3D Parton Distributions: Path to the LHC

November 29th - December 2nd, 2016 - LNF, Frascati, Italy

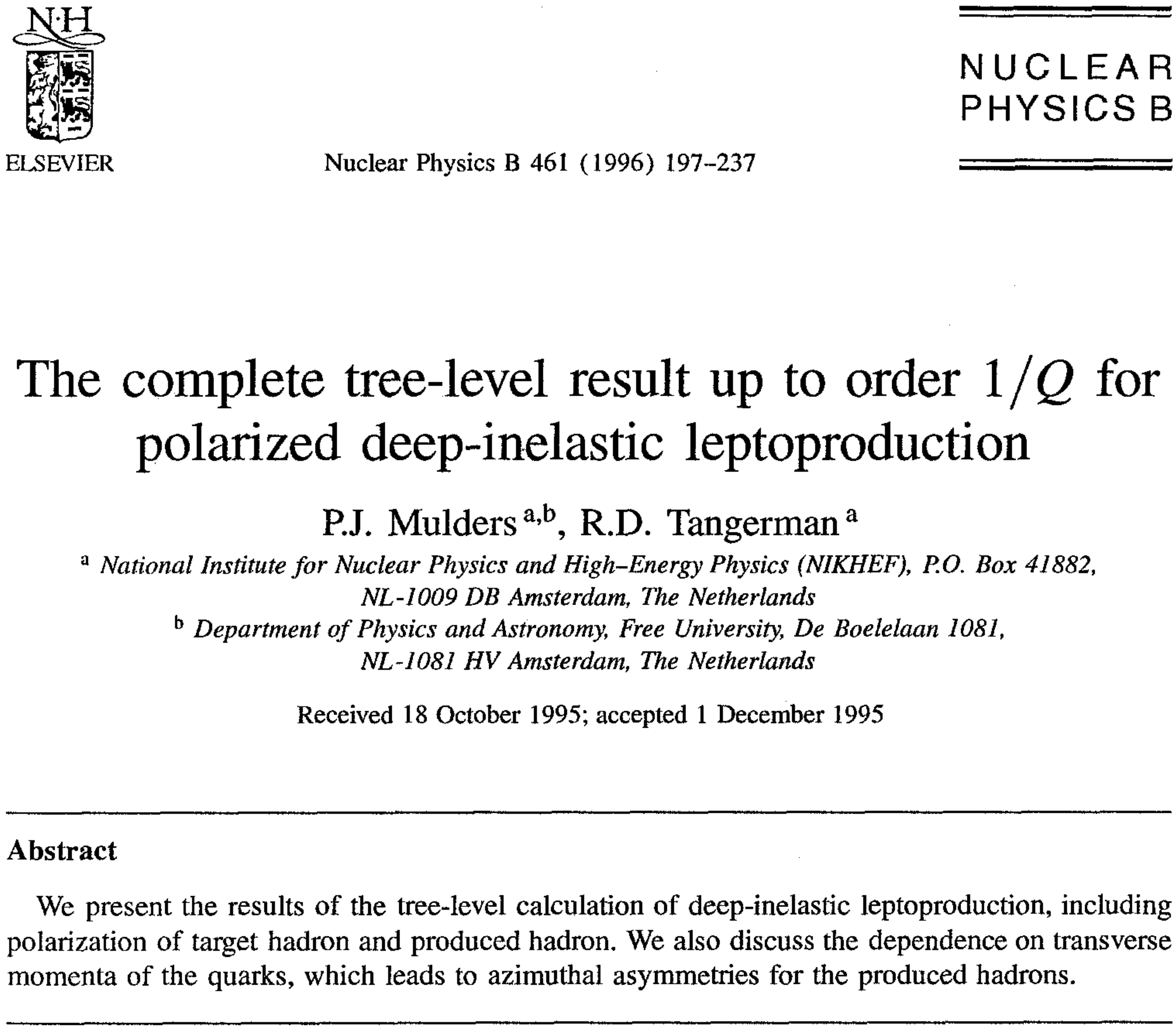
Studies of TMDs at hermes

Gunar.Schnell @ desy.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

21 years ago



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Nuclear Physics B 461 (1996) 197–237
NUCLEAR PHYSICS B

The complete tree-level result up to order $1/Q$ for polarized deep-inelastic leptoproduction

P.J. Mulders [a,b], R.D. Tangerman [a]

[a] *National Institute for Nuclear Physics and High–Energy Physics (NIKHEF), P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands*
[b] *Department of Physics and Astronomy, Free University, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands*

Received 18 October 1995; accepted 1 December 1995

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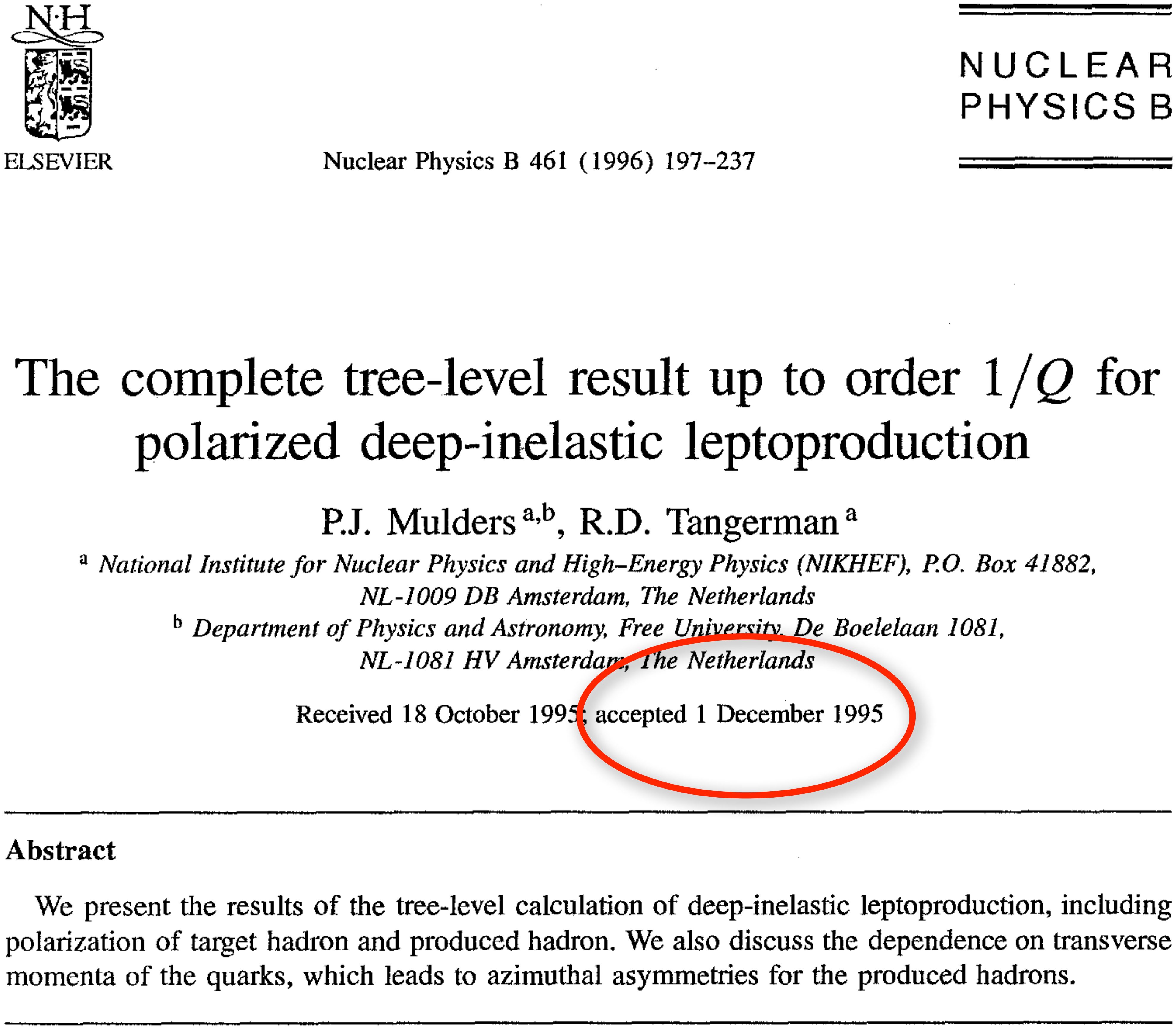

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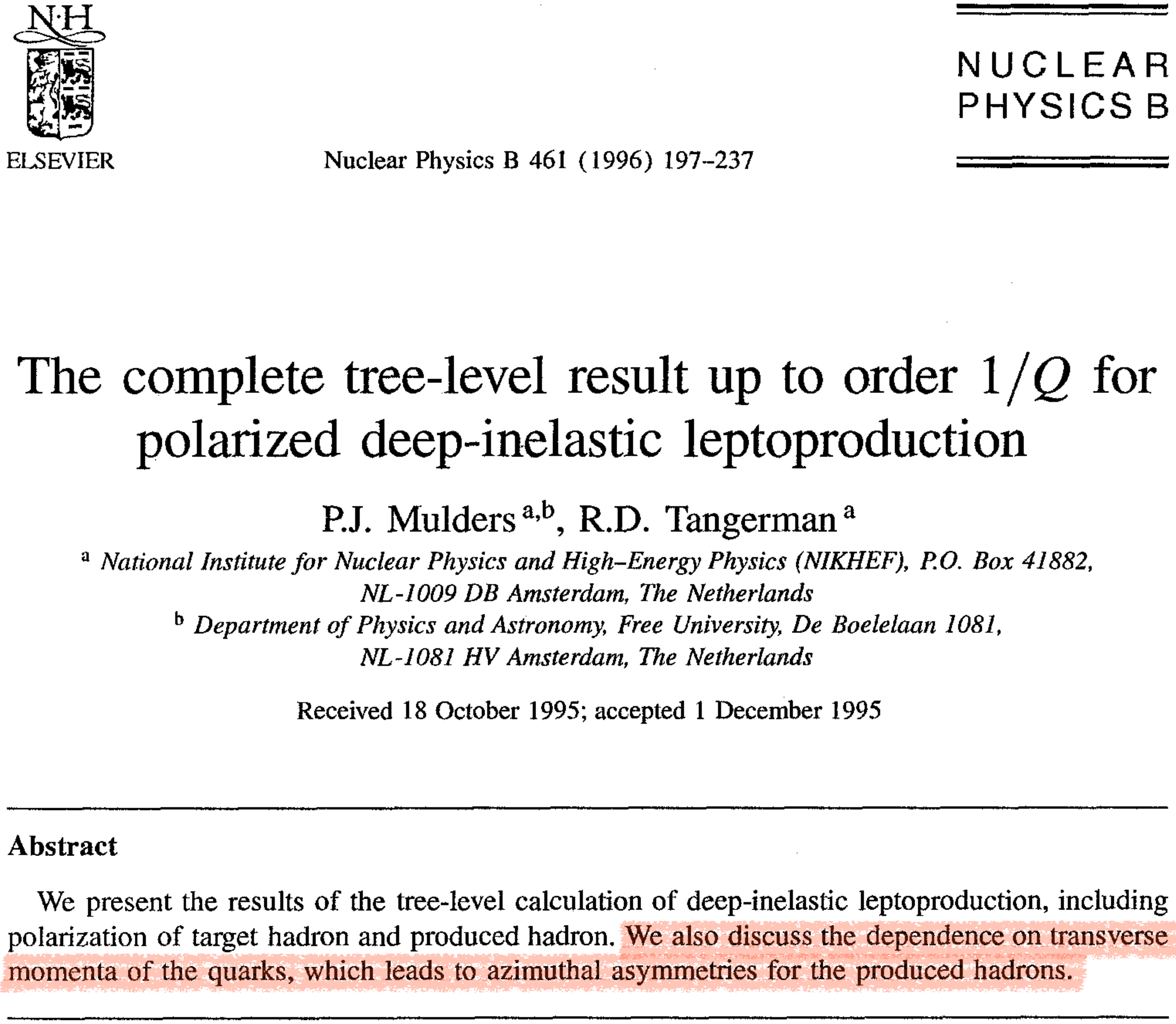

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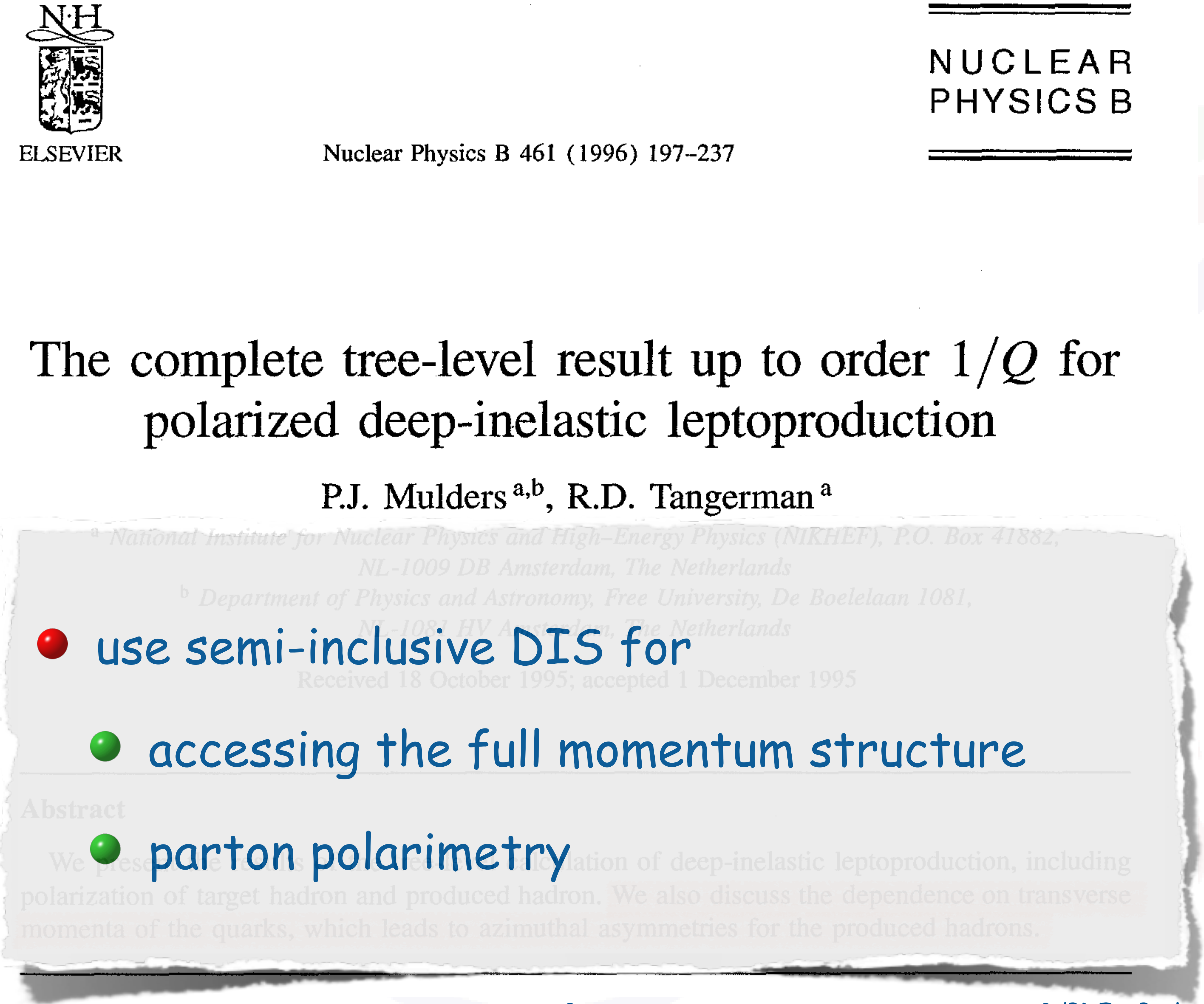

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- use semi-inclusive DIS for
  - accessing the full momentum structure
  - parton polarimetry

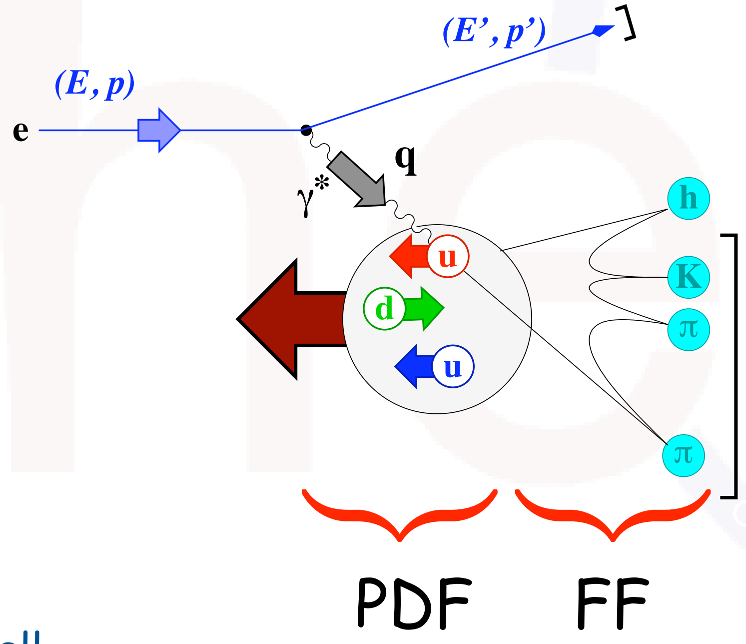
probing TMDs in semi-inclusive DIS

quark pol.

nucleon pol.

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

in SIDIS*) couple PDFs to:



*) semi-inclusive DIS with unpolarized final state

probing TMDs in semi-inclusive DIS

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

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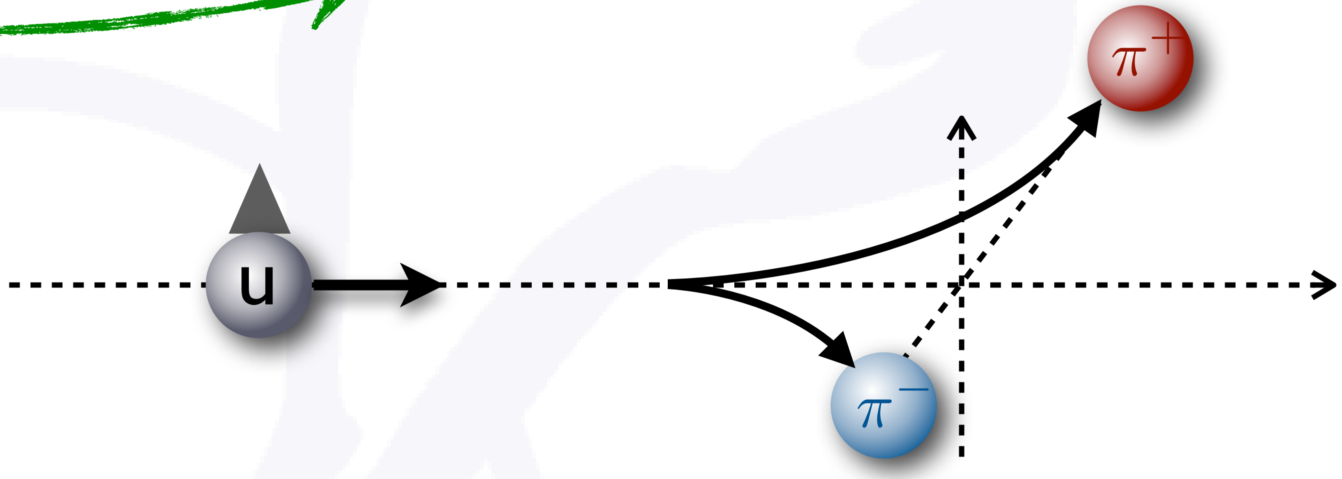
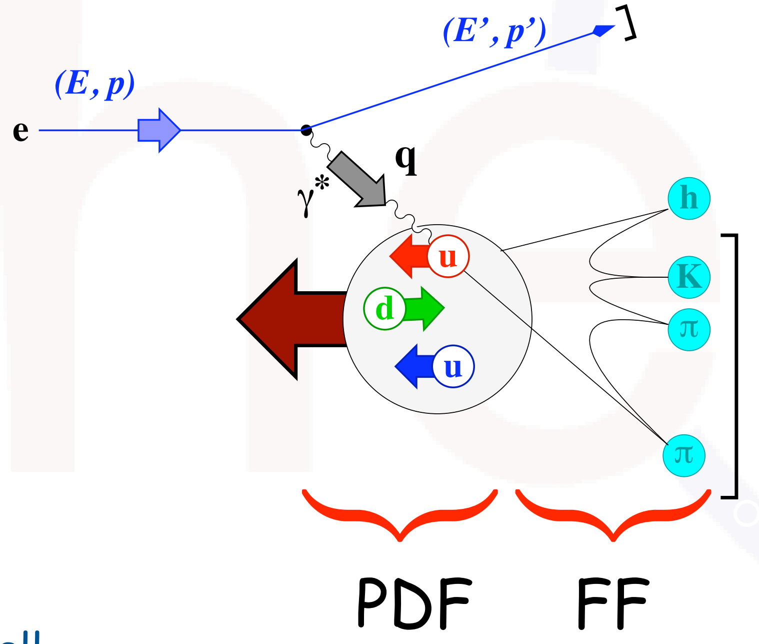
Collins FF: $H_1^{\perp,q\to h}$





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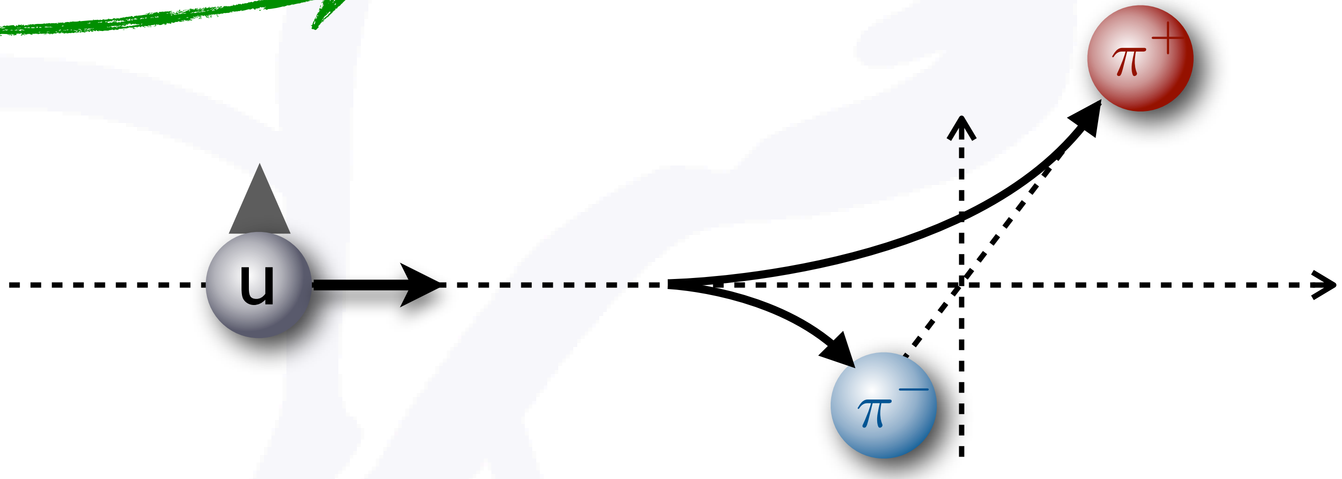

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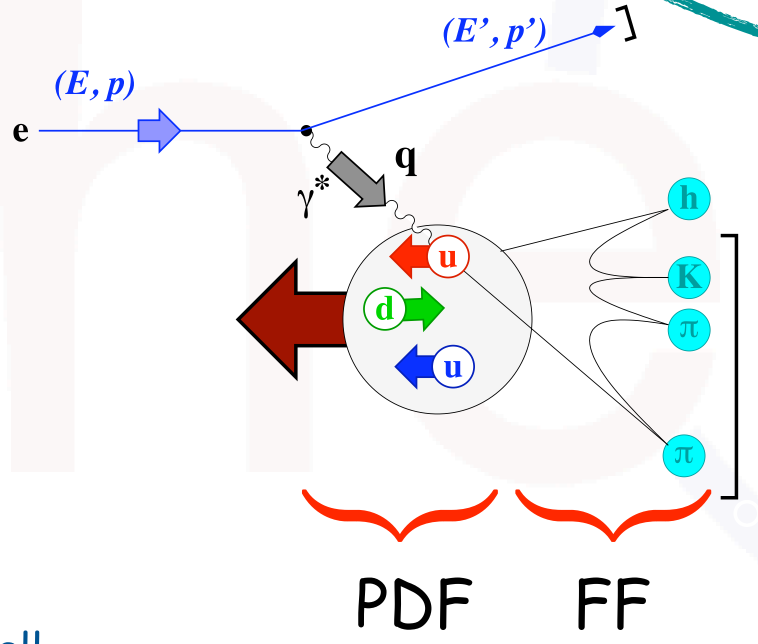

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probing TMDs in semi-inclusive DIS

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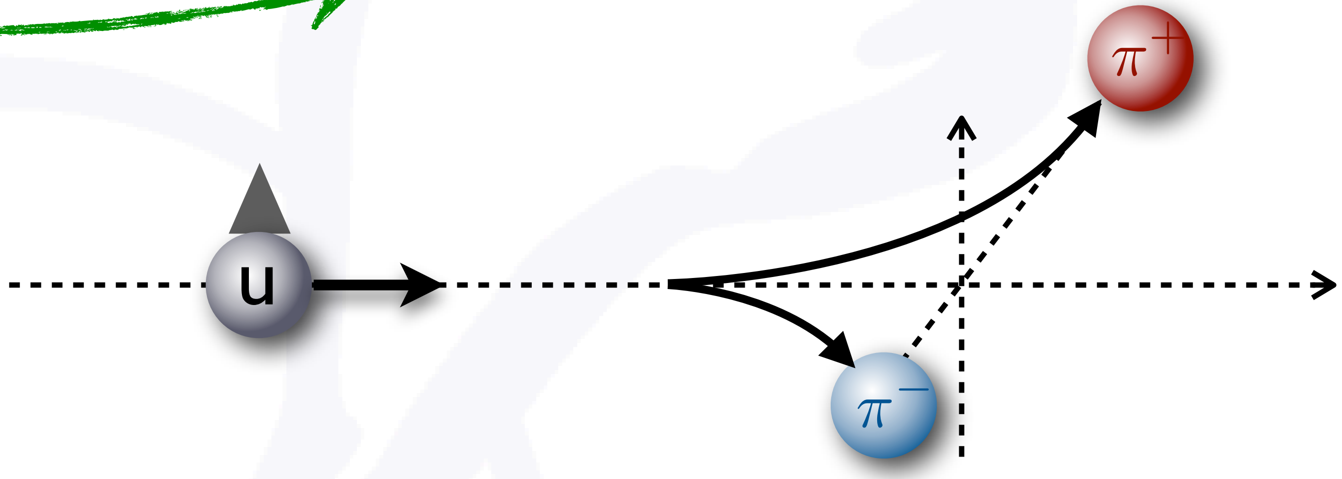


ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

one-hadron production (ep→ehX)

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

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

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

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

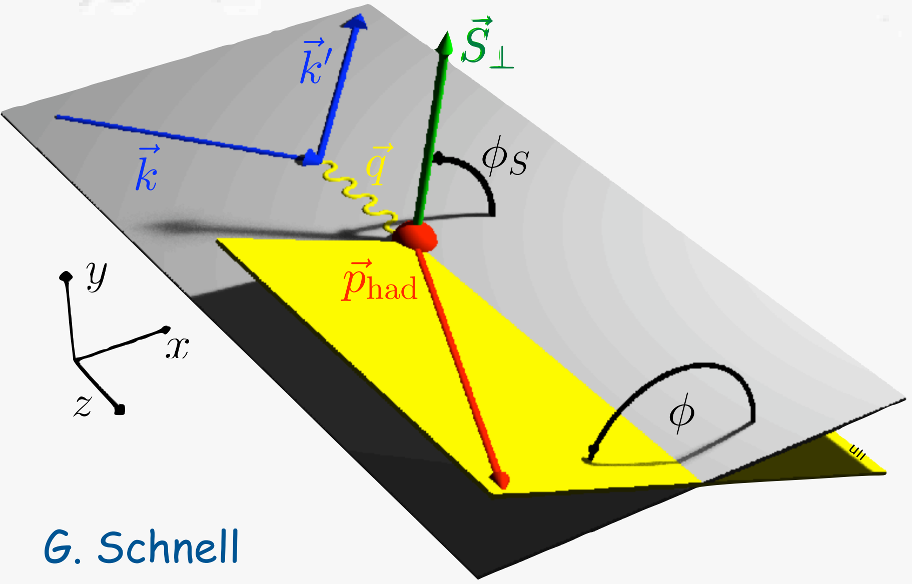
$$\left. +\lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT}\right) \right] \right\}$$

$$\sigma_{XY}$$

$$\swarrow \quad \searrow$$

Beam **Target**

Polarization



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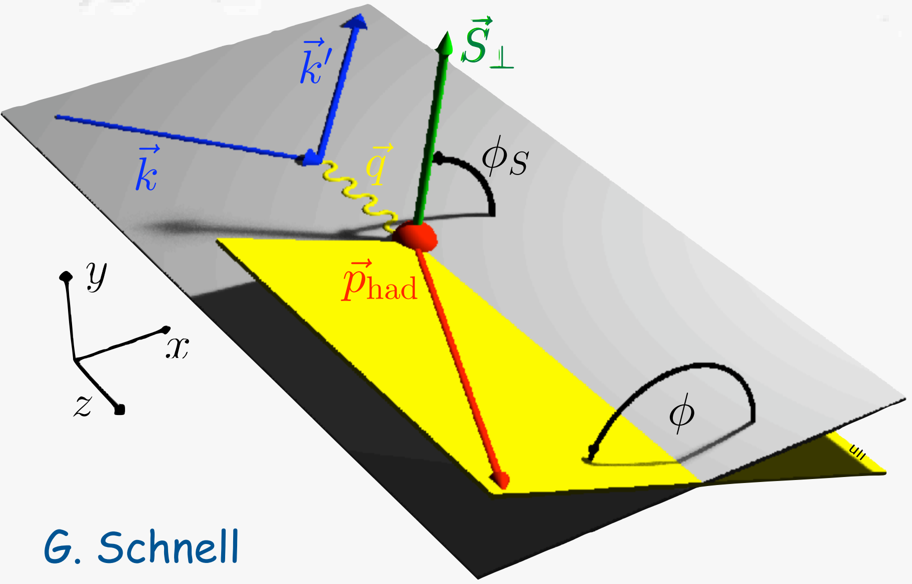
σ_{XY}

Beam **Target**
Polarization



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σ_{XY}

Beam **Target**

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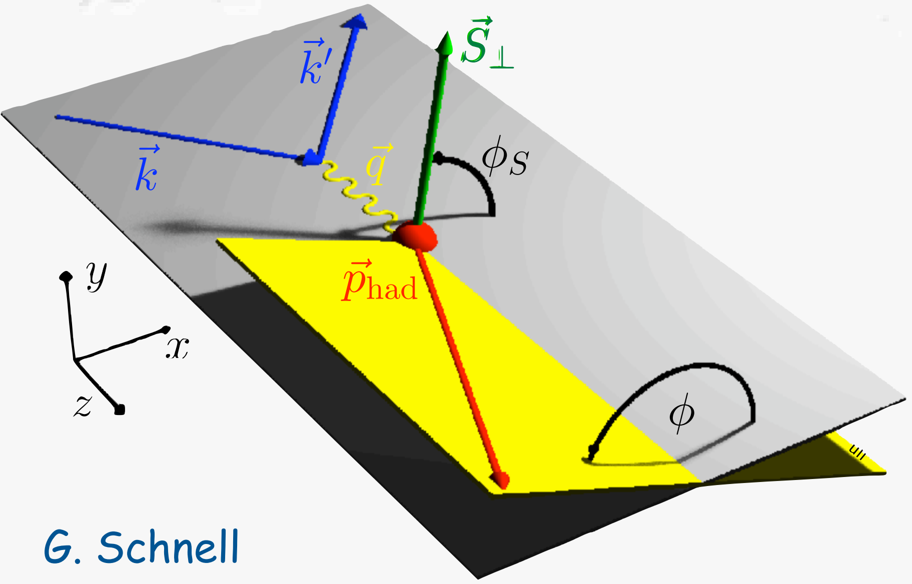

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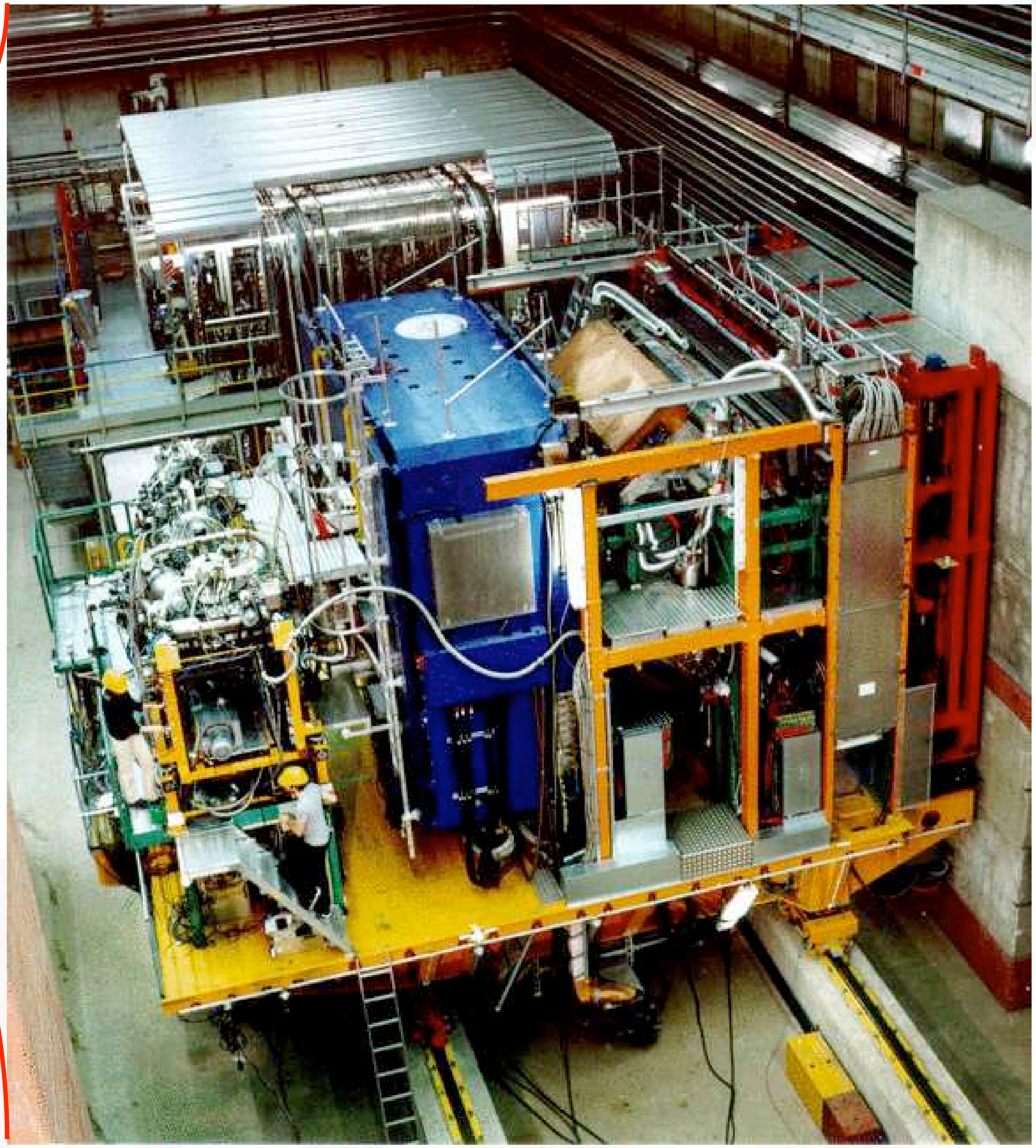
The HERMES Experiment

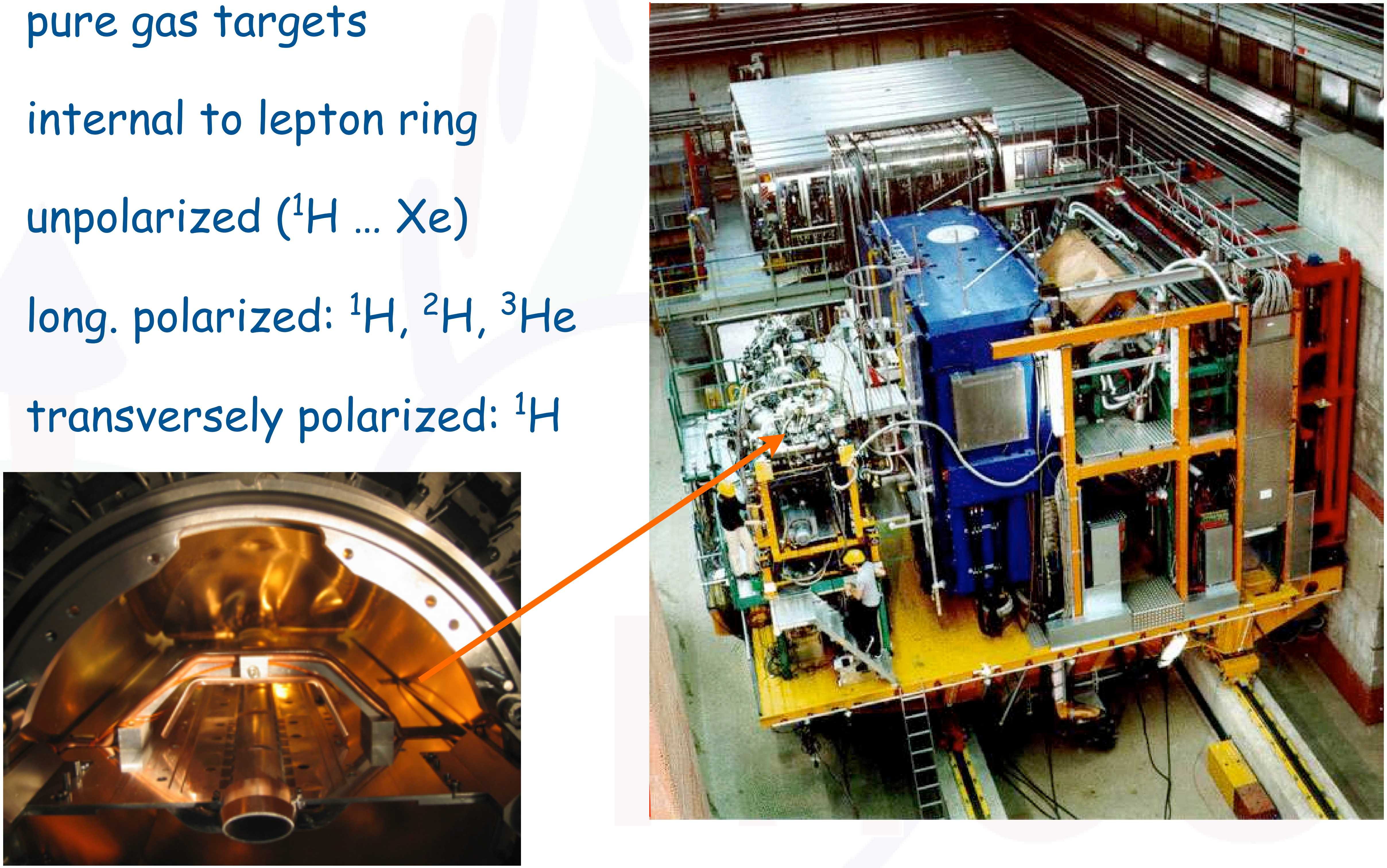
- 27.6 GeV HERA e^+/e^- beam



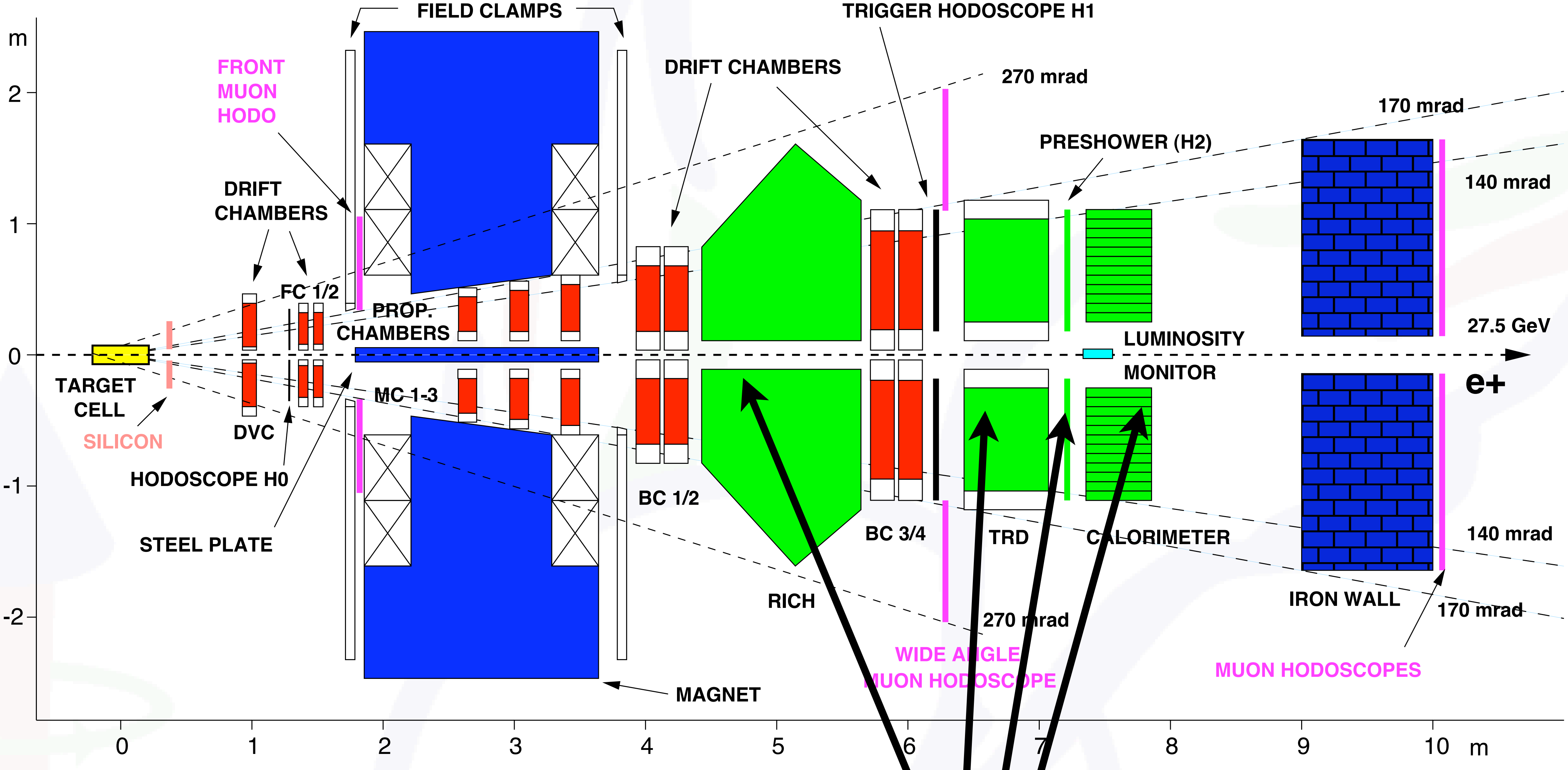
- longitudinally polarized

The HERMES Experiment

- pure gas targets
- internal to lepton ring
- unpolarized (^{1}H … Xe)
- long. polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H



HERMES schematically



- pure gas targets internal to HERA 27.6 GeV lepton ring
- unpolarized (^{1}H … Xe)
- long. polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

hadron multiplicities in DIS

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

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

$$F_{XY,Z} = F_{\underset{\underset{\text{beam polarization}}{\Uparrow}}{X}\overset{\overset{\text{target polarization}}{\Downarrow}}{Y},\underset{\underset{\text{virtual-photon polarization}}{\Uparrow}}{Z}}(x,y,z,P_{h\perp})$$

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

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

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

hadron multiplicities in DIS

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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

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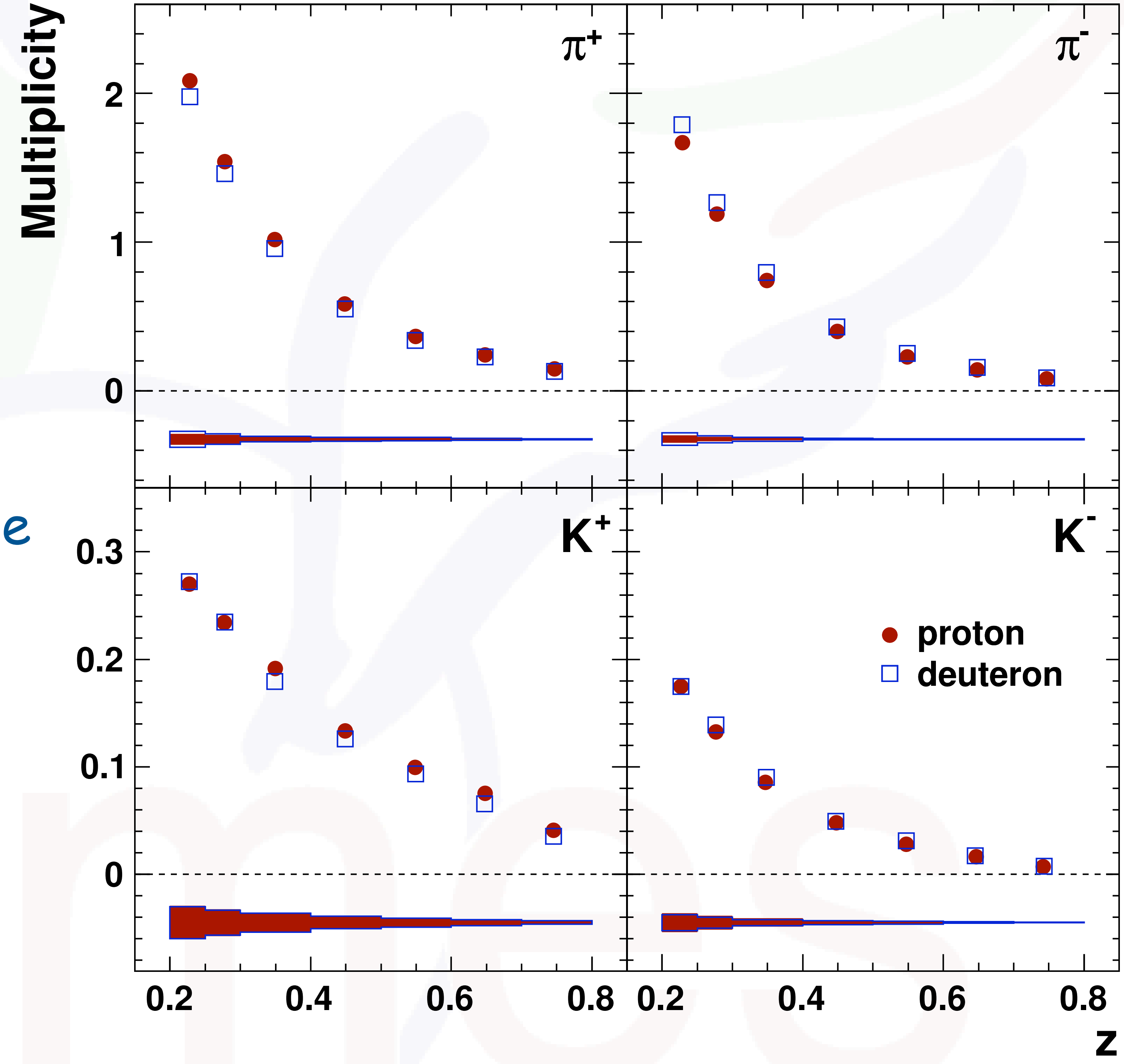
multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons http://www-hermes.desy.de/multiplicities
- extracted in a multi-dimensional unfolding procedure

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



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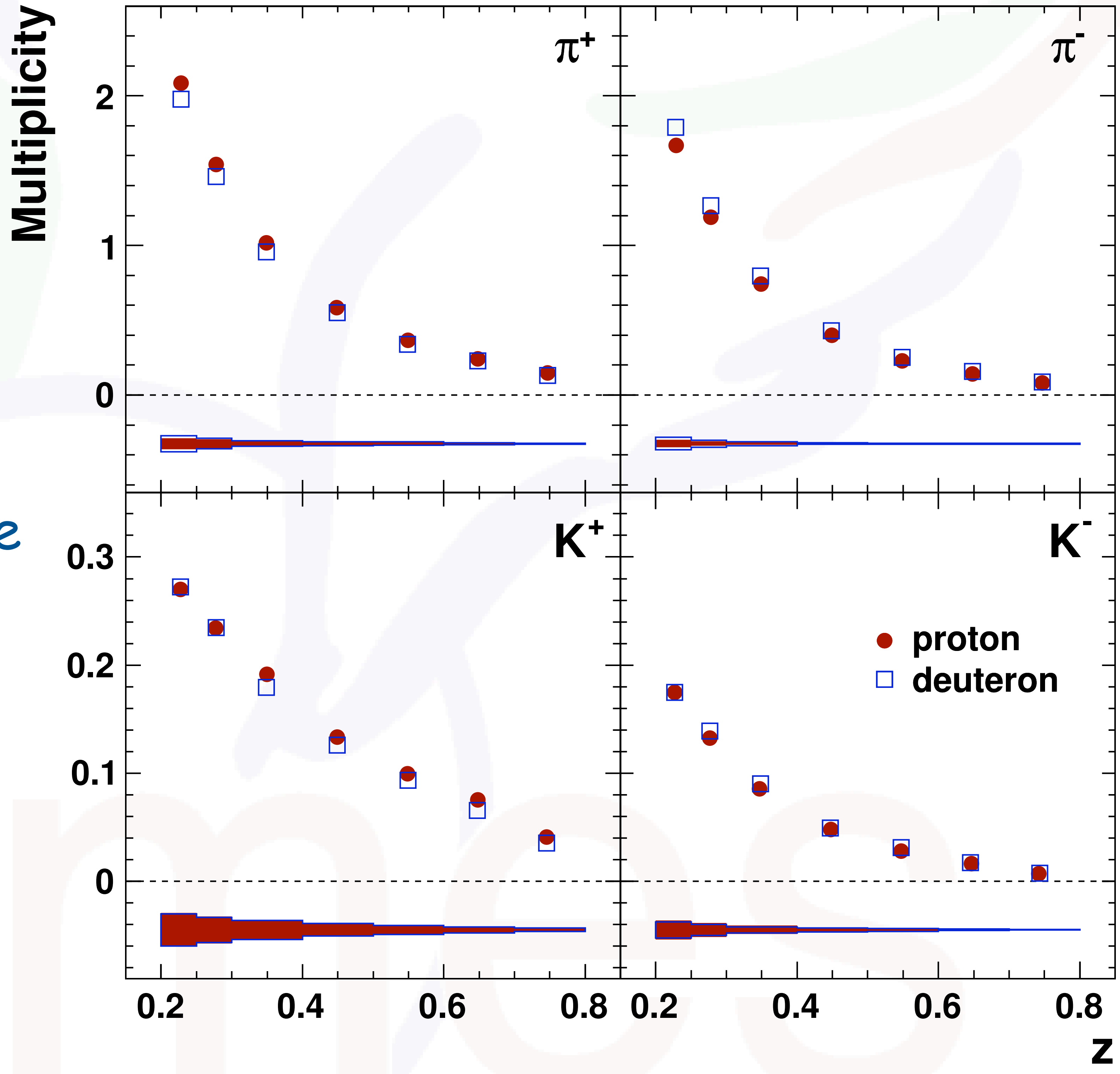

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- input to fragmentation function analyses

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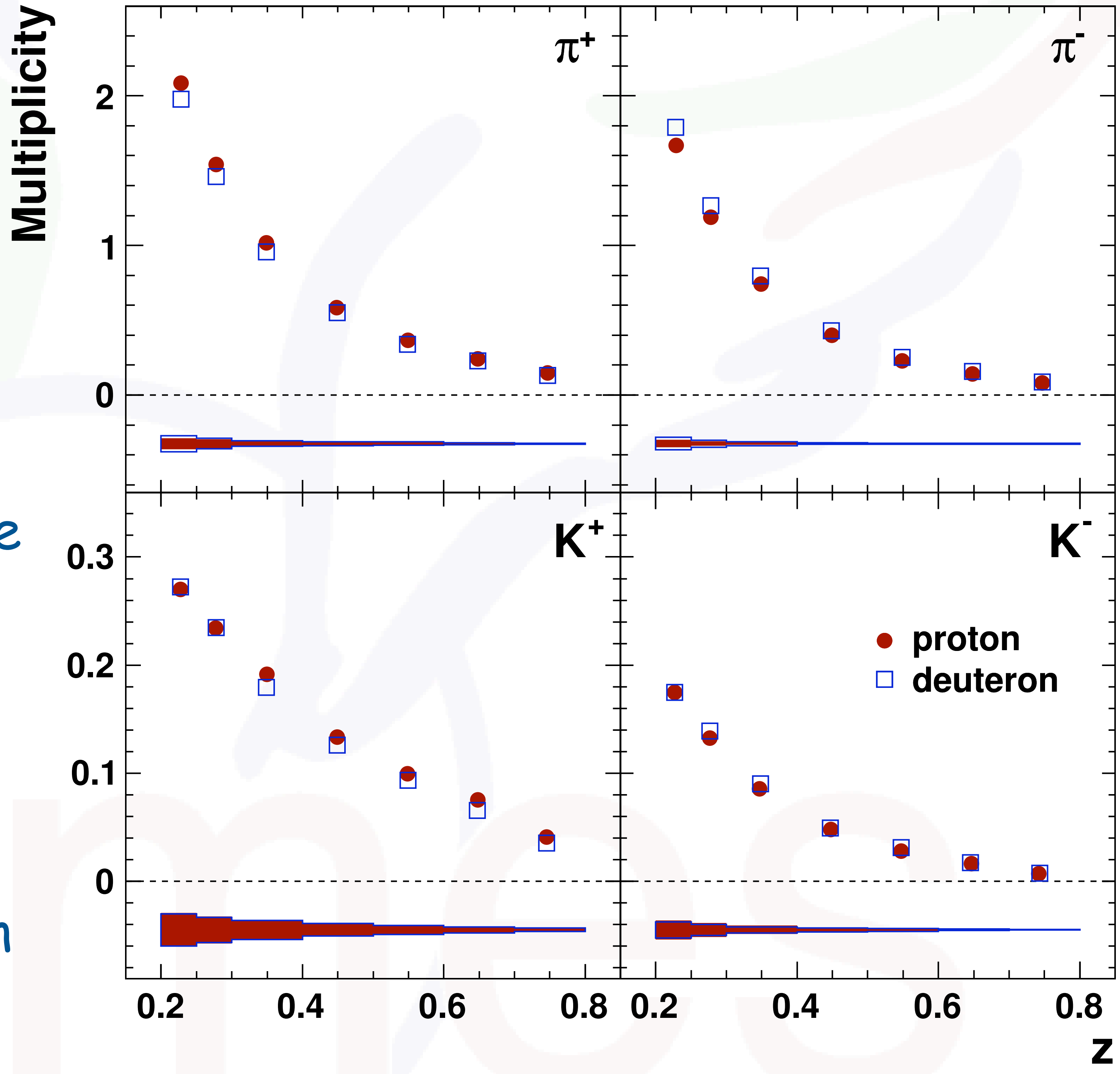
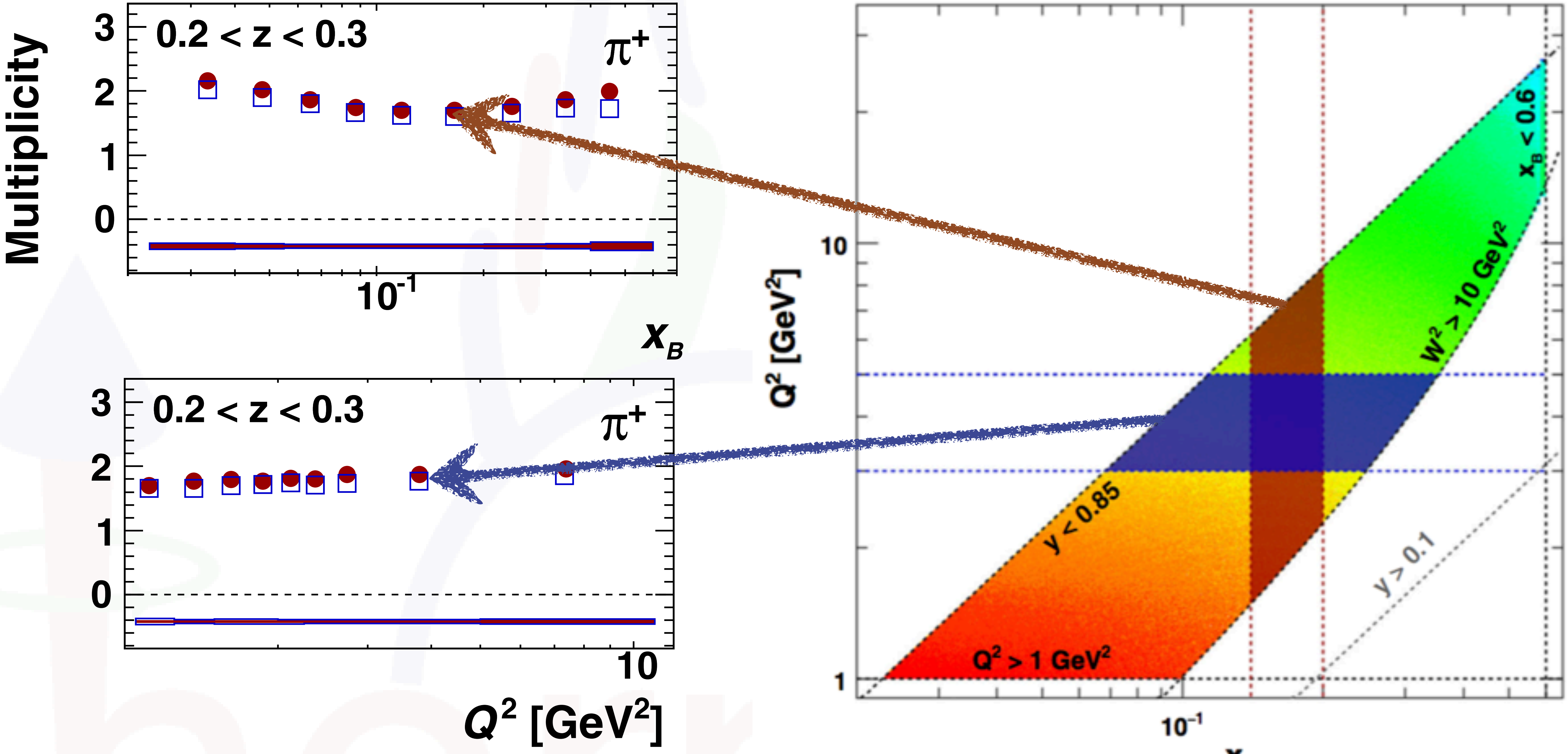


$$\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$$



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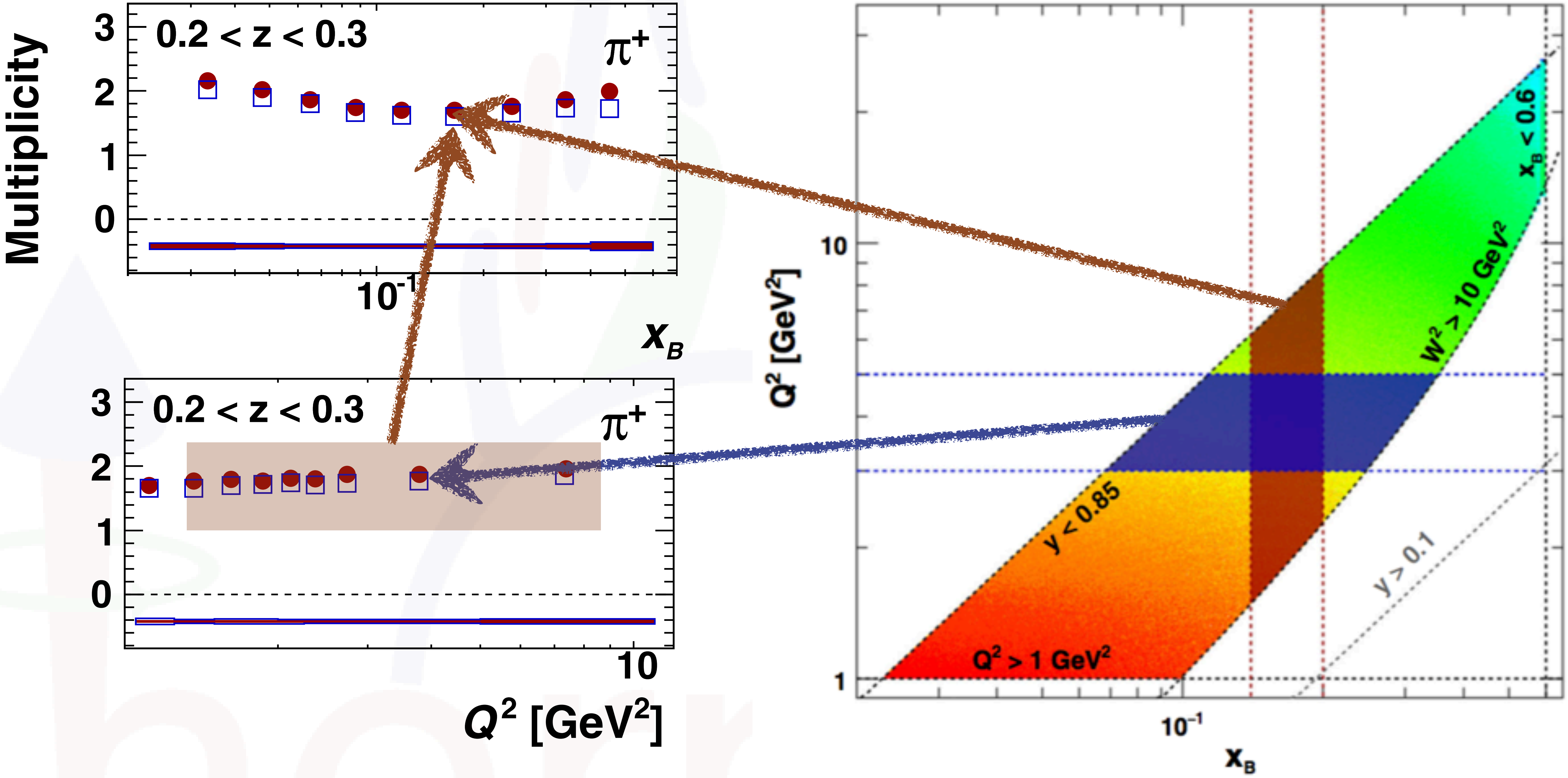

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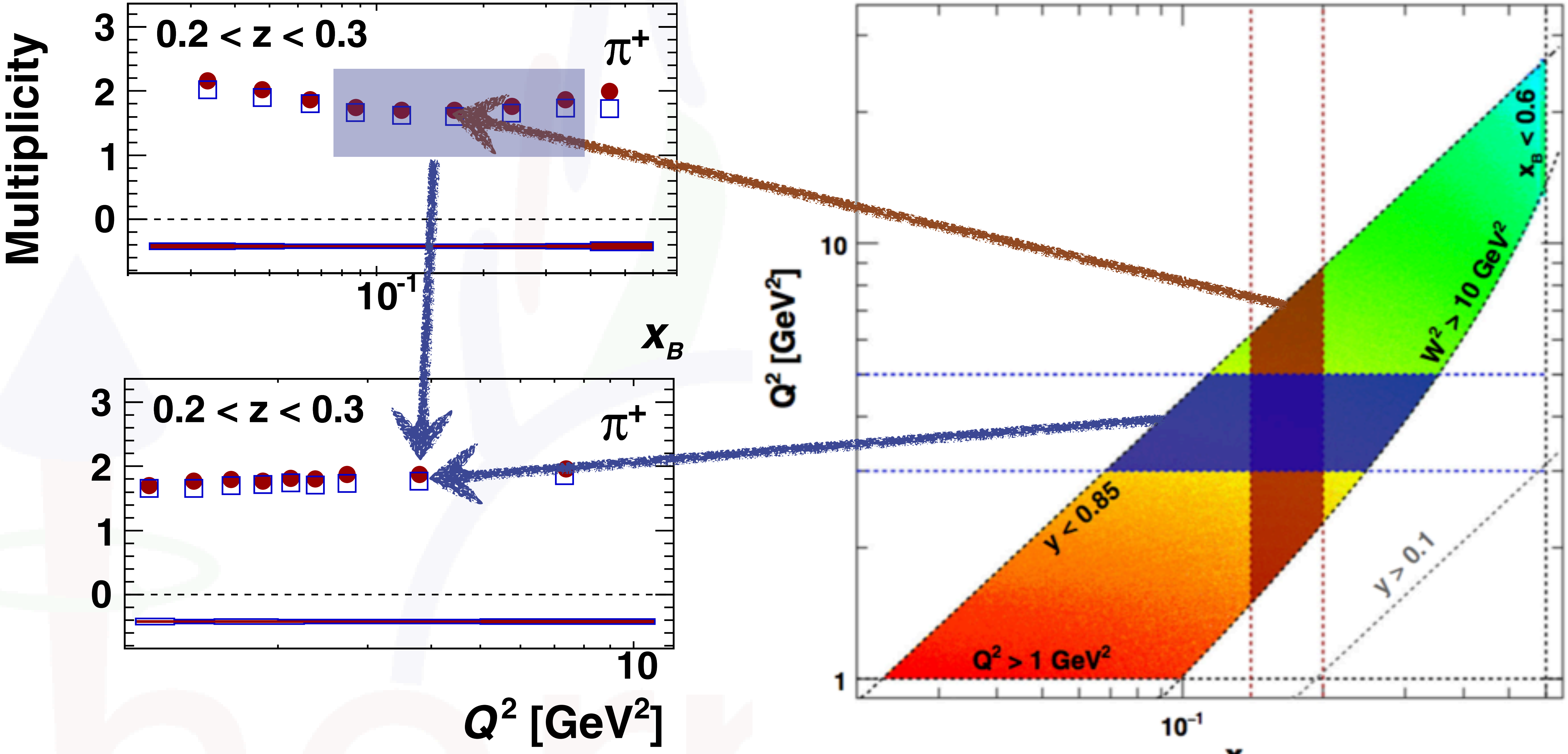

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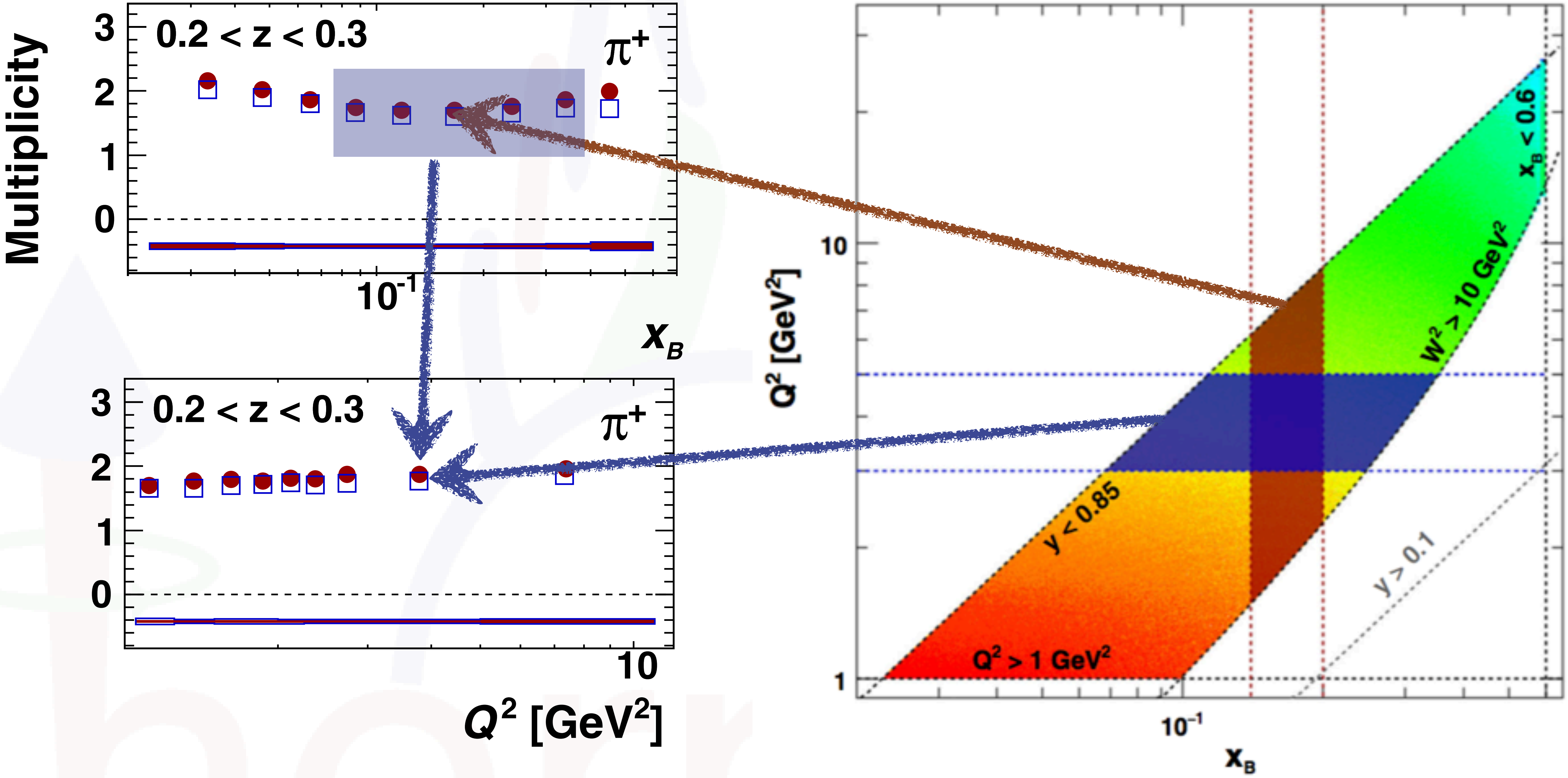
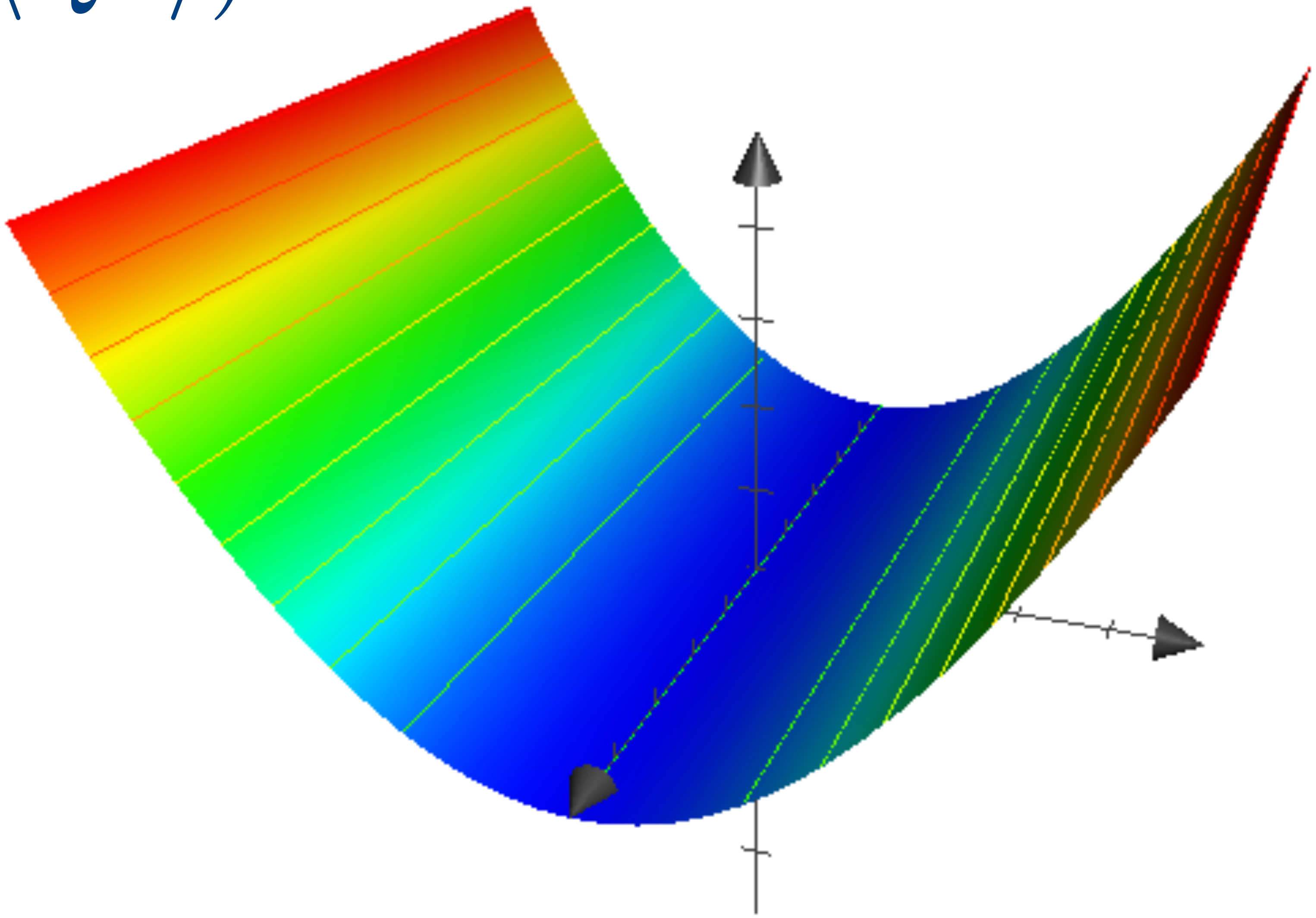


- even though having similar average kinematics, multiplicities in the two projections are different

$\langle \mathcal{M}(Q^2) \rangle_{Q^2} \neq \mathcal{M}(\langle Q^2 \rangle)$



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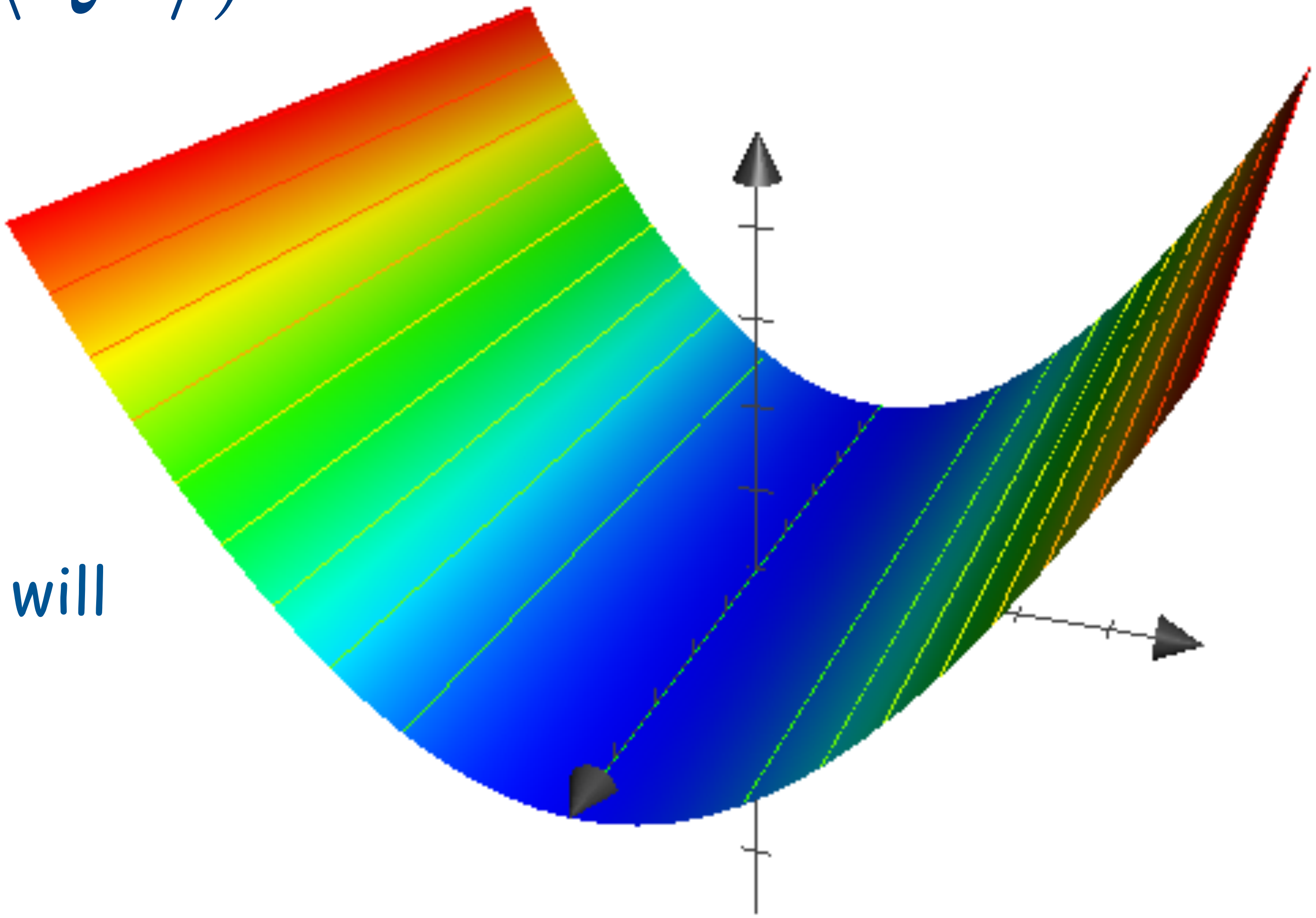

- the average along the valley will be smaller than the average along the gradient

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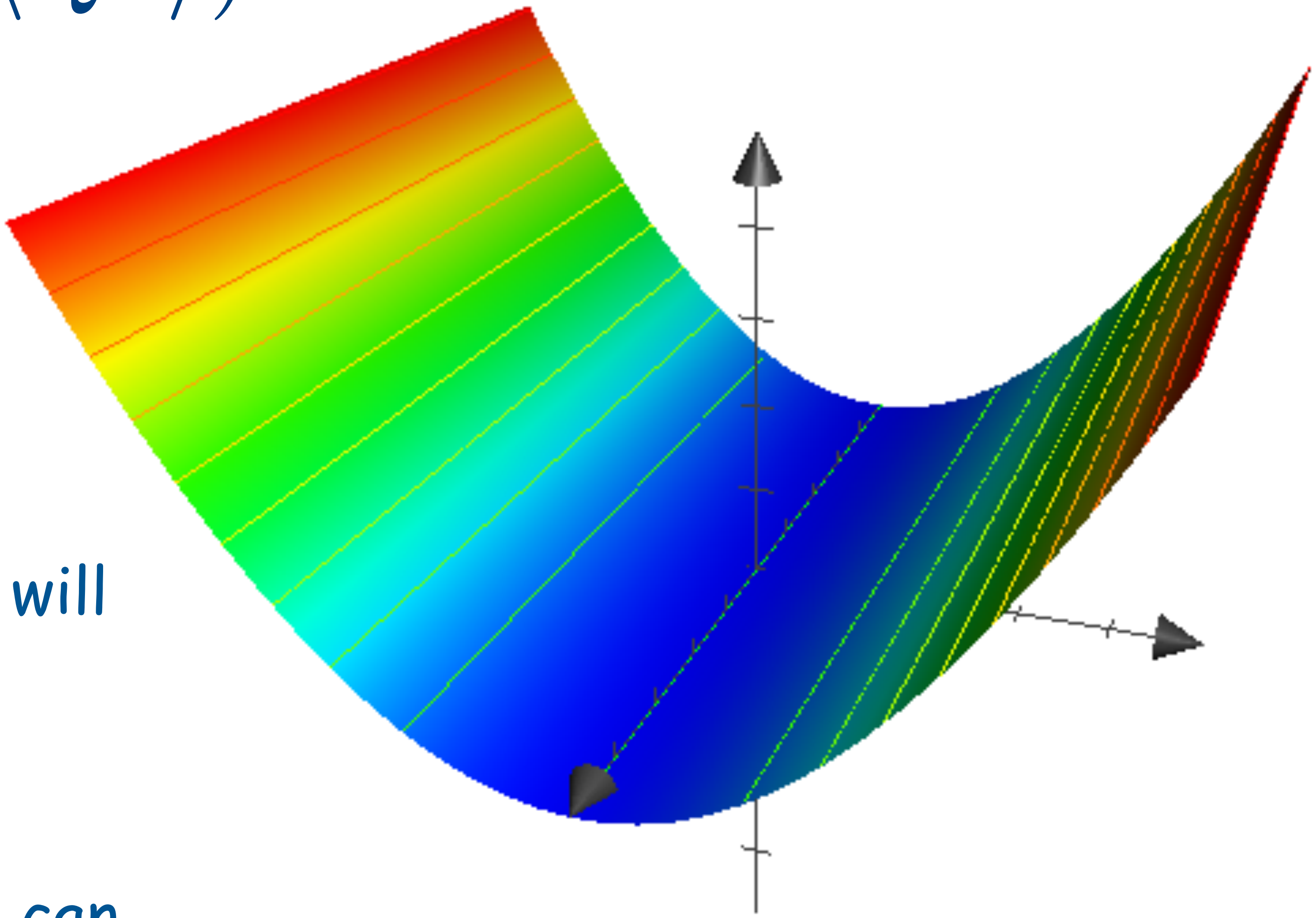

- the average along the valley will be smaller than the average along the gradient
- still the **average kinematics** can be the same

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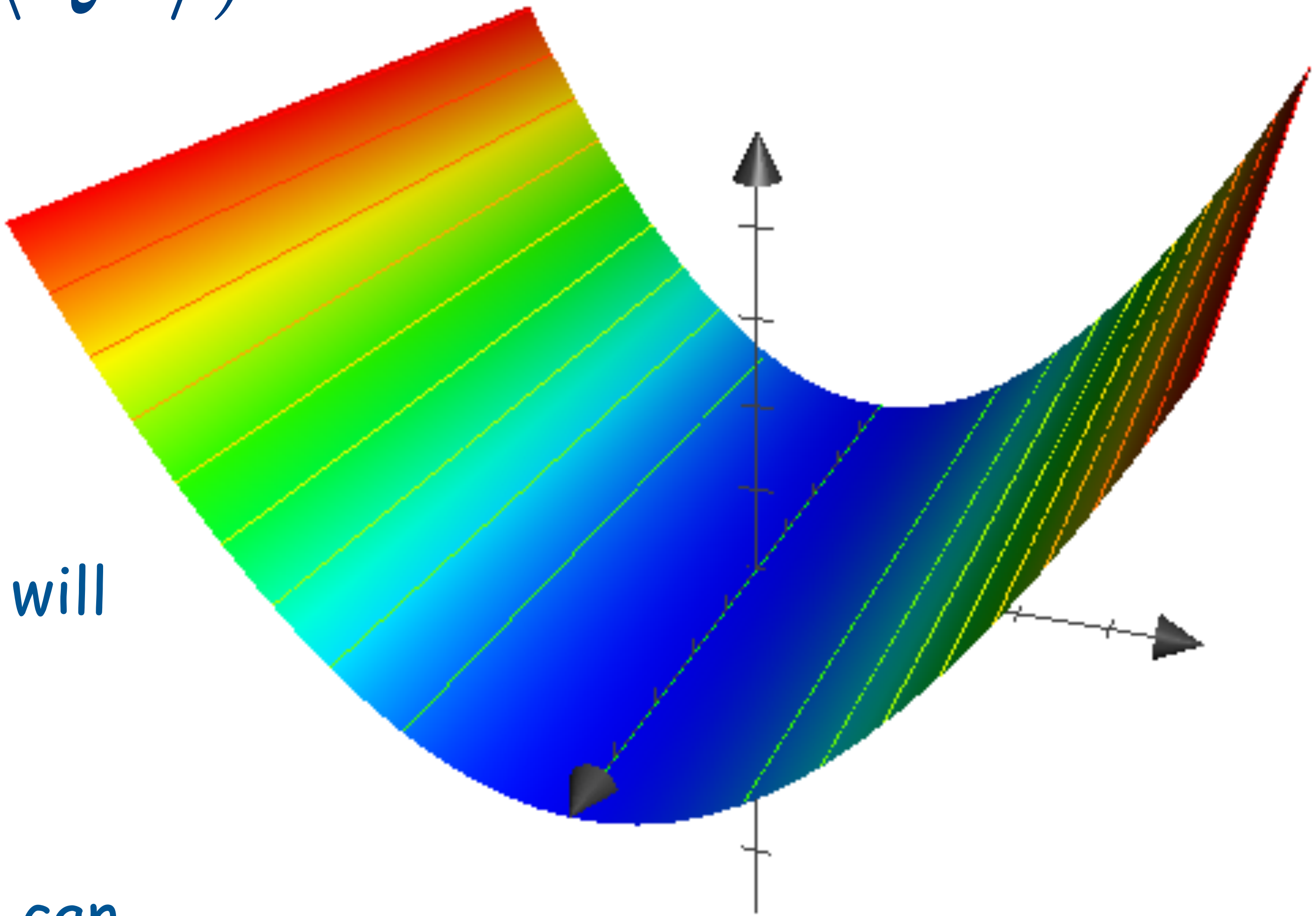


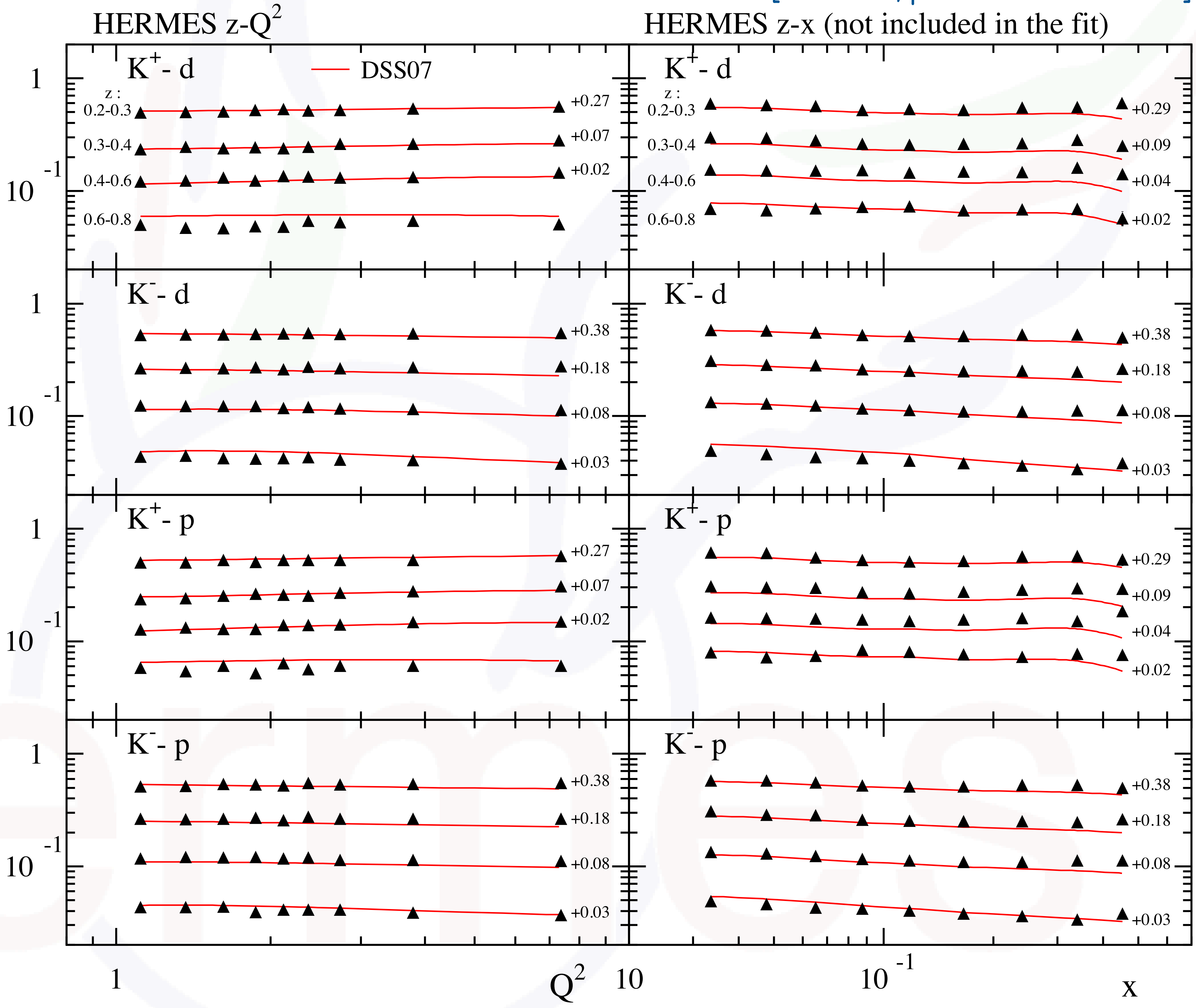
- the average along the valley will be smaller than the average along the gradient
- still the **average kinematics** can be the same

take-away message: integrate your cross sections over the kinematic ranges dictated by the experiment (and do not simply evaluate it at the average kinematics)

integrating vs. using average kinematics

- (by now old) **DSS07** FF fit to z-Q^2 projection

[R. Sassot, private communication]



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- z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)

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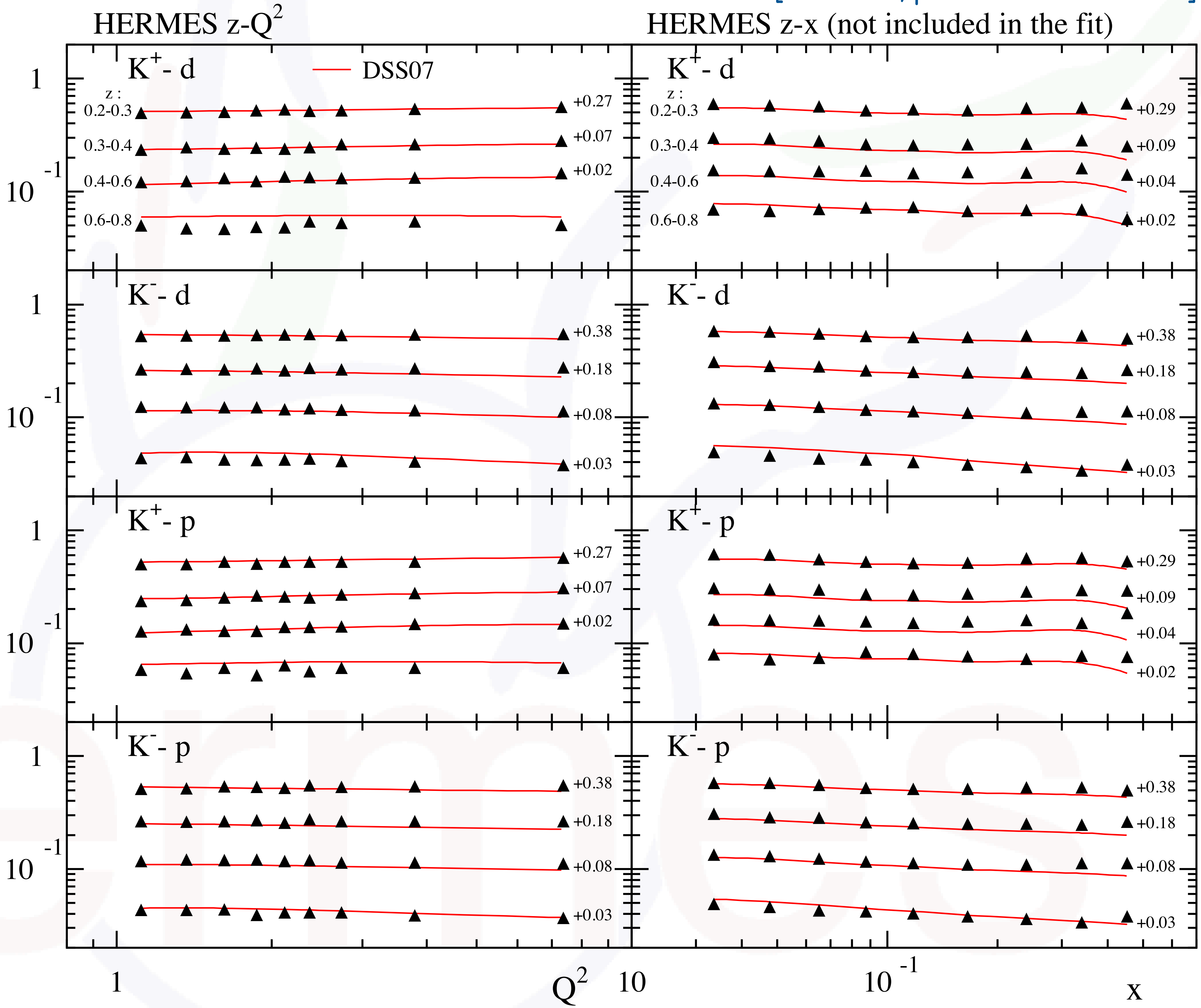
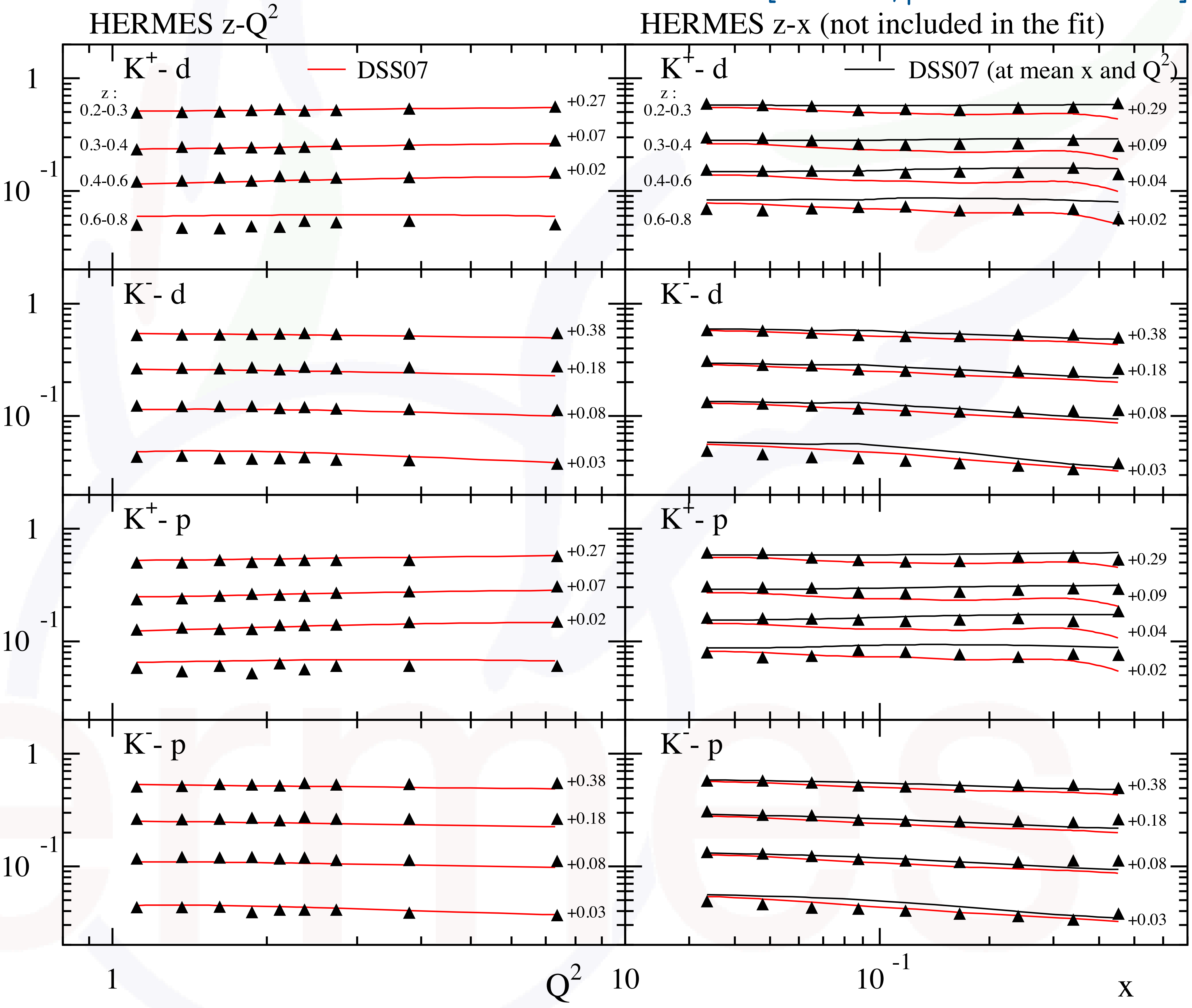


integrating vs. using average kinematics

- (by now old) **DSS07** FF fit to z-Q^2 projection
- z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)
- significant changes when using **average kinematics**

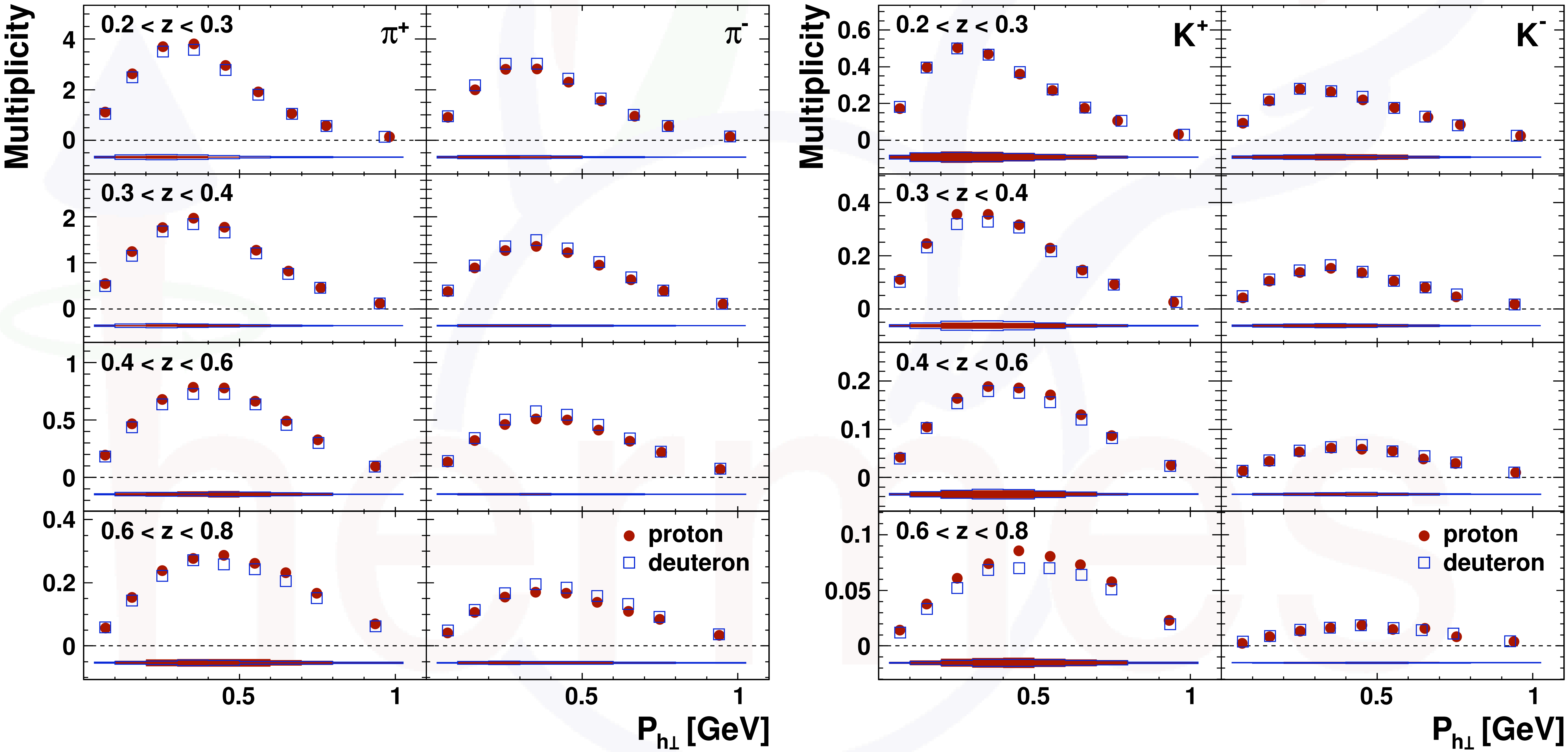
[R. Sassot, private communication]



transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

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

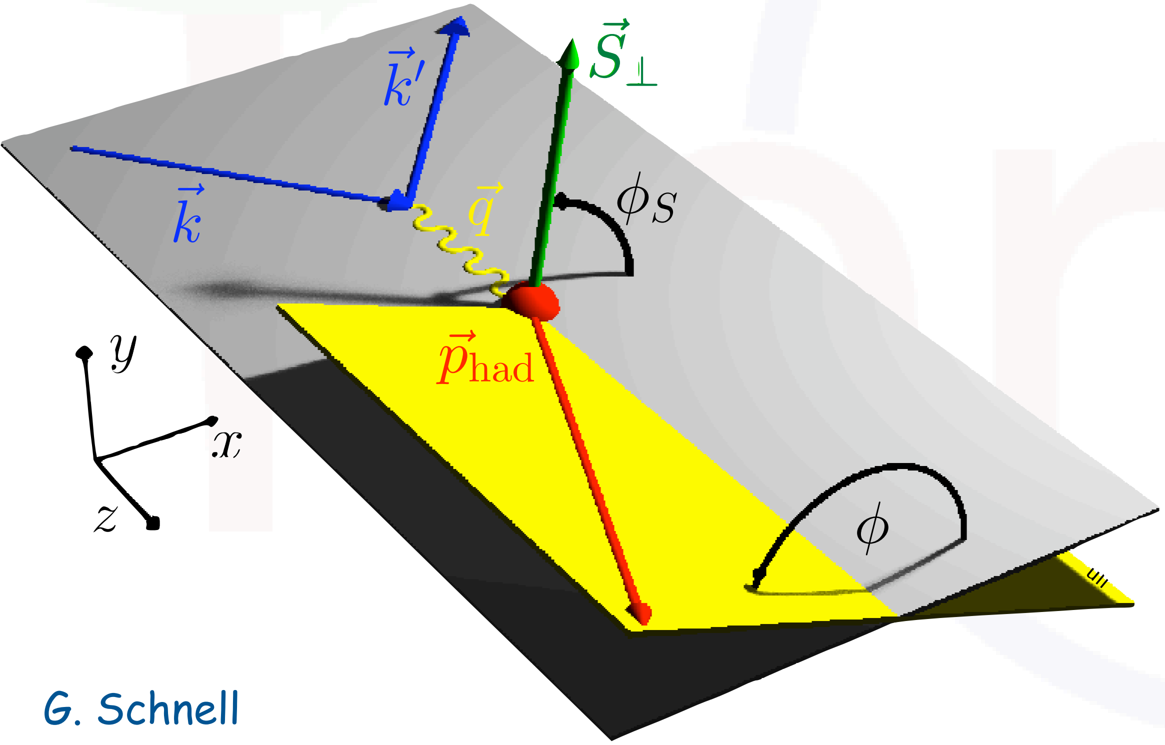


chiral-odd distributions

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

transversely polarized quarks?

- look at characteristic azimuthal dependence of single-hadron lepto-production cross section



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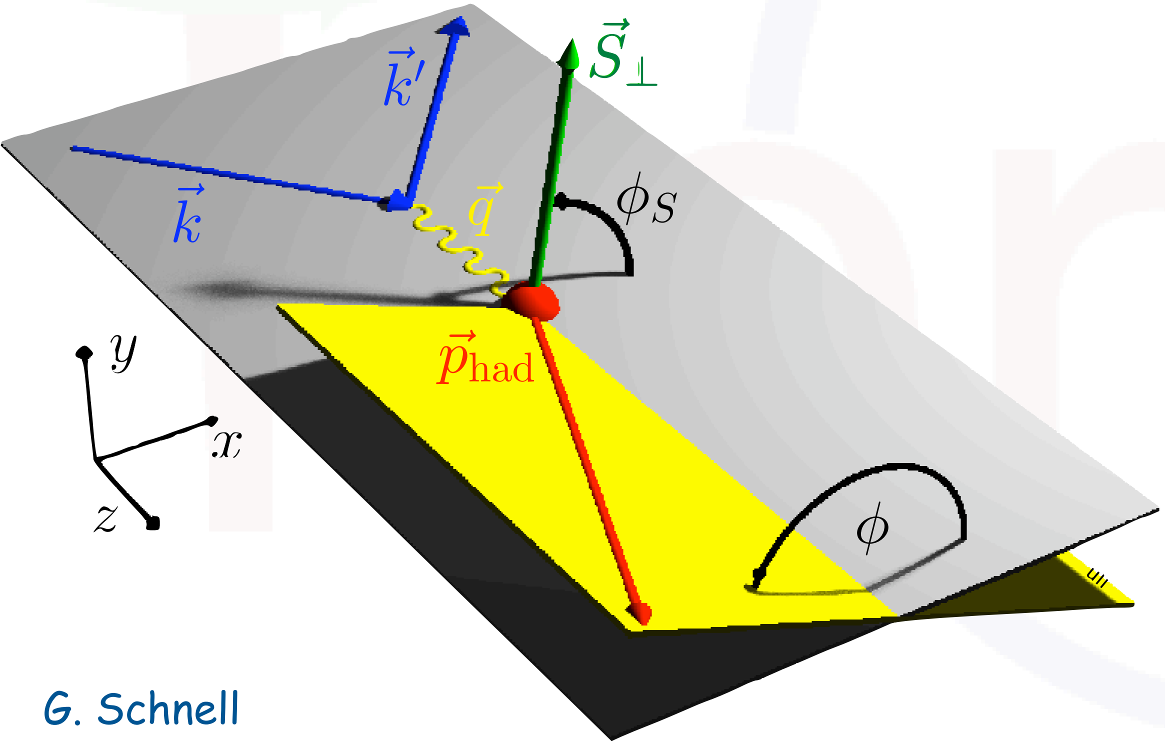
- in practice reverse nucleon-polarization orientation and form spin asymmetries



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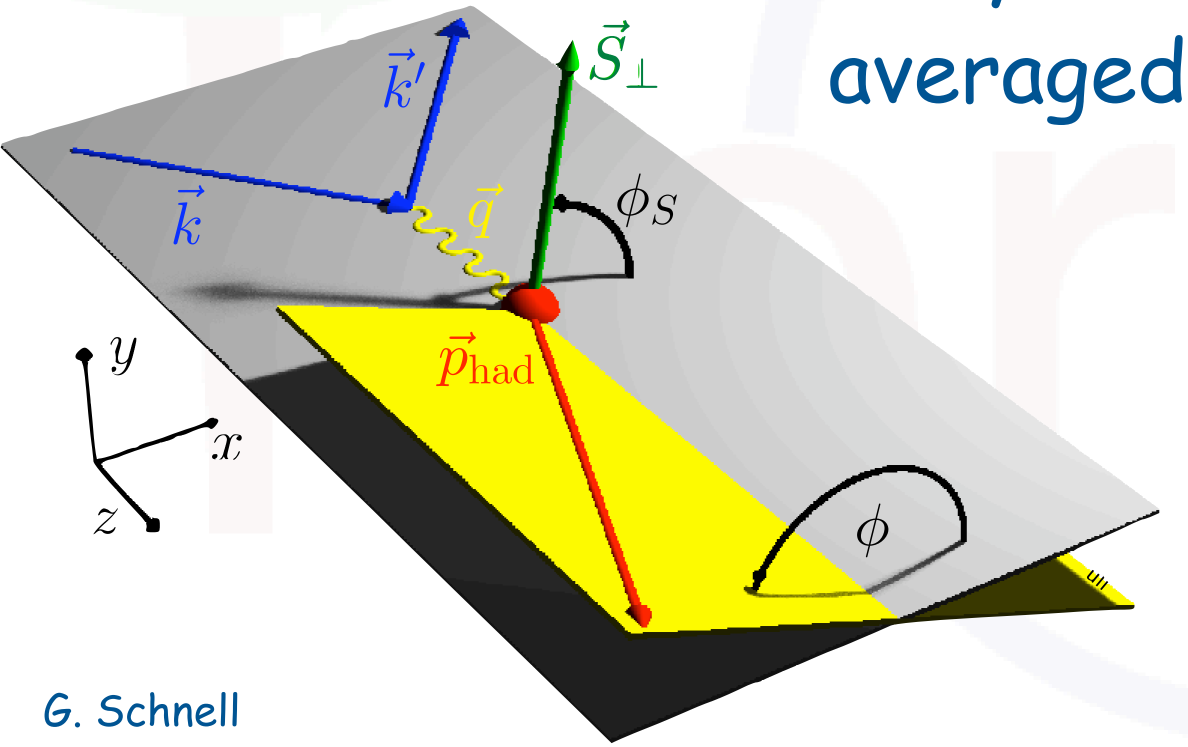
transversely polarized quarks?

- look at characteristic azimuthal dependence of single-hadron lepto-production cross section
- in practice reverse nucleon-polarization orientation and form spin asymmetries
  - many of the systematics of polarization-averaged observables cancel (e.g., luminosity)



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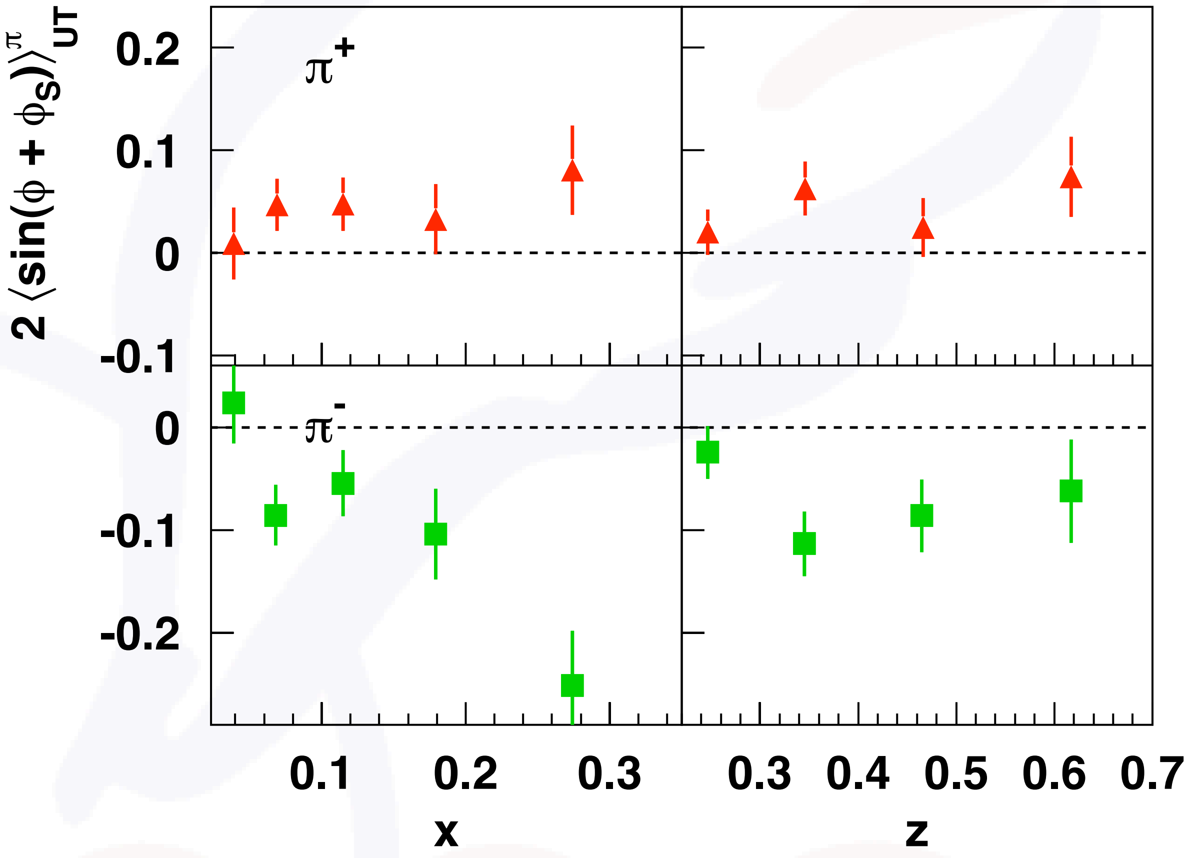
transversely polarized quarks?

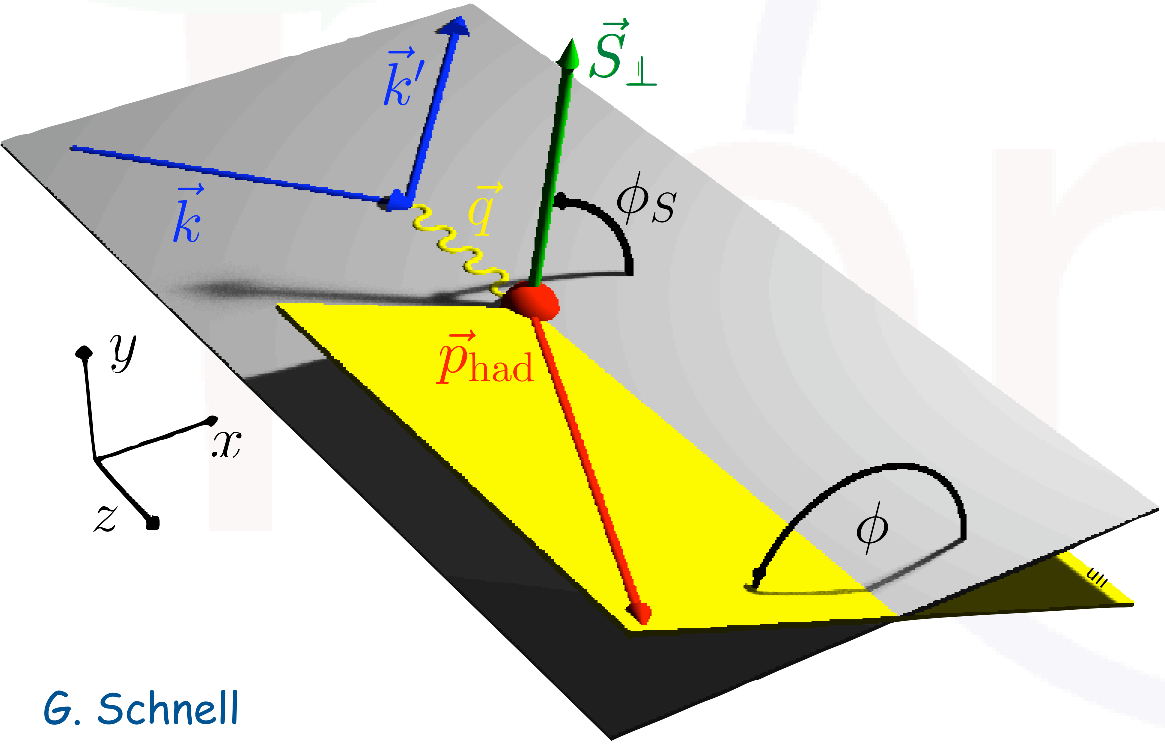
- transverse polarization of quarks leads to large effects!

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



2005: First evidence from HERMES
SIDIS on proton

Non-zero transversity
Non-zero Collins function



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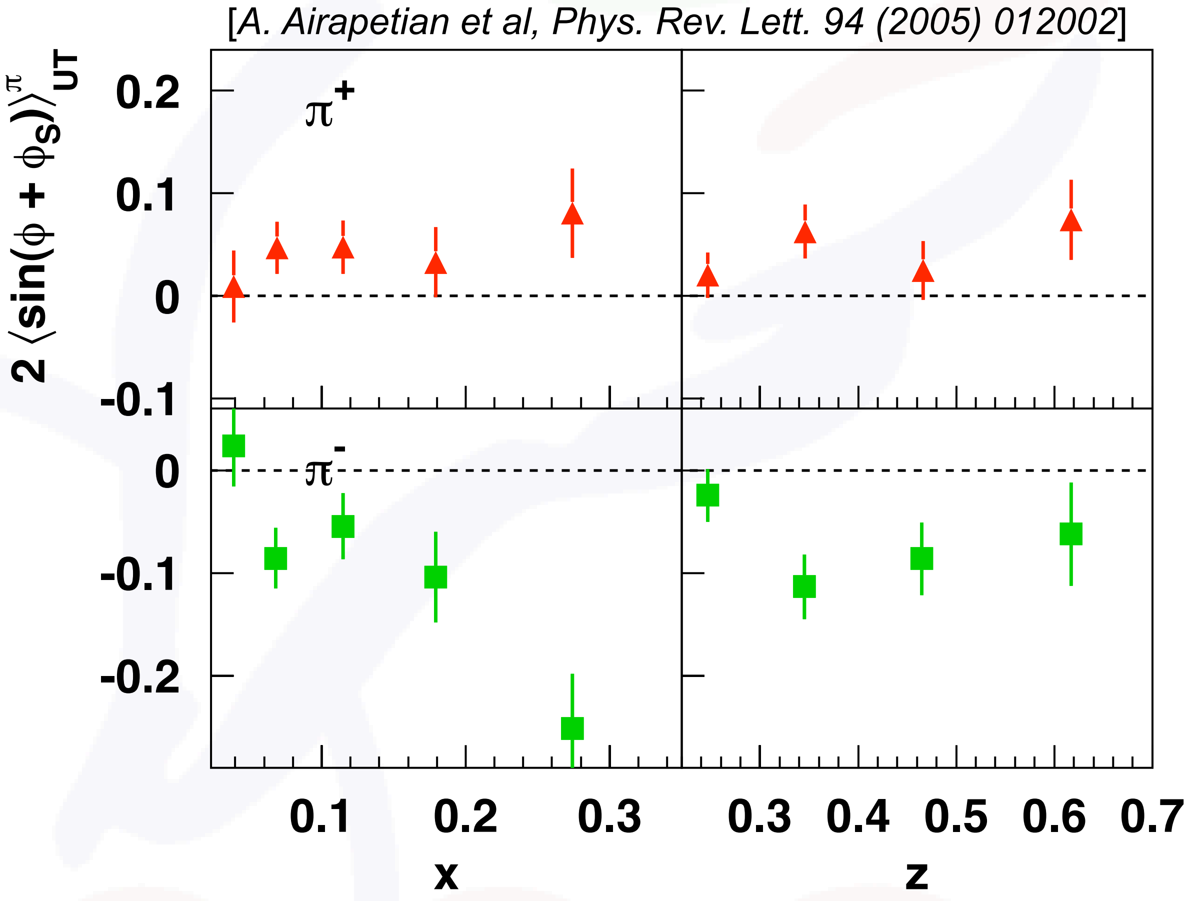
- opposite in sign for charged pions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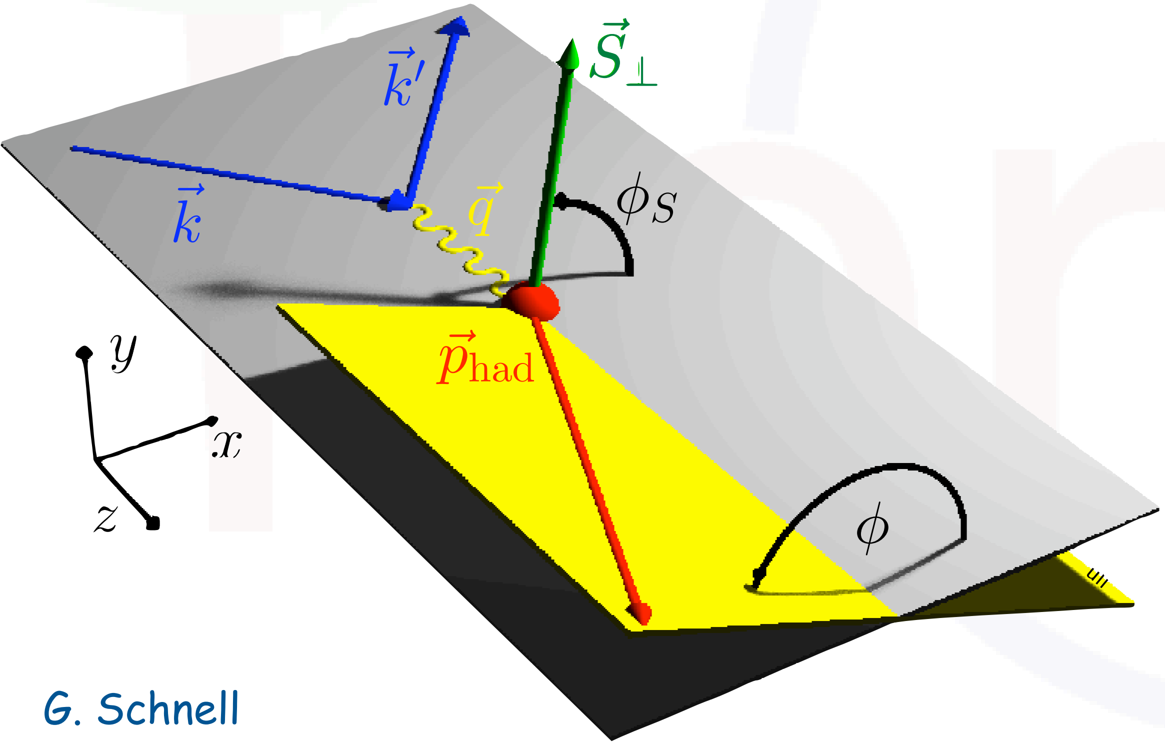

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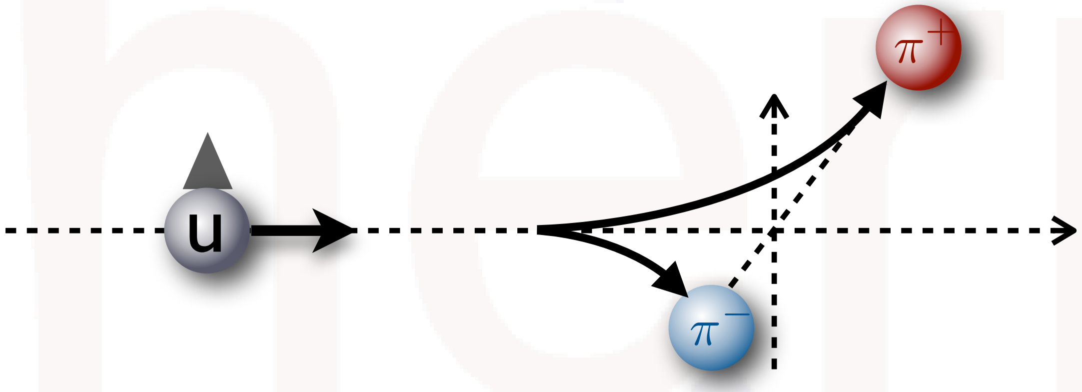

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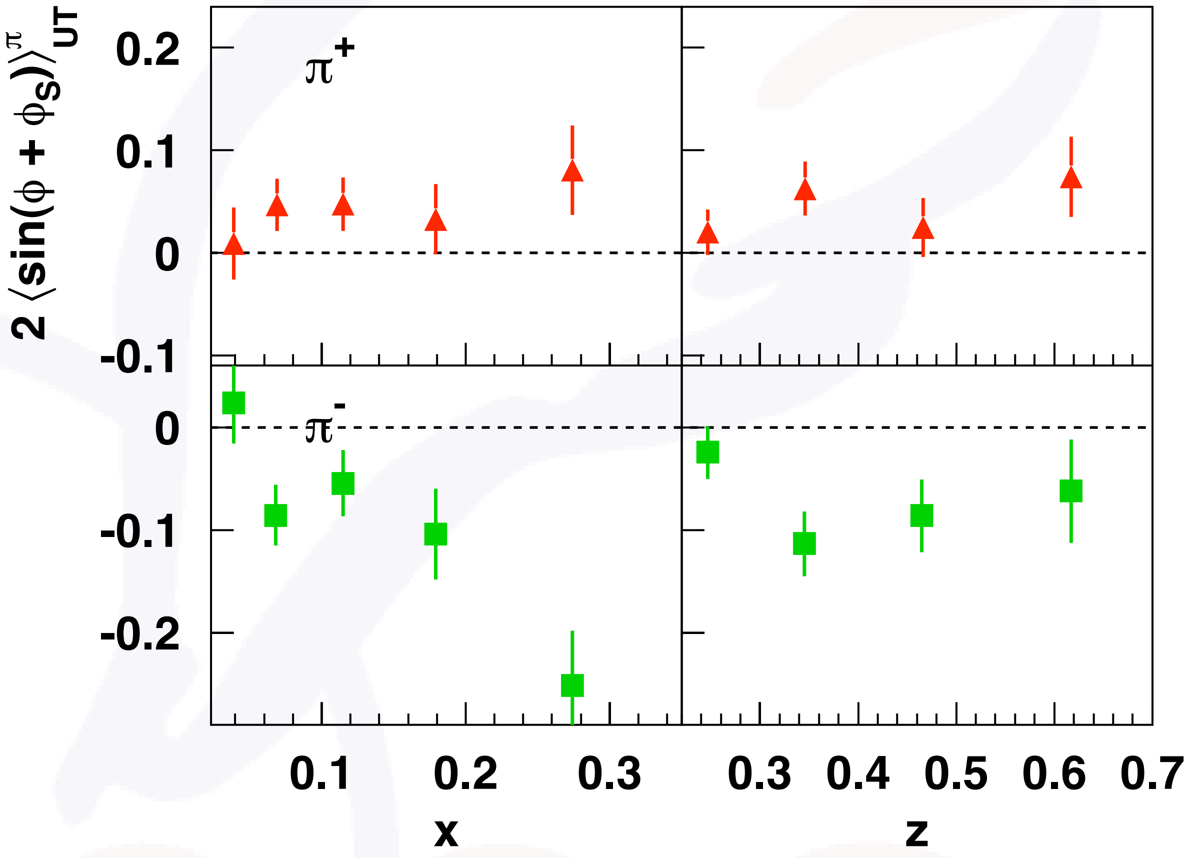

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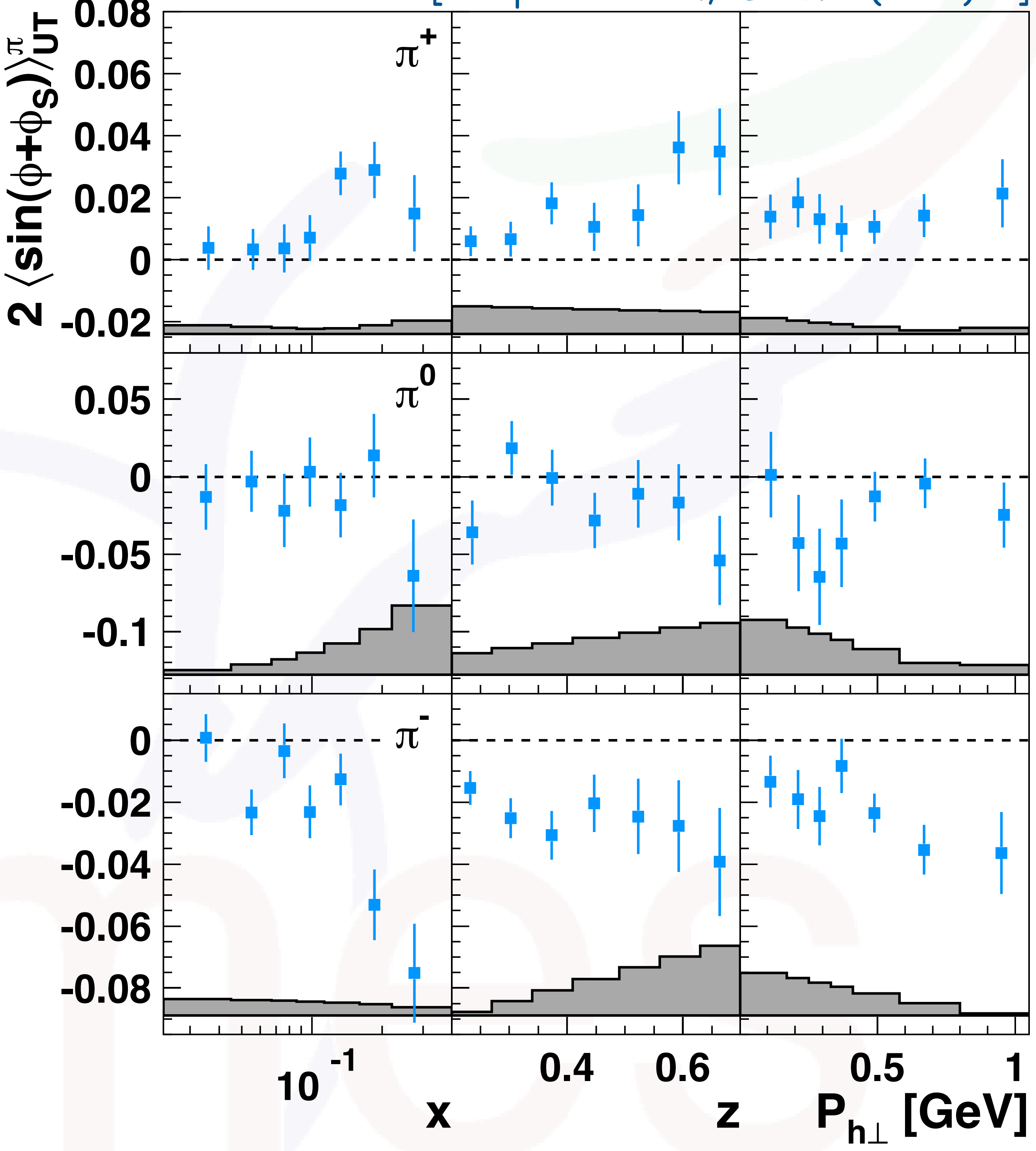
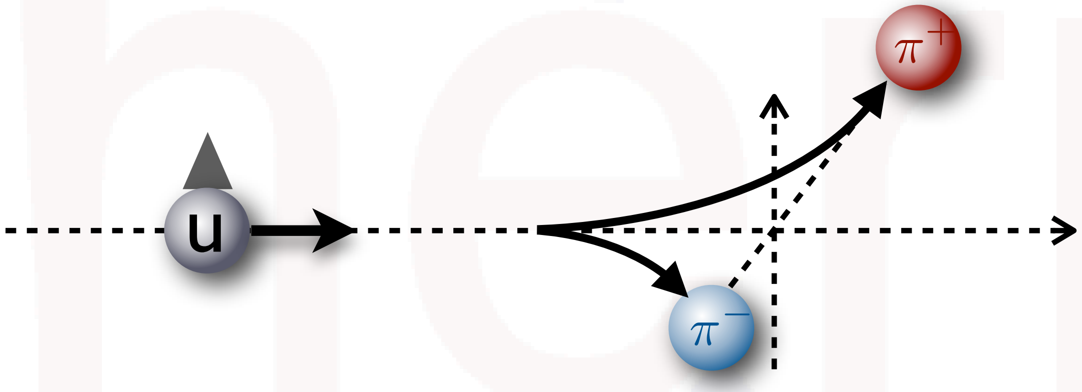


[Airapetian et al., PLB 693 (2010) 11]



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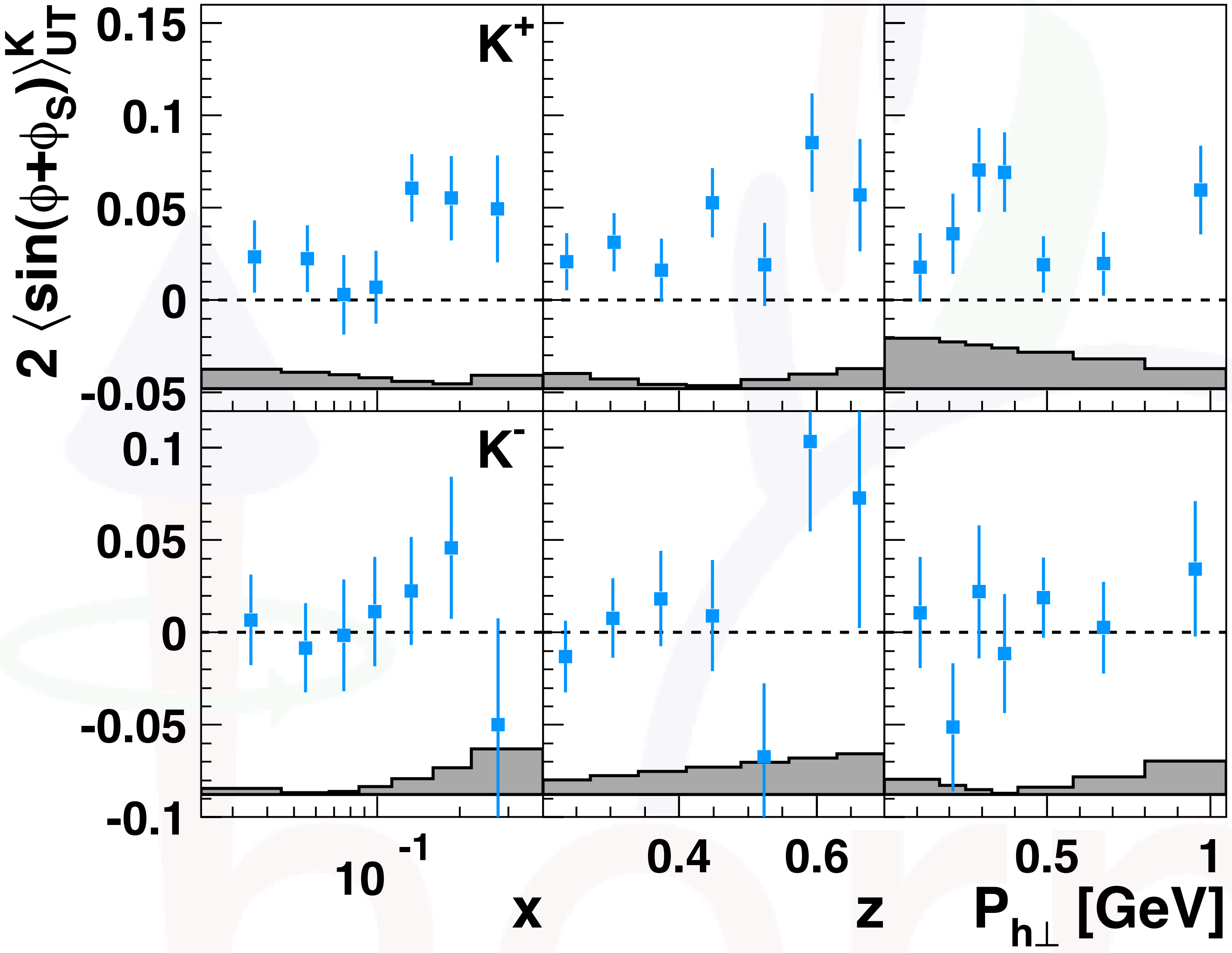
Collins effect for kaons and (anti) protons

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



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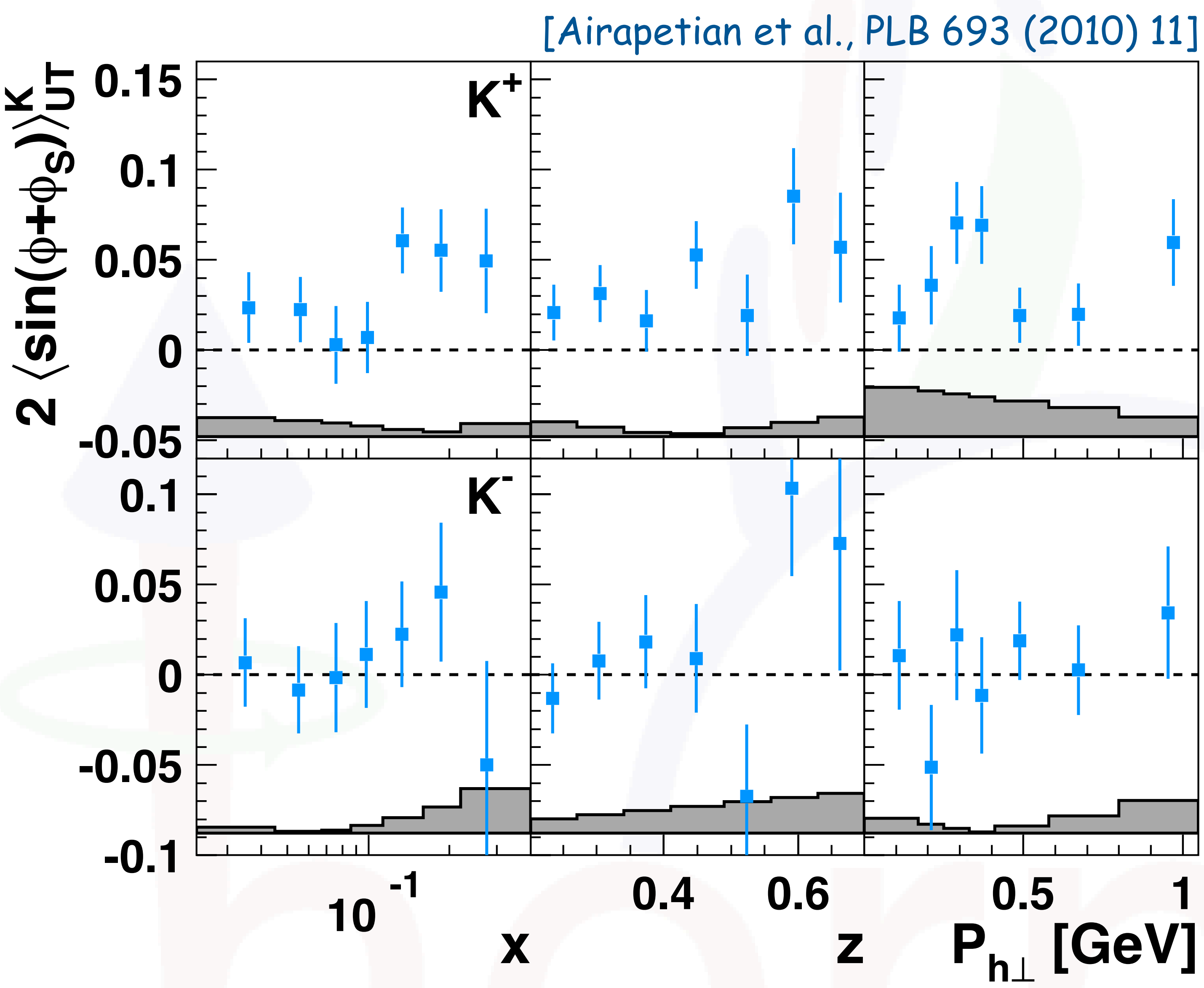
[Airapetian et al., PLB 693 (2010) 11]

- positive Collins SSA amplitude for positive kaons

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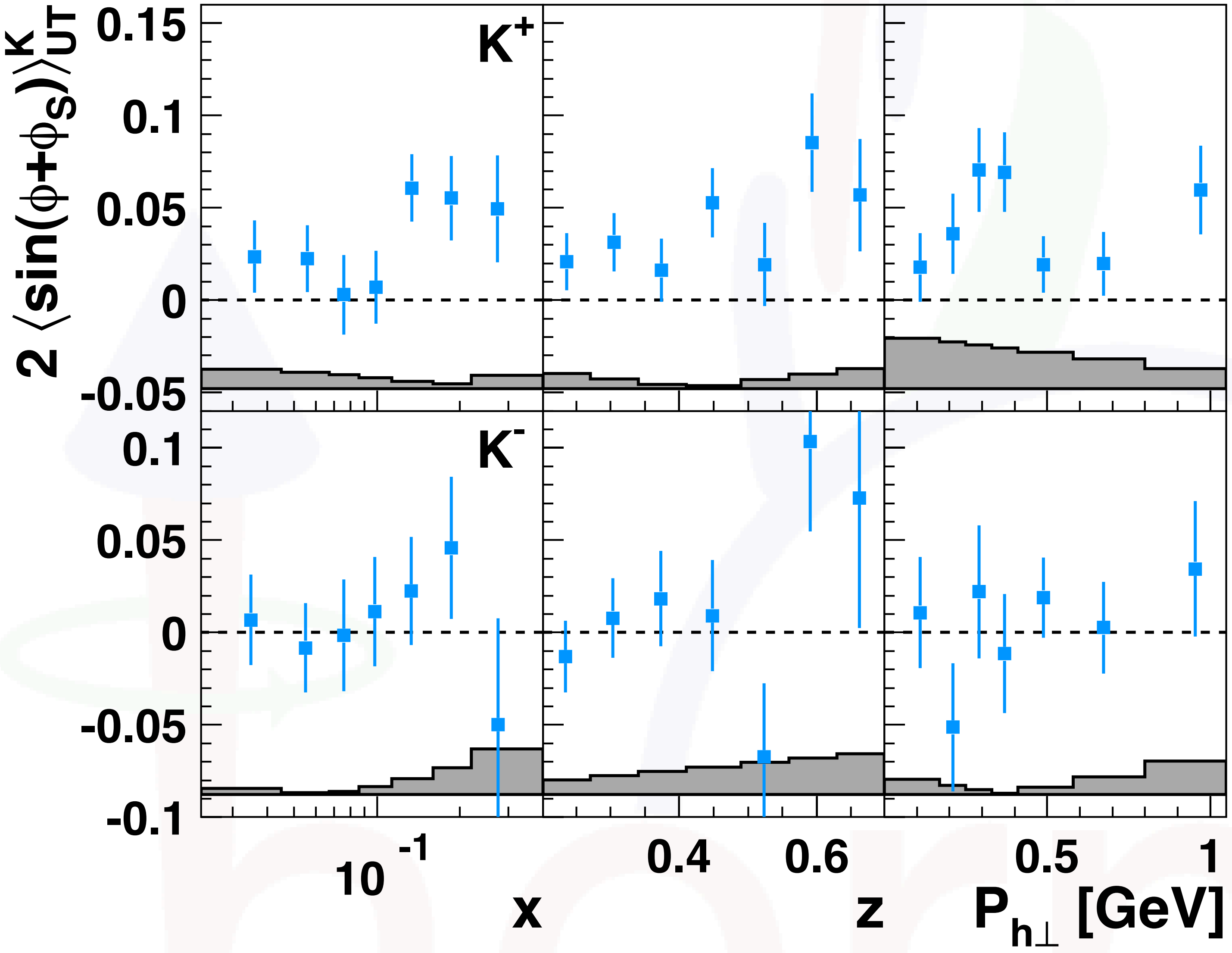
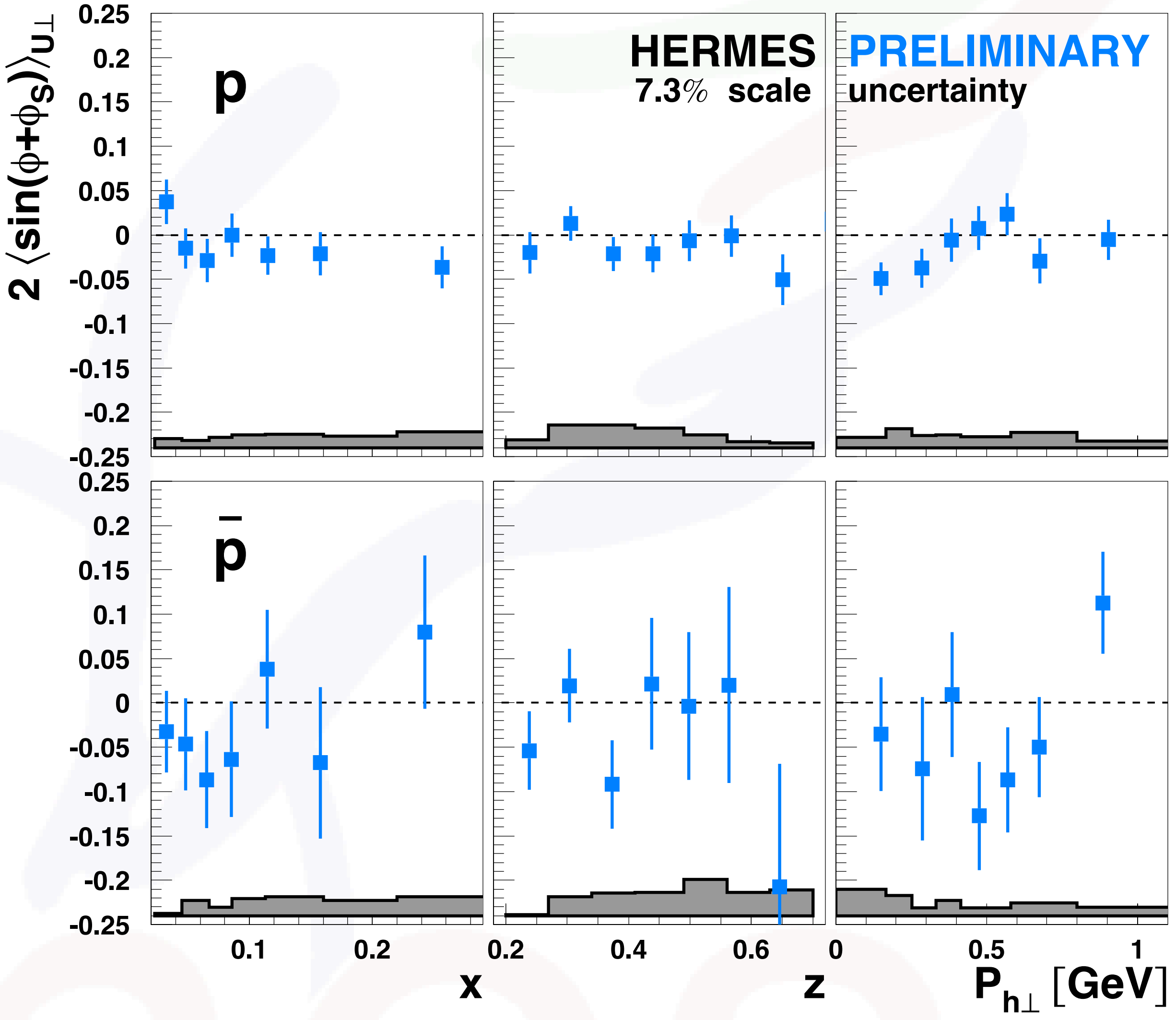


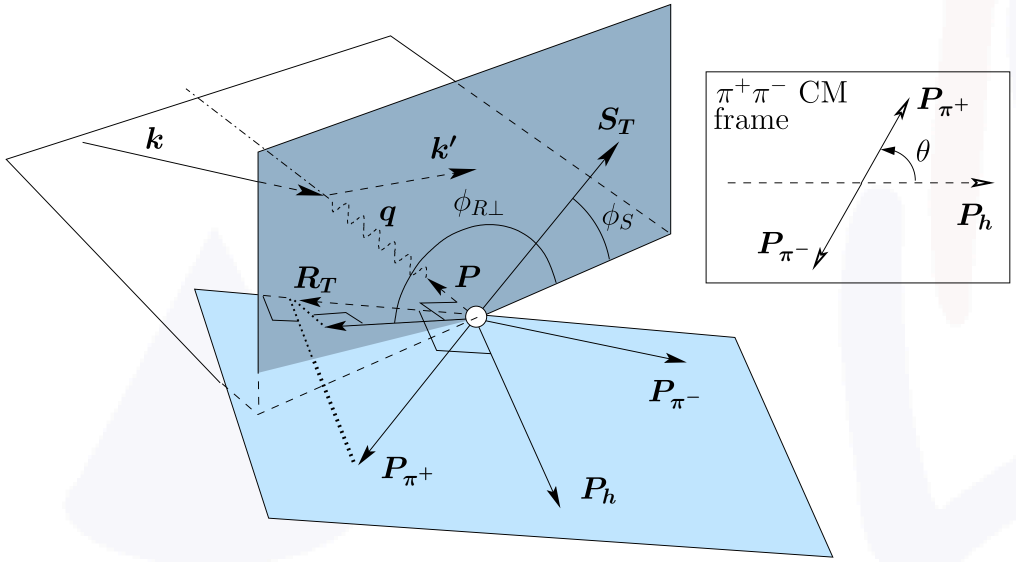


- positive Collins SSA amplitude for positive kaons
- consistent with zero for negative kaons and (anti)protons

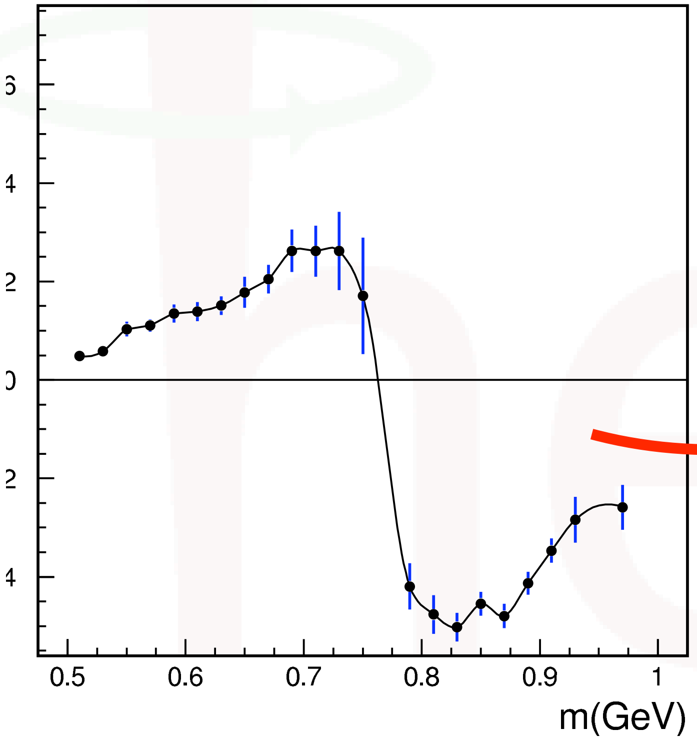
➡vanishing sea-quark transversity and baryon Collins effect?

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

Transversity through 2-hadron fragmentation



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



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

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

δ_0 (δ_1) → S(P)-wave phase shifts

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

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

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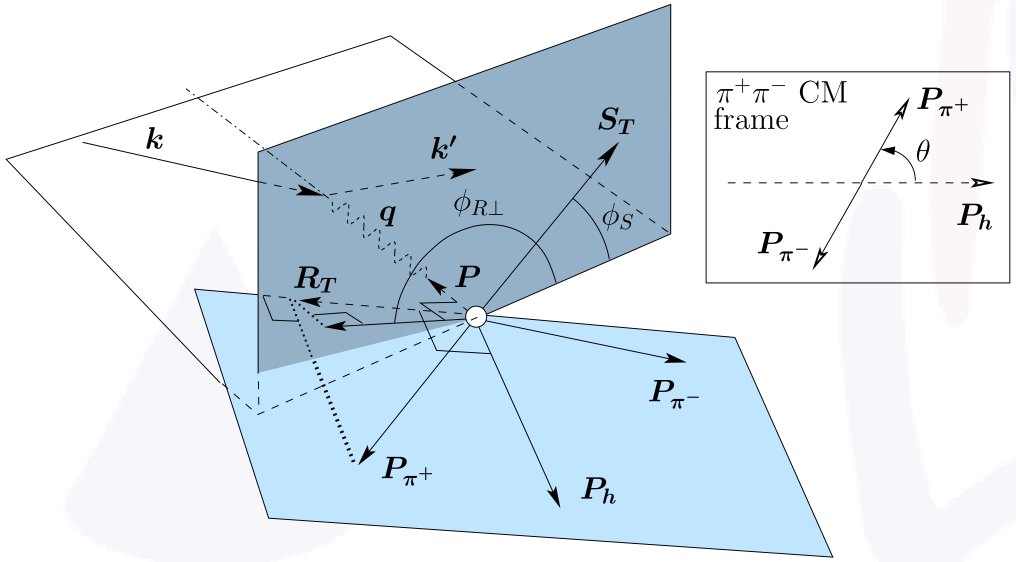

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- not only strong invariant-mass dependence, experimental challenges also because of
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  - theta dependence

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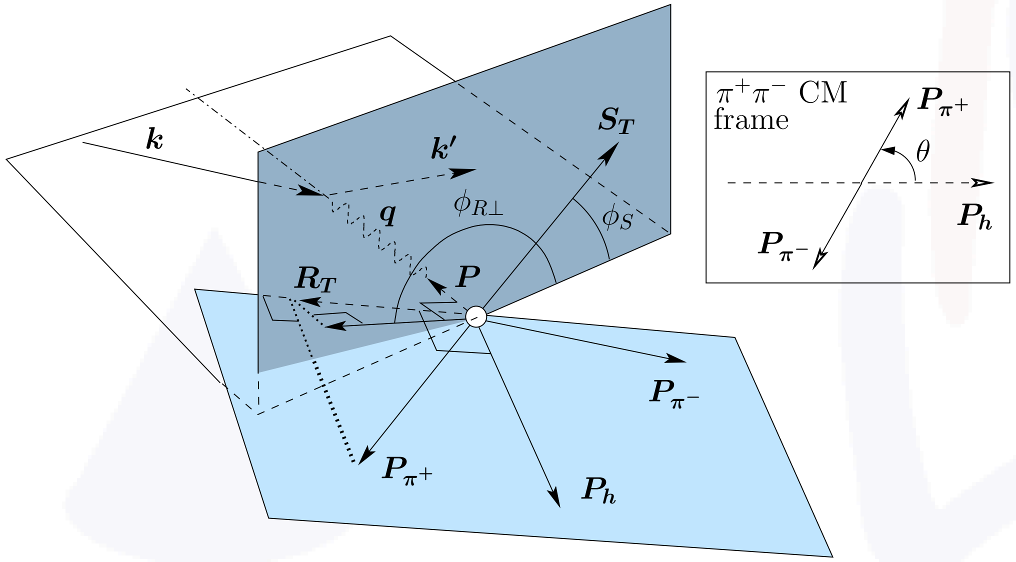

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- not only strong invariant-mass dependence, experimental challenges also because of
  - transverse-momentum dependence
  - theta dependence
- 9 vs. 6 (for single hadrons) dependences, too many to analyze simultaneously (at least with presently available data)

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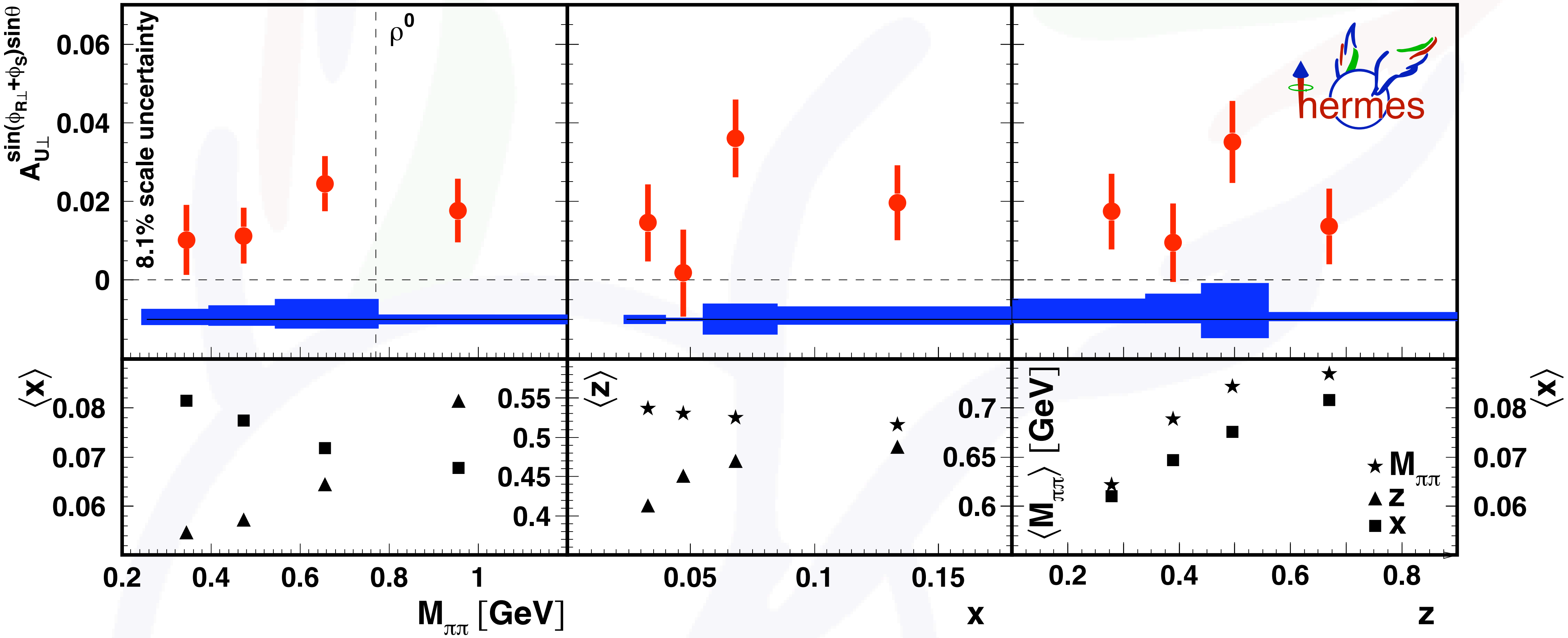

[A. Airapetian et al., JHEP 06 (2008) 017]

- systematics include
  - incomplete integration over transverse momentum (negligible)
  - contribution from higher partial waves in (unpolarized) denominator
  - integration over other variables, e.g., A(<kin.>) ≠ <A(kin.)>

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

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COMPASS 2007: [C. Adolph et al., Phys. Lett. B713 (2012) 10]
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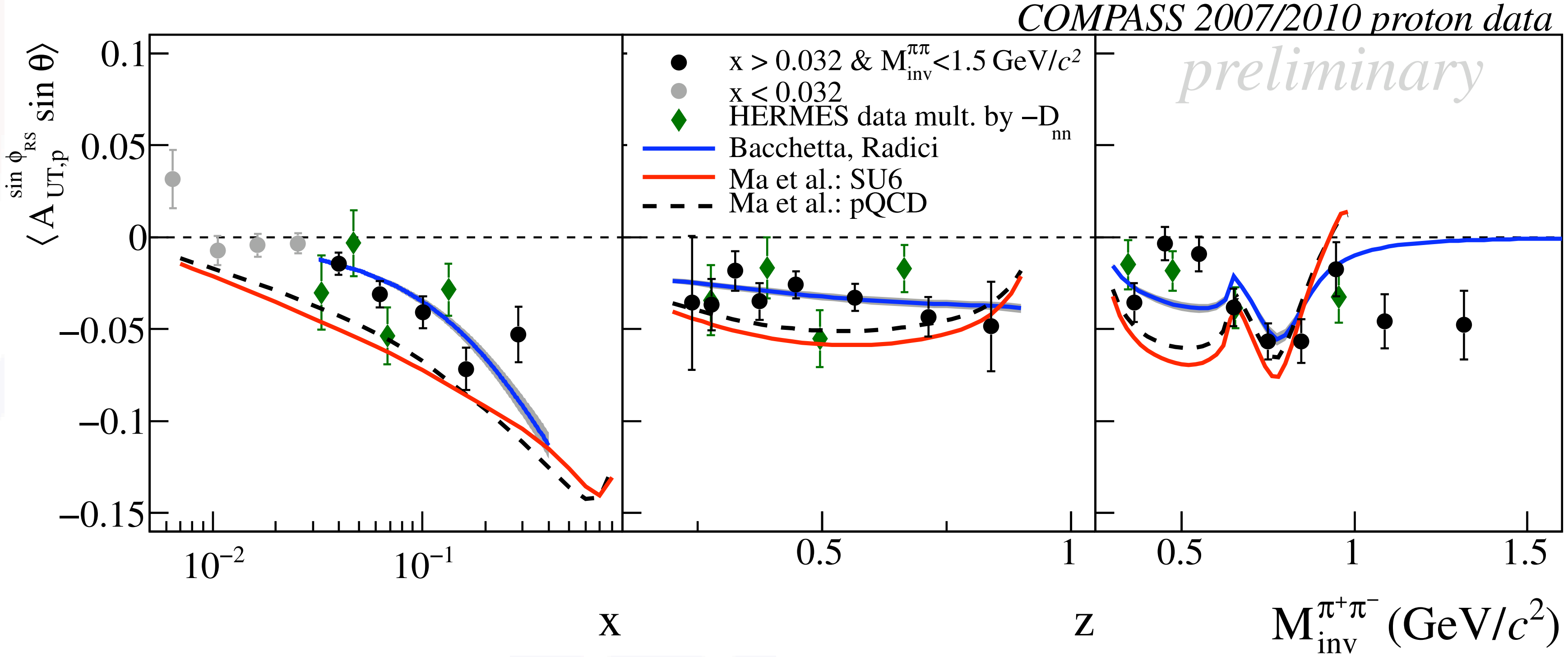

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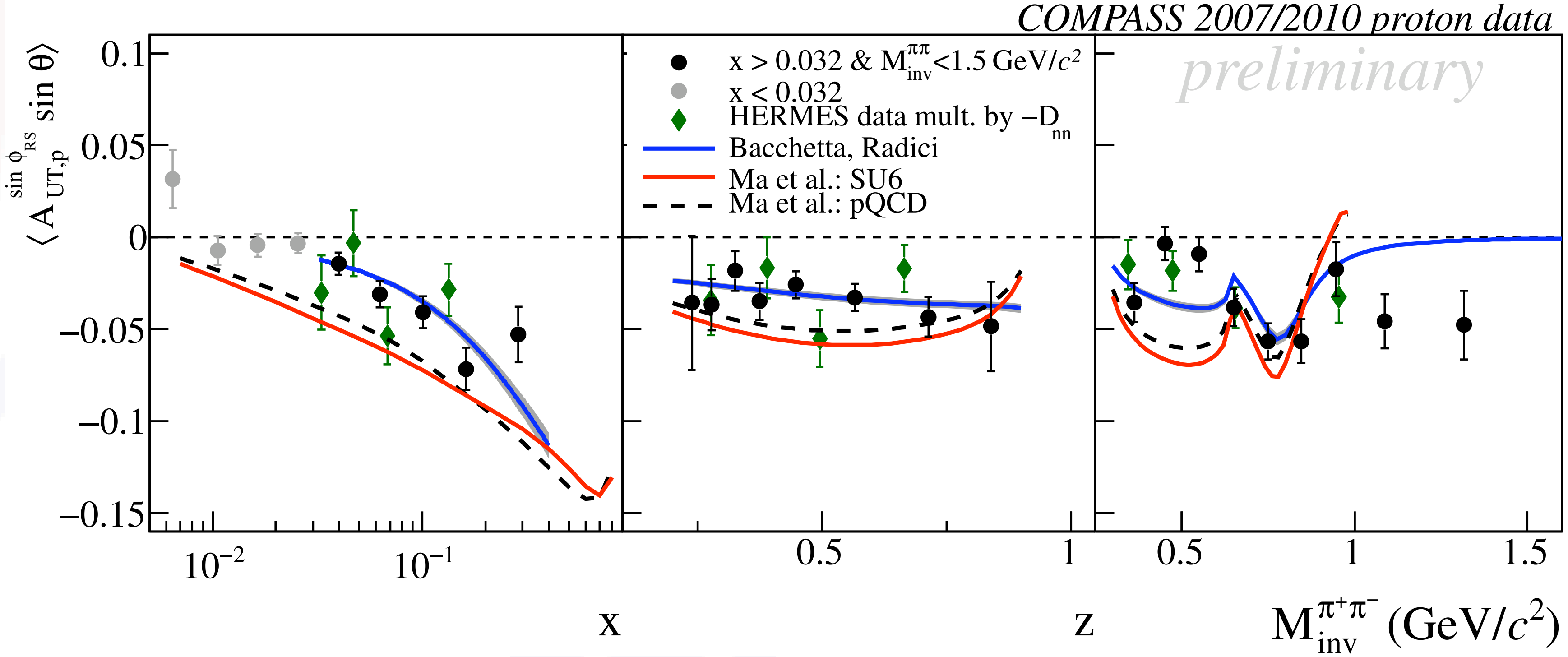

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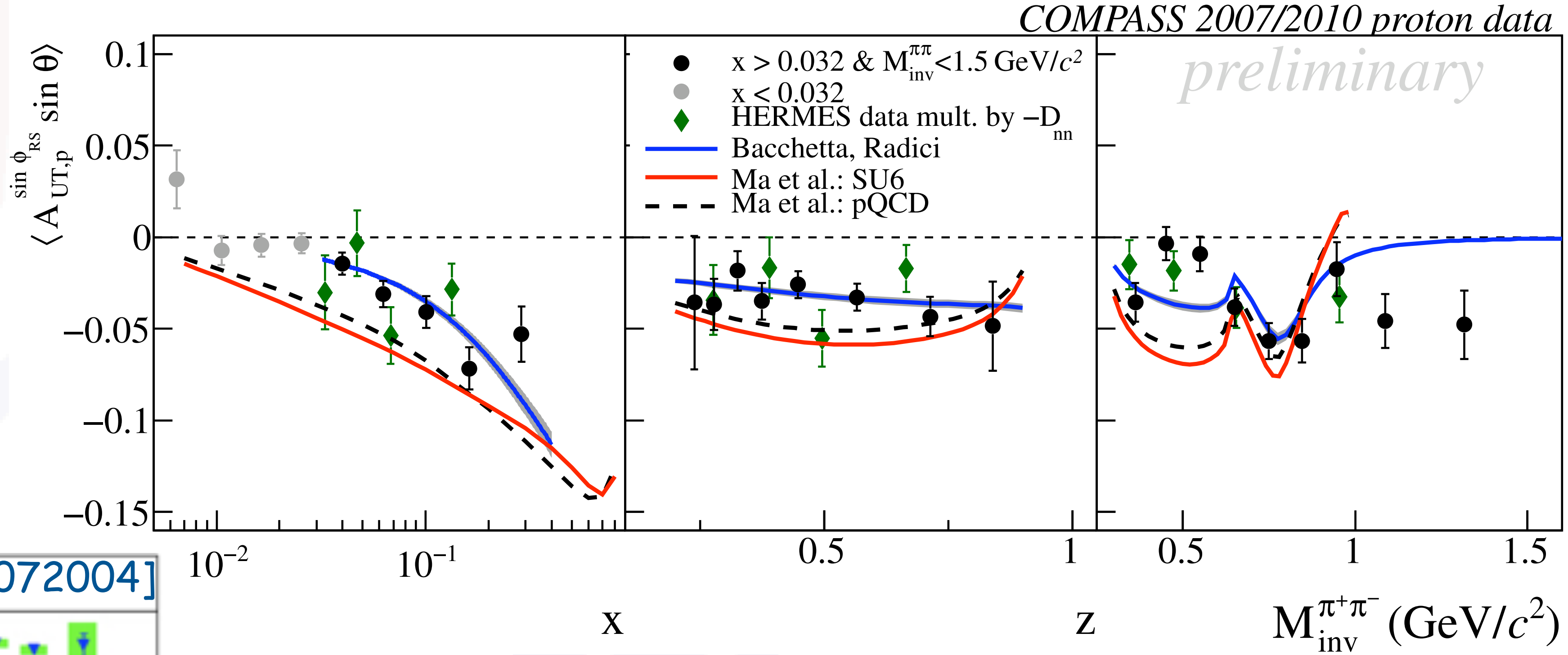

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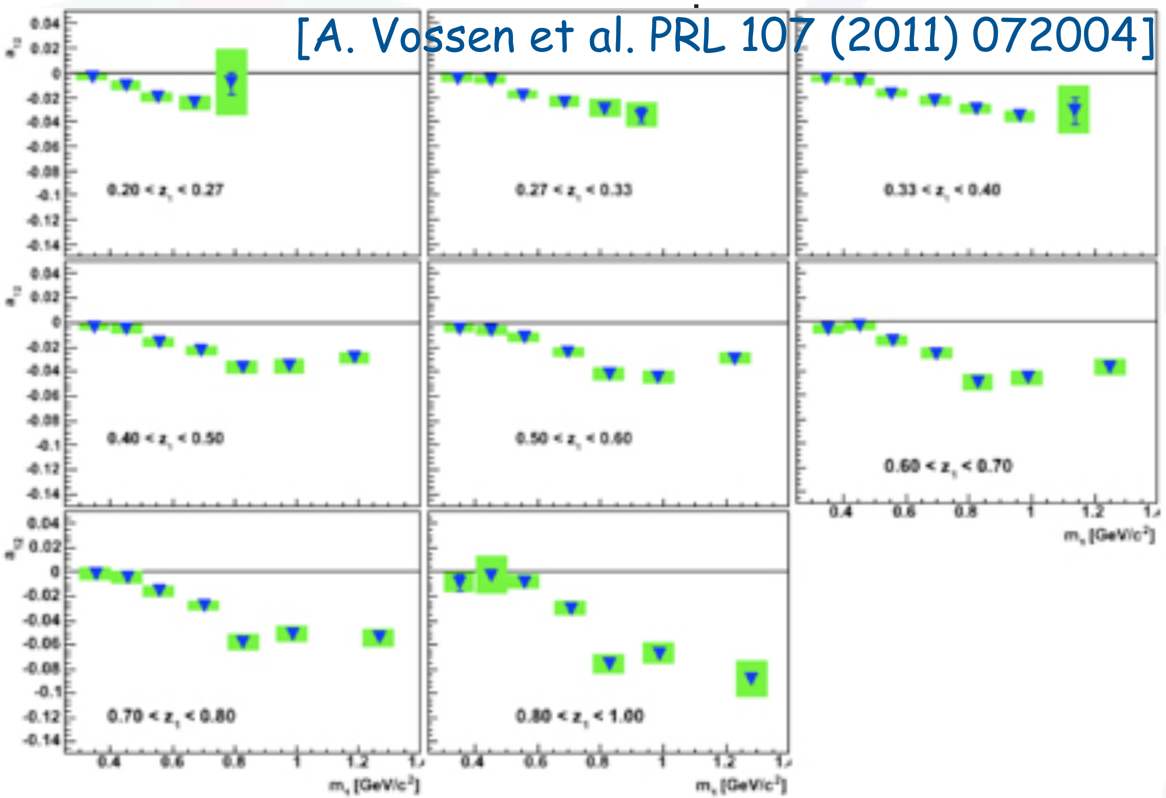
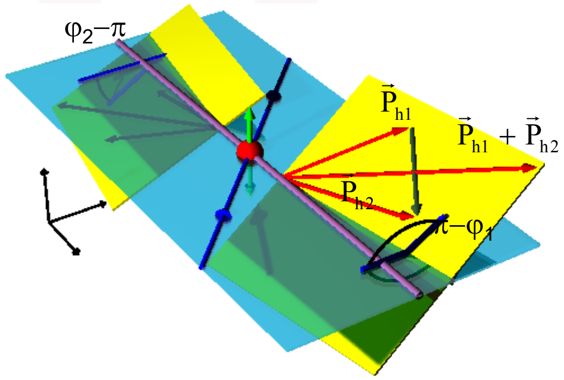


[A. Vossen et al. PRL 107 (2011) 072004]

- data from e$^+$e$^-$ by BELLE



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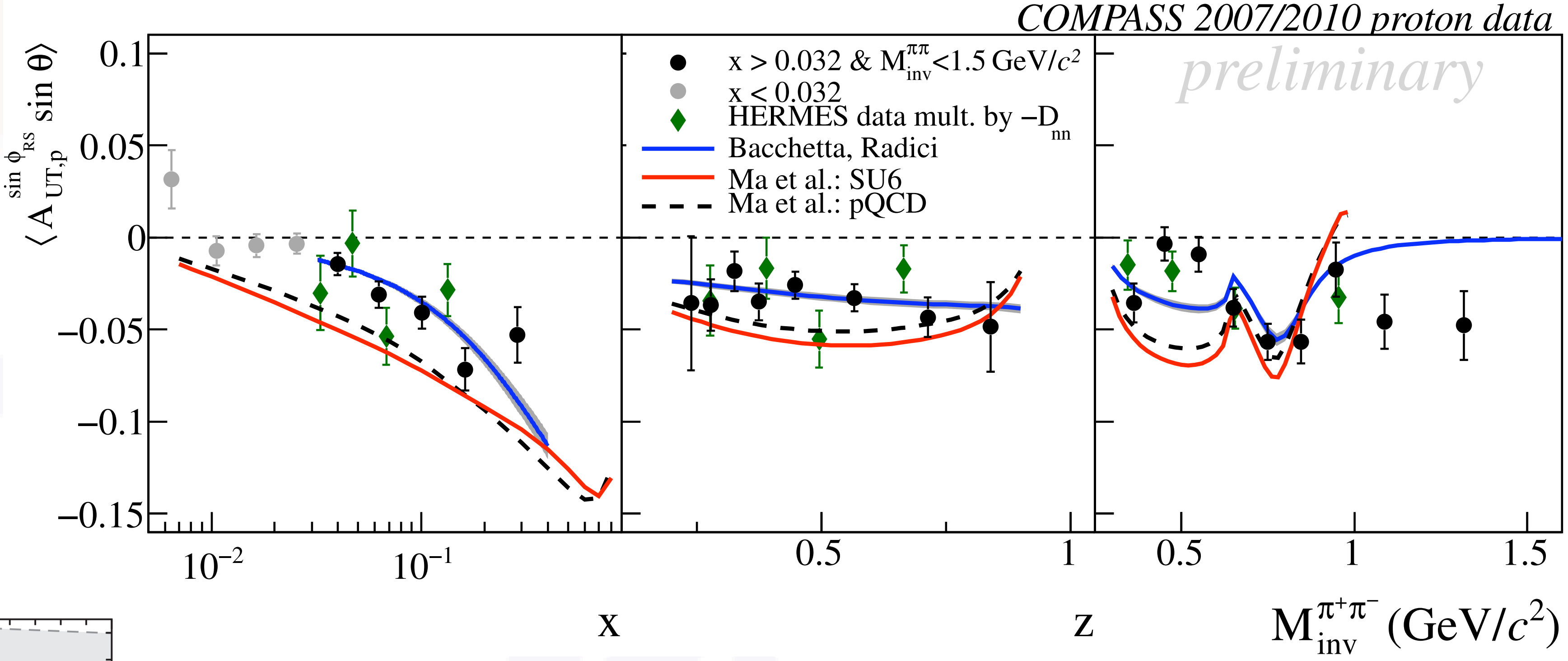
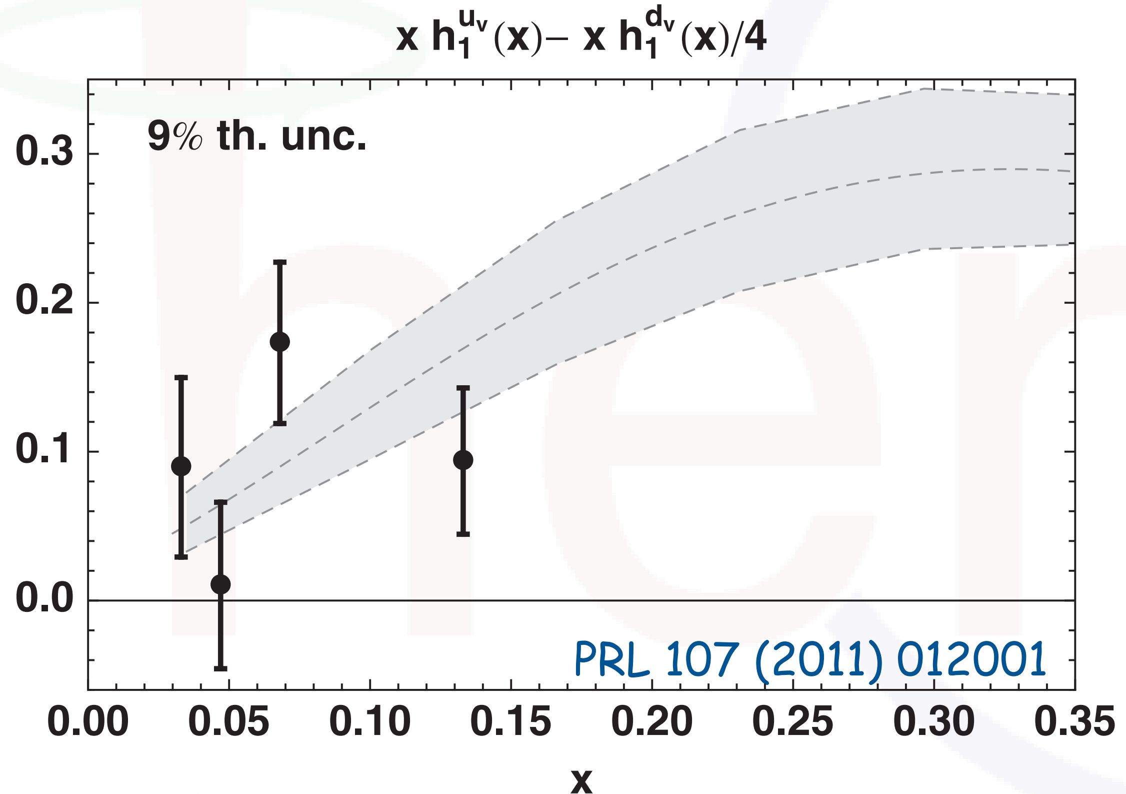
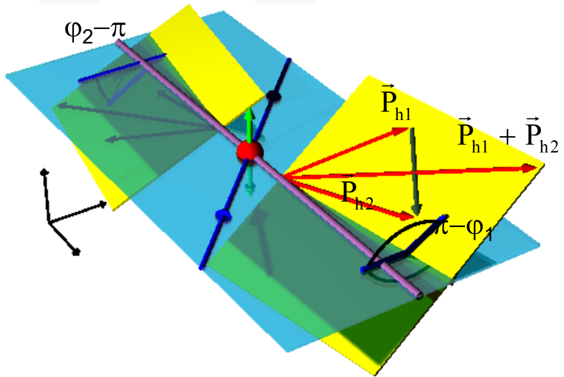




PRL 107 (2011) 012001

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



- updated analysis exists, not part of this talk

Transversity's friends

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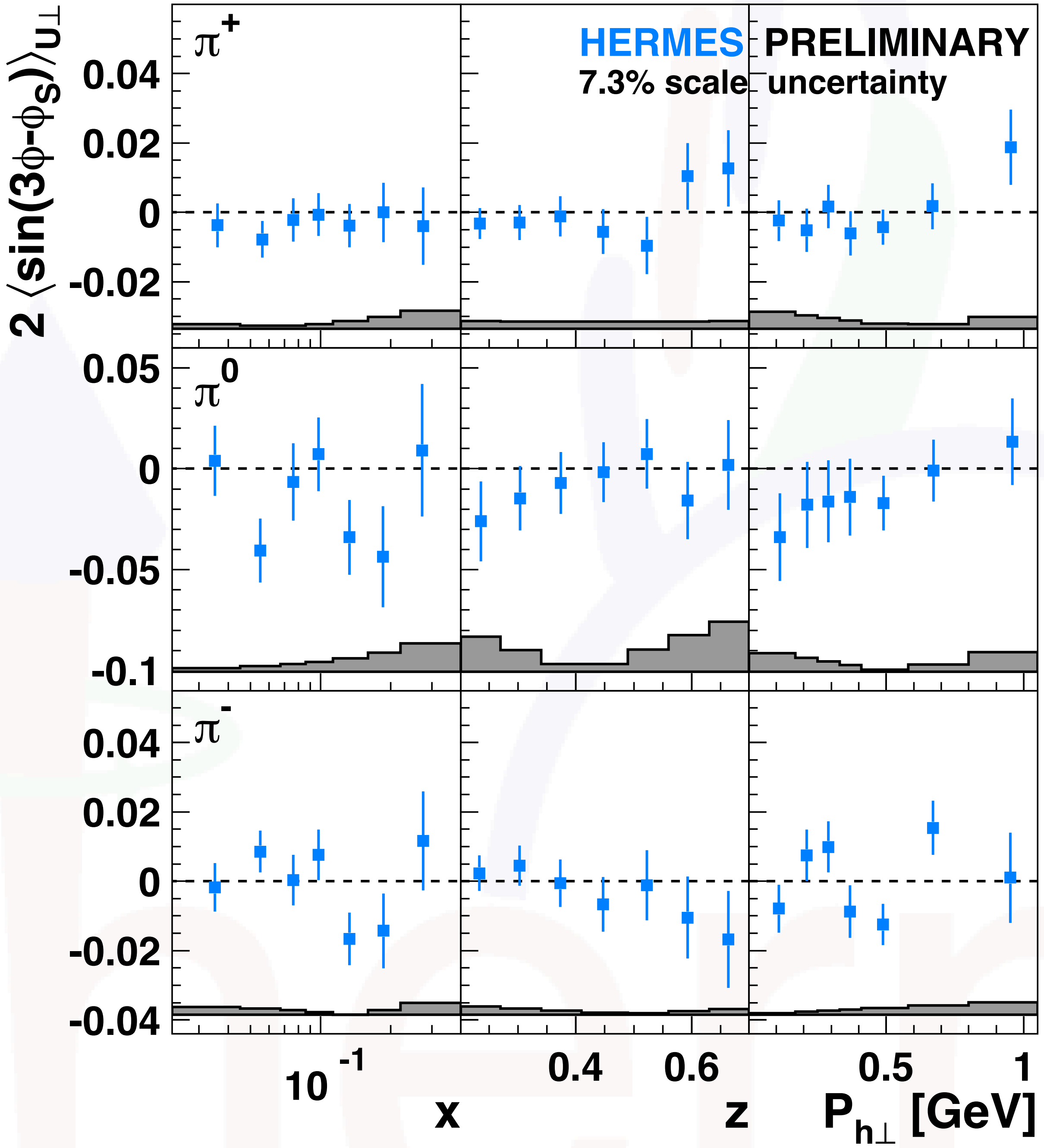
Pretzelosity?



- consistent with zero; but suppressed by two powers of $P_{h\perp}$ (compared to, e.g., transversity⊗Collins)

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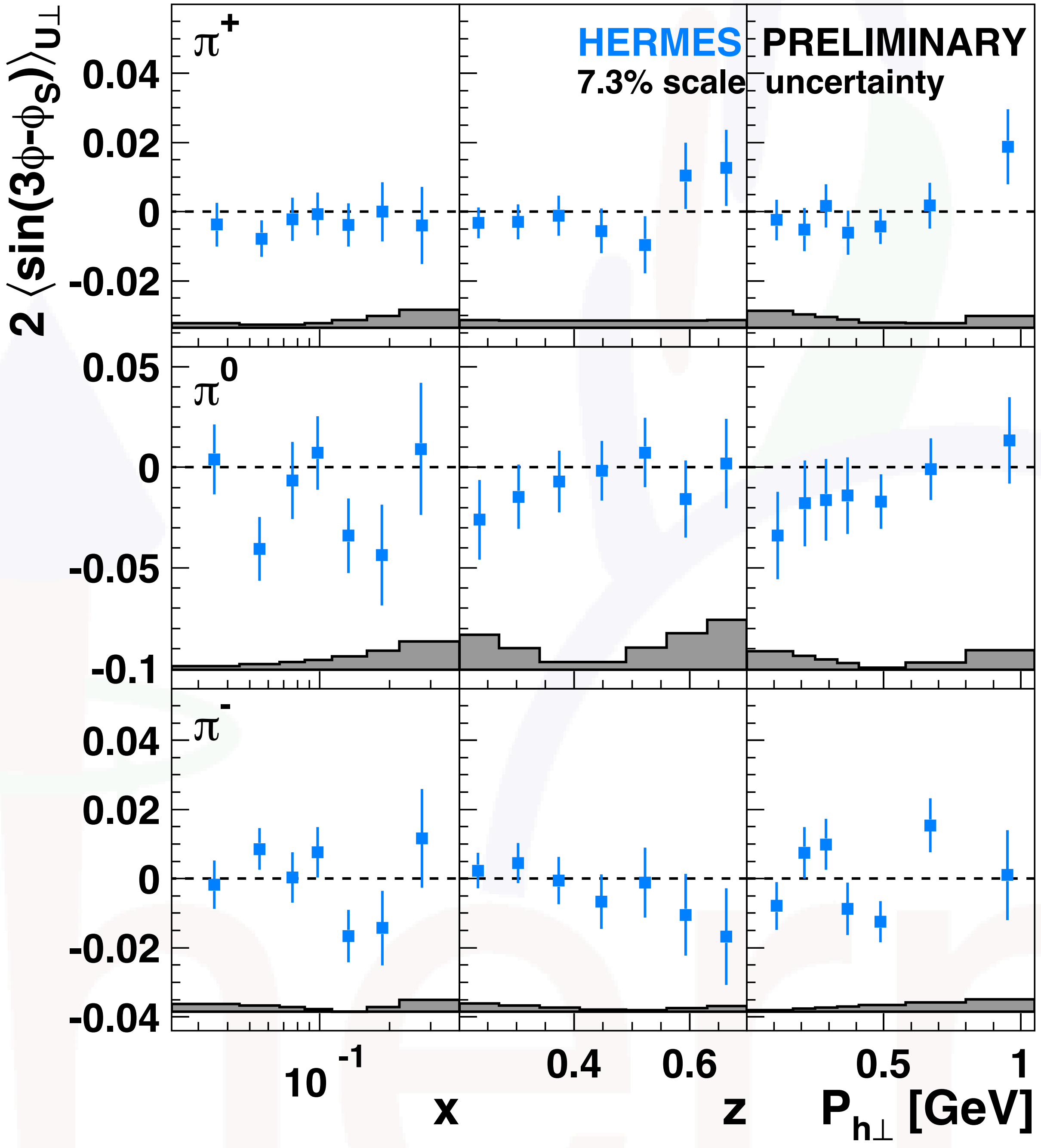

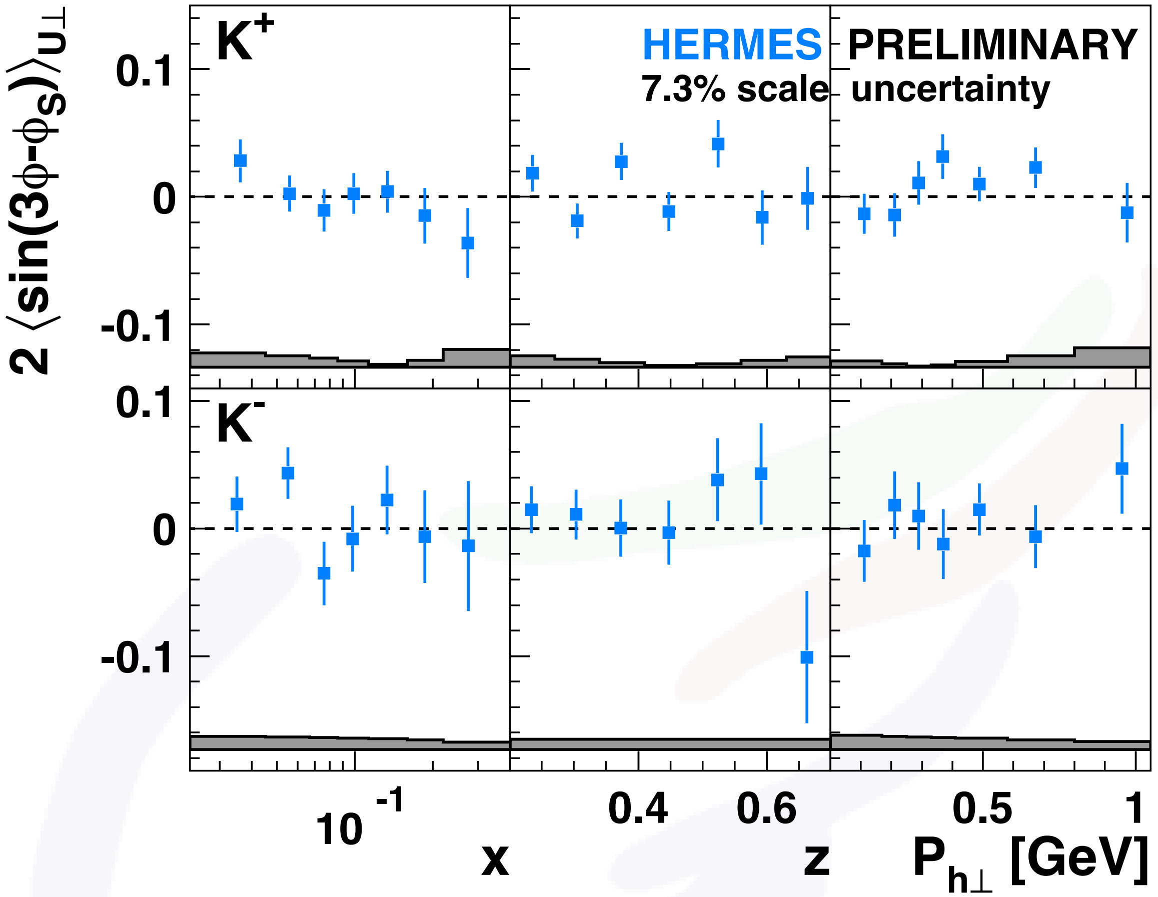

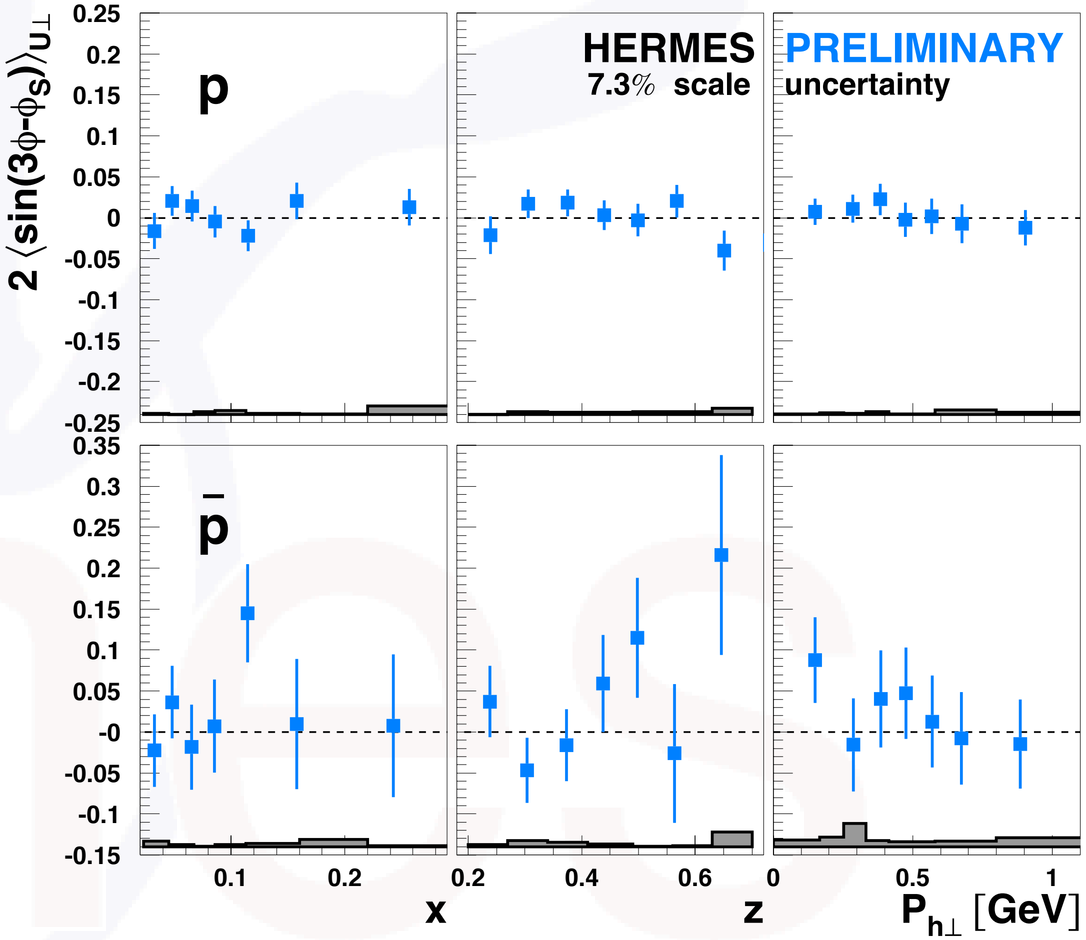

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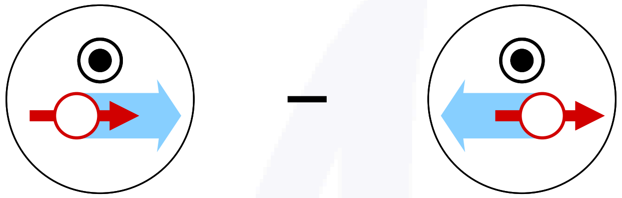

Worm-Gear I

- again: chiral-odd
- consistent with zero both for proton and deuteron

	Meson	Deuterium target	Proton target [2,3]
$A_{\mathrm{UL}}^{\sin 2\phi}$	π^+	$0.004 \pm 0.002 \pm 0.002$	$-0.002 \pm 0.005 \pm 0.003$
	π^0	$0.009 \pm 0.005 \pm 0.003$	$0.006 \pm 0.007 \pm 0.003$
	π^-	$0.001 \pm 0.003 \pm 0.002$	$-0.005 \pm 0.006 \pm 0.005$
	K^+	$-0.005 \pm 0.006 \pm 0.003$	–

[PLB 562 (2003) 182-192]

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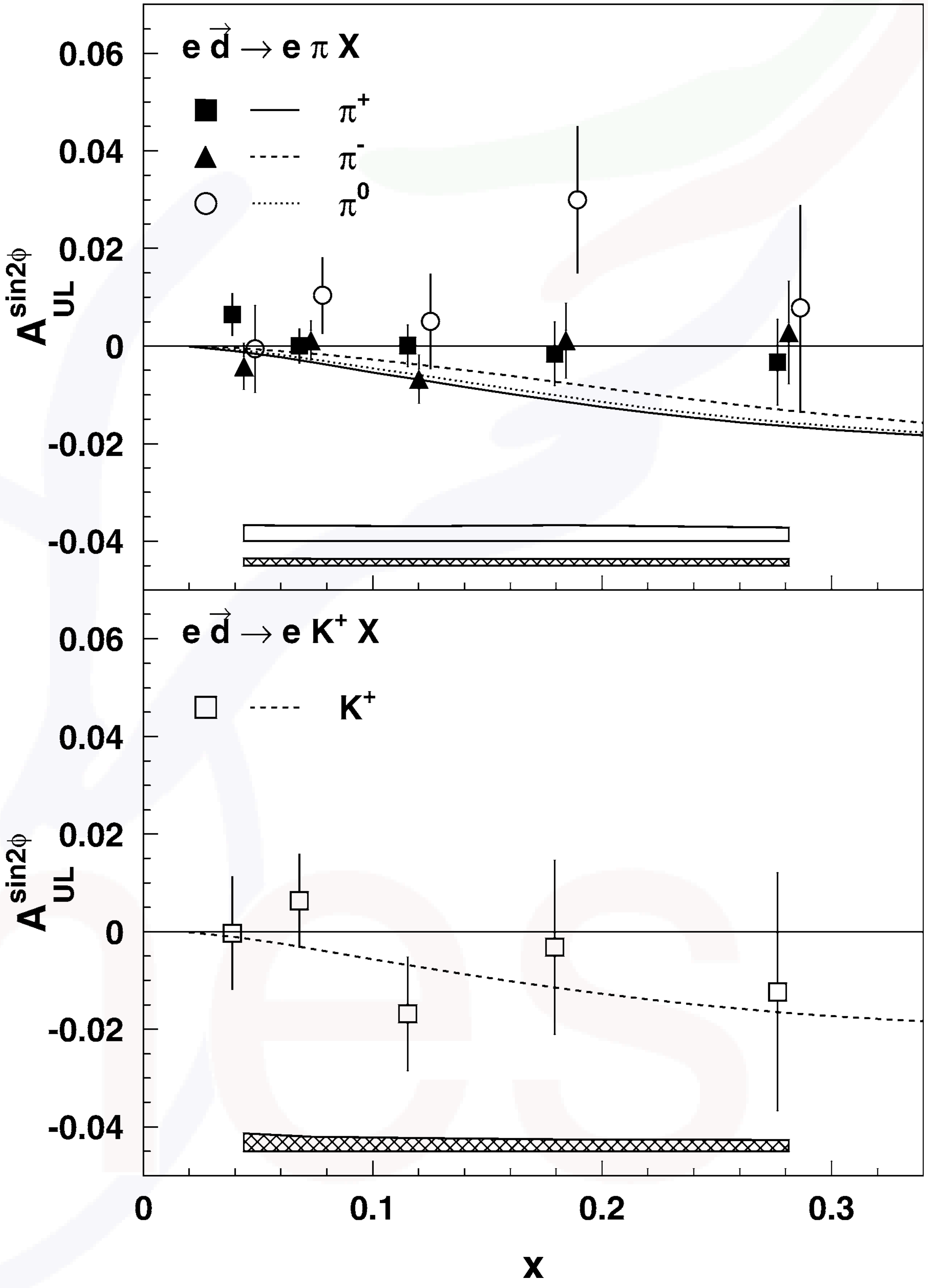
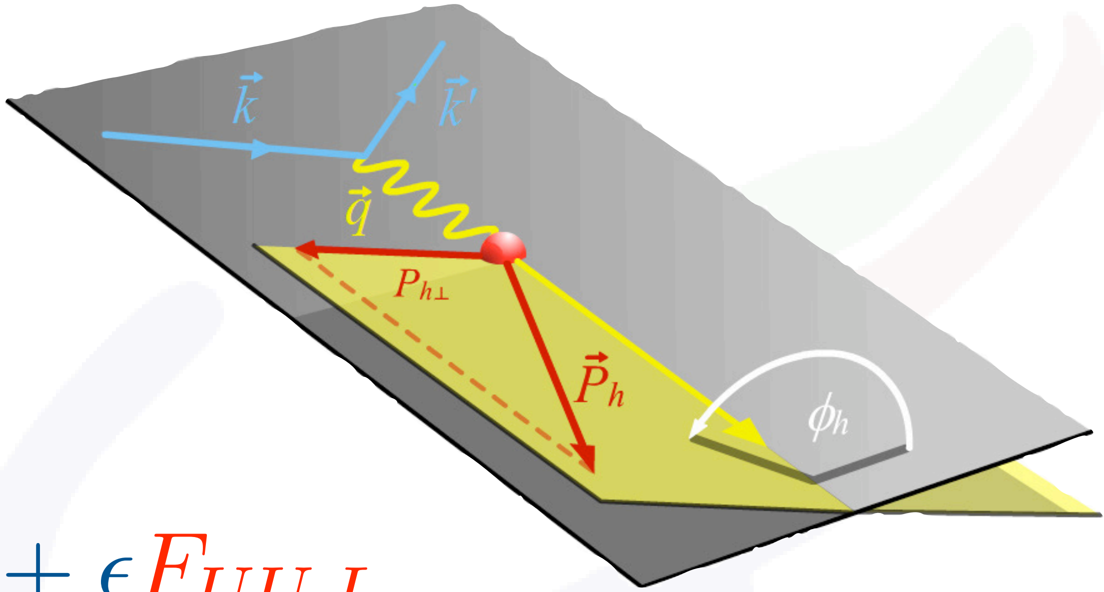


cross section without polarization



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

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

target polarization

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

beam polarization

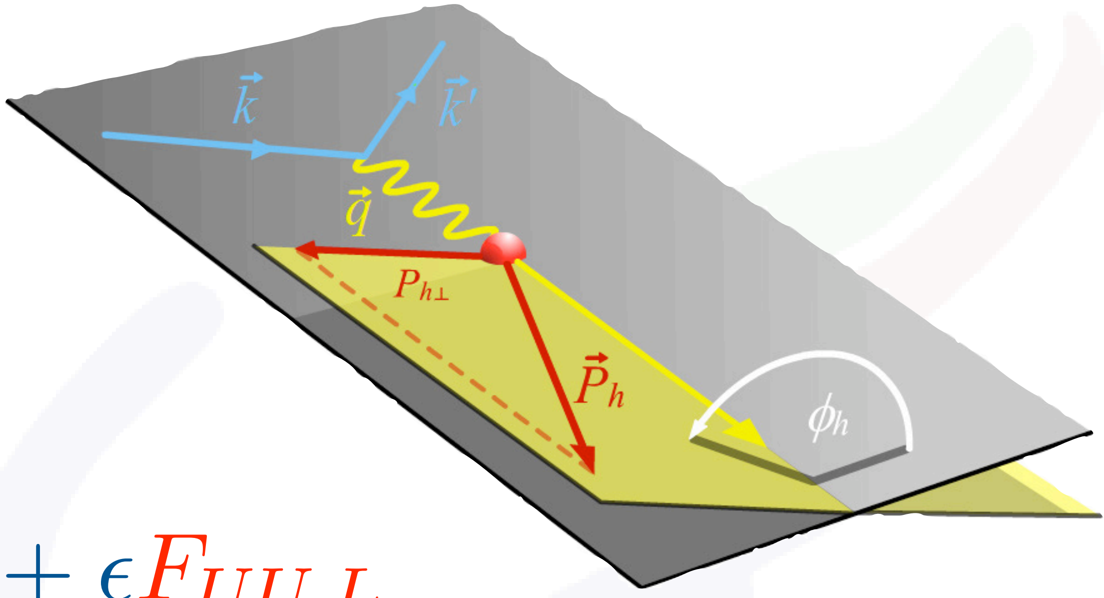
virtual-photon polarization

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

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

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

cross section without polarization



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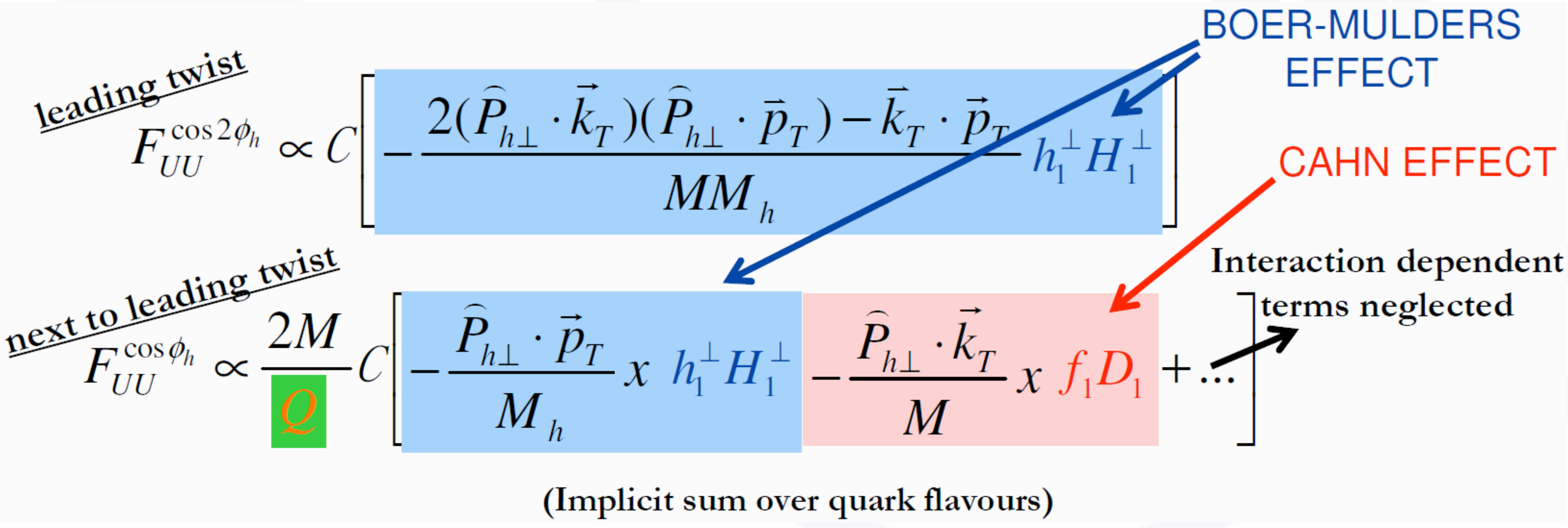
$$+\sqrt{2\epsilon(1-\epsilon)}\,\boxed{F_{UU}^{\cos\phi_h}}\cos\phi_h+\epsilon\boxed{F_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\}$$



leading twist

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

next to leading twist

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

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

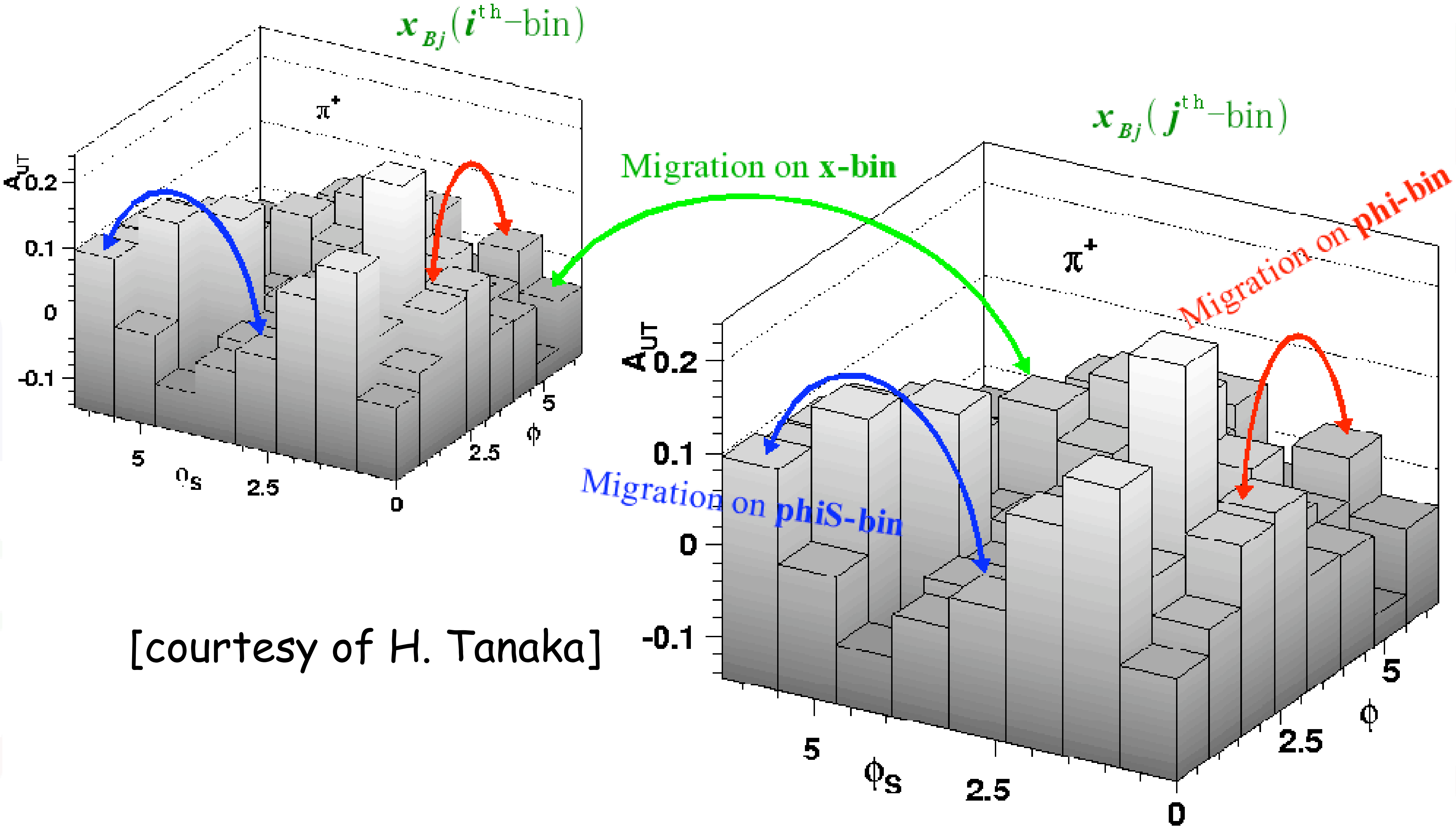
(Implicit sum over quark flavours)

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

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

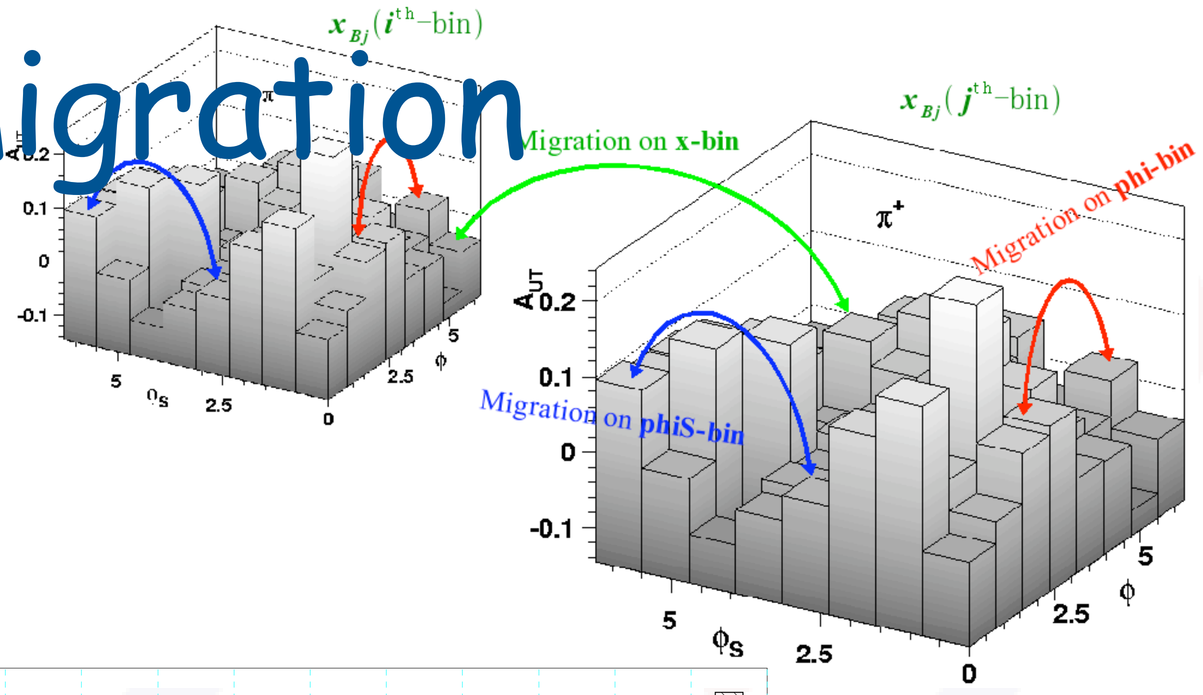
[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

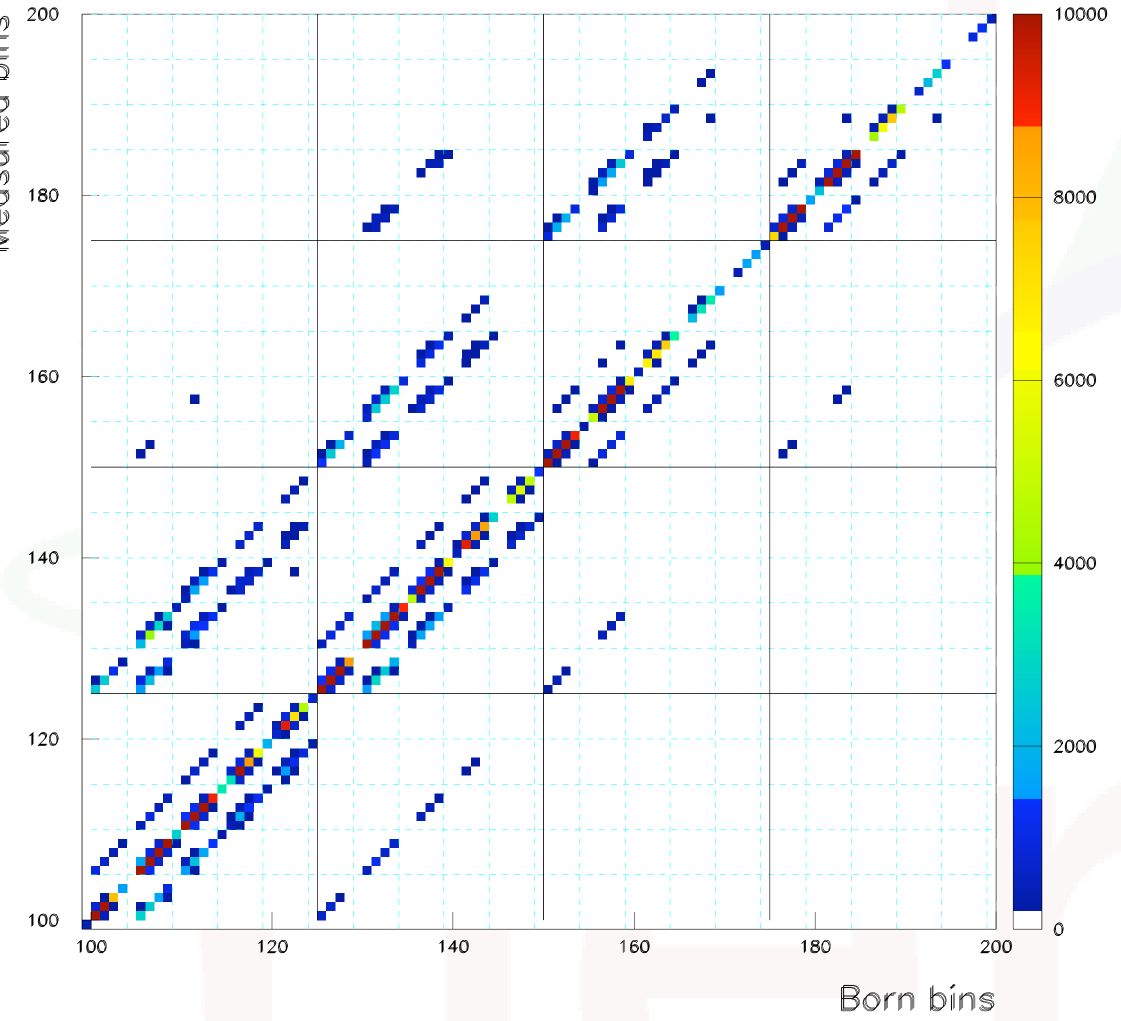
extraction I - event migration

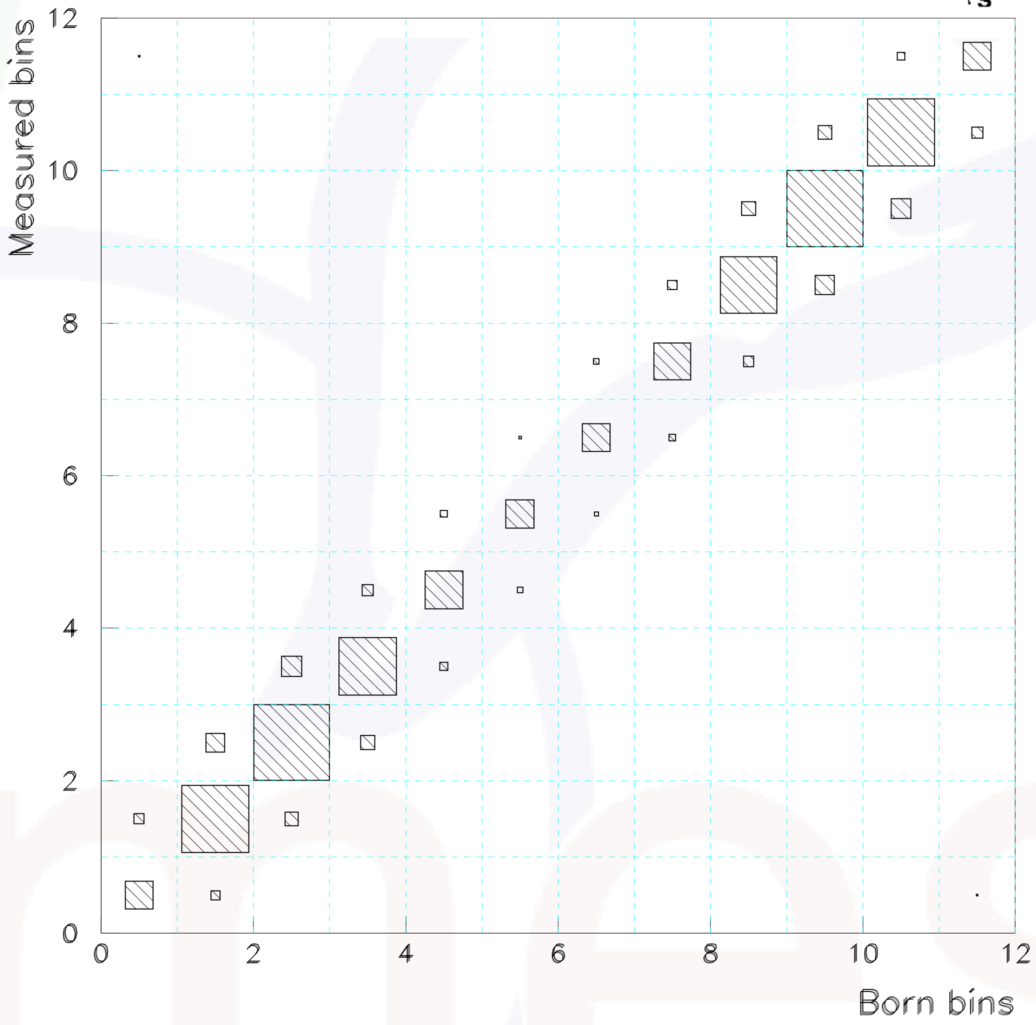


[courtesy of H. Tanaka]

extraction I - event migration

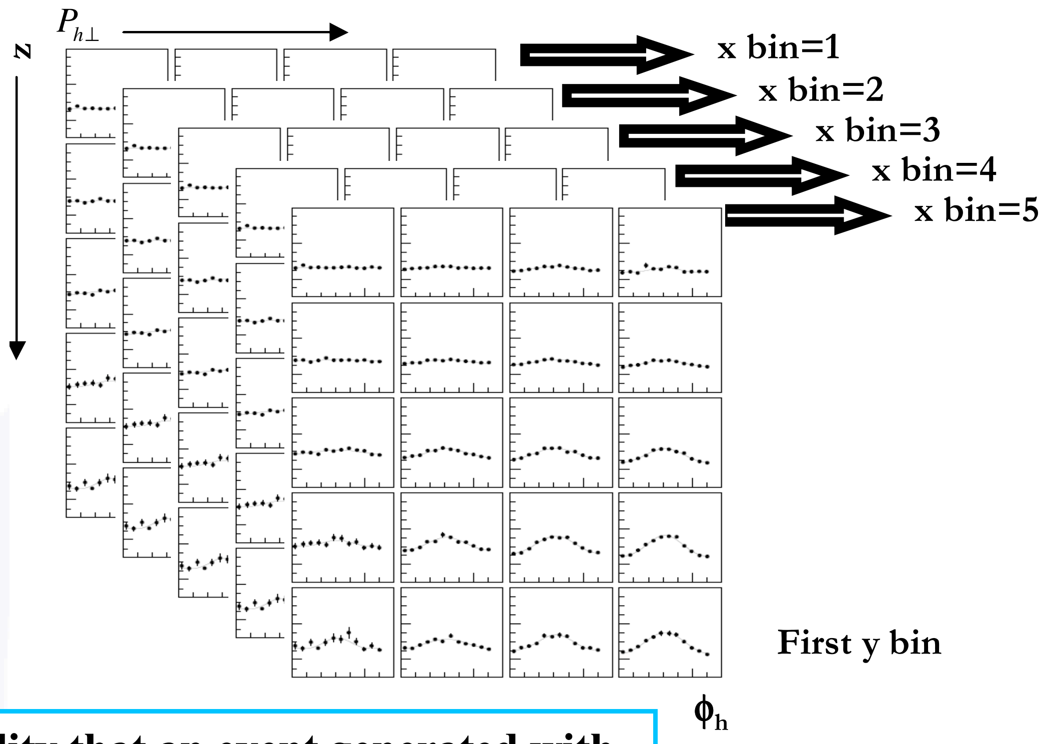






- migration correlates yields in different bins
- can't be corrected properly in bin-by-bin approach

extraction II - unfolding



- Fully differential analysis in $(x,y,z,P_{h\perp},\phi)$

- Multi-dimensional unfolding: correction for finite acceptance, QED radiation, kinematic smearing, detector resolution

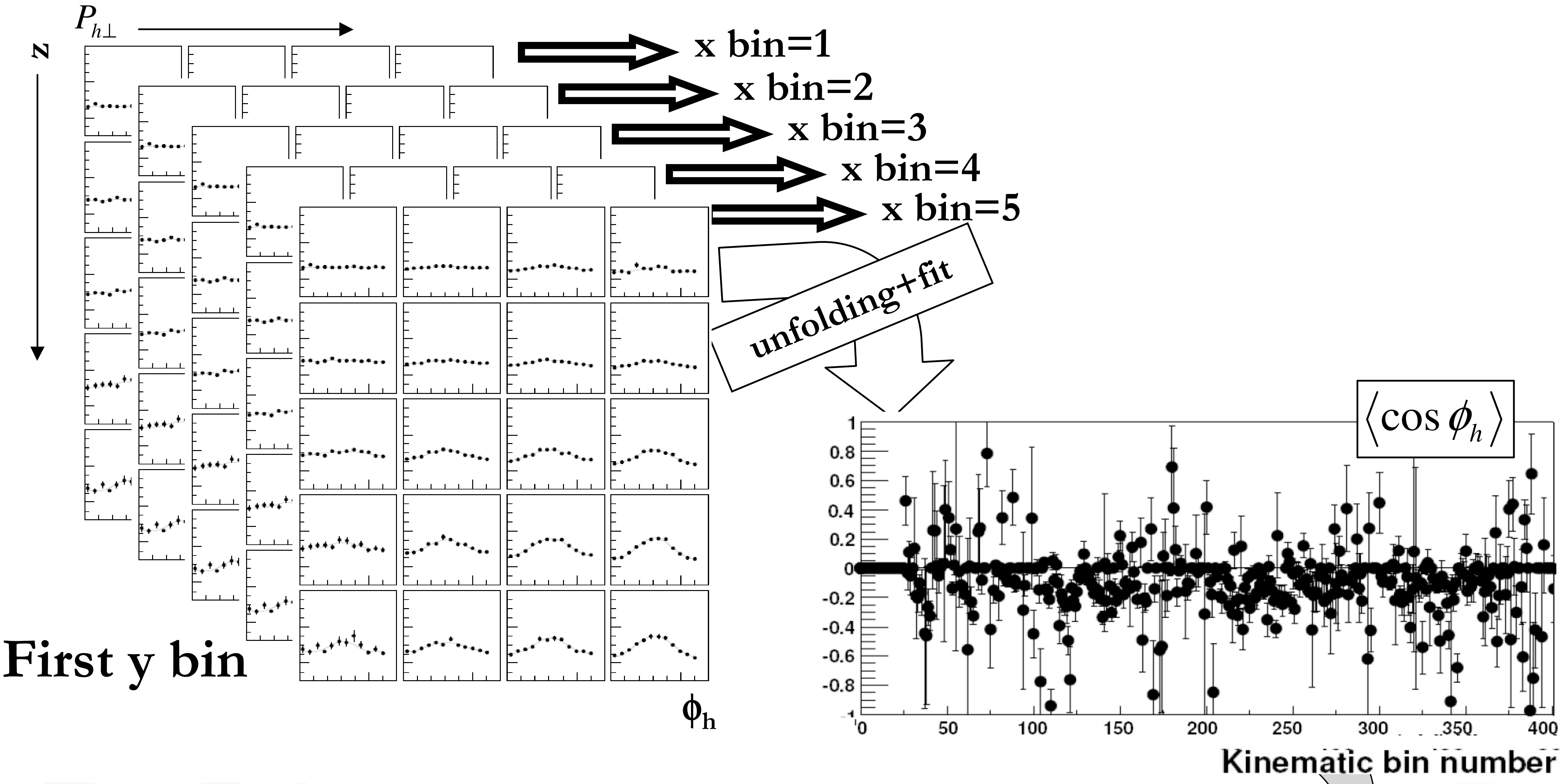
probability that an event generated with a certain kinematics is measured with a different kinematics

$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

includes the events smeared into the acceptance

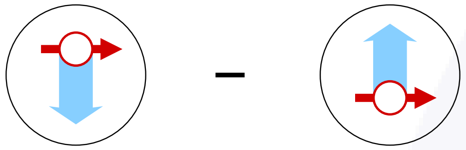
extraction III - projecting



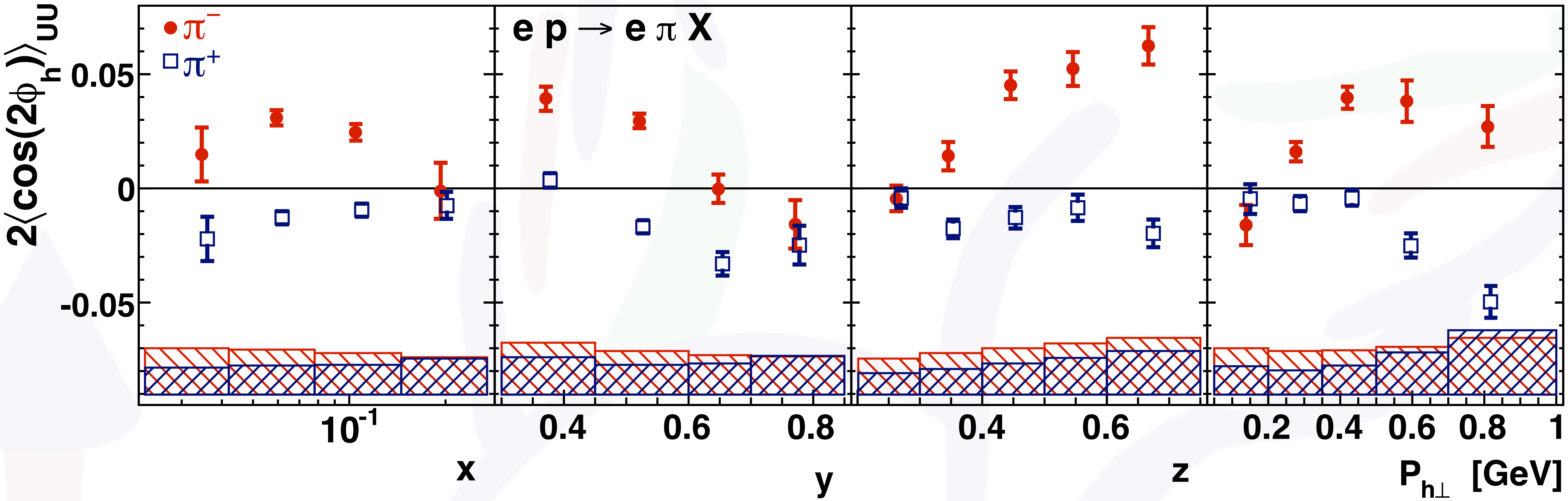
$$\langle\cos\phi\rangle(x_b) \approx \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b}) \langle\cos\phi\rangle_{x_i=x_b}}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b})}$$

signs of Boer-Mulders

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



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



signs of Boer-Mulders

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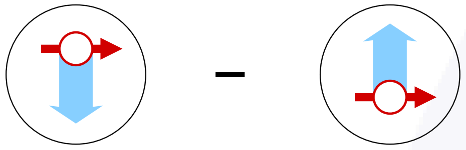
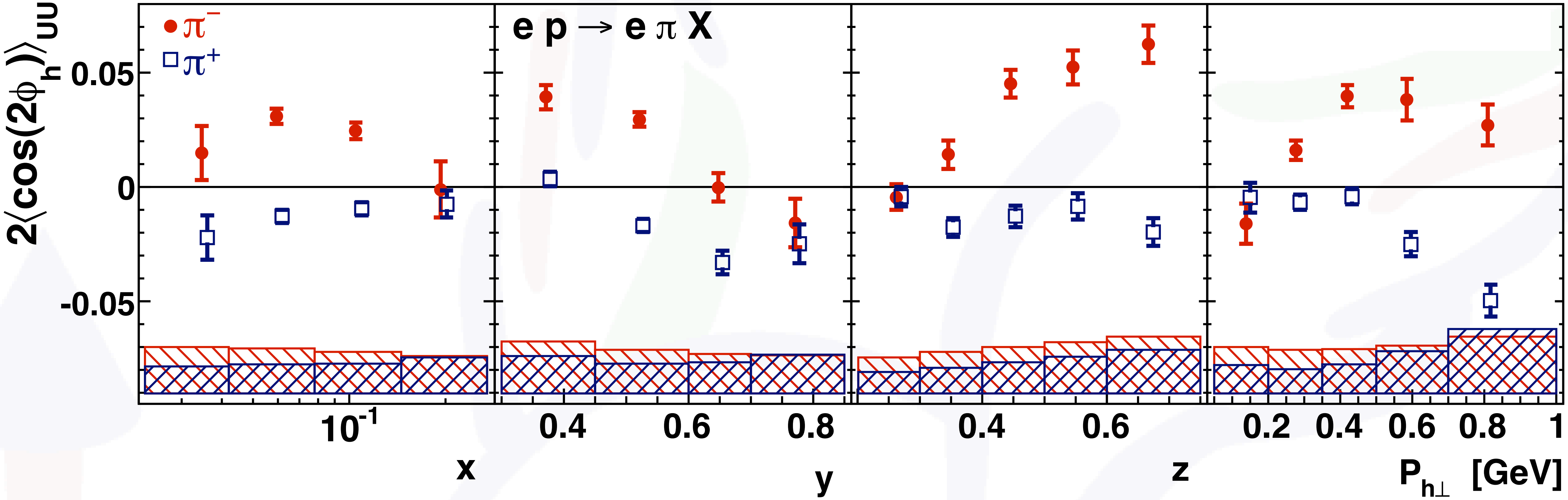


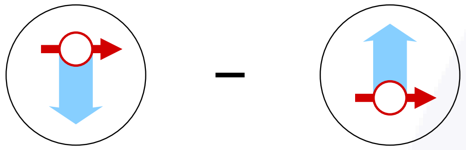
[Airapetian et al., PRD 87 (2013) 012010]



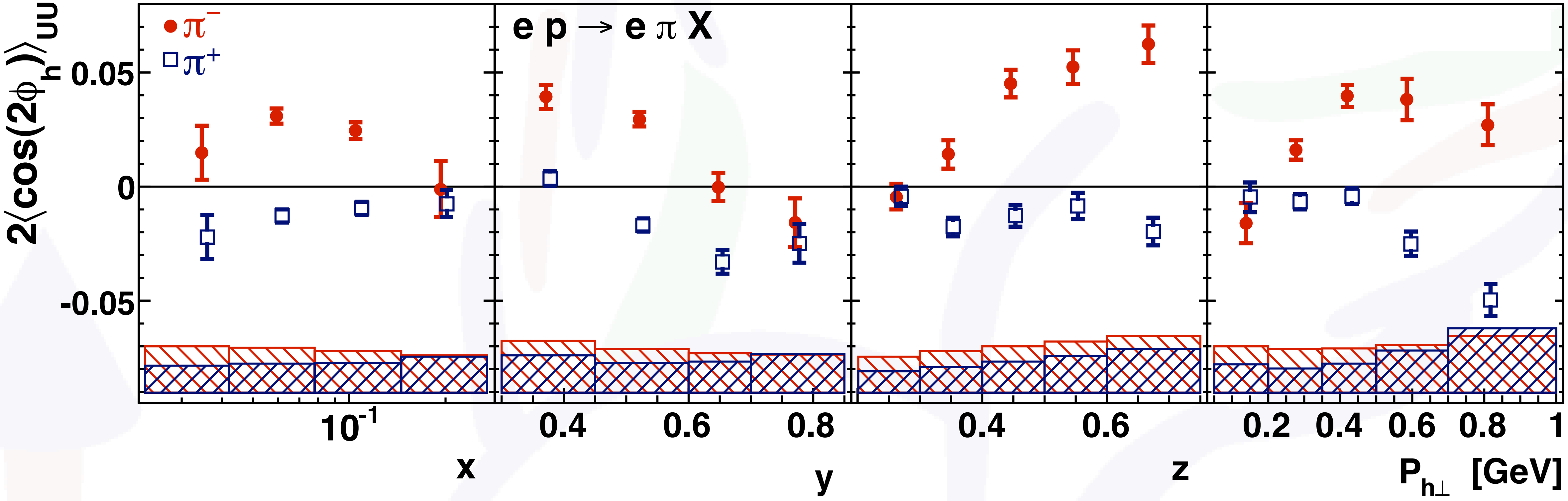
- modulations are not zero!

signs of Boer-Mulders

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

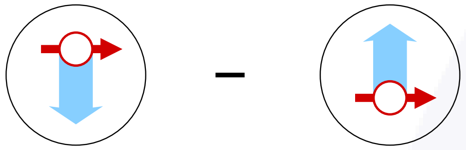


[Airapetian et al., PRD 87 (2013) 012010]



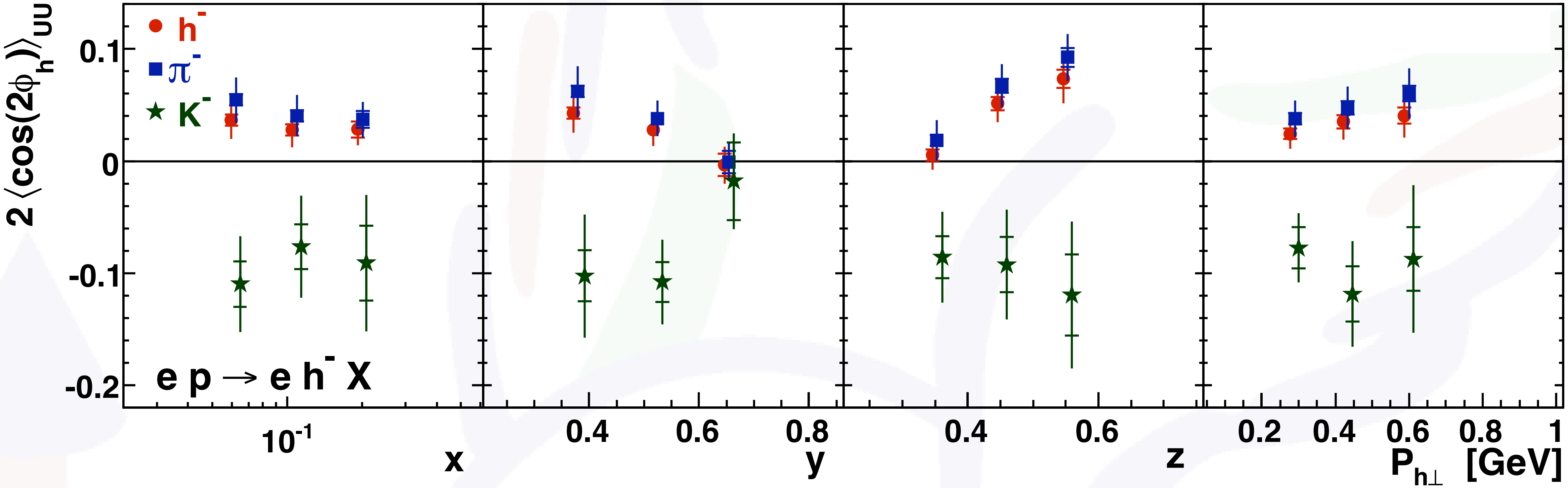
- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-

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



signs of Boer-Mulders

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



- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons

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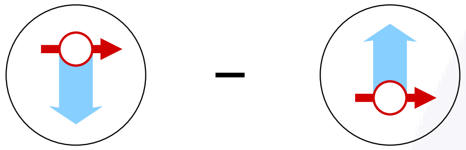
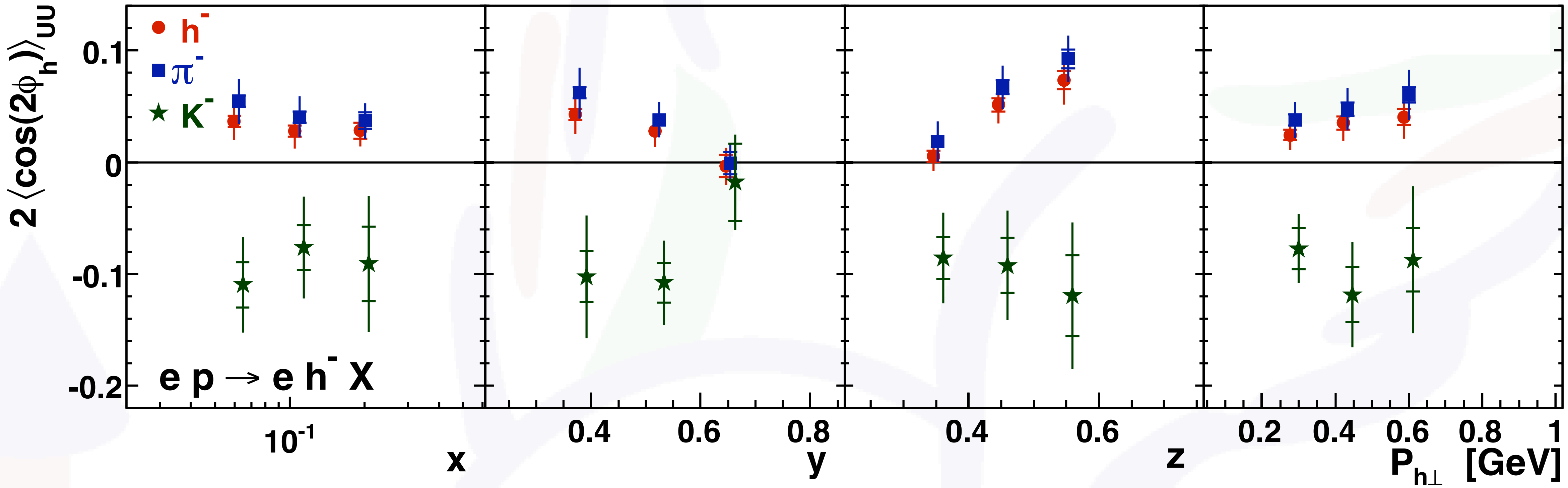


signs of Boer-Mulders

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



- modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons
- available in multidimensional binning, e.g., before projecting: http://www-hermes.desy.de/cosnphi/

Cahn effect?

BOER-MULDERS EFFECT

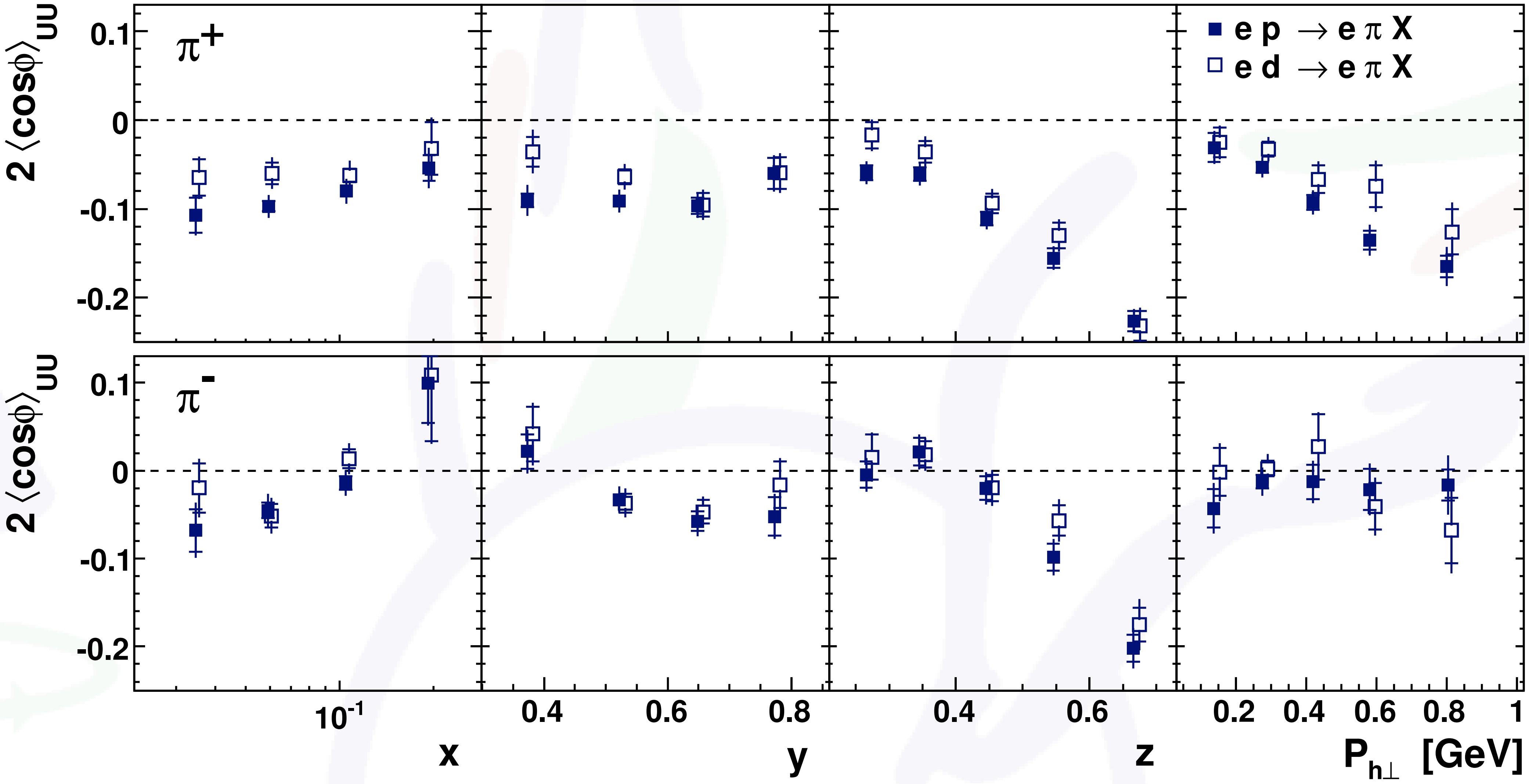
CAHN EFFECT

next to leading twist

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

Interaction dependent terms neglected

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



- no dependence on hadron charge **expected** for Cahn effect

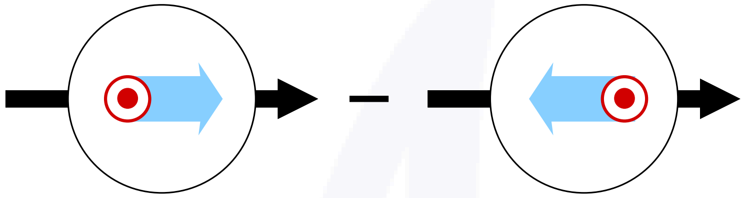
➡ flavor dependence of transverse momentum

➡ sign of Boer-Mulders in cosϕ modulation
(indeed, overall pattern resembles B-M modulations)

➡ additional “genuine” twist-3 contributions?

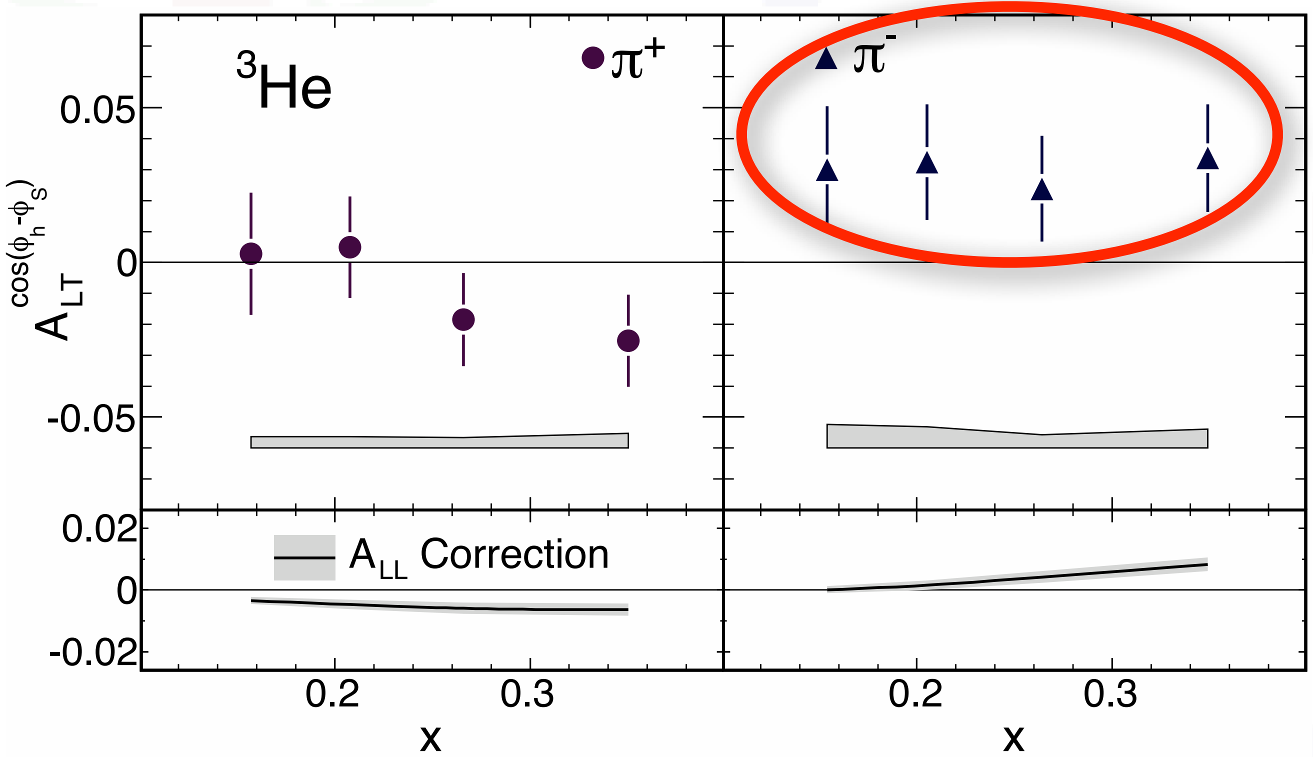
Worm-Gear

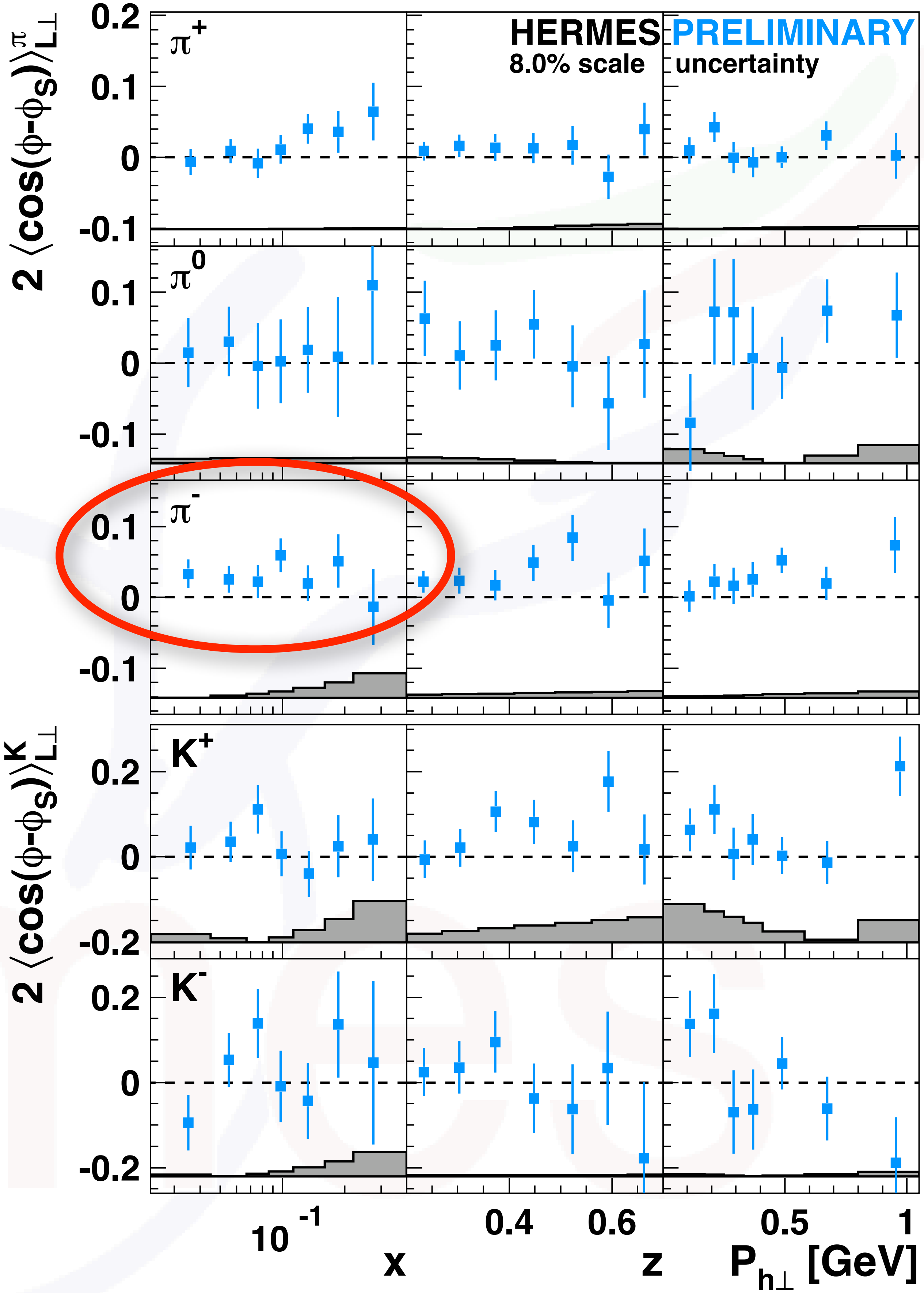
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



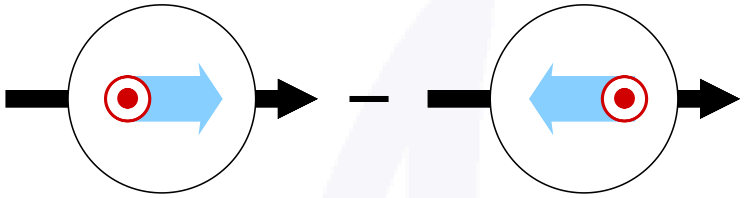
- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES

[PRL 108 (2012) 052001]



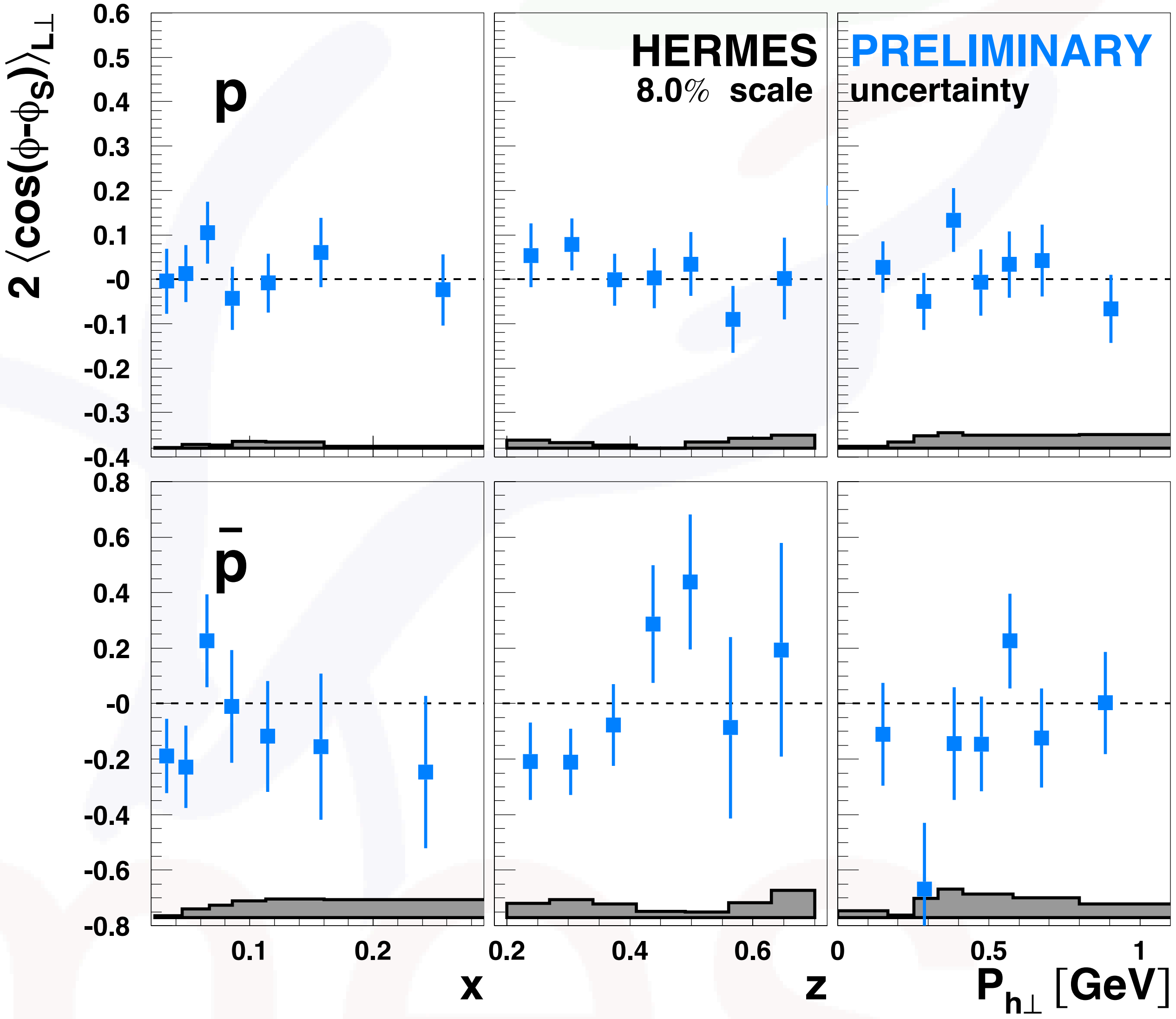


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



Worm-Gear

- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES
- results for protons and anti-protons consistent with zero

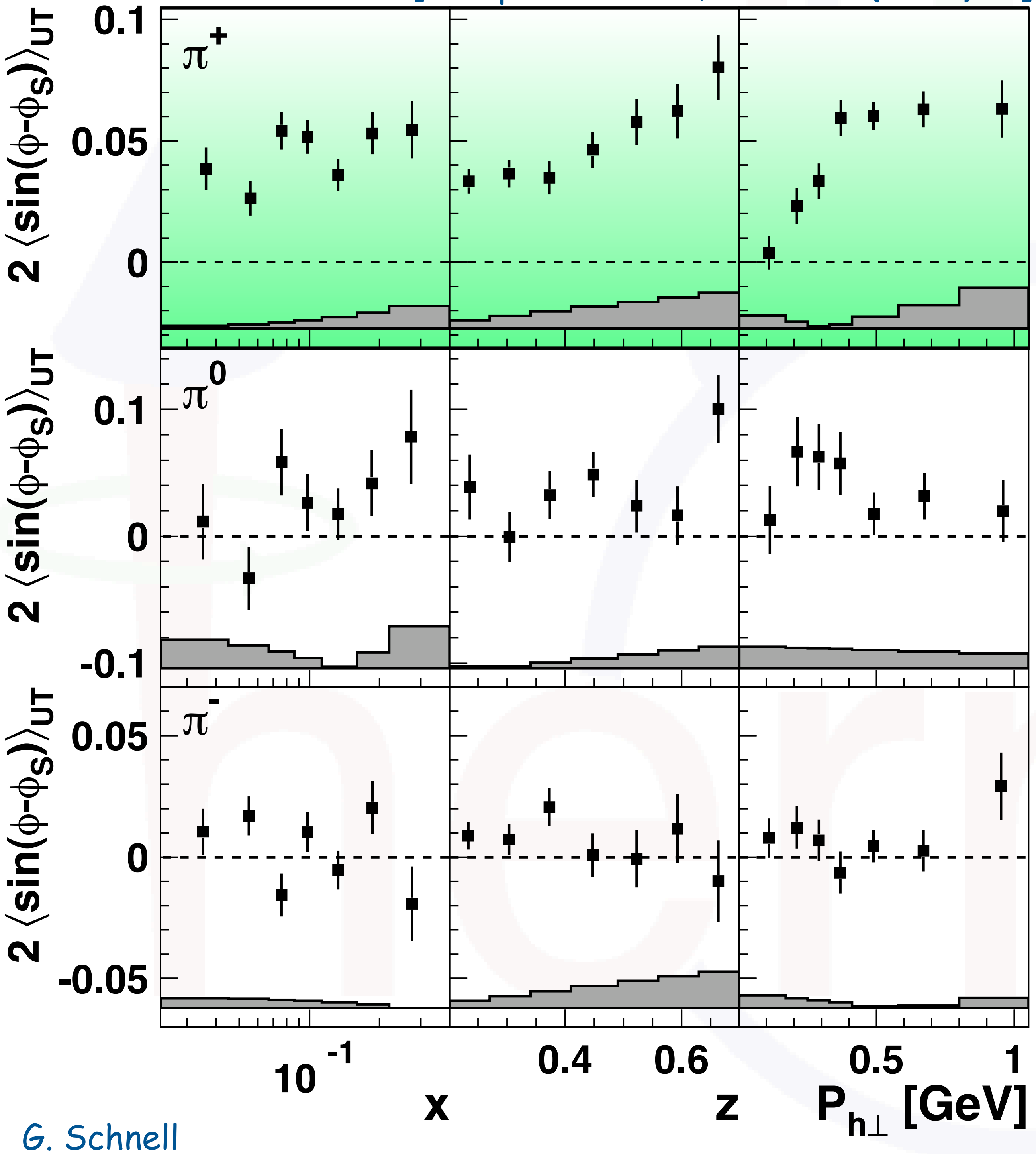


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

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

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



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, $h_{1T}^\perp$

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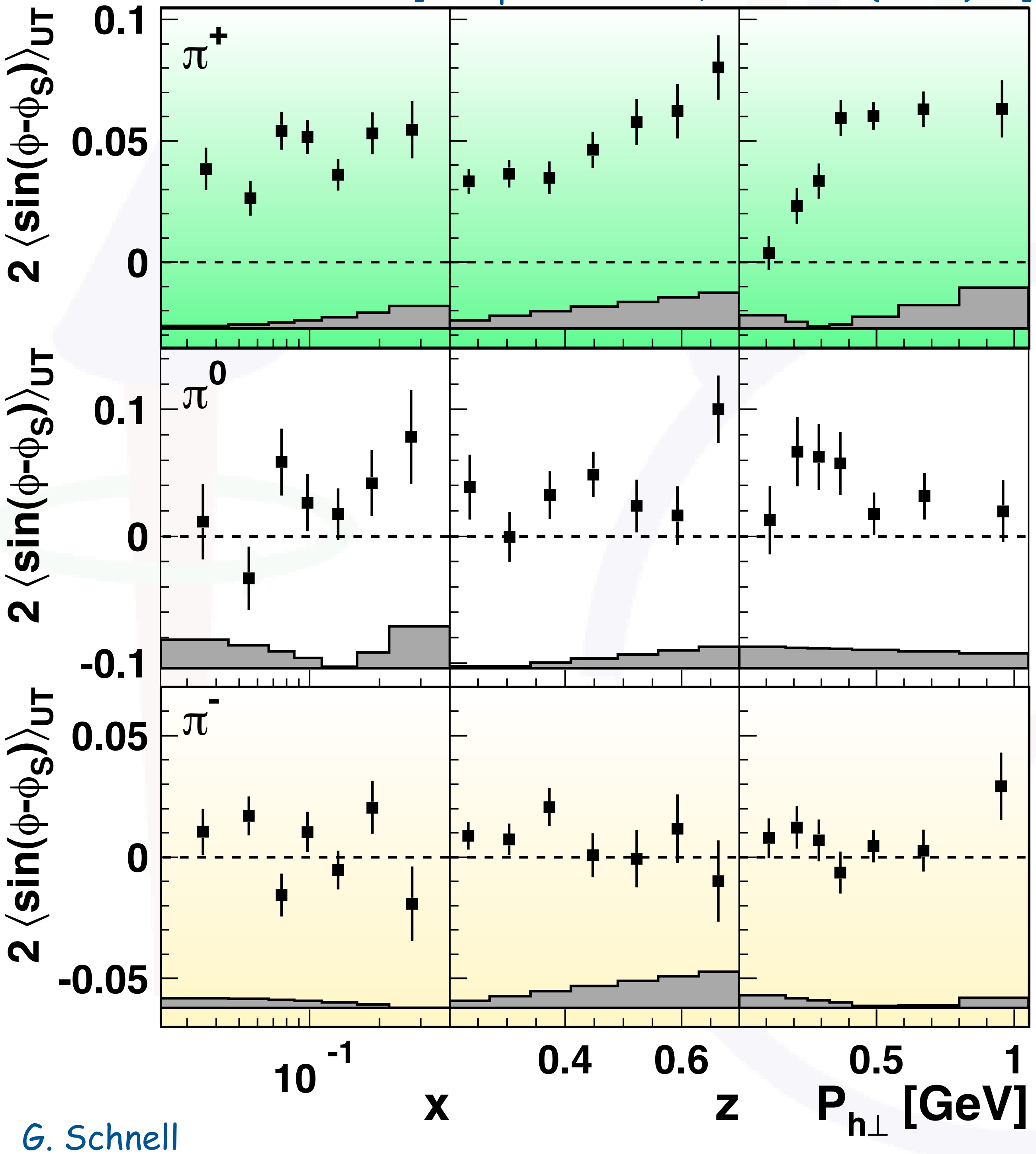
[Airapetian et al., PLB 693 (2010) 11]



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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

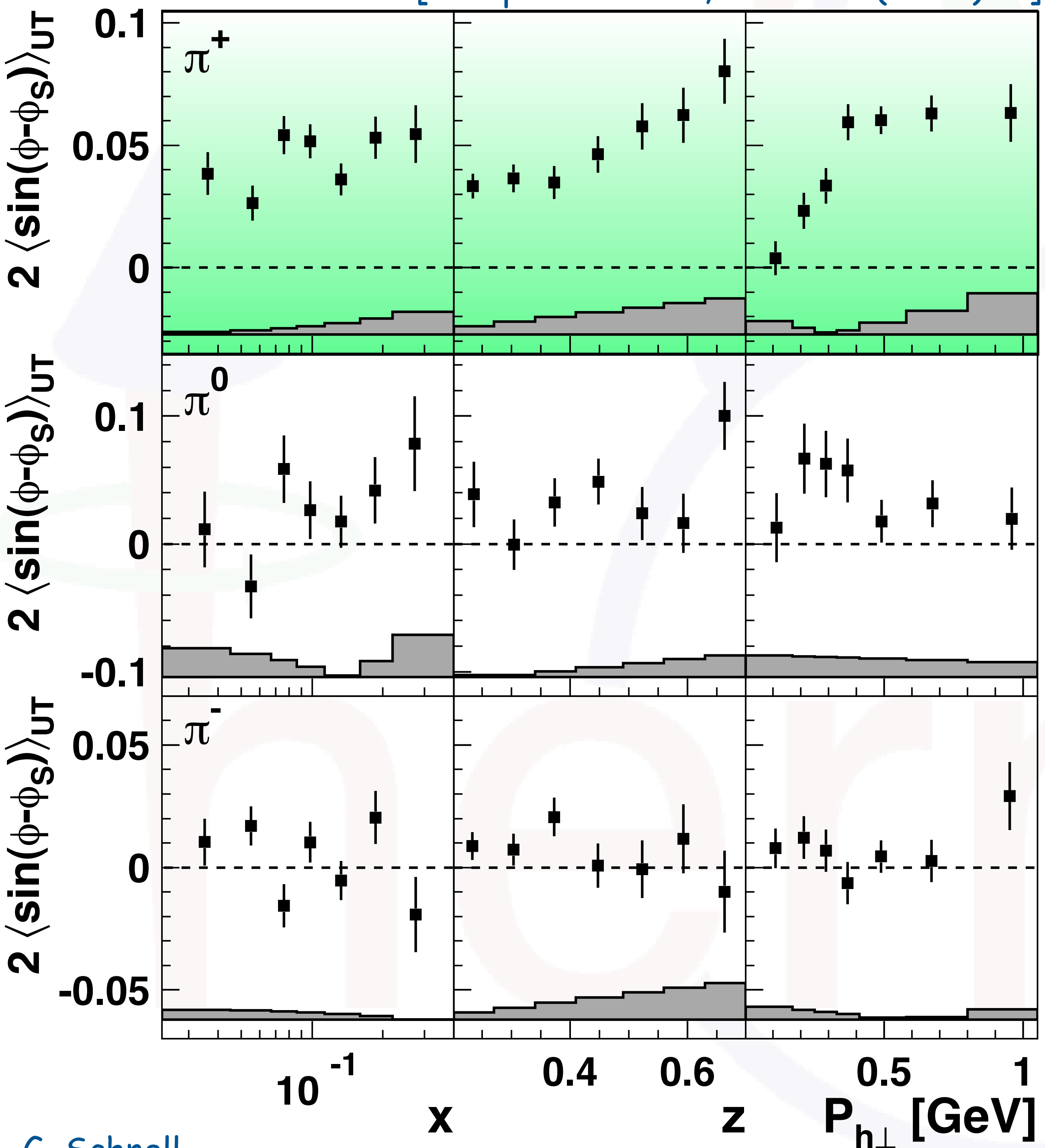
☛ d-quark Sivers DF > 0 (cancelation for π^-)

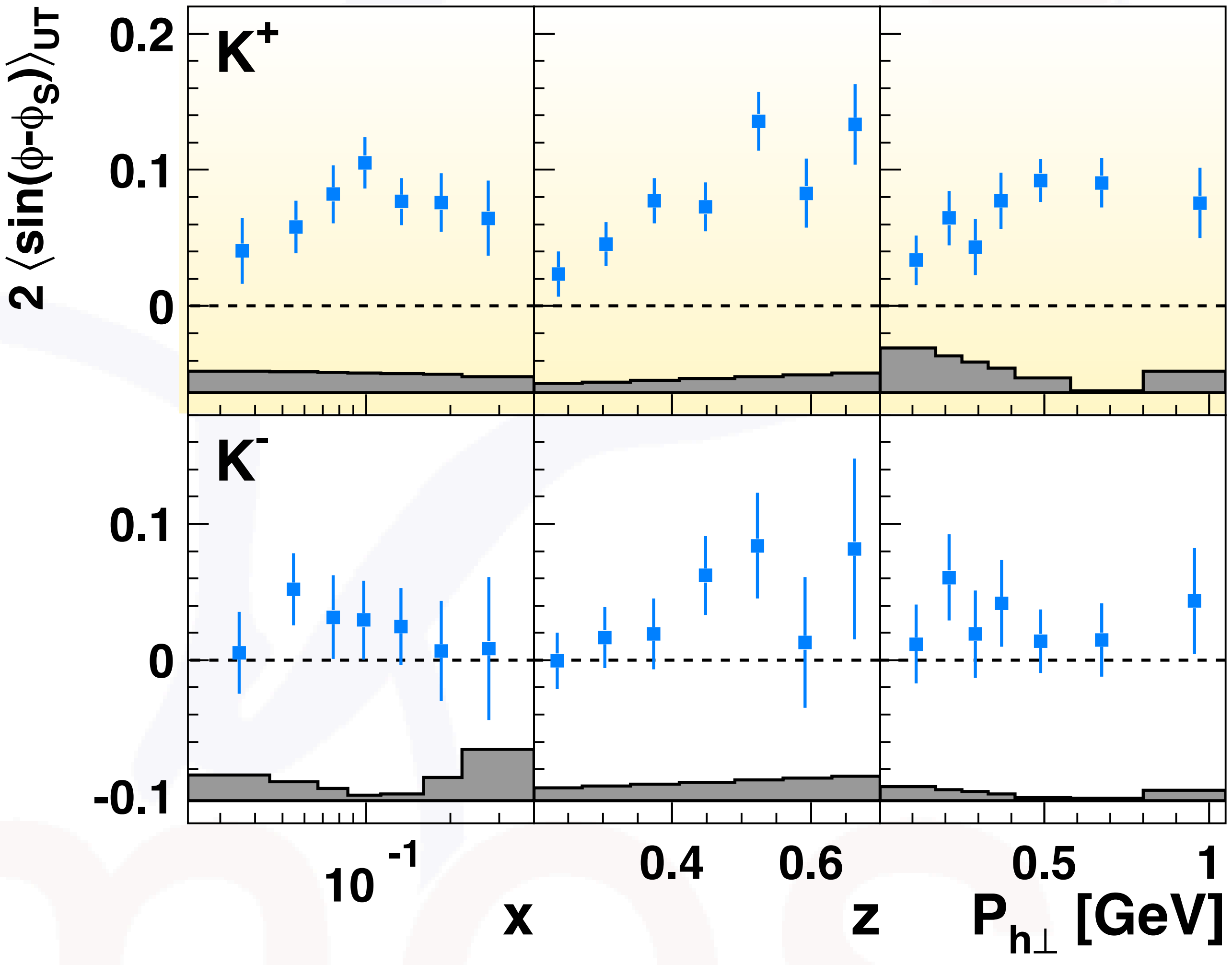
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for mesons

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

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





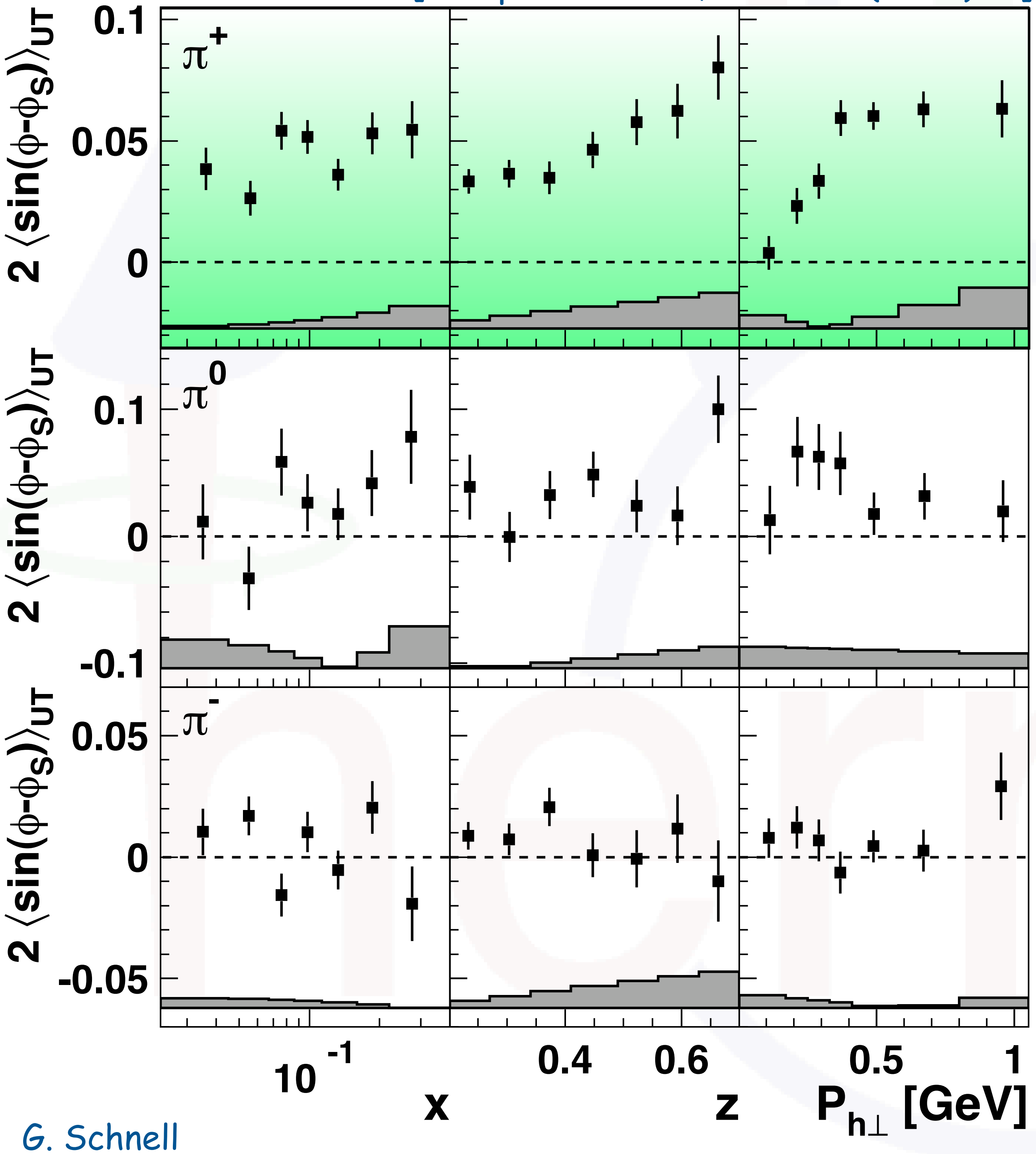
- ☛ larger amplitudes for positive kaons vs. pions

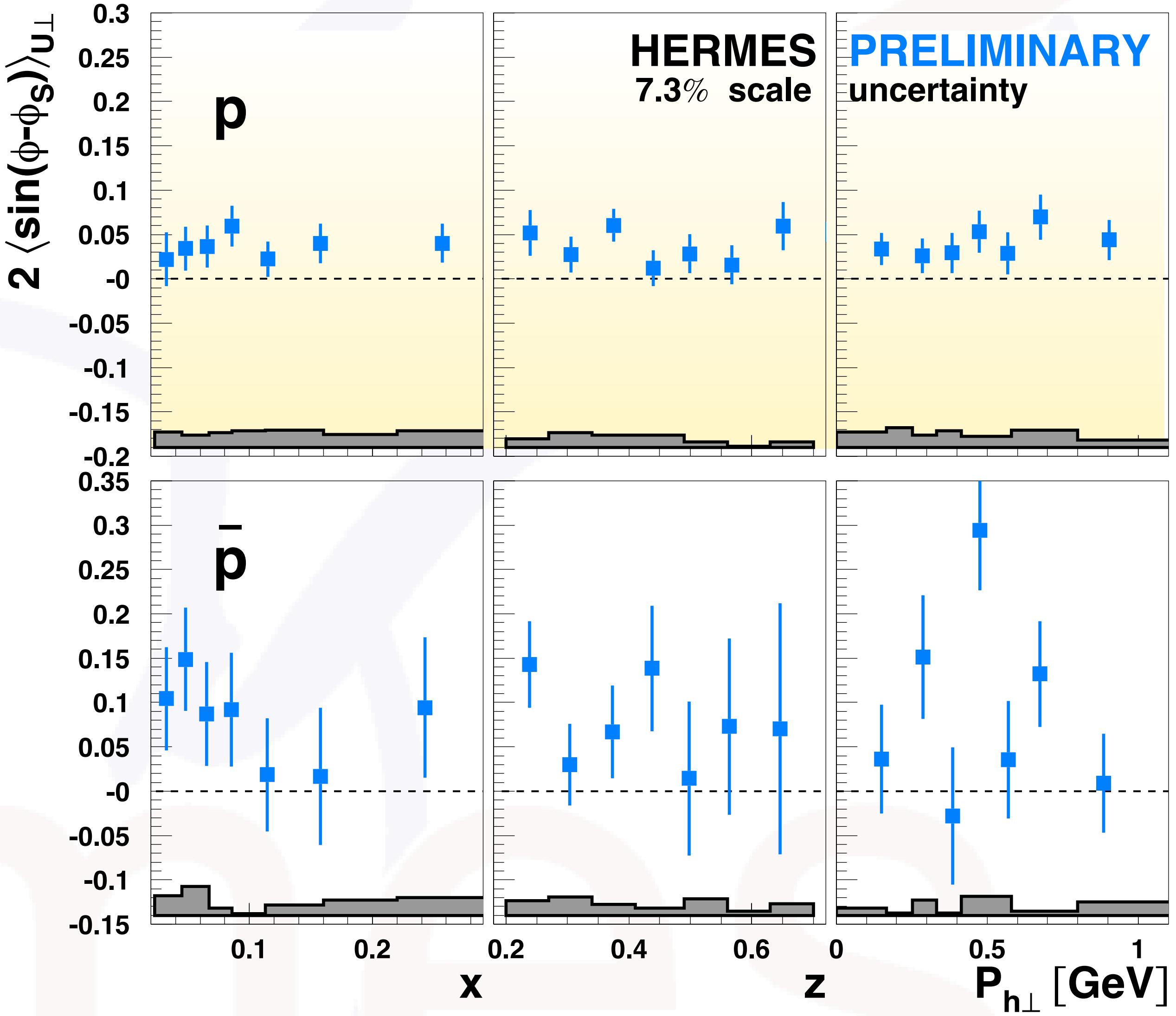
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for baryons

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

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

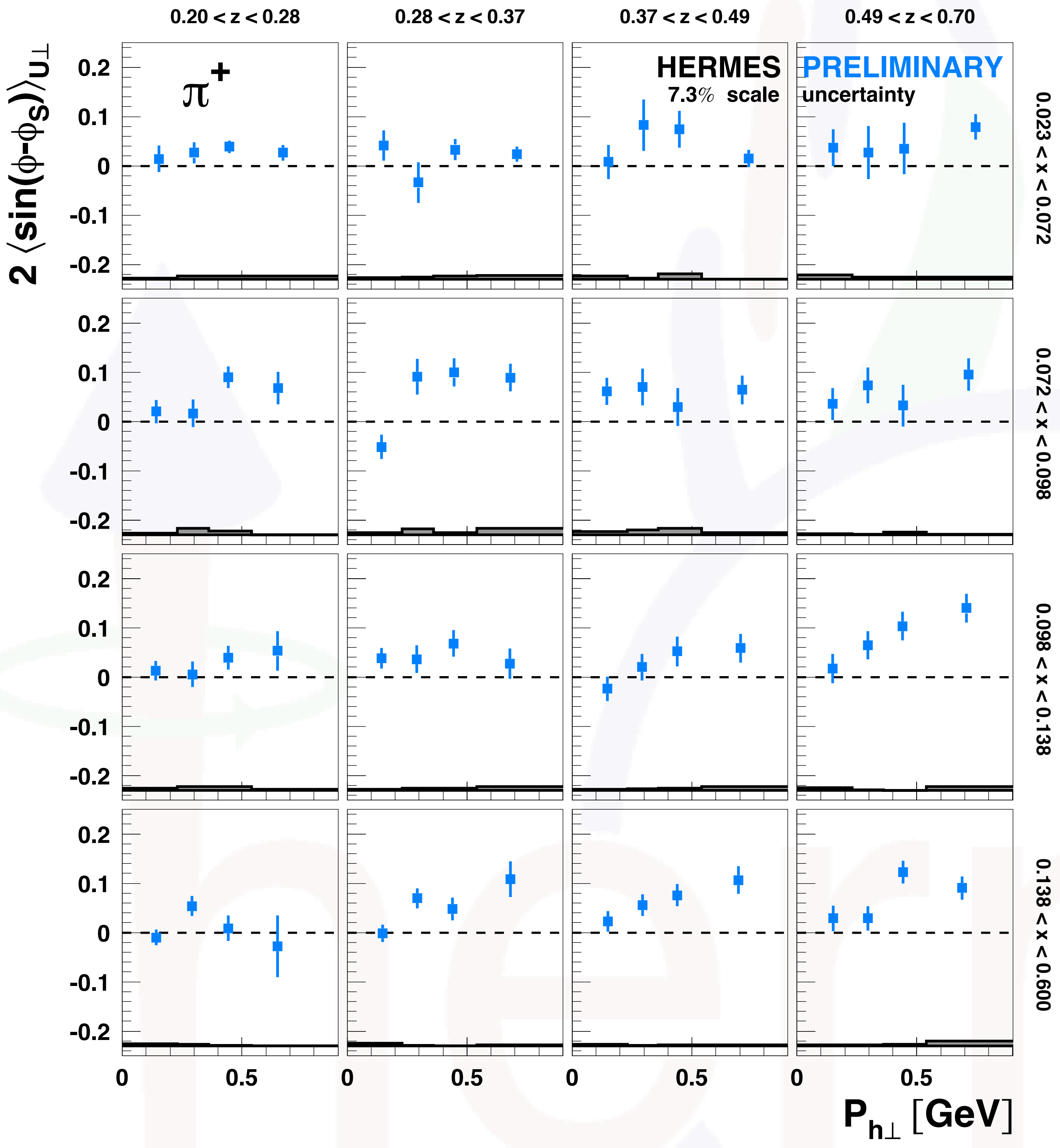




similar amplitudes for positive pions and protons ☛ u-quark dominance (and not a FF effect)?

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

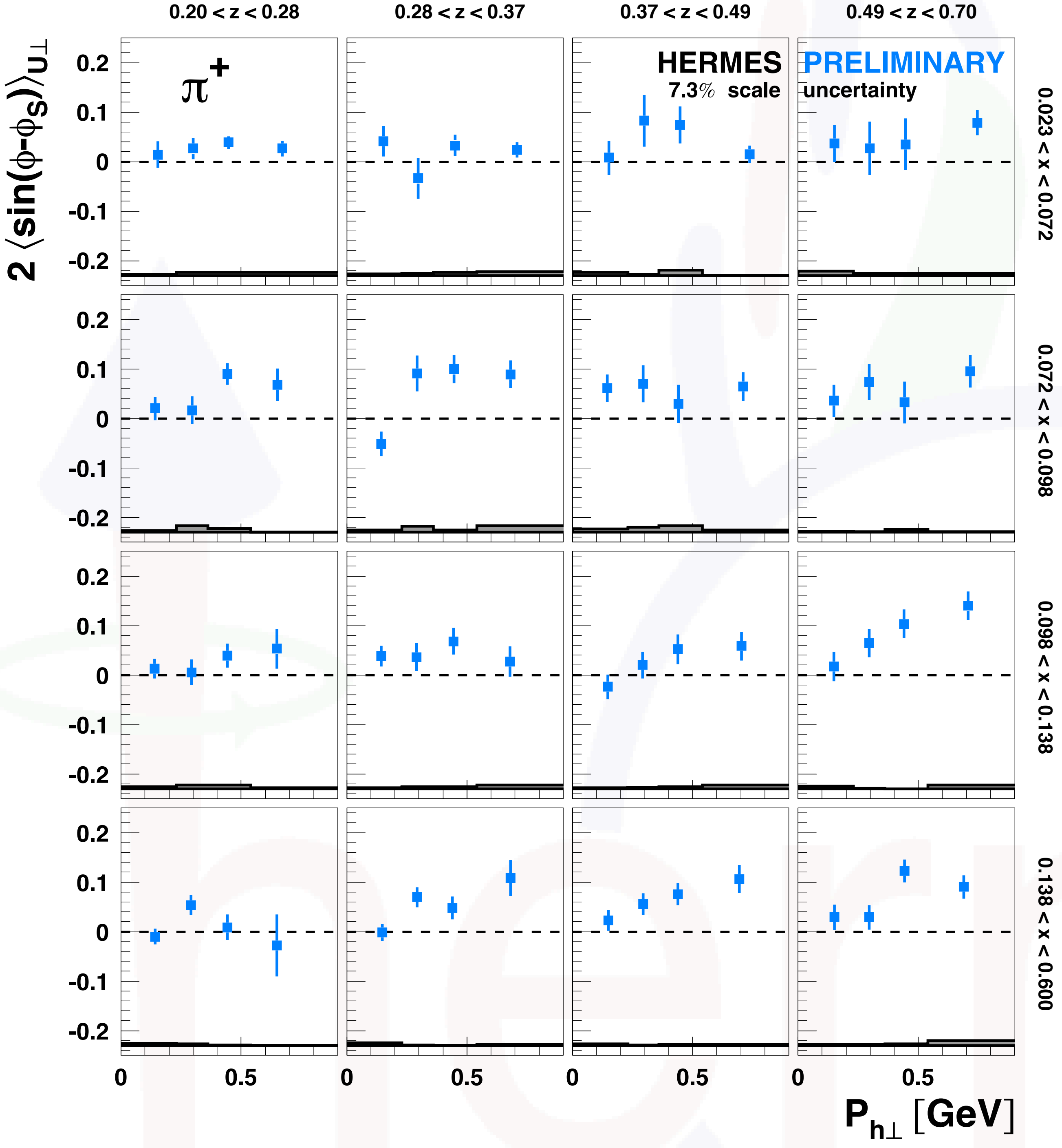
Sivers amplitudes - 3d binning



- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)

	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 - 3d binning



- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- disentangle correlations
- isolate phase-space region with strong signal strength

	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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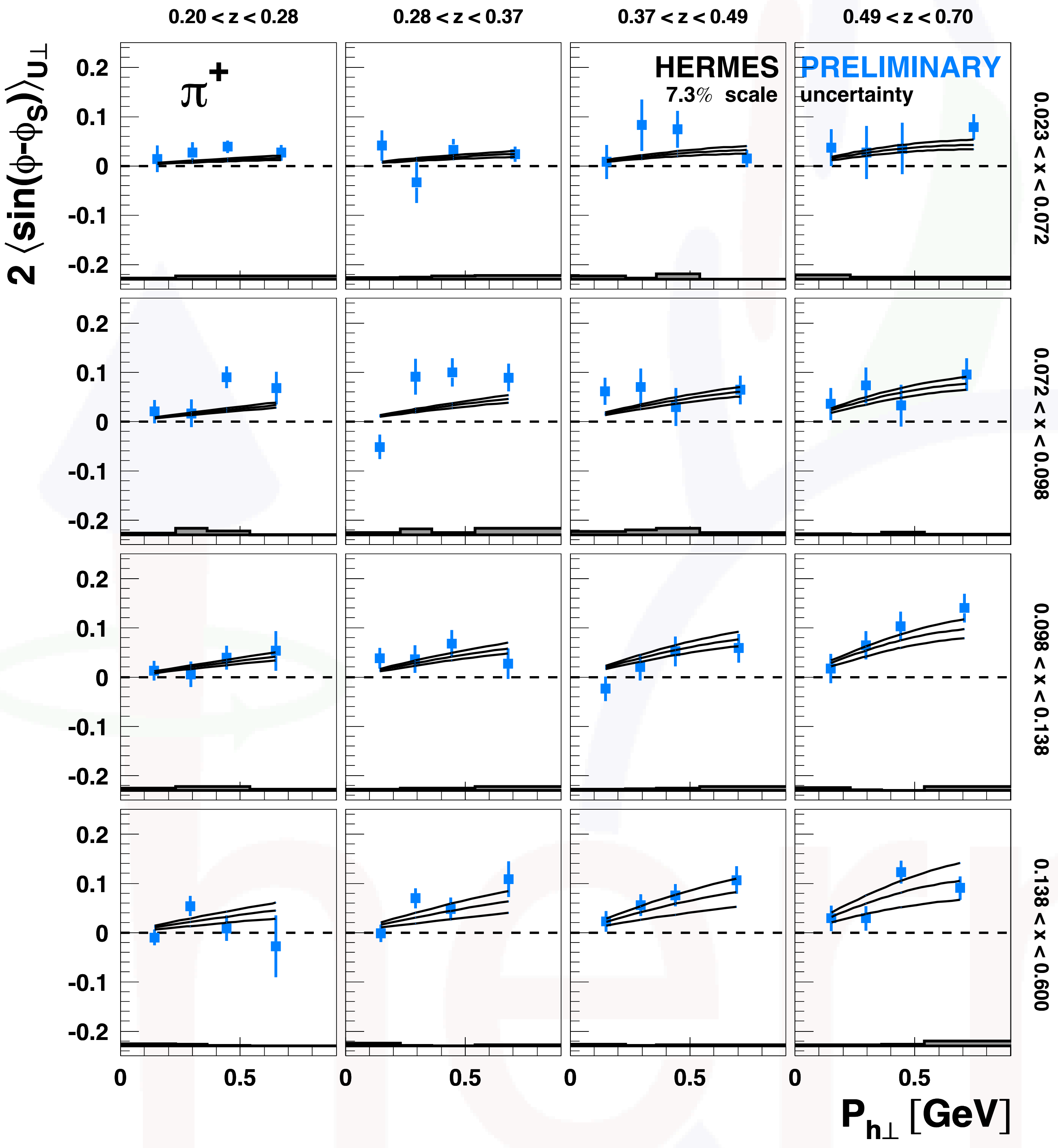
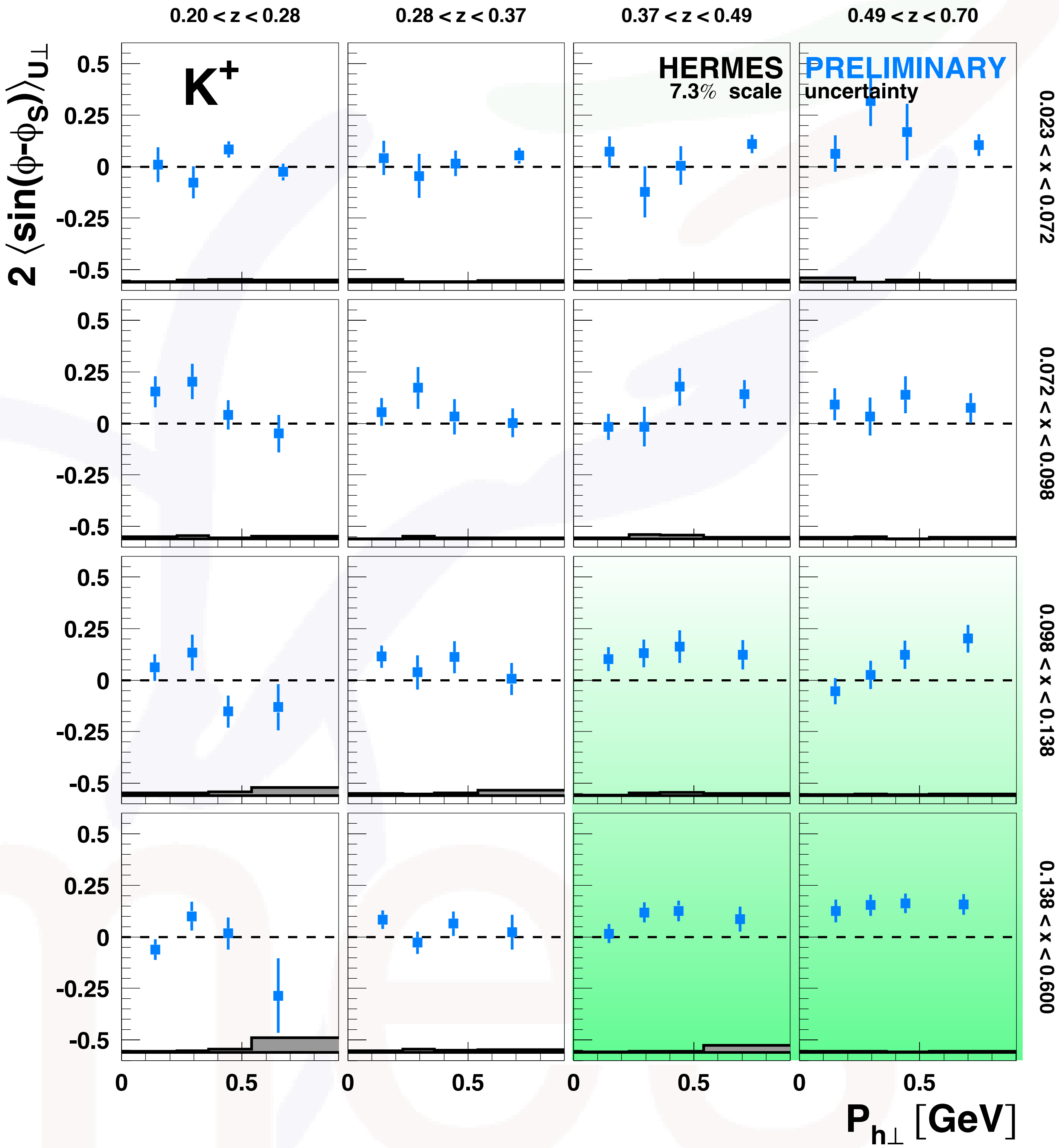


- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- disentangle correlations
- isolate phase-space region with strong signal strength
- allows more detailed comparison with calculations (e.g., "unofficial" results from Torino 10.1103/PhysRevD.86.014028 fit - courtesy M. Boglione)

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

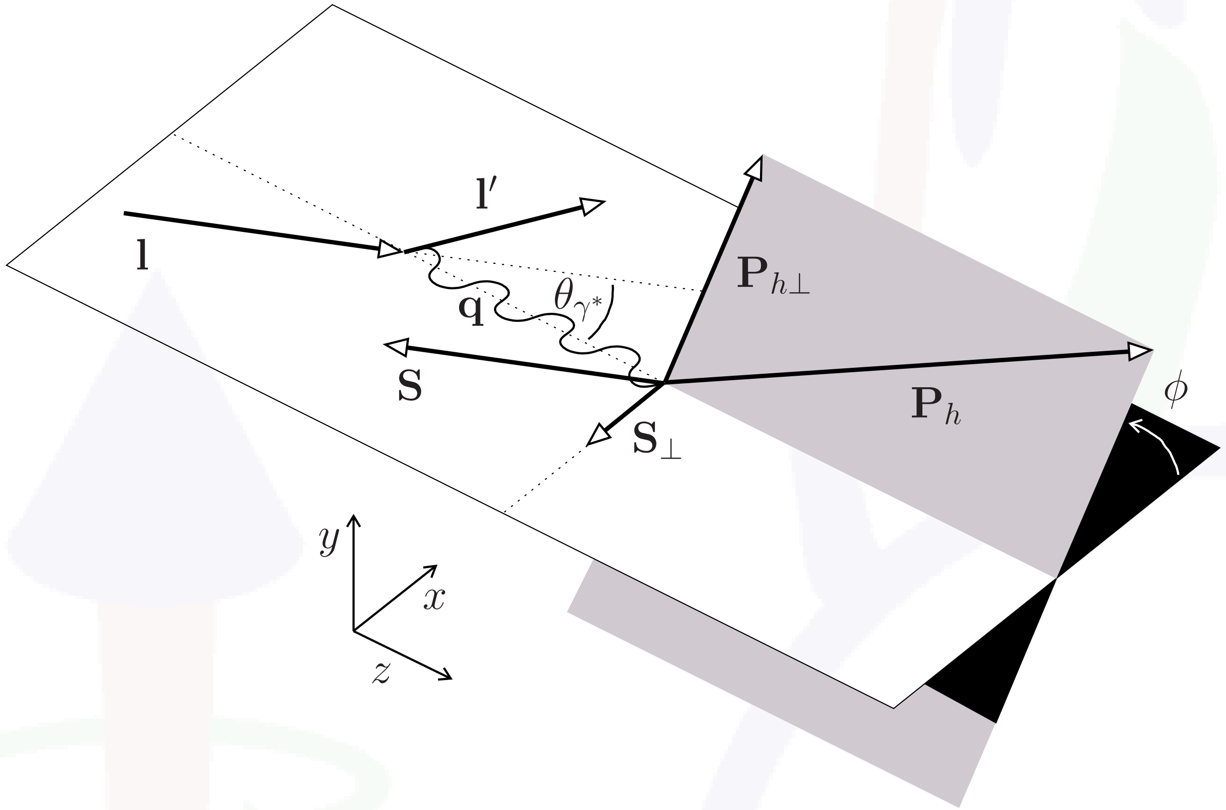
Sivers amplitudes - 3d binning



- large K^+ amplitudes O(20%) seen at large values of (x, z)
- region of purest "u-quark probe"

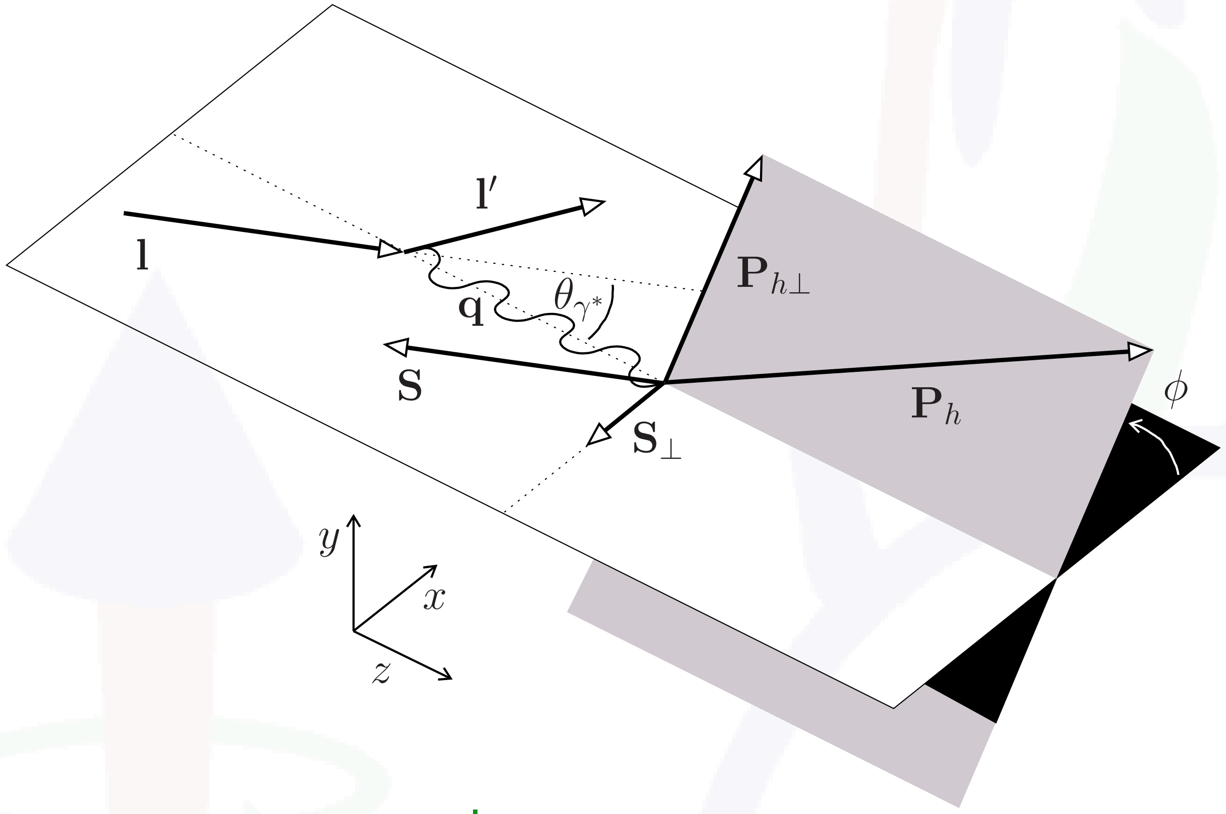
subleading twist

Subleading twist I - <sin(ϕ)>$_{UL}$



- in experiments: target polarized w.r.t. beam direction [Diehl&Sapeta EPJC41 (2005)]
  - small transverse component w.r.t. ritual-photon direction when longitudinally polarized
  - mixing of transverse and longitudinal target-spin asymmetries

Subleading twist I - <sin(ϕ)>$_{UL}$



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  - small transverse component w.r.t. ritual-photon direction when longitudinally polarized
  - mixing of transverse and longitudinal target-spin asymmetries

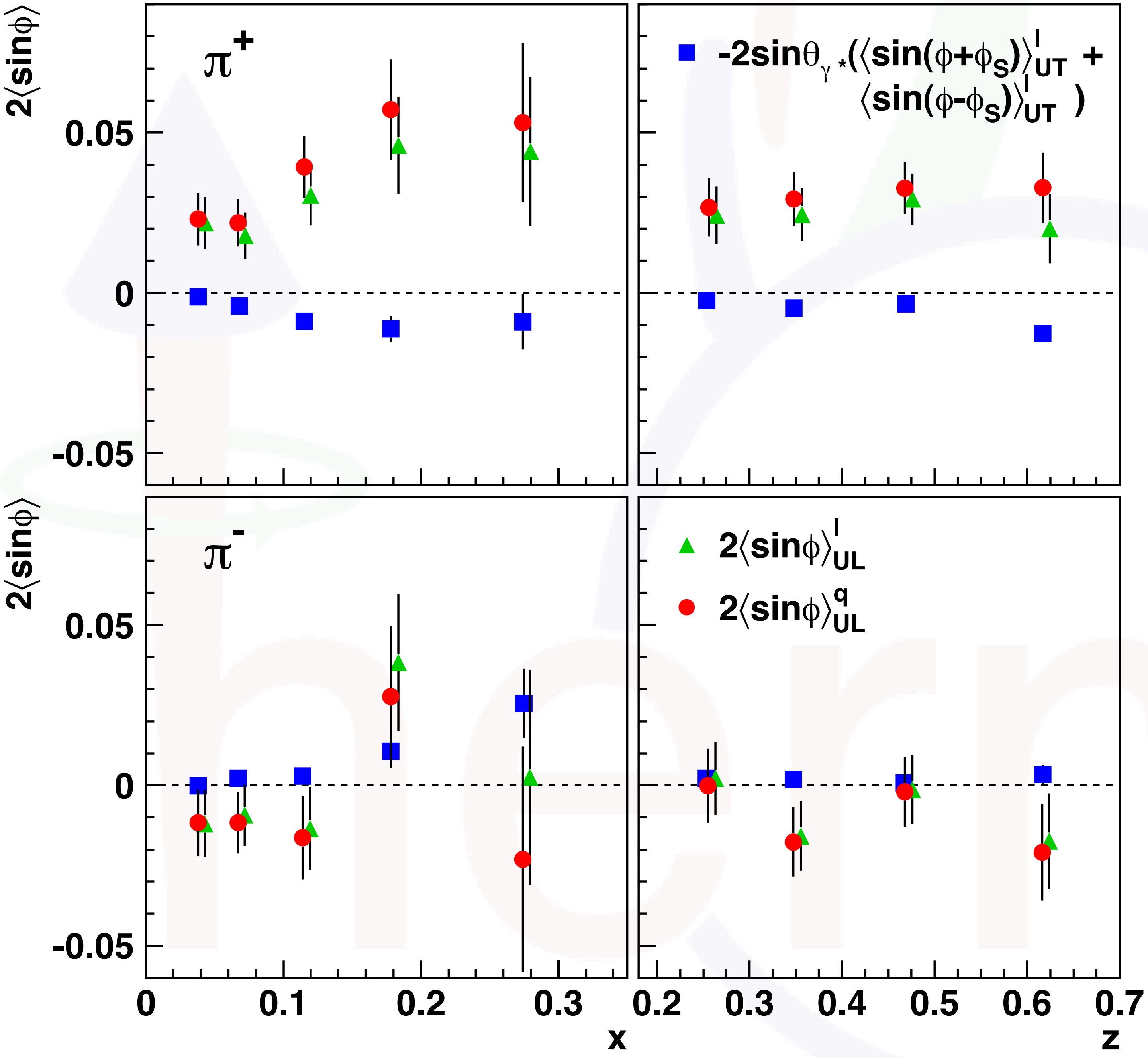
$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{\mathrm{l}} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{\mathrm{l}} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{\mathrm{l}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*}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

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

Subleading twist I - <sin(ϕ)>$_{UL}$

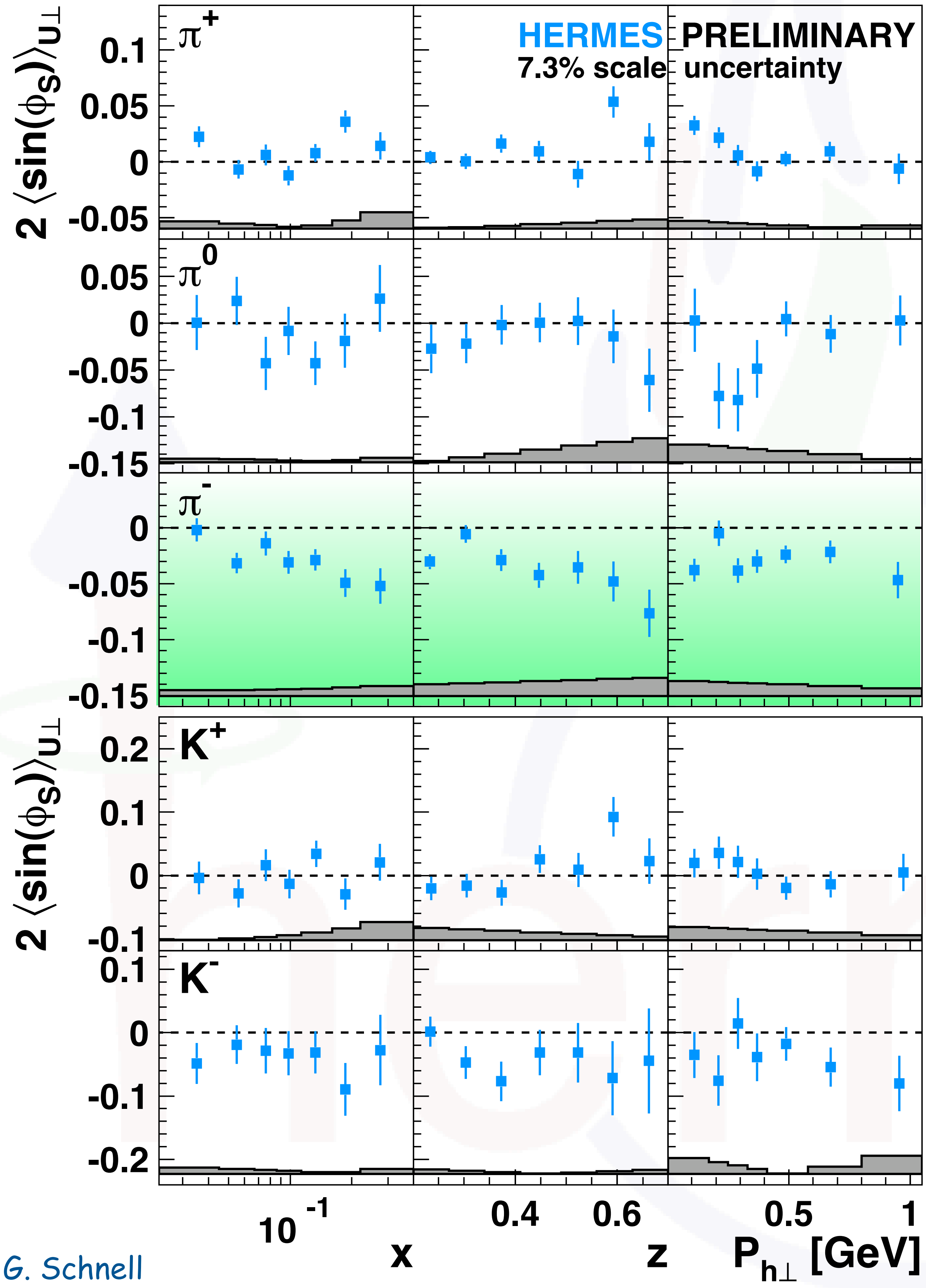
$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$

[Airapetian et al., PLB 622 (2005) 14]



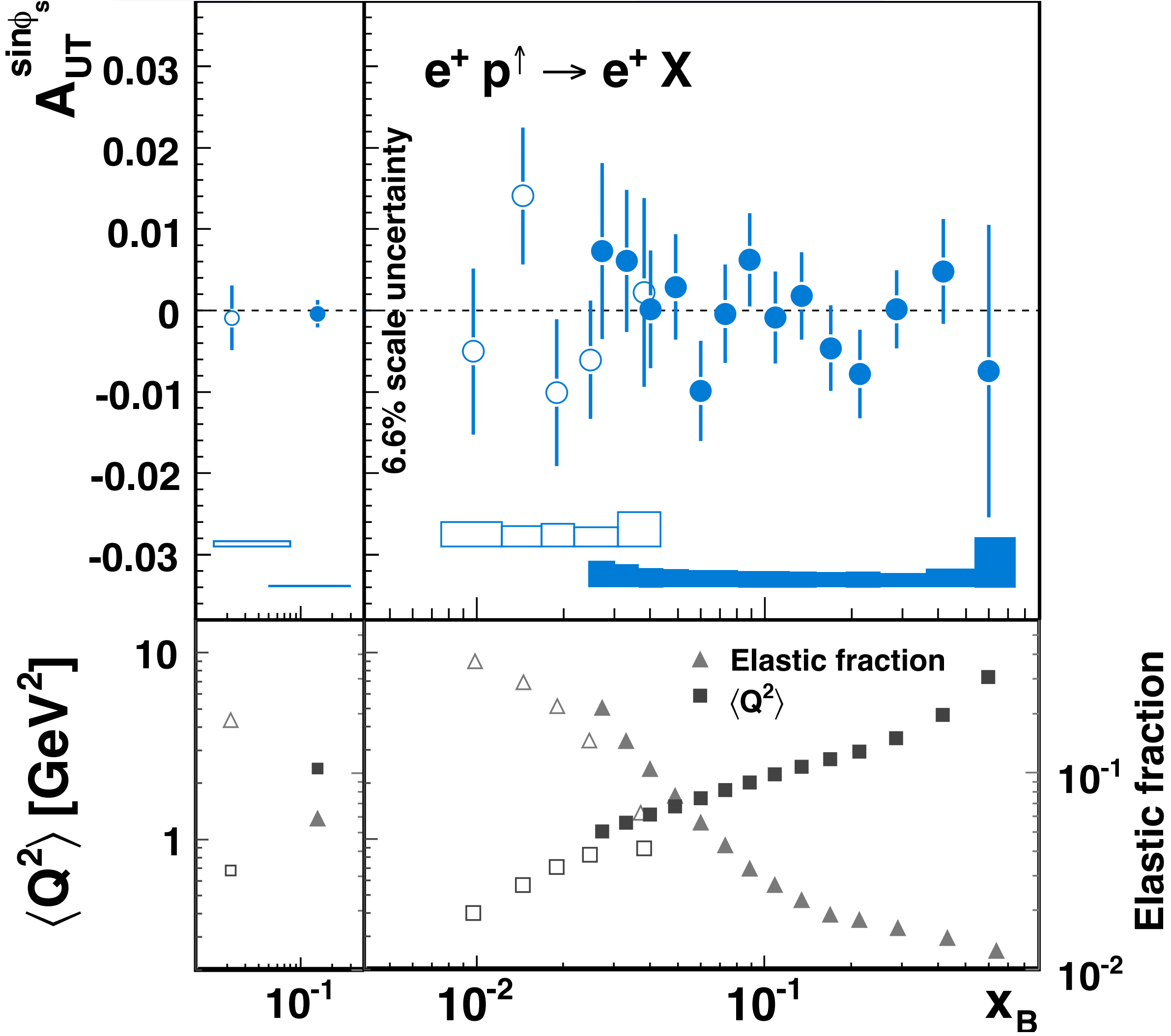
- experimental A_{UL} dominated by twist-3 contribution
  - correction for A_{UT} contribution increases purely longitudinal asymmetry for positive pions
  - consistent with zero for π⁻

Subleading twist II - $\langle\sin(\phi_s)\rangle_{UT}$

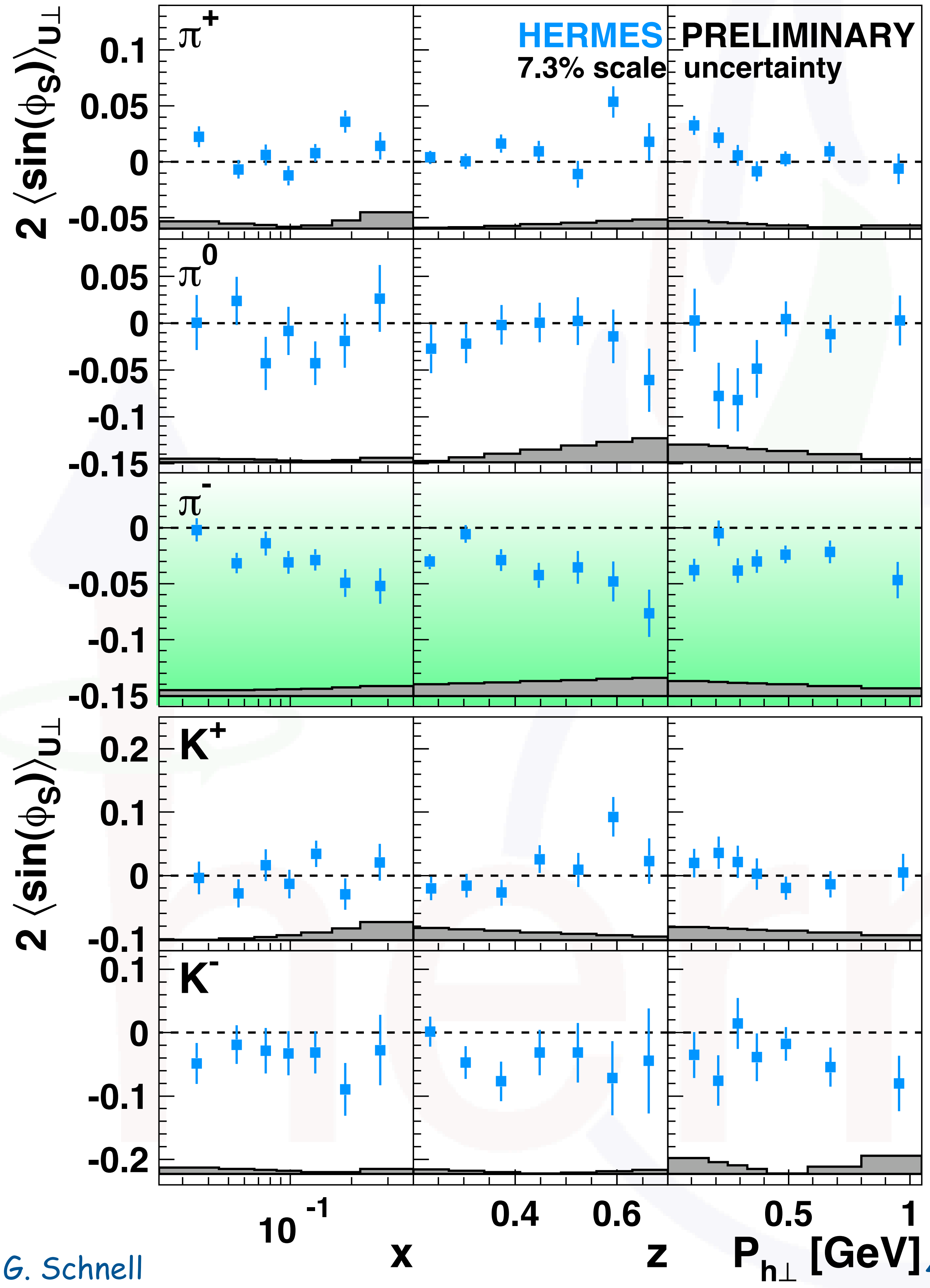


- significant non-zero signal observed for negatively charged mesons
- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons

[Phys. Lett. B682 (2010) 351]



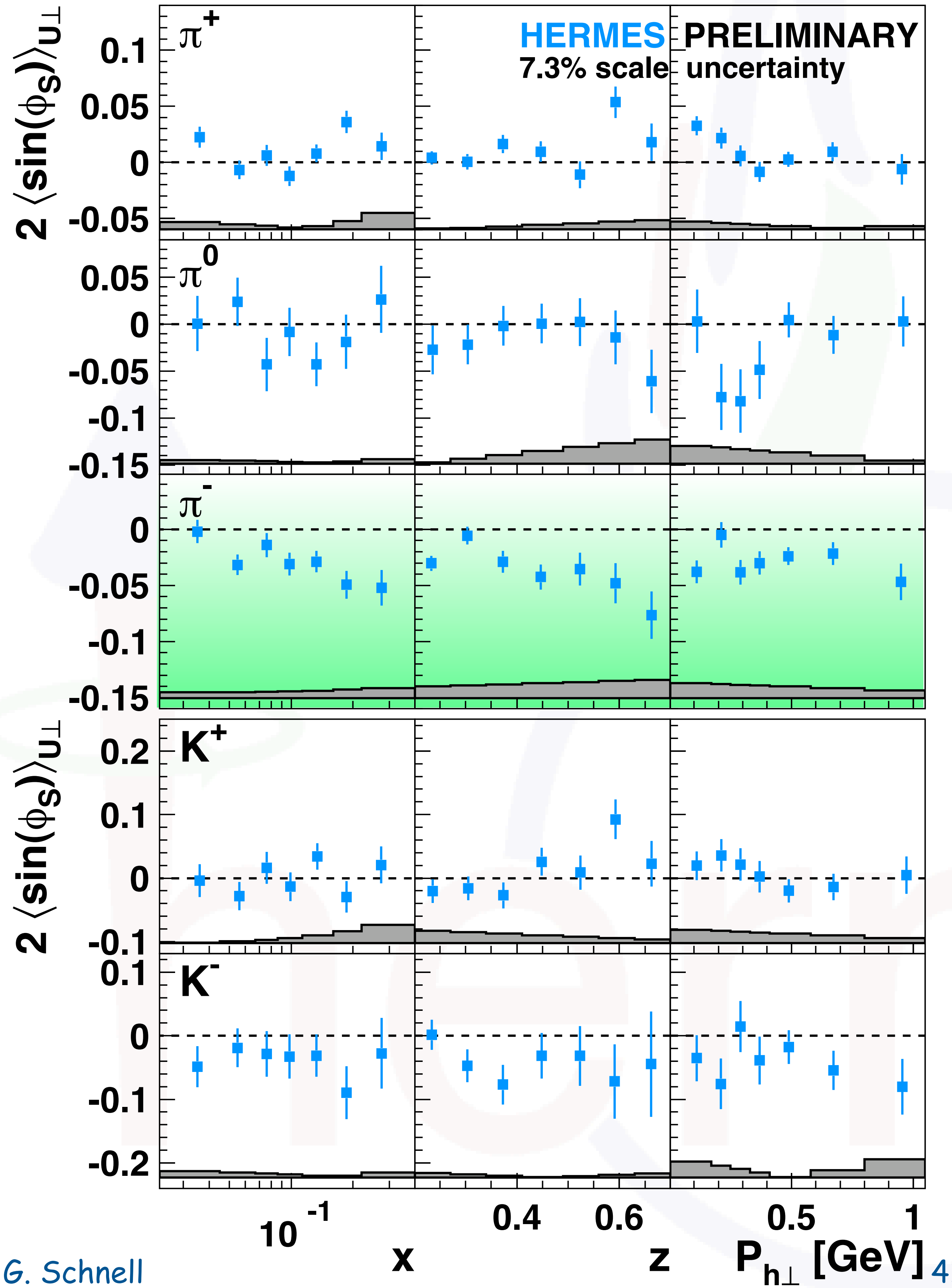
Subleading twist II - $\langle\sin(\phi_s)\rangle_{UT}$

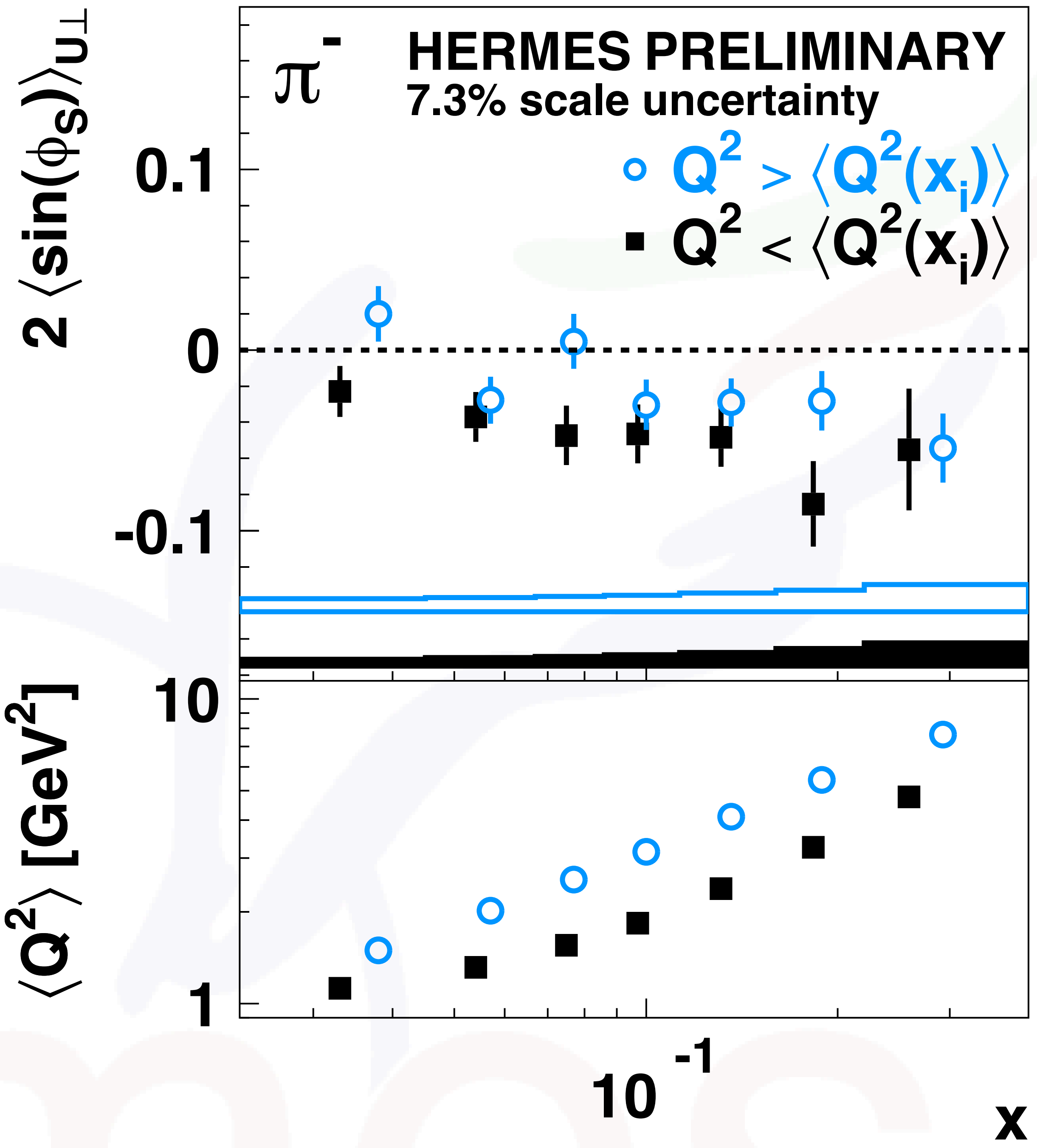


- significant non-zero signal observed for negatively charged mesons
- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

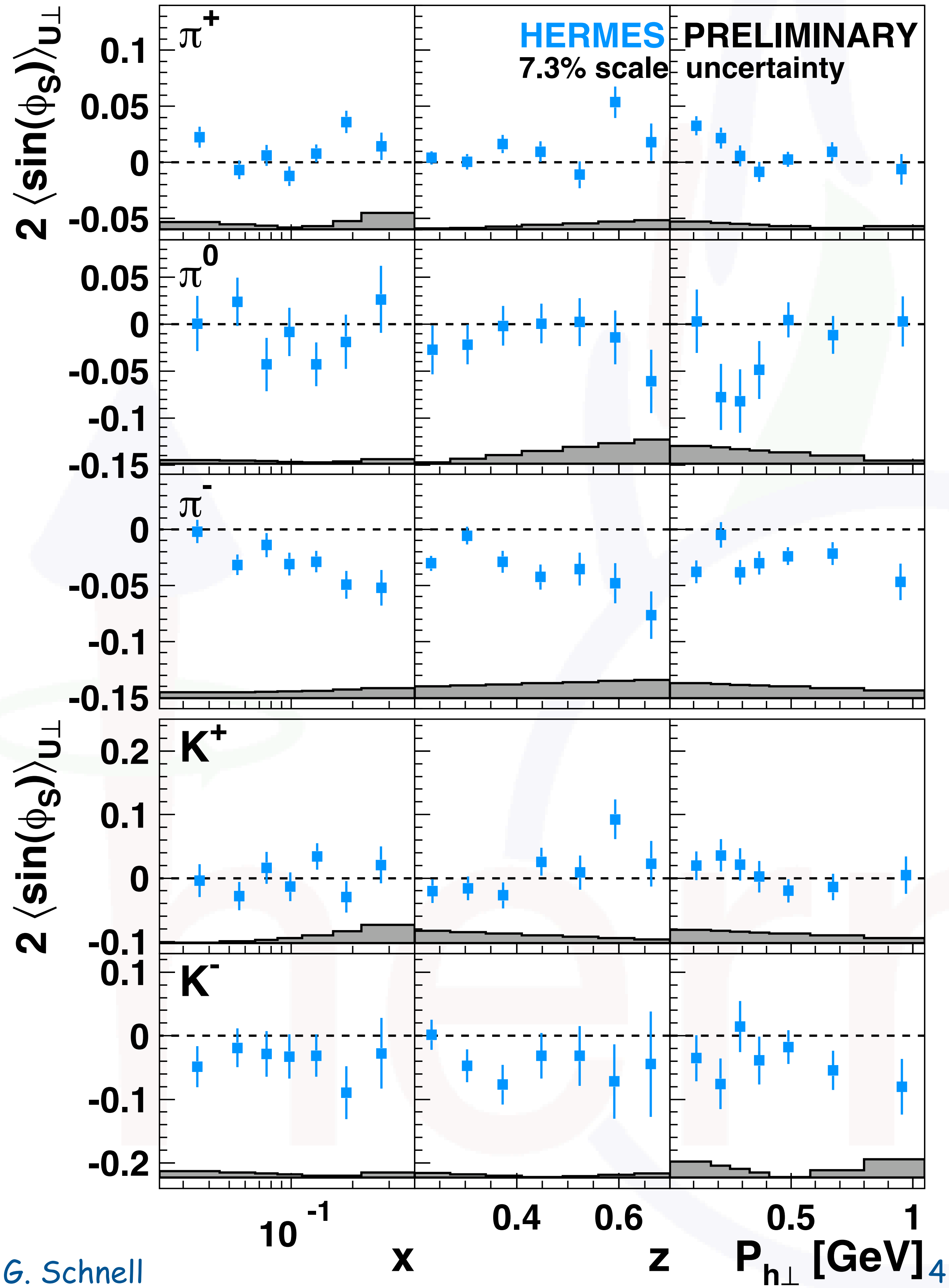
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$

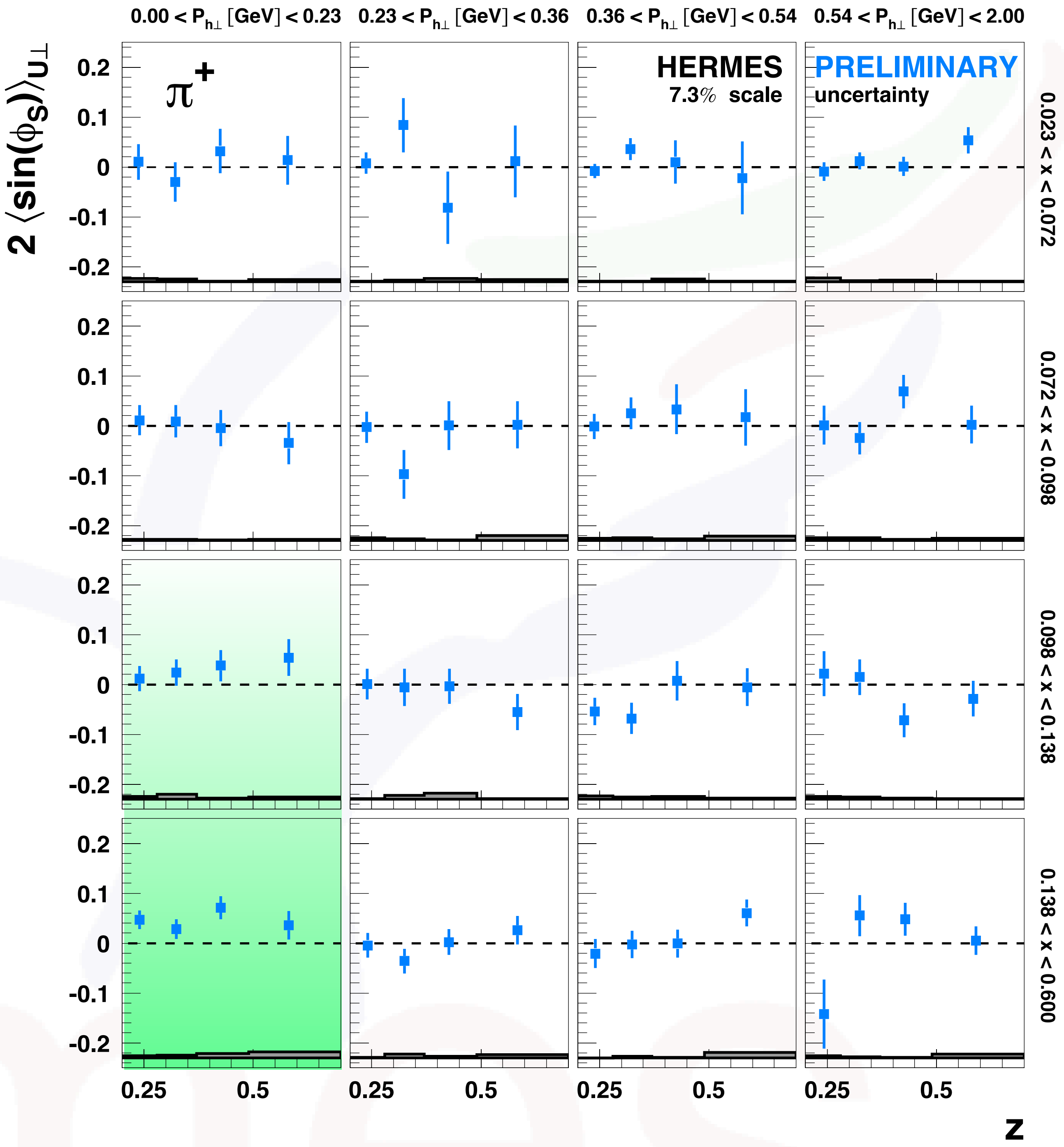




- hint of Q^2 dependence seen in signal for negative pions

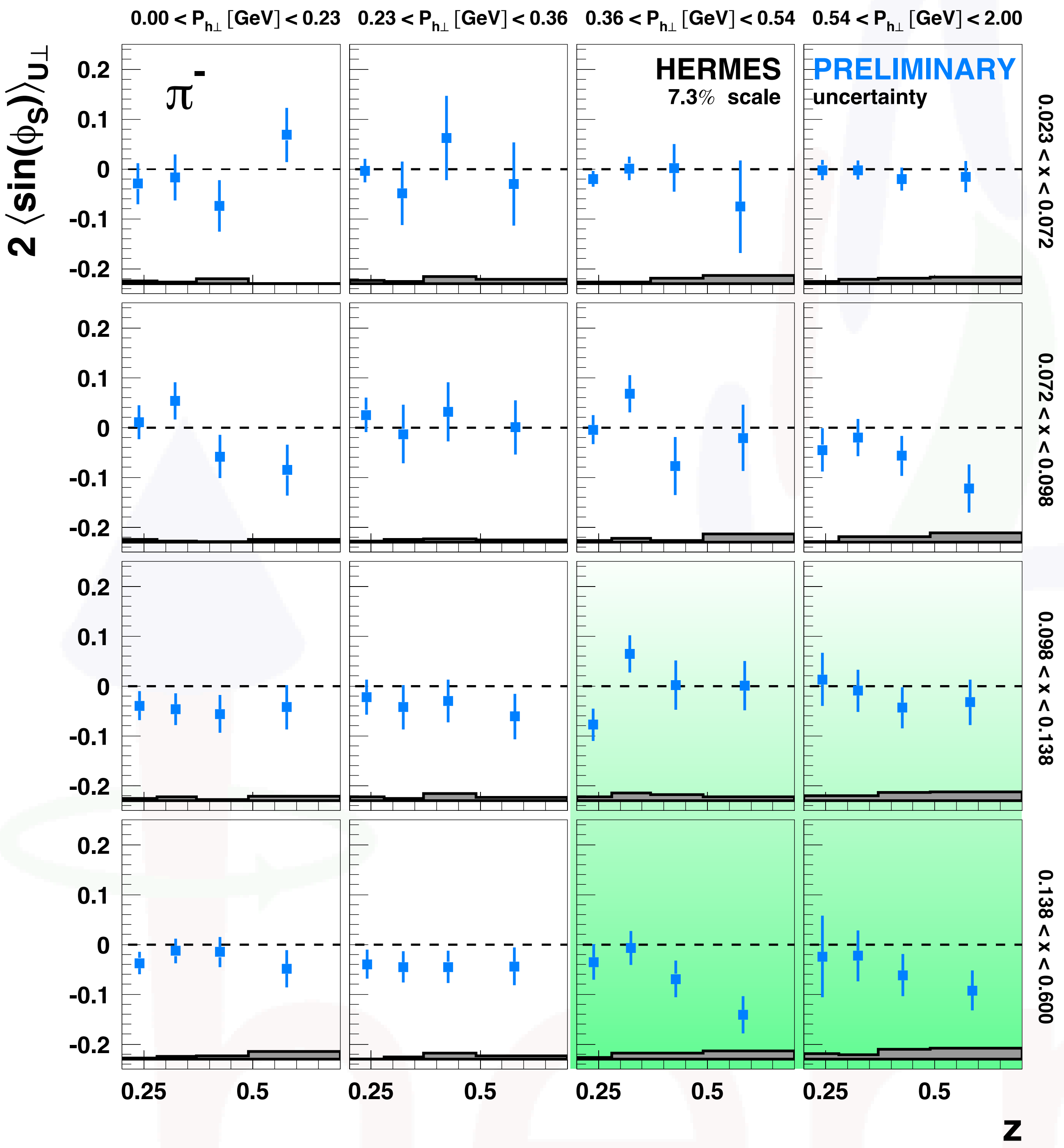
Subleading twist II - $\langle\sin(\phi_S)\rangle_{UT}$

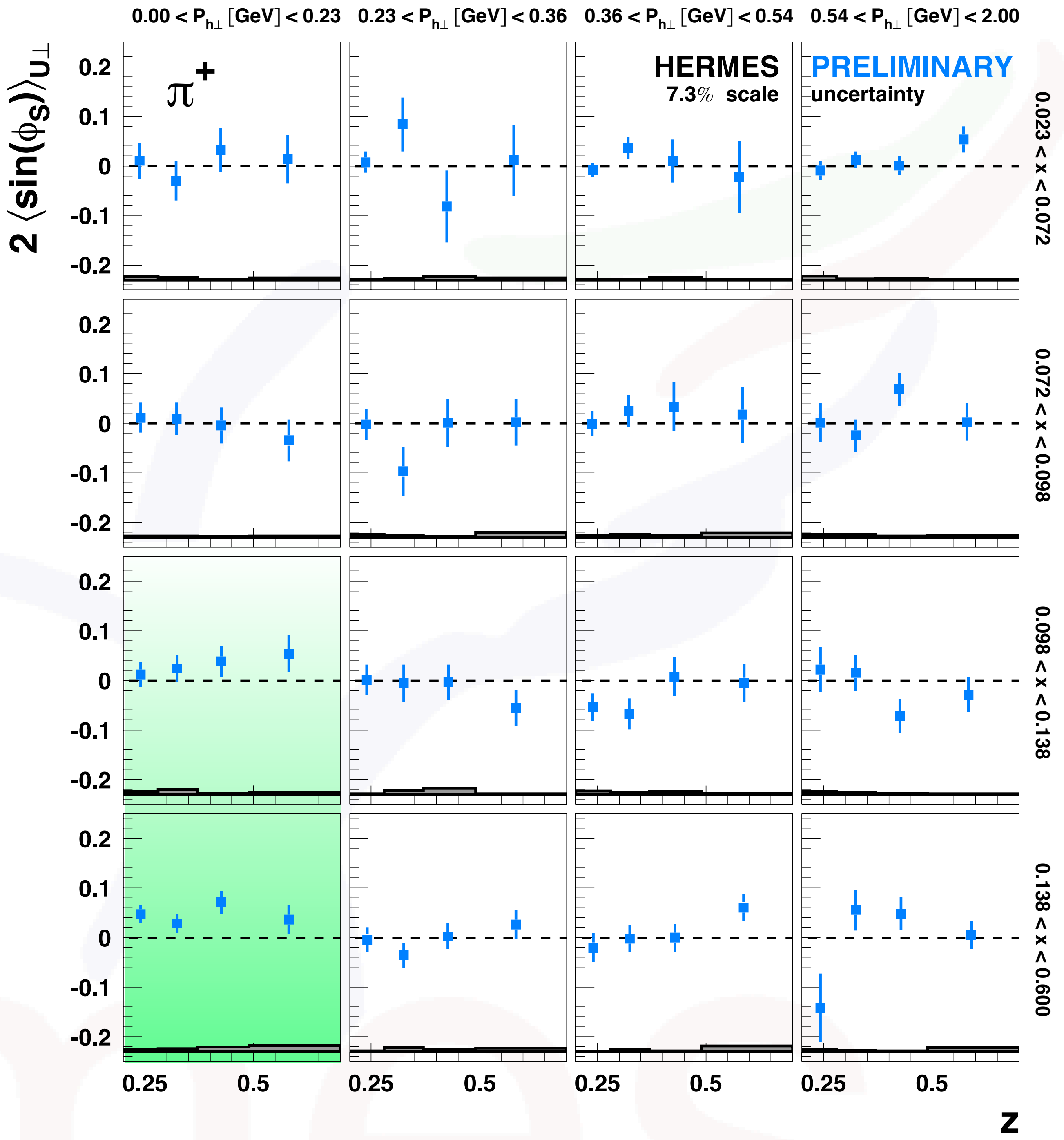




- positive amplitudes at low $P_{h\perp}$ also for positive pions

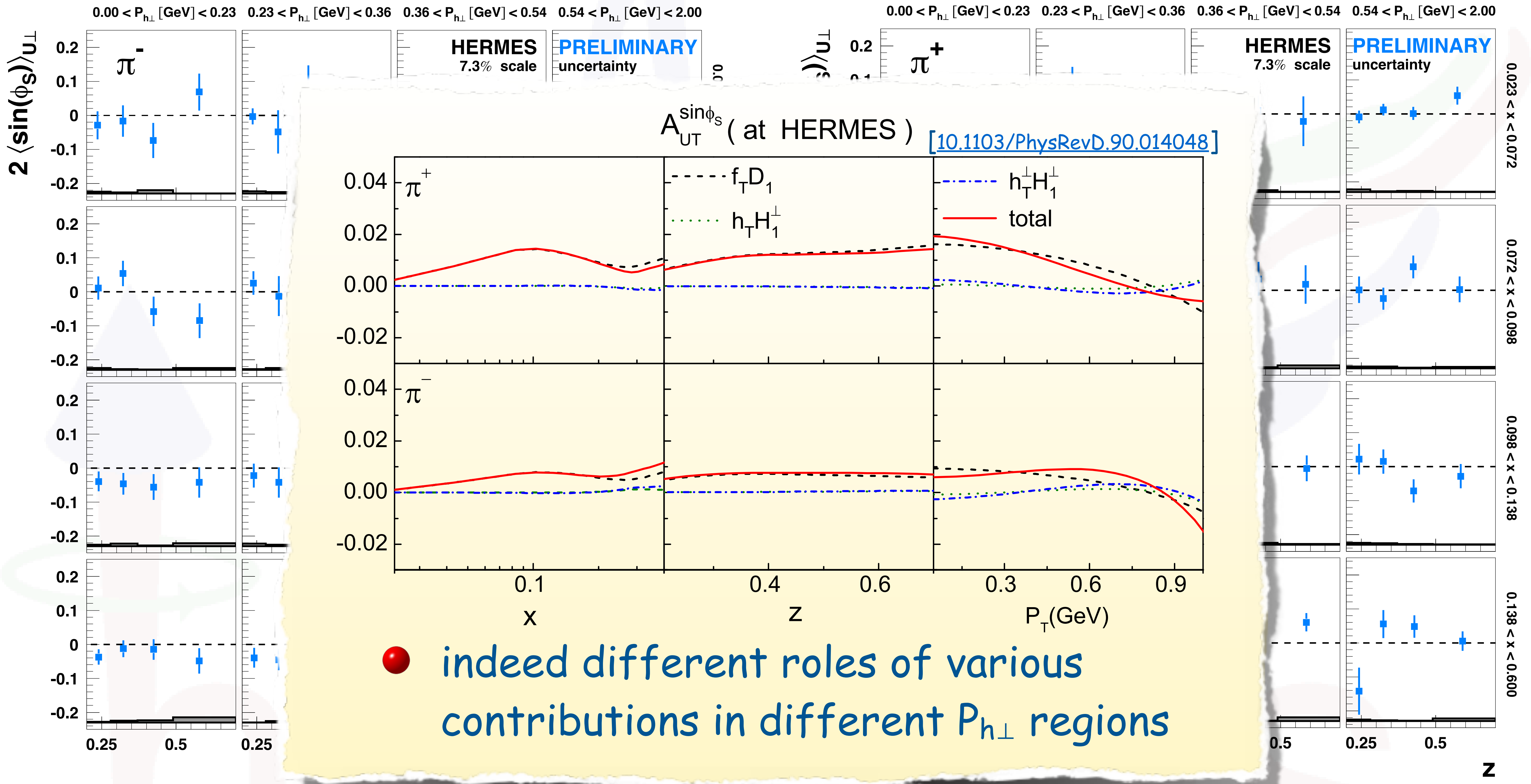
Subleading twist II - $\langle\sin(\phi_s)\rangle_{UT}$





- nonzero amplitudes mainly at large $P_{h\perp}$ in case of negative pions
- positive amplitudes at low $P_{h\perp}$ also for positive pions

Subleading twist II - <sin(ϕ_S)>$_{UT}$



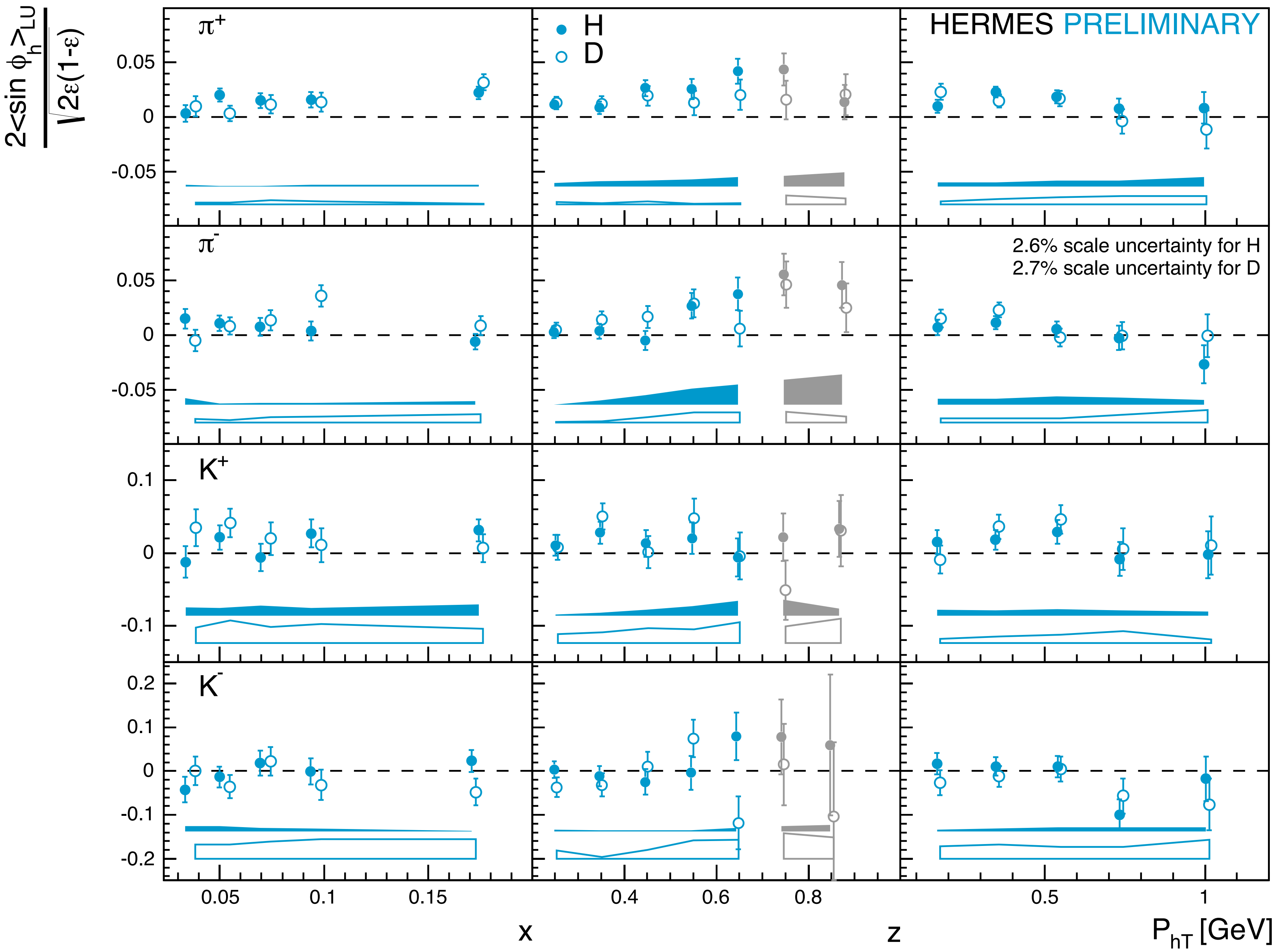
[10.1103/PhysRevD.90.014048]

- indeed different roles of various contributions in different $P_{h\perp}$ regions

- nonzero amplitudes mainly at large $P_{h\perp}$ in case of negative pions
- positive amplitudes at low $P_{h\perp}$ also for positive pions

Subleading twist III - <sin(ϕ)>$_{LU}$

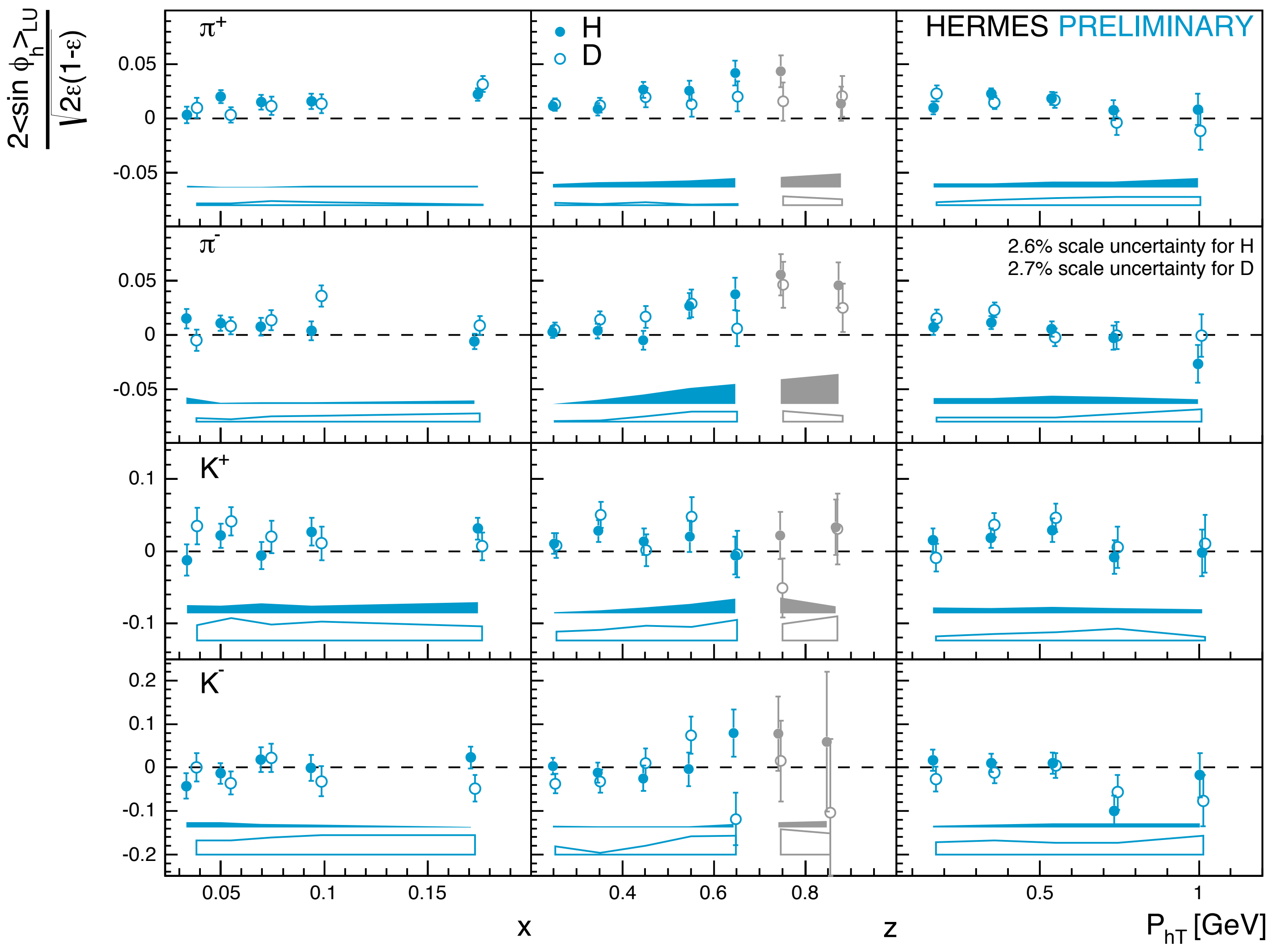
$$\frac{M_h}{Mz} h_1^\perp E \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 G^\perp \oplus x e H_1^\perp$$

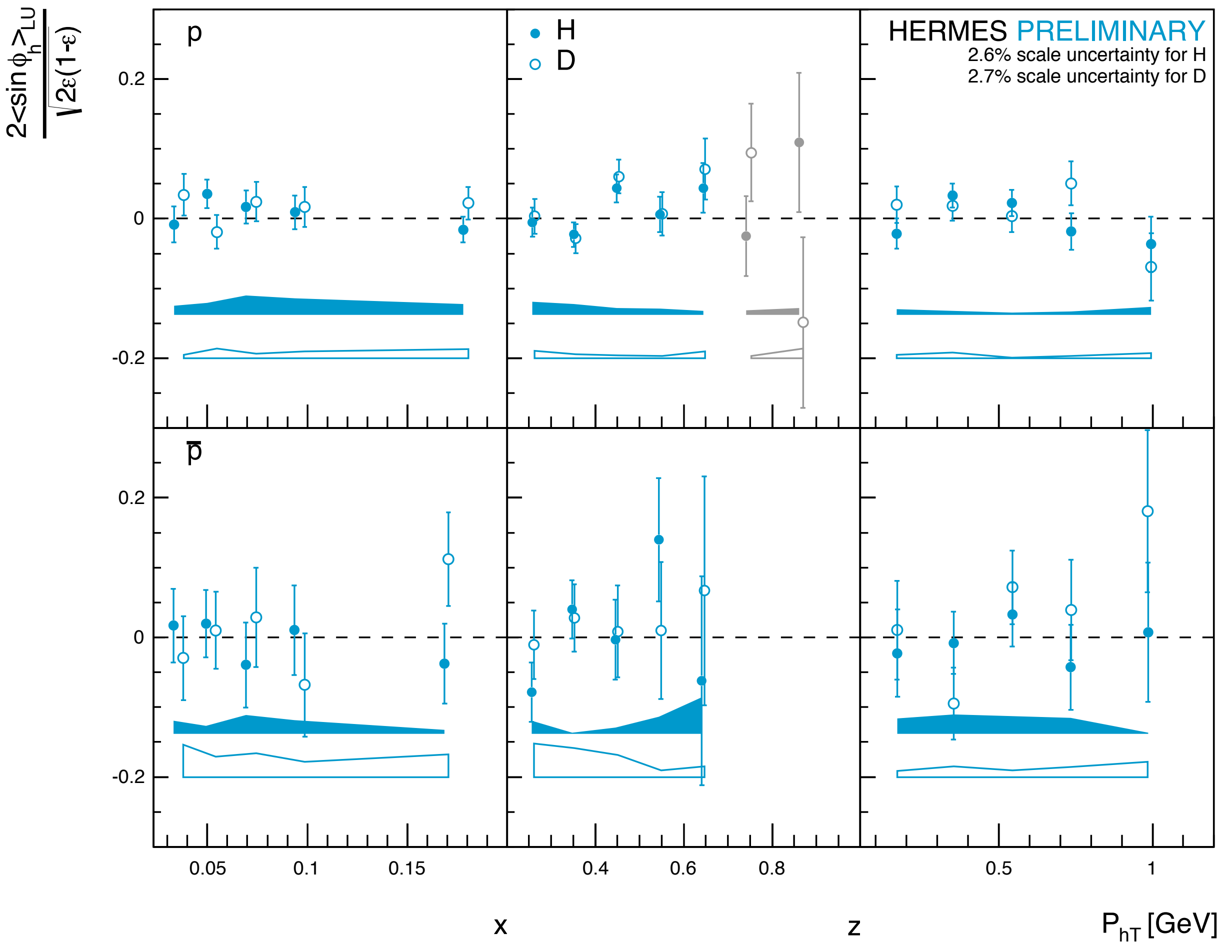


- significant positive amplitudes for (in particular positive) pions

Subleading twist III - <sin(ϕ)>$_{LU}$

$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus x e H_1^{\perp}$$

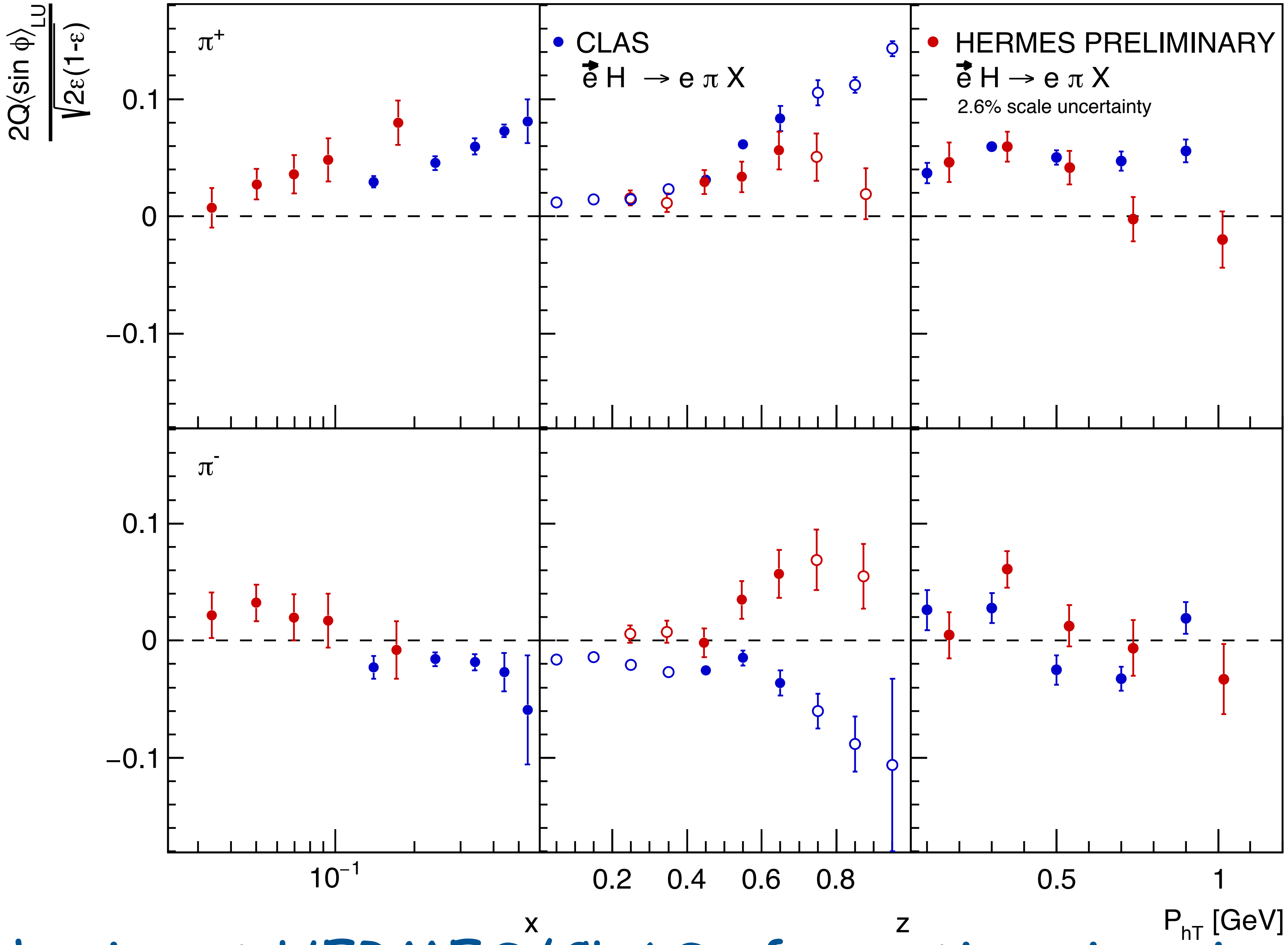




- mostly consistent w/ zero for other hadrons (except maybe K$^+$)

Subleading twist III - <sin(ϕ)>$_{LU}$

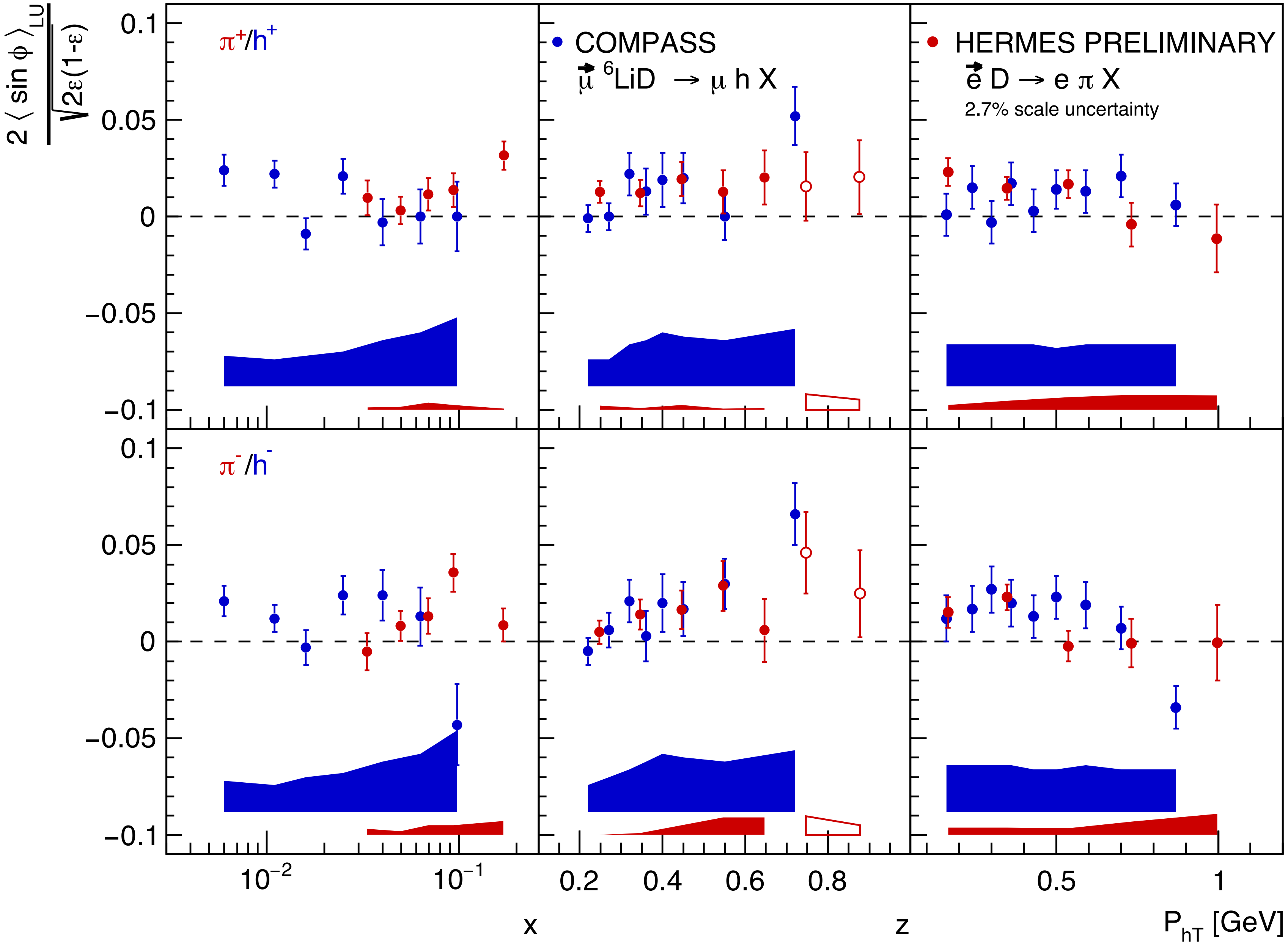
$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus x e H_1^{\perp}$$



- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x)Collins term due to higher x probed?

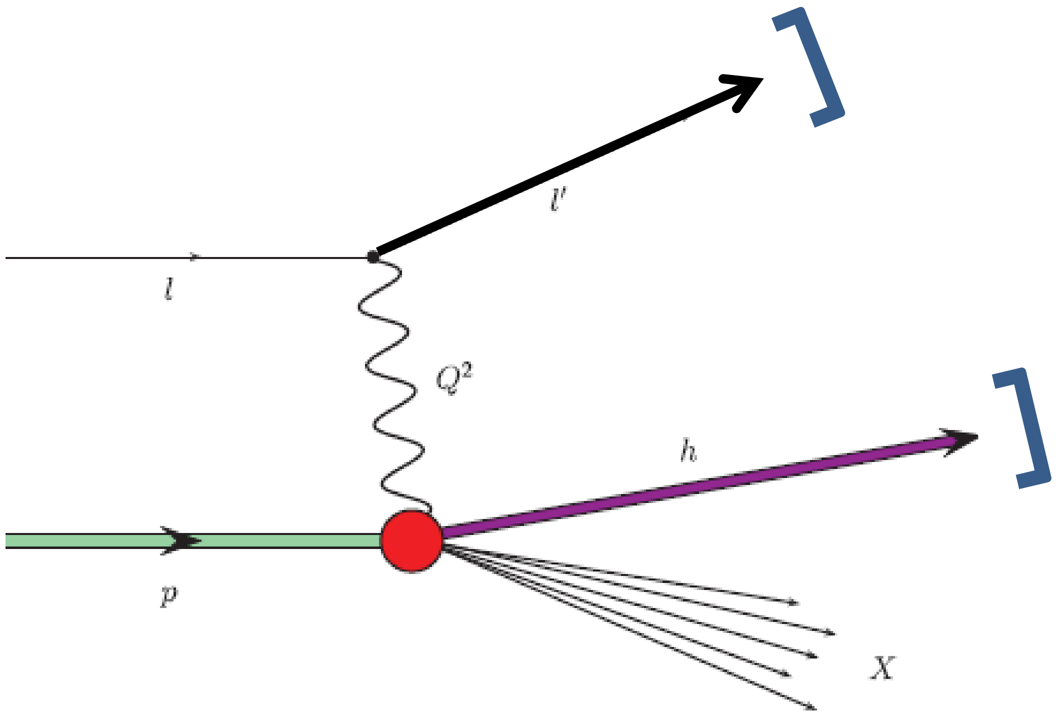
Subleading twist III - <sin(ϕ)>$_{LU}$

$$\frac{M_h}{Mz} h_1^\perp E \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 G^\perp \oplus x e H_1^\perp$$

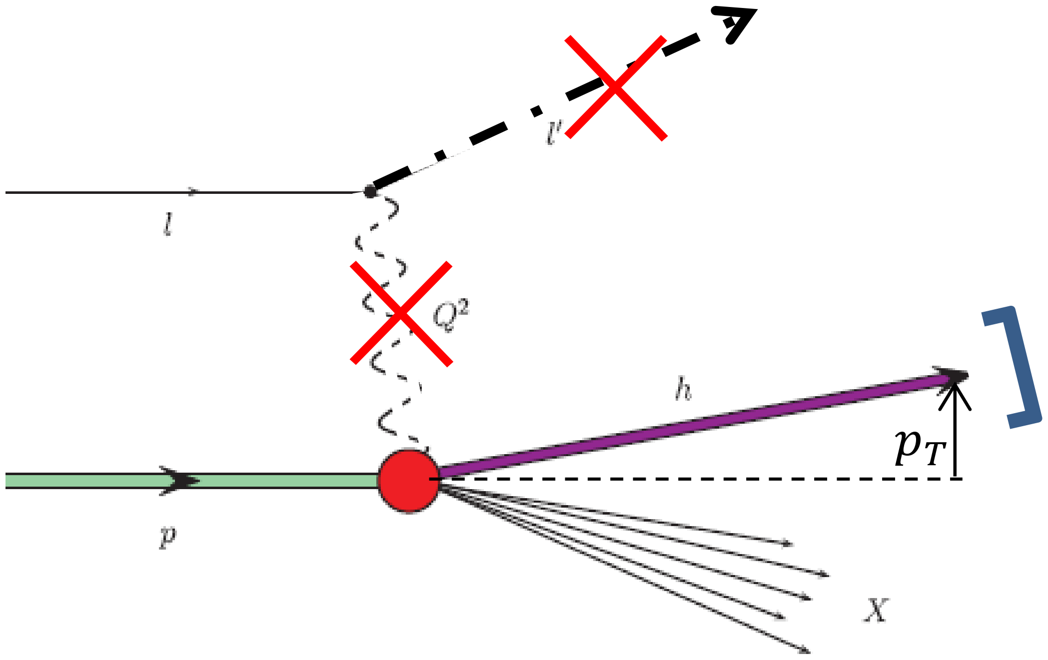


- consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets

Semi-inclusive hadrons



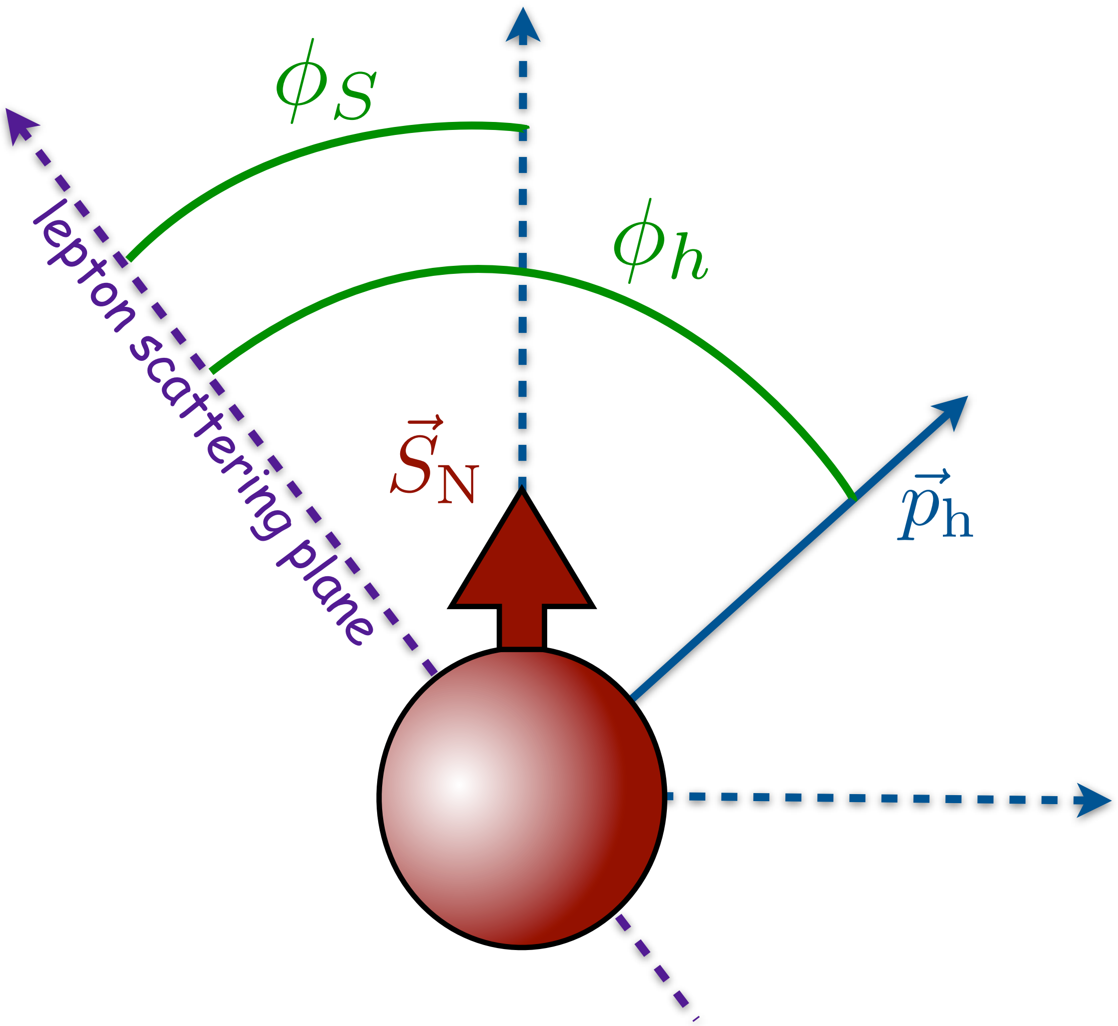
S~~e~~mi-inclusive hadrons

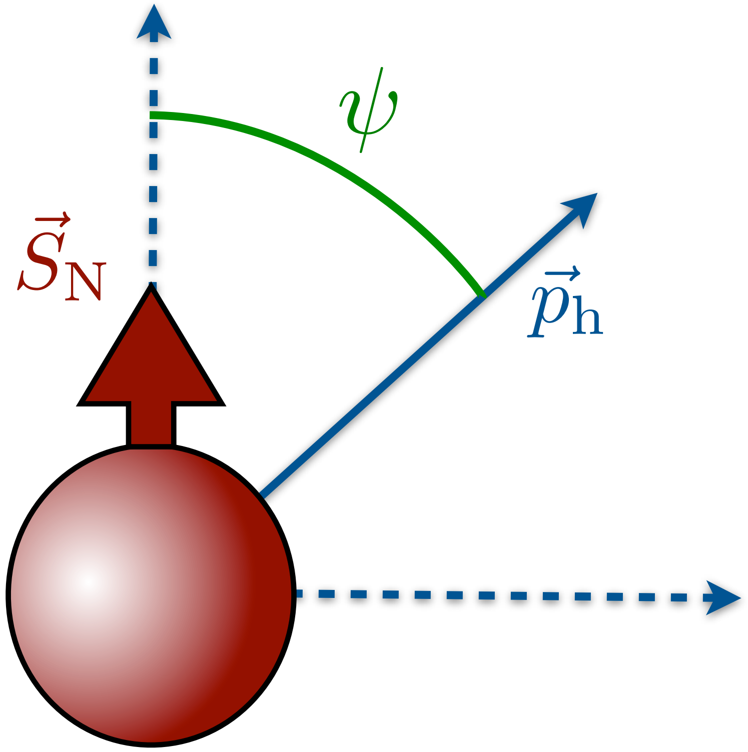


click here if (likely) out of time

Inclusive hadron electro-production

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





virtual photon going into the page

lepton beam going into the page

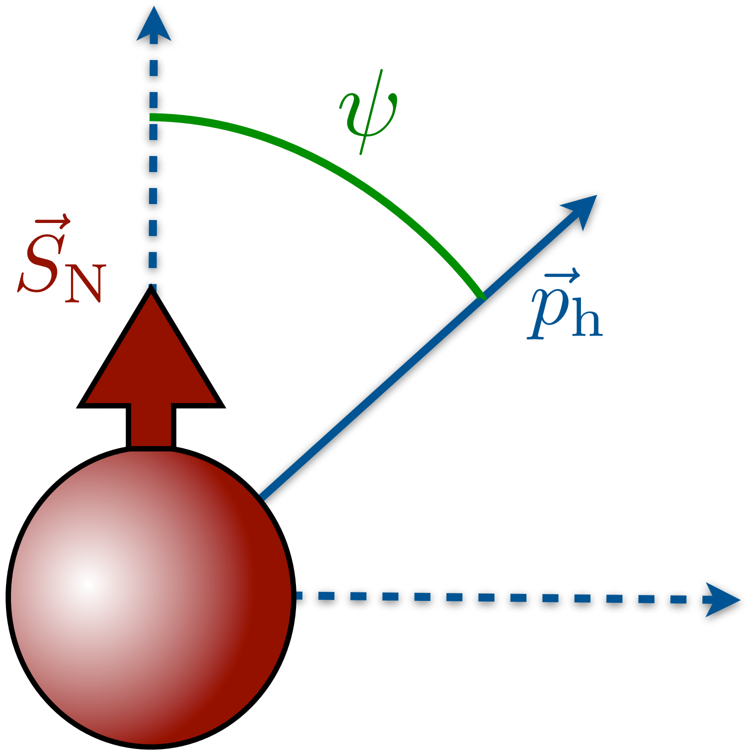
$$\psi \simeq \phi_h - \phi_S$$

➡ "Sivers angle"

Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

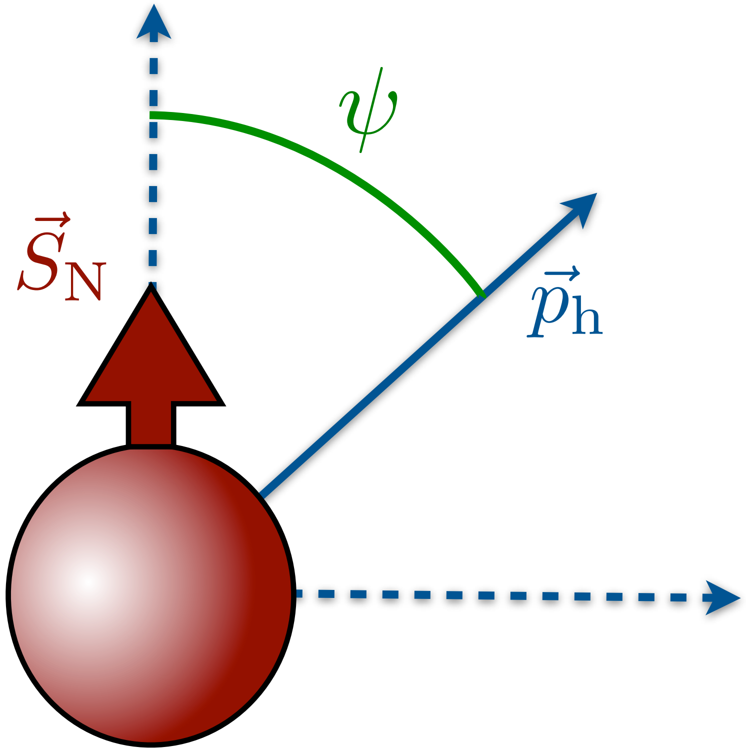
$$ep^{\uparrow} \rightarrow hX$$



Inclusive hadron electro-production

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

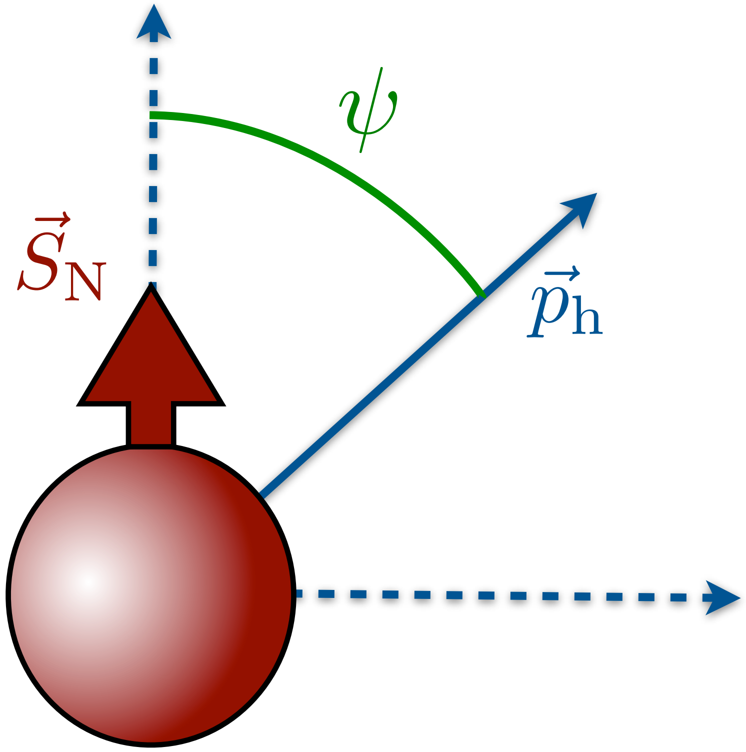
- scattered lepton undetected
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?



Inclusive hadron electro-production

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

- scattered lepton undetected
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to $S_N (k \times p_h) \sim \sin\psi$



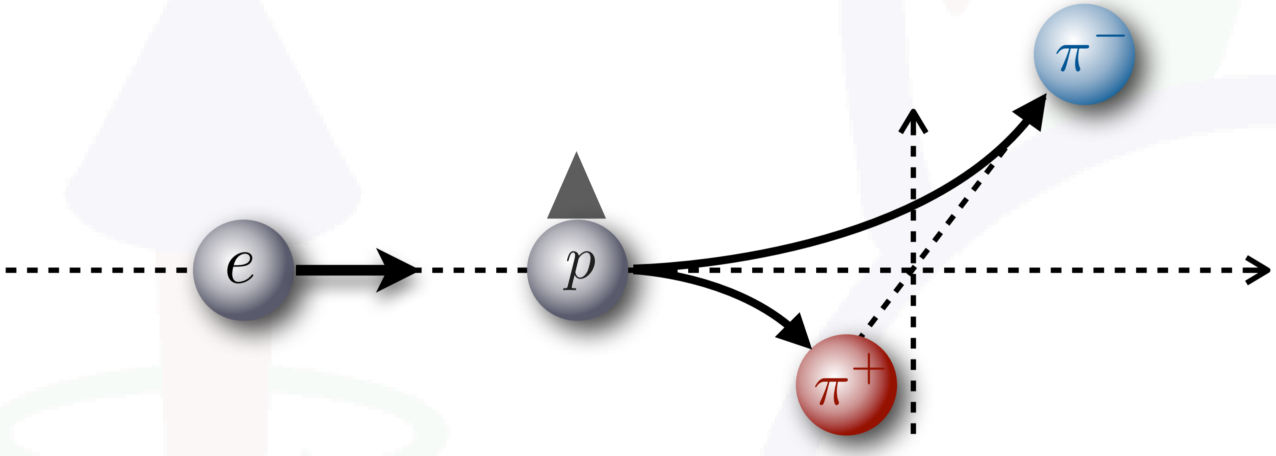
$$A_{\mathrm{UT}}(P_T, x_F, \psi) = A_{\mathrm{UT}}^{\sin\psi}(P_T, x_F) \sin\psi$$

$$A_{\mathrm{N}} \equiv \frac{\int_{\pi}^{2\pi} \mathrm{d}\psi \; \sigma_{\mathrm{UT}} \sin\psi - \int_{0}^{\pi} \mathrm{d}\psi \; \sigma_{\mathrm{UT}} \sin\psi}{\int_{0}^{2\pi} \mathrm{d}\psi \; \sigma_{\mathrm{UU}}}$$

$$= -\frac{2}{\pi} A_{\mathrm{UT}}^{\sin\psi}$$

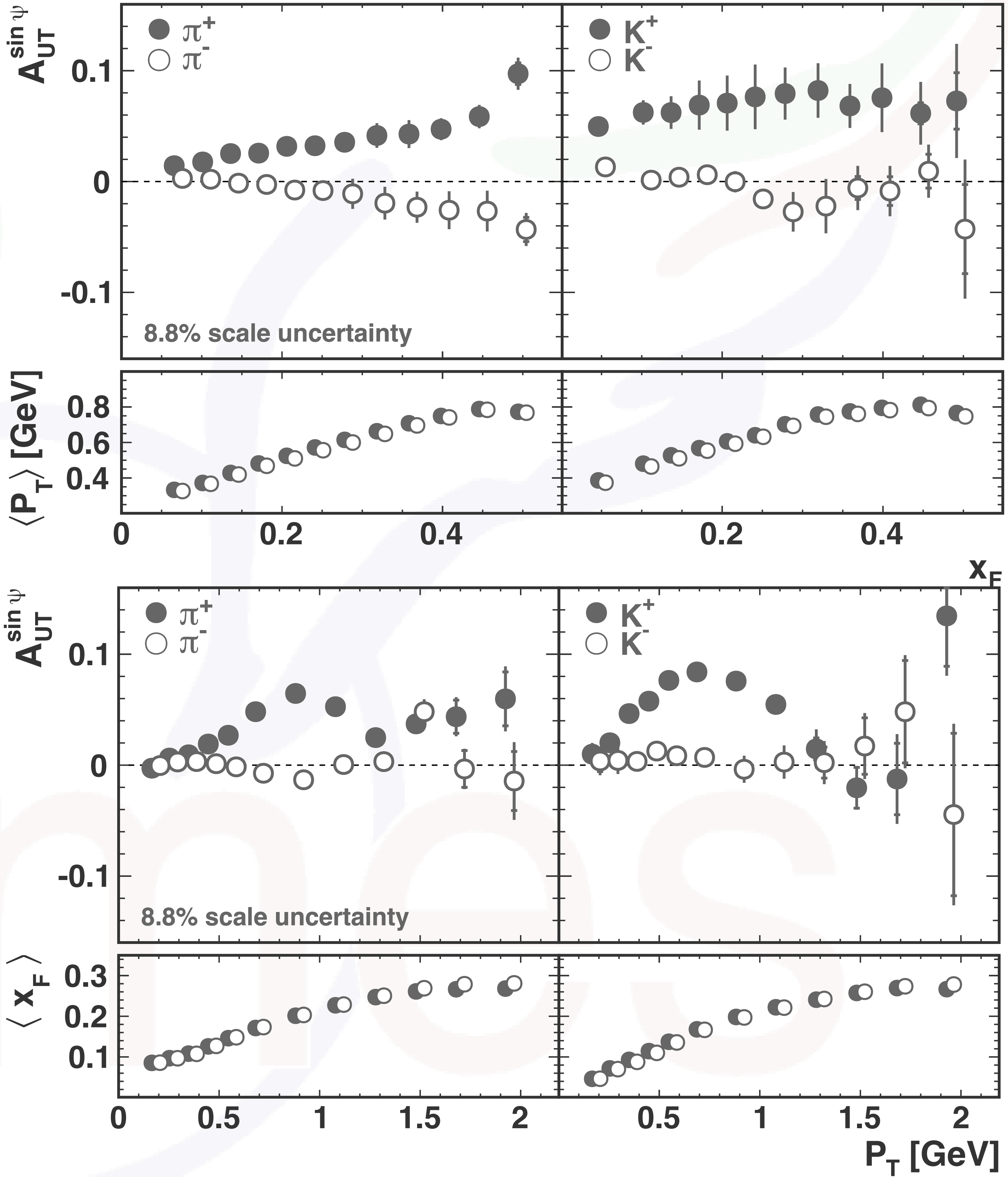
1D dependences of A_{UT} sinψ amplitude

- clear left-right asymmetries for pions and positive kaons
- increasing with x_F (as in pp)



- initially increasing with P_T with a fall-off at larger P_T

[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



1D dependences of A_{UT} sinψ amplitude

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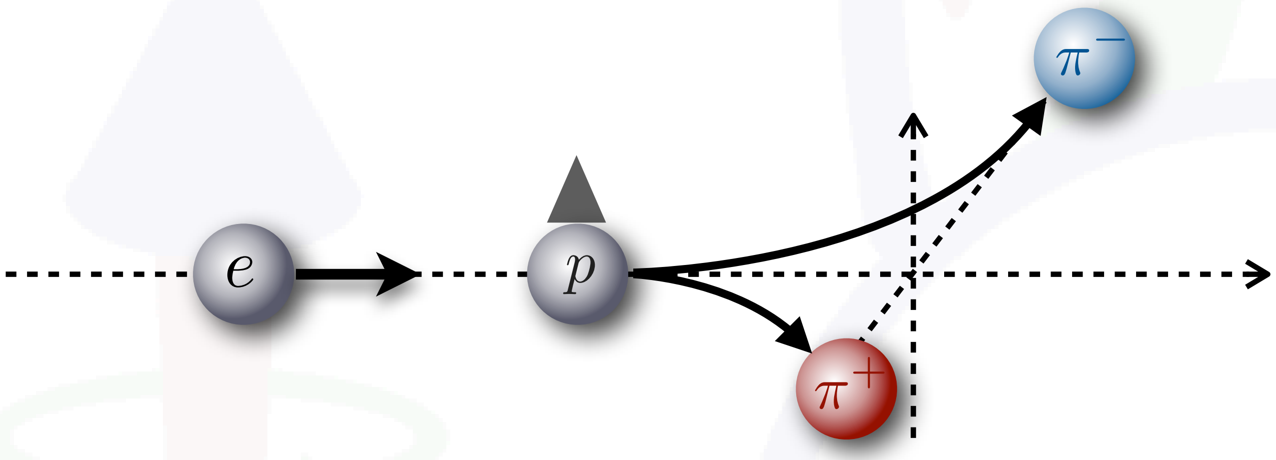
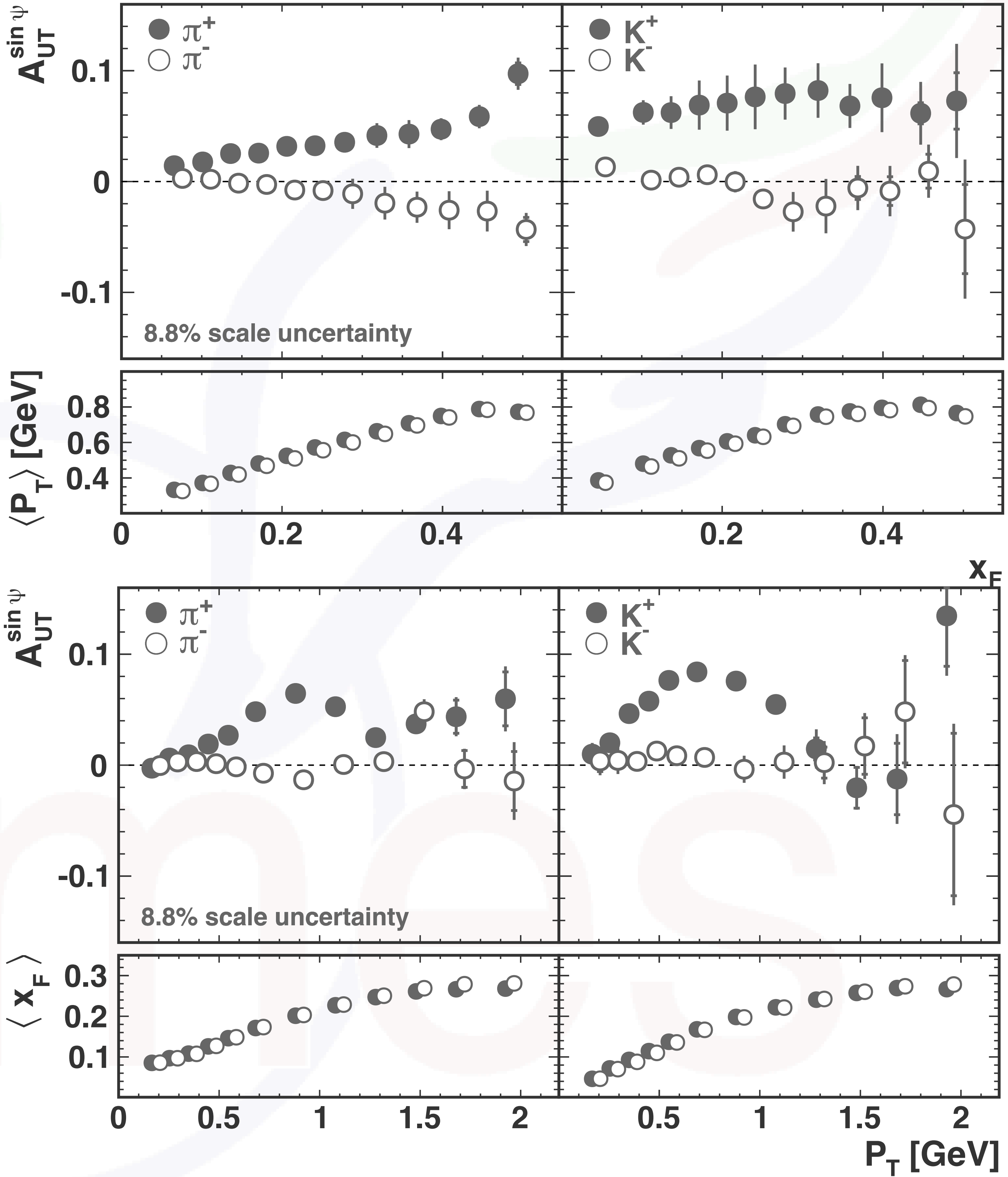


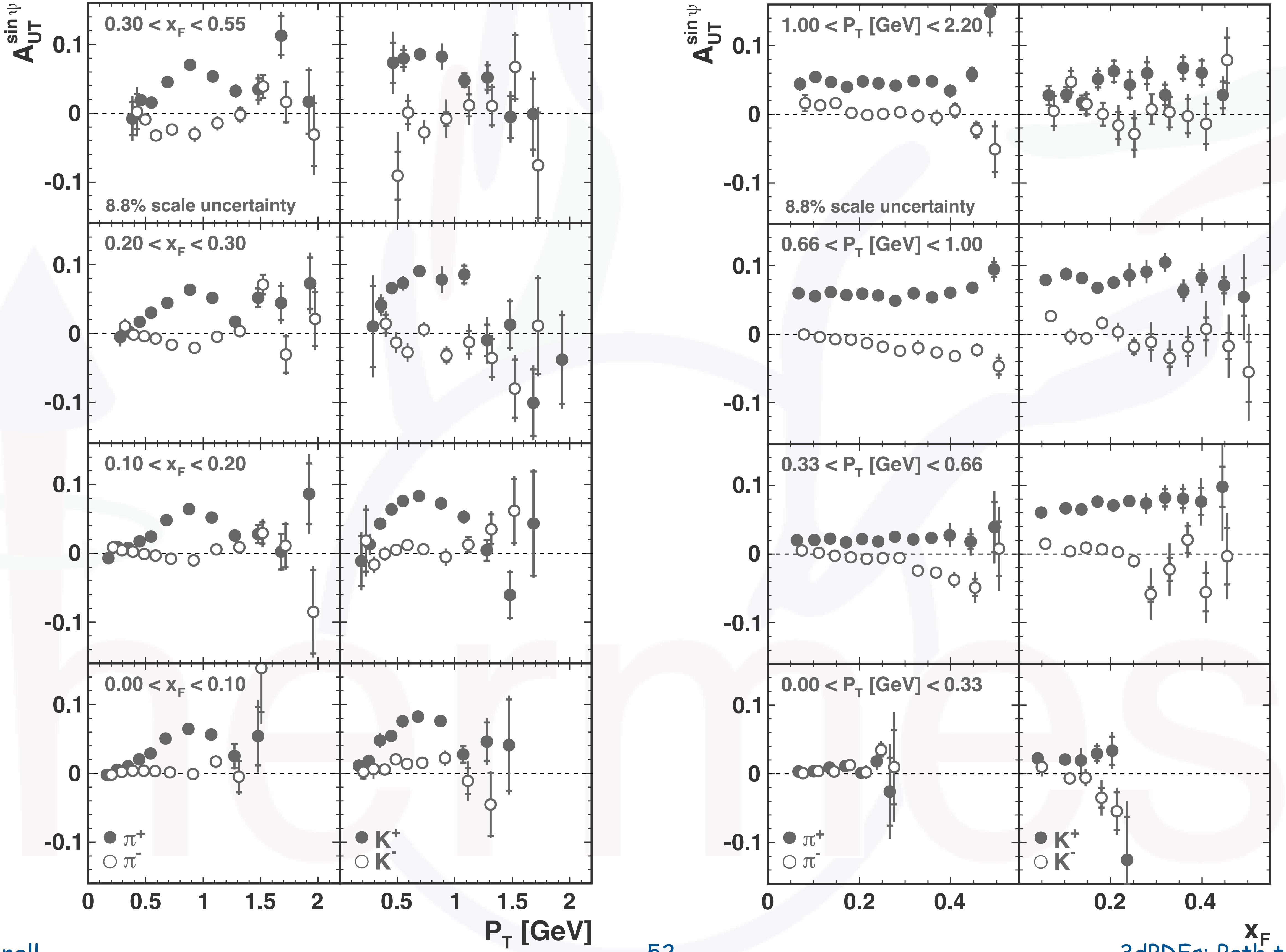
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➡ look at 2D dependences

[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



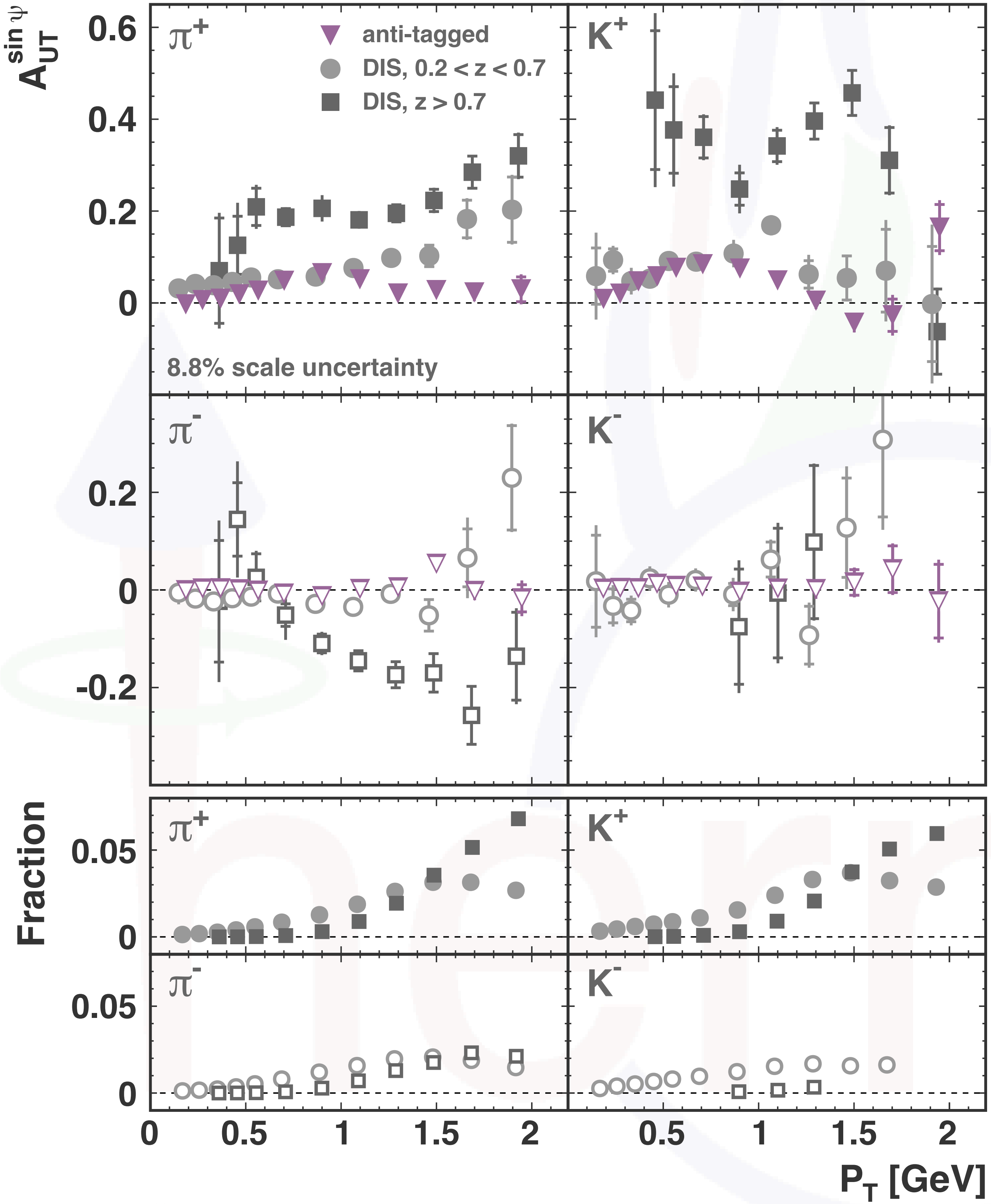
Inclusive hadrons: 2D dependences

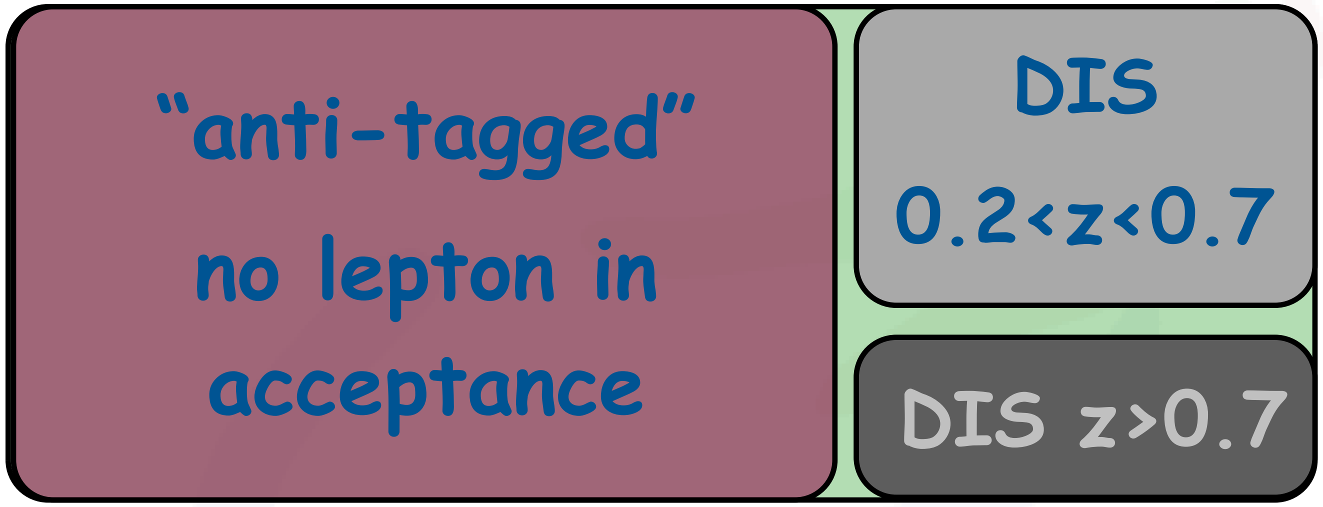
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



Asymmetries of subprocesses

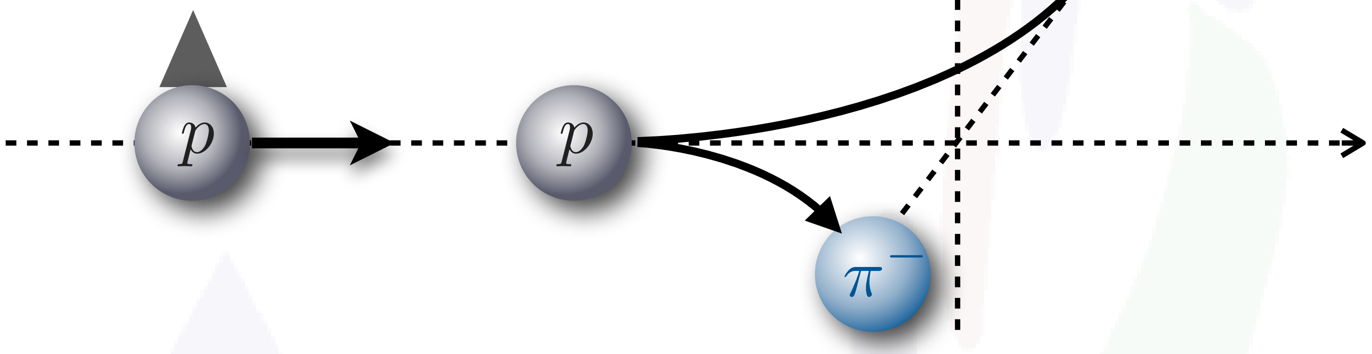
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



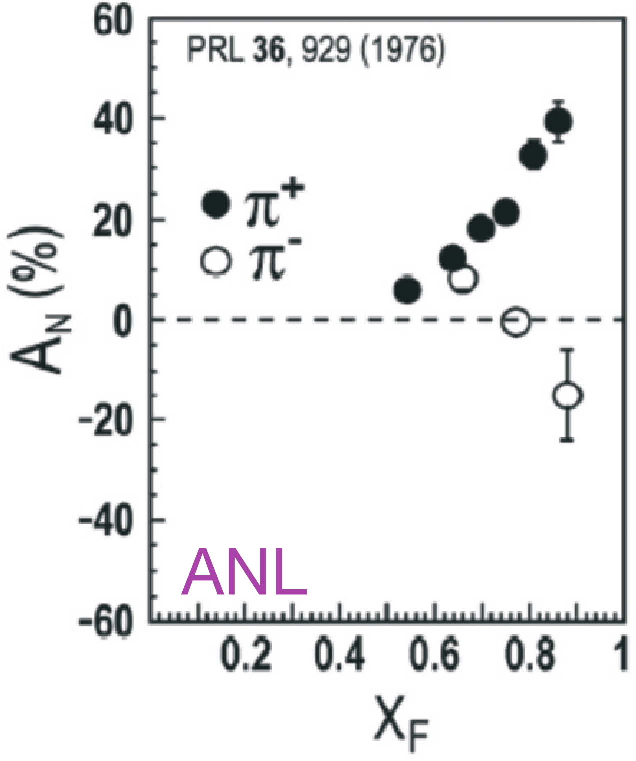


- at large P_T significant contribution from DIS events (Q^2>1)
- asymmetries increase with larger z
- large asymmetries also for π^- in case of z>0.7

the other inclusive SSA

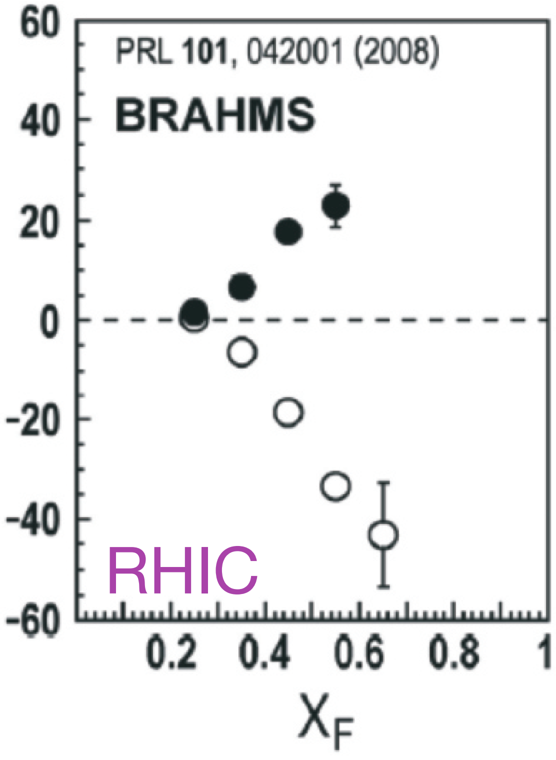


$\sqrt{s} = 4.9$ GeV



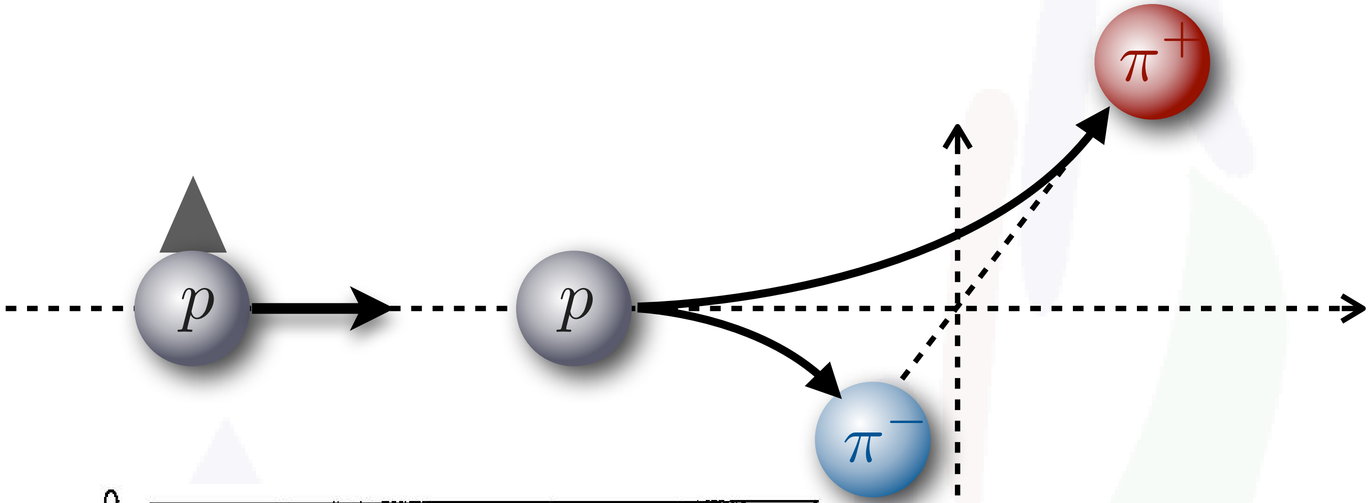
1976

62.4 GeV



2008

the other inclusive SSA



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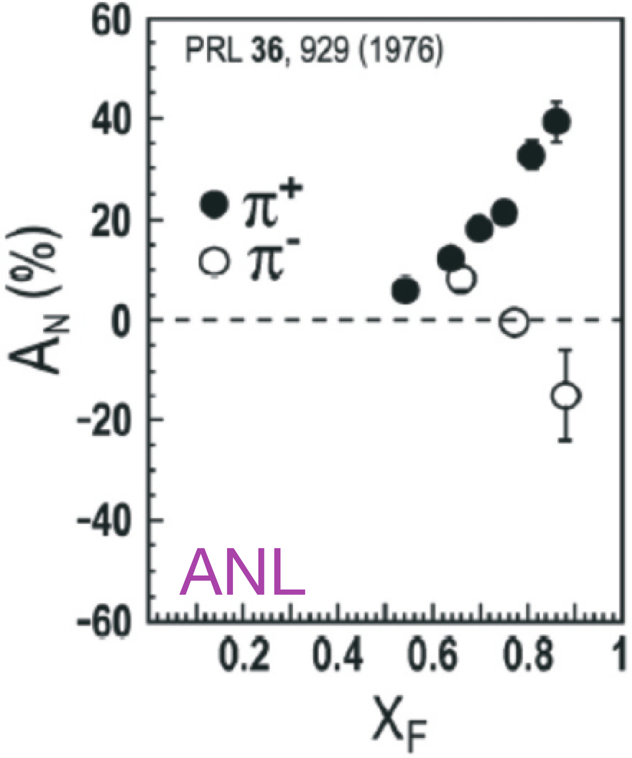

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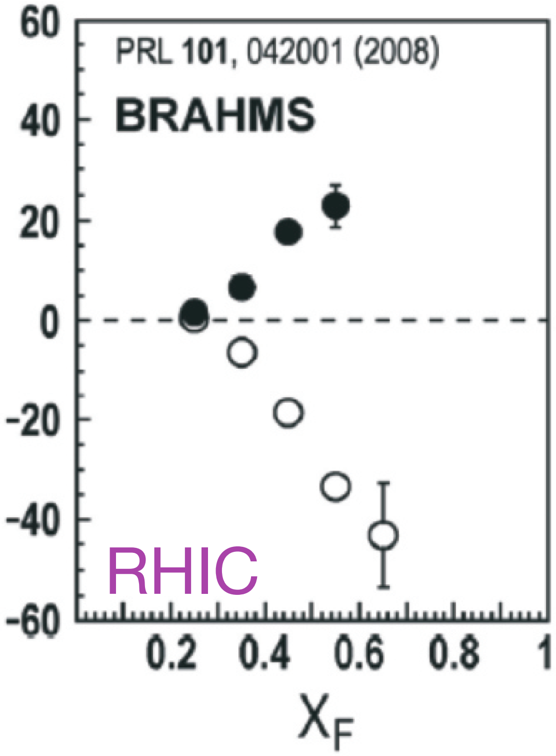
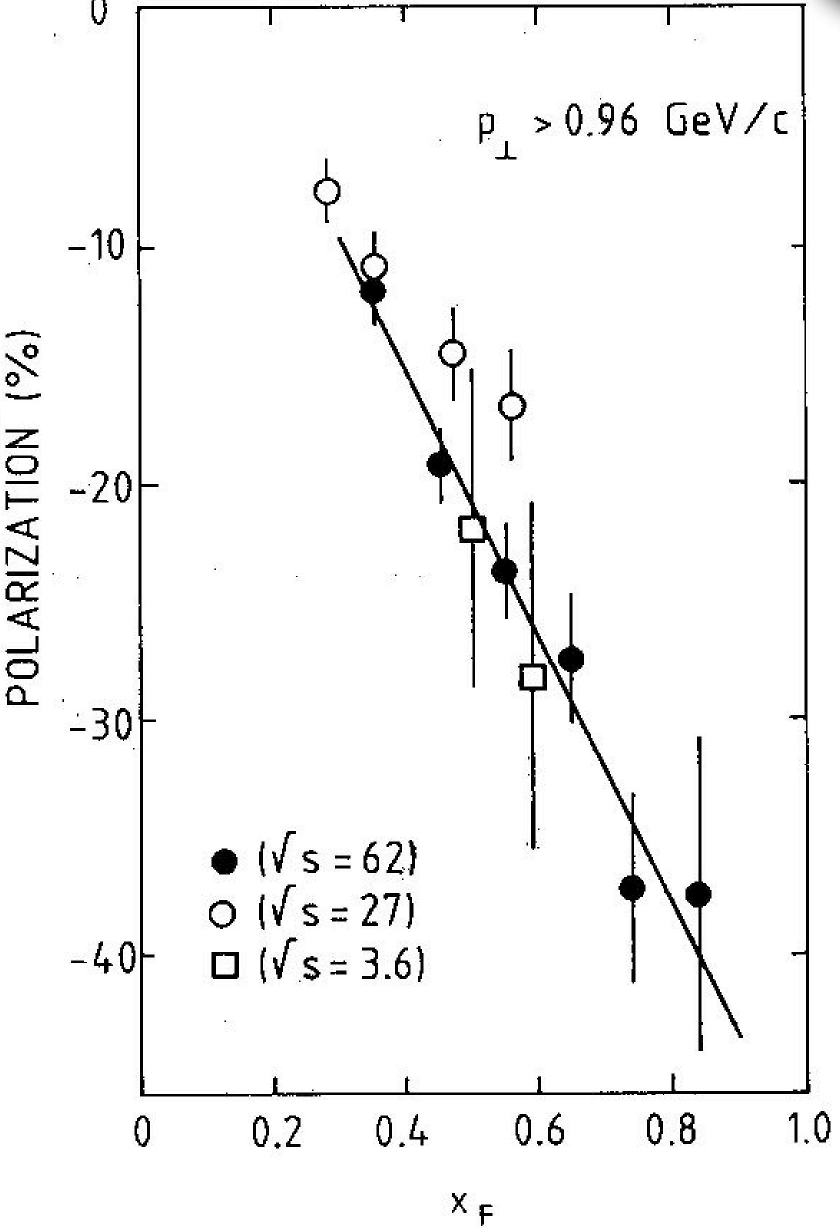
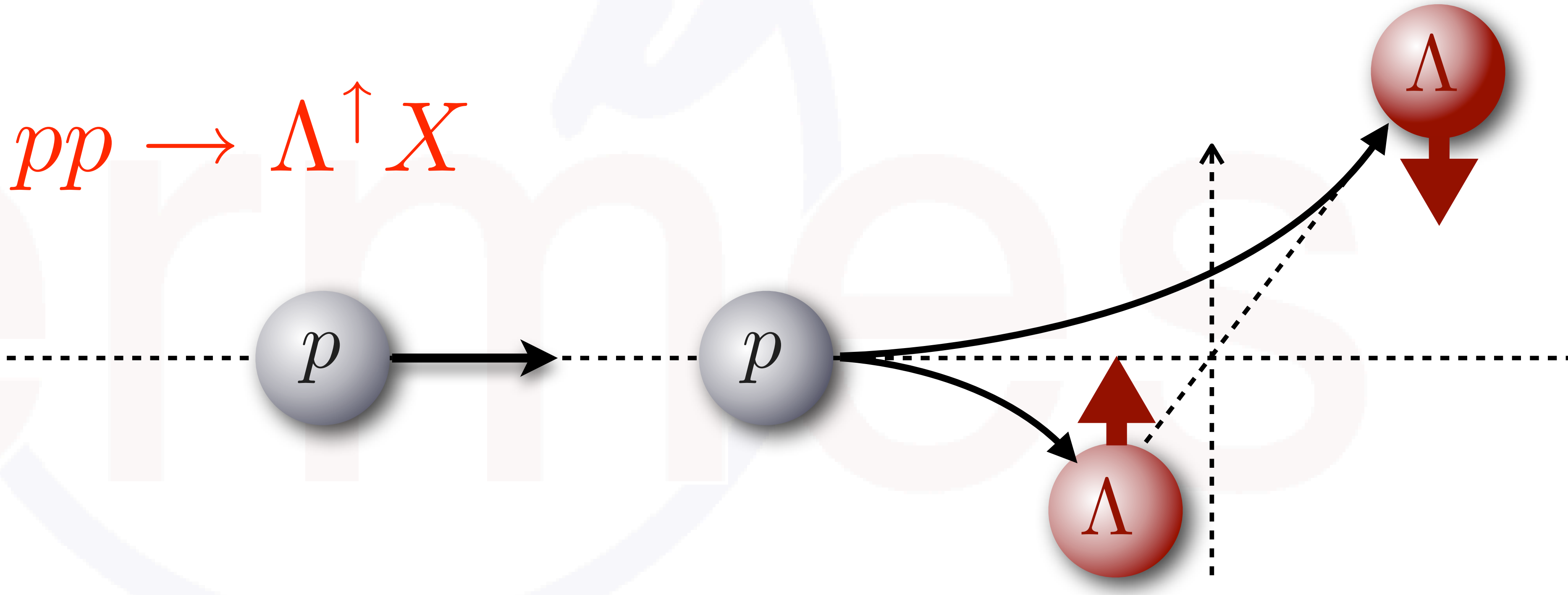


2008



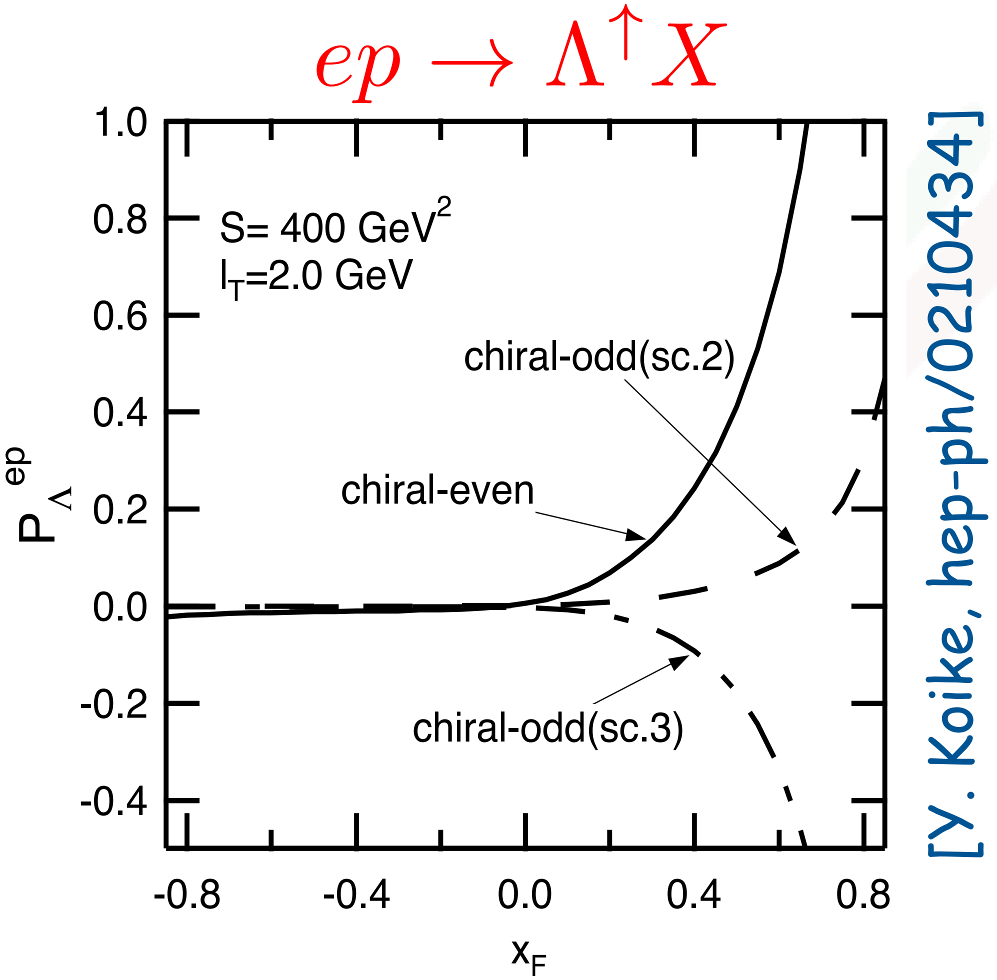
$pp \to \Lambda^{\uparrow} X$

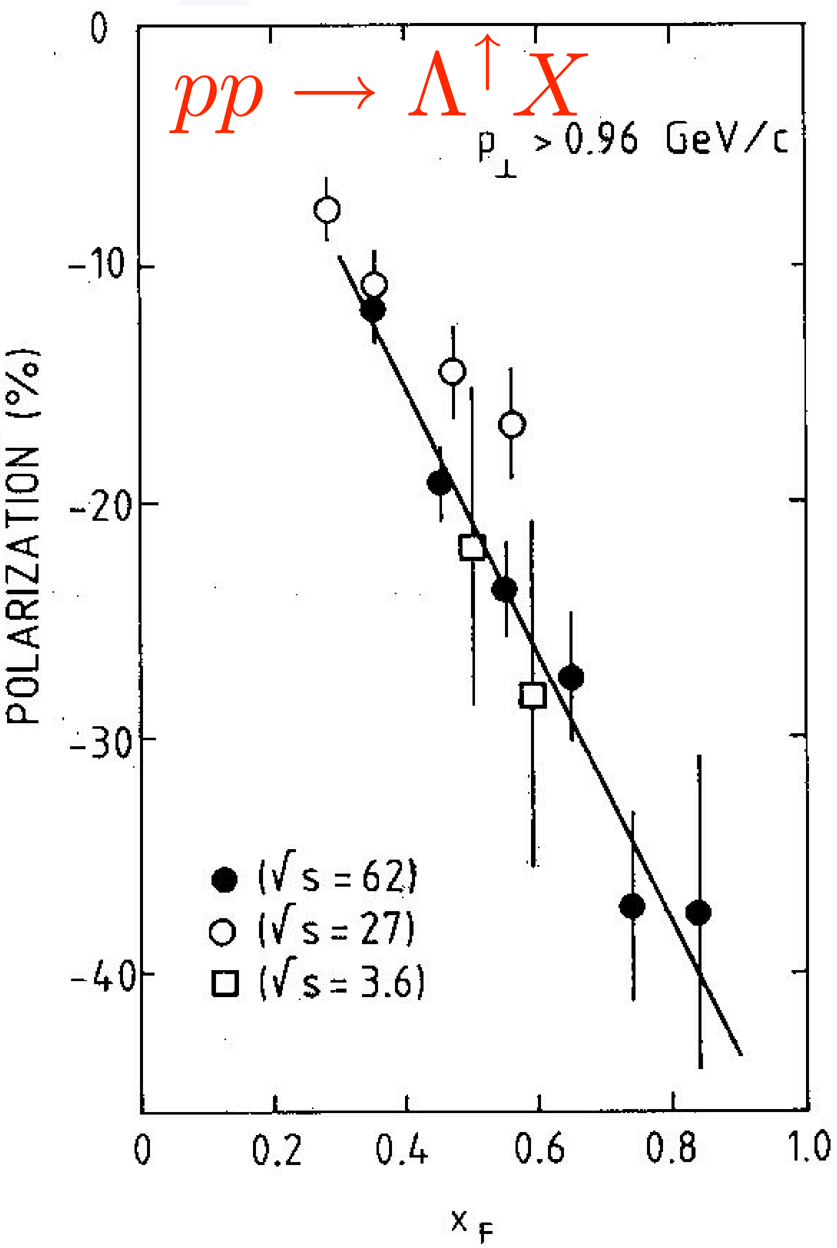


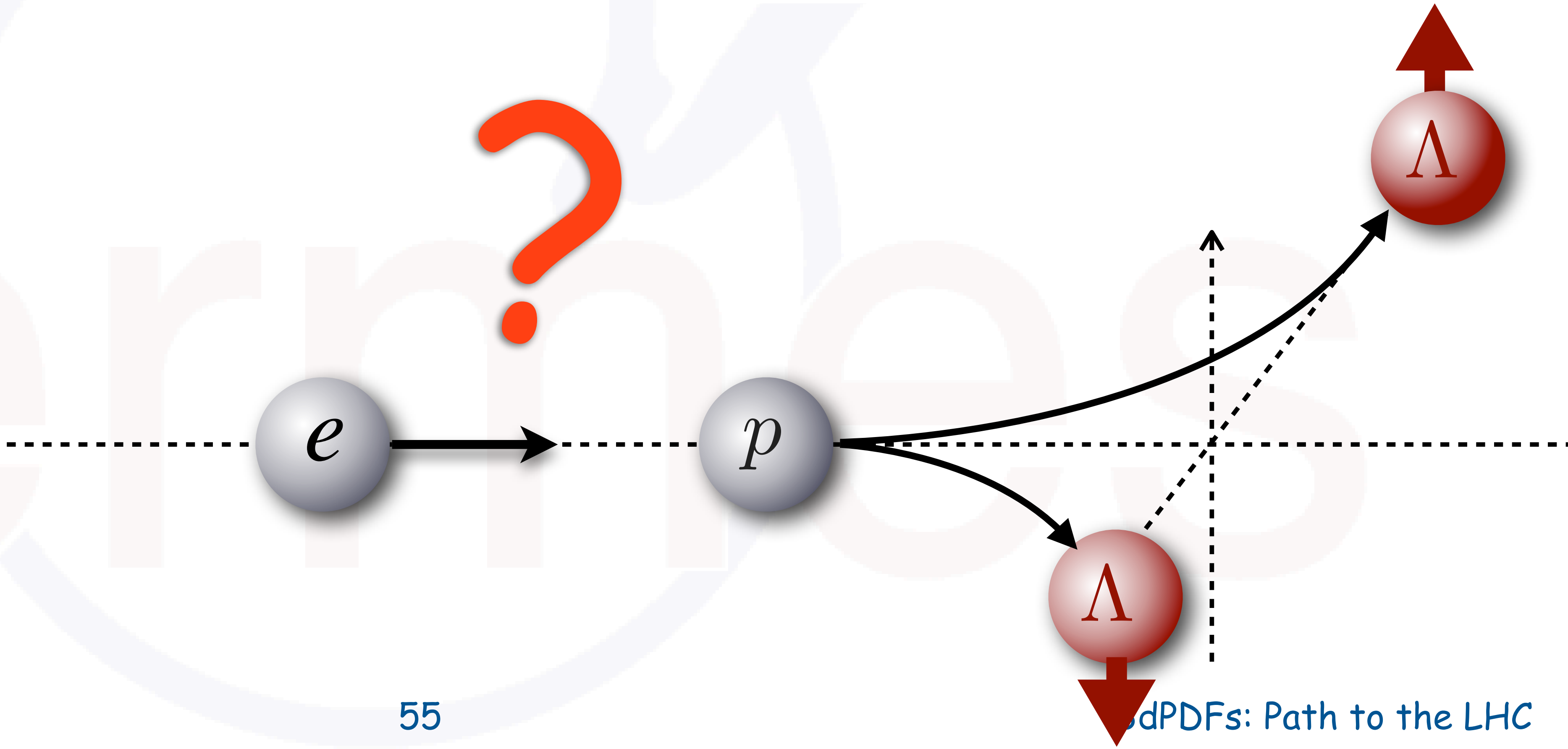
the other inclusive SSA

in SIDIS (large Q^2) proportional to polarizing FF $D_{1T}^{\perp}$ (naive T-odd, chiral-eve

in twist-3 factorization opposite sign to pp

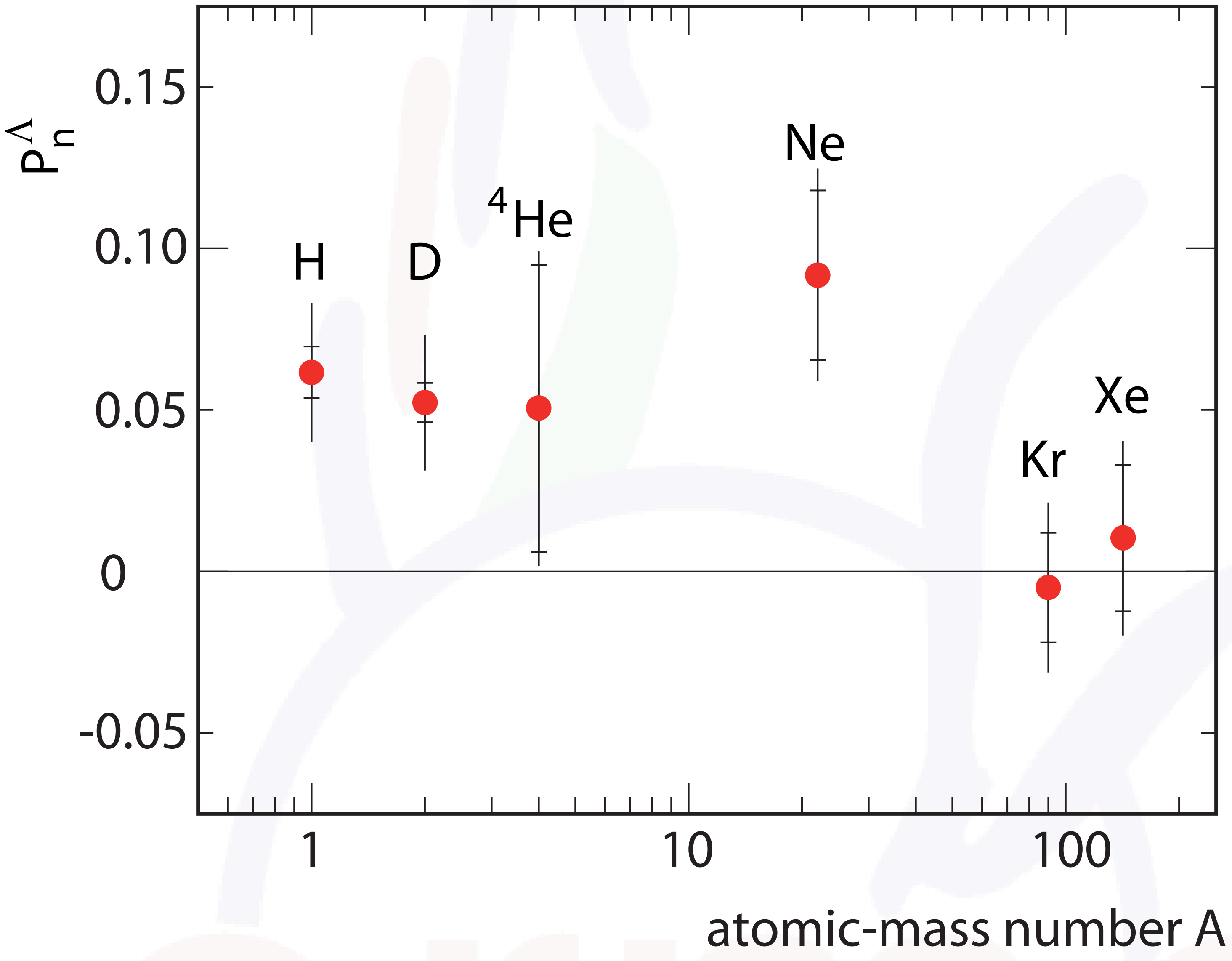






the other inclusive SSA

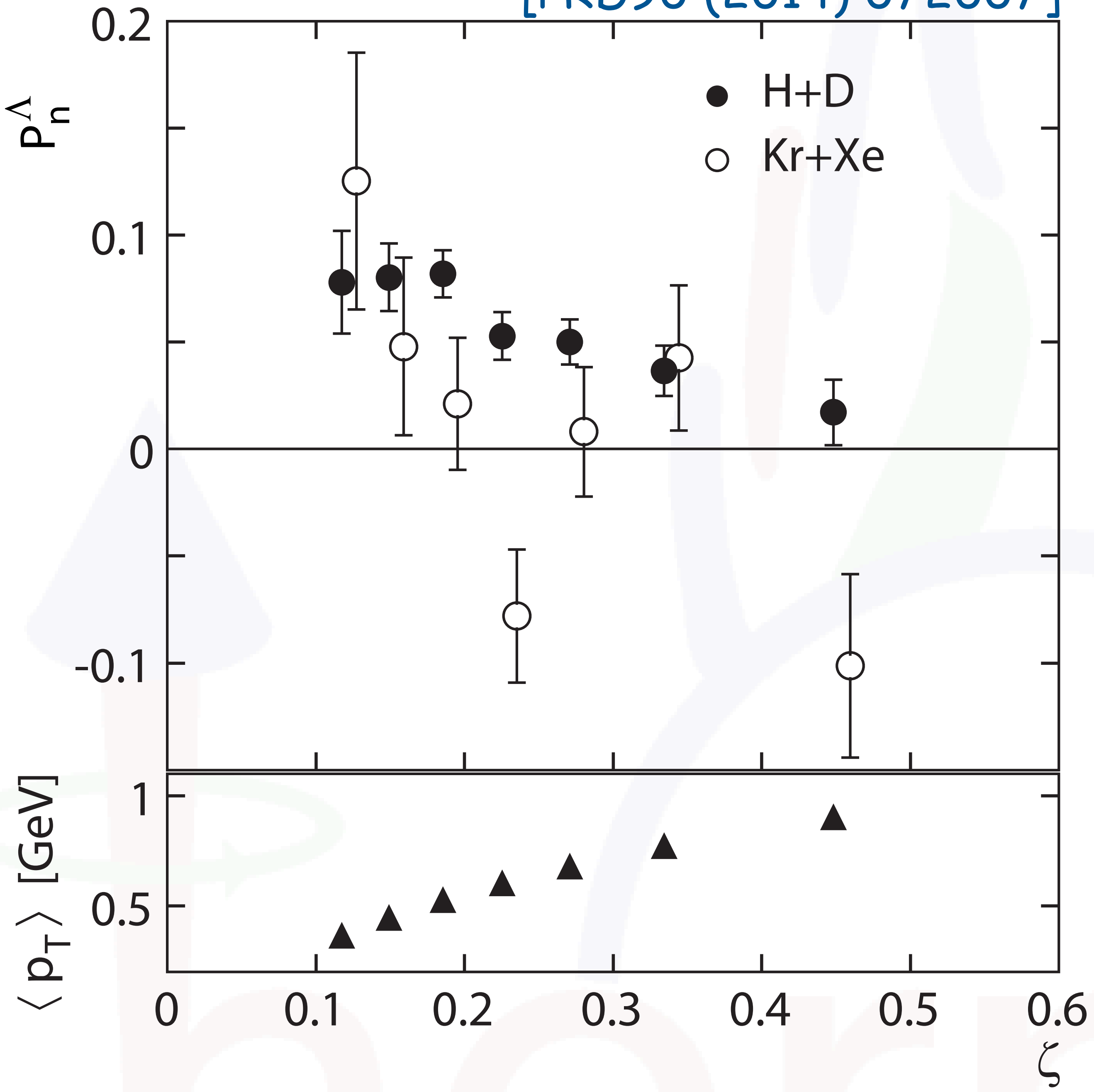
[PRD90 (2014) 072007]

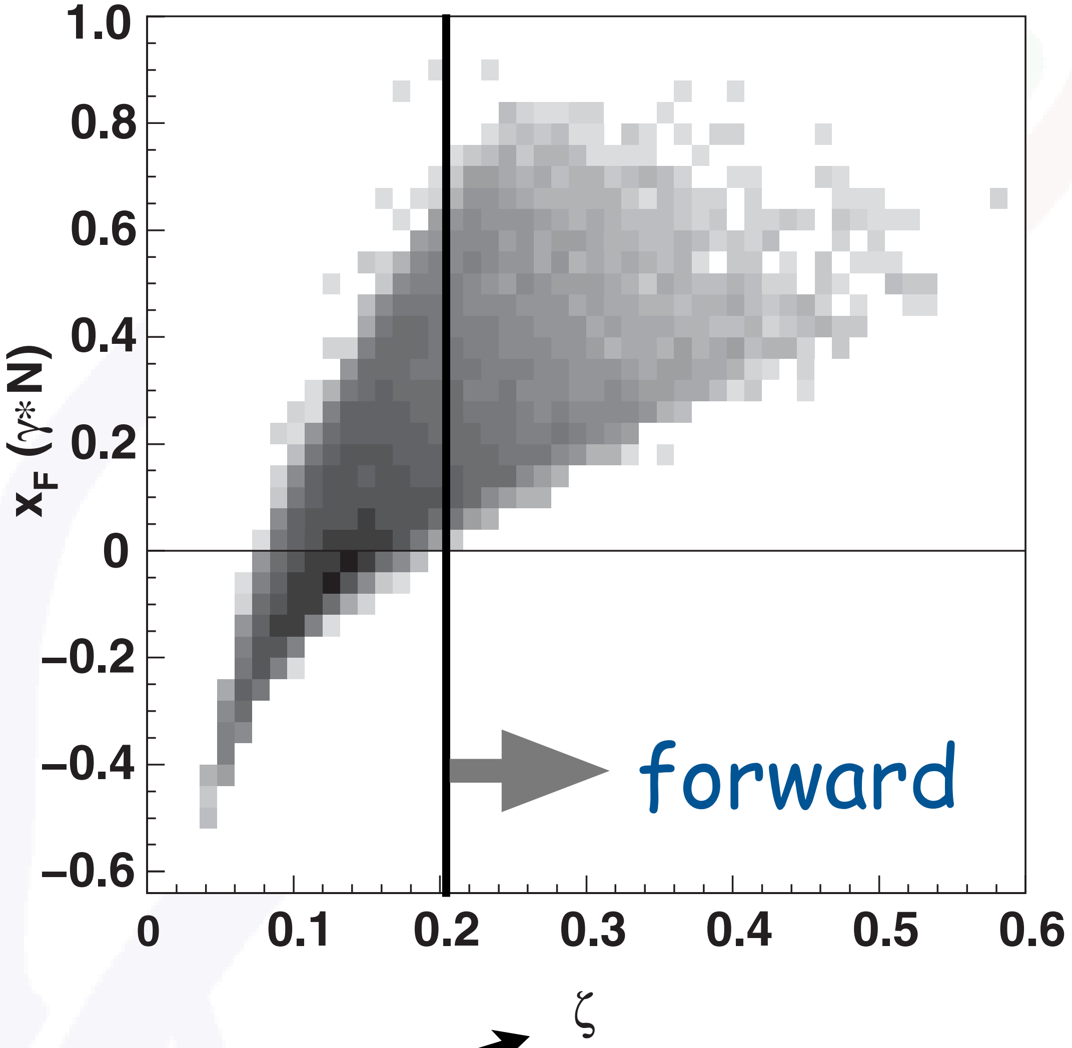


- clearly positive for light target nuclei
- consistent with zero for heavy targets

the other inclusive SSA

[PRD90 (2014) 072007]

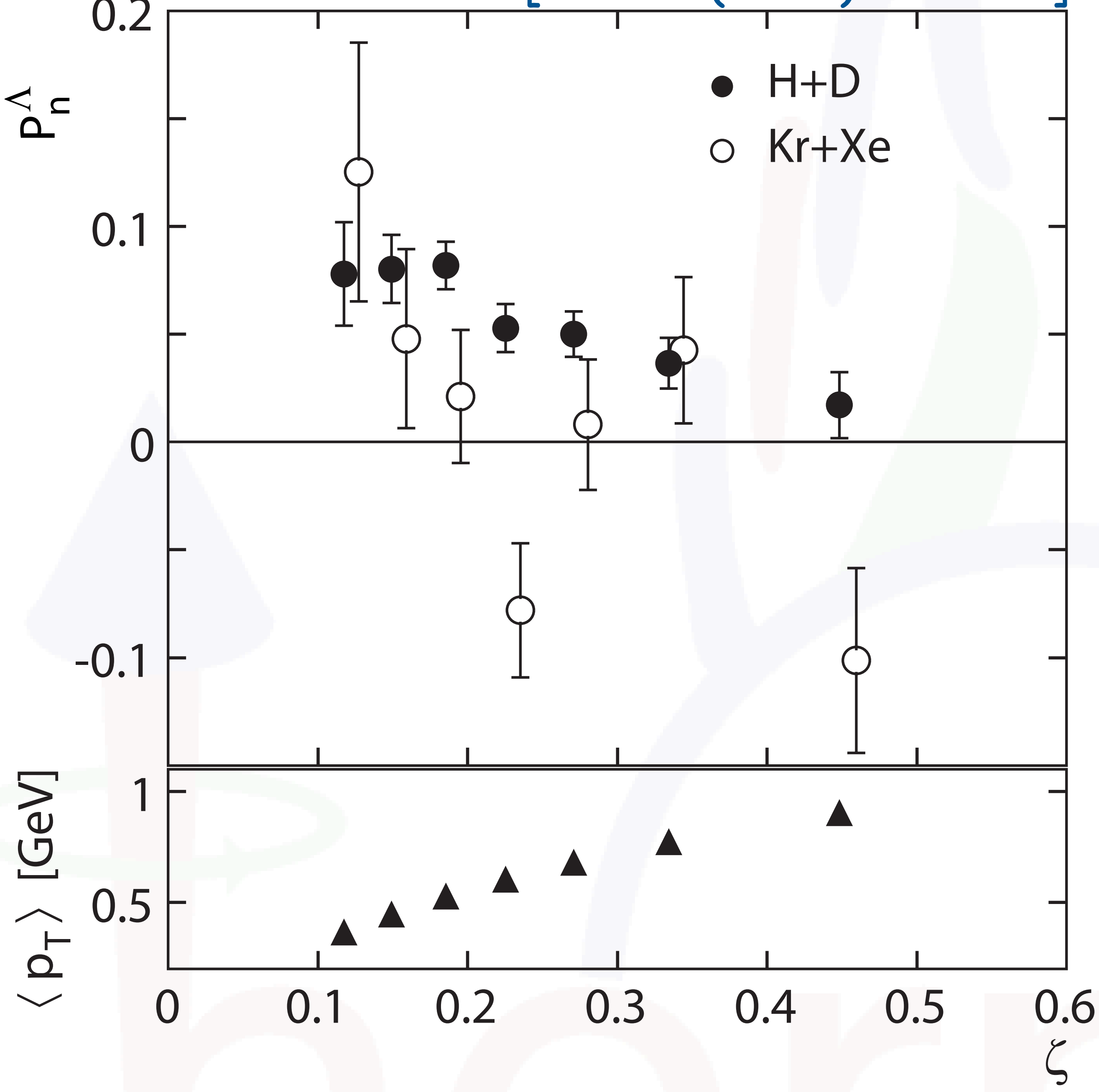




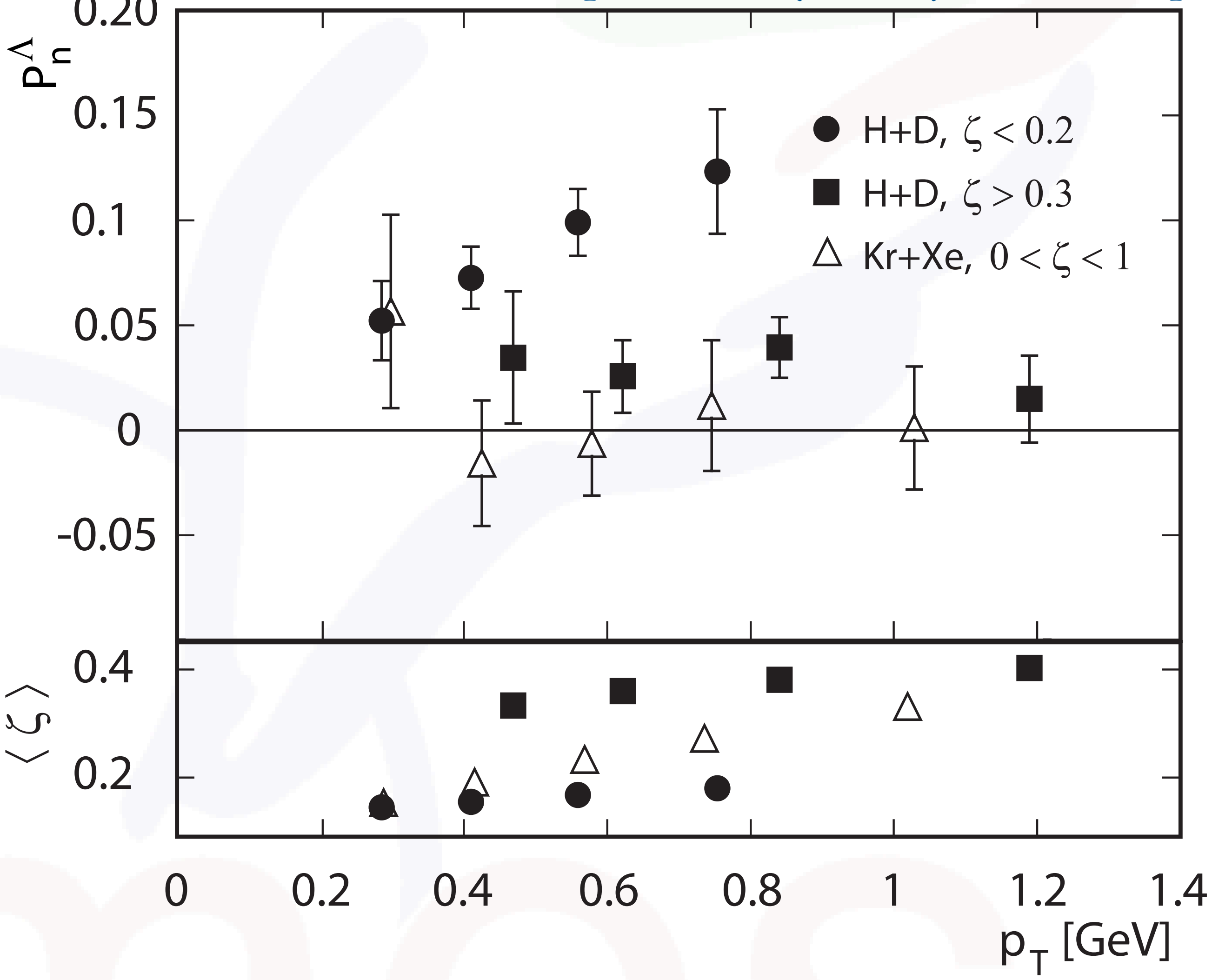
$$\zeta \equiv (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$$

- larger in backward direction w.r.t. incoming lepton
- consistent with x_F dependence of twist-3 calculation (opposite sign conventions for x_F !)

the other inclusive SSA



[PRD90 (2014) 072007]



[PRD90 (2014) 072007]

- larger in backward direction w.r.t. incoming lepton
- distinct p_T dependences in forward and backward directions: rising with p_T in backward direction as in pp

conclusions before the summary

- HERMES conceived almost 3 decades ago in order to solve the "spin crisis"
  - measure precisely the quark-spin and somewhat the gluon spin contribution to the proton spin
  - no orbital angular momentum on the menu
  - no real transverse-spin physics
    - up to g_2 and the Burkhardt-Cottingham S.R. …
      … and that mainly to have a more precise g_1 measurement

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- thanks also to the "believers" in the Frascati group, HERMES has published a wealth of transverse-spin results, among others, HERMES' most cited publications

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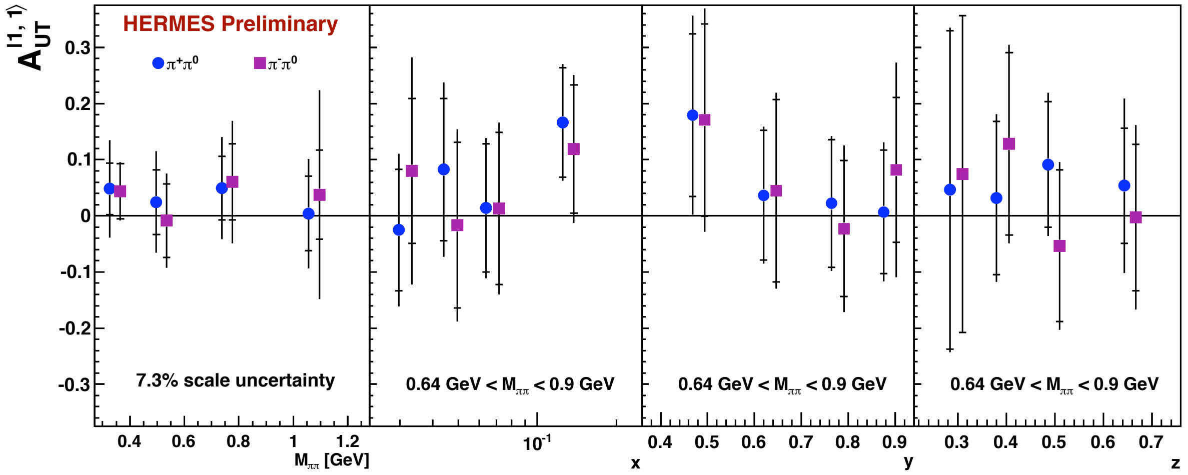
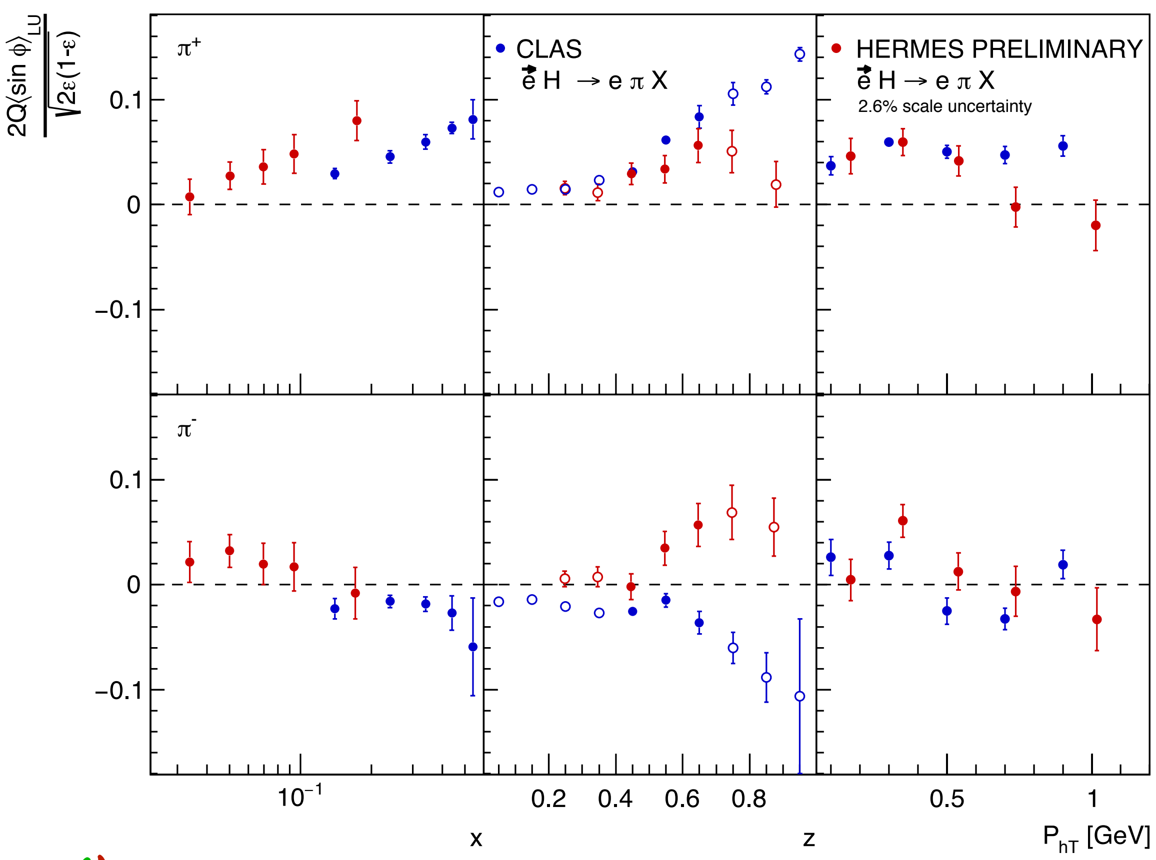
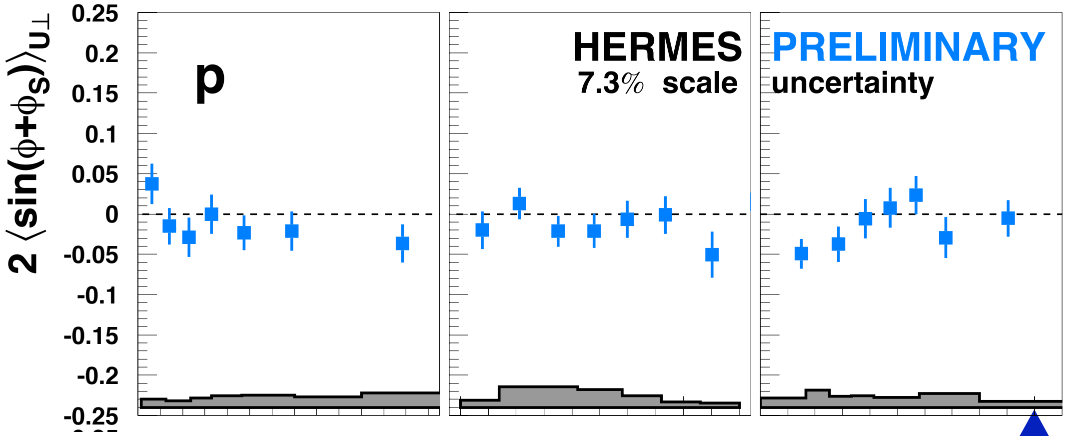
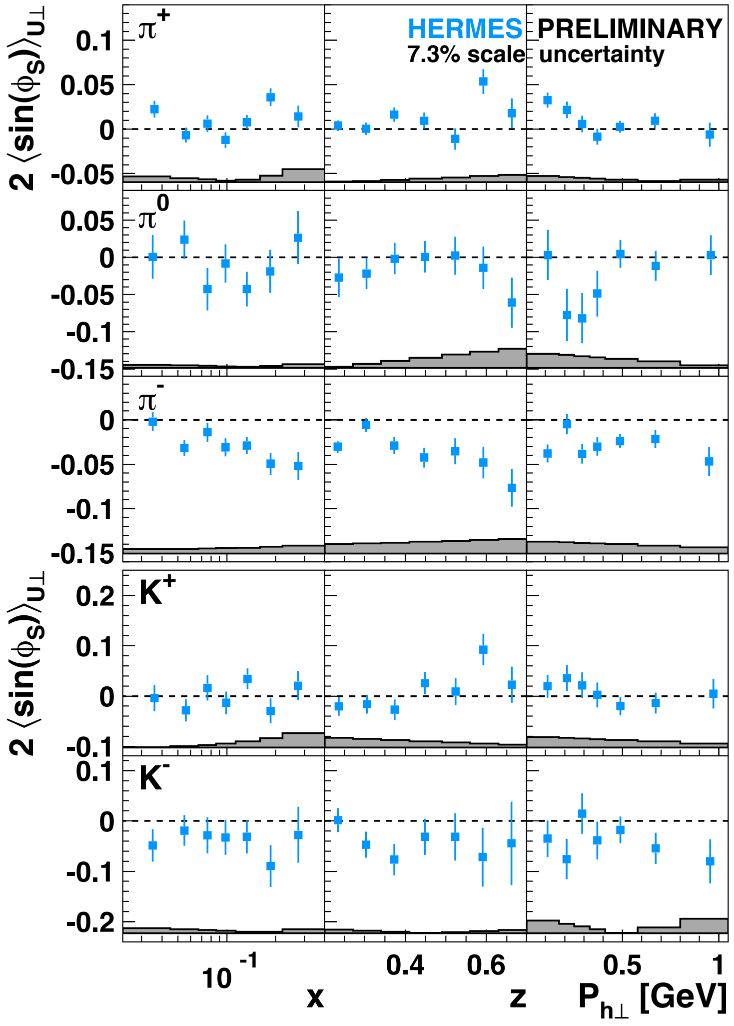
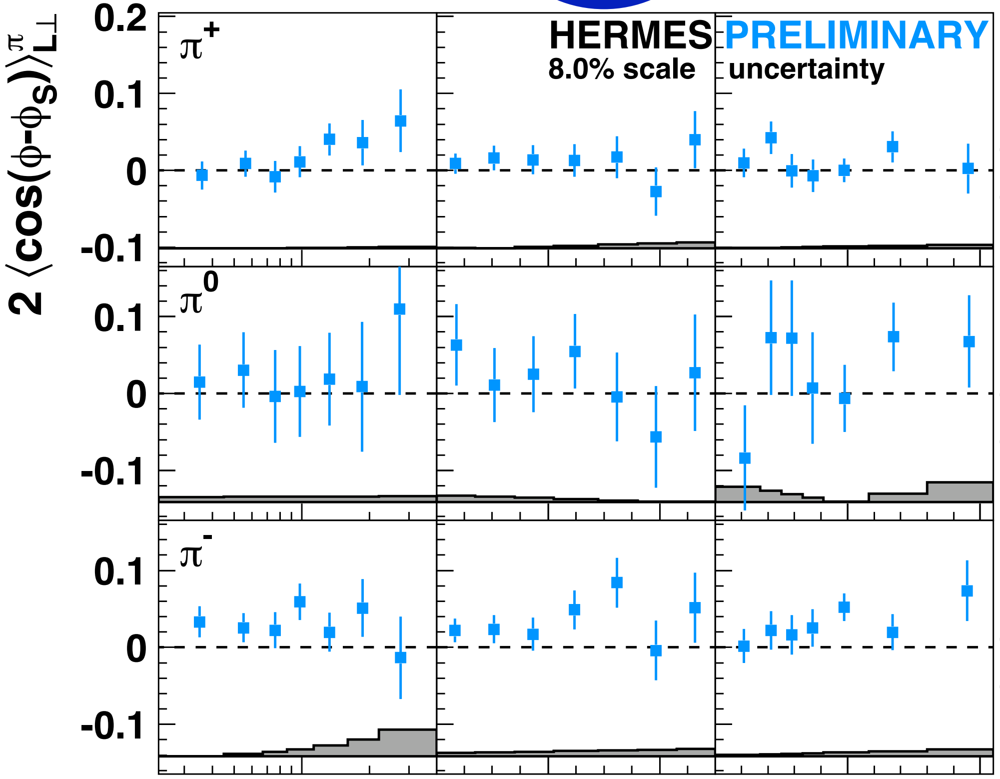
always be open to trying out new paths

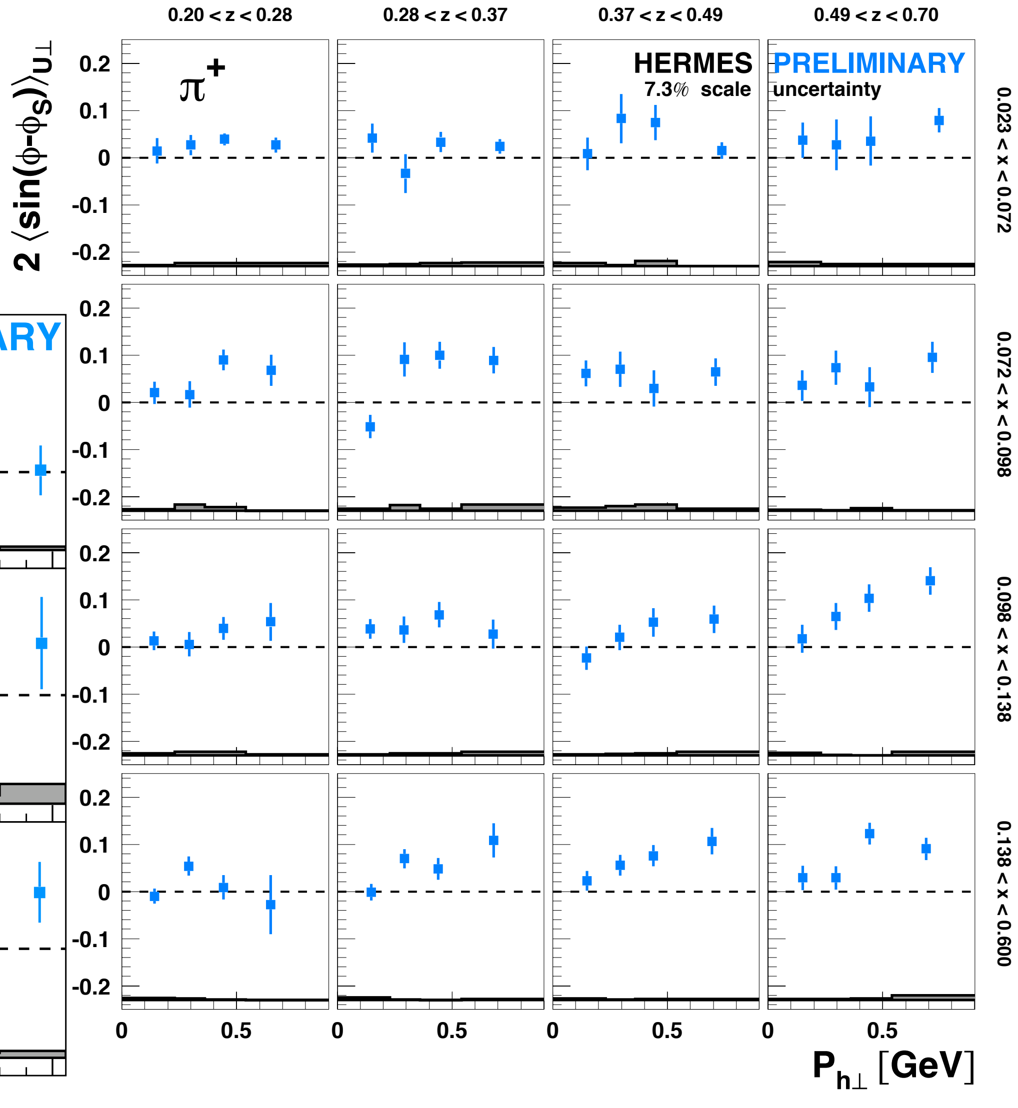

HERMES Preliminary
$A_{UT}^{(1,1)}$
$\pi^+\pi^0$
$\pi^-\pi^0$
7.3% scale uncertainty
0.64 GeV < $M_{\pi\pi}$ < 0.9 GeV
0.64 GeV < $M_{\pi\pi}$ < 0.9 GeV
0.64 GeV < $M_{\pi\pi}$ < 0.9 GeV
$M_{\pi\pi}$ [GeV]
x
y
z


$\frac{2Q\langle\sin\phi\rangle_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$
π^+
π^-
CLAS
$\vec{e}$ H → e π X
HERMES PRELIMINARY
$\vec{e}$ H → e π X
2.6% scale uncertainty
x
z
P_{hT} [GeV]


$2\langle\sin(\phi+\phi_S)\rangle_{U\perp}$
p
HERMES
7.3% scale
PRELIMINARY
uncertainty


$2\langle\sin(\phi_S)\rangle_{U\perp}$
π^+
HERMES
7.3% scale
PRELIMINARY
uncertainty
π^0
π^-
$2\langle\sin(\phi_S)\rangle_{U\perp}$
K^+
K^-
x
z
$P_{h\perp}$ [GeV]


$2\langle\cos(\phi-\phi_S)\rangle_{L\perp}^{\pi}$
π^+
HERMES
8.0% scale
PRELIMINARY
uncertainty
π^0
π^-


$2\langle\sin(\phi-\phi_S)\rangle_{U\perp}$
0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
π^+
HERMES
7.3% scale
PRELIMINARY
uncertainty
0.023 < x < 0.072
0.072 < x < 0.098
0.098 < x < 0.138
0.138 < x < 0.600
$P_{h\perp}$ [GeV]

hermes