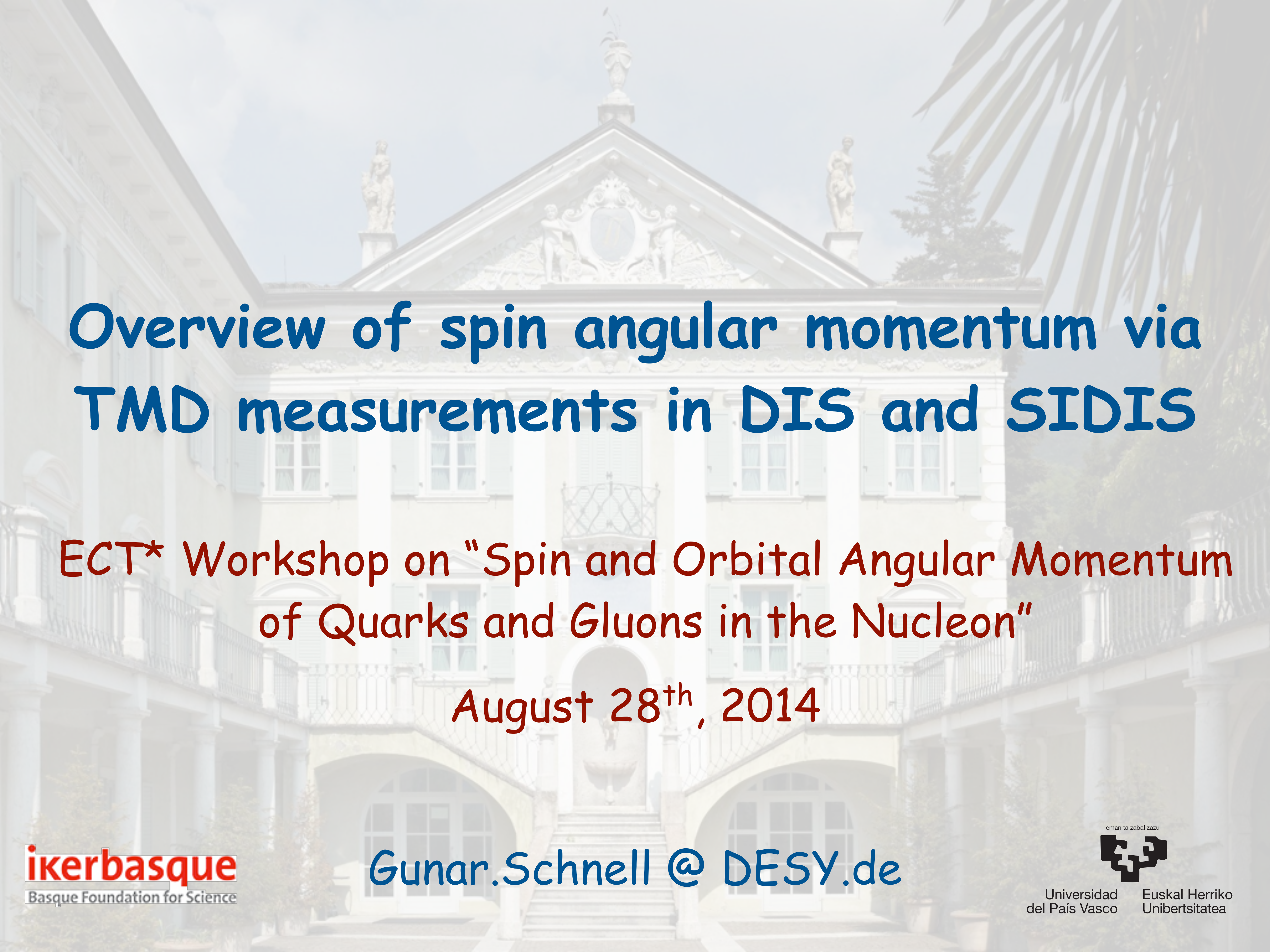


Overview of spin angular momentum via TMD measurements in DIS and SIDIS

ECT* Workshop on “Spin and Orbital Angular Momentum of Quarks and Gluons in the Nucleon”

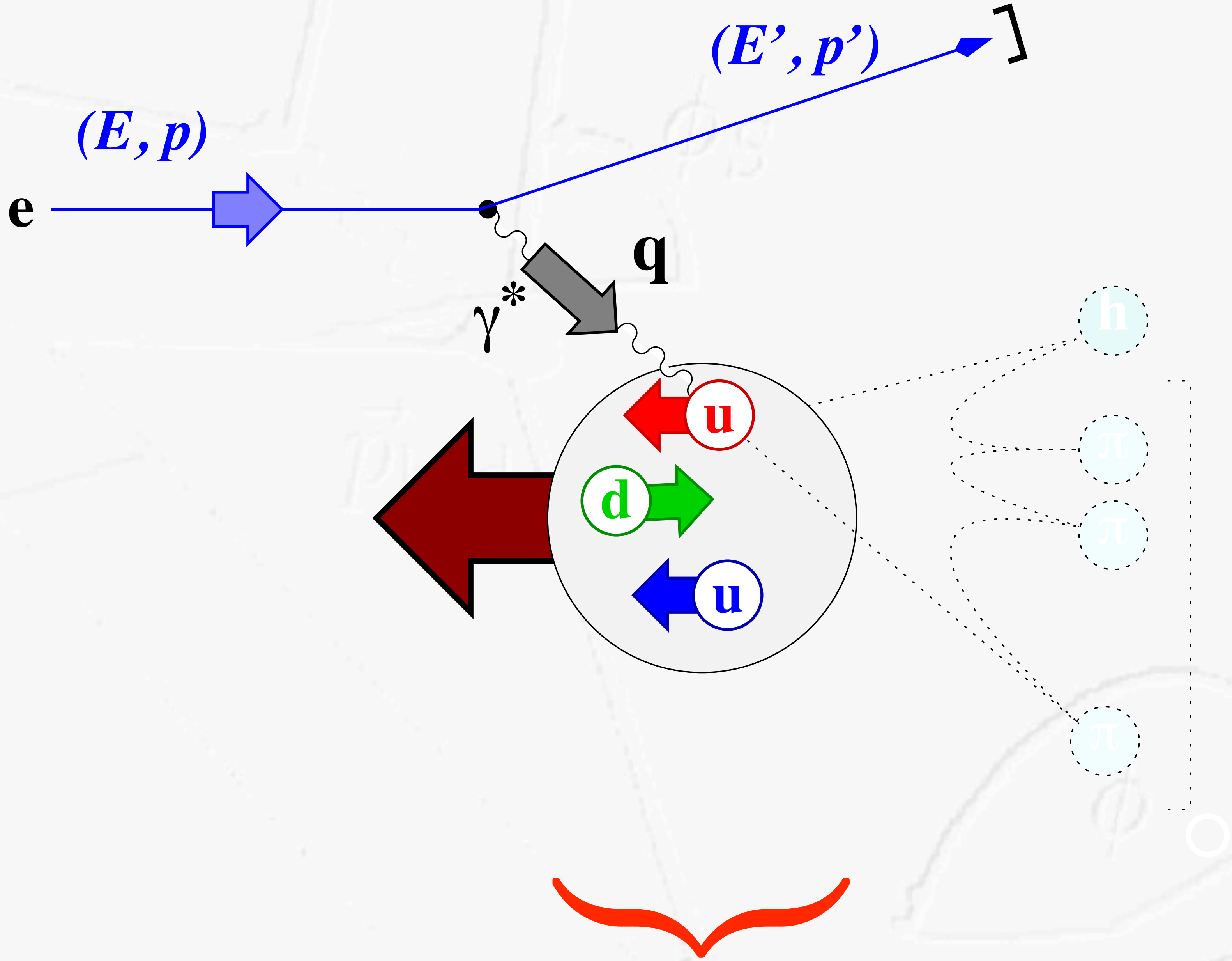
August 28th, 2014

Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Deep-inelastic scattering

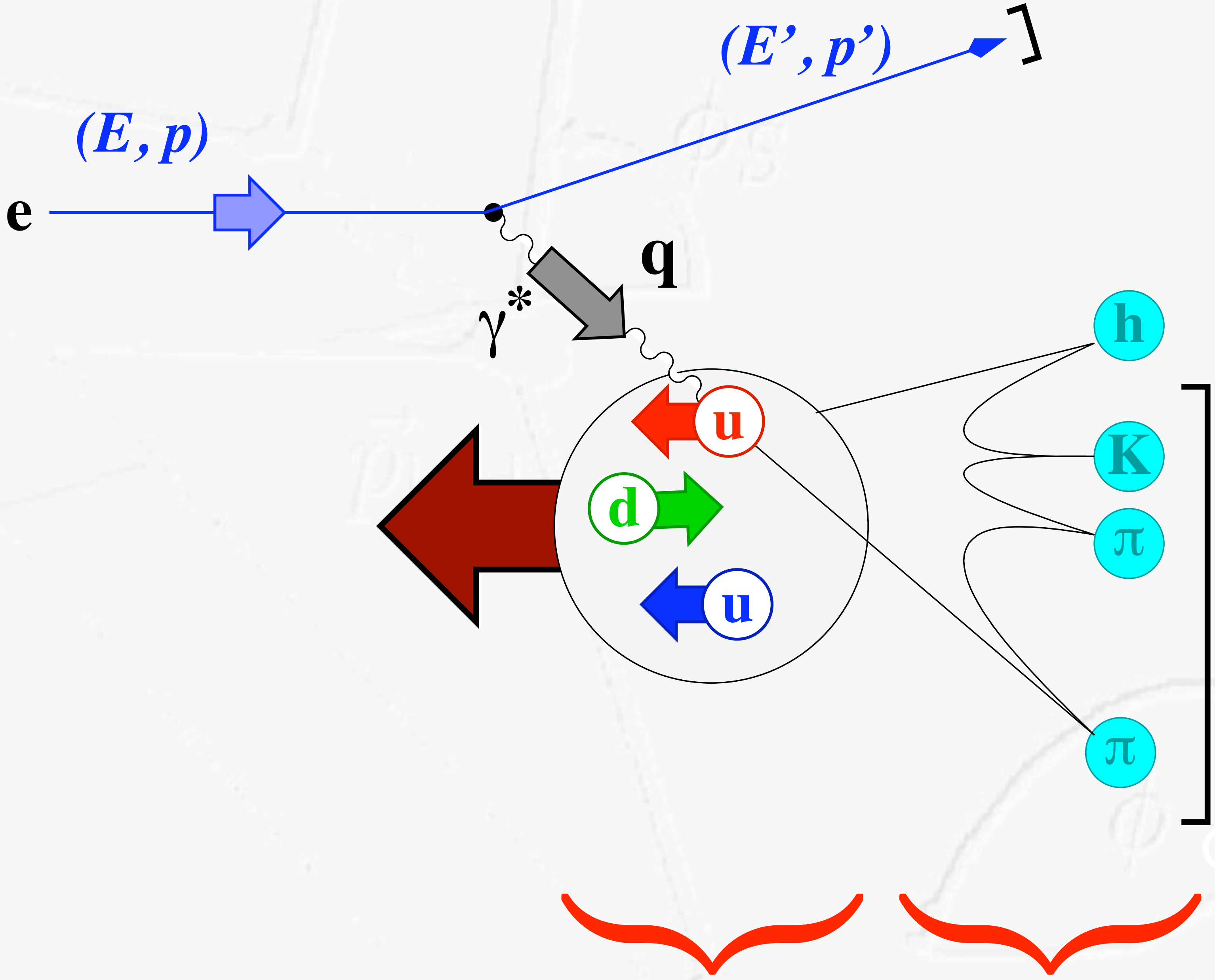


inclusive

factorization:

parton
distributions

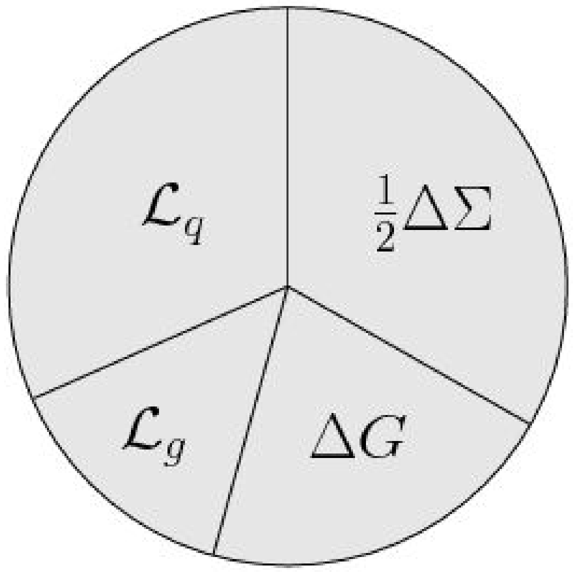
Deep-inelastic scattering



semi-inclusive

factorization: parton distributions fragmentation functions

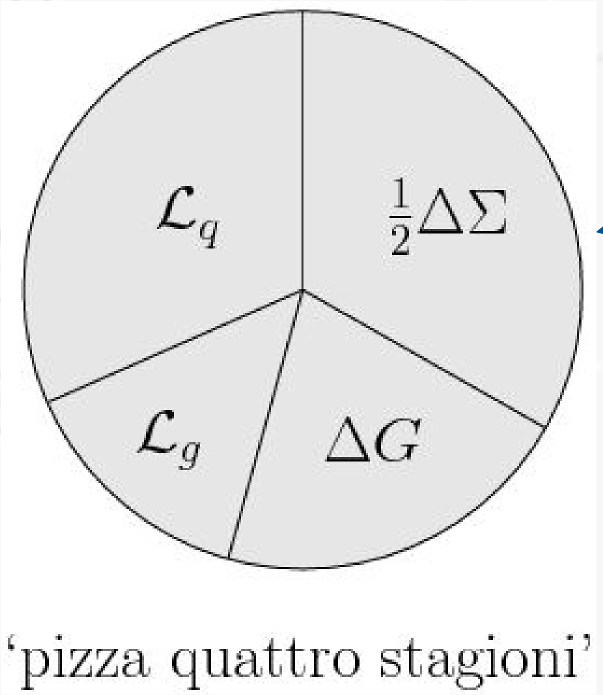
Access to angular momentum in (SI)DIS



‘pizza quattro stagioni’

[M. Burkardt]

Access to angular momentum in (SI)DIS

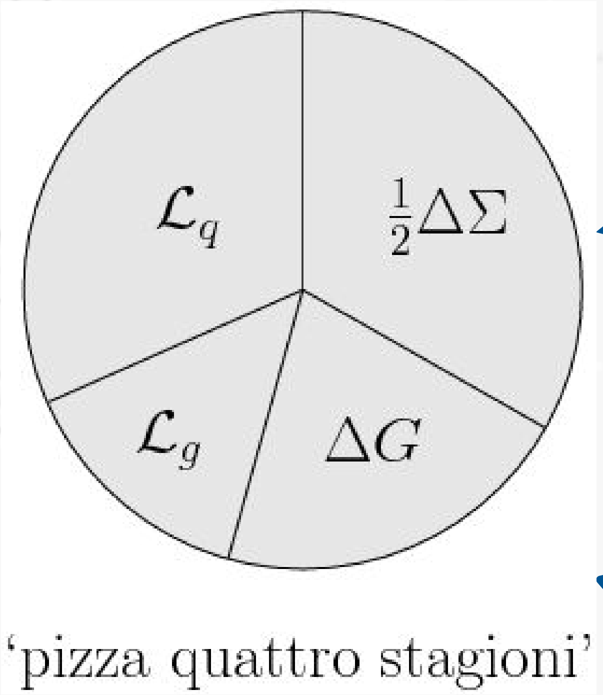


'pizza quattro stagioni'

[M. Burkardt]

(semi-)inclusive
longitudinal double-spin
asymmetries

Access to angular momentum in (SI)DIS



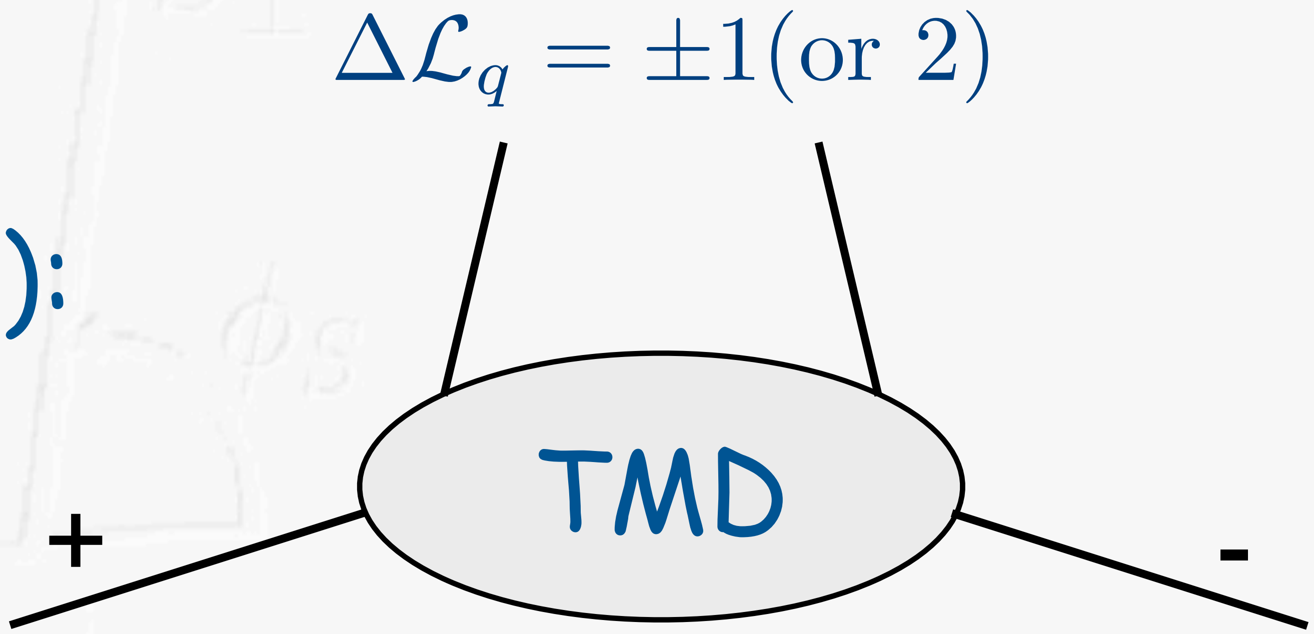
'pizza quattro stagioni'

[M. Burkardt]

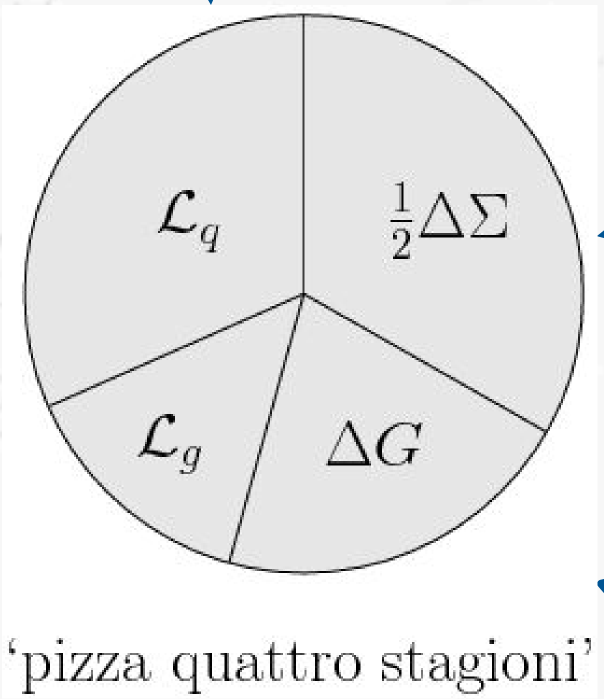
(semi-)inclusive longitudinal double-spin asymmetries

evolution

Access to angular momentum in (SI)DIS



TMDs? (SIDIS):



'pizza quattro stagioni'

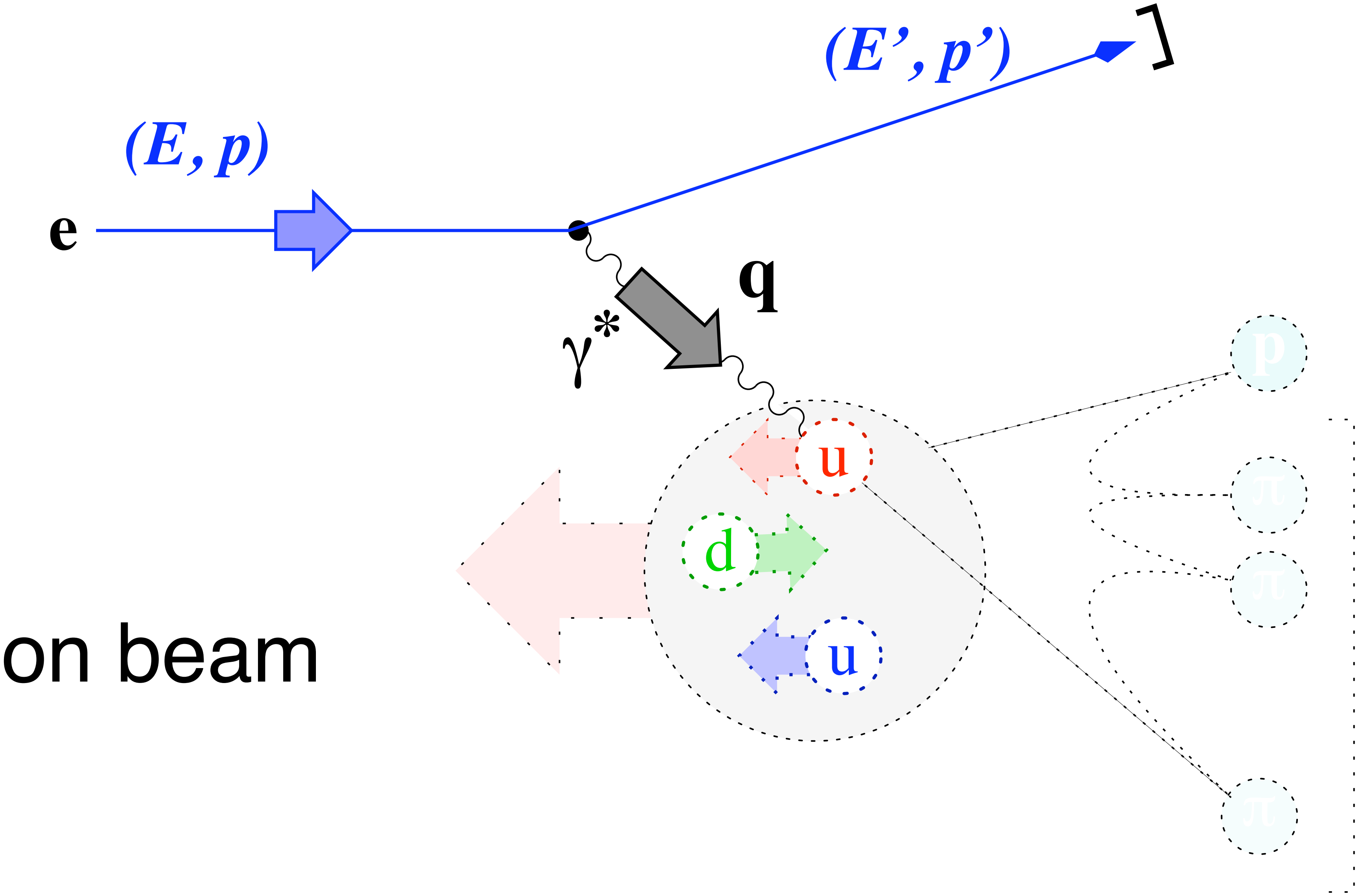
[M. Burkardt]

(semi-)inclusive longitudinal double-spin asymmetries

evolution

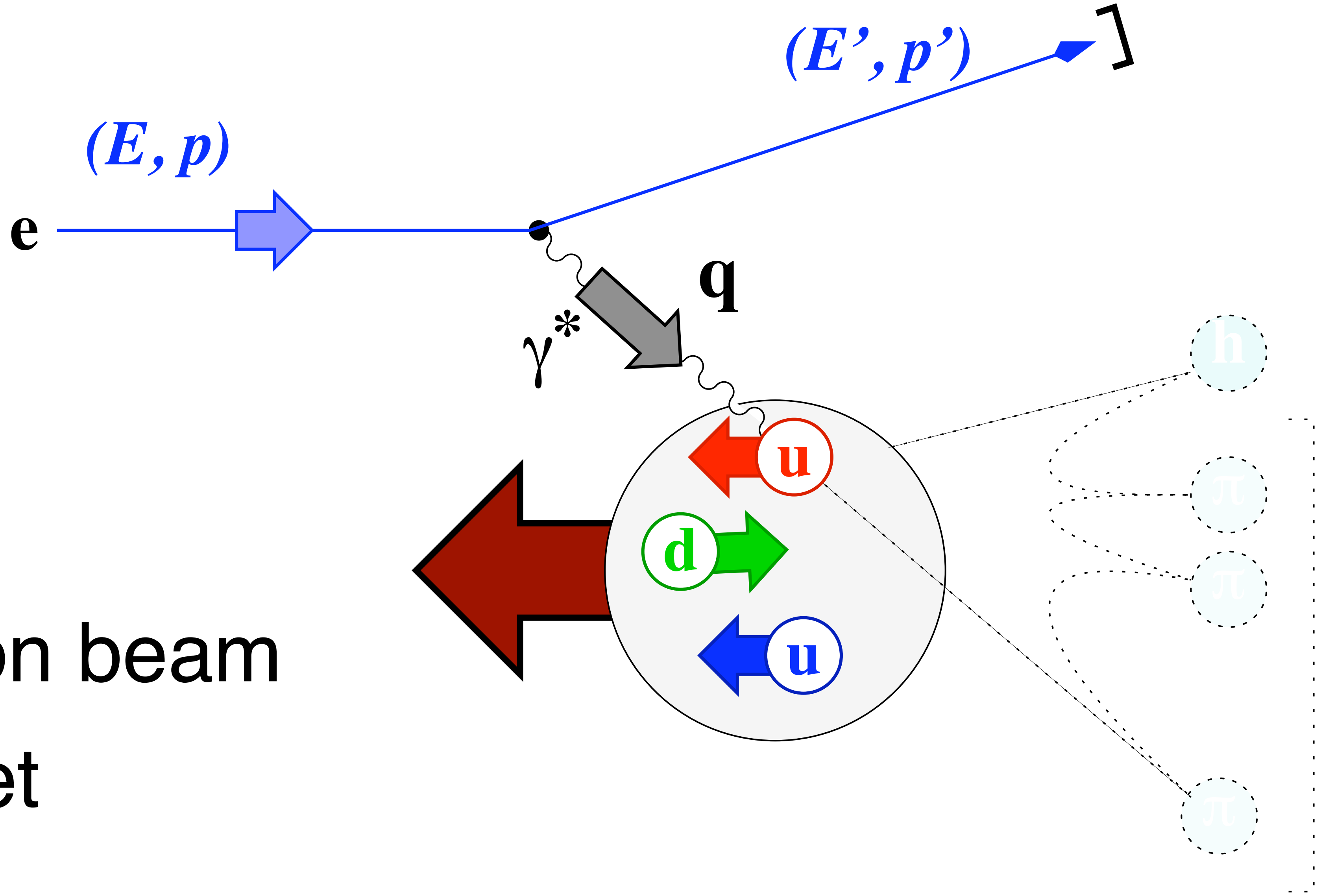
Overview of s~~p~~in angular momentum via T~~M~~D measurements in DIS and SIDIS

Experimental Prerequisites



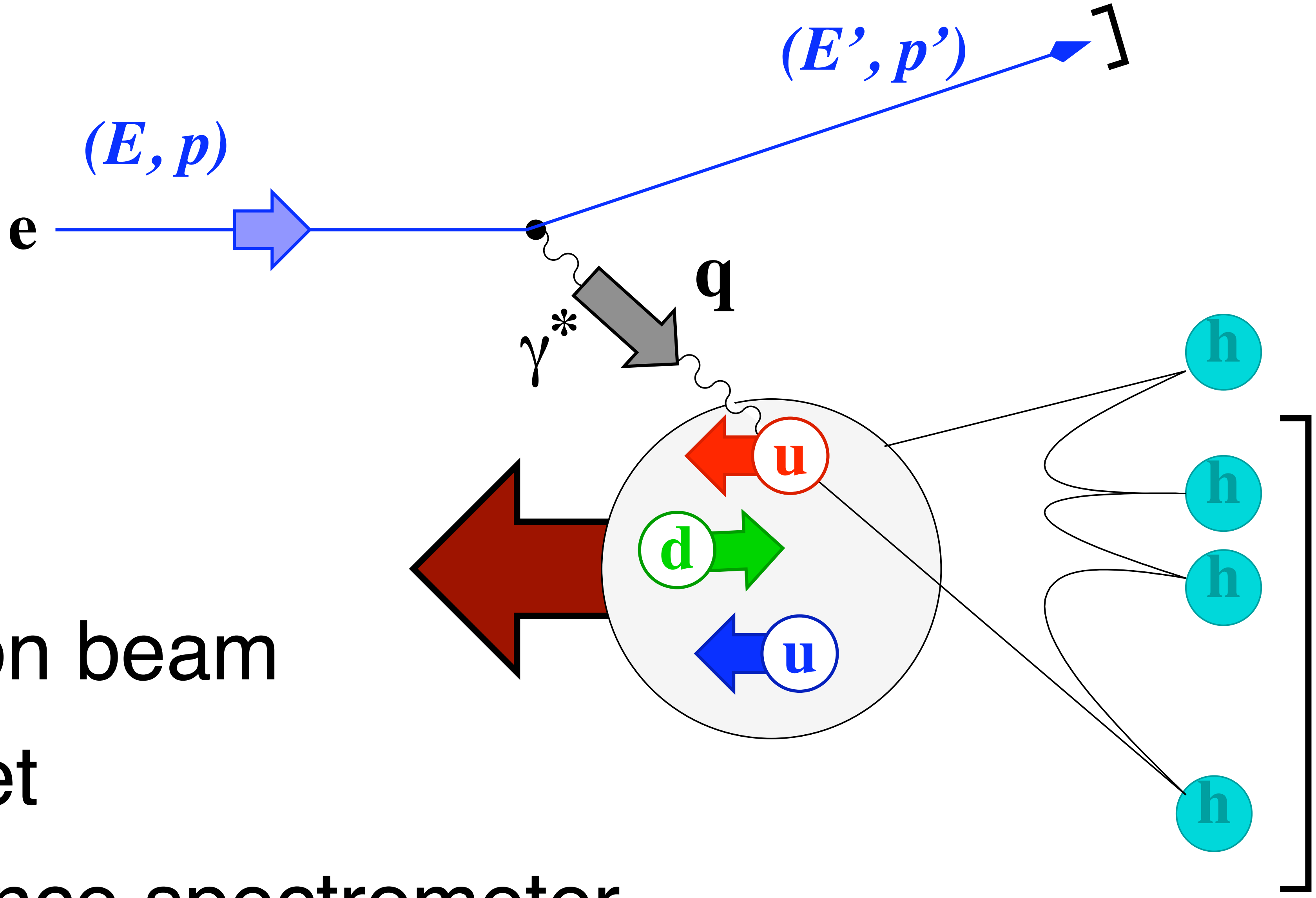
- Polarized lepton beam

Experimental Prerequisites



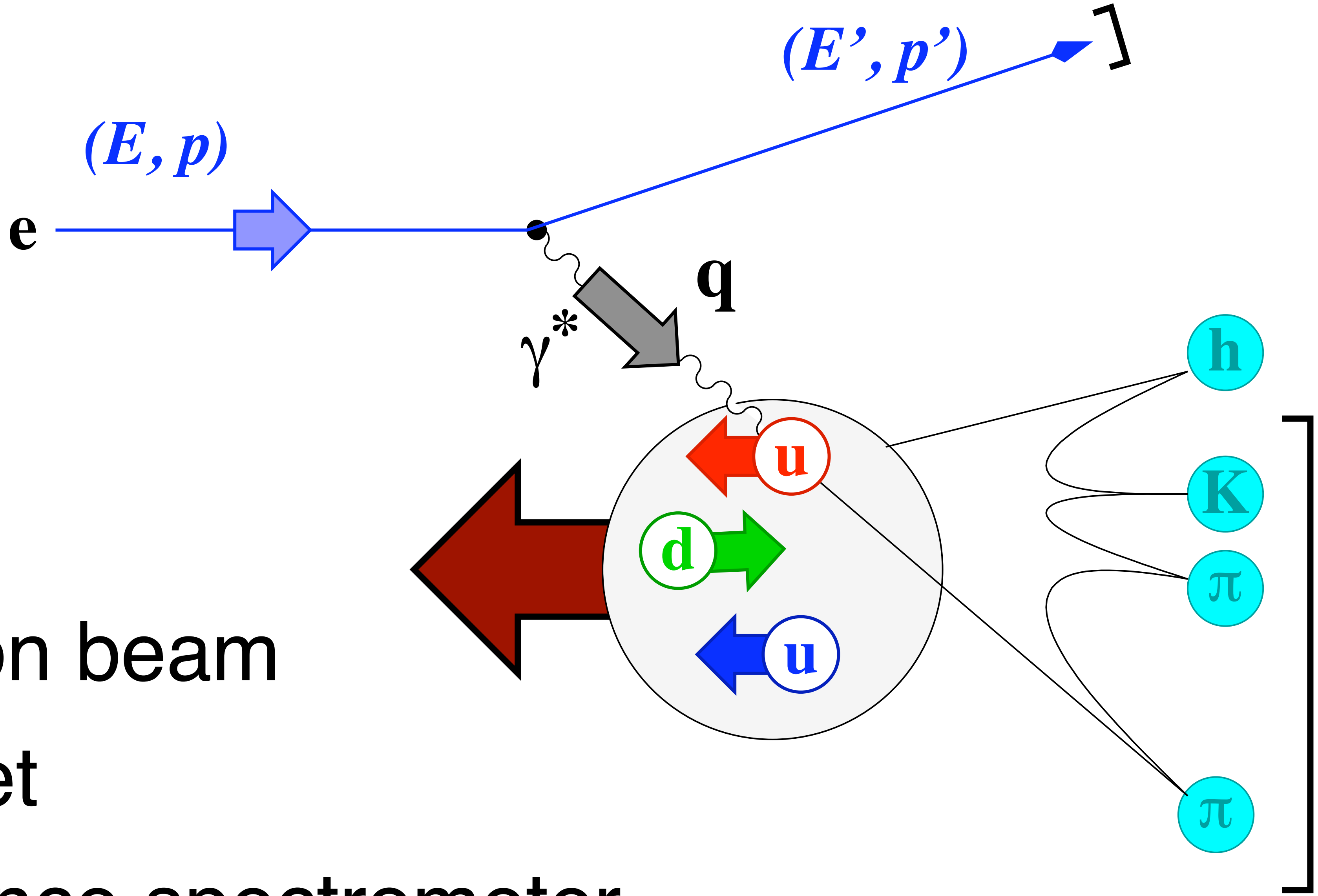
- Polarized lepton beam
- Polarized target

Experimental Prerequisites



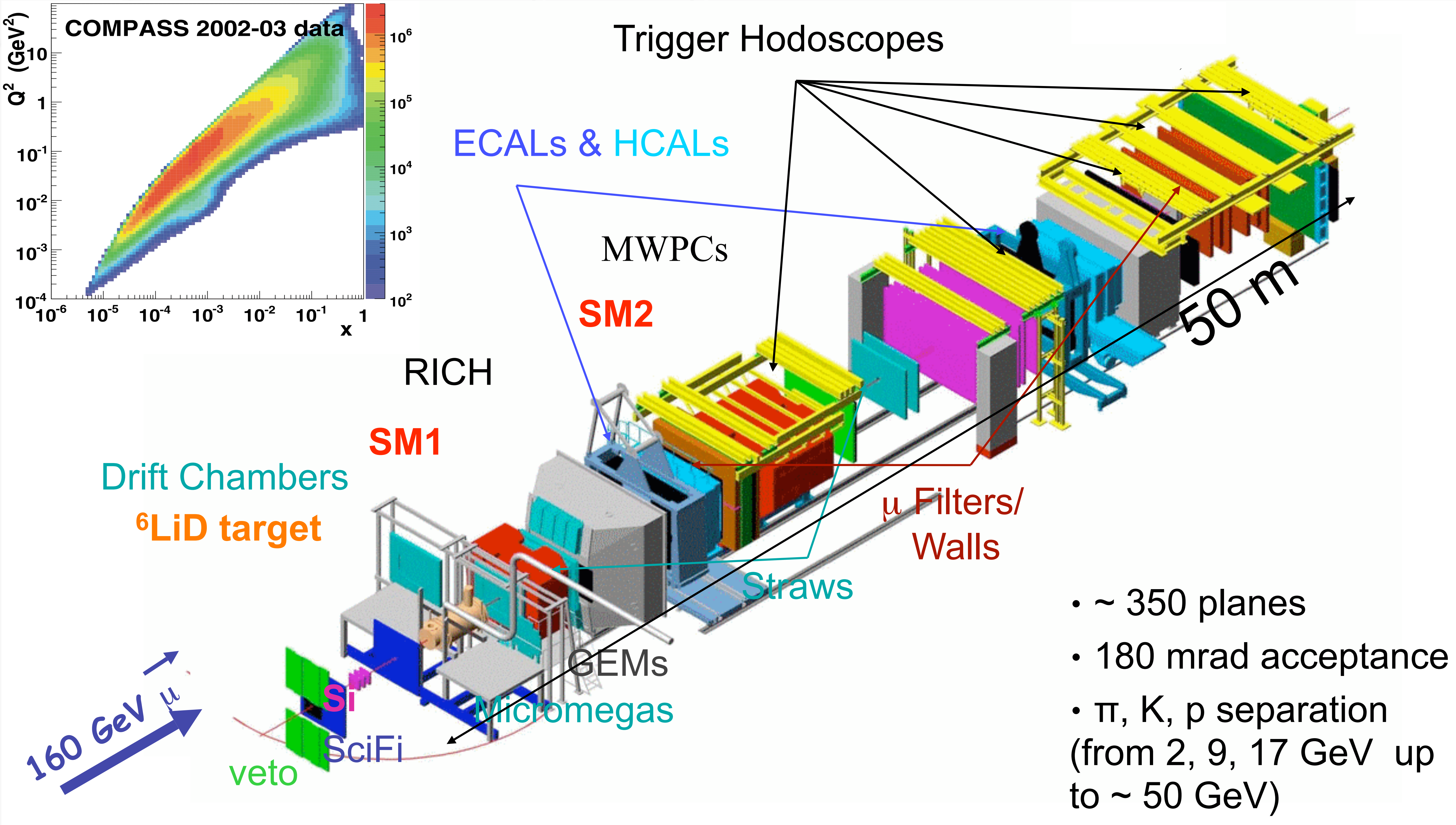
- Polarized lepton beam
- Polarized target
- Large acceptance spectrometer

Experimental Prerequisites



- Polarized lepton beam
- Polarized target
- Large acceptance spectrometer
- Good Particle IDentification (PID)

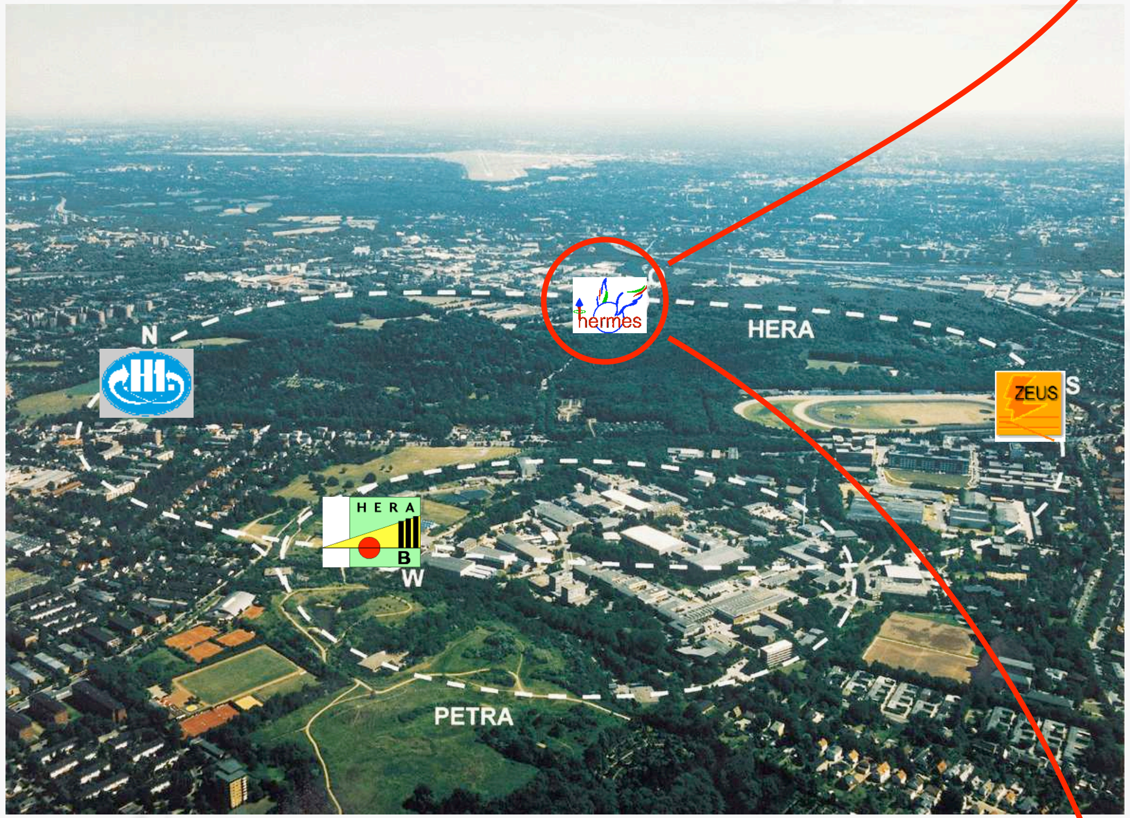
The COMPASS experiment @ CERN

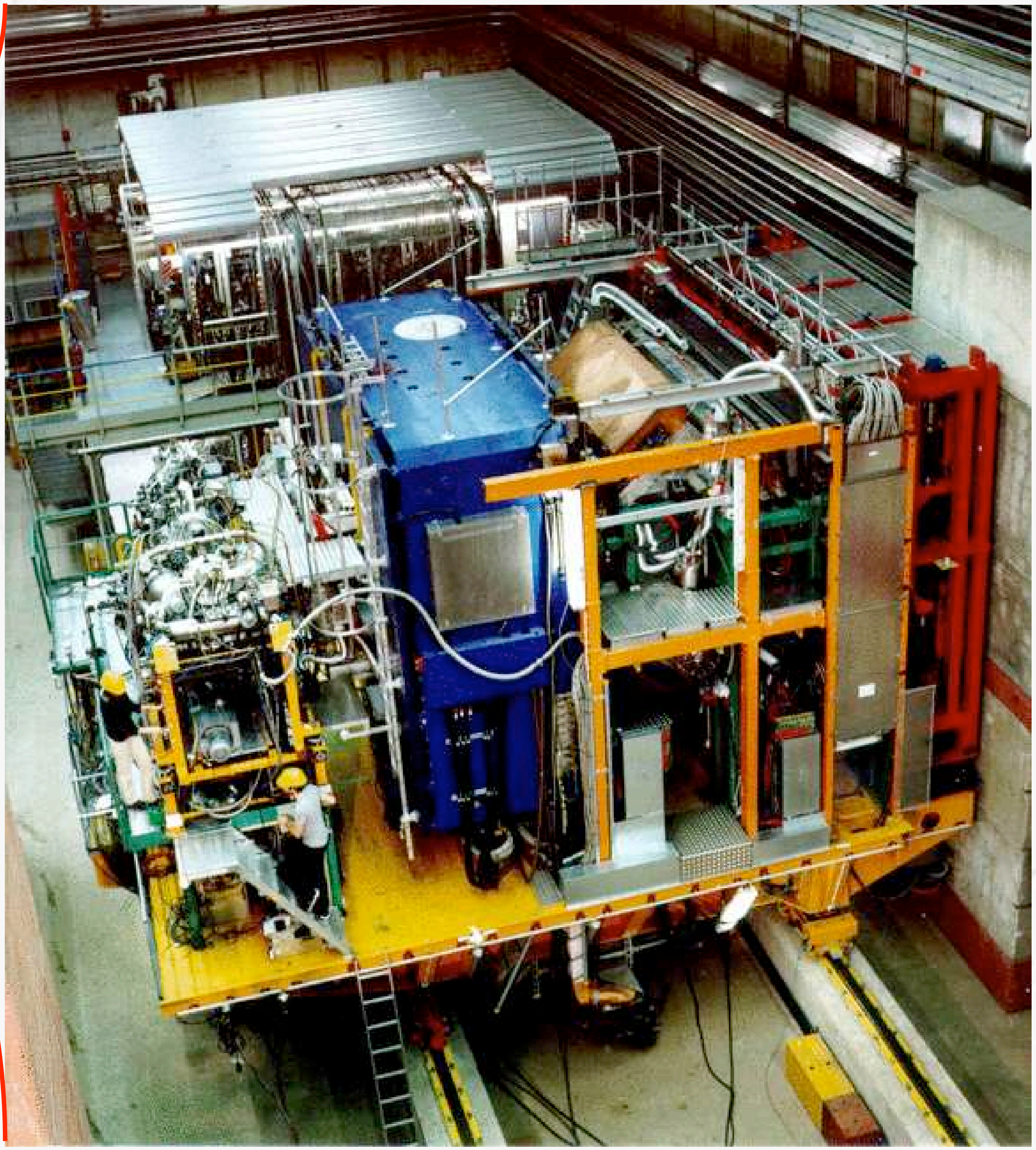


- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

HERMES Experiment (†2007) @ DESY

27.6 GeV polarized e^+/e^- beam scattered off ...

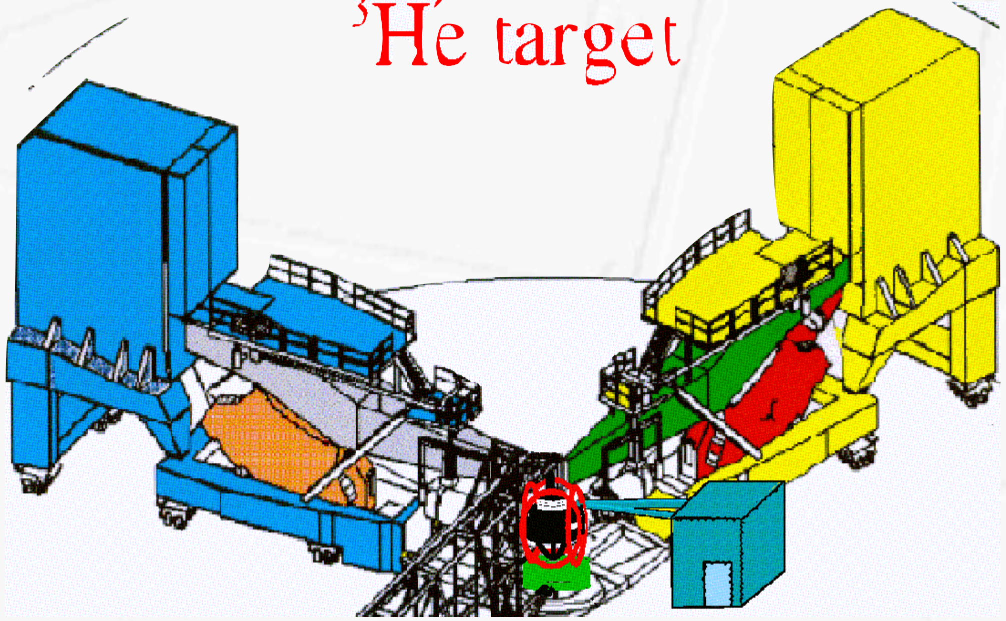


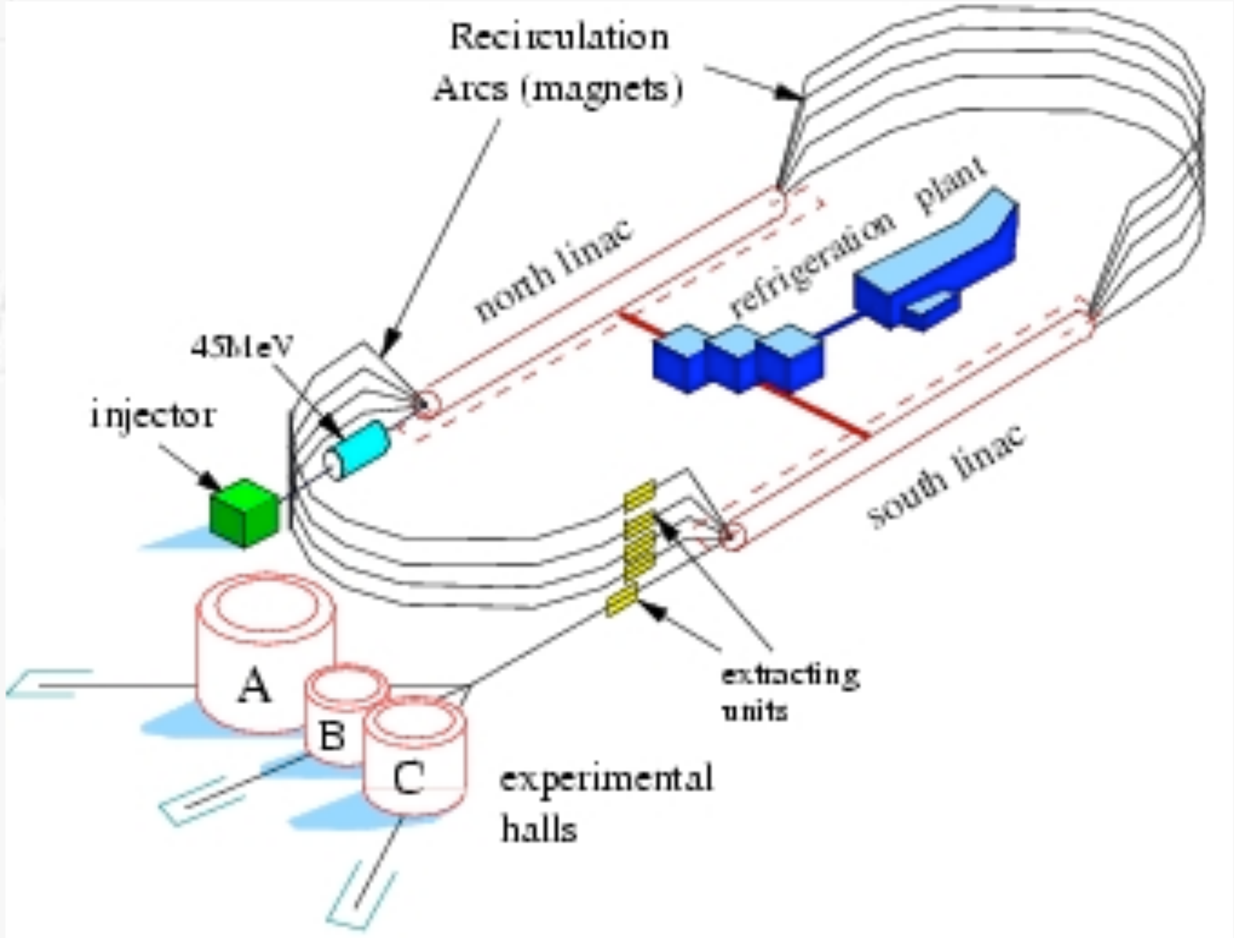


unpolarized (H, D, He,..., Xe) as well as **transversely (H)** and longitudinally (H, D, He) polarized (pure) gas targets

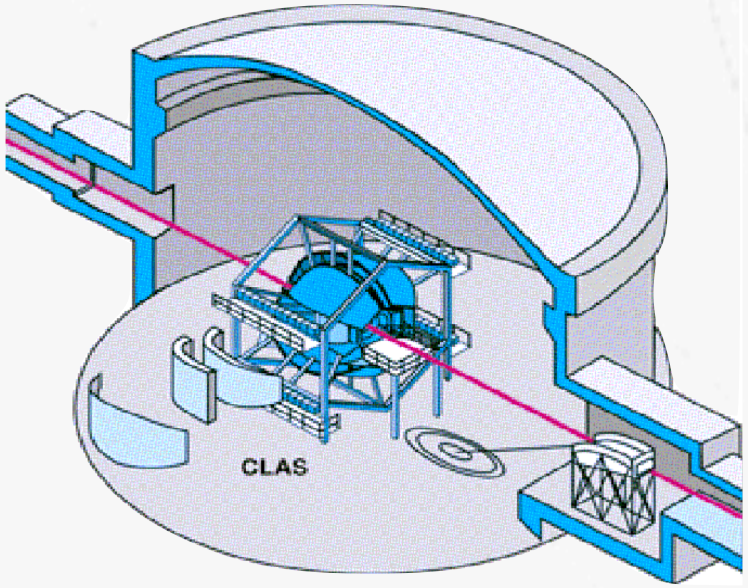
6GeV e^- @ Jefferson Lab

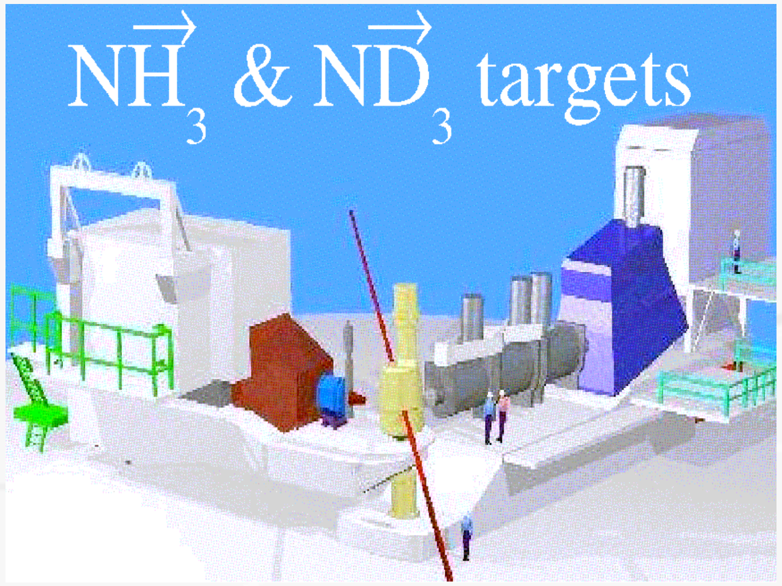
$^3\vec{He}$ target



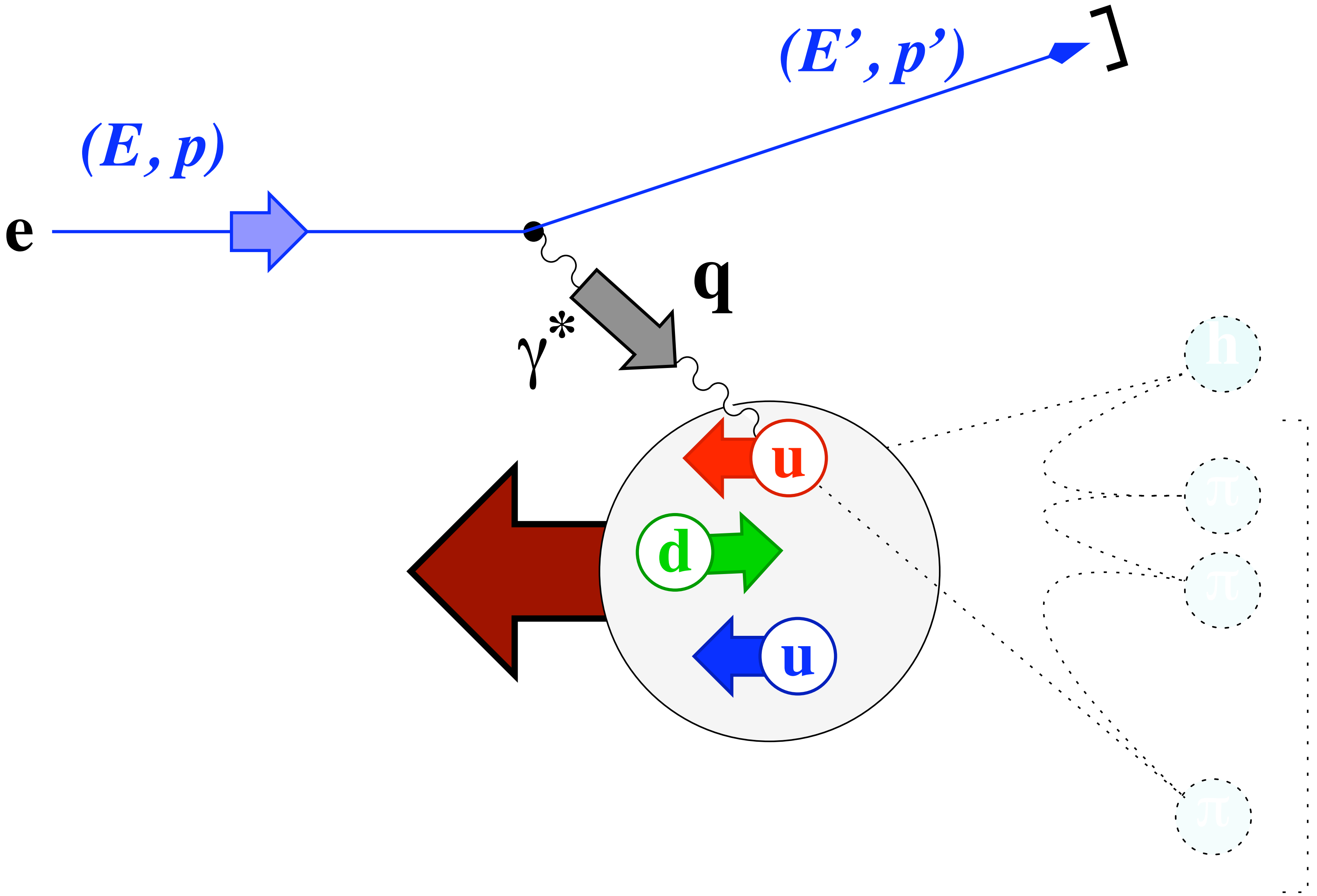


$\vec{NH_3}$ & $\vec{ND_3}$ targets



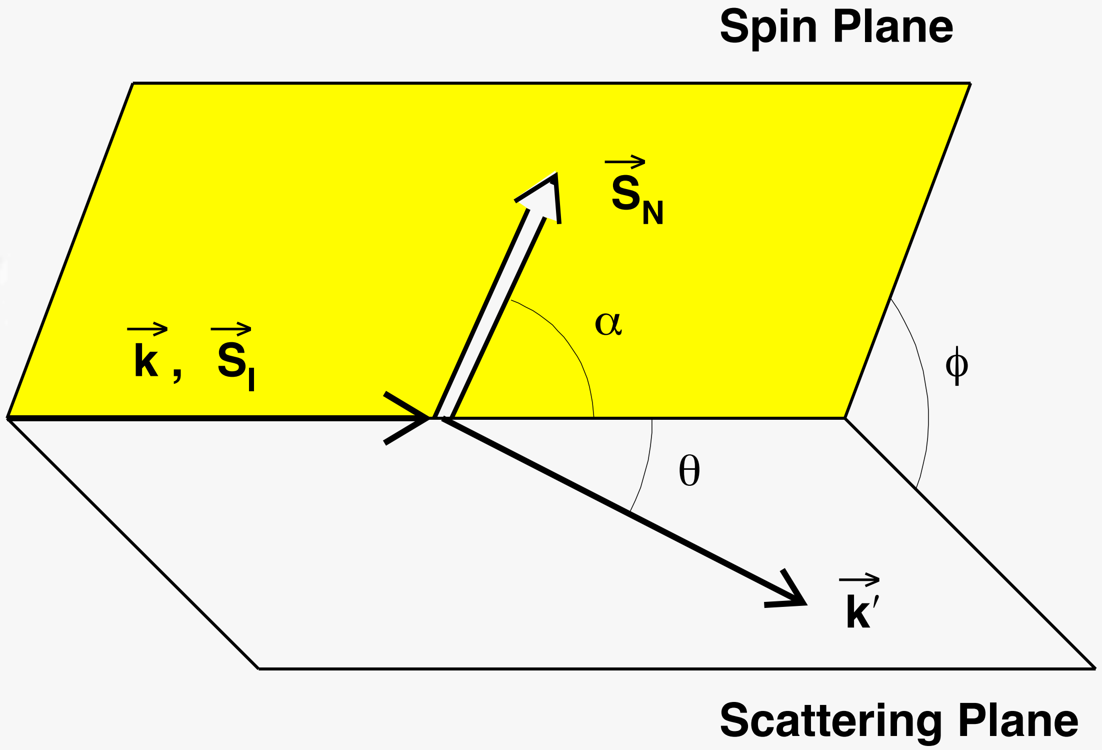

$\vec{NH_3}$ & $\vec{ND_3}$ targets

Inclusive DIS



Inclusive DIS (one-photon exchange)

$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\;\mathrm{d}Q^2}=\frac{2\pi\alpha^2y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$



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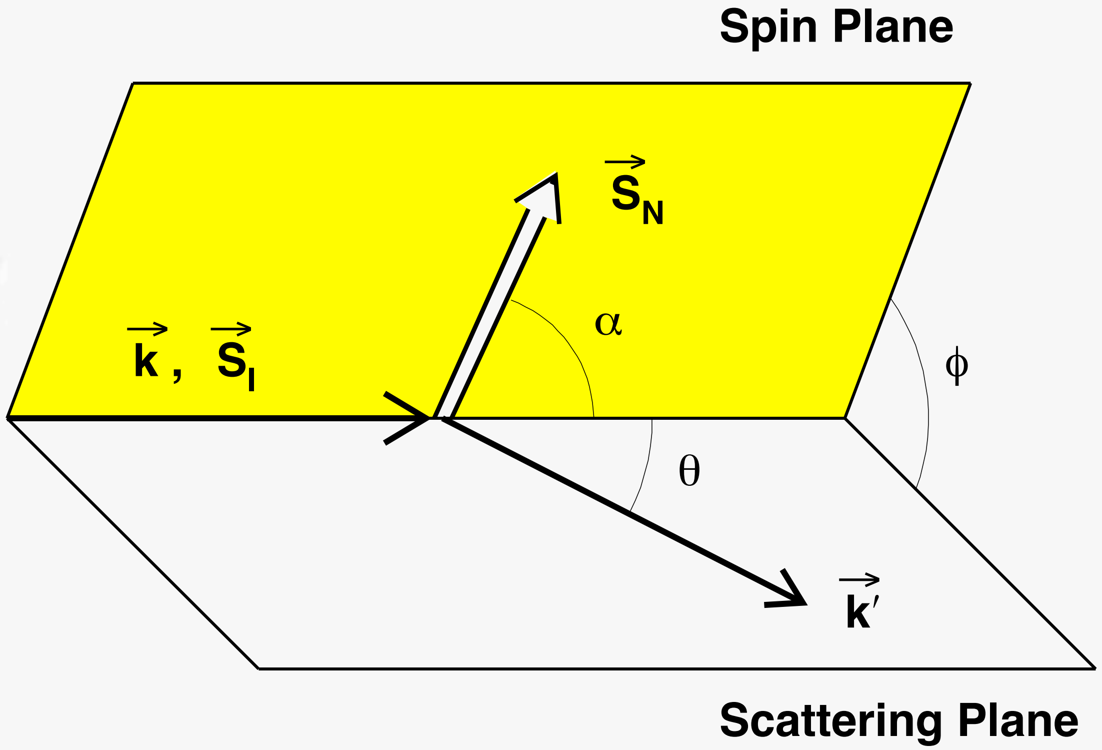
Lepton Tensor



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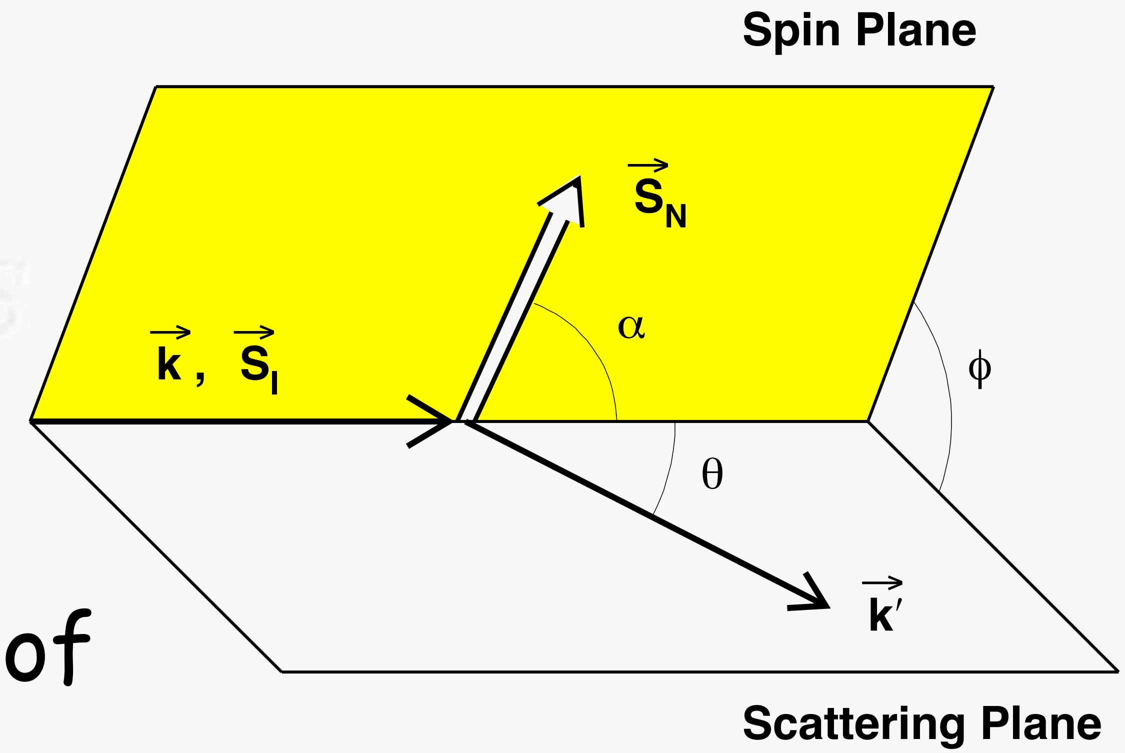
Lepton Tensor

Hadron Tensor parametrized in terms of Structure Functions



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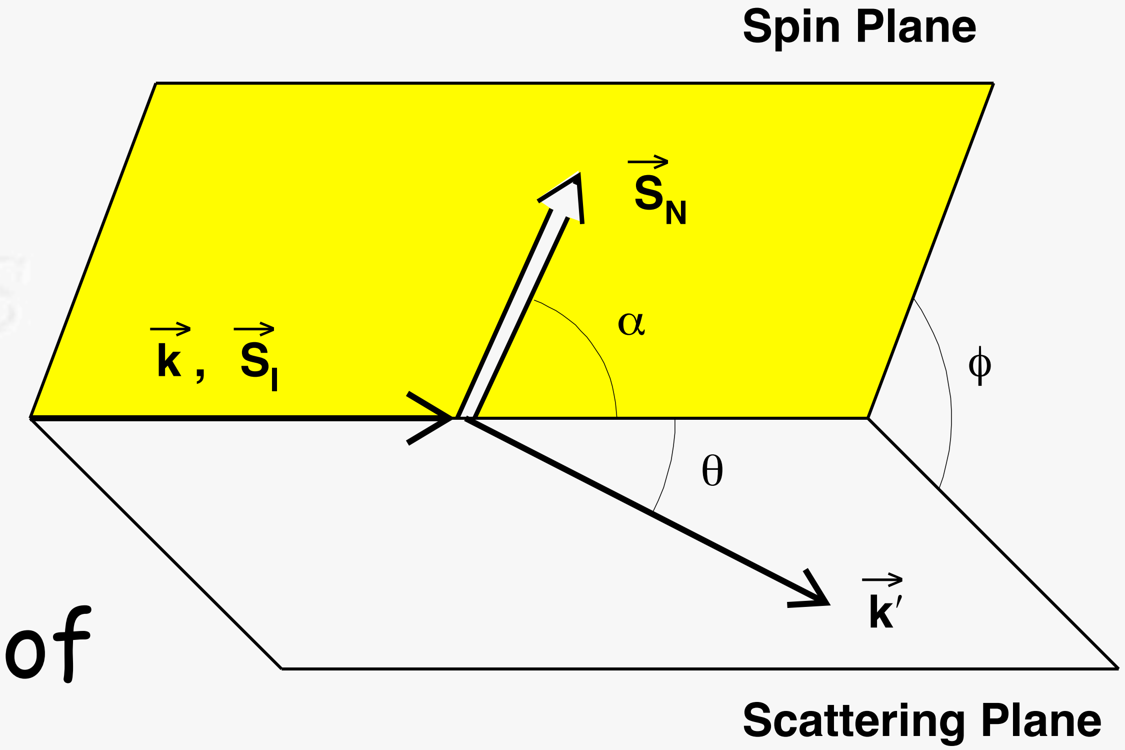
Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions



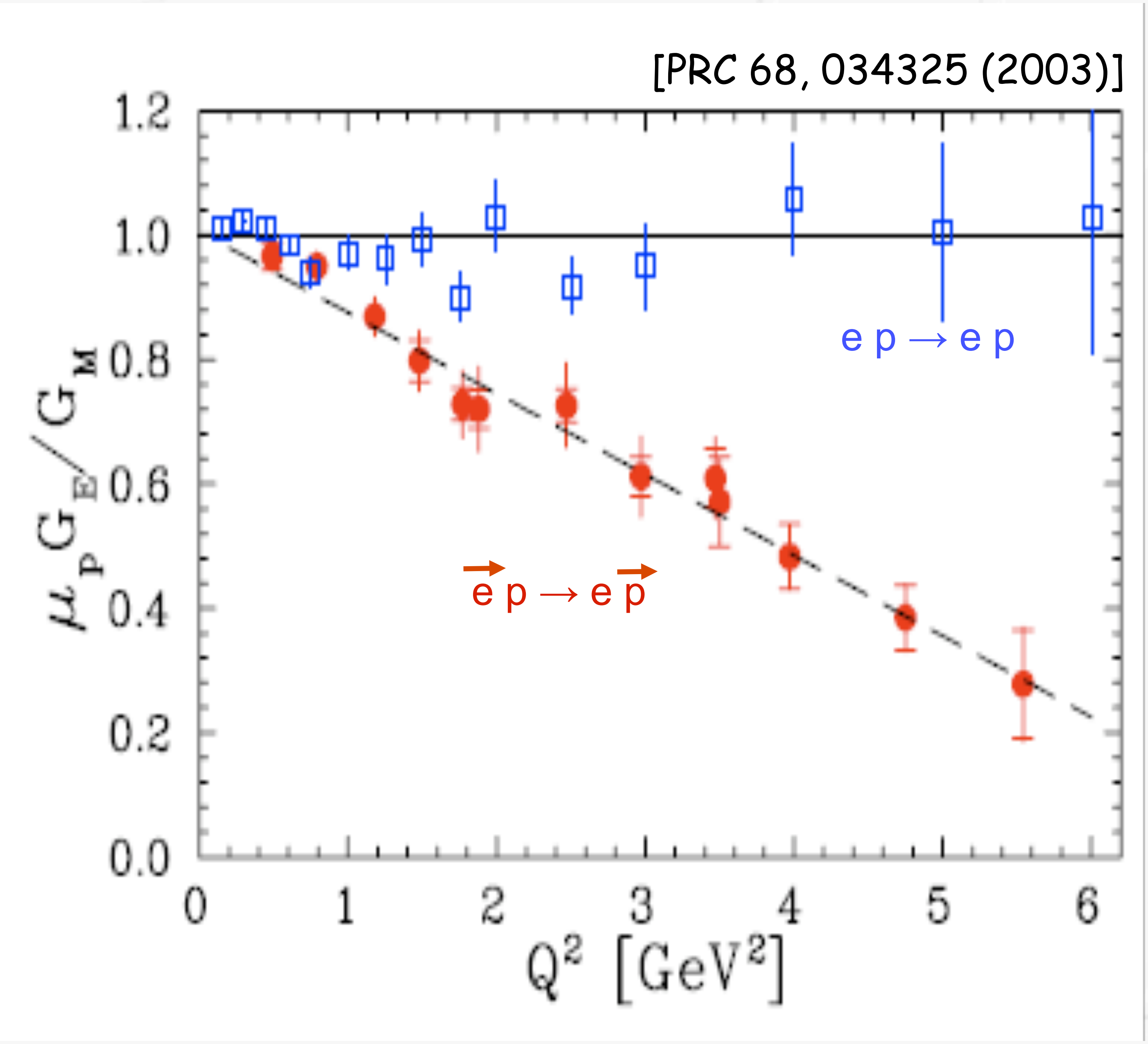
$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$

$$-S_l S_N\cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)\boxed{g_1(x,Q^2)} - \frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right]$$

$$+S_l S_N\sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}\boxed{g_1(x,Q^2)}+\boxed{g_2(x,Q^2)}\right)$$

Check the details!

Check the details!

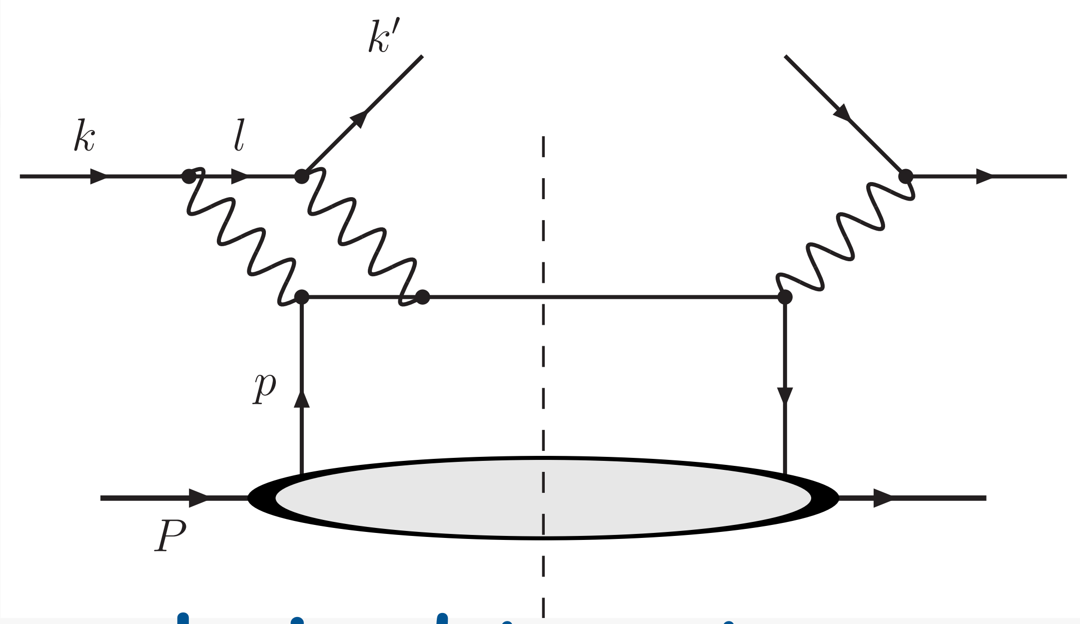


x_F

☛ **two-photon exchange can be important!**

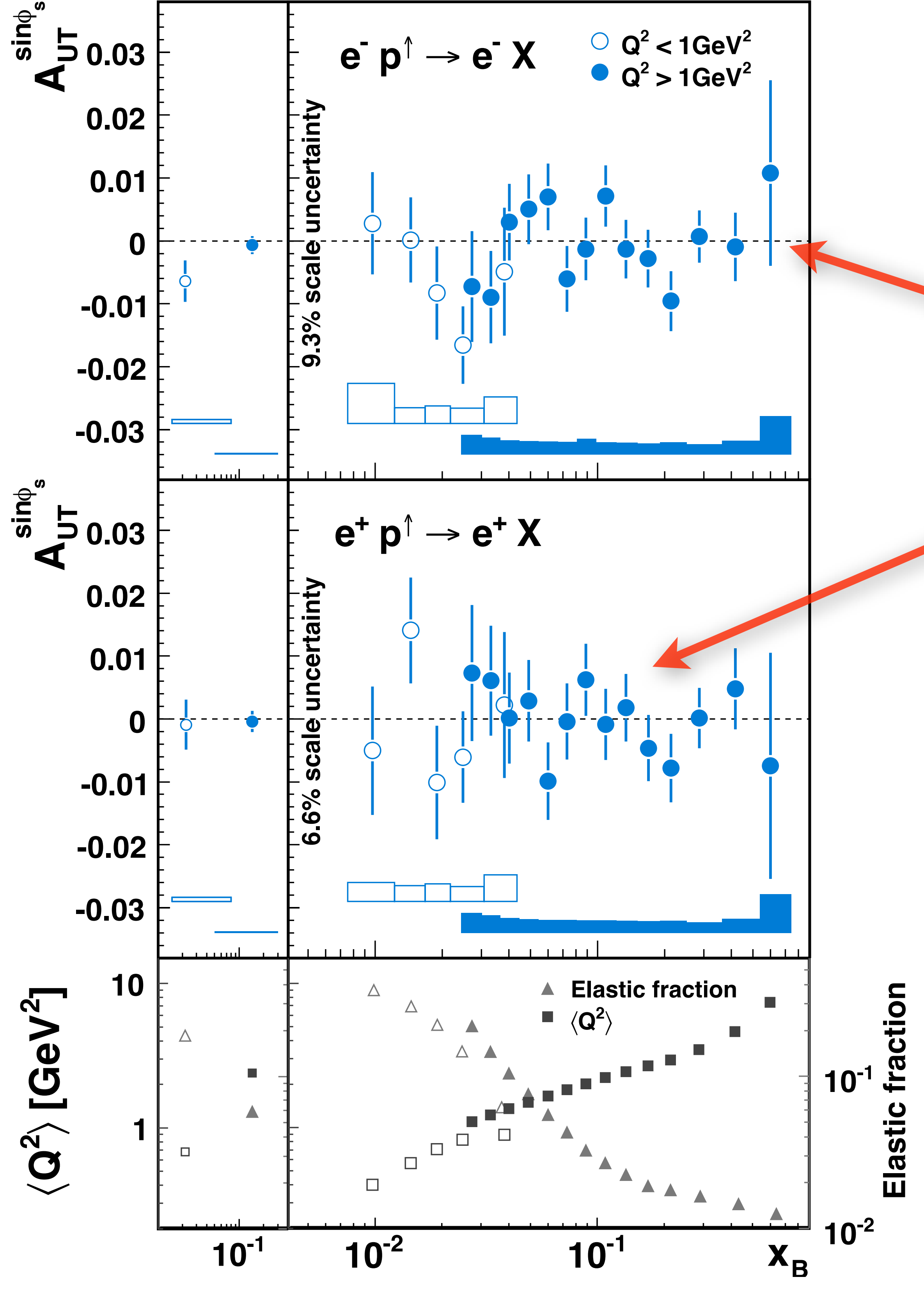
Two-photon exchange

- Candidate to explain discrepancy in form-factor measurements



- **Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets**
- **cross section proportional to S(kxk') - either measure left-right asymmetries or sine modulation**
- sensitive to beam charge due to odd number of e.m. couplings to beam

Signatures of two-photon exchange



A. Airapetian et al., PLB 682 (2010) 350

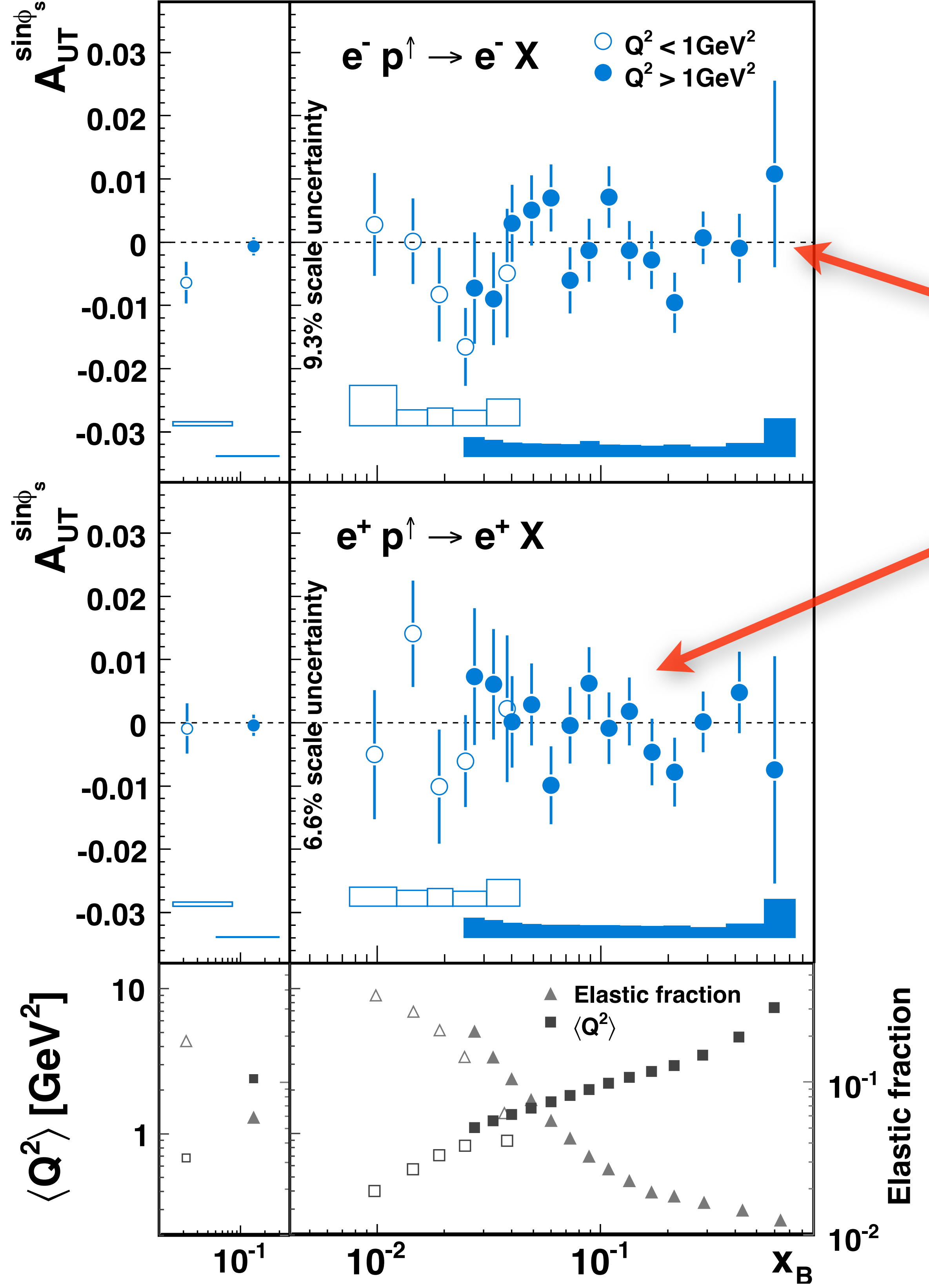
Beam	$A_{UT}^{\sin\phi_S}$ $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(stat.) $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(syst.) $\times 10^{-3}$	$\langle x_B \rangle$	$\langle Q^2 \rangle$ [GeV^2]
e^+	-0.61	3.97	0.63	0.02	0.68
e^-	-6.55	3.40	0.63		
e^+	-0.60	1.70	0.29	0.14	2.40
e^-	-0.85	1.50	0.29		

consistent with

zero for both e^+/e^-

Signatures of two-photon exchange

A. Airapetian et al., PLB 682 (2010) 350



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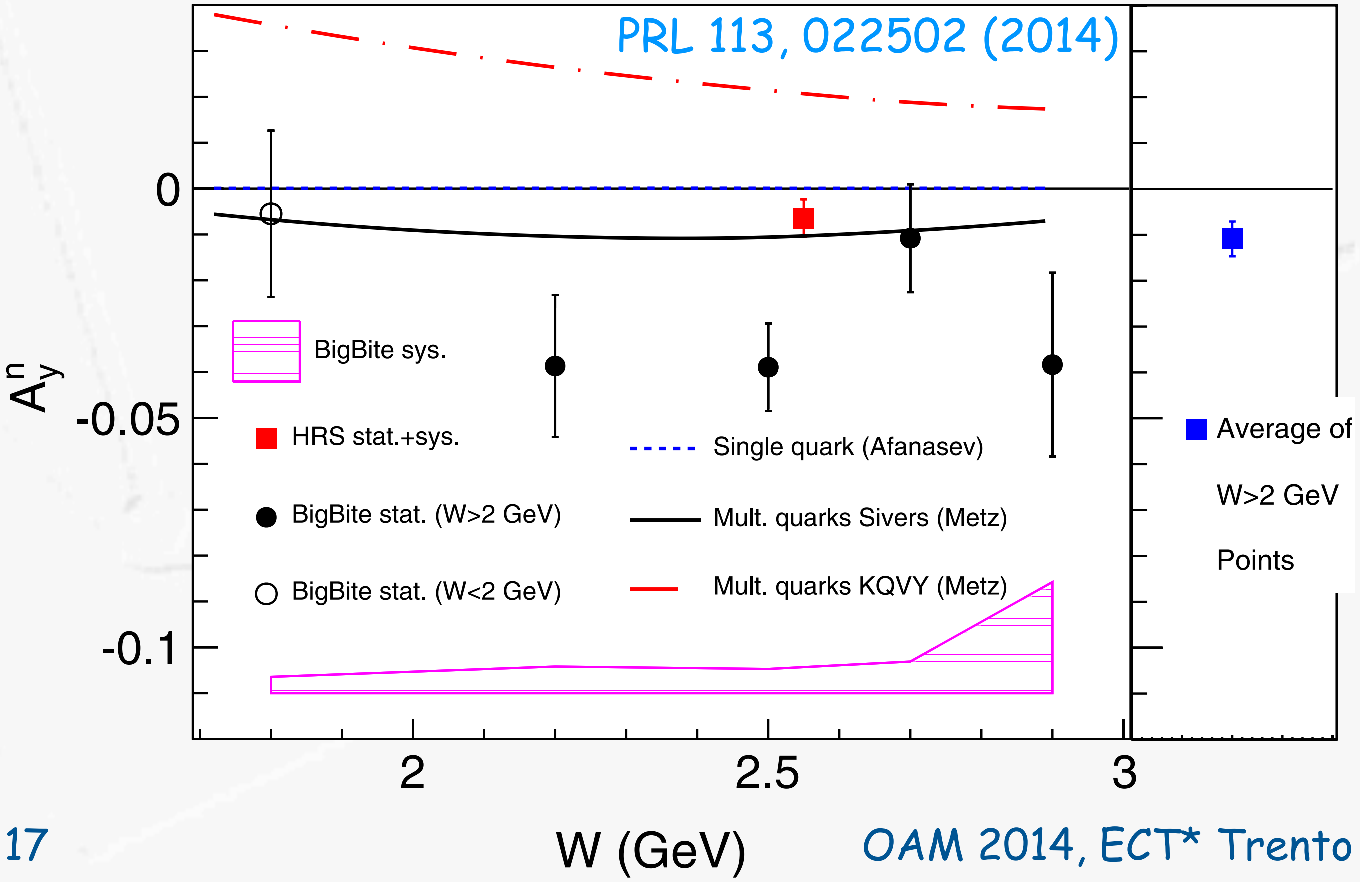
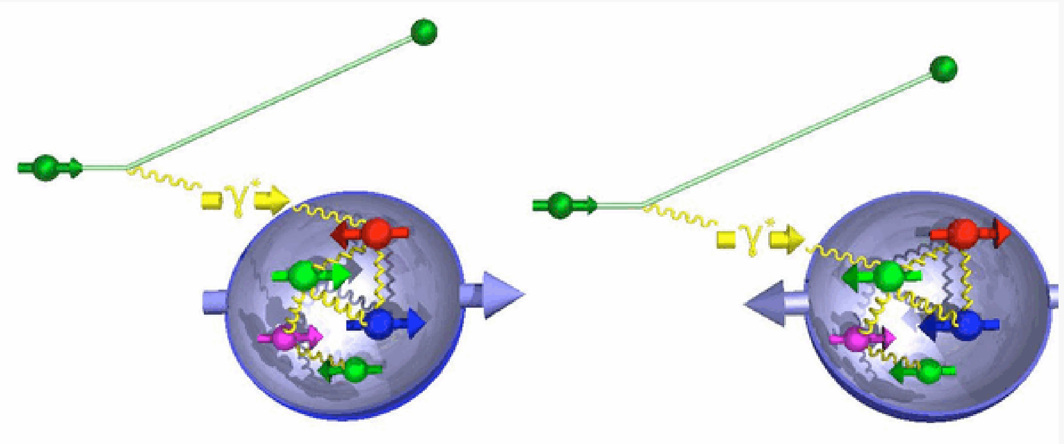
consistent with zero for both e^+/e^-

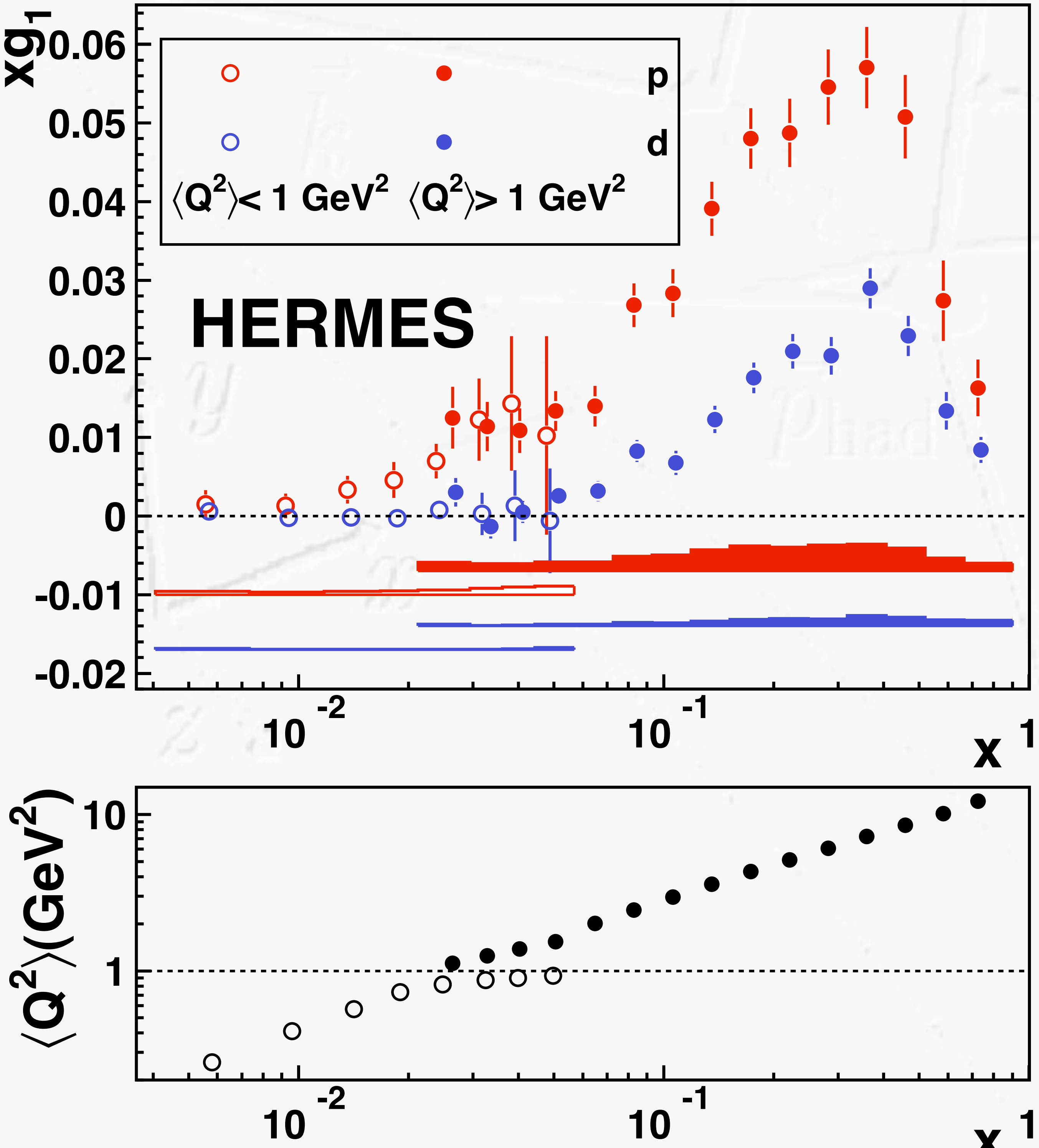
non-zero for neutrons @ lower W


PRL 113, 022502 (2014)

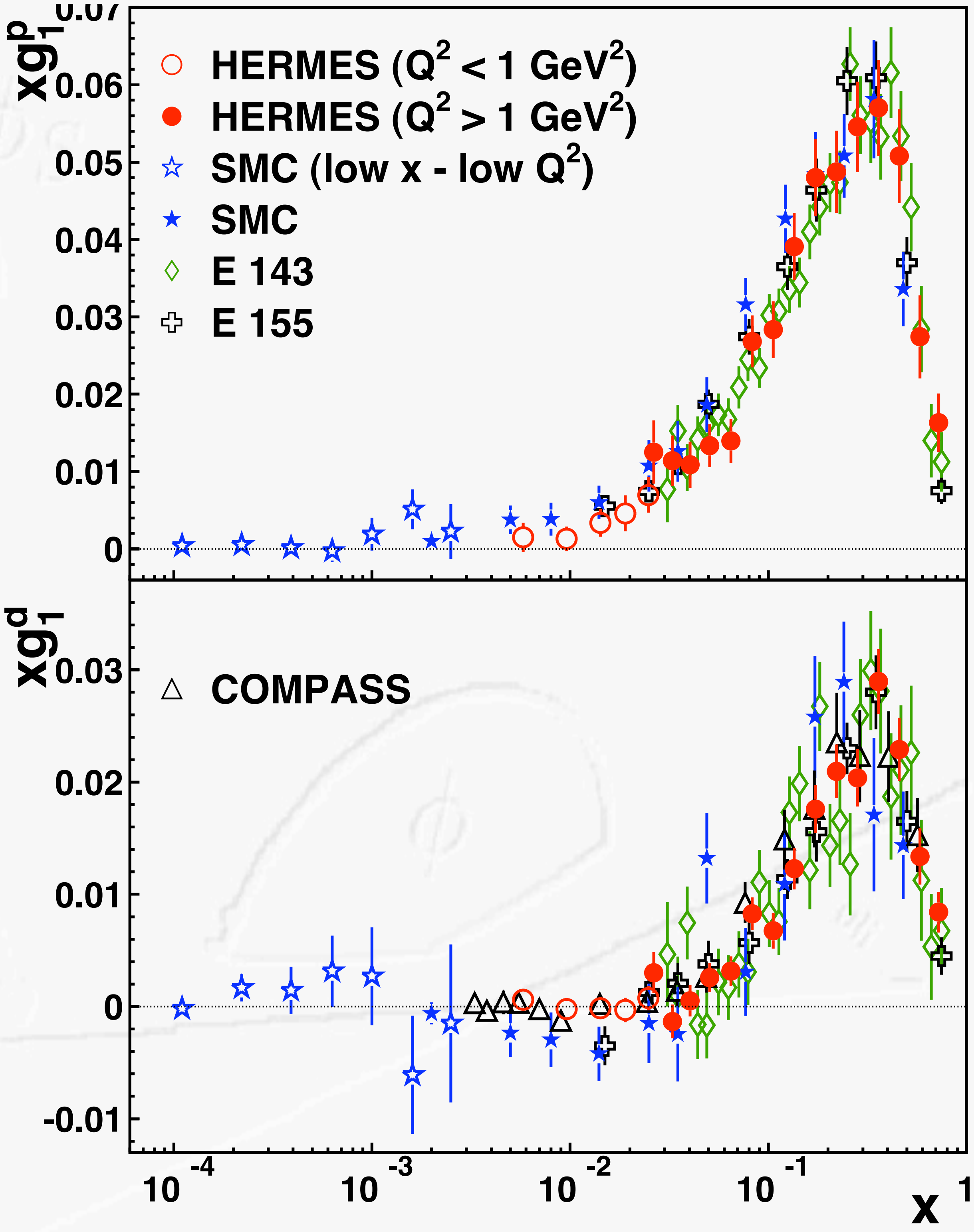
Hunting for the nucleon spin

Polarized SF g_1



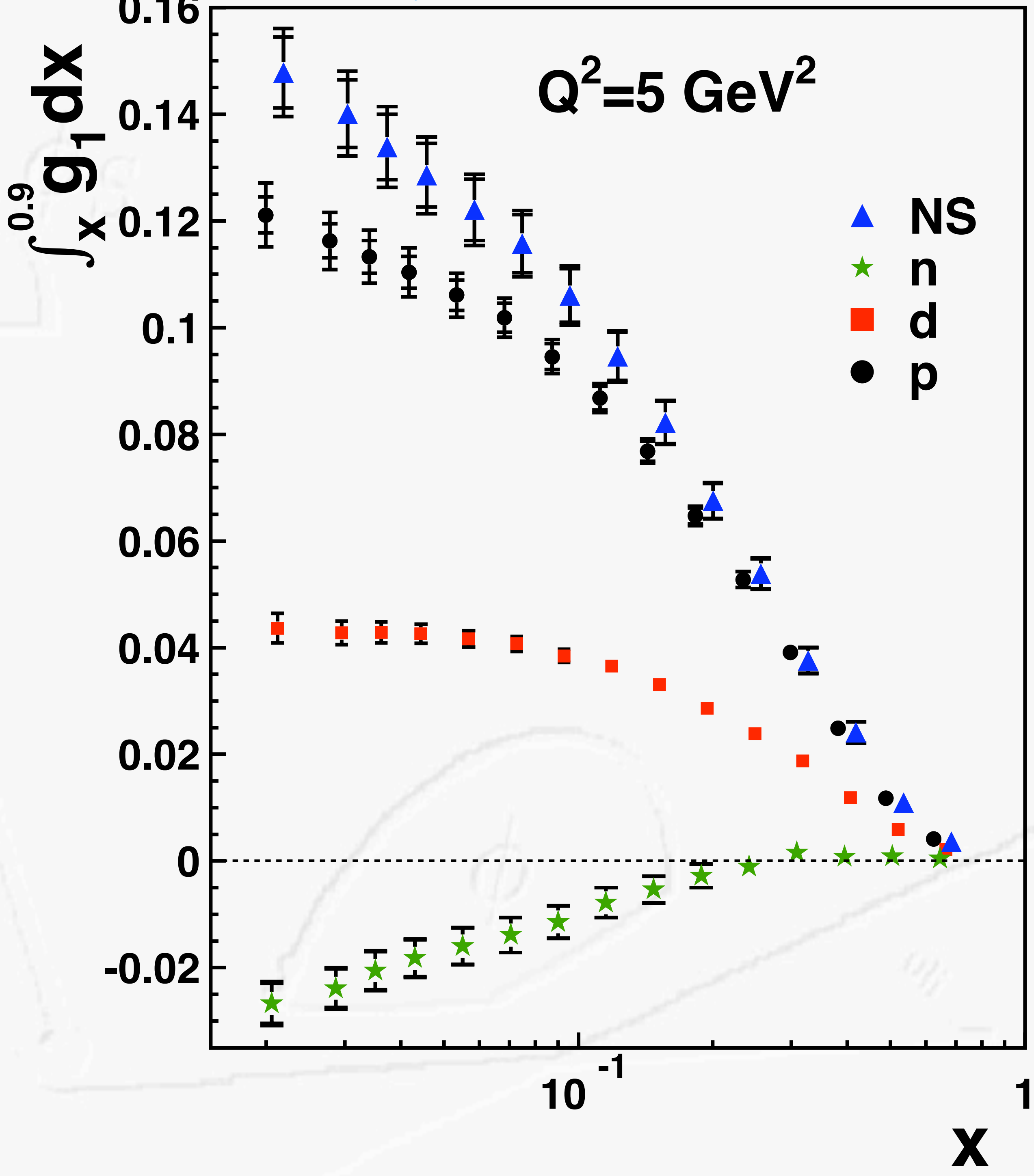


A. Airapetian et al., PRD 75 (2007) 012007



Polarized structure function g_1

A. Airapetian et al., PRD 75 (2007) 012007



Polarized structure function g_1

Saturation

➠ **close to full integral?**

$$\Delta\Sigma \overset{\overline{\rm MS}}{=} \frac{1}{\Delta C_{\rm S}}\left[\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D} - \frac{1}{4}a_8\Delta C_{\rm NS}\right]$$

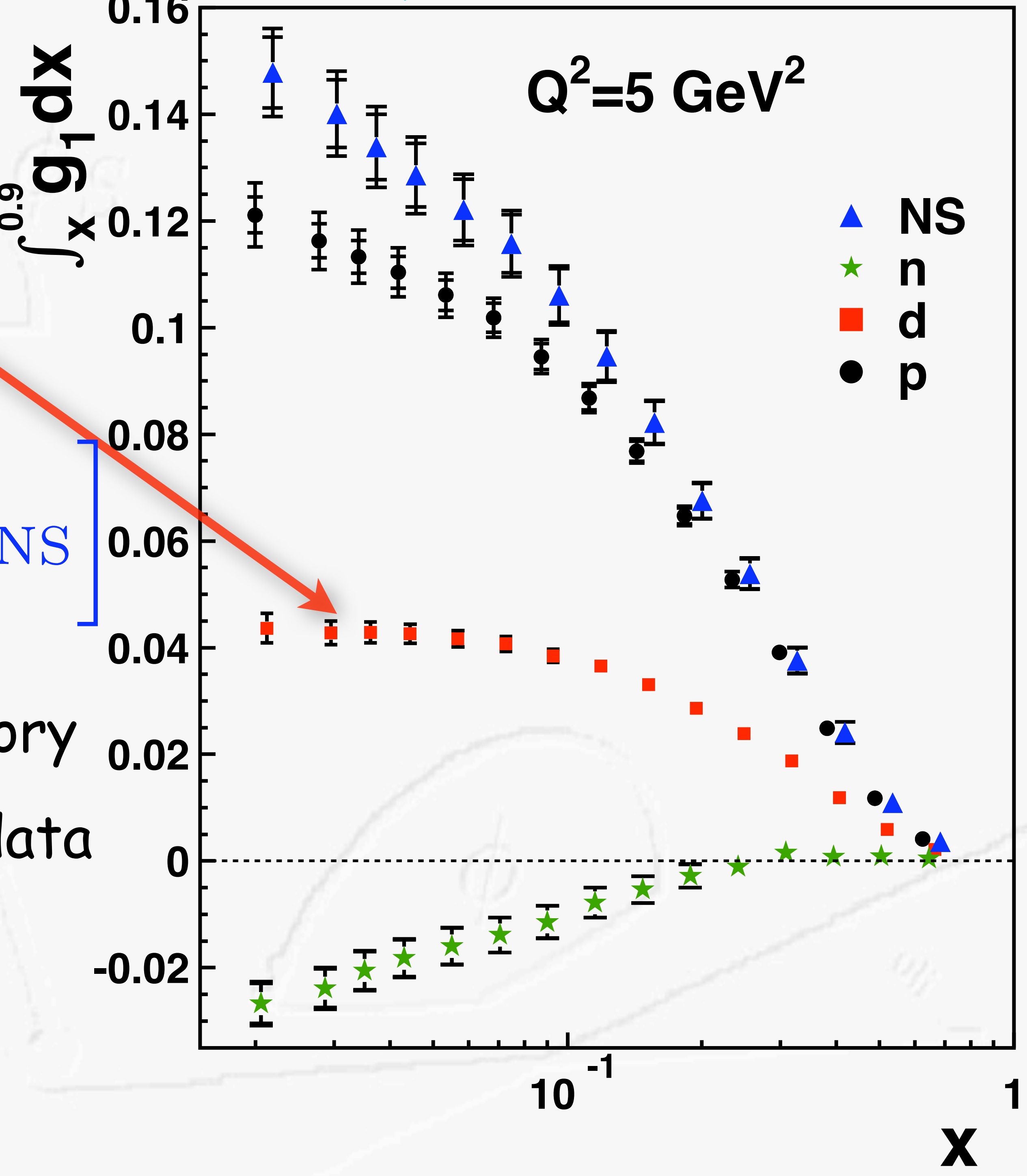
theory

0.05±0.05

hyperon-decay data

theory

A. Airapetian et al., PRD 75 (2007) 012007



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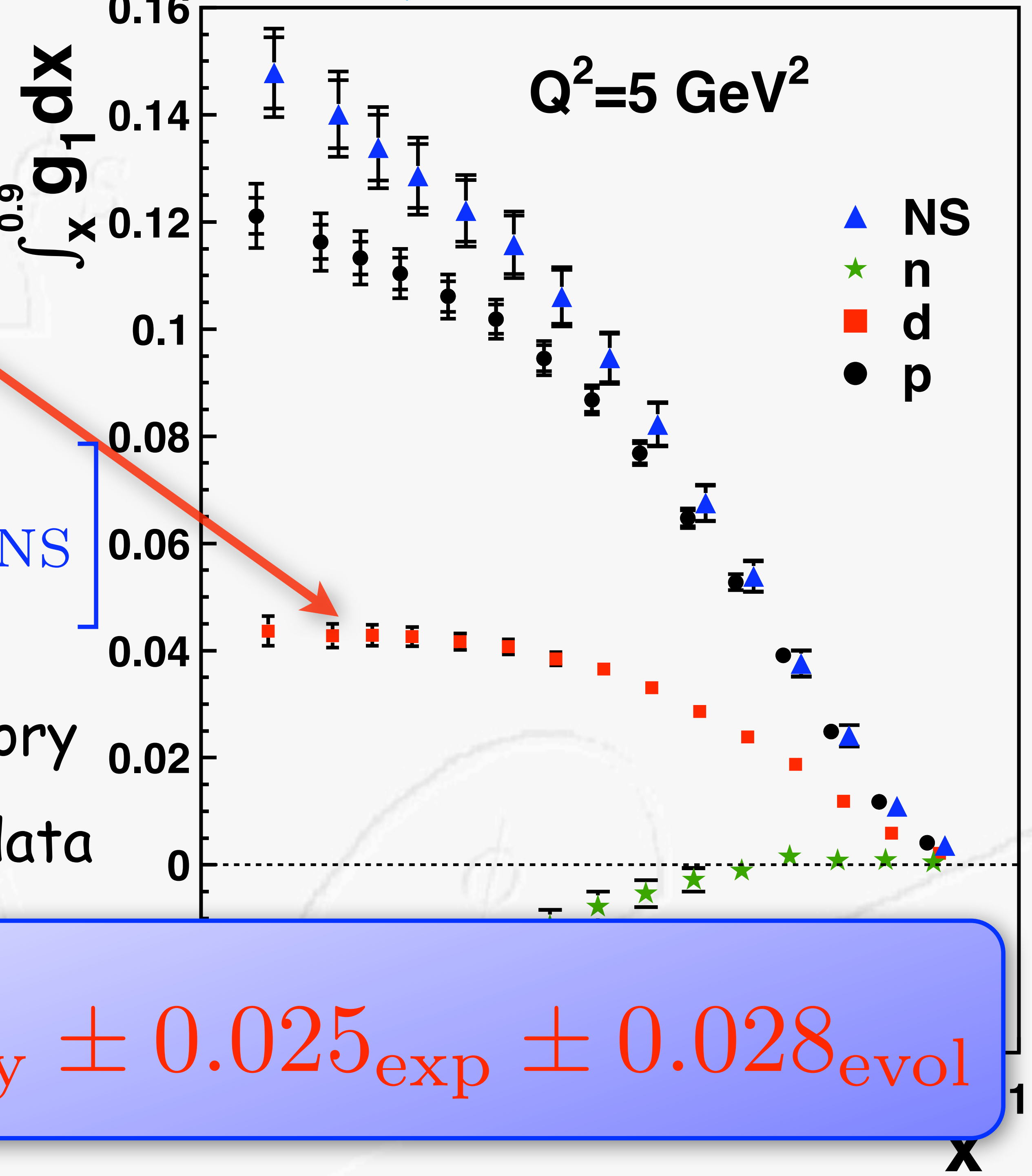


A. Airapetian et al., PRD 75 (2007) 012007

$$\boxed{\Delta\Sigma \overset{\overline{\text{MS}}}{=} 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}}$$

only 1/3 of nucleon spin from quarks

Polarized structure function g_1

Saturation

➟ **close to full integral?**

$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} \frac{1}{\Delta C_{\mathrm{S}}}\left[\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D} - \frac{1}{4}a_8\Delta C_{\mathrm{NS}}\right]$$

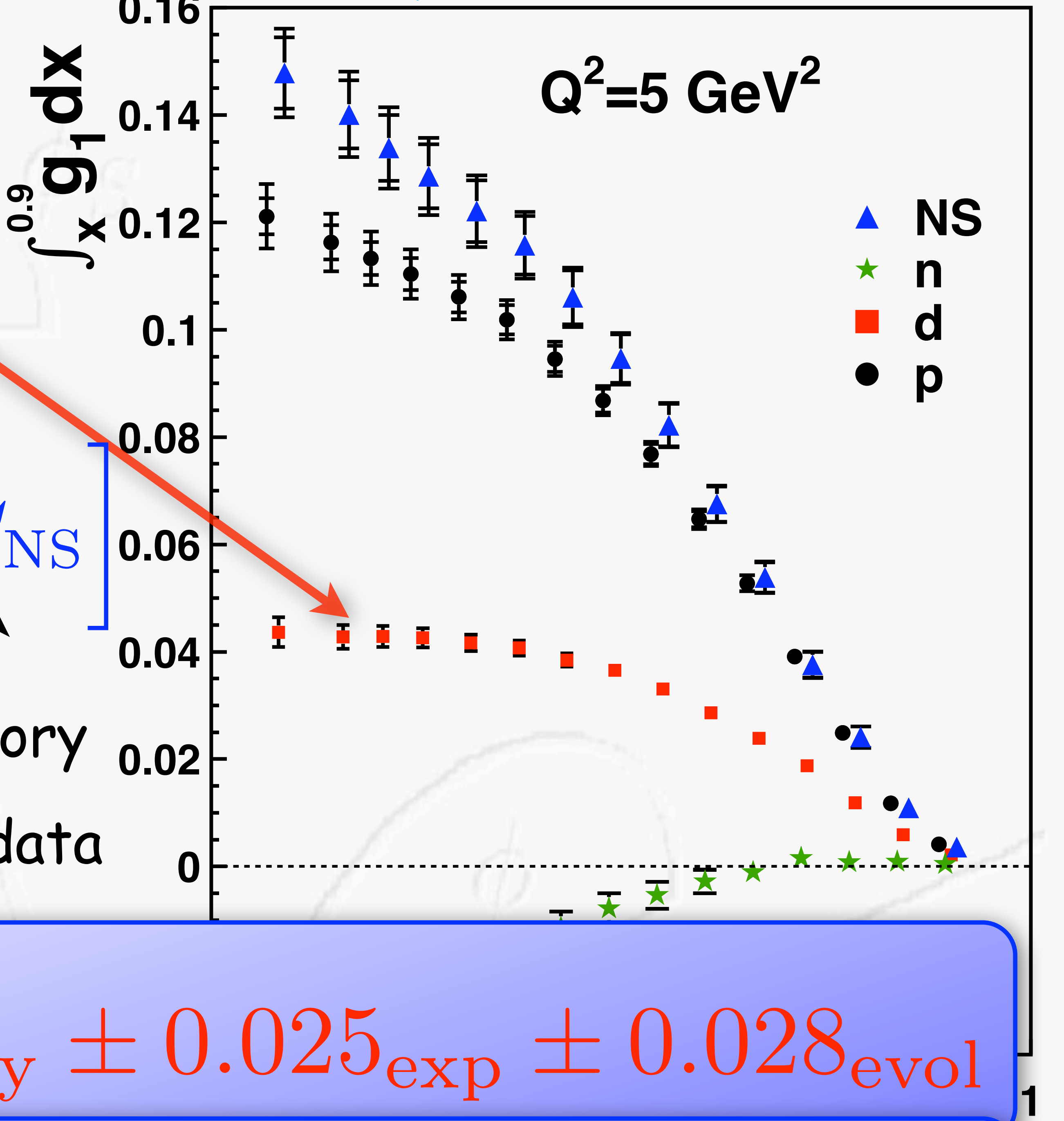
↑ theory

↑ 0.05±0.05

↑ hyperon-decay data

↑ theory

A. Airapetian et al., PRD 75 (2007) 012007

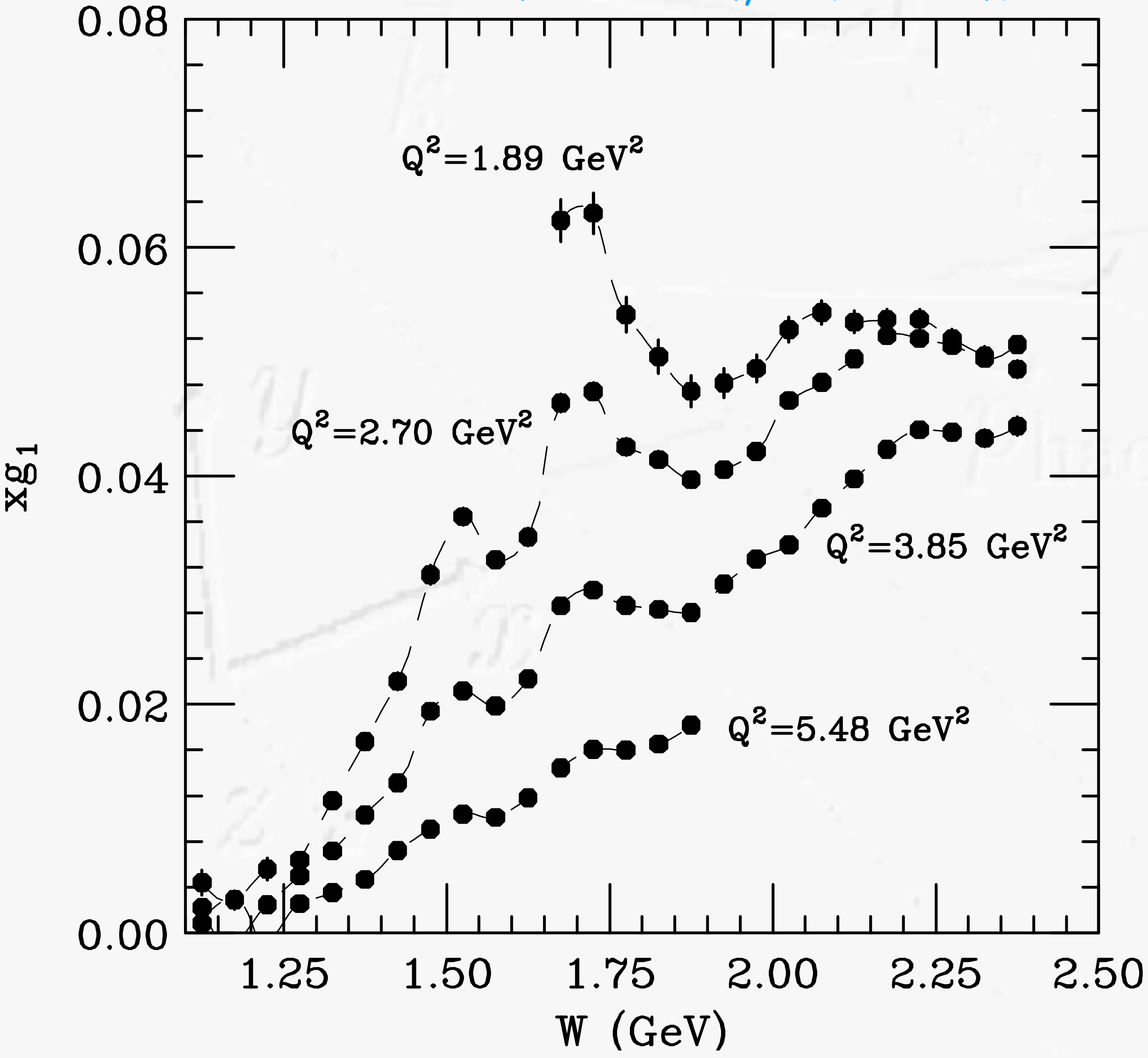


$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.35 \pm 0.03_{\mathrm{stat}} \pm 0.05_{\mathrm{sys}}$$ COMPASS

news from the low-energy frontier

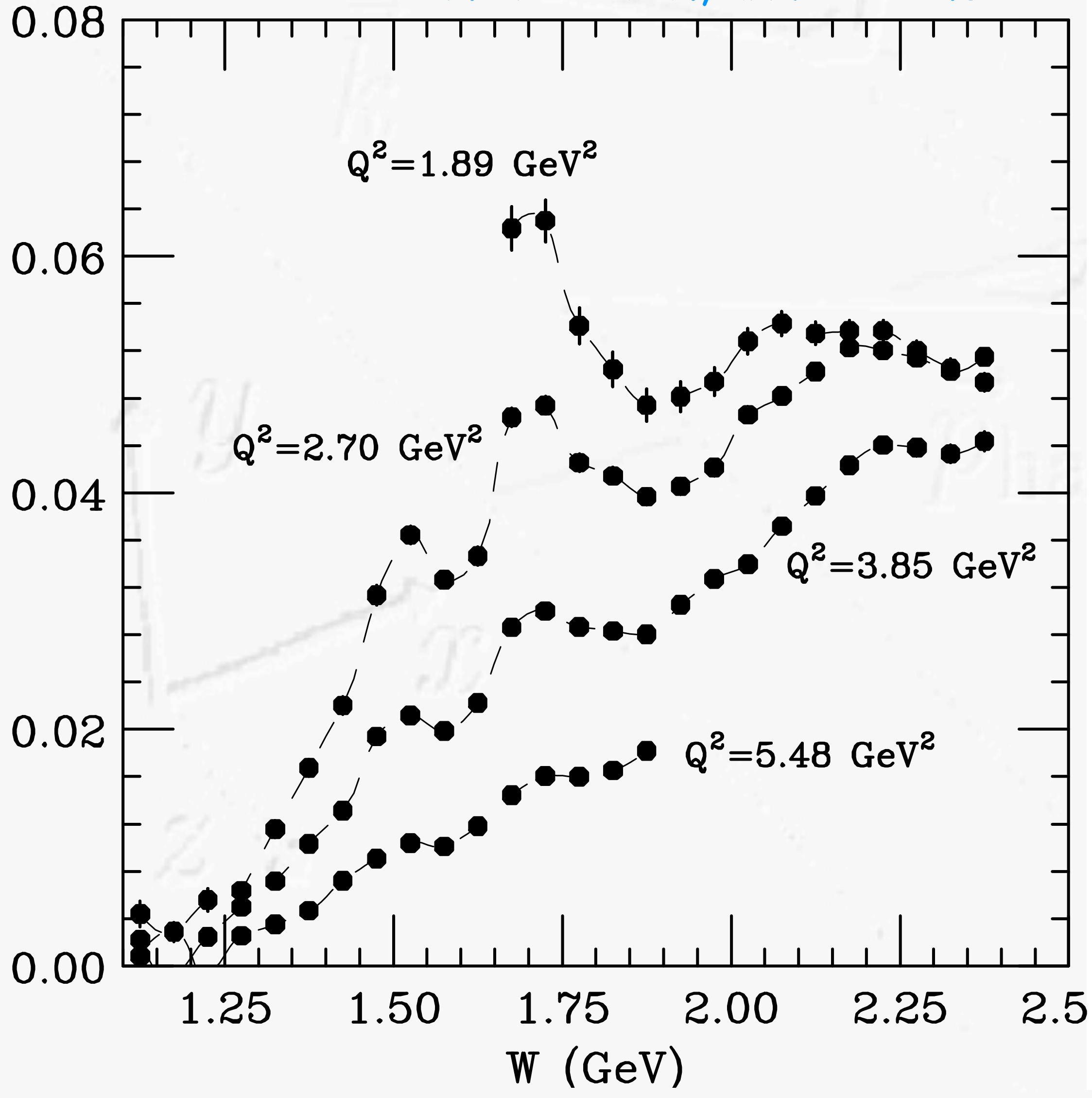
Y. Prok et al., arXiv:1404.6231



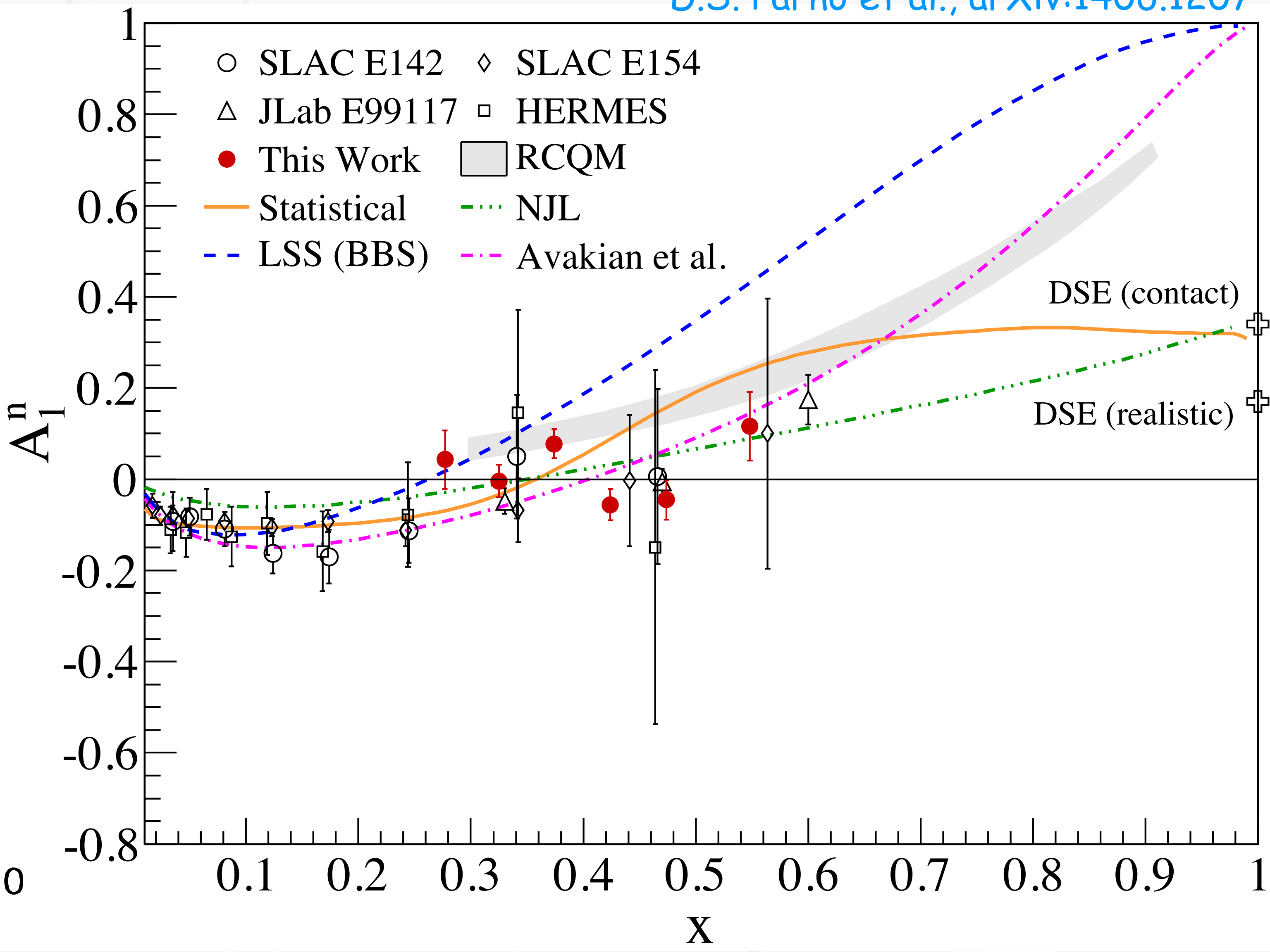
CLAS

news from the low-energy frontier

Y. Prok et al., arXiv:1404.6231



D.S. Parno et al., arXiv:1406.1207

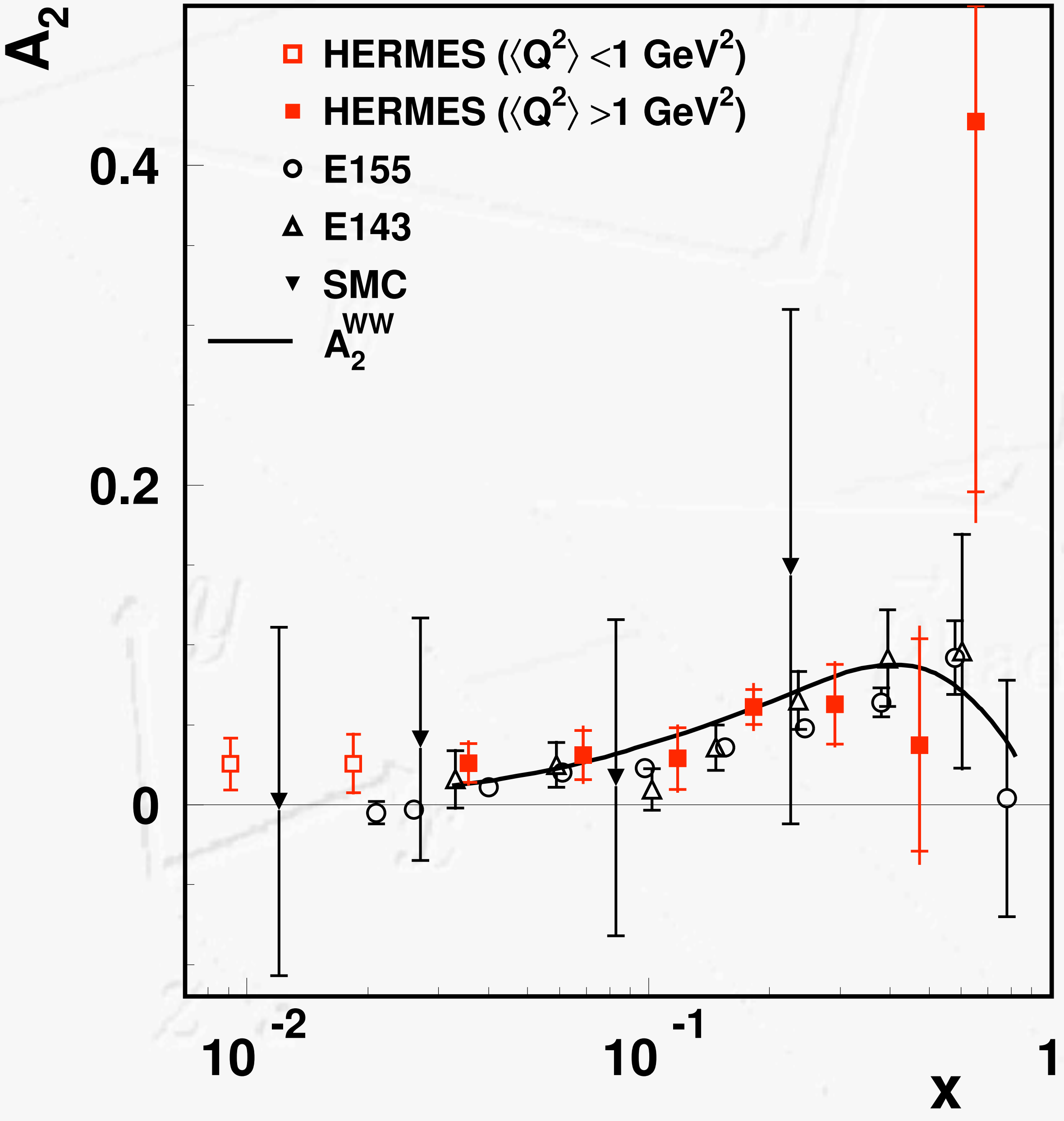


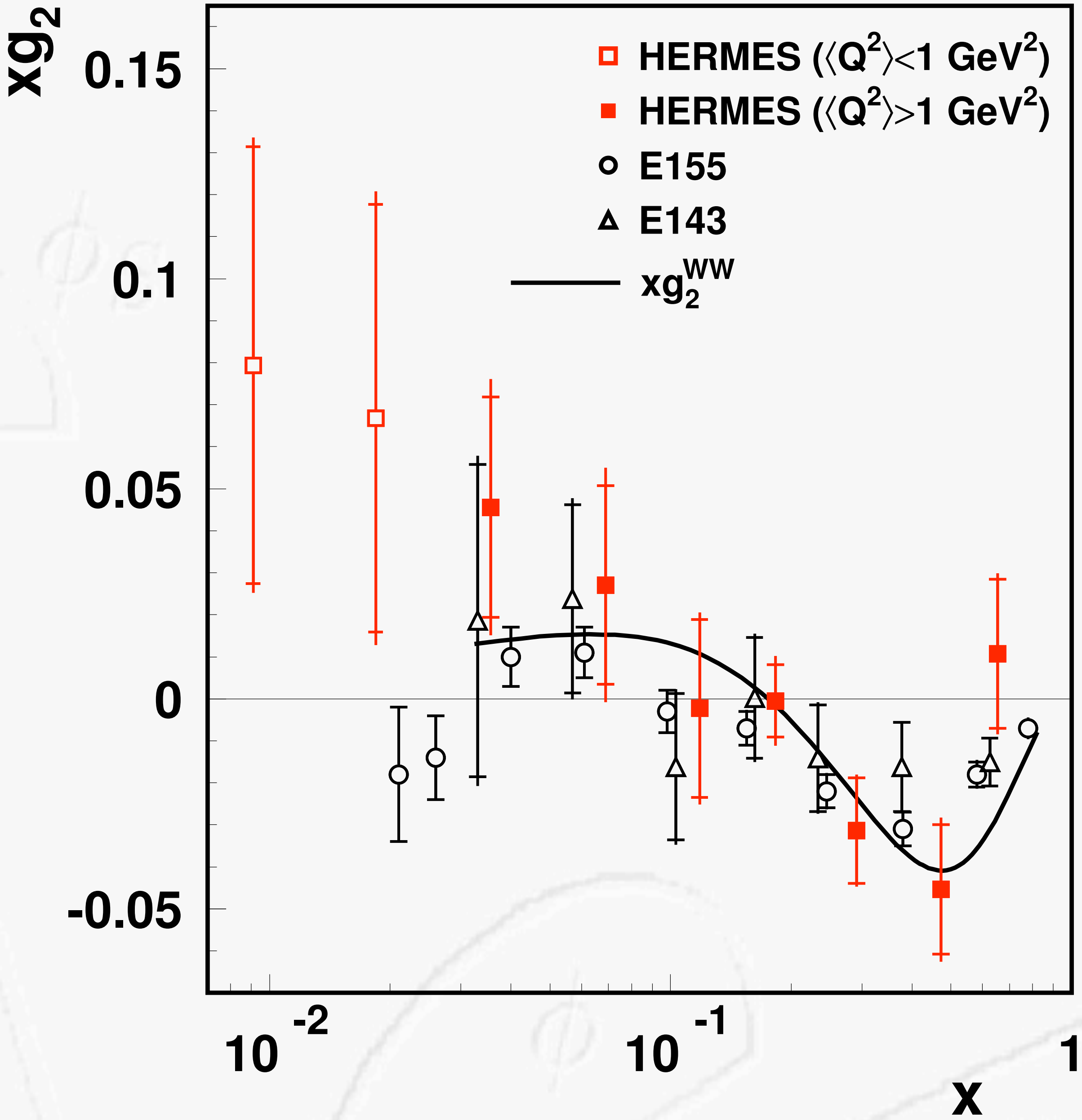
CLAS

Jefferson Lab Hall A

... the other polarized SF ...

Results on A_2 and xg_2

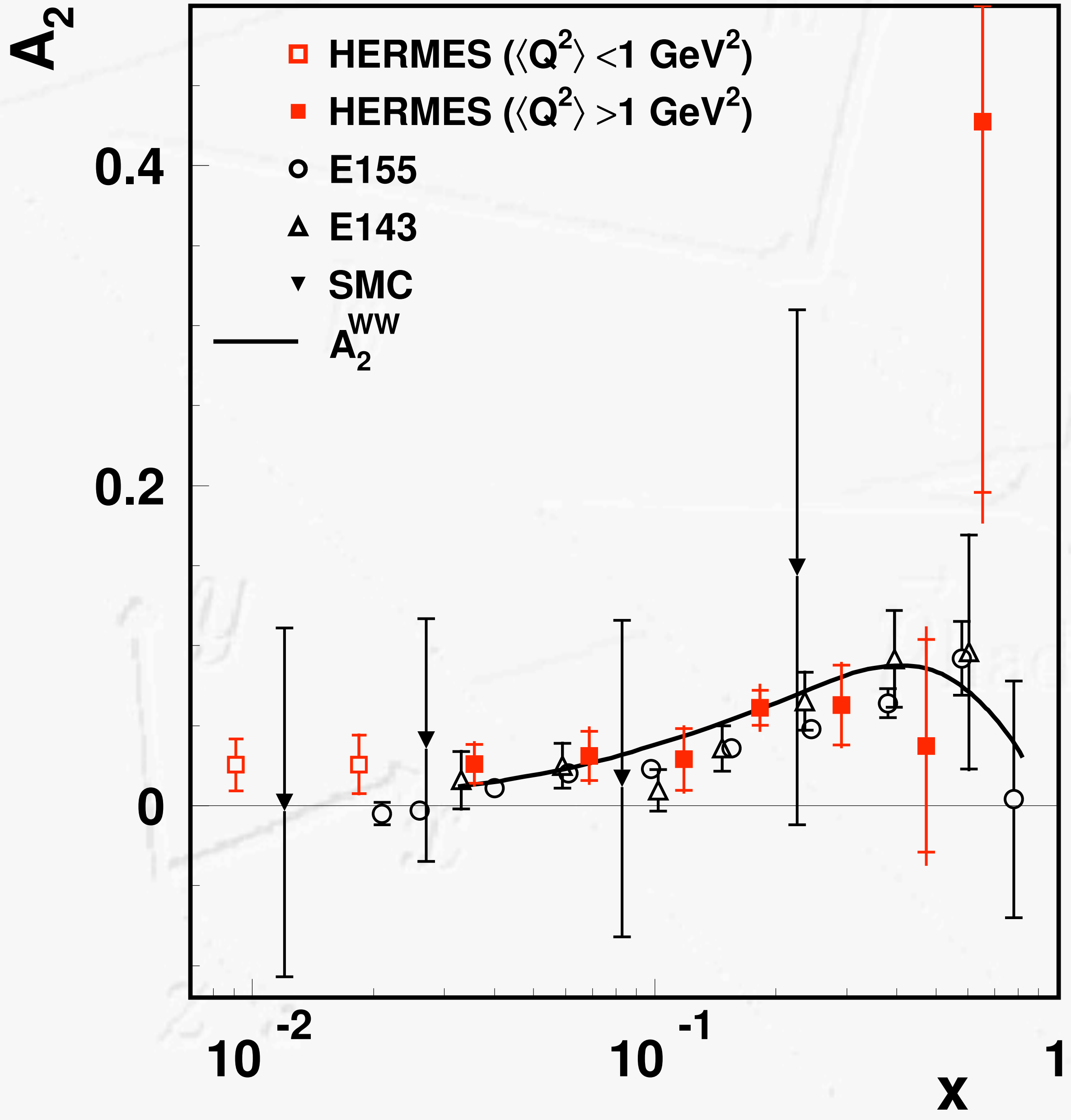

A. Airapetian et al., EPJ C72 (2012) 1921


A. Airapetian et al., EPJ C72 (2012) 1921

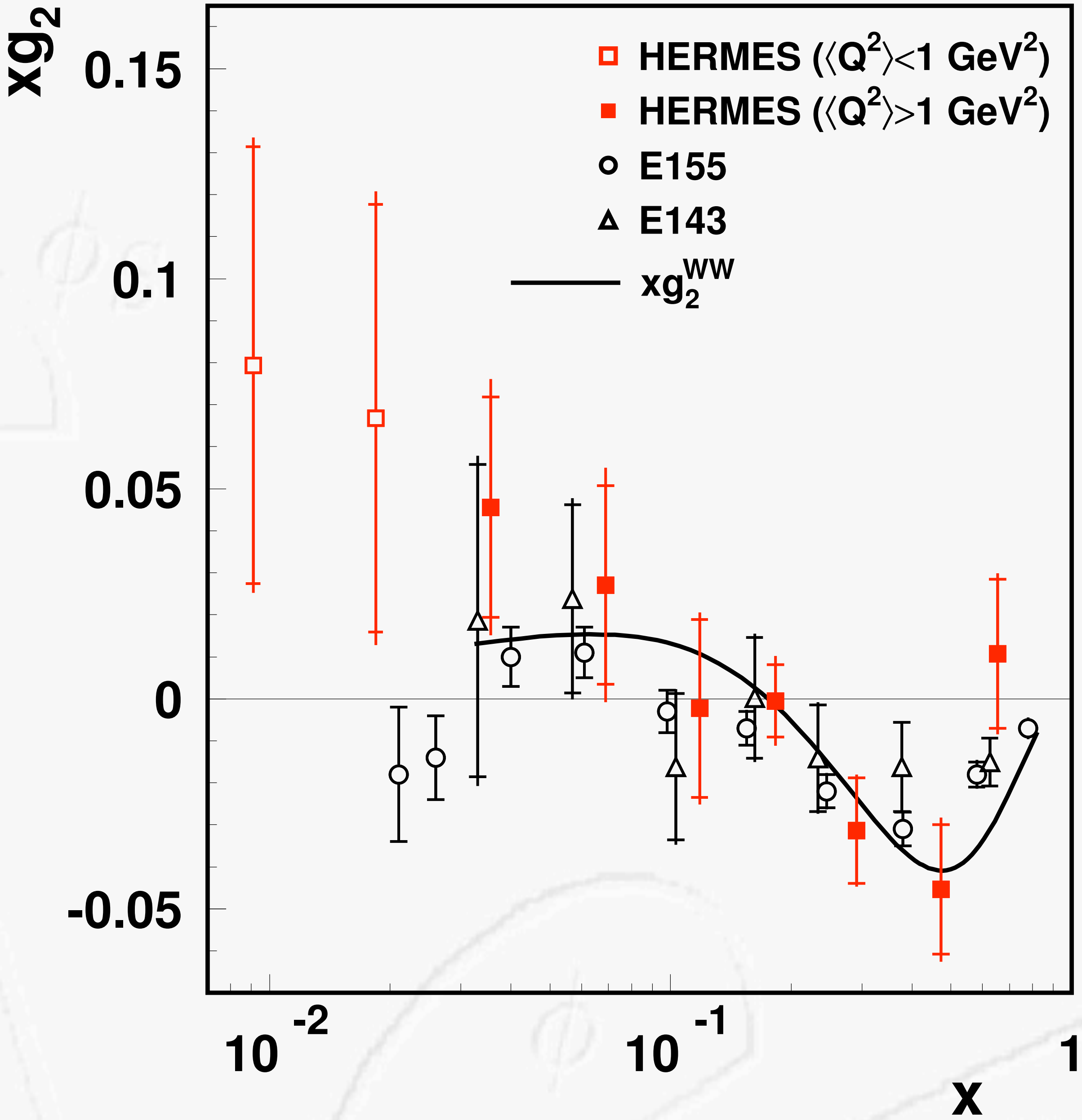
- latest HERMES data consistent with (sparse) world data
- rather low beam polarization during HERA II ➥ small f.o.m.

Results on A_2 and xg_2

A. Airapetian et al., EPJ C72 (2012) 1921



A. Airapetian et al., EPJ C72 (2012) 1921

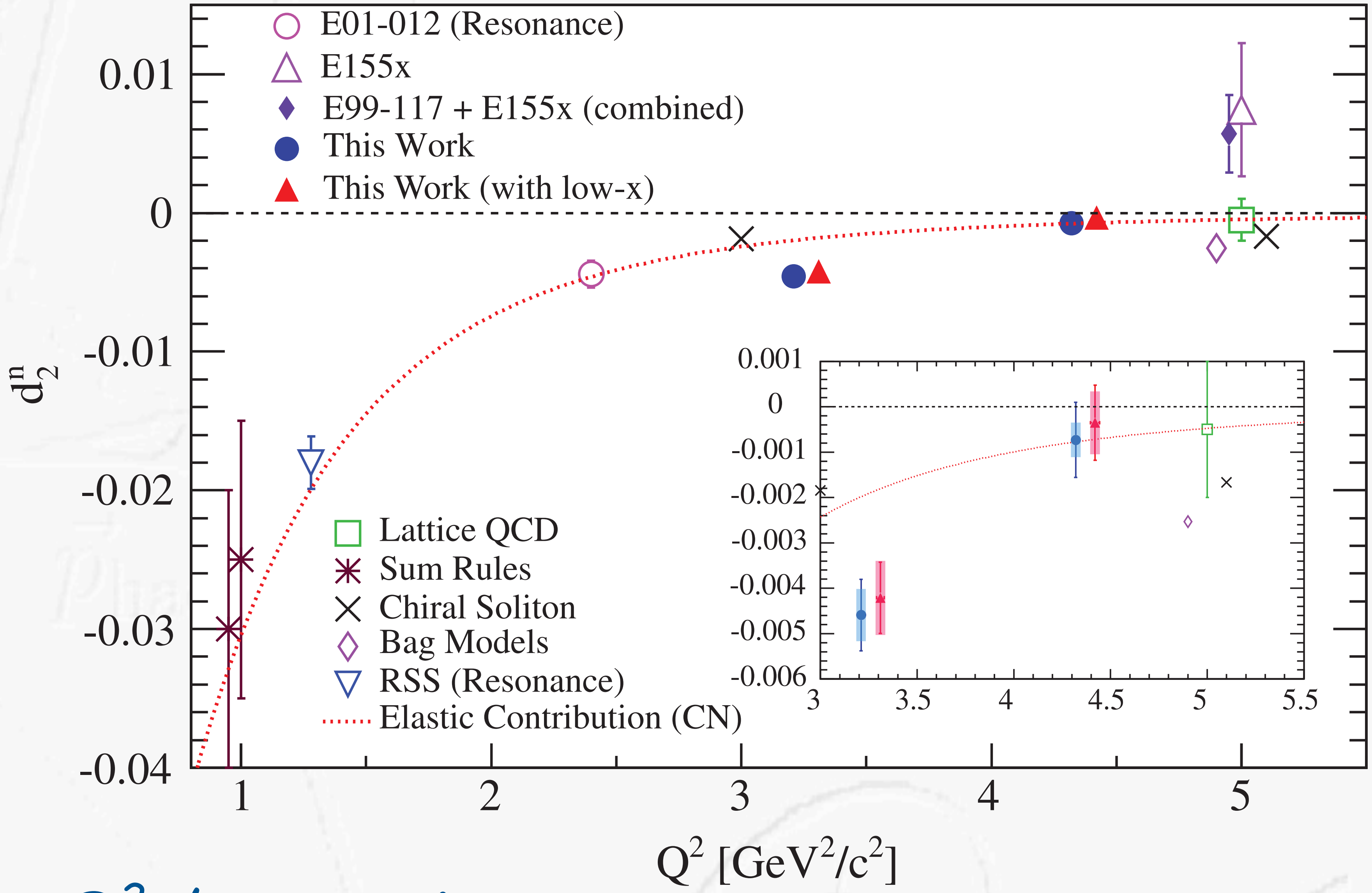


$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \begin{cases} \mathbf{0.006 \pm 0.024_{\rm stat} \pm 0.017_{\rm syst}} & \text{HERMES} \\ \mathbf{-0.042 \pm 0.008} & \text{E143+E155} \end{cases}$$

$$\mathbf{d_2(Q^2)} \equiv 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx = \begin{cases} \mathbf{0.0148 \pm 0.0096_{\rm stat} \pm 0.0048_{\rm syst}} & \text{HERMES} \\ \mathbf{0.0032 \pm 0.0017} & \text{E143+E155} \end{cases}$$

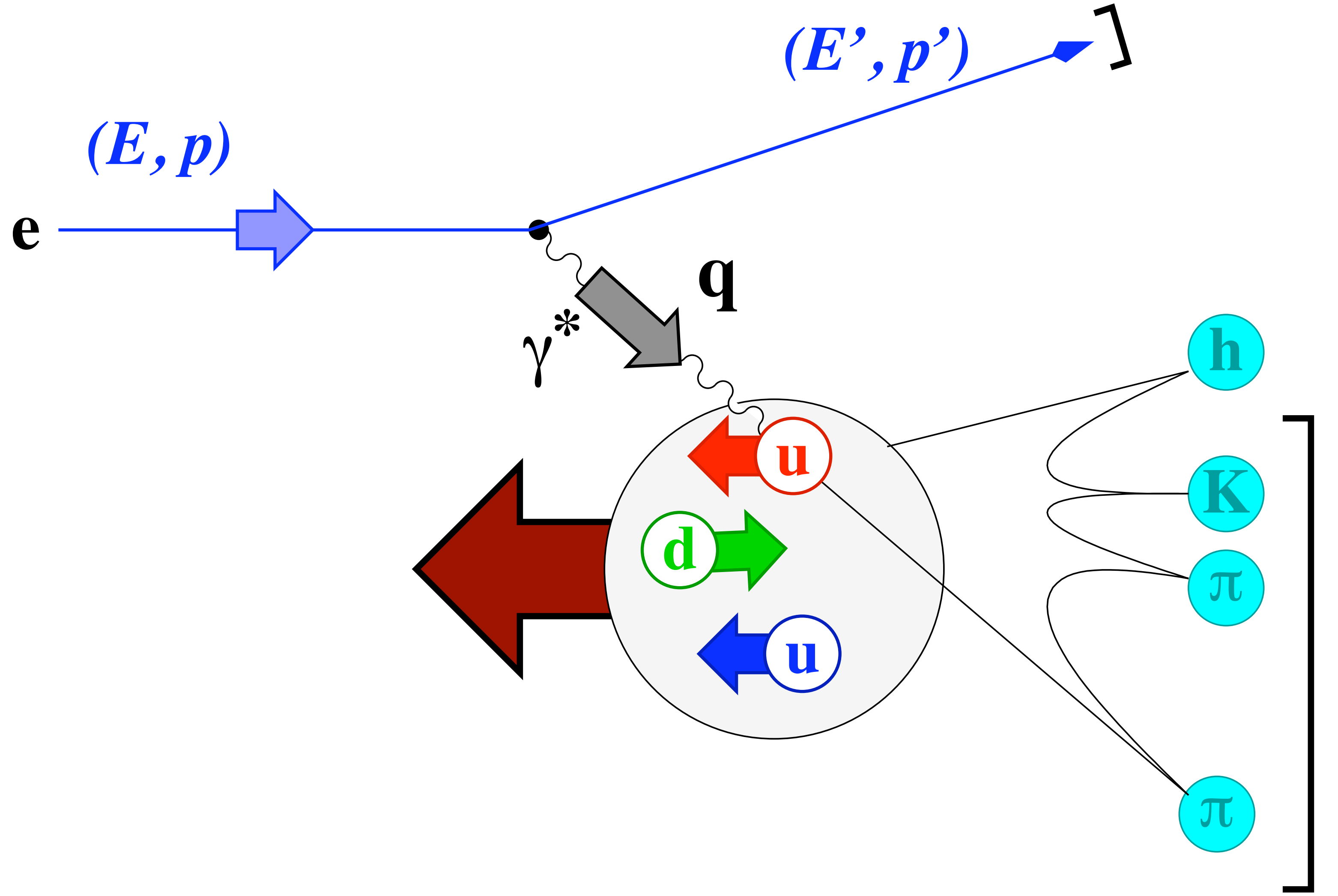
… the neutron case

[M. Posik et al., PRL 113, 022002 (2014)]



- sizable in the lower-Q^2 / -x region
- opposite sign compared to proton case
(as expected, e.g., by M. Burkardt, PRD 88, 114502 (2013)
due to “instantaneous transverse color force”)

Semi-inclusive DIS



Spin-momentum structure of the nucleon

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

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

quark pol.

nucleon pol.

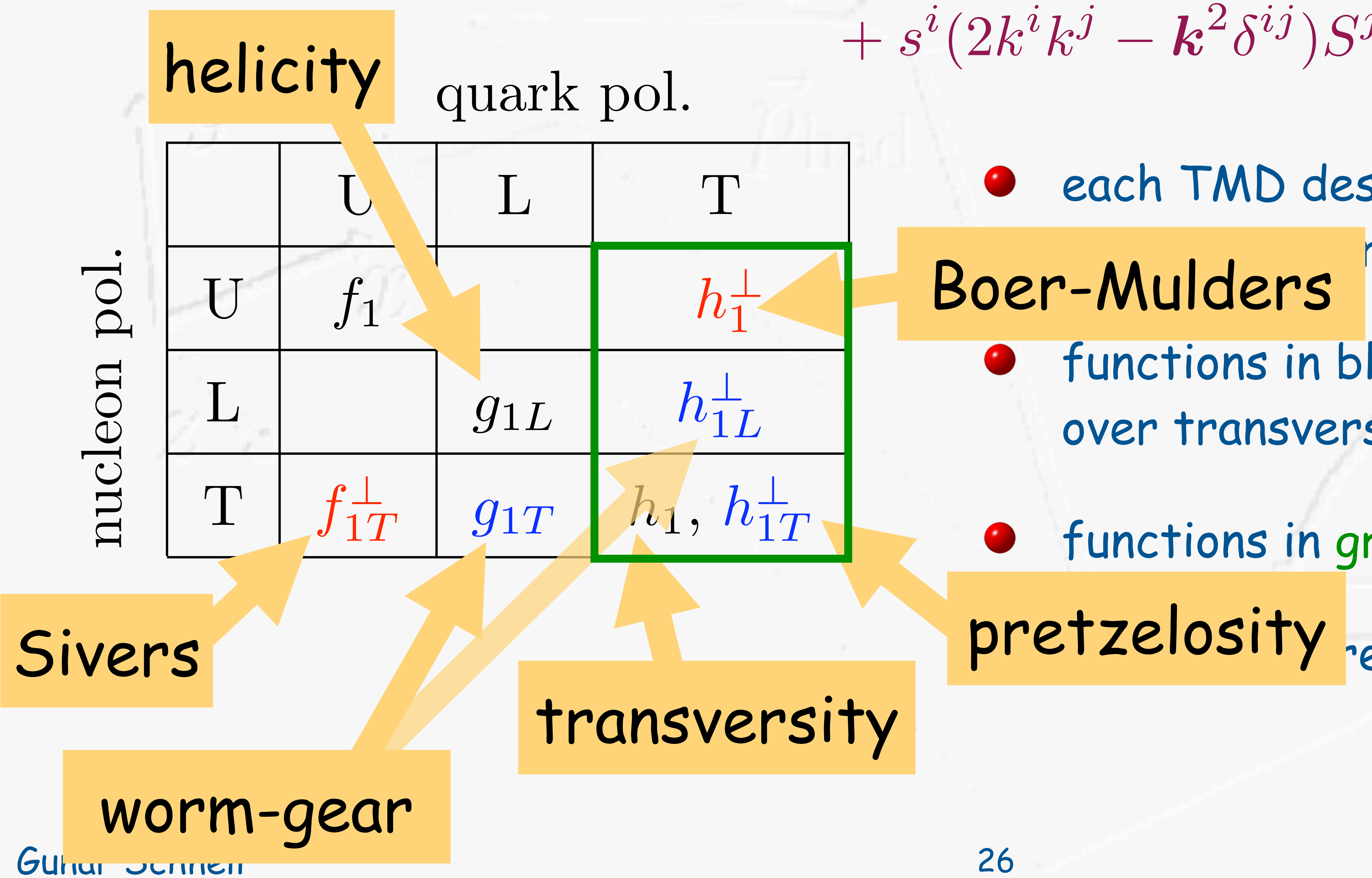
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

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

- 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

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**

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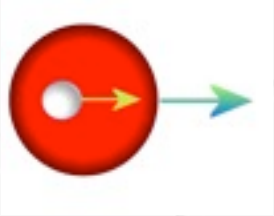
PDFs: f_1^q =

g_1^q =



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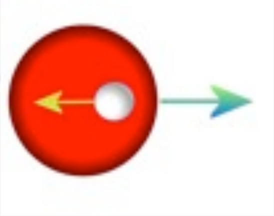
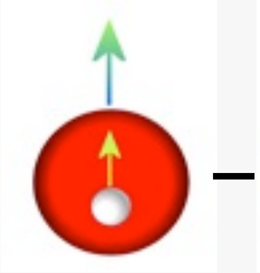


h_1^q =



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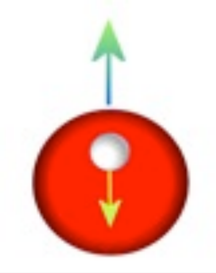

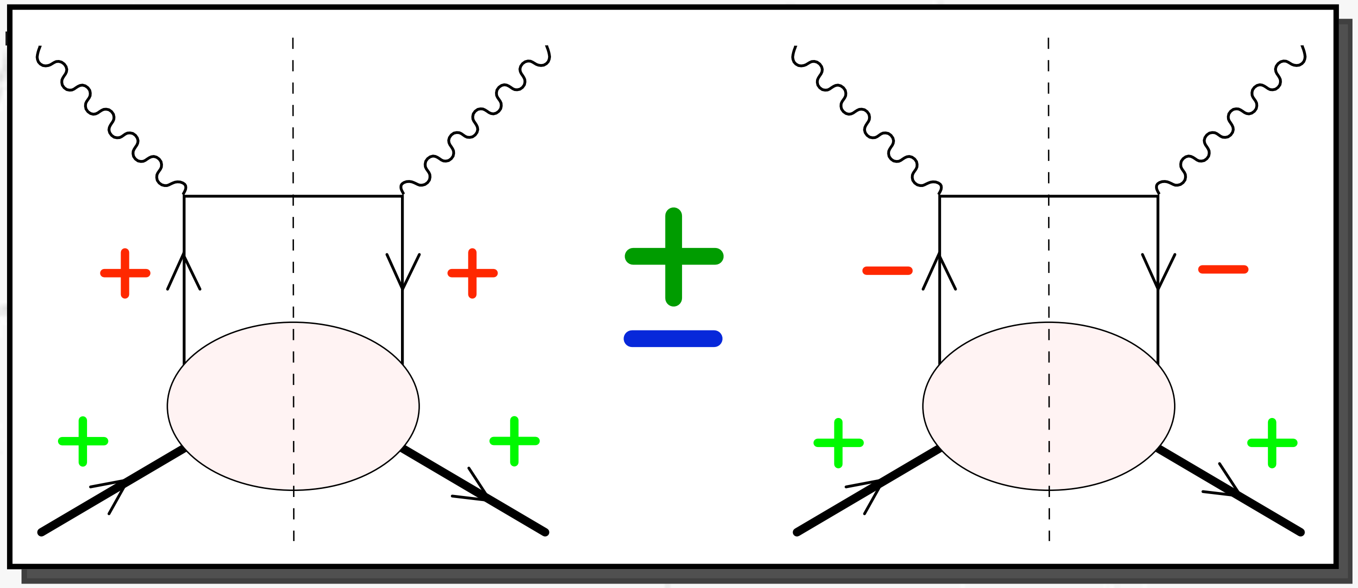

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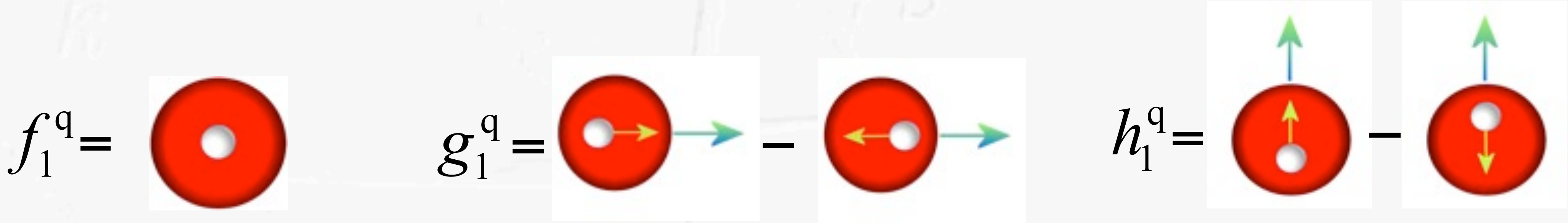
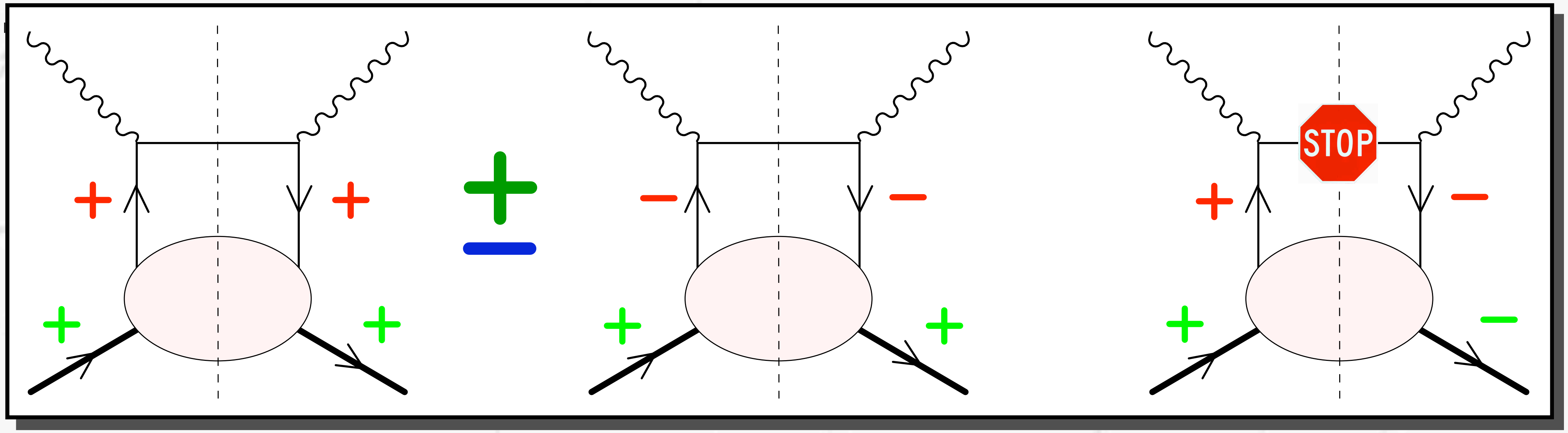


PDFs: $f_1^q =$ $g_1^q =$ − $h_1^q =$ −



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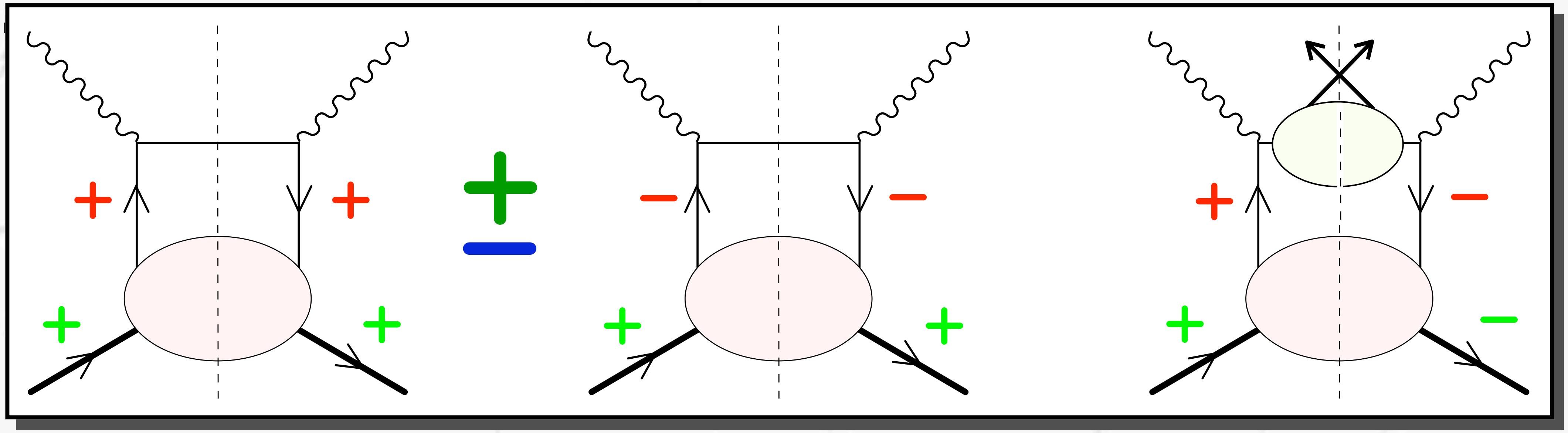
PDFs:

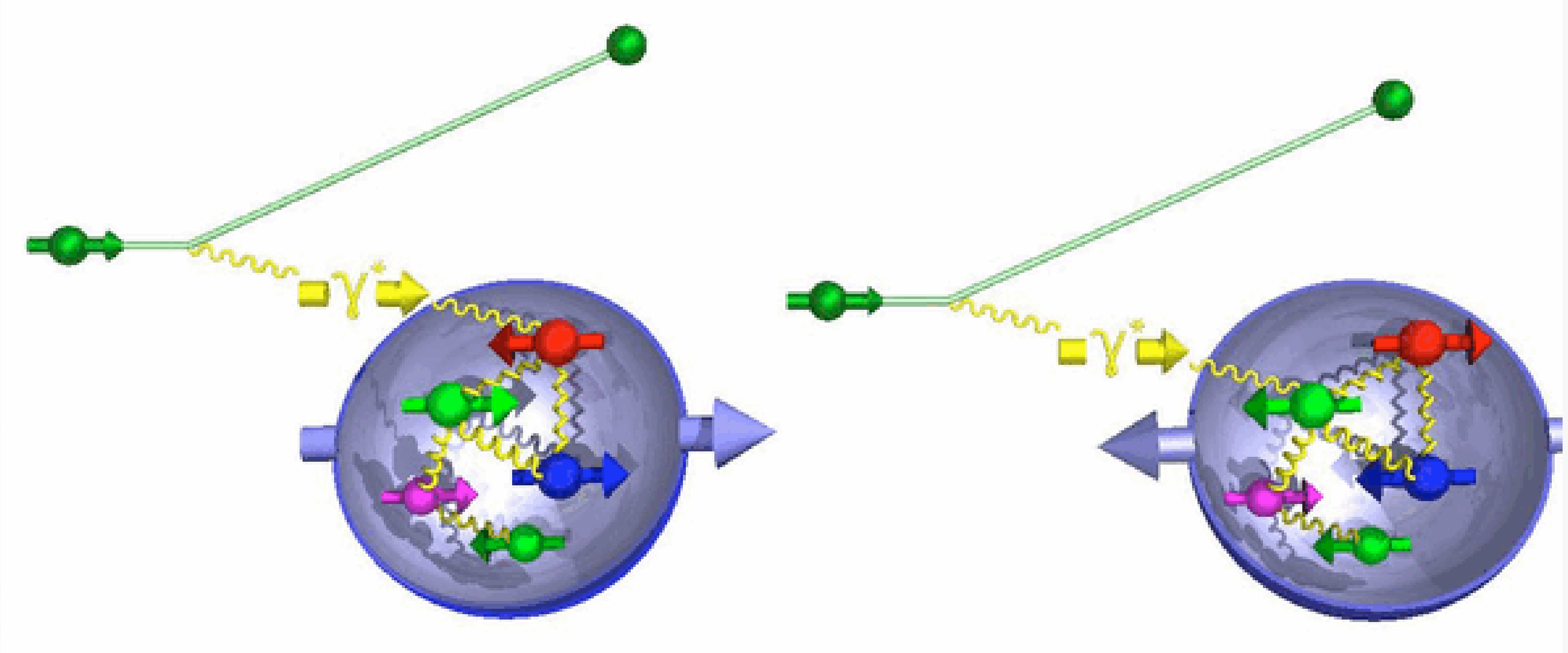


need to couple PDF to chiral-odd fragmentation function:

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

Quark polarimetry

- unpolarized quarks: easy - “just” hit them (and count)
- longitudinally polarized quarks: use polarized beam



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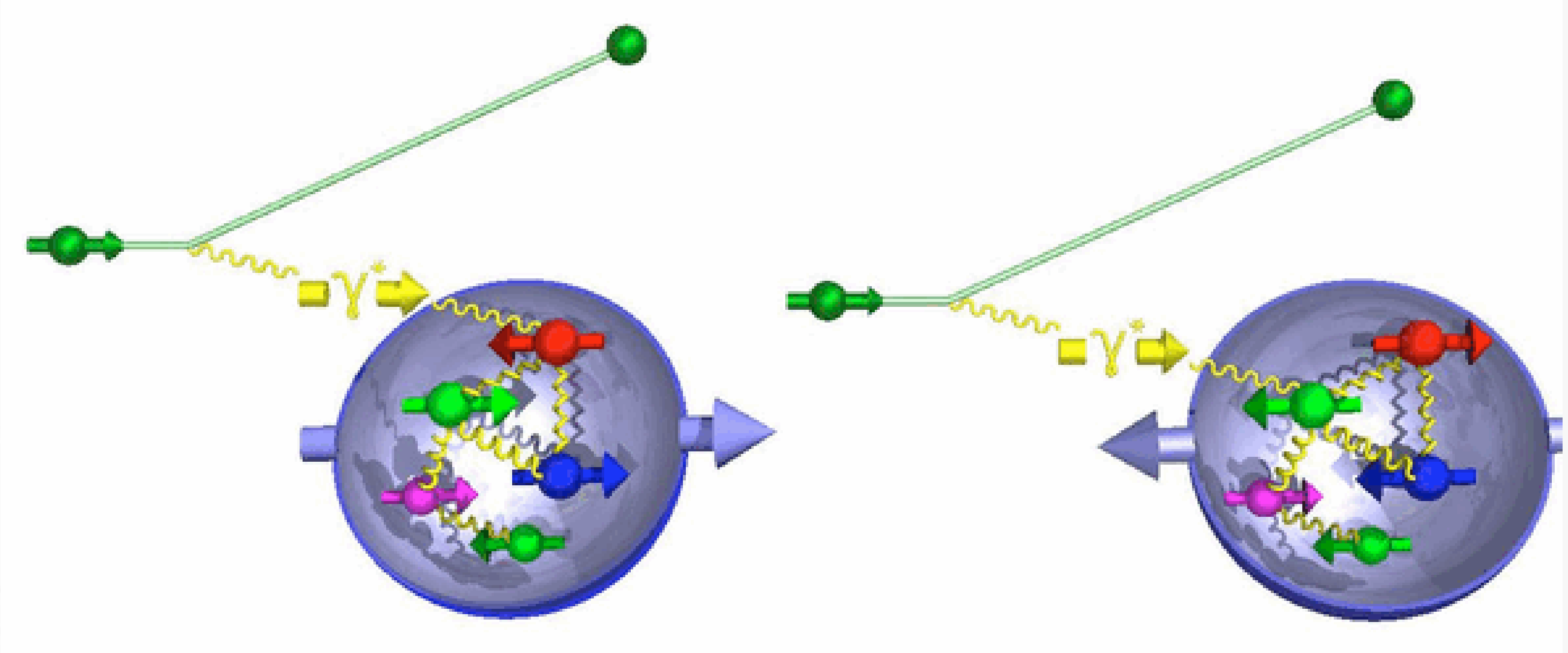
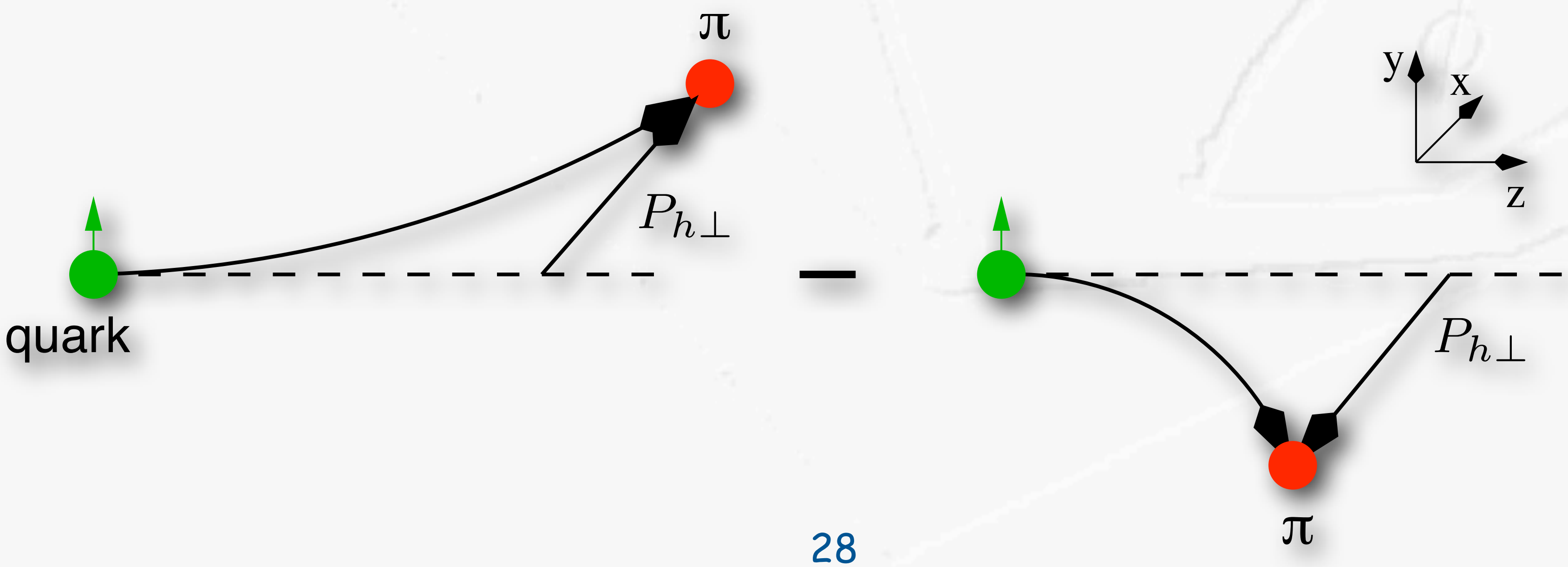


- transversely polarized quarks: need final-state polarimetry, e.g.



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

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	U	L	T
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☛ relevant for unpolarized final state

TMD fragmentation functions

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T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

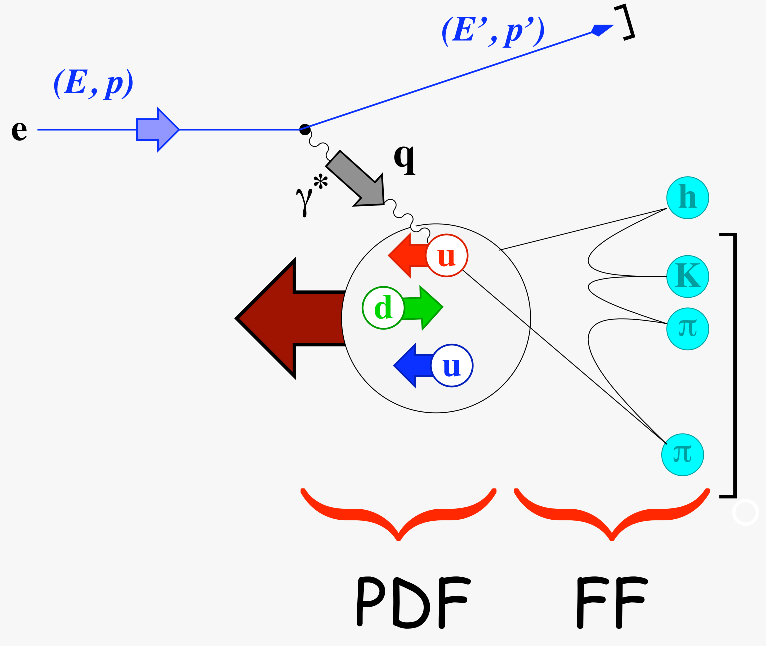
☛ relevant for unpolarized final state

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

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

Probing TMDs in semi-inclusive DIS

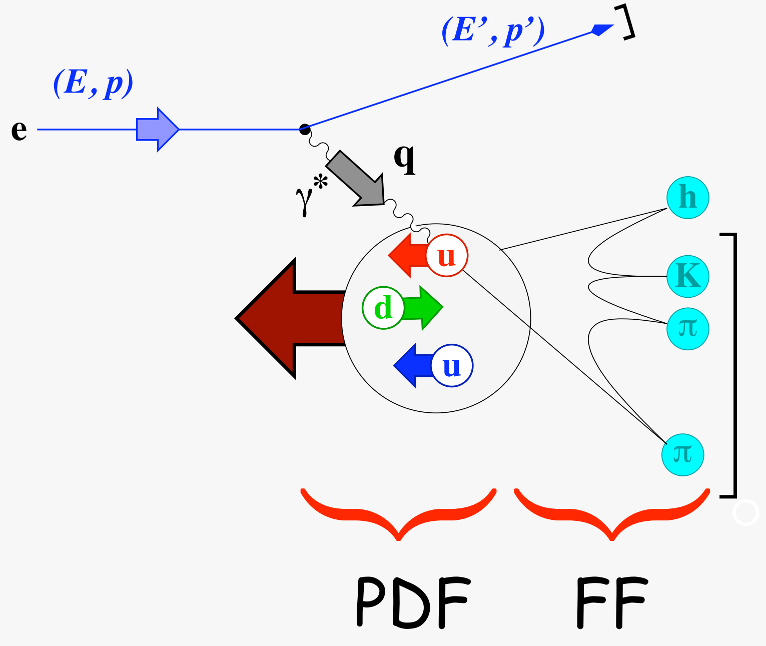
		quark pol.		
		U	L	T
nucleon pol.	U	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

Probing TMDs in semi-inclusive DIS



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U	f_1		$h_1^\perp$
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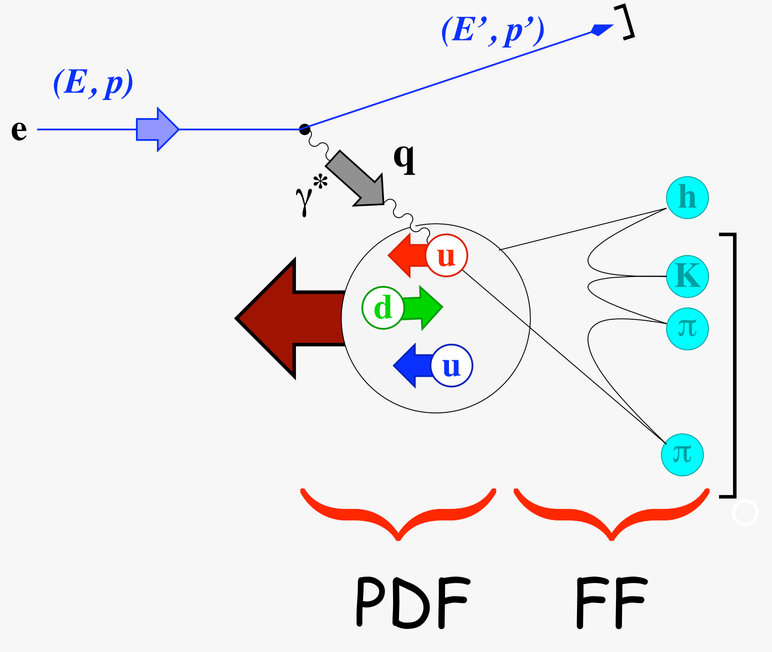
Probing TMDs in semi-inclusive DIS



quark pol.

nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
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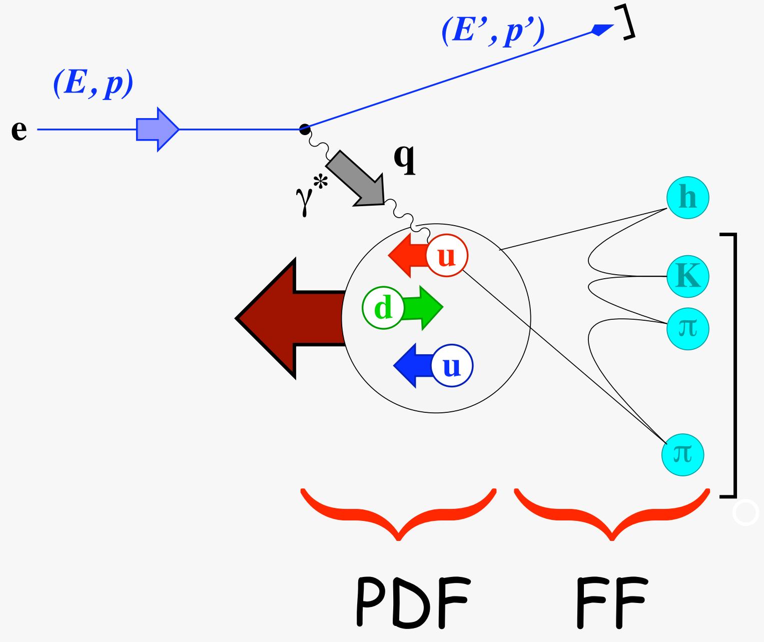
Probing TMDs in semi-inclusive DIS



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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)

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

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

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

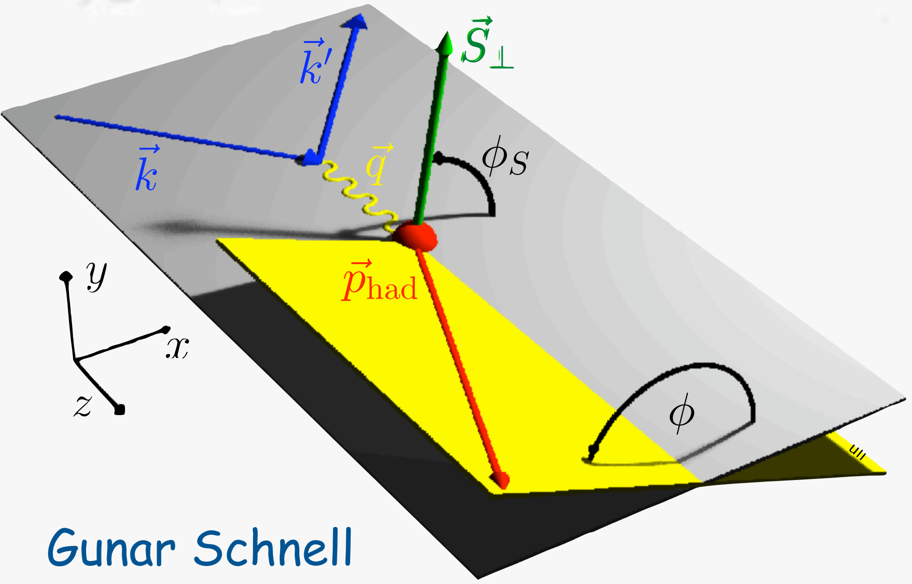
$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

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

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

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

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

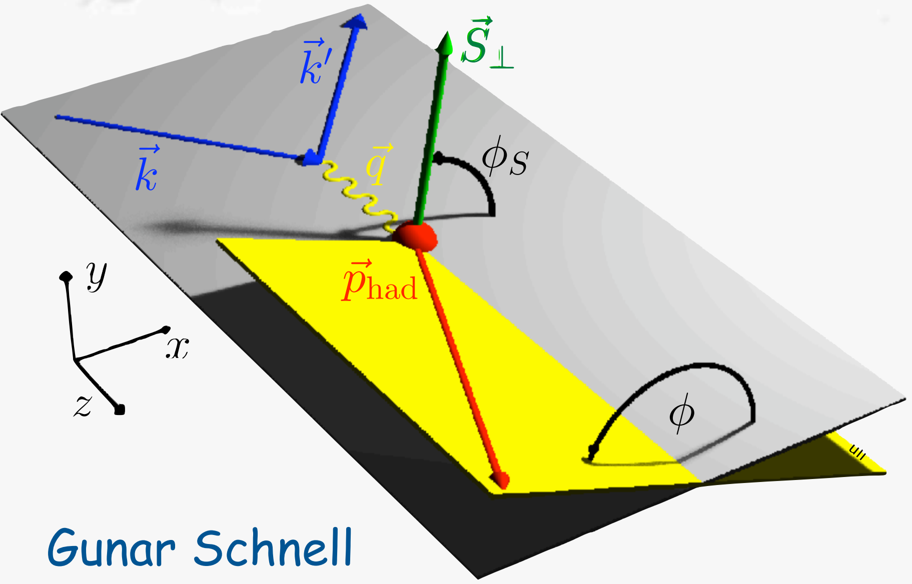
$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\,d\sigma_{UT}^{11}+\sin\phi_S\,d\sigma_{UT}^{12}\right)$$

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

σ_{XY}

Beam **Target**

Polarization



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

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

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

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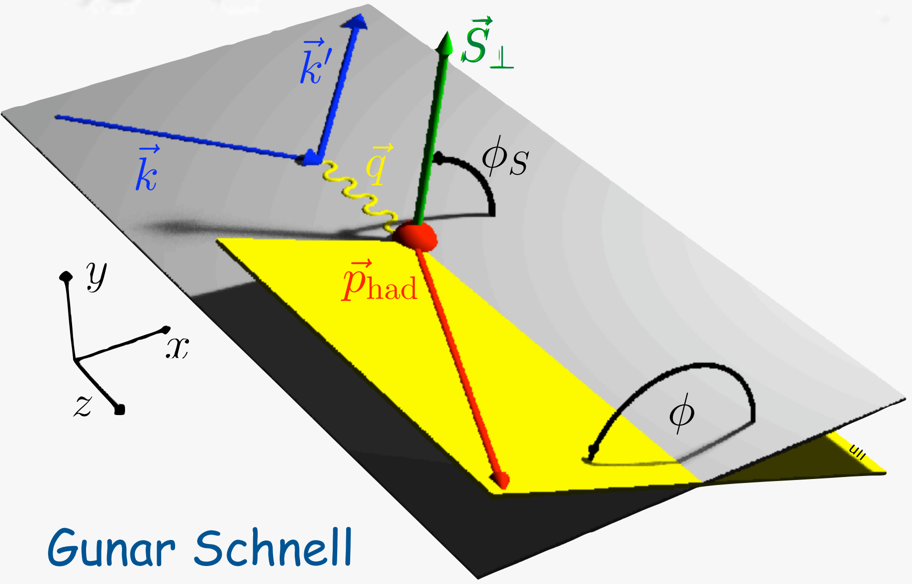
Beam **Target**

Polarization



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… possible measurements

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

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

… possible measurements

hadron multiplicity:

normalize to inclusive DIS cross section

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… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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

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

moments:
normalize to azimuth-independent cross-section

… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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normalize to azimuth-independent cross-section

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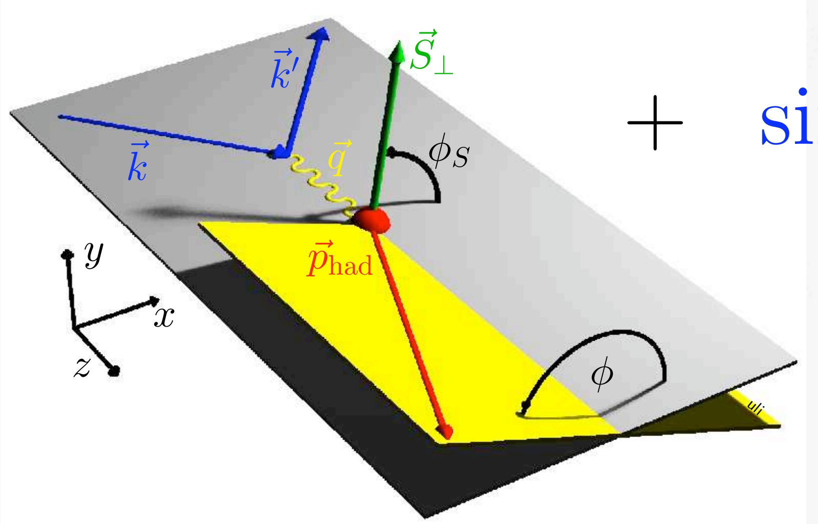
moments:
normalize to azimuth-independent cross-section

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

Azimuthal spin asymmetries

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

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



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

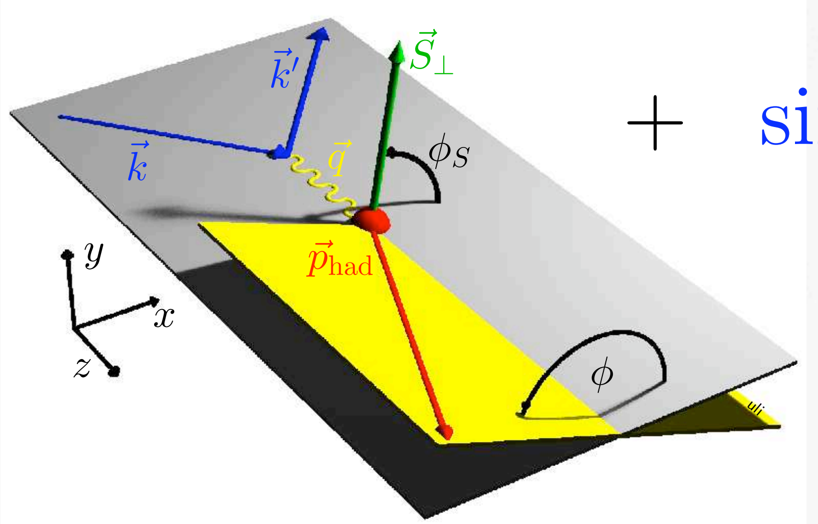
$$+ \quad \cdots$$

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

Azimuthal spin asymmetries

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

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



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

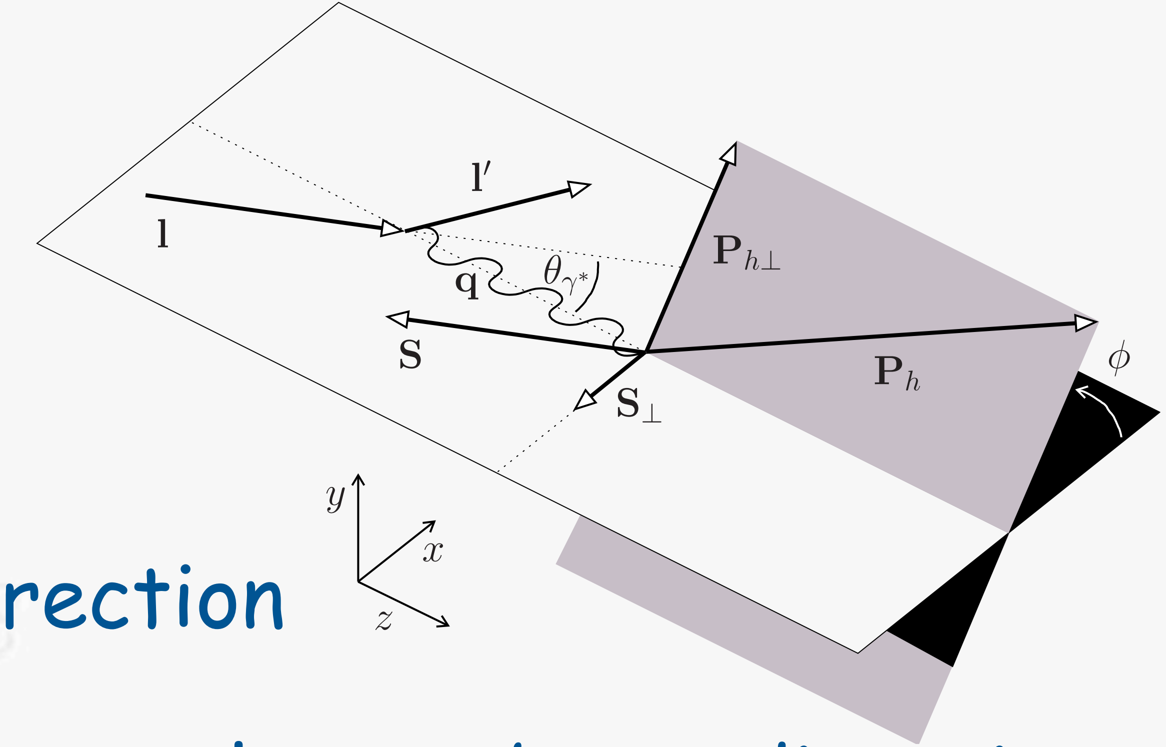
$$+\quad\cdots$$

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

Fit azimuthal modulations, e.g., using Max.Likelihood:

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

… some complications



- theory done w.r.t. virtual-photon direction
- experiments use targets polarized w.r.t. lepton-beam direction

➡ mixing of longitudinal and transverse polarization effects [Diehl & Sapeta, EPJ C 41 (2005) 515], e.g.,

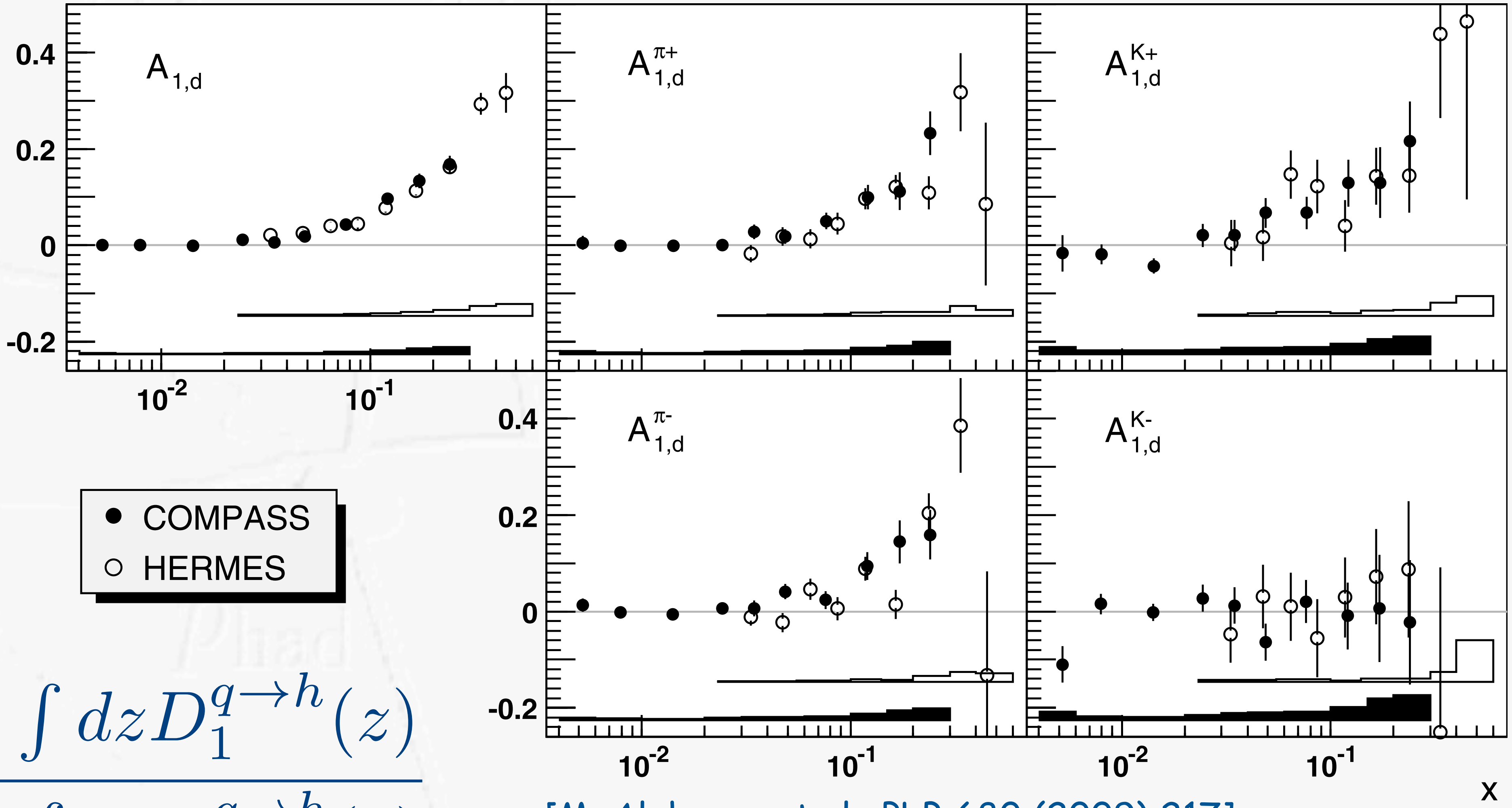
$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\mathsf{l}} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\mathsf{l}} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\mathsf{l}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\mathsf{q}} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT} \end{pmatrix}$$

($\cos\theta_{\gamma^*} \simeq 1$, $\sin\theta_{\gamma^*}$ up to 15% at HERMES energies)

… back to results …

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

Helicity density



[M. Alekseev et al., PLB 680 (2009) 217]
[A. Airapetian et al., PRL 92 (2004) 012005]

$$A_1^h(x) = \frac{\sum_q e_q^2 g_1^q(x) \int dz D_1^{q\to h}(z)}{\sum_q e_q^2 f_1^q(x) \int dz D_1^{q\to h}(z)}$$

$$= \sum_q \frac{e_q^2 \int dz D_1^{q\to h}(z)}{\sum_{q'} e_{q'}^2 f_1^{q'}(x) \int dz D_1^{q'\to h}(z)} g_1^q(x)$$

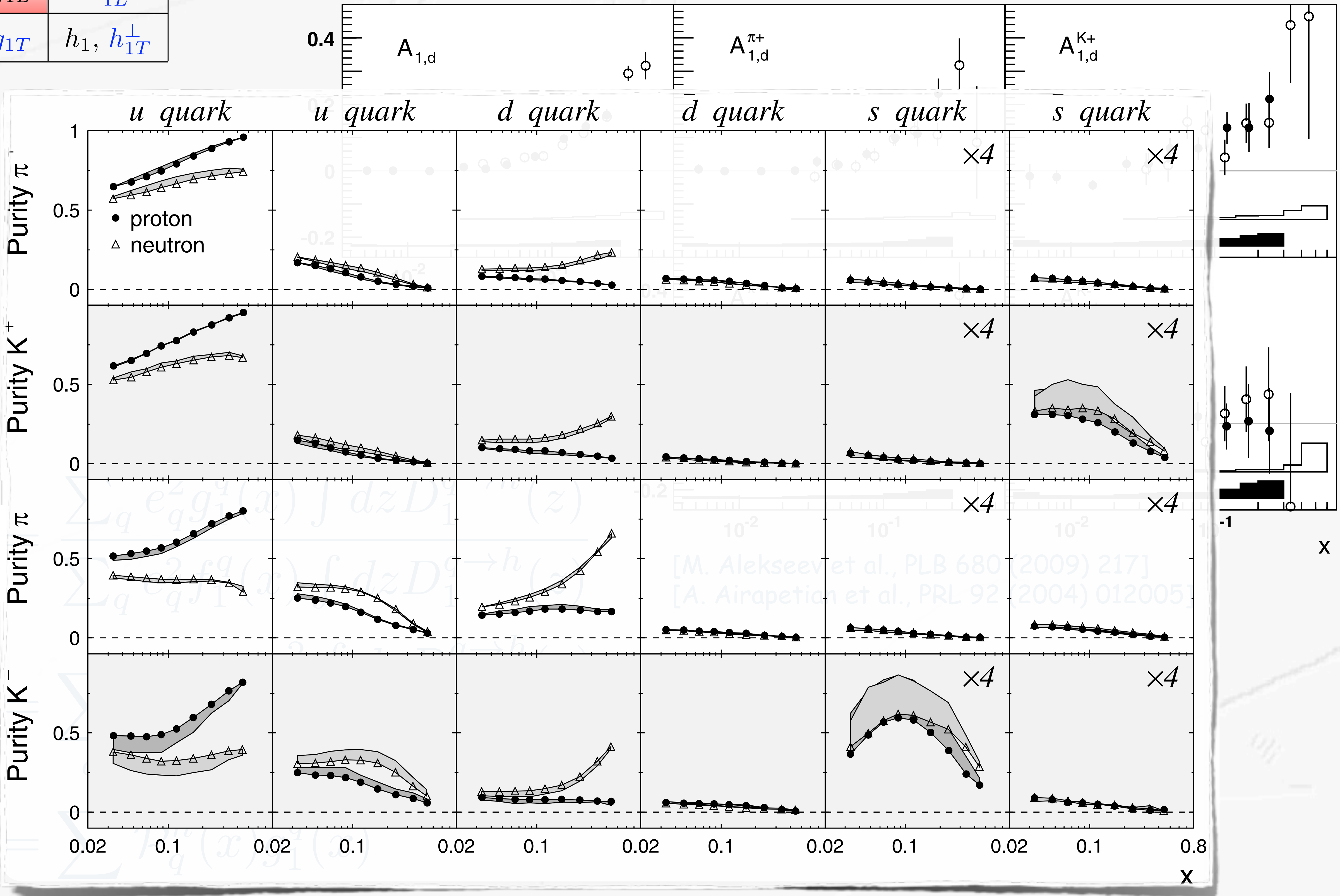
$$= \sum_q \mathcal{P}_q^h(x) g_1^q(x)$$

flavor separation via final-state hadron- flavor tagging

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

Helicity density

$\mathcal{P}_q^h(x)$



[M. Alekseev et al., PLB 680 (2009) 217]
[A. Airapetian et al., PRL 92 (2004) 012005]

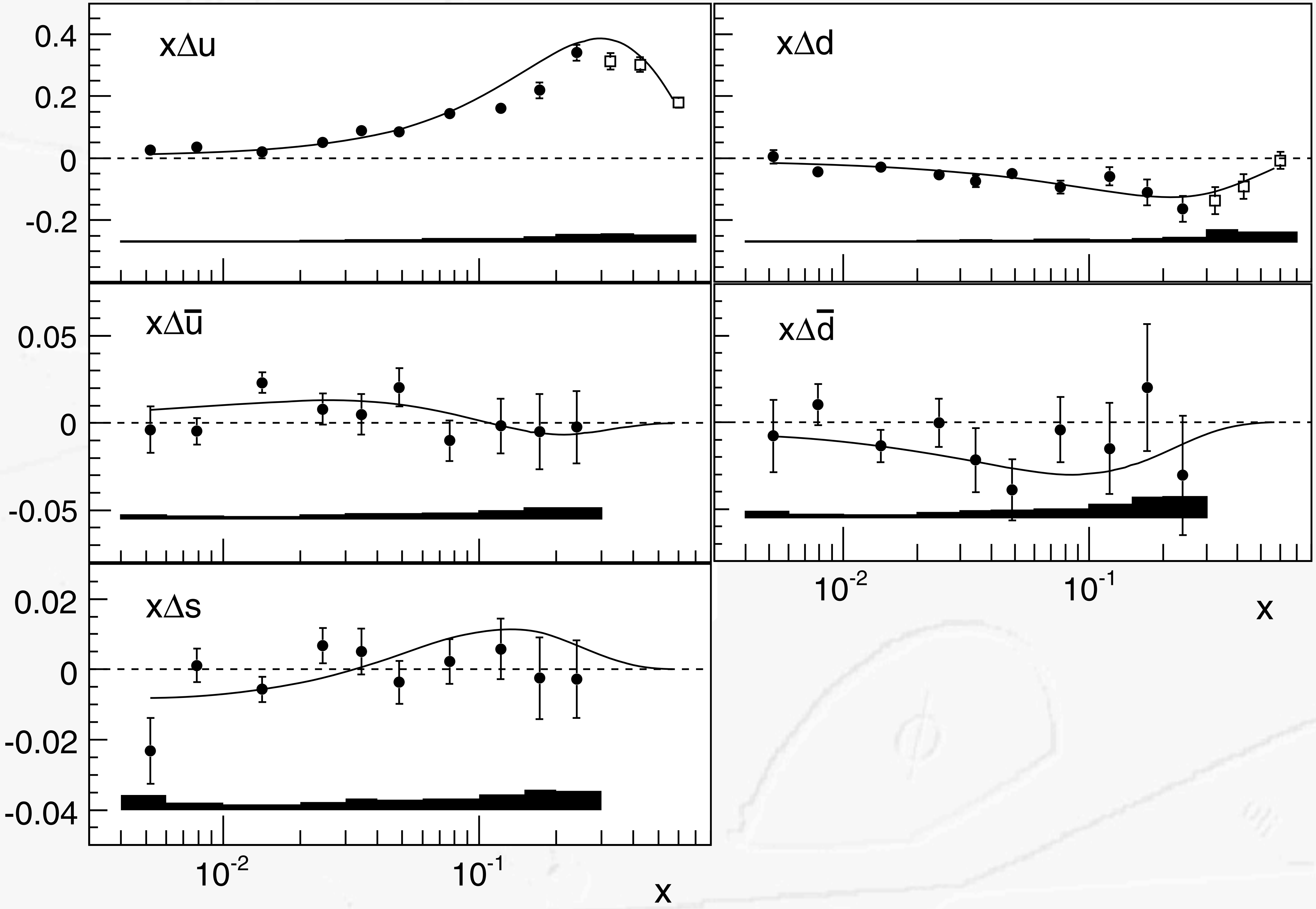
q

flavor separation via final-state hadron- flavor tagging

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

Helicity density

[M. Alekseev et al., PLB 693 (2010) 227]

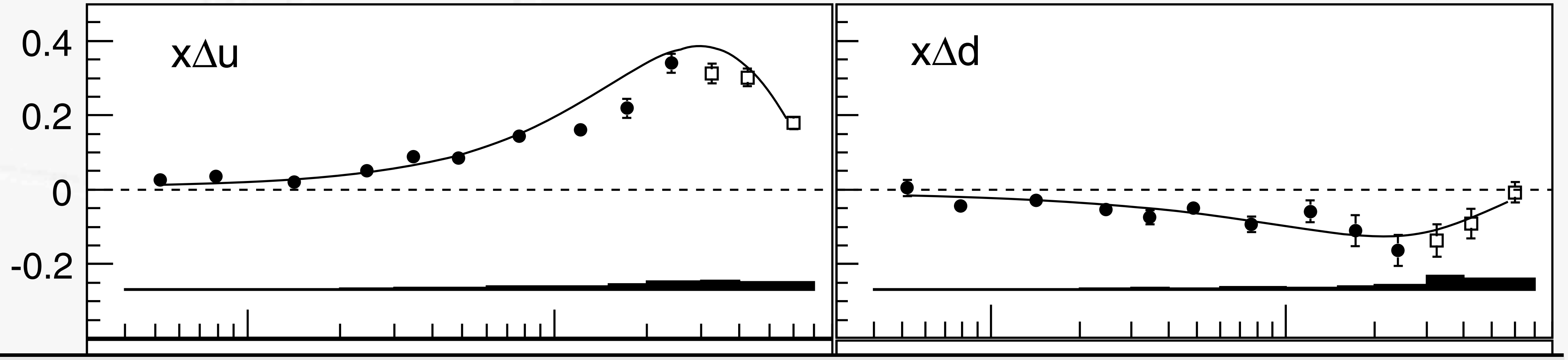


flavor separation of quark-helicity distribution using DIS data only

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

Helicity density

[M. Alekseev et al., PLB 693 (2010) 227]



	Extrapolation	DSSV
Δu	$0.71 \pm 0.02 \pm 0.03$	$0.71 \pm 0.02 \pm 0.03$
Δd	$-0.34 \pm 0.04 \pm 0.03$	$-0.35 \pm 0.04 \pm 0.03$
$\Delta \bar{u}$	$0.02 \pm 0.02 \pm 0.01$	$0.03 \pm 0.02 \pm 0.01$
$\Delta \bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	$-0.07 \pm 0.03 \pm 0.02$
$\Delta s (\Delta \bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	$-0.05 \pm 0.01 \pm 0.01$
Δu_v	$0.68 \pm 0.03 \pm 0.03$	$0.68 \pm 0.03 \pm 0.03$
Δd_v	$-0.29 \pm 0.06 \pm 0.03$	$-0.28 \pm 0.06 \pm 0.03$
$\Delta \Sigma$	$0.32 \pm 0.03 \pm 0.03$	$0.22 \pm 0.03 \pm 0.03$

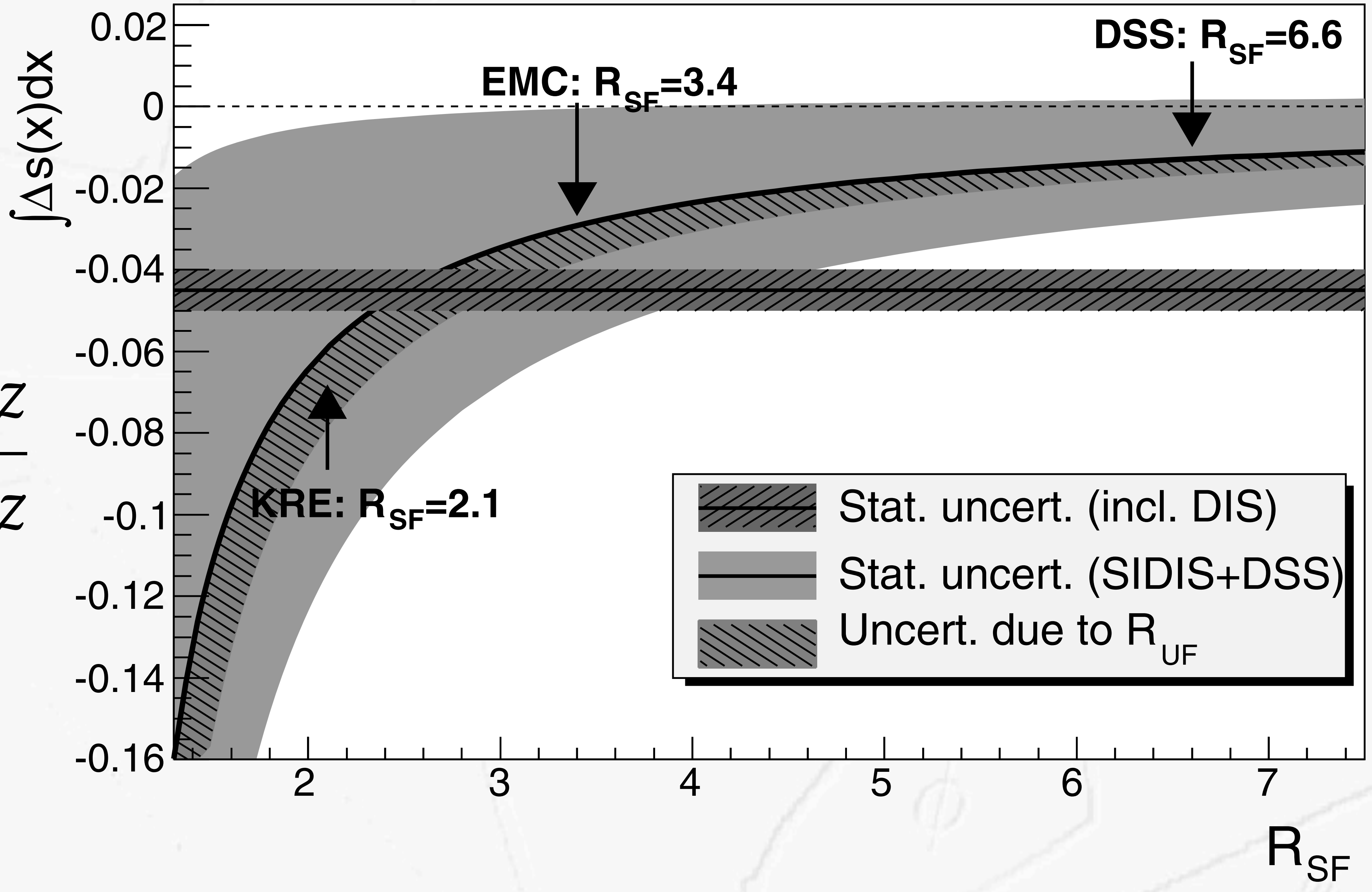
flavor separation of quark-helicity distribution using DIS data only

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

Helicity density

[M. Alekseev et al., PLB 680 (2009) 217]

$$R_{\mathrm{SF}} = \frac{\int D_{\bar{s}}^{K^+}(z)\,dz}{\int D_{u}^{K^+}(z)\,dz}$$



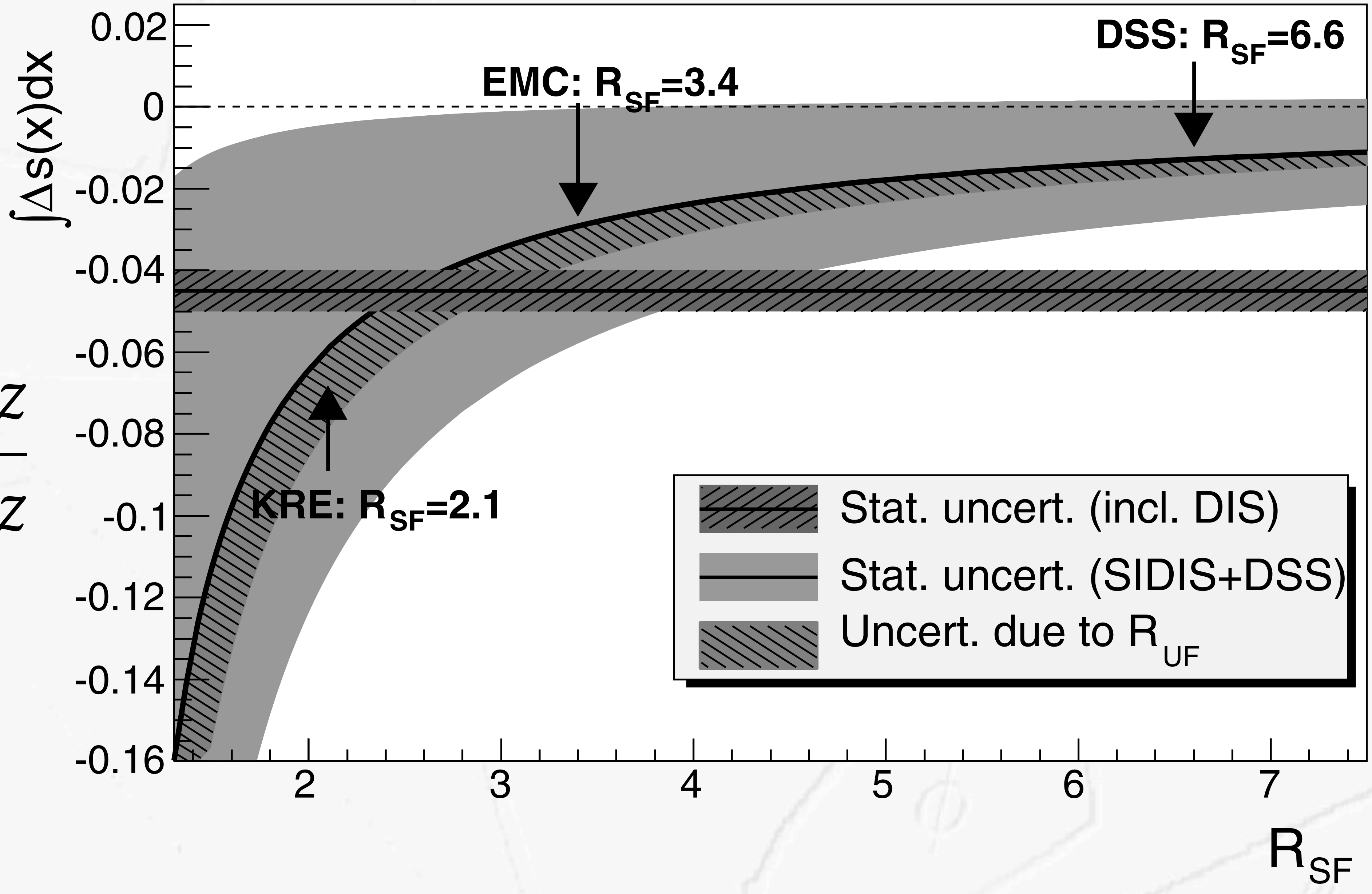
caveat: potentially large dependences on knowledge of FFs!

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

Helicity density

[M. Alekseev et al., PLB 680 (2009) 217]

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\,dz}{\int D_{u}^{K^+}(z)\,dz}$$



caveat: potentially large dependences on knowledge of FFs!

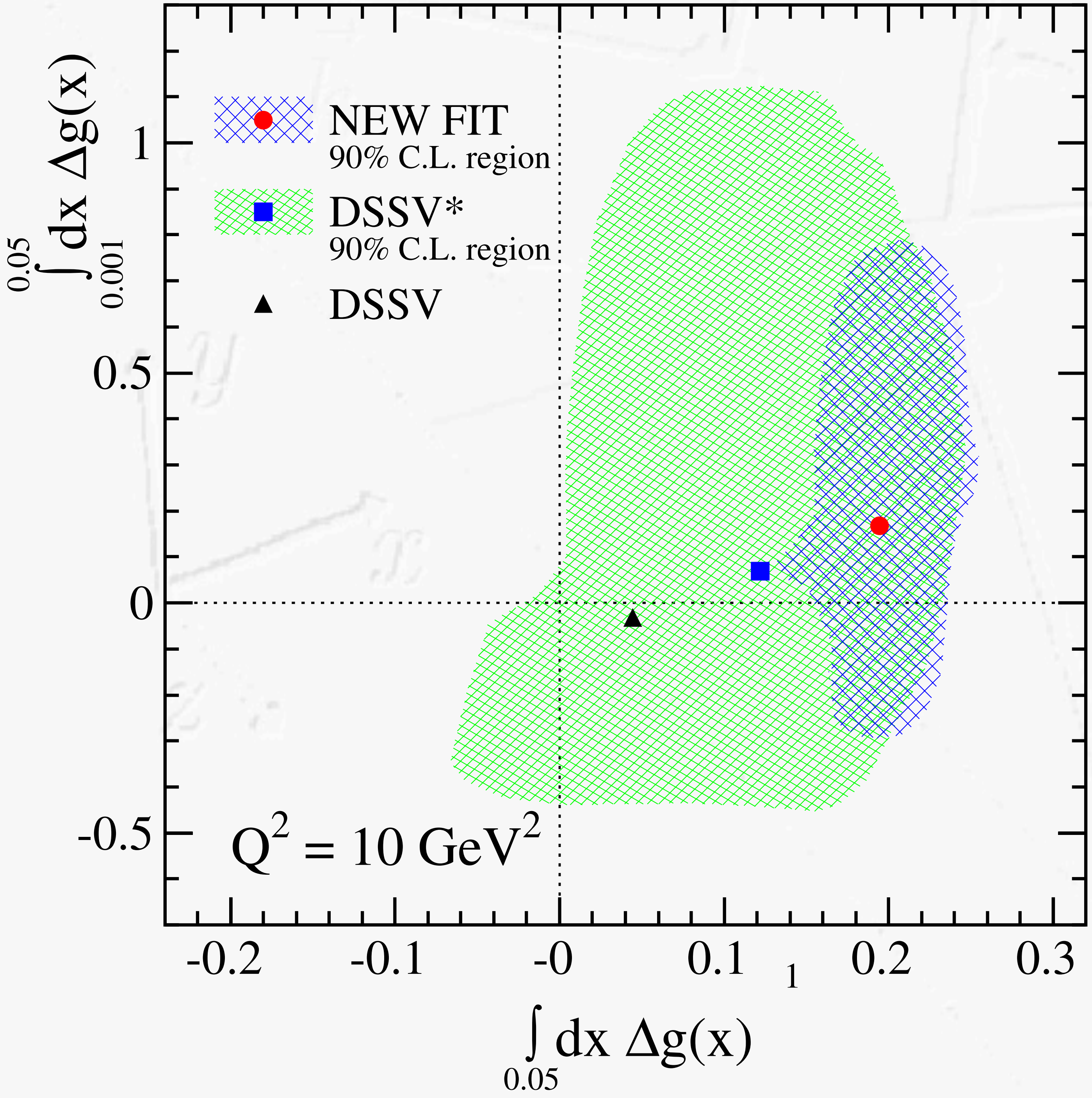
☛ global analysis of DIS, pp, and e^+e^- data

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

Helicity density

gluon helicity from (mainly) polarized pp collision

[de Florian et al., PRL 113, 012001 (2014)]



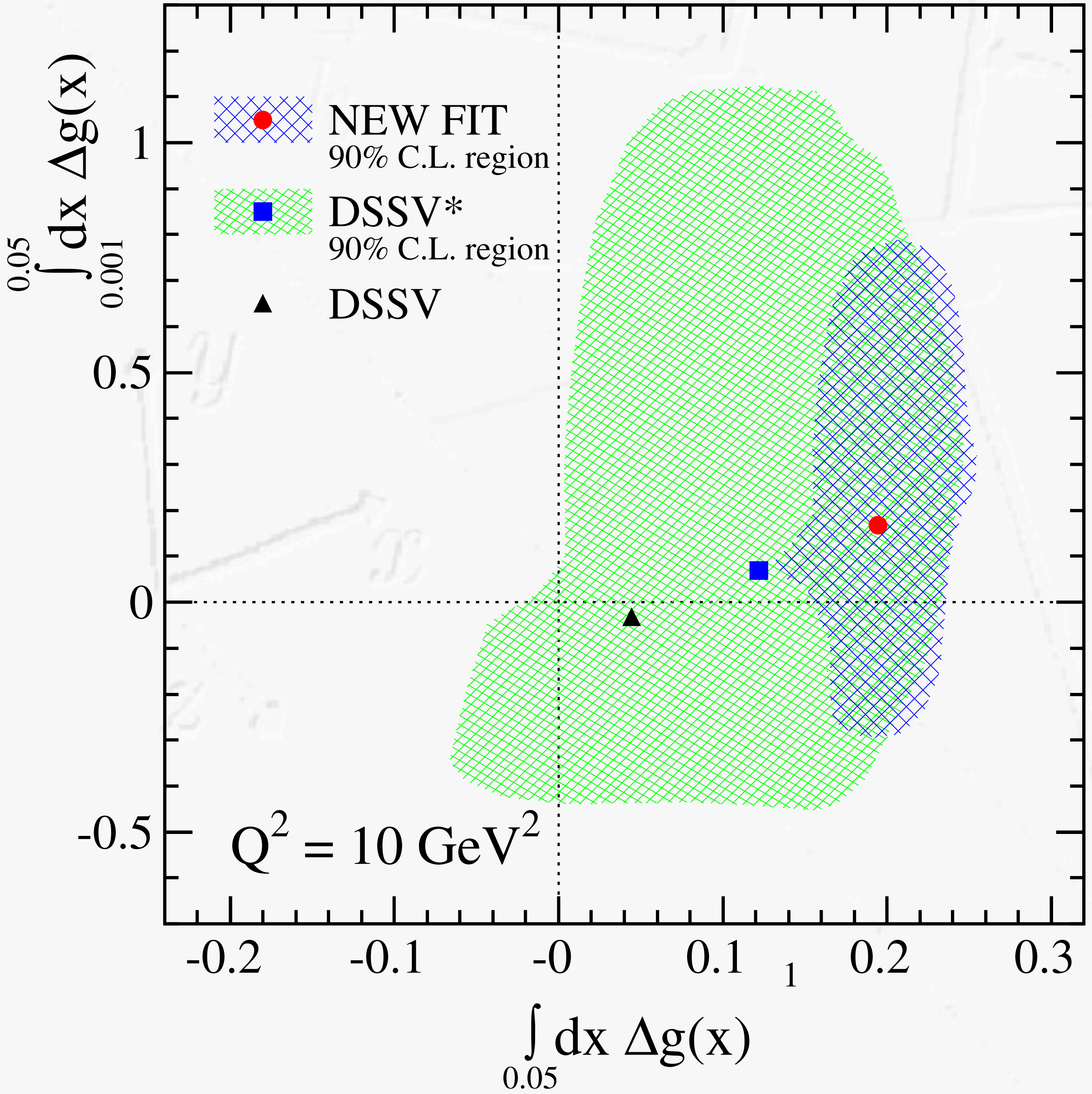
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Helicity density

gluon helicity from (mainly) polarized pp collision

☛ talk by L. Bland

[de Florian et al., PRL 113, 012001 (2014)]



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

Helicity density

gluon helicity from (mainly) polarized pp collision

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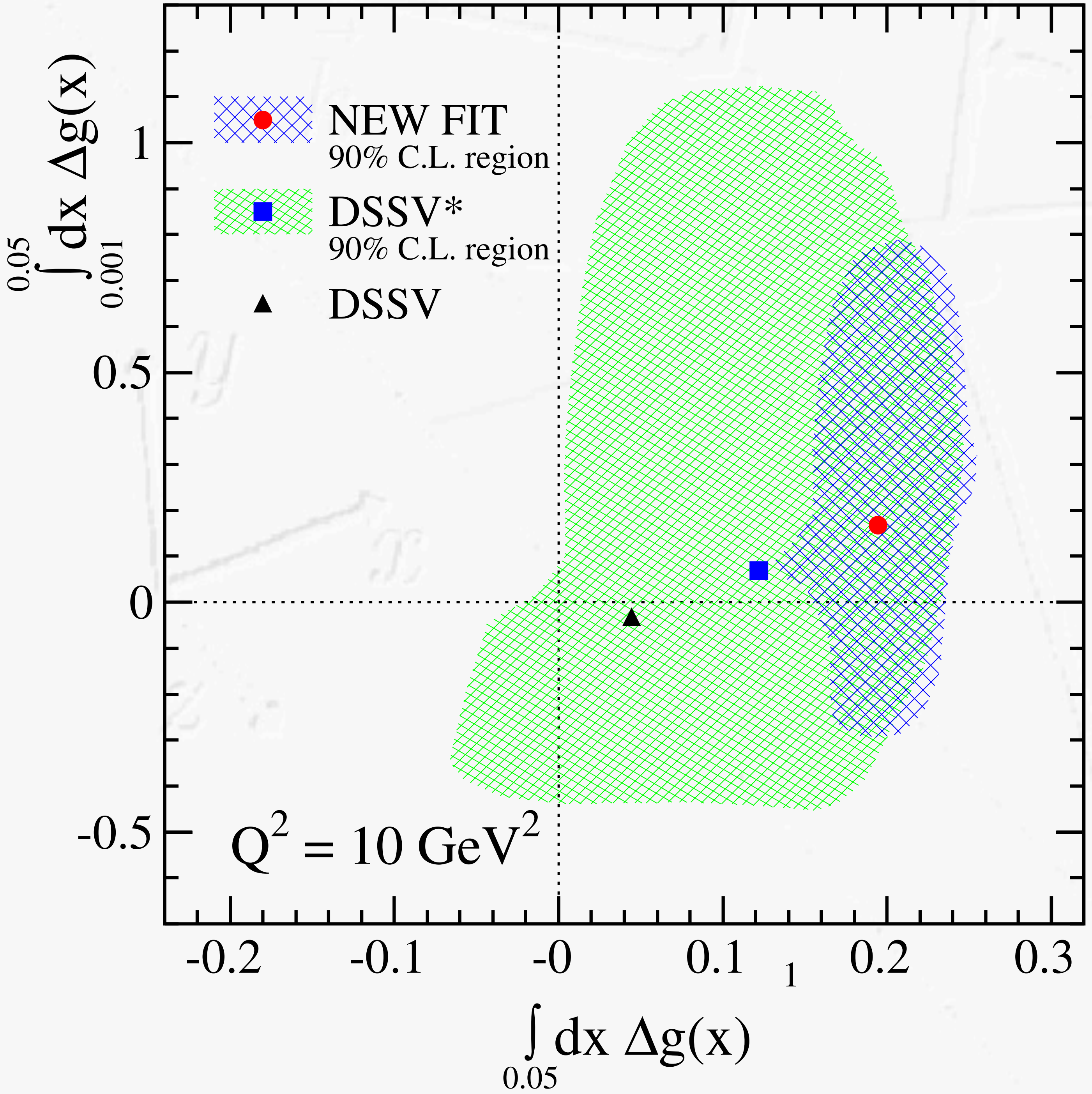
[de Florian et al., PRL 113, 012001 (2014)]



Contributions to nucleon spin:

$$\Delta\Sigma \approx (25 \ldots 33)\%$$

$$\Delta G \approx 40\%$$

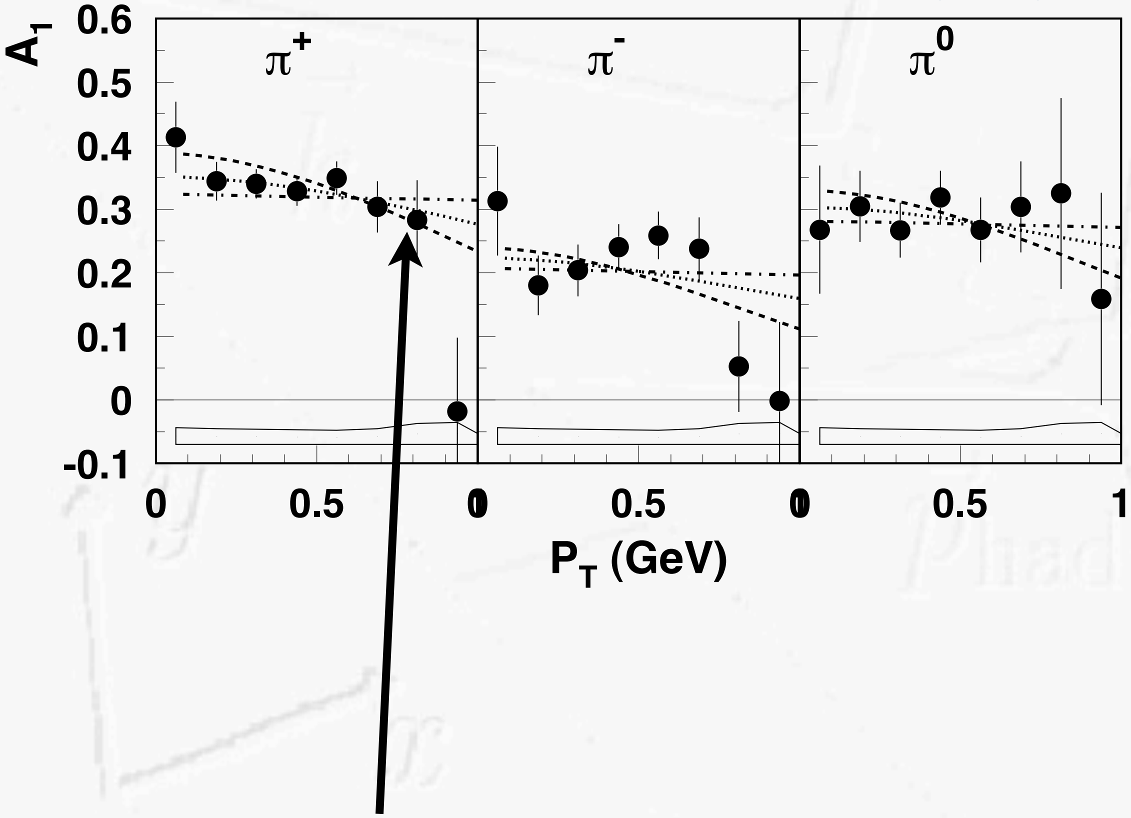
$$\hookrightarrow \mathcal{L} \approx (27 \ldots 35)\%$$

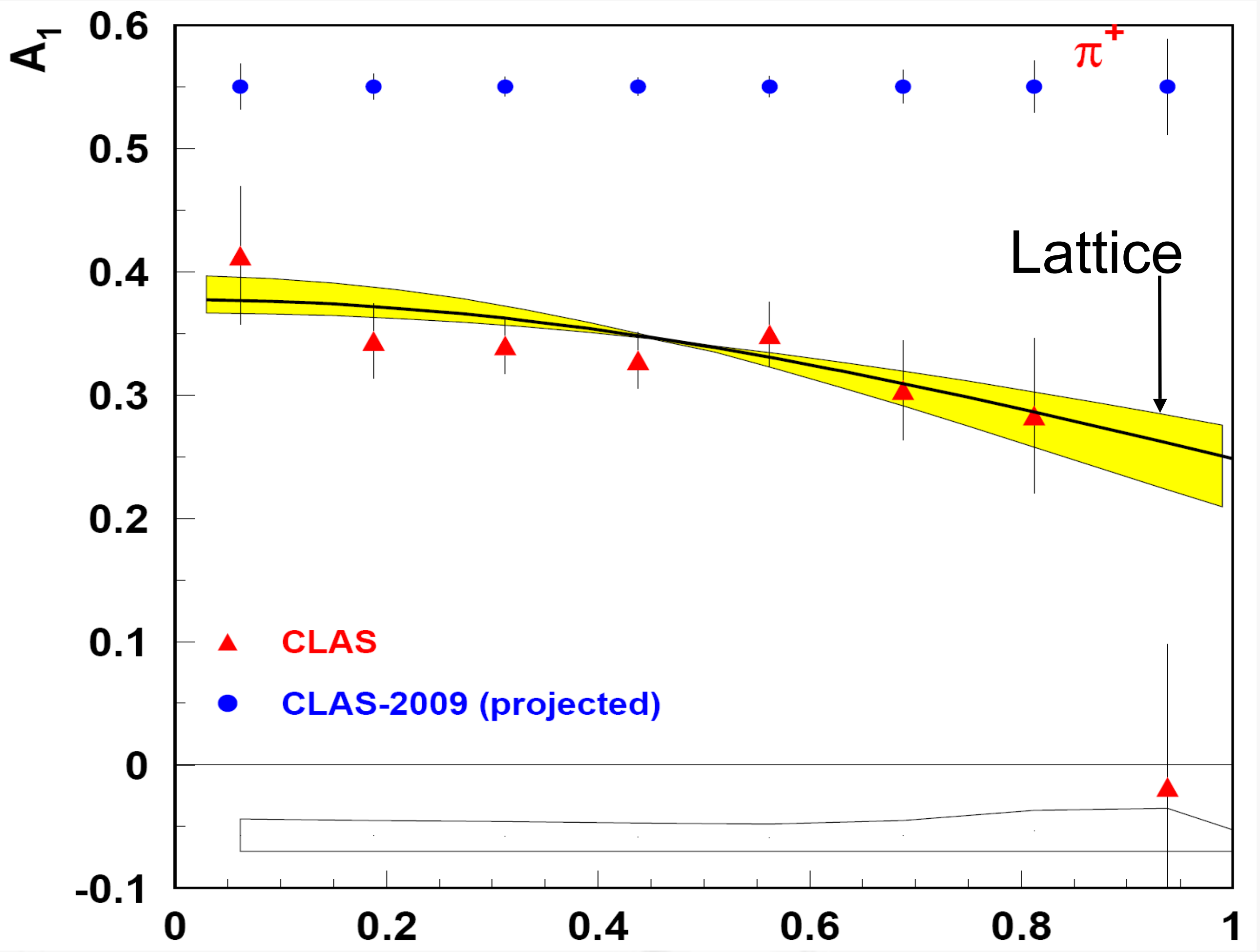
(with still large uncertainties!)

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

Helicity density

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





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

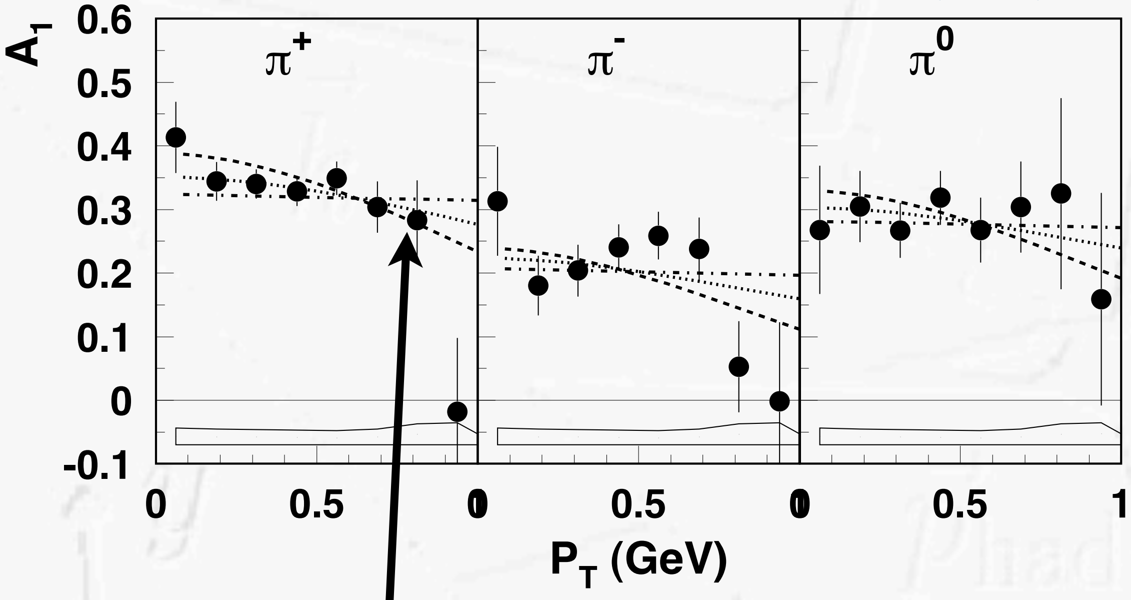
$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

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

Helicity density

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

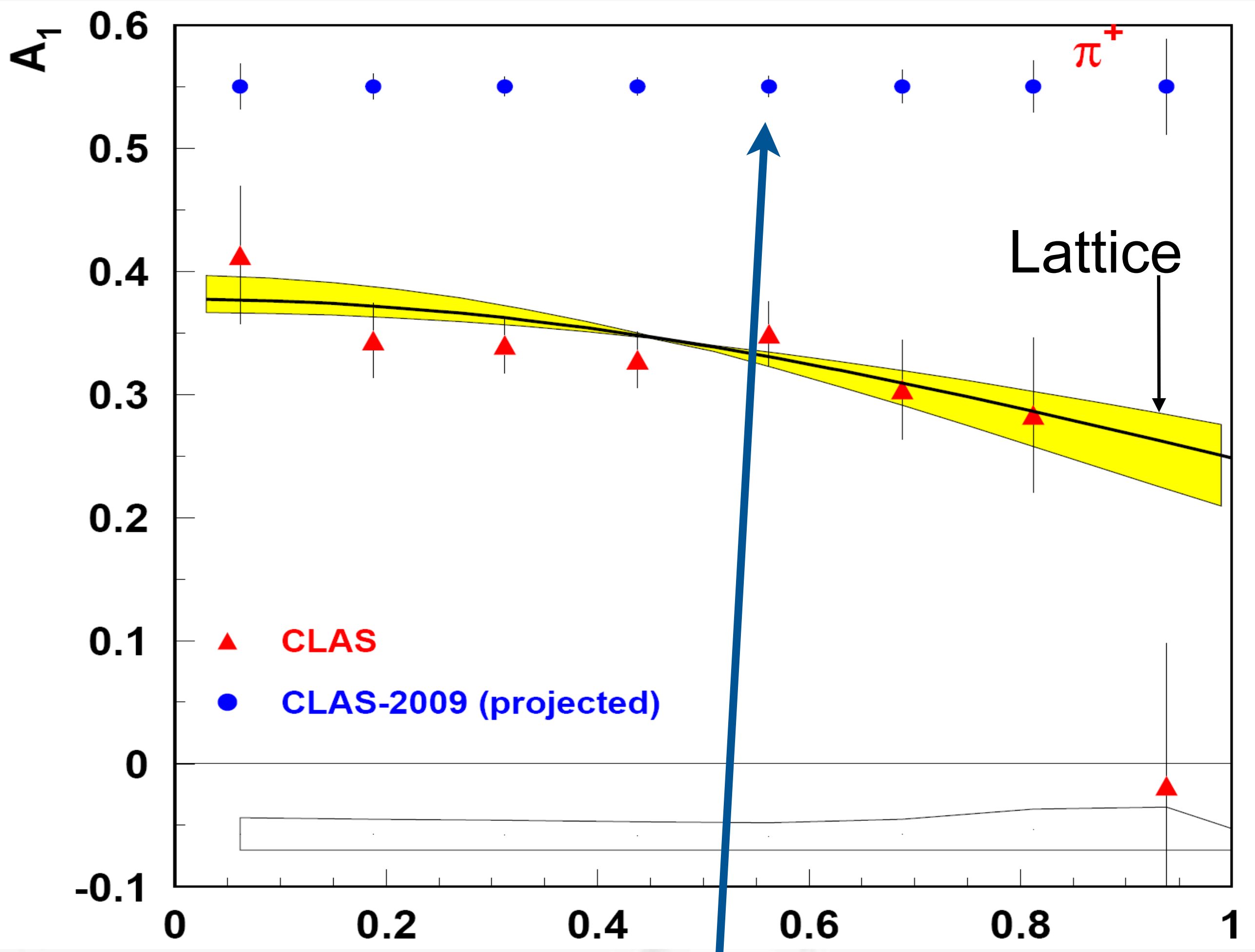
[Avakian et al. [CLAS], PRL 105, 262002 (2010)[



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

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

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



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

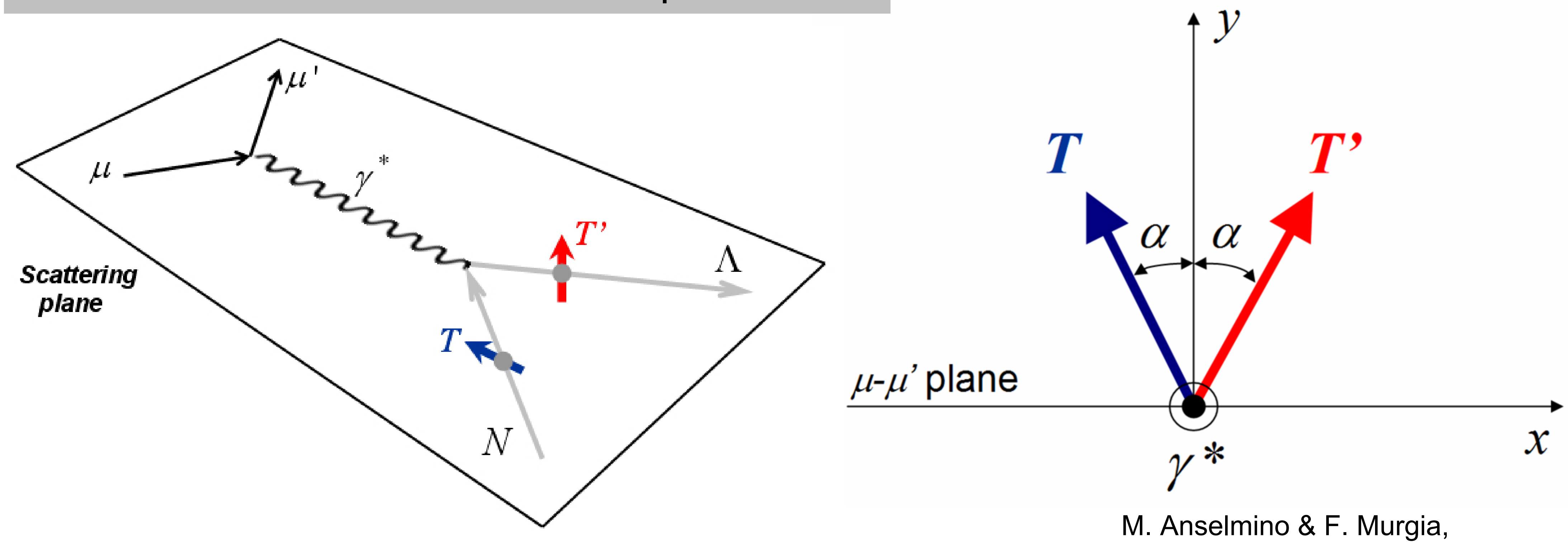
No significant $P_{h\perp}$ dependences seen at HERMES and COMPASS

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 (transverse-spin transfer)

Quantization axis for transverse Λ polarization

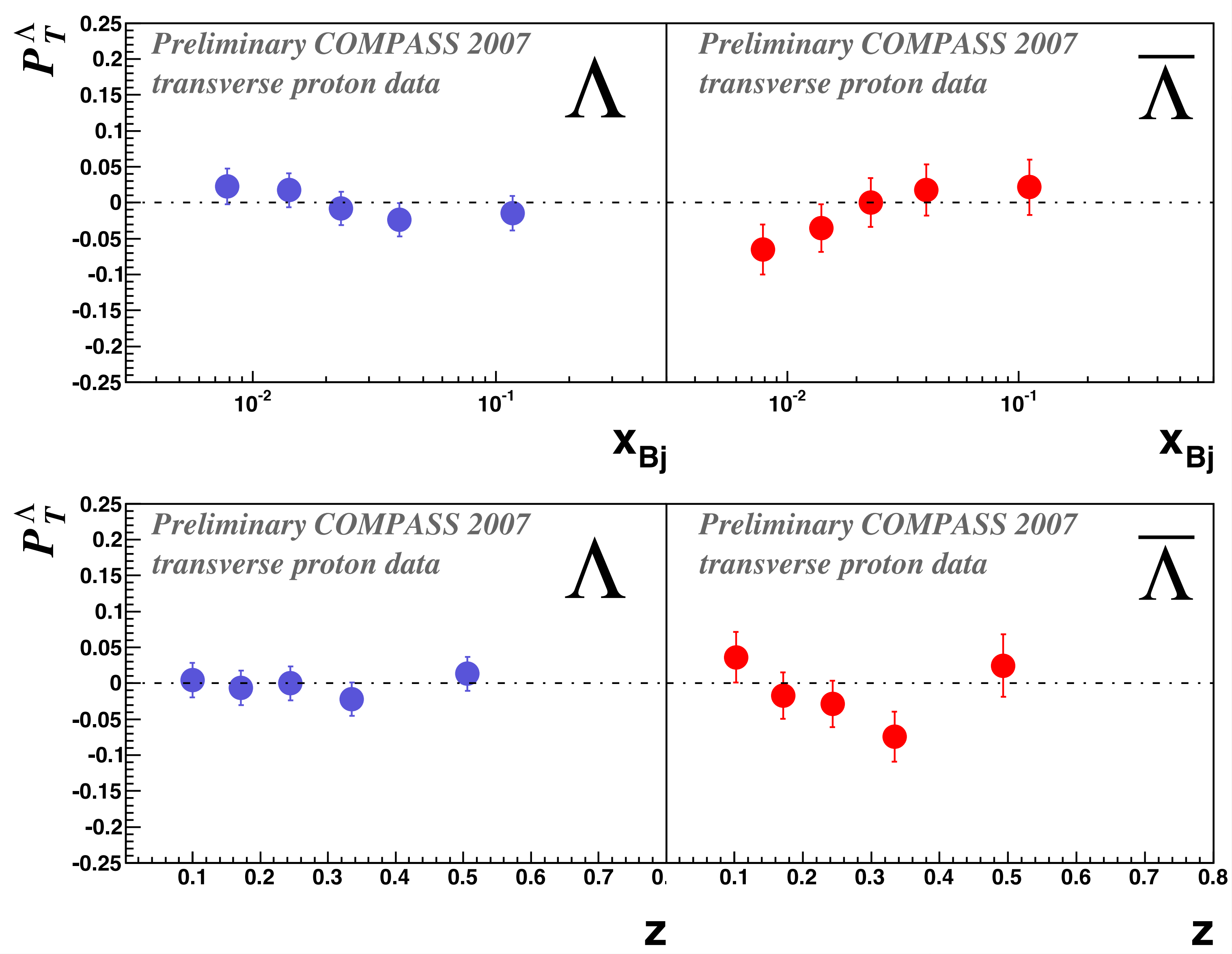


M. Anselmino & F. Murgia,
Physics Letters B 483 (2000) 74-86

T (initial quak spin) : component of target spin perpendicular to γ^*
T' (final quark spin) : symmetric of the ***T*** w.r.t. the normal to the scattering plane

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

Transversity (transverse-spin transfer)



- compatible with zero
- low sensitivity to u & d quark polarization?
- measured at lower x where transversity is expected not to be large
- 2010 data will reduce statistical uncertainty by factor 2
- if spin transfer related to hyperon spin structure, Lambda potentially bad probe

Quark polarizations in hyperons

[G.S., Ph.D. thesis, NMSU (1999)]

	Δu		Δd		Δs	
p	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05
n	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05
Σ^+	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^0	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Λ	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma + 2D)$	0.58 ± 0.04
Ξ^0	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04
Ξ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04

Quark polarizations in hyperons

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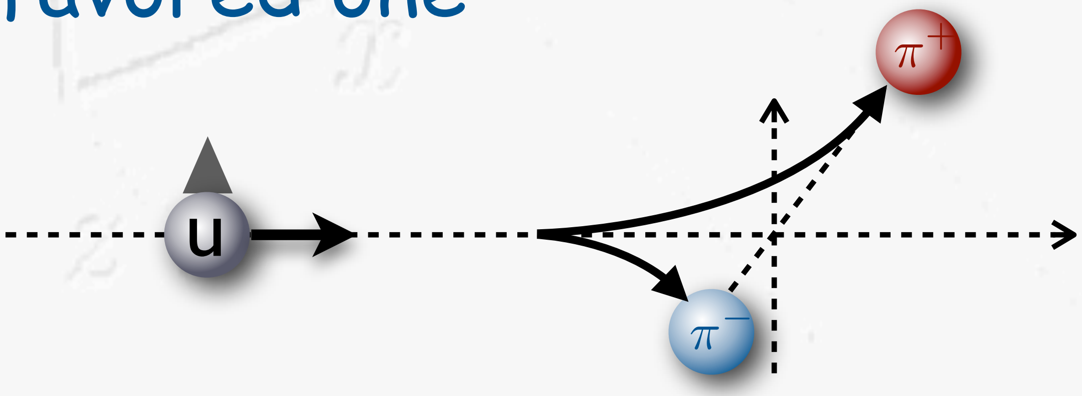
Σ^+	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^0	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D)$	0.32 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Σ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04
Λ	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma - D)$	-0.20 ± 0.04	$\frac{1}{3}(\Delta\Sigma + 2D)$	0.58 ± 0.04
Ξ^0	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04
Ξ^-	$\frac{1}{3}(\Delta\Sigma + D - 3F)$	-0.16 ± 0.05	$\frac{1}{3}(\Delta\Sigma - 2D)$	-0.45 ± 0.04	$\frac{1}{3}(\Delta\Sigma + D + 3F)$	0.79 ± 0.04

- better sensitivity to u and d quarks via charged Sigma's
- large analyzing power of the parity-violating decay $\Sigma^+ \rightarrow p\pi^0$
  - good probe of u-quark polarization
  - need good acceptance and neutral pion reconstruction

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

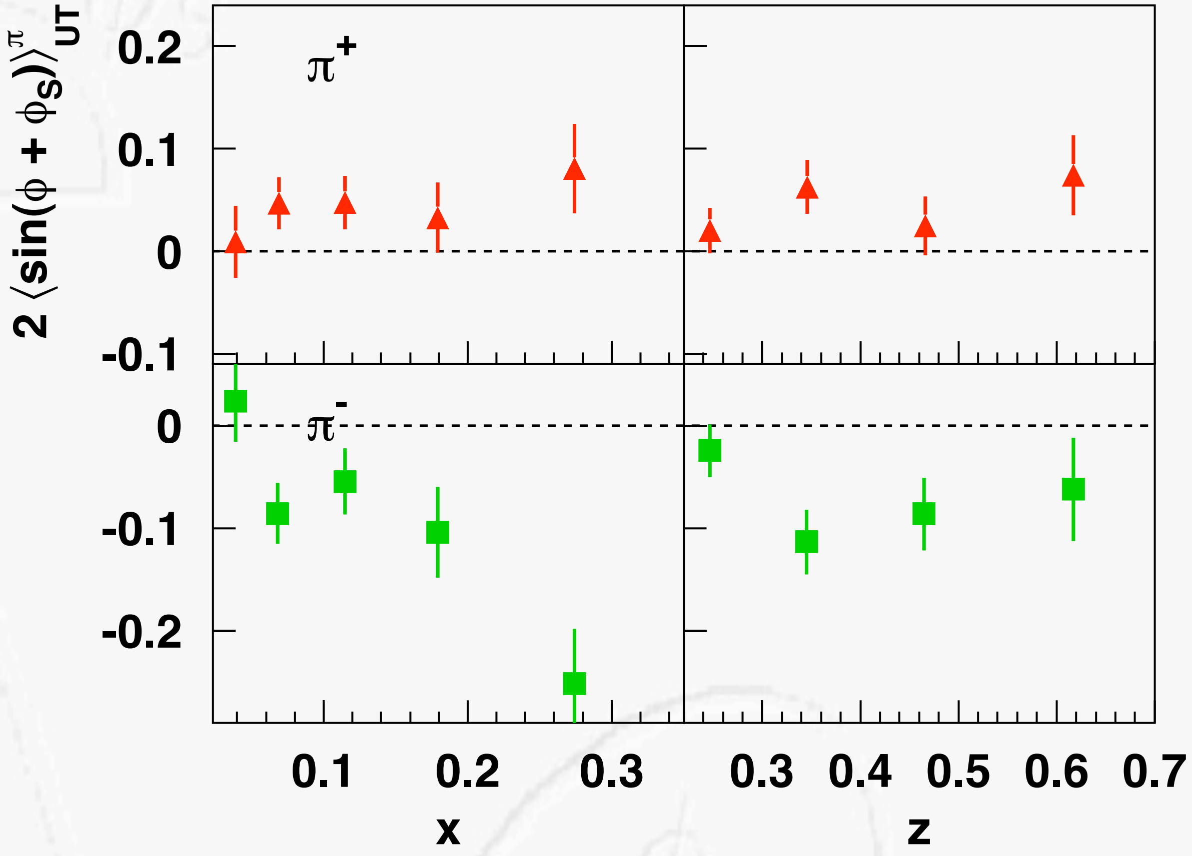
Transversity (Collins fragmentation)

- 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, PRL 94 (2005) 012002]



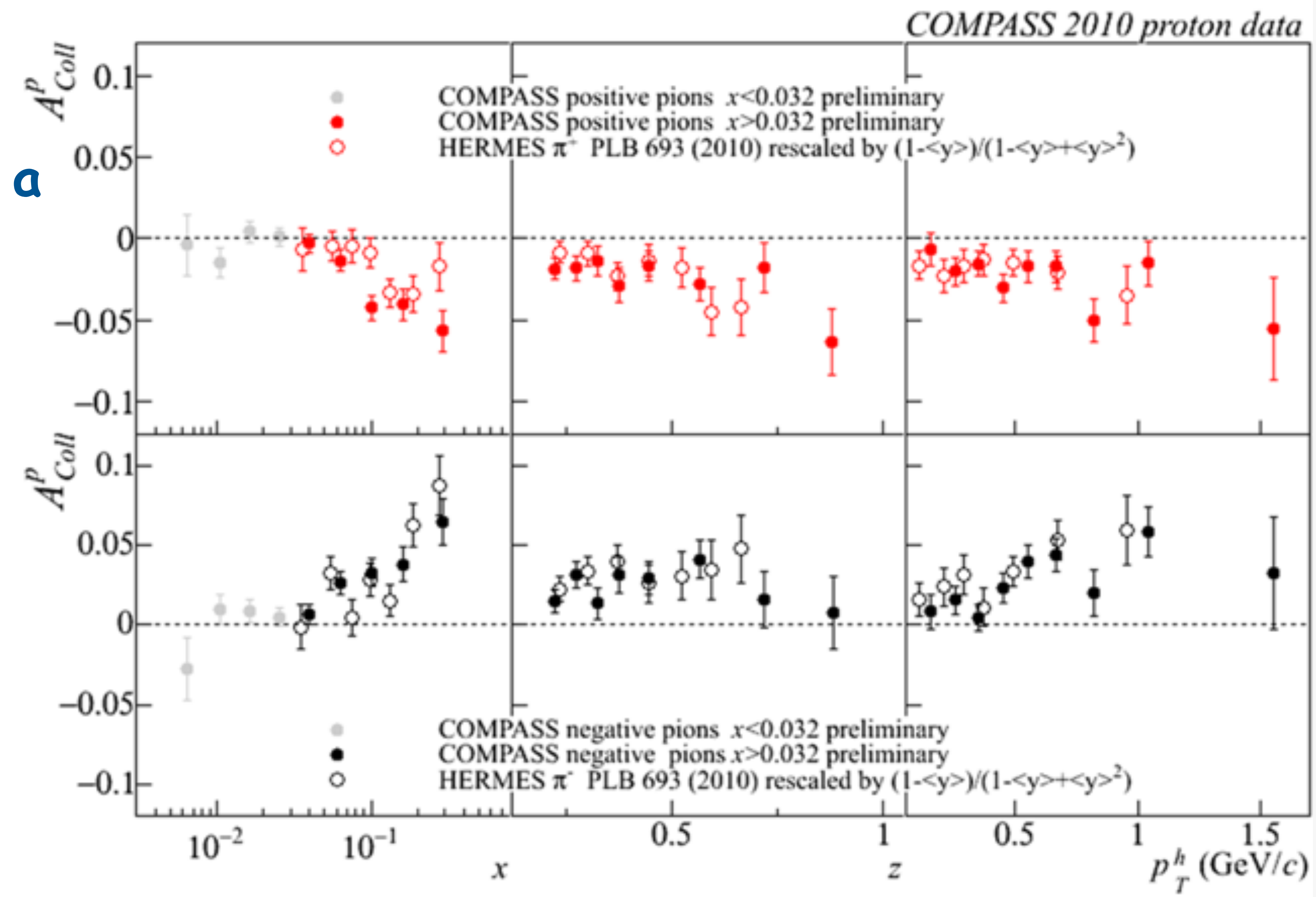
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

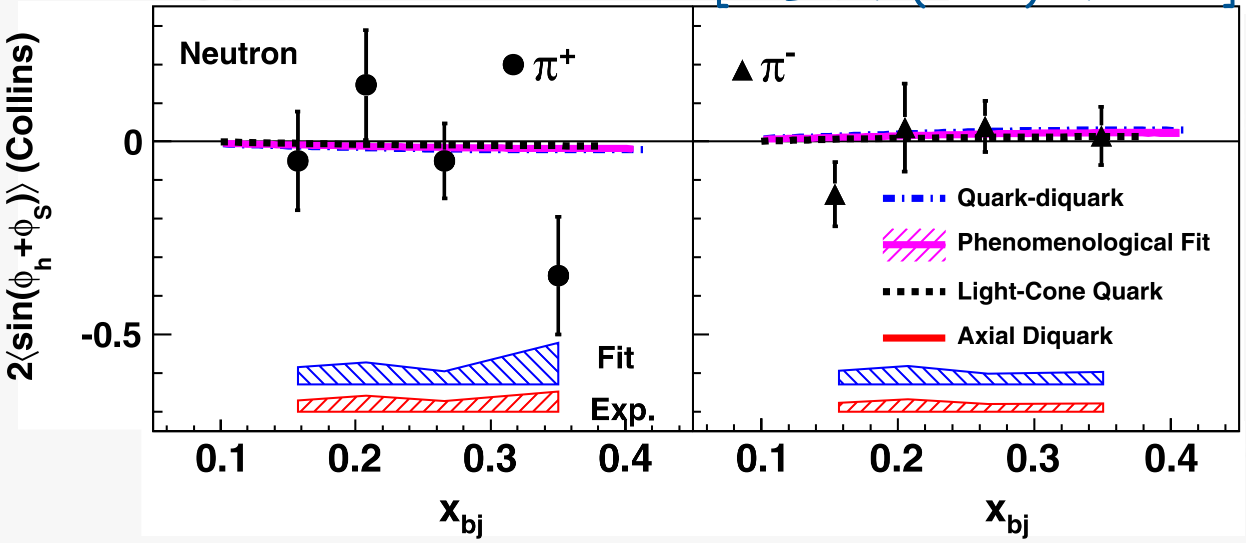
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes

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



[PRL 107 (2011) 072003]



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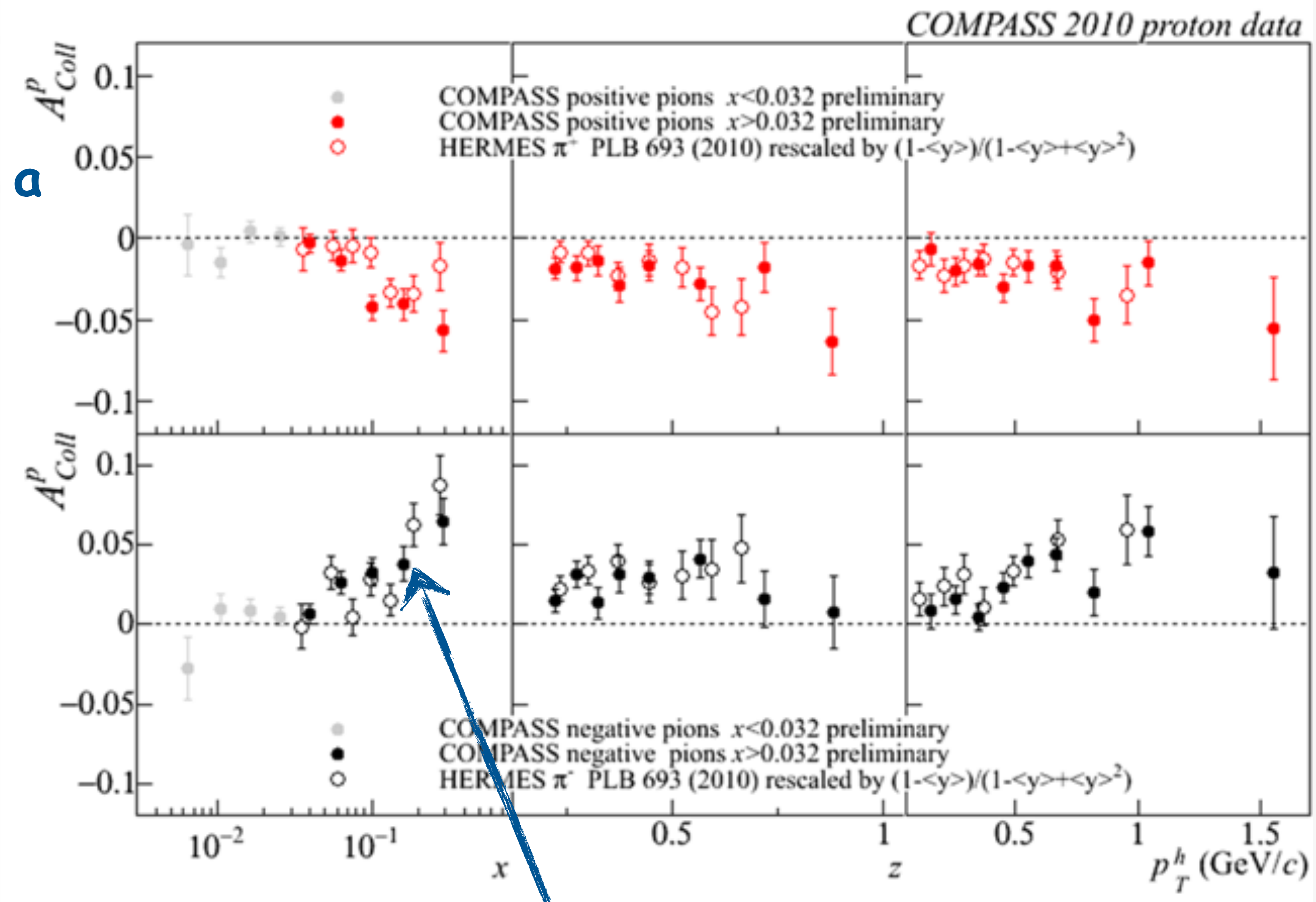
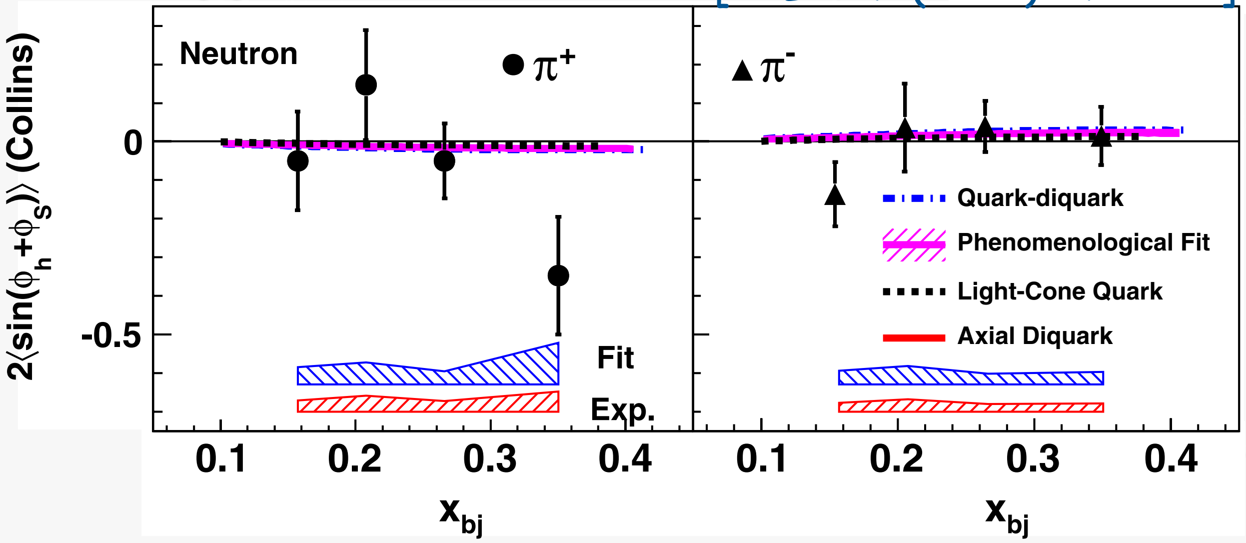


[PRL 107 (2011) 072003]



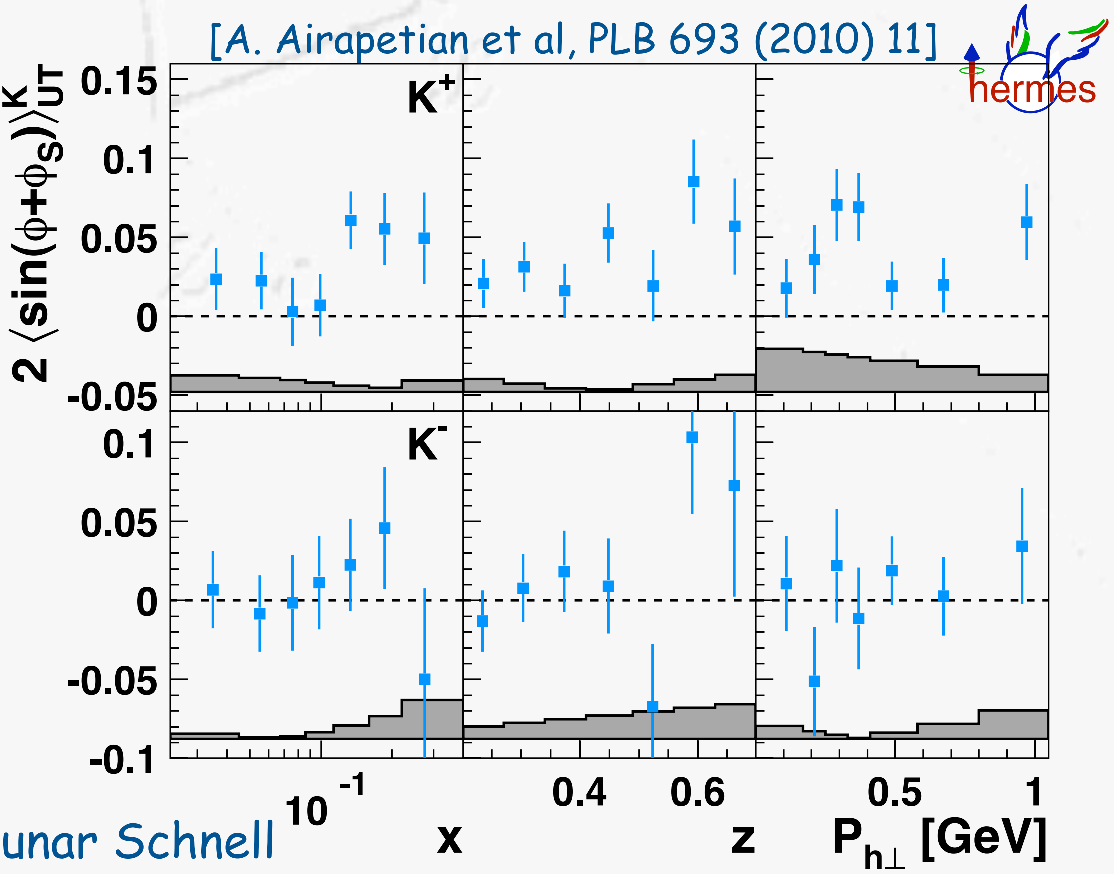
excellent agreement of various proton data, also with neutron results

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

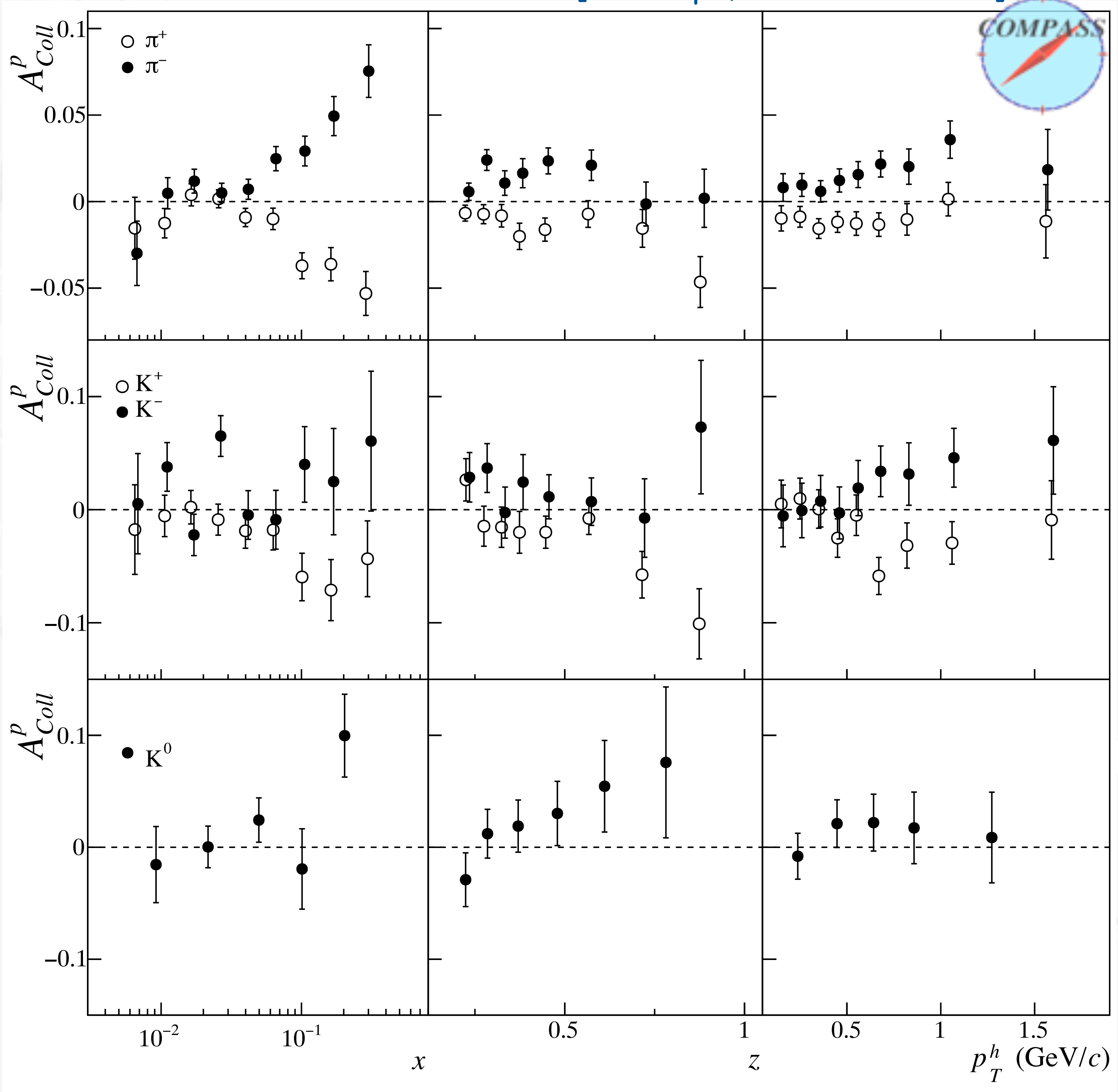
Collins amplitudes

- **since those early days, a wealth of new results:**
  - COMPASS
    [PLB 692 (2010) 240,
    PLB 717 (2012) 376, arXiv:1408.4405]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]

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



[C. Adolph, arXiv:1408.4405]

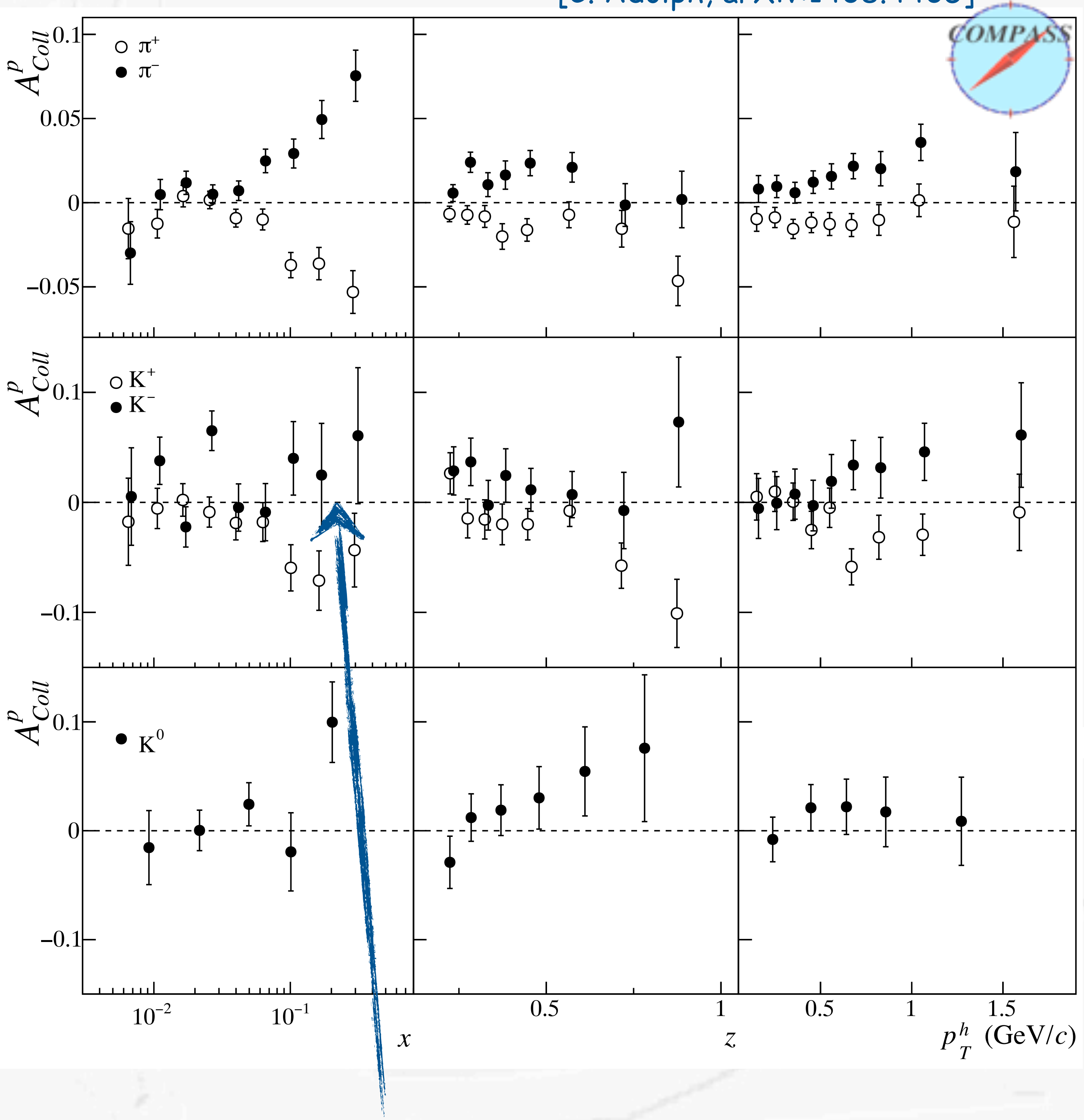


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

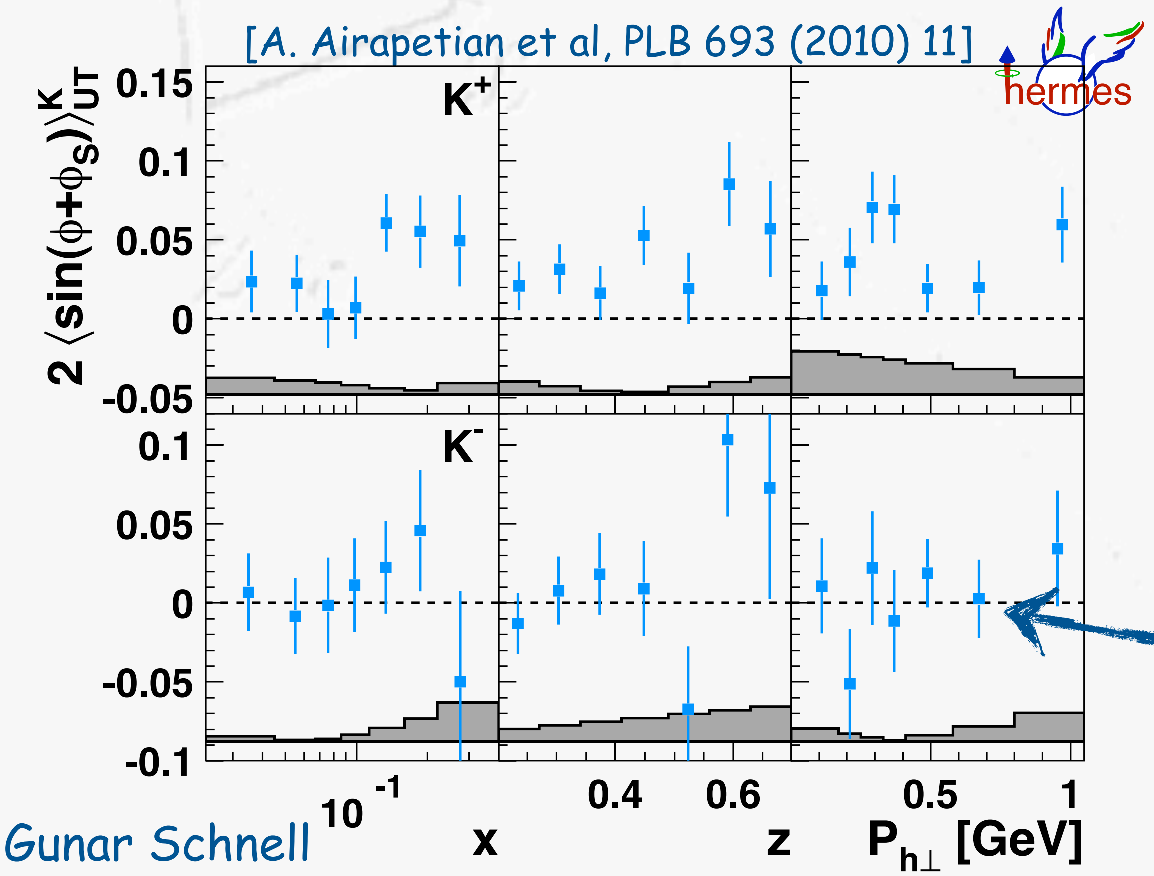
Collins amplitudes

- **since those early days, a wealth of new results:**
  - COMPASS
    [PLB 692 (2010) 240,
    PLB 717 (2012) 376, arXiv:1408.4405]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]

[C. Adolph, arXiv:1408.4405]



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



cancelation of (unfavored) u and d fragmentation (opposite signs of up and down transversity)?

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

Collins amplitudes

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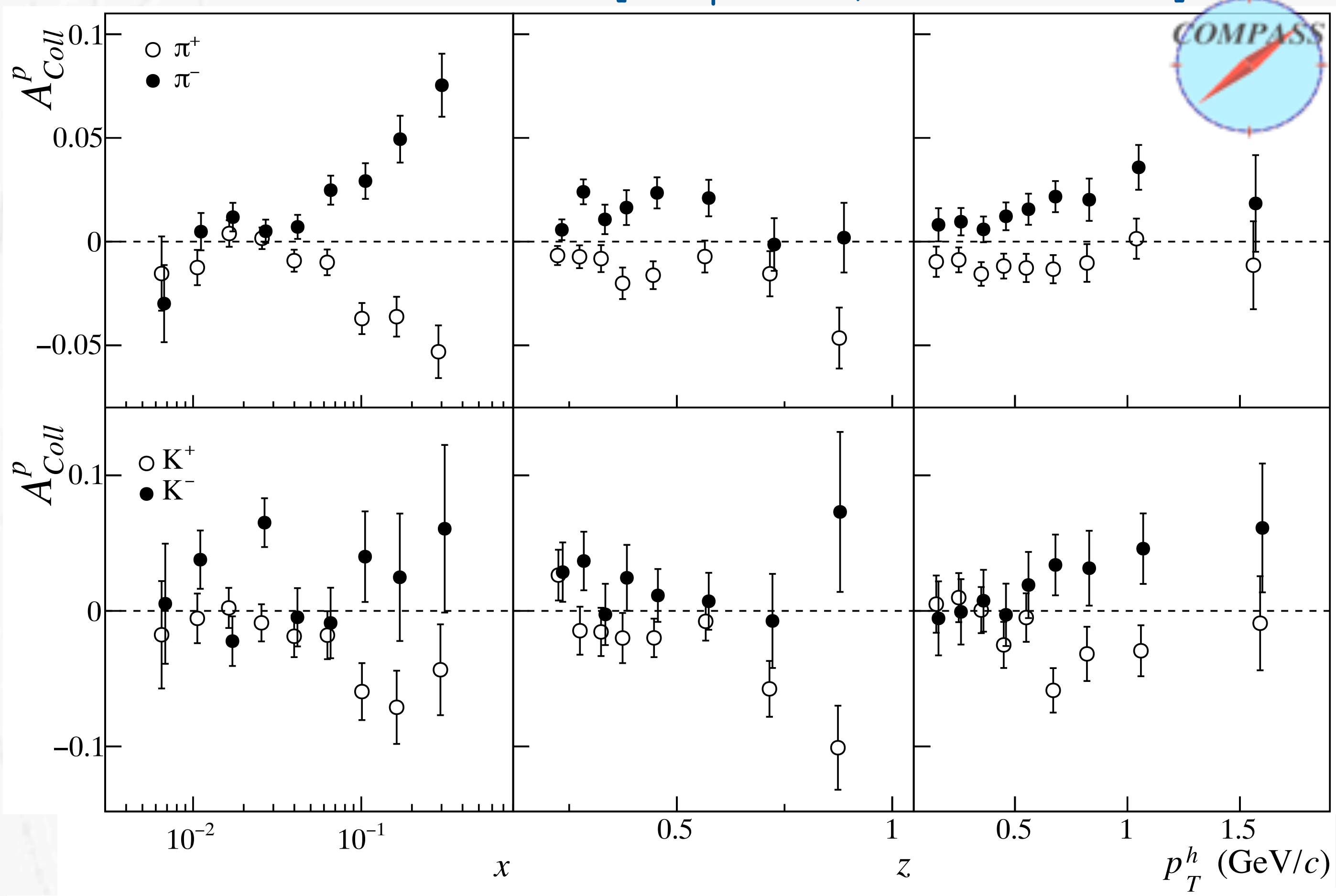
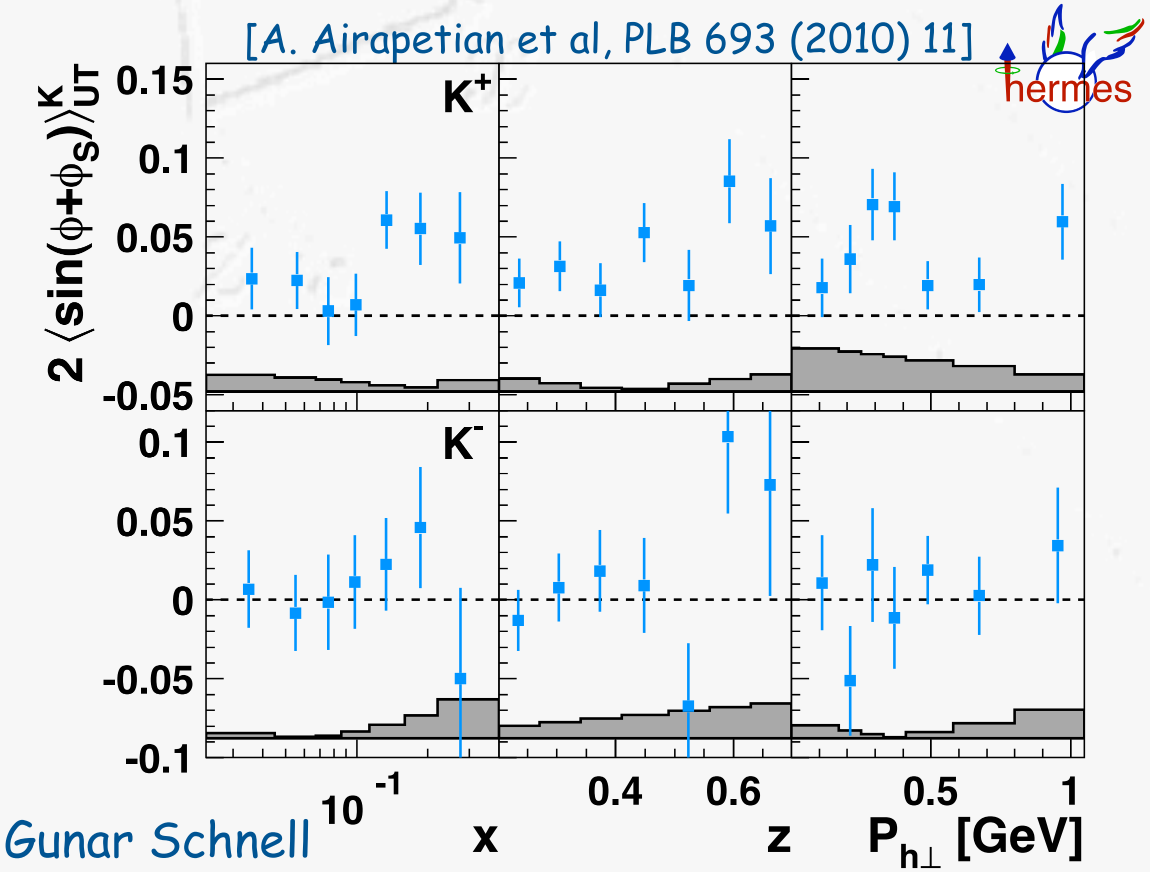
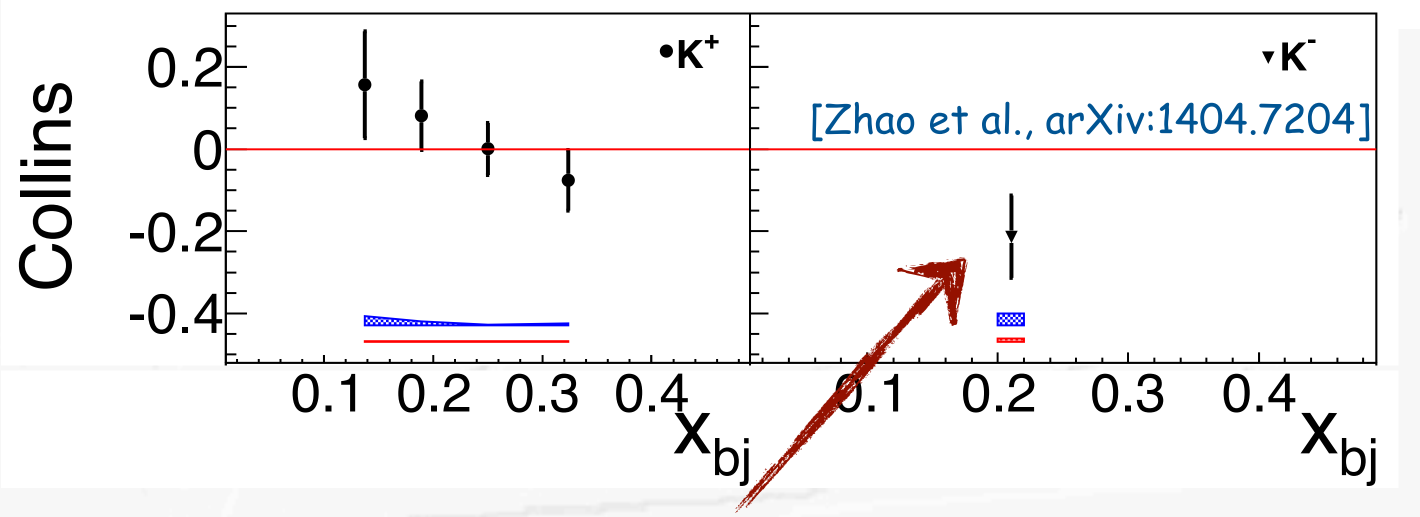


[A. Airapetian et al, PLB 693 (2010) 11]



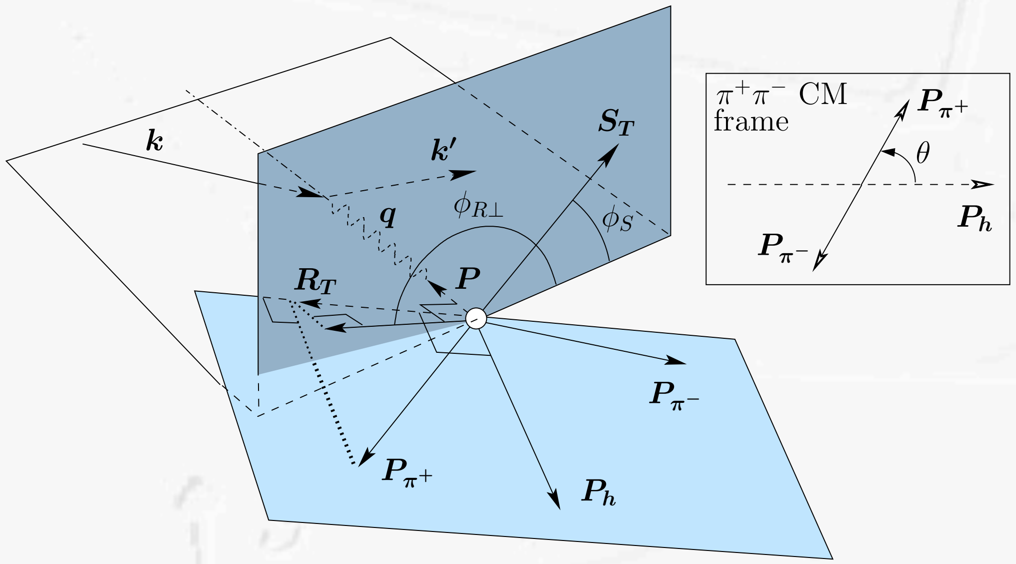
[Zhao et al., arXiv:1404.7204]



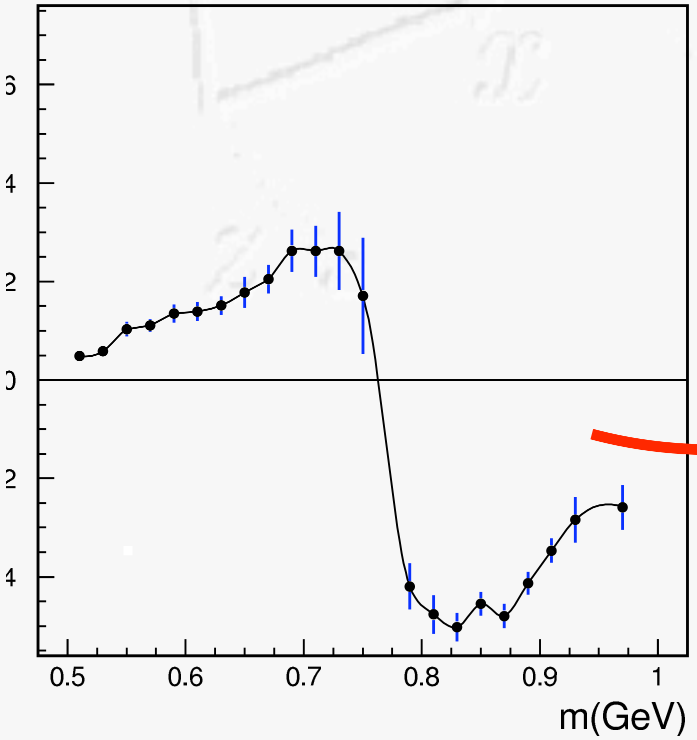
but relatively large K- asymmetry on ^{3}He?
(however, no full Fourier decomposition in JLab analysis -> possible mixing with other moments?)

	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 (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

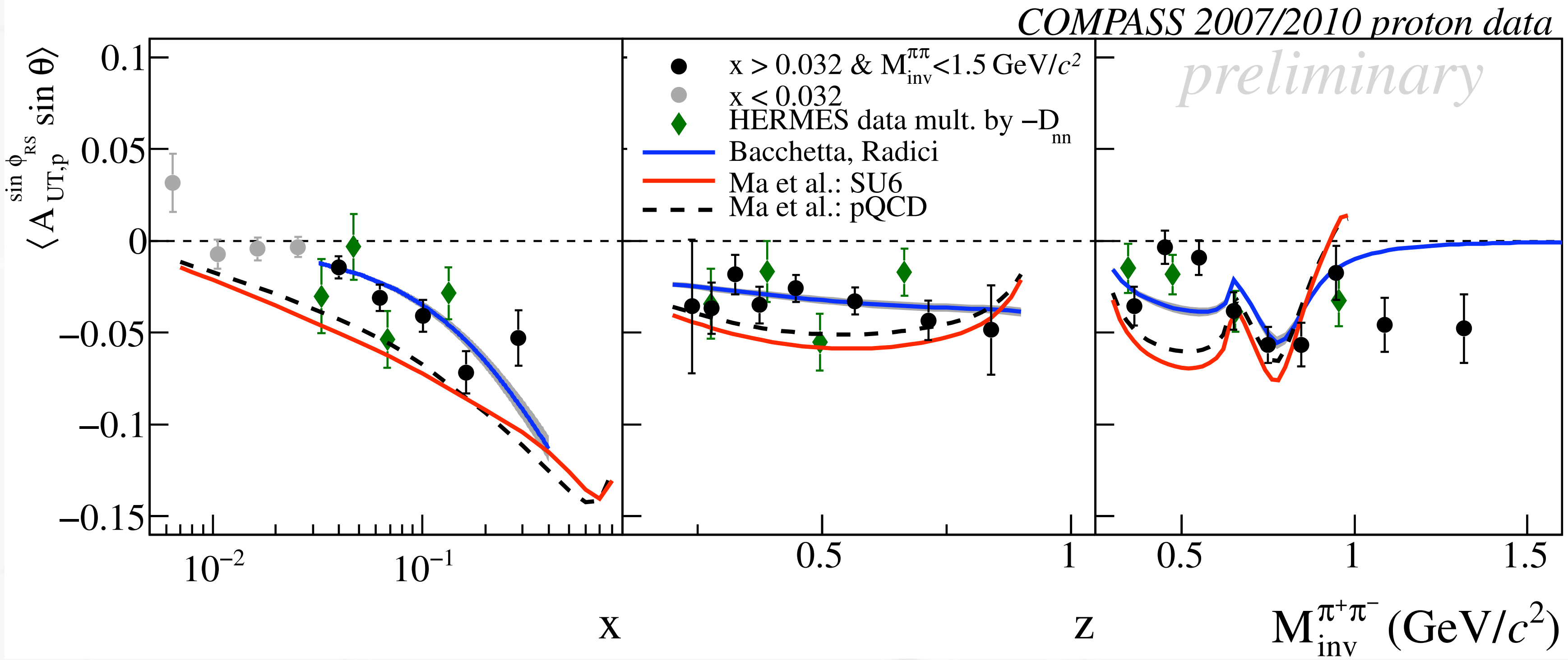
$$= \mathcal{P}(M_{\pi\pi}^2)H_1^{\sphericalangle,sp'}(z)$$

$\Rightarrow$ 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 (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]



	U	L	T
U	f_1		$h_1^\perp$
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- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign

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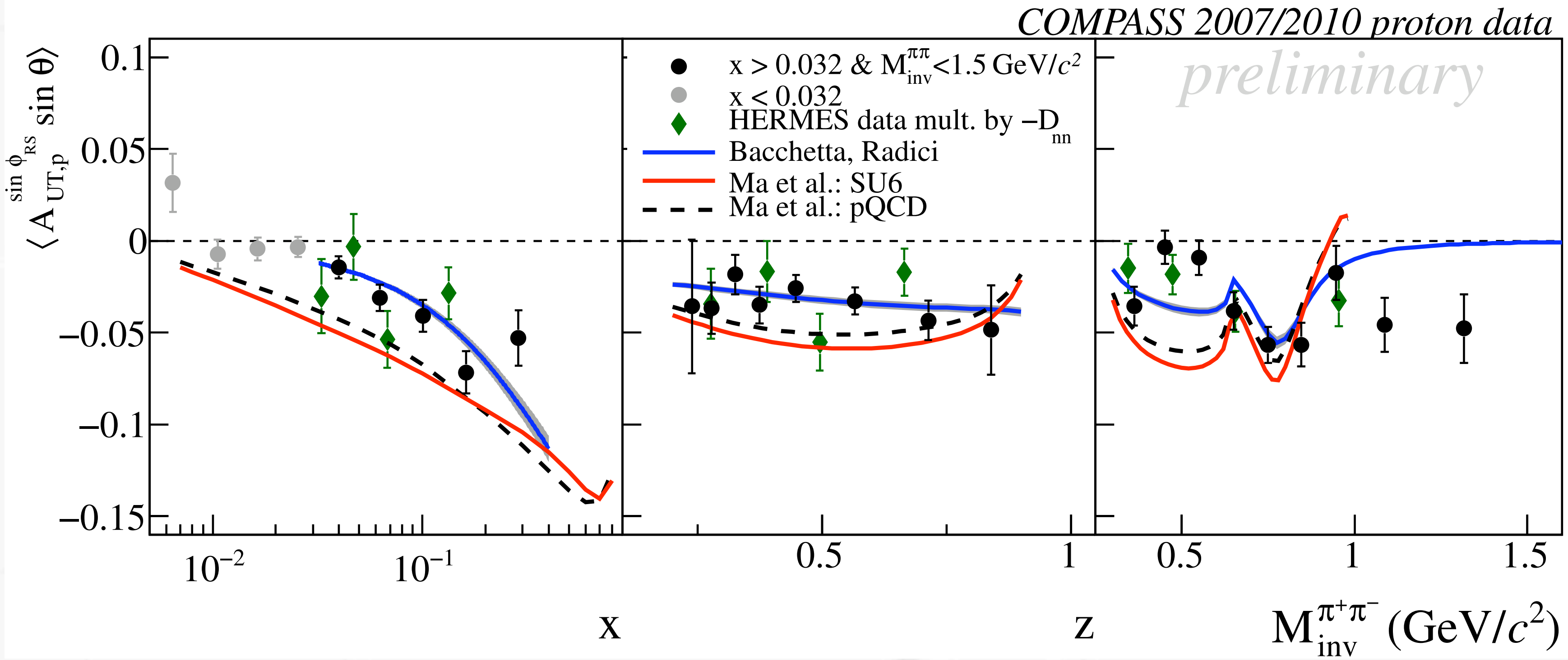

	U	L	T
U	f_1		$h_1^\perp$
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T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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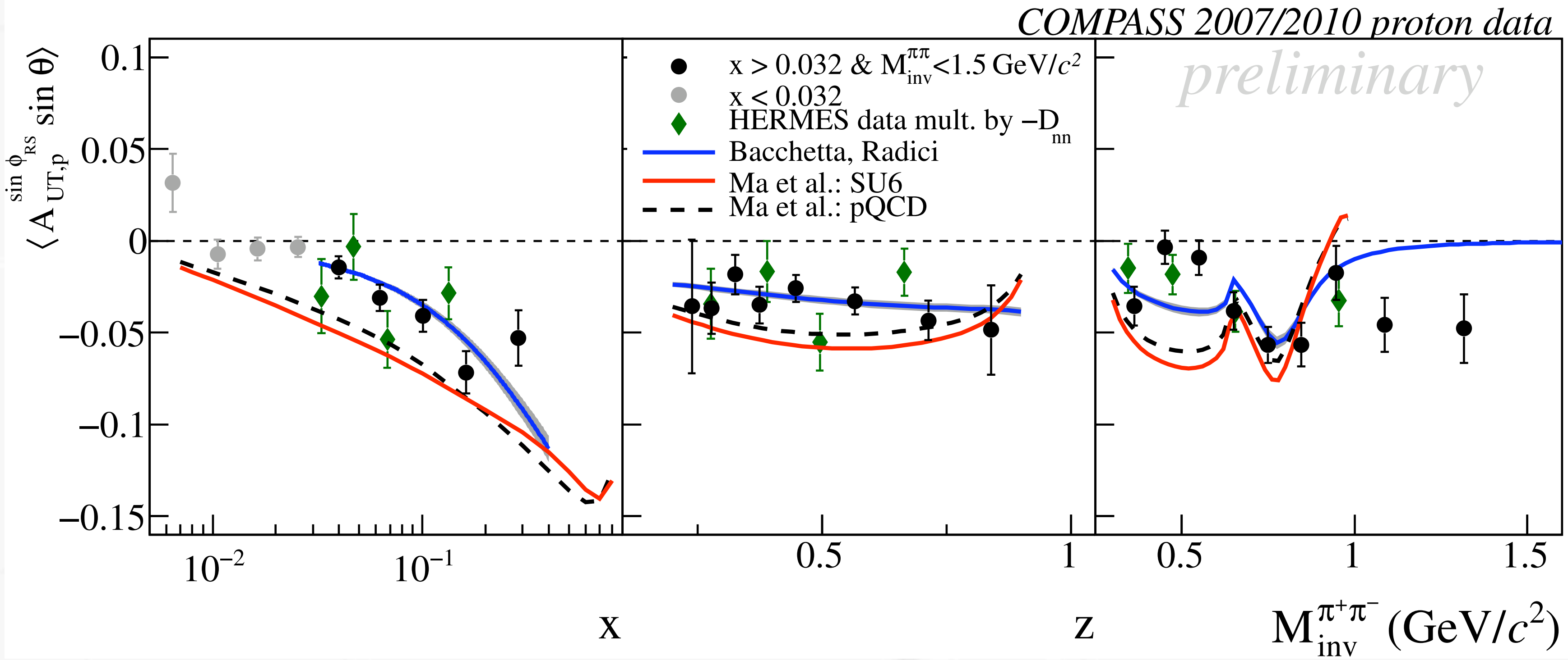

	U	L	T
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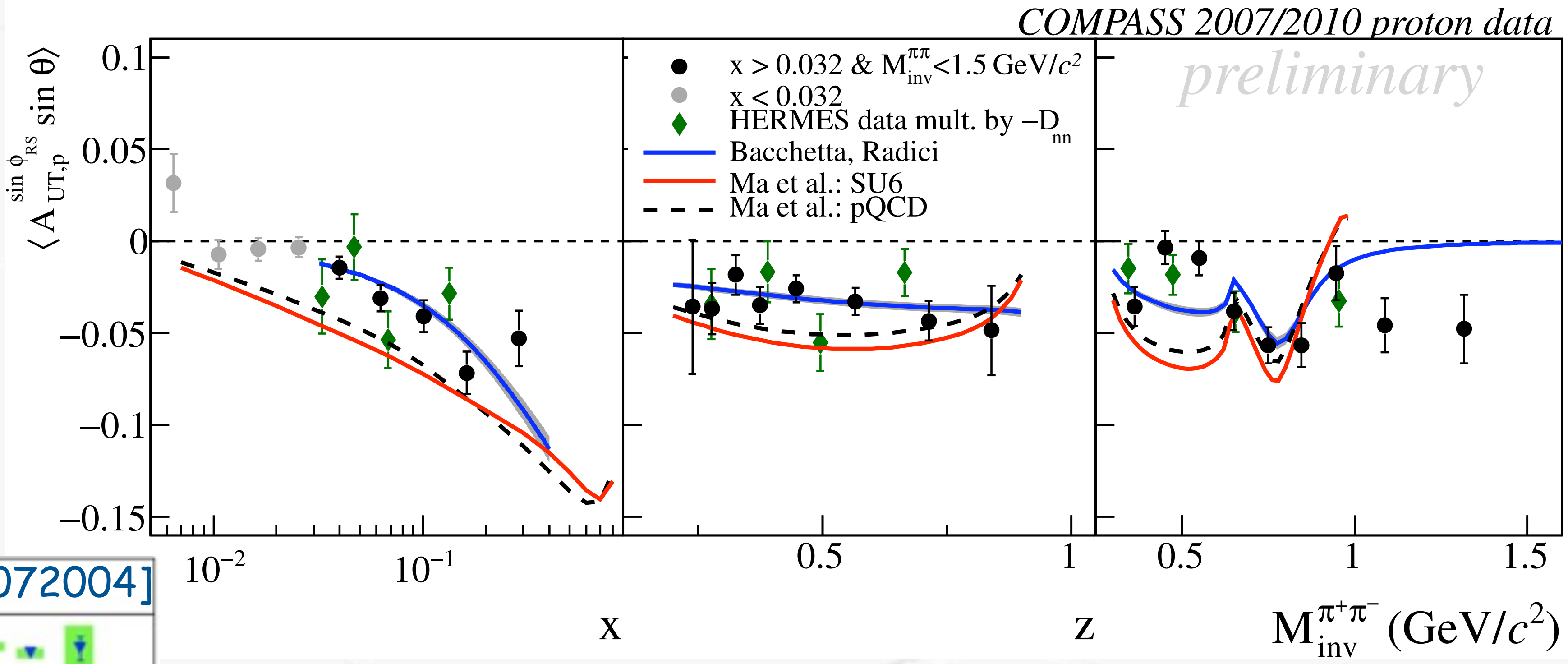
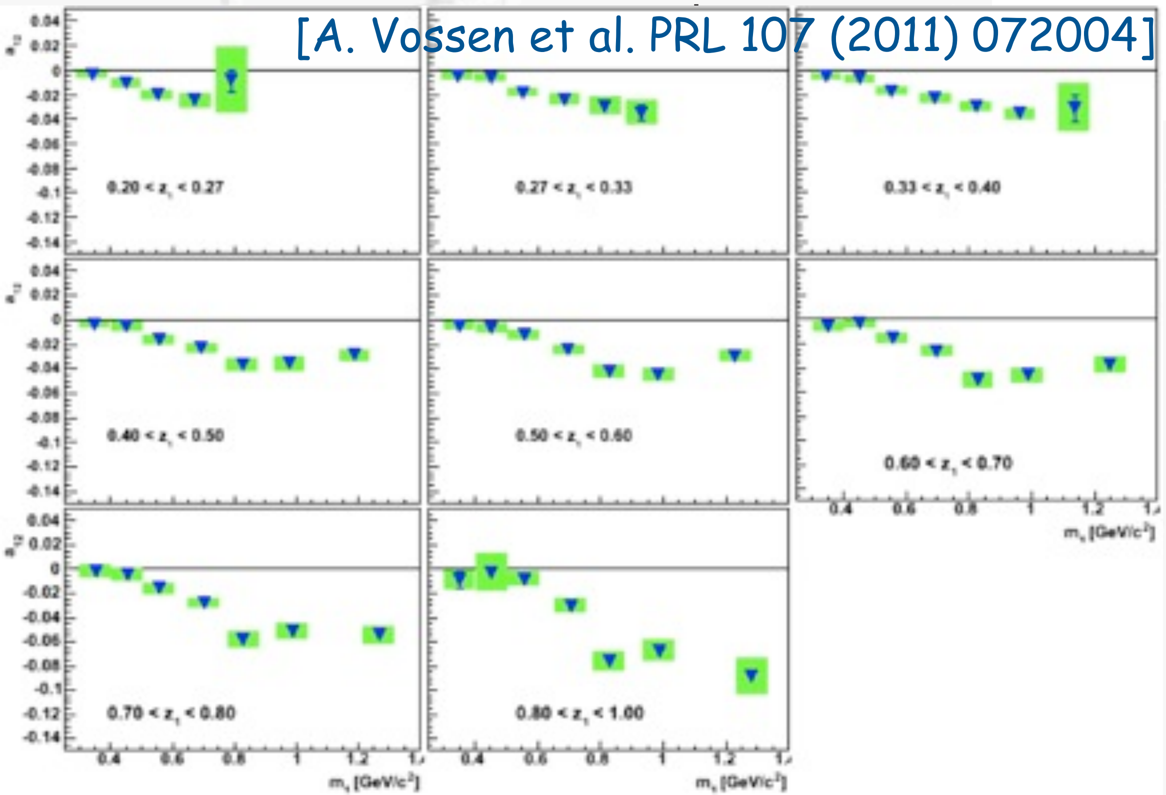
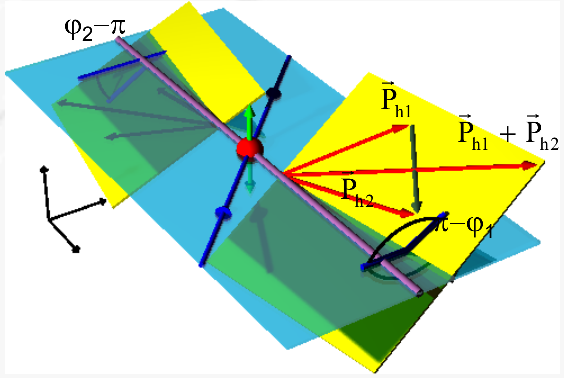



[A. Vossen et al. PRL 107 (2011) 072004]

- data from e^+e^- by BELLE



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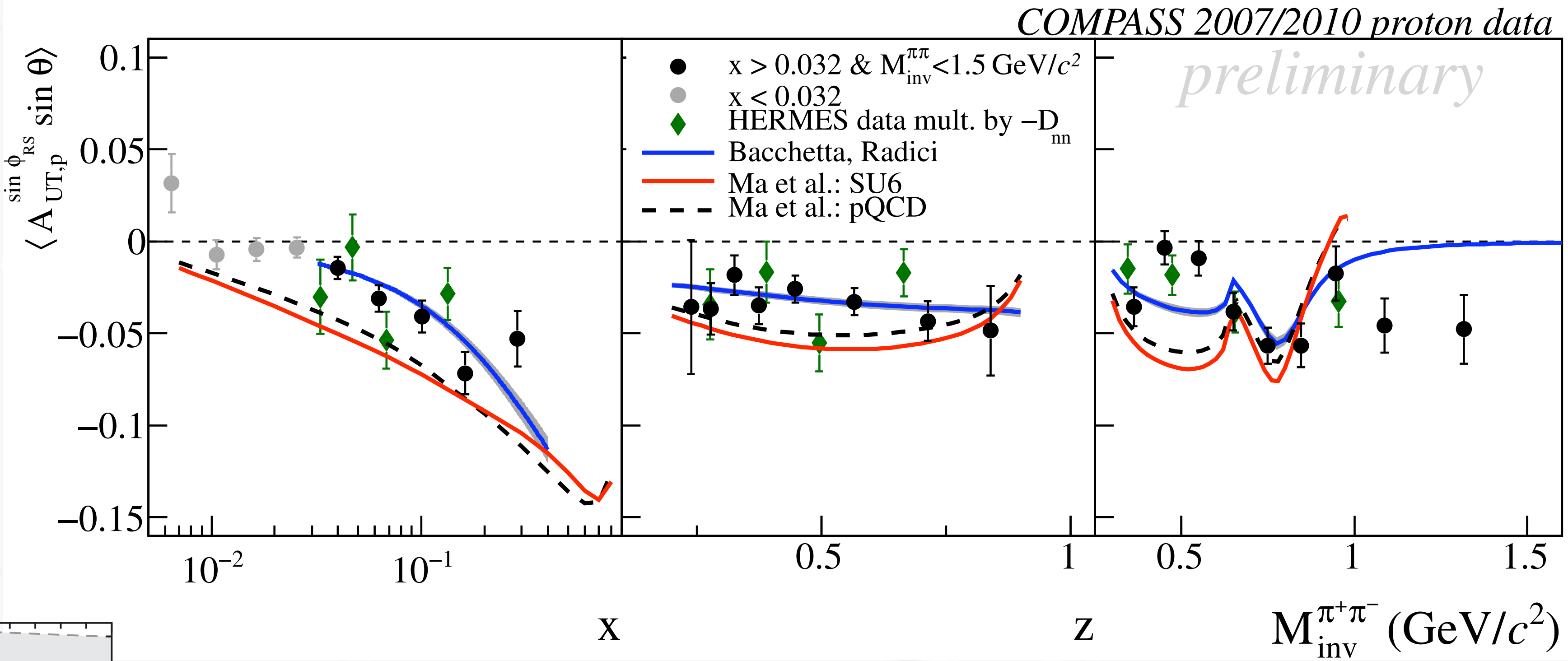
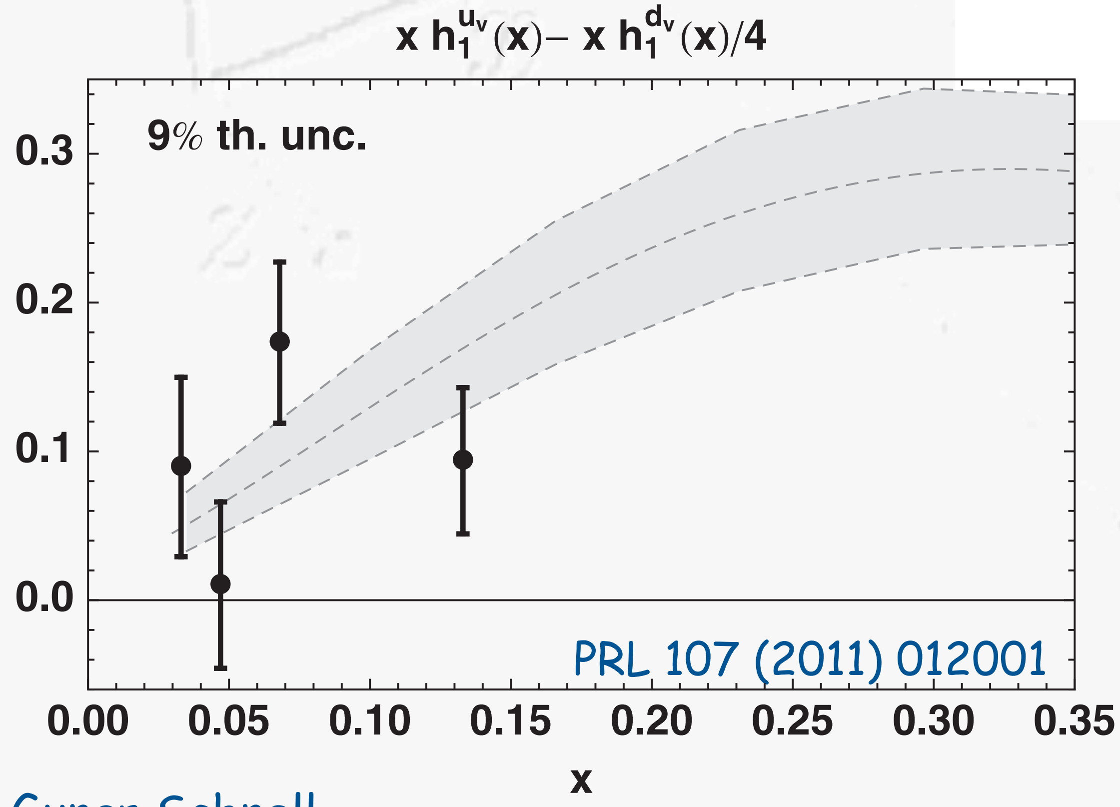
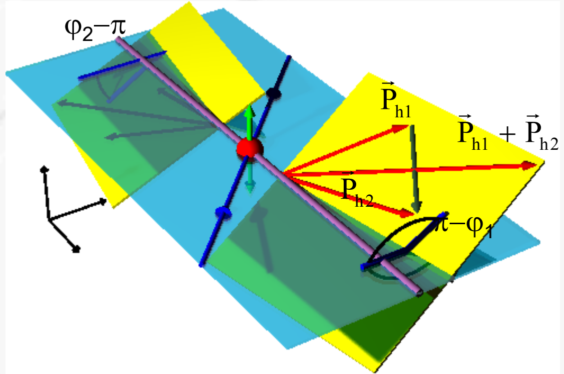




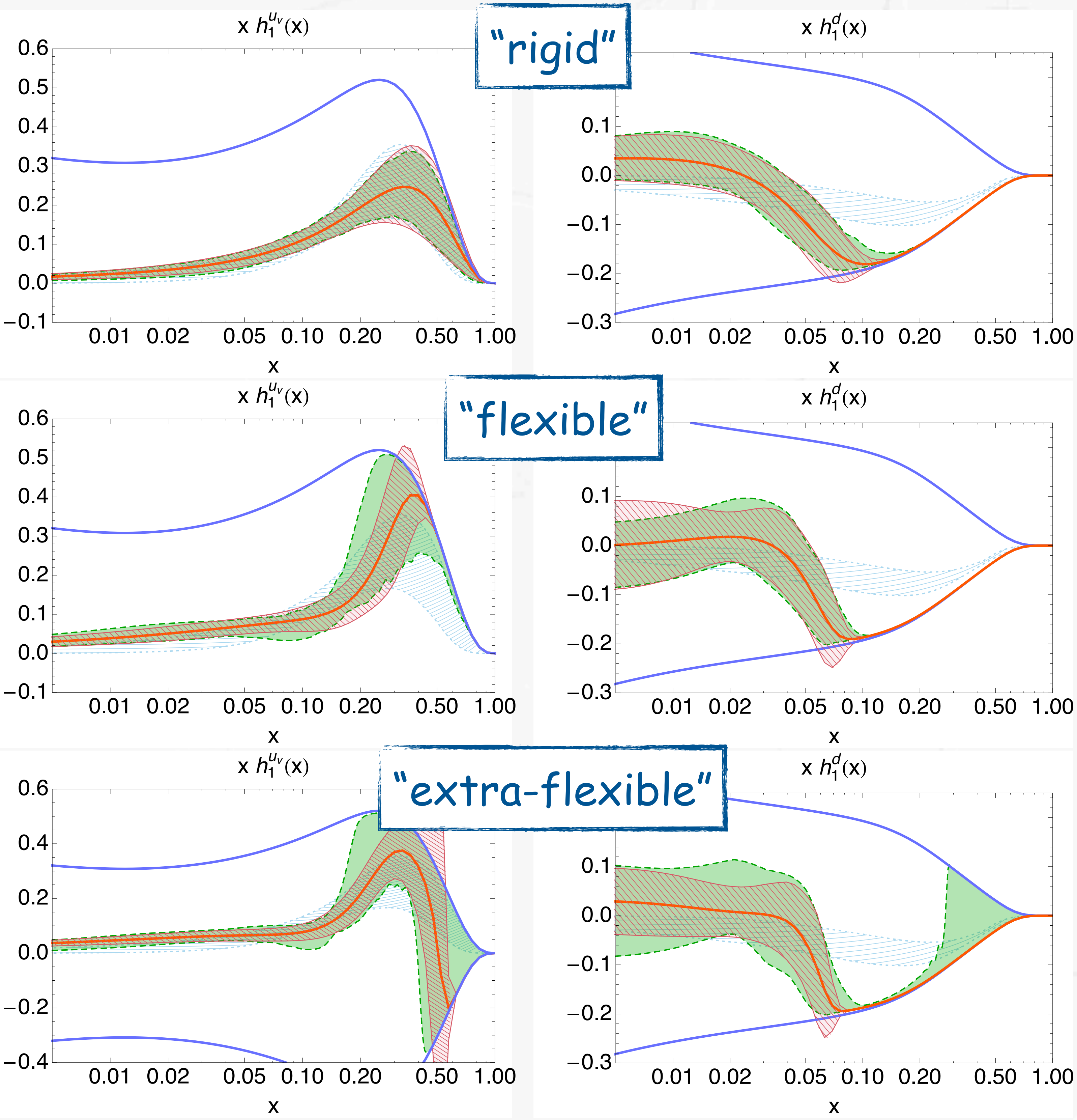
- data from e^+e^- by BELLE allow **first (collinear) extraction of transversity** (compared to Anselmino et al.)



- updated analysis available (incl. COMPASS)

collinear extraction of valence transversity

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

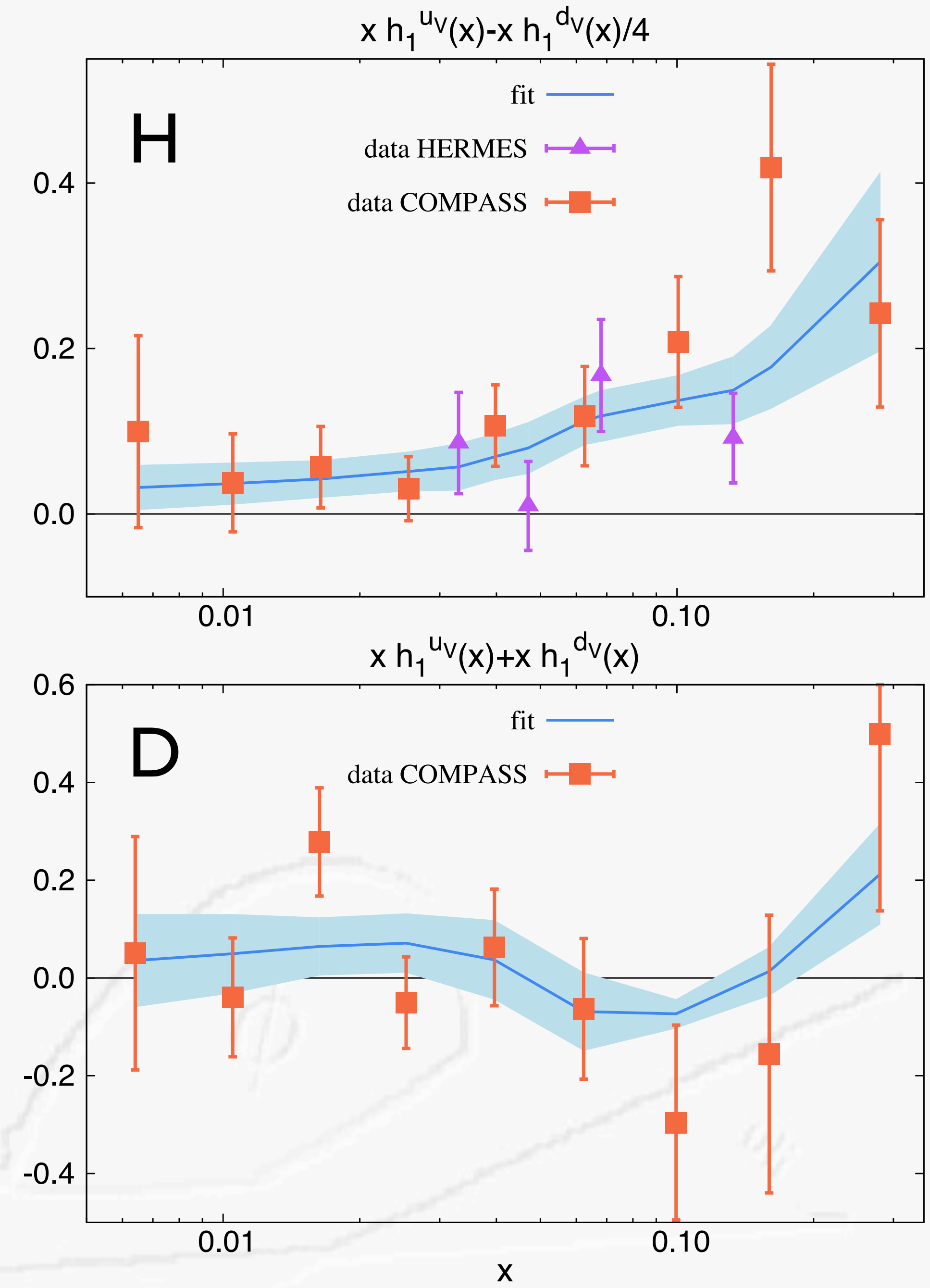


“rigid”

“flexible”

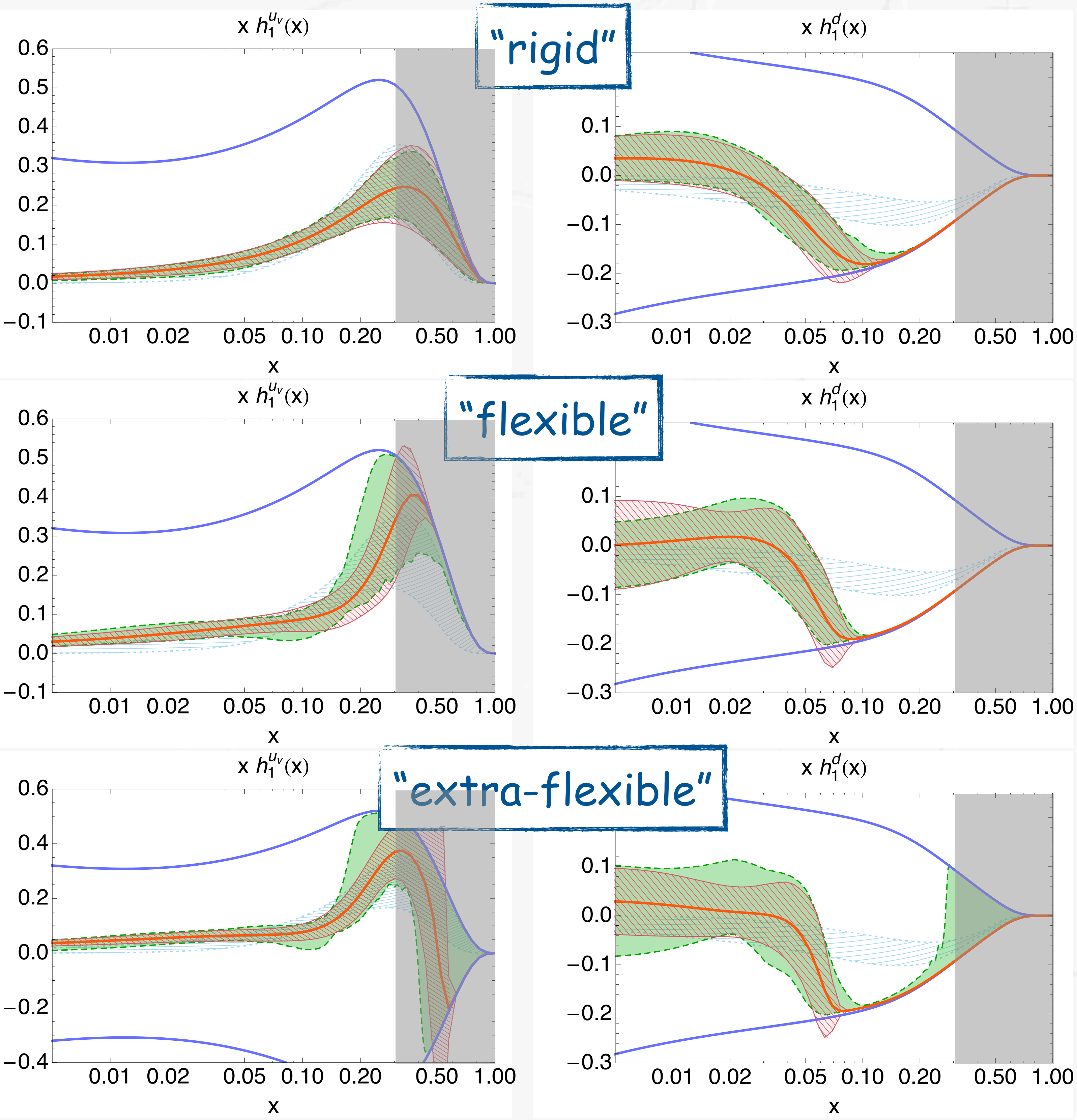
“extra-flexible”

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



collinear extraction of valence transversity

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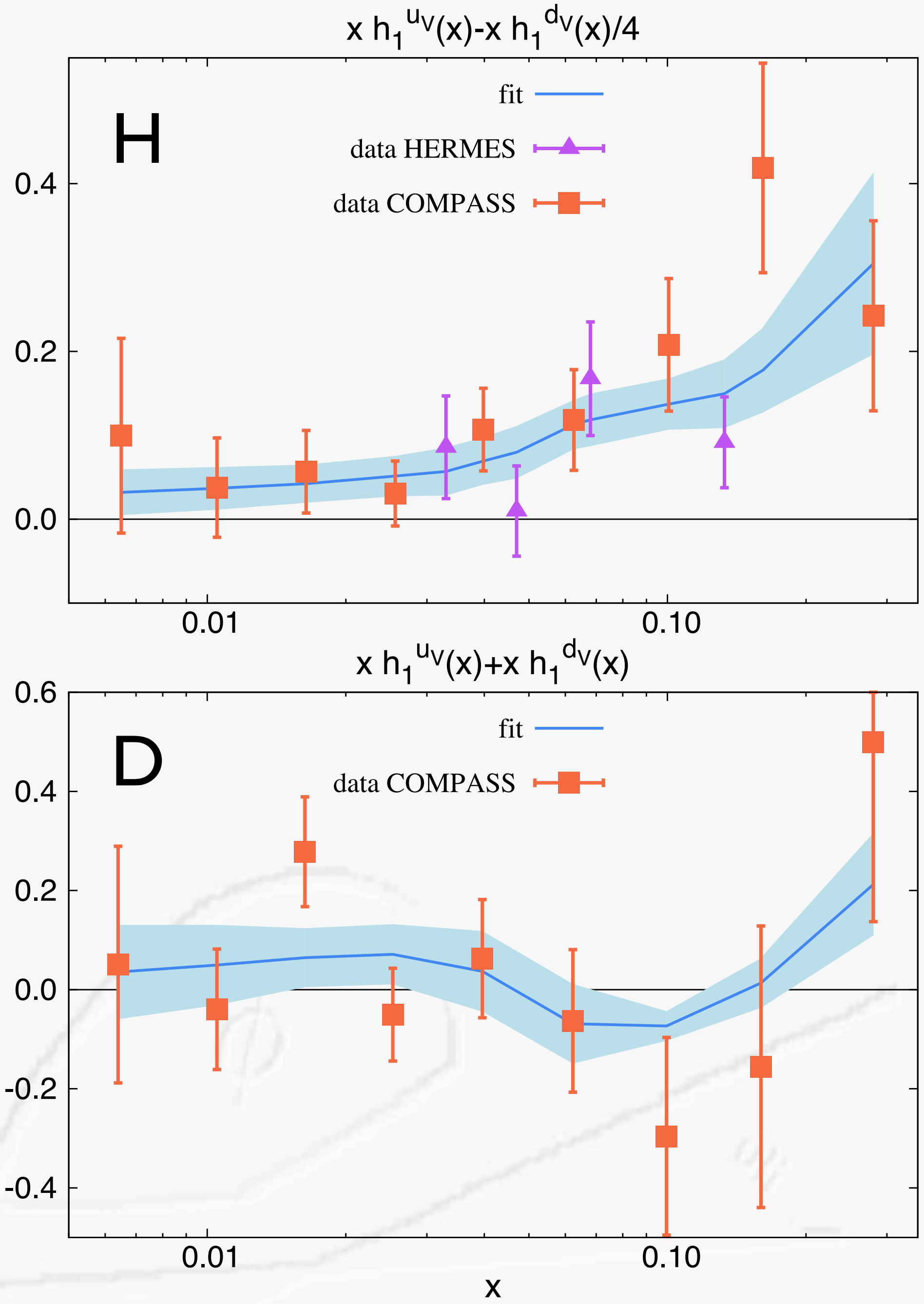

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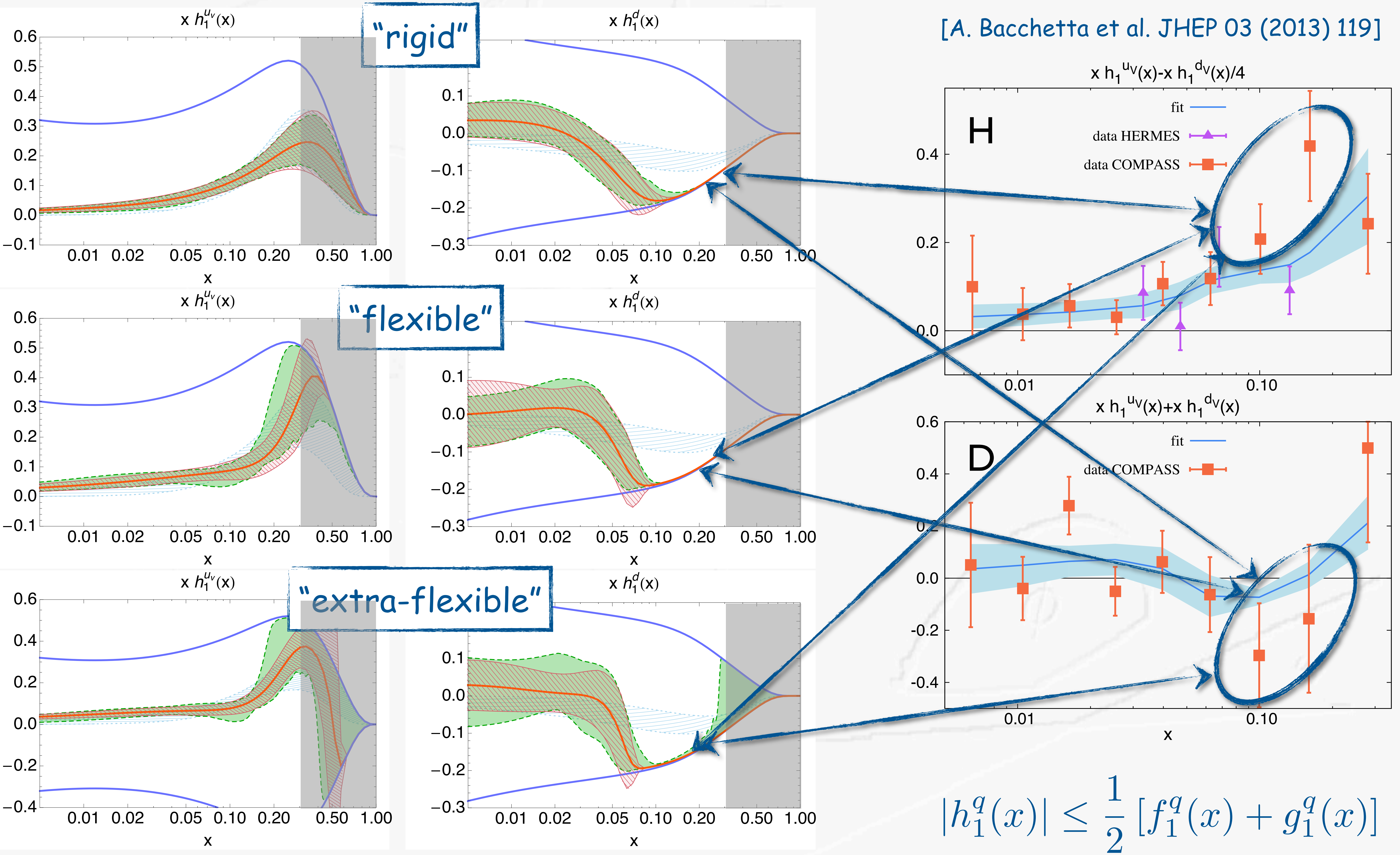
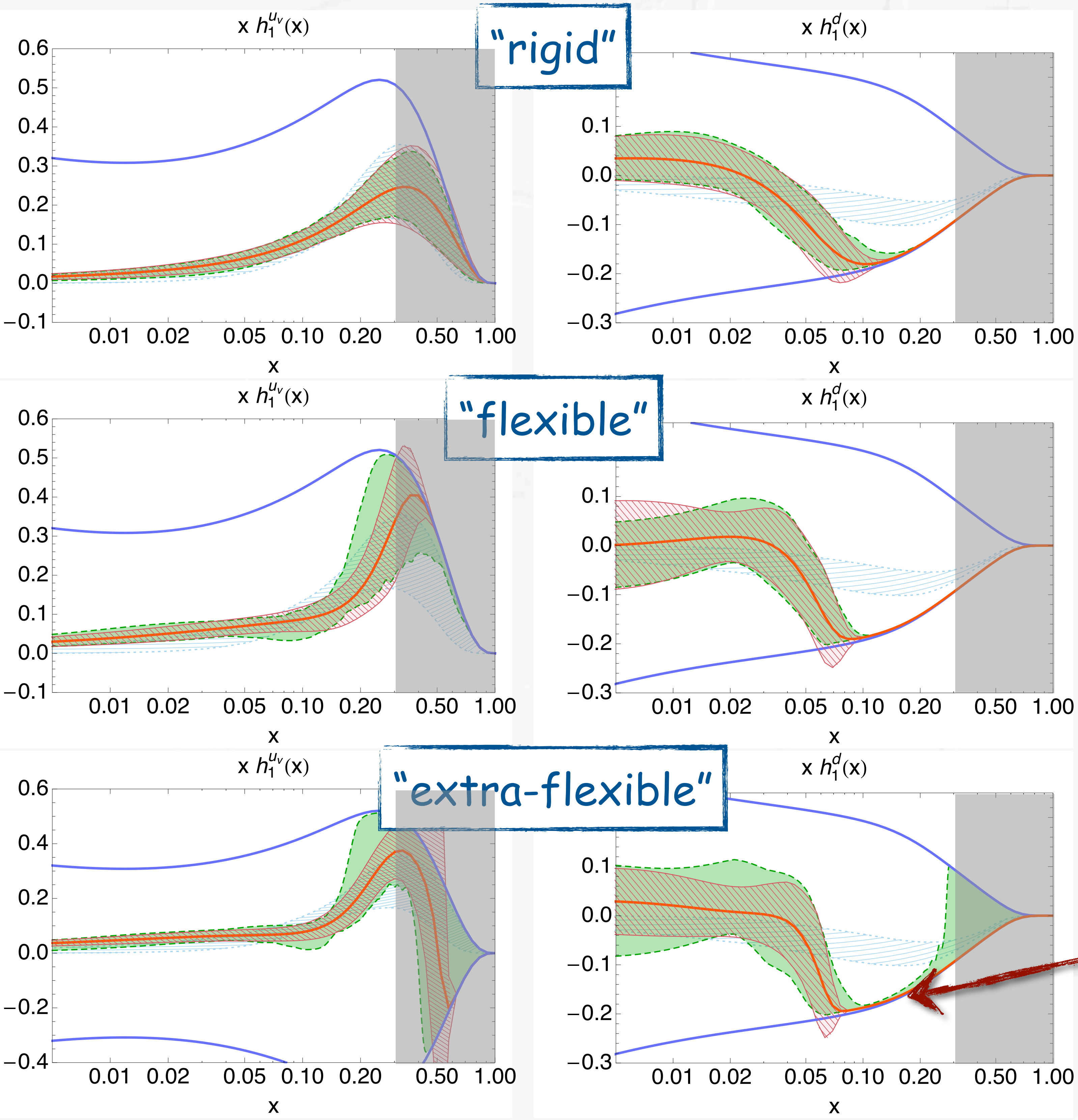


[A. Bacchetta et al. JHEP 03 (2013) 119]

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

d_v-transversity Soffer bound

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

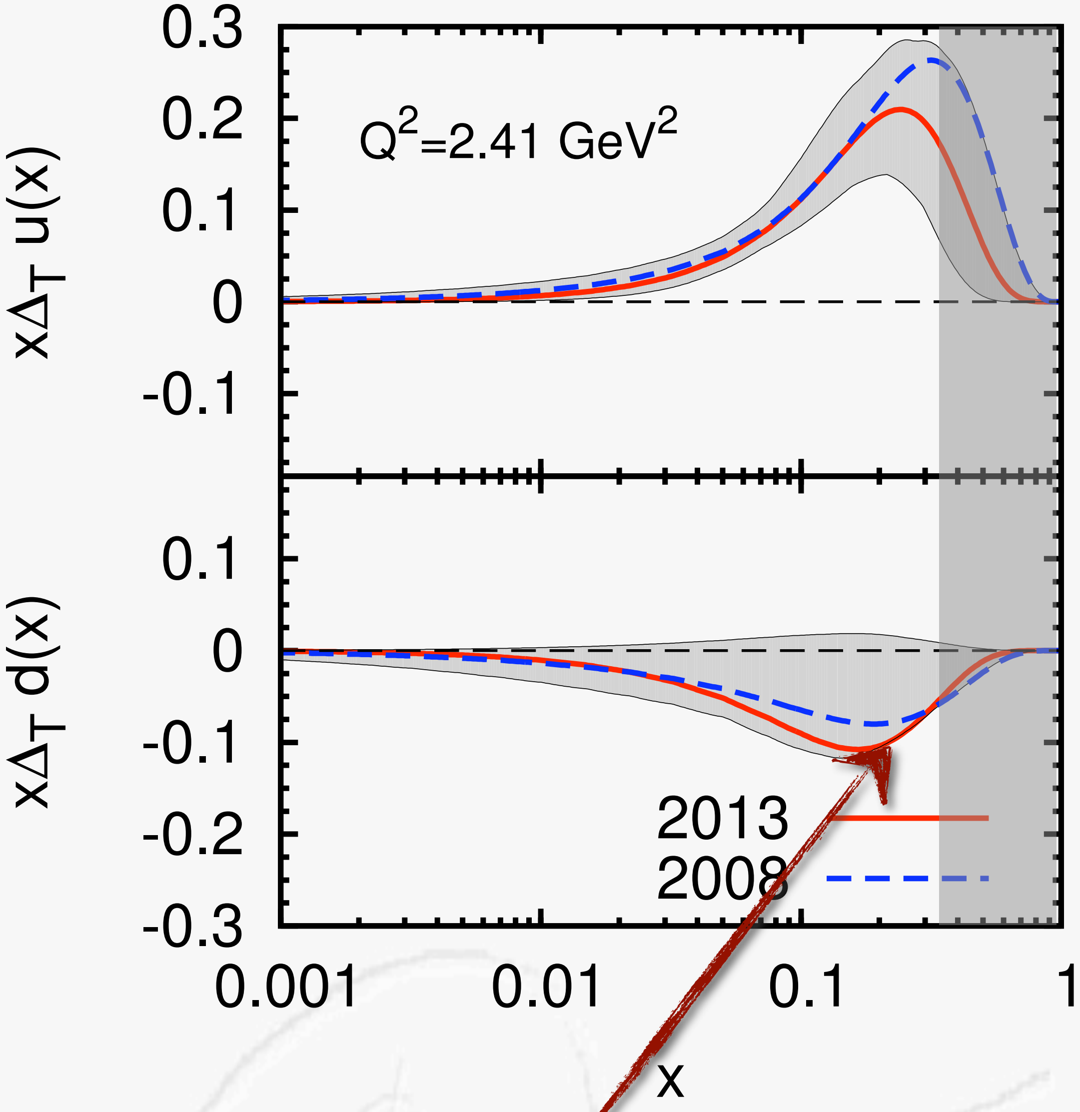


“rigid”

“flexible”

“extra-flexible”

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

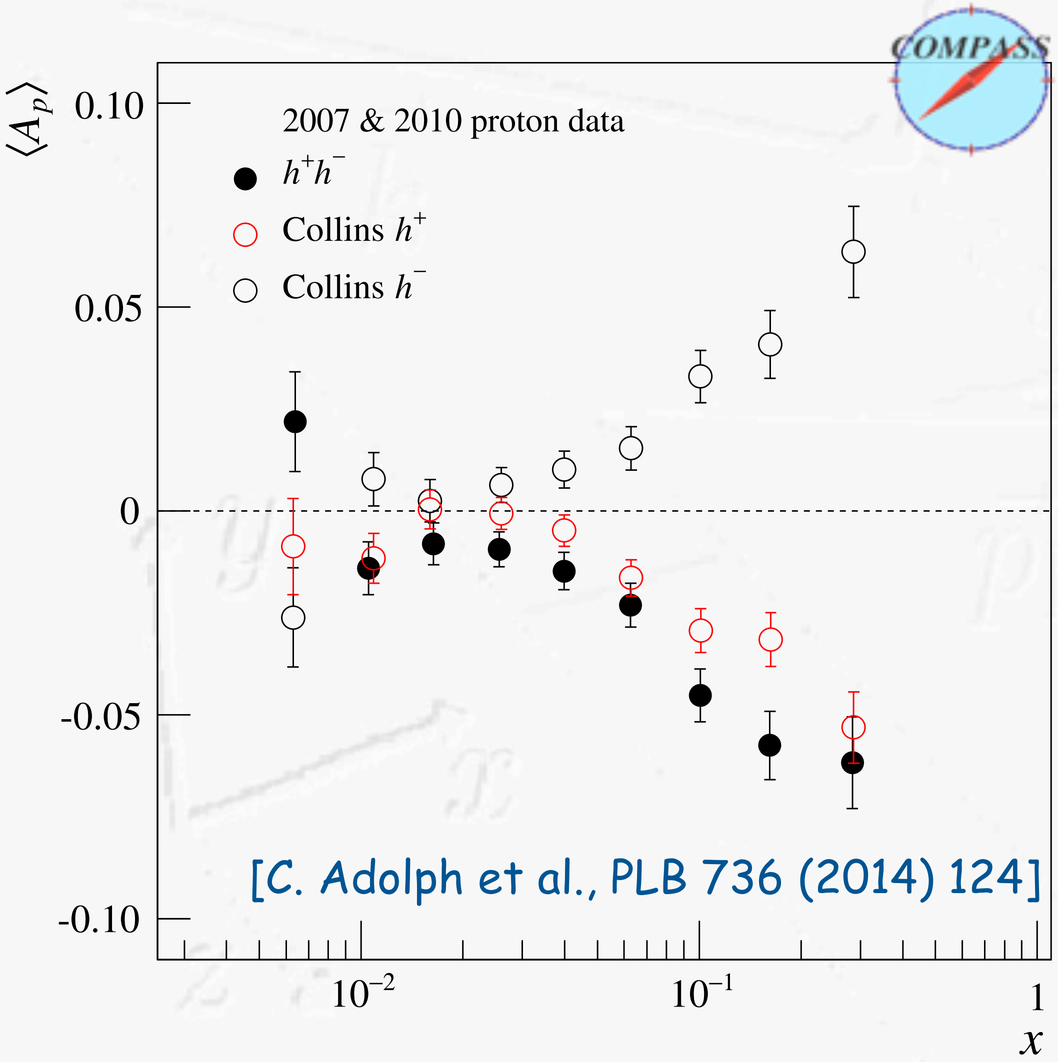


general trend towards violating d-Soffer bound?

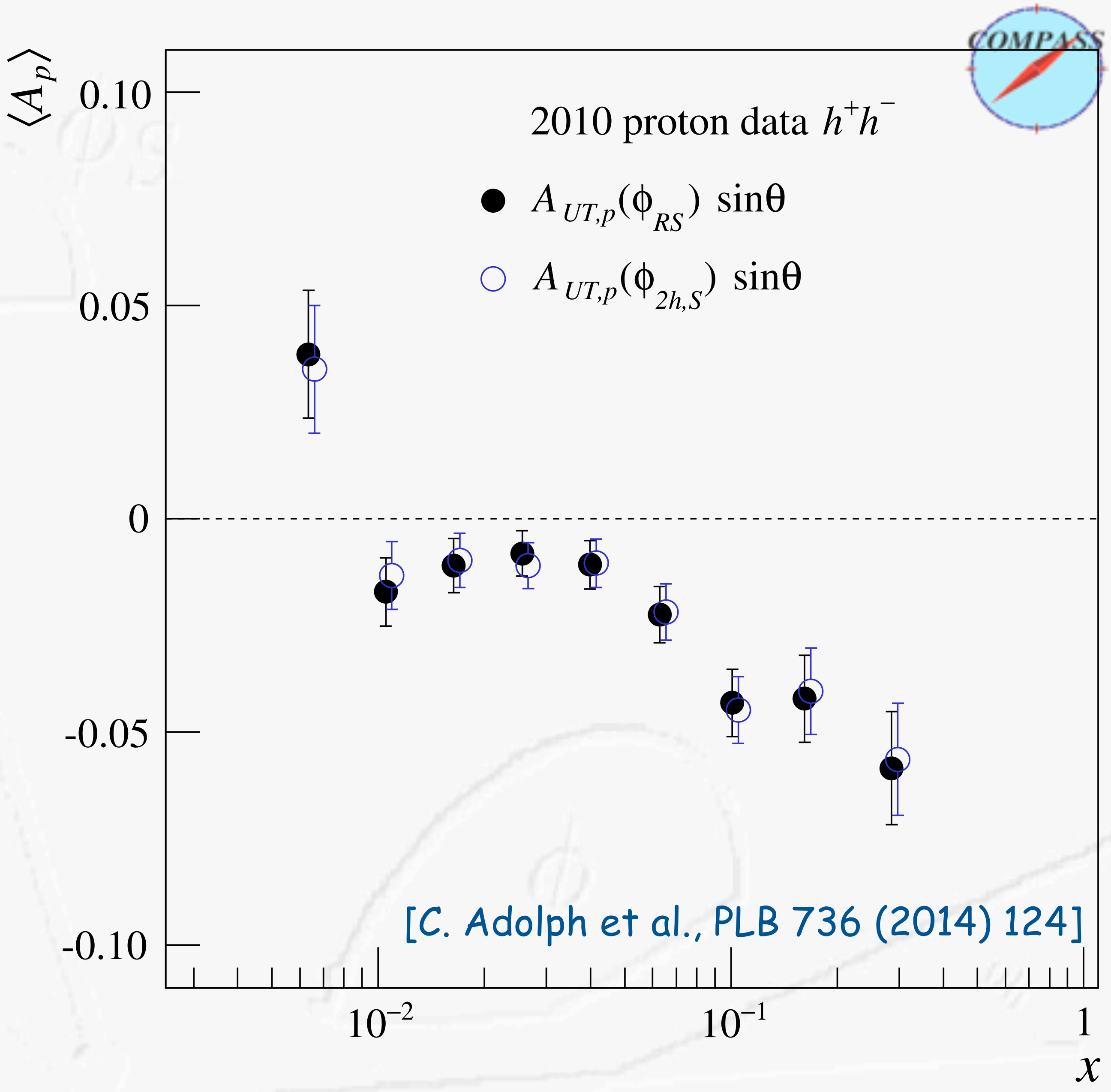
$$|h_1^q(x)| \leq \frac{1}{2}\left[f_1^q(x) + g_1^q(x)\right]$$

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

Di-hadron vs. Collins fragmentation



[C. Adolph et al., PLB 736 (2014) 124]



[C. Adolph et al., PLB 736 (2014) 124]

- apparent similarity of Collins and di-hadron asymmetries
- suggested common origin of Collins and di-hadron FF in PLB 736 (2014) 124

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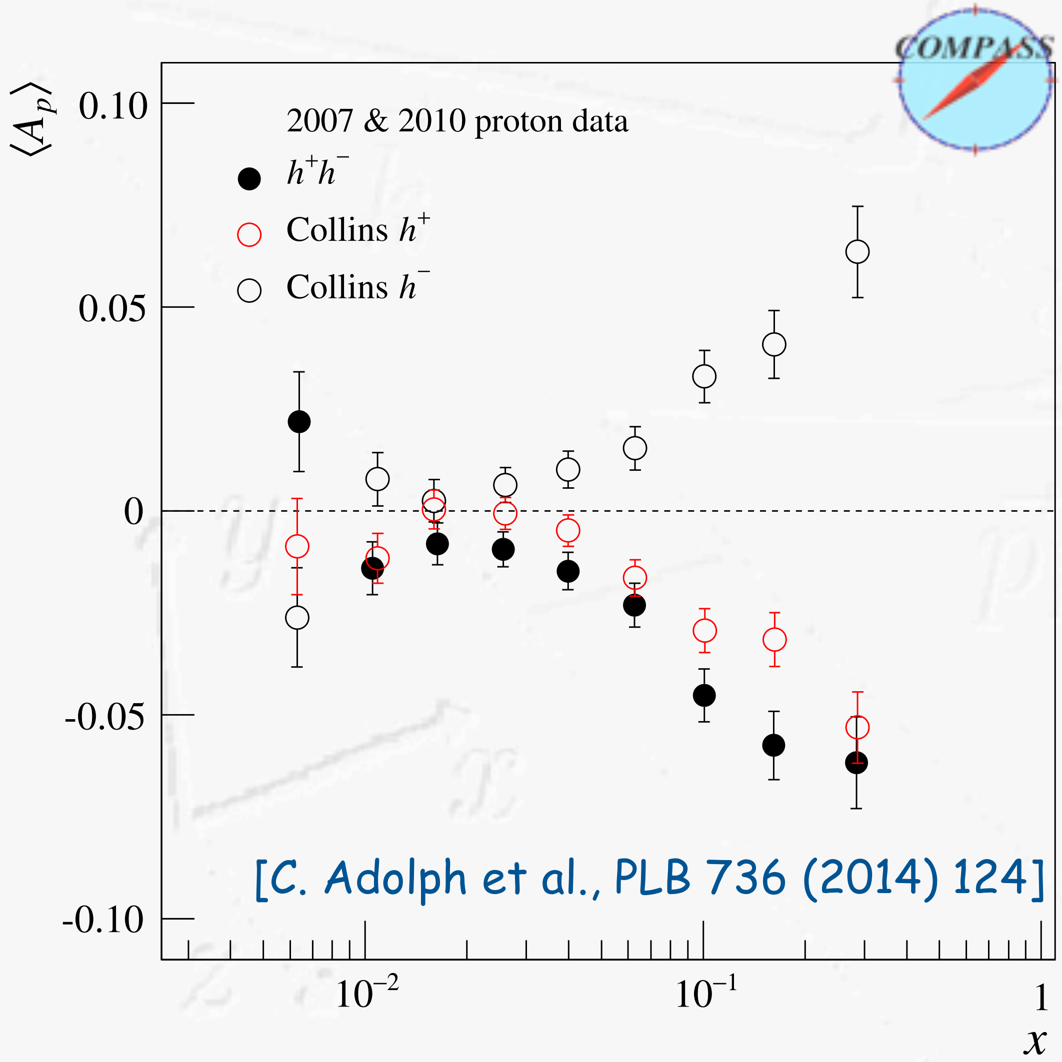
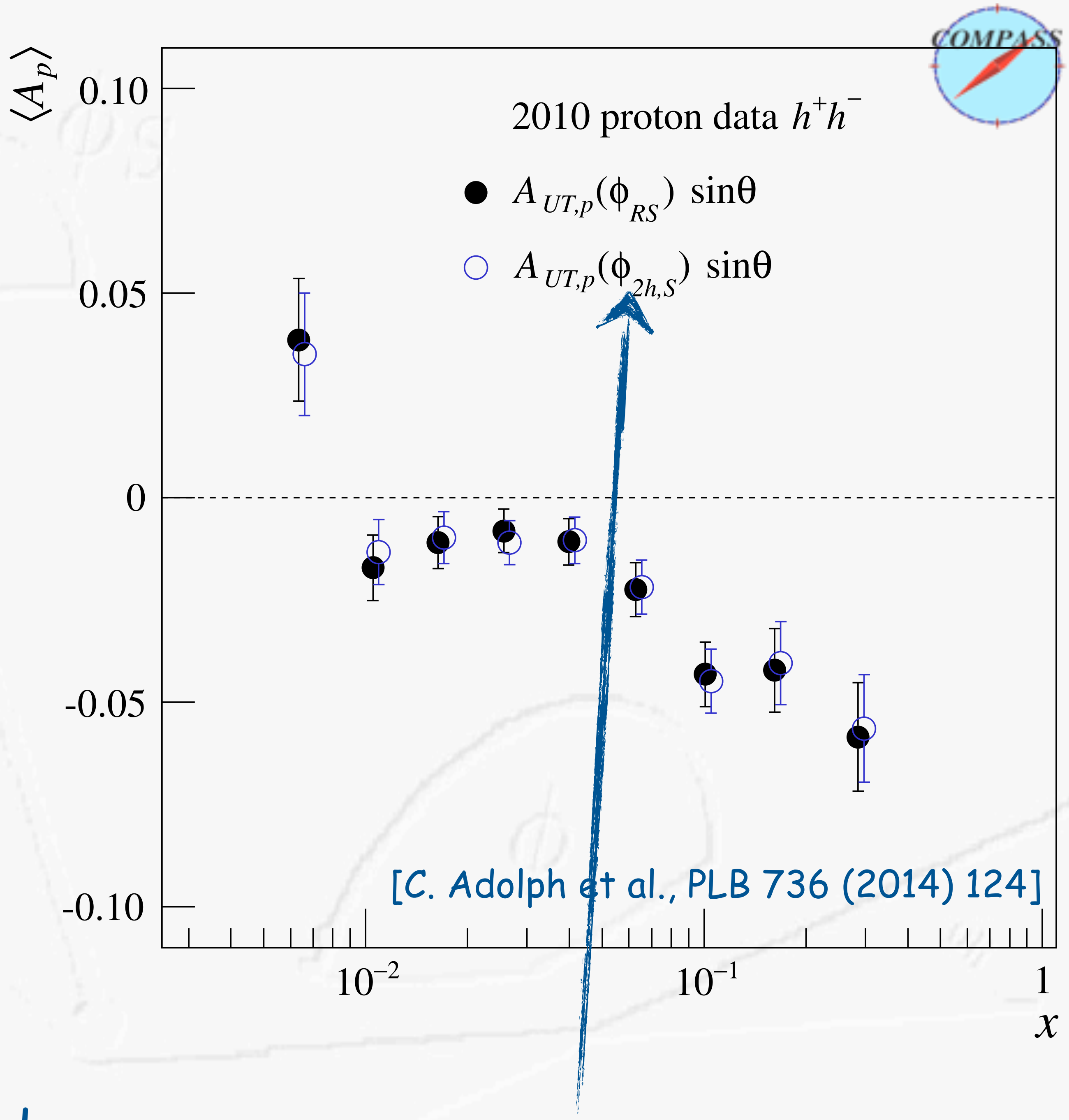


[C. Adolph et al., PLB 736 (2014) 124]



[C. Adolph et al., PLB 736 (2014) 124]

"Collins angle" of $\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$

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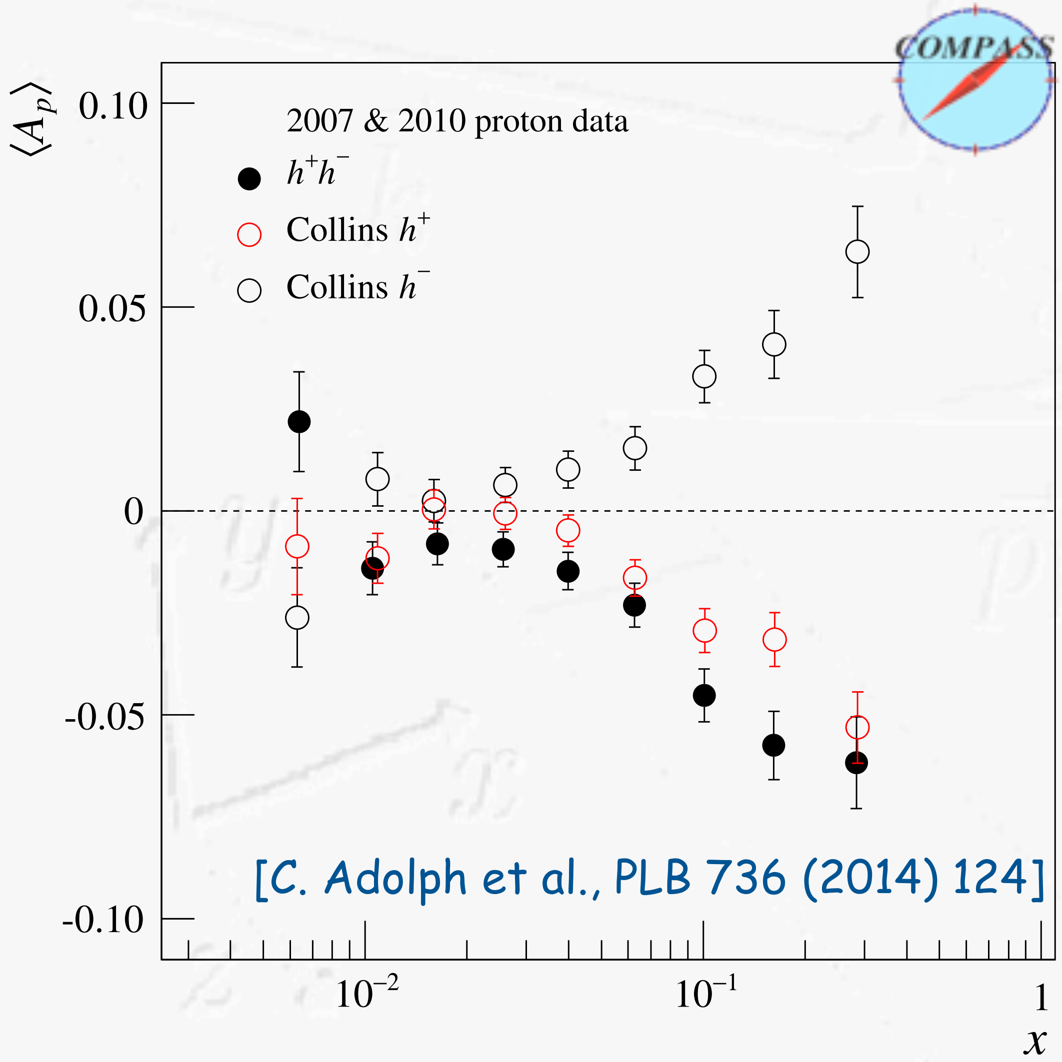
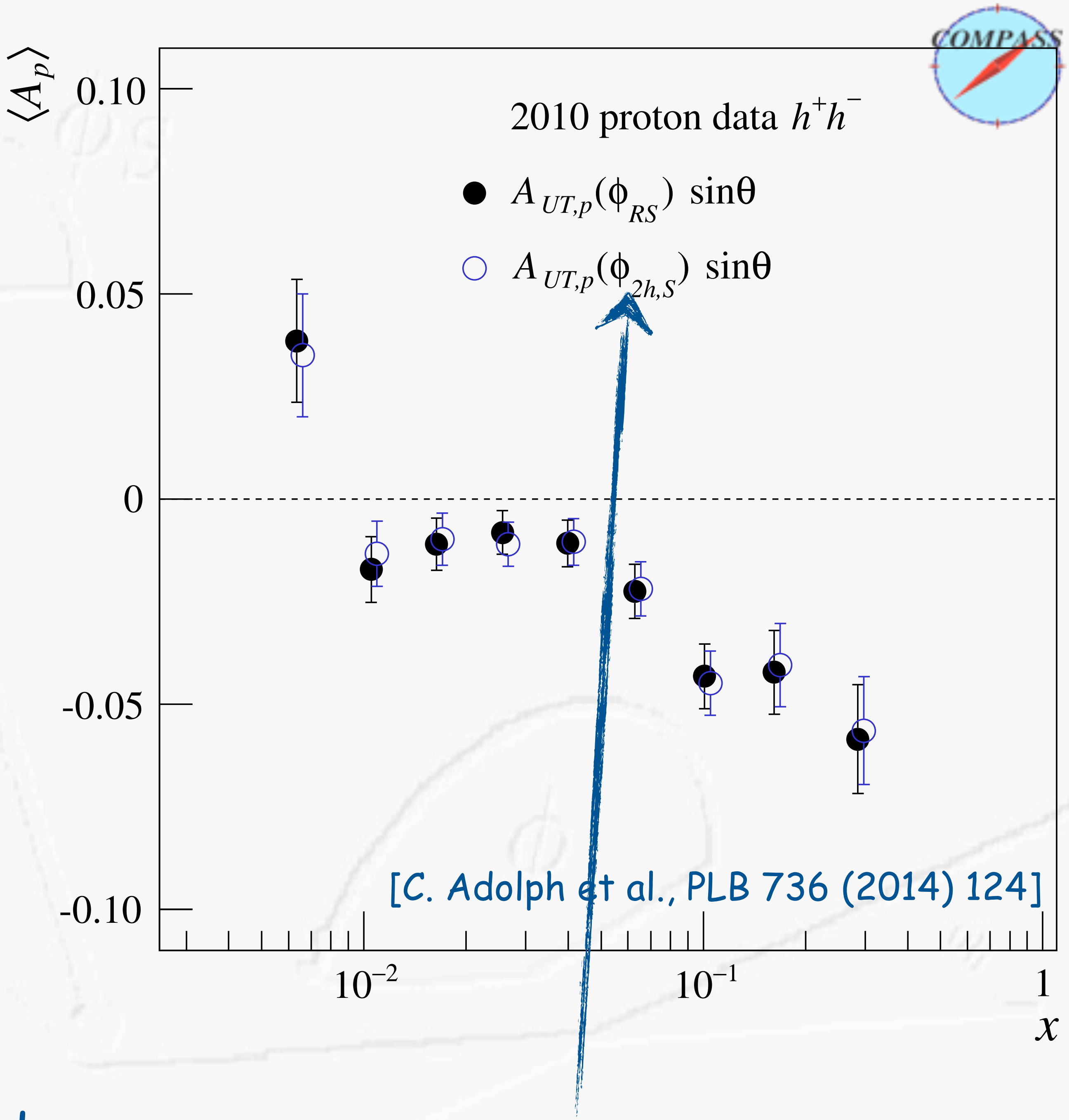


[C. Adolph et al., PLB 736 (2014) 124]



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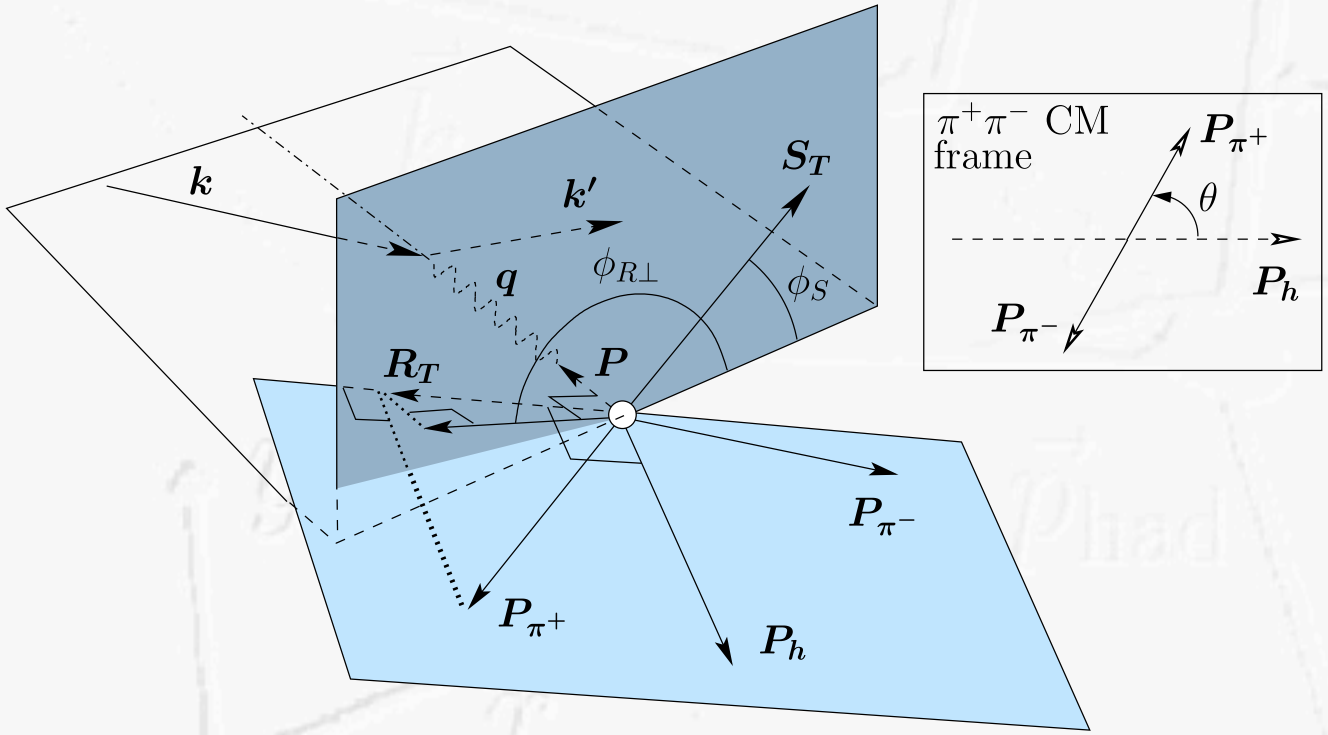
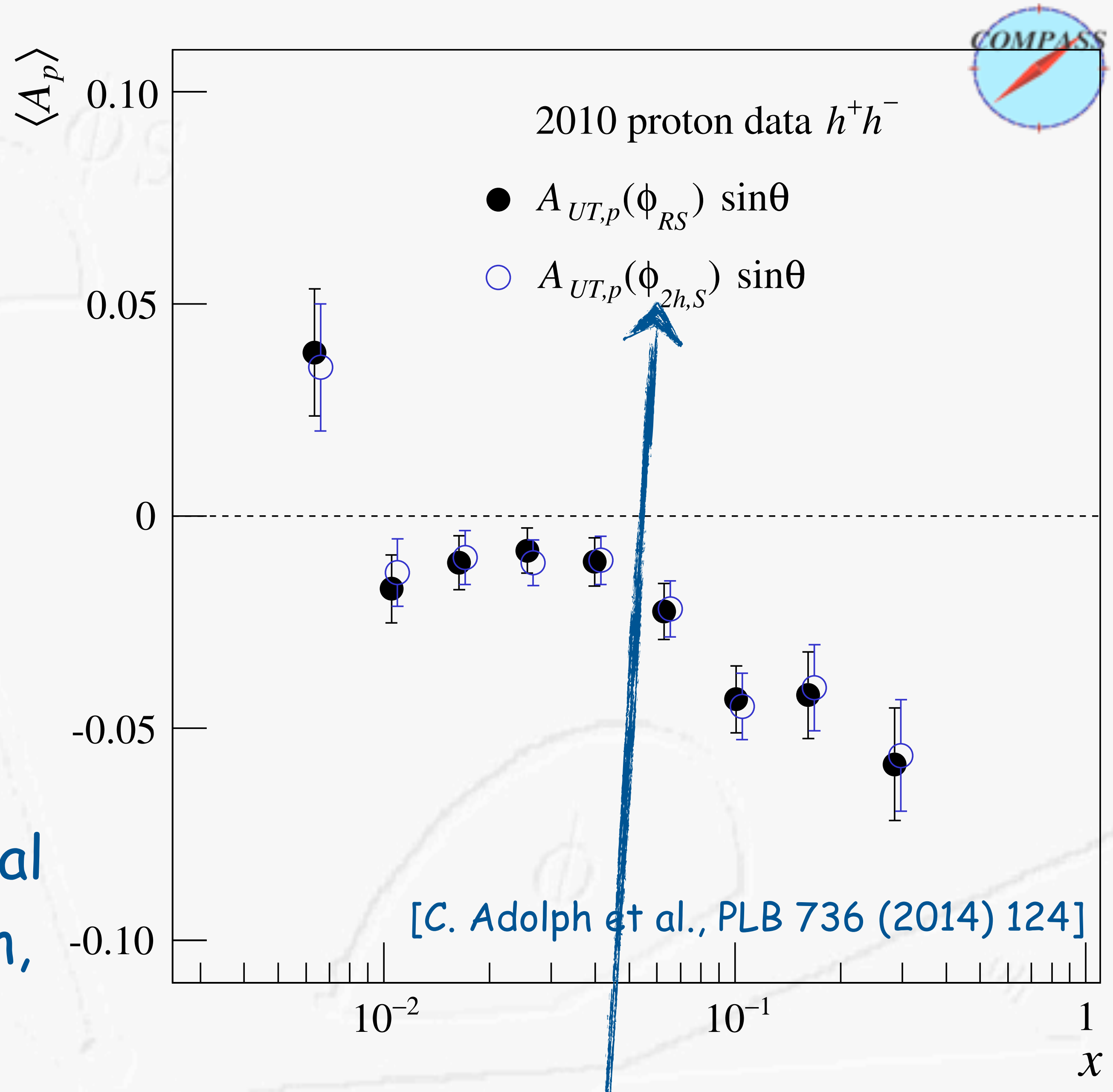
Di-hadron vs. Collins fragmentation





[C. Adolph et al., PLB 736 (2014) 124]

- in the limit of collinear P_h (w.r.t. virtual photon), e.g., in collinear factorization, $\phi_{2h,S}$ reduces just to ϕ_{RS}

➡ no big surprise that those two asymmetries are very similar?

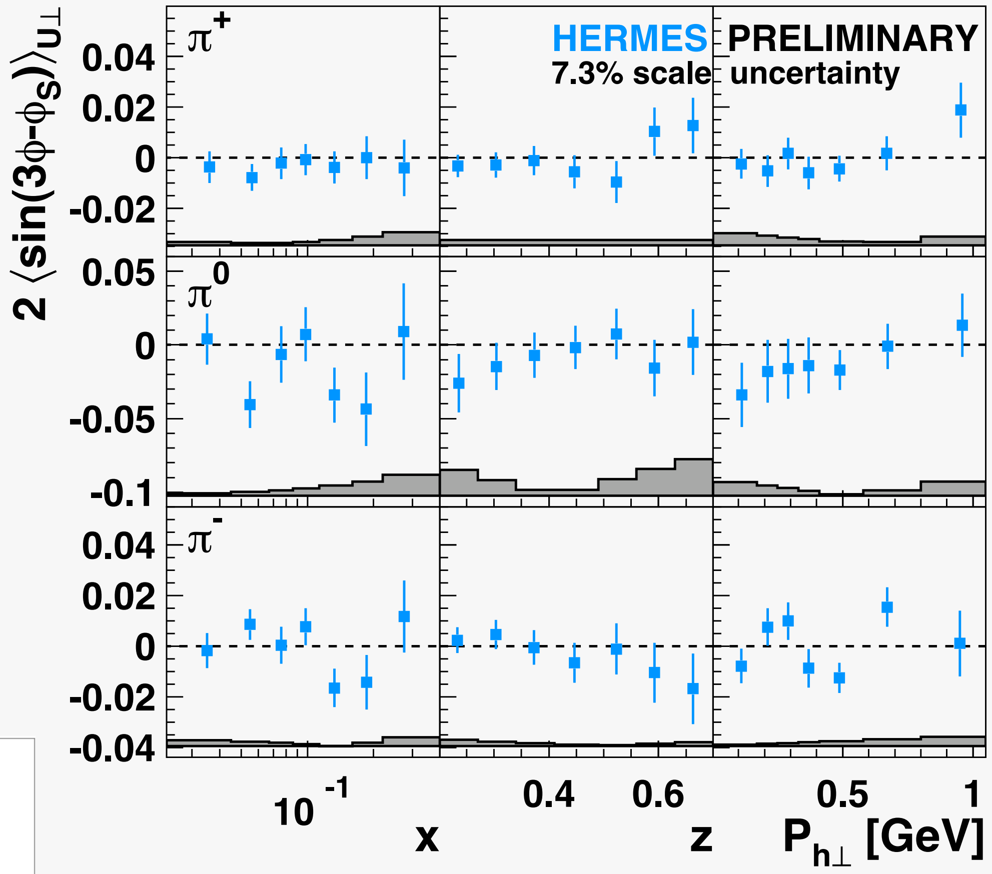
"Collins angle" of $\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$

Transversity's friends

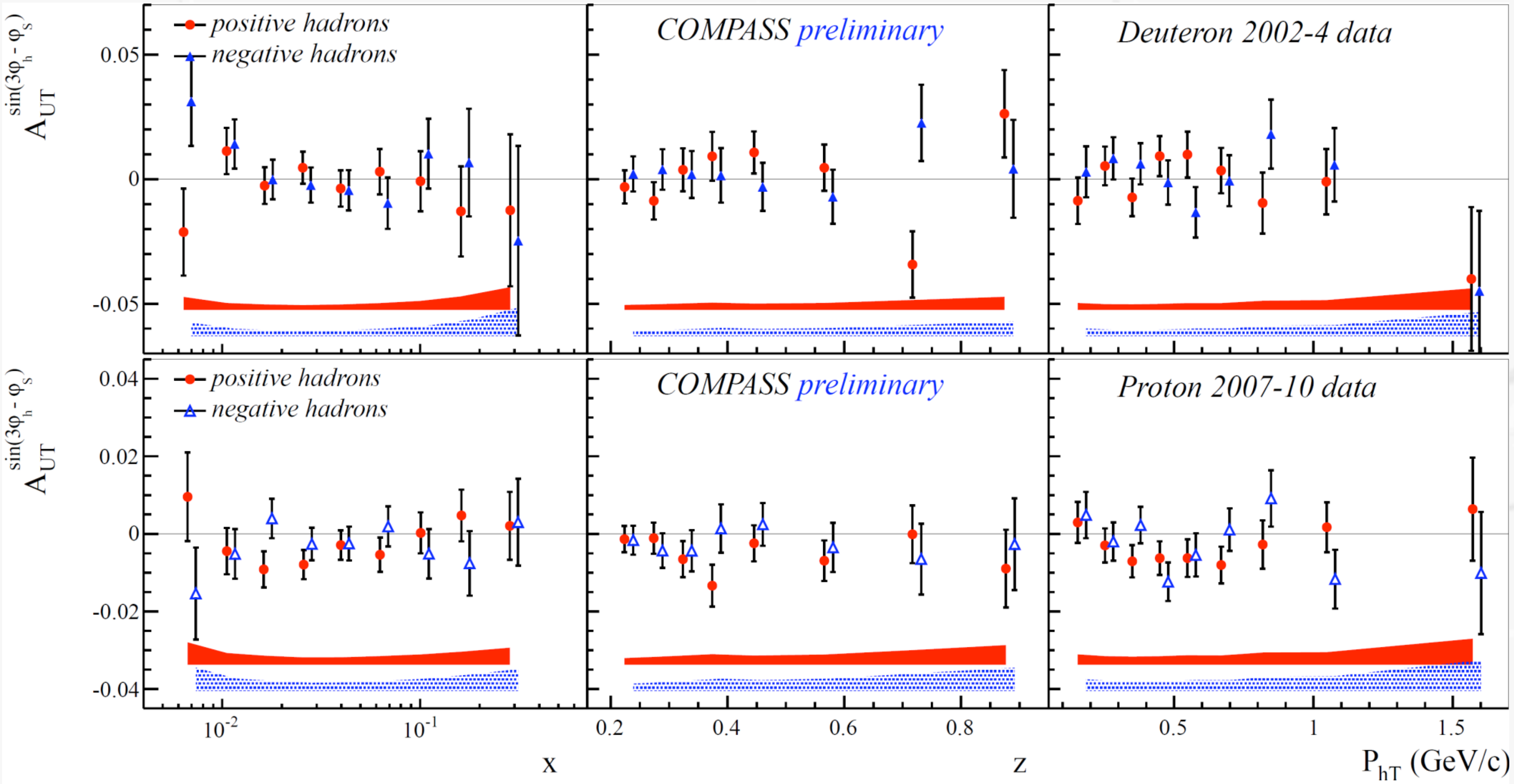
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

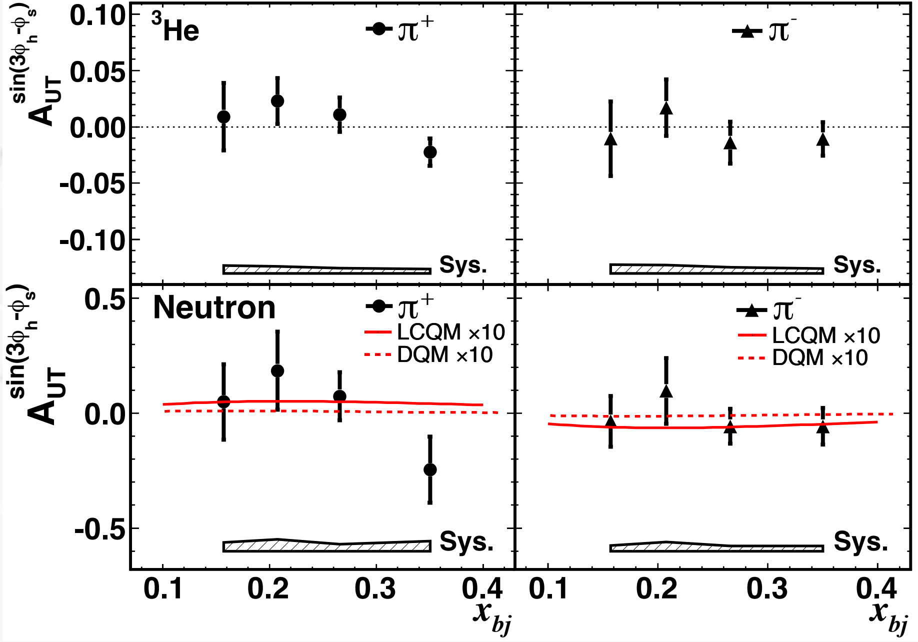
Pretzelosity

- chiral-odd ➥ needs Collins FF (or similar)
- ^{1}H, ^{2}H & ^{3}He data consistently small
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$



[arXiv:1312.3047]





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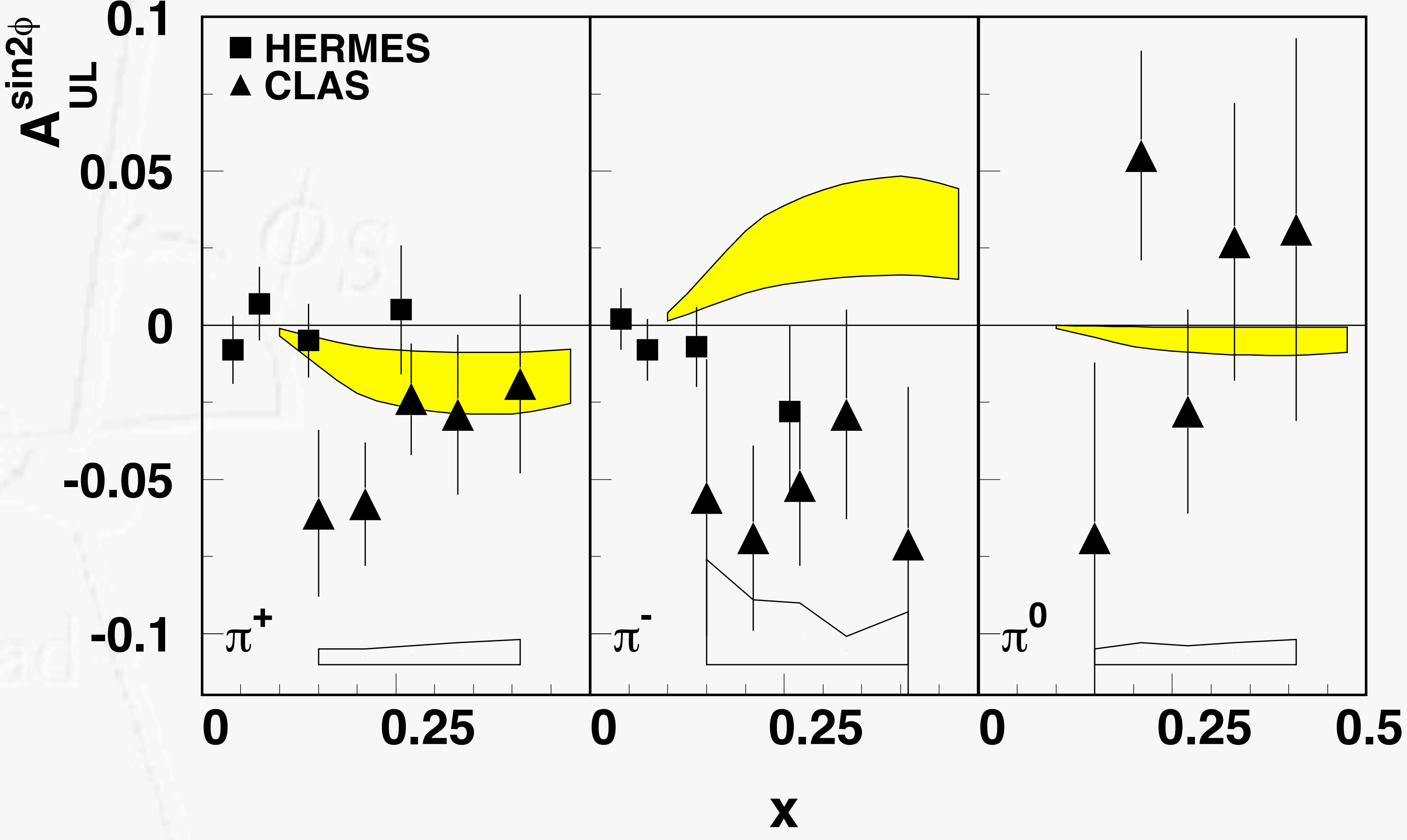
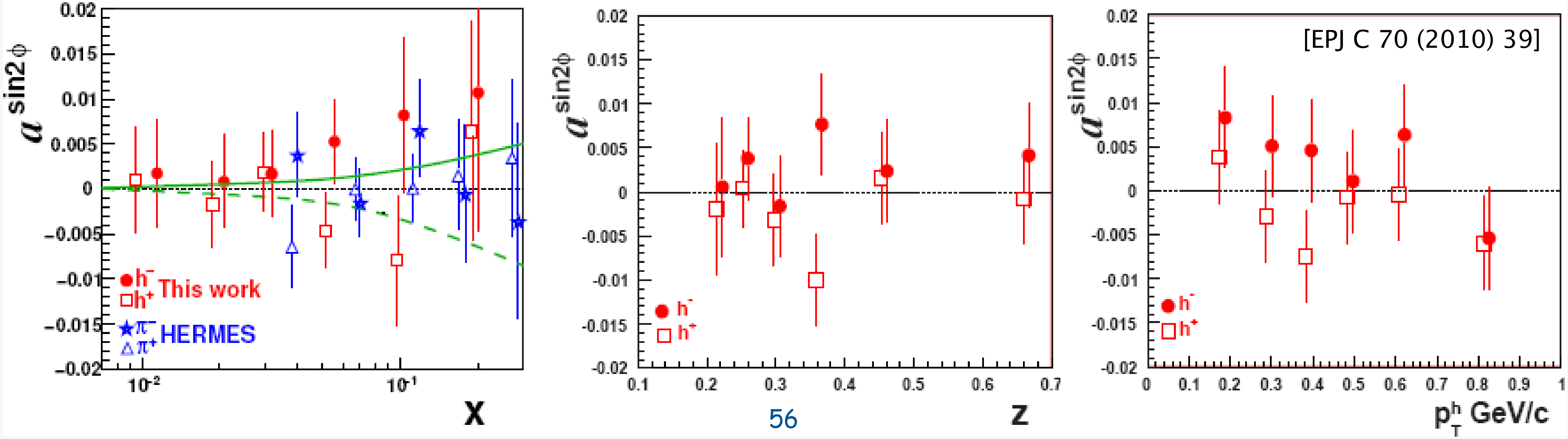
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Worm-Gear I

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

[CLAS, PRL 105 (2010) 262002]





[EPJ C 70 (2010) 39]

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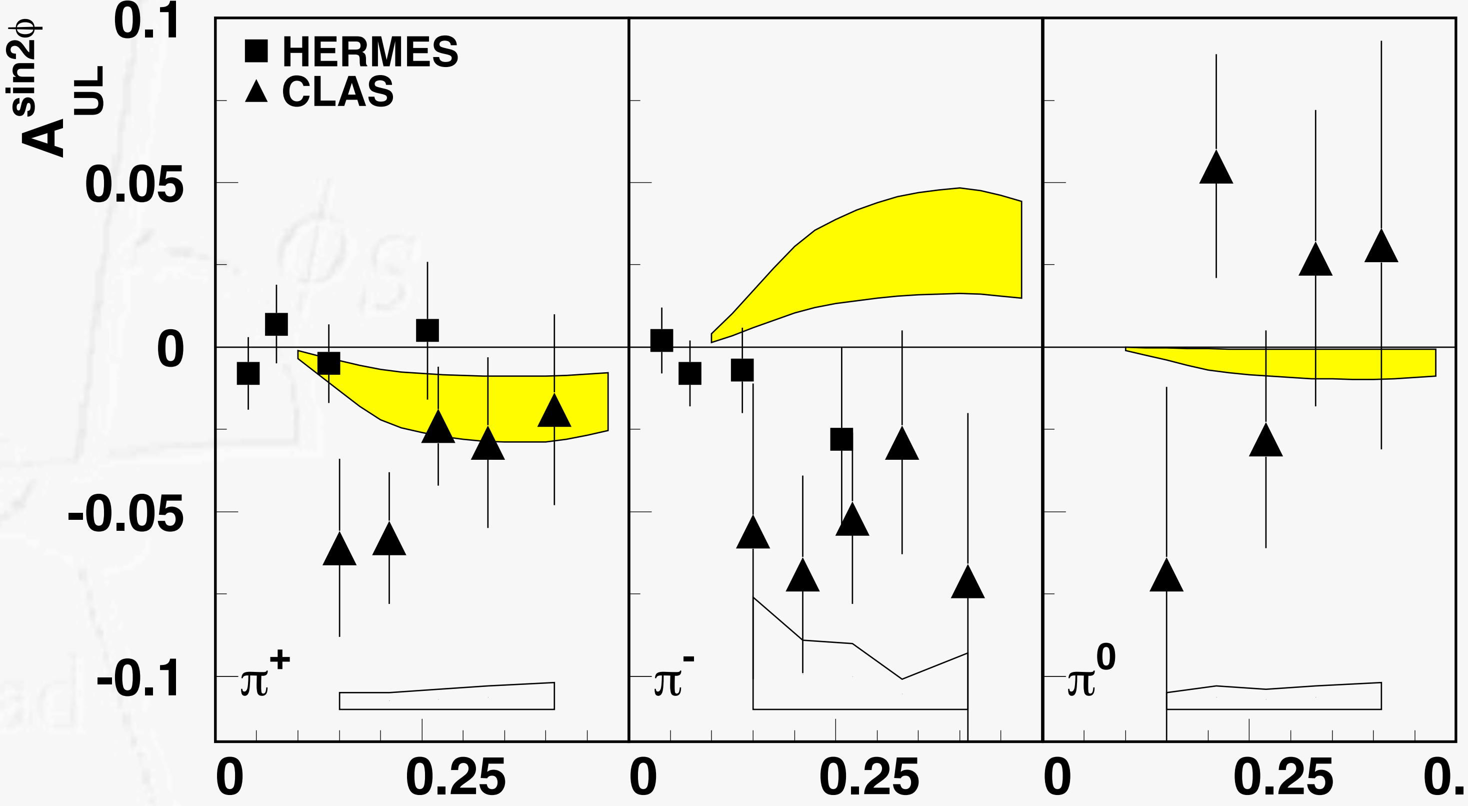
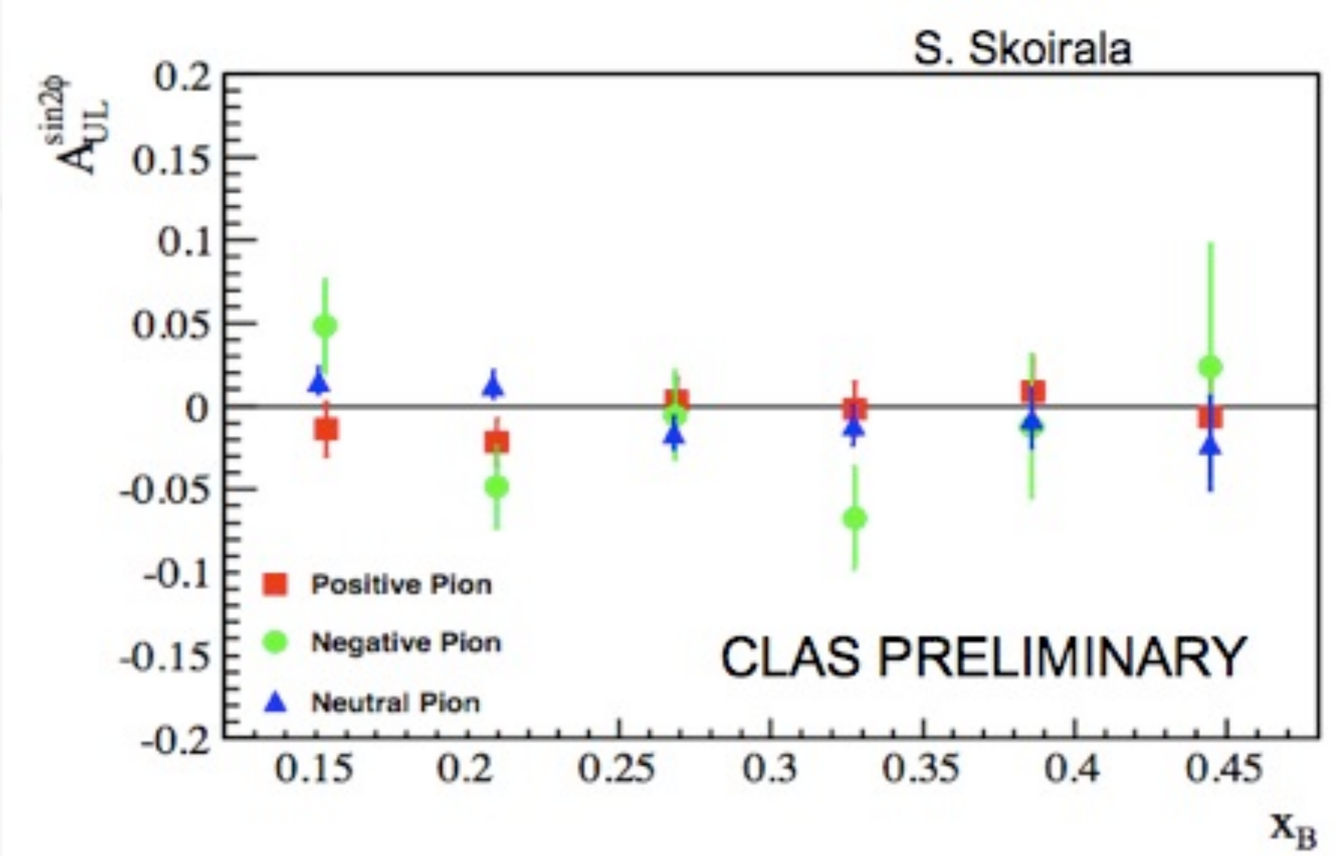
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Worm-Gear I

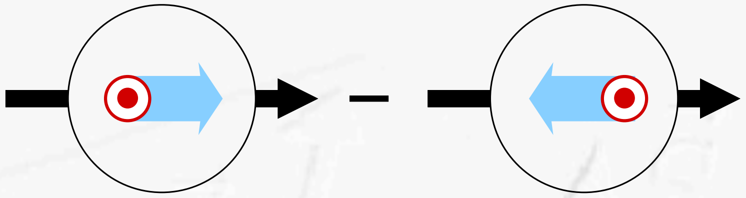
- again: chiral-odd
- evidence from CLAS (violating isospin symmetry?)
- consistent with zero at COMPASS and HERMES
- new preliminary data from CLAS closer to HERMES/ COMPASS (and to zero)

[CLAS, PRL 105 (2010) 262002]

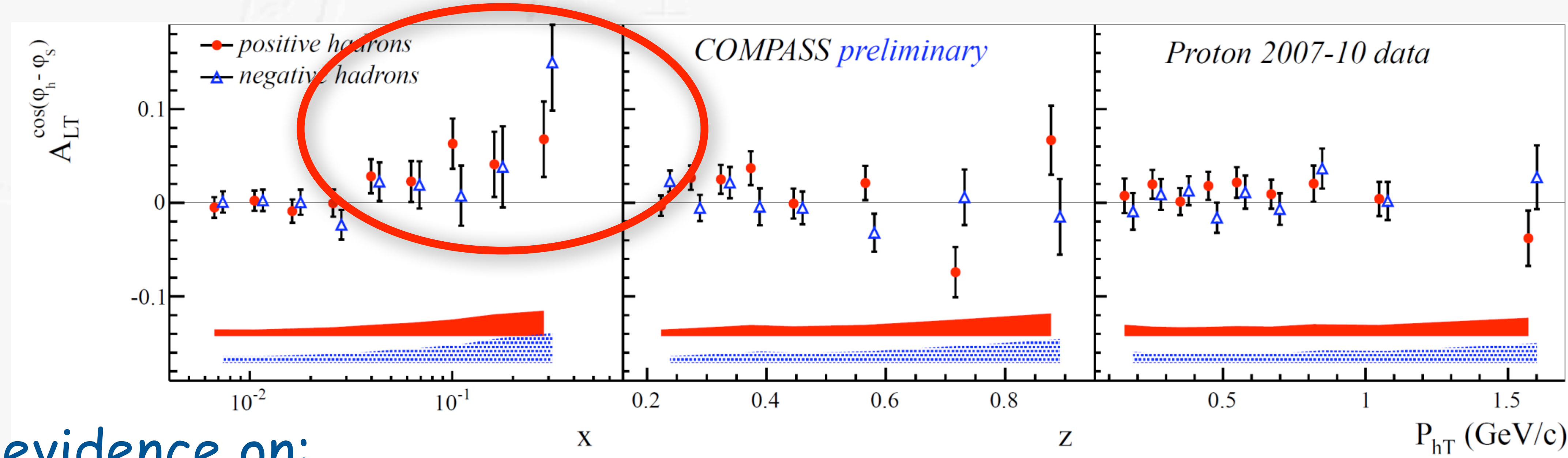




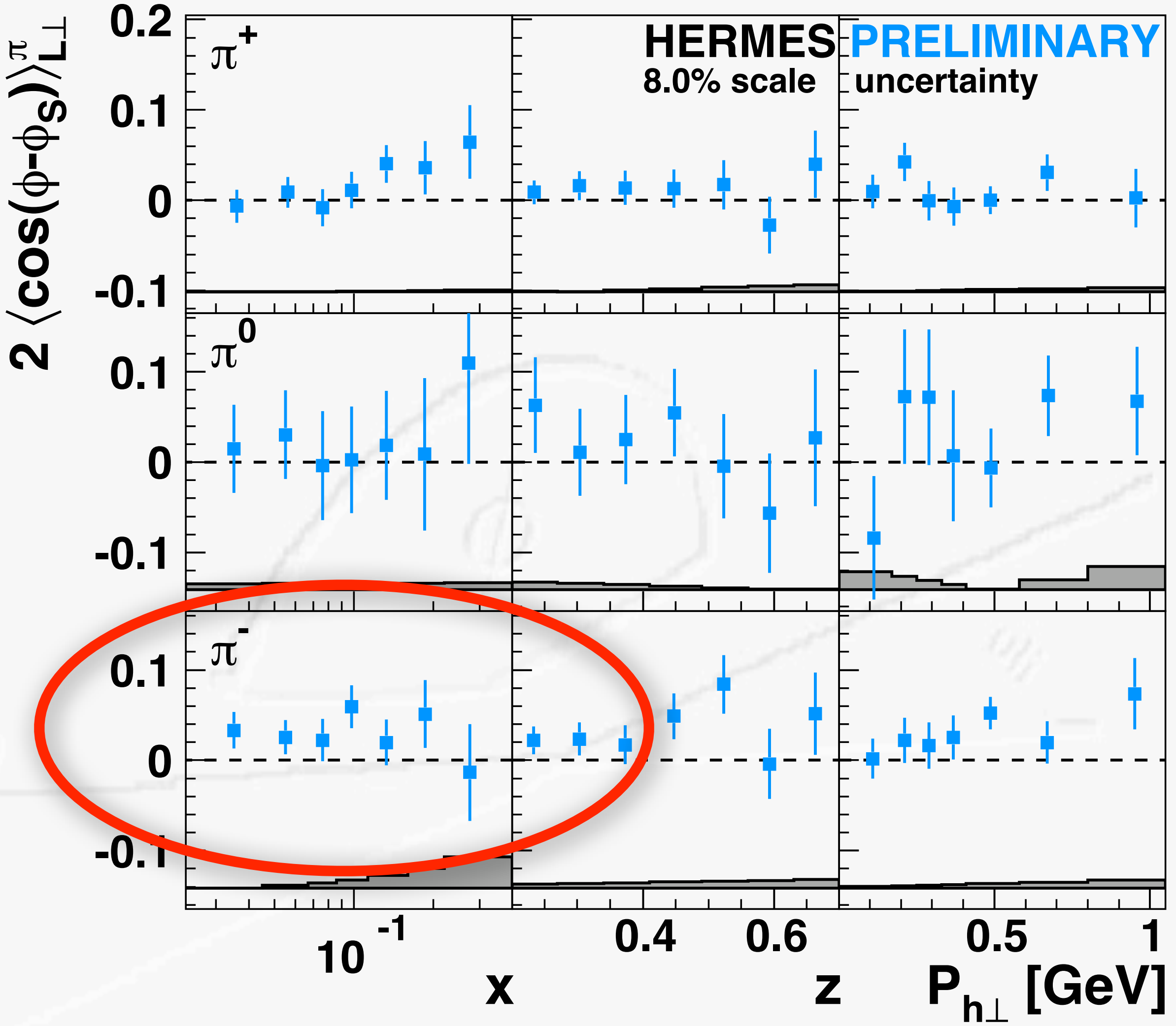
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



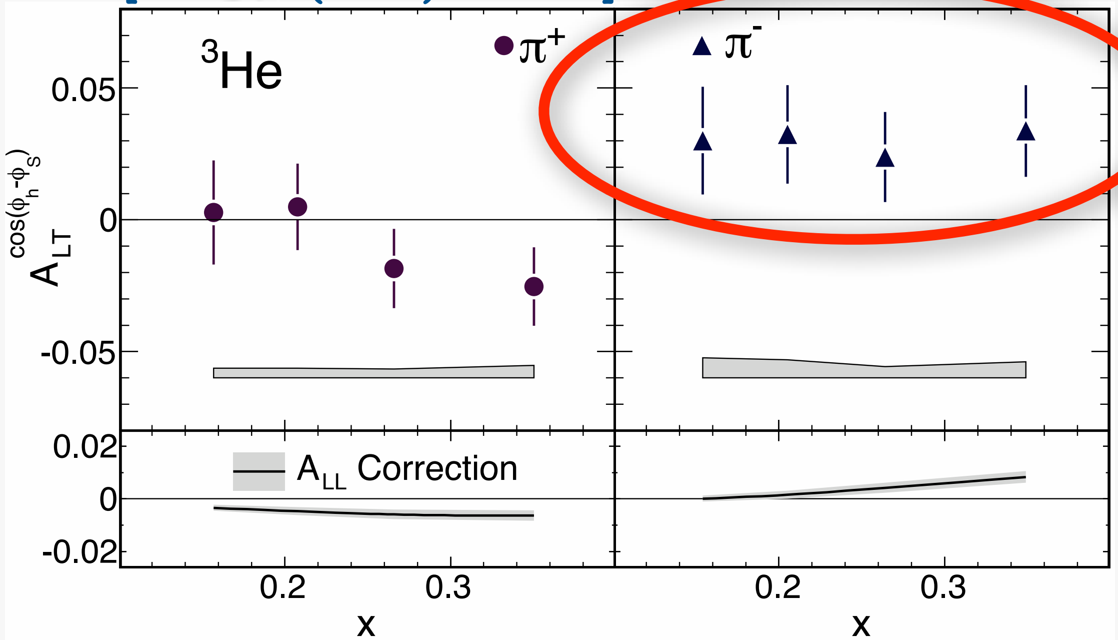
Worm-Gear II

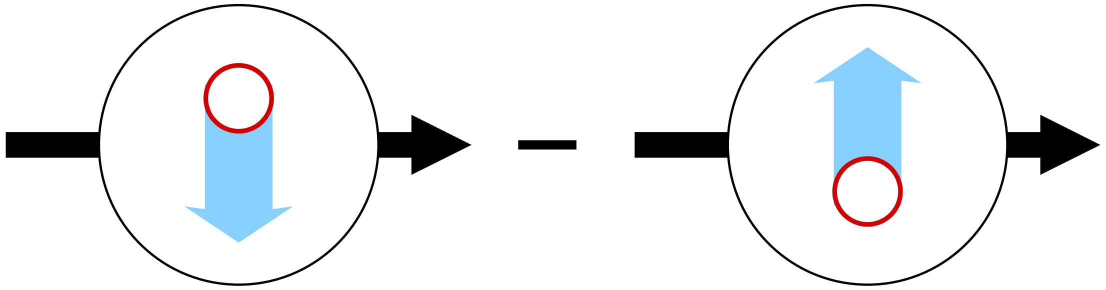


- first direct evidence on:
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

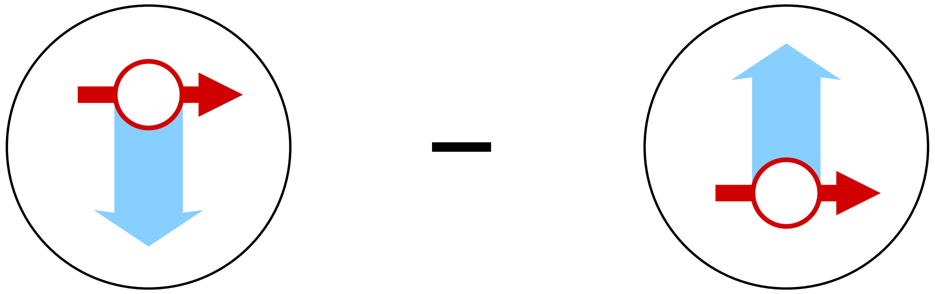


[PRL 108 (2012) 052001]





"Wilson-line physics" naively T-odd distributions

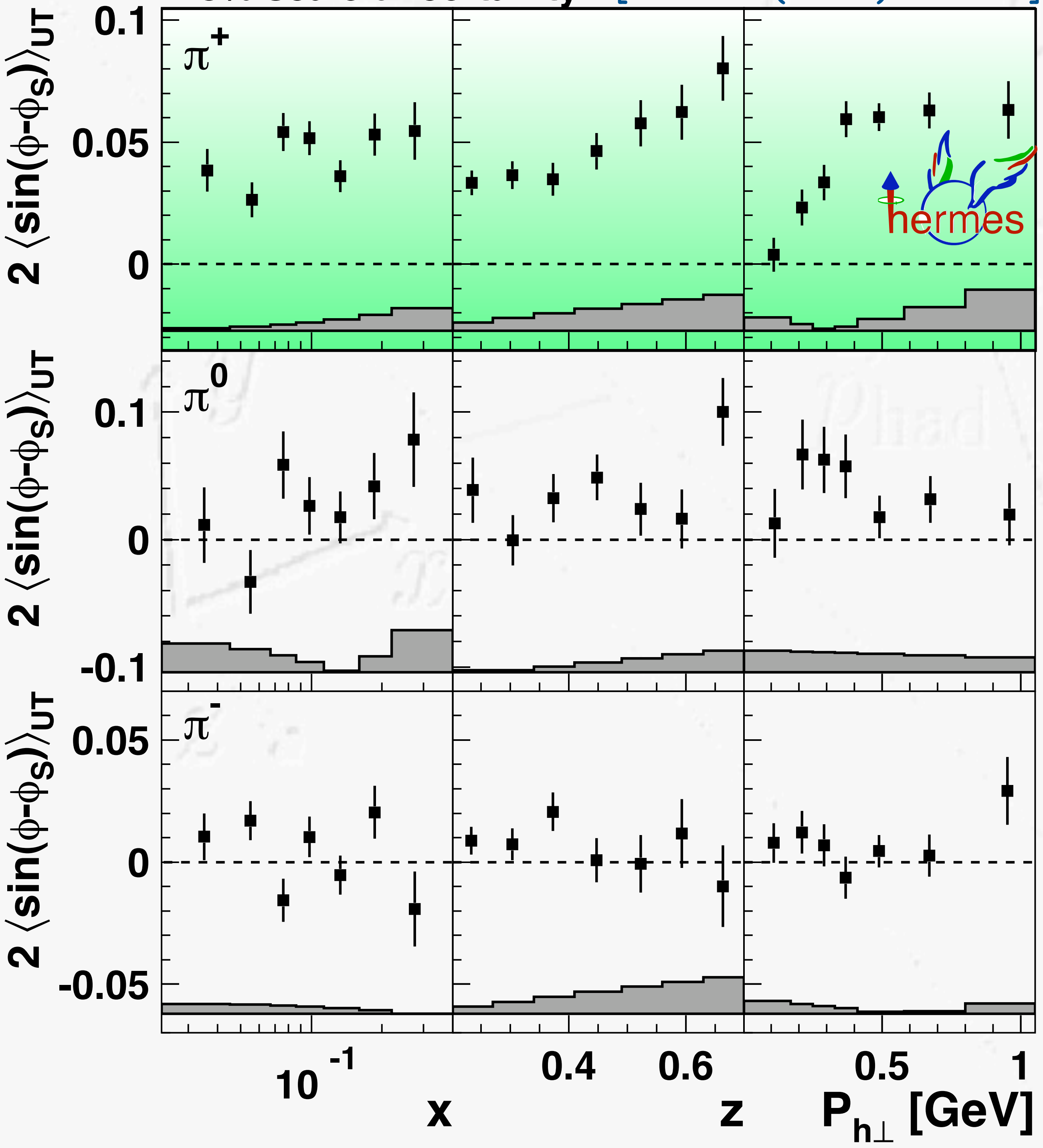


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

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

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



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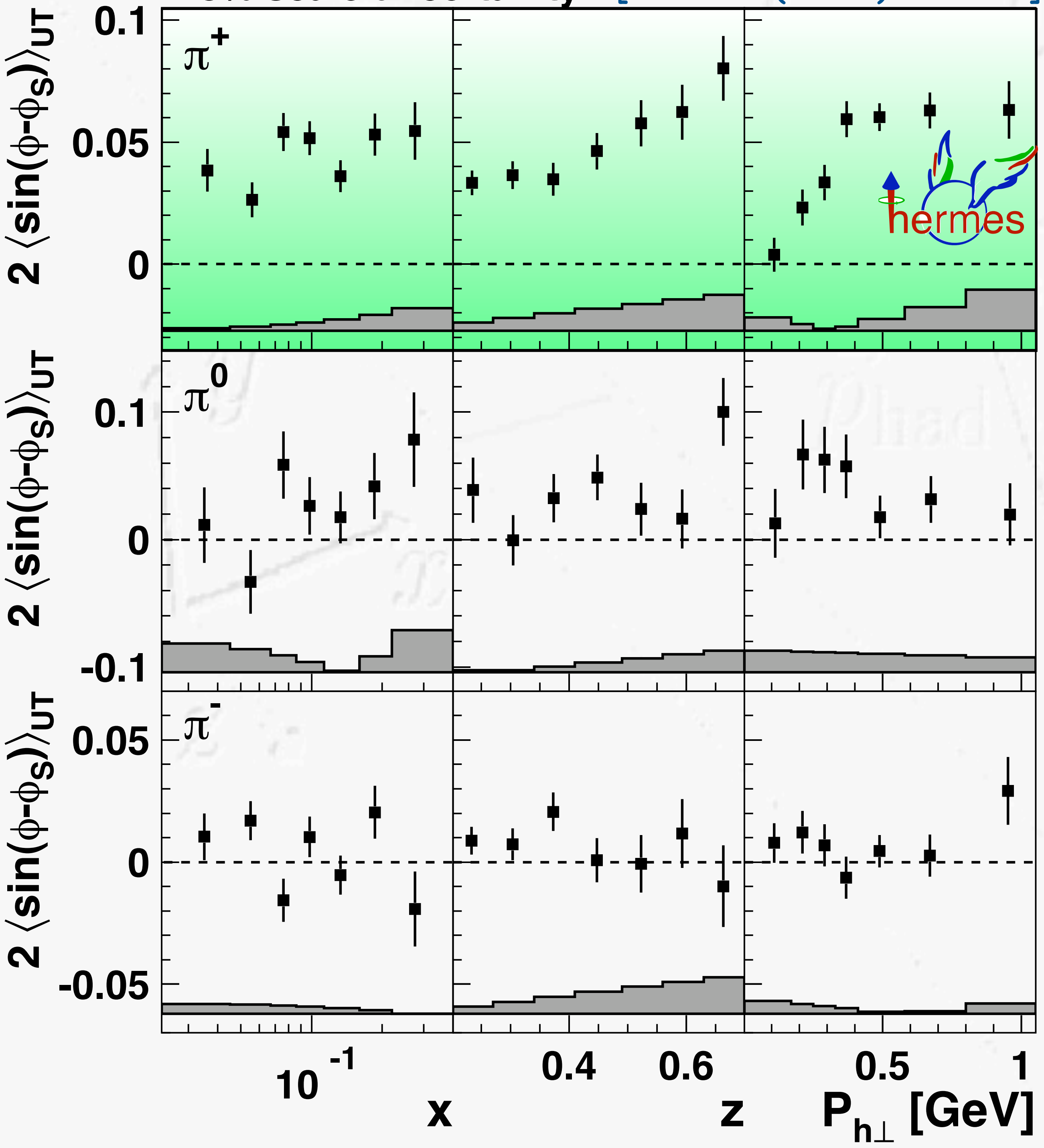

π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

	U	L	T
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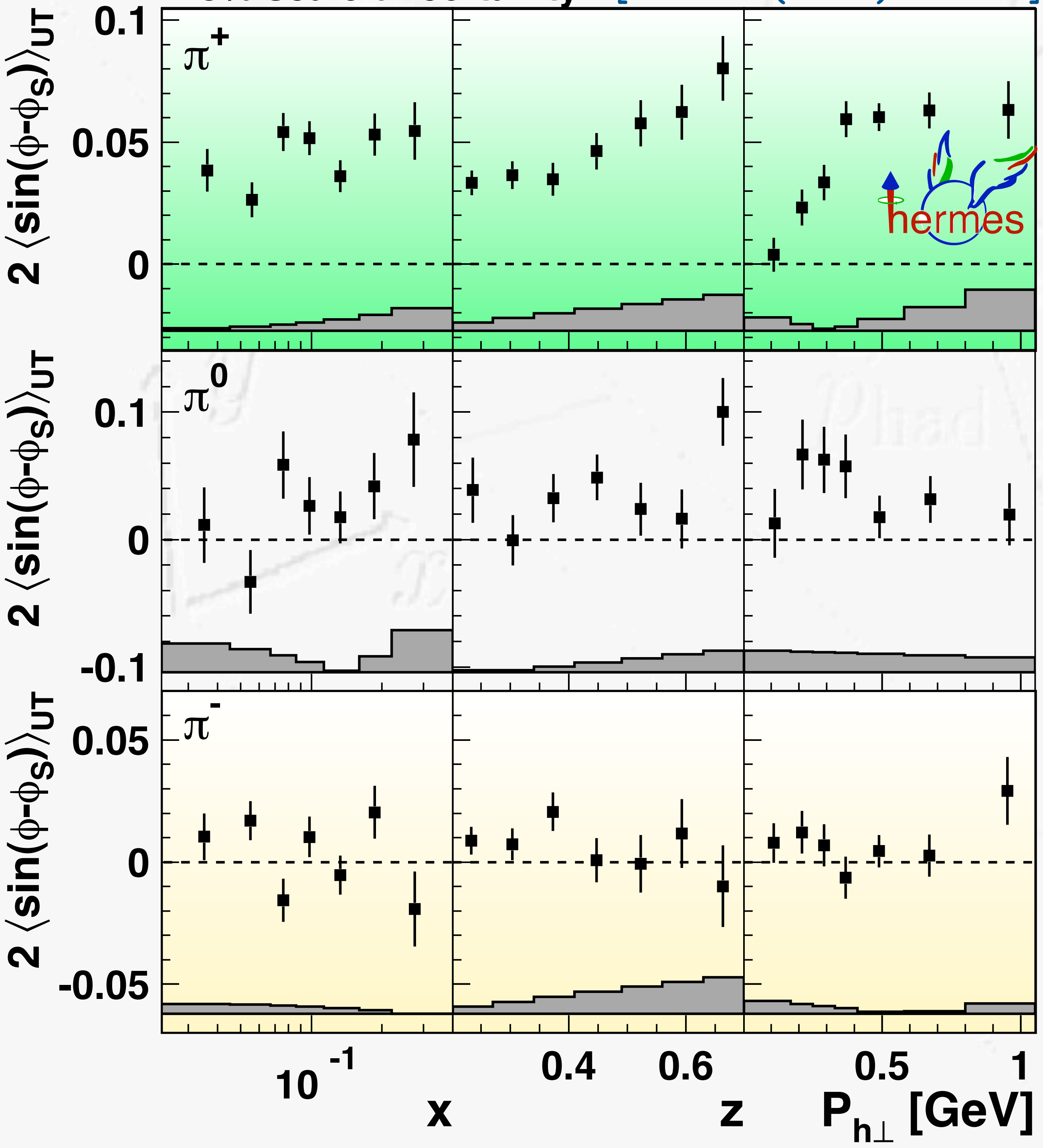

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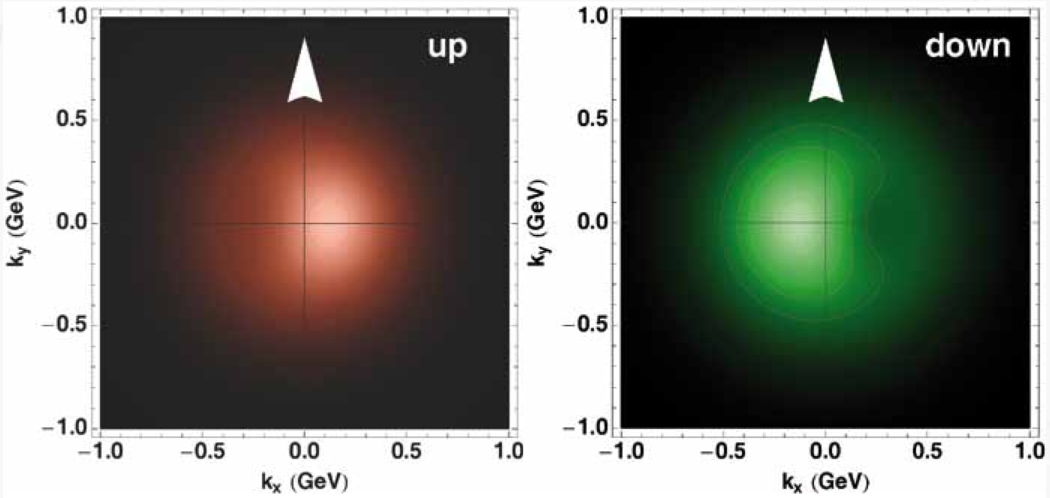
☛ u-quark Sivers DF < 0

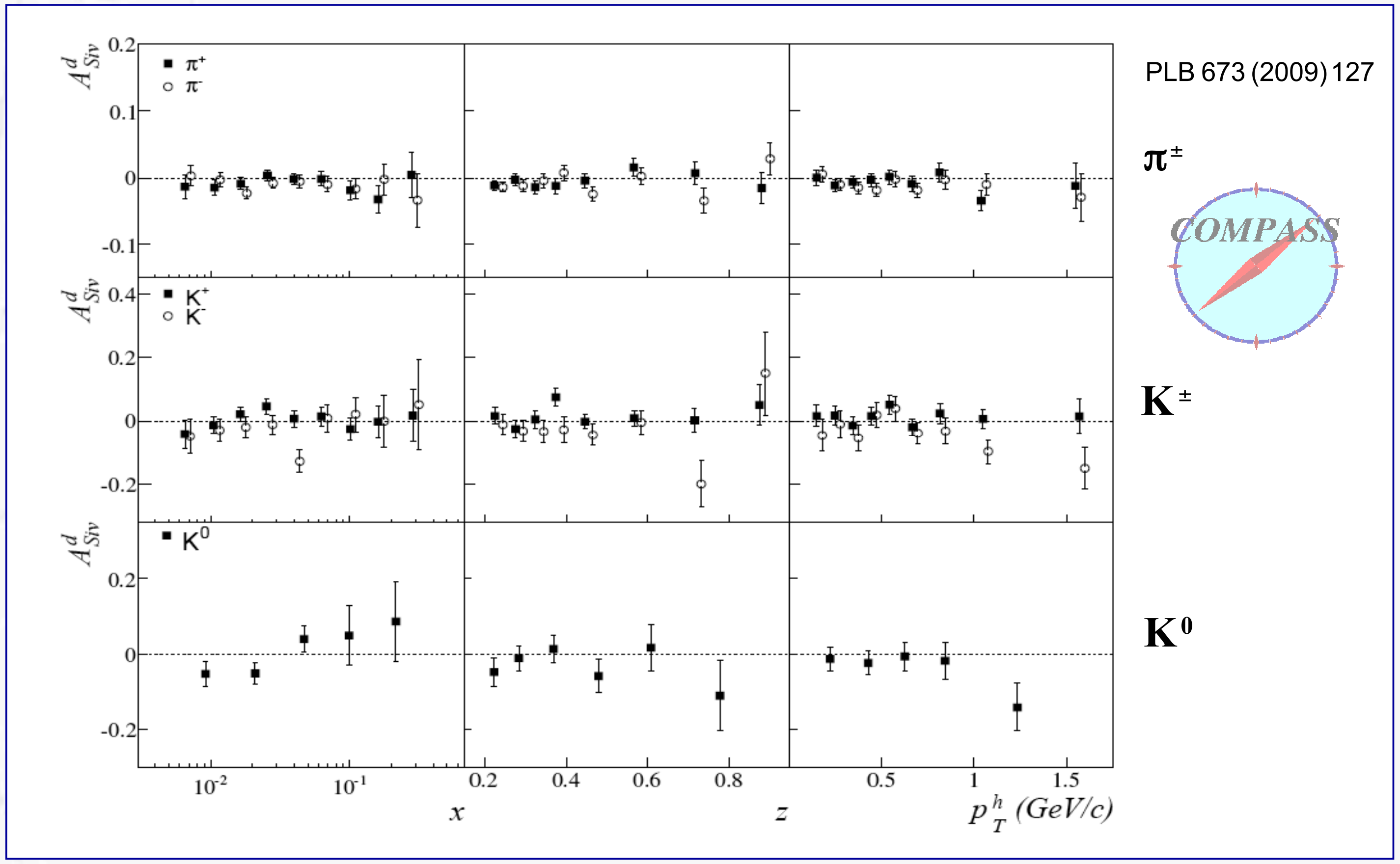
☛ d-quark Sivers DF > 0 (cancelation for π^-)

Sivers amplitudes

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



[A. Bacchetta et al.]



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

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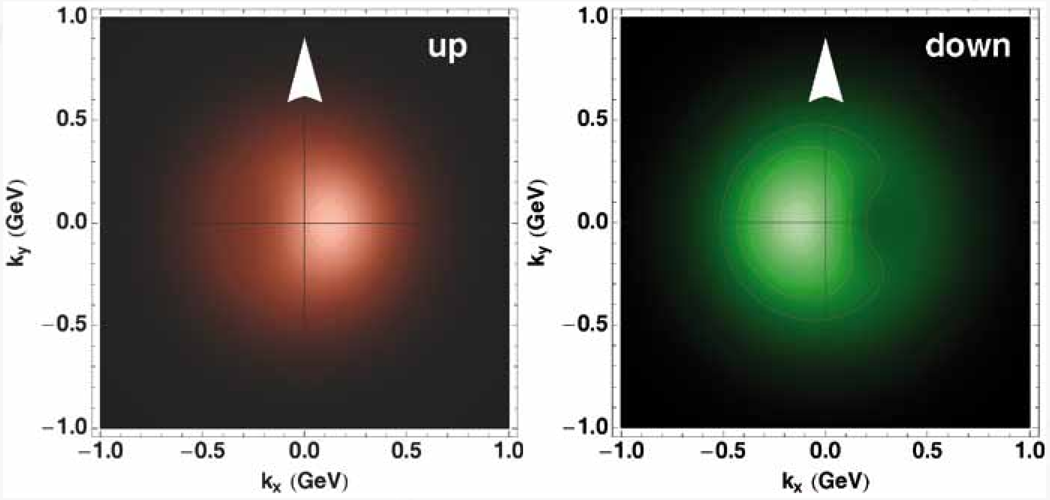
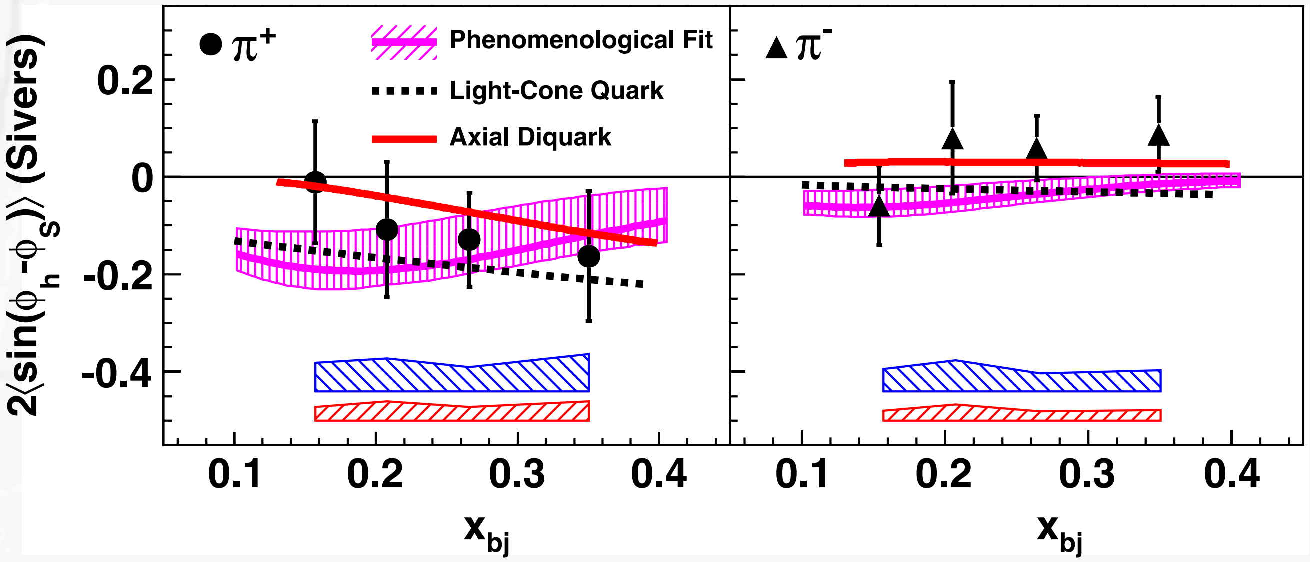
Sivers amplitudes

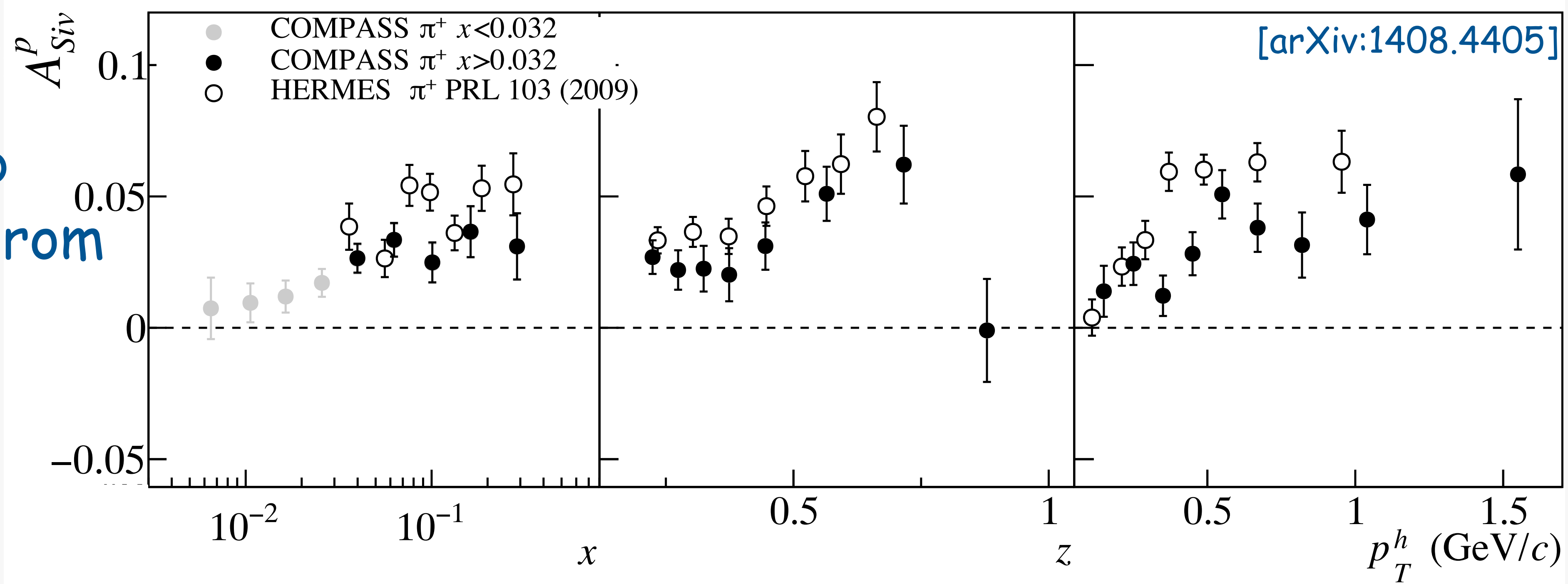


[A. Bacchetta et al.]

[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



[arXiv:1408.4405]

	U	L	T
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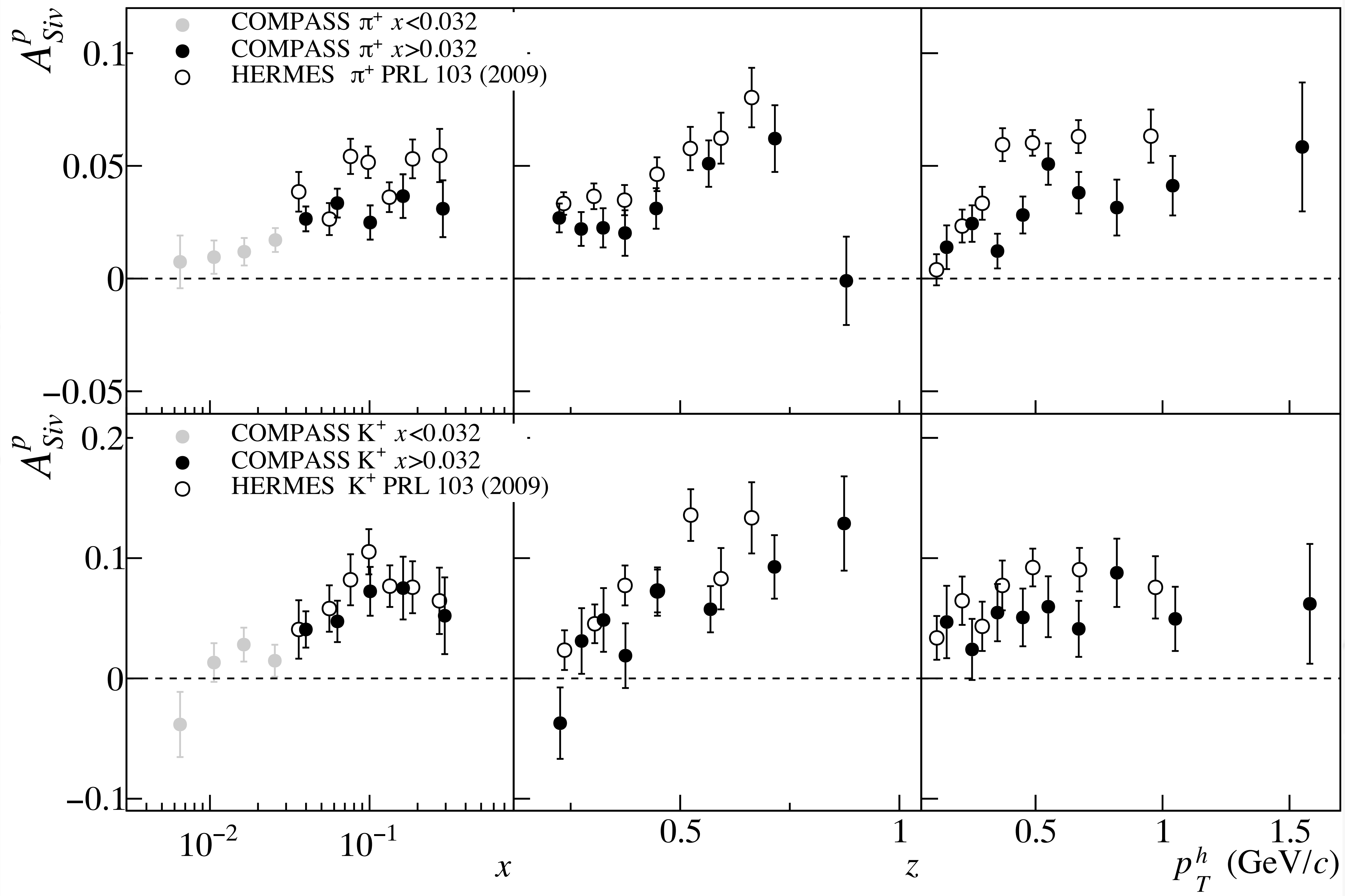
Sivers amplitudes
COMPASS vs. HERMES

[arXiv:1408.4405]



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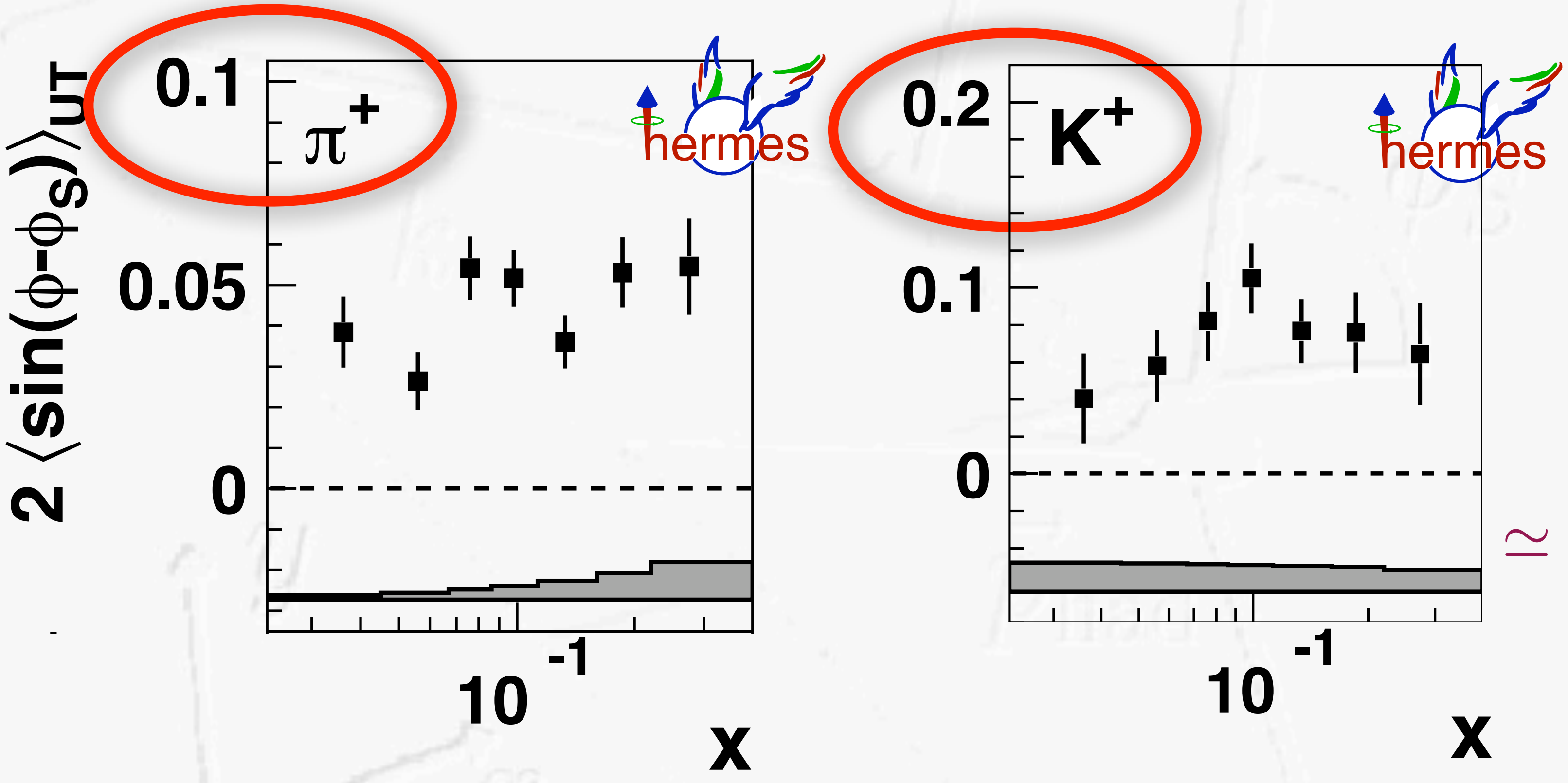
Sivers amplitudes pions vs. kaons



somewhat unexpected if dominated by scattering off u-quarks:

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

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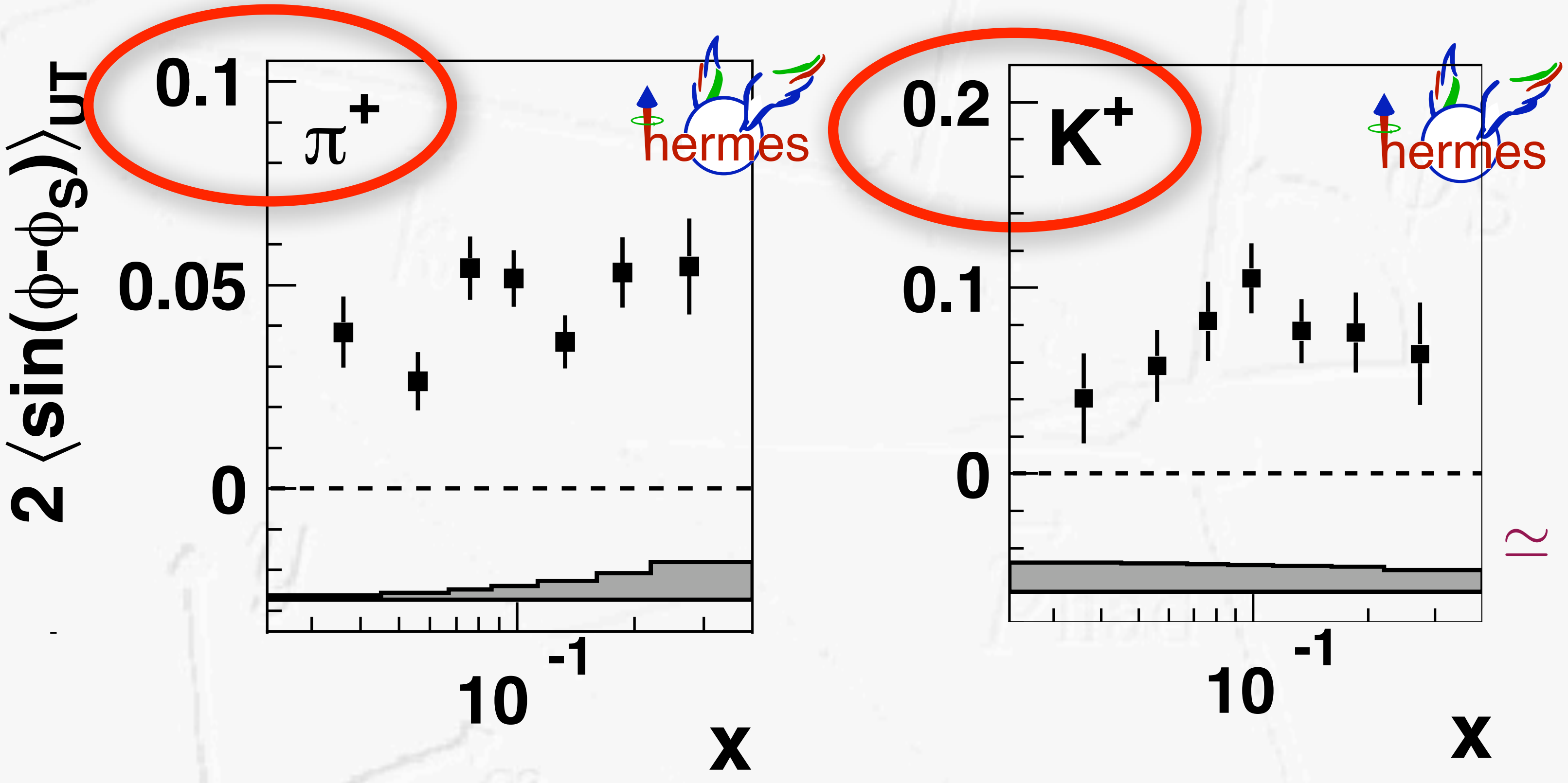

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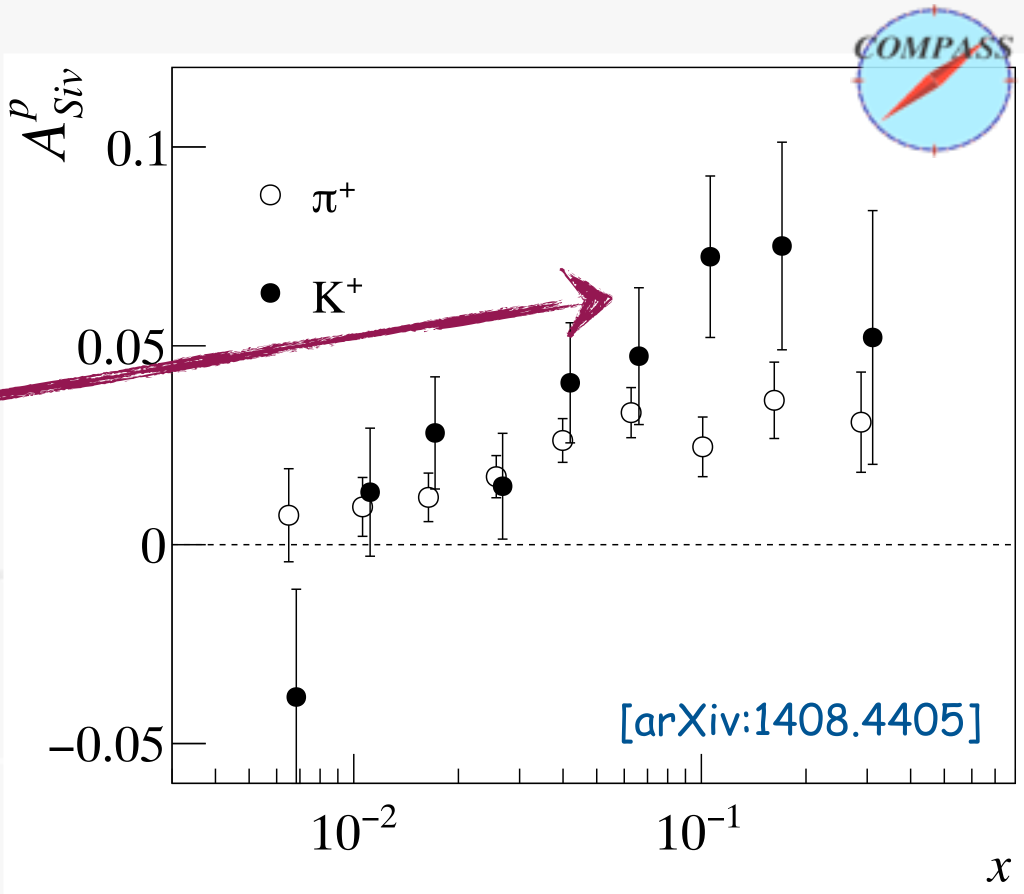
larger amplitudes seen also by COMPASS



[arXiv:1408.4405]

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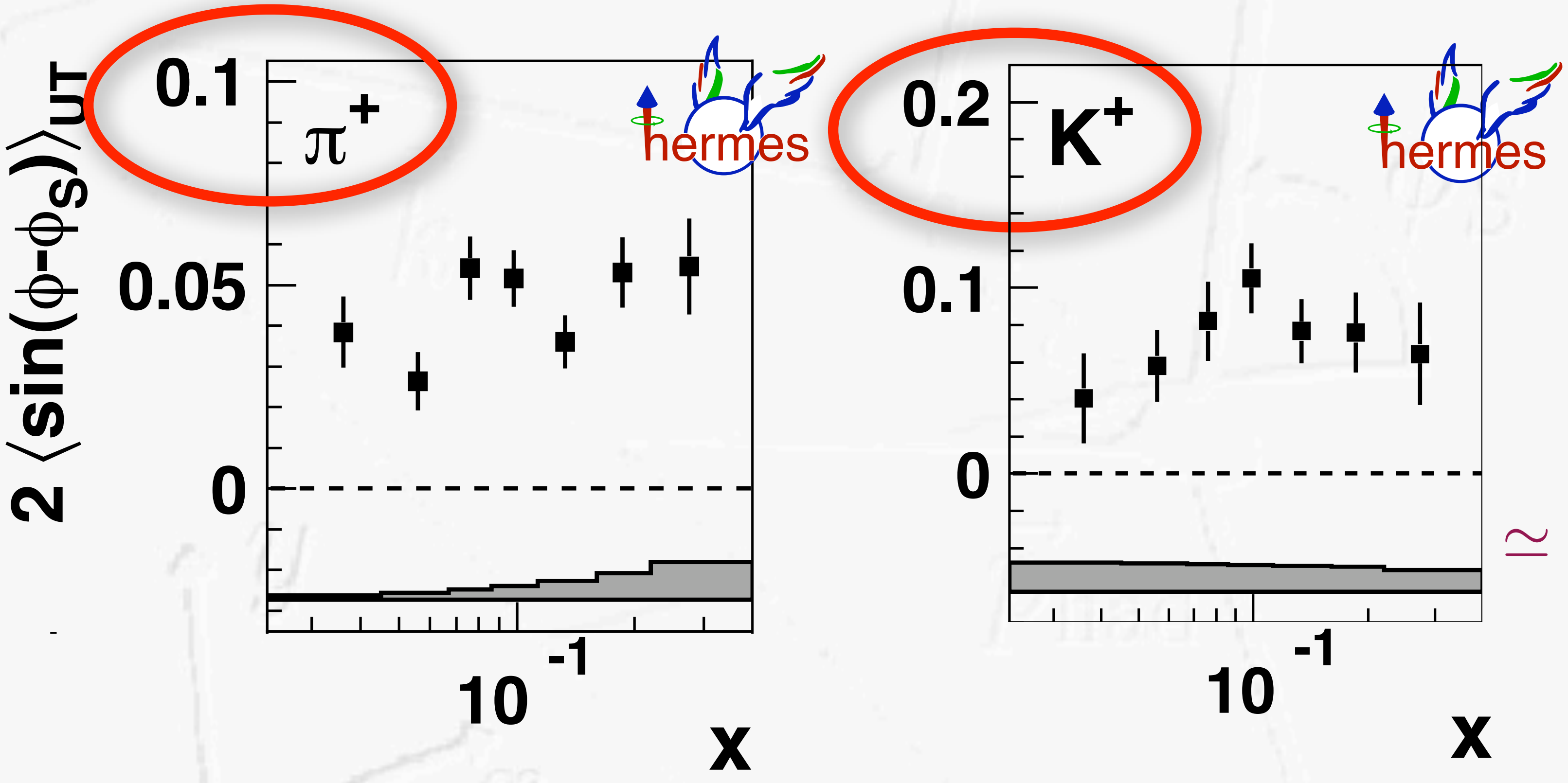
Sivers amplitudes pions vs. kaons



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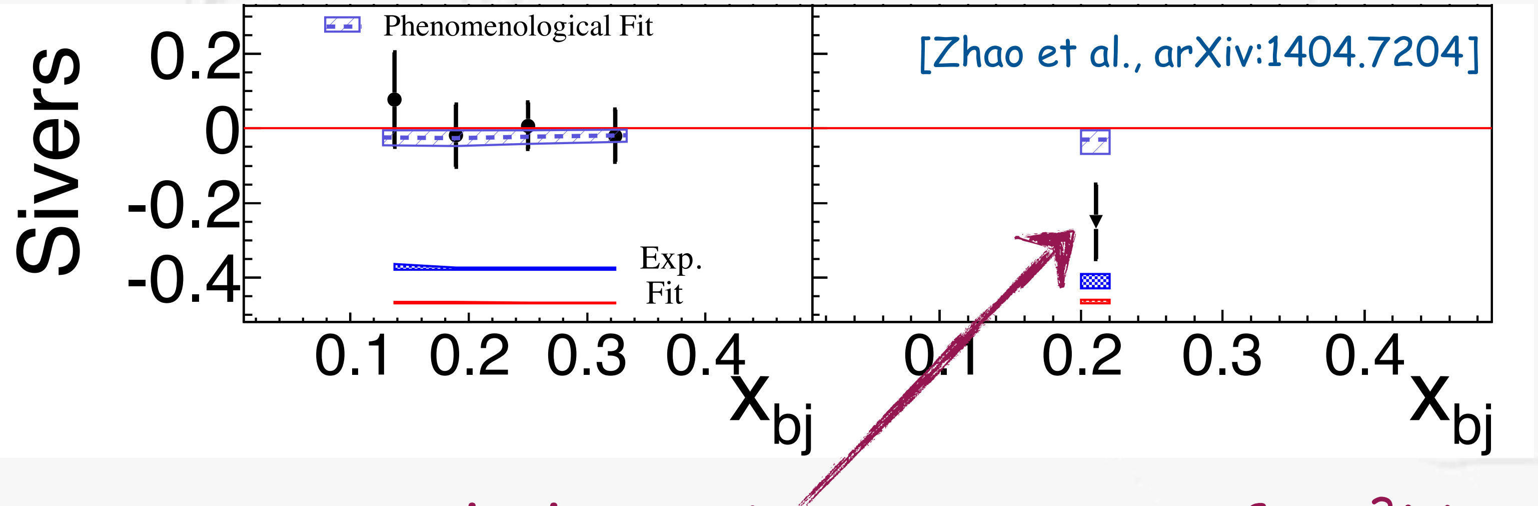
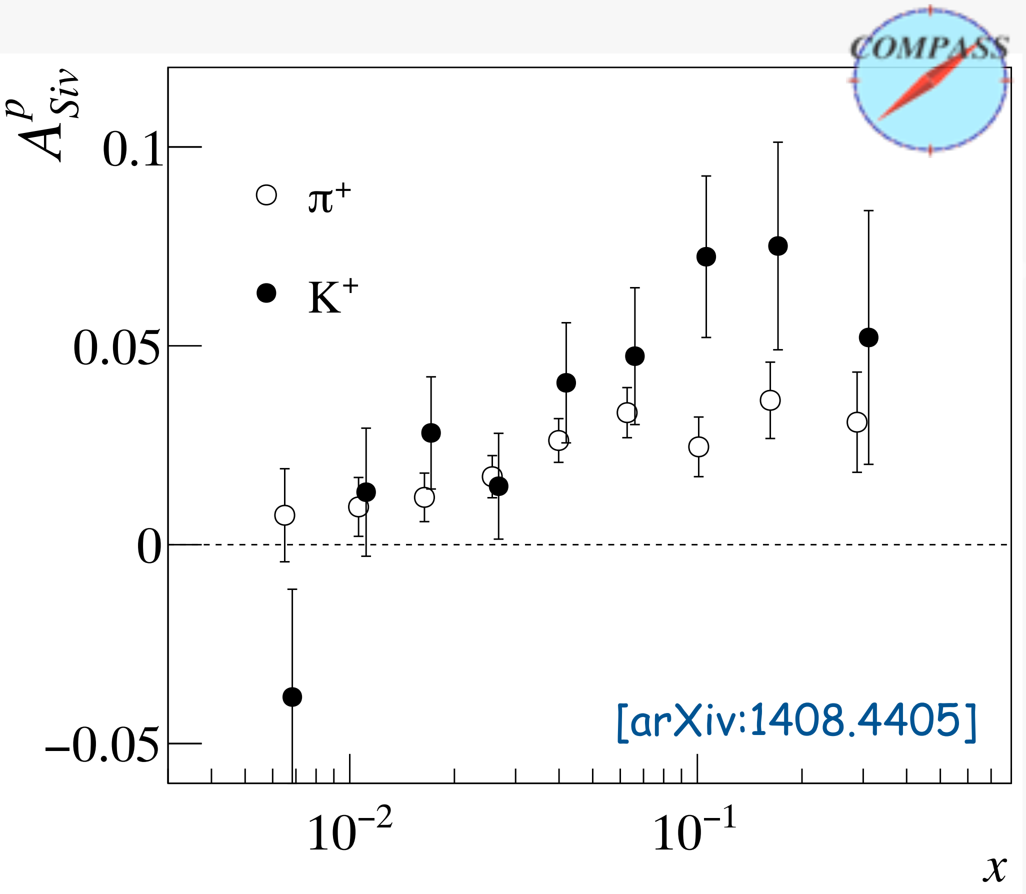


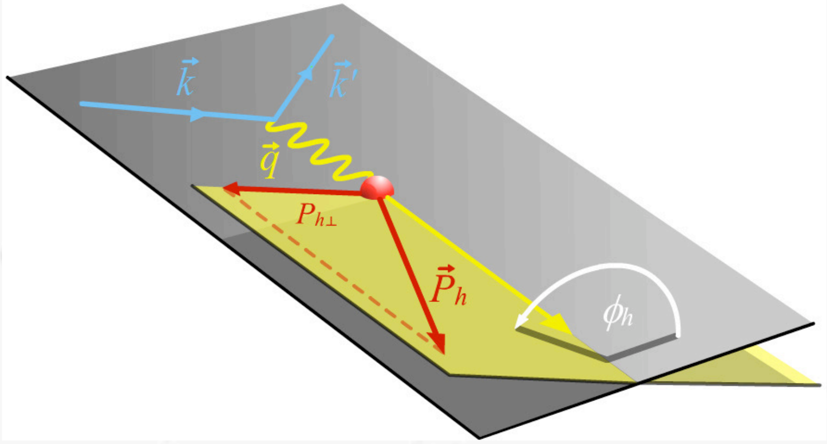
[Zhao et al., arXiv:1404.7204]

surprisingly large K^- asymmetry for ^{3}He target (but zero for K^+?!)



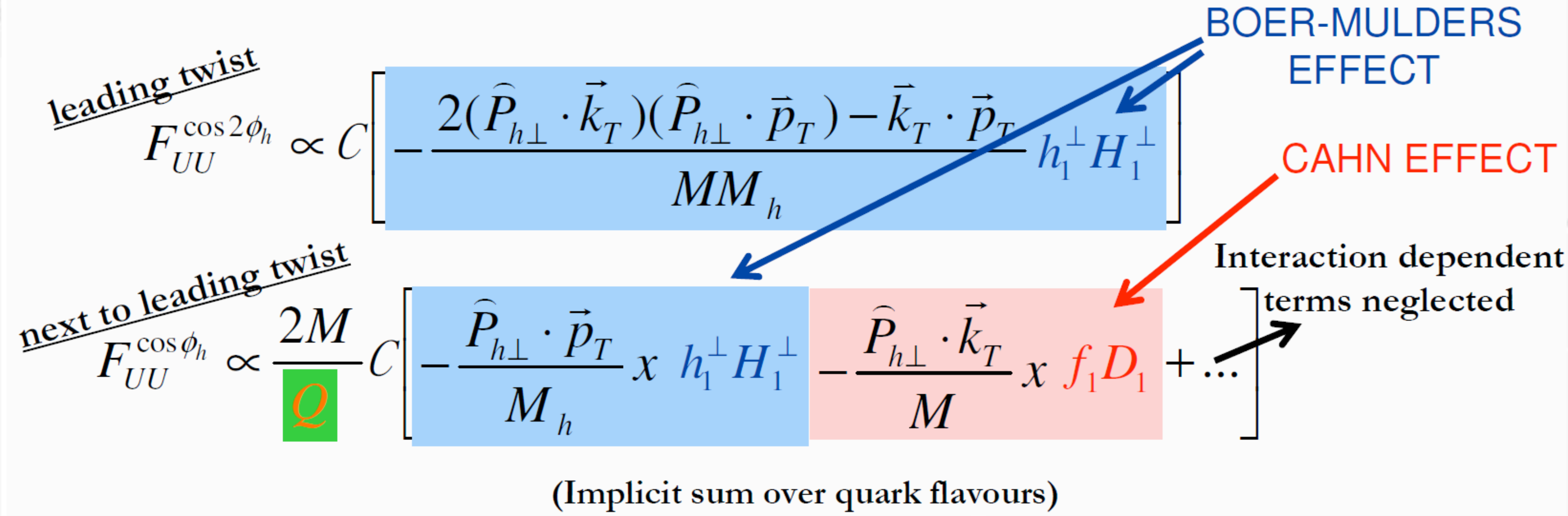
[arXiv:1408.4405]

Modulations in spin-independent SIDIS cross section



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

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



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

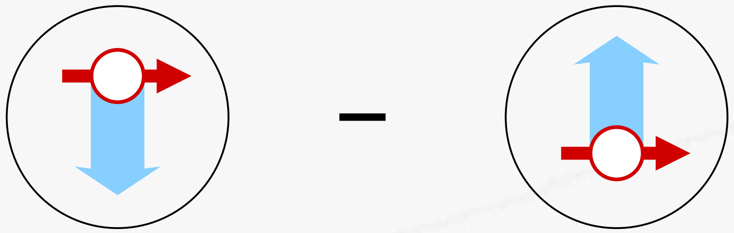
next to leading twist

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

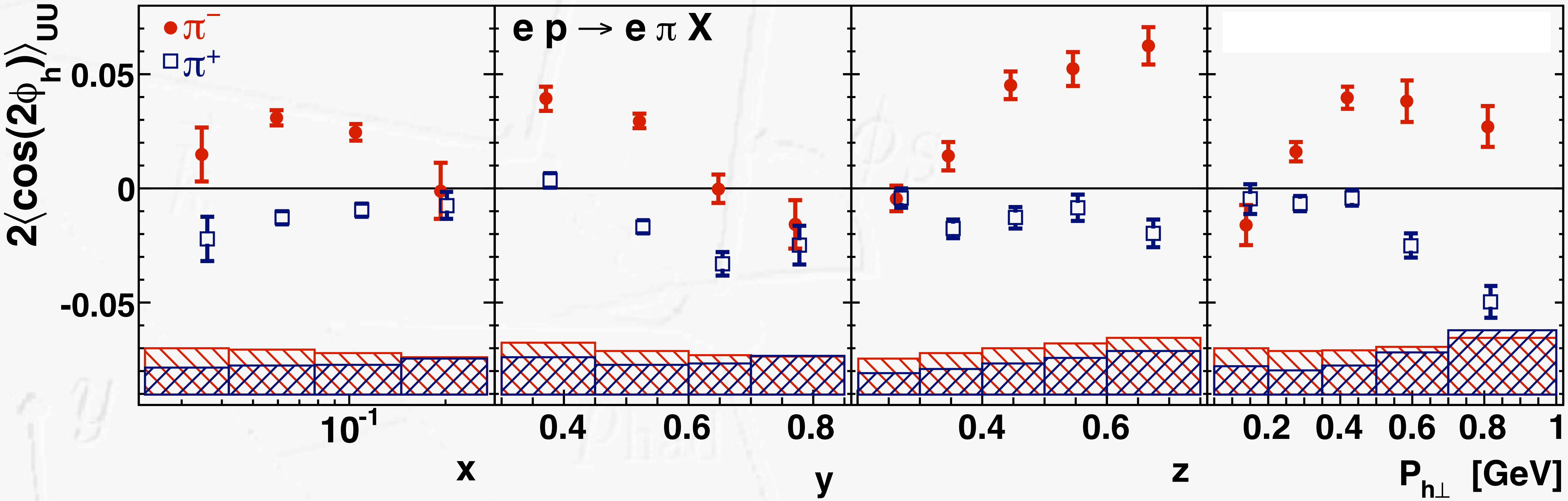
Interaction dependent terms neglected

(Implicit sum over quark flavours)

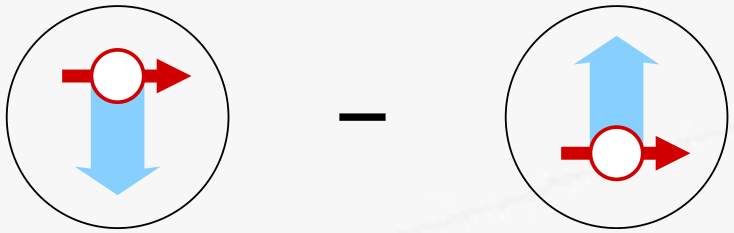
signs of Boer-Mulders



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



- not zero!



signs of Boer-Mulders

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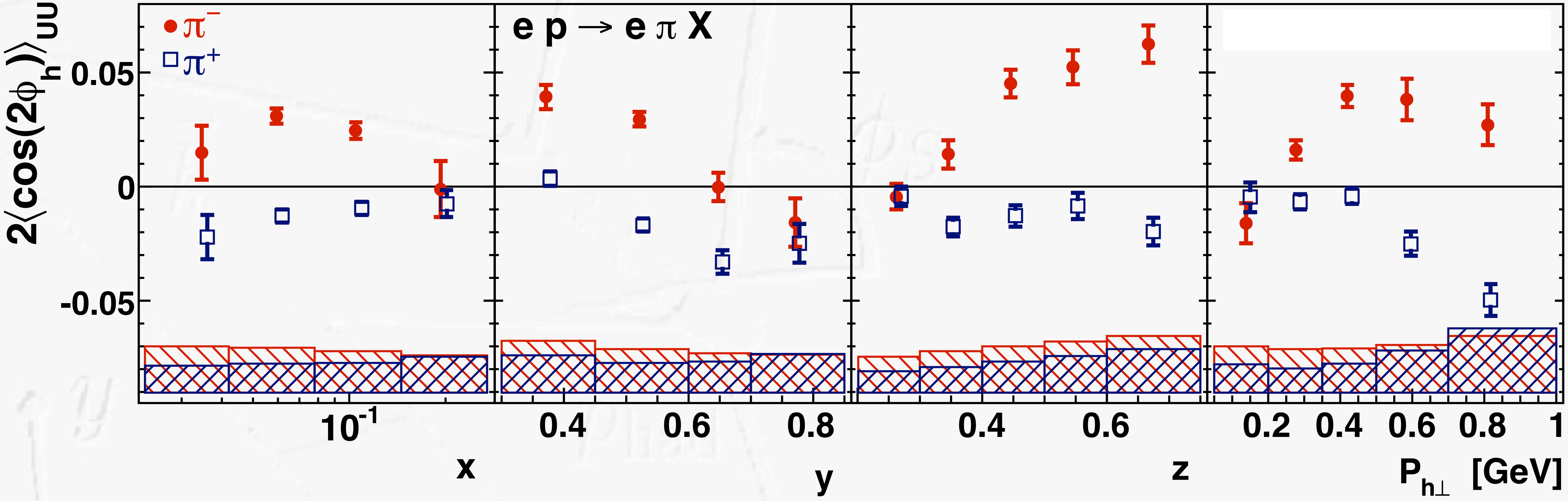
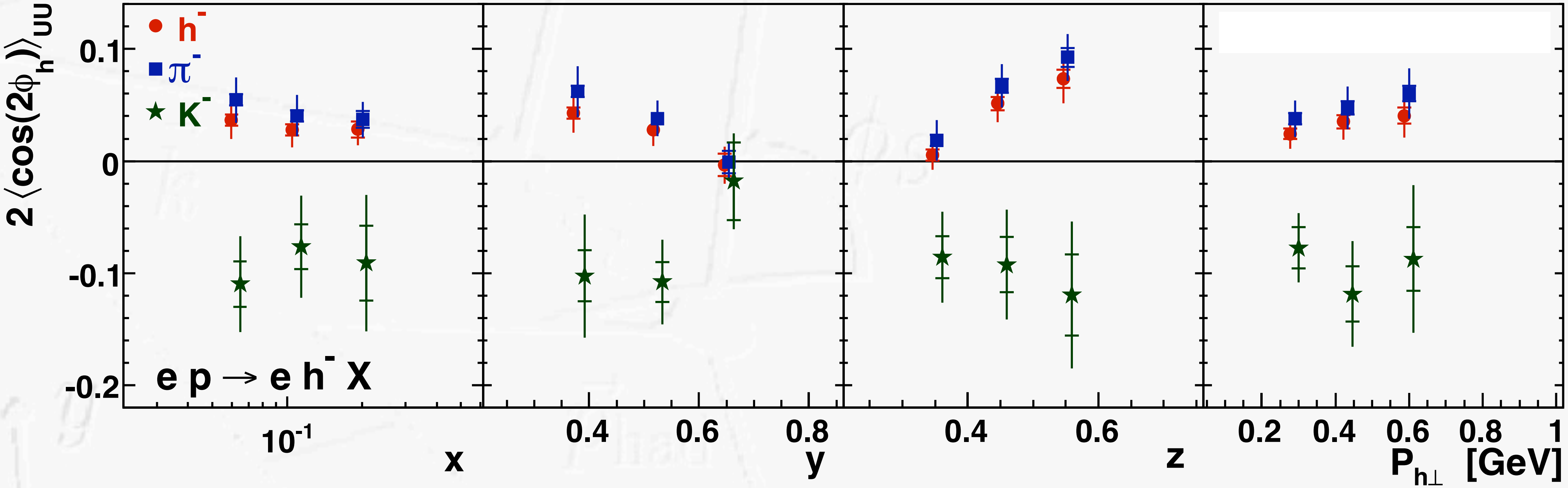


- not zero!
- opposite sign for charged pions with larger magnitude for π^-
  -> same-sign BM-function for valence quarks?

signs of Boer-Mulders



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

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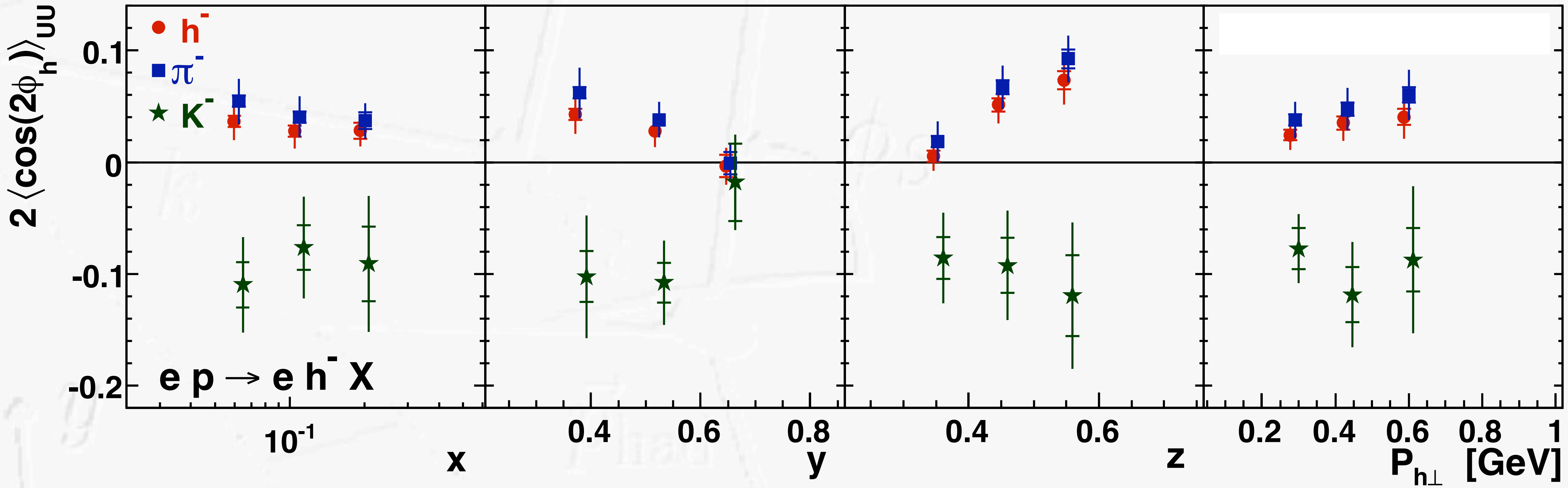
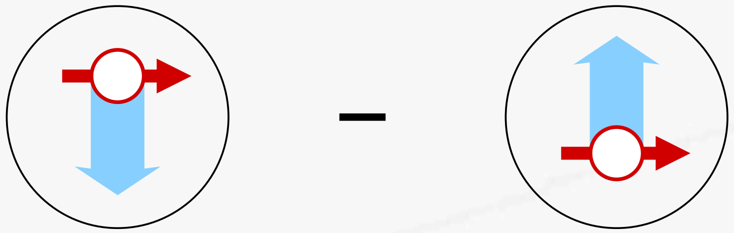


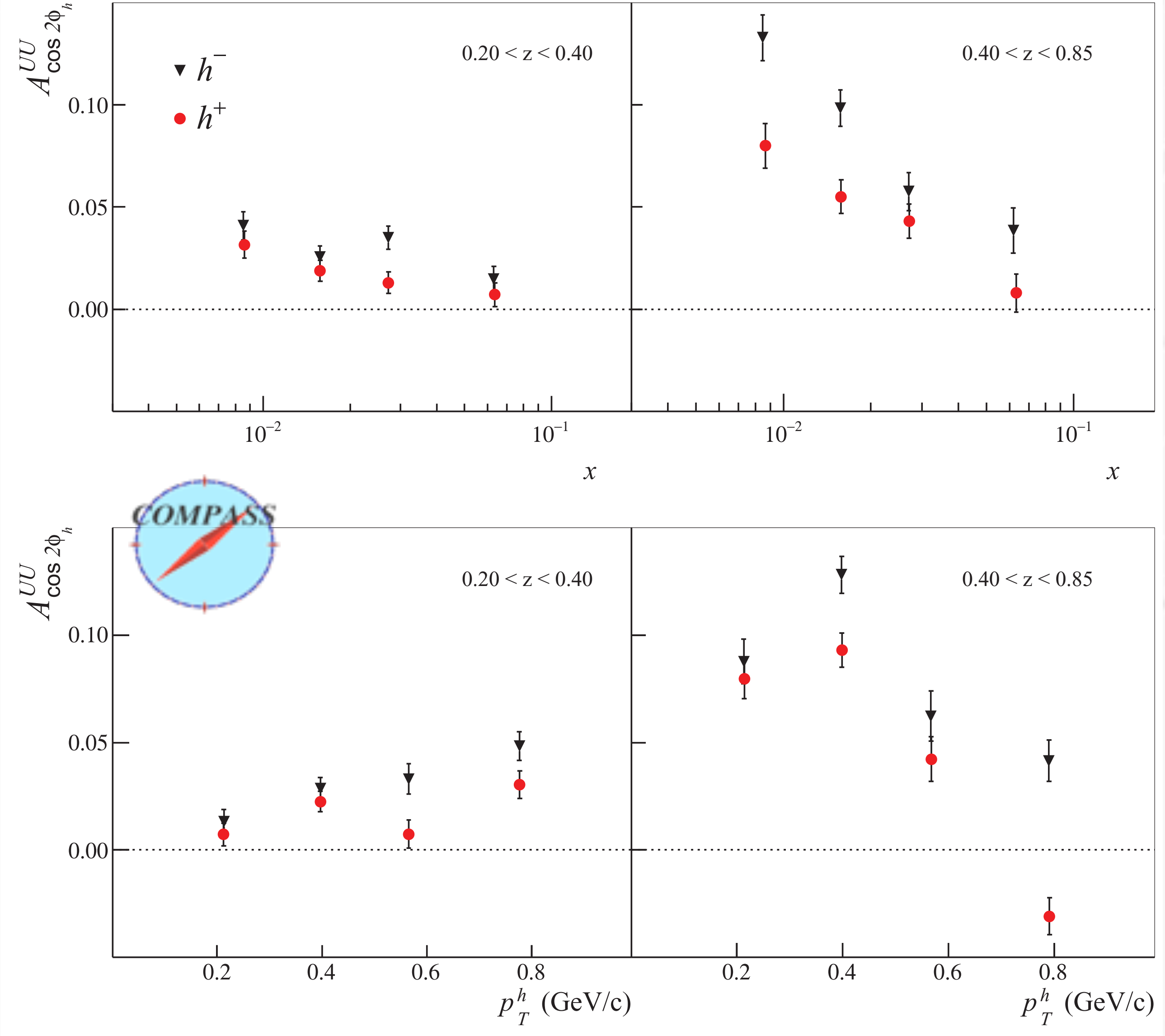
[Airapetian et al., PRD 87 (2013) 012010]

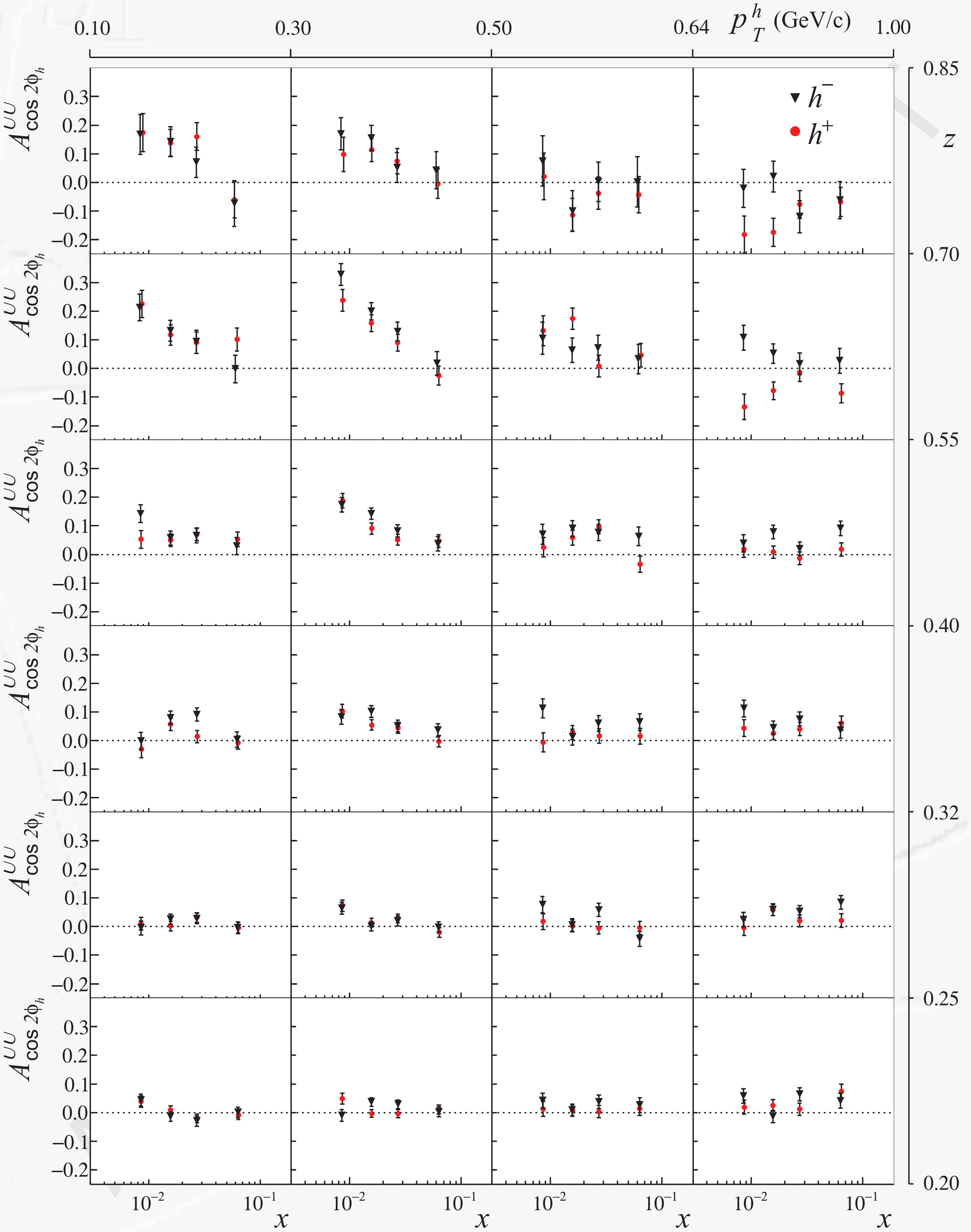
- not zero!
- opposite sign for charged pions with larger magnitude for π^- -> same-sign BM-function for valence quarks?
- intriguing behavior for kaons
- available in multidimensional binning both from HERMES and from COMPASS

signs of Boer-Mulders



10.1016/j.nuclphysb.2014.07.019





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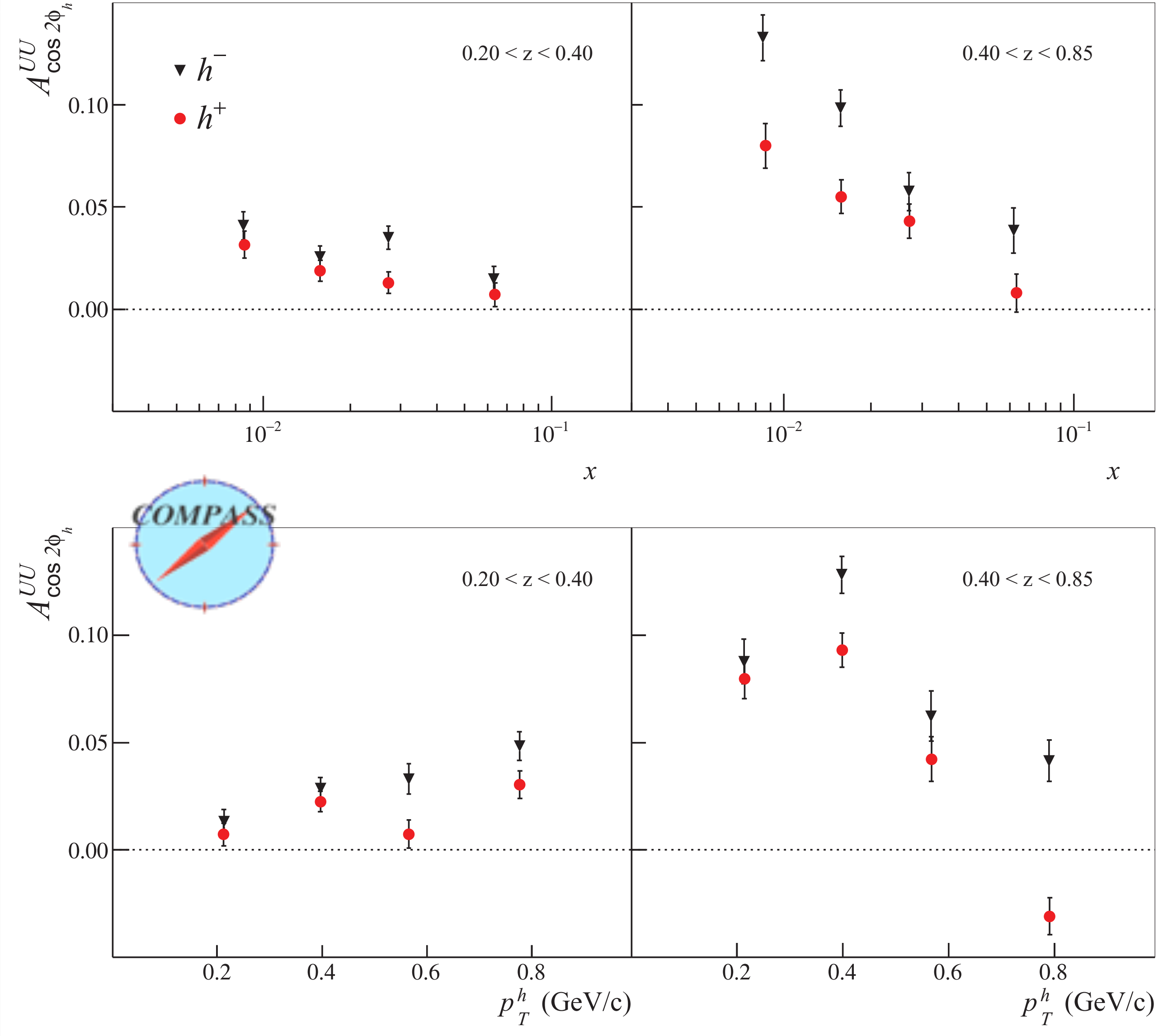

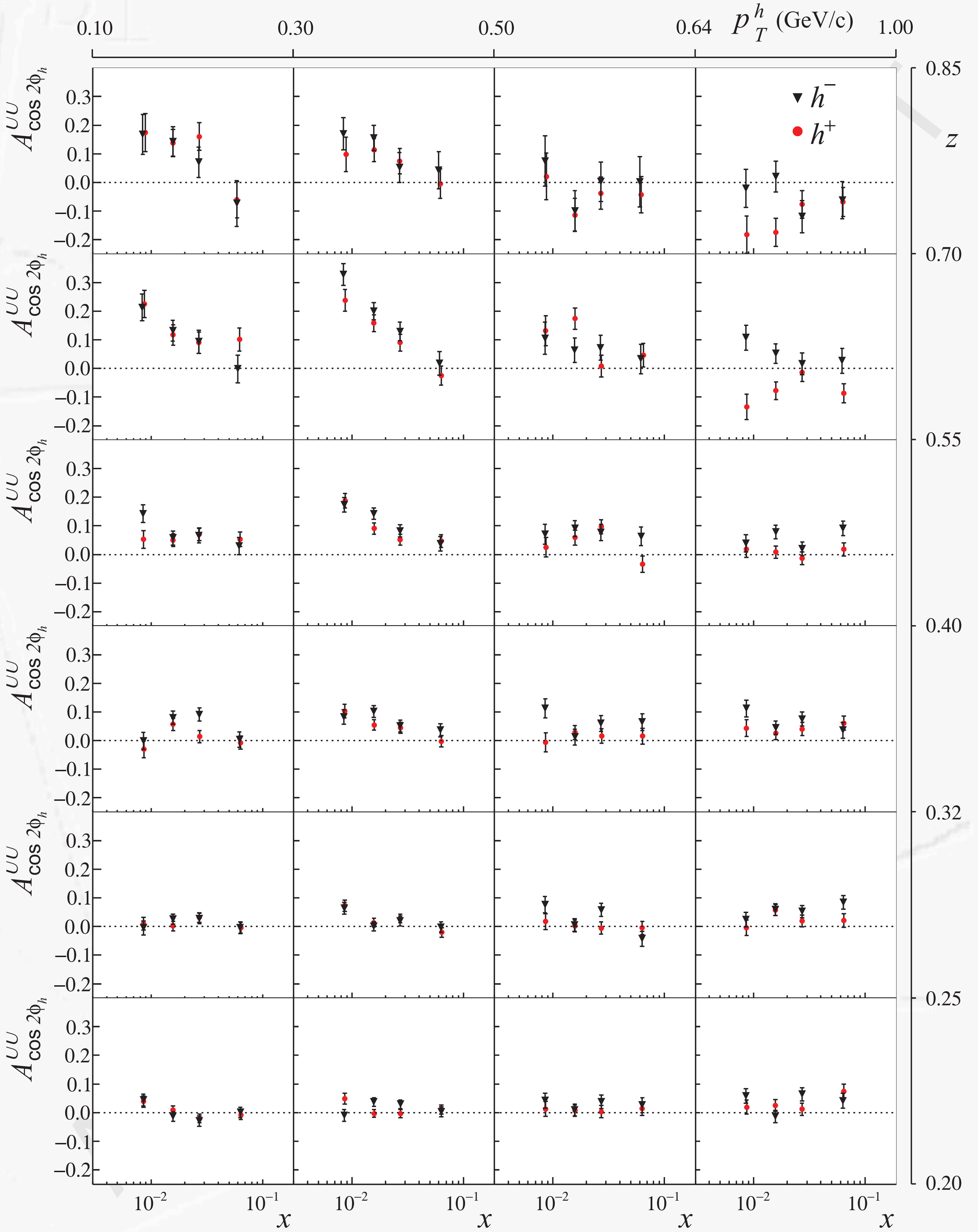

- unlike HERMES same sign for h^+ and h^-, though still different

Summary

- first round of SIDIS measurements coming to an end
- current knowledge on quark- and gluon-spin contribution to nucleon spin leaves room for orbital angular momentum
- 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
  - Sivers: opposite sign for up and down quarks in line with their contributions to the nucleon's anomalous magnetic moment
- so far no sign of a non-zero pretzelosity distribution
- first evidences for non-vanishing worm-gear functions
- precision measurements at ongoing and future SIDIS facilities needed to fully map TMD landscape