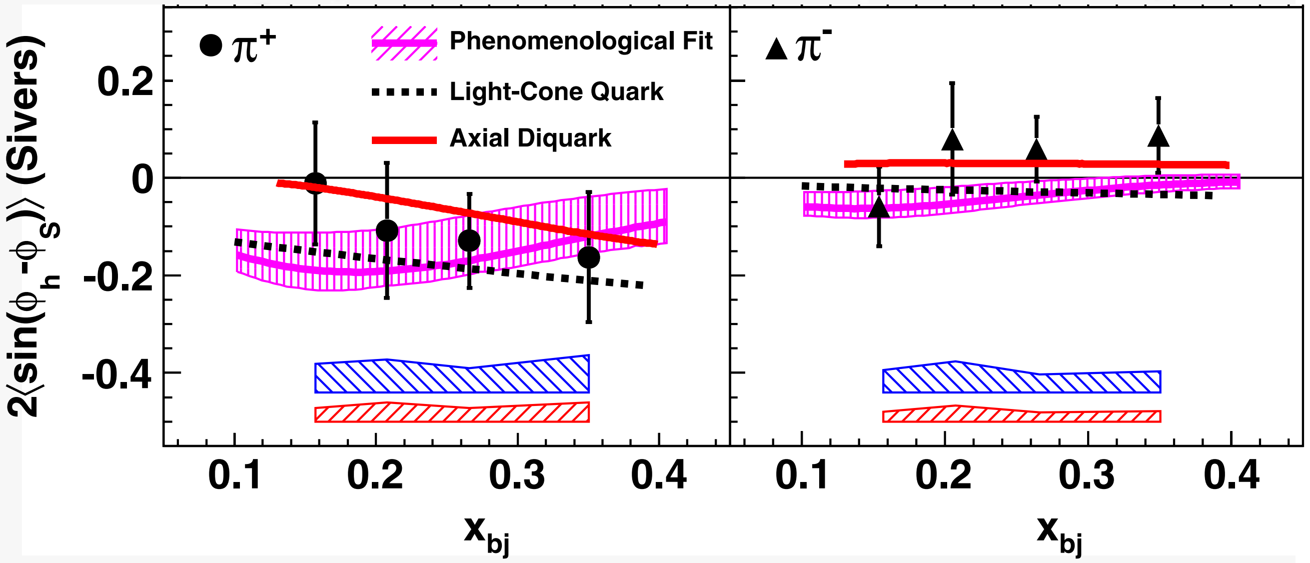
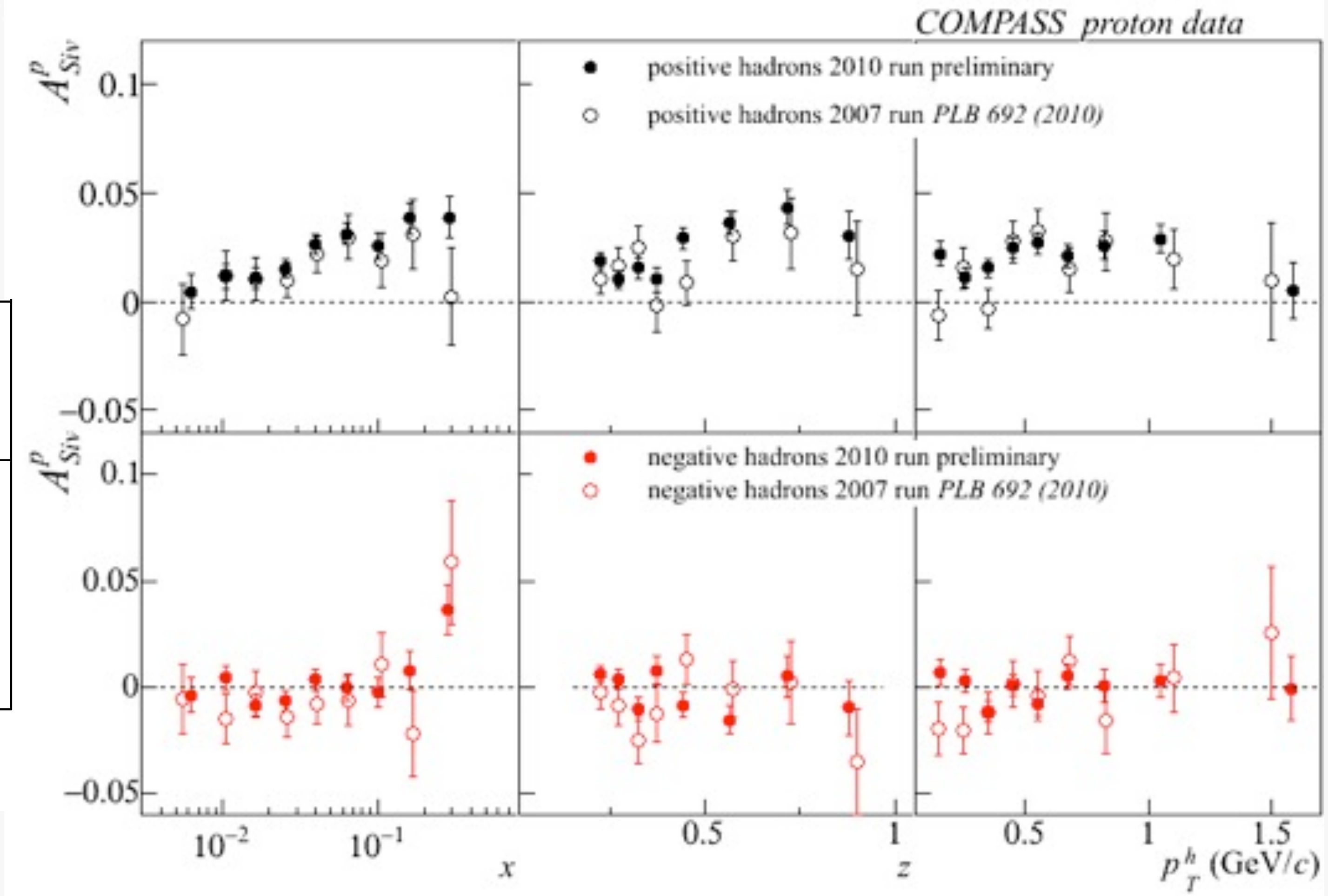
Sivers function



- cancelation for D target supports opposite signs of u and d Sivers
- new results from JLab using ^{3}He target and from COMPASS for proton target

[PRL 107 (2011) 072003]





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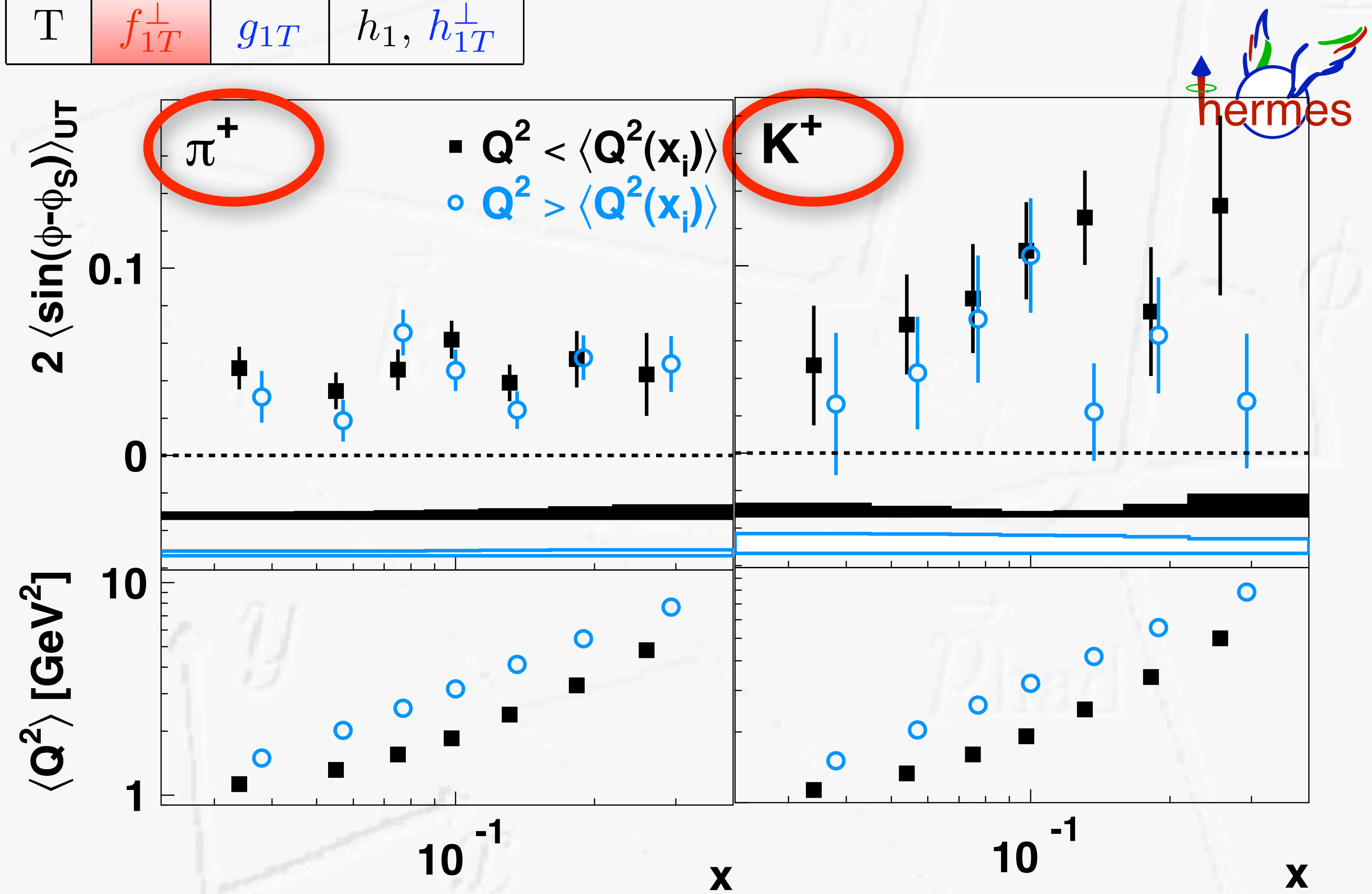

somewhat unexpected if dominated by scattering off u-quarks:

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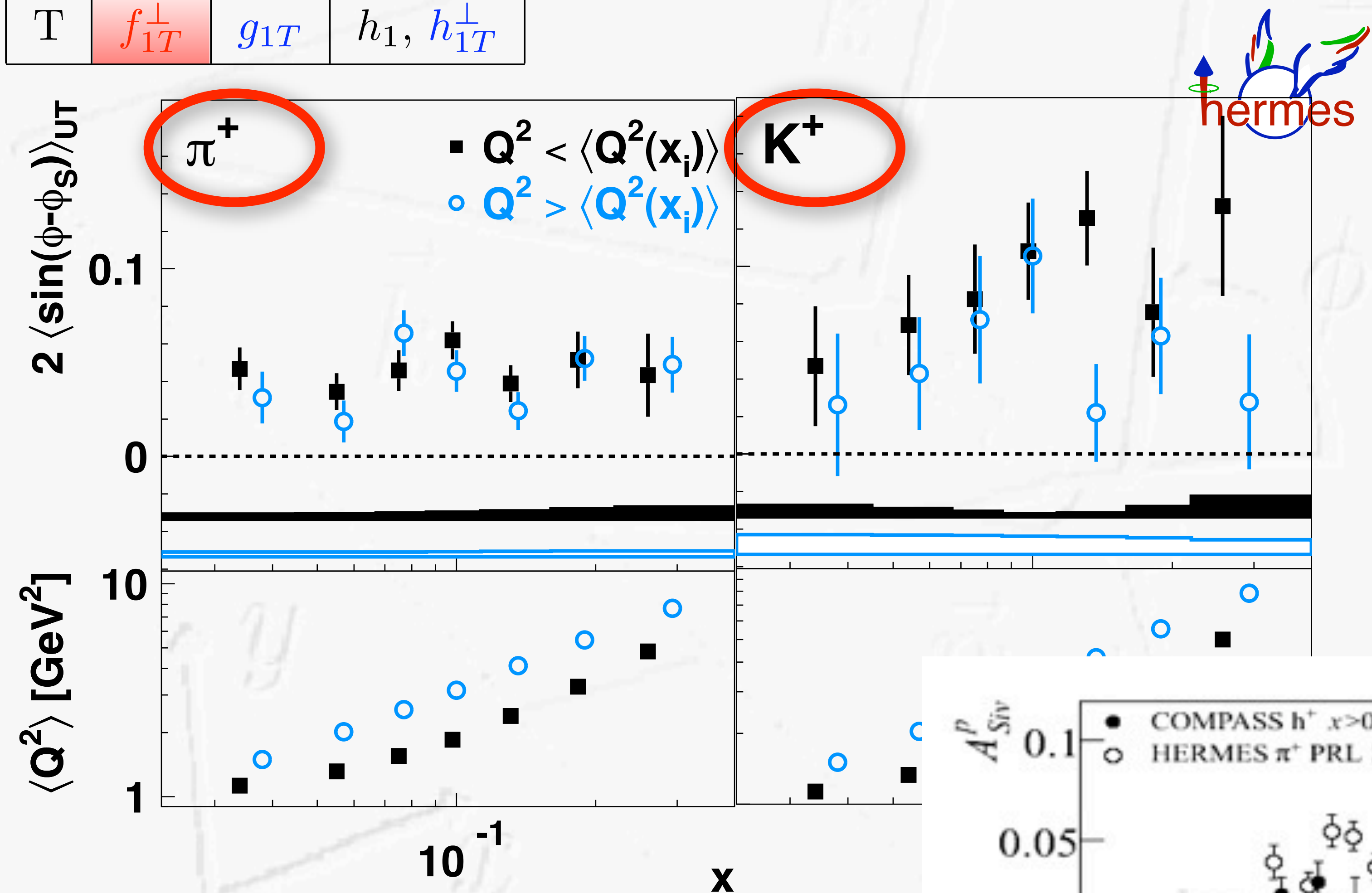

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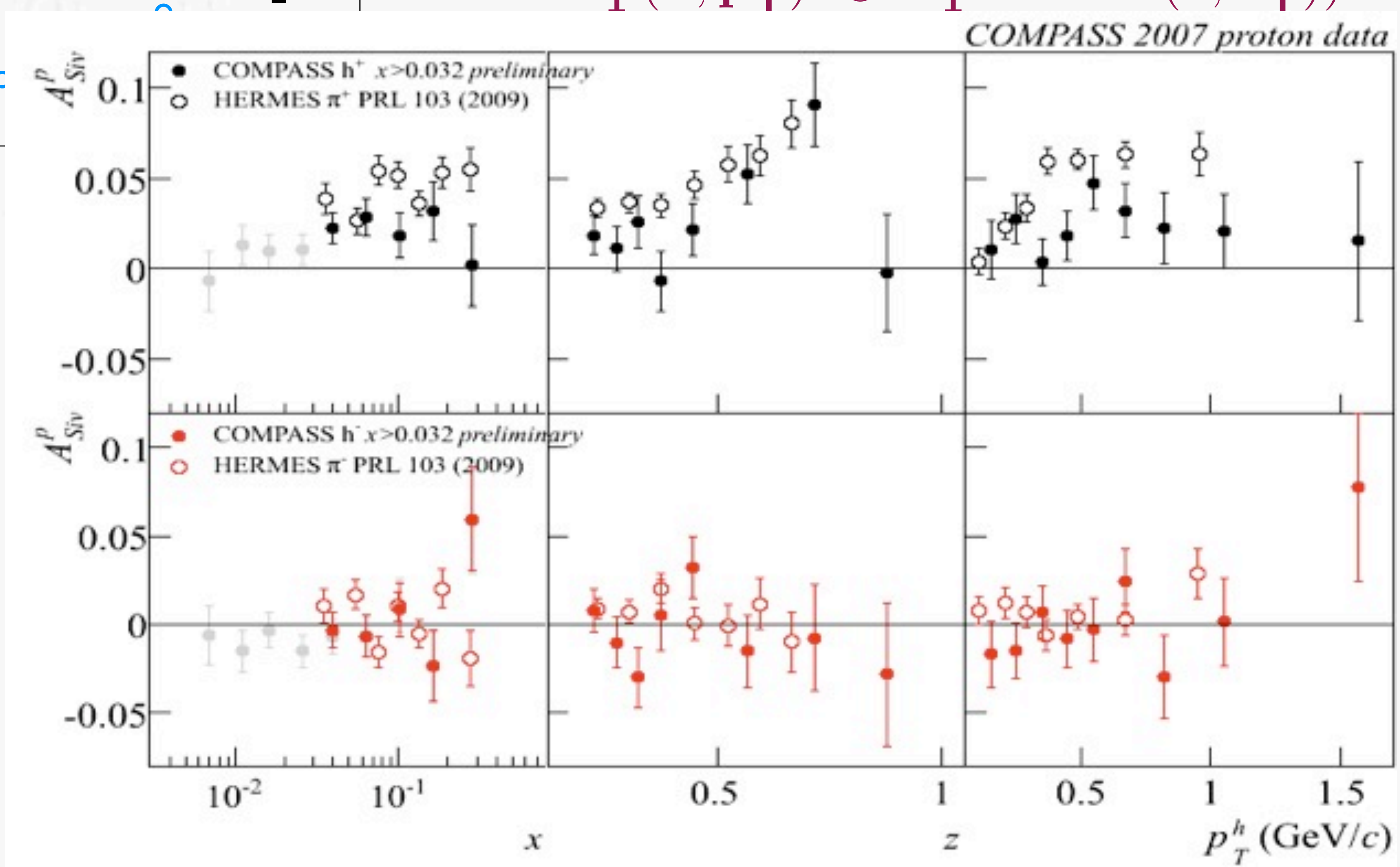

smaller pion amplitudes seen by COMPASS

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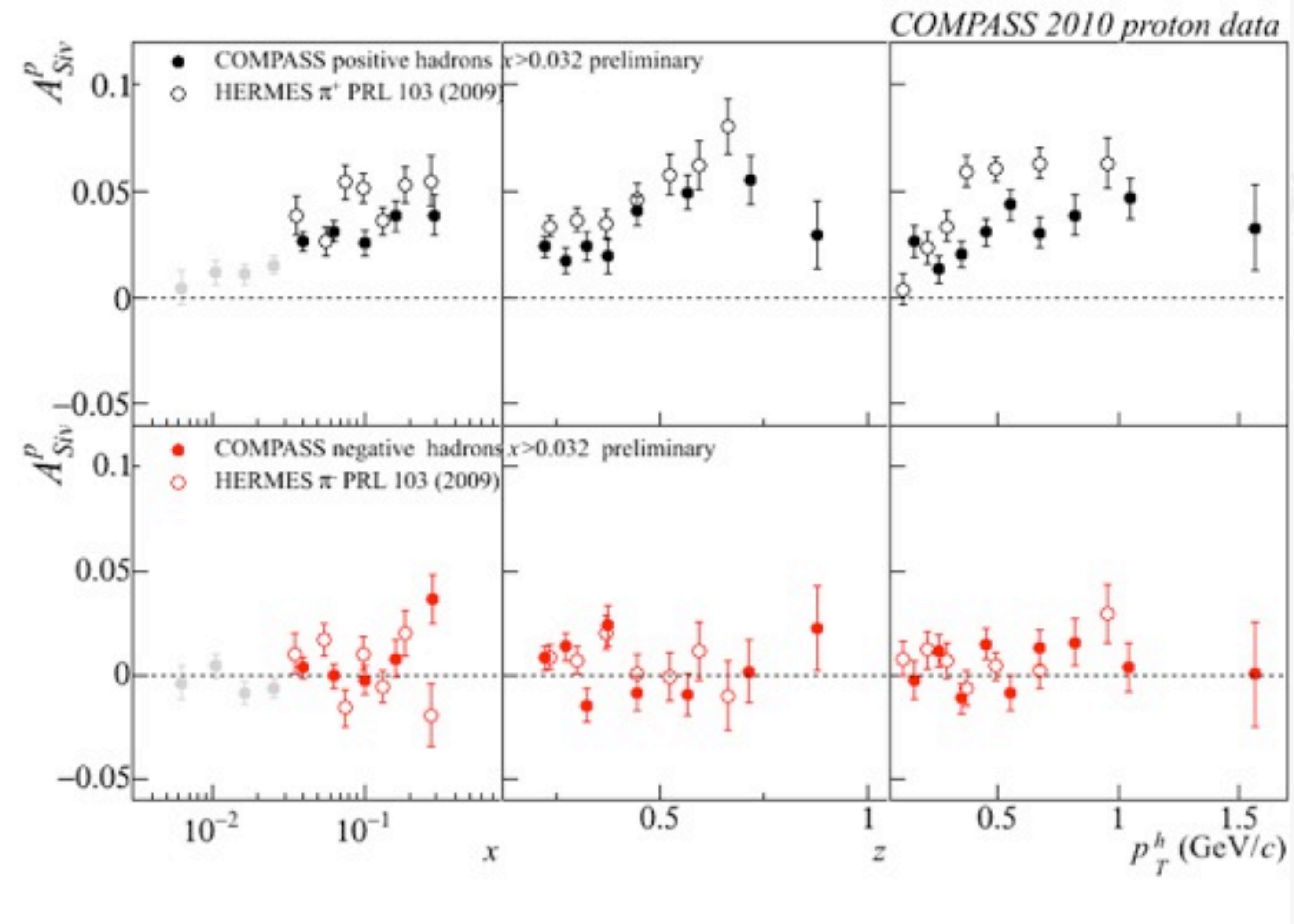
Sivers amplitudes



2010 Compass data closer to HERMES

Sivers amplitudes

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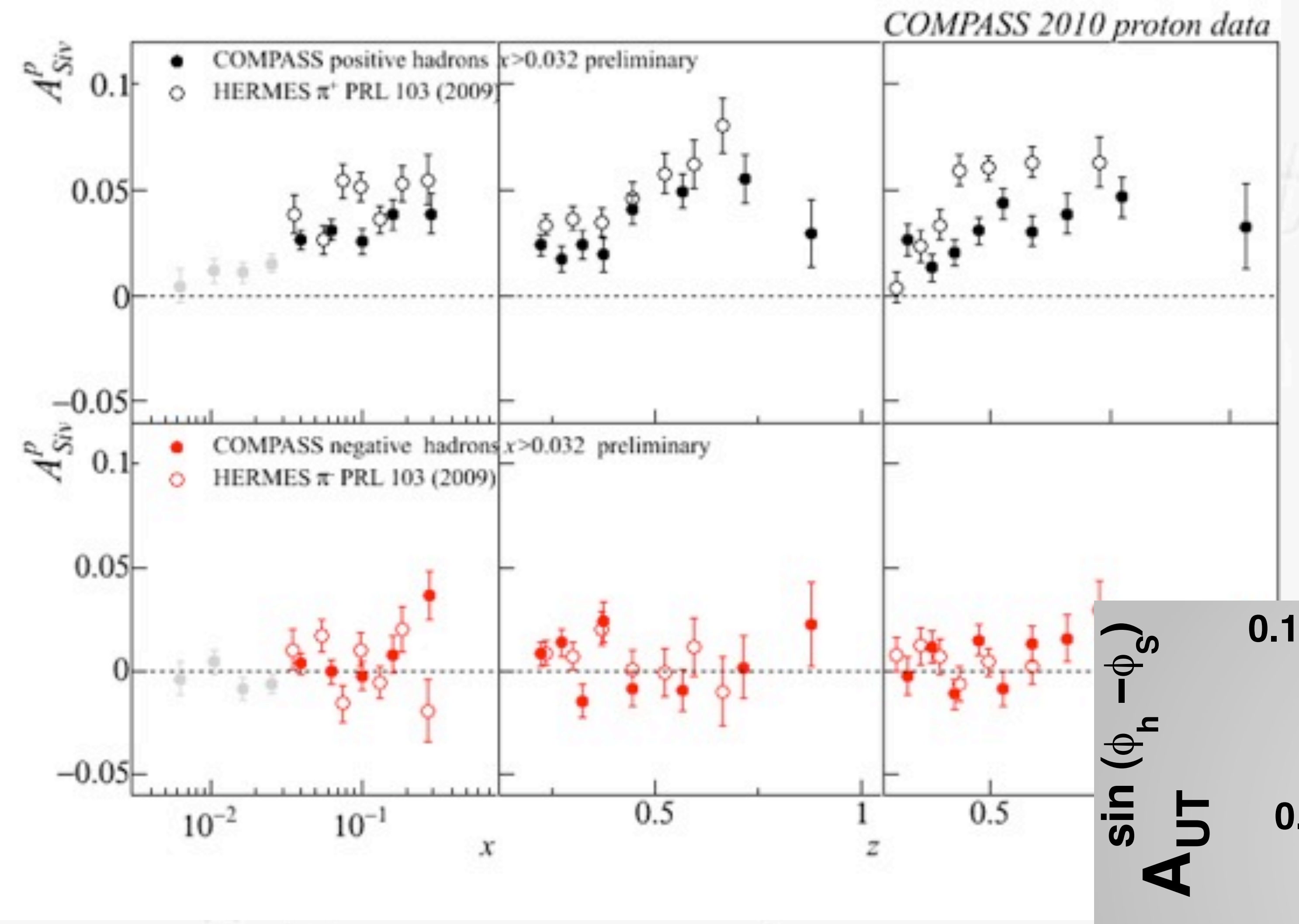
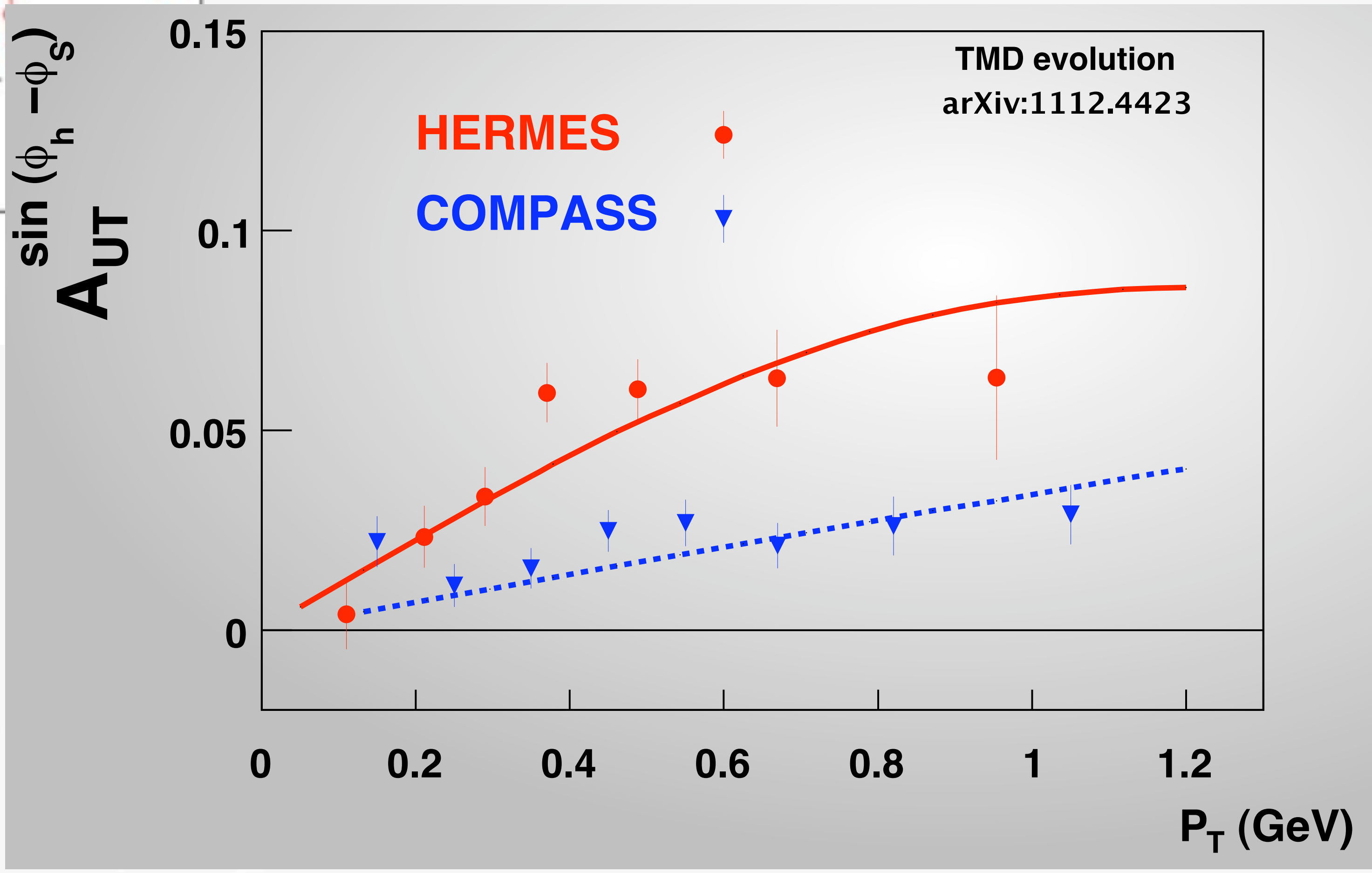


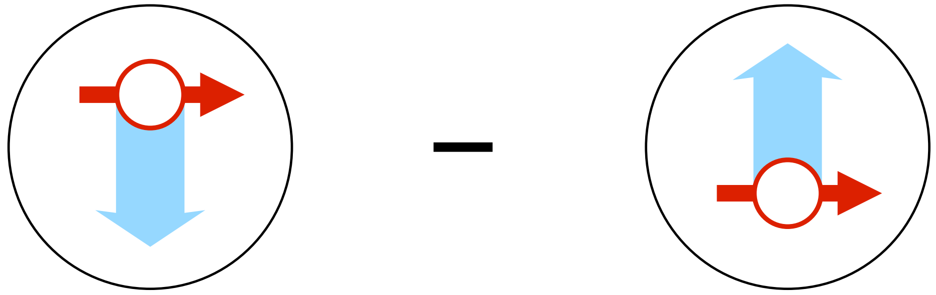
2010 Compass data closer to HERMES

difference from evolution?



Boer-Mulders

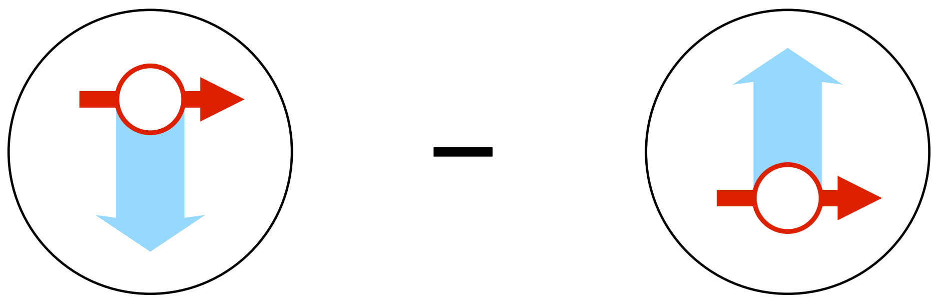
the other naively T-odd distribution



spin effects in unpolarized reactions

Boer-Mulders

the other naively T-odd distribution



... moment measurements

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dxdy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dxdydzdP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon F_{UU,L}}{F_T+\epsilon F_L}$$

$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

$$\frac{d^5\sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

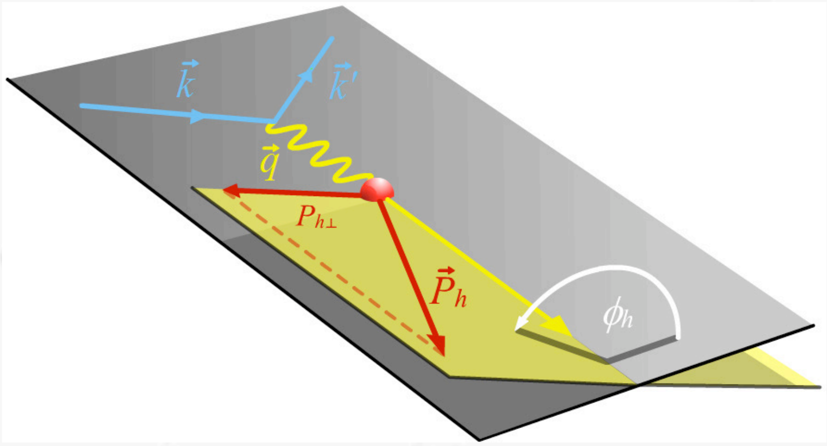
$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

$$2\langle\cos 2\phi\rangle_{UU} \equiv 2\frac{\int d\phi_h \cos 2\phi\, d\sigma}{\int d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T}+\cancel{\epsilon F_{UU,L}}}$$

$$\approx \epsilon\frac{\sum_q e_q^2\; h_1^{\perp,q}(x,p_T^2)\otimes_{\text{BM}} H_1^{\perp,q\to h}(z,K_T^2)}{\sum_q e_q^2\; f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}$$

moments:
normalize to azimuth-independent cross-section

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

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

CAHN EFFECT

next to leading twist

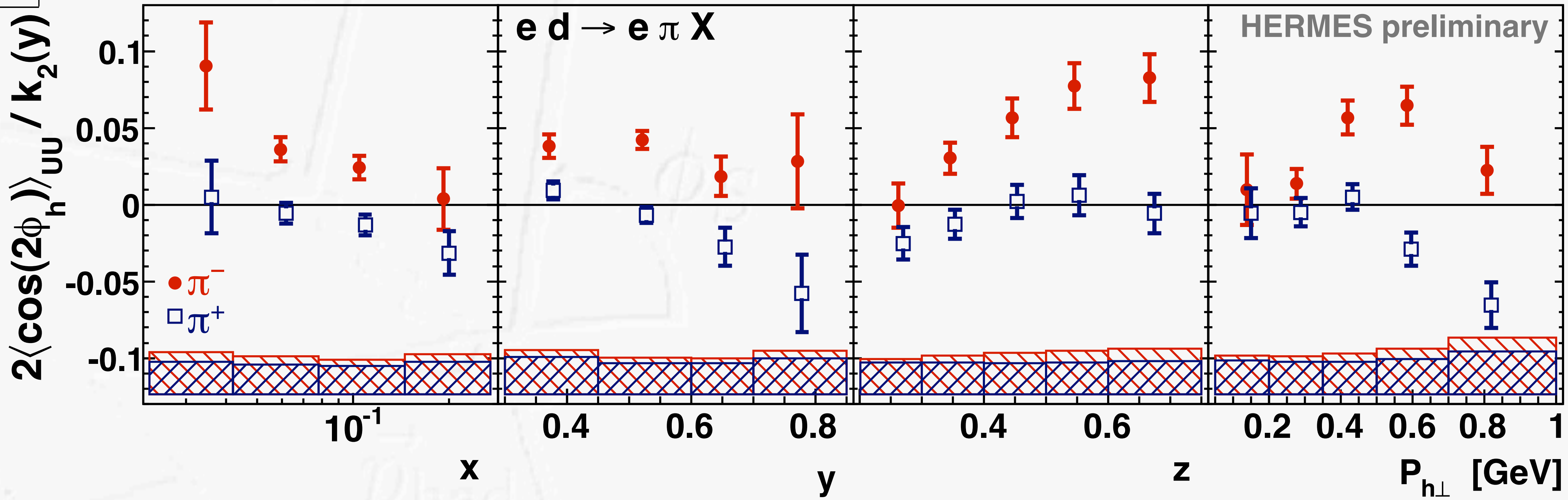
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\widehat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\ h_1^\perp H_1^\perp - \frac{\widehat{P}_{h\perp}\cdot\vec{k}_T}{M}x\ f_1 D_1 + \ldots\right]$$

Interaction dependent terms neglected

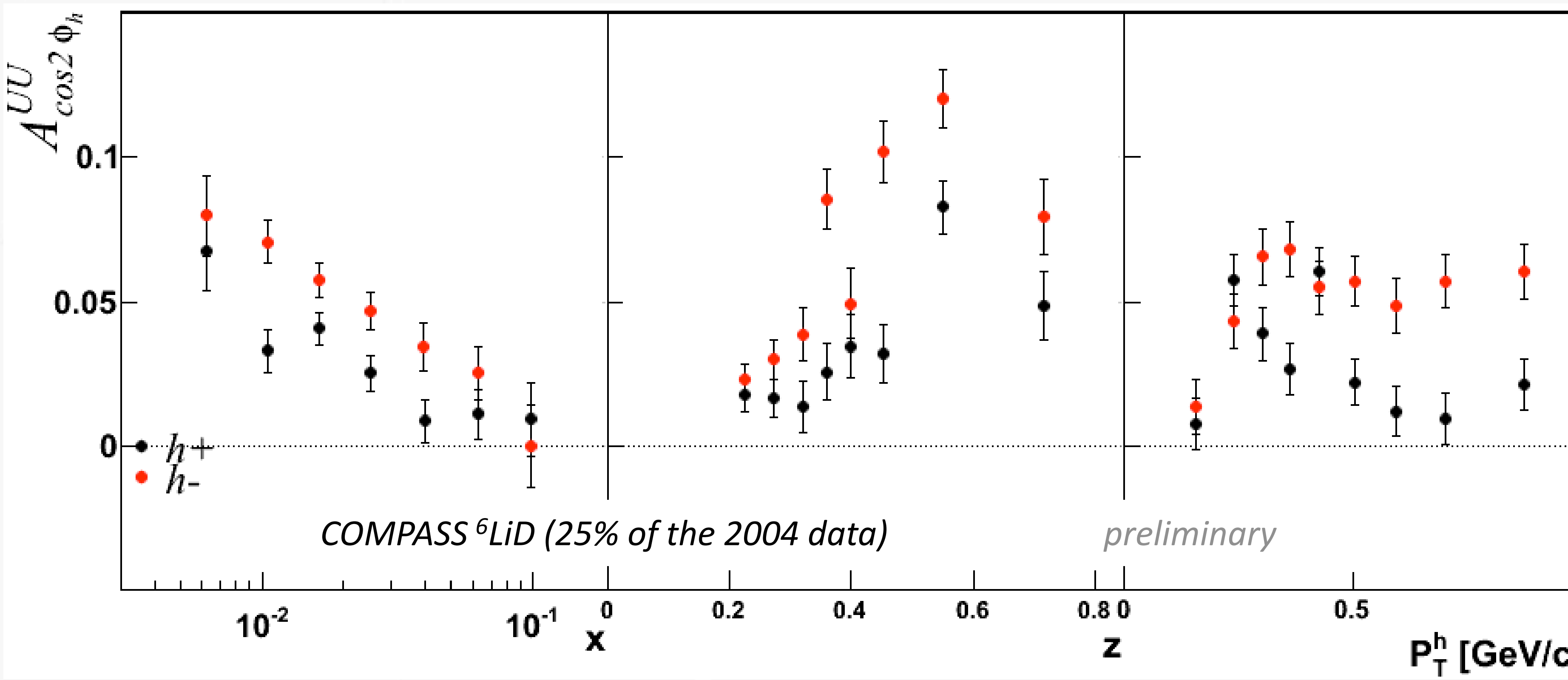
(Implicit sum over quark flavours)

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

Signs of Boer-Mulders



non-zero!



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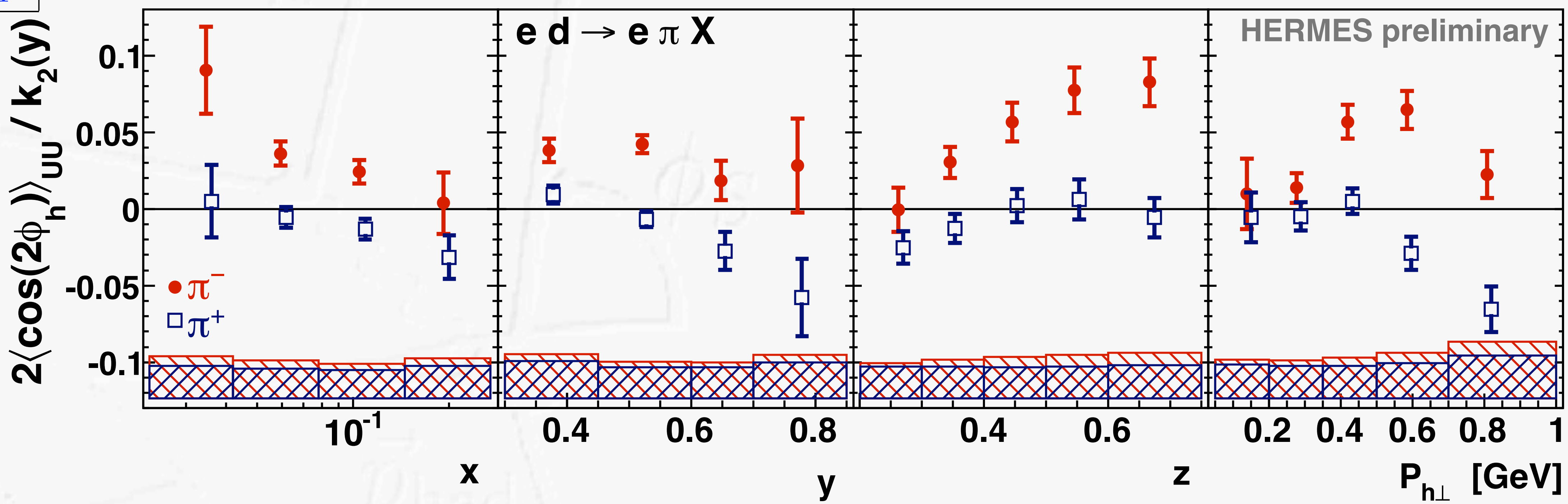
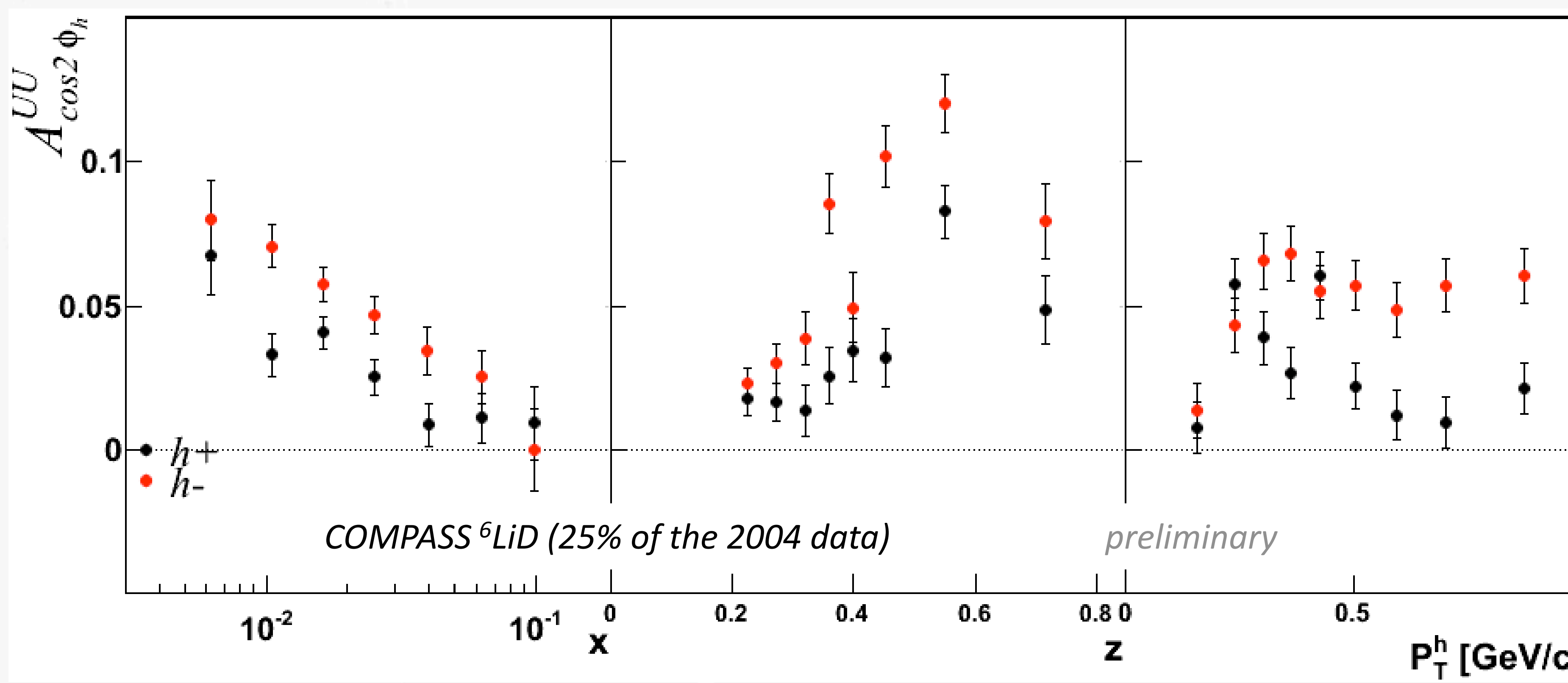


non-zero!

data consistency?



Signs of Boer-Mulders

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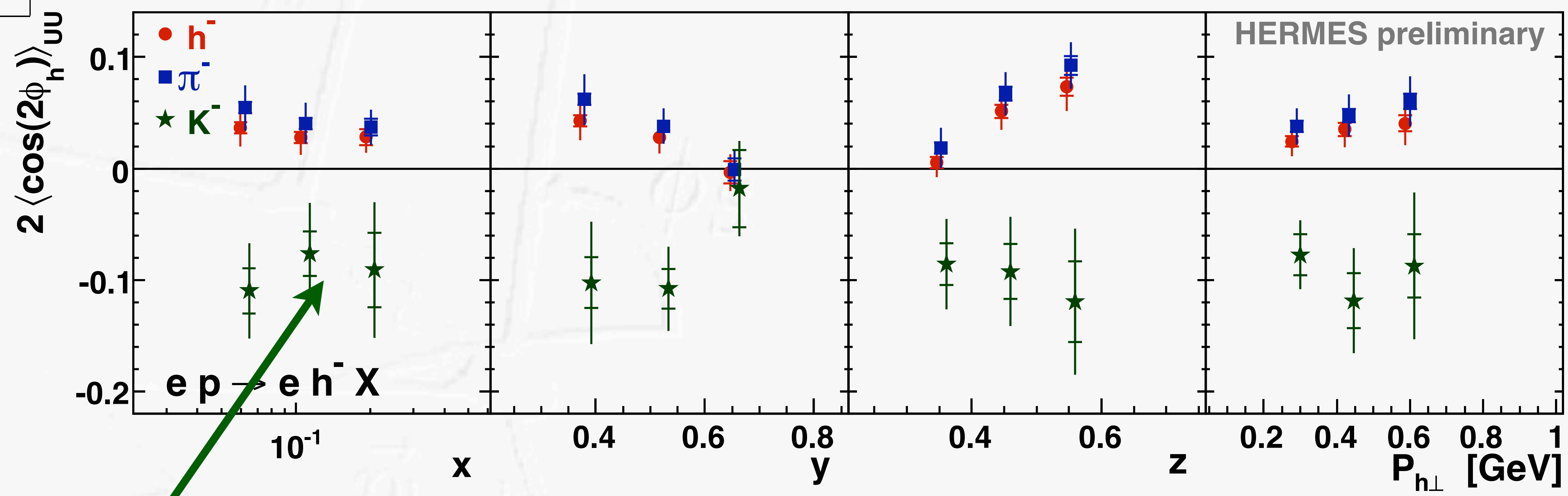
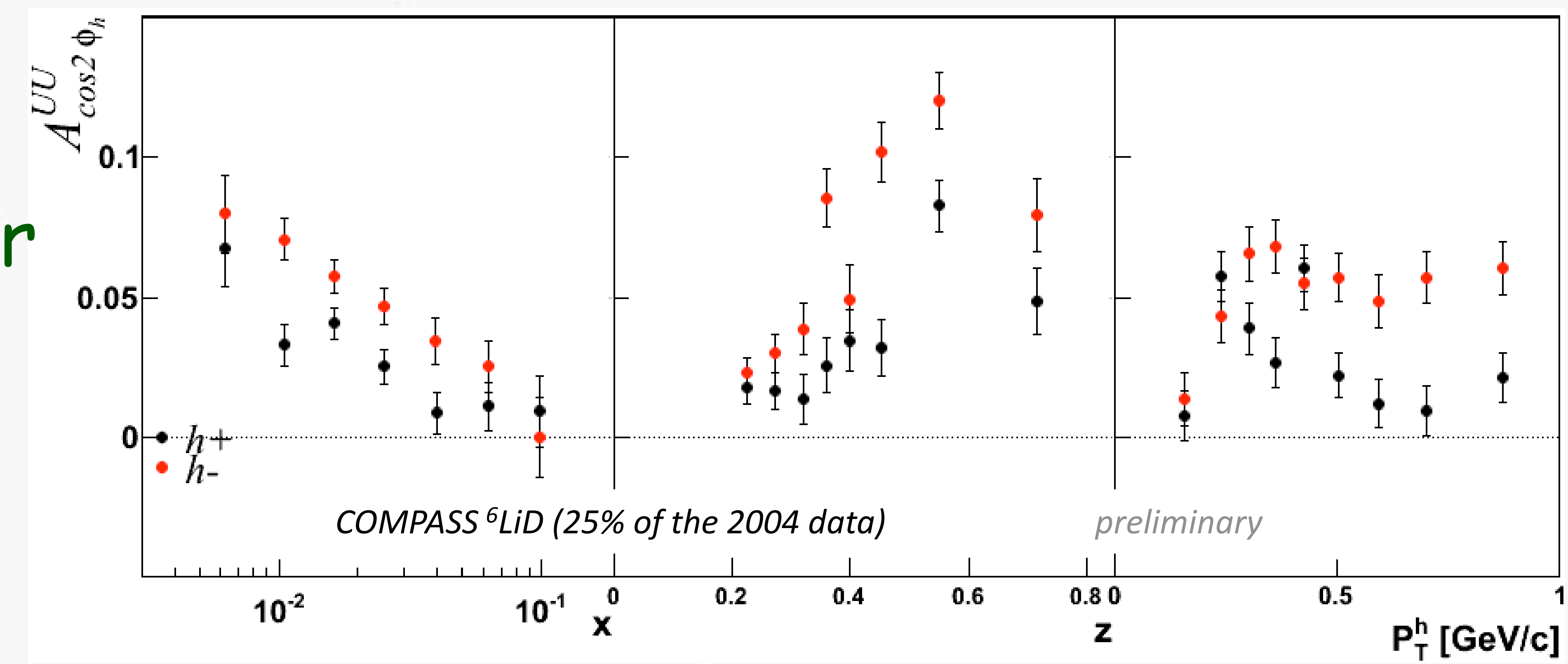


intriguing behavior for kaons



Cahn effect?

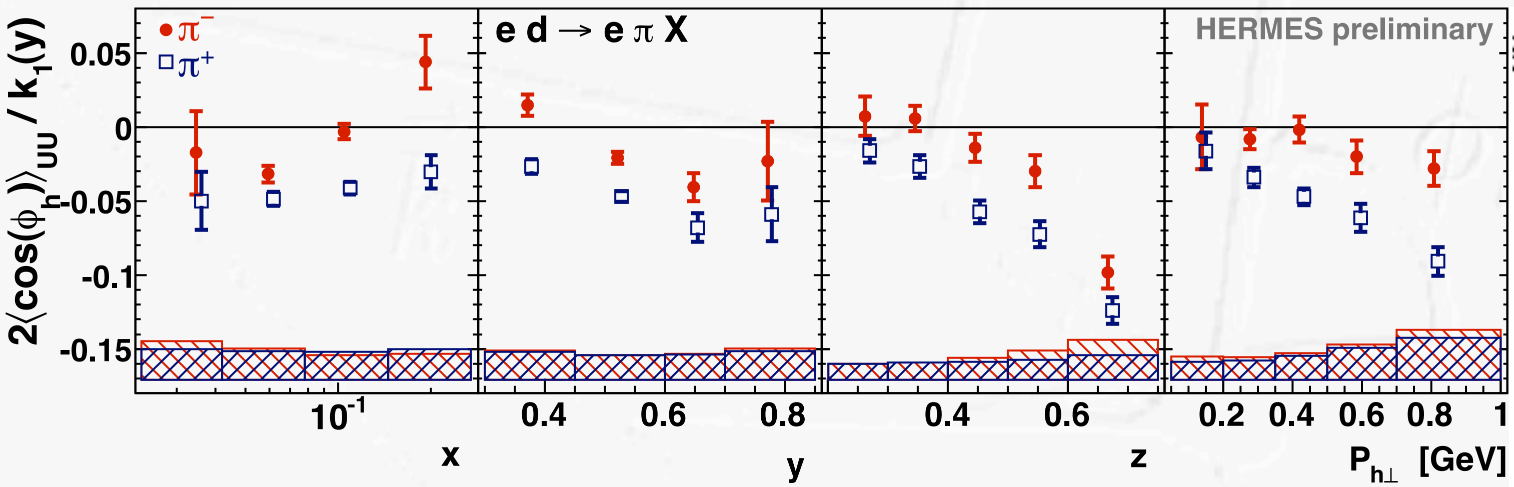
BOER-MULDERS EFFECT

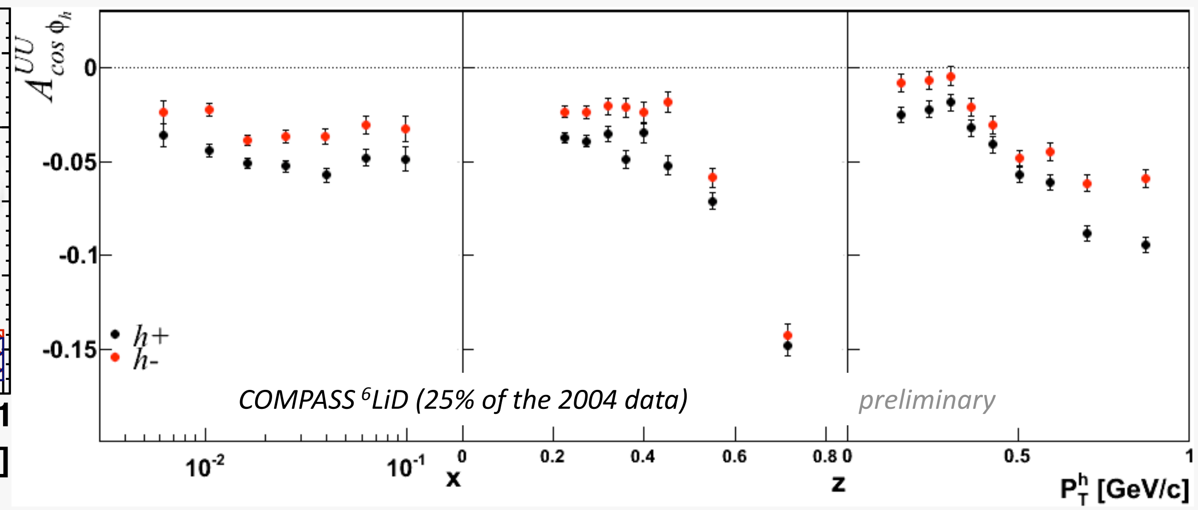
CAHN EFFECT

next to leading twist

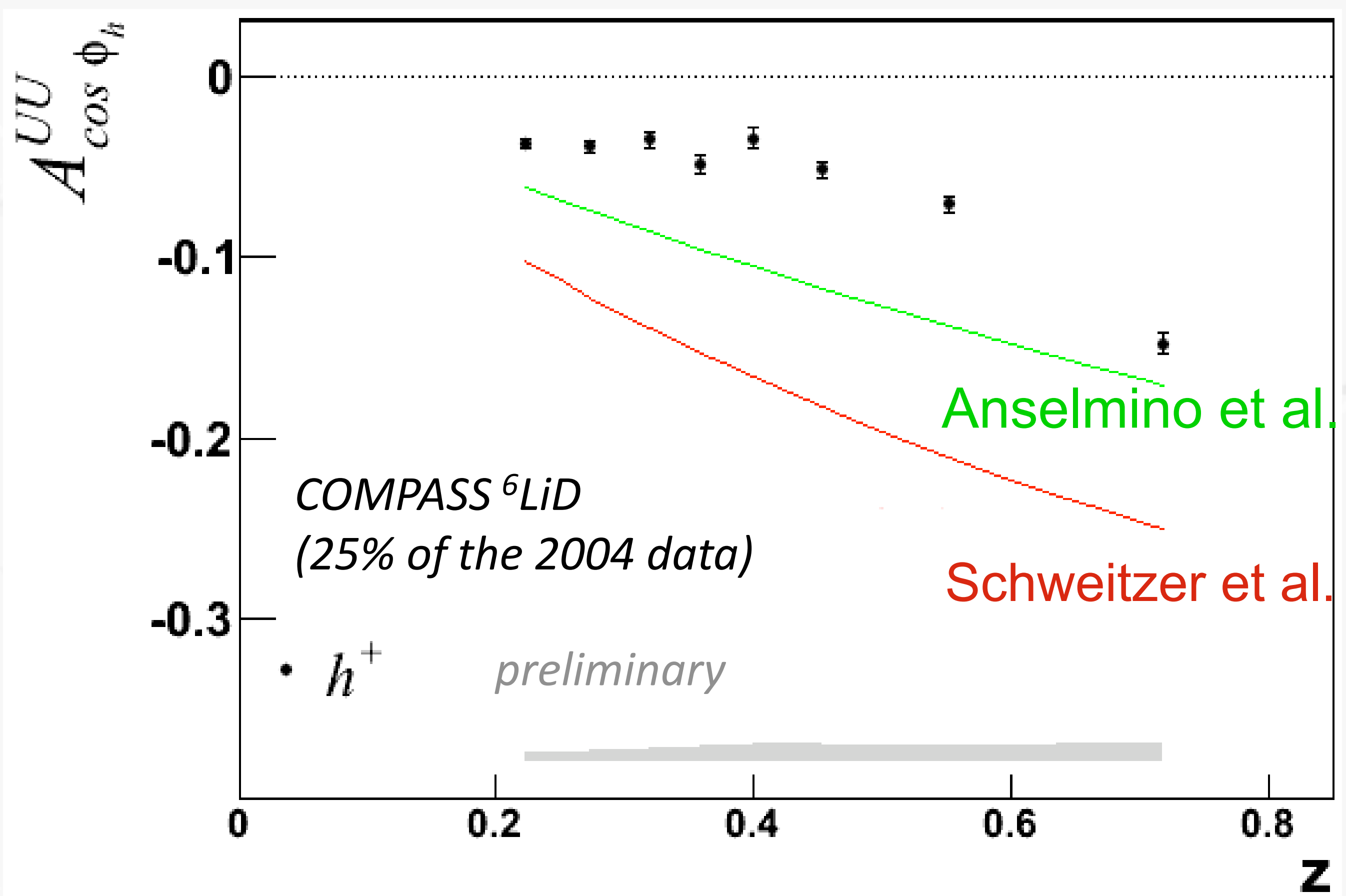
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

Interaction dependent terms neglected





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



Cahn effect?

BOER-MULDERS EFFECT

CAHN EFFECT

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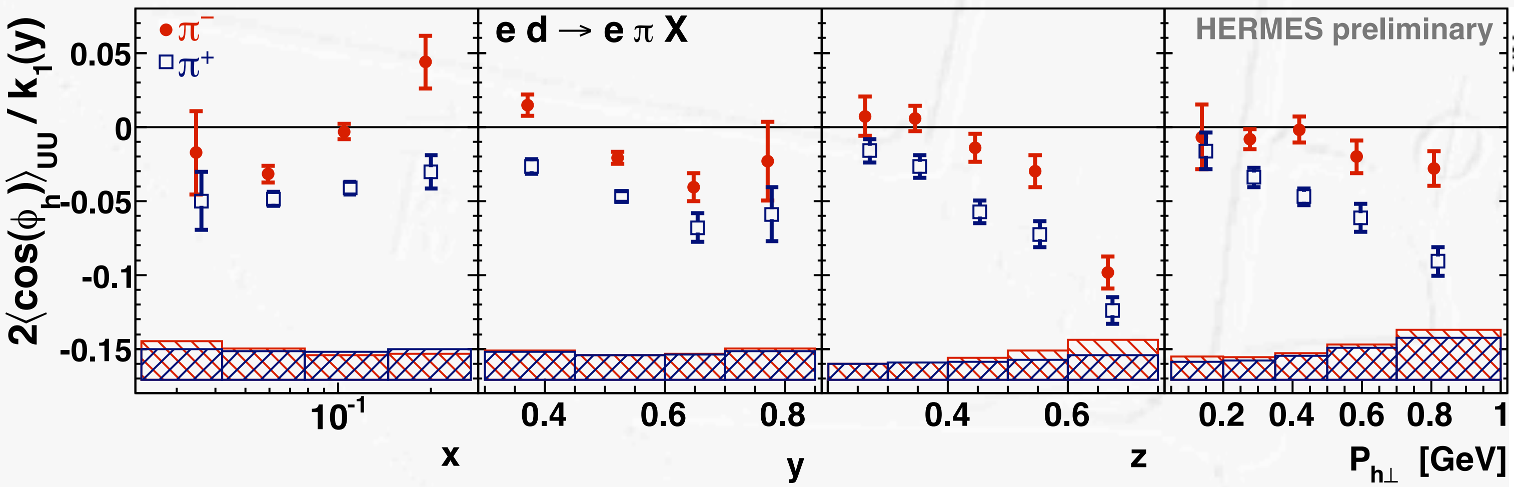

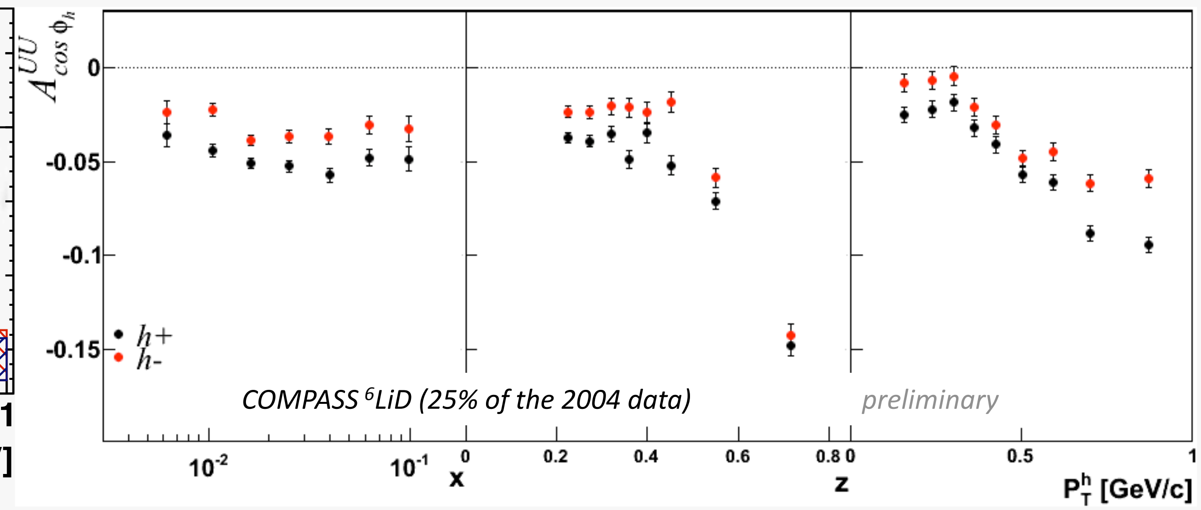

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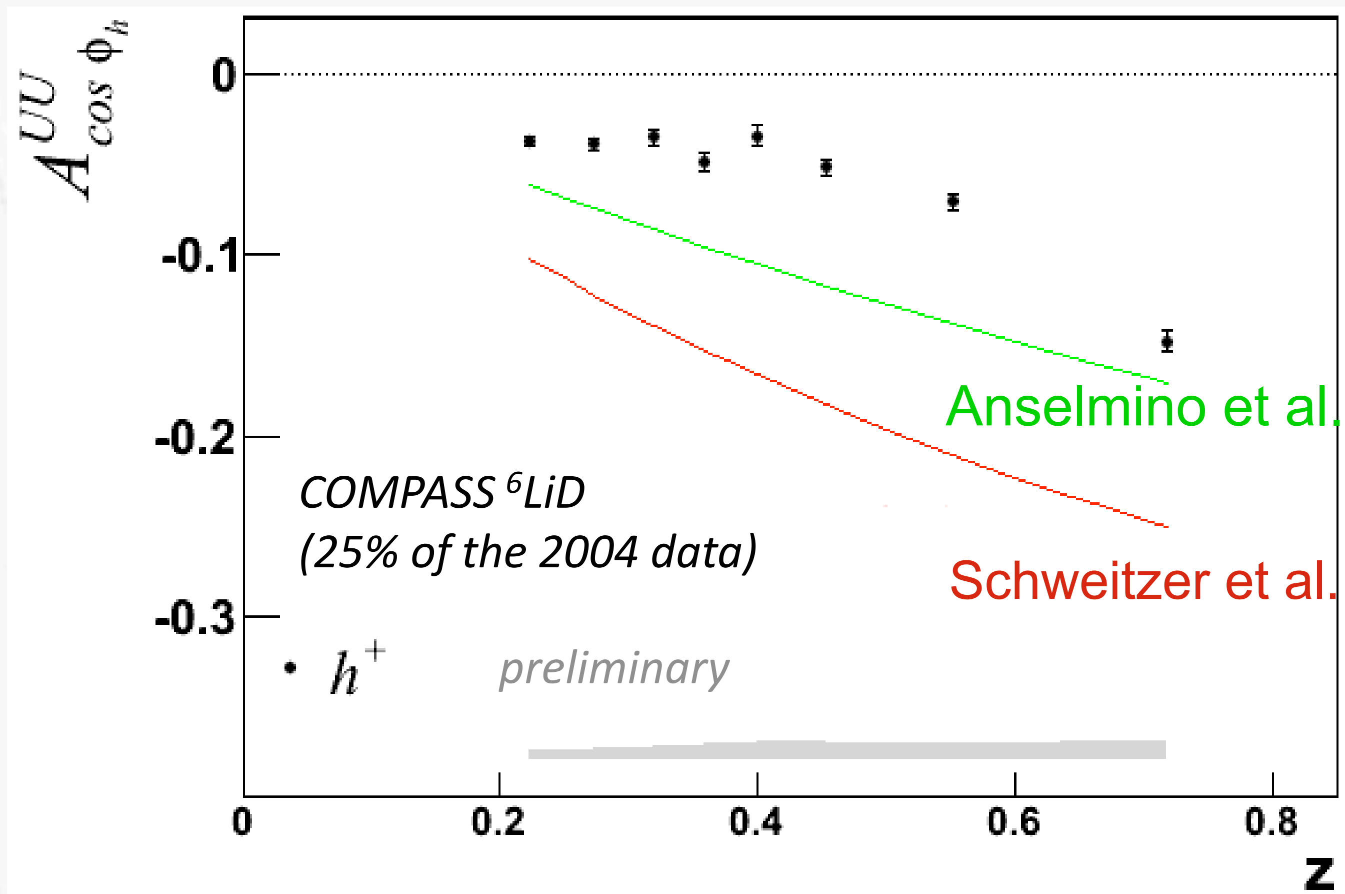
➡ sign of Boer-Mulders in $\cos\phi$ modulation or genuin twist-3?



Summary

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

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http://tp.lc.ehu.es/QCD-N2012/qcdn2012.html

You are all invited to indulge in Spanish wine and Basque cuisine