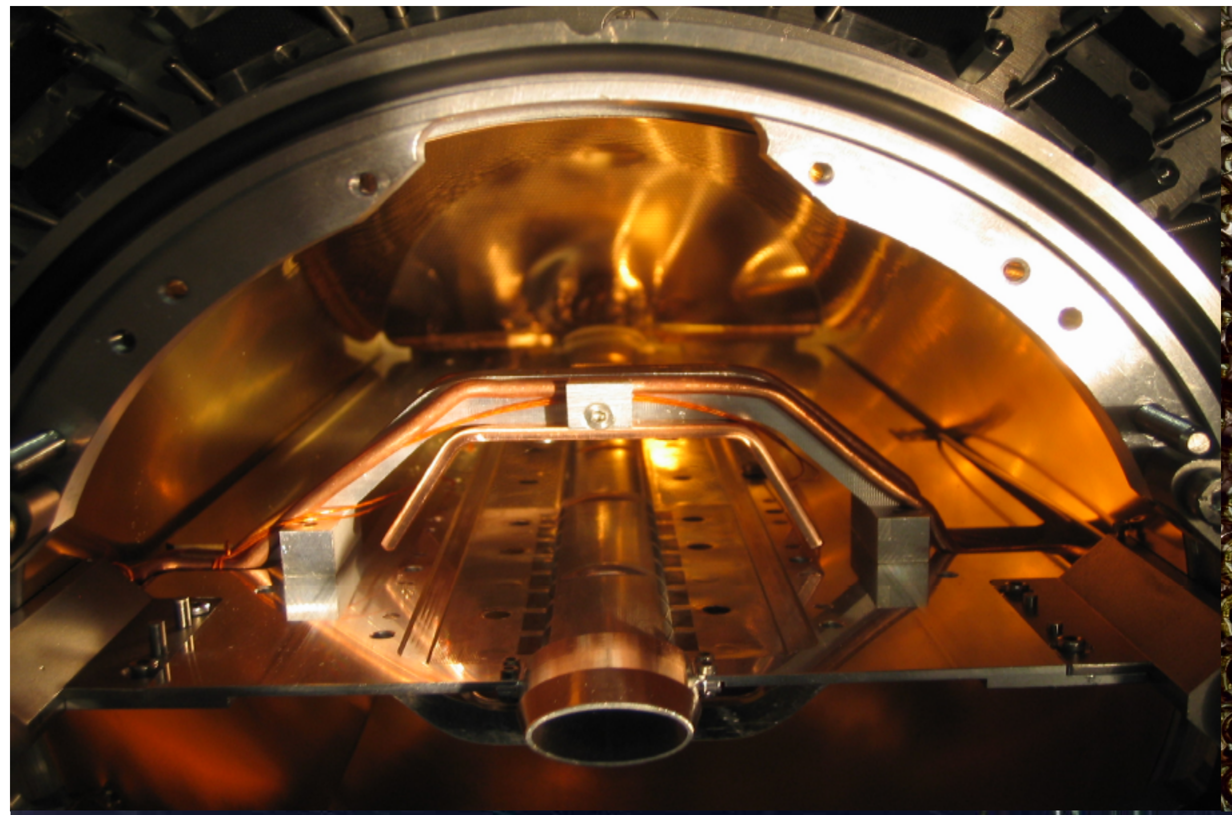
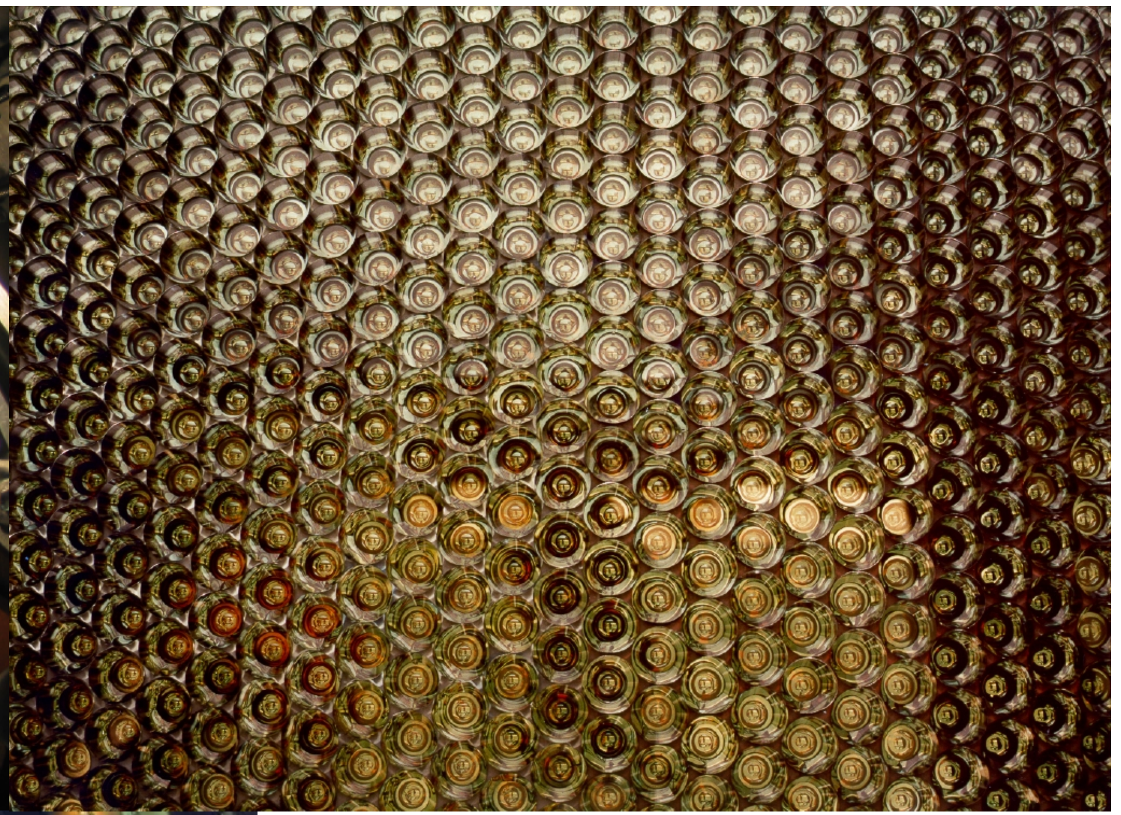
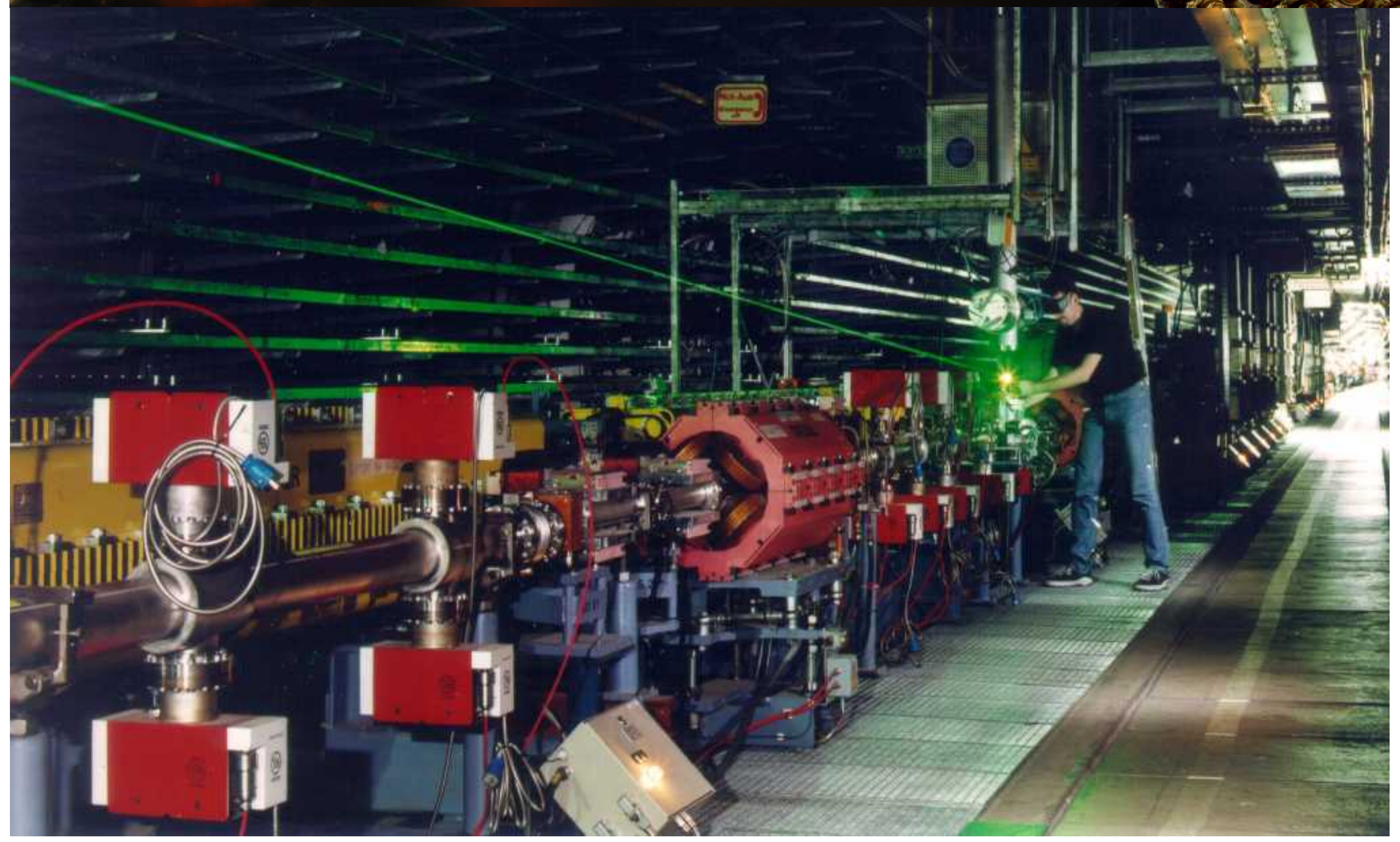
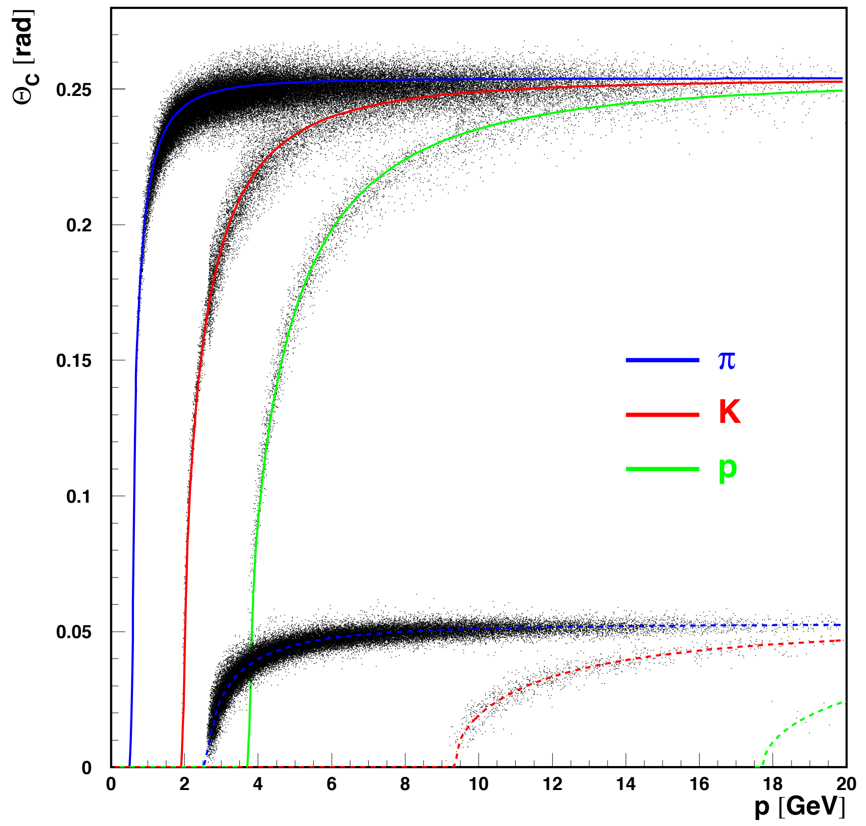




HERA-4-EIC

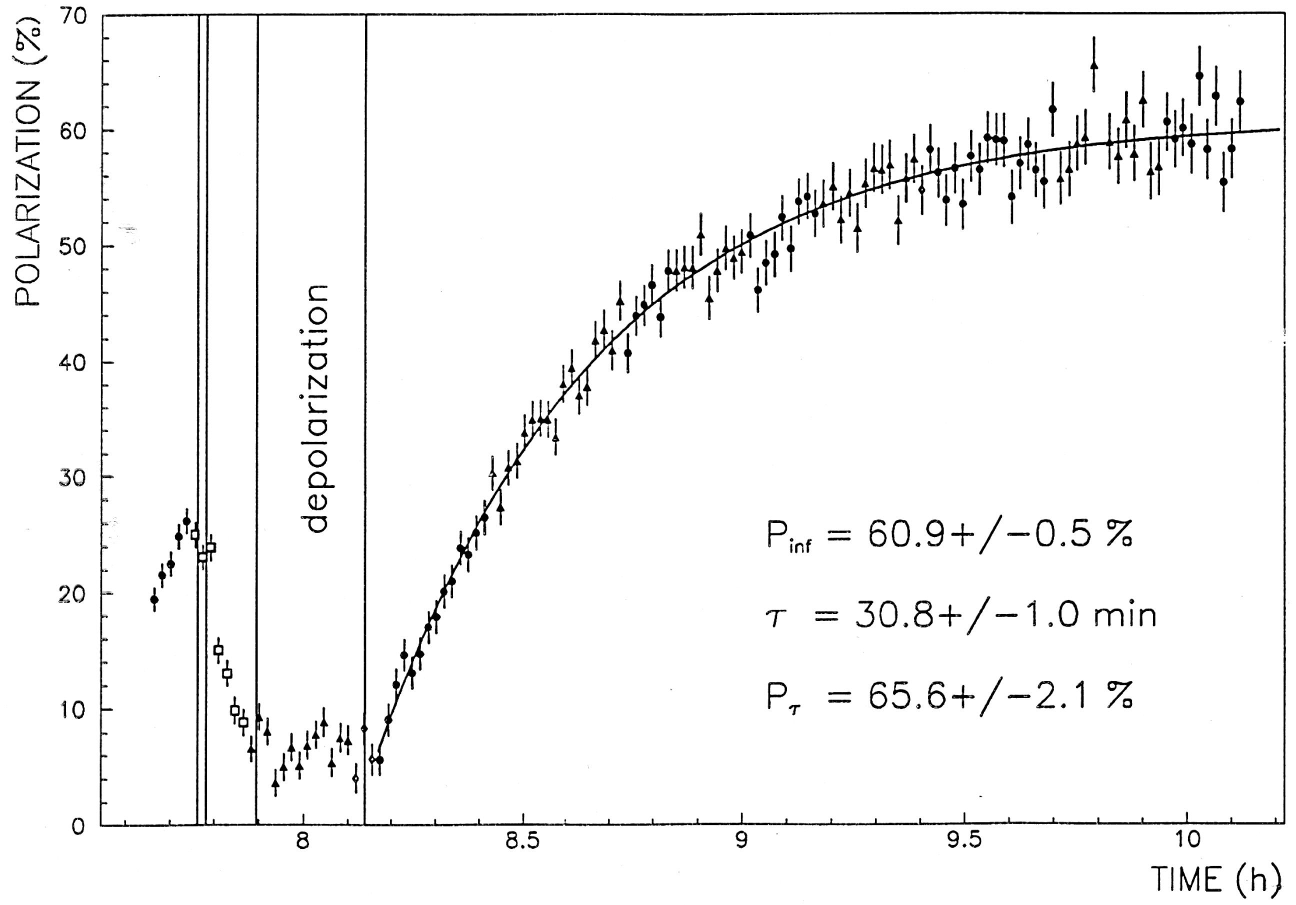
Stony Brook (virtual) June 8-10, 2021





HERMES Overview

a personal perspective mainly on semi-inclusive DIS



hermes

Gunar.Schnell @ DESY.de

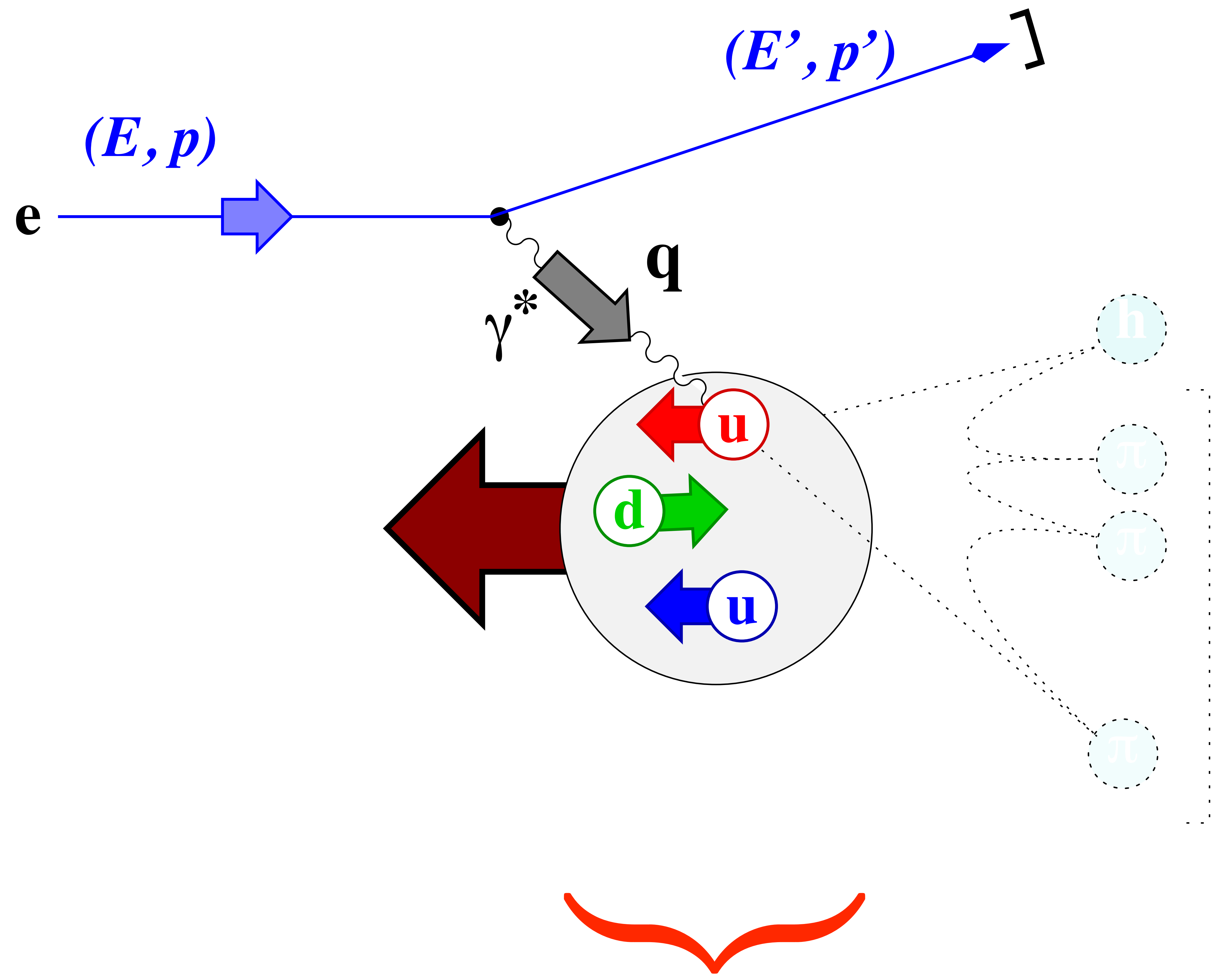
ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

outline

- introduction
- some recent HERMES highlights
- the devil is in the details
- achievements and opportunities

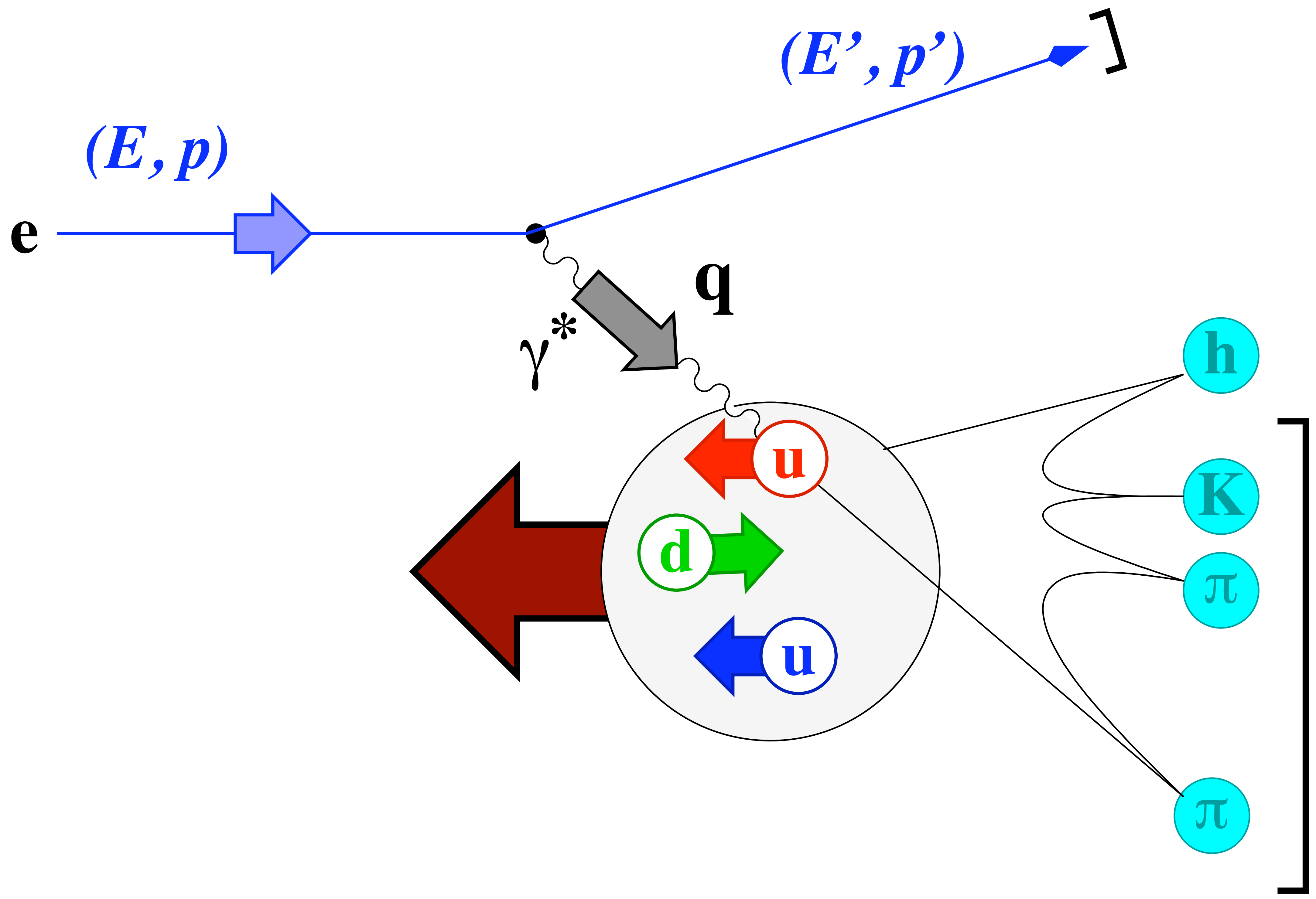
deep-inelastic scattering



inclusive

factorization: parton distributions

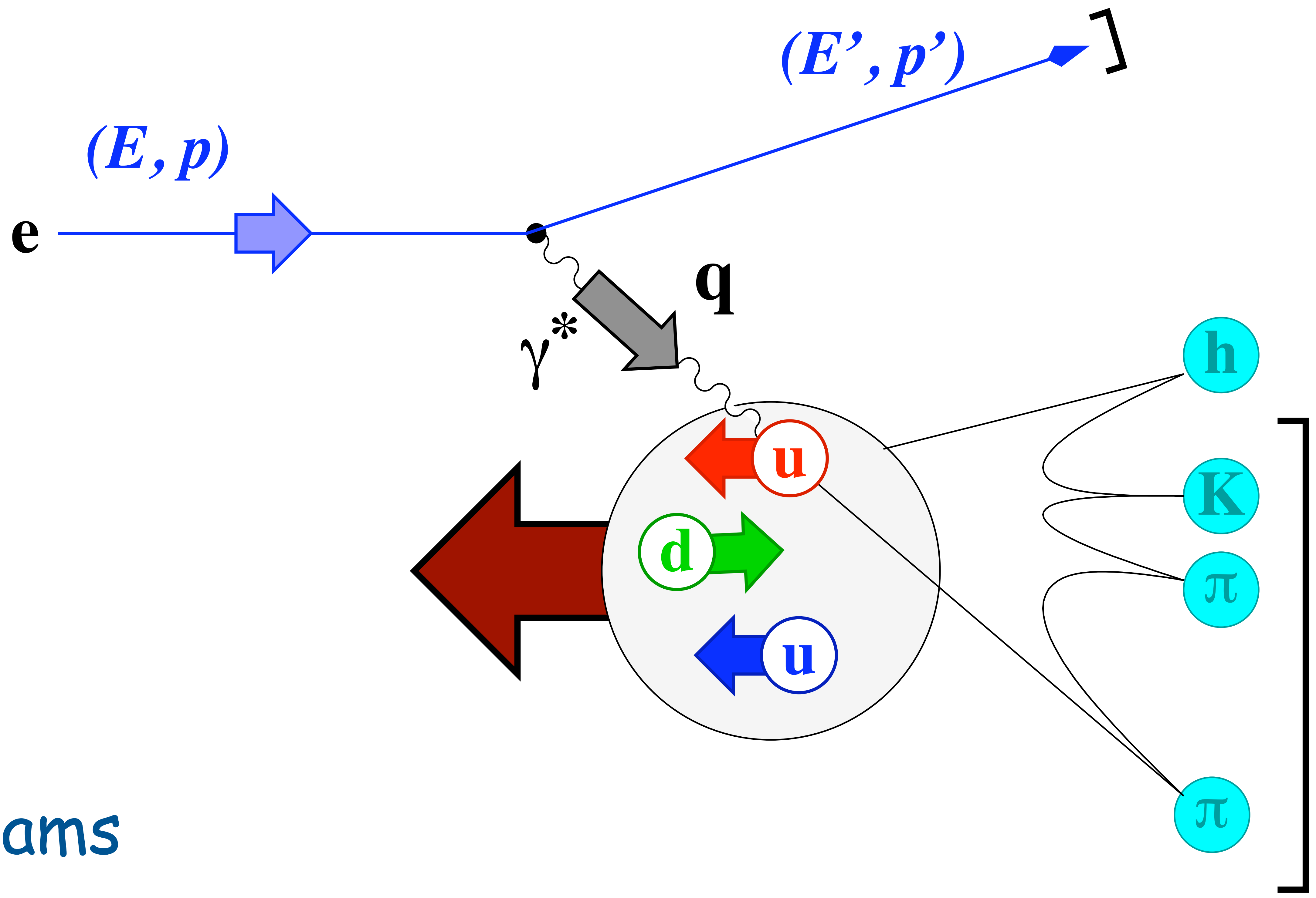
deep-inelastic scattering



semi-
inclusive

factorization: $\underbrace{}$ parton distributions $\underbrace{}$ fragmentation functions

deep-inelastic scattering

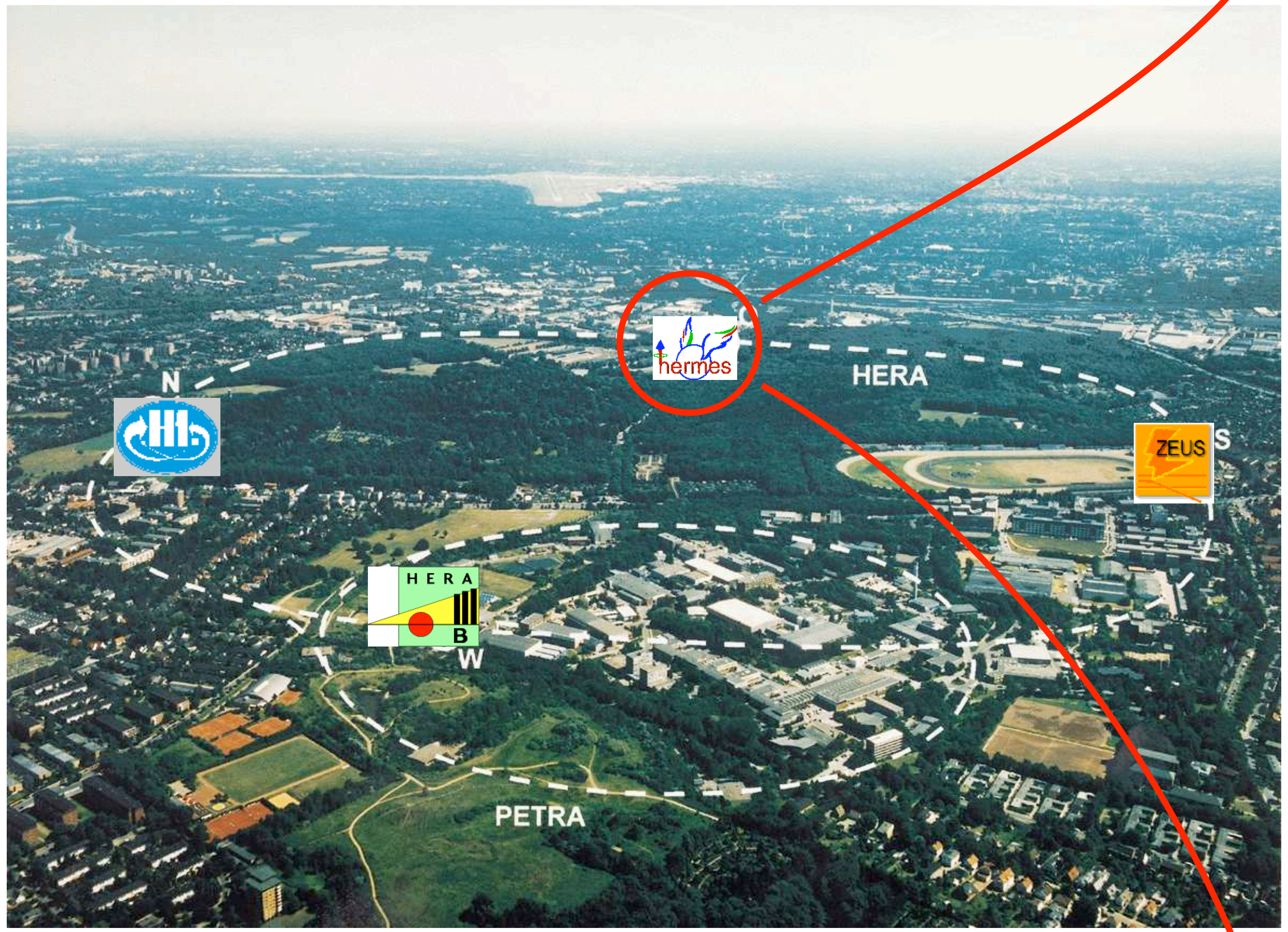


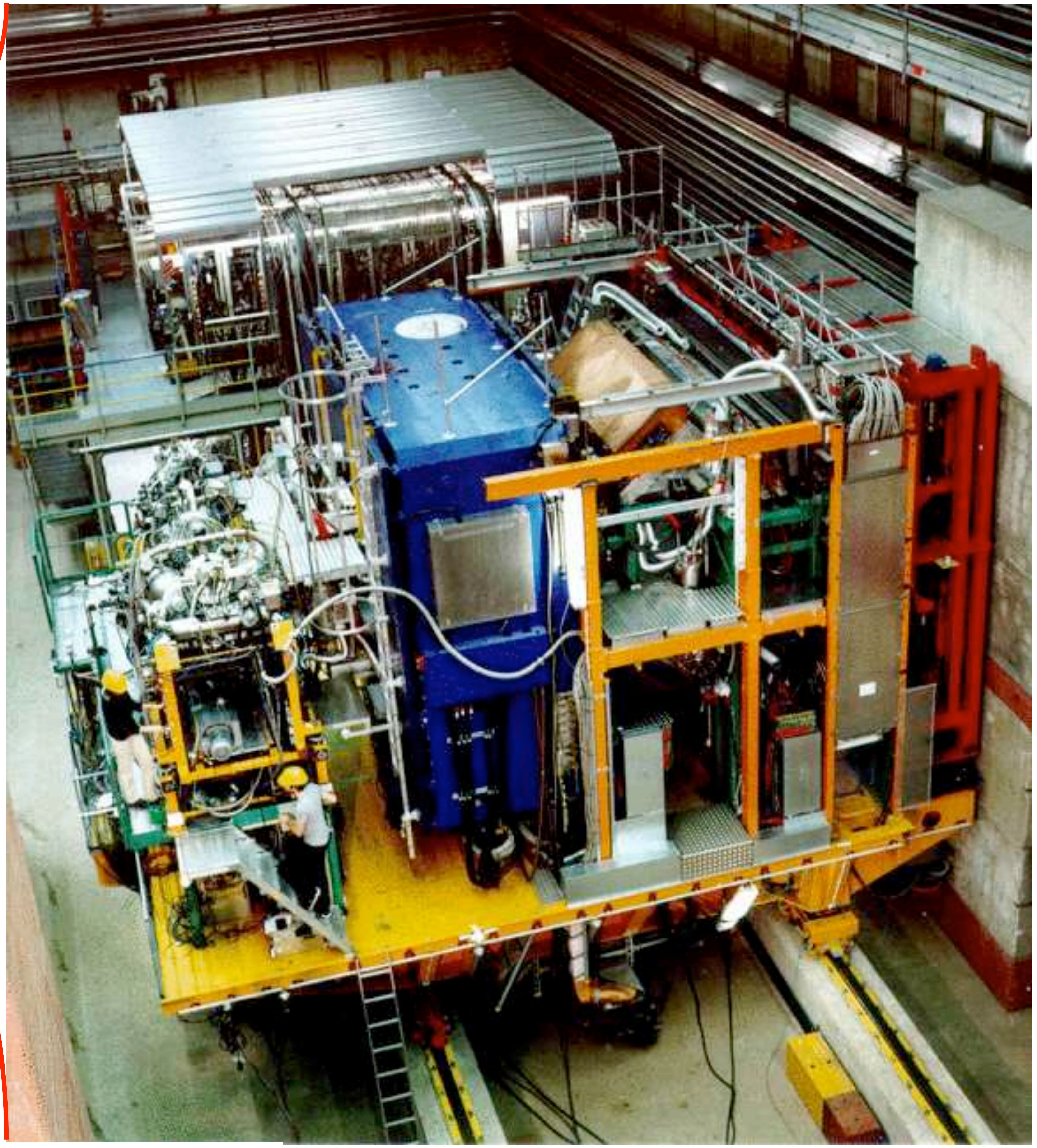
semi-
inclusive

- polarized lepton beams
- polarized targets
- large-acceptance spectrometer
- good particle identification (PID)

HERMES (1995-2007) @ HERA

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

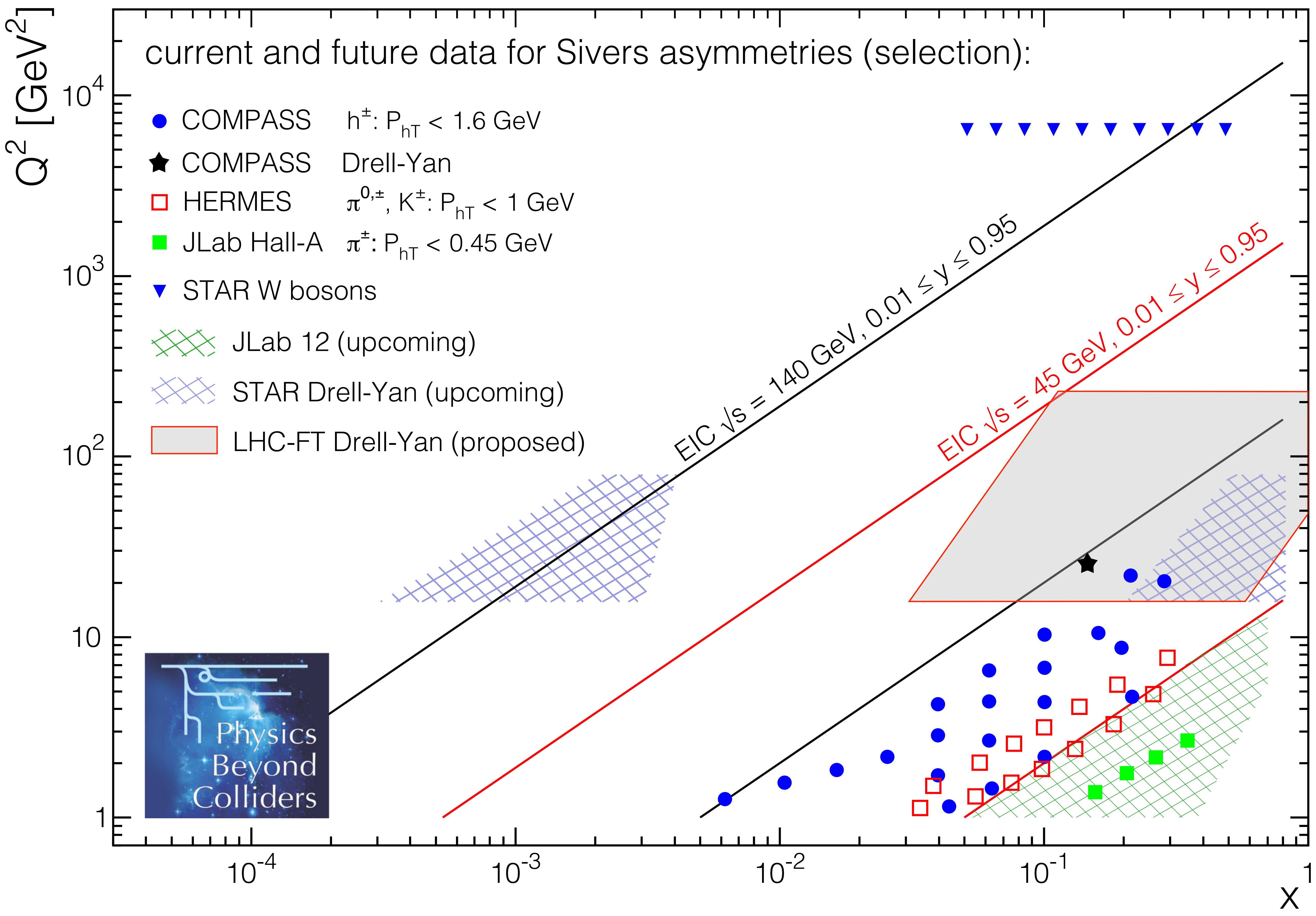




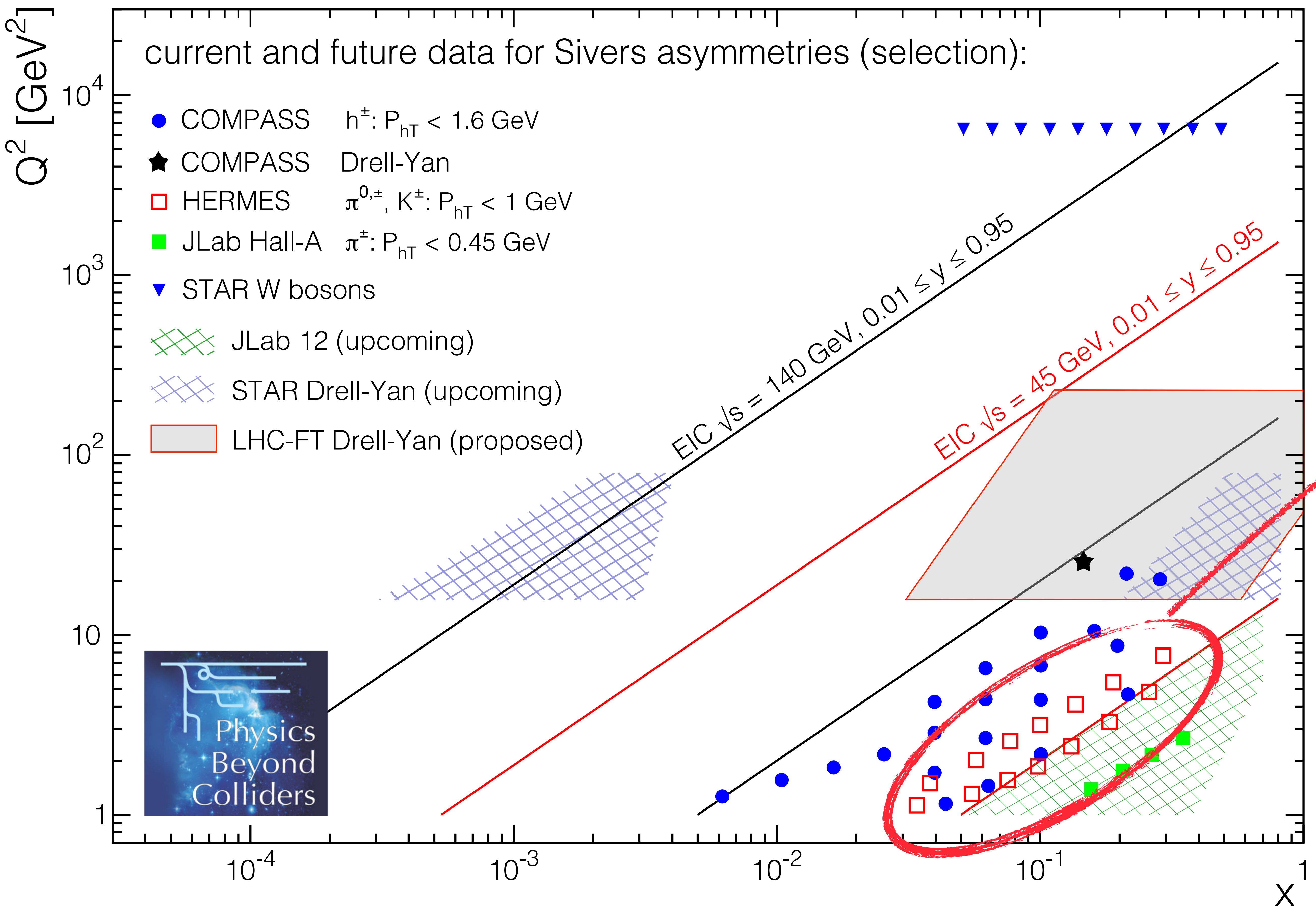
- unpolarized (H, D, He,..., Xe) as well as
- **transversely (H)** or
- longitudinally (H, D, He) polarized

pure gas targets

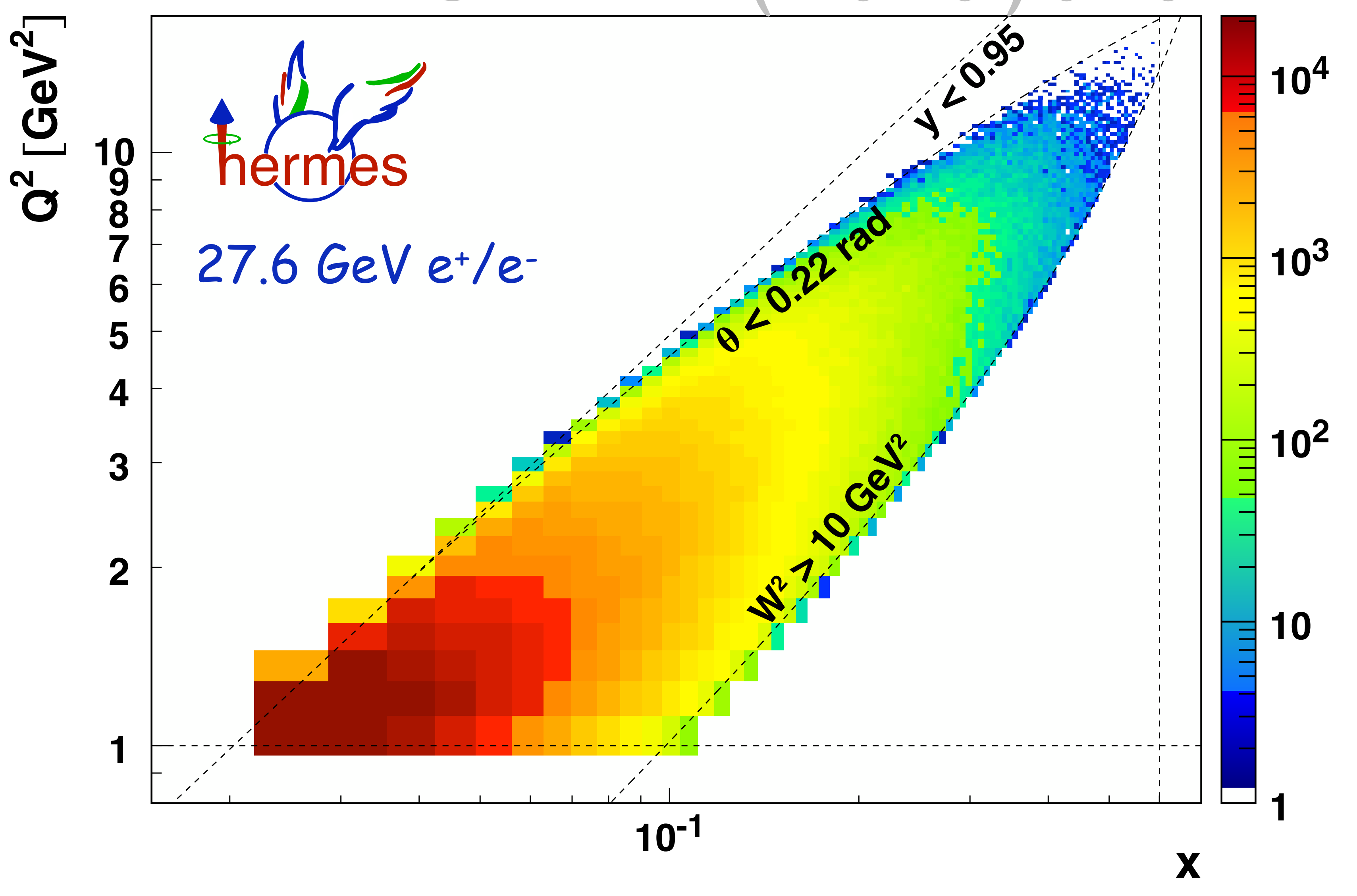
2d kinematic phase space



2d kinematic phase space



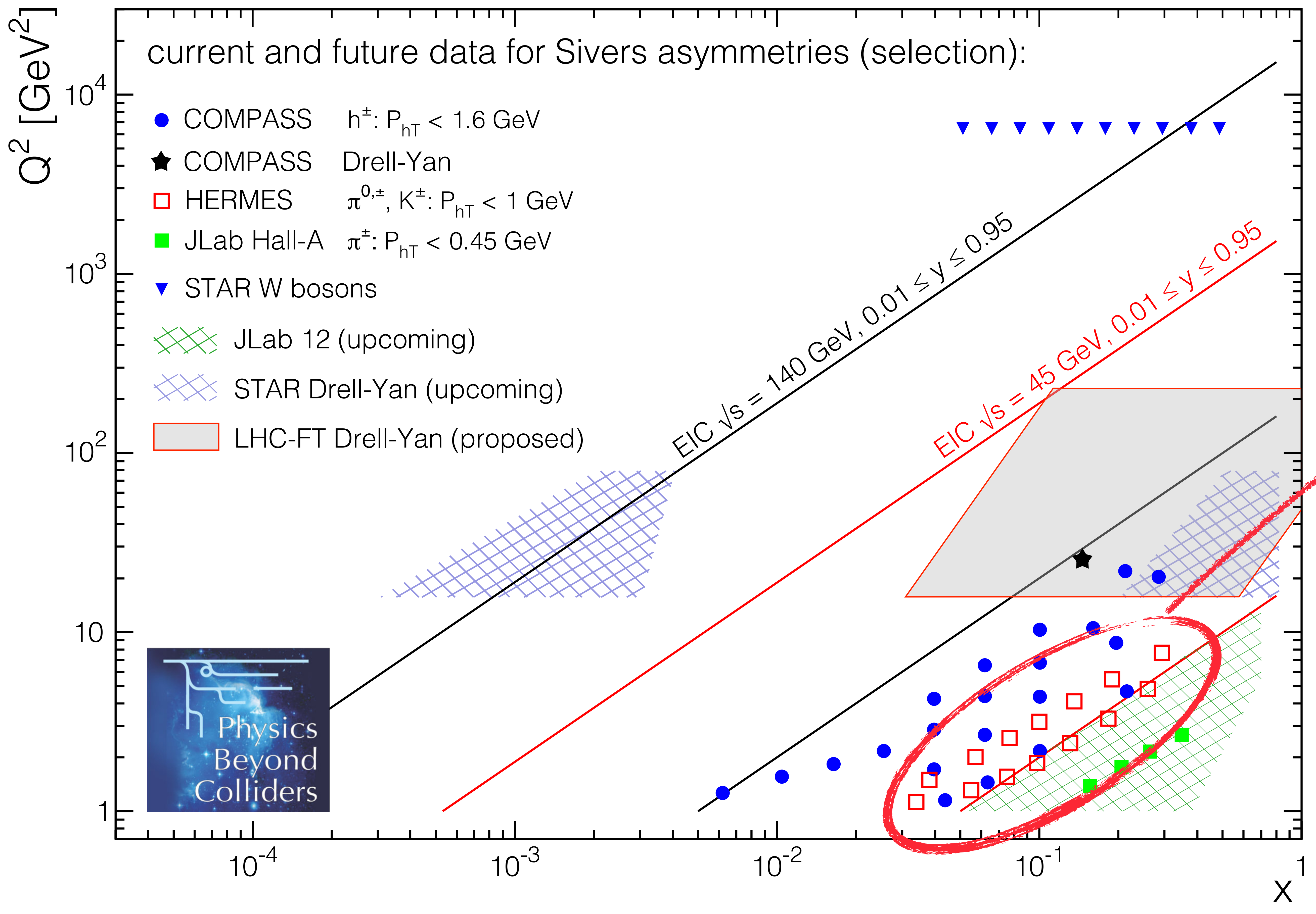
JHEP12(2020)010



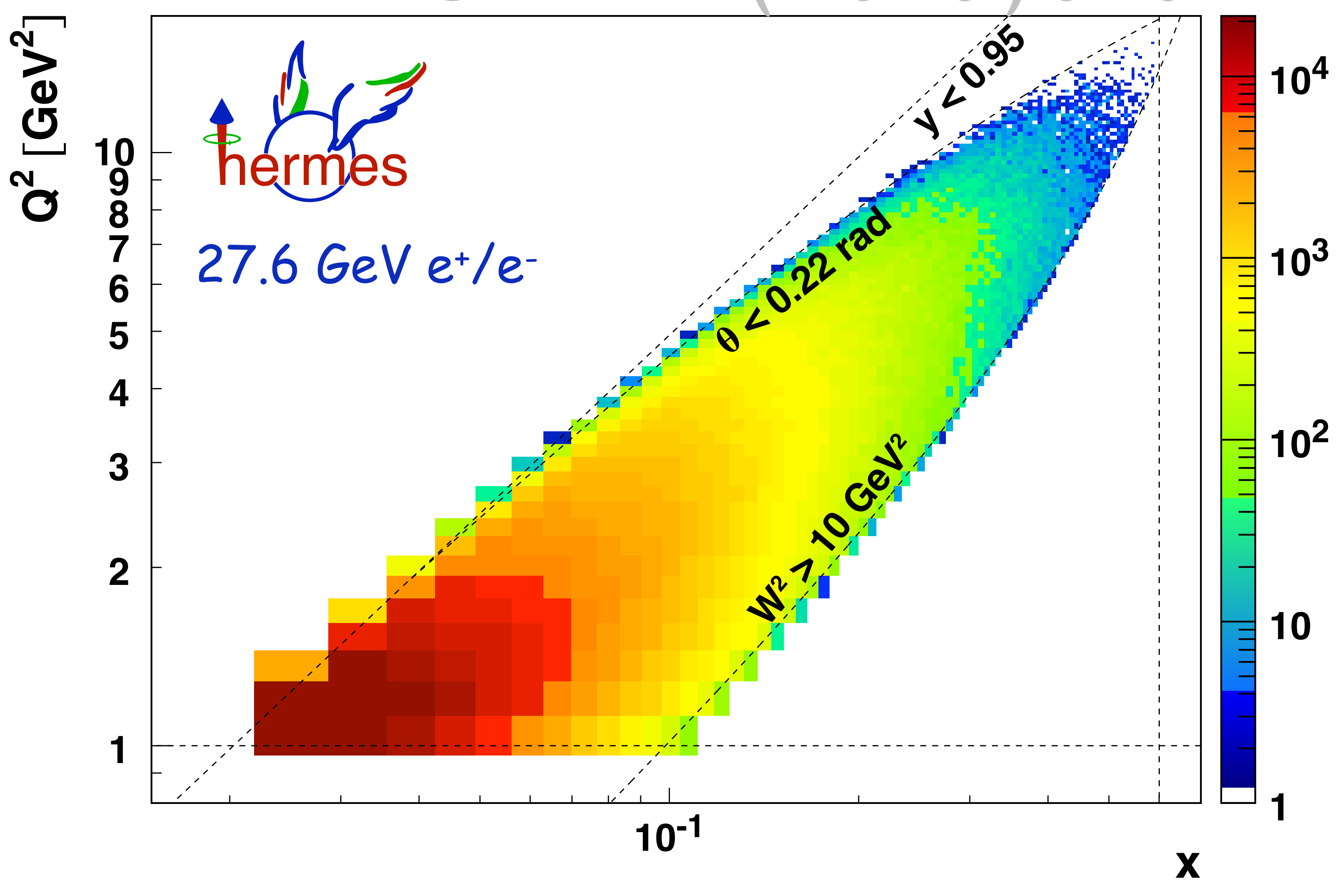
Scattered lepton:		Q^2	$> 1\,\mathrm{GeV}^2$	
		W^2	$> 10\,\mathrm{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	charged mesons
	$4\,\mathrm{GeV} <$	$\lvert\mathbf{P}_h\rvert$	$< 15\,\mathrm{GeV}$	(anti)protons
		$\lvert\mathbf{P}_h\rvert$	$> 2\,\mathrm{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\mathrm{GeV}$	
	$0.2 <$	z	< 0.7 (1.2 for the "semi-exclusive" region)	

Table 3. Restrictions on selected kinematics variables. The upper limit on z of 1.2 applies only to the analysis of the z dependence.

2d kinematic phase space

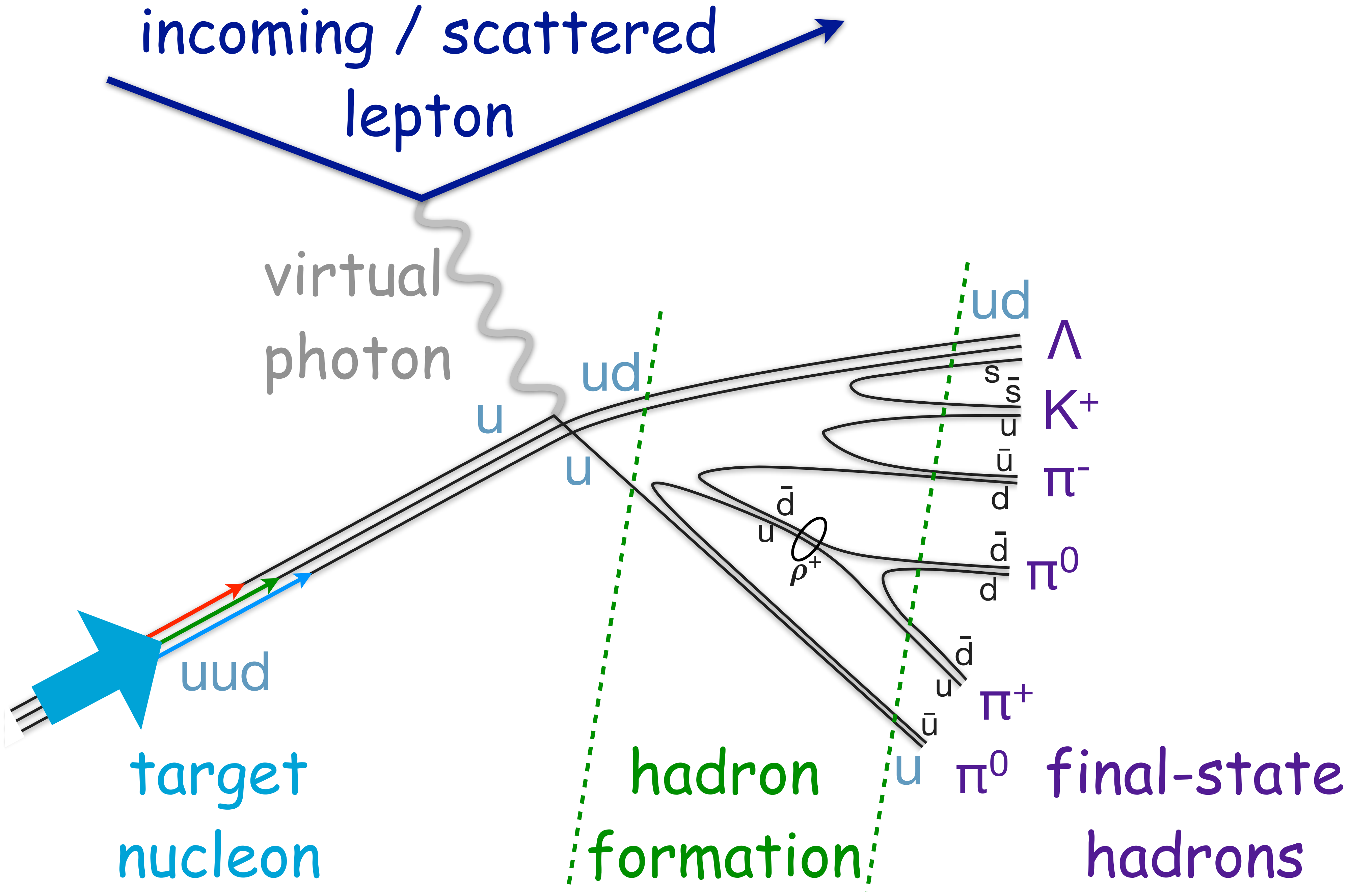


JHEP12(2020)010

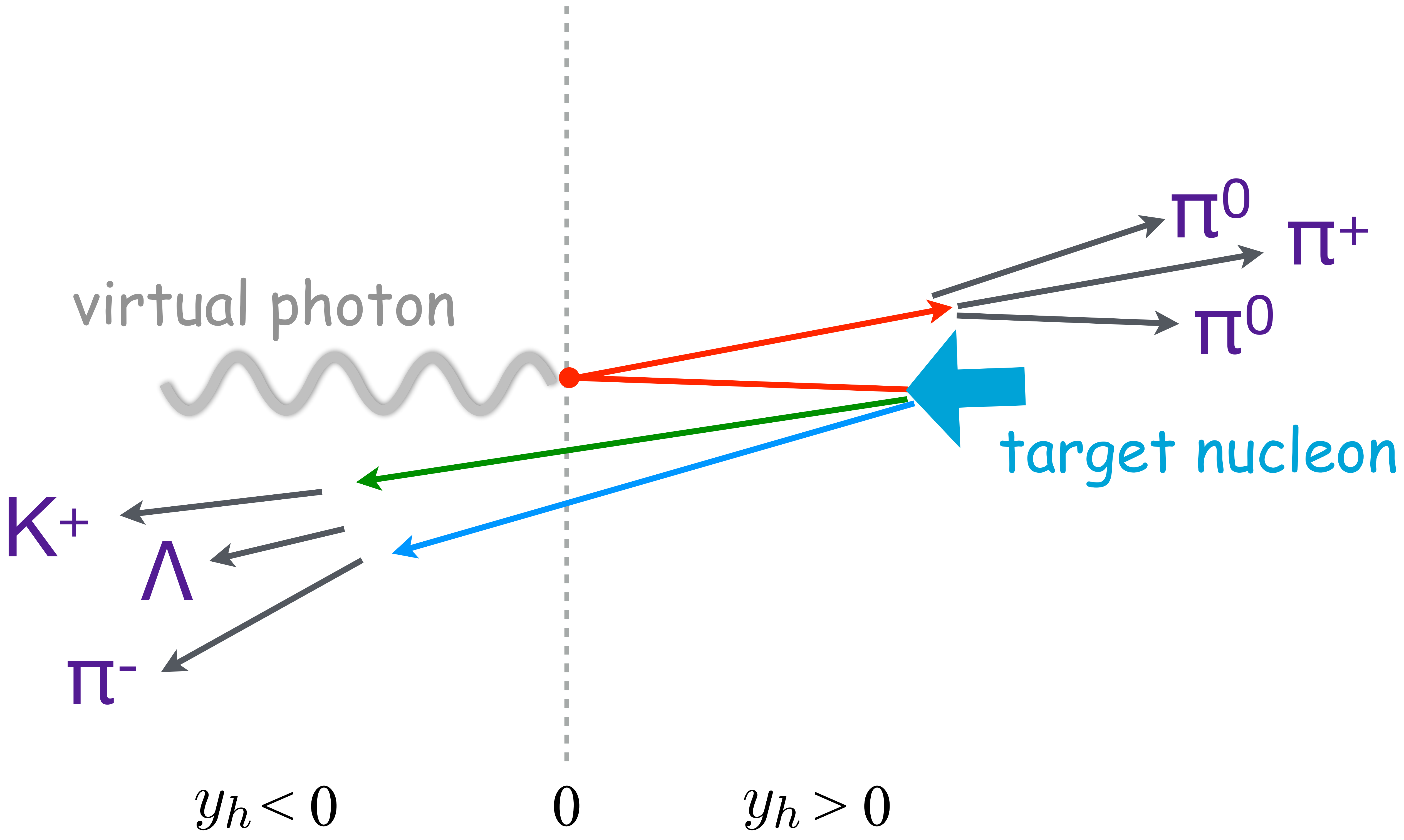


2d (x-Q^2) kinematic space not the only relevant one for SIDIS interpretation

current vs. target fragmentation



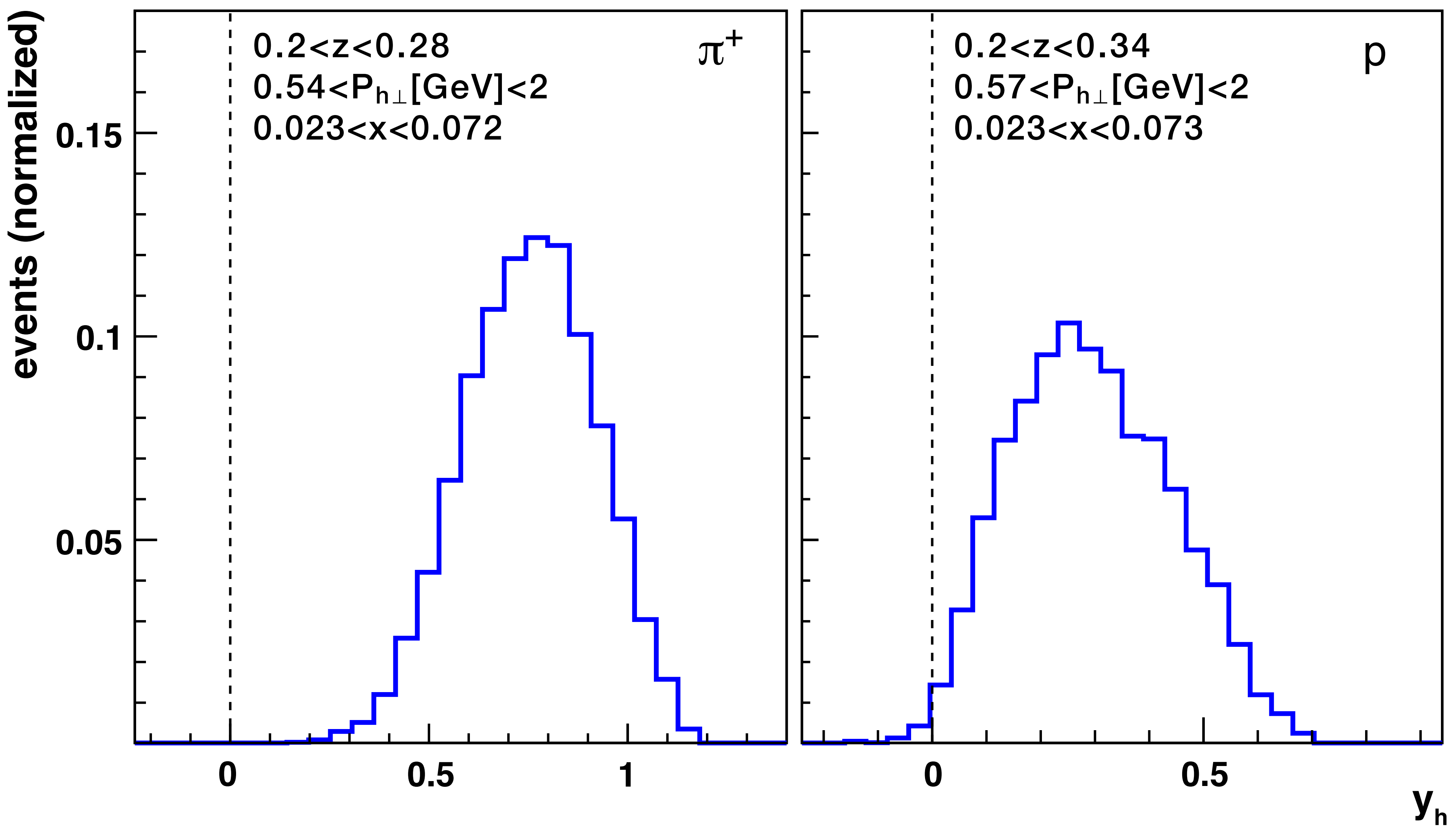
virtual-photon—nucleon c.m.s



$$y_h \equiv \frac{1}{2}\ln\frac{P_h^+}{P_h^-}$$

$P_h^{\pm}$ ... light-cone momenta

current vs. target fragmentation



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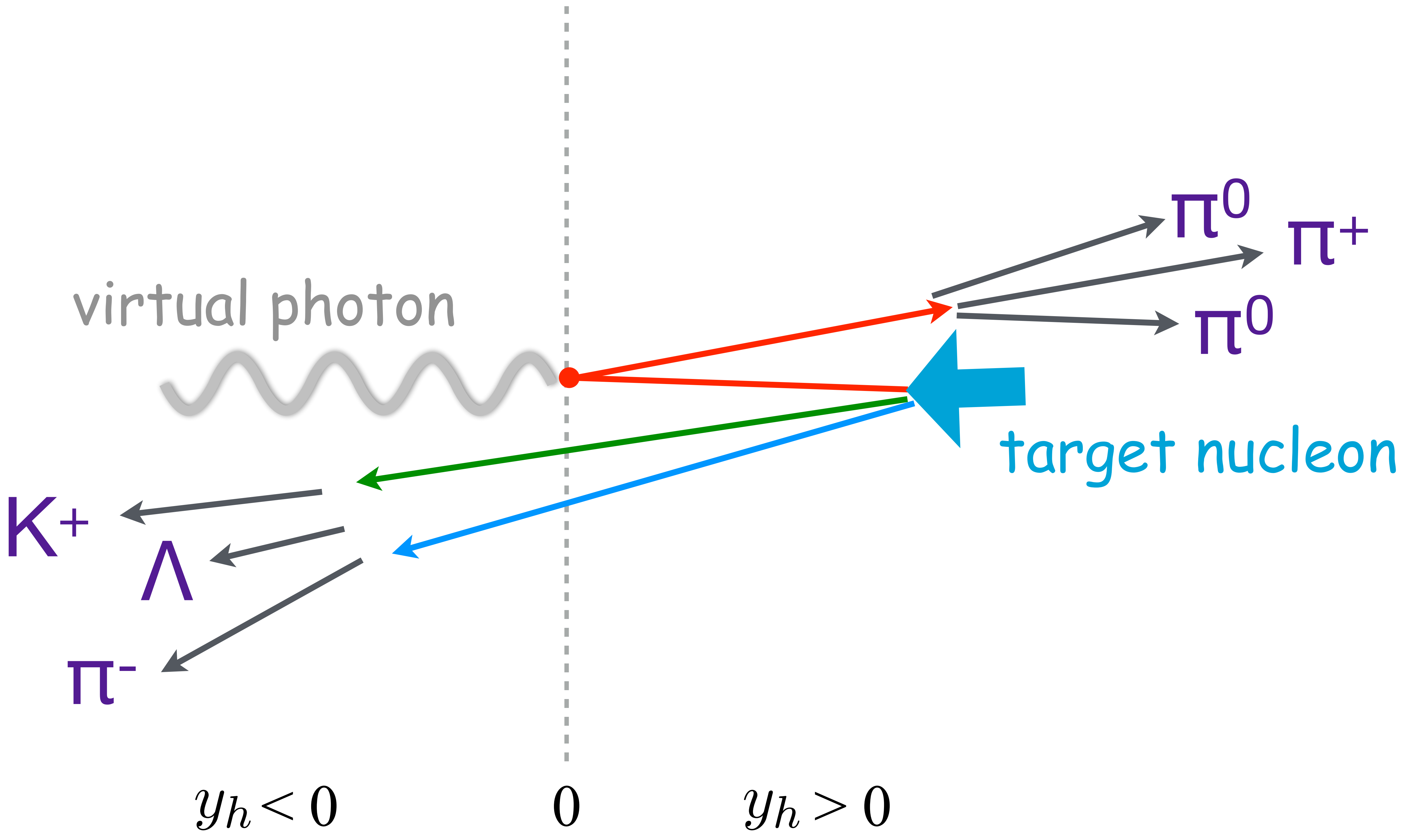

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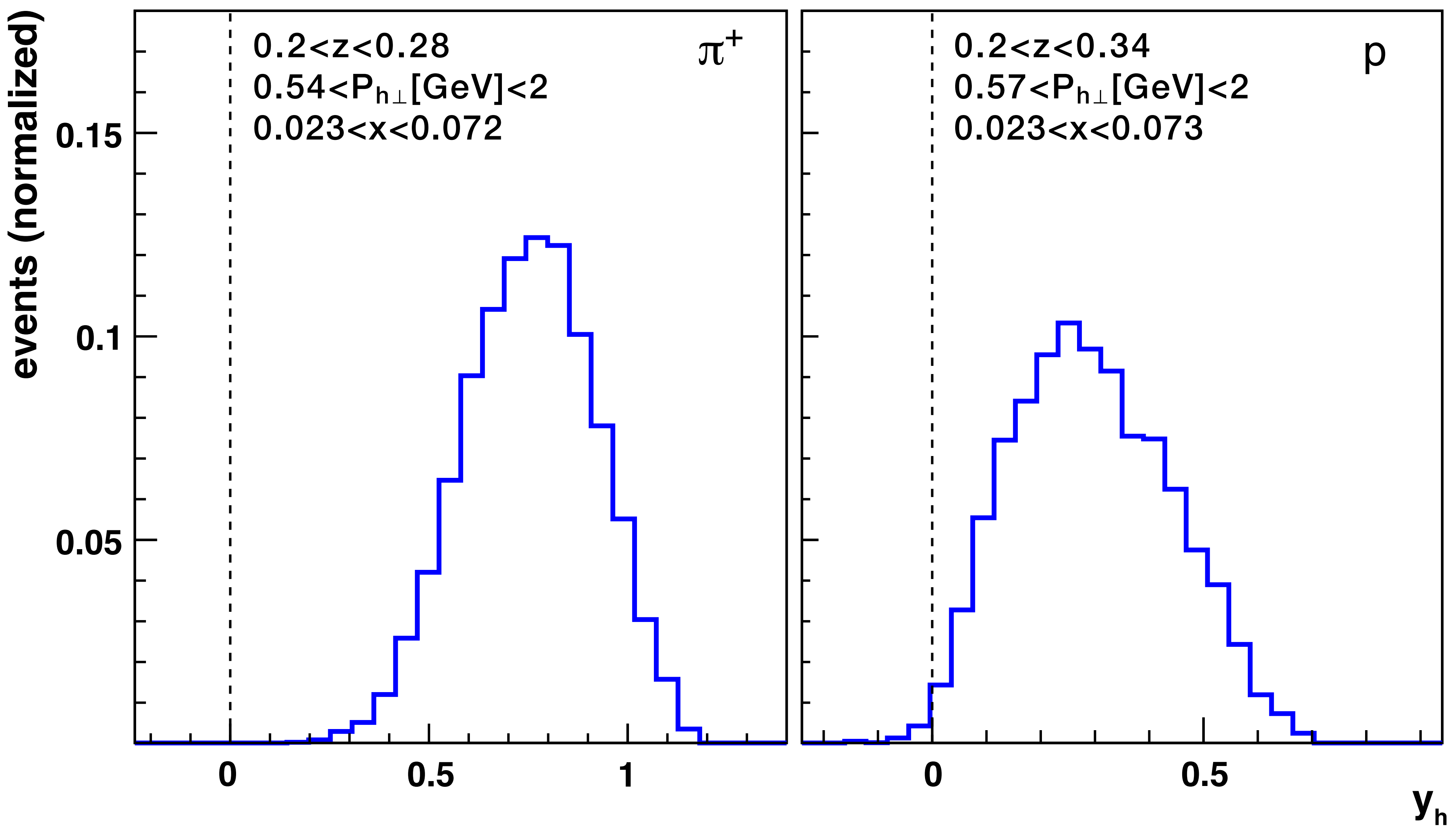
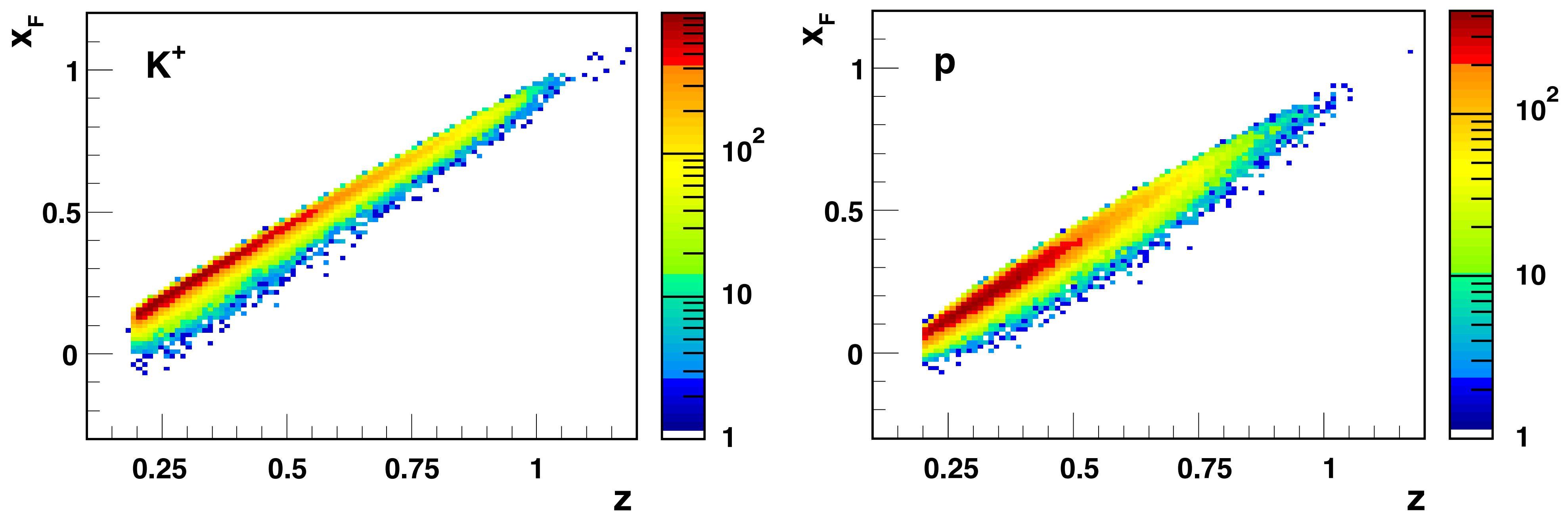
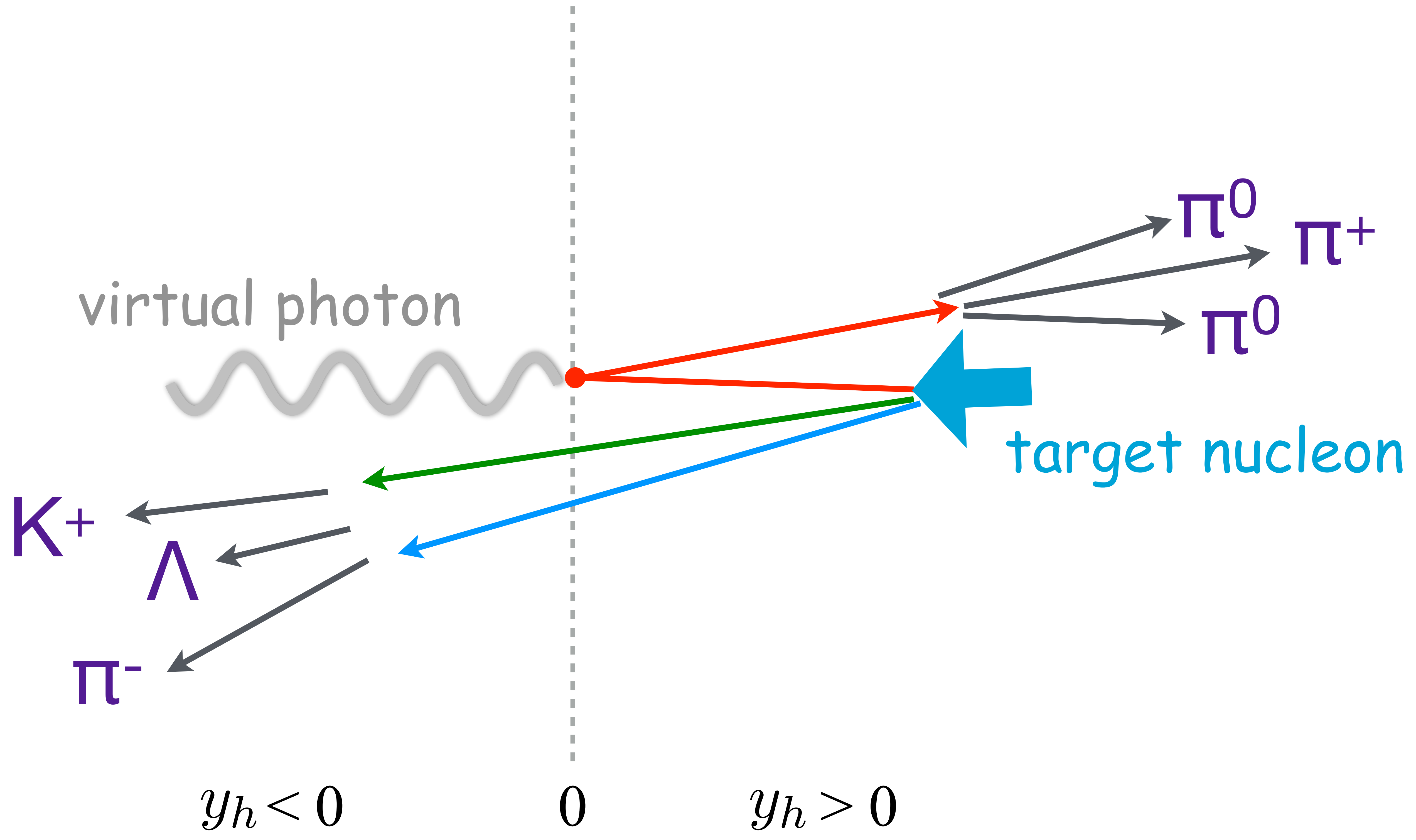




x_F … Feynman x

selected hadrons at HERMES mainly forward-going in photon-nucleon c.m.s.

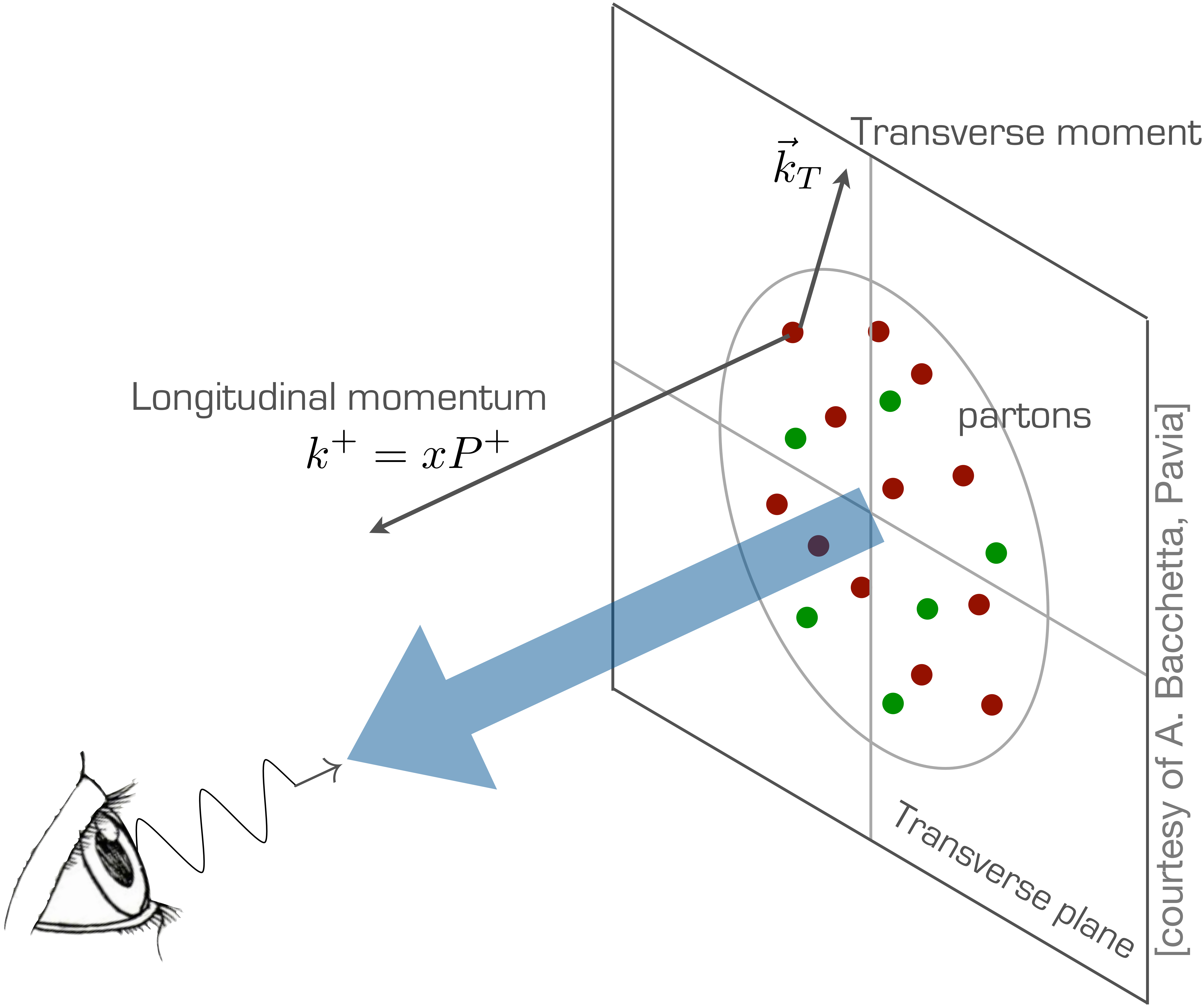
virtual-photon—nucleon c.m.s



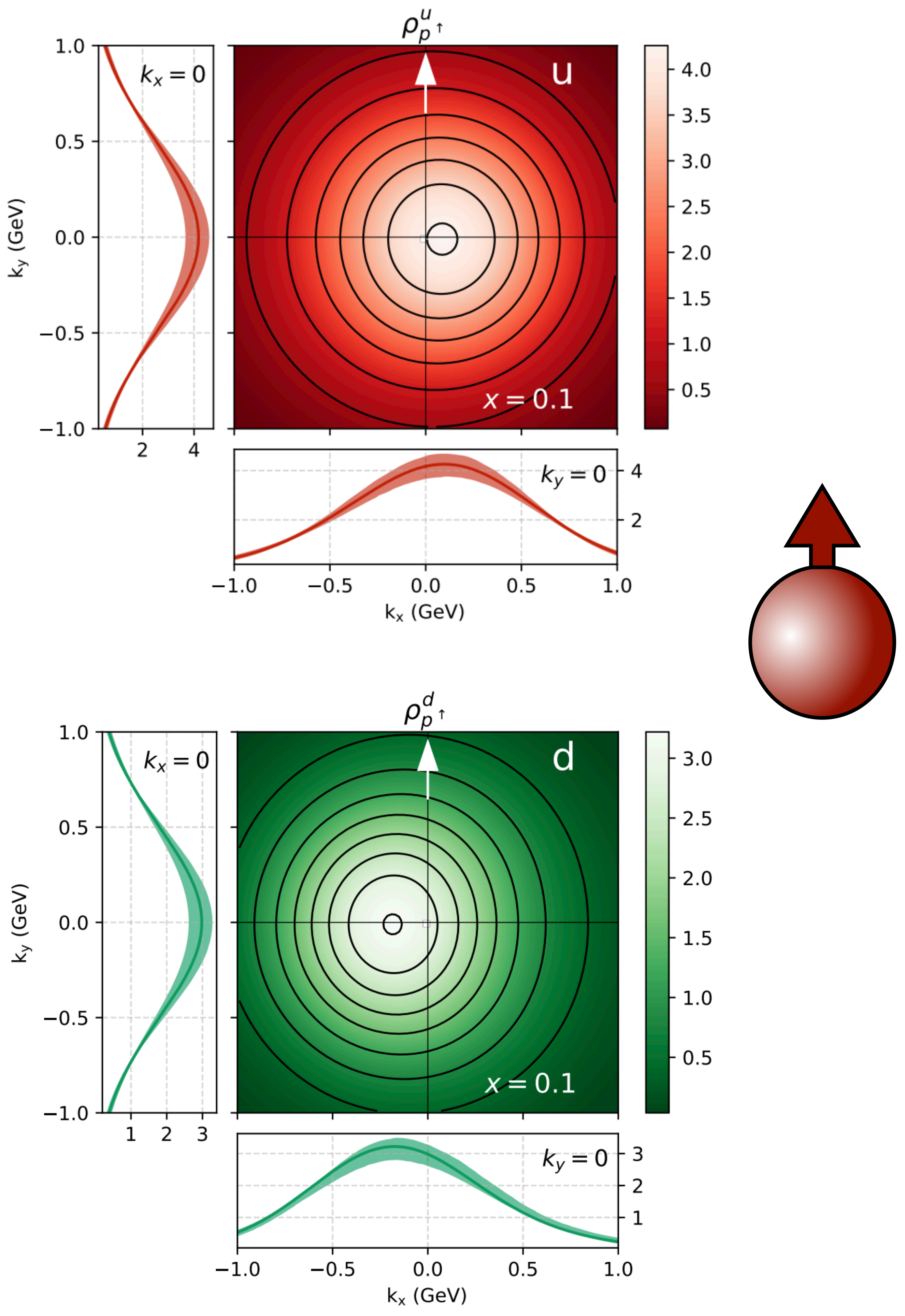
$$y_h \equiv \frac{1}{2} \ln \frac{P_h^+}{P_h^-}$$

$P_h^\pm$ … light-cone momenta

transverse-momentum distributions (TMDs)



[courtesy of A. Bacchetta, Pavia]



🔗 [A. Bacchetta et al. (2021)]

spin-momentum structure of the nucleon

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

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^iS^ih_1 + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]$$

quark pol.

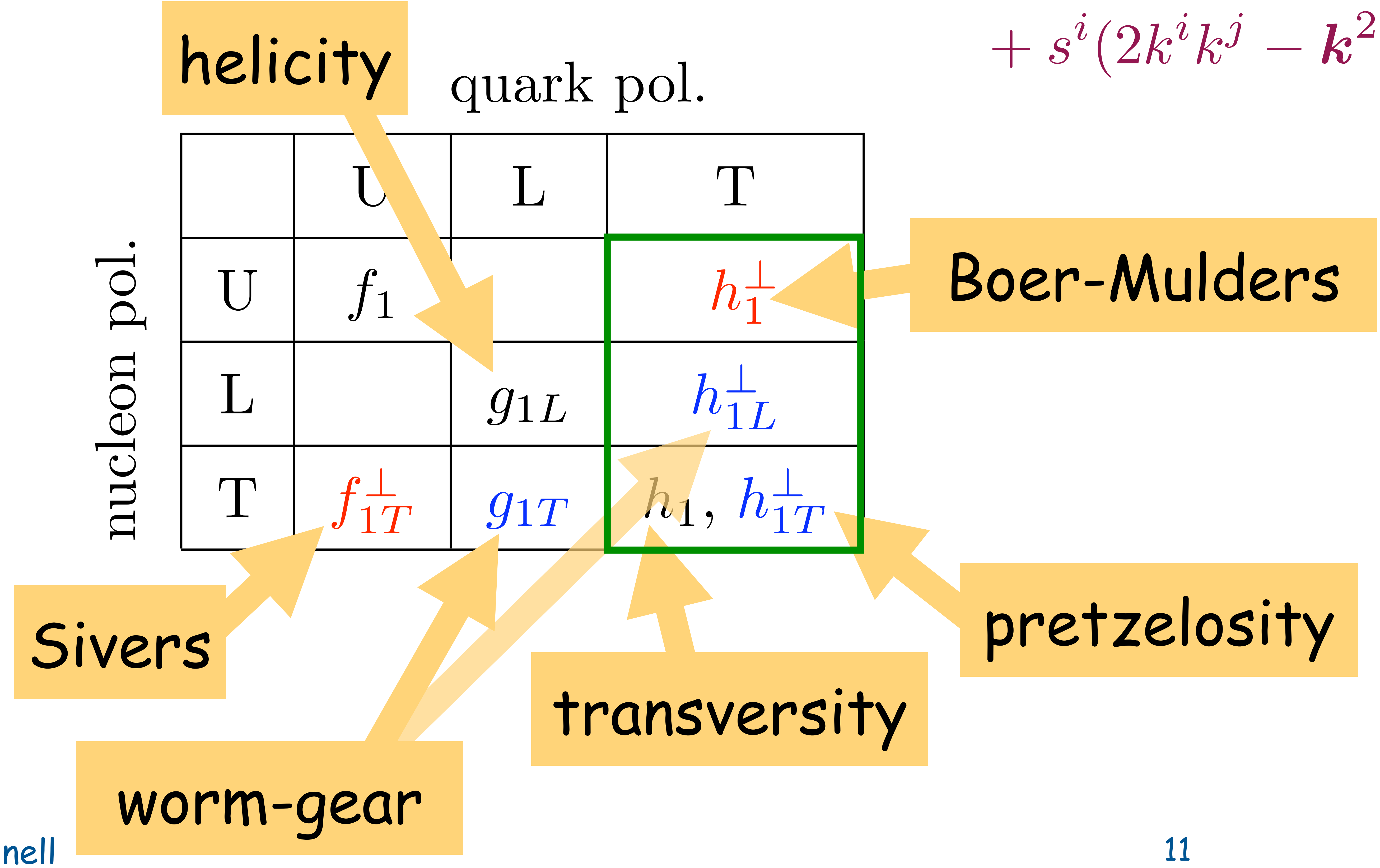
nucleon pol.

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

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

spin-momentum structure of the nucleon

$$\begin{aligned}
\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\Big] &= \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + \lambda\Lambda\,g_1 + \lambda\,S^ik^i\,\frac{1}{m}\,g_{1T}\Big] \\
\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] &= \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^iS^ih_1 \\
&\qquad + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]
\end{aligned}$$



helicity

quark pol.

nucleon pol.

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

Boer-Mulders

Sivers

pretzelosity

transversity

worm-gear

- each TMD describes a particular spin-momentum correlation
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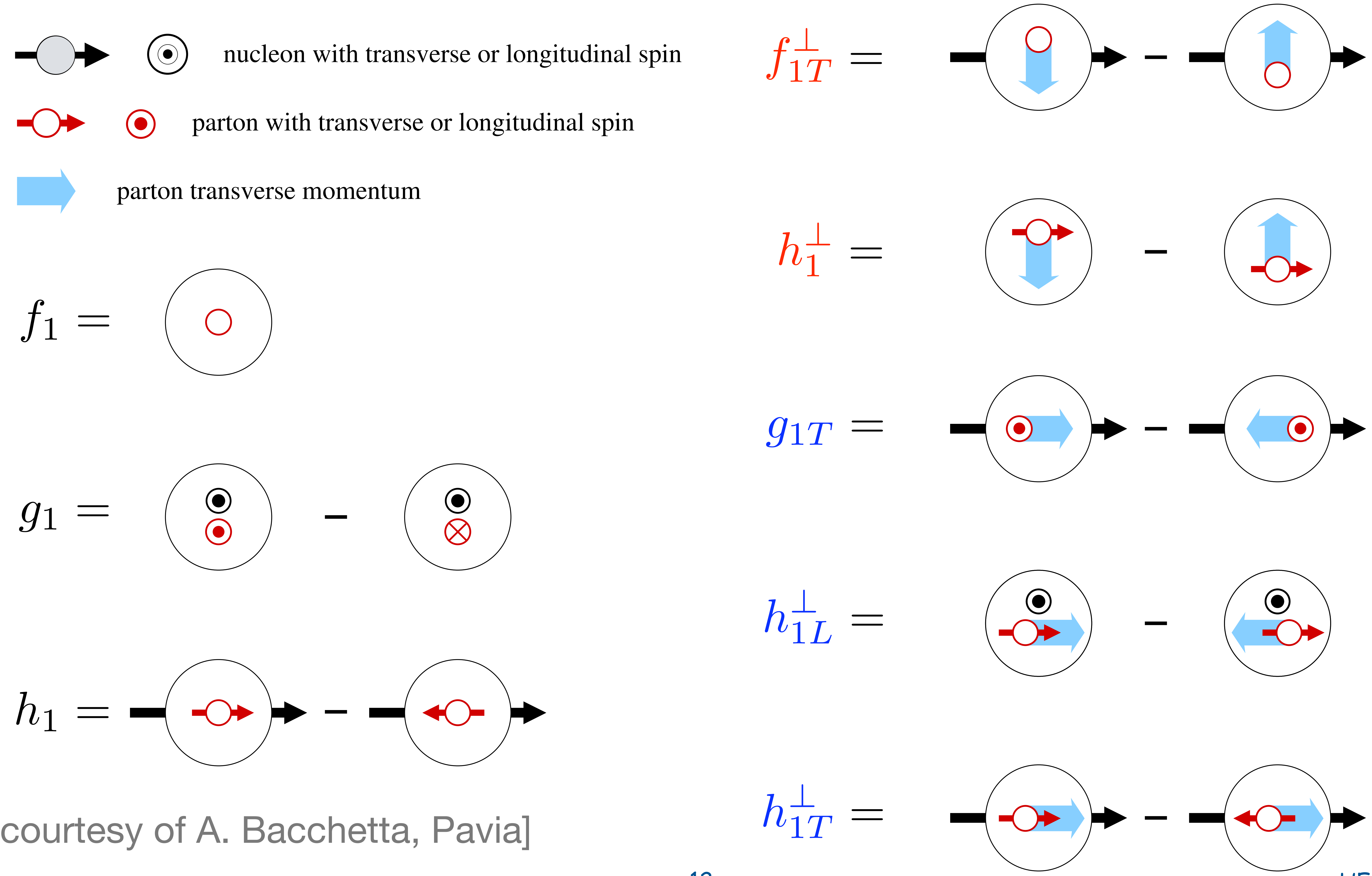
TMDs - probabilistic interpretation

proton goes out of the screen / photon goes into the screen



nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

$f_1 =$

$g_1 =$ –

$h_1 =$ –

$f_{1T}^{\perp} =$ –

$h_1^{\perp} =$ –

$g_{1T} =$ –

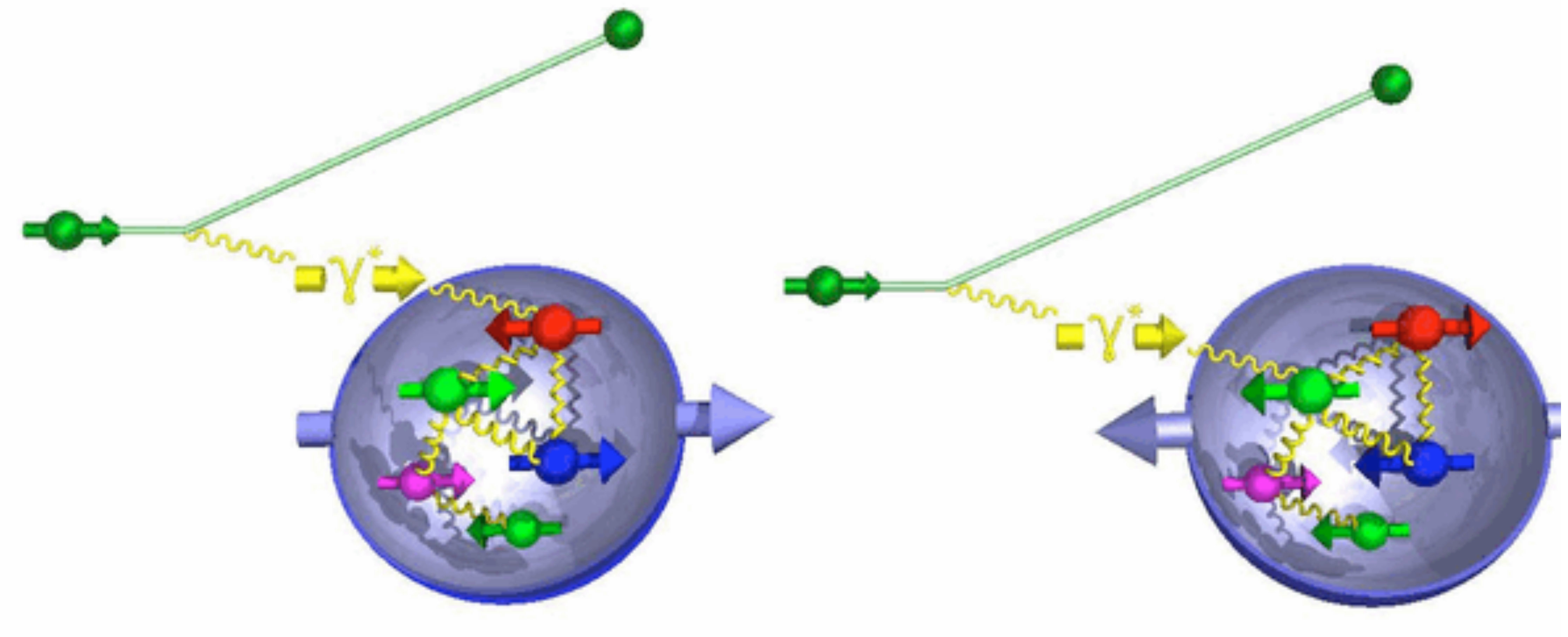
$h_{1L}^{\perp} =$ –

$h_{1T}^{\perp} =$ –

[courtesy of A. Bacchetta, Pavia]

quark polarimetry

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



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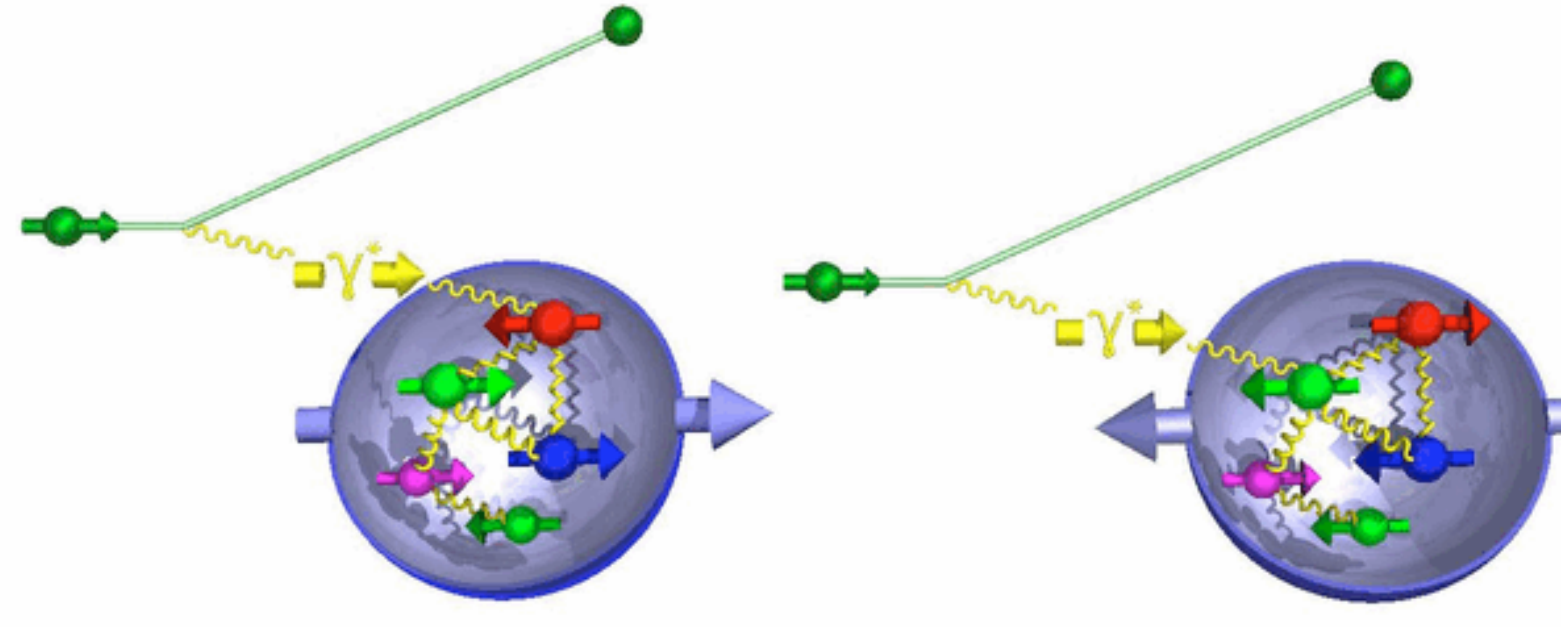
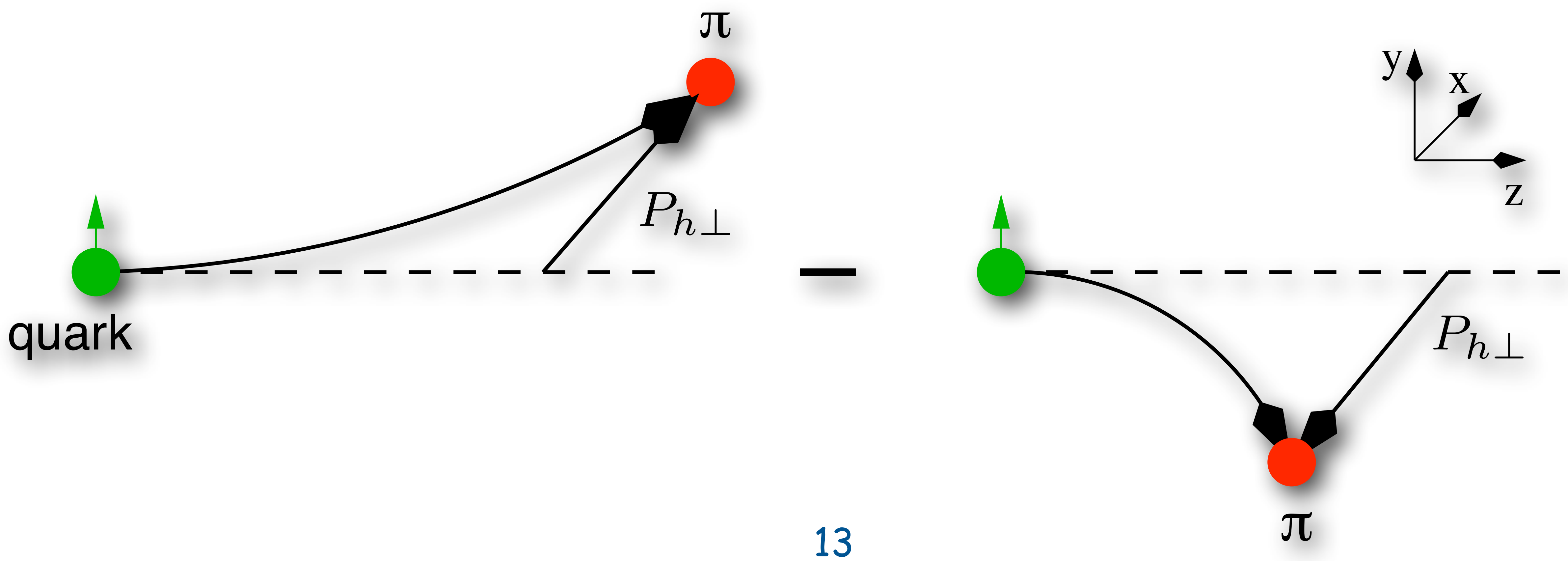


- transversely polarized quarks: need final-state polarimetry, e.g.



TMDs in hadronization

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

TMDs in hadronization

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

☚ relevant for unpolarized final state

TMDs in hadronization

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

☛ relevant for unpolarized final state

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

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

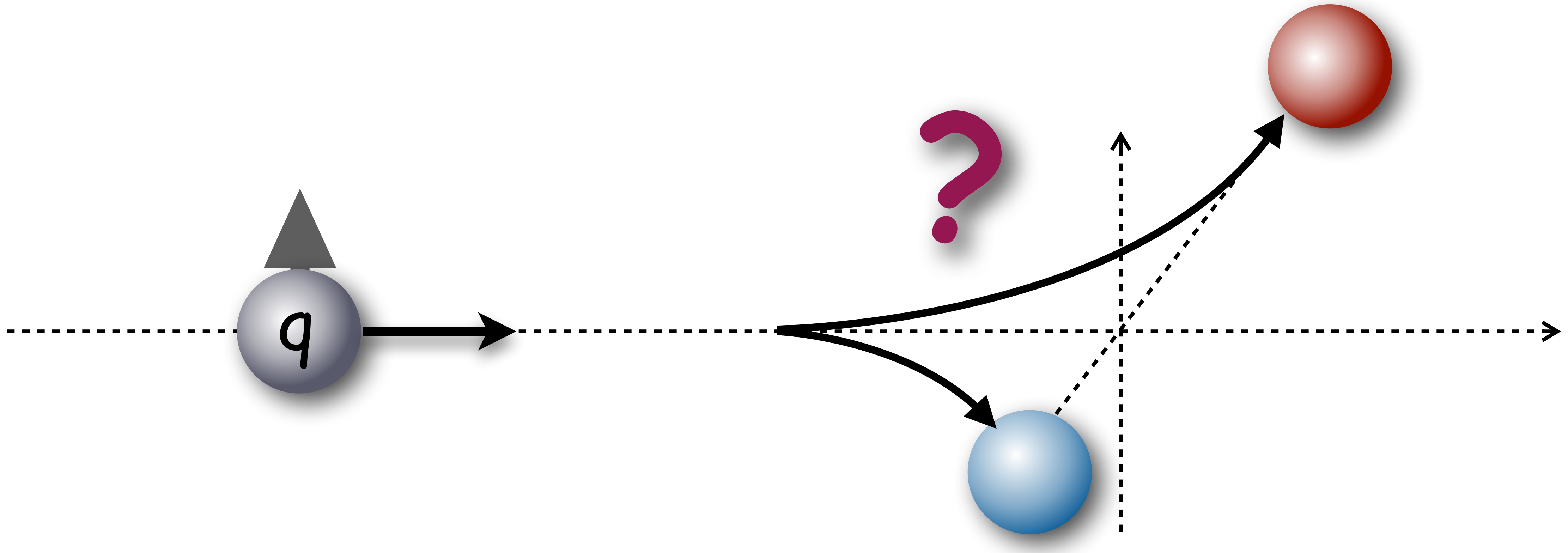
TMDs in hadronization

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

☚ relevant for unpolarized final state

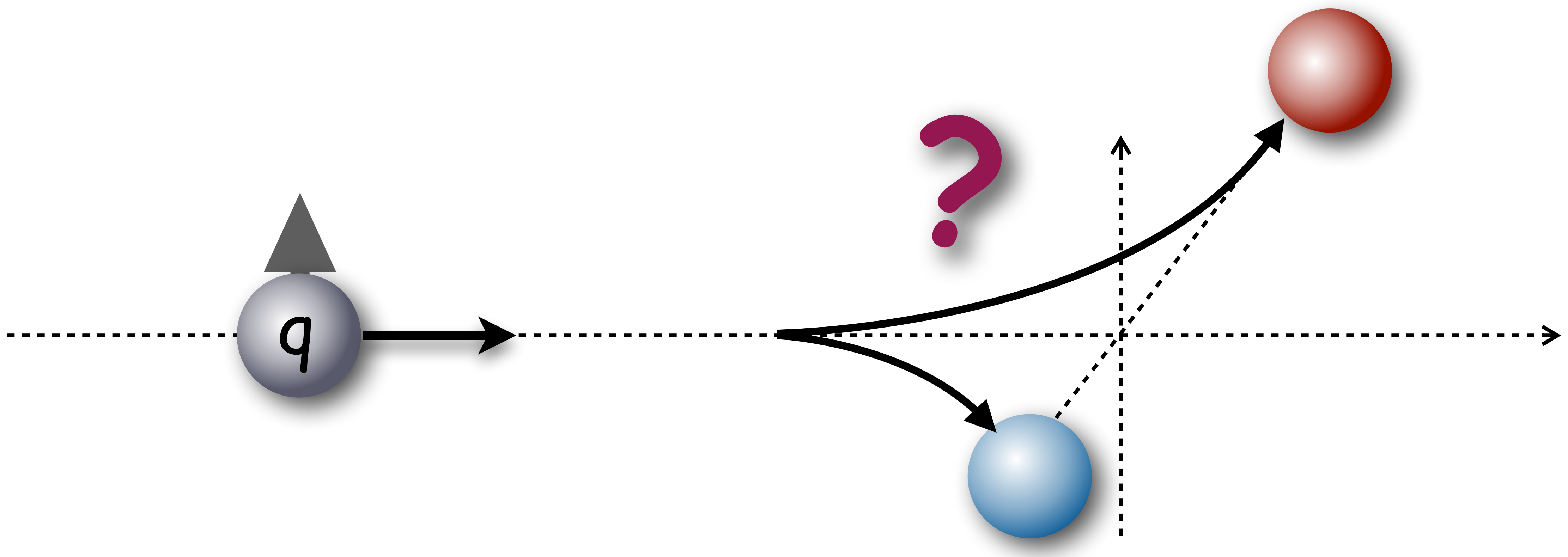
polarized final-state hadrons
(e.g., hyperons)

Collins function - chiral-odd fragmentation



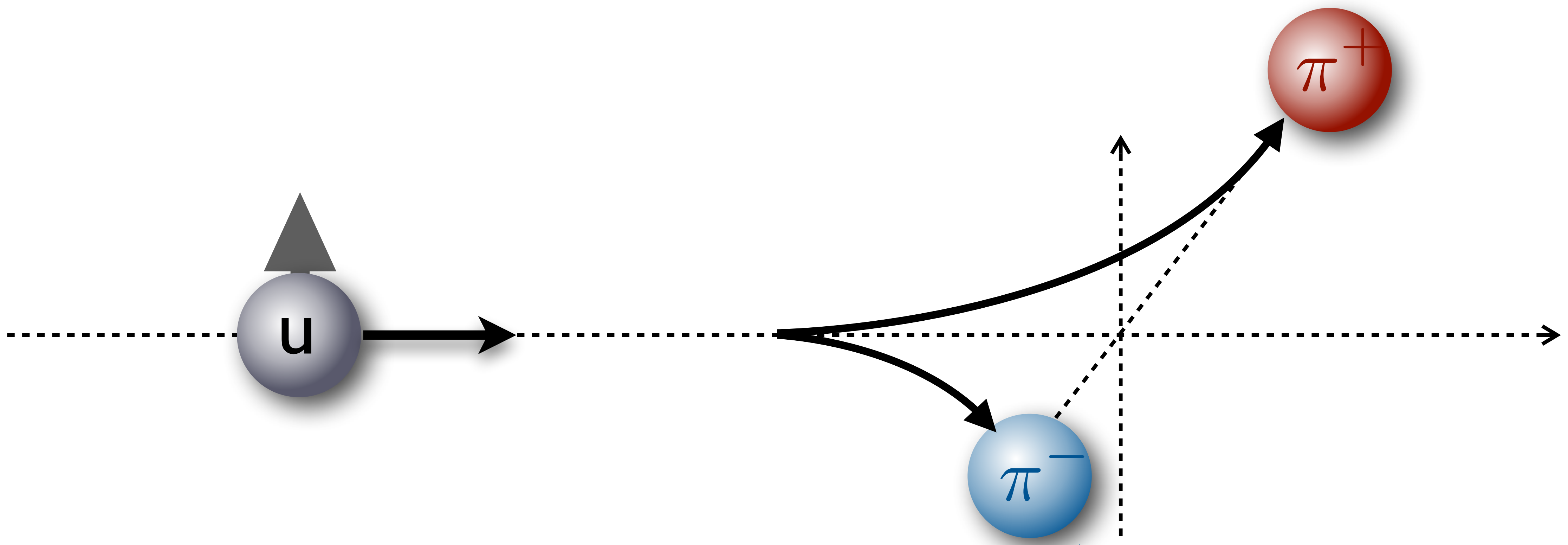
- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum

Collins function - chiral-odd fragmentation



- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum
- extracted from SIDIS and e^+e^- annihilation data

Collins function - chiral-odd fragmentation



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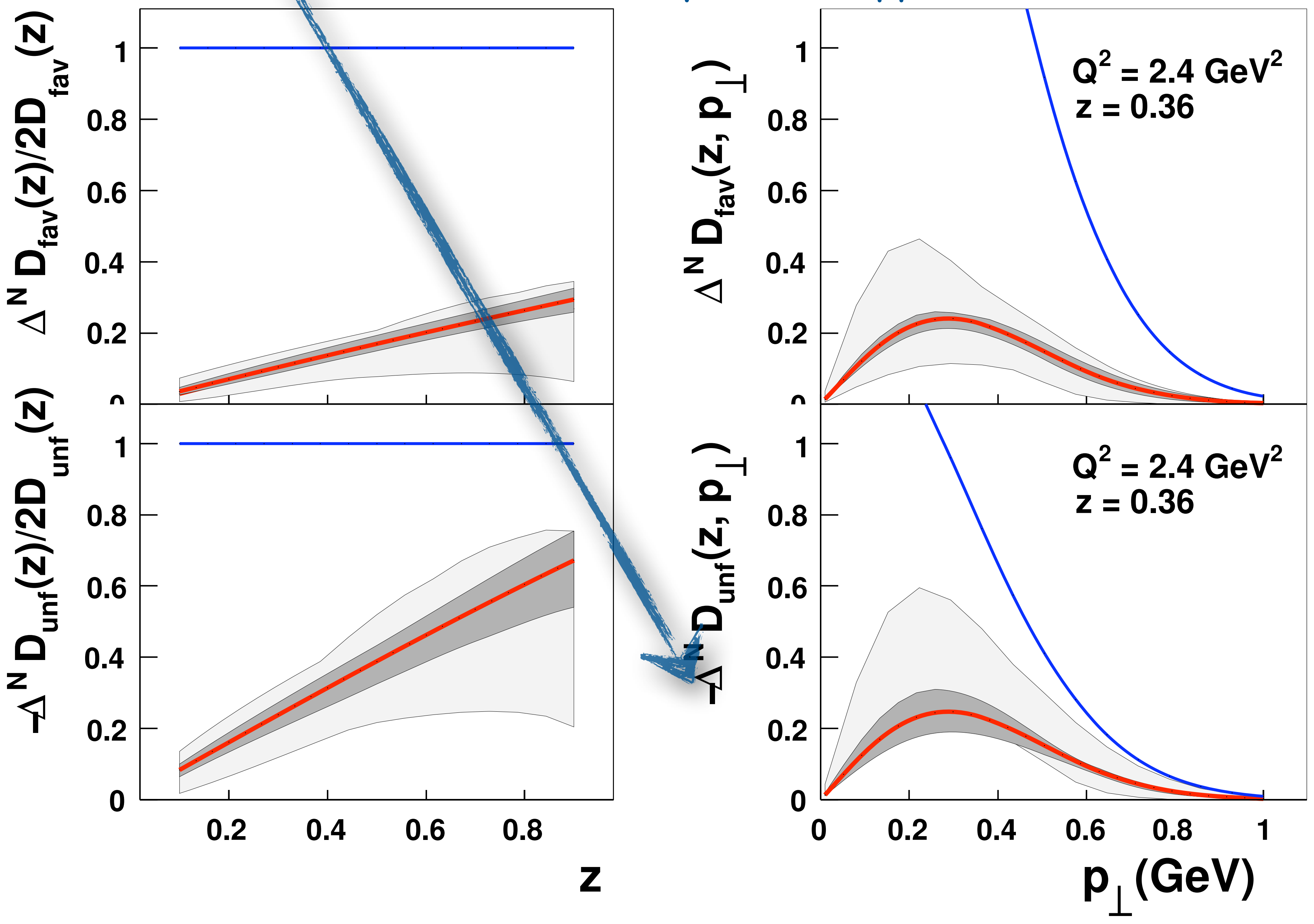
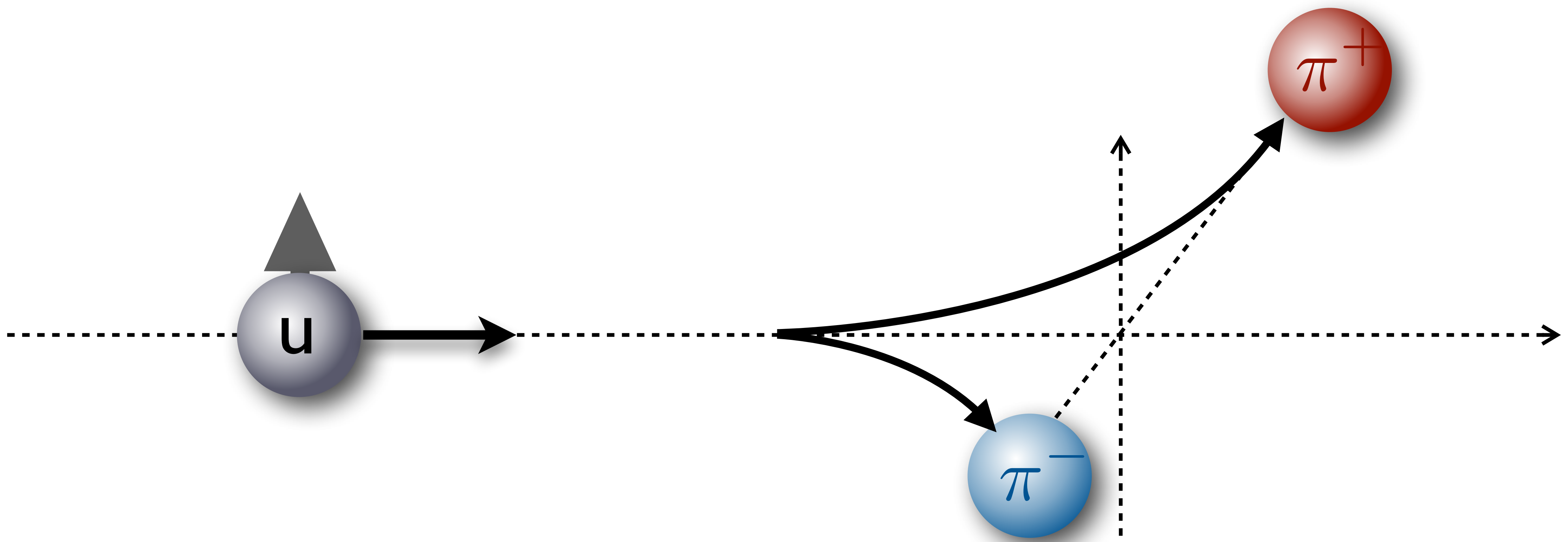
[Anselmino et al., Nucl.Phys.Proc.Suppl.191 (2009) 98]

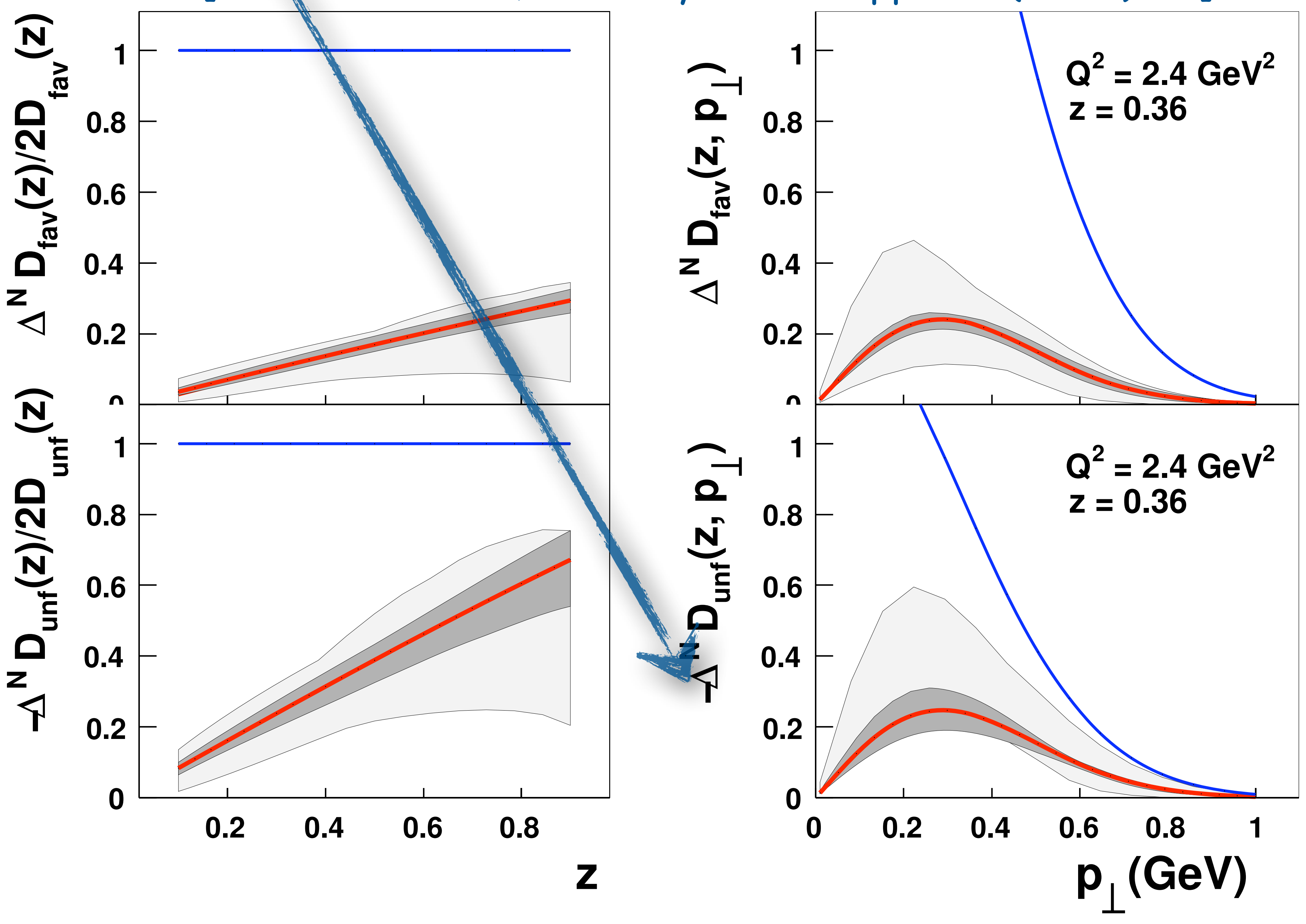


Collins function - chiral-odd fragmentation

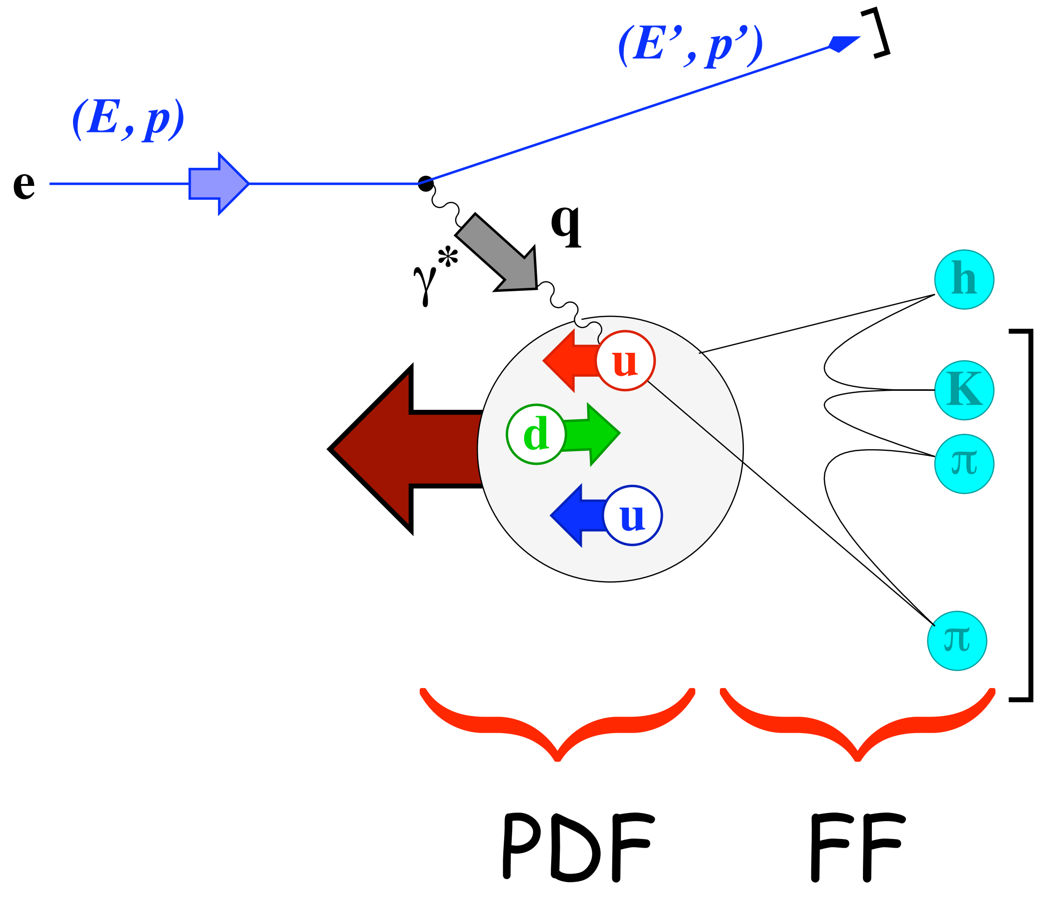


- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum
- extracted from SIDIS and e^+e^- annihilation data
- spin average gives “ordinary” D_1

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



probing TMDs in semi-inclusive DIS



quark pol.

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

in SIDIS*) couple PDFs to:

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

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

➟ give rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

semi-inclusive DIS

- excluding transverse polarization:

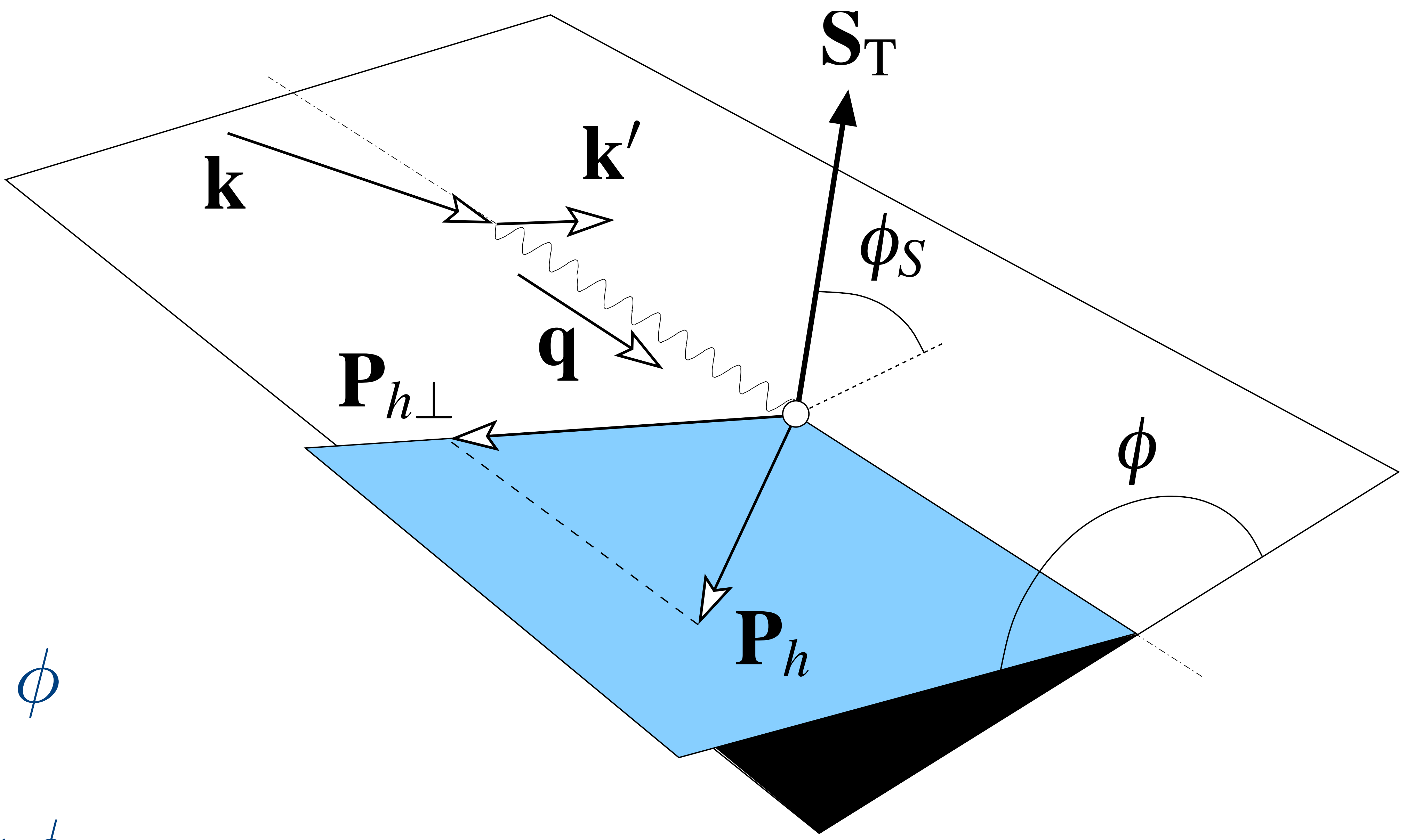
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \Big\}$$



$$F_{XY}^{h,\mathrm{mod}} = F_{XY}^{h,\mathrm{mod}}(x, Q^2, z, P_{h\perp})$$

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

- excluding transverse polarization:

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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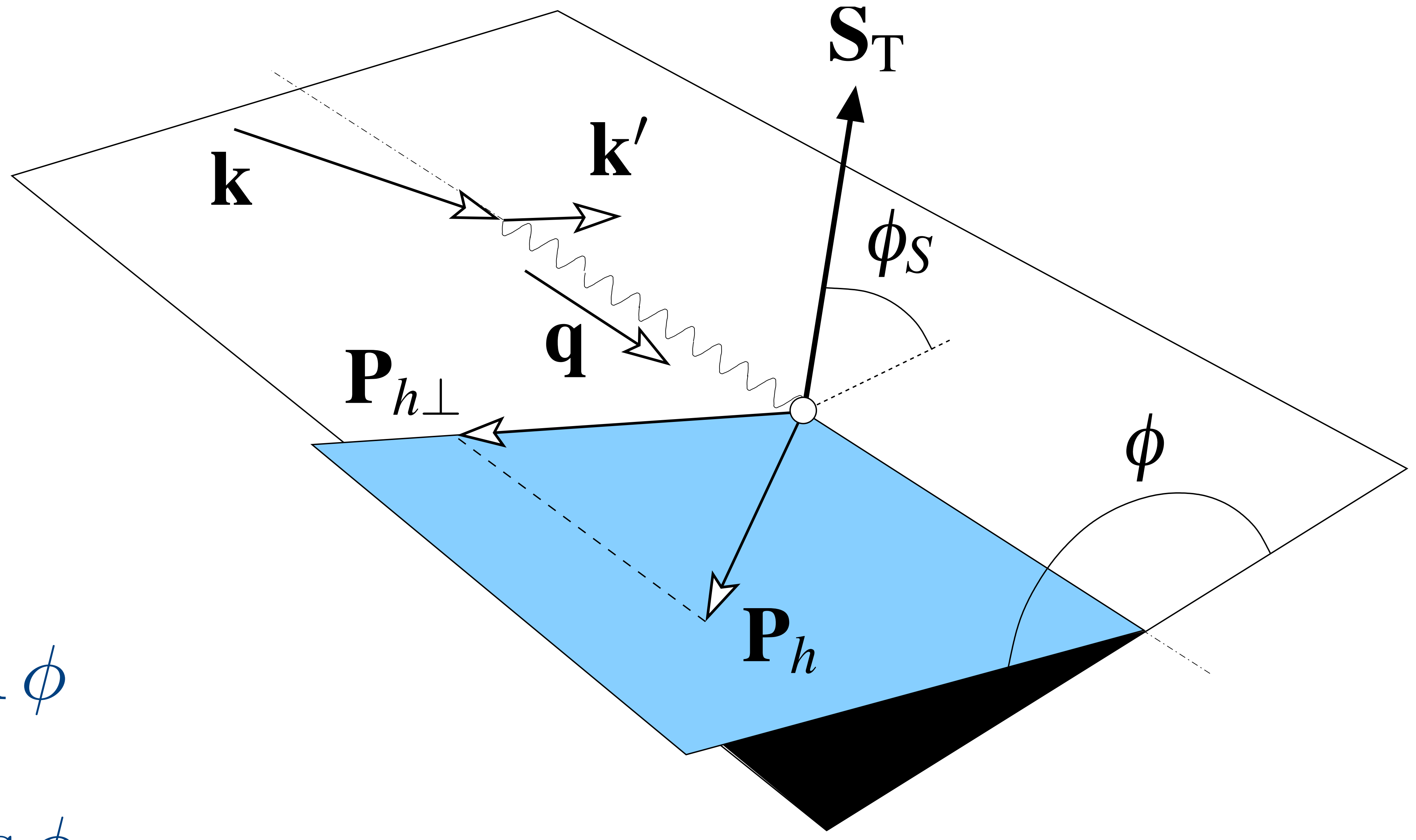
$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \Big\}$$



$$F_{XY}^{h,\mathrm{mod}} = F_{XY}^{h,\mathrm{mod}}(x, Q^2, z, P_{h\perp})$$

Beam (λ) / Target (Λ)

helicities

semi-inclusive DIS

- excluding transverse polarization:

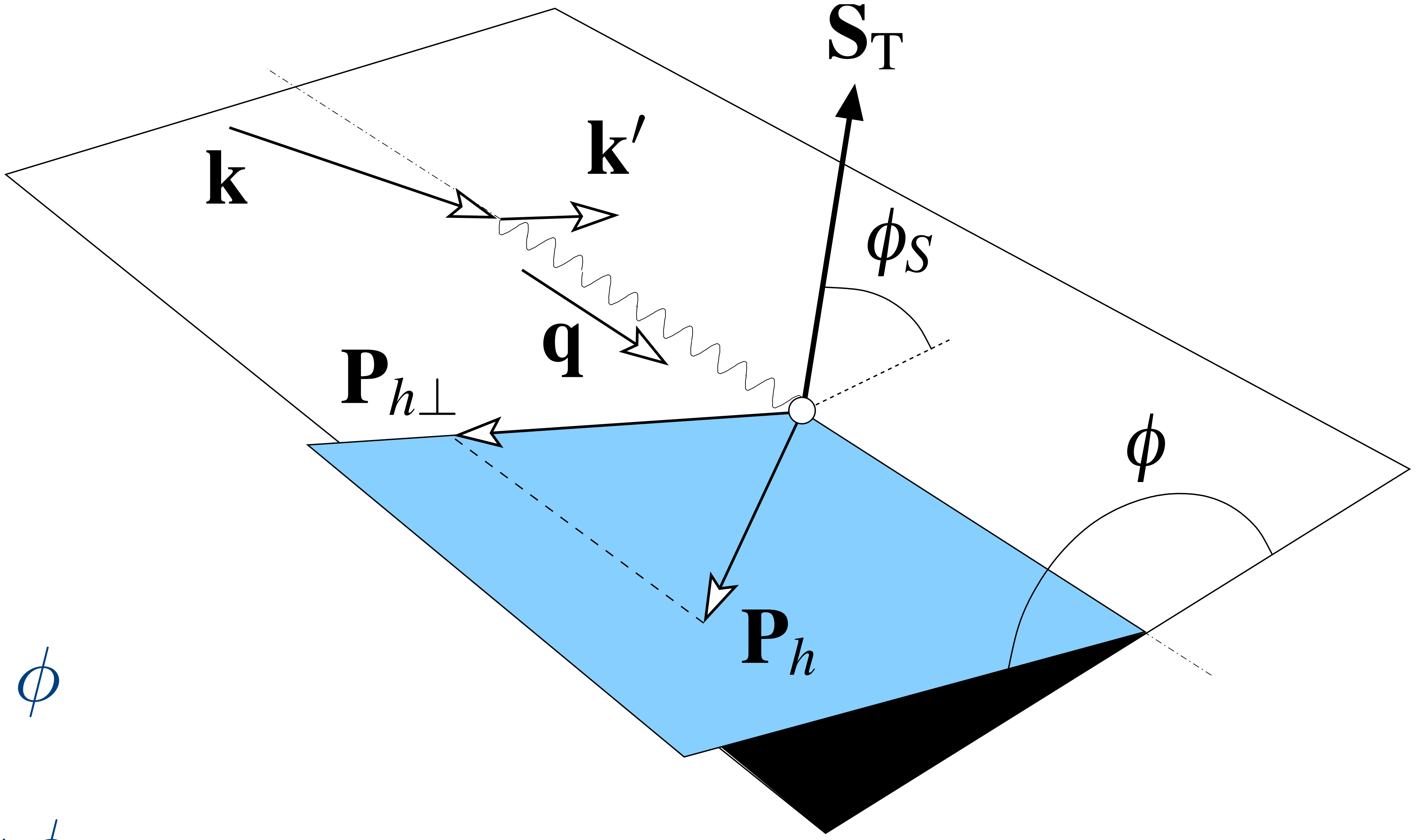
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\left\{F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}\,F_{LL}^h\right.$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$\left.+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi\right\}$$



- double-spin asymmetry:

$$A_{LL}^h \equiv \frac{\sigma_{++}^h - \sigma_{+-}^h + \sigma_{--}^h - \sigma_{-+}^h}{\sigma_{++}^h + \sigma_{+-}^h + \sigma_{--}^h + \sigma_{-+}^h}$$

semi-inclusive DIS

- excluding transverse polarization:

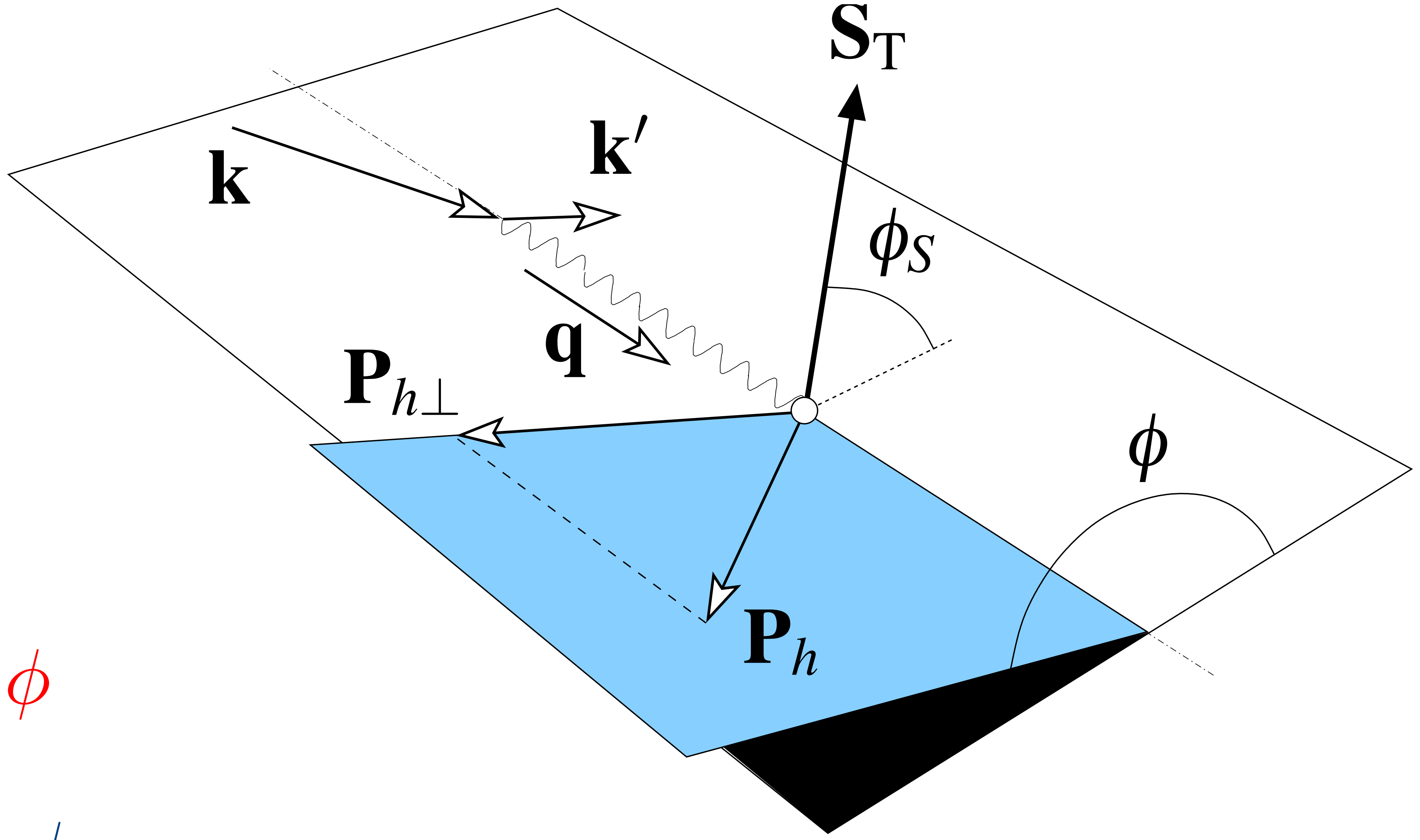
$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\left\{F_{UU,T}^h + \epsilon F_{UU,L}^h + \lambda\Lambda\sqrt{1-\epsilon^2}F_{LL}^h \right.$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$\left. +\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi \right\}$$

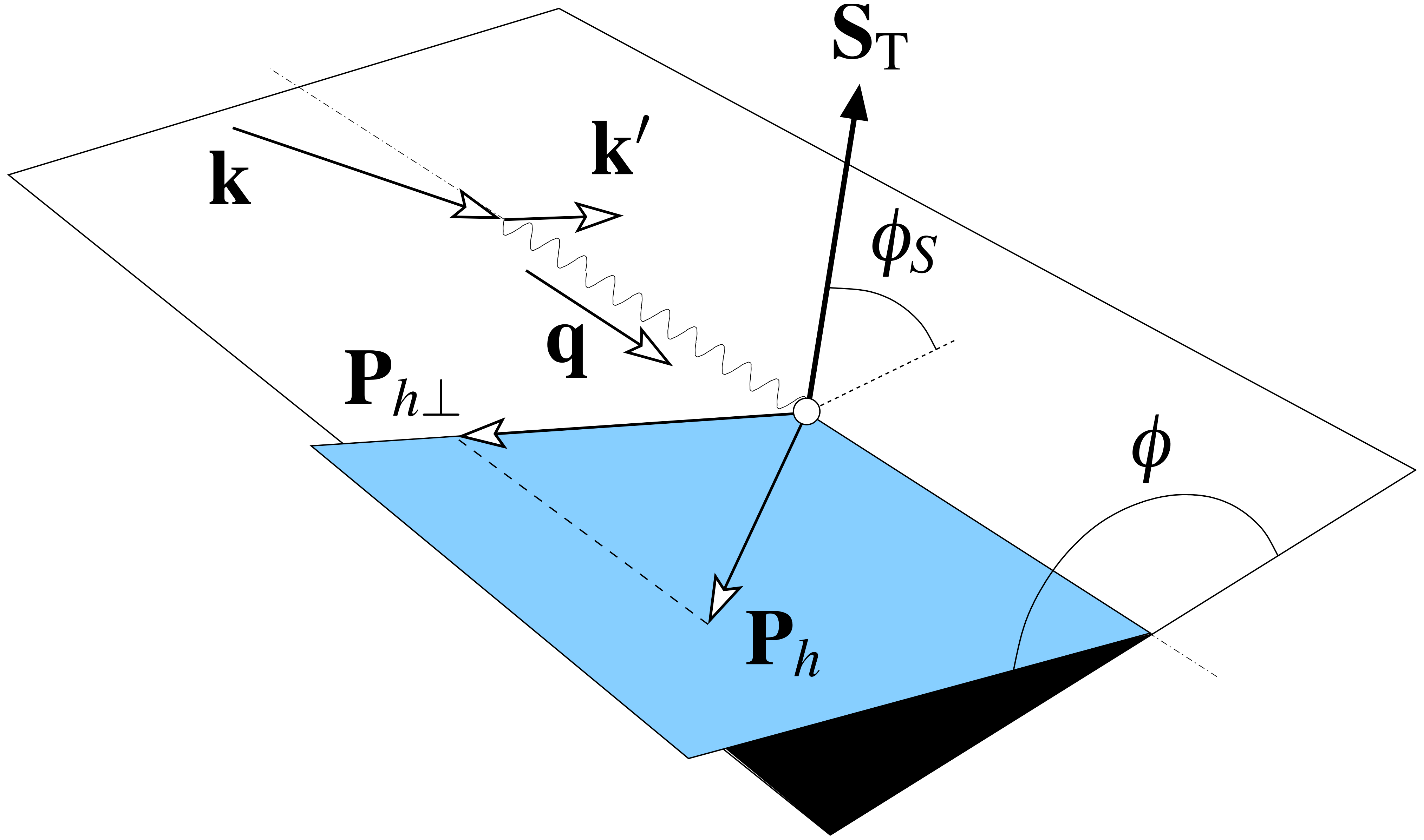


- single-spin asymmetry:
  - explicit angular dependence to be analyzed

$$A_{LU}^h \equiv \frac{\sigma_{+-}^h + \sigma_{++}^h - \sigma_{-+}^h - \sigma_{--}^h}{\sigma_{+-}^h + \sigma_{++}^h + \sigma_{-+}^h + \sigma_{--}^h}$$

semi-inclusive DIS

- with **transverse** target polarization:



$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi\,\mathrm{d}\phi_s} = \frac{2\pi\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Bigg\{ F_{UU,T}^h + \epsilon F_{UU,L}^h + \text{terms not involving transv. polarization}$$

$$+ S_T \left[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)}\right)\sin(\phi-\phi_s)\right.$$

$$+ \epsilon\, F_{UT}^{h,\sin(\phi+\phi_s)} \sin(\phi+\phi_s) + \epsilon\, F_{UT}^{h,\sin(3\phi-\phi_s)} \sin(3\phi-\phi_s)$$

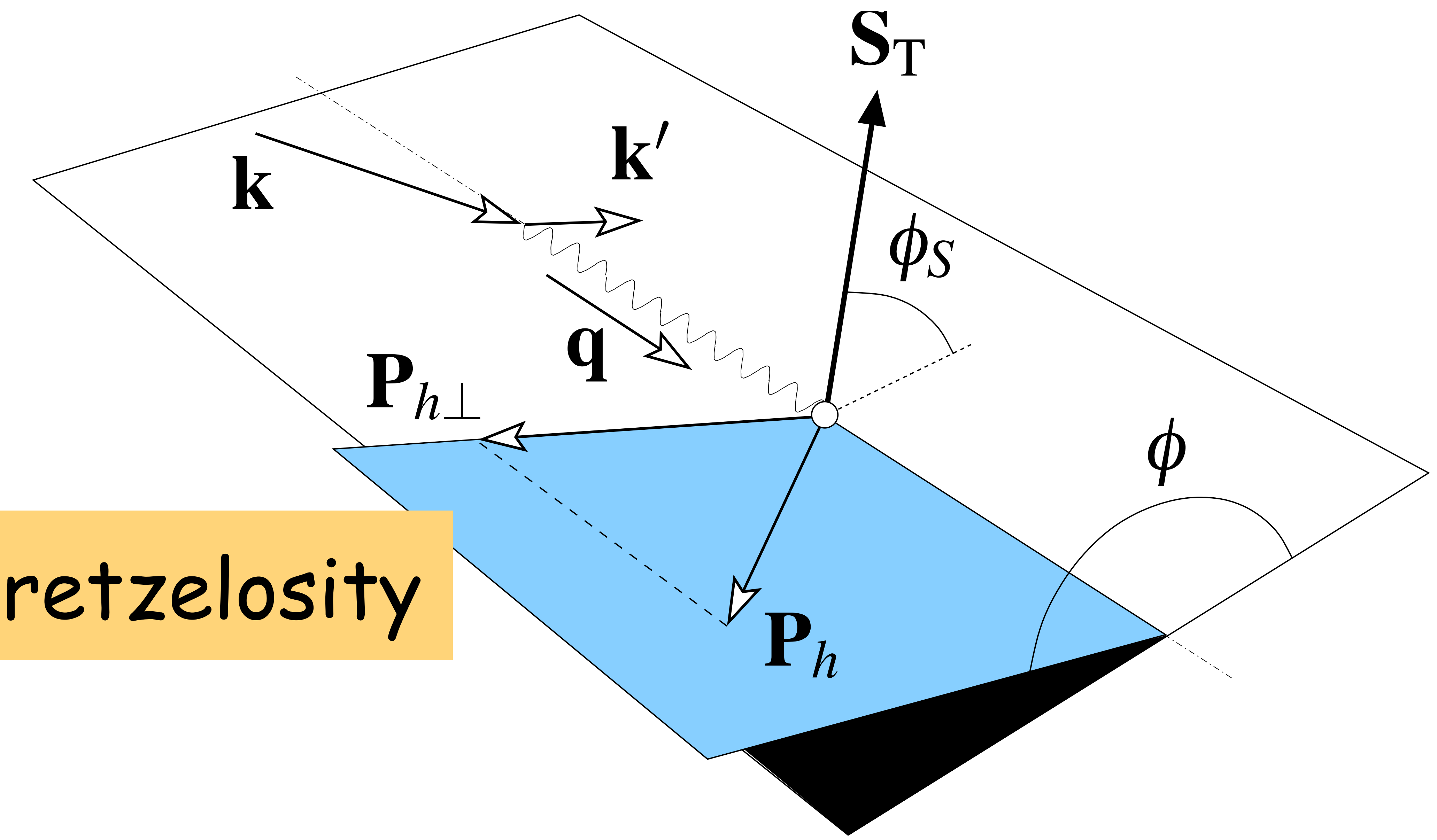
$$\left. + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin\phi_s} \sin\phi_s + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin(2\phi-\phi_s)} \sin(2\phi-\phi_s)\right]$$

$$+ S_T\lambda \left[\sqrt{1-\epsilon^2}\, F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi-\phi_s)\right.$$

$$\left. + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi-\phi_s)\right]\Bigg\}$$

semi-inclusive DIS

- with **transverse** target polarization:



$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi\,\mathrm{d}\phi_s} = \frac{2\pi\alpha^2}{\quad}\,\frac{y^2}{(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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$$+ S_T \left[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi-\phi_s) \right.$$

$$+ \epsilon\, F_{UT}^{h,\sin(\phi+\phi_s)} \sin(\phi+\phi_s) + \epsilon\, F_{UT}^{h,\sin(3\phi-\phi_s)} \sin(3\phi-\phi_s)$$

$$\left. + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin\phi_s} \sin\phi_s + \sqrt{2\,\epsilon(1+\epsilon)}\, F_{UT}^{h,\sin(2\phi-\phi_s)} \sin(2\phi-\phi_s) \right]$$

$$+ S_T\lambda \left[\sqrt{1-\epsilon^2}\, F_{LT}^{h,\cos(\phi-\phi_s)} \cos(\phi-\phi_s) \right.$$

$$\left. + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi-\phi_s) \right] \Bigg\}$$

Sivers

pretzelosity

transversity

worm-gear

some highlights: inclusive DIS

inclusive DIS (one-photon exchange)

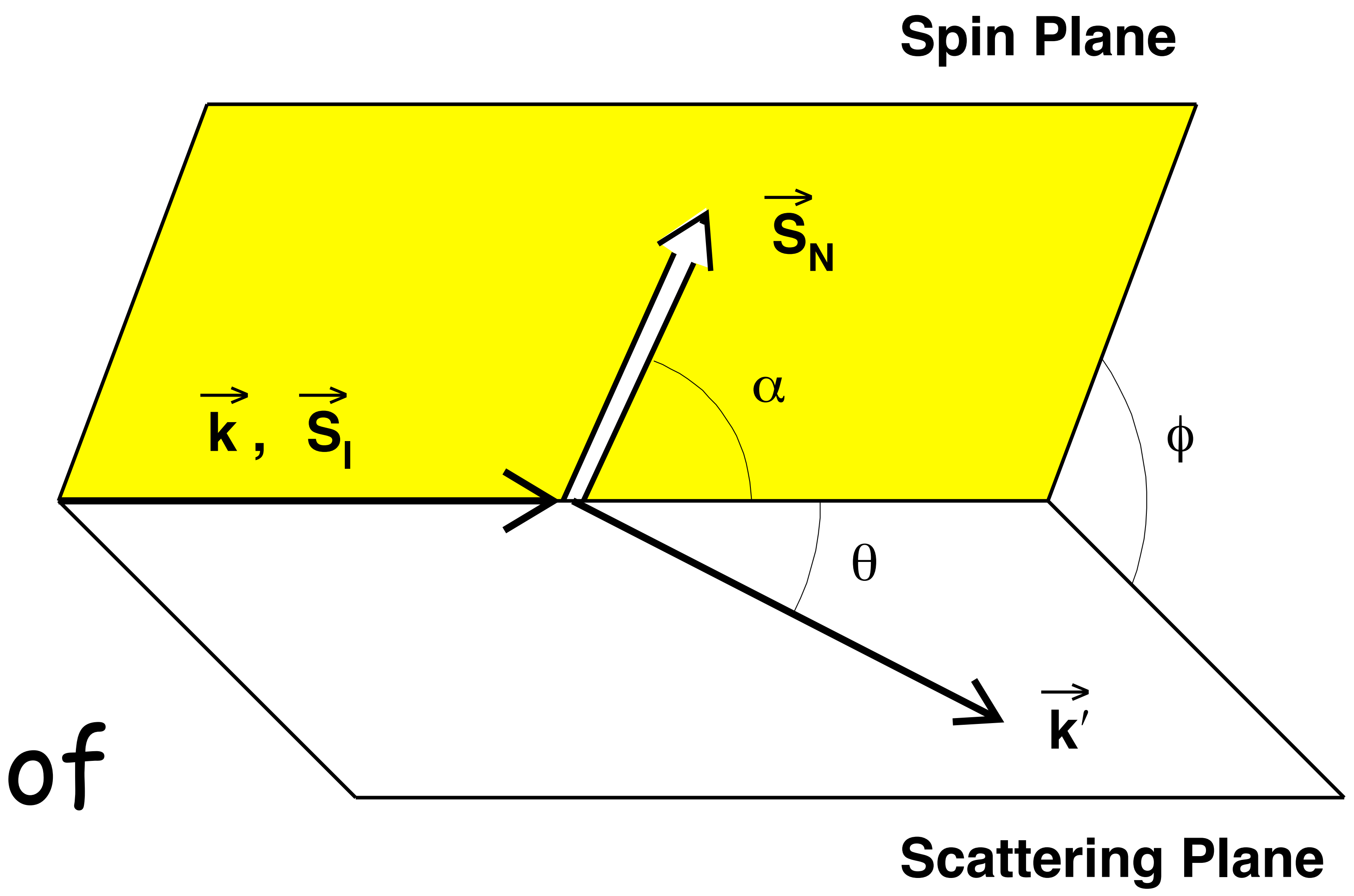
$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\;\mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions



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

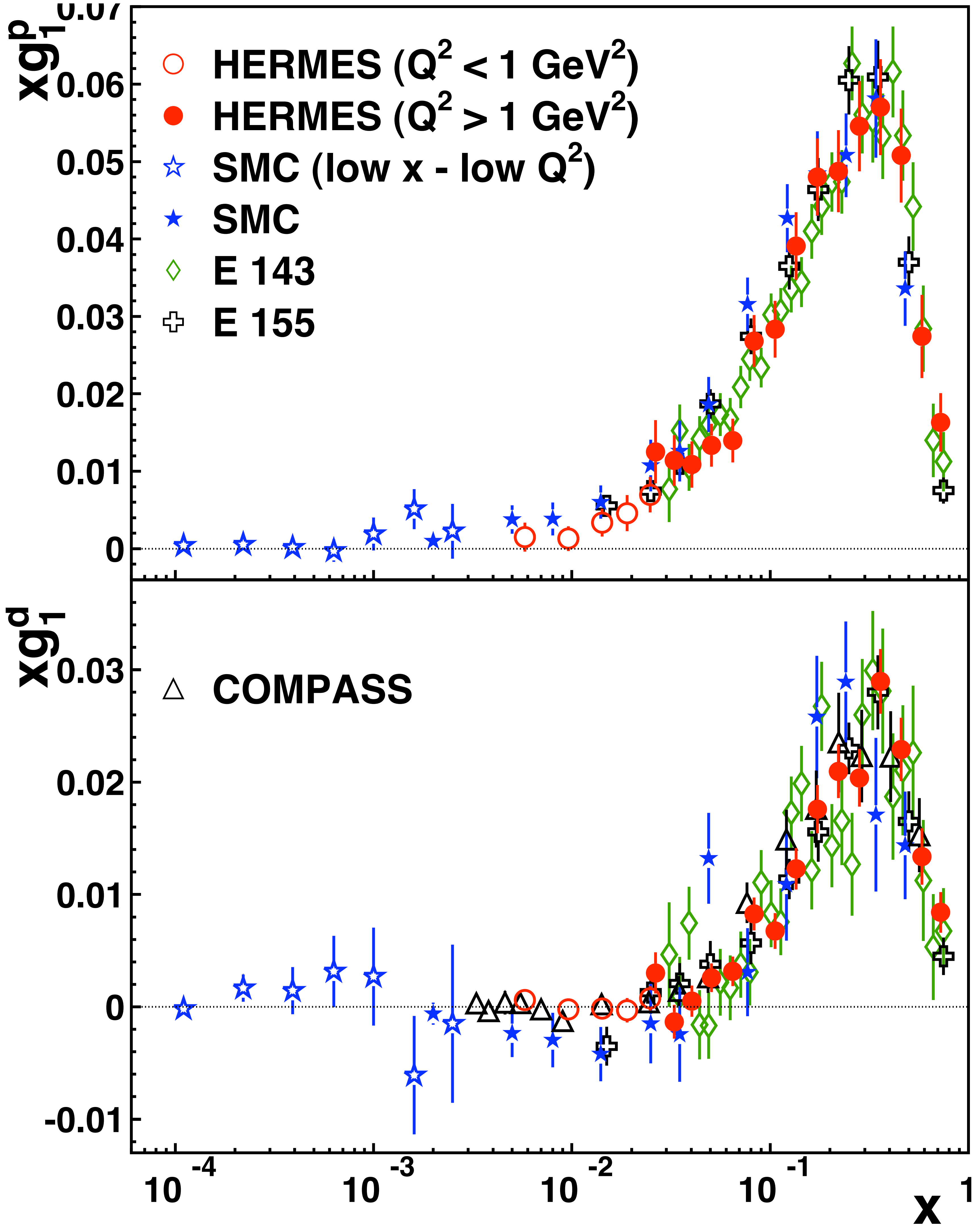
$$-S_l S_N \cos\alpha \left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)\boxed{g_1(x,Q^2)} - \frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right]$$

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

polarized structure function $g_1(x)$

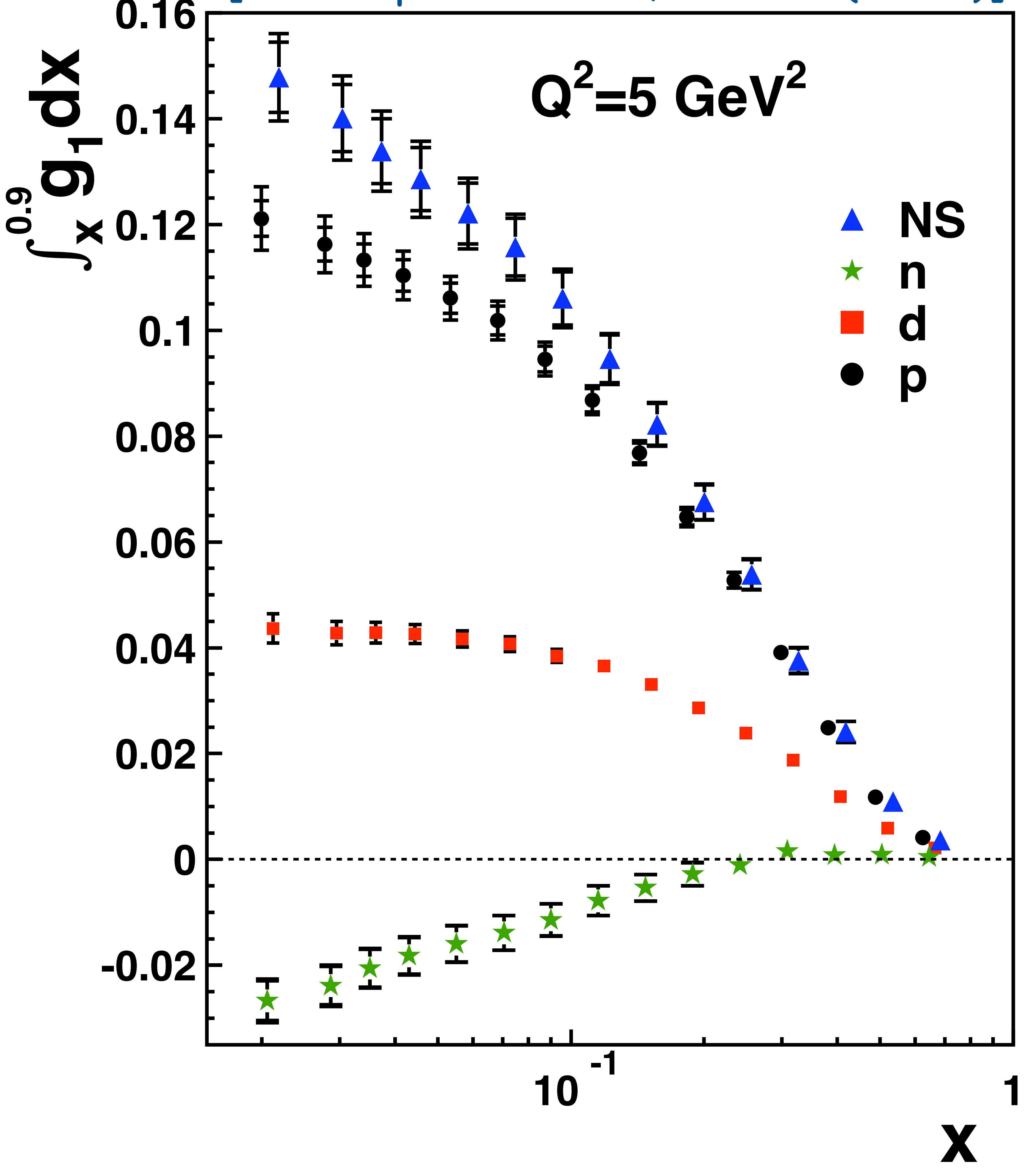
- **unfolded** for radiative and detector smearing
- unknown systematic correlations transformed into known statistical correlations
- uncertainties plotted only reflect diagonal elements of covariance -> “underestimates” statistical precision

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



Γ_1 … integral of $g_1(x)$

[A. Airapetian et al., PRD 75 (2007)]



Γ_1 … integral of $g_1(x)$

Saturation

➠ close to full integral?

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

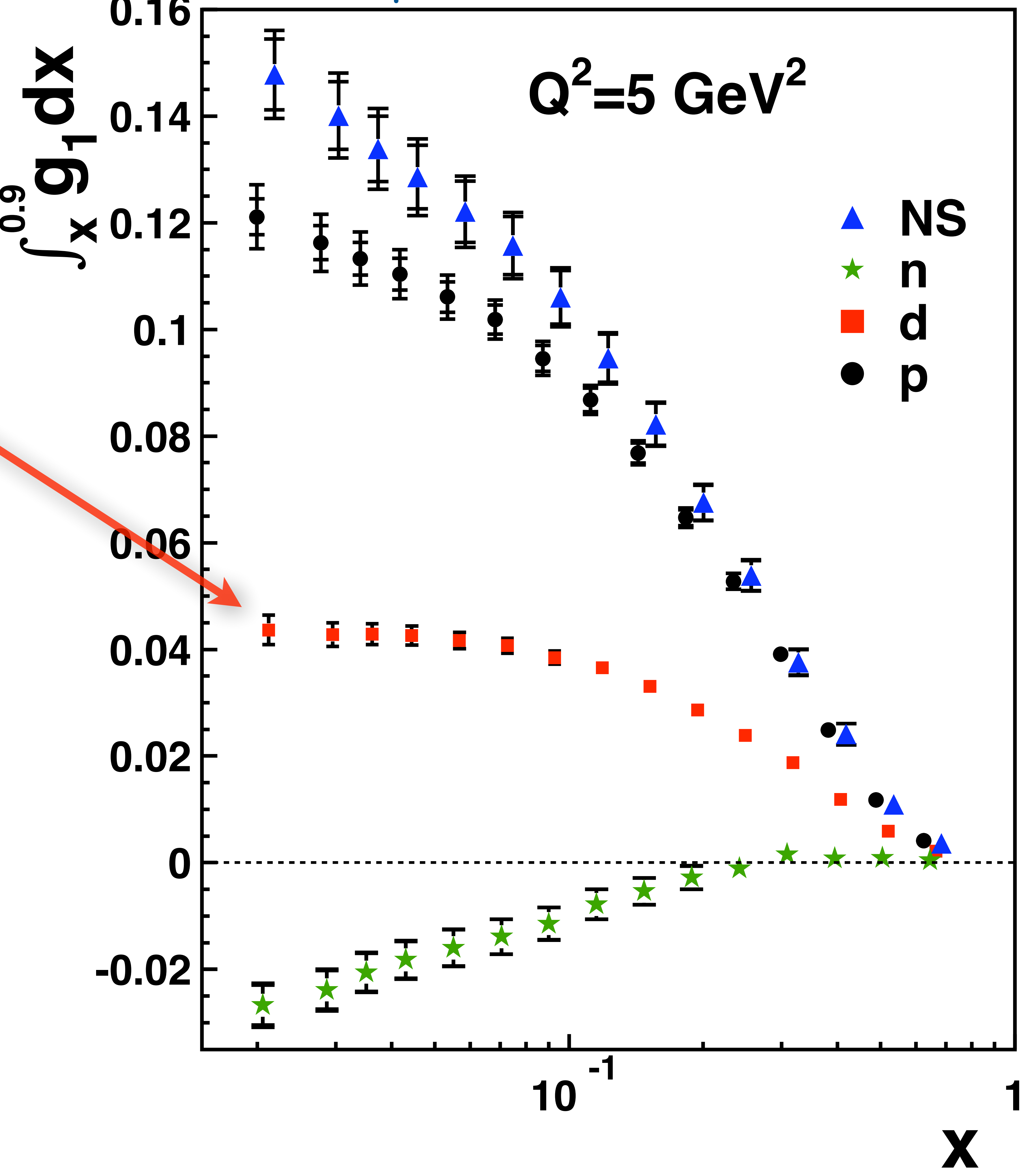
ΔC_{S} ↑ theory

ω_D ↑ 0.05±0.05

a_8 ↑ hyperon-decay data

ΔC_{NS} ↑ theory

[A. Airapetian et al., PRD 75 (2007)]



Γ_1 … integral of $g_1(x)$

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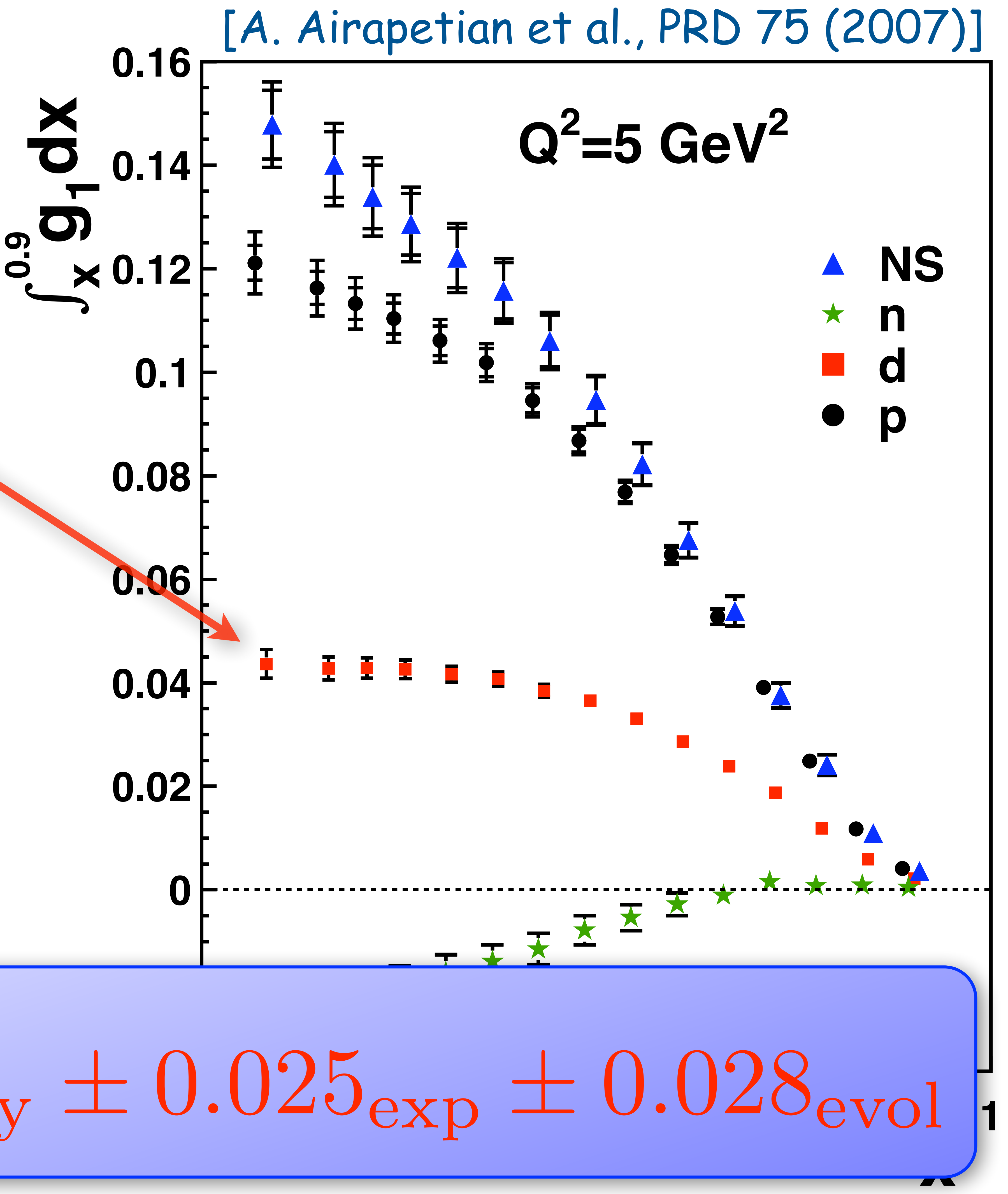
theory

0.05±0.05

hyperon-decay data

theory



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

most precise single-experiment result: only 1/3 of nucleon spin from quarks

Can HERMES do more than “just” inclusive g_1?

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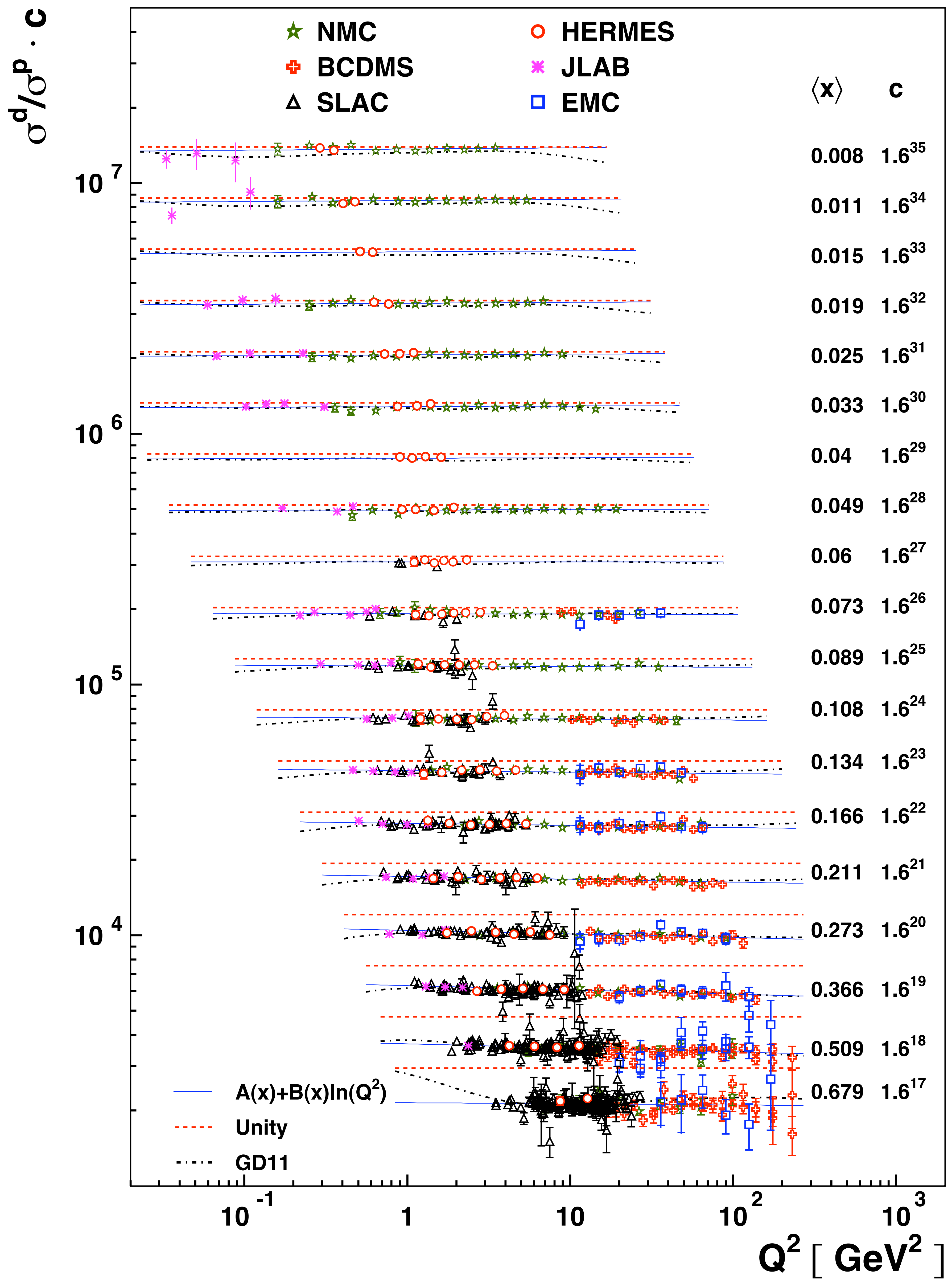
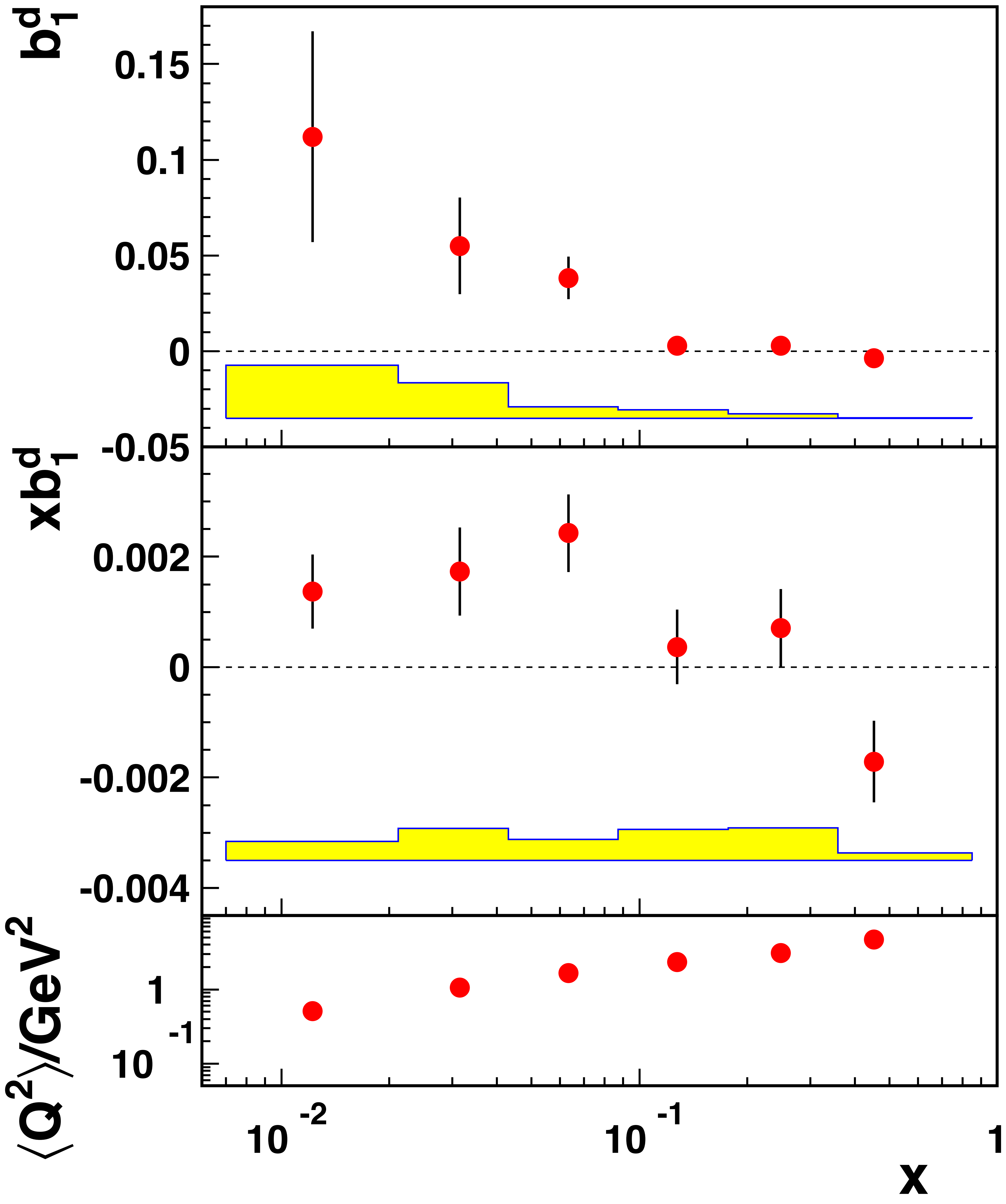
☑ unpolarized DIS: F_2 & σ^d/σ^p



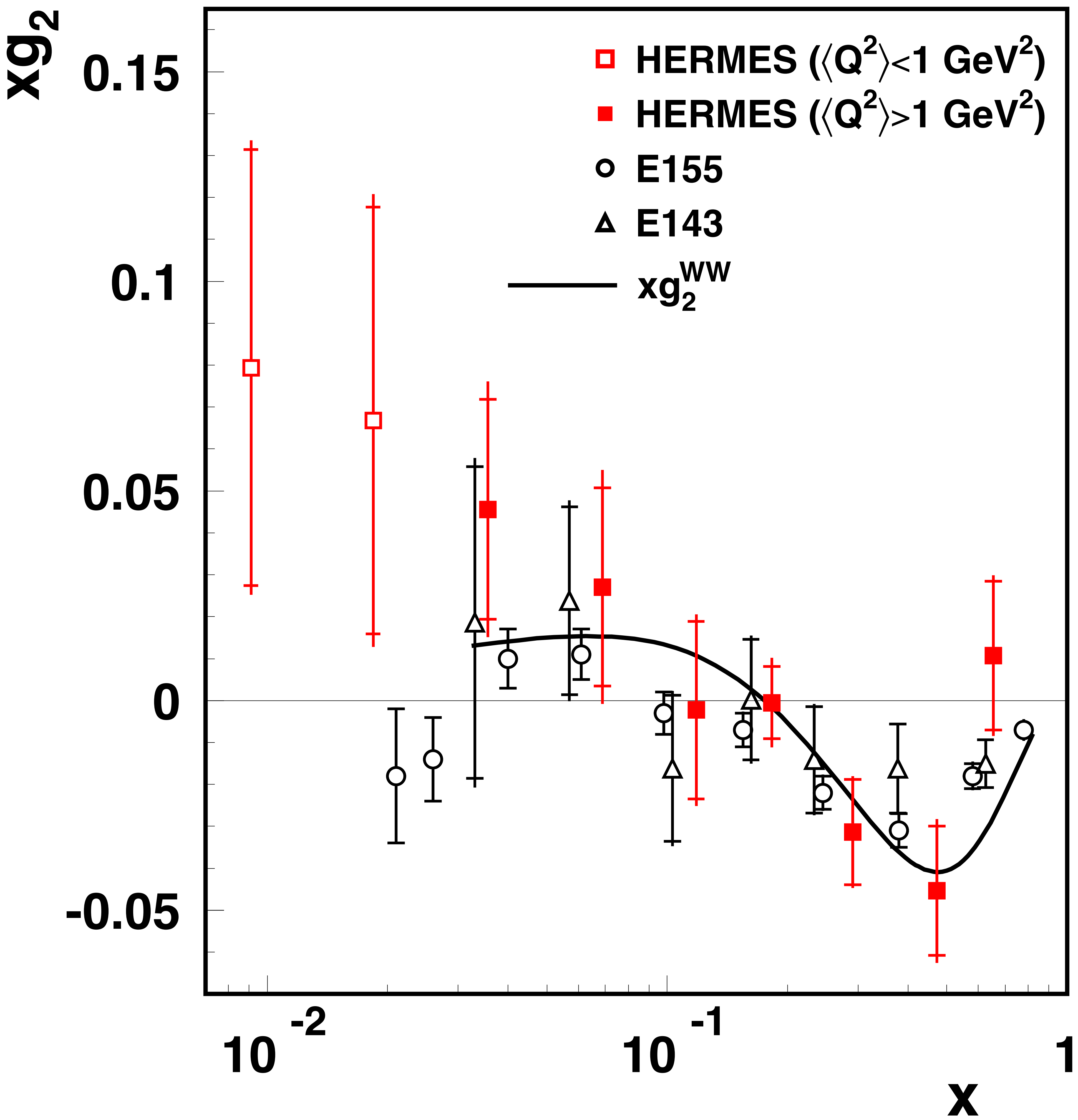
Can HERMES do more than "just" inclusive g_1?

- ☑ unpolarized DIS: F_2 & σ^d/σ^p
- ☑ tensor structure function b_1



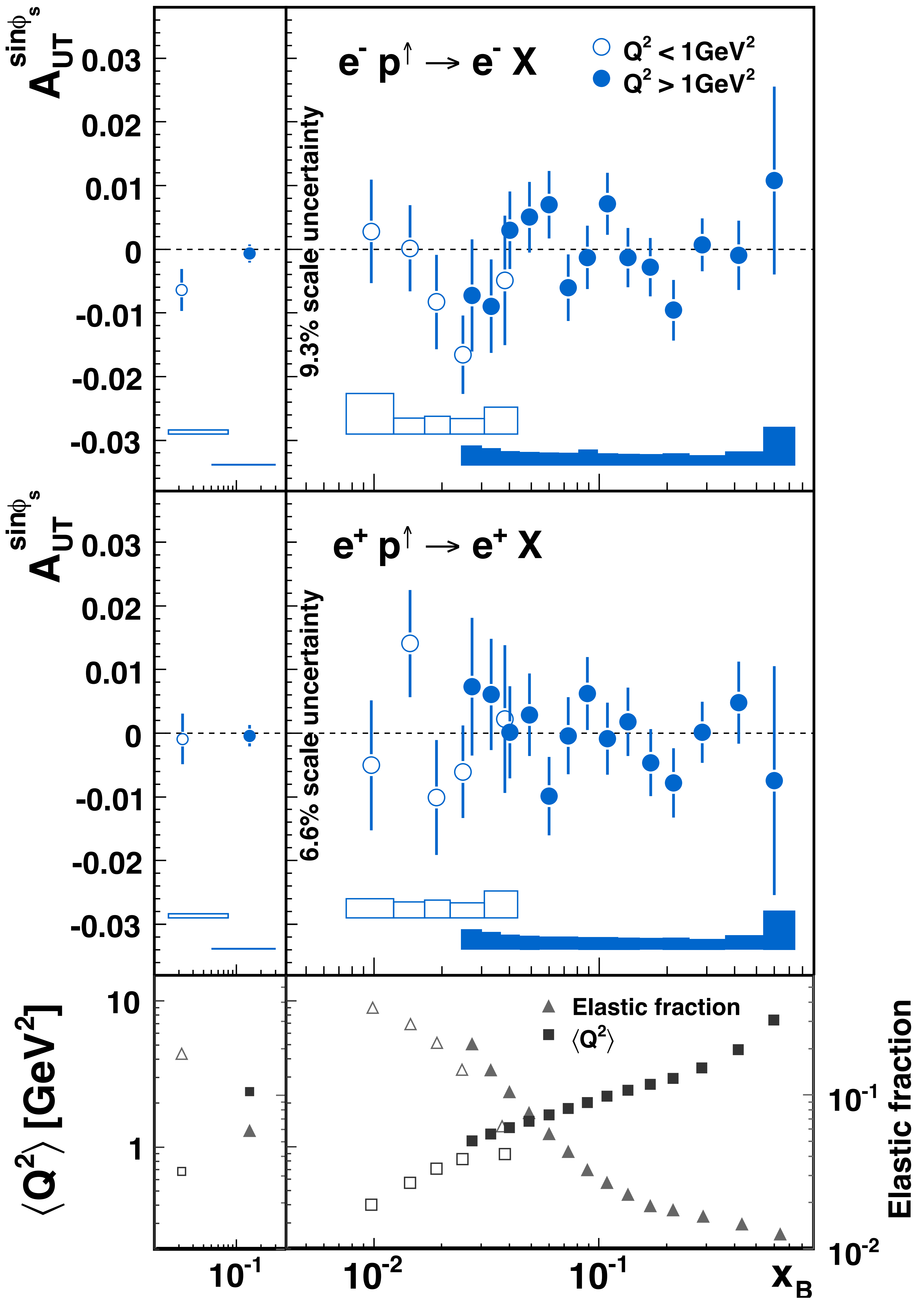
Can HERMES do more than “just” inclusive g_1?

- ☑ unpolarized DIS: F_2 & σ^d / σ^p
- ☑ tensor structure function b_1
- ☑ transverse: g_2



Can HERMES do more than “just” inclusive g_1?

- ☑ unpolarized DIS: F_2 & σ^d/σ^p
- ☑ tensor structure function b_1
- ☑ transverse: g_2
- ☑ 2-photon exchange in incl. DIS



Can HERMES do more than “just” inclusive g_1?

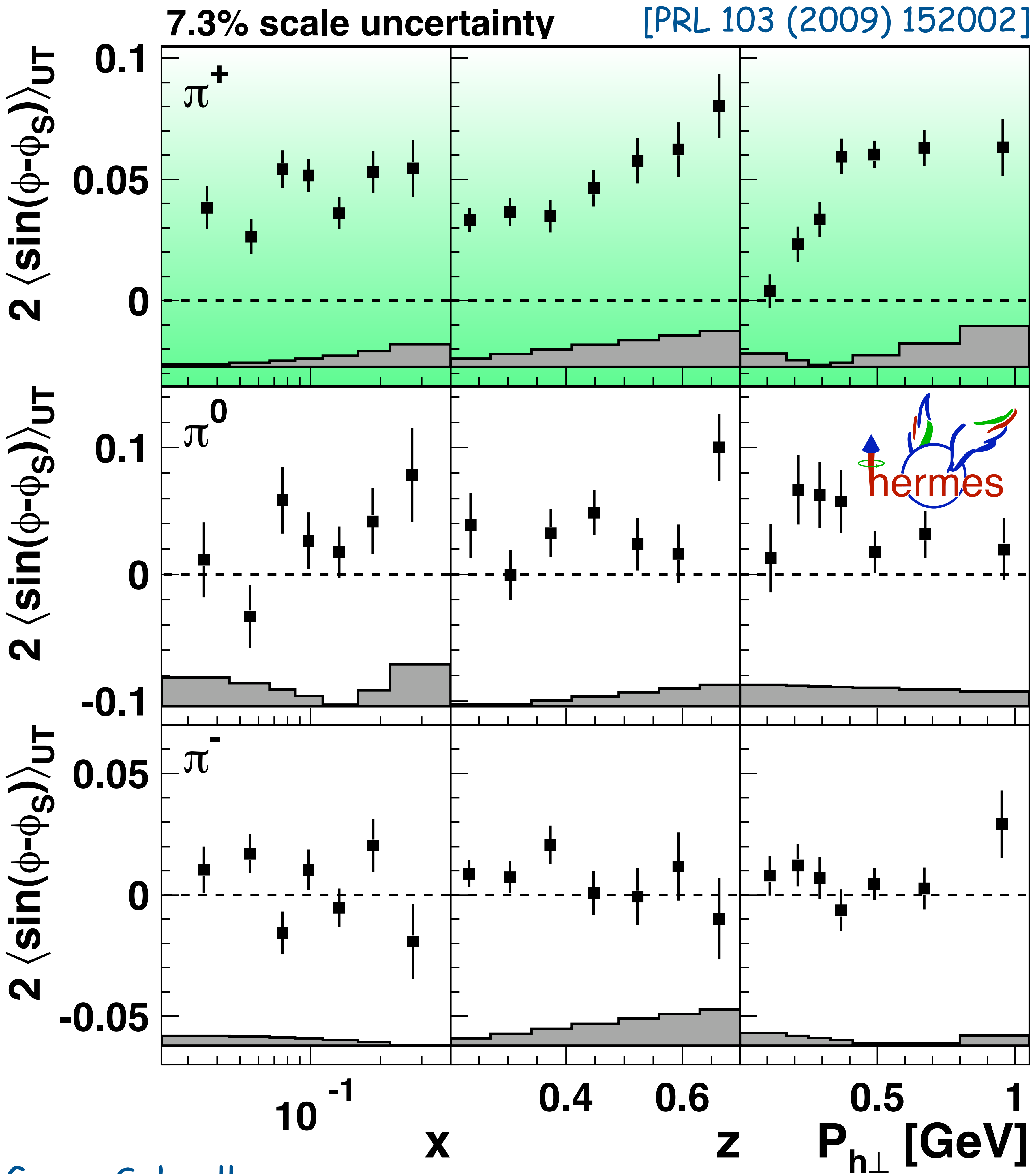
- ☑ unpolarized DIS: F_2 & σ^d/σ^p
- ☑ tensor structure function b_1
- ☑ transverse: g_2
- ☑ 2-photon exchange in incl. DIS
- ☑ ...

some highlights: semi-inclusive DIS

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

Sivers amplitudes for pions

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



[PRL 103 (2009) 152002]

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

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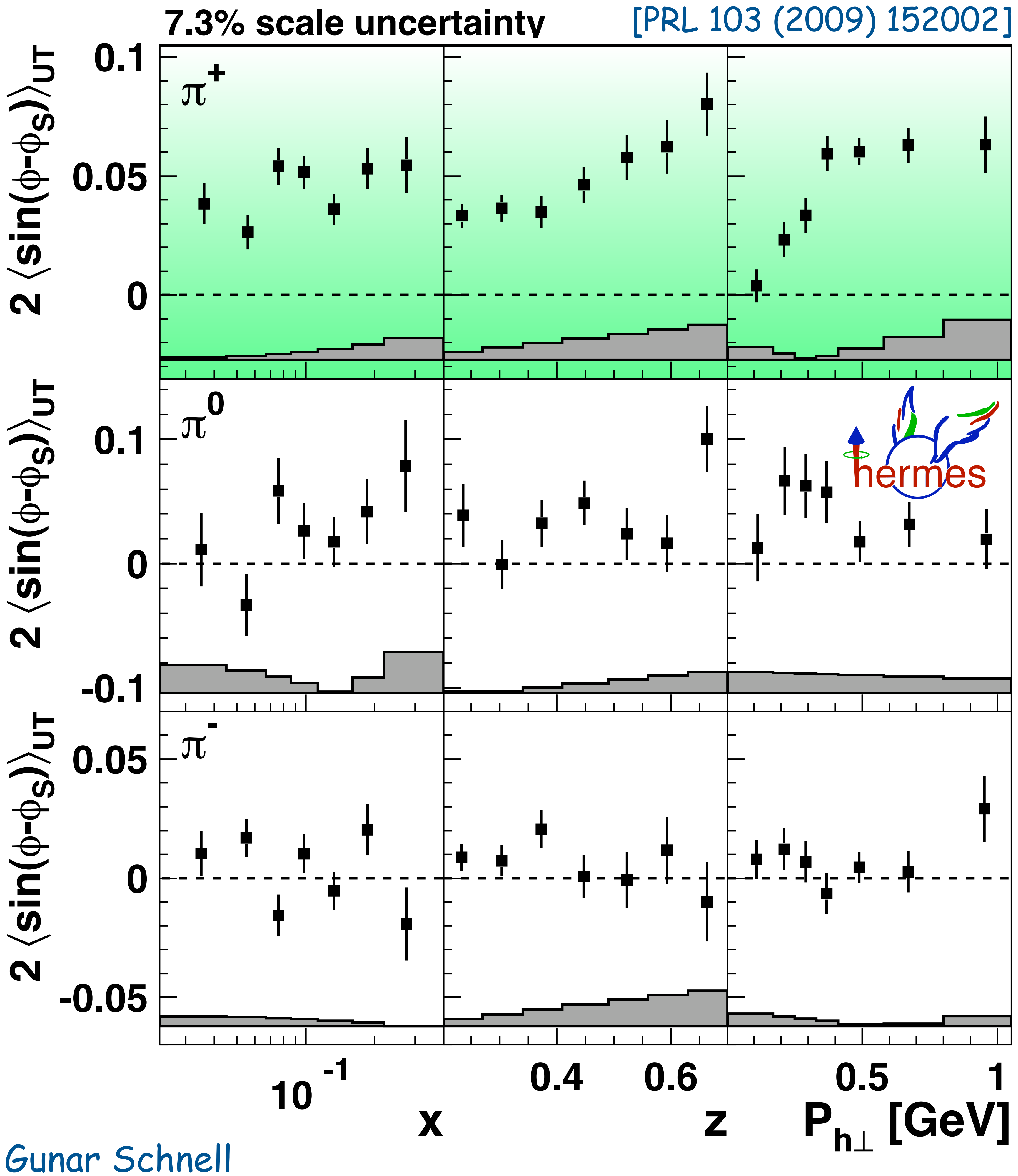


[PRL 103 (2009) 152002]

π^+ production dominated by u-quark scattering:

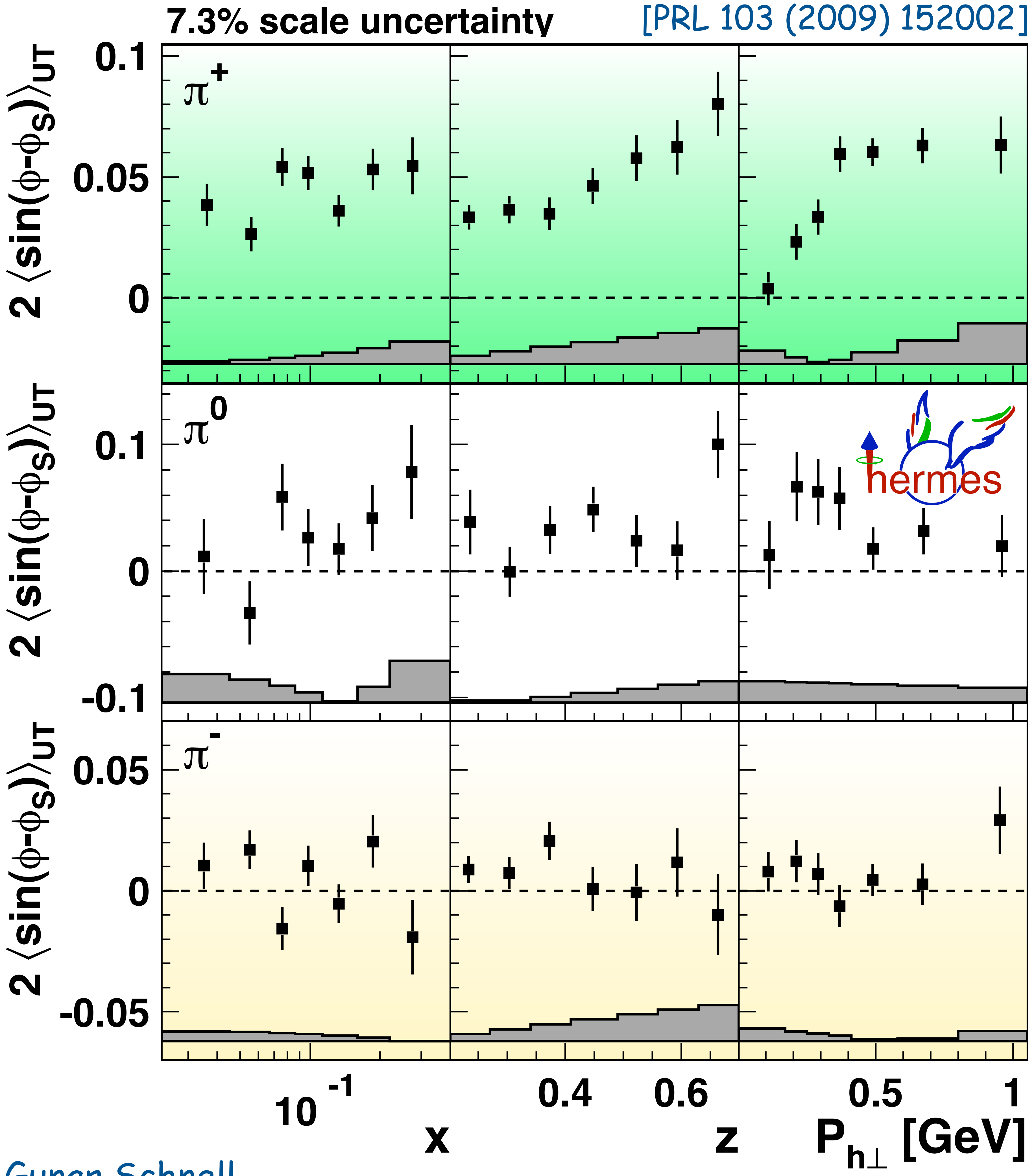
$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

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

Sivers amplitudes for pions

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


7.3% scale uncertainty

[PRL 103 (2009) 152002]

π^+ production dominated by u-quark scattering:

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

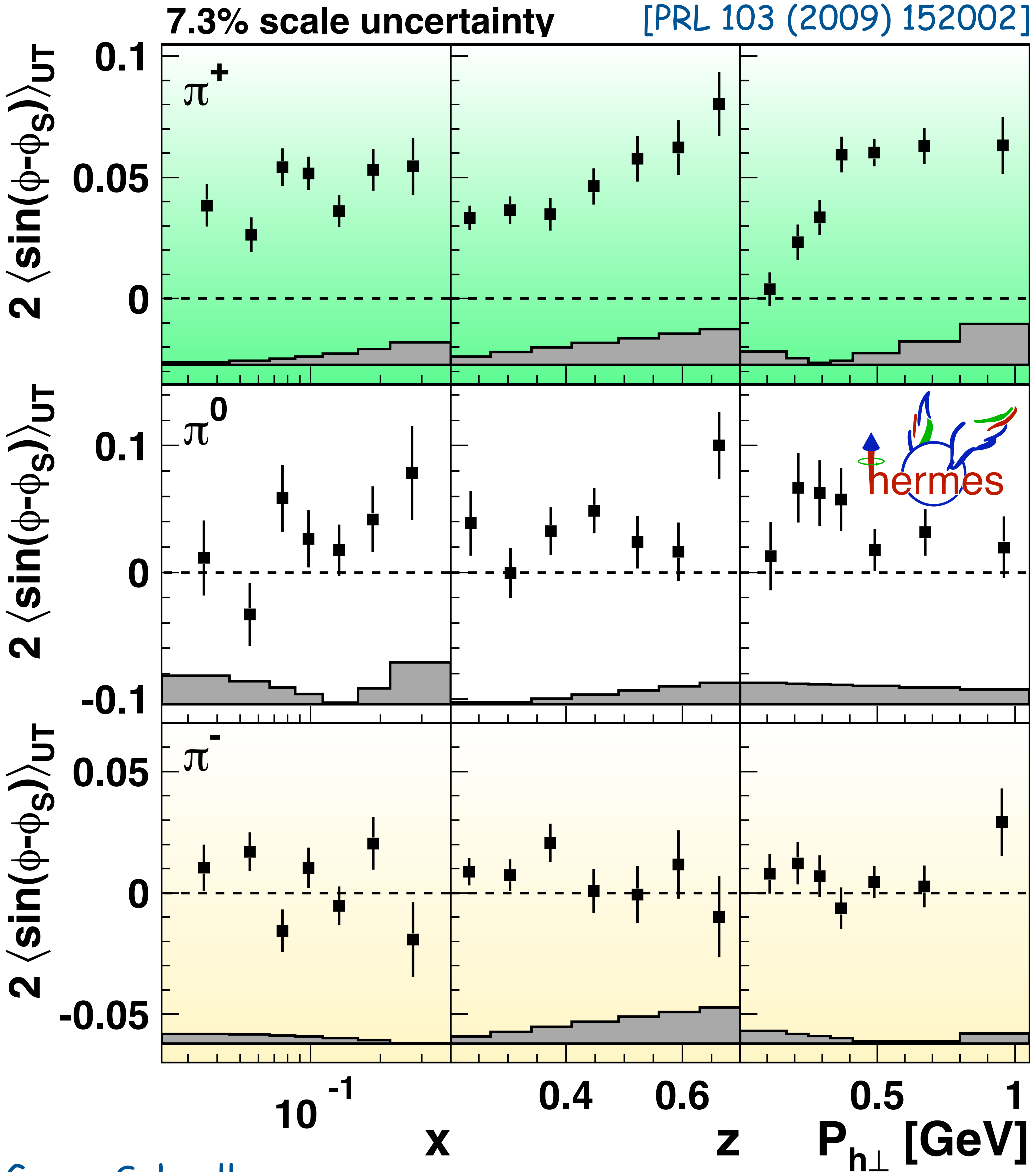
- ☛ u-quark Sivers DF < 0

- ☛ 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 pions

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

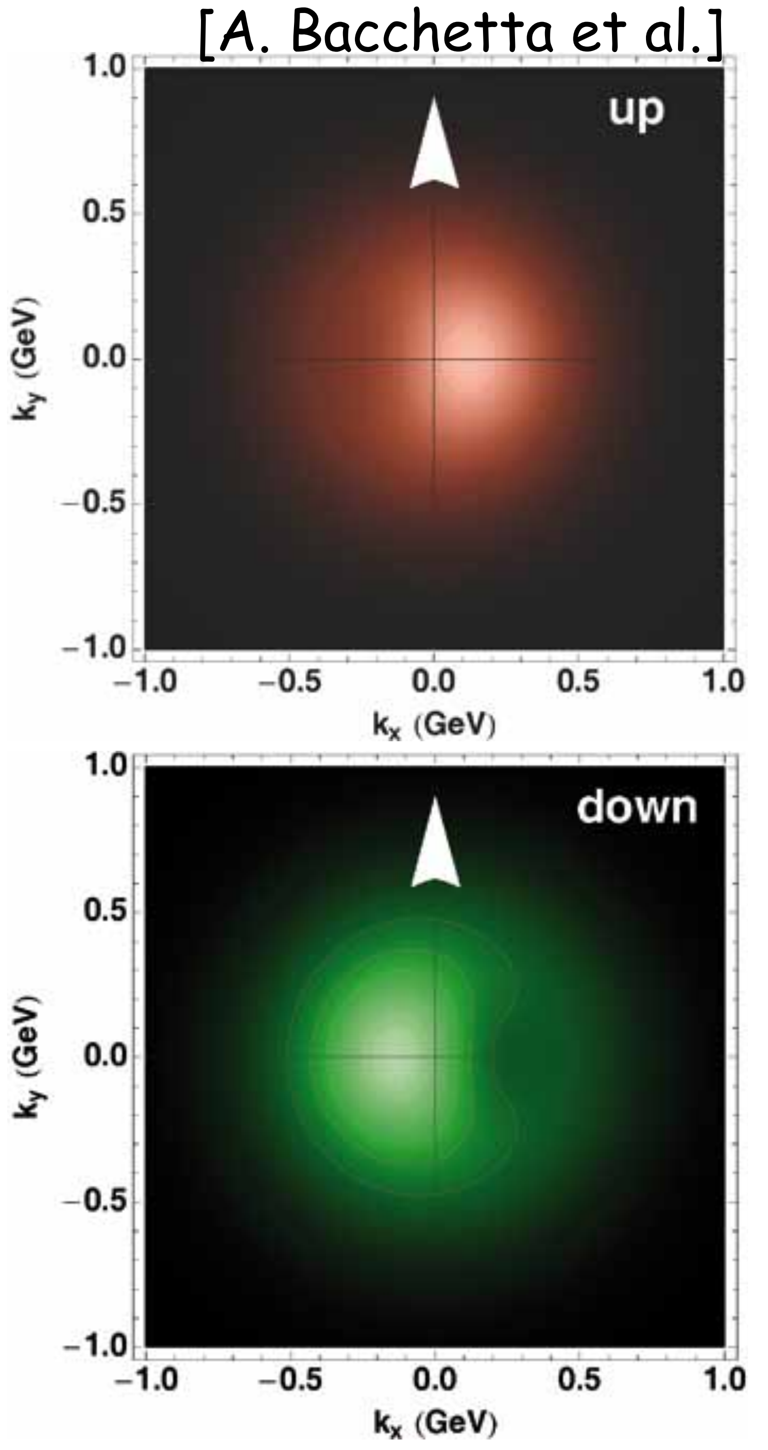

7.3% scale uncertainty [PRL 103 (2009) 152002]

π^+ production dominated by u-quark scattering:

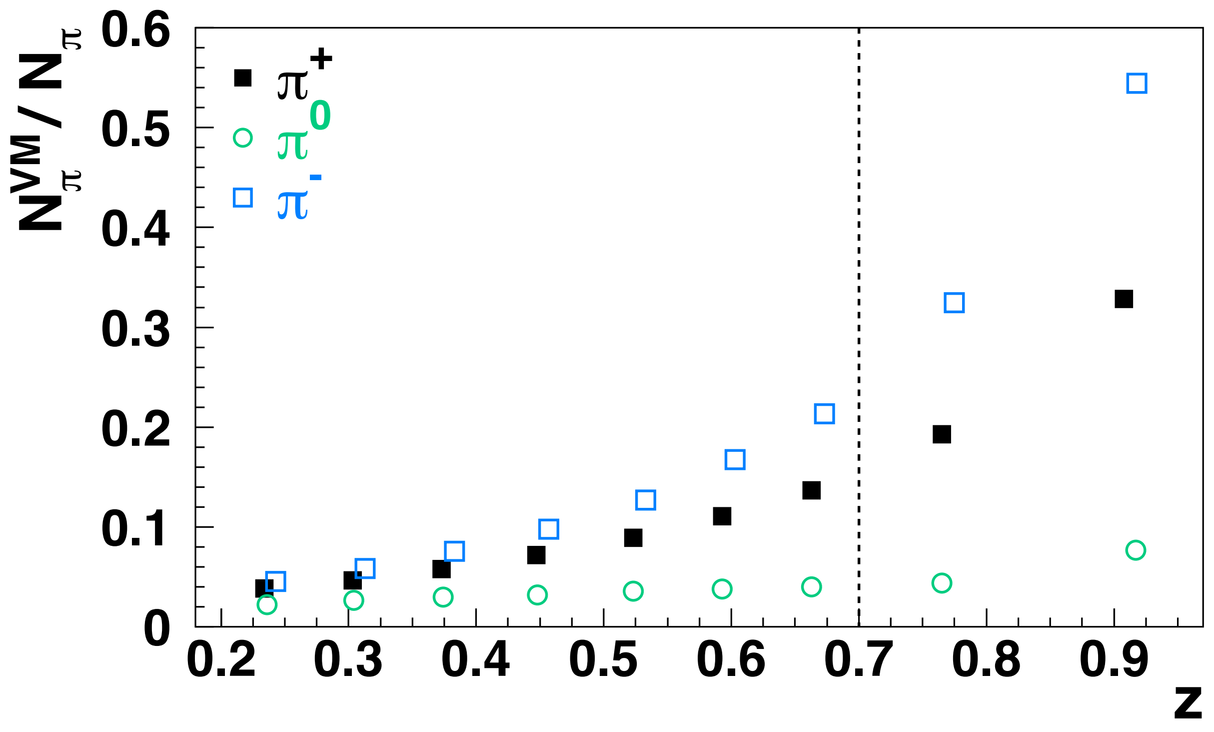
$$\simeq -\frac{f_{1\rm T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

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


[A. Bacchetta et al.]

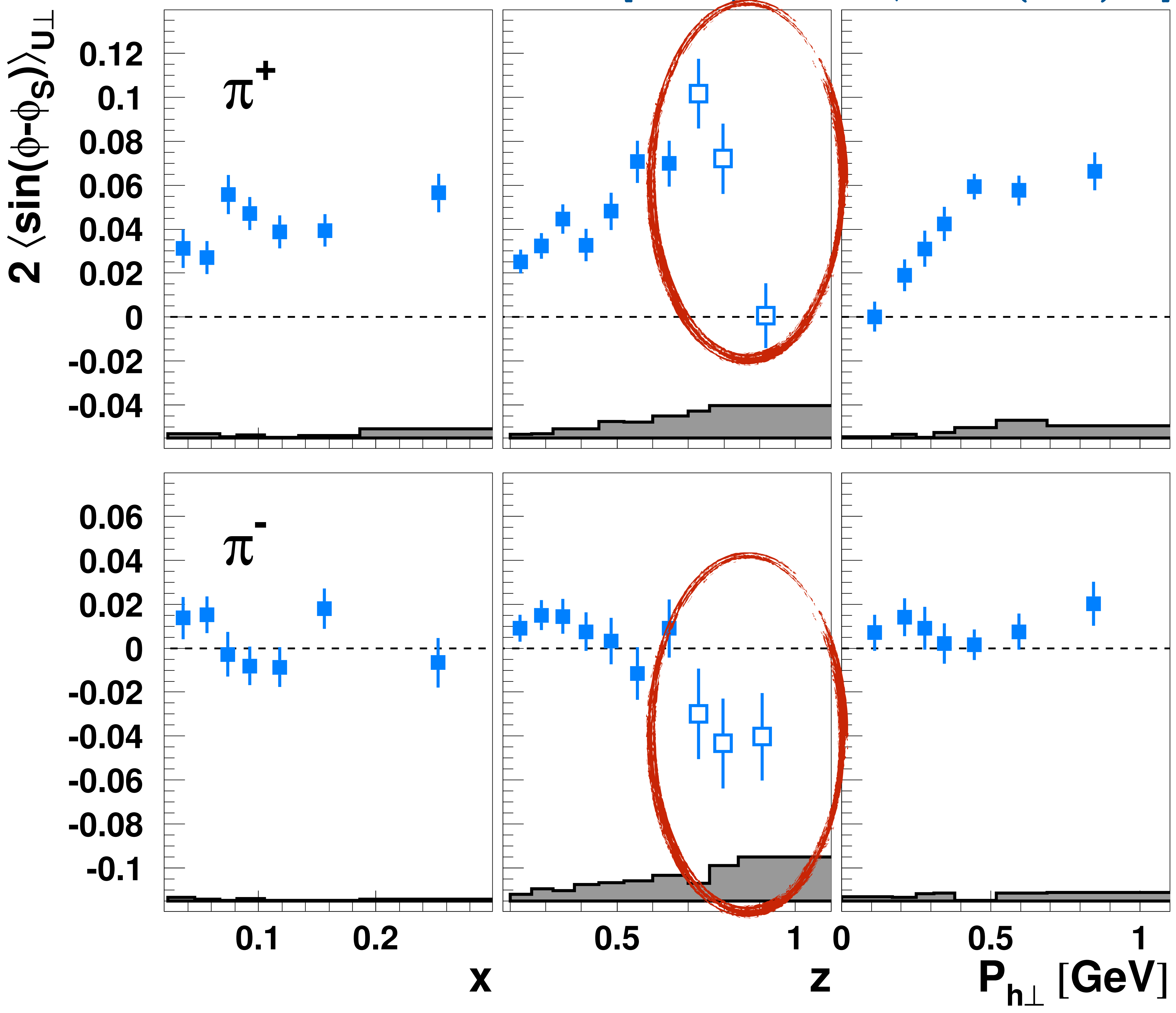
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

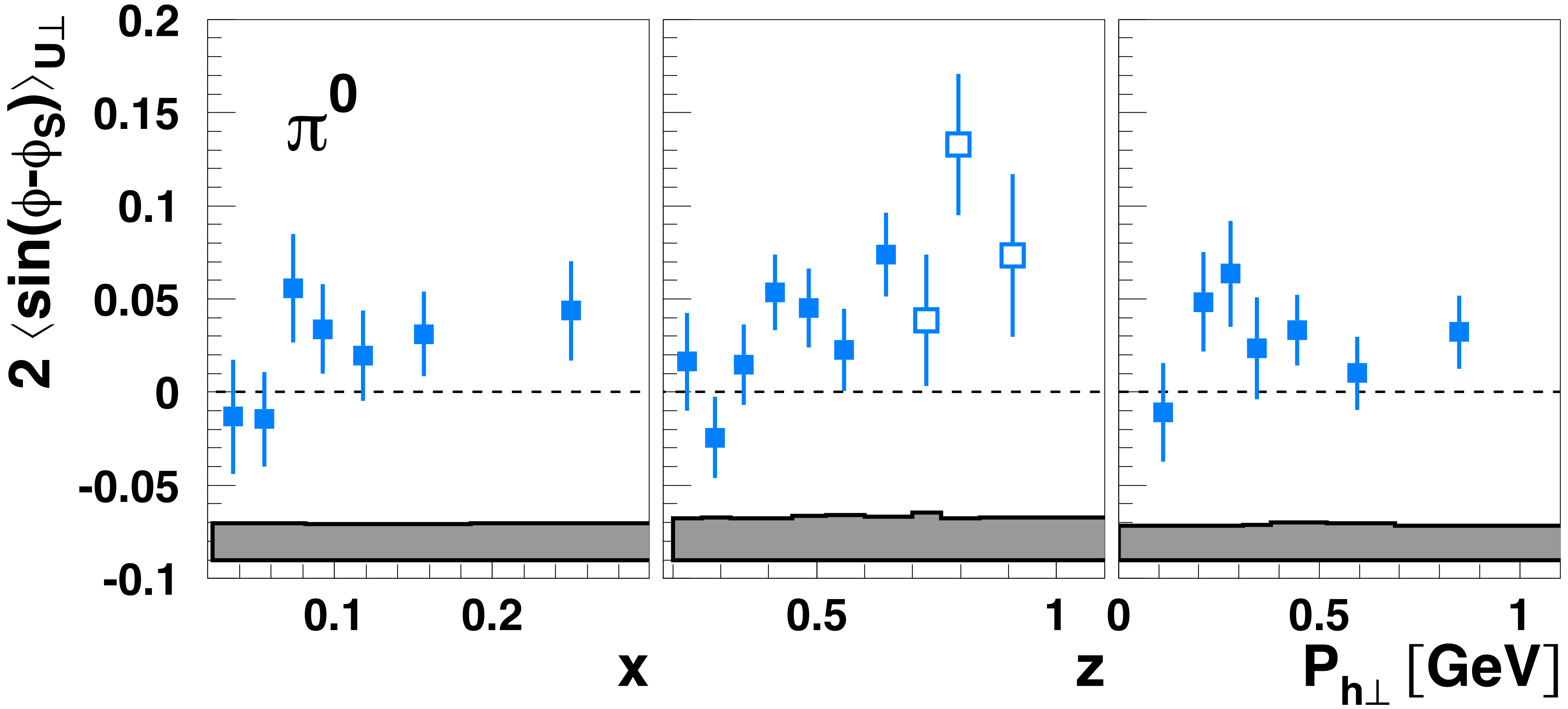


Sivers amplitudes for pions

- **high-z data** probes region of **increased flavor sensitivity** to struck quark
  (but also where contributions from exclusive vector-meson production becomes significant)

[A. Airapetian et al., JHEP12(2020)010]





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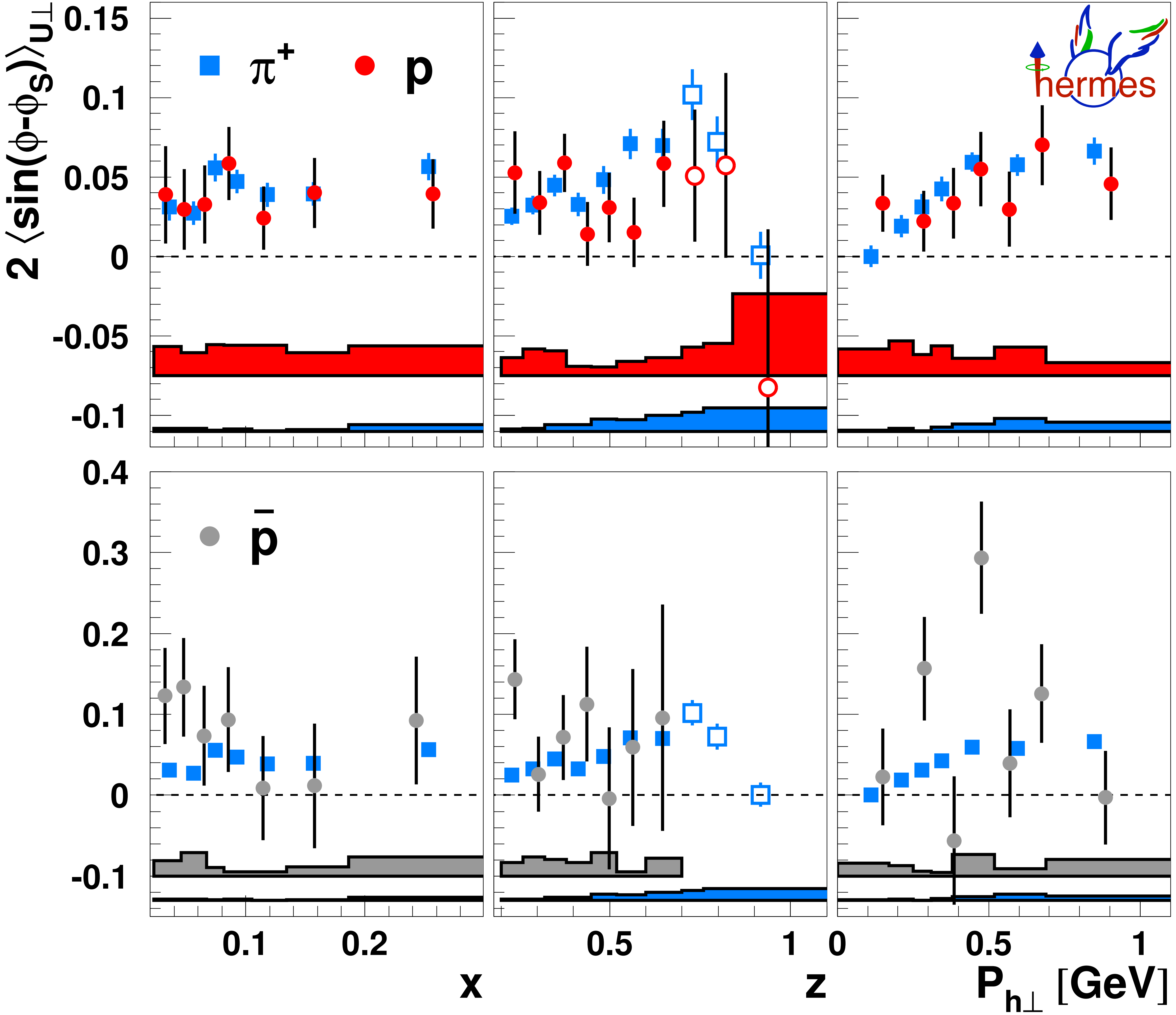
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes
pions vs. (anti)protons

[A. Airapetian et al., JHEP12(2020)010]



similar-magnitude asymmetries for (anti)protons and pions

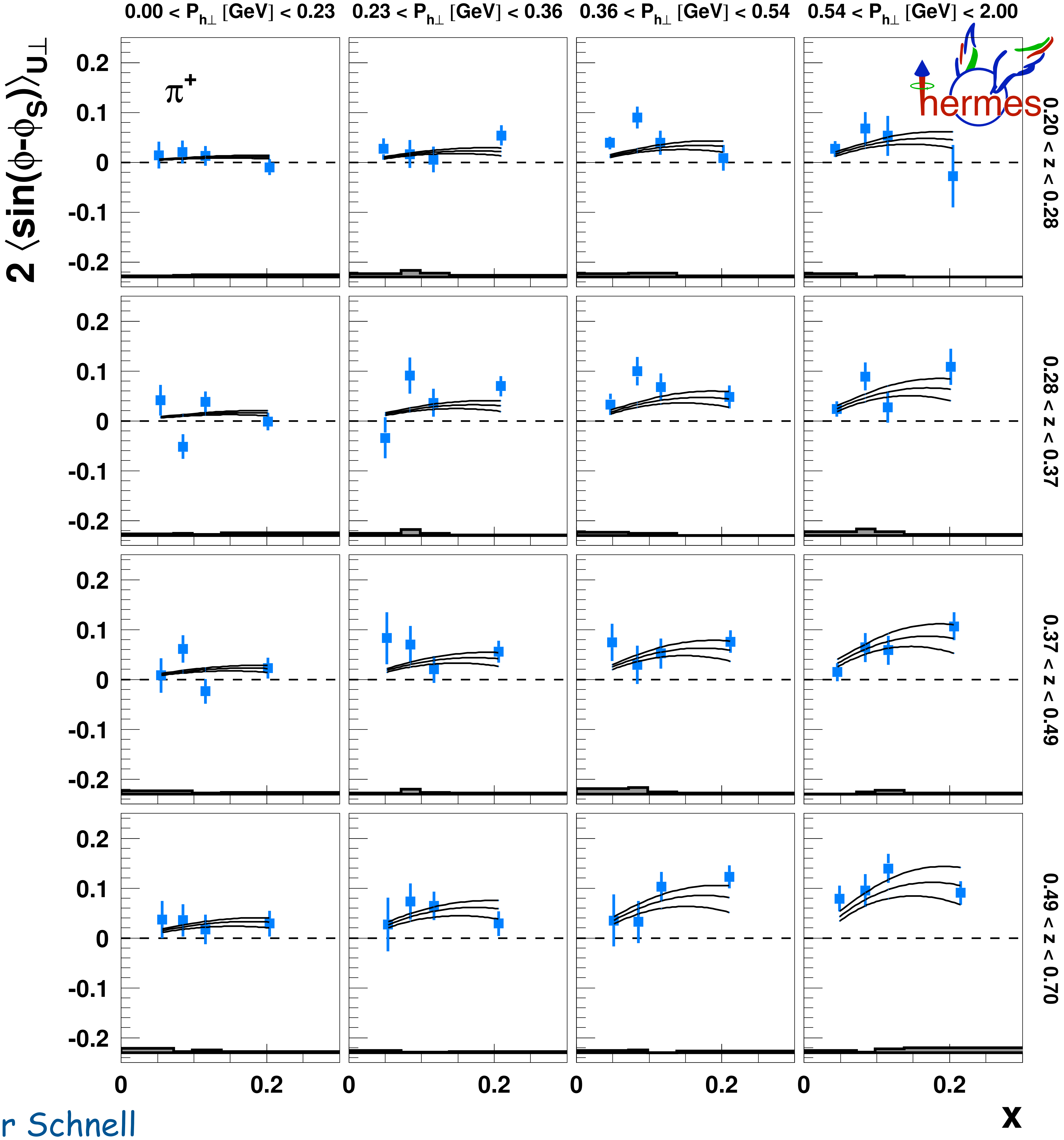
➥consequence of u-quark dominance in both cases?

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

	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
multi-dimensional analysis

[A. Airapetian et al., JHEP12(2020)010]

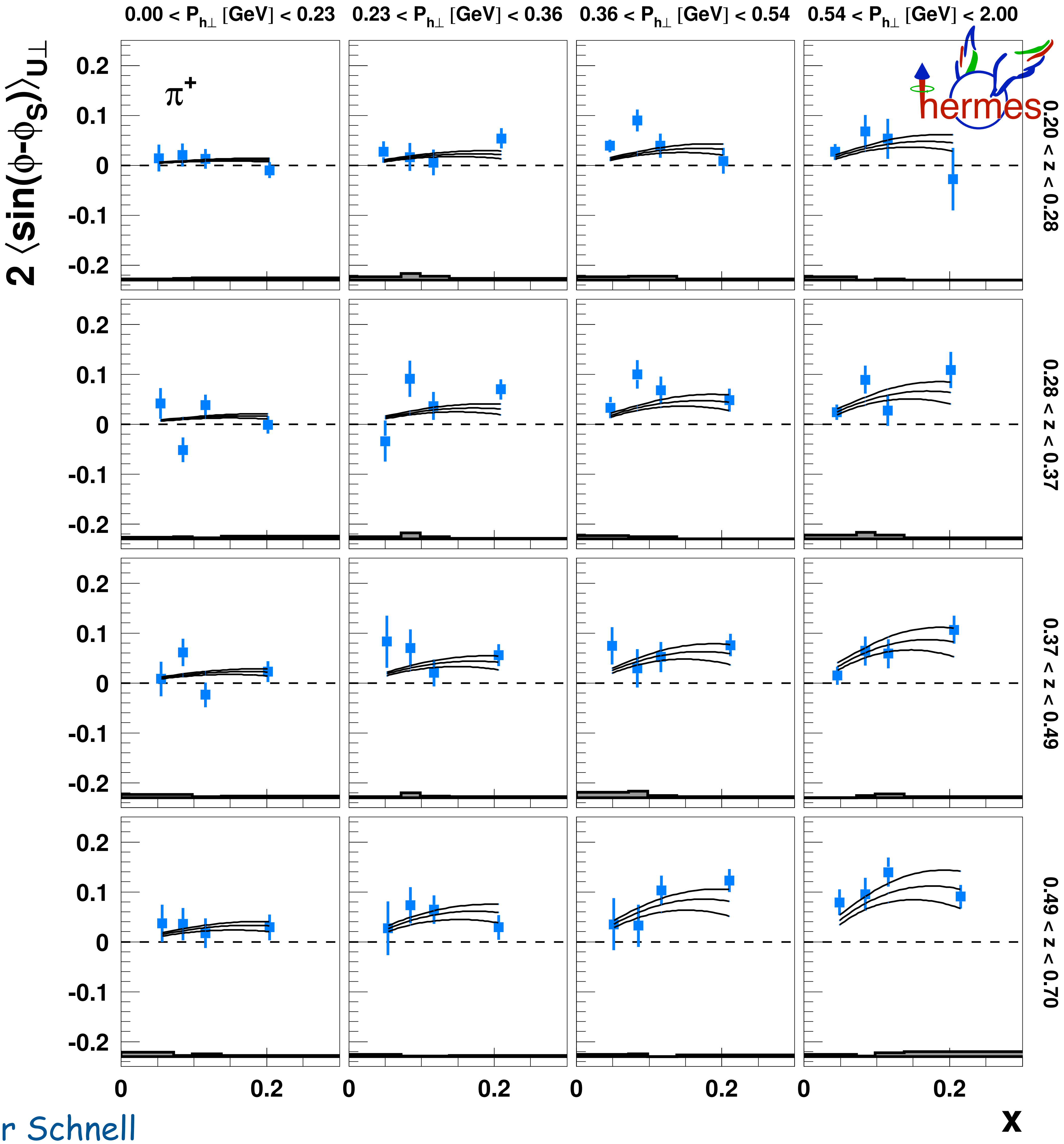


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$

Sivers amplitudes multi-dimensional analysis

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

[A. Airapetian et al., JHEP12(2020)010]



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

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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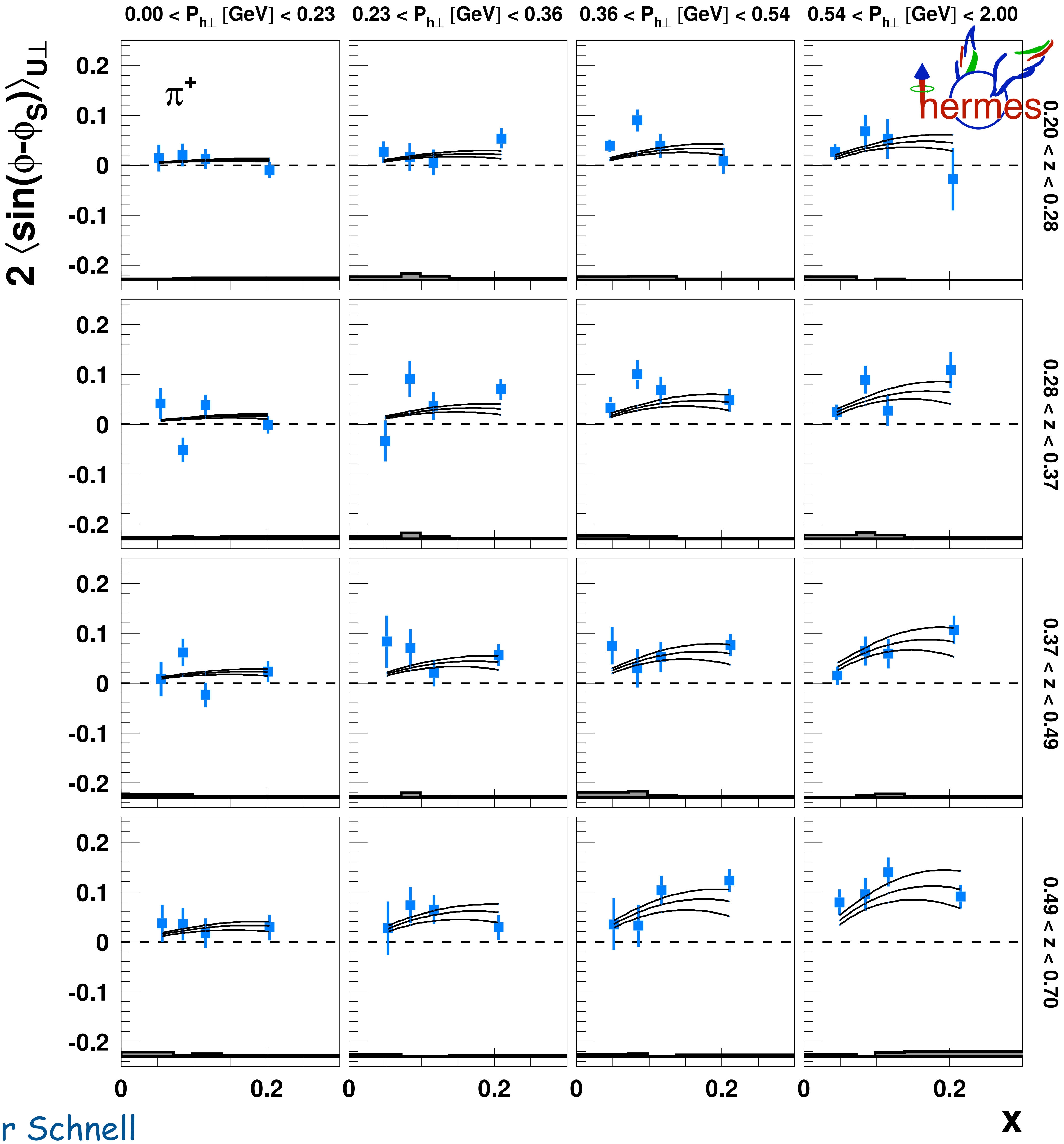
Sivers amplitudes multi-dimensional analysis

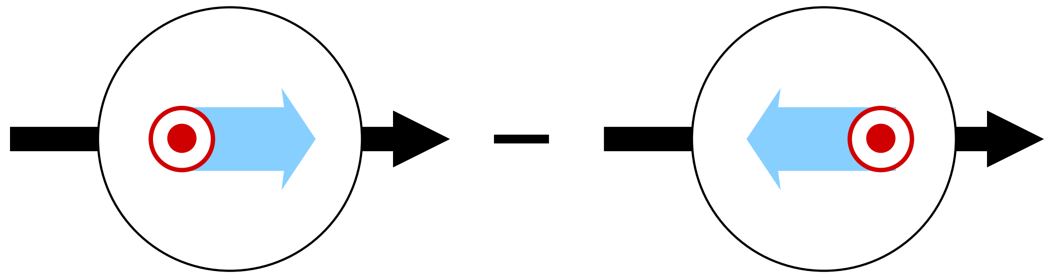
[A. Airapetian et al., JHEP12(2020)010]



- 3d analysis: 4x4x4 bins in (x,z, $P_{h\perp}$)
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations

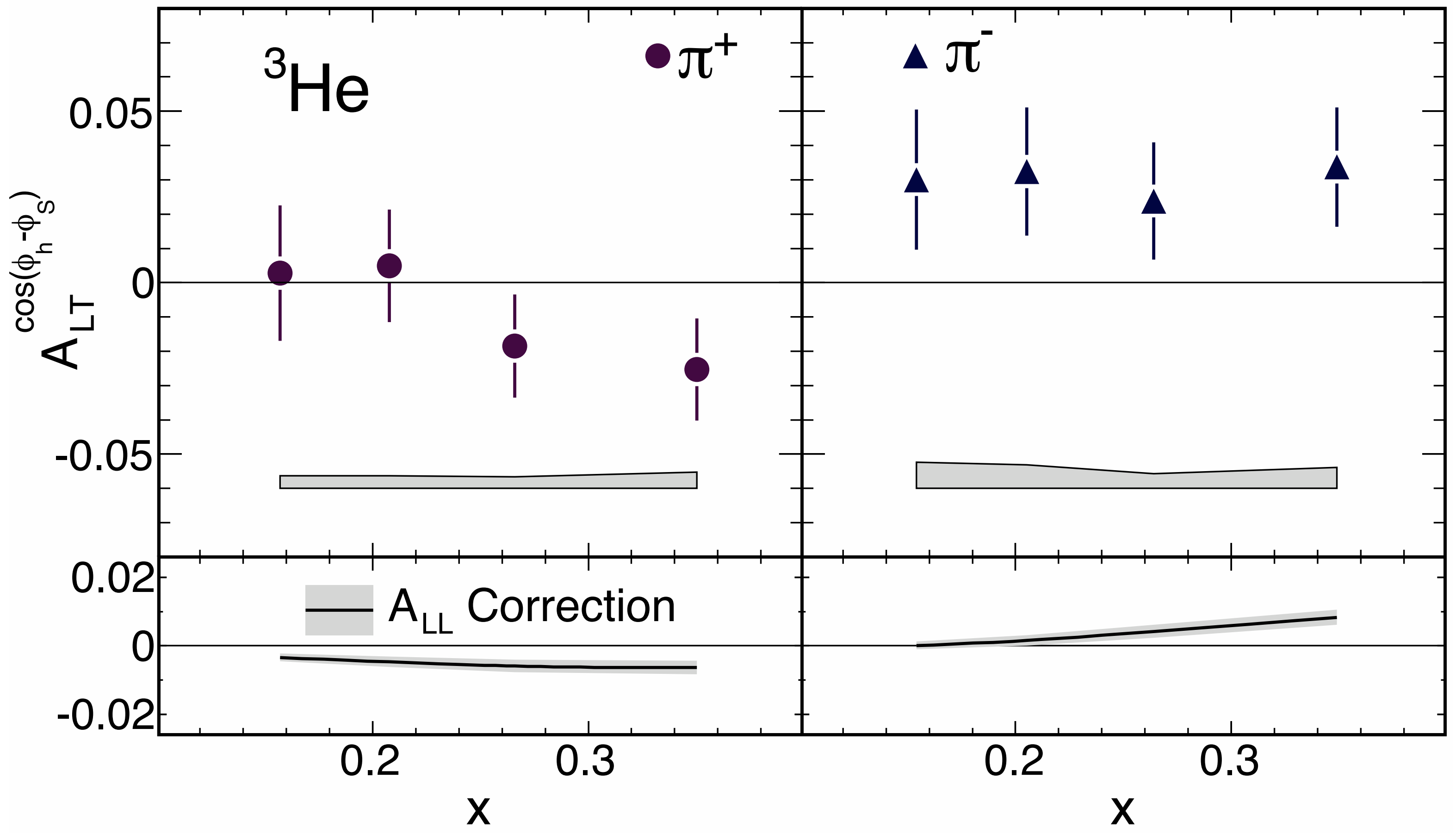
worm-gear II

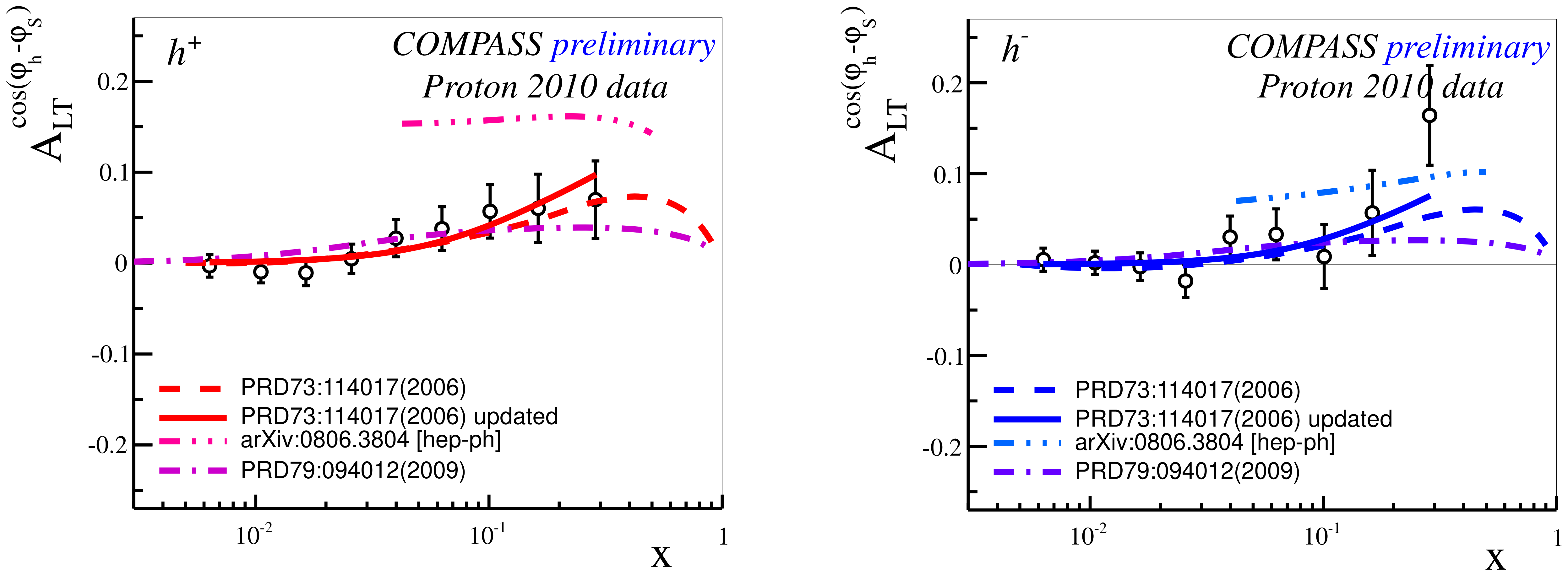
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



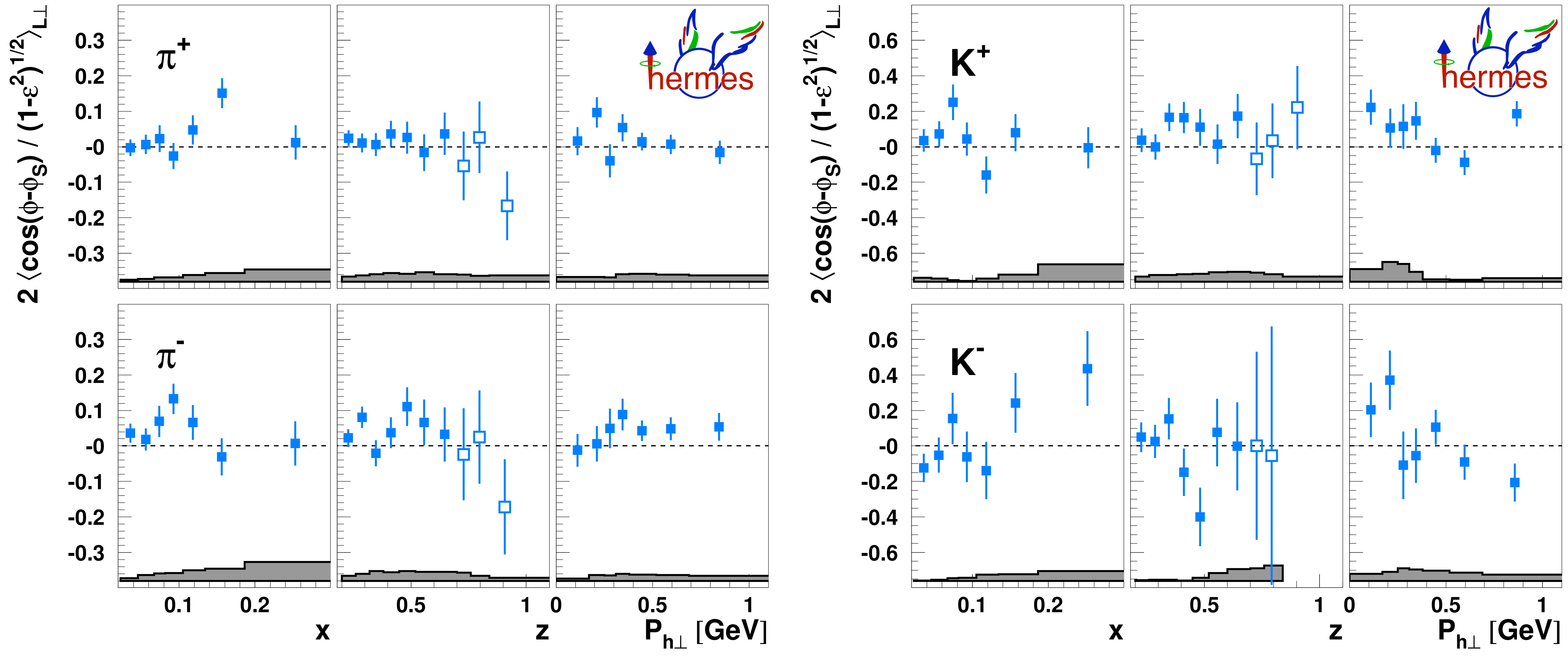
- quark-helicity asymmetry in transversely polarized nucleon
- evidences from
  - ^{3}He target at JLab
  - H target at COMPASS & HERMES

[PRL 108 (2012) 052001]





[HERMES, JHEP12(2020)010]



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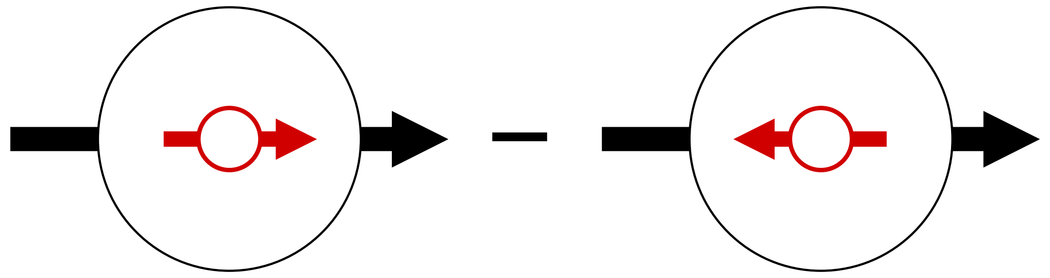
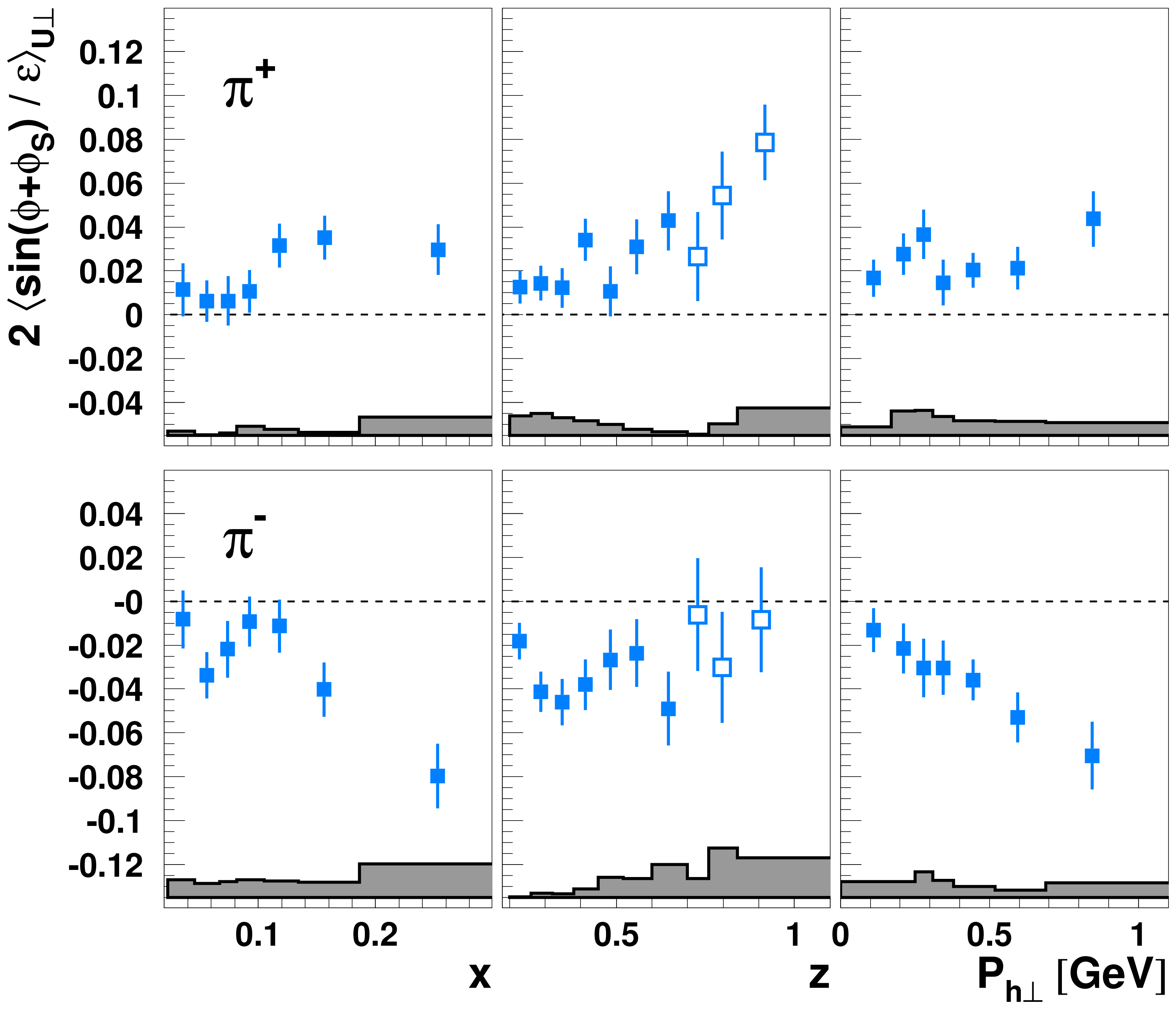


Transversity (Collins fragmentation)

[HERMES, JHEP12(2020)010]

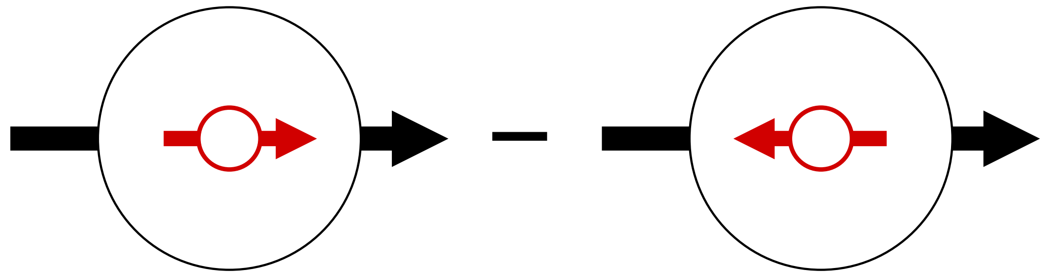


2005: first evidence from HERMES
semi-inclusive DIS on proton

confirmed in later analyses by HERMES and others

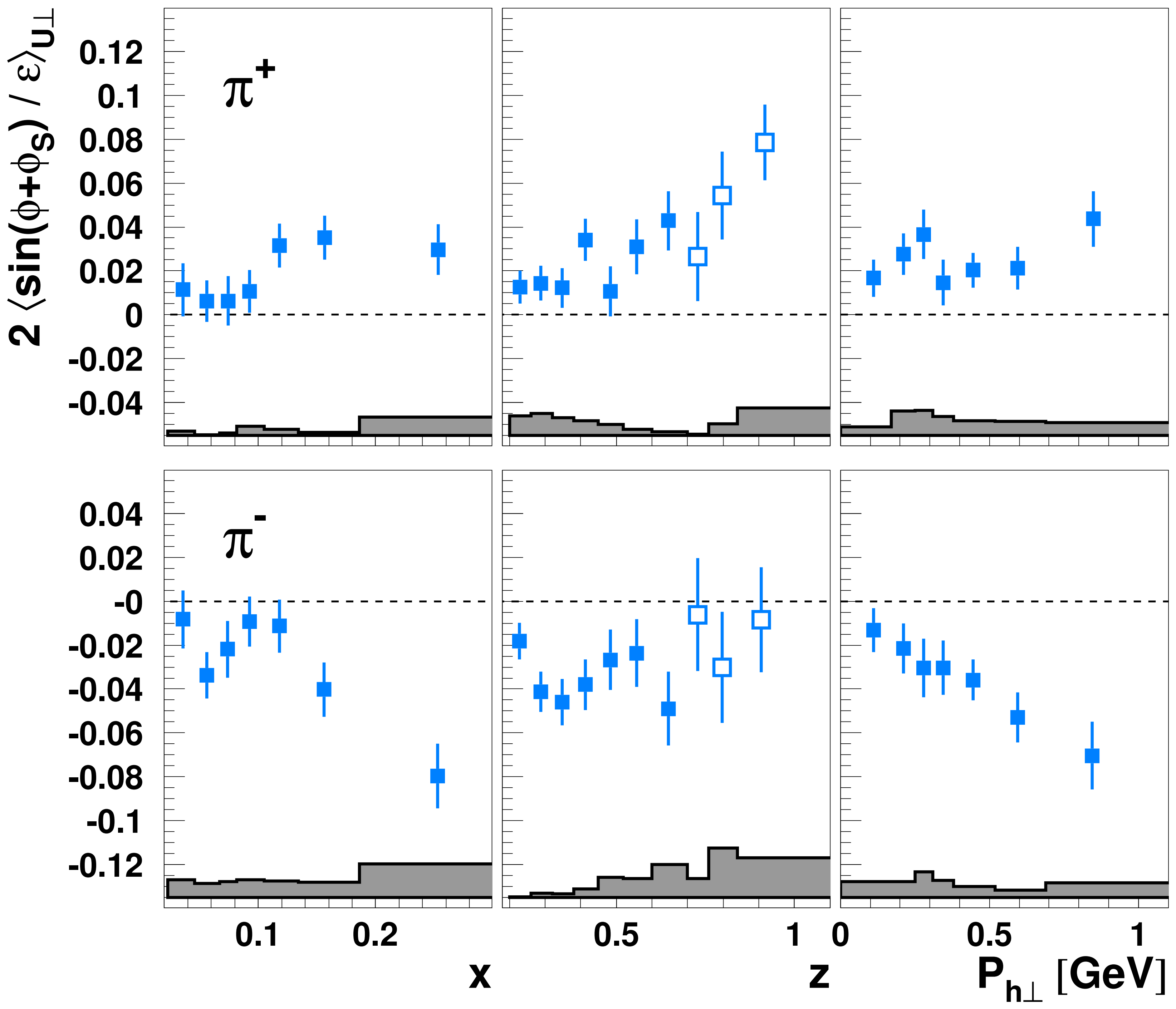
- significant in size and opposite in sign for charged pions
  - non-zero transversity!
  - non-zero Collins function!

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



Transversity (Collins fragmentation)

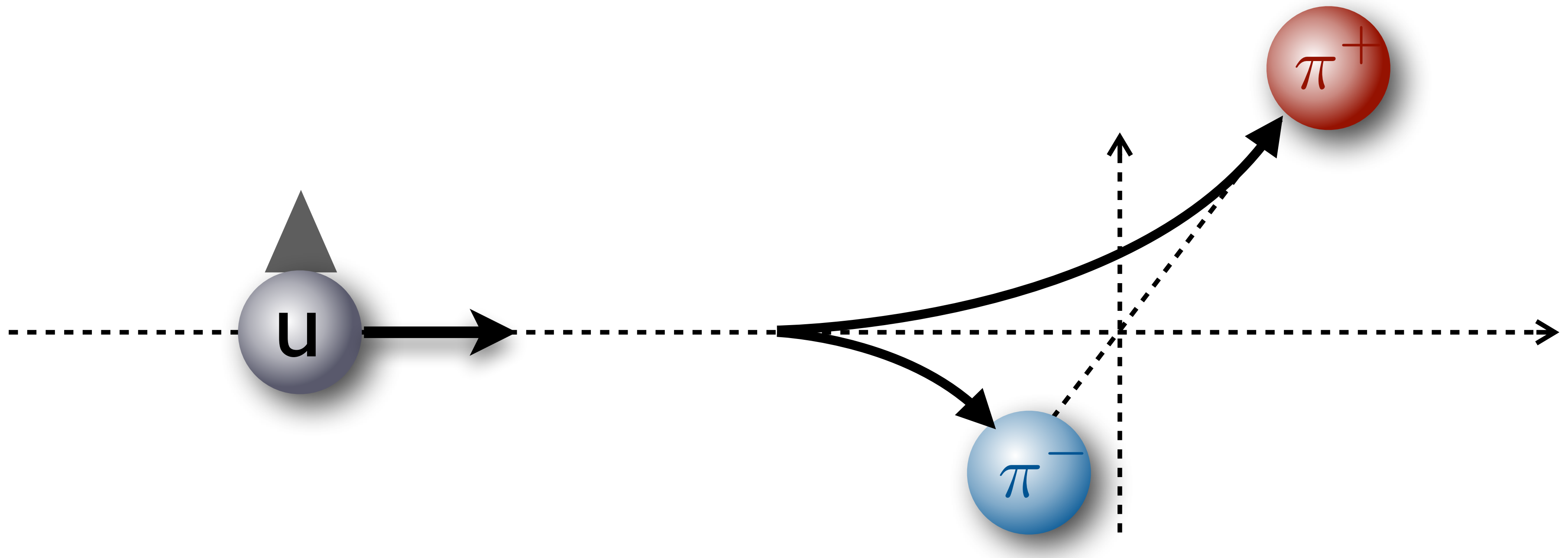
[HERMES, JHEP12(2020)010]



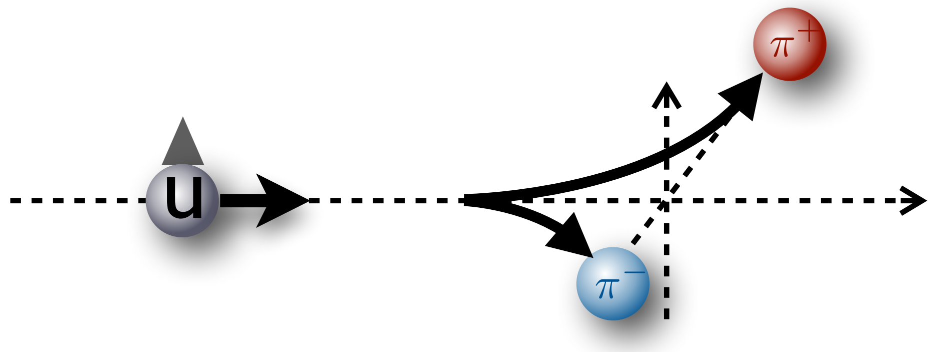
2005: first evidence from HERMES
semi-inclusive DIS on proton

confirmed in later analyses by HERMES and others

- significant in size and opposite in sign for charged pions
  - non-zero transversity!
  - non-zero Collins function!
- **disfavored** Collins FF **large** and **opposite in sign** to favored one

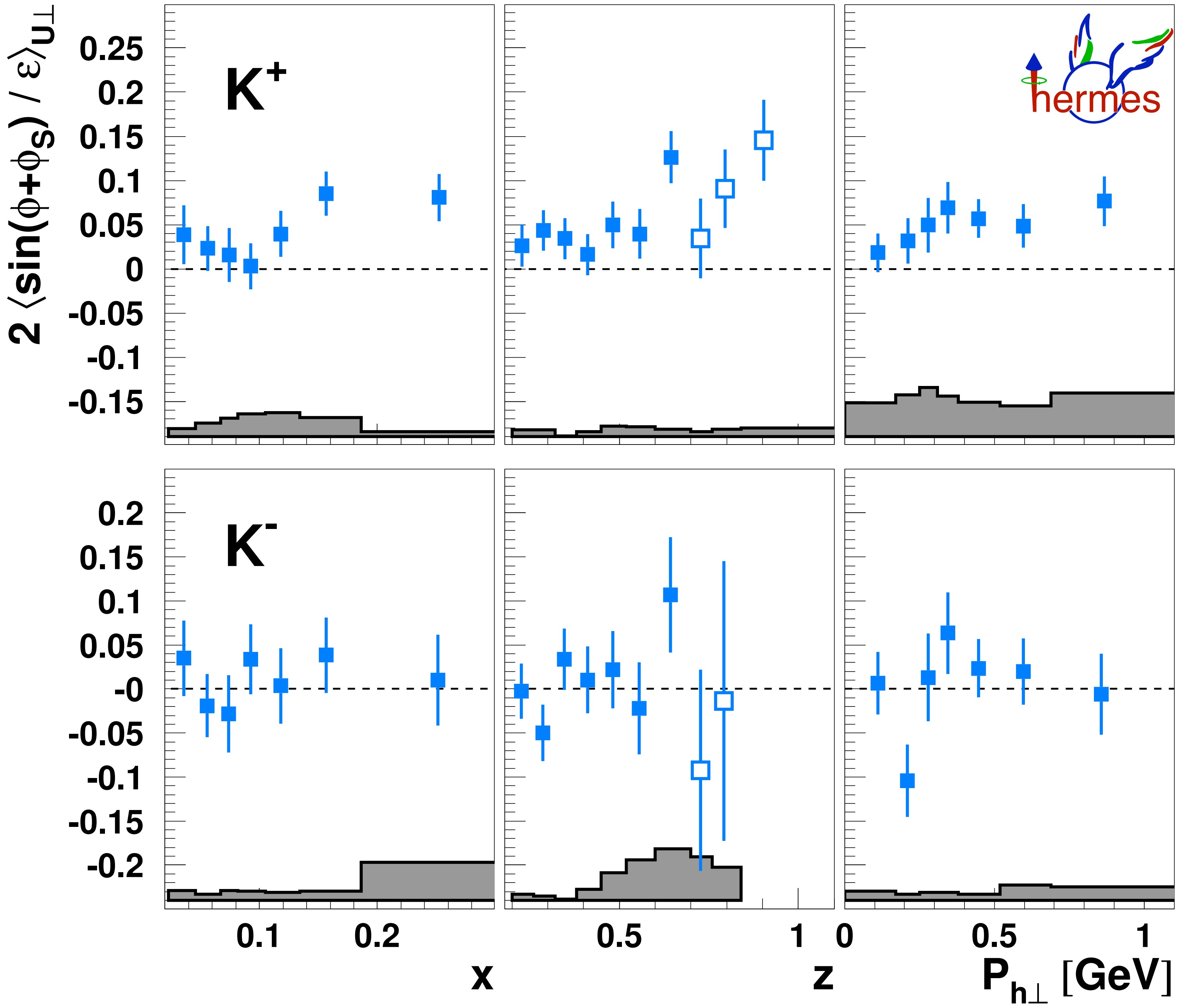


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\, h_{1T}^\perp$

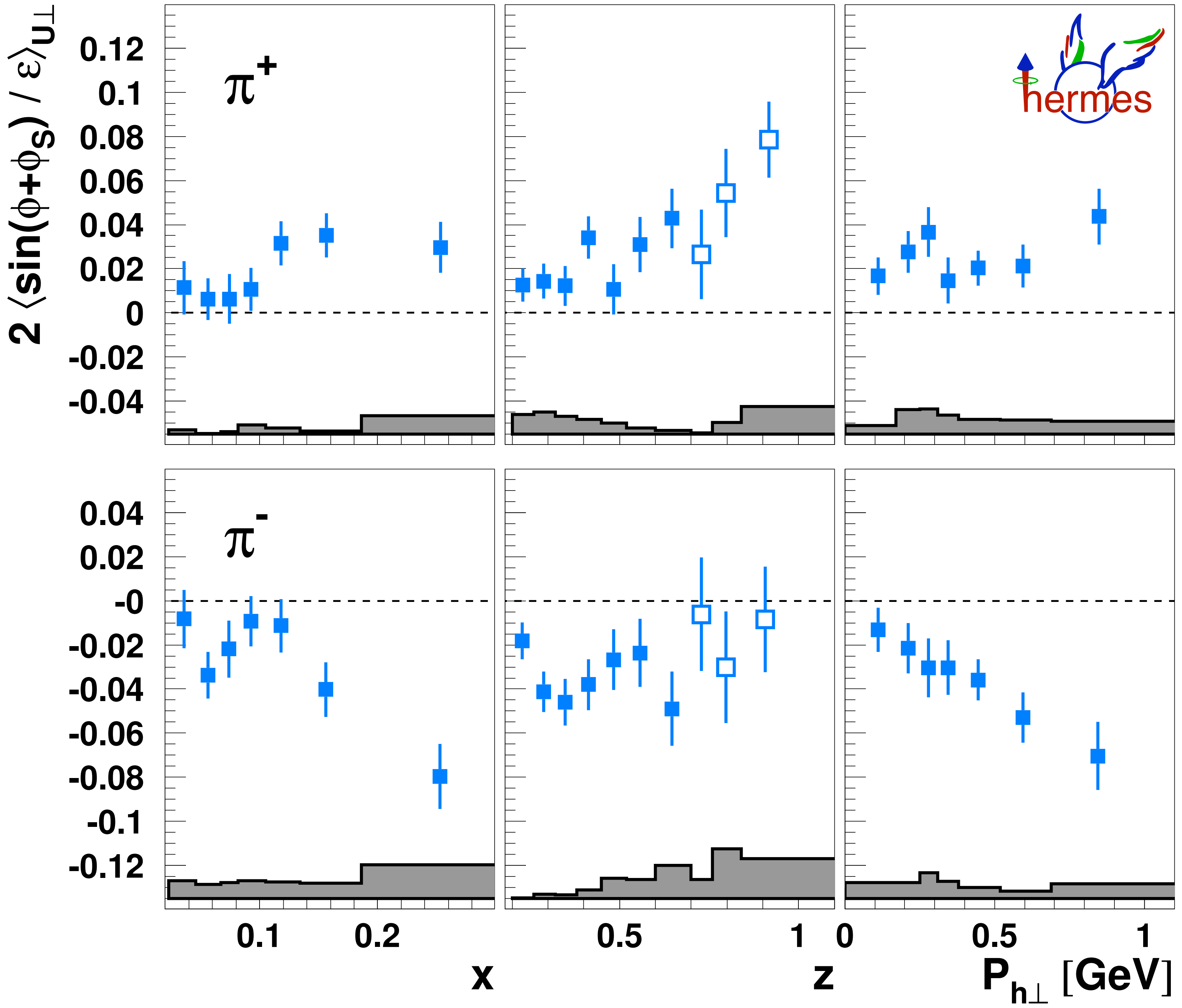


Collins asymmetry amplitudes

[HERMES, JHEP12(2020)010]

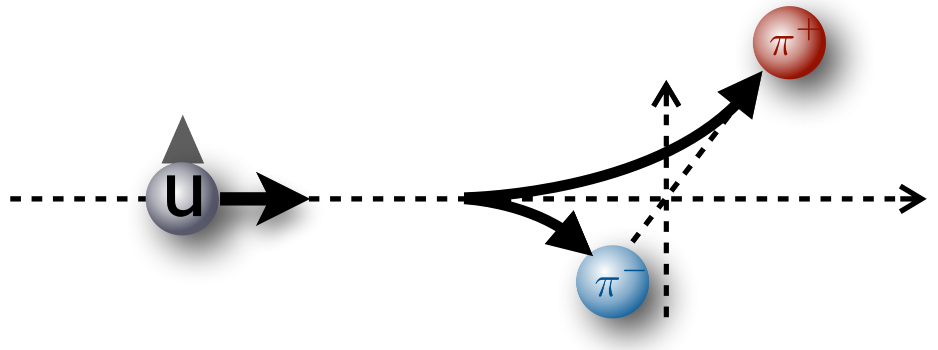


[HERMES, JHEP12(2020)010]



- even larger effect for kaons
- **high-z region** probes region of increased flavor sensitivity of struck quark

	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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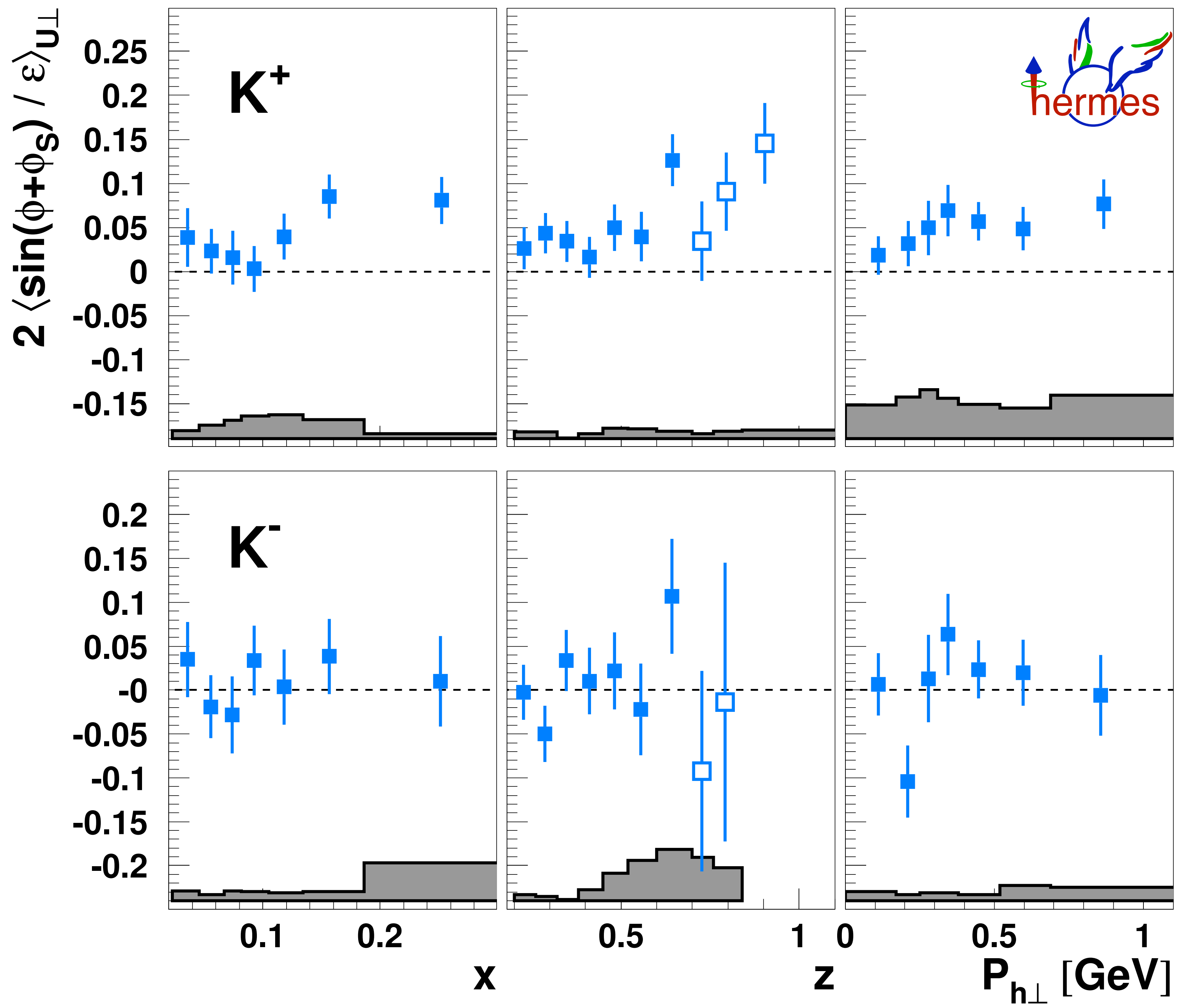
[HERMES, JHEP12(2020)010]



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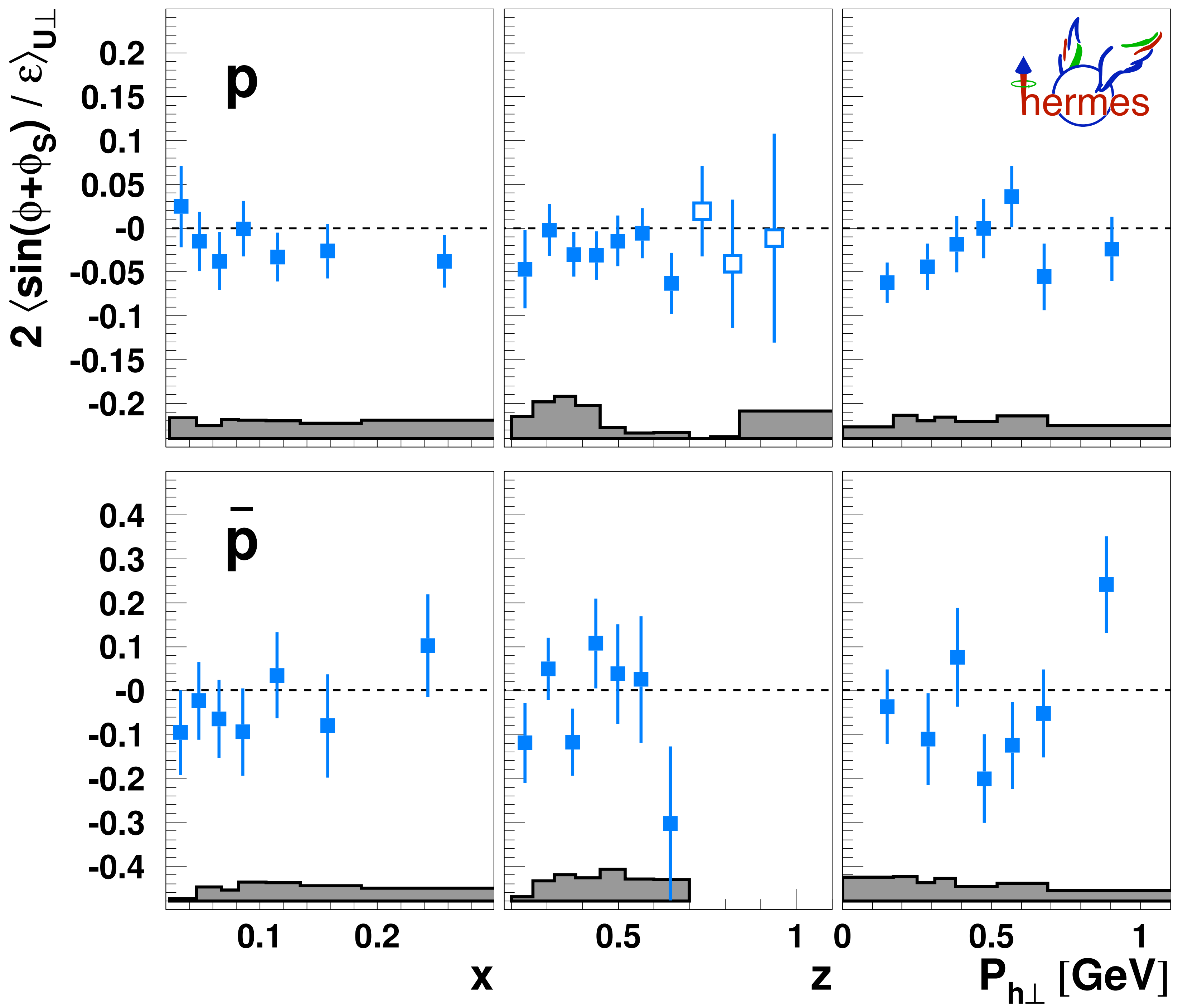


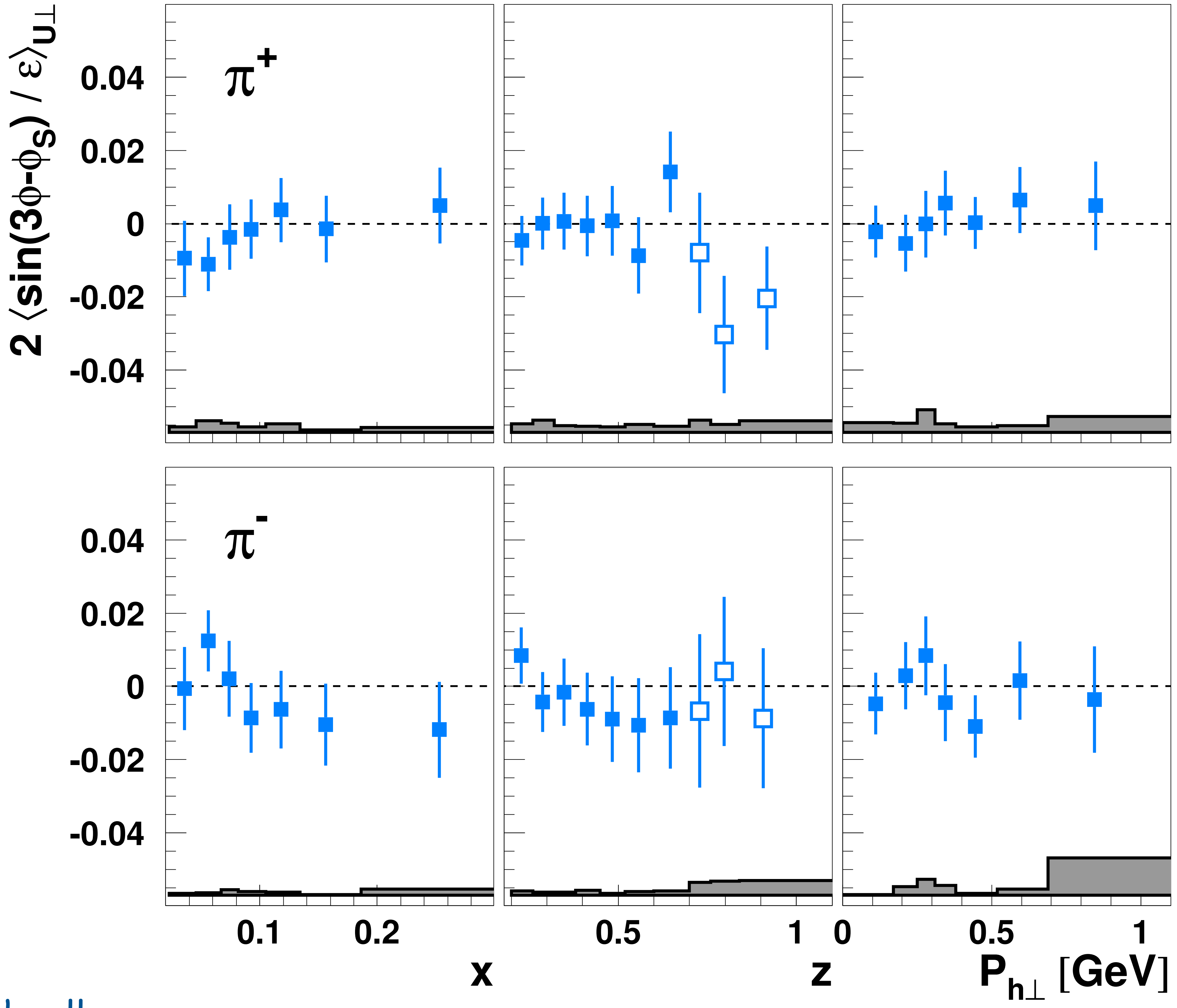
- even larger effect for kaons
- **high-z region** probes region of increased flavor sensitivity of struck quark
- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?

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

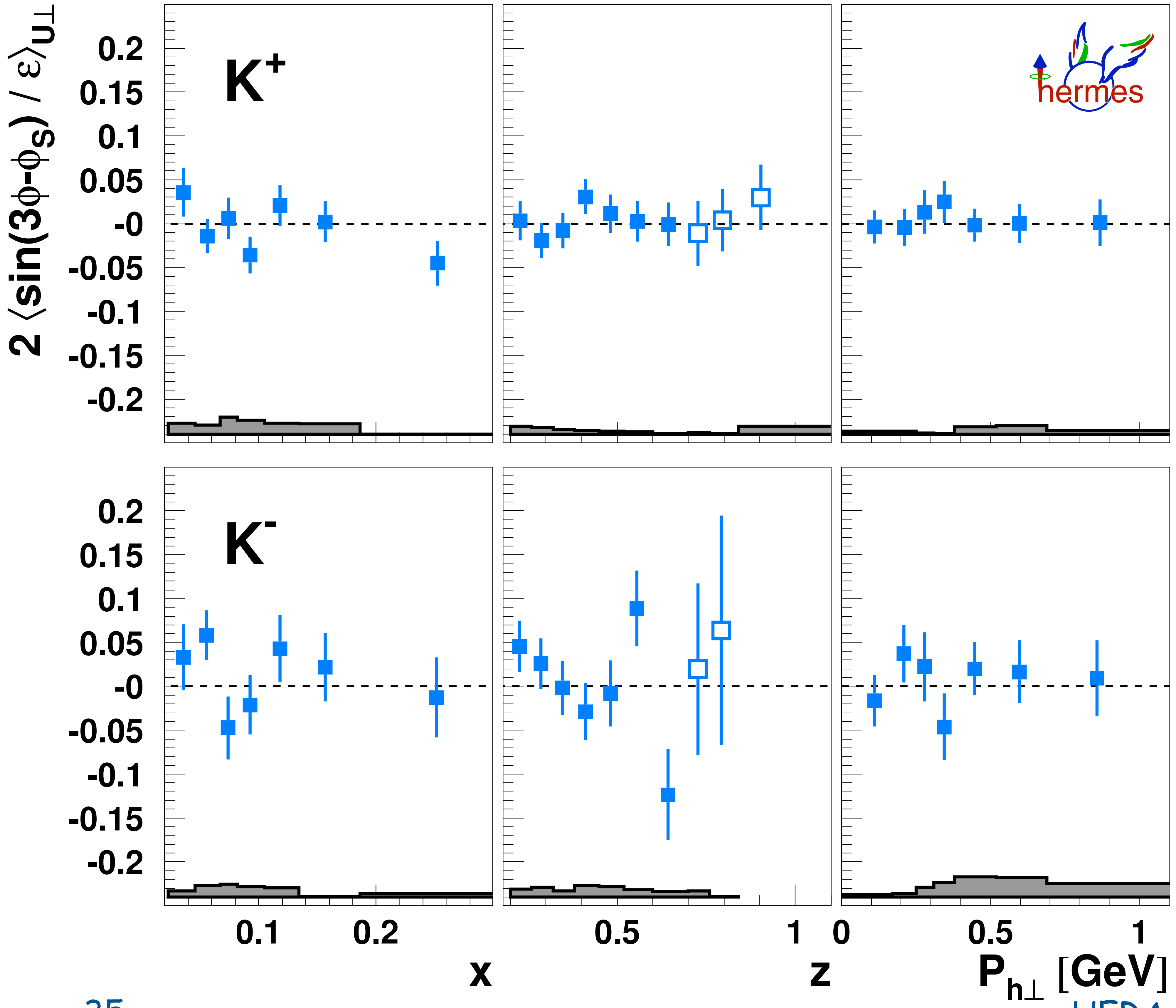
Pretzelosity

- quadrupole deformation in momentum space
- chiral-odd ➥ needs Collins FF (or similar)
- ^{1}H, ^{2}H & ^{3}He data from various experiments consistently small/vanishing
- cancelations? pretzelosity=zero? or just the additional general suppression of the asymmetry by two powers of $P_{h\perp}/M_N$

[HERMES, JHEP12(2020)010]

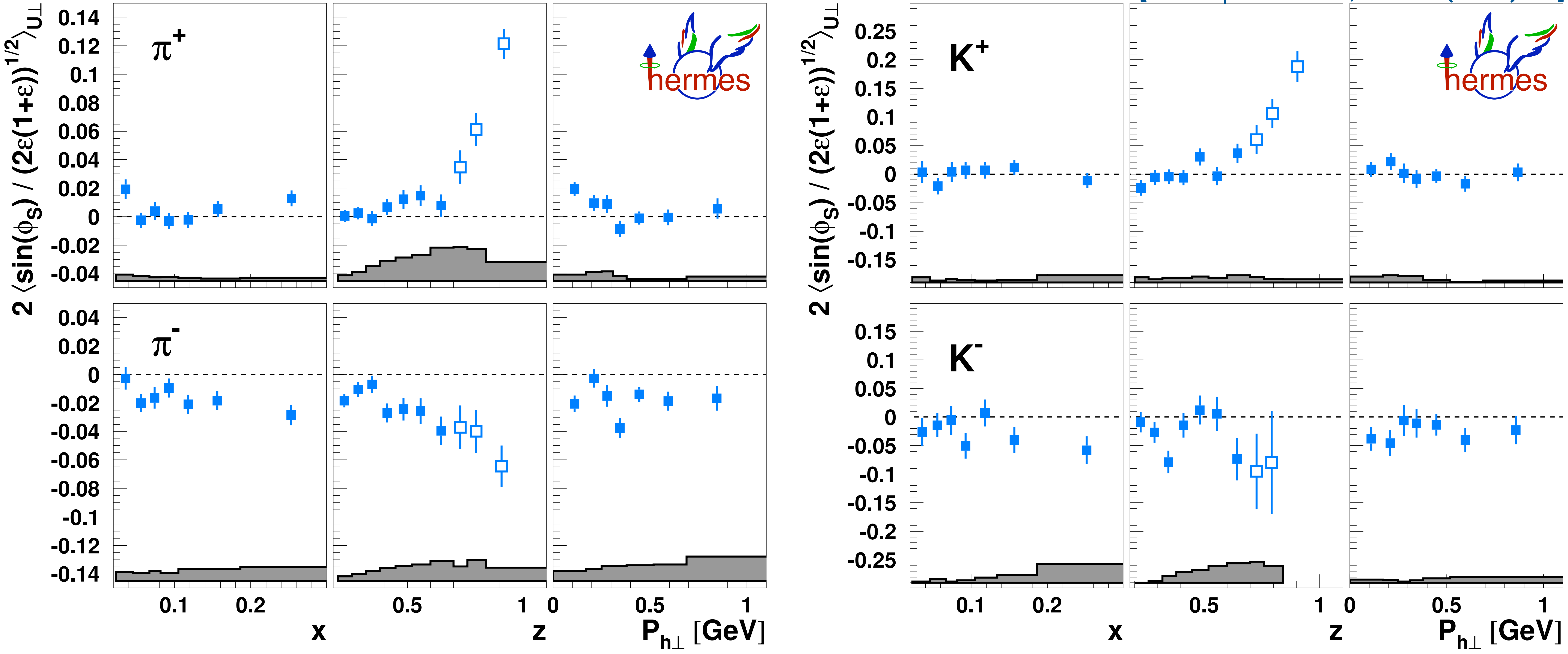


[HERMES, JHEP12(2020)010]

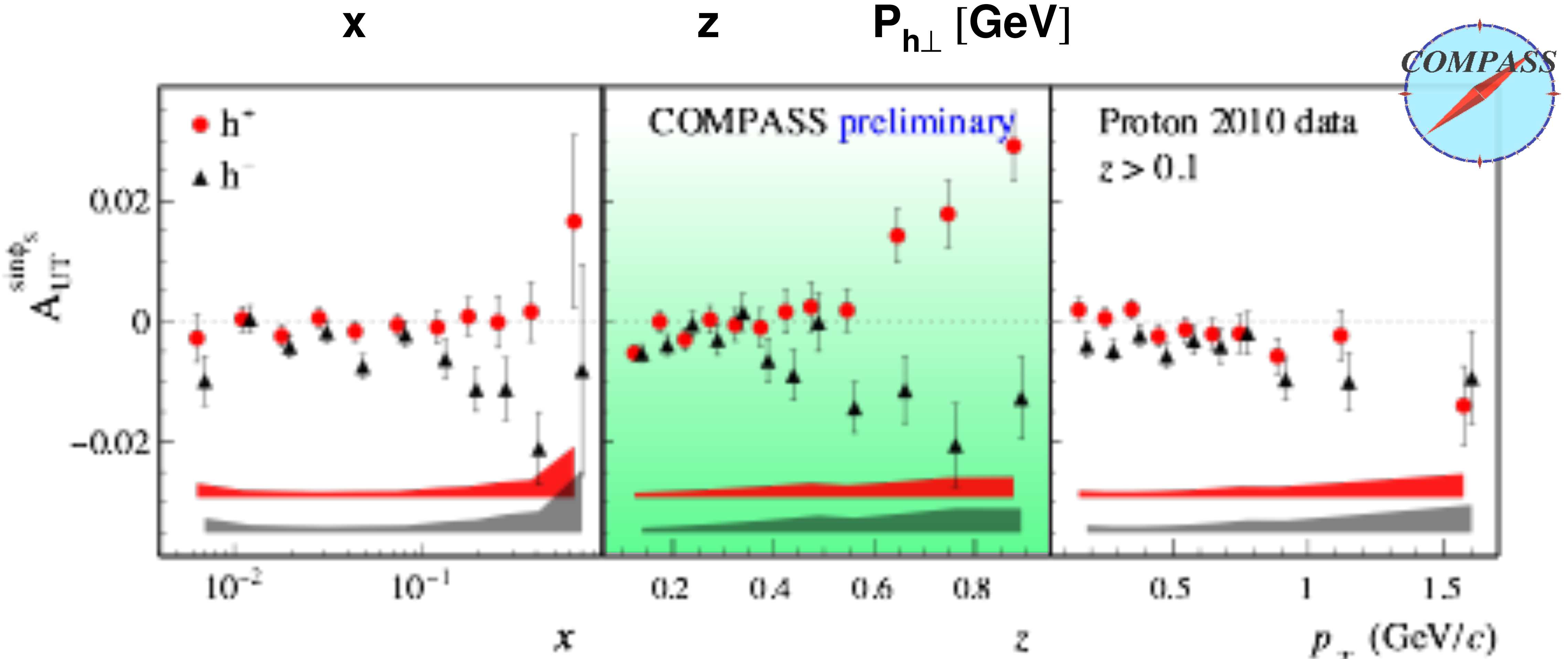


surprises: subleading twist, e.g., $\langle\sin(\phi_s)\rangle_{UT}$

[A. Airapetian et al., JHEP12(2020)010]



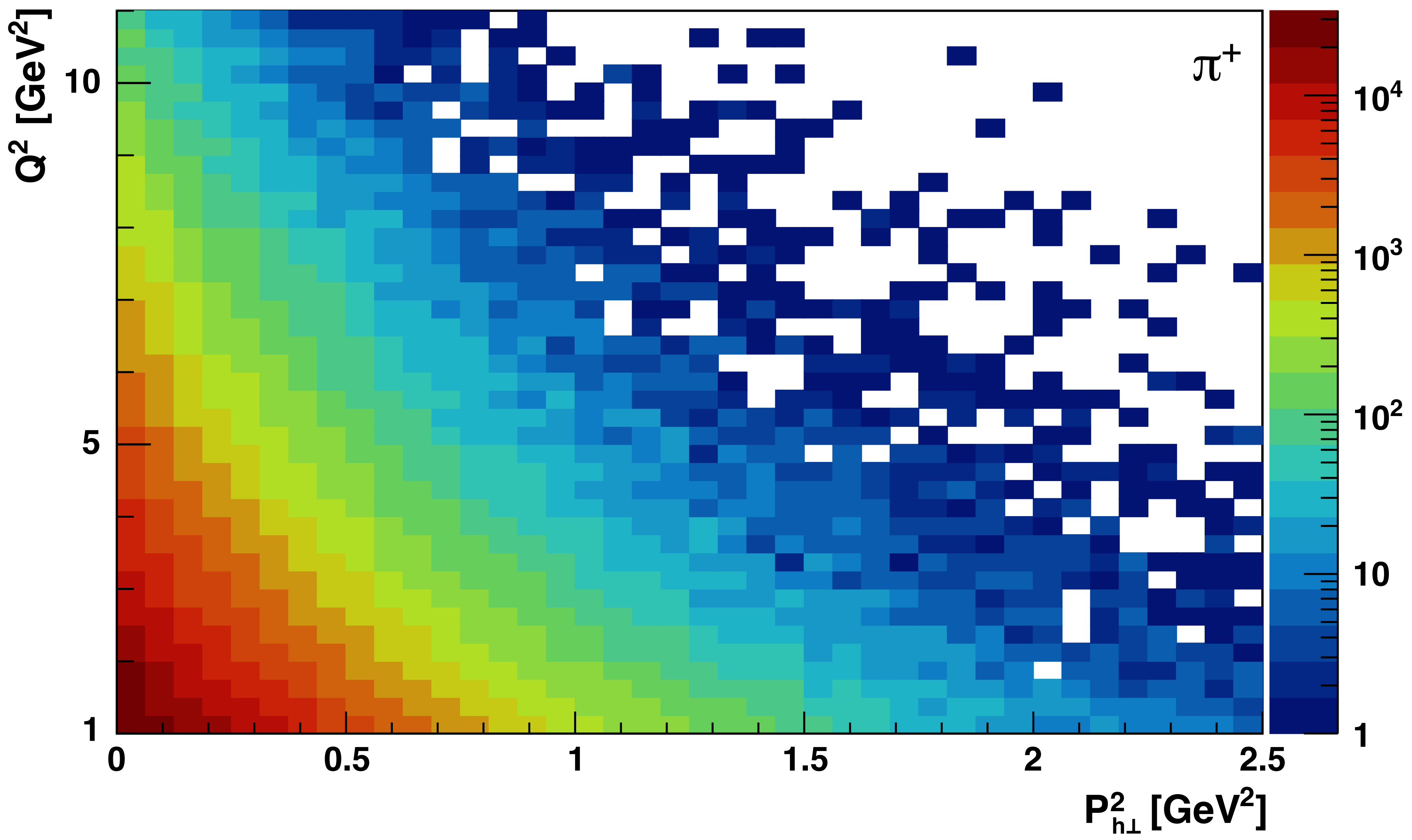
- clearly non-zero asymmetries
- opposite sign for charged pions (Collins-like behavior)
- striking z dependence and in particular magnitude
- similar observation at COMPASS



devil in the details & lessons learnt on the way

TMD factorization: a 2-scale problem

all events



- TMD factorization requires a large scale (Q^2) and small transverse momentum
- overall, Q mainly larger than $P_{h\perp}$
- not fulfilled in all kinematic bins
- more challenging, especially at low x (=low Q^2), for more stringent constraint of $zQ \gg P_{h\perp}$

choice of fitting function

$$A_{LU}^{h} \simeq \sqrt{2\epsilon(1-\epsilon)}\,\frac{F_{LU}^{h,\sin\phi}}{F_{UU}^{h}}\,\sin\phi$$

$$A_{LU}^{h} \overset{\text{M.L. fit}}{\simeq} \sqrt{2\epsilon(1-\epsilon)}\,A_{LU}^{h,\sin\phi}\,\sin\phi$$

$$A_{LU}^{h} \overset{\text{M.L. fit}}{\simeq} \tilde{A}_{LU}^{h,\sin\phi}\,\sin\phi$$

$$\frac{\mathrm{d}\sigma^{h}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^{2}\,\mathrm{d}\phi} = \frac{2\pi\alpha^{2}}{xyQ^{2}}\,\frac{y^{2}}{2(1-\epsilon)}\left(1+\frac{\gamma^{2}}{2x}\right)$$

$$\Big\{F_{UU,T}^{h} + \epsilon F_{UU,L}^{h} + \lambda\Lambda\sqrt{1-\epsilon^{2}}F_{LL}^{h}$$

$$+\sqrt{2\epsilon}\left[\lambda\sqrt{1-\epsilon}\,F_{LU}^{h,\sin\phi} + \Lambda\sqrt{1+\epsilon}\,F_{UL}^{h,\sin\phi}\right]\sin\phi$$

$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\,\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\,\cos 2\phi\Big\}$$

$$A_{LU}^{h} \equiv \frac{\sigma_{+-}^{h} + \sigma_{++}^{h} - \sigma_{-+}^{h} - \sigma_{--}^{h}}{\sigma_{+-}^{h} + \sigma_{++}^{h} + \sigma_{-+}^{h} + \sigma_{--}^{h}}$$

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$$A_{LU}^{h} \overset{\text{M.L. fit}}{\simeq} \tilde{A}_{LU}^{h,\sin\phi}\,\sin\phi$$

- asymmetry amplitudes extracted by minimizing, e.g.,

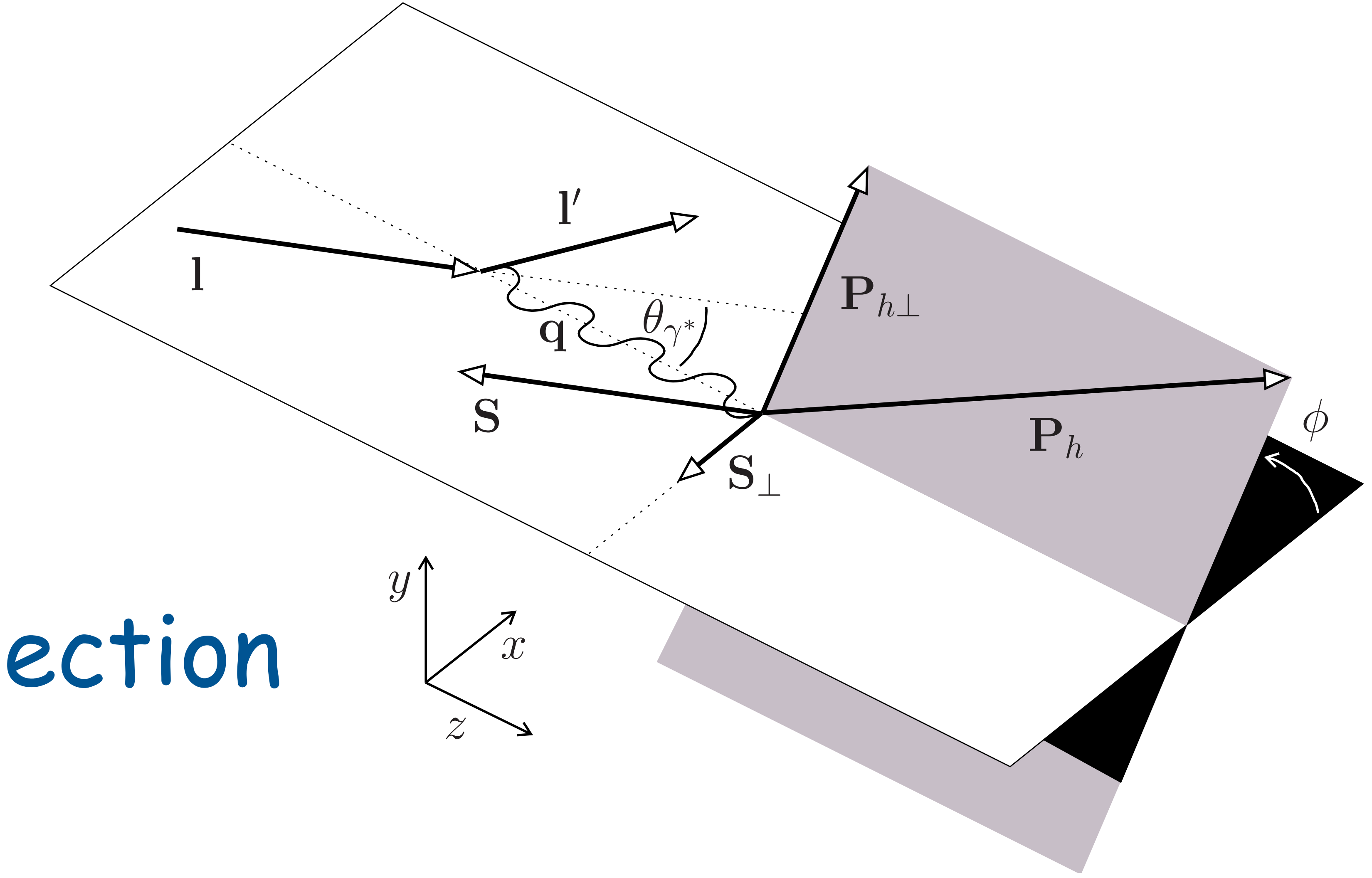
$$-\ln\mathbb{L} = -\sum_{i} w_i\,\ln\left[1 + P_{B,i}\,\sqrt{2\epsilon_i(1-\epsilon_i)}\,A_{LU}^{h,\sin(\phi)}\,\sin(\phi_i)\right]$$

where w_i is event weight from hadron-ID, charge-symmetric BG etc.

- need to include all possible modulations in fit

mixing of target polarizations

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



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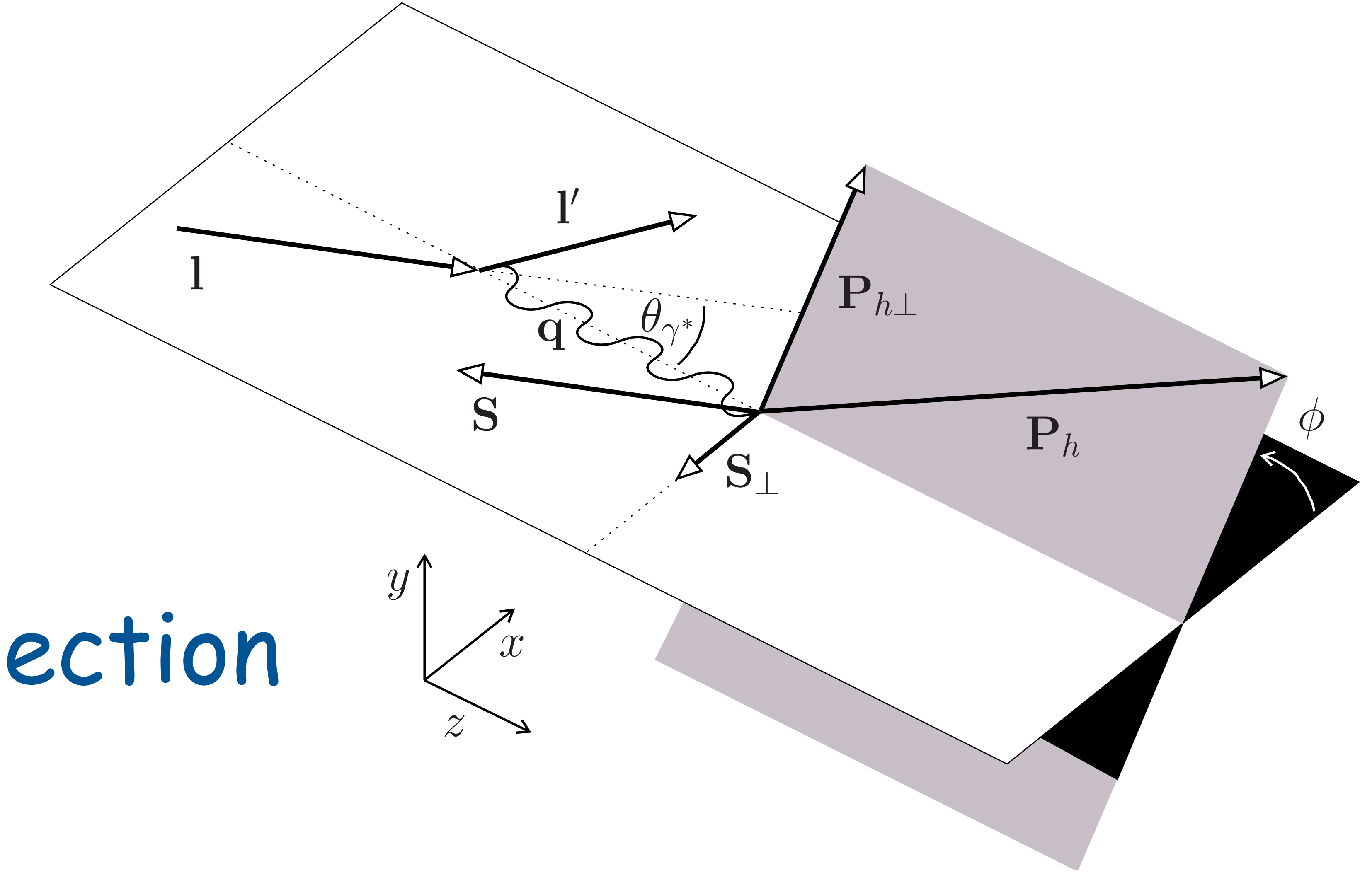

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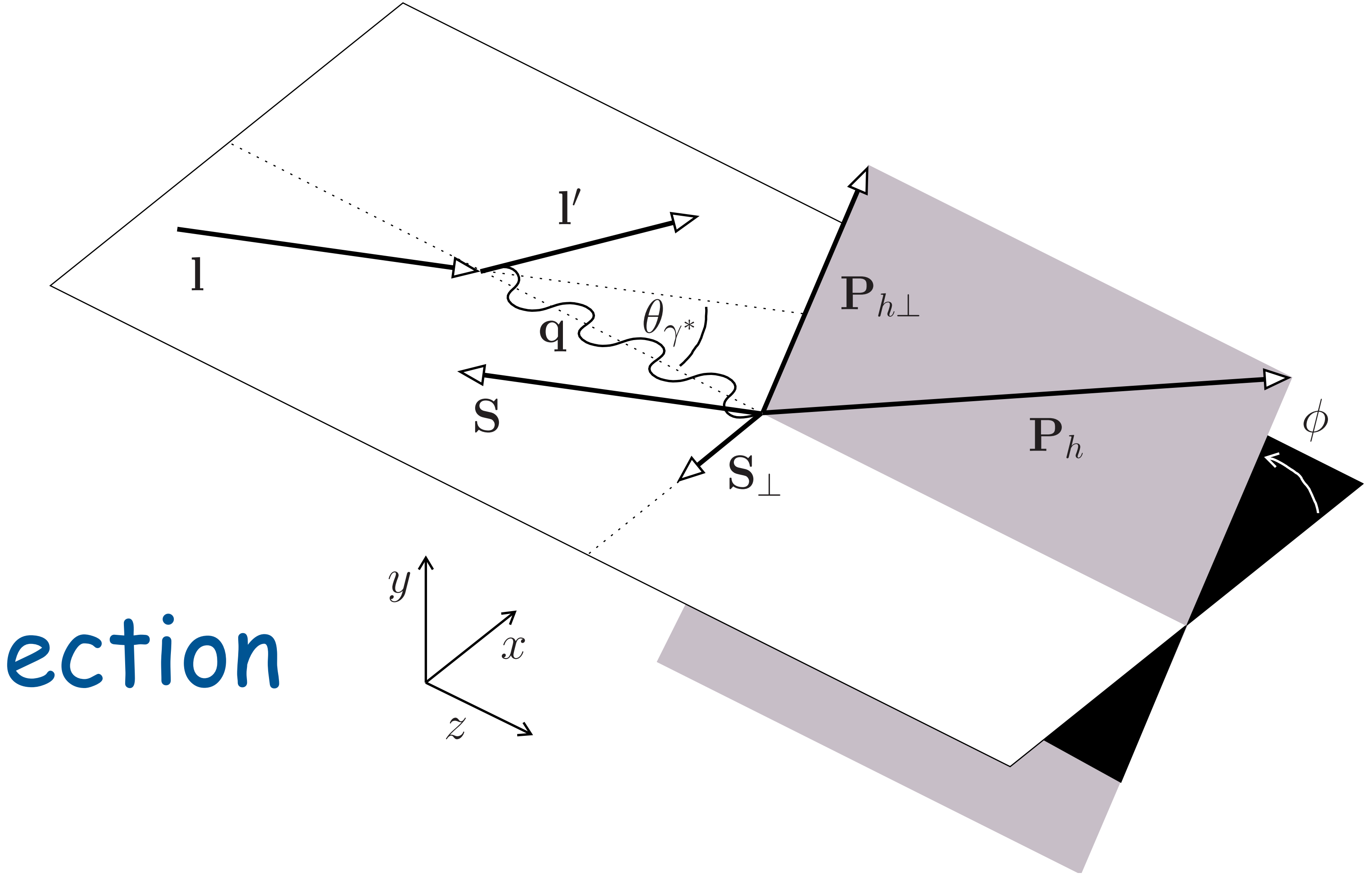
- experiments use targets polarized w.r.t. lepton-beam direction

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

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

mixing of target polarizations



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➡ need data on same target for both polarization orientations!

detector effects — need for multi-d analyses

$$\frac{N^+(x) - N^-(x)}{N^+(x) + N^-(x)} = \frac{\int \mathrm{d}\omega\, \epsilon(x,\omega)\, \Delta\sigma(x,\omega)}{\int \mathrm{d}\omega\, \epsilon(x,\omega)\, \sigma(x,\omega)}$$

- measured cross sections / asymmetries often contain “remnants” of experimental acceptance ϵ

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- measured cross sections / asymmetries often contain “remnants” of experimental acceptance ϵ
- difficult to evaluate precisely in absence of good physics model
    - general challenge to statistically precise data sets
    - avoid 1d binning/presentation of data

detector effects — need for multi-d analyses

- inclusive DIS: relatively simple as only 2d (and generally weak Q^2 dependence)

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  - e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$

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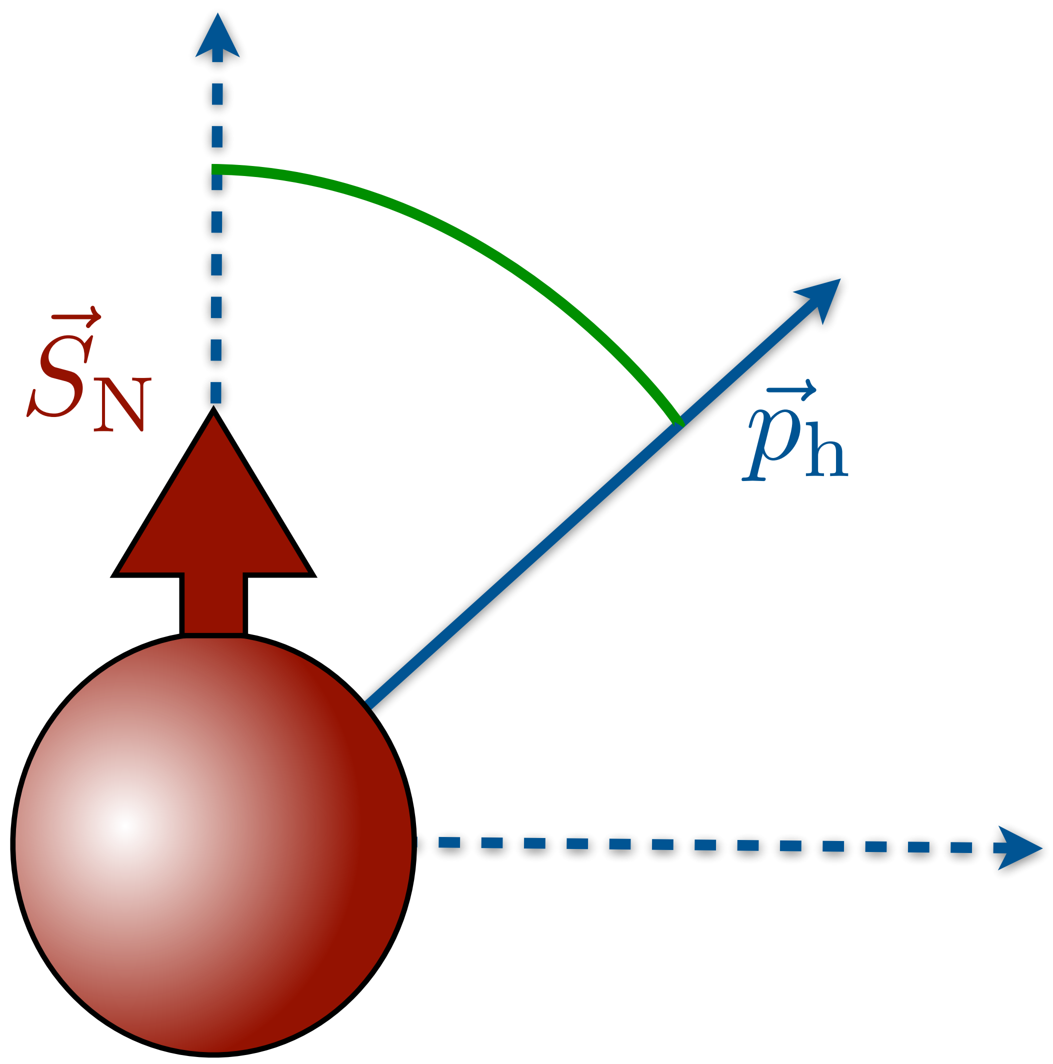
  - e.g., binning in x involves [incomplete] integration(s) over $P_{h\perp}$
- further complication: physics (cross sections) folded with acceptance
  - NO experiment has flat acceptance in full multi-d kinematic space

inclusive hadrons: A_{UT} sinψ amplitude

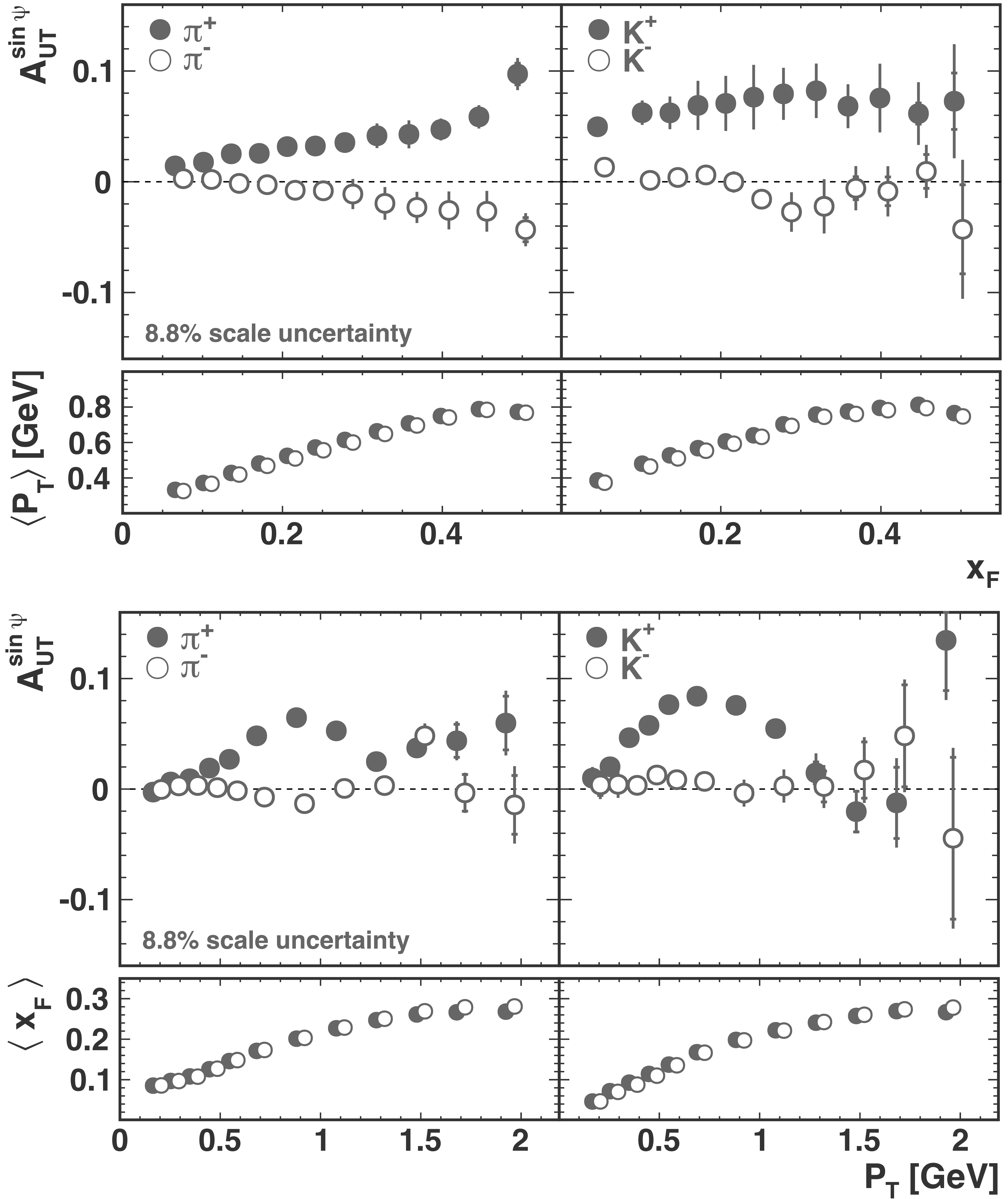
- clear left-right asymmetries for pions and positive kaons

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



lepton going into the plane

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



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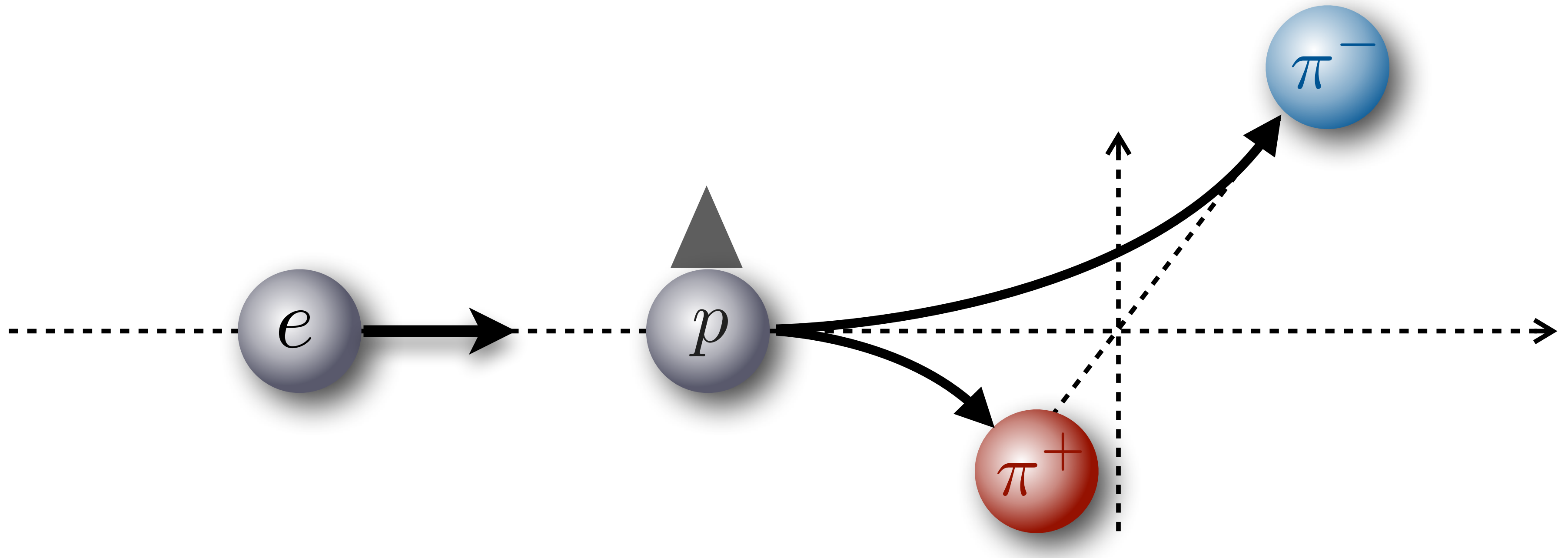
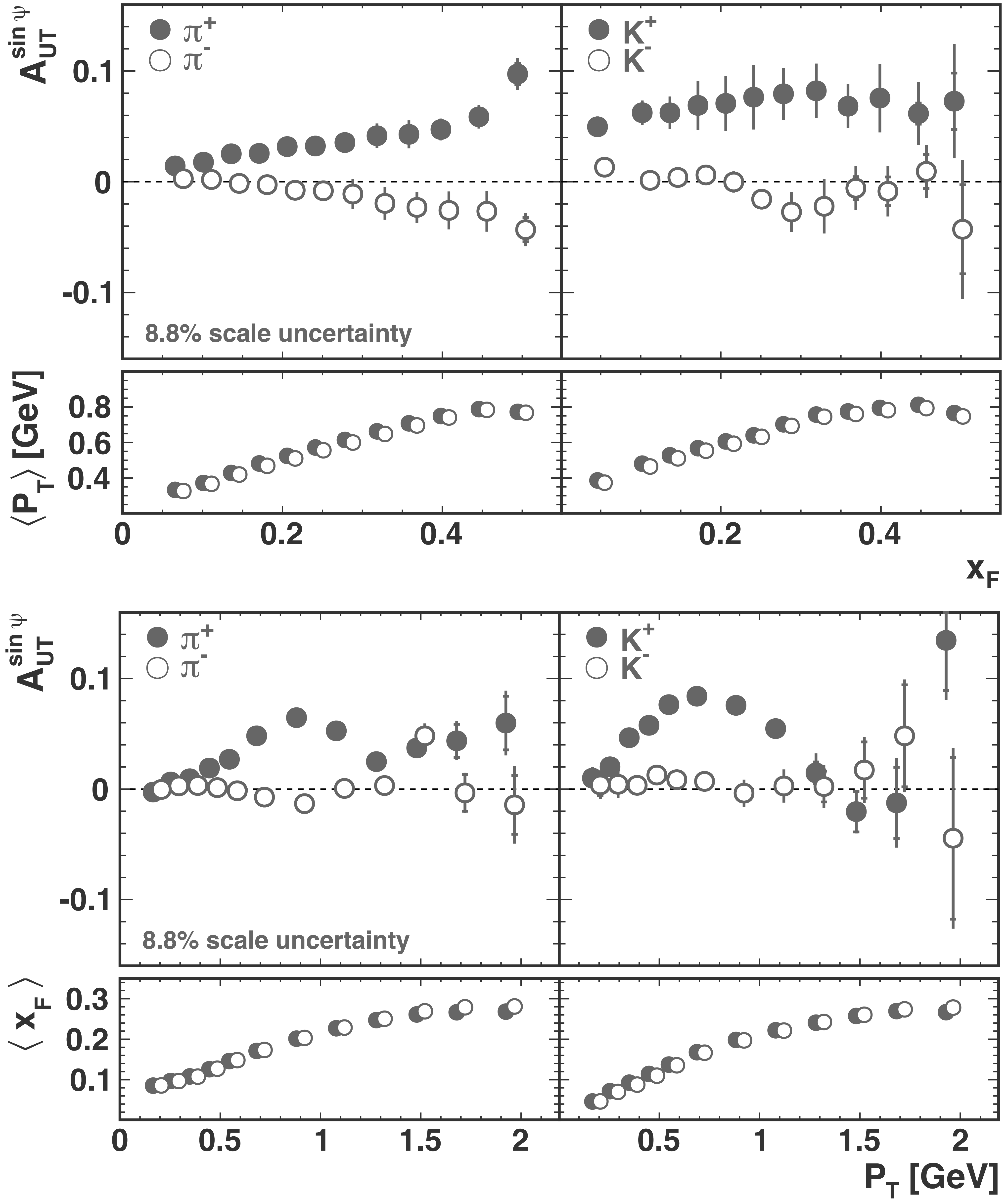


- initially increasing with P_T with a fall-off at larger P_T



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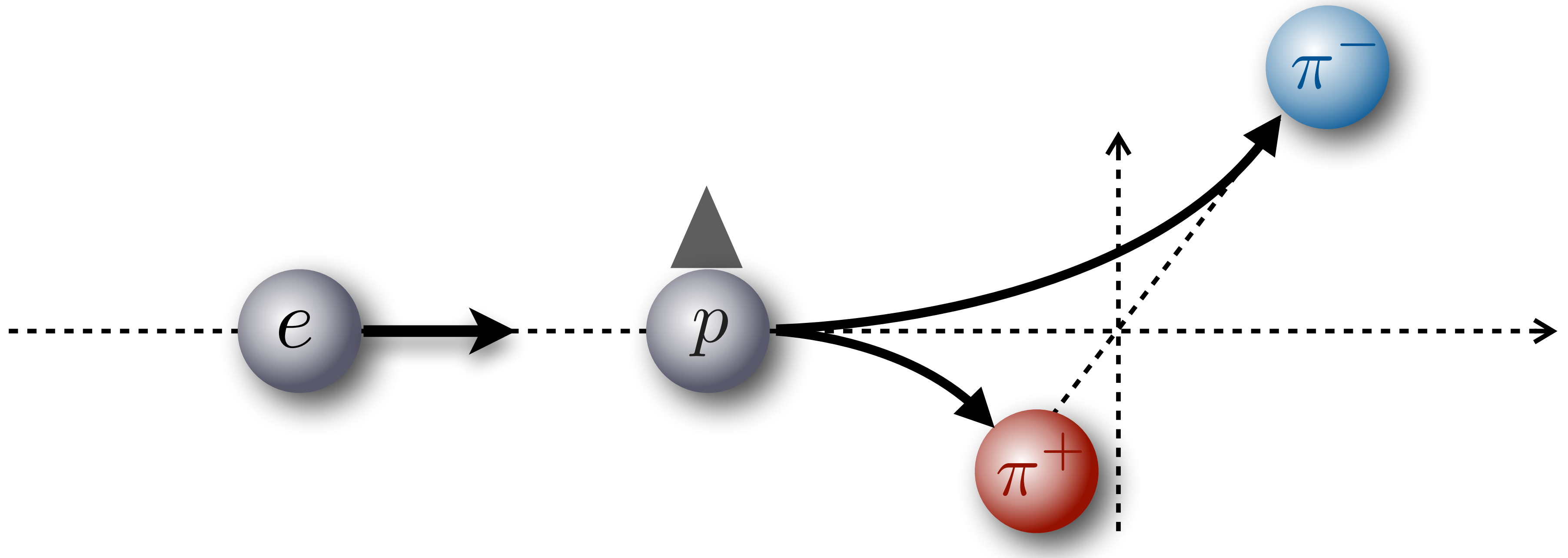
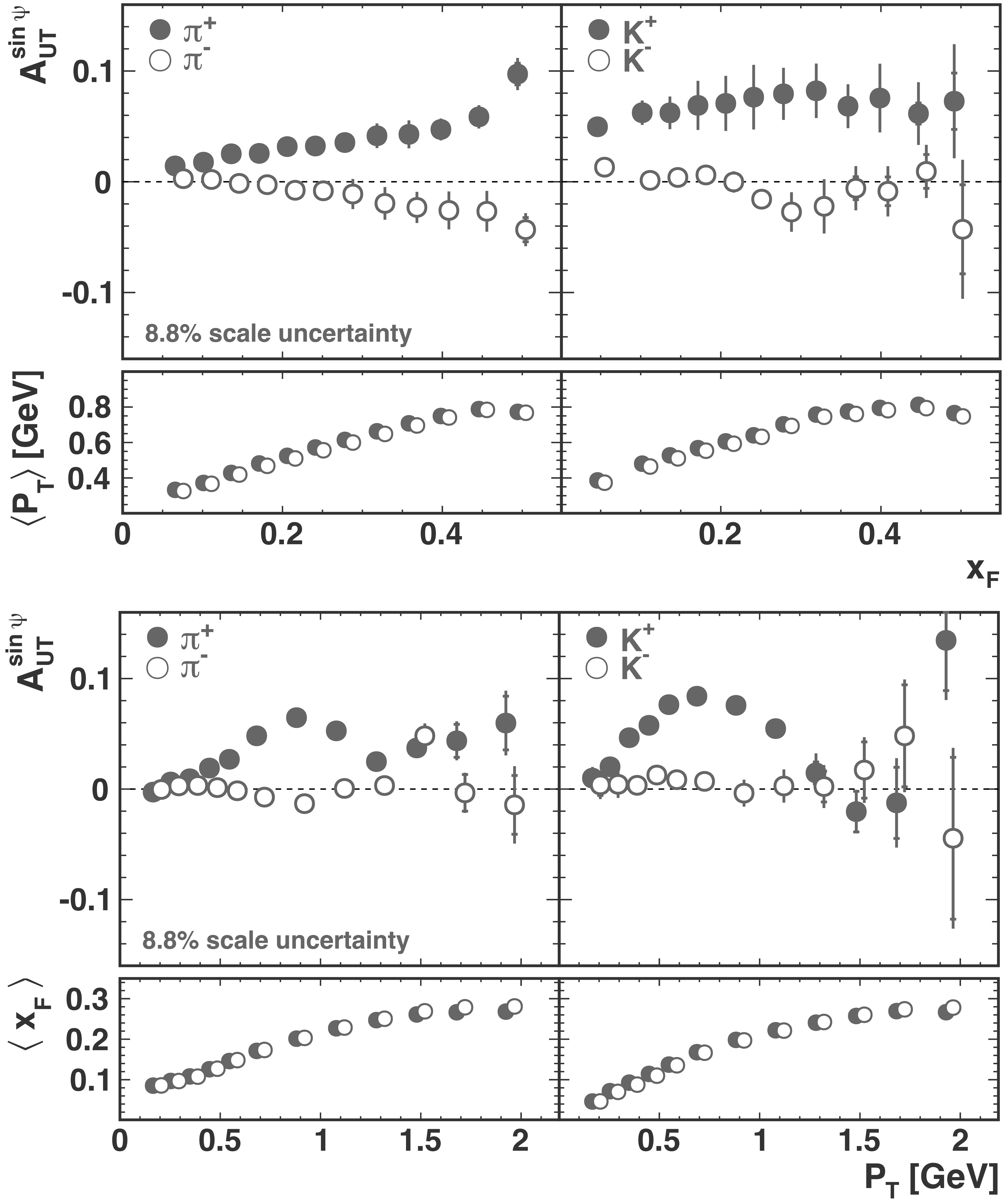


- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated
  ➥ look at 2D dependences

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



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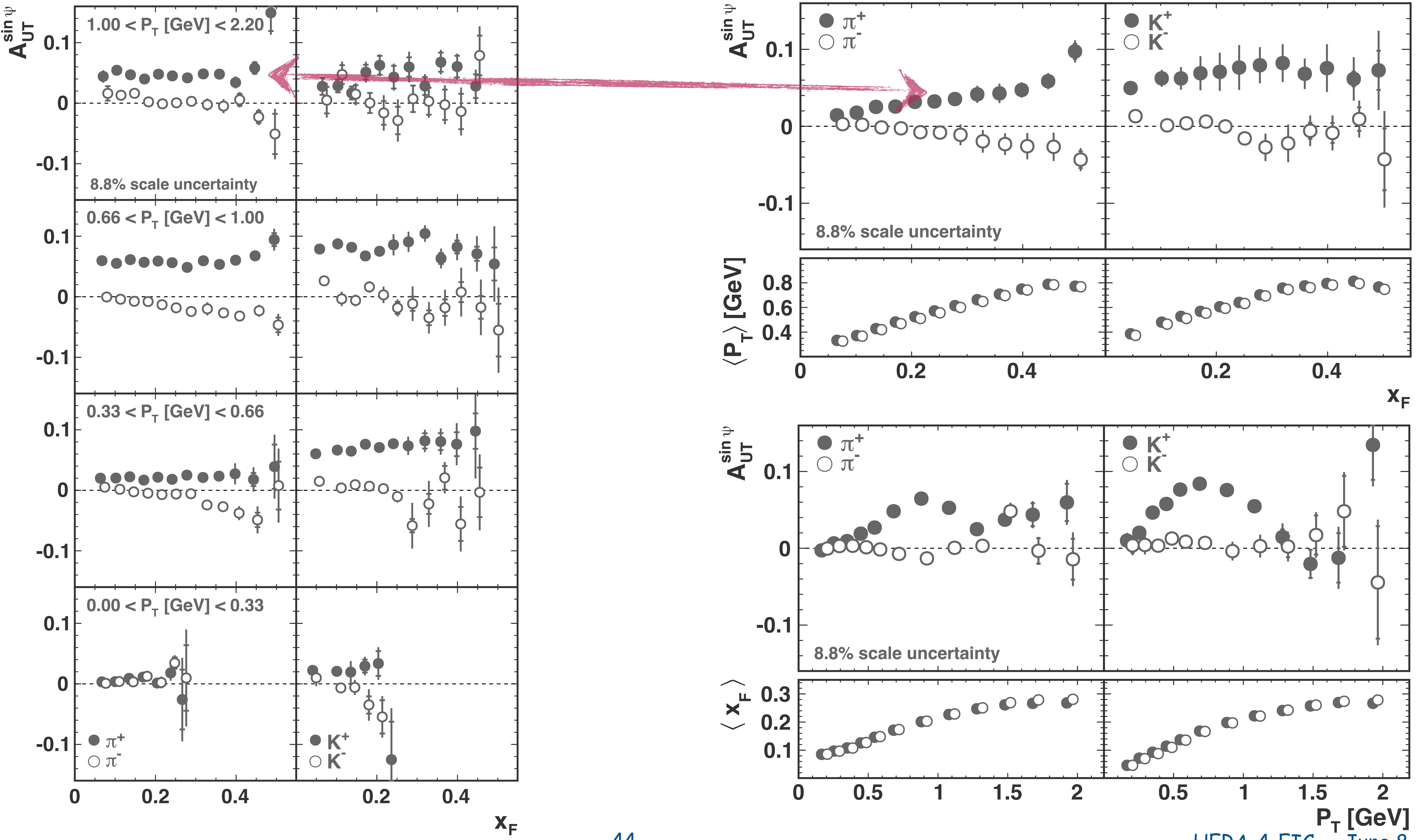
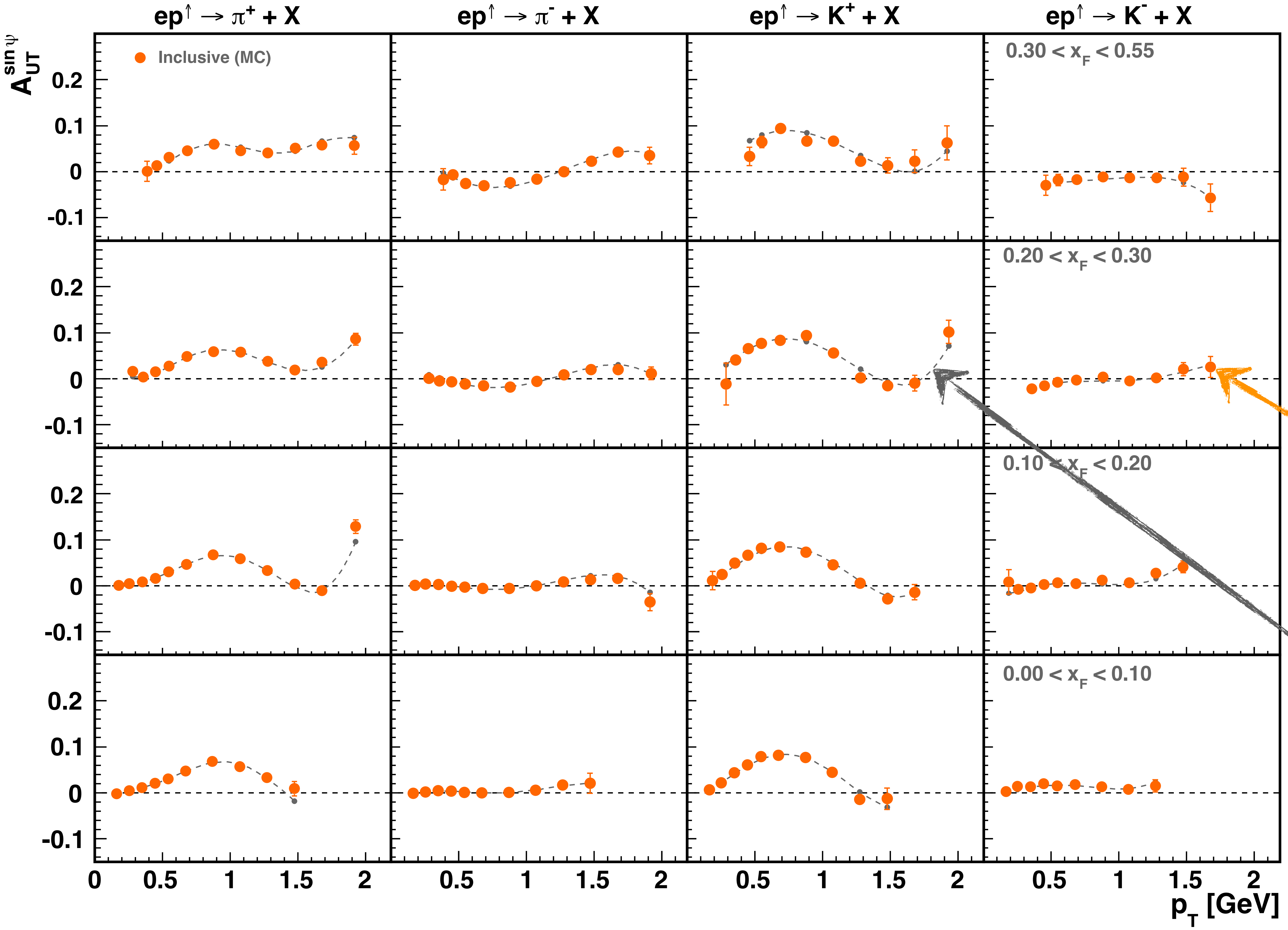
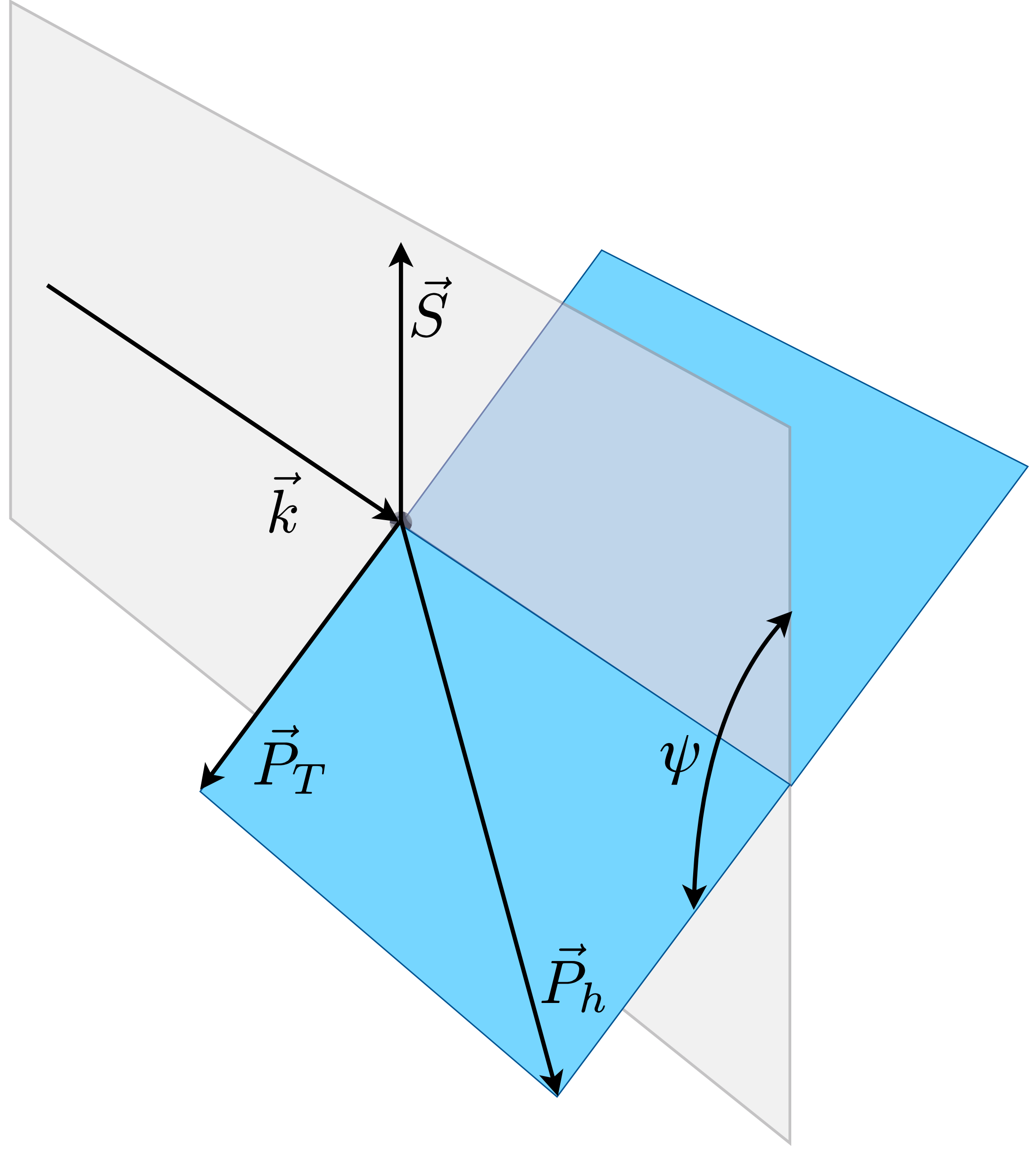


inclusive hadrons: A_{UT} sinψ amplitude

“closure test”





reconstructed MC

input model (fit to data)

small detector effects in fully differential analysis

inclusive hadrons: A_{UT} sinψ amplitude

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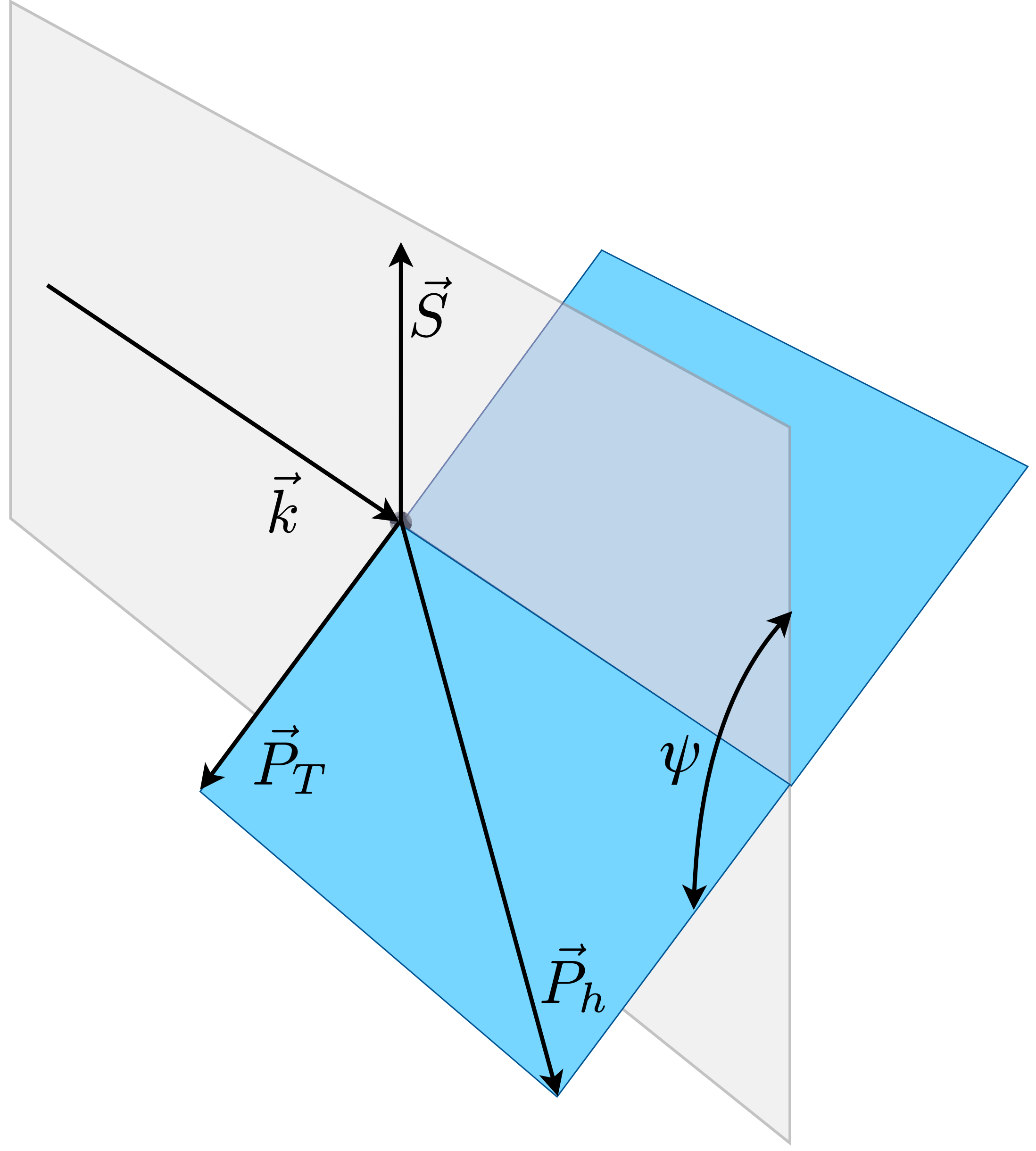

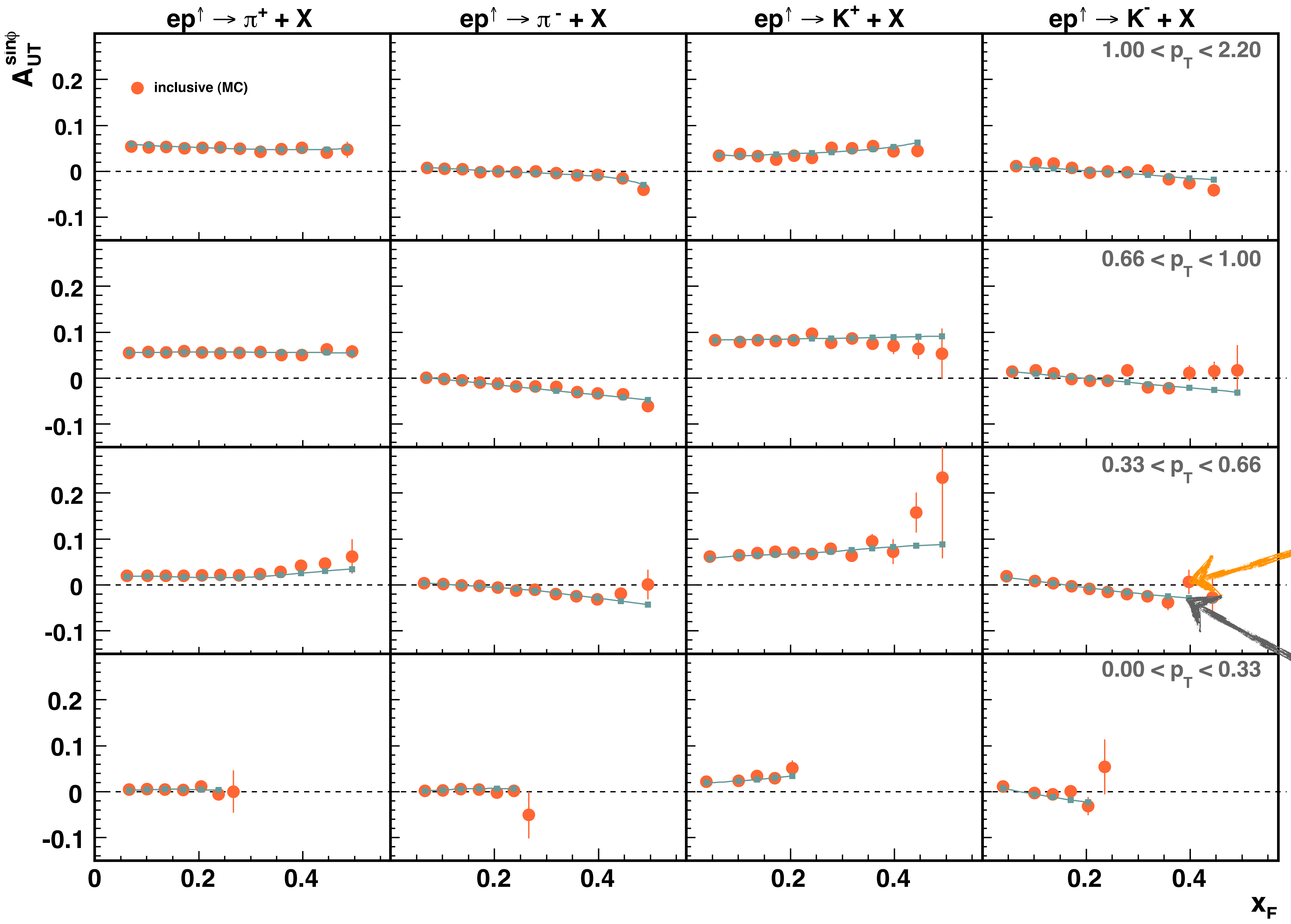

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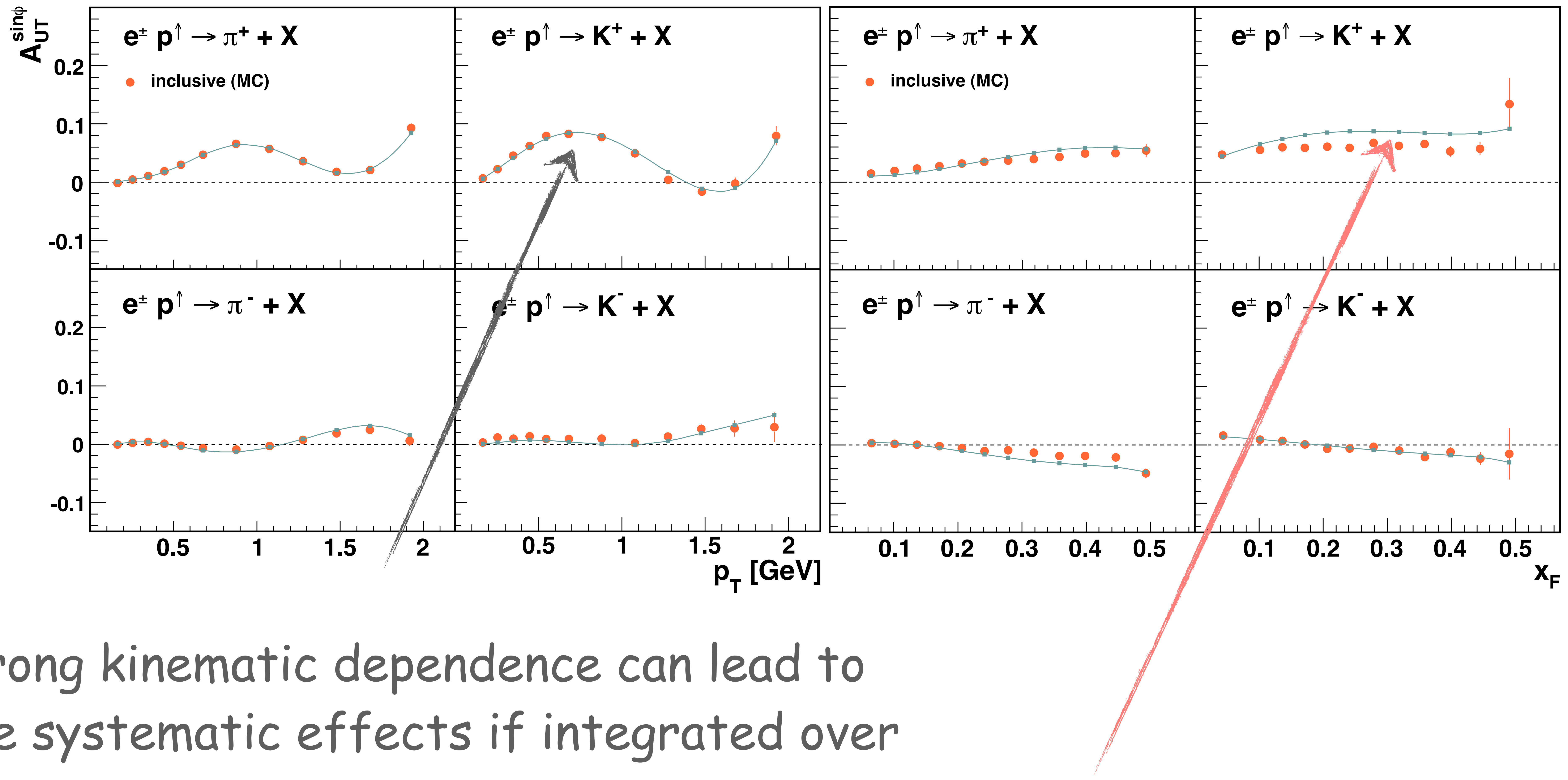


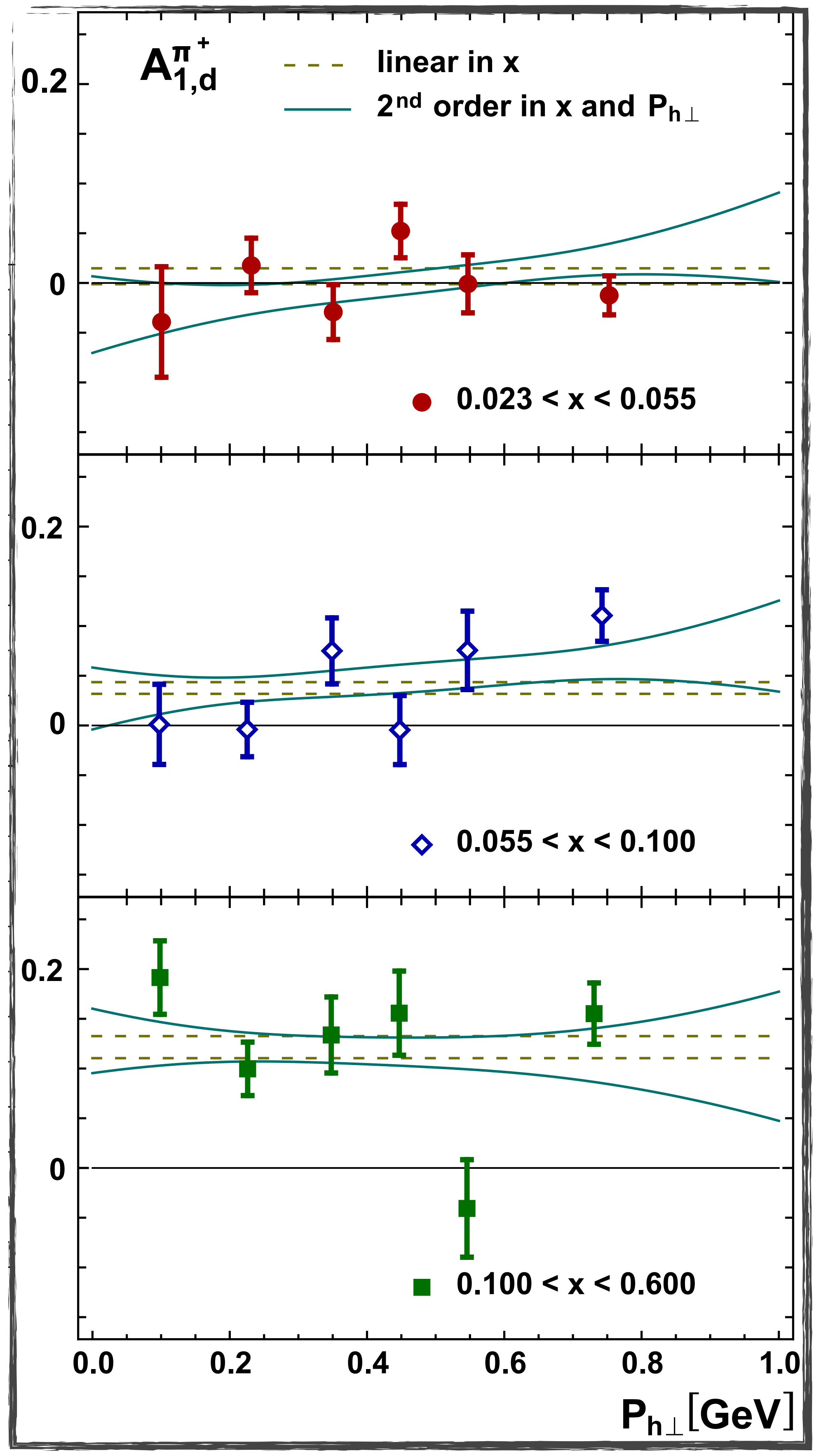
strong kinematic dependence can lead to large systematic effects if integrated over

not so small detector effects in 1D analysis

detector effects — need for multi-d analyses

- Why have 1d projections survived for so long?
  - faster to catch features of functional dependence
  - most prominent asymmetry was A_{LL} (or A_1)
    - viewed with "collinear monocles" - thus blind for 3d effects
    - no strong dependence on hadron kinematics observed

[HERMES, PRD 99 (2019) 112001]



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  - TMD physics with strong dependence on hadron kinematics
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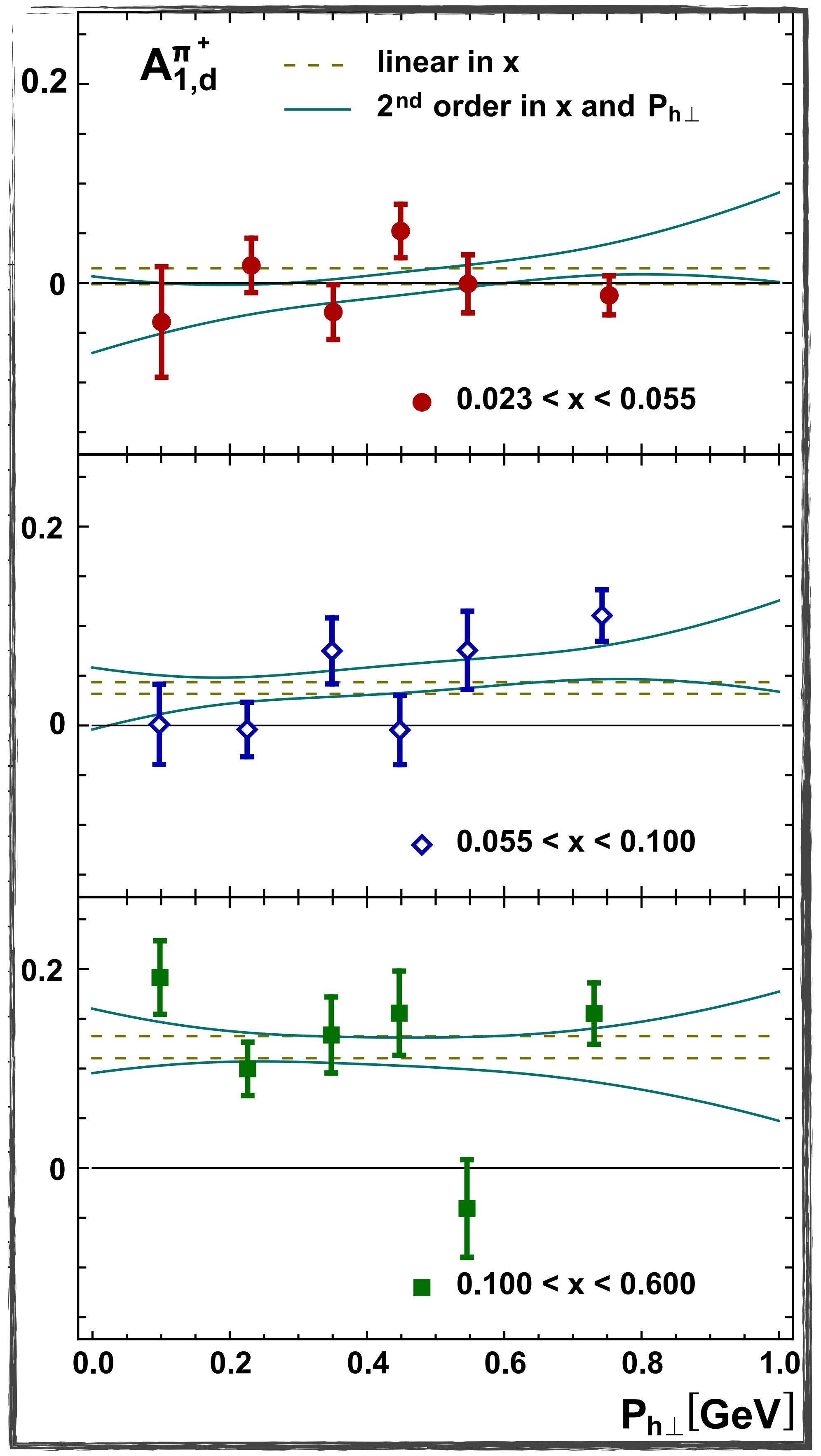

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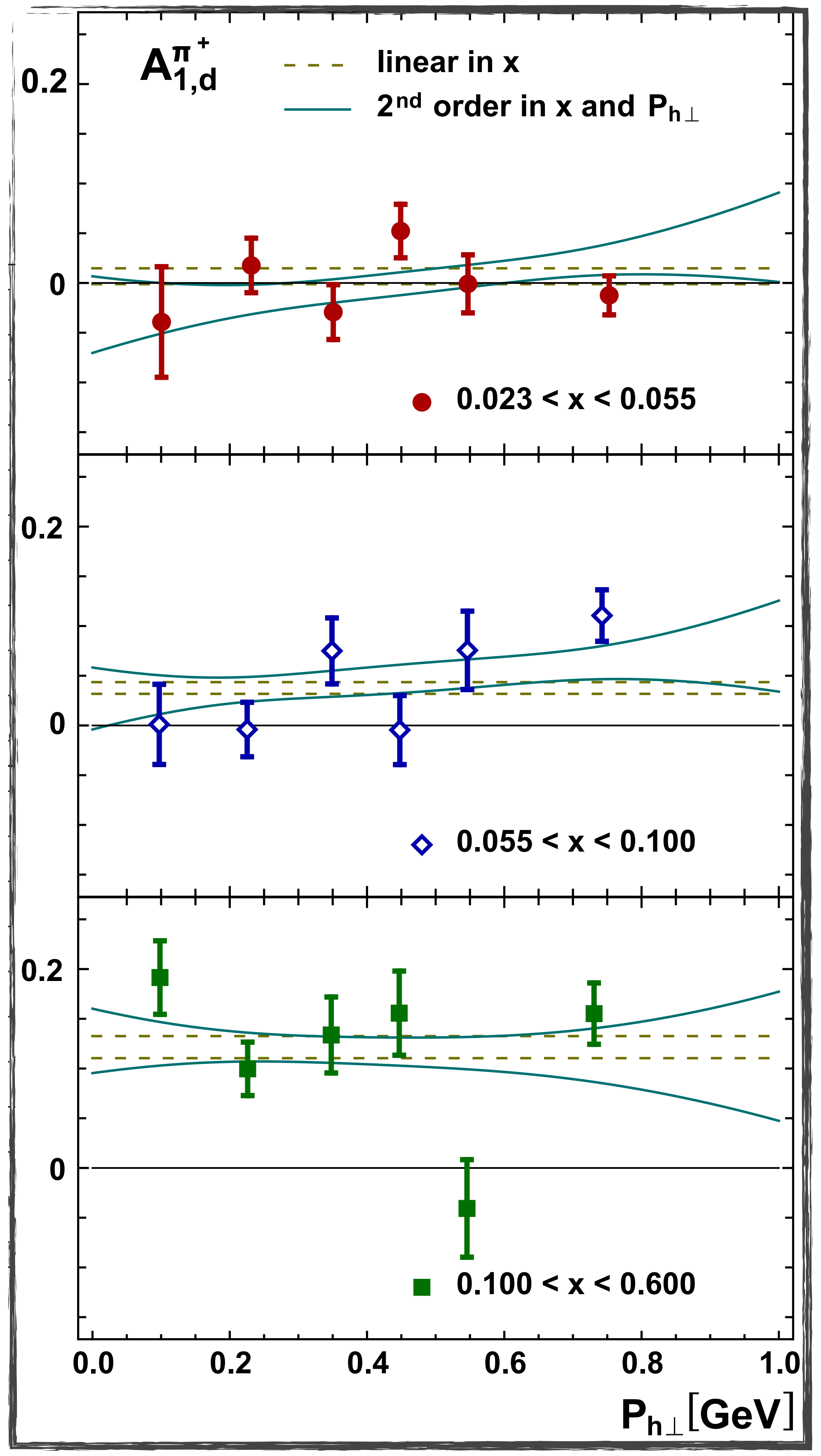
- need to evaluate systematics due to integration over phase space => Monte Carlo



[HERMES, PRD 99 (2019) 112001]

correcting for geometric acceptance

extract acceptance from Monte Carlo simulation?

$$\epsilon(\phi,\Omega) \quad = \quad \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \qquad\qquad \Omega = x, y, z, ..$$

simulated acceptance

simulated cross section

correcting for geometric acceptance

extract acceptance from Monte Carlo simulation?

$$\epsilon(\phi,\Omega) = \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \neq \frac{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)}$$

$$\Omega = x, y, z, \ldots$$

correcting for geometric acceptance

extract acceptance from Monte Carlo simulation?

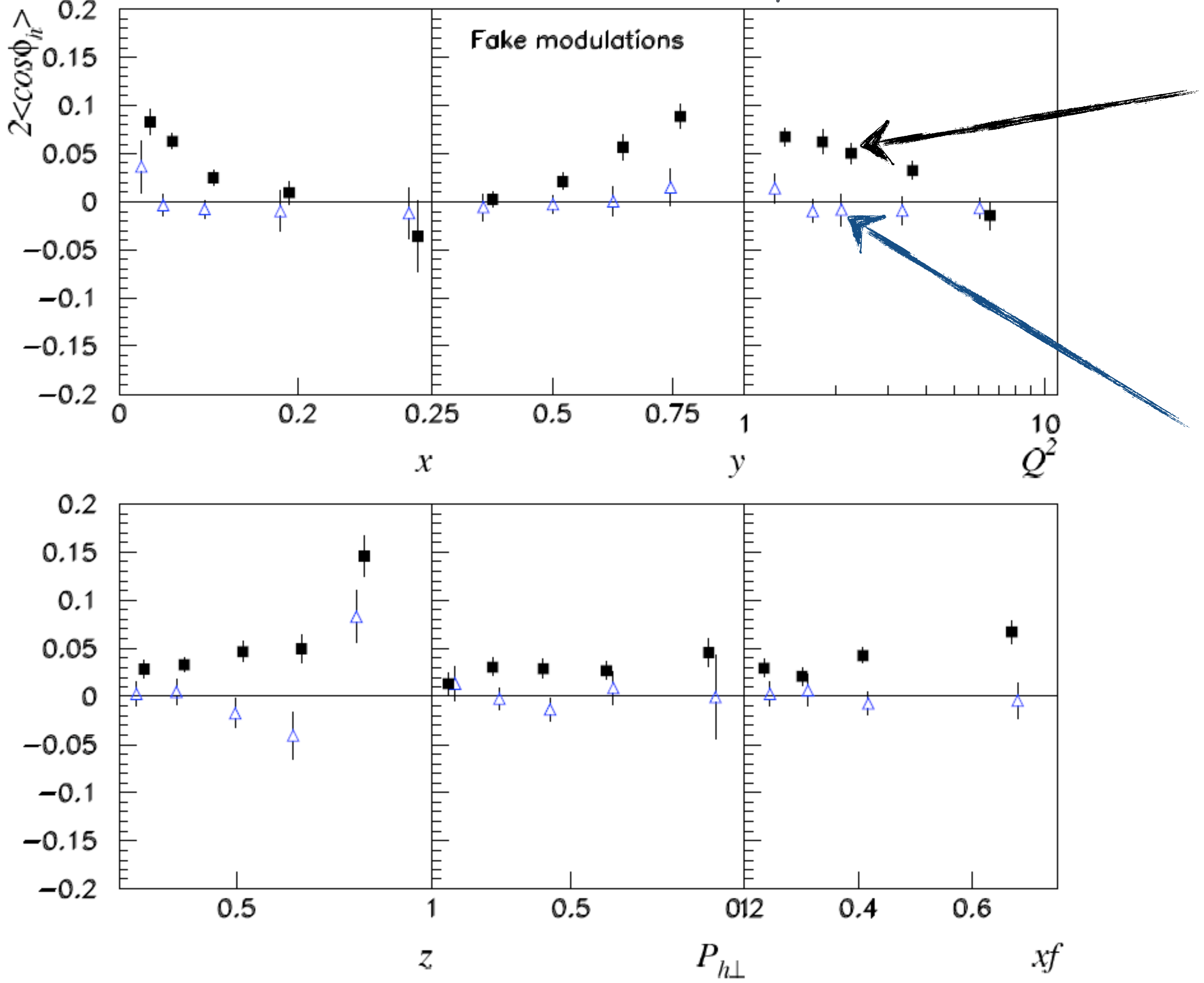
$$\begin{aligned}\epsilon(\phi,\Omega) &= \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \\ &\neq \frac{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\,\sigma_{UU}(\phi,\Omega)} \\ &\neq \int \mathrm{d}\Omega\,\epsilon(\phi,\Omega) \equiv \epsilon(\phi)\end{aligned}$$

$$\Omega = x, y, z, \ldots$$

cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!

“classique” example: $\langle\cos\phi\rangle_{UU}$

[F. Giordano, Transversity 2008, Ferrara]

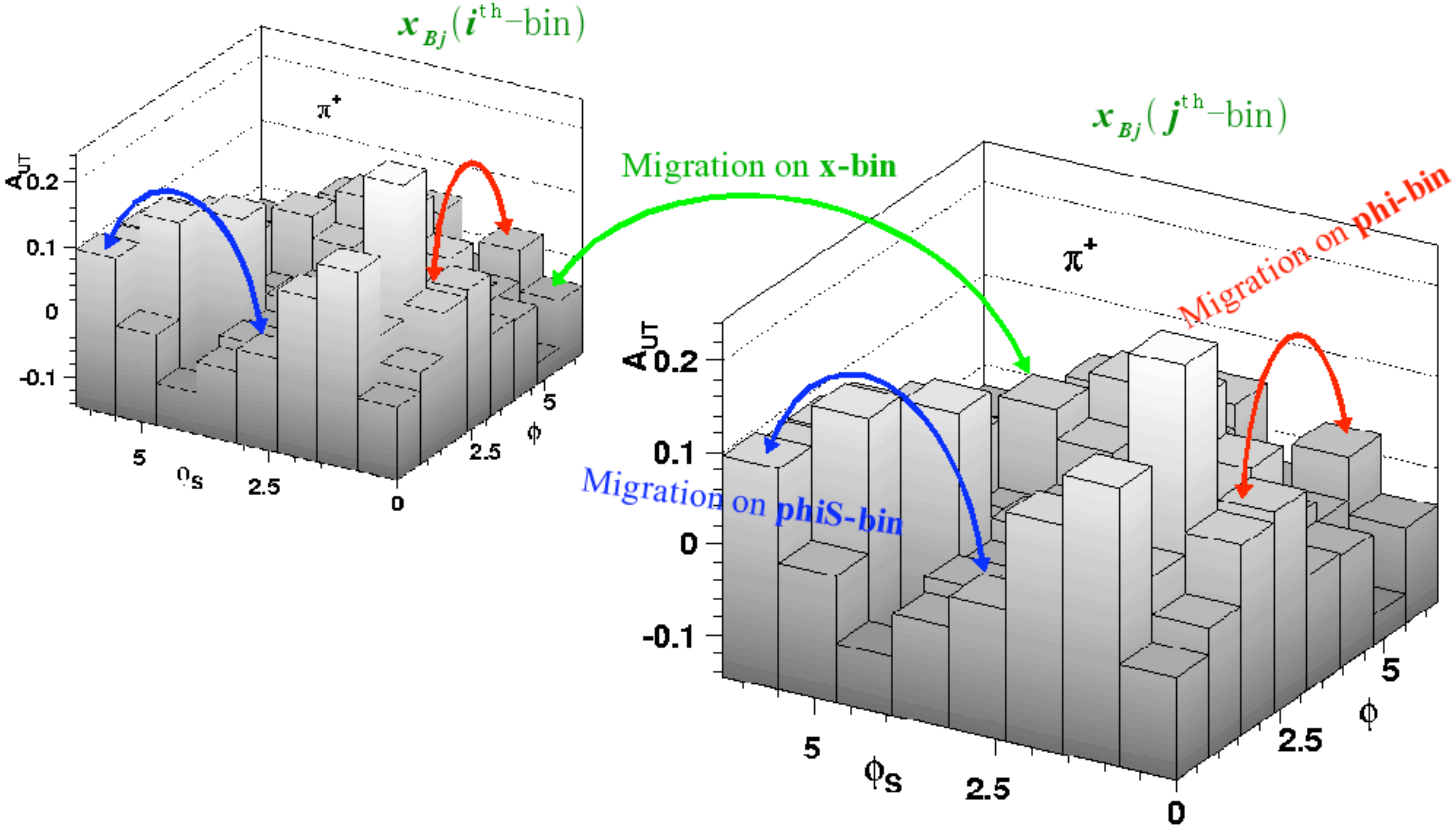


1D correction

(input: MC without azimuthal modulation)

full 5D correction

further complication: event migration

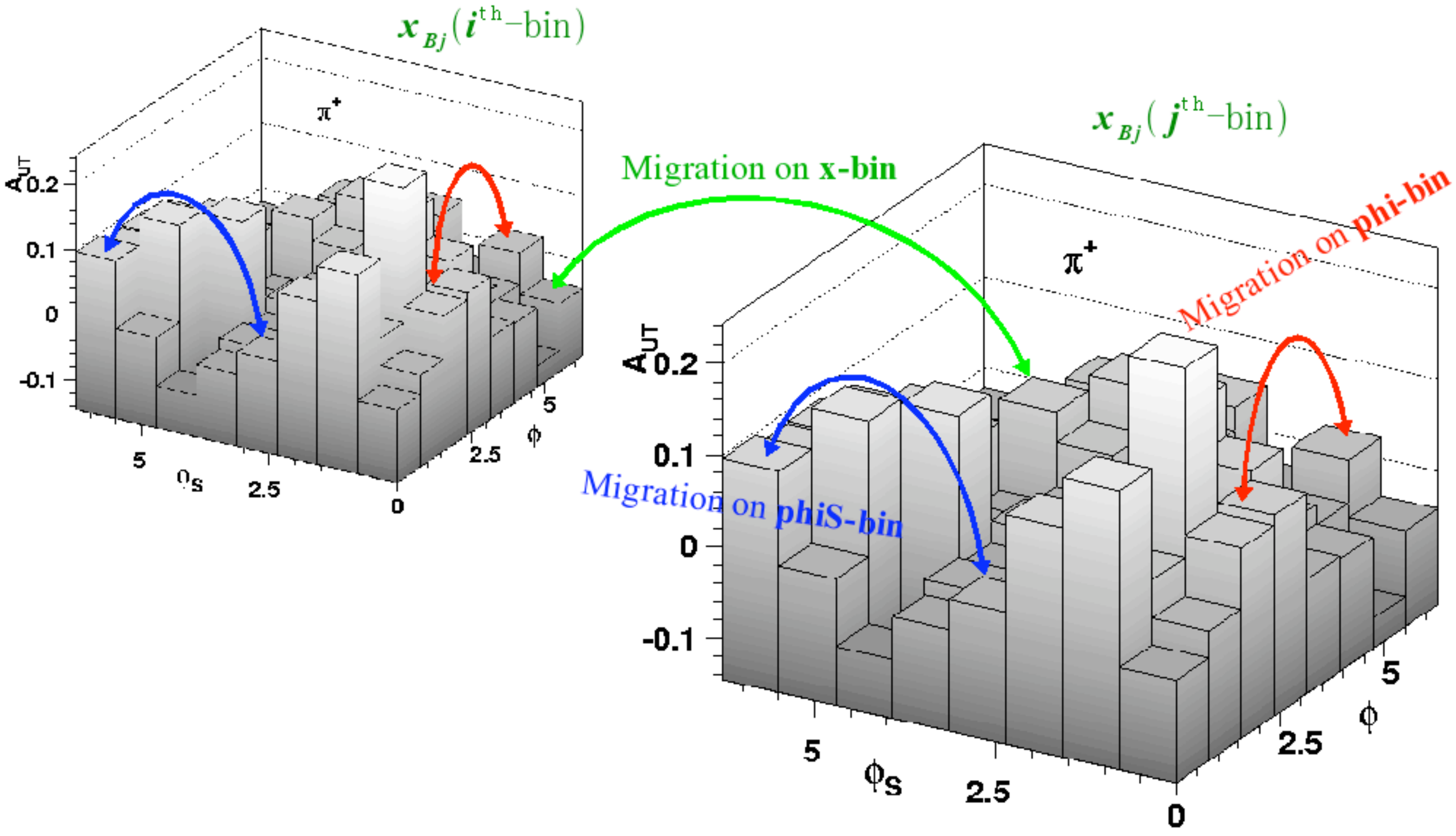


Migration on **x-bin**

Migration on **phi-bin**

Migration on **phiS-bin**

further complication: event migration



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

further complication: event migration -> unfolding

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

- experimental yield in ith bin depends on all Born bins j ...
- ... and on BG entering kinematic range from outside region

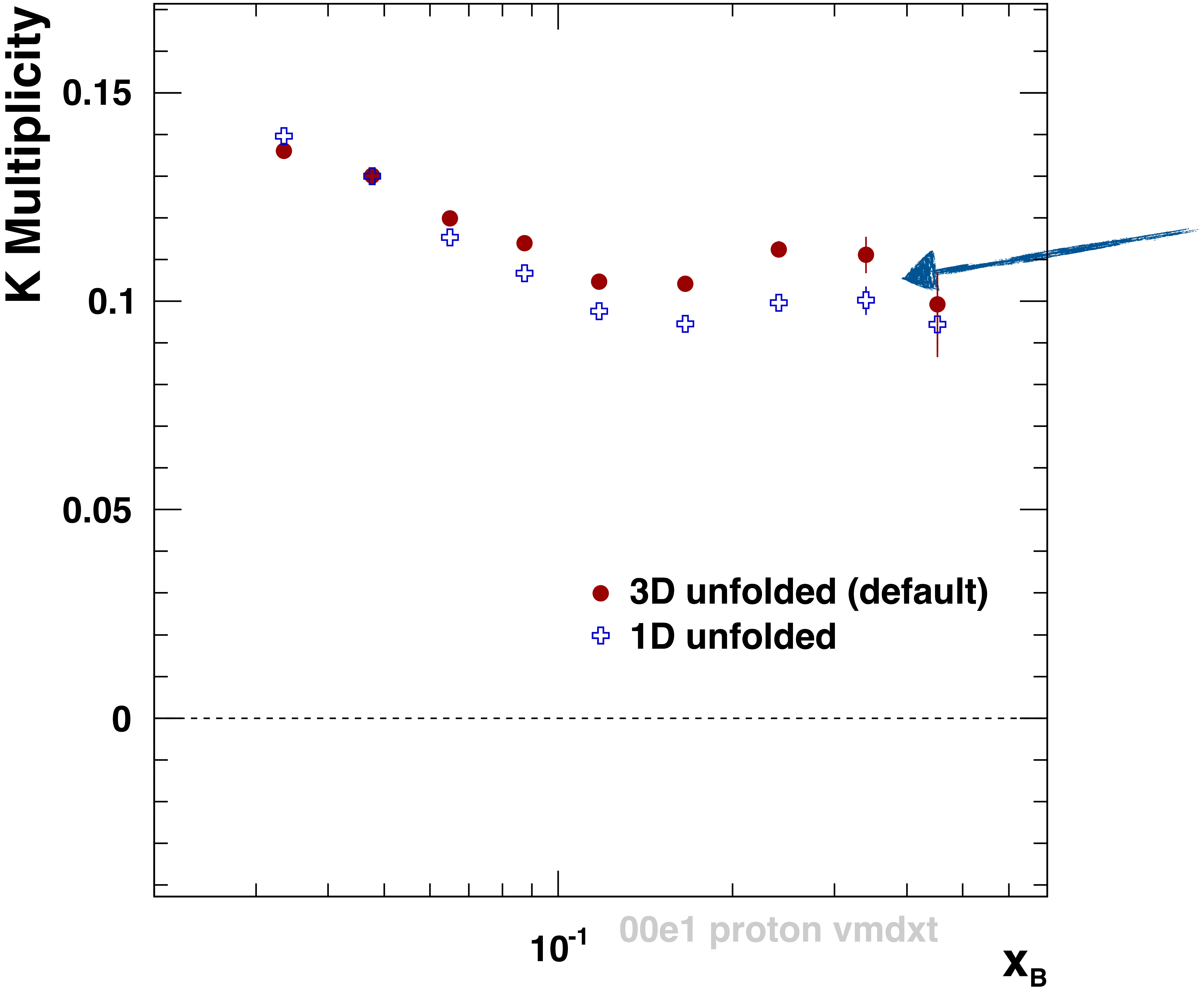
further complication: event migration -> unfolding

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

- experimental yield in ith 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

multi-D vs. 1D unfolding

[S.J. Joosten, PhD thesis UIUC (2013)]



Neglecting to unfold in z changes x dependence dramatically

➡ 1D unfolding clearly insufficient

multi-D vs. 1D unfolding

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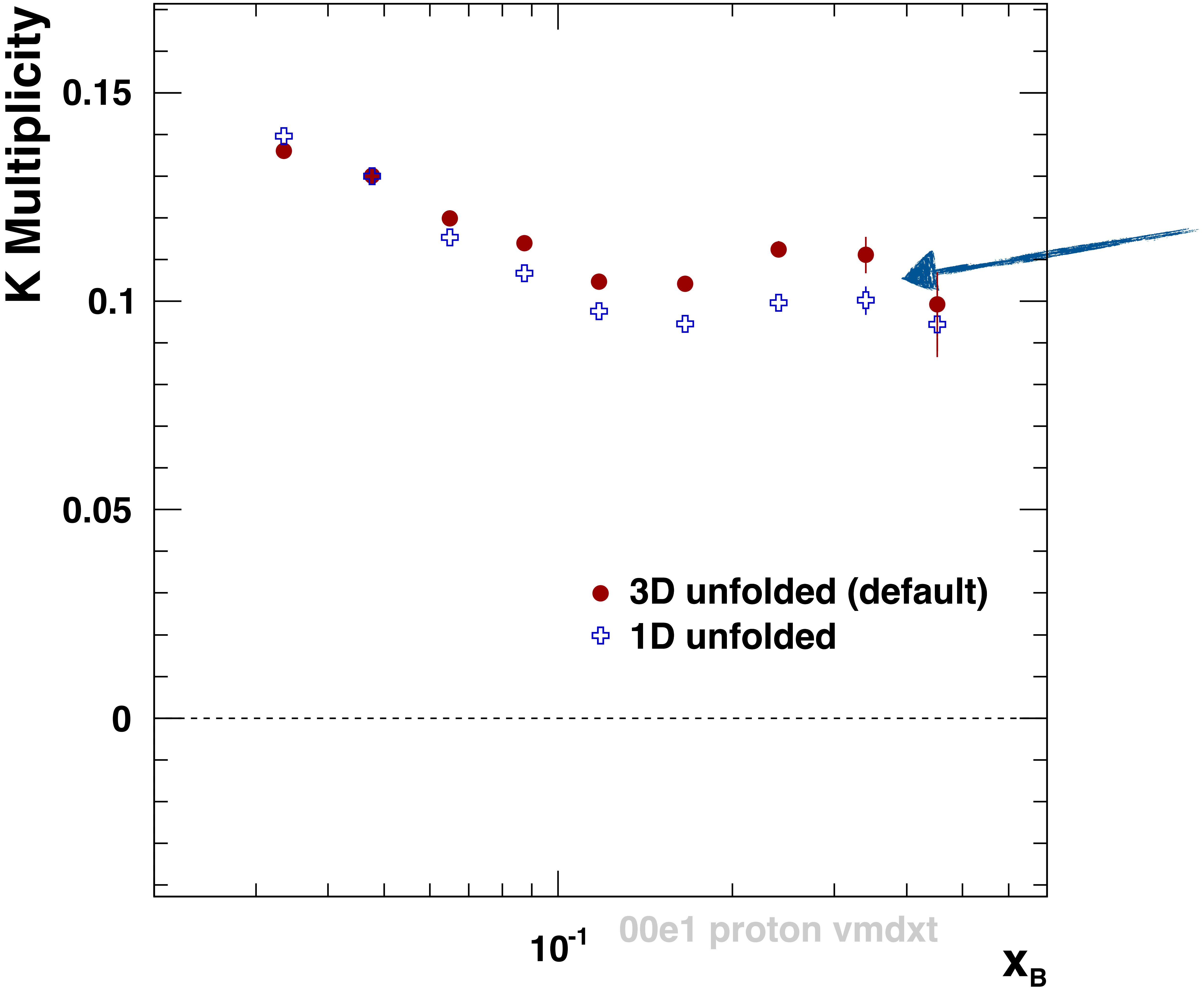
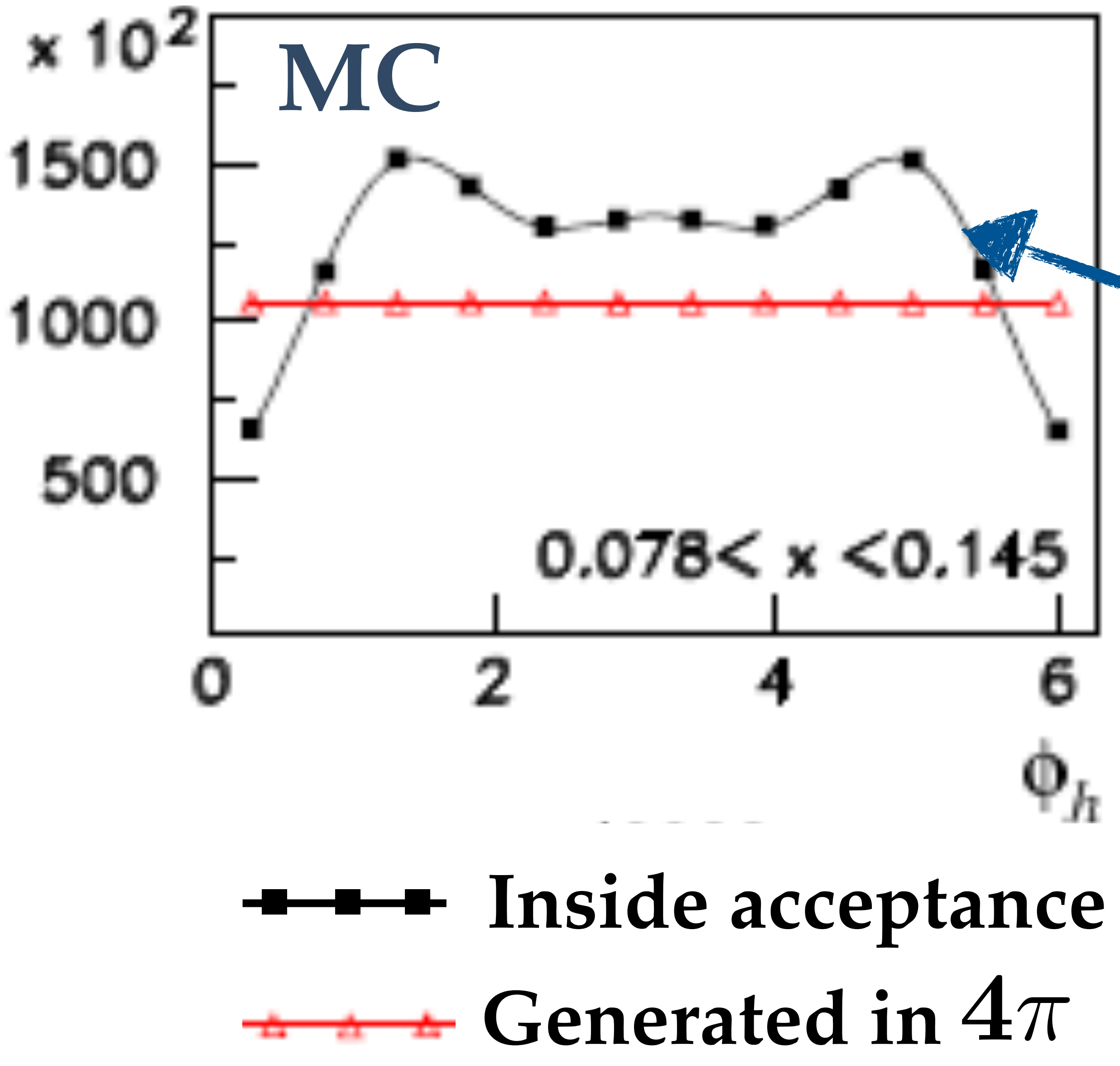


Neglecting to unfold in z changes x dependence dramatically

➡ 1D unfolding clearly insufficient

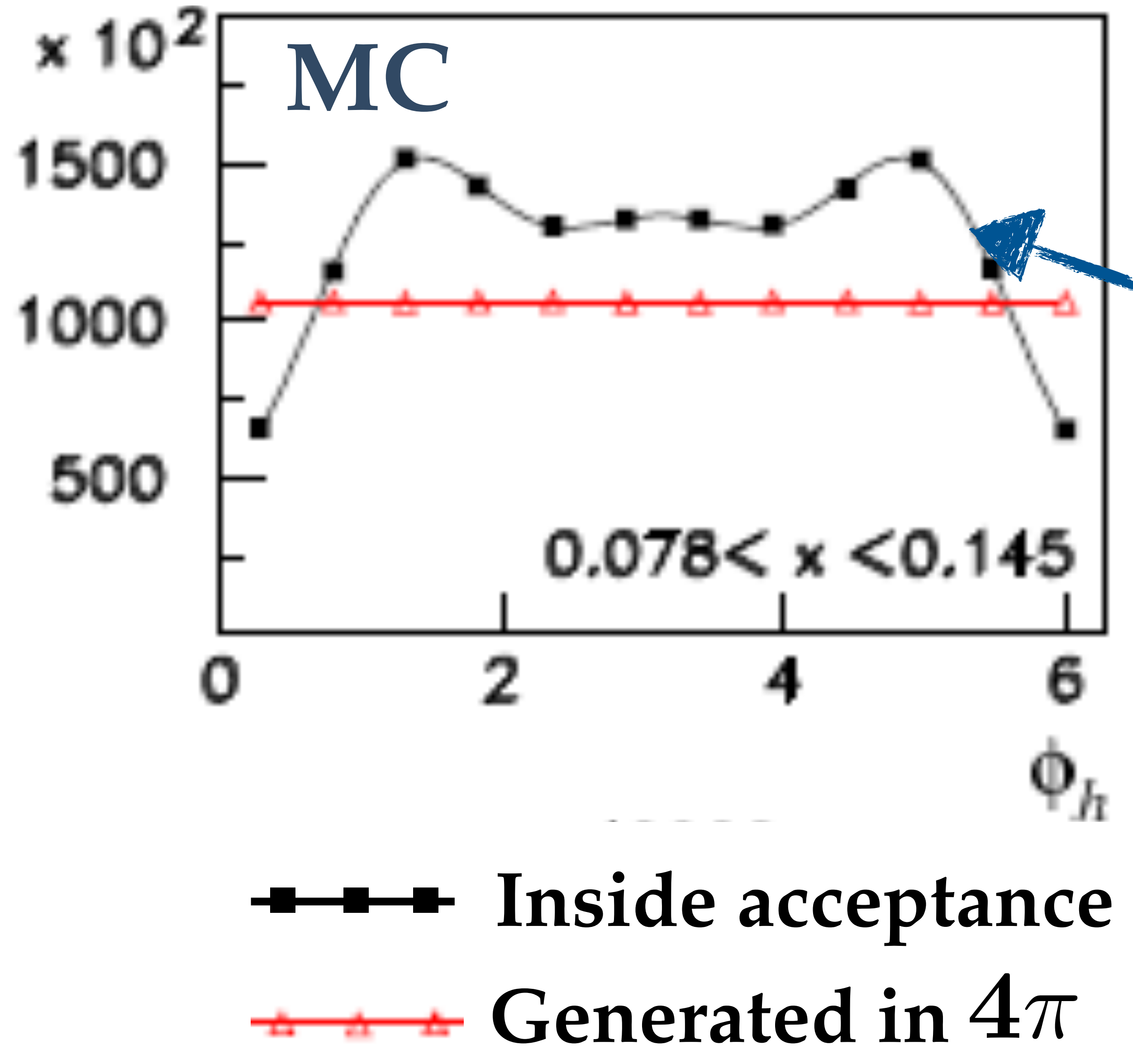
even though only interested in collinear observable, need to carefully consider all, e.g., also transverse, d.o.f.

multi-D vs. 1D unfolding



fully simulated yield with clear cosine modulations from migration and acceptance

multi-D vs. 1D unfolding



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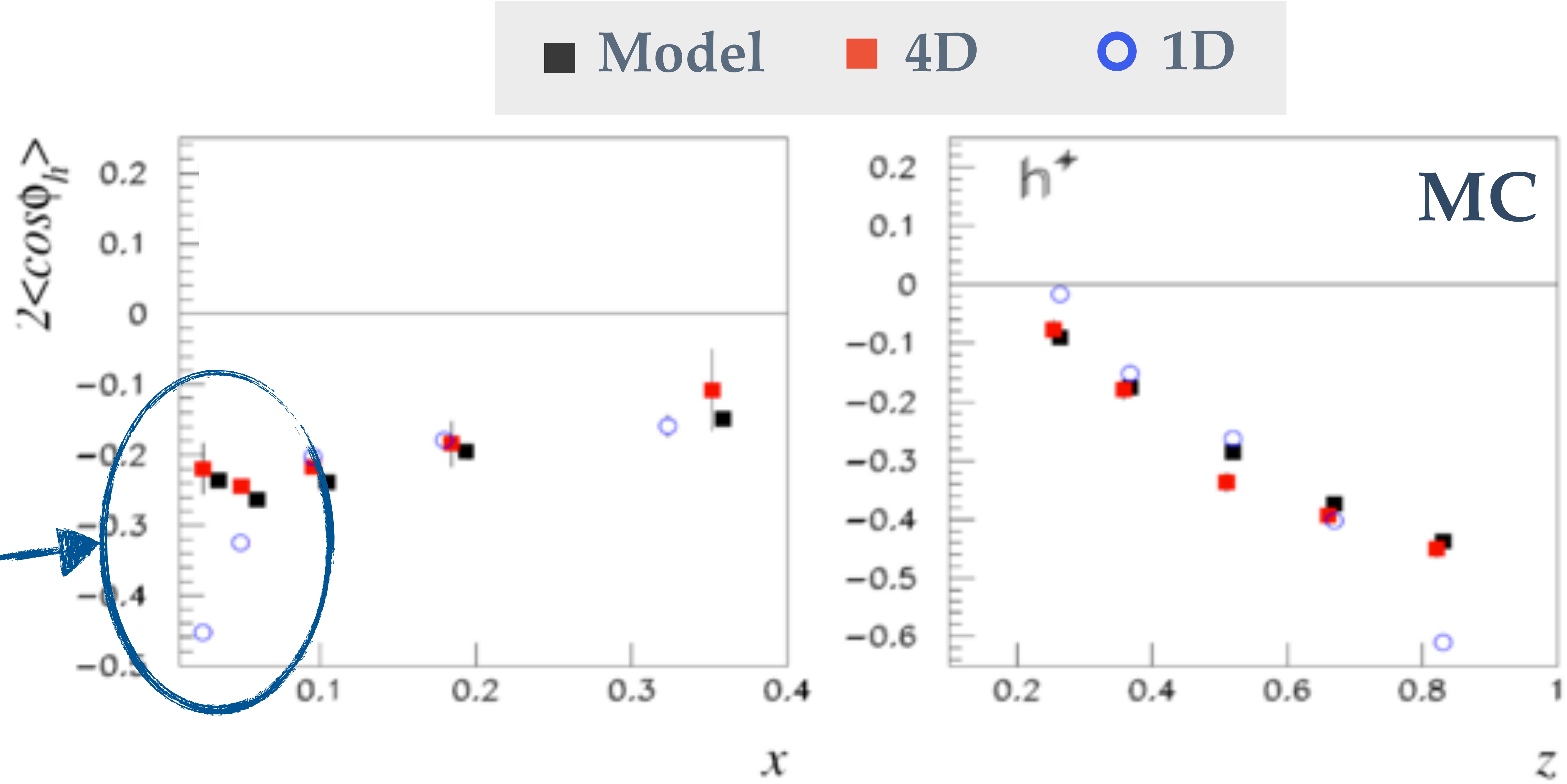
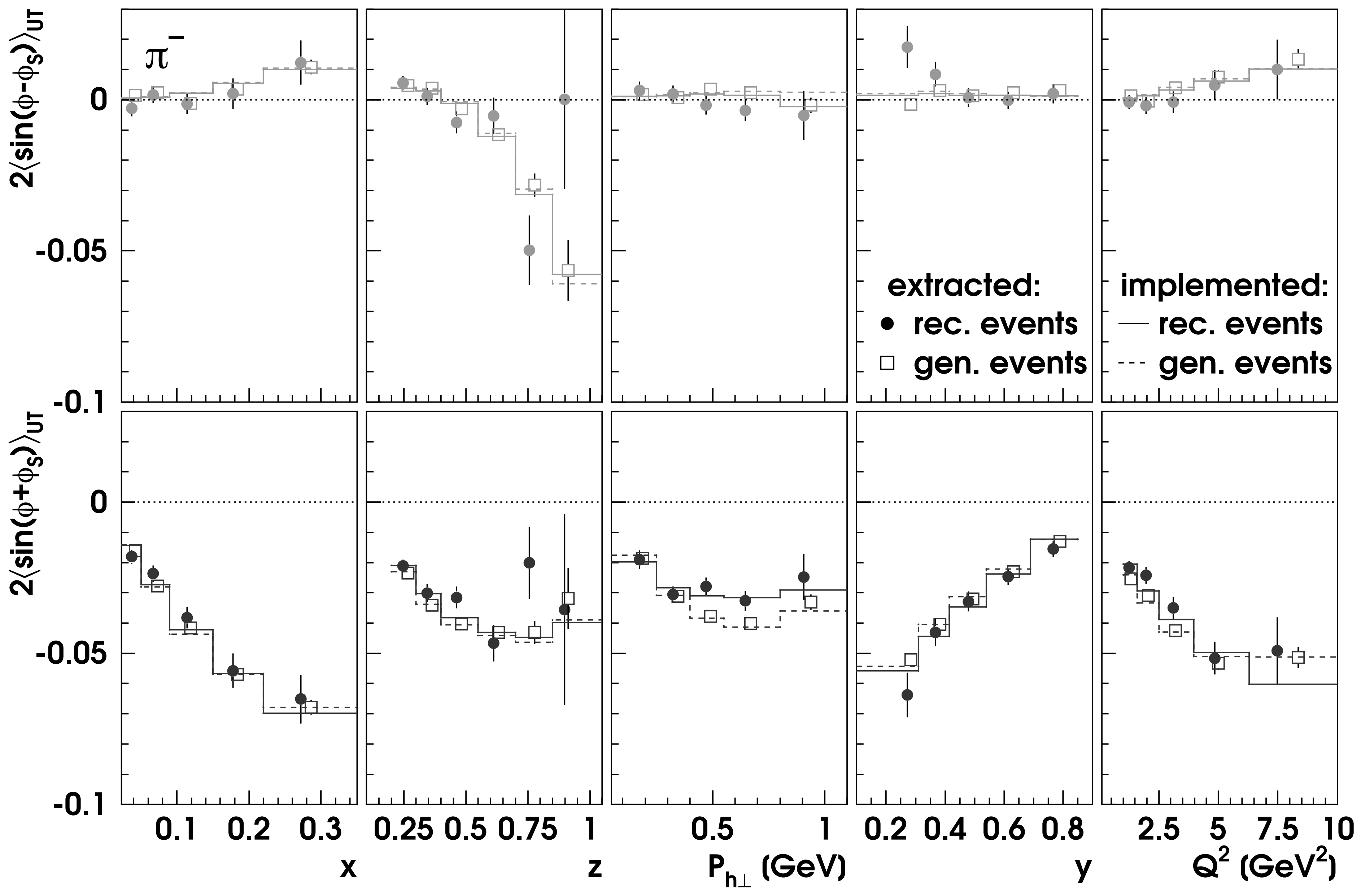


1D clearly not sufficient

Monte Carlo simulation for TMD analyses

- early Collins and Sivers analyses used dedicated TMD single-hadron MC: gmcTRANS based on Gaussian Ansatz
  - fully analytic, but no full-blown “event generator”



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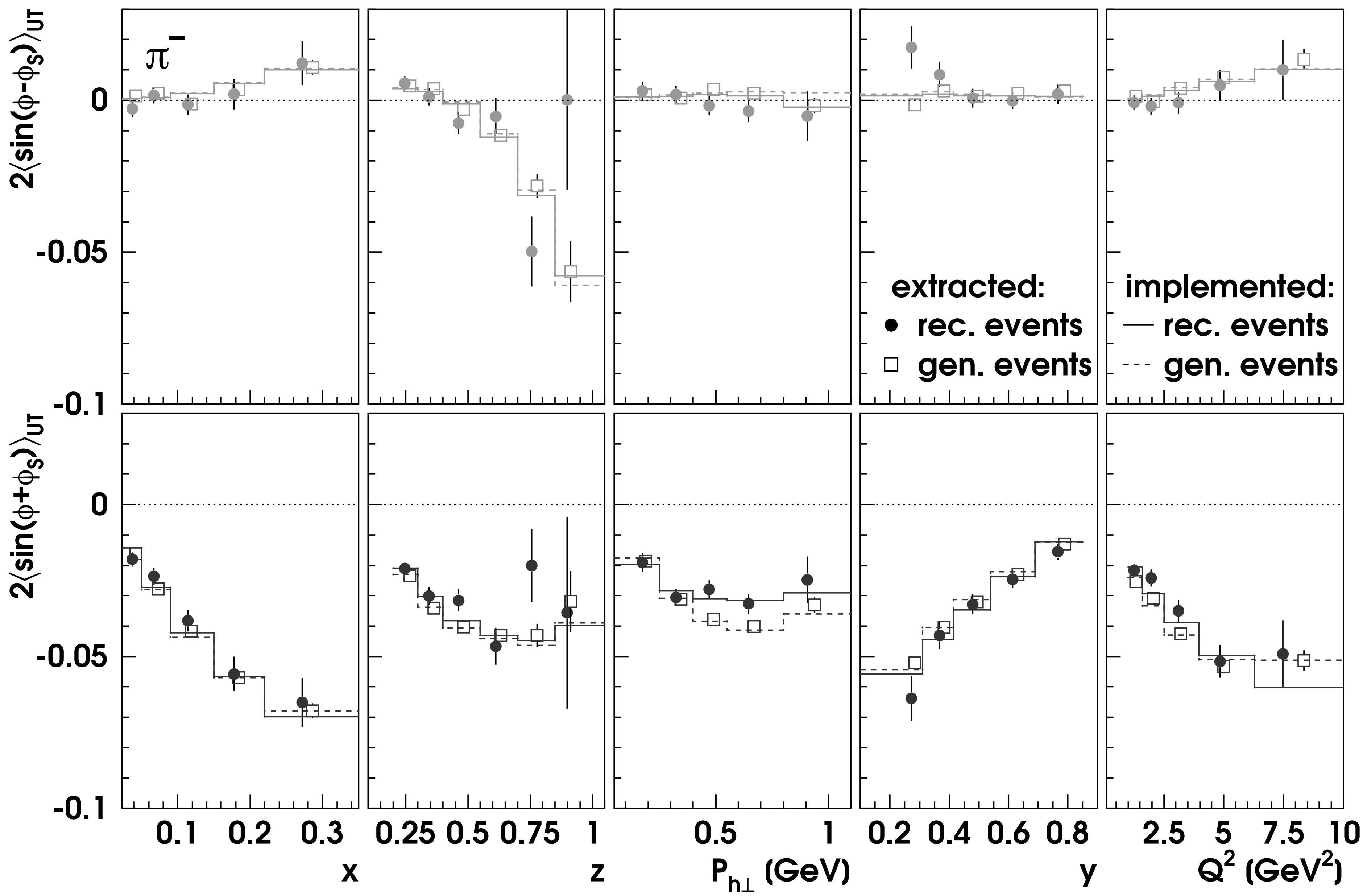
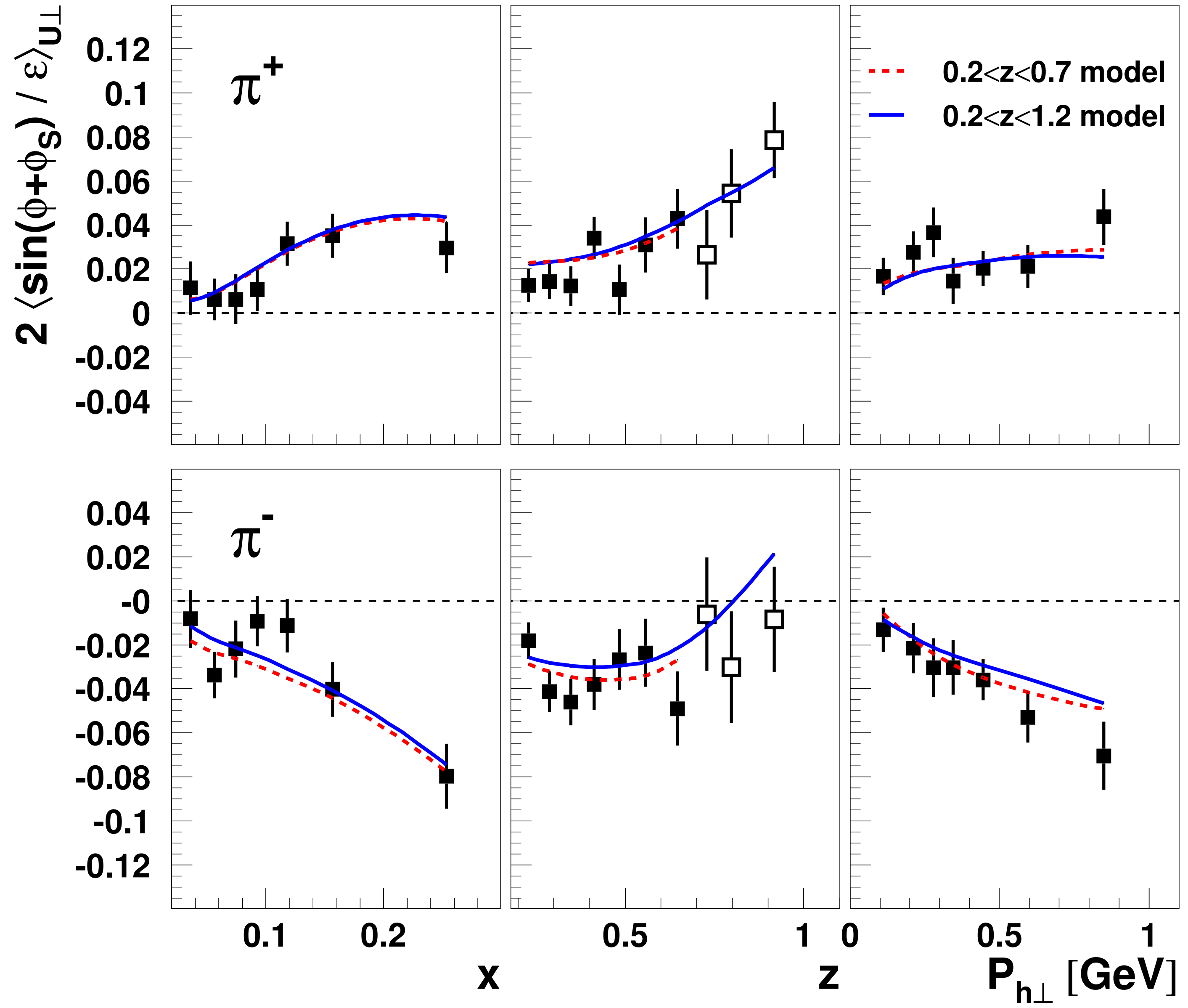
$$\rho < \frac{1}{2}\left[1 + \mathcal{A}_{\mathrm{U}\perp}^{\sin(\phi-\phi_S)}(\Omega^i)\sin(\phi^i-\phi_S^i)\right] \quad \Rightarrow \quad \mathcal{P} = +1$$

$$\rho > \frac{1}{2}\left[1 + \mathcal{A}_{\mathrm{U}\perp}^{\sin(\phi-\phi_S)}(\Omega^i)\sin(\phi^i-\phi_S^i)\right] \quad \Rightarrow \quad \mathcal{P} = -1$$

throwing a random variable $0<\rho<1$

  - model: fully differential Taylor series fit to HERMES data





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throwing a random variable 0<ρ<1

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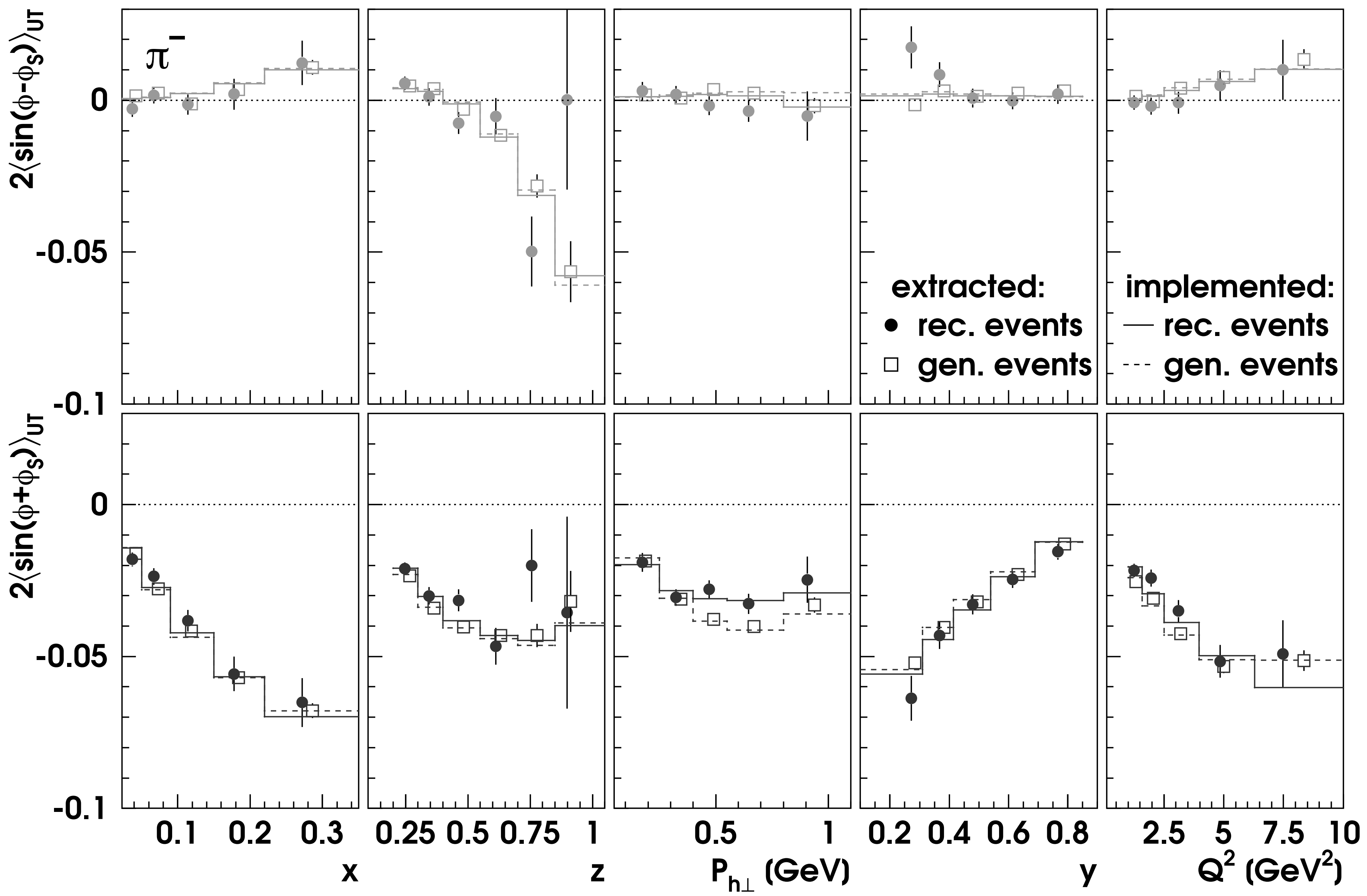
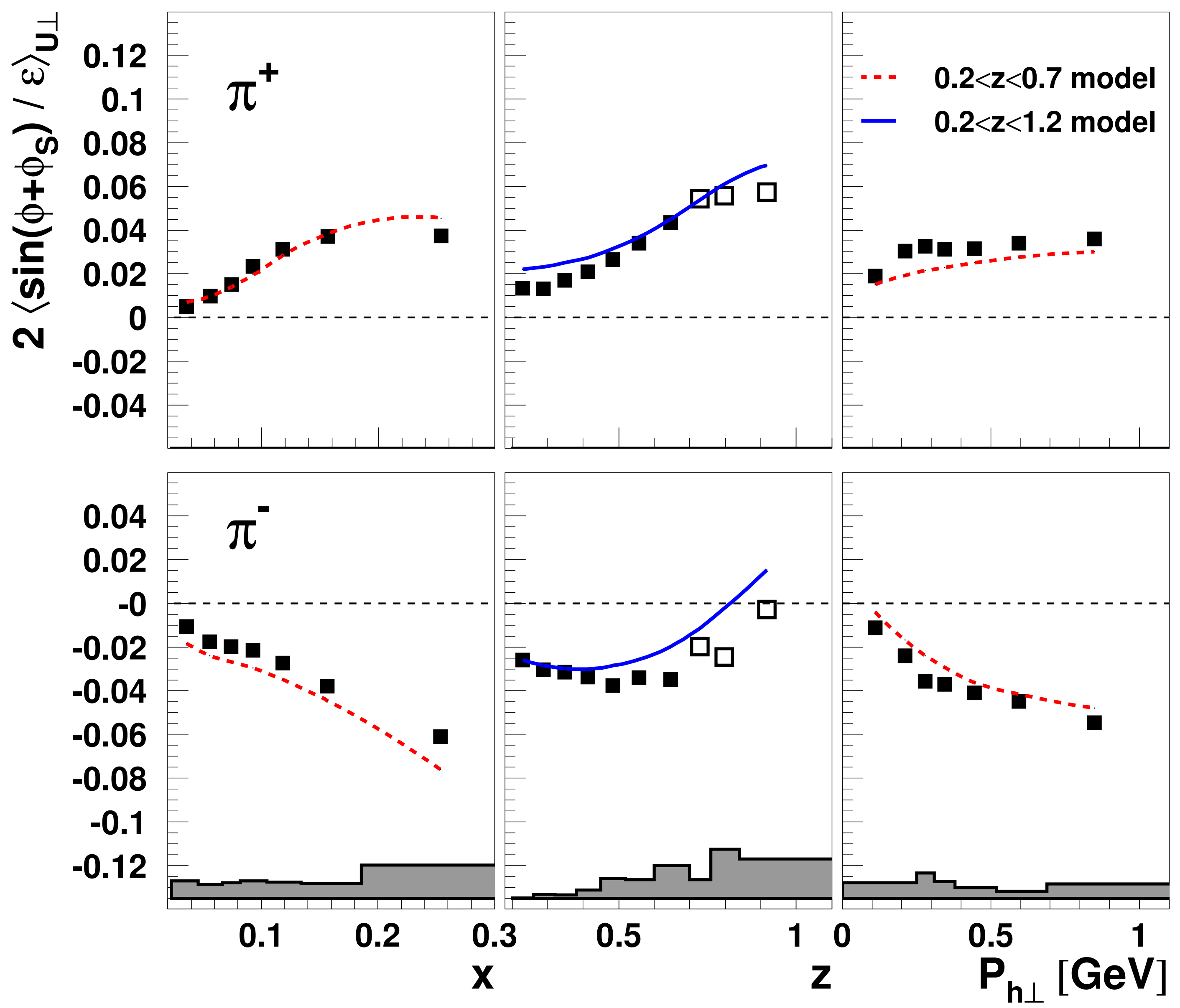
- systematics: extracted asymmetry vs. asymmetry model evaluated at average kinematics





Monte Carlo simulation for TMD an s

for EIC: need reliable MC simulations with realistic physics models!

- early Collins and Sivers analyses used dedicated TMD single-hadron MC: gmcTRANS based on Gaussian Ansatz
  - fully analytic, but no full-blown "event generator"
- adopted "polarizing" procedure for PYTHIA, introducing spin states according to model for s dependent cross section:

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throwing a random 1

  - model: f ial Taylor series fit to HE
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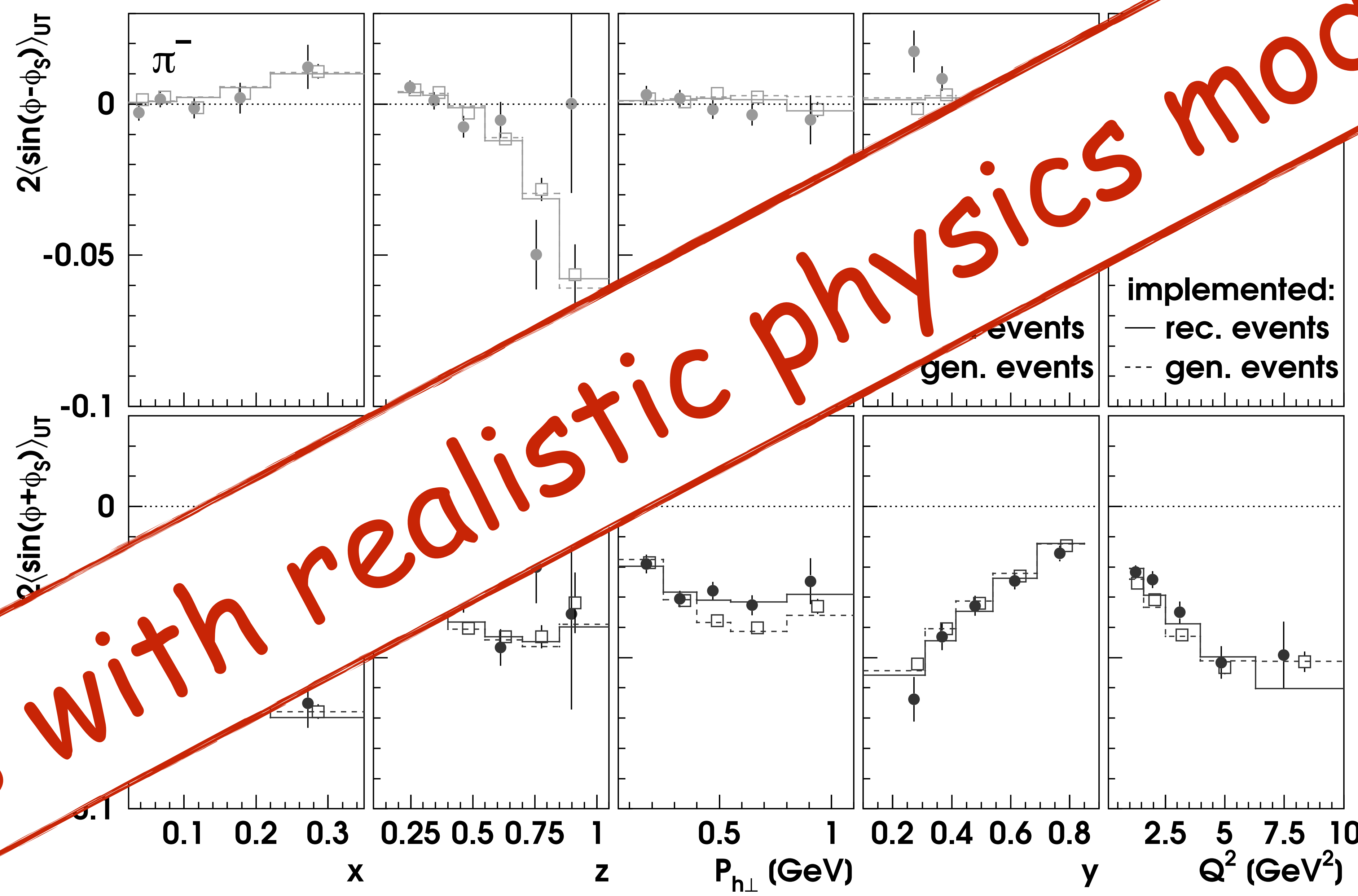
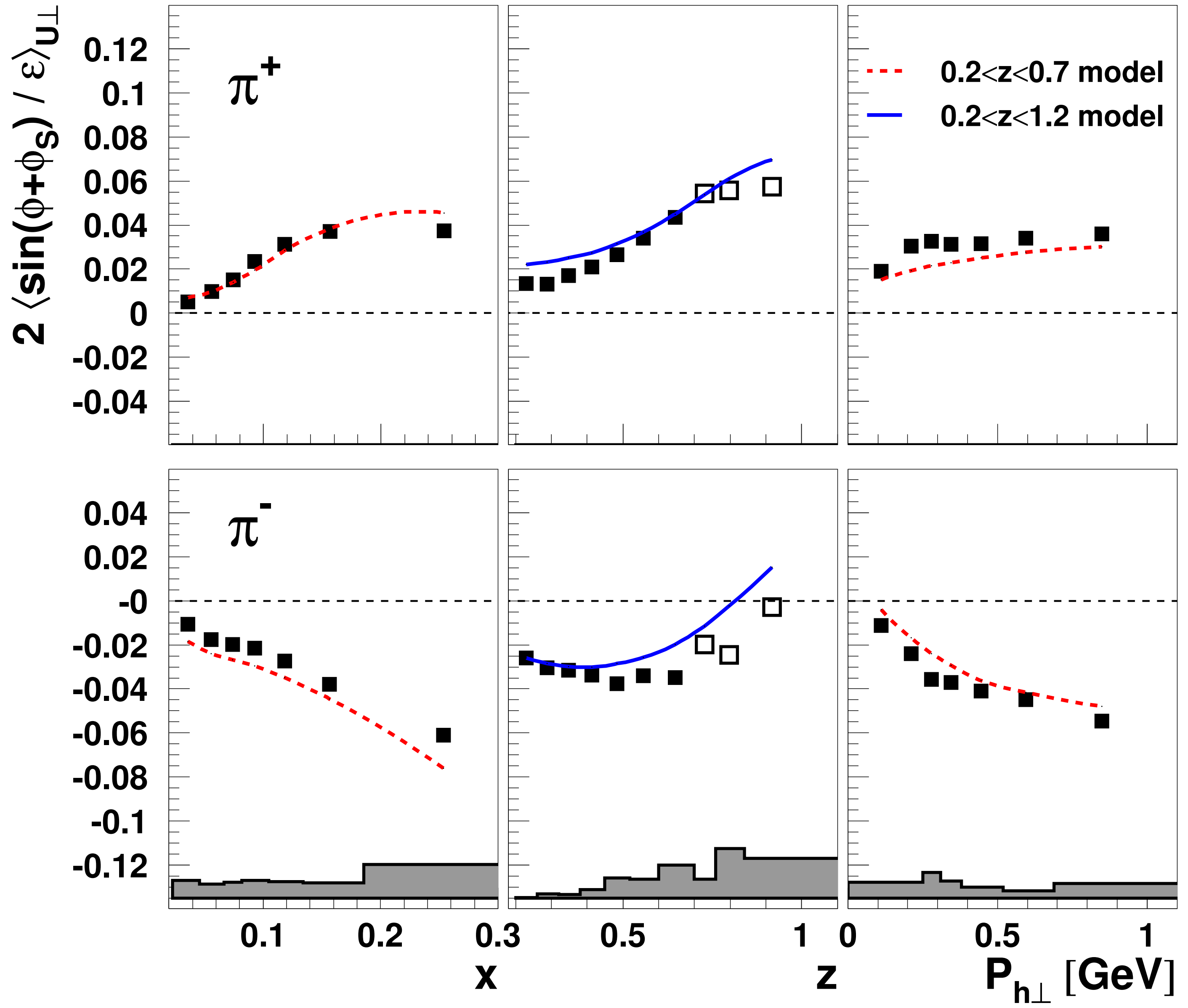


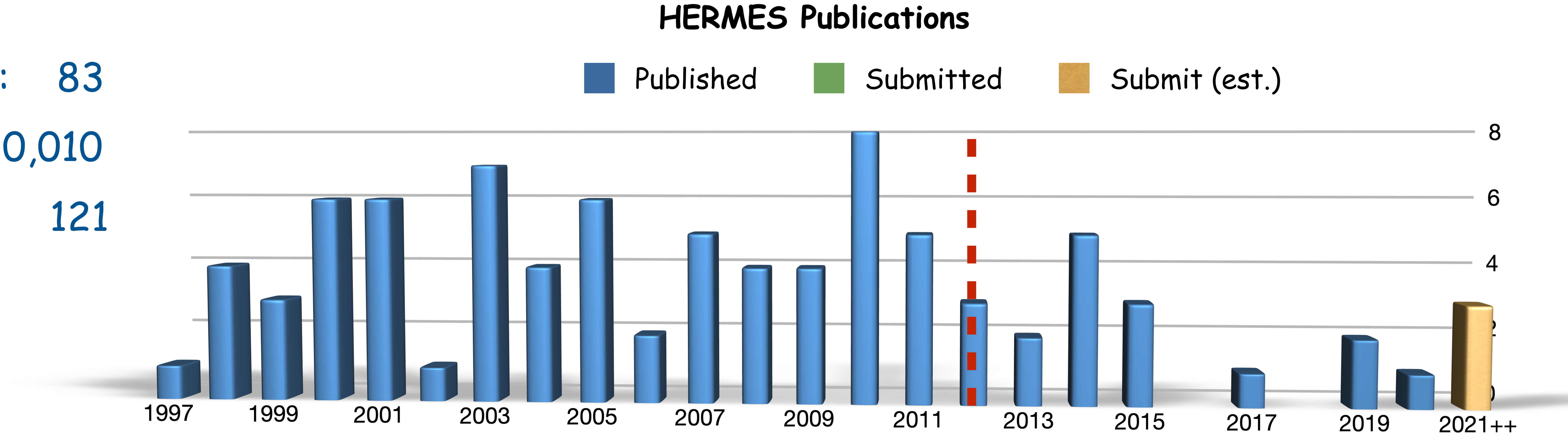


achievements & future opportunities

HERMES publication statistics (March 2022)

- Total number of published HERMES papers: 83
  - Total number of citations: 10,010
  - Average citations per paper: 121
  - **2 top-cite 500+** & 9 topcite 250+

  [inspirehep.net as of March. 29, 2022]



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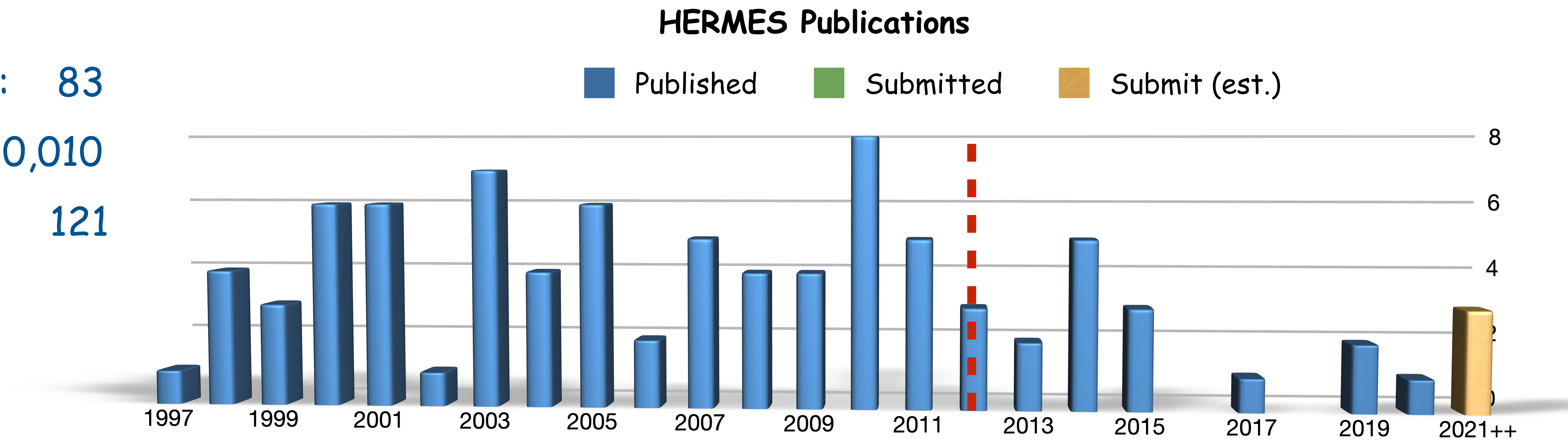
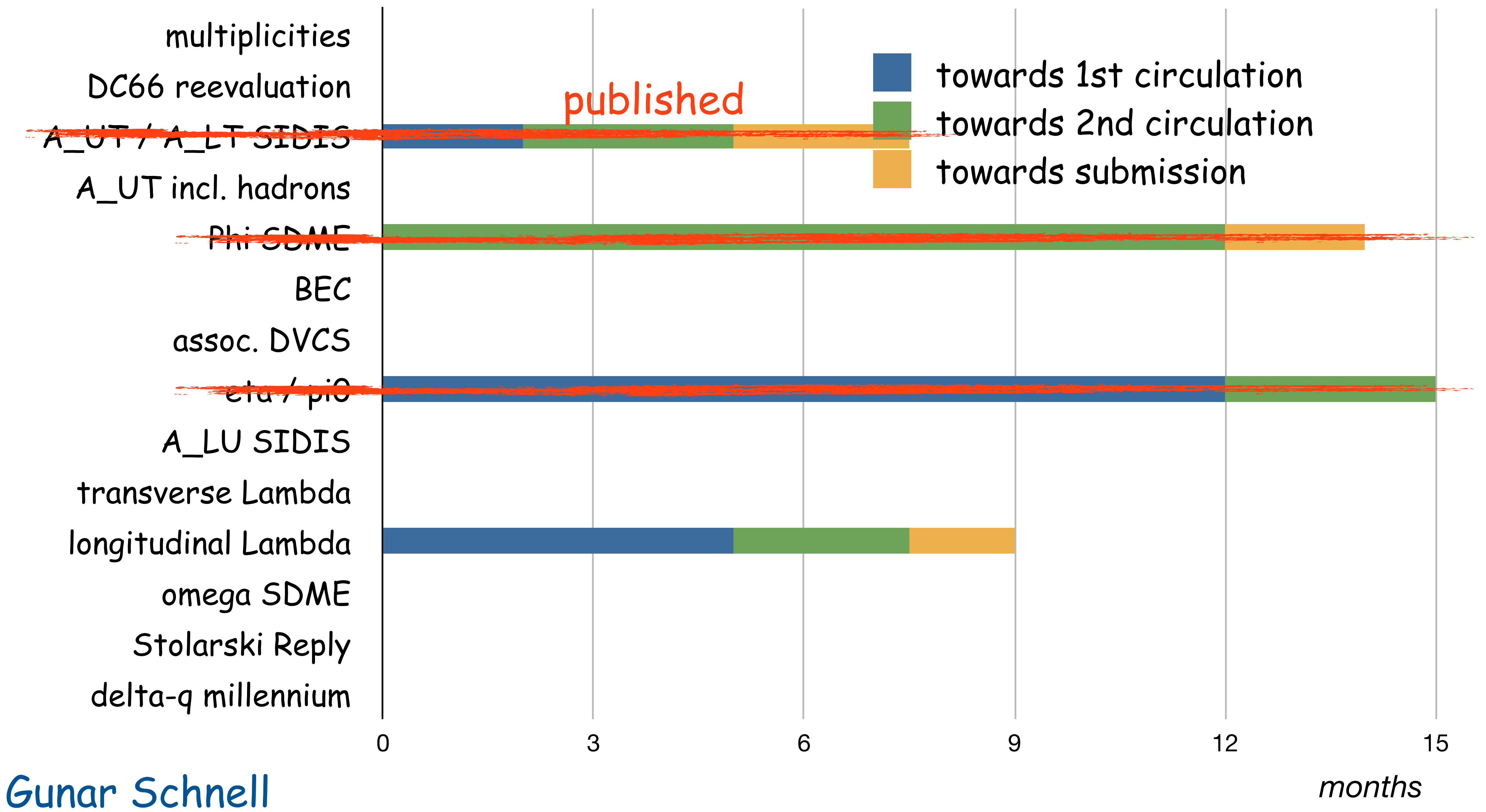
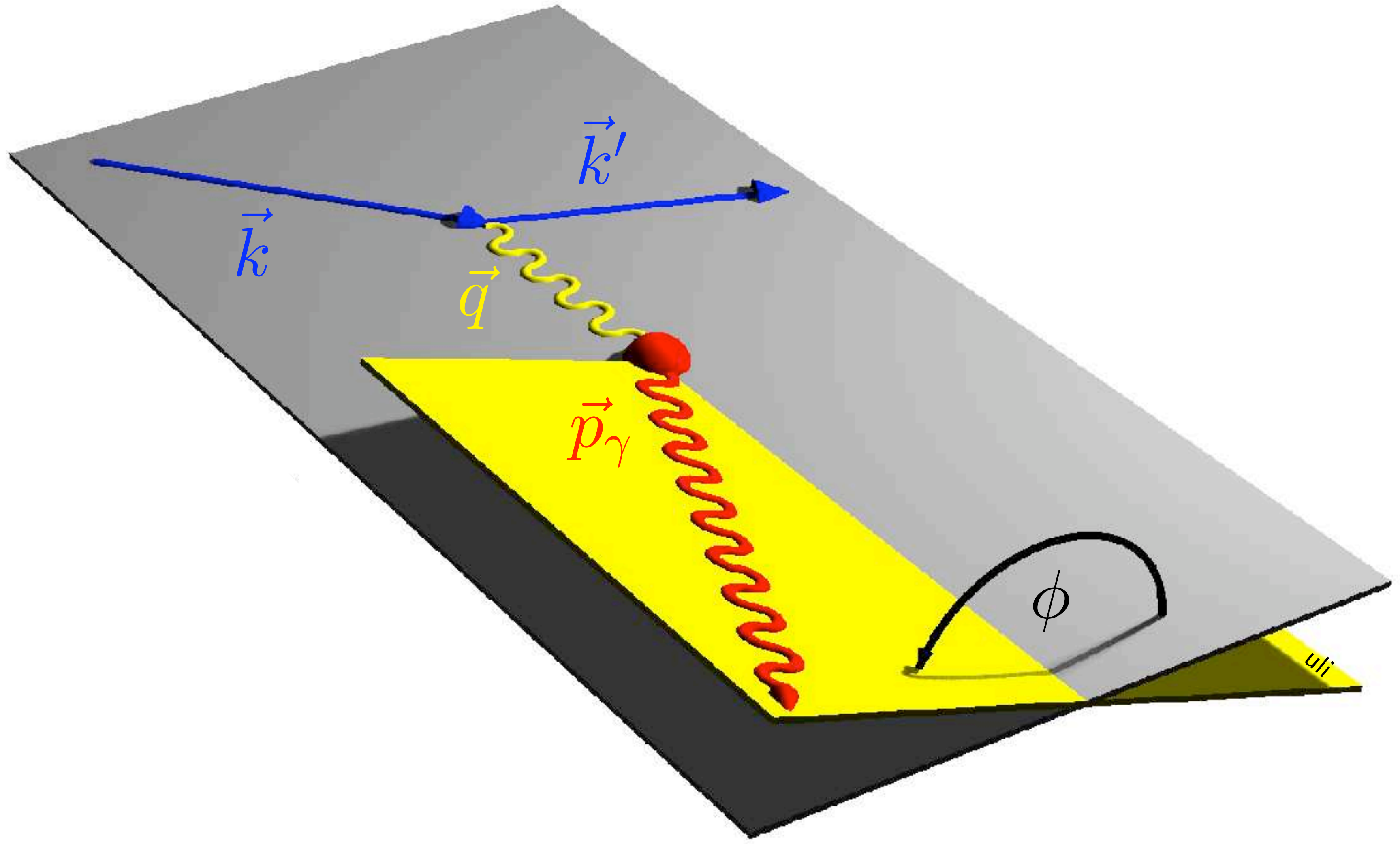


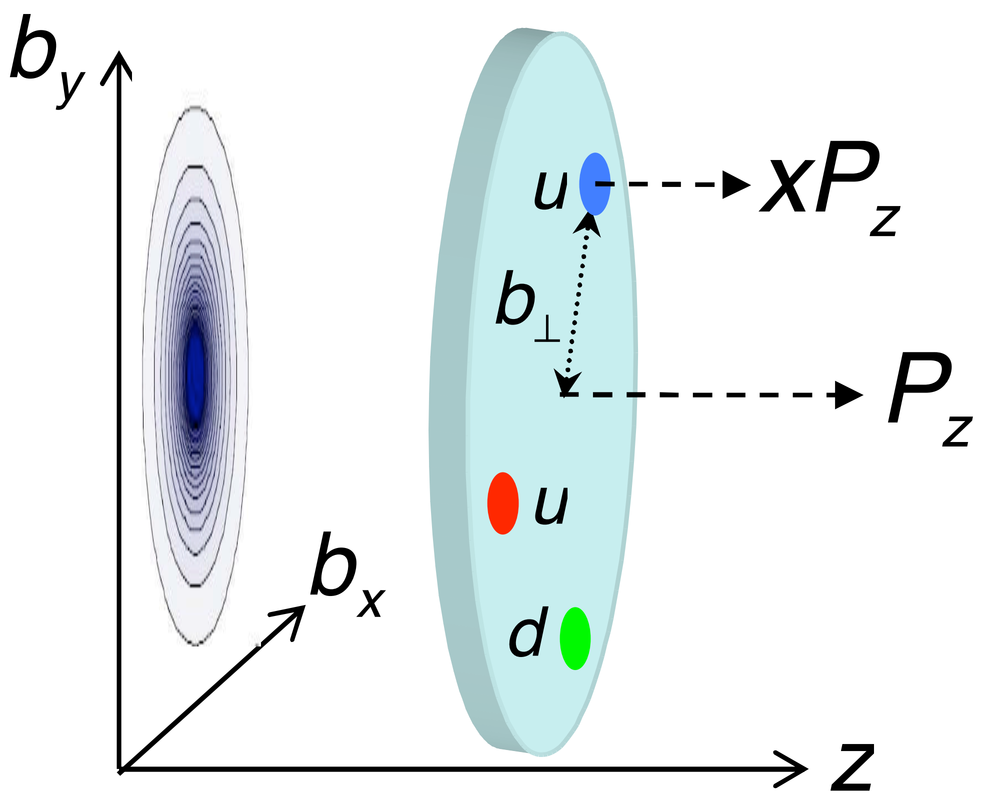
Publication schedule for **2012 priority** analysis (March 2022)

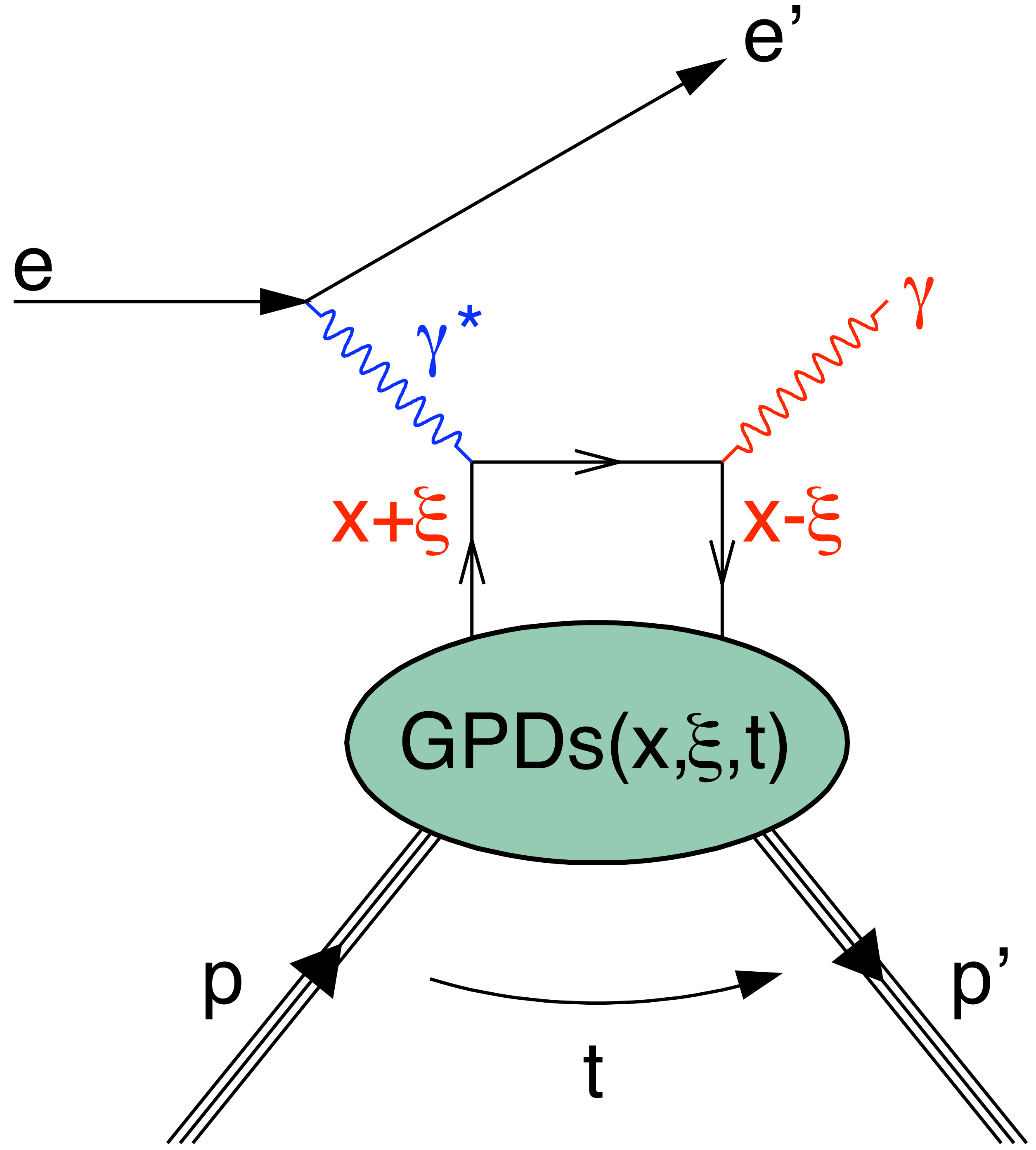


- despite tremendous drop in analysis manpower, almost all priority analyses identified finished
  - two analyses dropped
  - one still ongoing in advanced state
- at same time **new ideas**; partially already published, others **waiting for manpower** ...

DVCS







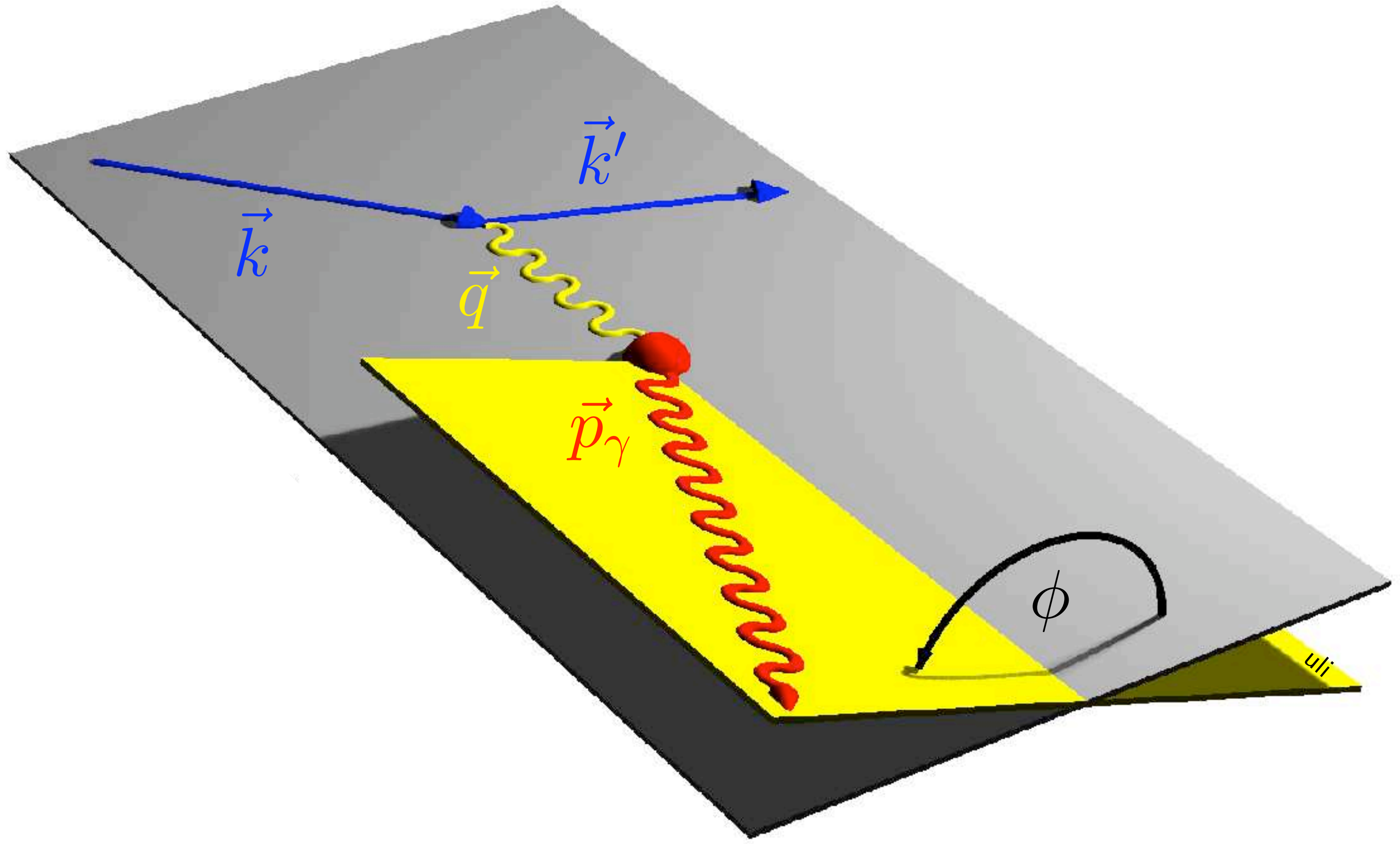
- beam polarization P_B
- beam charge C_B
- here: unpolarized target (many more modulations for polarized targets)

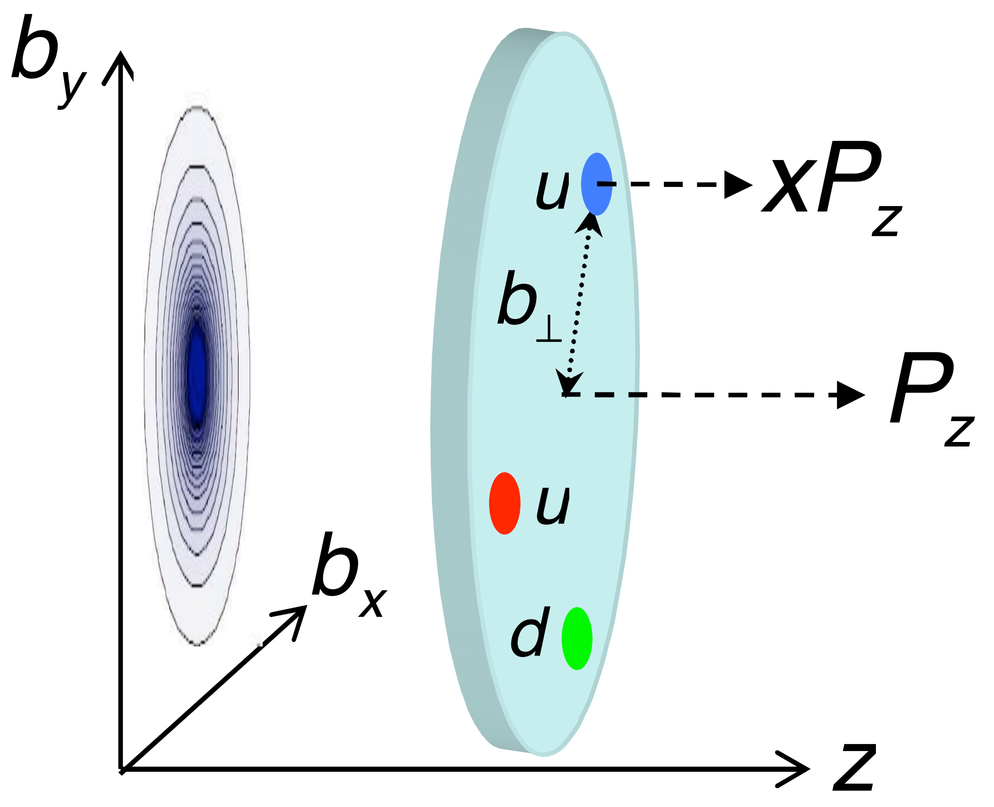
Fourier expansion for ϕ:

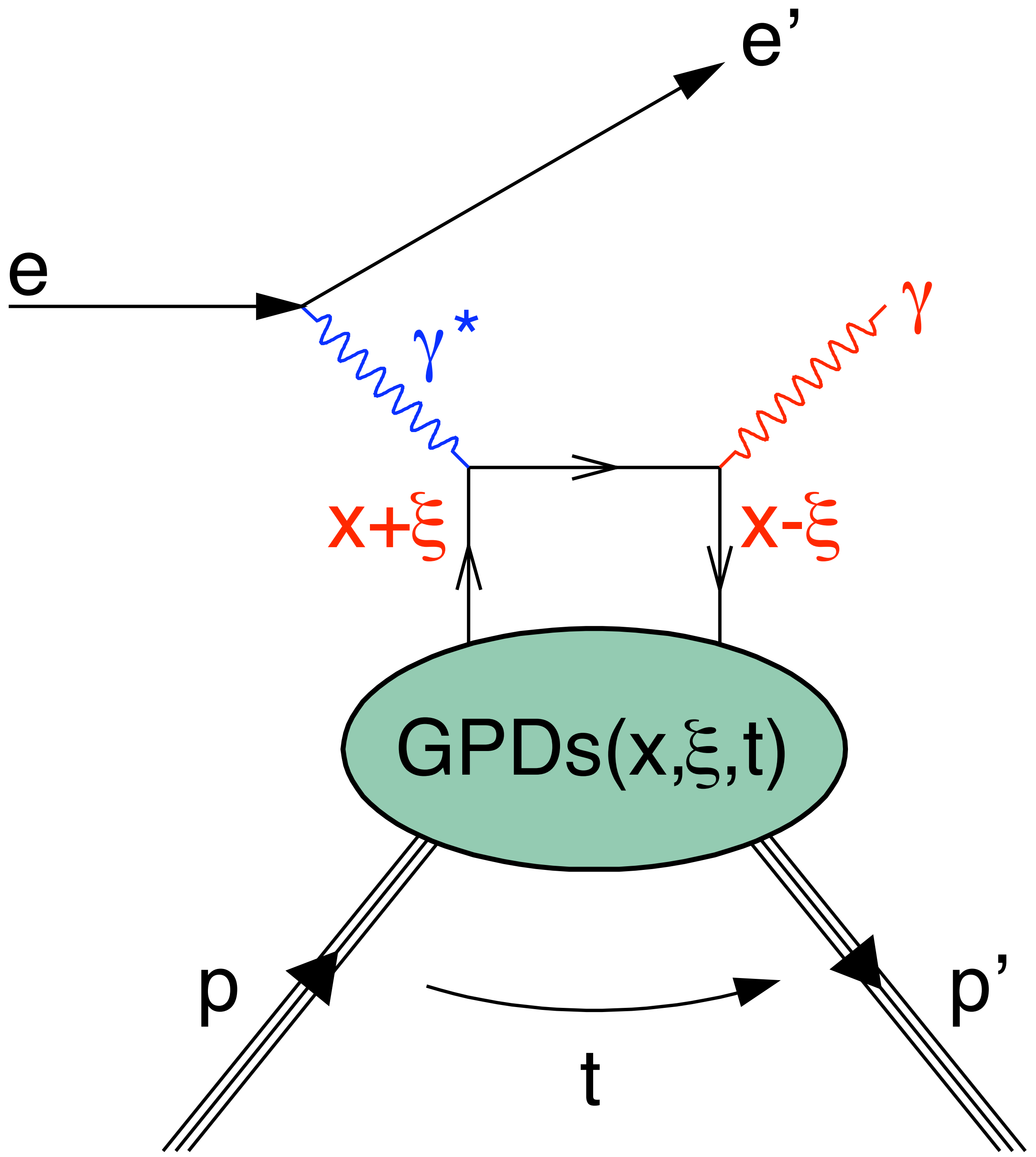
$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

calculable in QED
(using form-factor measurements)

DVCS







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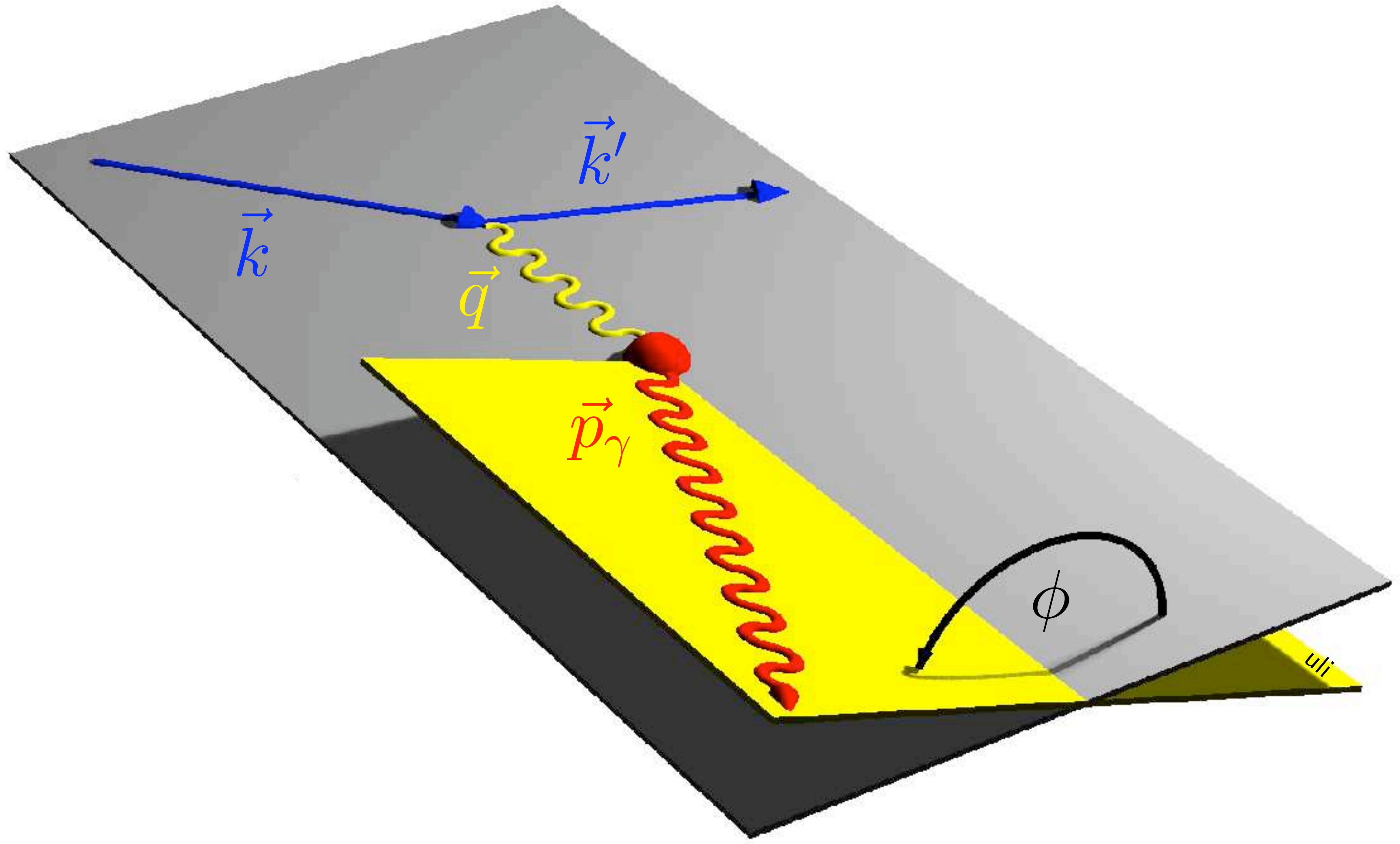
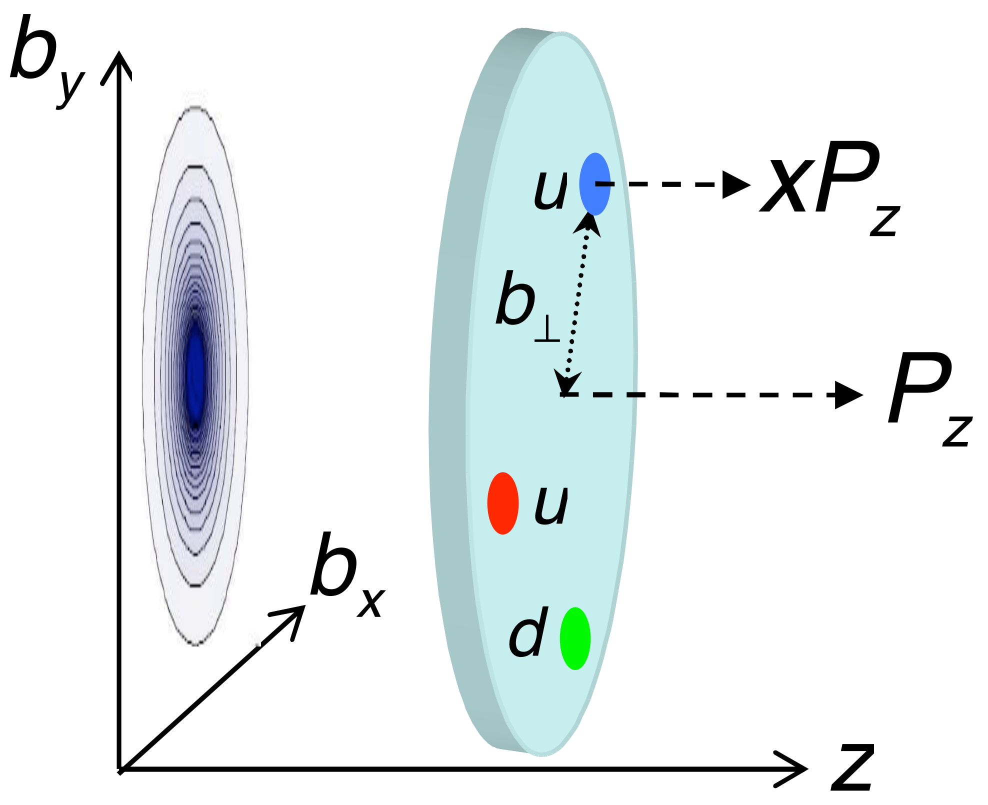
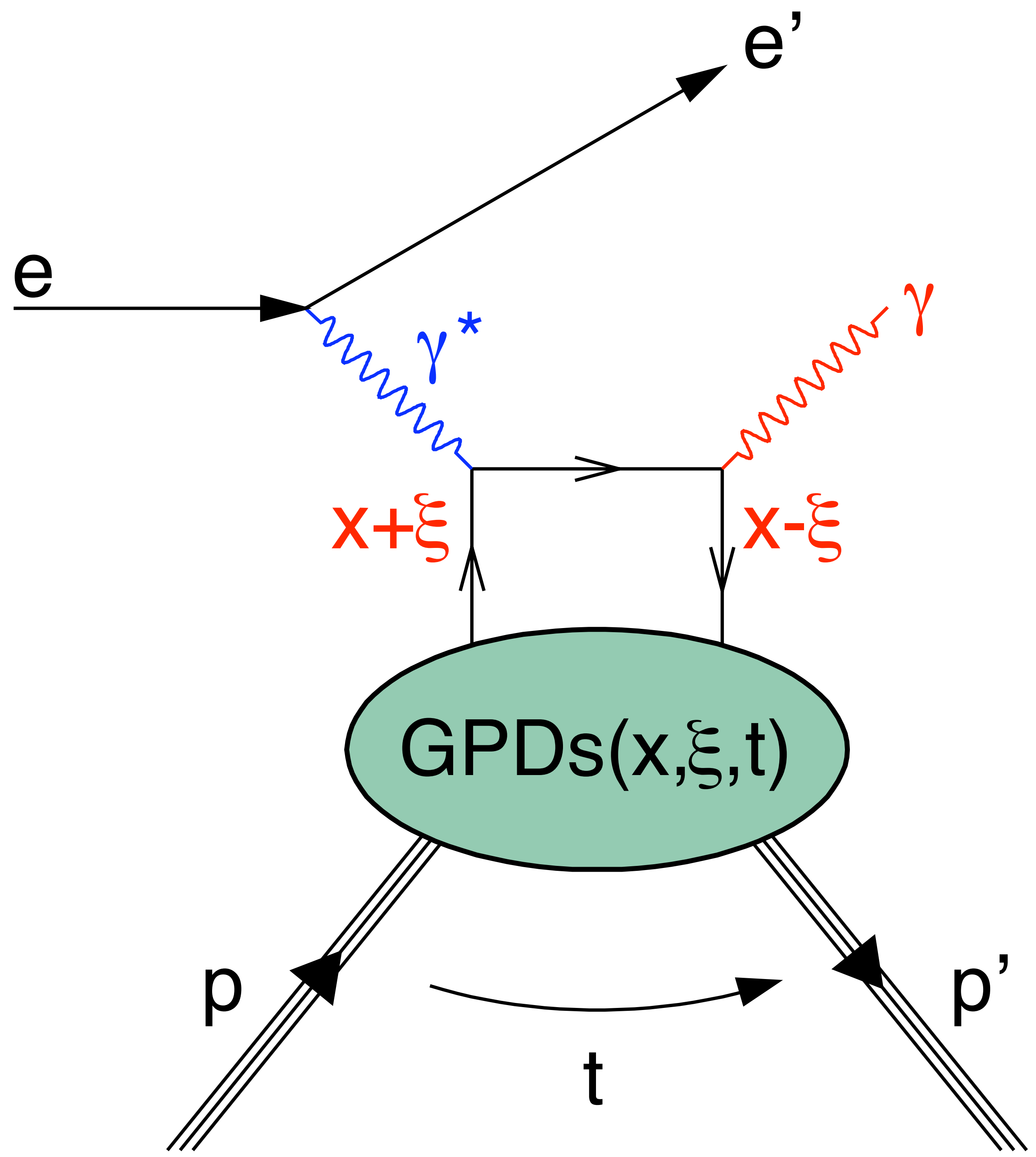
DVCS







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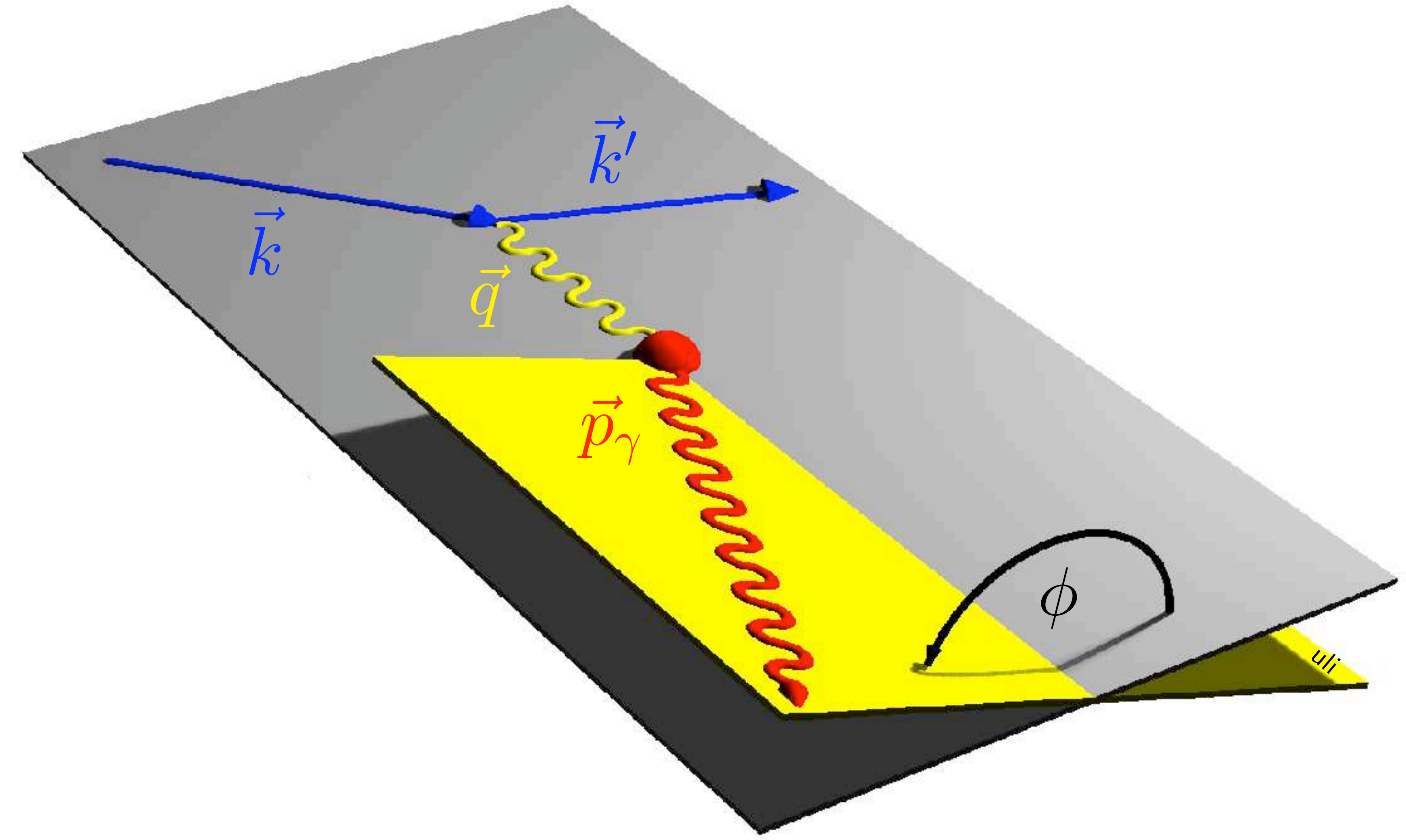
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$



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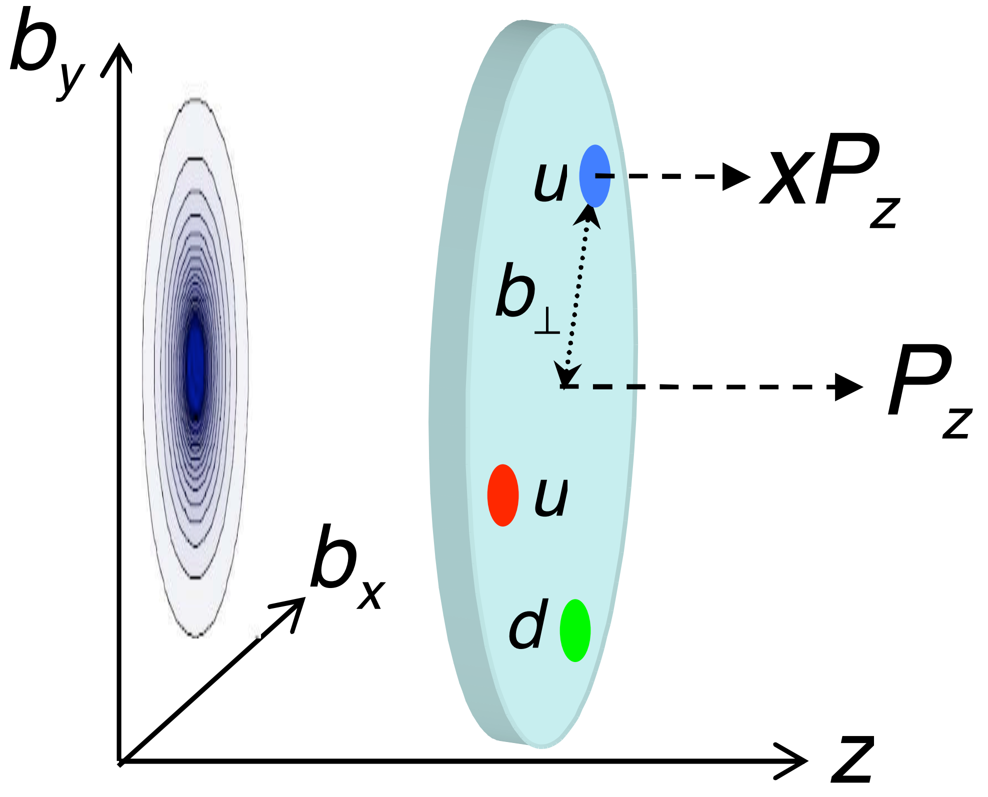

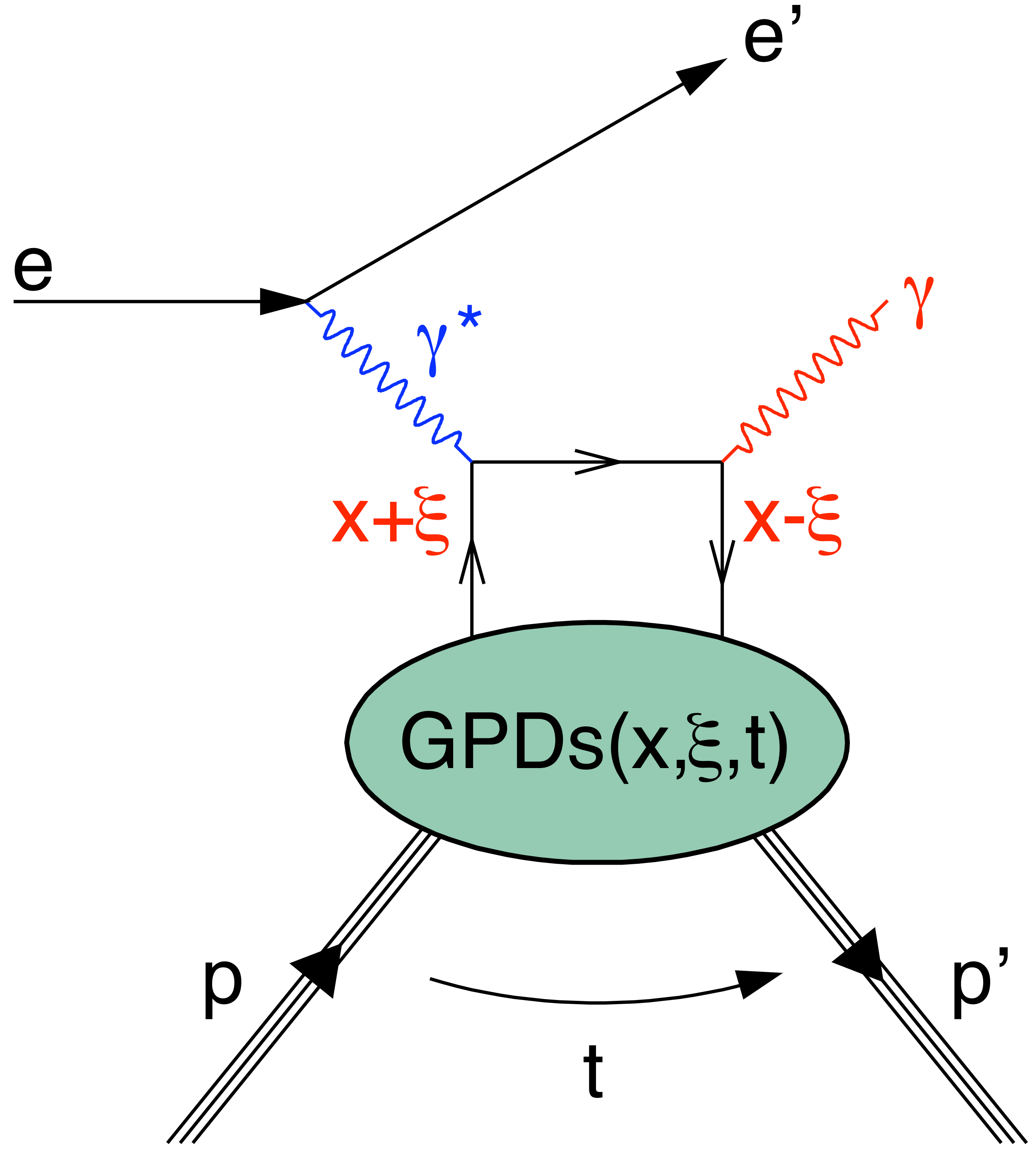

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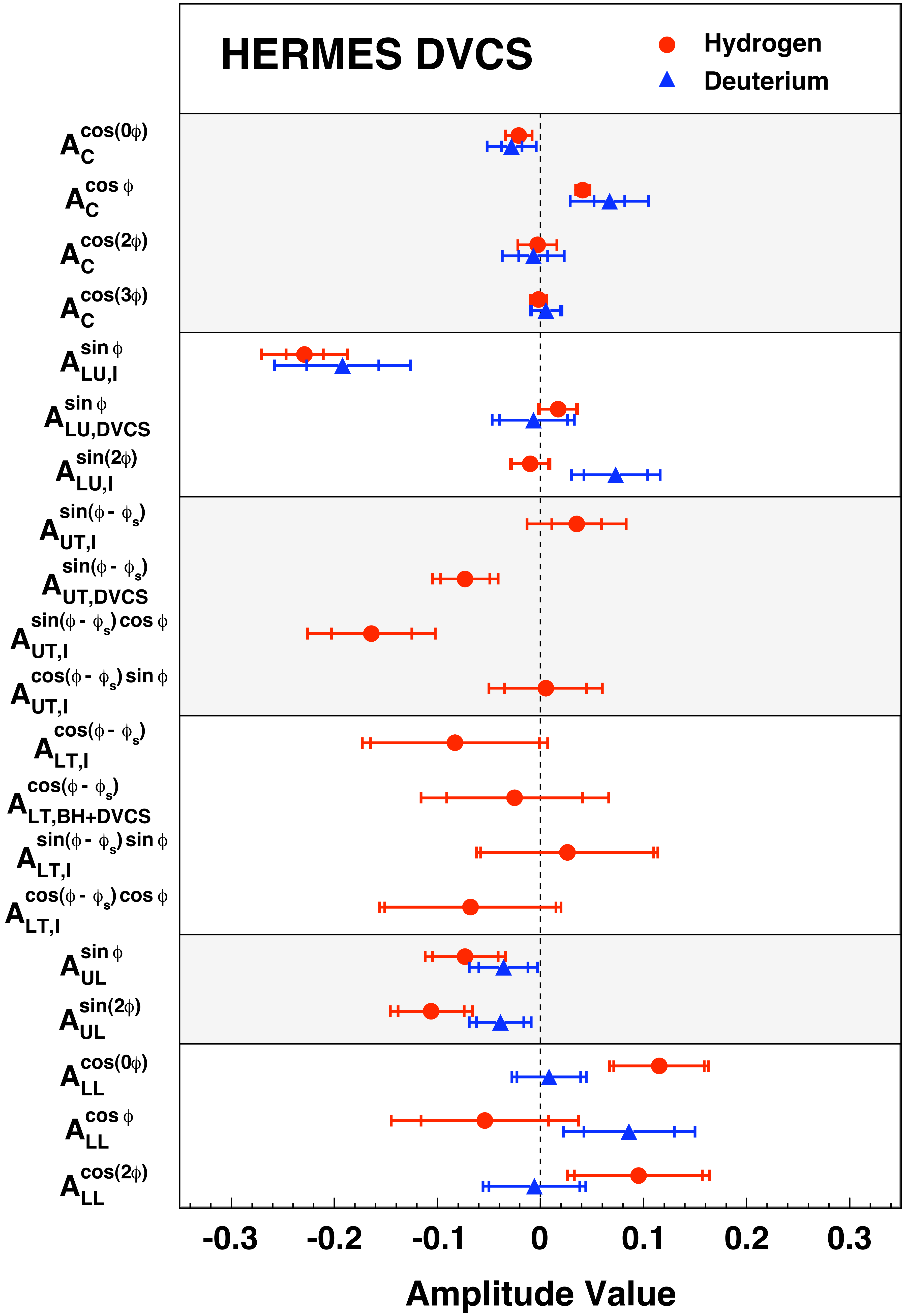
bilinear ("DVCS") or linear in GPDs



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103

NPB 829 (2010) 1

JHEP 11 (2009) 083

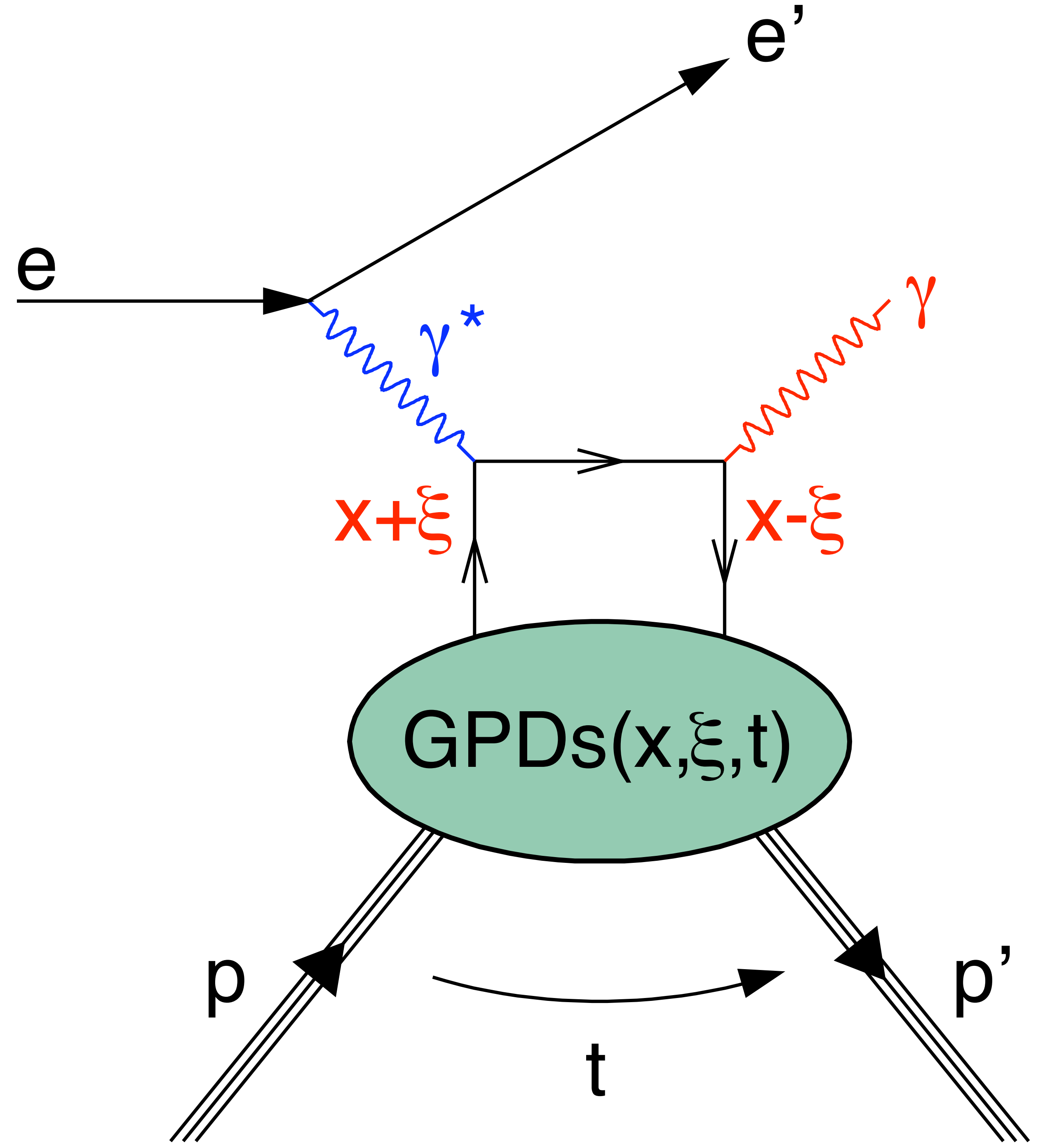
Beam-helicity asymmetry:

PRC 81 (2010) 035202

GPD H

PRL 87 (2001) 182001

JHEP 07 (2012) 032



Transverse target spin asymmetries:

GPD E from proton target

JHEP 06 (2008) 066
PLB 704 (2011) 15

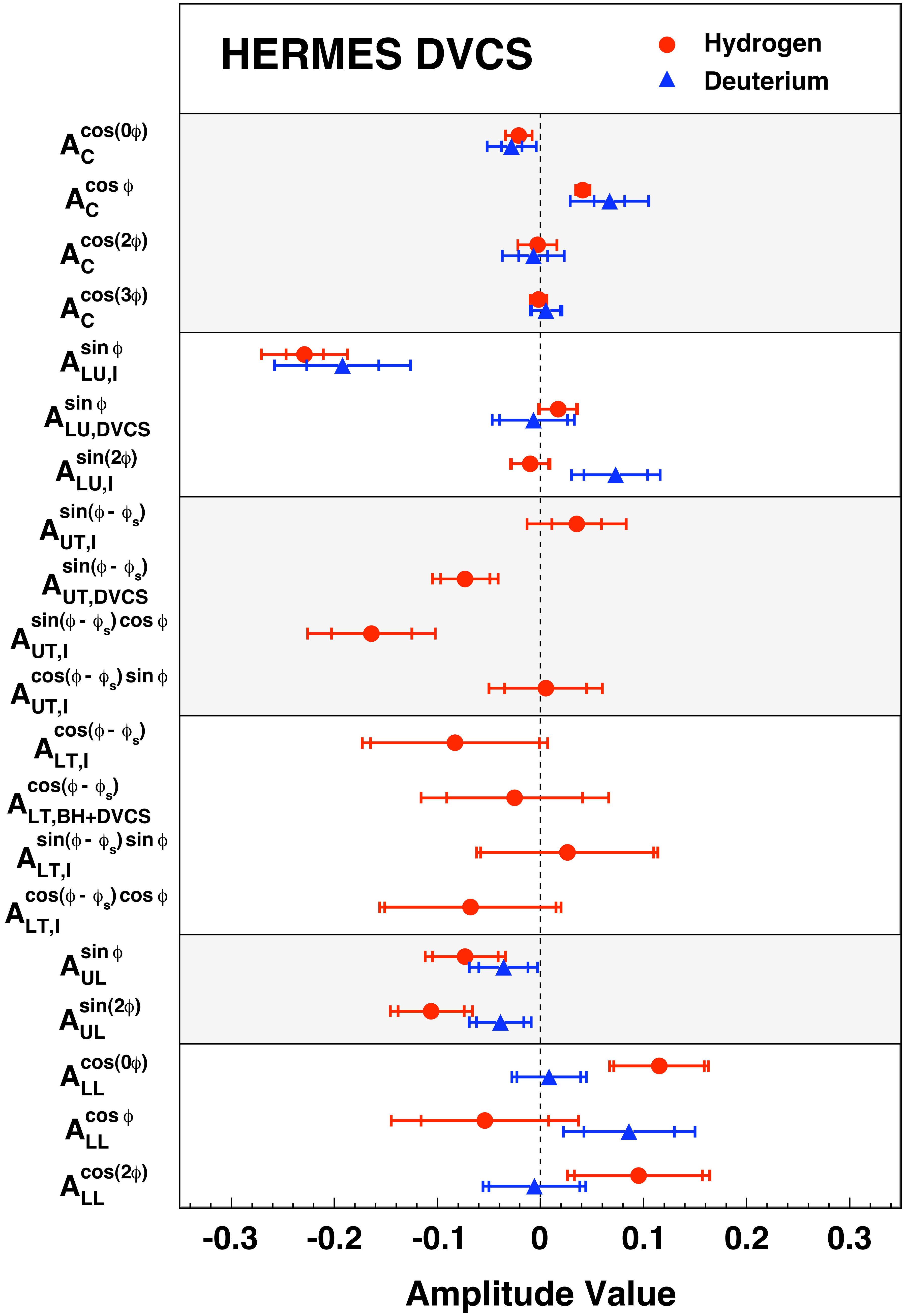
Longitudinal target spin asymmetry:

GPD $\tilde{H}$

JHEP 06 (2010) 019
NPB 842 (2011) 265

Double-spin asymmetry:

GPD $\tilde{H}$



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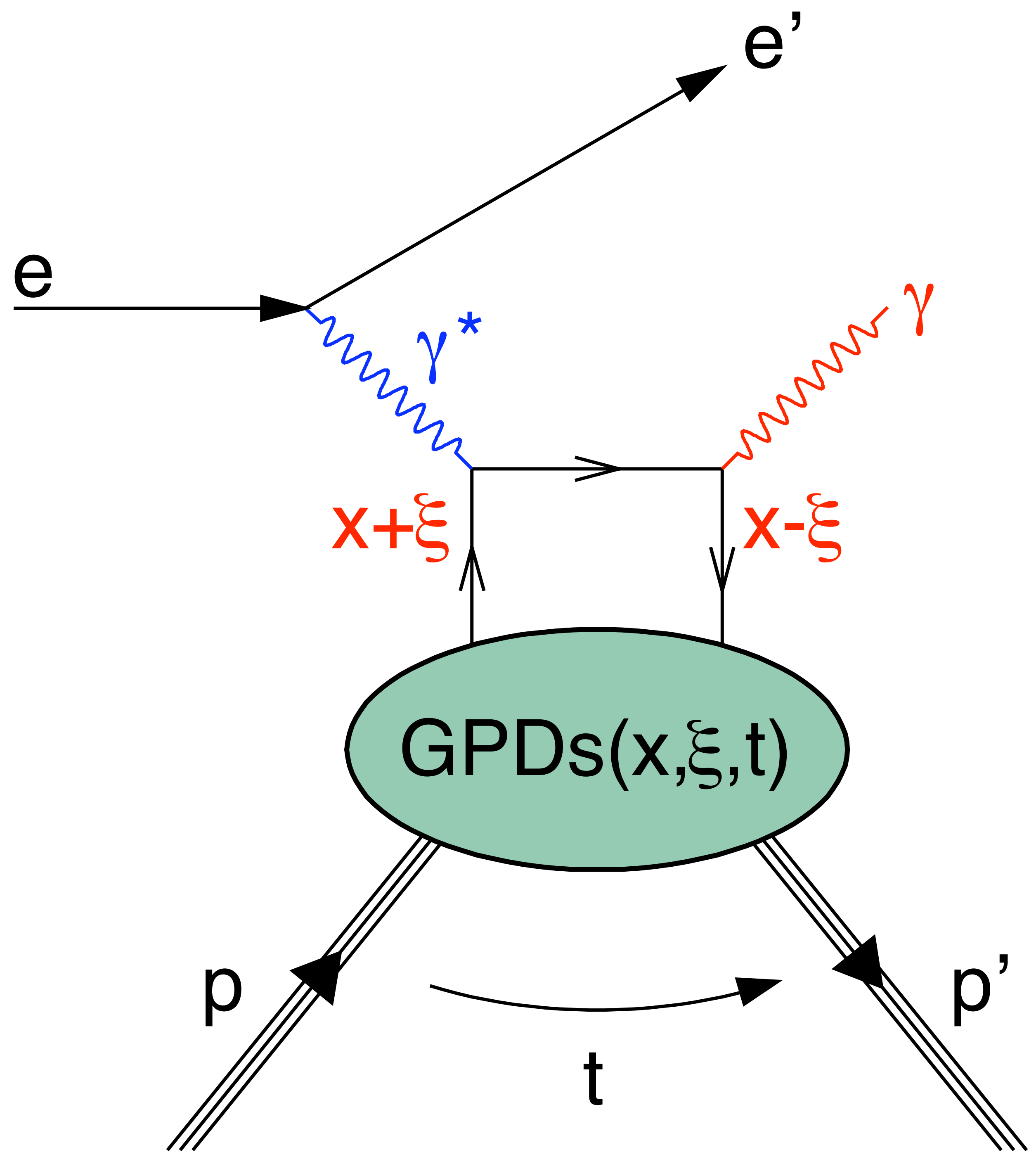
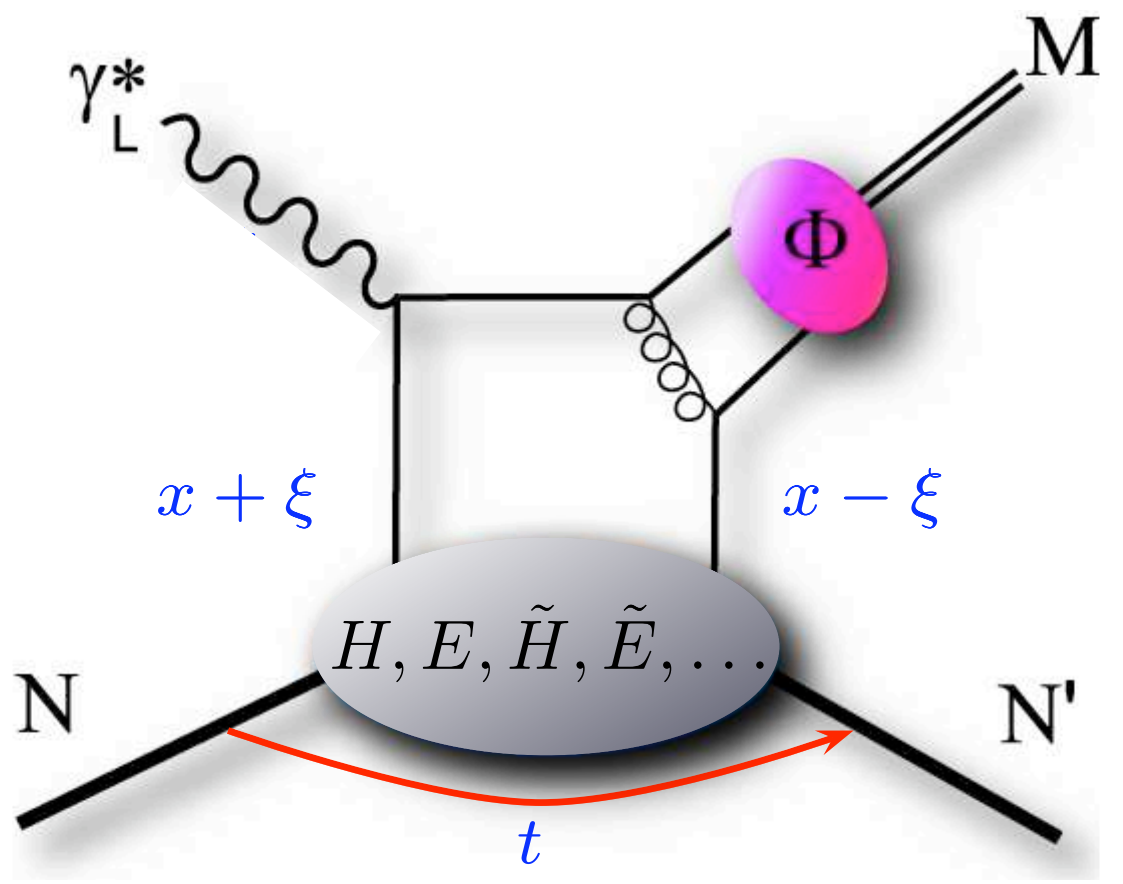


however, no cross-section measurement so far at HERMES kinematics!

exclusive meson production

- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model

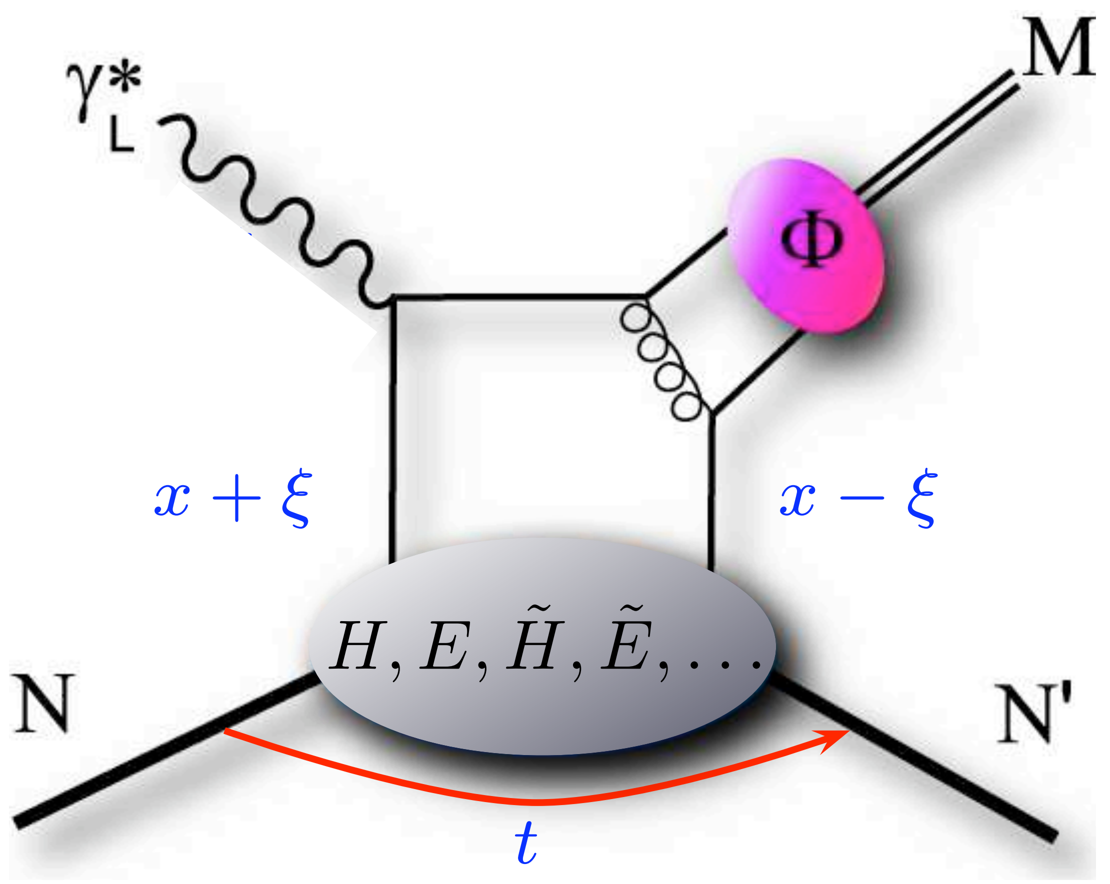


π^0	2Δu+Δd
η	2Δu–Δd

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

GK ... S. Goloskokov & P. Kroll, e.g., EPJ C50 (2007) 829; C53 (2008) 367

exclusive meson production



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ρ^0	2u+d, 9g/4
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- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model
- vector-meson cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi_S\,\mathrm{d}\phi\,\mathrm{d}\cos\theta\,\mathrm{d}\varphi} = \frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t} W(x_B, Q^2, t, \phi_S, \phi, \cos\theta, \varphi)$$

$$W = W_{UU} + P_B W_{LU} + S_L W_{UL} + P_B S_L W_{LL} + S_T W_{UT} + P_B S_T W_{LT}$$

look at various angular (decay) distributions to study helicity transitions
[“spin-density matrix elements” (SDMEs), “amplitude ratios”]

SDMEs from angular decay distribution

unpolarized beam

long. polarized beam

(angle definitions in backup)

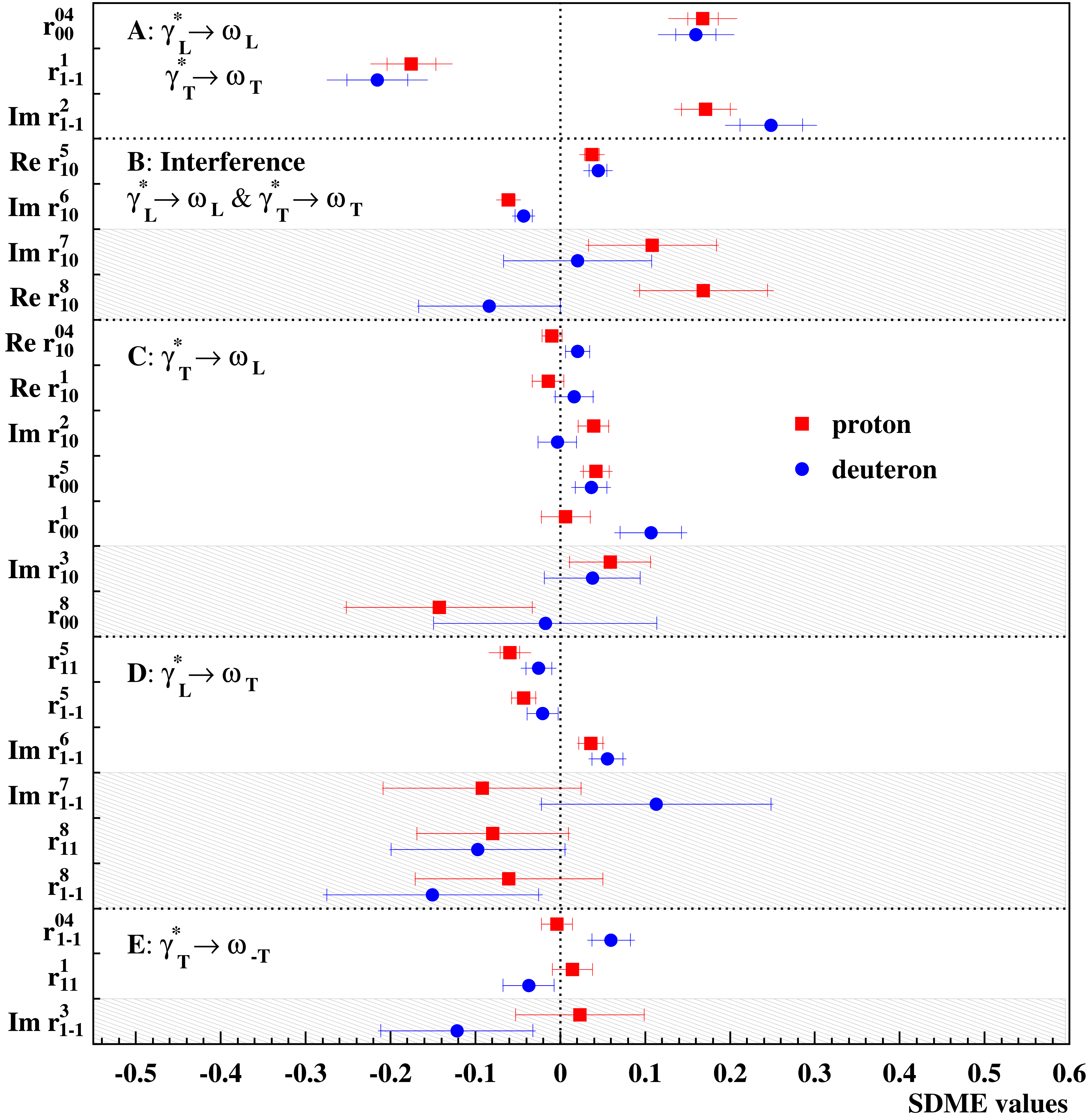
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + \mathcal{W}^{L}(\Phi,\phi,\cos\Theta),$$

$$\begin{aligned}
\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[& \frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\,\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi \\
& - \epsilon\cos 2\Phi \left(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta - \sqrt{2}\,\mathrm{Re}\{r^{1}_{10}\}\sin 2\Theta\cos\phi - r^{1}_{1-1}\sin^2\Theta\cos 2\phi \right) \\
& - \epsilon\sin 2\Phi \left(\sqrt{2}\,\mathrm{Im}\{r^{2}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{2}_{1-1}\}\sin^2\Theta\sin 2\phi \right) \\
& + \sqrt{2\epsilon(1+\epsilon)}\cos\Phi \left(r^{5}_{11}\sin^2\Theta + r^{5}_{00}\cos^2\Theta - \sqrt{2}\,\mathrm{Re}\{r^{5}_{10}\}\sin 2\Theta\cos\phi - r^{5}_{1-1}\sin^2\Theta\cos 2\phi \right) \\
& + \sqrt{2\epsilon(1+\epsilon)}\sin\Phi \left(\sqrt{2}\,\mathrm{Im}\{r^{6}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{6}_{1-1}\}\sin^2\Theta\sin 2\phi \right) \Bigg],
\end{aligned}$$

$$\begin{aligned}
\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2} P_{\mathrm{beam}}\Bigg[& \sqrt{1-\epsilon^2} \left(\sqrt{2}\,\mathrm{Im}\{r^{3}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{3}_{1-1}\}\sin^2\Theta\sin 2\phi \right) \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos\Phi \left(\sqrt{2}\,\mathrm{Im}\{r^{7}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{7}_{1-1}\}\sin^2\Theta\sin 2\phi \right) \\
& + \sqrt{2\epsilon(1-\epsilon)}\sin\Phi \left(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta - \sqrt{2}\,\mathrm{Re}\{r^{8}_{10}\}\sin 2\Theta\cos\phi - r^{8}_{1-1}\sin^2\Theta\cos 2\phi \right) \Bigg].
\end{aligned}$$

ω & ρ SDMEs (here, mainly for illustration)

[A. Airapetian et al., EPJ C74 (2014) 3110]



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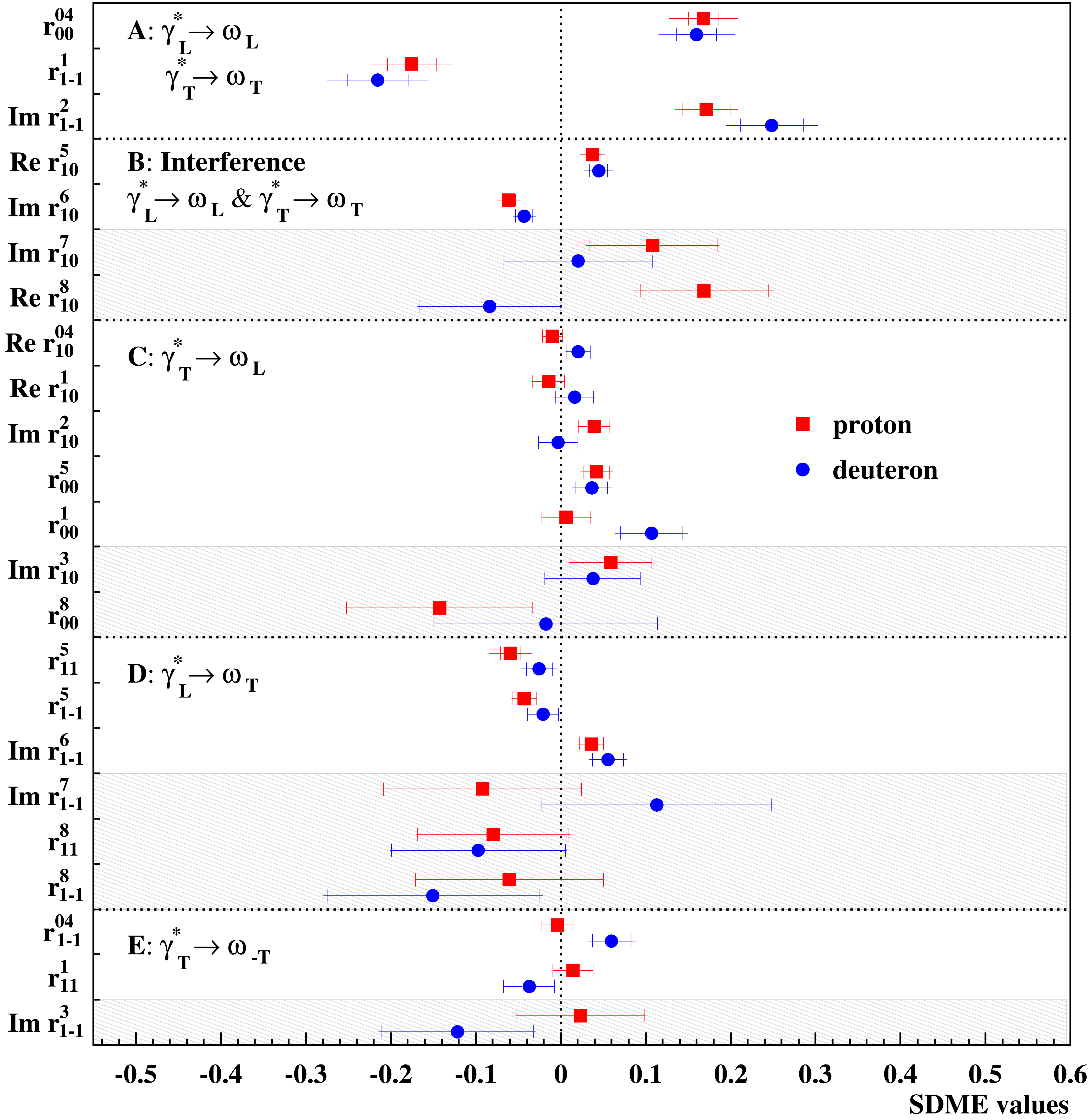

- helicity-conserving SDMEs dominate

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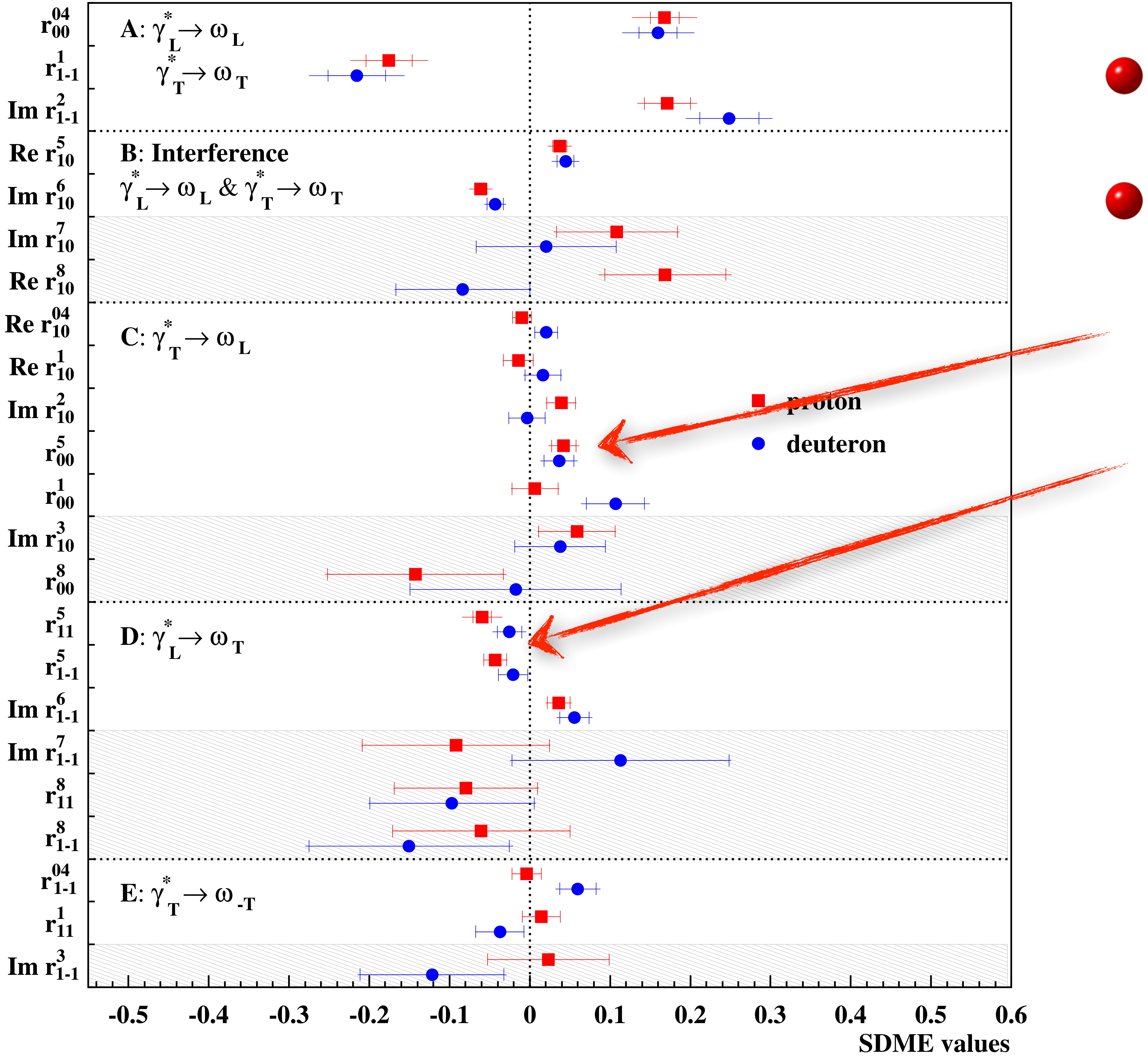
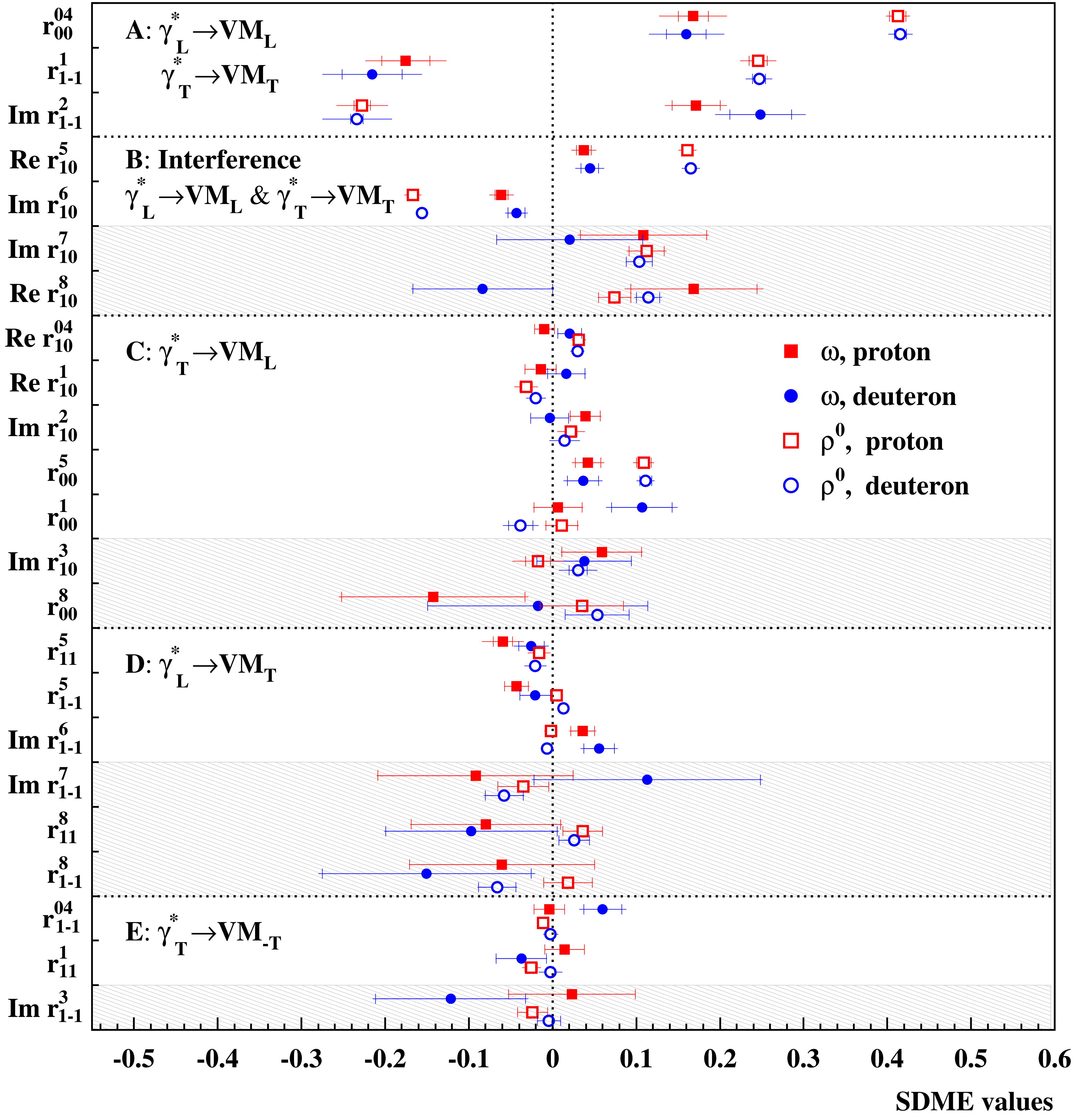
[A. Airapetian et al., EPJ C74 (2014) 3110]



- helicity-conserving SDMEs dominate
- hardly any violation of SCHC, except maybe for
  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$

ω & ρ SDMEs (here, mainly for illustration)



[A. Airapetian et al., EPJ C74 (2014) 3110]

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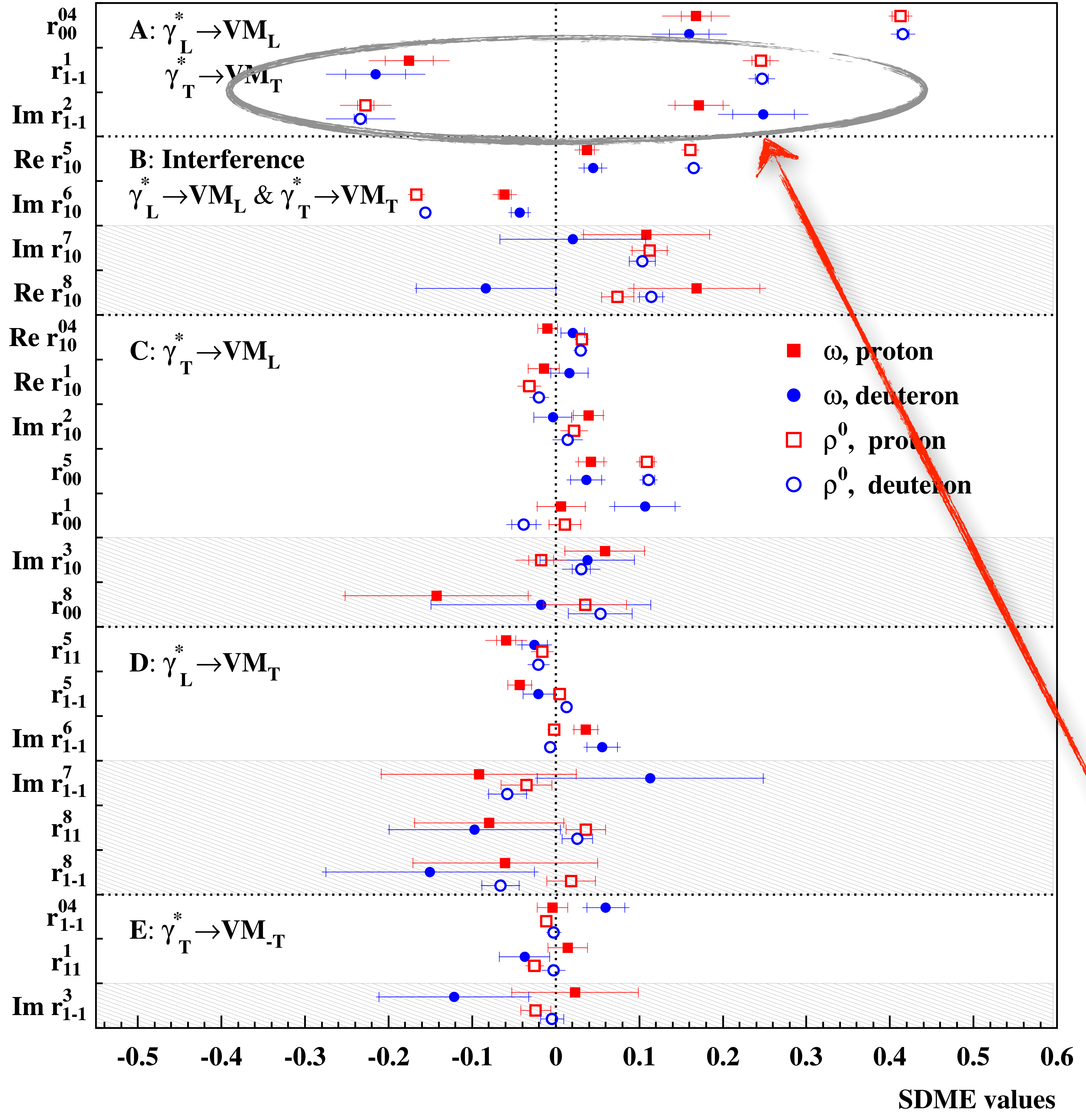


- helicity-conserving SDMEs dominate
- hardly any violation of SCHC, except maybe for
  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$
- interference smaller than for ρ^0 …
- … and opposite signs for

$r^1_{1\text{-}1}$ & $\Im r^2_{1\text{-}1}$

exclusive meson production

- analyses only use subset of data
  - high-statistics data set from 2006/07 with dedicated recoil-proton detector not used so far
- corresponding analysis for ϕ started but not finished / published
- analysis can be expanded to, e.g., pion-pairs
  - only HERA-I data published: PLB 599 (2004) 212
- exclusive pion/kaon cross sections
  - only pions (w/o 2006/07 data) published: PLB 659 (2008) 486
- exclusive kaon spin-asymmetries
  - only pions published with partially surprisingly large asym's: PLB 682 (2010) 345
  - kaons in SIDIS exhibit large asymmetries!

(semi)-inclusive hadron production

- beam-helicity transfer to Lambda being analyzed in DIS regime (spin-dependent fragmentation function)
  - preliminary results for high-statistics quasi-photoproduction, but not published
- longitudinal and transverse target-spin transfer in quasi-photoproduction
  - preliminary results, but not published
- charged pion and kaon multiplicities: subset of data published: PRD 87 (2013) 074029
  - high-statistics 2006/07 data set not included; fully differential analysis missing
  - pi0 and eta also interesting, preliminary studies exist
- hadron production in nuclear environment; K^- enhancement at large x&z ongoing

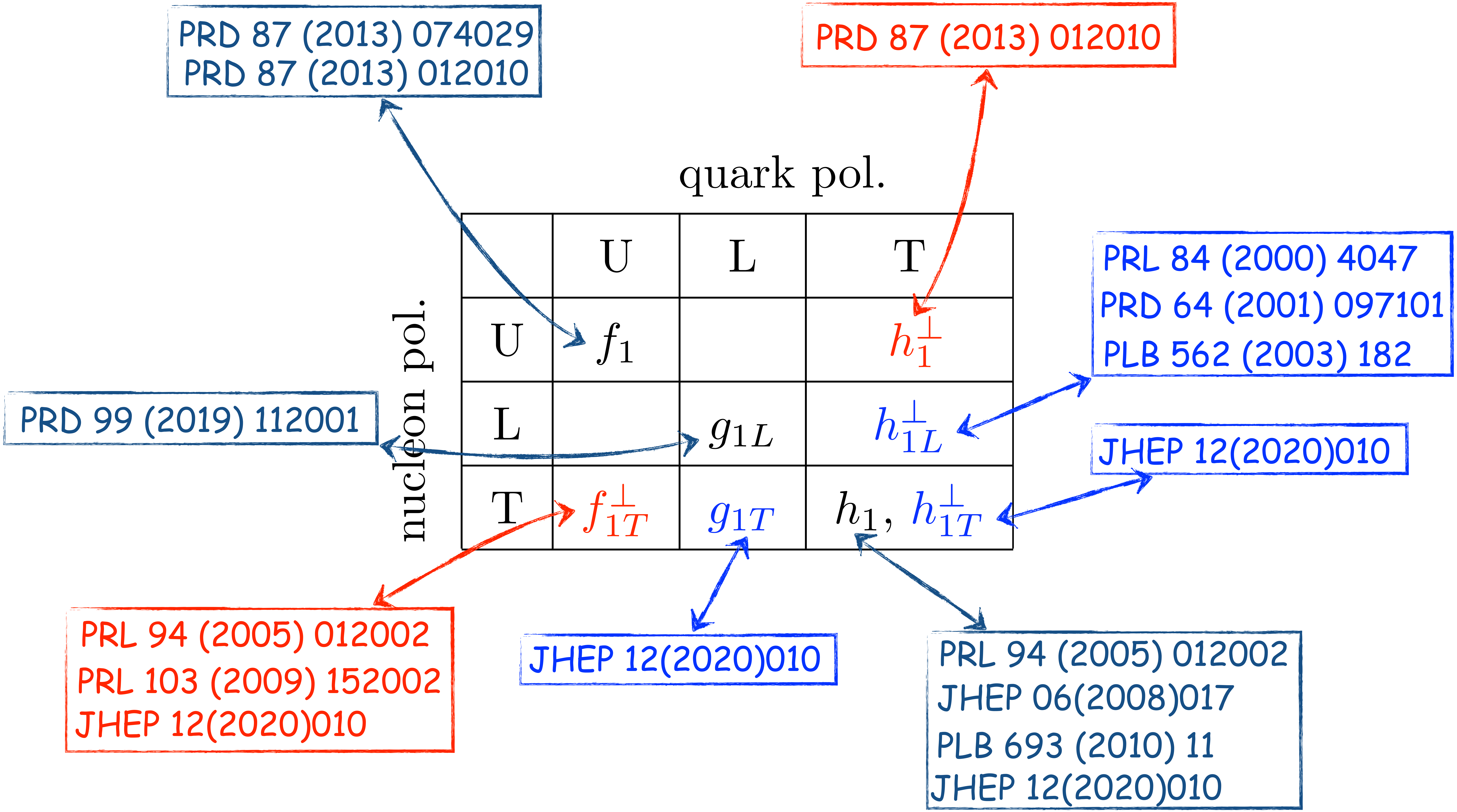
(semi)-inclusive hadron production

- A_{LT} in inclusive pion and kaon production
  - A_{UT} published; sneak-preview of A_{LT} exists coming out from summer-student project
- beam-spin asymmetry in target-current-region hadron correlations
  - novel distributions (fracture functions etc.)
- beam-spin asymmetry in di-hadron production
  - transverse target-spin asymmetry published for pion pairs: JHEP 06 (2008) 017
- in general, hadron production data in RIVET for Monte Carlo tuning
  - important kinematic region between high-energy and photo-production domains

summary

- HERMES was a latecomer to HERA
  - brought a new, exciting, and very successful spin to the physics program
  - focus on spin asymmetries in inclusive, semi-inclusive, and exclusive processes, but also on hadronization studies (including hadronization in nuclear environment)
- kinematic regime complementary to that of the EIC and the other HERA exp's
- analyses still ongoing with still a quite range of topics … limited mainly by manpower
- while not 1:1 transferable to the EIC (e.g., fixed-target vs. collider), many analysis concepts can serve as a blue print for several studies to come at the EIC, but also at JLab
  - worthwhile to put some effort in keeping the knowledge alive until first related EIC data becomes available

backup slides



PRD 87 (2013) 074029
PRD 87 (2013) 012010

PRD 87 (2013) 012010

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, $h_{1T}^\perp$

PRL 84 (2000) 4047
PRD 64 (2001) 097101
PLB 562 (2003) 182

JHEP 12(2020)010

PRD 99 (2019) 112001

PRL 94 (2005) 012002
PRL 103 (2009) 152002
JHEP 12(2020)010

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PRL 94 (2005) 012002
JHEP 06(2008)017
PLB 693 (2010) 11
JHEP 12(2020)010

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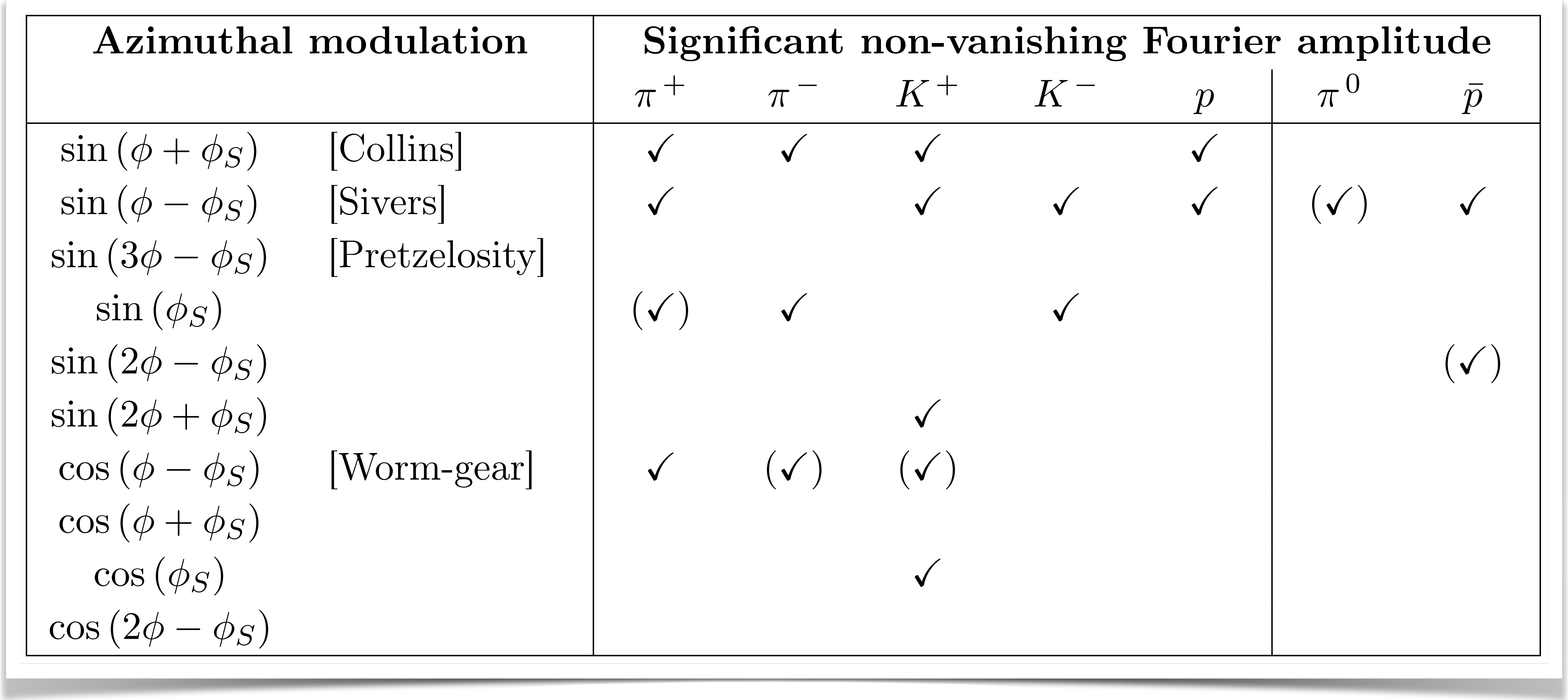

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$\sin(\phi-\phi_S)$	[Sivers]	✓		✓	✓	✓	(✓)	✓
$\sin(3\phi-\phi_S)$	[Pretzelosity]							
$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

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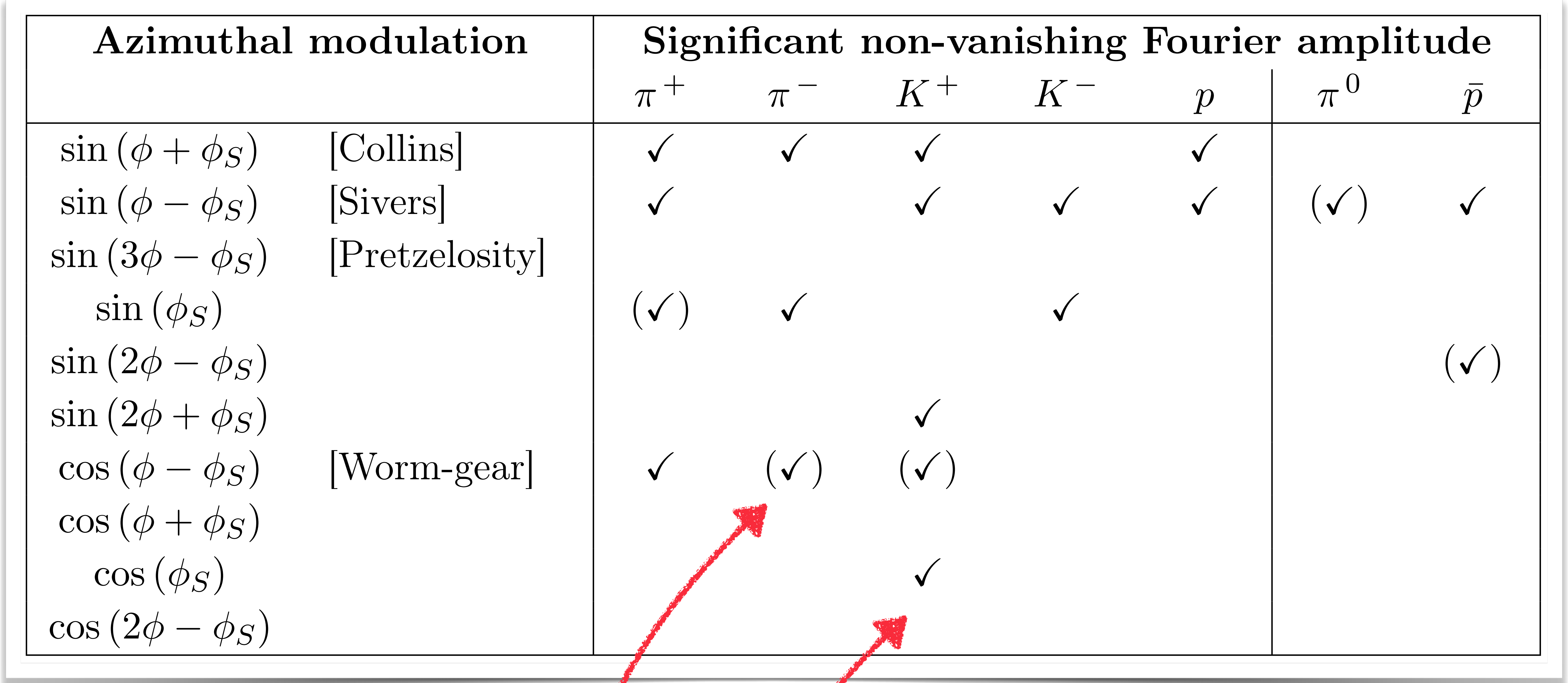

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$\sin(\phi_S)$		(✓)	✓		✓			
$\sin(2\phi-\phi_S)$								(✓)
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$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

95%

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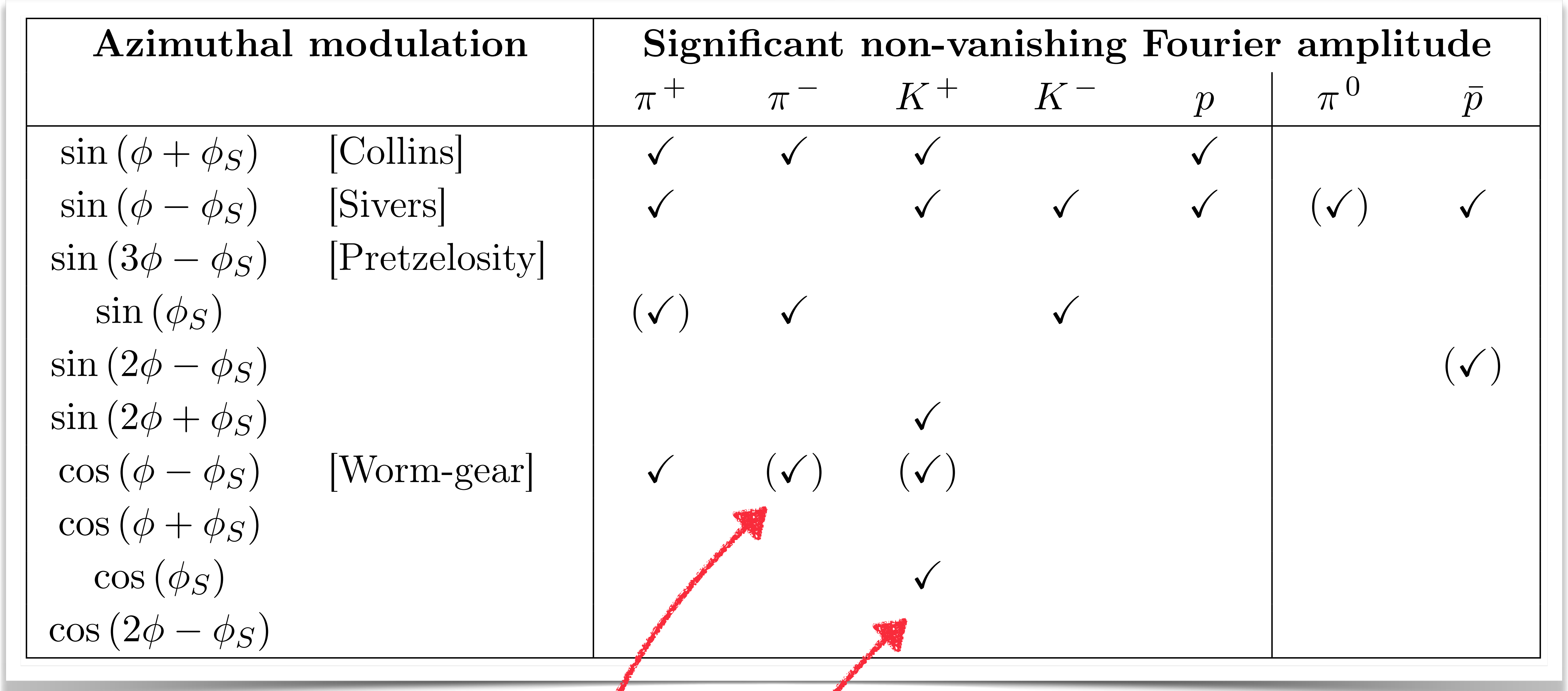
3d

1d



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$\sin(2\phi+\phi_S)$				✓				
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$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
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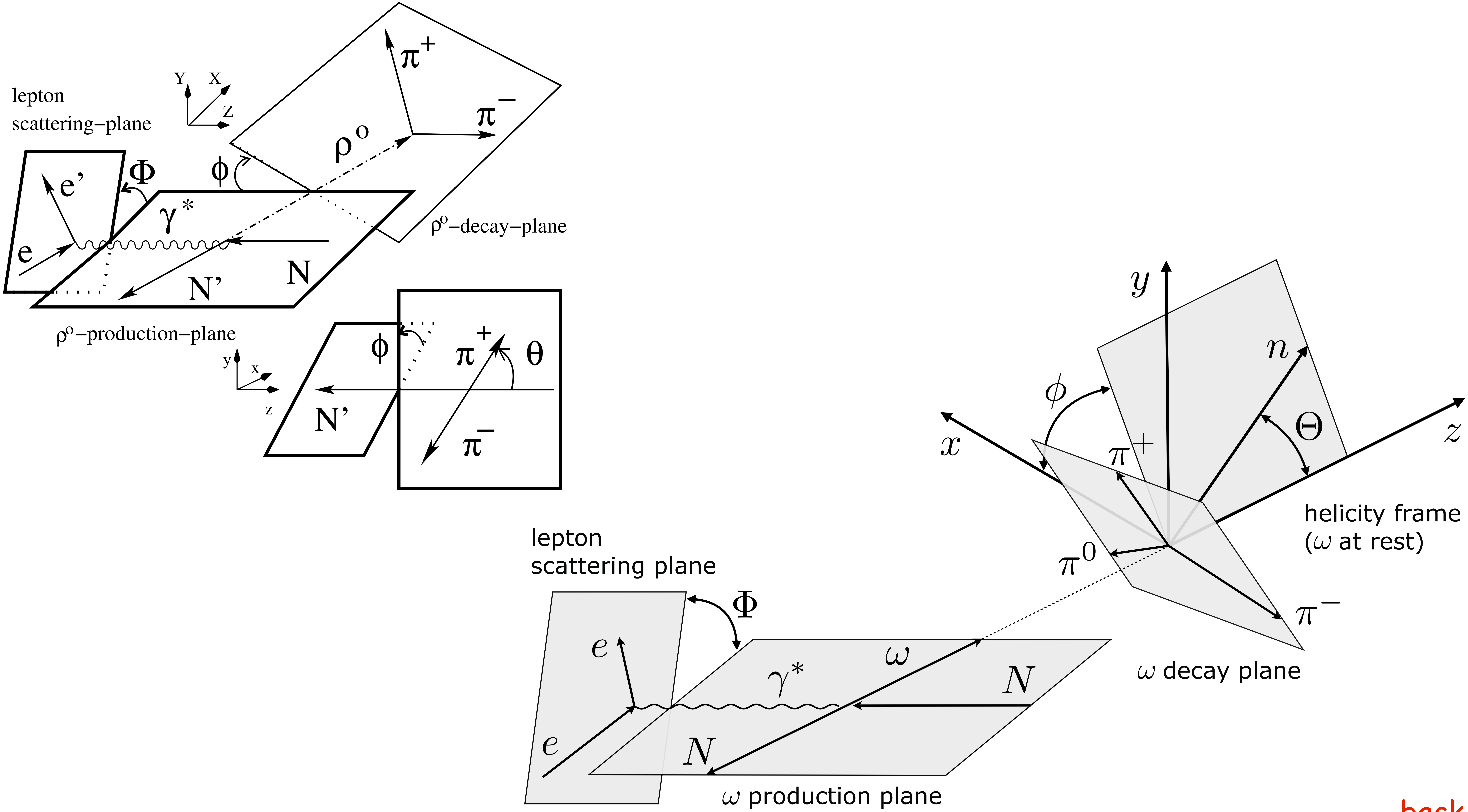
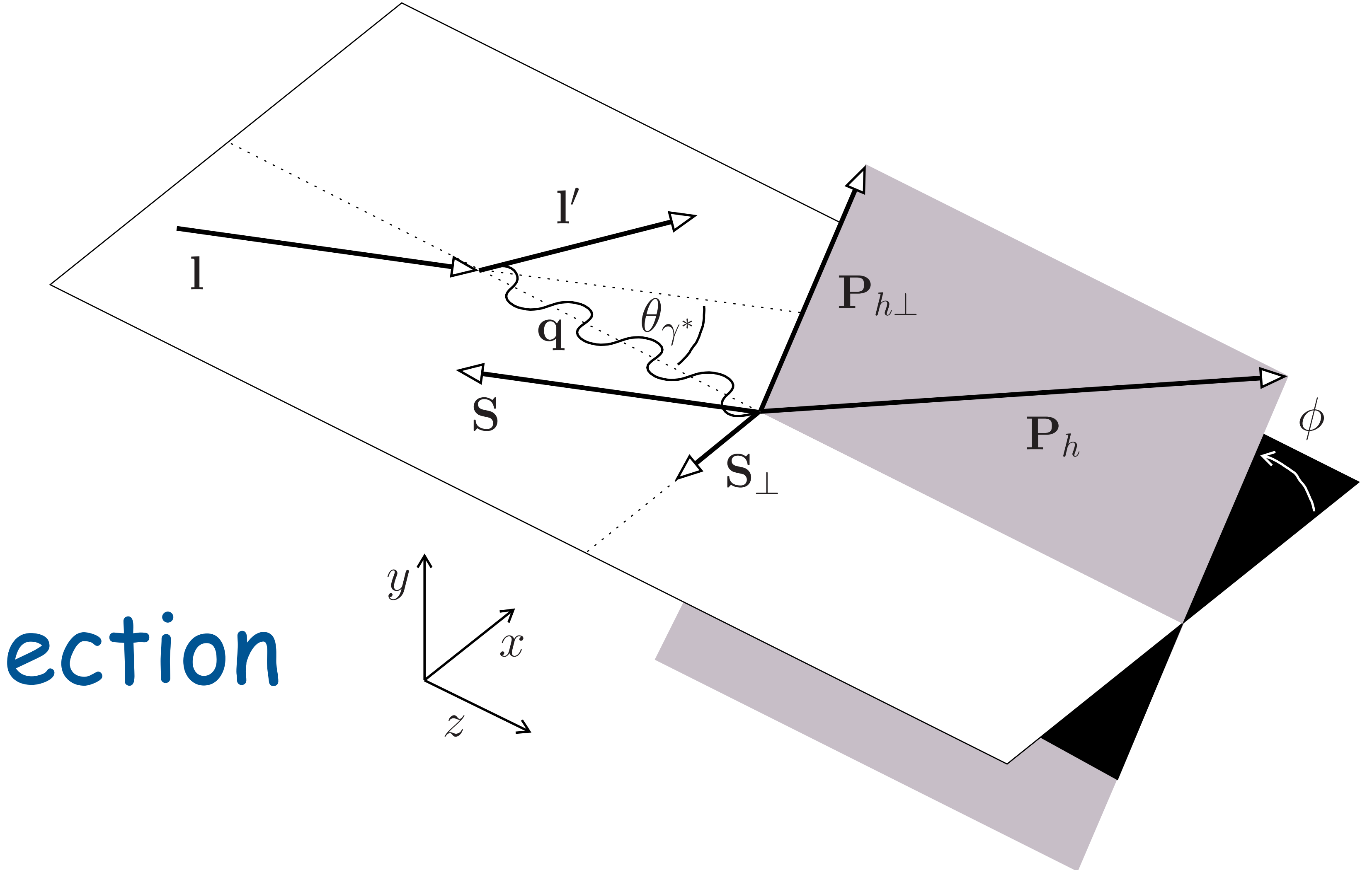

lepton
scattering−plane
Y
X
Z
Φ
e’
e
γ*
ϕ
ρ o
π+
π−
ρo−decay−plane
N
N’
ρo−production−plane
y
x
z
ϕ
π+
θ
N’
π−
y
n
ϕ
Θ
x
z
π+
π0
π−
helicity frame
(ω at rest)
lepton
scattering plane
Φ
e
e
γ*
ω
N
N
ω decay plane
ω production plane

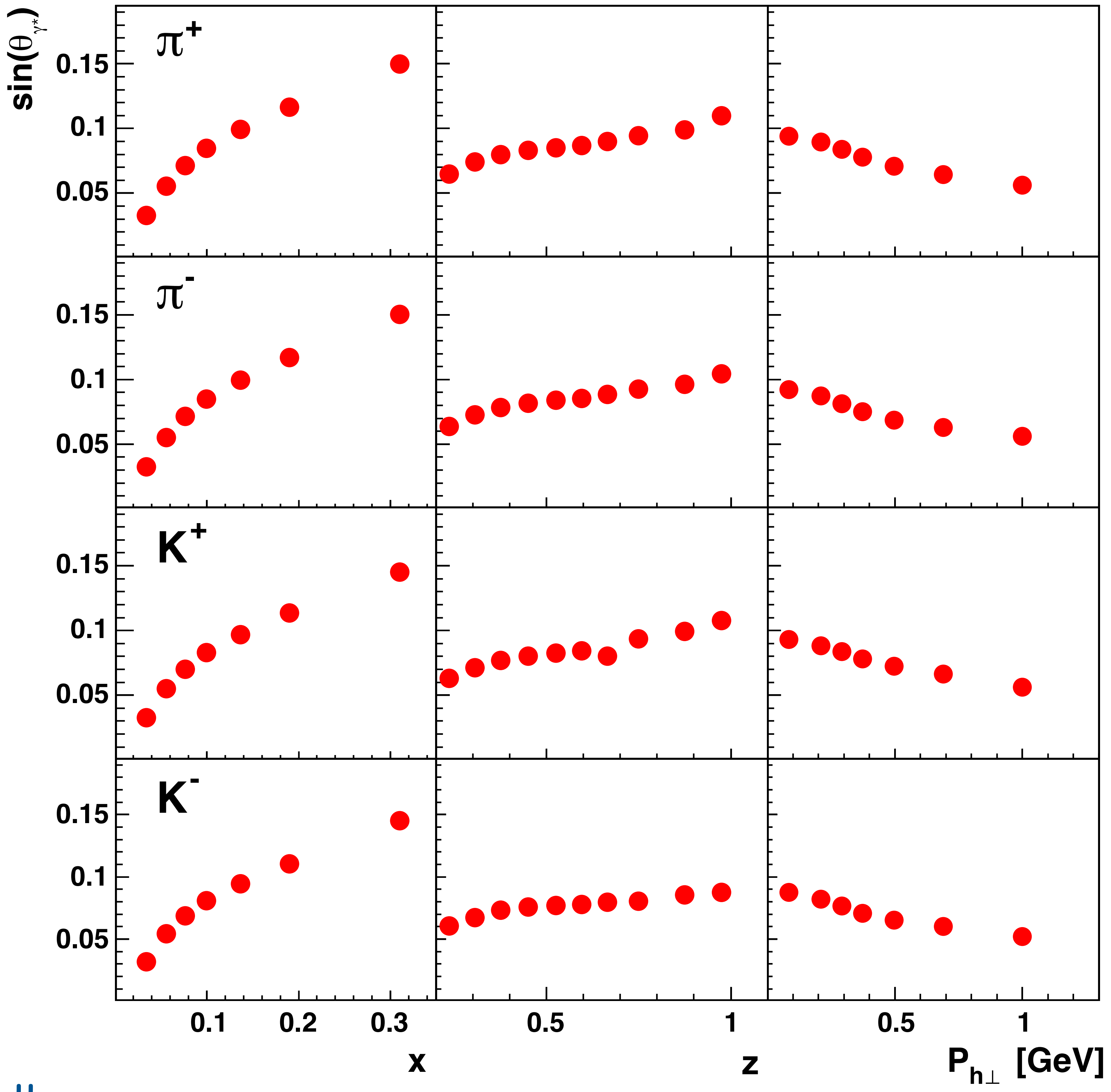
back

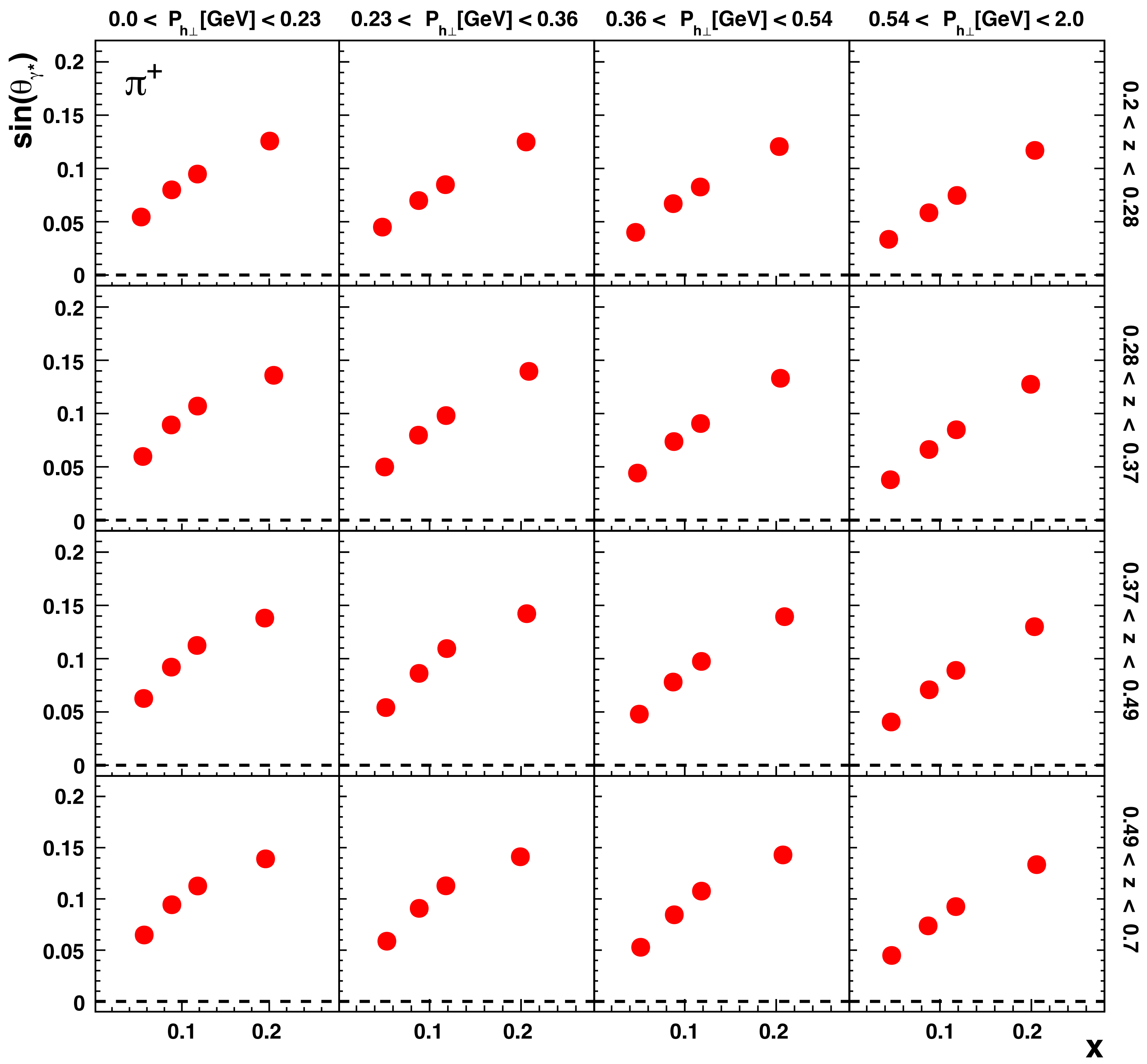
mixing of target polarizations



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

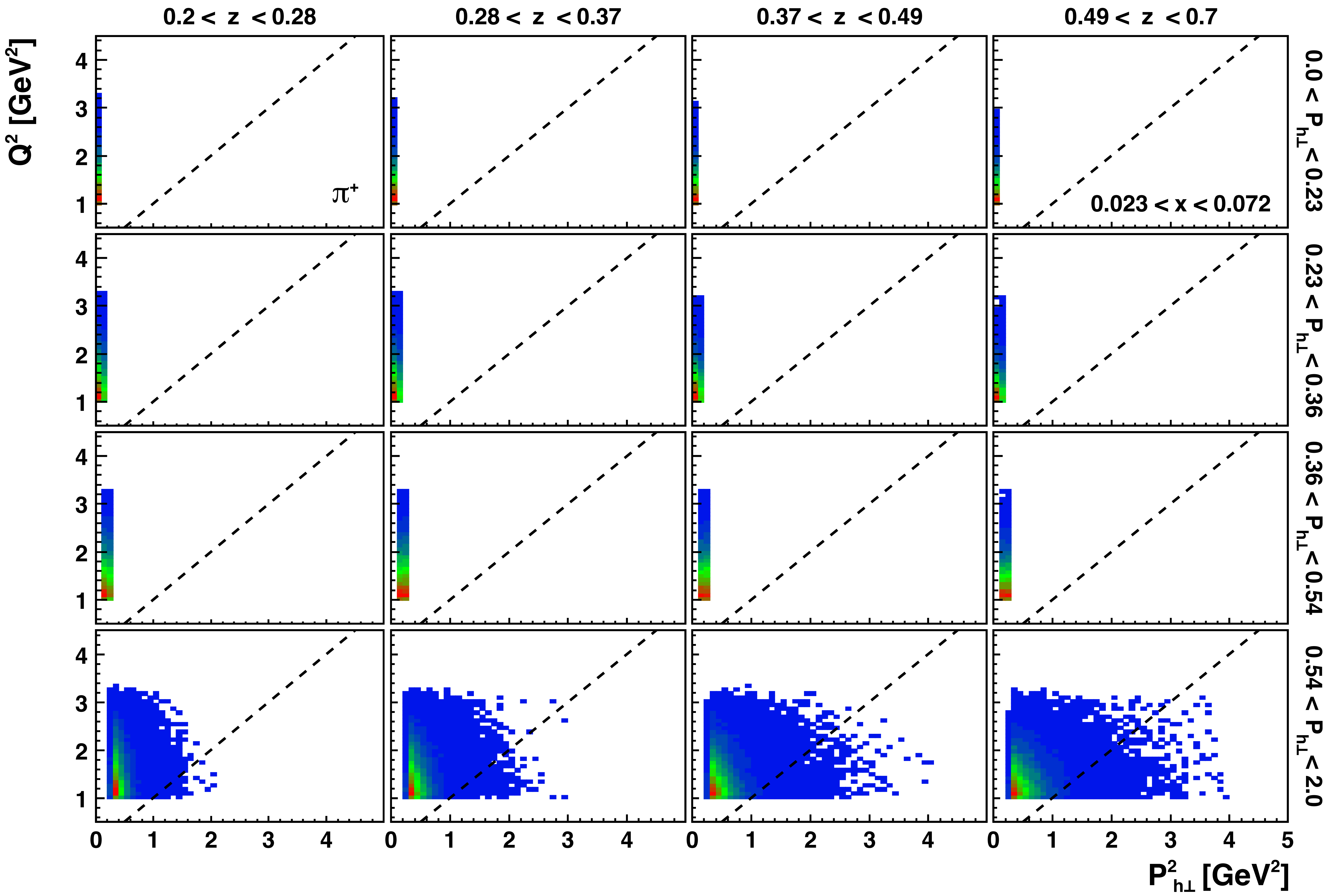
➡ mixing of longitudinal and transverse polarization effects





TMD factorization: a 2-scale problem

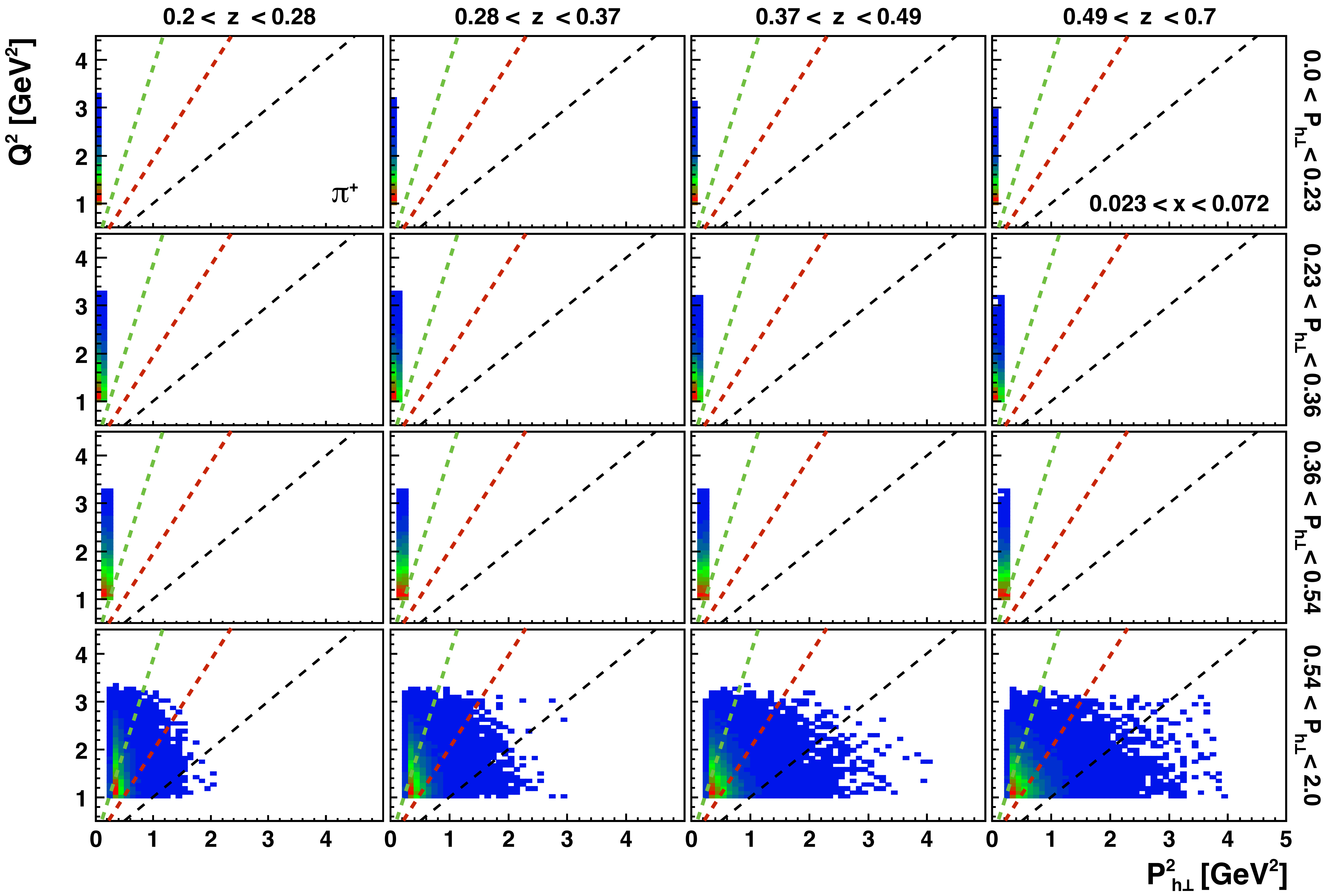
lowest x bin



- - - $Q^2 = P^2_{h\perp}$

TMD factorization: a 2-scale problem

lowest x bin



$Q^2 = P^2_{h\perp}$

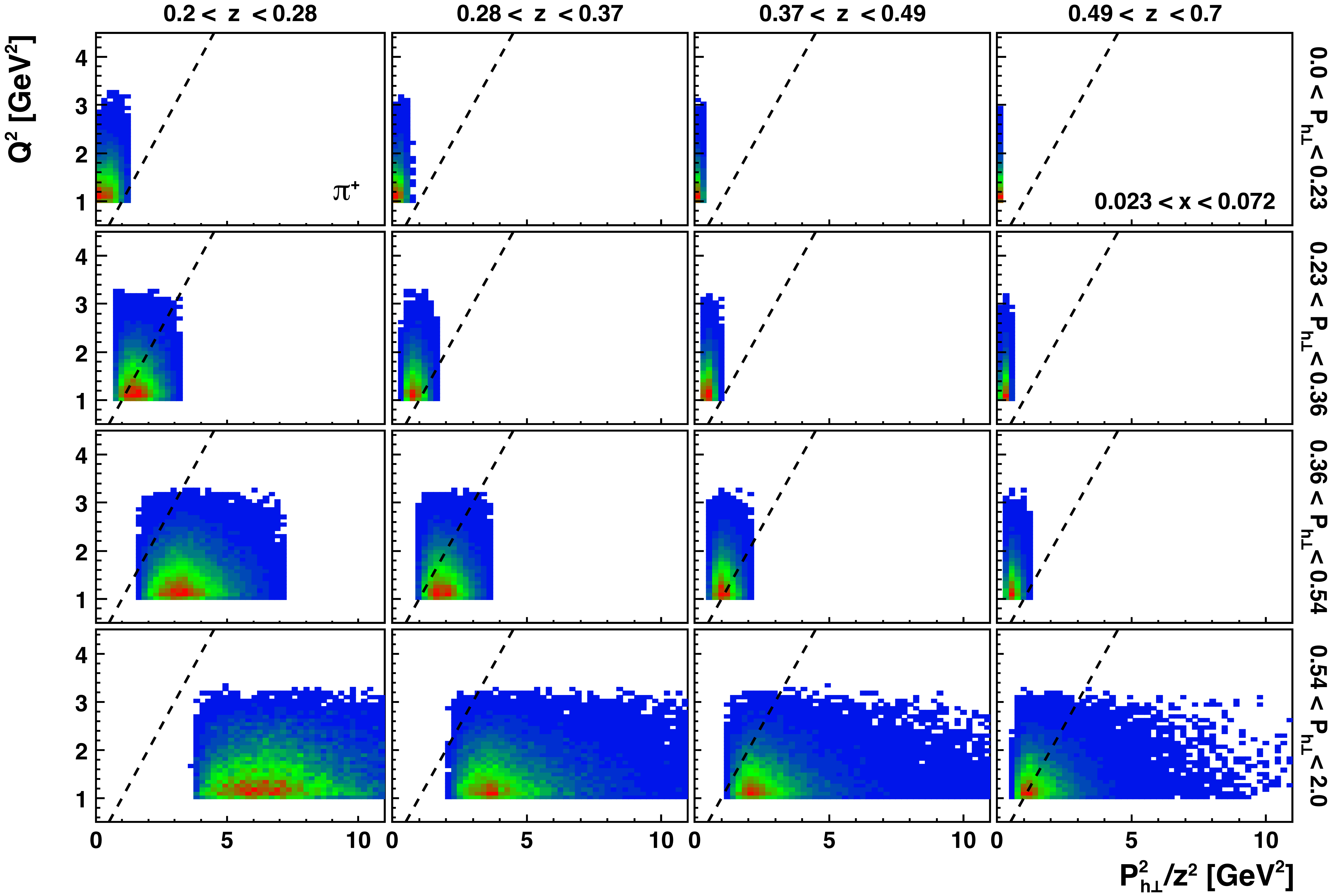
$Q^2 = 2\ P^2_{h\perp}$

$Q^2 = 4\ P^2_{h\perp}$

disclaimer: coloured lines drawn by hand

TMD factorization: a 2-scale problem

lowest x bin



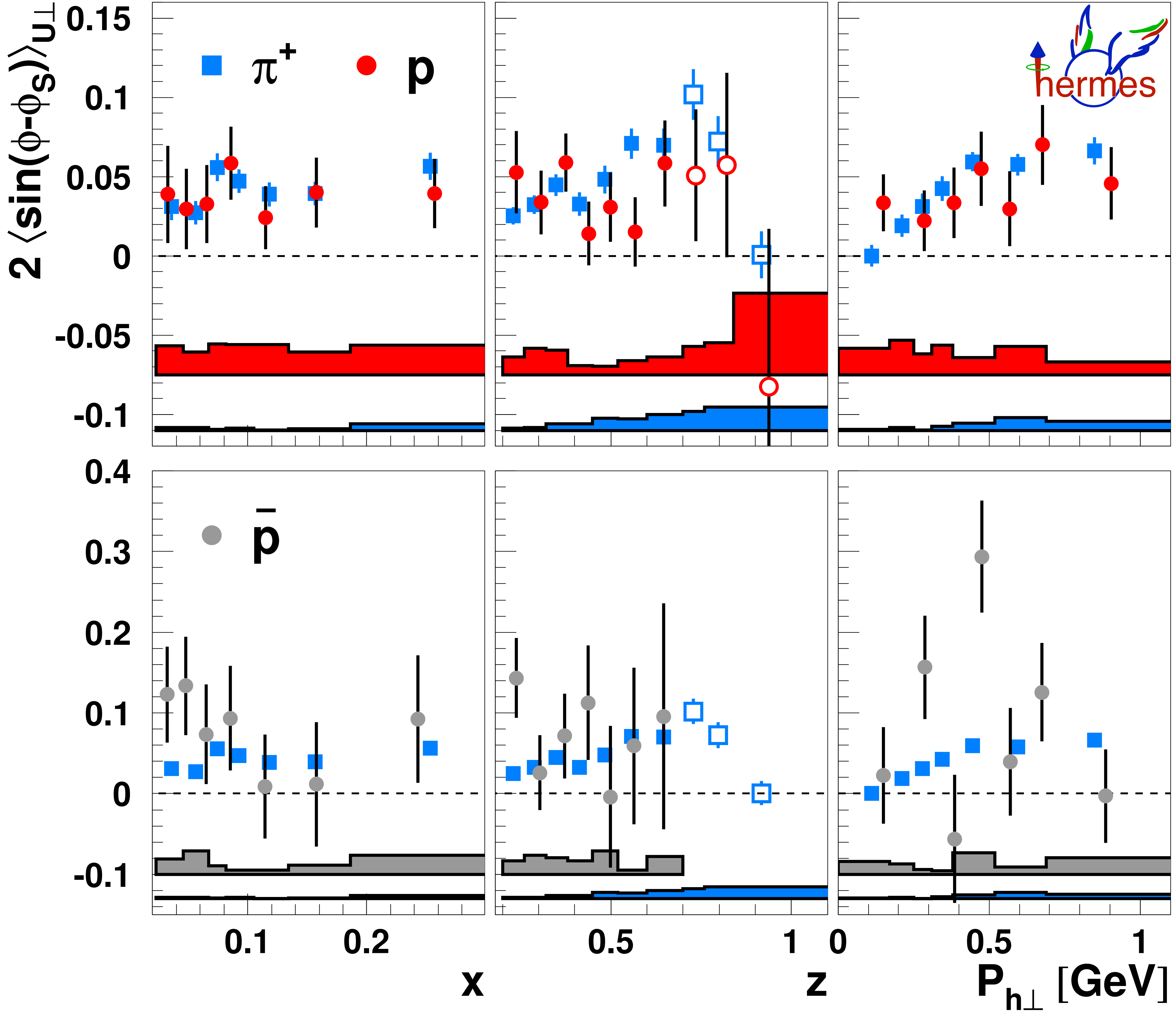
- - - $Q^2 = P^2_{h\perp}/z^2$

all other x-bins included in the Supplemental Material of JHEP12(2020)010

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

Sivers amplitudes
pions vs. (anti)protons

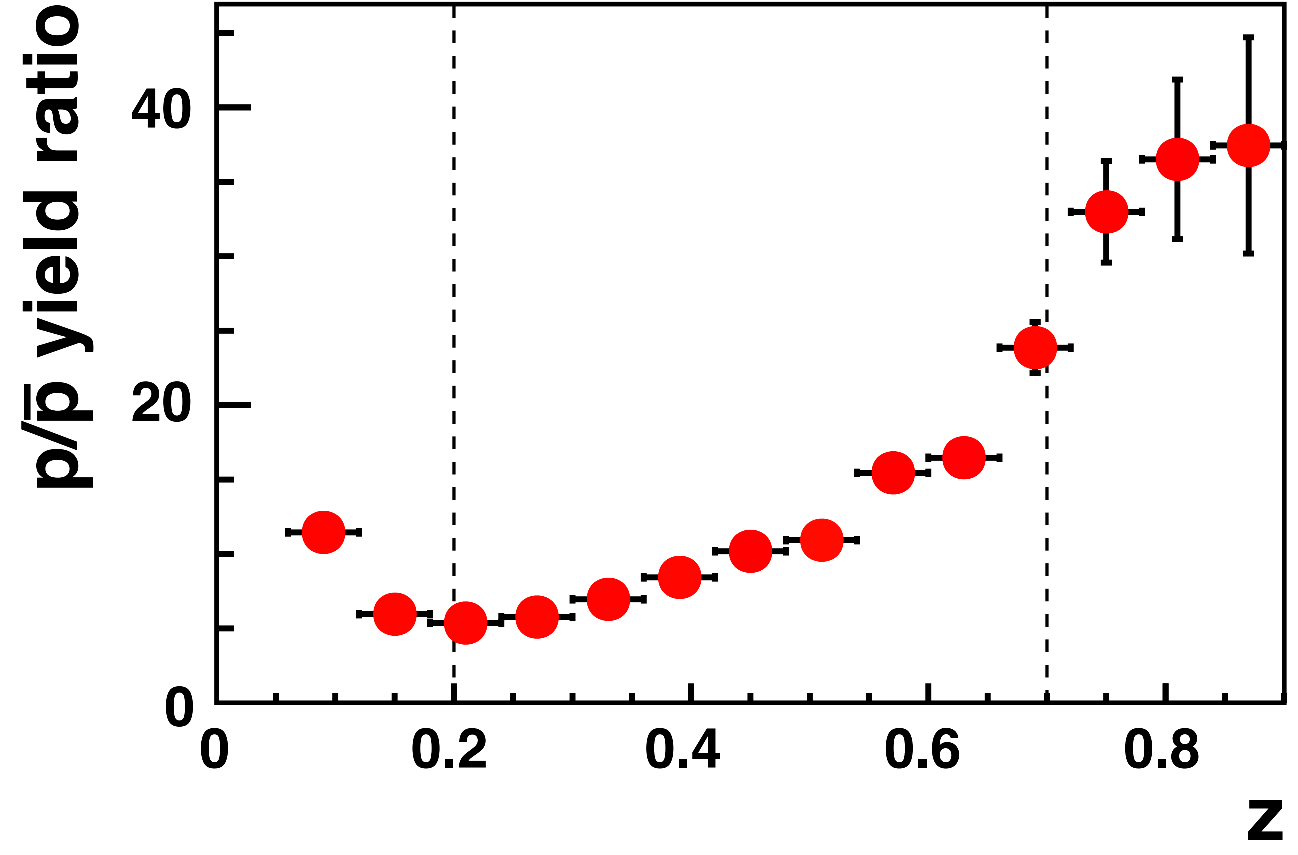
[A. Airapetian et al., JHEP12(2020)010]



similar-magnitude asymmetries for (anti)protons and pions

➥consequence of u-quark dominance in both cases?

[A. Airapetian et al., JHEP12(2020)010]



possibly, onset of target fragmentation only at lower z

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

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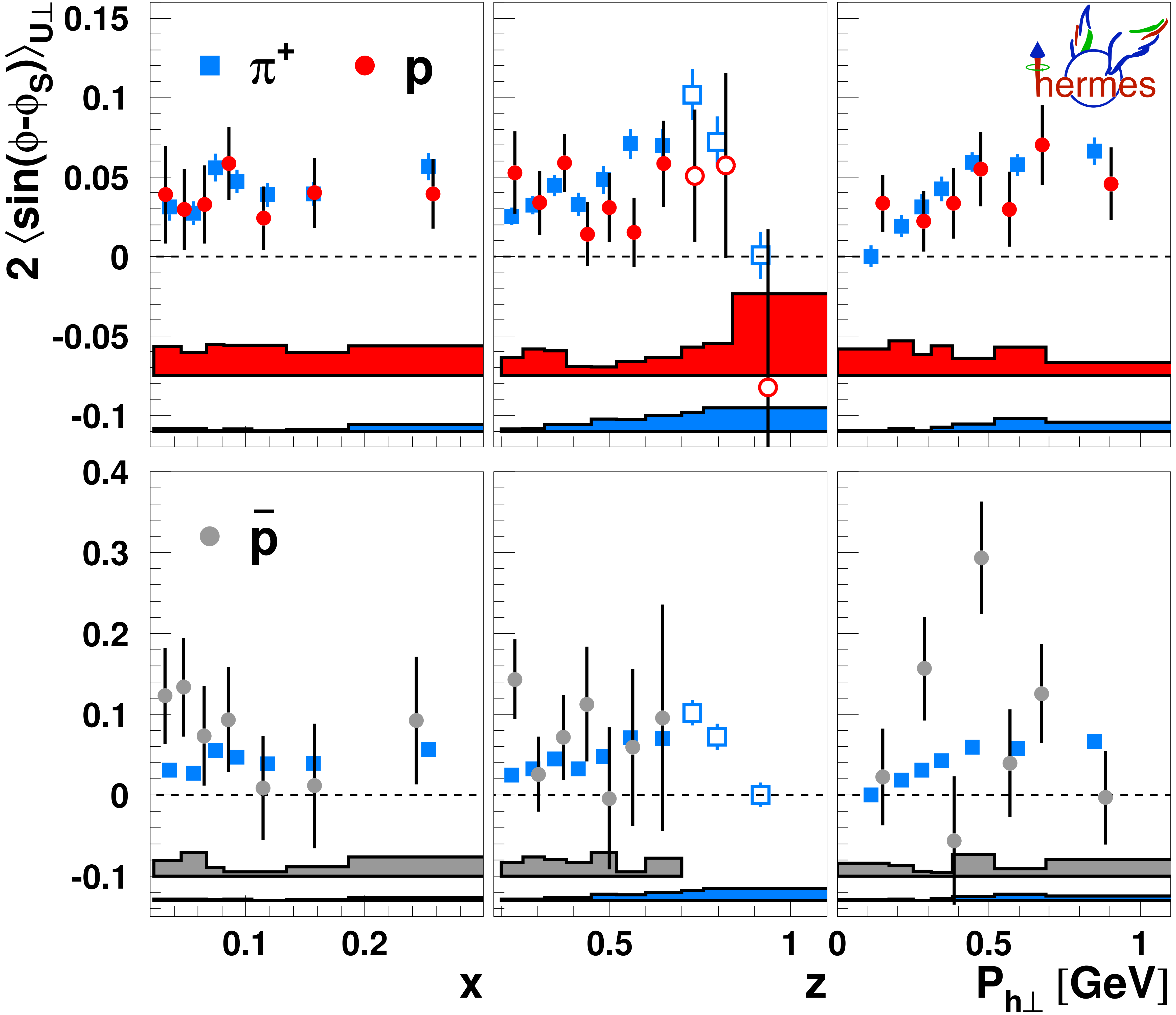

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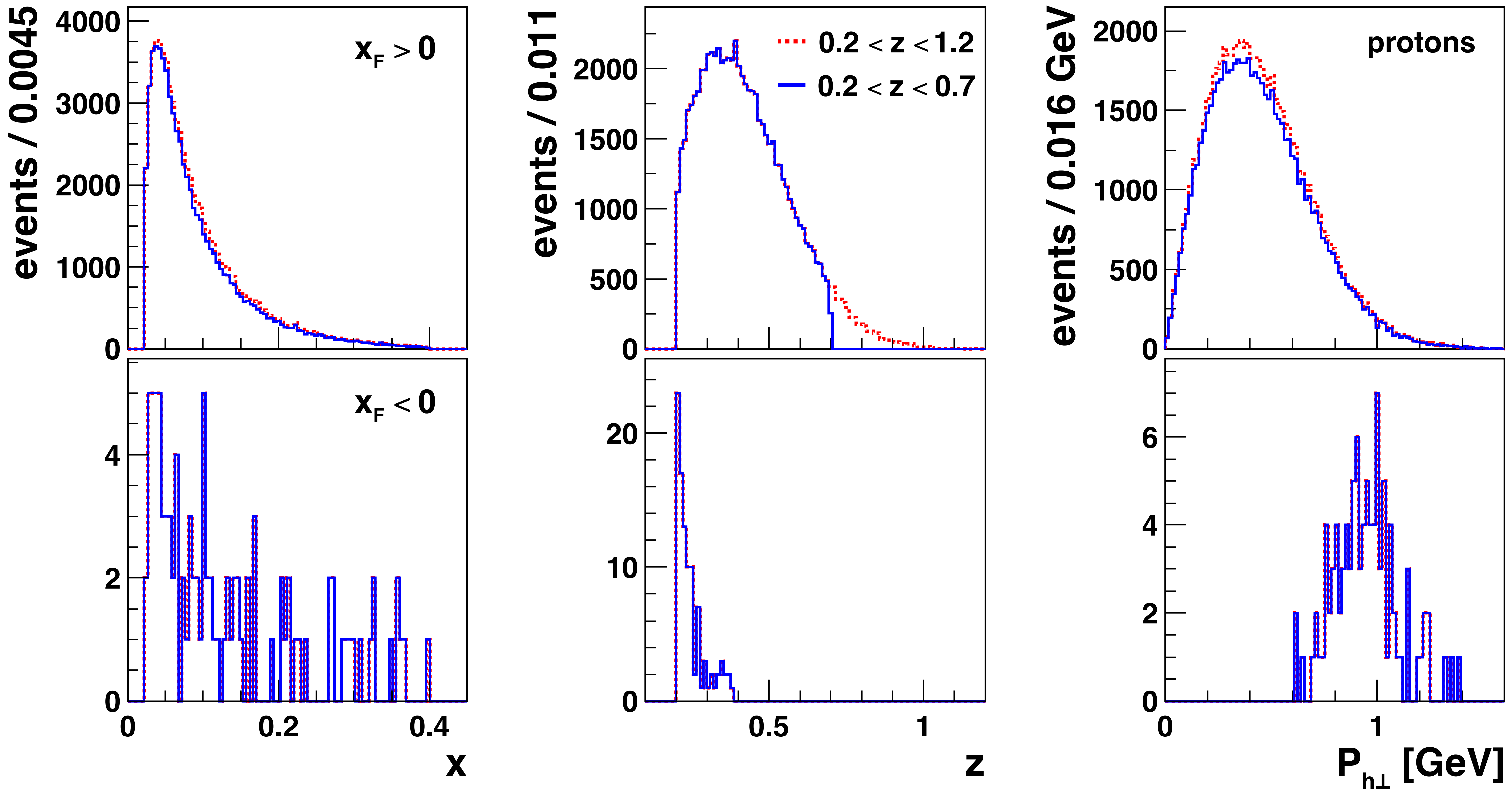
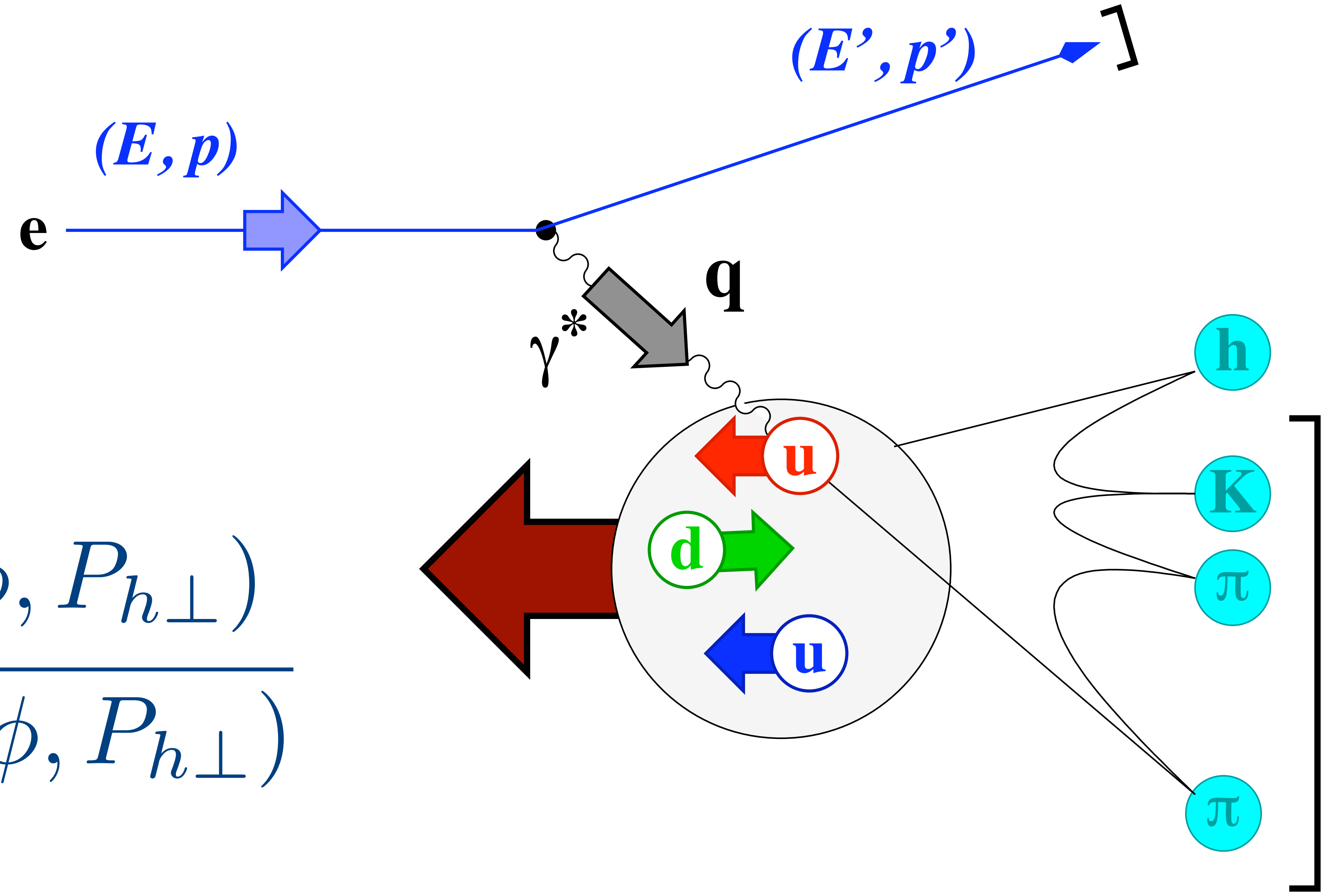


possibly, onset of target fragmentation only at lower z

detector effects in SIDIS

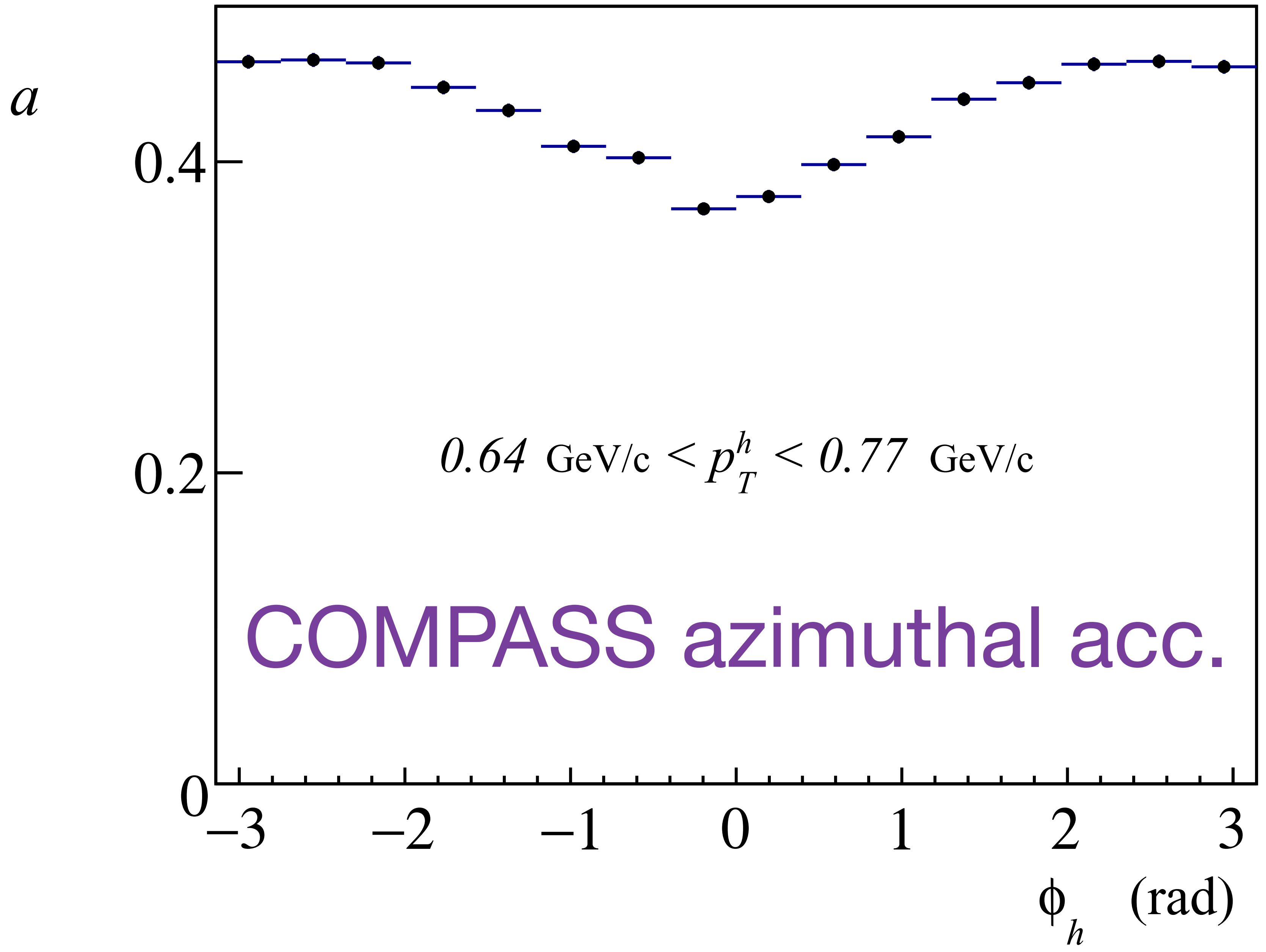


- one example of "collinear case": $A_{||}(x,z,Q^2)$
  - involves integration over typical TMD variables

$$\tilde{A}_{\|}^{h}(x,Q^2,z) = \frac{\int \mathrm{d}P_{h\perp}\,\mathrm{d}\phi\ \sigma_{\|}^{h}\left(x,Q^2,z,P_{h\perp},\phi\right)\ \xi(\phi,P_{h\perp})}{\int \mathrm{d}P_{h\perp}\,\mathrm{d}\phi\ \sigma_{UU}^{h}\left(x,Q^2,z,P_{h\perp},\phi\right)\ \xi(\phi,P_{h\perp})}$$

  - both cross sections depend on TMD variables, and this correlated with kinematics
    ➥ couples to acceptance dependence on those variables
    ➥ can easily reduce/increase observed asymmetry
    [same is true for hadron multiplicities]

[Nucl. Phys. B 886 (2014) 1046–1077]



- ideally, fully differential analysis
  ➥ in practice, resort to more approximate methods with reliable systematics