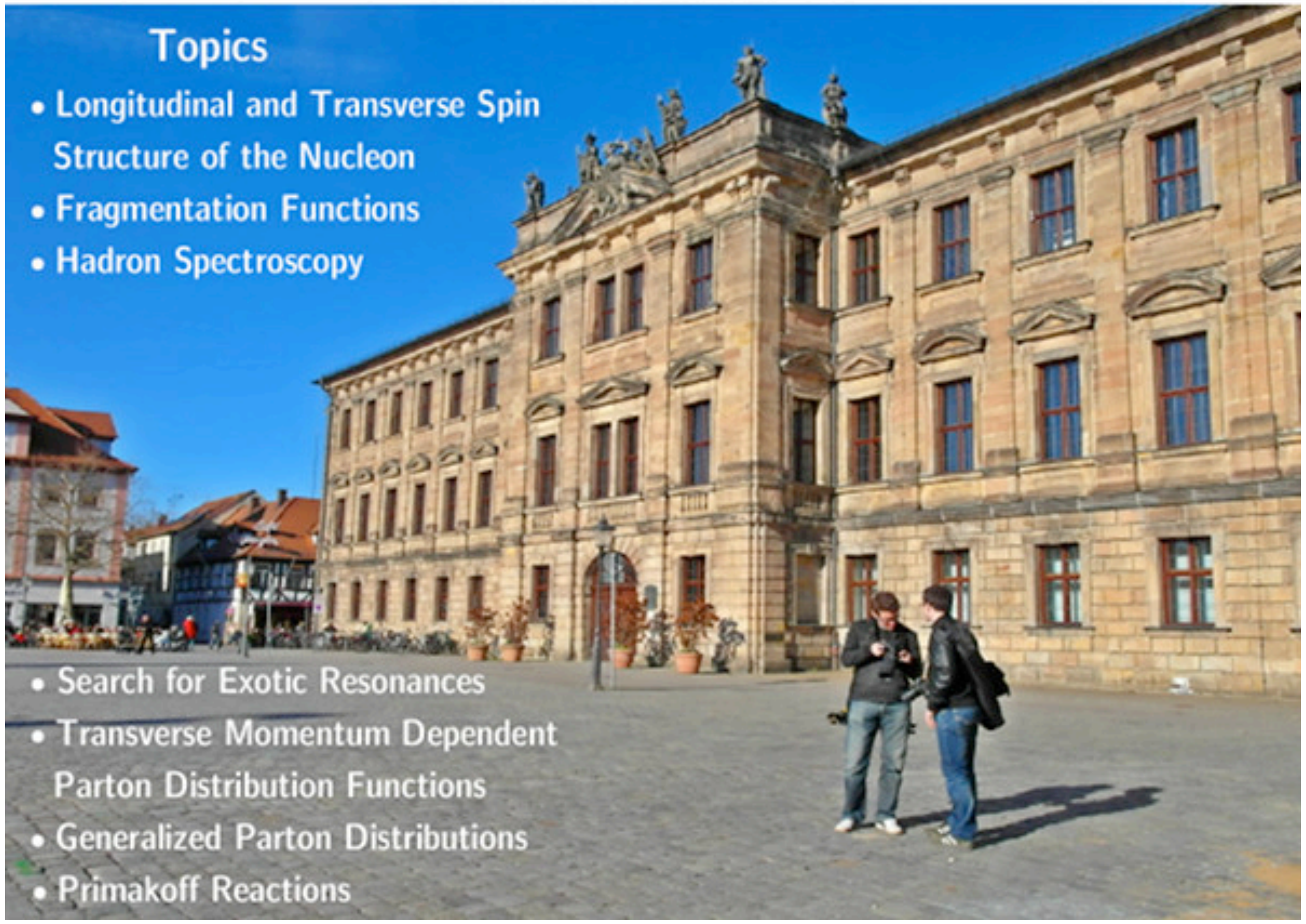
COMPASS

IWHSS 2013

International Workshop on Hadron Structure and Spectroscopy 2013,
Erlangen, Germany, 22-24 July


Topics
- Longitudinal and Transverse Spin Structure of the Nucleon
- Fragmentation Functions
- Hadron Spectroscopy
- Search for Exotic Resonances
- Transverse Momentum Dependent Parton Distribution Functions
- Generalized Parton Distributions
- Primakoff Reactions

Experimental review of transverse-spin physics

ikerbasque
Basque Foundation for Science

Gunar.Schnell @ DESY.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Transverse spin - a bumpy road

- largely neglected

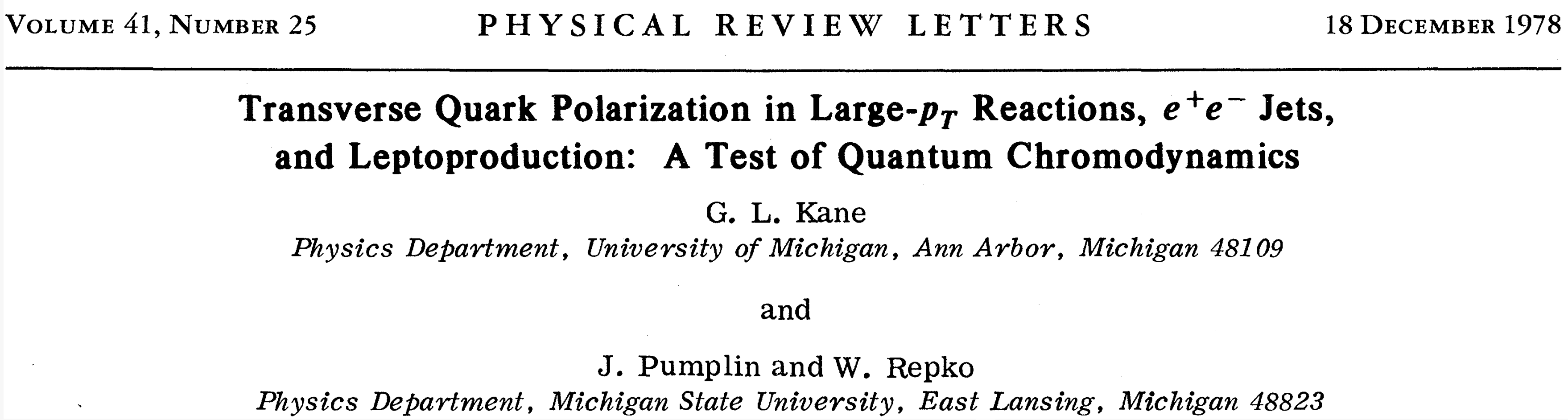
Transverse spin - a bumpy road

- largely neglected
- "transverse spin" structure function g_2 small (vanishing in parton model)

Transverse spin - a bumpy road

- largely neglected
- "transverse spin" structure function g_2 small (vanishing in parton model)
- transverse-spin effects suppressed in pQCD:

$$A_N \propto \alpha_S \frac{m_q}{Q^2}$$



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

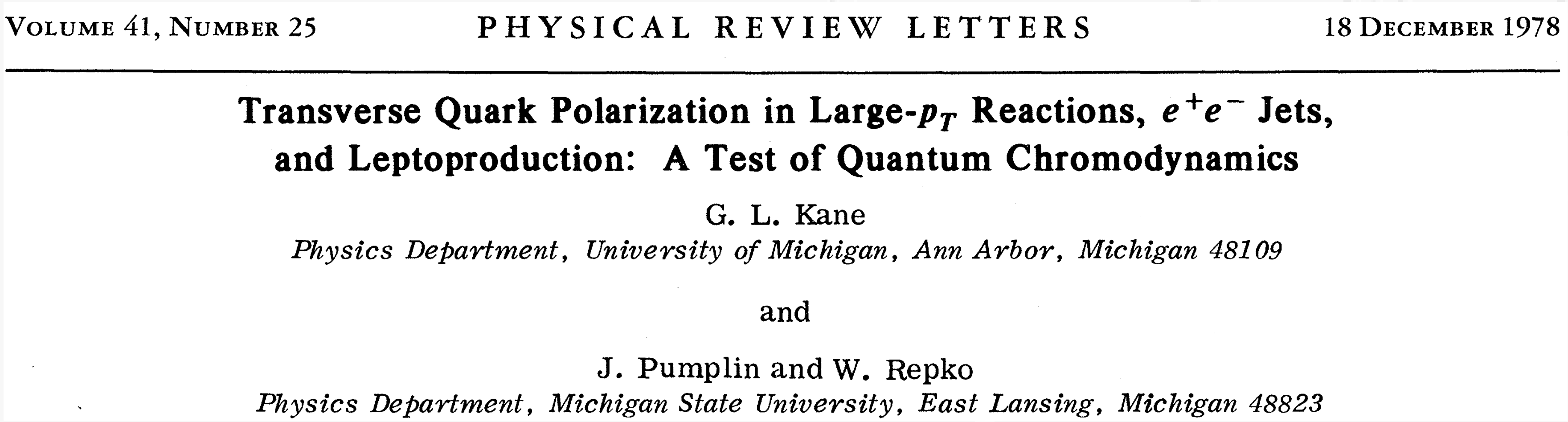
Transverse spin - a bumpy road

- largely neglected
- “transverse spin” structure function g_2 small (vanishing in parton model)
- transverse-spin effects suppressed in pQCD:

$$A_N \propto \alpha_S \frac{m_q}{Q^2}$$

quark mass

energy scale



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

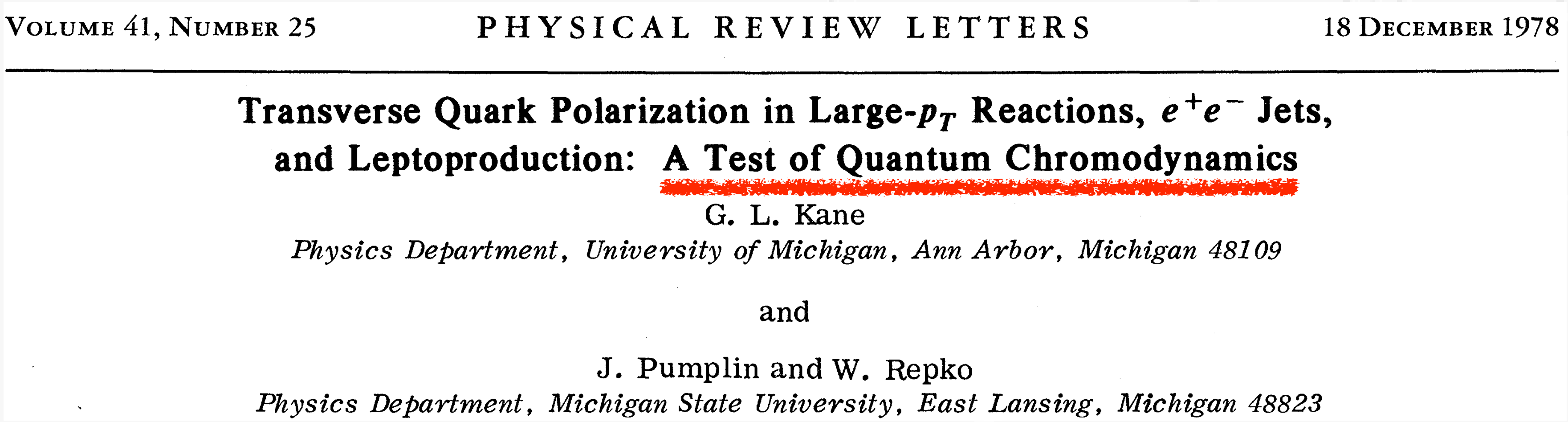
Transverse spin - a bumpy road

- largely neglected
- "transverse spin" structure function g_2 small (vanishing in parton model)
- transverse-spin effects suppressed in pQCD:

$$A_N \propto \alpha_S \frac{m_q}{Q^2}$$

← quark mass

← energy scale



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

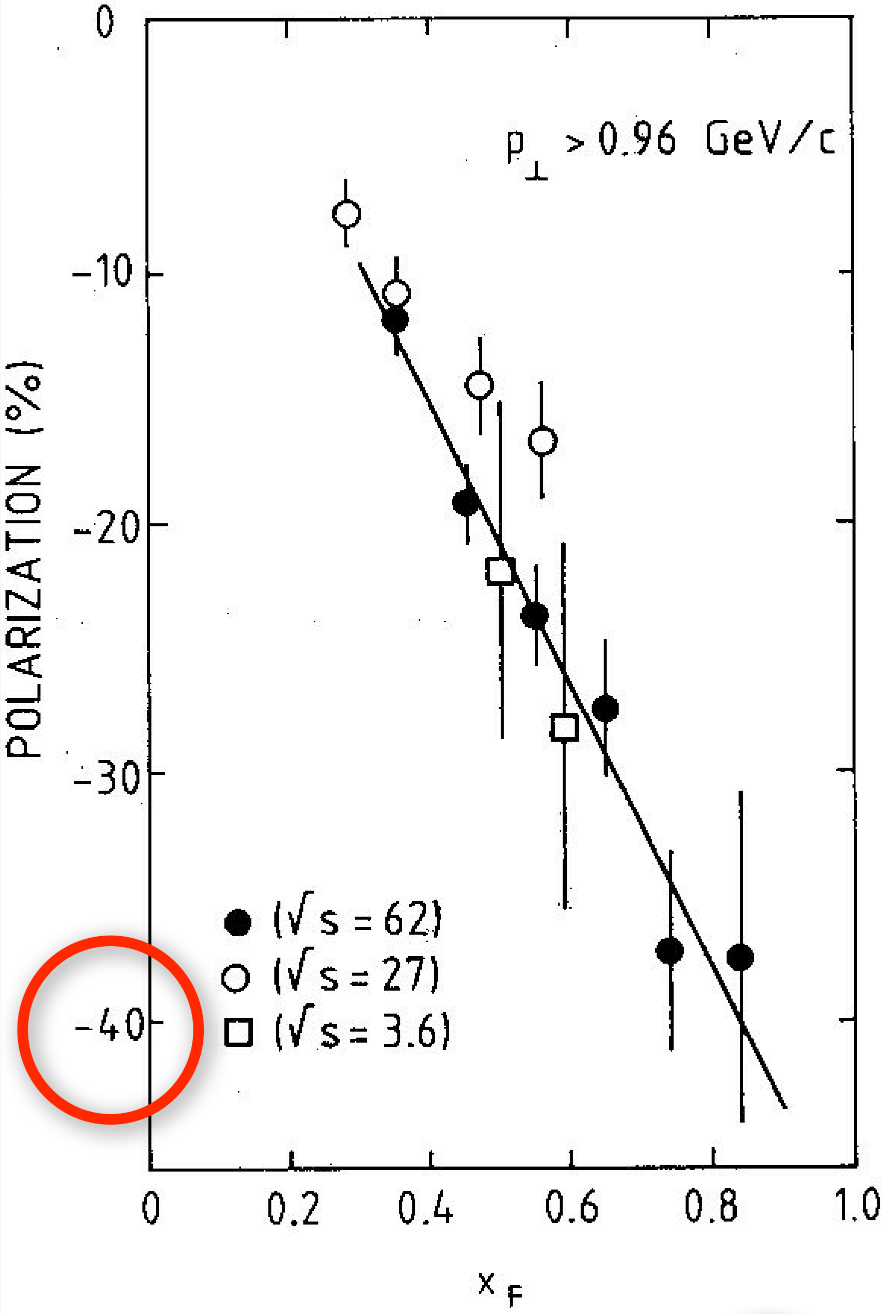
G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

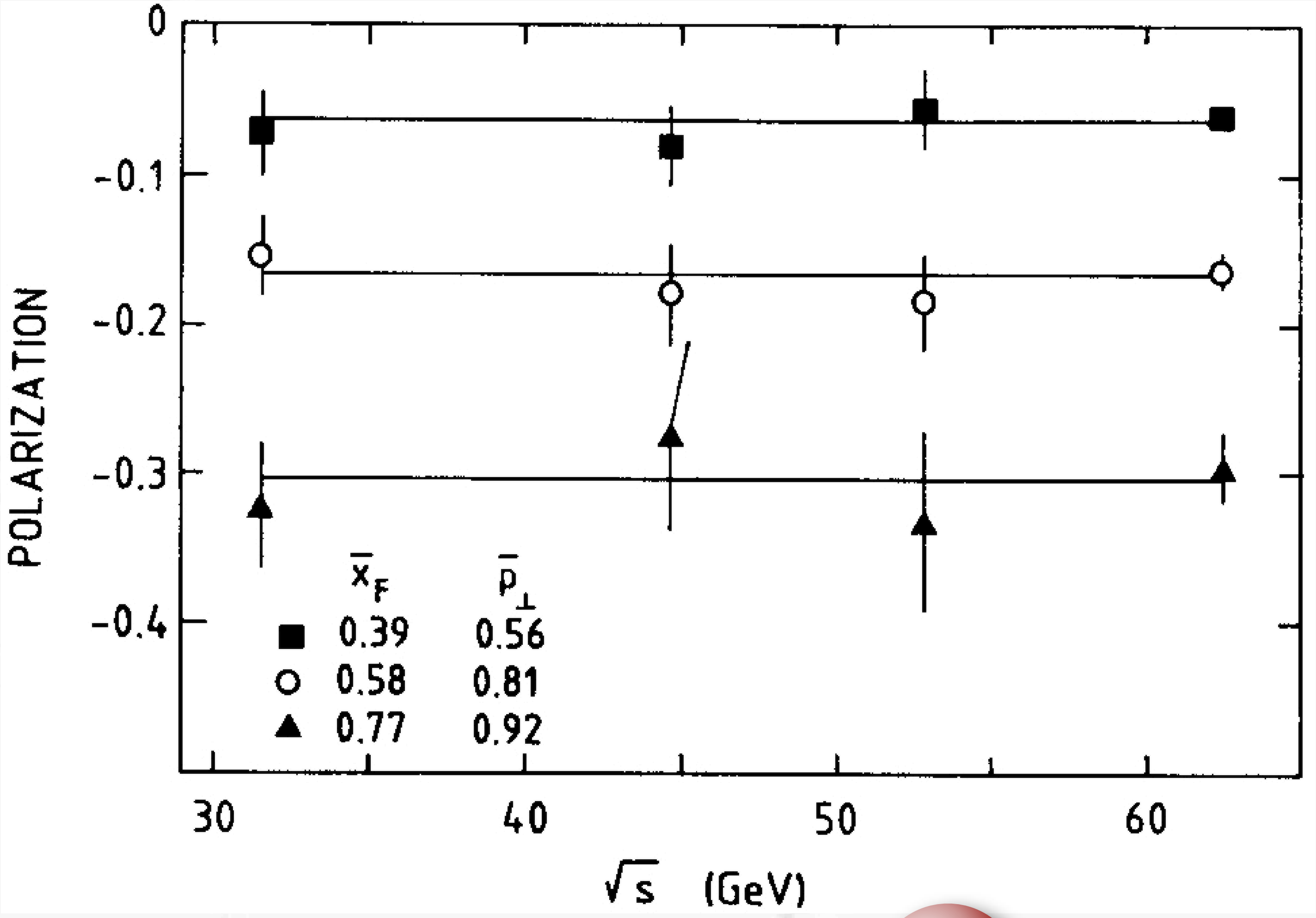
and

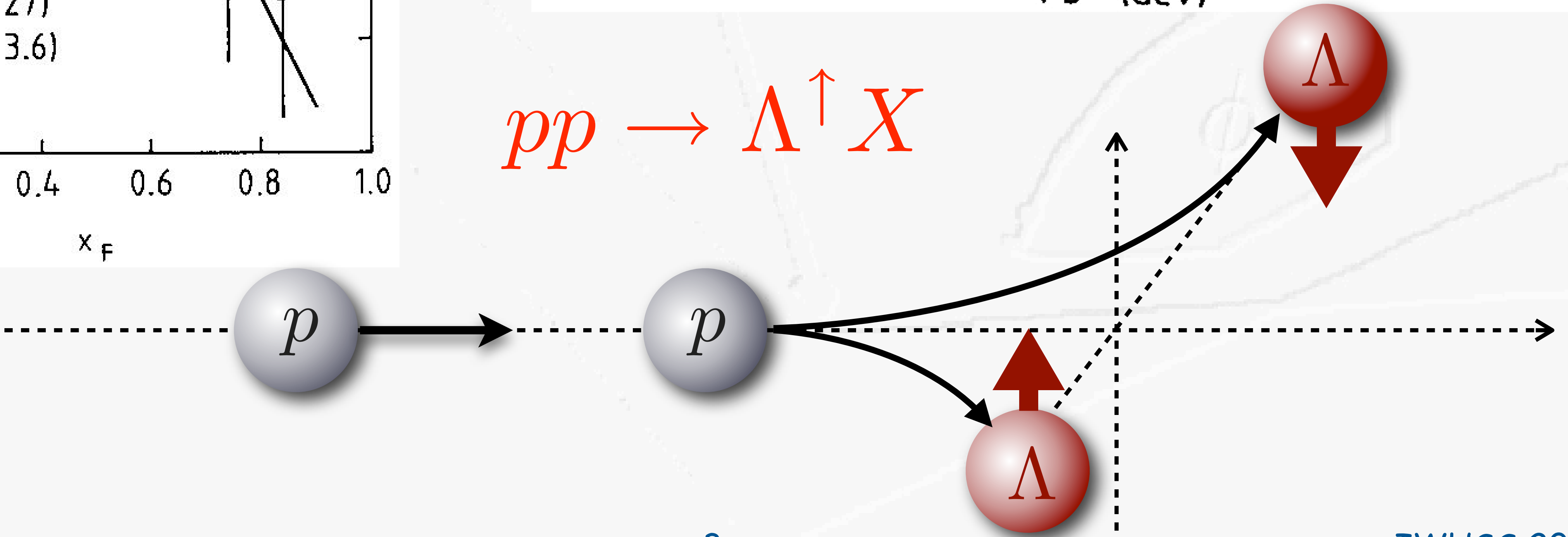
J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

Nature does not seem to cooperate

Comprehensive review of data by A.D. Panagiotou (Int. J. Mod. Phys. A5 (1990) 1197)



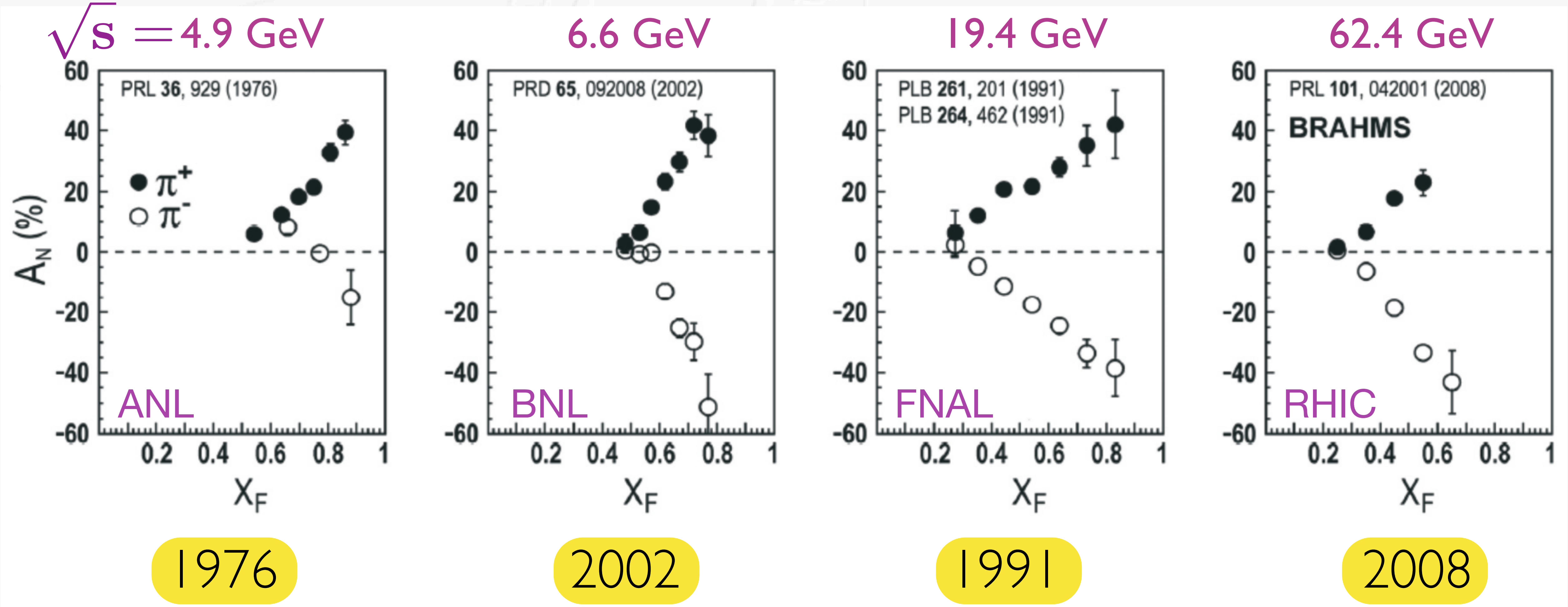


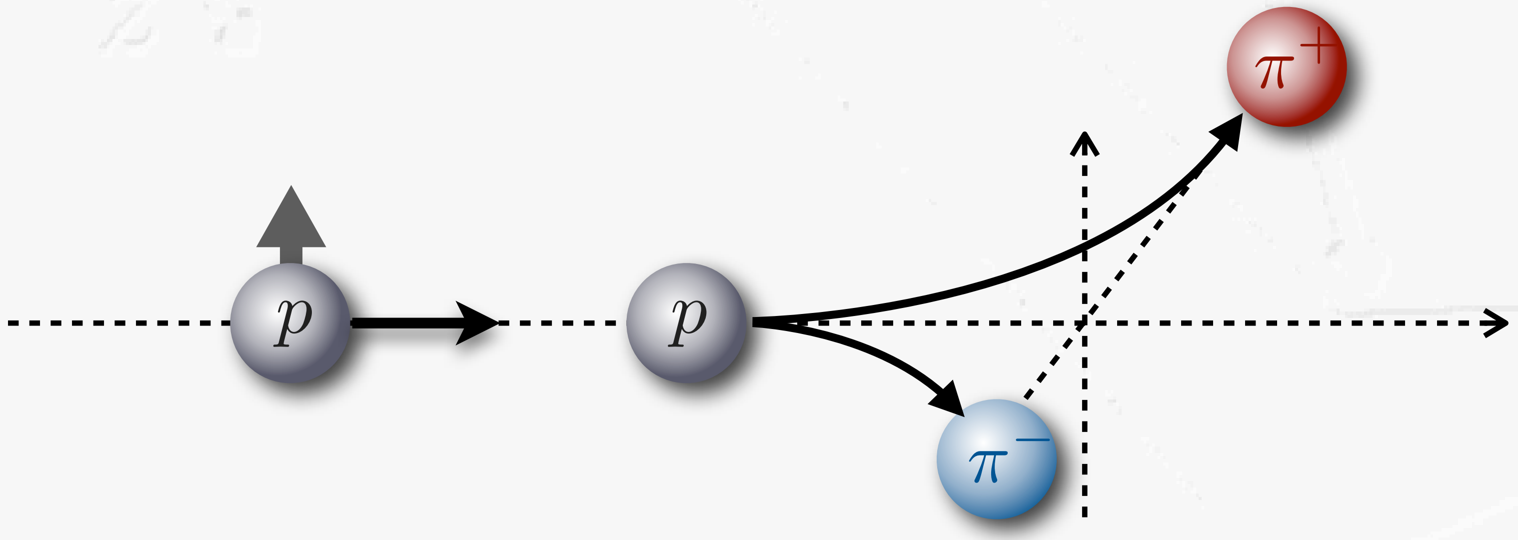


$pp \to \Lambda^\uparrow X$

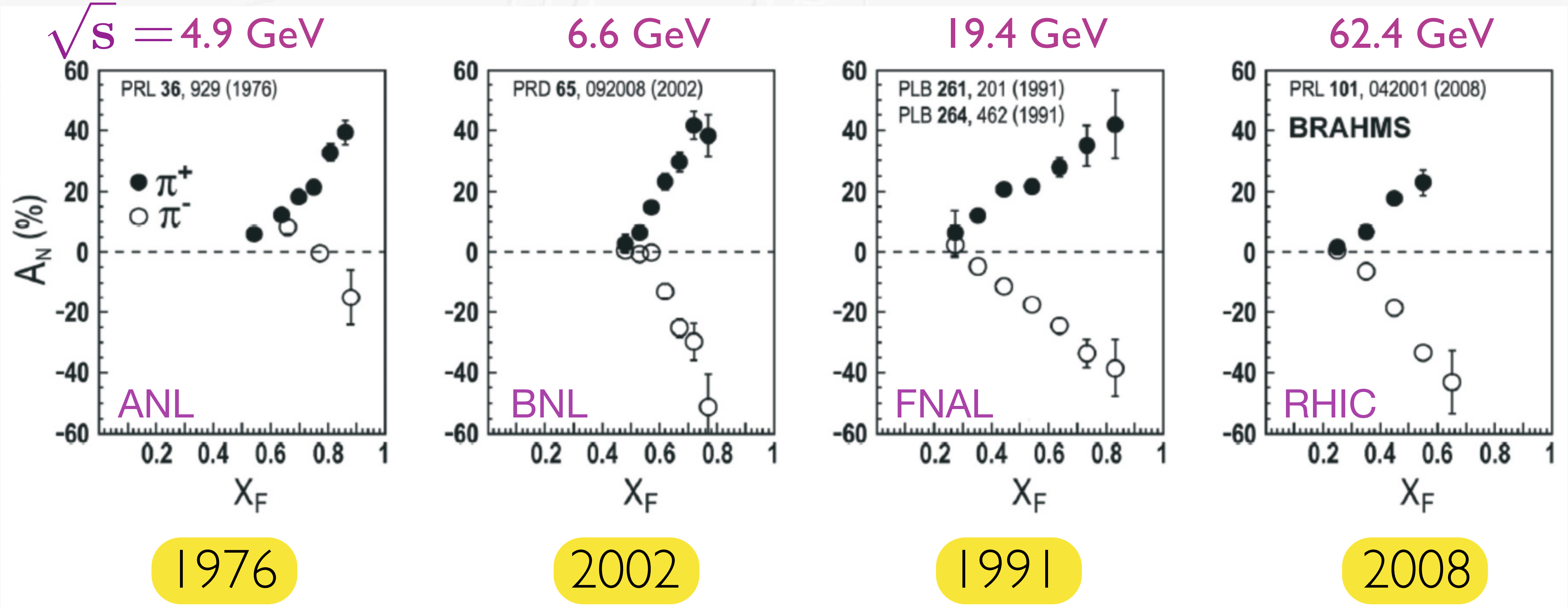
… also not for pion production …

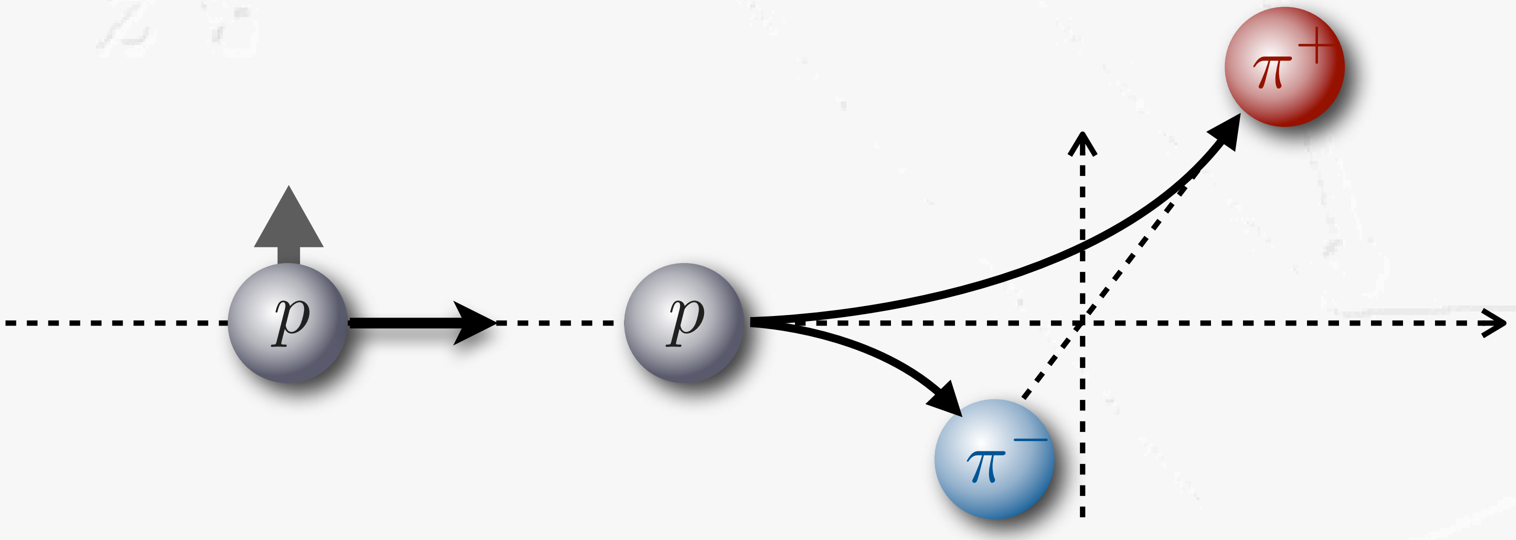
… also not for pion production …





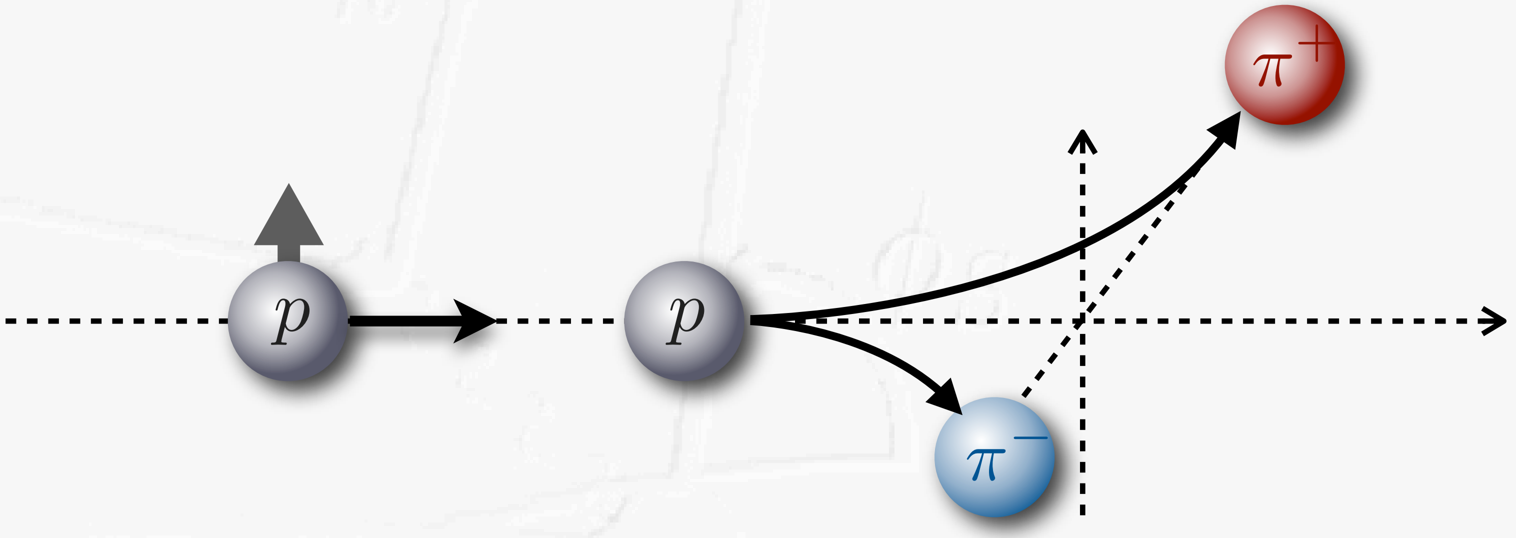
… also not for pion production …



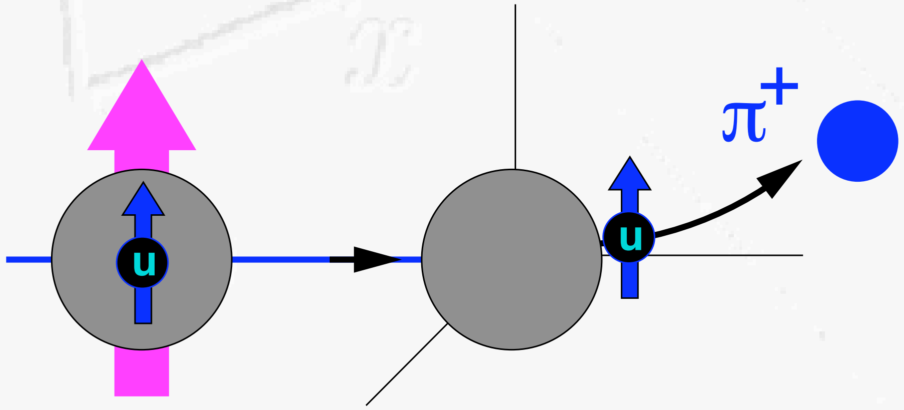


- large left-right asymmetries persist even at RHIC energies

What's the origin of these SSA?



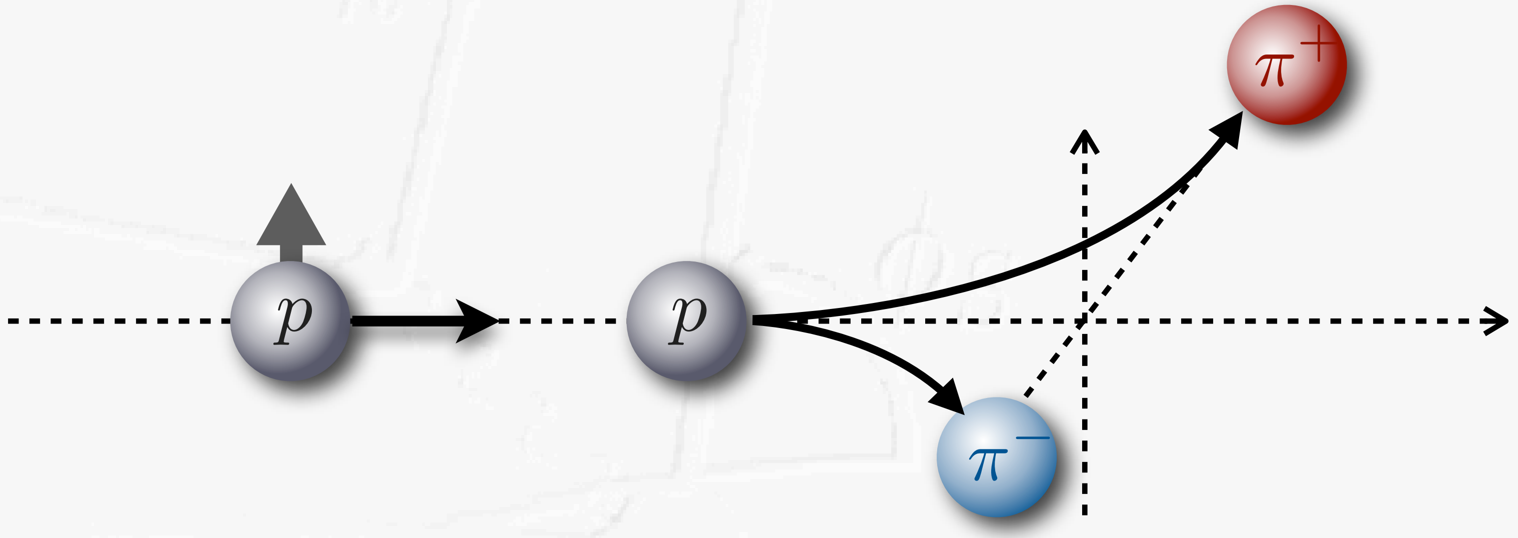
- fragmentation effect?



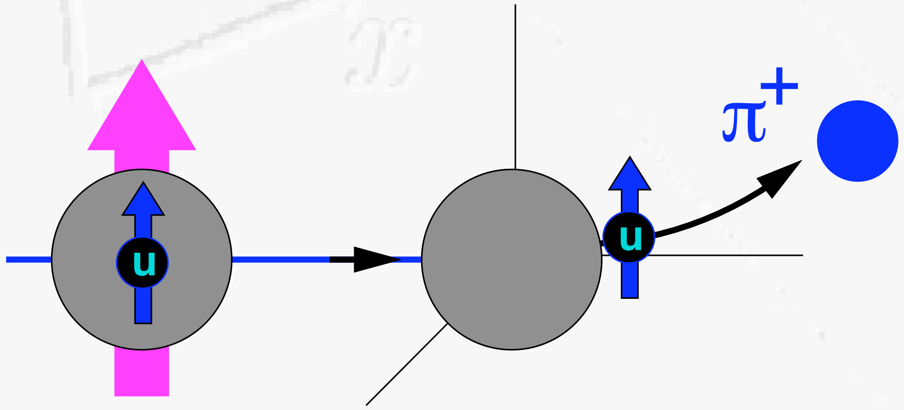
[J.C. Collins, NPB 396 (1993) 161]

- correlating transverse quark spin with transverse momentum

What's the origin of these SSA?



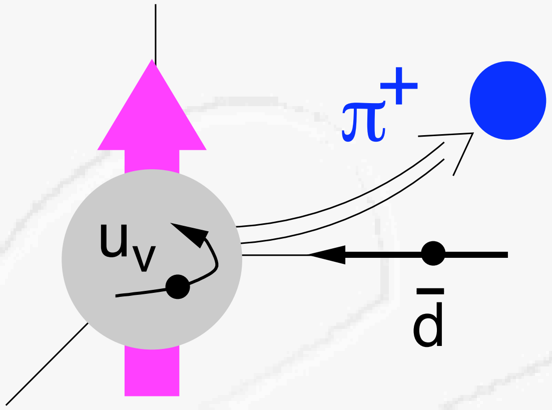
- fragmentation effect?



[J.C. Collins, NPB 396 (1993) 161]

- correlating transverse quark spin with transverse momentum

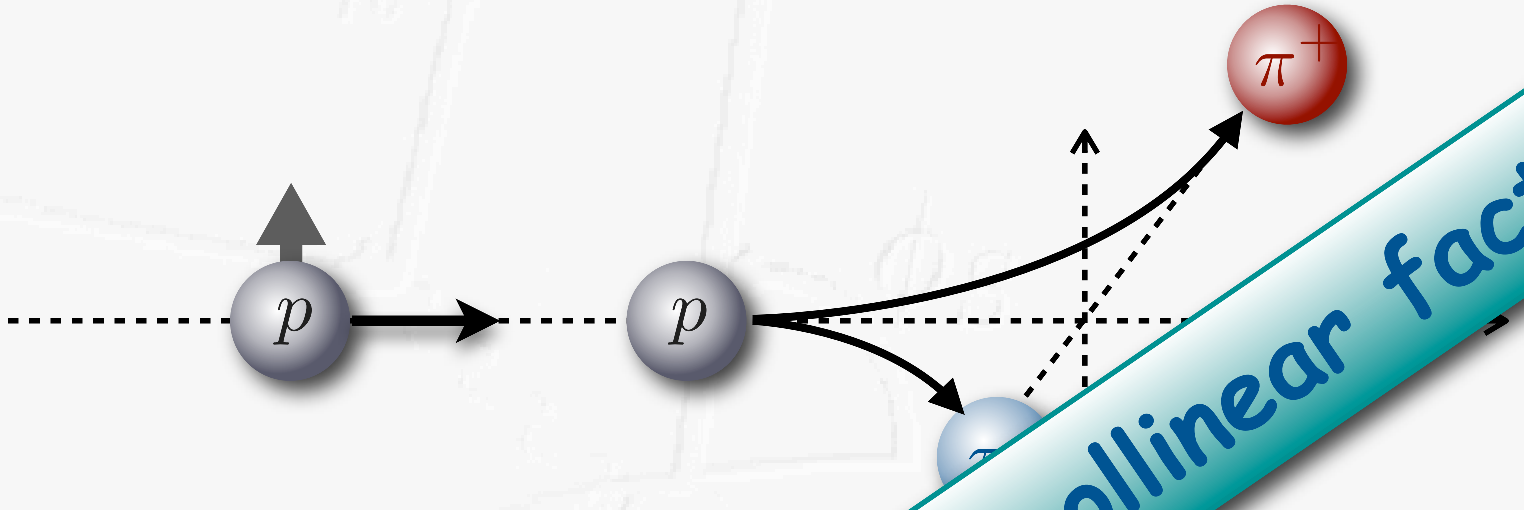
- quark-distribution effect?



[D.W. Sivers, PRD 41 (1990) 83]

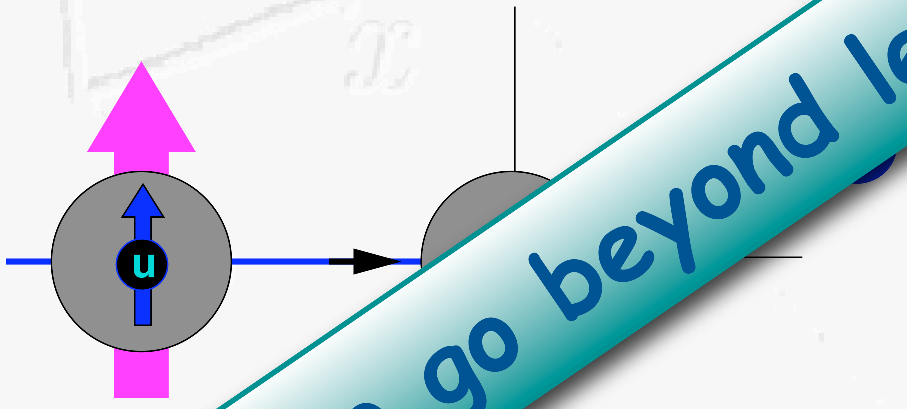
- correlating transverse quark momentum with transverse spin of nucleon

What's the origin of these SSA?



need to go beyond leading-twist collinear factorization

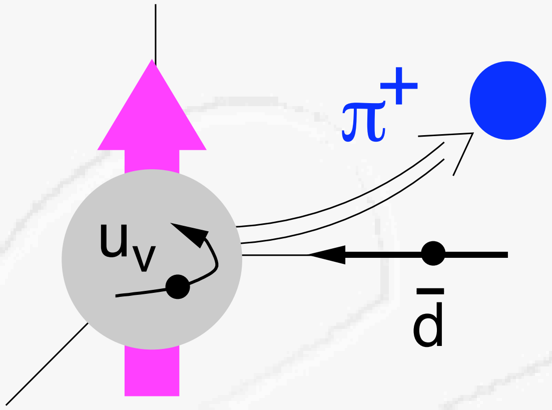
- fragmentation effect?



[J.C. Collins, NPB 396 (1993) 161]

- relating transverse quark spin with transverse momentum

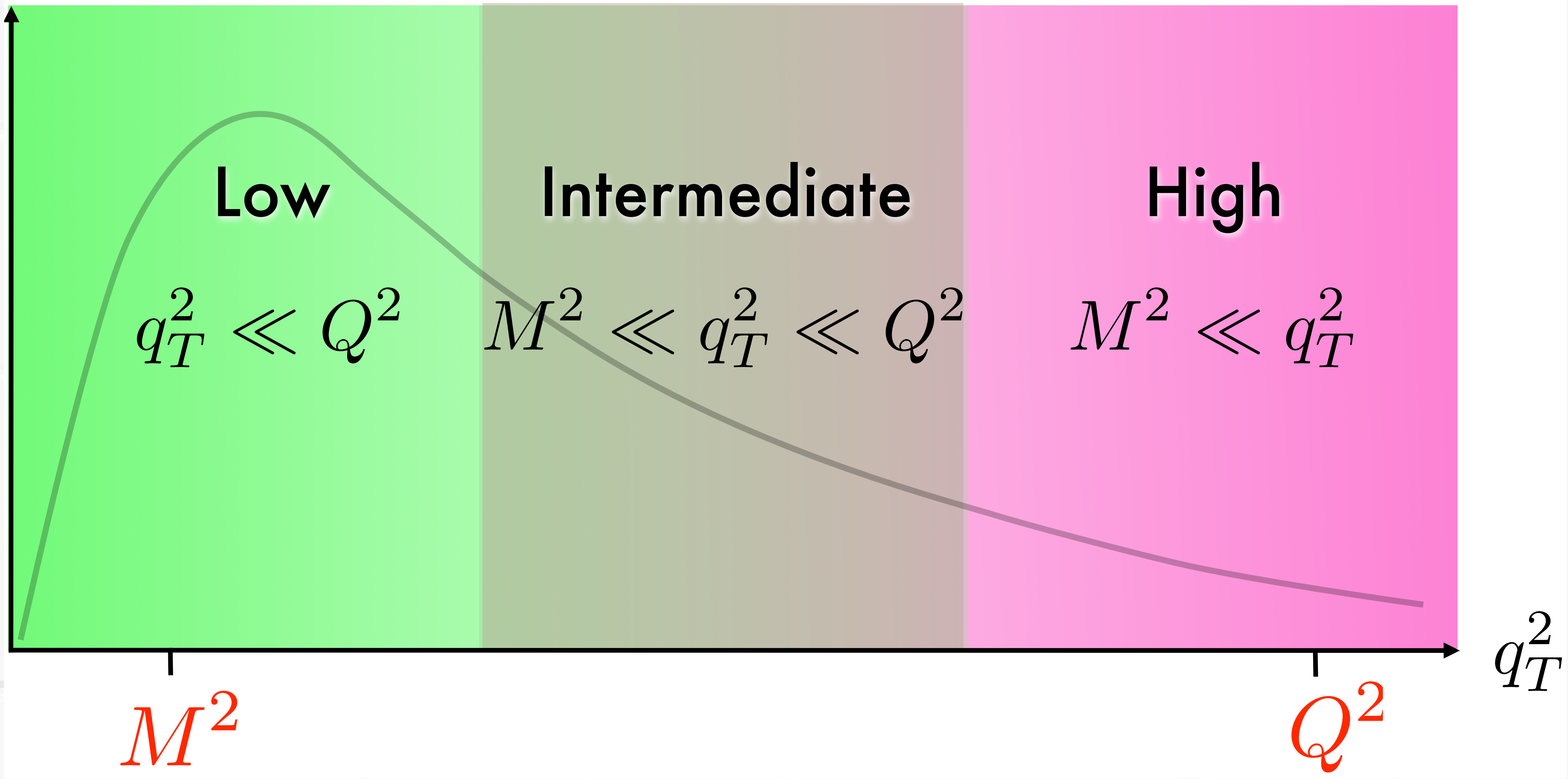
- quark-distribution effect?



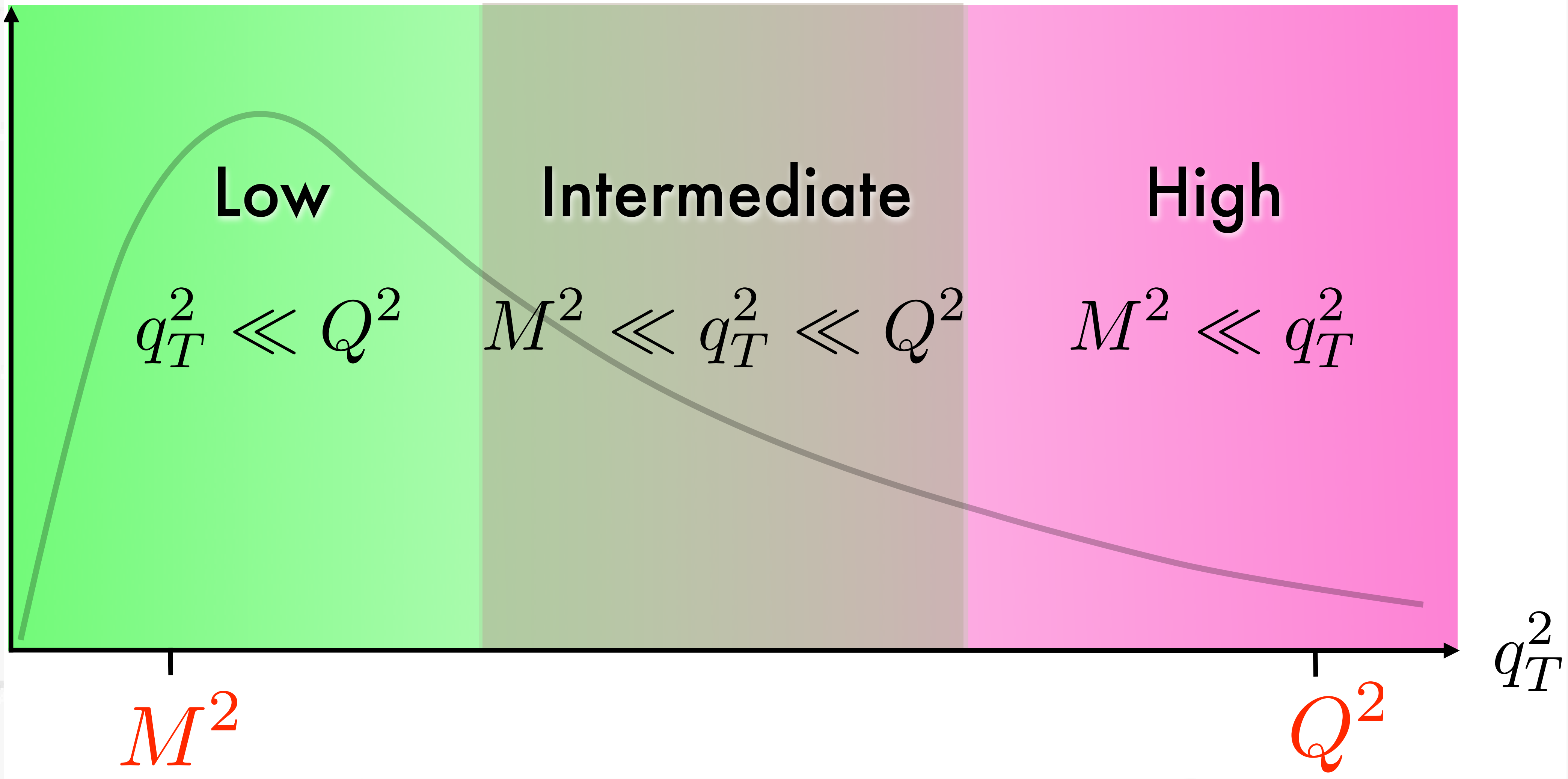
[D.W. Sivers, PRD 41 (1990) 83]

- correlating transverse quark momentum with transverse spin of nucleon

going beyond leading-twist collinear approach



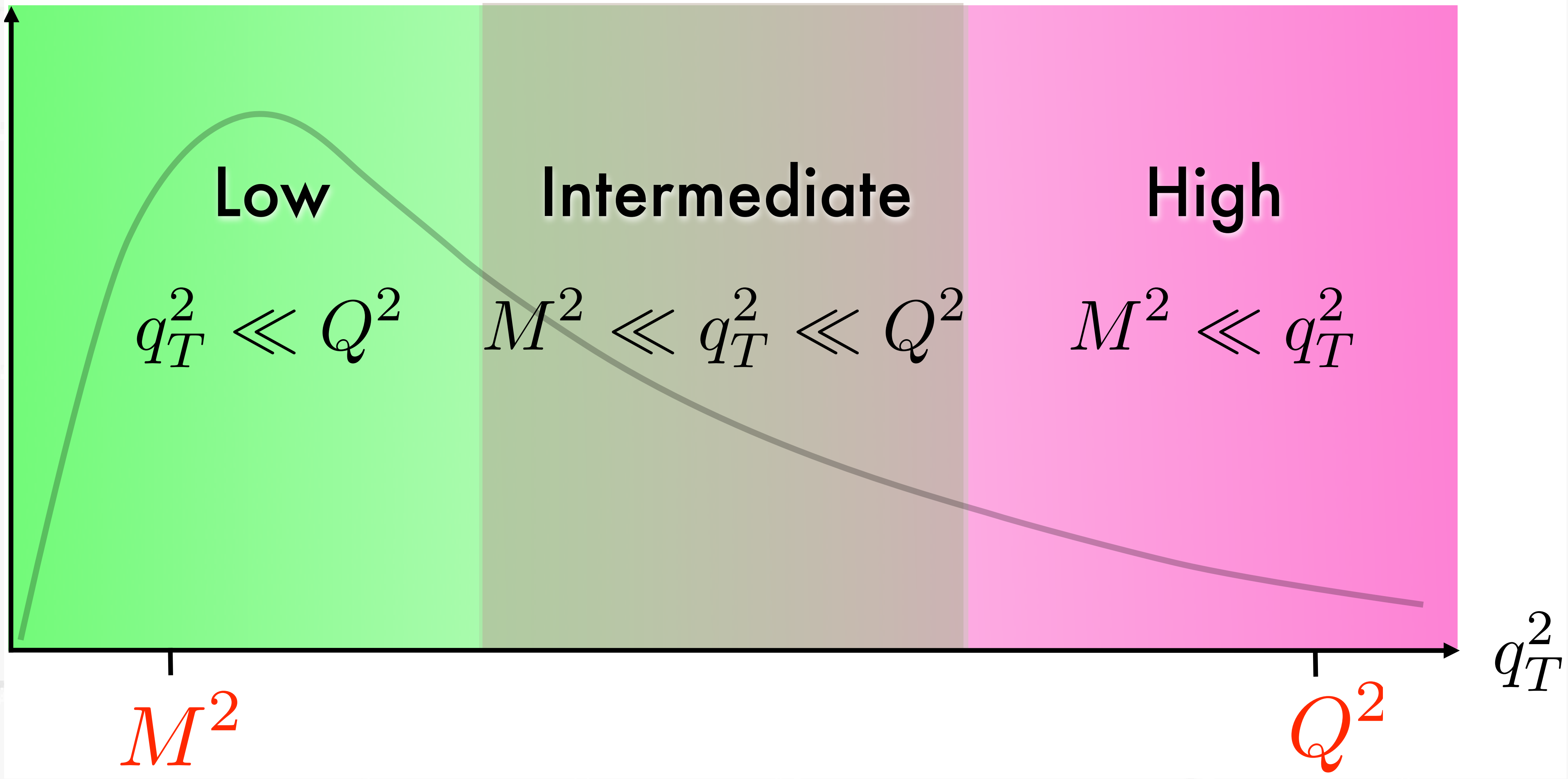
going beyond leading-twist collinear approach



TMD
factorization

TMD: transverse-momentum-dependent distributions

going beyond leading-twist collinear approach

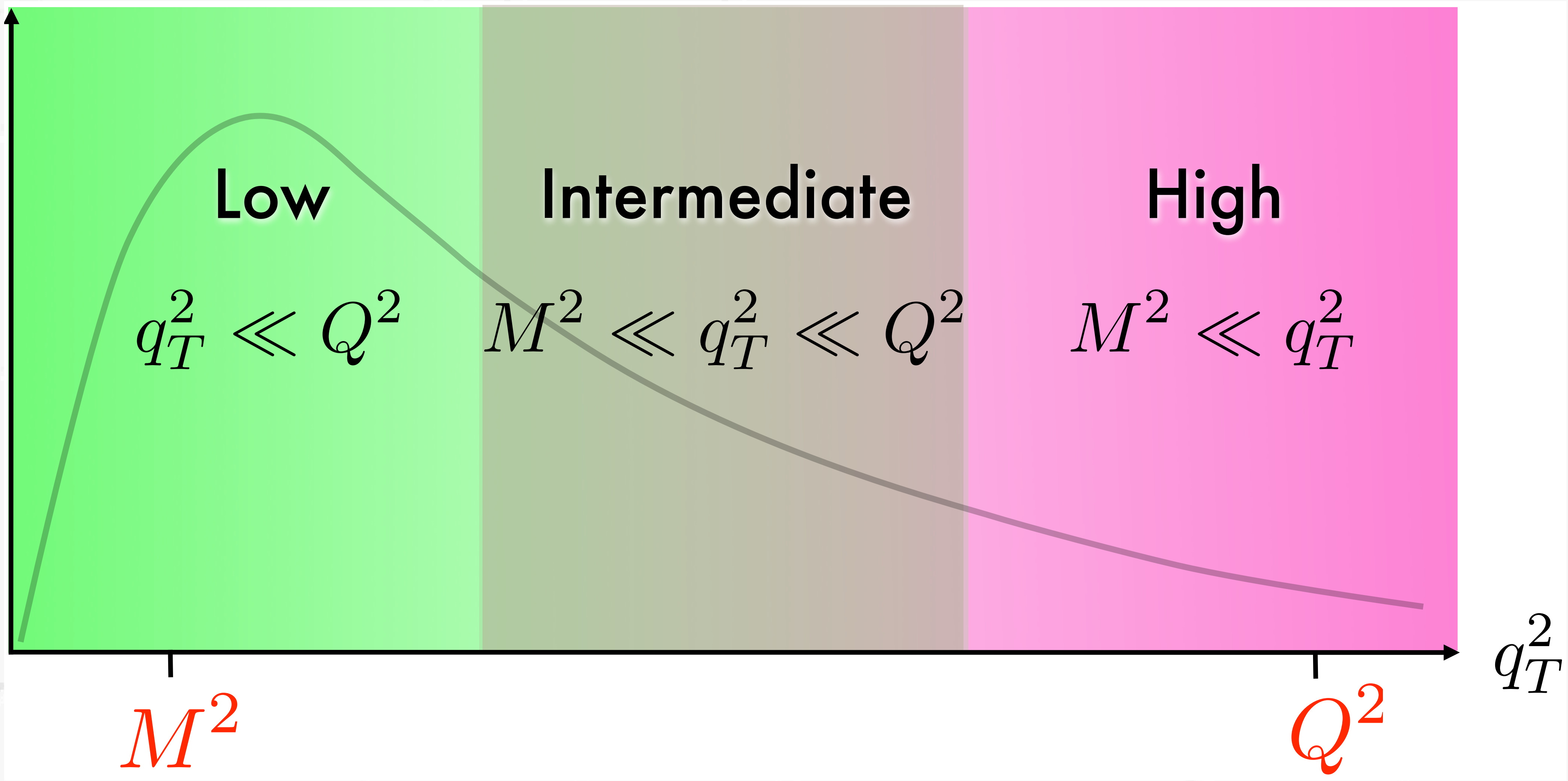


TMD factorization

twist-3 collinear factorization

TMD: transverse-momentum-dependent distributions

going beyond leading-twist collinear approach



TMD factorization

overlap region

twist-3 collinear factorization

TMD: transverse-momentum-dependent distributions

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.		
		U	L	T
nucleon pol.	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

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.

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, $h_{1T}^\perp$

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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

details ☛ M. Radici, M. Boglione

Transverse spin $|\uparrow\downarrow\rangle = \frac{1}{2}\left(|+\rangle \pm |-\rangle\right)$

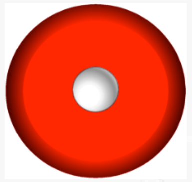
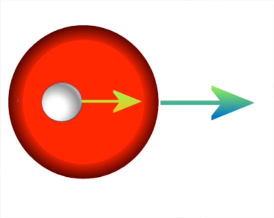
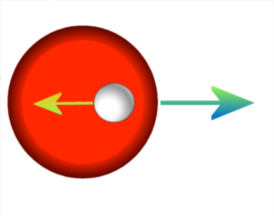
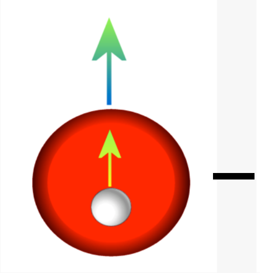
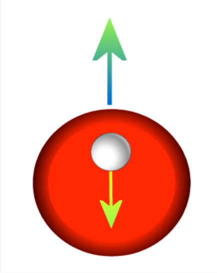
$$\langle\uparrow|\,\hat{O}\,|\uparrow\rangle - \langle\downarrow|\,\hat{O}\,|\downarrow\rangle \propto \langle+|\,\hat{O}\,|-\rangle - \langle-|\,\hat{O}\,|+\rangle$$

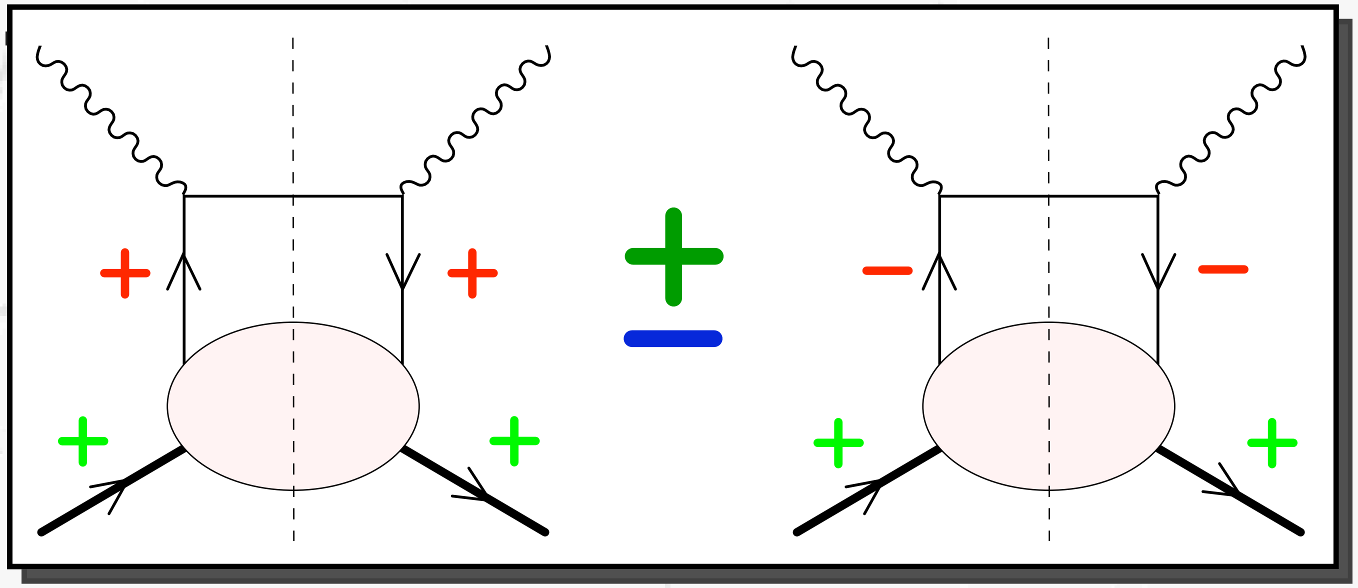
transverse-spin asymmetries involve **helicity flip**

Transverse spin $|\uparrow\downarrow\rangle = \frac{1}{2}\left(|+\rangle \pm |-\rangle\right)$

$$\langle\uparrow|\,\hat{O}\,|\uparrow\rangle - \langle\downarrow|\,\hat{O}\,|\downarrow\rangle \propto \langle+|\,\hat{O}\,|-\rangle - \langle-|\,\hat{O}\,|+\rangle$$

transverse-spin asymmetries involve **helicity flip**

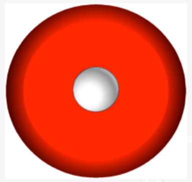
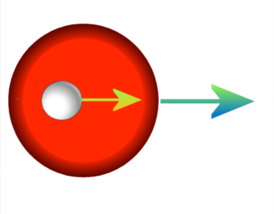
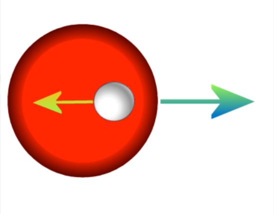
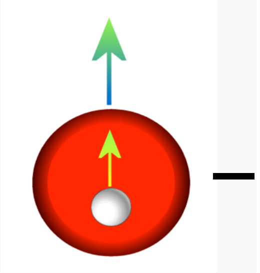
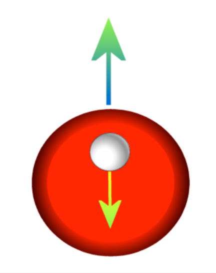
PDFs: f_1^q =  g_1^q =  −  h_1^q =  − 

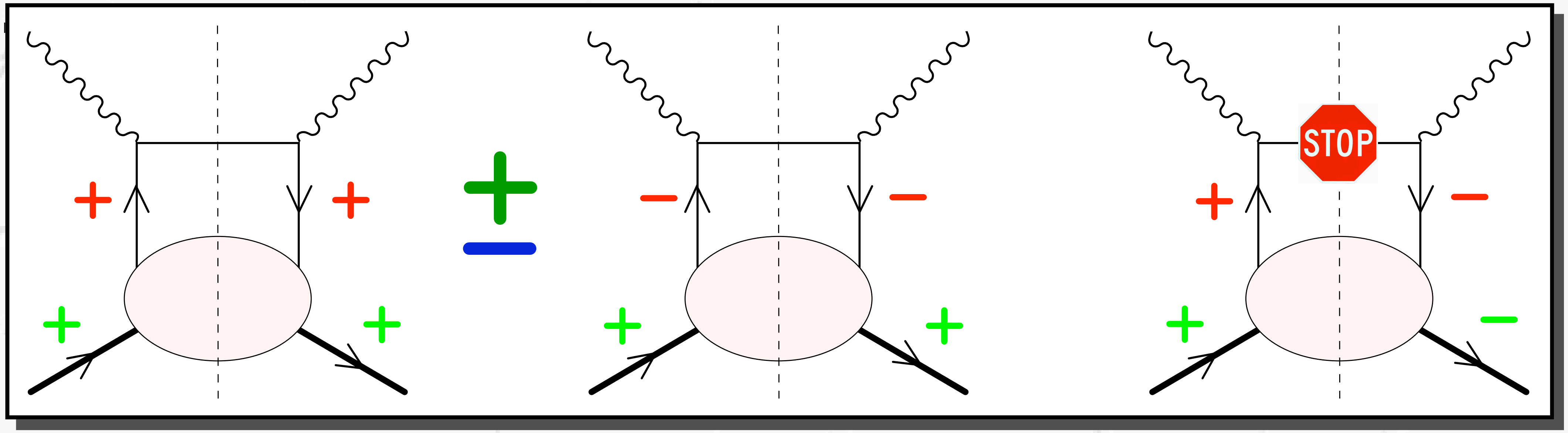


Transverse spin $|\uparrow\downarrow\rangle = \frac{1}{2}\left(|+\rangle \pm |-\rangle\right)$

$$\langle\uparrow|\,\hat{O}\,|\uparrow\rangle - \langle\downarrow|\,\hat{O}\,|\downarrow\rangle \propto \langle+|\,\hat{O}\,|-\rangle - \langle-|\,\hat{O}\,|+\rangle$$

transverse-spin asymmetries involve **helicity flip**

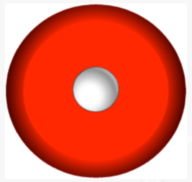
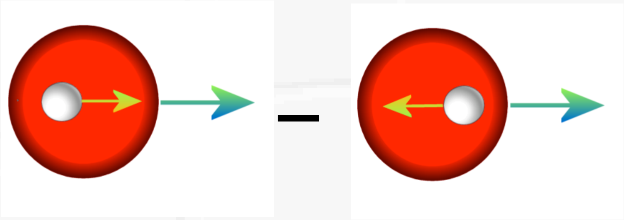
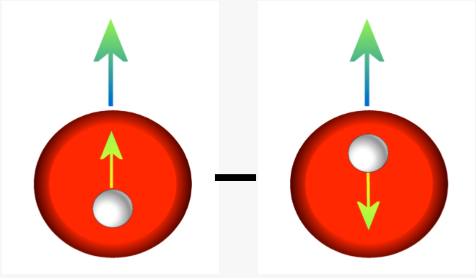
PDFs: $f_1^q =$  $g_1^q =$  –  $h_1^q =$  – 

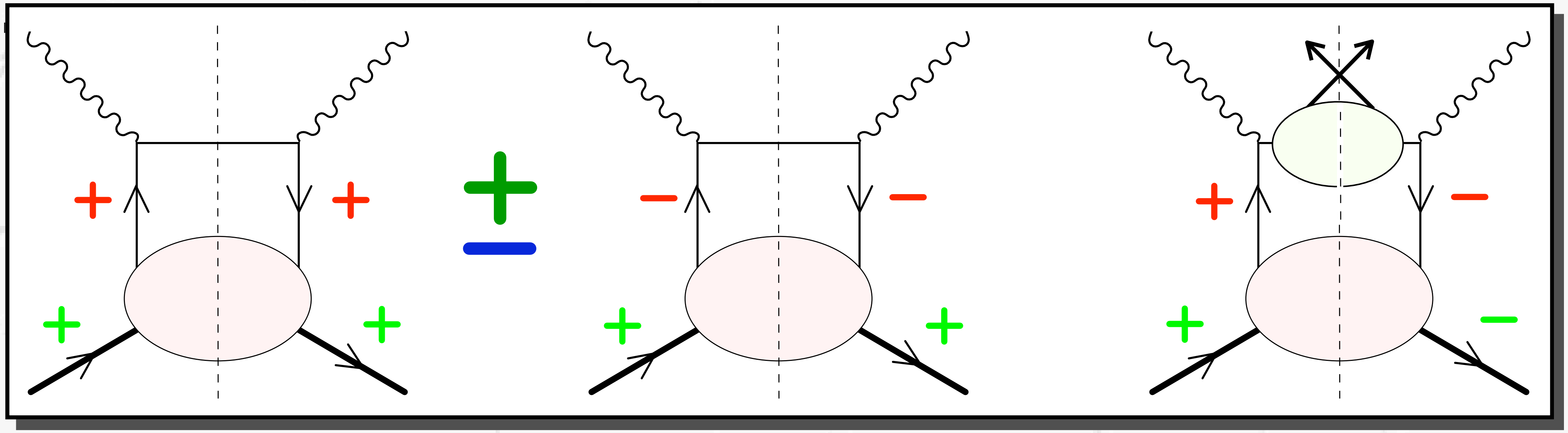


Transverse spin $|\uparrow\downarrow\rangle = \frac{1}{2}\left(|+\rangle \pm |-\rangle\right)$

$$\langle\uparrow|\,\hat{O}\,|\uparrow\rangle - \langle\downarrow|\,\hat{O}\,|\downarrow\rangle \propto \langle +|\,\hat{O}\,|-\rangle - \langle -|\,\hat{O}\,|+\rangle$$

transverse-spin asymmetries involve **helicity flip**

PDFs: $f_1^q=$  $g_1^q=$  $h_1^q=$ 



need to couple to chiral-odd fragmentation function:

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

TMD fragmentation functions

quark pol.

hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

TMD fragmentation functions

quark pol.

hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☚ relevant for unpolarized final state

TMD fragmentation functions

quark pol.

hadron pol.

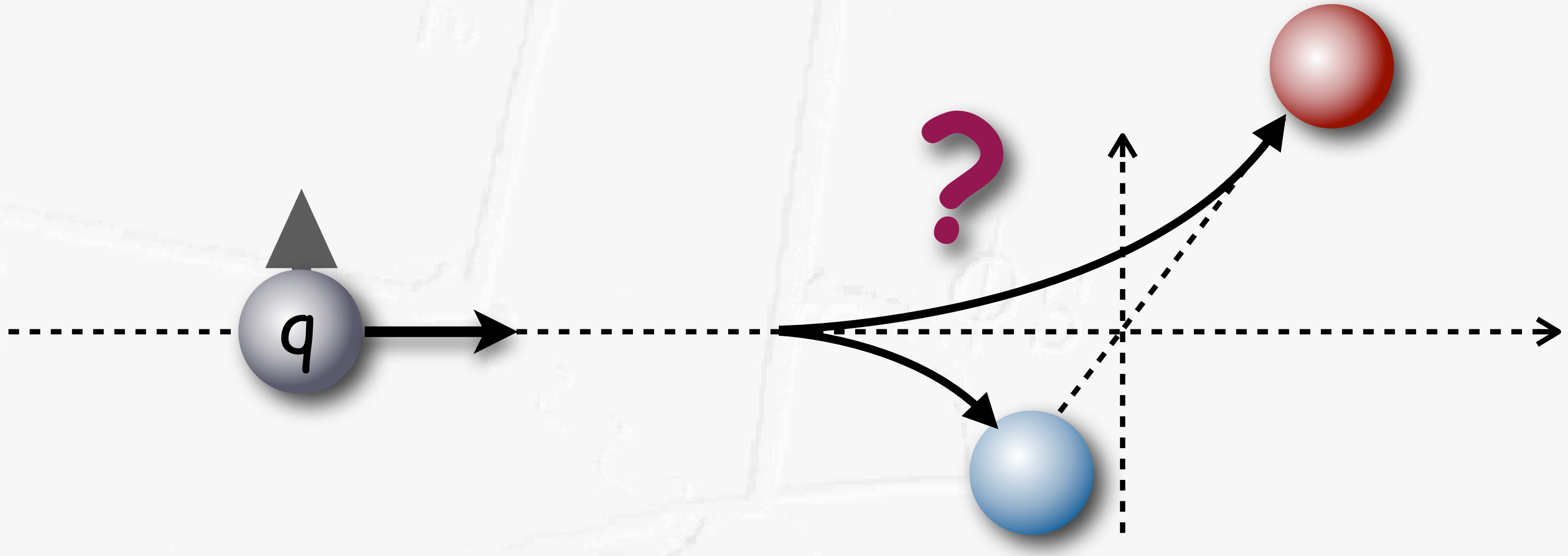
	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☚ relevant for unpolarized final state

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

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

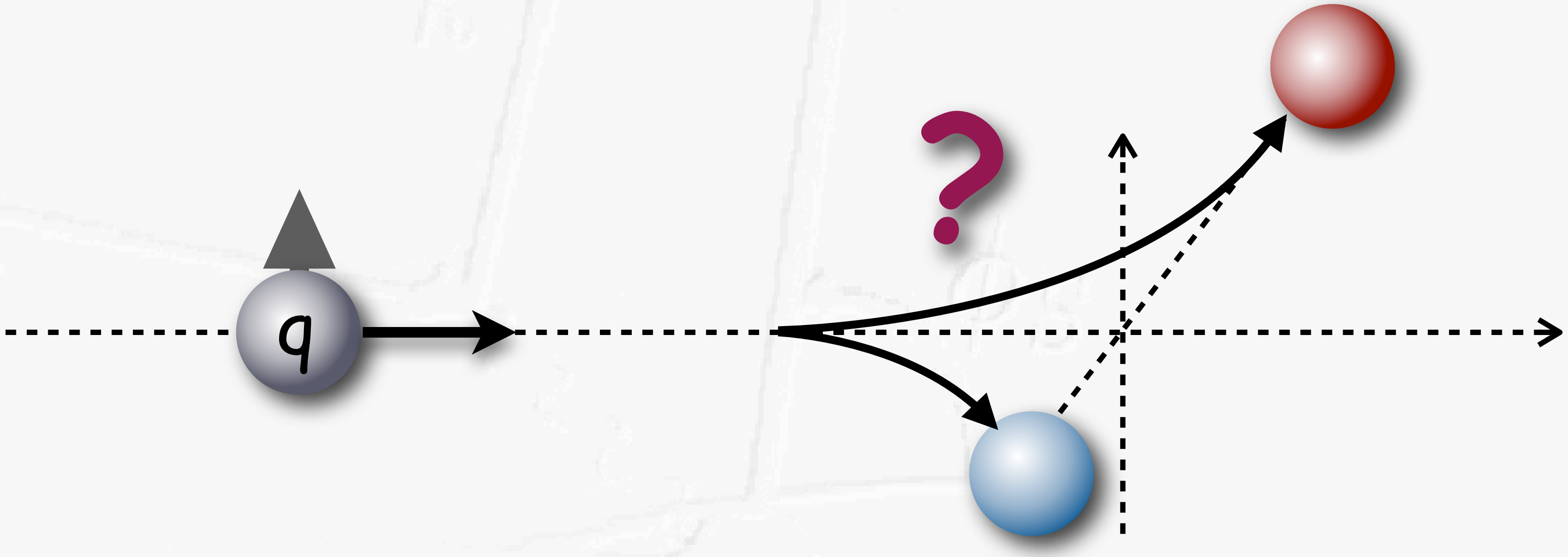
Collins fctn. - chiral-odd fragmentation



- spin-dependence in fragmentation into unpolarized final state:

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

Collins fctn. - chiral-odd fragmentation

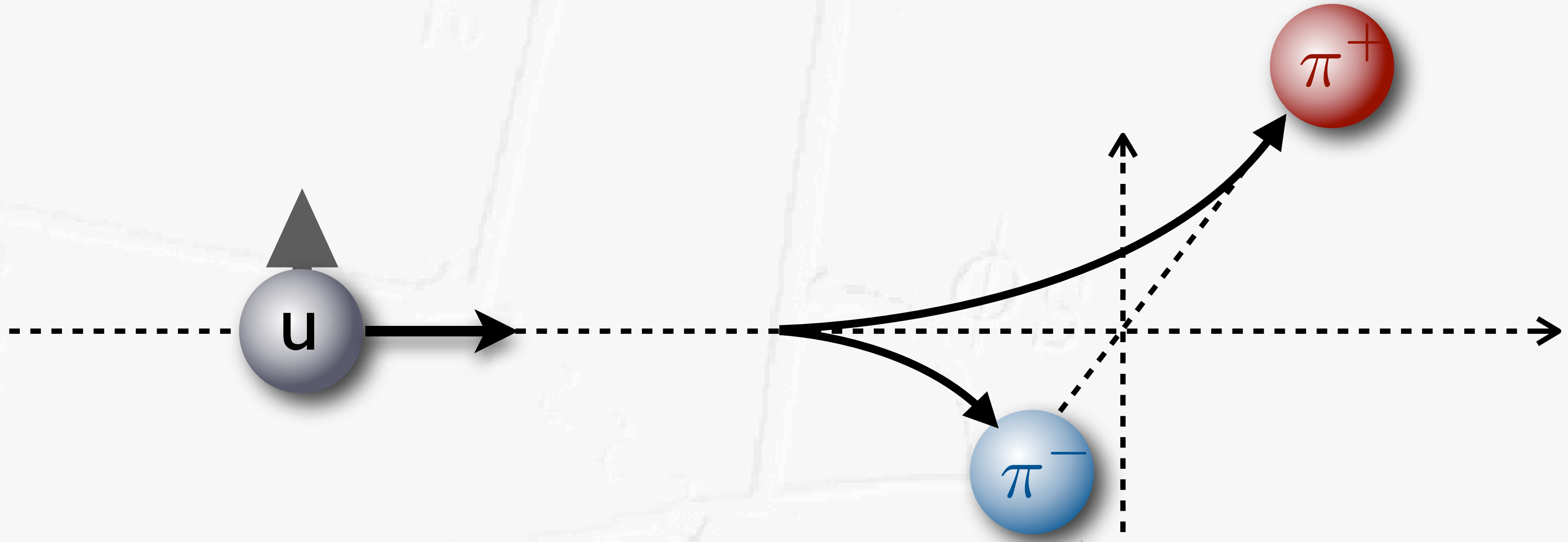


- spin-dependence in fragmentation into unpolarized final state:

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

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

Collins fctn. - chiral-odd fragmentation

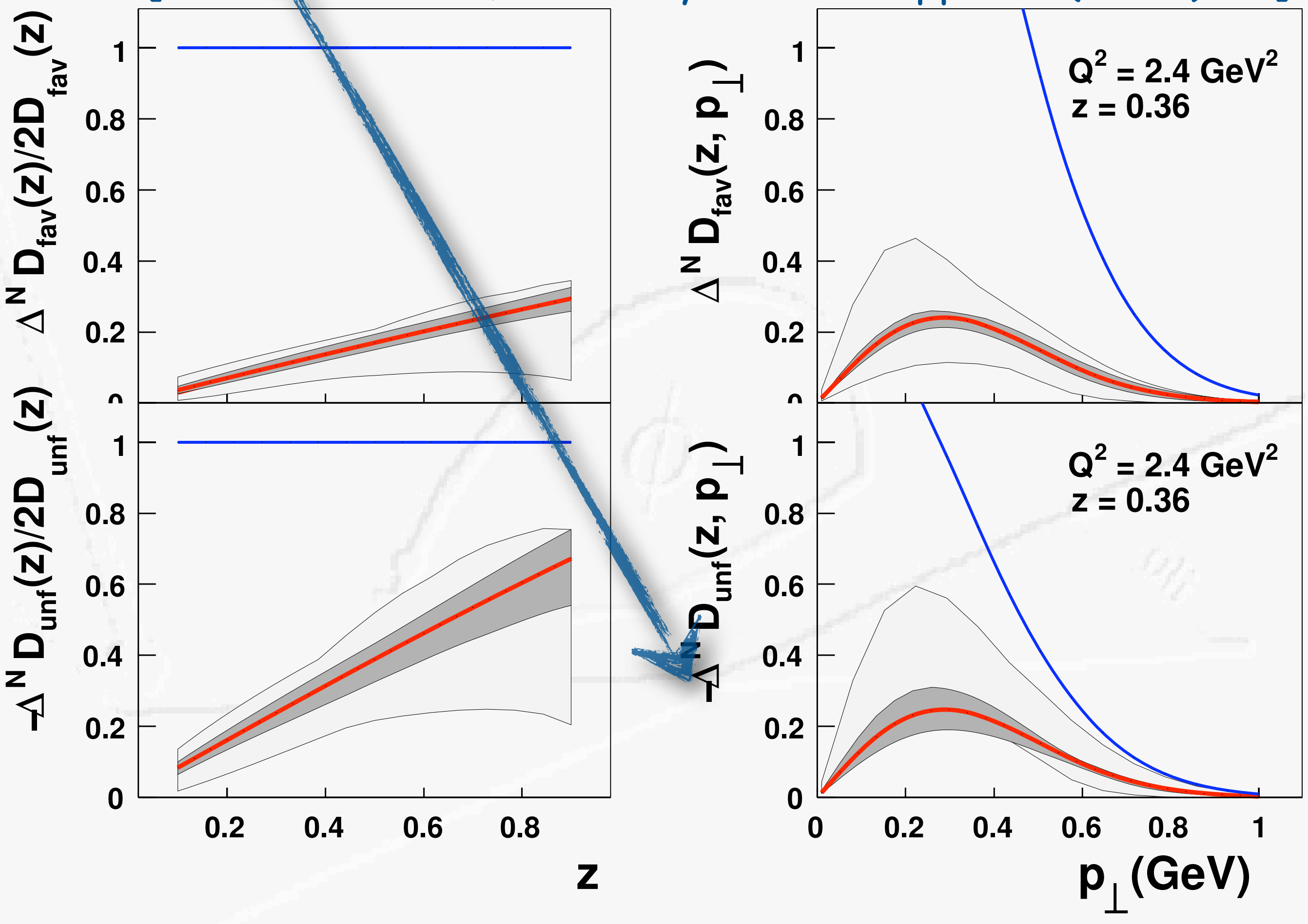


- spin-dependence in fragmentation into unpolarized final state:

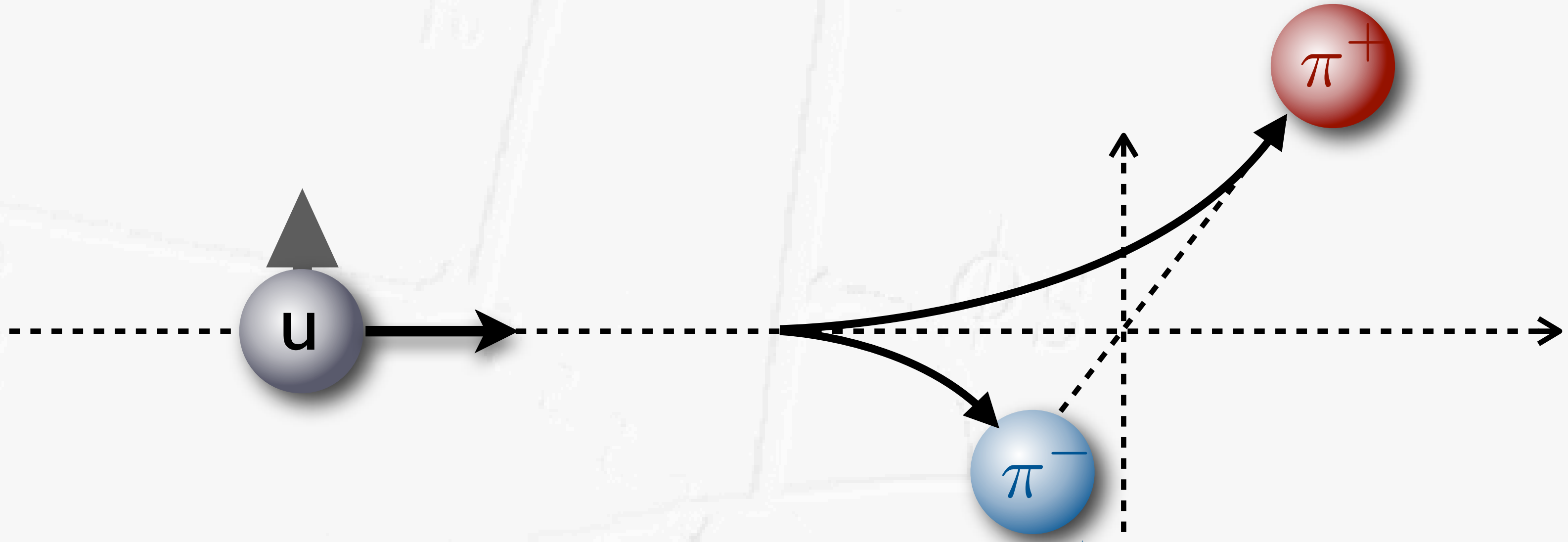
  left-right asymmetry in hadron direction transverse to both quark spin and momentum

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

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



Collins fctn. - chiral-odd fragmentation



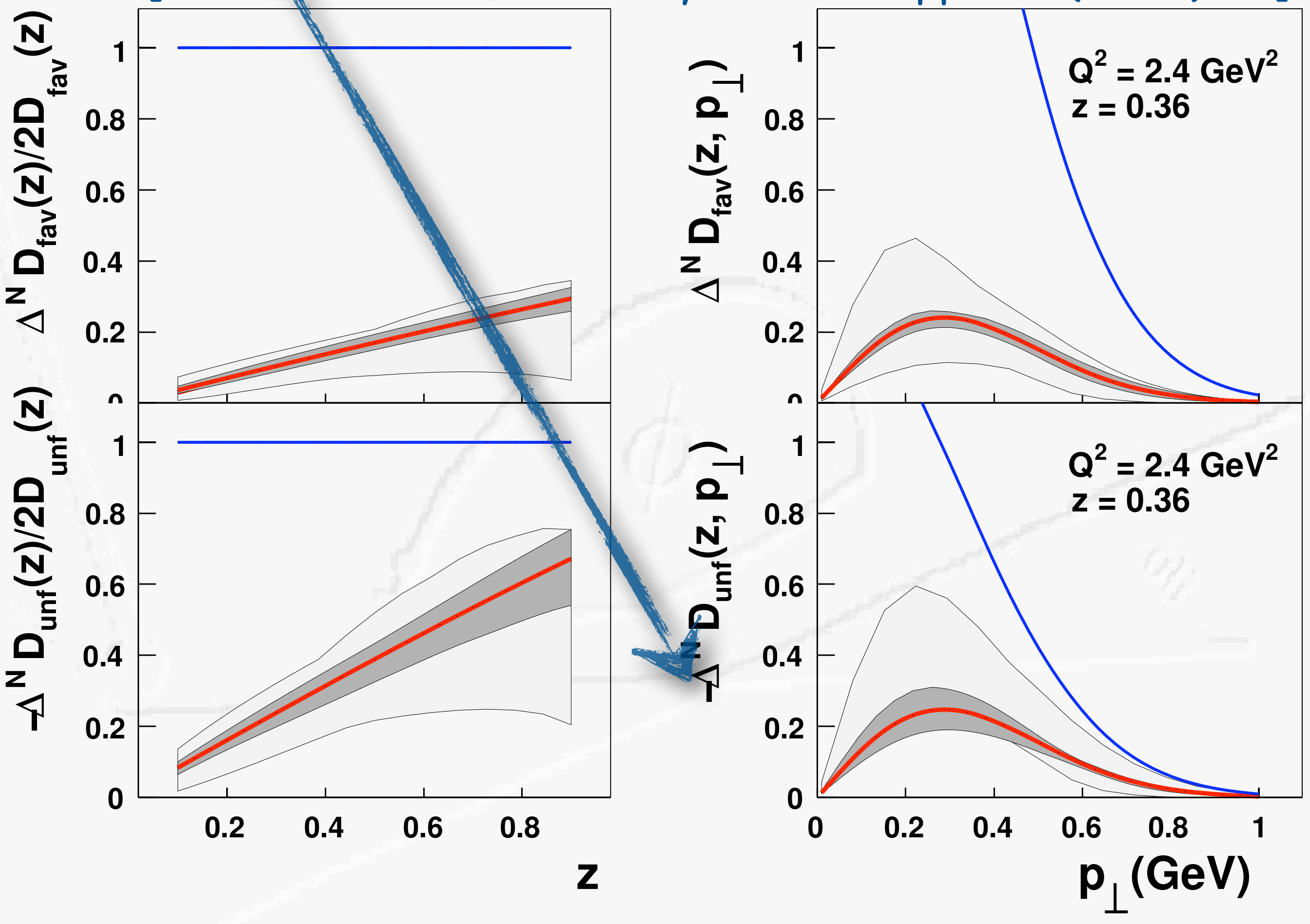
- spin-dependence in fragmentation into unpolarized final state:

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

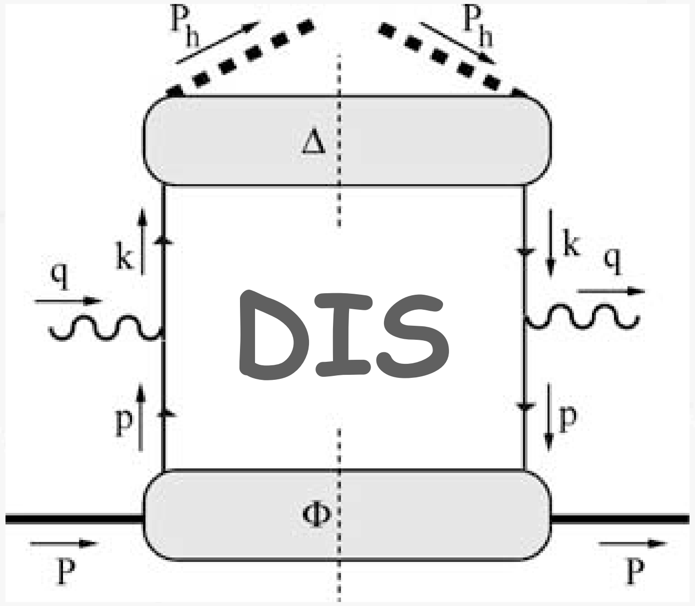
- extracted from SIDIS and e^+e^- annihilation data

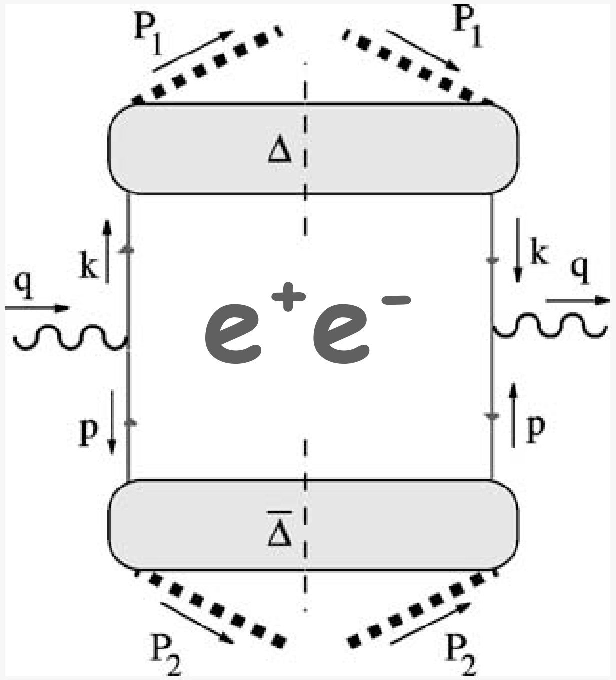
- spin average gives “ordinary” D_1

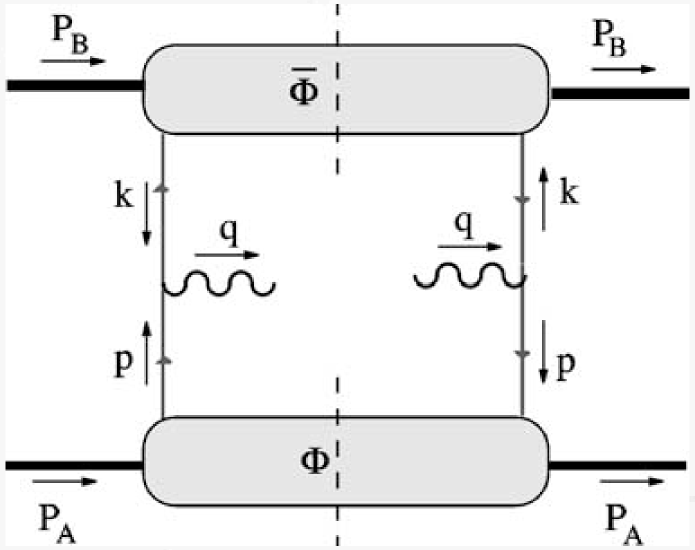
[Anselmino et al., Nucl. Phys. Proc. Suppl.191 (2009) 98]



a QCD laboratory

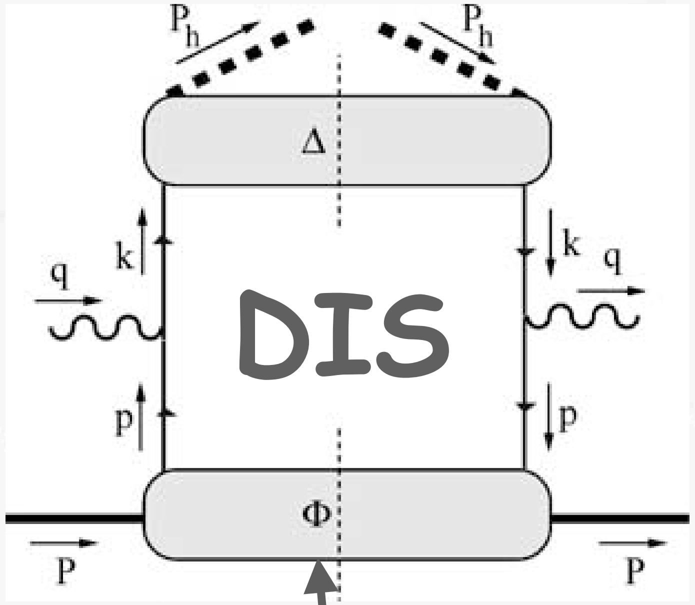


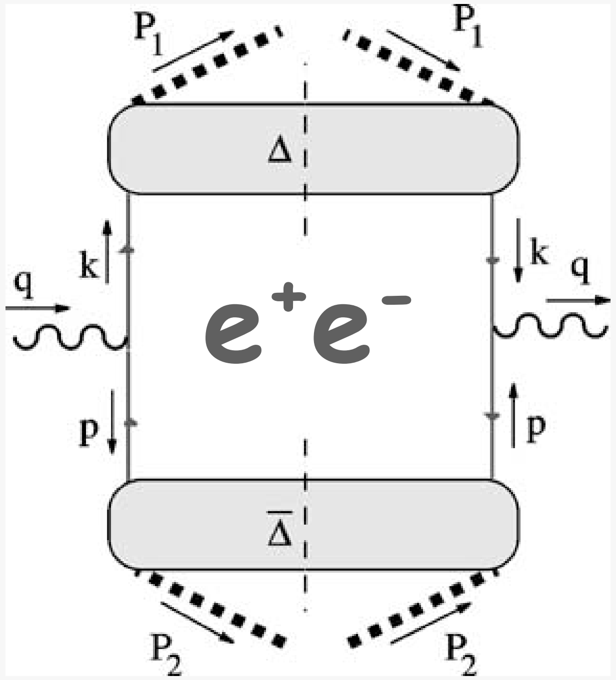




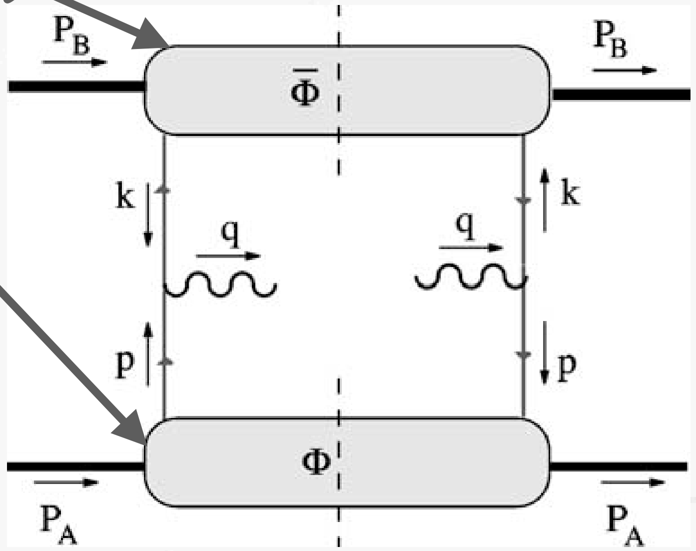
Drell-Yan

a QCD laboratory



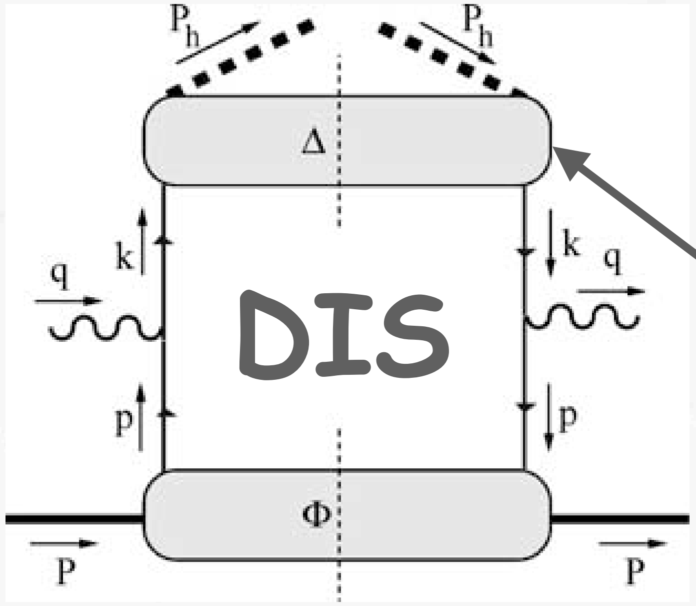


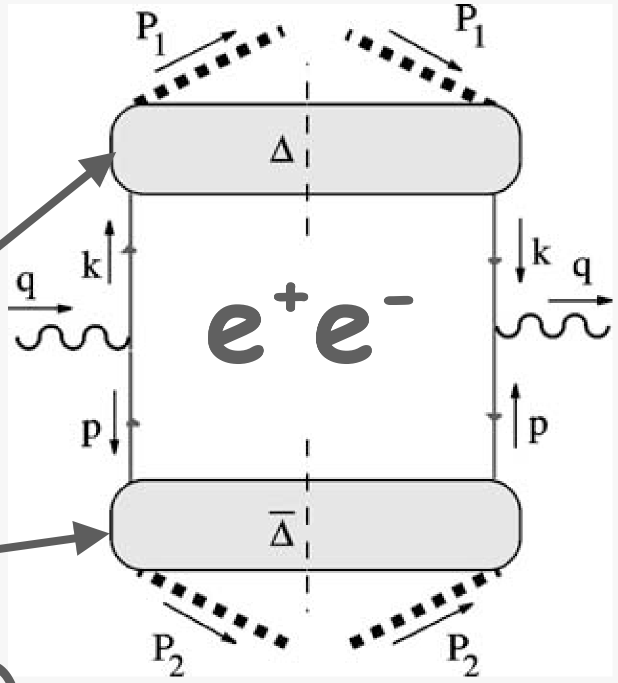
hadron structure
(distribution functions)



Drell-Yan

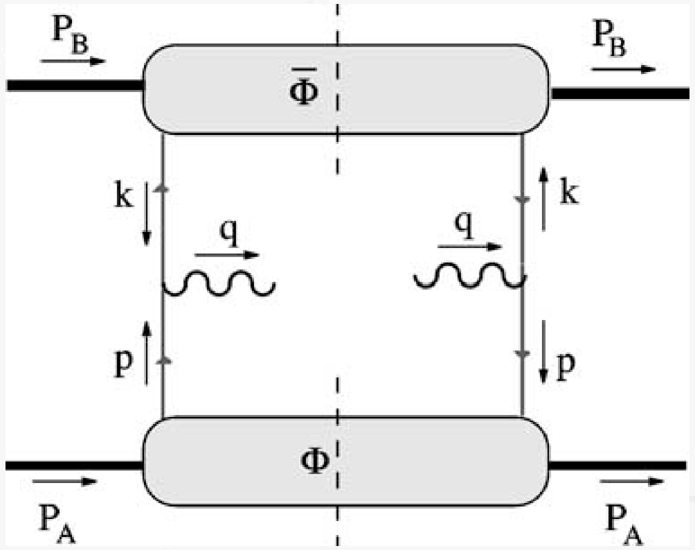
a QCD laboratory





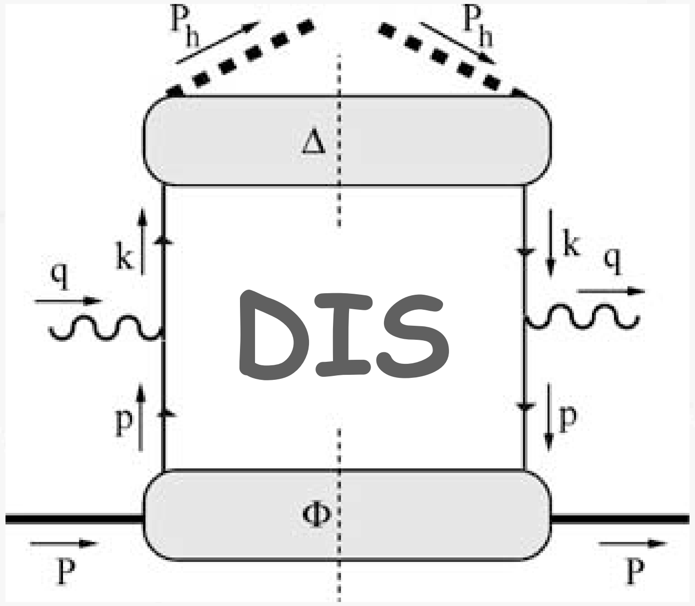
hadronization

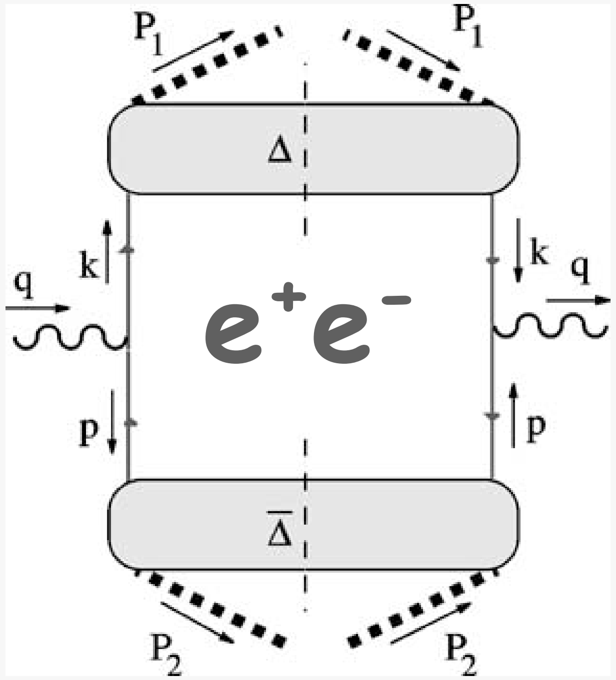
(fragmentation functions)



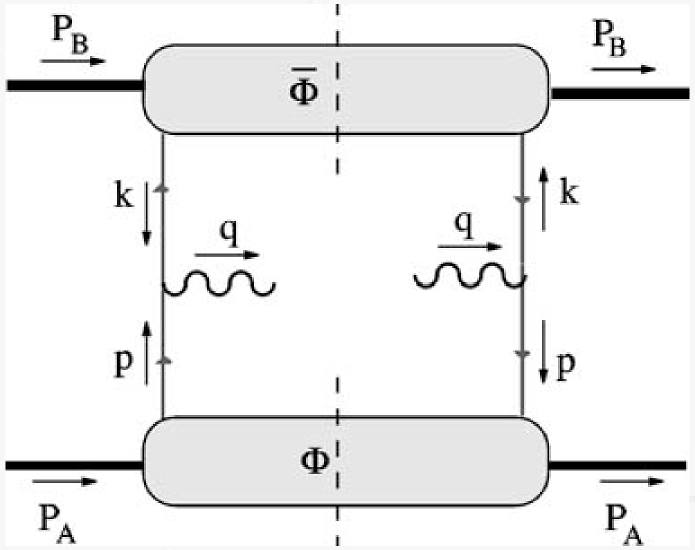
Drell-Yan

a QCD laboratory



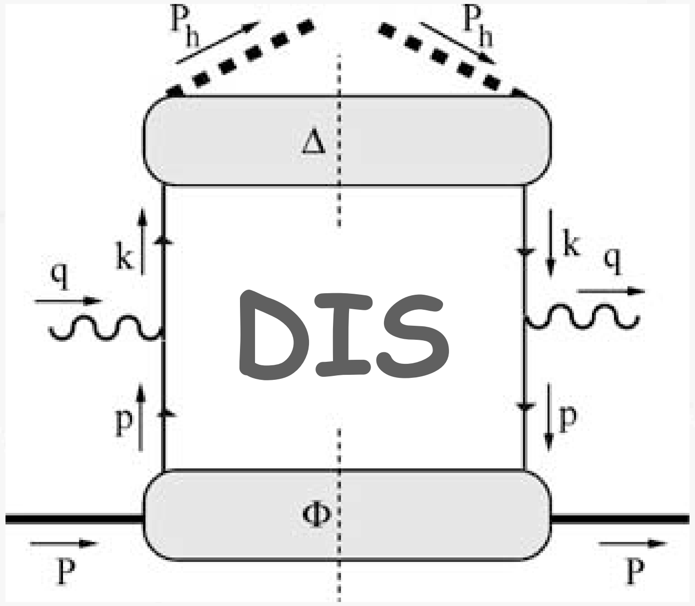


- **data from COMPASS, HERMES, and JLab; planned for future EIC**
- convolutes parton distribution (Φ) and fragmentation (Δ) functions $\Phi \otimes \Delta$
- **need fragmentation function to extract distribution functions**

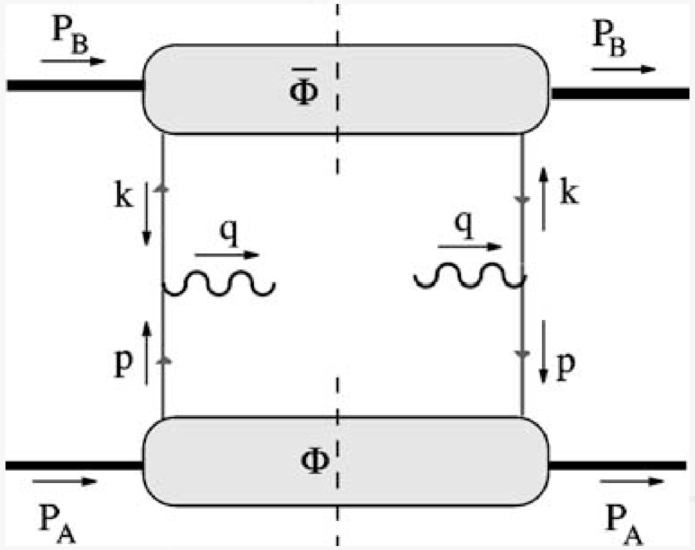


Drell-Yan

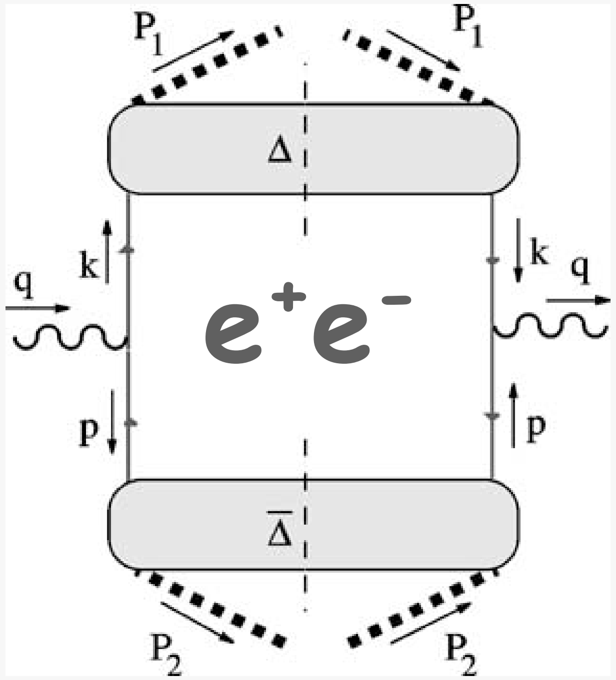
a QCD laboratory



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

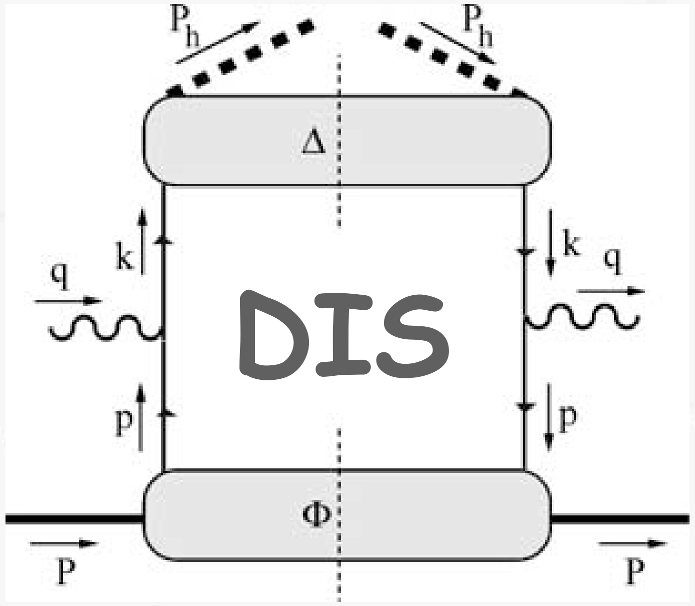


Drell-Yan



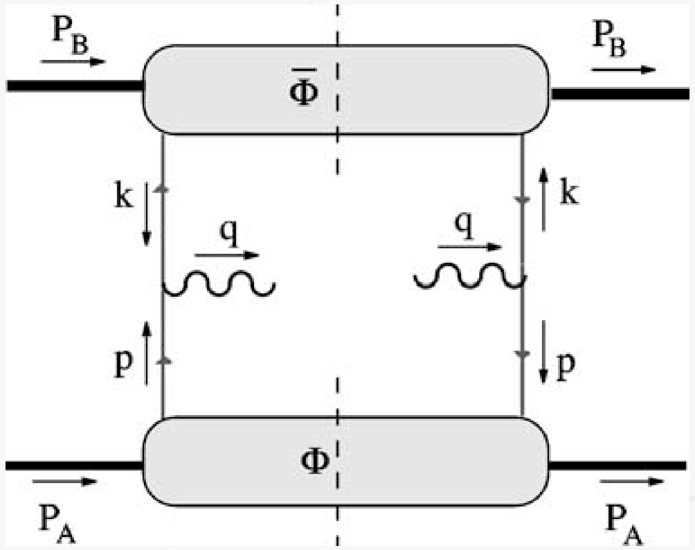
- **ideal place to study hadronization**
- convolutes parton fragmentation functions $\Delta \otimes \Delta$
- **wealth of ("raw") data from Belle and BaBar**

a QCD laboratory

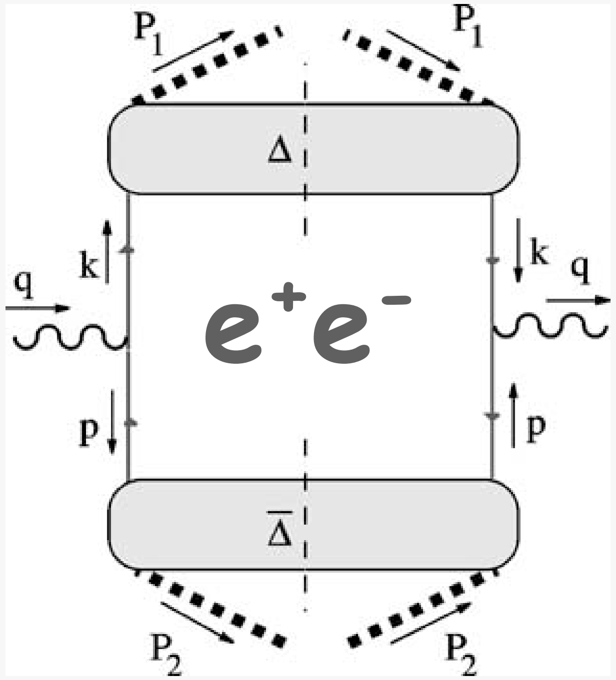


- **data from COMPASS, HERMES, and JLab; planned for future EIC**
- convolutes parton distribution (Φ) and fragmentation (Δ) functions $\Phi \otimes \Delta$
- **need fragmentation function to extract distribution functions**

- convolutes parton distribution functions $\Phi \otimes \Phi$
- **testing ground for sign reversal of naive-T-odd distributions**
- **hardly any data**



Drell-Yan



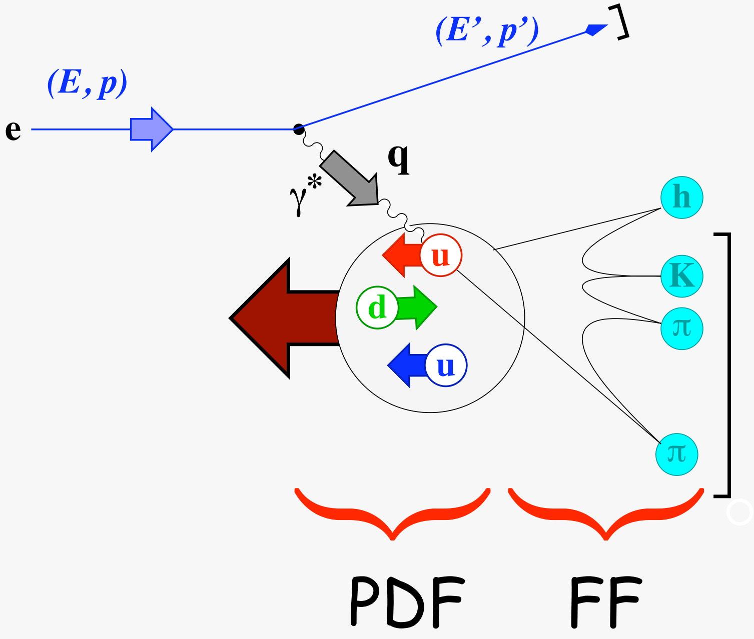
- **ideal place to study hadronization**
- convolutes parton fragmentation functions $\Delta \otimes \Delta$
- **wealth of ("raw") data from Belle and BaBar**

Probing TMDs in semi-inclusive DIS

quark pol.

nucleon pol.

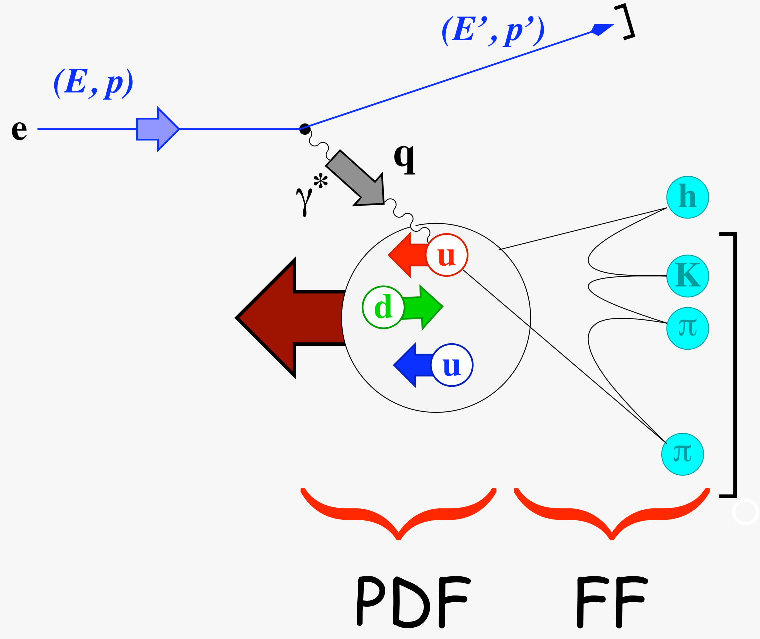
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

Probing TMDs in semi-inclusive DIS



quark pol.

nucleon pol.

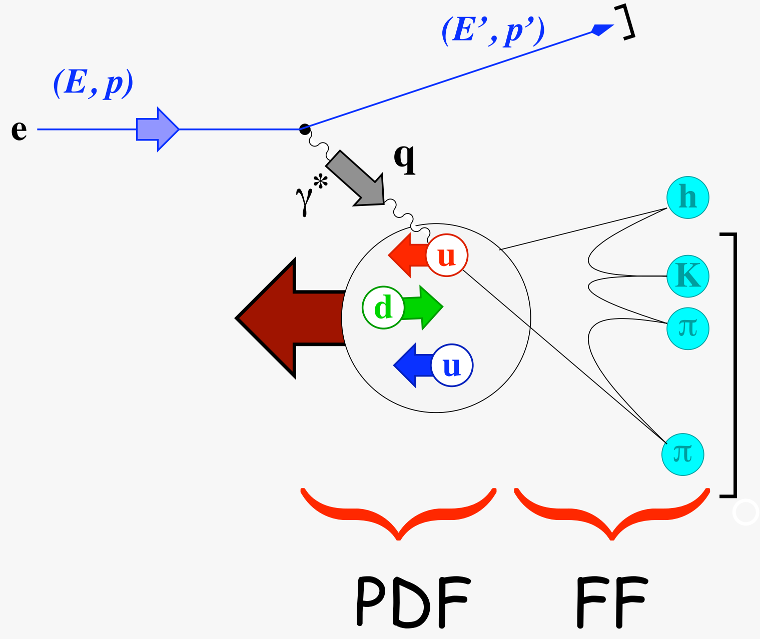
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

in SIDIS*) couple PDFs to:

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

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

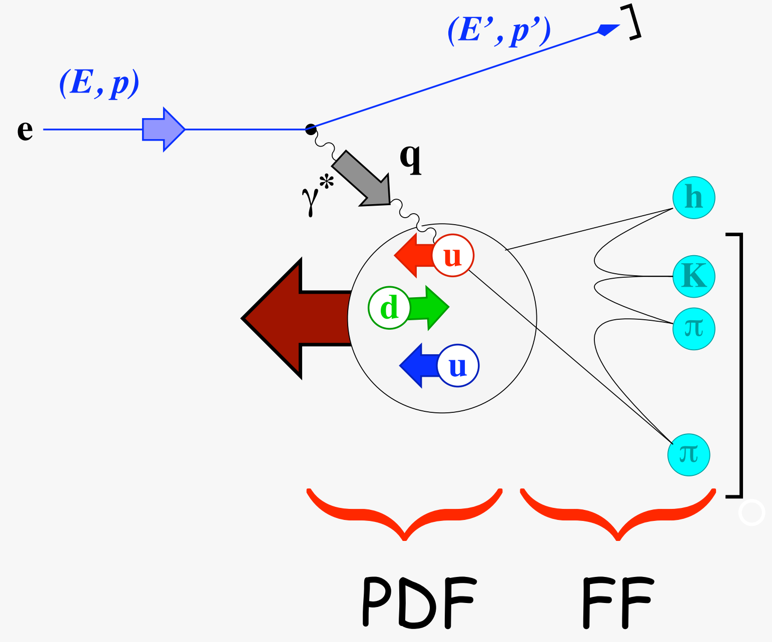
in SIDIS*) couple PDFs to:

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

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

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

in SIDIS*) couple PDFs to:

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

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

➡ give rise to characteristic azimuthal dependences

---

*) semi-inclusive DIS with unpolarized final state

1-hadron production (ep→ehX)

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

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

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

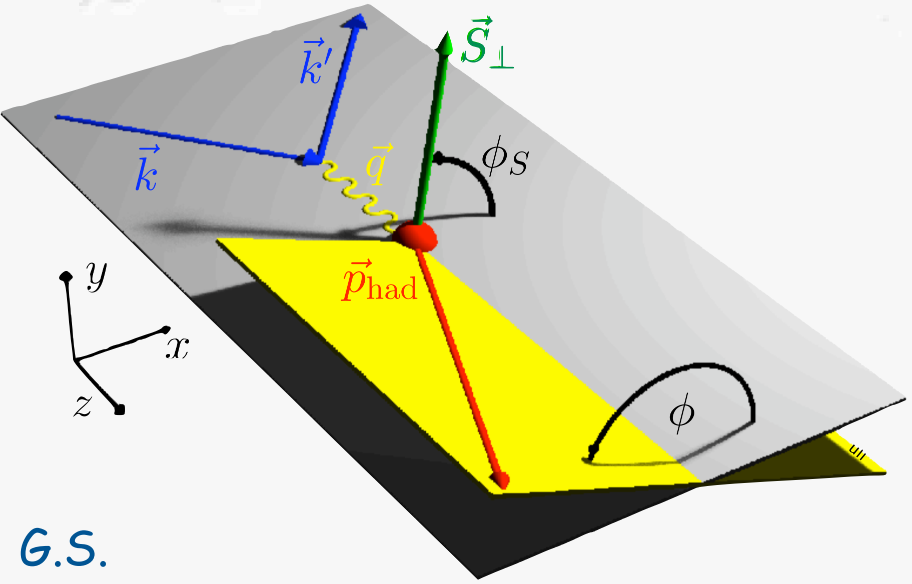
$$+\frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

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

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

1-hadron production (ep→ehX)

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

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

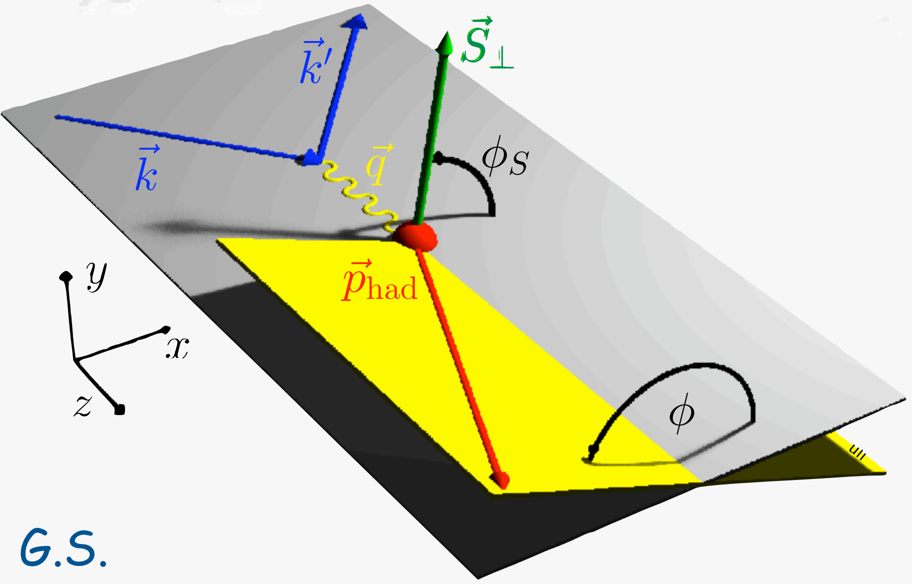
$$+ S_T \left\{ \boxed{\sin(\phi - \phi_S) \, d\sigma^{8}_{UT}} + \boxed{\sin(\phi + \phi_S) \, d\sigma^{9}_{UT}} + \boxed{\sin(3\phi - \phi_S) \, d\sigma^{10}_{UT}} \right.$$

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

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

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

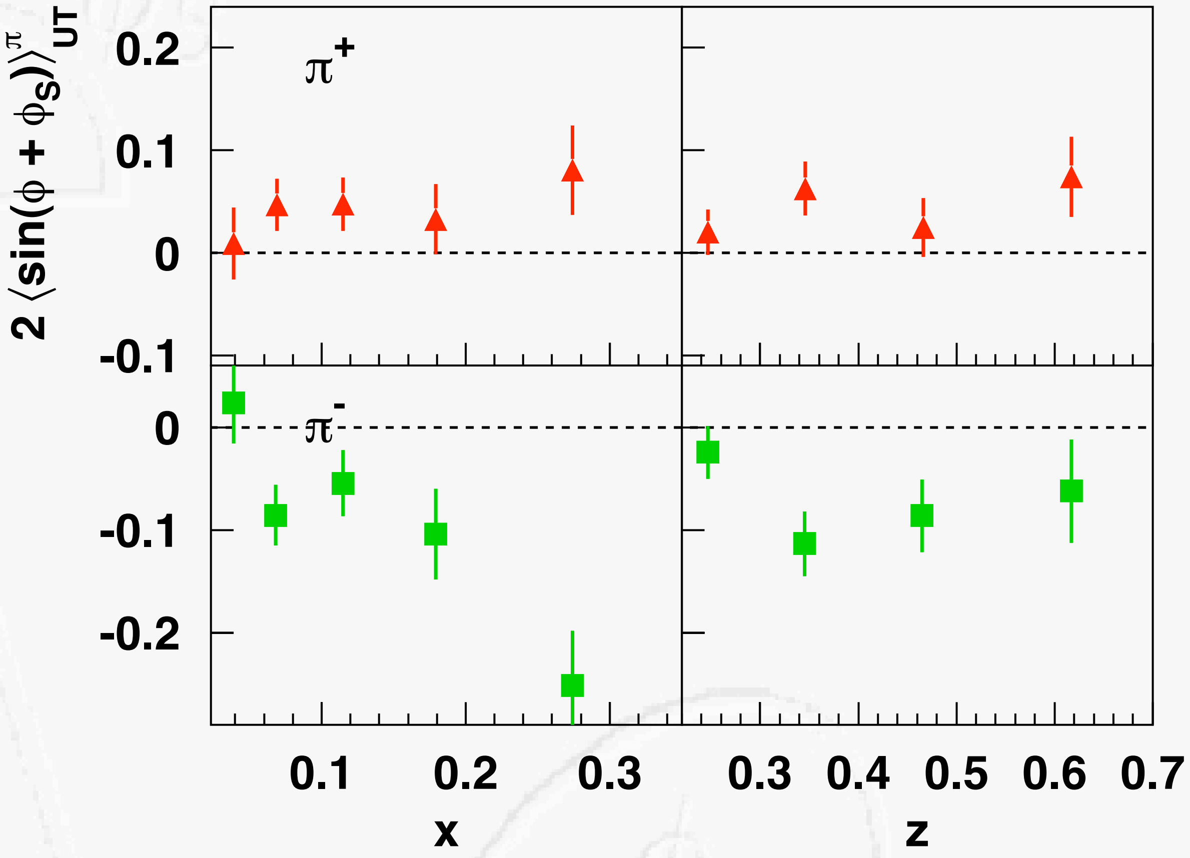
“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

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)

- significant in size and opposite in sign for charged pions



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

2005: First evidence from HERMES SIDIS on proton

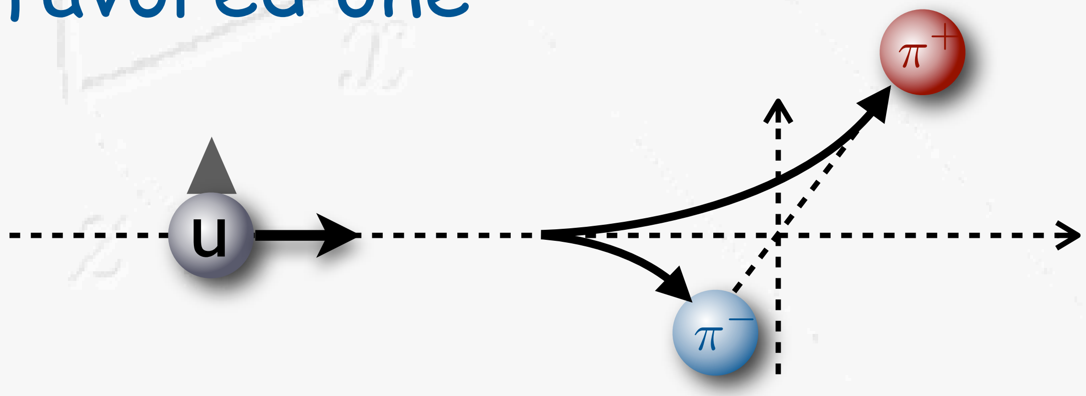
Non-zero transversity
Non-zero Collins function

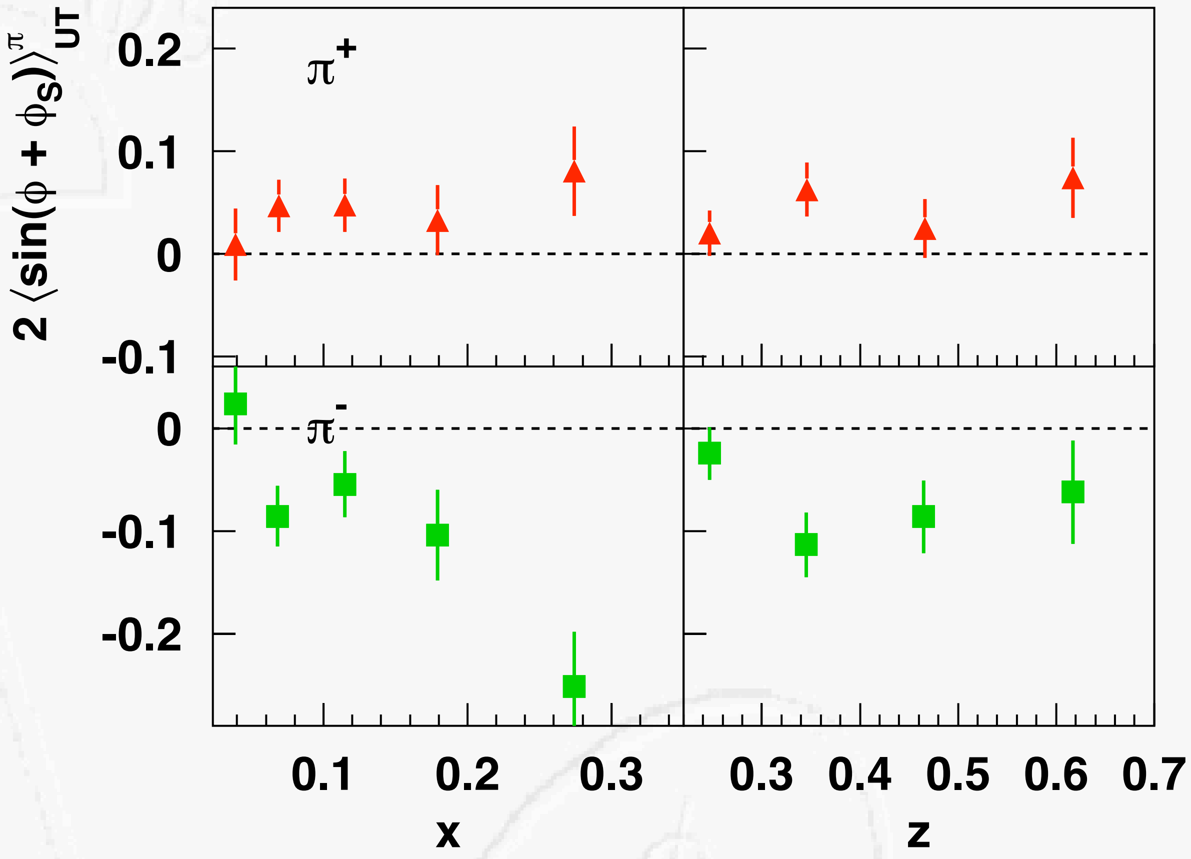
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (Collins fragmentation)

- significant in size and opposite in sign for charged pions

- **disfavored** Collins FF **large** and **opposite in sign** to favored one





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

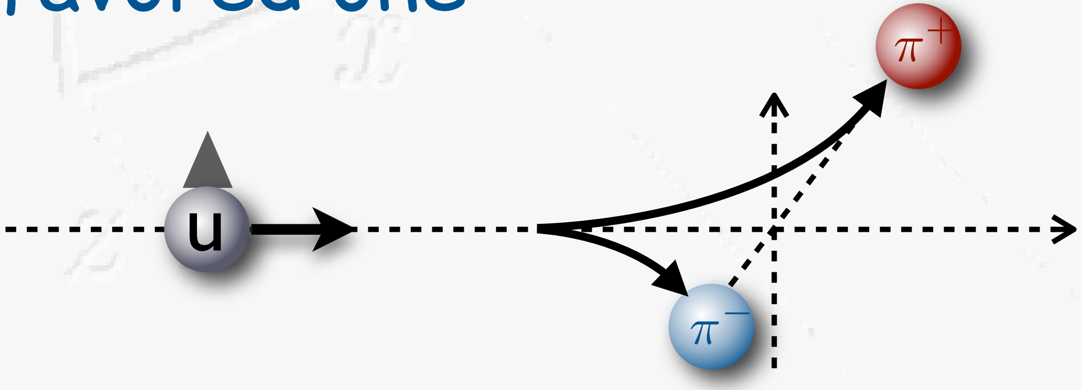
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

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

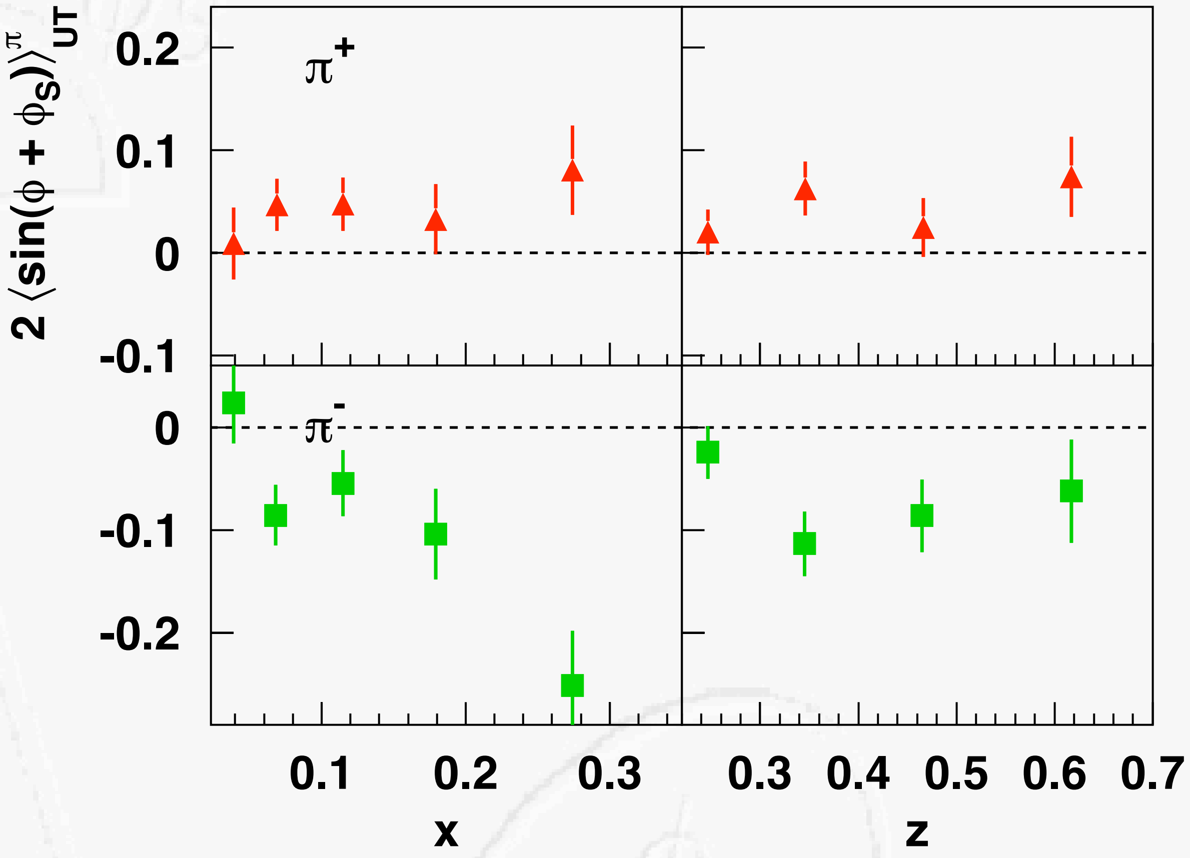
Transversity distribution (Collins fragmentation)

- 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]



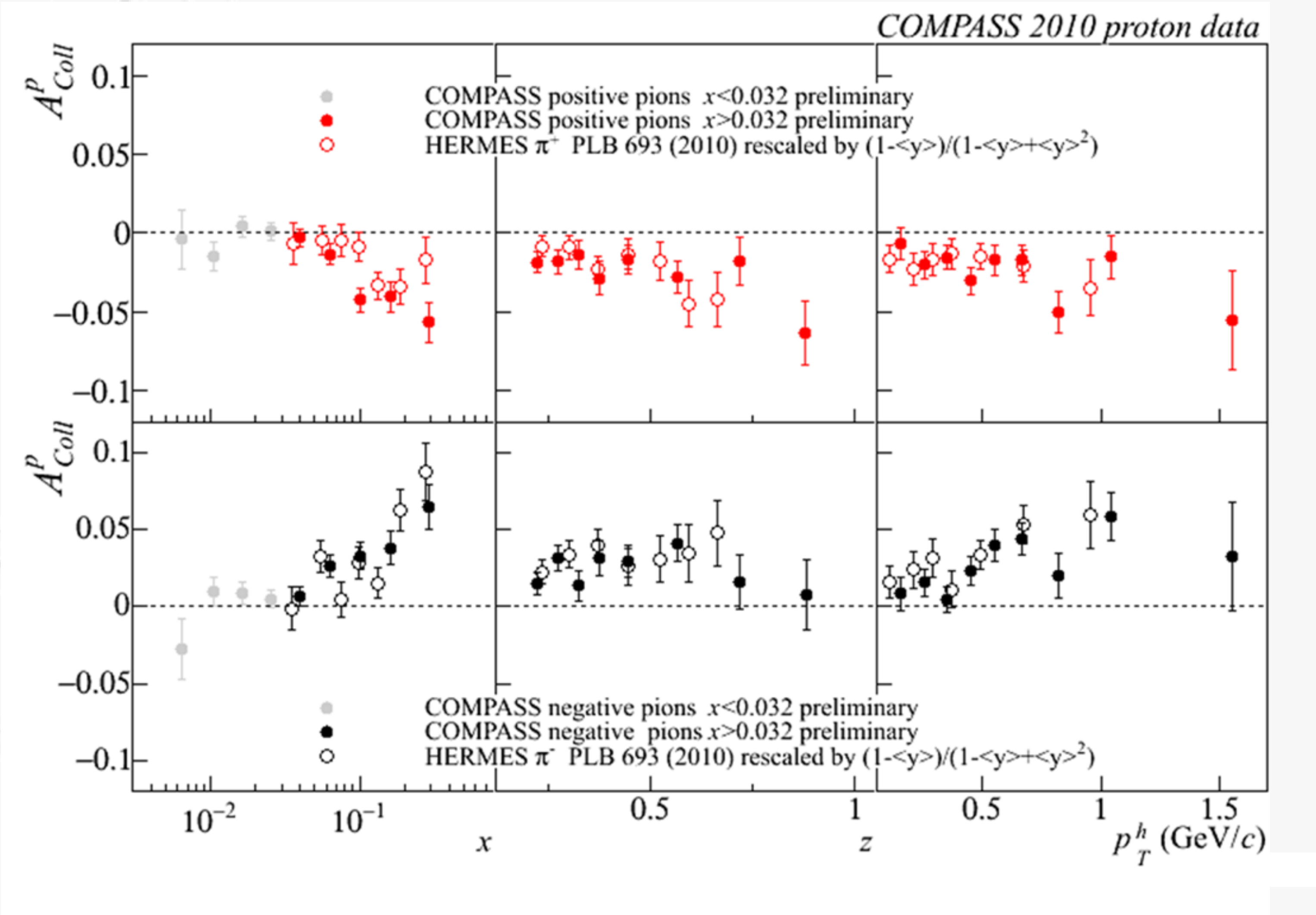
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

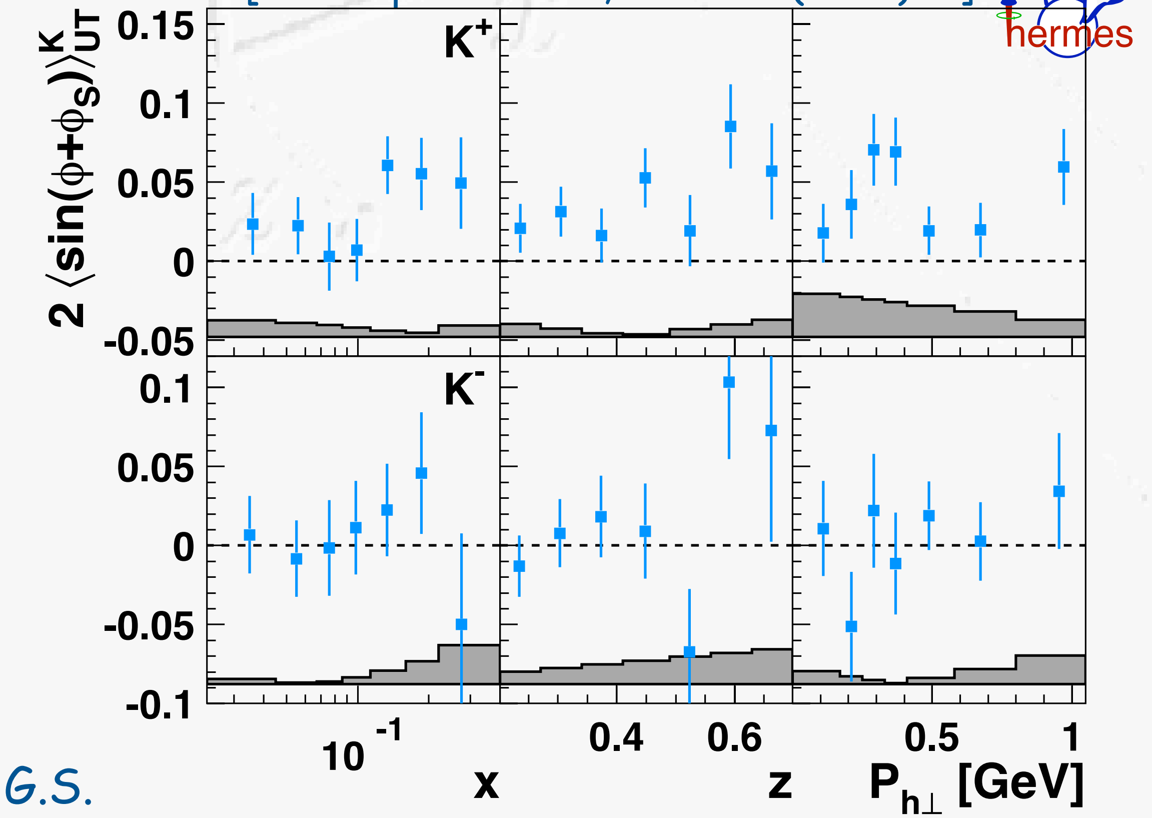
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

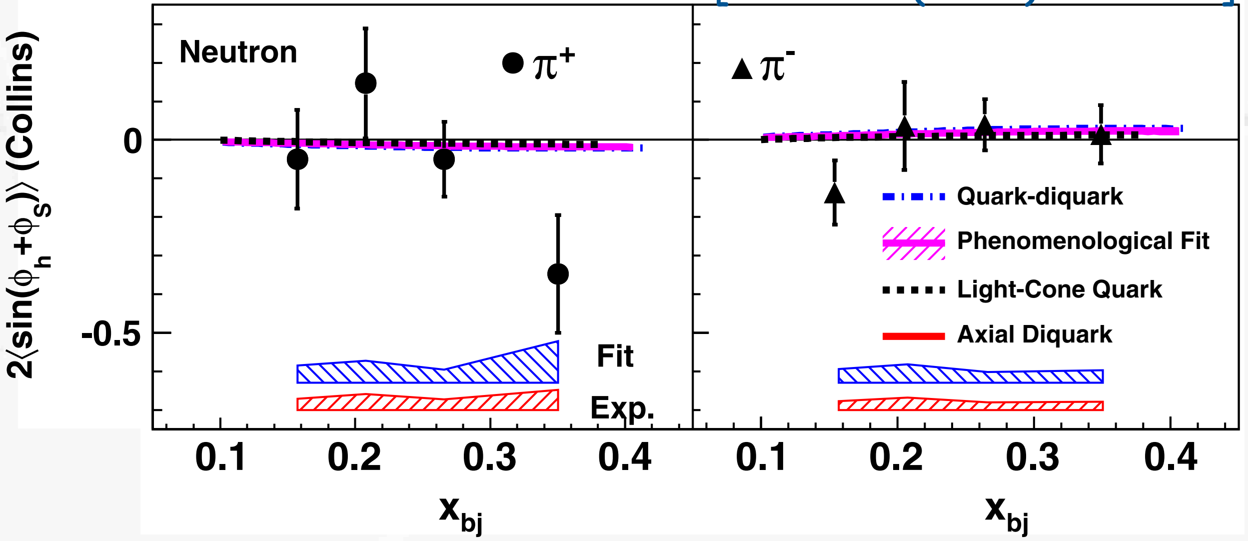
- **wealth of new results:**
  - COMPASS
    [PLB 692 (2010) 240,
    PLB 717 (2012) 376]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]



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

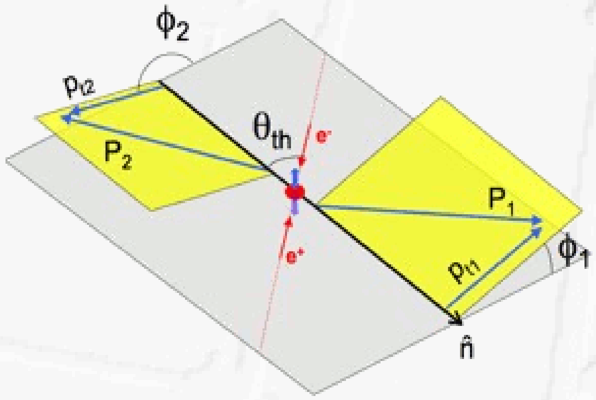


[PRL 107 (2011) 072003]

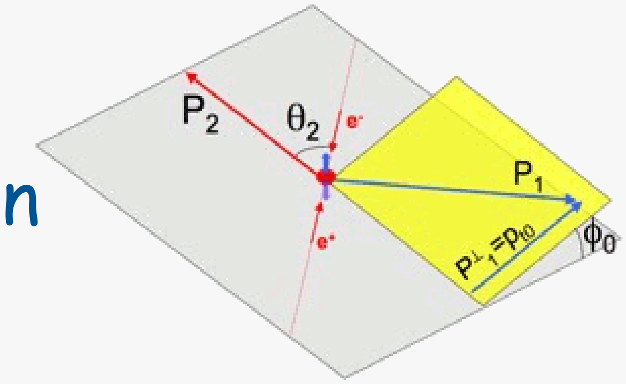


Collins FF from e^+e^-

- analyzed in different frames:
  - Collins-Soper



vs. Gottfried-Jackson



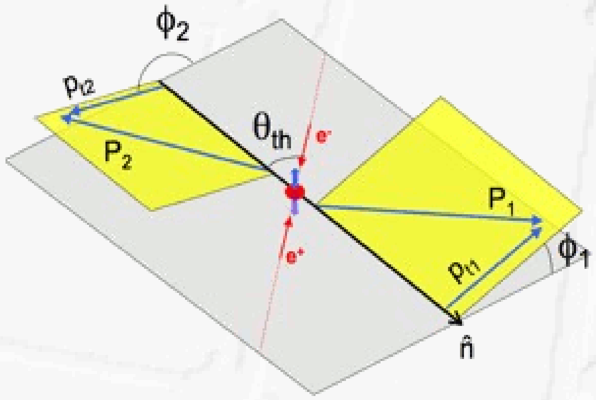
➡ **different convolutions over transverse momenta:**

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

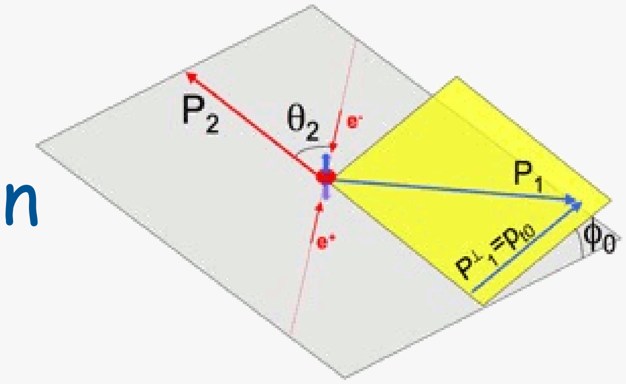
$$F^{[n]} = \int d|\mathbf{k}_T|^2 \left[\frac{|\mathbf{k}_T|}{M_h}\right]^n F(z,\mathbf{k}_T^2)$$

Collins FF from e^+e^-

- analyzed in different frames:

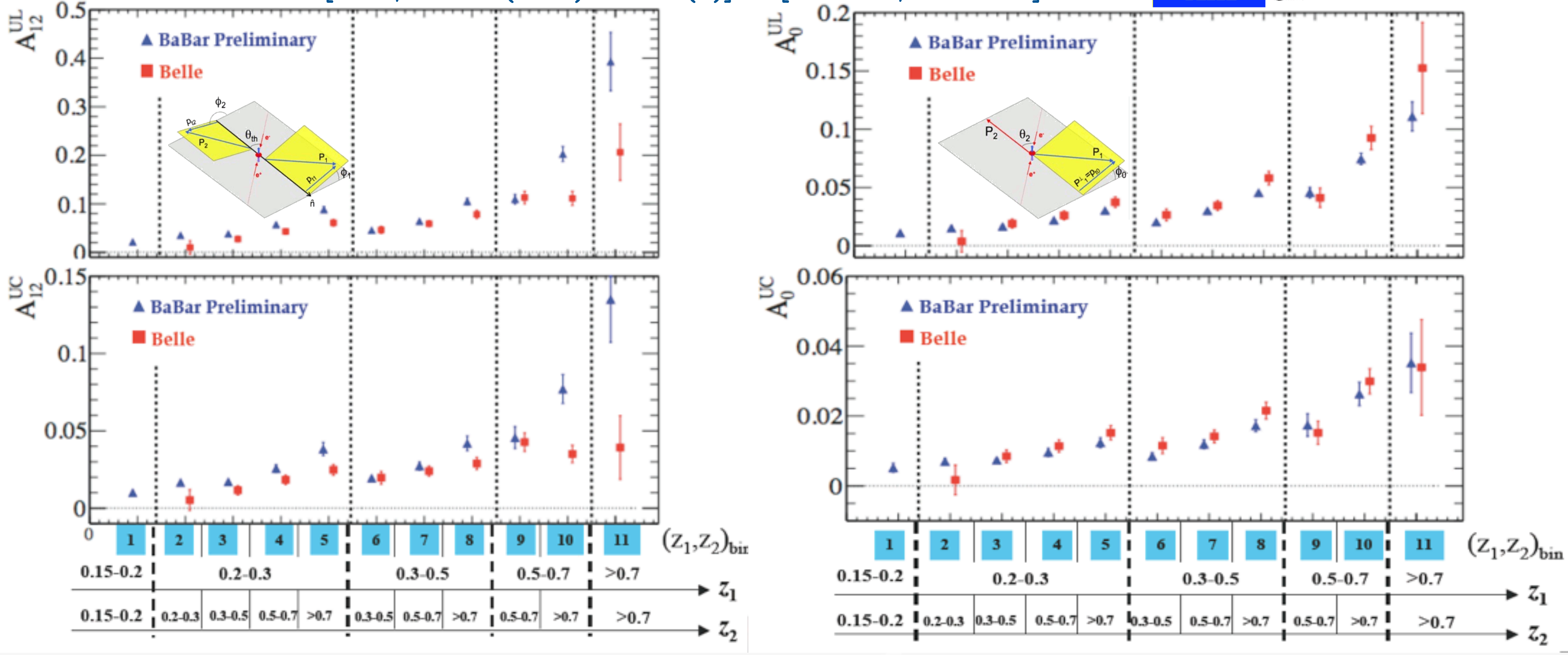


- Collins-Soper vs. Gottfried-Jackson



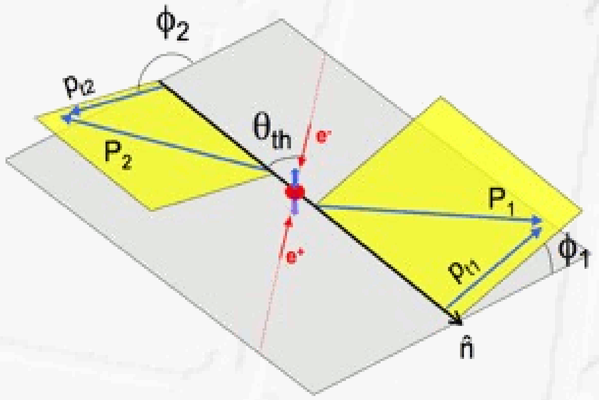
➡ **different convolutions over transverse momenta:**

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

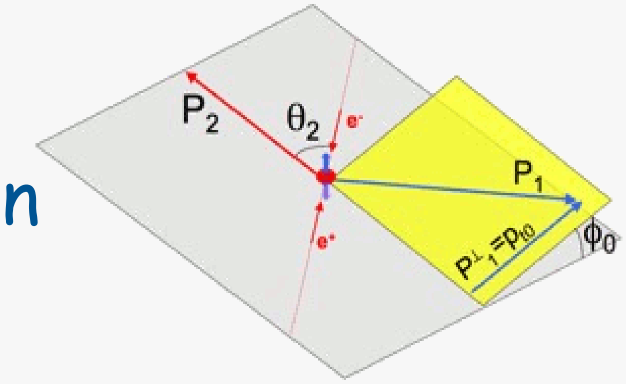


Collins FF from e^+e^-

- analyzed in different frames:
  - Collins-Soper

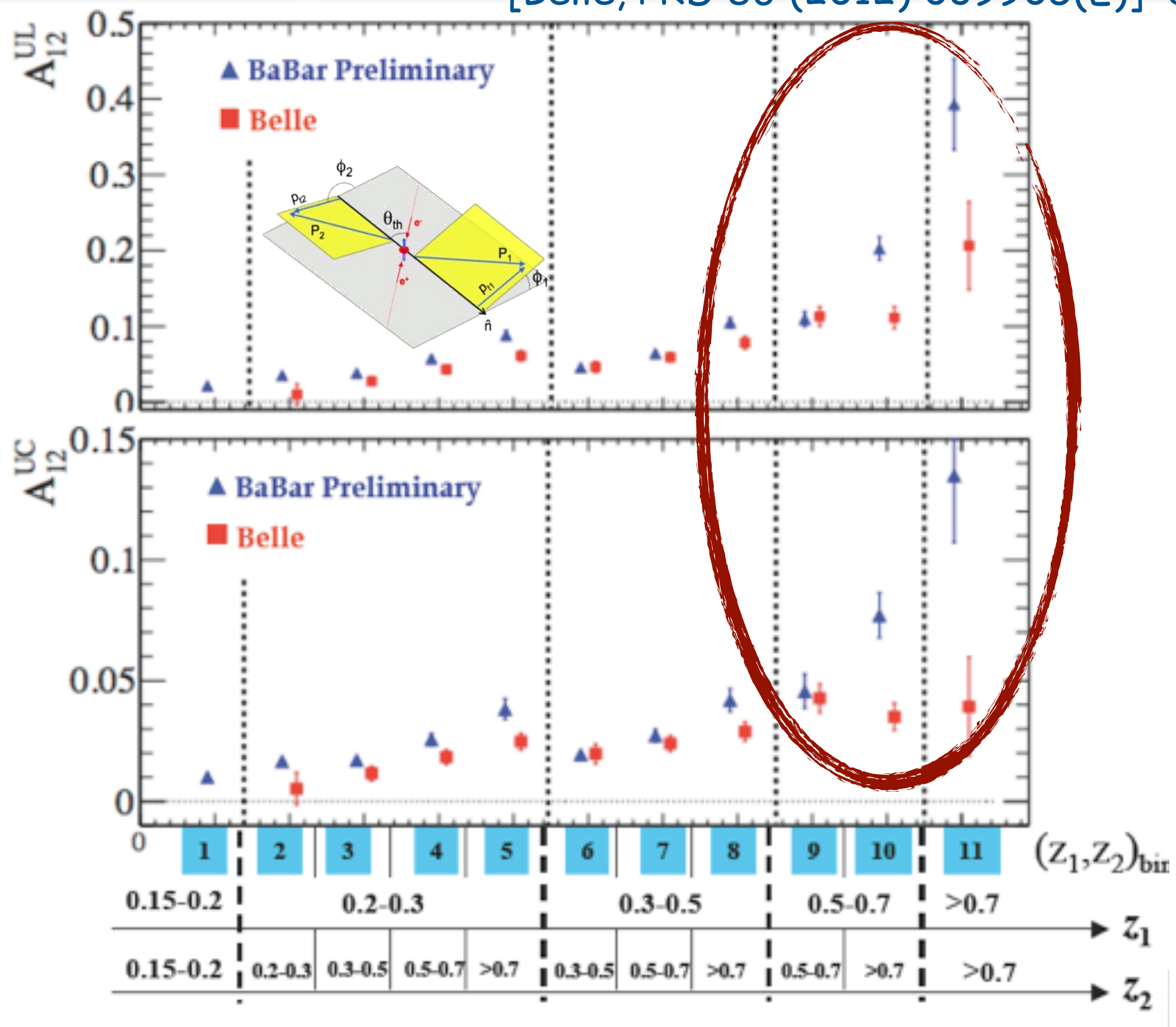


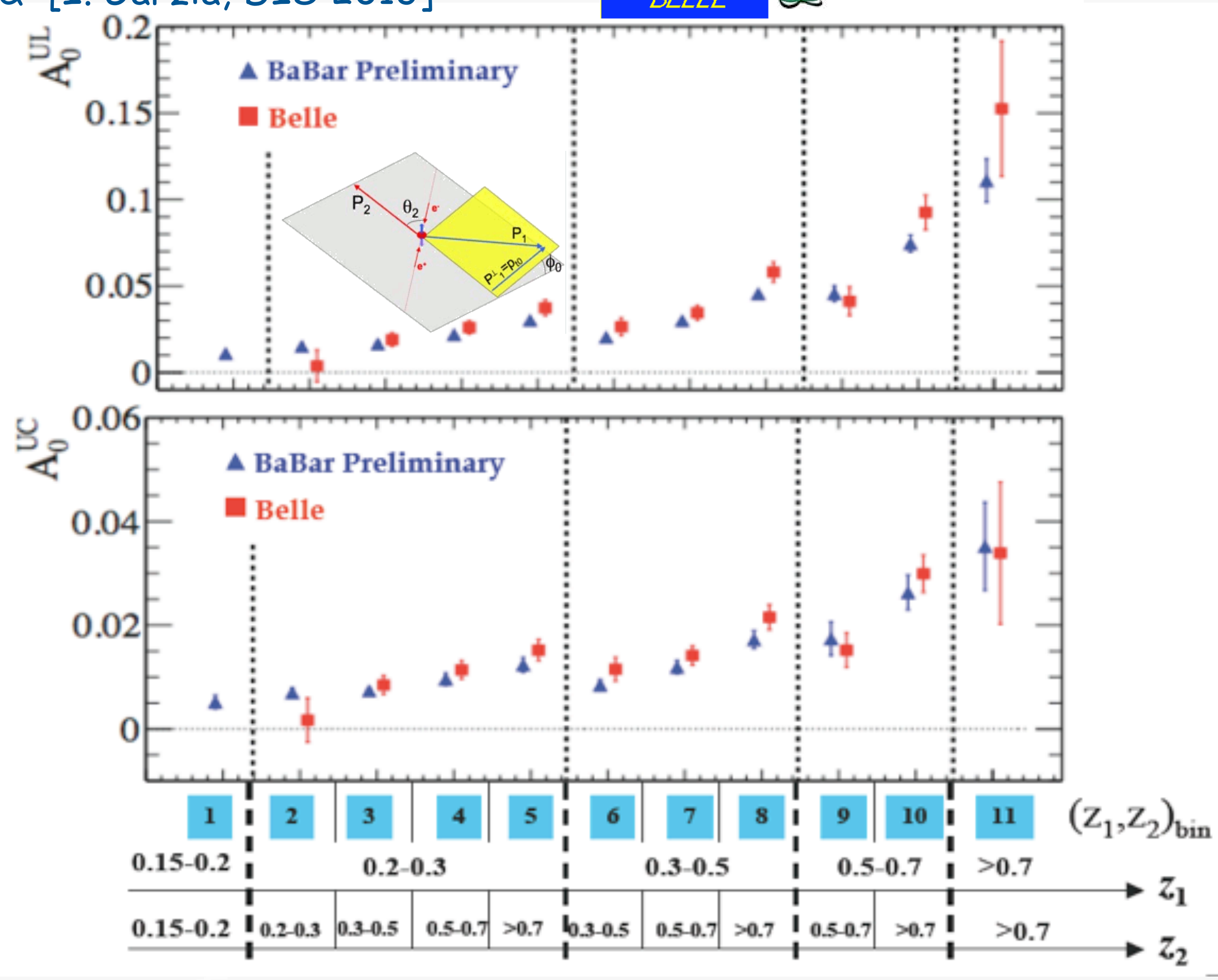
vs. Gottfried-Jackson



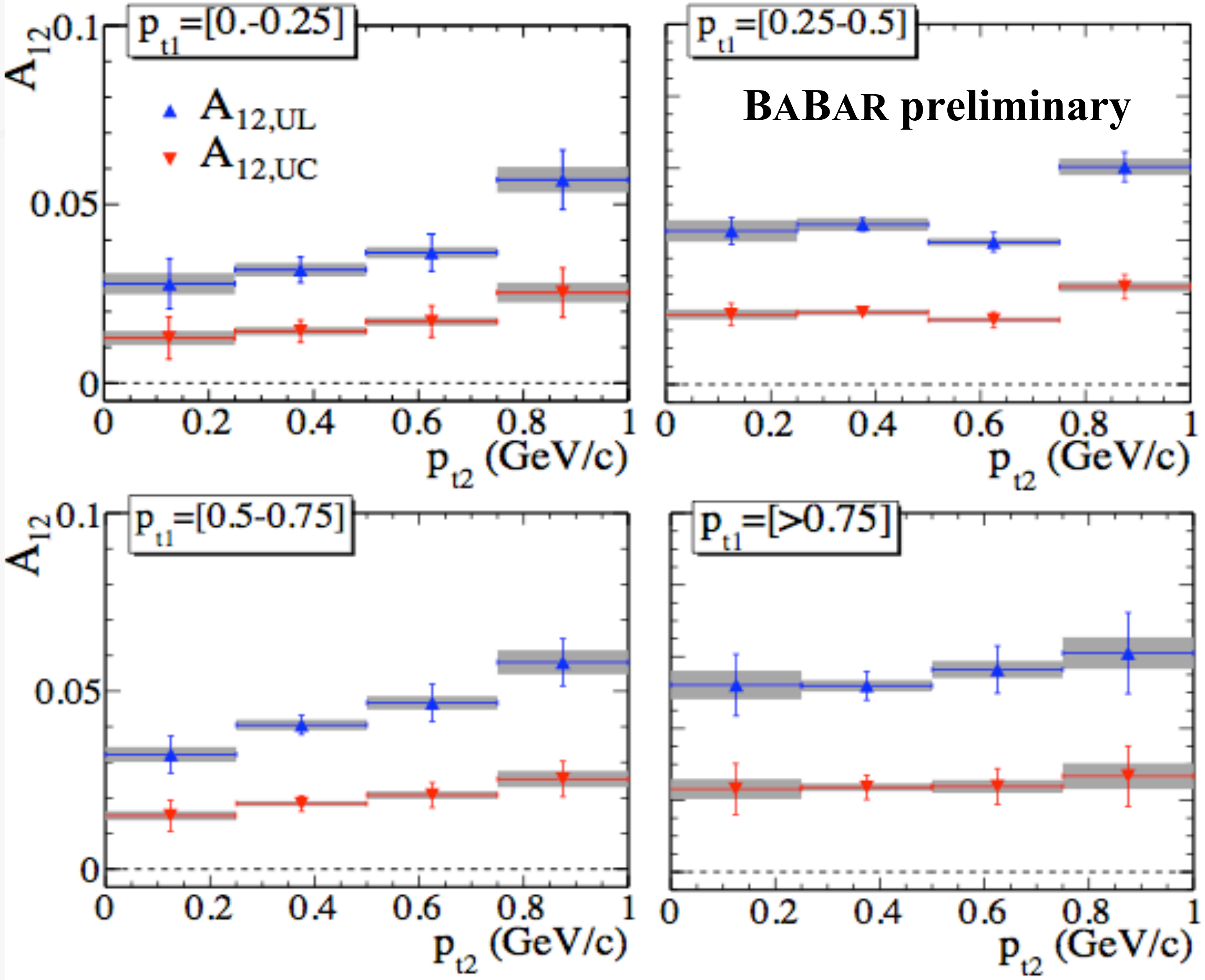
➡ **different convolutions over transverse momenta:**

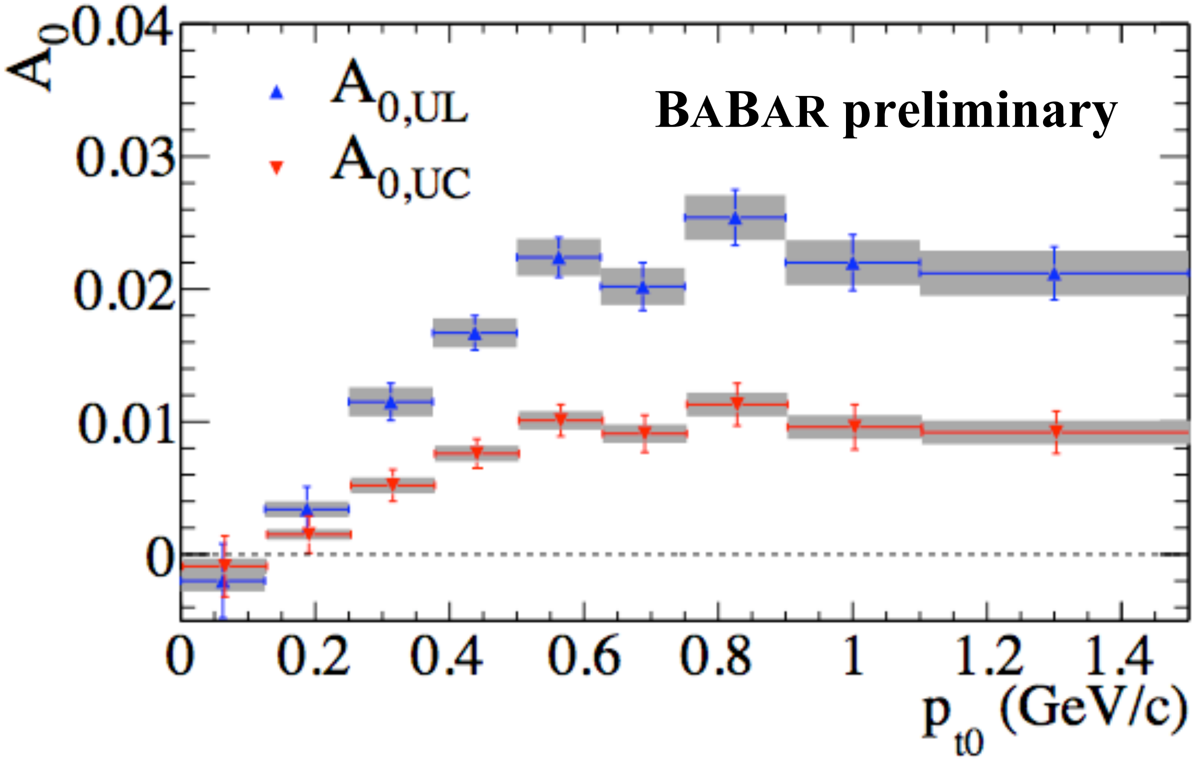
[Belle, PRD 86 (2012) 039905(E)] & [I. Garzia, DIS 2013]





Collins FF from e^+e^-





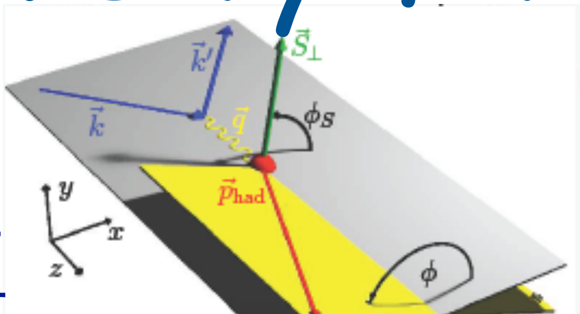
FIRST MEASUREMENT of Collins asymmetries *vs.* p_t in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$ (time-like region)

- **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]

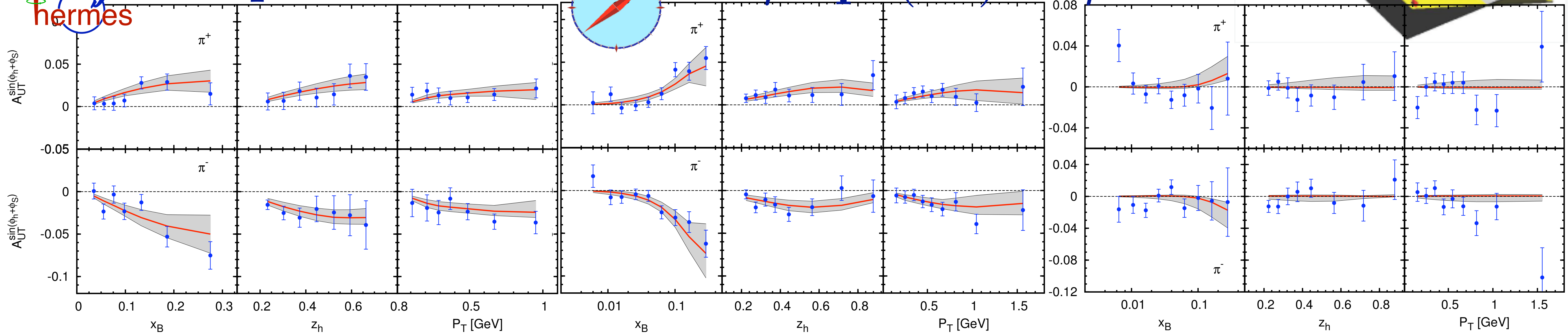
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

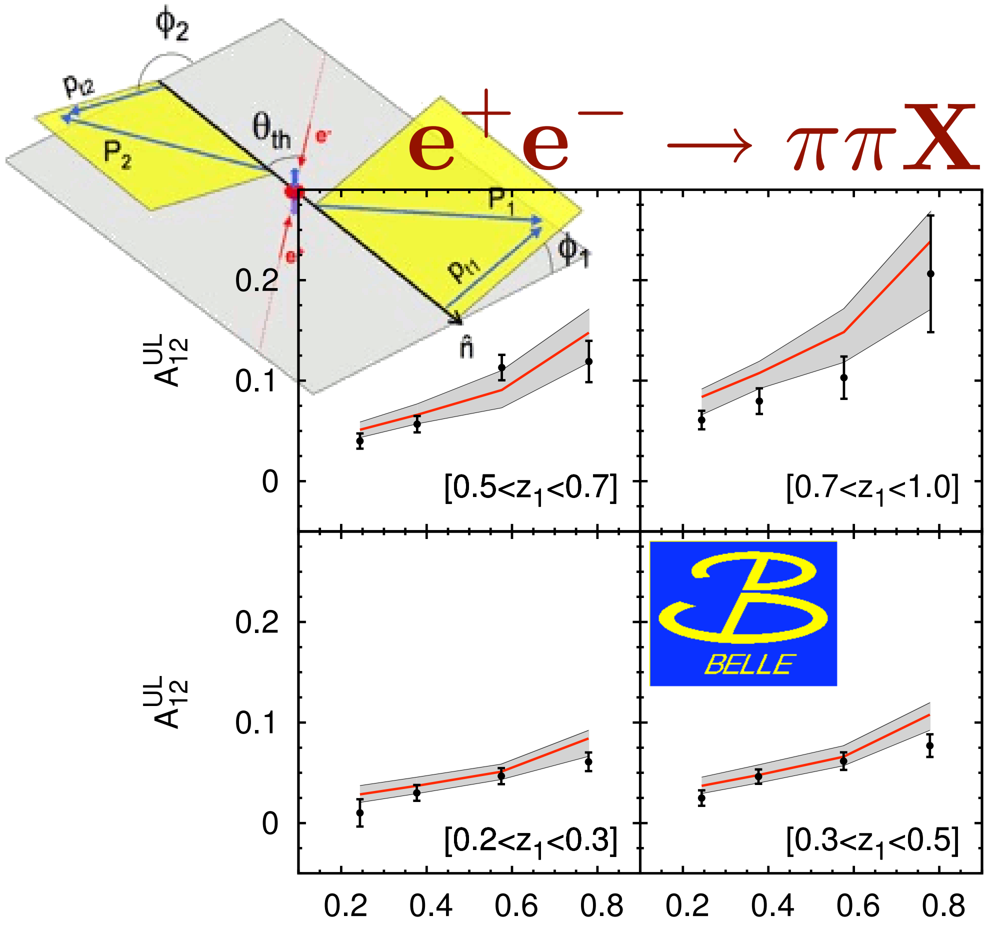
Collins FF and transversity fit



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

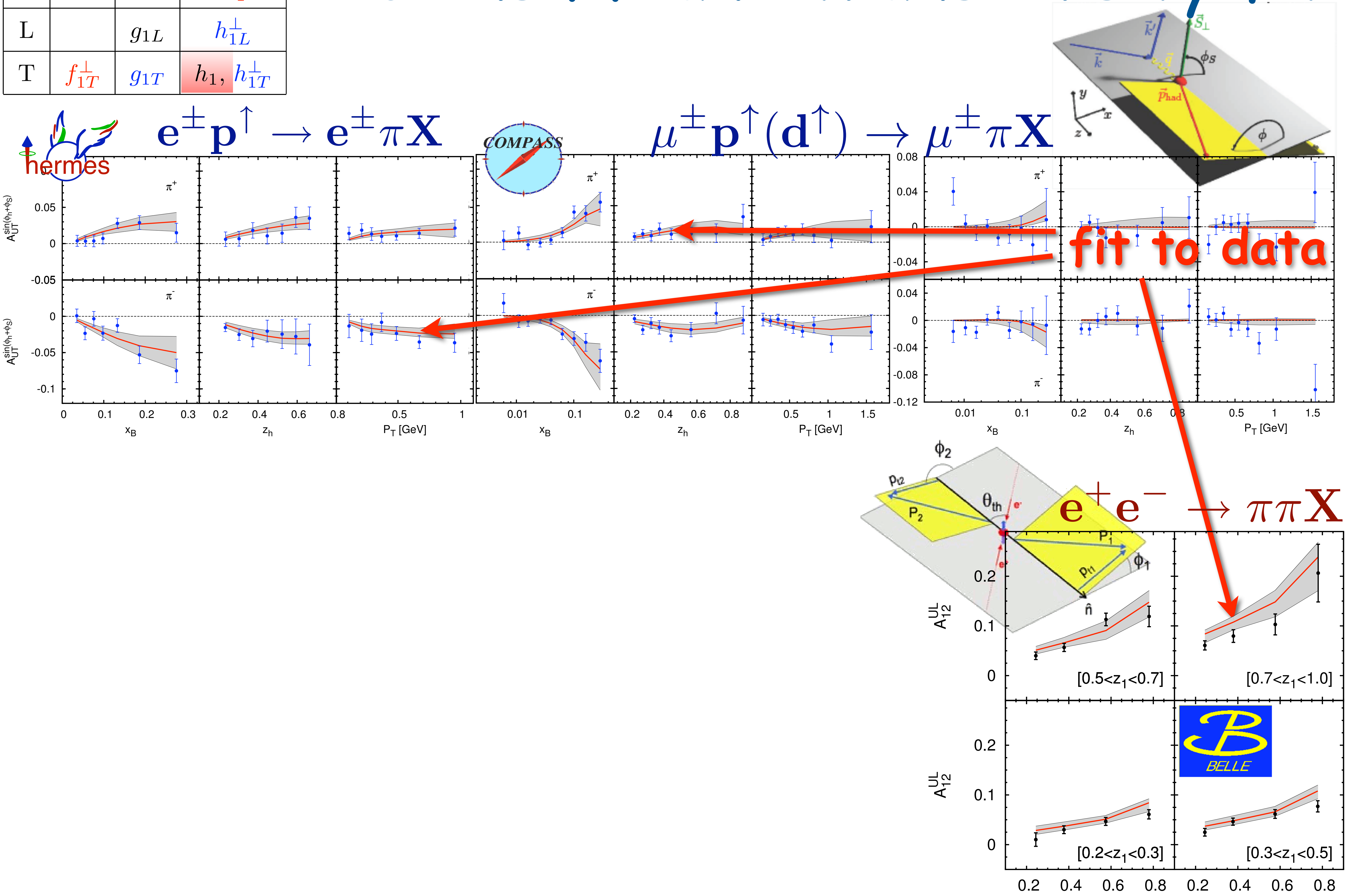
$\mu^\pm \mathbf{p}^\uparrow(\mathbf{d}^\uparrow) \to \mu^\pm \pi \mathbf{X}$





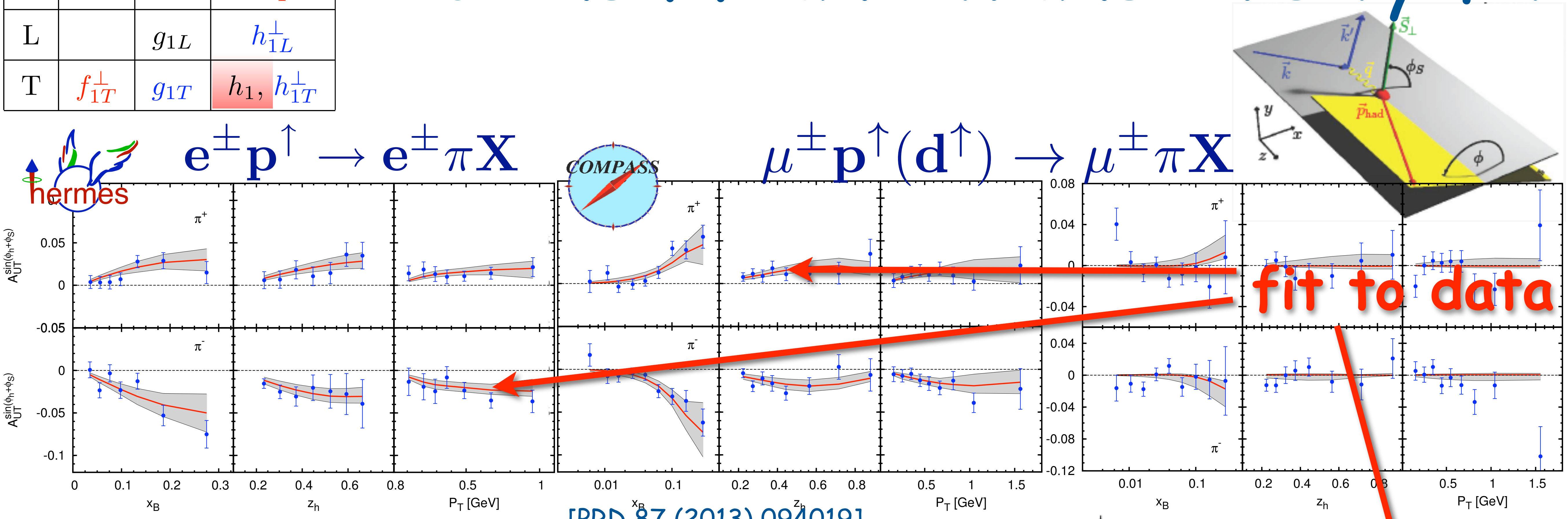
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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

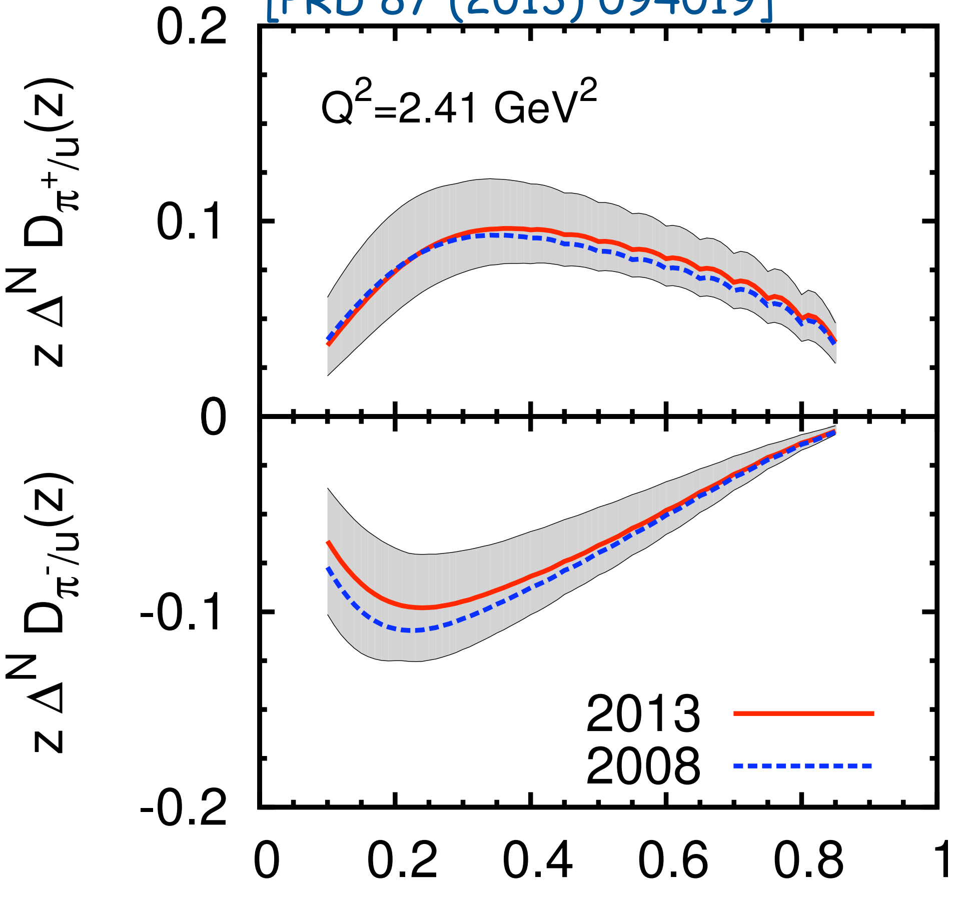


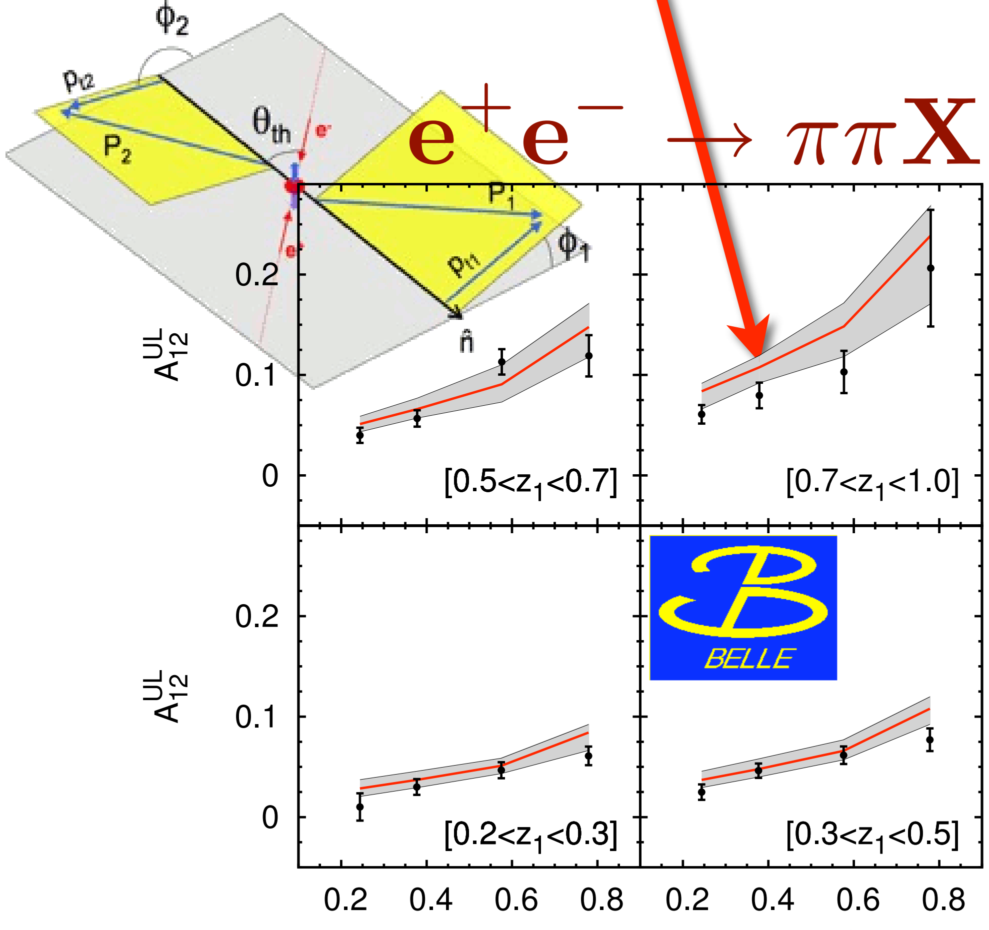
$\mathbf{e^{\pm}p^{\uparrow} \rightarrow e^{\pm}\pi X}$

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

fit to data

[PRD 87 (2013) 094019]

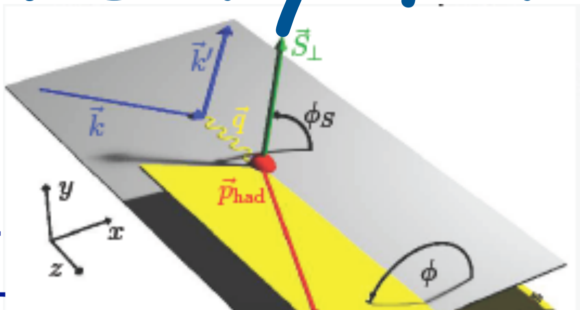




$\mathbf{e^+e^- \rightarrow \pi\pi X}$

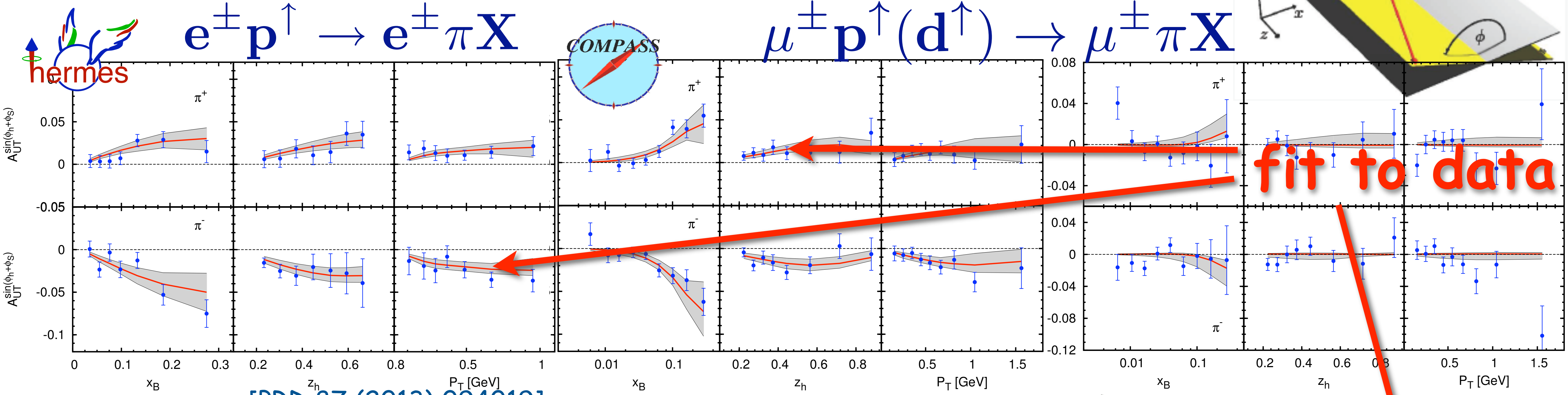
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins FF and transversity fit

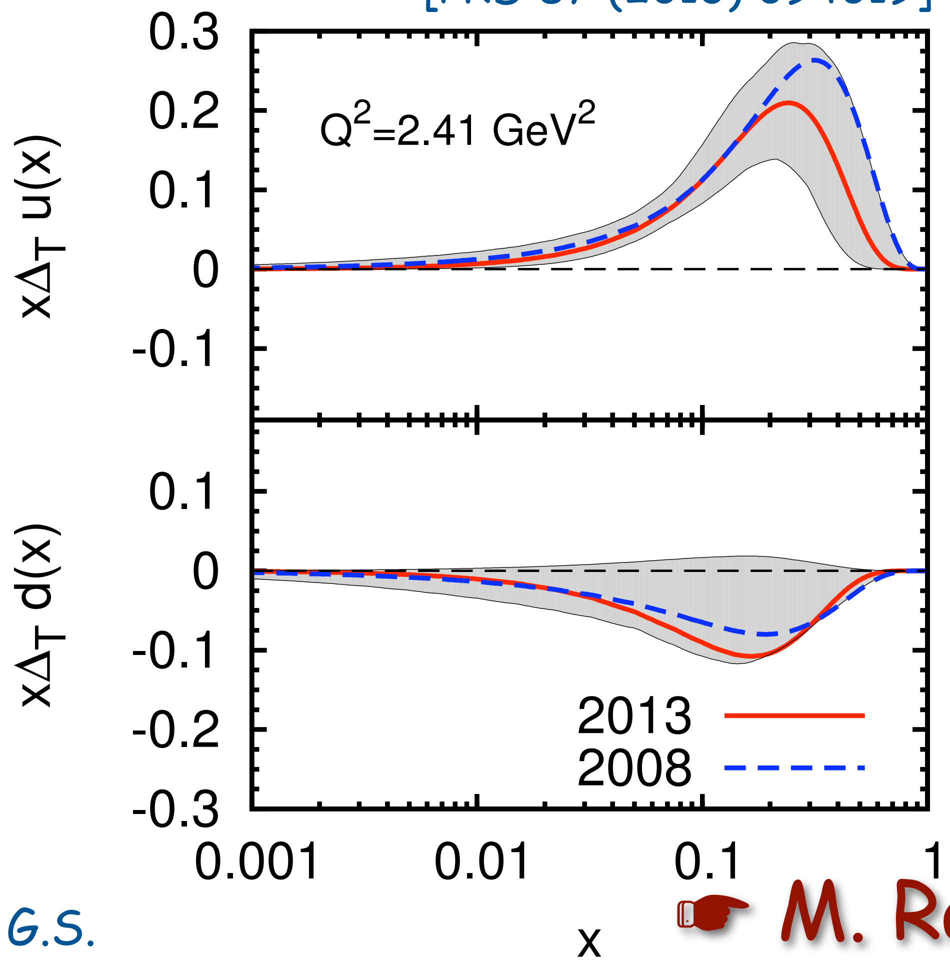


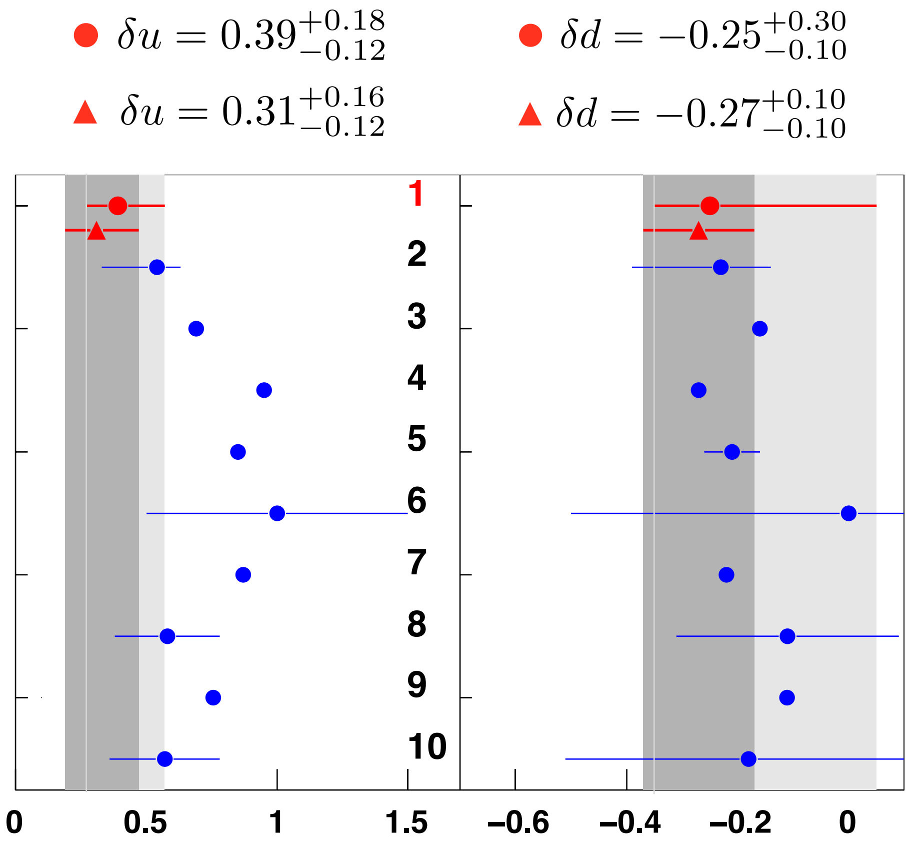
$\mathbf{e^\pm p^\uparrow \to e^\pm \pi X}$

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

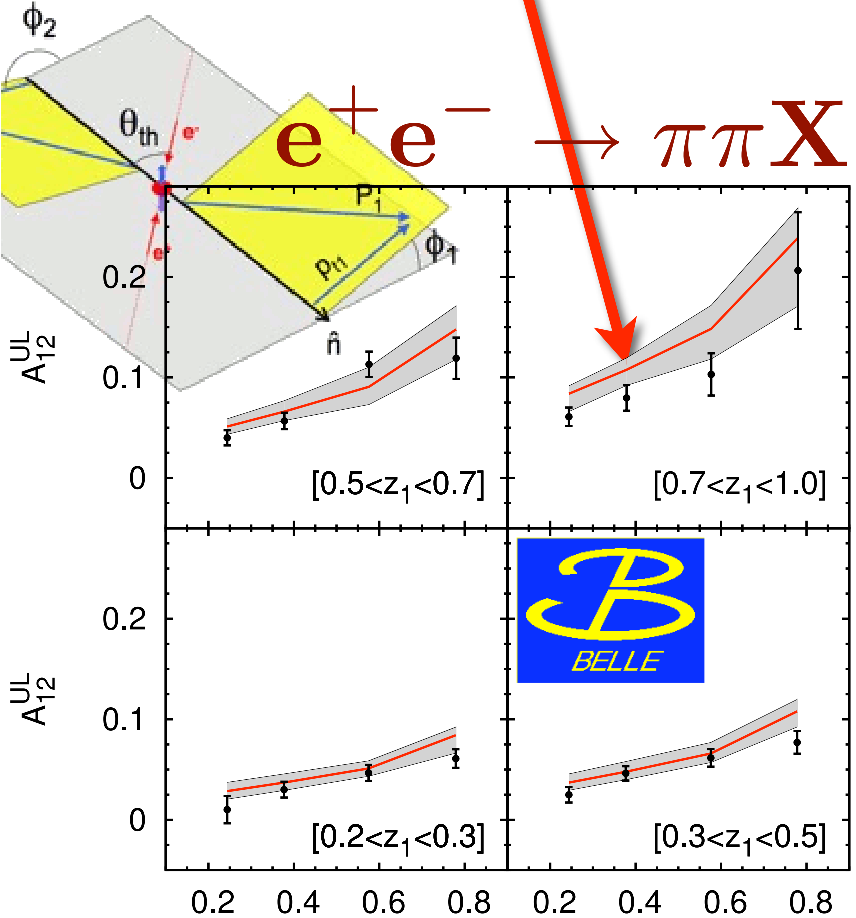


[PRD 87 (2013) 094019]





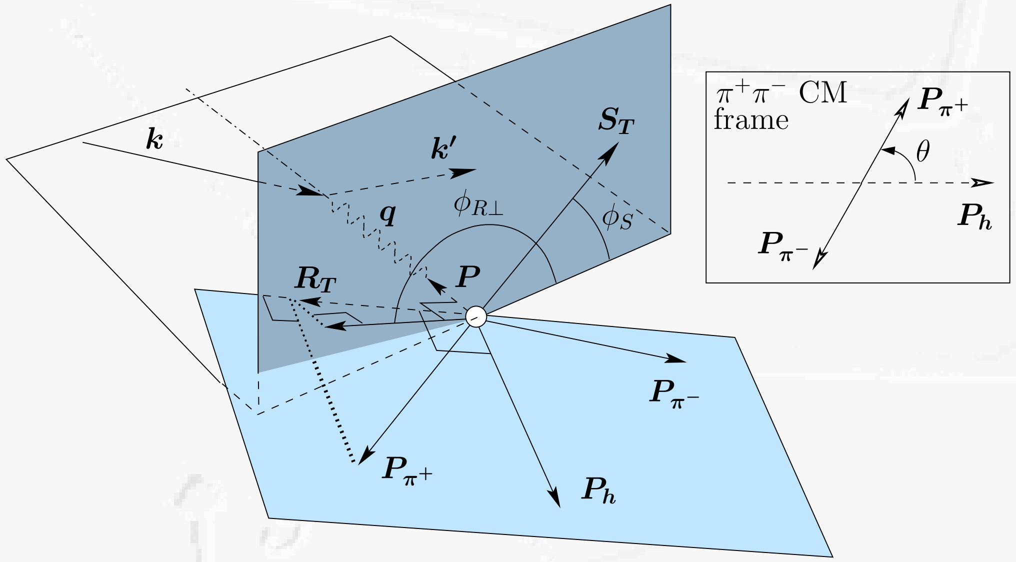
$\mathbf{e^+e^- \to \pi\pi X}$



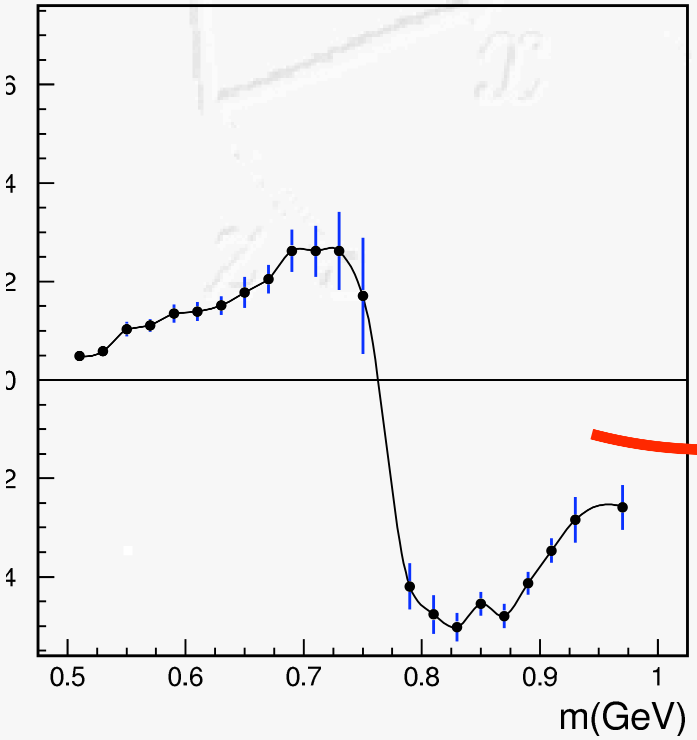
☛ M. Radici & M. Boglione

	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) → S(P)-wave phase shifts

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

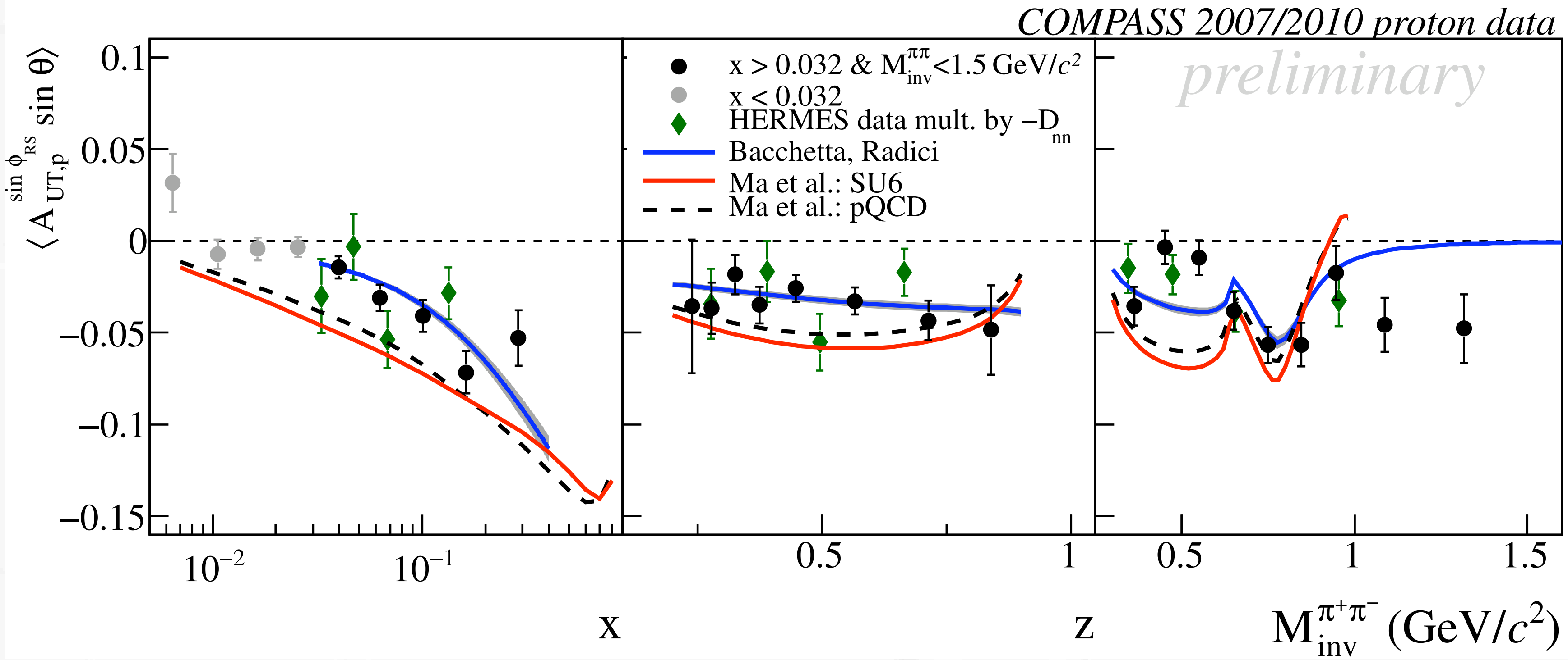
⇒ A_{UT} might depend strongly on $M_{\pi\pi}$

	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]

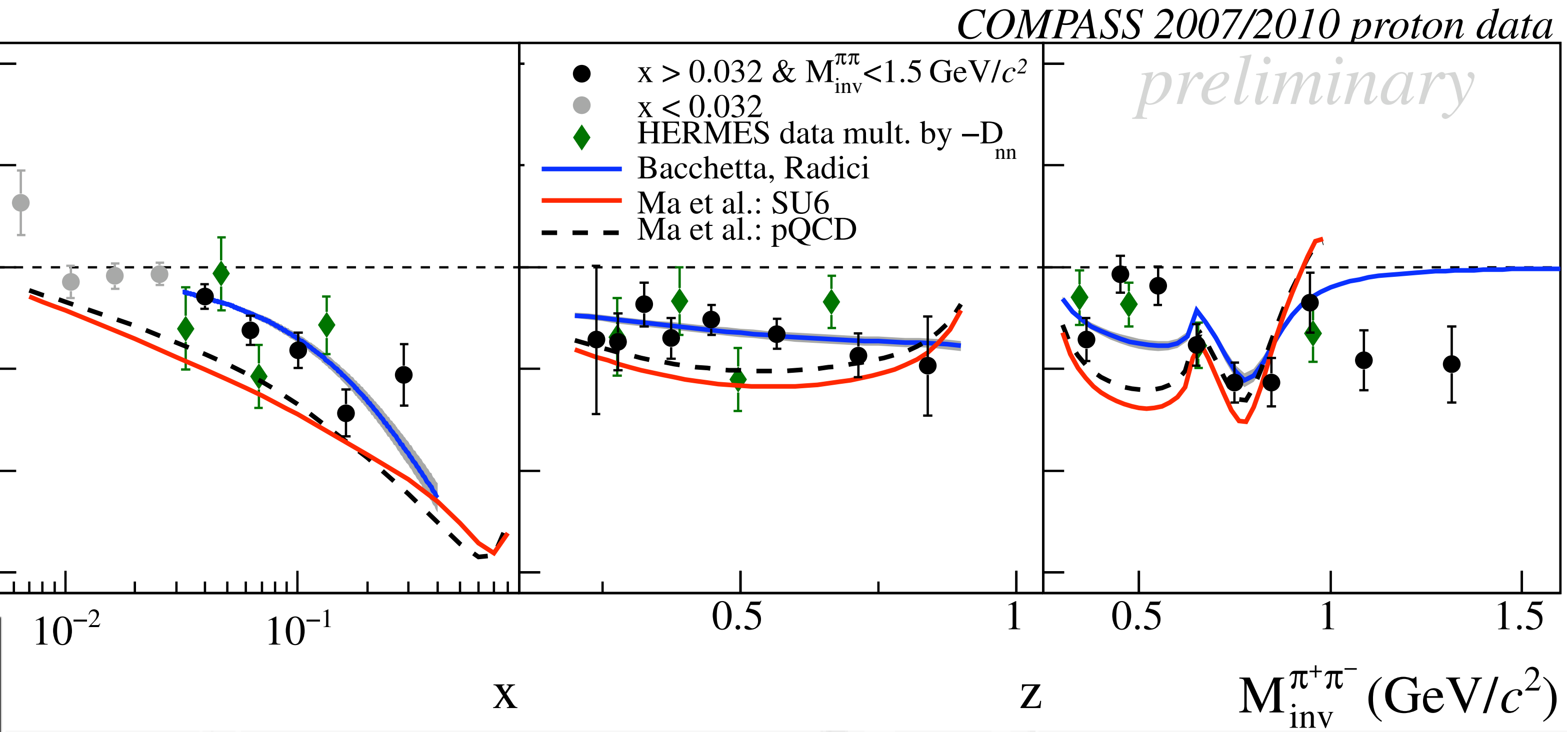


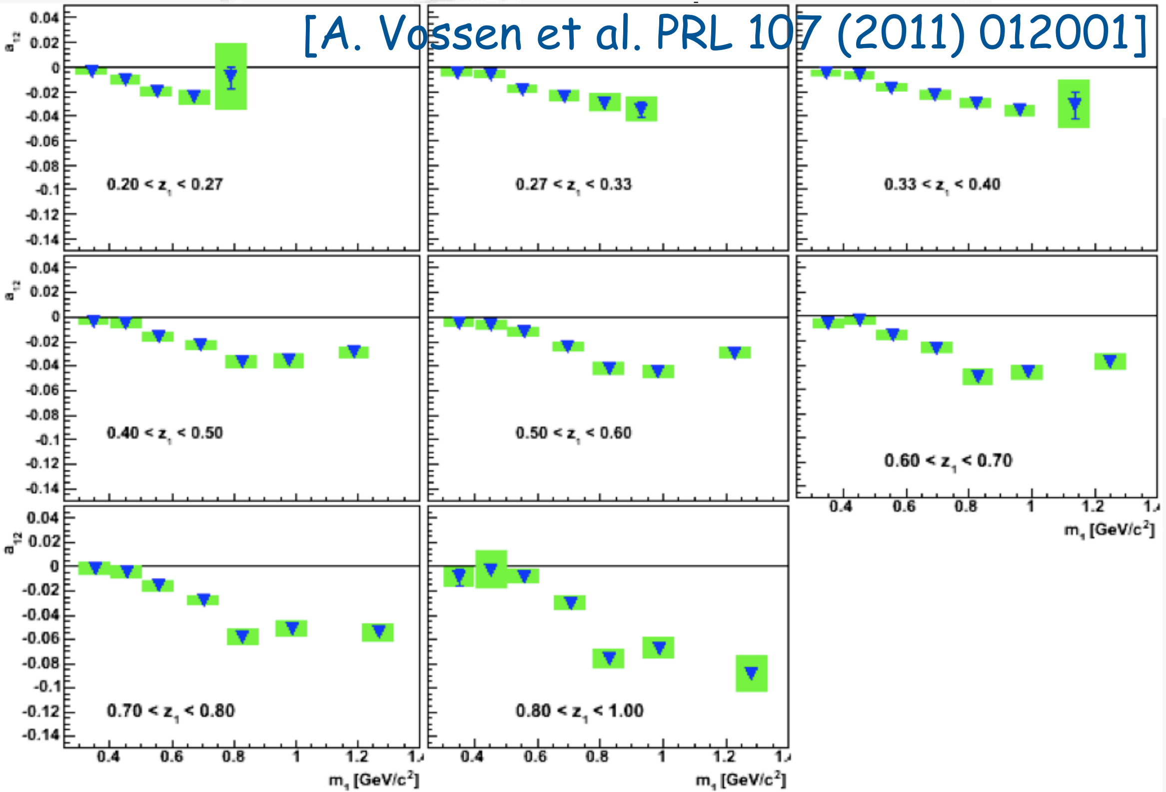
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

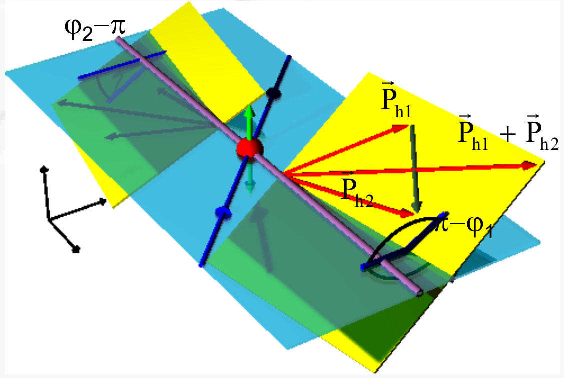
[A. Airapetian et al., JHEP 06 (2008) 017]
COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10]
COMPASS 2010: [C. Braun et al., Nuovo Cimento C 035 (2012) 02]

- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign
- ^{2}H results consistent with zero




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

- data from e^+e^- by BELLE

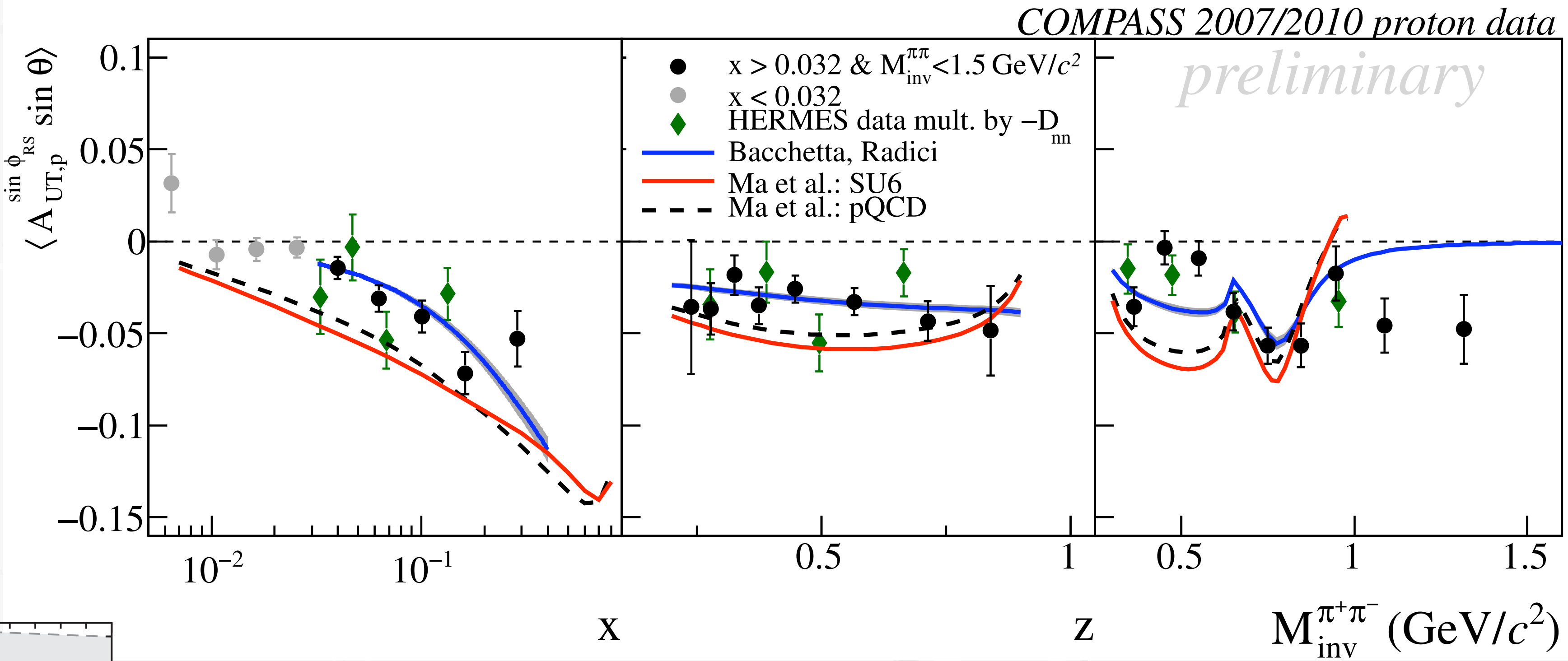


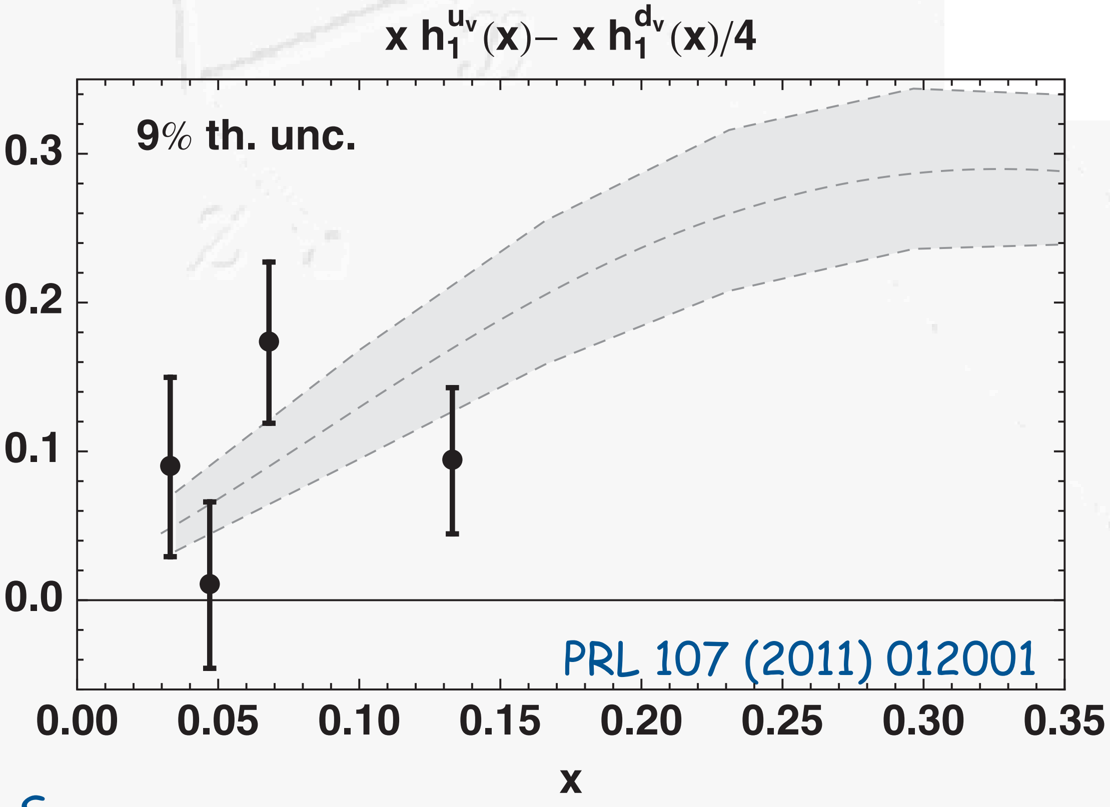
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign
- ^{2}H results consistent with zero

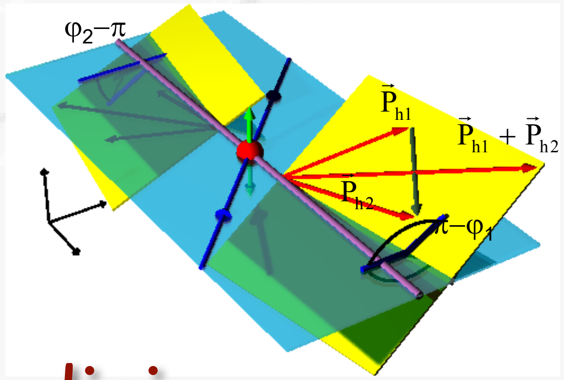
[A. Airapetian et al., JHEP 06 (2008) 017]
COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10]
COMPASS 2010: [C. Braun et al., Nuovo Cimento C 035 (2012) 02]





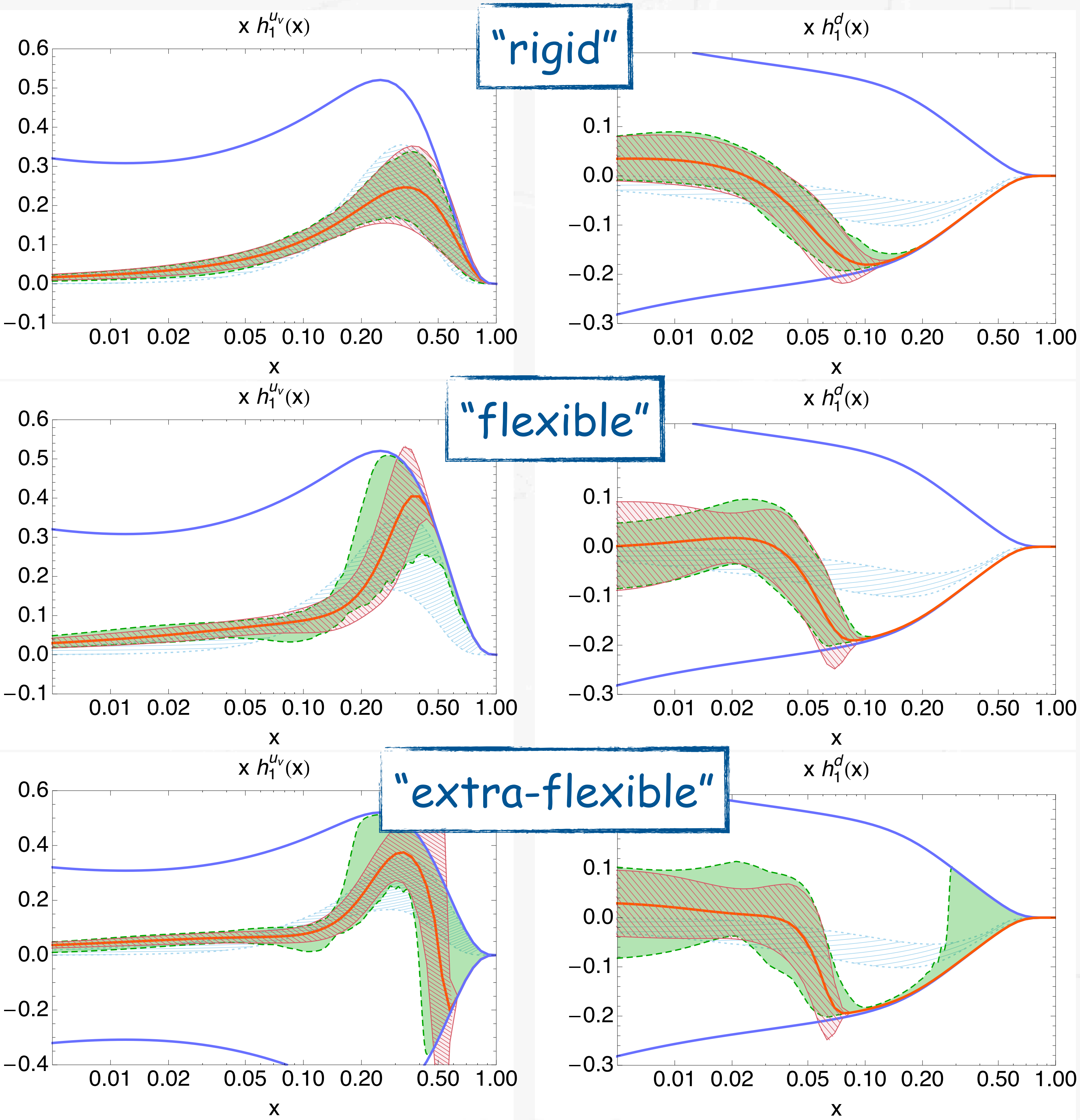
PRL 107 (2011) 012001

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



- updated analysis ☛ **M. Radici**

collinear extraction of valence transversity

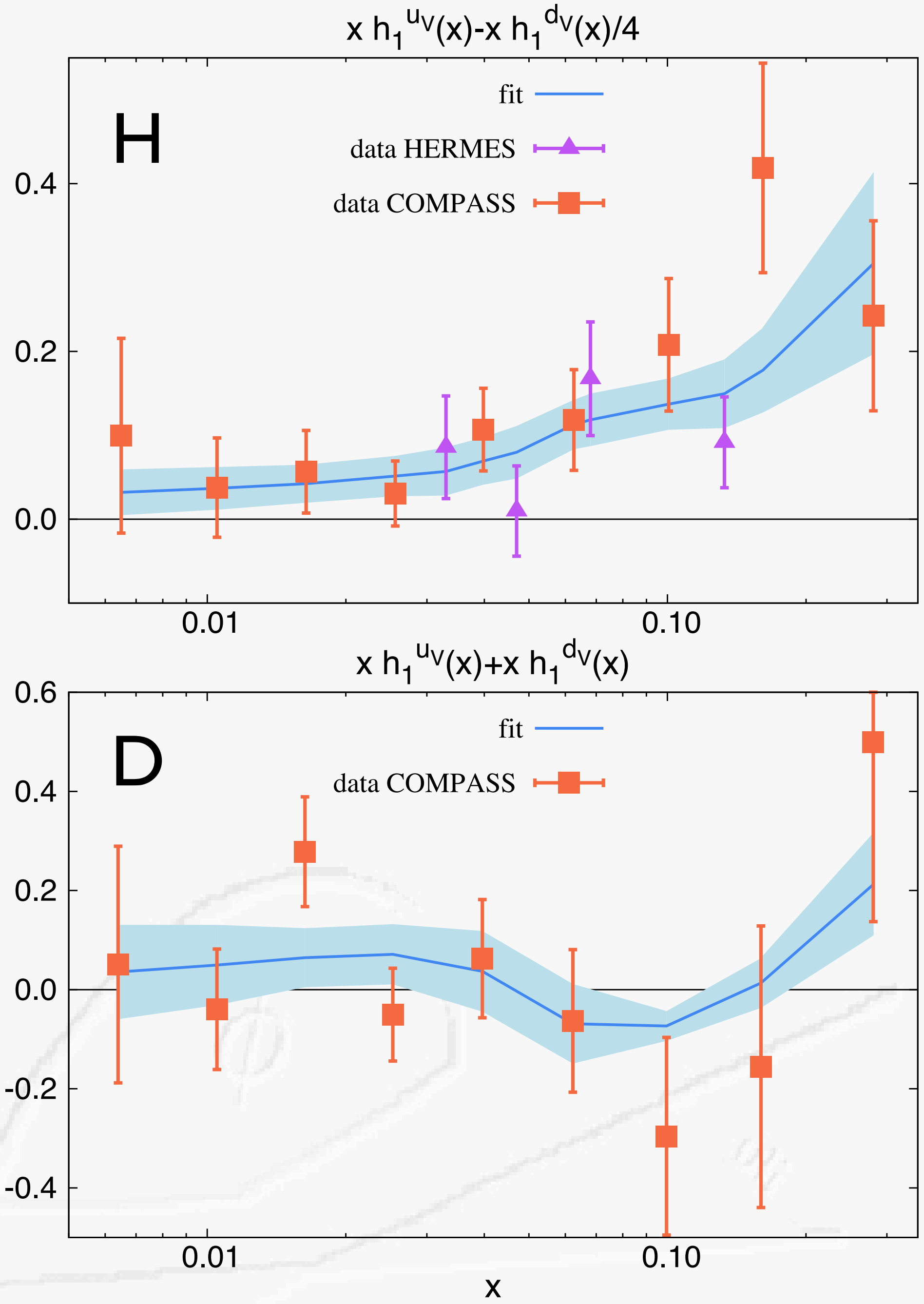


"rigid"

"flexible"

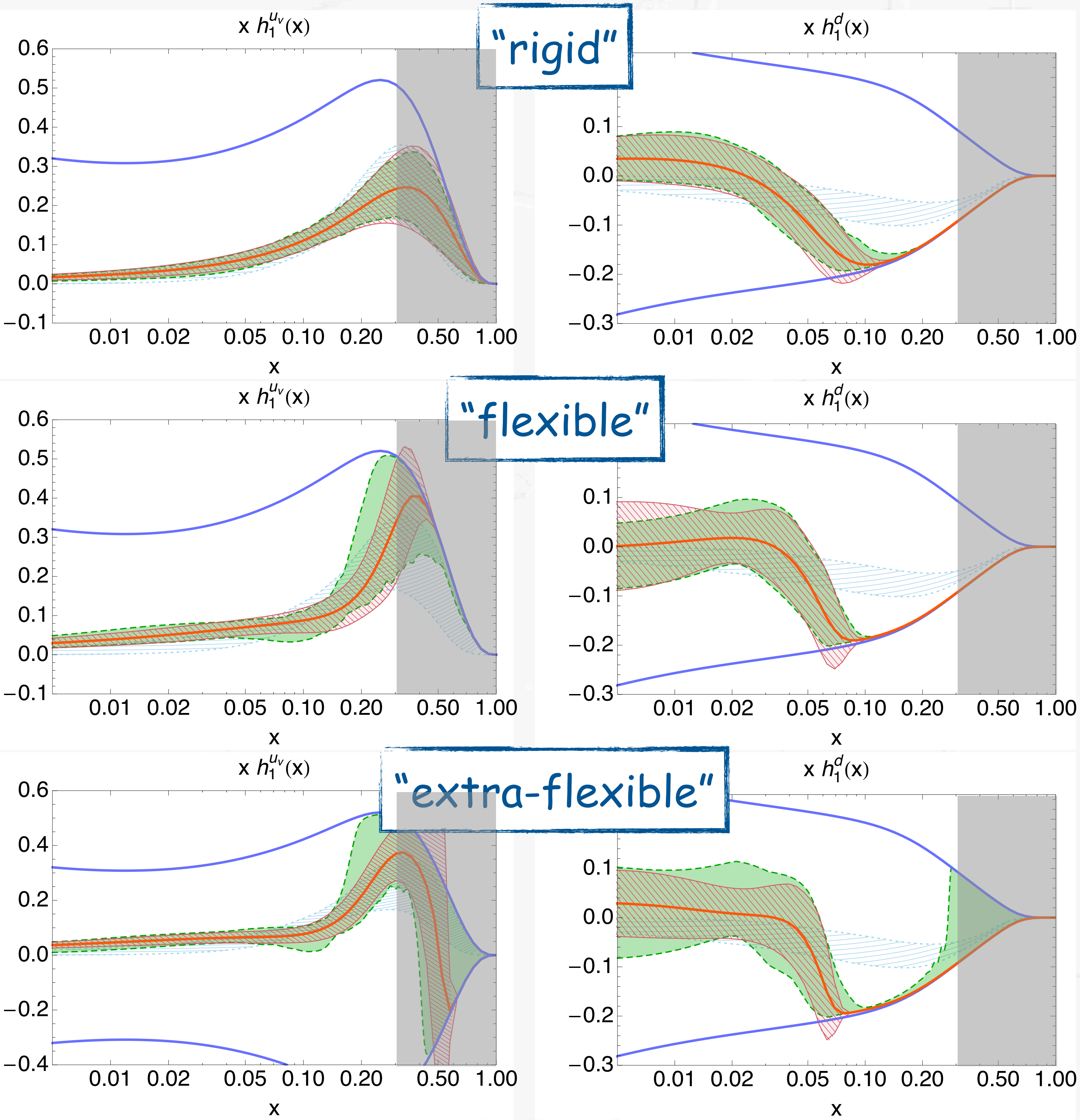
"extra-flexible"

[A. Bacchetta et al. JHEP 03 (2013) 119]



☛ **M. Radici**

collinear extraction of valence transversity

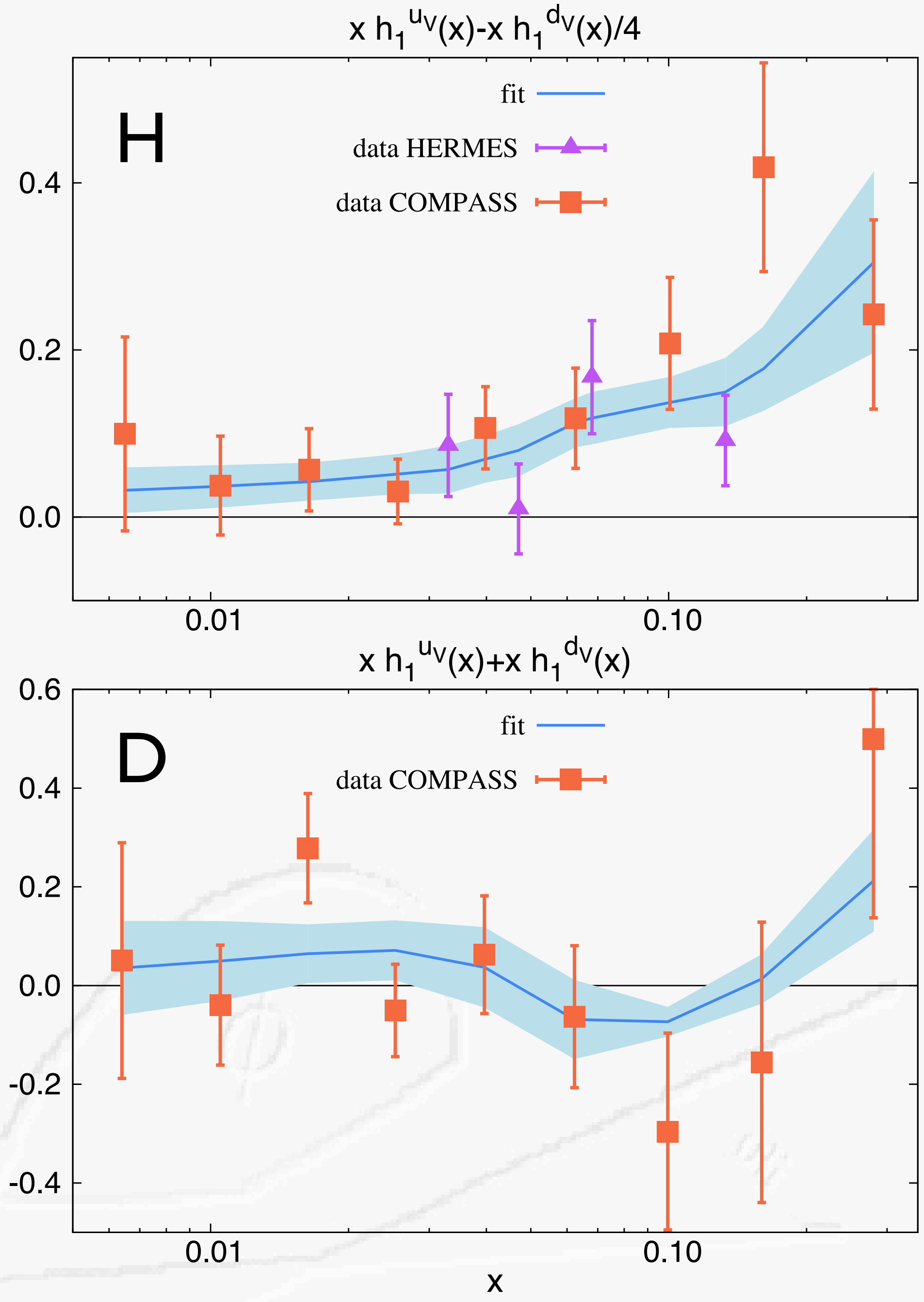


“rigid”

“flexible”

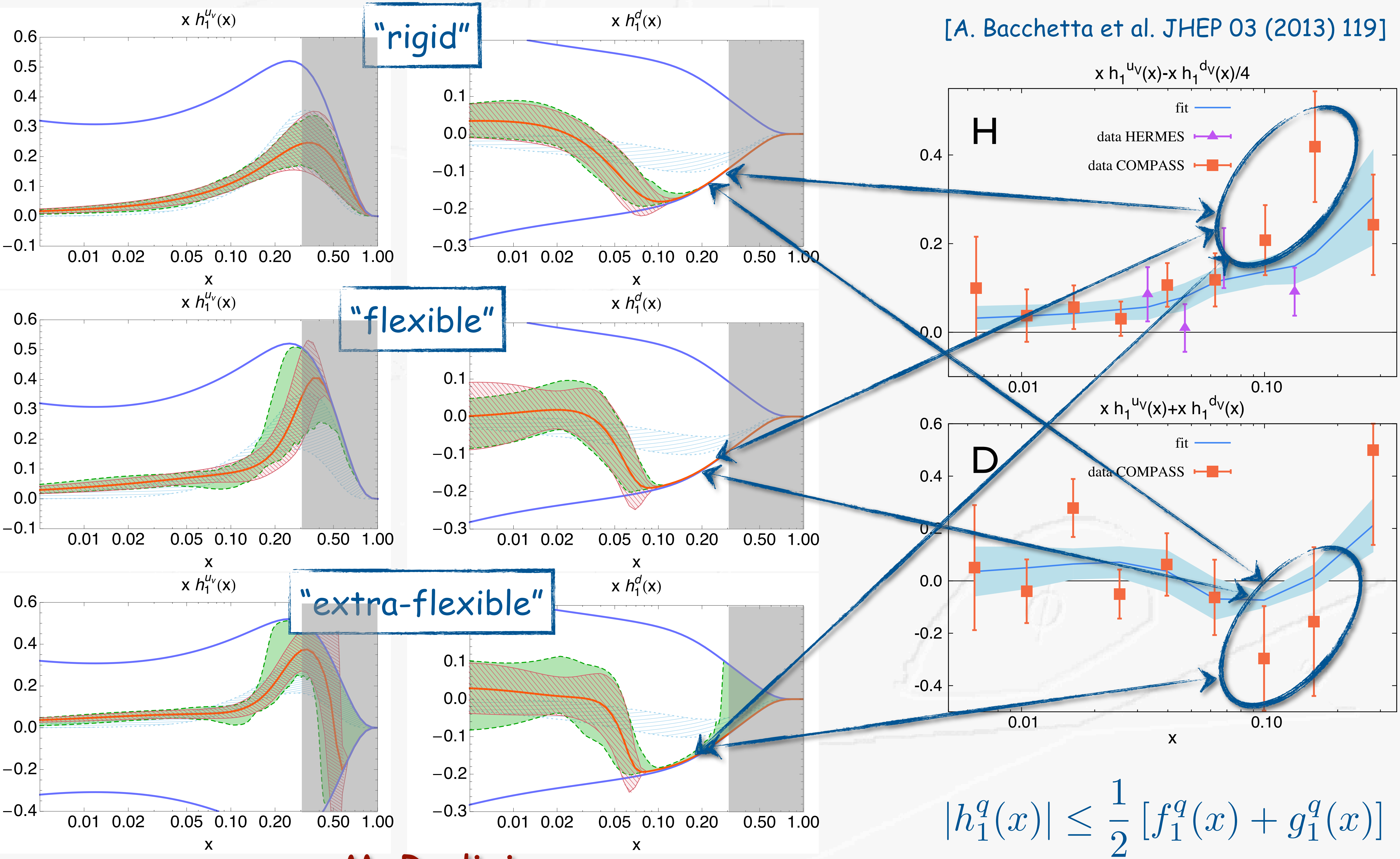
“extra-flexible”

[A. Bacchetta et al. JHEP 03 (2013) 119]



☛ M. Radici

collinear extraction of valence transversity



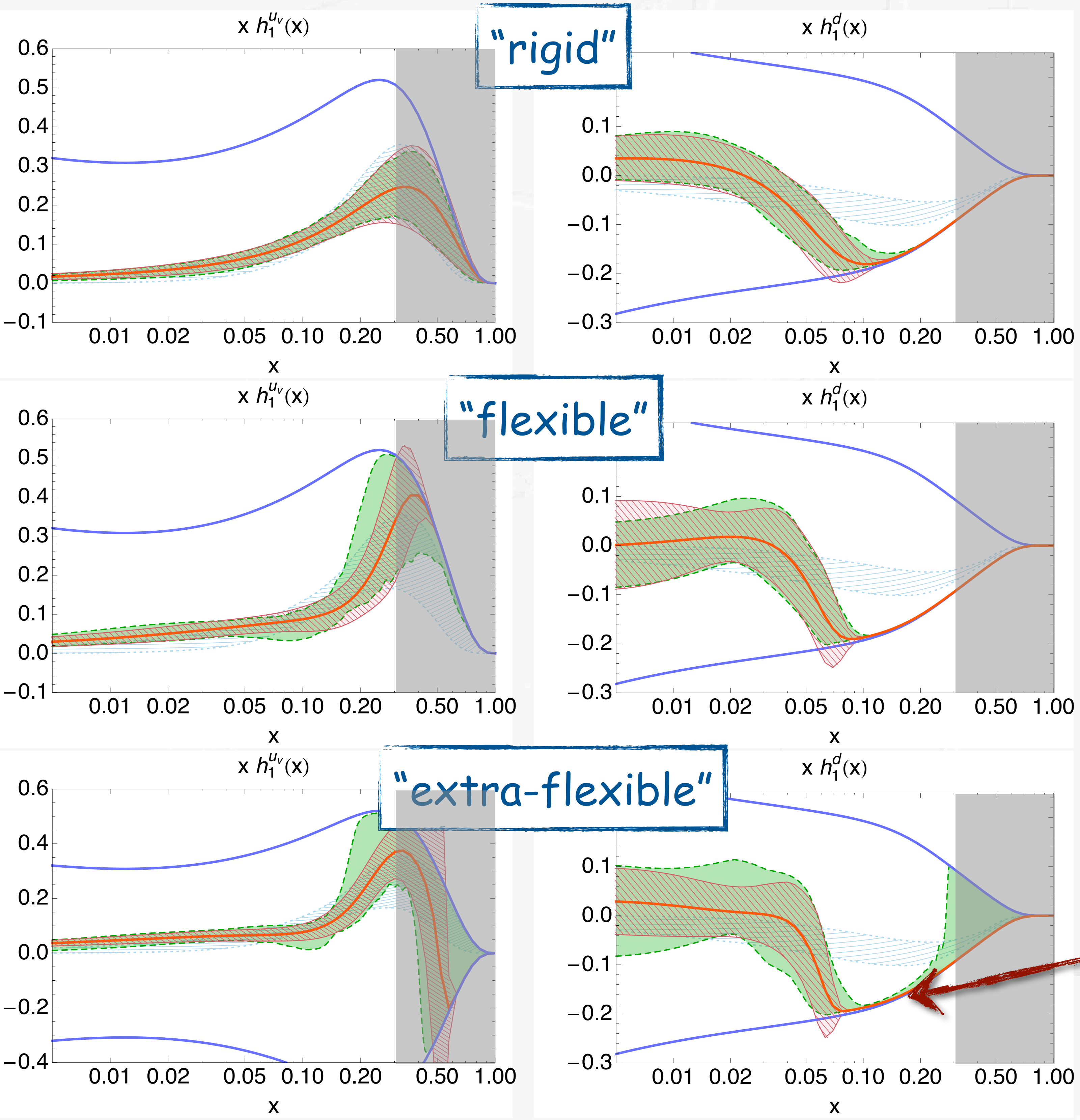
[A. Bacchetta et al. JHEP 03 (2013) 119]

$$|h_1^q(x)| \leq \frac{1}{2}\left[f_1^q(x) + g_1^q(x)\right]$$

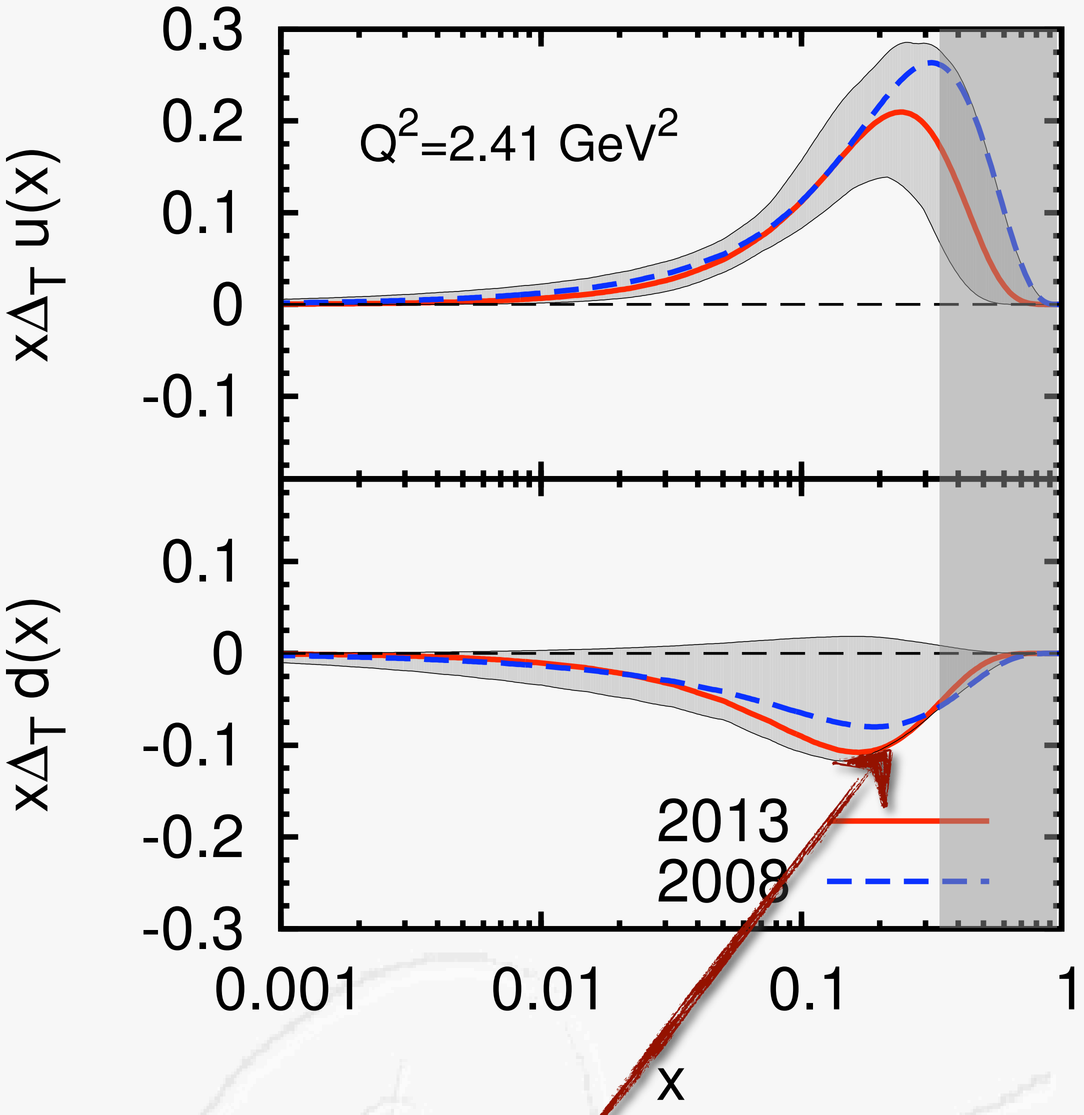
☛ M. Radici

d_v-transversity Soffer bound

[A. Bacchetta et al. JHEP 03 (2013) 119]



[M. Anselmino et al., PRD 87 (2013) 094019]



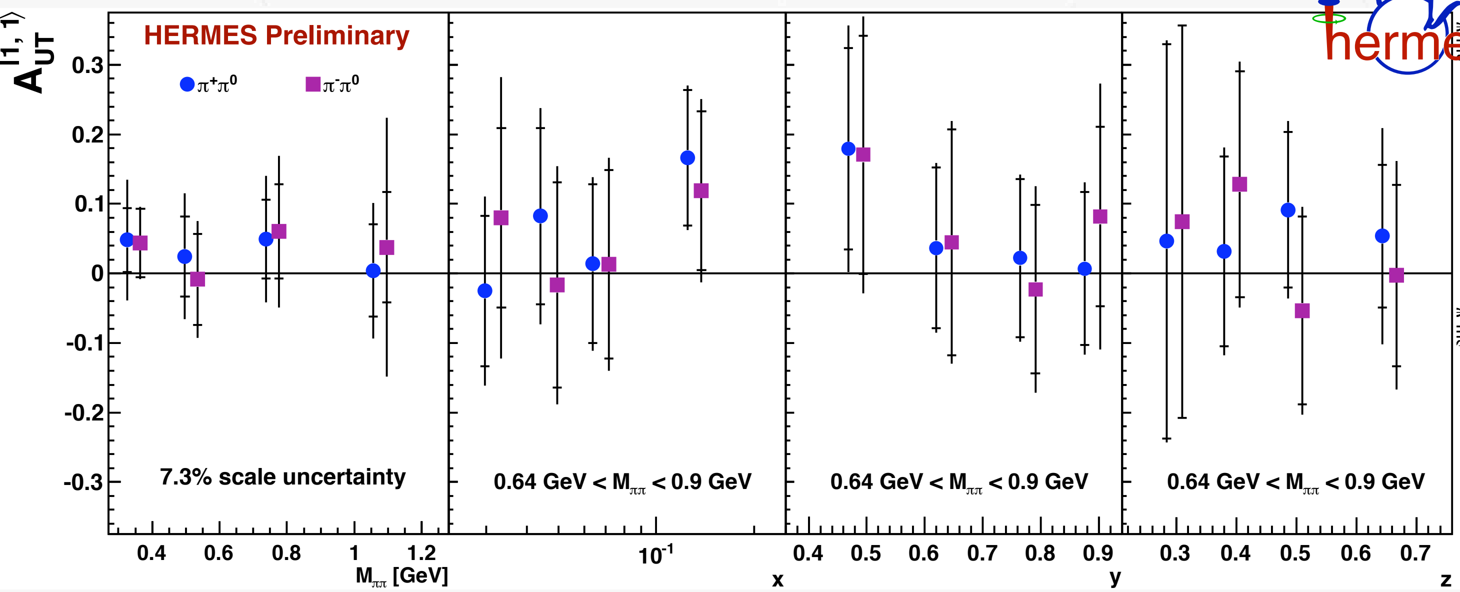
general trend towards violating d-Soffer bound?

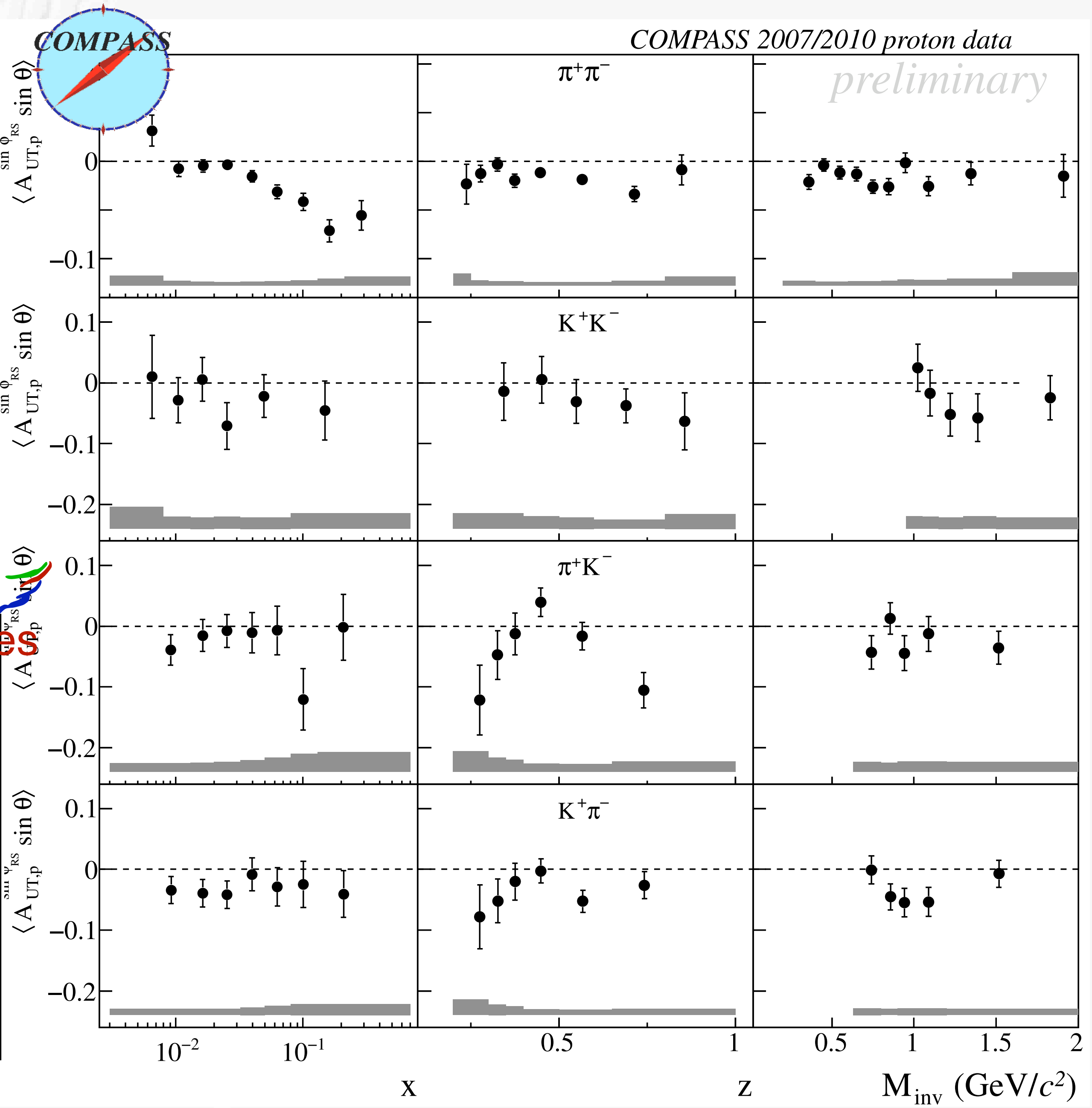
$$|h_1^q(x)| \leq \frac{1}{2}\left[f_1^q(x) + g_1^q(x)\right]$$

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

Transversity distribution (2-hadron fragmentation)

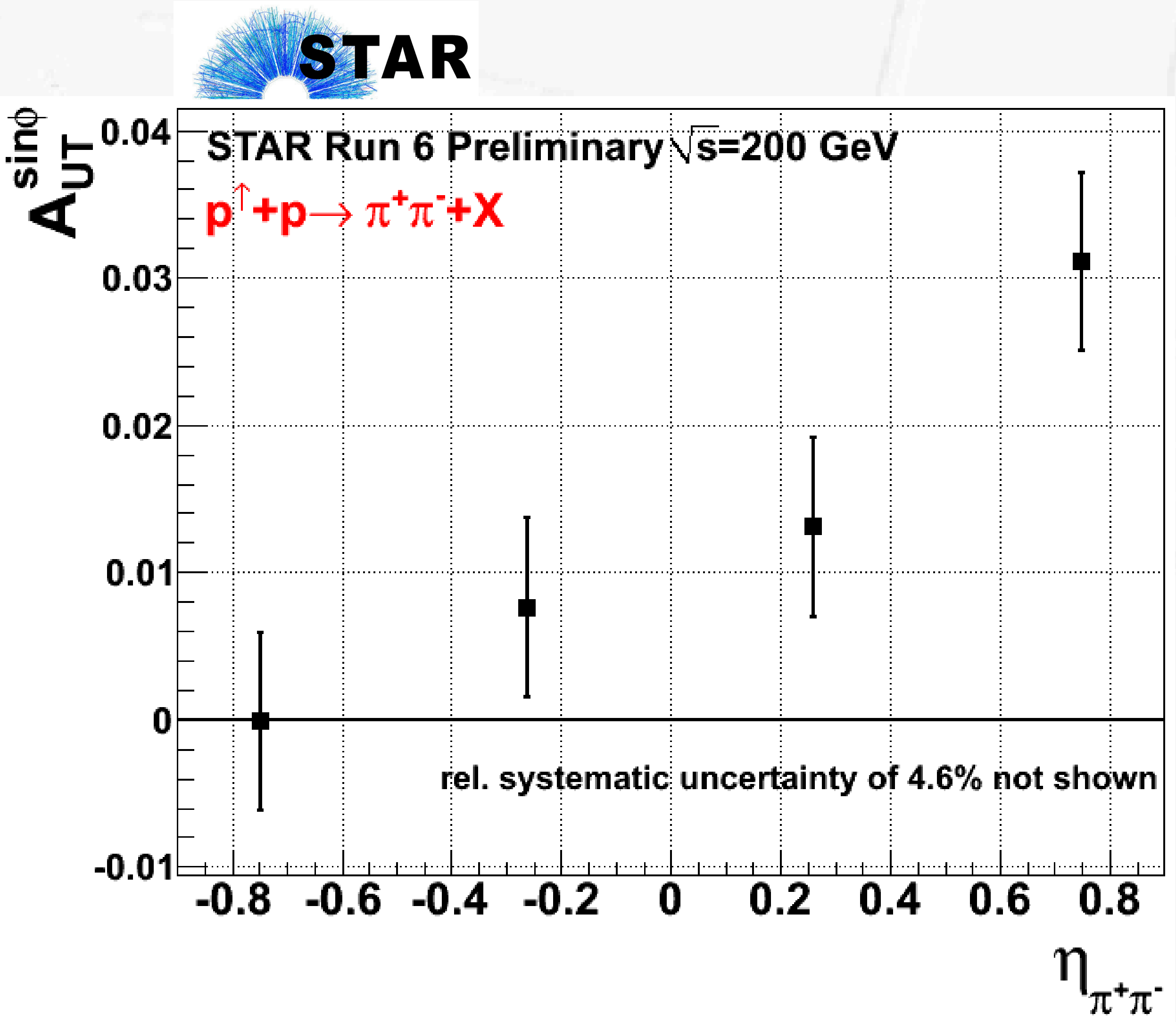
- new preliminary results on various other hadron combinations
  - COMPASS: charged $\pi^\pm K^\mp$
  - HERMES: $\pi^\pm\pi^0$

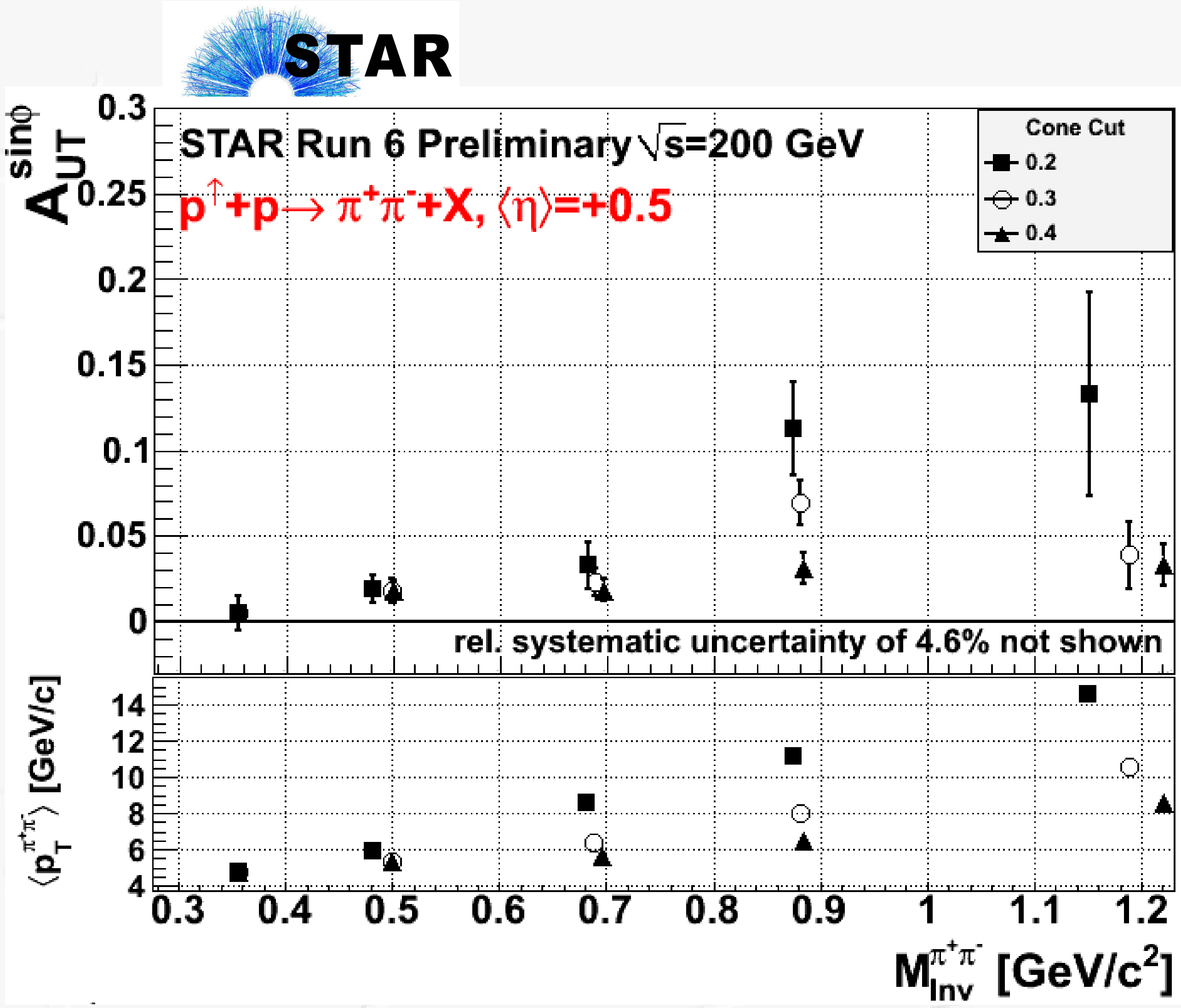




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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





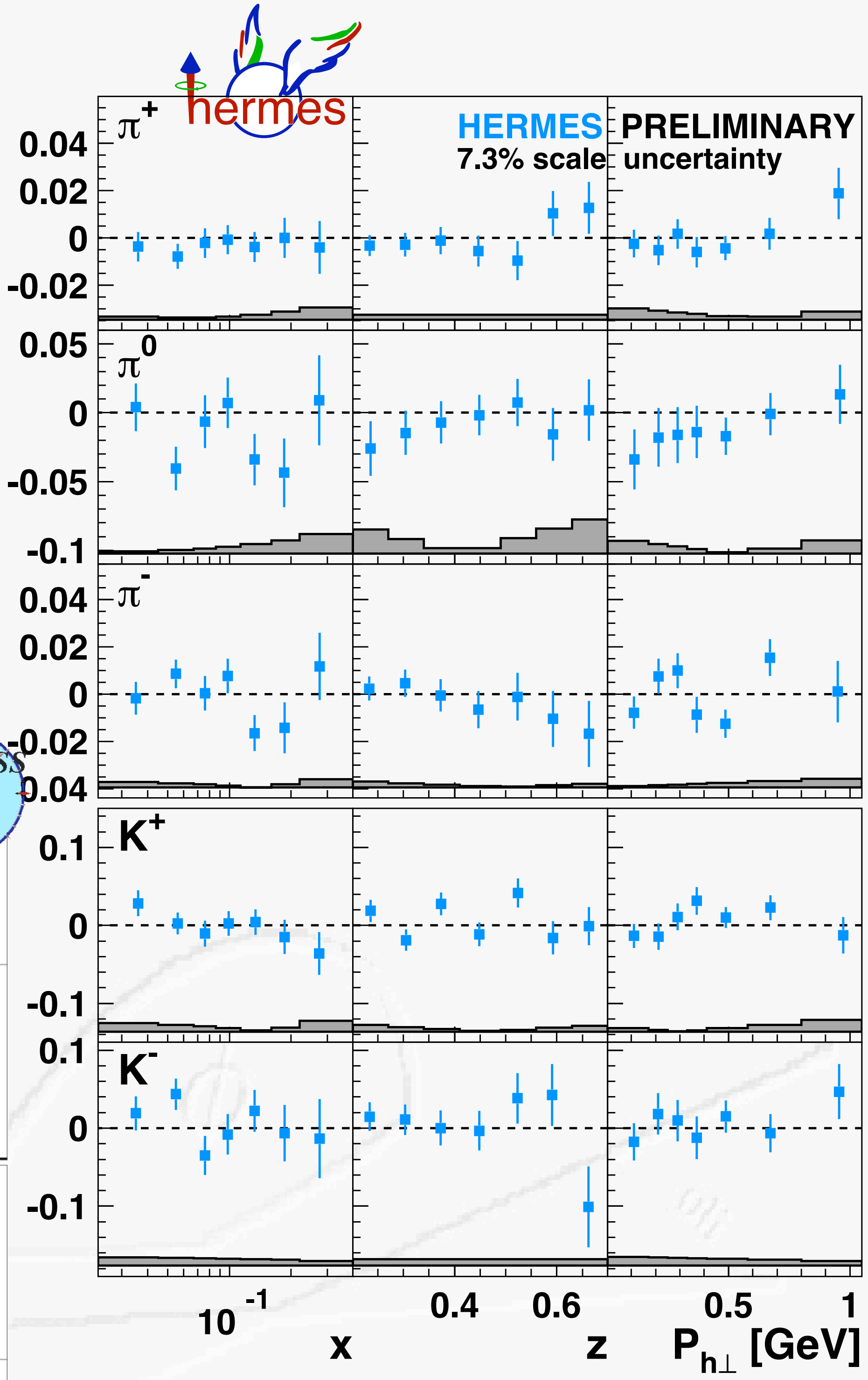
- forward region -> valence effect from polarized (beam) proton?
- previous mid-rapidity preliminary data from PHENIX consistent with zero
- dependence on cone cut; due to underlying p_T dependence?

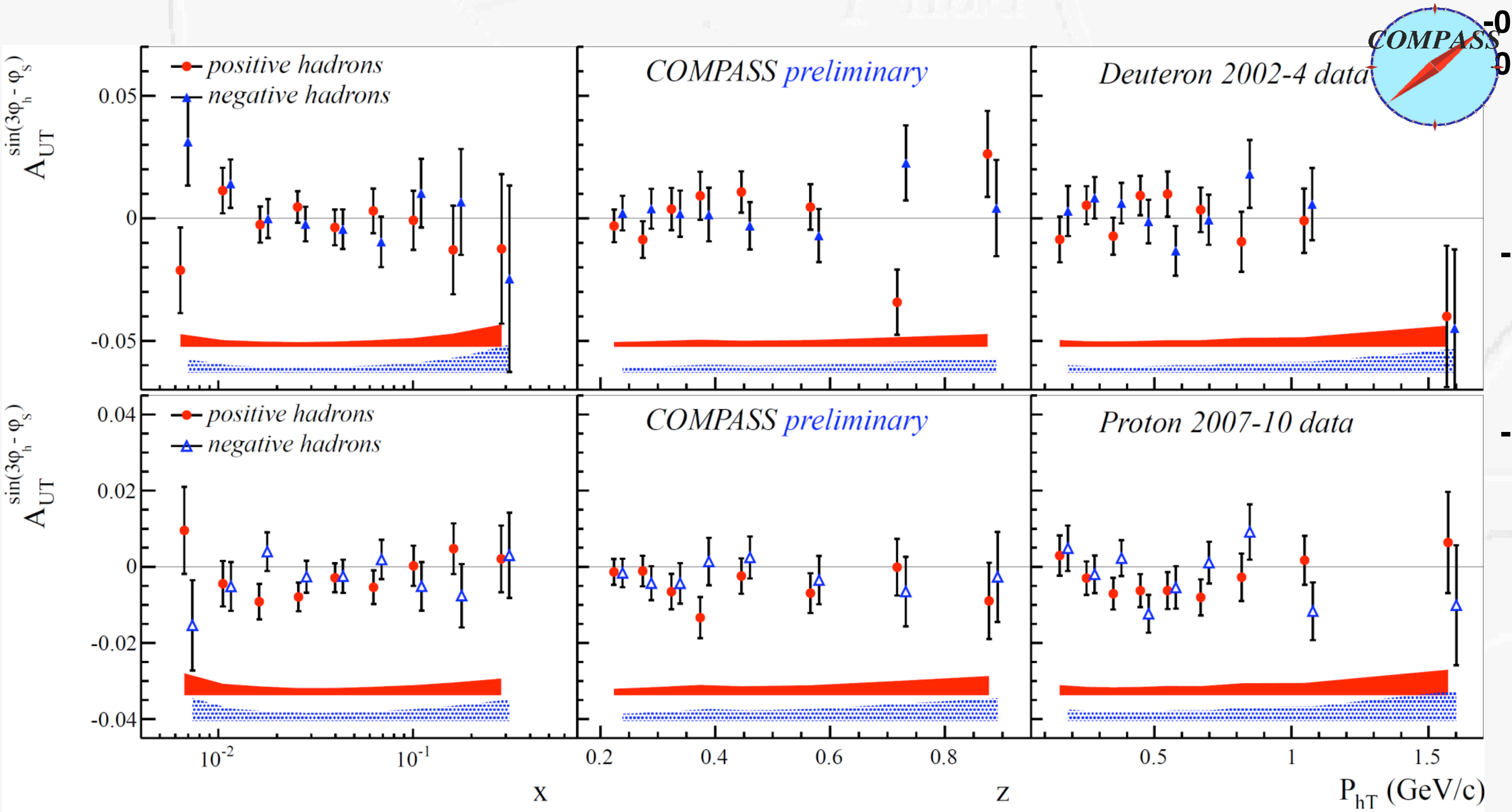
Transversity's friends

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

Pretzelosity

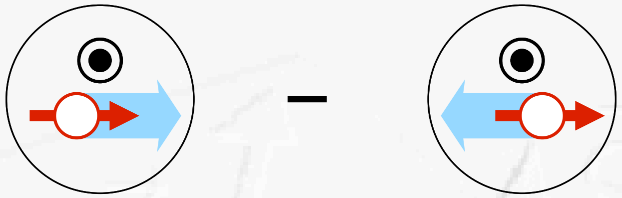
- chiral-odd ➥ needs Collins FF (or similar)
- proton & deuteron data consistently small
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$



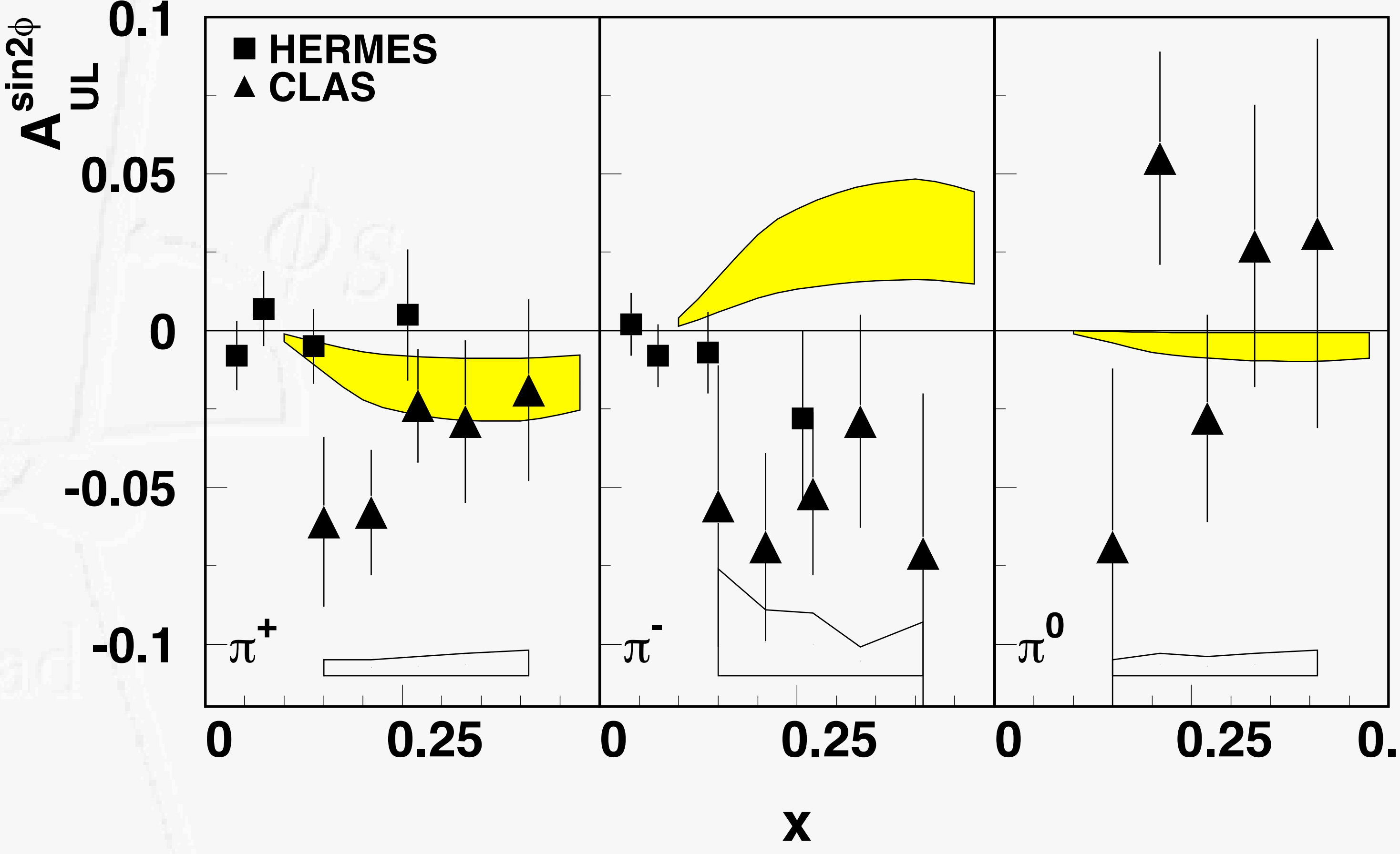


Worm-Gear I

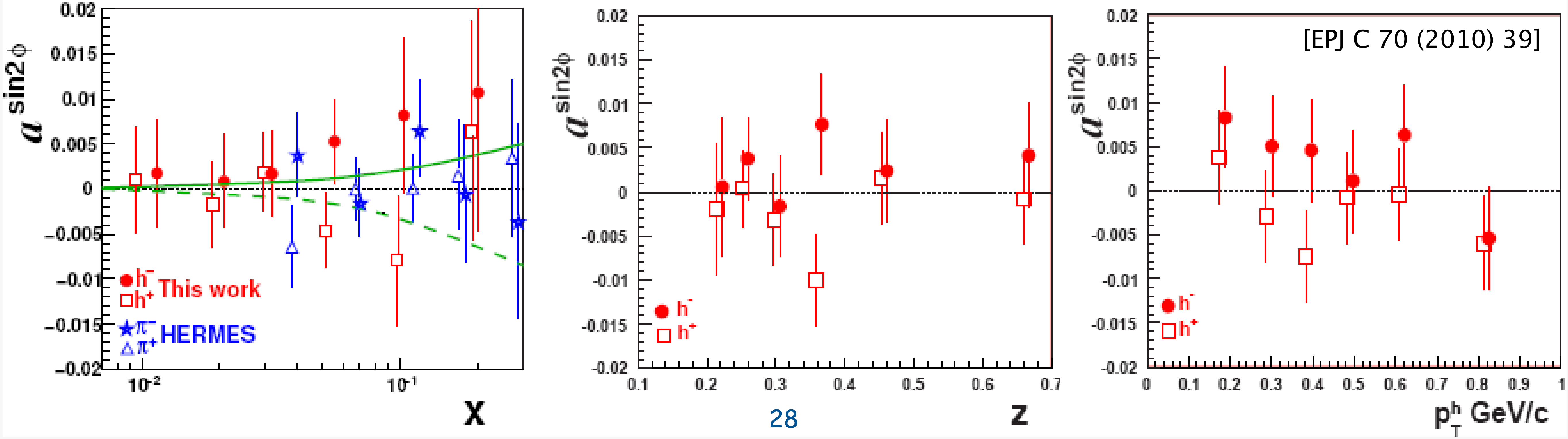
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



[CLAS, PRL 105 (2010) 262002]



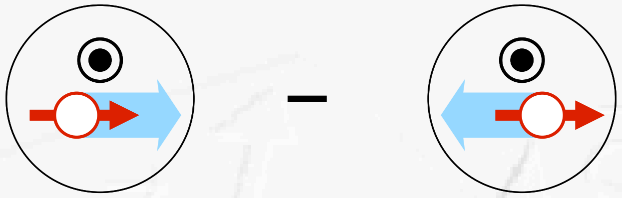
- again: chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES



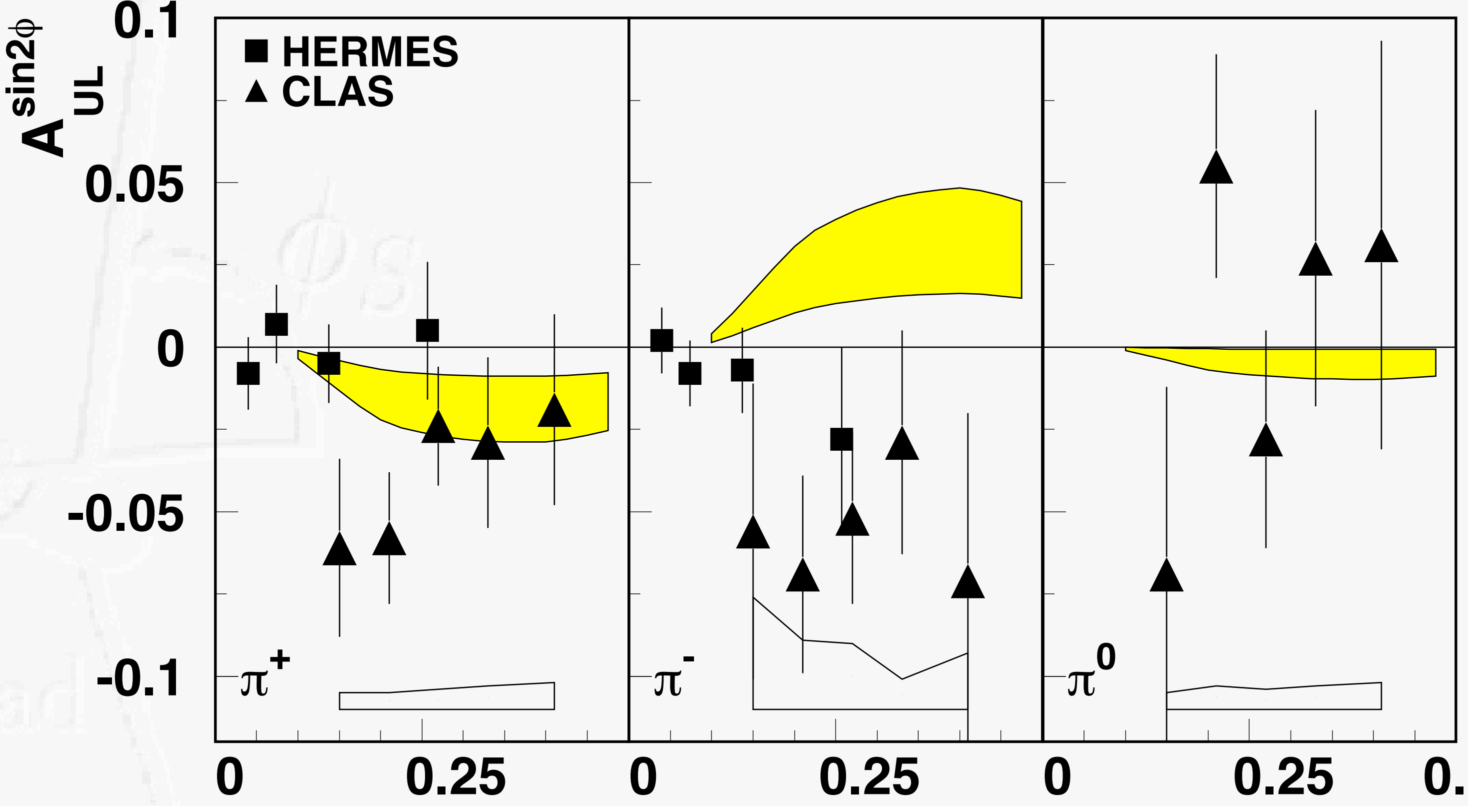
[EPJ C 70 (2010) 39]

Worm-Gear I

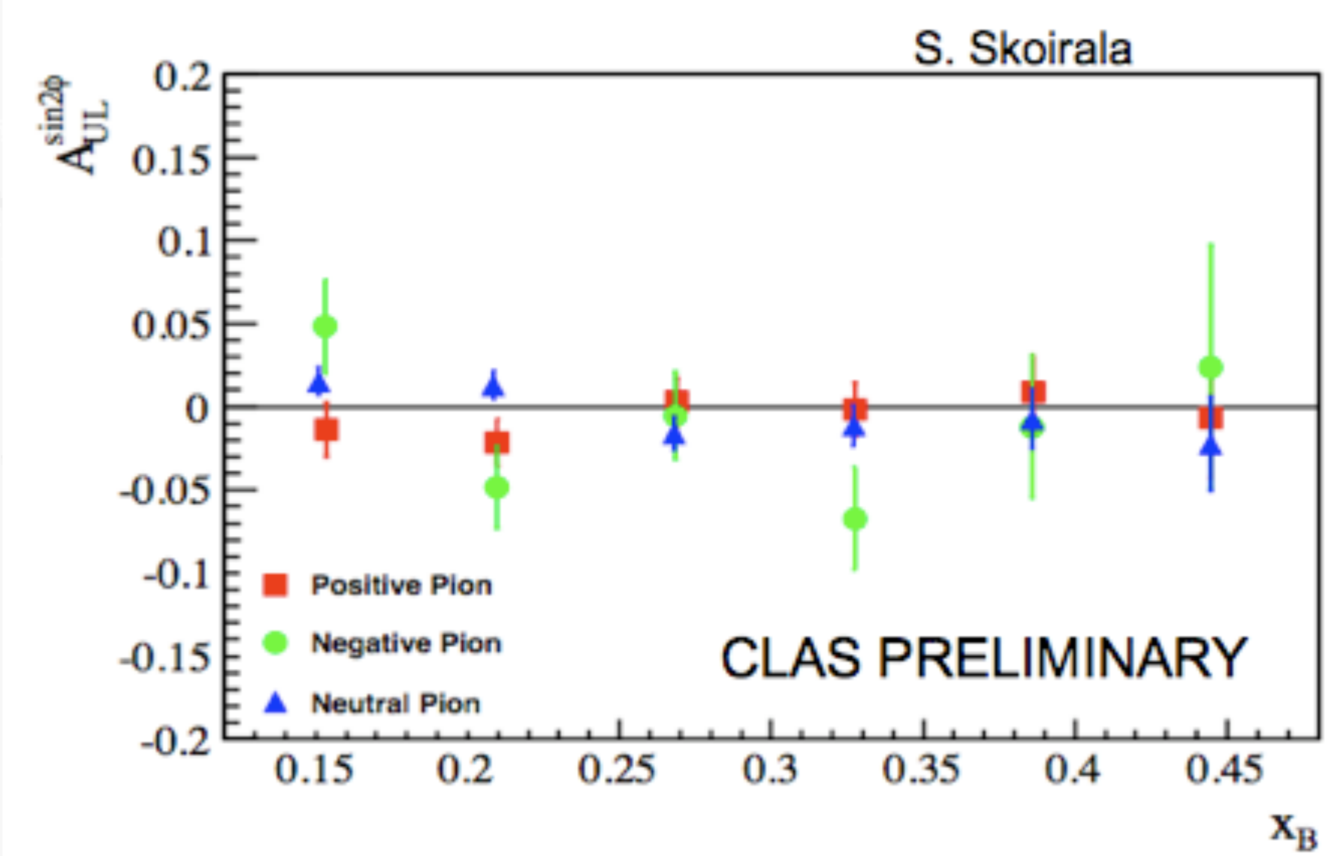
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



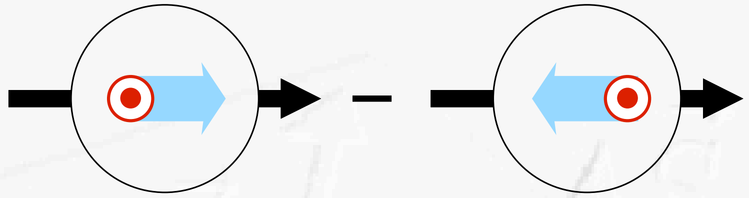
- again: chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES
- new preliminary data from CLAS closer to HERMES/ COMPASS (and to zero)



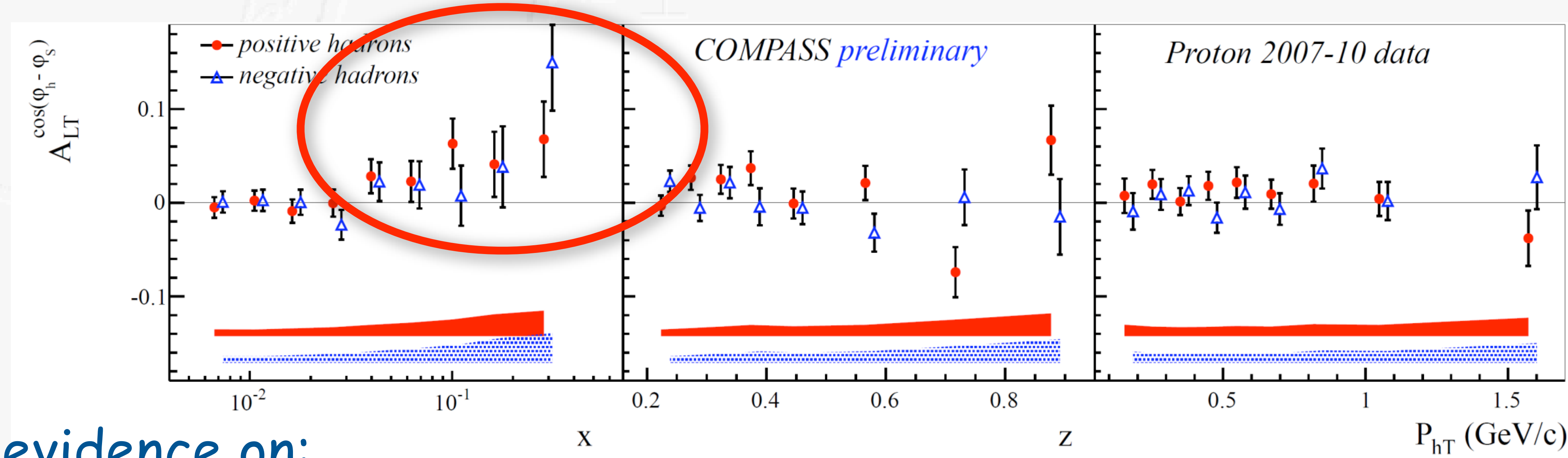
[CLAS, PRL 105 (2010) 262002]



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

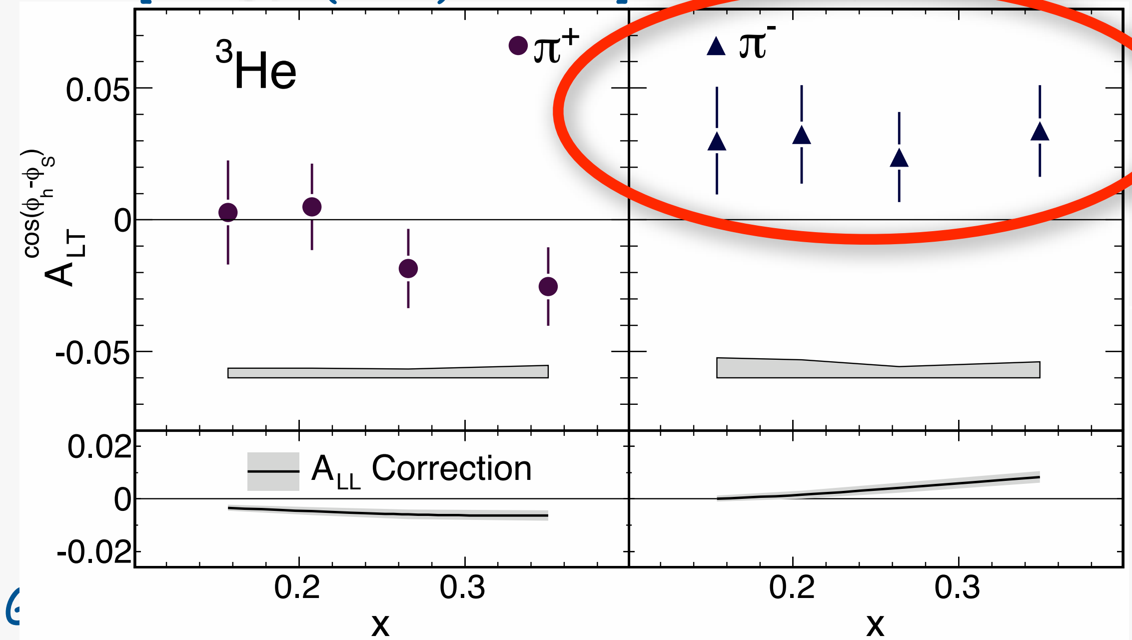


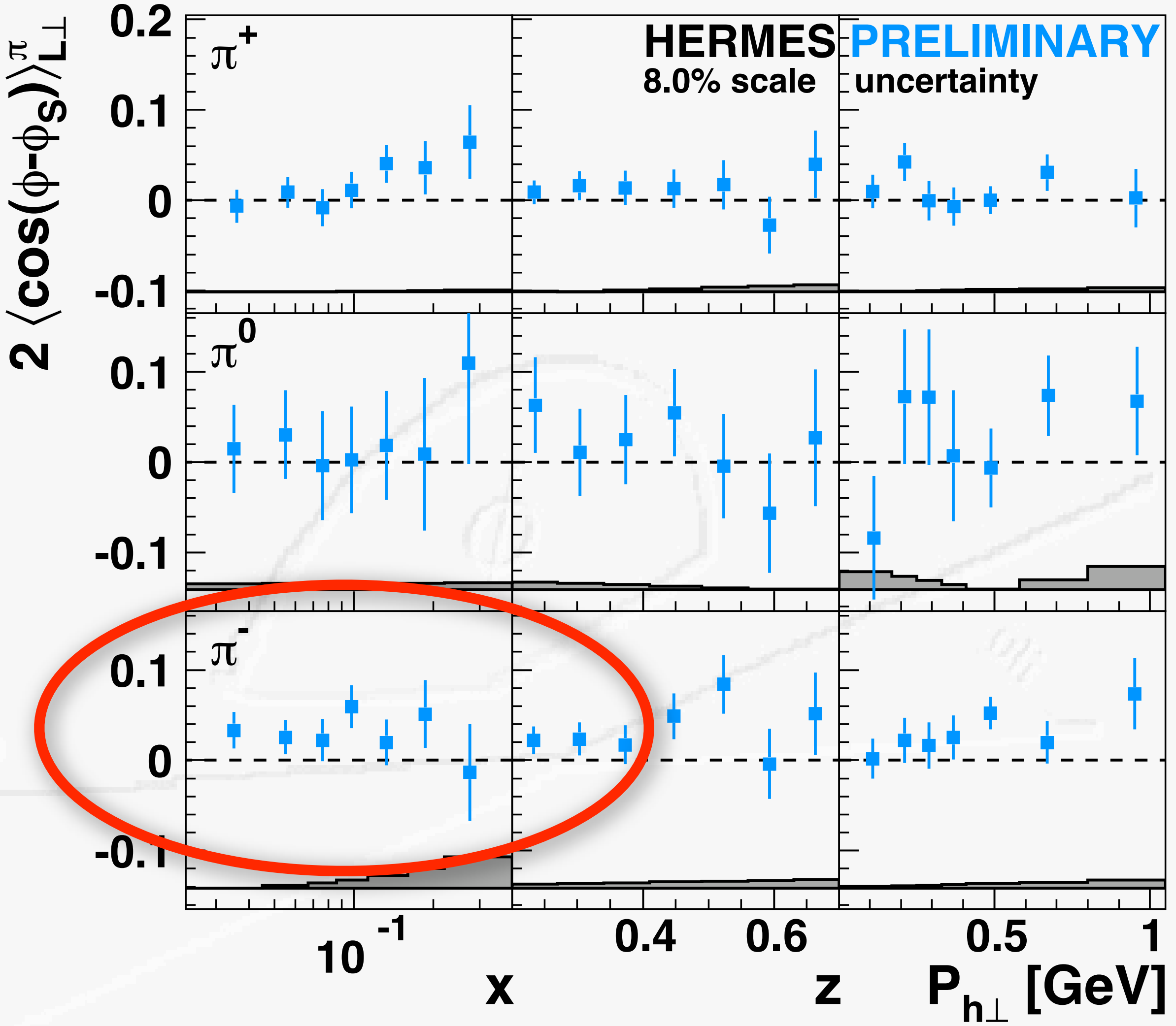
Worm-Gear II

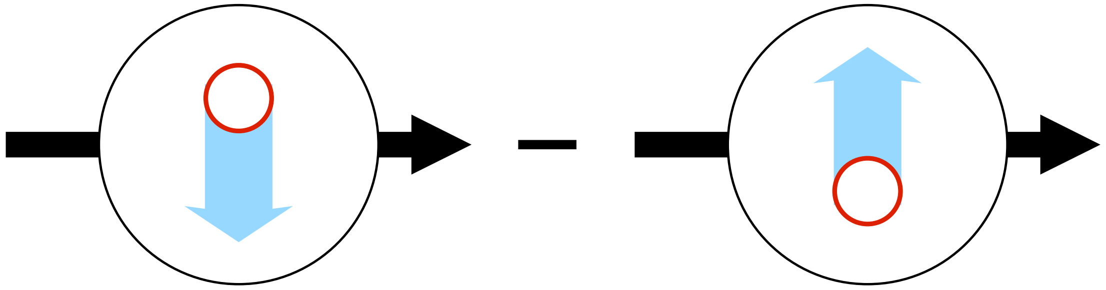


- first direct evidence on:
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

[PRL 108 (2012) 052001]

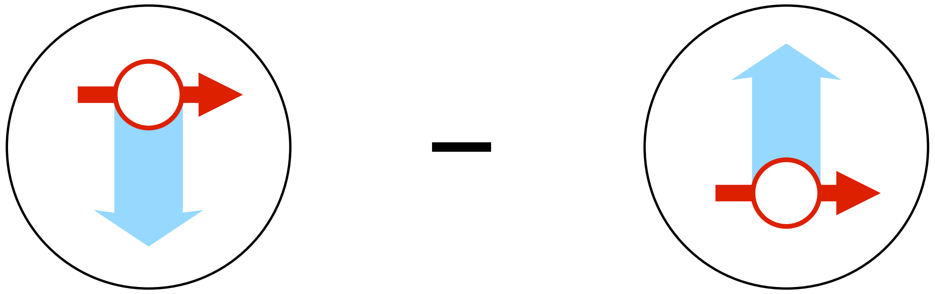






"Wilson-line physics"

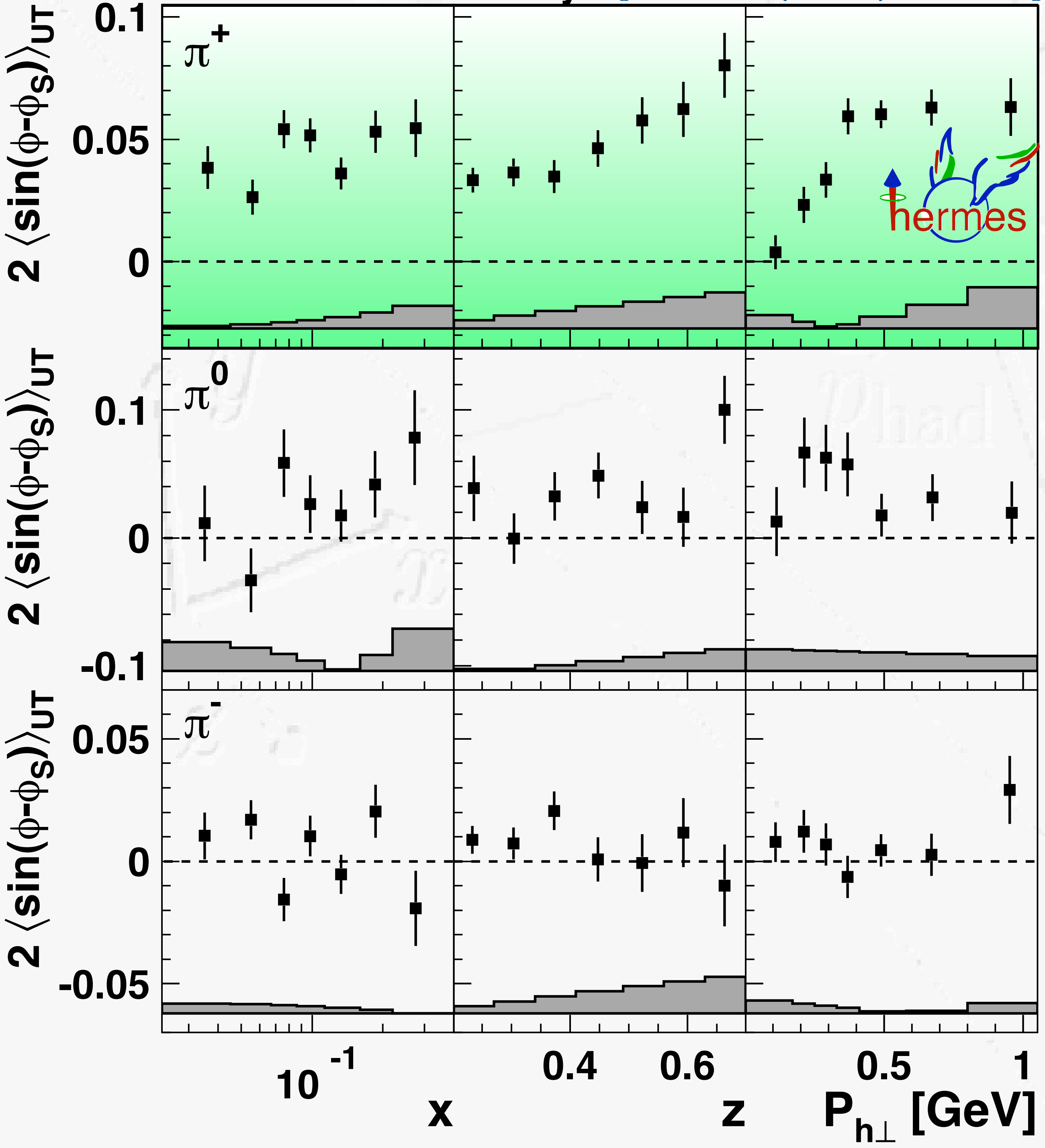
naively T-odd distributions



	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

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

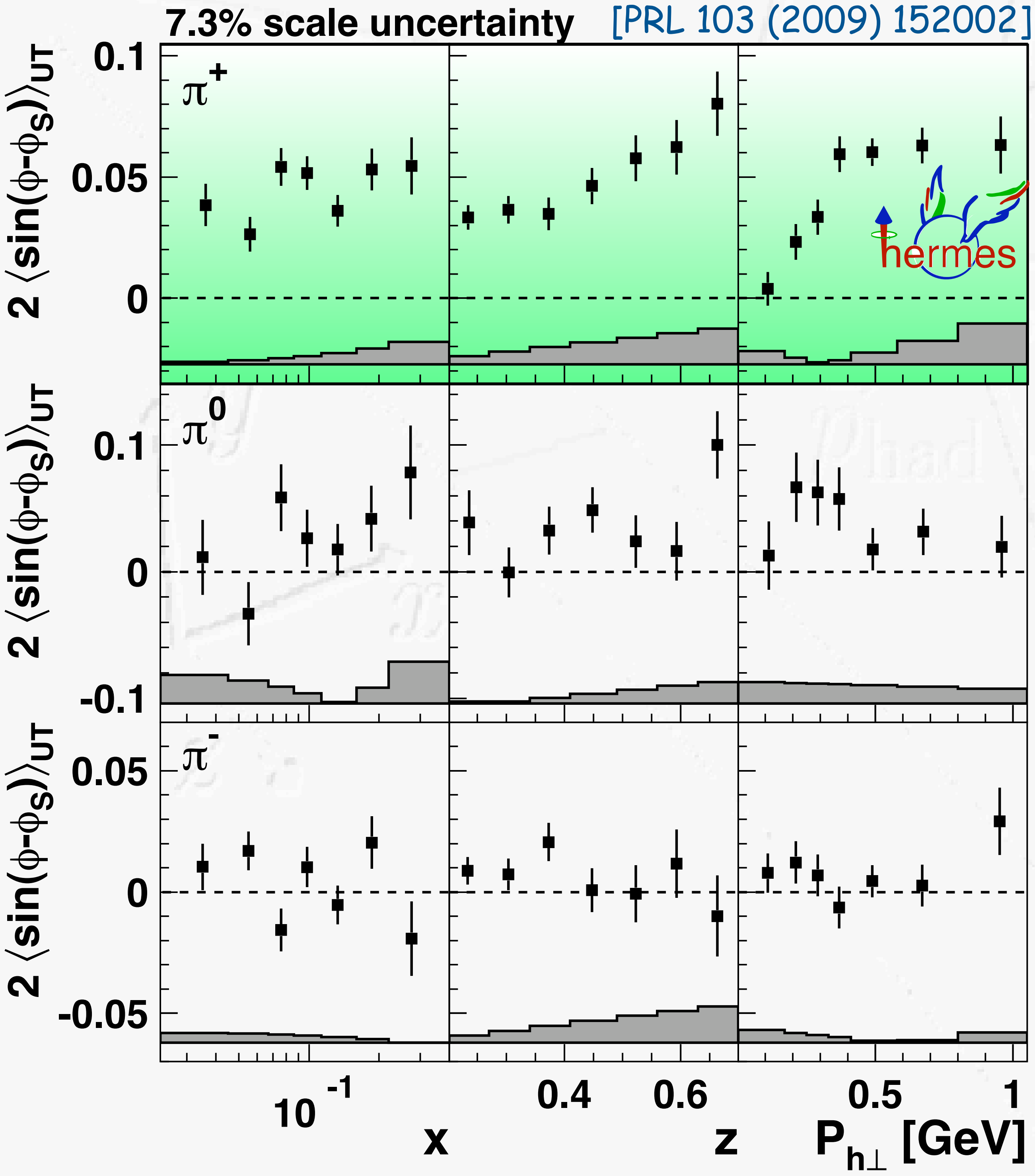


7.3% scale uncertainty [PRL 103 (2009) 152002]

	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:

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

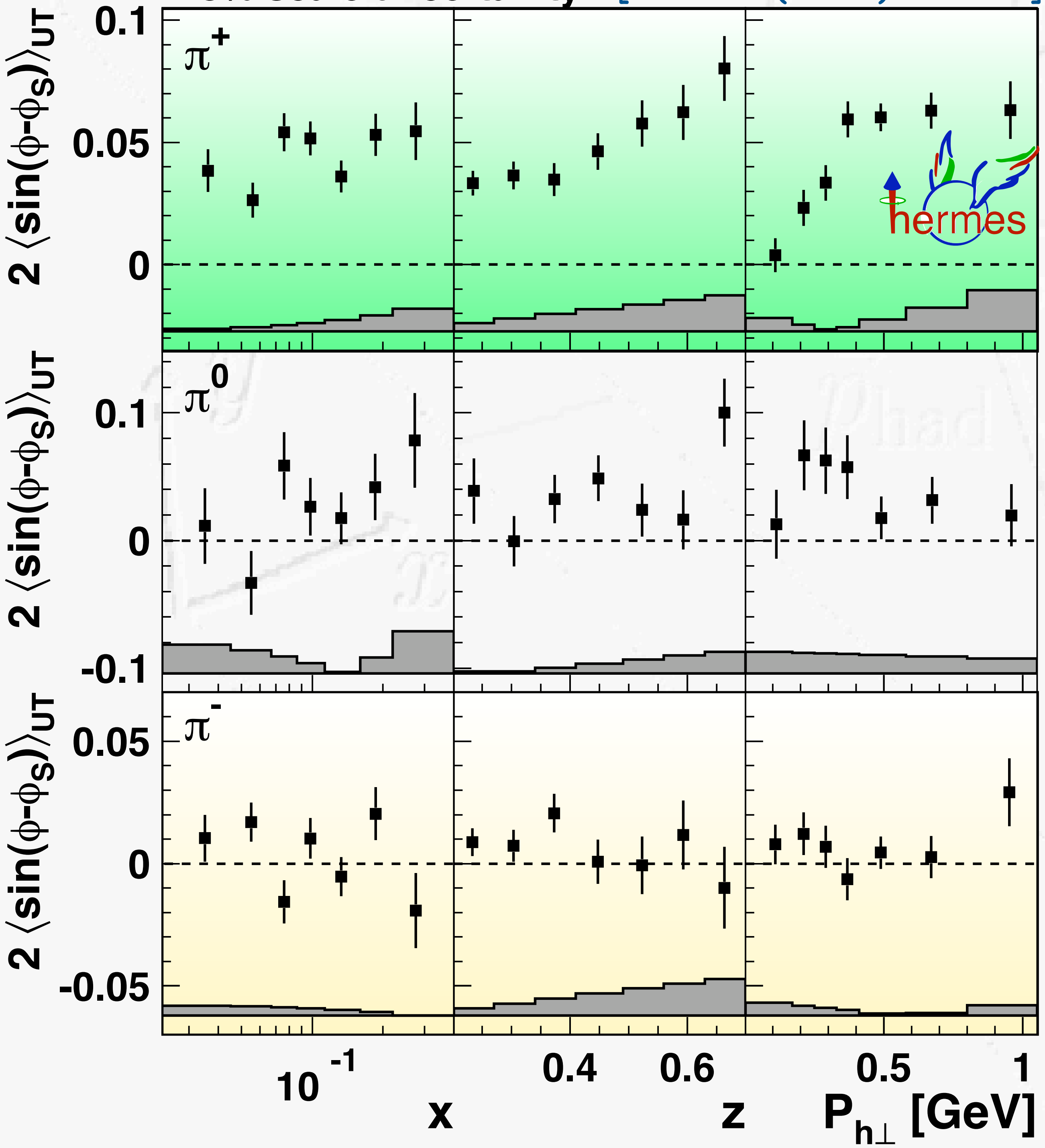
☛ u-quark Sivers DF < 0

	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

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

7.3% scale uncertainty [PRL 103 (2009) 152002]



π^+ dominated by u-quark scattering:

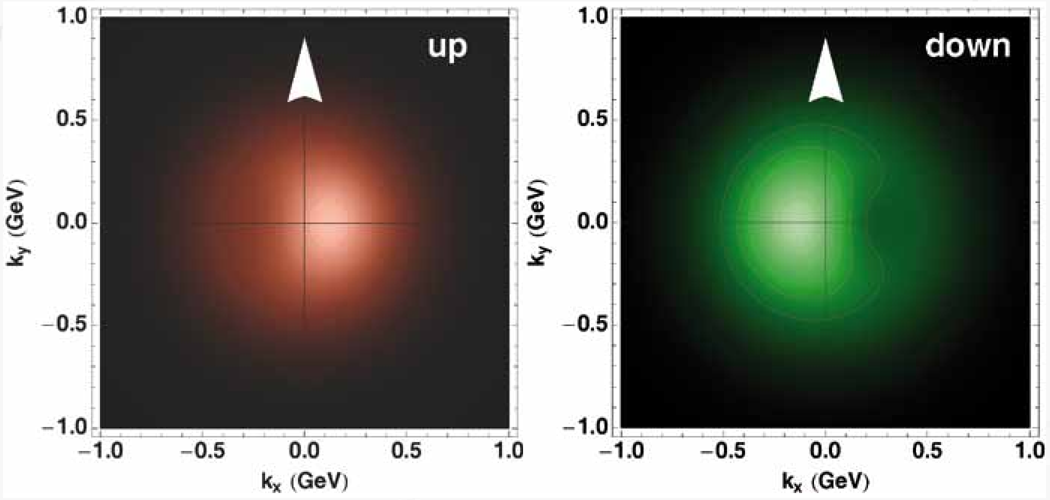
$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

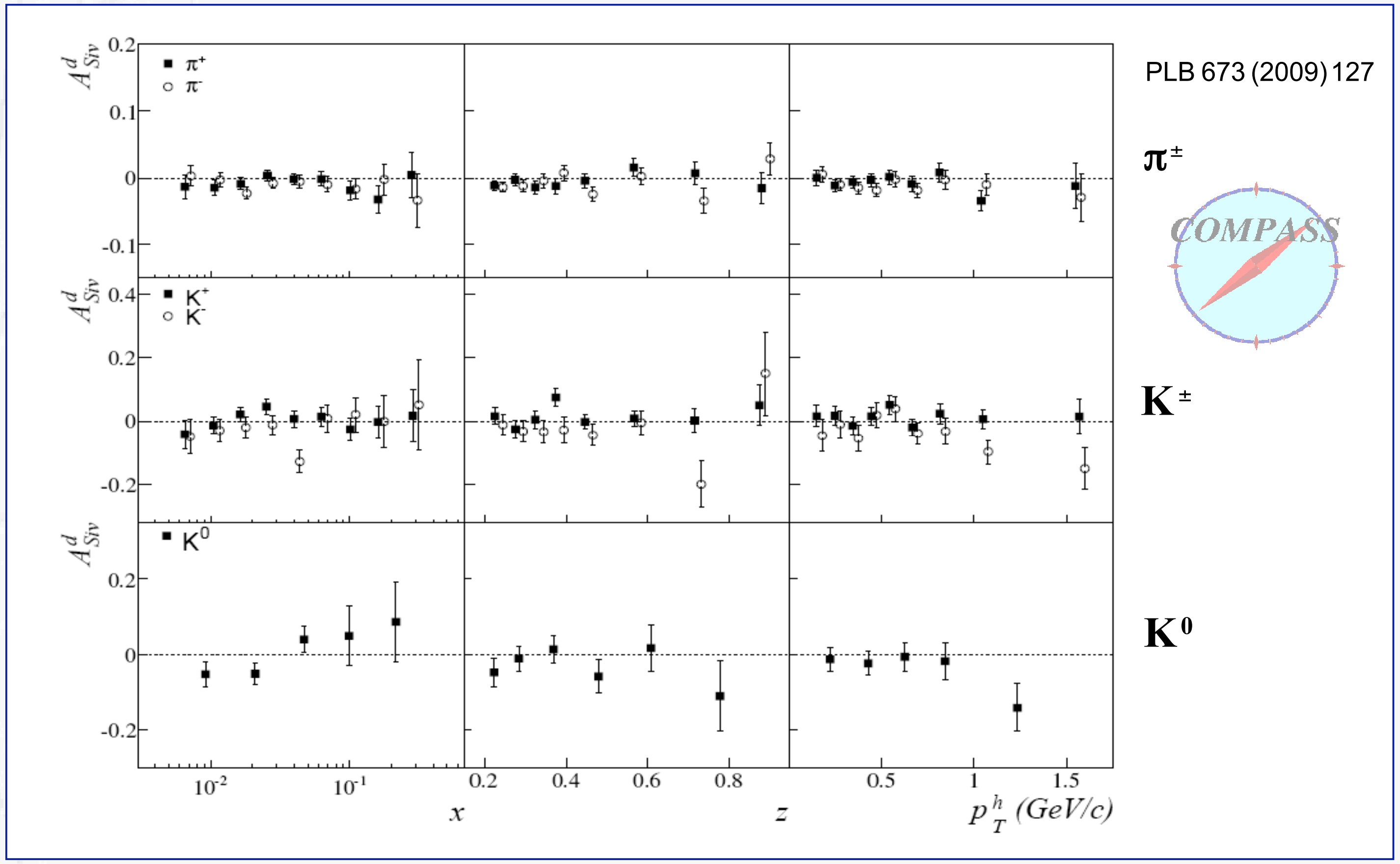
☛ d-quark Sivers DF > 0 (cancelation for π^-)

	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]

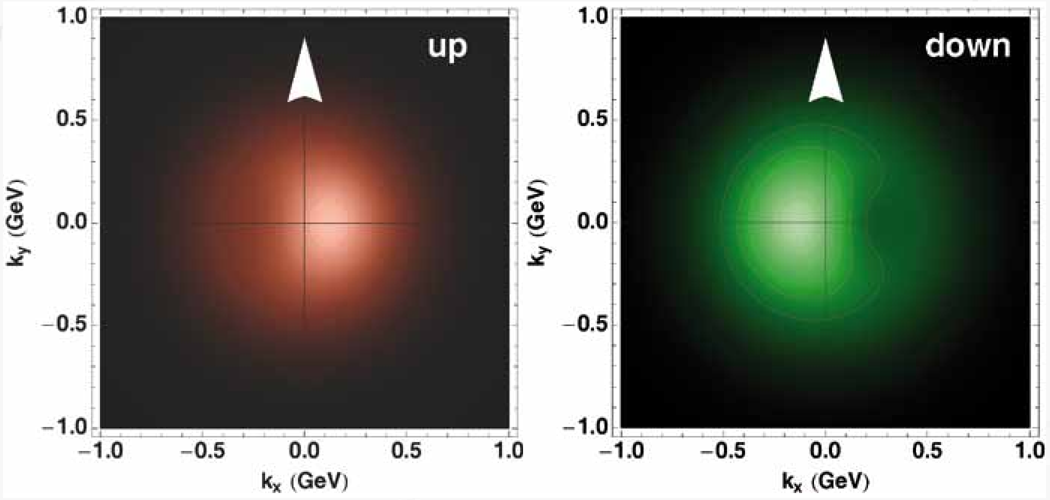


PLB 673 (2009) 127

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

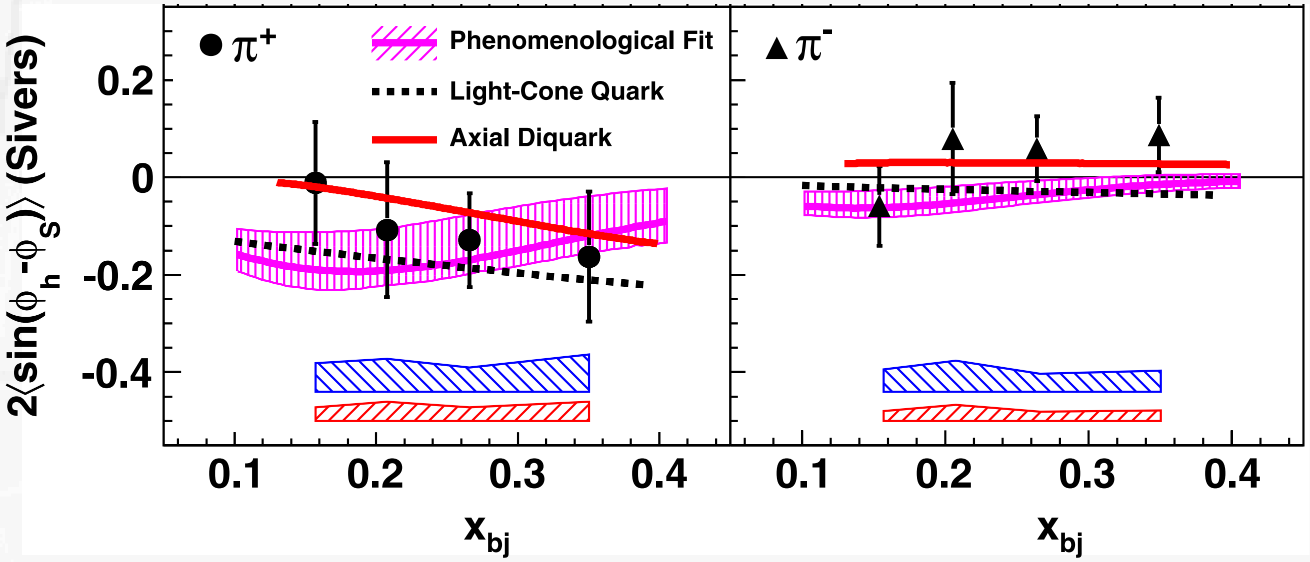
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes

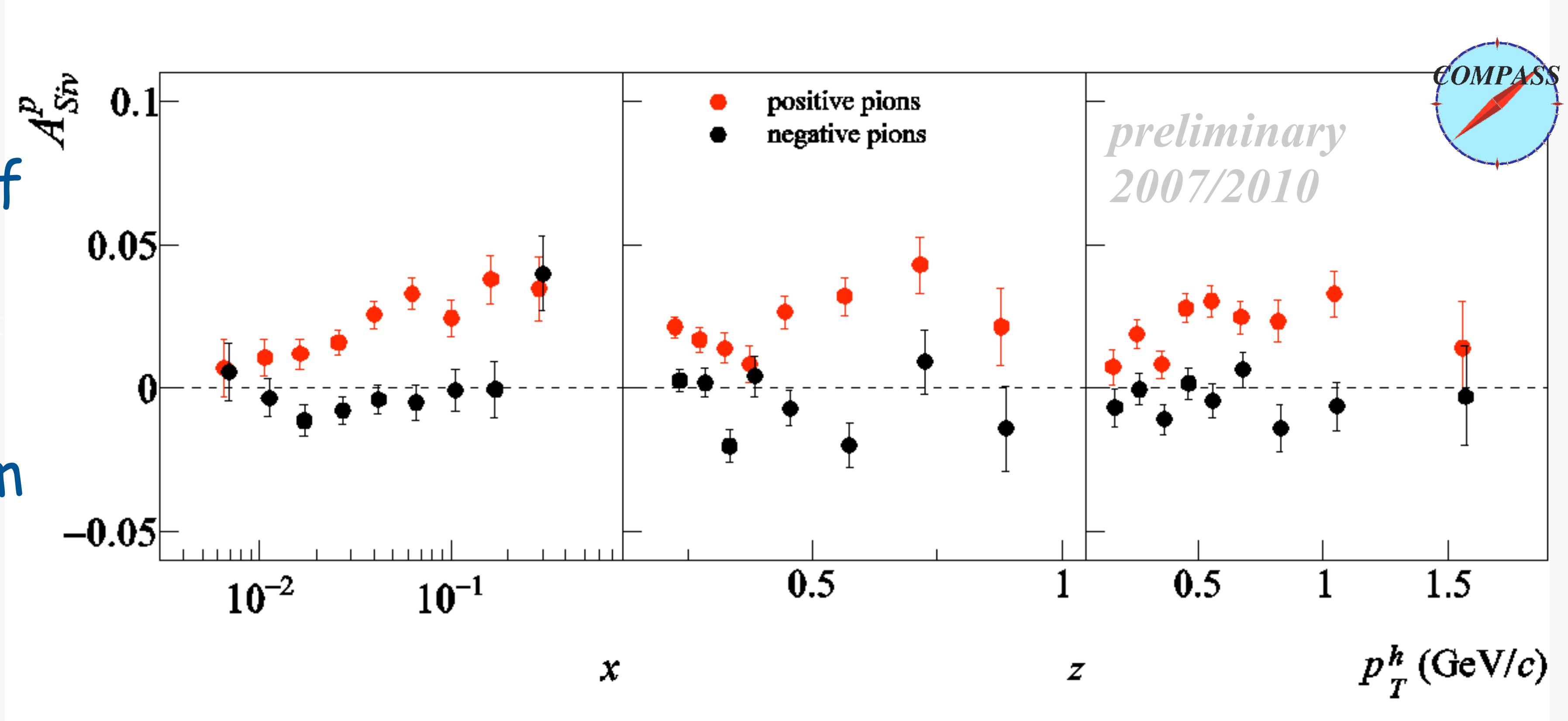


[courtesy of A. Bacchetta]

[PRL 107 (2011) 072003]



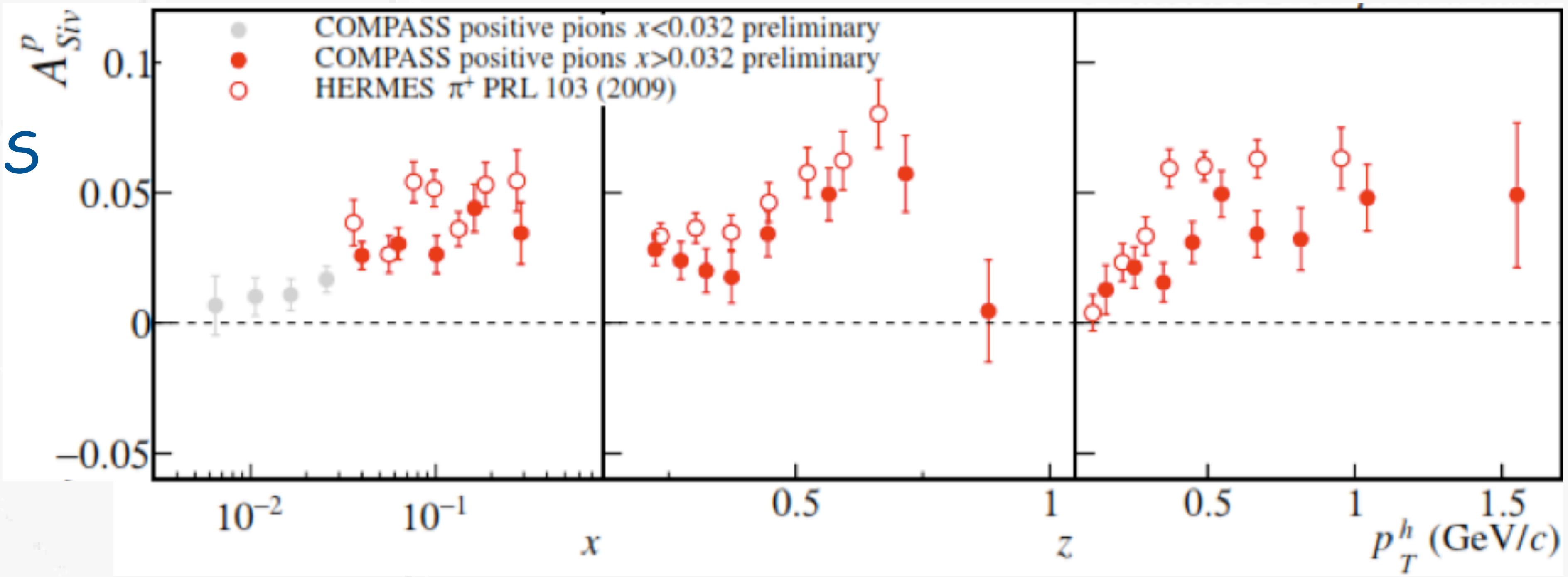
- cancelation for D target supports opposite signs of up and down Sivers
- new results from JLab using ^{3}He target and from COMPASS for proton target



	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?

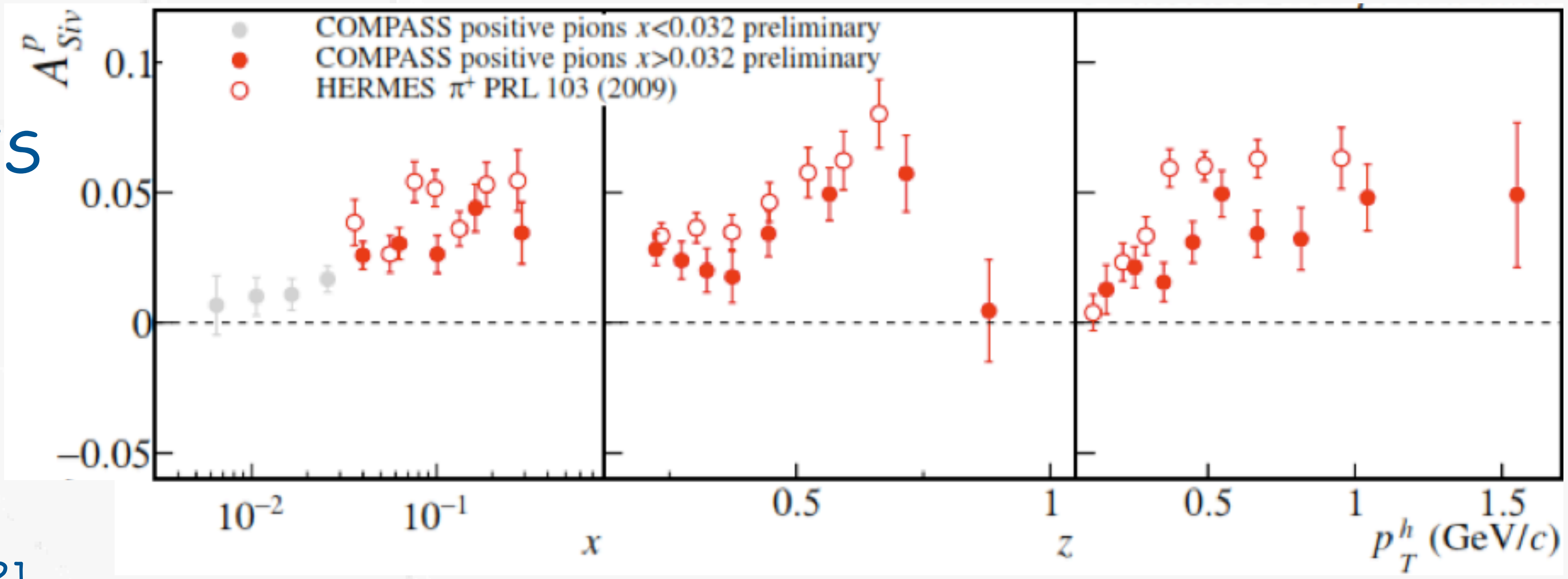
- slightly larger amplitudes at HERMES
- average Q^2 about factor 3 larger at COMPASS



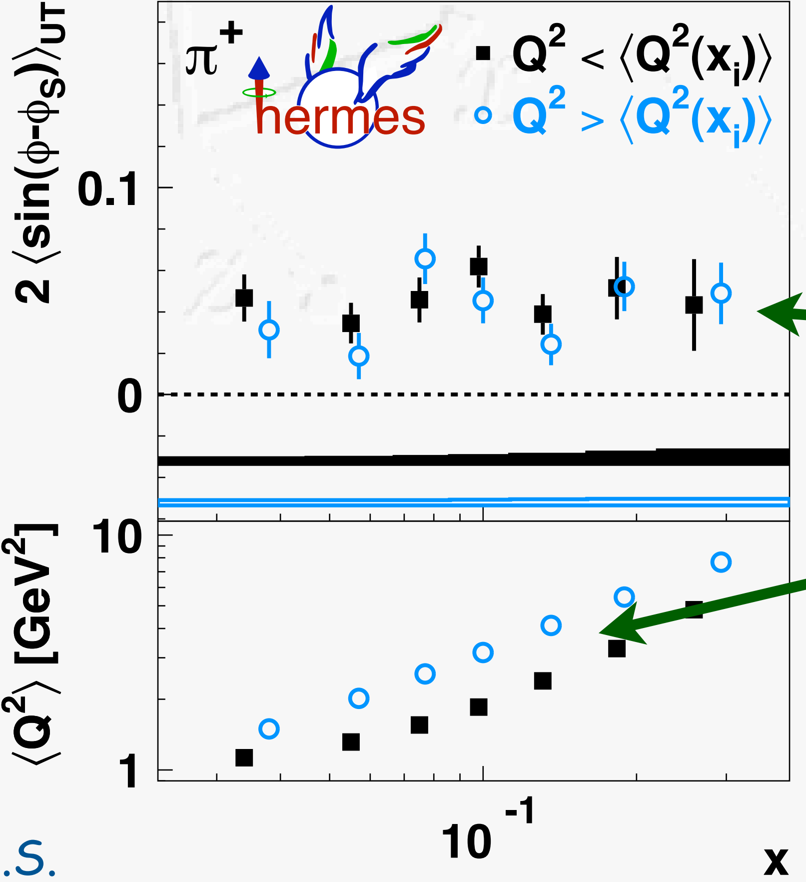
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes Q^2 dependence?

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



[PRL 103 (2009) 152002]

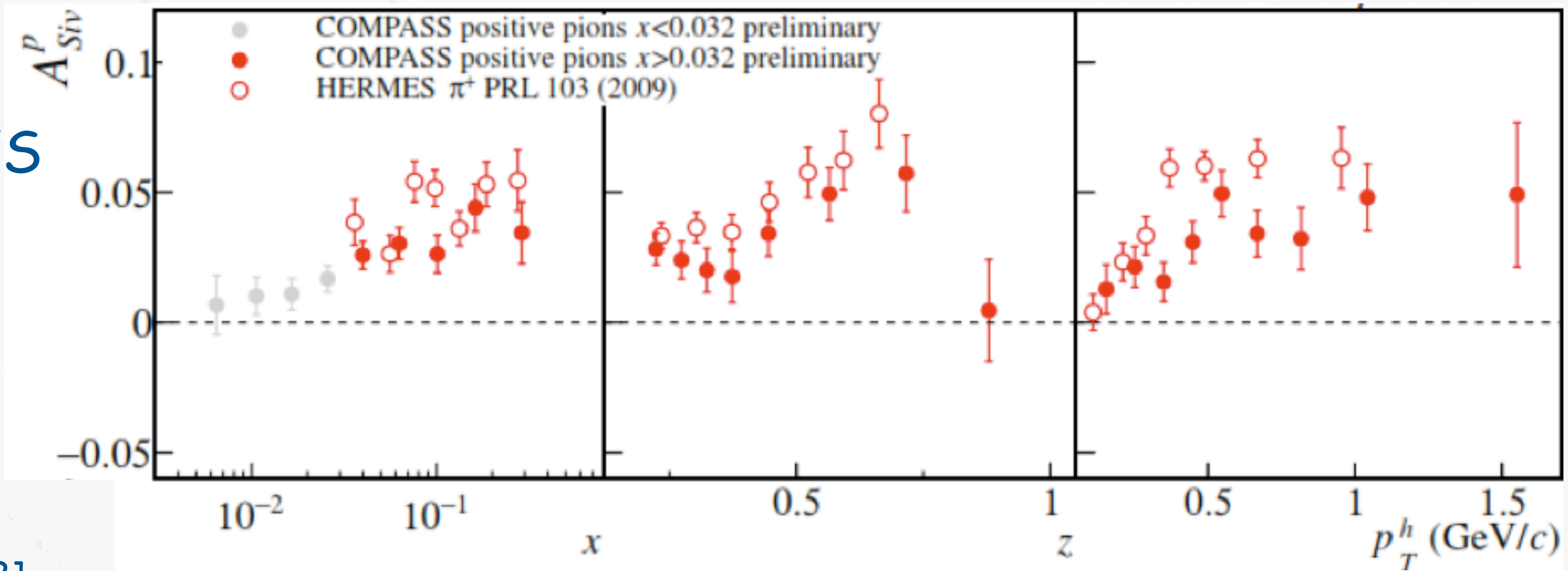


nothing seen at HERMES

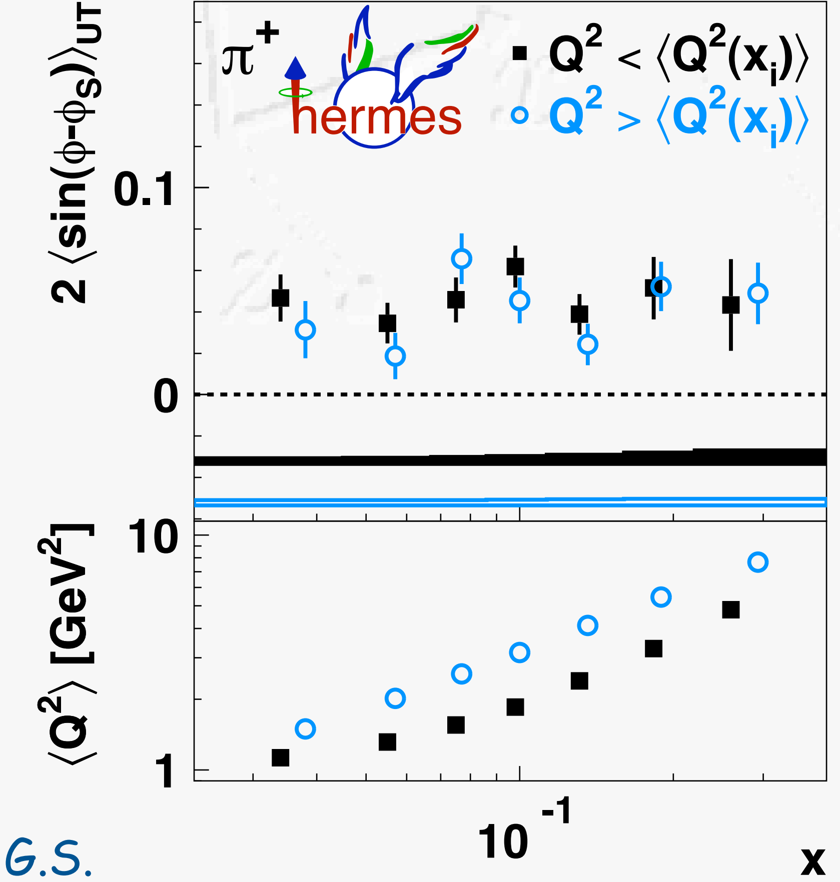
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

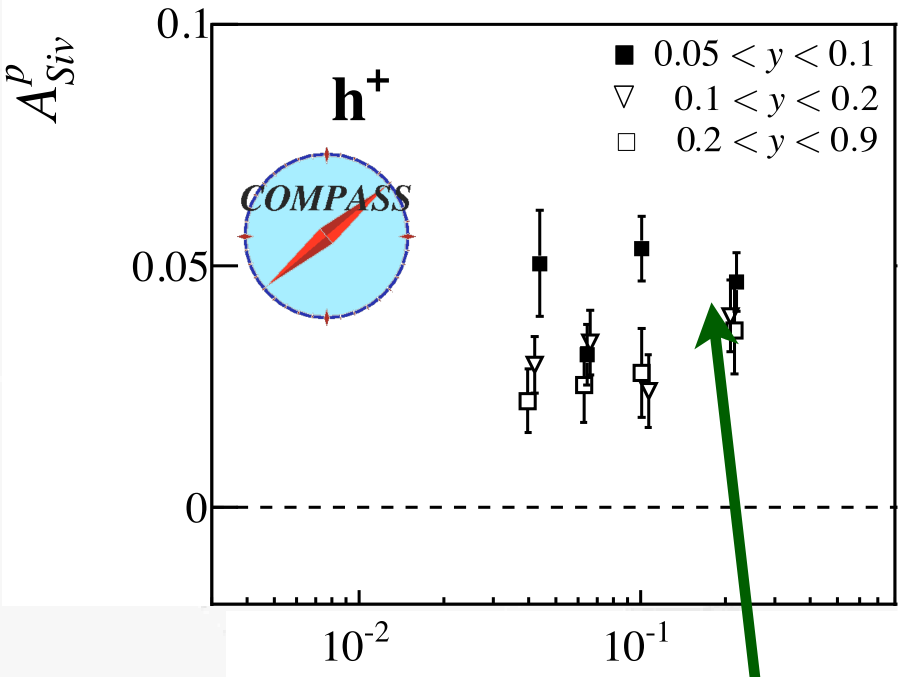
Sivers amplitudes Q^2 dependence?

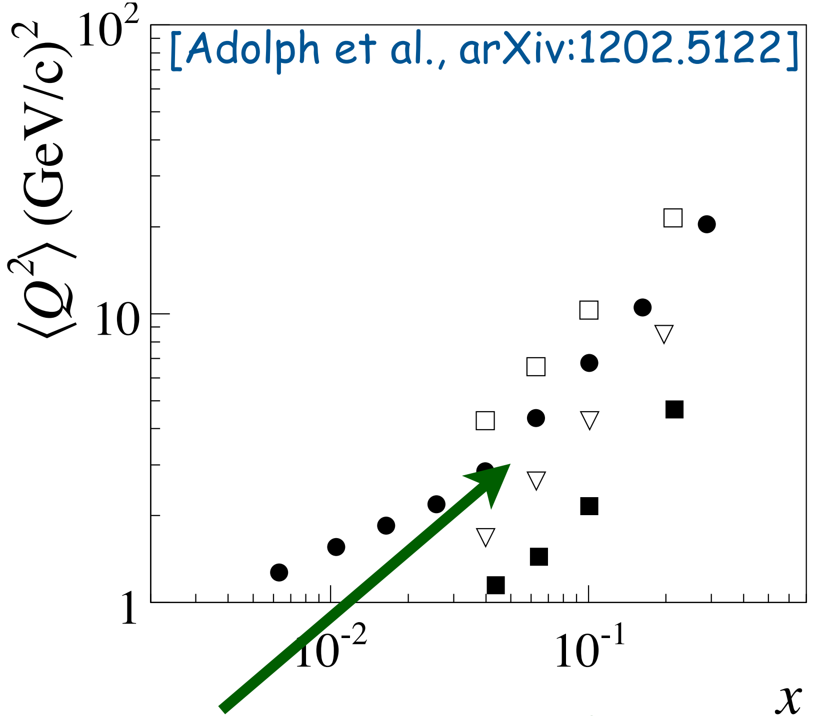
- slightly larger amplitudes at HERMES
- average Q^2 about factor 3 larger at COMPASS



[PRL 103 (2009) 152002]







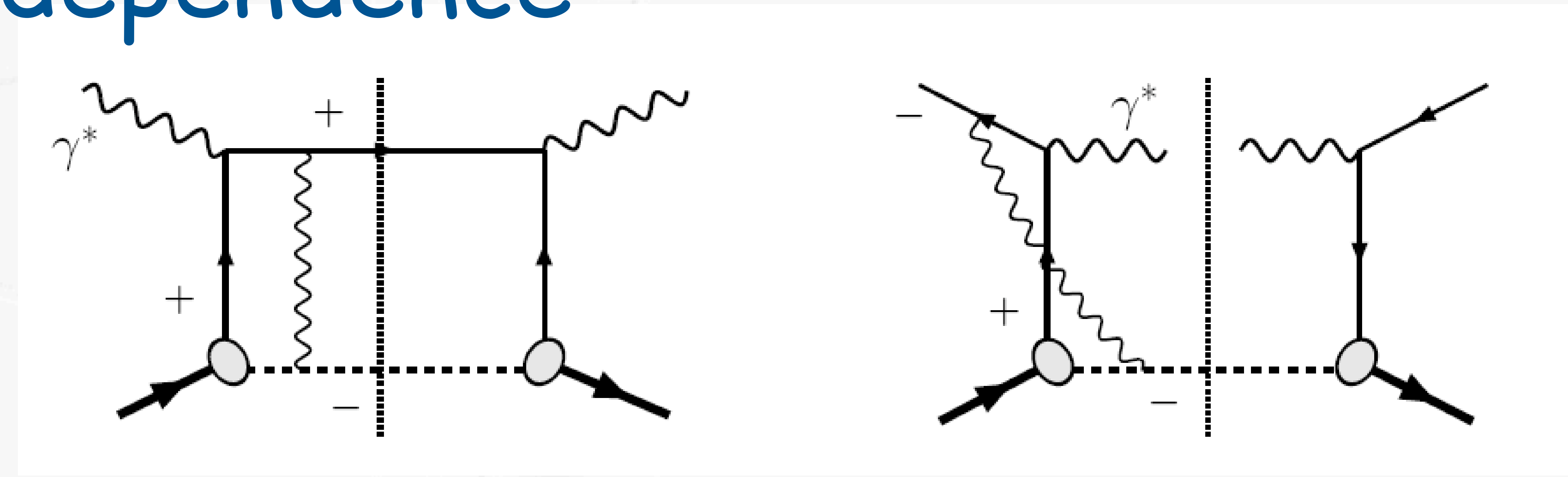
[Adolph et al., arXiv:1202.5122]

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

☛ M. Boglione

Process dependence

simple QED
example

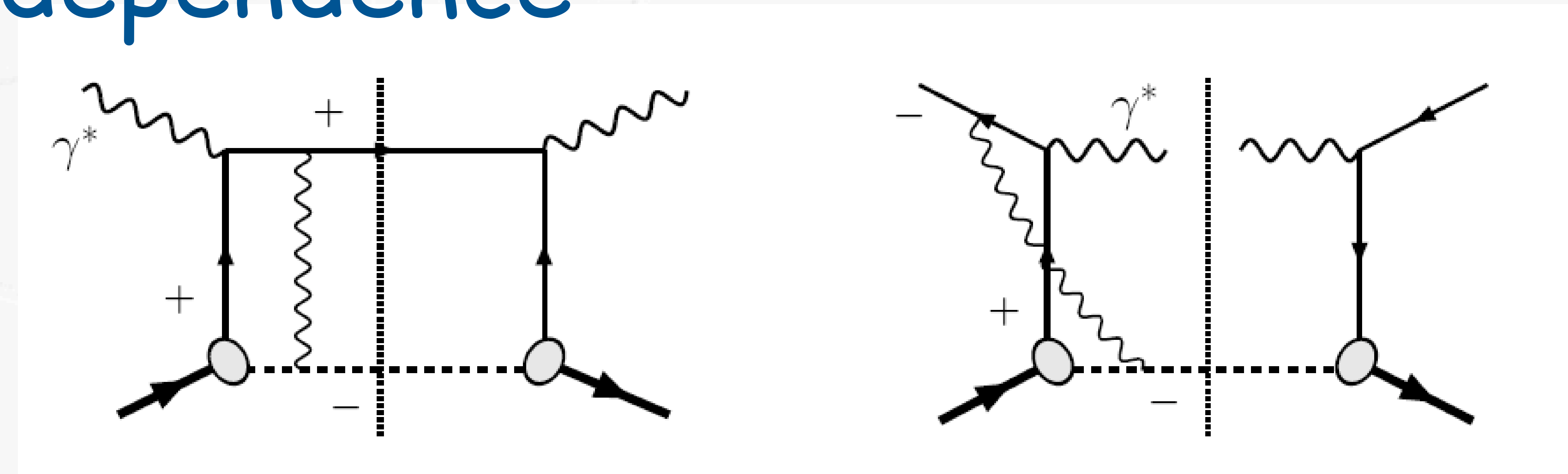


DIS: attractive

Drell-Yan: repulsive

Process dependence

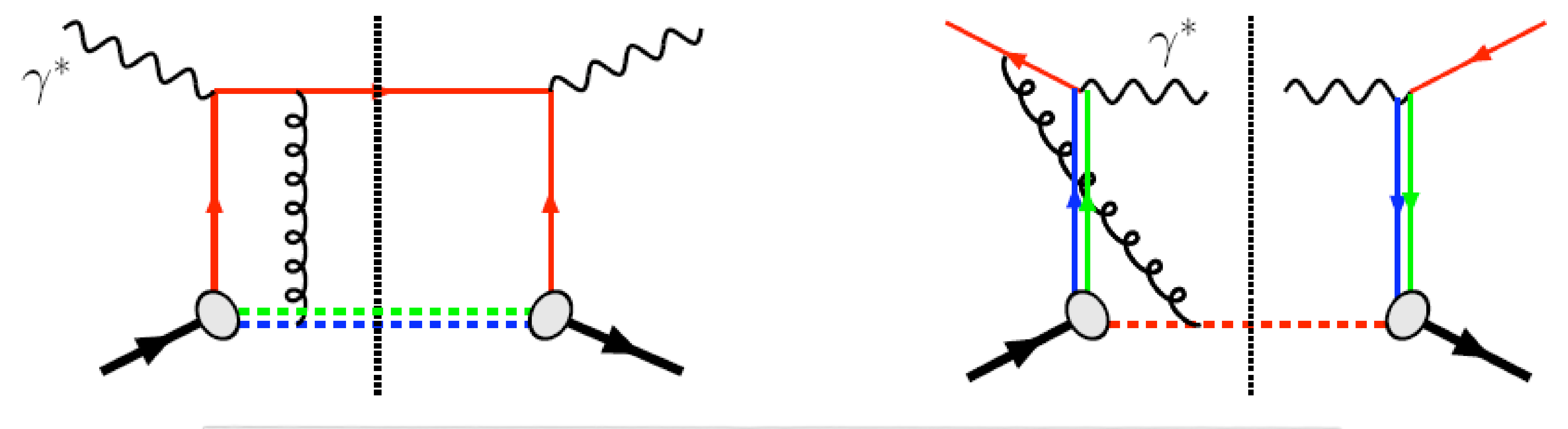
simple QED
example



DIS: attractive

Drell-Yan: repulsive

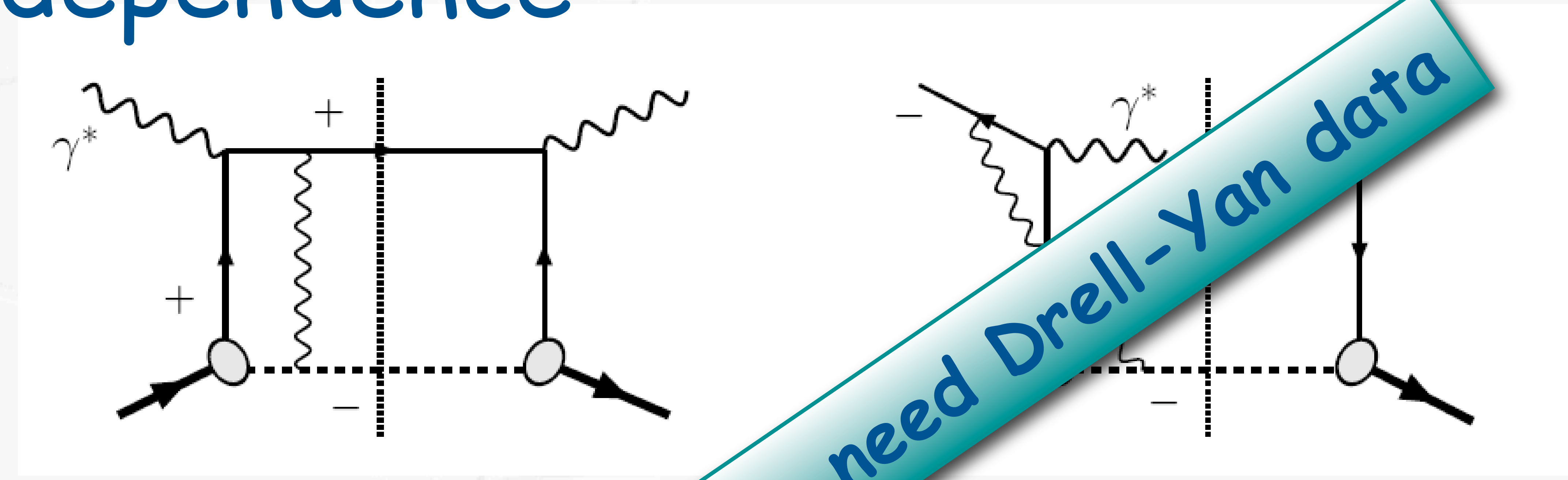
add color:
QCD



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

Process dependence

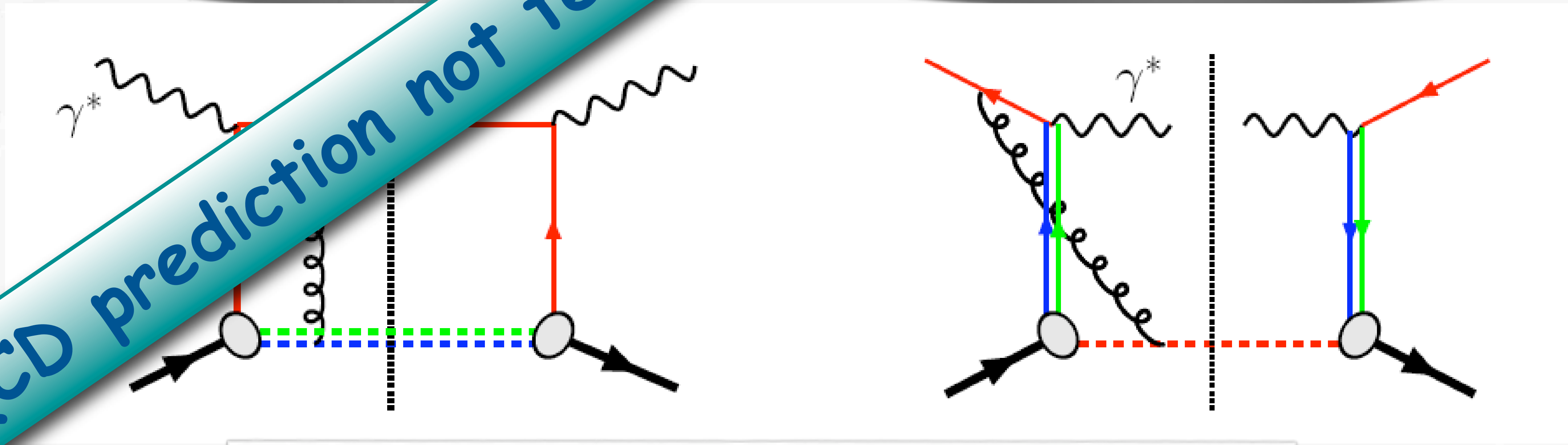
simple QED
example



DIS: attracti

Drell-Yan: repulsive

add color:
QCD



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

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

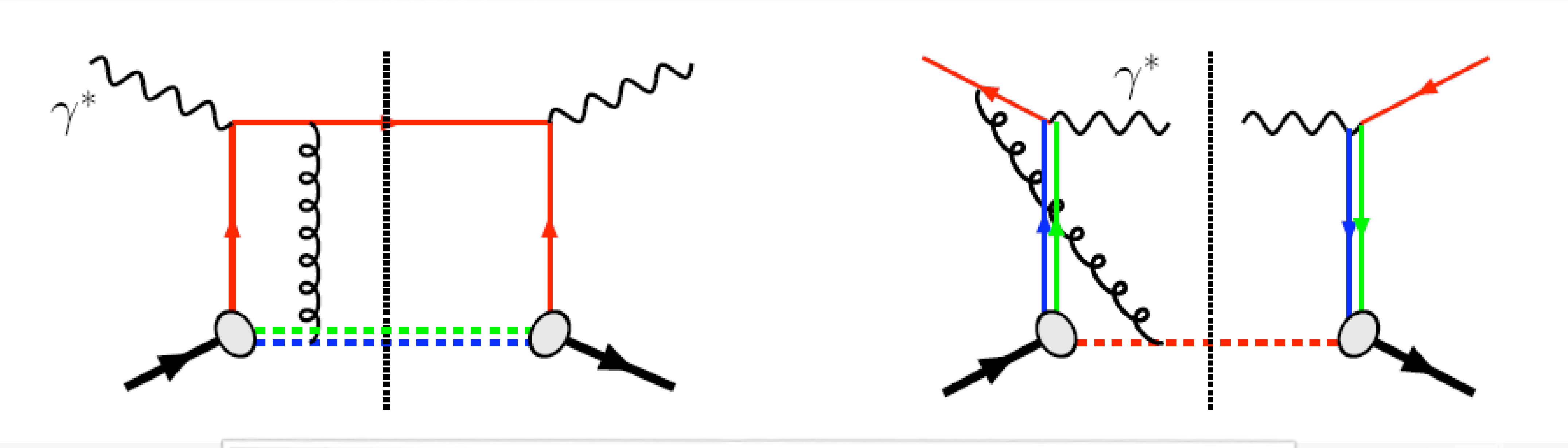
Process dependence

need Drell-Yan experiments with transverse polarization:

COMPASS, transverse SeaQuest, RHIC, … ☛ C. Riedl

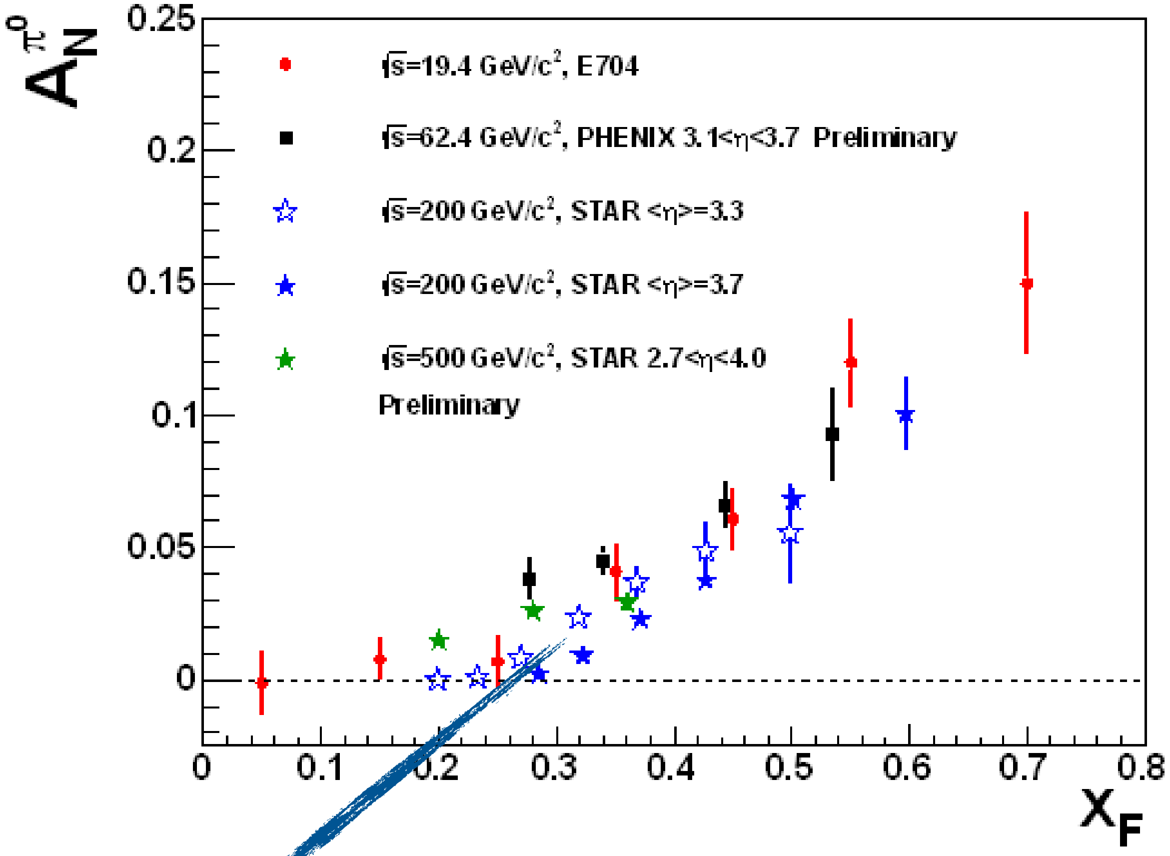
add color:

QCD



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

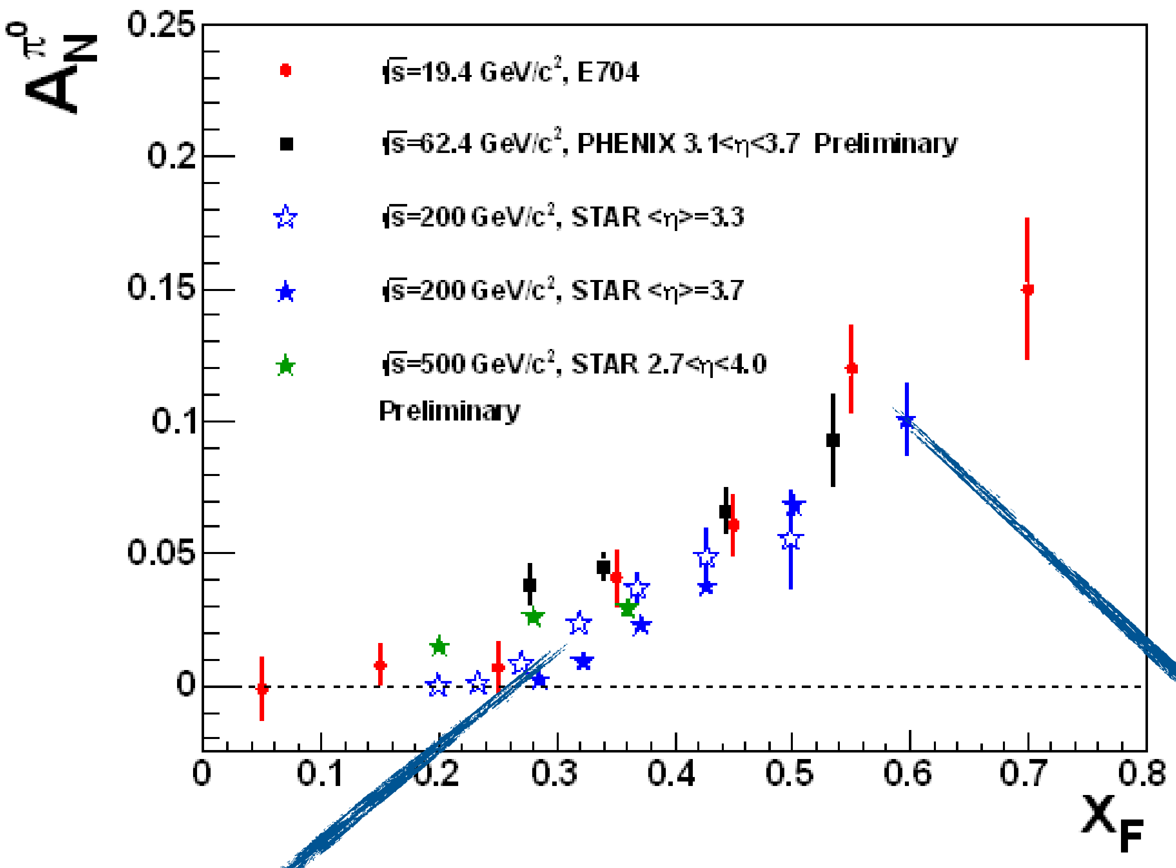
$p^{\uparrow}p \rightarrow \pi X$



“generalized parton model”

no rigorous TMD factorization!

$p^{\uparrow}p \to \pi X$



“generalized parton model”

no rigorous TMD factorization!

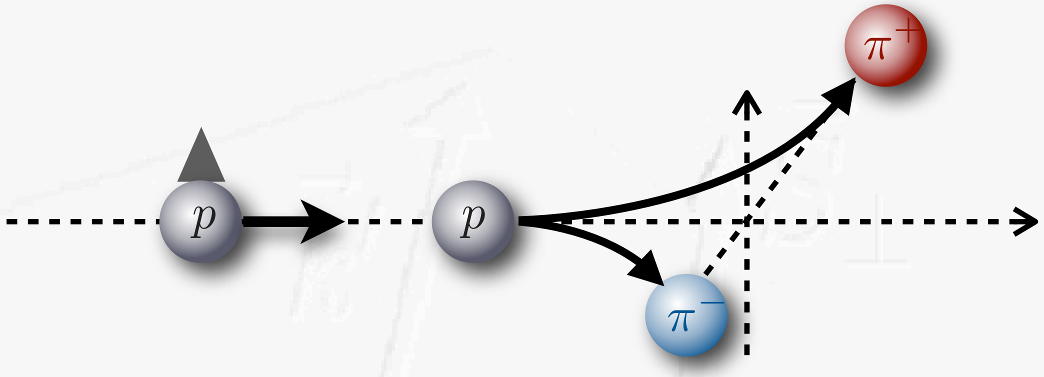
collinear twist-3

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$

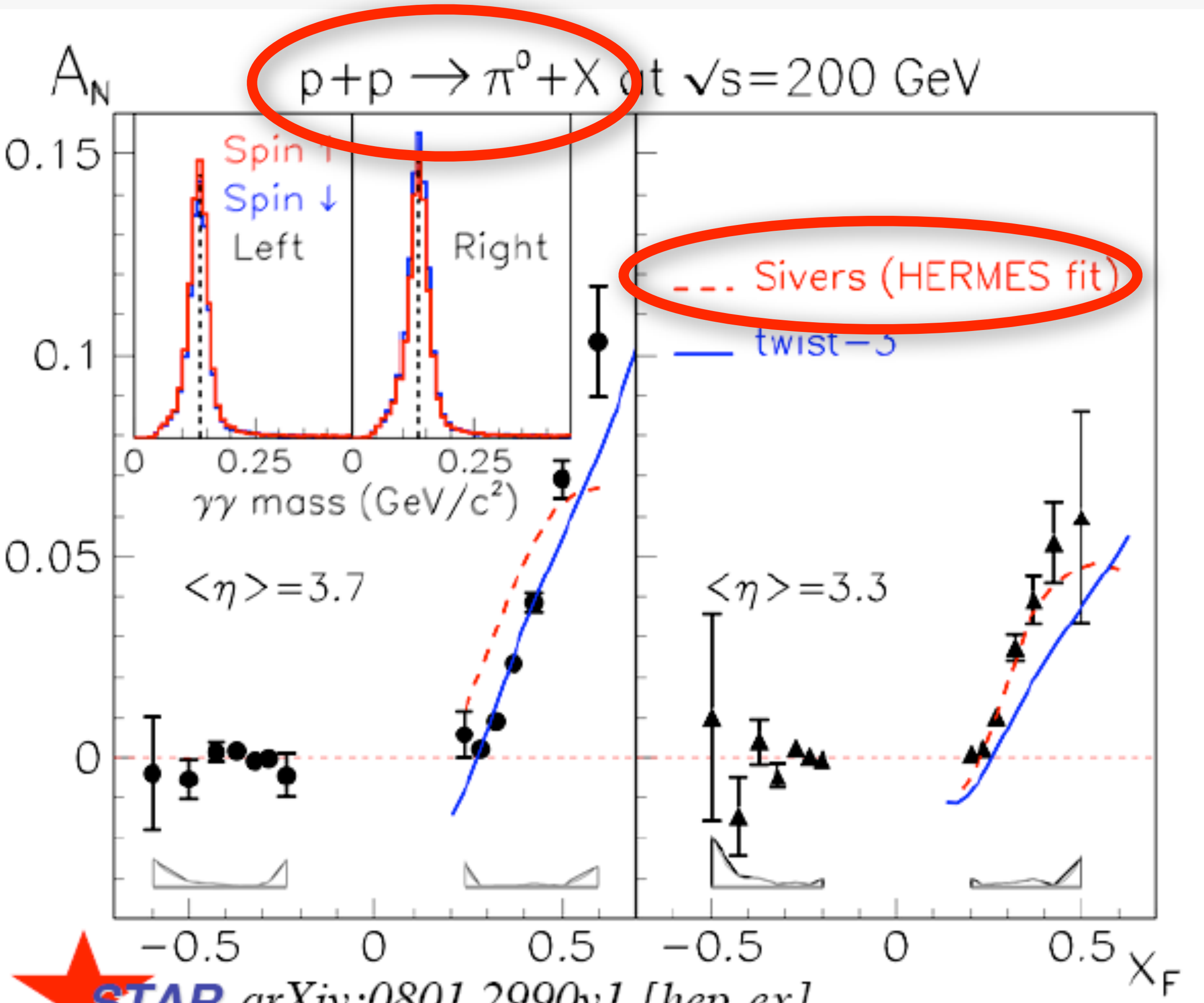
TMD factorization

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

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



- Sivers fit to HERMES data nicely described A_N in pp

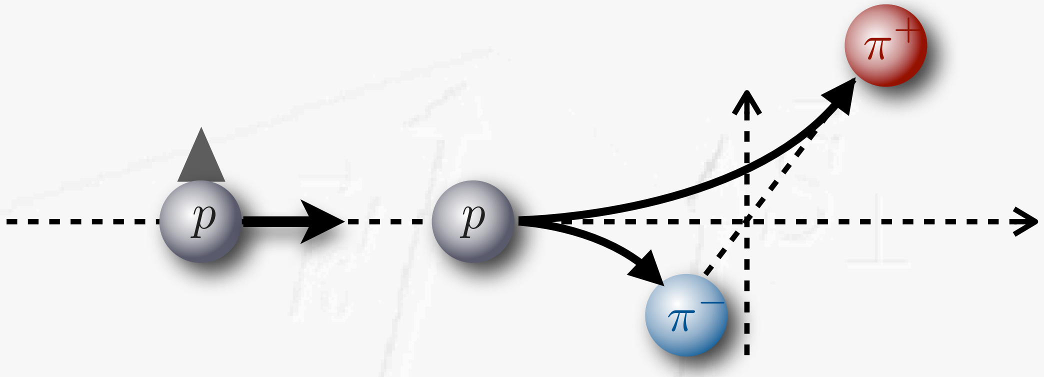


STAR *arXiv:0801.2990v1 [hep-ex]*

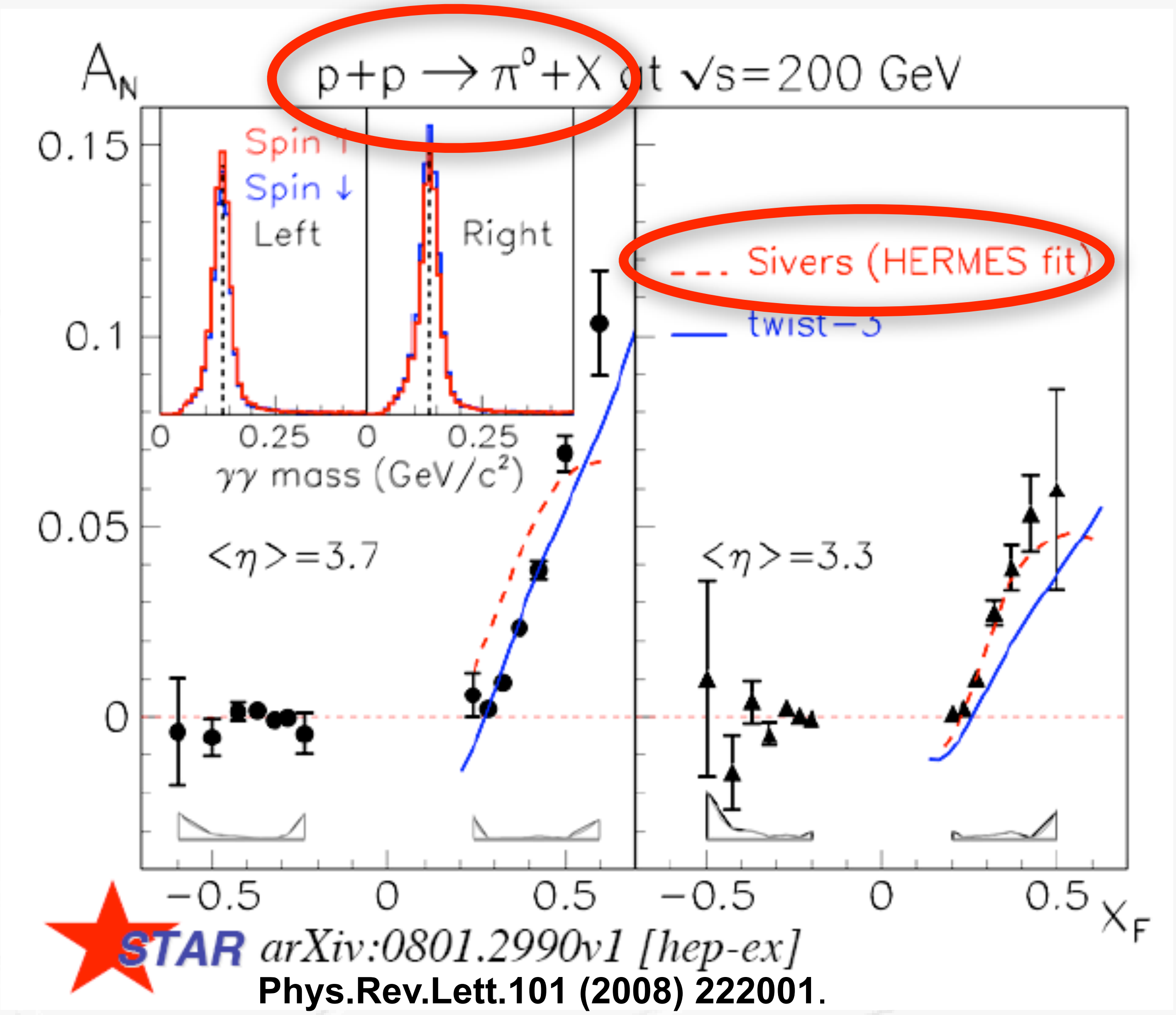
Phys.Rev.Lett.101 (2008) 222001.

$p^{\uparrow}p \to \pi X$

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



- Sivers fit to HERMES data nicely described A_N in pp
- may also originate from Collins effect or twist-3 effects

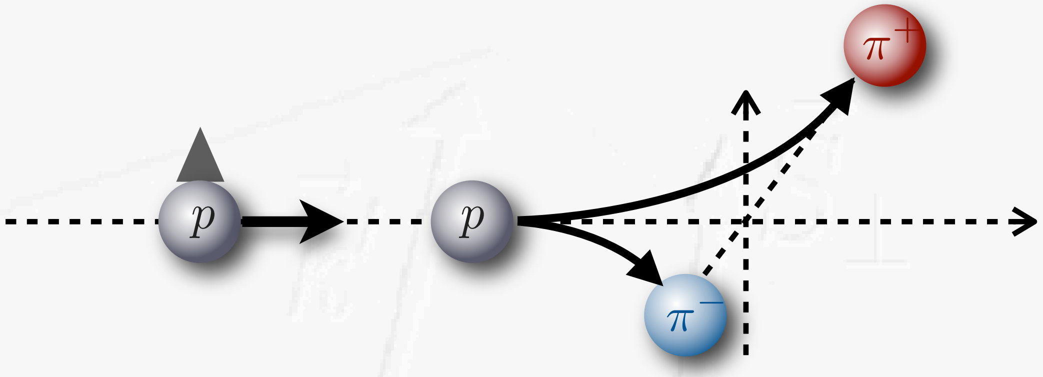


STAR arXiv:0801.2990v1 [hep-ex]

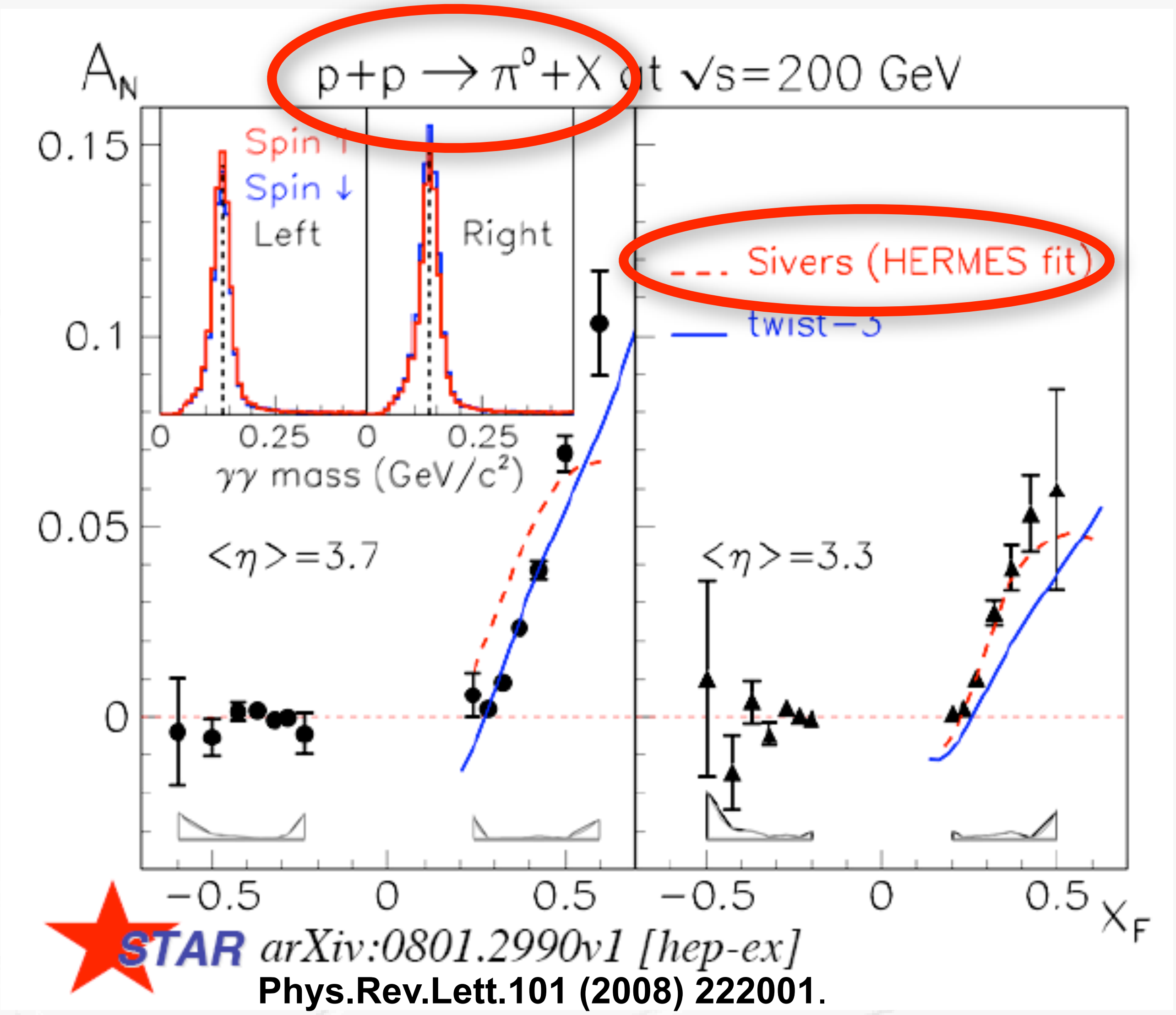
Phys.Rev.Lett.101 (2008) 222001.

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

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



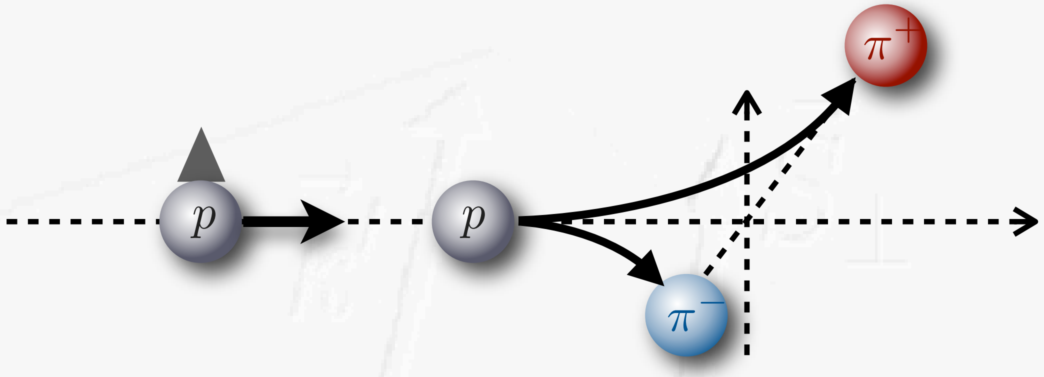
- Sivers fit to HERMES data nicely described A_N in pp
- may also originate from Collins effect or twist-3 effects
- only sizable in forward direction



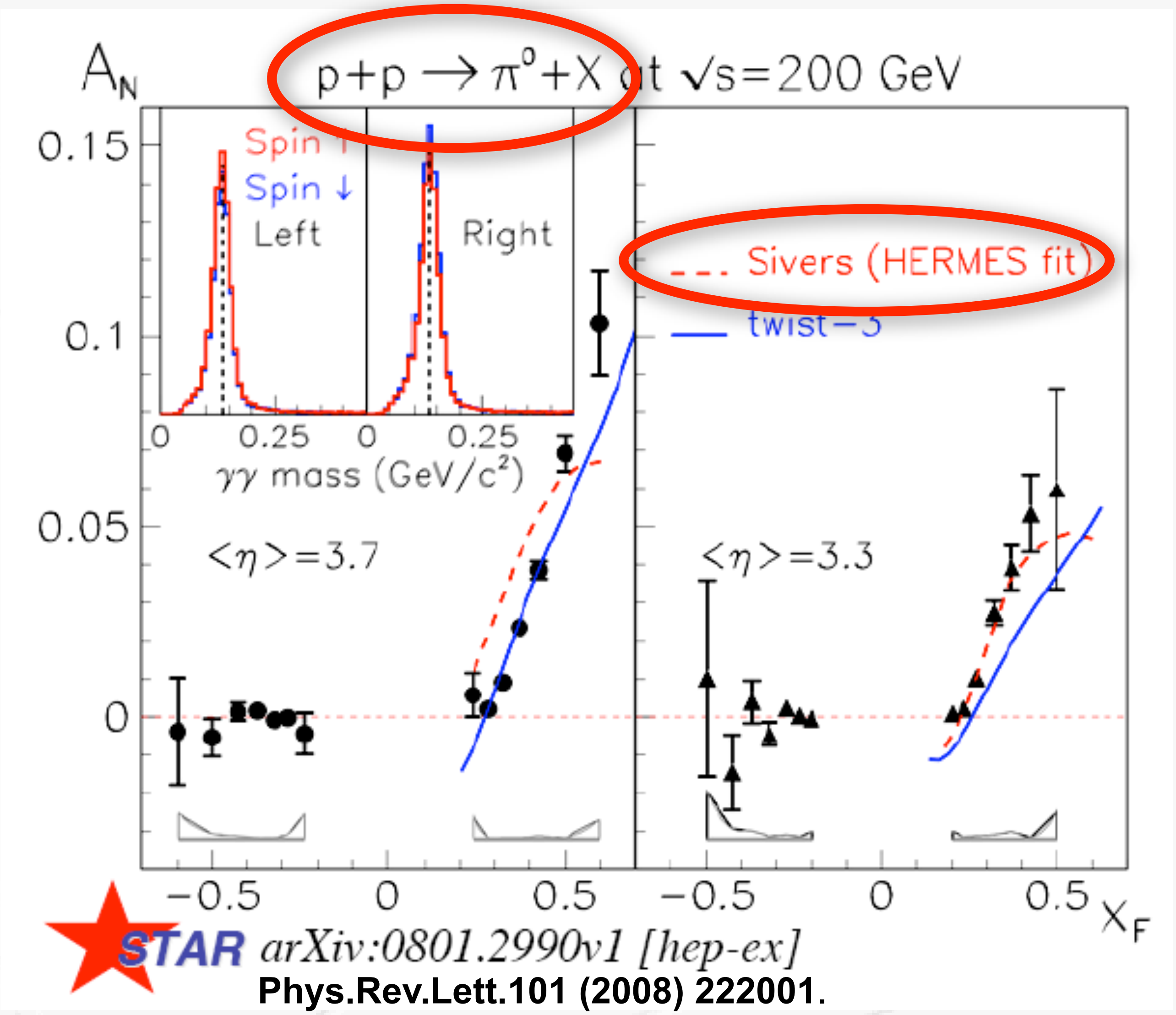
STAR *arXiv:0801.2990v1 [hep-ex]*
Phys.Rev.Lett.101 (2008) 222001.

$p^{\uparrow}p \to \pi X$

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



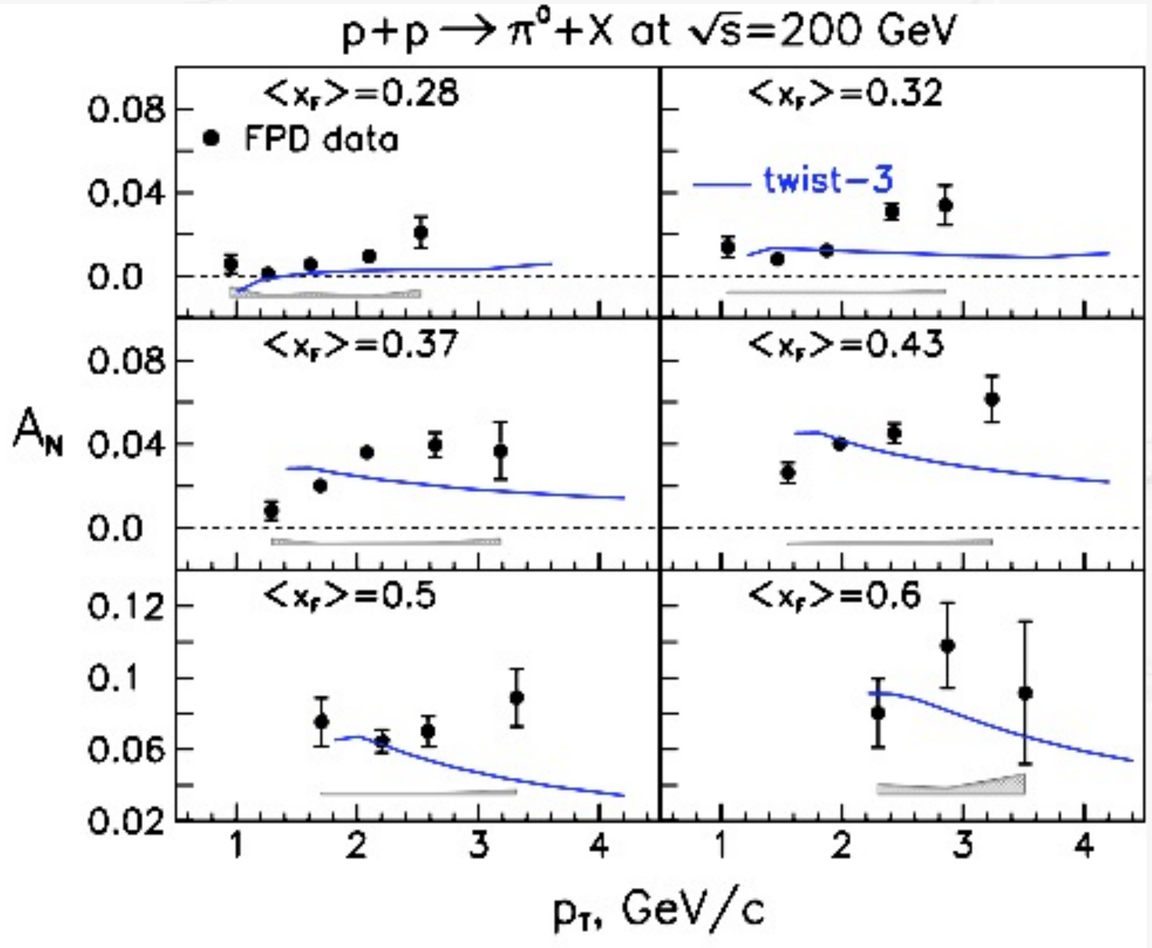
- Sivers fit to HERMES data nicely described A_N in pp
- may also originate from Collins effect or twist-3 effects
- only sizable in forward direction
- after early success of linking twist-3 with Sivers, sign mismatch discovered:



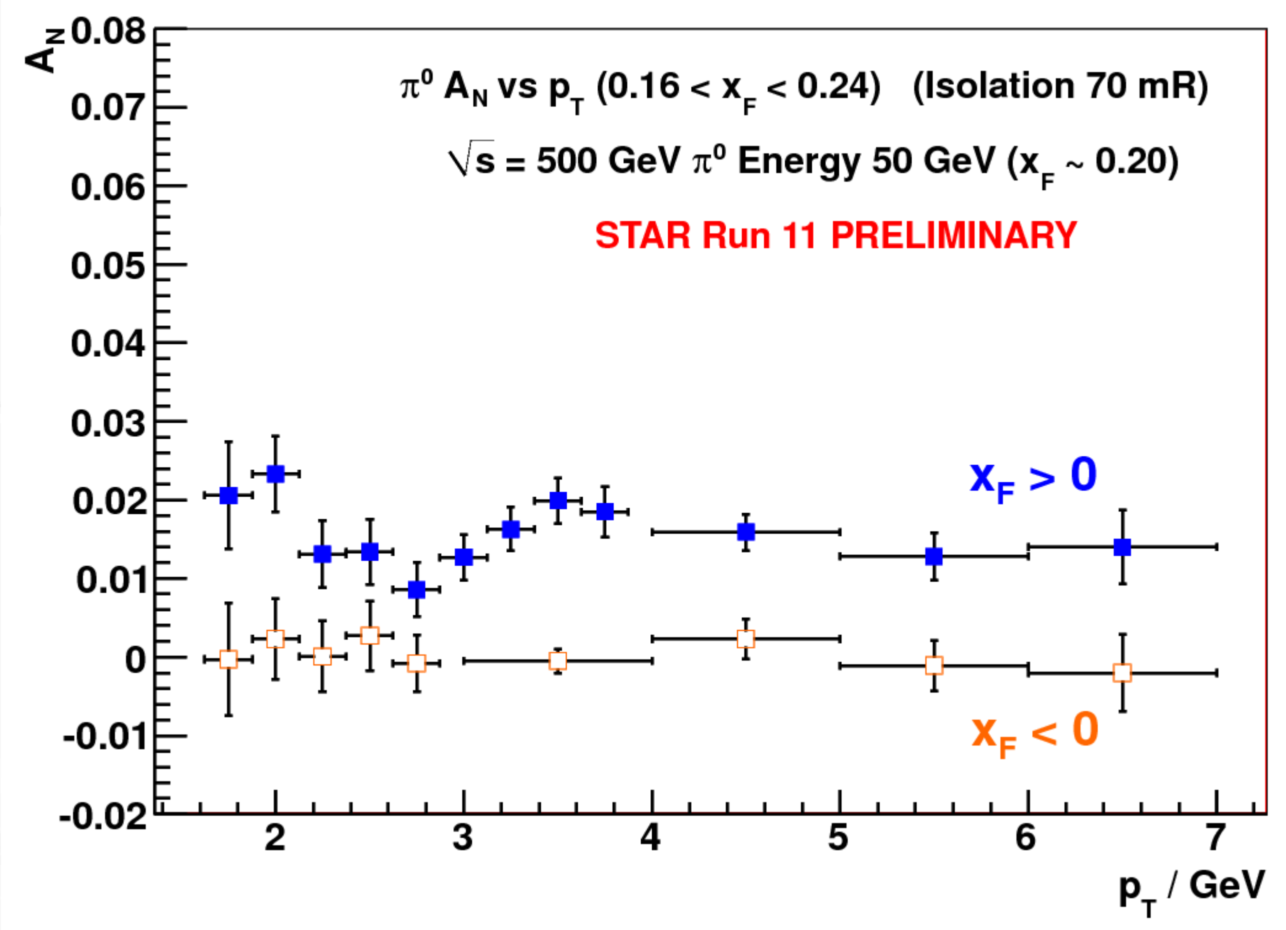
STAR arXiv:0801.2990v1 [hep-ex]
Phys.Rev.Lett.101 (2008) 222001.

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)\,|_{\text{SIDIS}}$$

$p^{\uparrow}p \rightarrow \pi X$ - p_T dependence



STAR, PRL 101 (2008) 222001

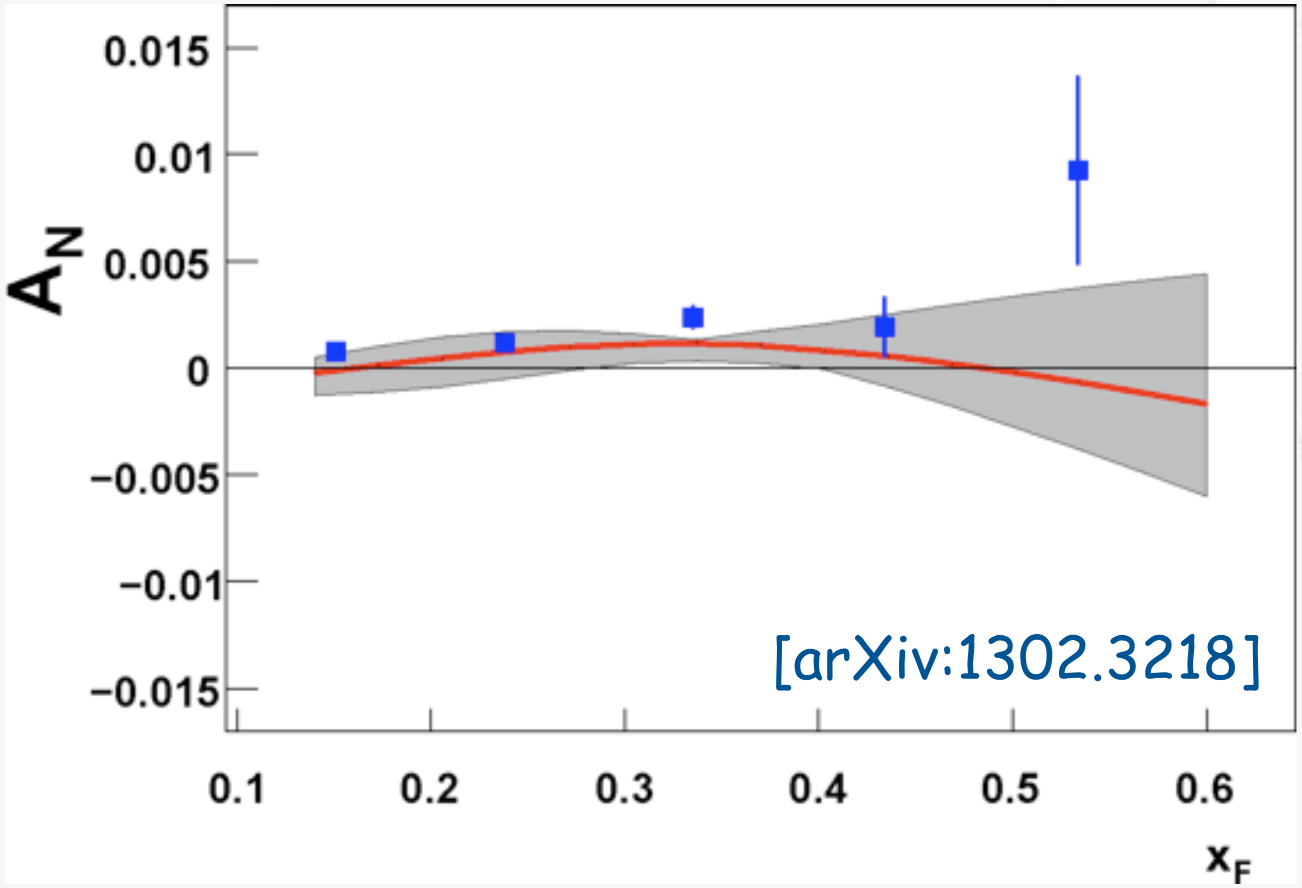


- clean approach: collinear twist-3
  - but expected p_T fall-off not seen; or at least it's very slow

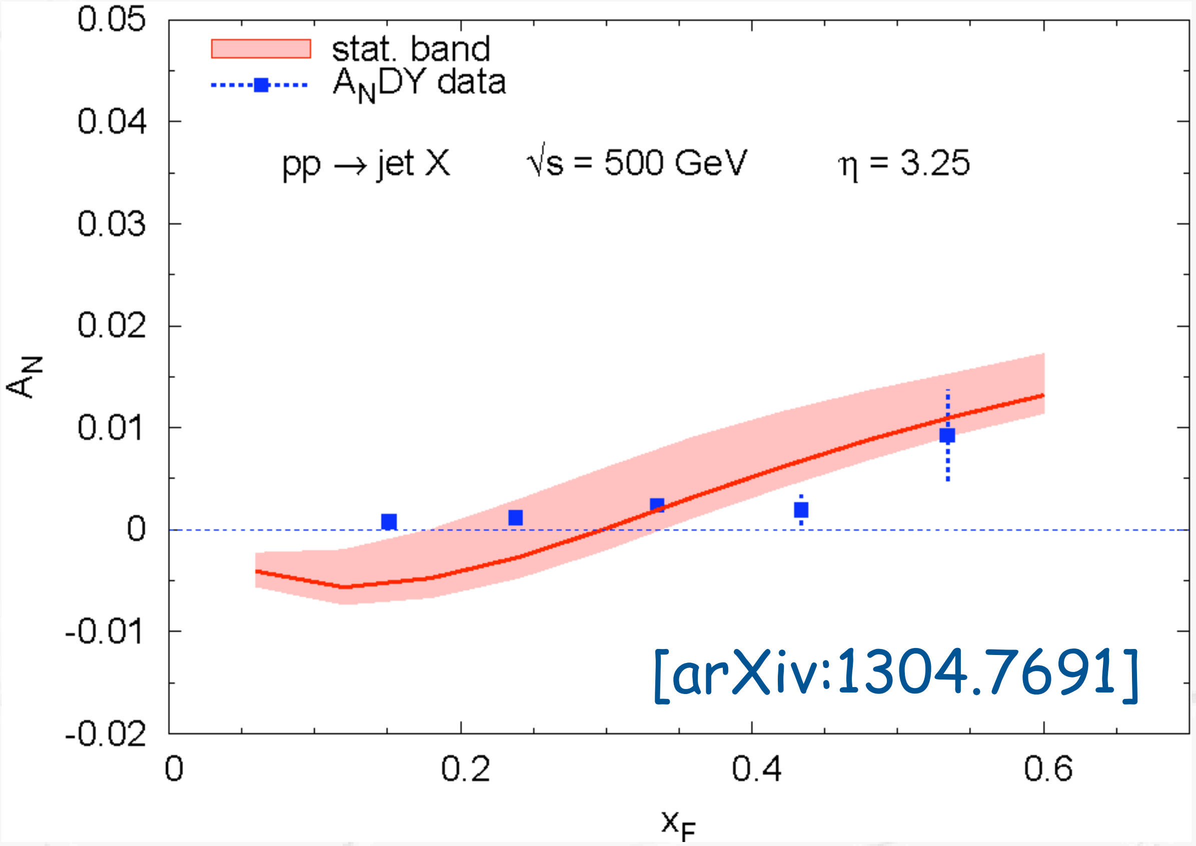
… not quite Drell-Yan yet: jet SSA

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

data from [A$_N$DY Collaboration, arXiv:1304.1454]



[arXiv:1302.3218]



[arXiv:1304.7691]

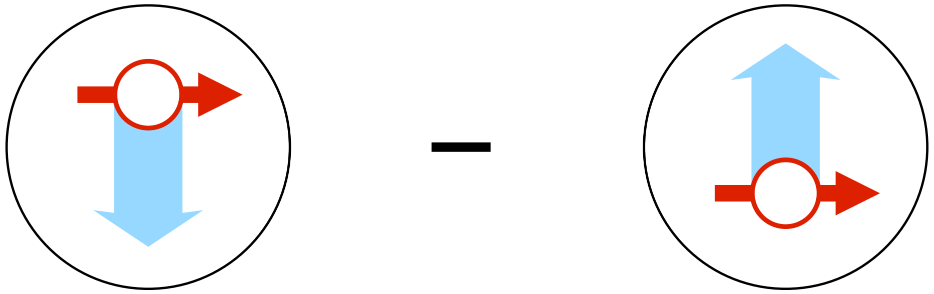
Includes initial- and final-state color-charge interactions

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

Excludes initial- and final-state color-charge interactions

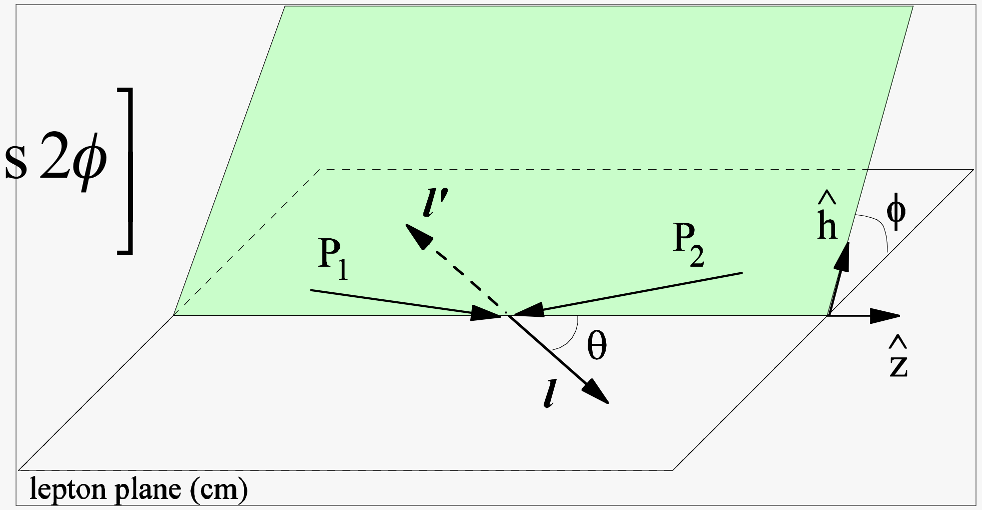
Boer-Mulders

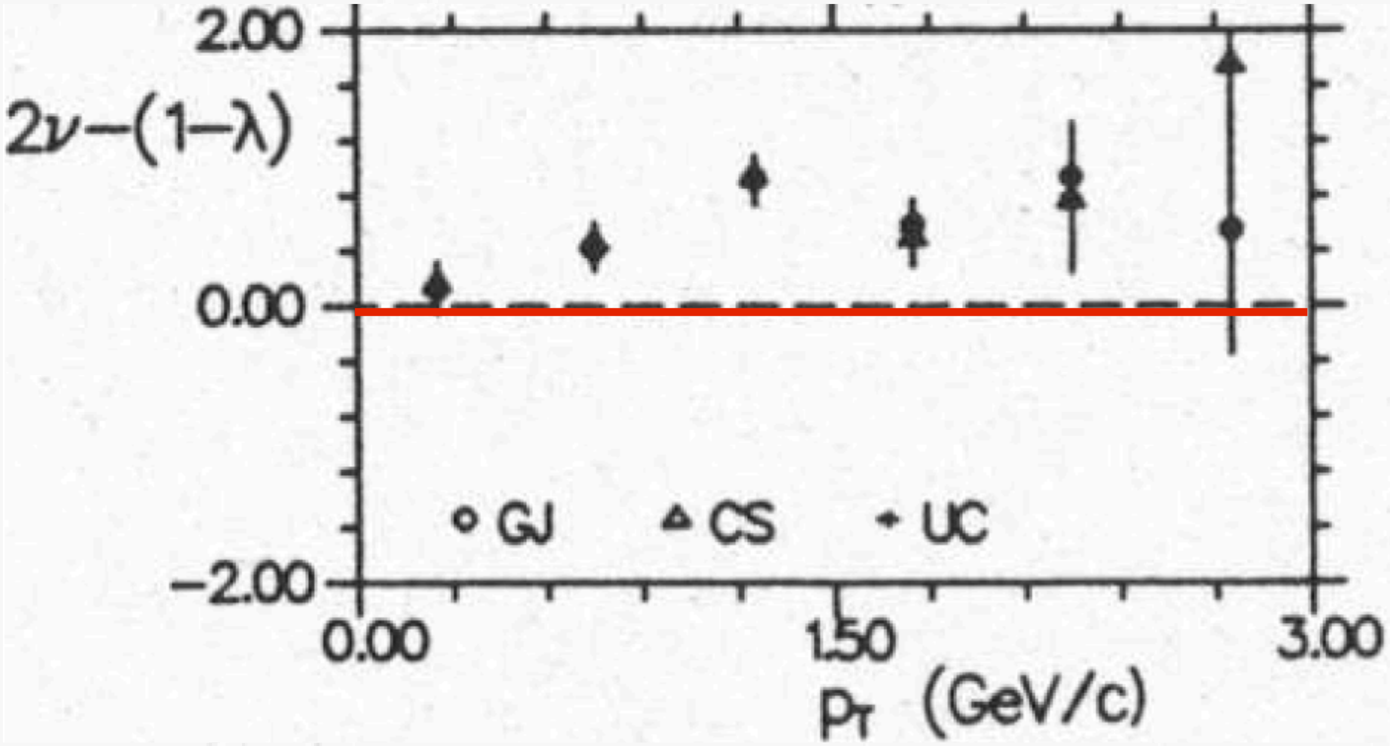
spin-effects in unpolarized reactions



Unpolarized Drell-Yan

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





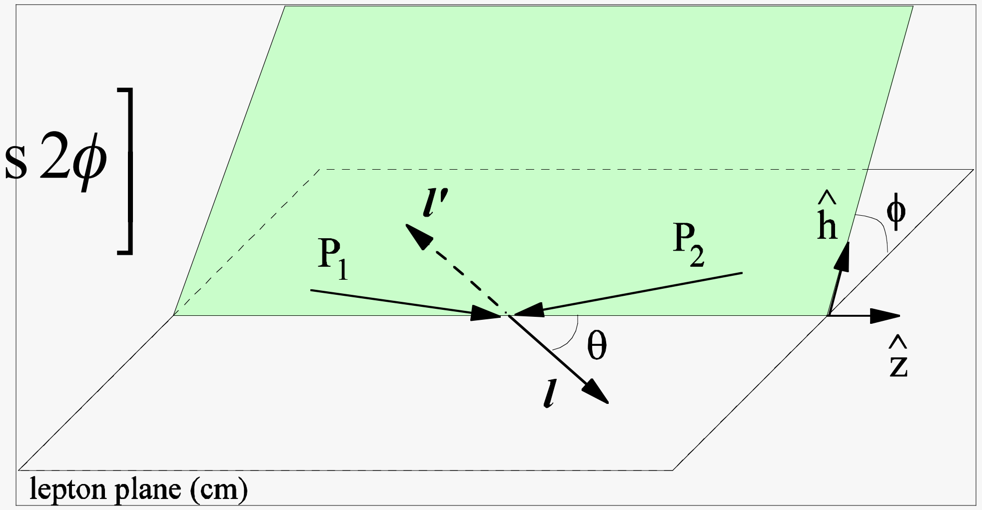
$$\boxed{1-\lambda-2\nu=0}$$

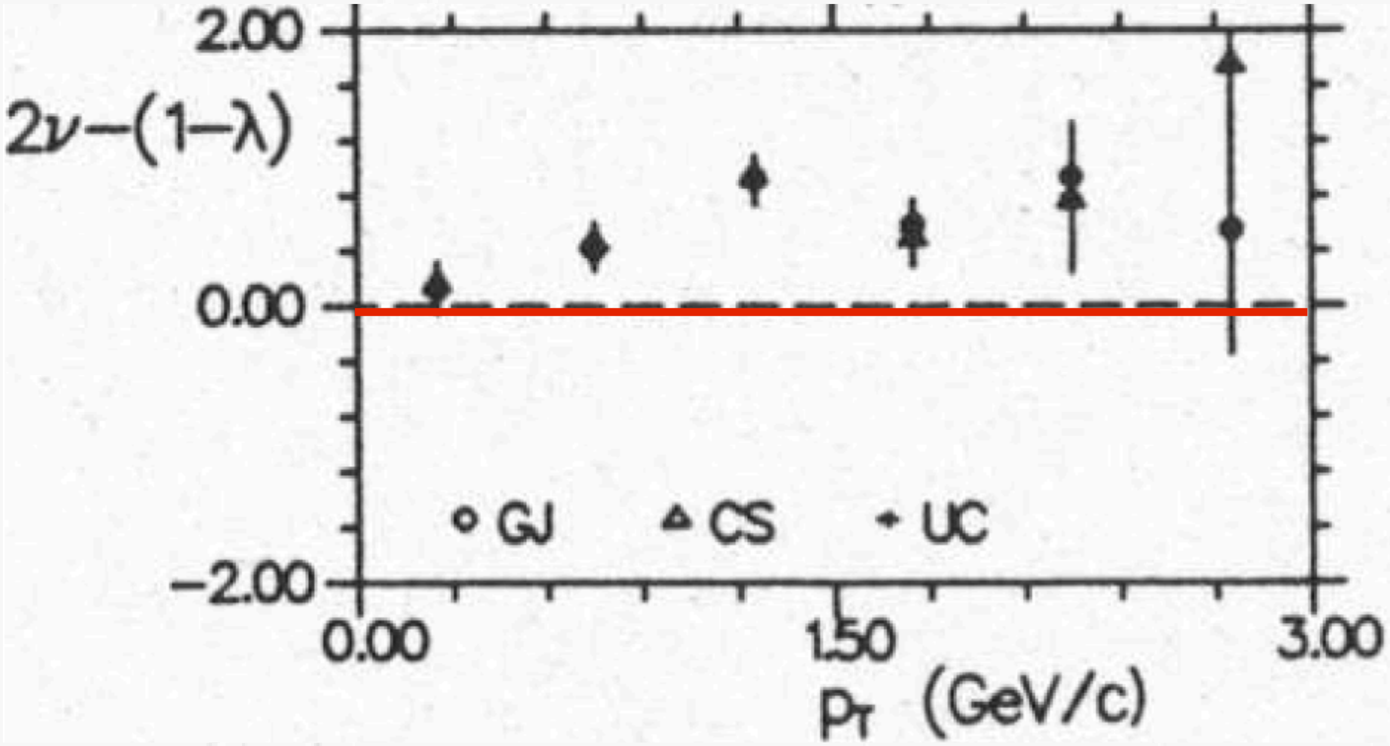
Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

☛ C. Riedl

Unpolarized Drell-Yan

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





$$\boxed{1-\lambda-2\nu=0}$$

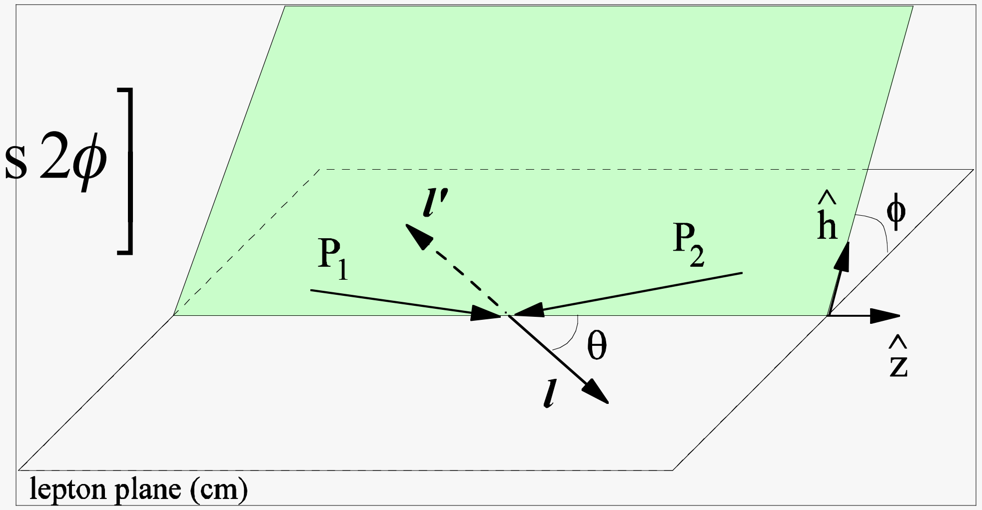
Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

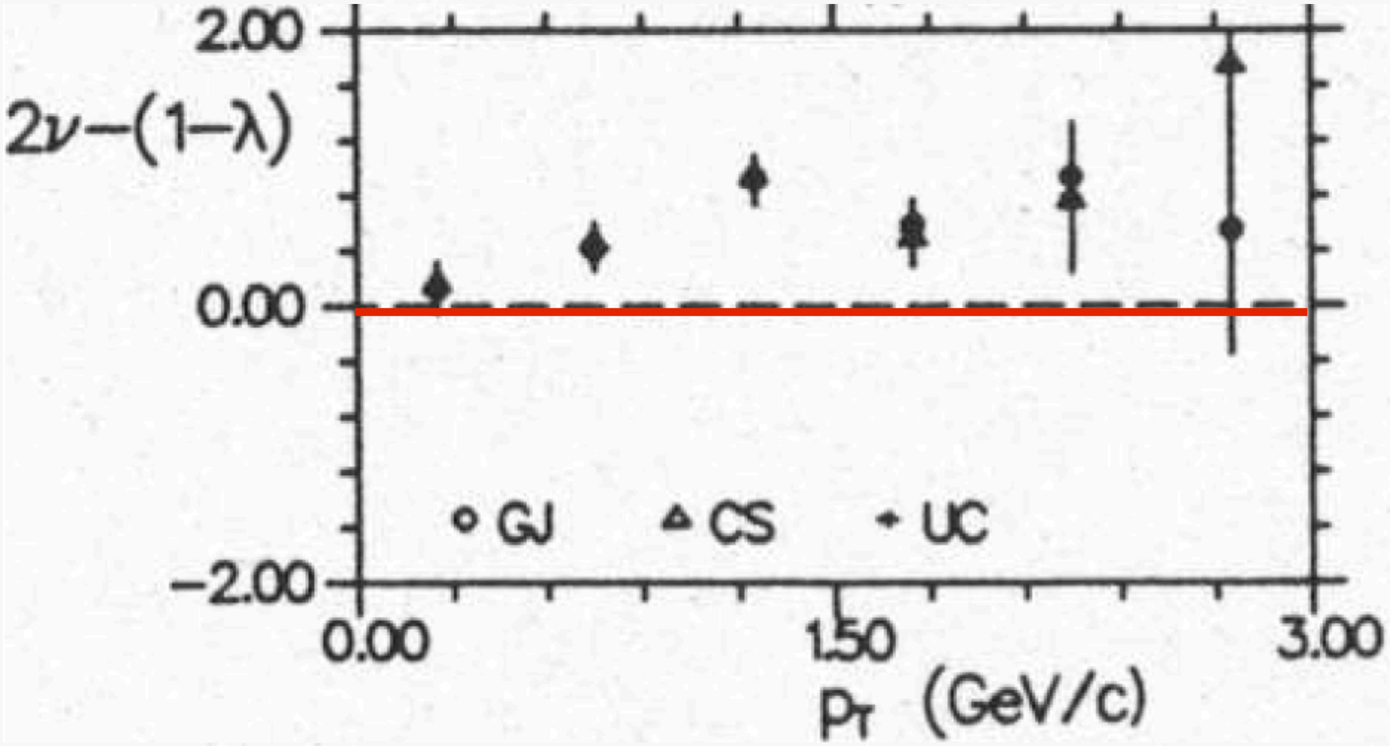
- "failure" of collinear pQCD

☛ C. Riedl

Unpolarized Drell-Yan

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





$$\boxed{1-\lambda-2\nu=0}$$

Large deviations from Lam-Tung relation observed in DY

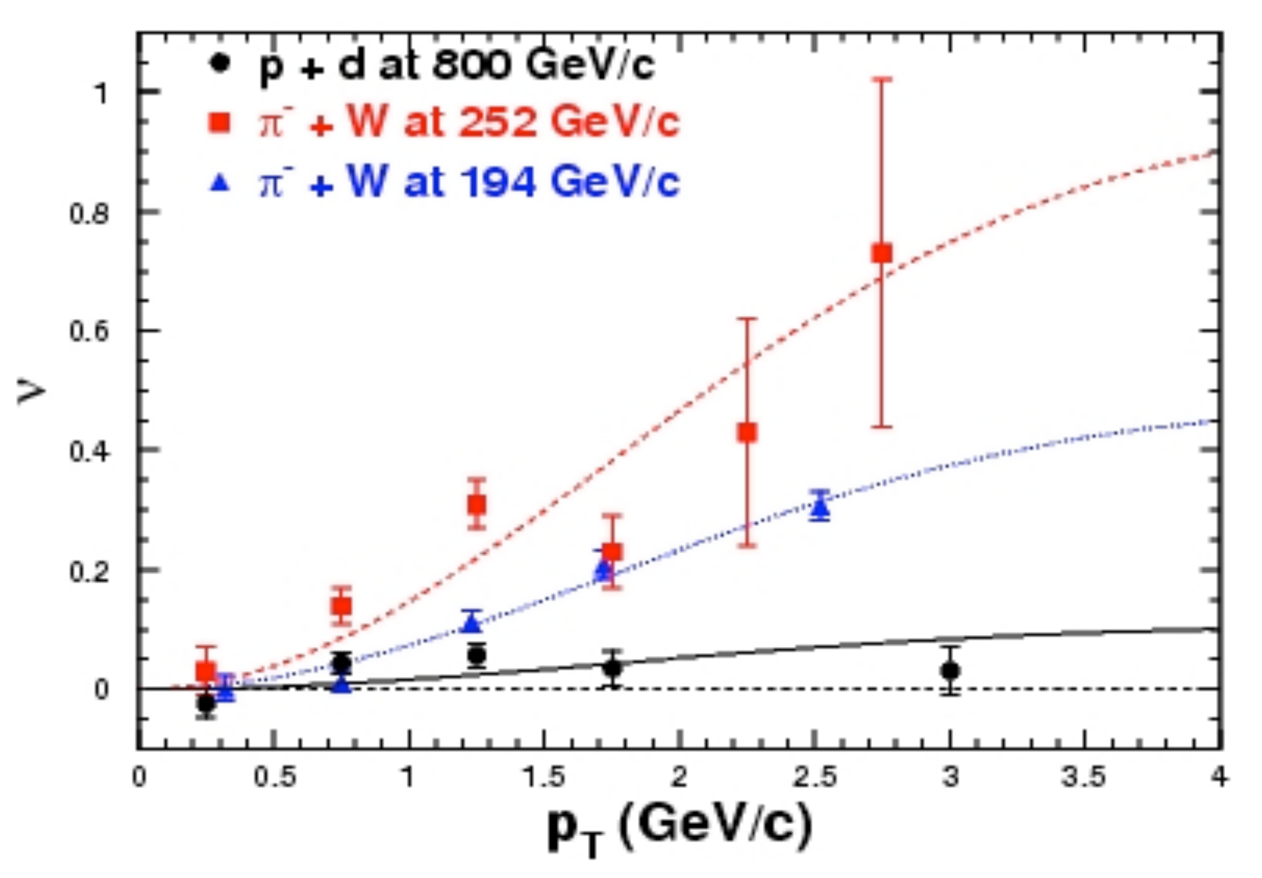
[NA10 ('86/'88) & E615 ('89)]

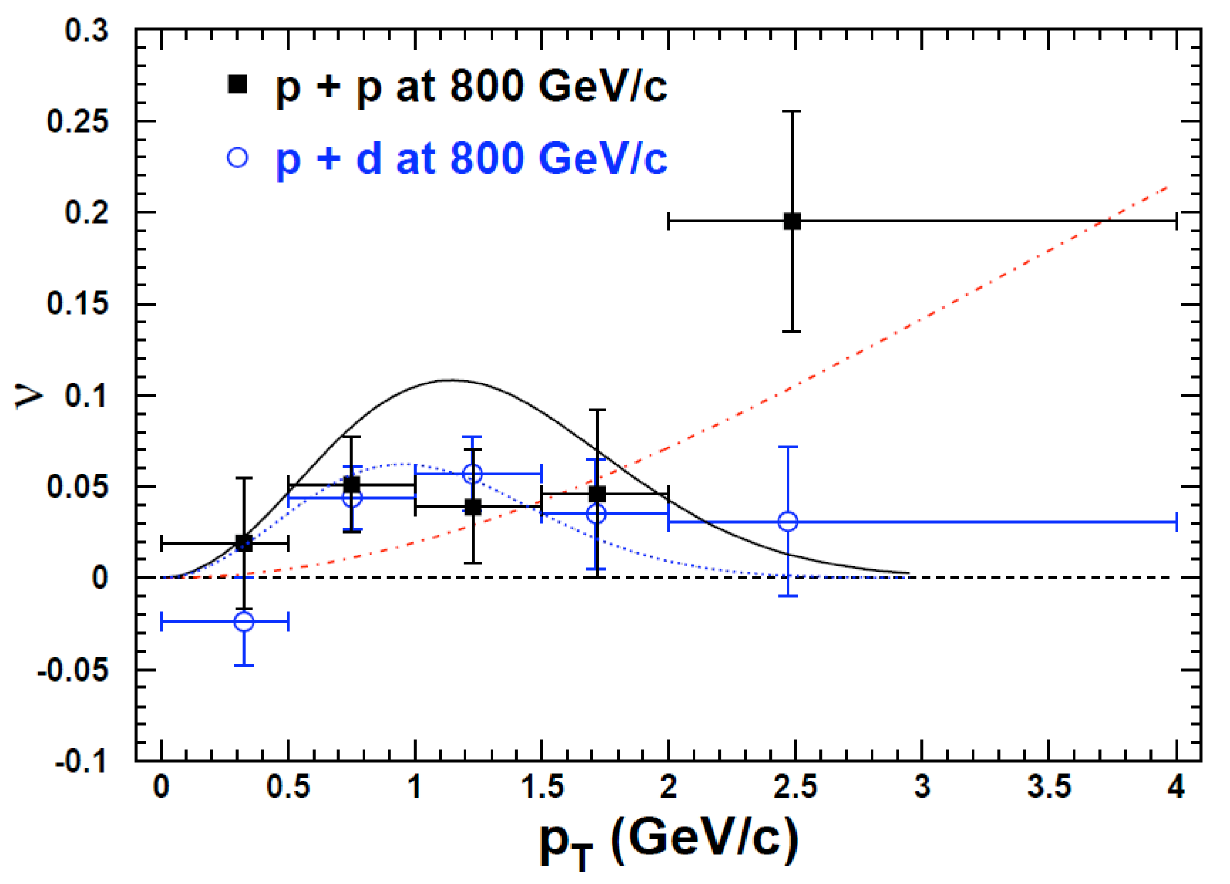
- "failure" of collinear pQCD
- possible source: Boer-Mulders effect

☛ C. Riedl

	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

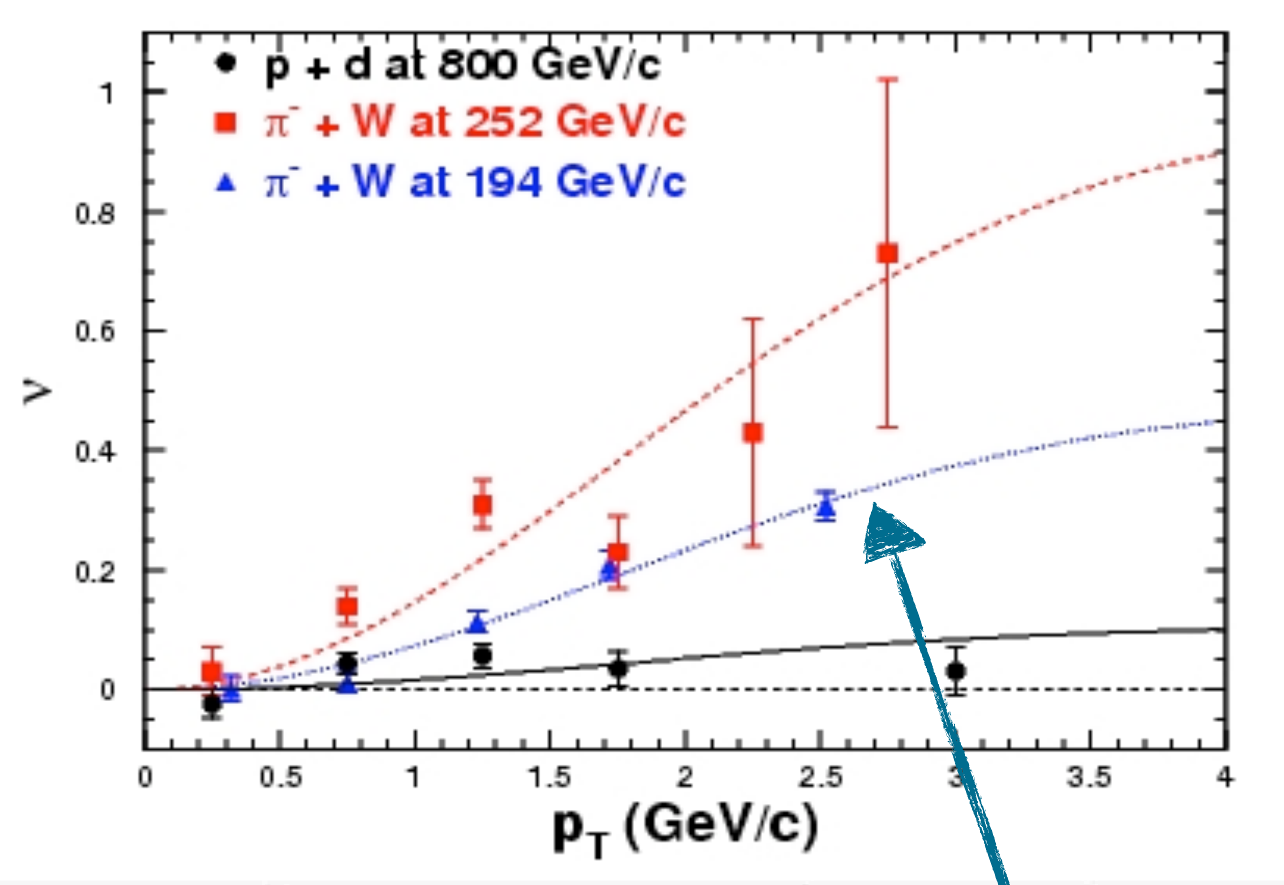


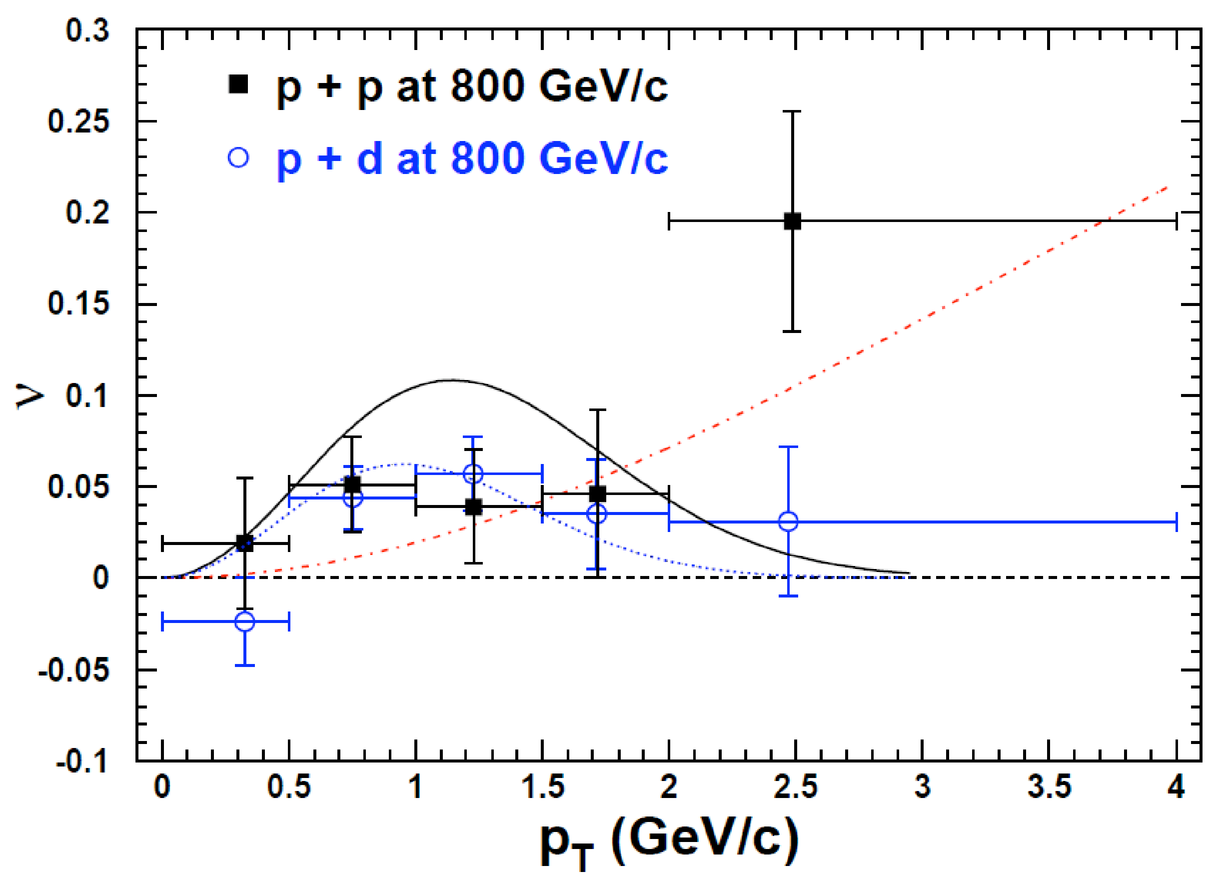


☛ C. Riedl

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

Signs of Boer-Mulders



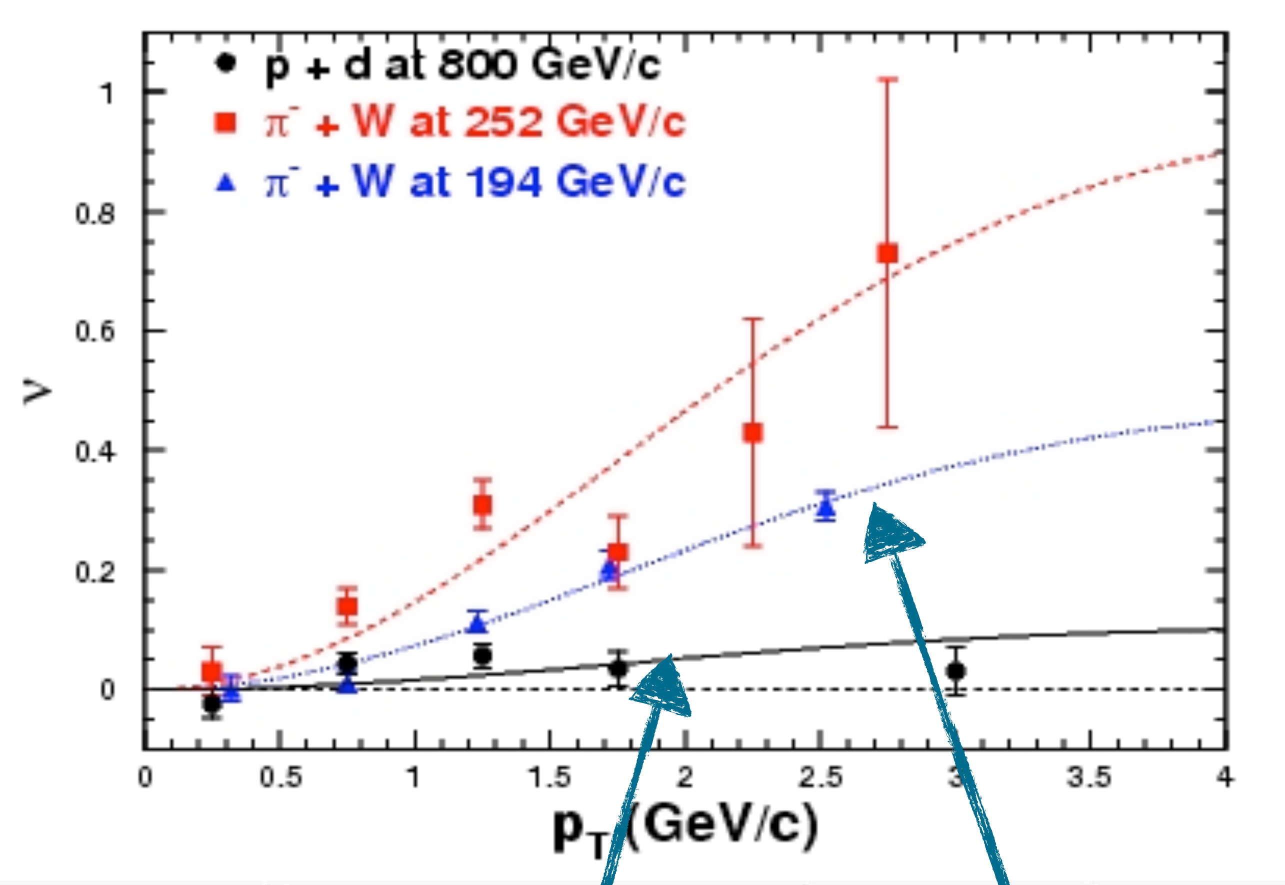


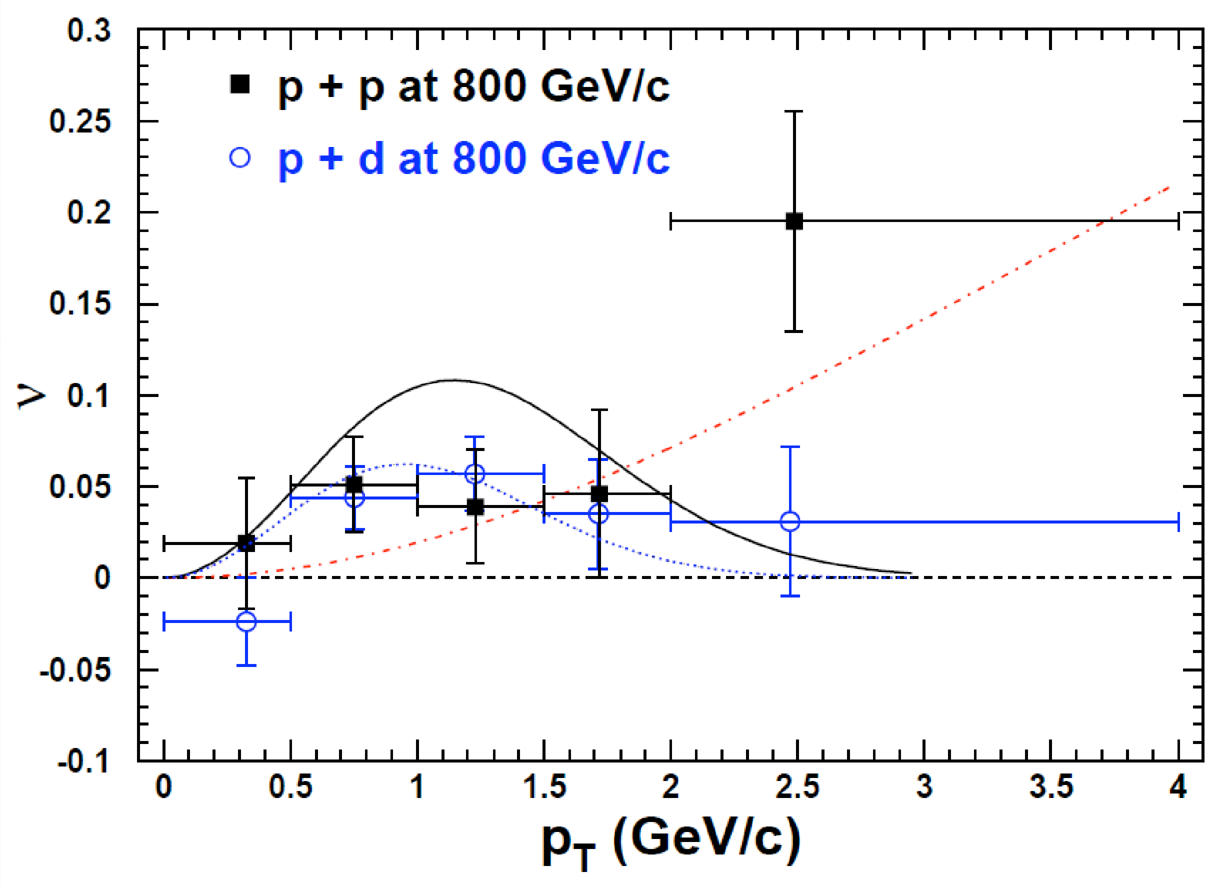
valence BM fctn

☞ C. Riedl

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

Signs of Boer-Mulders





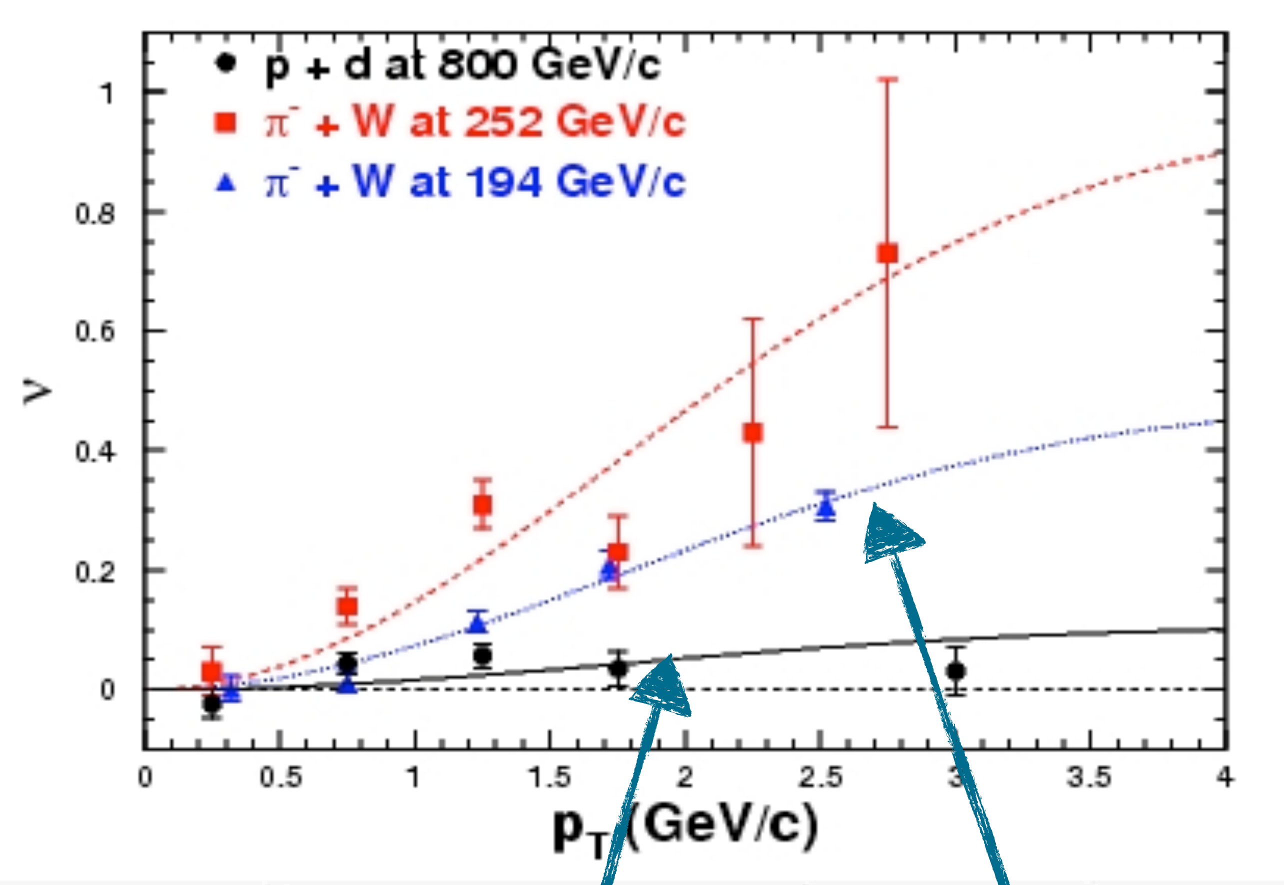
valence and sea BM fctn

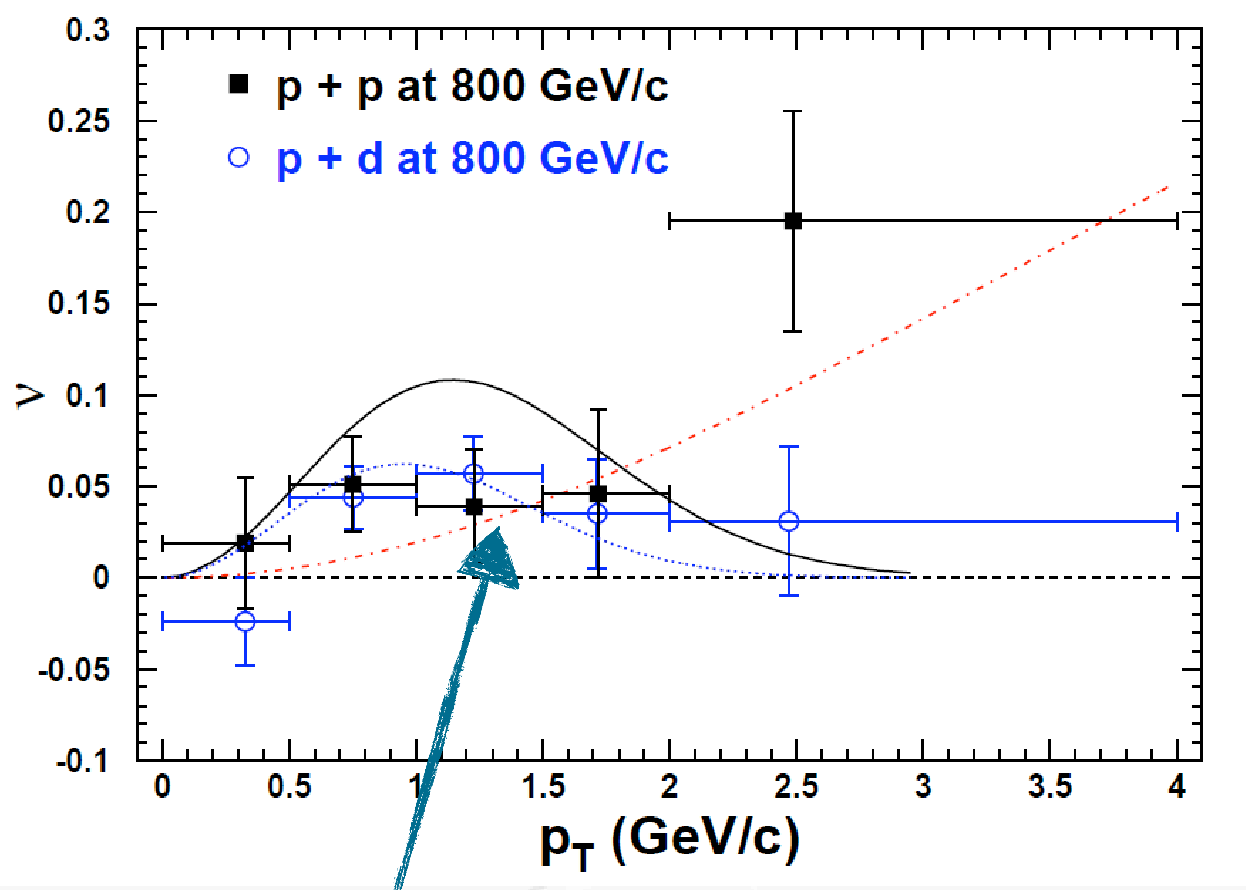
valence BM fctn

☞ C. Riedl

Signs of Boer-Mulders

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





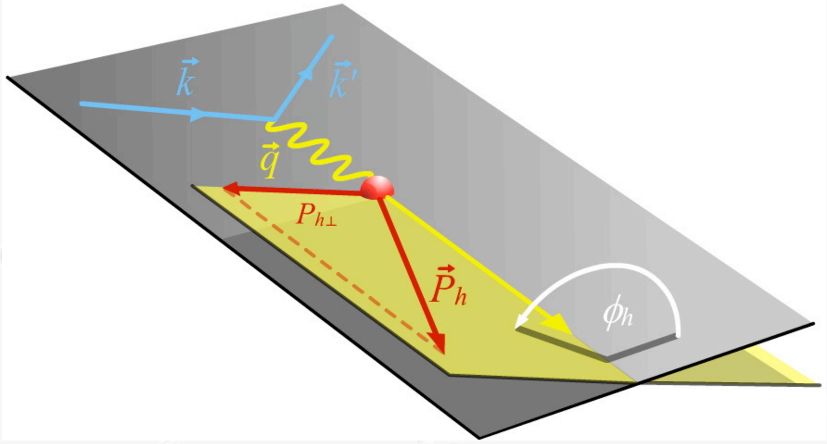
similar BM fctn for up and down quarks?

valence and sea BM fctn

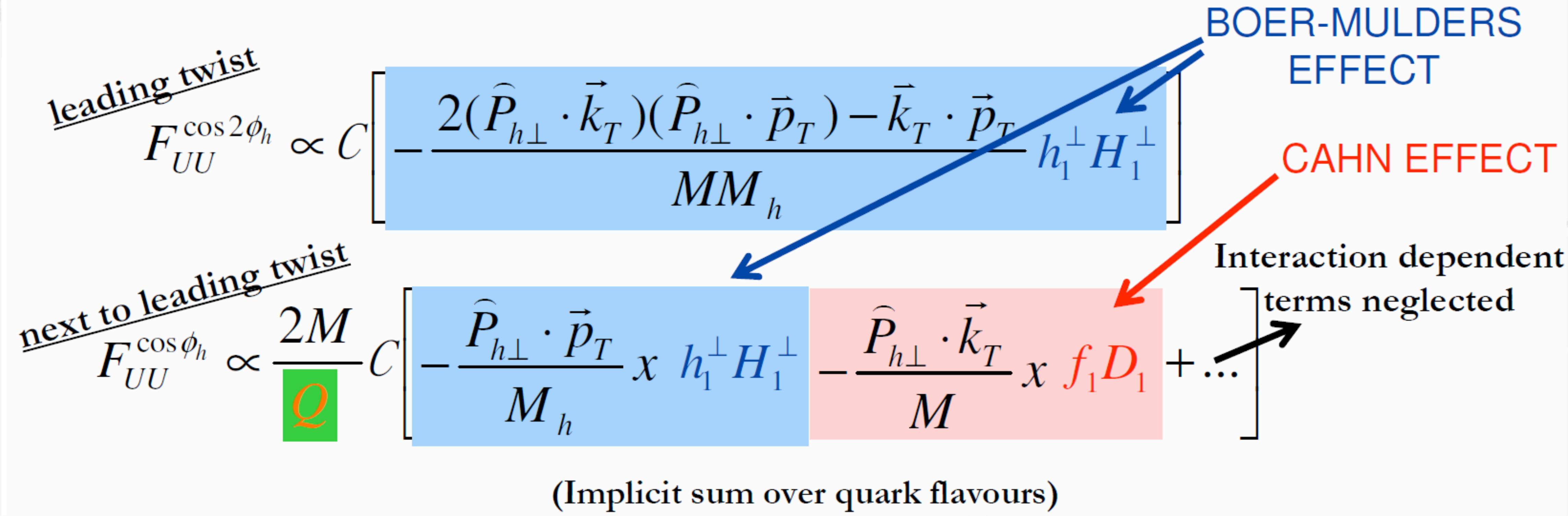
valence BM fctn

☛ C. Riedl

Modulations in spin-independent SIDIS cross section



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



leading twist

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

next to leading twist

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

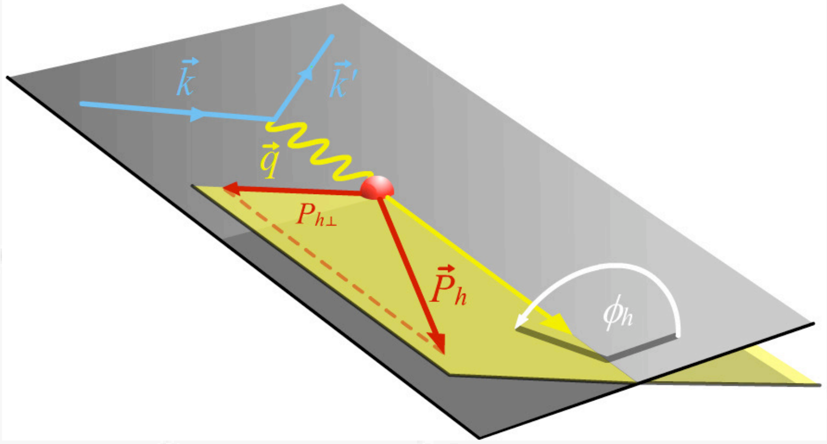
BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

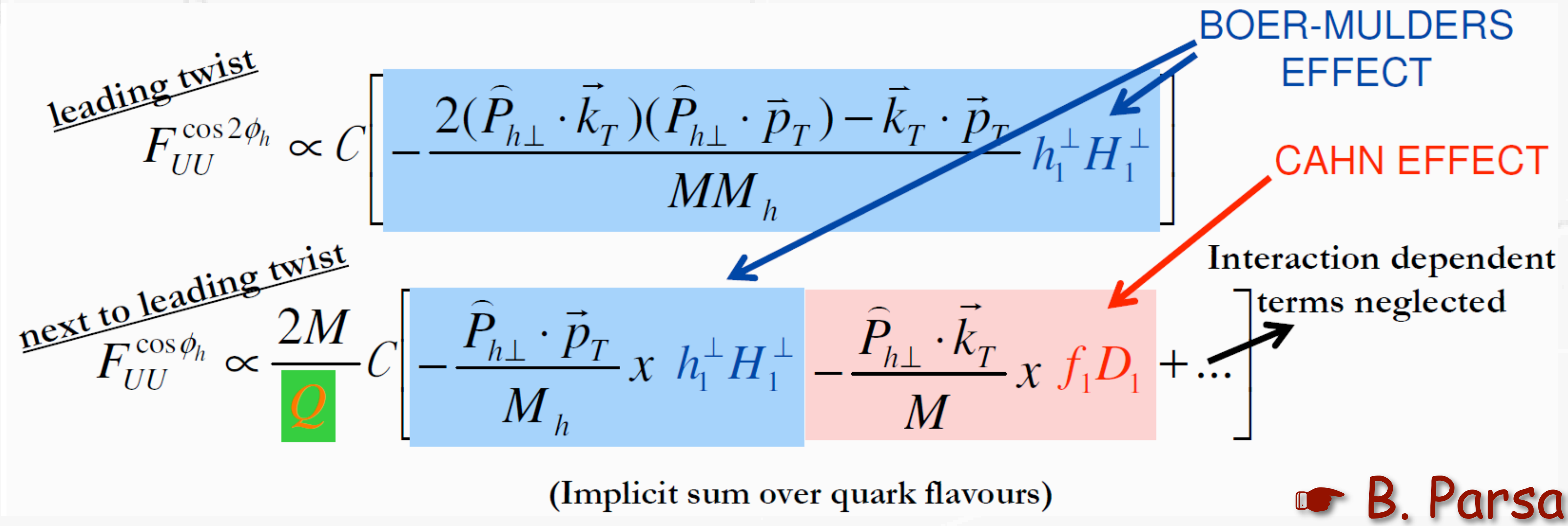
(Implicit sum over quark flavours)

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

next to leading twist

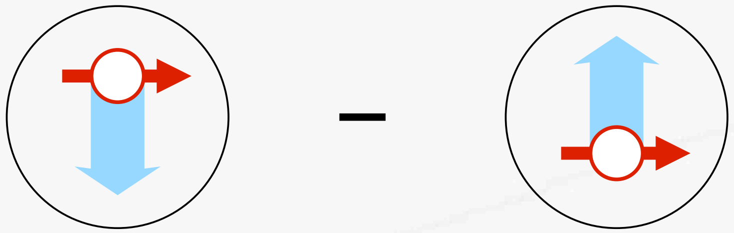
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\ h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\ f_1 D_1 + \ldots\right]$$

CAHN EFFECT

Interaction dependent terms neglected

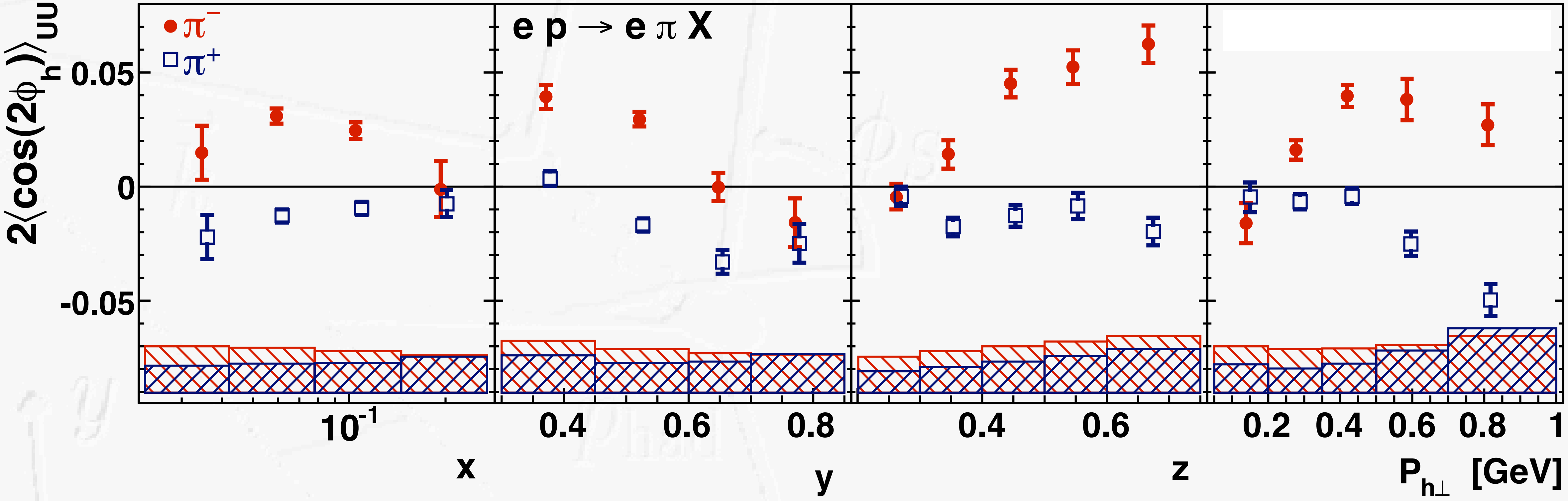
(Implicit sum over quark flavours)

☛ **B. Parsamyan**



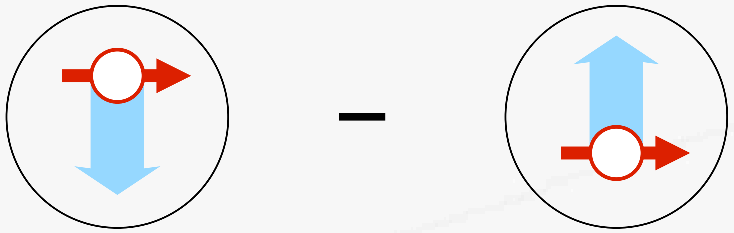
signs of Boer-Mulders

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



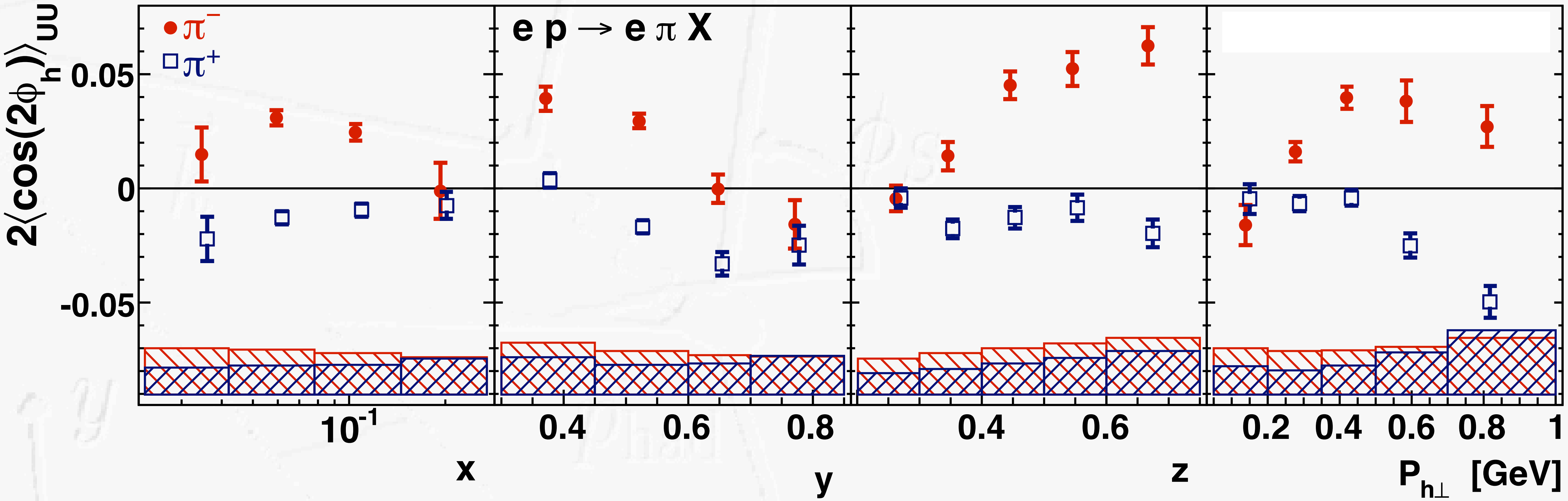
- not zero!

☛ B. Parsamyan



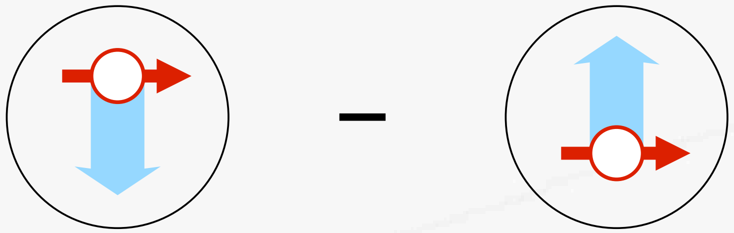
signs of Boer-Mulders

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



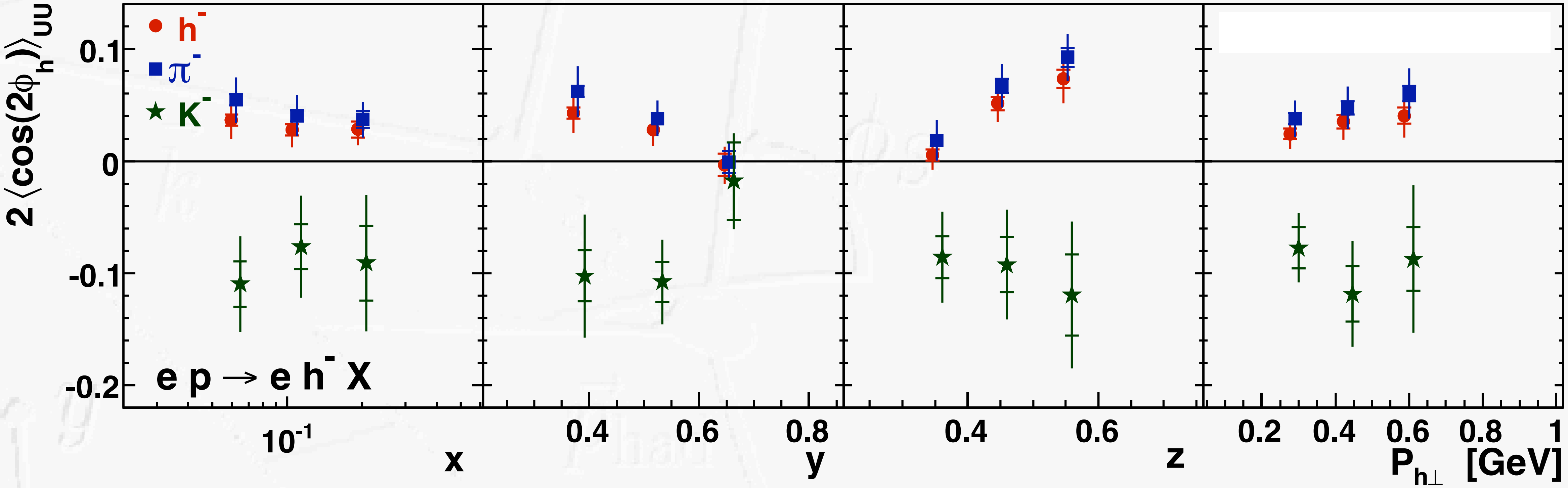
- not zero!
- opposite sign for charged pions with larger magnitude for π^-
  -> same-sign BM-function for valence quarks?

☛ B. Parsamyan



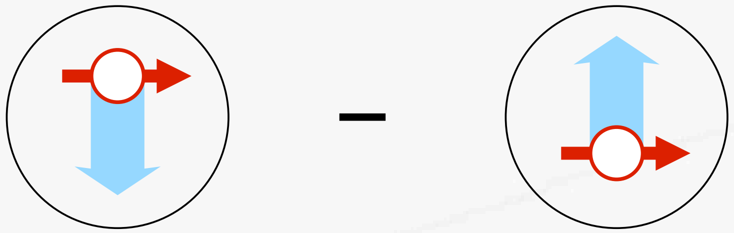
signs of Boer-Mulders

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

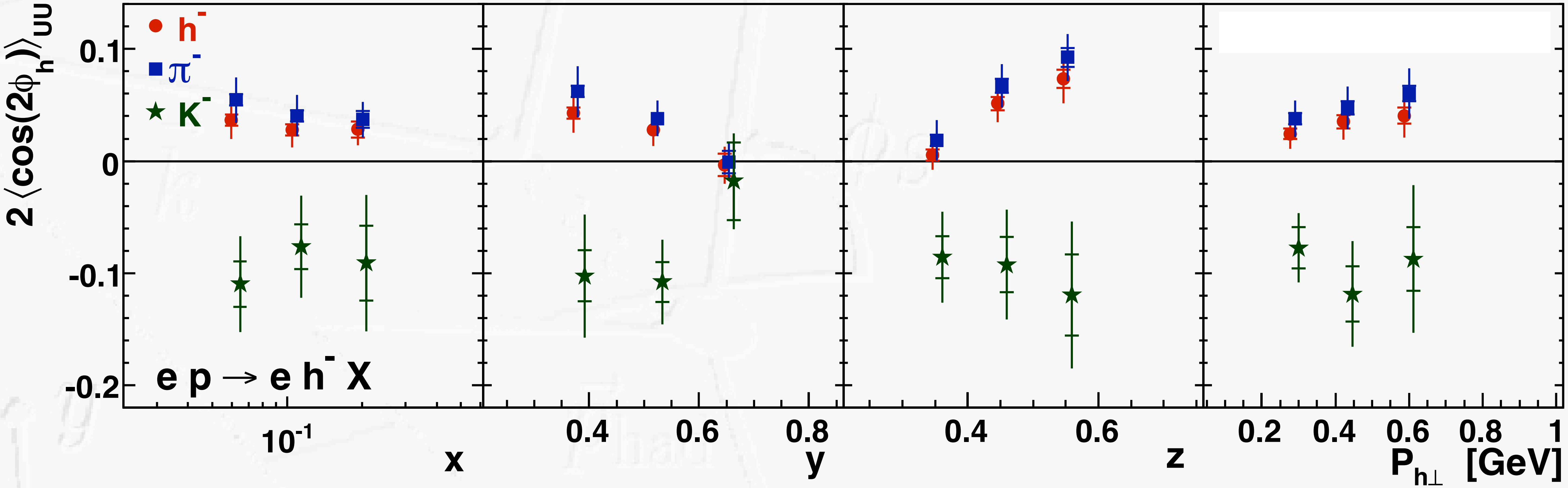


- not zero!
- opposite sign for charged pions with larger magnitude for π^-
  -> same-sign BM-function for valence quarks?
- intriguing behavior for kaons

☛ B. Parsamyan



signs of Boer-Mulders

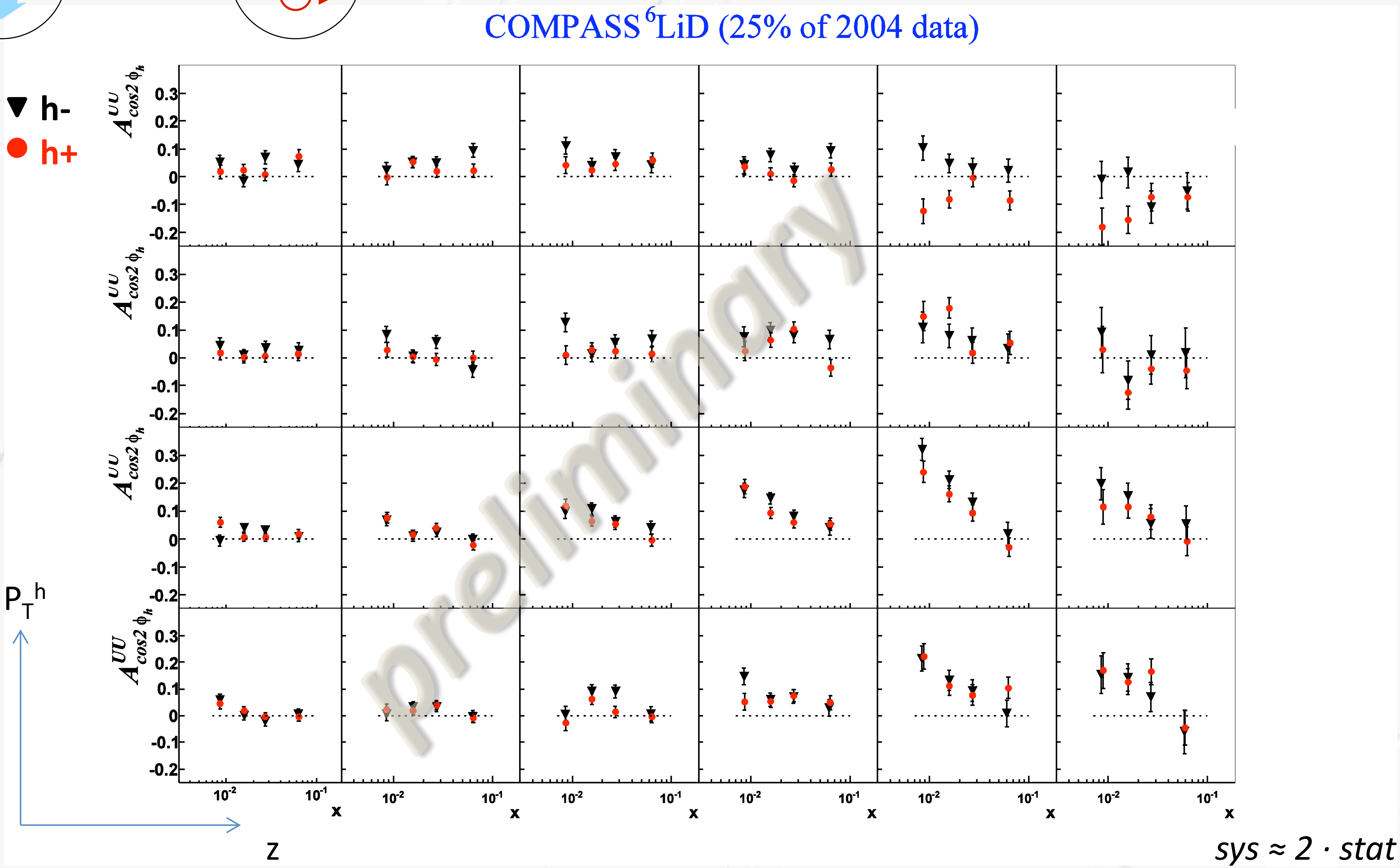


[Airapetian et al., PRD 87 (2013) 012010]

- not zero!
- opposite sign for charged pions with larger magnitude for π^- -> same-sign BM-function for valence quarks?
- intriguing behavior for kaons
- available in multidimensional binning both from HERMES and soon from COMPASS

☛ B. Parsamyan

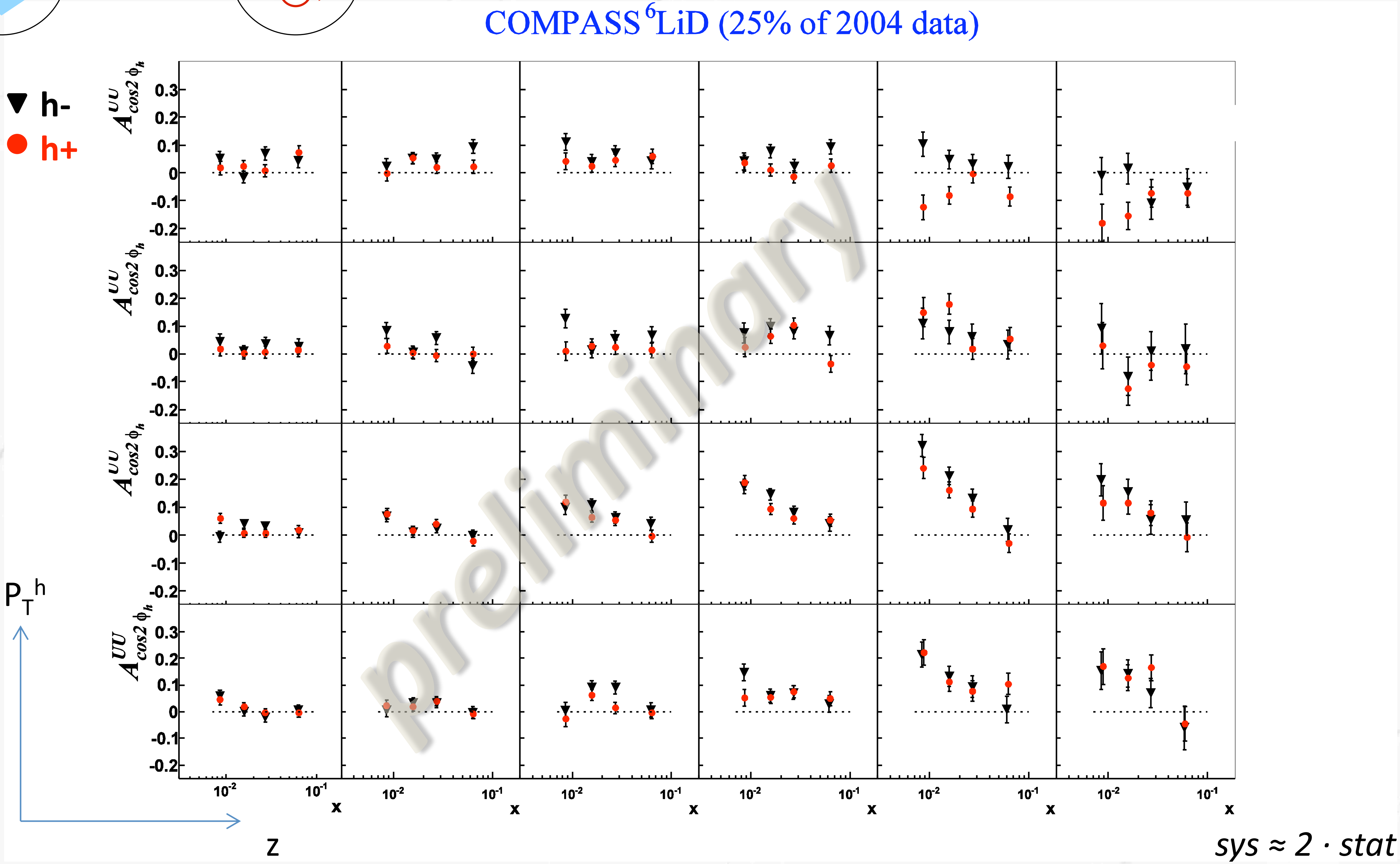
signs of Boer-Mulders


COMPASS ^{6}LiD (25% of 2004 data)

sys ≈ 2 · stat

☛ B. Parsamyan

signs of Boer-Mulders

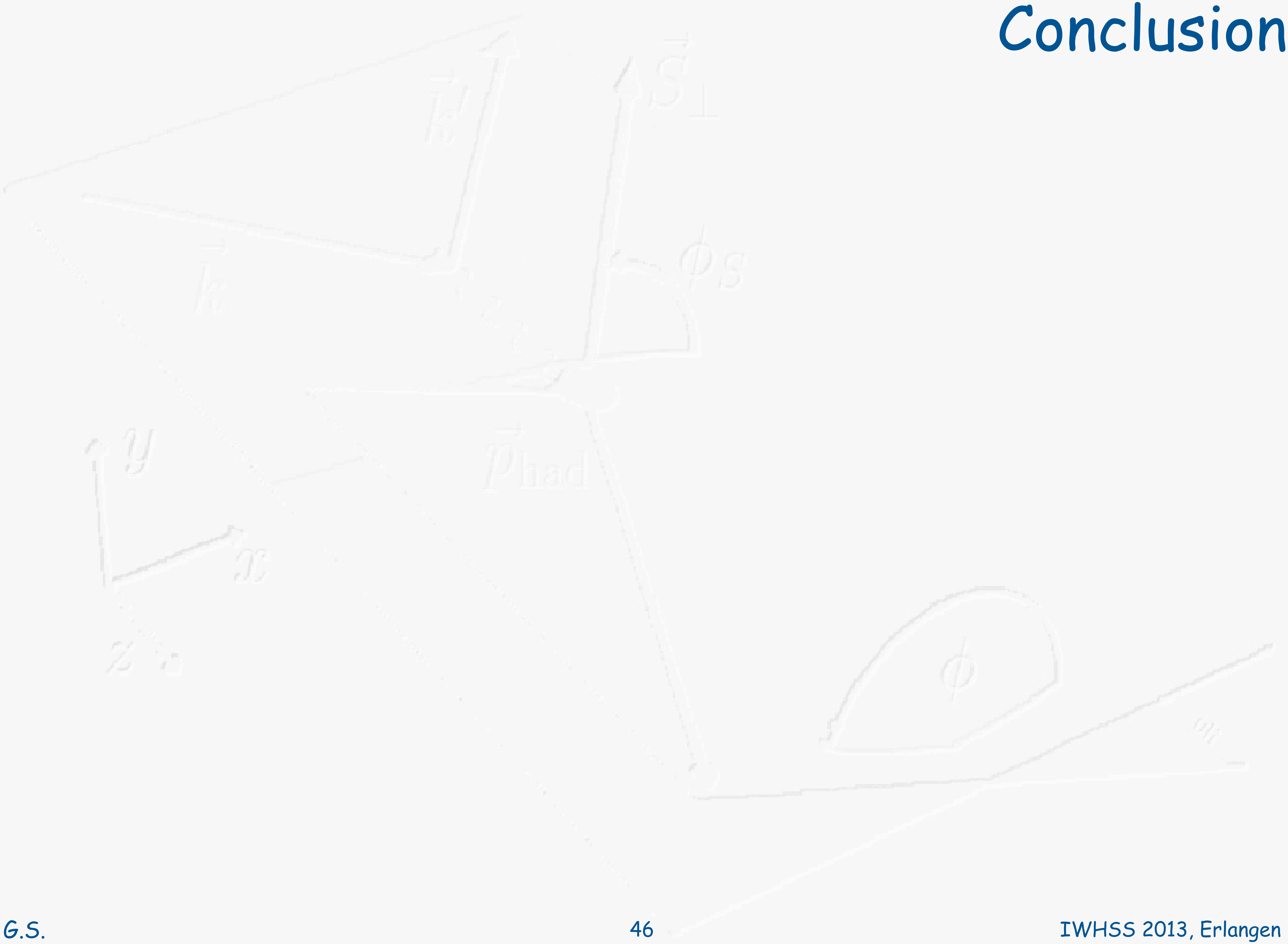

COMPASS ^{6}LiD (25% of 2004 data)

$sys \approx 2 \cdot stat$

- available in multidimensional binning both from HERMES and soon from COMPASS

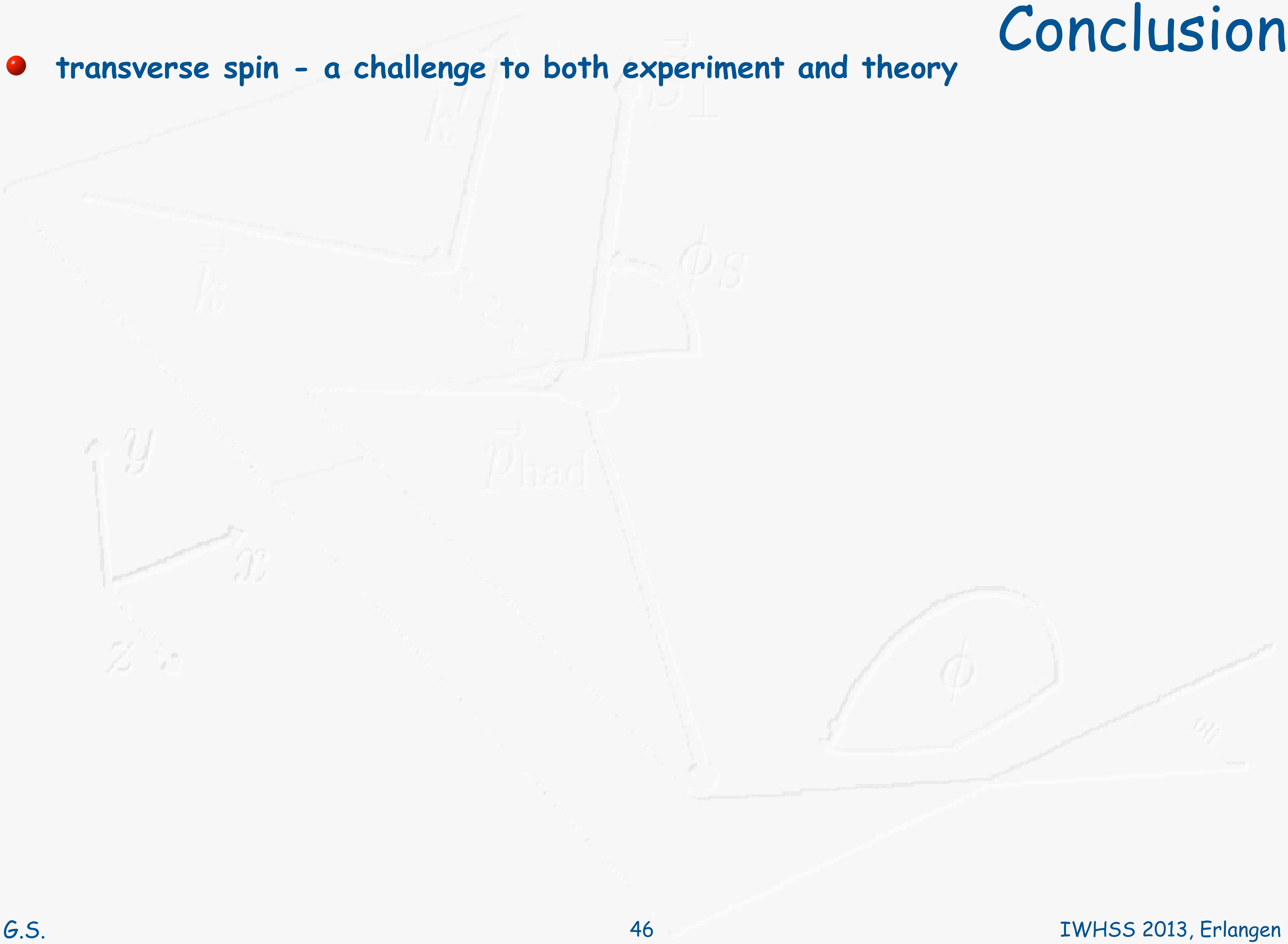
☛ B. Parsamyan

Conclusion



Conclusion

- **transverse spin - a challenge to both experiment and theory**



Conclusion

- **transverse spin - a challenge to both experiment and theory**
- TMD factorization applied to SIDIS:
  - non-zero correlation between quark transverse momentum and nucleon transverse polarization **(Sivers effect)**
  - non-zero **transversity**, and correlation between transverse hadron momentum and transverse spin of fragm. quark **(Collins effect)**
  - **dihadron** fragmention as tool to measure transversity
  - **worm-gear** g_{1T} is non-vanishing

Conclusion

- **transverse spin - a challenge to both experiment and theory**
- TMD factorization applied to SIDIS:
  - non-zero correlation between quark transverse momentum and nucleon transverse polarization **(Sivers effect)**
  - non-zero **transversity**, and correlation between transverse hadron momentum and transverse spin of fragm. quark **(Collins effect)**
  - **dihadron** fragmention as tool to measure transversity
  - **worm-gear** g_{1T} is non-vanishing
- hadron production in pp:
  - no clear interpretation of A_N (sign mismatch between Sivers and twist-3, large asymmetries even at high p_T, ...)
  - preliminary signals of dihadron fragmentation (and of Collins effect)

Conclusion

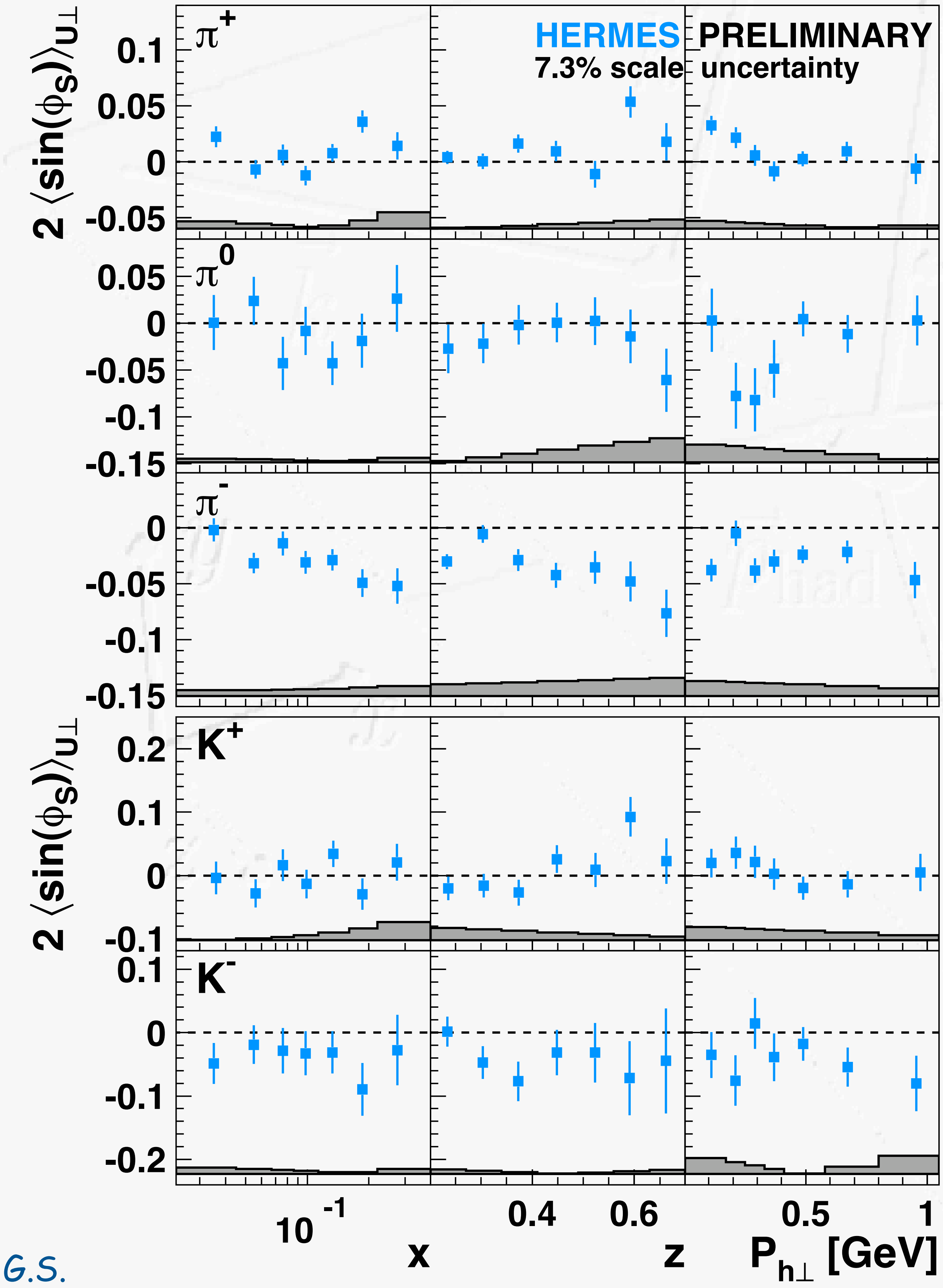
- **transverse spin - a challenge to both experiment and theory**
- TMD factorization applied to SIDIS:
  - non-zero correlation between quark transverse momentum and nucleon transverse polarization **(Sivers effect)**
  - non-zero **transversity**, and correlation between transverse hadron momentum and transverse spin of fragm. quark **(Collins effect)**
  - **dihadron** fragmention as tool to measure transversity
  - **worm-gear** g_{1T} is non-vanishing
- hadron production in pp:
  - no clear interpretation of A_N (sign mismatch between Sivers and twist-3, large asymmetries even at high p_T, …)
  - preliminary signals of dihadron fragmentation (and of Collins effect)
- hint of a non-zero **valence Boer-Mulders** function from DY and SIDIS

Conclusion

- **transverse spin - a challenge to both experiment and theory**
- TMD factorization applied to SIDIS:
  - non-zero correlation between quark transverse momentum and nucleon transverse polarization **(Sivers effect)**
  - non-zero **transversity**, and correlation between transverse hadron momentum and transverse spin of fragm. quark **(Collins effect)**
  - **dihadron** fragmention as tool to measure transversity
  - **worm-gear** g_{1T} is non-vanishing
- hadron production in pp:
  - no clear interpretation of A_N (sign mismatch between Sivers and twist-3, large asymmetries even at high p_T, …)
  - preliminary signals of dihadron fragmentation (and of Collins effect)
- hint of a non-zero **valence Boer-Mulders** function from DY and SIDIS
- let's prepare for
  - precision measurements at ongoing and future facilities
  - fundamental QCD tests in Drell-Yan experiments

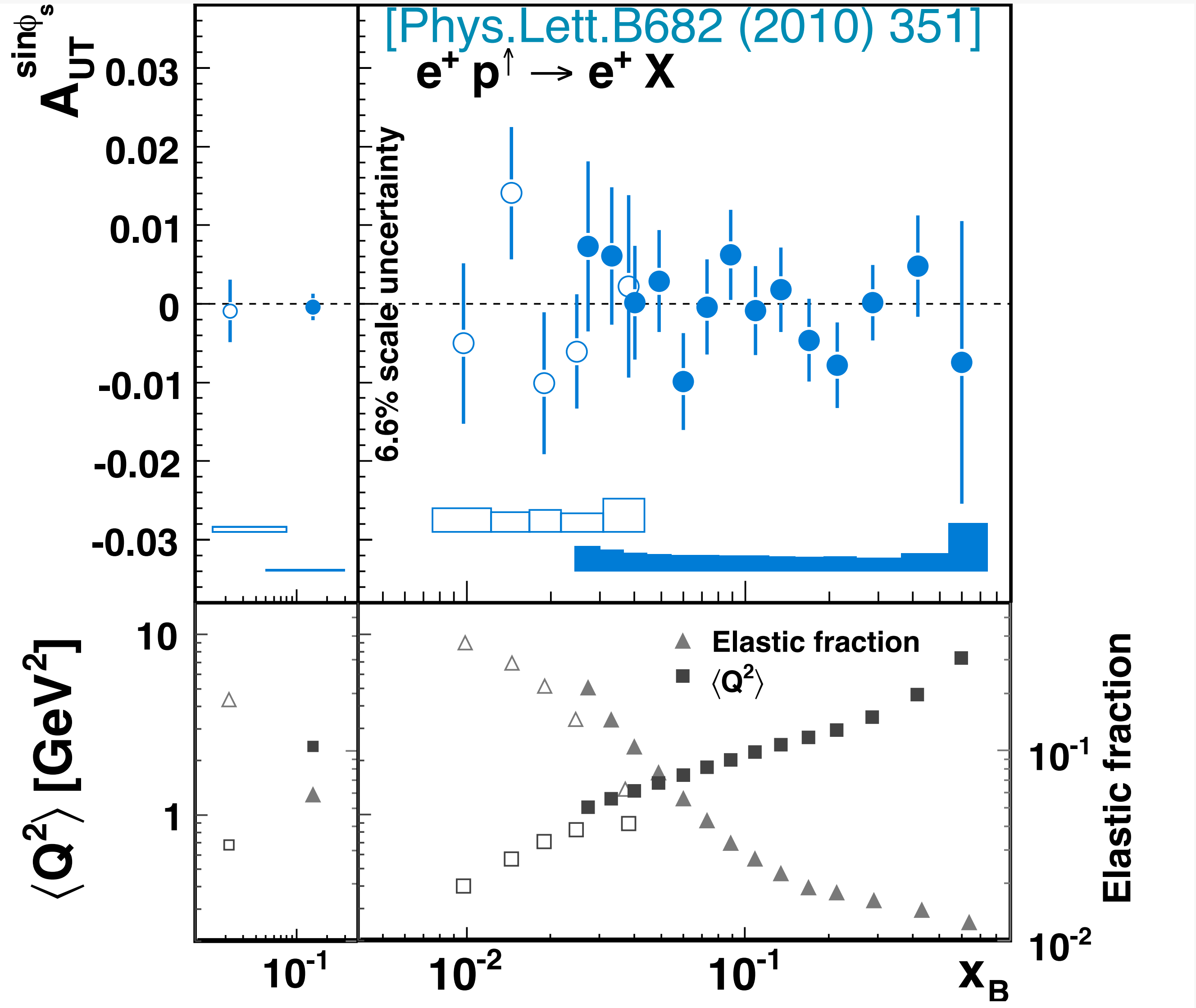
some backup slides

Subleading twist - sin(ϕ_s)

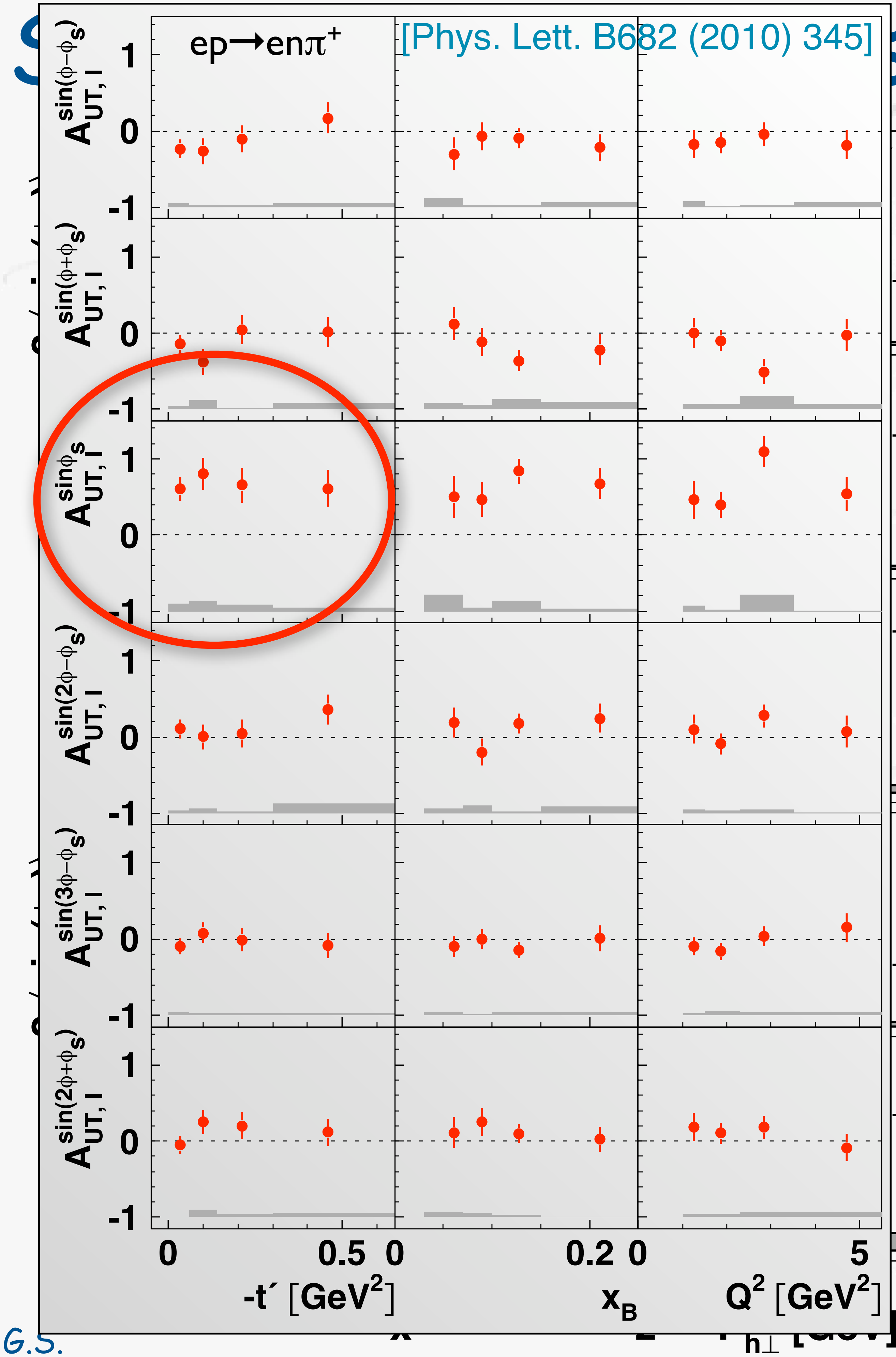


- significant non-zero signal observed for negatively charged mesons also at COMPASS
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons

$\propto$

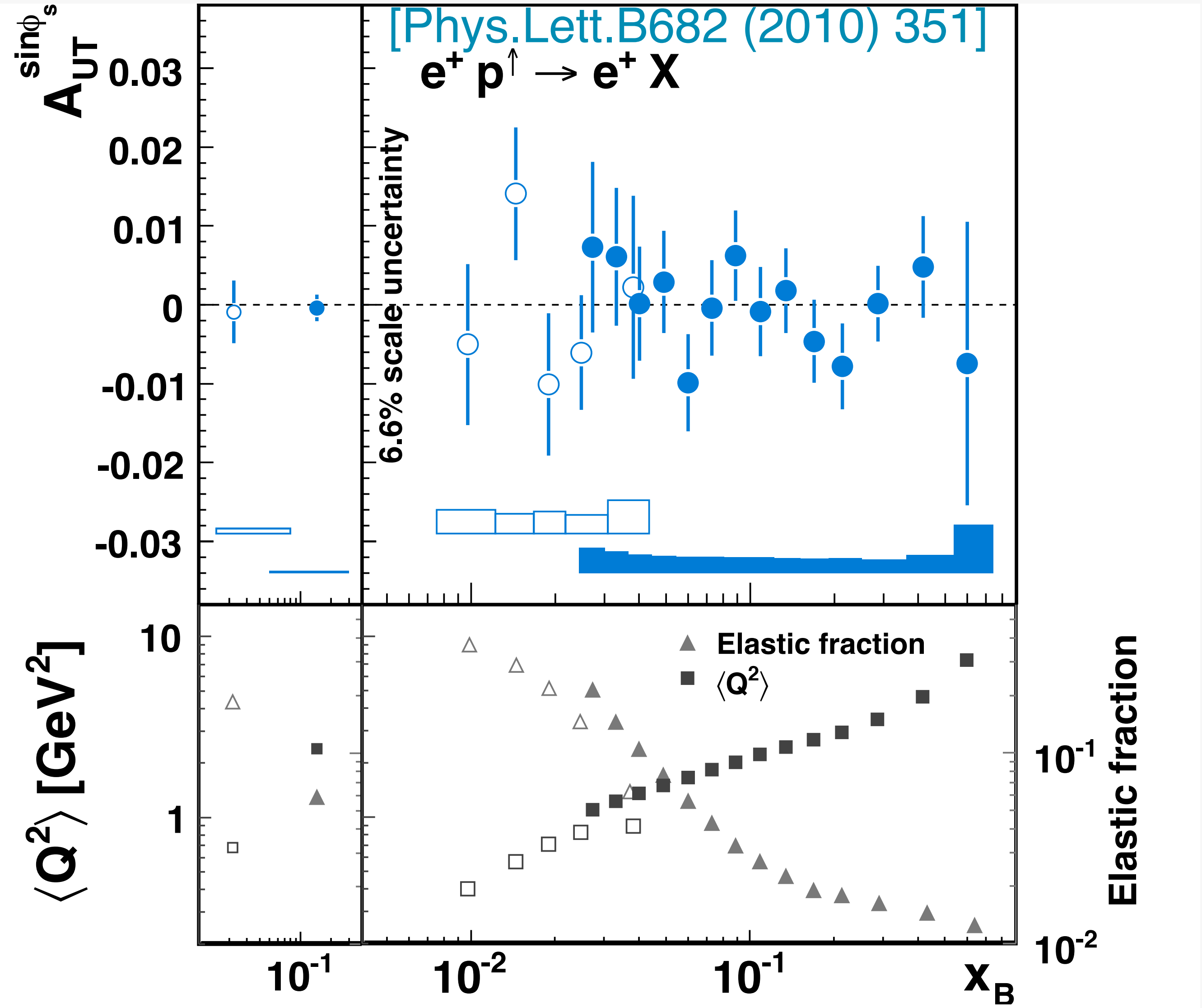


S sin(ϕ_s)



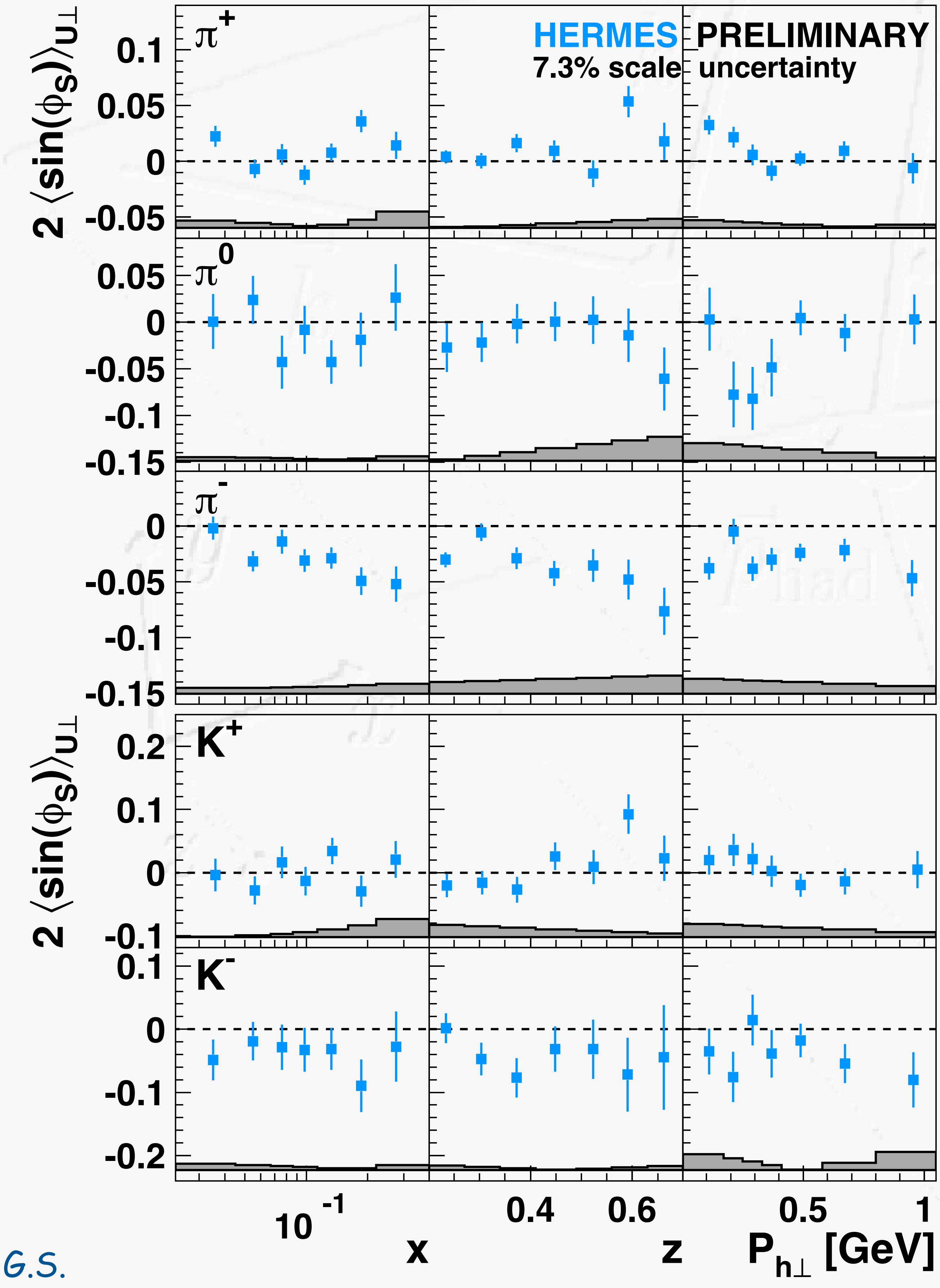
[Phys. Lett. B682 (2010) 345]

- significant non-zero signal observed for negatively charged mesons also at COMPASS
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons



[Phys.Lett.B682 (2010) 351]

Subleading twist - $\sin(\phi_S)$

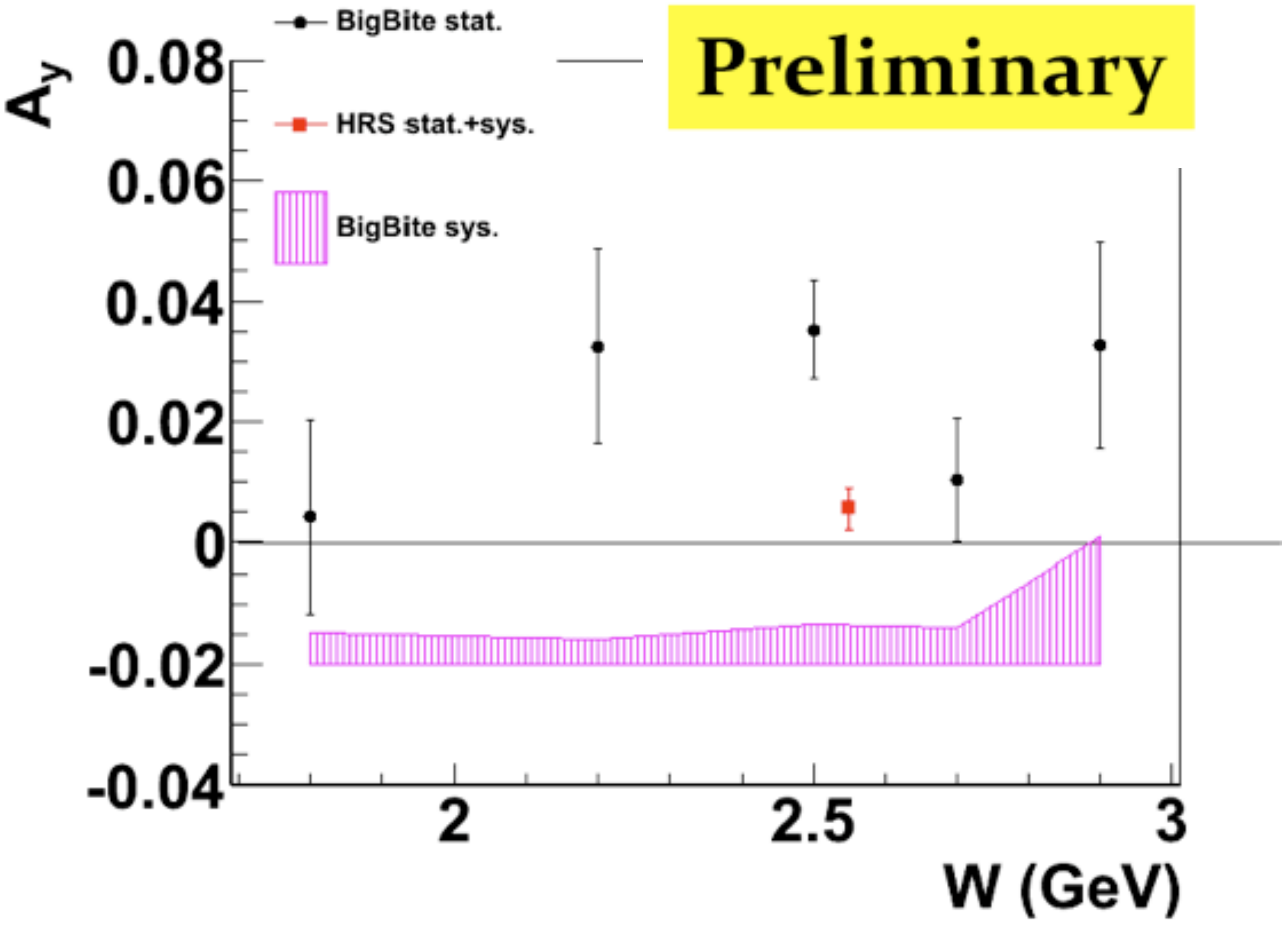


- significant non-zero signal observed for negatively charged mesons also at COMPASS
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

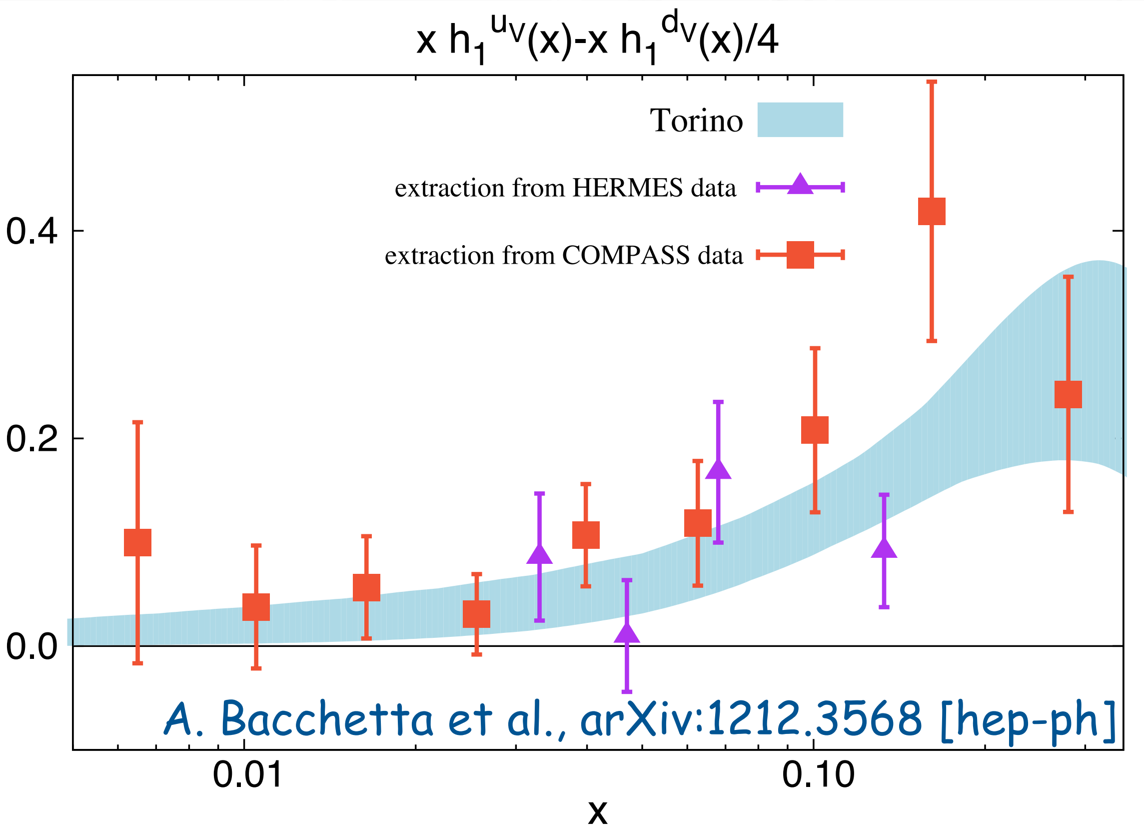
2-photon exchange signal from JLab

- non-zero inclusive LR asymmetry on neutron
- goes beyond single-photon exchange interpretation

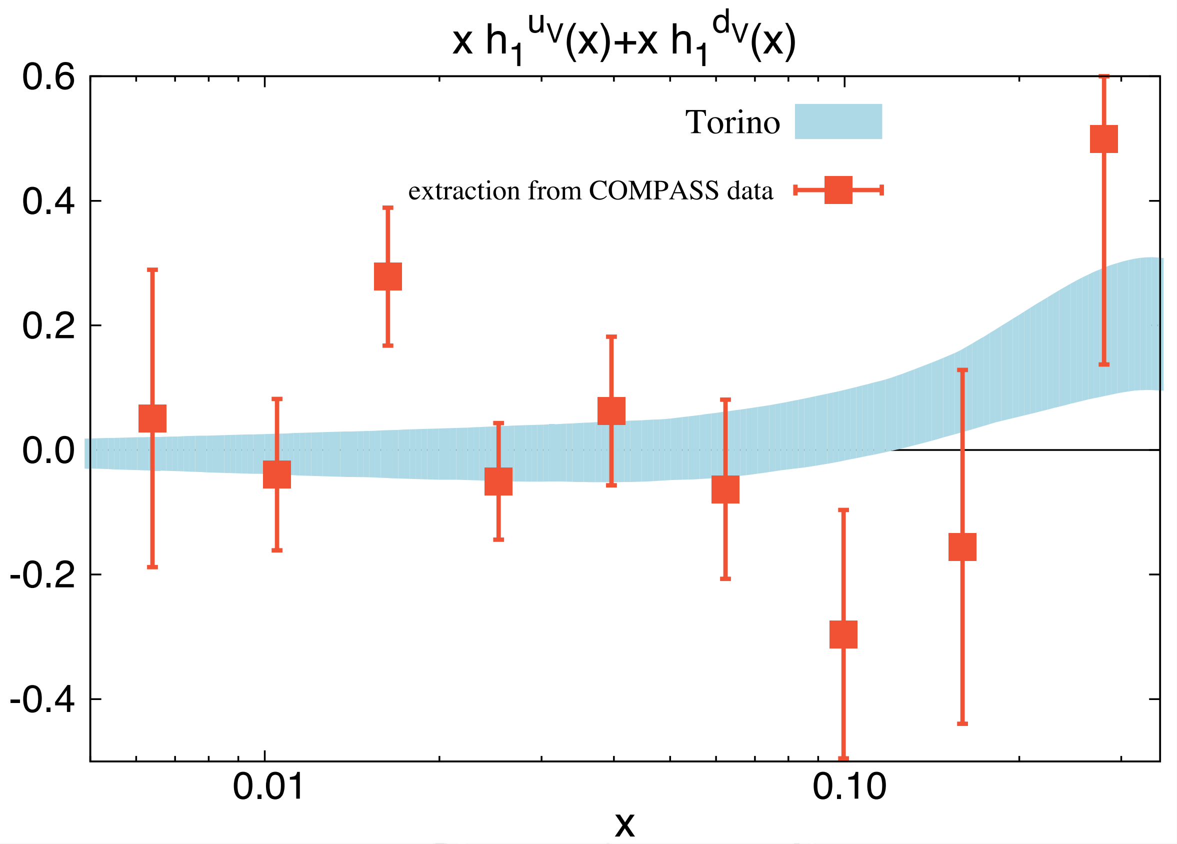


transversity extraction

- **combining SIDIS (COMPASS & HERMES) and e^+e^- data (BELLE):**



A. Bacchetta et al., arXiv:1212.3568 [hep-ph]



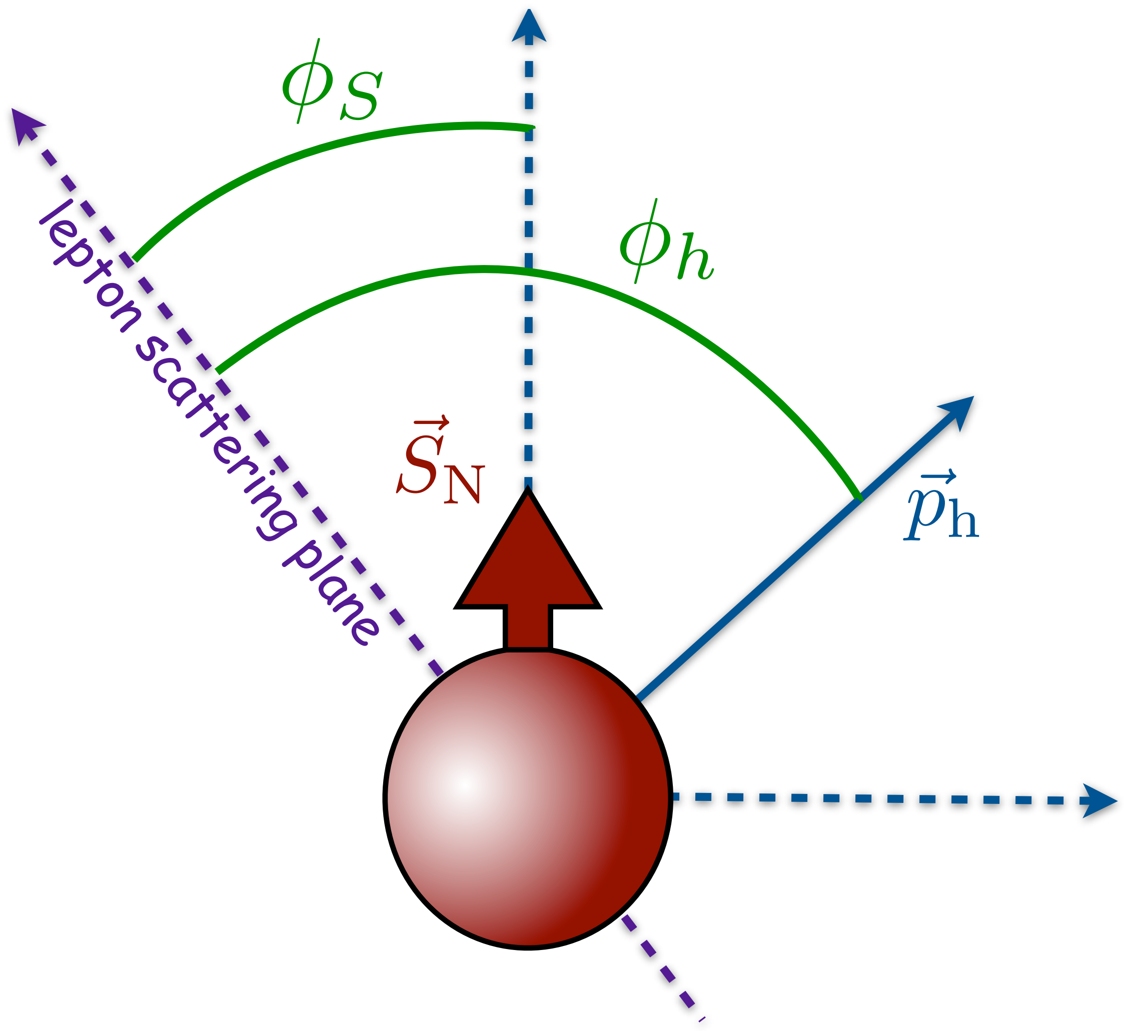
- **promising agreement between collinear and TMD extraction of transversity**

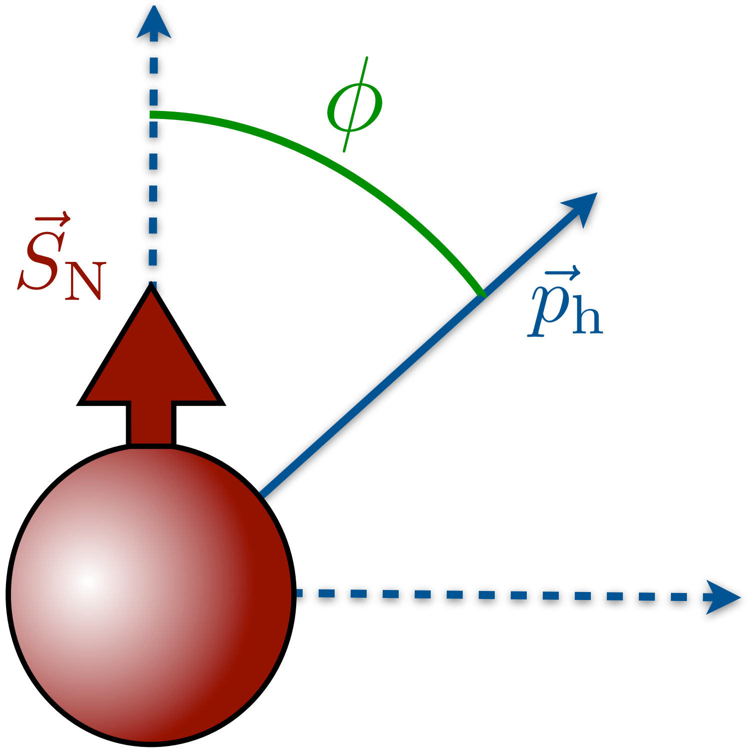
- **no obvious sign of difference in TMD (Collins) from collinear (dihadron)**

Inclusive hadron electro-production

$ep^{\uparrow} \rightarrow ehX$

$ep^{\uparrow} \rightarrow hX$





virtual photon going into the page

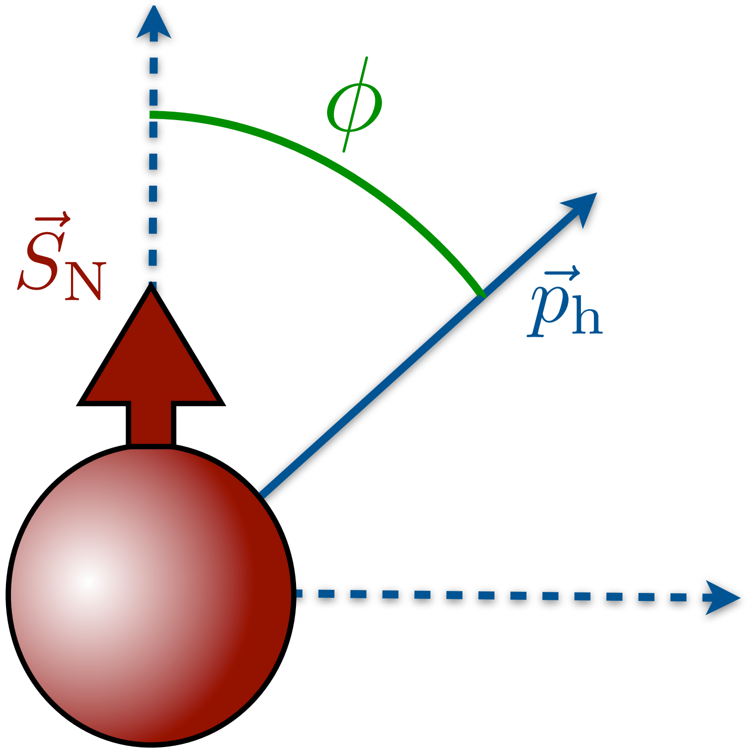
lepton beam going into the page

$\phi \simeq \phi_h - \phi_S$

➡ "Sivers angle"

Inclusive hadron electro-production

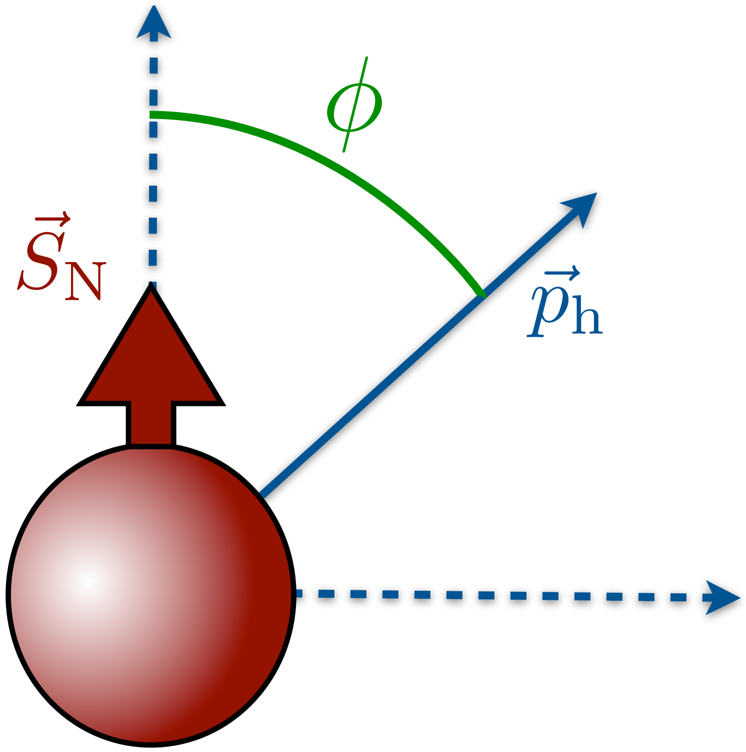
$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

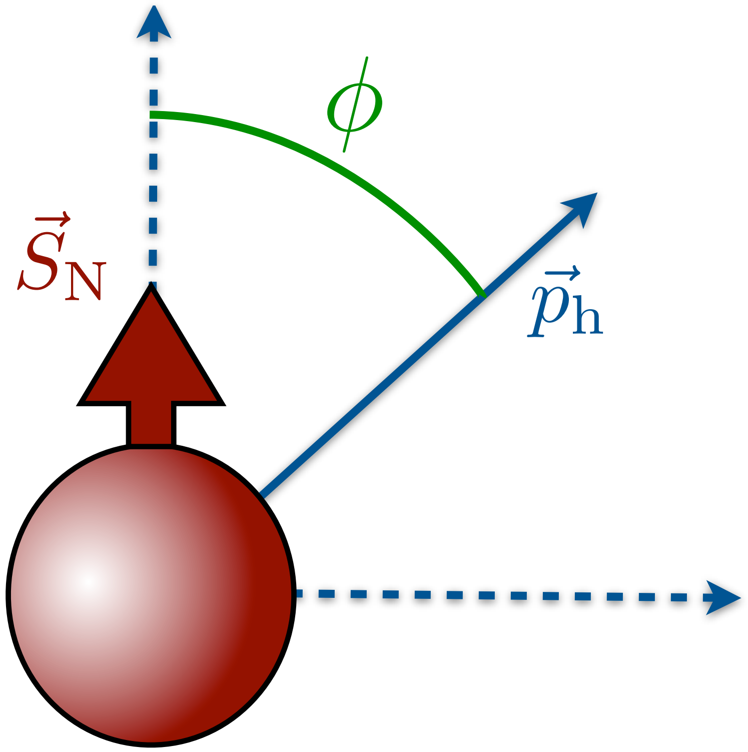
$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

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

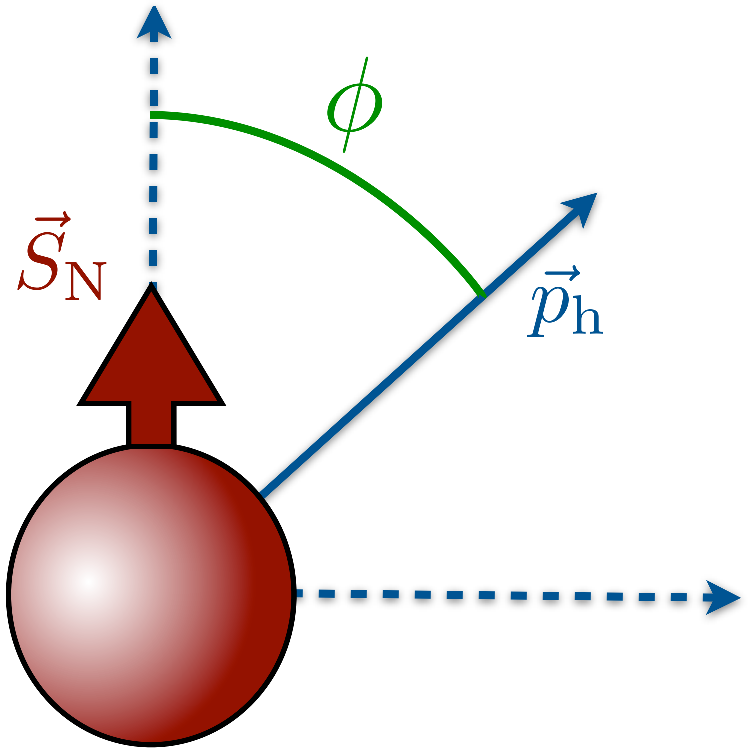
$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

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

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



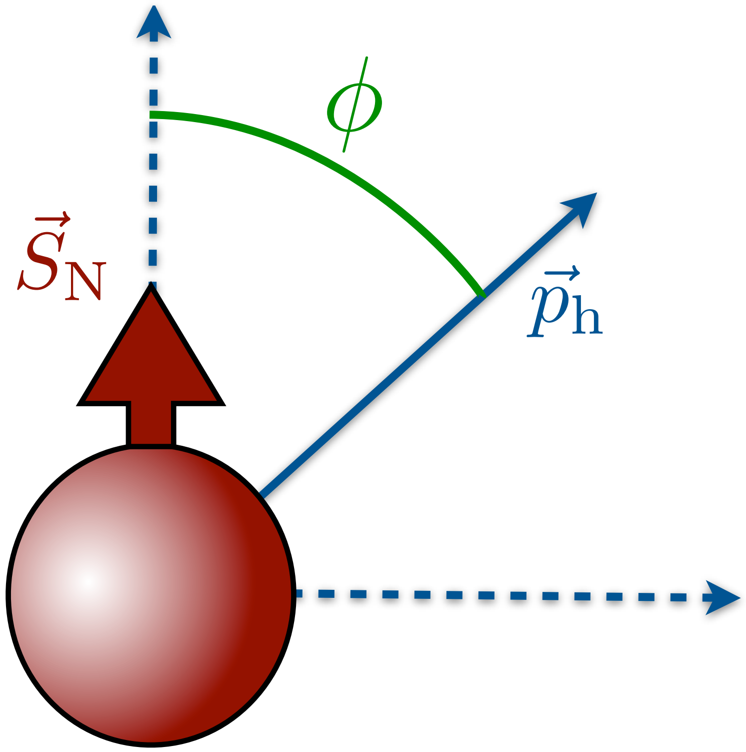
Inclusive hadron electro-production

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

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

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

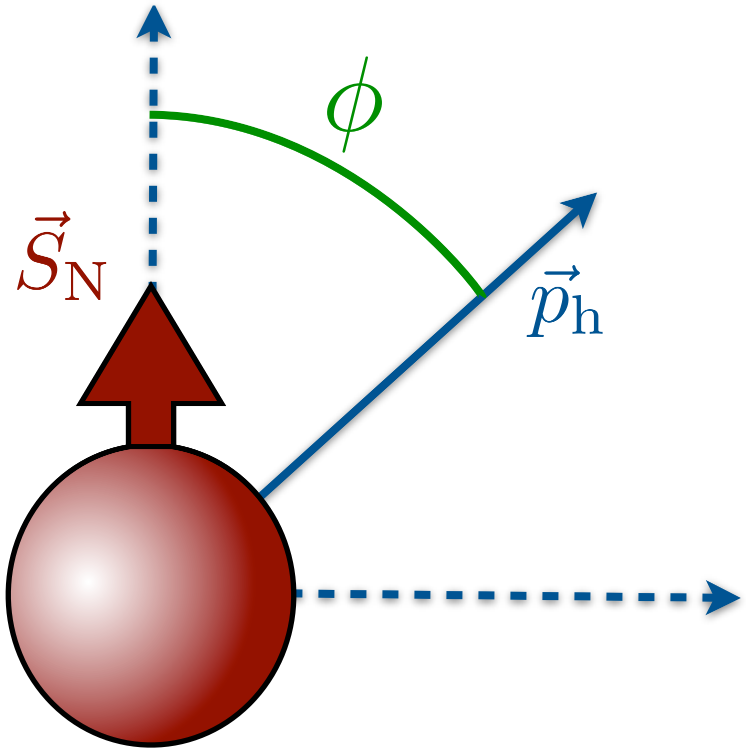
$$A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$



Inclusive hadron electro-production

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

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

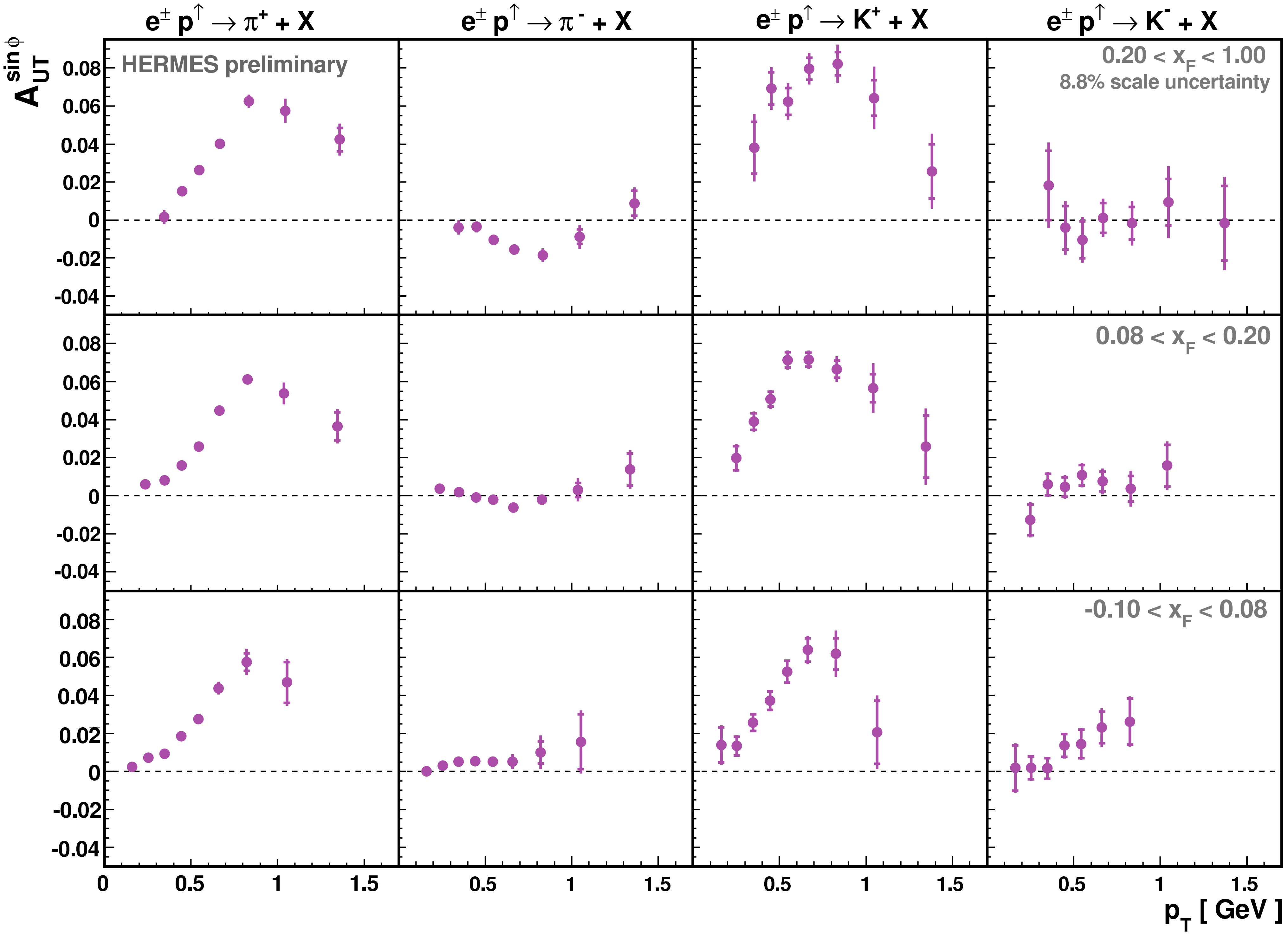


$$A_{UT}(p_T, x_F, \phi) =$$
$$A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

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

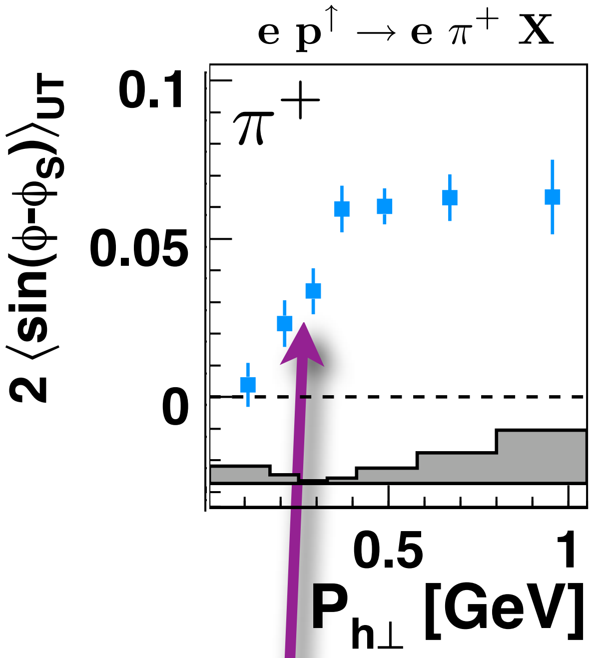
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

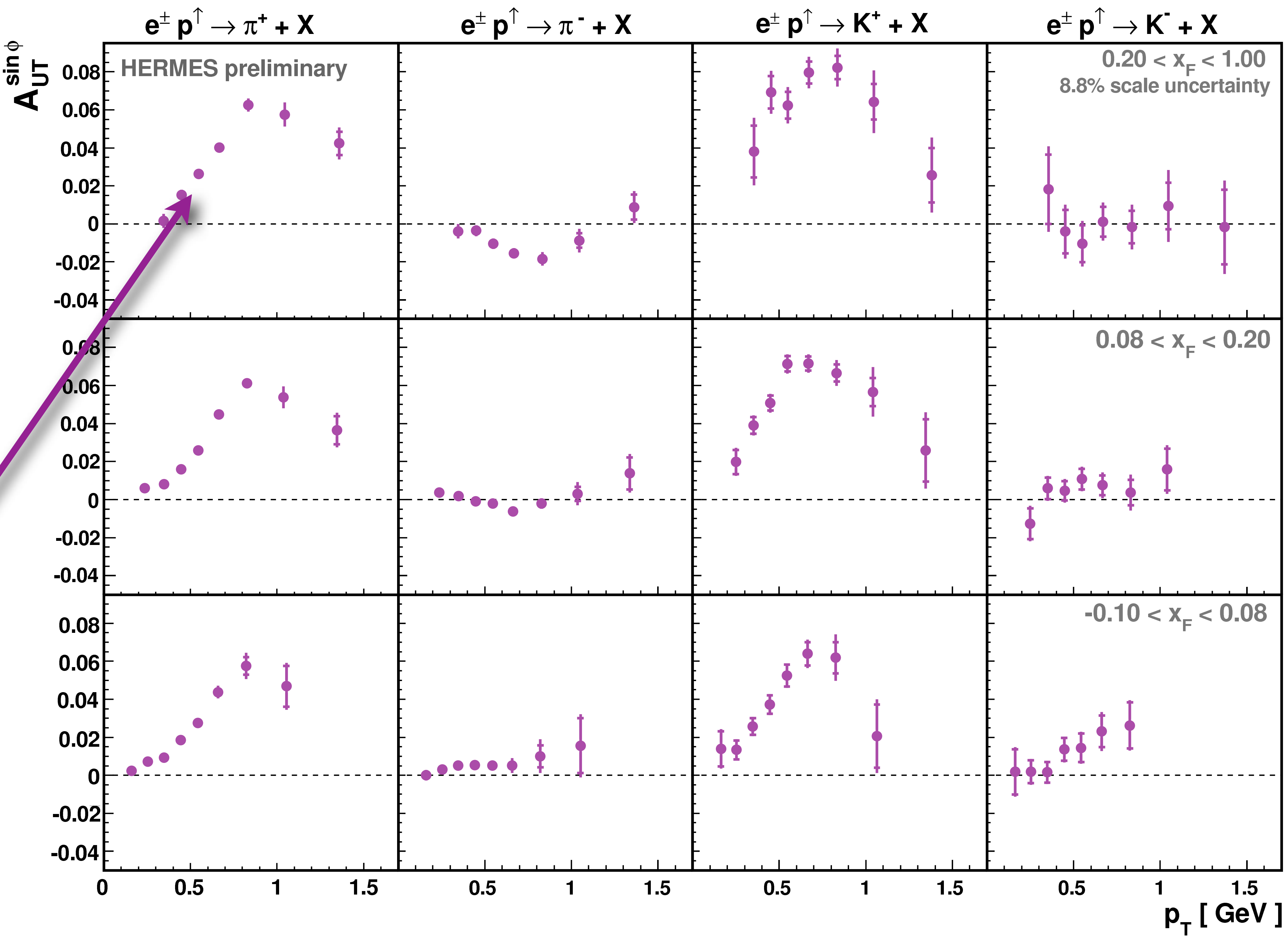
Inclusive hadrons in ep



	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