Spatial and Momentum Tomography of Hadrons and Nuclei

INT-17-3 - week 4

August 28th - September 27th, 2017 - INT, Seattle, WA, USA

Lessons learnt on TMD measurements at hermes

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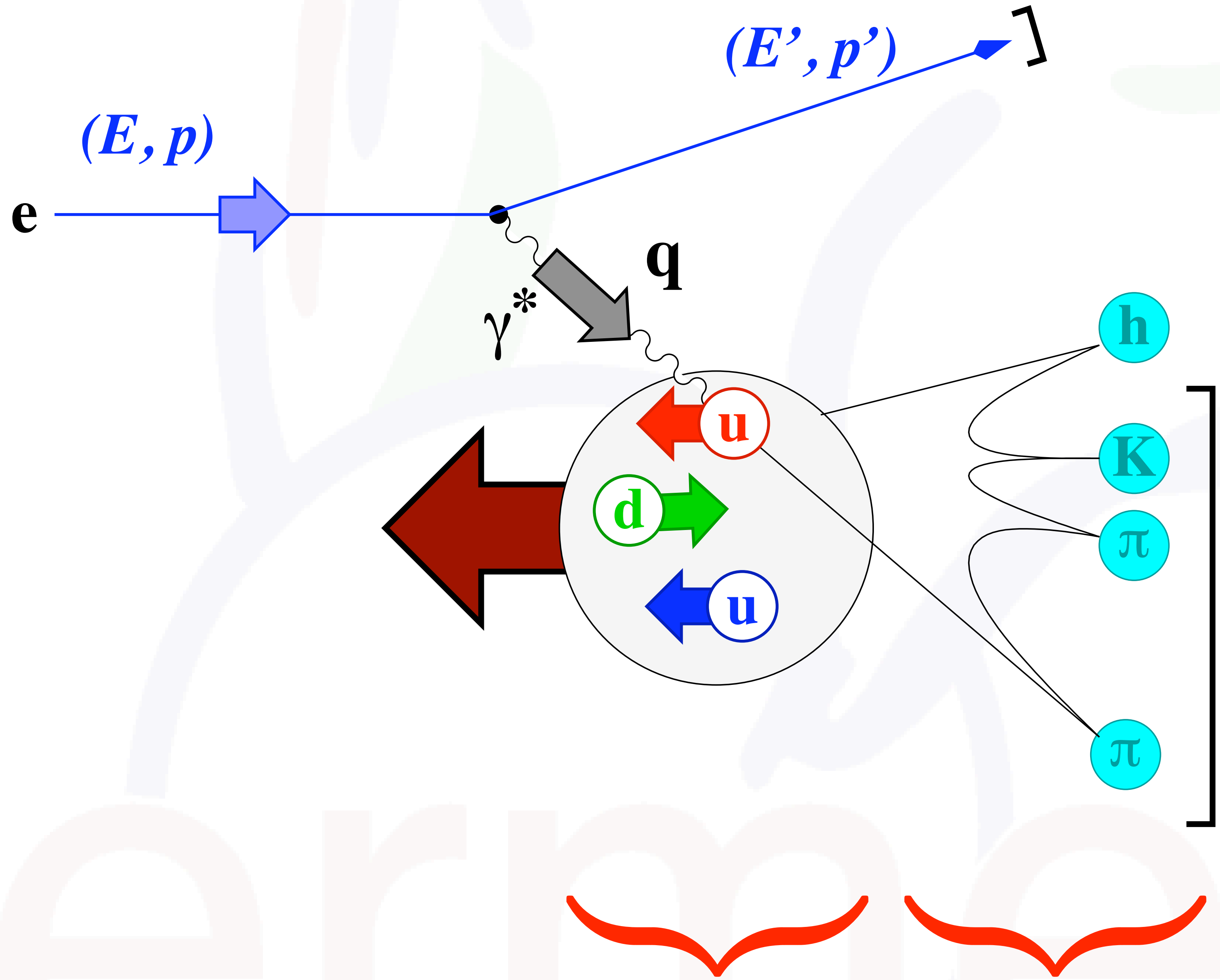
eman ta zabal zazu

Universidad del País Vasco Euskal Herriko Unibertsitatea

semi-inclusive DIS



factorization: parton distributions fragmentation functions

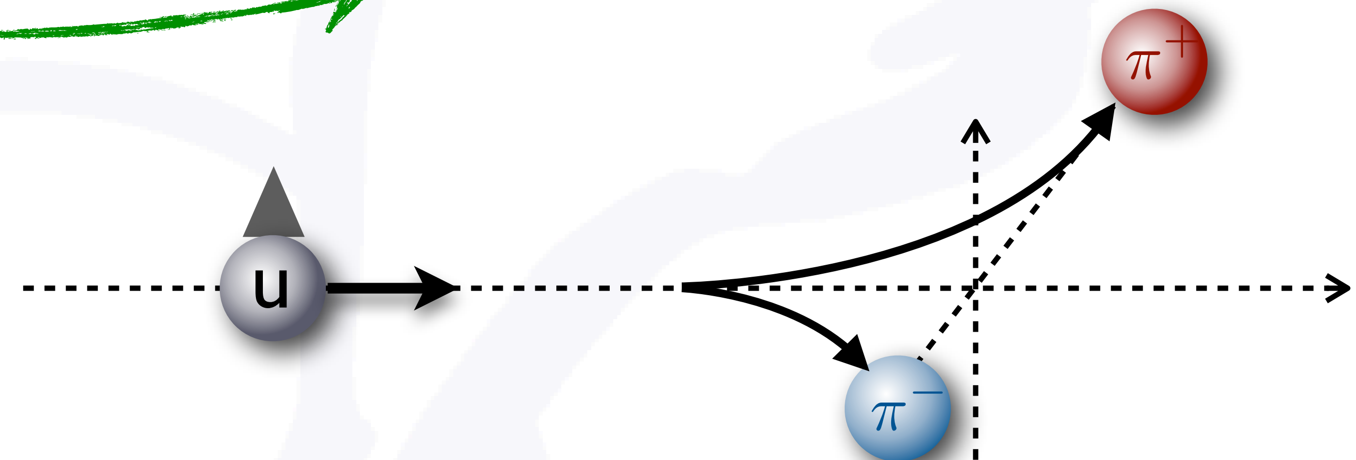
probing TMDs in semi-inclusive DIS

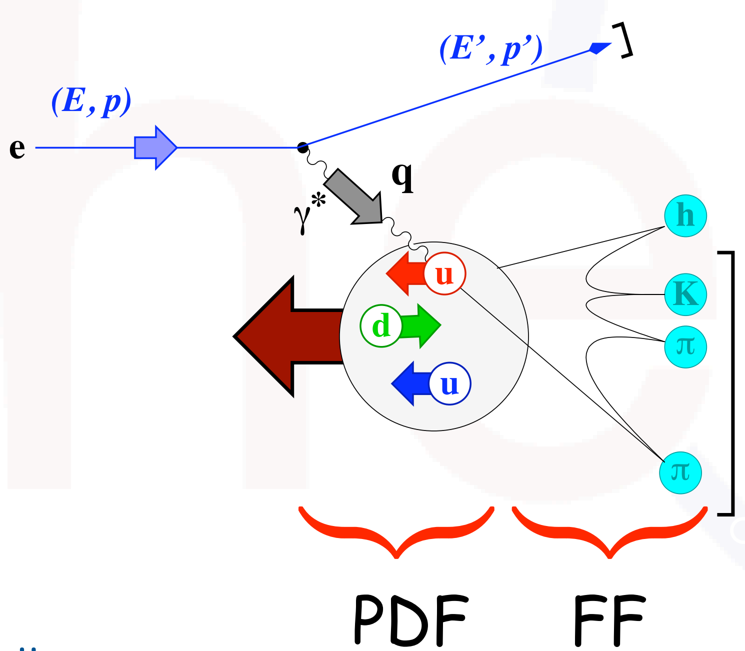
quark pol. (columns) / nucleon pol. (rows)

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

in SIDIS*) couple PDFs to:

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





*) semi-inclusive DIS with unpolarized final state

probing TMDs in semi-inclusive DIS

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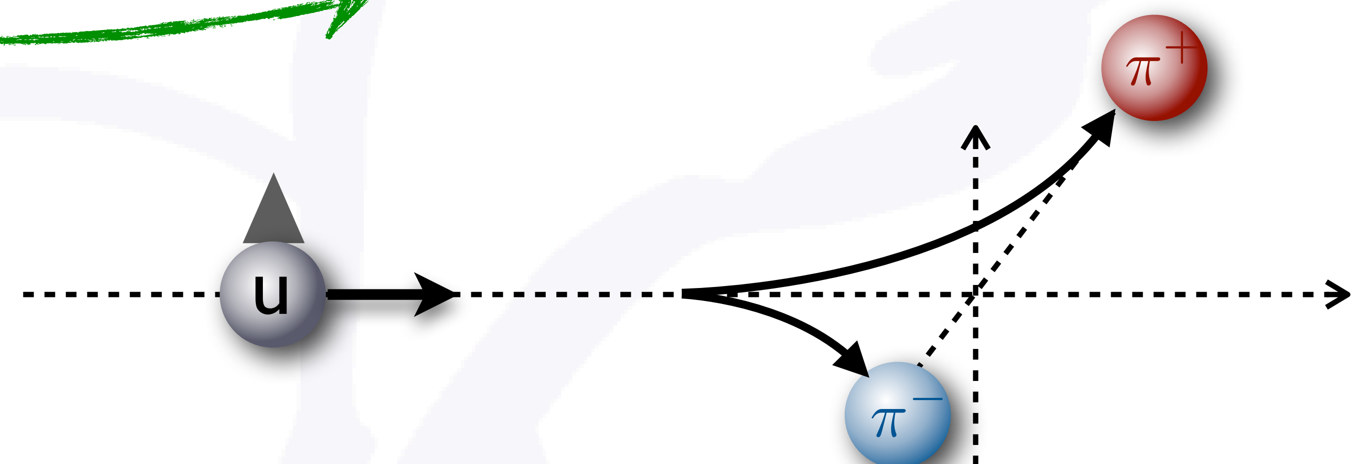
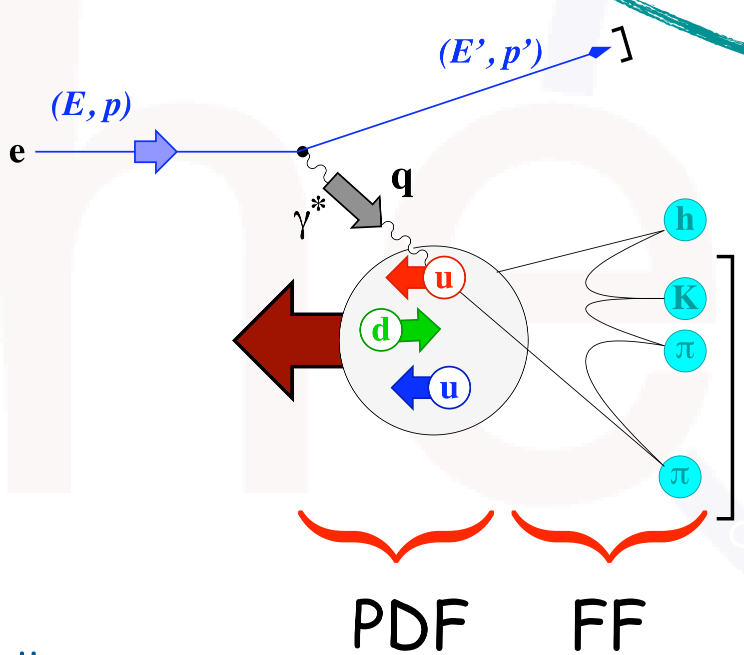


ordinary FF: $D_1^{q\to h}$



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probing TMDs in semi-inclusive DIS

quark pol.

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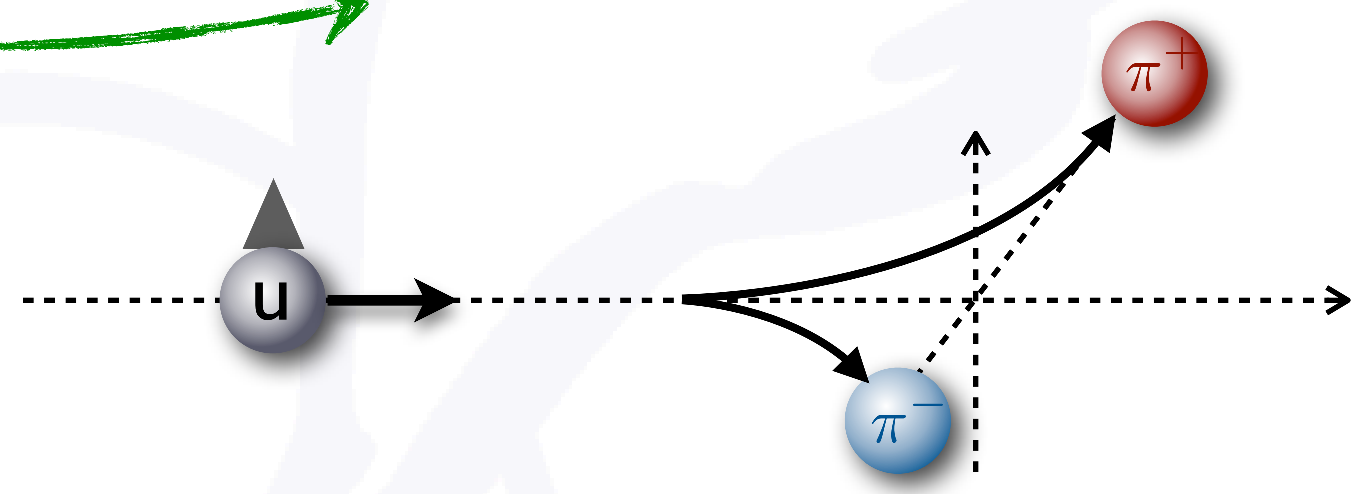


ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

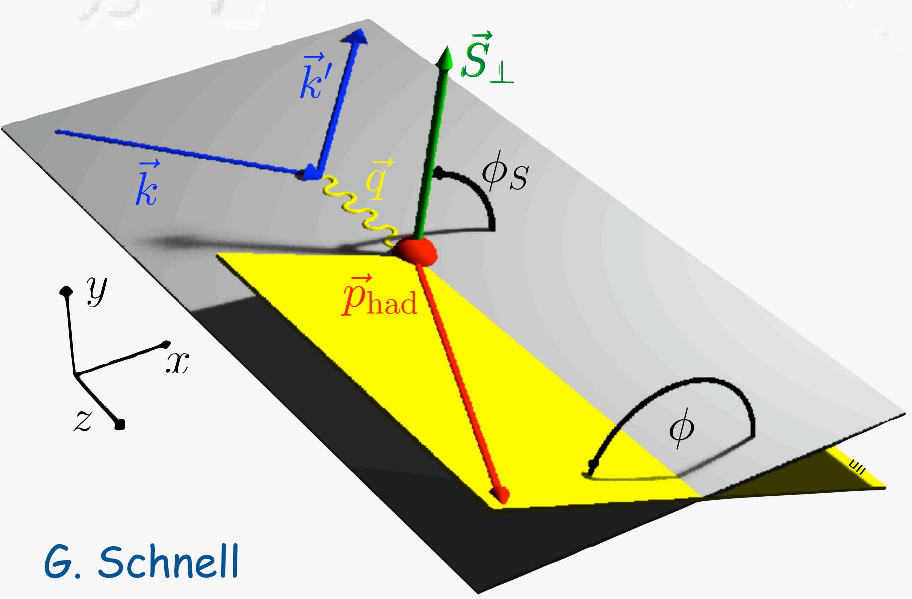
one-hadron production (ep→ehX)

$$
\begin{aligned}
d\sigma =\ & d\sigma^{0}_{UU} + \cos 2\phi\, d\sigma^{1}_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^{3}_{LU} \\
& + S_L \left\{ \sin 2\phi\, d\sigma^{4}_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^{7}_{LL} \right] \right\} \\
& + S_T \Big\{ \sin(\phi-\phi_S)\, d\sigma^{8}_{UT} + \sin(\phi+\phi_S)\, d\sigma^{9}_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \\
& \quad + \frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT} \right) \\
& \quad + \lambda_e \left[\cos(\phi-\phi_S)\, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S\, d\sigma^{14}_{LT} + \cos(2\phi-\phi_S)\, d\sigma^{15}_{LT} \right) \right] \Big\}
\end{aligned}
$$

σ_{XY}

Beam **Target**

Polarization



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

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

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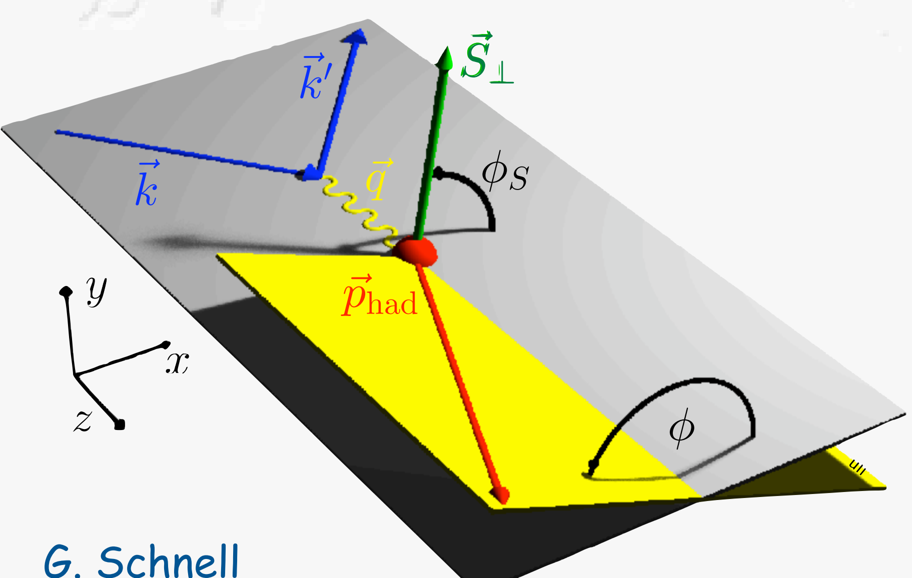
σ_{XY}

Beam Target
Polarization



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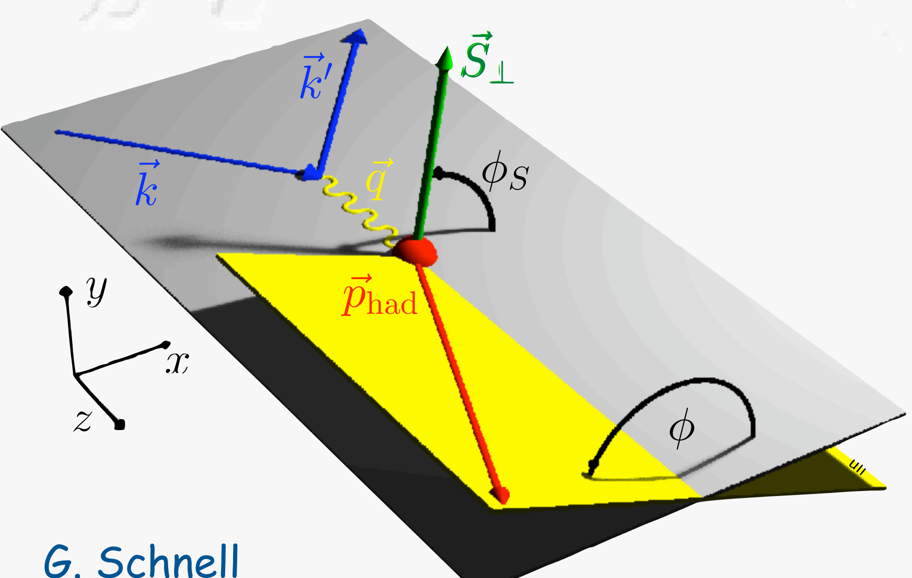
\end{aligned}
$$

σ_{XY}: X → **Beam**, Y → **Target**

Polarization



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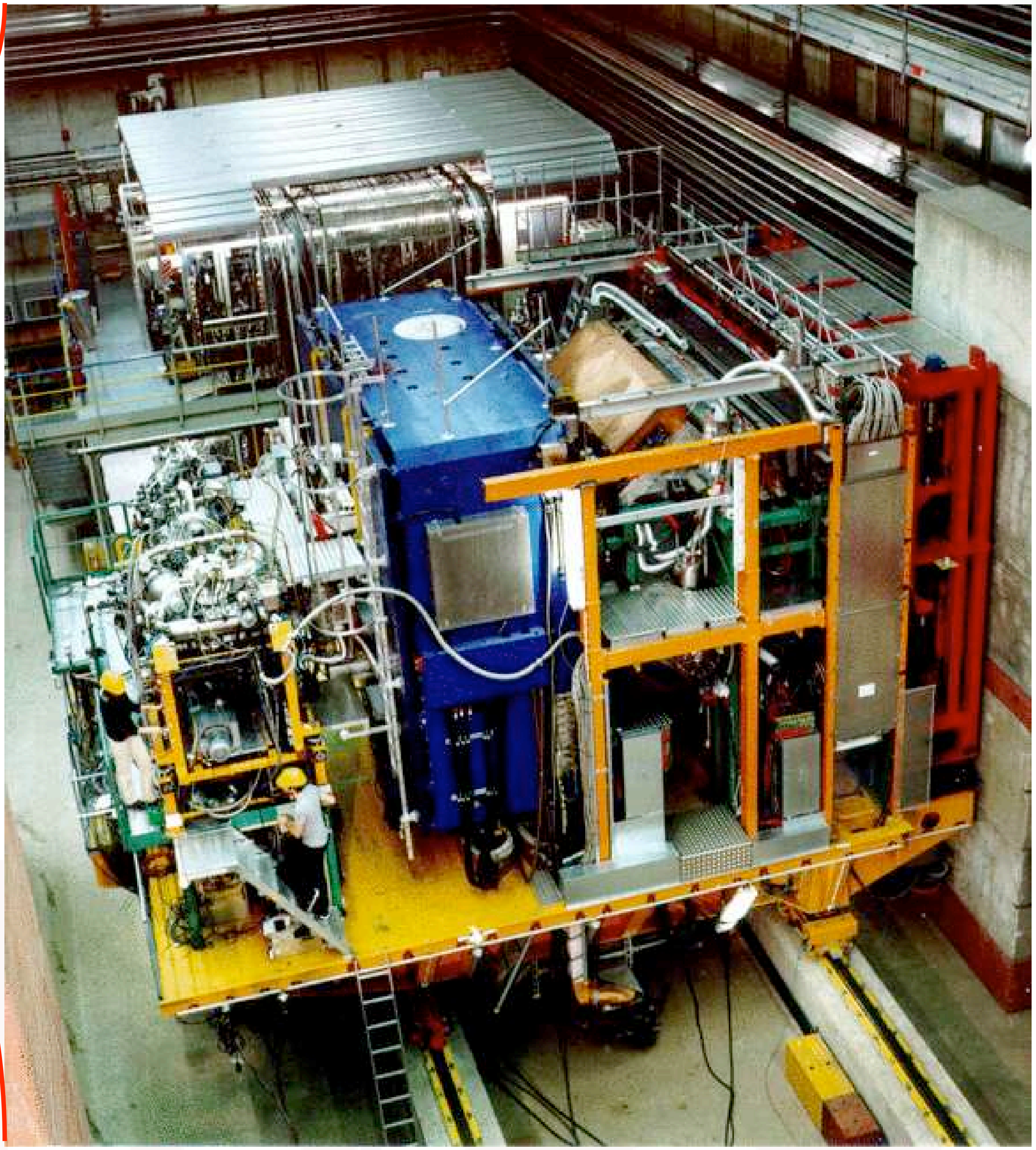
HERMES experiment @ DESY

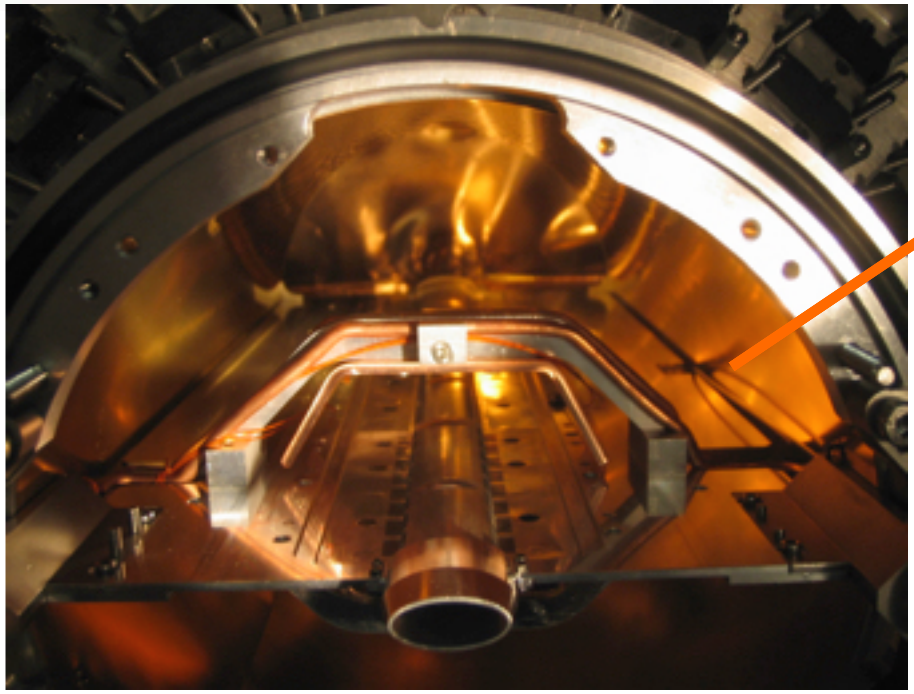
- 27.6 GeV HERA e^+/e^- beam

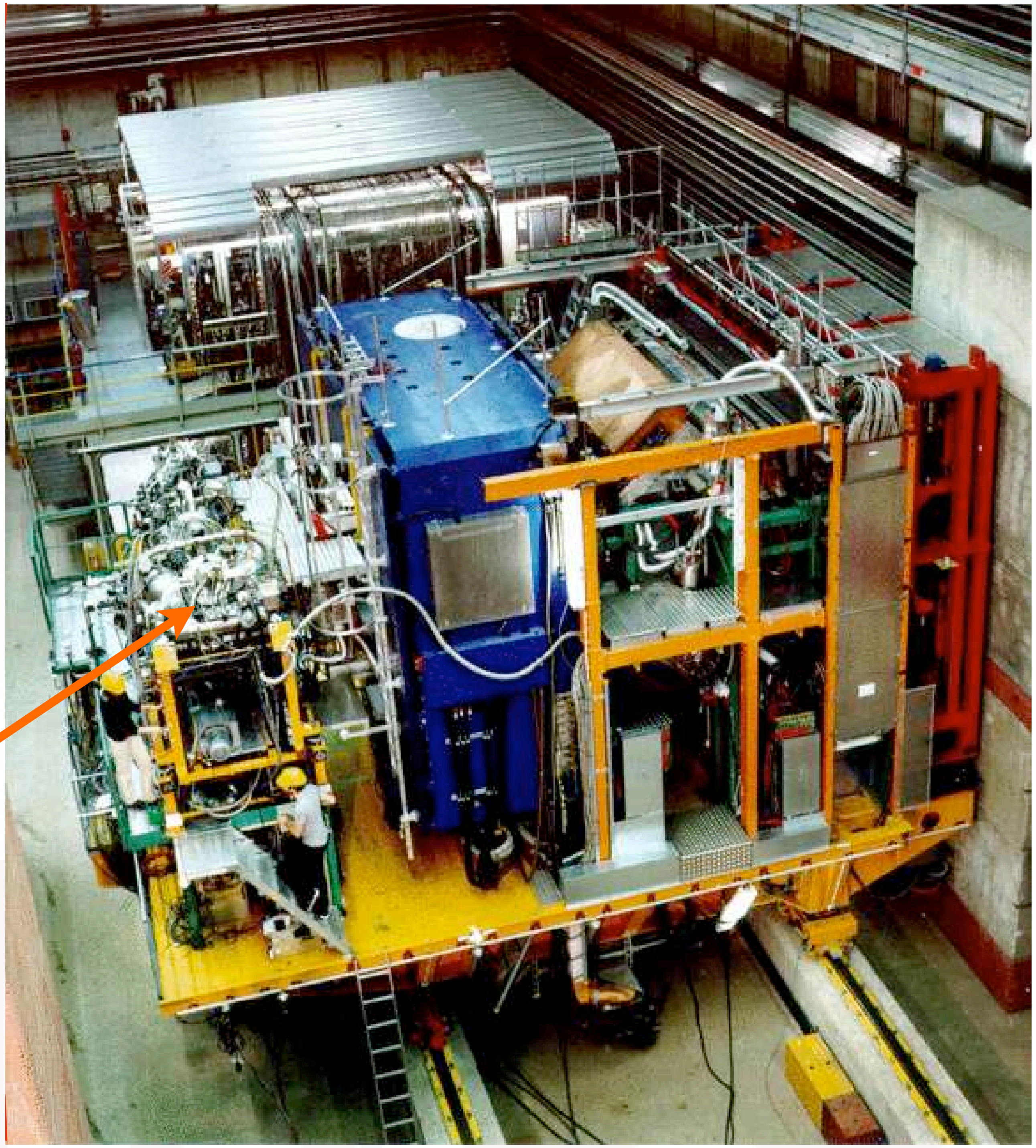


- longitudinally polarized

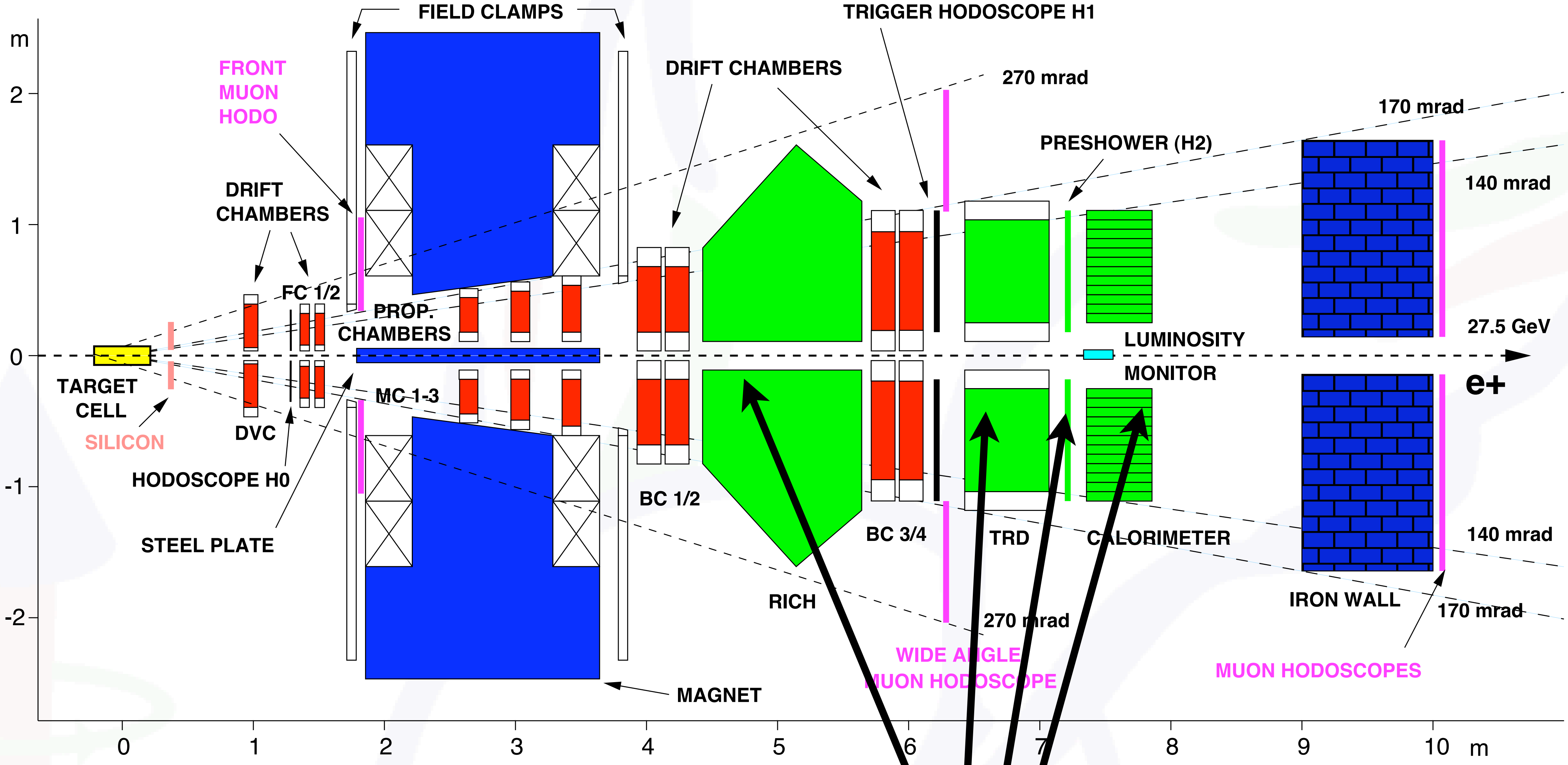
HERMES experiment @ DESY

- 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

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

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

target polarization

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

beam polarization

virtual-photon polarization

[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

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

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

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

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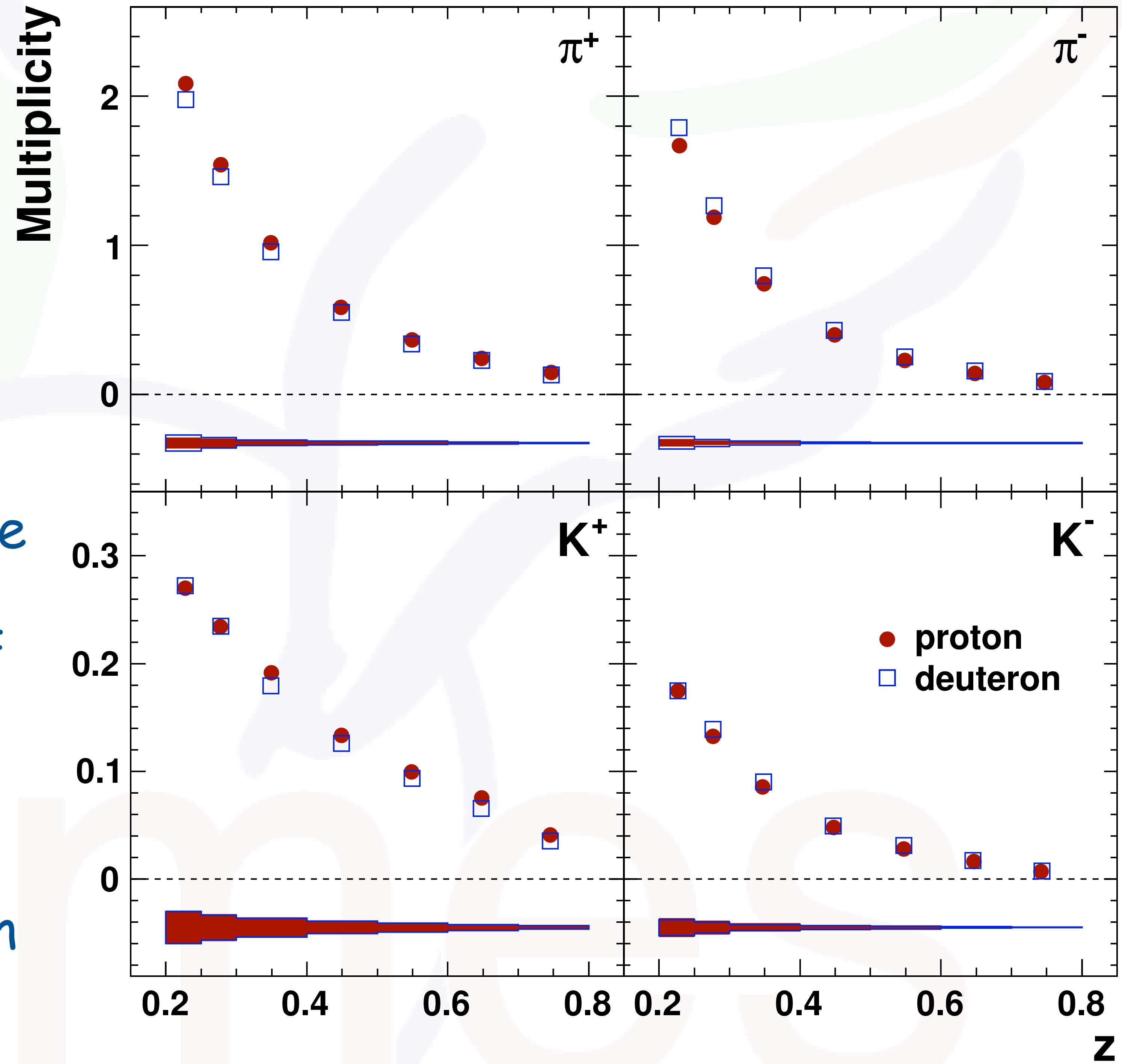
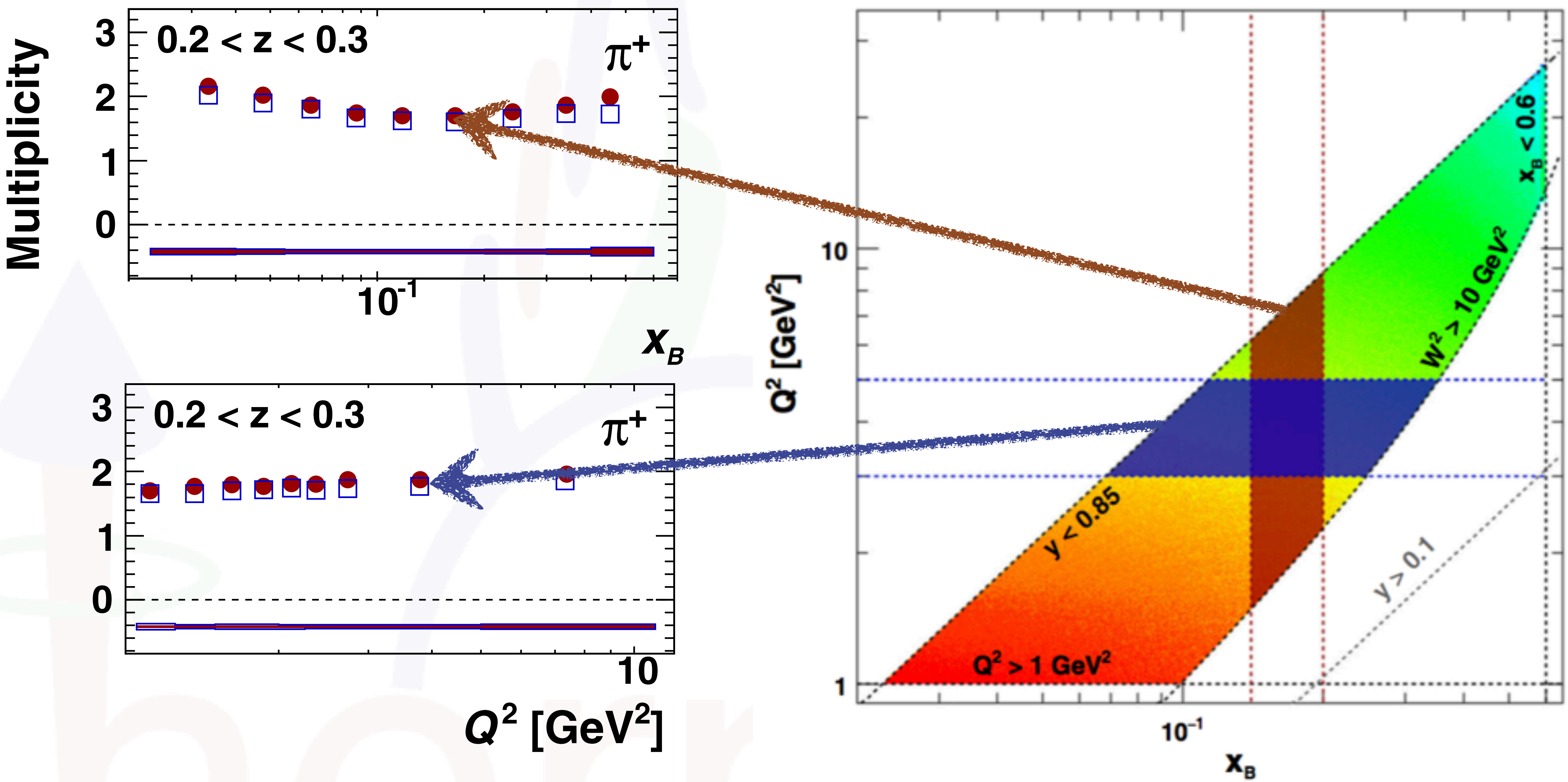
multiplicities @ HERMES

- 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
- access to flavor dependence of fragmentation through different mesons and targets
- input to fragmentation function analyses

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



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



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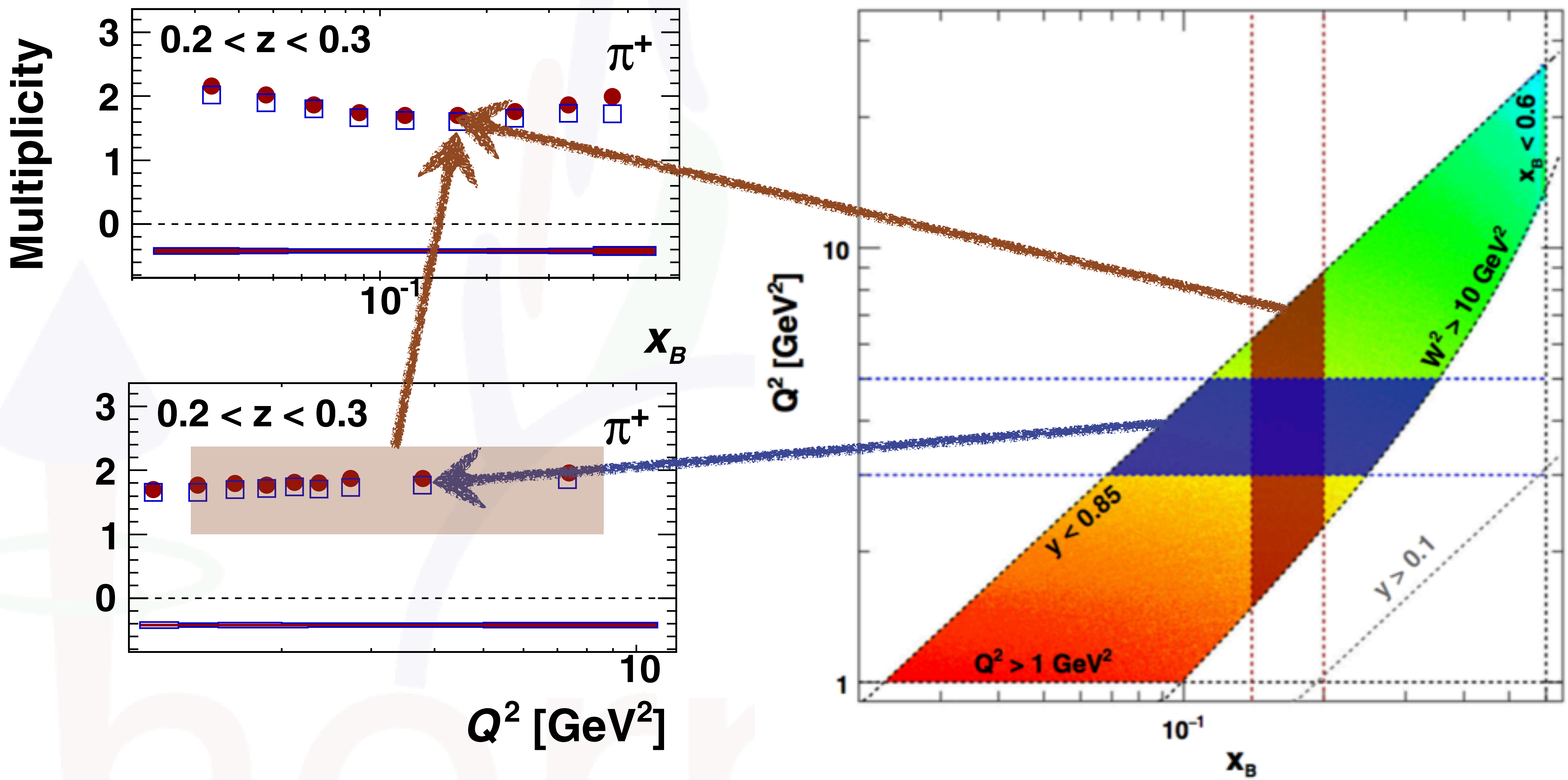

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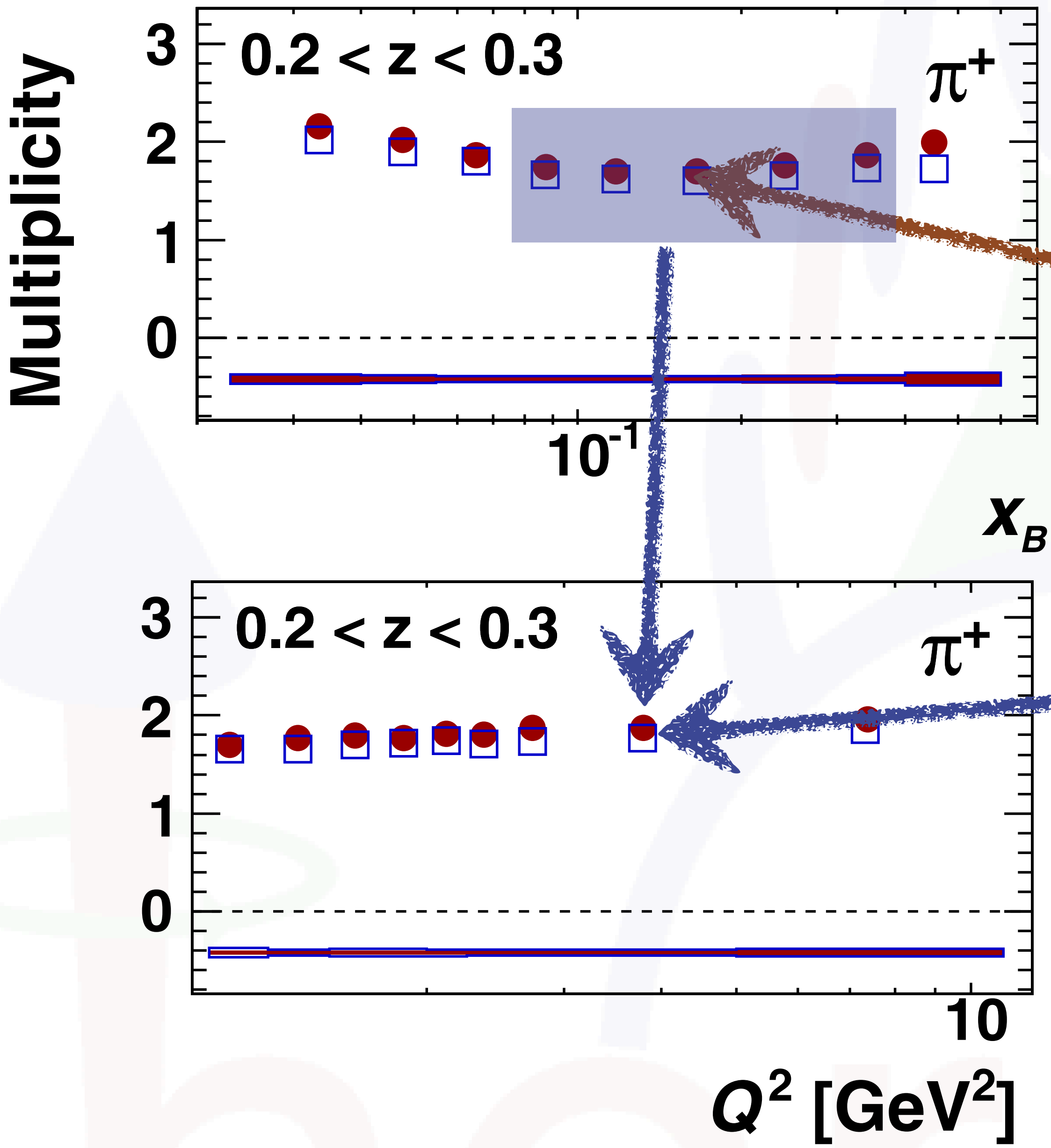

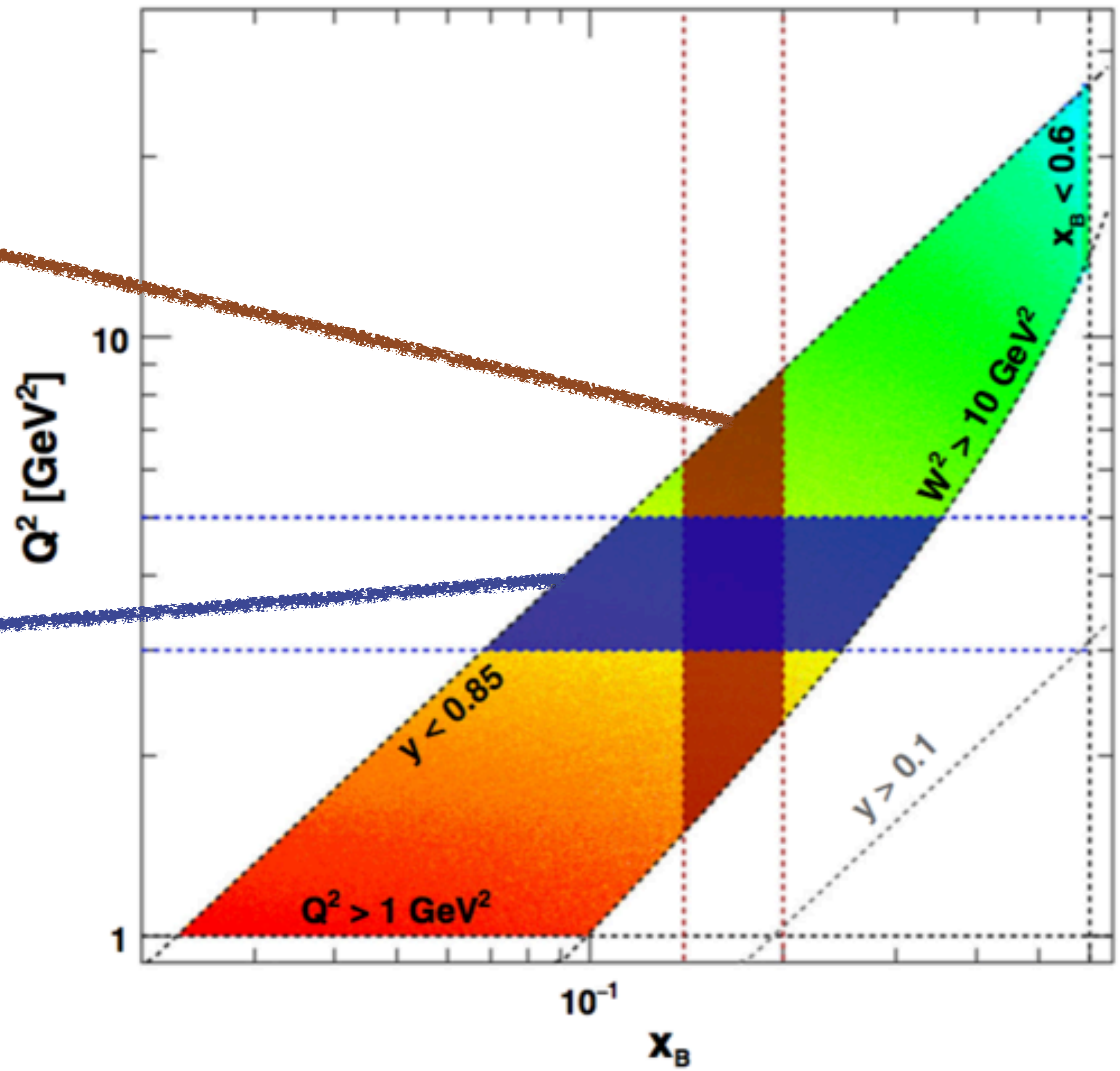

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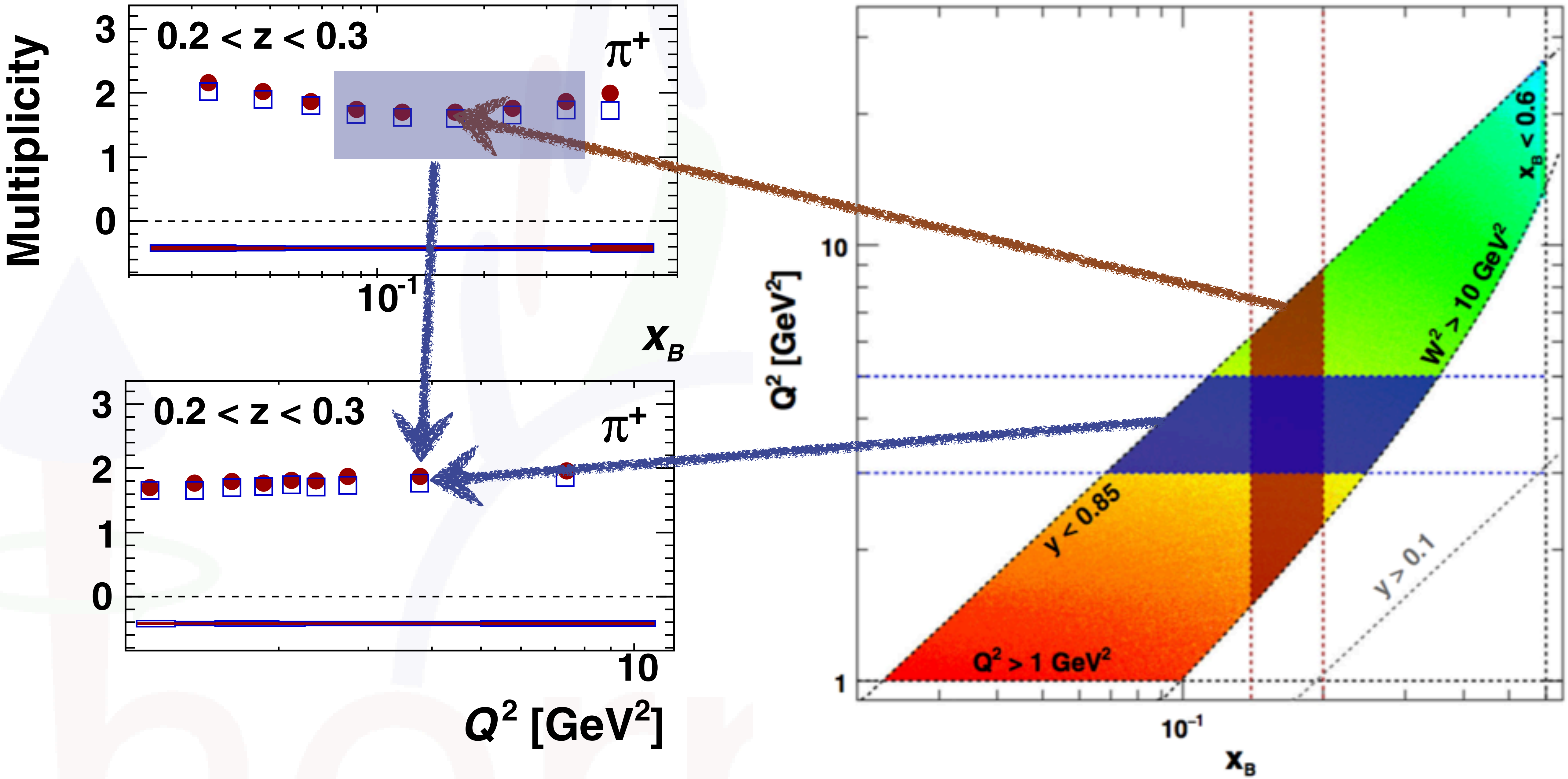
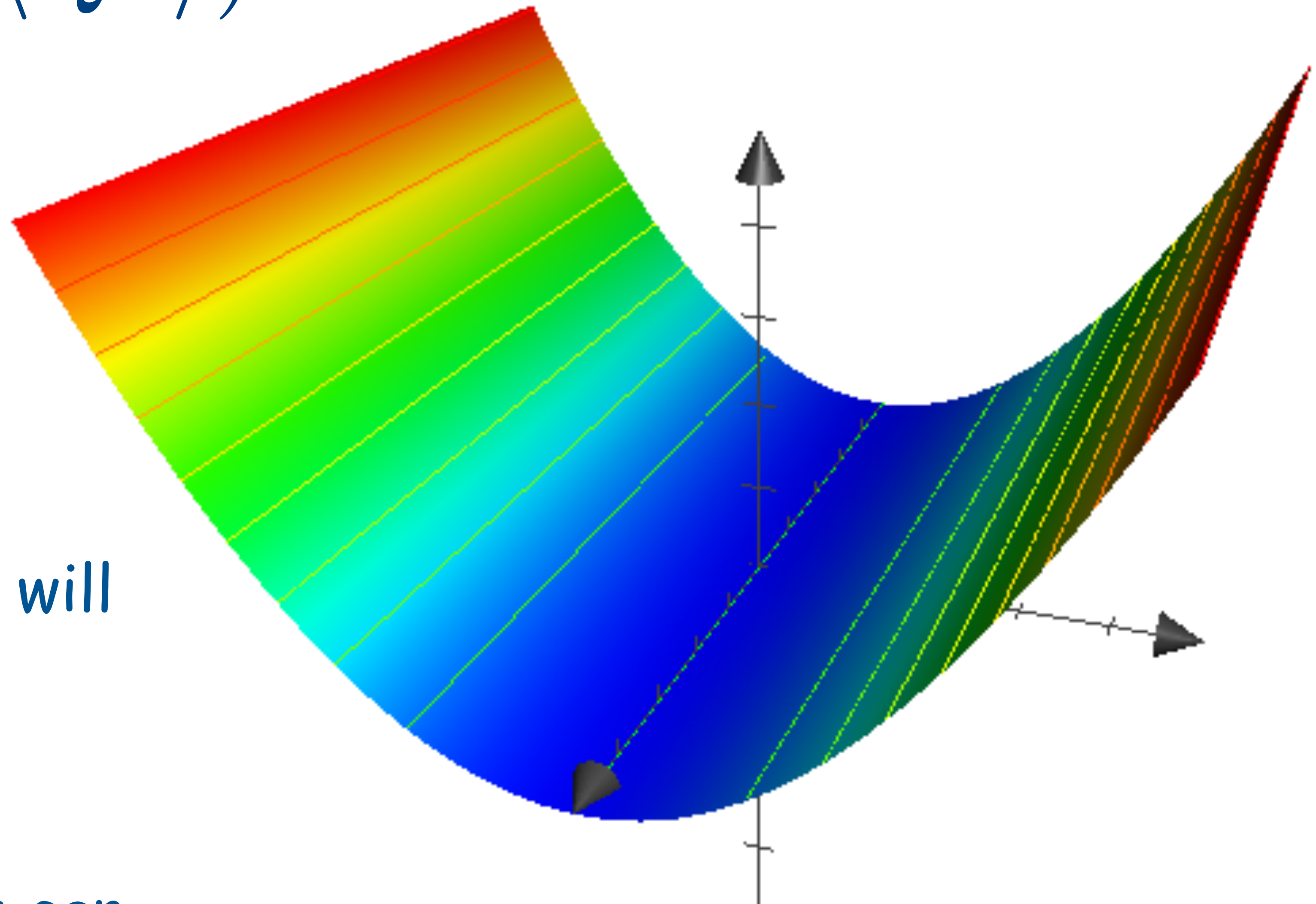


- even though having similar average kinematics, multiplicities in the two projections are different

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



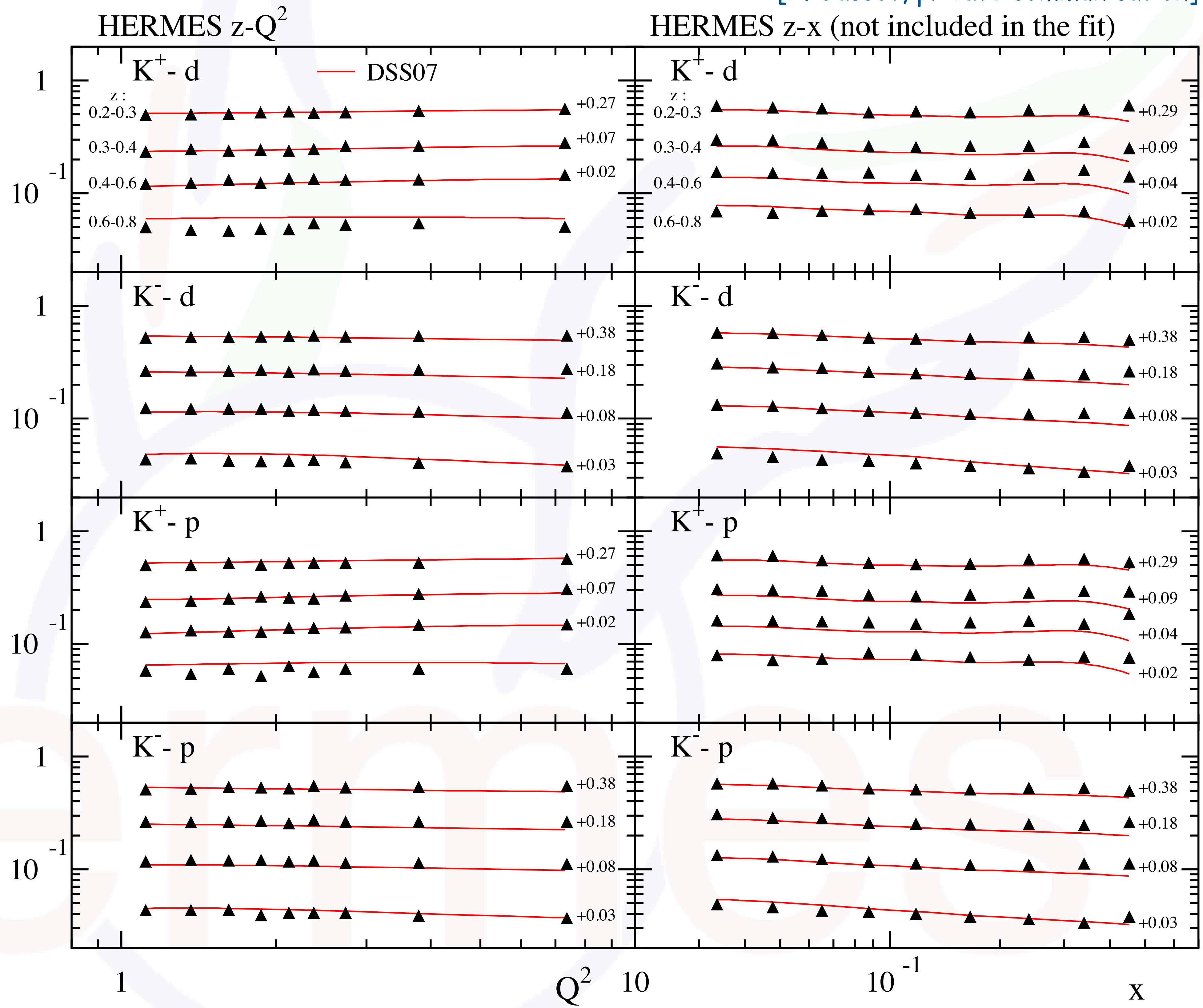
- the average along the valley will be smaller than the average along the gradient
- still the **average kinematics** can be the same

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

[R. Sassot, private communication]

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



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

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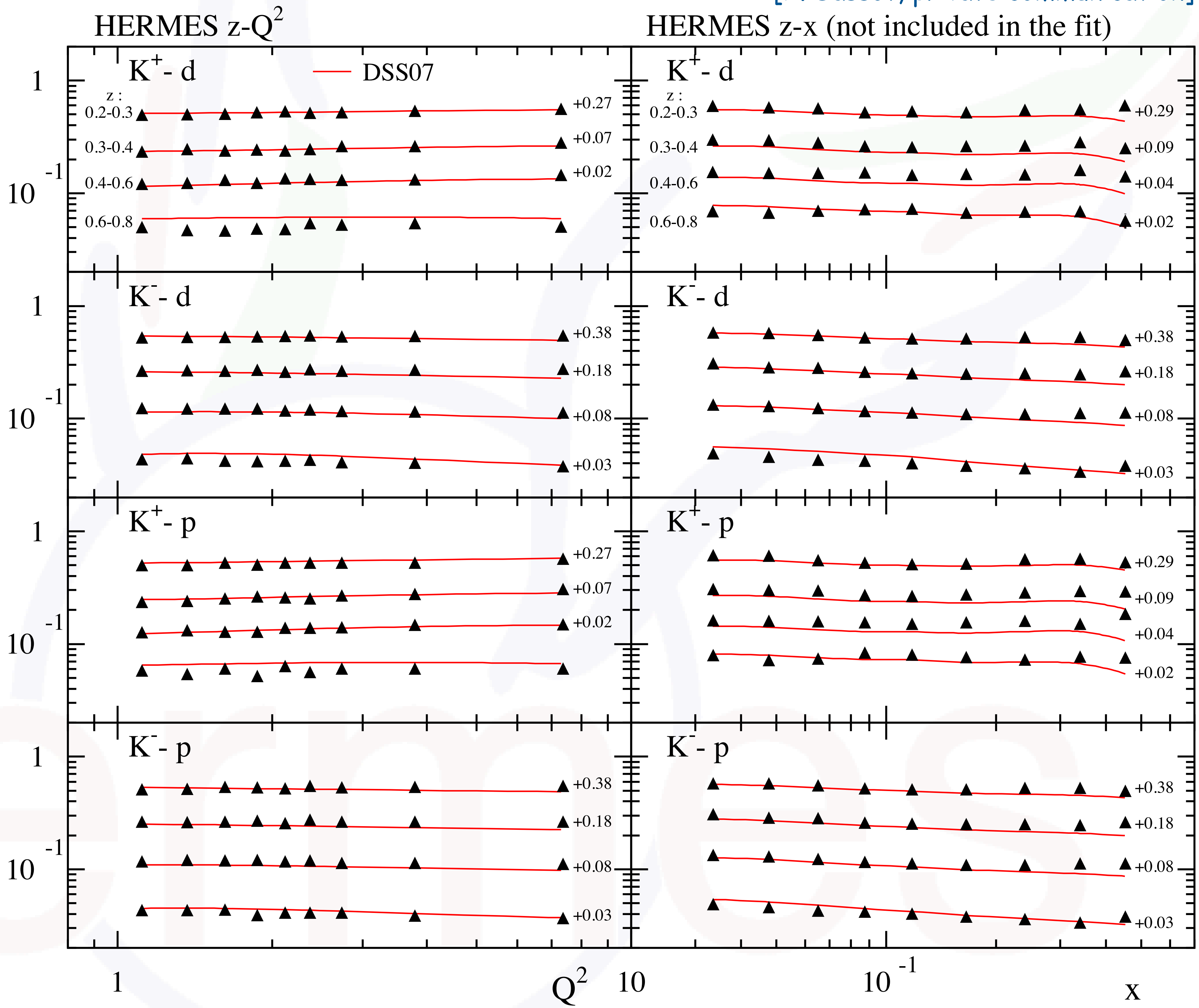

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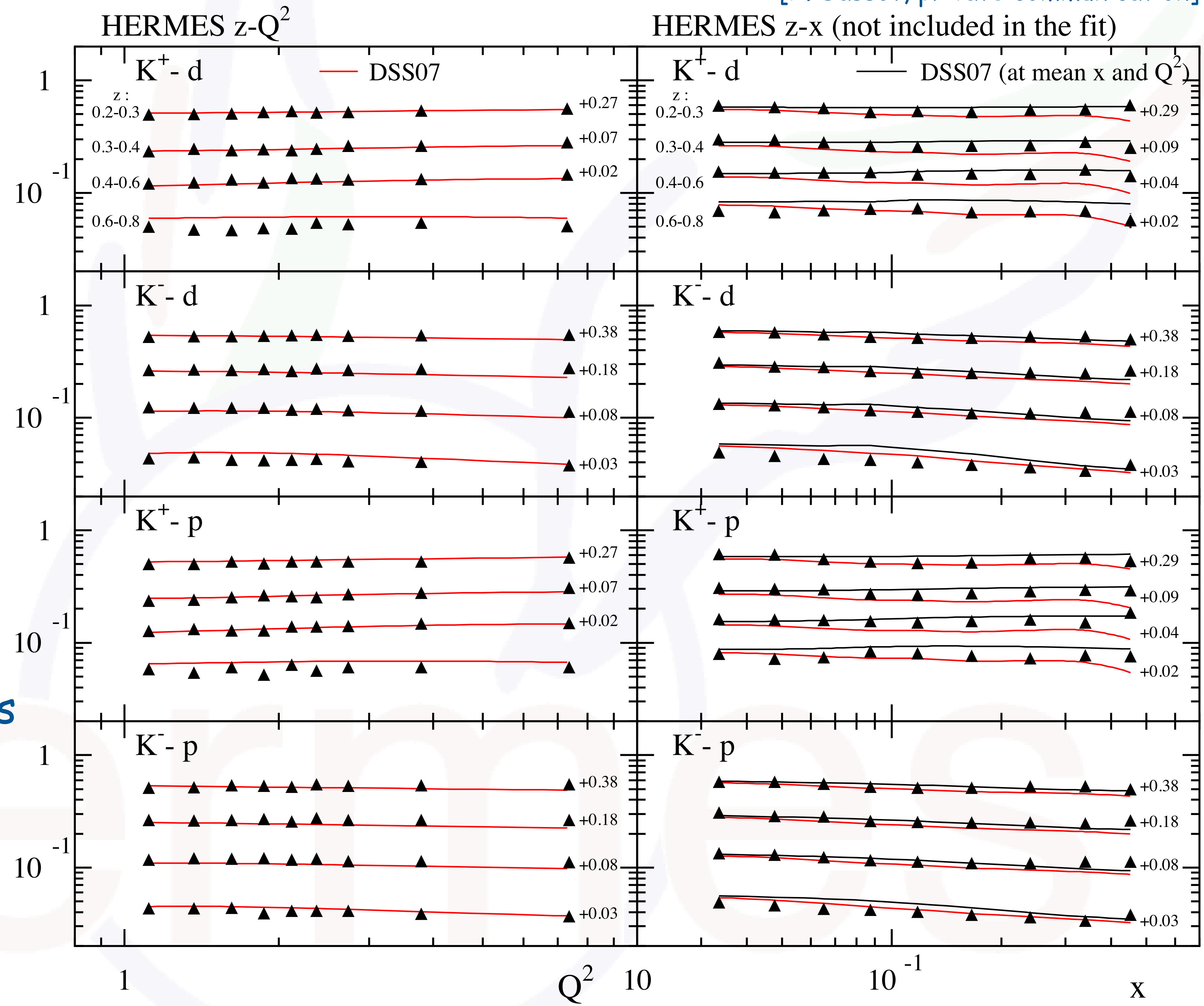

- (by now old) **DSS07** FF fit to z-Q^2 projection
- z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)
- significant changes when using **average kinematics**

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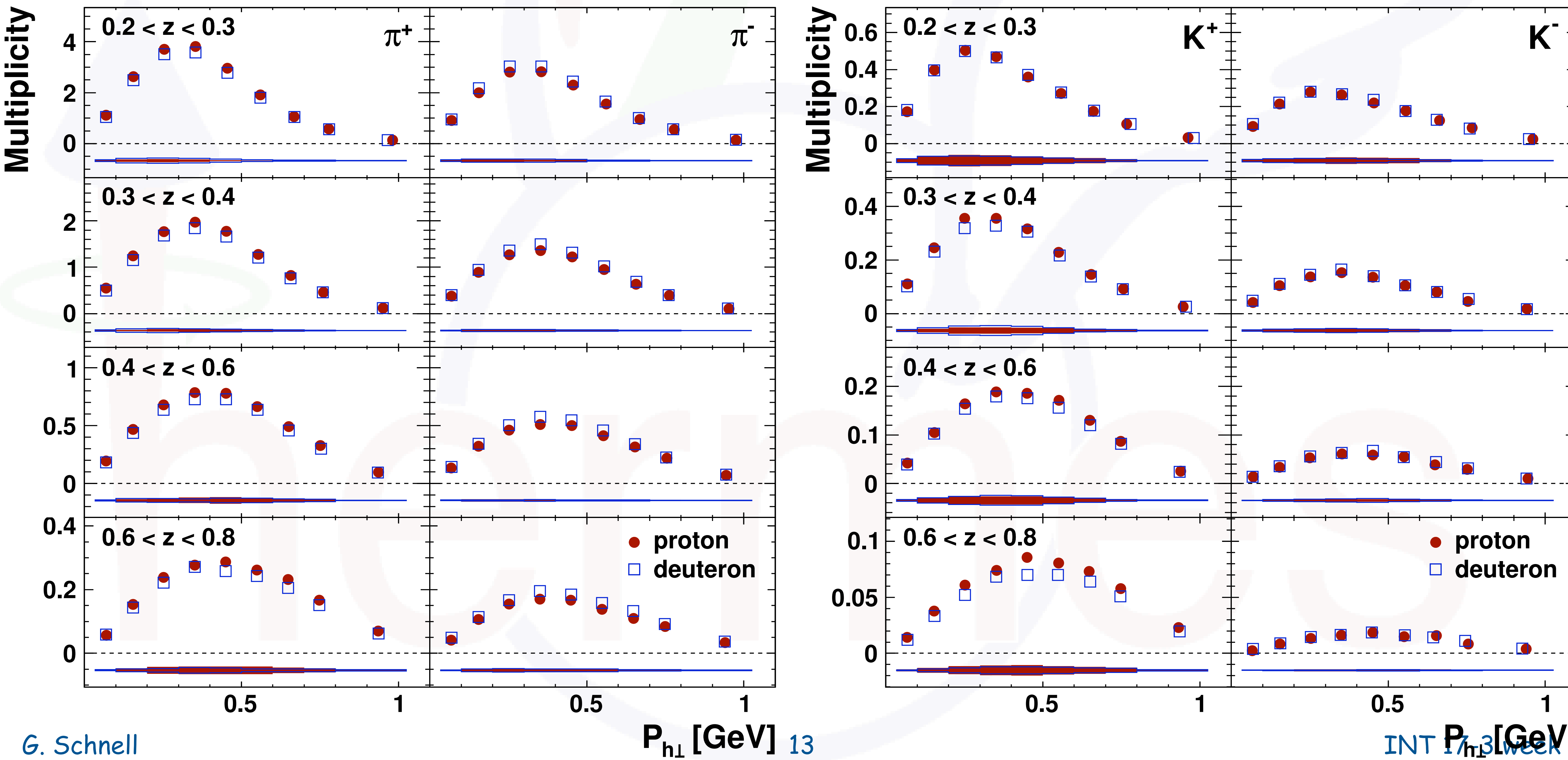
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

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]



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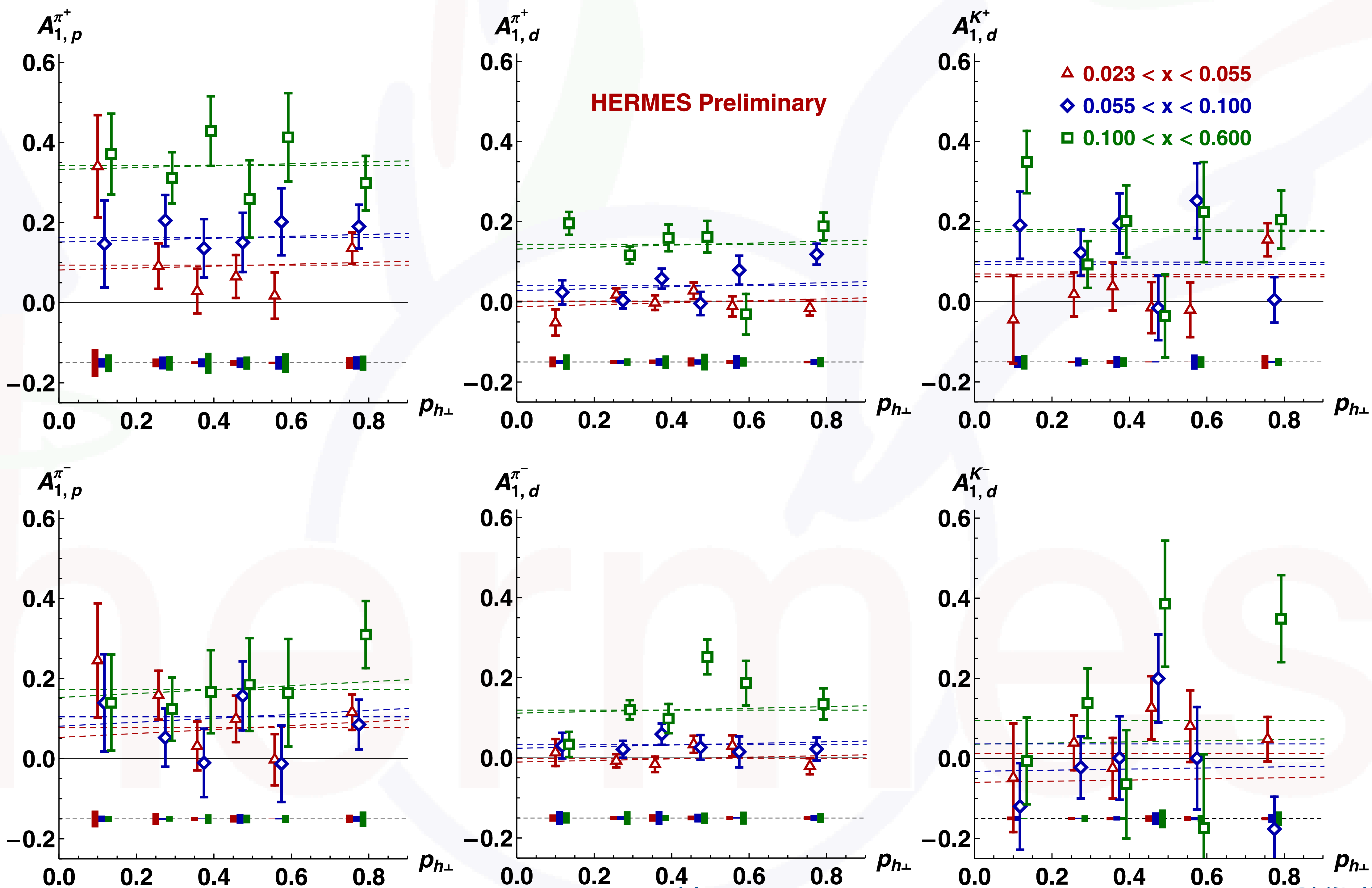
helicity distribution

- extensive data set on collinear extraction of helicity PDF published in PRD 71 (2005) 012003
- here: (not so significant) transverse momentum dependence



chiral-odd distributions

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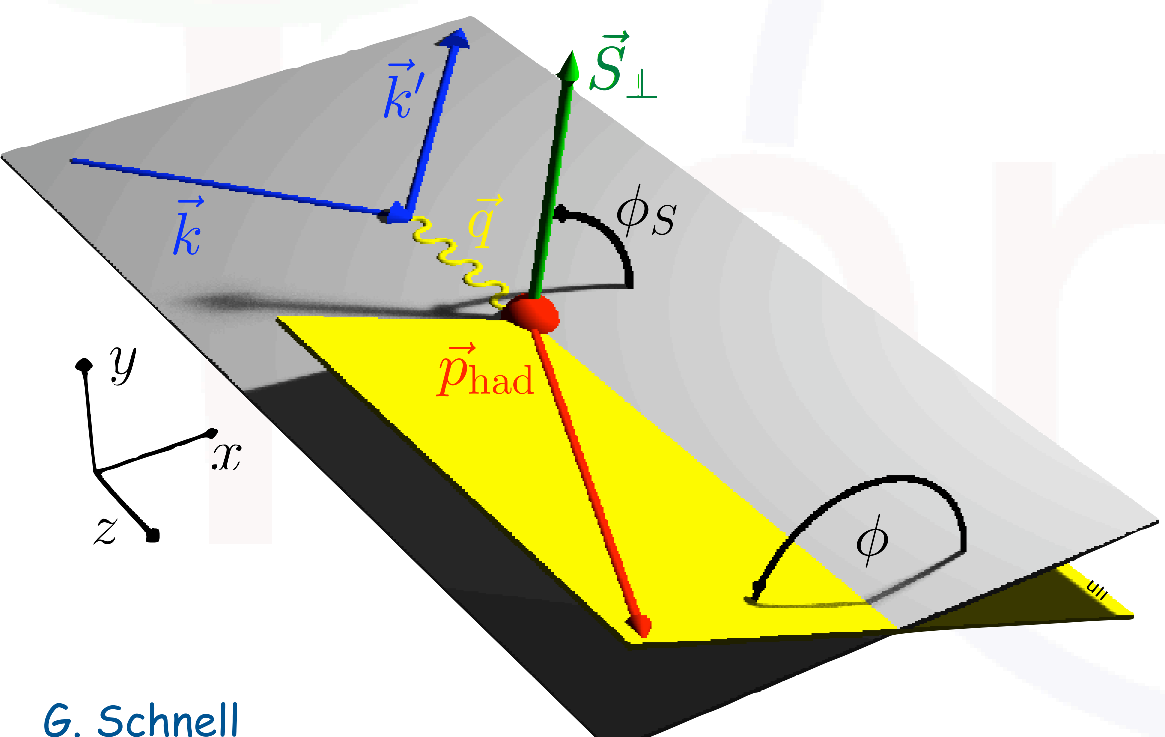
transversely polarized quarks?

- look at characteristic azimuthal dependence of single-hadron lepto-production cross section
  - many of the systematics of polarization-averaged observables cancel in spin asymmety



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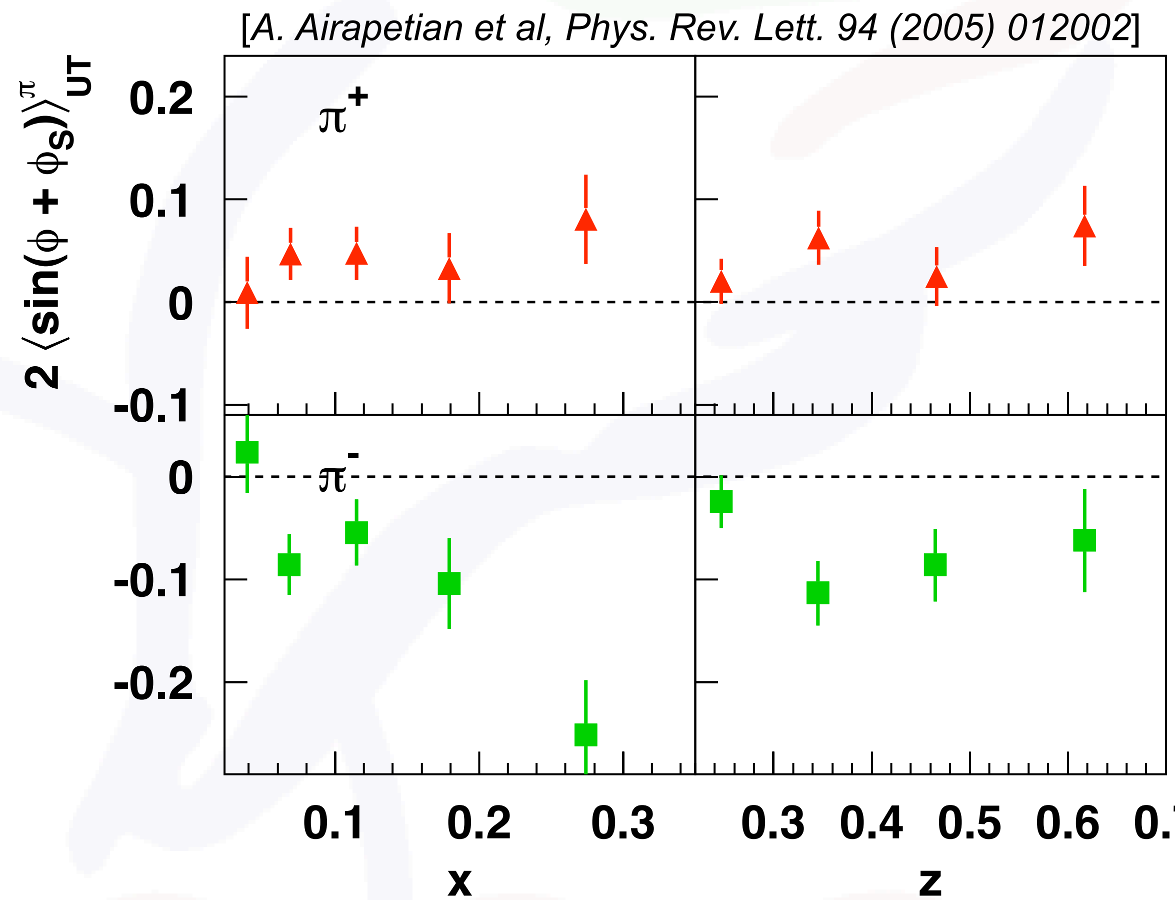
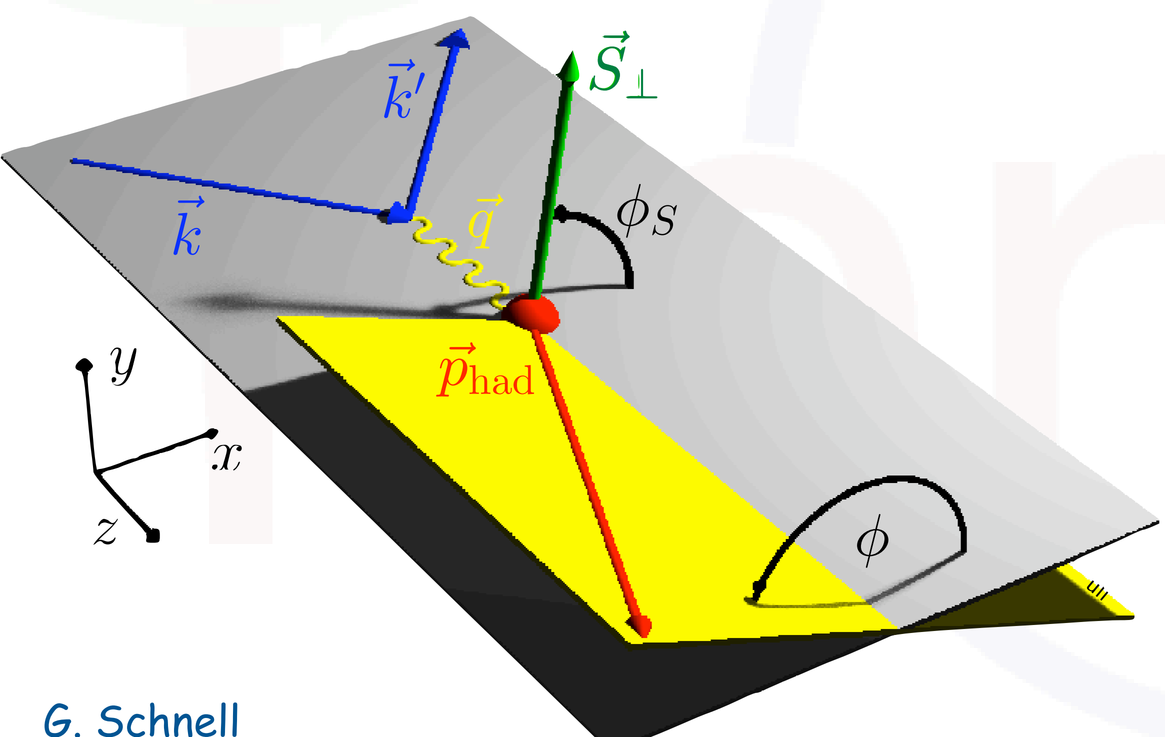
transversely polarized quarks?

- transverse polarization of quarks leads to large effects!
- opposite in sign for charged pions



2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function



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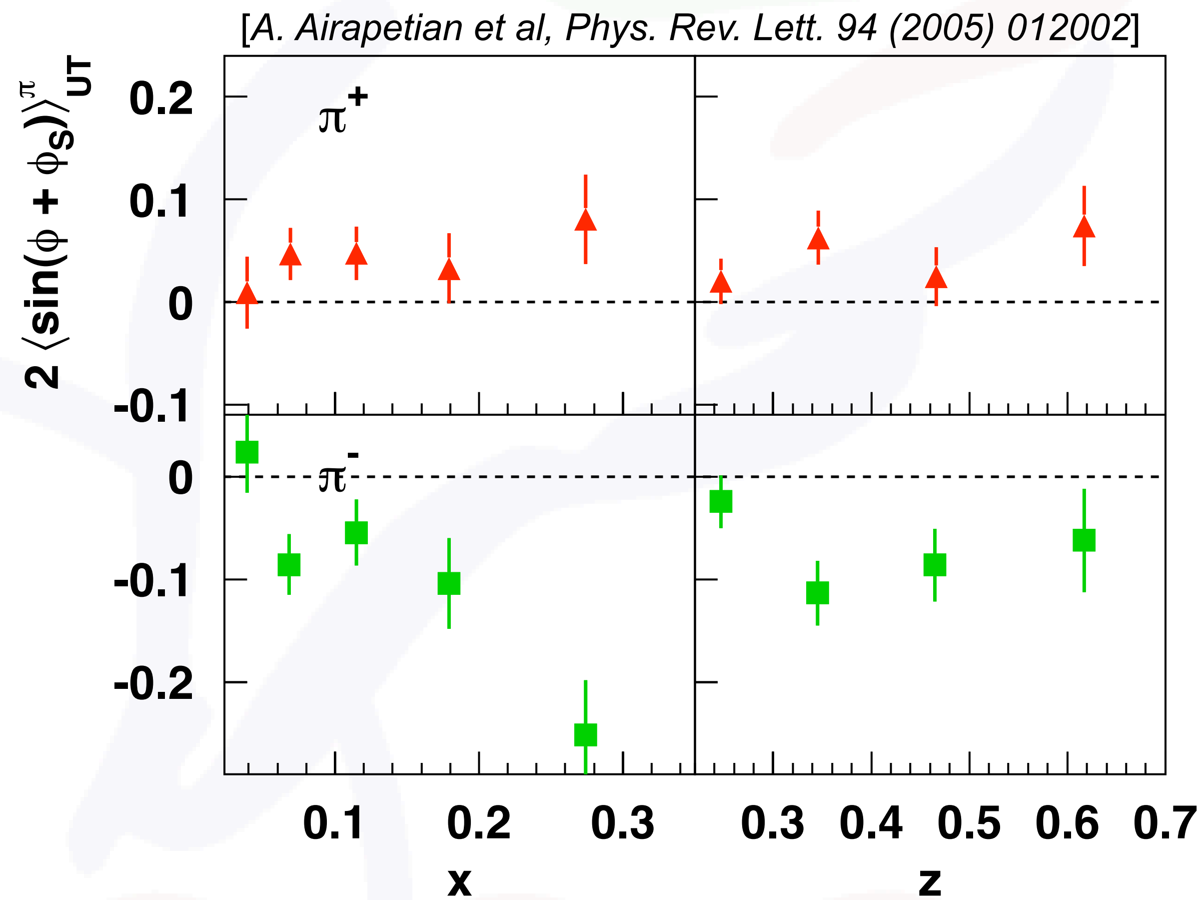

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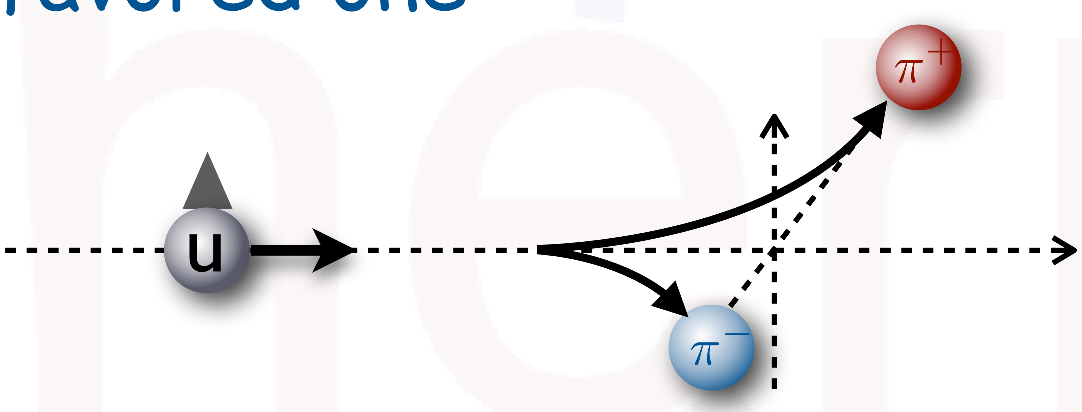

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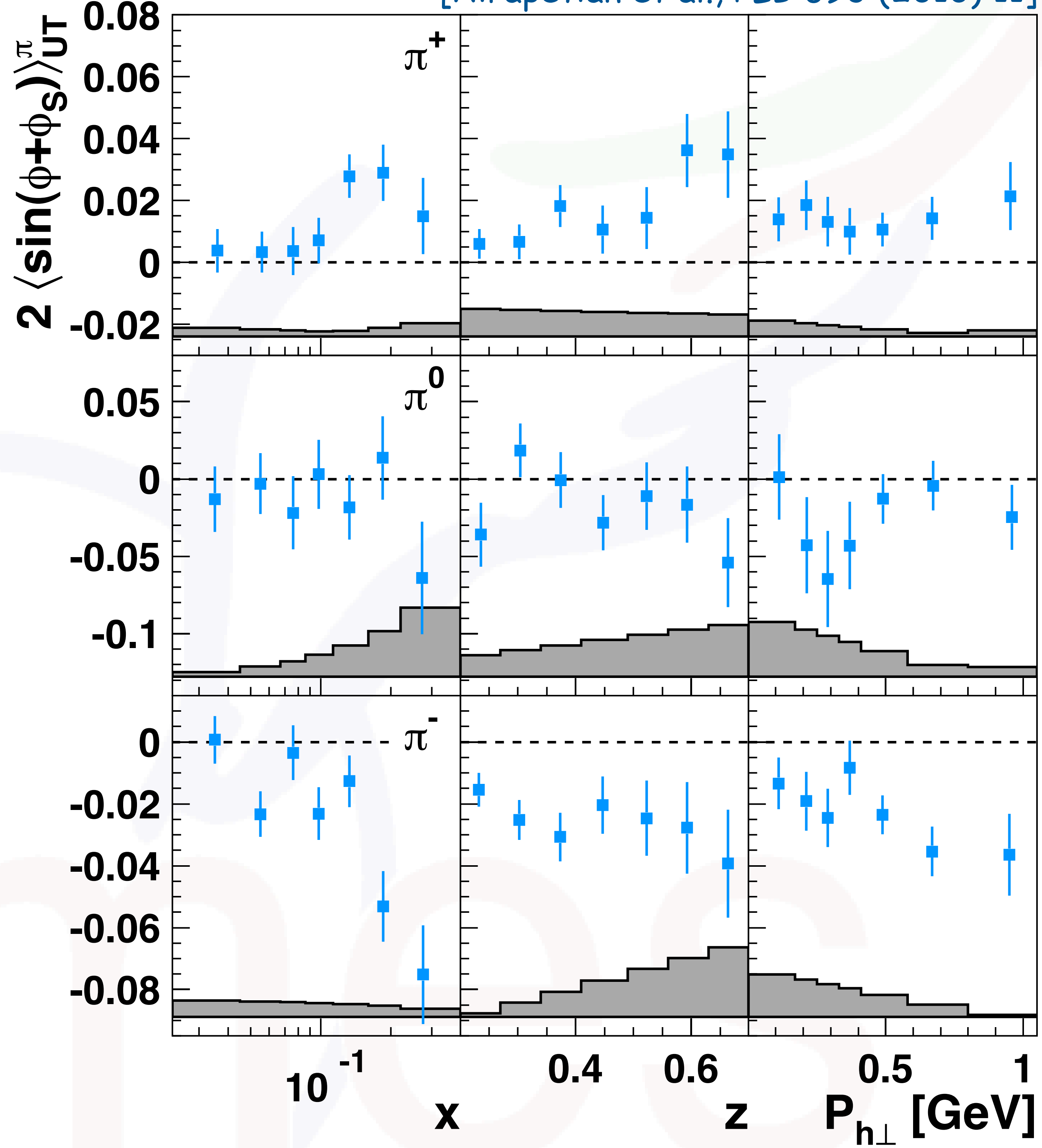
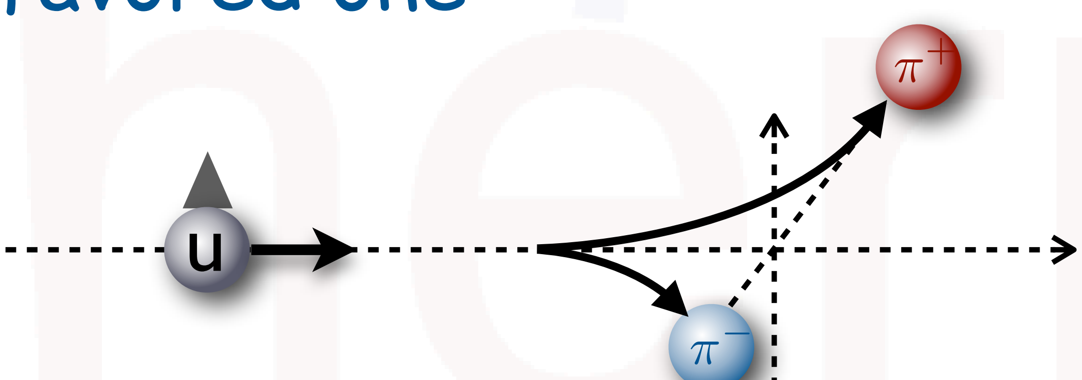
[Airapetian et al., PLB 693 (2010) 11]





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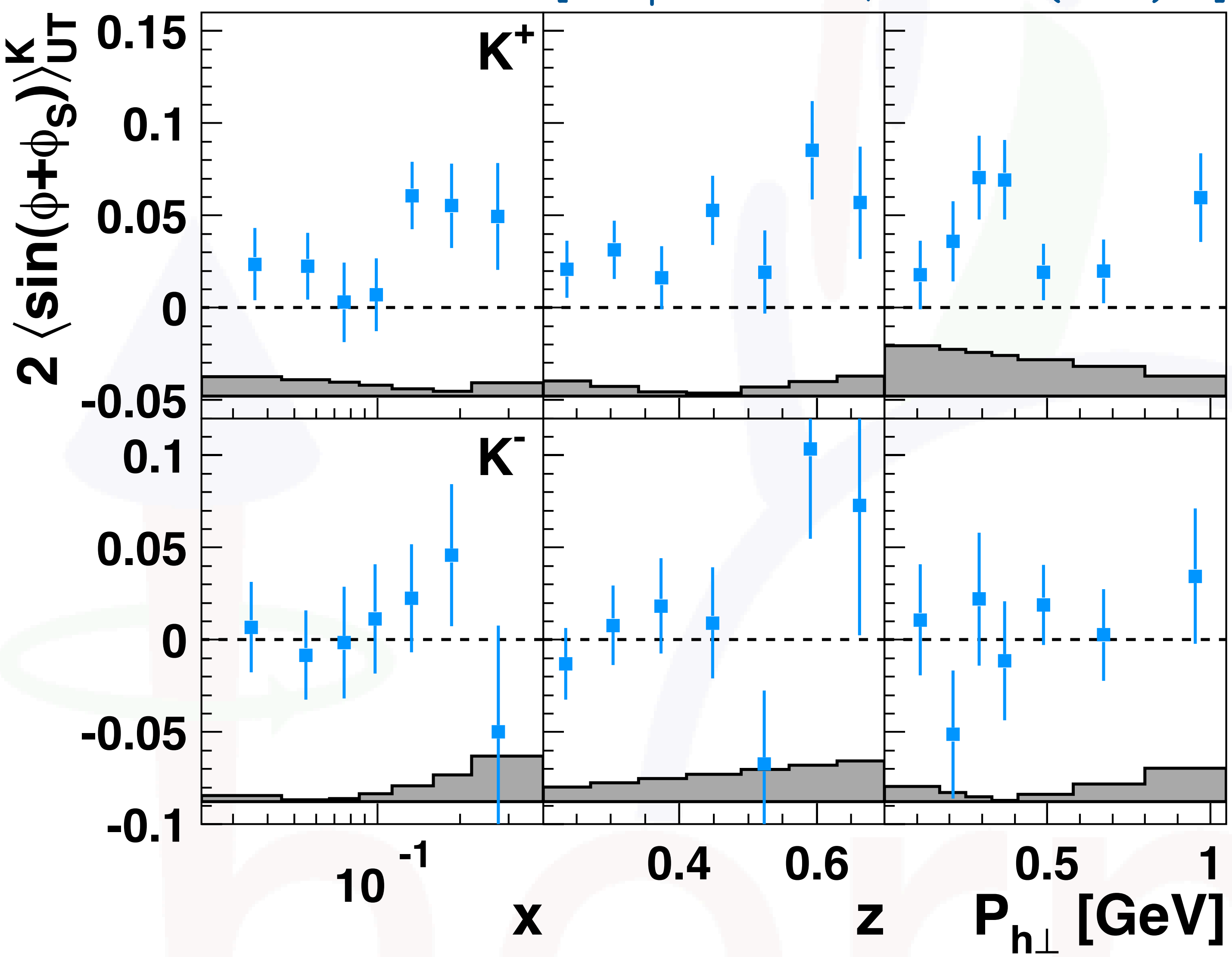
Collins effect for kaons and (anti) protons

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



- positive Collins SSA amplitude for positive kaons

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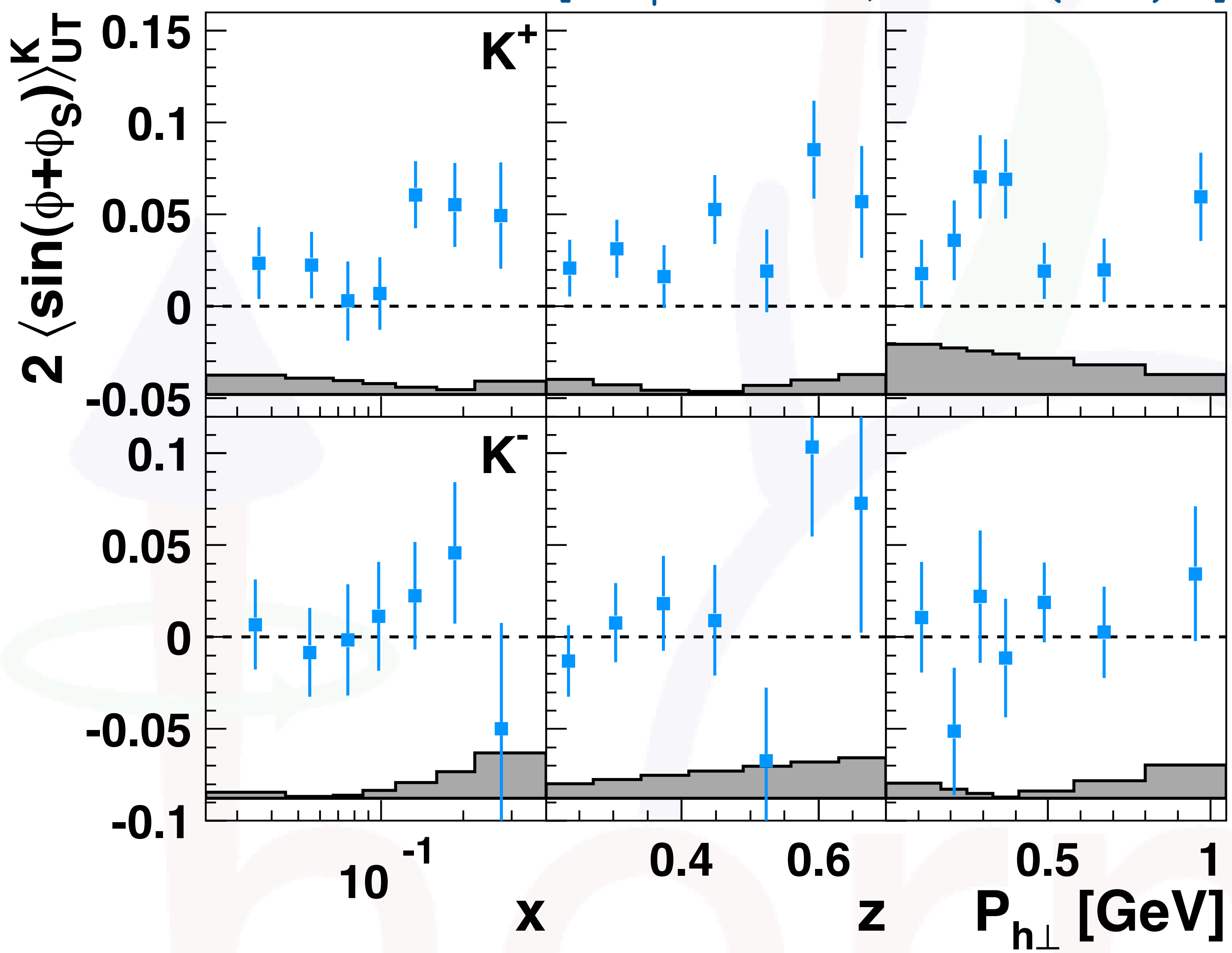
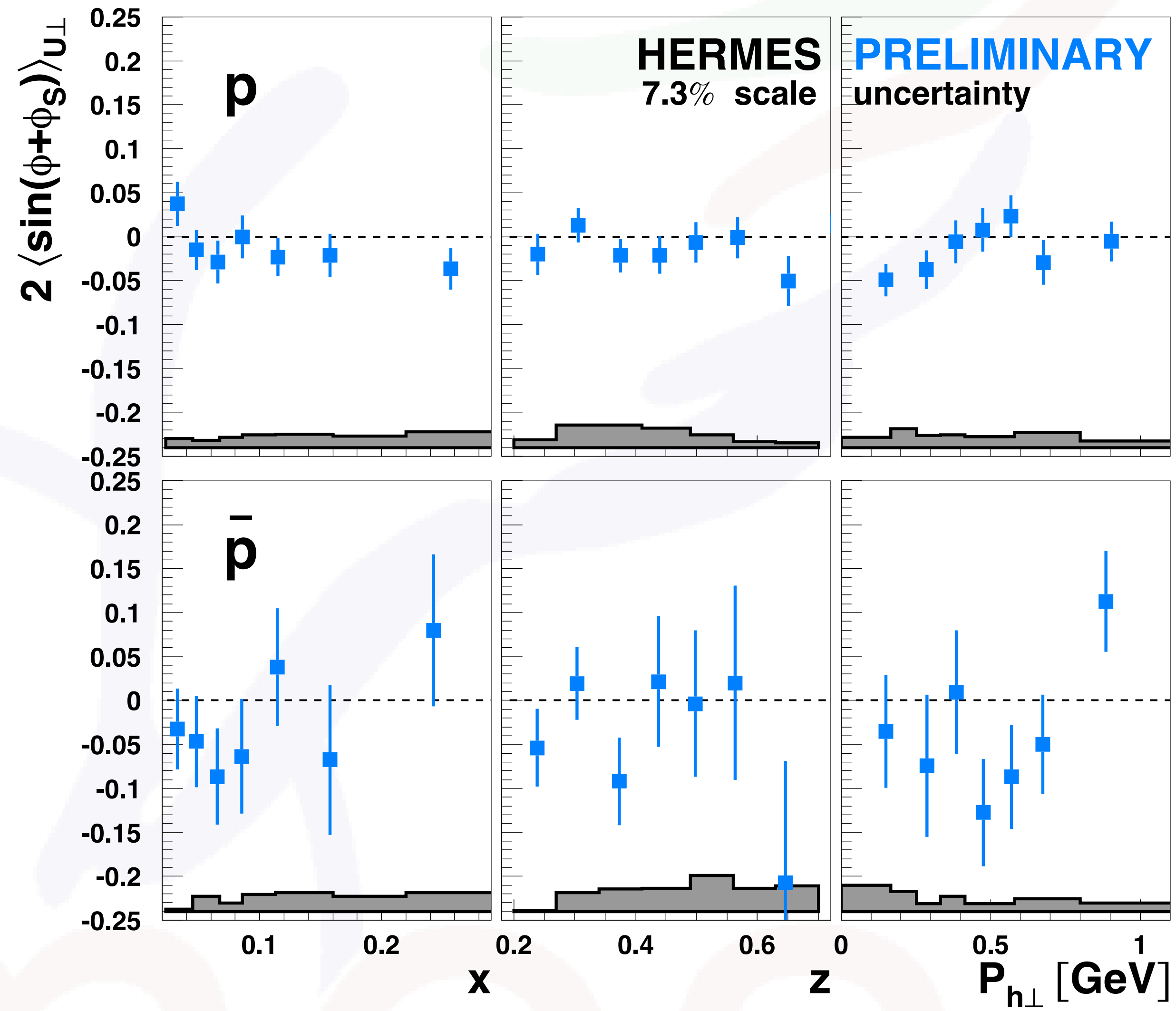
[Airapetian et al., PLB 693 (2010) 11]



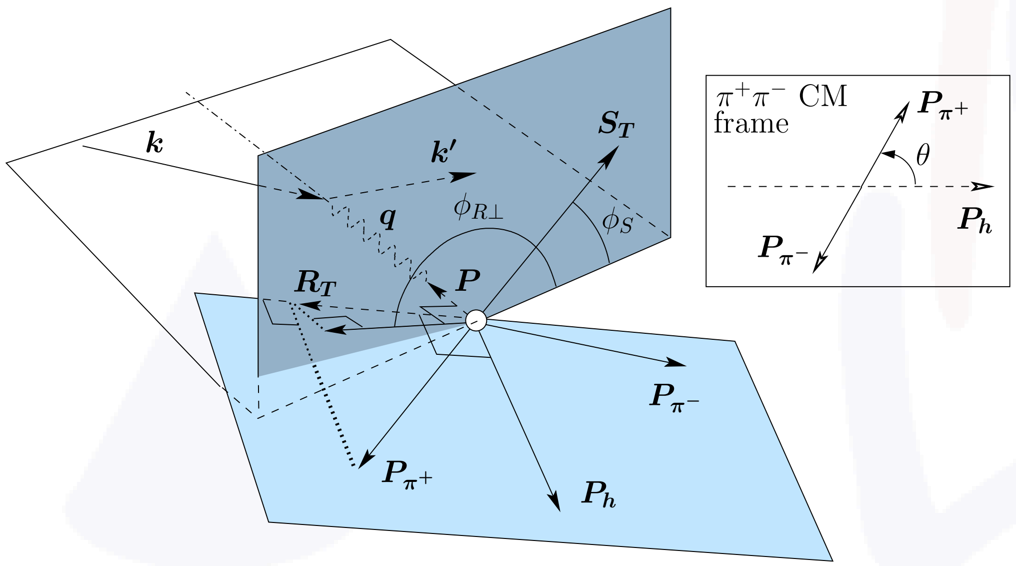


- positive Collins SSA amplitude for positive kaons
- consistent with zero for negative kaons and (anti)protons

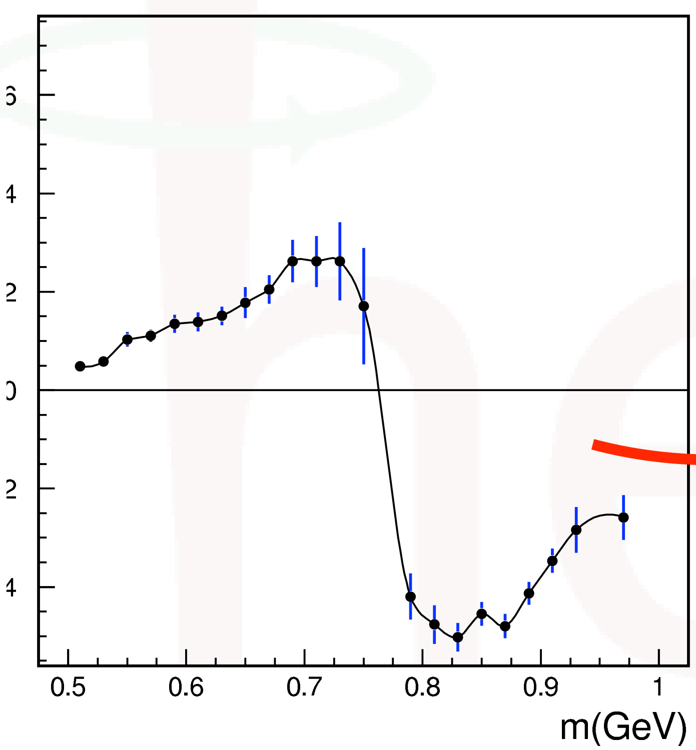
➡vanishing sea-quark transversity and baryon Collins effect?

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

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

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

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

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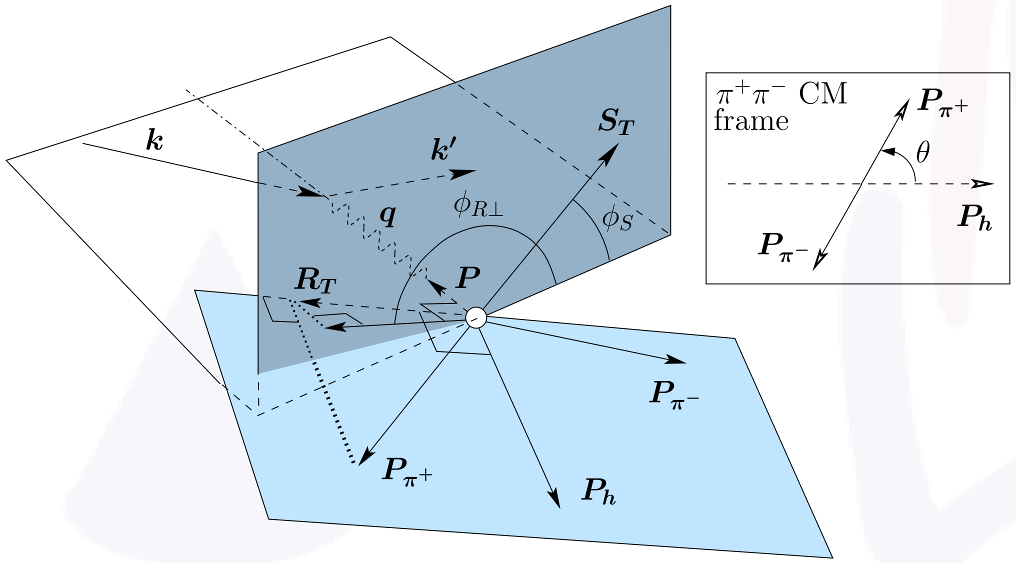


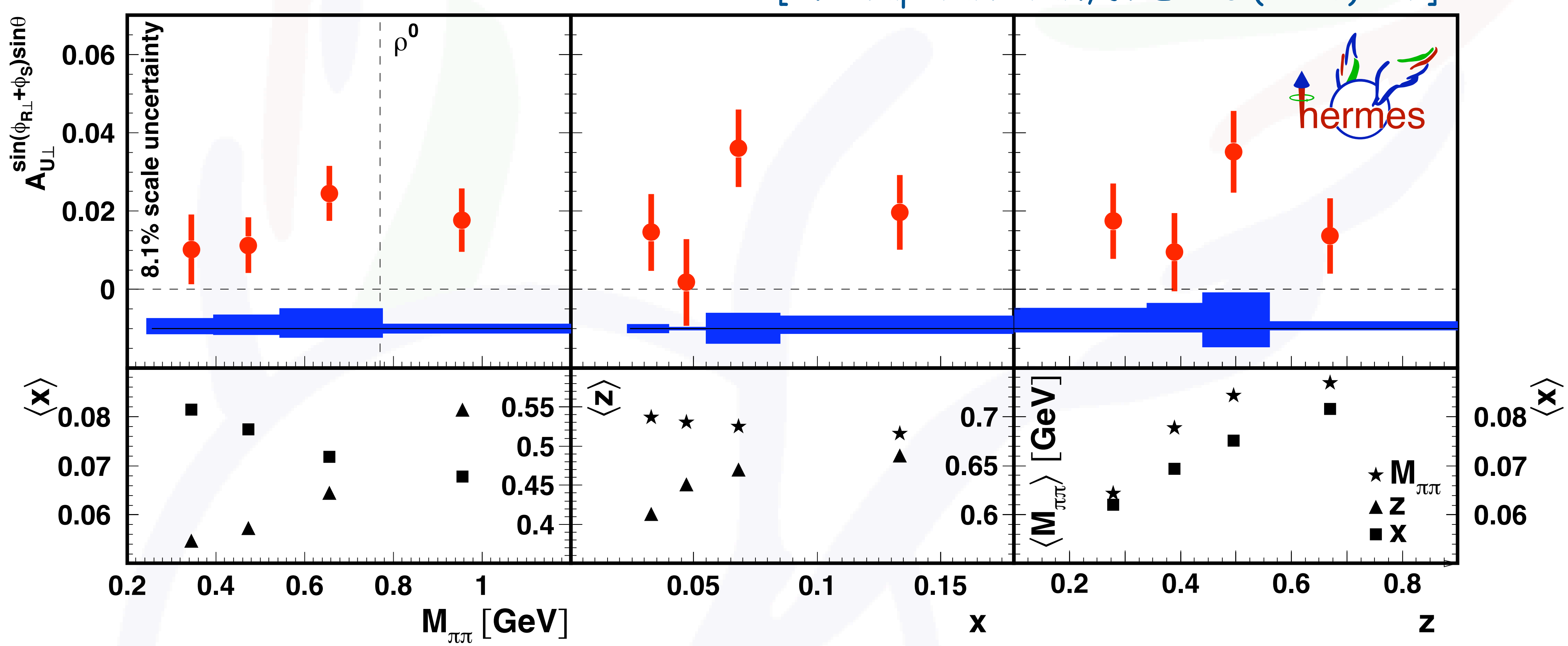
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

- 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)

	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. 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.)>

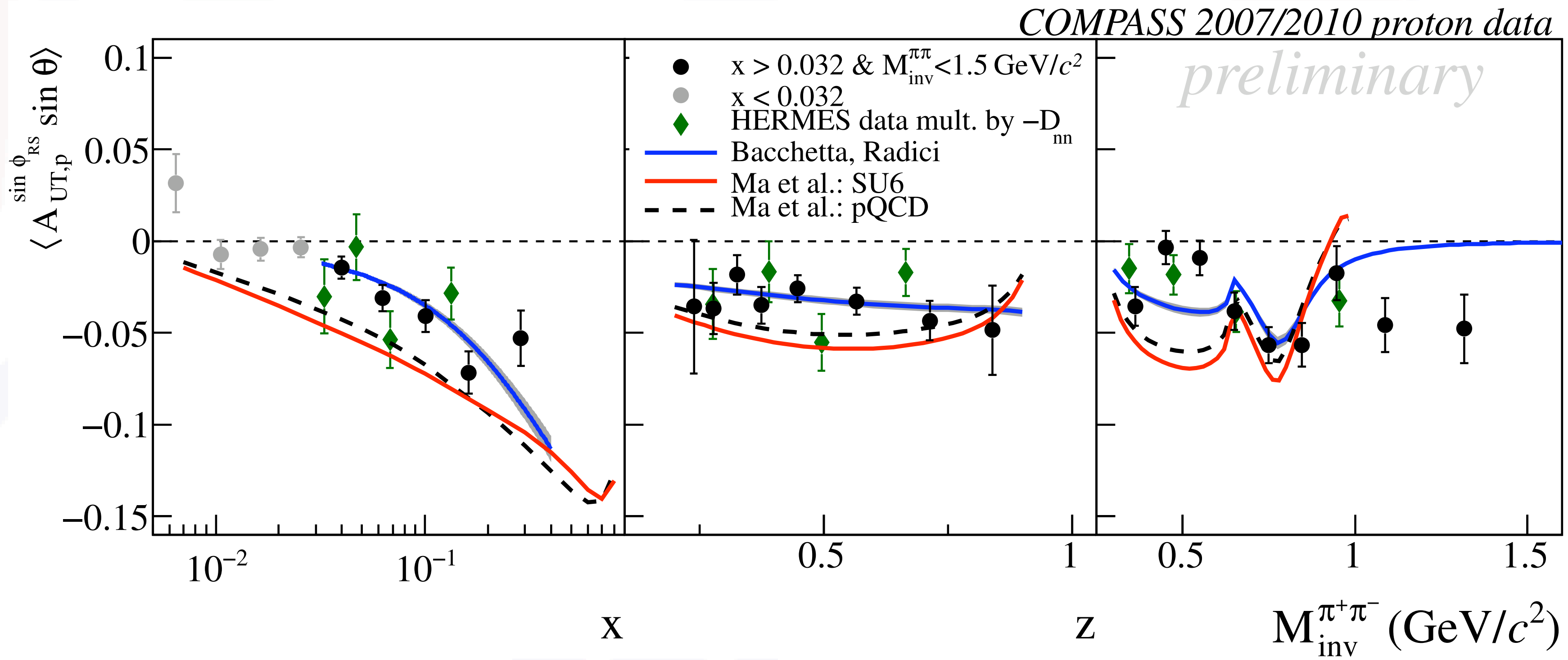
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity through 2-hadron fragmentation

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

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

- ^{2}H results consistent with zero



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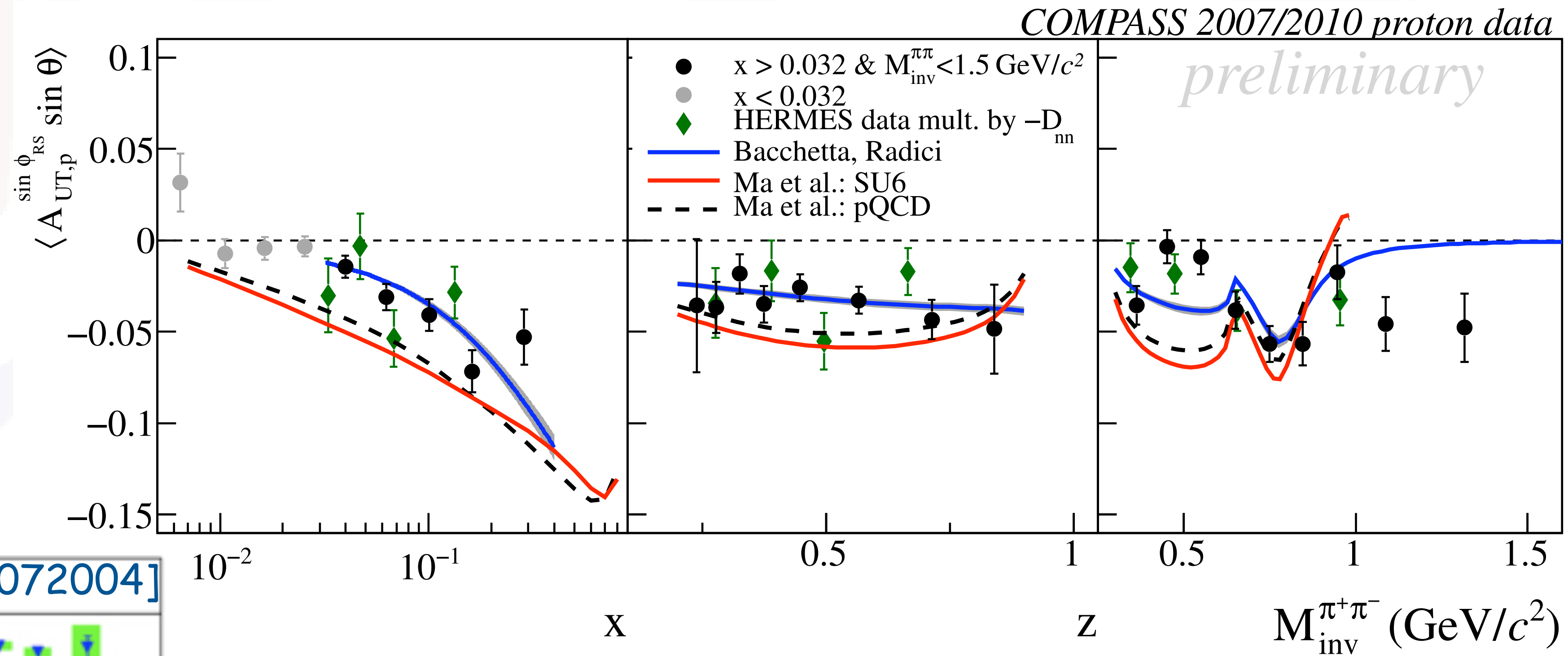
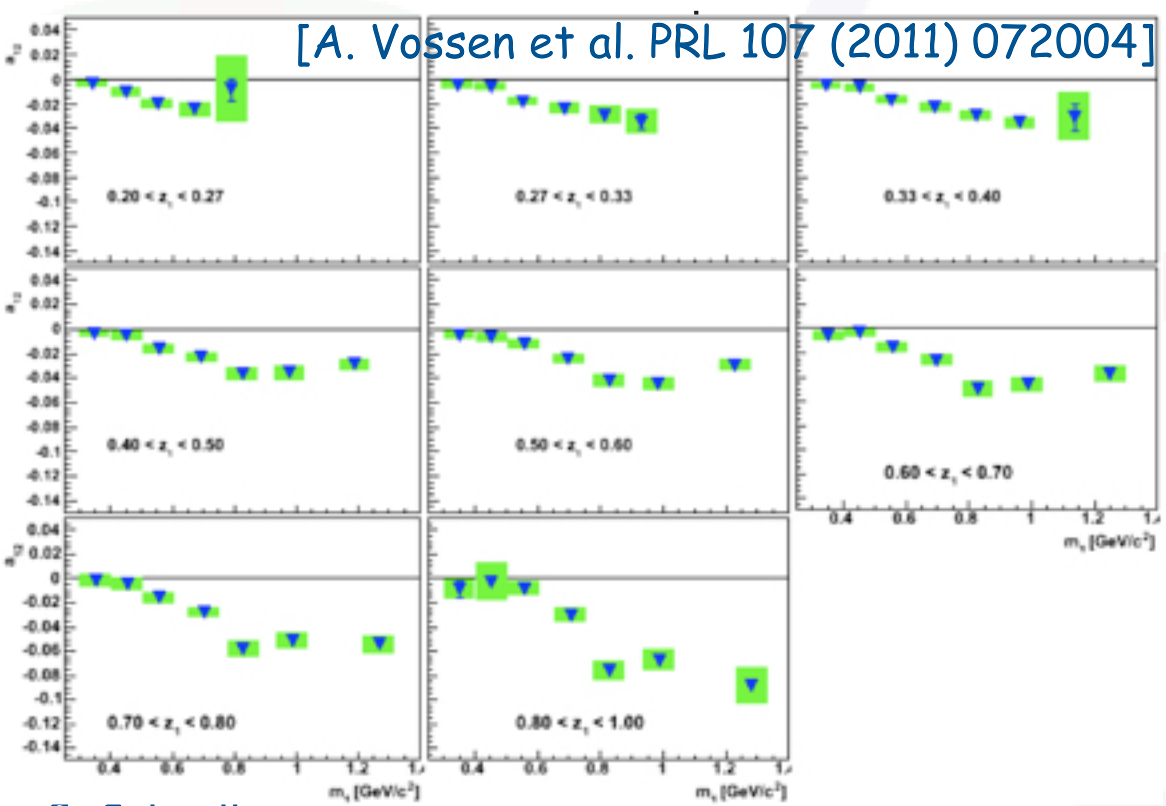
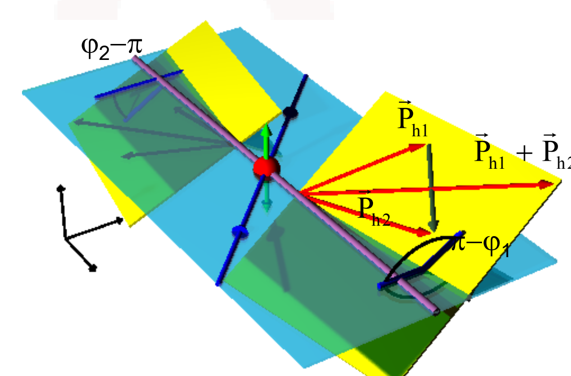


[A. Vossen et al. PRL 107 (2011) 072004]



- data from e^+e^- by BELLE



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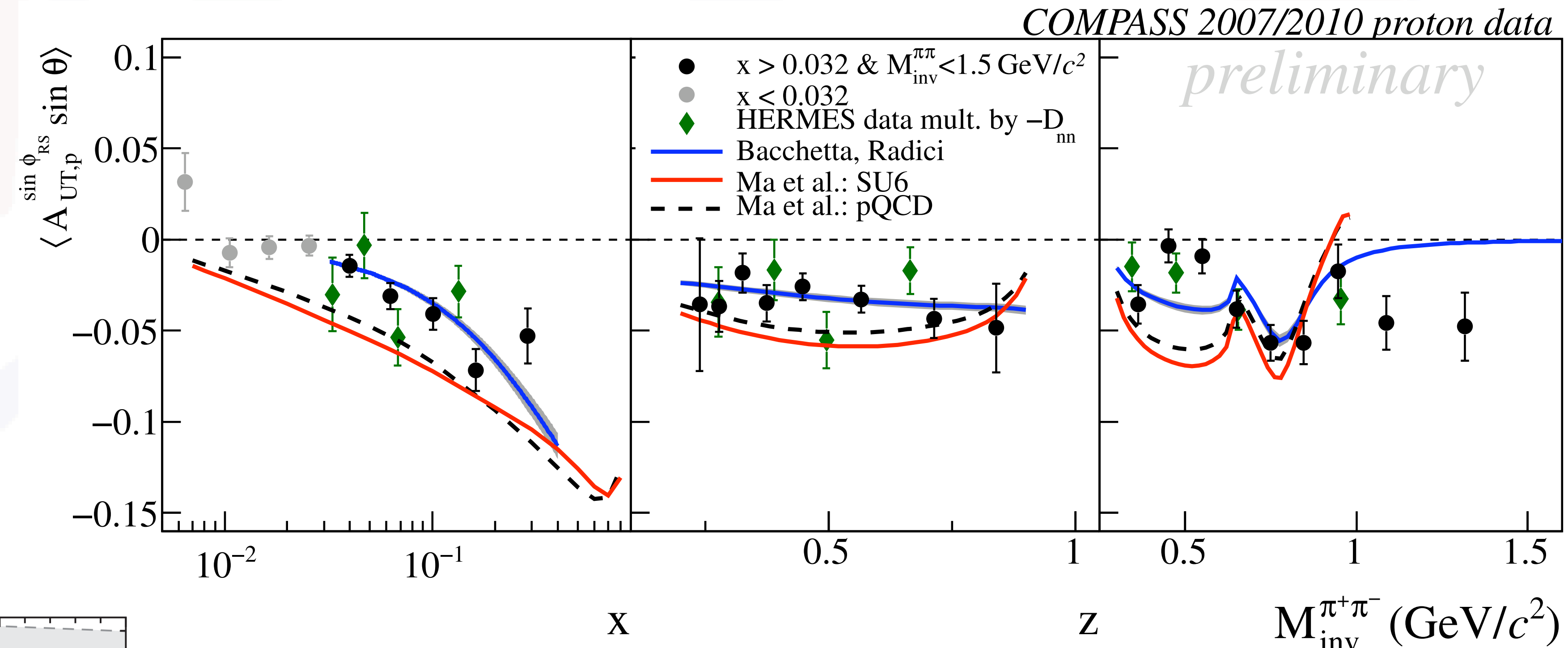
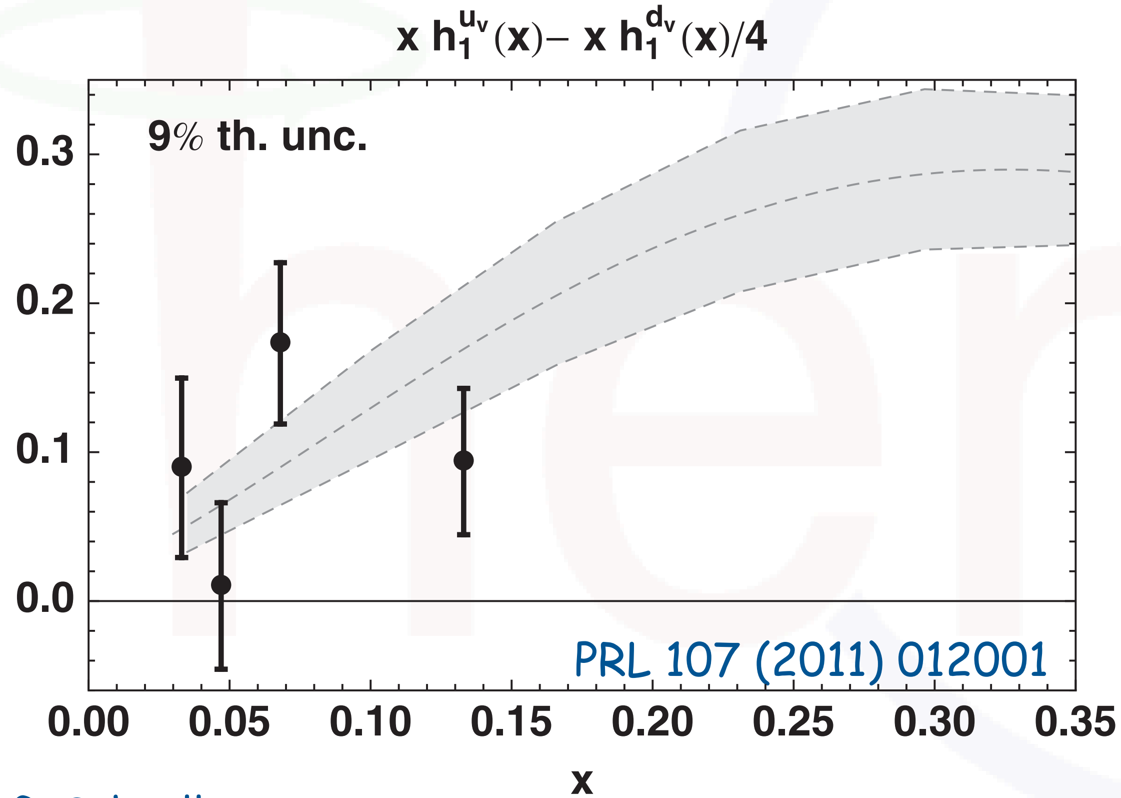
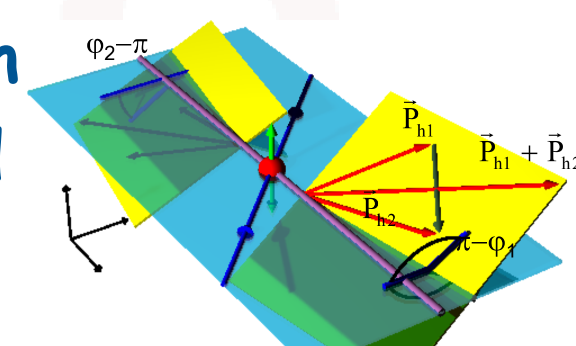




- data from e^+e^- by BELLE allow **first (collinear) extraction of transversity** (compared to Anselmino et al.)

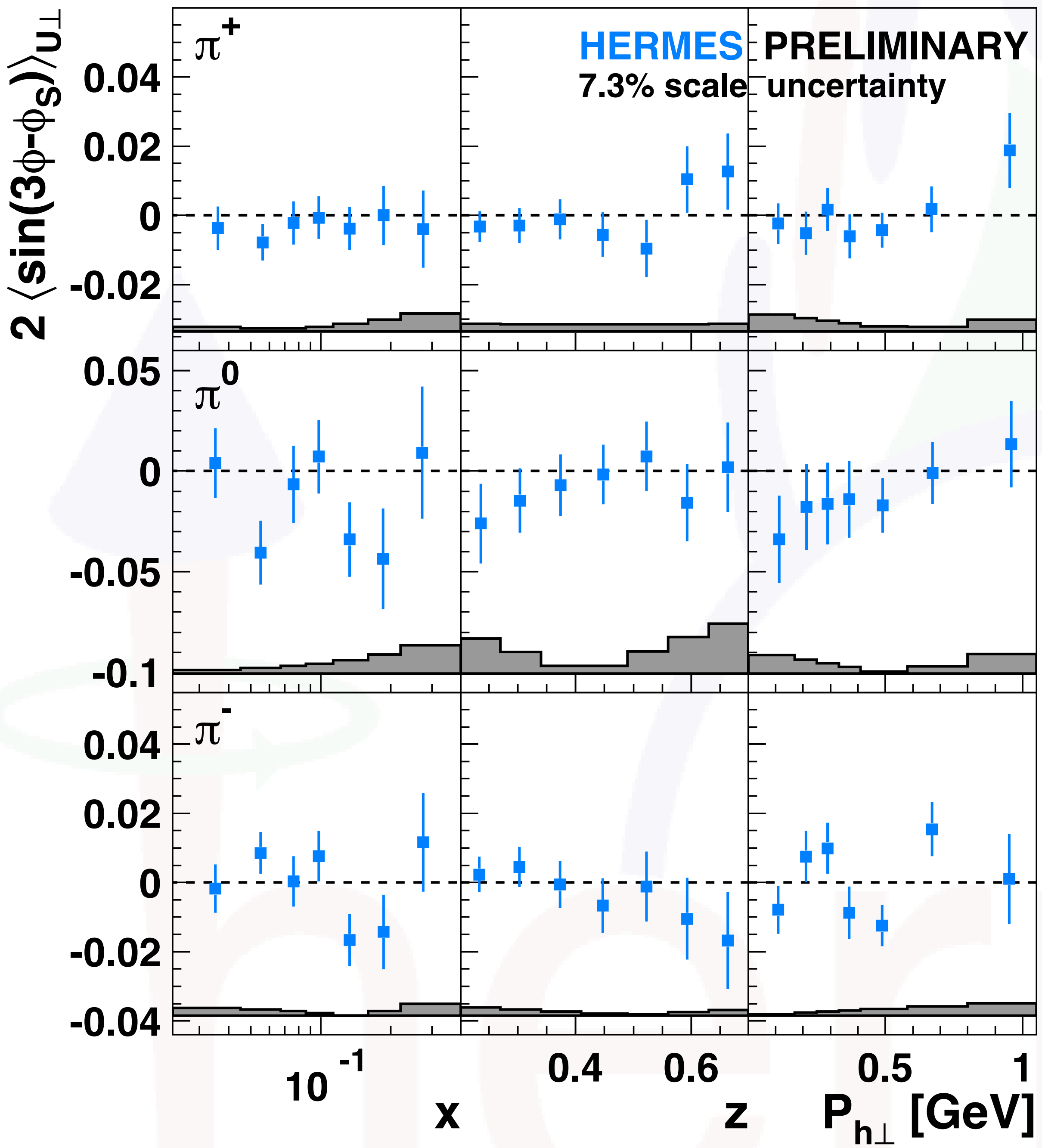


- updated analysis exists, not part of this talk

Transversity's friends

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

Pretzelosity?



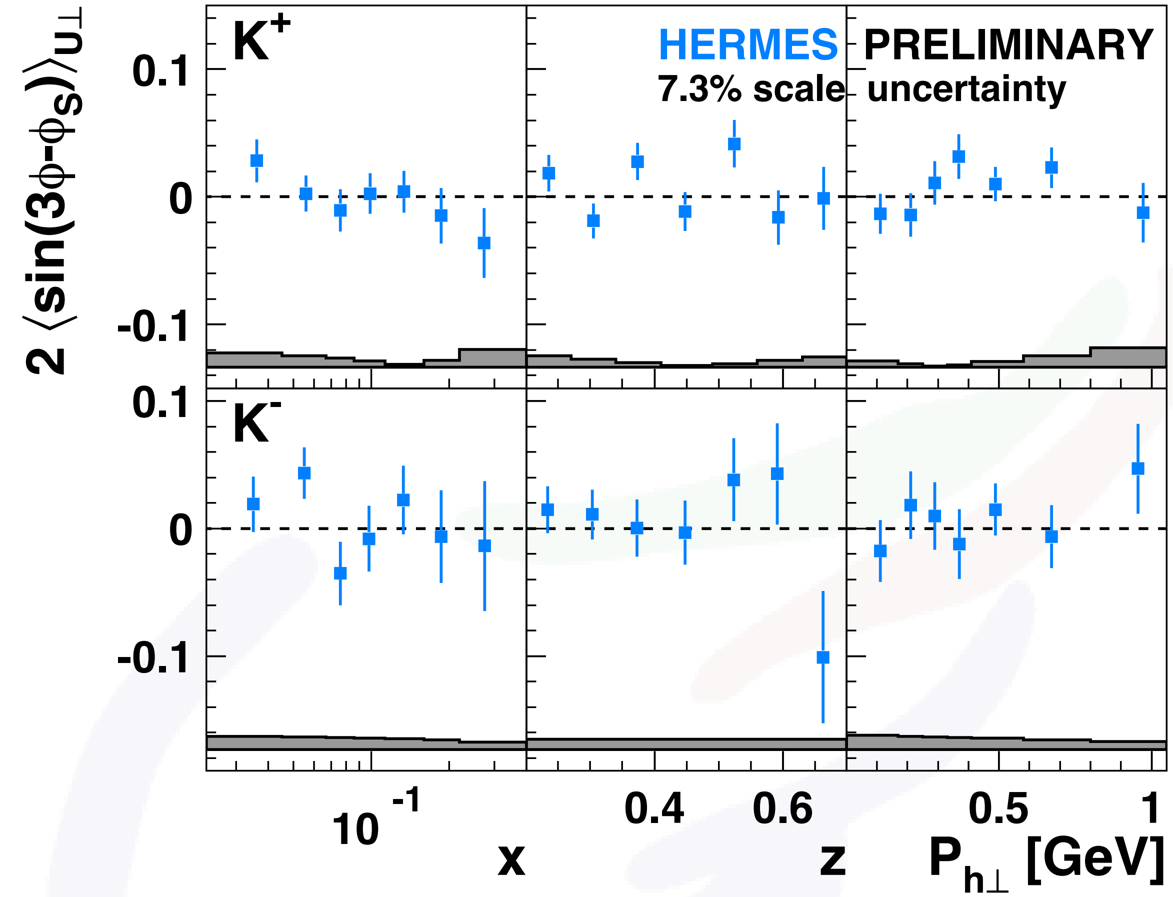
$$\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\, h_1^q\, H_1^{\perp,q\to h}\right]$$

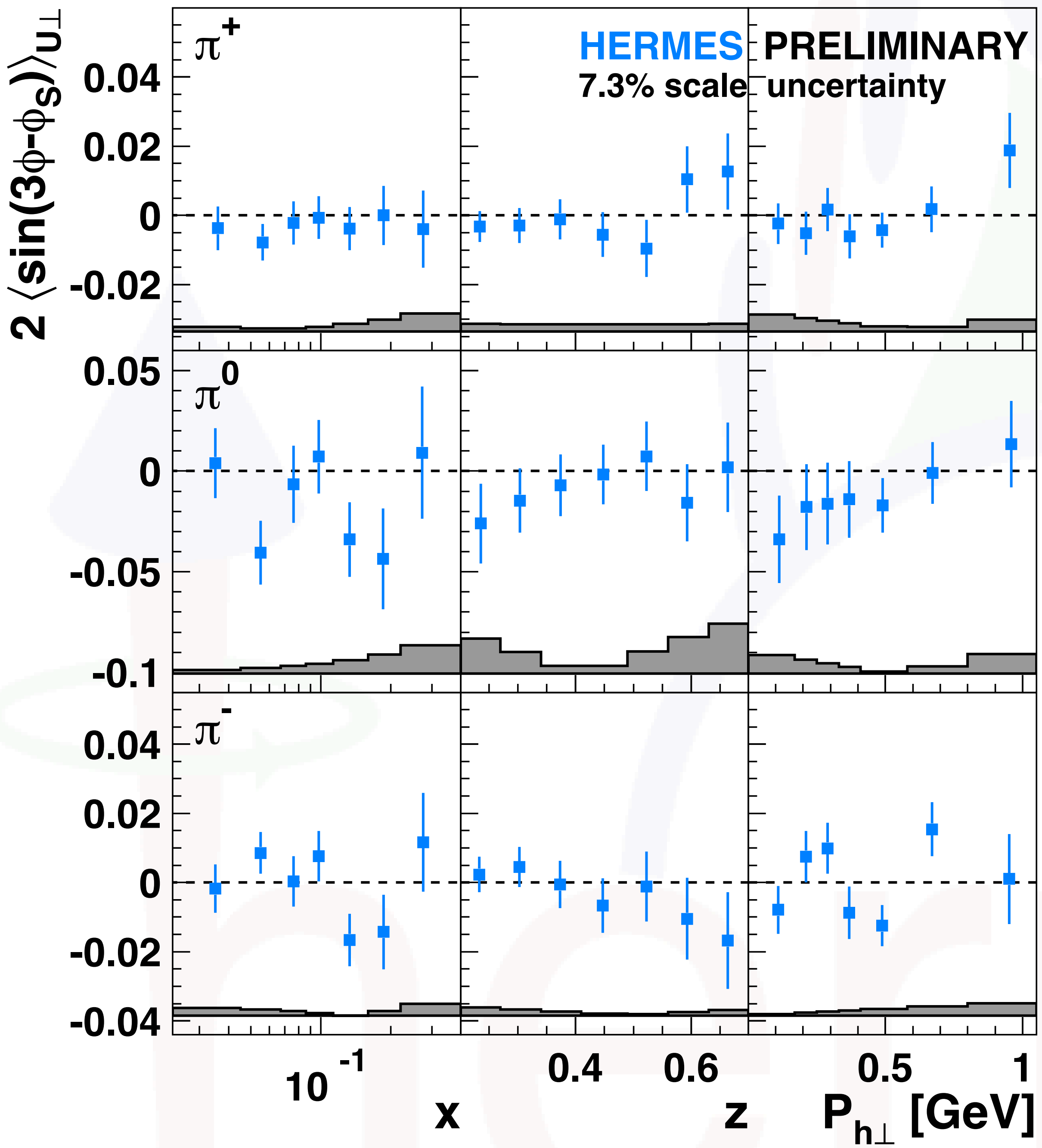
$$\mathcal{C}\left[\frac{2\left(\hat{\mathbf{h}}\cdot\mathbf{p}_T\right)\left(\mathbf{p}_T\cdot\mathbf{k}_T\right)+\mathbf{p}_T^2\left(\hat{\mathbf{h}}\cdot\mathbf{k}_T\right)-4\left(\hat{\mathbf{h}}\cdot\mathbf{p}_T\right)^2\left(\hat{\mathbf{h}}\cdot\mathbf{k}_T\right)}{2M^2M_h}\, h_{1\mathrm{T}}^{\perp,q}\, H_1^{\perp,q\to h}\right]$$

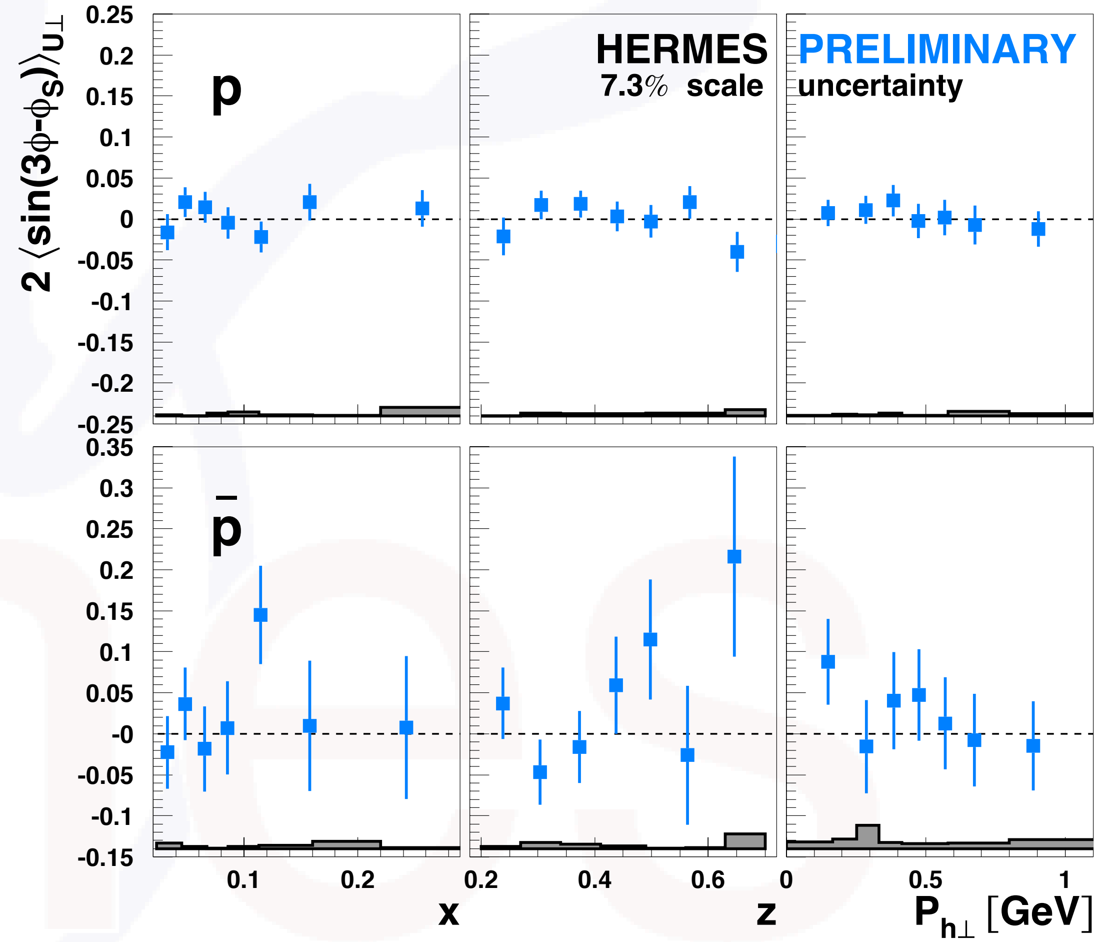
- consistent with zero; but **suppressed** by two powers of $P_{h\perp}$ (compared to, e.g., transversity⊗Collins)

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

Pretzelosity?

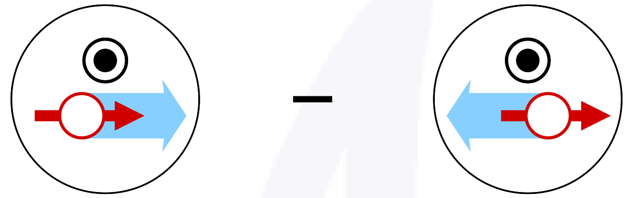






- consistent with zero; but **suppressed** by two powers of $P_{h\perp}$ (compared to, e.g., transversity⊗Collins)

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



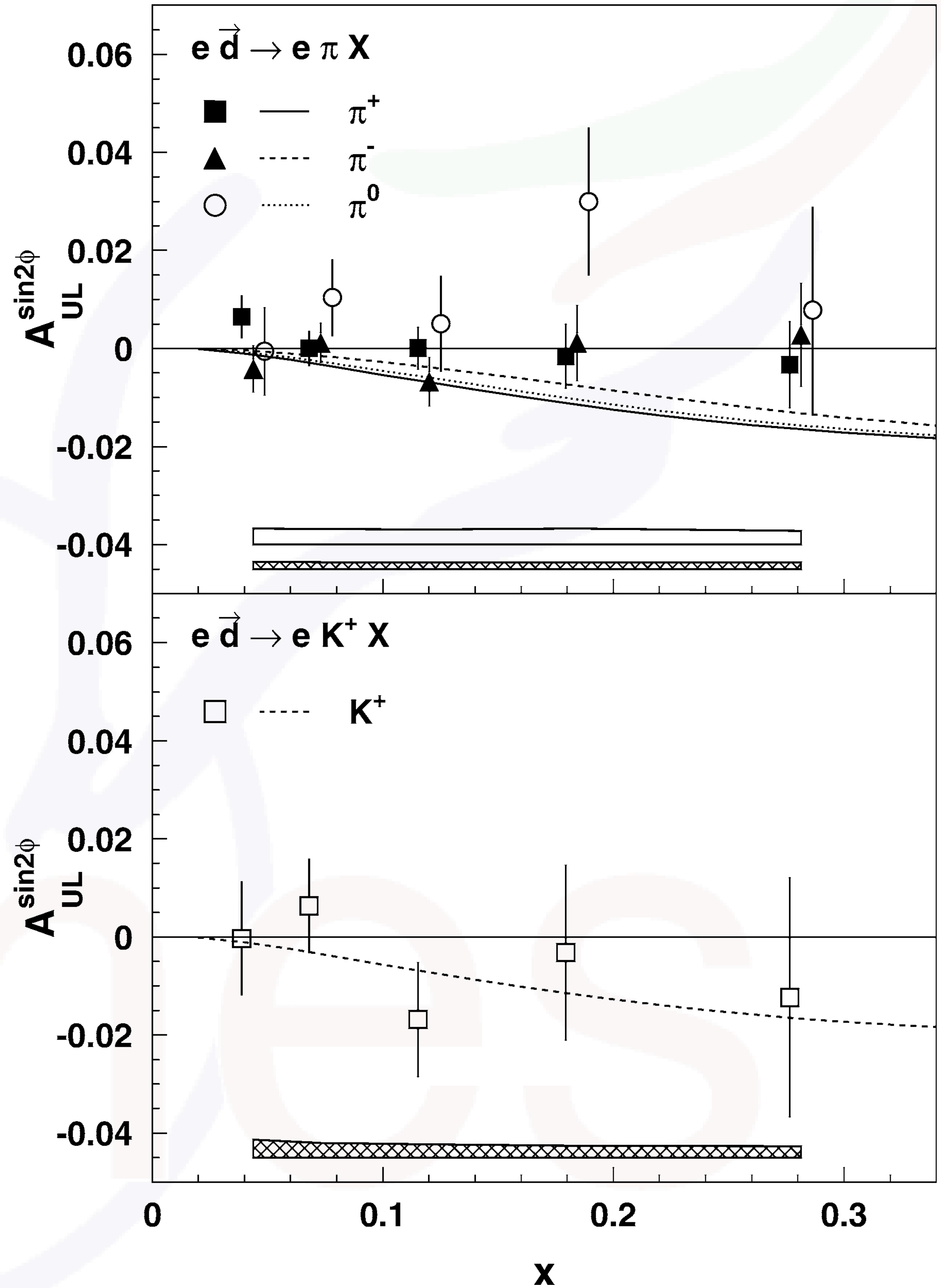
Worm-Gear I

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

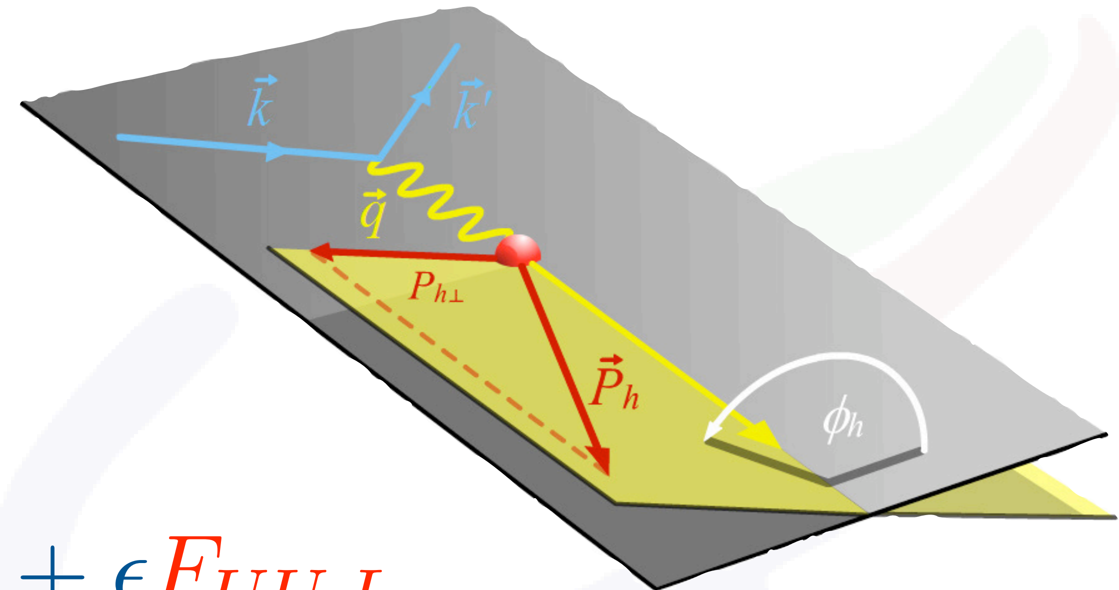
	Meson	Deuterium target	Proton target [2,3]
$A_{UL}^{\sin 2\phi}$	π^+	$0.004 \pm 0.002 \pm 0.002$	$-0.002 \pm 0.005 \pm 0.003$
	π^0	$0.009 \pm 0.005 \pm 0.003$	$0.006 \pm 0.007 \pm 0.003$
	π^-	$0.001 \pm 0.003 \pm 0.002$	$-0.005 \pm 0.006 \pm 0.005$
	K^+	$-0.005 \pm 0.006 \pm 0.003$	–

[PLB 562 (2003) 182-192]

[PLB 562 (2003) 182-192]



cross section without beam/target 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

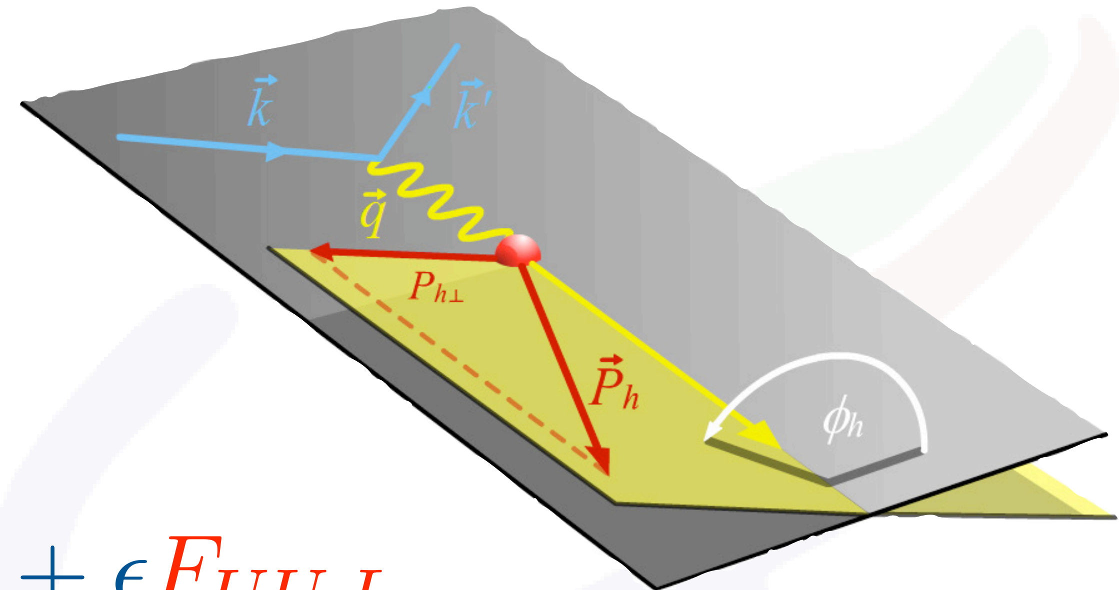
virtual-photon polarization

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

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

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

cross section without beam/target polarization



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

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

BOER-MULDERS EFFECT

CAHN EFFECT

leading twist

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

next to leading twist

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

Interaction dependent terms neglected

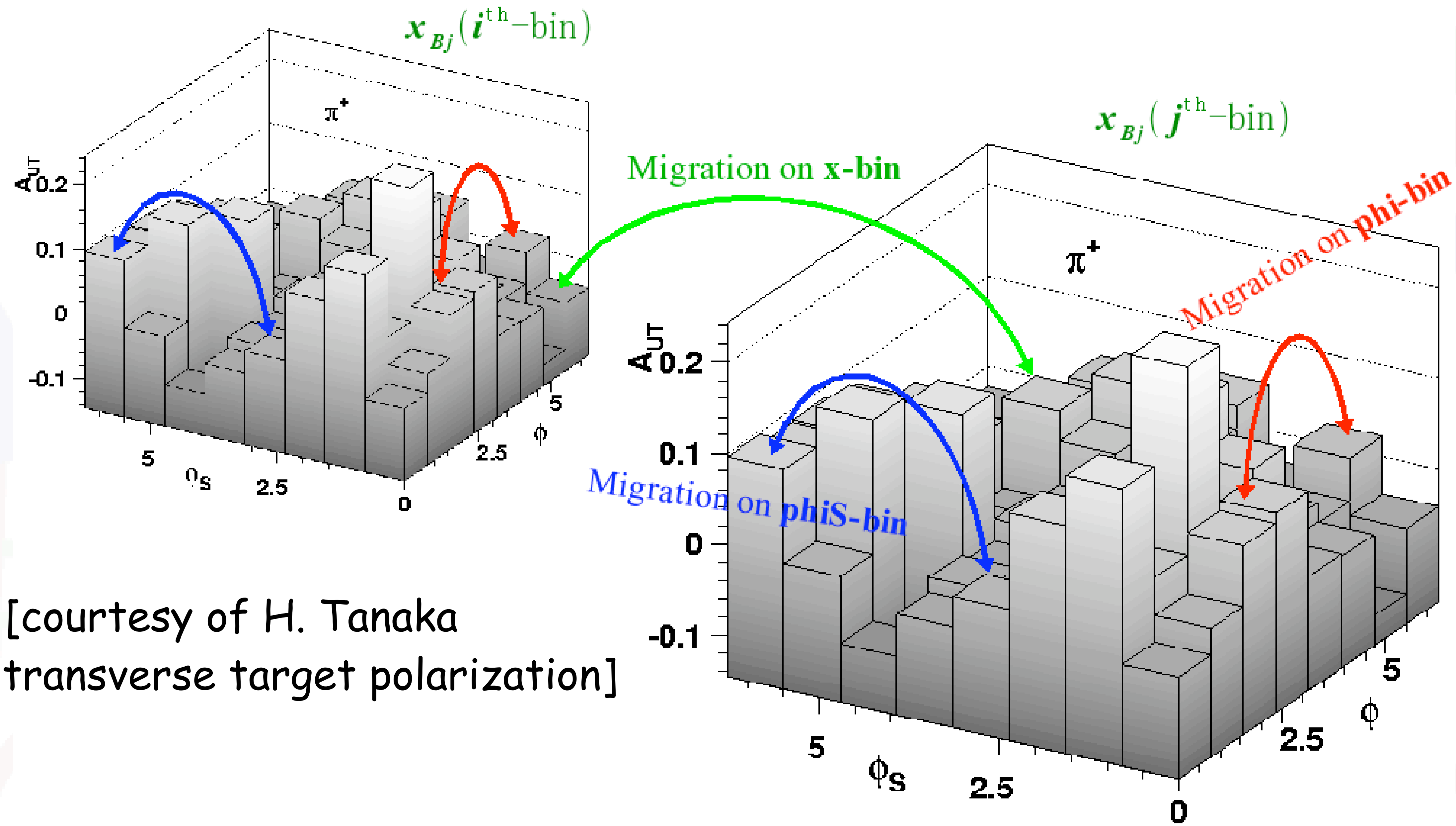
(Implicit sum over quark flavours)

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

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

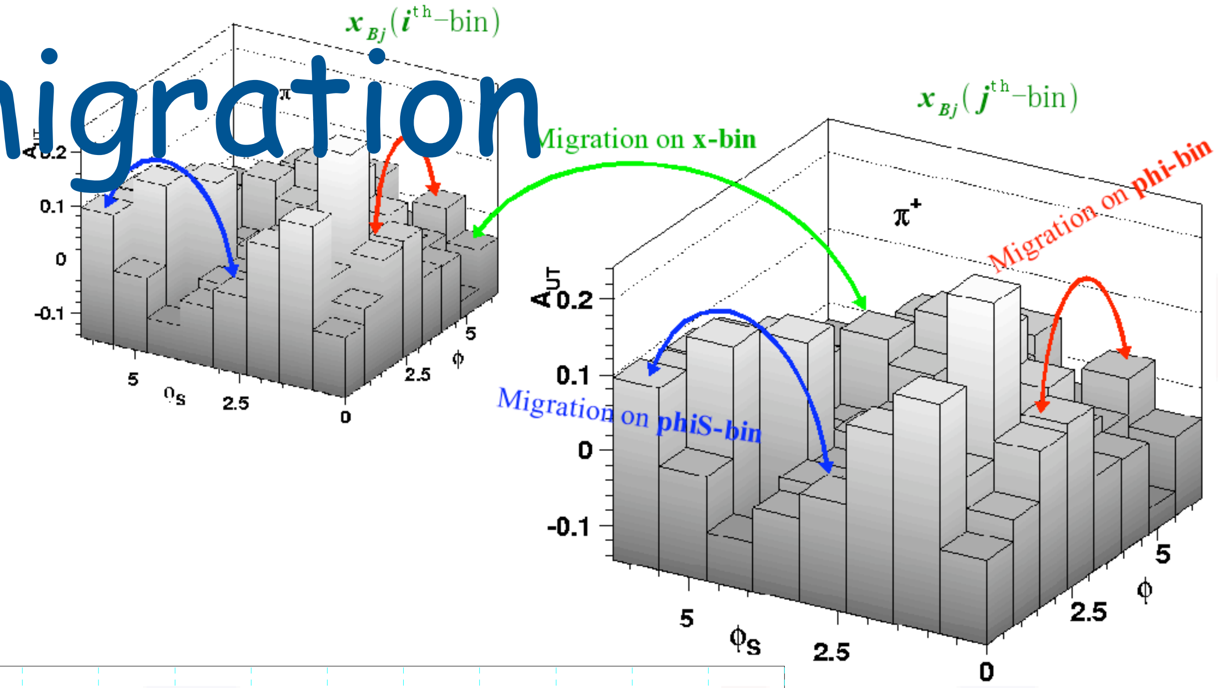
[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

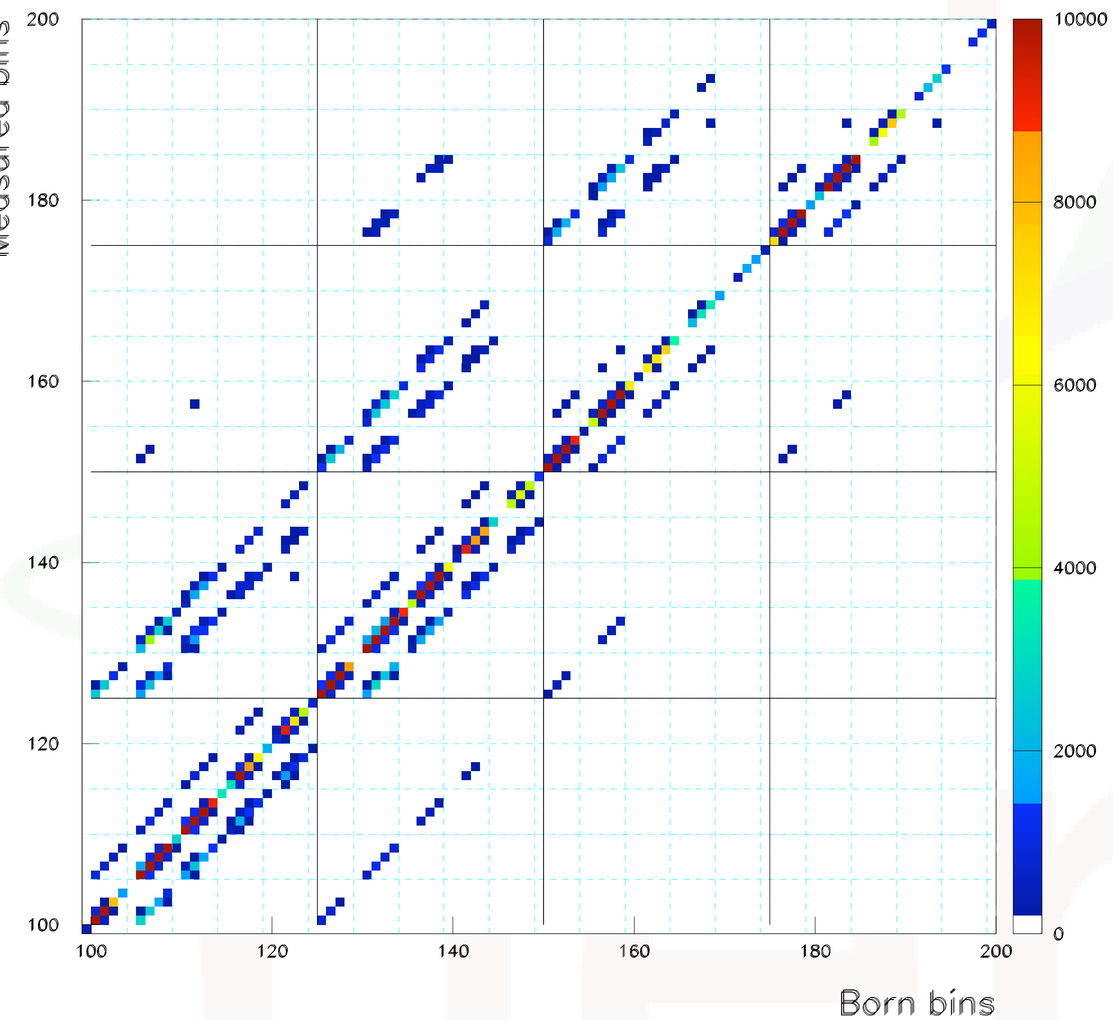
extraction I - event migration

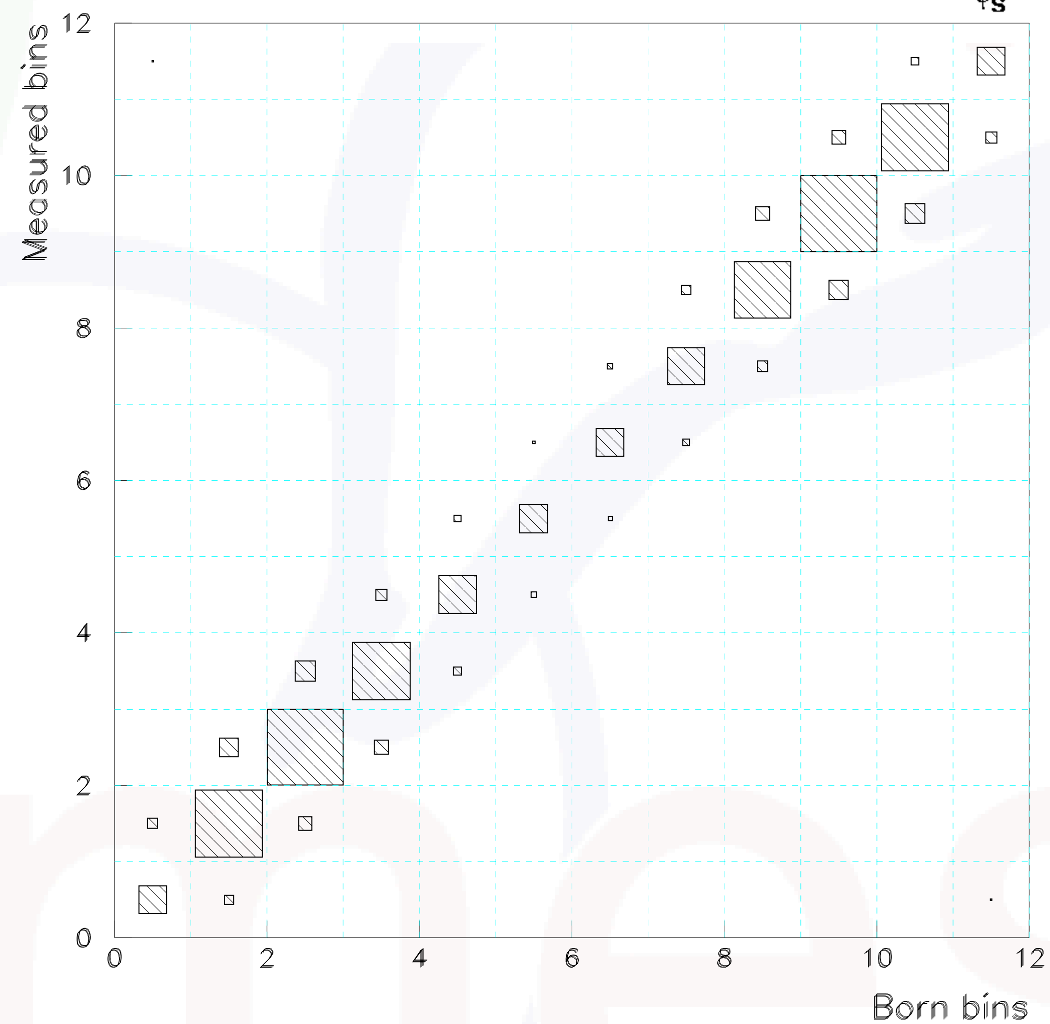


[courtesy of H. Tanaka
case of transverse target polarization]

extraction I - event migration







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

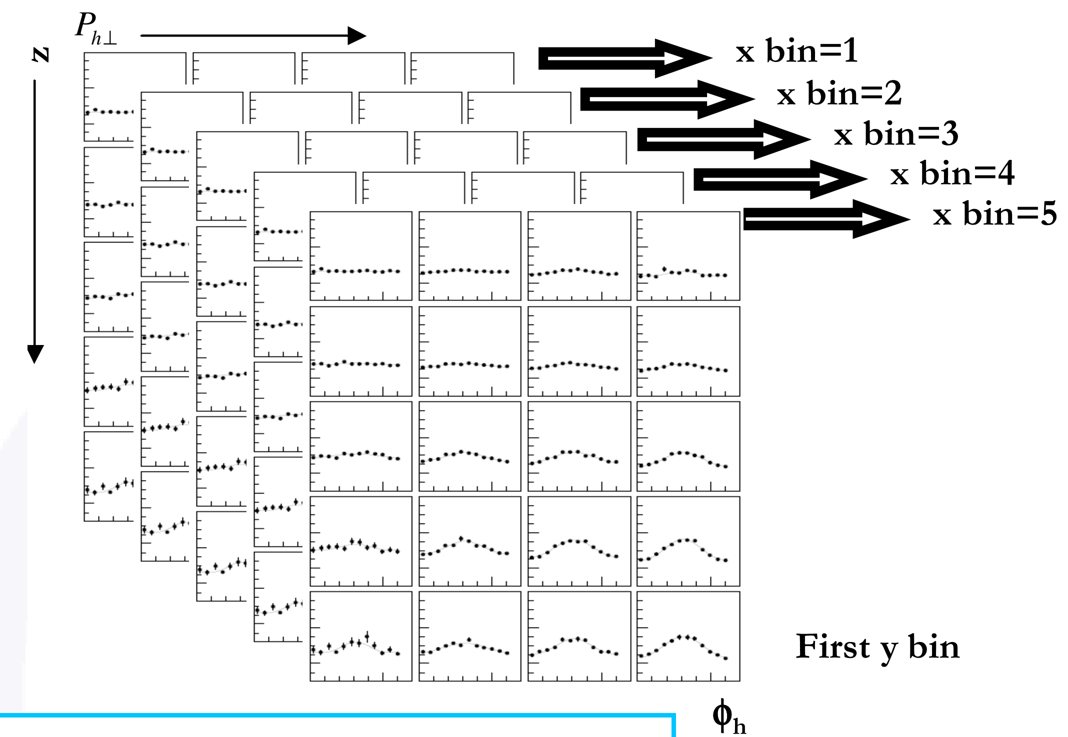
extraction I - event migration

$$\mathcal{Y}^{\exp}(\Omega_i) \propto \sum_{j=1}^{N} S_{ij} \int_j d\Omega \, d\sigma(\Omega) + \mathcal{B}(\Omega_i)$$

- experimental yield in i^{th} bin depends on all Born bins j ...
- ... and on BG entering kinematic range from outside region
- smearing matrix S_{ij} embeds information on migration
- determined from Monte Carlo - independent of physics model in limit of infinitesimally small bins and/or flat acceptance/cross-section in every bin
- in real life: dependence on BG and physics model due to finite bin sizes
- inversion of relation gives Born cross section from measured yields

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



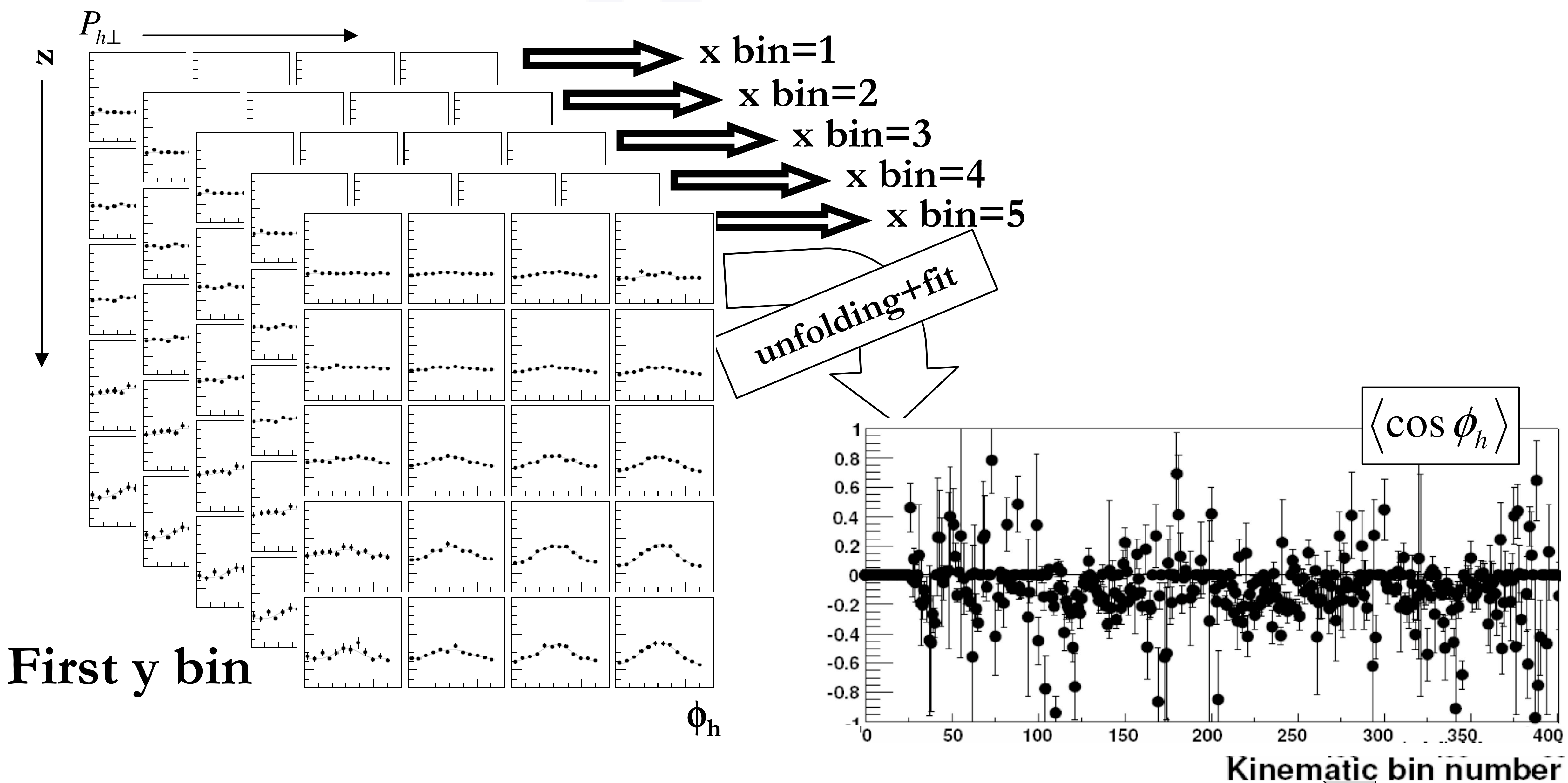
probability that an event generated with a certain kinematics is measured with a different kinematics

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

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

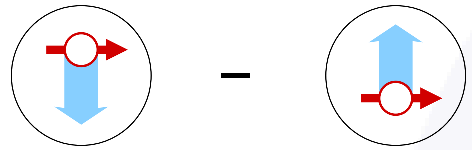
includes the events smeared into the acceptance

extraction III - projecting



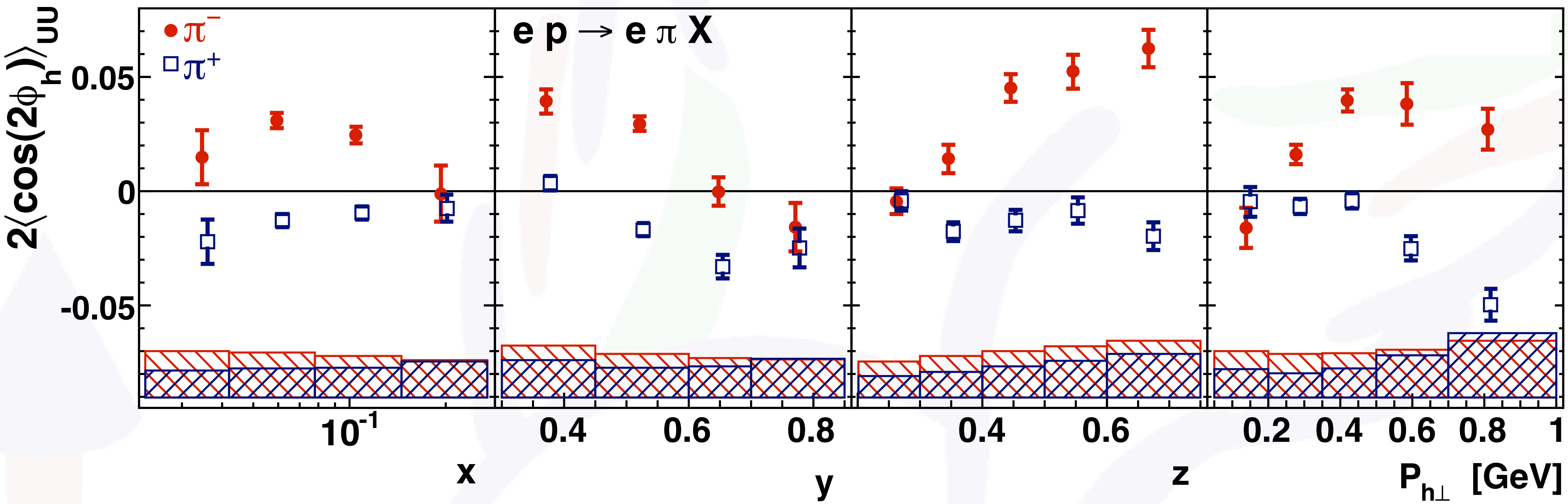
$$\langle\cos\phi\rangle(x_b) \approx \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b}) \langle\cos\phi\rangle_{x_i=x_b}}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b})}$$

	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]



- cos2ϕ modulations are not zero!

	U	L	T
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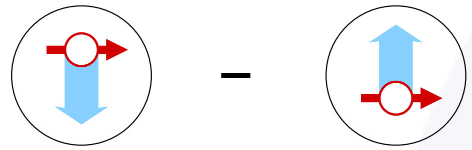

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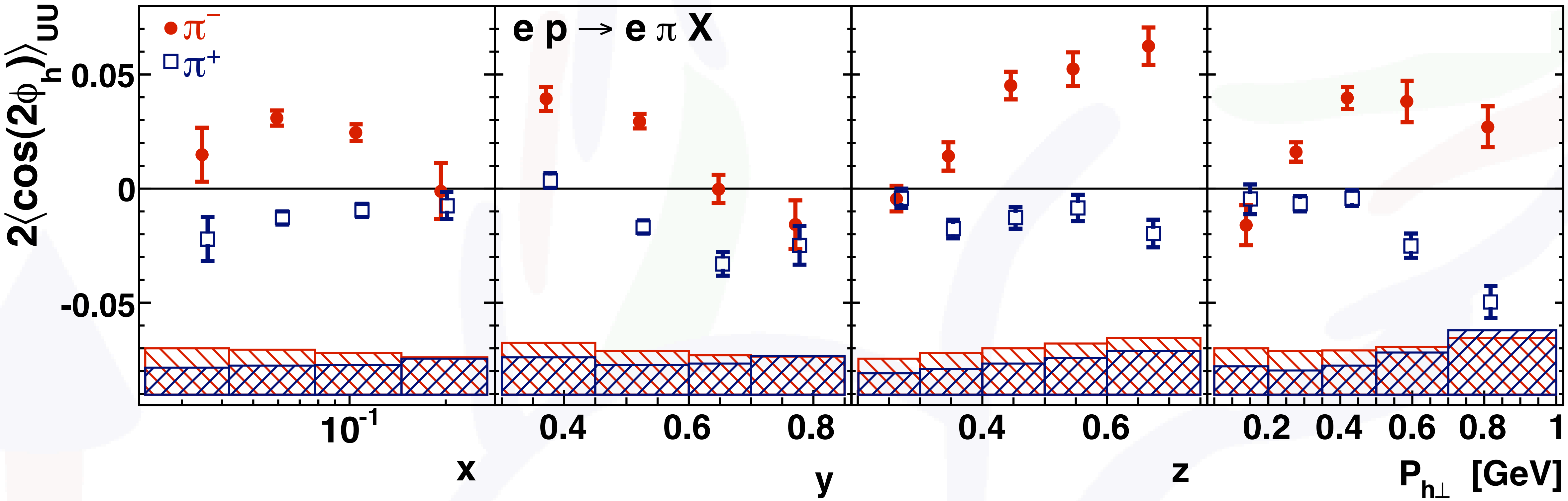

- $\cos 2\phi$ modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-

	U	L	T
U	f_1		$h_1^\perp$
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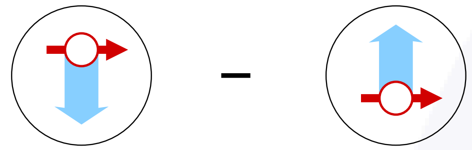
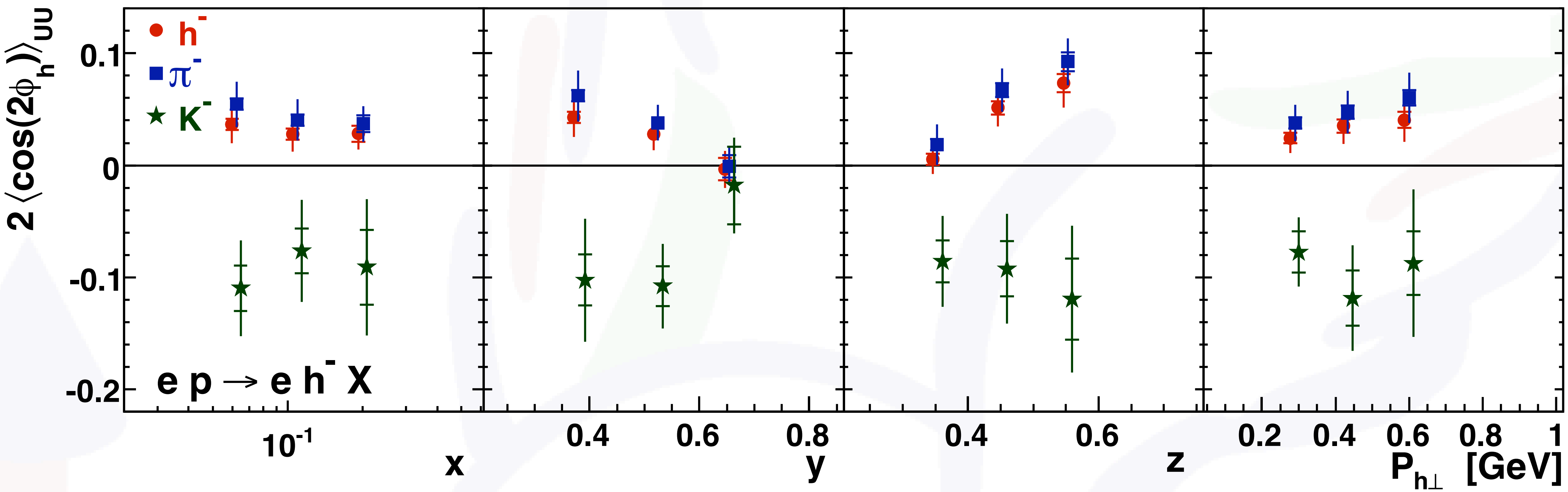


signs of Boer-Mulders

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



- $\cos2\phi$ modulations are not zero!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons

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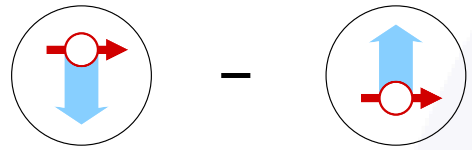
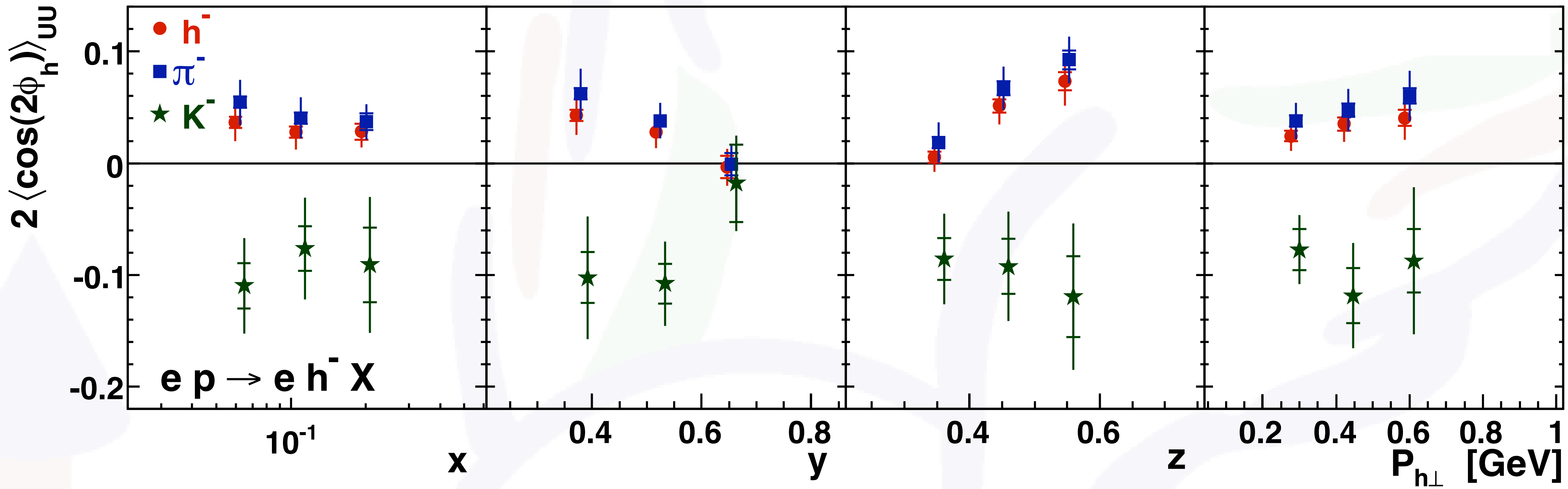


signs of Boer-Mulders

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



- cos2ϕ 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

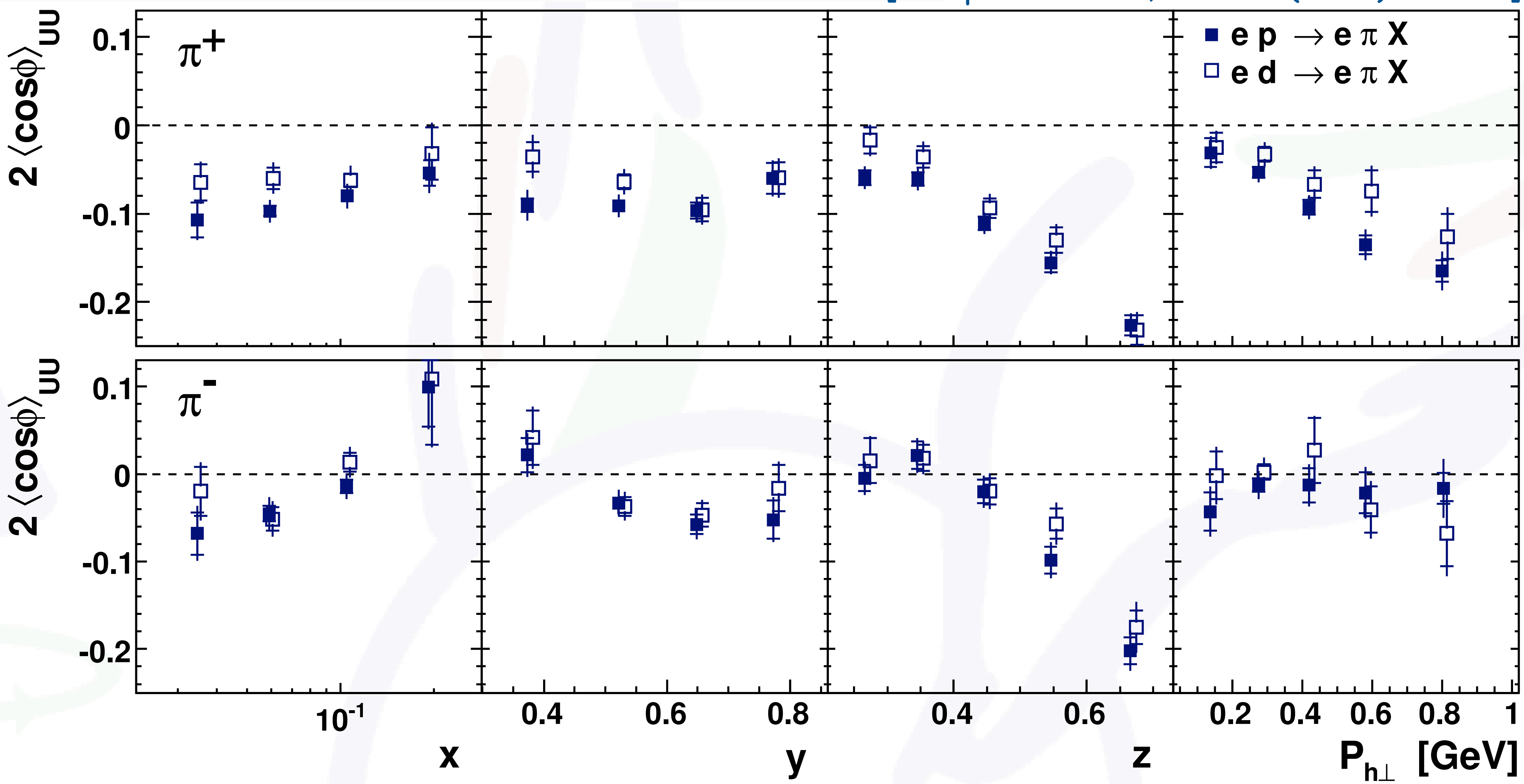
CAHN EFFECT

next to leading twist

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

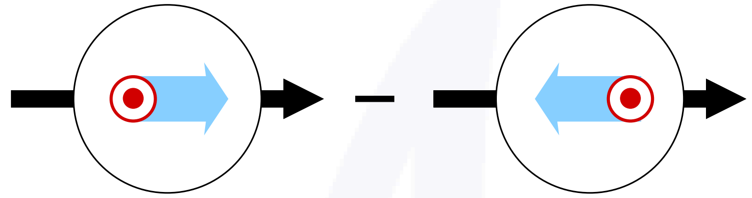
Interaction dependent terms neglected

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



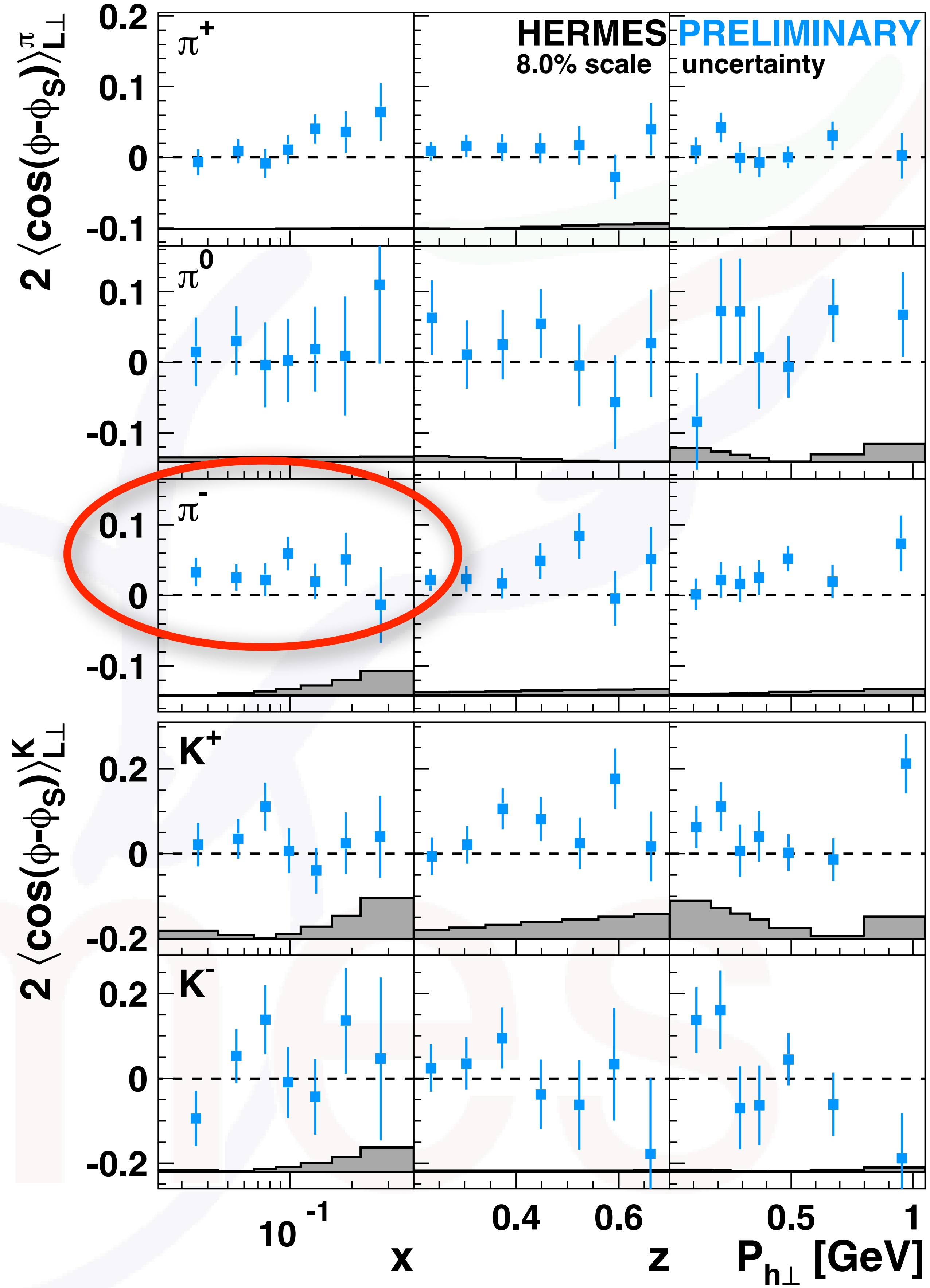
- no dependence on hadron charge **was expected** for Cahn effect
- ➡ flavor dependence of transverse momentum
- ➡ sign of Boer-Mulders in $\cos\phi$ modulation
- ➡ additional "genuine" twist-3 contributions?

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

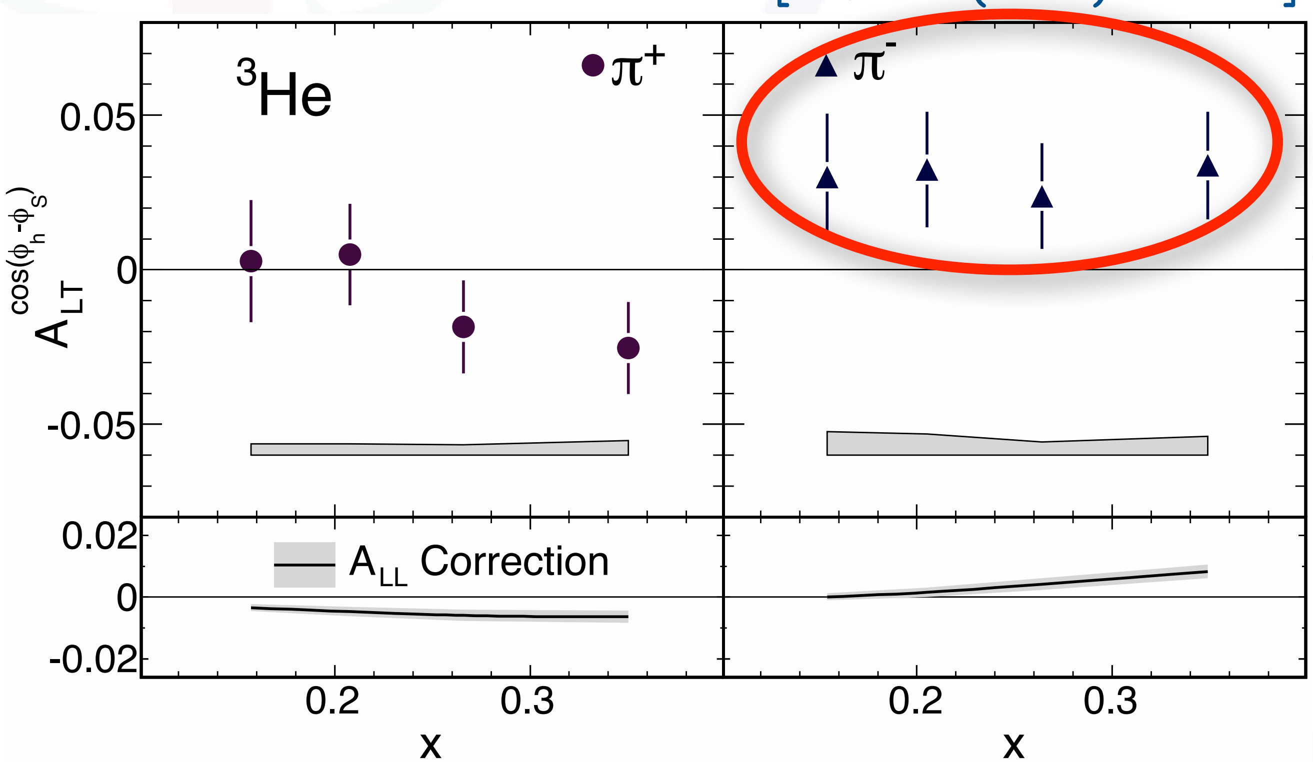


Worm-Gear

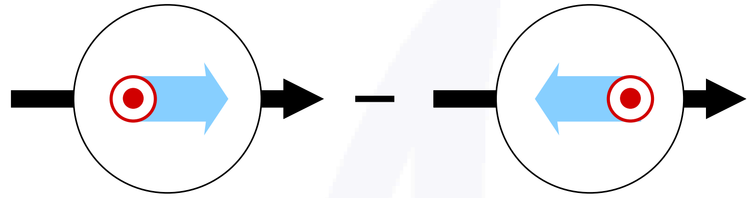
- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}He target at JLab
  - H target at HERMES



[PRL 108 (2012) 052001]

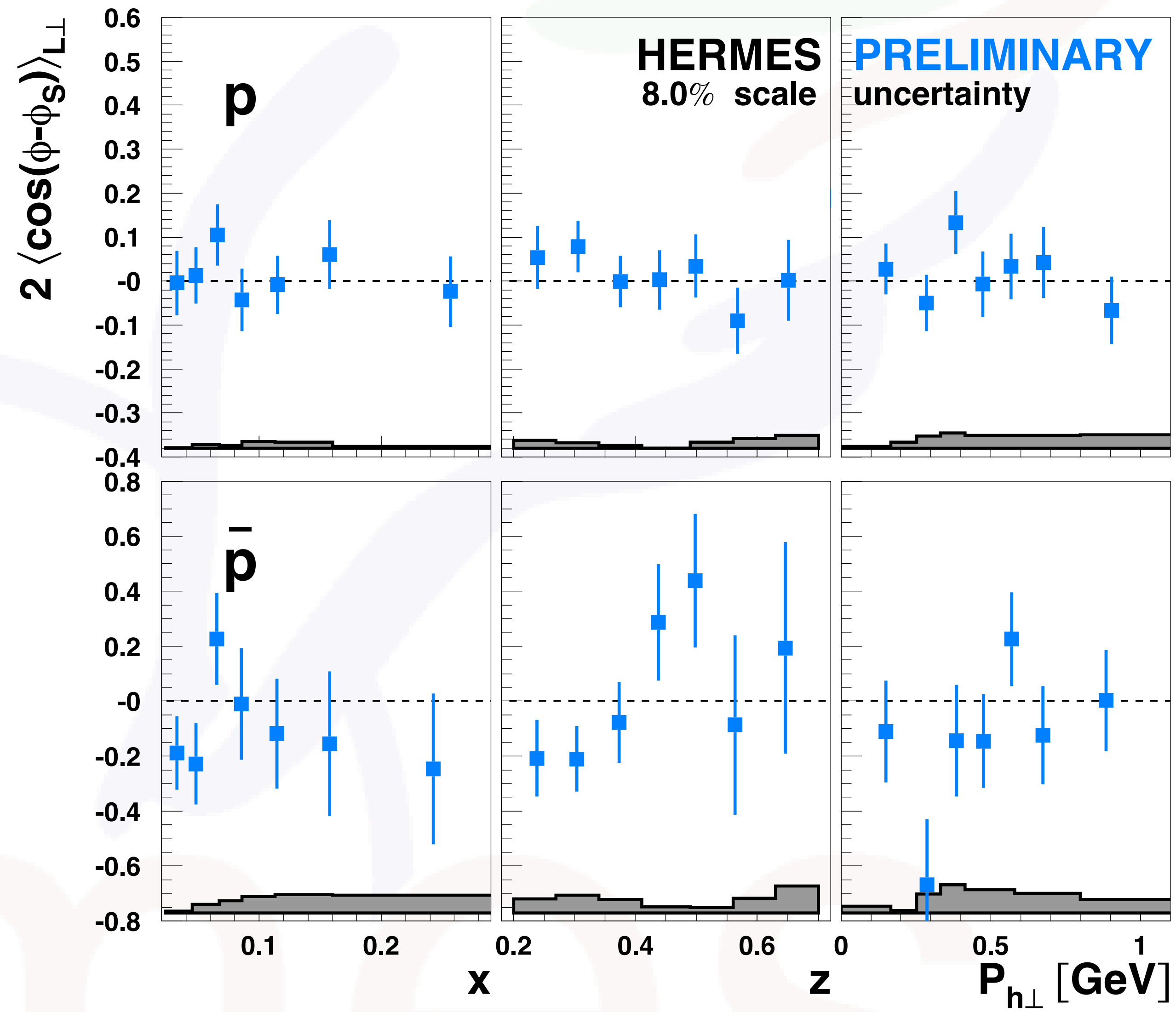


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



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

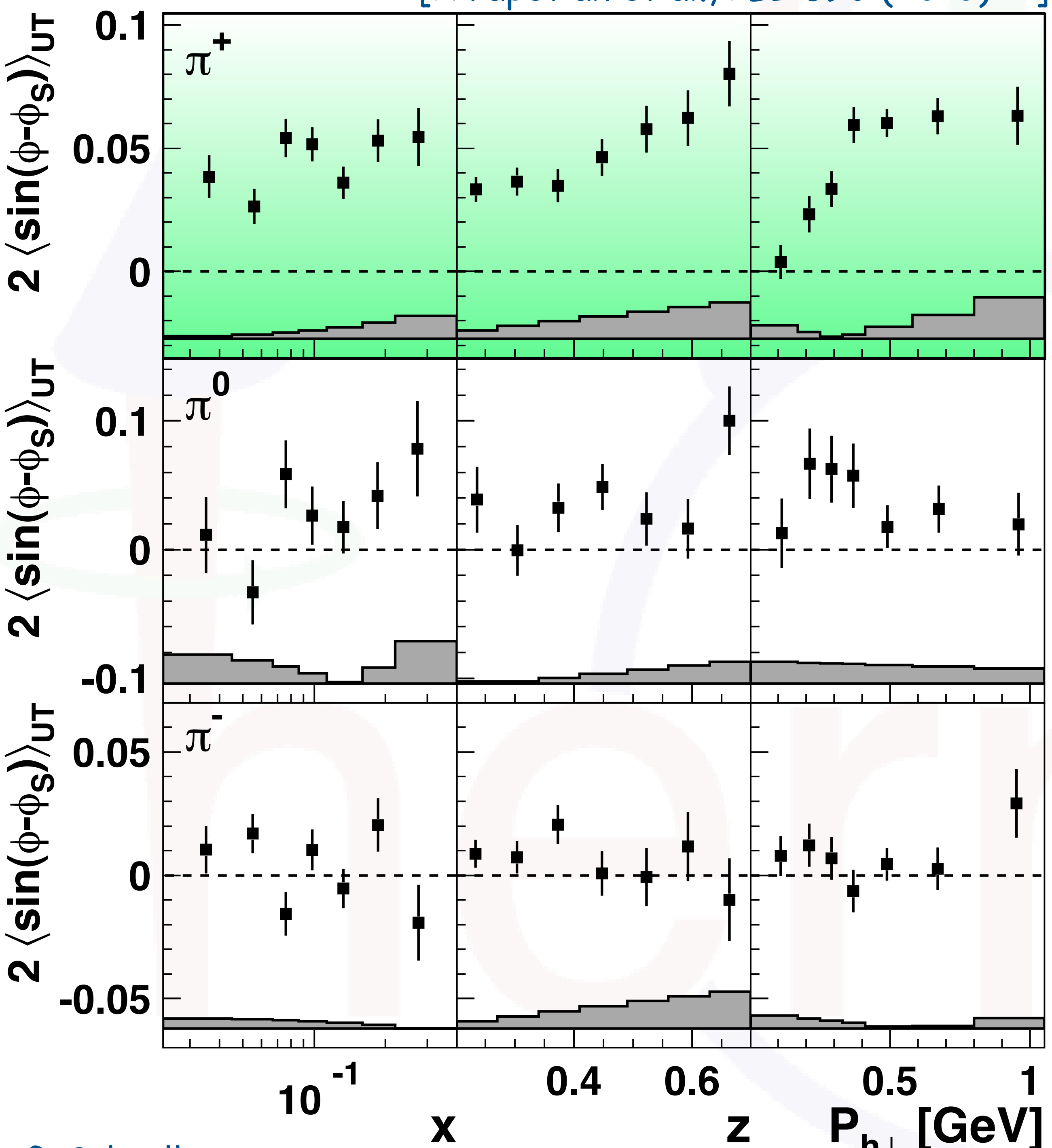


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

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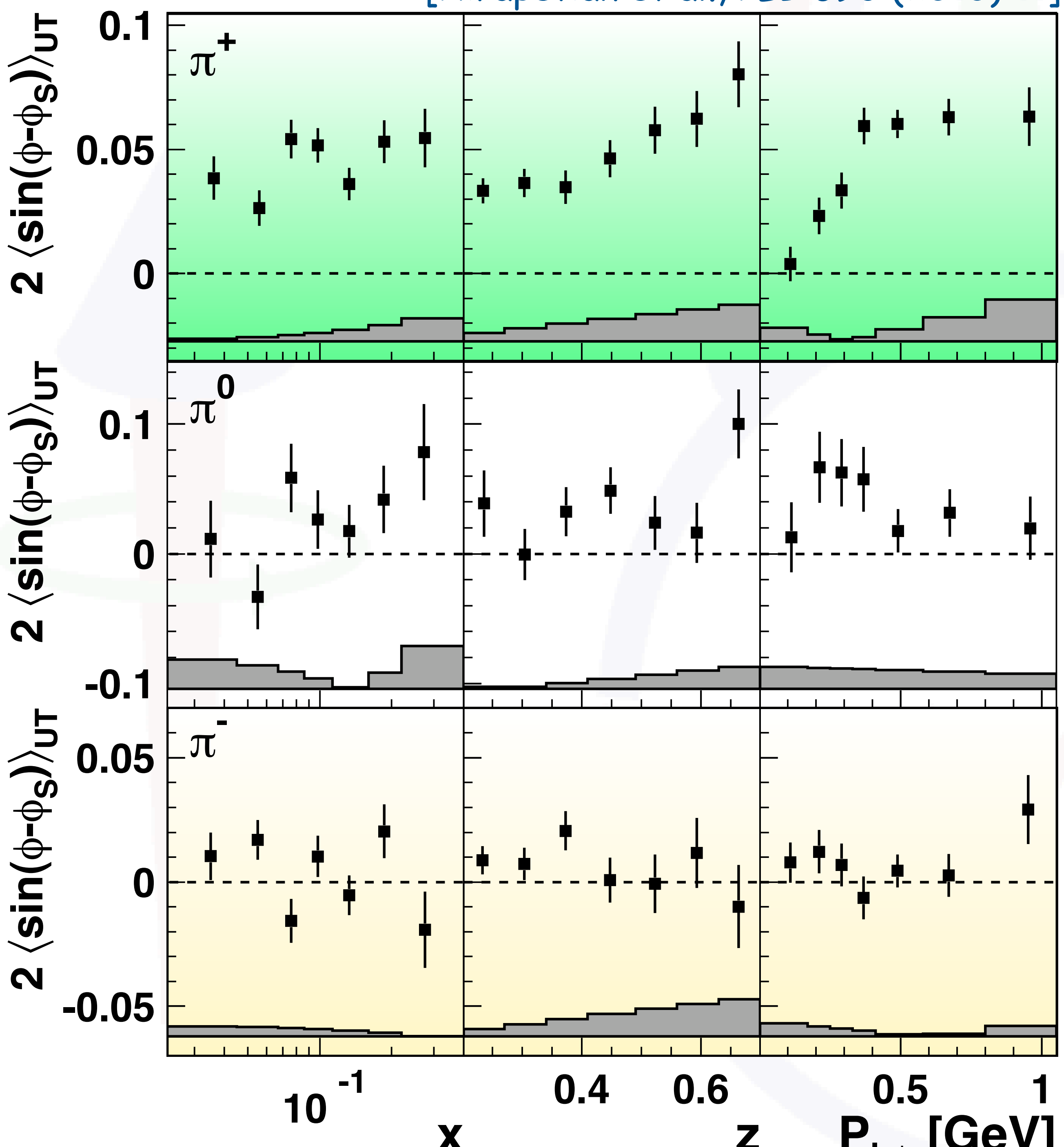
[Airapetian et al., PLB 693 (2010) 11]



π^+ dominated by u-quark scattering:

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

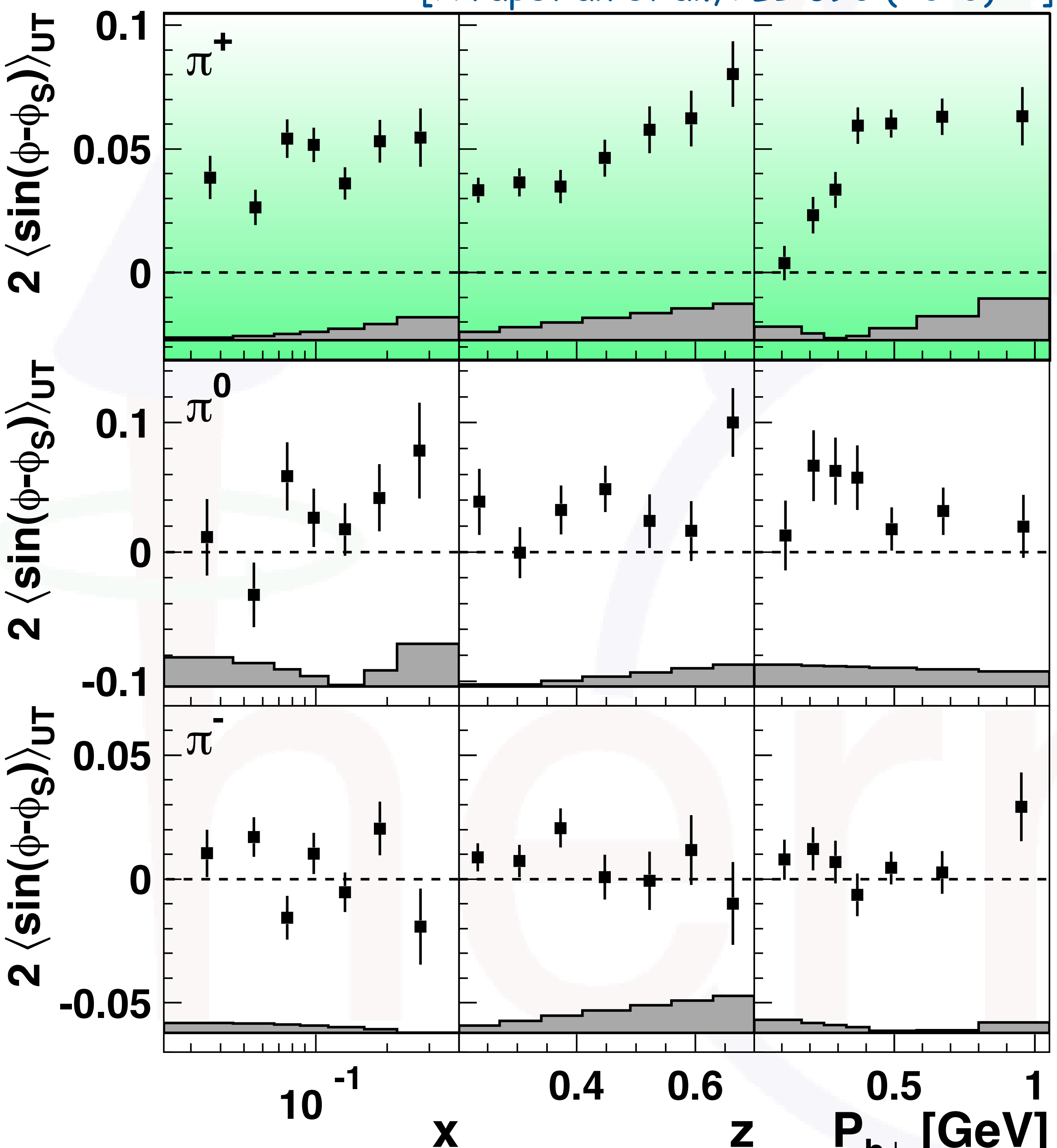
- ☛ **u-quark Sivers DF < 0**
- ☛ **d-quark Sivers DF > 0 (cancelation for π^-)**

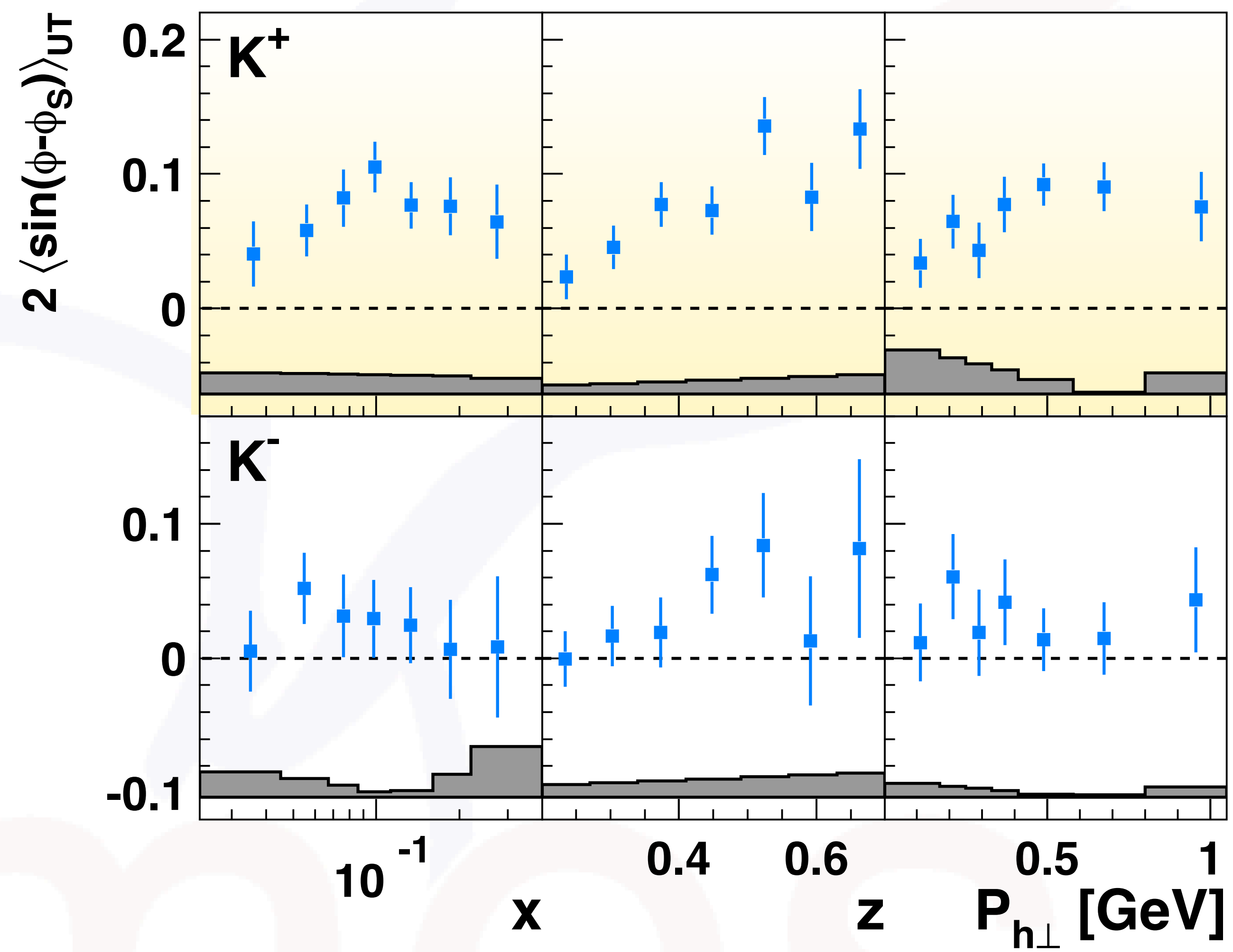
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes 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]





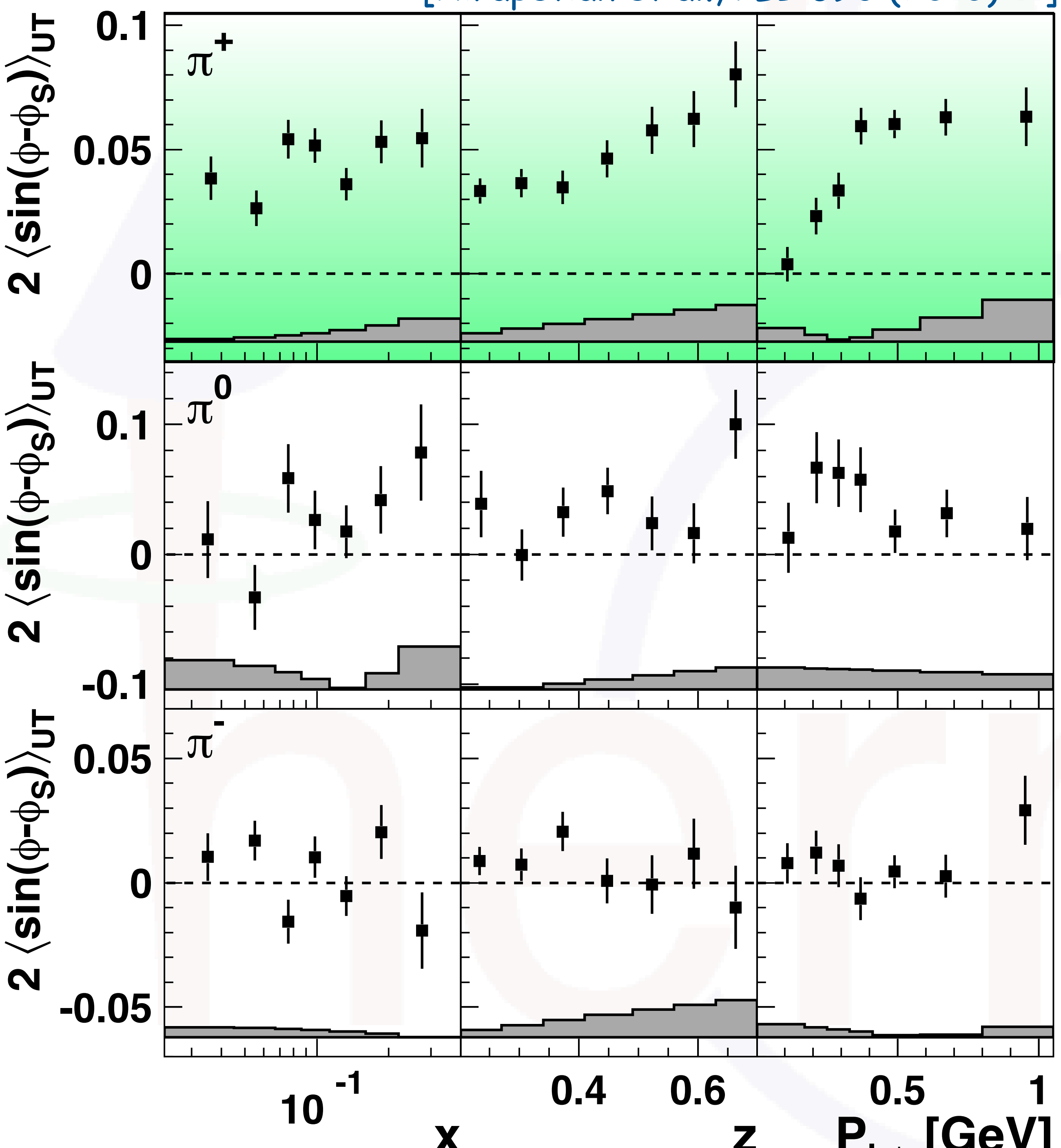
☛ larger amplitudes for positive kaons vs. pions

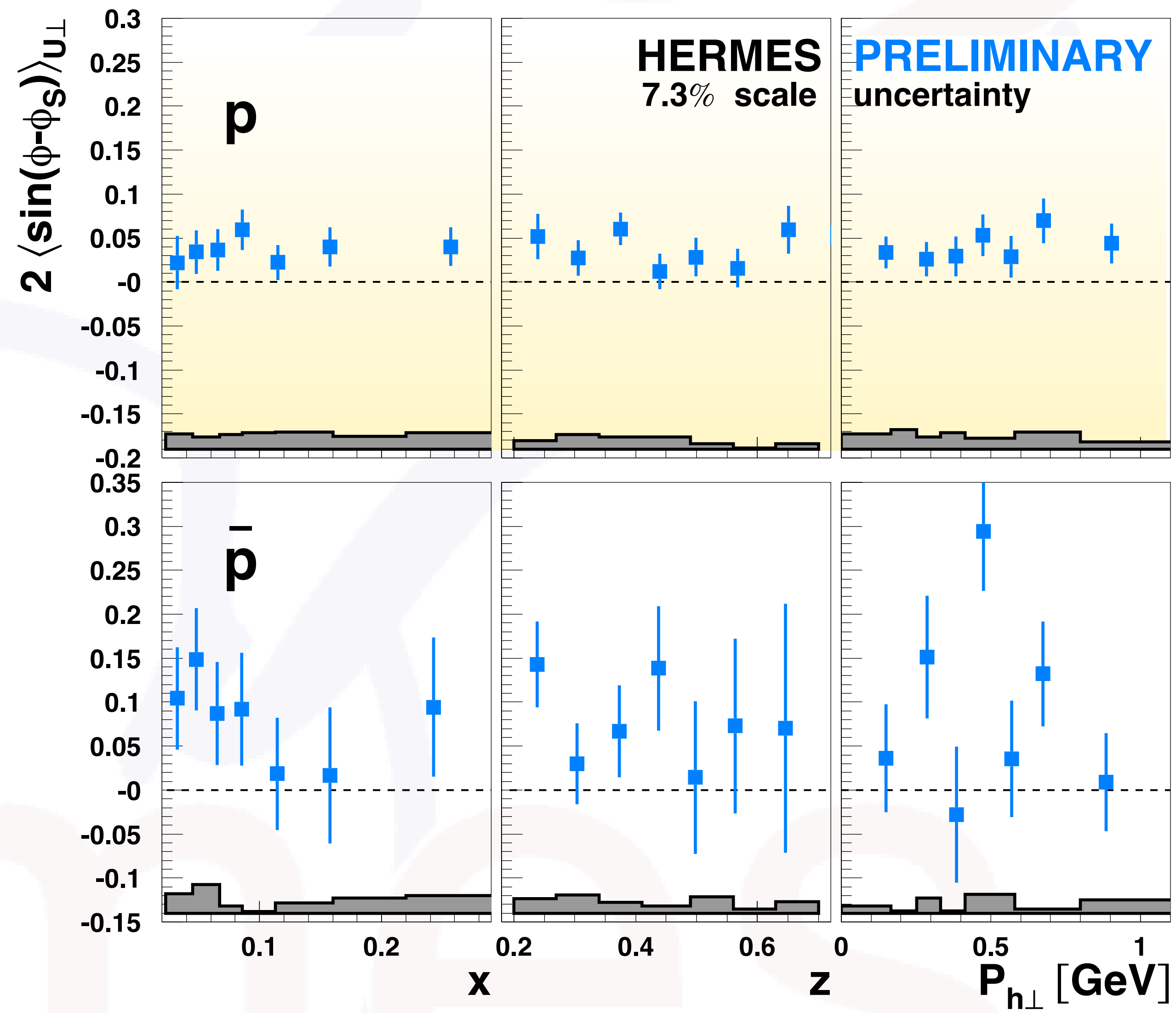
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

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]

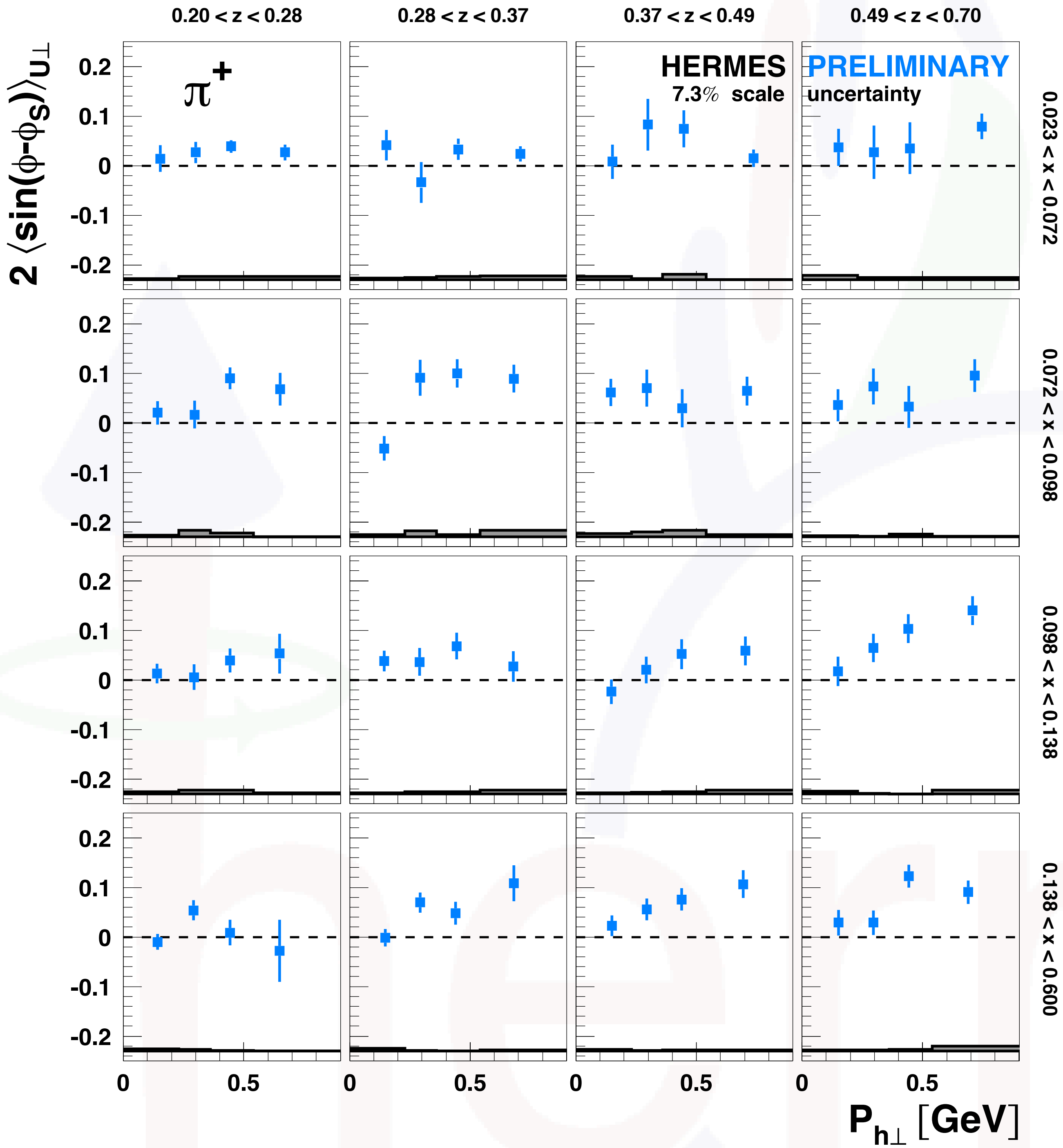




similar amplitudes for positive pions and protons ☛ u-quark dominance (and not a FF effect)?

	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, $P_{h\perp}$)
- much reduced systematics
- disentangle correlations
- isolate phase-space region with strong signal strength

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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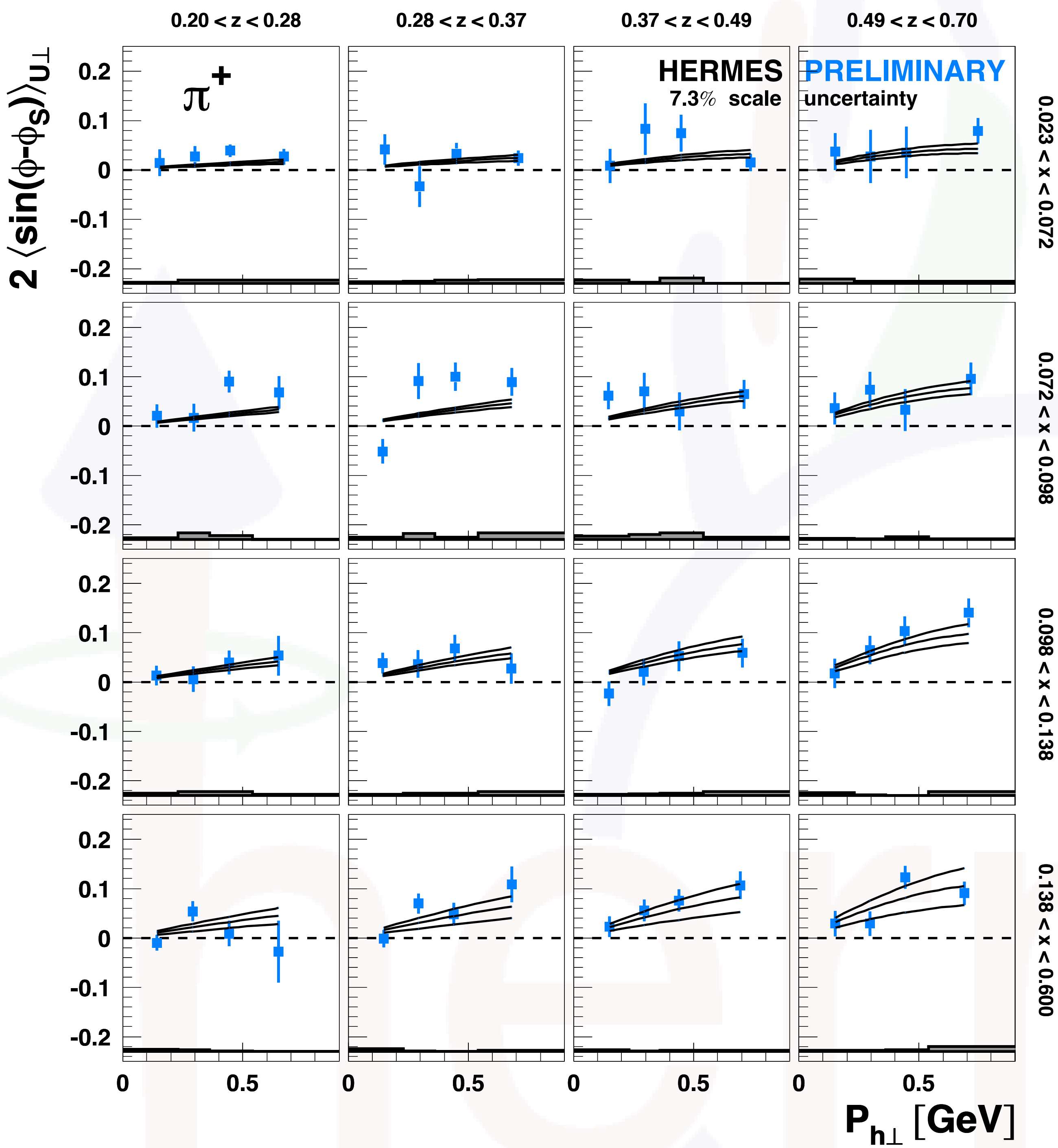
Sivers amplitudes - 3d binning

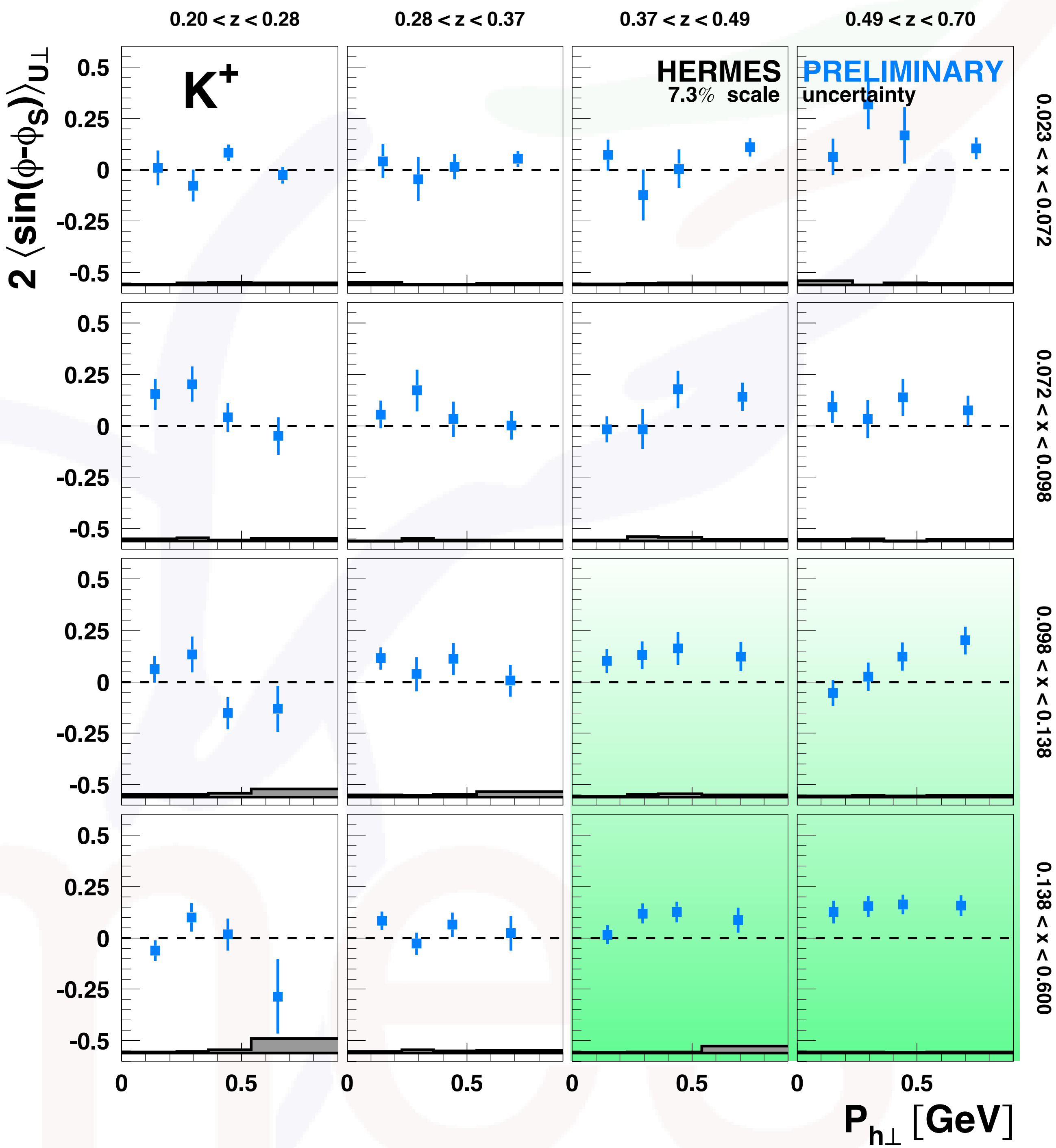


- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- much reduced systematics
- disentangle correlations
- isolate phase-space region with strong signal strength
- allows more detailed comparison with calculations (e.g., "unofficial" results from Torino 10.1103/PhysRevD.86.014028 fit - courtesy M. Boglione)

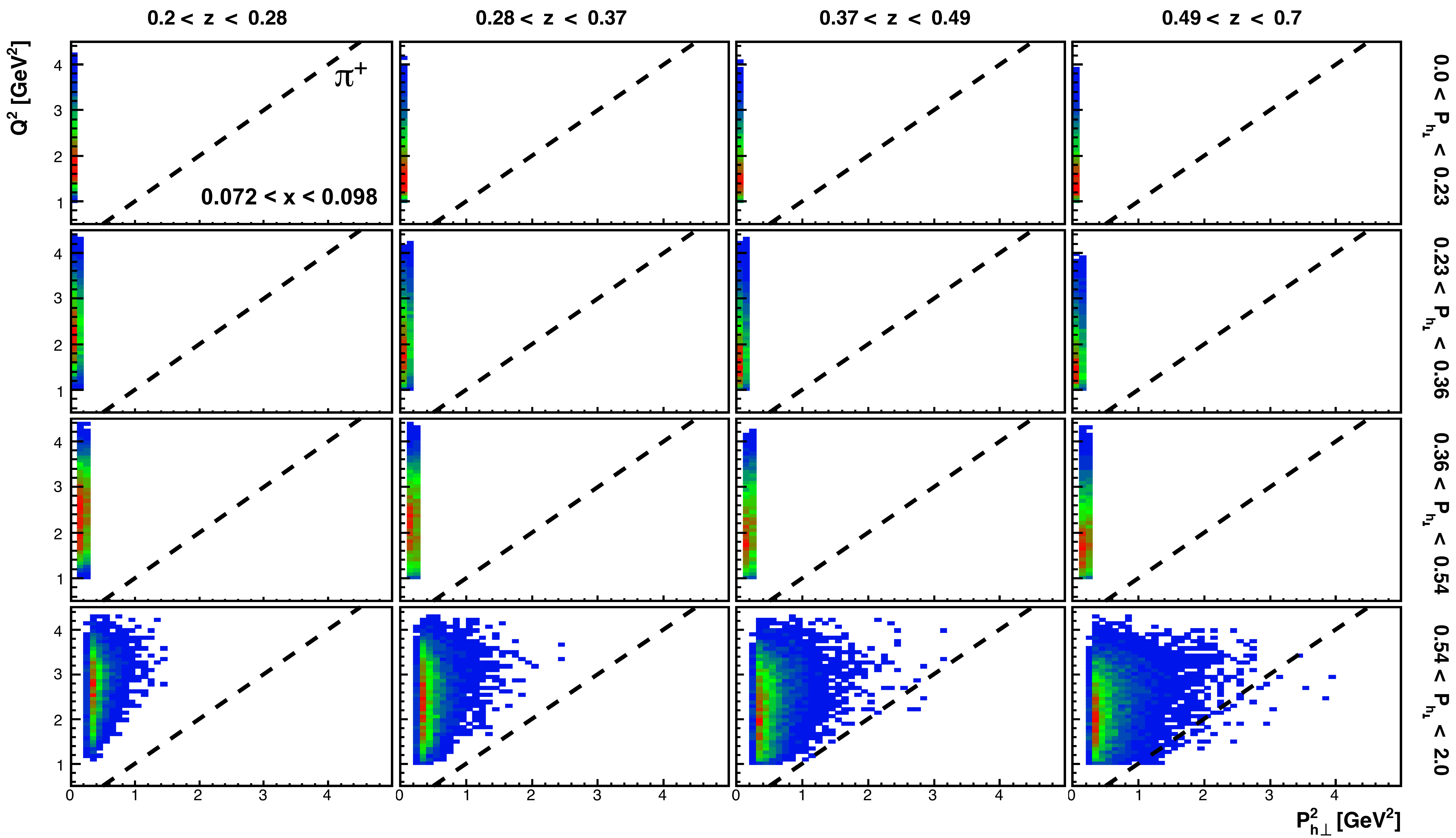
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes - 3d binning

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

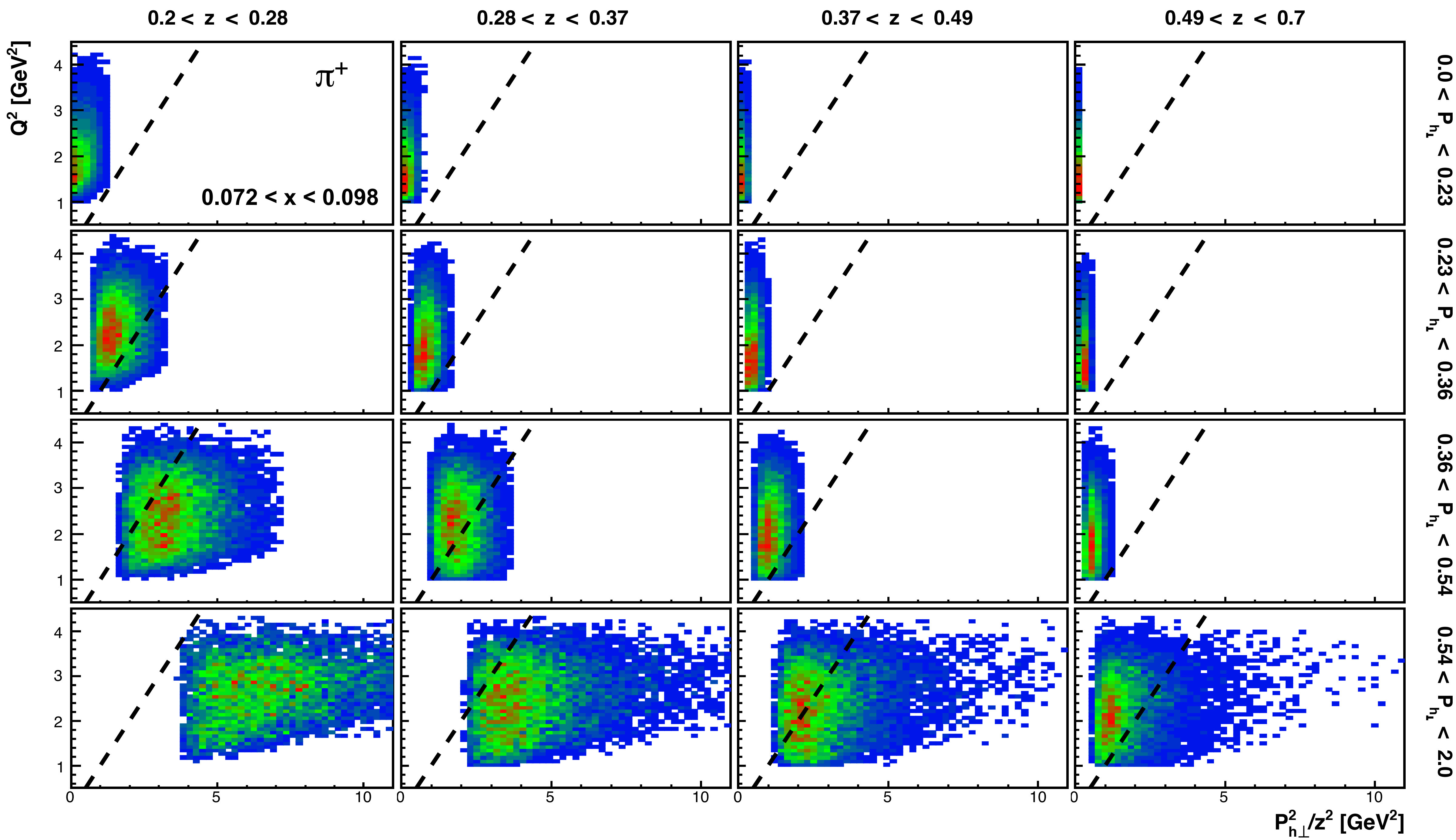


TMD factorization scale $Q^2 \gg P_{h\perp}^2/z^2$



- less stringent requirement fulfilled in basically all bins
- more stringent requirement violated at low z & large $P_{h\perp}$ (especially @ low x)

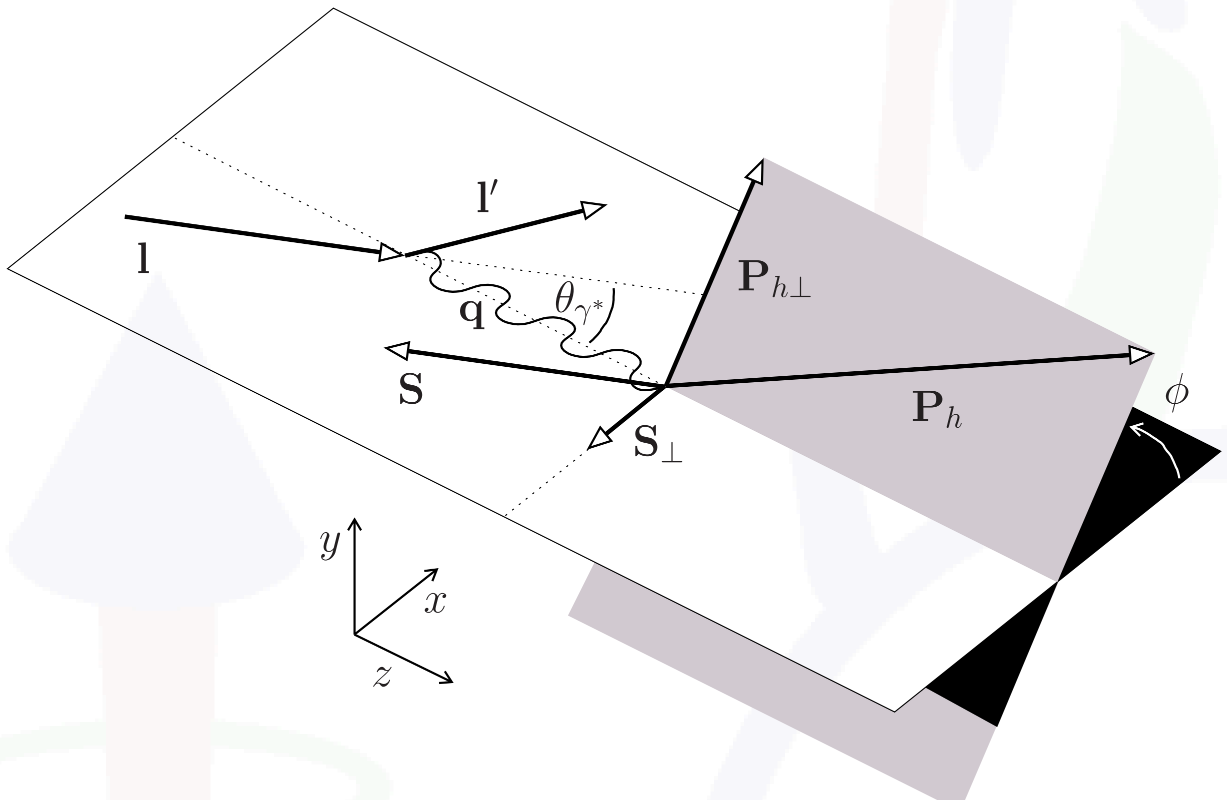
TMD factorization scale $Q^2 \gg P_{h\perp}^2 / z^2$



- less stringent requirement fulfilled in basically all bins
- more stringent requirement violated at low z & large $P_{h\perp}$ (especially @ low x)

subleading twist

Subleading twist I - $\langle \sin(\phi) \rangle_{UL}$



- 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

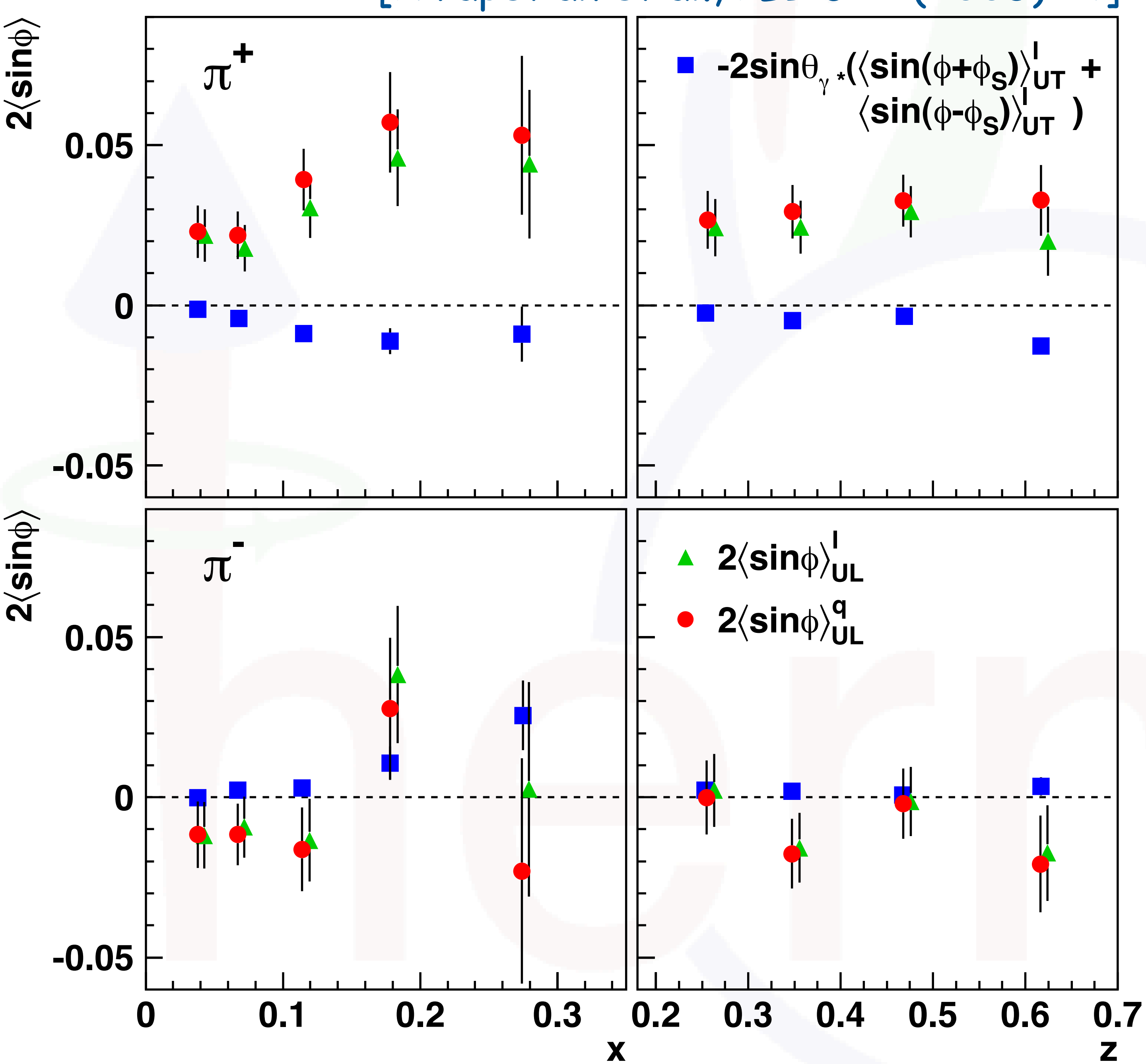
$$\begin{pmatrix} \left\langle \sin\phi \right\rangle_{UL}^{l} \\ \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \\ \left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*}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

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

Subleading twist I - <sin(ϕ)>$_{UL}$

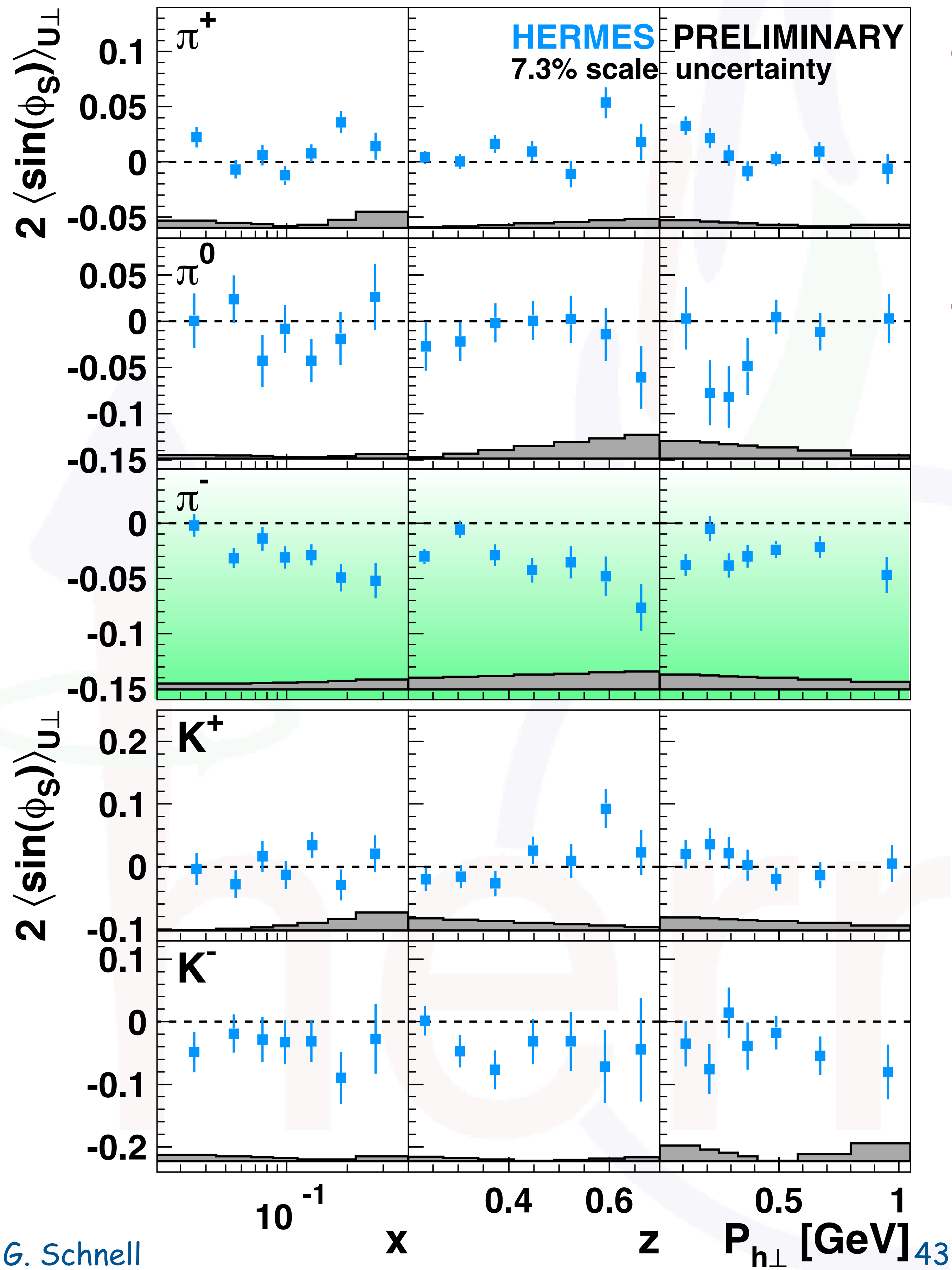
$$\left\langle \sin\phi \right\rangle_{UL}^{q} = \left\langle \sin\phi \right\rangle_{UL}^{l} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle_{UT}^{l} + \left\langle \sin(\phi-\phi_S) \right\rangle_{UT}^{l} \right)$$

[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^-

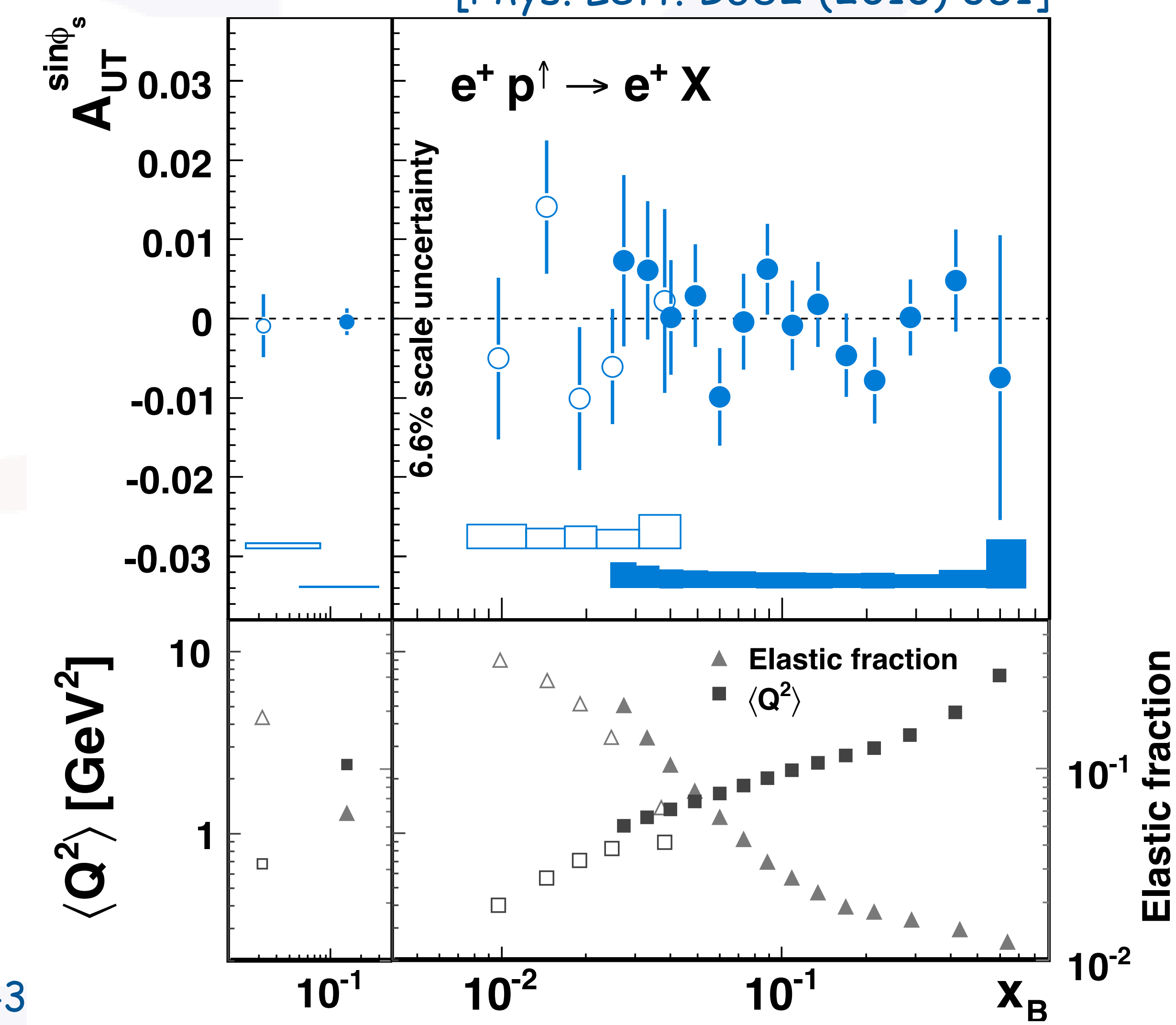
Subleading twist II - $\langle\sin(\phi_S)\rangle_{UT}$



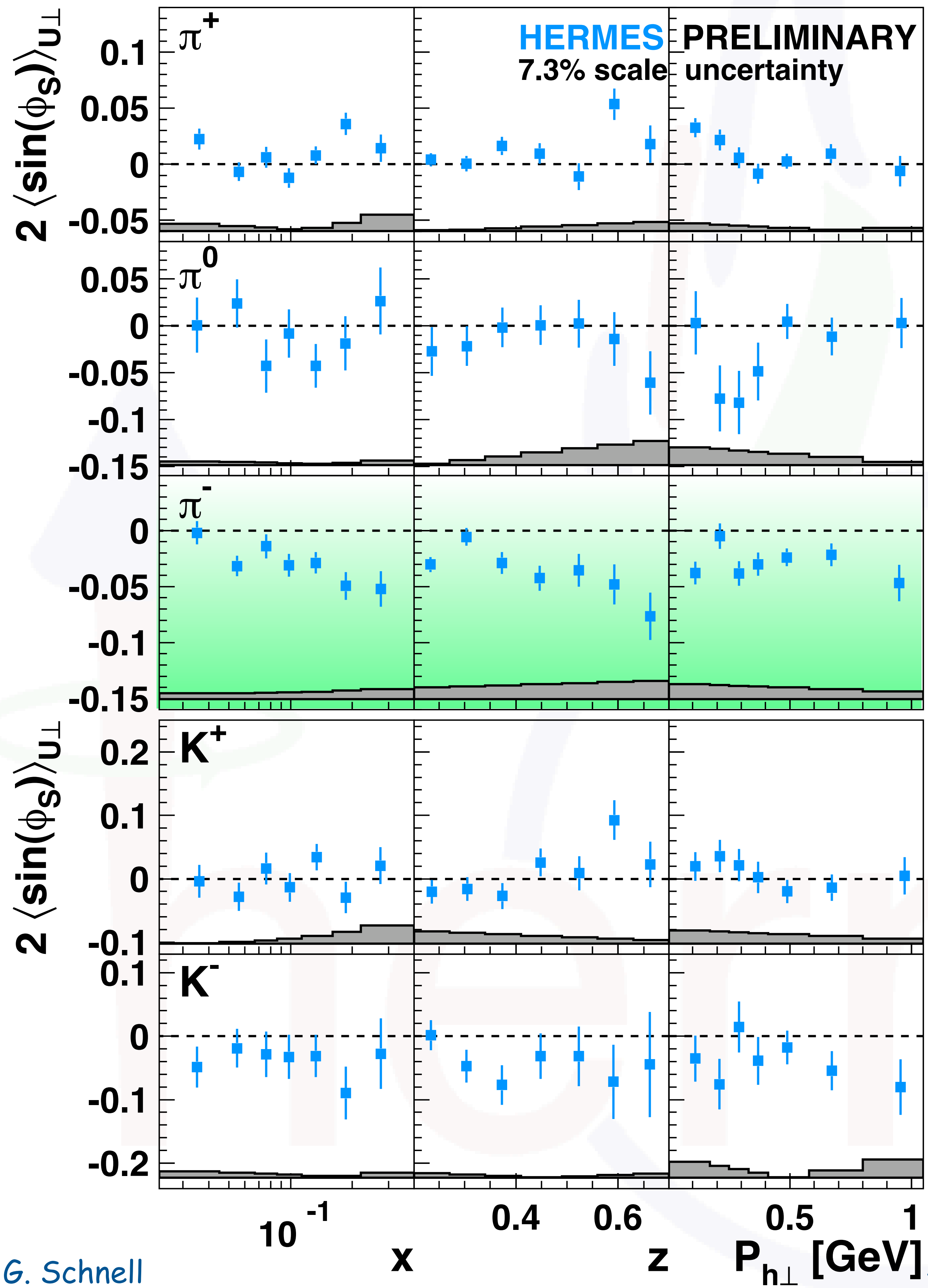
- significant non-zero signal observed for negatively charged mesons

- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons

[Phys. Lett. B682 (2010) 351]



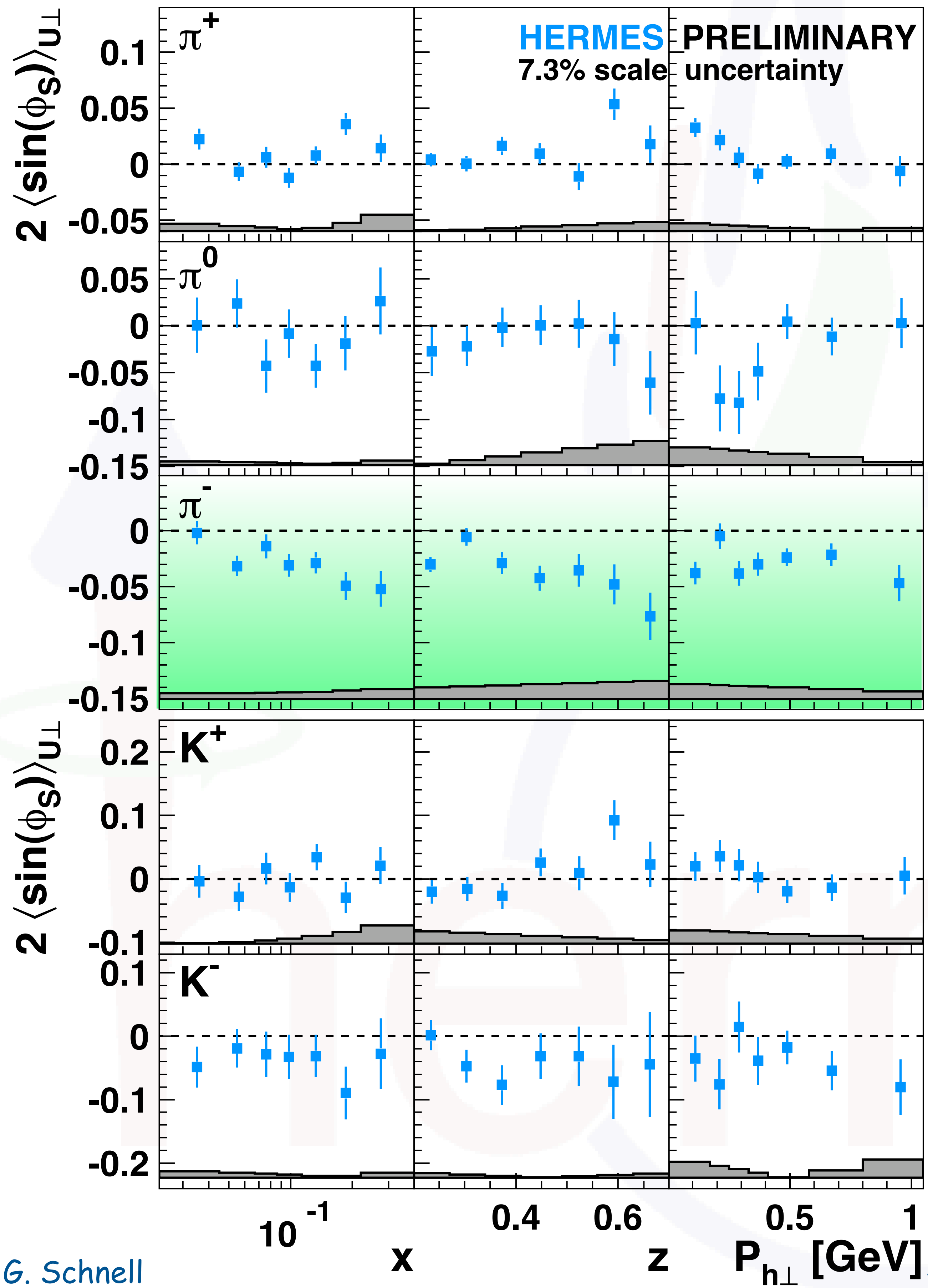
Subleading twist II - $\langle \sin(\phi_s) \rangle_{UT}$

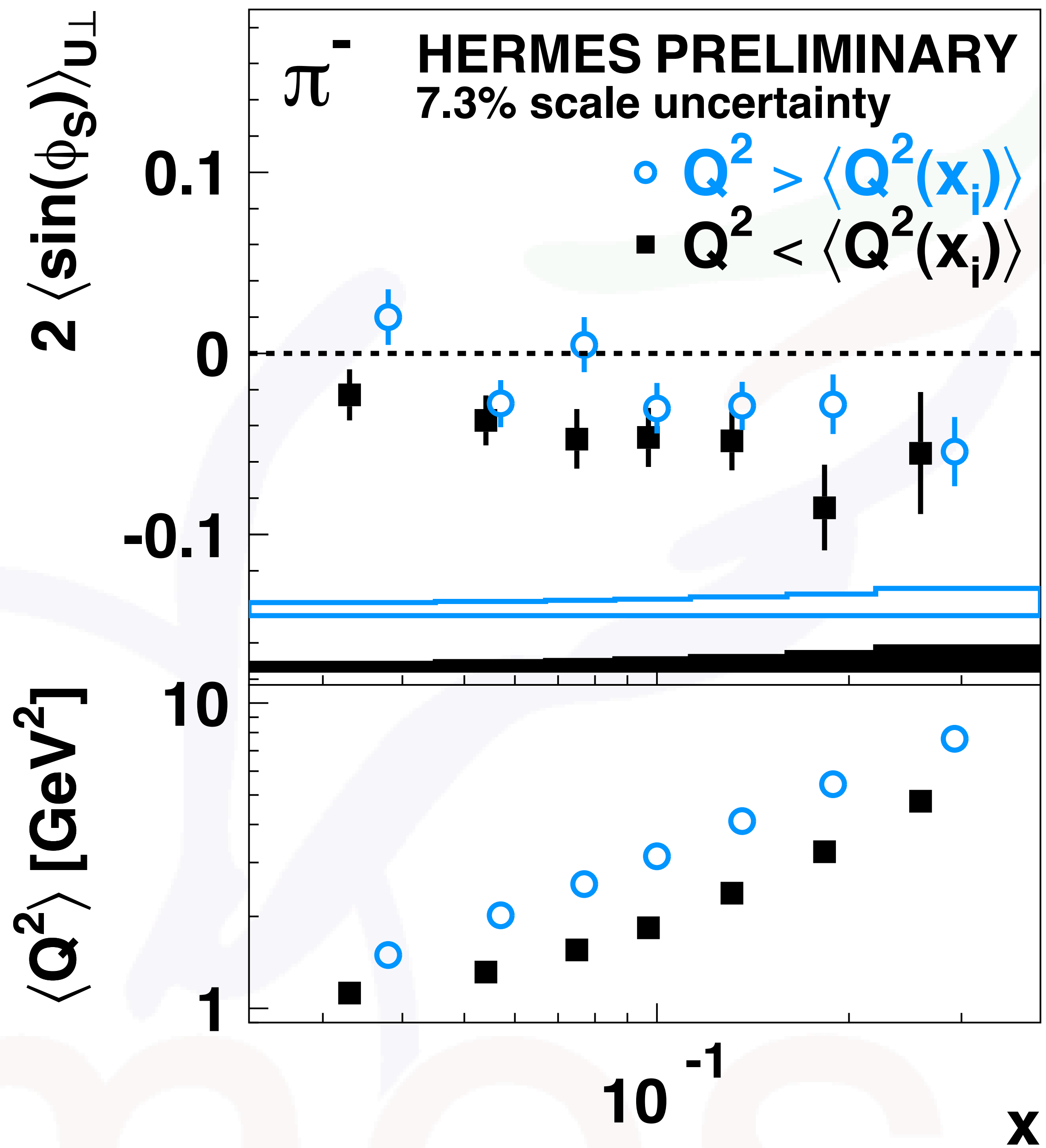


- significant non-zero signal observed for negatively charged mesons
- vanishes in inclusive limit, e.g. after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

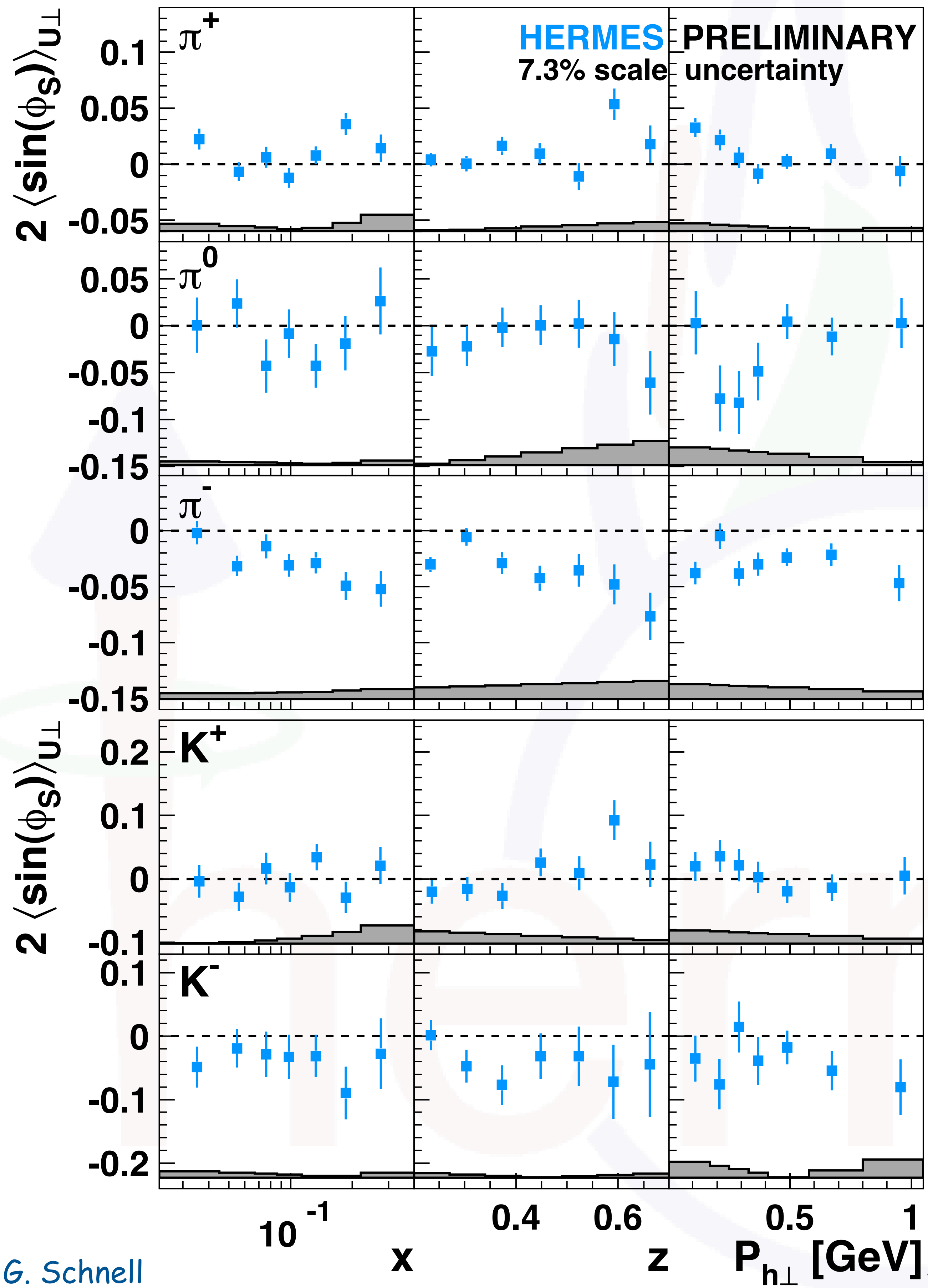
Subleading twist II - $\langle \sin(\phi_s) \rangle_{UT}$

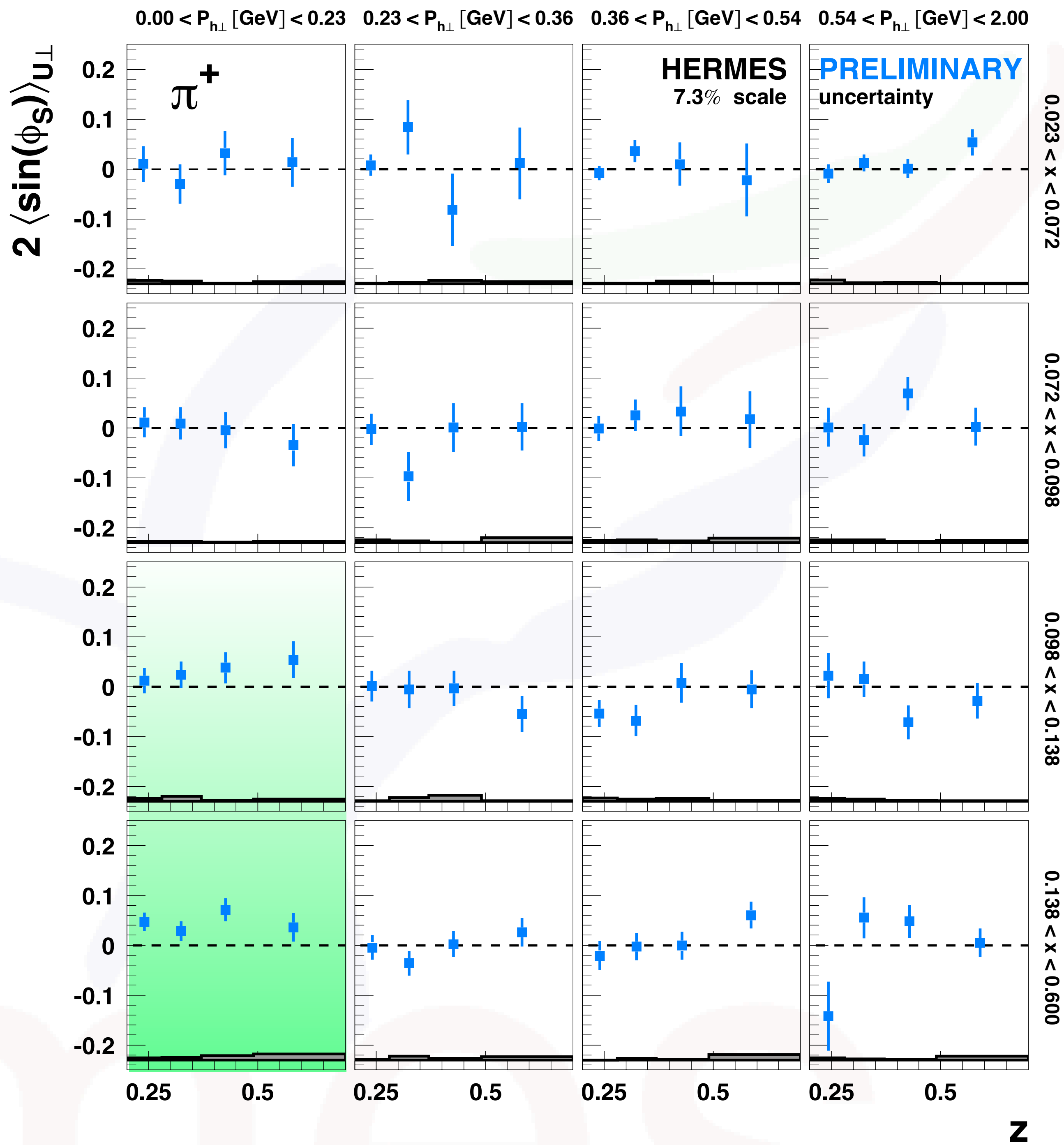




- hint of Q^2 dependence seen in signal for negative pions

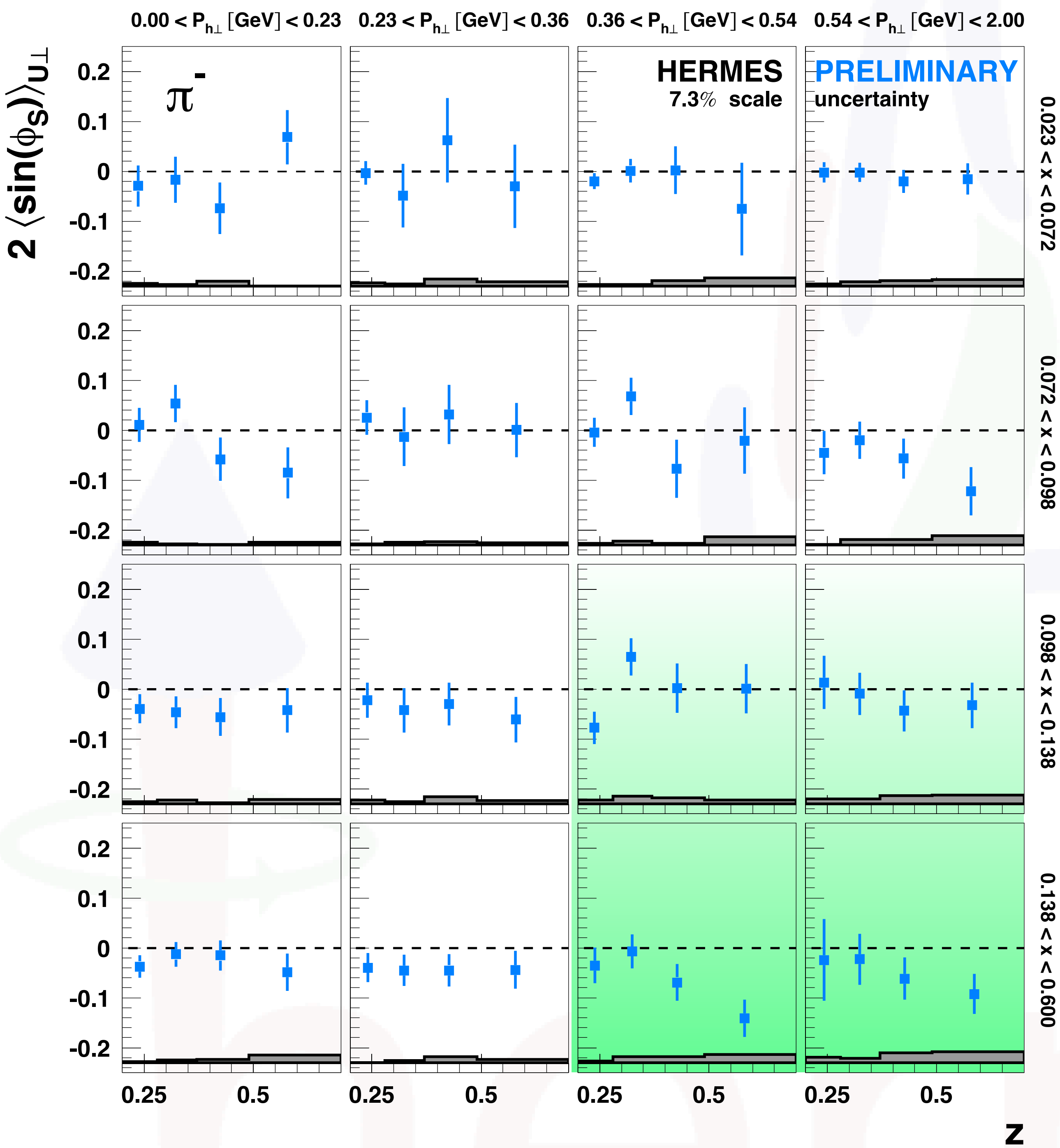
Subleading twist II - $\langle\sin(\phi_S)\rangle_{UT}$

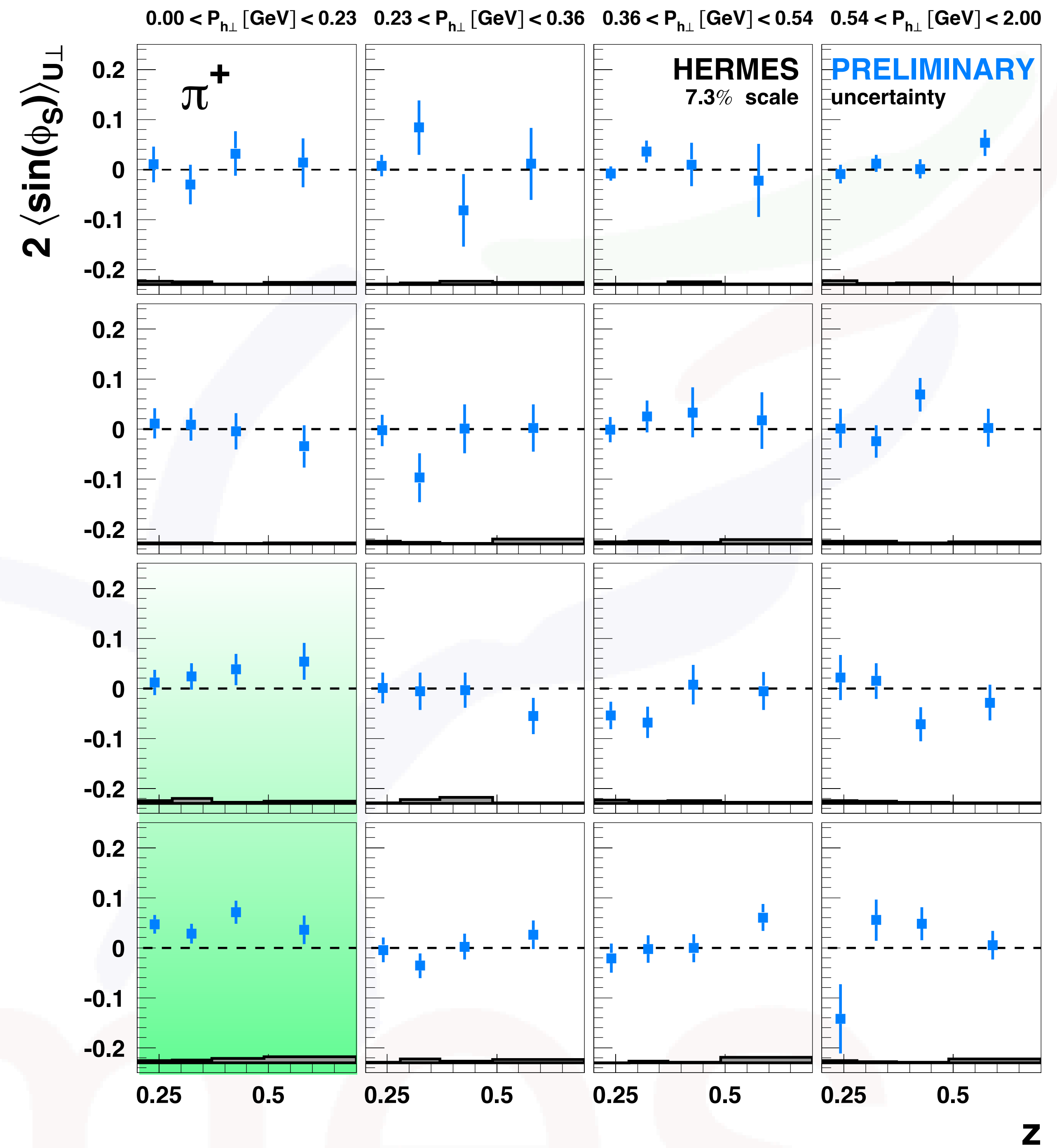




- positive amplitudes at low $P_{h\perp}$ also for positive pions

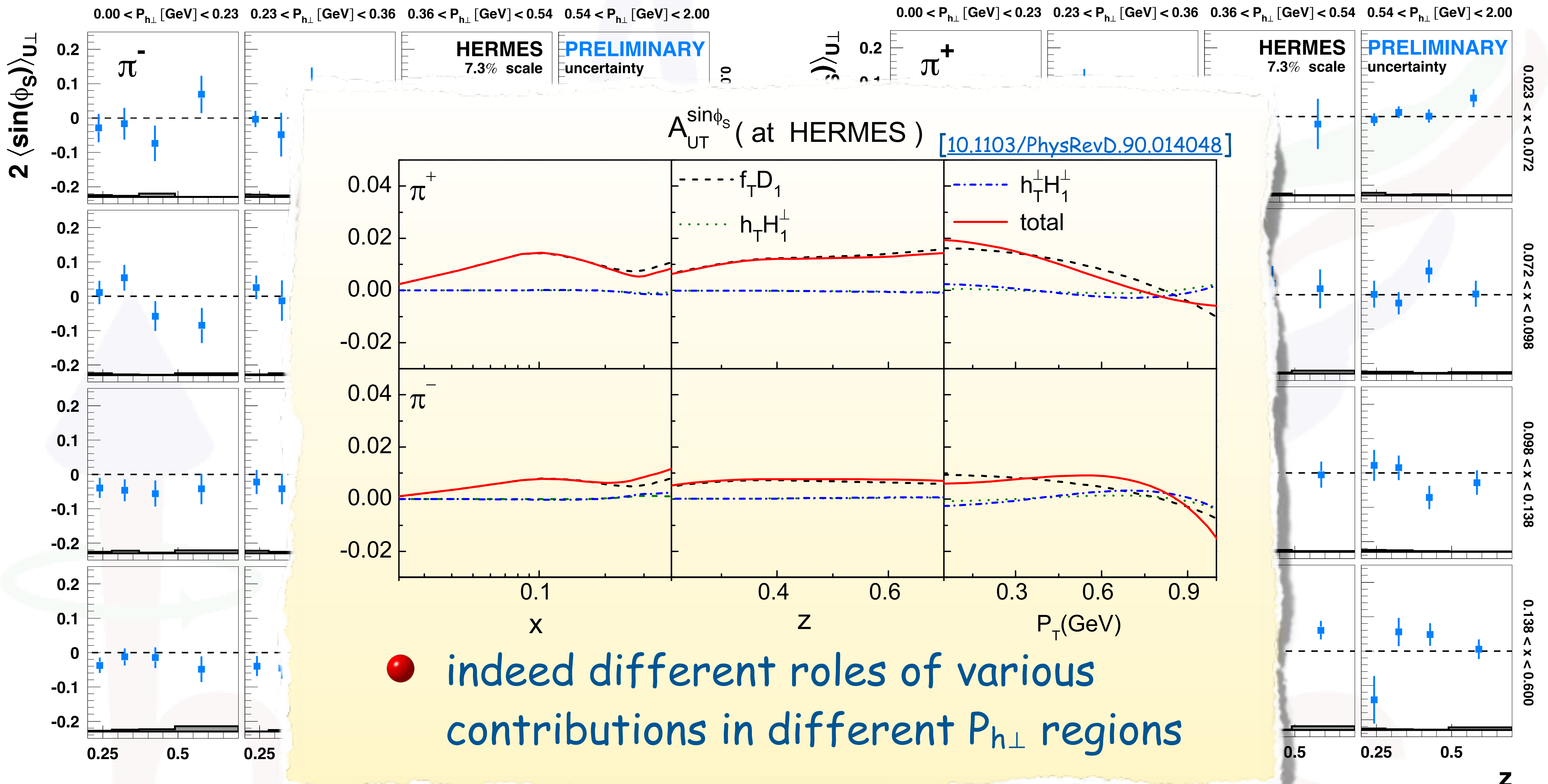
Subleading twist II - $\langle \sin(\phi_S) \rangle_{UT}$





- 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)>$_{UT}$

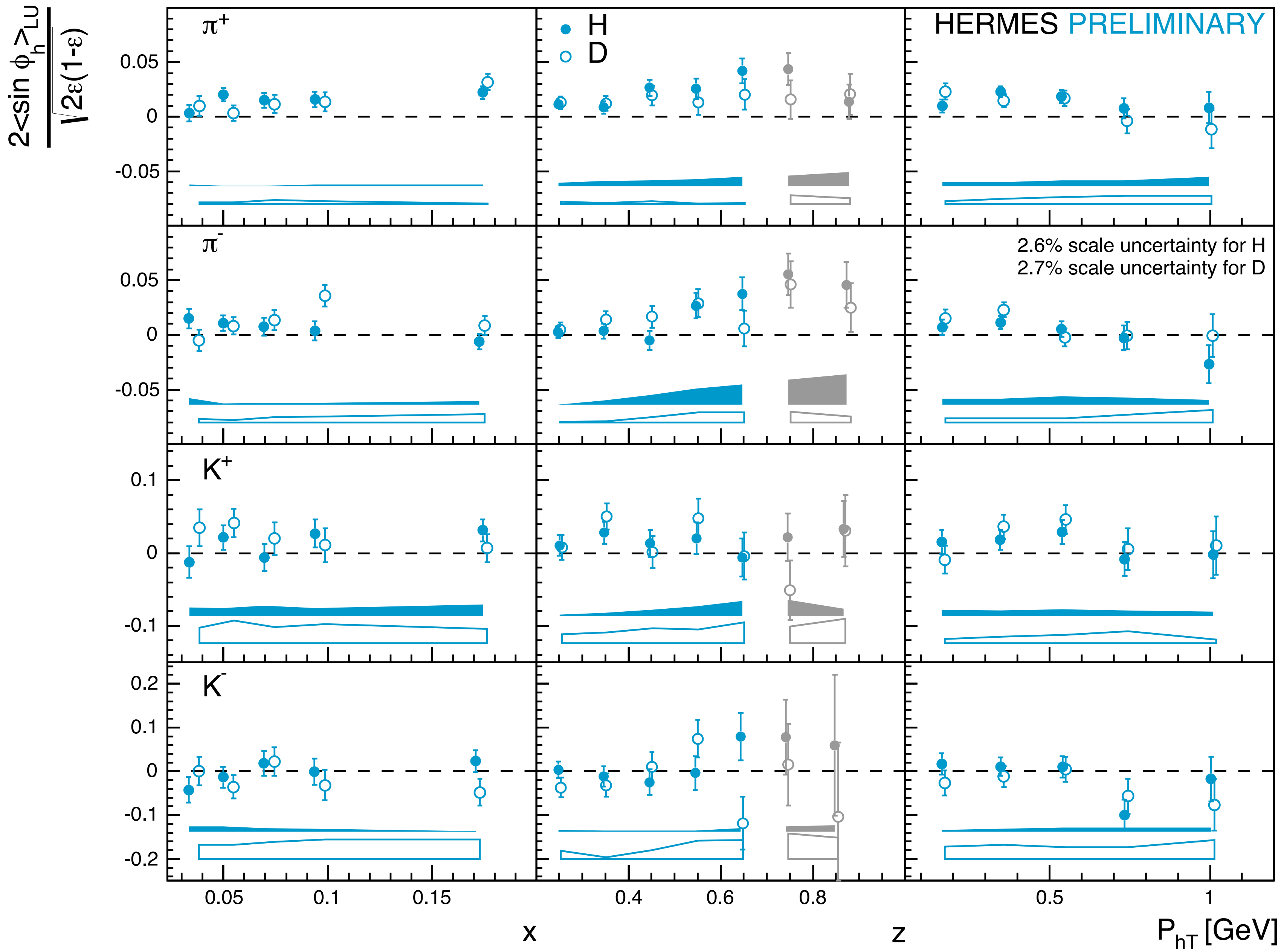


- indeed different roles of various contributions in different $P_{h\perp}$ regions

- 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)>$_{LU}$

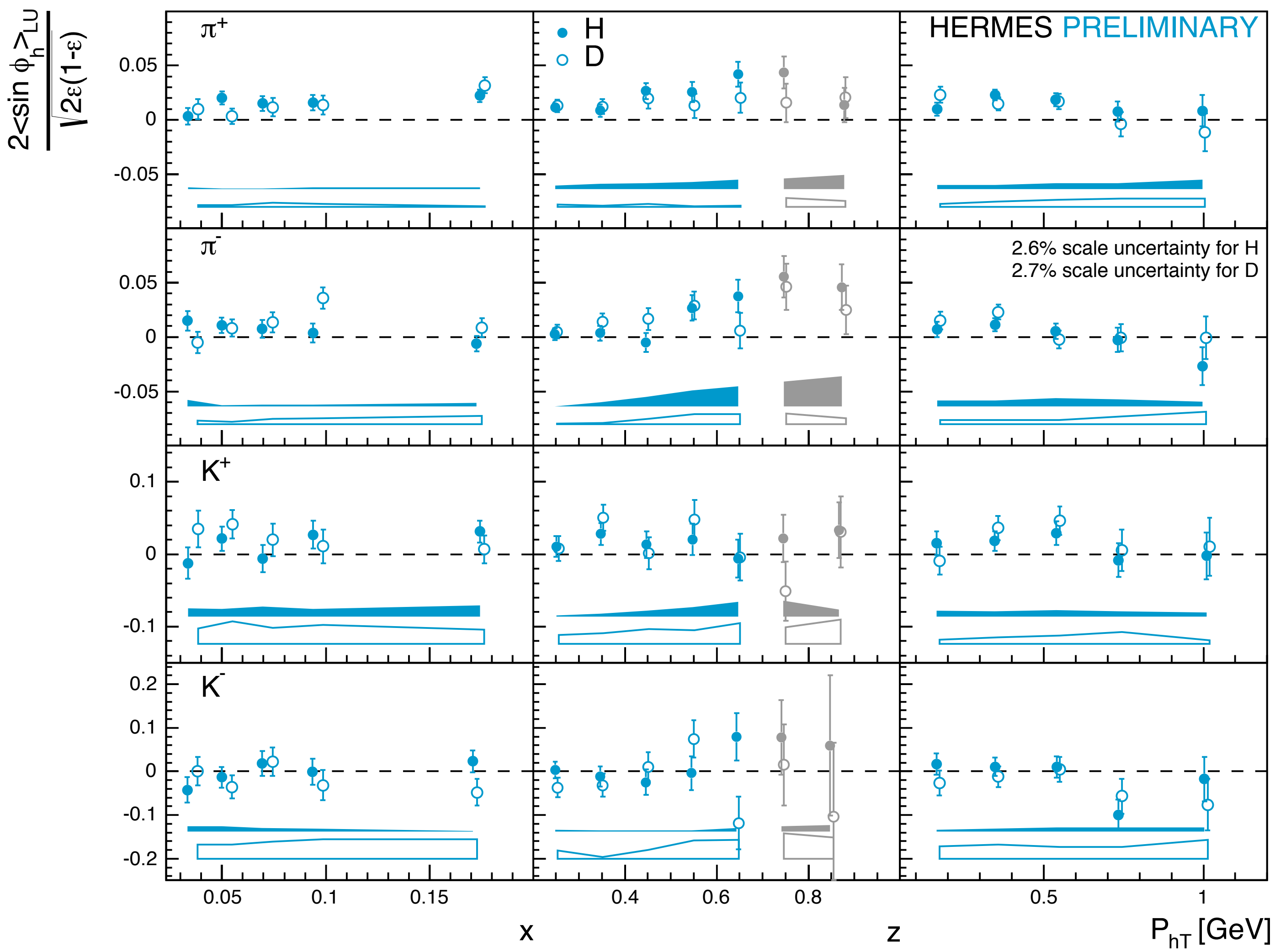
$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus x e H_1^{\perp}$$

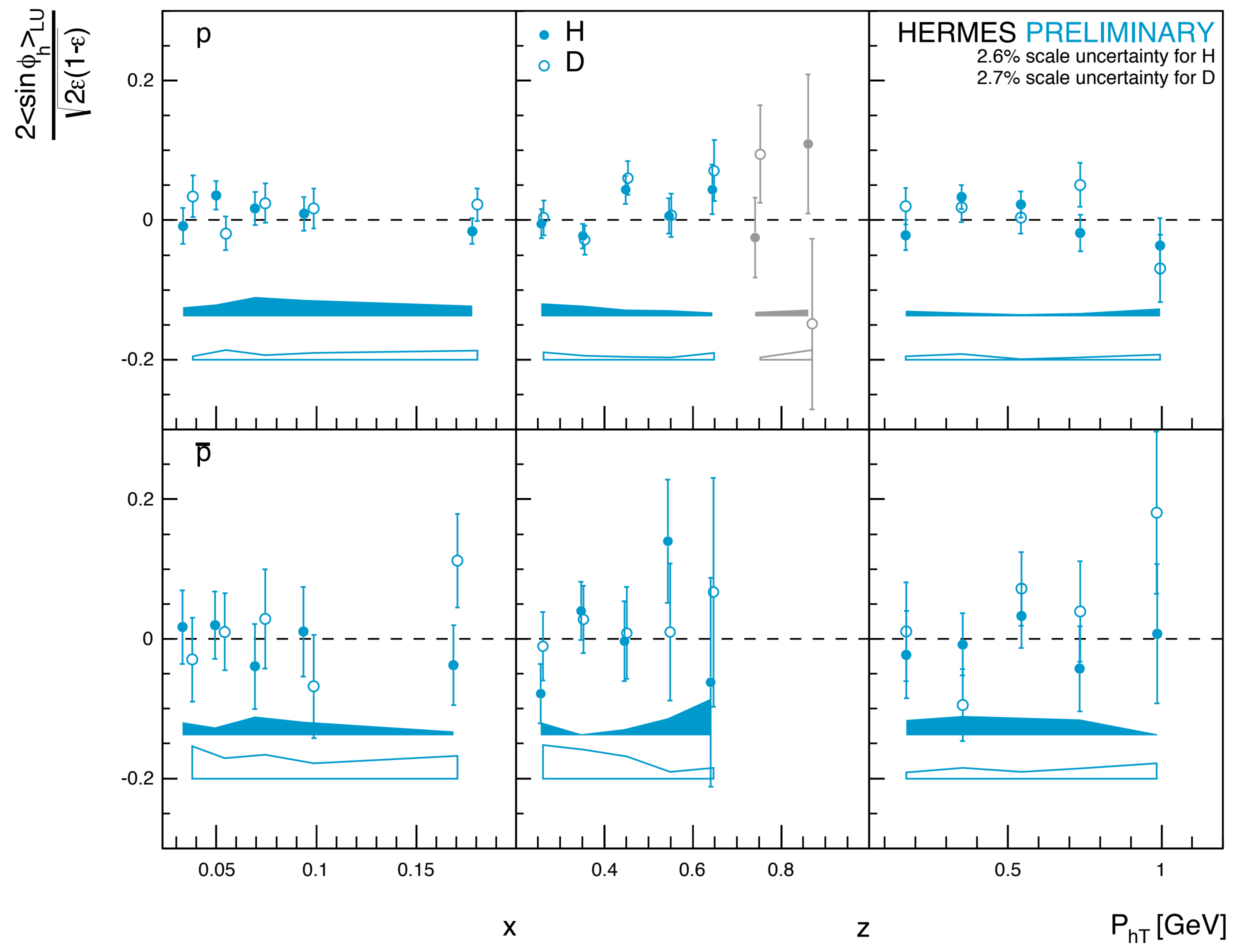


- significant positive amplitudes for (in particular positive) pions

Subleading twist III - $\langle\sin(\phi)\rangle_{LU}$

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

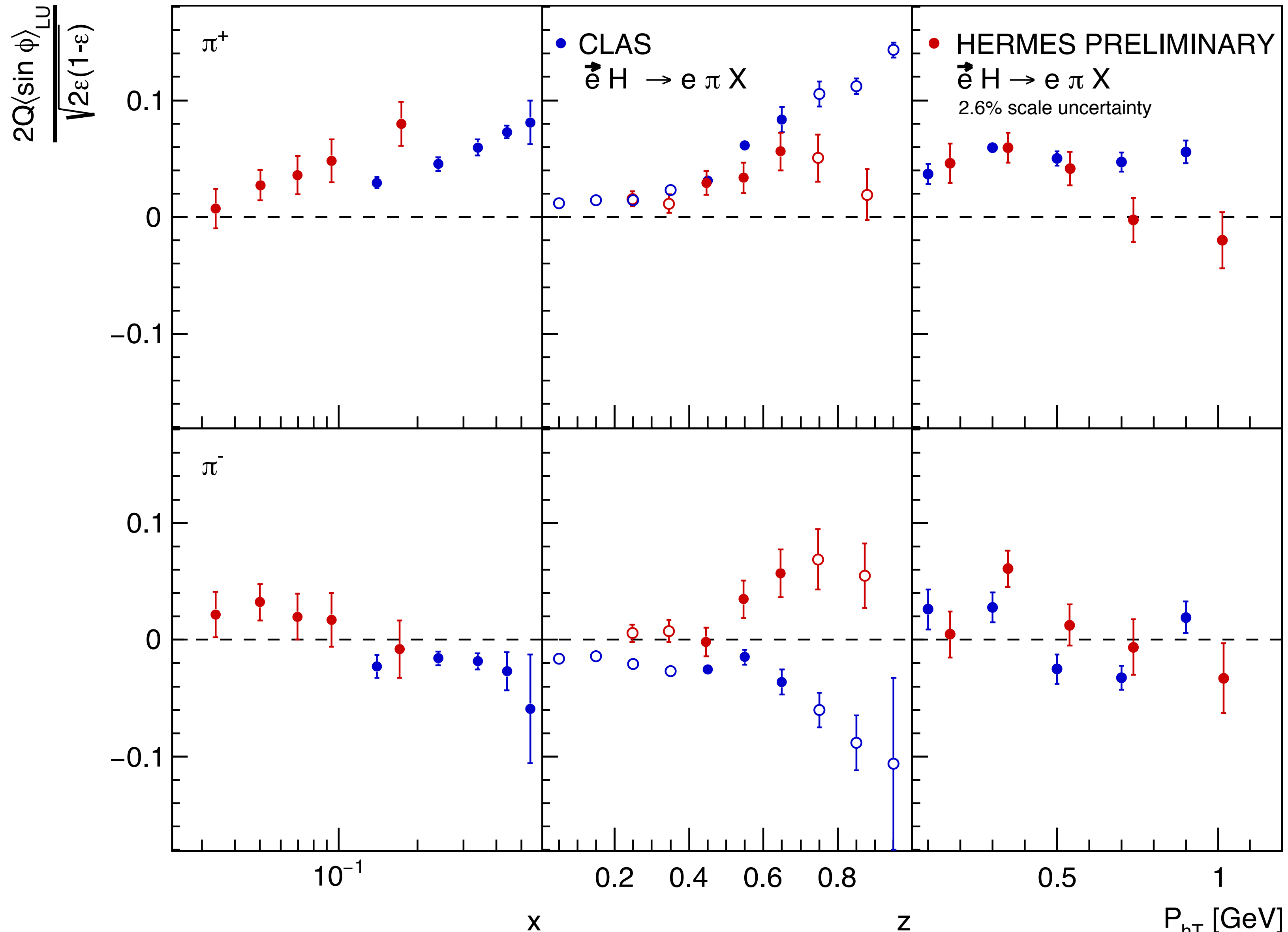




- mostly consistent w/ zero for other hadrons (except maybe K+)

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

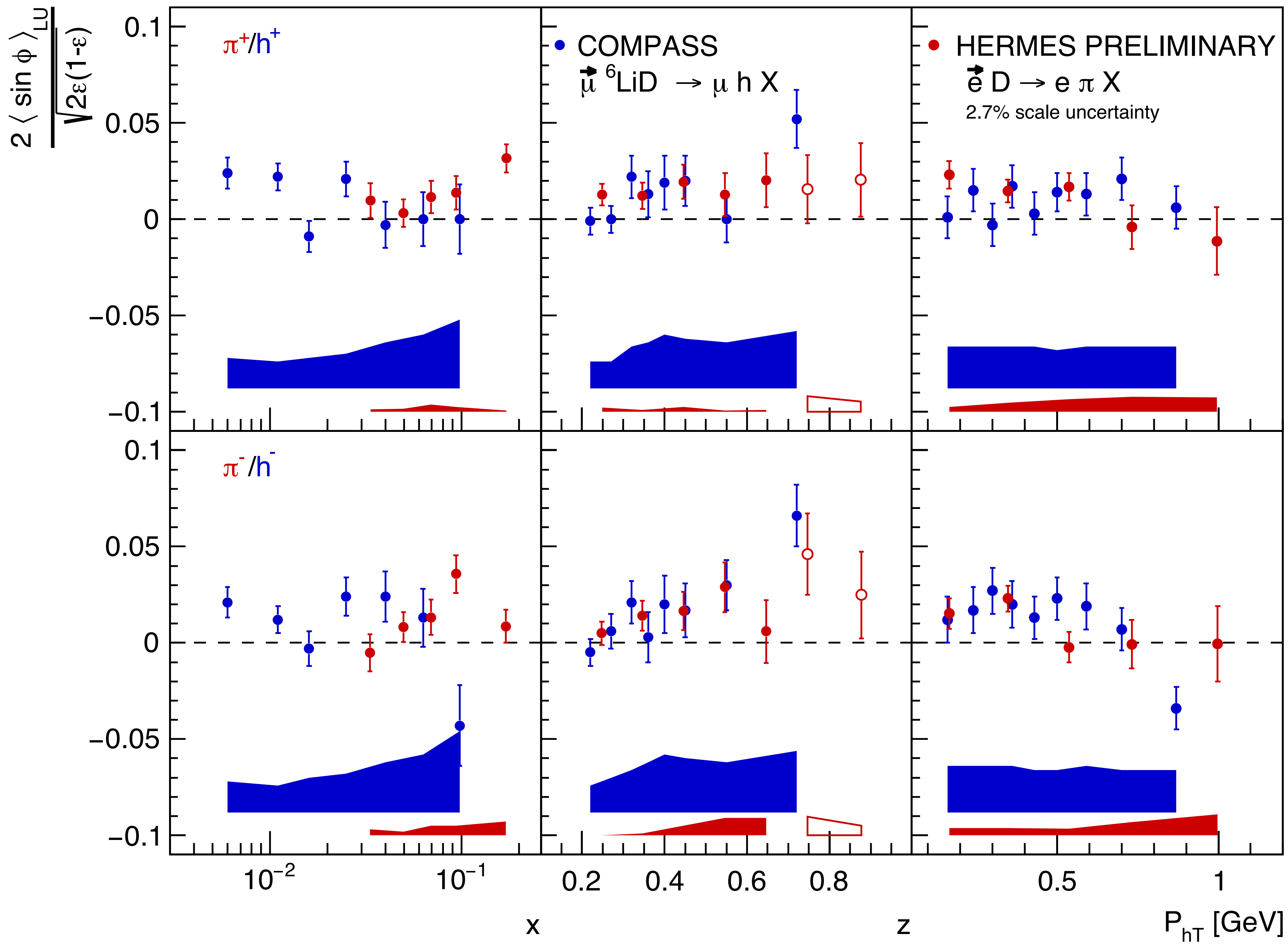
$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus x e H_1^{\perp}$$



- 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)>$_{LU}$

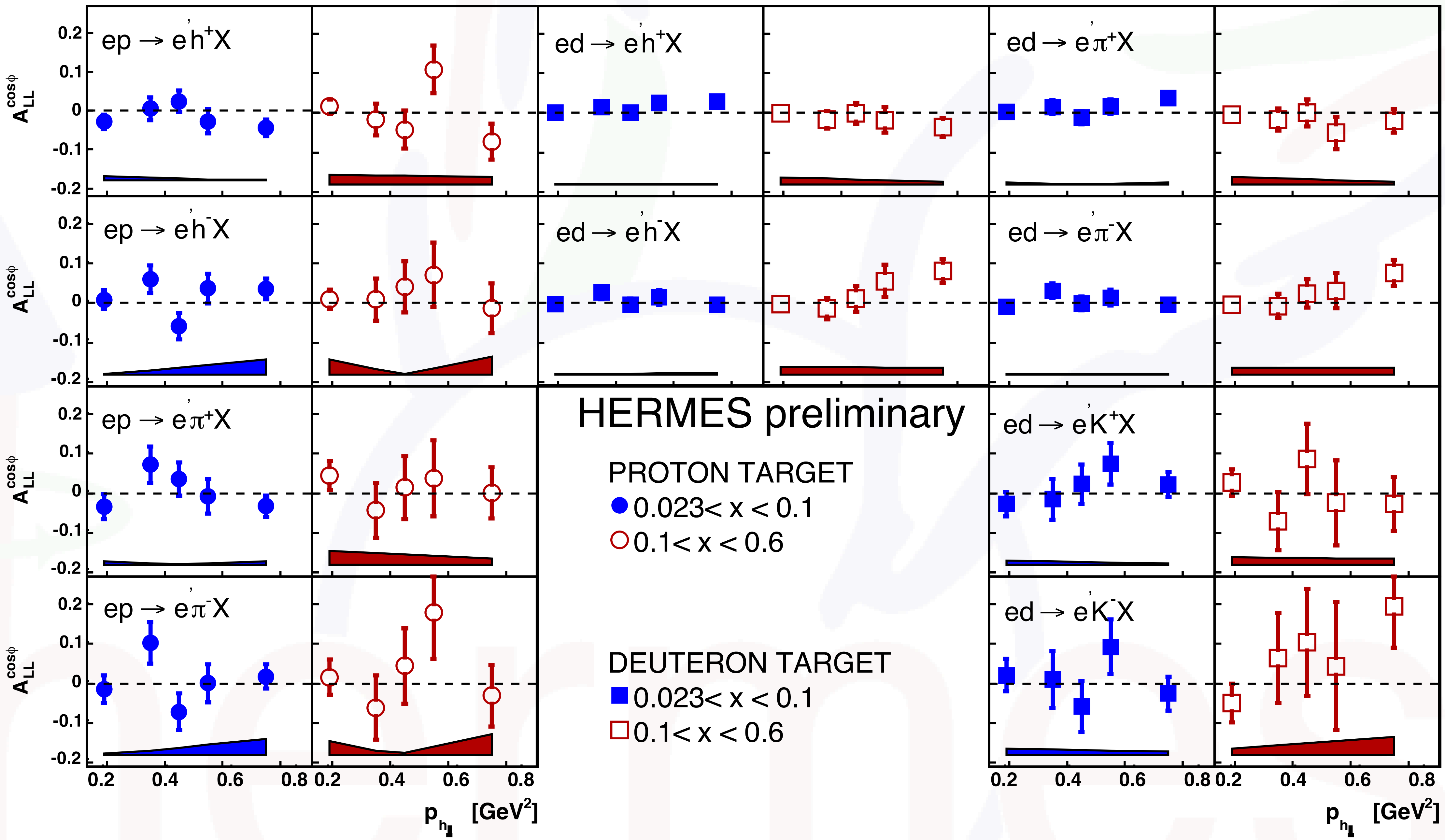
$$\frac{M_h}{Mz} h_1^\perp E \oplus x g^\perp D_1 \oplus \frac{M_h}{Mz} f_1 G^\perp \oplus x e H_1^\perp$$



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

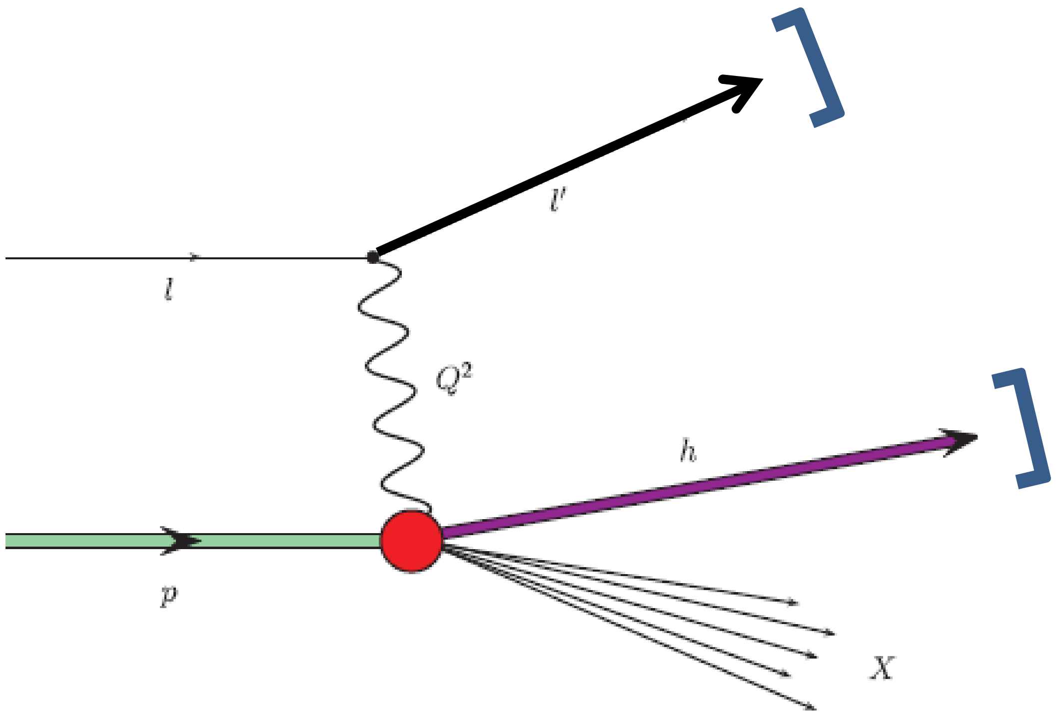
Subleading twist IV - <cos(ϕ)>$_{LL}$

$$F_{LL}^{\cos\phi} \overset{\text{WW}}{\simeq} g_{1L}(x, p_T^2) \otimes D_1(z, k_T^2)$$

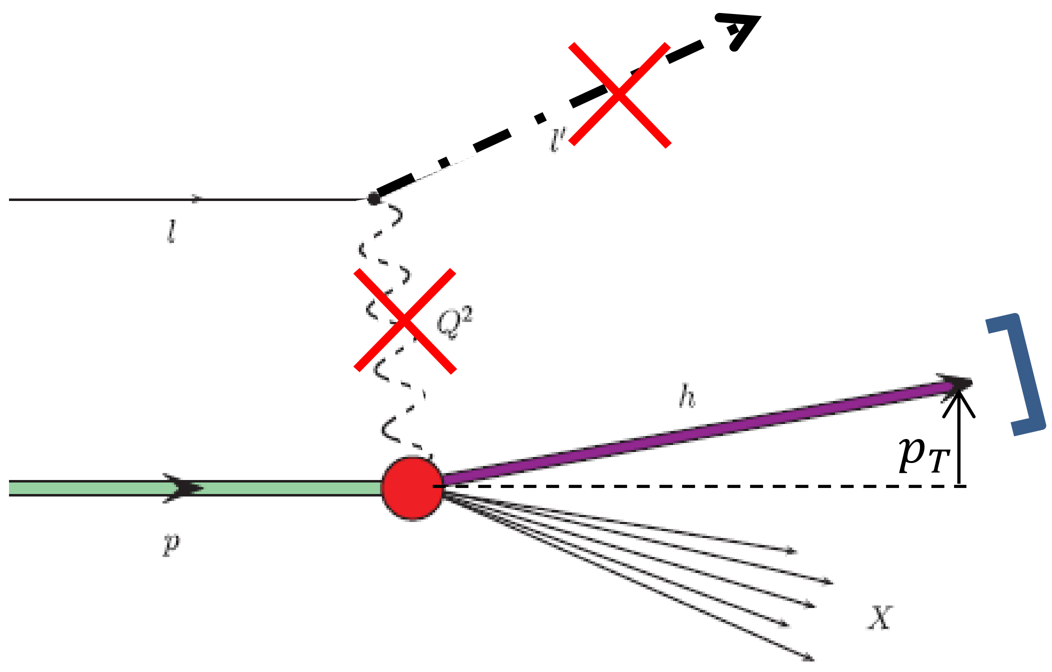


- "polarized" Cahn effect largely consistent with zero

Semi-inclusive hadrons



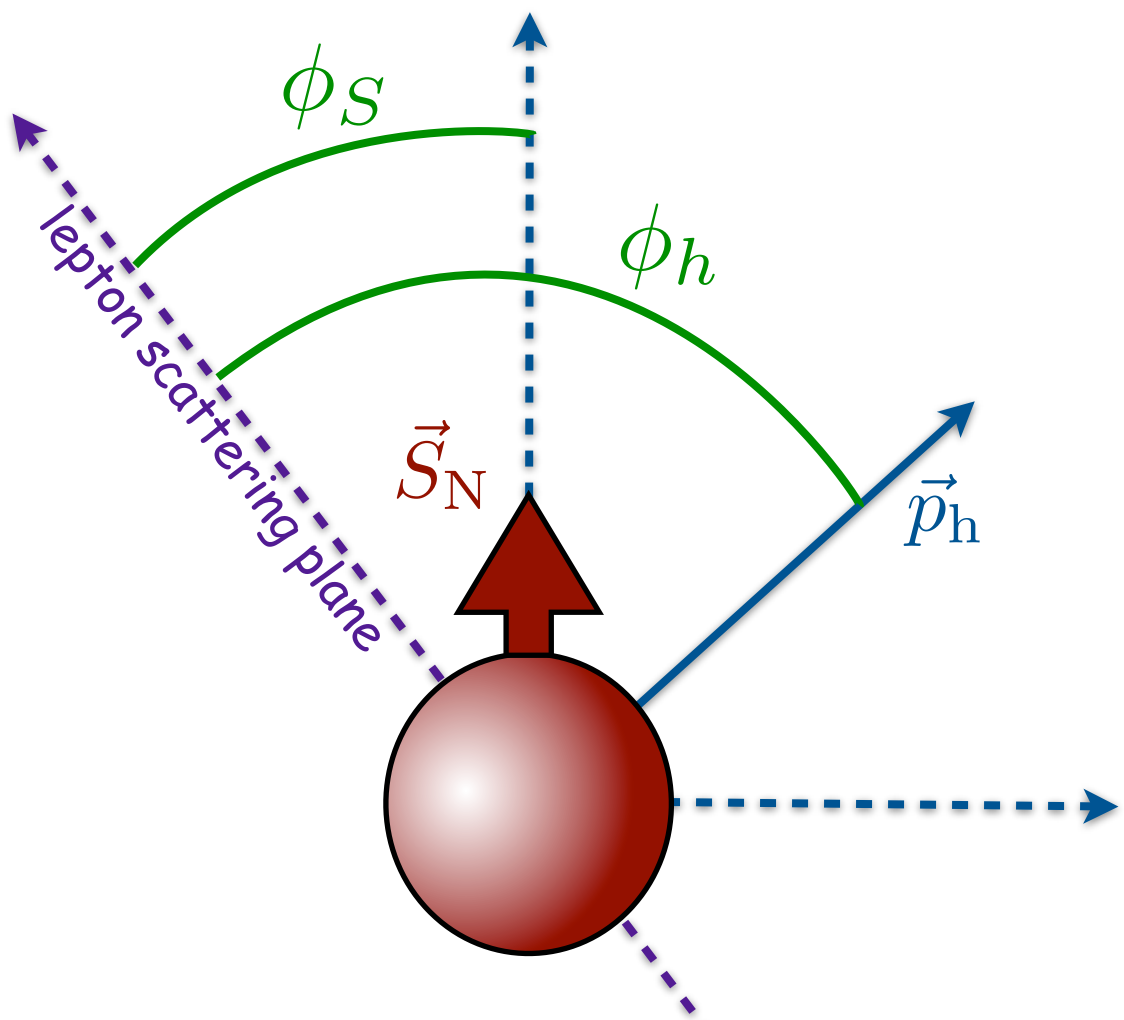
S~~e~~mi-inclusive hadrons



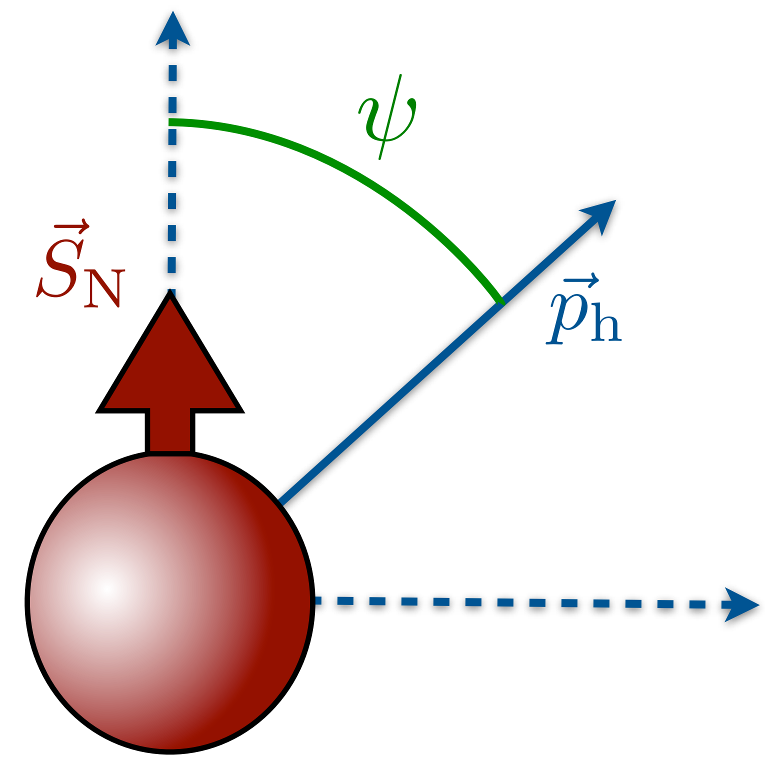
click here if (likely) out of time

Inclusive hadron electro-production

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



virtual photon going into the page



lepton beam going into the page

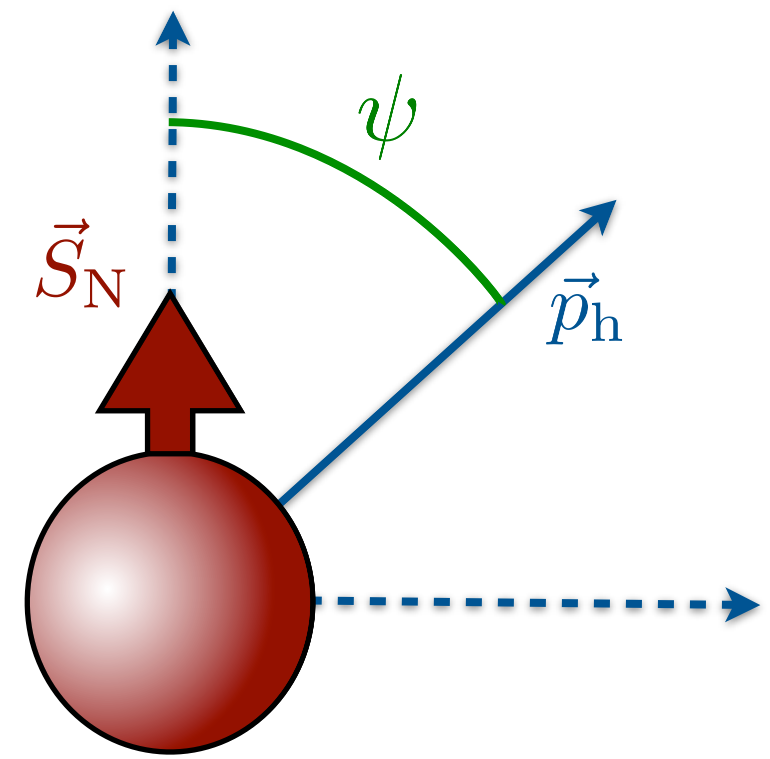
$$\psi \simeq \phi_h - \phi_S$$

➡ "Sivers angle"

Inclusive hadron electro-production

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

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



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

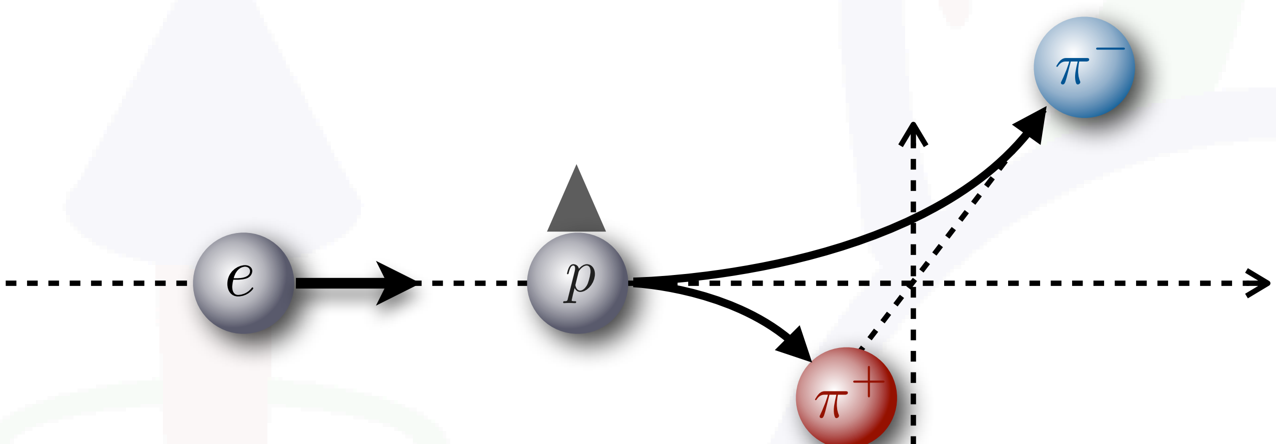
$$A_{\rm N} \equiv \frac{\int_{\pi}^{2\pi} d\psi\ \sigma_{\rm UT}\sin\psi - \int_0^{\pi} d\psi\ \sigma_{\rm UT}\sin\psi}{\int_0^{2\pi} d\psi\ \sigma_{\rm UU}}$$

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

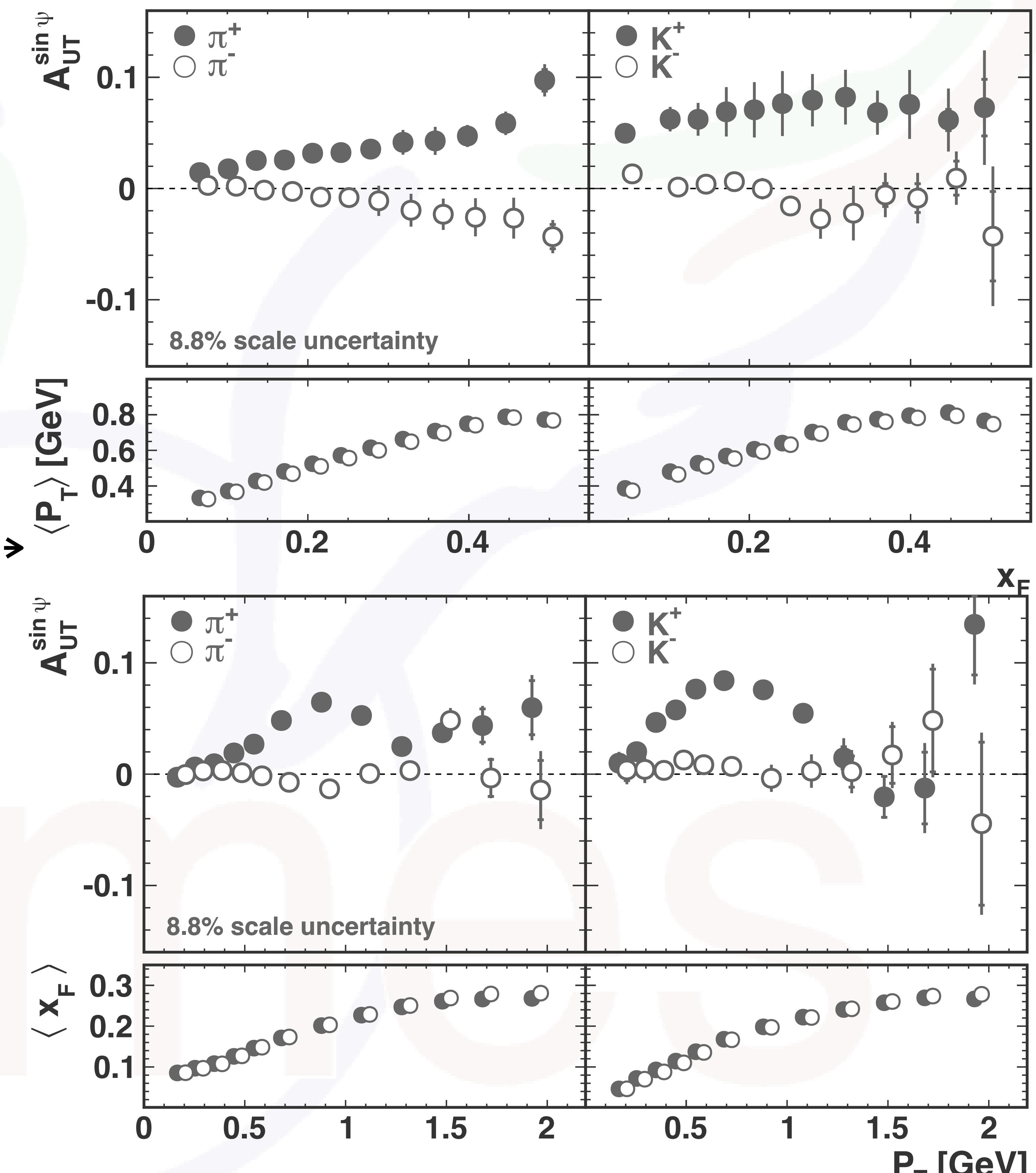
1D dependences of A_{UT} $\sin\psi$ amplitude

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

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

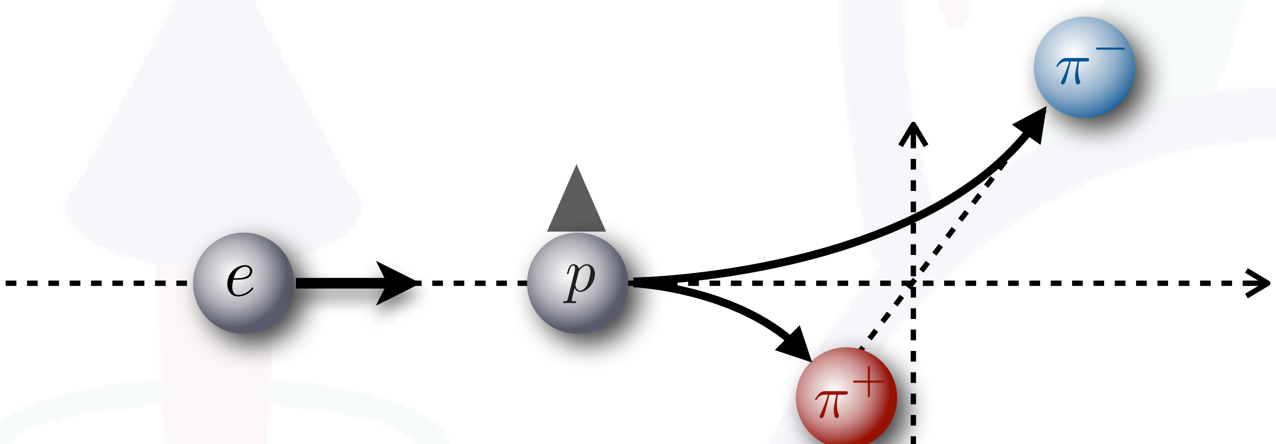


- initially increasing with P_T with a fall-off at larger P_T



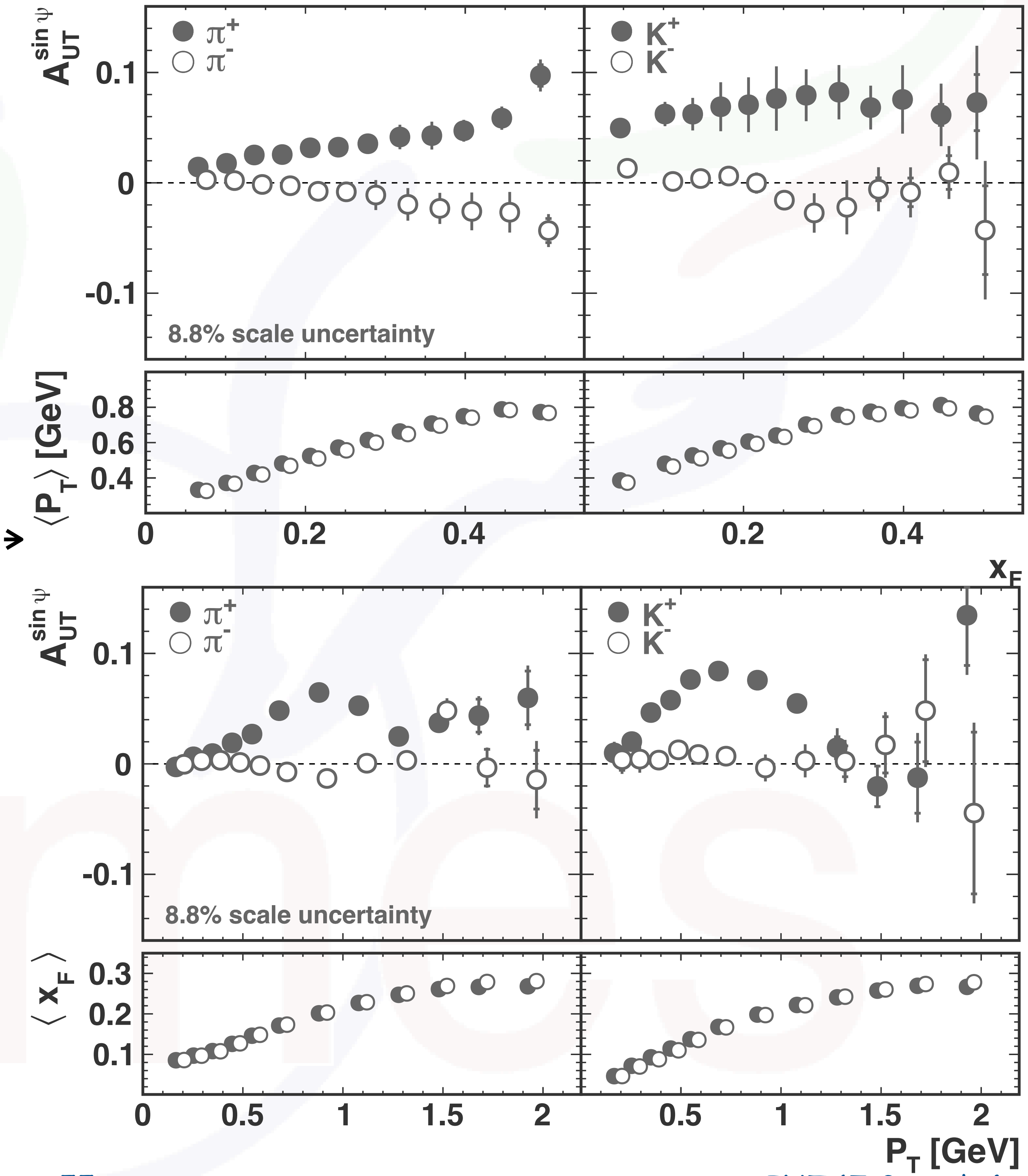
1D dependences of A_{UT} $\sin\psi$ amplitude

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



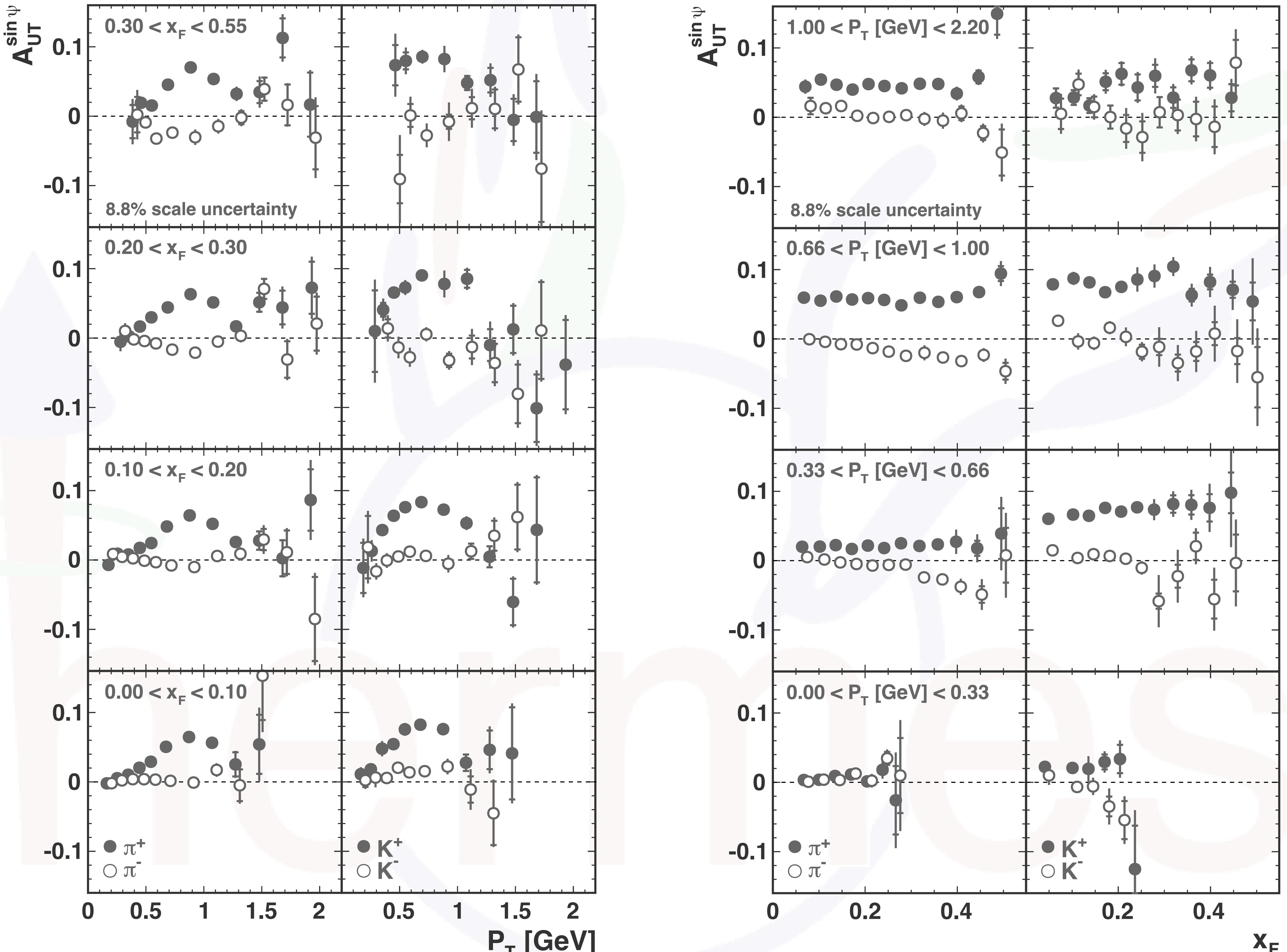
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➡ look at 2D dependences

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



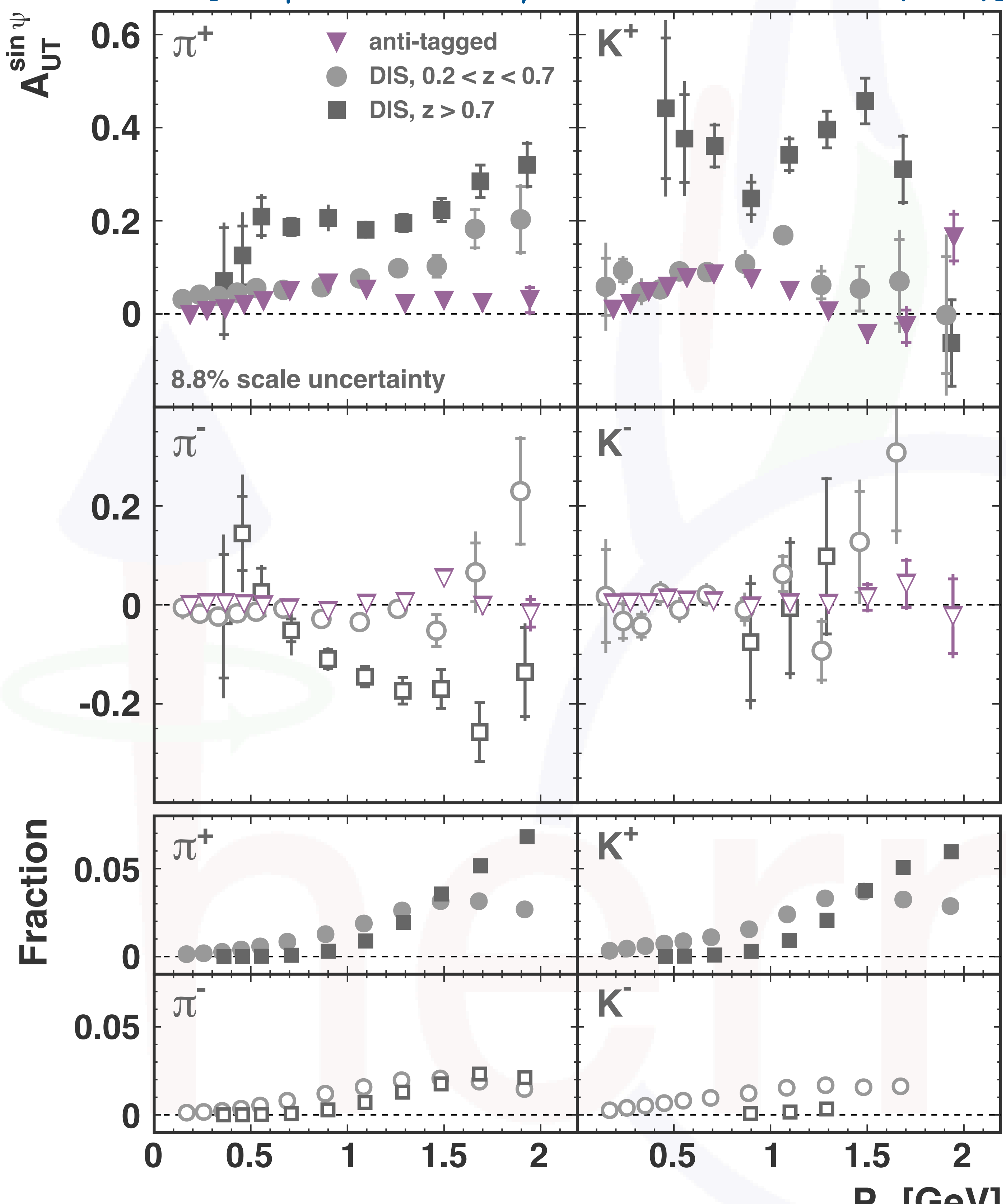
Inclusive hadrons: 2D dependences

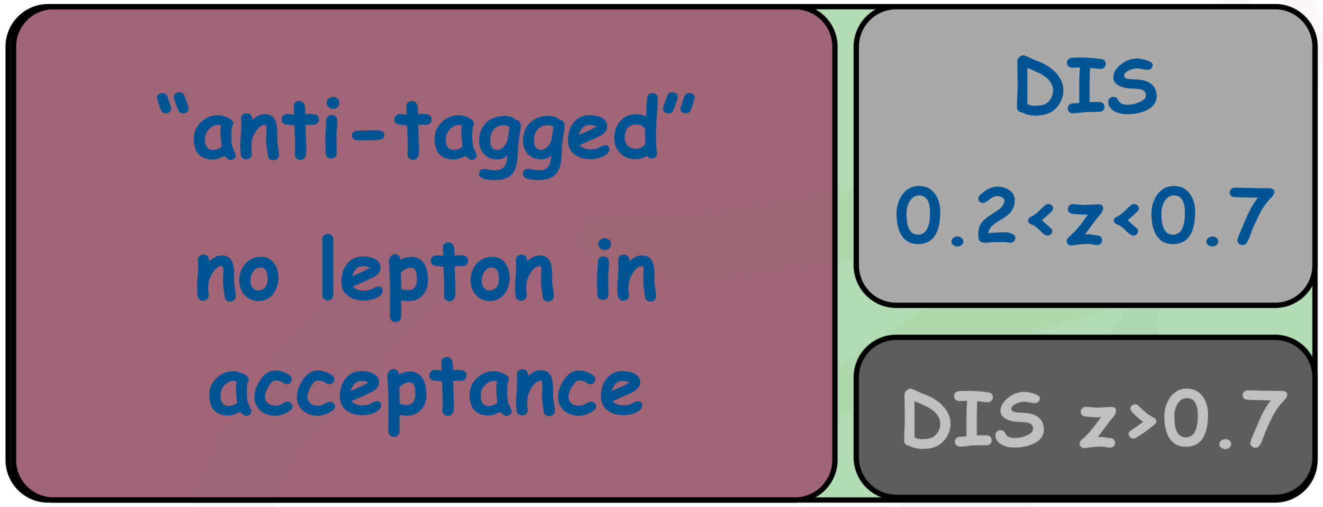
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



Asymmetries of subprocesses

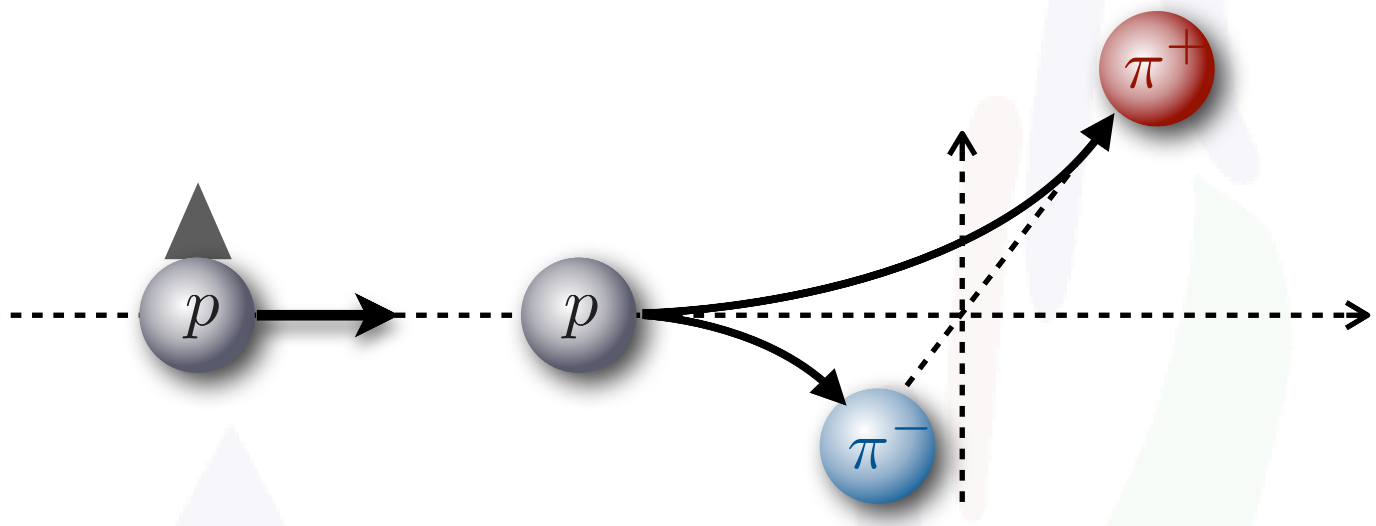
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]

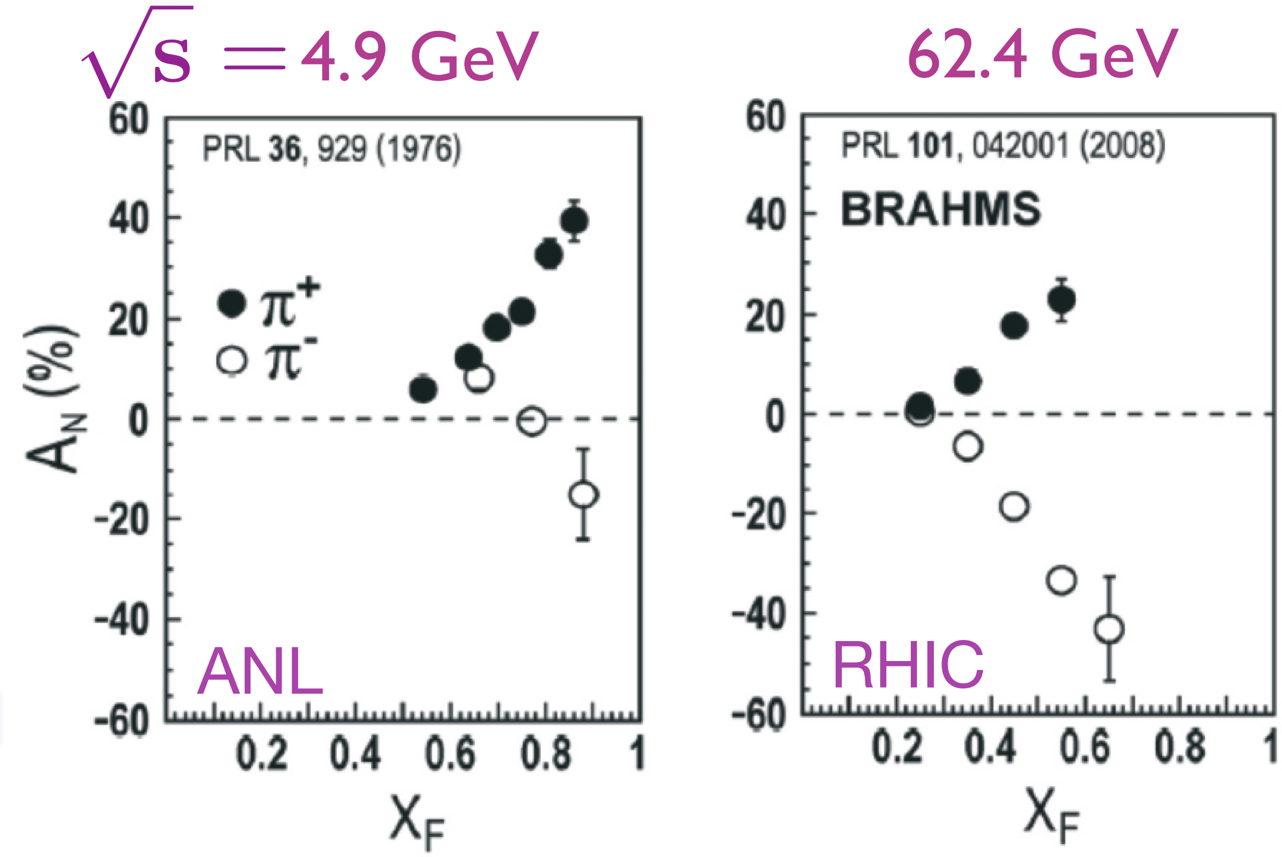




- at large P_T significant contribution from DIS events (Q^2>1)
- asymmetries increase with larger z
- large asymmetries also for π^- in case of z>0.7

the other inclusive SSAs

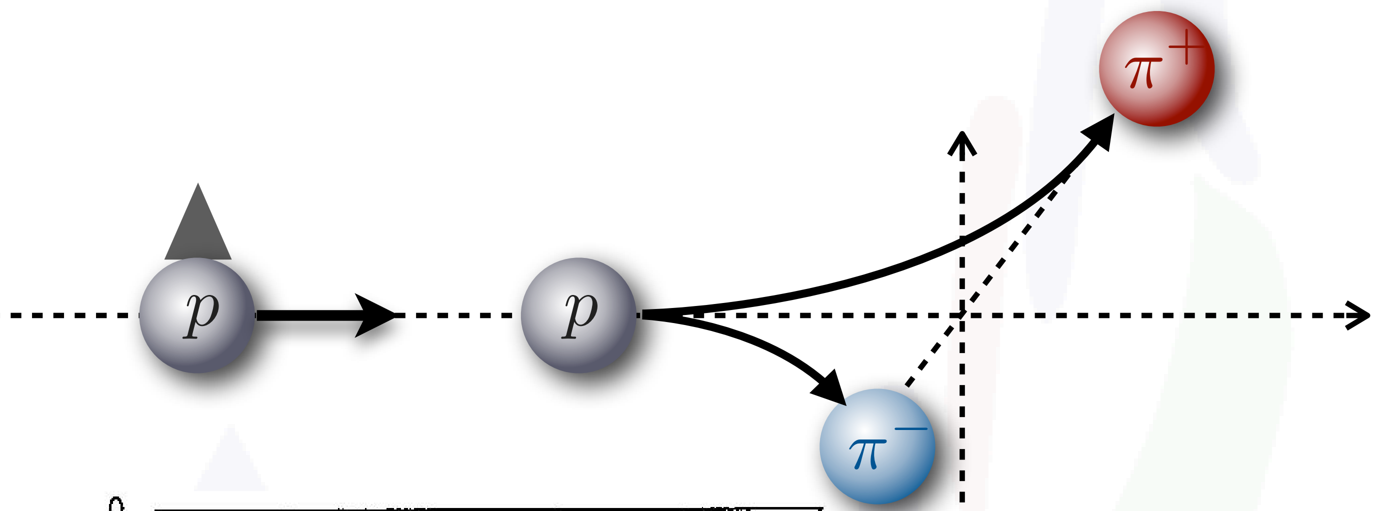


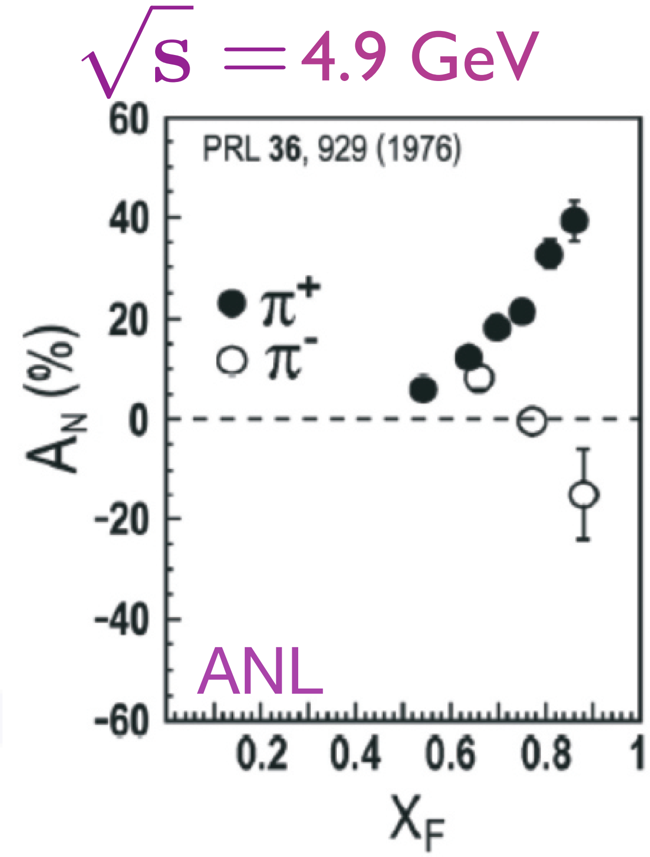


1976

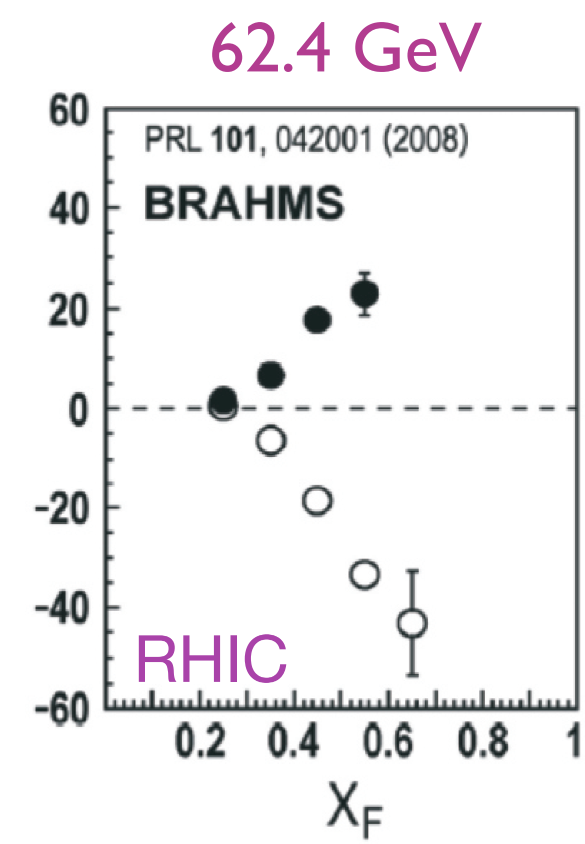
2008

the other inclusive SSAs

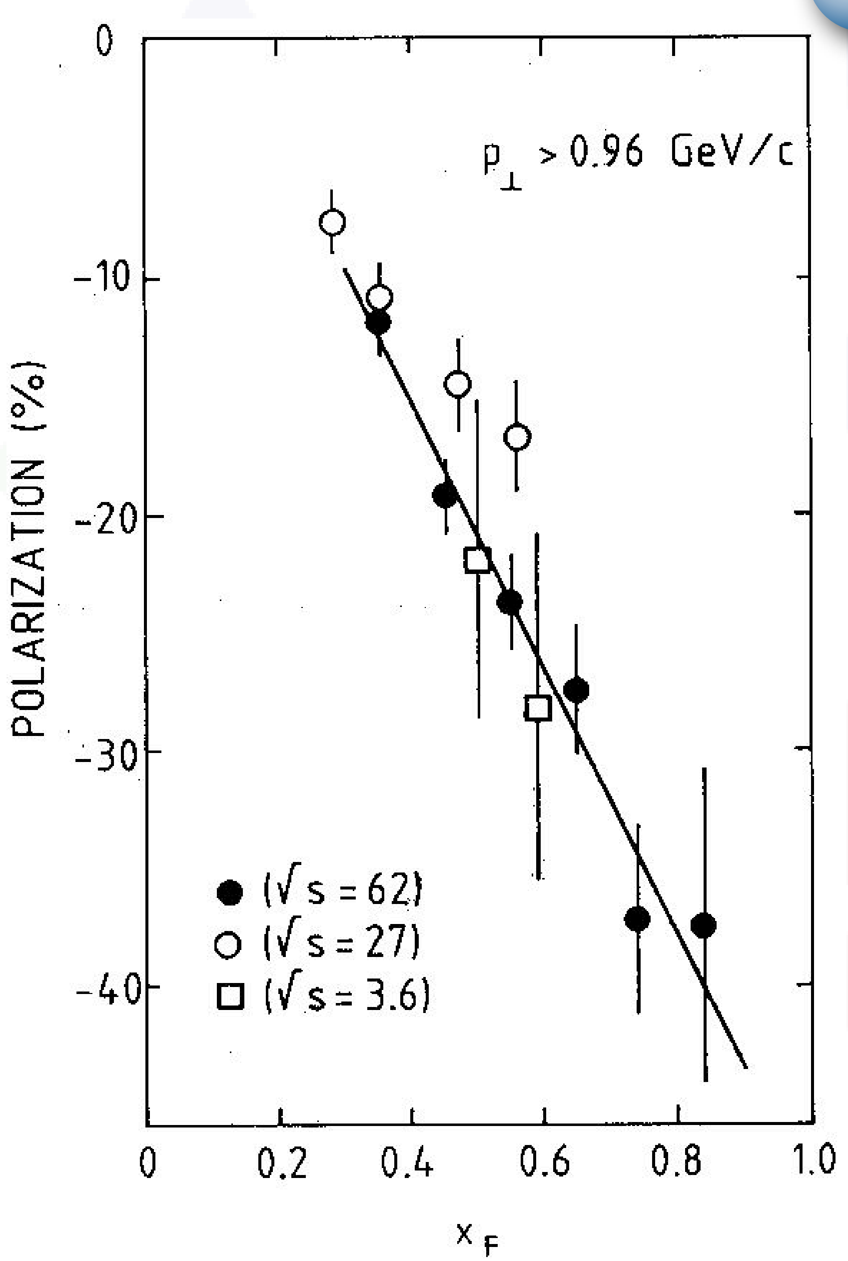




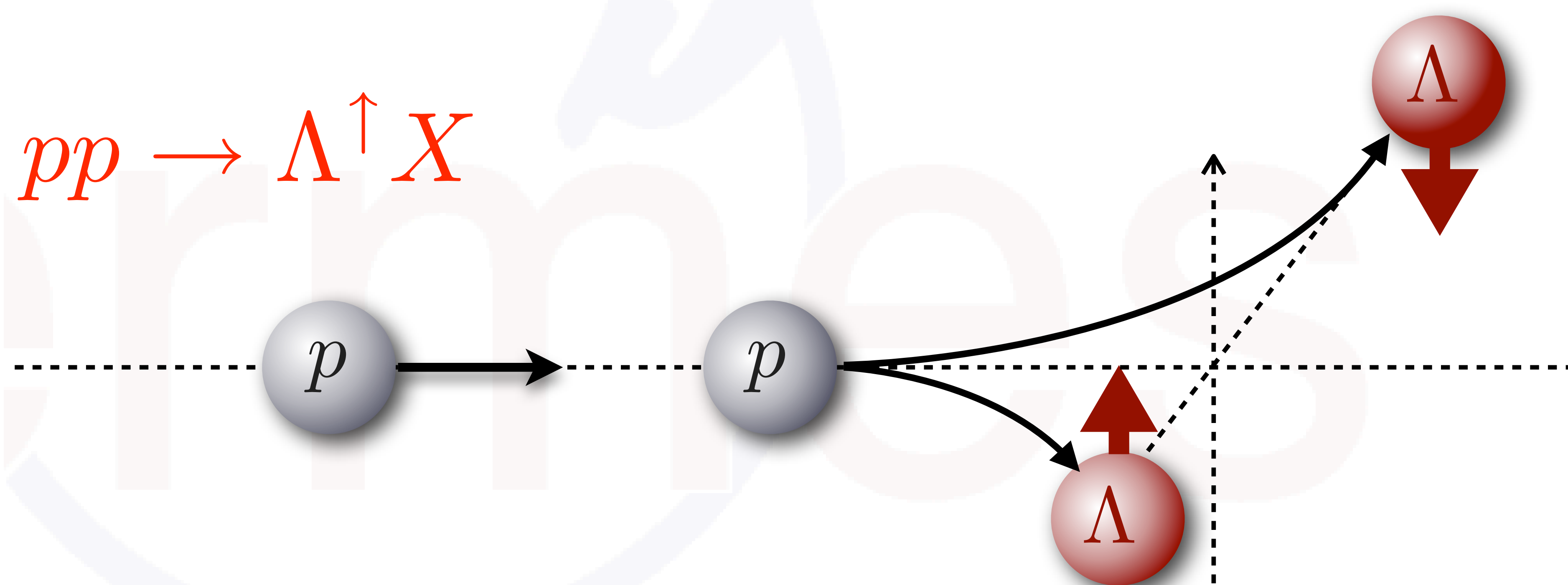
1976



2008

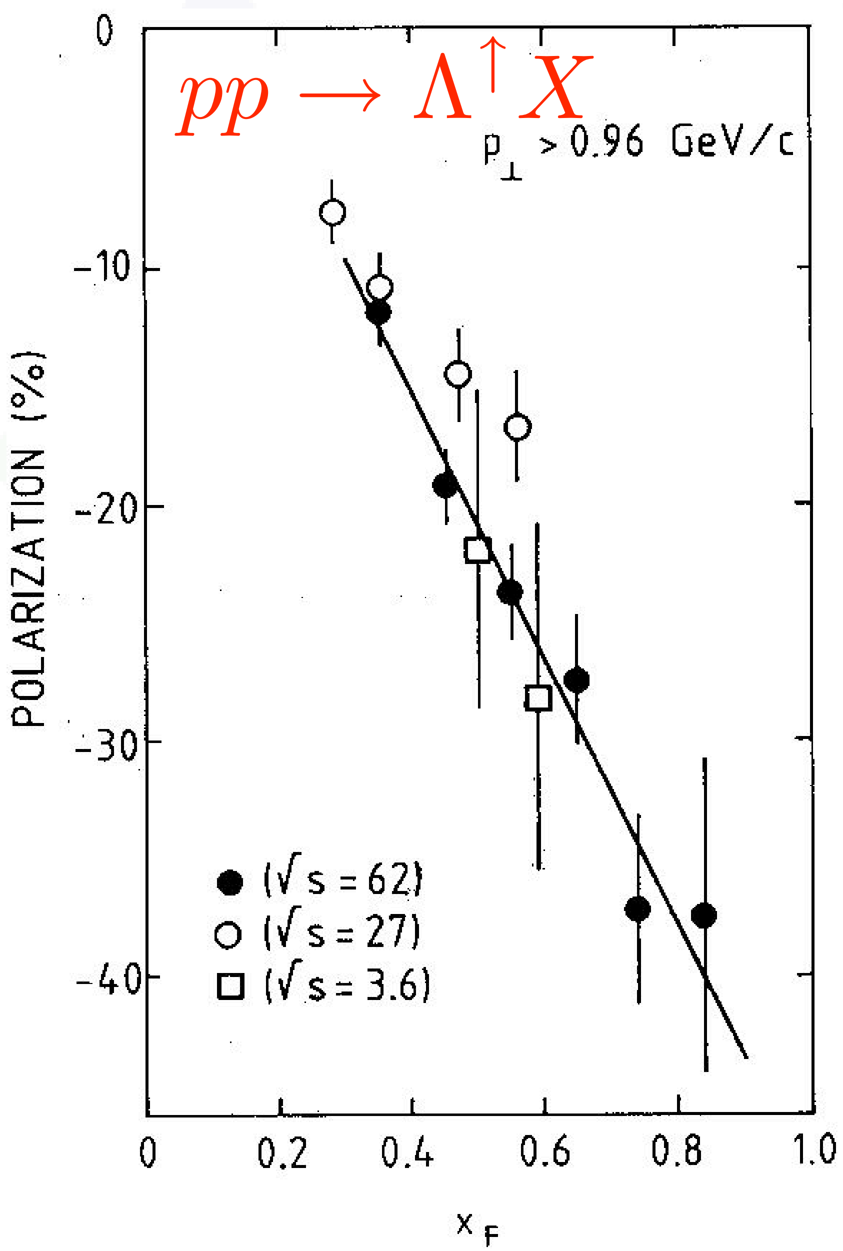


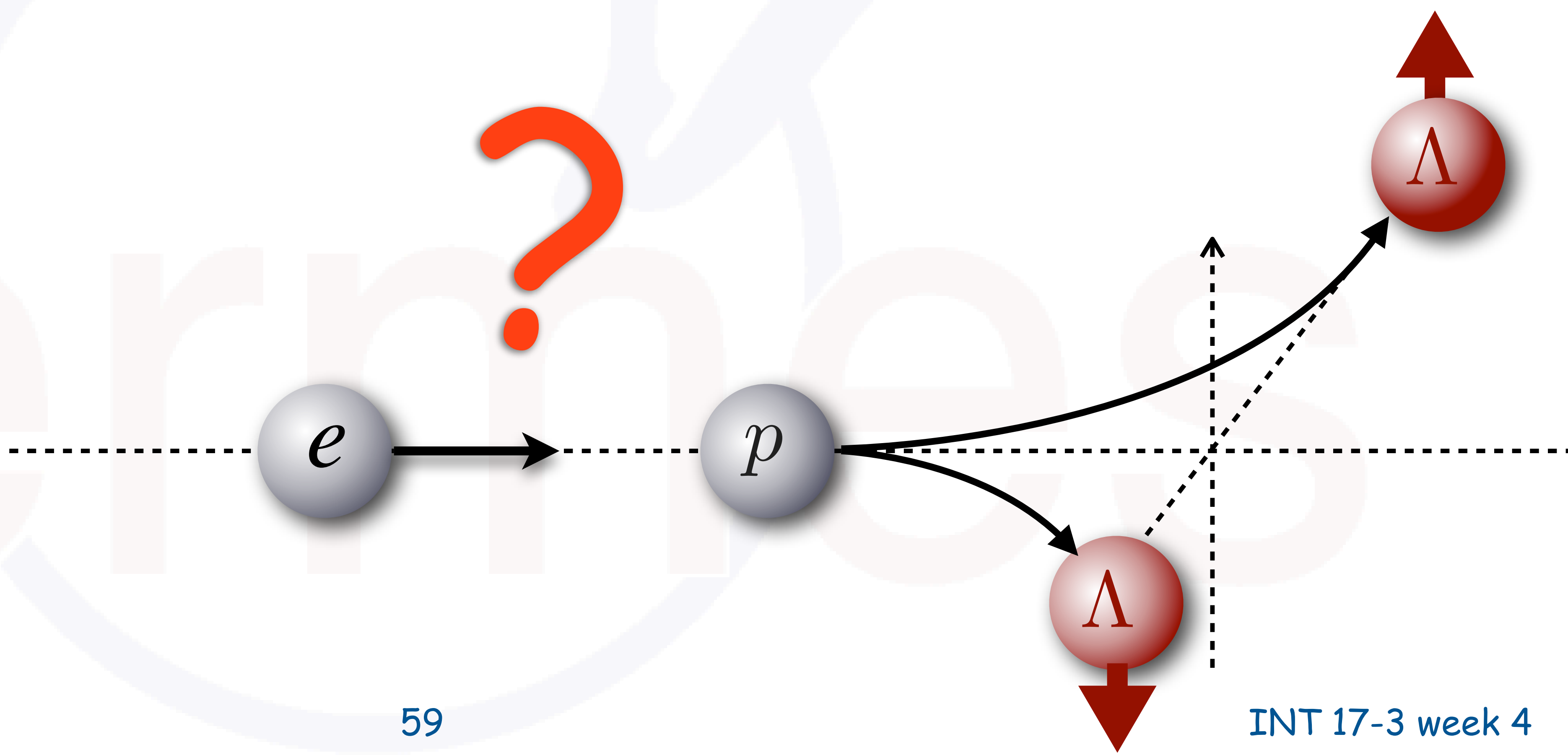
$$pp \to \Lambda^\uparrow X$$



the other inclusive SSA

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

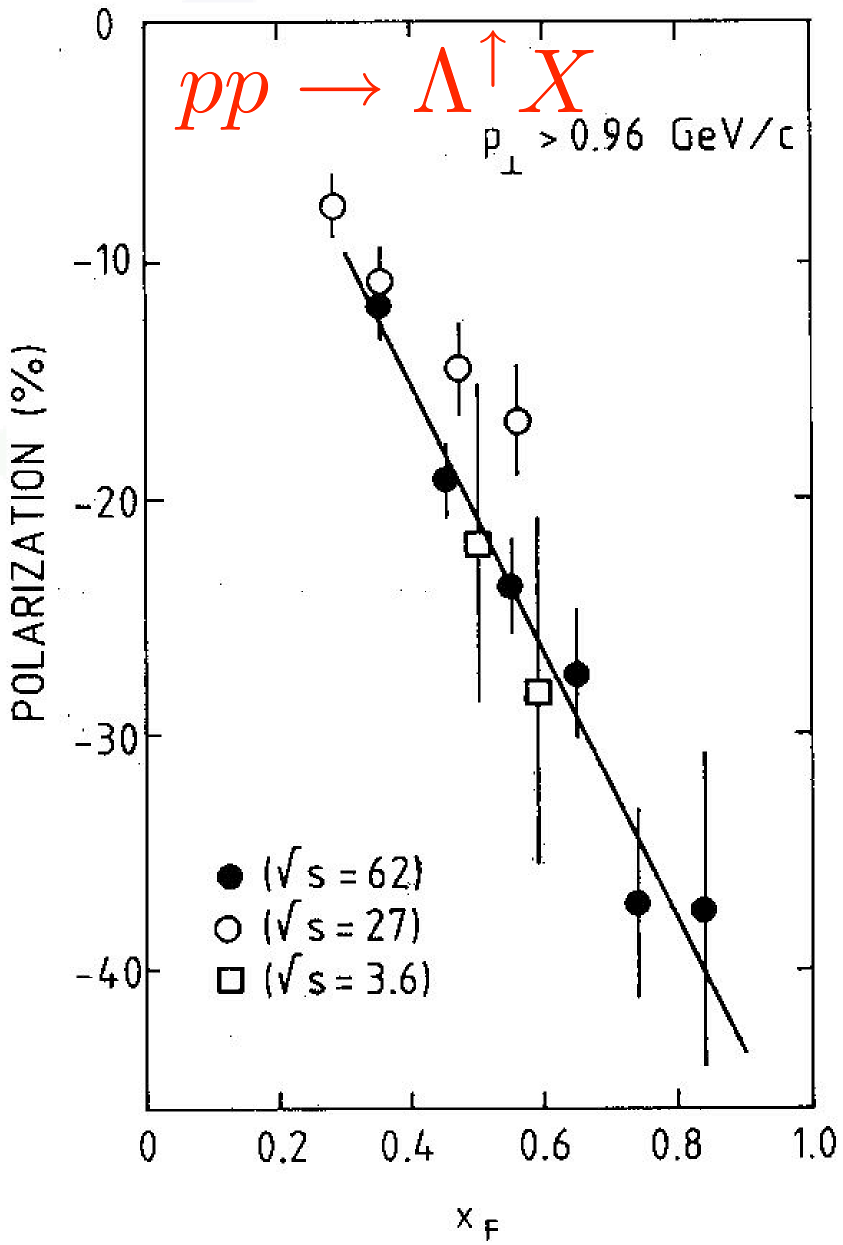


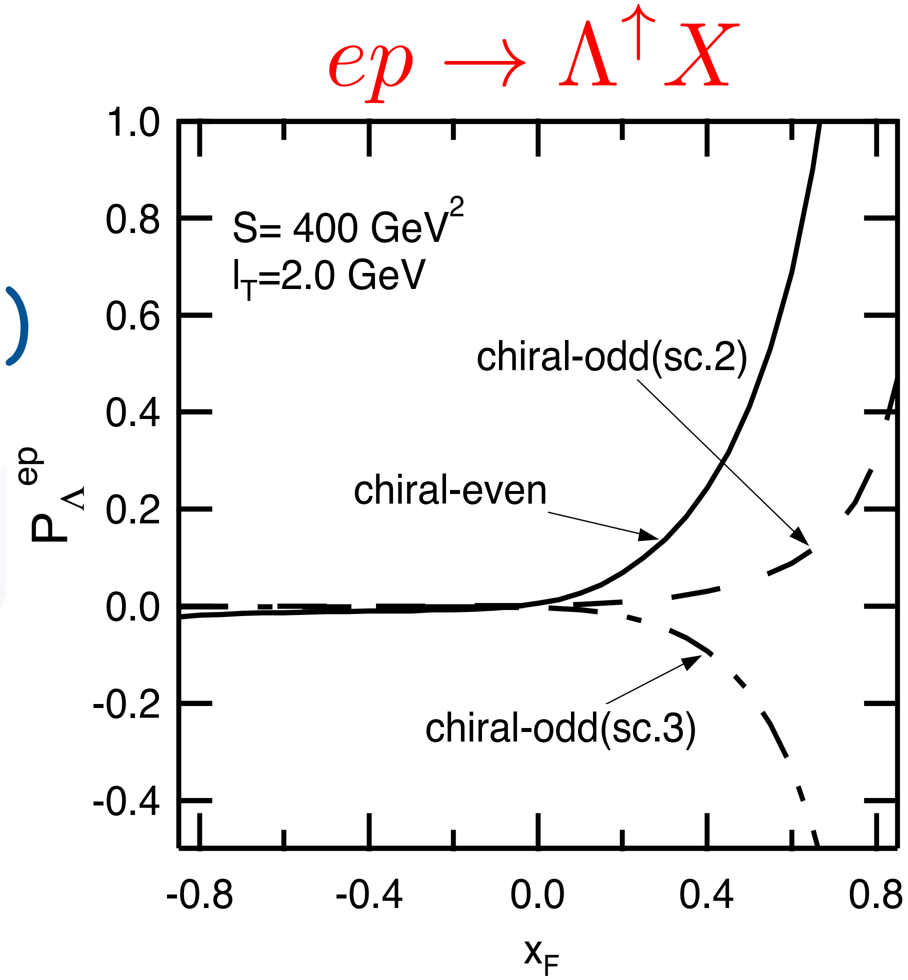


the other inclusive SSA

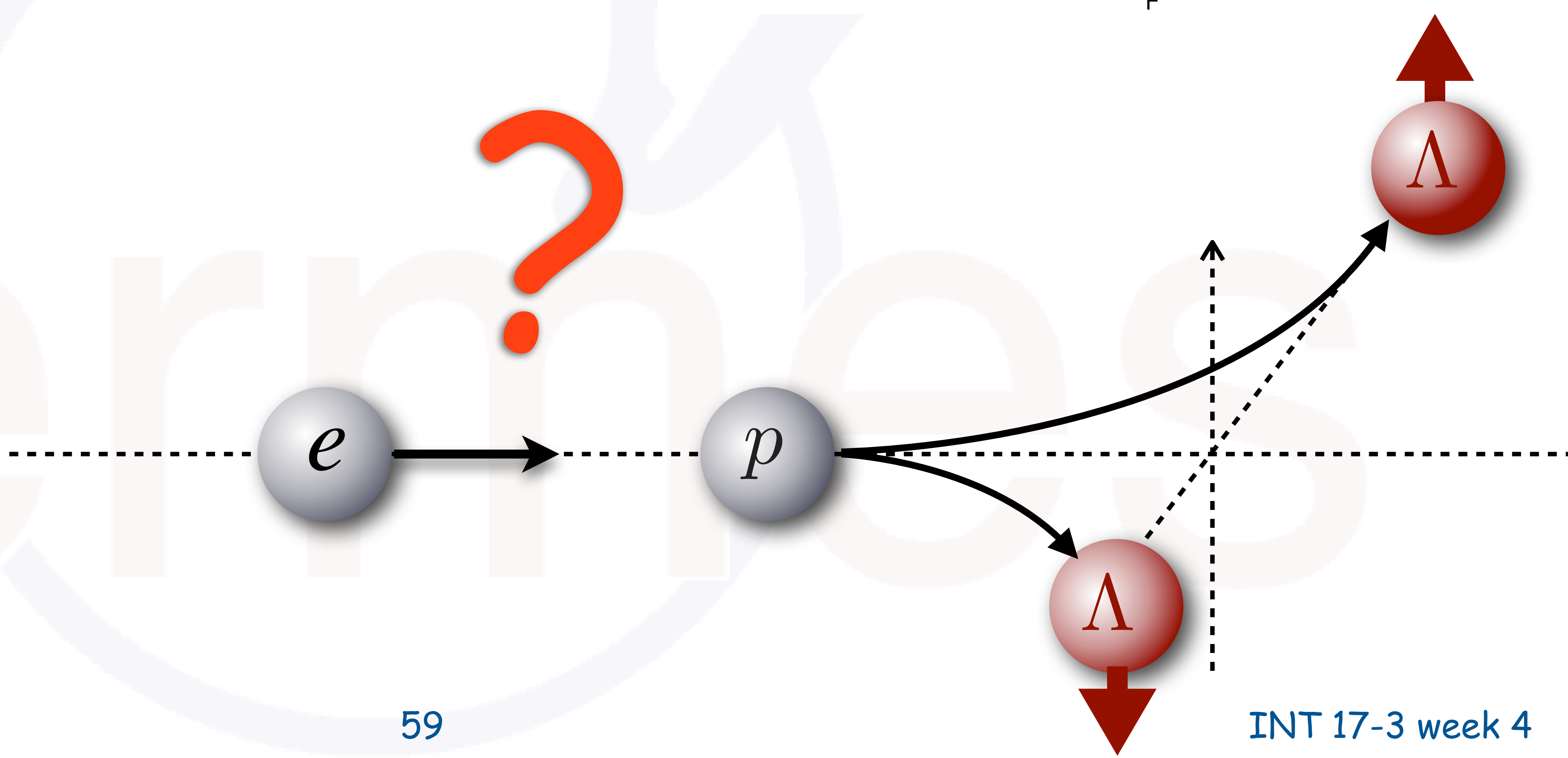
in SIDIS (large Q^2) proportional to polarizing FF $D_{1T}^{\perp}$ (naive T-odd, chiral-even)

in twist-3 factorization opposite sign to pp



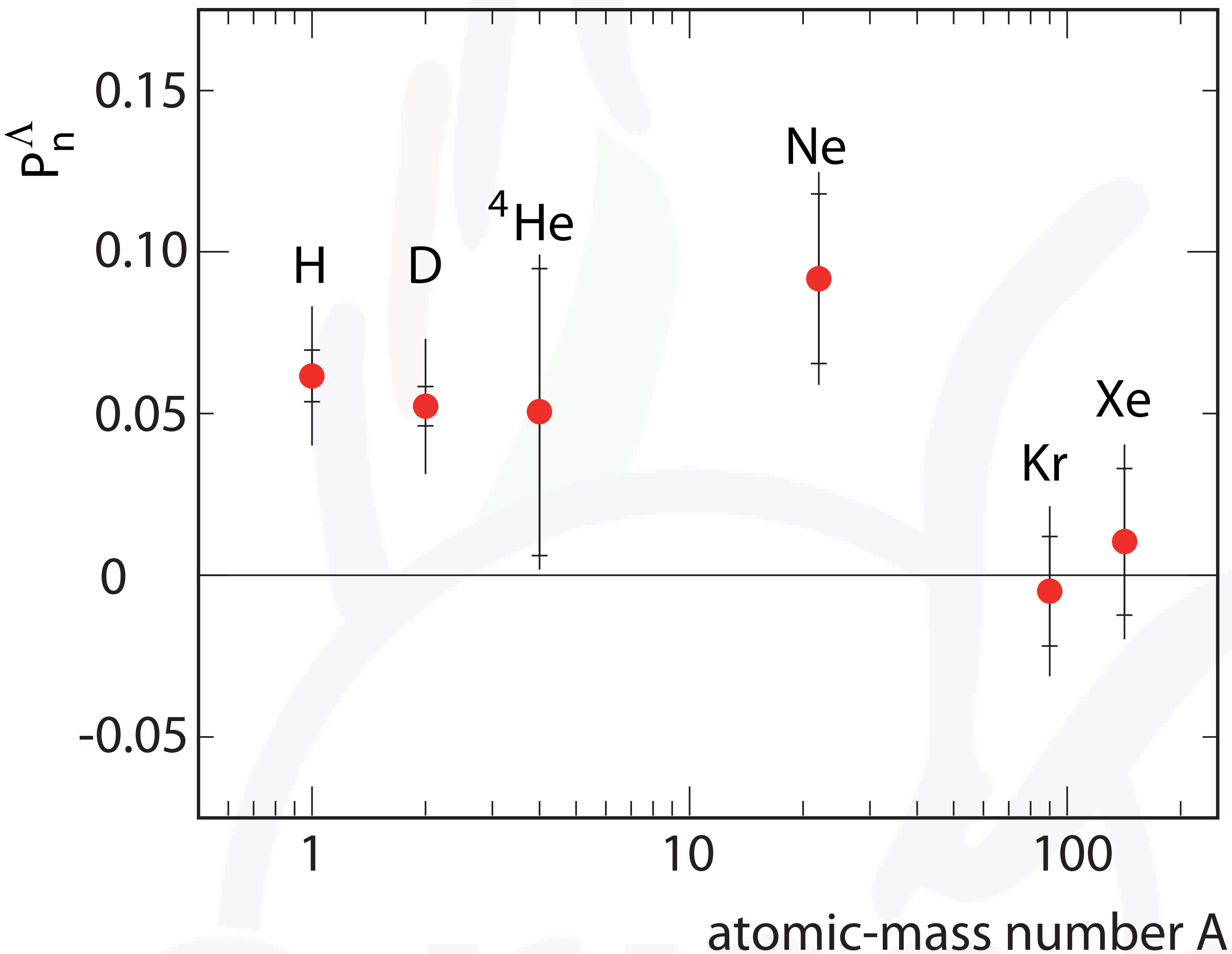


[Y. Koike, hep-ph/0210434]

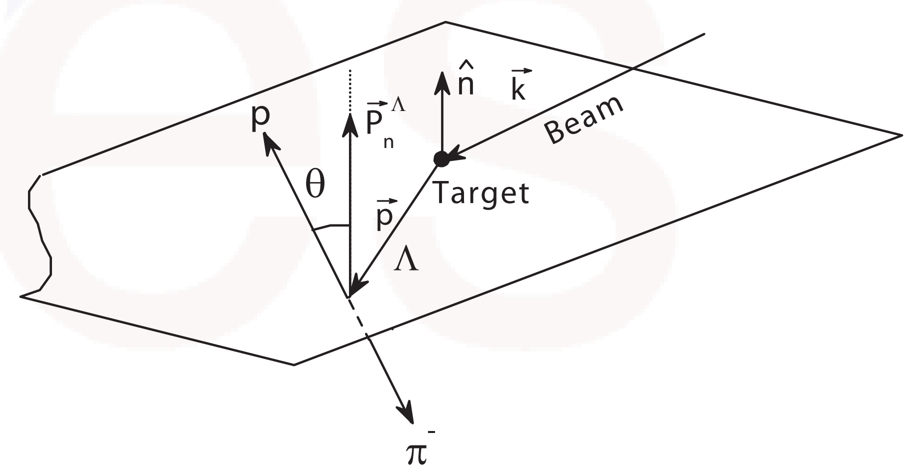


the other inclusive SSA

[PRD90 (2014) 072007]

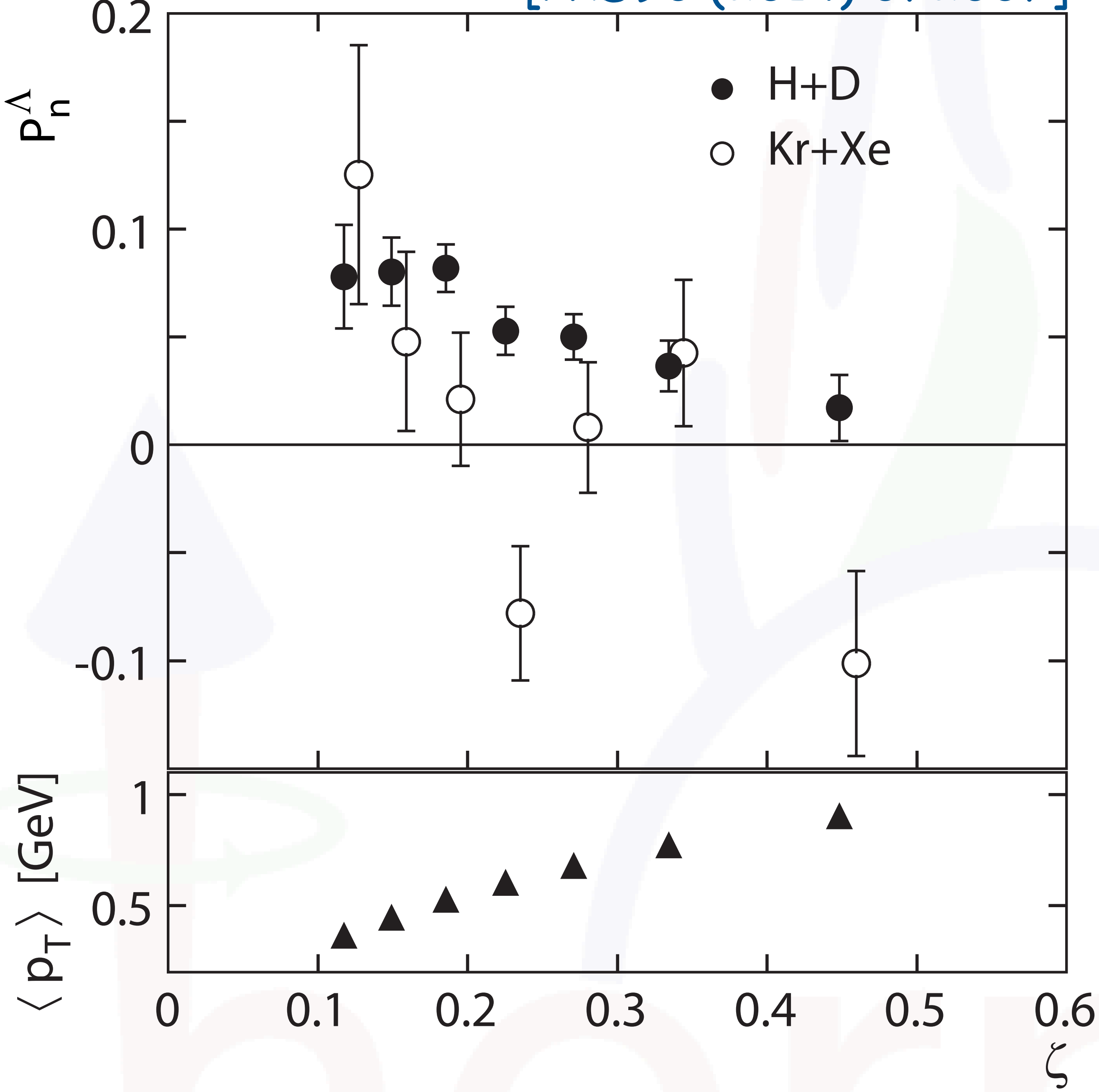


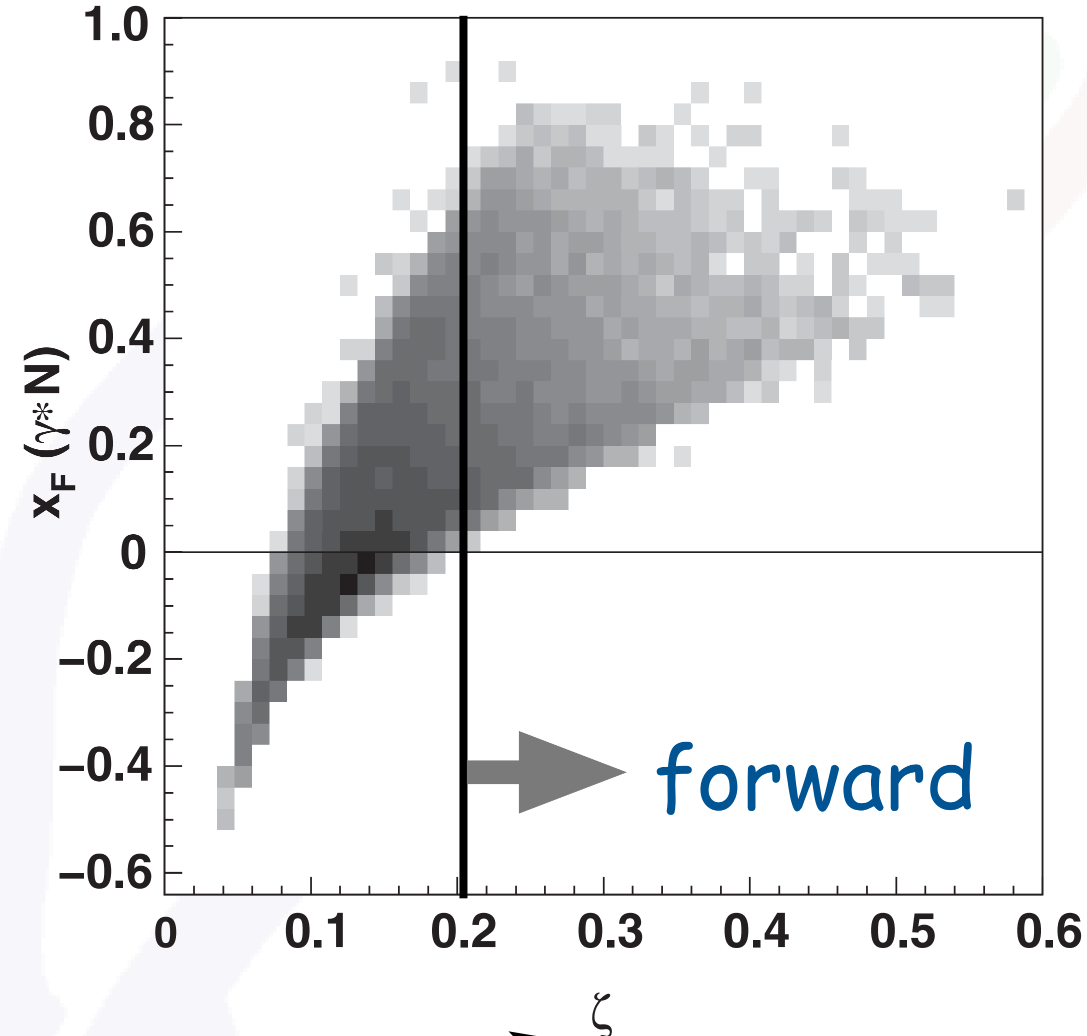
- clearly positive for light target nuclei
- consistent with zero for heavy targets



the other inclusive SSA

[PRD90 (2014) 072007]



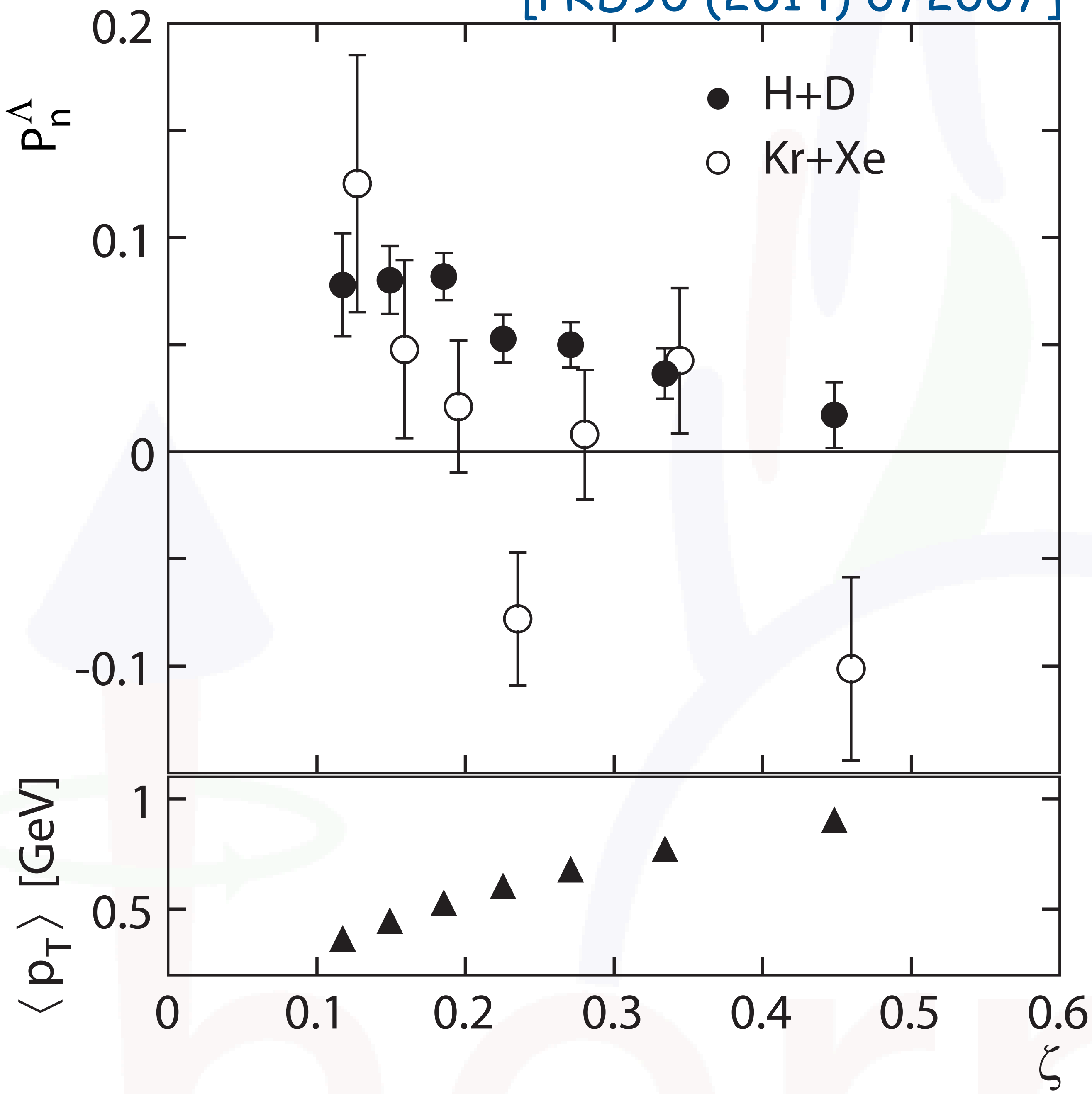


$$\zeta \equiv (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$$

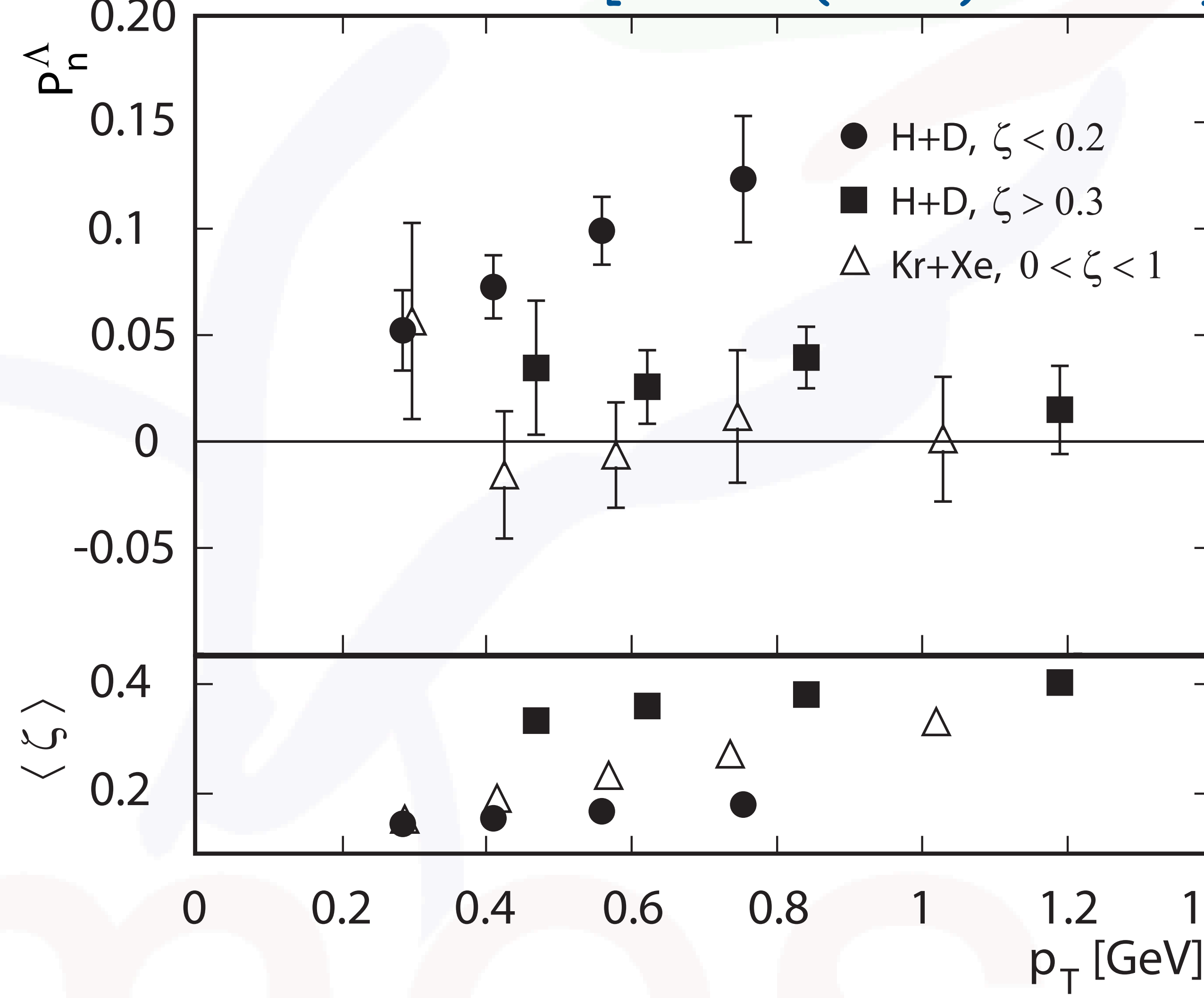
- larger in backward direction w.r.t. incoming lepton
- consistent with x_F dependence of twist-3 calculation (note: opposite sign conventions for x_F!)

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

conclusions before the summary

- HERMES conceived almost 3 decades a… to solve the "spin crisis"
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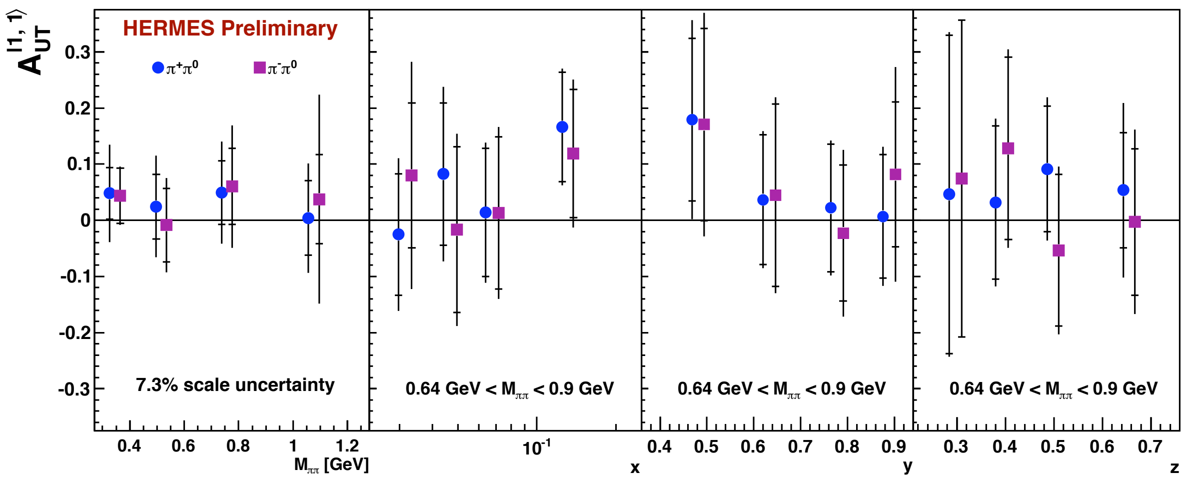
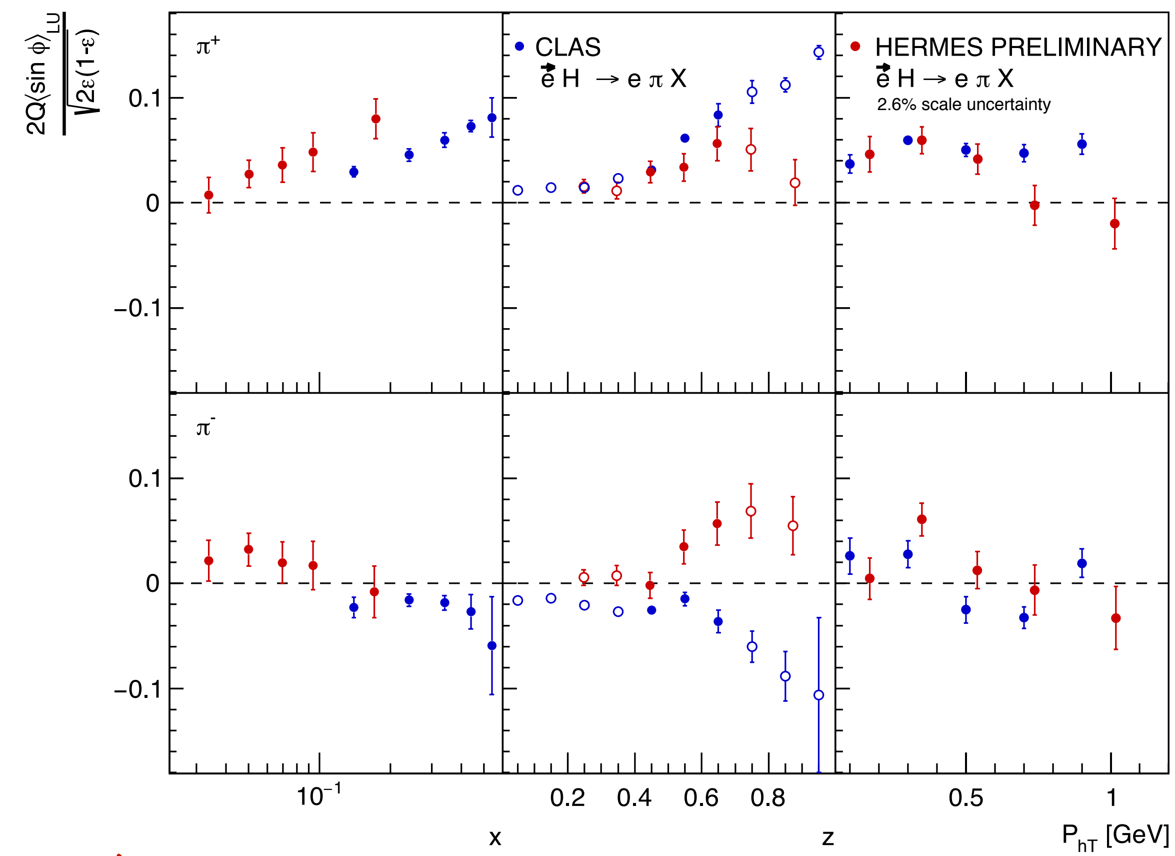
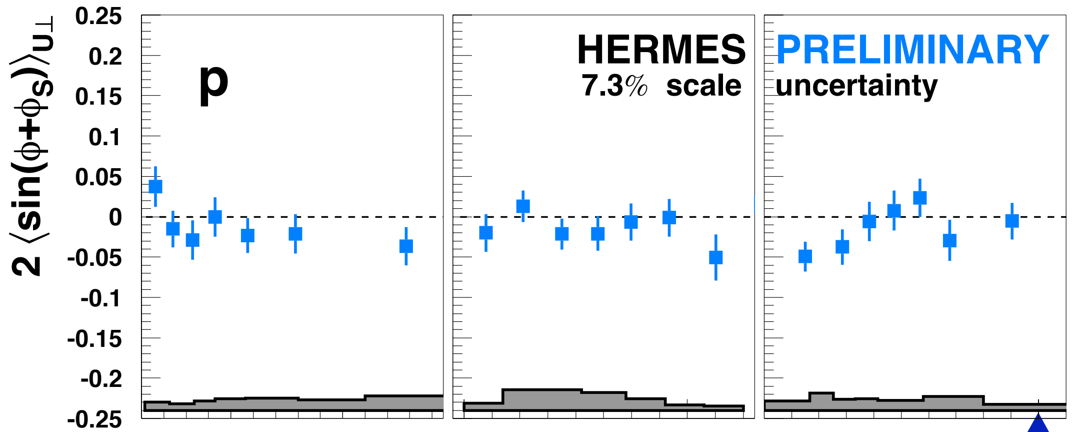
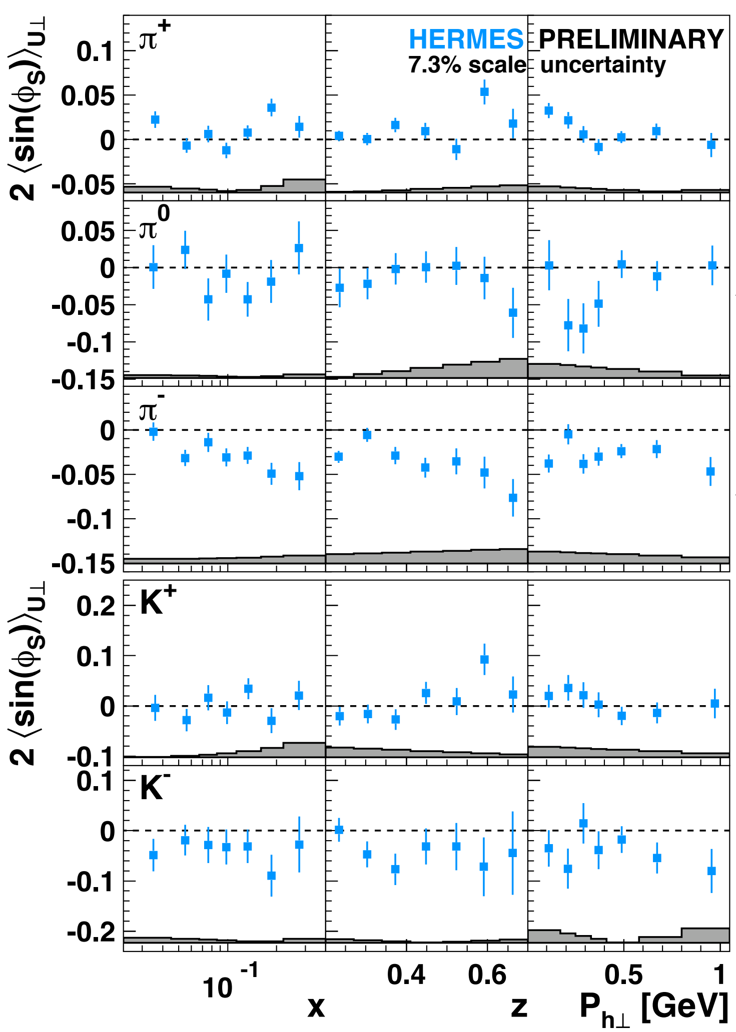
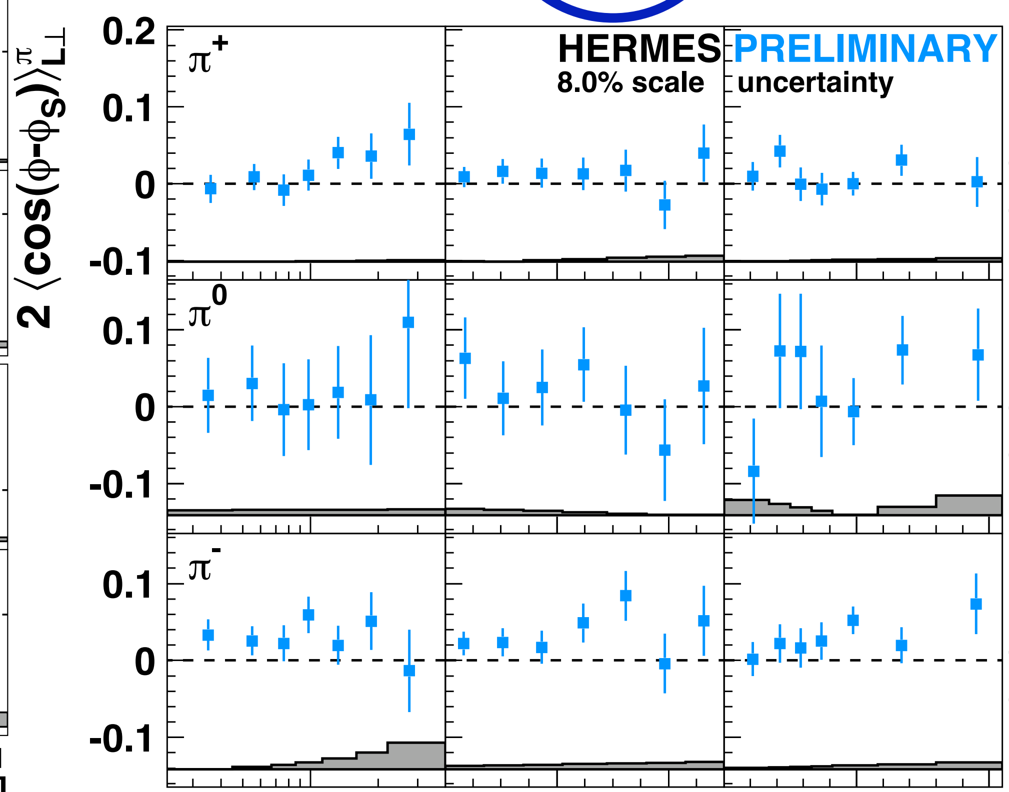
always be open to trying out new paths

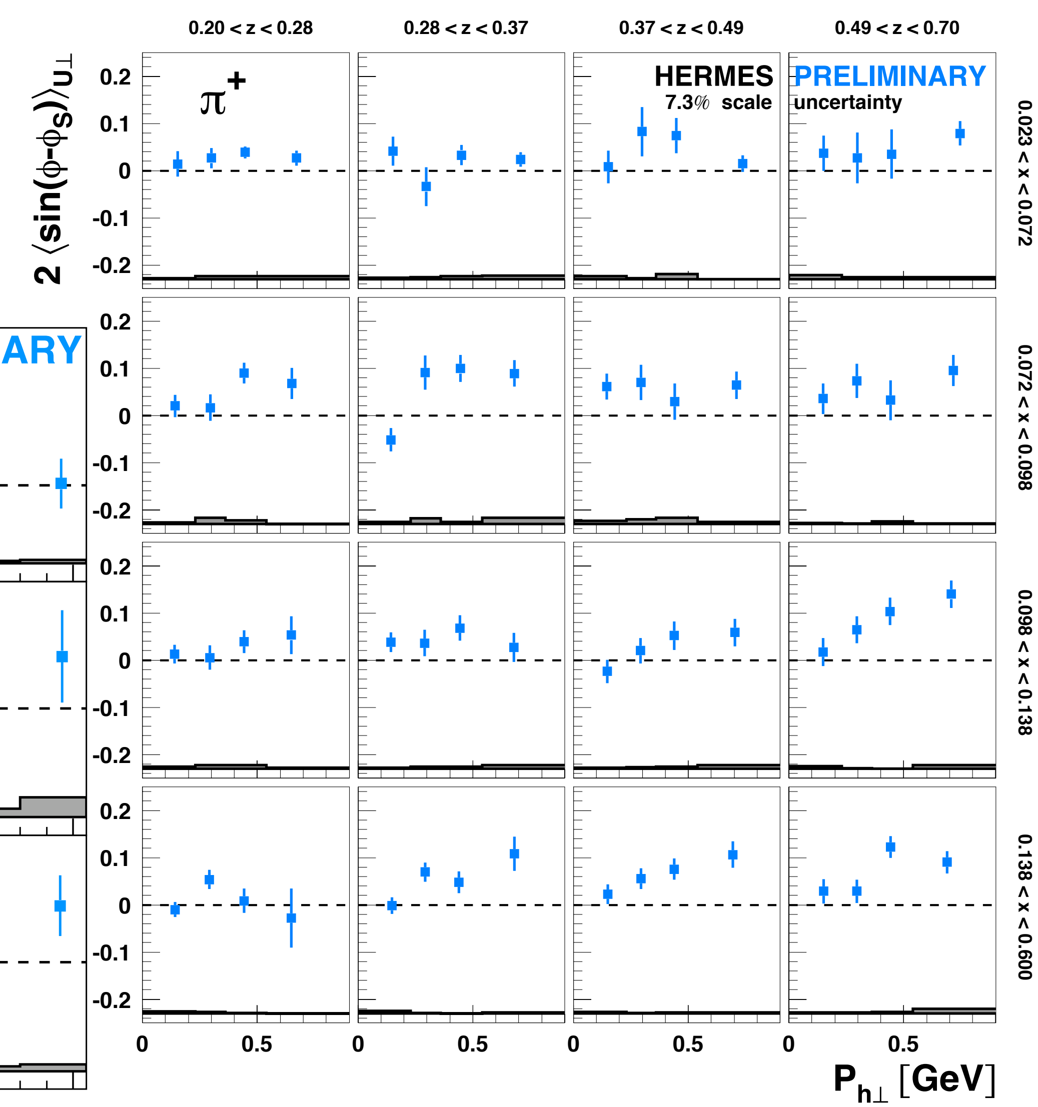

HERMES Preliminary
7.3% scale uncertainty
0.64 GeV < $M_{\pi\pi}$ < 0.9 GeV
$M_{\pi\pi}$ [GeV]
x
y
z


CLAS
HERMES PRELIMINARY
2.6% scale uncertainty
$2Q\langle \sin\phi \rangle_{LU} / \sqrt{2\varepsilon(1-\varepsilon)}$
x
z
P_{hT} [GeV]


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


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


HERMES PRELIMINARY
8.0% scale uncertainty
$2\langle \cos(\phi-\phi_S) \rangle^{\pi}_{L\perp}$


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