5th Workshop on Hadron Physics in China and Opportunities in US, Huangshan, July 2-5, 2013

Experimental data on TMDs from ep, pp, and e^+e^-

Gunar.Schnell @ DESY.de

ikerbasque
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Disclaimer

- very active field!
  - too many results to be covered

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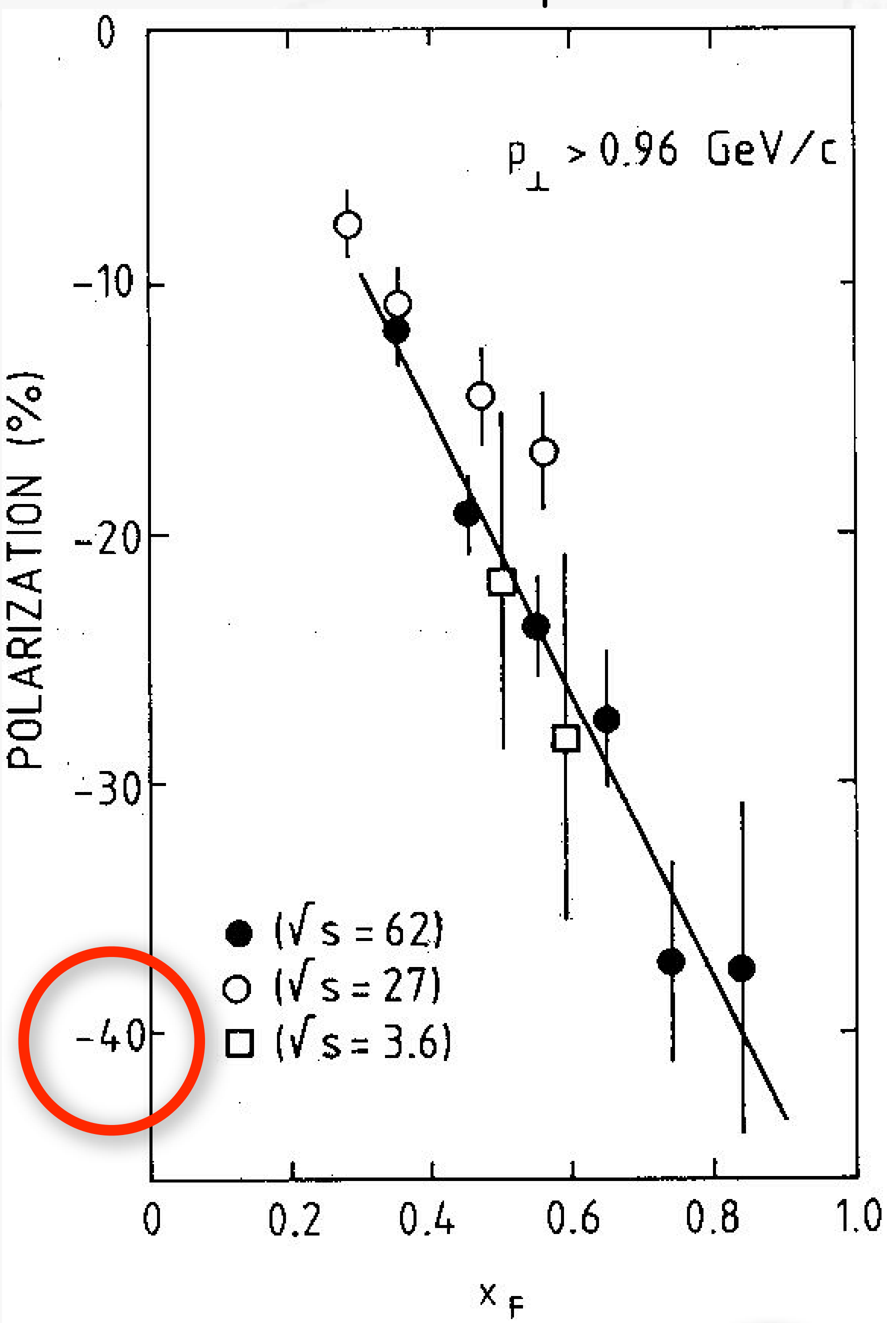
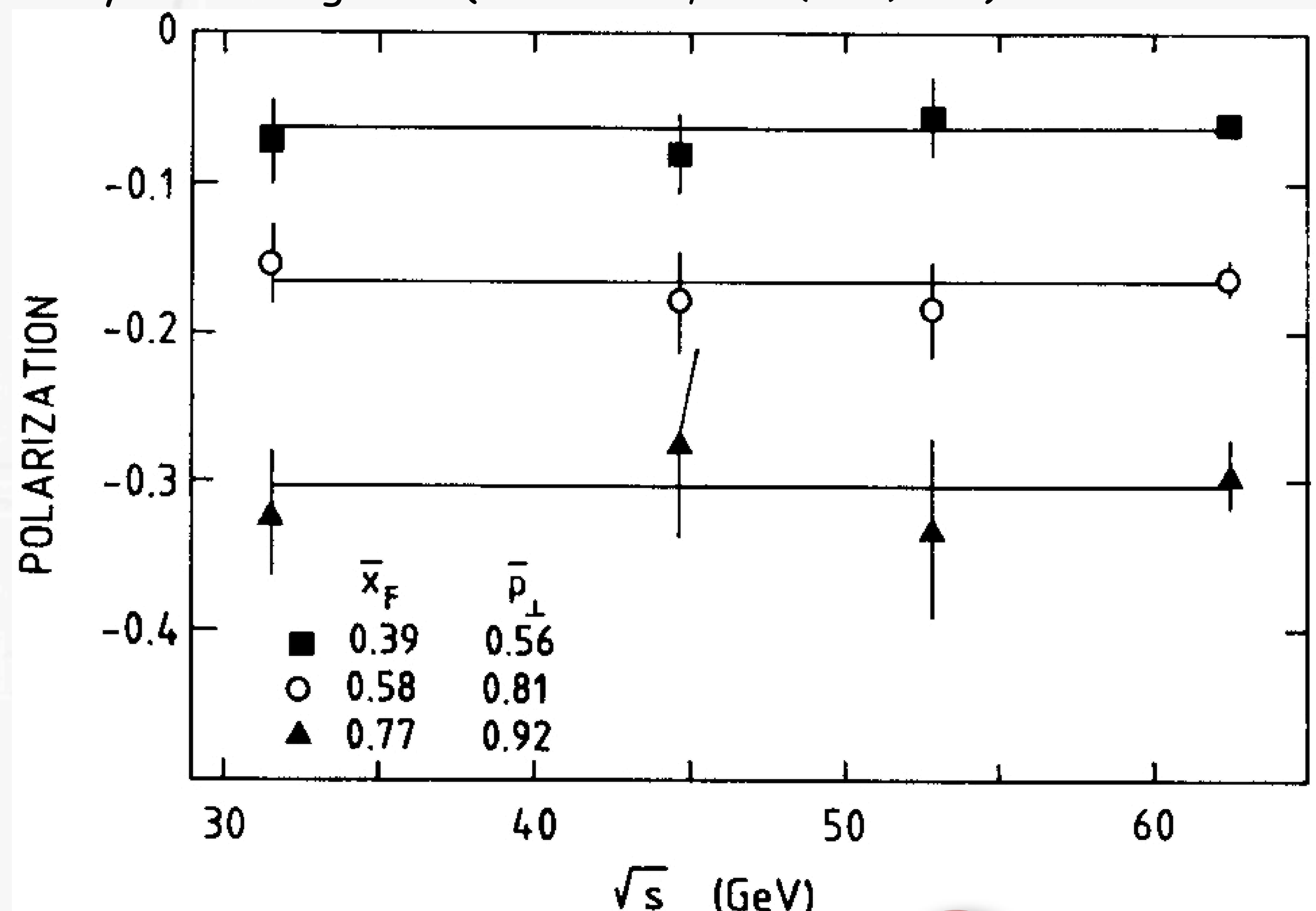
  - too many results to be covered
- have to make a choice:
  - highlight published results
  - preliminary results if outstanding
  - focus on leading-twist TMDs
  - skip as much phenomenology as possible (apologies to the theorists, but also two theory overviews on TMDs at the workshop)

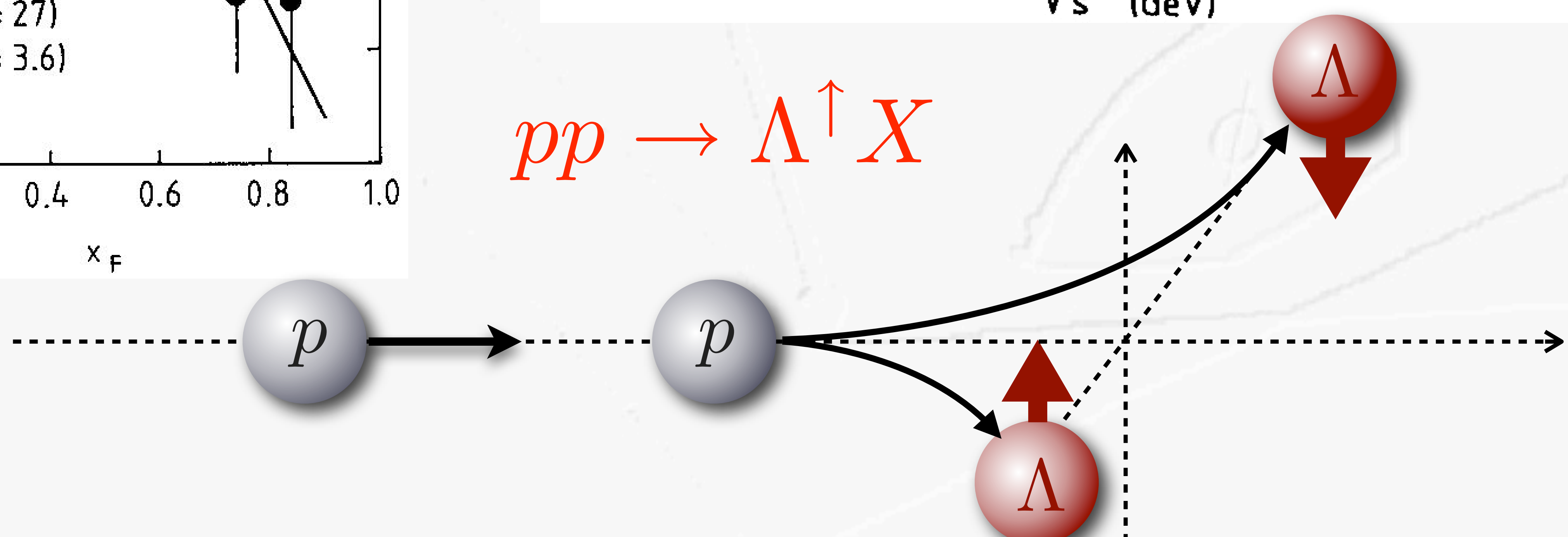
A tribute to some founding figures

Comprehensive review of data by A.D. Panagiotou (Int.J.Mod.Phys.A 5 (1990) 1197)

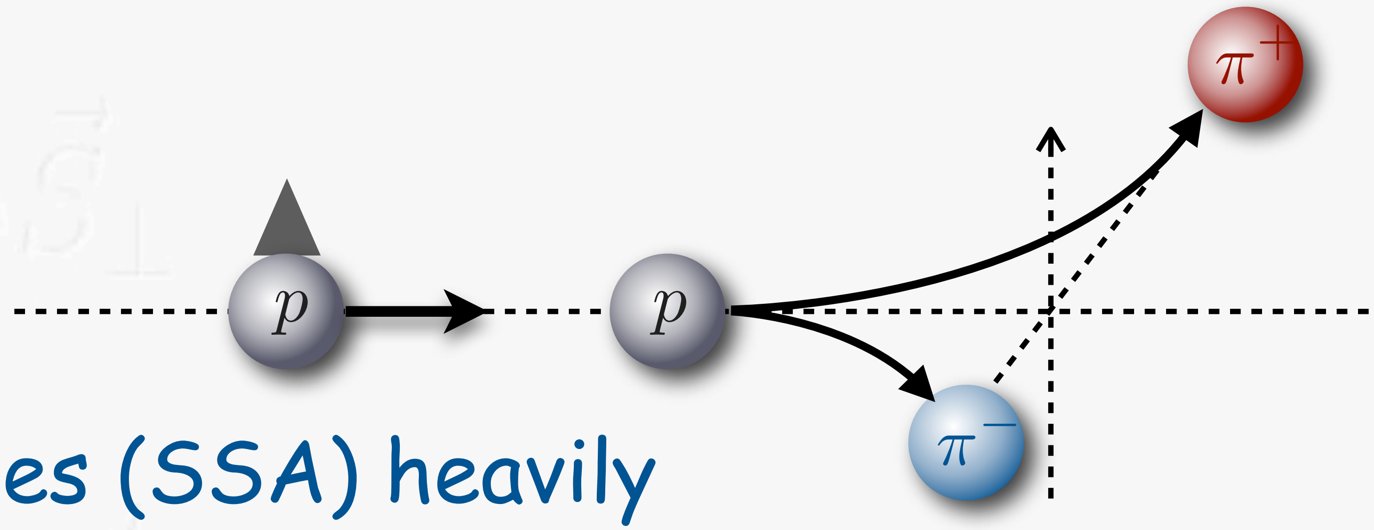




$$pp \rightarrow \Lambda^{\uparrow} X$$



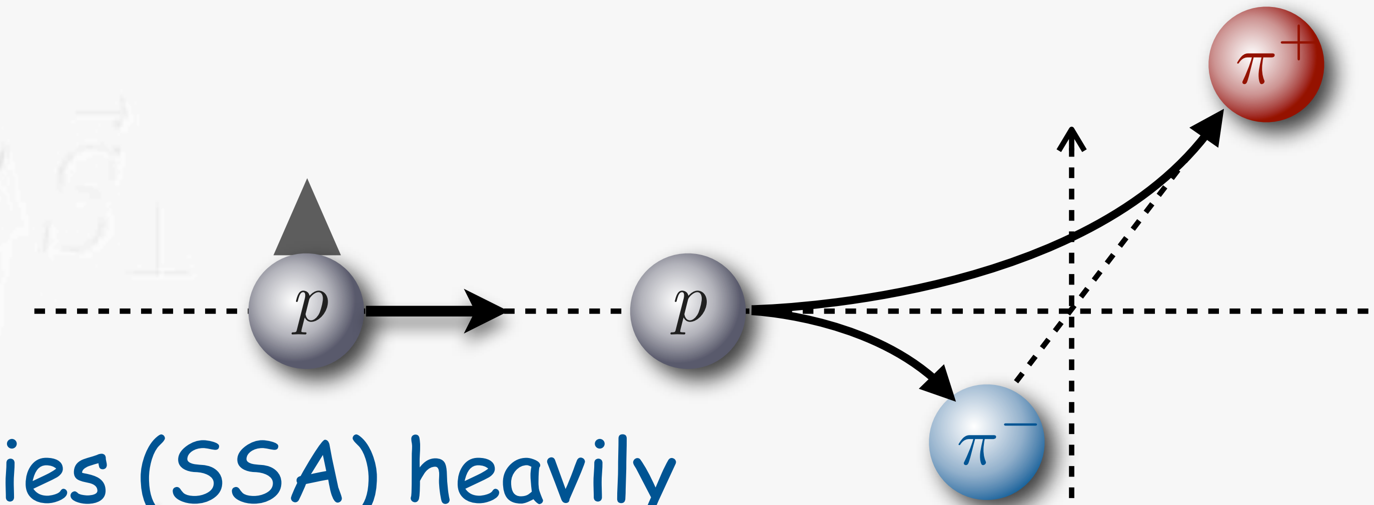
… founding figures



- pQCD: single-spin asymmetries (SSA) heavily suppressed:

$$A_N \propto \alpha_S \frac{m_q}{Q^2}$$ [Kane, Repko, Pumplin, 1978]

... founding figures



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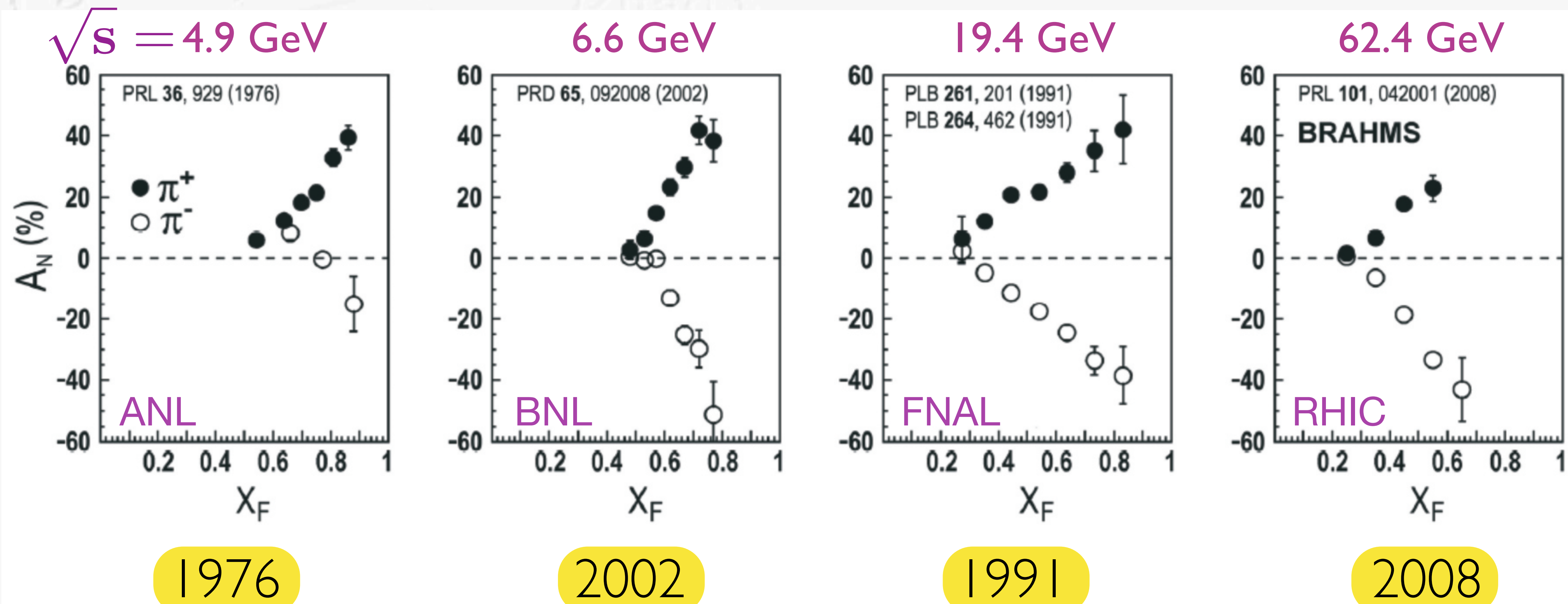
- BUT: large SSA in pp collision and semi-inclusive DIS



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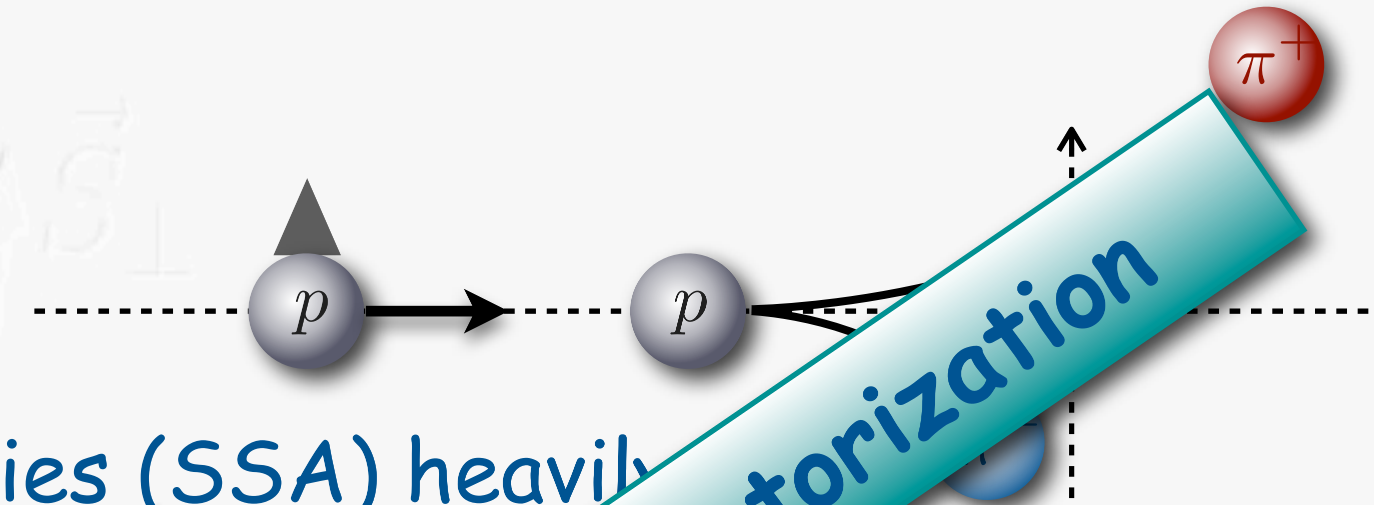

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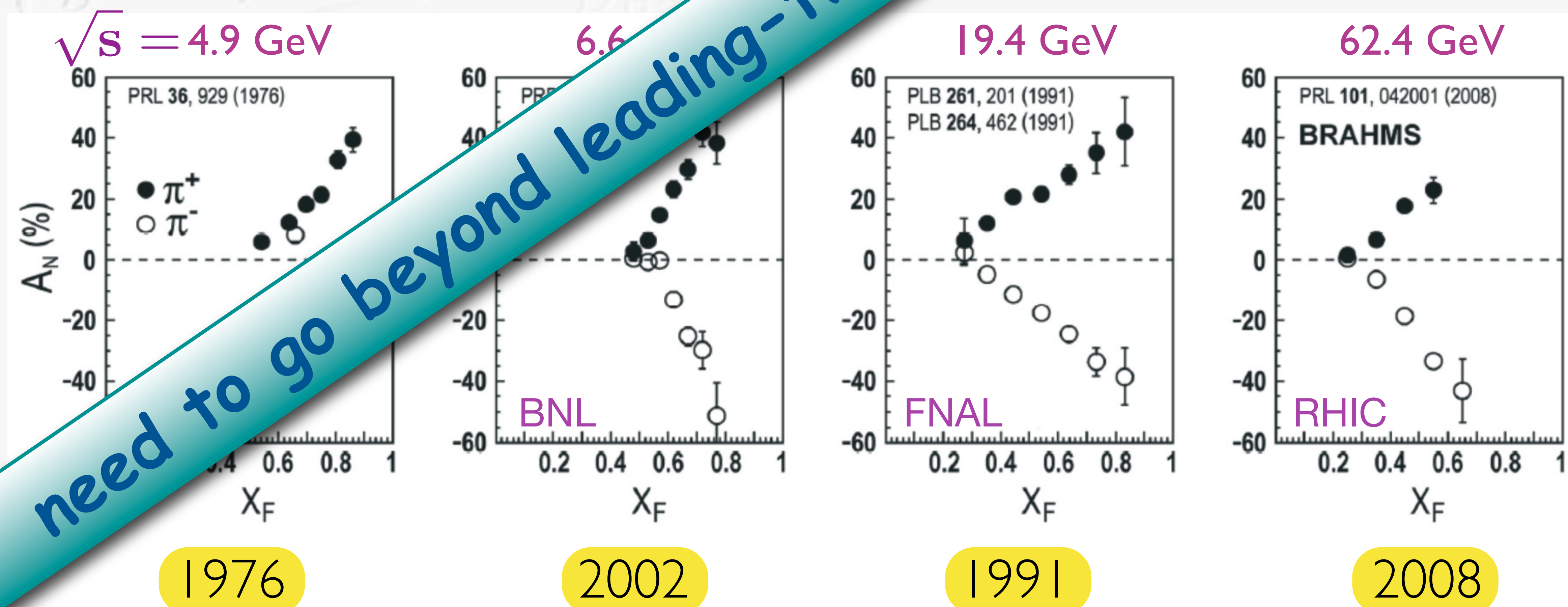
need to go beyond leading-twist collinear factorization



Spin-momentum structure of the nucleon

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

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

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

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

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

- 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

- each TMD describes a particular spin-
 ...rrelation
- functions in black survive integration over transverse momentum
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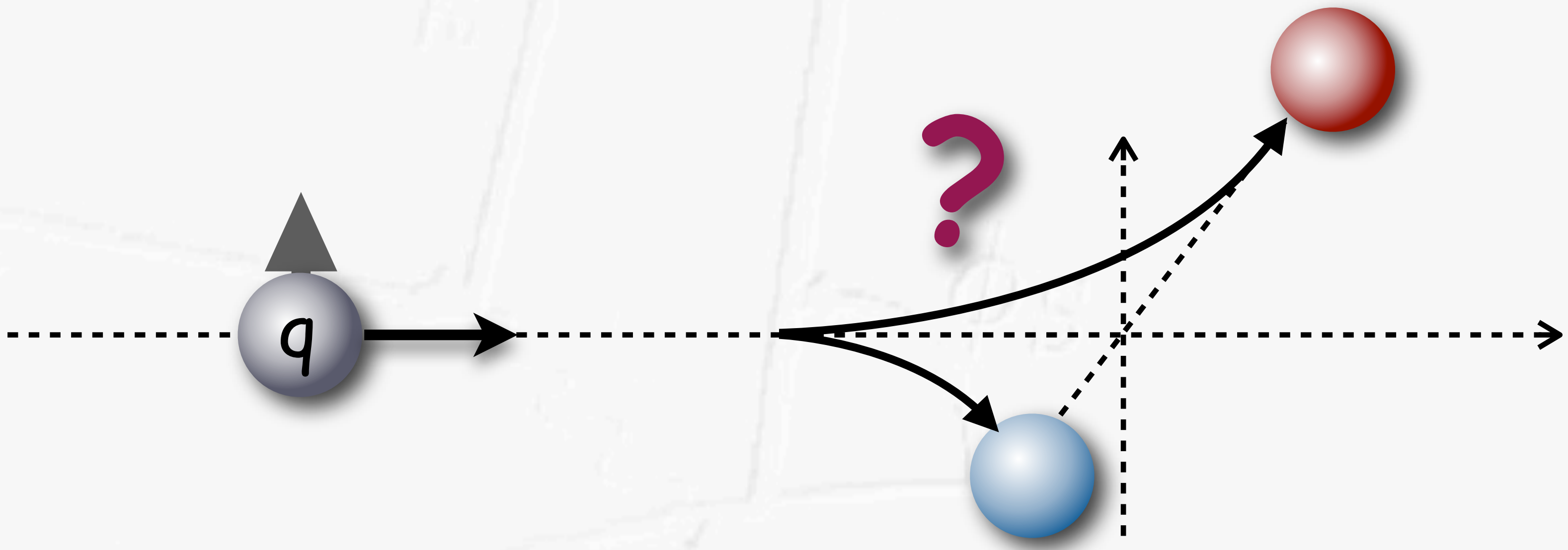
- ...red are naive T-odd

details ☛ A. Prokudin

Collins fctn. - chiral-odd fragmentation



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

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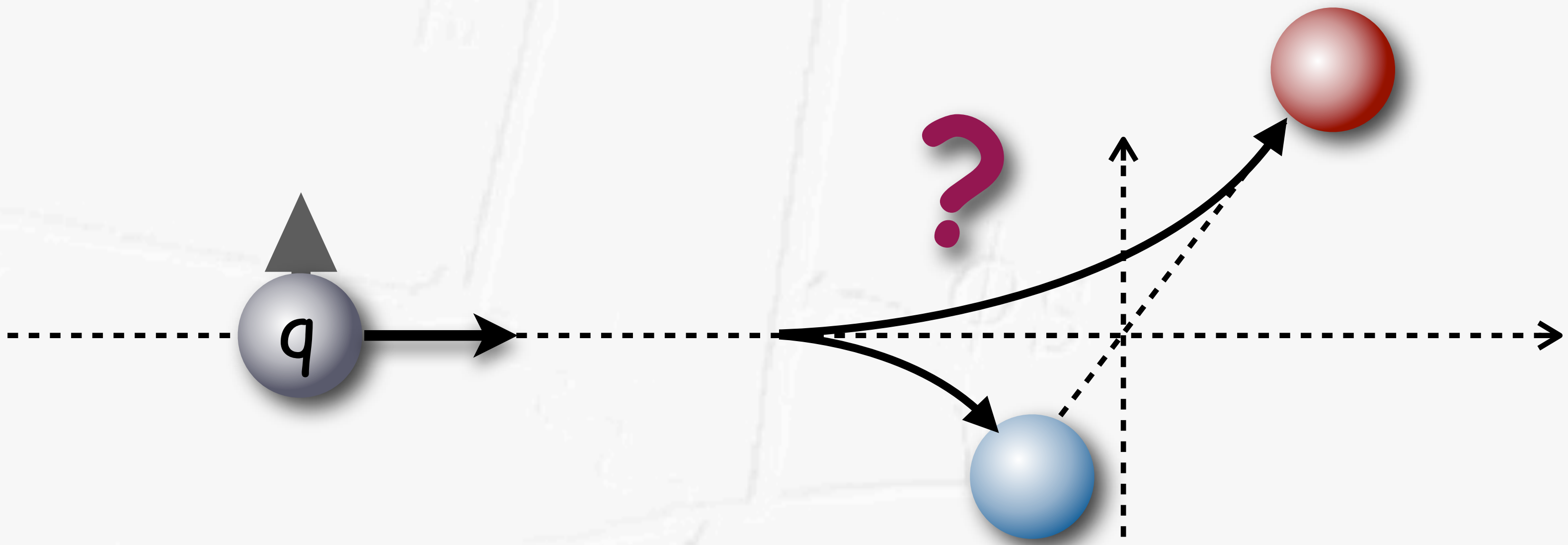

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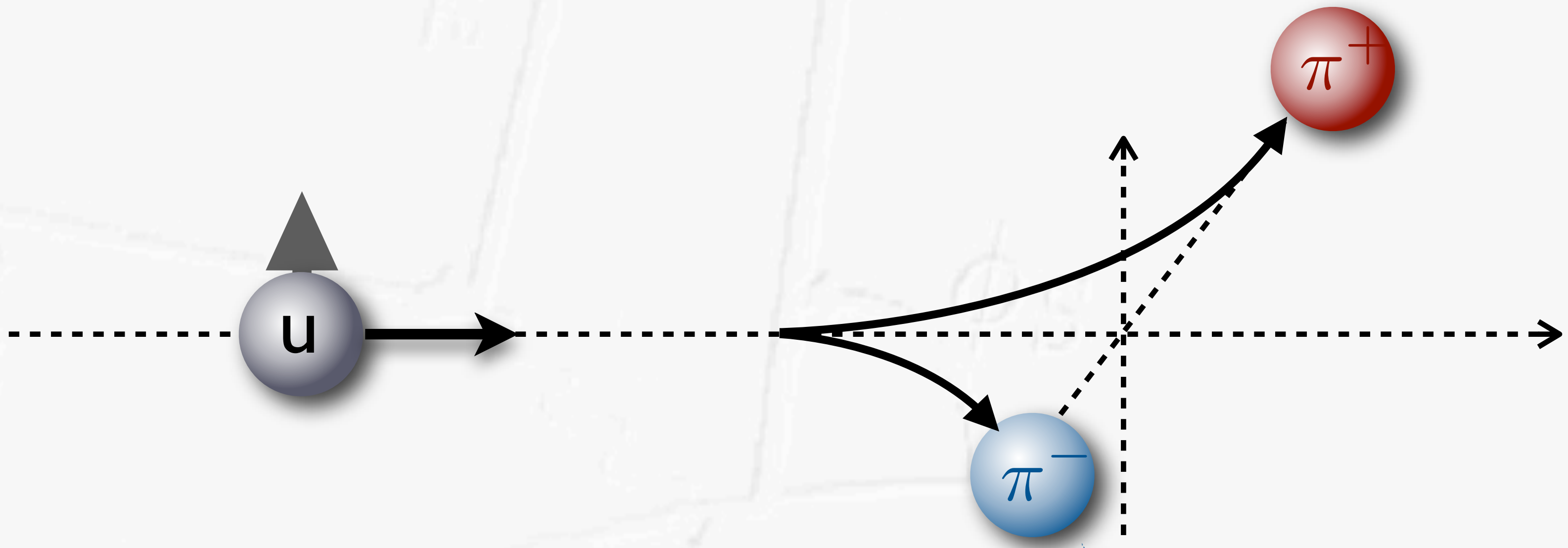

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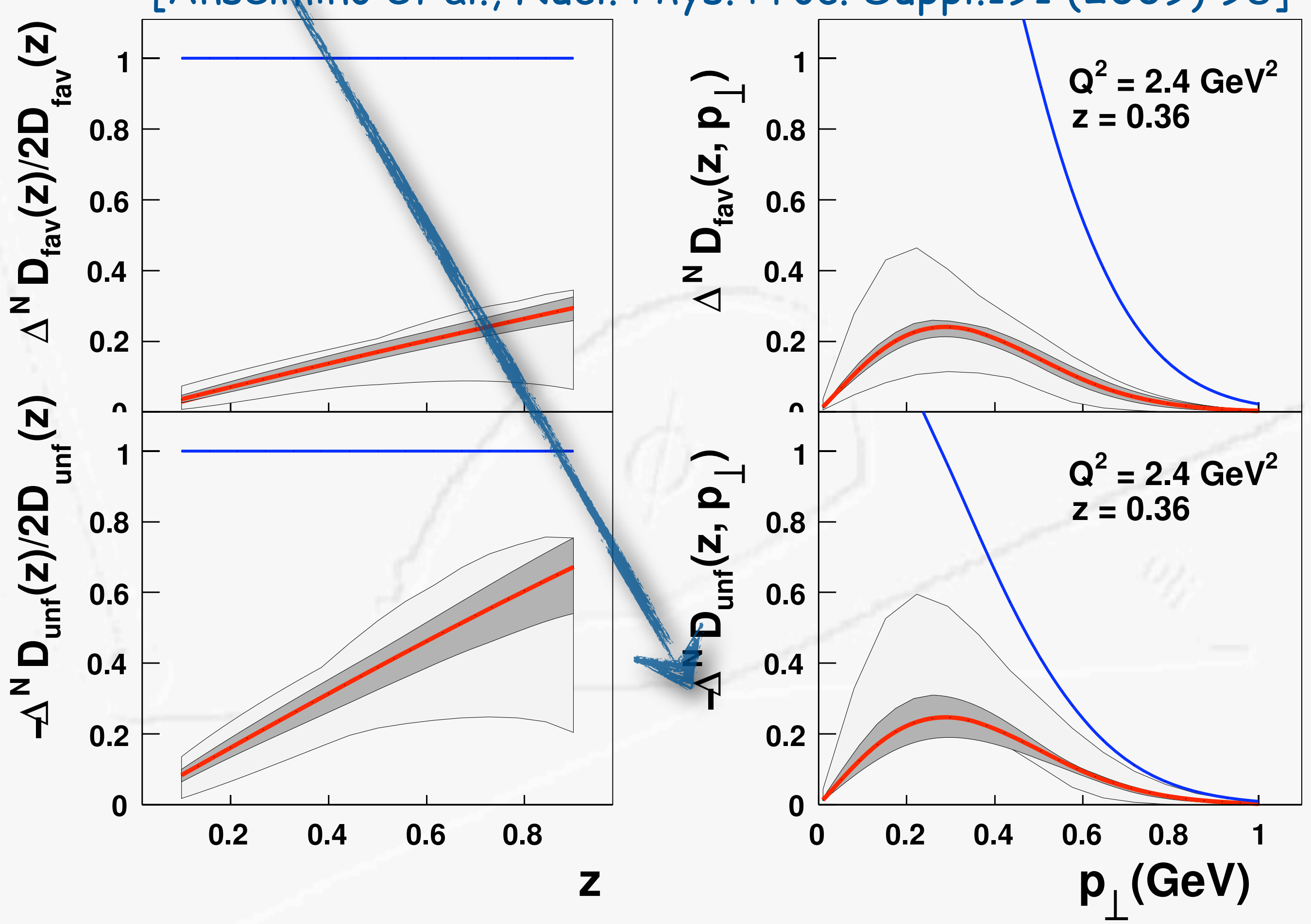
[Anselmino et al., Nucl. Phys. Proc. Suppl.191 (2009) 98]



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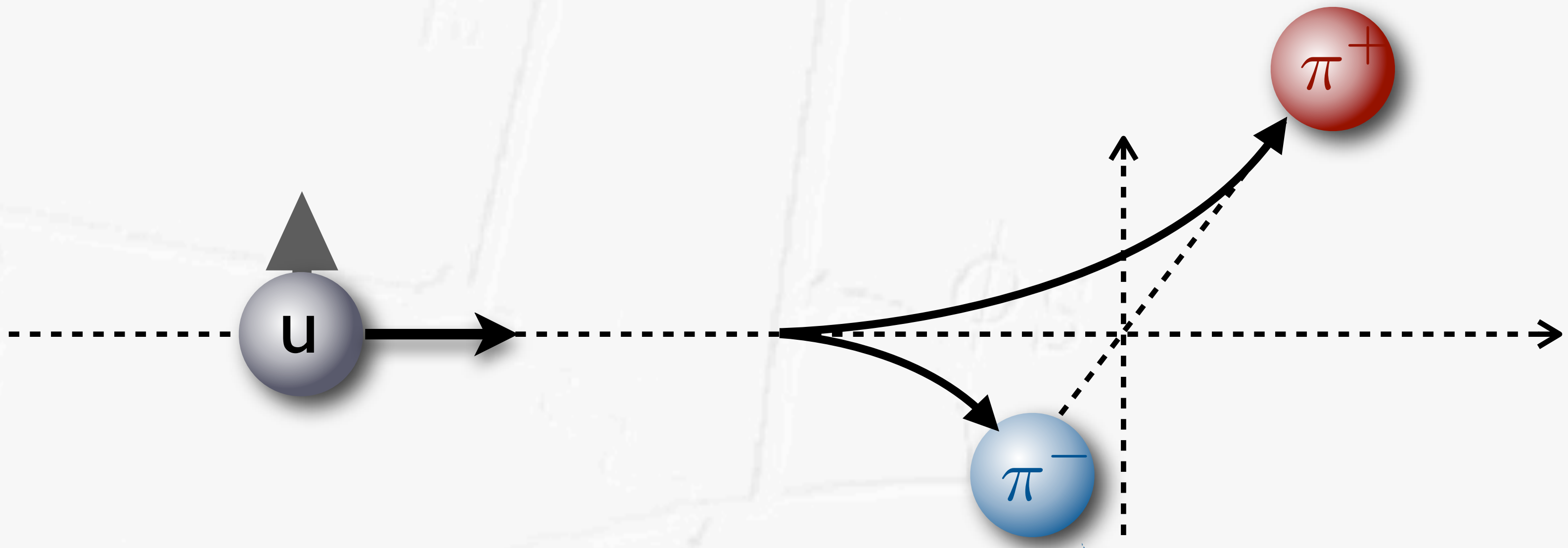
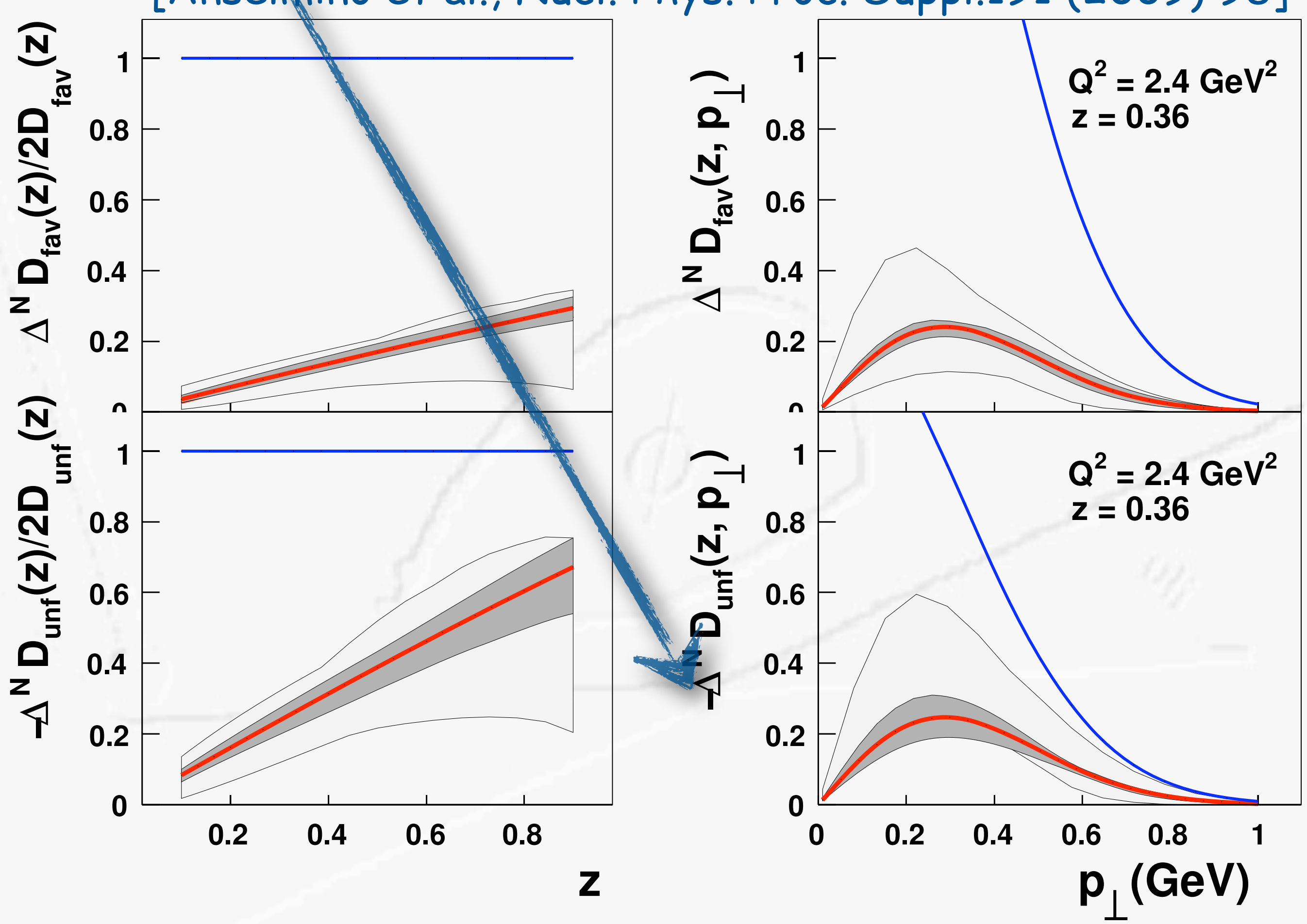
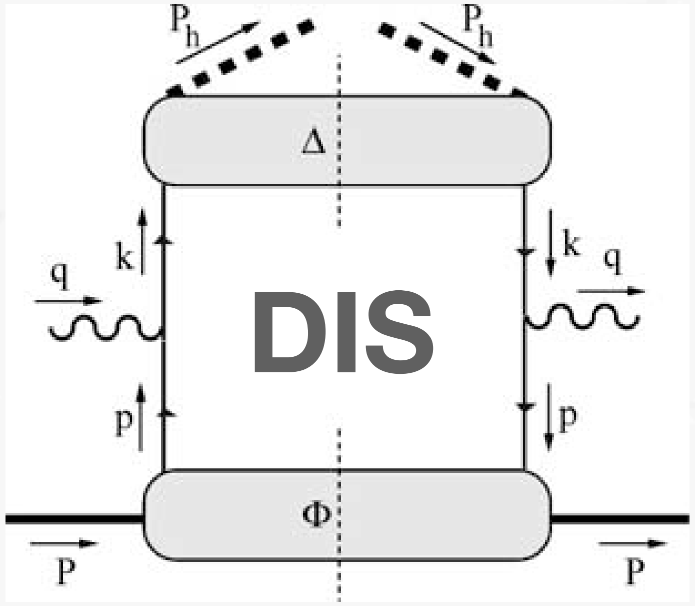


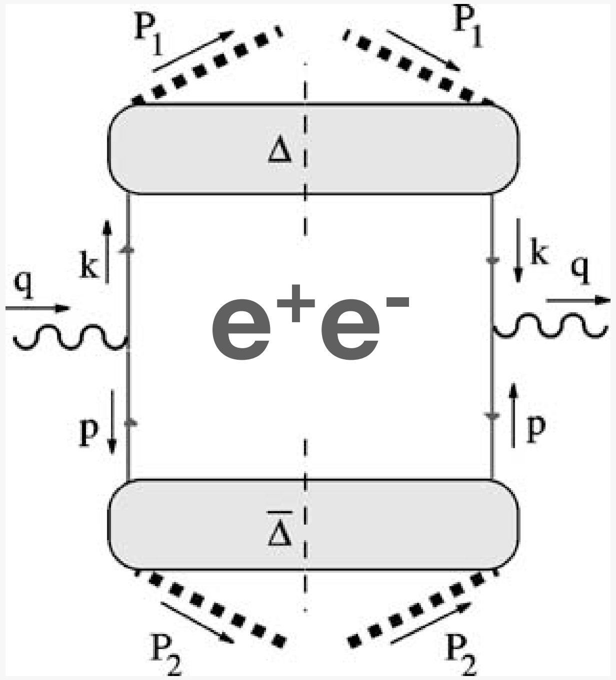
- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum
- extracted from SIDIS and e^+e^- annihilation data
- spin average gives "ordinary" D_1

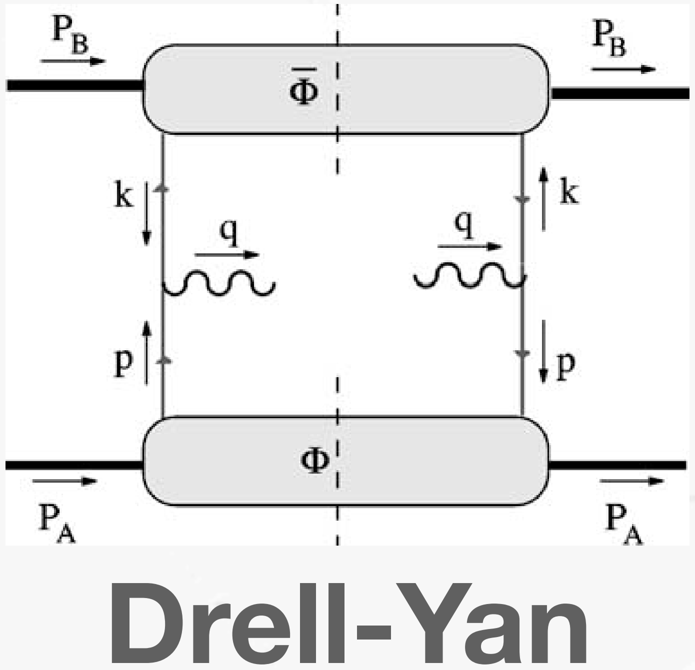
[Anselmino et al., Nucl. Phys. Proc. Suppl.191 (2009) 98]



a QCD laboratory







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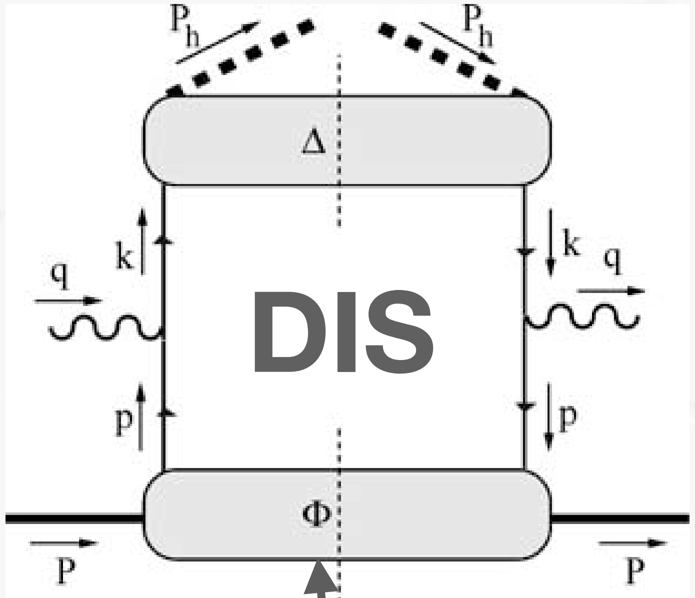
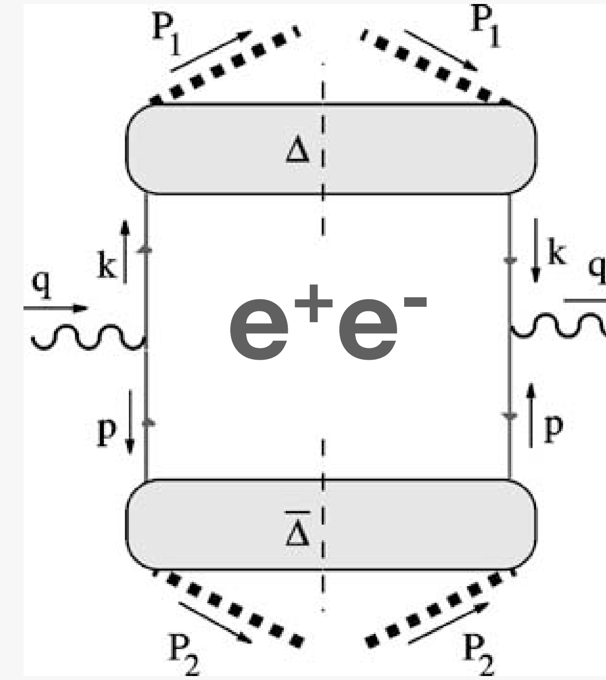
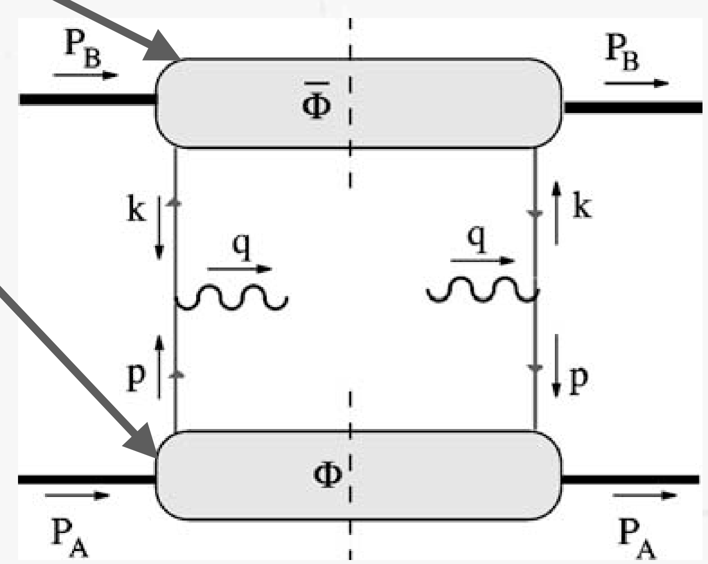


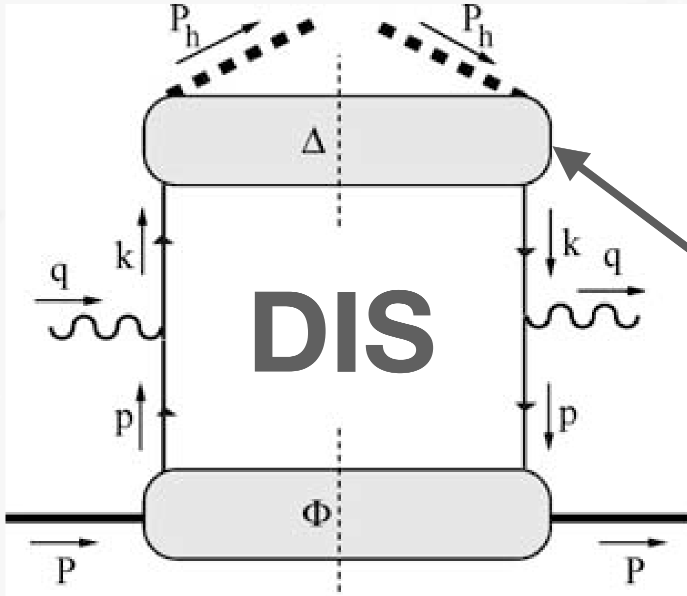


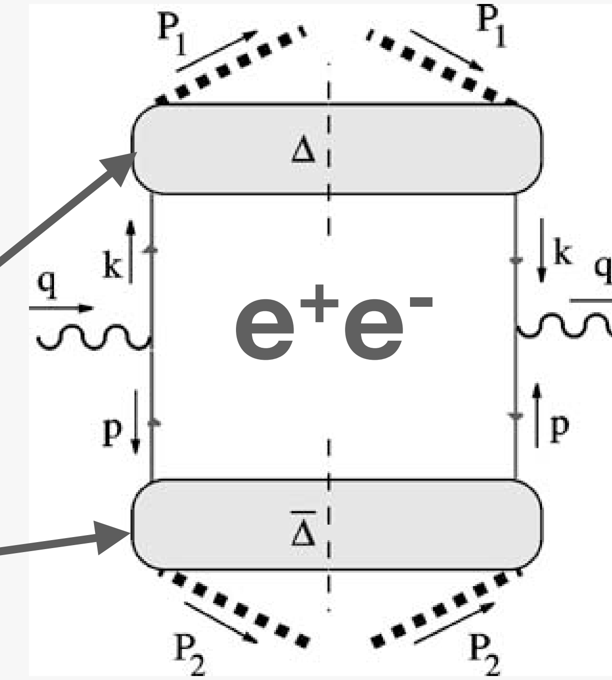
hadron structure
(distribution functions)



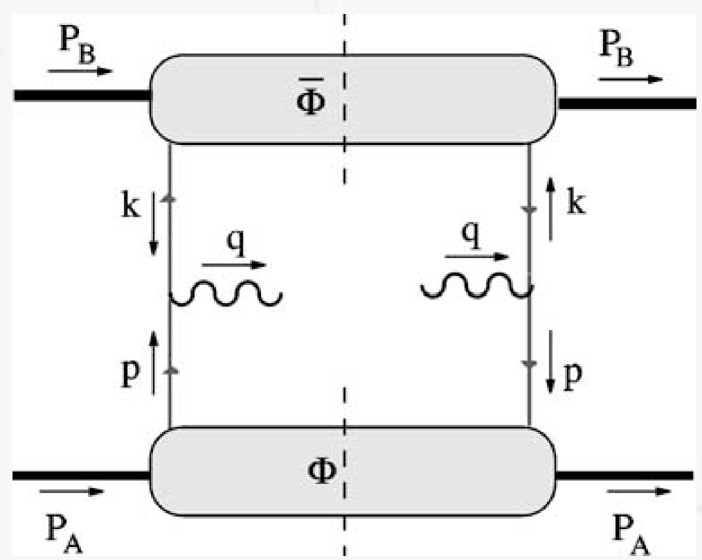
Drell-Yan

a QCD laboratory



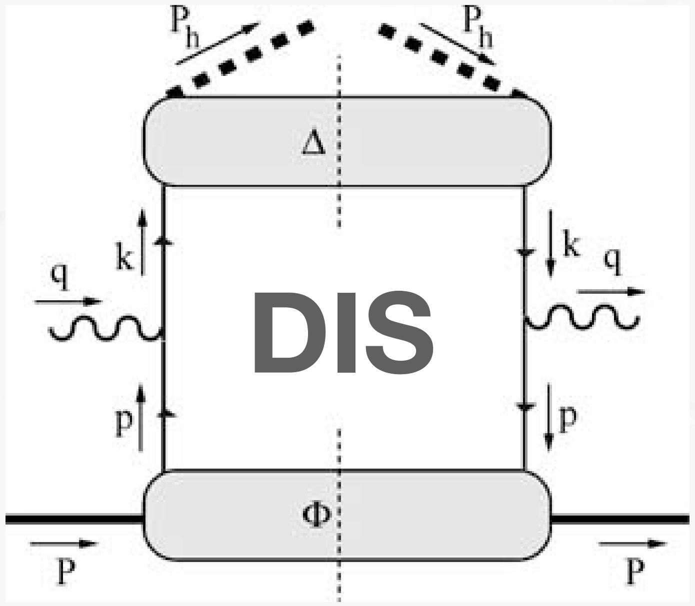


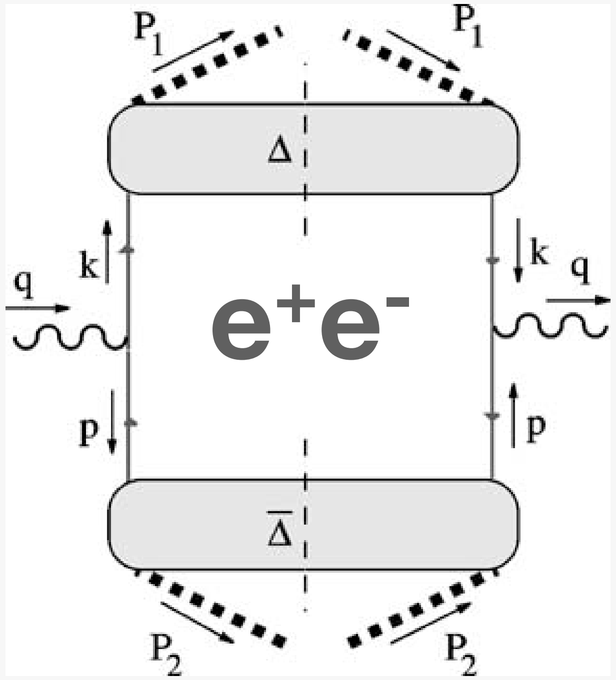
hadronization
(fragmentation functions)



Drell-Yan

a QCD laboratory

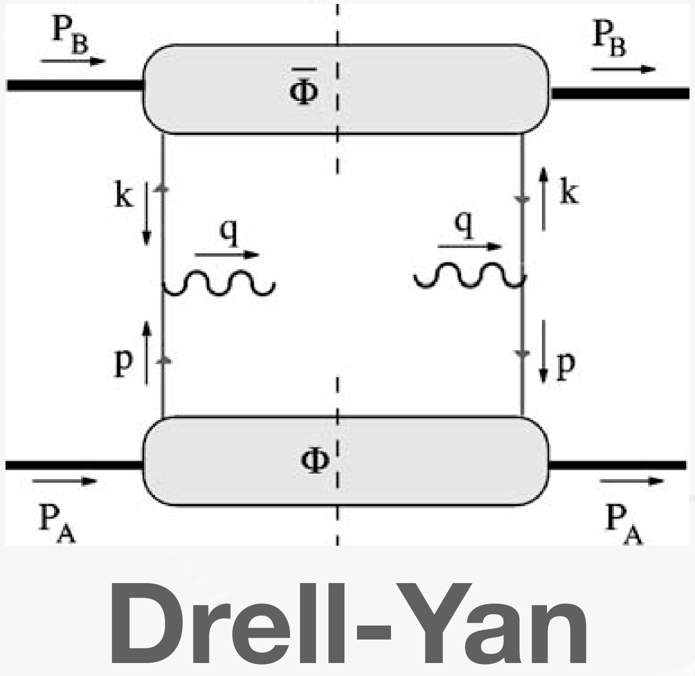




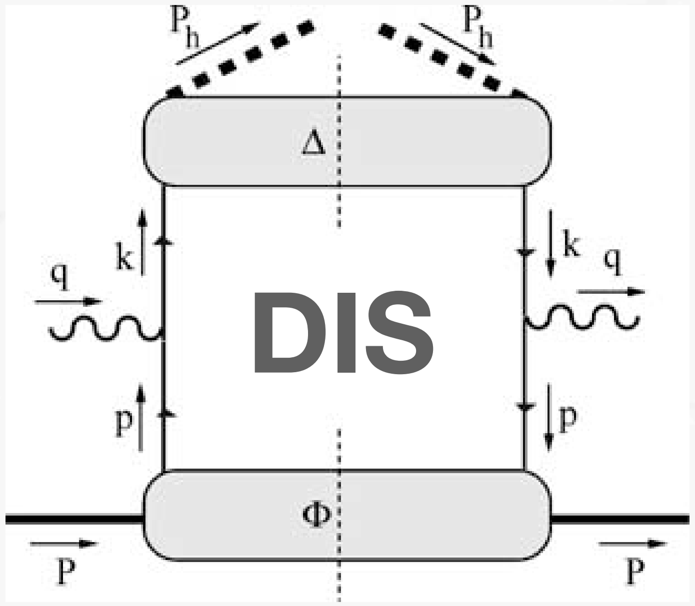
- **data from COMPASS, HERMES, and JLab; planned for future EIC**

- convolutes parton distribution (Φ) and fragmentation (Δ) functions Φ⊗Δ

- **need fragmentation function to extract distribution functions**



a QCD laboratory



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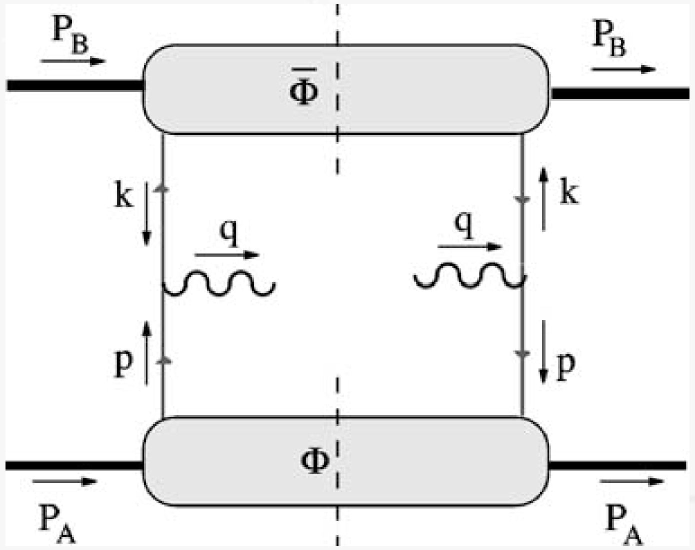
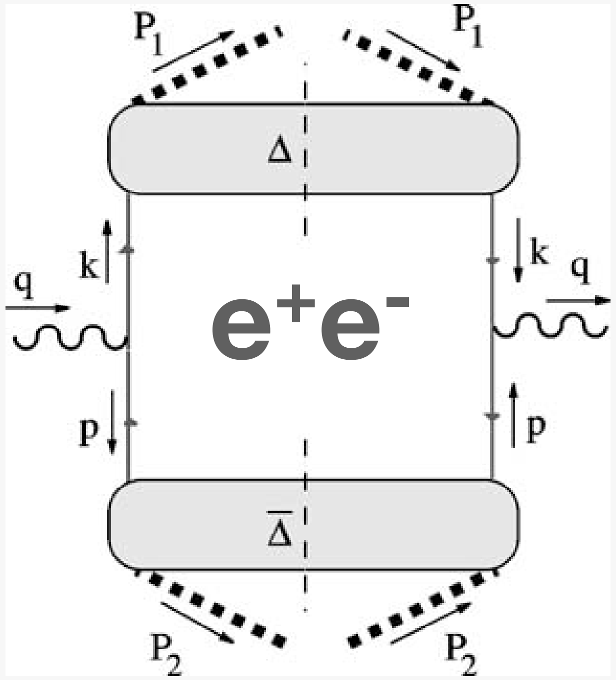
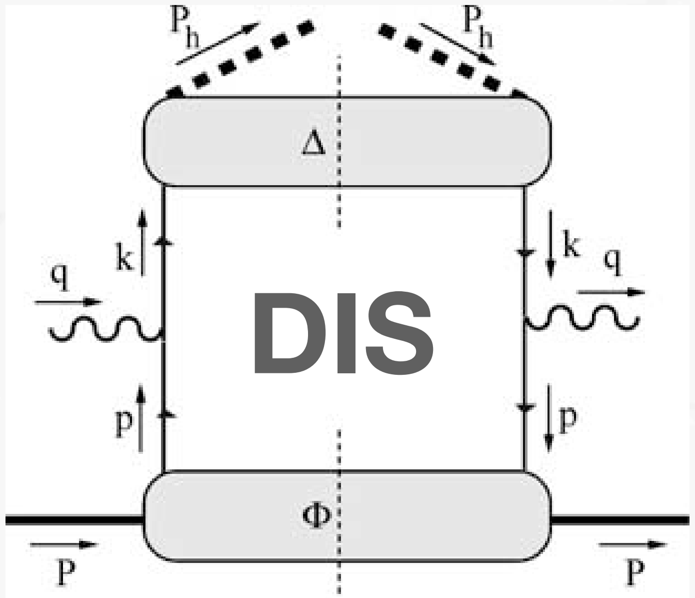


Drell-Yan



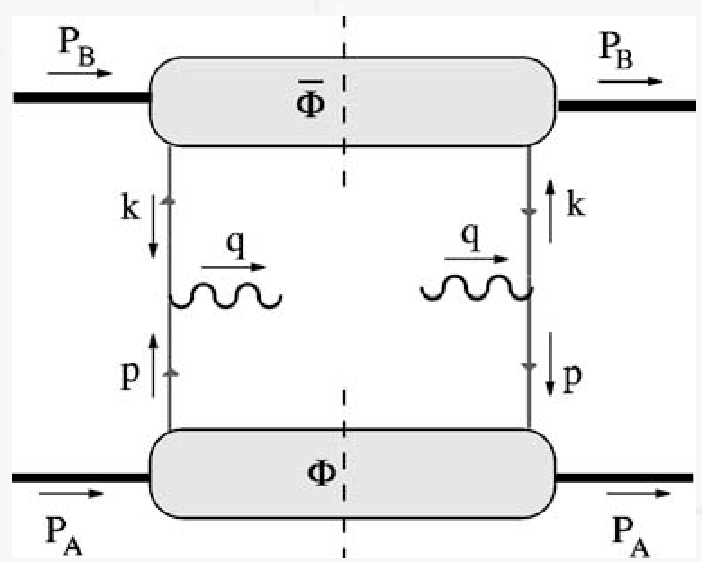
- ideal place to study hadronization
- convolutes parton fragmentation functions $\Delta \otimes \Delta$
- wealth of ("raw") data from Belle and BaBar, possibly BESIII

a QCD laboratory

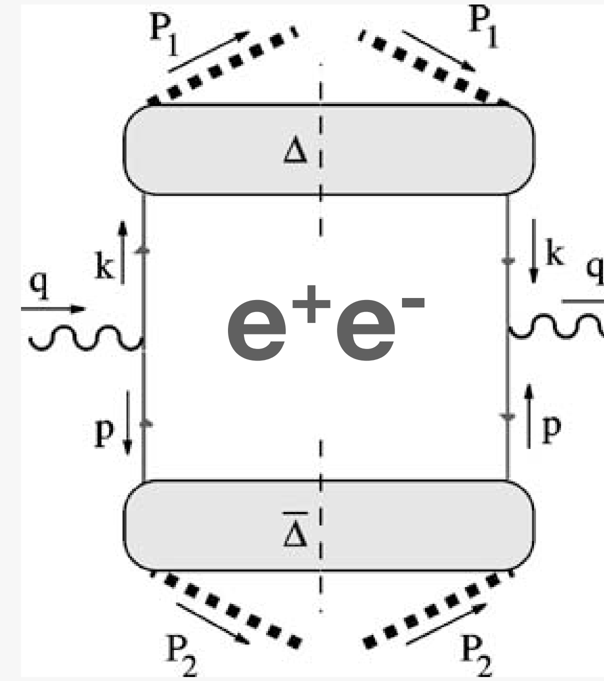


- data from COMPASS, HERMES, and JLab; planned for future EIC
- convolutes parton distribution (Φ) and fragmentation (Δ) functions Φ⊗Δ
- **need fragmentation function to extract distribution functions**

- convolutes parton distribution functions Φ⊗Φ
- **testing ground for sign reversal of naive-T-odd distributions**
- **hardly any data**



Drell-Yan



- **ideal place to study hadronization**
- convolutes parton fragmentation functions Δ⊗Δ
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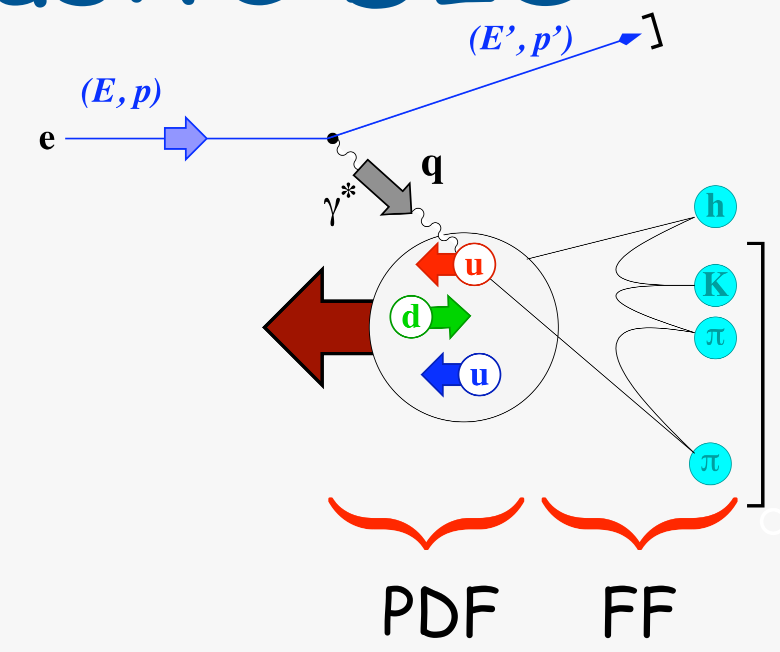
Probing TMDs in semi-inclusive DIS

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

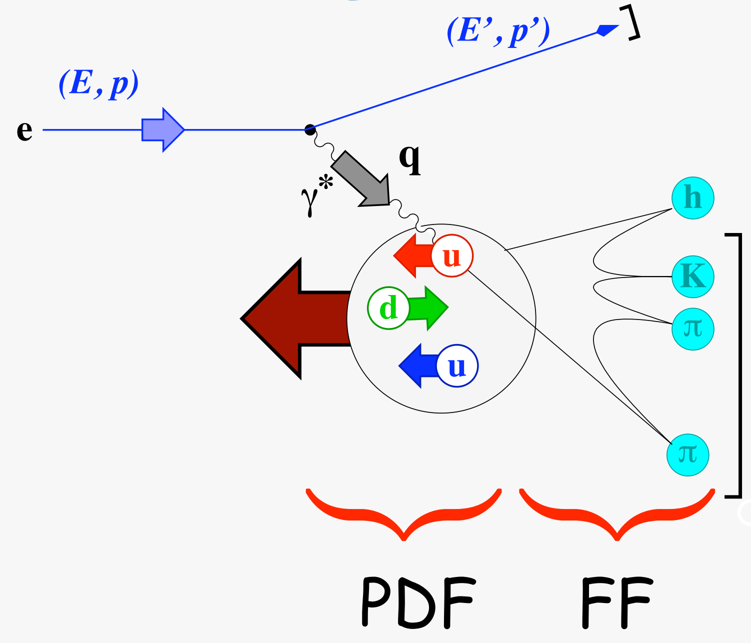
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

Probing TMDs in semi-inclusive DIS



quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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Collins FF: $H_1^{\perp,q\to h}$

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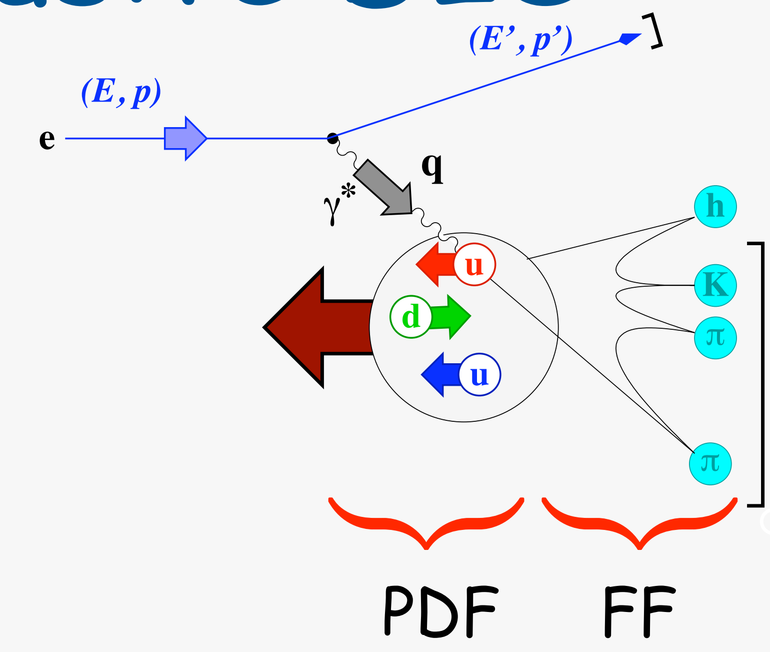

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
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in SIDIS*) couple PDFs to:

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ordinary FF: $D_1^{q\rightarrow h}$

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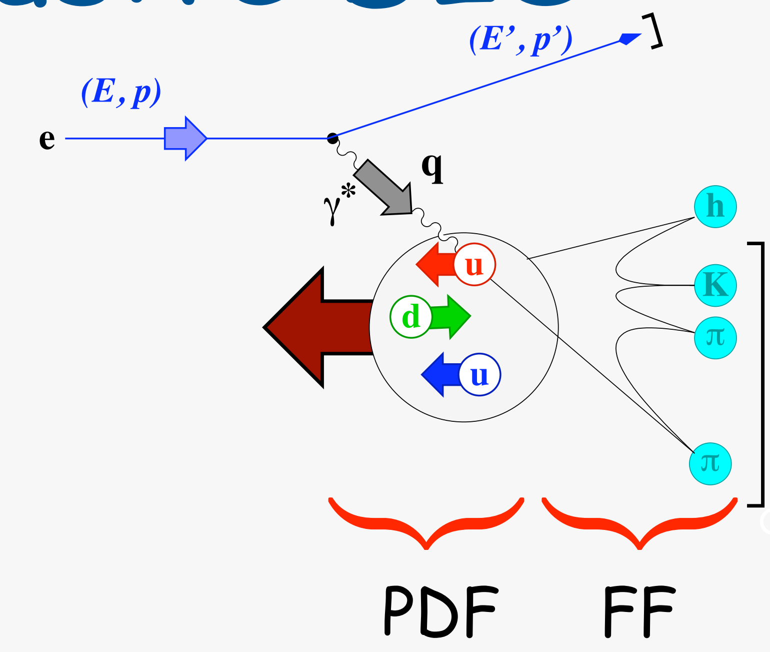
Probing TMDs in semi-inclusive DIS



	quark pol. U	quark pol. L	quark pol. T
nucleon pol. U	f_1		$h_1^\perp$
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in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\rightarrow h}$

ordinary FF: $D_1^{q\rightarrow h}$

➡ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

1-Hadron production (ep→ehX)

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

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

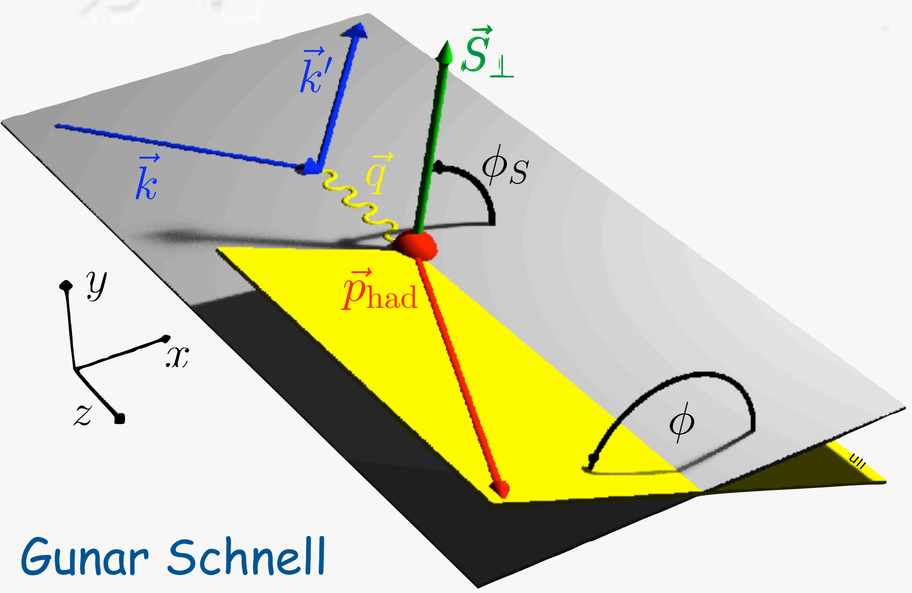
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right.$$

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

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

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

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

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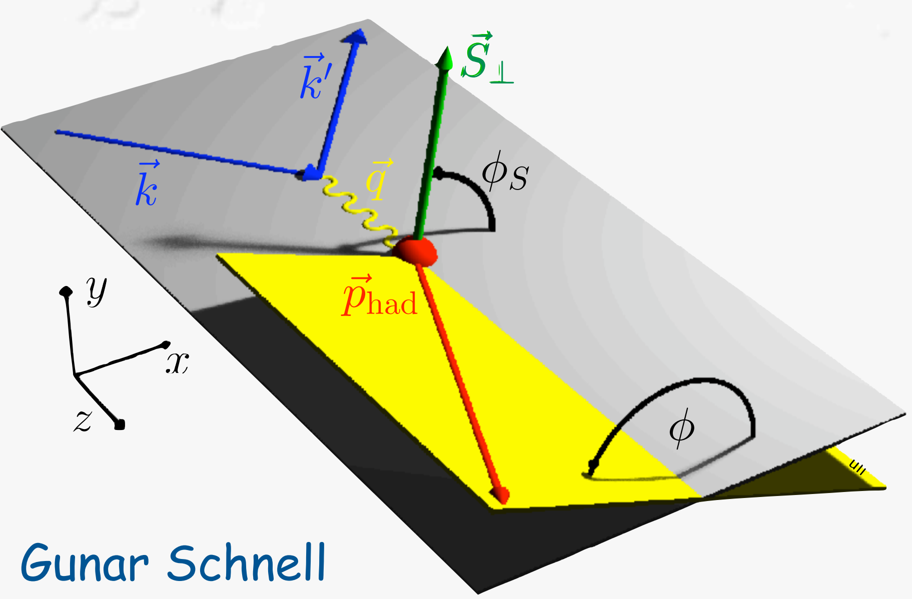
σ_{XY}: X = **Beam**, Y = **Target**

Polarization



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$$
\begin{aligned}
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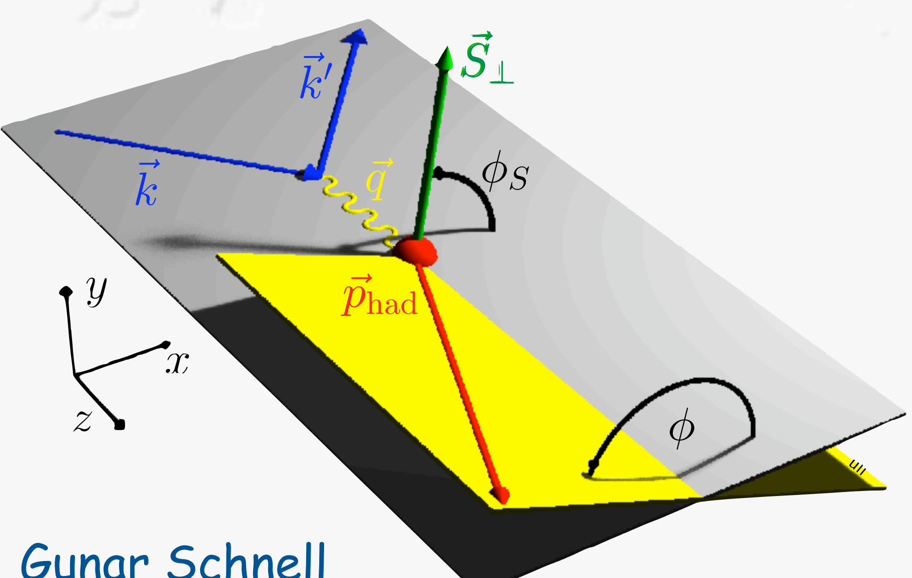
& + S_L \left\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^{7}_{LL} \right] \right\} \\
& + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^{8}_{UT} + \sin(\phi + \phi_S) \, d\sigma^{9}_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right. \\
& \quad + \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \quad \left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

σ_{XY}

Beam (X) **Target** (Y)

Polarization



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

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

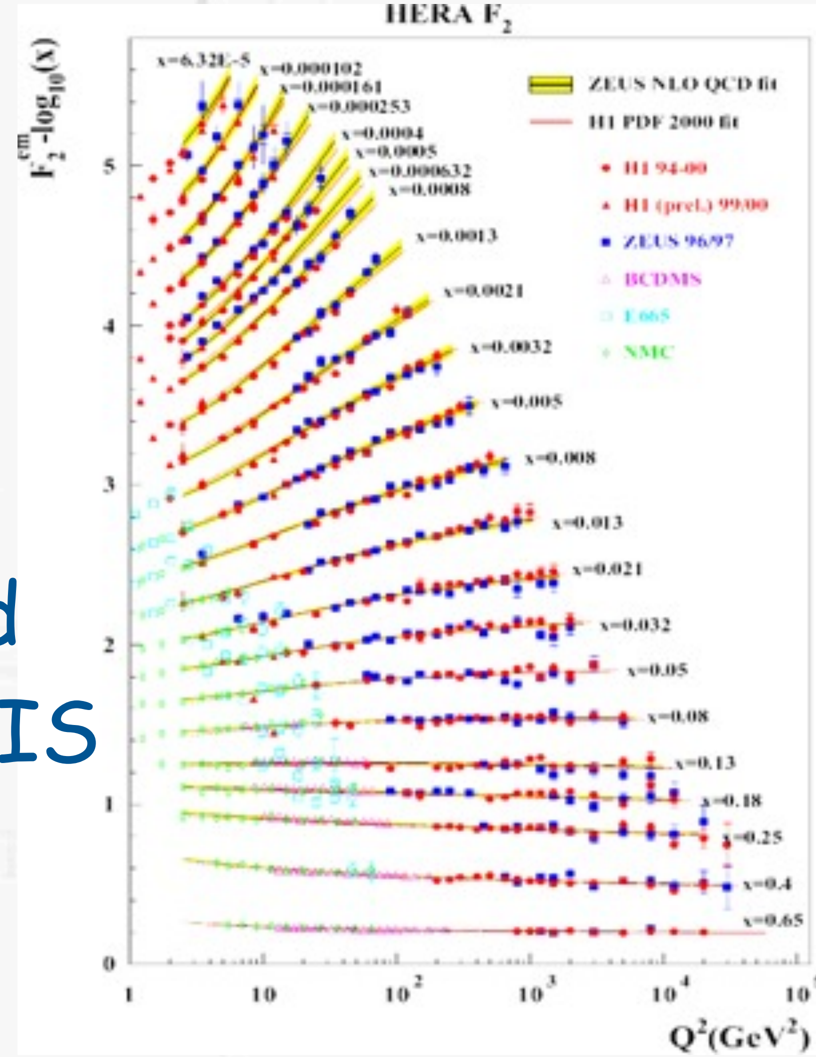
Bacchetta et al., JHEP 0702 (2007) 093

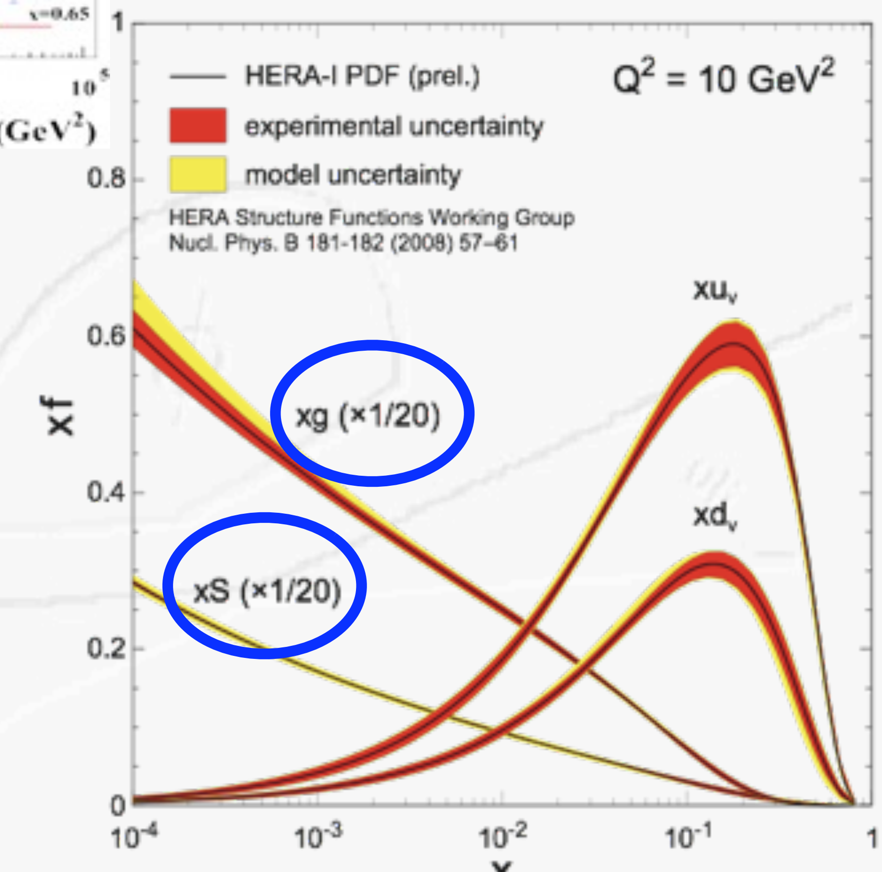
"Trento Conventions", Phys. Rev. D 70 (2004) 117504

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

Momentum density

- plenty of data available
- but mainly for integrated version of f_1 from incl. DIS





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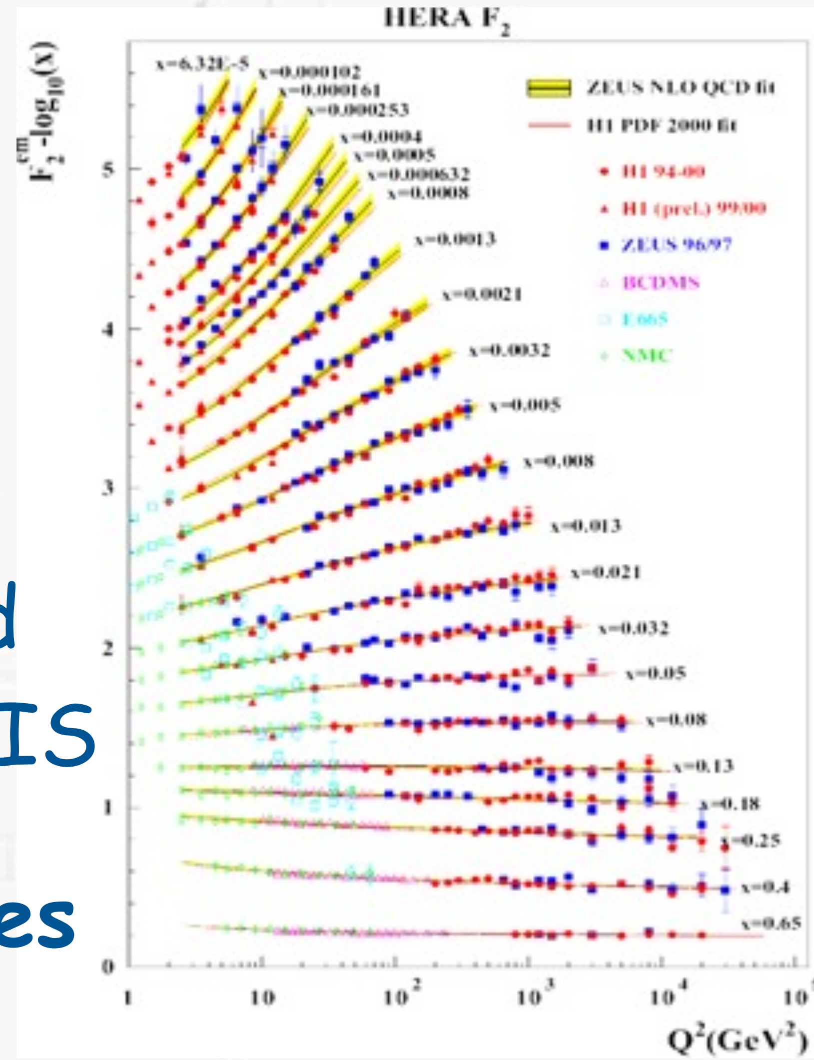
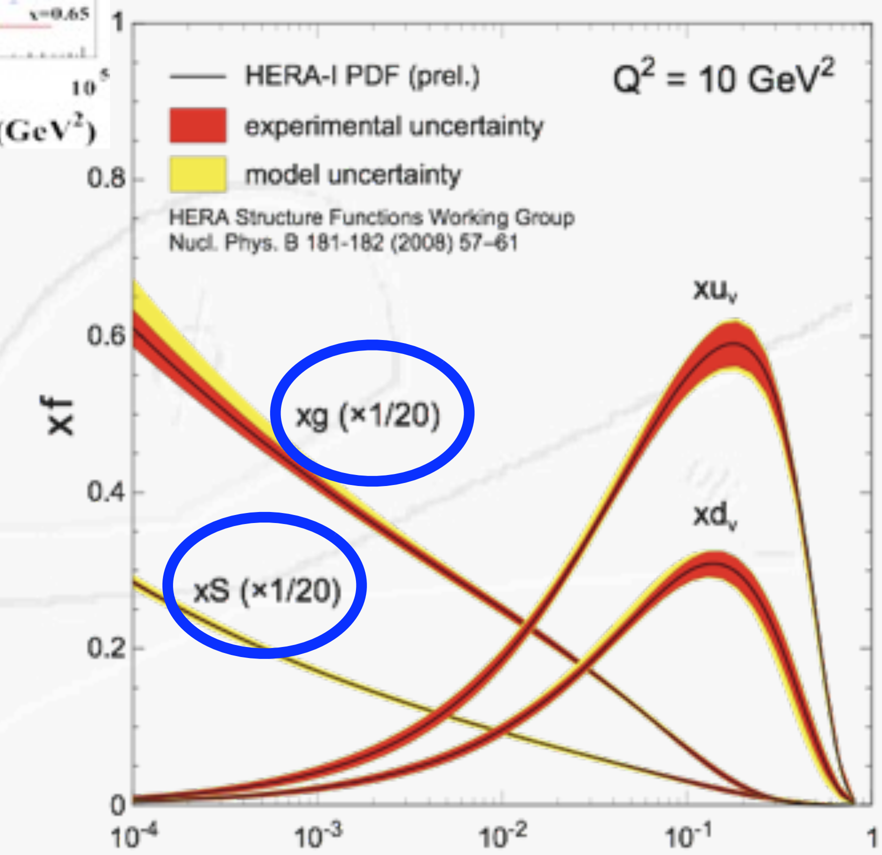
Momentum density

- plenty of data available
- but mainly for integrated version of f_1 from incl. DIS
- **all azimuthal asymmetries involve unintegrated f_1** (at least) in denominator!





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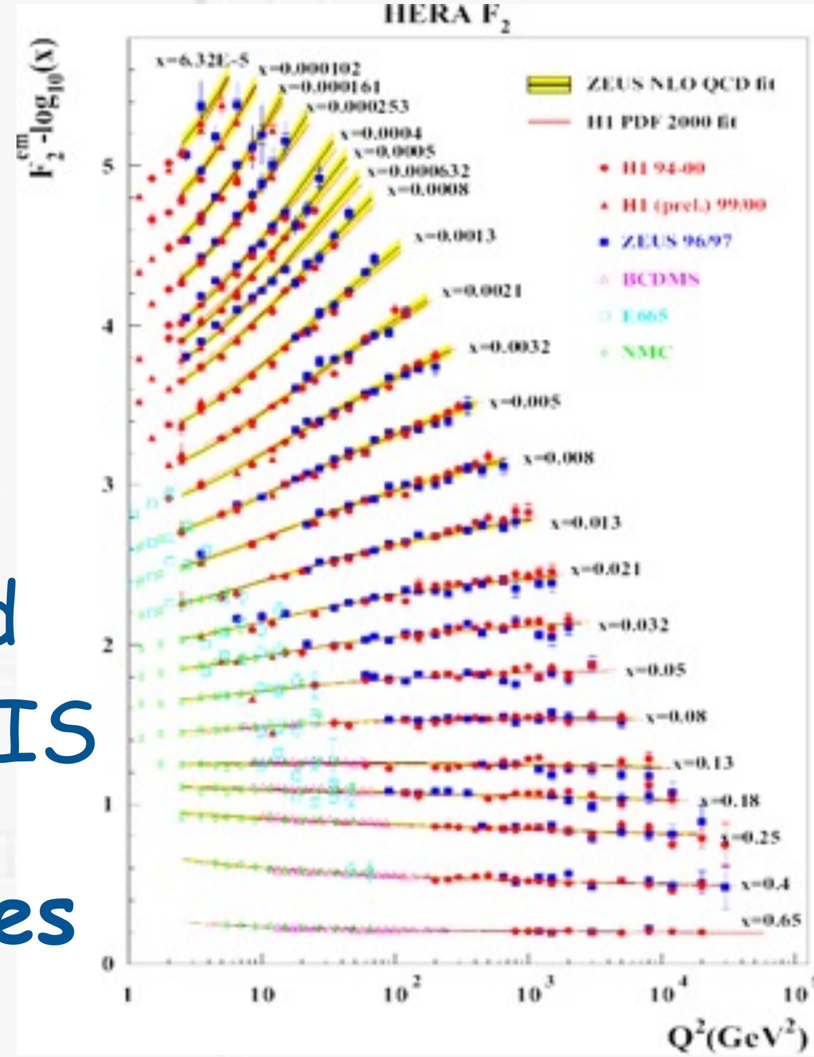
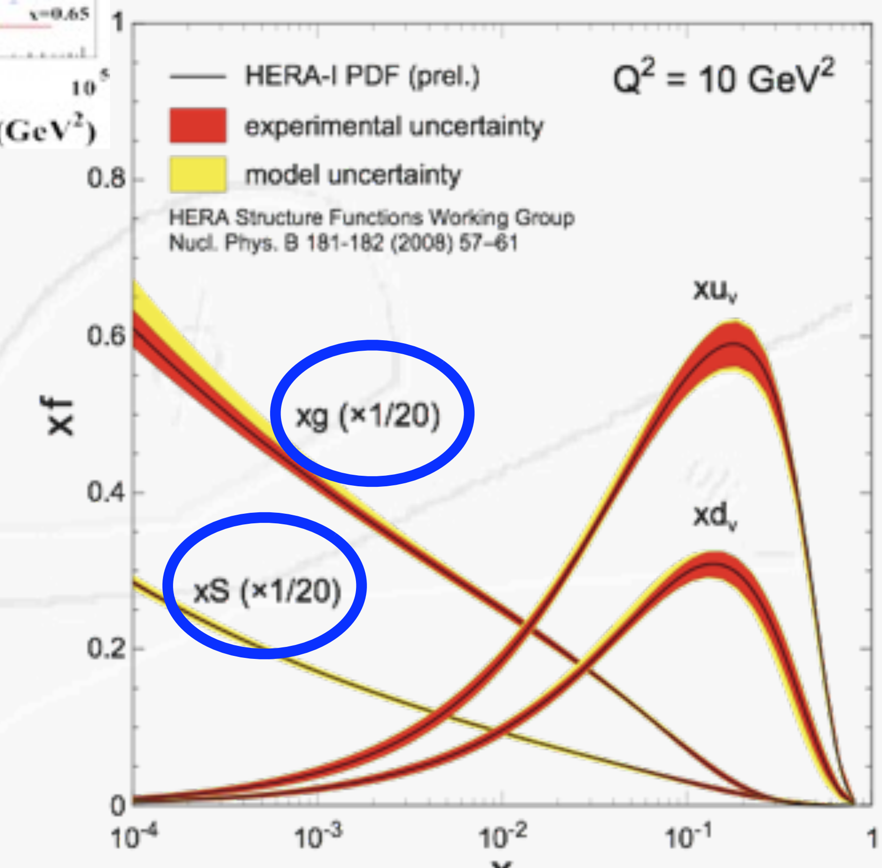
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Momentum density



- plenty of data available
- but mainly for integrated version of f_1 from incl. DIS
- **all azimuthal asymmetries involve unintegrated f_1** (at least) in denominator!
- **need hadron multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$**



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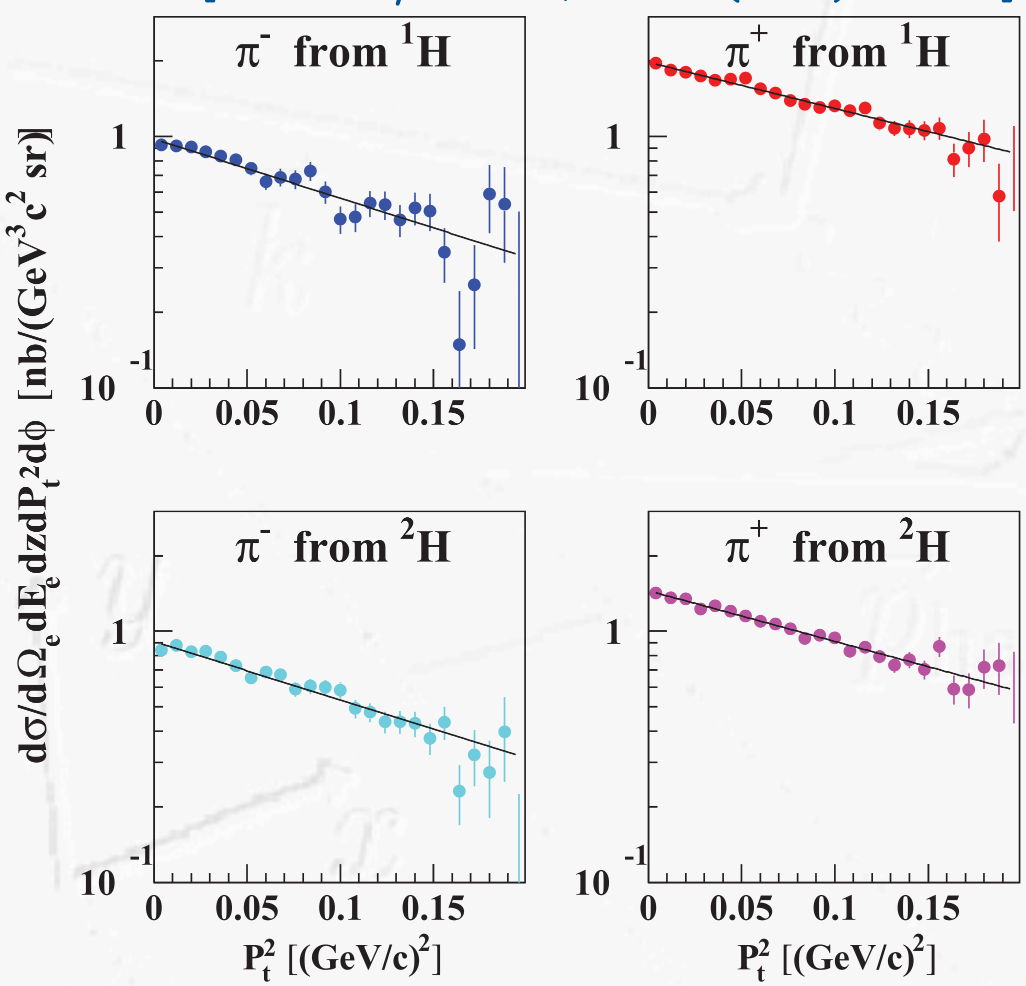
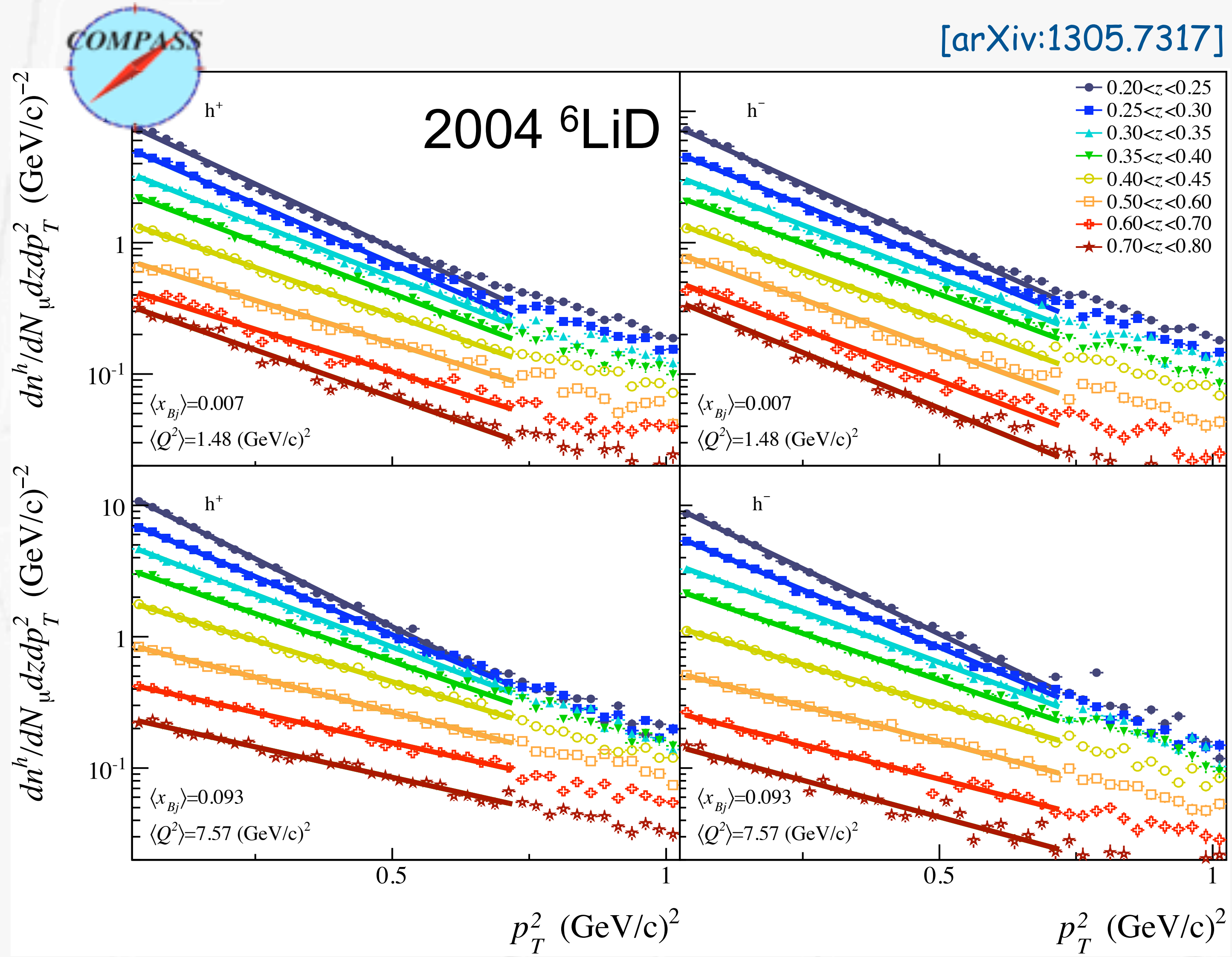
Disentangle z and $P_{h\perp}$-dependence

[R. Asaturyan et al., PRC 85 (2012) 015202]



[arXiv:1305.7317]



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

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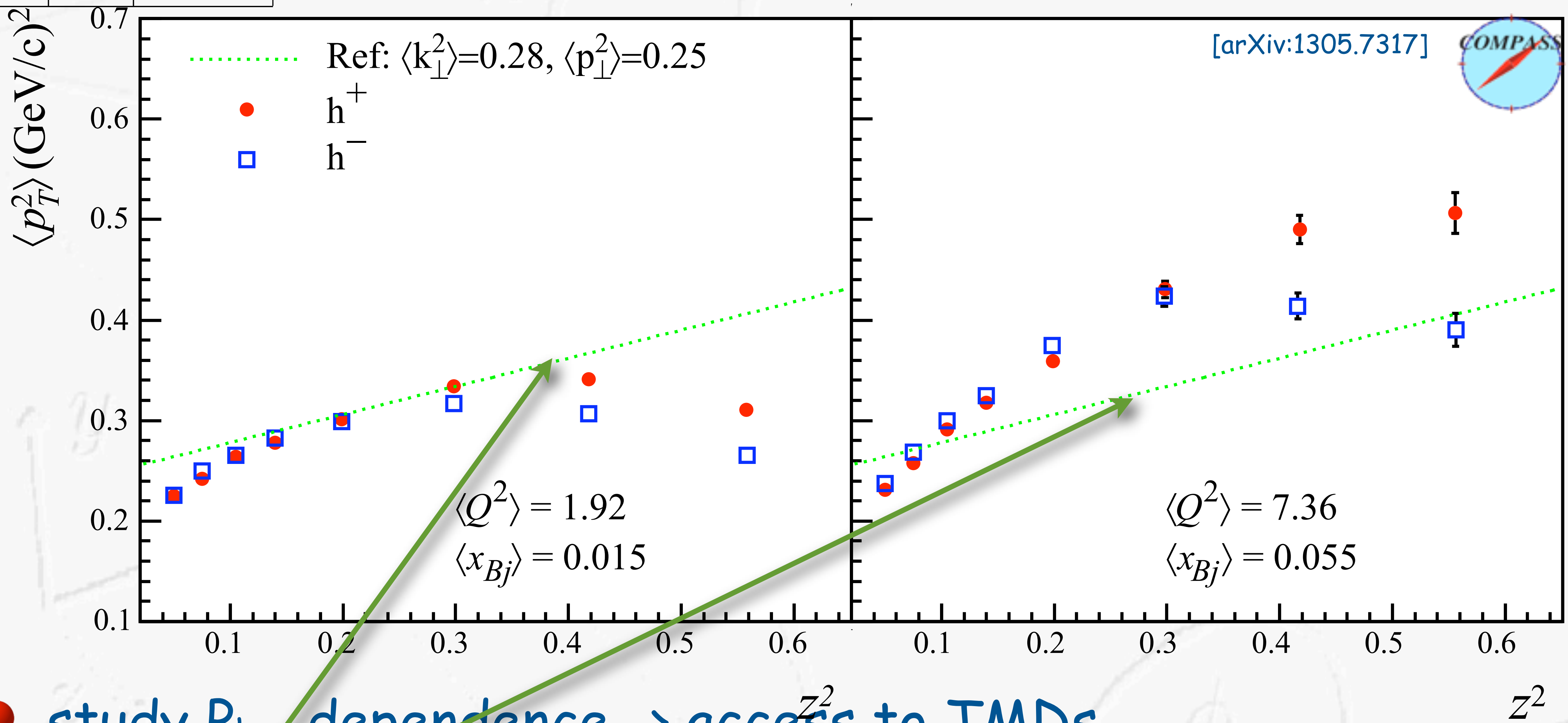

- study $P_{h\perp}$-dependence -> access to TMDs
- constant average (fragmentation) $p_\perp$ excluded

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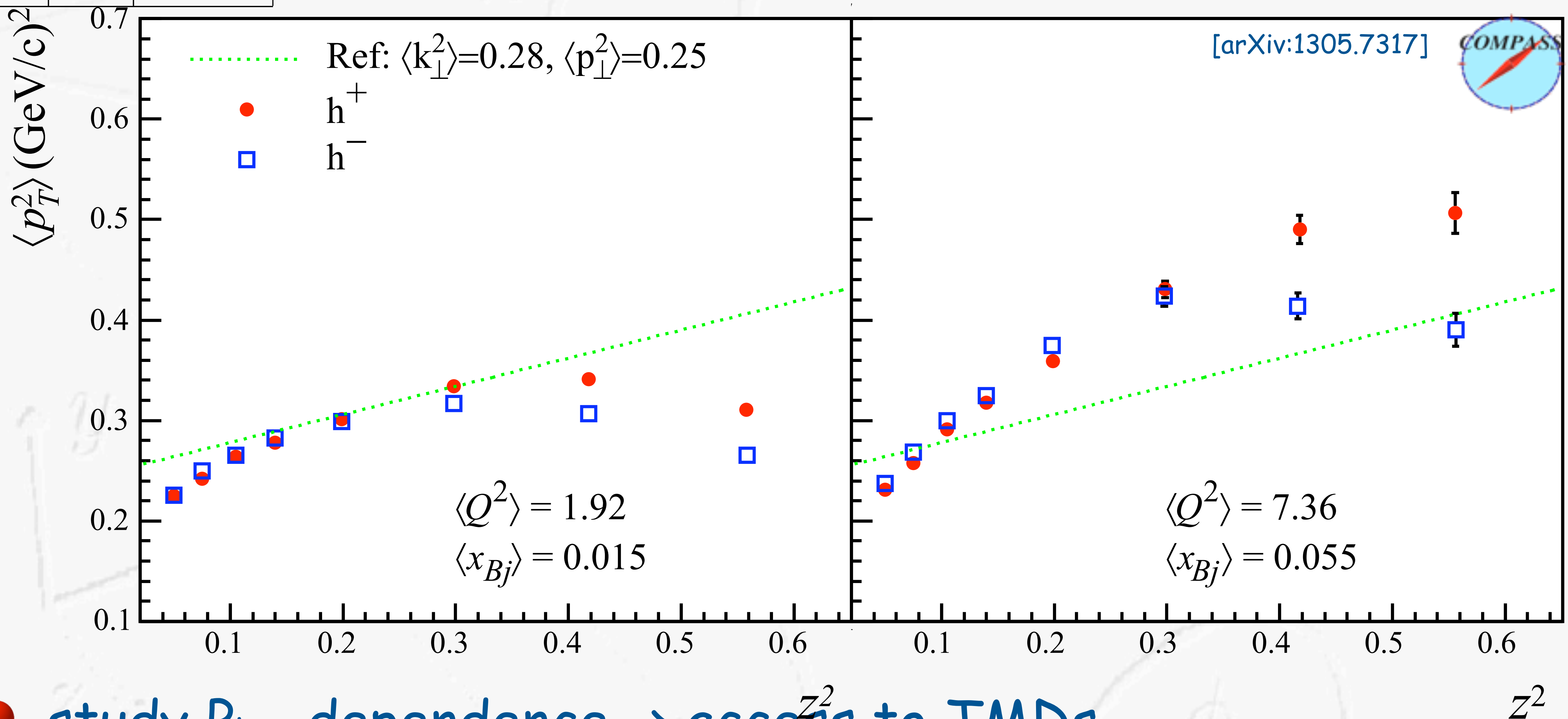


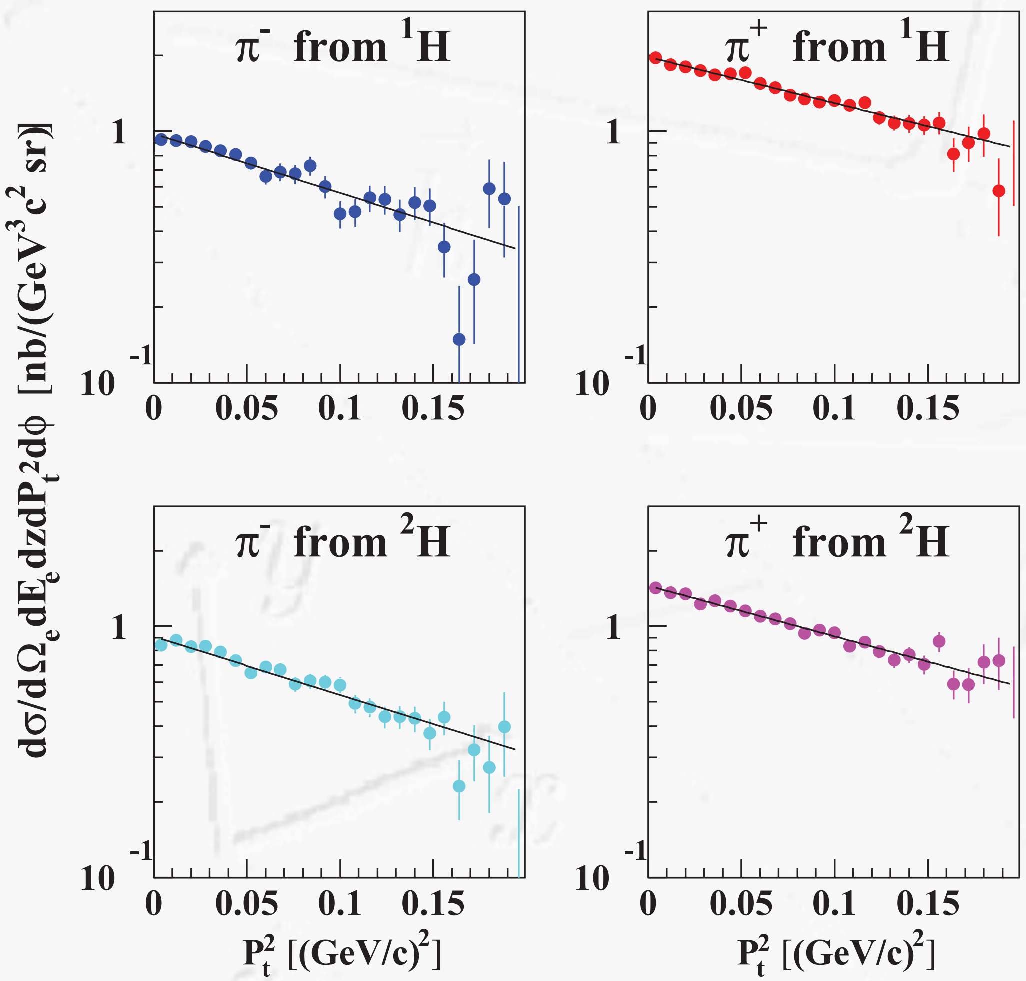
- study $P_{h\perp}$-dependence -> access to TMDs
- constant average (fragmentation) $p_\perp$ excluded
- difference in h^+ and h^- behavior ☛ flavor dependence

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

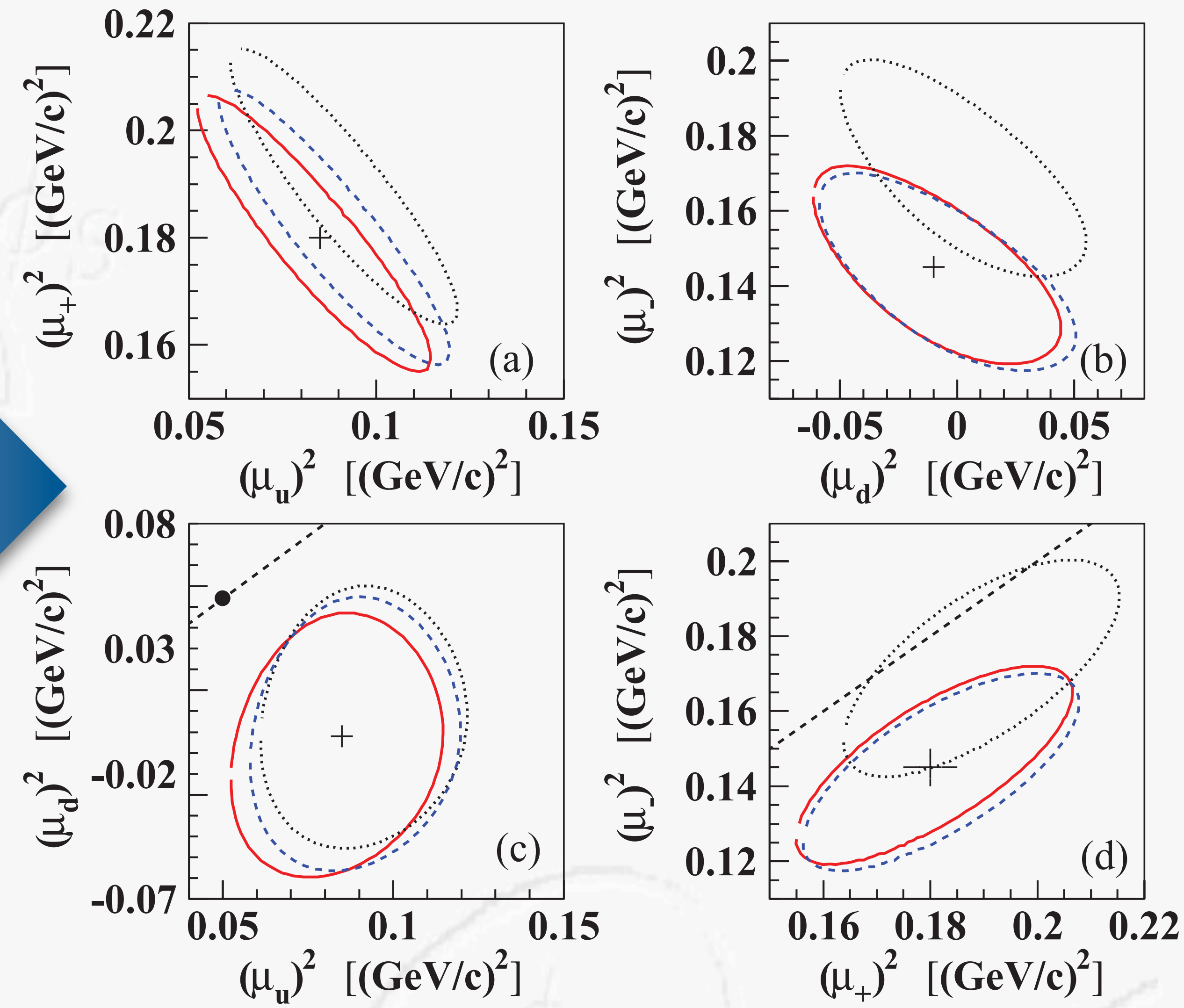
Flavor dependence

Jefferson Lab Hall C

[R. Asaturyan et al., PRC 85 (2012) 015202]



Gaussian width



Gaussian widths of

D_1^{fav} : μ_+

D_1^{dis} : μ_-

f_1^u : μ_u

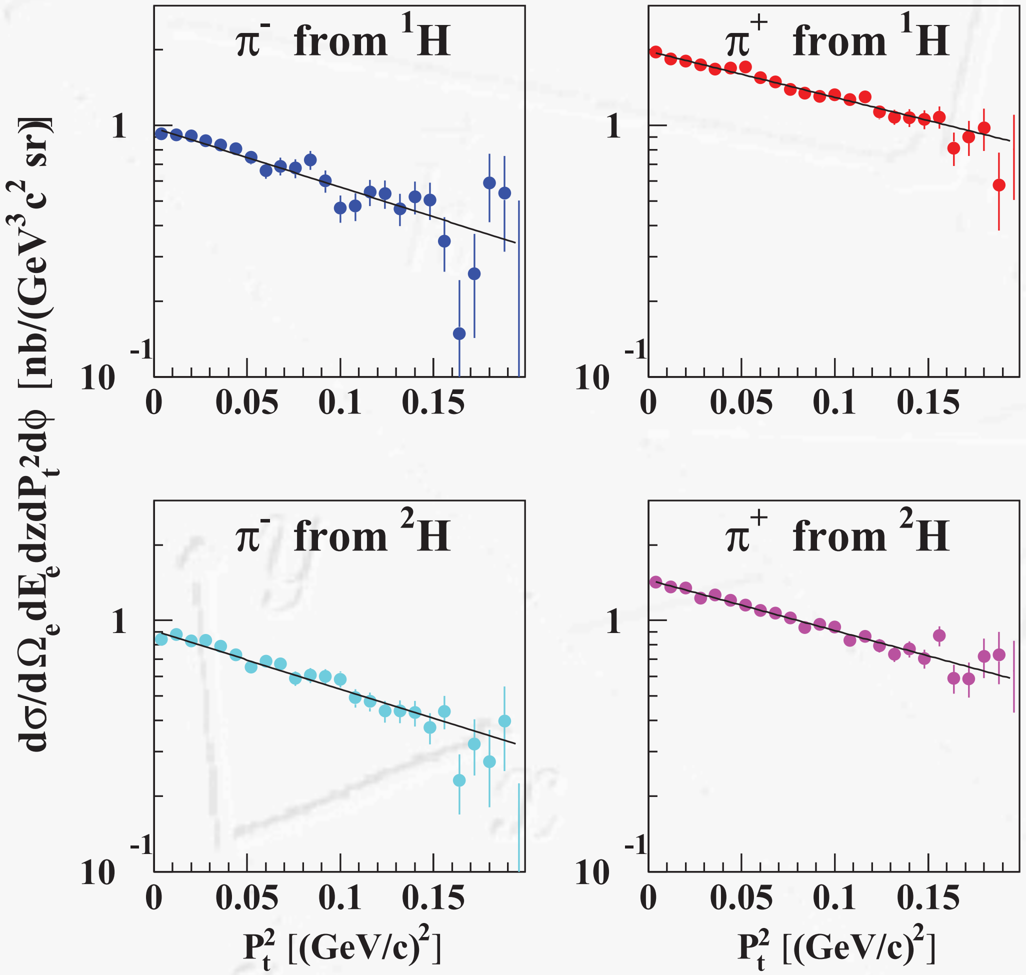
f_1^d : μ_d

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

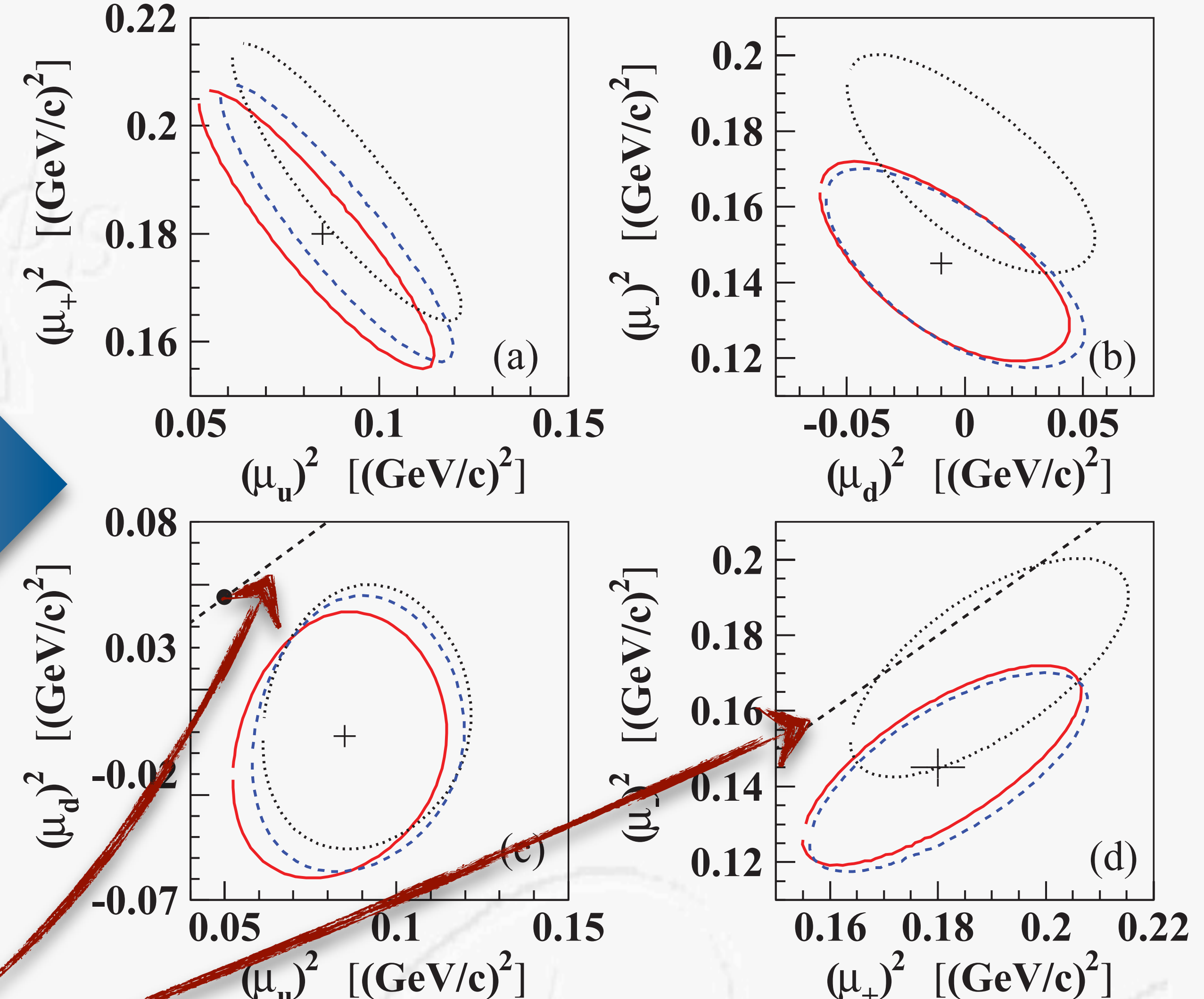
Flavor dependence

Jefferson Lab Hall C

[R. Asaturyan et al., PRC 85 (2012) 015202]



Gaussian width



equal widths for
u and d quarks disfavored

Gaussian widths of
$D_1^{\rm fav}$: μ_+
$D_1^{\rm dis}$: μ_-
f_1^u : μ_u
f_1^d : μ_d

	U	L	T
U	f_1		$h_1^\perp$
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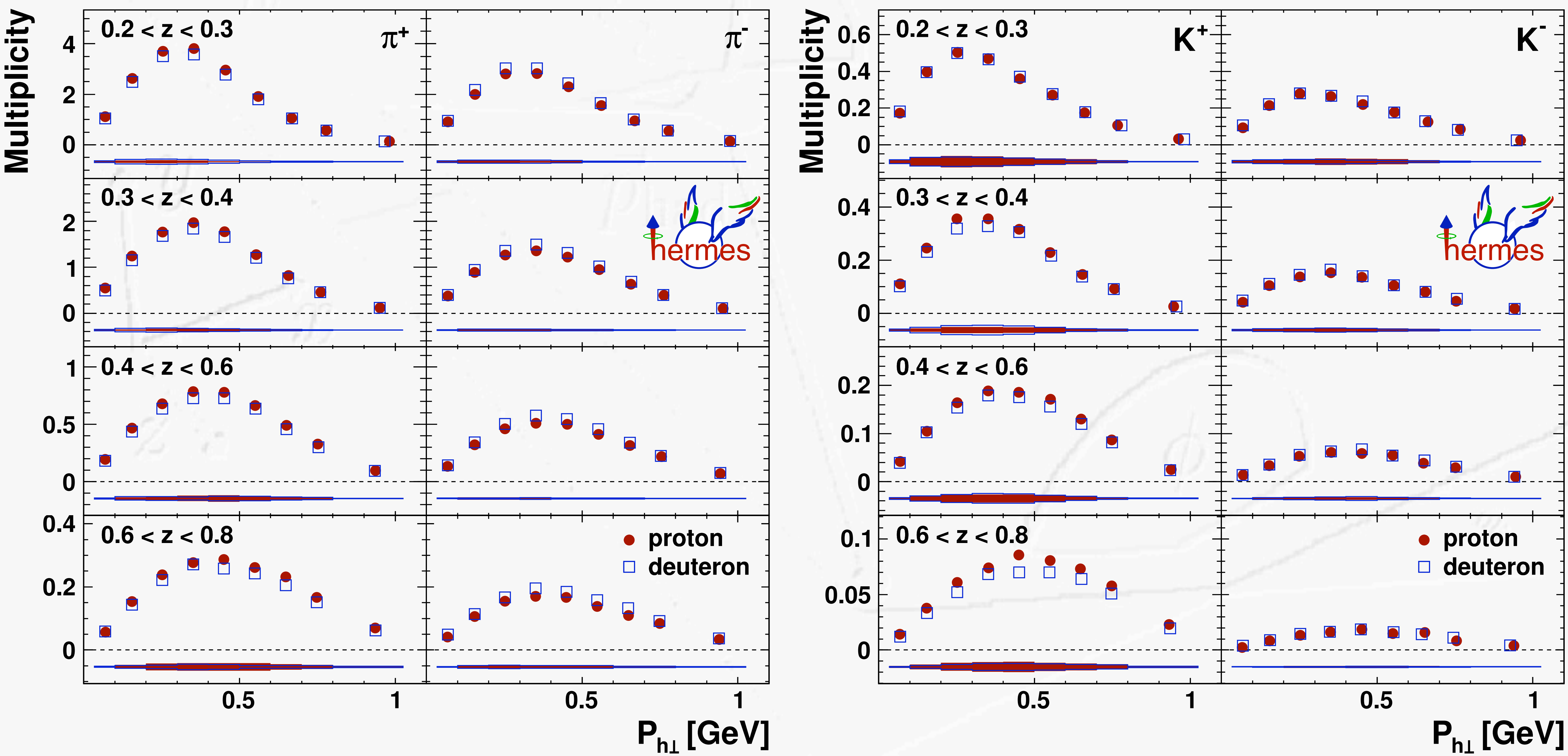
Flavor dependence

- further flavor information via target variation and hadron ID

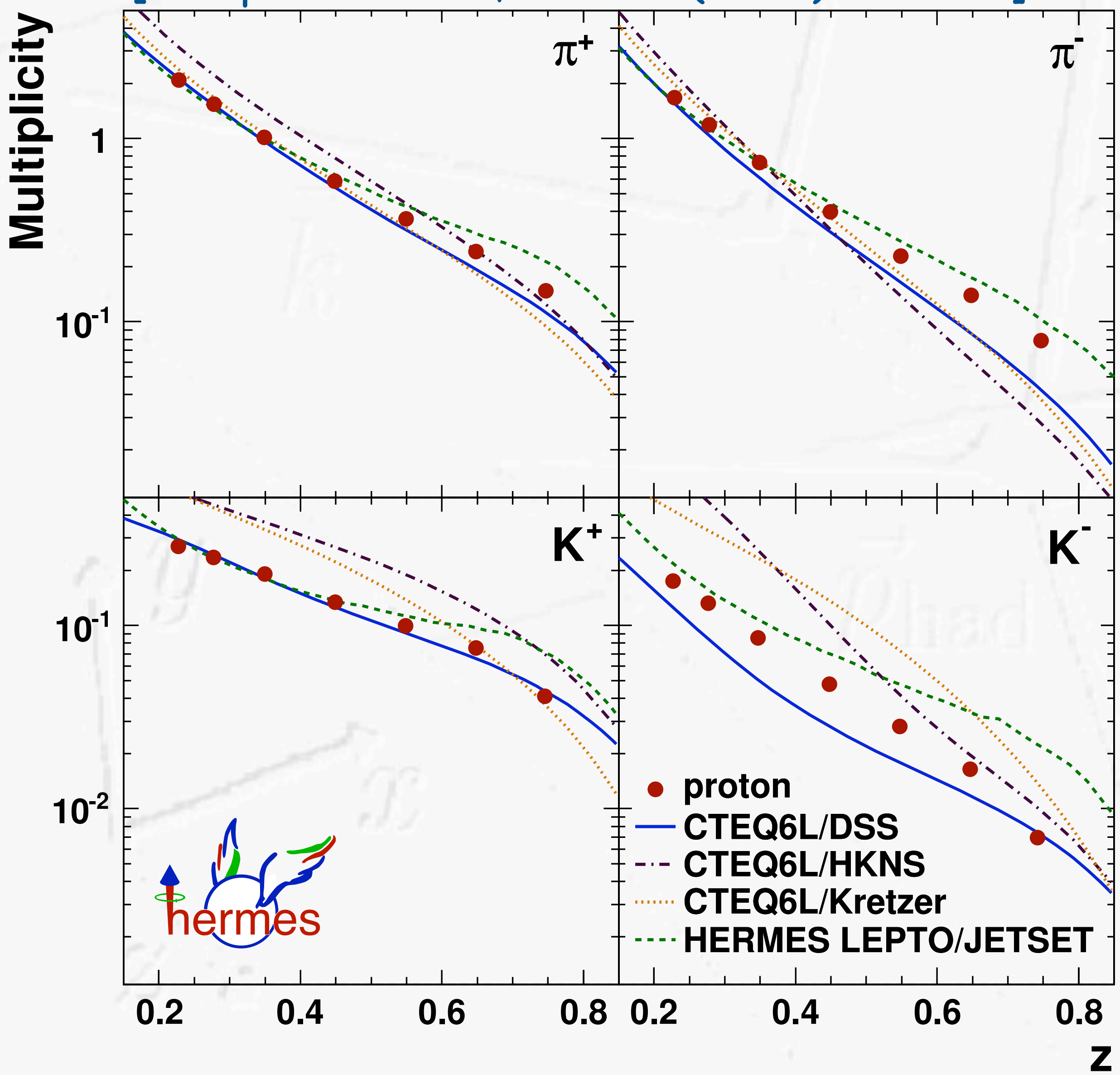
[Airapetian et al., PRD 87 (2013) 074029]

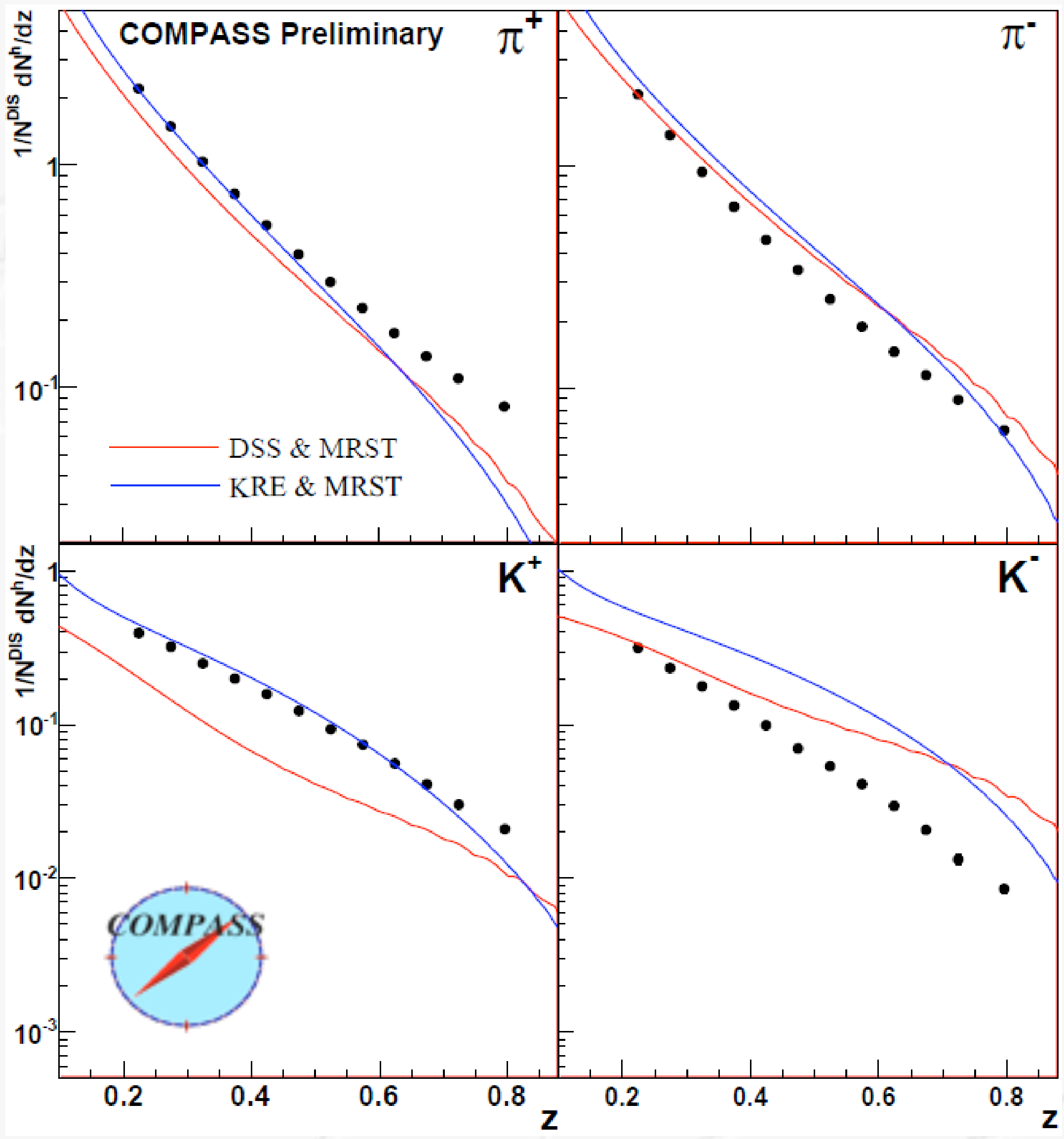


Multiplicities

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dx\,dy\,dz\,dP_{h\perp}^2} \propto \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

[Airapetian et al., PRD 87 (2013) 074029]





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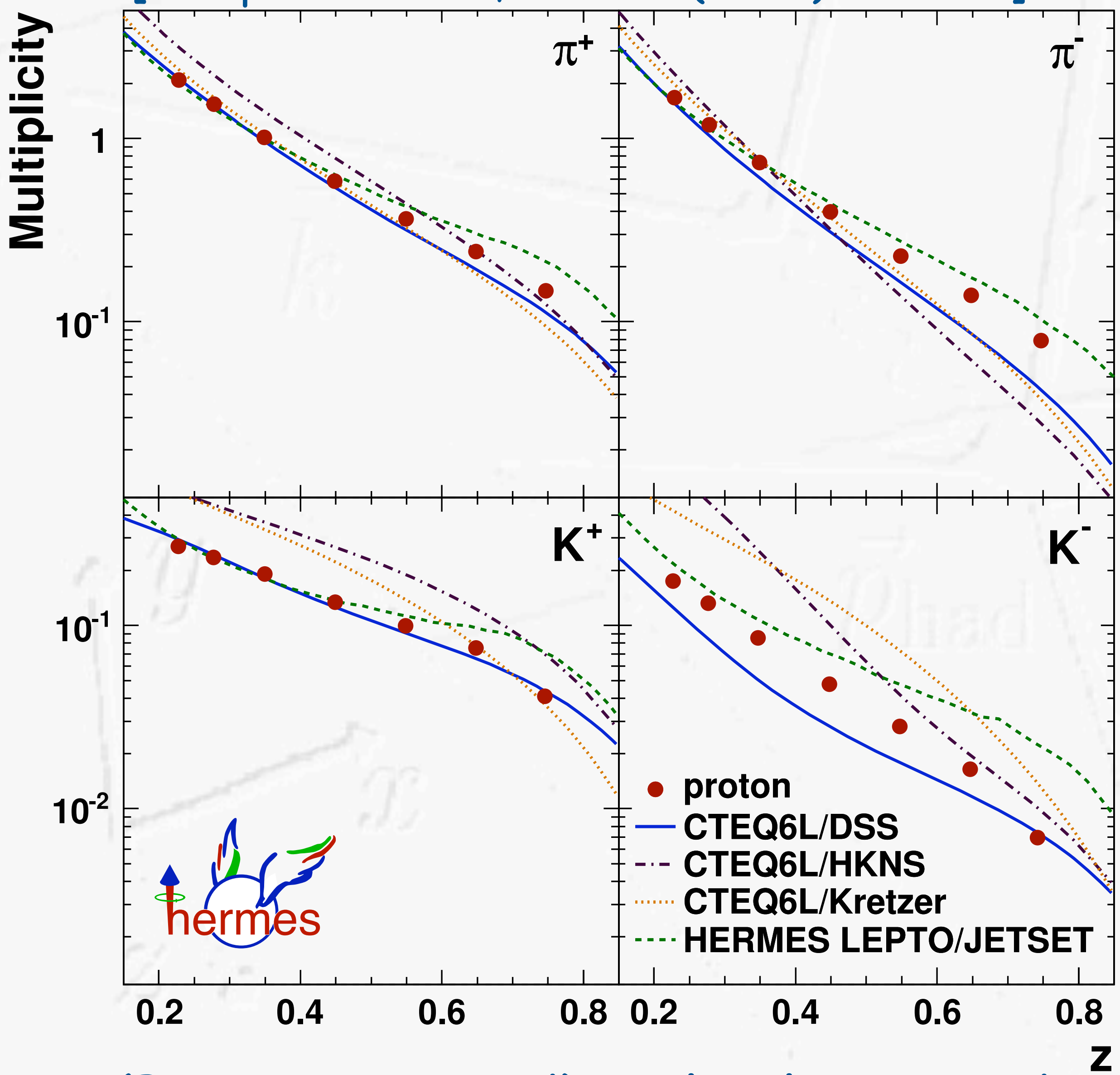

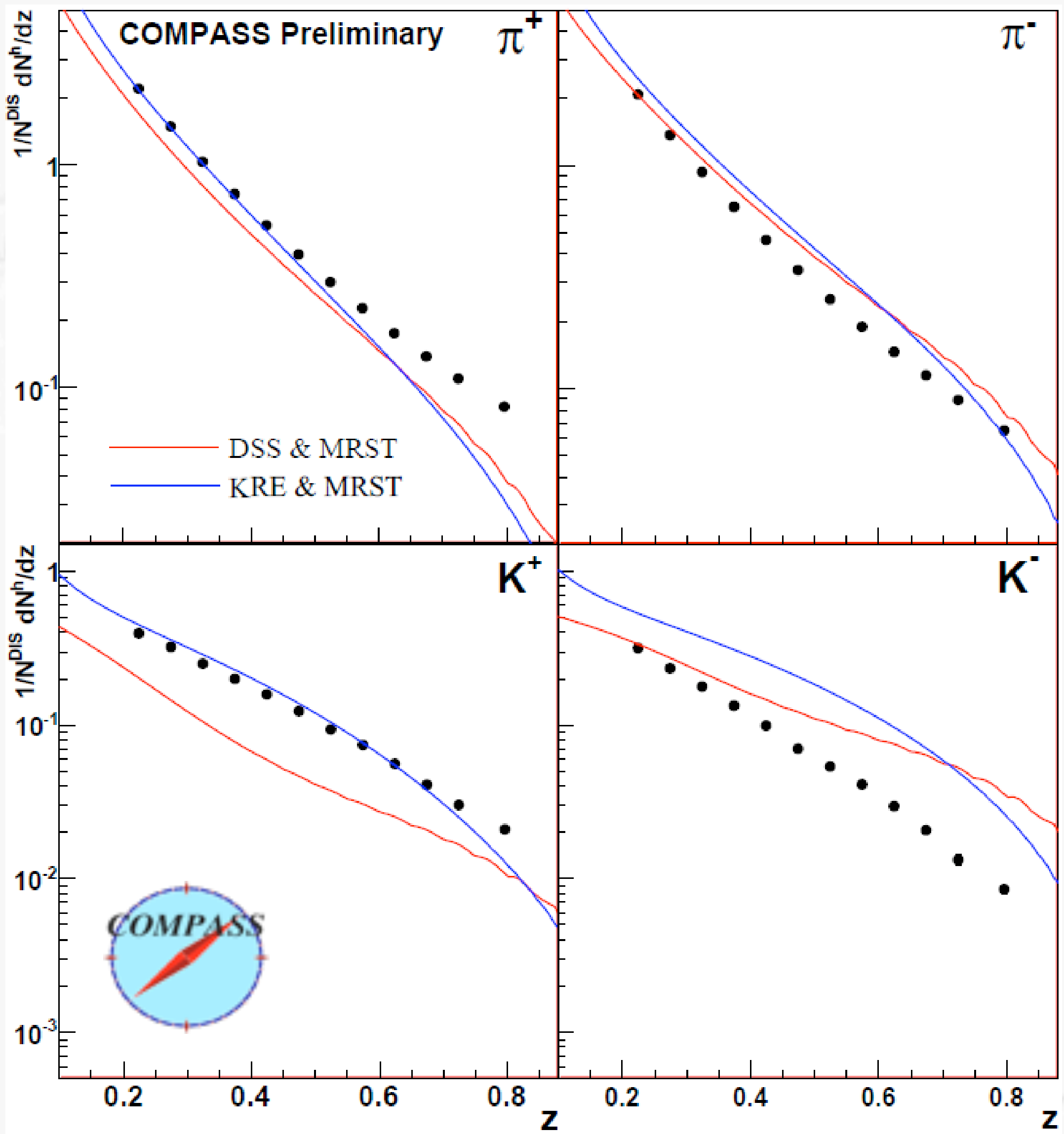

- ($P_{h\perp}$-integrated) multiplicities ideal input for FF fits and tests

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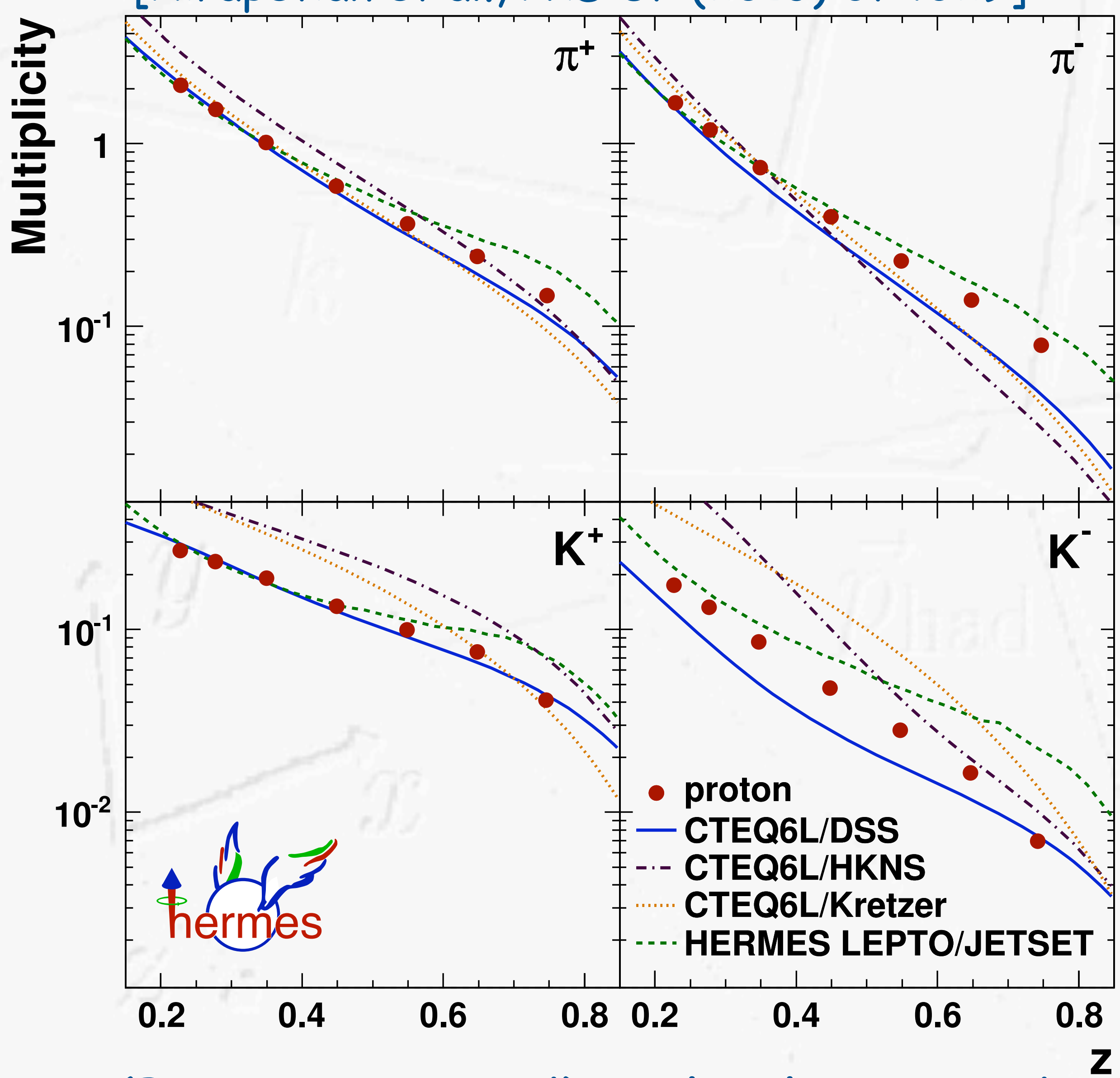

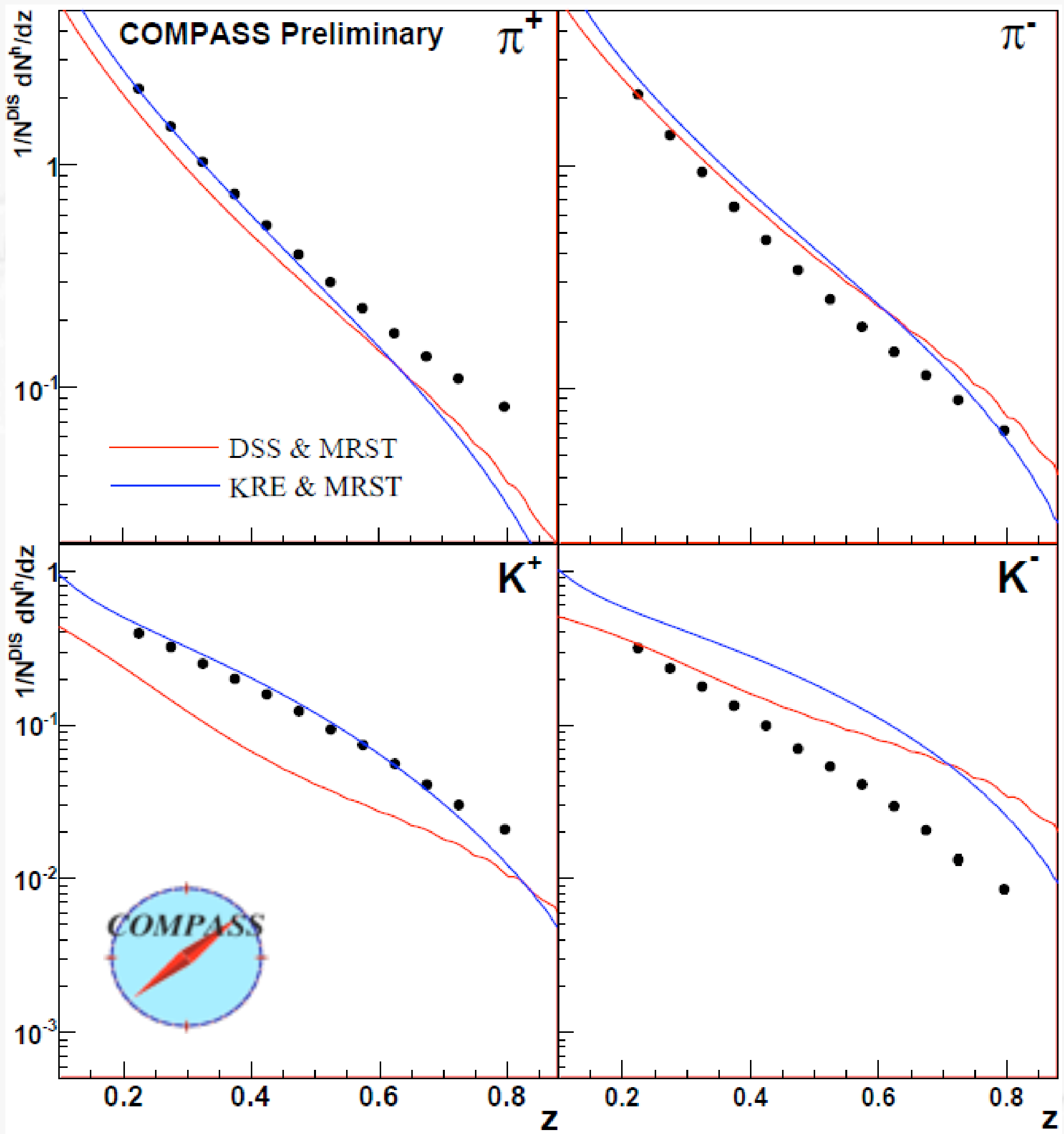

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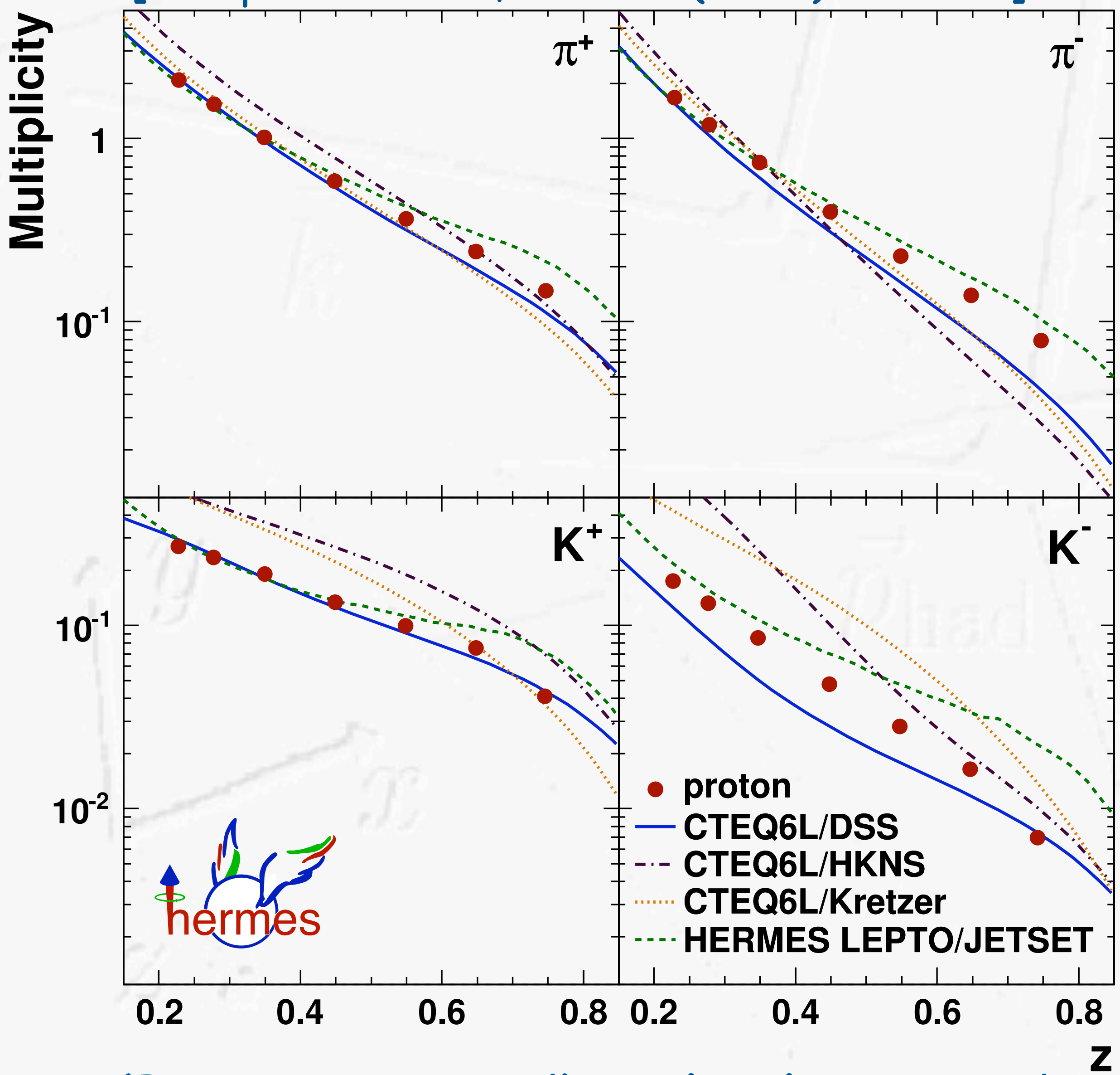

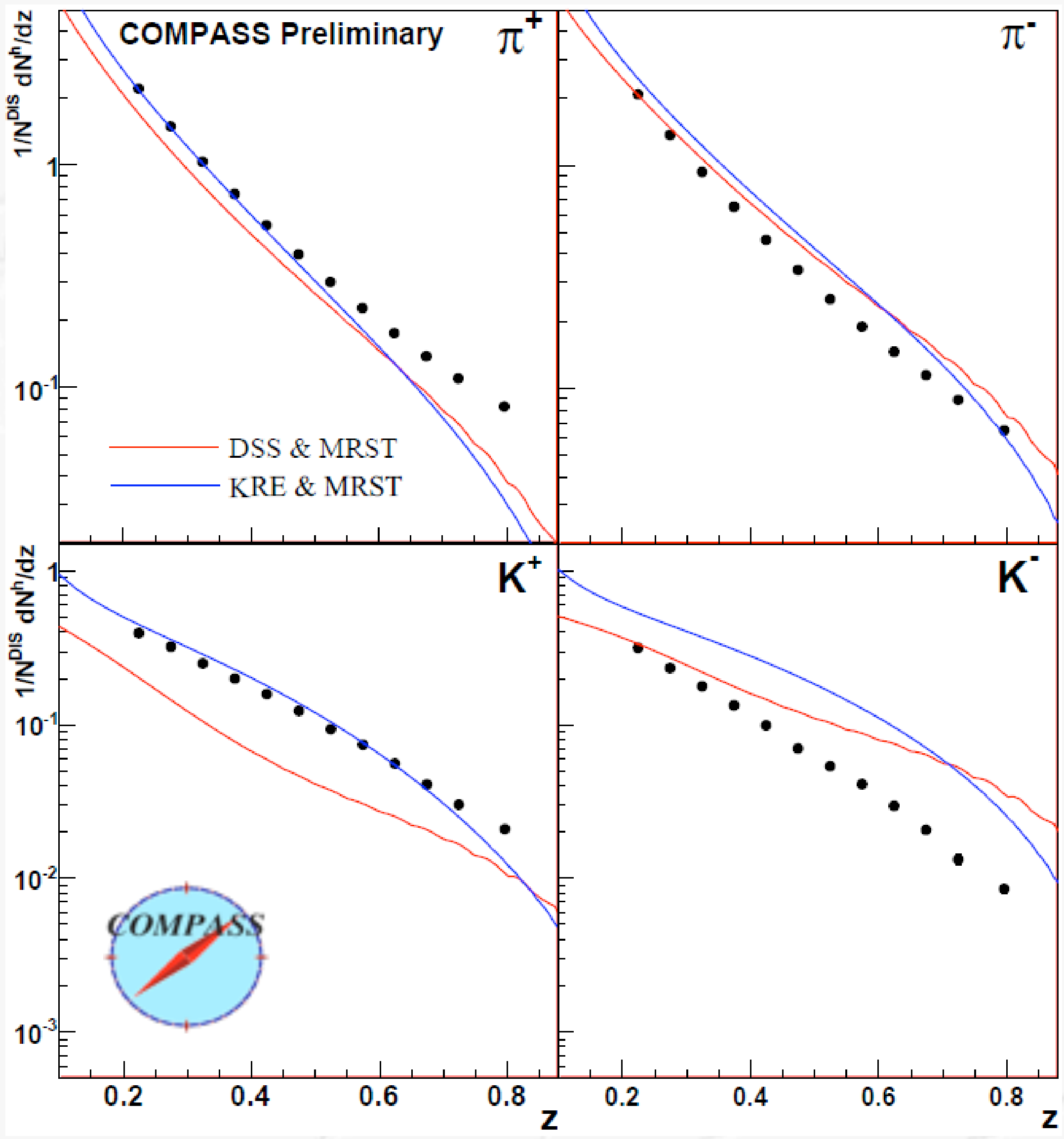

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- charge-separation unlike e^+e^- data

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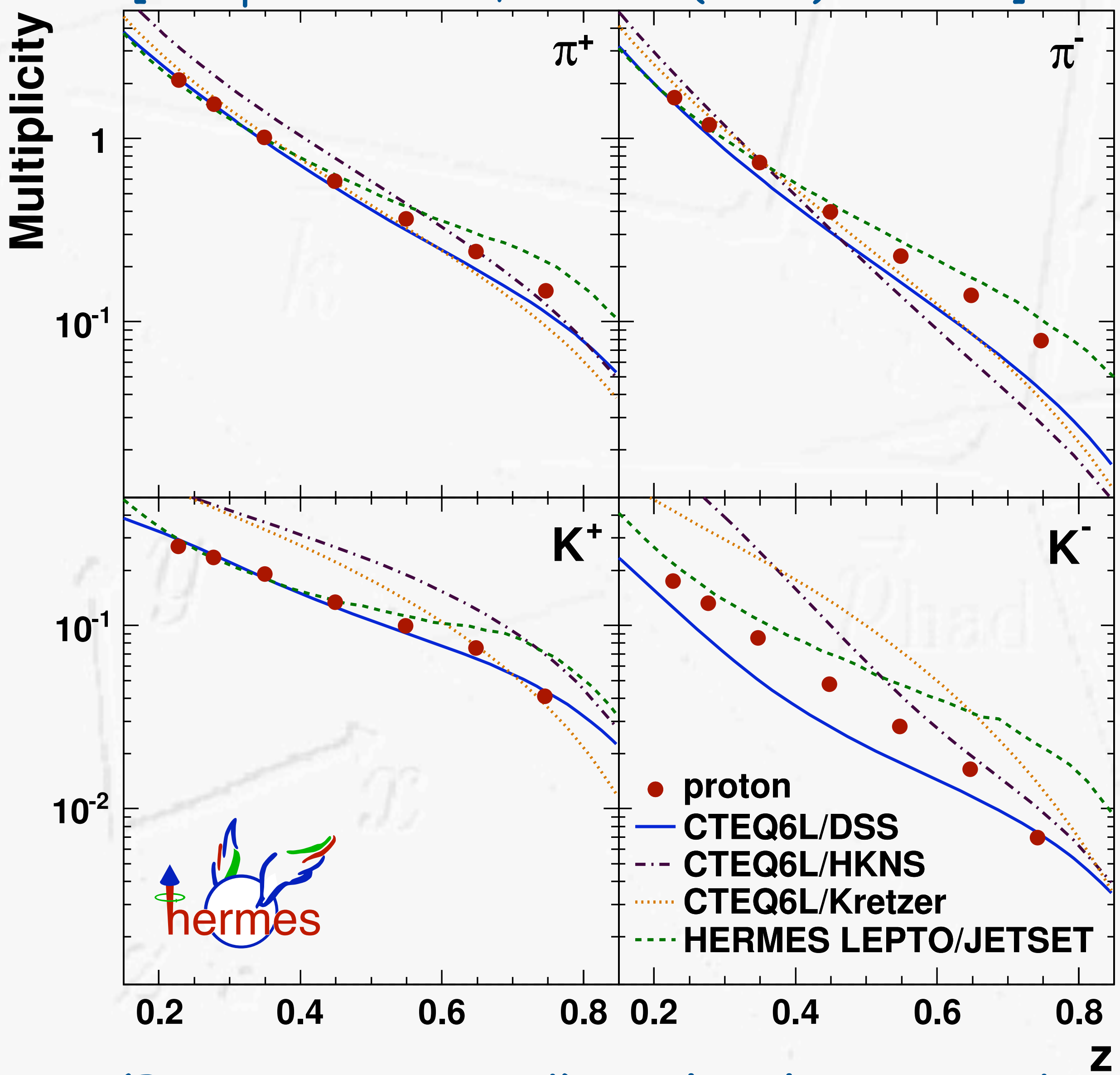
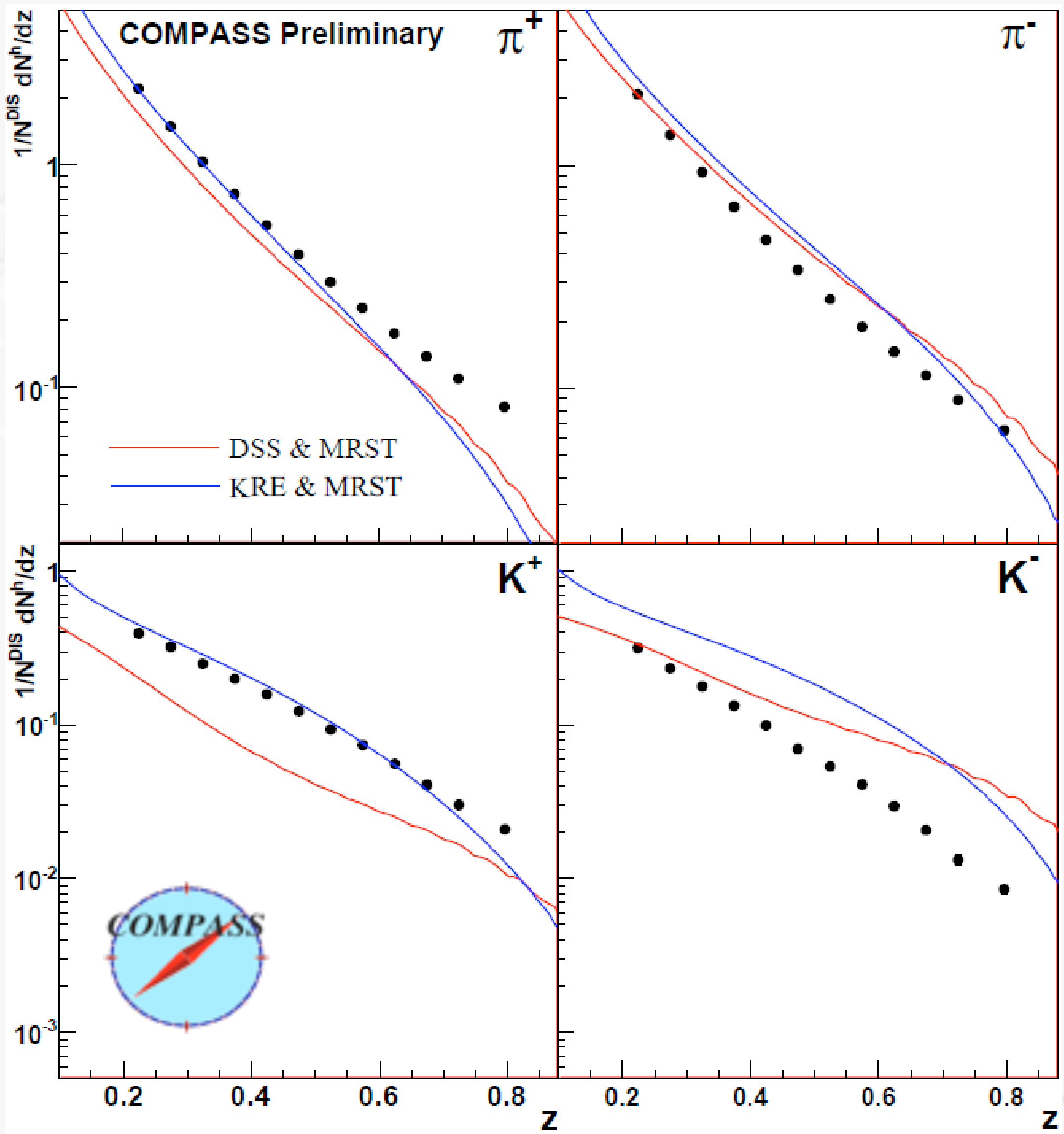
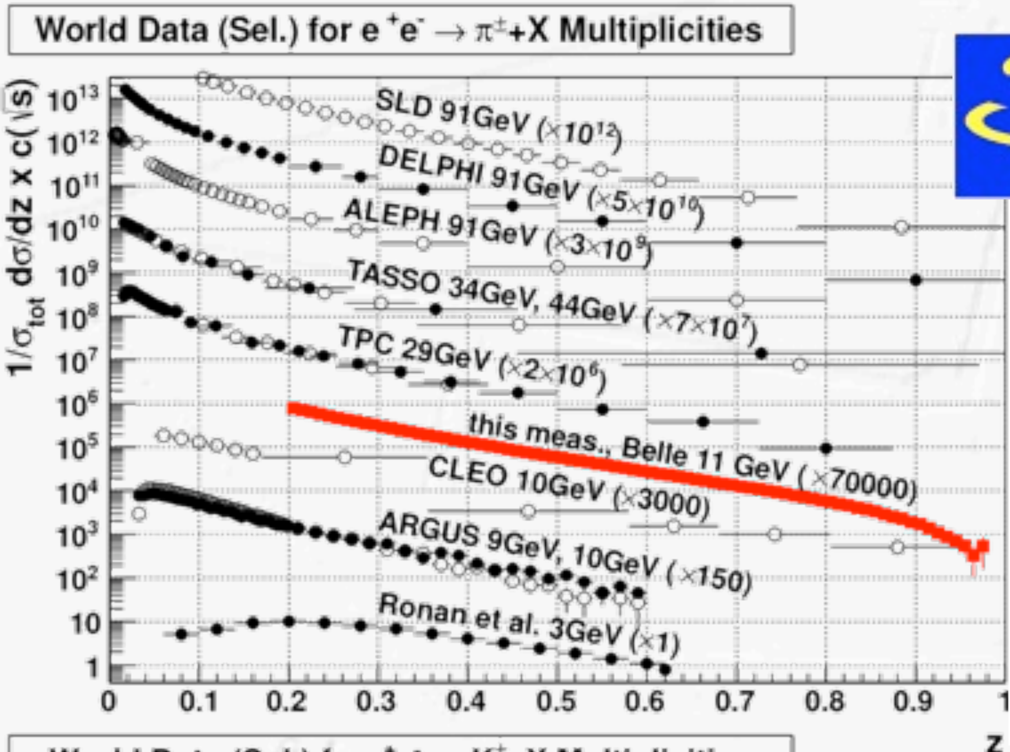
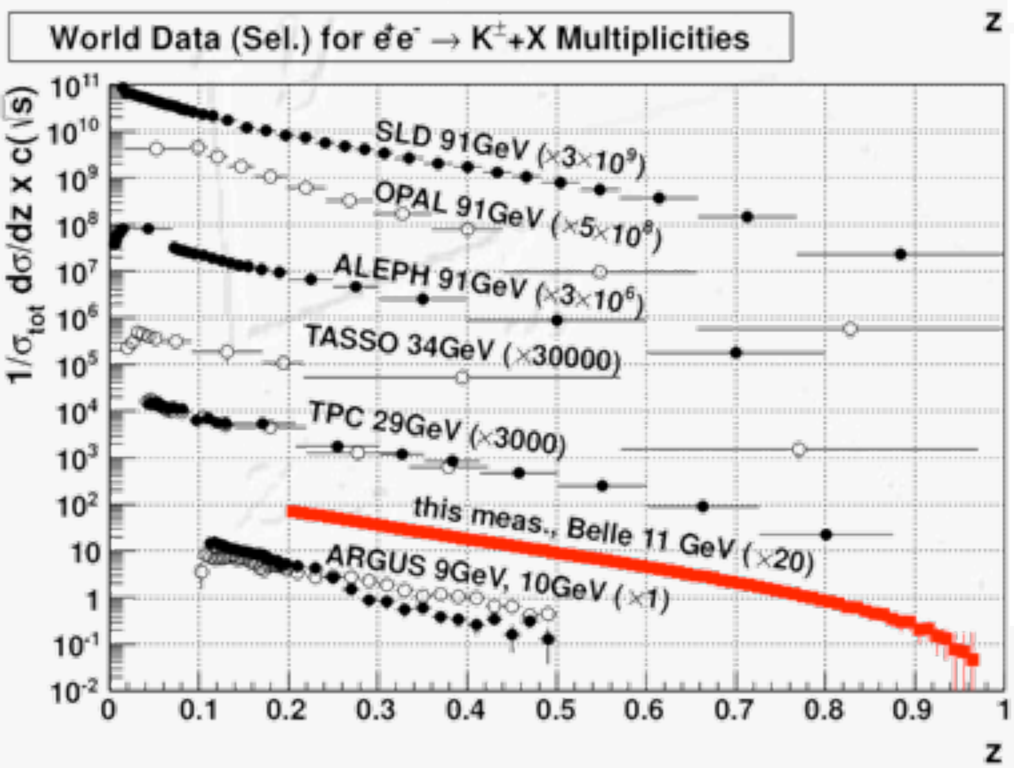




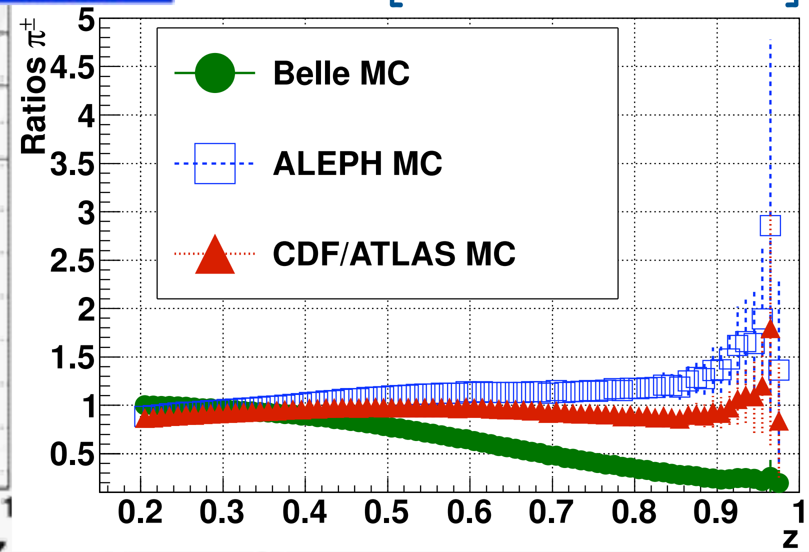
- ($P_{h\perp}$-integrated) multiplicities ideal input for FF fits and tests
- kaons difficult to describe
- charge-separation unlike e^+e^- data
- complemented by new high-precision data from e^+e^- by Belle and BaBar

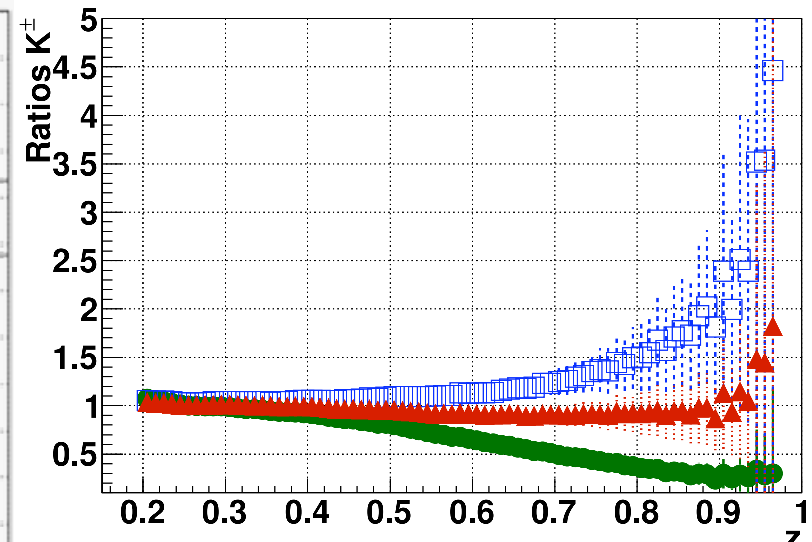
Hadron production @ B-factories



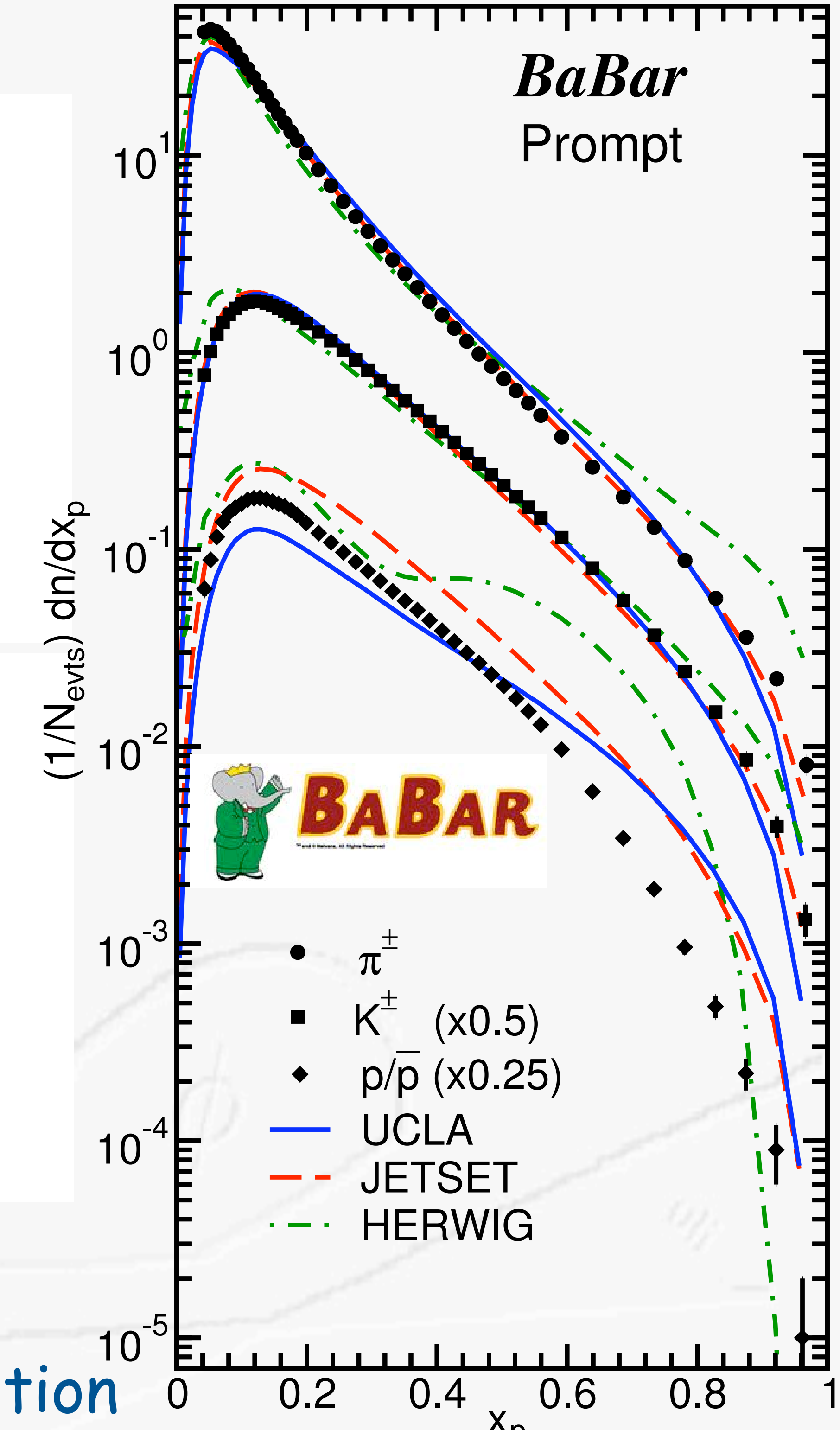


[arXiv:1301.6183]





[arXiv:1306.2895]



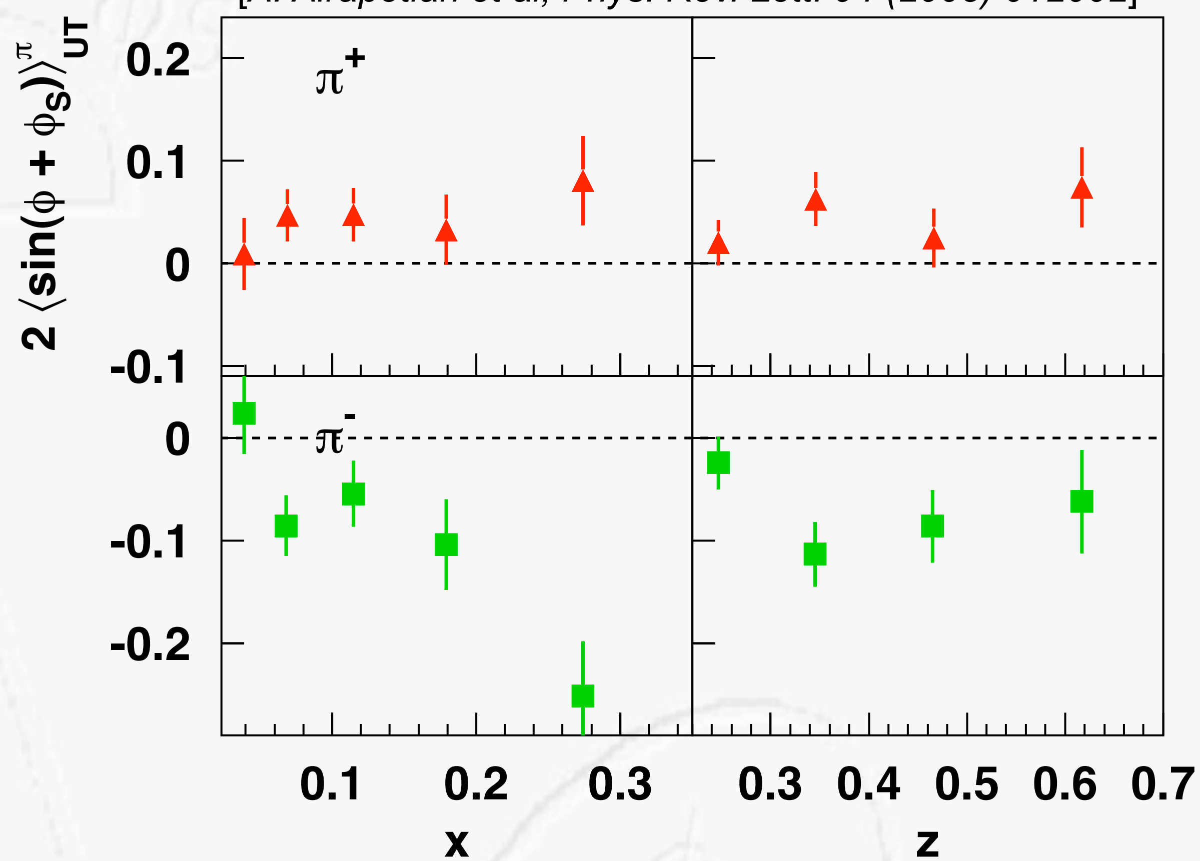
- precision measurements of hadron production
- explore z-region not probed before
- clear impact on available MC tunes

The quest for transversity

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

Transversity distribution (Collins fragmentation)

[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

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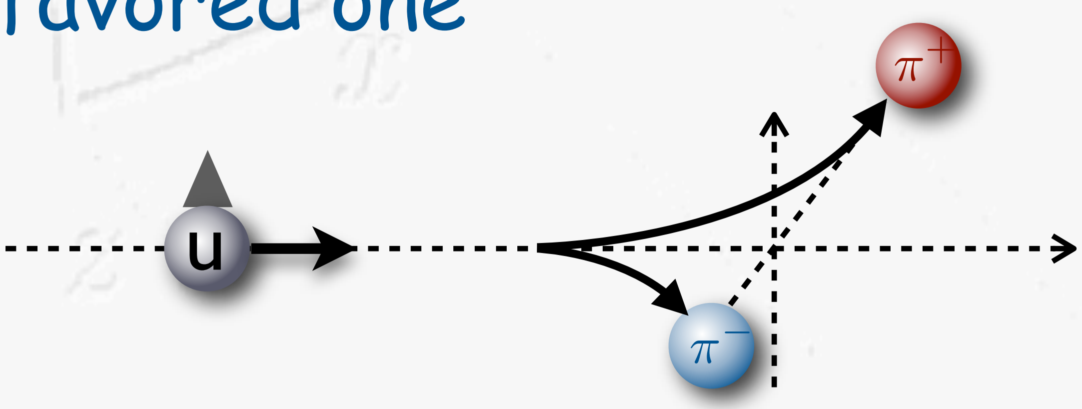
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

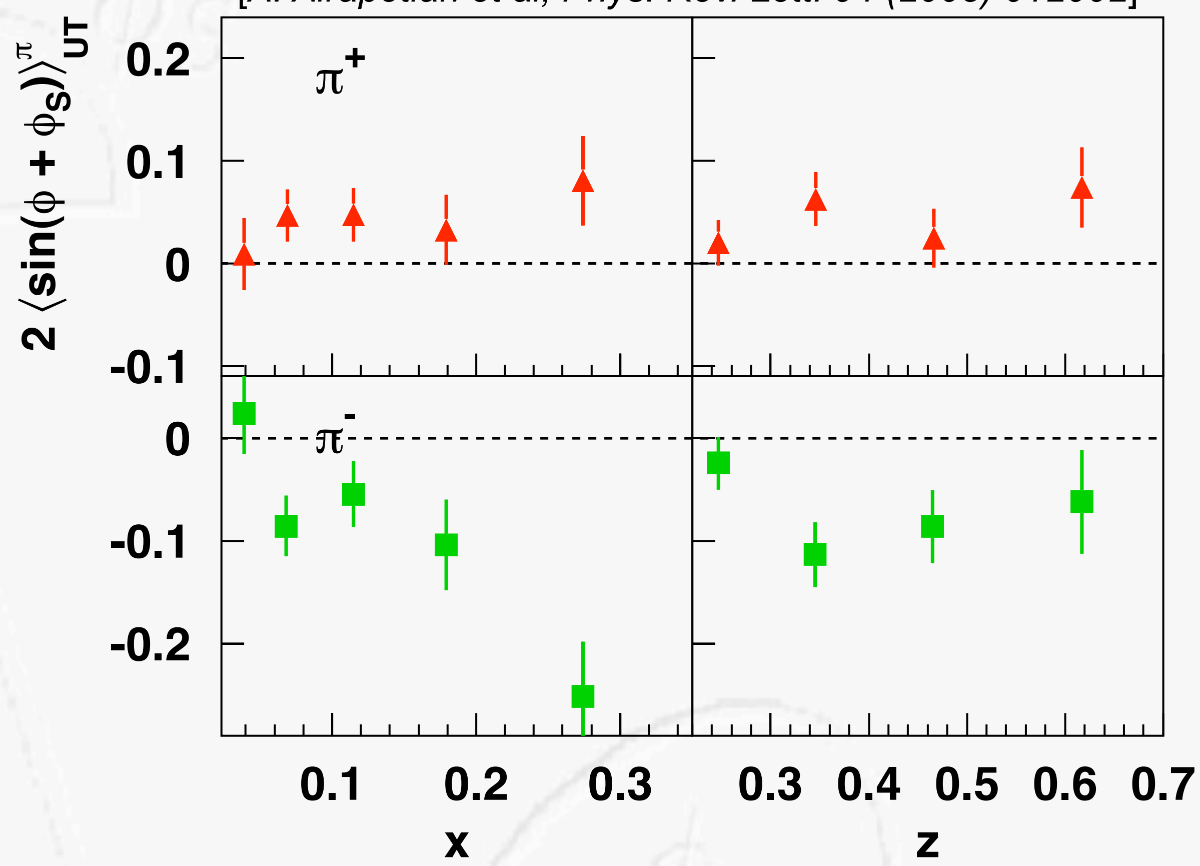
Transversity distribution (Collins fragmentation)

- 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

Collins amplitudes

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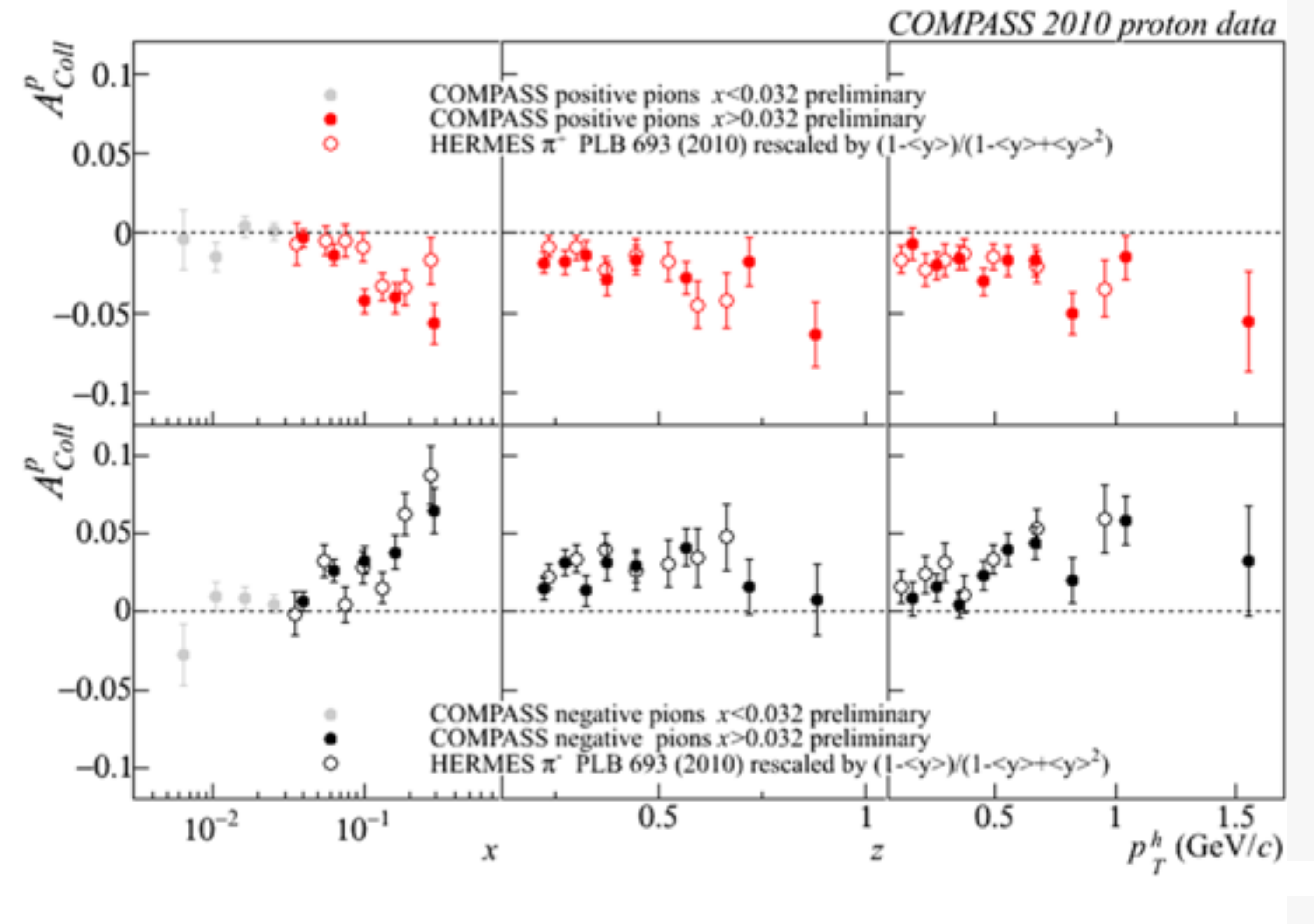
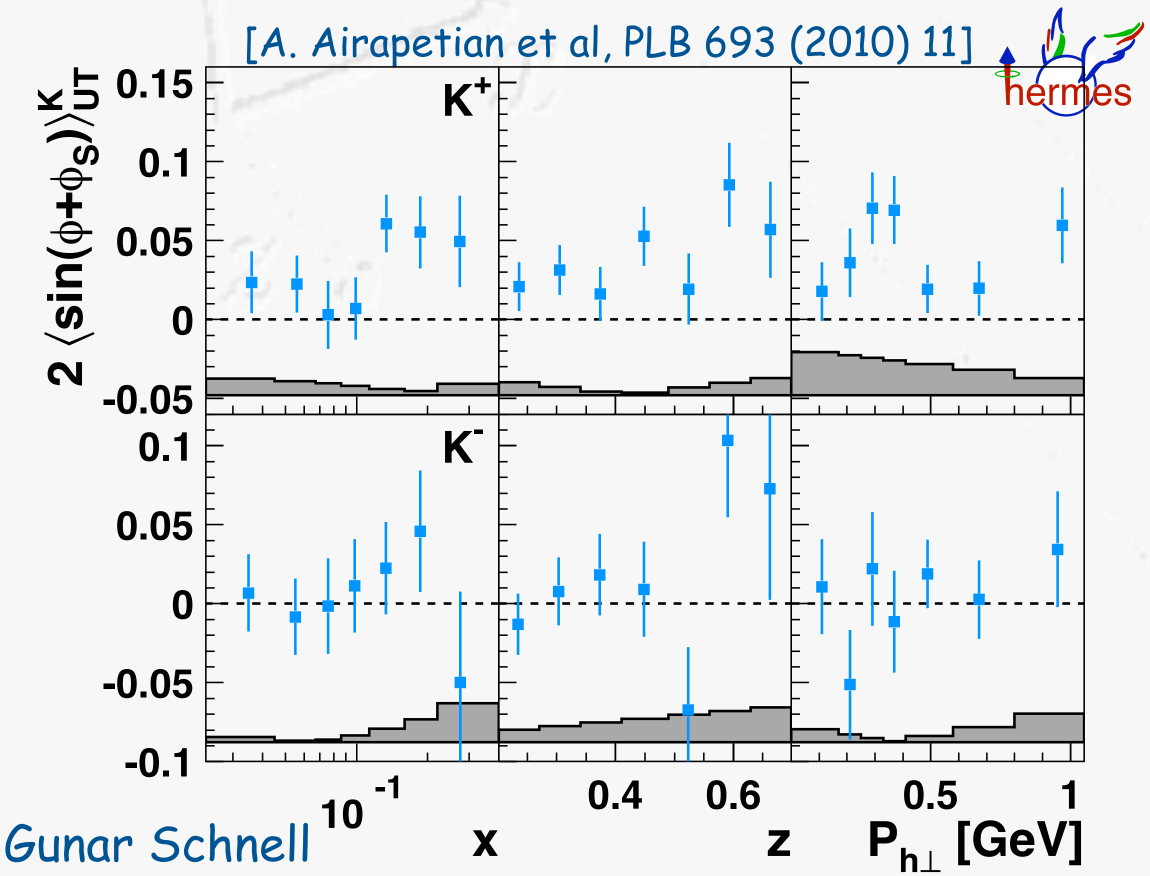
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

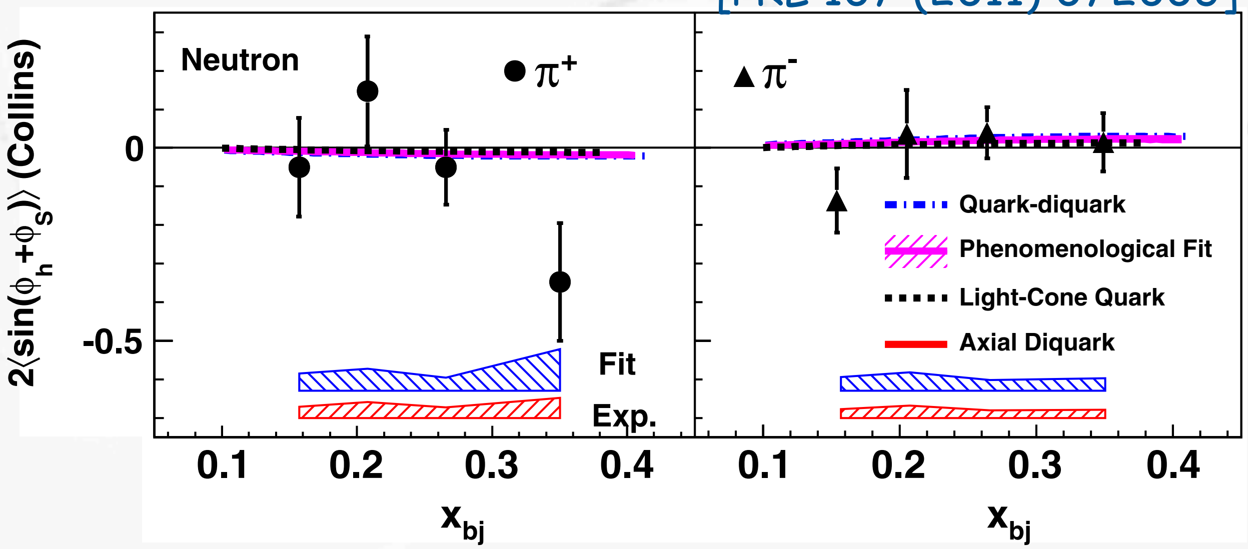
- **wealth of new results:**
  - COMPASS
    [PLB 692 (2010) 240,
    PLB 717 (2012) 376]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]



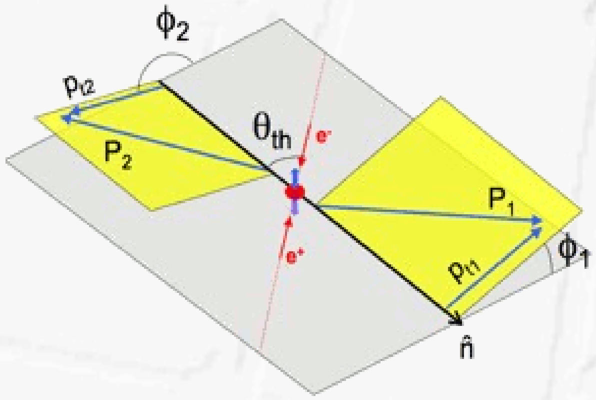
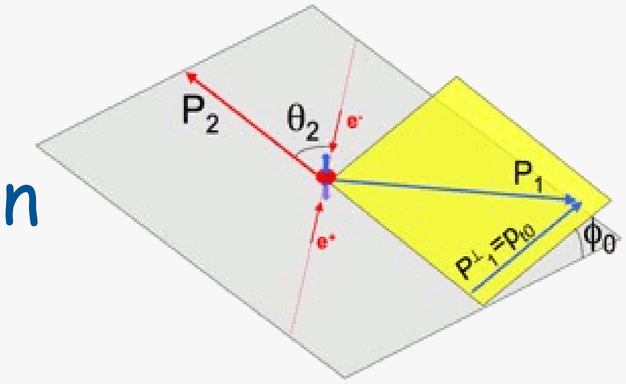
[A. Airapetian et al, PLB 693 (2010) 11]



[PRL 107 (2011) 072003]



Collins FF from e^+e^-

- analyzed in different frames:
  - Collins-Soper  vs. Gottfried-Jackson 

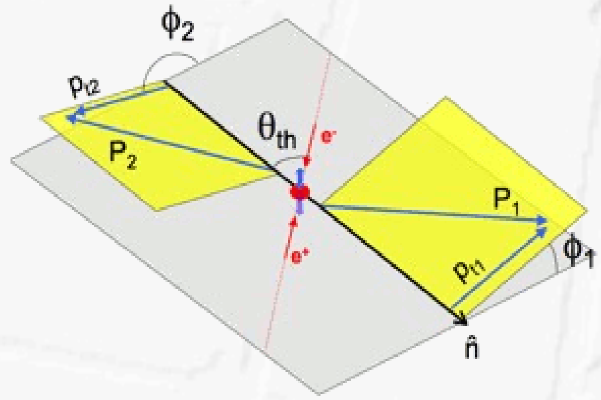
➡ **different convolution over transverse momenta**

$$A_{12} \propto \cos(\phi_1 + \phi_2) \frac{H_1^{\perp,[1]} \bar{H}_1^{\perp,[1]}}{D_1^{[0]} \bar{D}_1^{[0]}} \qquad A_0 \propto \cos(2\phi_0) \frac{\mathcal{F}[\mathcal{W} H_1^{\perp} \bar{H}_1^{\perp}]}{\mathcal{F}[D_1 \bar{D}_1]}$$

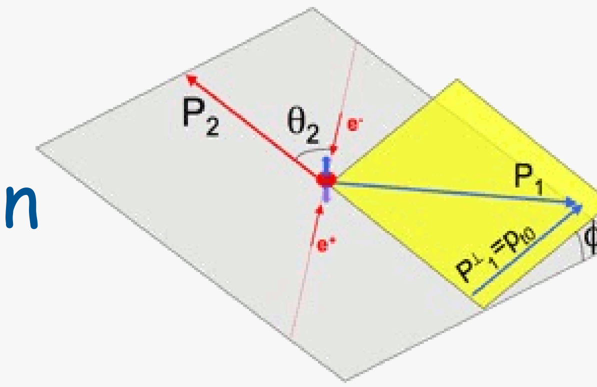
$$F^{[n]} = \int d|\mathbf{k}_T|^2 \left[\frac{|\mathbf{k}_T|}{M_h}\right]^n F(z, \mathbf{k}_T^2)$$

Collins FF from e^+e^-

- analyzed in different frames:
  - Collins-Soper



vs. Gottfried-Jackson



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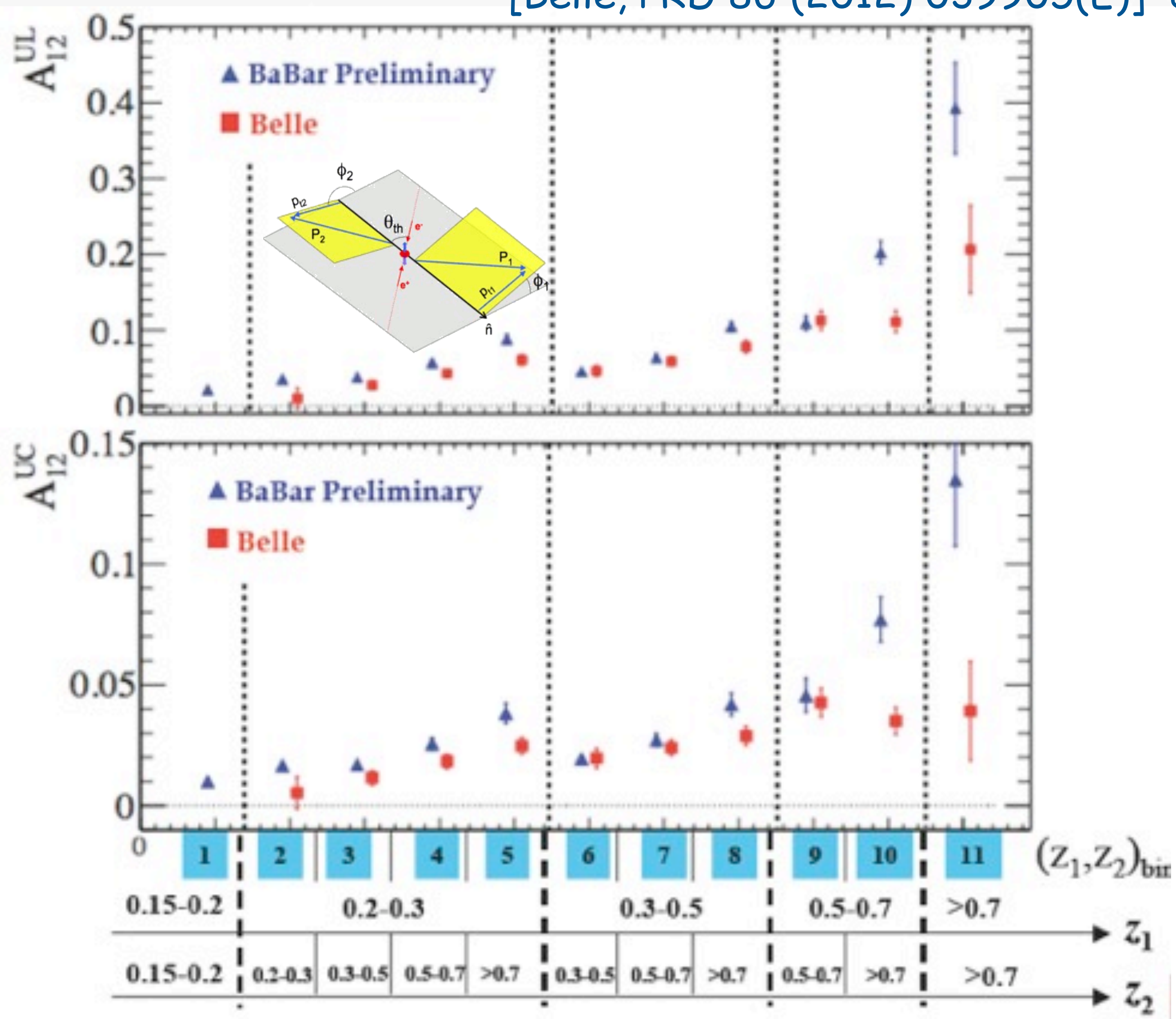
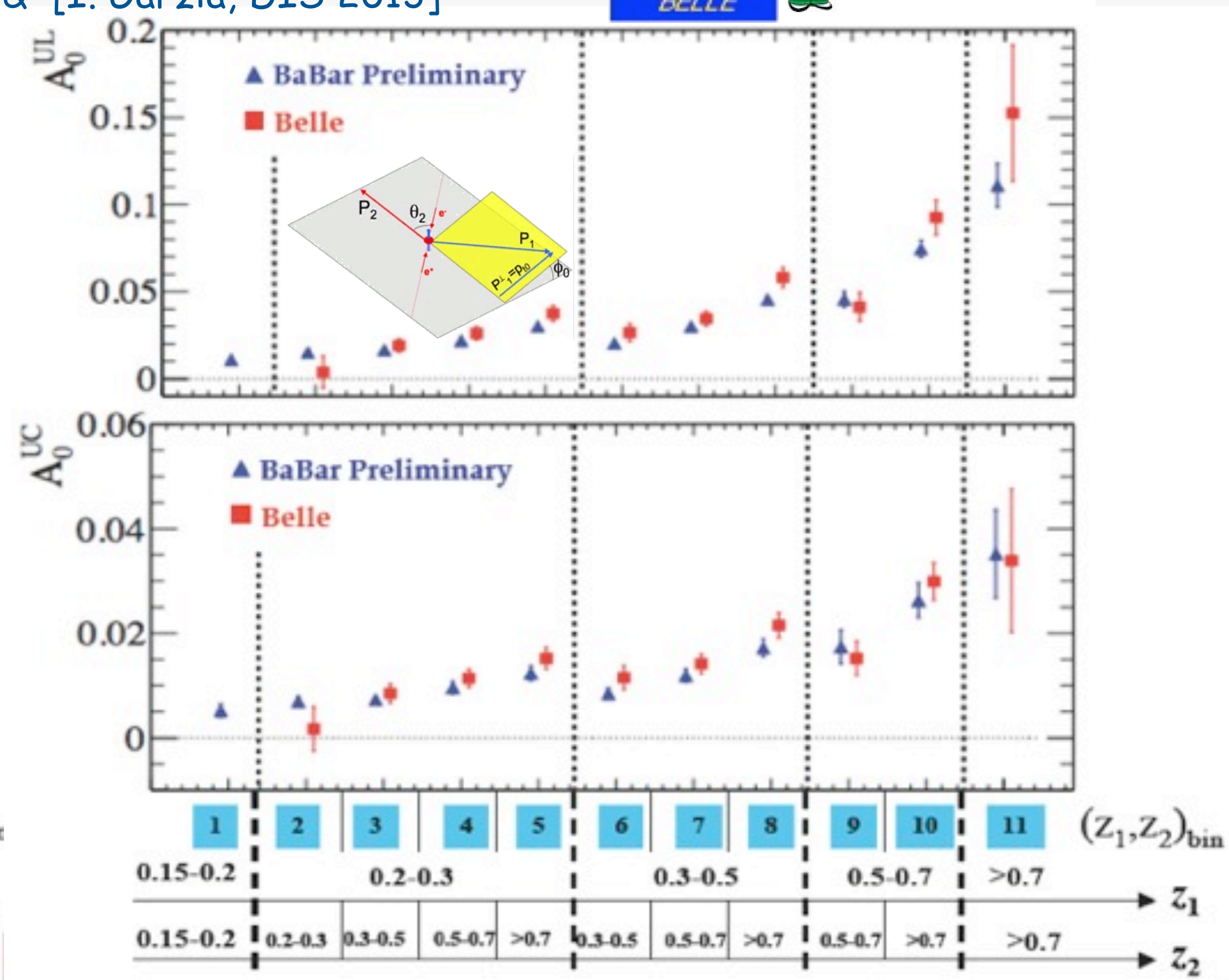
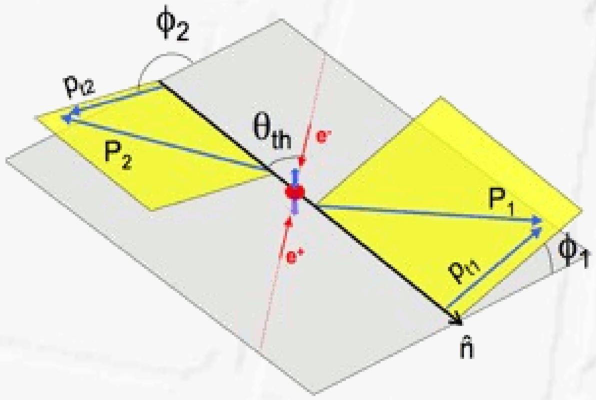
[Belle, PRD 86 (2012) 039905(E)] & [I. Garzia, DIS 2013]

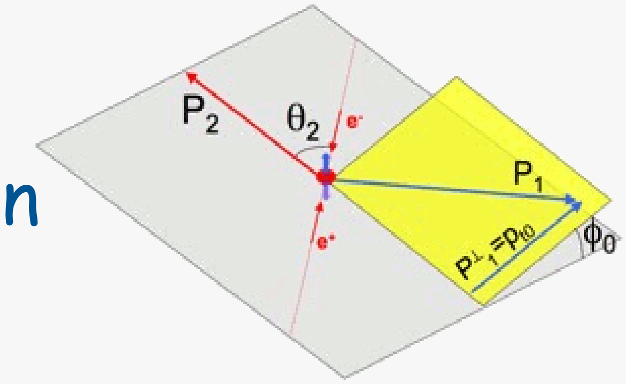




Collins FF from e^+e^-

- analyzed in different frames:
  - Collins-Soper vs. Gottfried-Jackson





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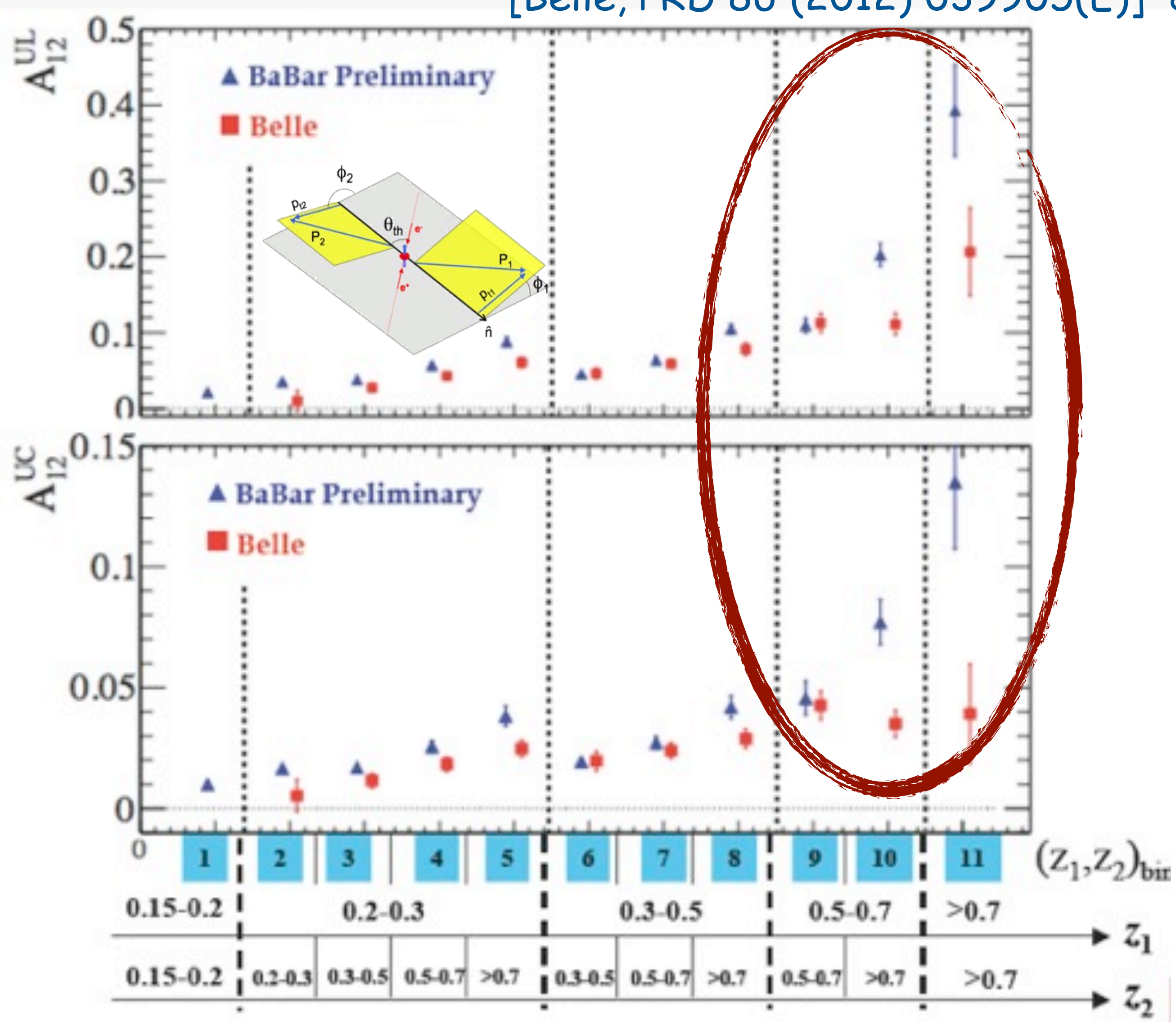
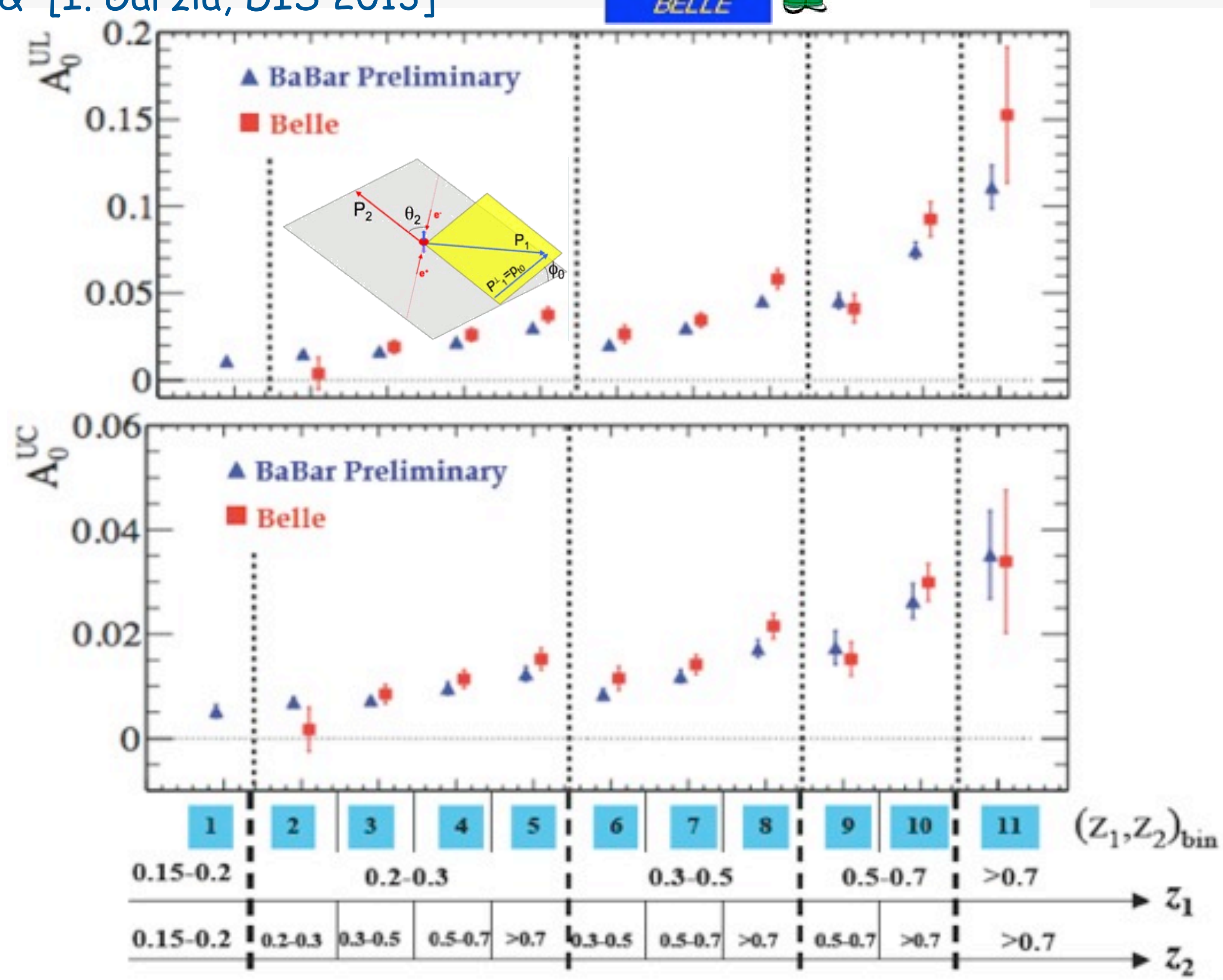
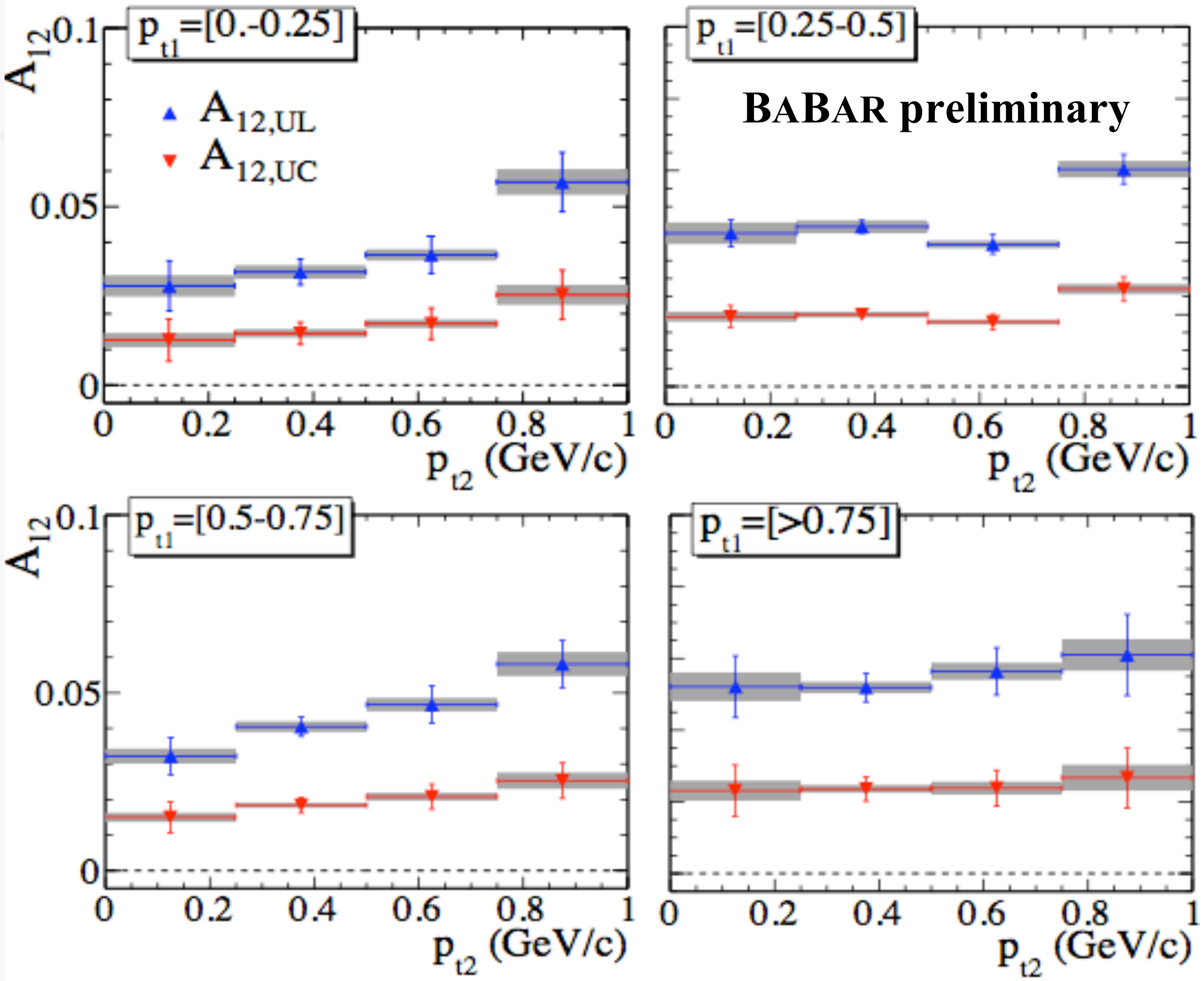
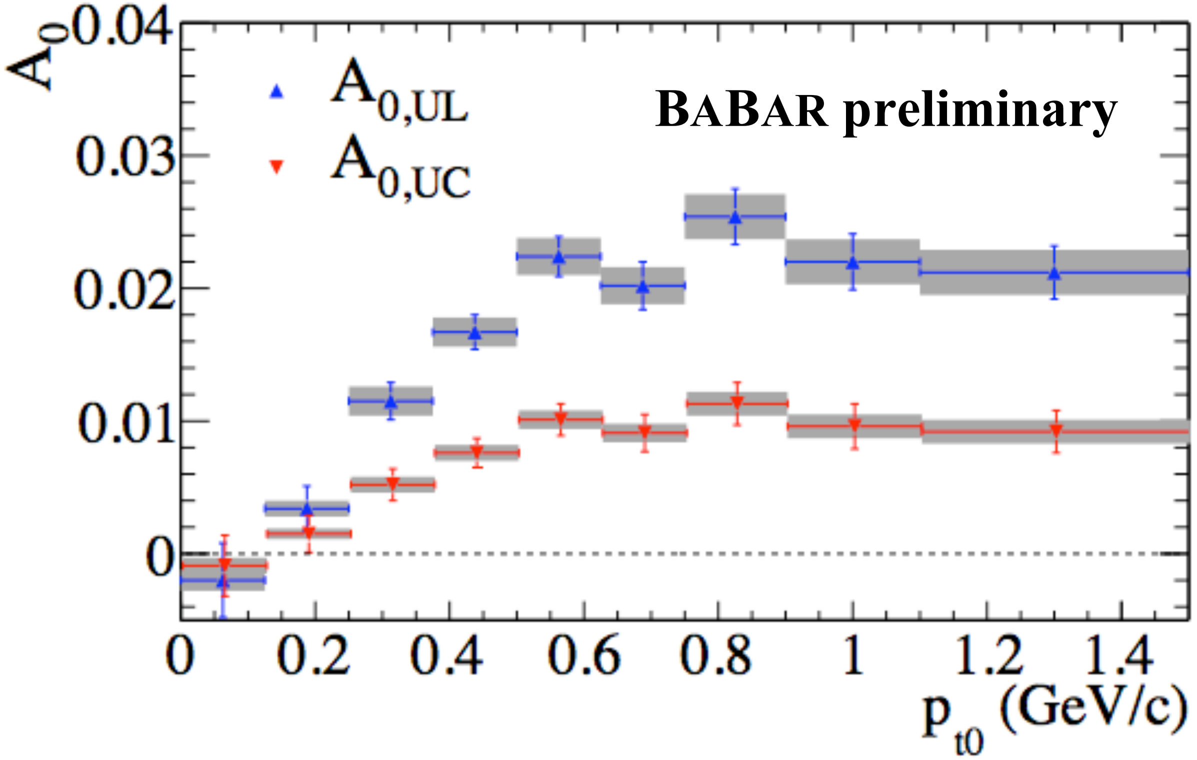




Collins FF from e^+e^-





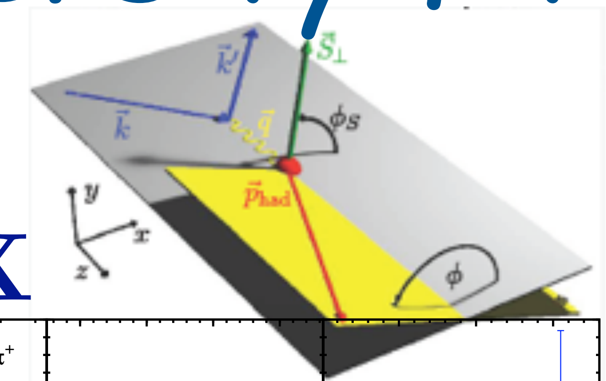
FIRST MEASUREMENT of Collins asymmetries *vs.* p_t in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$ (time-like region)

- **nonzero A^{UL} and A^{UC}**
  - ⇒ only modest dependence on (p_{t1},p_{t2})
  - ⇒ $A^{UC} < A^{UL}$; complementary information on $H_1^{\perp,\,fav}$ and $H_1^{\perp,\,dis}$
  - ⇒ $A_0 < A_{12}$, but interesting structure in p_t

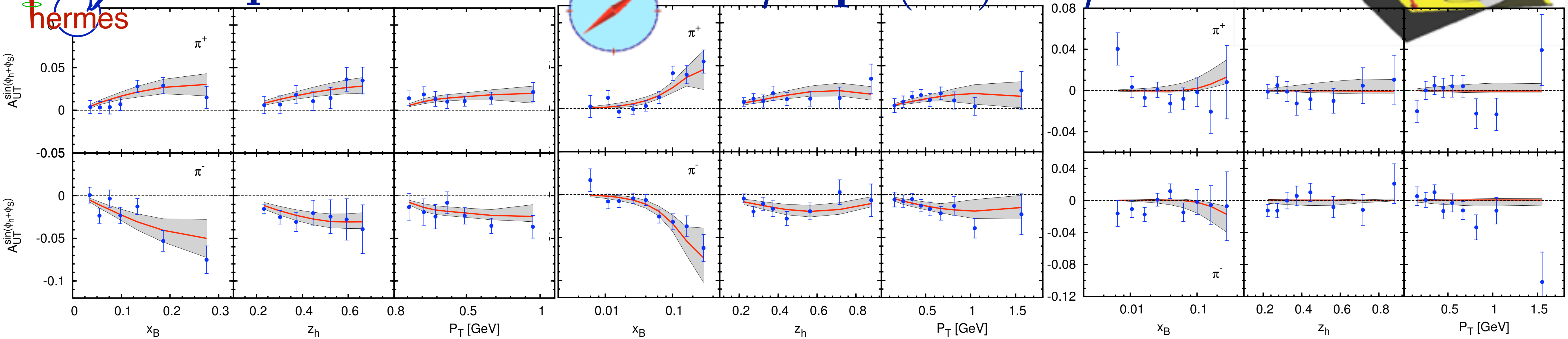
slide taken from [I. Garzia, DIS 2013]

Collins FF and transversity fit

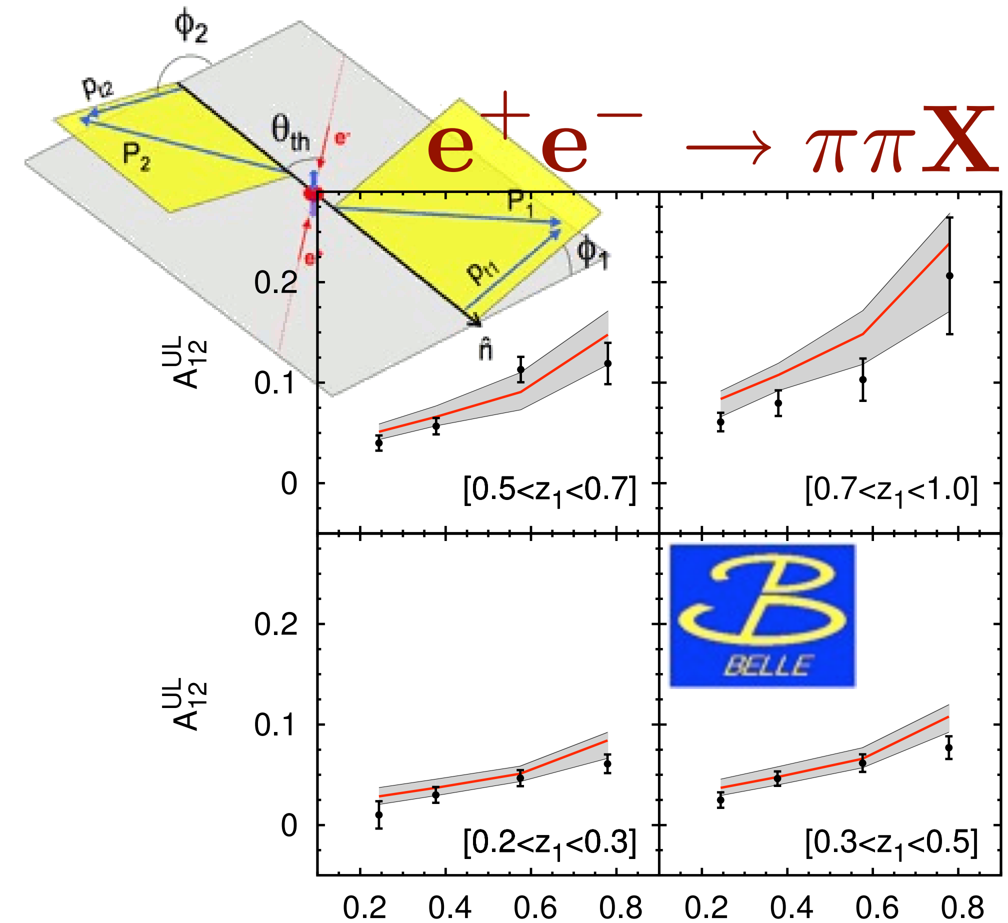
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



$\mathbf{e^\pm p^\uparrow \to e^\pm \pi X}$ $\mu^\pm \mathbf{p}^\uparrow(\mathbf{d}^\uparrow) \to \mu^\pm \pi \mathbf{X}$

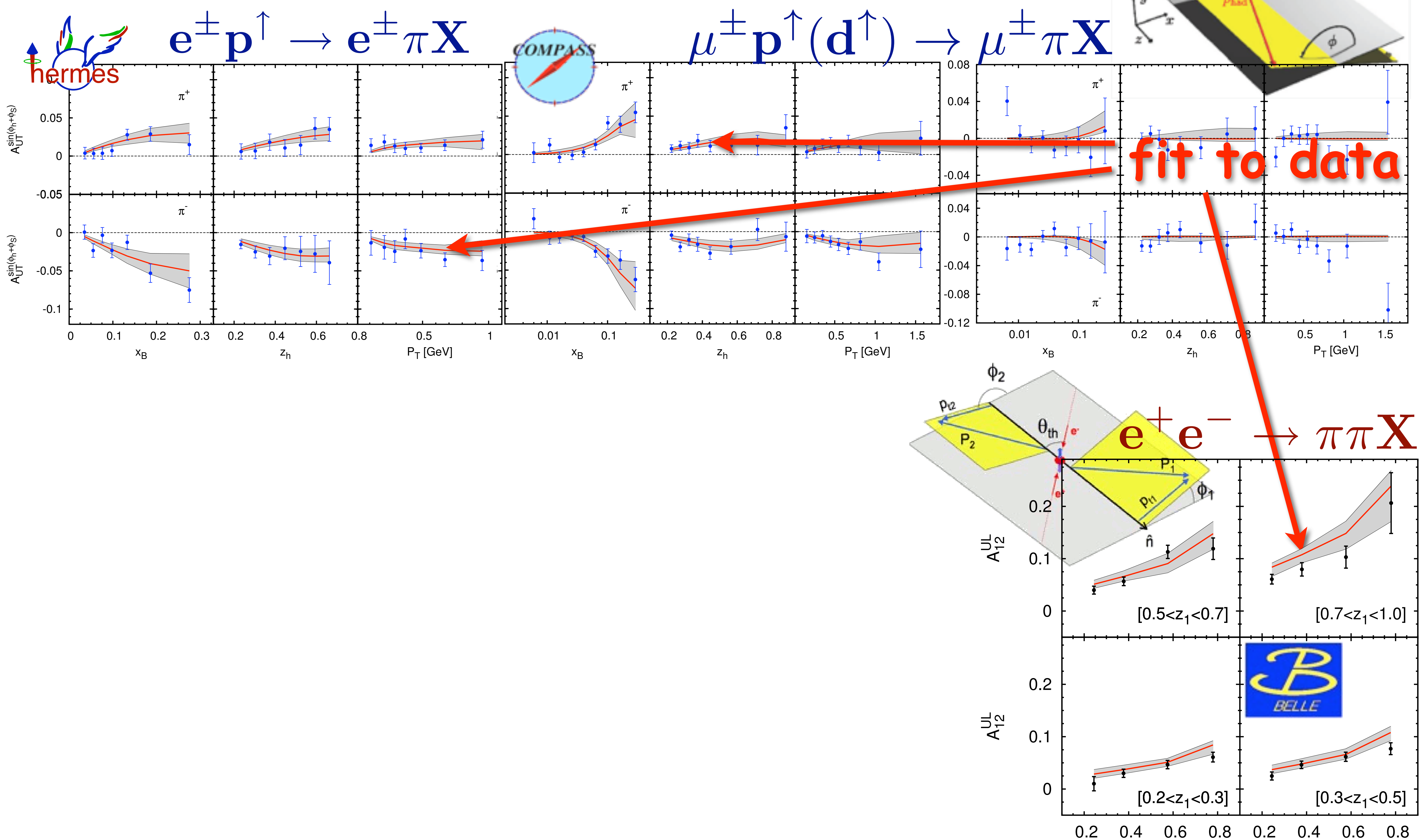


$\mathbf{e^+e^- \to \pi\pi X}$



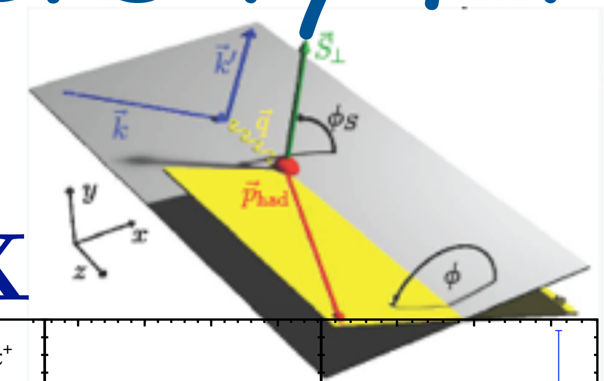
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins FF and transversity fit



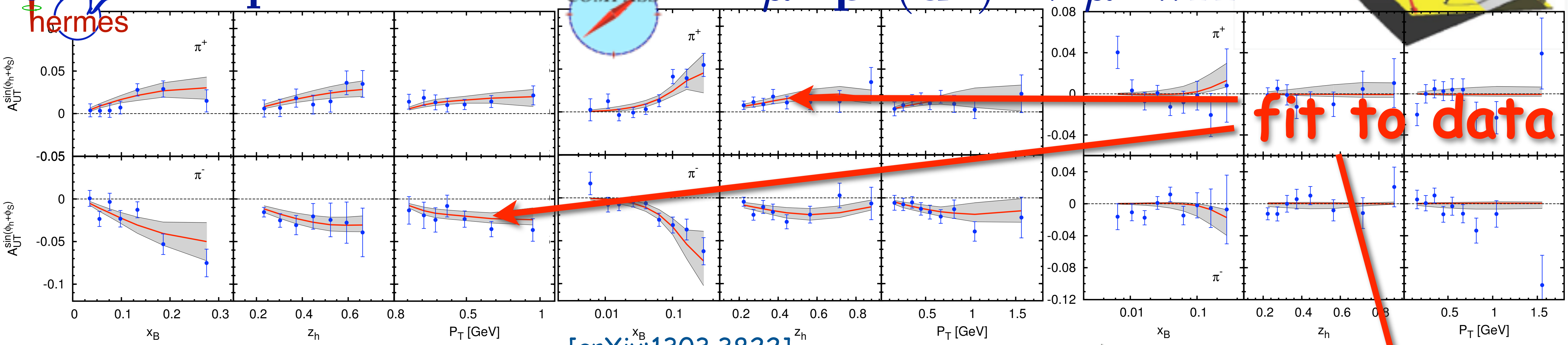
Collins FF and transversity fit

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

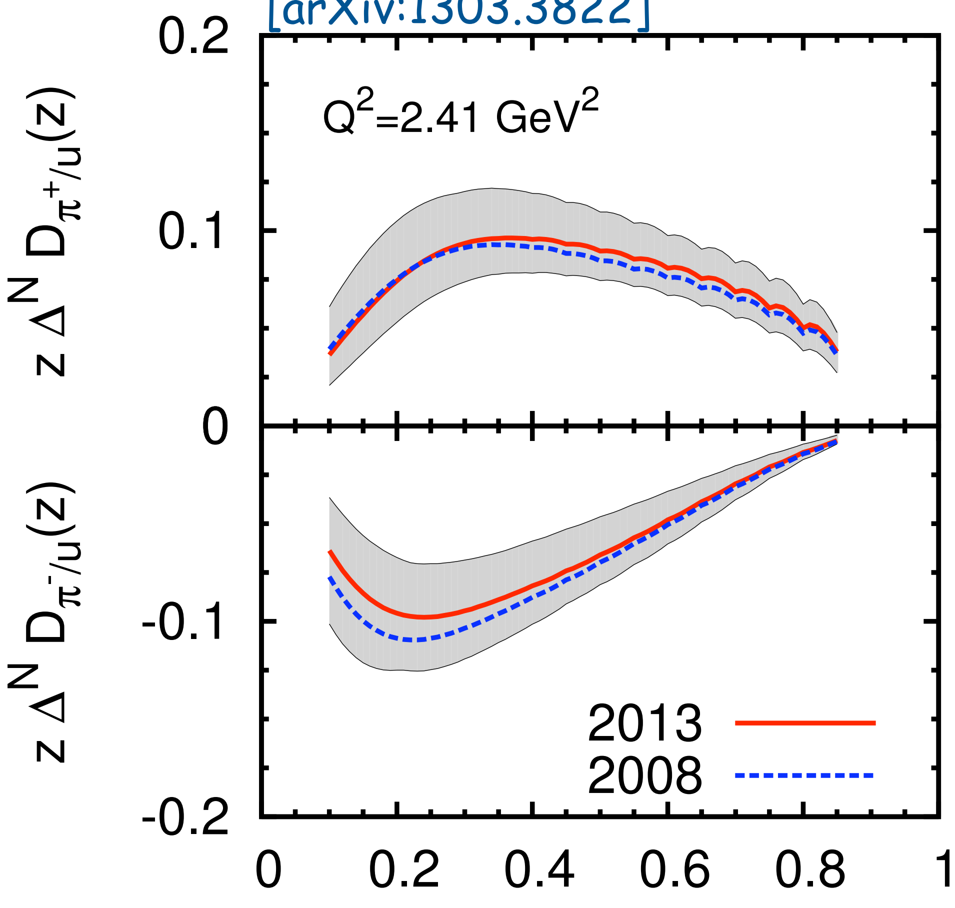


$e^\pm p^\uparrow \rightarrow e^\pm \pi X$

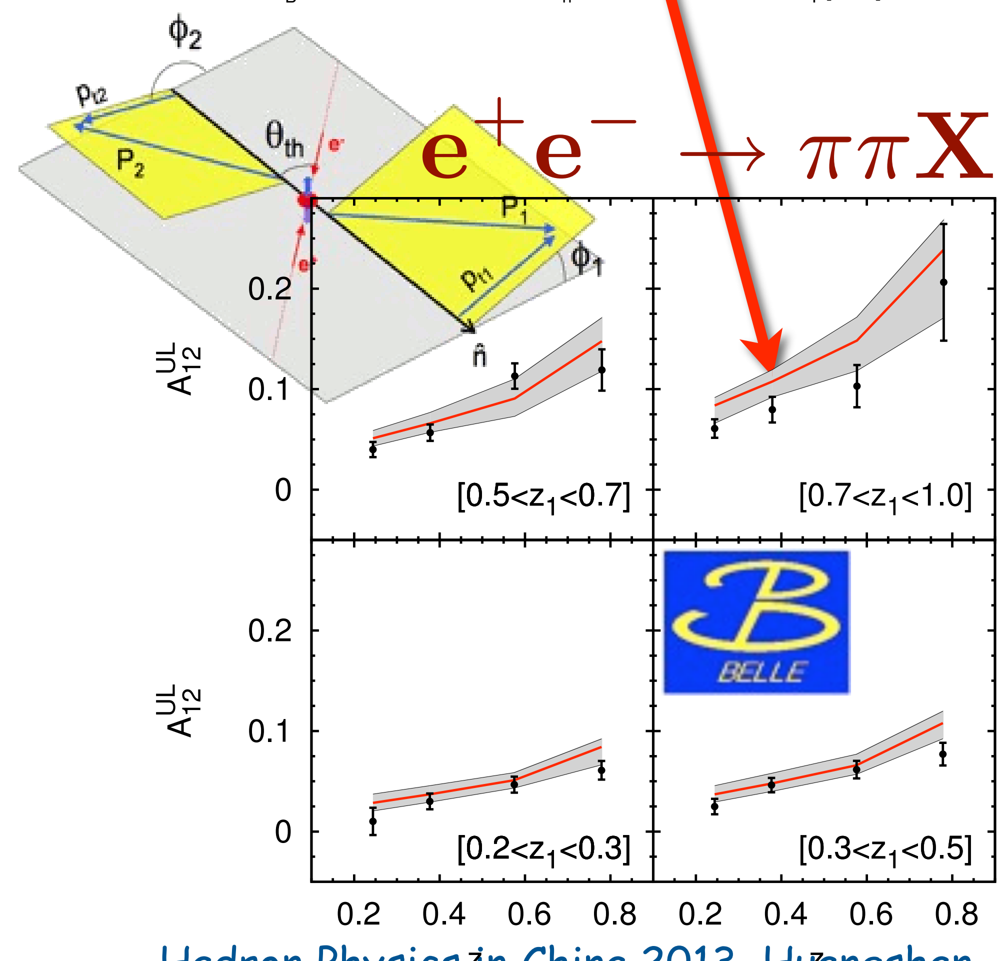
$\mu^\pm p^\uparrow(d^\uparrow) \rightarrow \mu^\pm \pi X$



[arXiv:1303.3822]

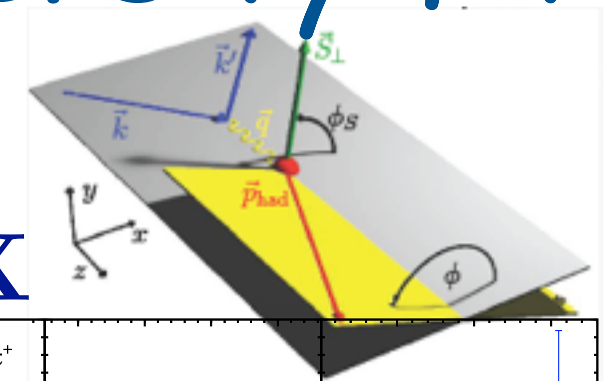


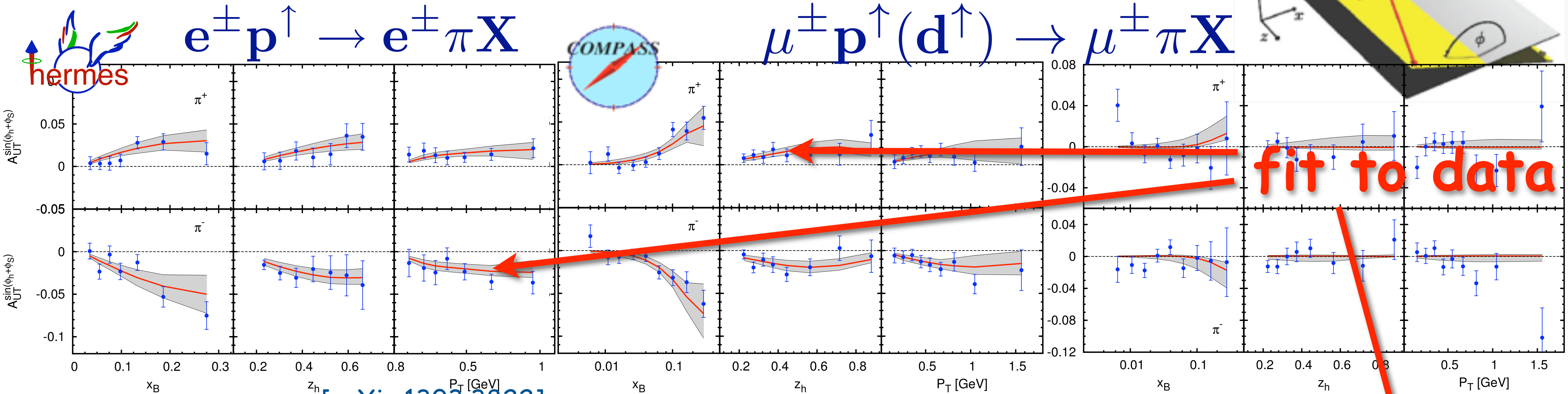
$e^+e^- \rightarrow \pi\pi X$

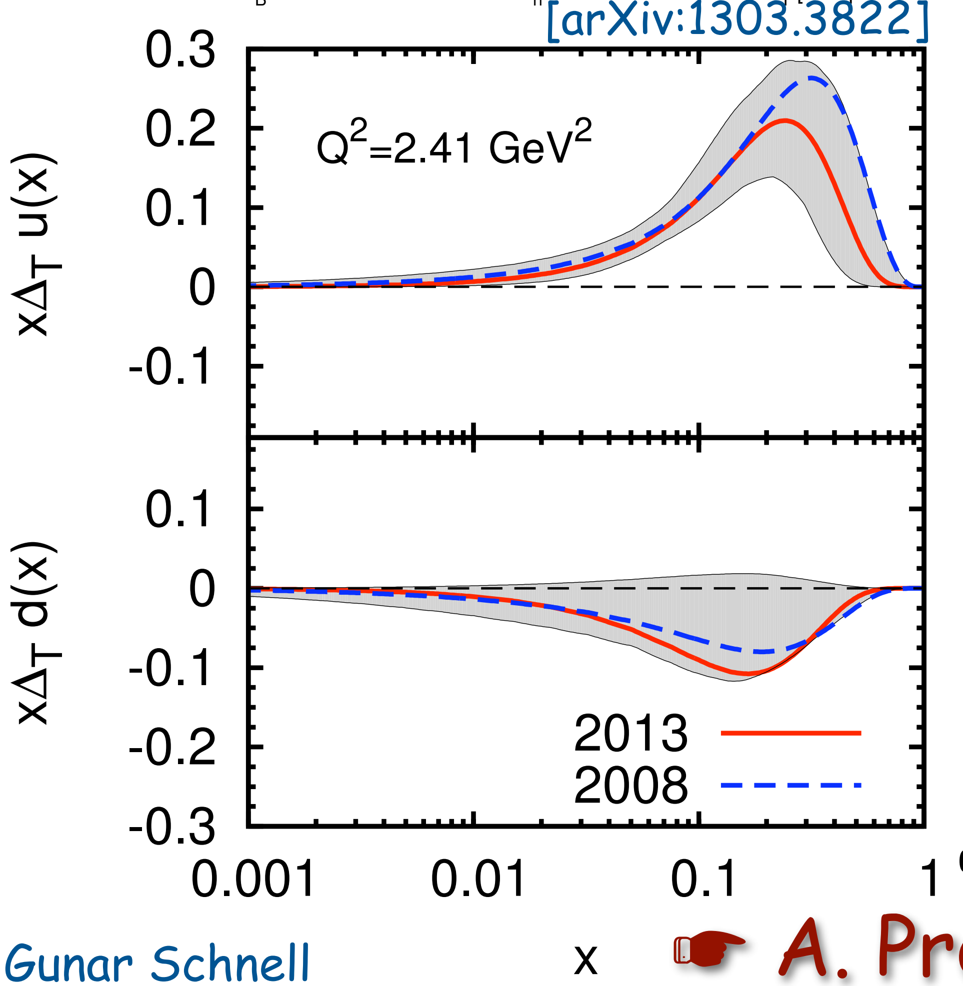


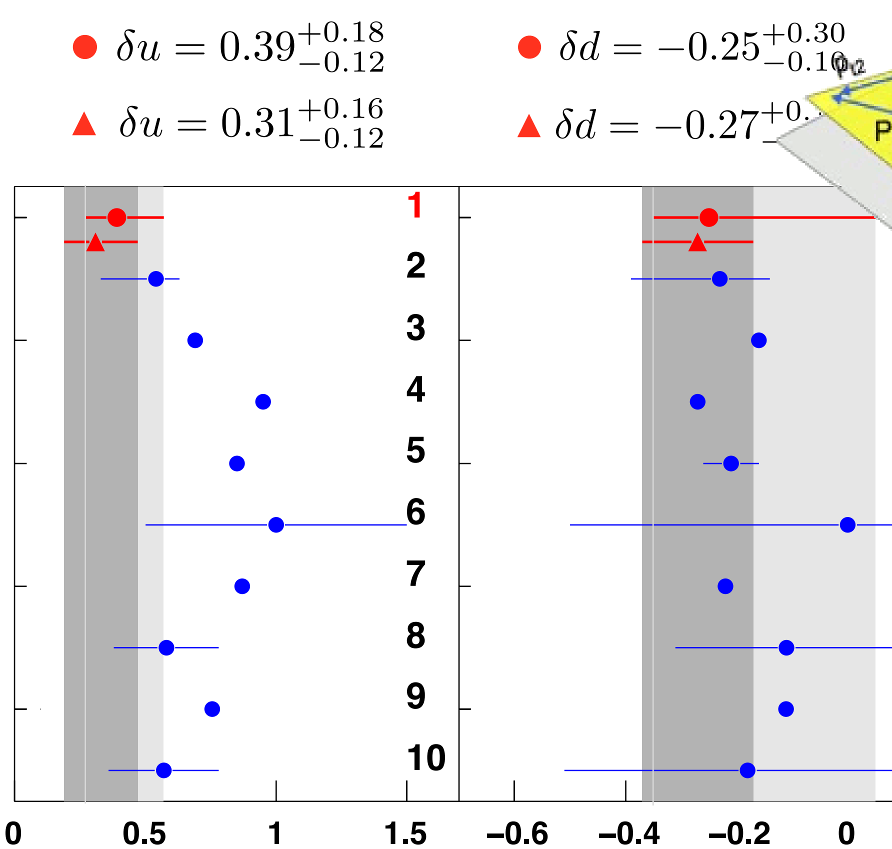
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

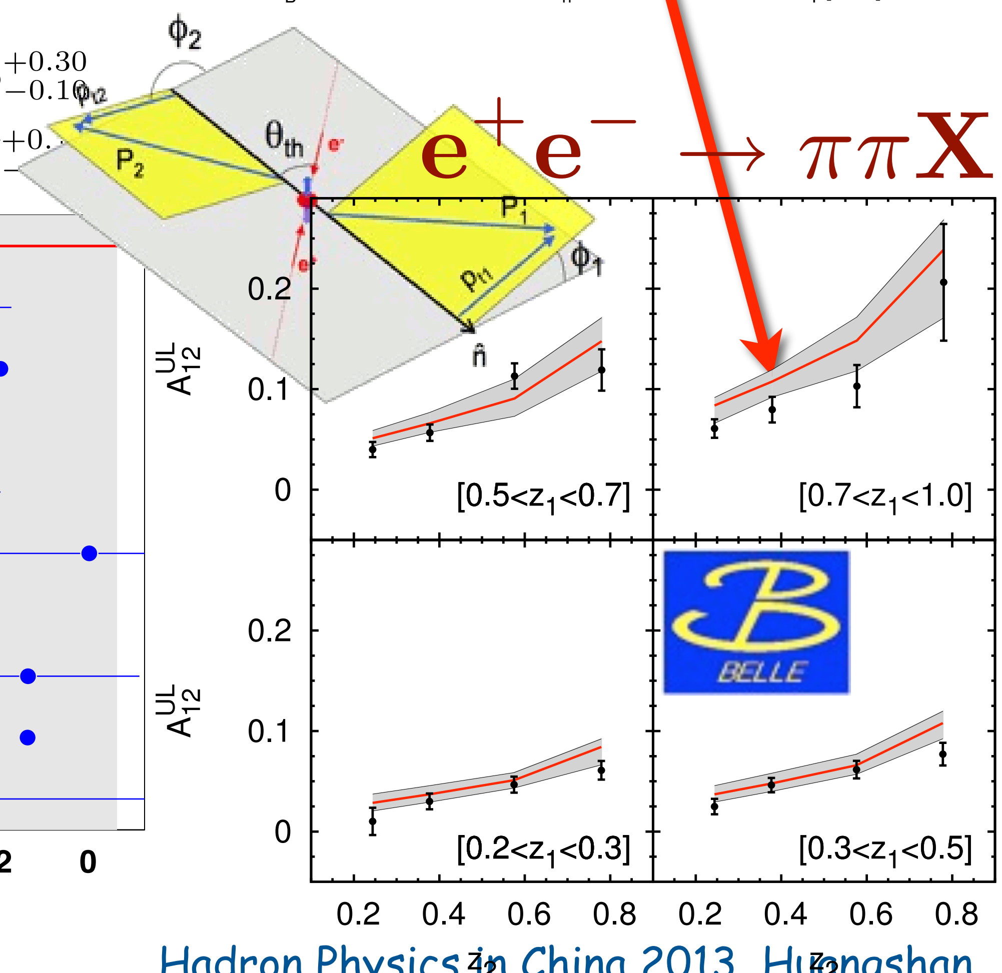
Collins FF and transversity fit







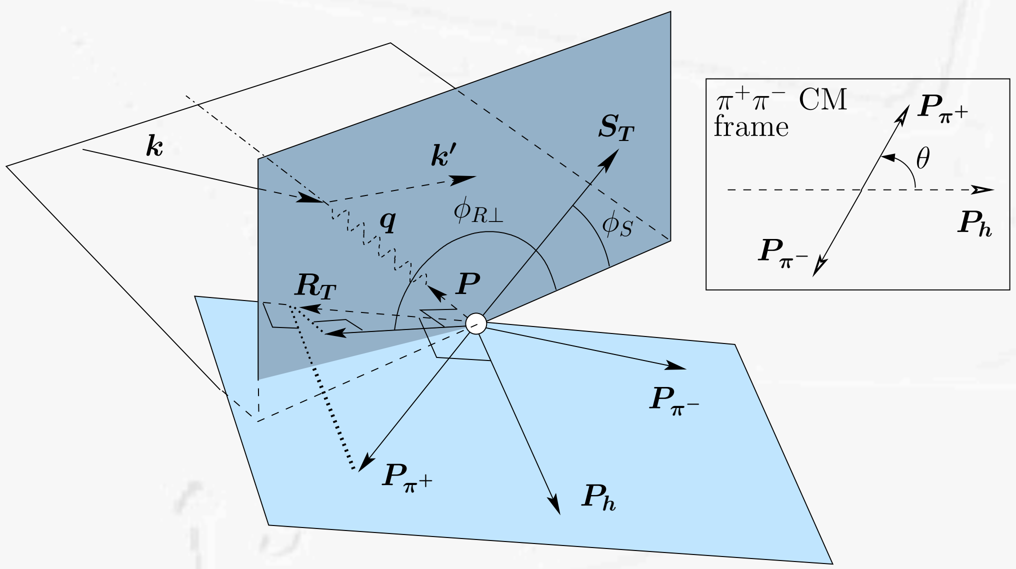




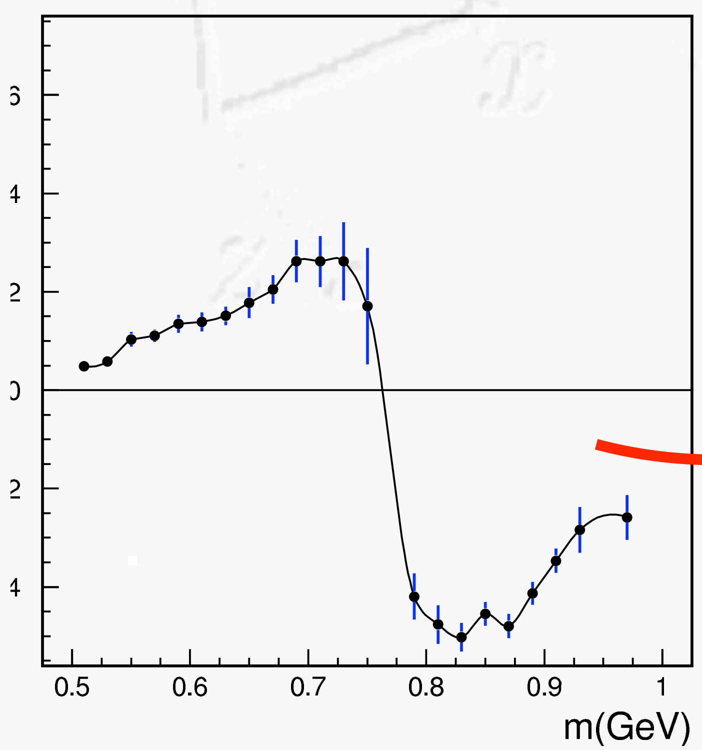
☛ A. Prokudin

	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 through 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**]:

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

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

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

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

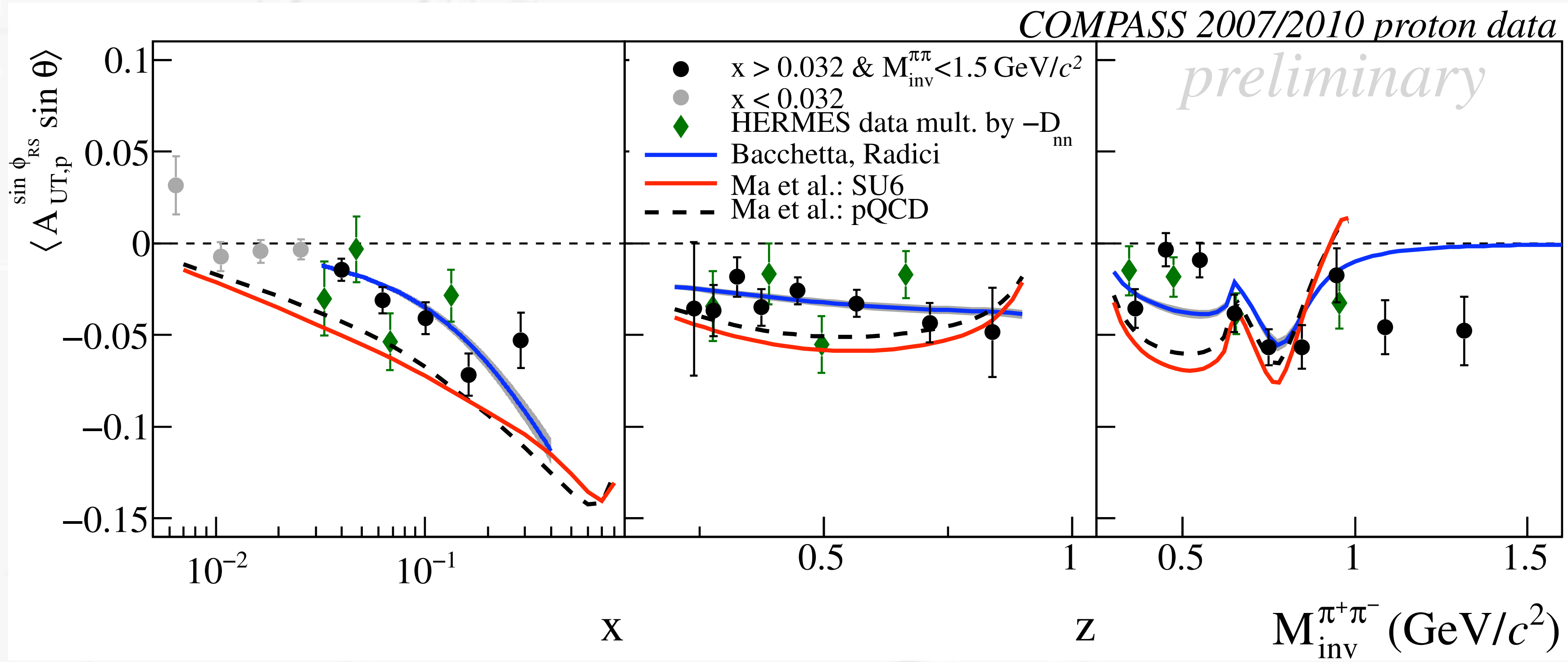
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign

- ^{2}H results consistent with zero

[A. Airapetian et al., JHEP 06 (2008) 017]
COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10]
COMPASS 2010: [C. Braun et al., Nuovo Cimento C 035 (2012) 02]



	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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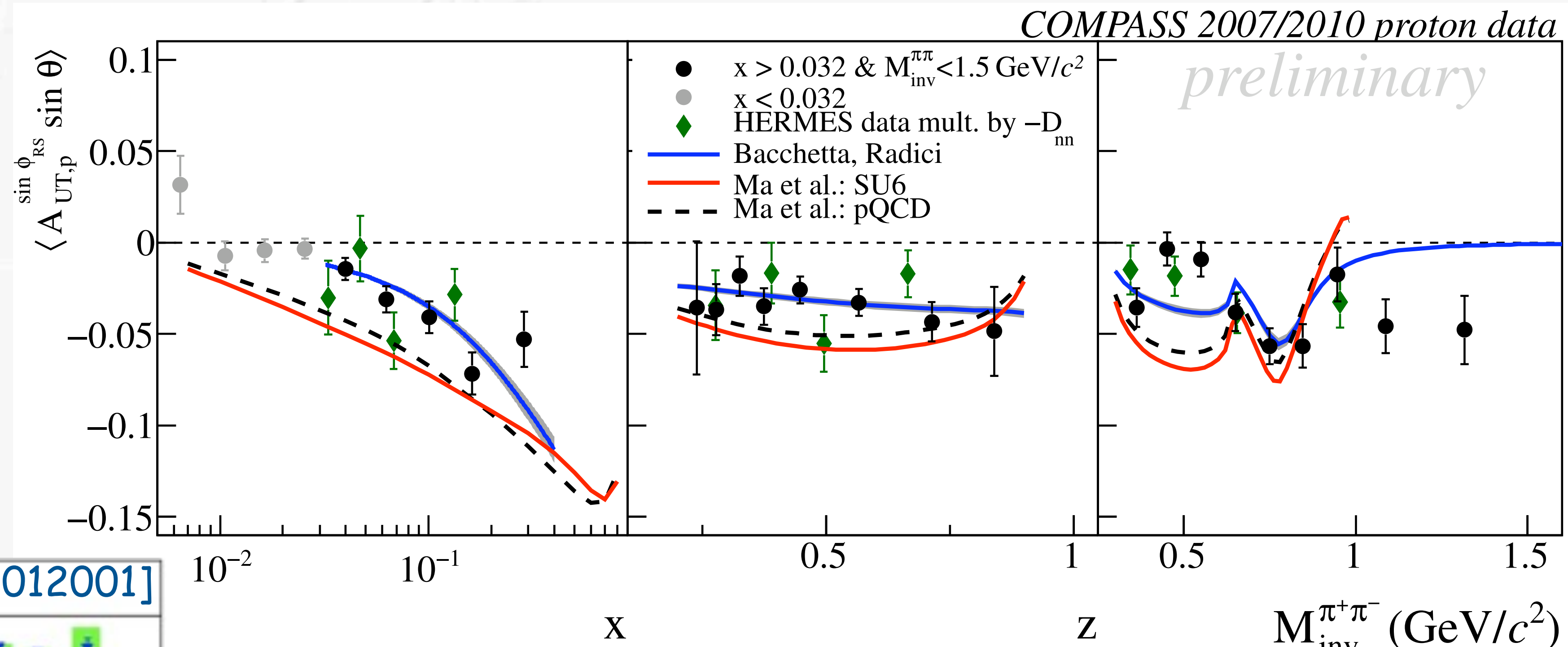
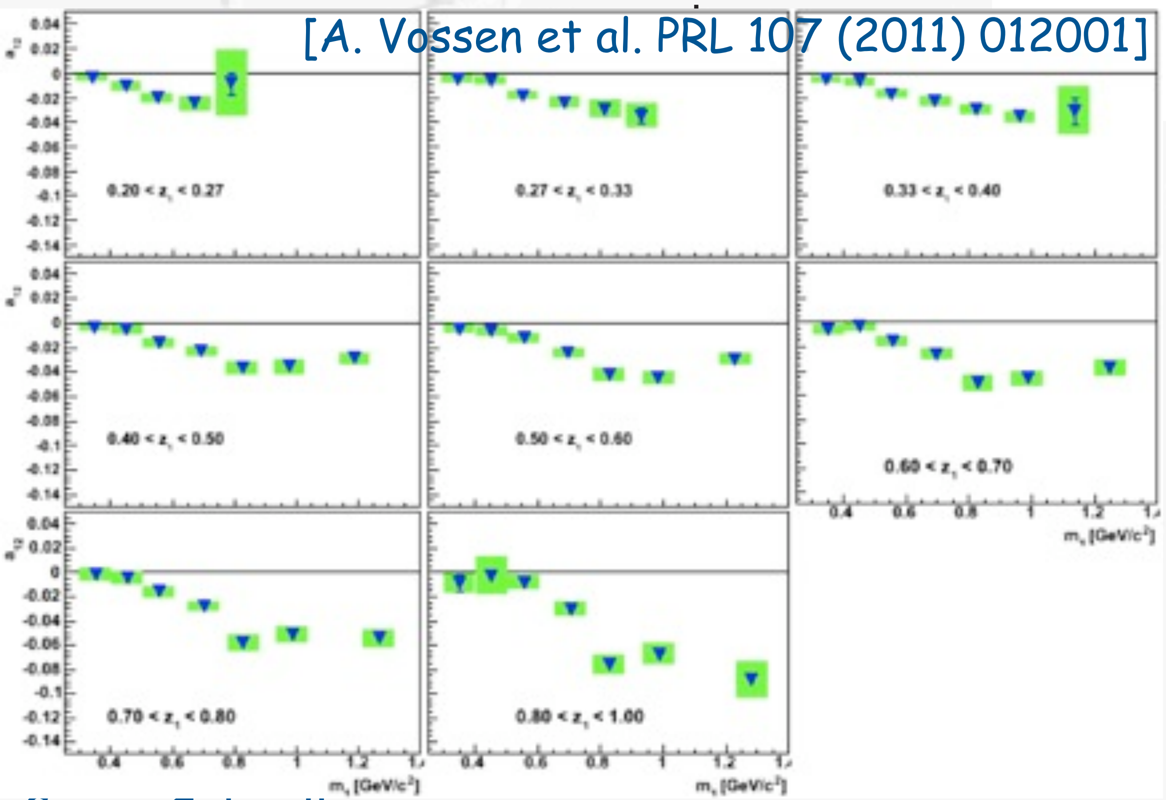
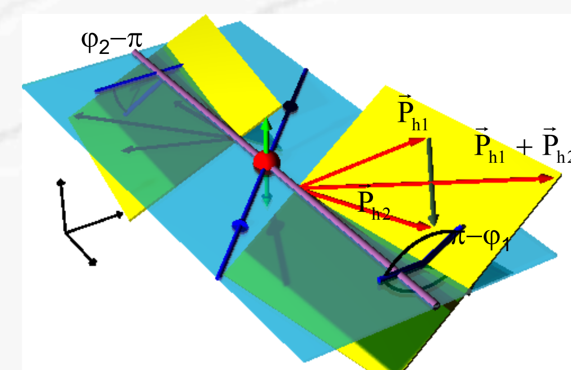


[A. Vossen et al. PRL 107 (2011) 012001]



- data from e^+e^- by BELLE



	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)

- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign
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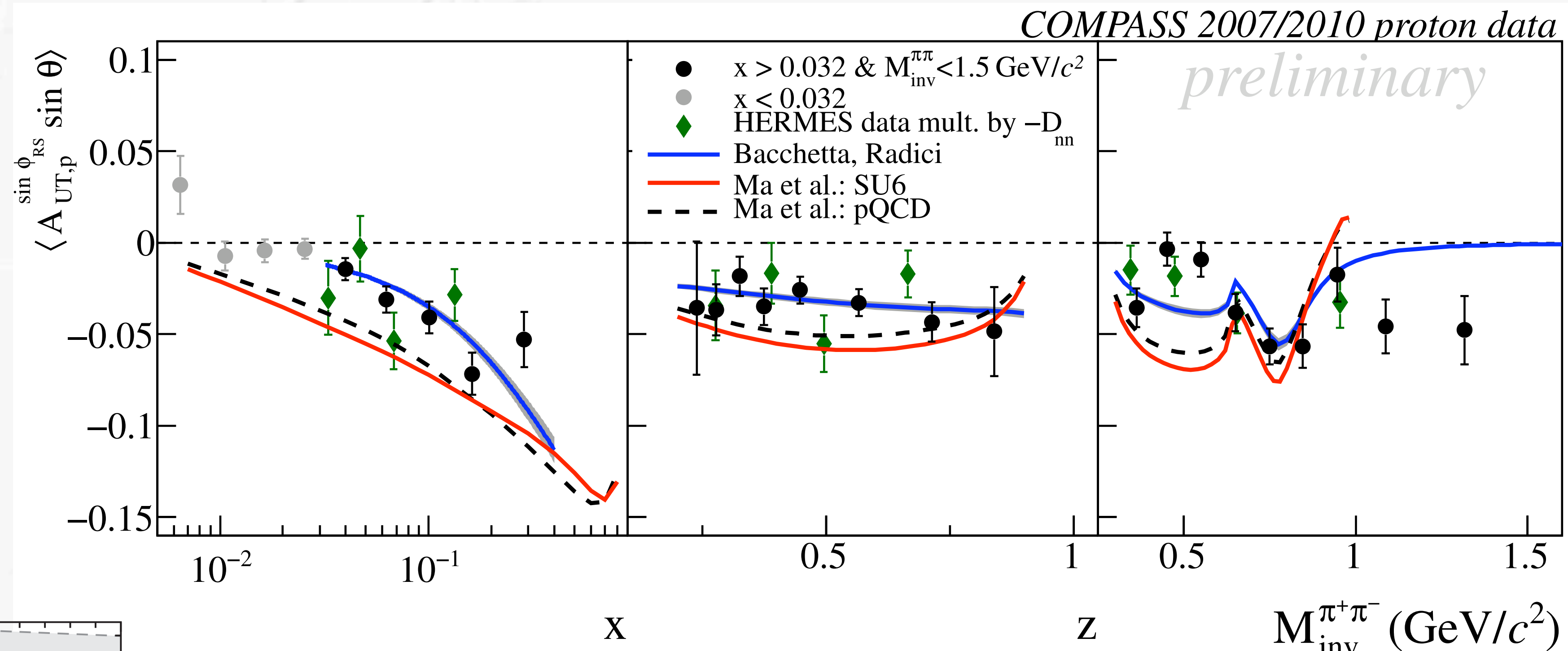
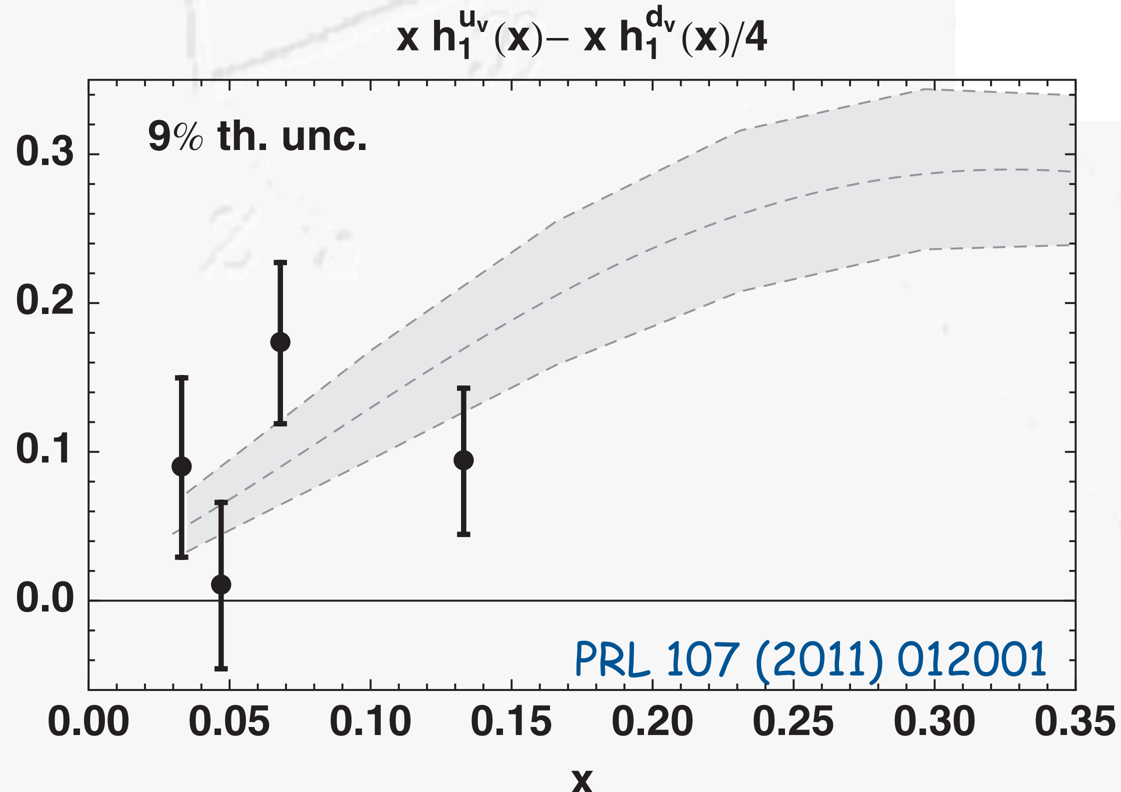
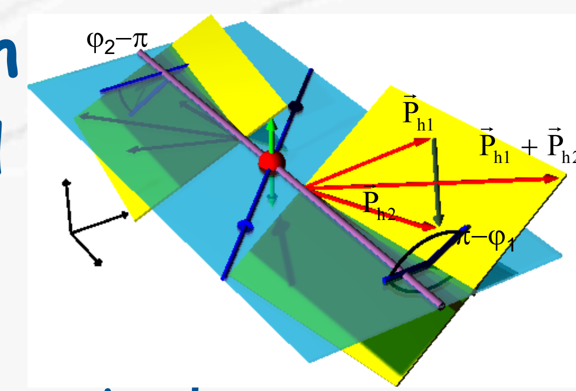




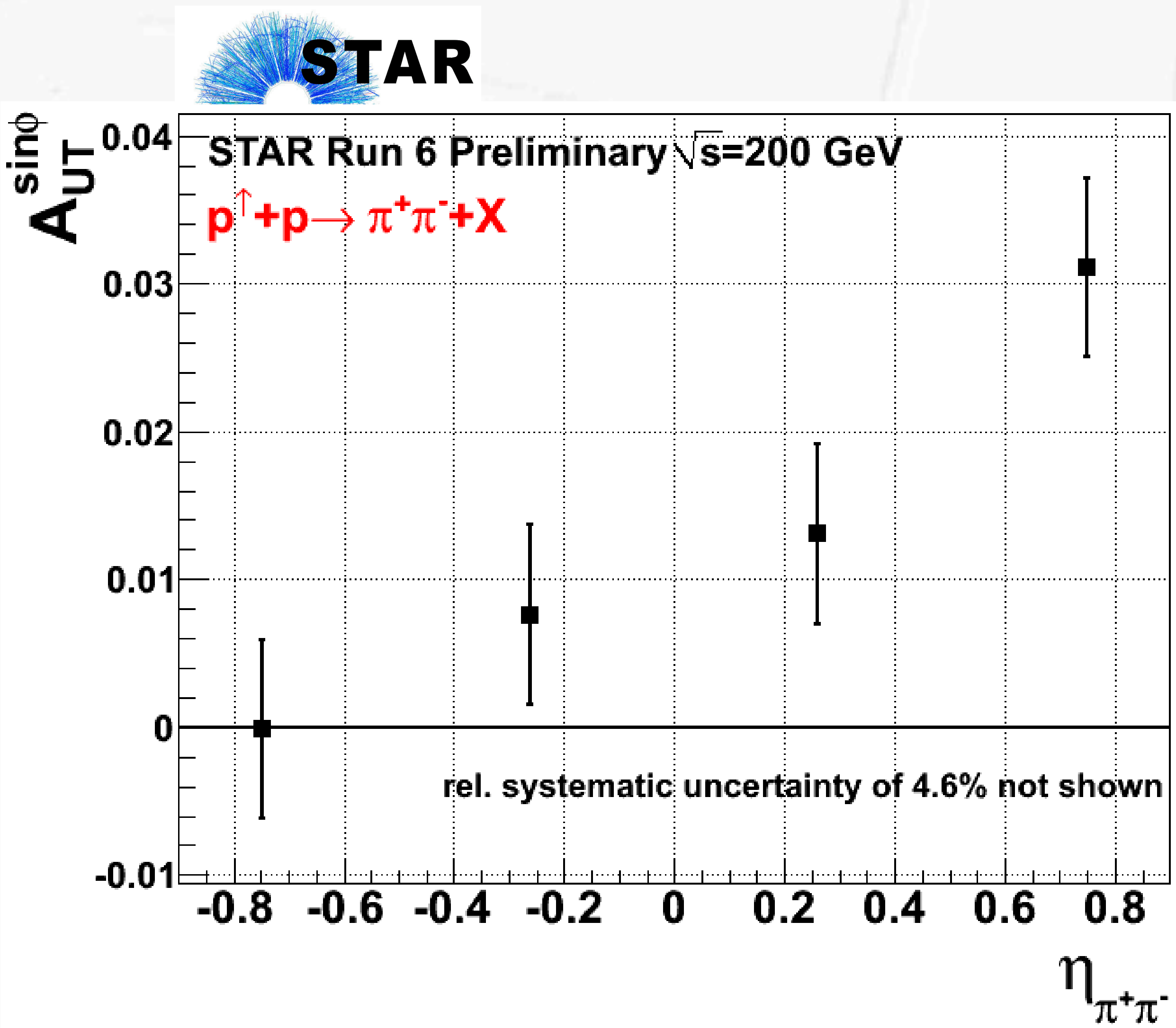
- data from e^+e^- by BELLE allow **first (collinear) extraction of transversity** (compared to Anselmino et al.)

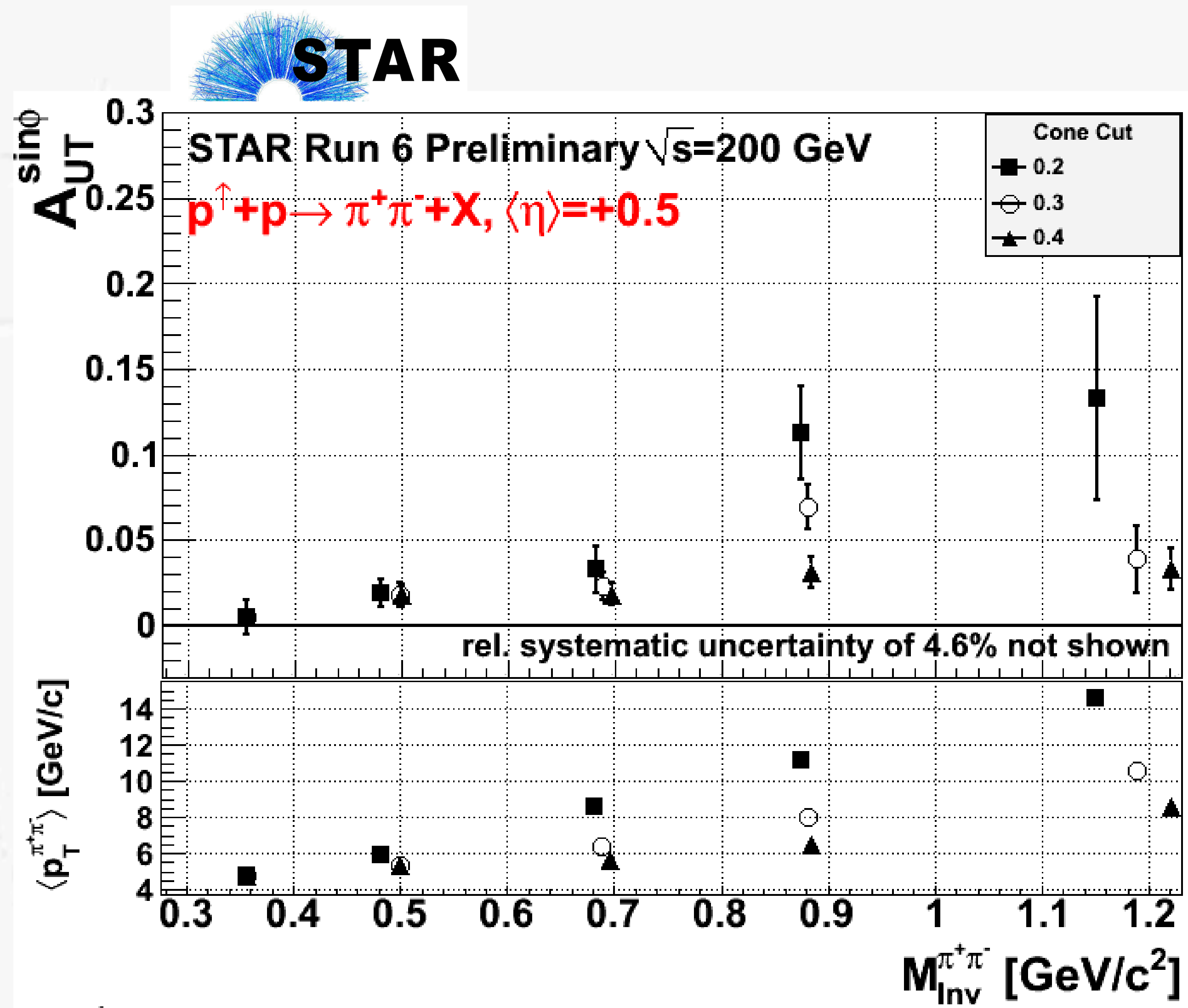


- updated analysis, but no time today

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

First signal of transversity from polarized $p^\uparrow p \to \pi^+\pi^- X$





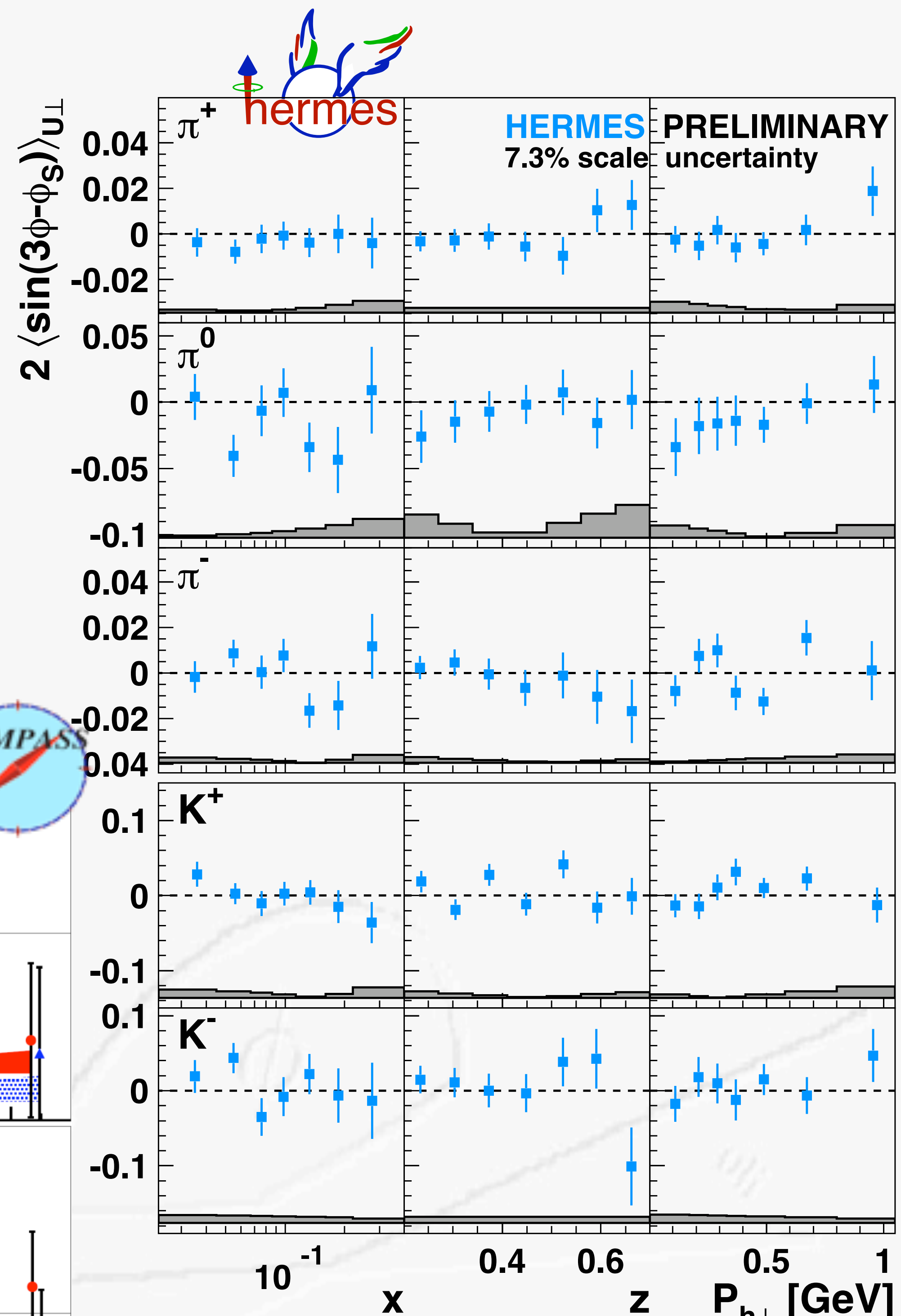
- forward region -> valence effect from polarized (beam) proton
- dependence on cone cut due to underlying p_T dependence?

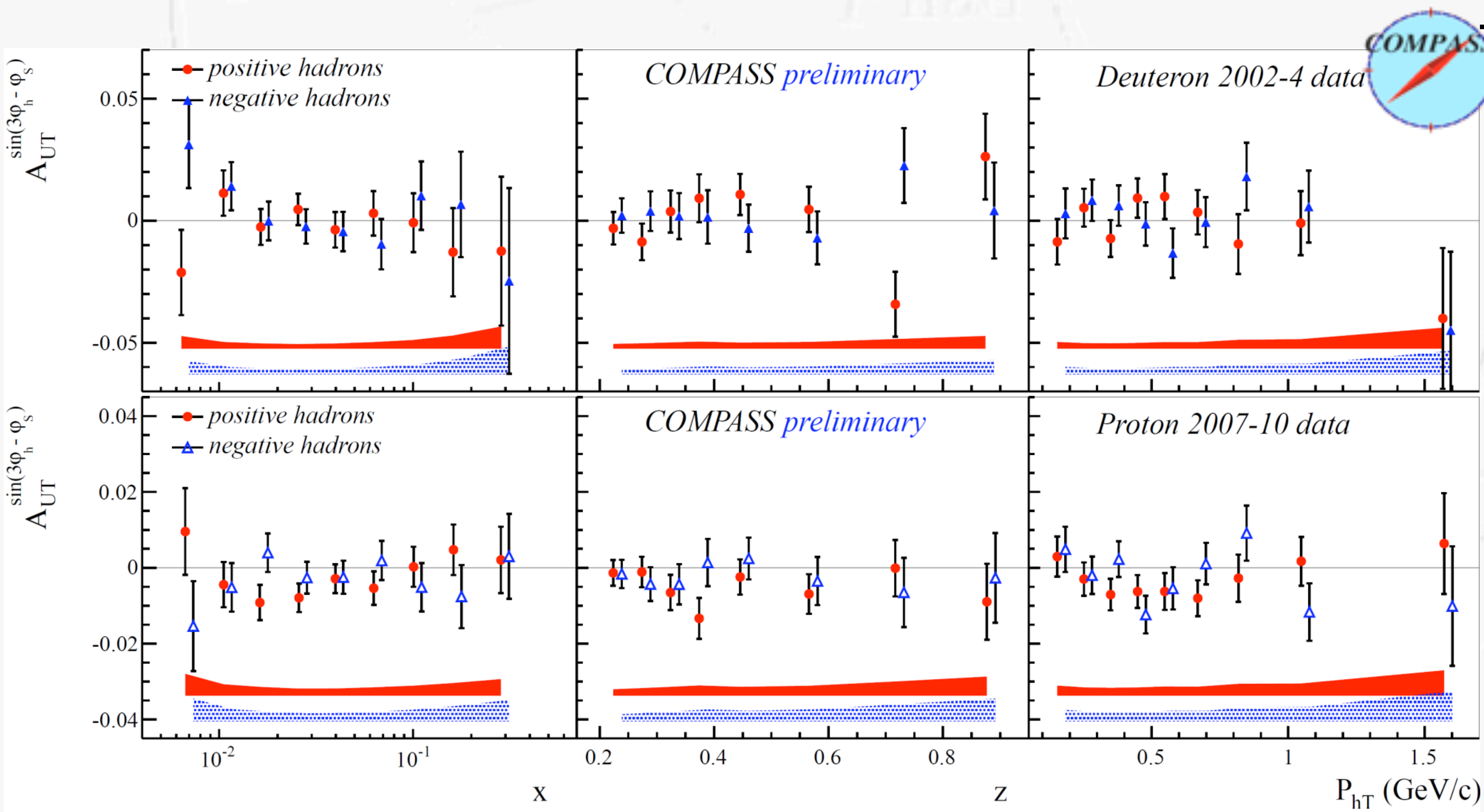
Transversity's friends

Pretzelosity

	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 ➥ needs Collins FF (or similar)
- proton & deuteron data consistently small
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$



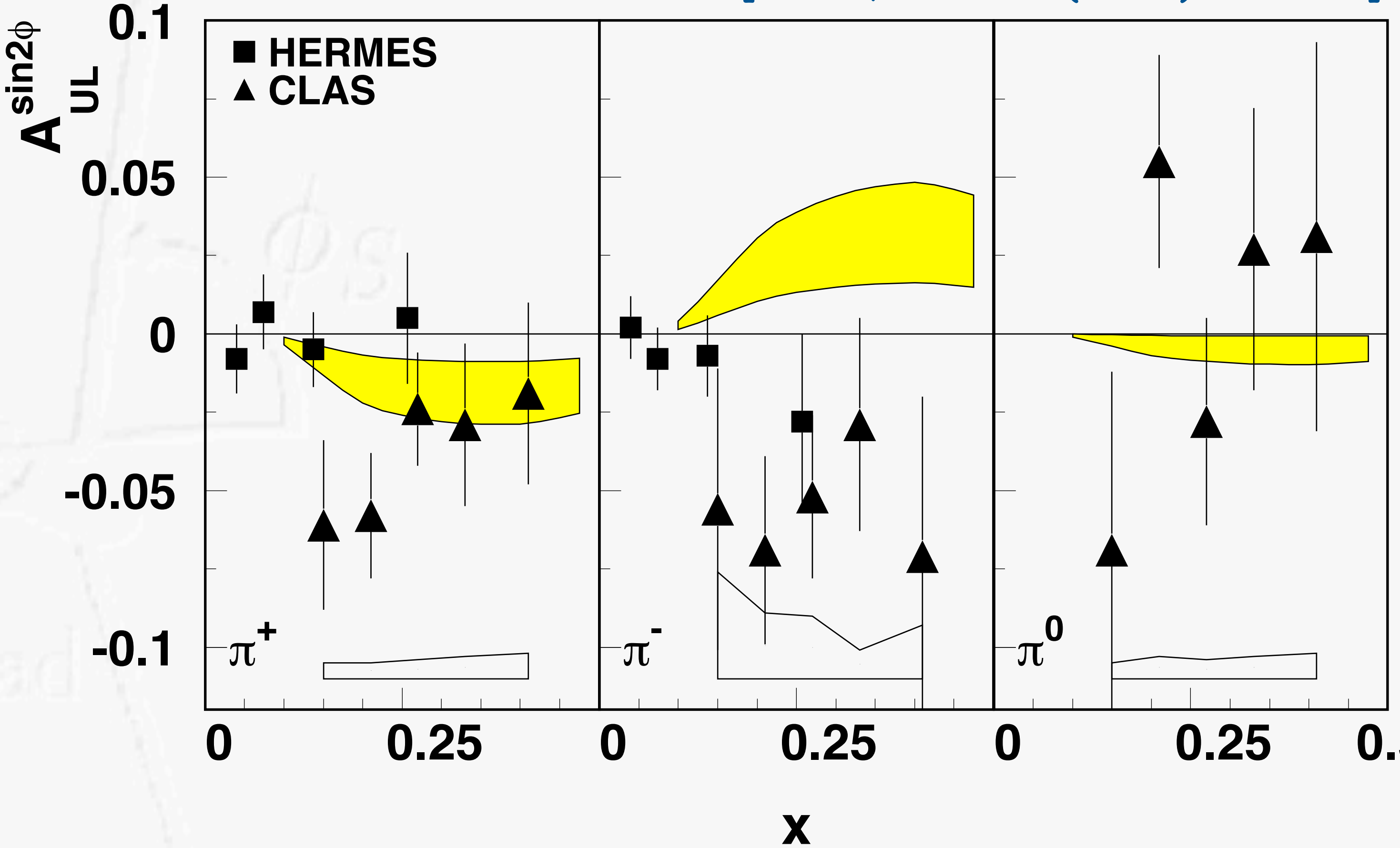


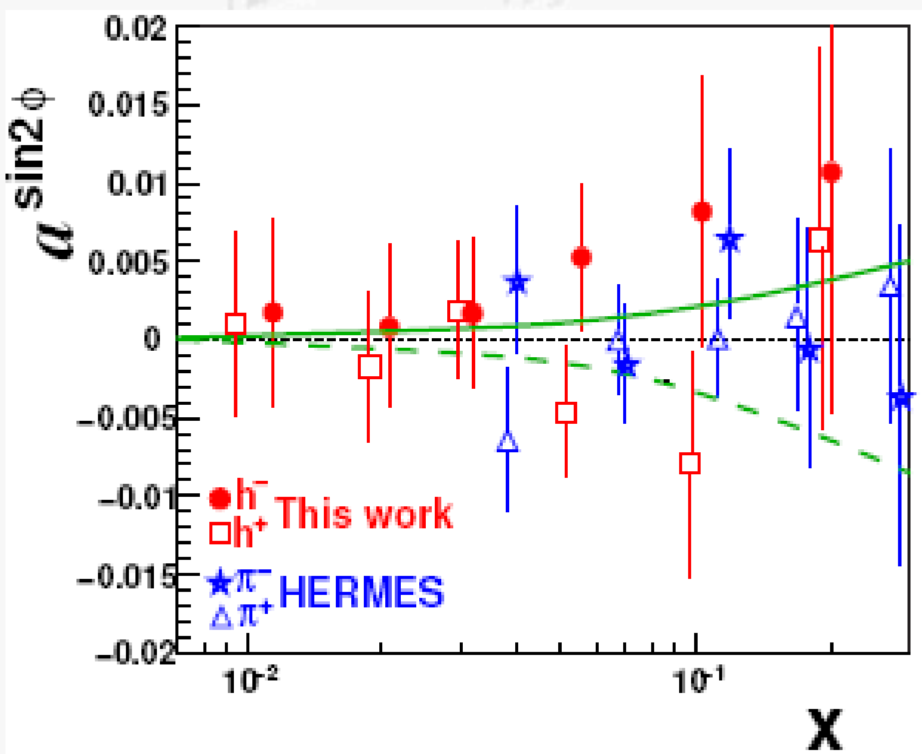
Worm-Gear I

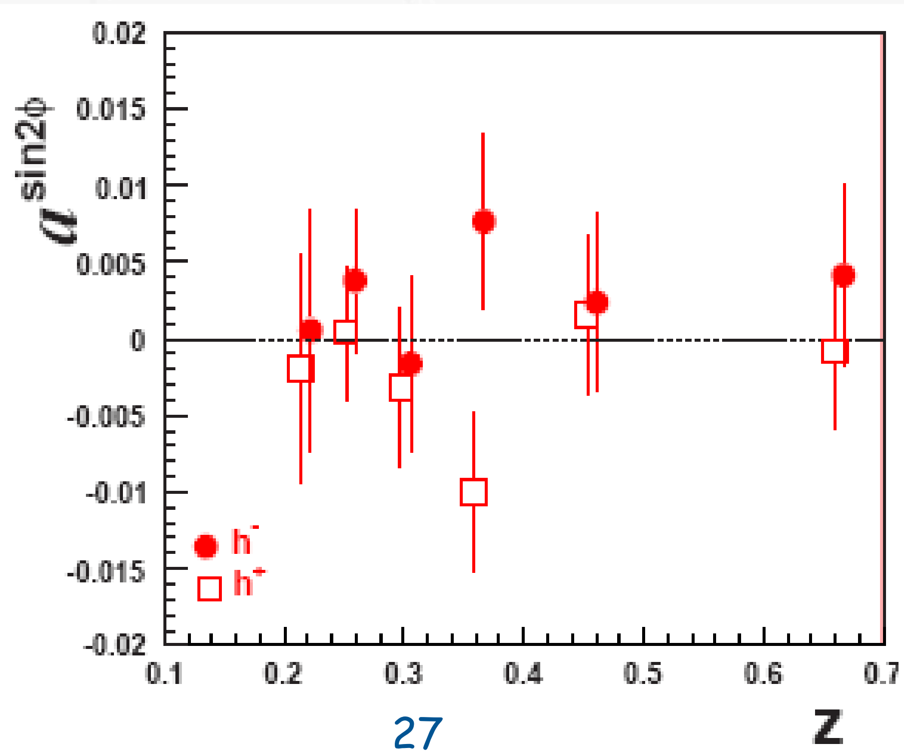
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

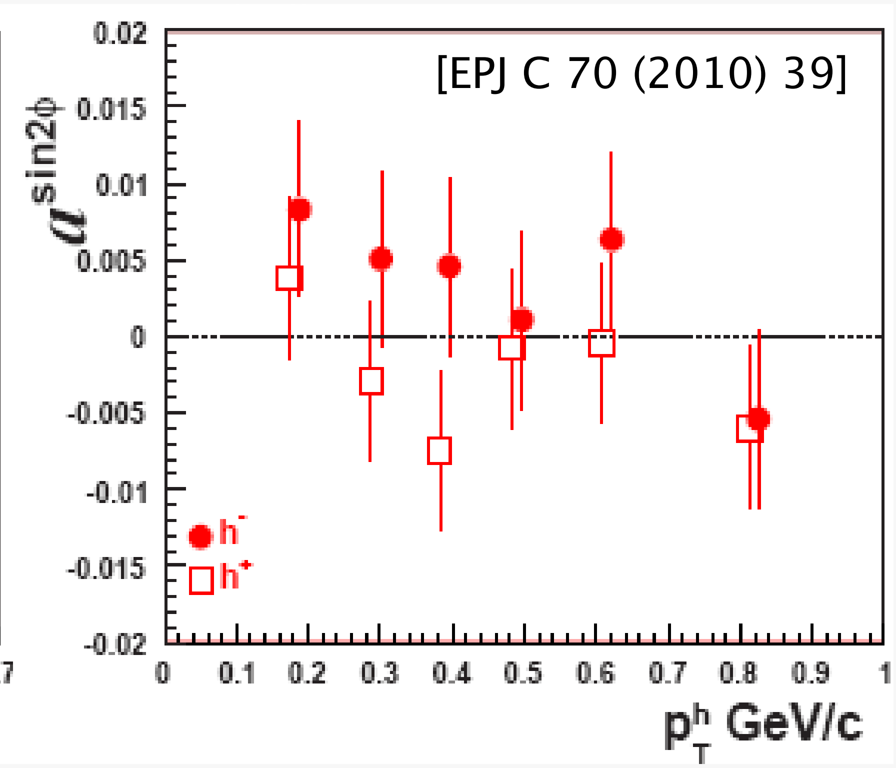
- again: chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES

[CLAS, PRL 105 (2010) 262002]







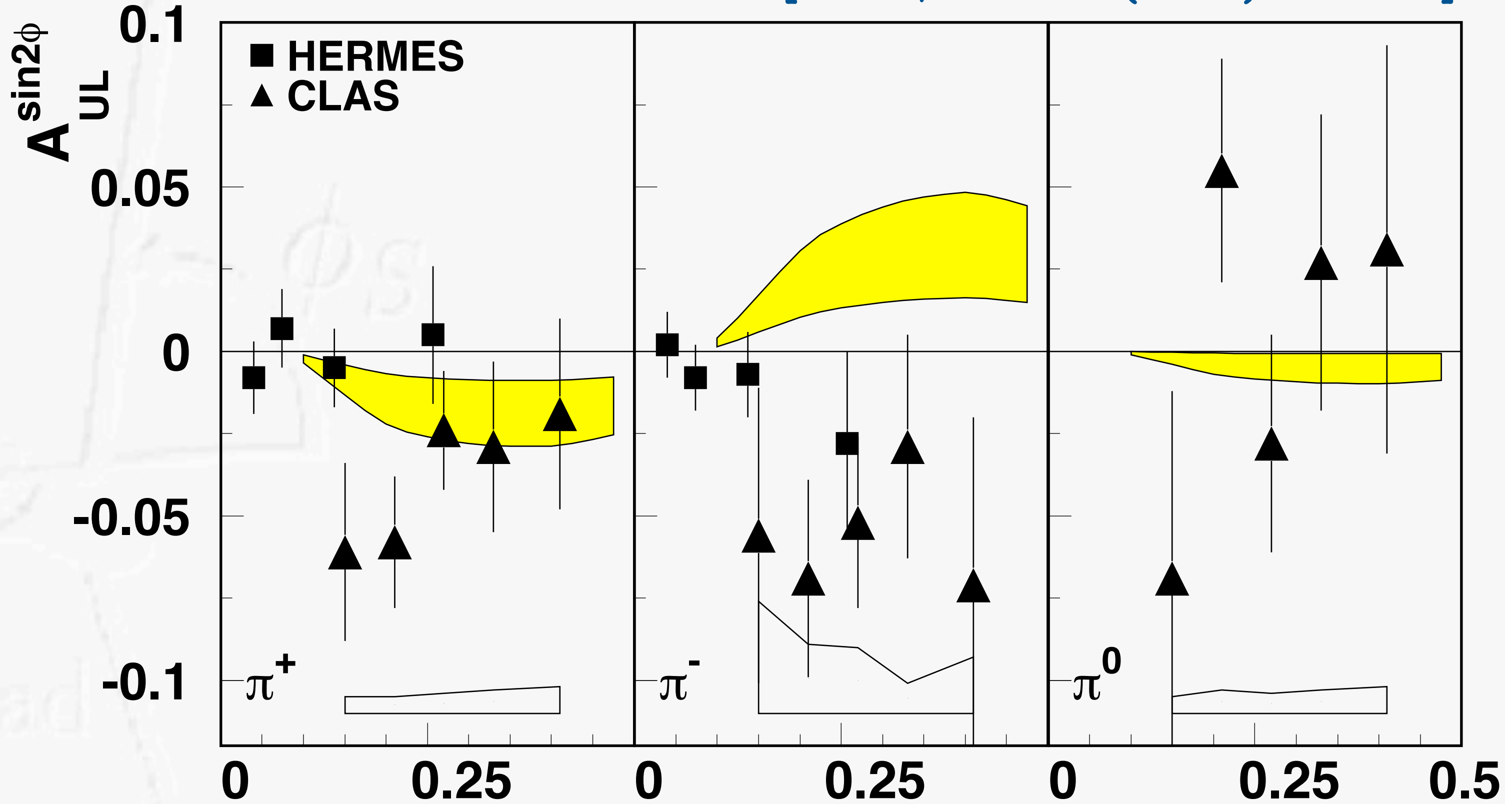


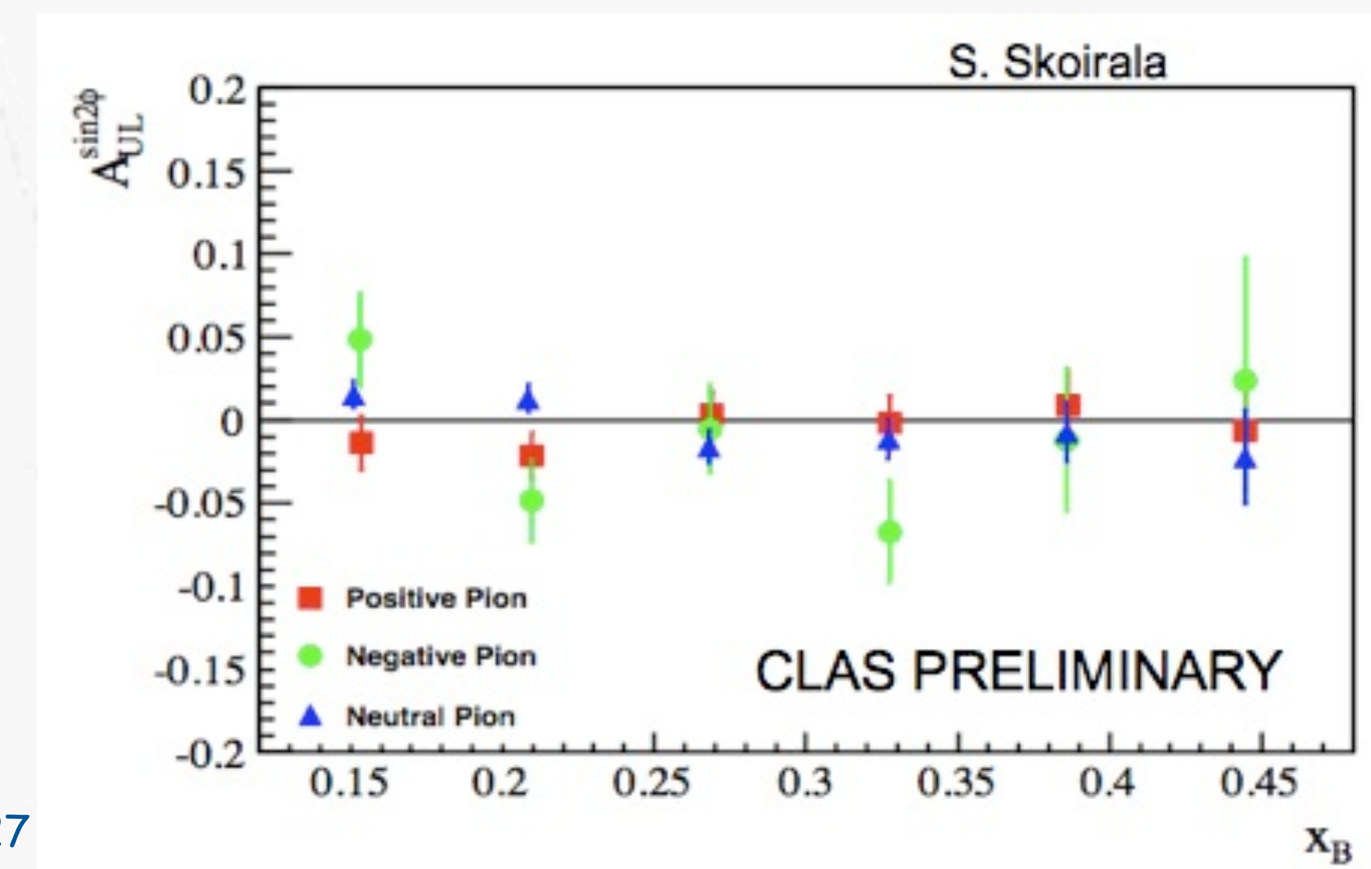
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Worm-Gear I

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

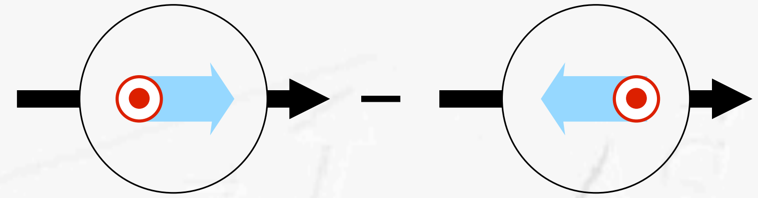
[CLAS, PRL 105 (2010) 262002]

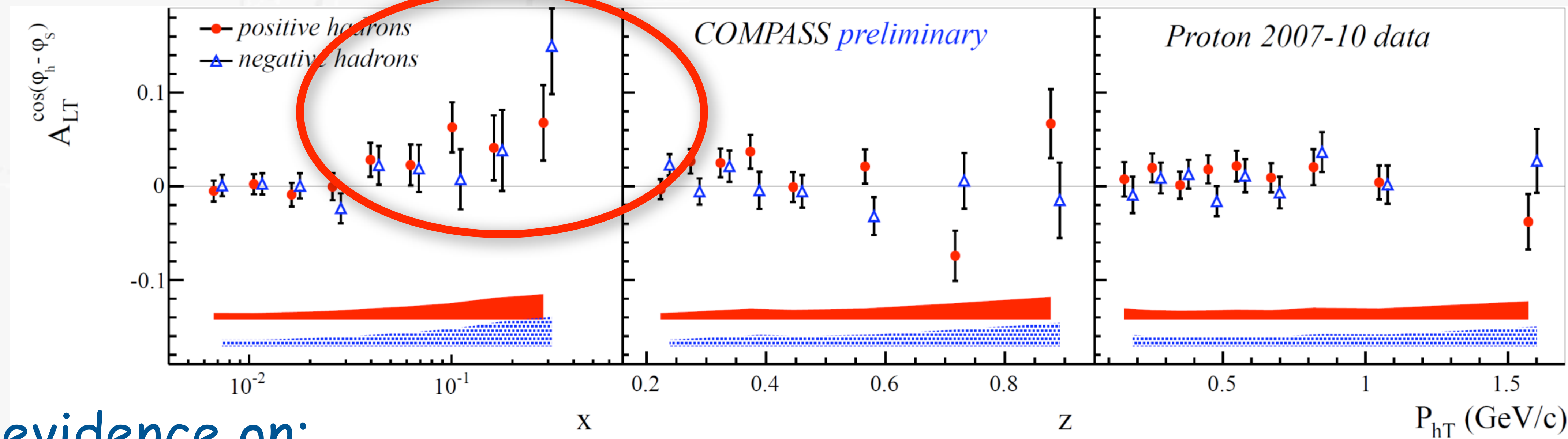




Worm-Gear II

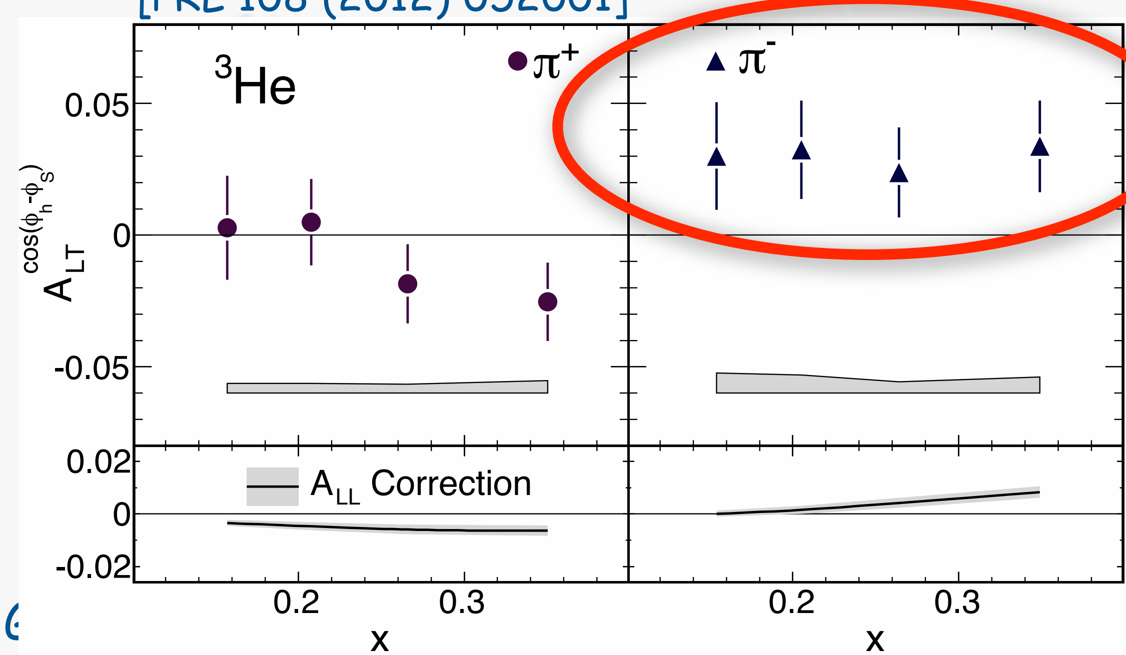
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

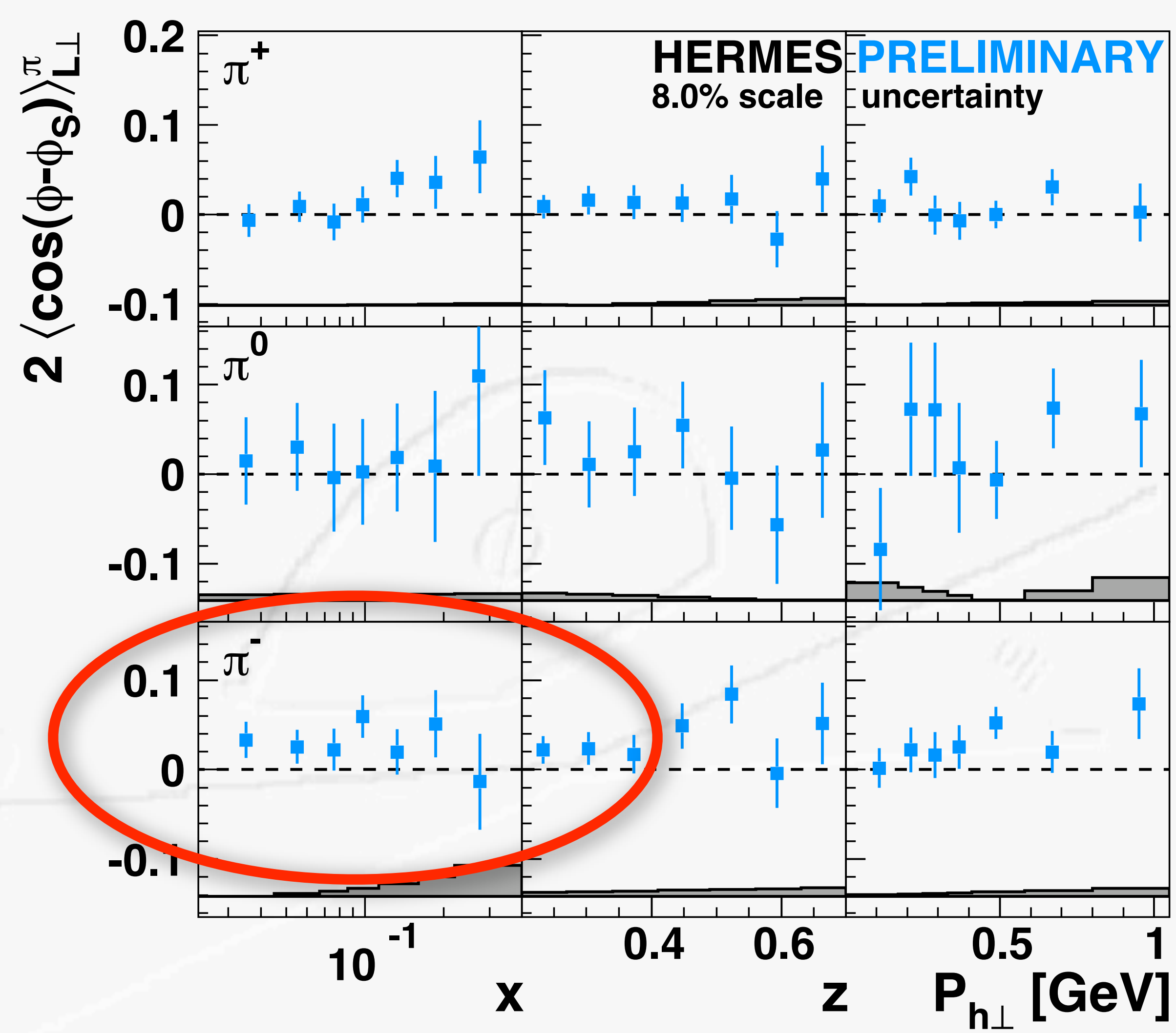


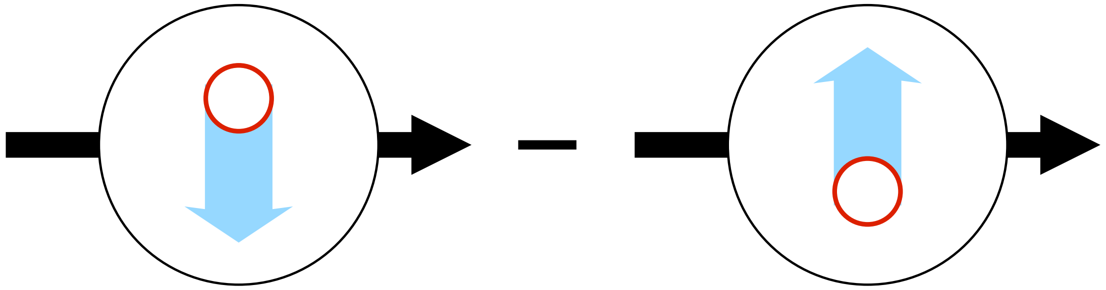


- first direct evidence on:
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

[PRL 108 (2012) 052001]

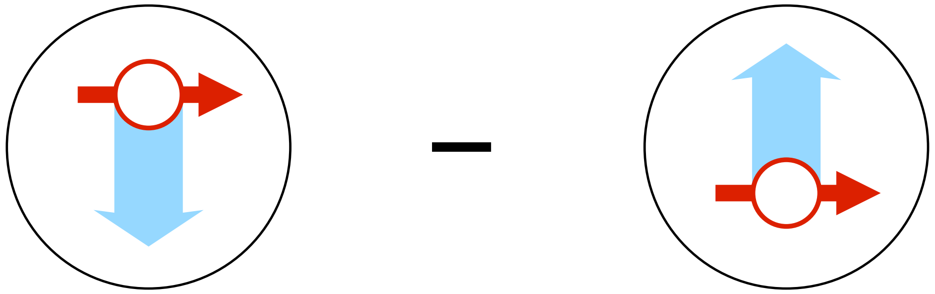






“Wilson-line physics”

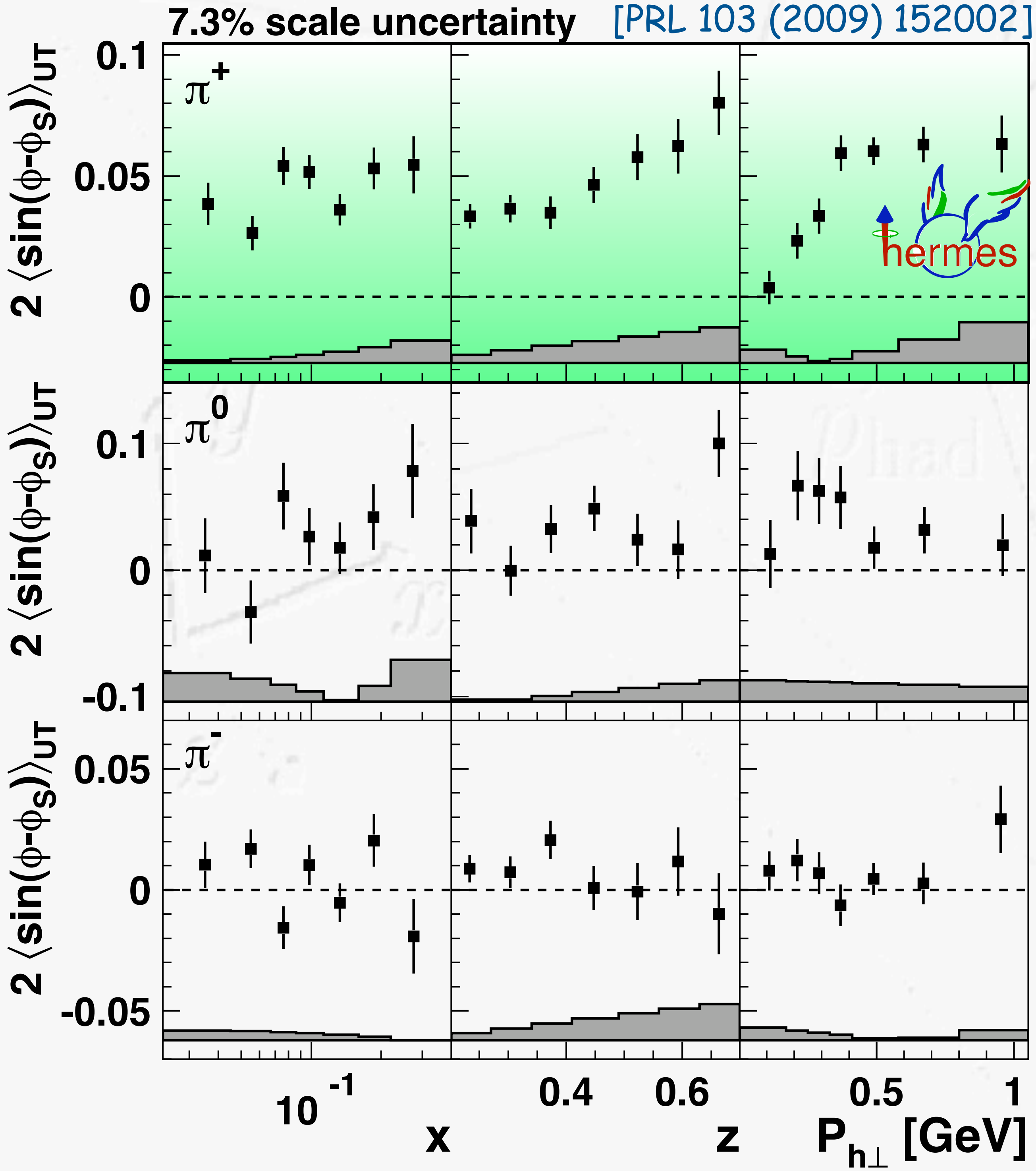
naively T-odd distributions



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

Sivers amplitudes for pions

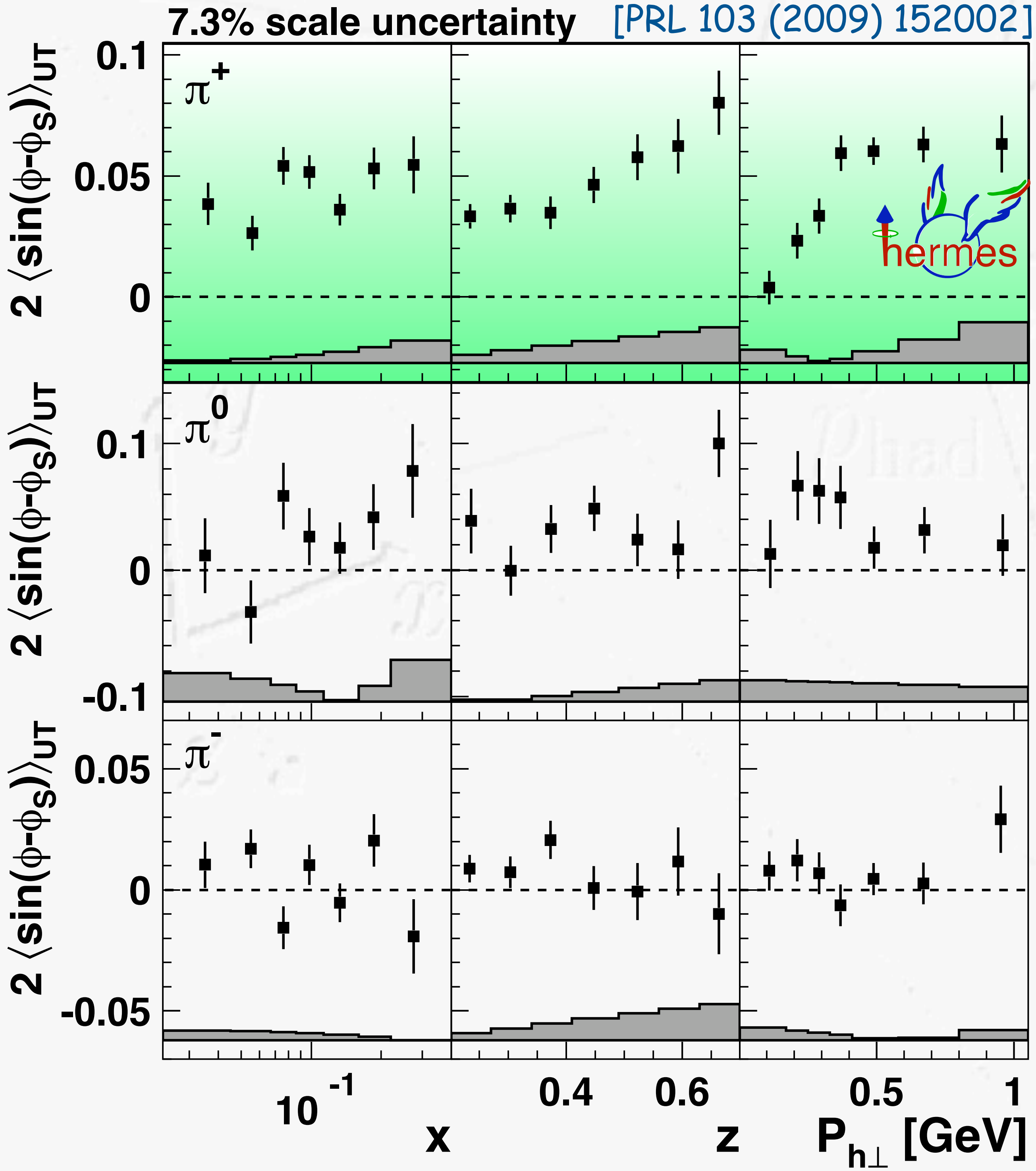
$$2\langle\sin(\phi-\phi_S)\rangle_{\rm UT} = -\frac{\sum_q e_q^2 f_{1\rm T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$



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

Sivers amplitudes for pions

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



π^+ dominated by u-quark scattering:

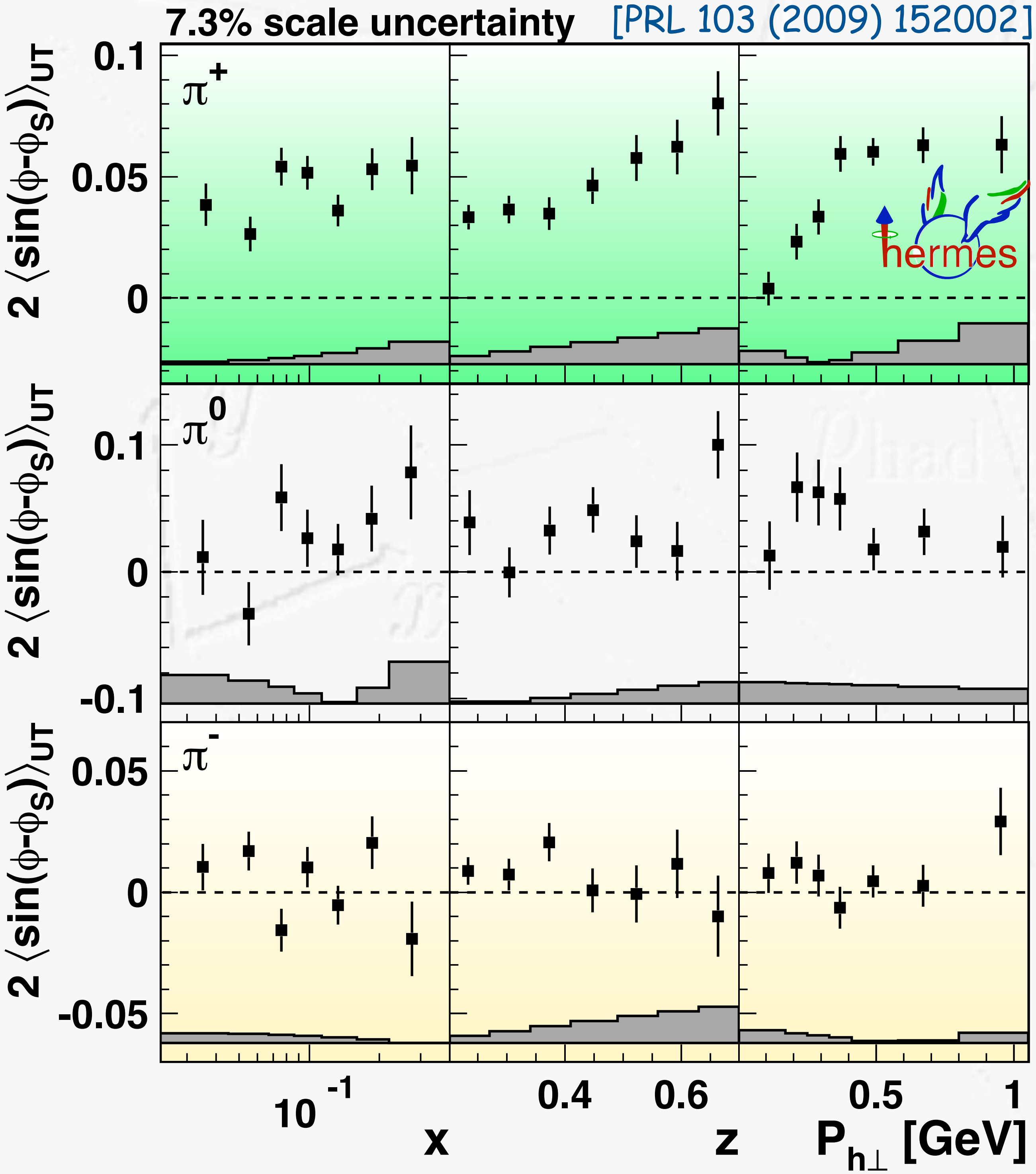
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

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

Sivers amplitudes for pions

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



π^+ dominated by u-quark scattering:

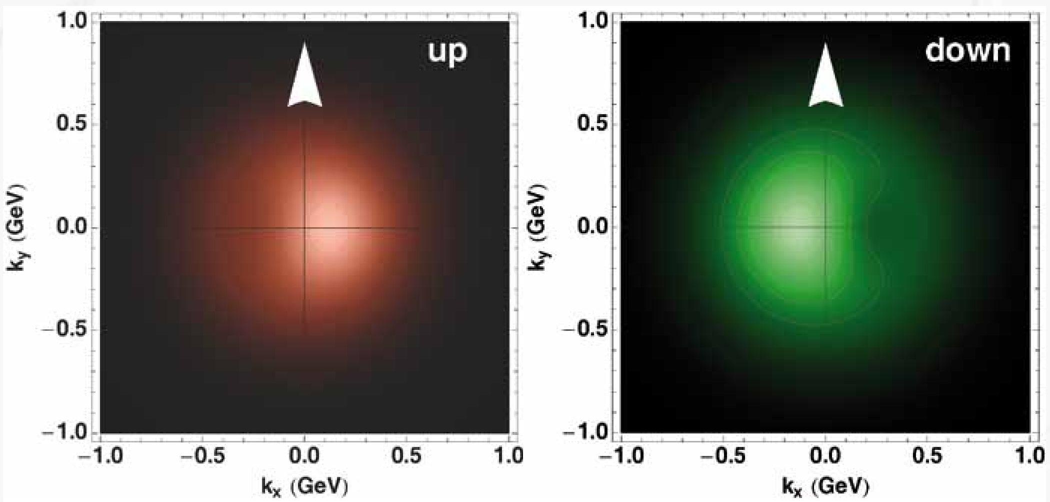
$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

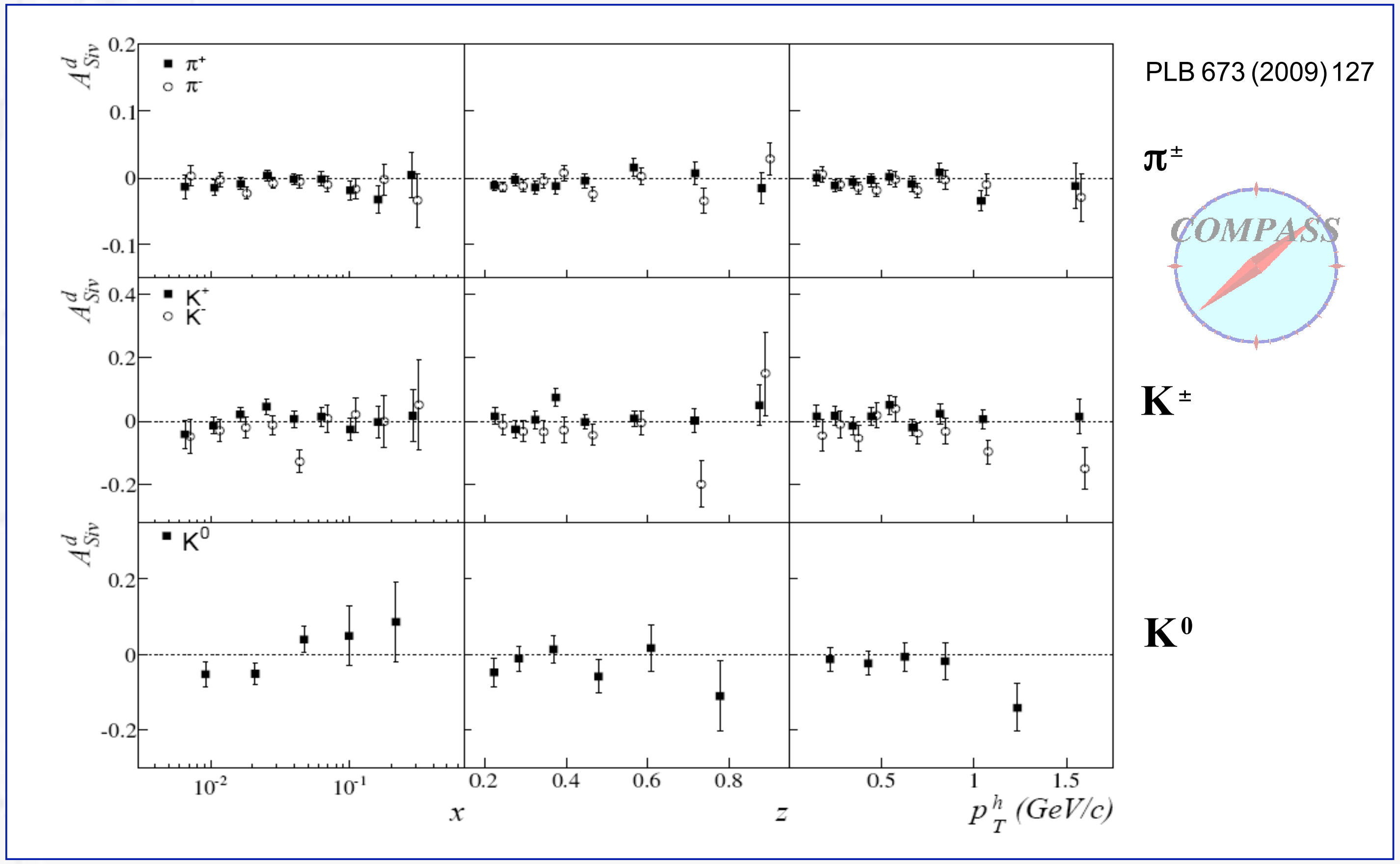
☛ d-quark Sivers DF > 0 (cancelation for π^-)

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

Sivers amplitudes



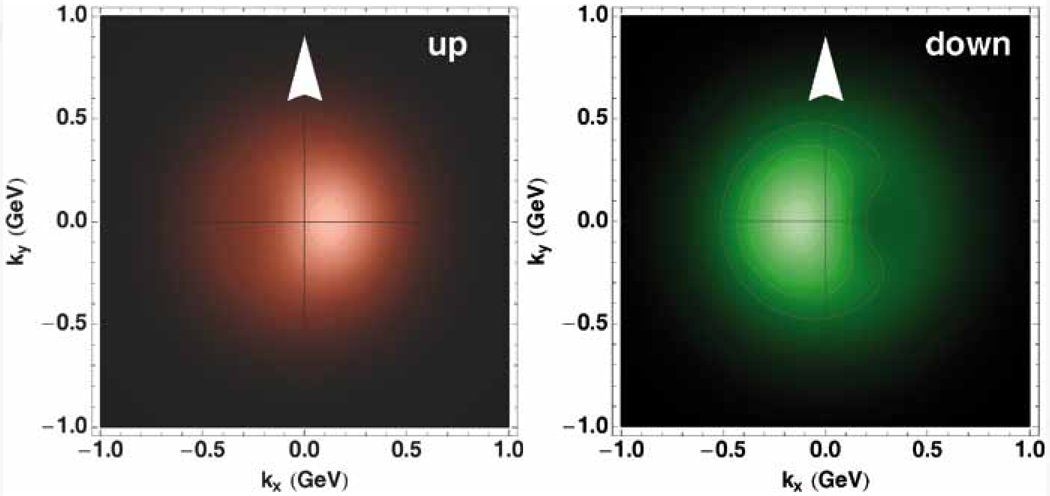
[courtesy of A. Bacchetta]



- cancelation for D target supports opposite signs of up and down Sivers

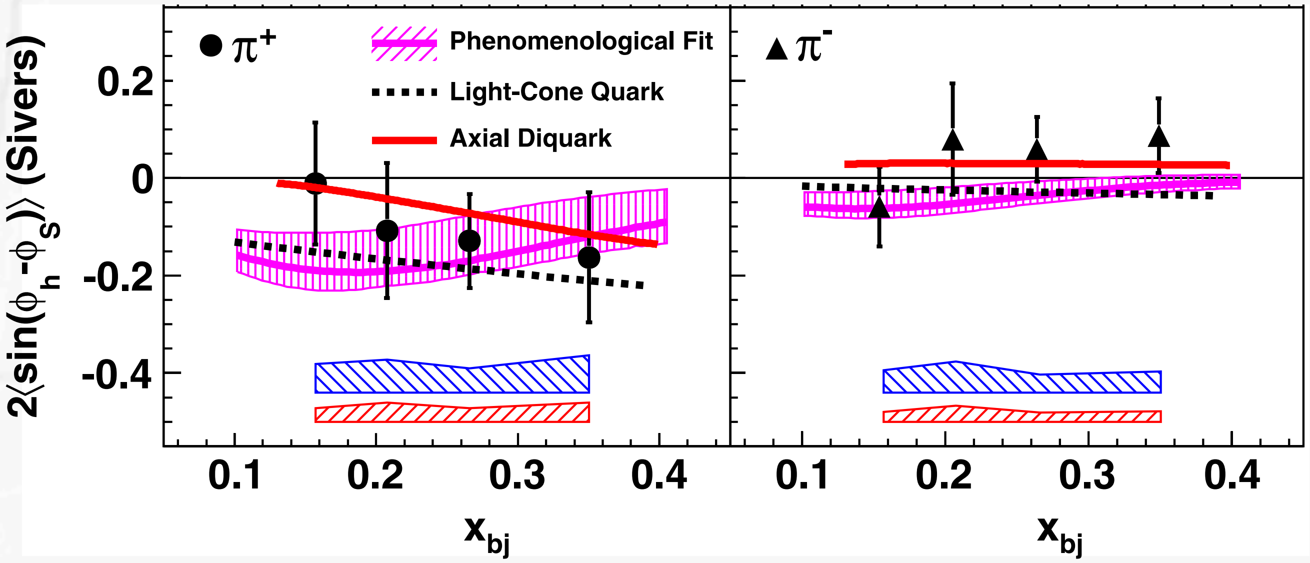
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

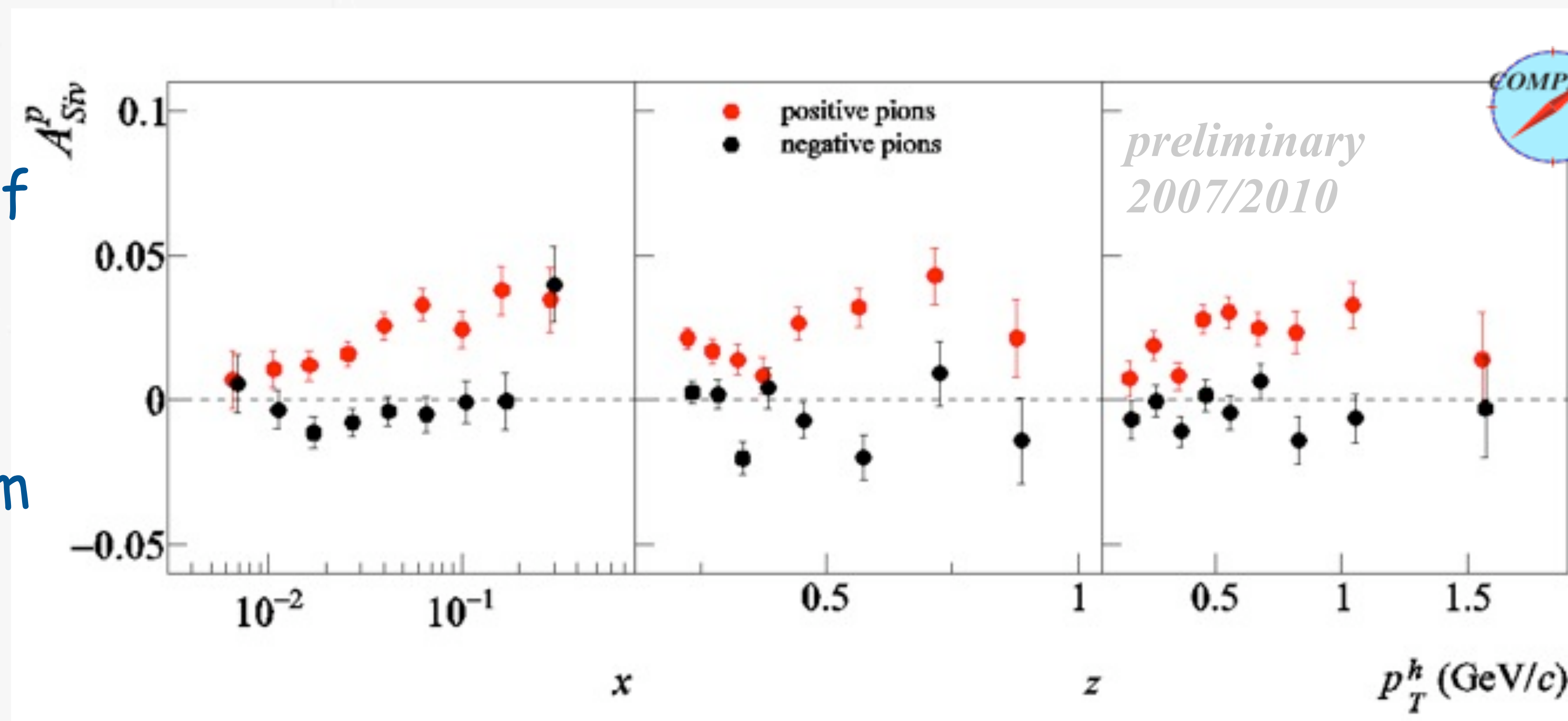
Sivers amplitudes



[courtesy of A. Bacchetta]

[PRL 107 (2011) 072003]



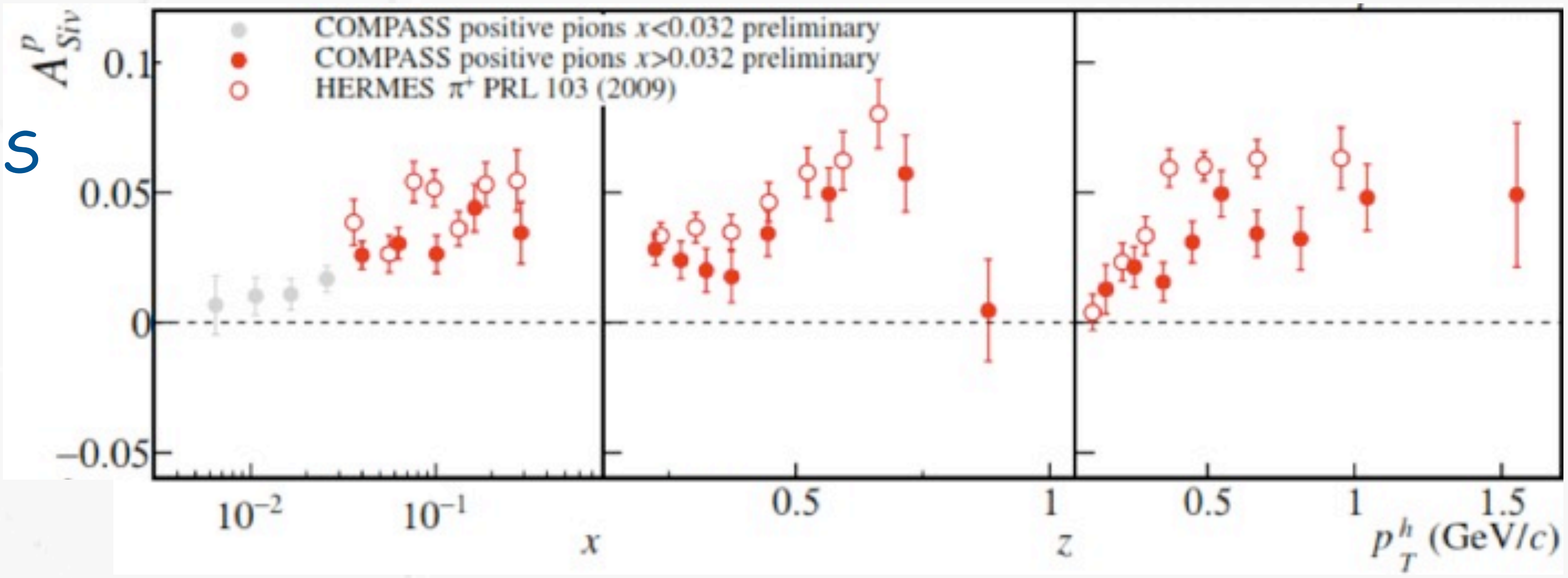


- cancelation for D target supports opposite signs of up and down Sivers
- new results from JLab using ^{3}He target and from COMPASS for proton target

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

Sivers amplitudes Q^2 dependence?

- slightly larger amplitudes at HERMES
- average Q^2 about factor 3 larger at COMPASS



	U	L	T
U	f_1		$h_1^\perp$
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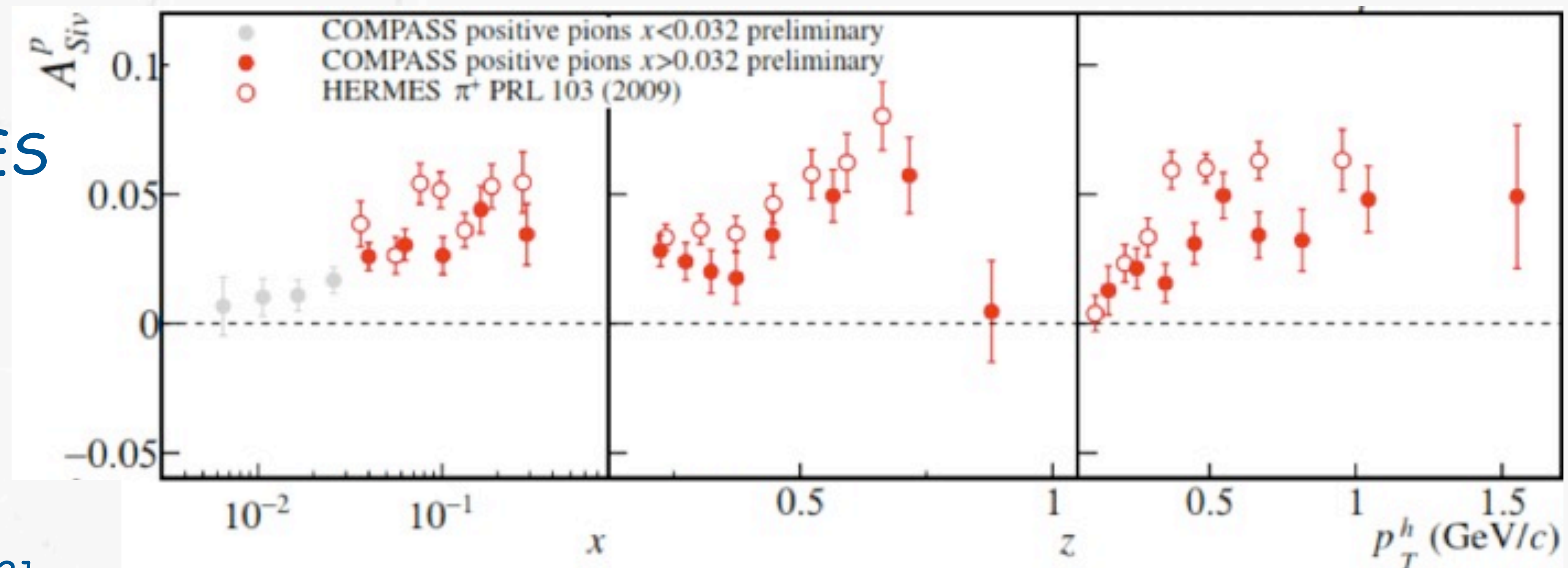
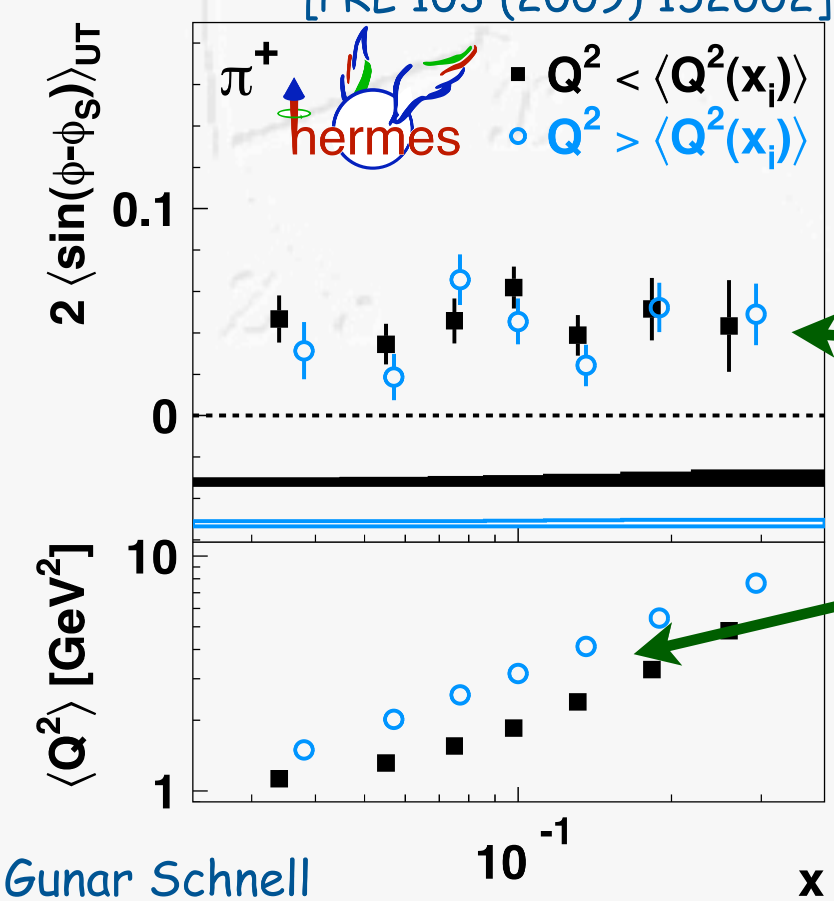
Sivers amplitudes Q^2 dependence?

- slightly larger amplitudes at HERMES
- average Q^2 about factor 3 larger at COMPASS



[PRL 103 (2009) 152002]



nothing seen at HERMES

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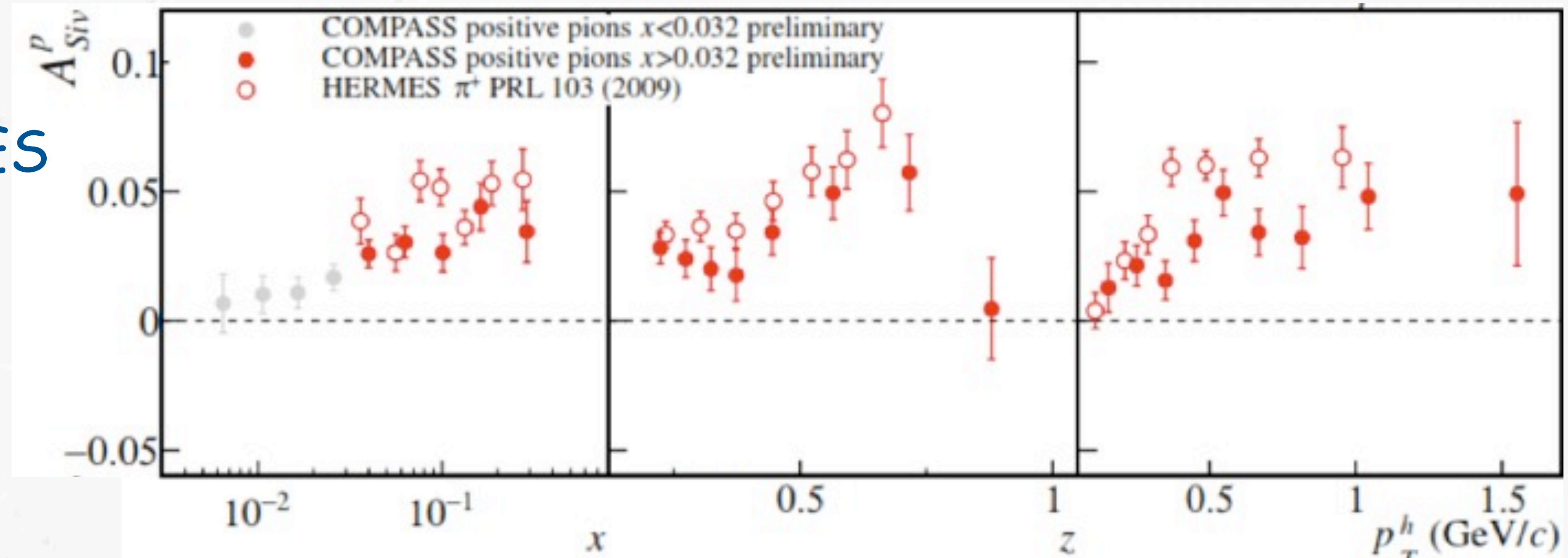
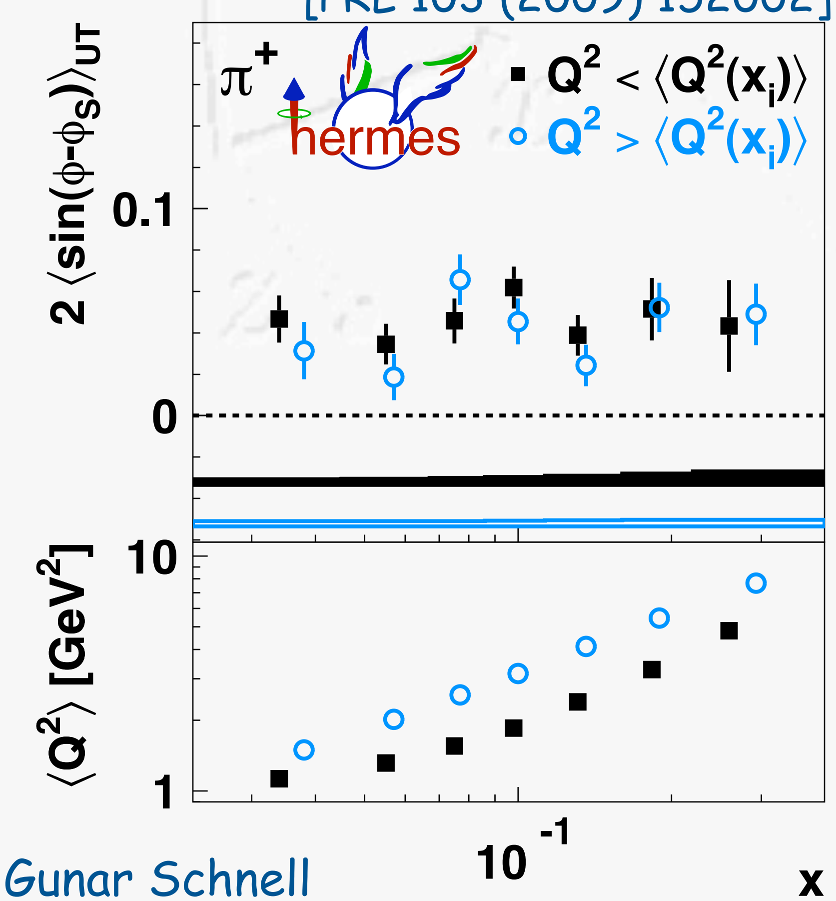
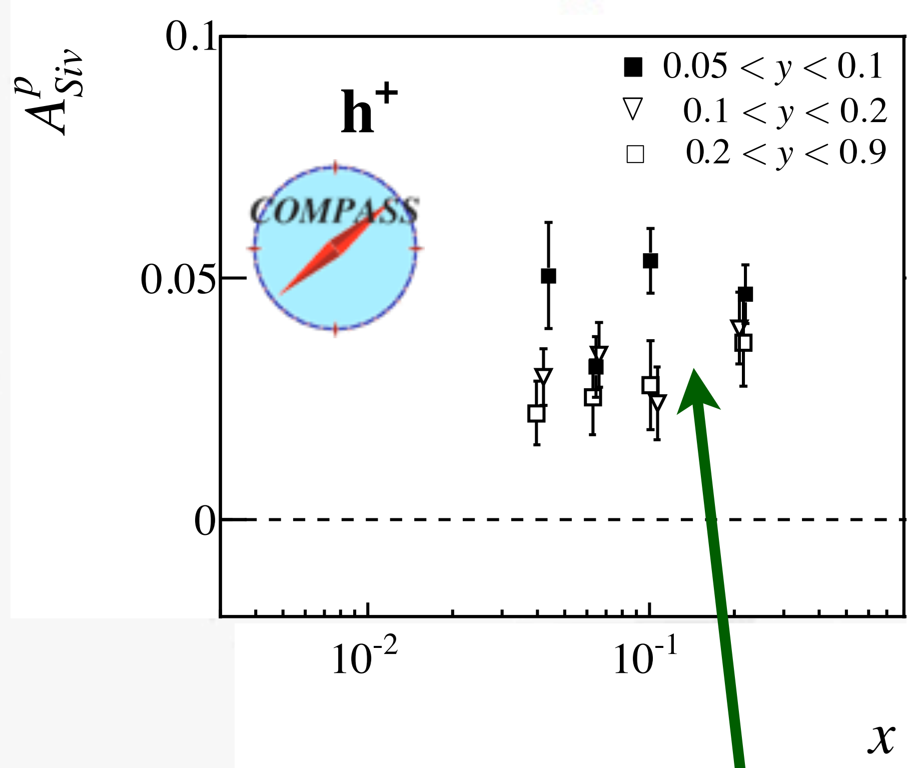
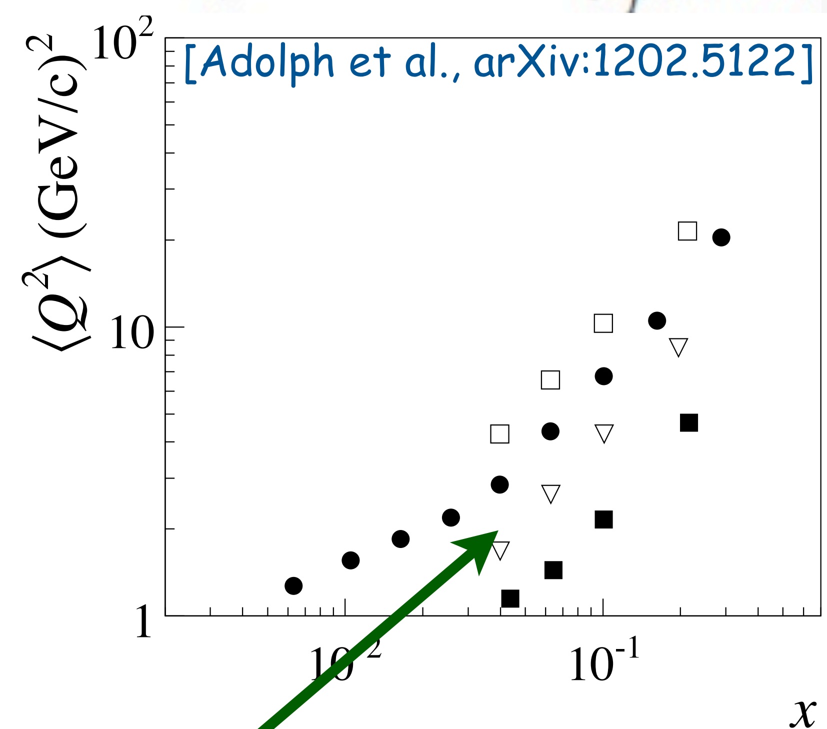


[PRL 103 (2009) 152002]



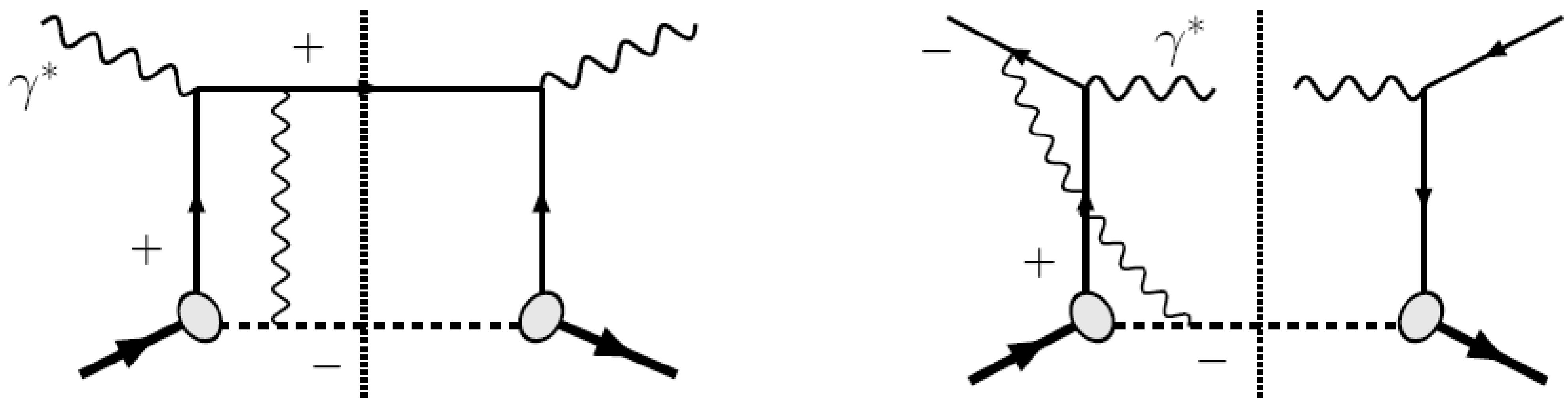




is y-dependence a Q^2 dependence? Evolution?

Process dependence

simple QED example



DIS: attractive

Drell-Yan: repulsive

Process dependence

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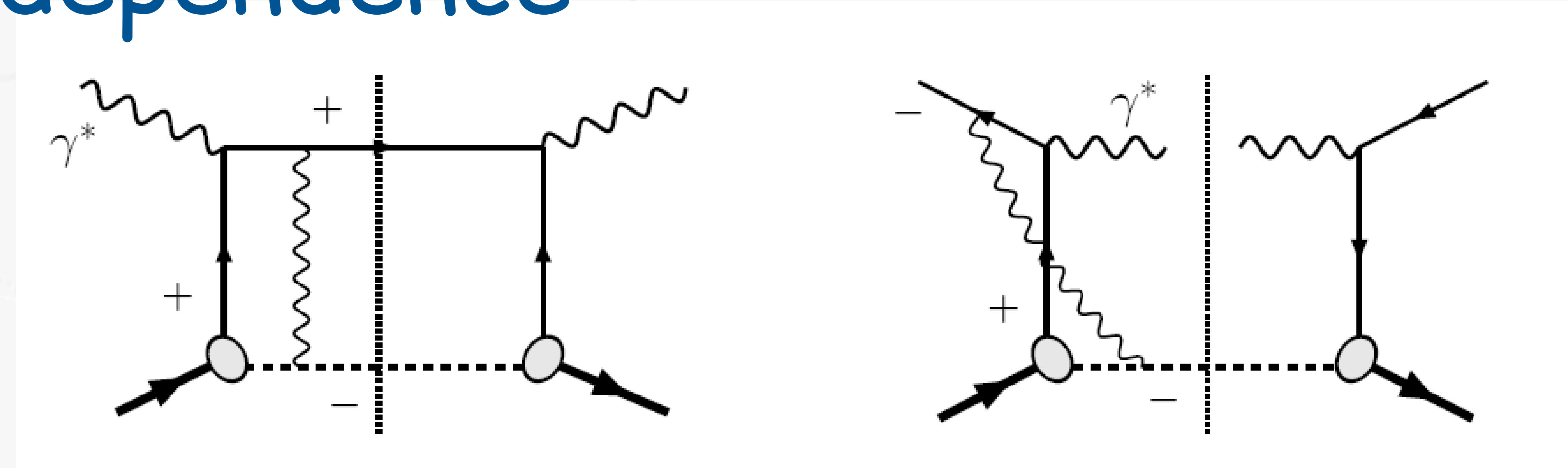
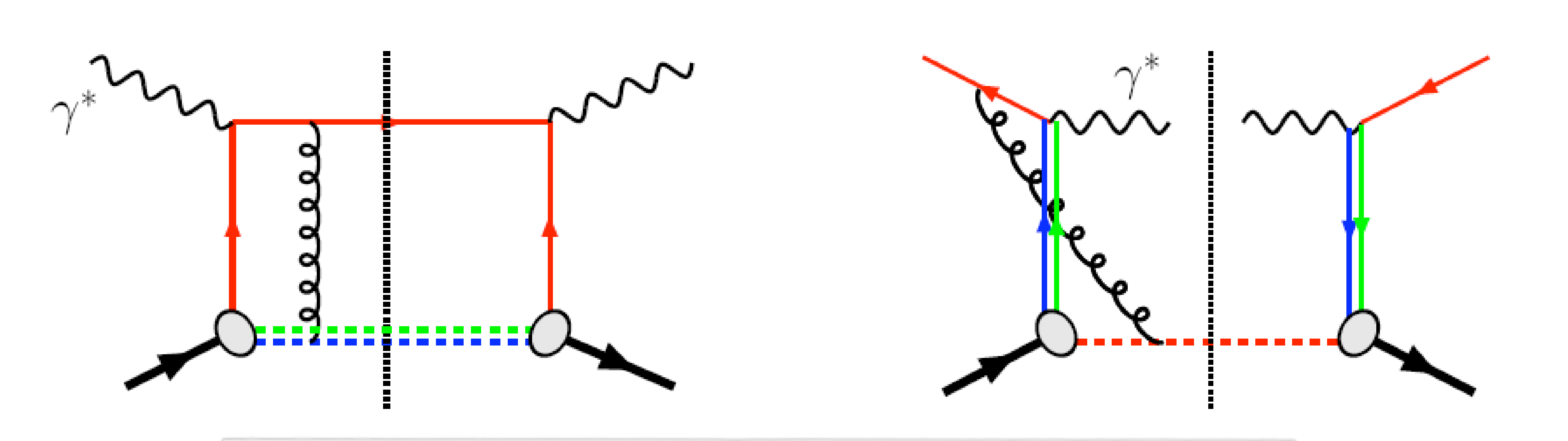


DIS: attractive

Drell-Yan: repulsive

add color: QCD



result: Sivers$|_{DIS}$ = - Sivers$|_{DY}$

Process dependence

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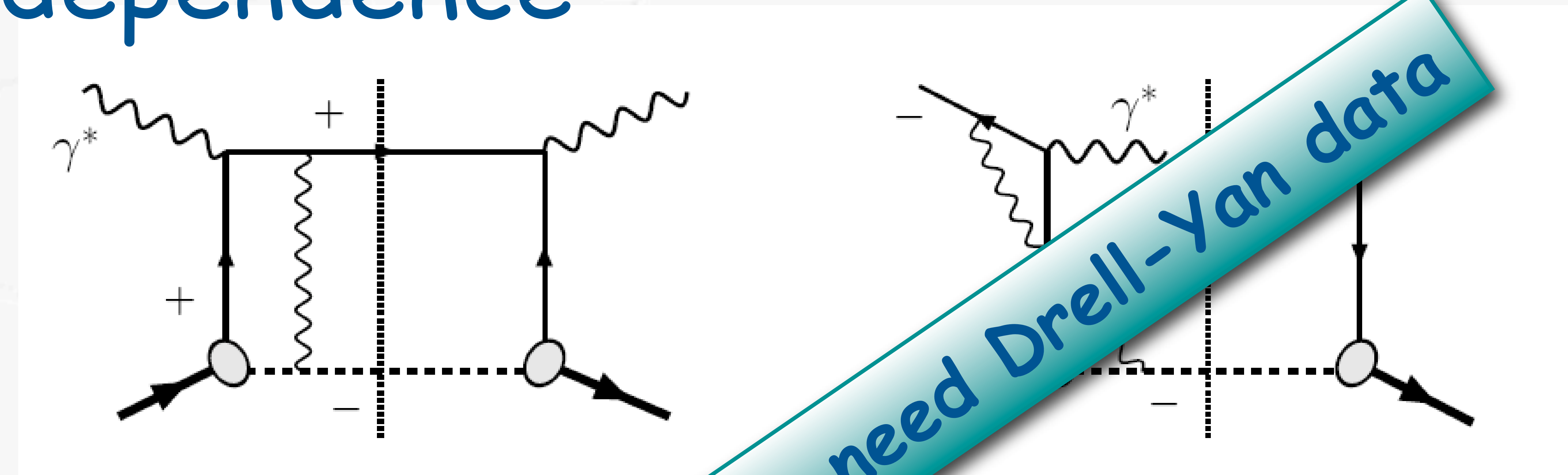

DIS: attracti[...] | Drell-Yan: repulsive

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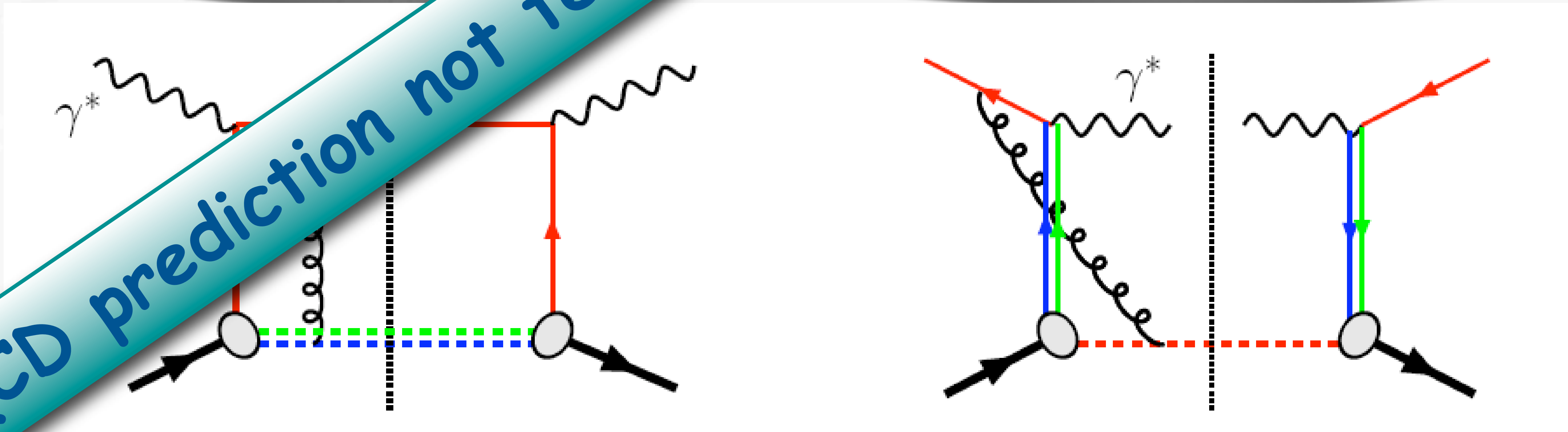


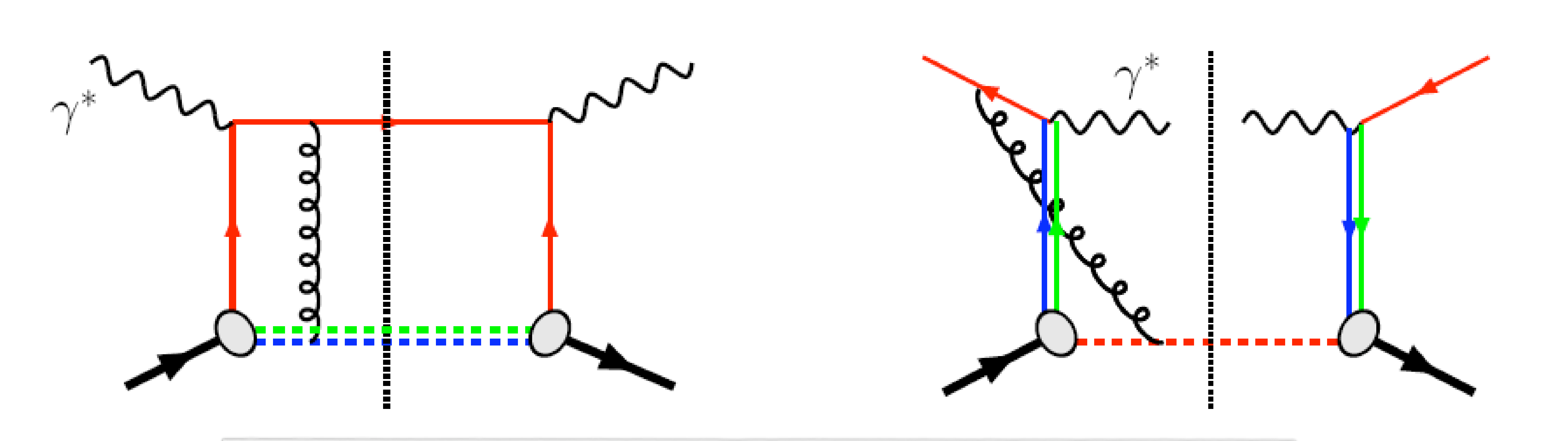
result: Sivers|DIS = - Sivers|DY

rigorous QCD prediction not tested!! - need Drell-Yan data

Process dependence

need Drell-Yan experiments with transverse polarization:
COMPASS, transverse SeaQuest, RHIC, ... ?

add color:
QCD

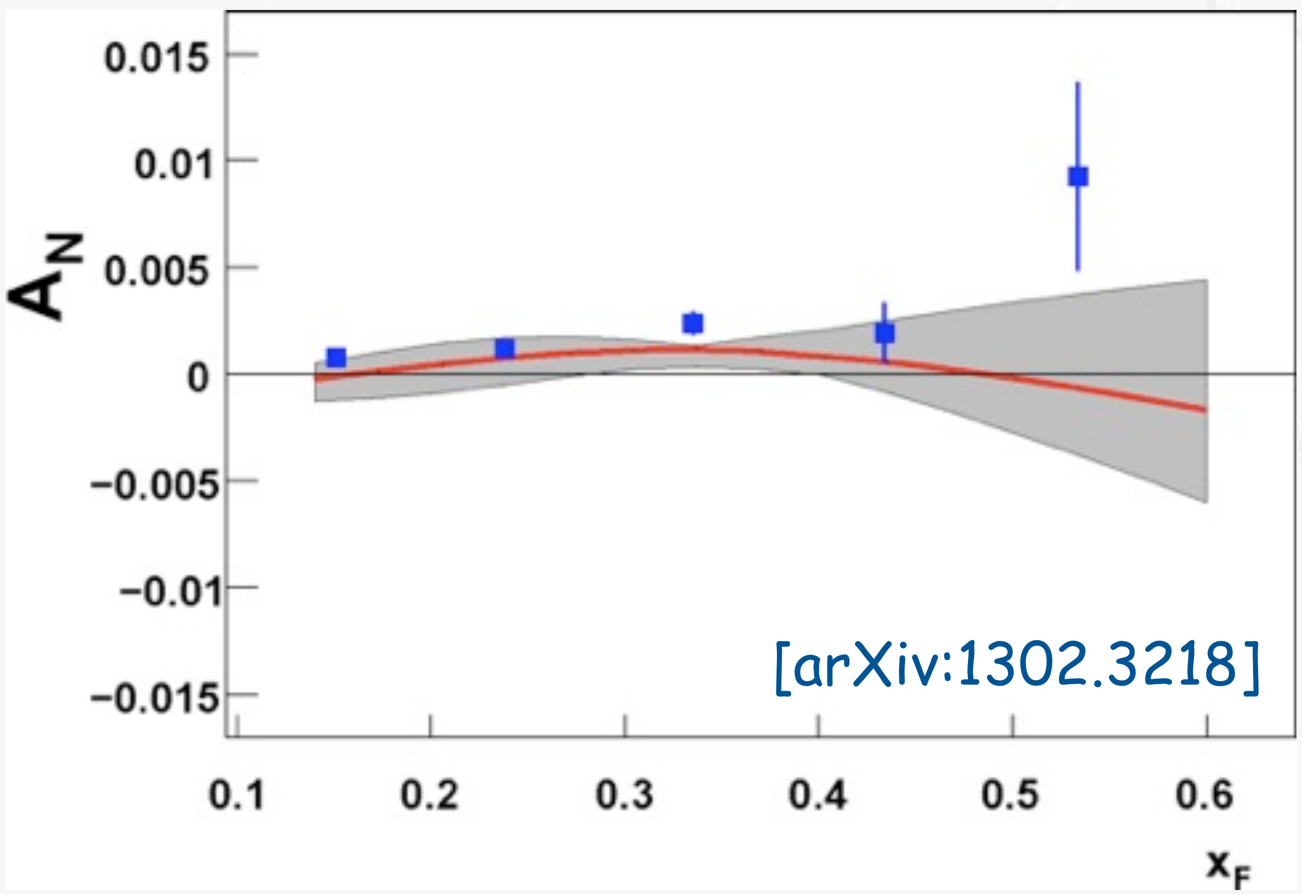


result: Sivers$|_{DIS}$ = - Sivers$|_{DY}$

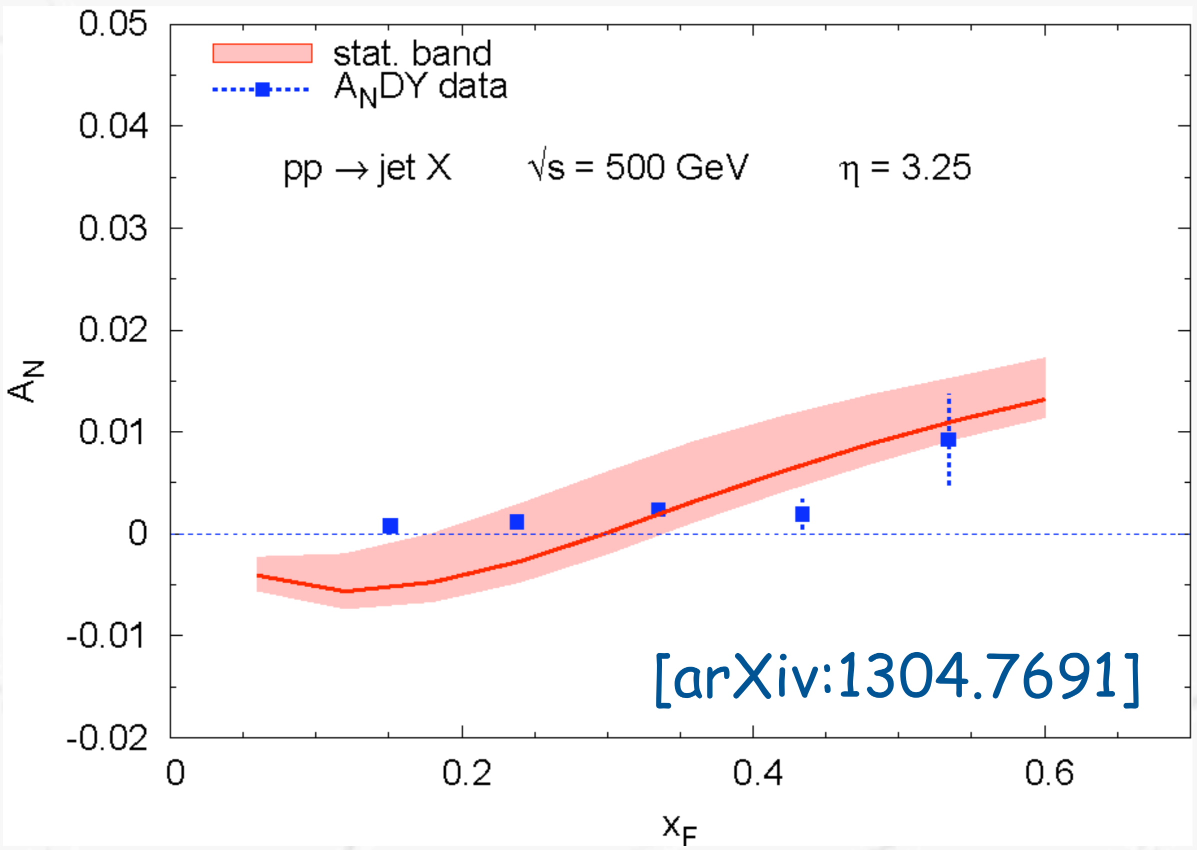
… not quite Drell-Yan yet: jet SSA

- no sensitivity to fragmentation details: $p^{\uparrow}p \rightarrow \text{jet} + X$
  - Sivers-type mechanism (use Sivers fctn from SIDIS fits)

data from [A_NDY Collaboration, arXiv:1304.1454]



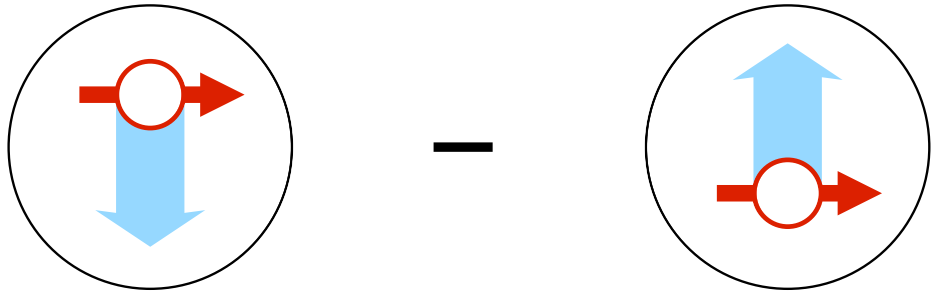
Includes initial- and final-state color-charge interactions



Excludes initial- and final-state color-charge interactions

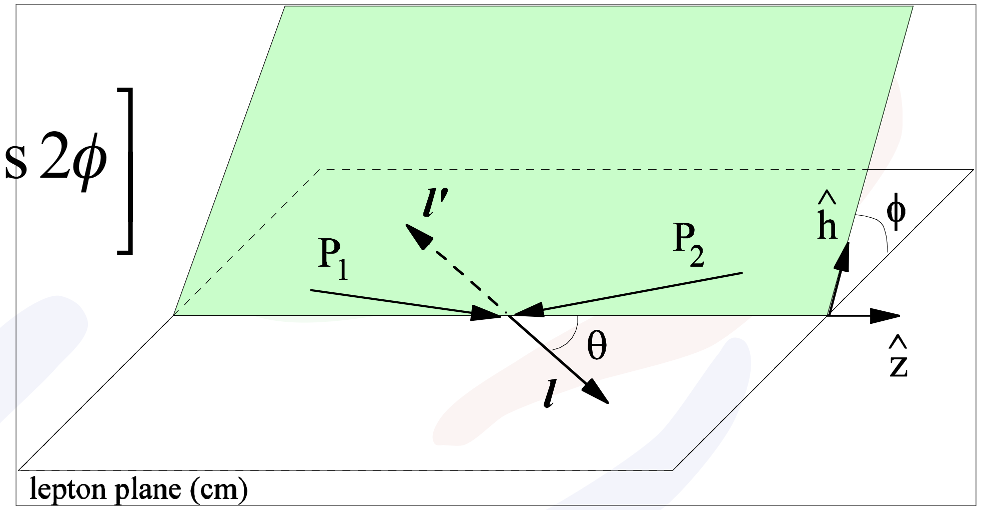
Boer-Mulders

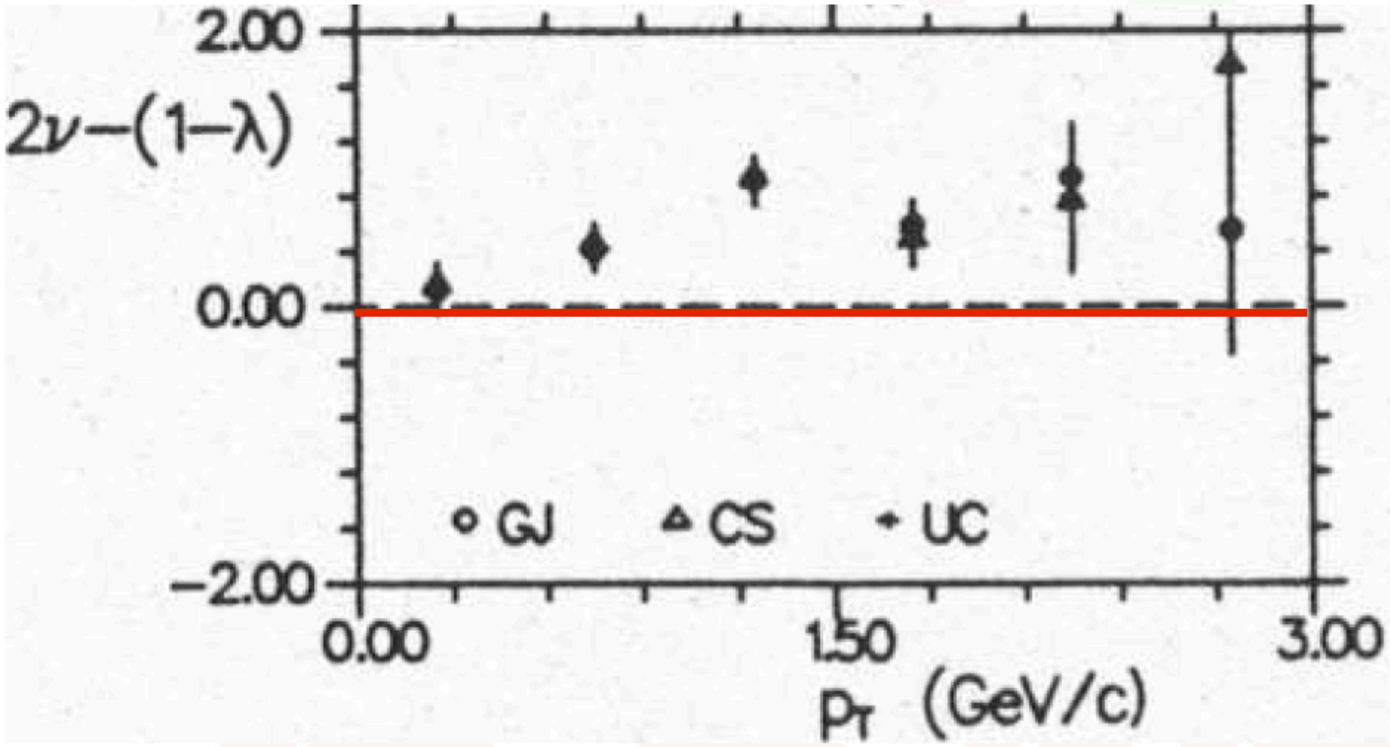
spin-effects in unpolarized reactions



Unpolarized Drell-Yan

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





$$1 - \lambda - 2\nu = 0$$

Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

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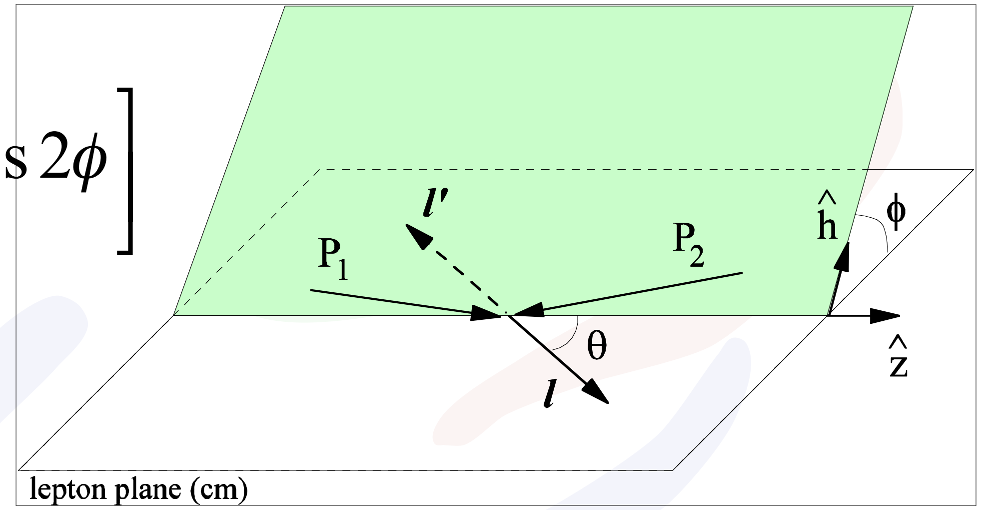

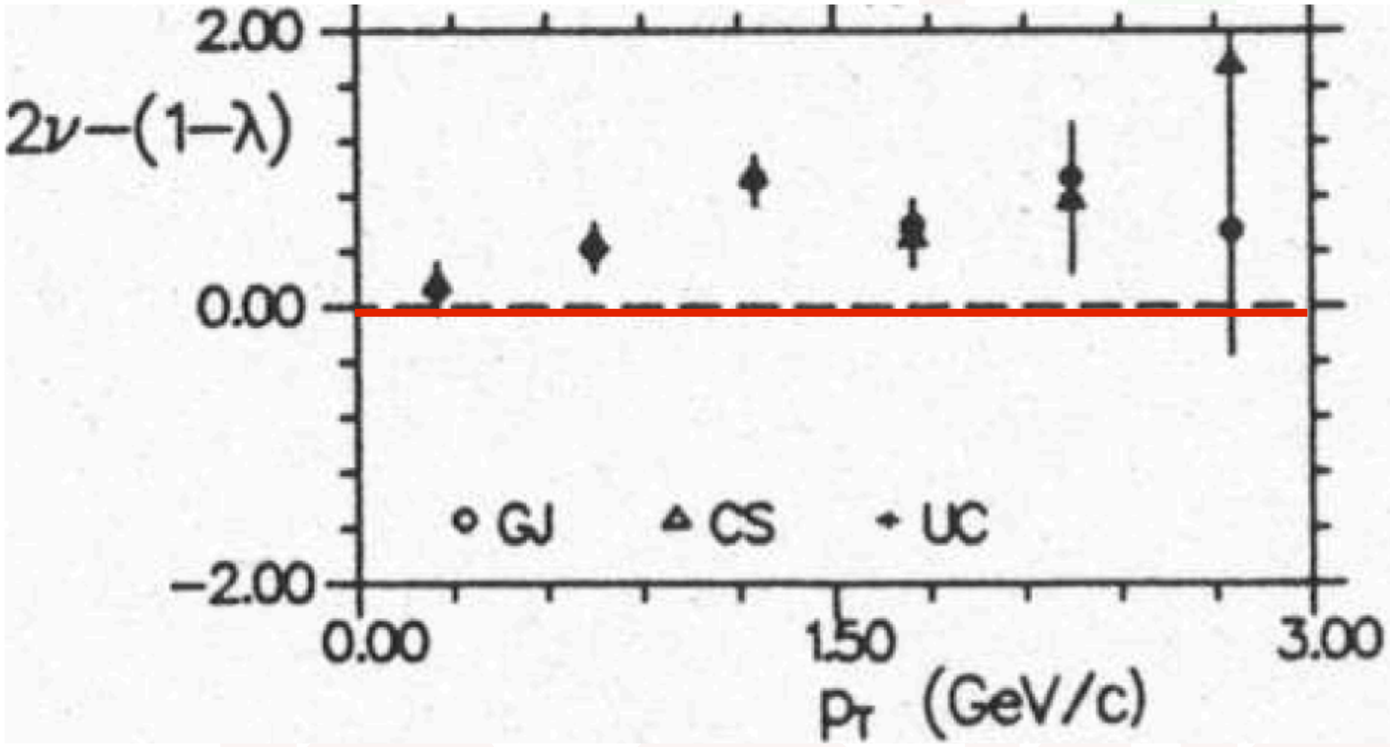

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- "failure" of collinear pQCD

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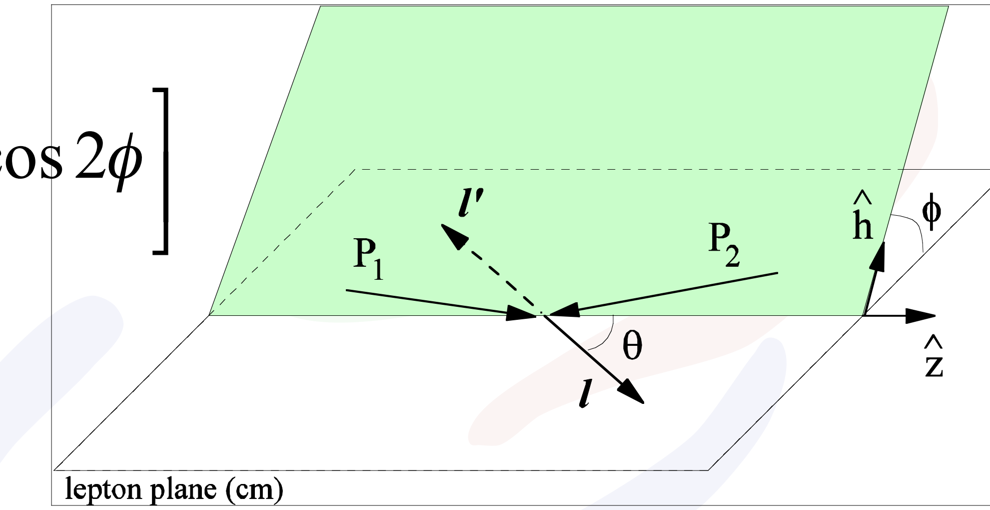

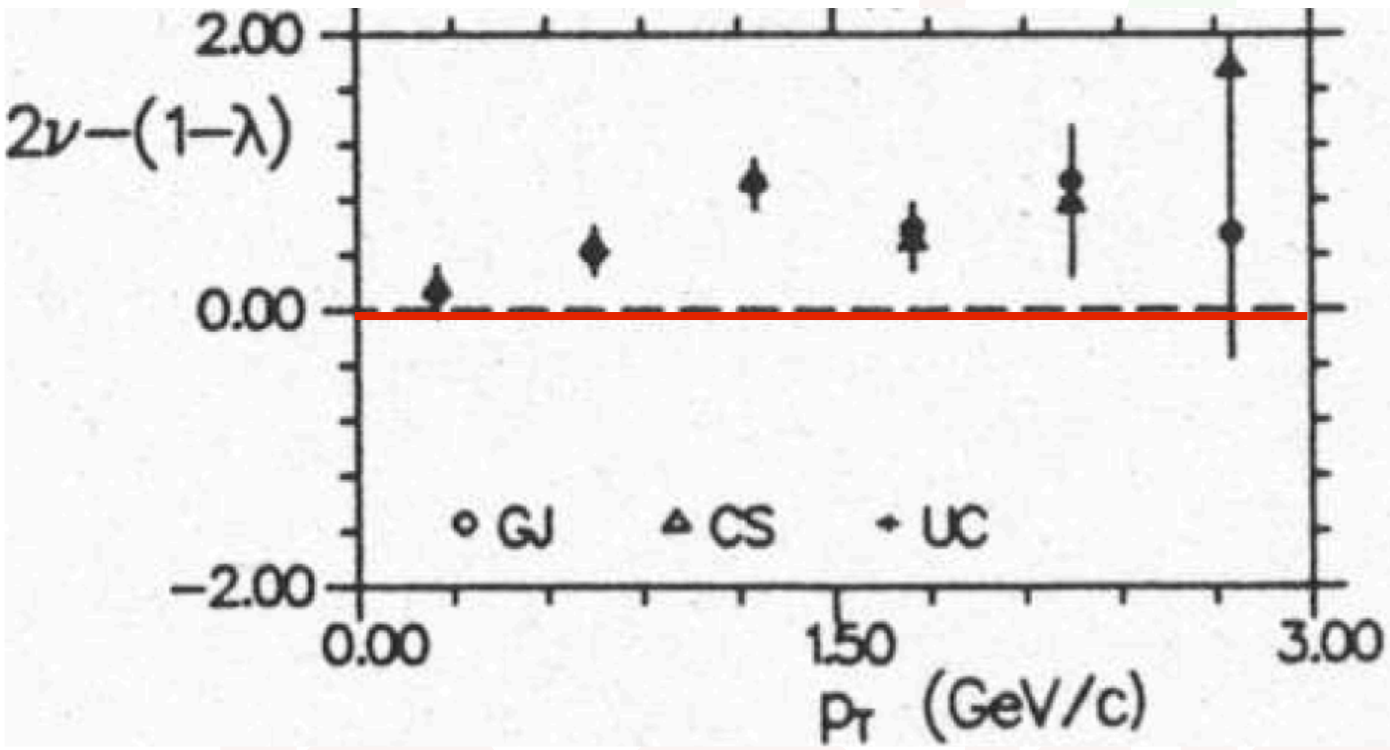

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Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

- **"failure" of collinear pQCD**
- **possible source: Boer-Mulders effect**

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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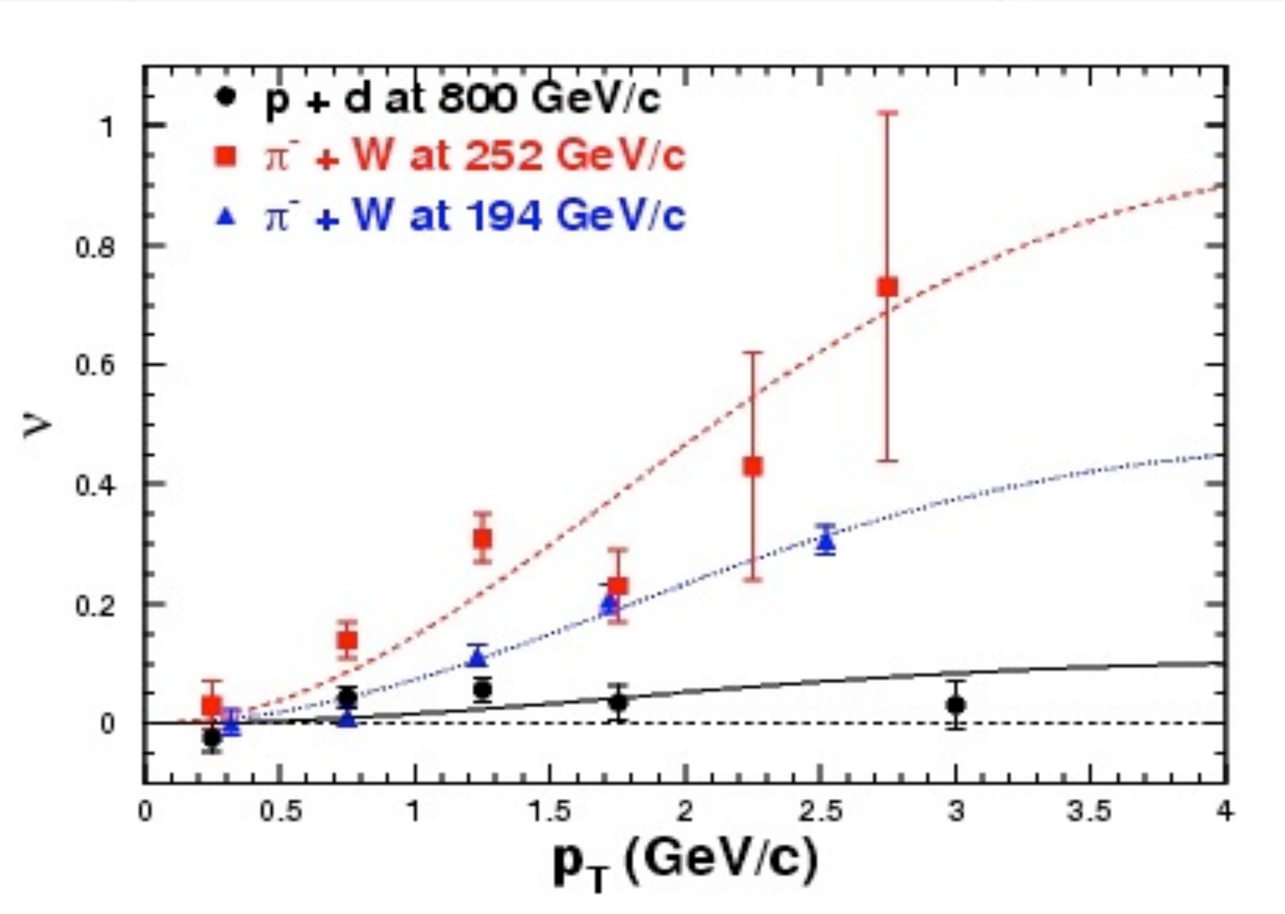
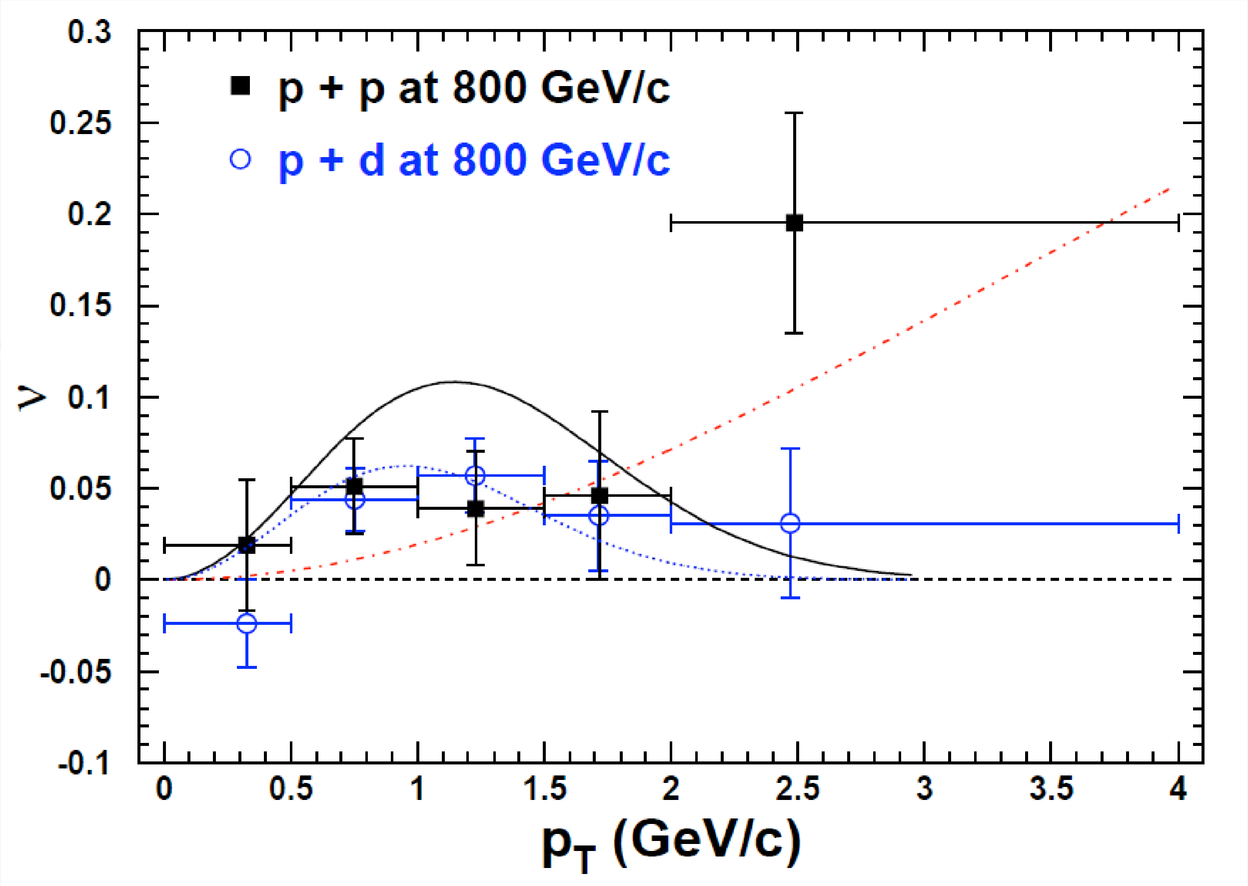
Signs of Boer-Mulders





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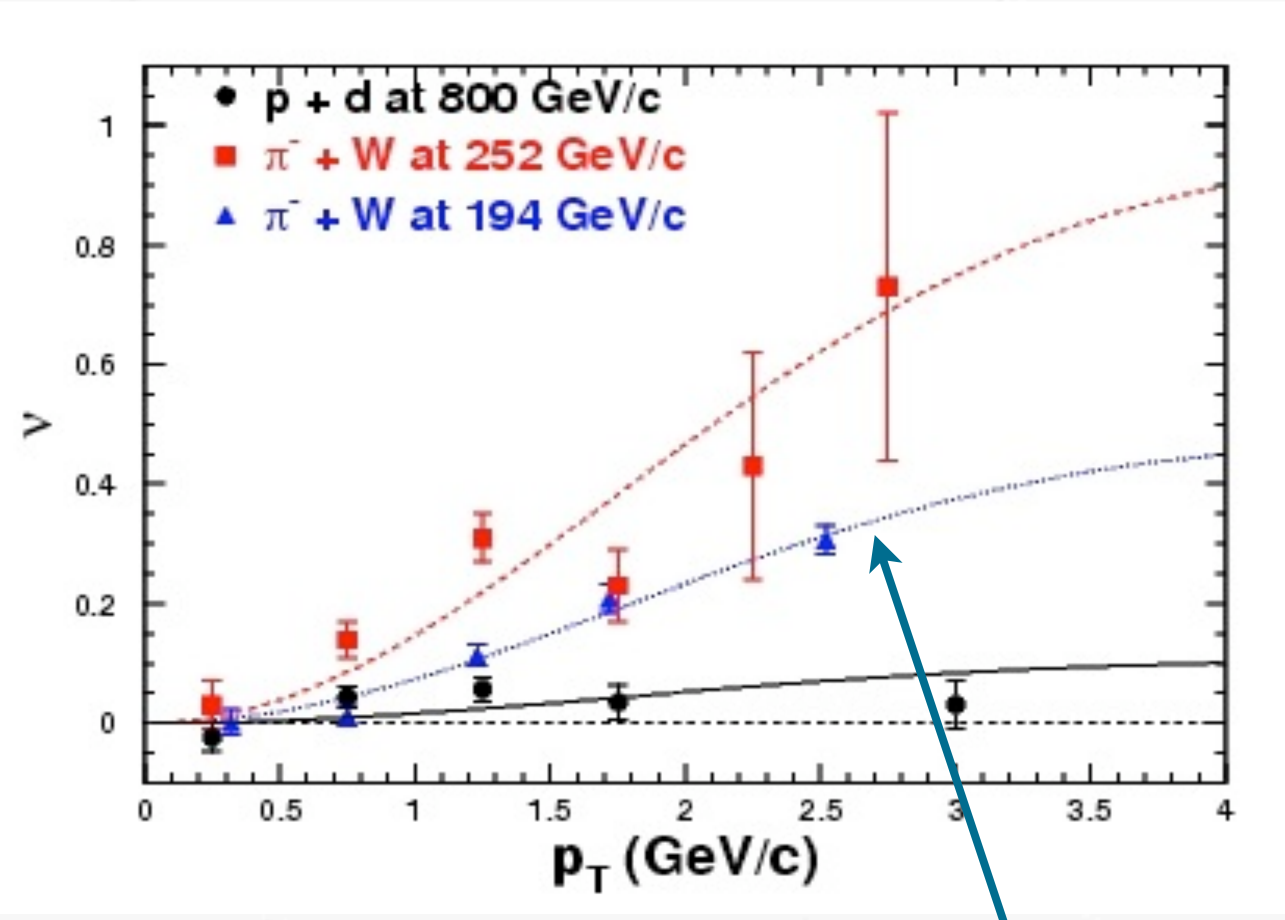

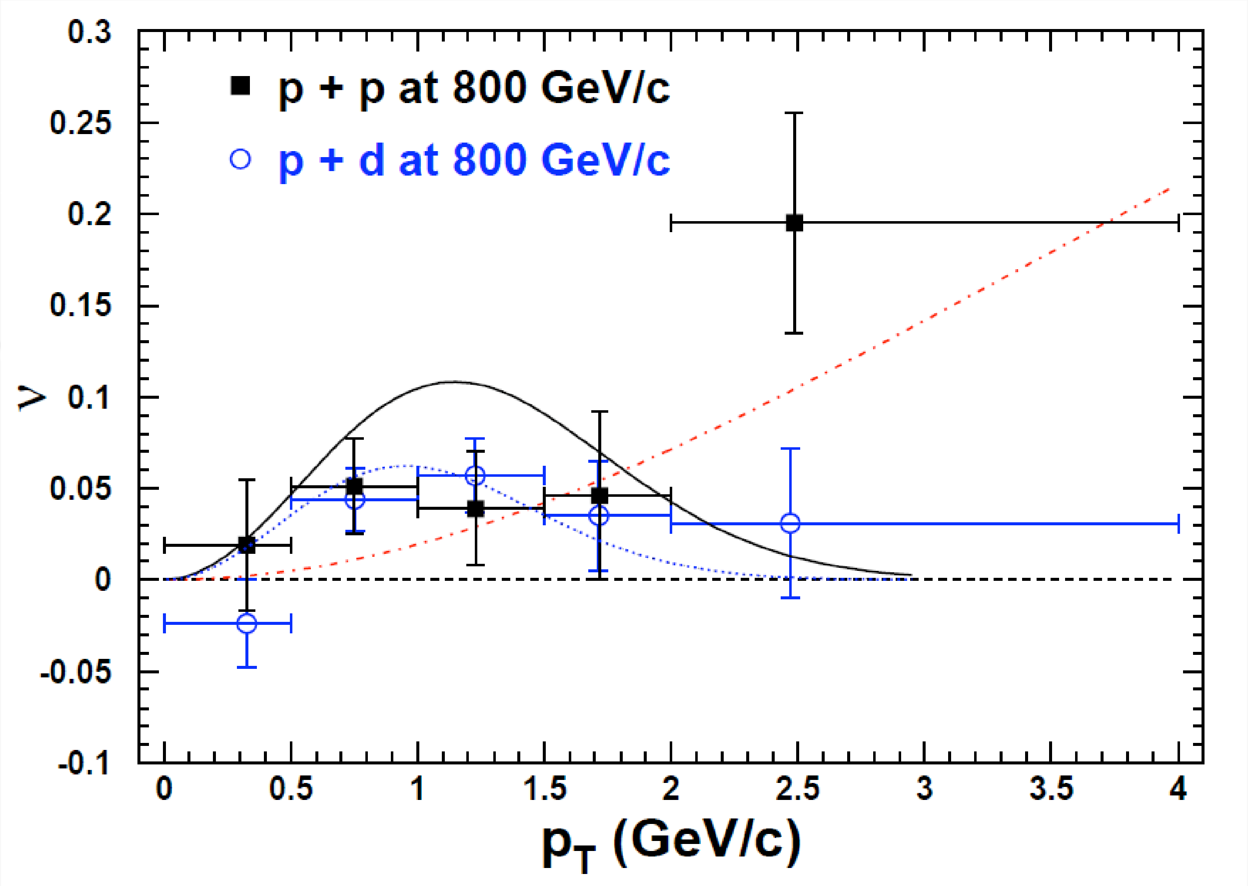

valence BM fctn

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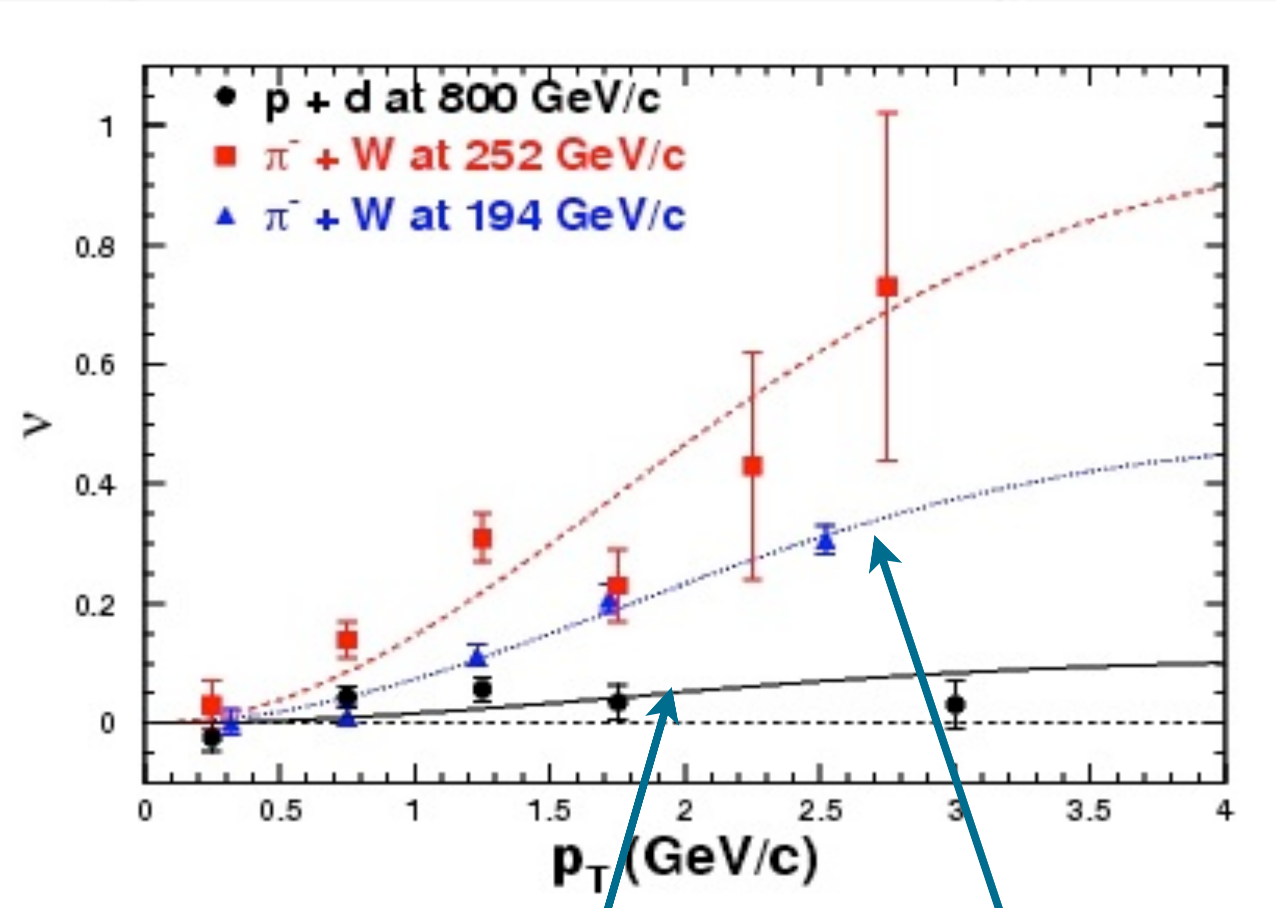

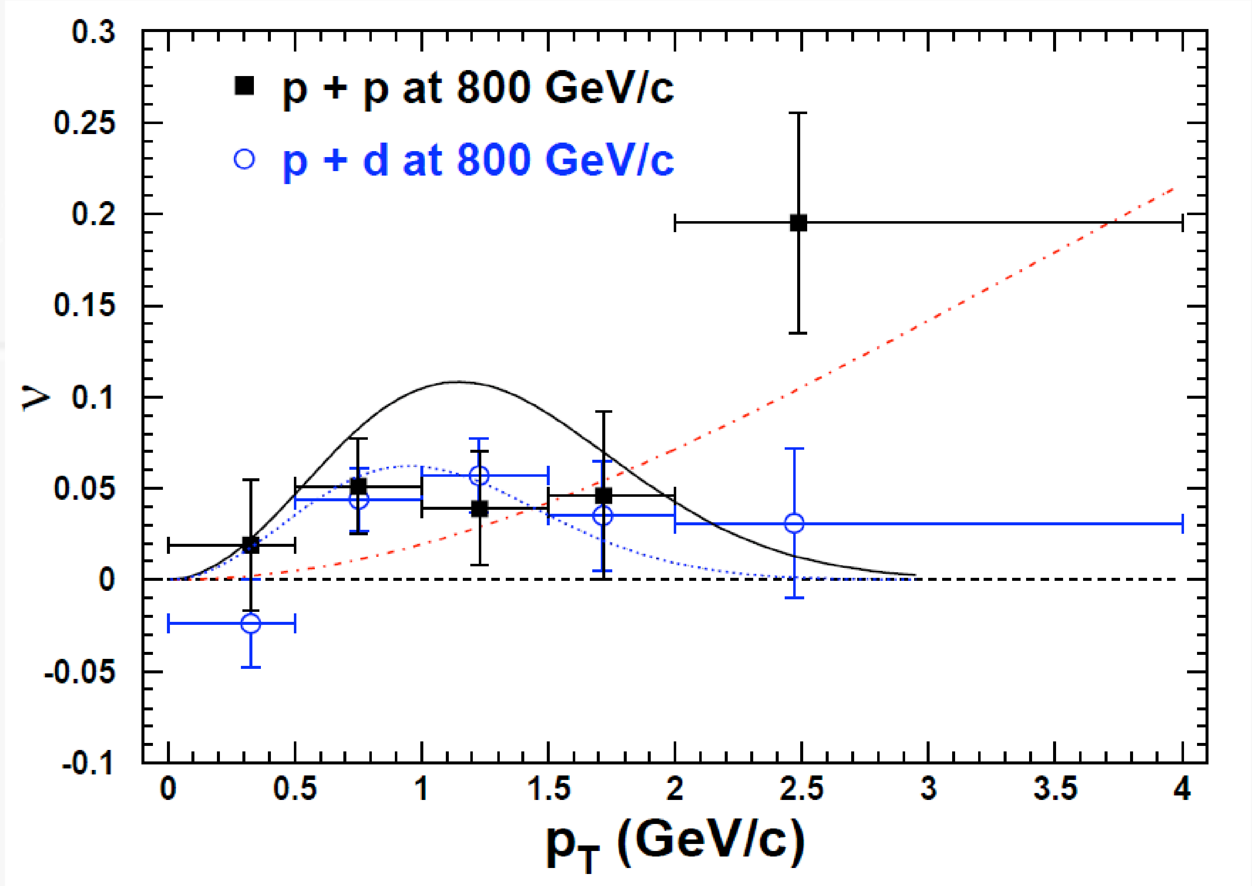

valence and sea BM fctn

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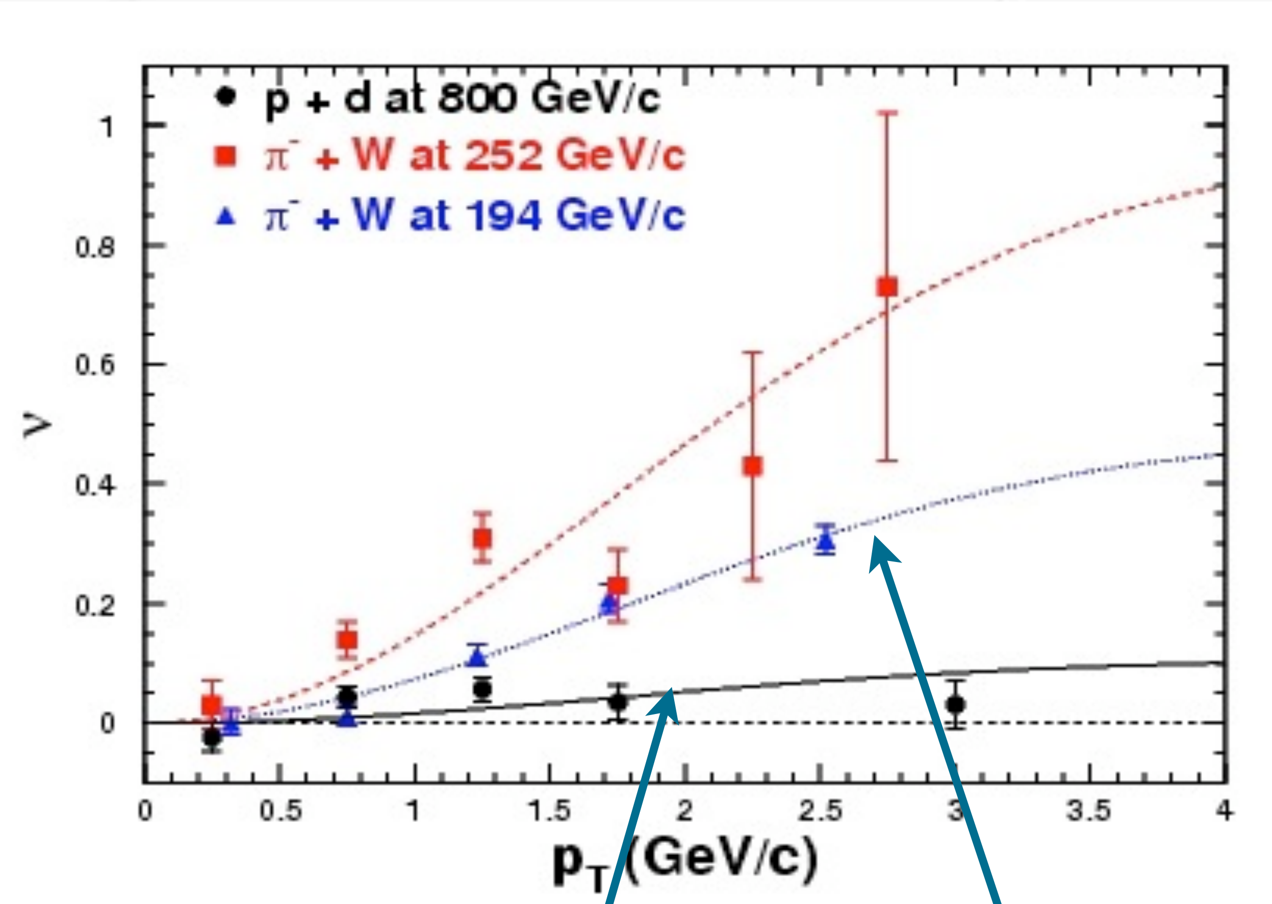
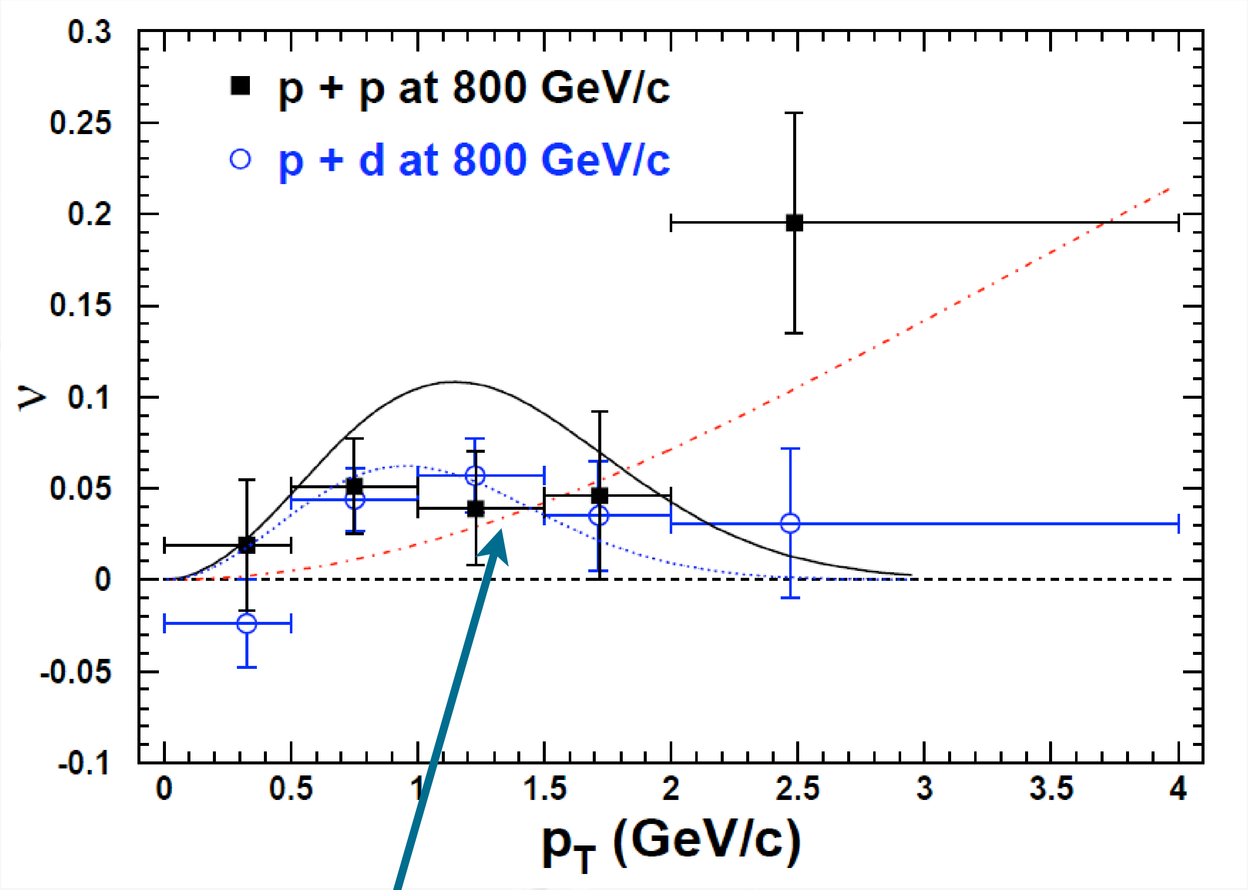


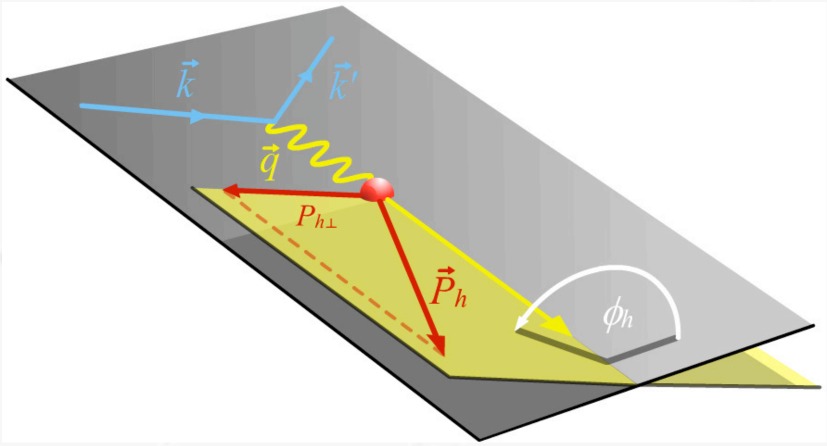


similar BM fctn for up and down quarks?

valence and sea BM fctn

valence BM fctn

Modulations in spin-independent SIDIS cross section



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

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

leading twist

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

BOER-MULDERS EFFECT

CAHN EFFECT

next to leading twist

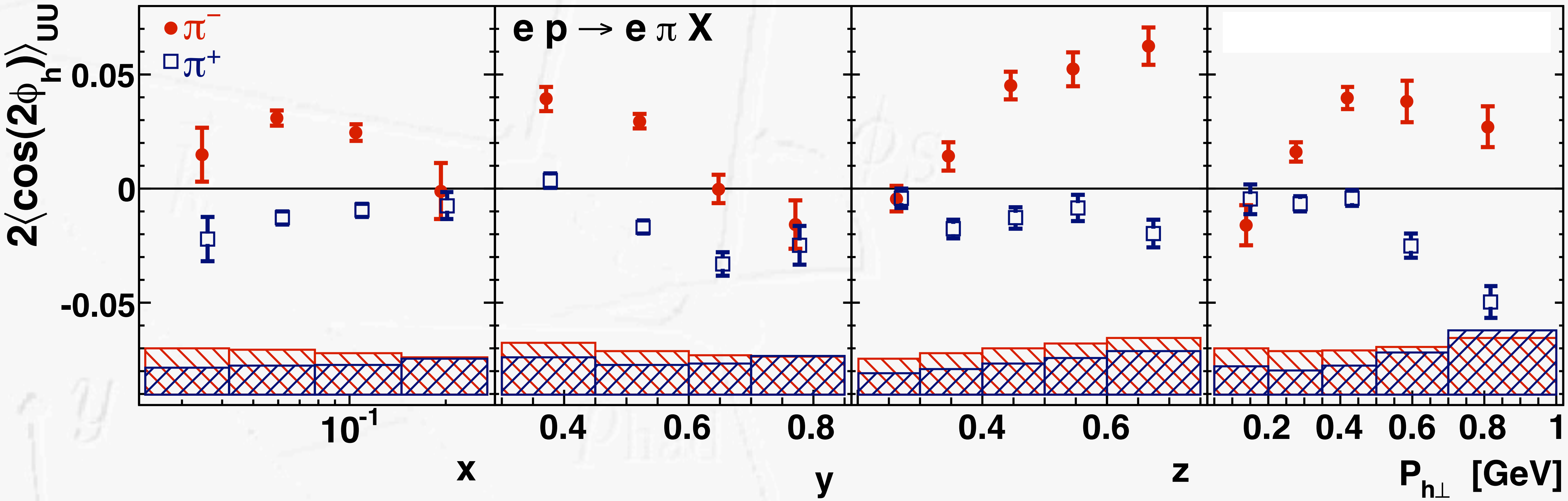
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\,h_1^{\perp}H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\,f_1D_1 + \ldots\right]$$

Interaction dependent terms neglected

(Implicit sum over quark flavours)

signs of Boer-Mulders

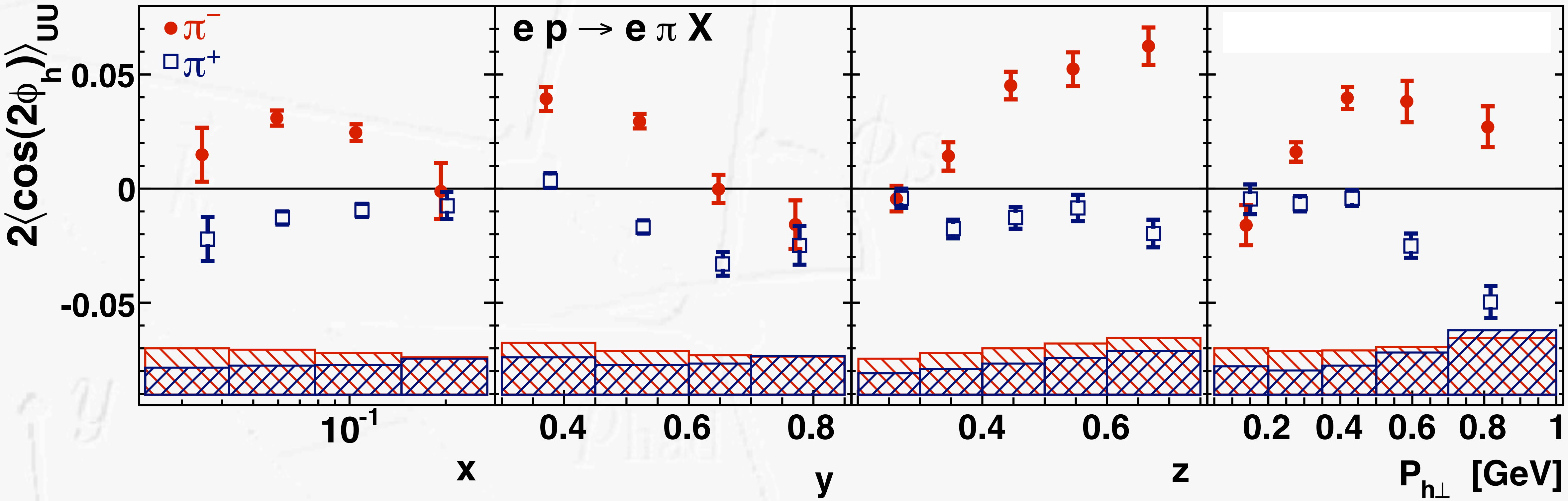
[Airapetian et al., PRD 87 (2013) 012010]



- not zero!

signs of Boer-Mulders

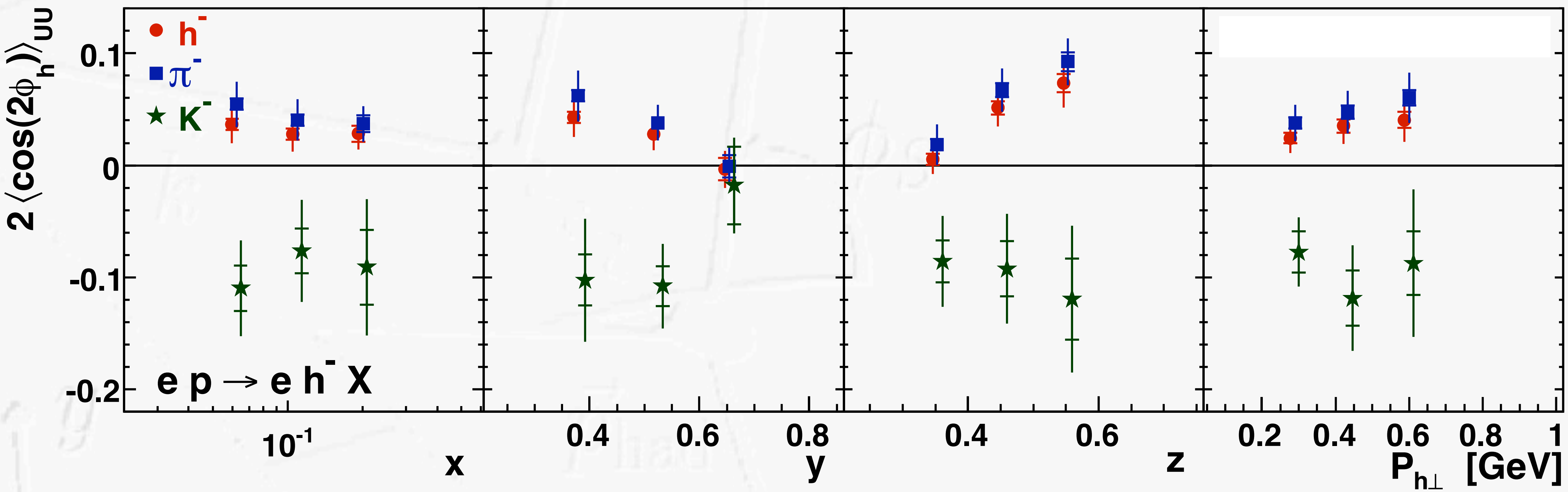
[Airapetian et al., PRD 87 (2013) 012010]



- not zero!
- opposite sign for charged pions with larger magnitude for π^-
  -> same-sign BM-function for valence quarks?

signs of Boer-Mulders

[Airapetian et al., PRD 87 (2013) 012010]



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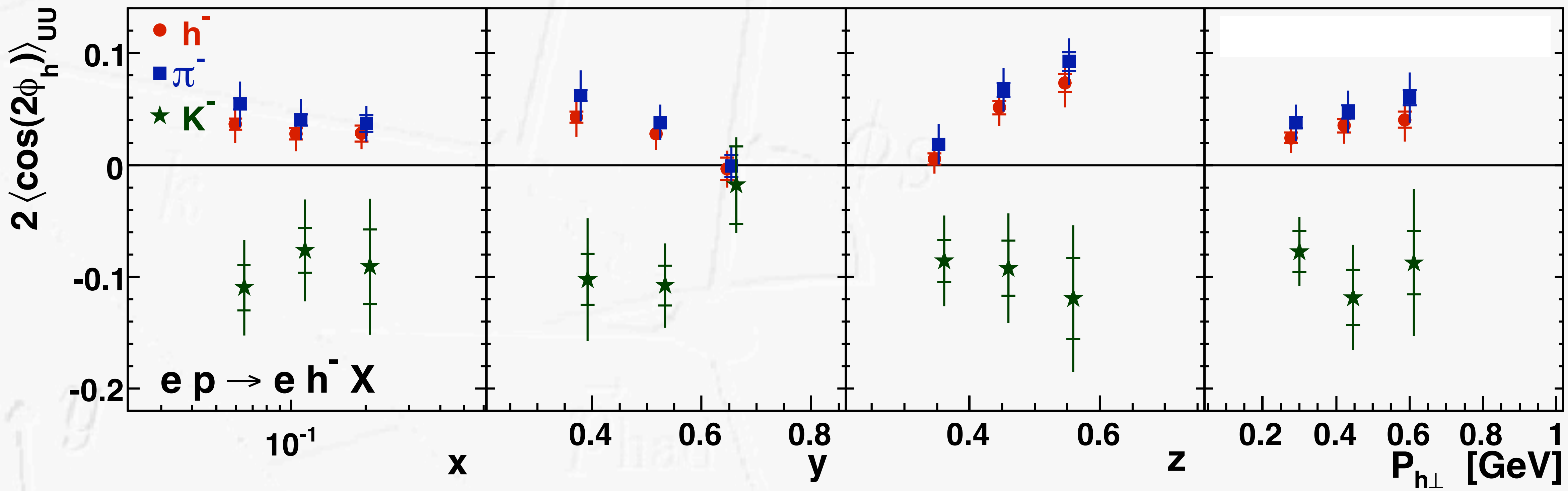

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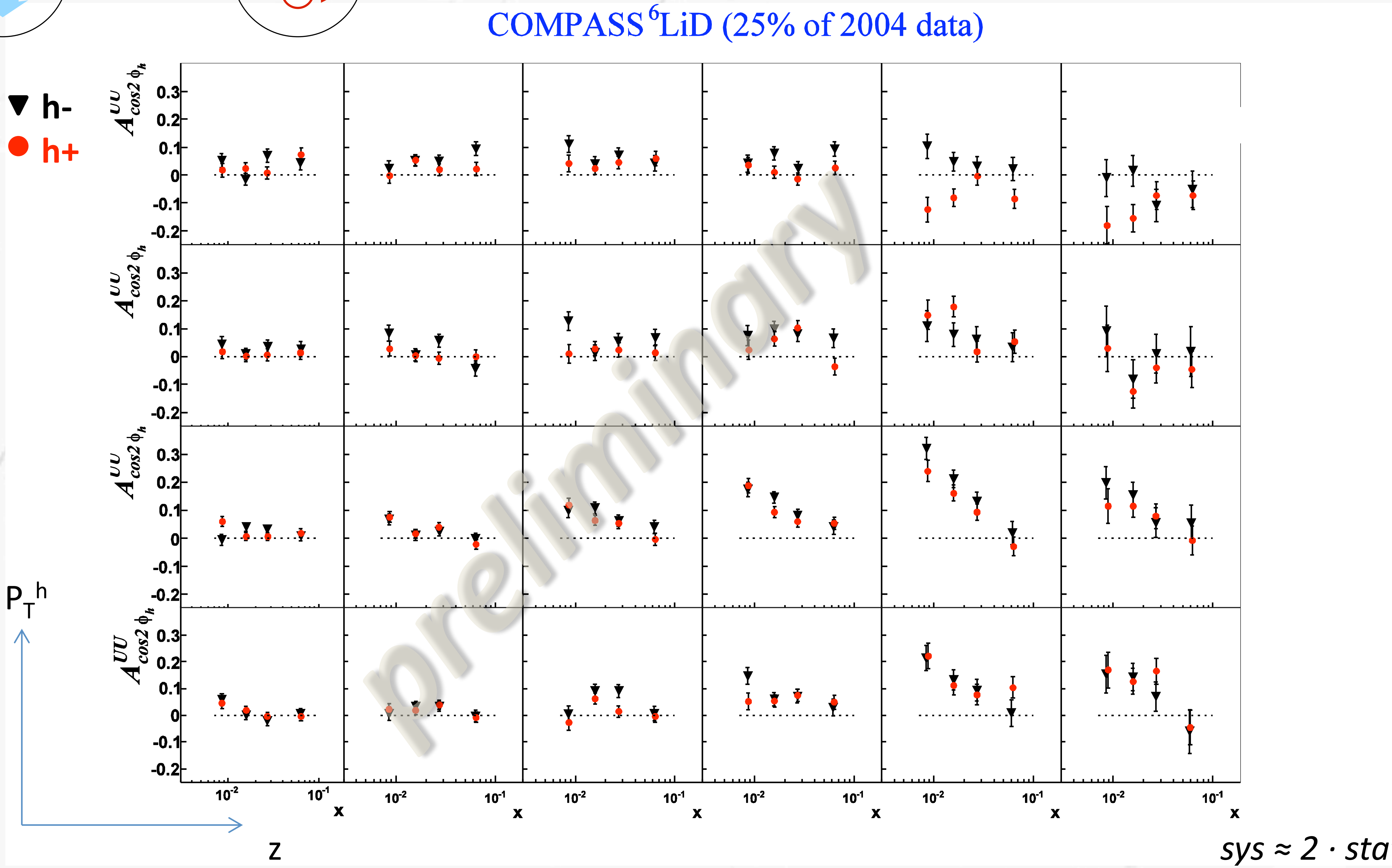

sys ≈ 2 · stat

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Summary

- first round of SIDIS measurements coming to an end
- precision data on fragmentation from e^+e^- annihilation
- 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 Wilson line"
  - possibly large evolution effects
- so far no sign of a non-zero pretzelosity distribution
- first evidences for non-vanishing worm-gear functions

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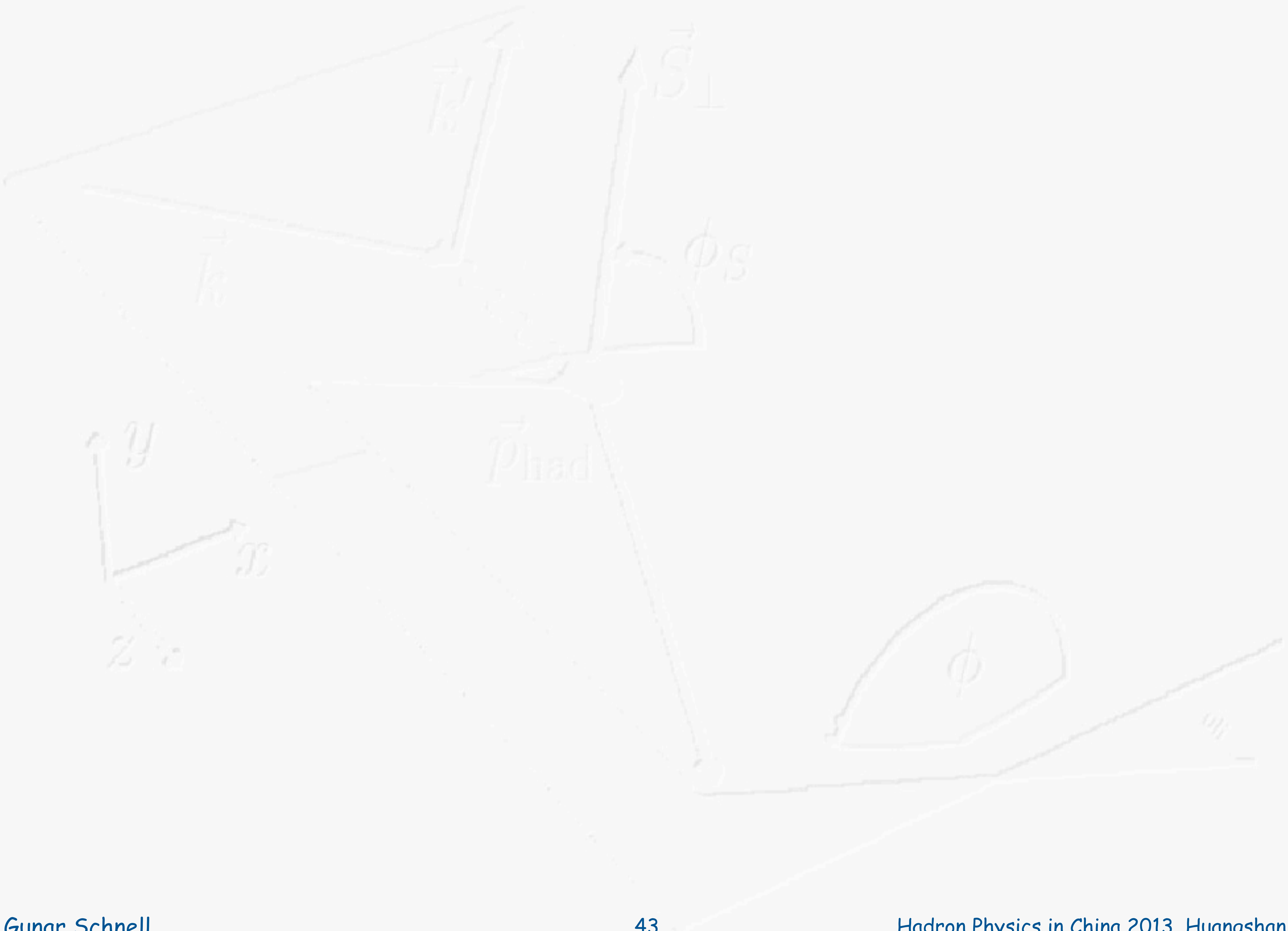
- first evidences for non-vanishing worm-gear functions
- let’s prepare for
    - precision measurements at ongoing and future facilities
    - fundamental QCD tests in Drell-Yan experiments


$\vec{k}'$
$\vec{S}_\perp$
$\vec{k}$
ϕ_S
y
$\vec{P}_{had}$
x
z
ϕ

pp collisions

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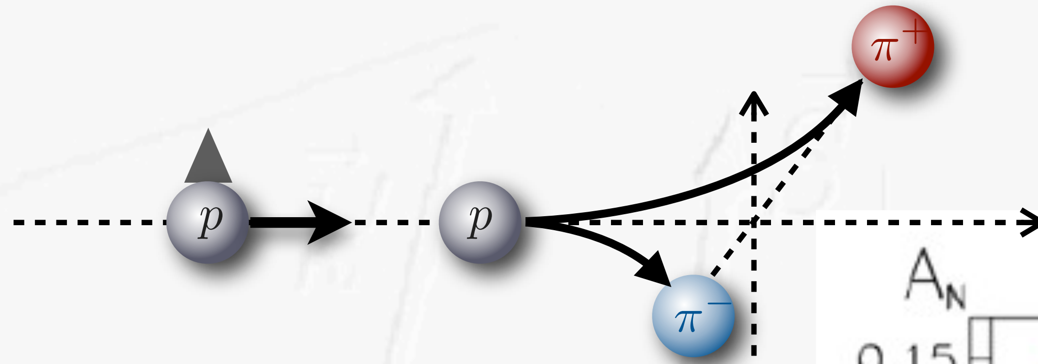

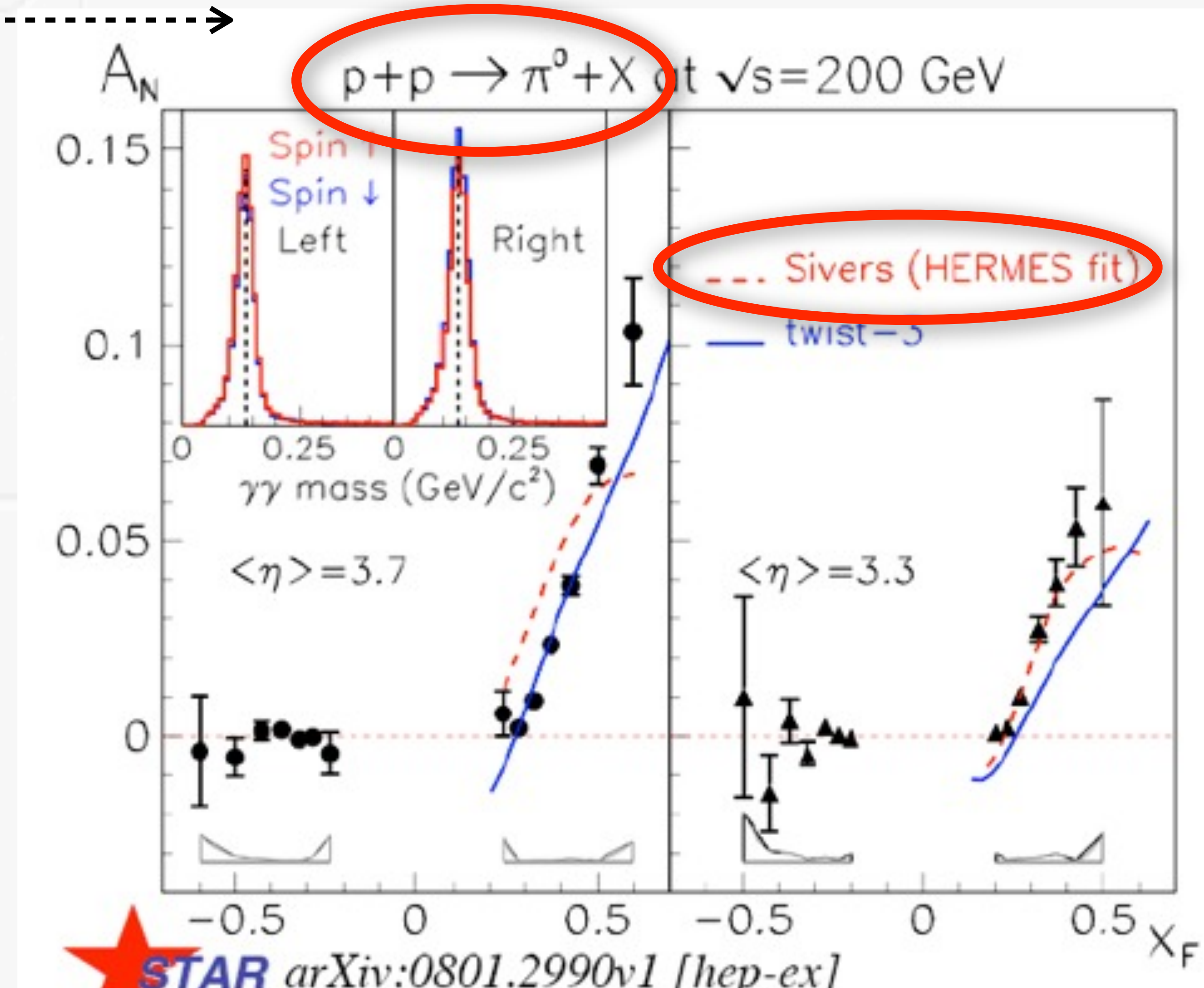

Phys.Rev.Lett.101 (2008) 222001.

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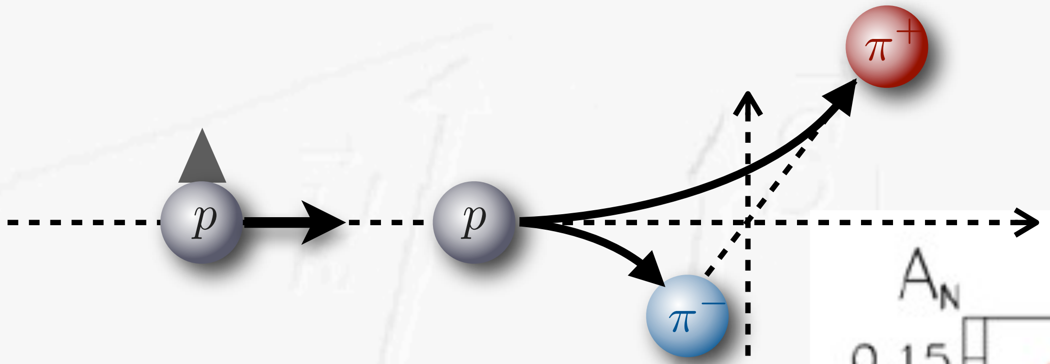
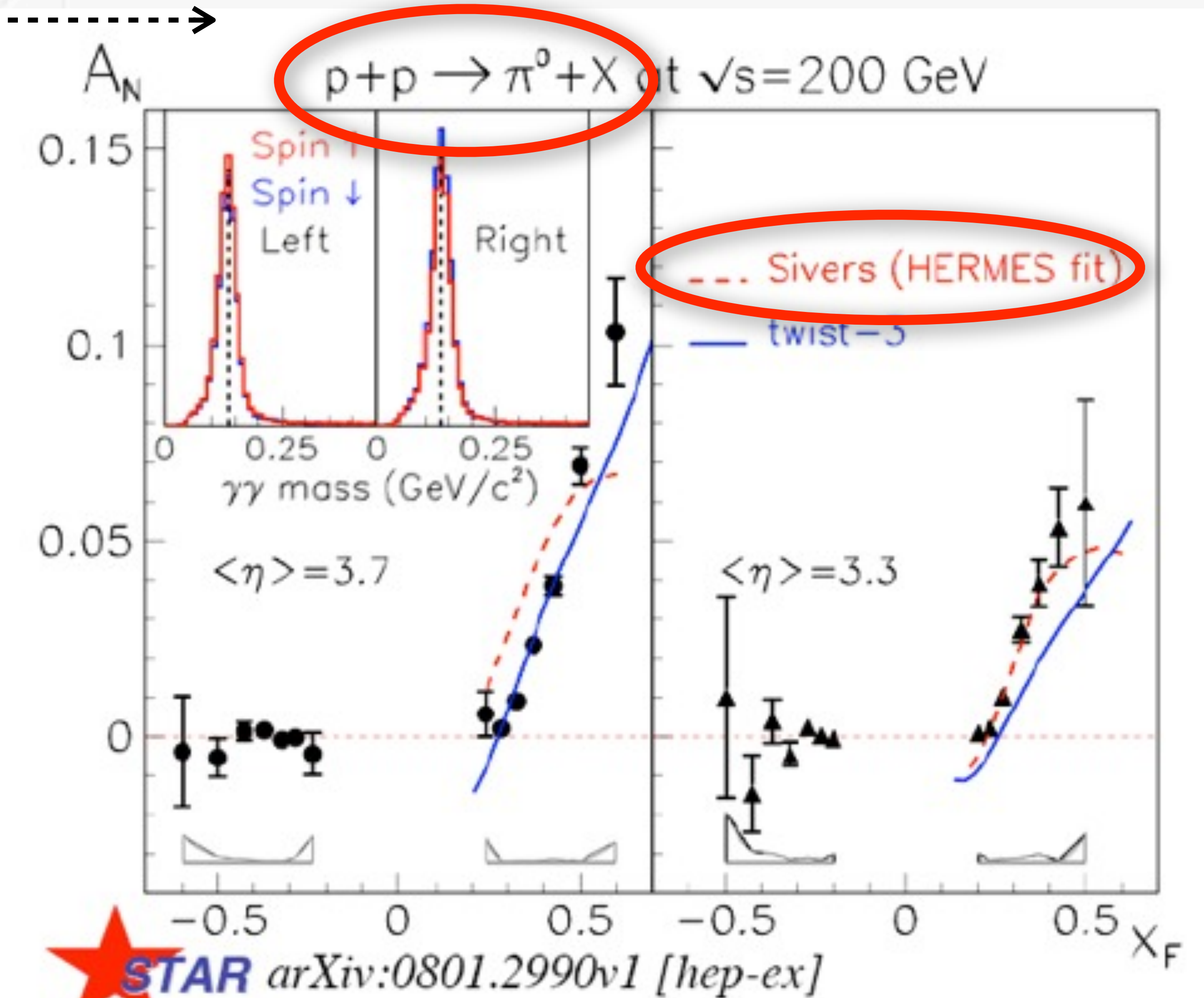


pp collisions

- Sivers fit to HERMES data nicely describes A_N in pp



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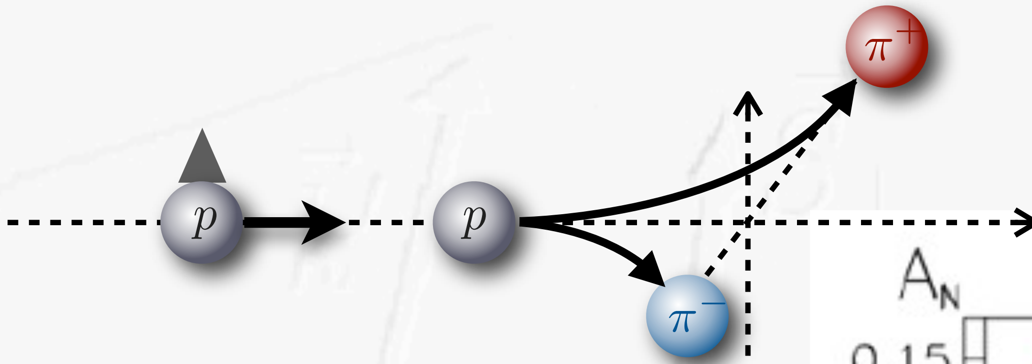

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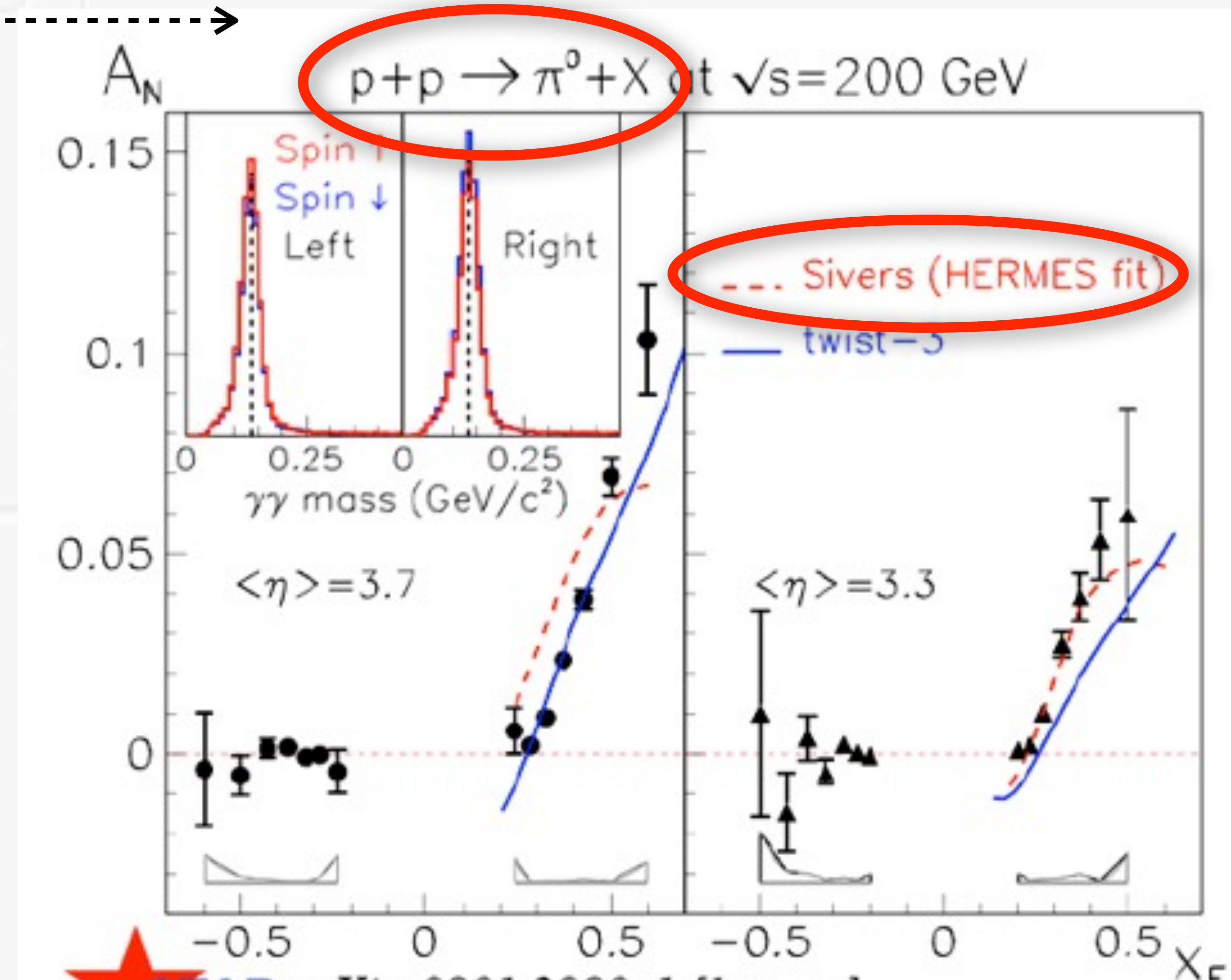

STAR arXiv:0801.2990v1 [hep-ex]
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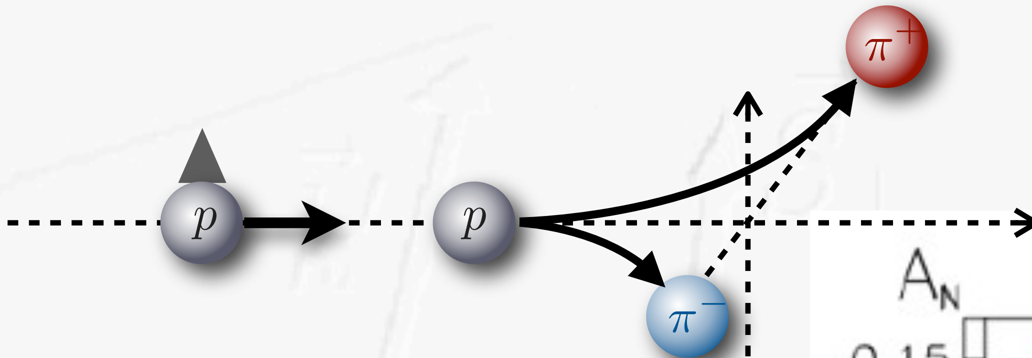

- Sivers fit to HERMES data nicely describes A_N in pp
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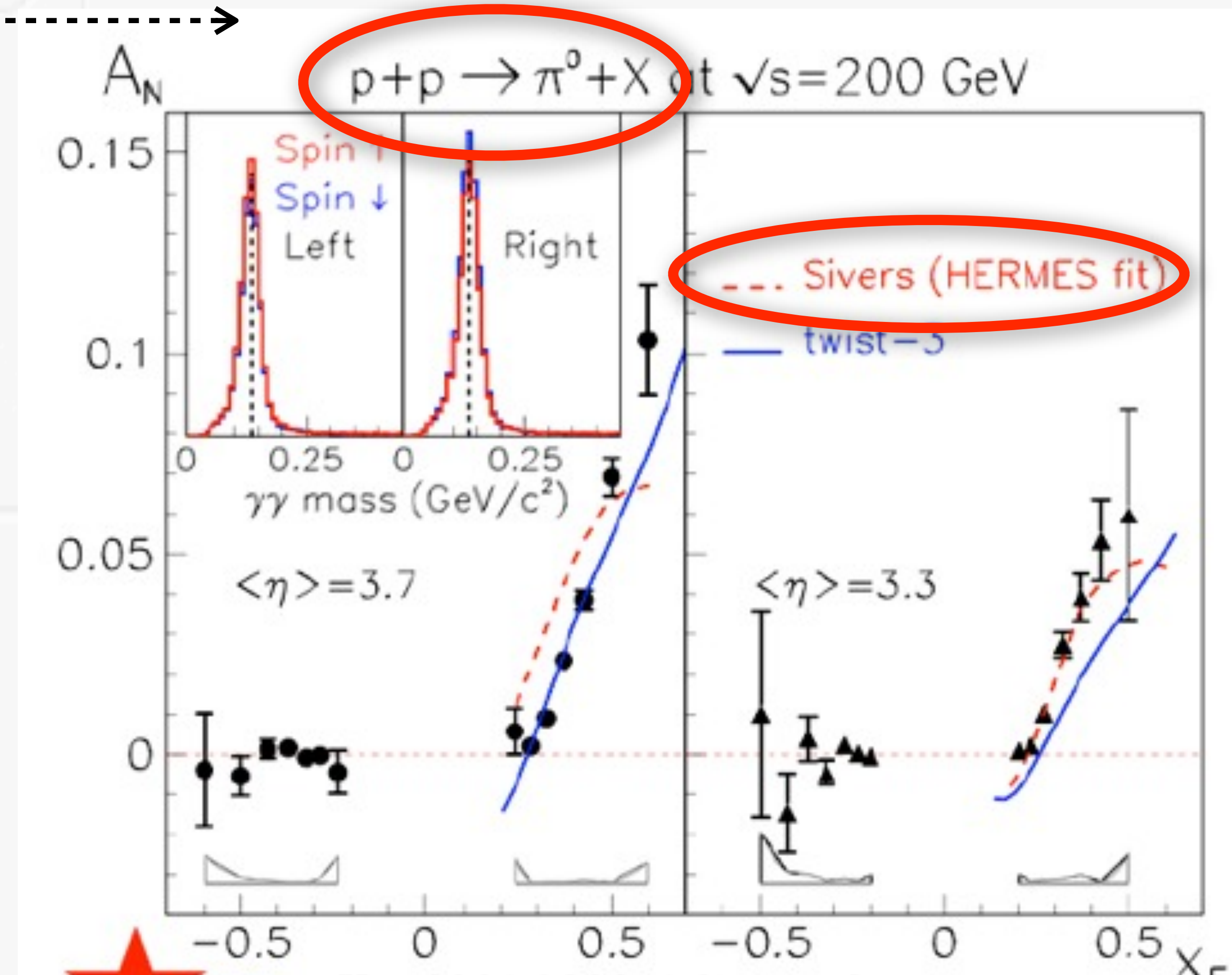
- only sizable in forward direction



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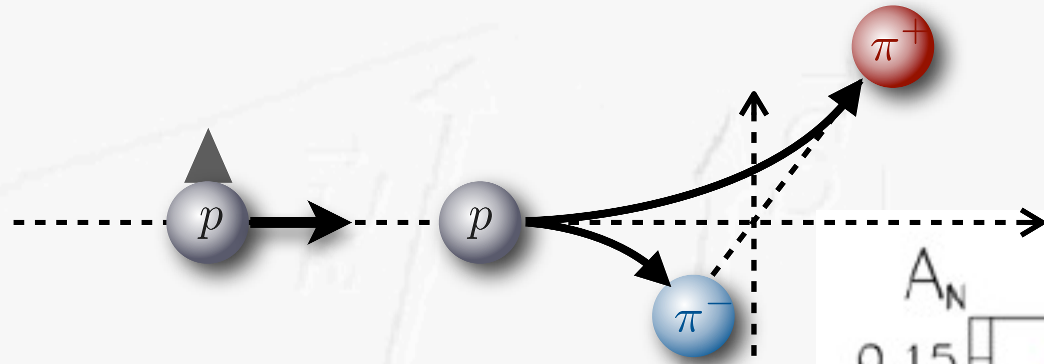
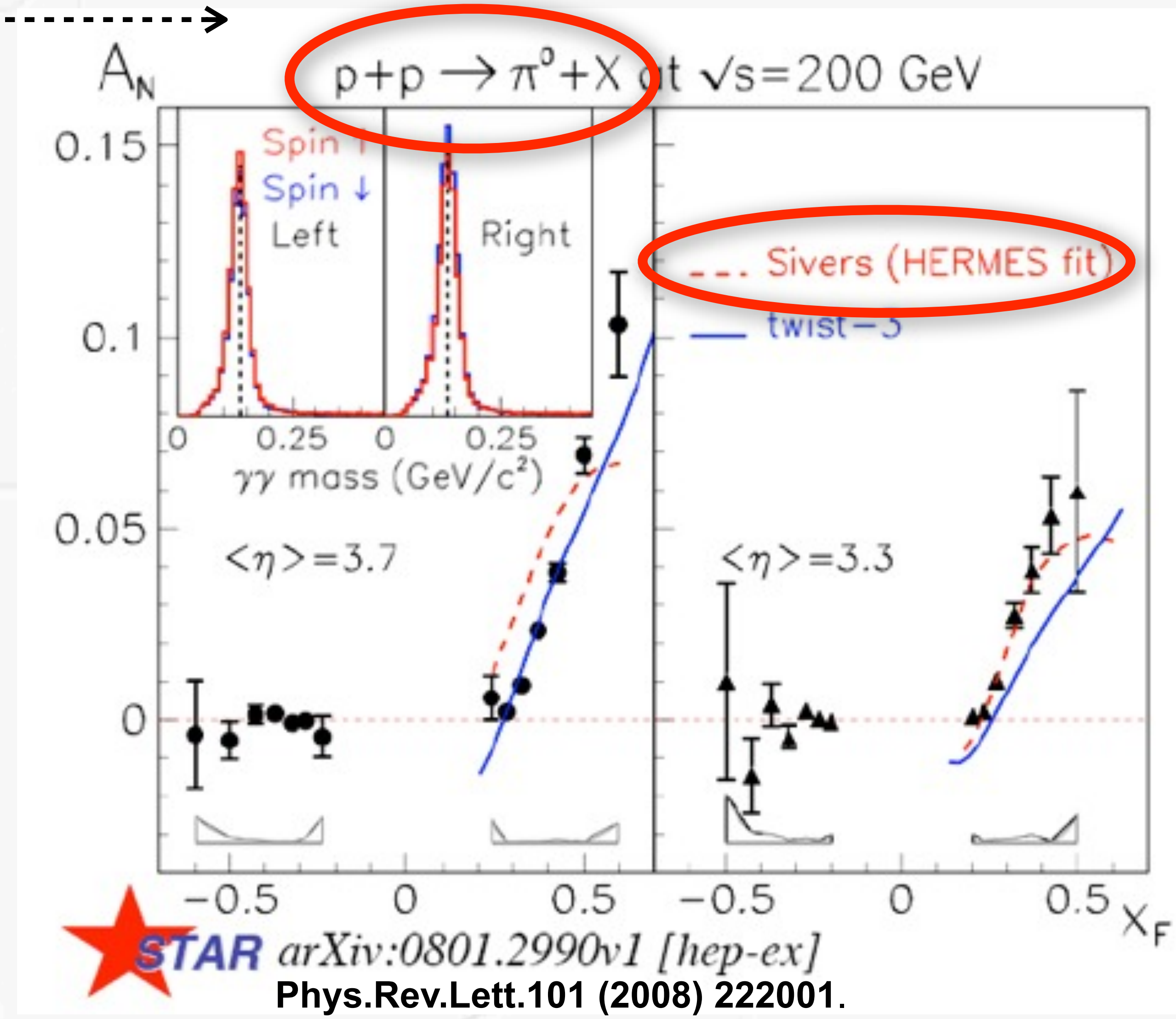
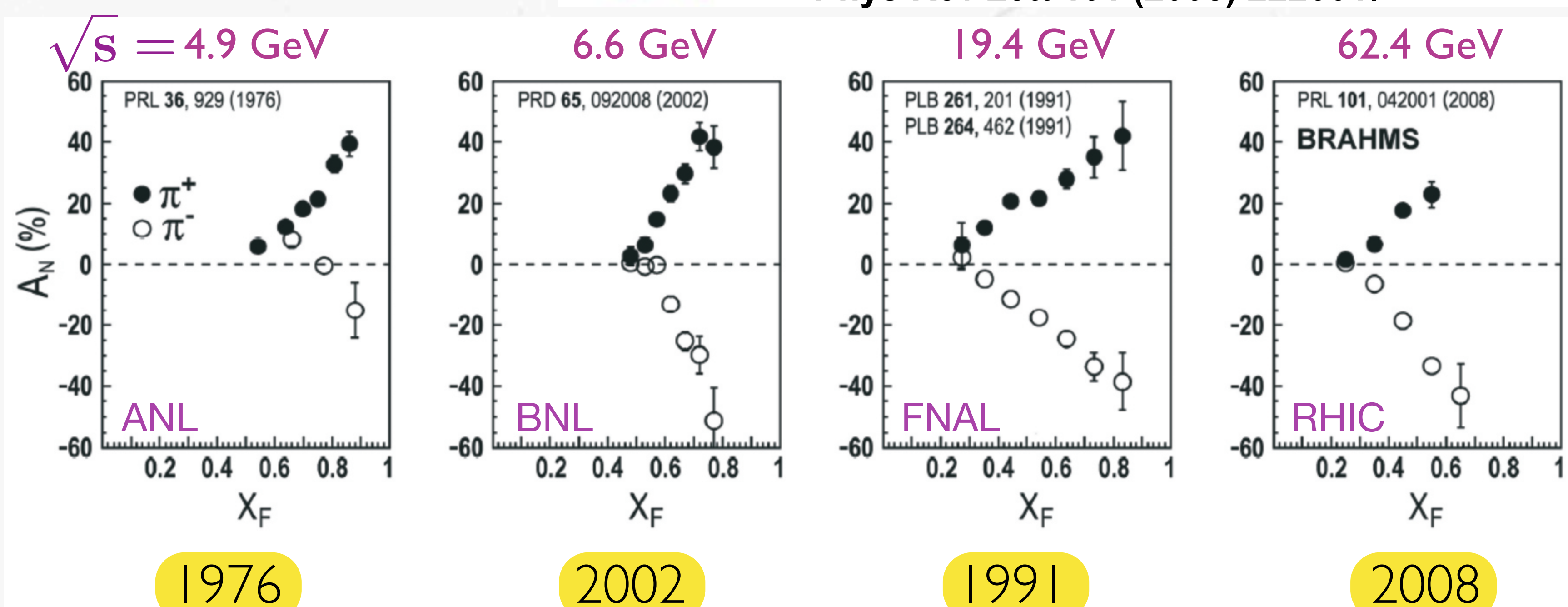


pp collisions

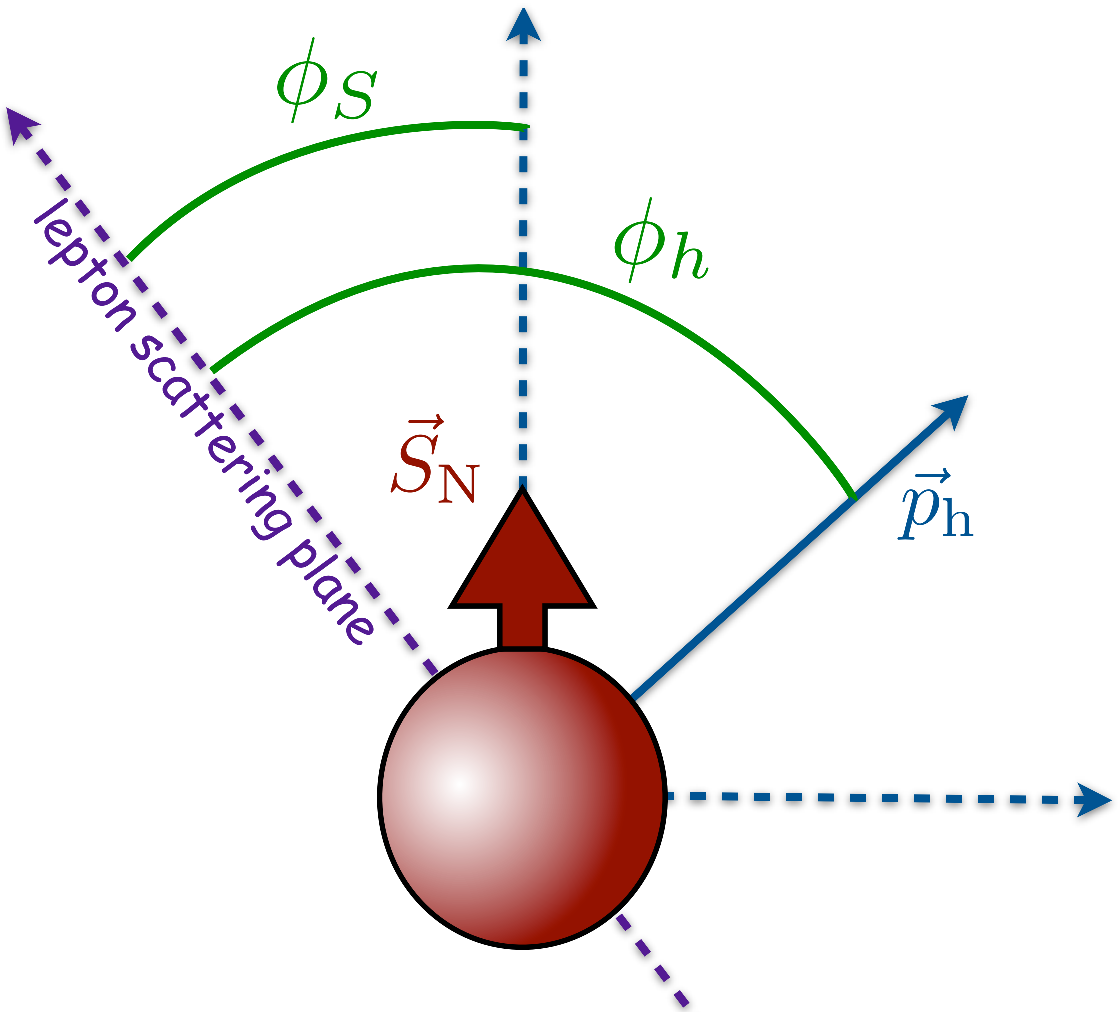
- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect
- only sizable in forward direction
- A_N in pp persist over wide energy range:





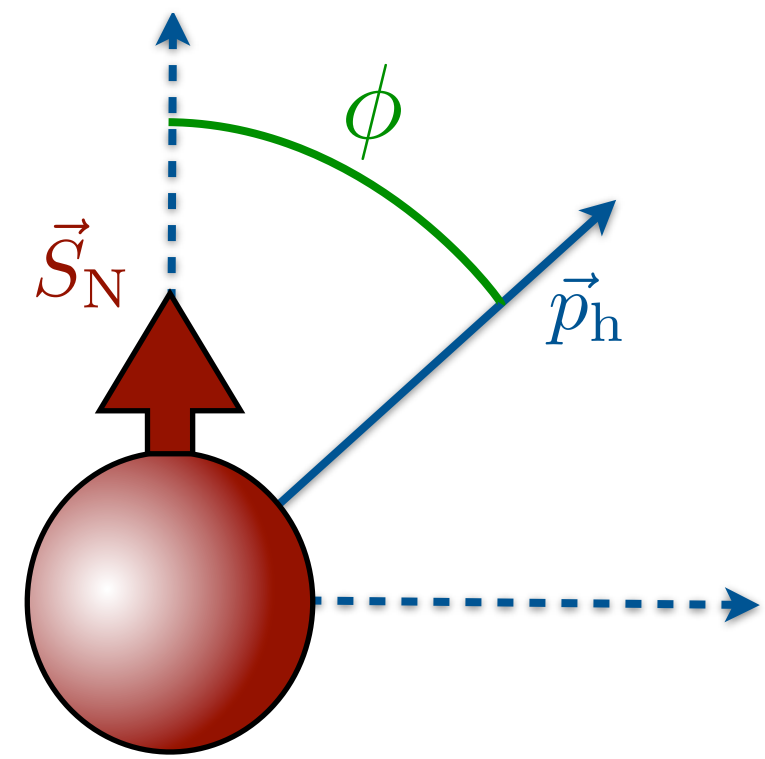
Inclusive hadron electro-production

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



virtual photon going into the page

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



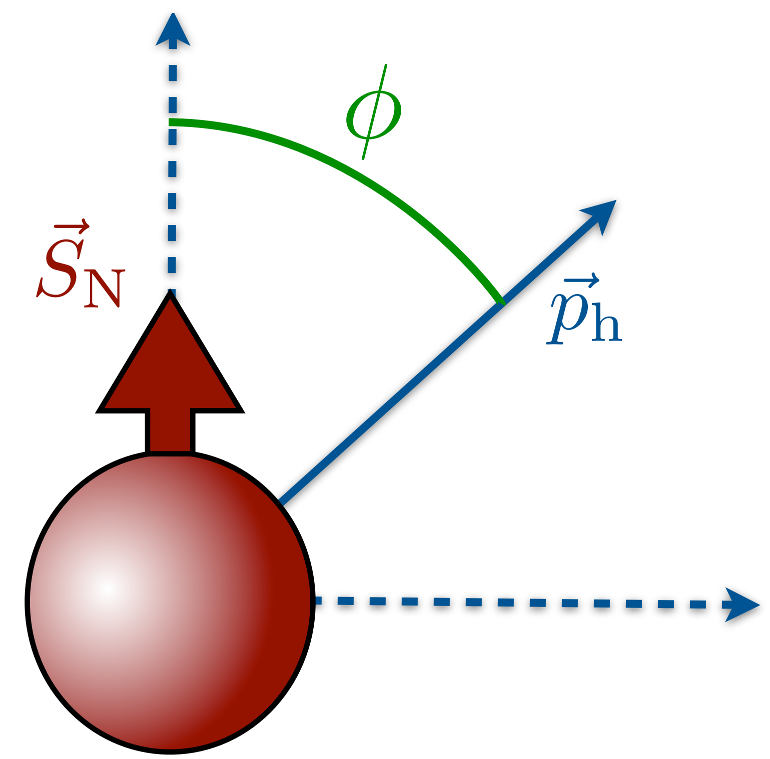
lepton beam going into the page

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

➡ "Sivers angle"

Inclusive hadron electro-production

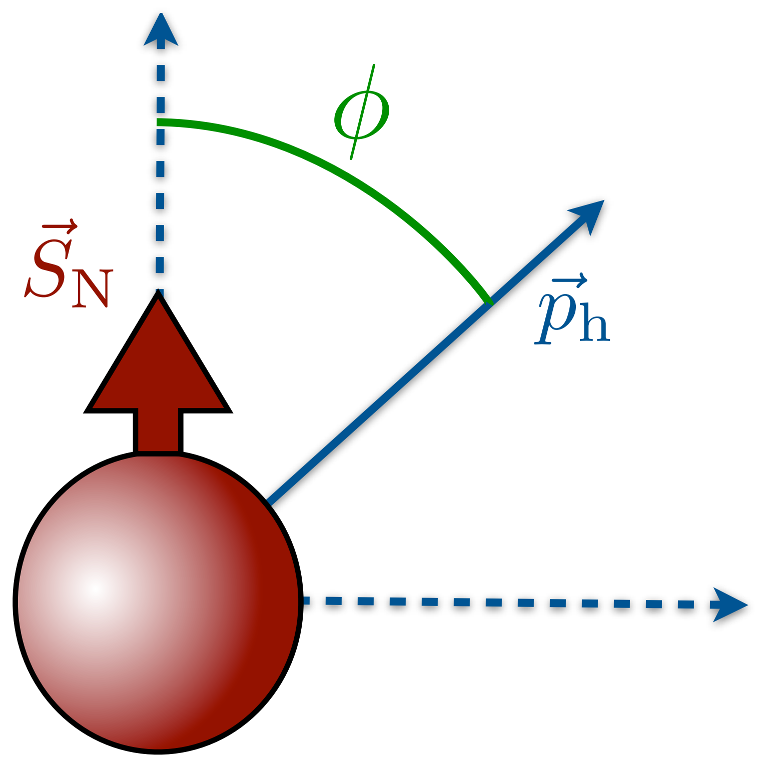
$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

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

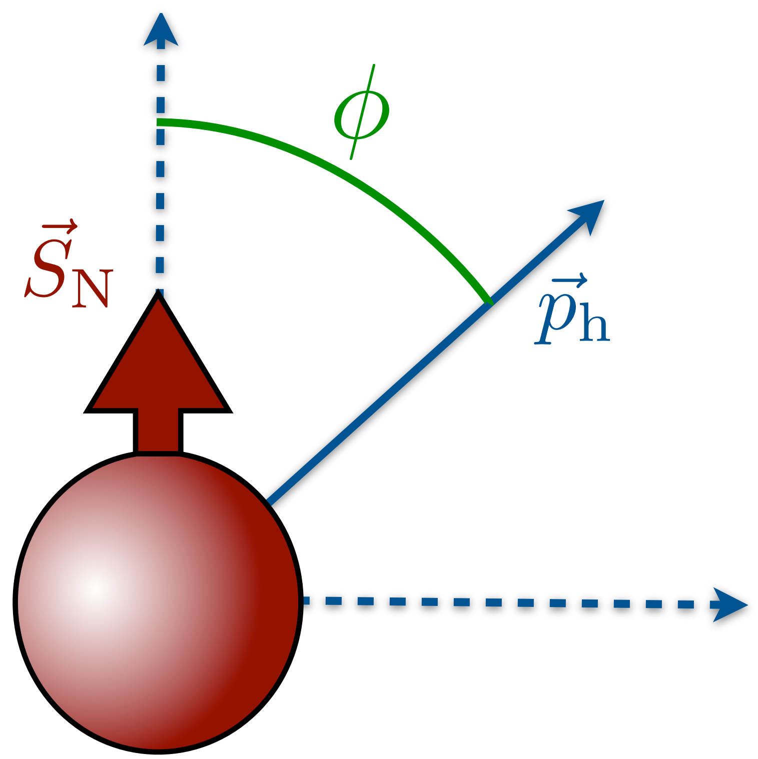


Inclusive hadron electro-production

- scattered lepton undetected
  ➡ lepton kinematics unknown

- dominated by quasi-real photo-production (low Q^2)
  ➡ hadronic component of photon relevant?

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



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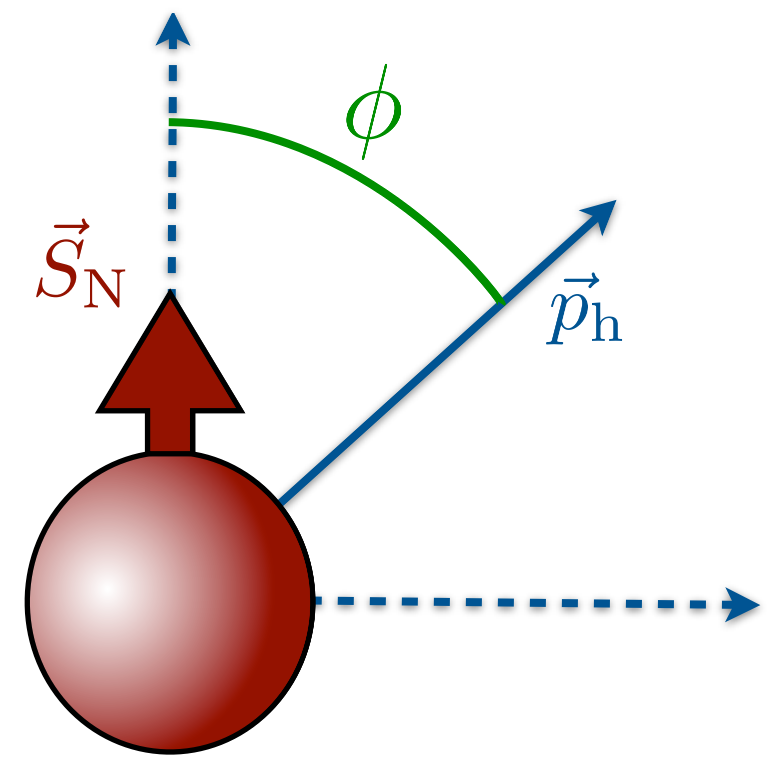
- cross section proportional to S_N ($k \times p_h$) ~ $\sin\phi$



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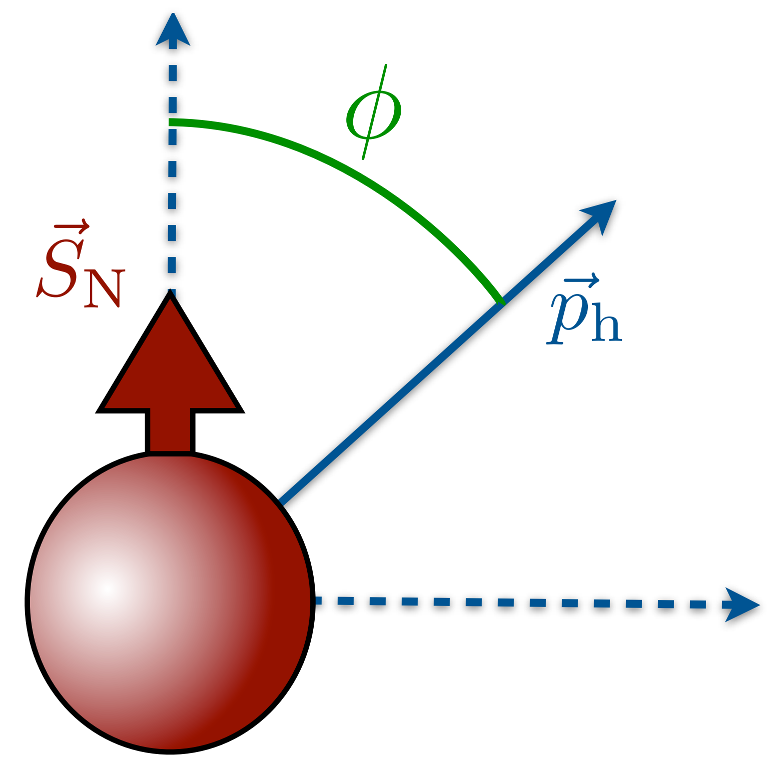
$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$



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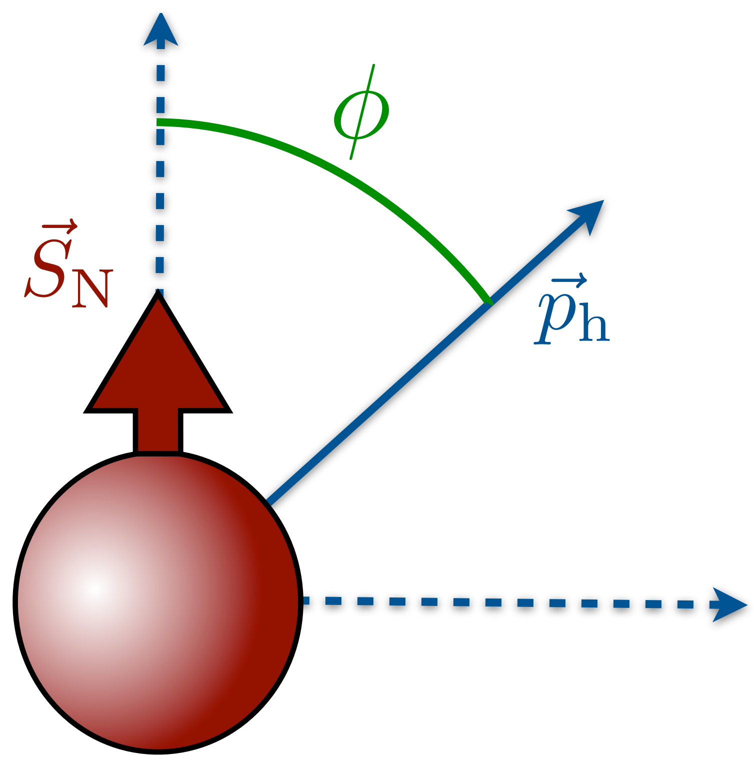
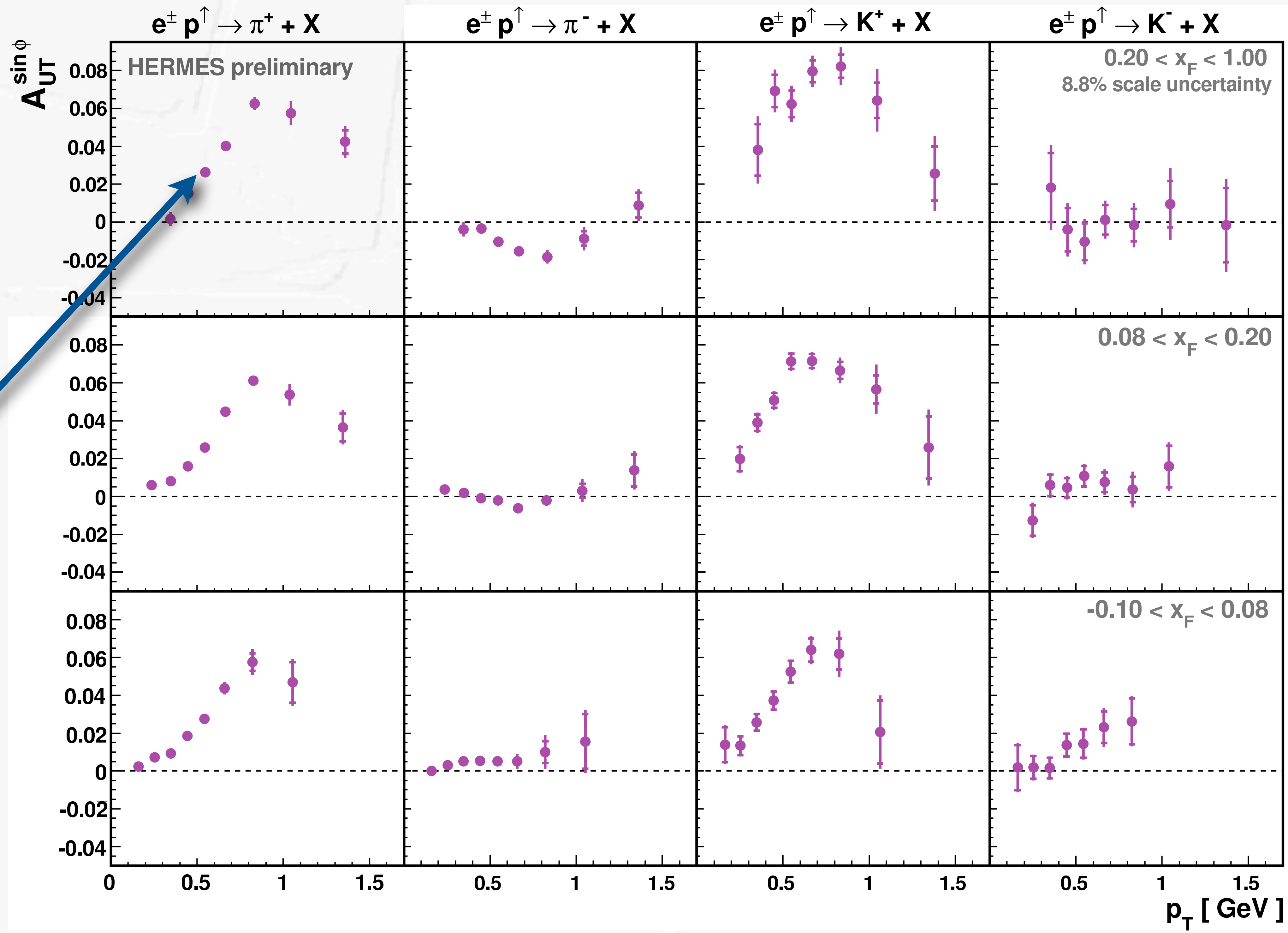


$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F)\sin\phi$$

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

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

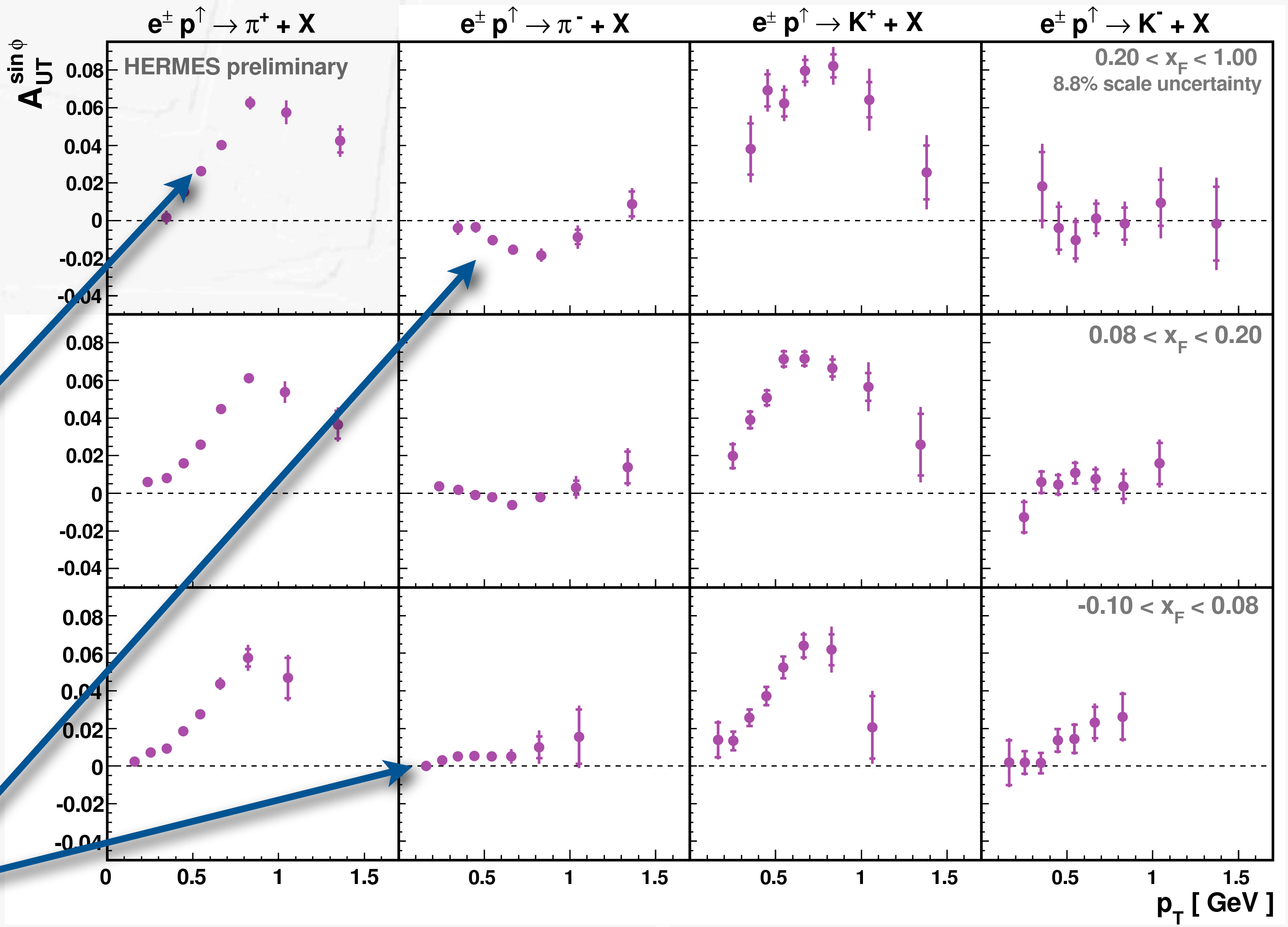
Inclusive hadrons in ep



increase at low p_T

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

Inclusive hadrons in ep

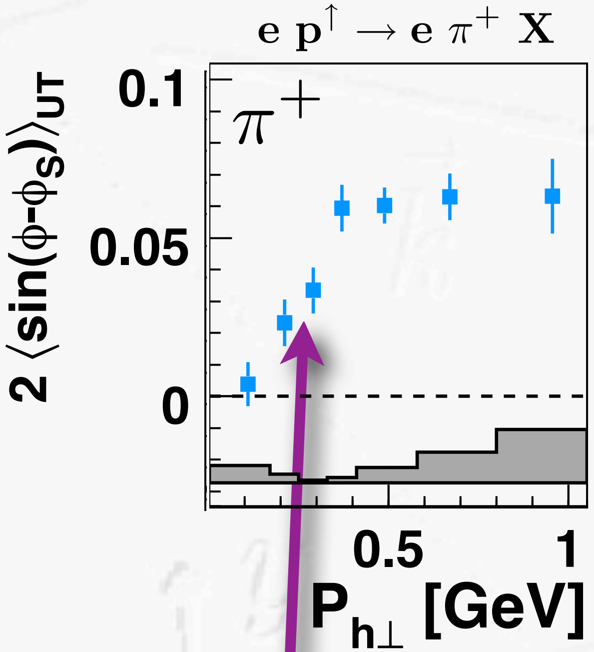


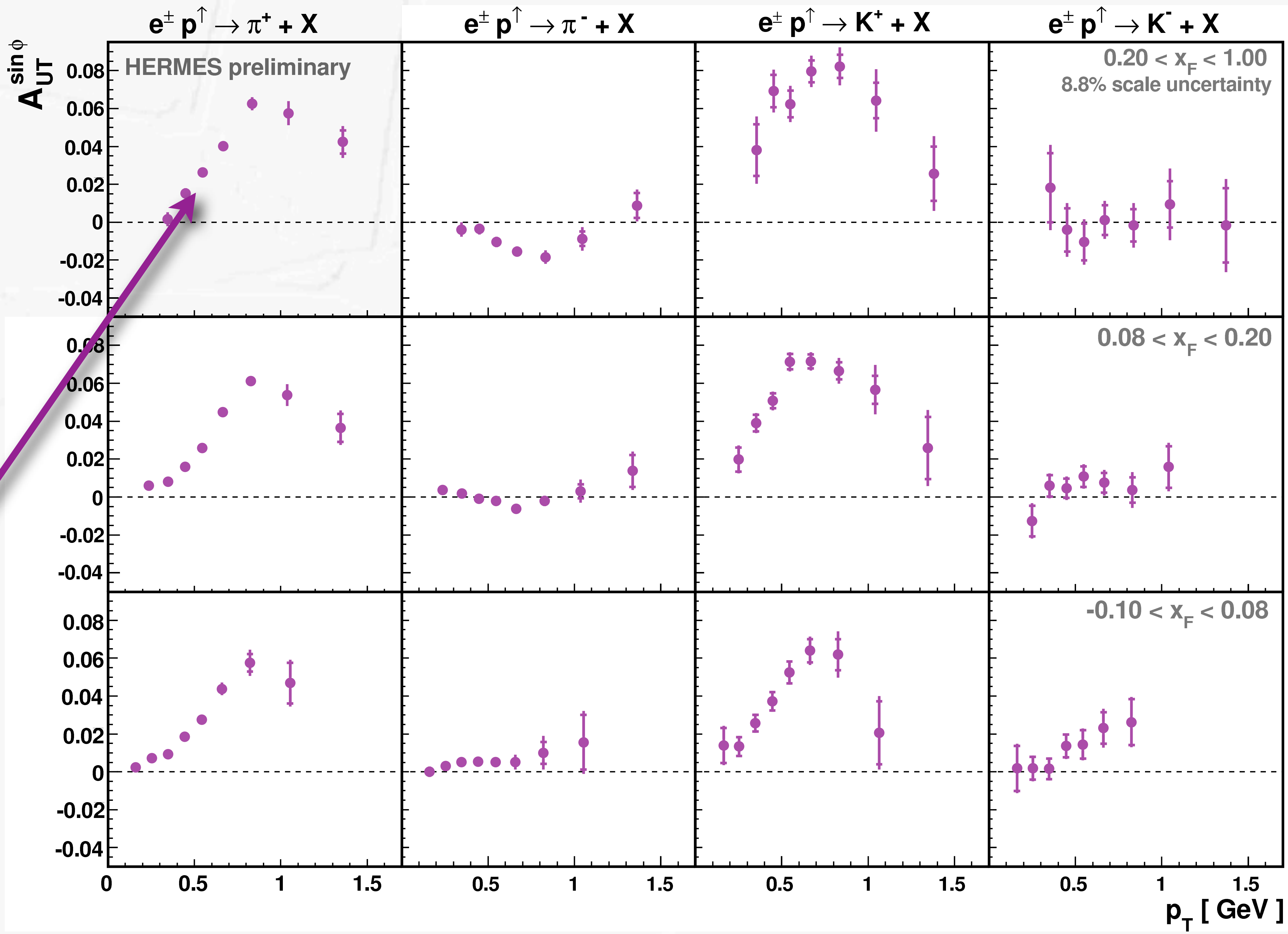
increase at low p_T

sign change

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

Inclusive hadrons in ep

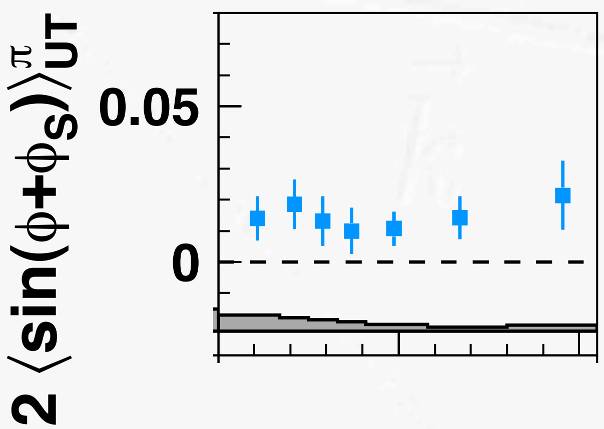


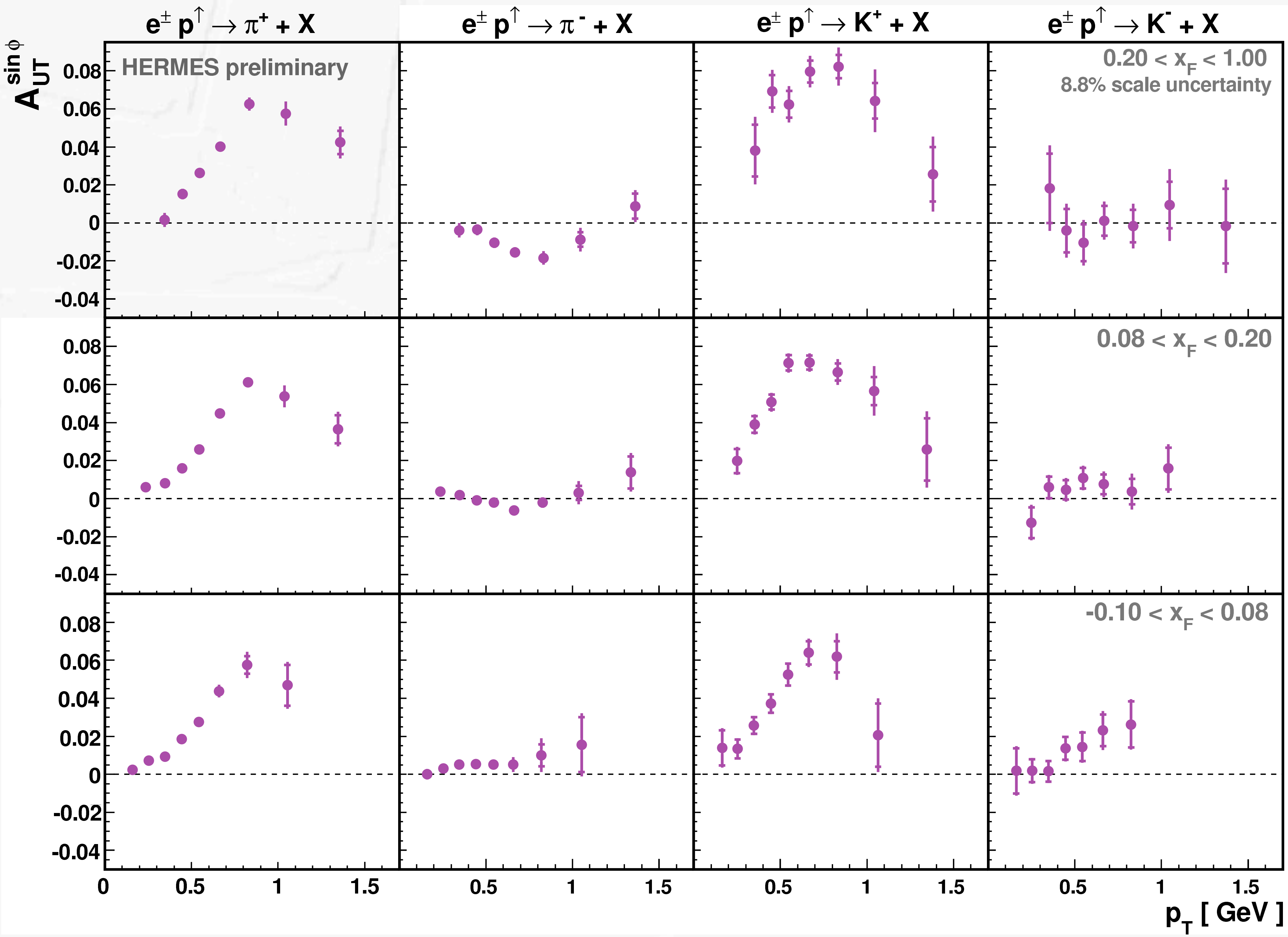


behavior and size similar to SIDIS Sivers

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

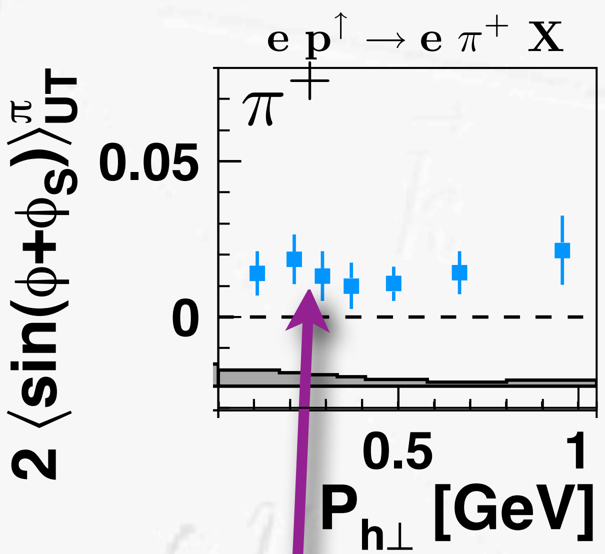
Inclusive hadrons in ep

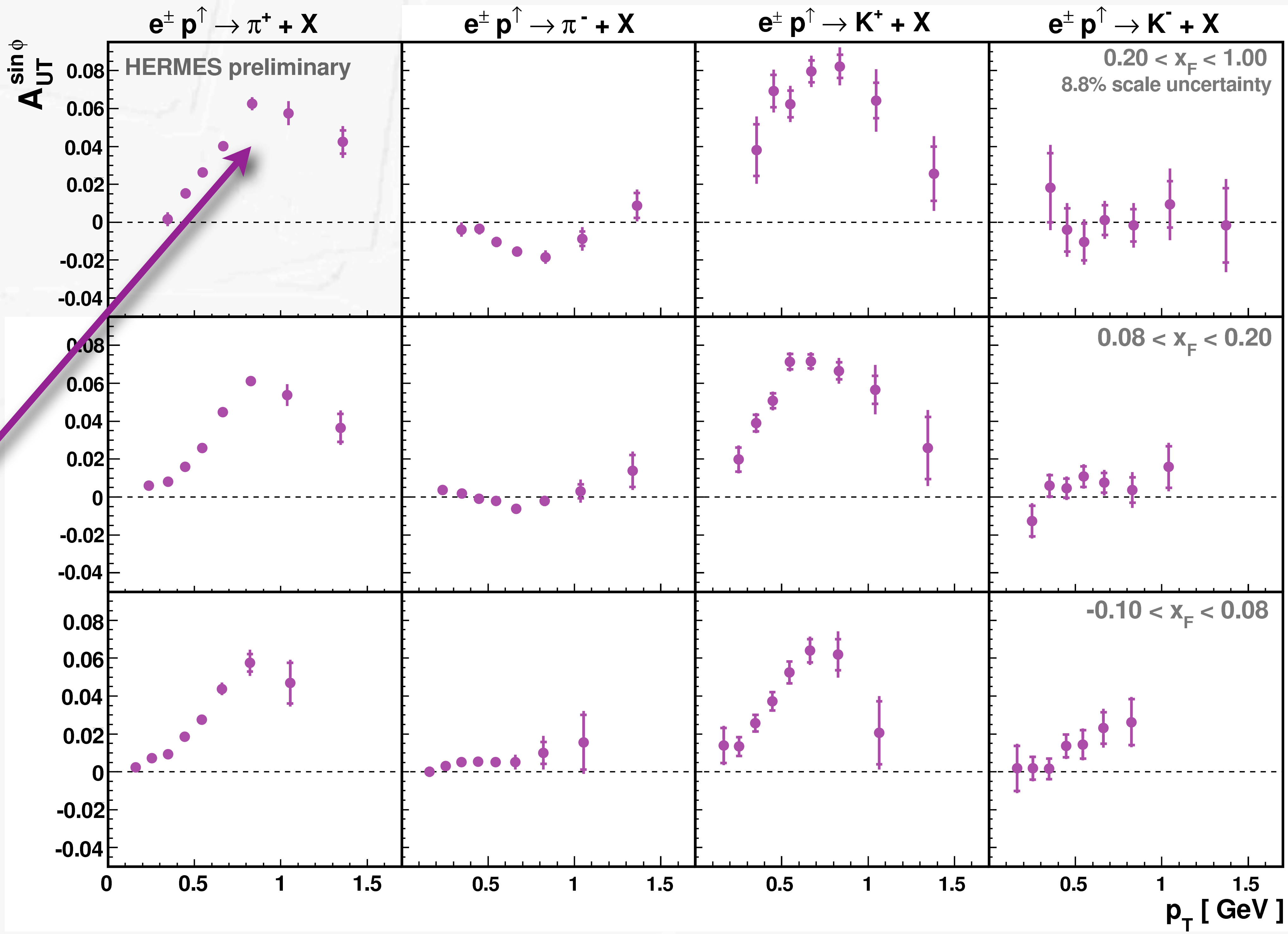




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Inclusive hadrons in ep





no similarity to SIDIS Collins