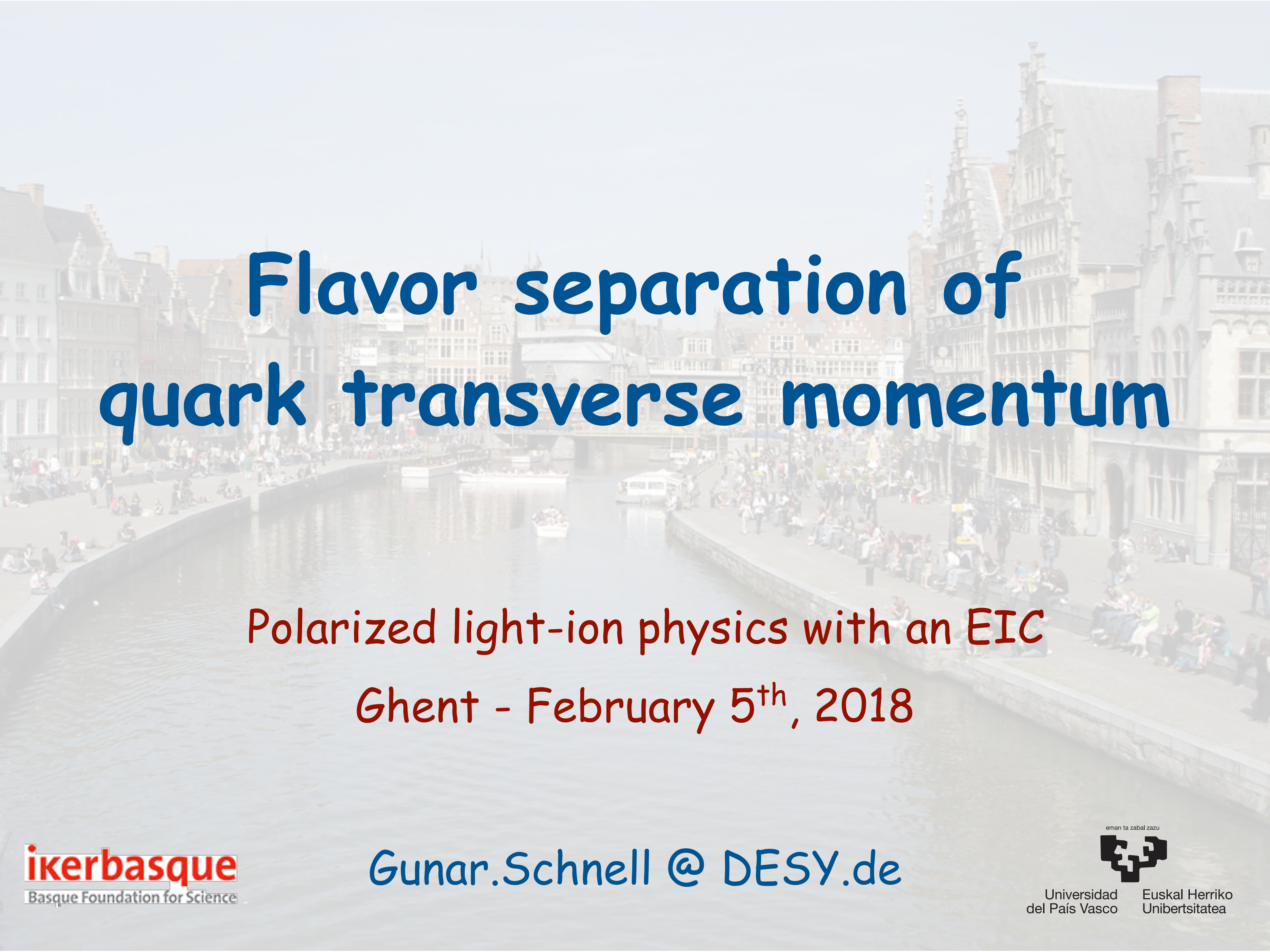


Flavor separation of quark transverse momentum

Polarized light-ion physics with an EIC

Ghent - February 5th, 2018

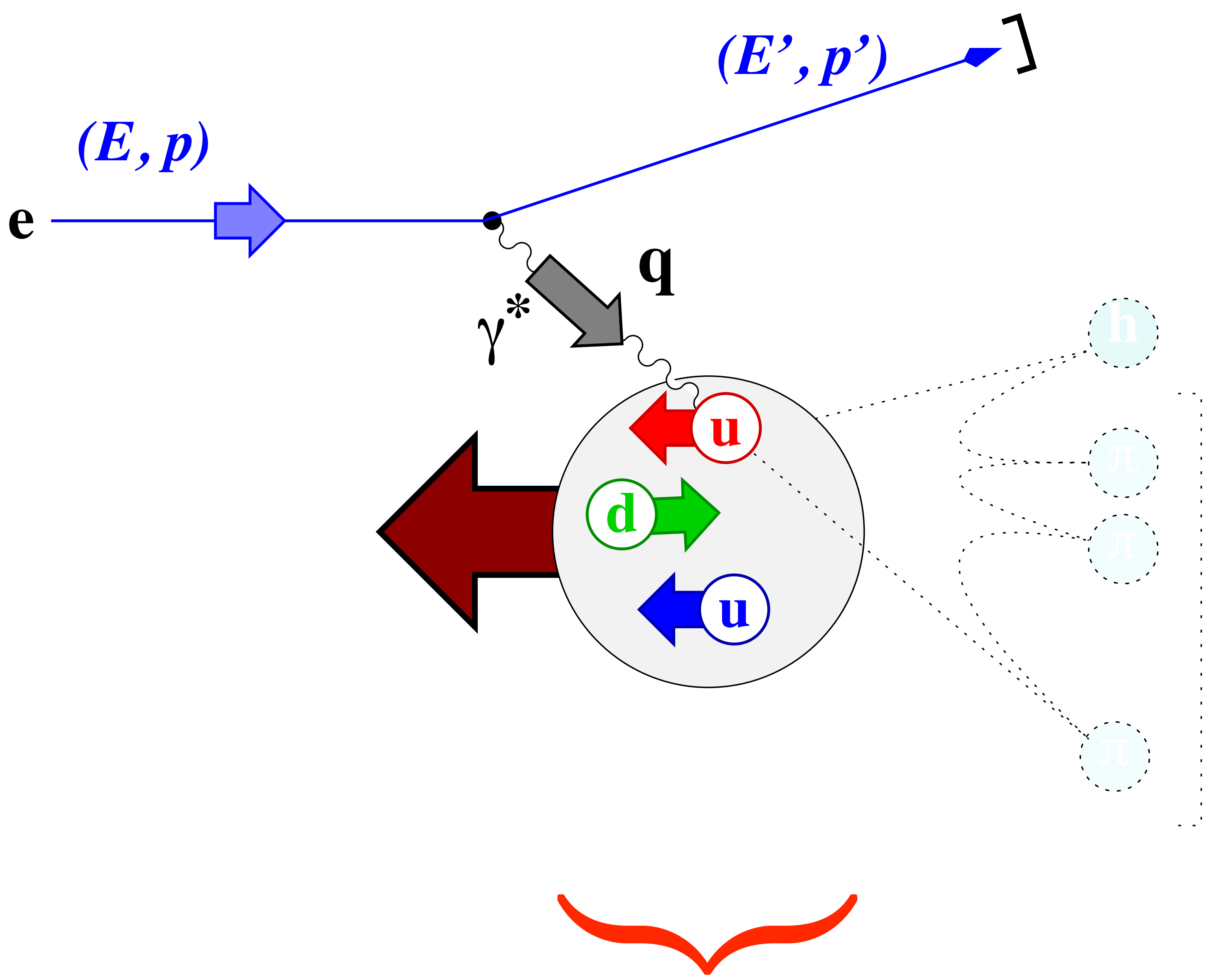
Gunar.Schnell @ DESY.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Deep-inelastic scattering

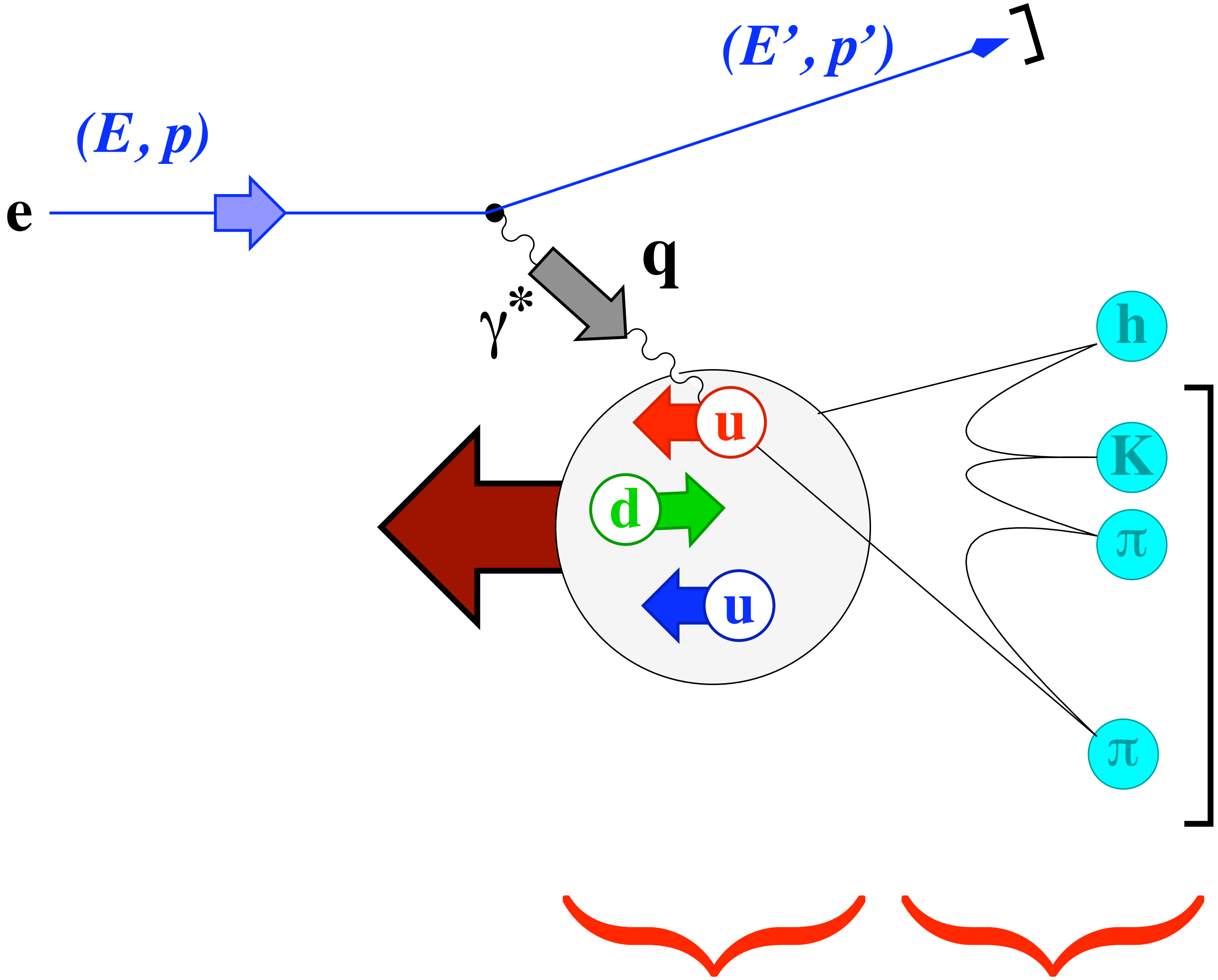
inclusive



factorization:

parton distributions

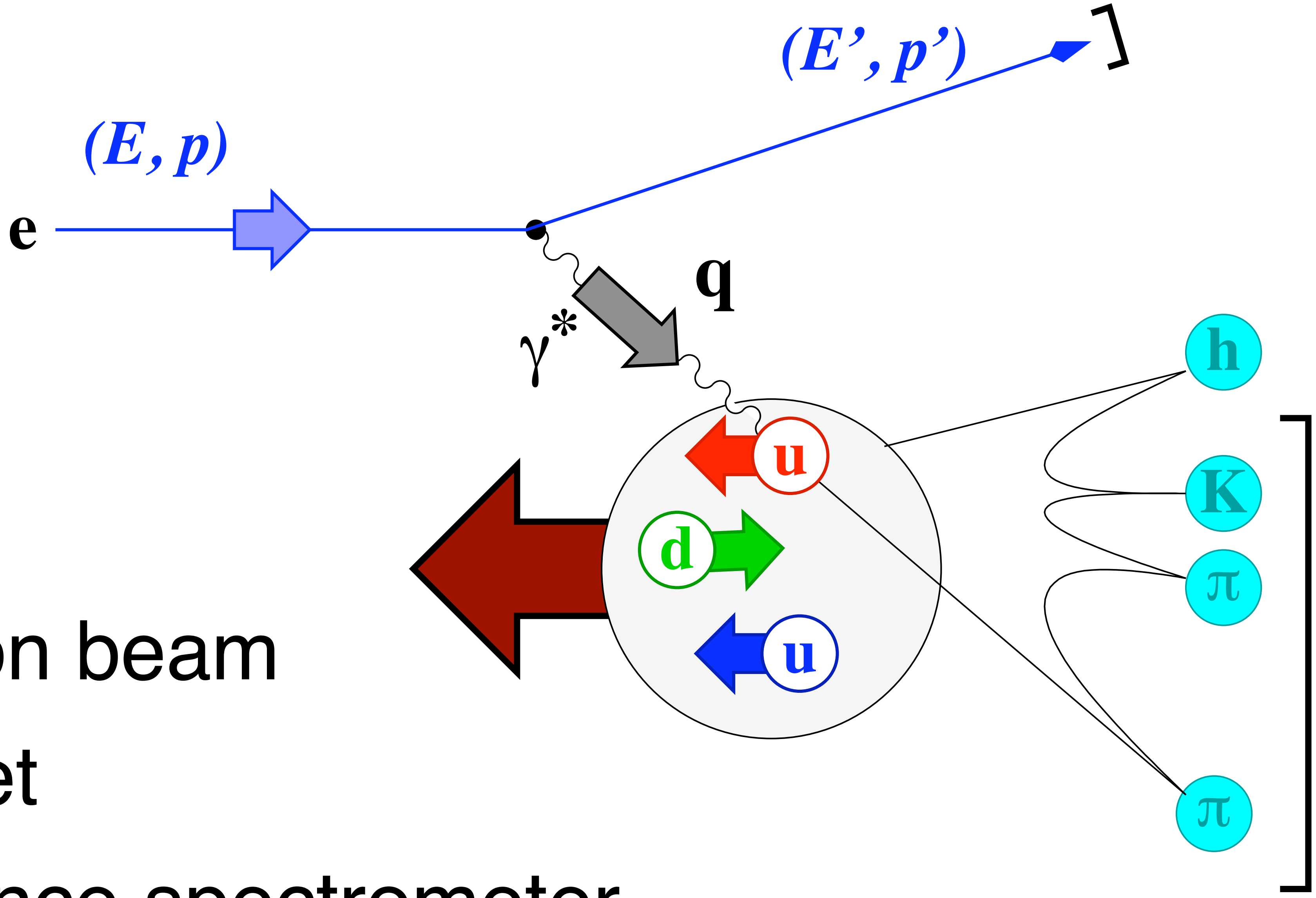
Deep-inelastic scattering



semi-inclusive

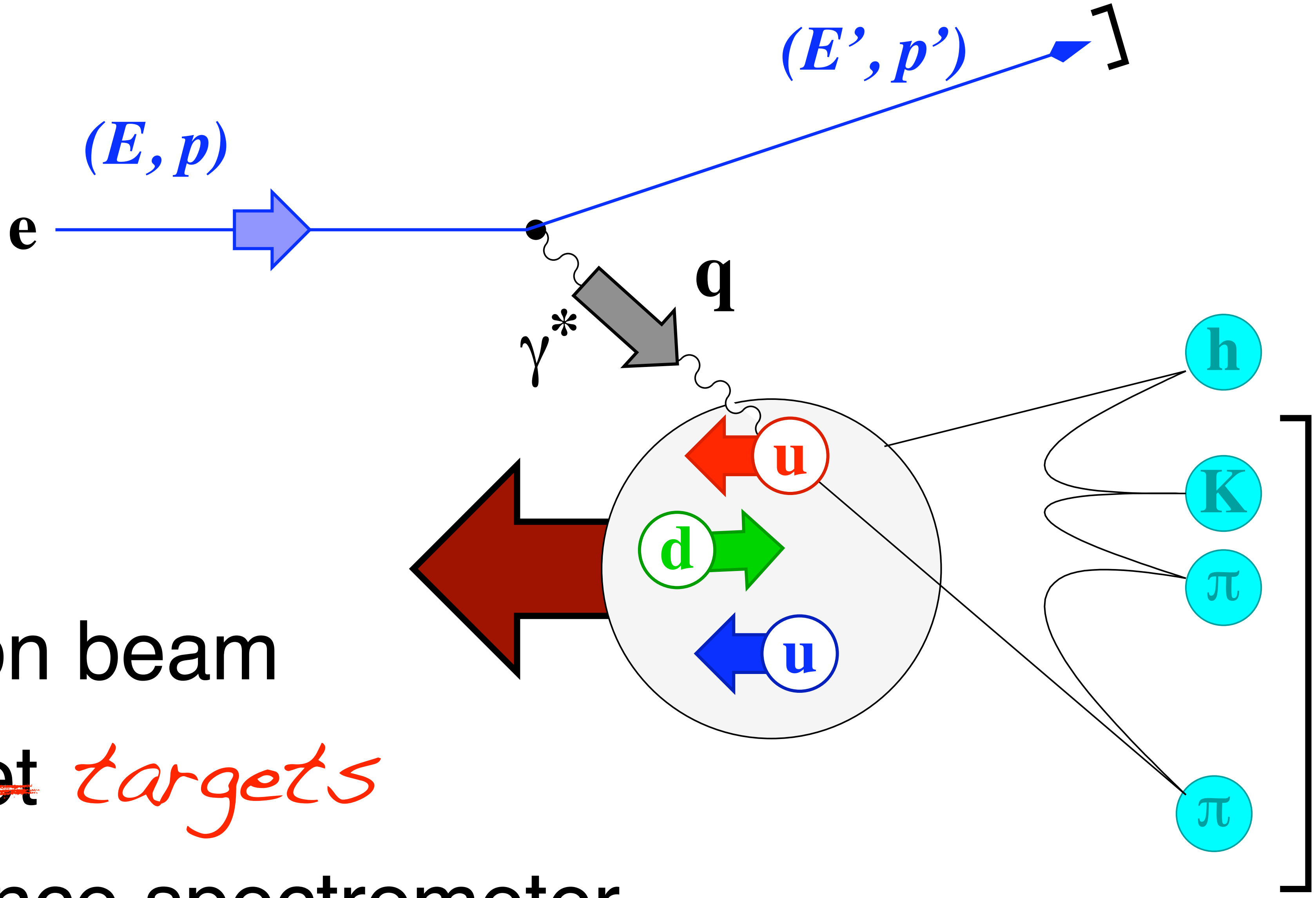
factorization: parton distributions fragmentation functions

Experimental Prerequisites



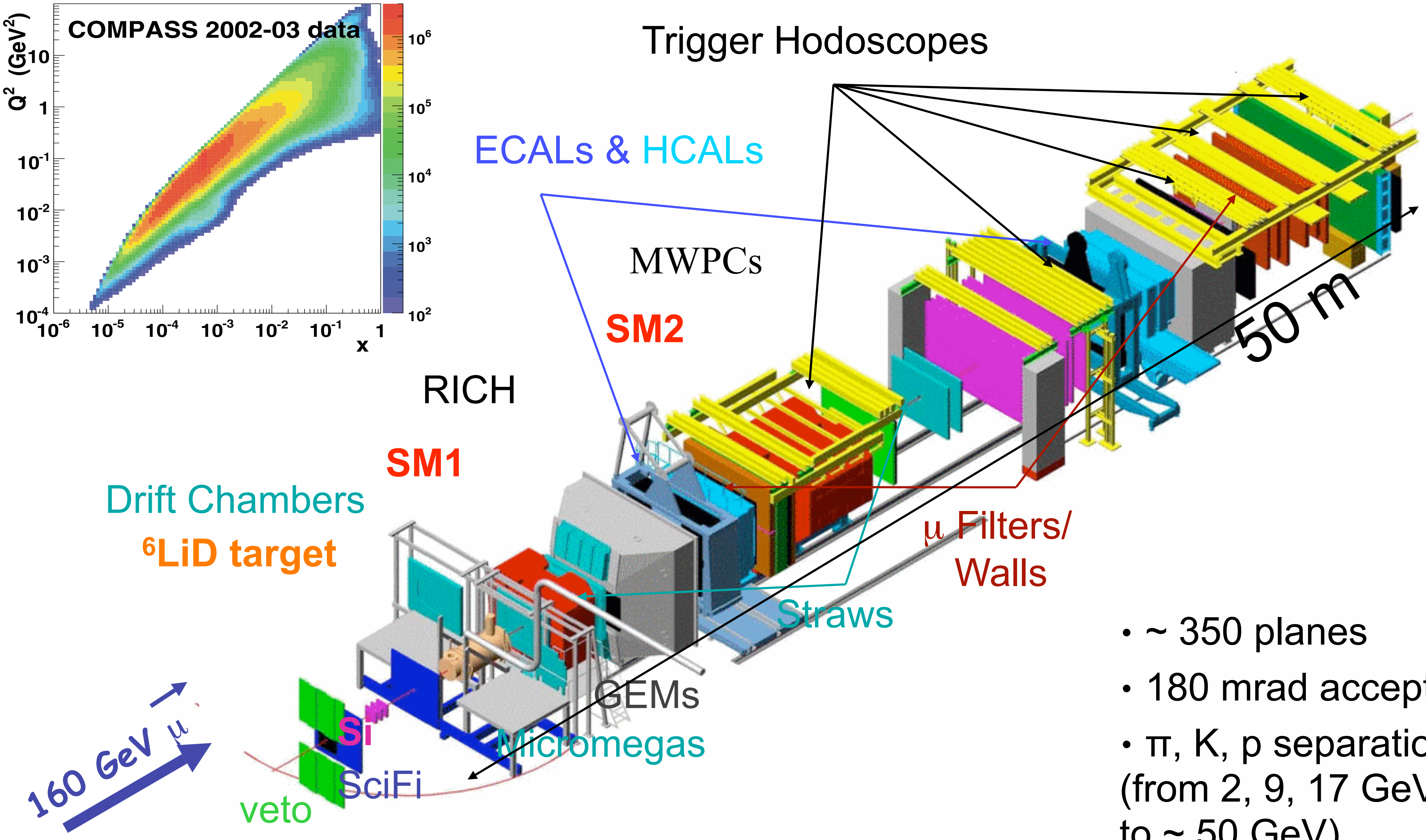
- Polarized lepton beam
- Polarized target
- Large acceptance spectrometer
- Good Particle IDentification (PID)

Experimental Prerequisites



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

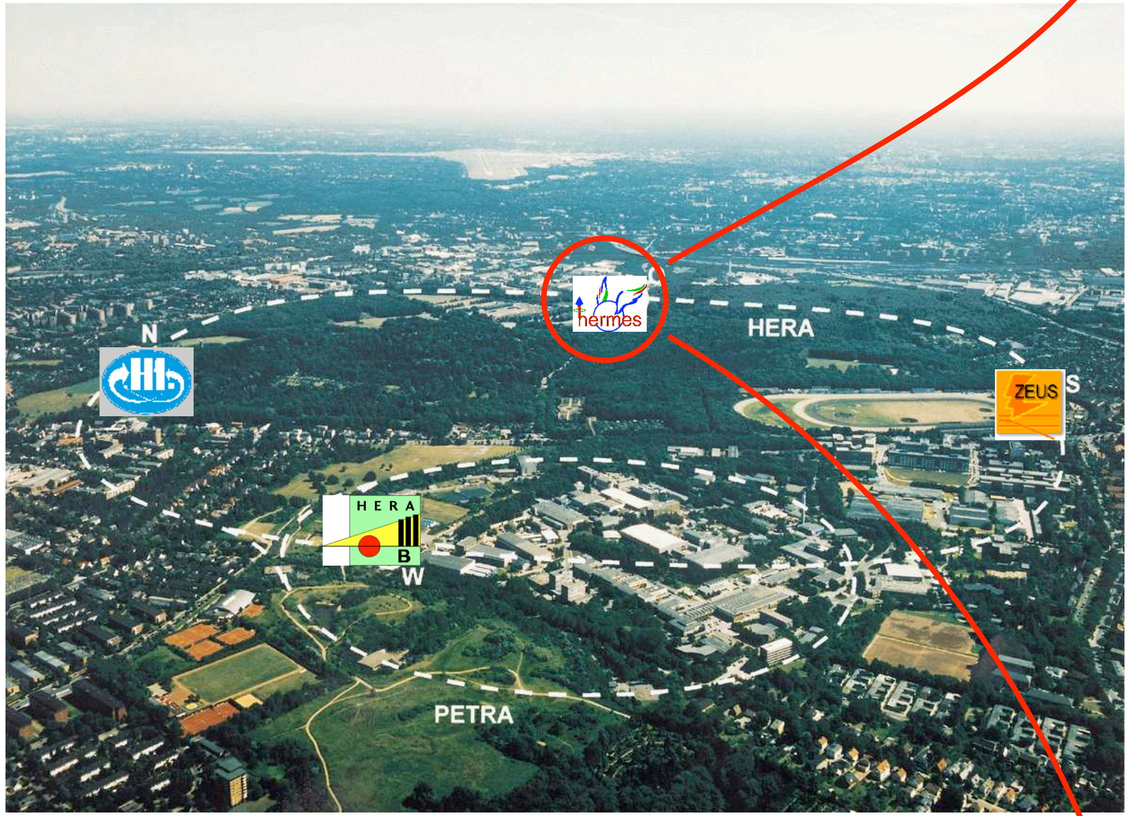
The COMPASS experiment @ CERN

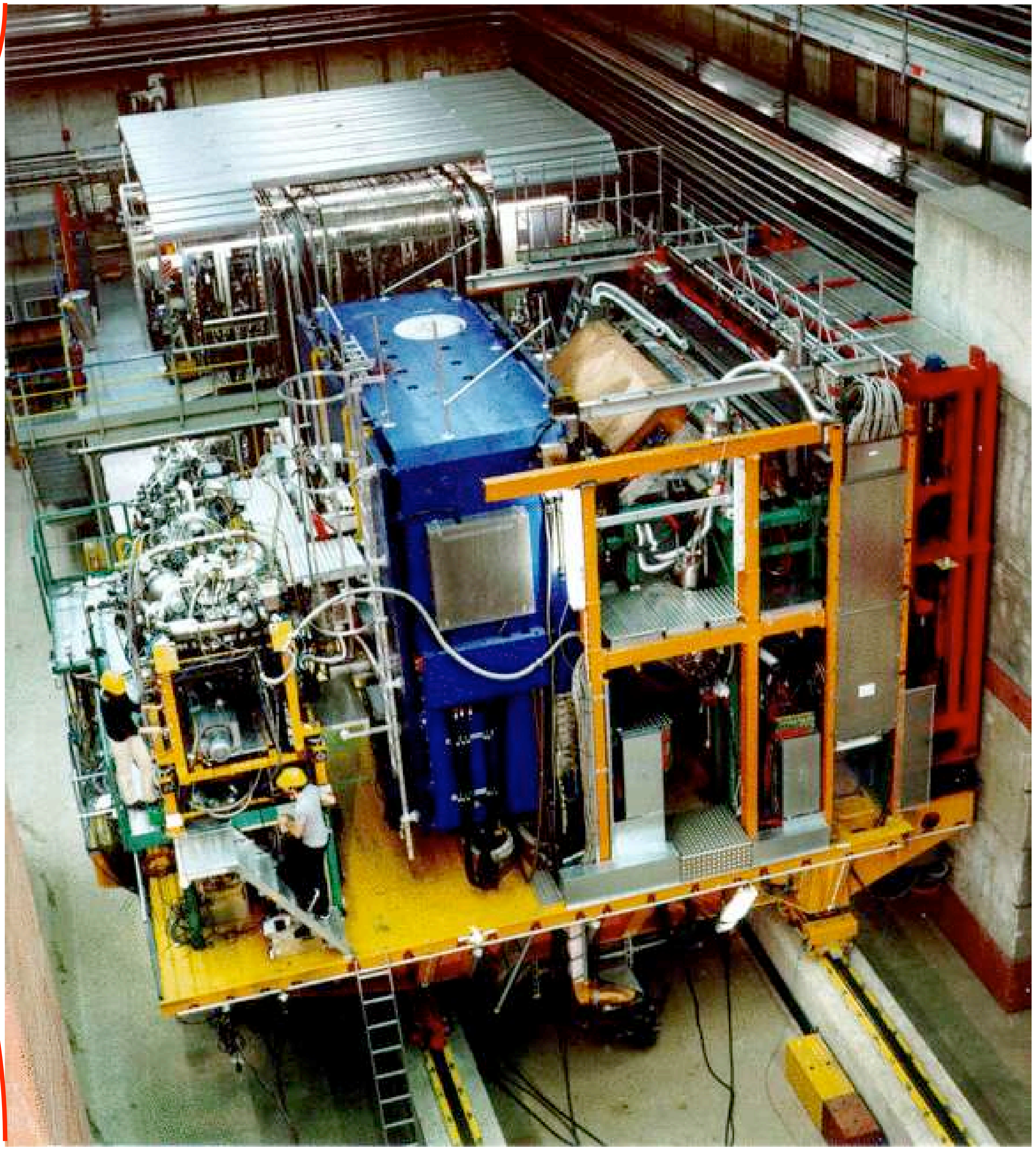


- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

HERMES Experiment (†2007) @ DESY

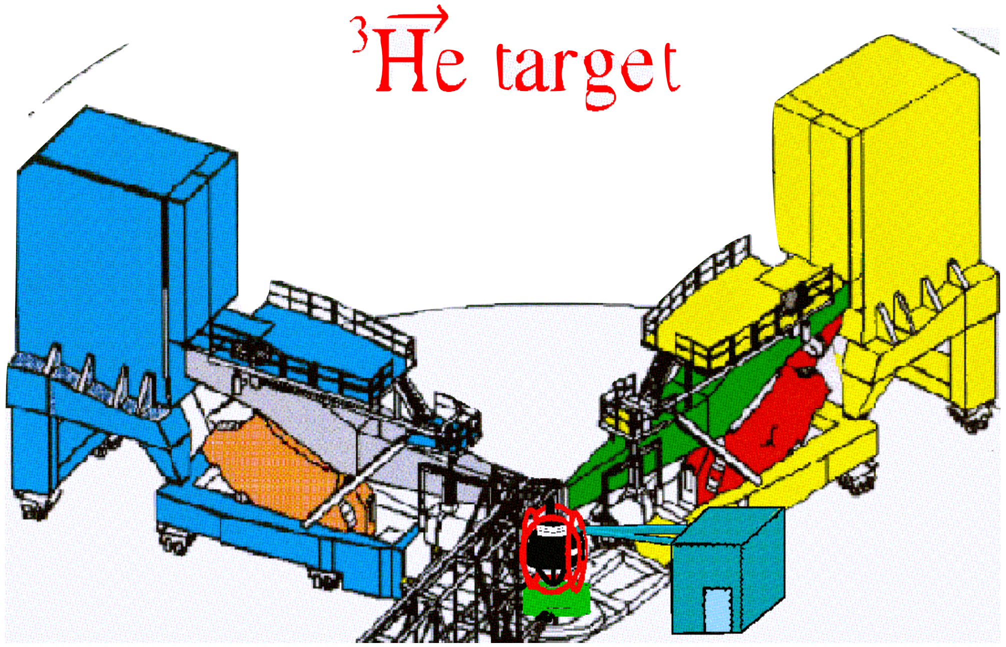
27.6 GeV polarized e^+/e^- beam scattered off ...

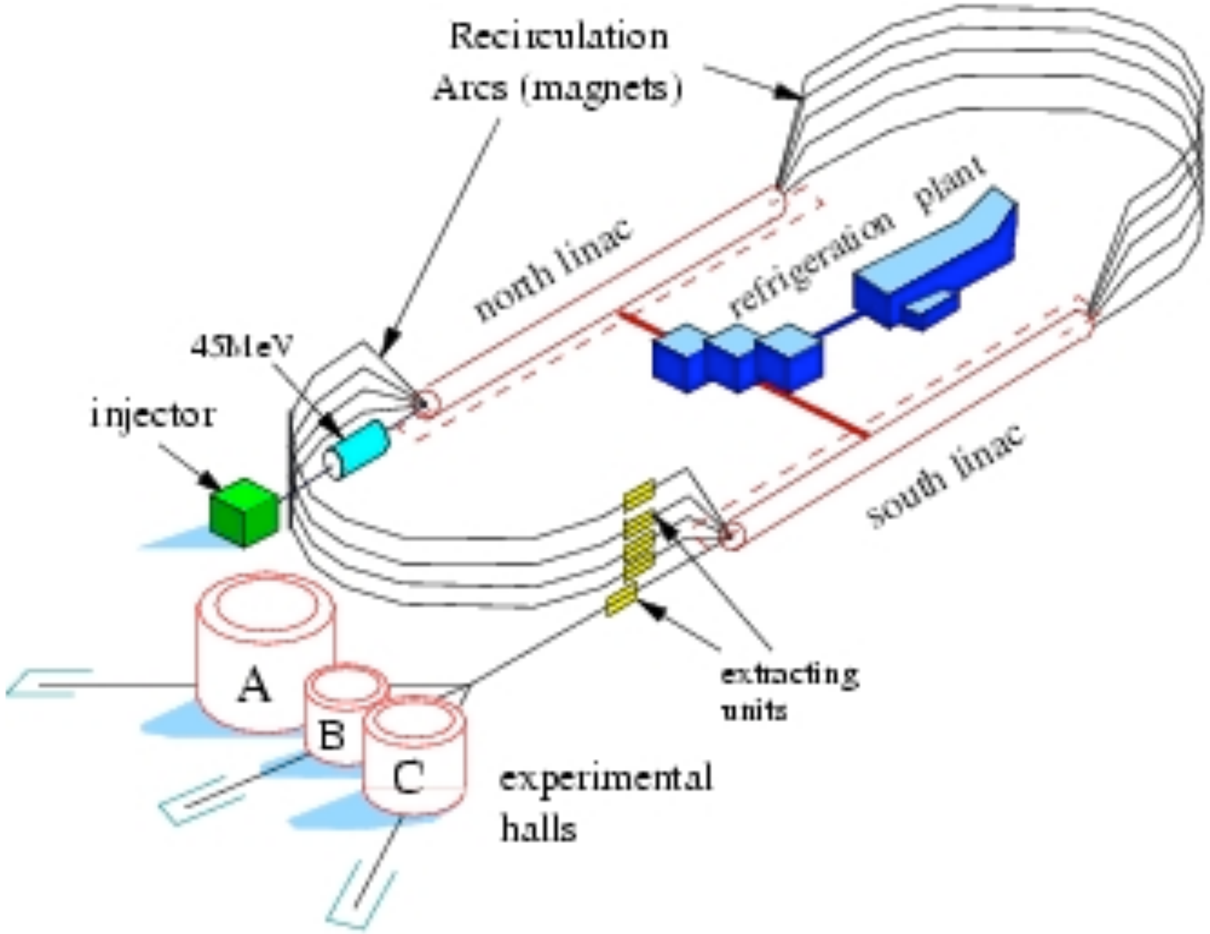




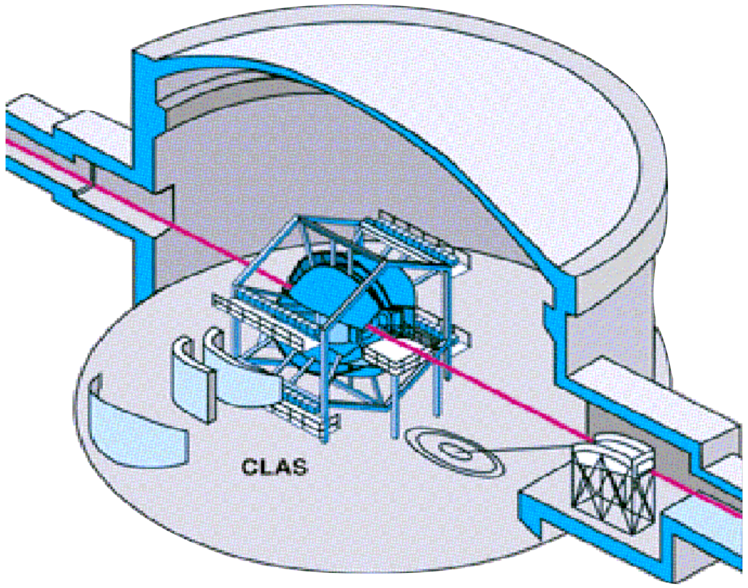
unpolarized (H, D, He,..., Xe) as well as **transversely (H)** and longitudinally (H, D, He) polarized (pure) gas targets

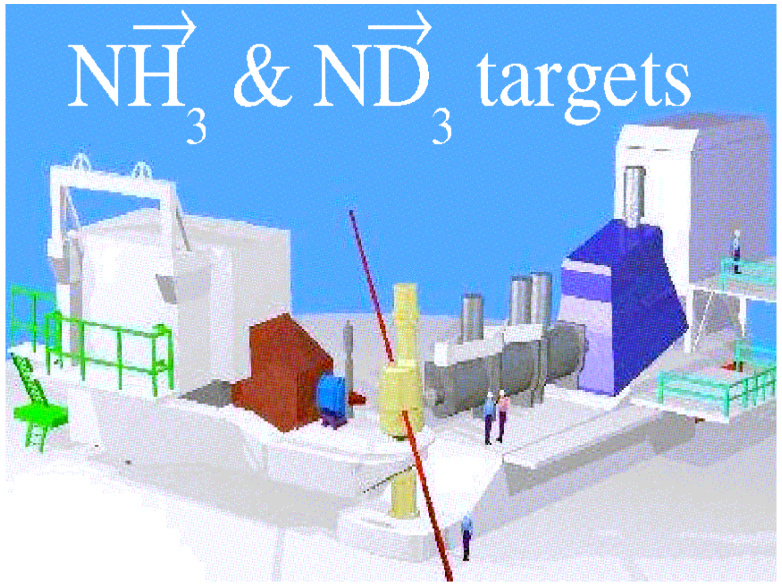
6GeV e^- @ Jefferson Lab



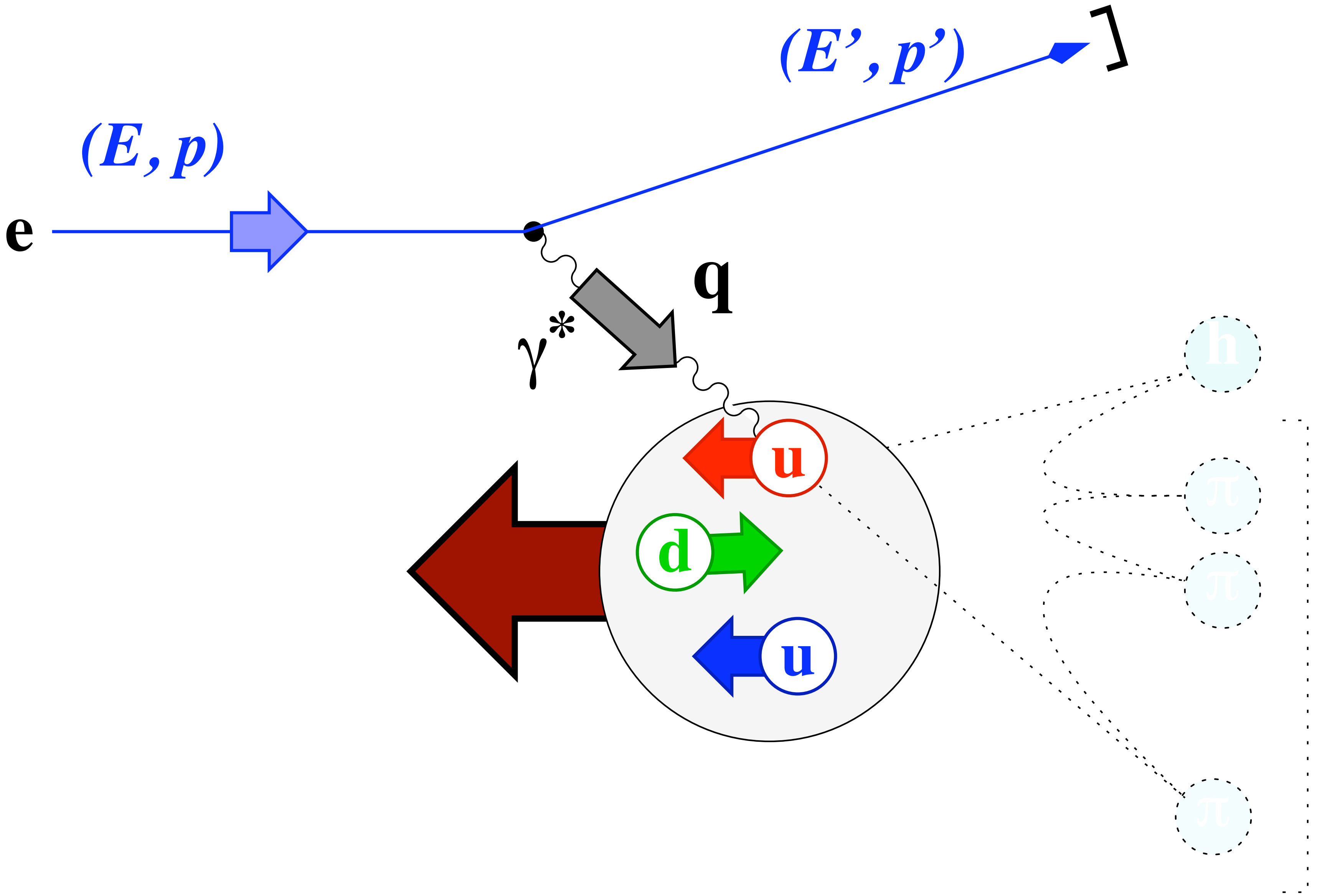


$\vec{\mathrm{NH}}_3$ & $\vec{\mathrm{ND}}_3$ targets



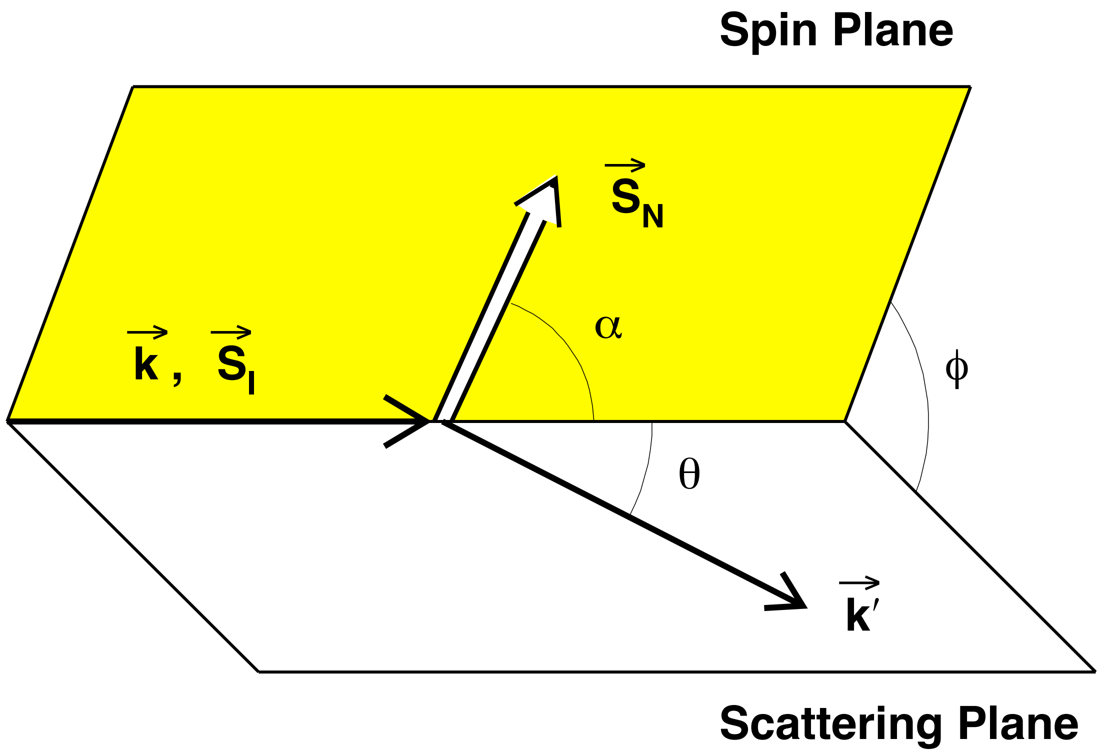


Inclusive DIS



Inclusive DIS (one-photon exchange)

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



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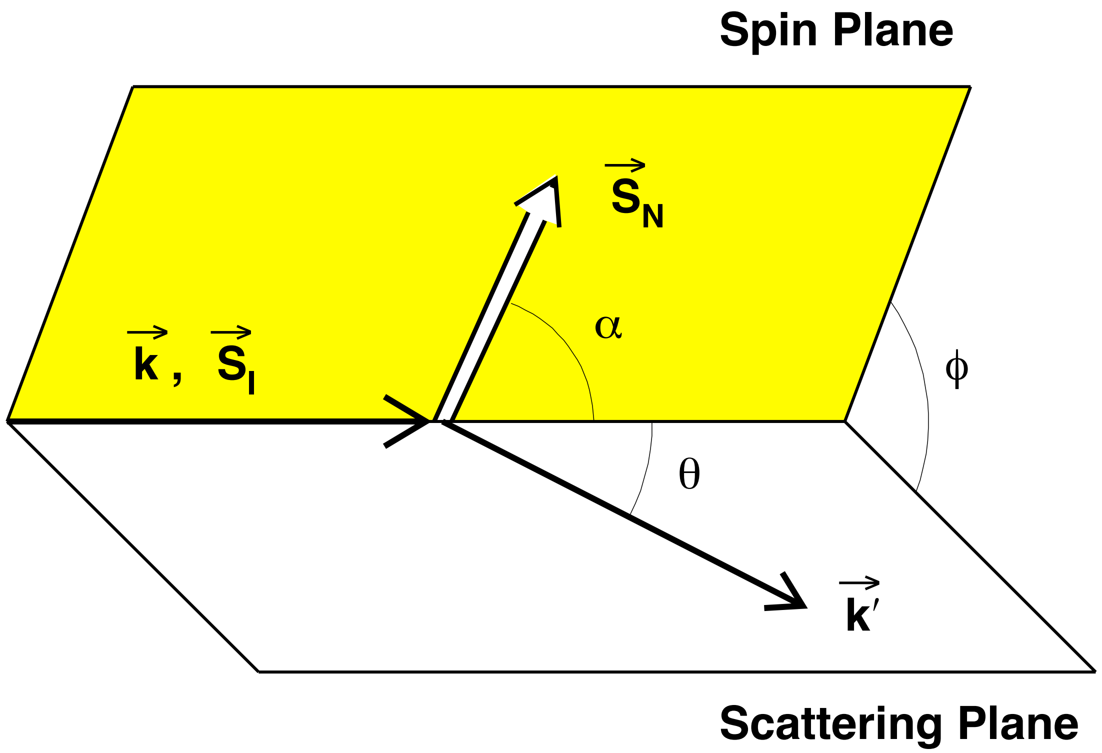
Lepton Tensor



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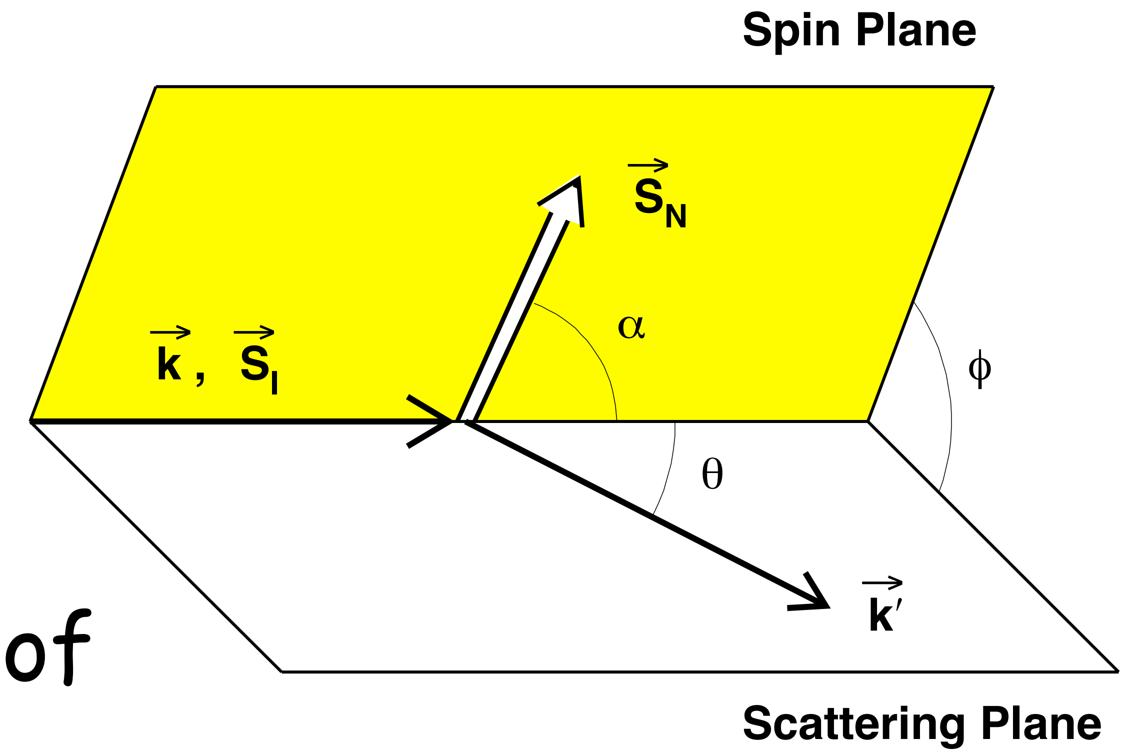
Lepton Tensor

Hadron Tensor
parametrized in terms of
Structure Functions



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Lepton Tensor

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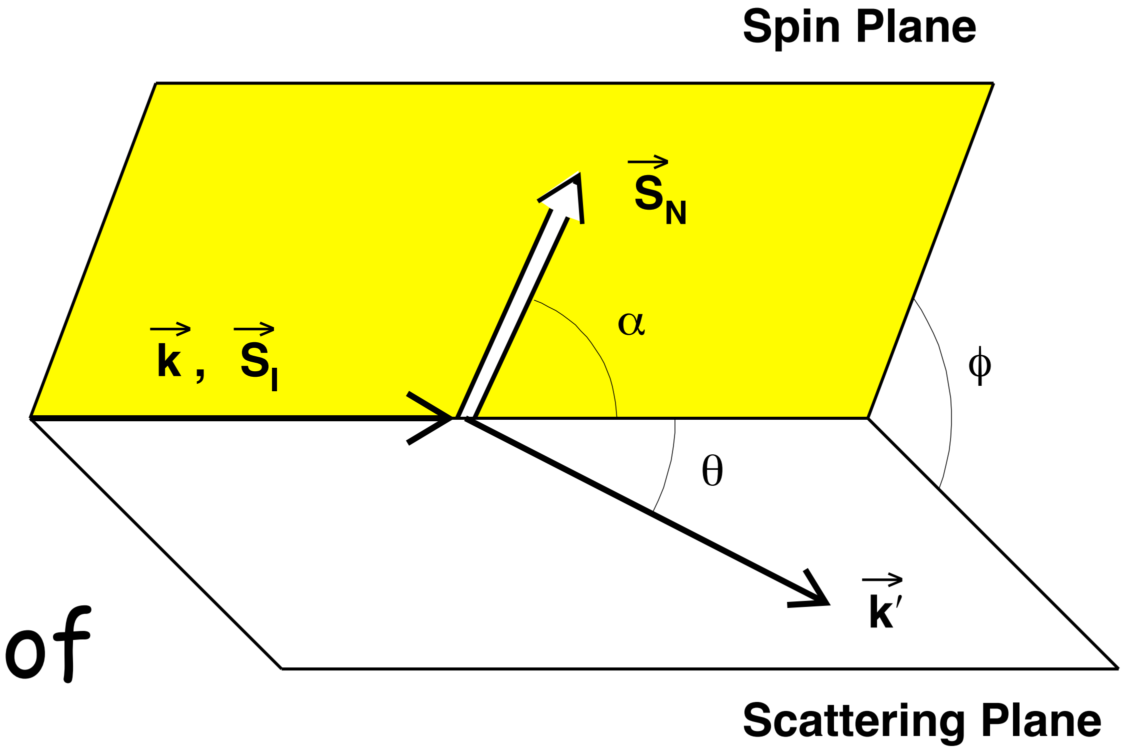


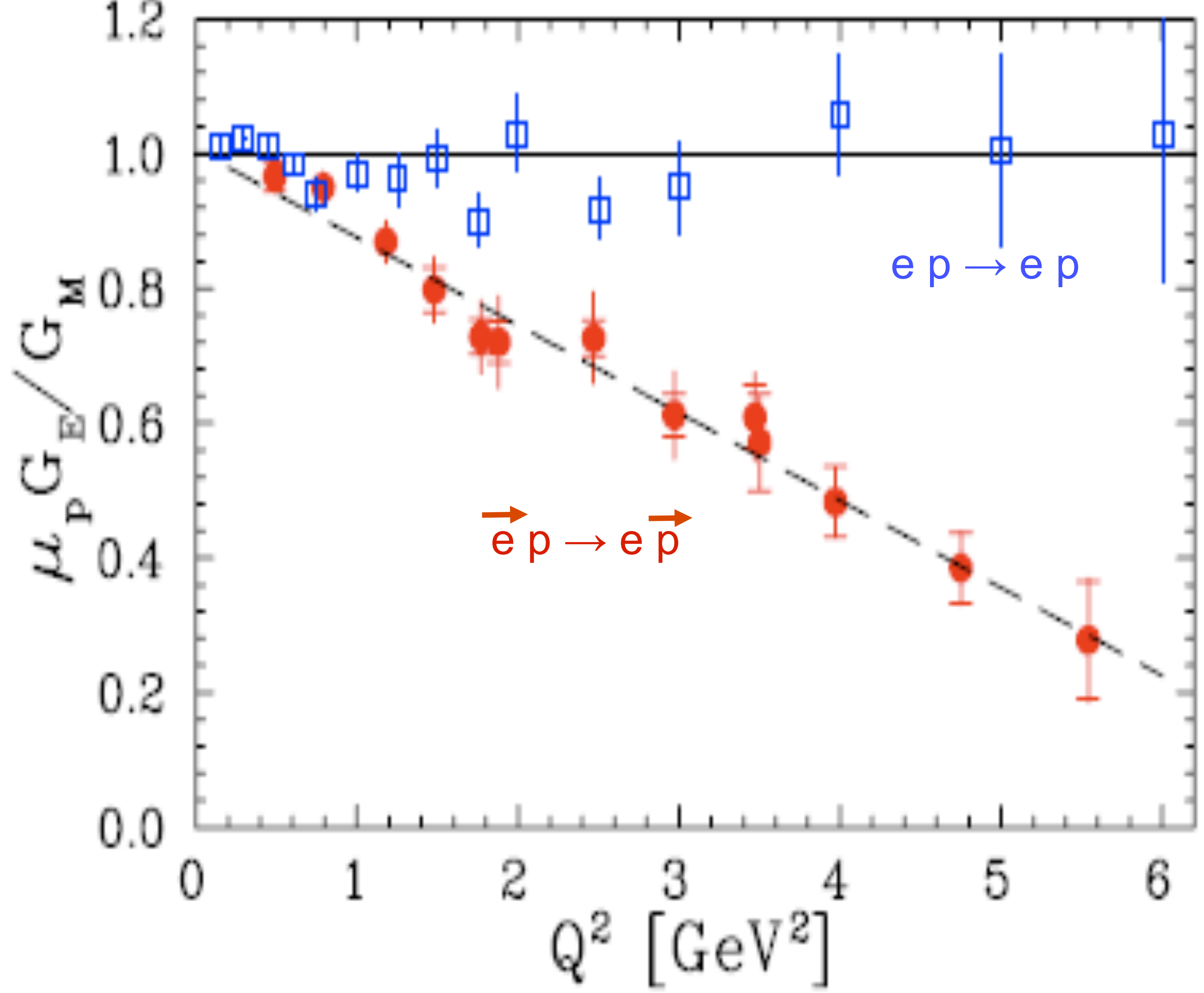
$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$

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

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

Check the details!

[PRC 68, 034325 (2003)]

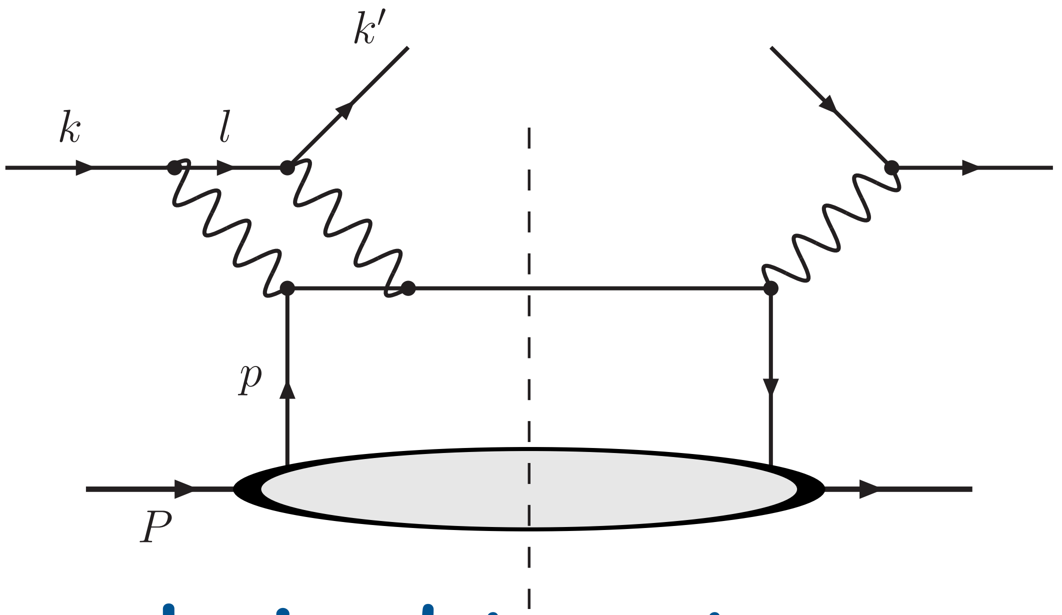


x_F

☛ two-photon exchange can be important!

Two-photon exchange

- candidate to explain discrepancy in form-factor measurements



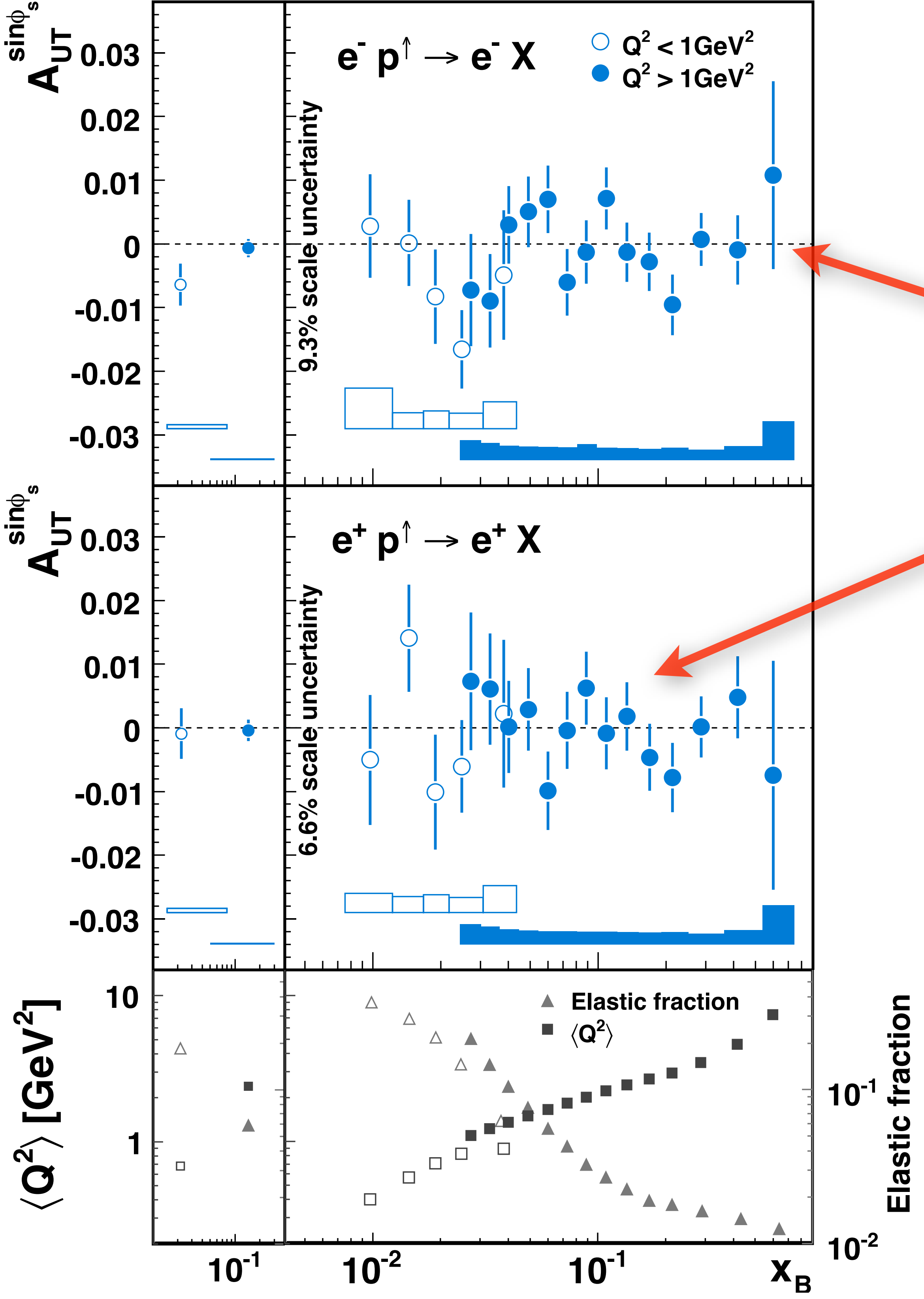
- **interference** between one- and two-photon exchange amplitudes leads to **SSAs in inclusive DIS off transversely polarized targets**

- 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^-
in case of protons

Signatures of two-photon exchange

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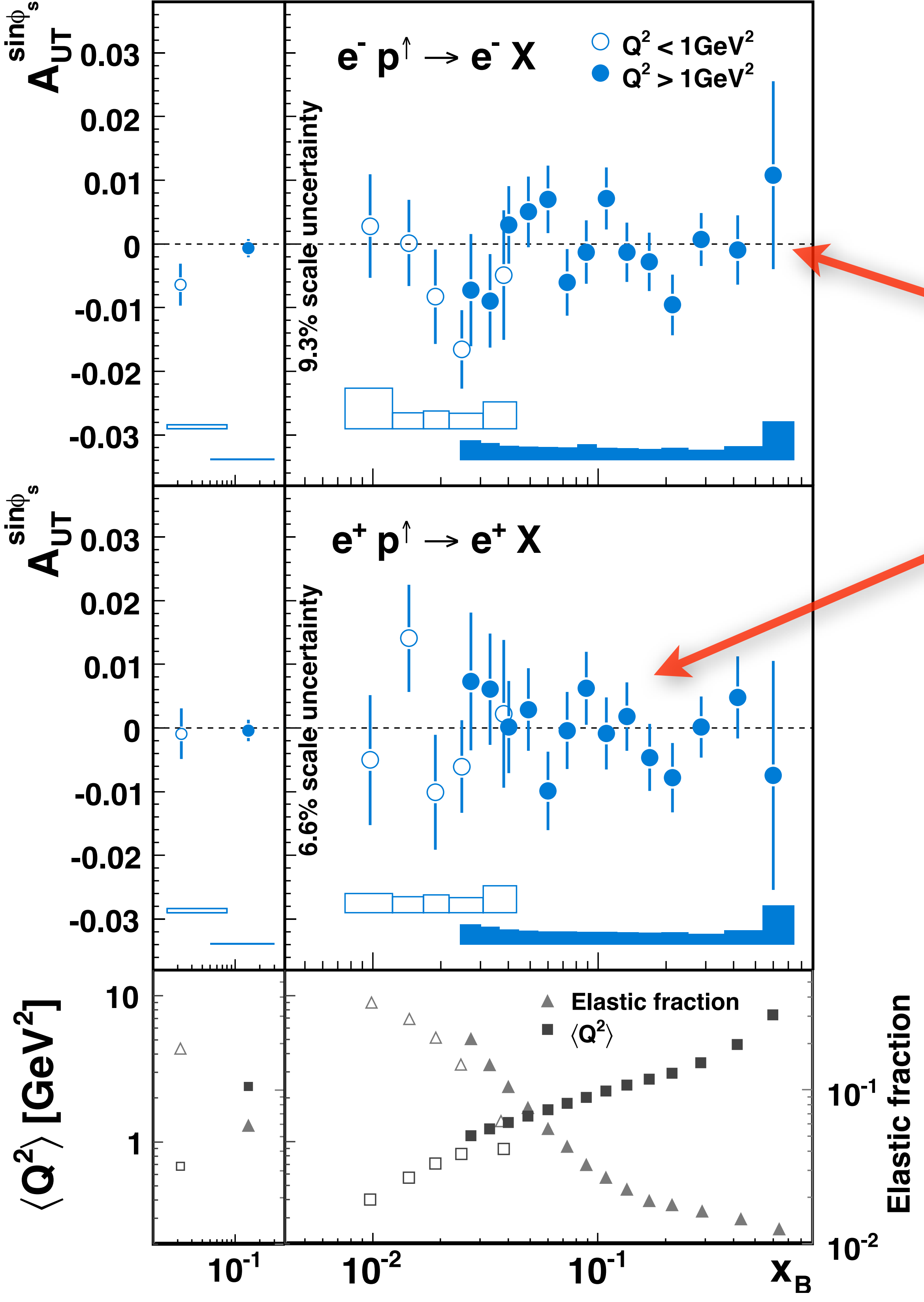

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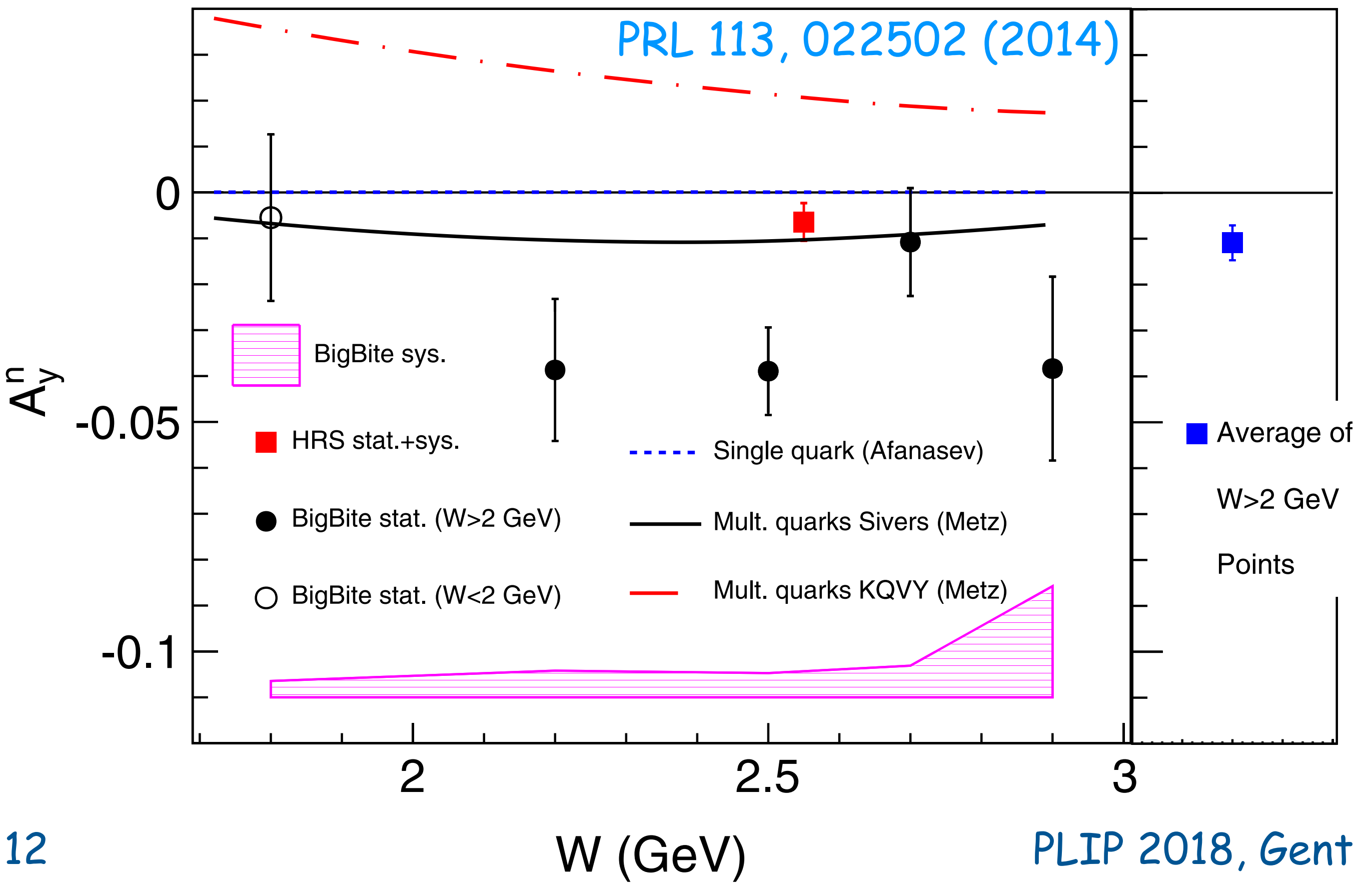
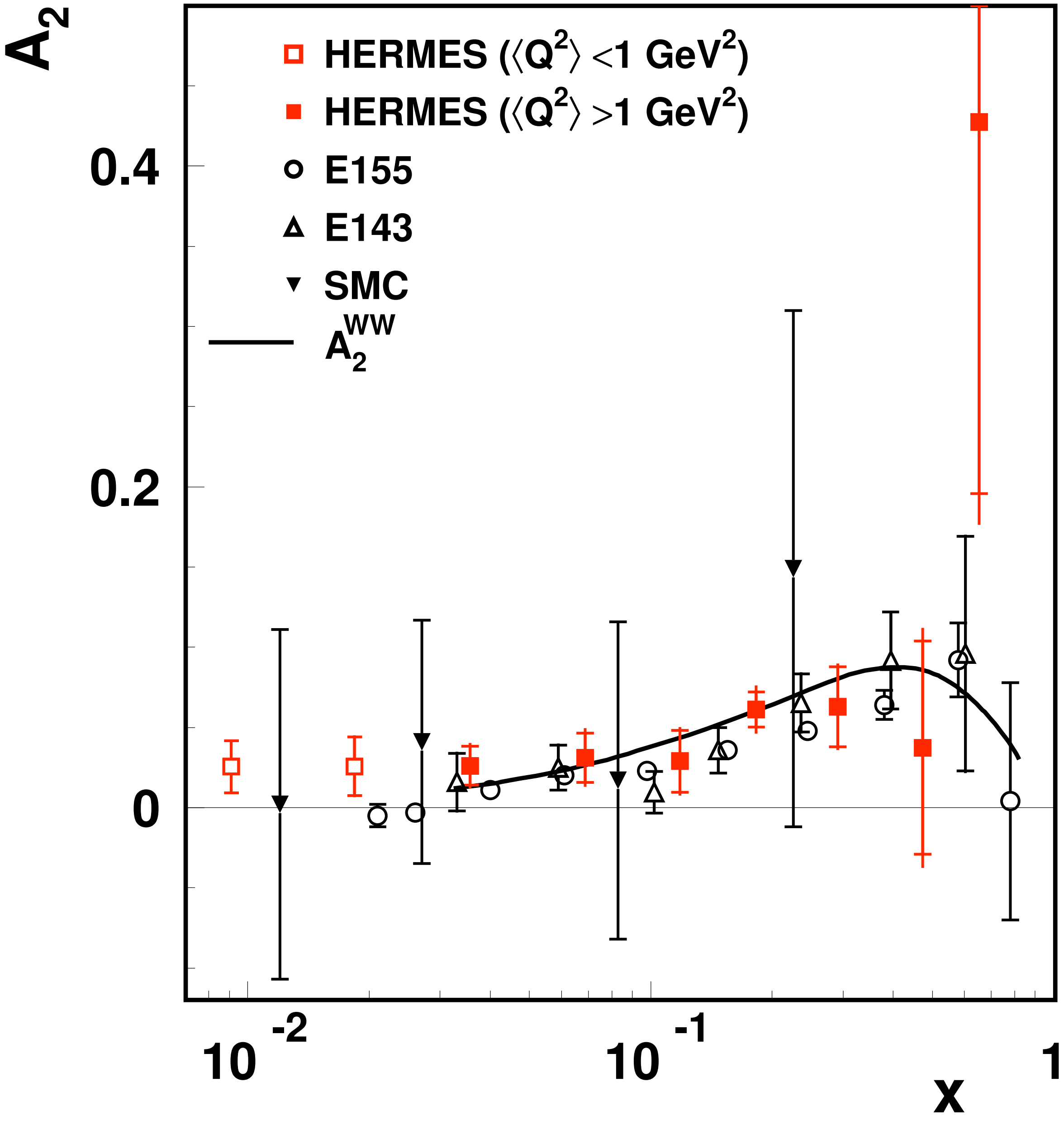
consistent with
zero for both e^+/e^-
in case of protons

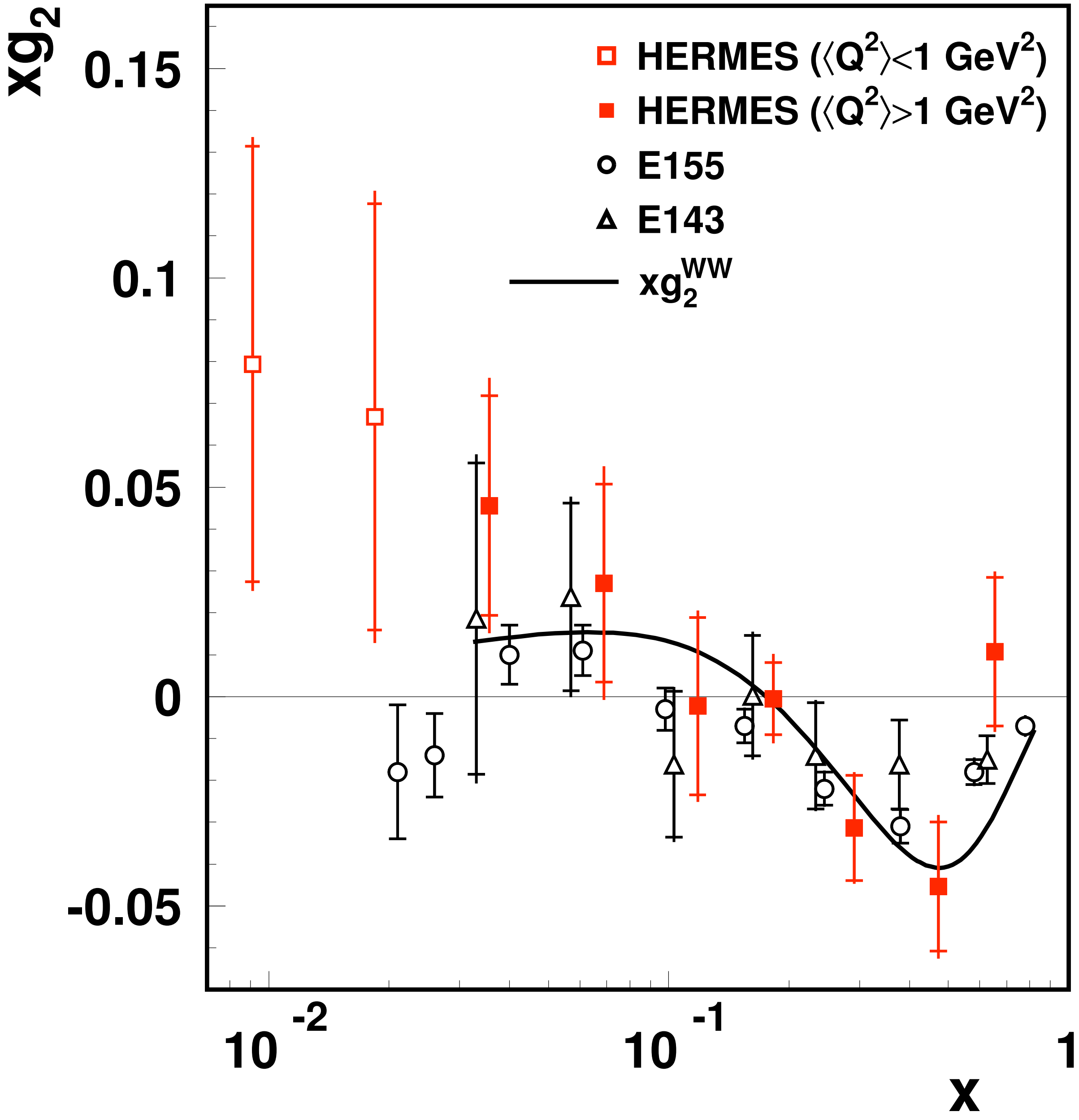
non-zero for neutrons!


PRL 113, 022502 (2014)

… the other polarized SF …

A_2 and xg_2 on the proton

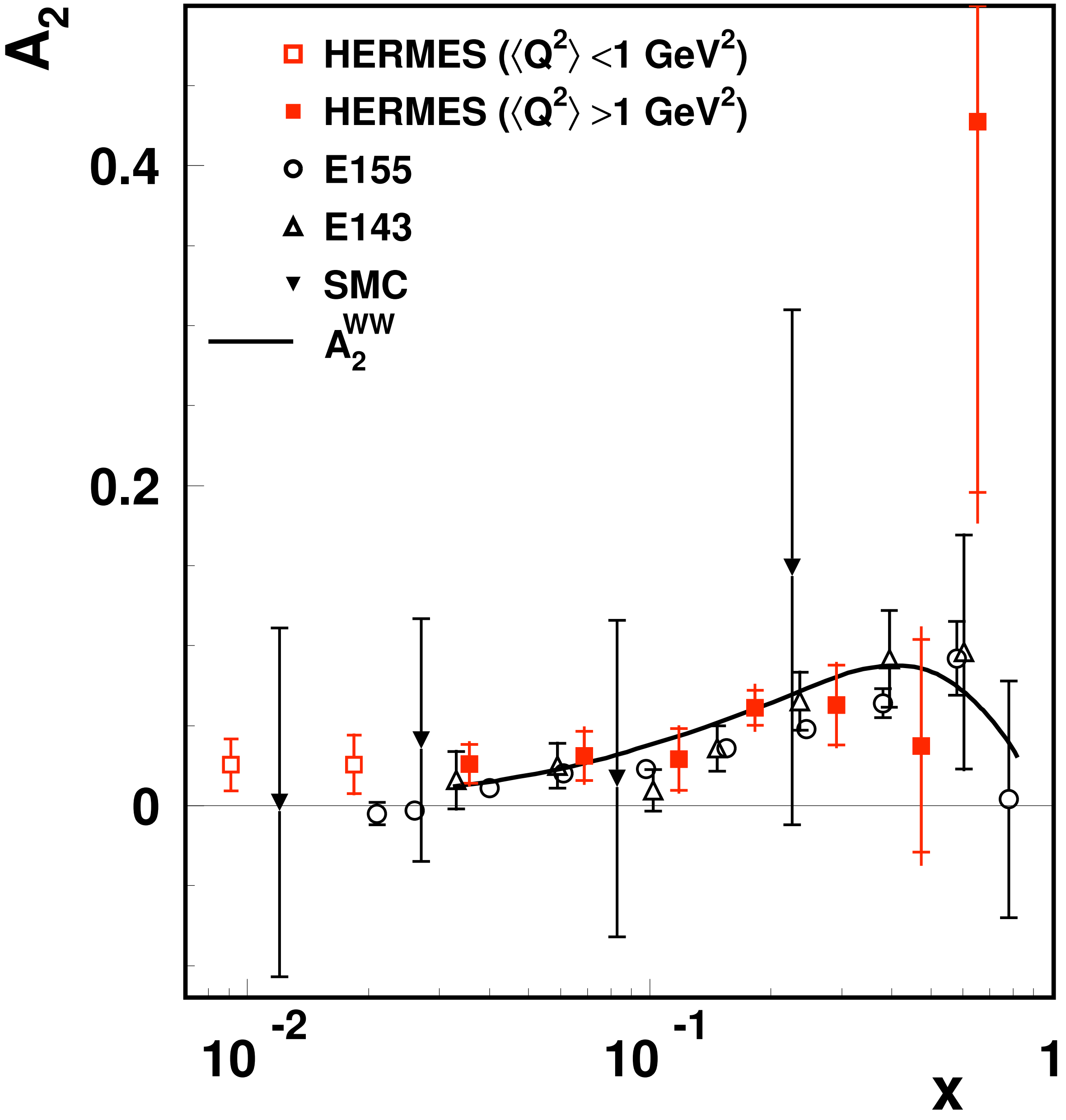

A. Airapetian et al., EPJ C72 (2012) 1921


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.

A_2 and xg_2 on the proton

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



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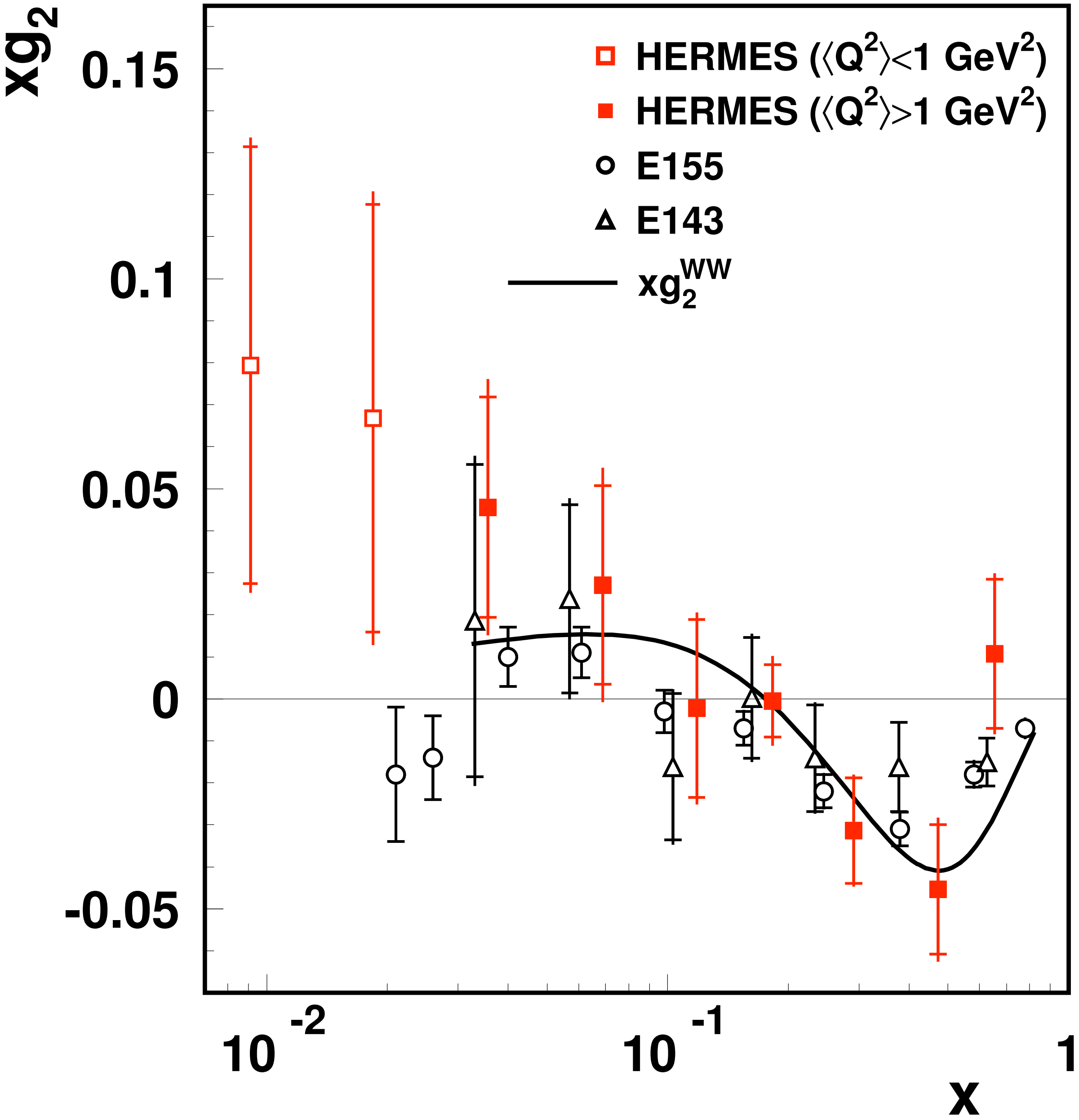
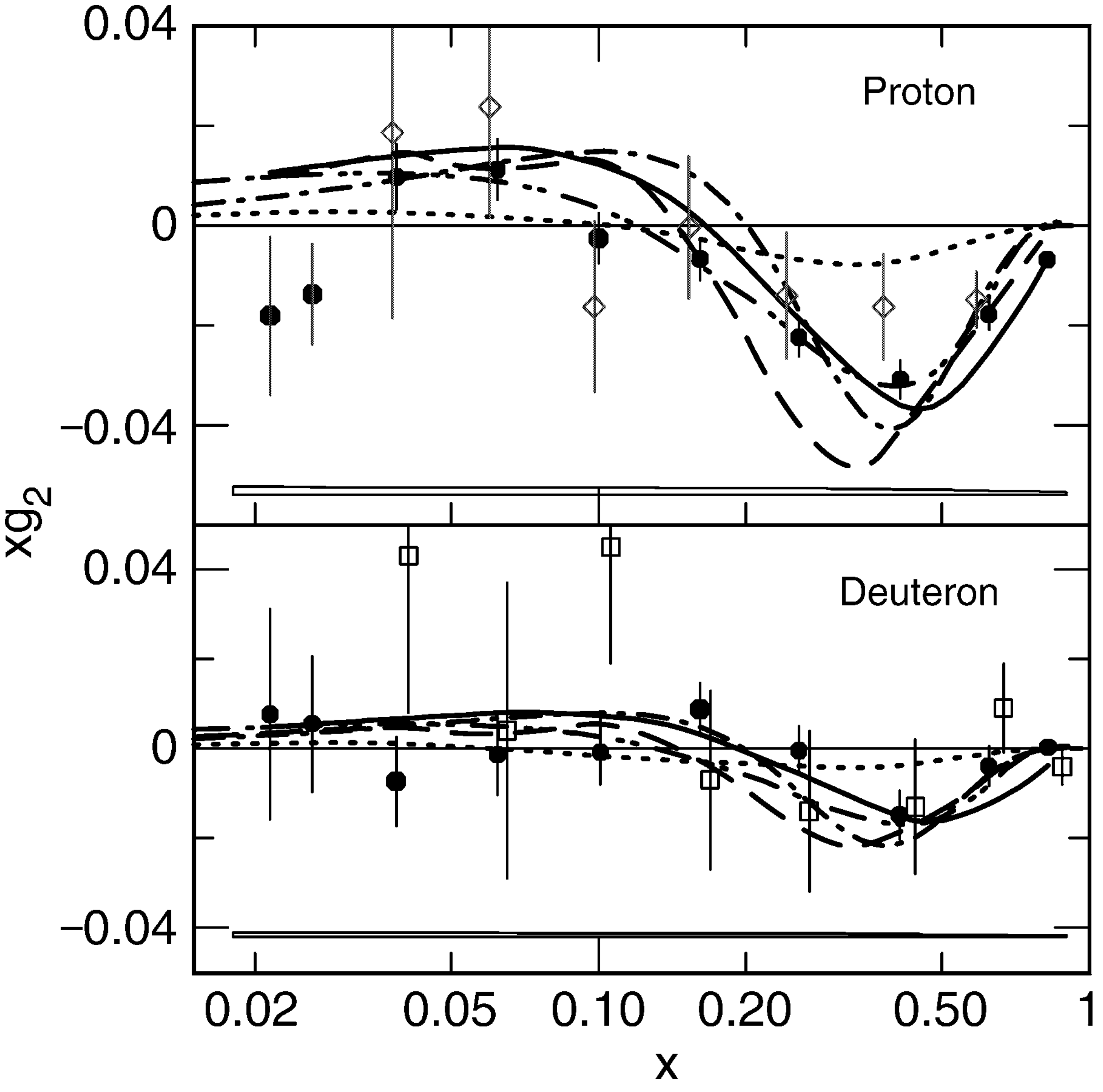


$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \begin{cases} \mathbf{0.006 \pm 0.024_{stat} \pm 0.017_{syst}} & \text{HERMES} \\ \mathbf{-0.042 \pm 0.008} & \text{E143+E155} \end{cases}$$

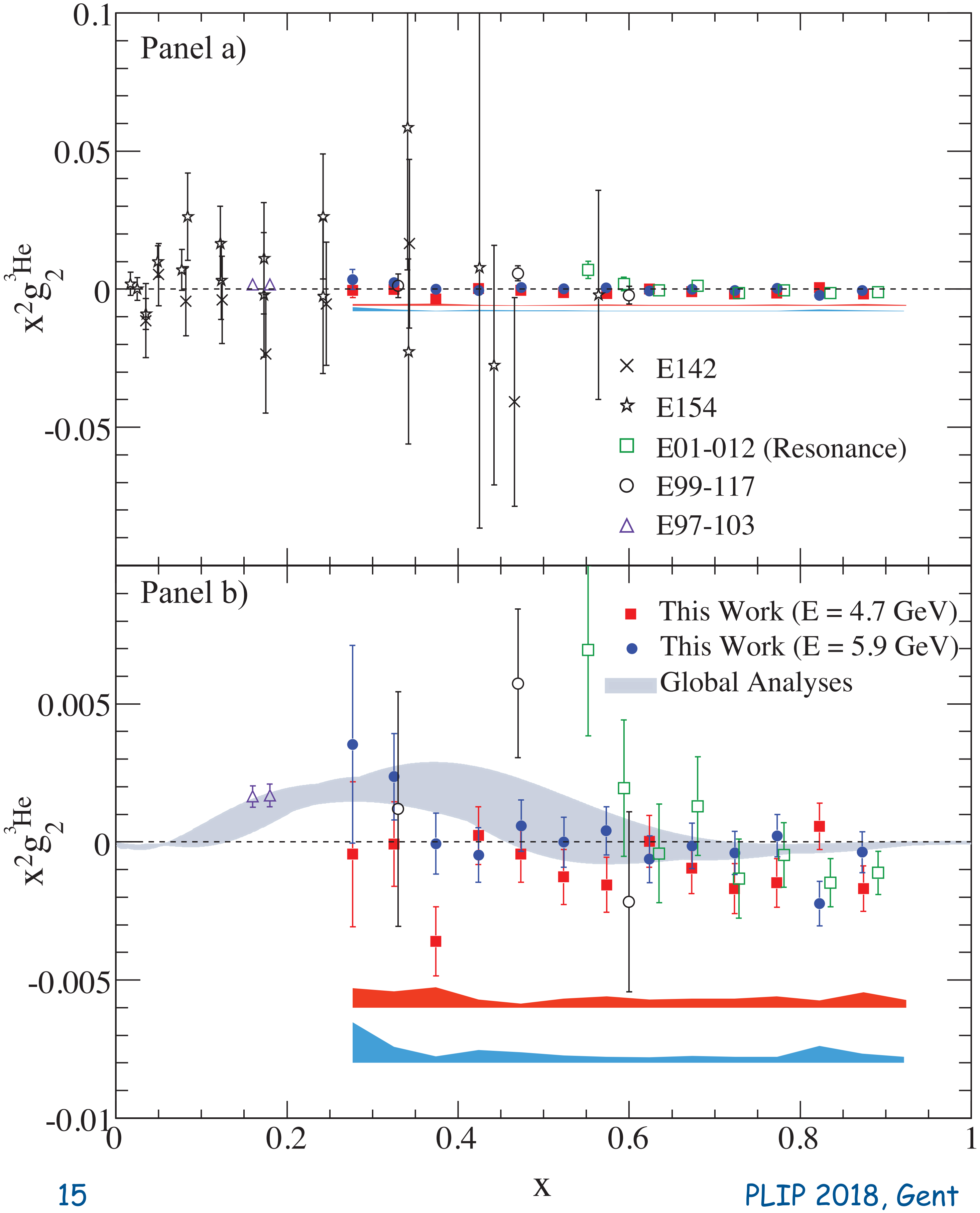
$$\mathbf{d_2(Q^2)} \equiv 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx = \begin{cases} \mathbf{0.0148 \pm 0.0096_{stat} \pm 0.0048_{syst}} & \text{HERMES} \\ \mathbf{0.0032 \pm 0.0017} & \text{E143+E155} \end{cases}$$

… the neutron case

[E155, PLB 553 (2003) 18-24]

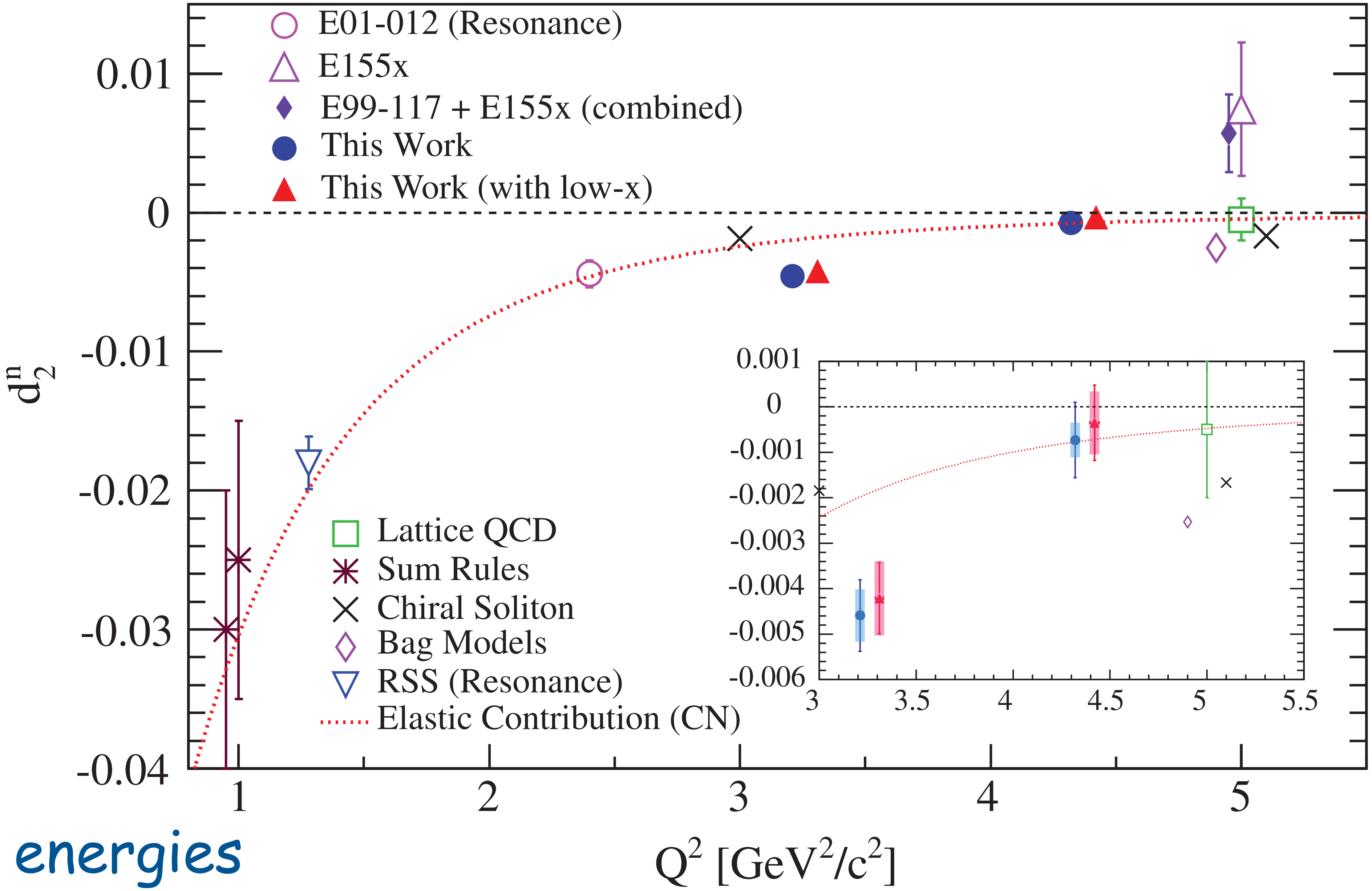


[M. Posik et al., PRL 113, 022002 (2014)]



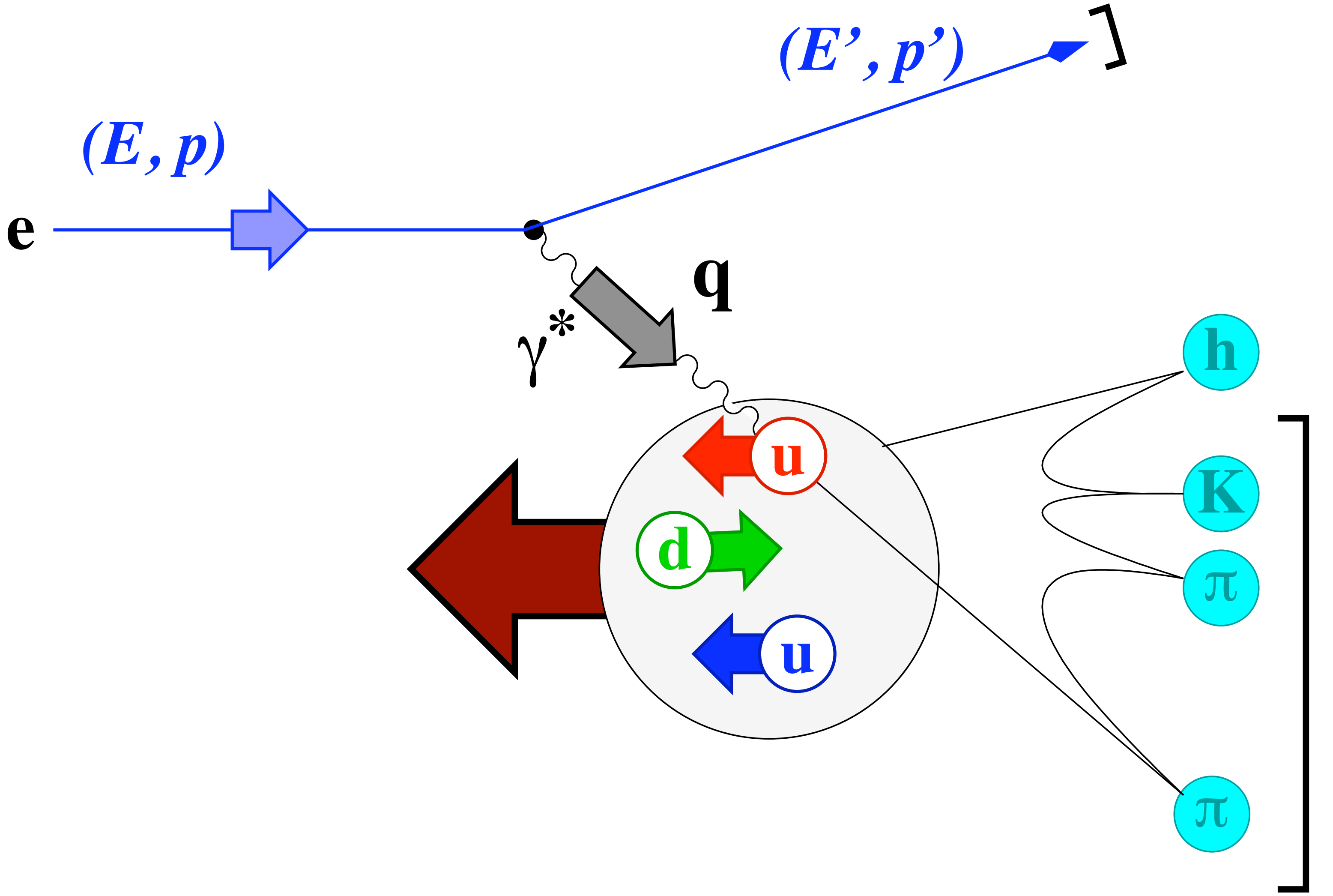
… the neutron case

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



- d_2 sizable at lower energies
  - opposite sign compared to proton case (and SLAC measurements) (expected, e.g., by M. Burkardt, PRD 88, 114502 (2013) due to "instantaneous transverse color force")
- desirable to have more precise large-Q^2 data covering wide x range

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.

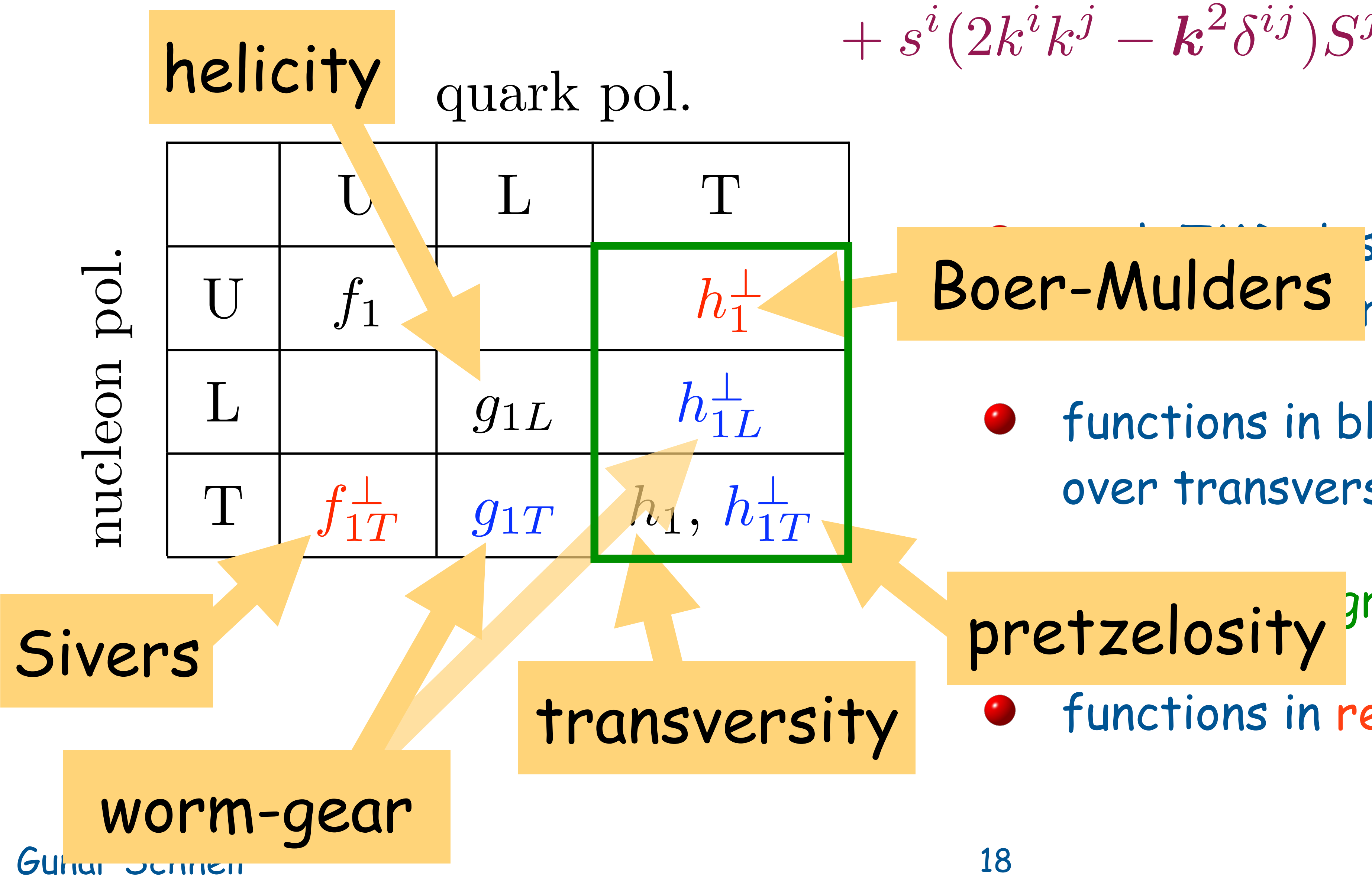
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

- 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

$$\frac{1}{2}\mathrm{Tr}\Big[\left(\gamma^{+}+\lambda\gamma^{+}\gamma_{5}\right)\Phi\Big] \quad = \quad \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + \lambda\Lambda\,g_1 + \lambda\,S^ik^i\,\frac{1}{m}\,g_{1T}\Big]$$

$$\frac{1}{2}\mathrm{Tr}\Big[\left(\gamma^{+}-s^{j}i\sigma^{+j}\gamma_{5}\right)\Phi\Big] \quad = \quad \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_{1}^{\perp} + s^iS^ih_1$$
$$+\,s^i(2k^ik^j-\boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]$$



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

- scribes a particular spin-
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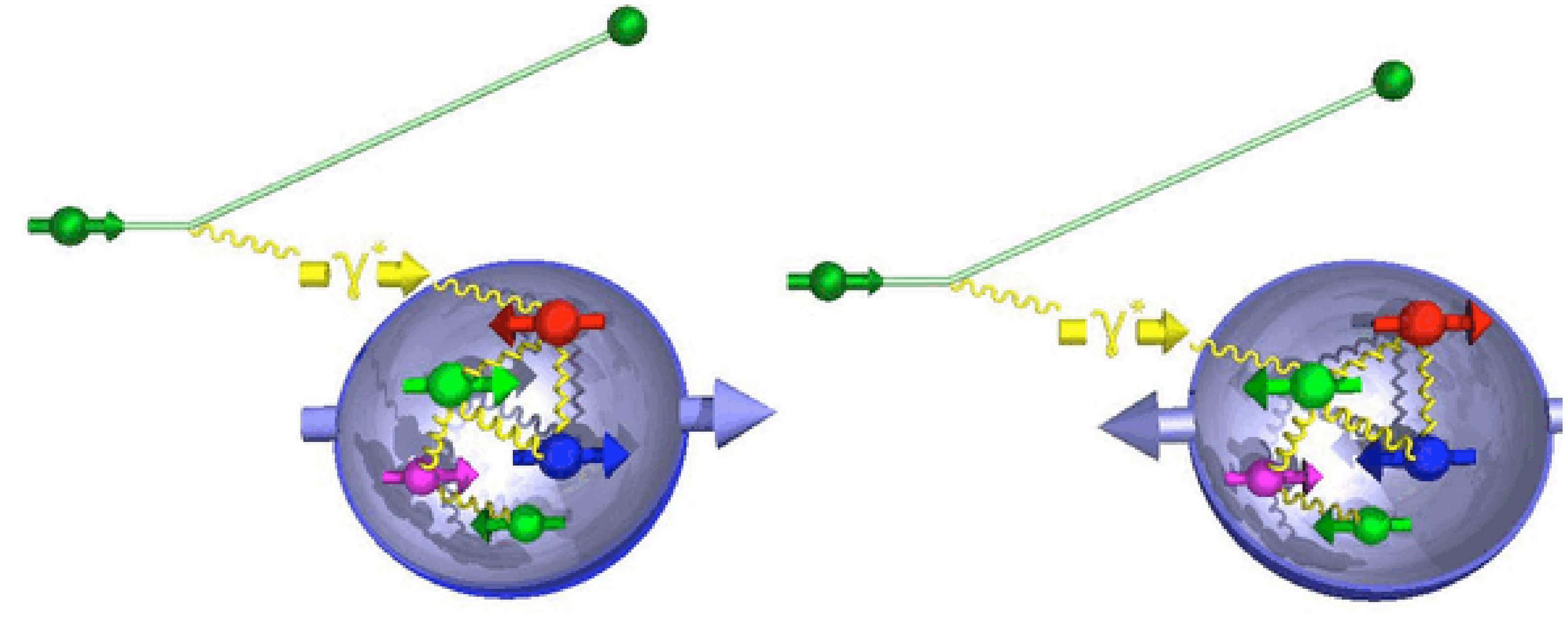
Quark polarimetry

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



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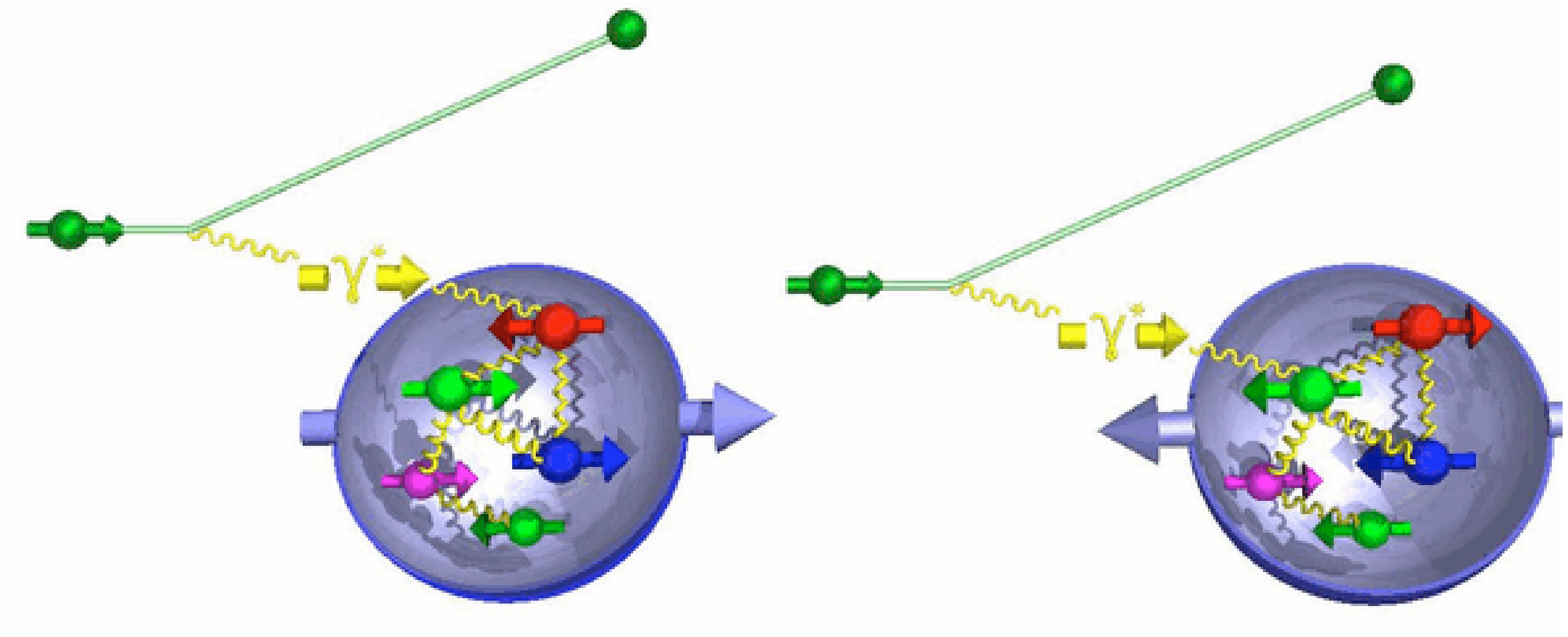
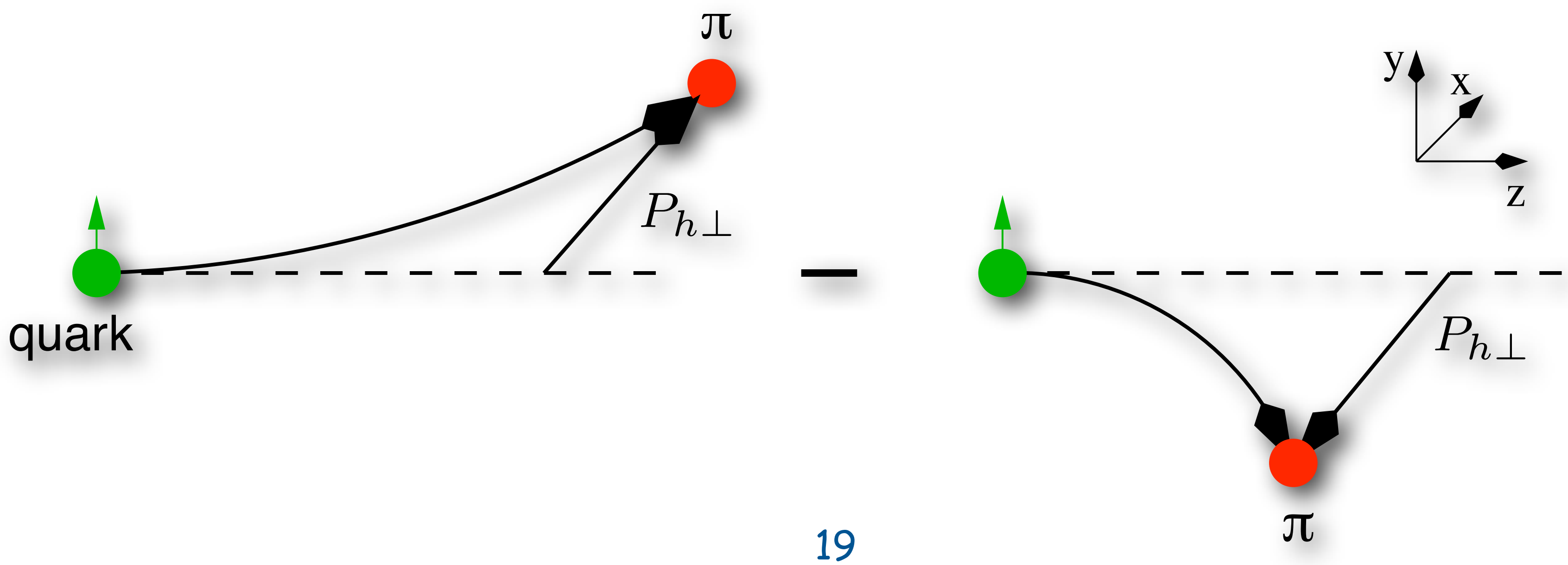


- transversely polarized quarks: need final-state polarimetry, e.g.



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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hadron pol.

	U	L	T
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☛ relevant for unpolarized final state

TMD fragmentation functions

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

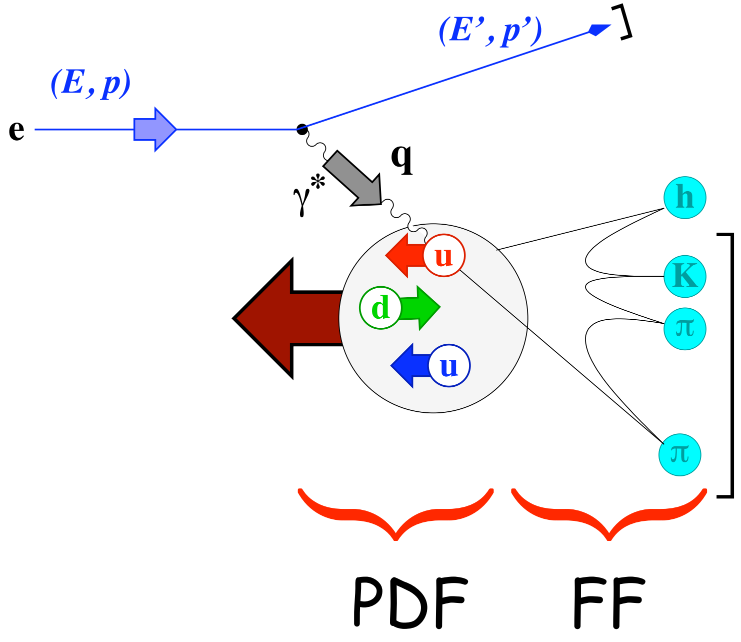
☛ relevant for unpolarized final state

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

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

Probing TMDs in semi-inclusive DIS

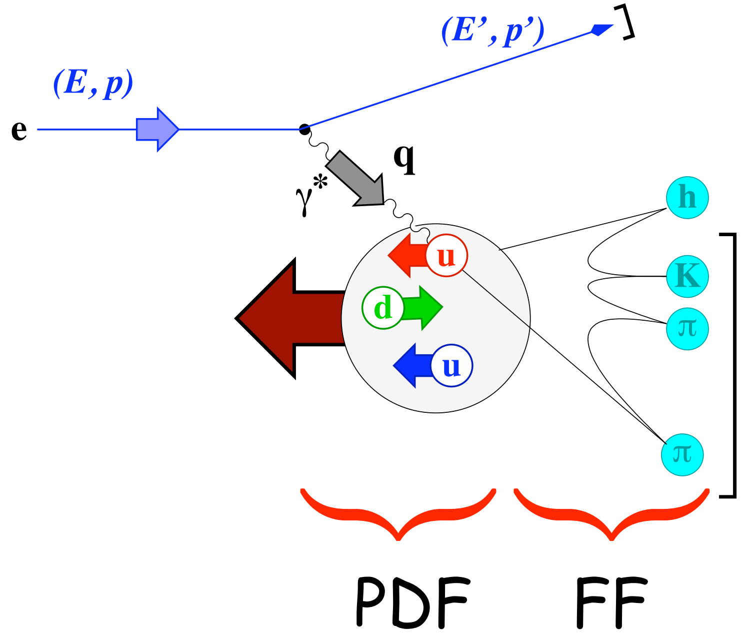
		quark pol.		
		U	L	T
nucleon pol.	U	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

Probing TMDs in semi-inclusive DIS



quark pol.

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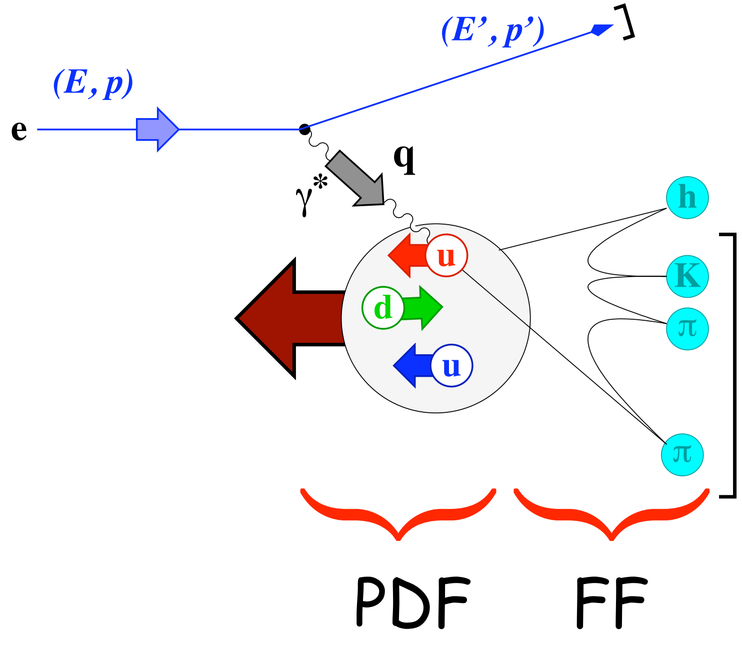
	T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

in SIDIS*) couple PDFs to:

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

*) semi-inclusive DIS with unpolarized final state

Probing TMDs in semi-inclusive DIS



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

in SIDIS*) couple PDFs to:

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

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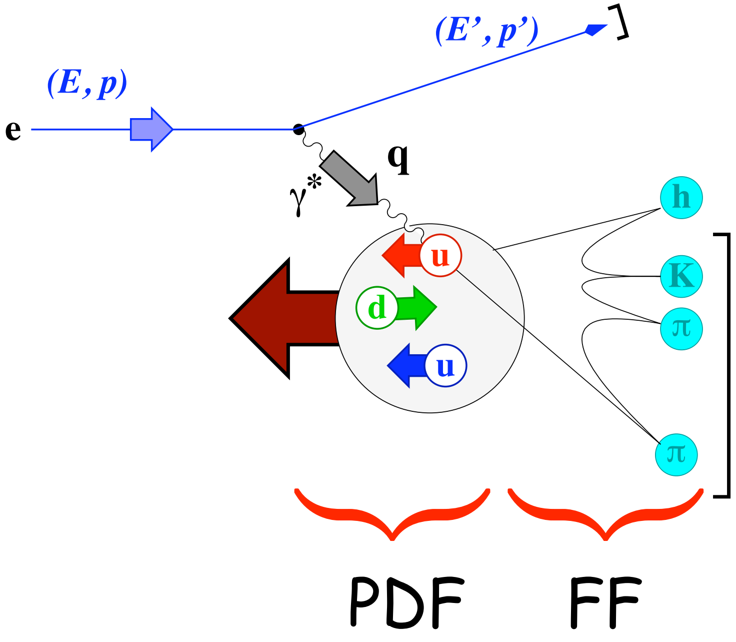
Probing TMDs in semi-inclusive DIS



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nucleon pol.

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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)

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

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

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

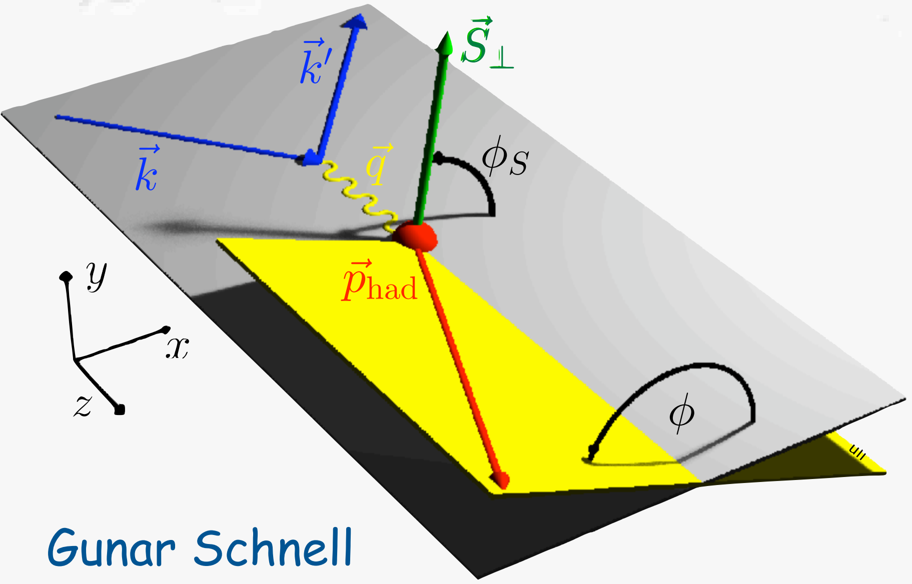
$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right)$$

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

σ_{XY}

Beam **Target**

Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

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

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

Bacchetta et al., JHEP 0702 (2007) 093

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

1-Hadron production (ep→ehX)

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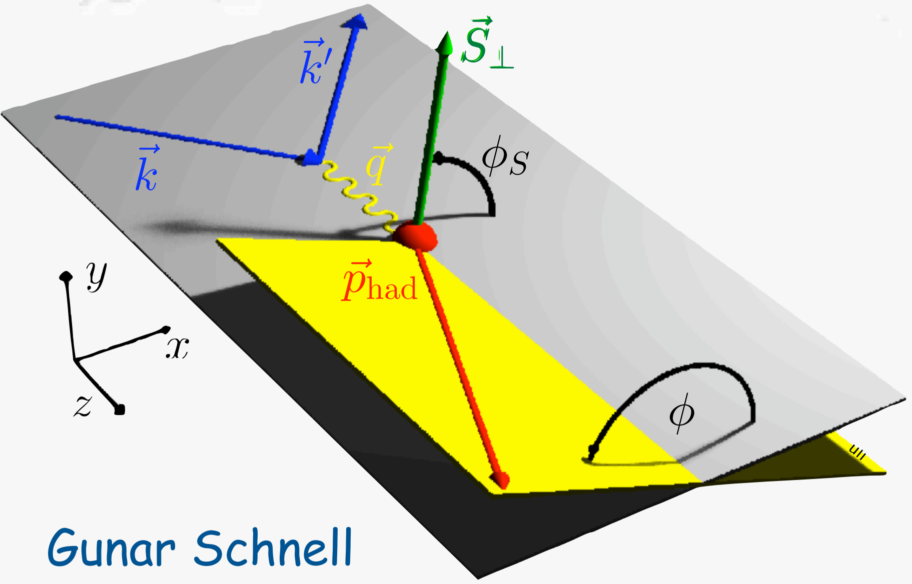
Polarization



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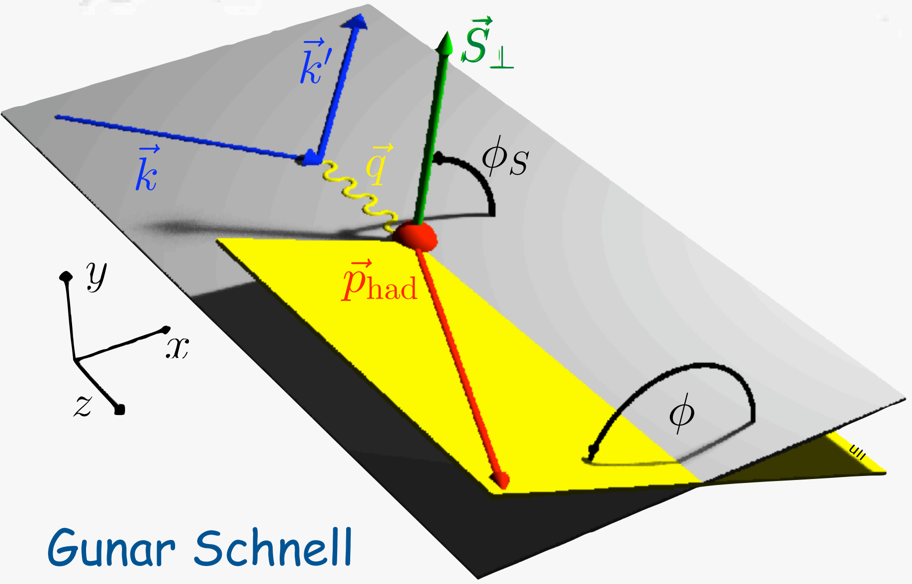
σ_{XY}

↙ ↘

Beam **Target**

Polarization



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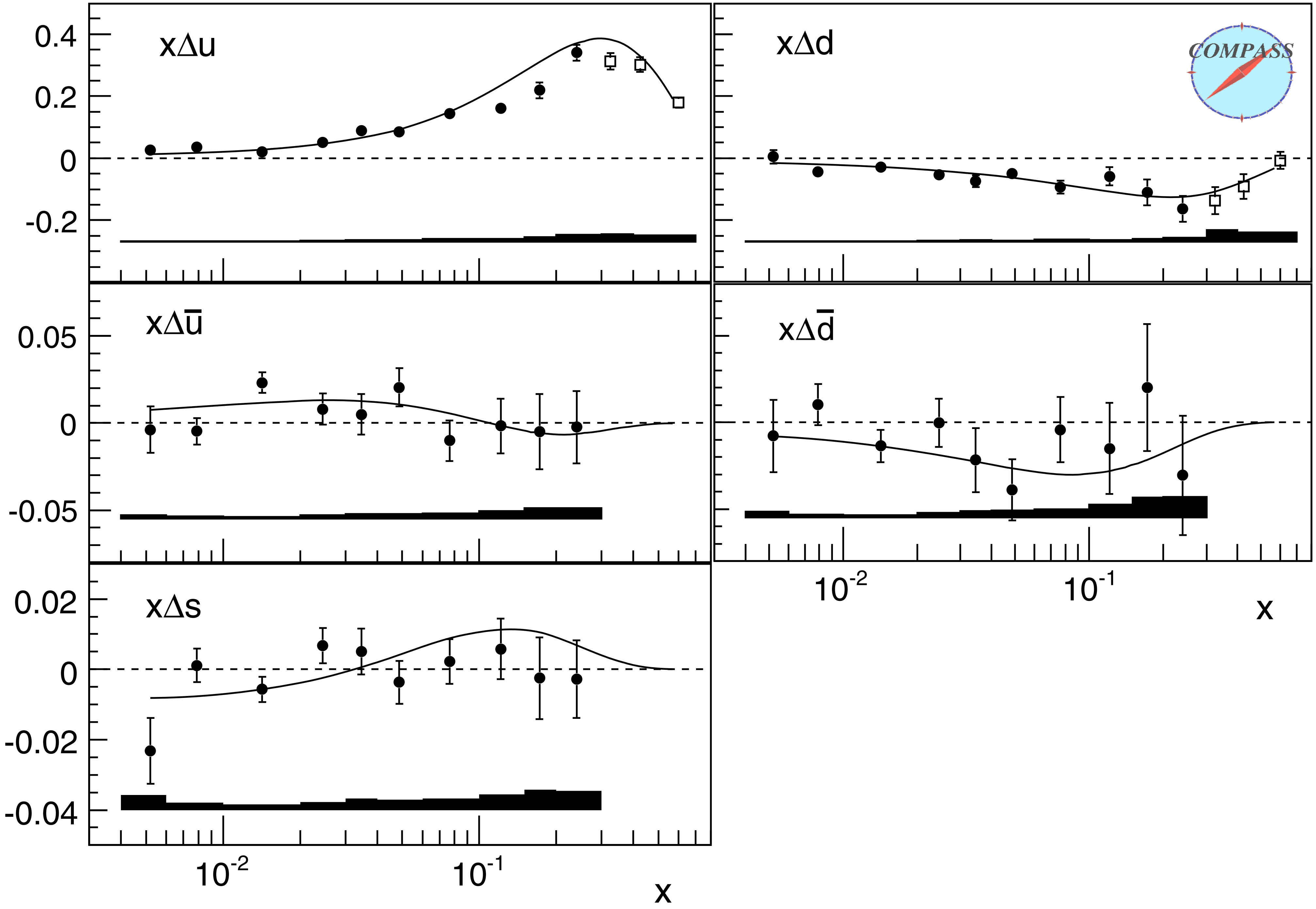
... back to results ...

	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 693 (2010) 227]



flavor separation of LO quark-helicity distribution using H and D DIS data

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

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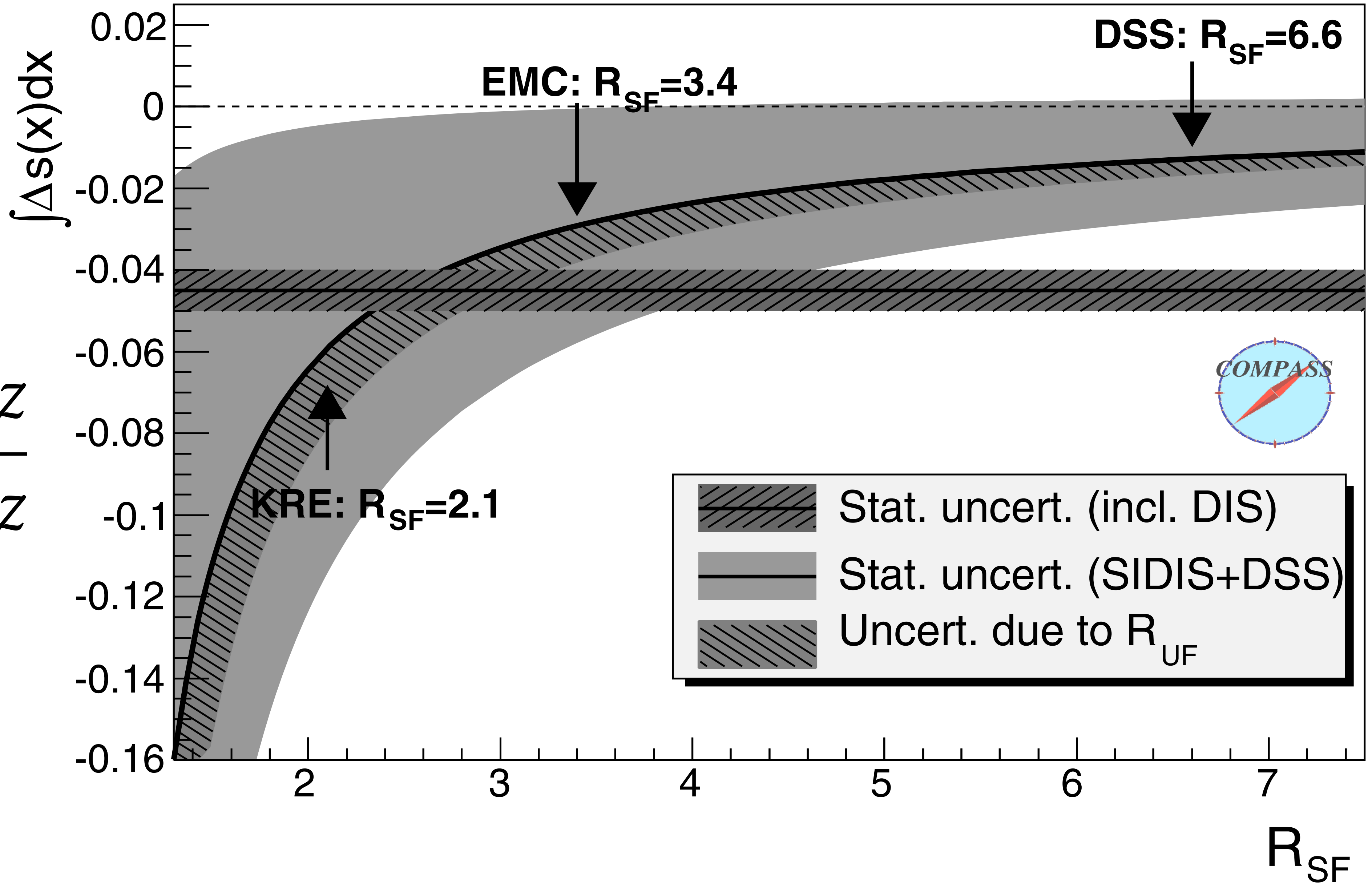

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\,dz}{\int D_{u}^{K^+}(z)\,dz}$$

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, $h_{1T}^\perp$

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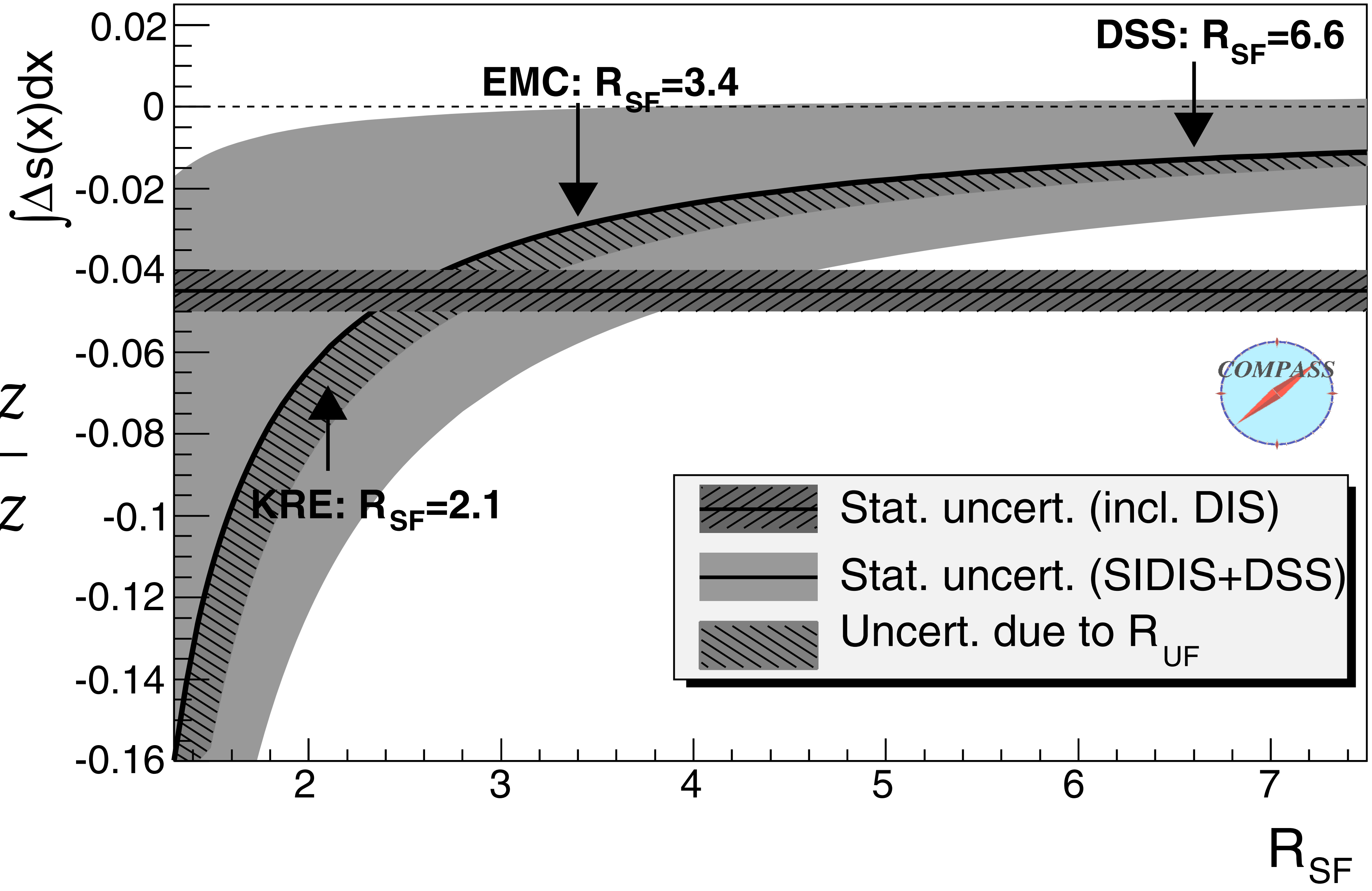


caveat: potentially large dependences on knowledge of FFs!

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

polarized light ions?

- case for iso-scalar target as less (& more convenient?) FFs involved:

$$A_{\parallel,d}^{K^\pm}(x)\,\frac{\mathrm{d}^2 N^K(x)}{\mathrm{d}x\,\mathrm{d}Q^2} = \mathcal{K}_{LL}\left(x,\,Q^2\right)\left[\Delta Q(x)\int \mathcal{D}_Q^K(z)\,\mathrm{d}z + \Delta S(x)\int \mathcal{D}_S^K(z)\,\mathrm{d}z\right]$$

- measure strange helicity distribution using polarized D (unpolarized D can be used to constrain strangeness and fragmentation functions involved)

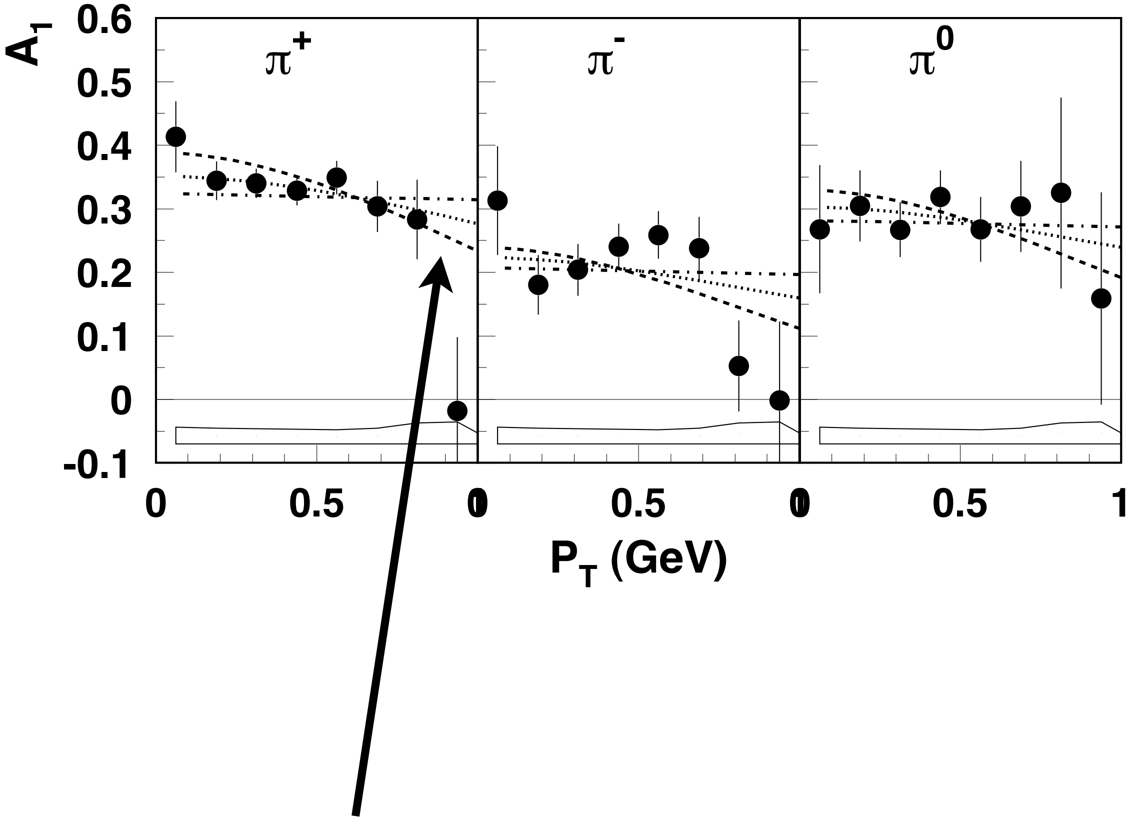
$$\mathcal{D}_{\mathbf{S}}^{\mathbf{K}} = \mathbf{D}_{\mathbf{1}}^{\mathbf{s}\to\mathbf{K}^+} + \mathbf{D}_{\mathbf{1}}^{\bar{\mathbf{s}}\to\mathbf{K}^+} + \mathbf{D}_{\mathbf{1}}^{\mathbf{s}\to\mathbf{K}^-} + \mathbf{D}_{\mathbf{1}}^{\bar{\mathbf{s}}\to\mathbf{K}^-}$$

$$\mathcal{D}_{\mathbf{Q}}^{\mathbf{K}} = \mathbf{4D}_{\mathbf{1}}^{\mathbf{u}\to\mathbf{K}^+} + \mathbf{4D}_{\mathbf{1}}^{\bar{\mathbf{u}}\to\mathbf{K}^+} + \mathbf{D}_{\mathbf{1}}^{\mathbf{d}\to\mathbf{K}^+} + \mathbf{D}_{\mathbf{1}}^{\bar{\mathbf{d}}\to\mathbf{K}^+} + \ldots$$

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

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

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

	U	L	T
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Helicity density

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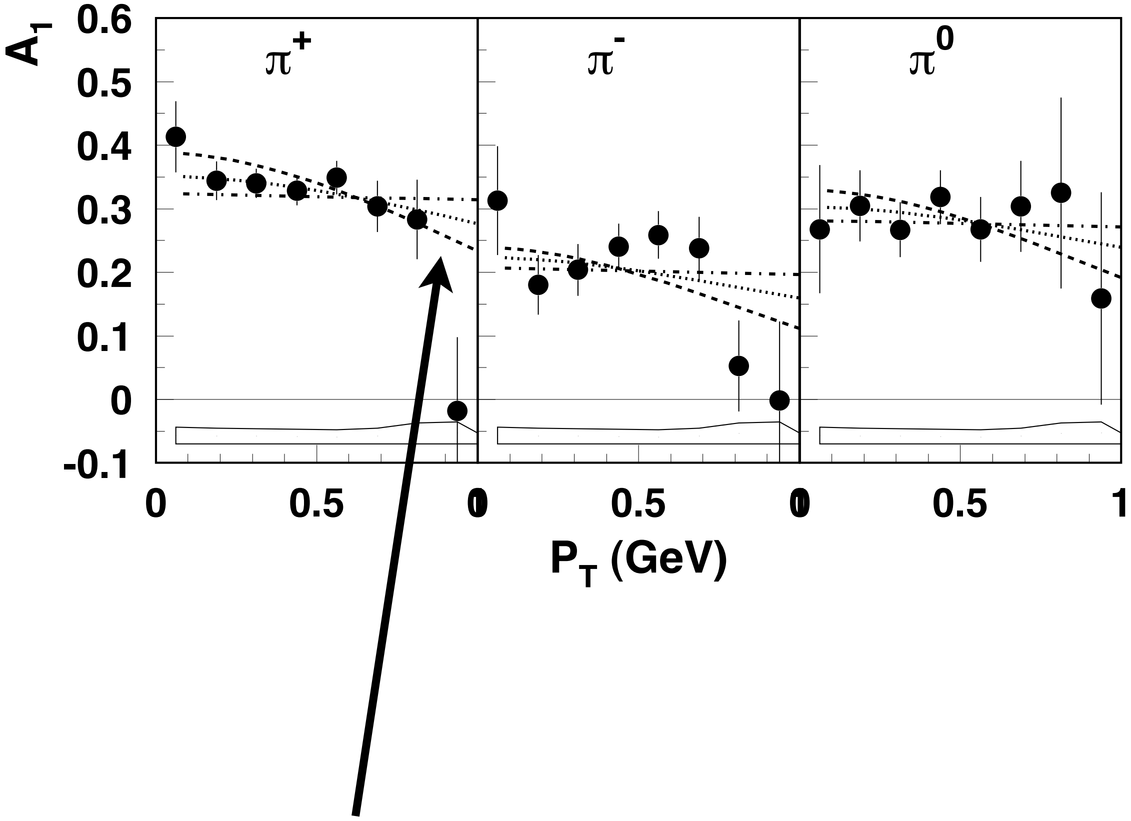

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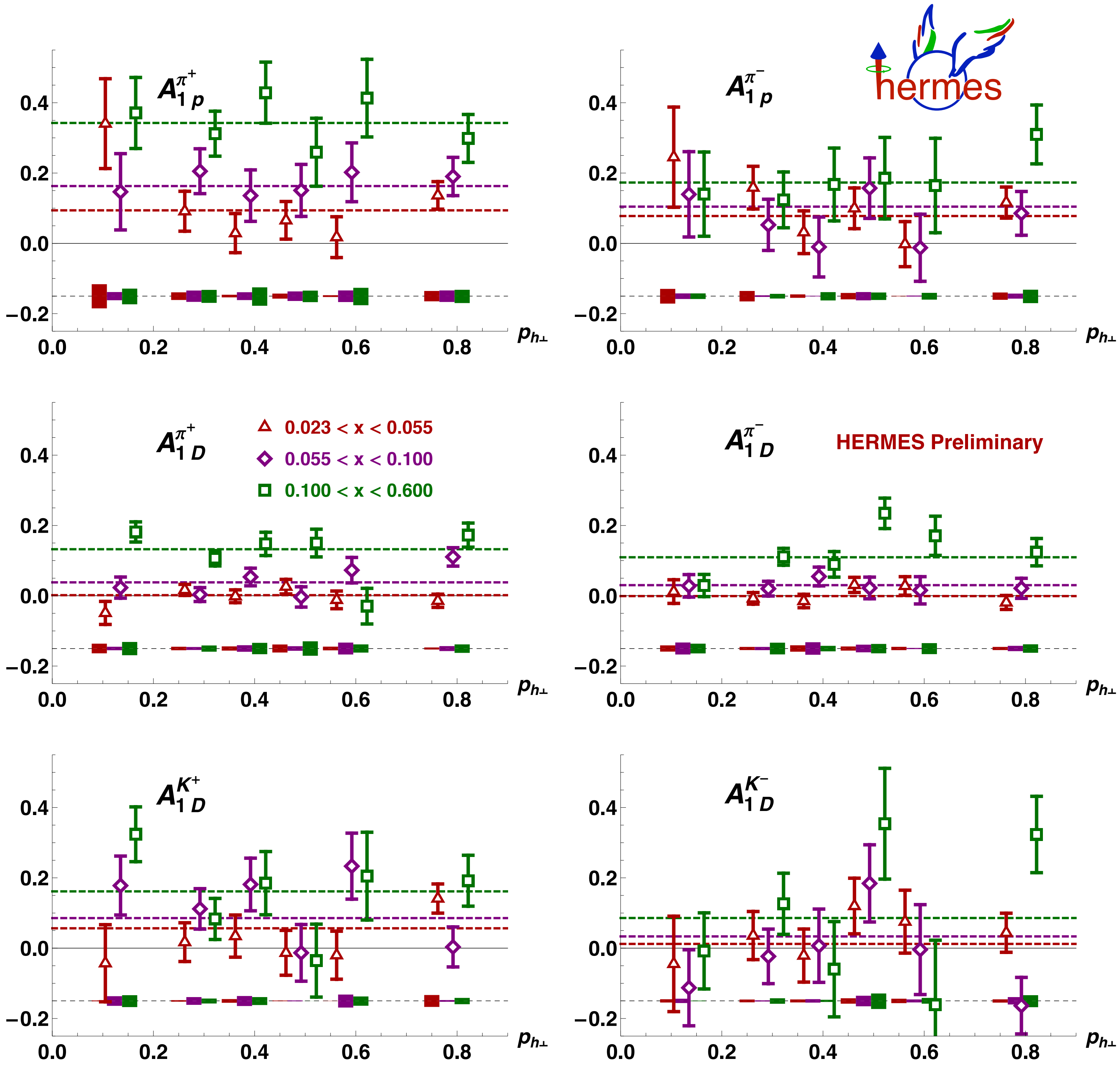


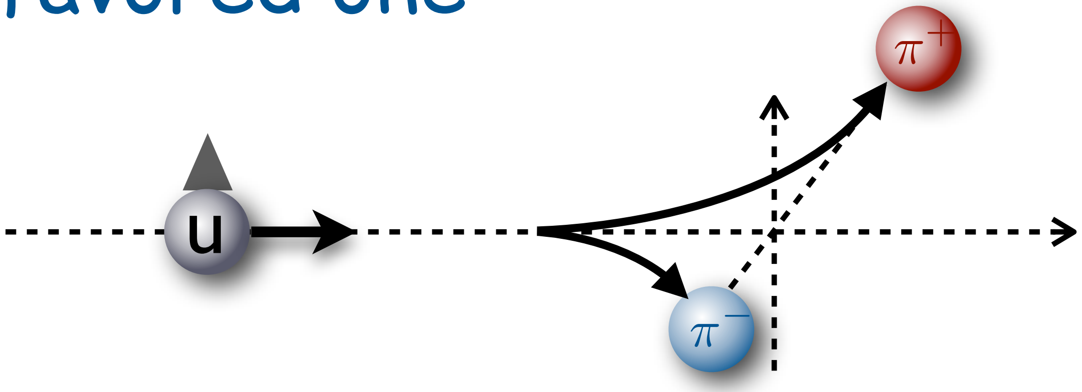
no significant $P_{h\perp}$ dependences seen at HERMES and COMPASS

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, $h_{1T}^\perp$

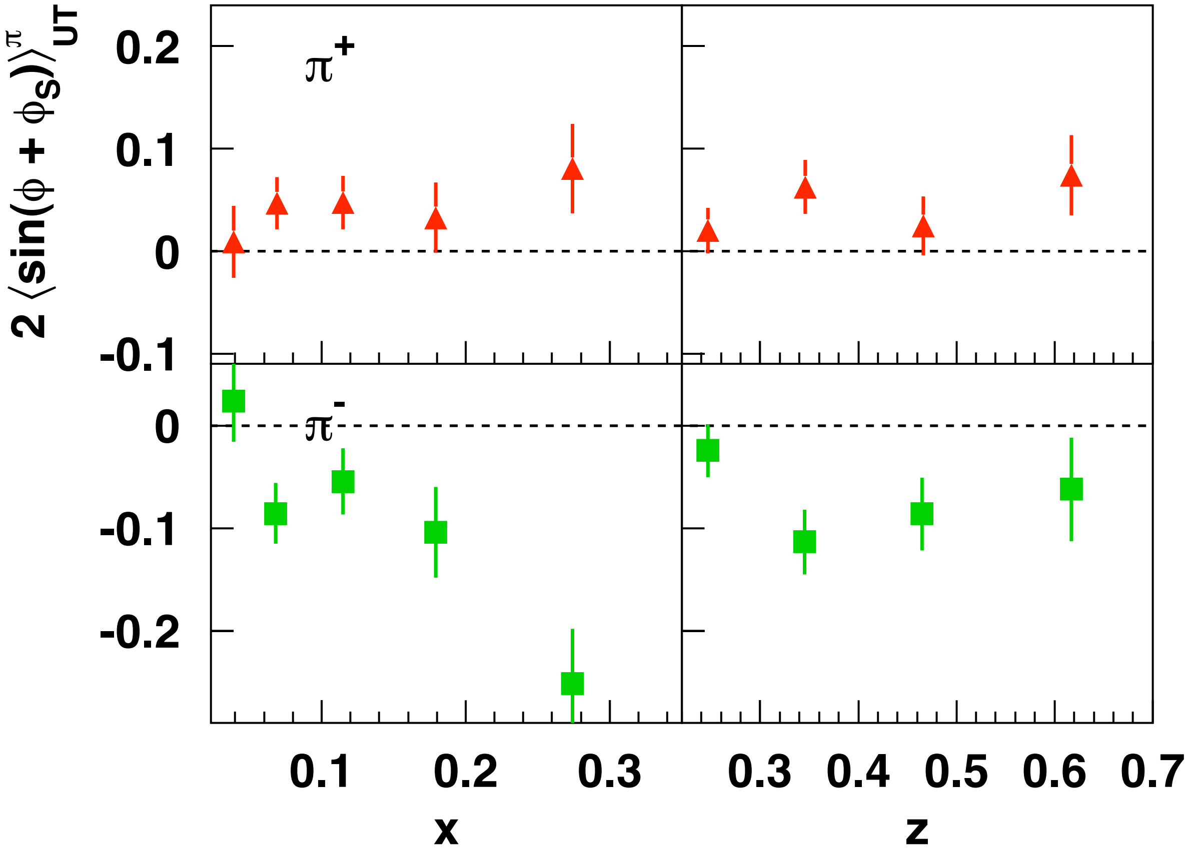
Transversity (Collins fragmentation)

- 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]



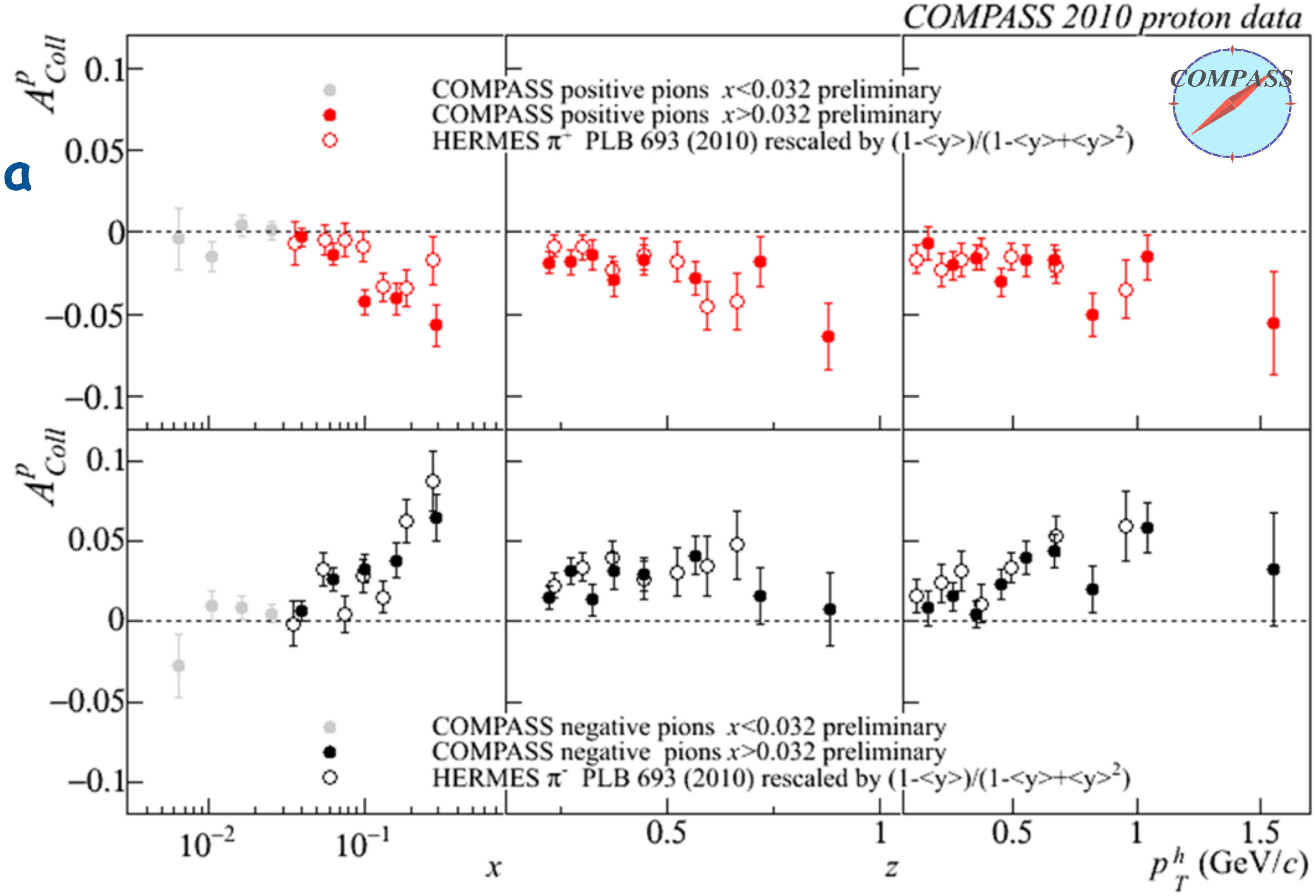
2005: First evidence from HERMES SIDIS on proton

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]



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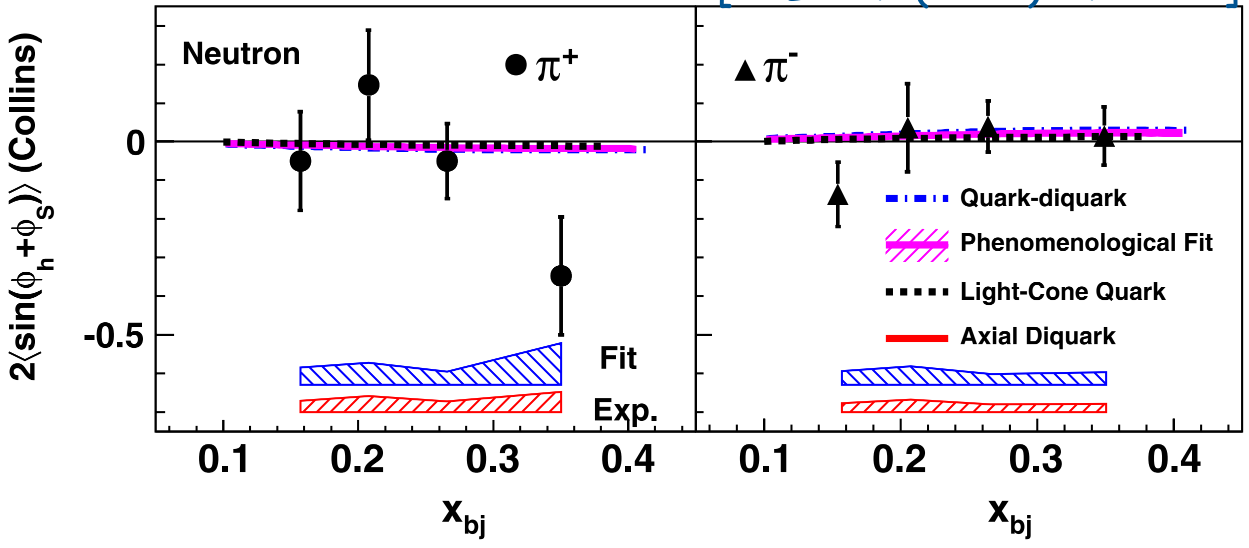

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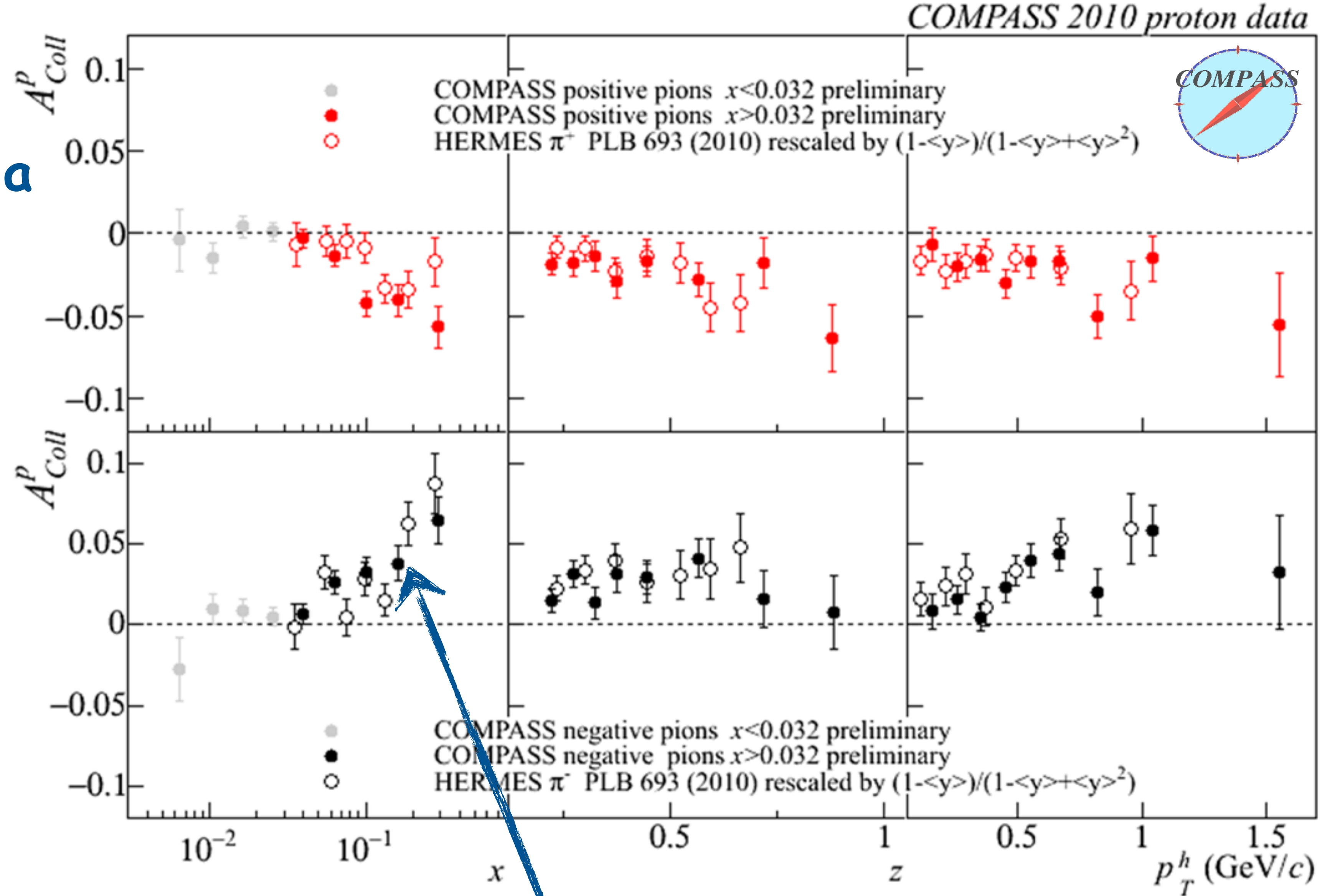

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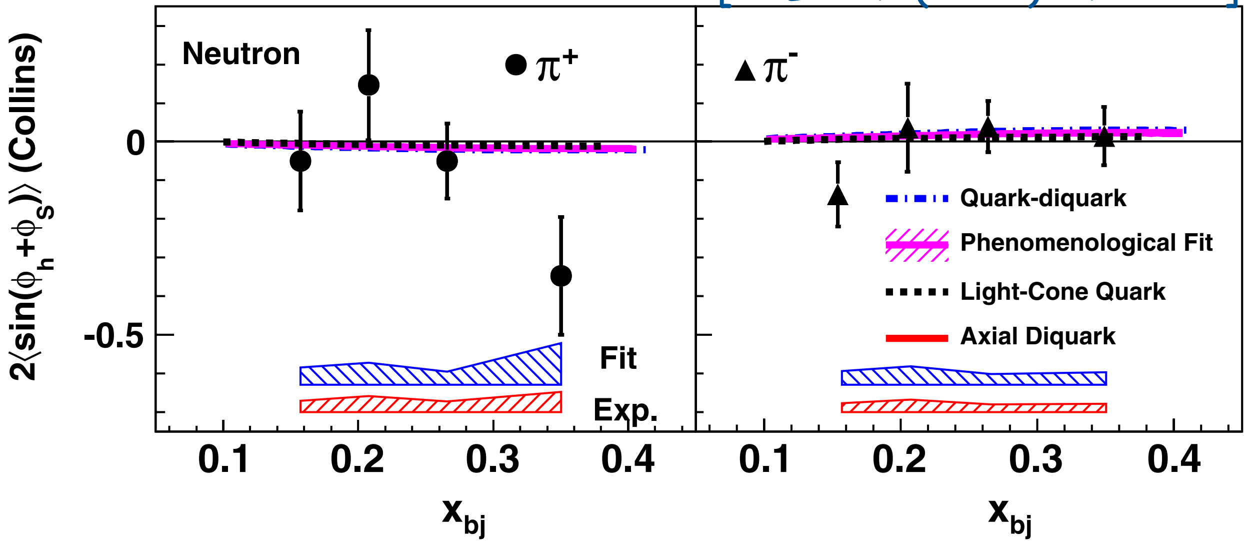

excellent agreement of various proton data, also with neutron results

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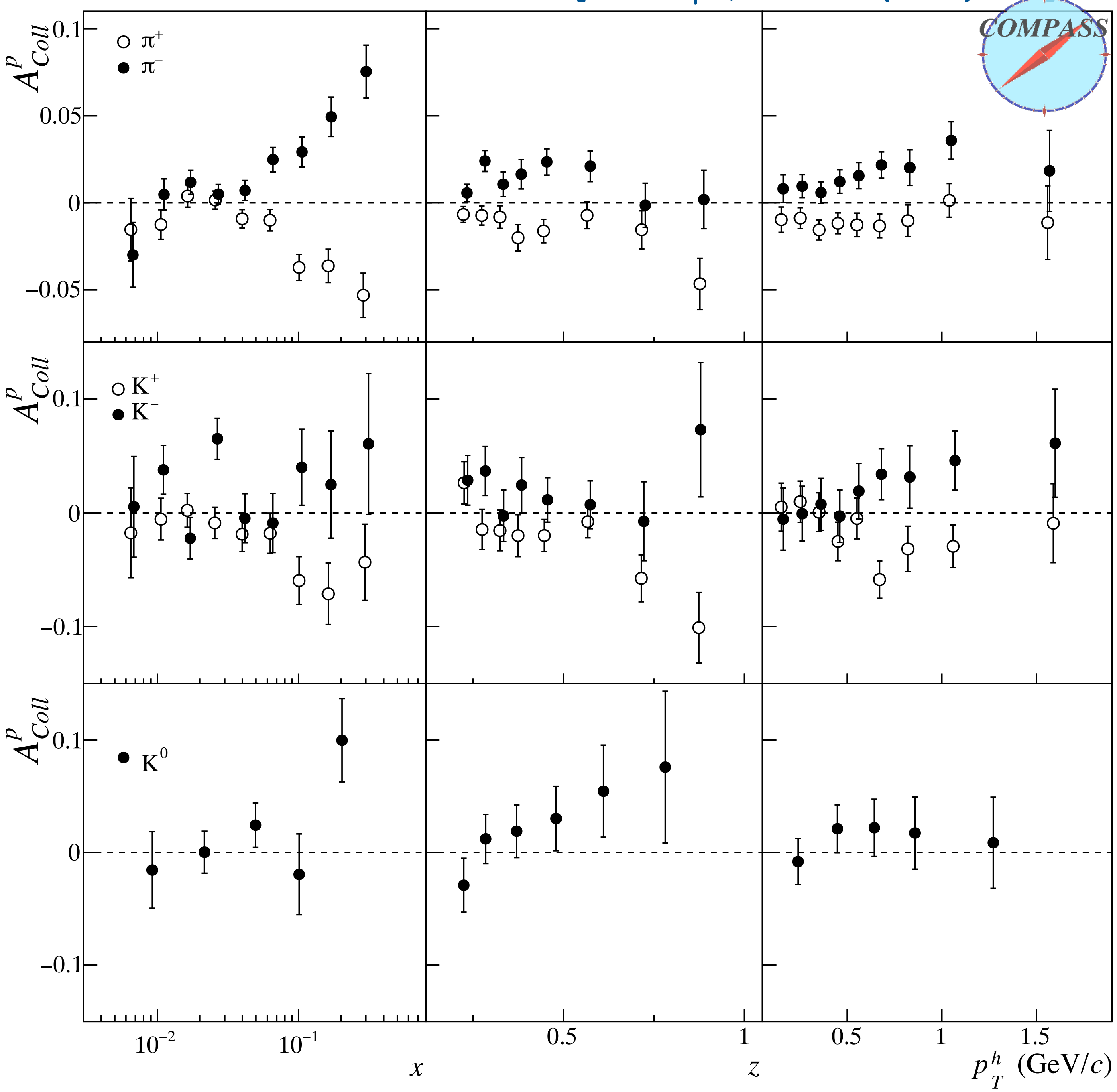
[C. Adolph, PLB 744 (2015) 250]



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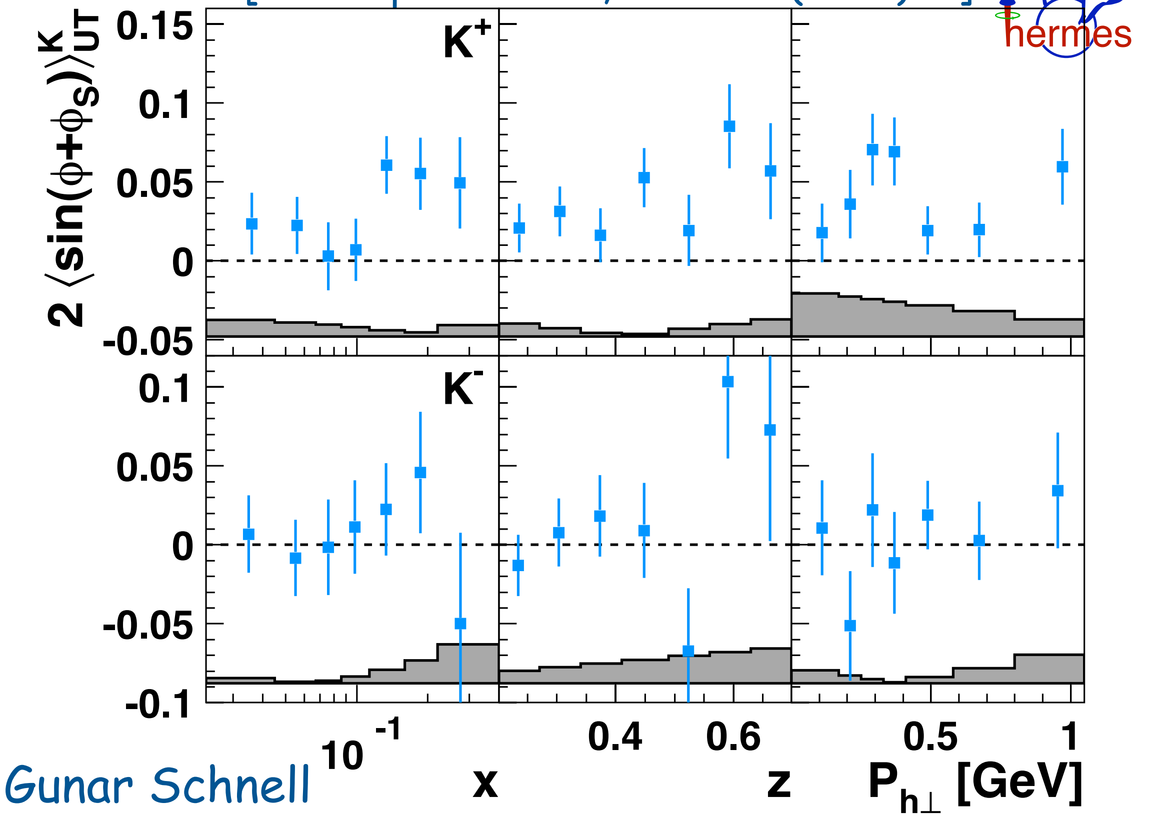

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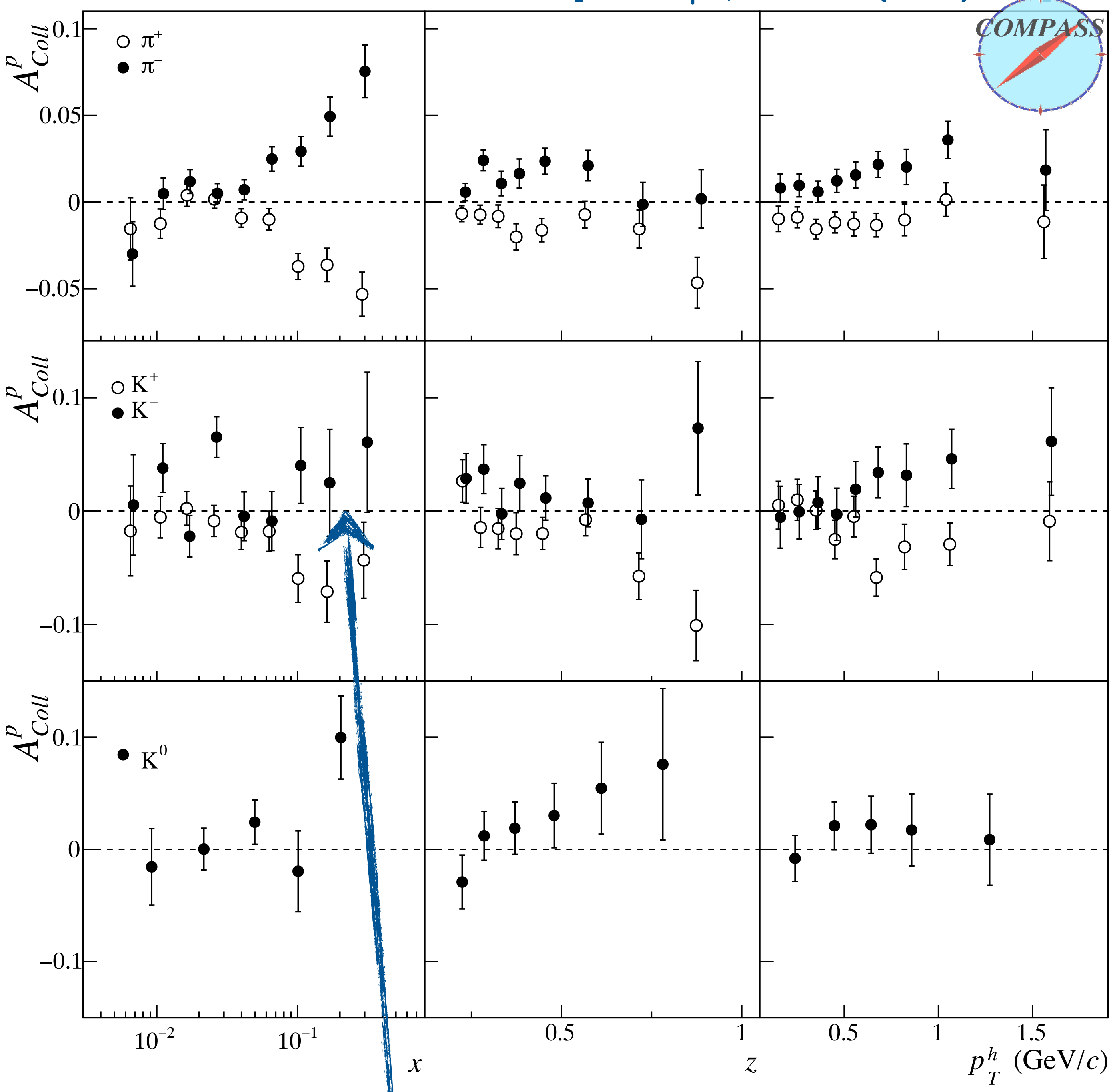

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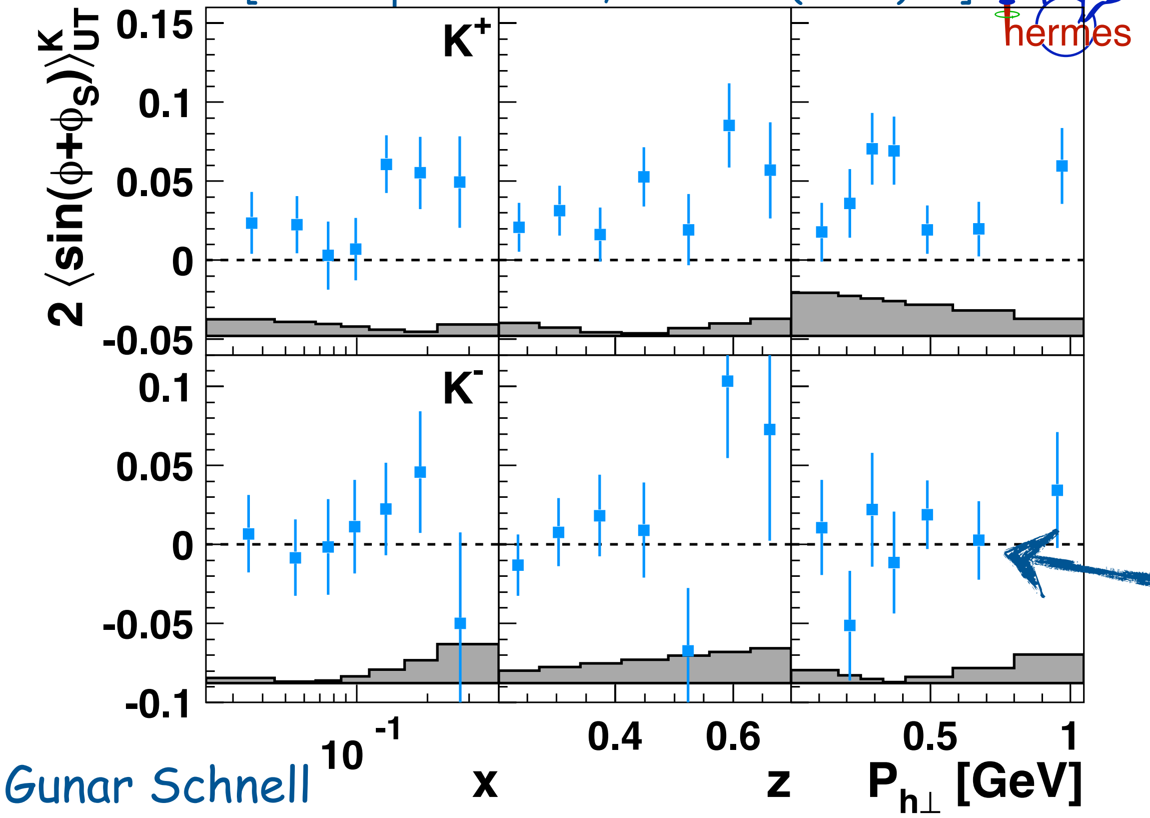

cancelation of (unfavored) u and d fragmentation (opposite signs of up and down transversity)?

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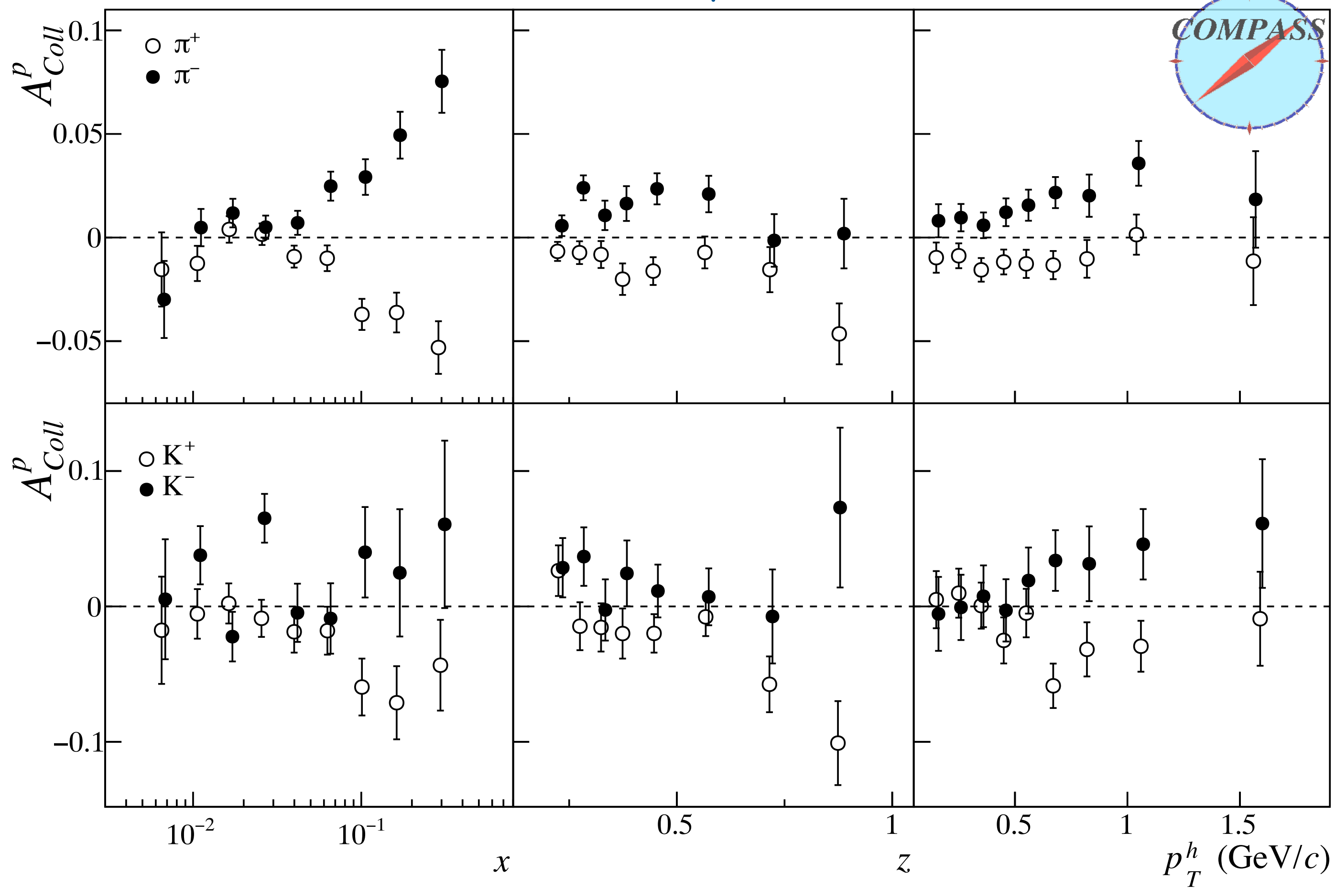

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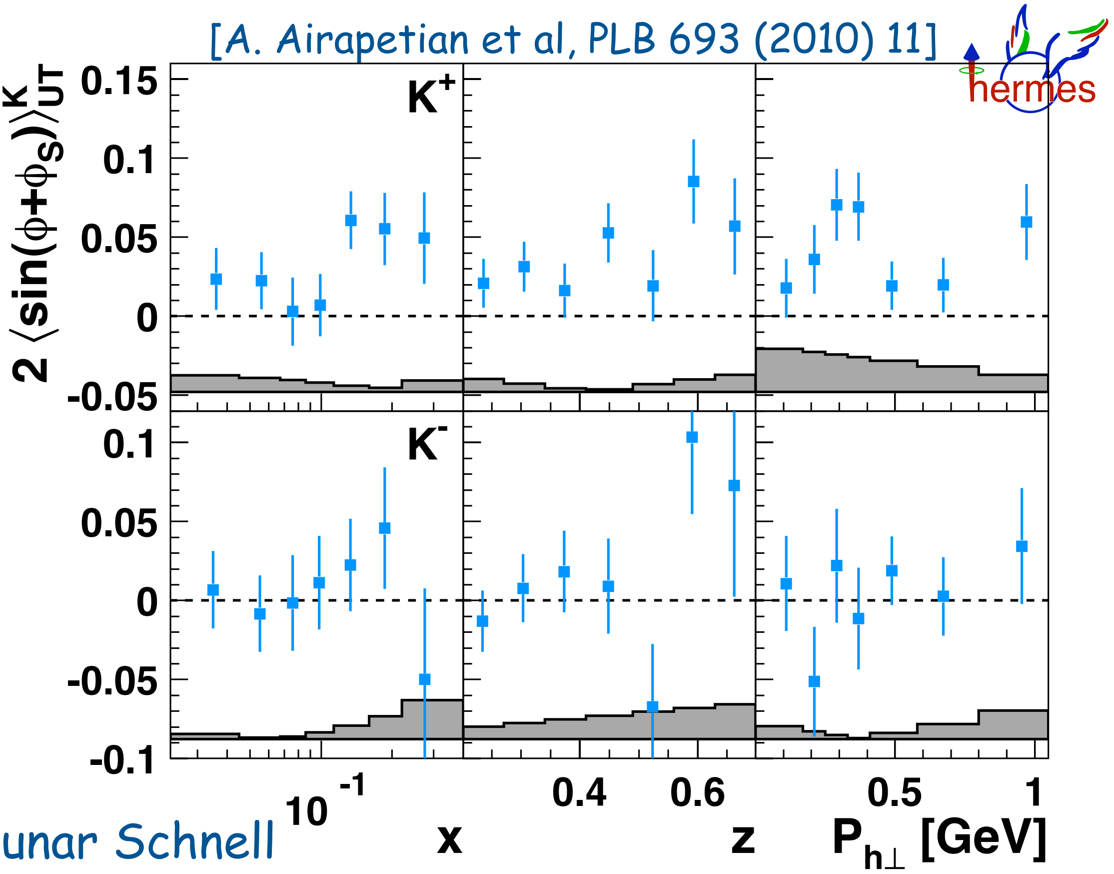

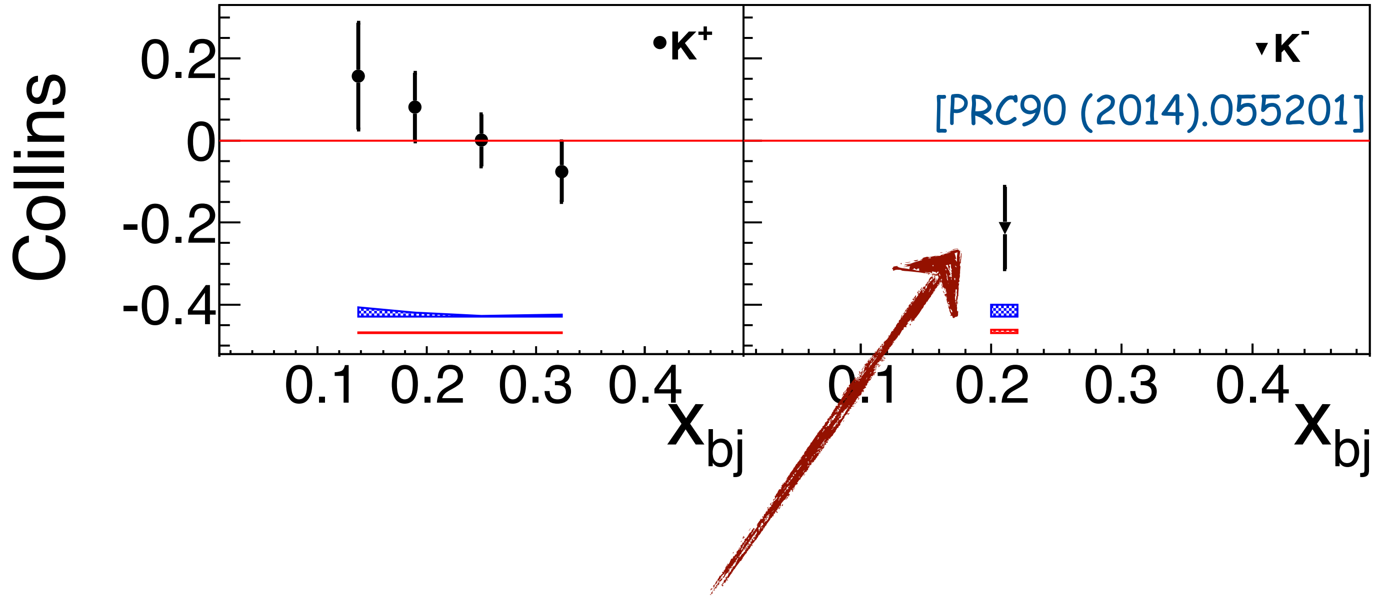

but relatively large K⁻ asymmetry on ^{3}He?

flashback

EINN 2005

A Closer Look at Collins Asymmetries II

express asymmetries in terms of flavor ratios:

$$\tilde{A}_C^{\pi^+} = \mathcal{K}(x,z)\frac{4+\delta r\mathcal{H}}{4+r\mathcal{D}}$$

$$\tilde{A}_C^{\pi^-} = \mathcal{K}(x,z)\frac{4\mathcal{H}+\delta r}{4\mathcal{D}+r}$$

$$\tilde{A}_C^{\pi^0} = \mathcal{K}(x,z)\frac{(4+\delta r)(1+\mathcal{H})}{(4+r)(1+\mathcal{D})}$$

Polarized Objects

$$\mathcal{H} = \frac{H_d}{H_f}$$

$$\delta r = \frac{\delta d + 4\delta\bar{u}}{\delta u + \frac{1}{4}\delta\bar{d}}$$

Unpolarized Objects

$$\mathcal{D} = \frac{D_d}{D_f}$$

$$r = \frac{d+4\bar{u}}{u+\frac{1}{4}\bar{d}}$$

e.g., CTEQ6,R1990 and Kretzer et al.

Mixed

$$\mathcal{K} = \frac{(\delta u+\frac{1}{4}\delta\bar{d})zH_f}{(u+\frac{1}{4}\bar{d})D_f}$$

$\Rightarrow$ 3 constraints and 3 unknowns!

flashback

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The three asymmetries are not independent ($C(x,z) \equiv \frac{r(x)+4\mathcal{D}(z)}{r(x)\mathcal{D}(z)+4}$):

$$\tilde{A}_C^{\pi^+}(x,z) + C(x,z)\tilde{A}_C^{\pi^-}(x,z) - (1+C(x,z))\tilde{A}_C^{\pi^0}(x,z) = 0$$

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flashback

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\tilde{A}_C^{\pi^0} &= \mathcal{K}(x,z)\,\frac{(4+\delta r)(1+\mathcal{H})}{(4+r)(1+\mathcal{D})}
\end{aligned}$$

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⇒ ~~3~~ constraints and 3 unknowns!

2

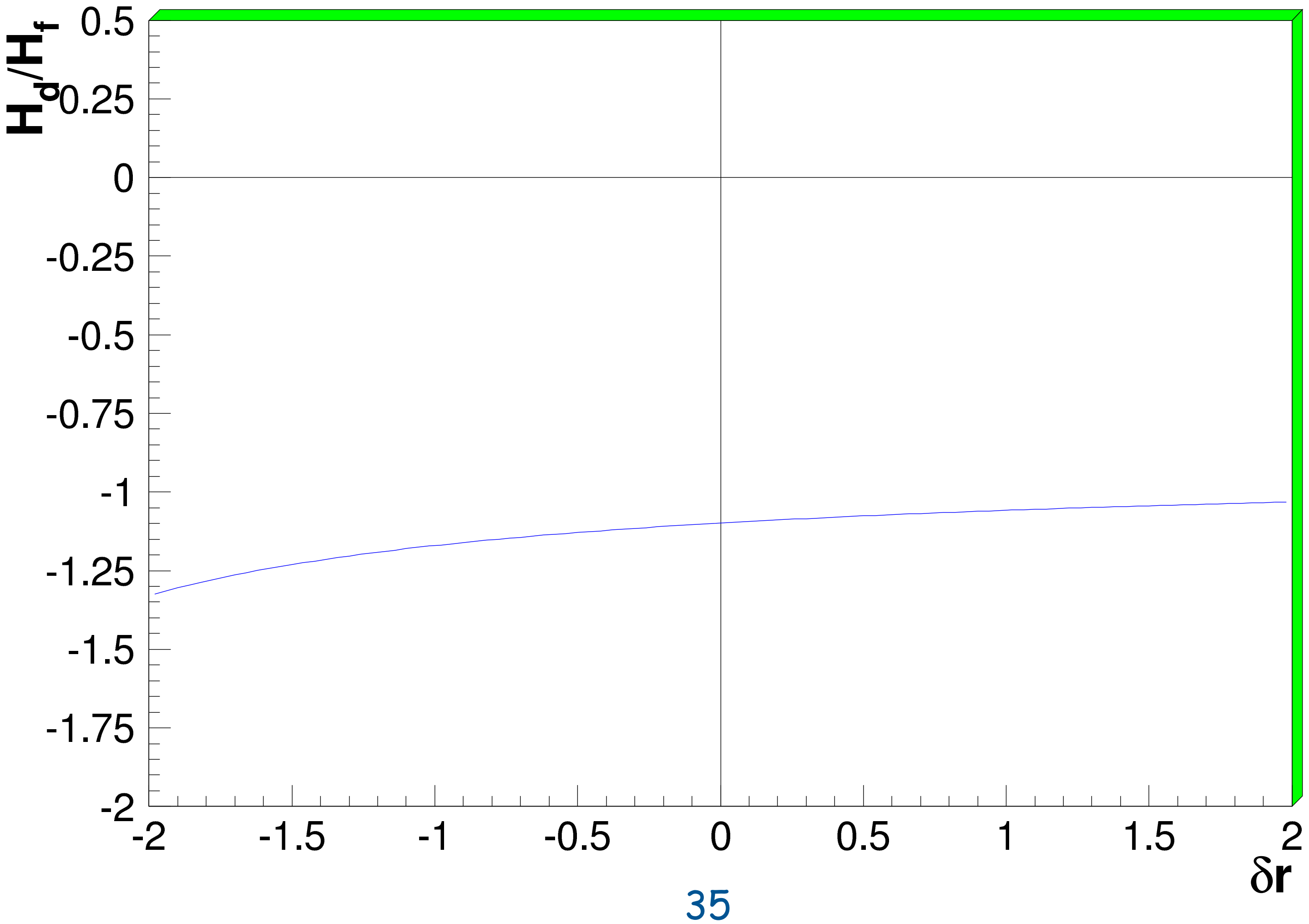
EINN 2005

A Closer Look at Collins Asymmetries III

eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to δr

$\Rightarrow$ scan solution space for $\mathcal{H}$ and δr by sampling set of $(\tilde{A}_C^{\pi^+}, \tilde{A}_C^{\pi^-}, \tilde{A}_C^{\pi^0})$

(around measured values according to statistical uncertainty)



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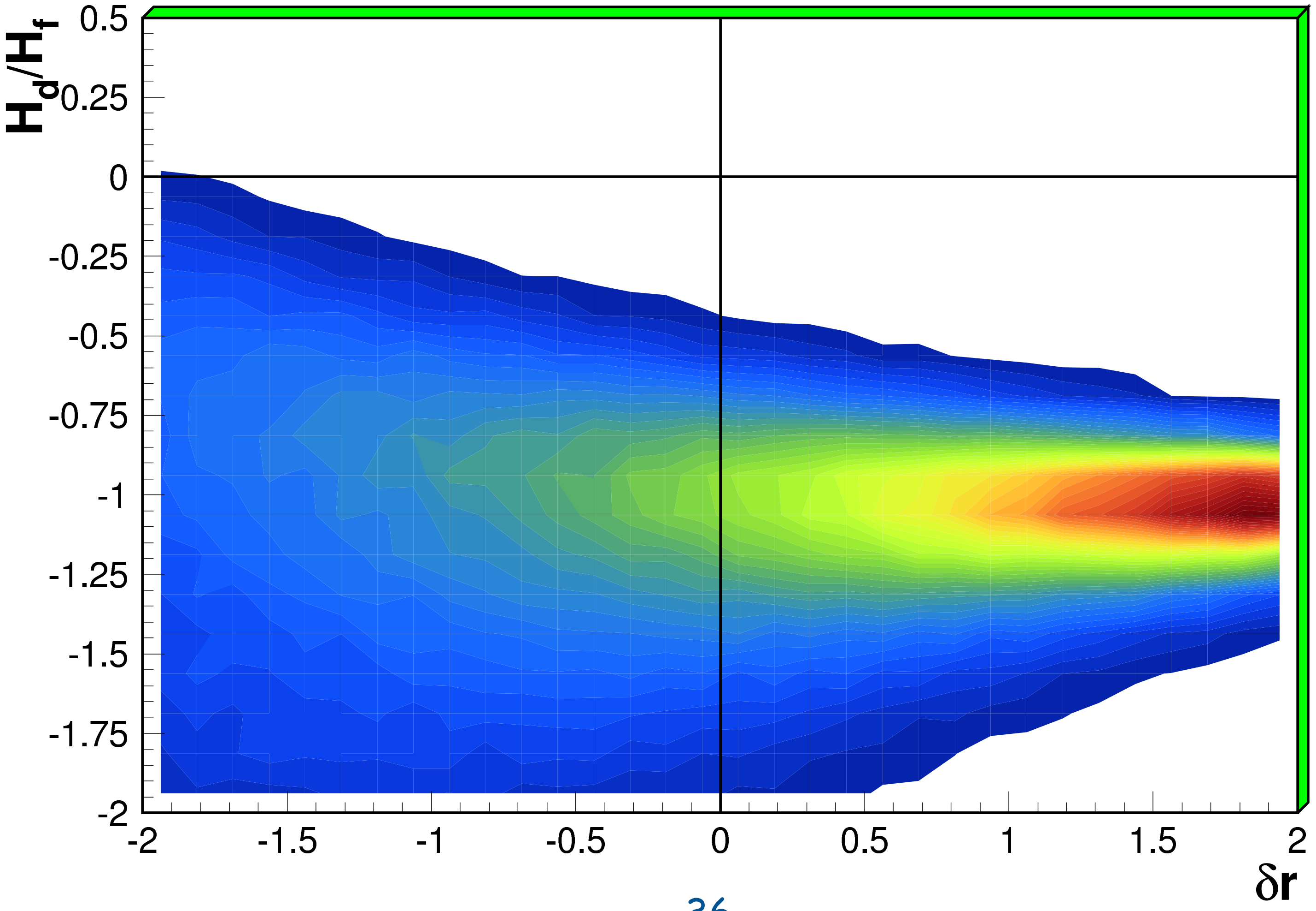
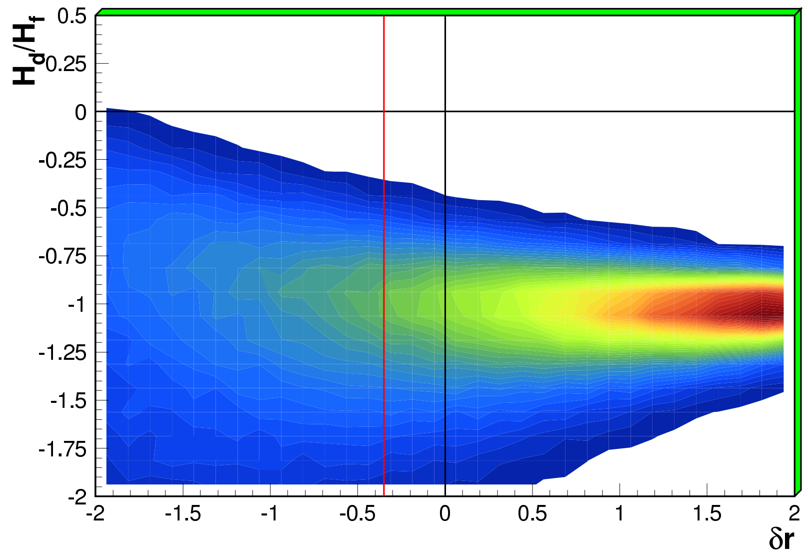


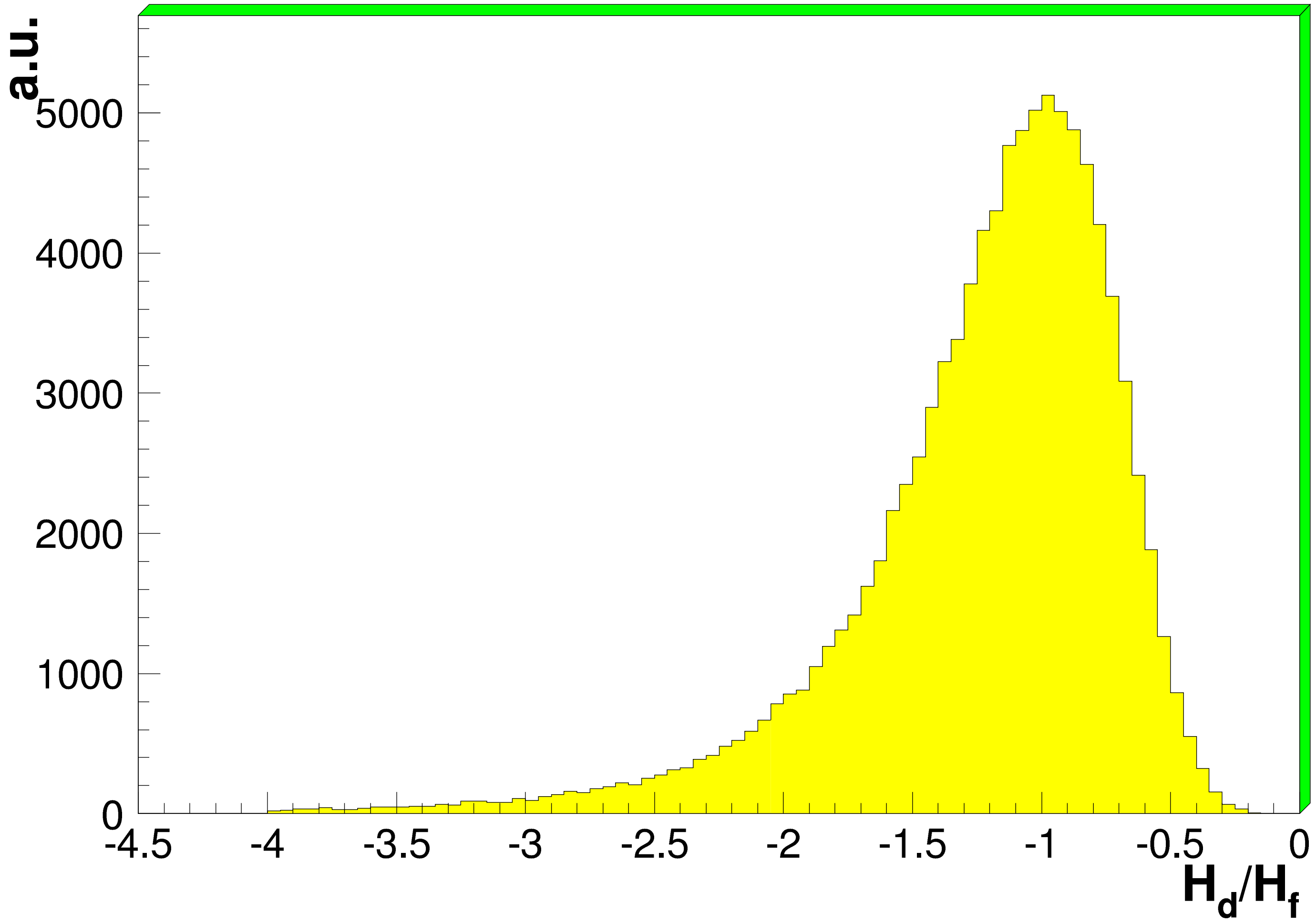
flashback

Limits on Transversity and Collins FF

$\delta r \approx \delta d/\delta u$ from χQSM

look at slice of distribution:





strong hint for H_d/H_f negative

flashback

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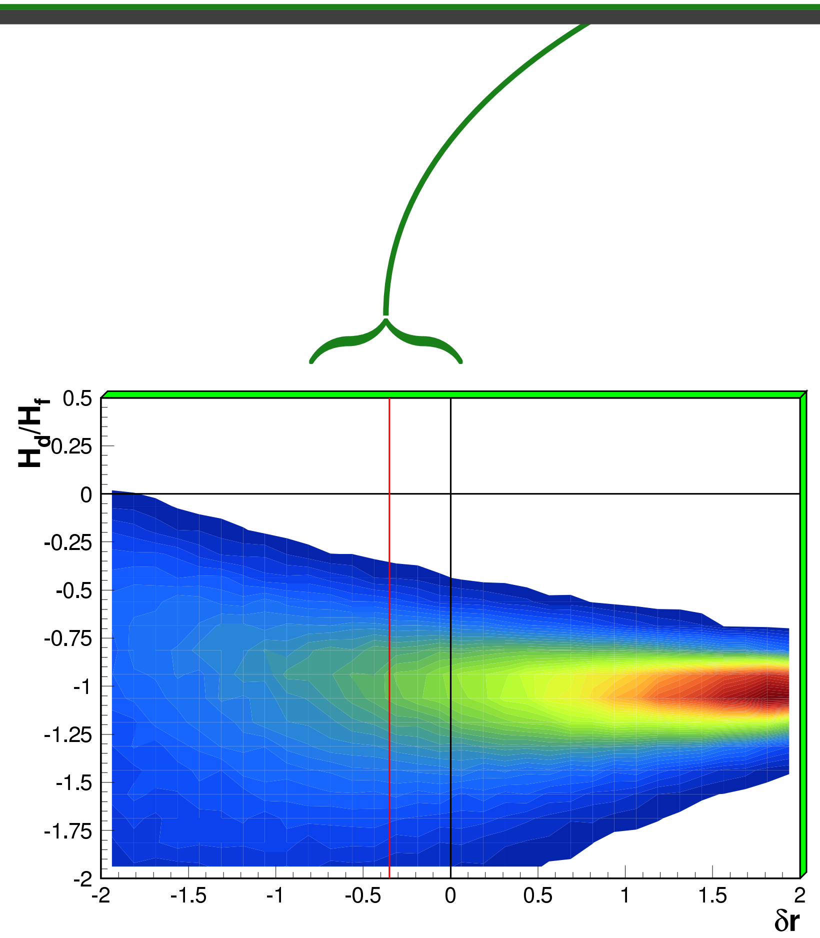
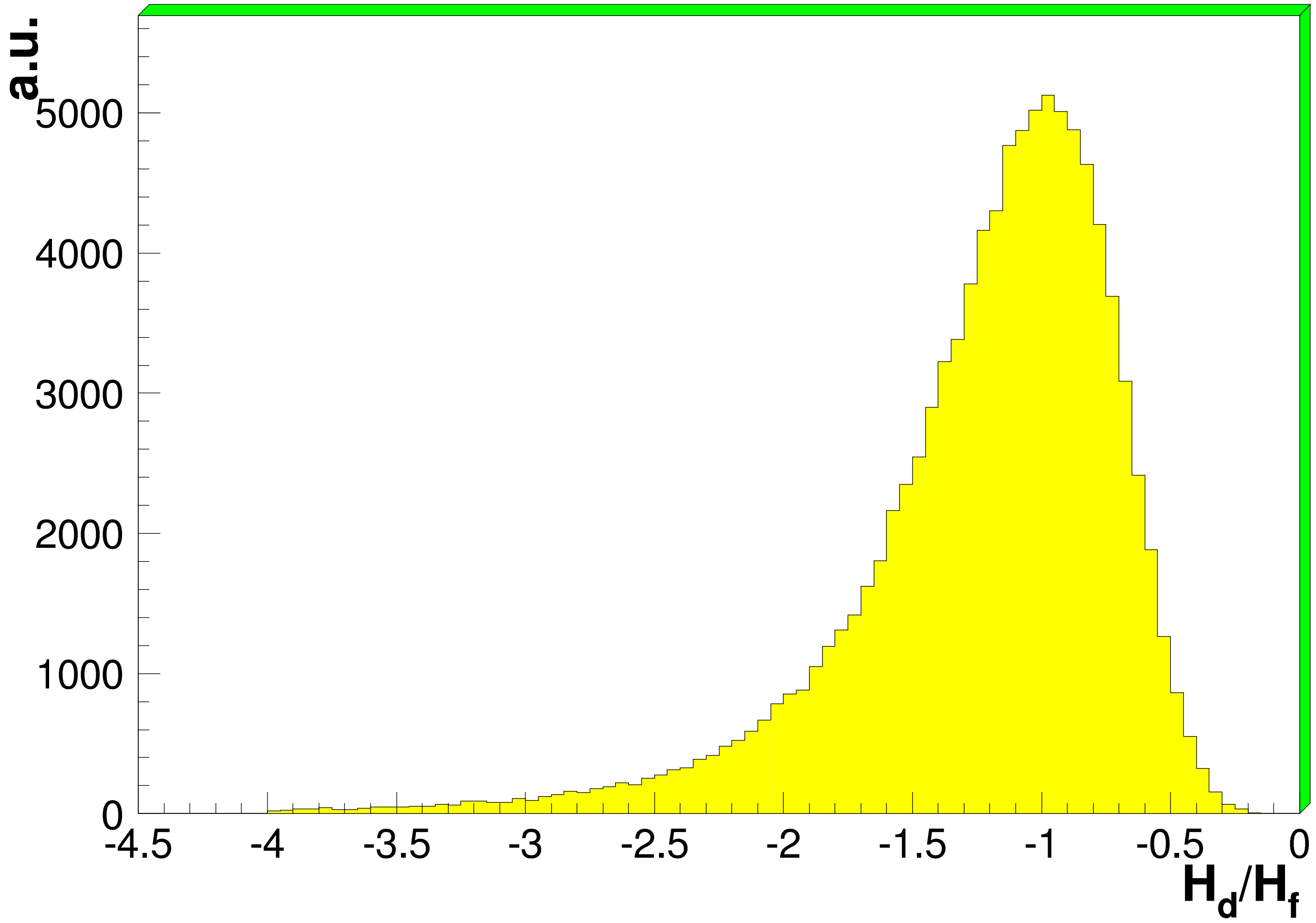
$\delta r \approx \delta d/\delta u$ from χQSM

look at slice of distribution:



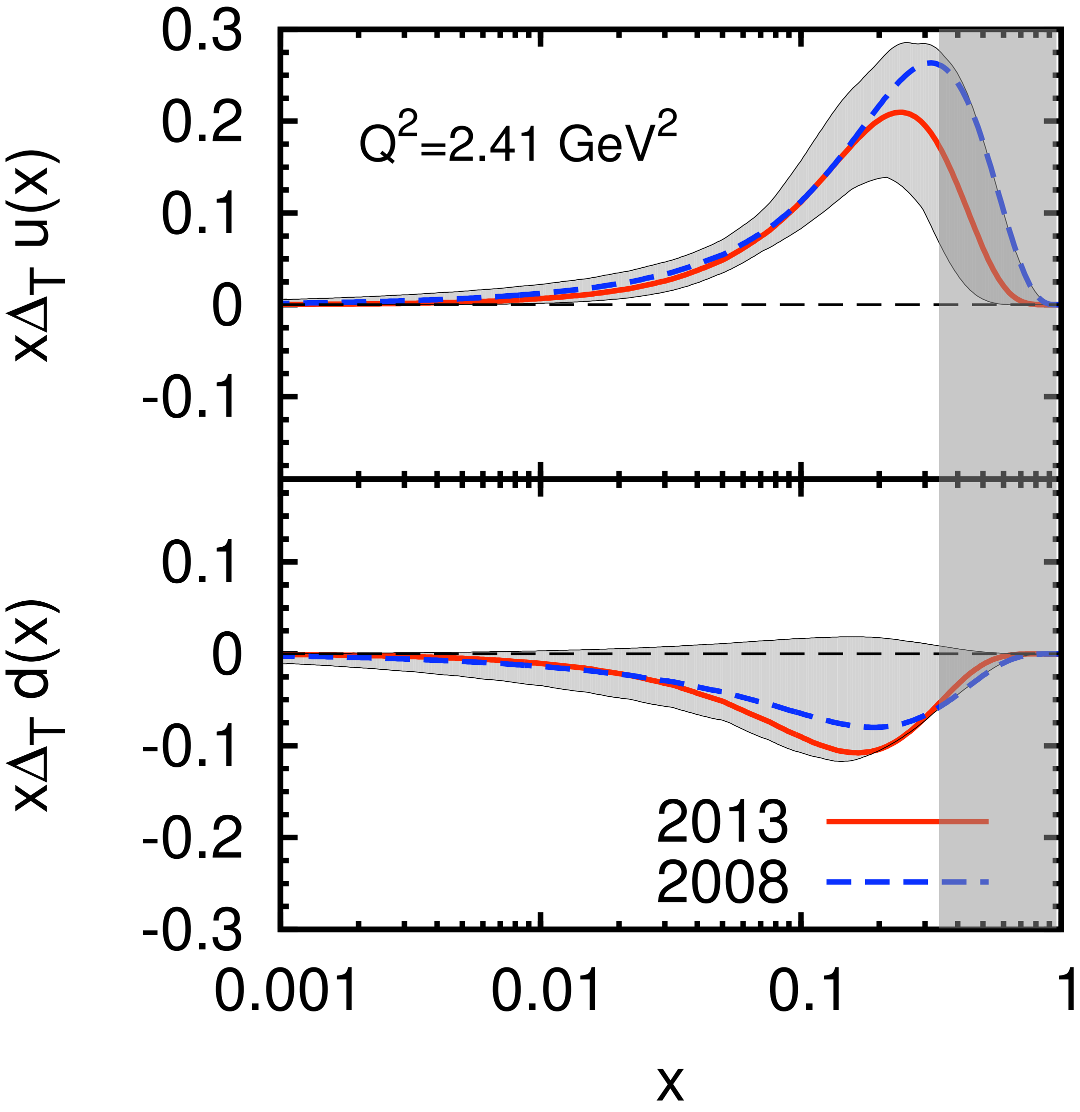


but transversity ratio hardly constrained

strong hint for H_d/H_f negative

the “Collins trap“

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



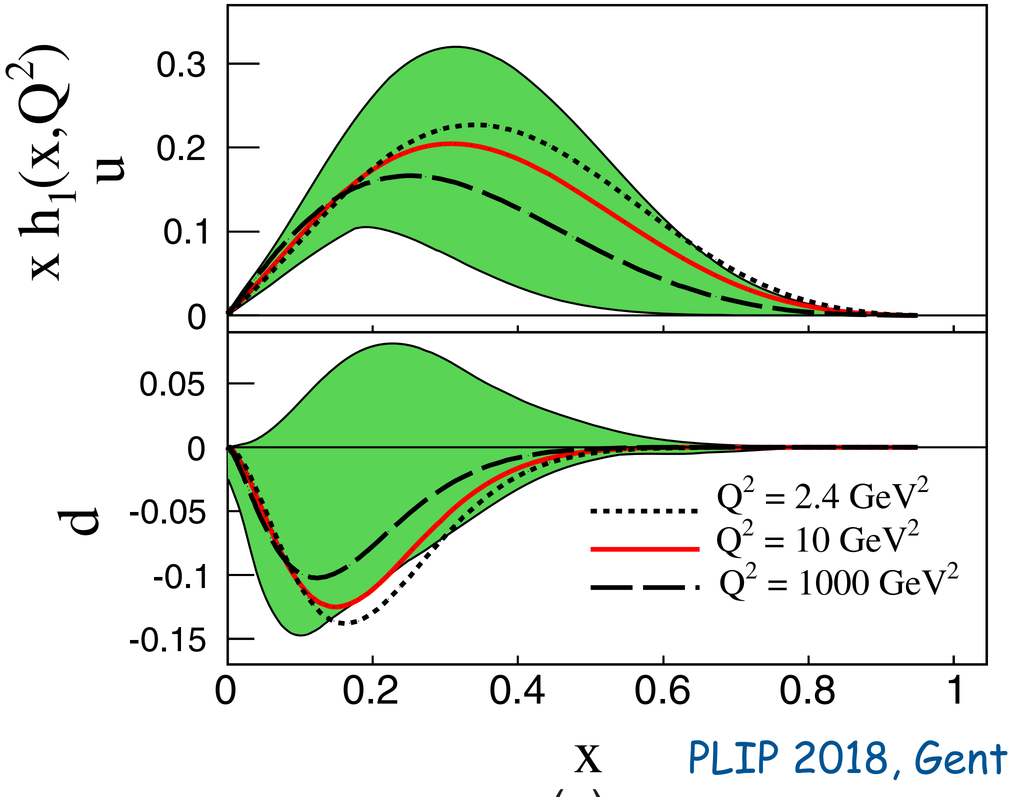
$$H^{\perp}_{1,\text{fav}} \simeq -H^{\perp}_{1,\text{dis}}$$

thus

$$\langle\sin(\phi+\phi_S)\rangle^{\pi^+}_{UT} \sim \left(4h_1^u - h_1^d\right) H^{\perp}_{1,\text{fav}}$$

$$\langle\sin(\phi+\phi_S)\rangle^{\pi^-}_{UT} \sim -\left(4h_1^u - h_1^d\right) H^{\perp}_{1,\text{fav}}$$

[Z.B. Kang et al. PRD93 (2016) 014009]



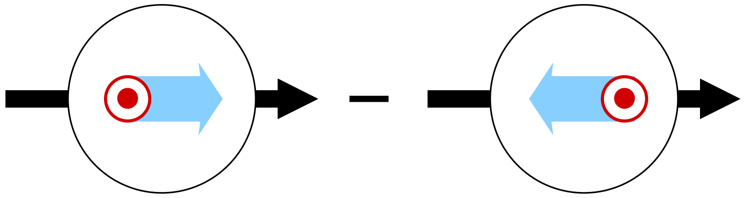
clearly need precise data from “neutron” target(s)

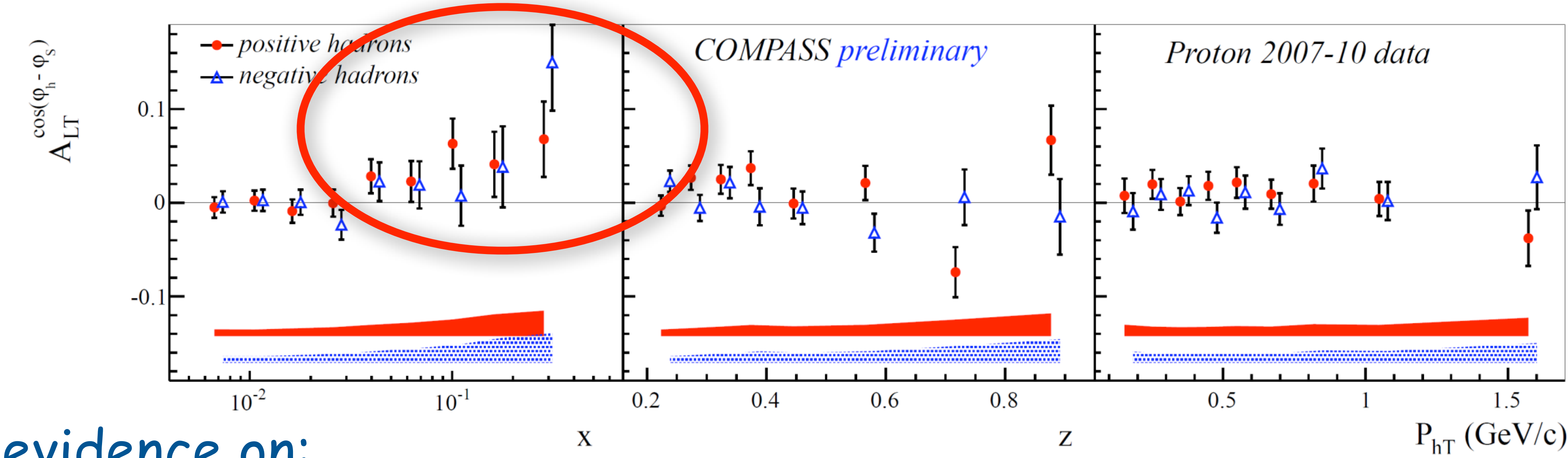
(valid for all chiral-odd TMDs)

Transversity's friends

Worm-Gear II

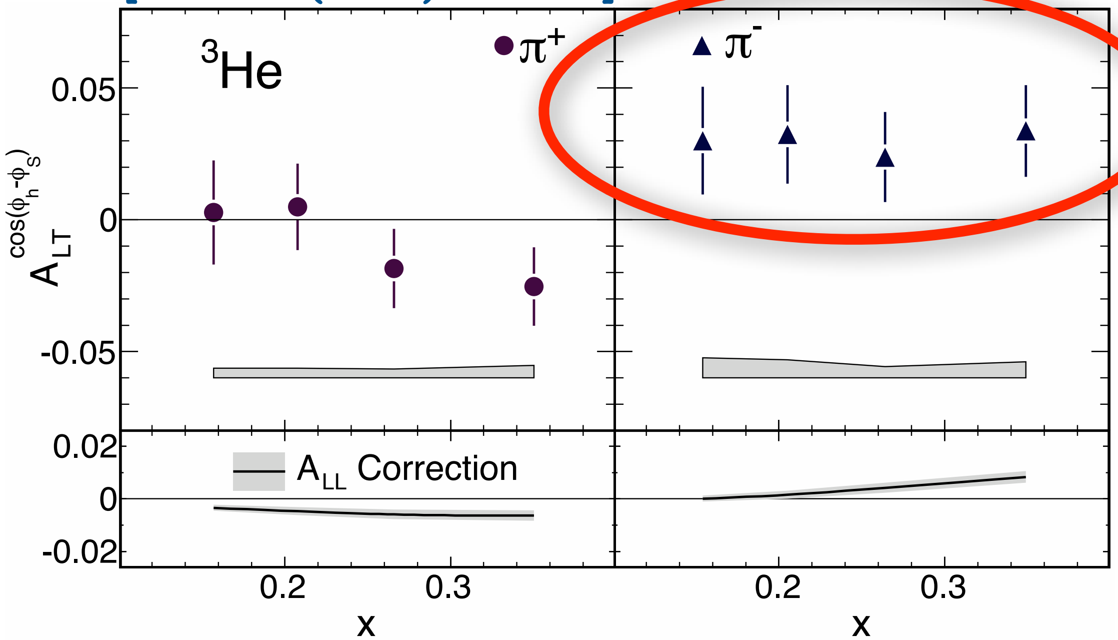
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

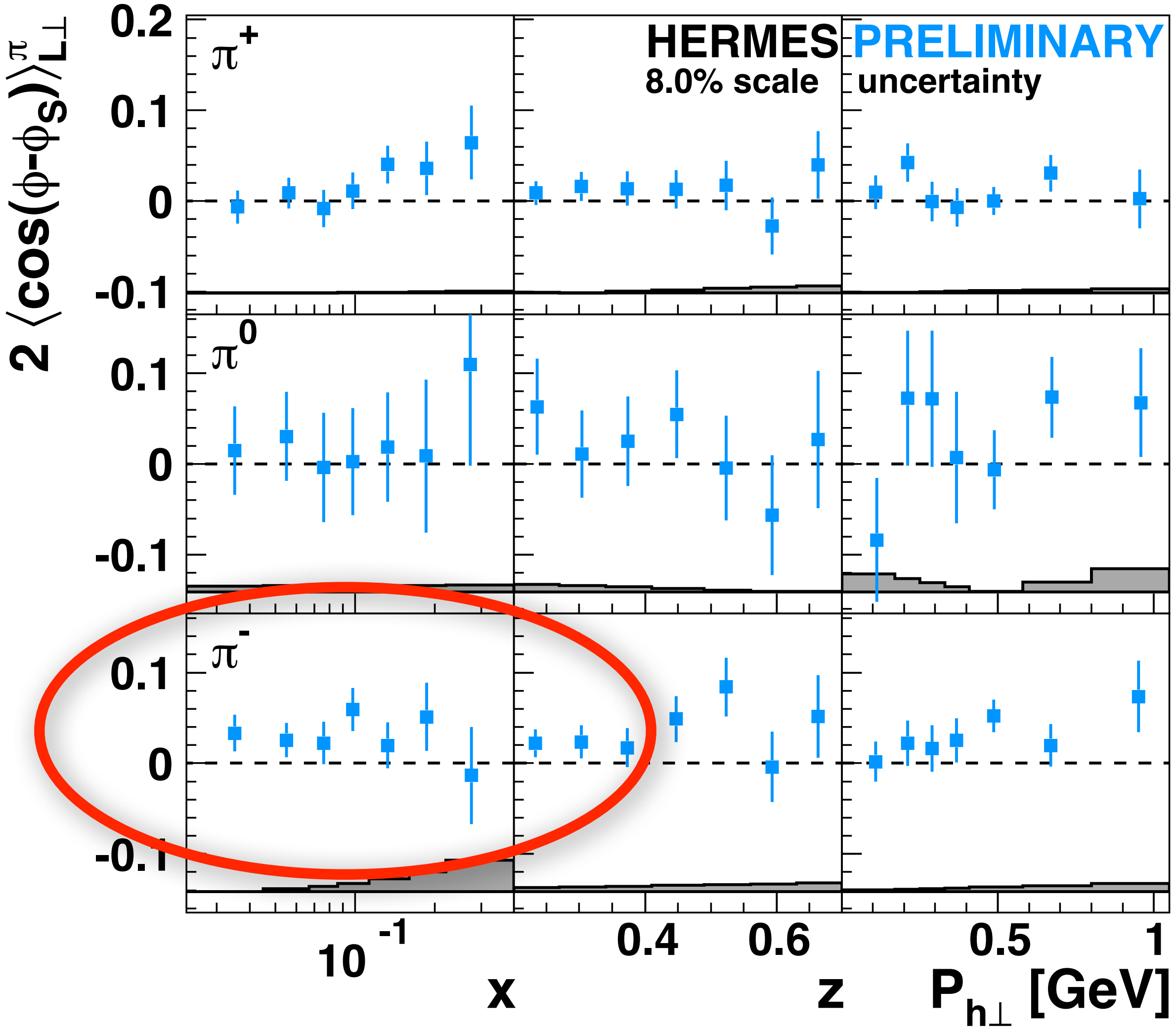




- first direct evidence on:
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

[PRL 108 (2012) 052001]

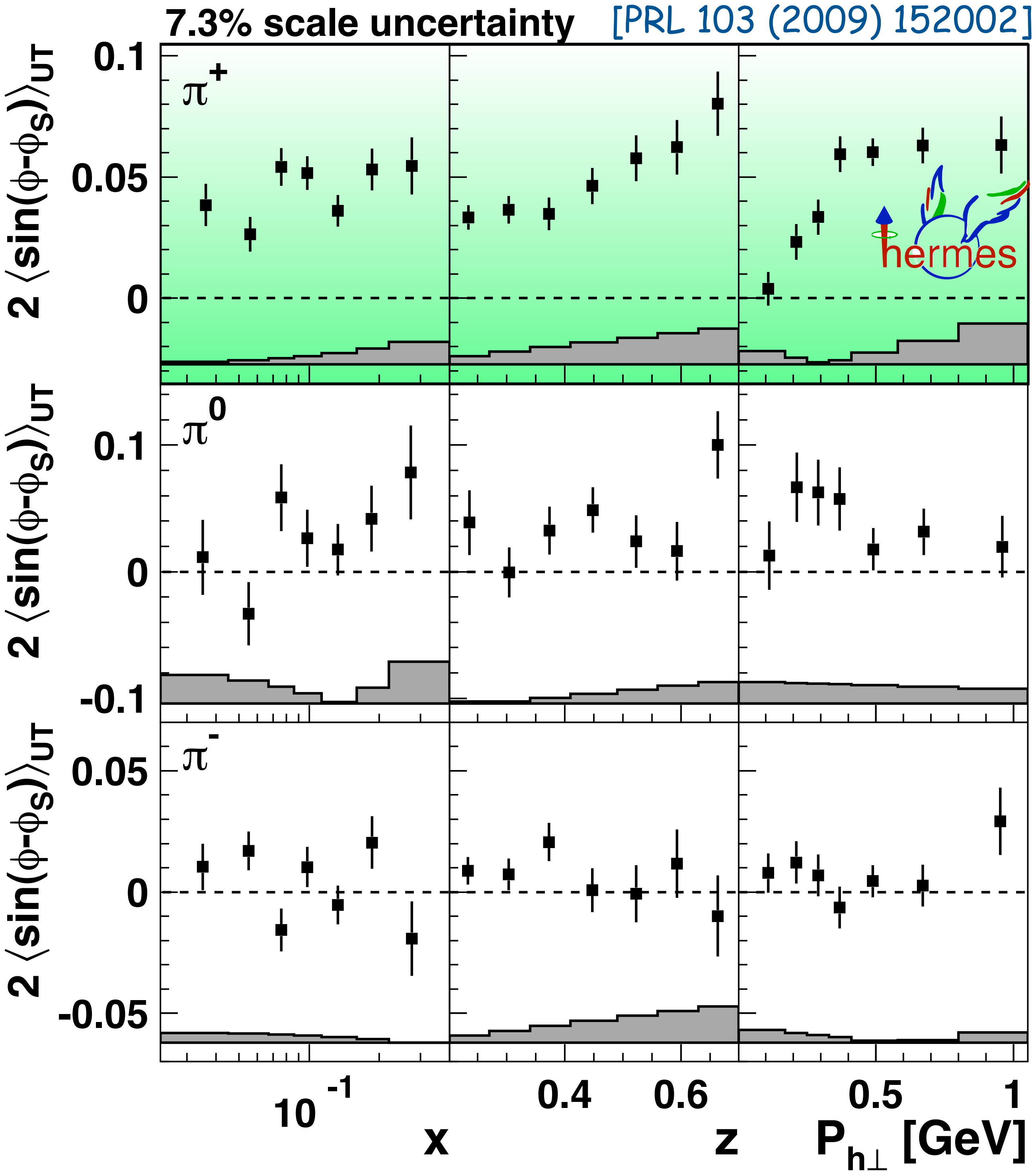




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

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



[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}	$h_1,\ h_{1T}^\perp$

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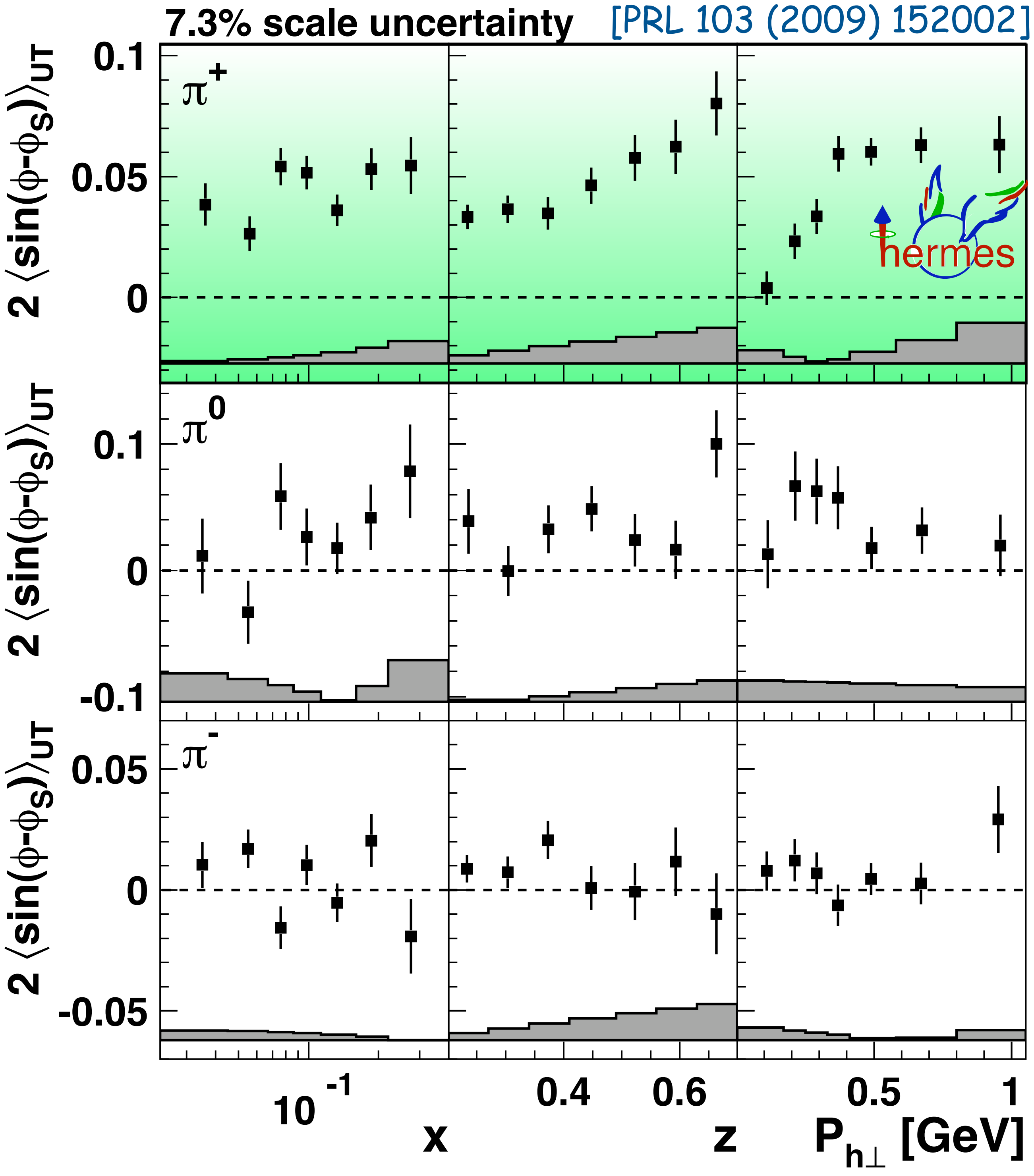

π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

	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

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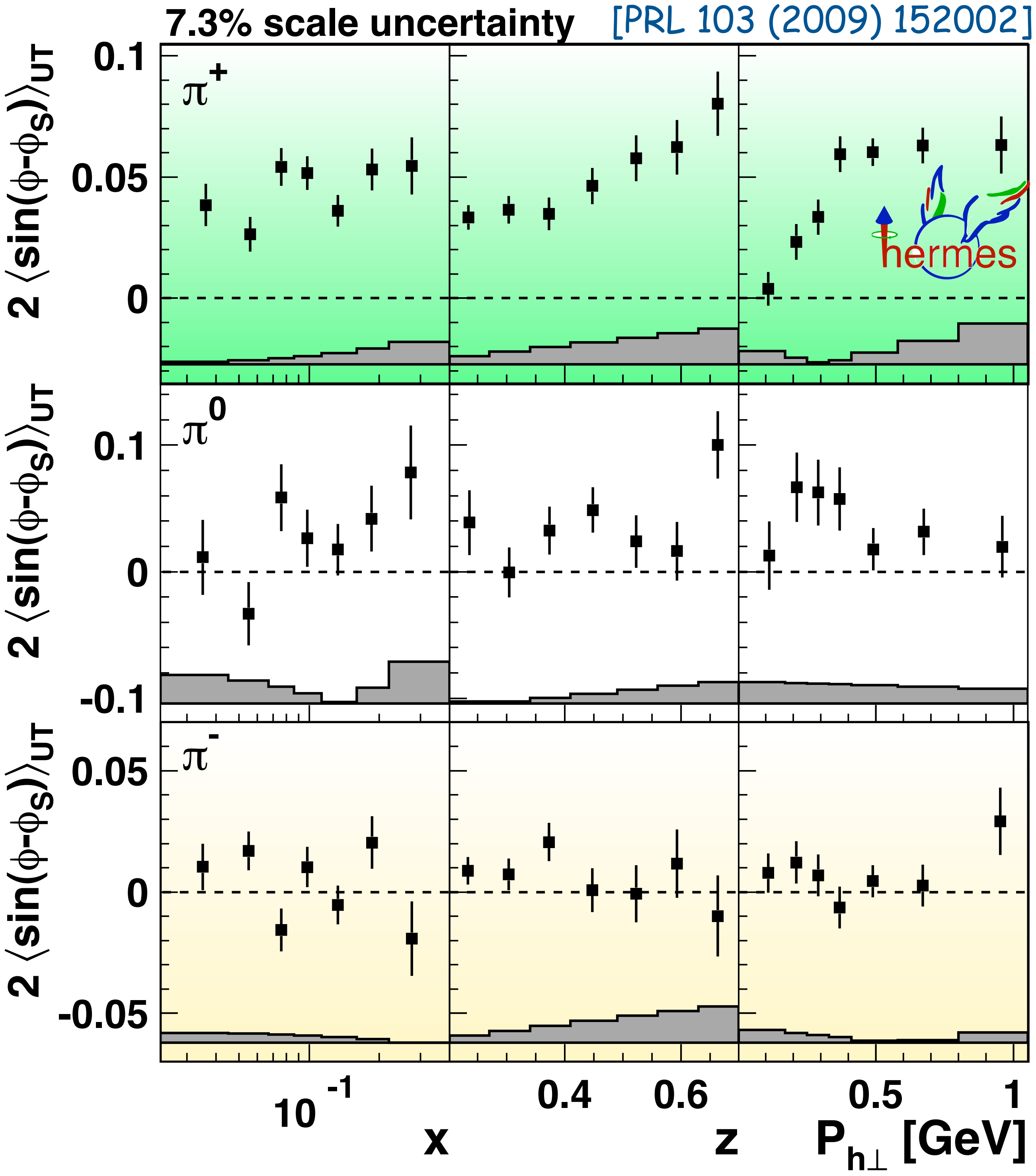

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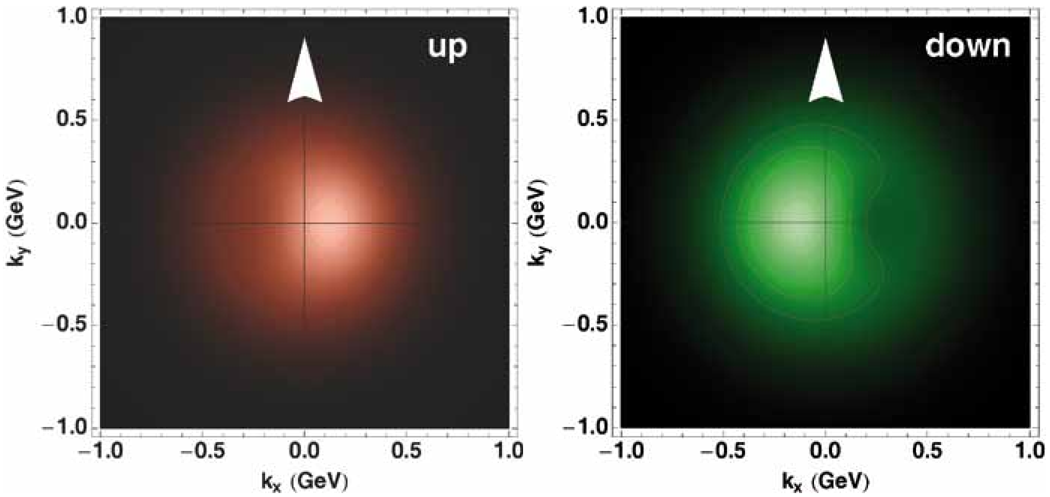
$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

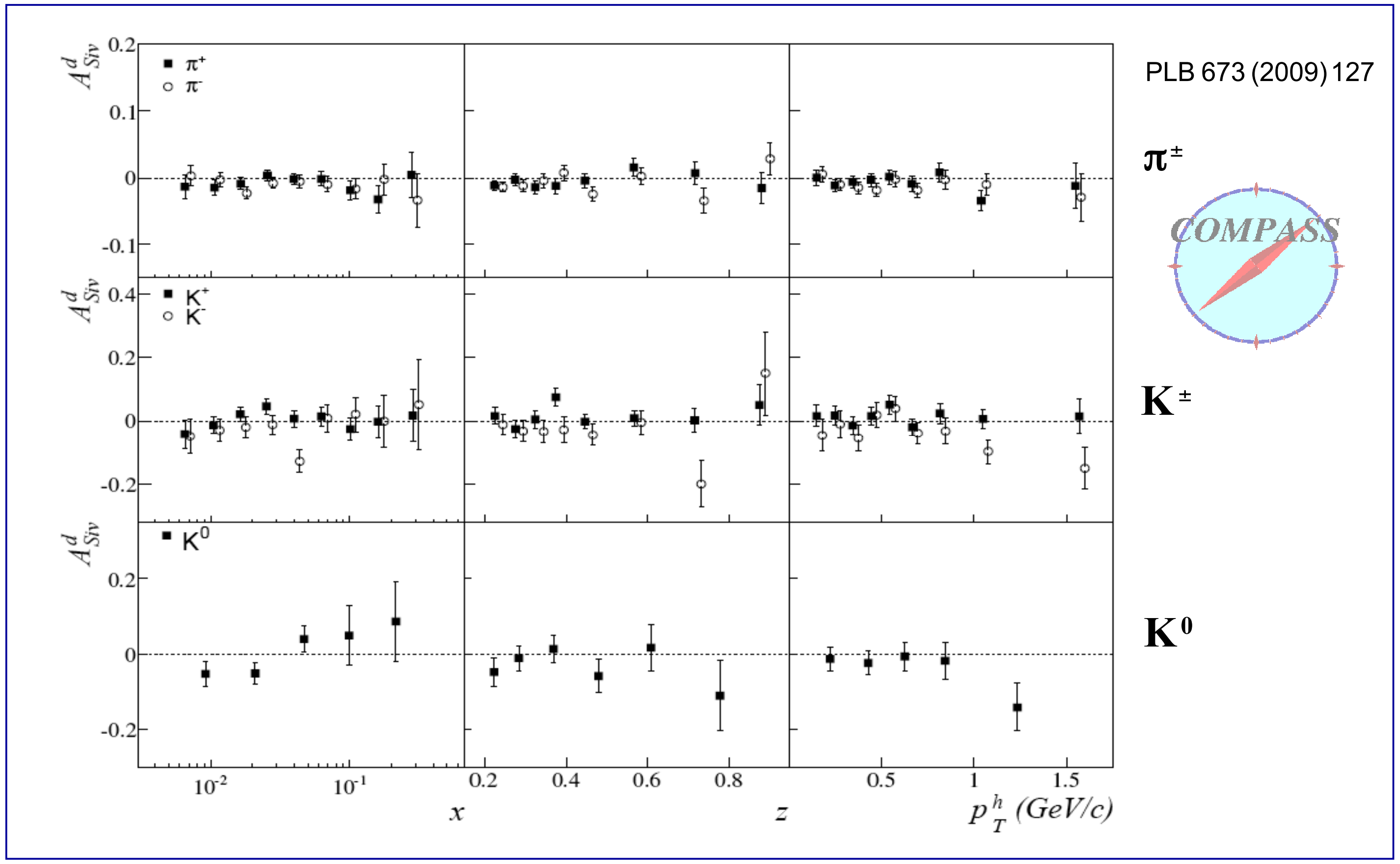
☛ d-quark Sivers DF > 0 (cancelation for π^-)

	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



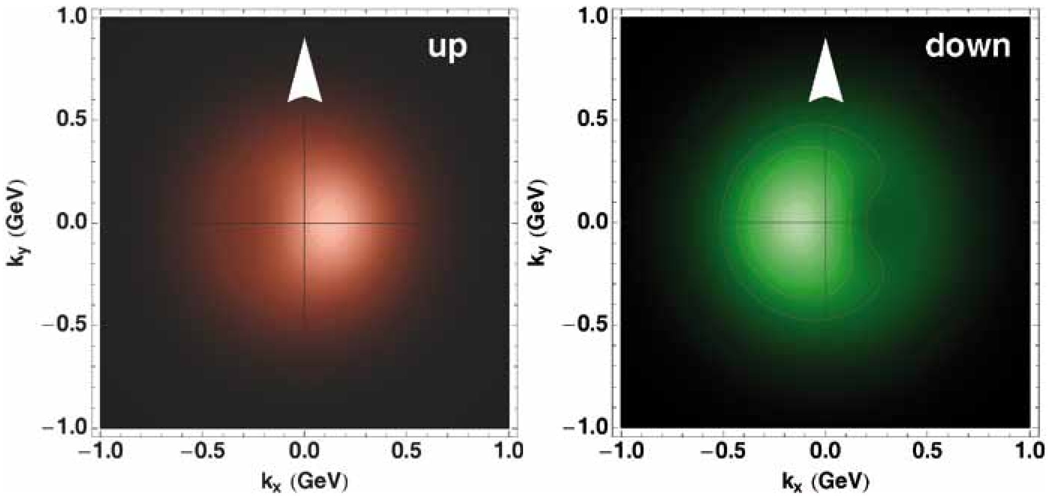
[A. Bacchetta et al.]



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

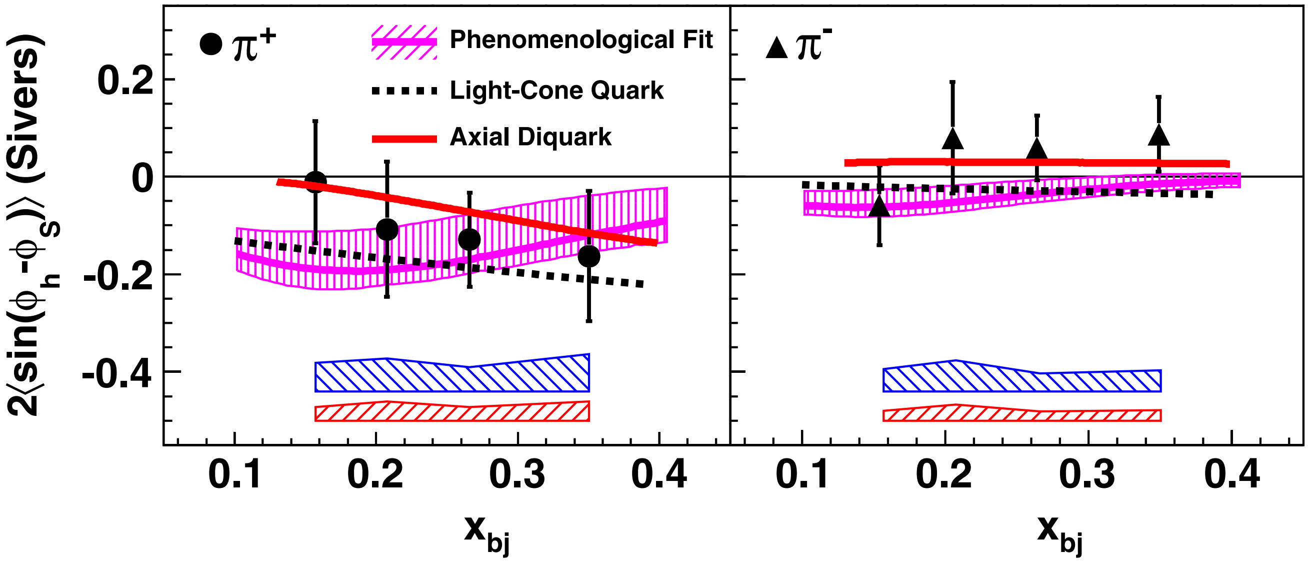
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes

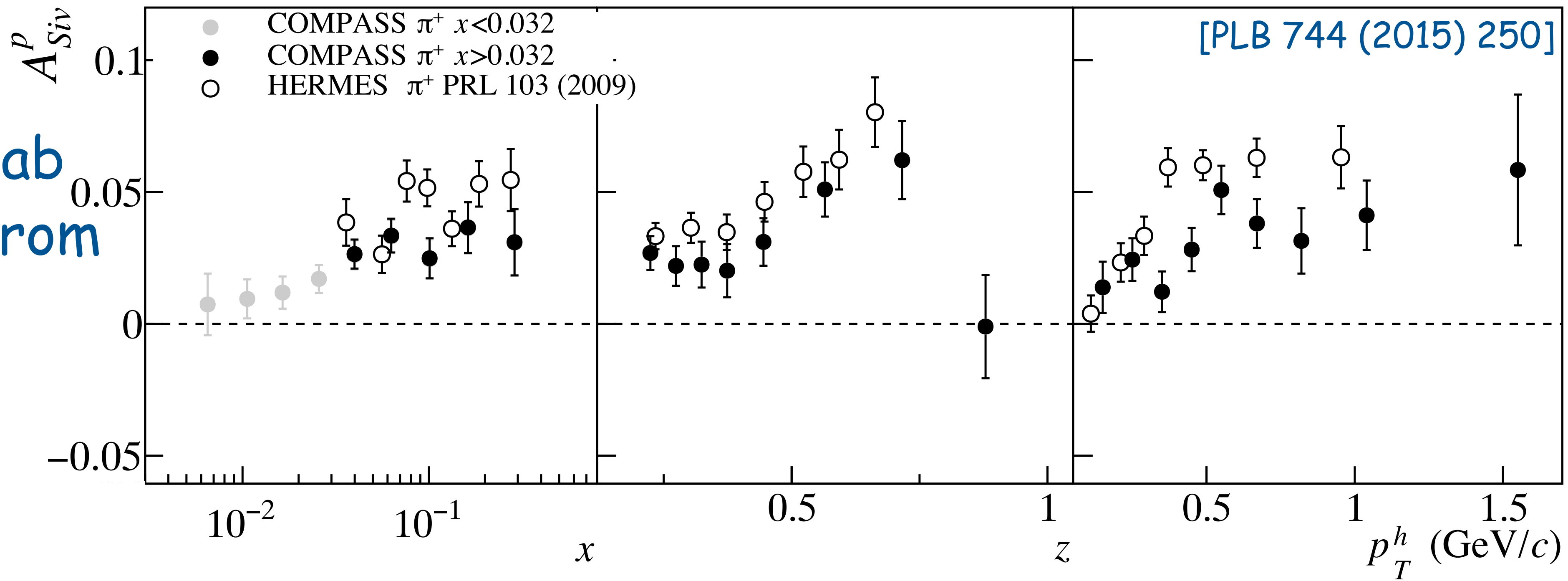


[A. Bacchetta et al.]

[PRL 107 (2011) 072003]



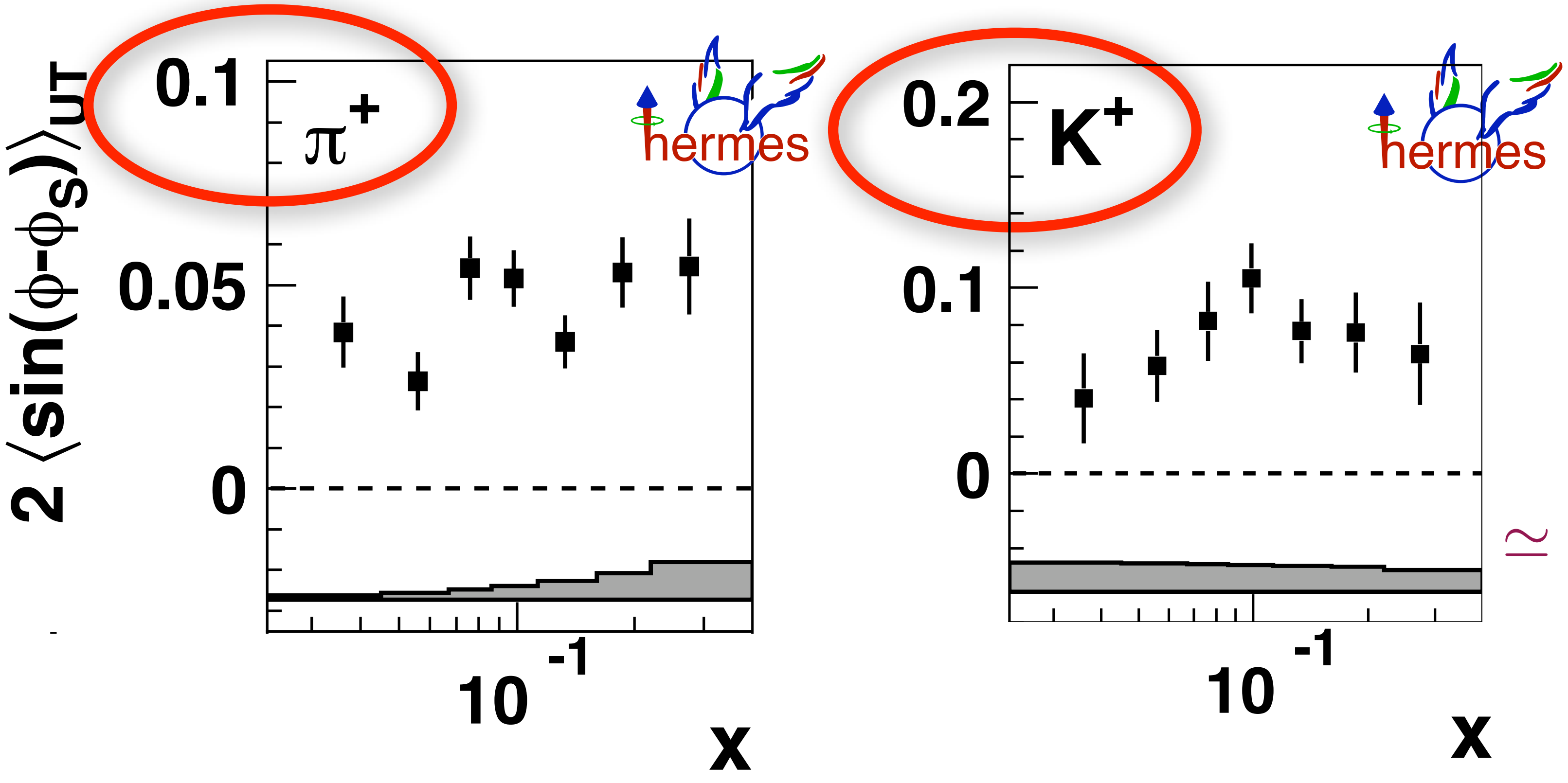
- cancelation for D target supports opposite signs of up and down Sivers
- newer results from JLab using ^{3}He target and from COMPASS for proton target (also multi-d)



[PLB 744 (2015) 250]

	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 pions vs. kaons



somewhat unexpected if dominated by scattering off u-quarks:

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

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

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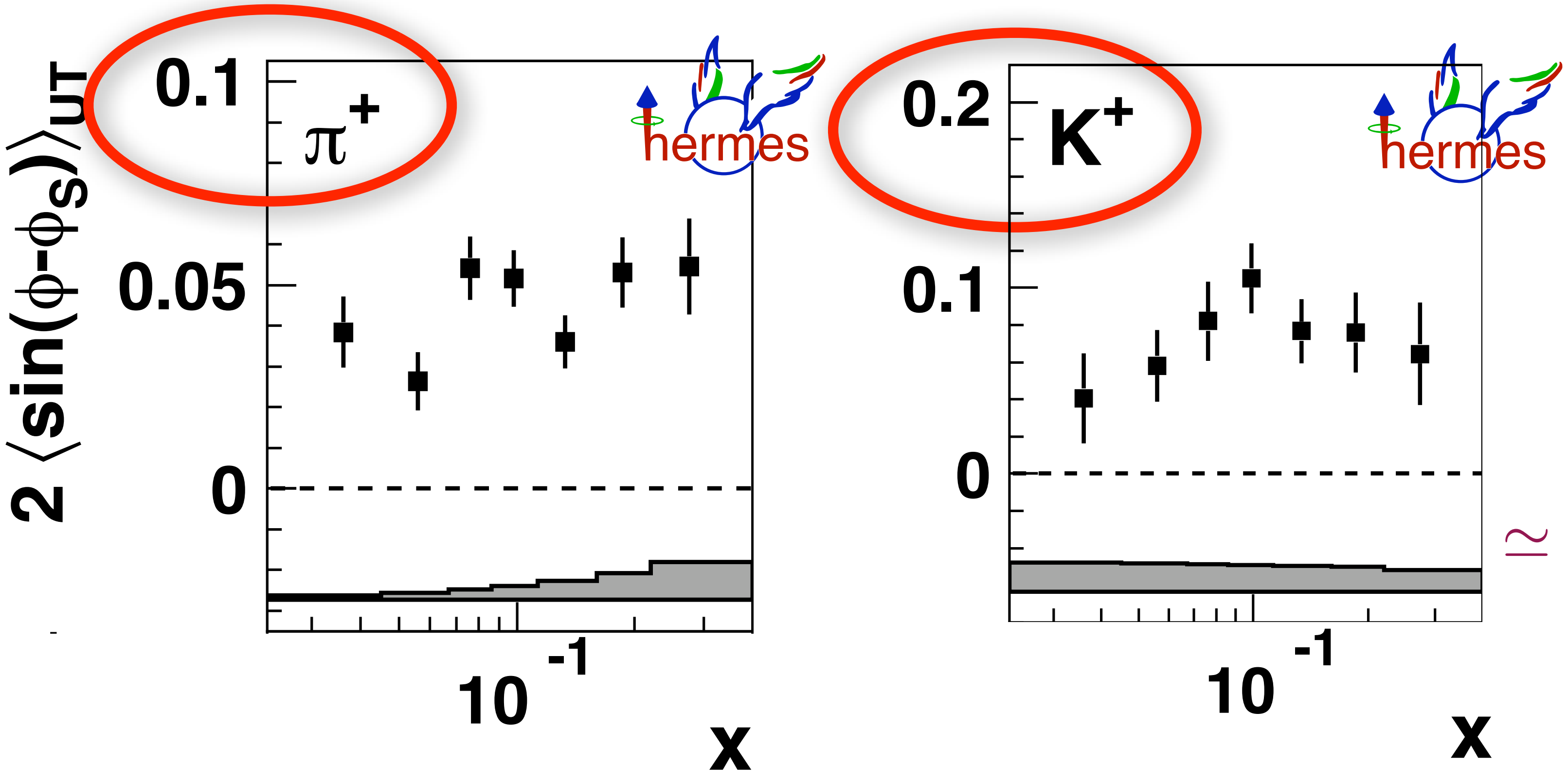

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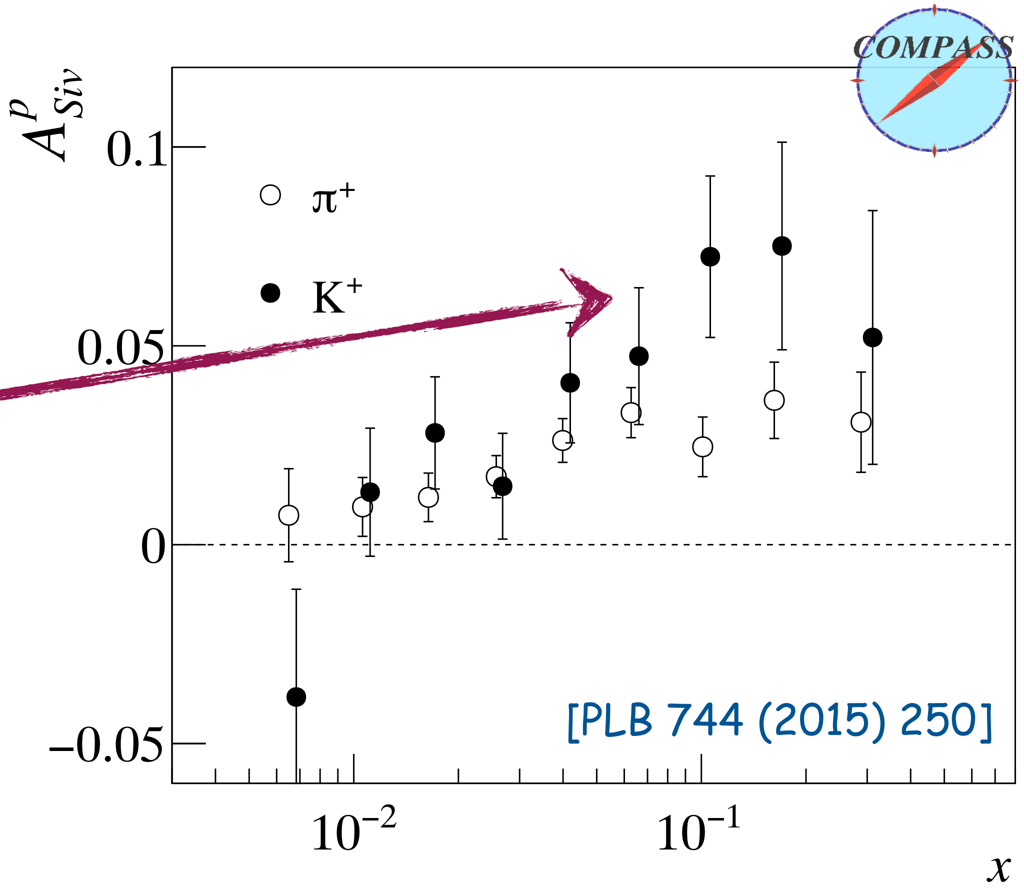
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$$

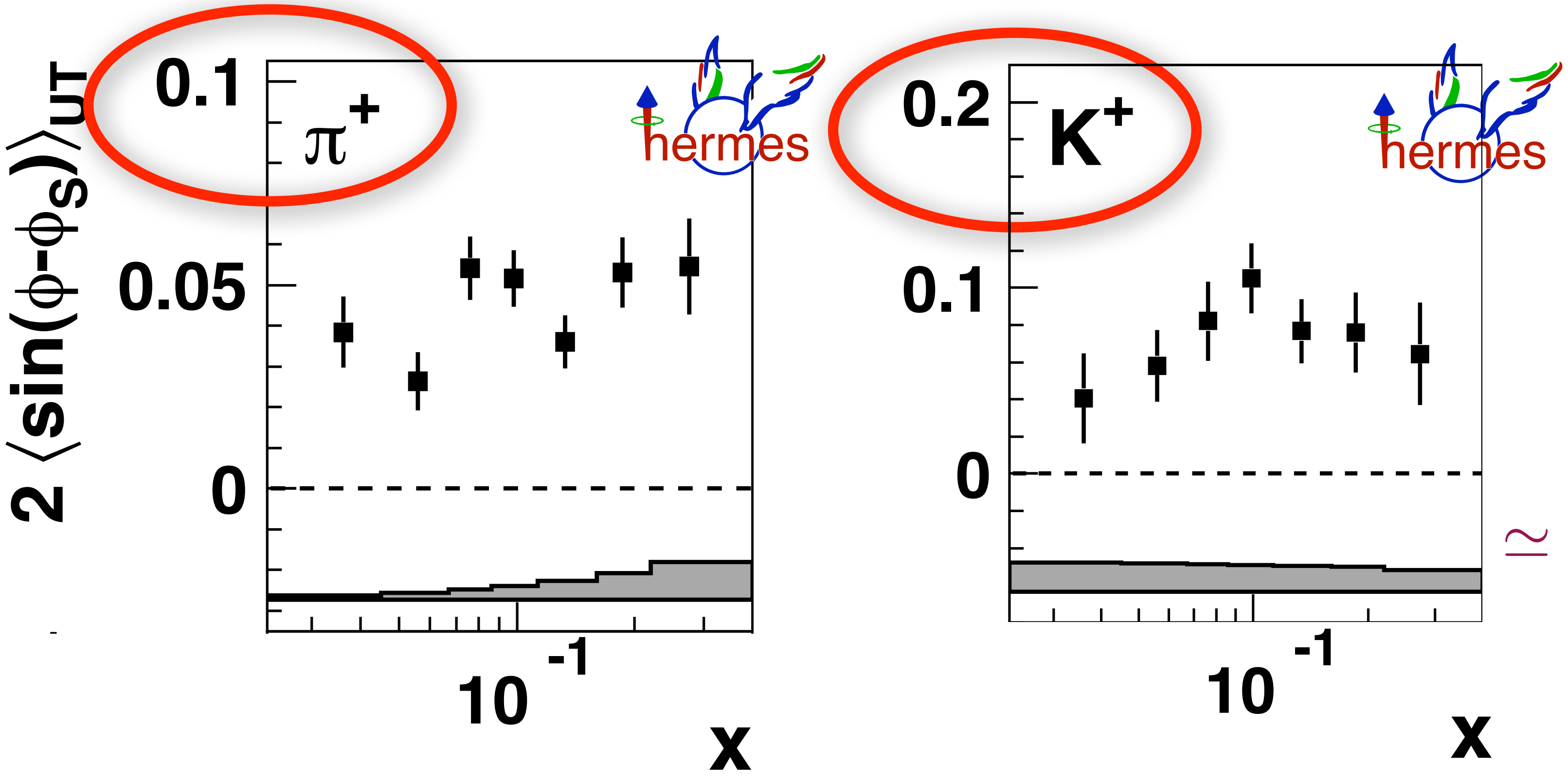
larger amplitudes seen also by COMPASS



[PLB 744 (2015) 250]

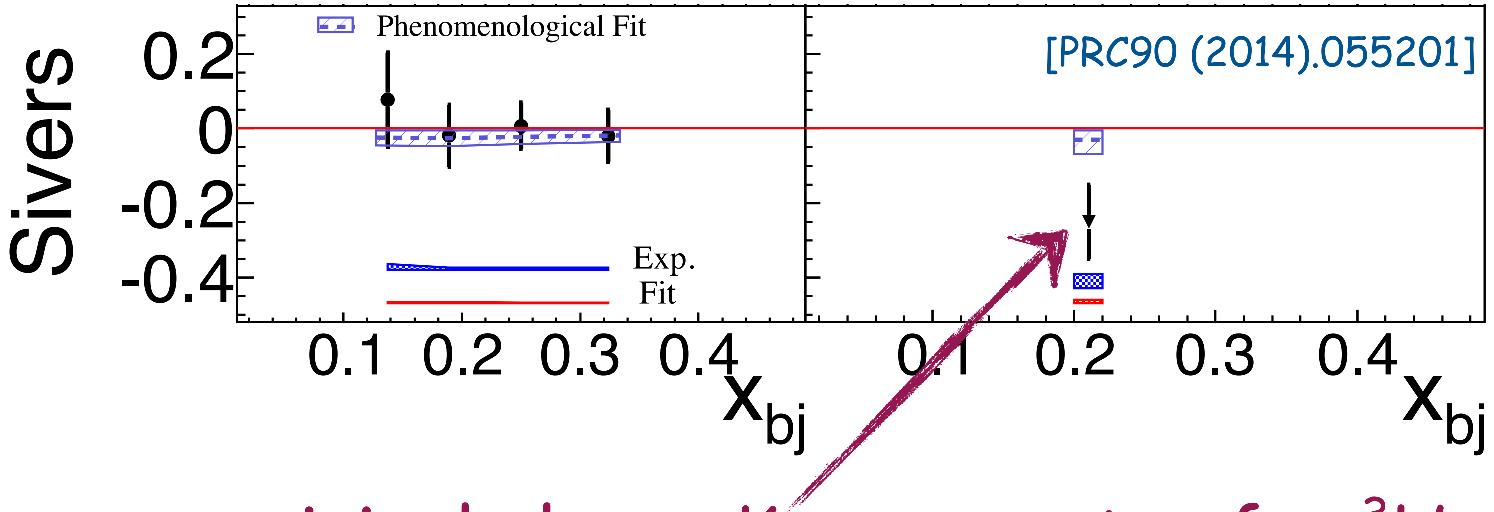
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes pions vs. kaons



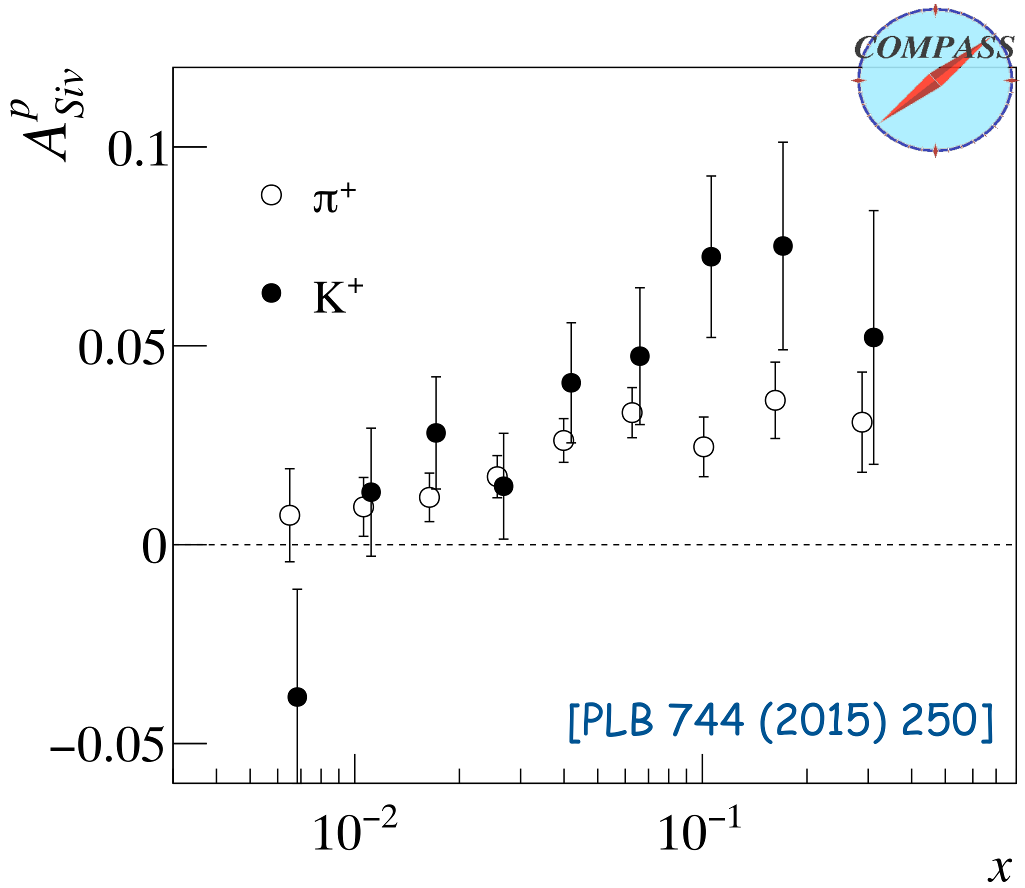
somewhat unexpected if dominated by scattering off u-quarks:

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



[PRC90 (2014).055201]

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



[PLB 744 (2015) 250]

conclucions

- first round of SIDIS measurements coming to an end
- various indications of flavor-dependent transverse momentum
- transversity is non-zero and quite sizable
  - can be measured, e.g., via Collins effect
  - d-quark transversity difficult to access with only proton targets
- Sivers function also clearly non-zero
  - opposite sign for up and down quarks in line with their contributions to the nucleon's anomalous magnetic moment
- precision measurements at ongoing and future SIDIS facilities needed to fully map TMD landscape
- in particular, several intriguing results for neutron targets motivate program with polarized D and ^{3}He