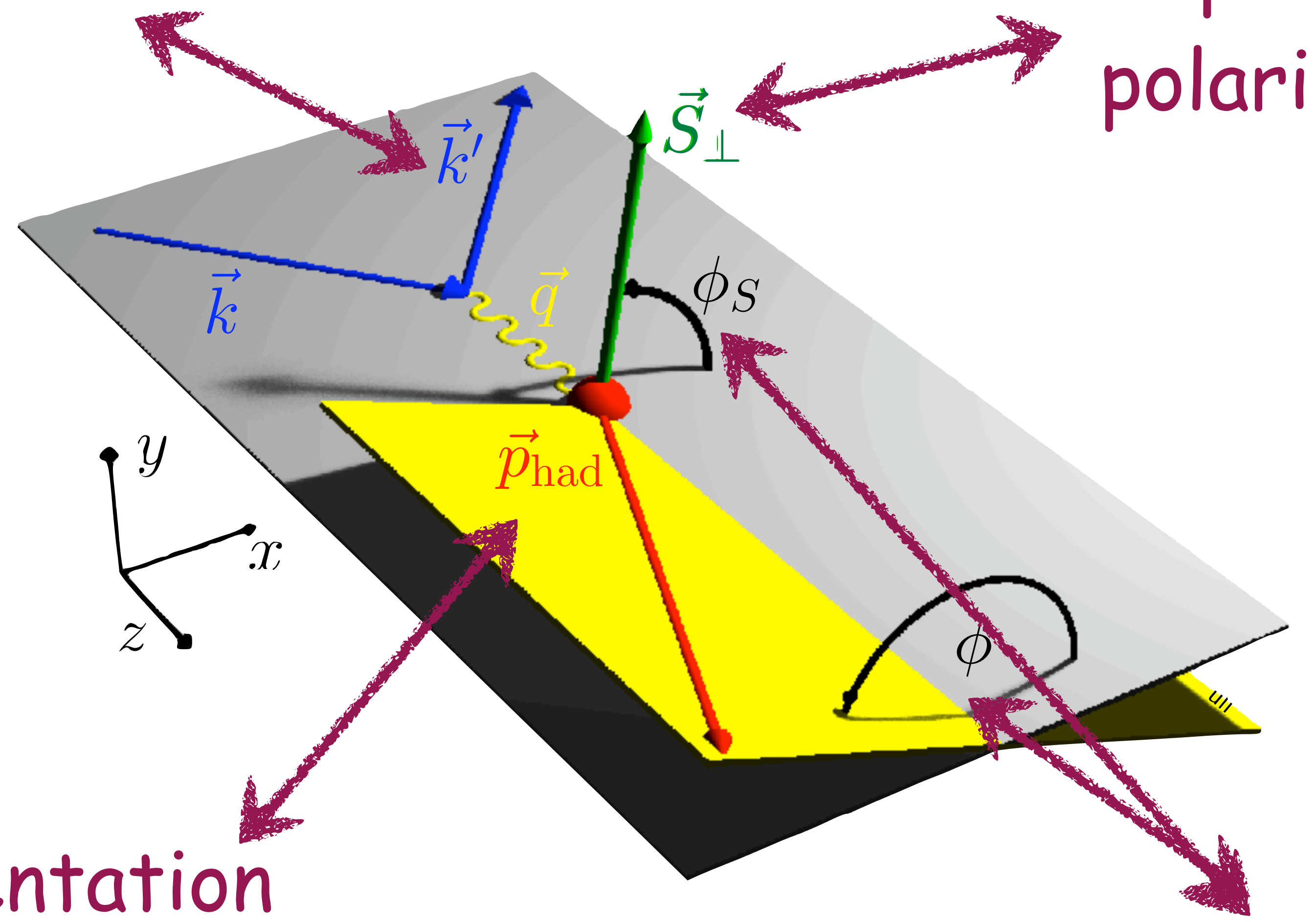
From Quarks and Gluons to the Internal Dynamics of Hadrons
CFNS@Stony Brook — May 15-17, 2024



Multi-d SIDIS Analyses

a personal HERMES-biased perspective on challenges and achievements

Gunar.Schnell @ DESY.de

STRONG-2020
ikerbasque Basque Foundation for Science
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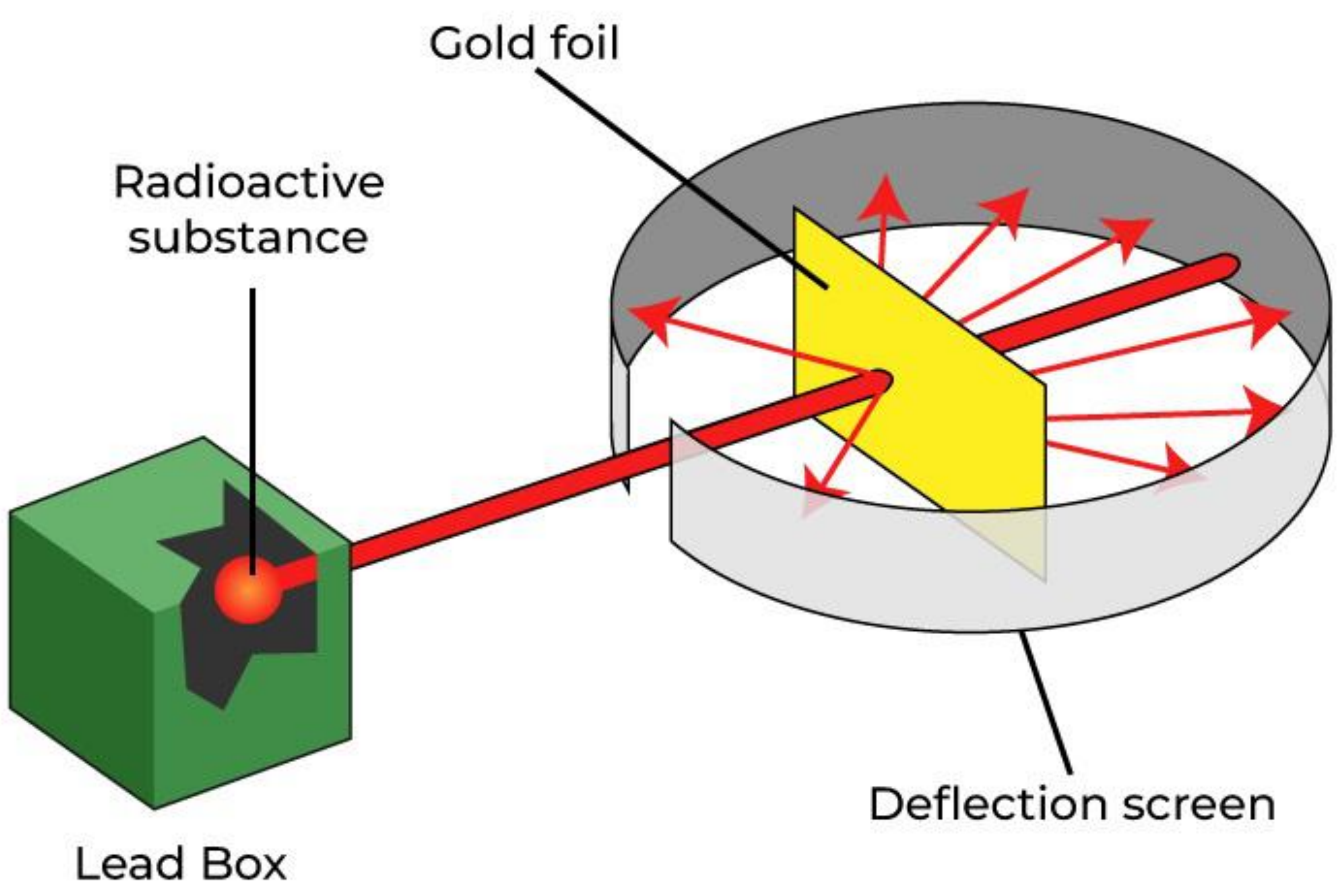
Universidad del País Vasco Euskal Herriko Unibertsitatea

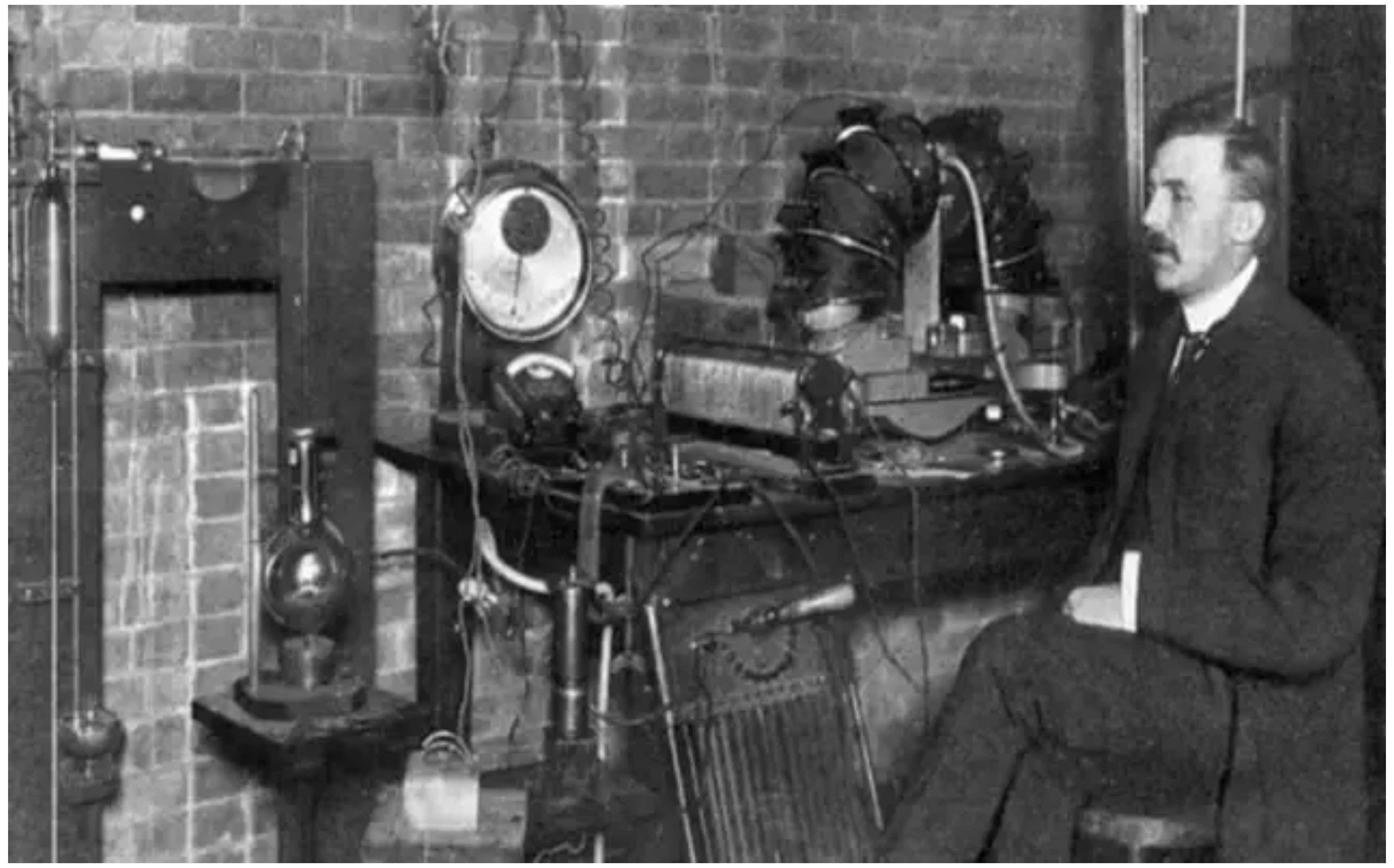
disclaimer: after two and a half days of intense
discussion, refrain from introducing
basics of SIDIS and PDFs, TMDs, and FFs

➟ cf. Ralf's talk yesterday

from 1d to 9d

- a century ago, things were “simple”:





from 1d to 9d

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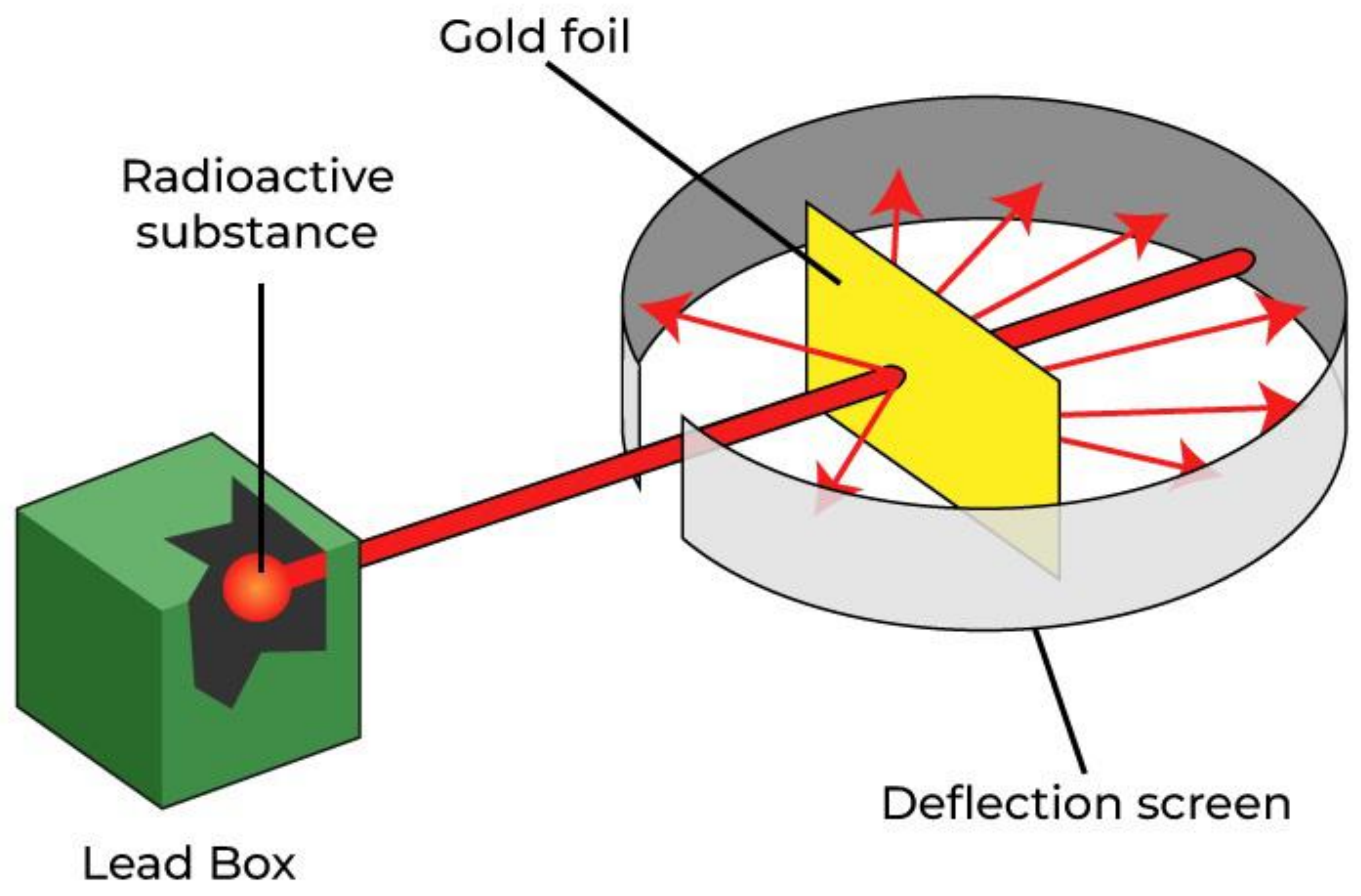
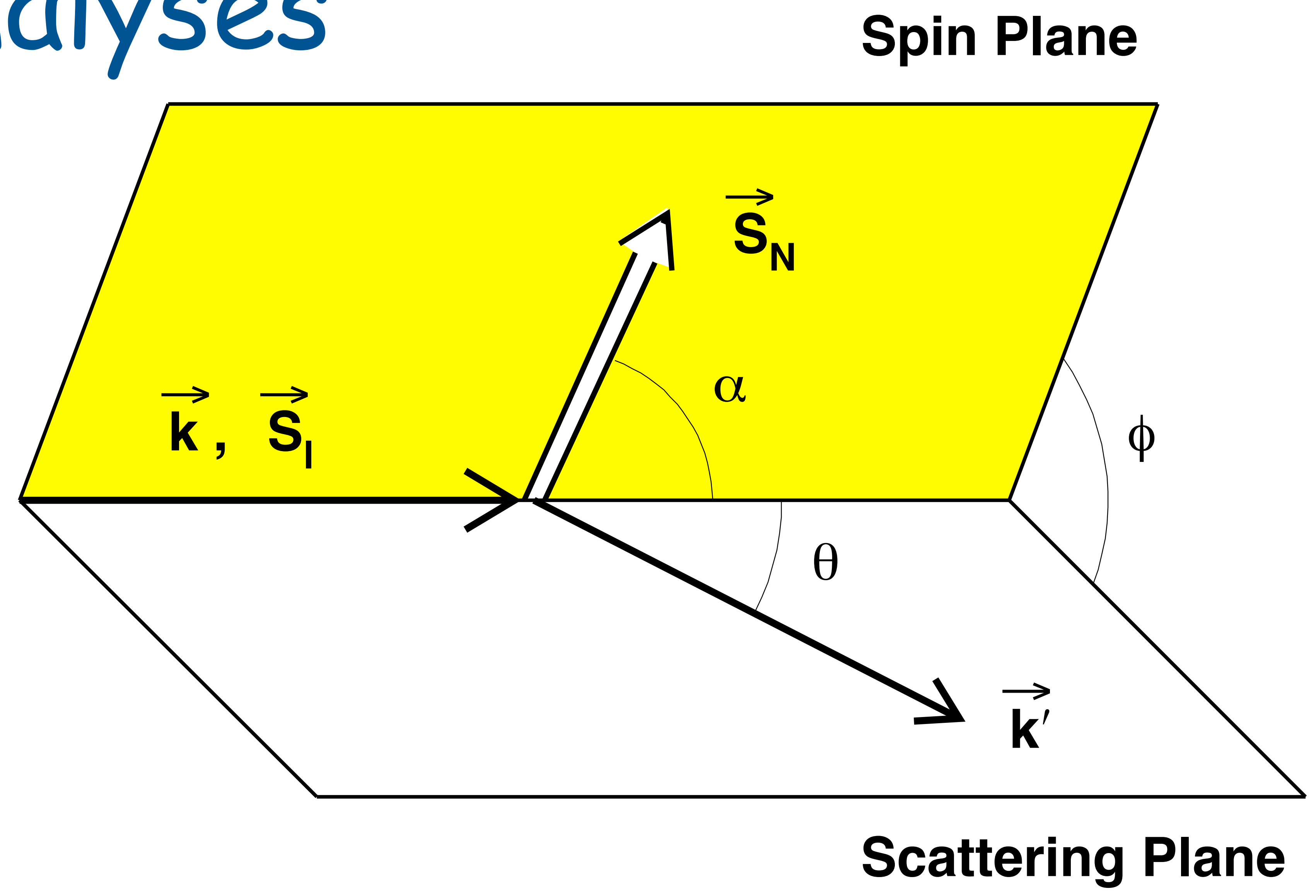


- inclusive DIS already requires 2d or 3d analyses



from 1d to 9d

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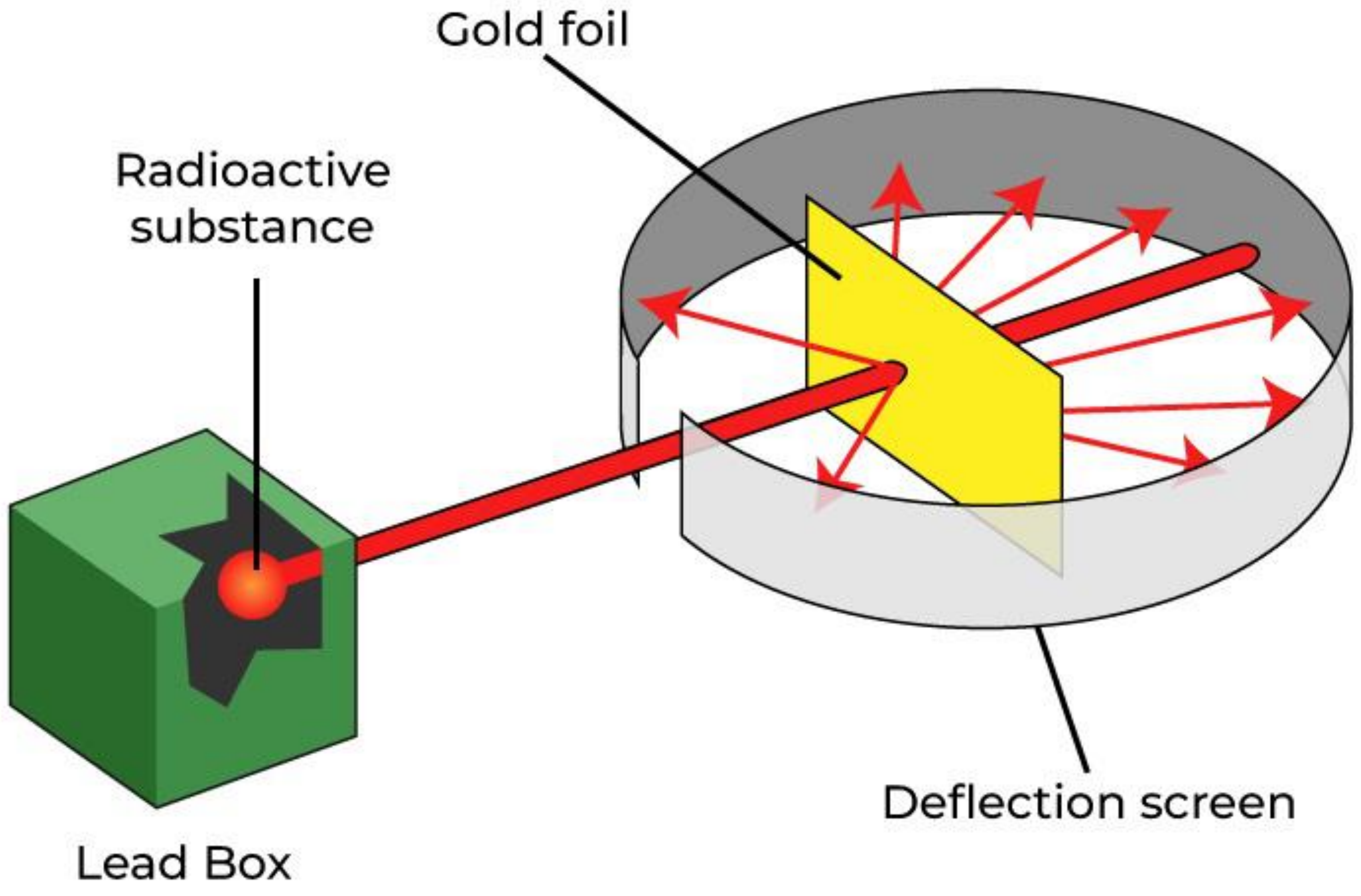
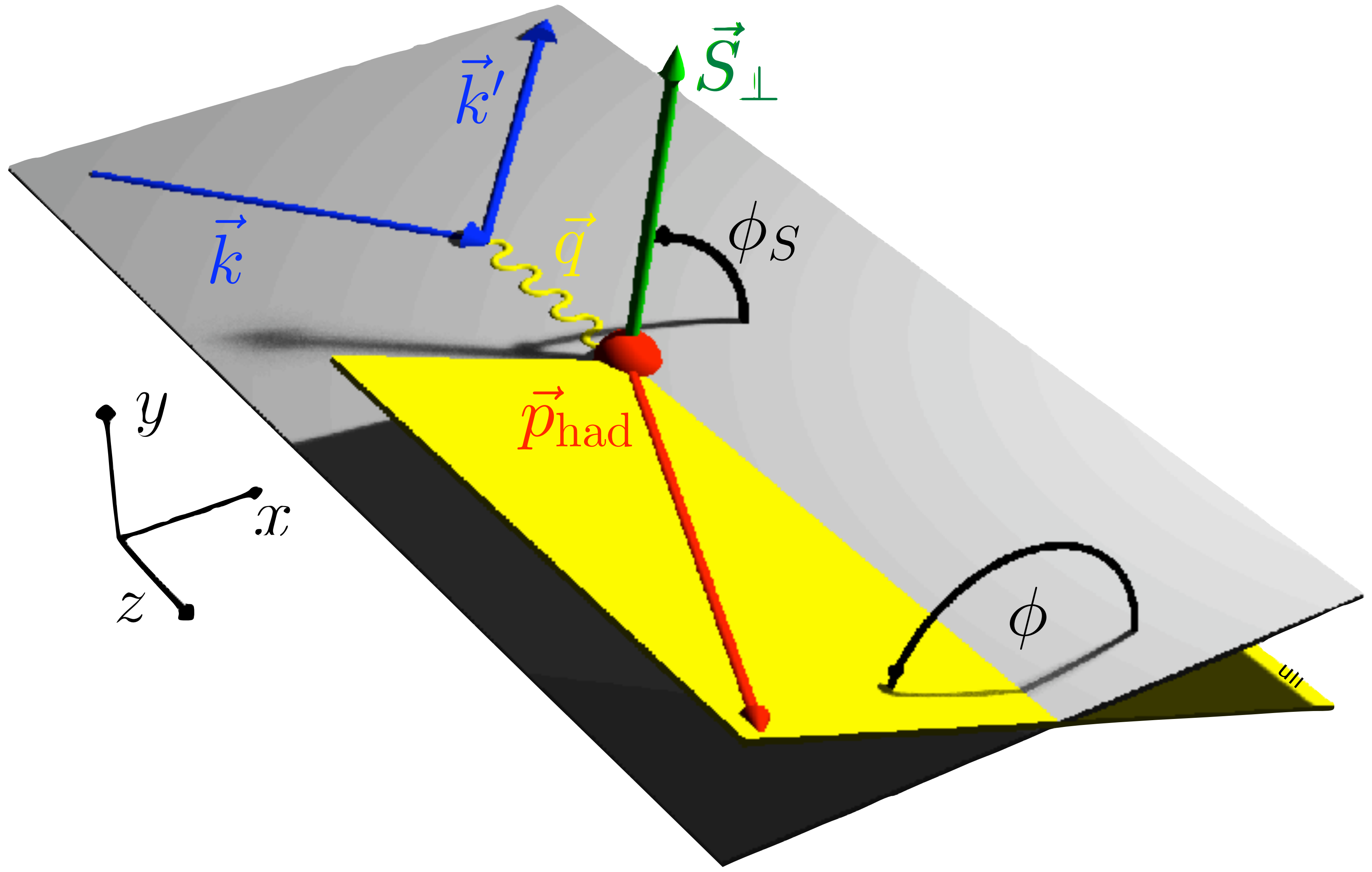


- inclusive DIS already requires 2d or 3d analyses
- semi-inclusive single-hadron DIS: up to 6d



from 1d to 9d

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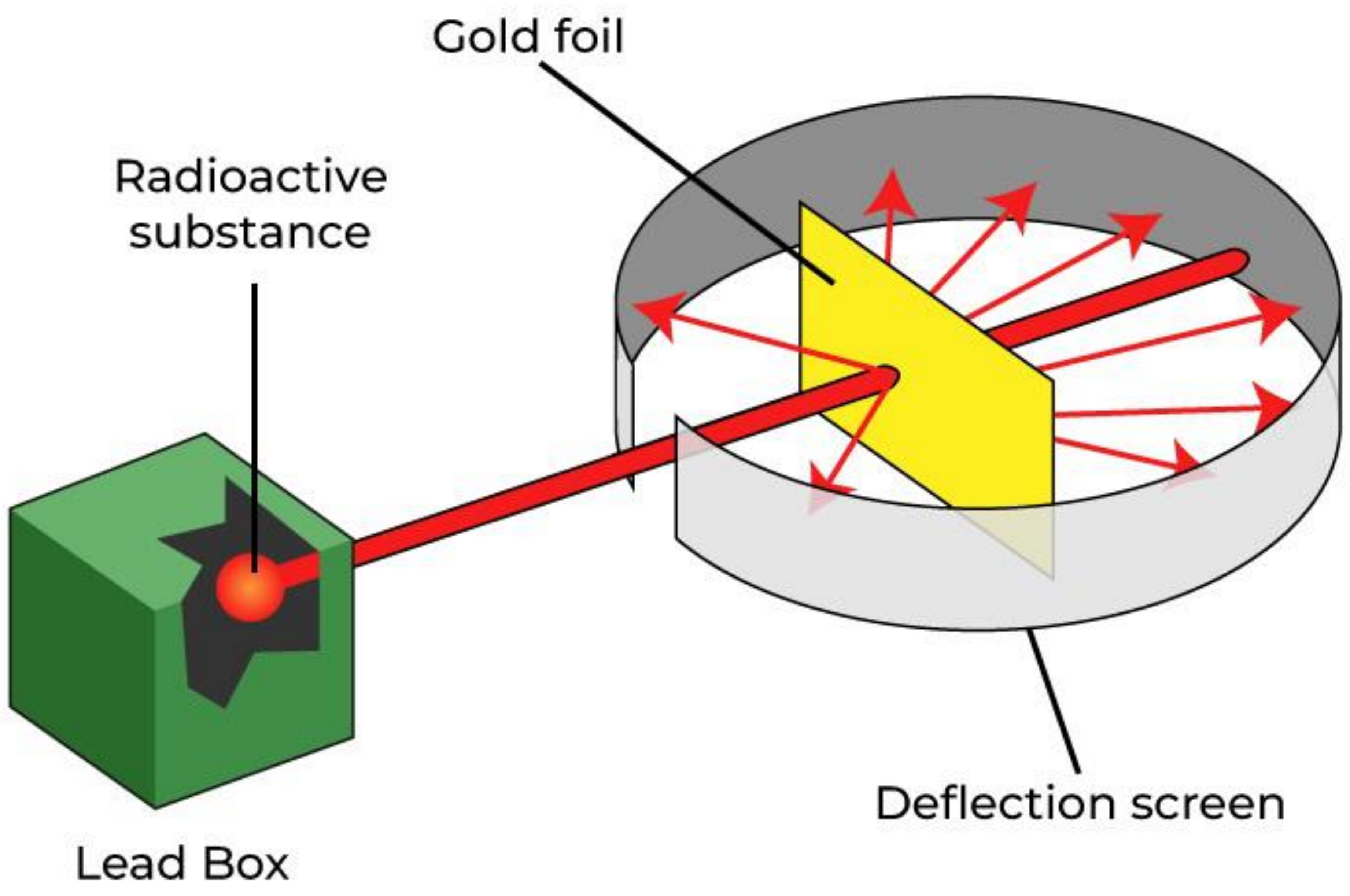
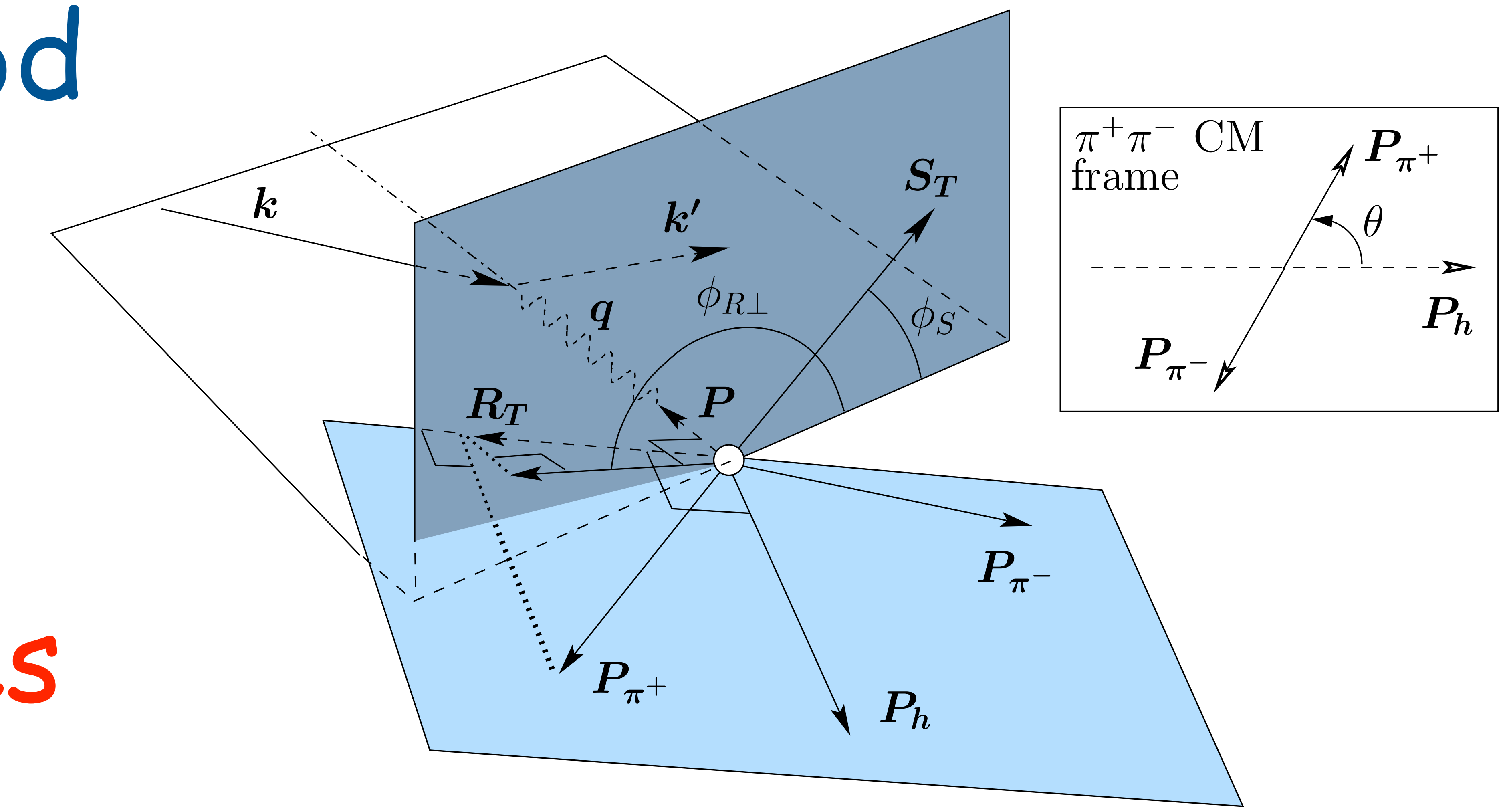


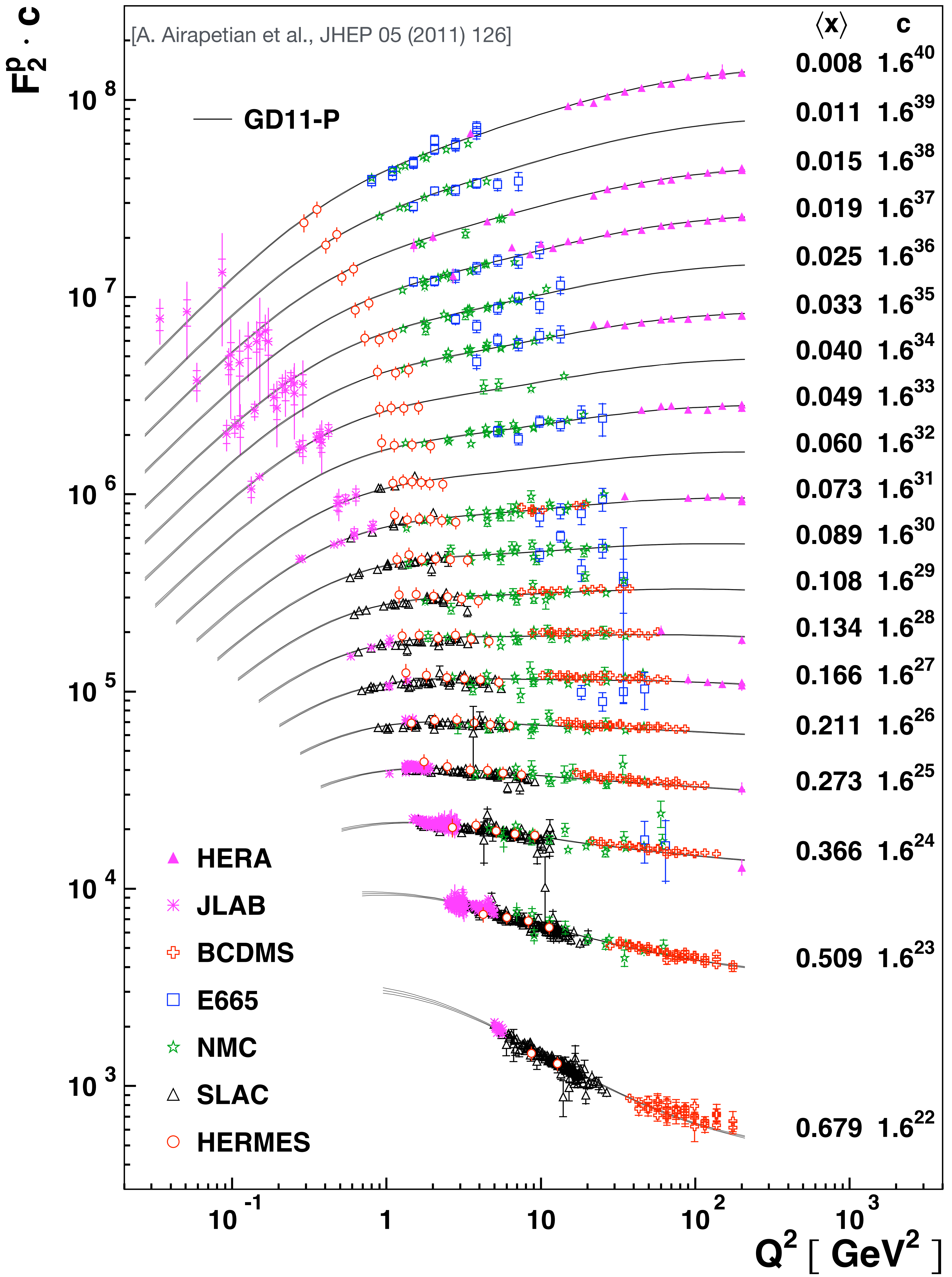
- inclusive DIS already requires 2d or 3d analyses
- semi-inclusive single-hadron DIS: up to 6d
- semi-inclusive di-hadron DIS: up to 9d



➡ both theoretical & experimental challenges

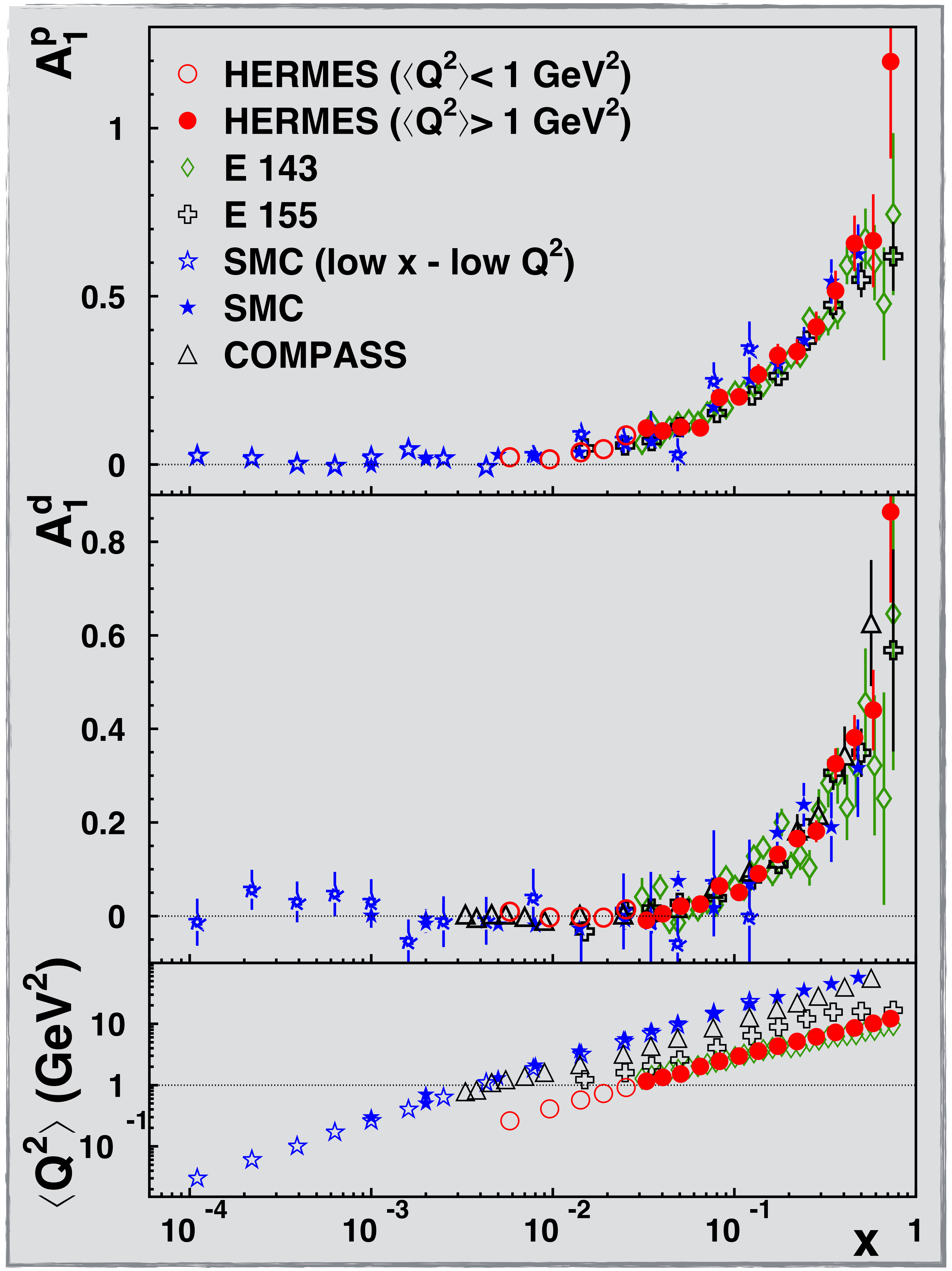
from 1d to 9d

- unpolarised DIS: obviously bin and unfold in 2d



from 1d to 9d

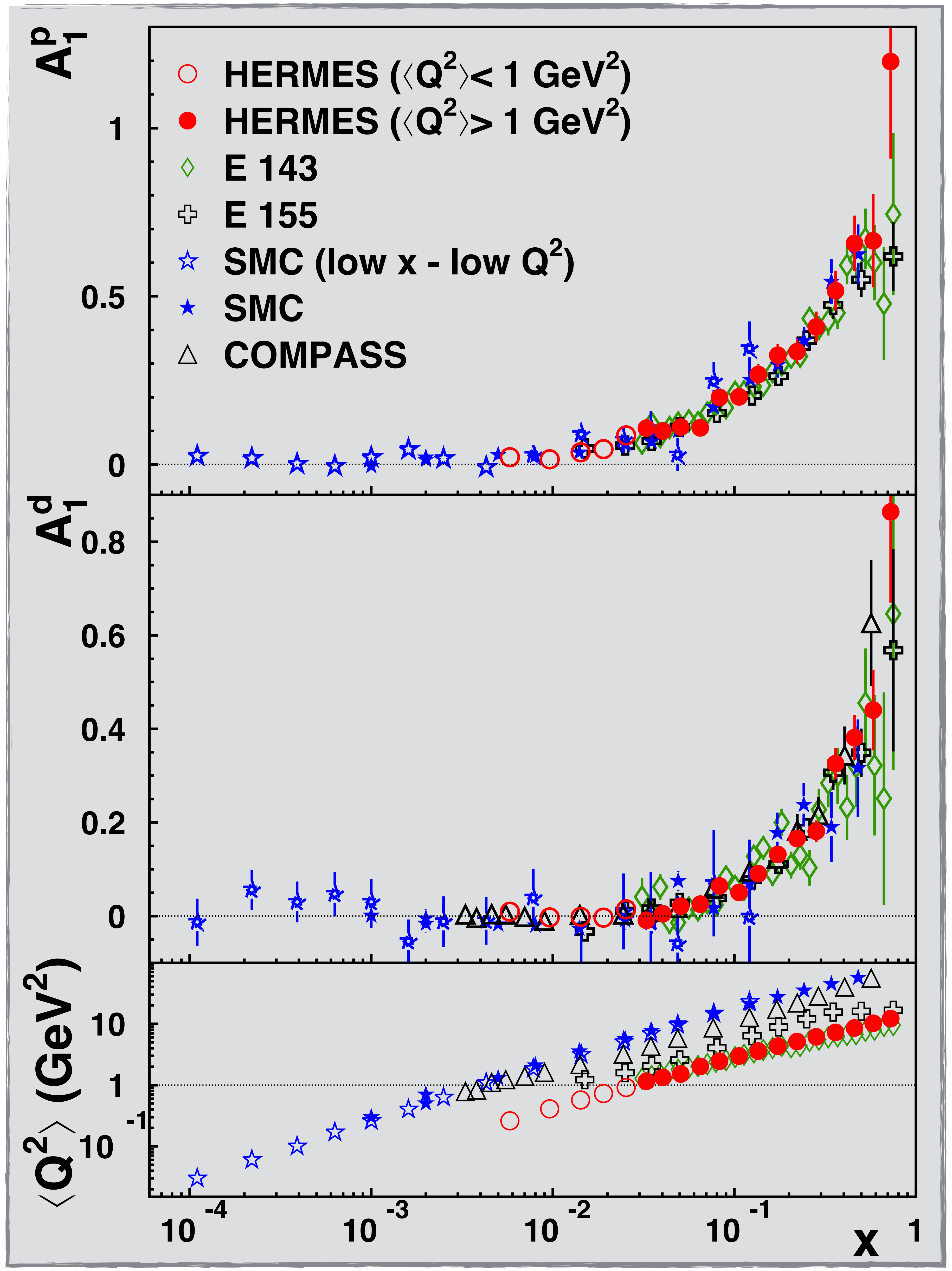
- unpolarised DIS: obviously bin and unfold in 2d
- inclusive scattering spin-asymmetries: "saved" by weak Q^2 dependence of longitudinally double-polarised DIS



from 1d to 9d

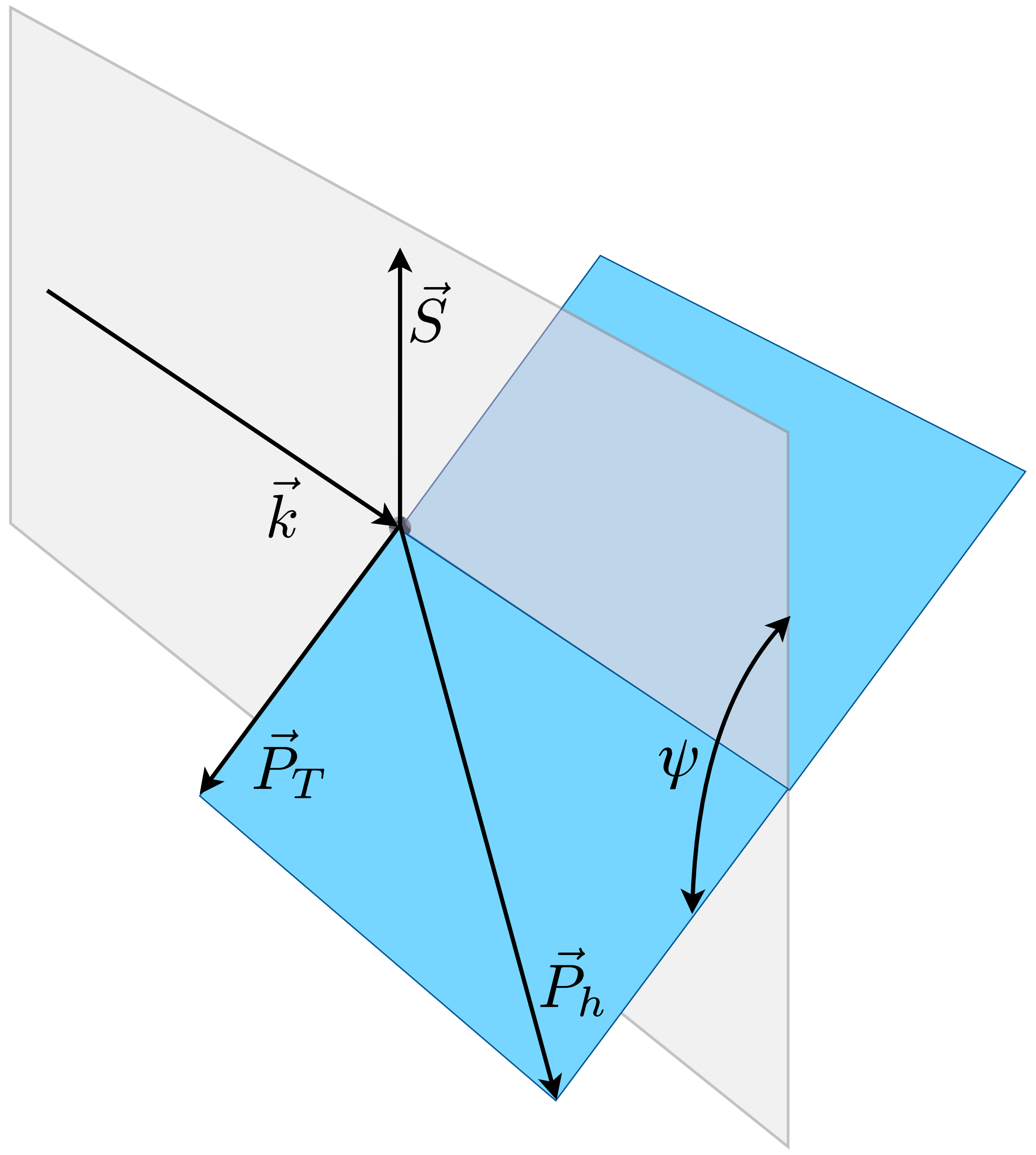
- unpolarised DIS: obviously bin and unfold in 2d
- inclusive scattering spin-asymmetries: "saved" by weak Q^2 dependence of longitudinally double-polarised DIS
- however, don't be misled!
  - g_2, A_{UT}, ...

➡ binning in only one variable might hide dependence on other variable(s)

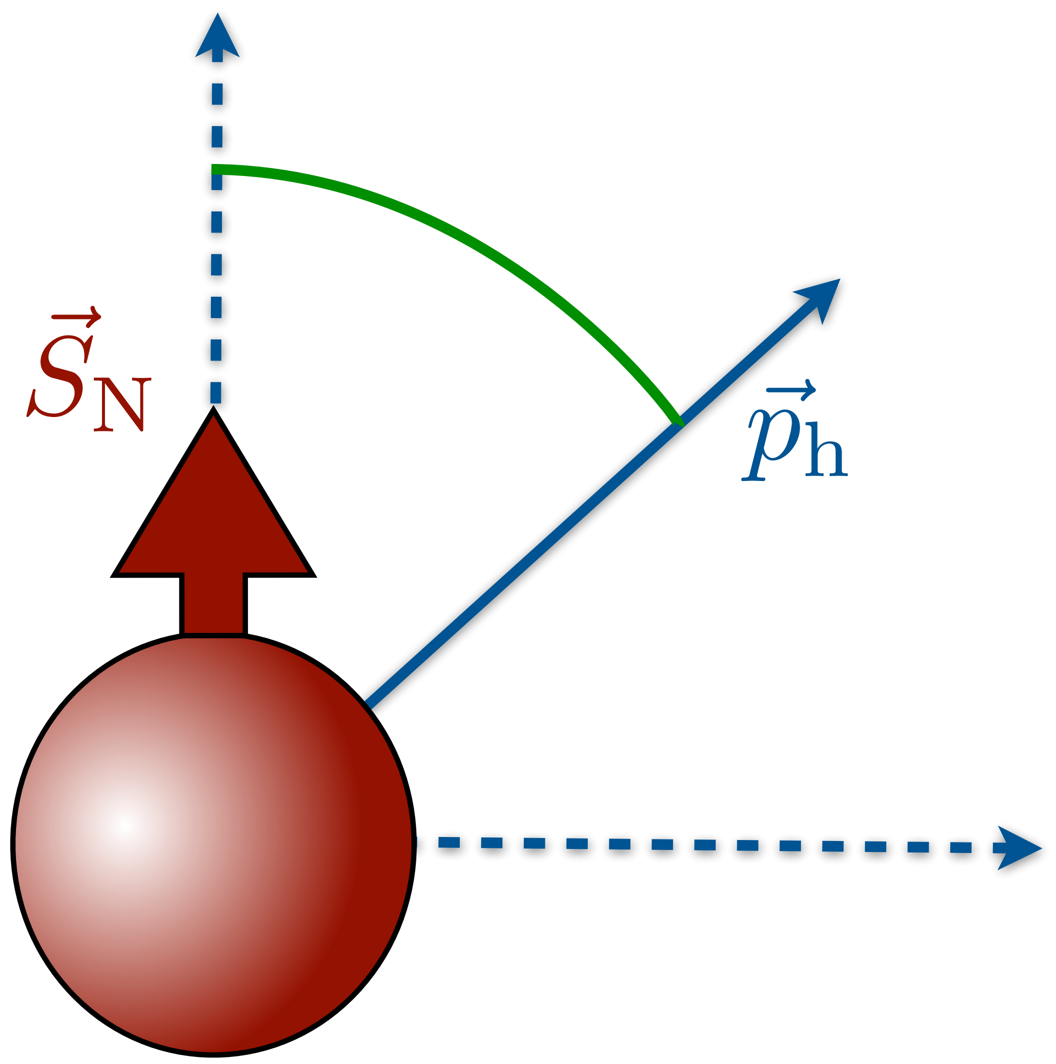


inclusive hadrons: A_{UT} sinψ amplitude

- clear left-right asymmetries for pions and positive kaons

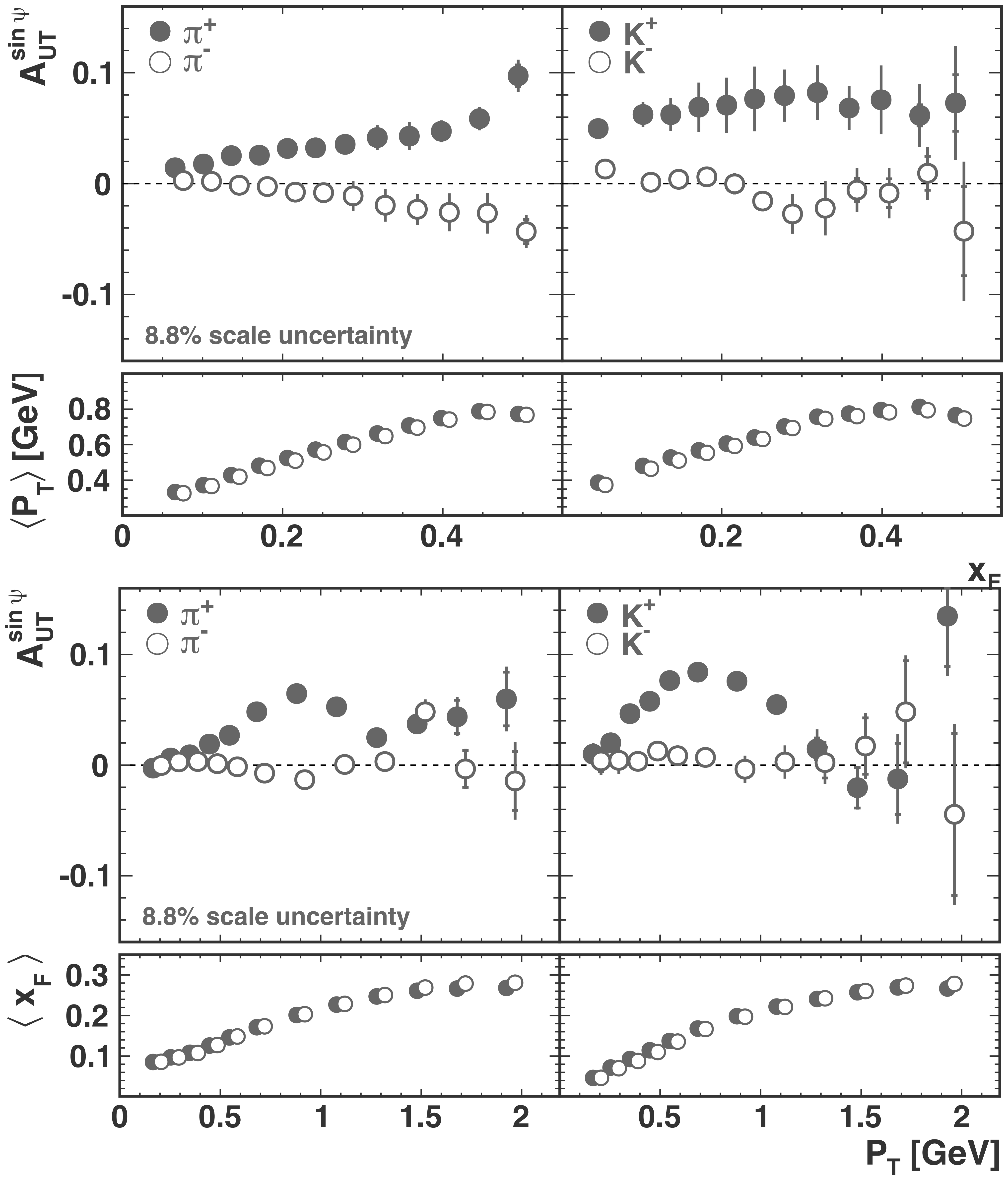


$$ep^{\uparrow} \rightarrow hX$$



lepton going into the plane

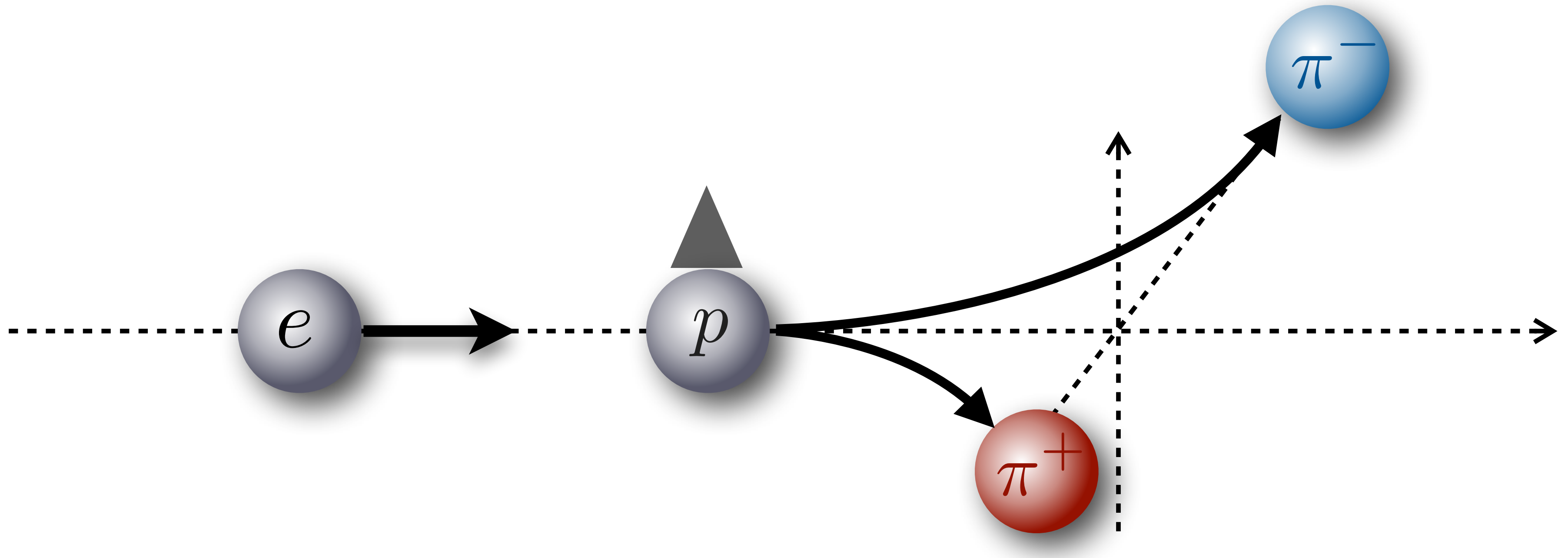
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



inclusive hadrons: A_{UT} sinψ amplitude

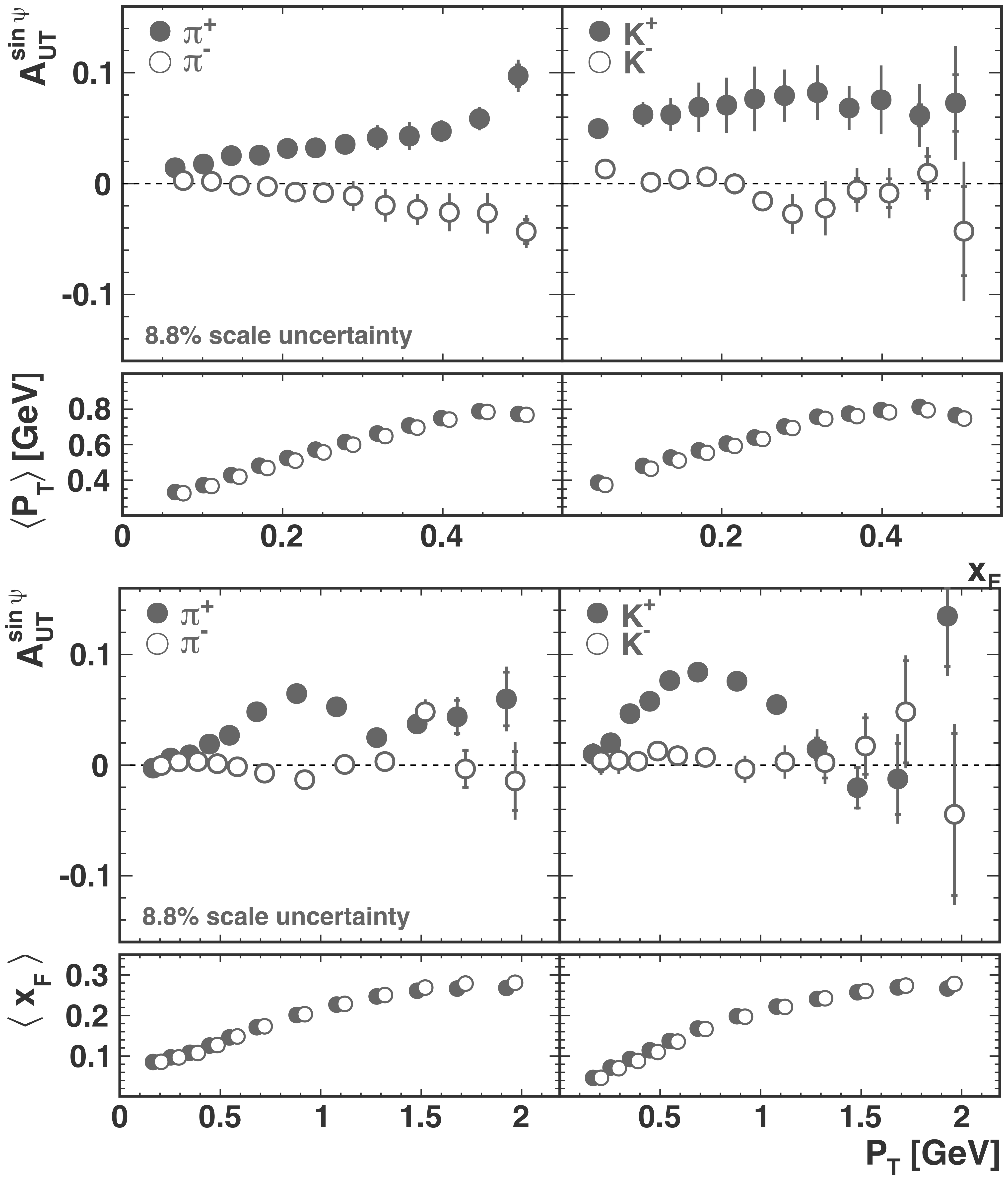
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]

- 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
- x_F and P_T correlated

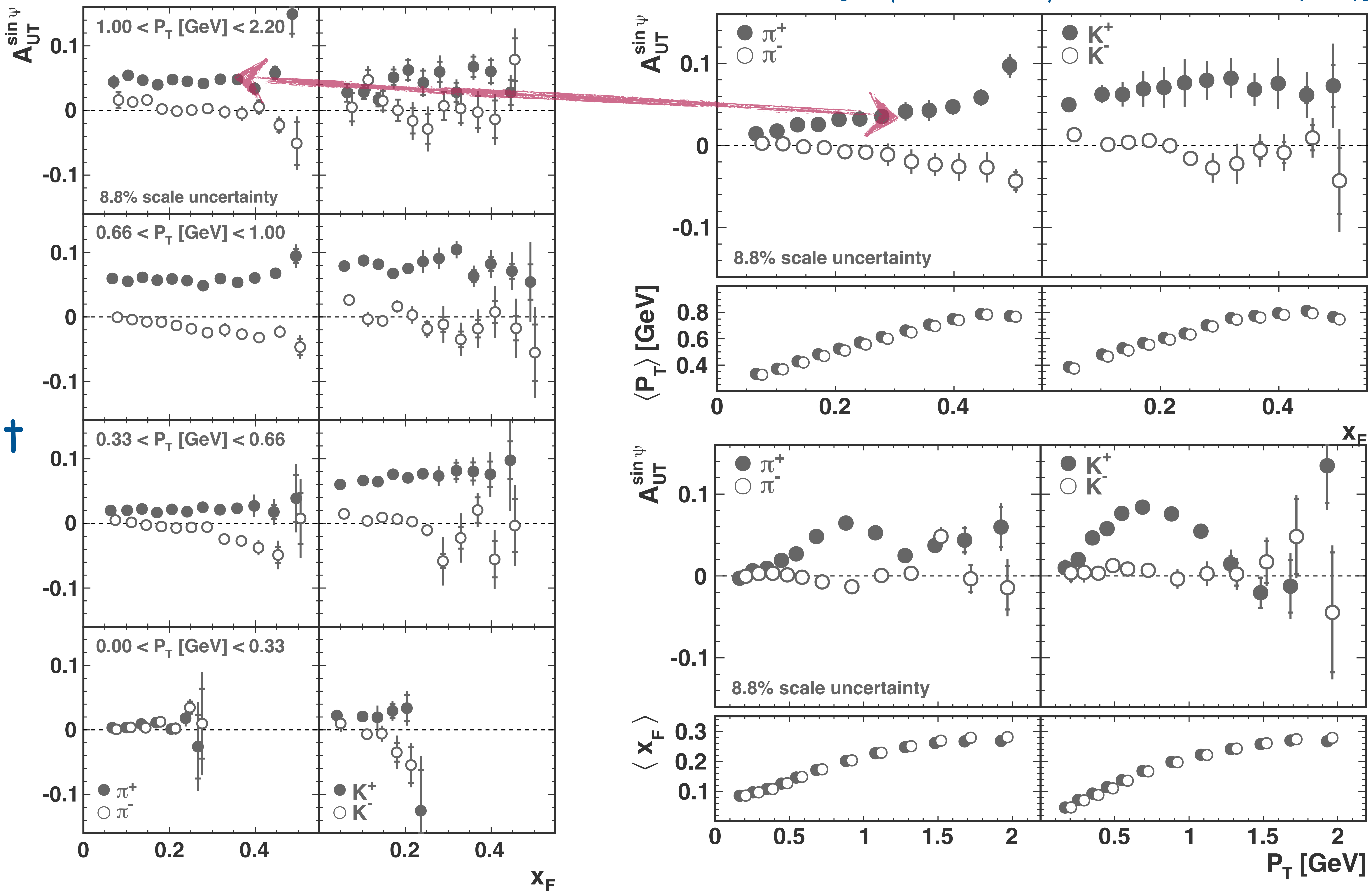
➥ look at 2D dependences



inclusive hadrons: A_{UT} sinψ amplitude

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

- increase with x_F disappears in 2d binning
- increase in 1d presentation result of underlying P_T dependence



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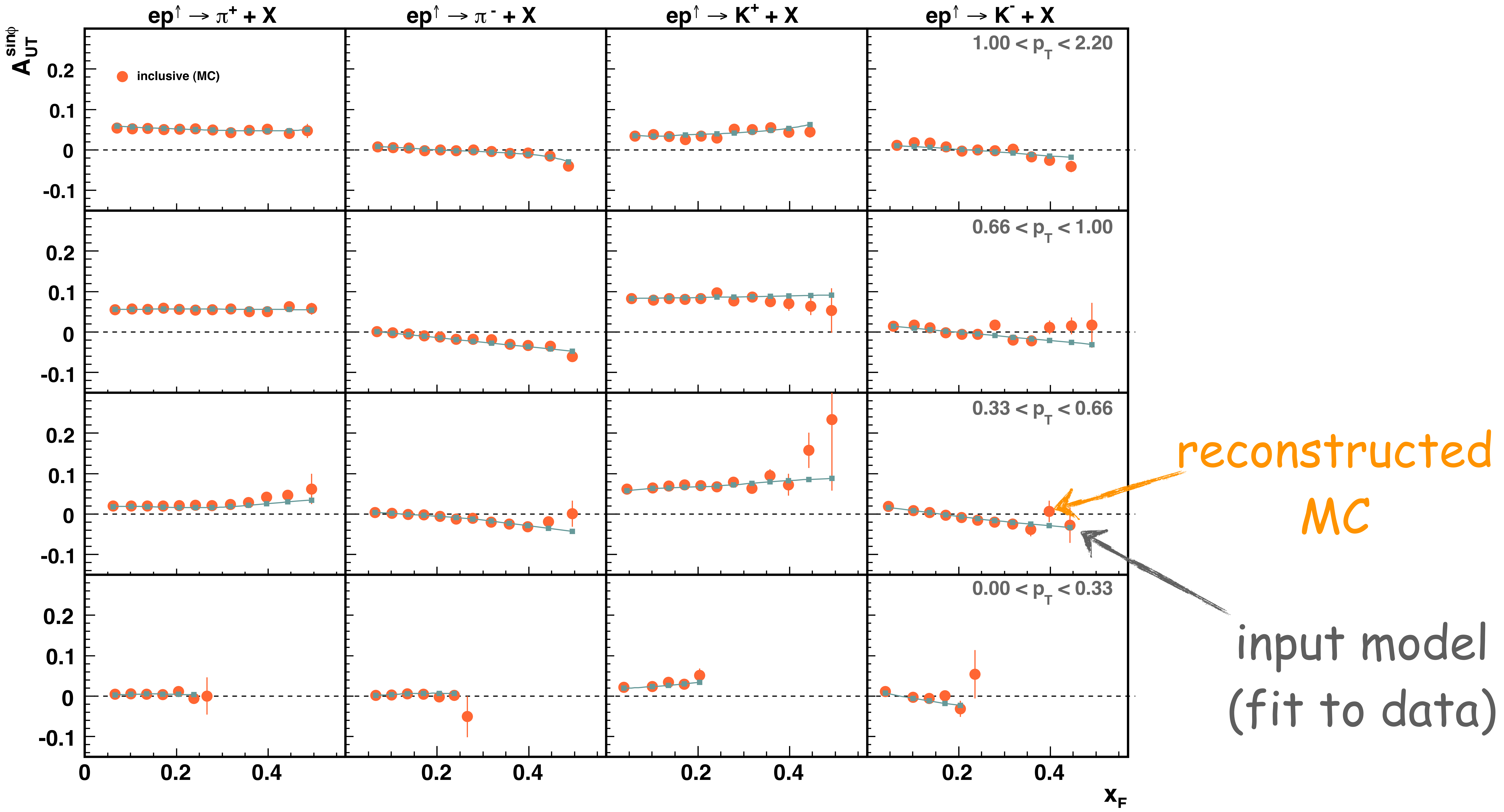
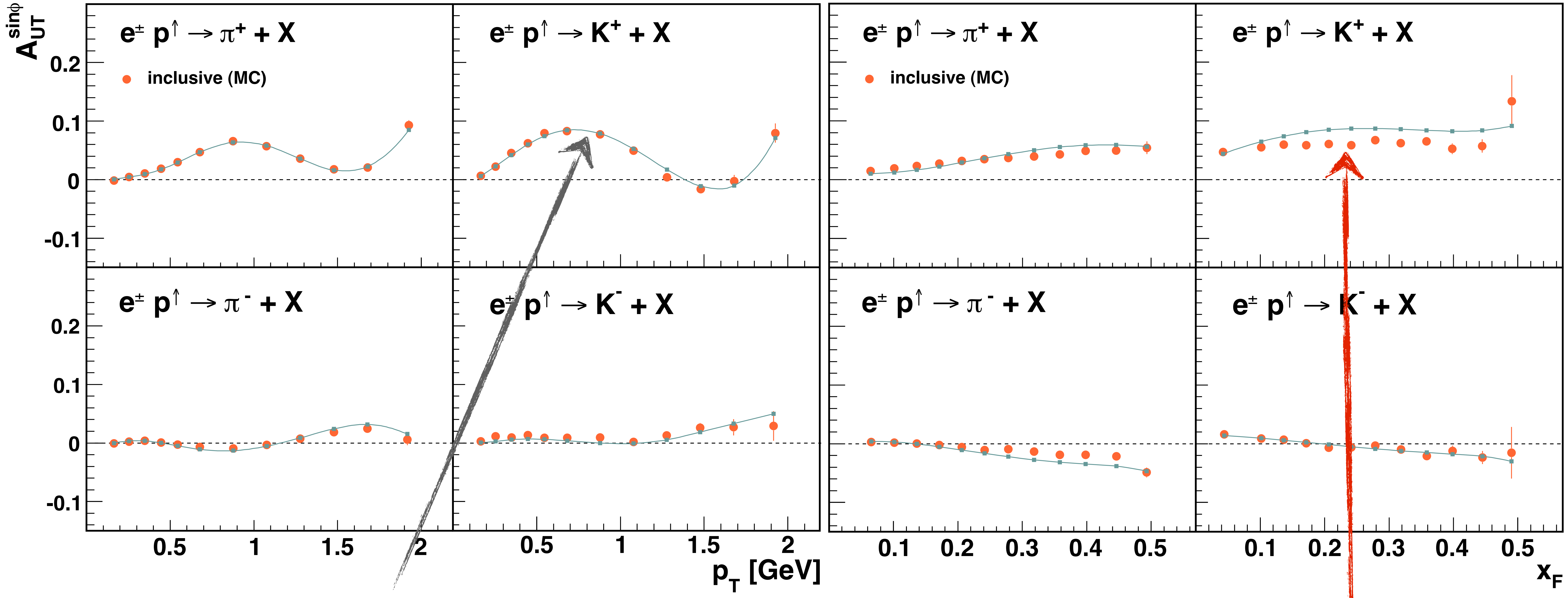


small detector effects in fully differential analysis

inclusive hadrons: A_{UT} sinψ amplitude



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

not so small detector effects in 1D analysis

➟ need a good MC model for realistic uncertainty estimate

so why have we stayed with 1d?

- somewhat more objective reasoning: e.g.,
  - weak Q^2 dependence of asymmetries
- some pragmatic reasoning: e.g.,
  - less precision
  - less phase space and thus less variation of cross sections, …
- some plainly wrong reasoning: e.g.,
  - stick to the approach that seemed to work before
  - multi-d dependences difficult to visualise
  - "we are doing collinear physics, no need for TMD d.o.f.

… example measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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

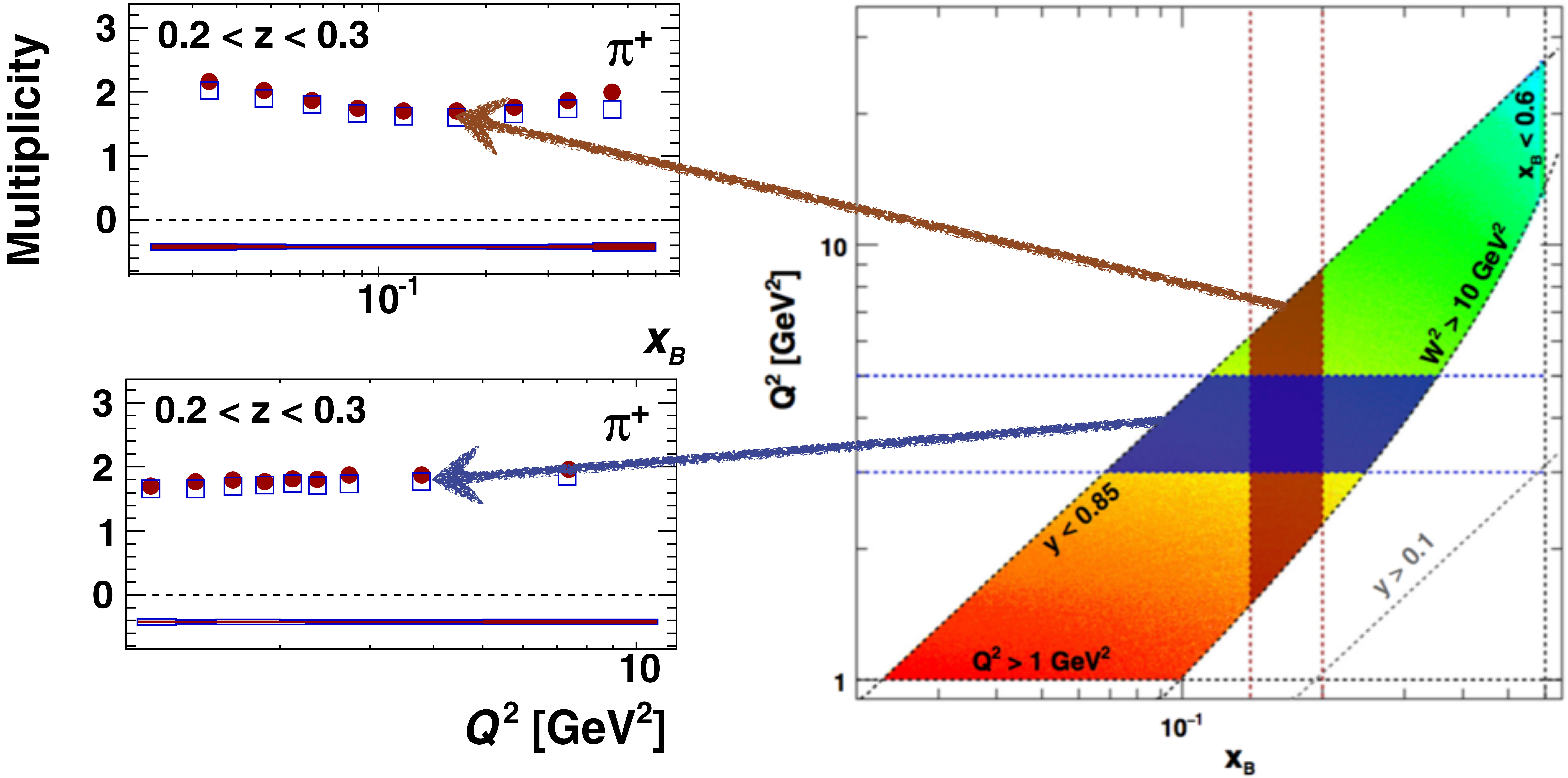
$$\frac{d^5\sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

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

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

moments:
normalize to azimuth-independent cross-section

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



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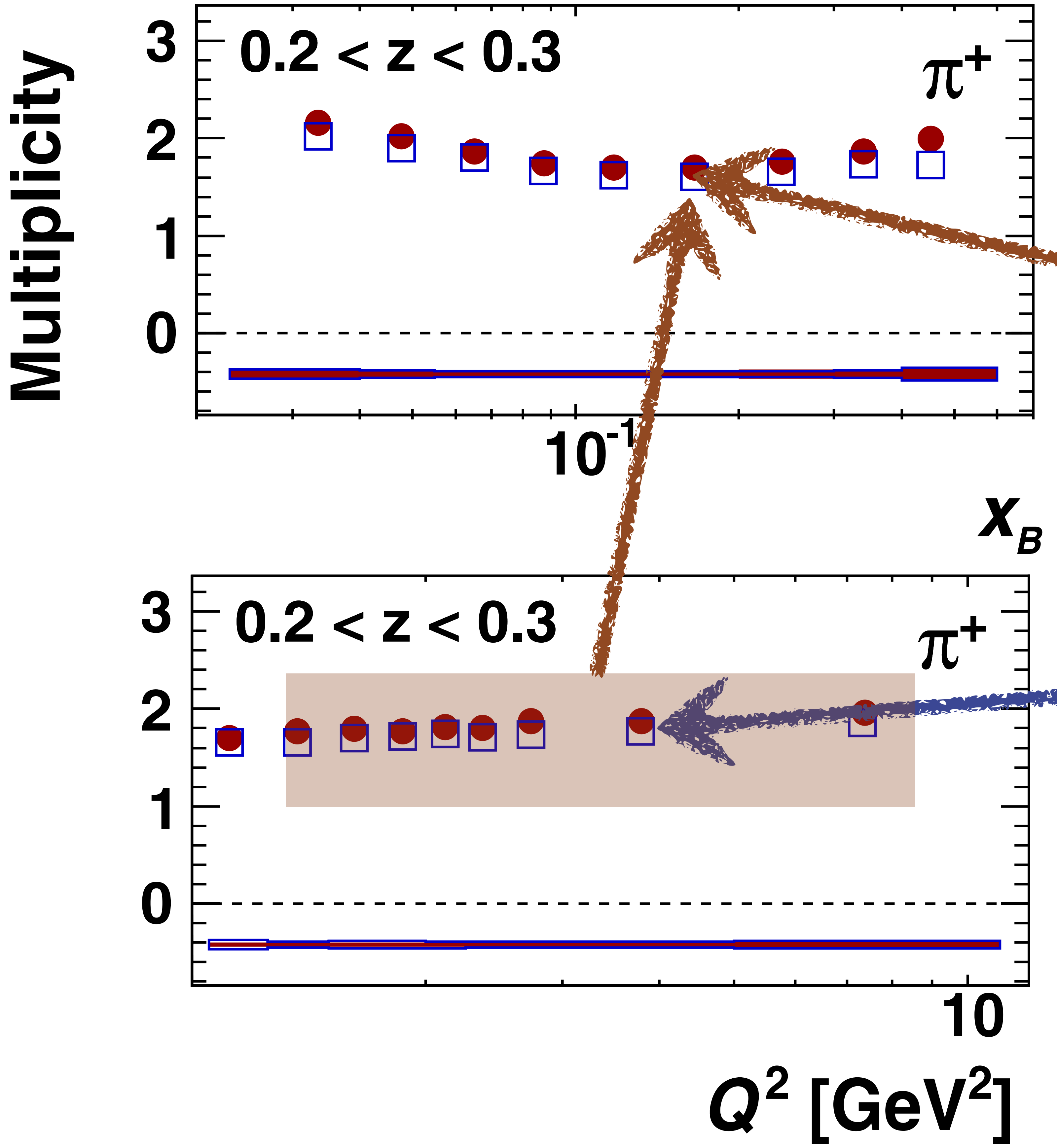

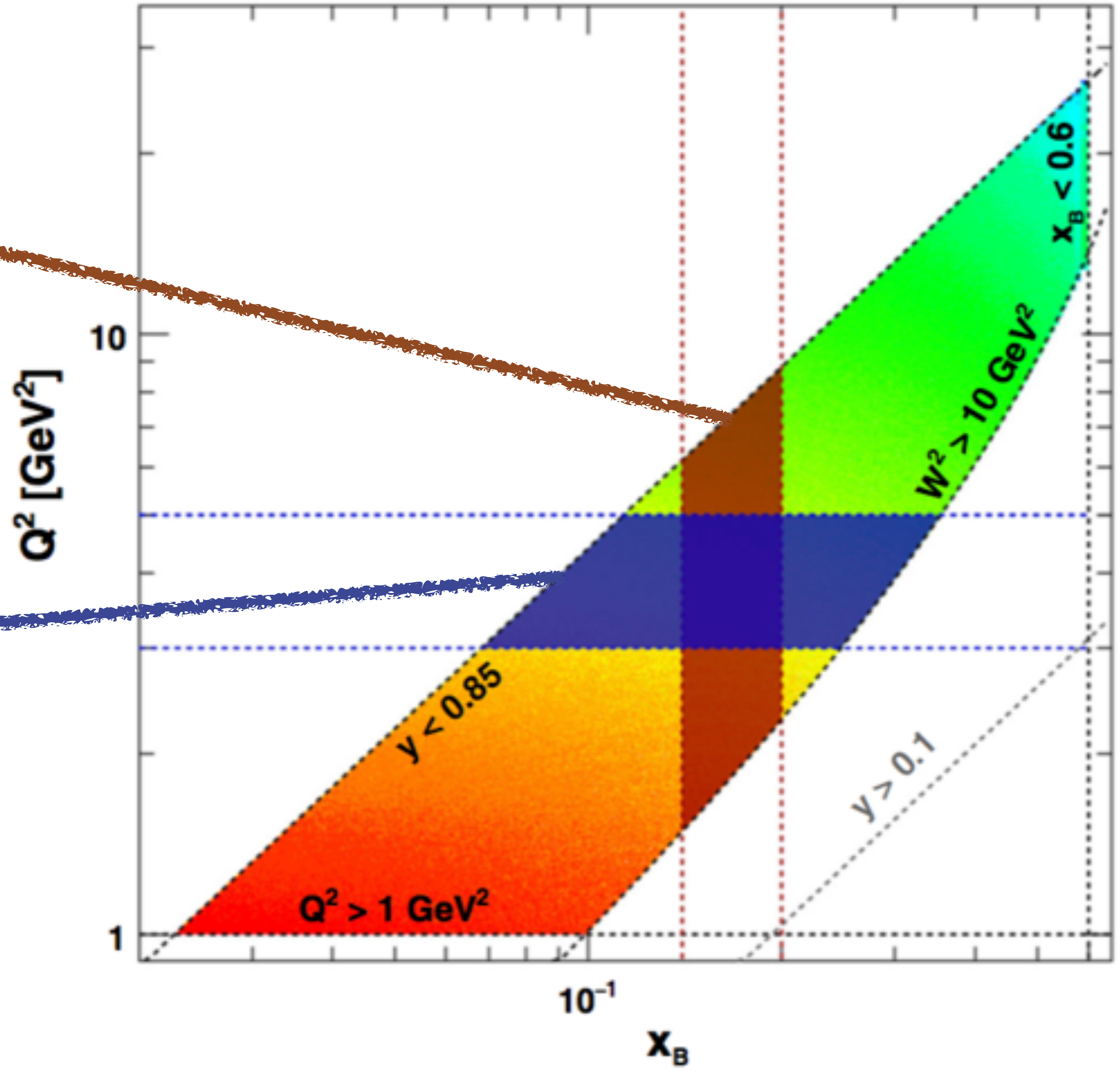

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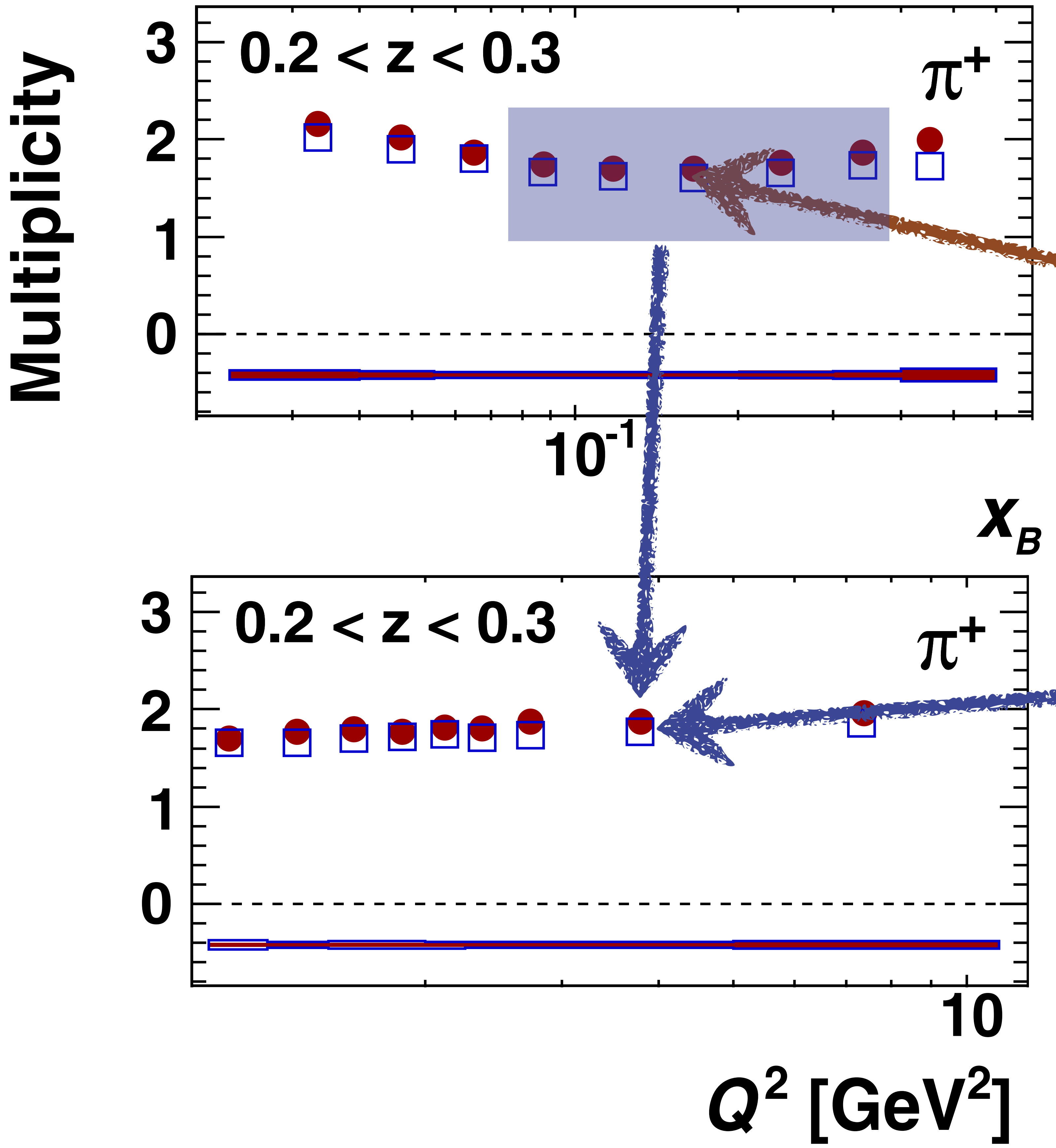

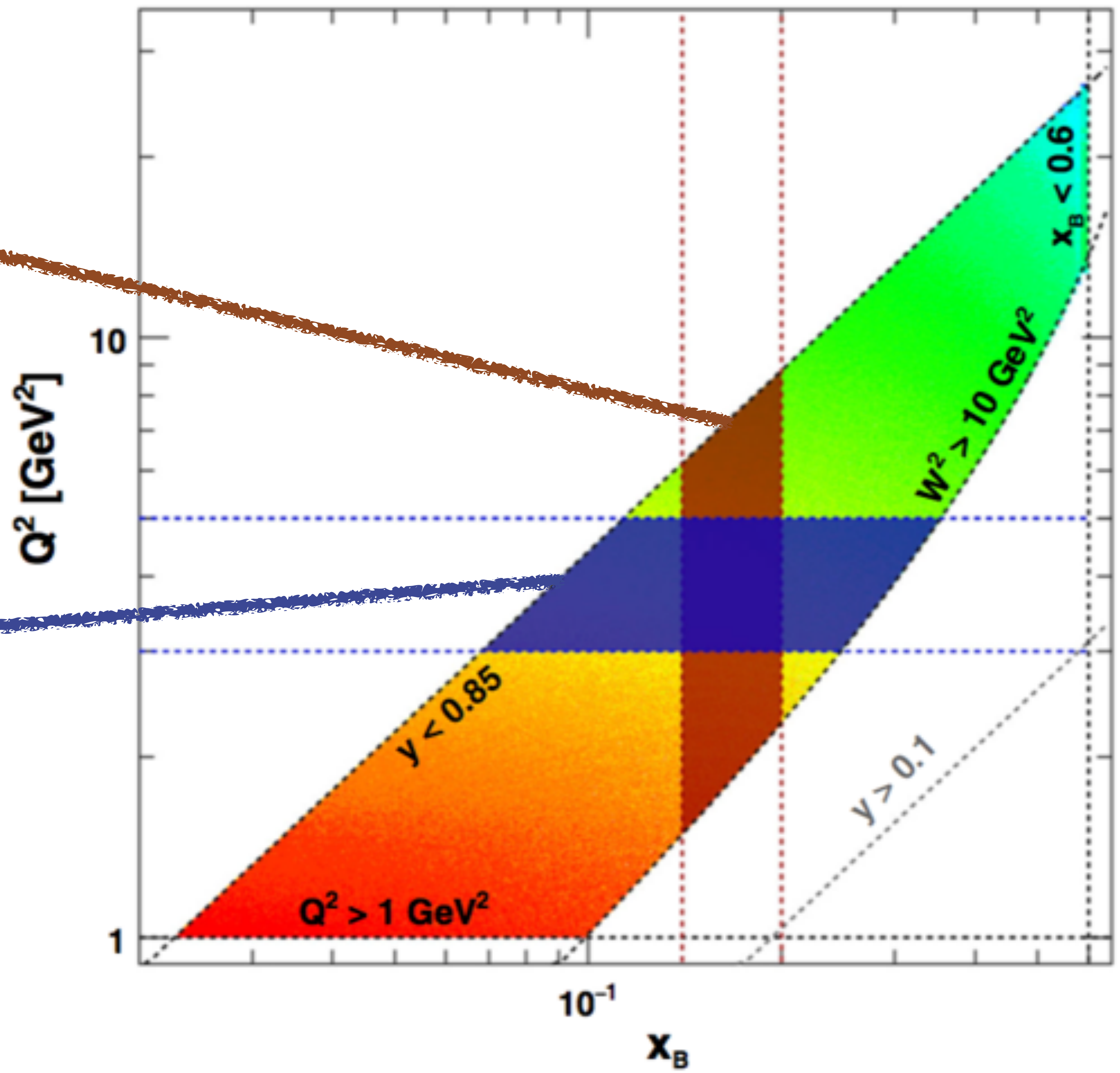

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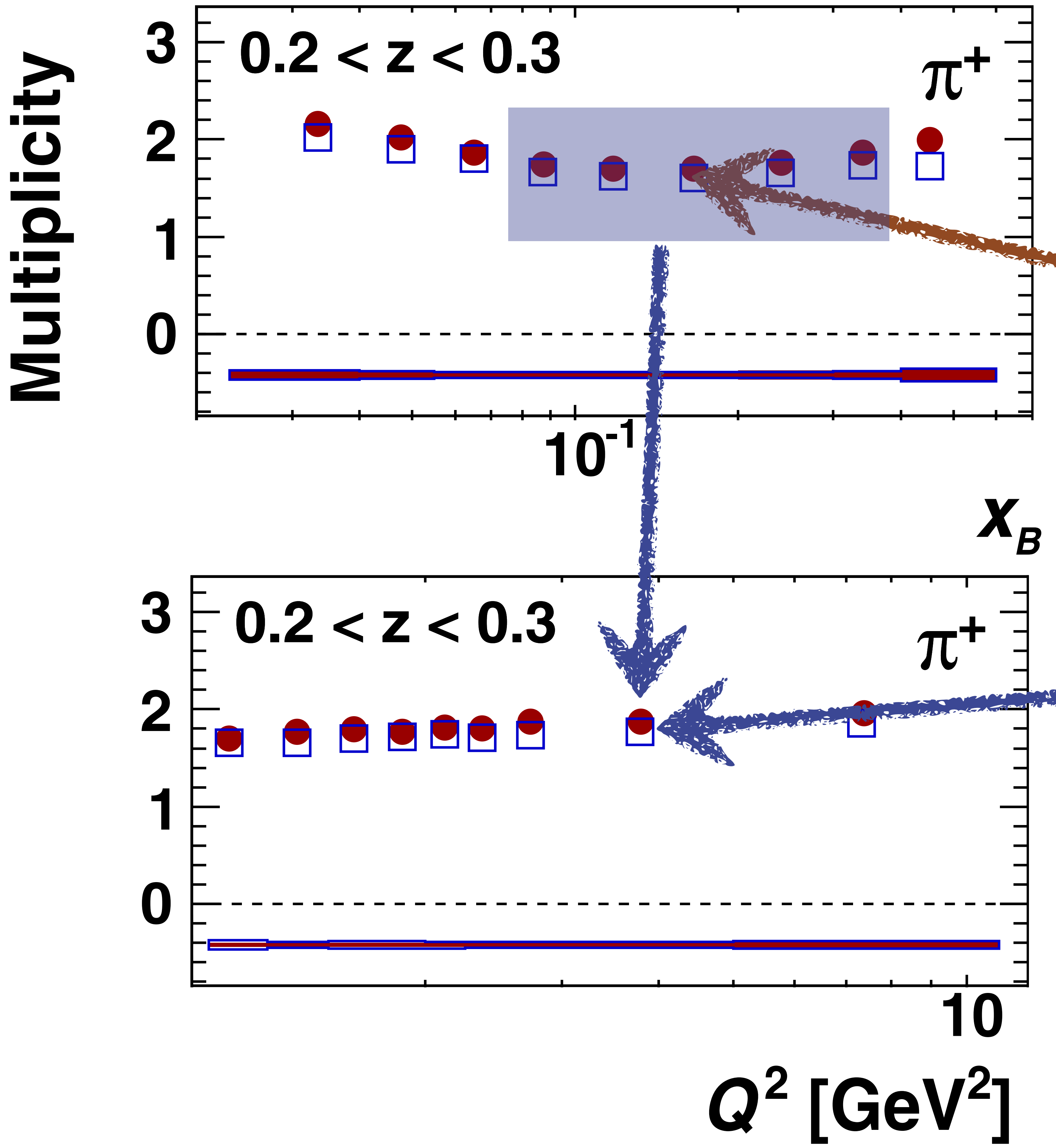
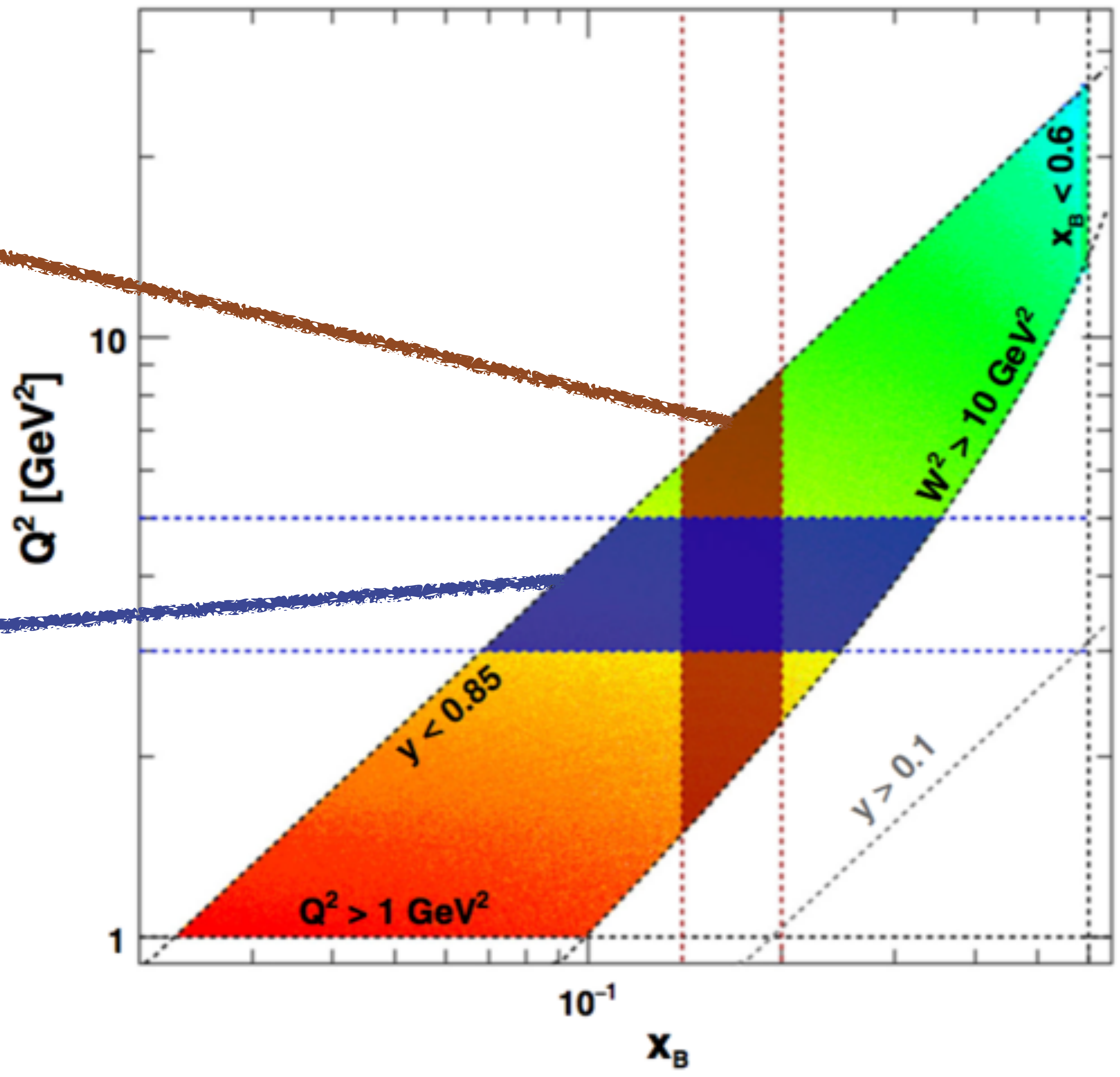
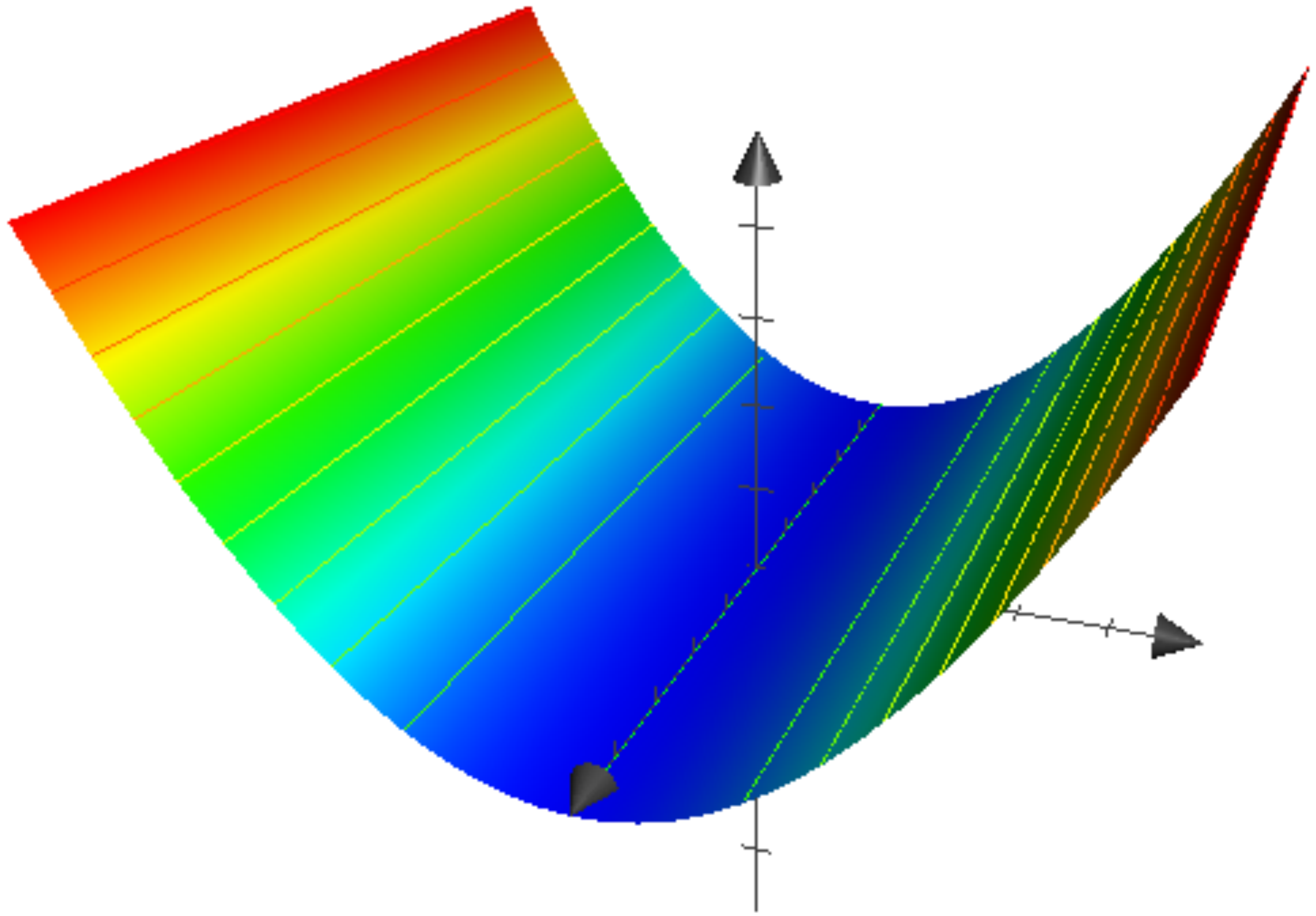




➟ even though two data points might have similar average kinematics, multiplicities in the two projections can be different

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

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

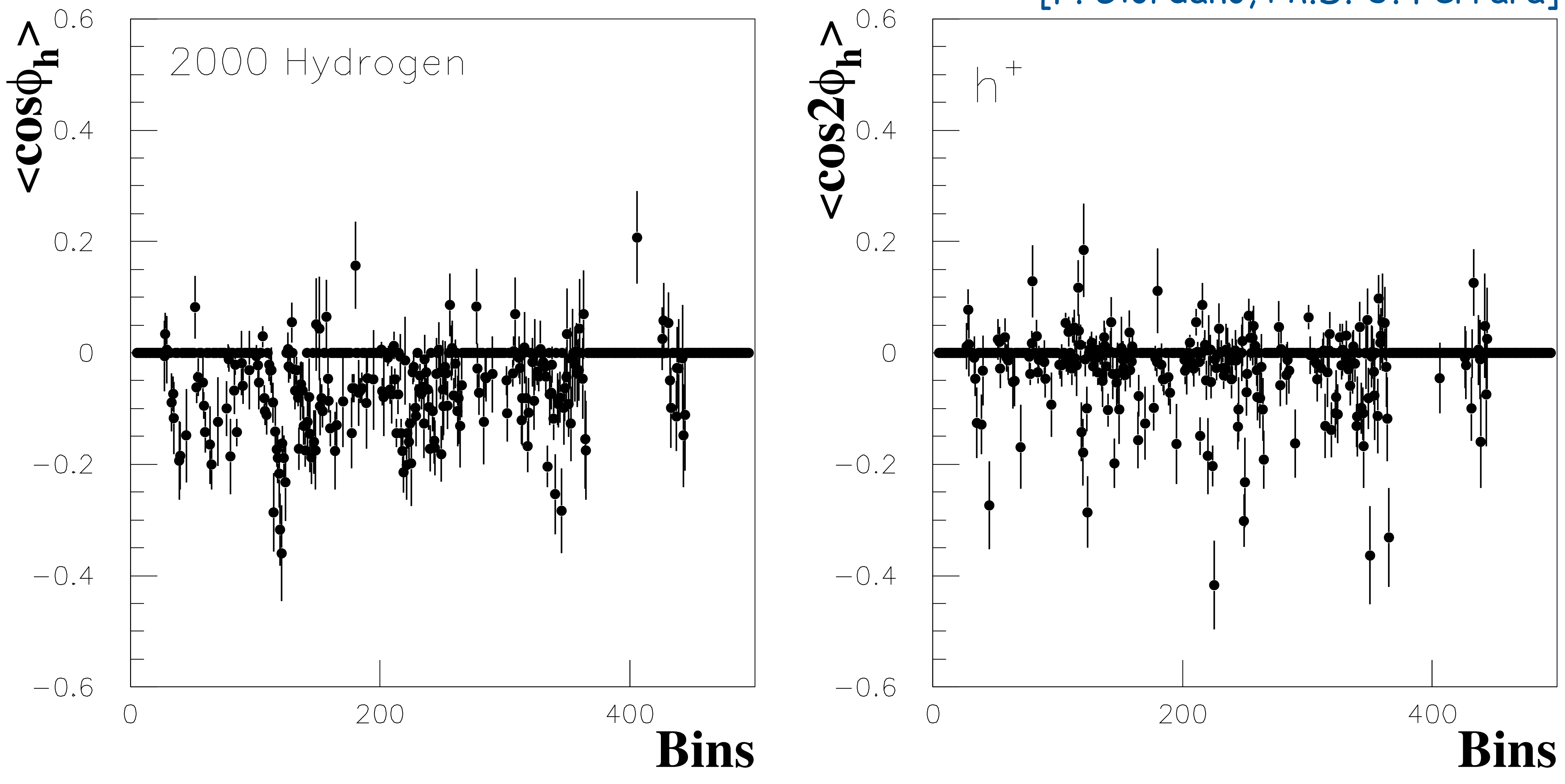


take-away message: (when told so) integrate your cross section over the kinematic ranges dictated by the experiment (e.g., do not simply evaluate it at the average kinematics)

to experiments: fully differential analyses!

back from 5d to 1d

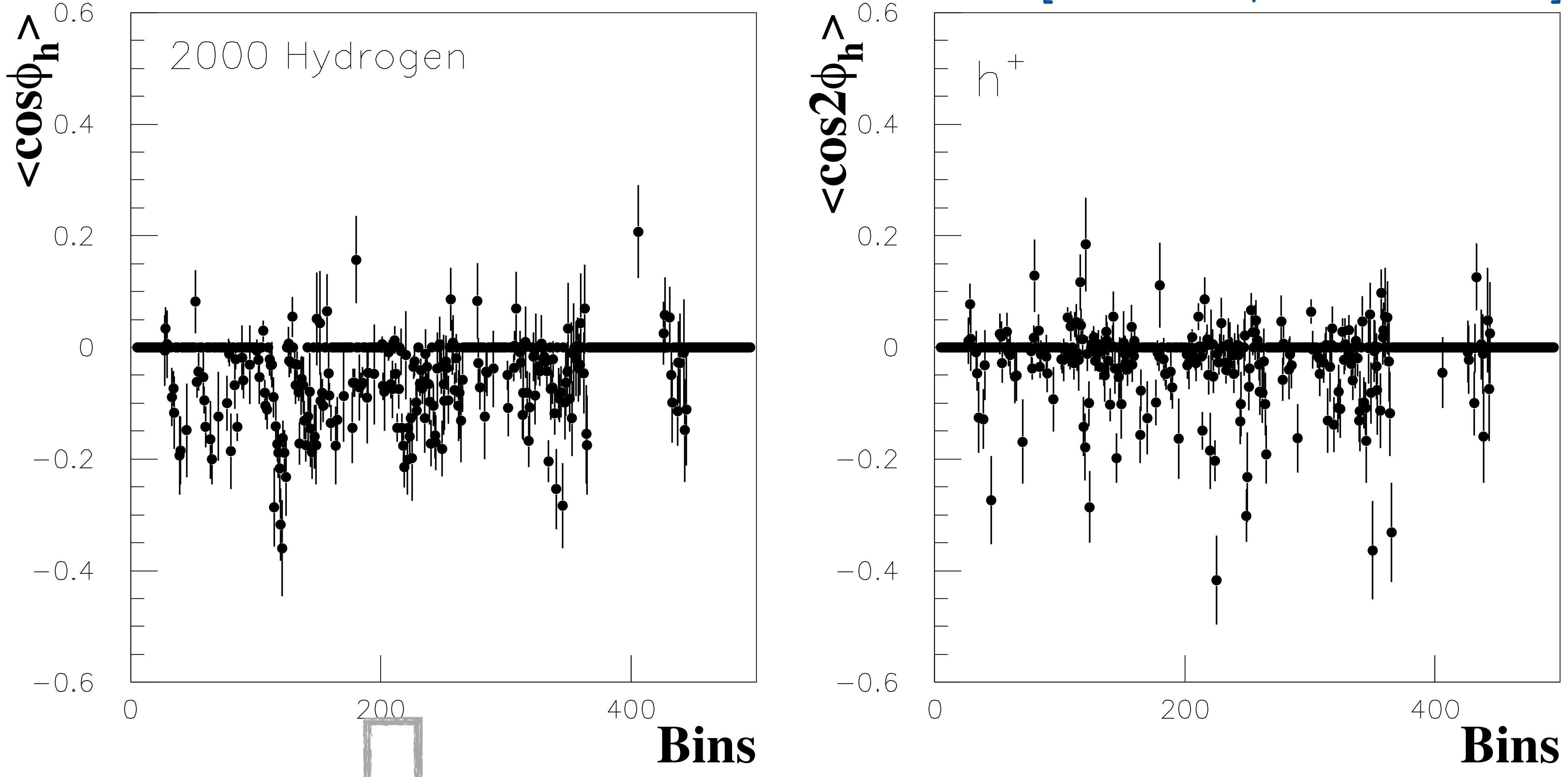
[F. Giordano, Ph.D. U. Ferrara]



- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
  - either directly in fully differential fits

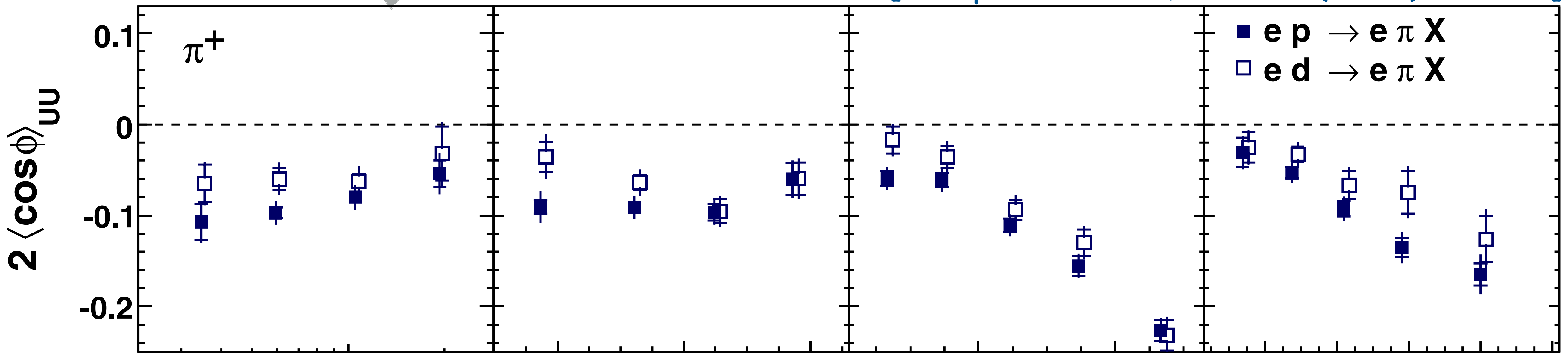
back from 5d to 1d

[F. Giordano, Ph.D. U. Ferrara]



$$\langle \cos n\phi \rangle (x) \simeq \frac{\sum_i \sigma_i^{4\pi} \langle \cos n\phi \rangle_i}{\sum_i \sigma_i^{4\pi}}$$

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



- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
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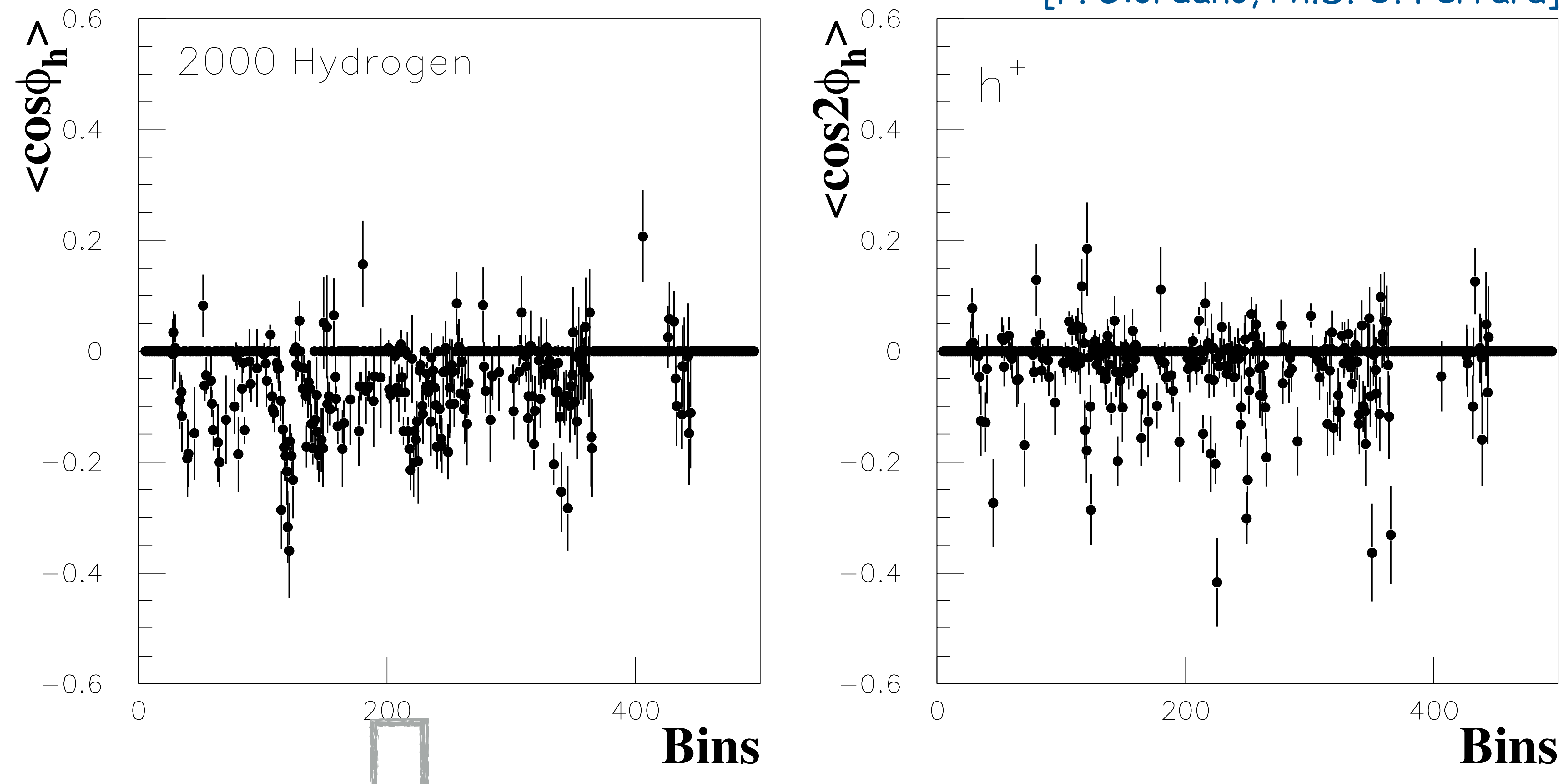
back from 5d to 1d

[F. Giordano, Ph.D. U. Ferrara]



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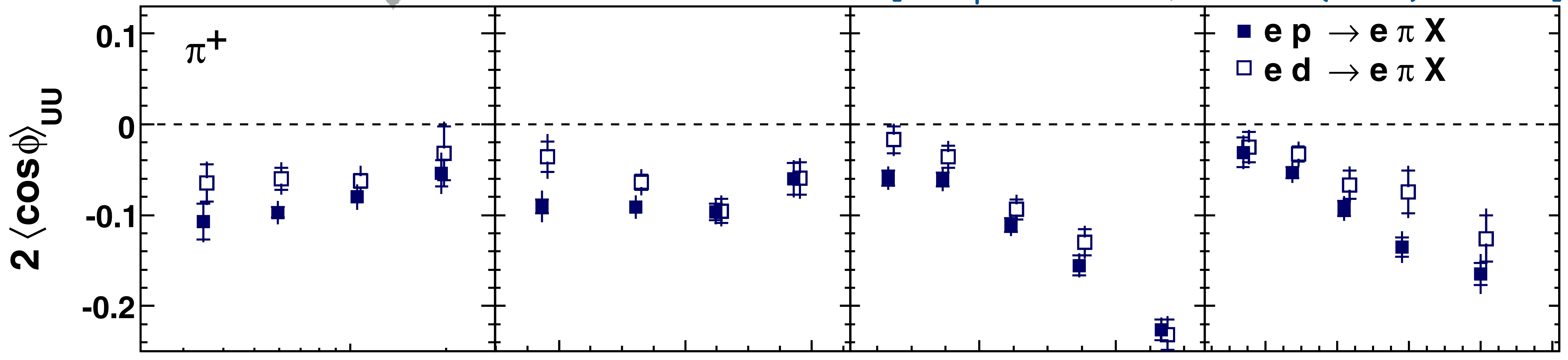


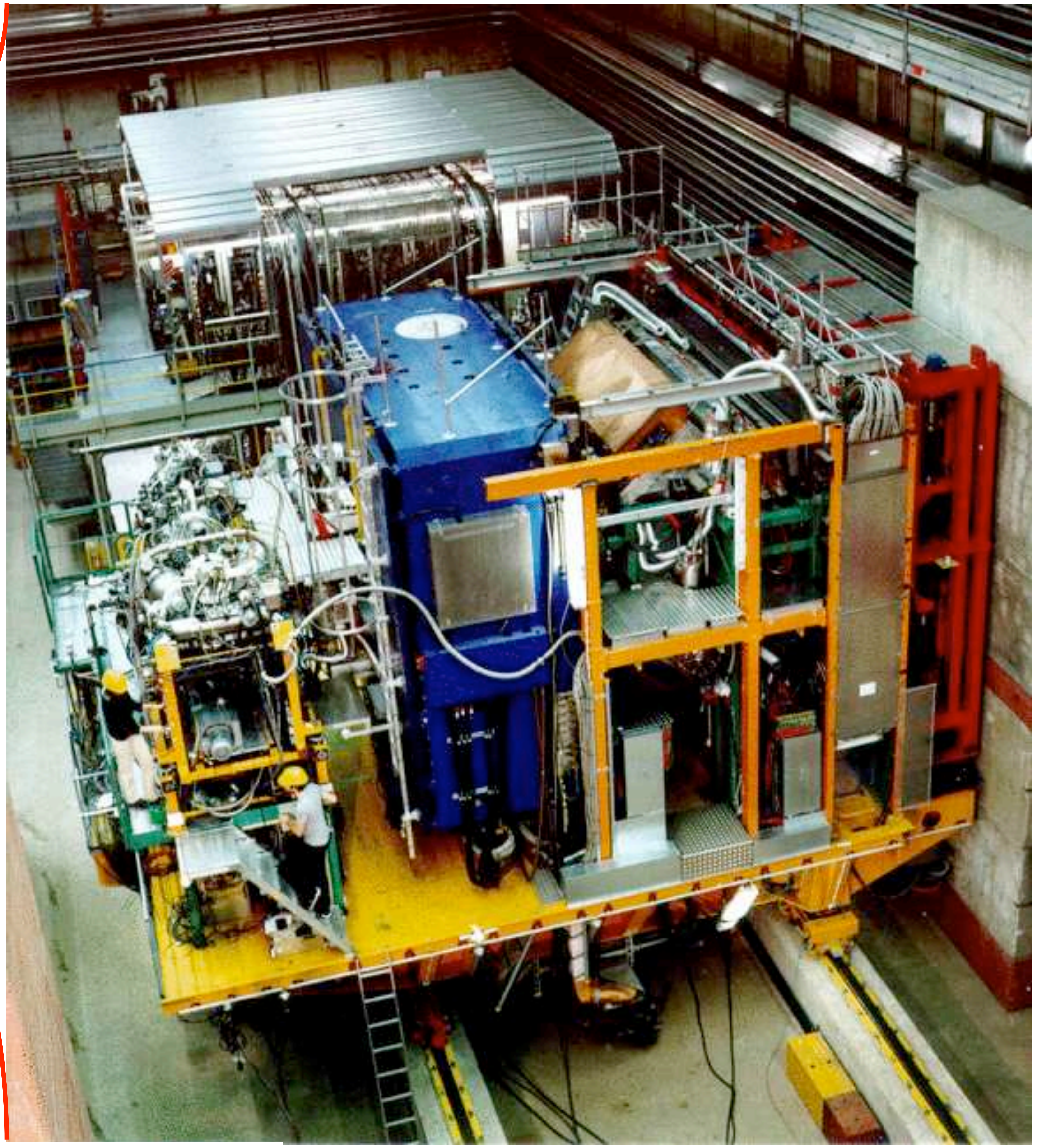
- how to use fully differential results, e.g., cosine moments of unpolarised cross section?
  - either directly in fully differential fits
  - project back to 1d for vizualization

➡ requires good knowledge of unpolarized cross section

➠ when using 1d projections, ask yourself and your experiment's friends why 1d is sufficient and why not go multi-d?

HERMES (1995-2007) @ HERA

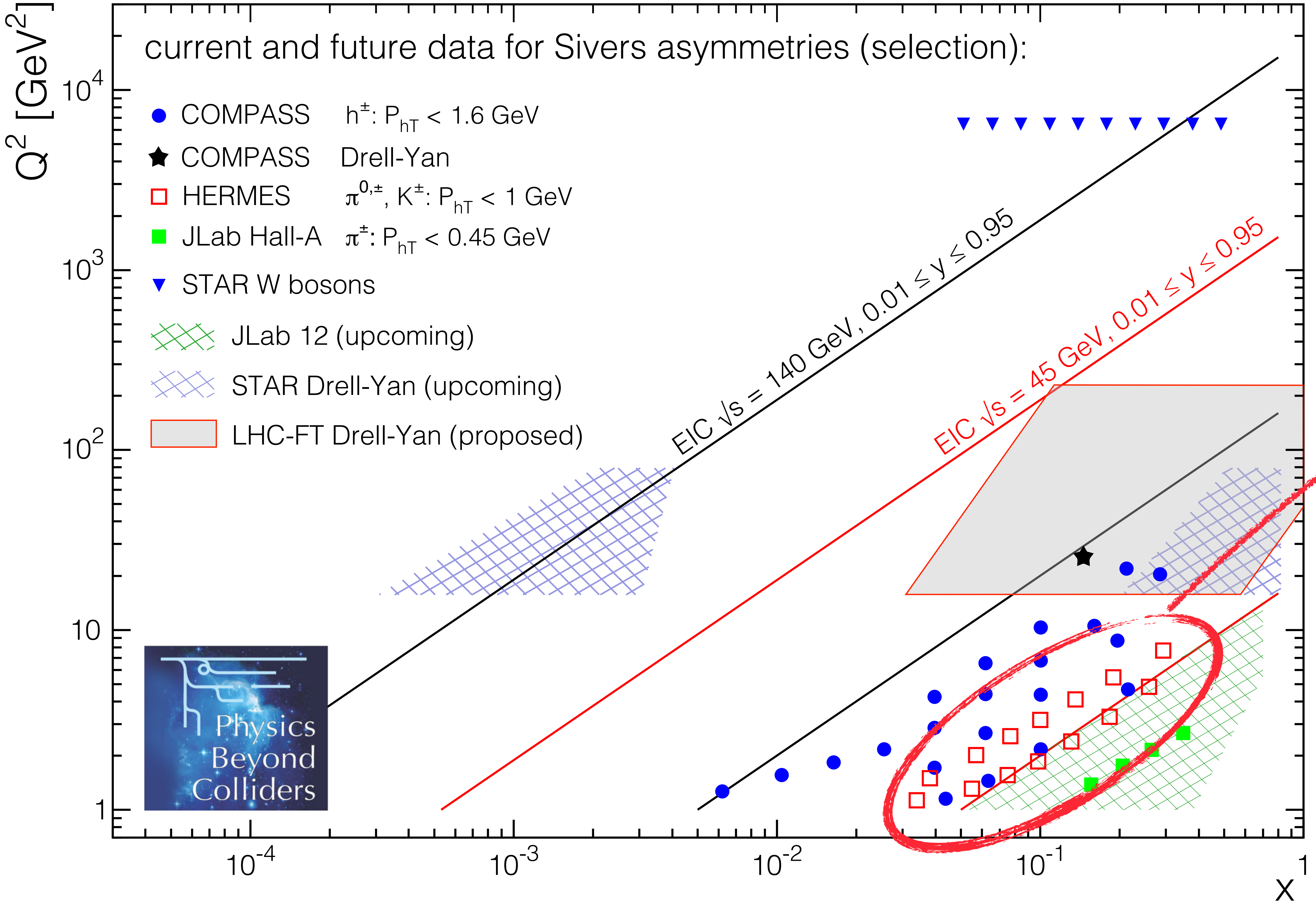
27.6 GeV polarized e^+/e^- beam scattered off ...



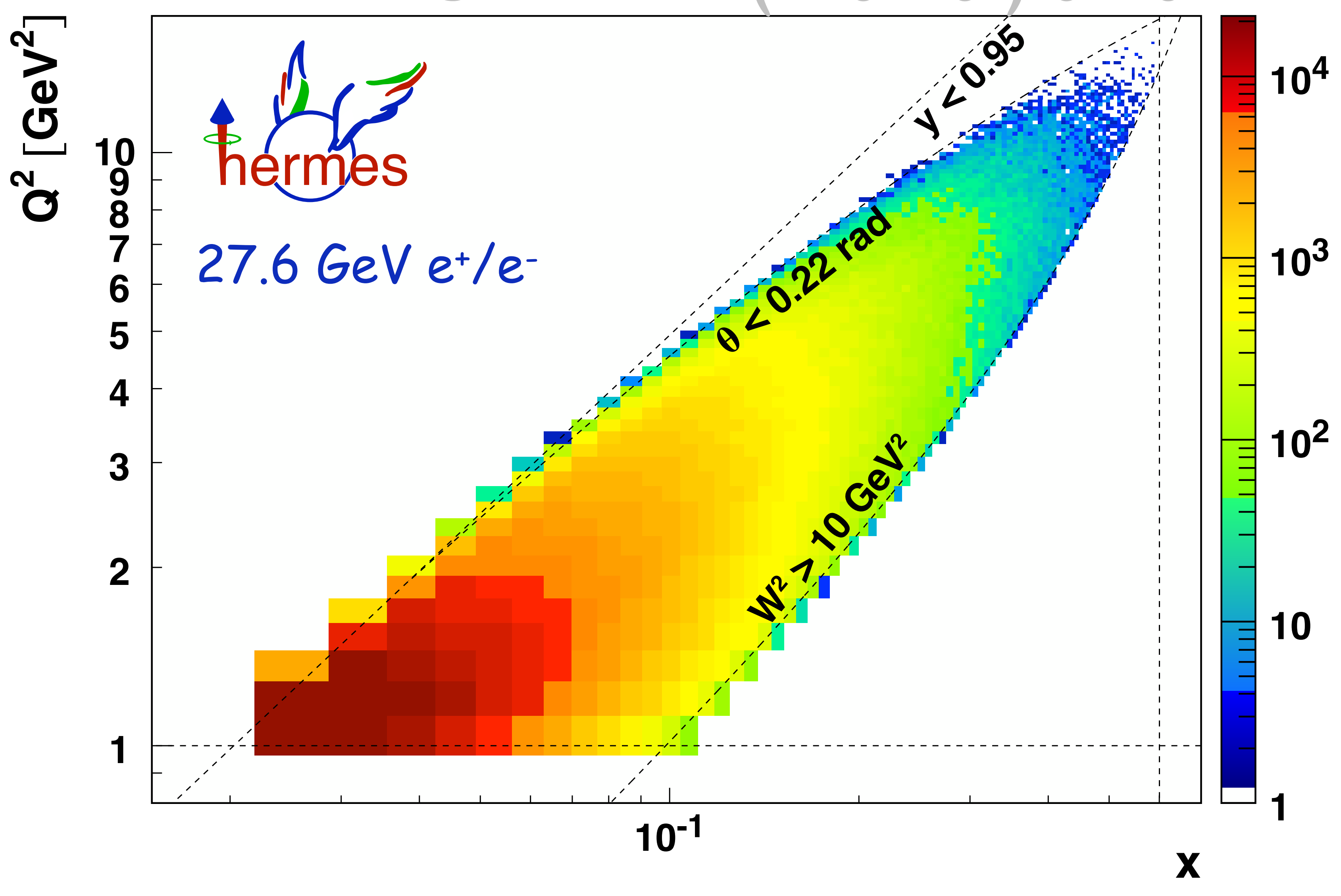
- unpolarized (H, D, He,..., Xe) as well as
- **transversely** (H) or
- **longitudinally** (H, D, He) polarized

pure gas targets

2d kinematic phase space



JHEP12(2020)010



Scattered lepton:		Q^2	$> 1\,\text{GeV}^2$	
		W^2	$> 10\,\text{GeV}^2$	
	$0.023 <$	x	< 0.6	
	$0.1 <$	y	< 0.95	
Detected hadrons:	$2\,\text{GeV} <$	$\lvert \mathbf{P}_h \rvert$	$< 15\,\text{GeV}$	charged mesons
	$4\,\text{GeV} <$	$\lvert \mathbf{P}_h \rvert$	$< 15\,\text{GeV}$	(anti)protons
		$\lvert \mathbf{P}_h \rvert$	$> 2\,\text{GeV}$	neutral pions
		$P_{h\perp}$	$< 2\,\text{GeV}$	
	$0.2 <$	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.

semi-inclusive DIS

- excluding transverse polarization:

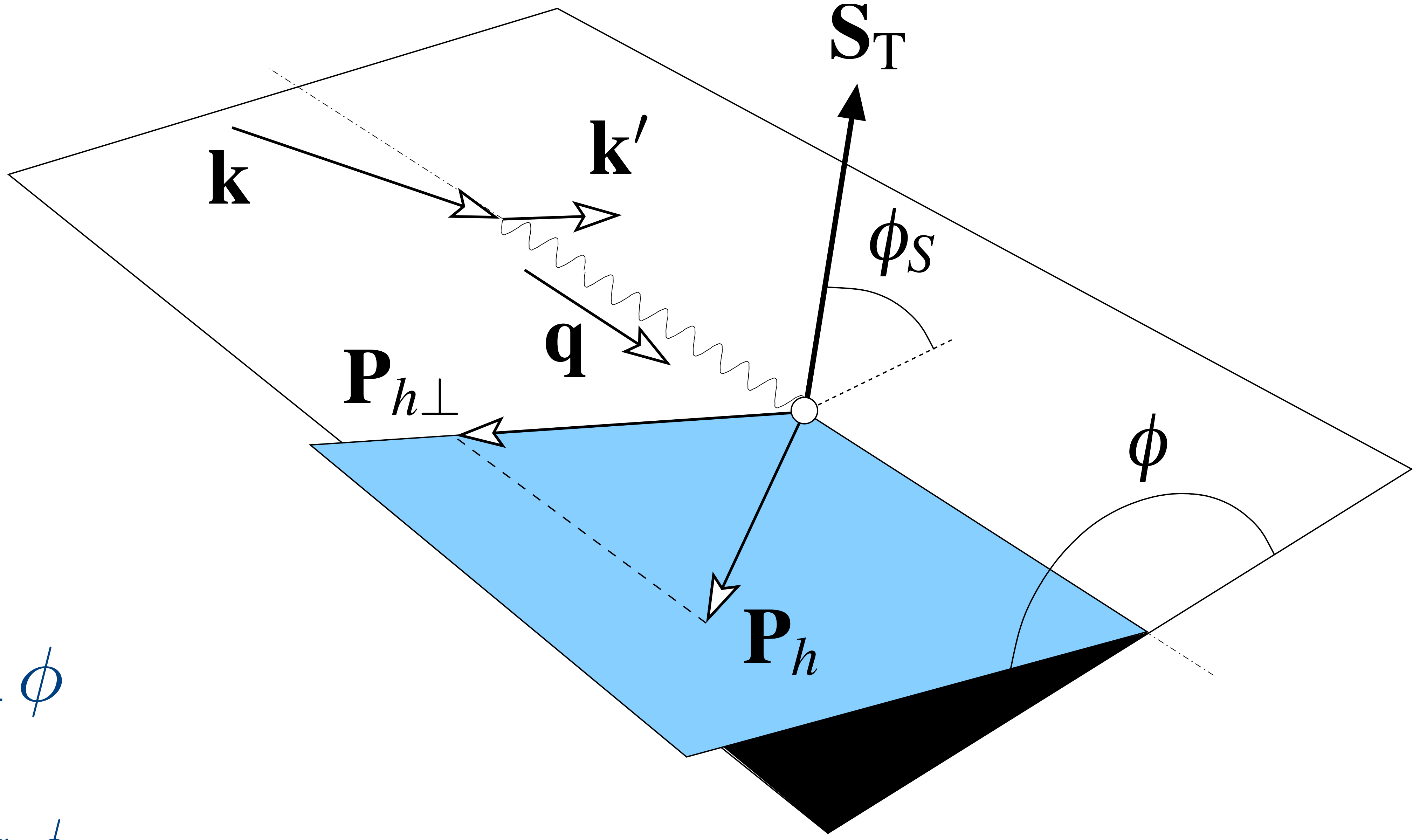
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



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

Beam (λ) / Target (Λ)

helicities

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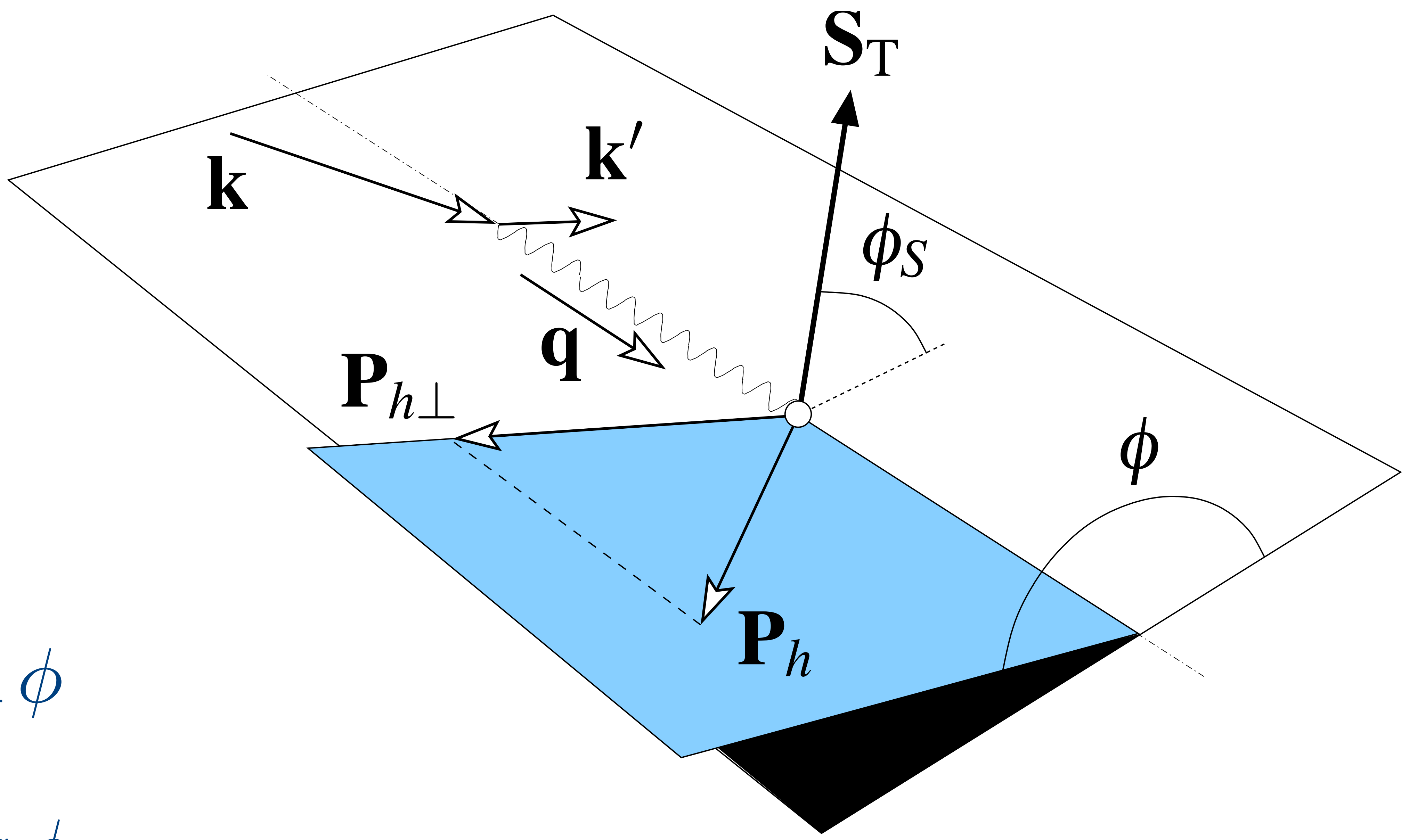

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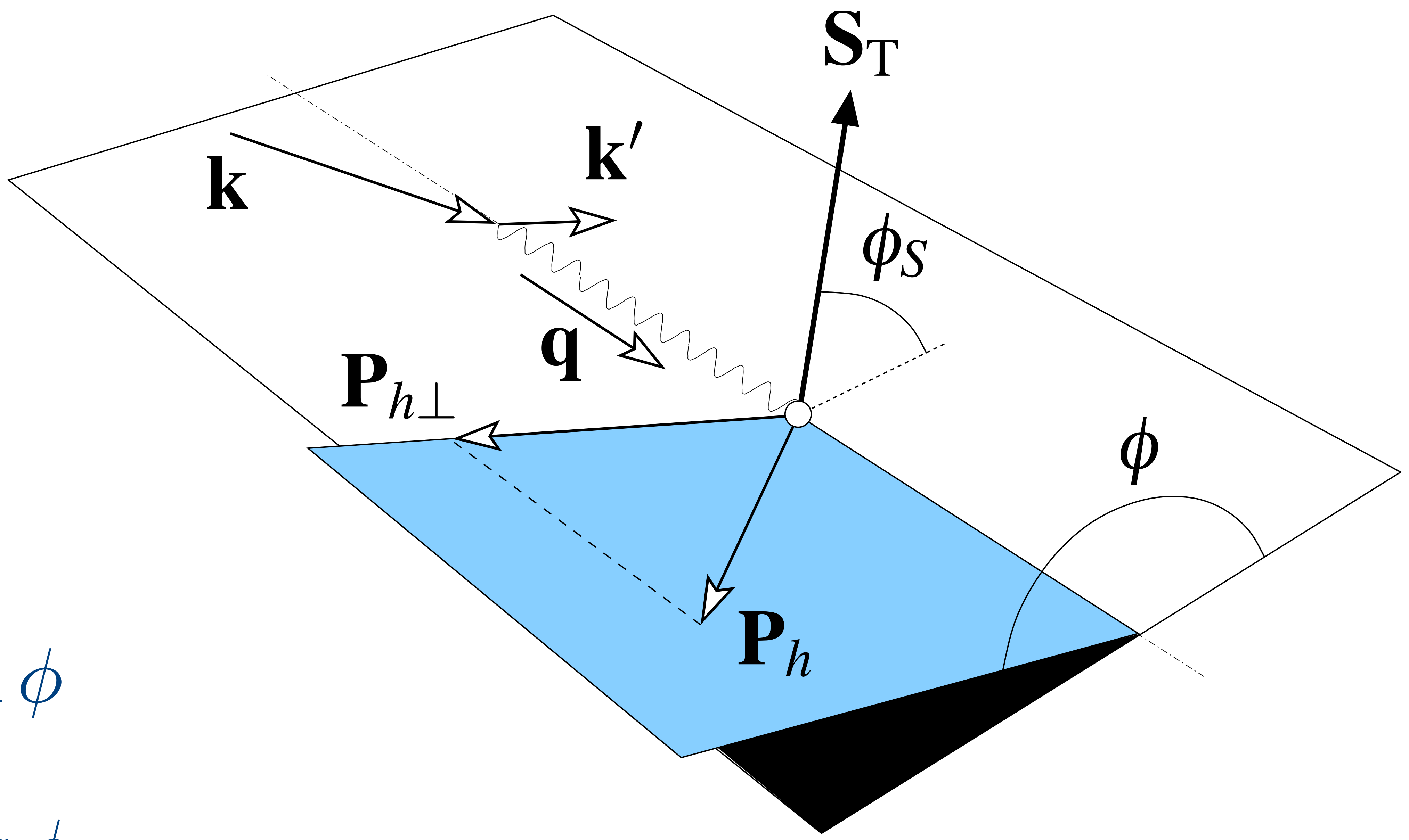

- double-spin asymmetry:

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

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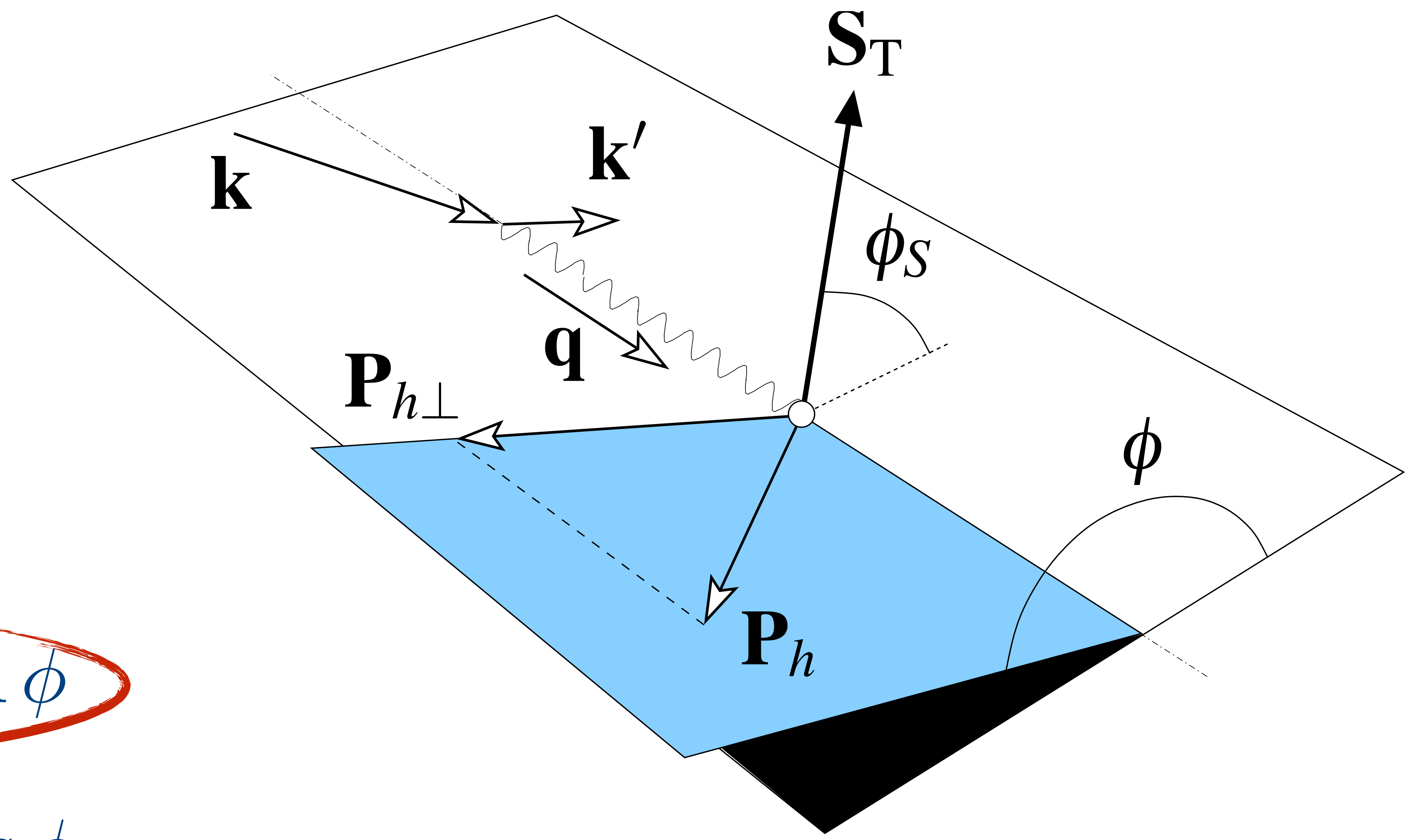

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semi-inclusive DIS

- excluding transverse polarization:

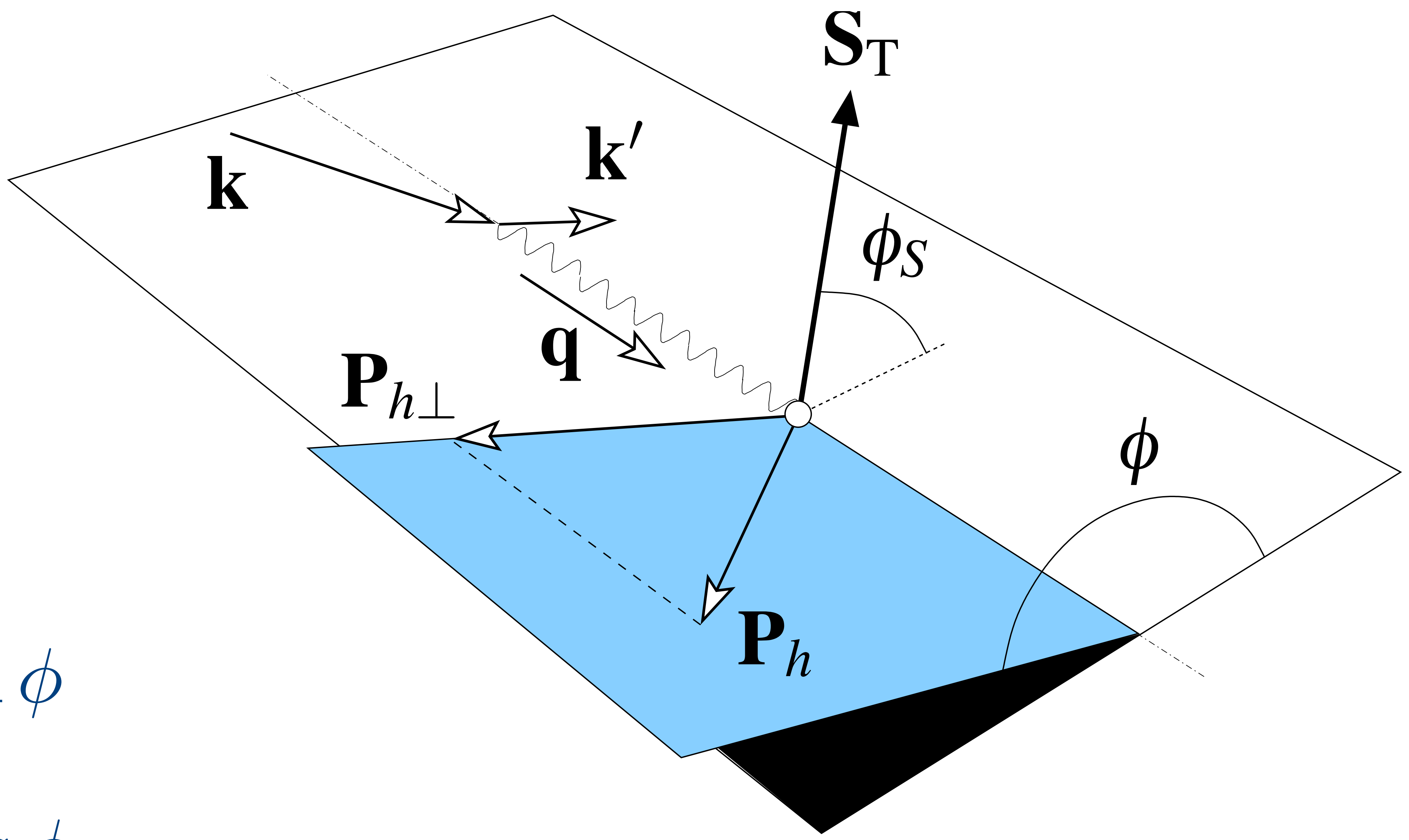
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- 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:

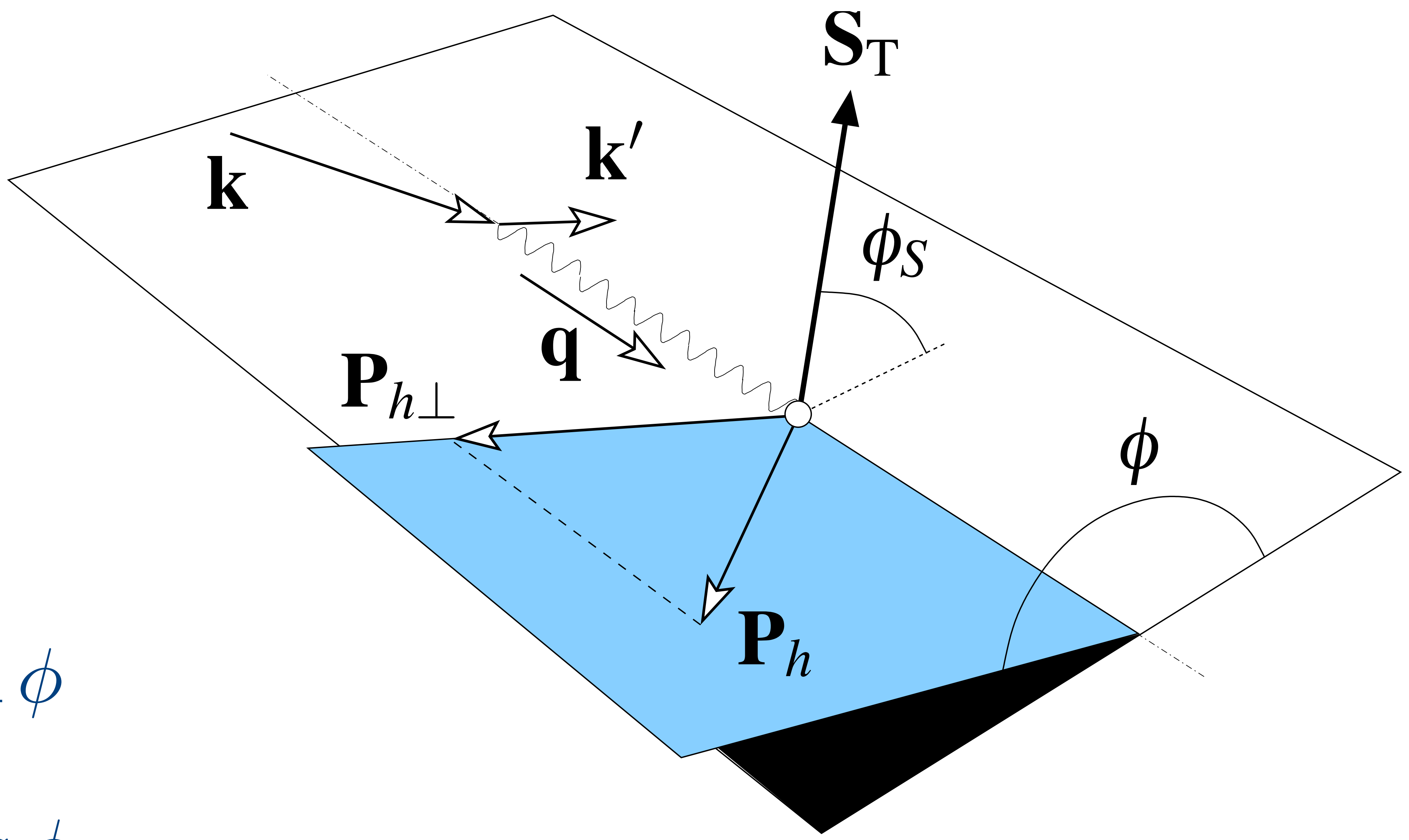
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- double-spin asymmetry:

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

- excluding transverse polarization:

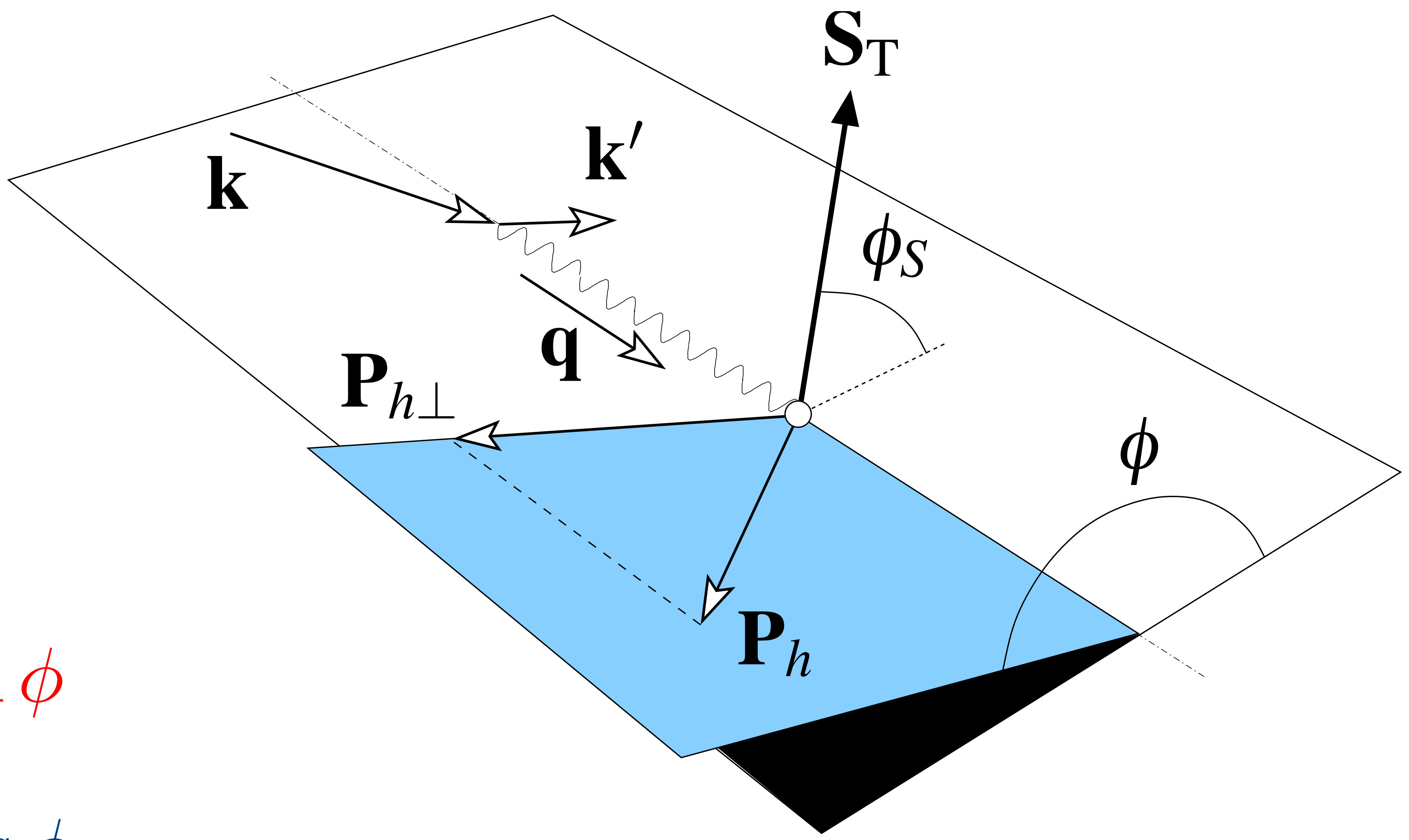
$$\frac{d\sigma^h}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

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



- single-spin asymmetry:

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

  - explicit angular dependence to be analyzed

semi-inclusive DIS

- with **transverse** target polarization:

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

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

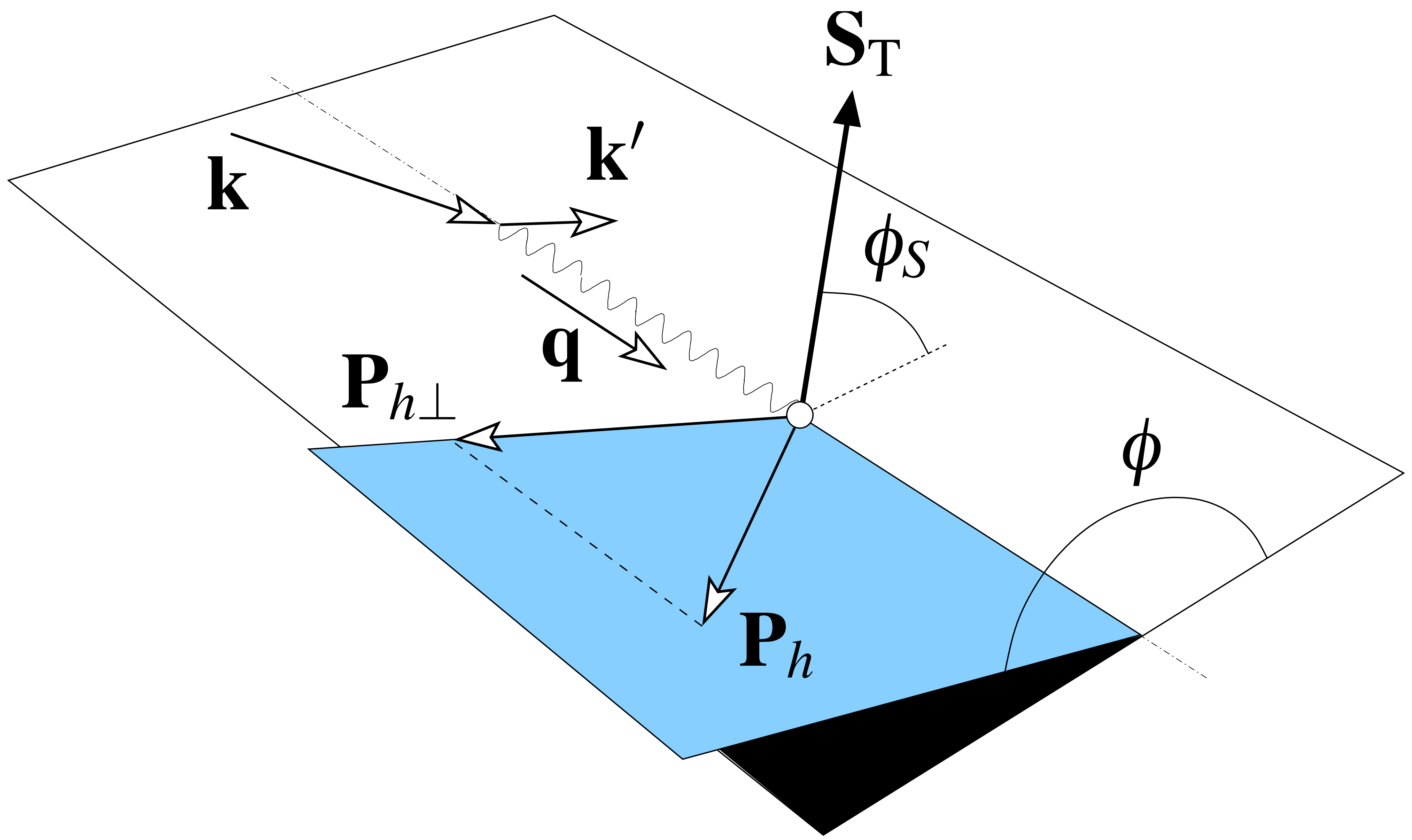
$$+ S_T \left[\left(F_{UT,T}^{h,\sin(\phi-\phi_s)} + \epsilon\, F_{UT,L}^{h,\sin(\phi-\phi_s)} \right) \sin(\phi-\phi_s) \right.$$

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

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

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

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



semi-inclusive DIS

- with **transverse** target polarization:

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

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

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

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

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

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

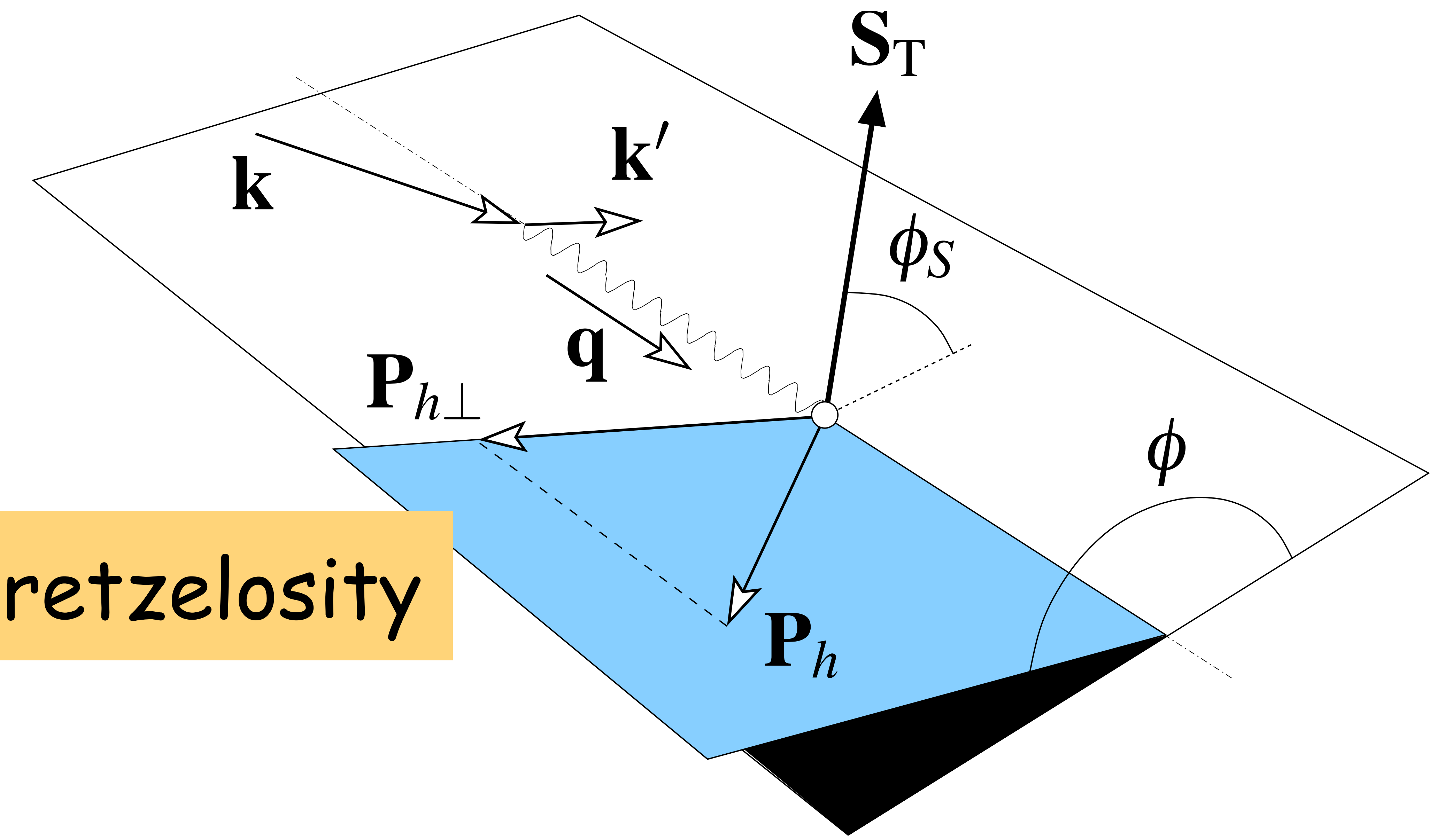
$$+ \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos\phi_s} \cos\phi_s + \sqrt{2\,\epsilon(1-\epsilon)}\, F_{LT}^{h,\cos(2\phi-\phi_s)} \cos(2\phi-\phi_s) \Big] \Big\}$$

Sivers

pretzelosity

transversity

worm-gear



PHYSICAL REVIEW D **99**, 112001 (2019)

Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E. C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26] A. Avetissian,[26] S. Belostotski,[19] H. P. Blok,[18,24] A. Borissov,[6] V. Bryzgalov,[20] G. P. Capitani,[11] E. Cisbani,[21] G. Ciullo,[10] M. Contalbrigo,[10] P. F. Dalpiaz,[10] W. Deconinck,[6] R. De Leo,[2] L. De Nardo,[6,12,22] E. De Sanctis,[11] M. Diefenthaler,[9] P. Di Nezza,[11] M. Düren,[13] G. Elbakian,[26] F. Ellinghaus,[5] A. Fantoni,[11] L. Felawka,[22] S. Frullani,[21,*] G. Gavrilov,[6,19,22] V. Gharibyan,[26] F. Giordano,[10] S. Gliske,[16] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H. E. Jackson,[1] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[26] T. Keri,[13,14] E. Kinney,[5] A. Kisselev,[19] V. Korotkov,[20,*] V. Kozlov,[17] P. Kravchenko,[9,19] V. G. Krivokhijine,[8] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] W. Lorenzon,[16] B.-Q. Ma,[3] D. Mahon,[14] S. I. Manaenkov,[19] Y. Mao,[3] B. Marianski,[25] H. Marukyan,[26] Y. Miyachi,[23] A. Movsisyan,[10,26] V. Muccifora,[11] A. Mussgiller,[6,9] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L. L. Pappalardo,[10] R. Perez-Benito,[13] A. Petrosyan,[26] P. E. Reimer,[1] A. R. Reolon,[11] C. Riedl,[7,15] K. Rith,[9] G. Rosner,[14] A. Rostomyan,[6] J. Rubin,[15] D. Ryckbosch,[12] Y. Salomatin,[20,*] G. Schnell,[4,12] B. Seitz,[14] T.-A. Shibata,[23] M. Statera,[10] E. Steffens,[9] J. J. M. Steijger,[18] S. Taroian,[26] A. Terkulov,[17] R. Truty,[15] A. Trzcinski,[25,*] M. Tytgat,[12] P. B. van der Nat,[18] Y. Van Haarlem,[12] C. Van Hulse,[4,12] D. Veretennikov,[4,19] V. Vikhrov,[19] I. Vilardi,[2] C. Vogel,[9] S. Wang,[3] S. Yaschenko,[9] B. Zihlmann,[6] and P. Zupranski[25]

(The HERMES Collaboration)

re-analysis of longitudinal double-spin asymmetries

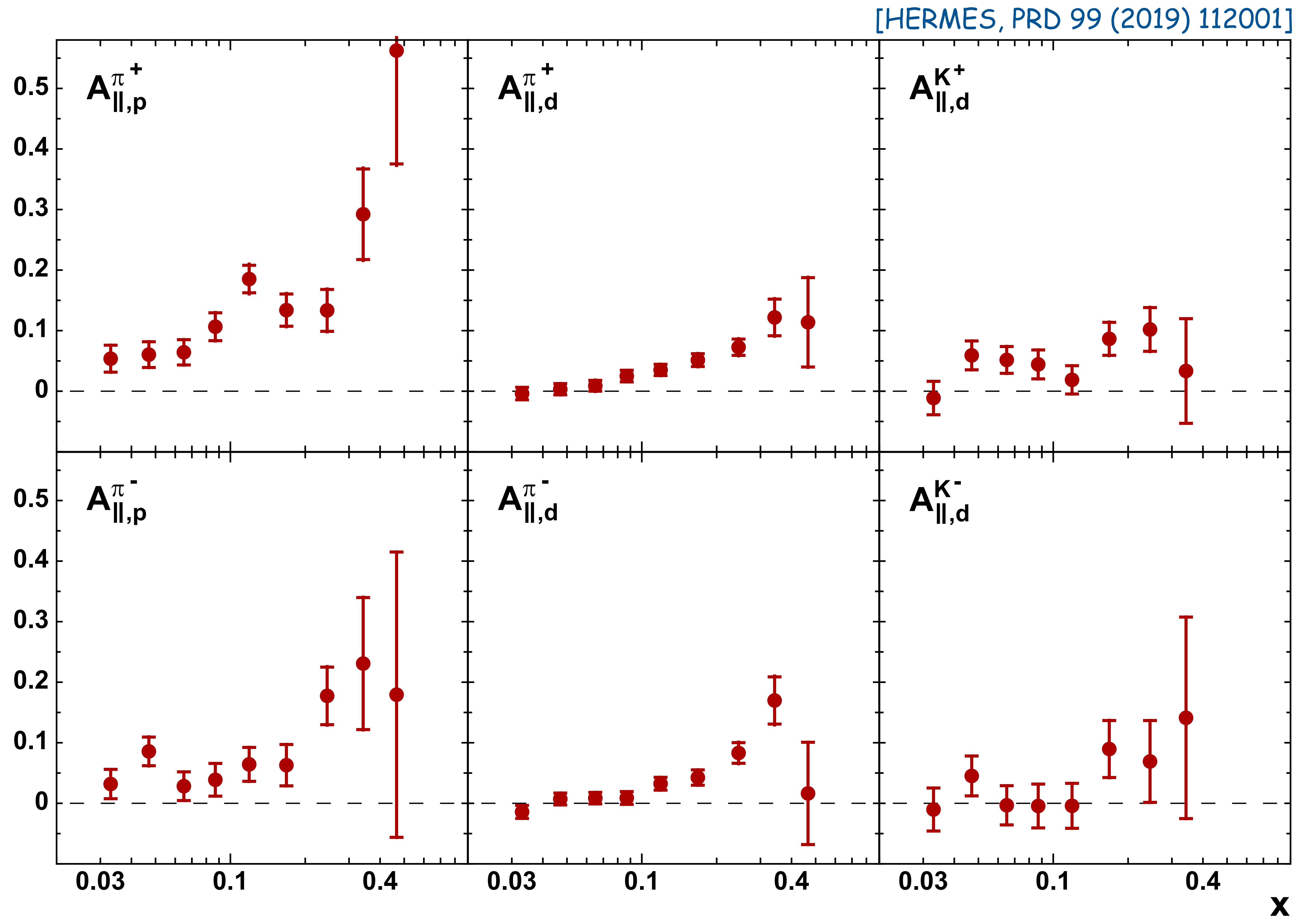
- revisited [PRD 71 (2005) 012003] A_1 analysis at HERMES in order to
  - exploit slightly larger data set (less restrictive momentum range)
  - **provide $A_\parallel$ in addition to A_1**

$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_\parallel^h \qquad D = \frac{1-(1-y)\epsilon}{1+\epsilon R}$$

R (ratio of longitudinal-to-transverse cross-sec'n) still to be measured!
[only available for inclusive DIS data, e.g., used in g_1 SF measurements]

  - correct for D-state admixture (deuteron case) on asymmetry level
  - correct better for azimuthal asymmetries coupling to acceptance
  - **look at multi-dimensional (x, z, $P_{h\perp}$) dependences**
  - **extract twist-3 cosine modulations … consistent with zero**

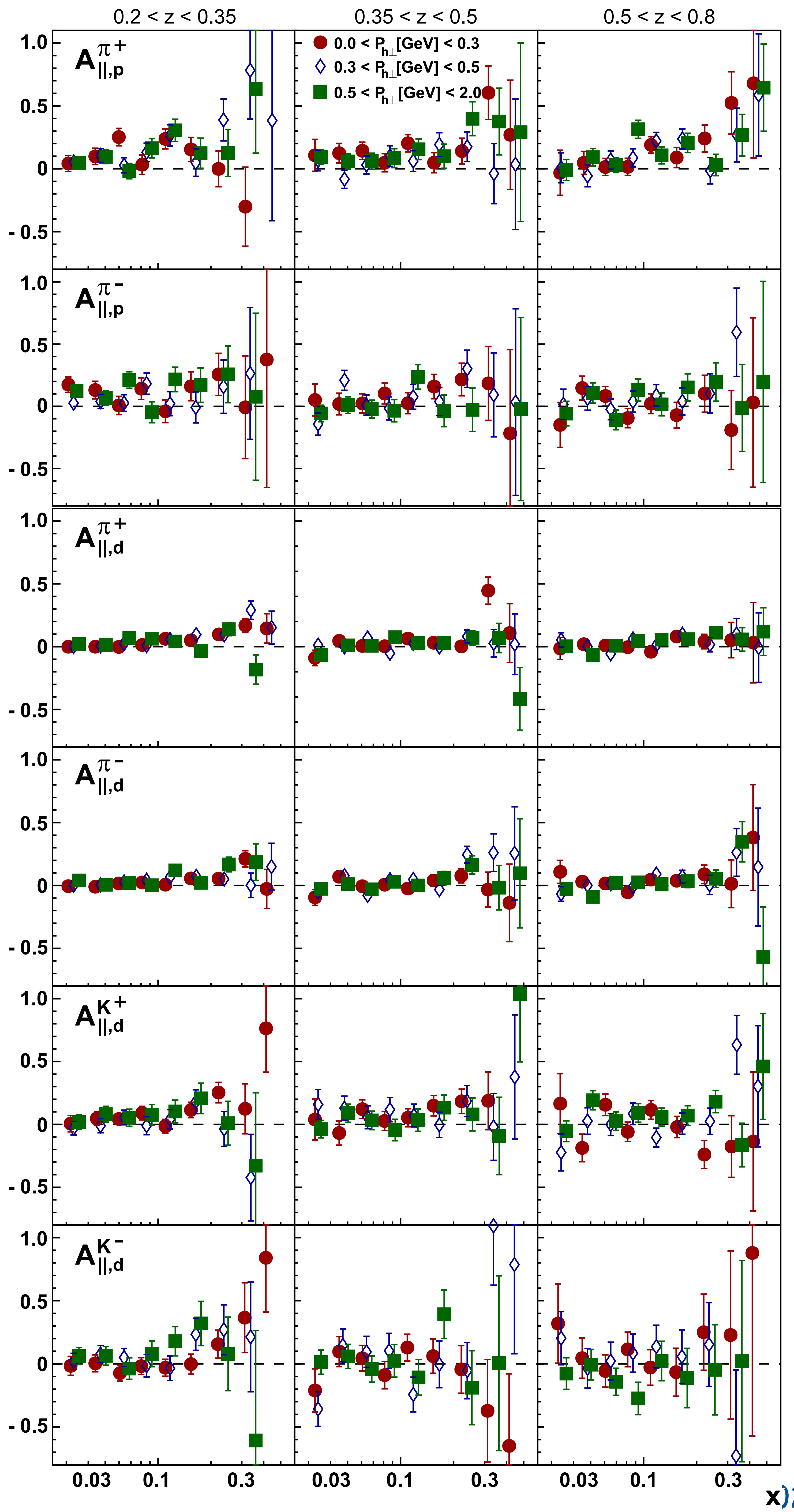
x dependence of $A_{||}$



- ☑ fully consistent with previous HERMES publication [PRD 71 (2005) 012003]

3-dimensional binning

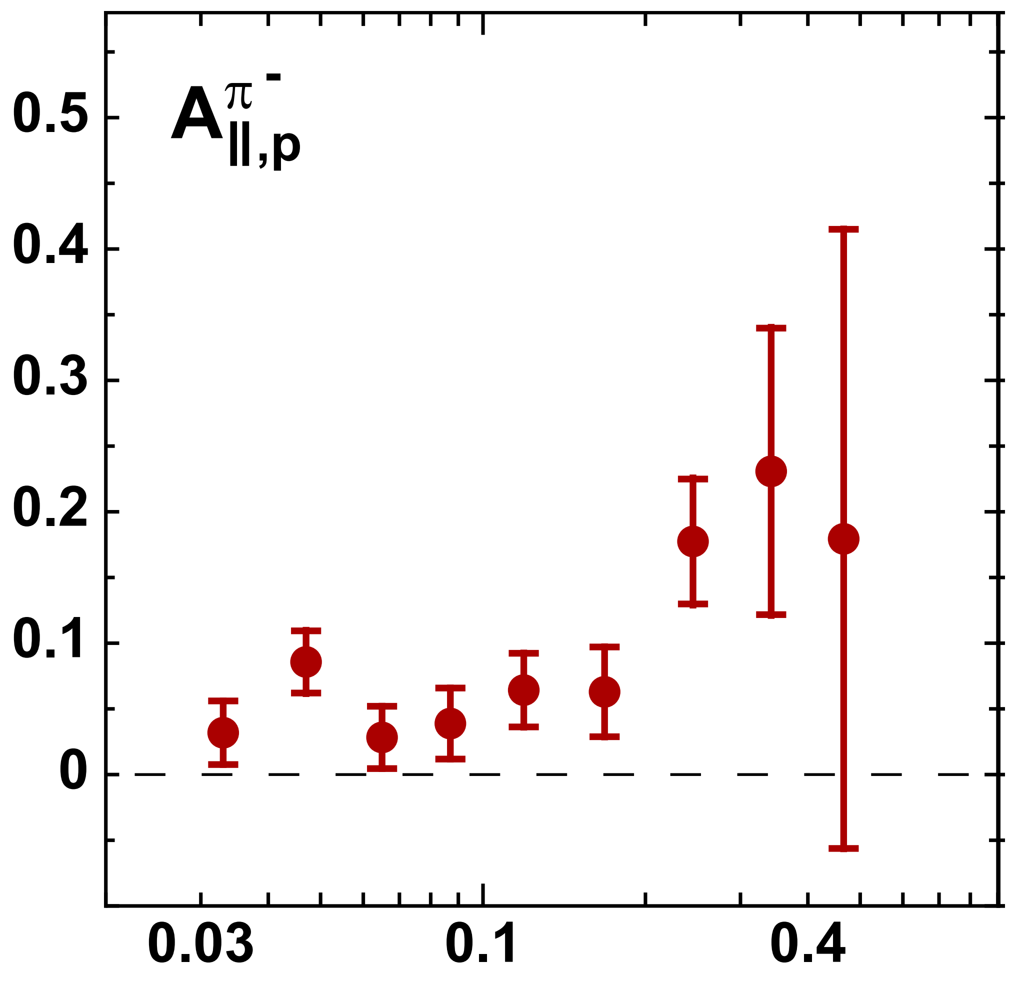
- **first-ever 3d binning** provides transverse-momentum dependence

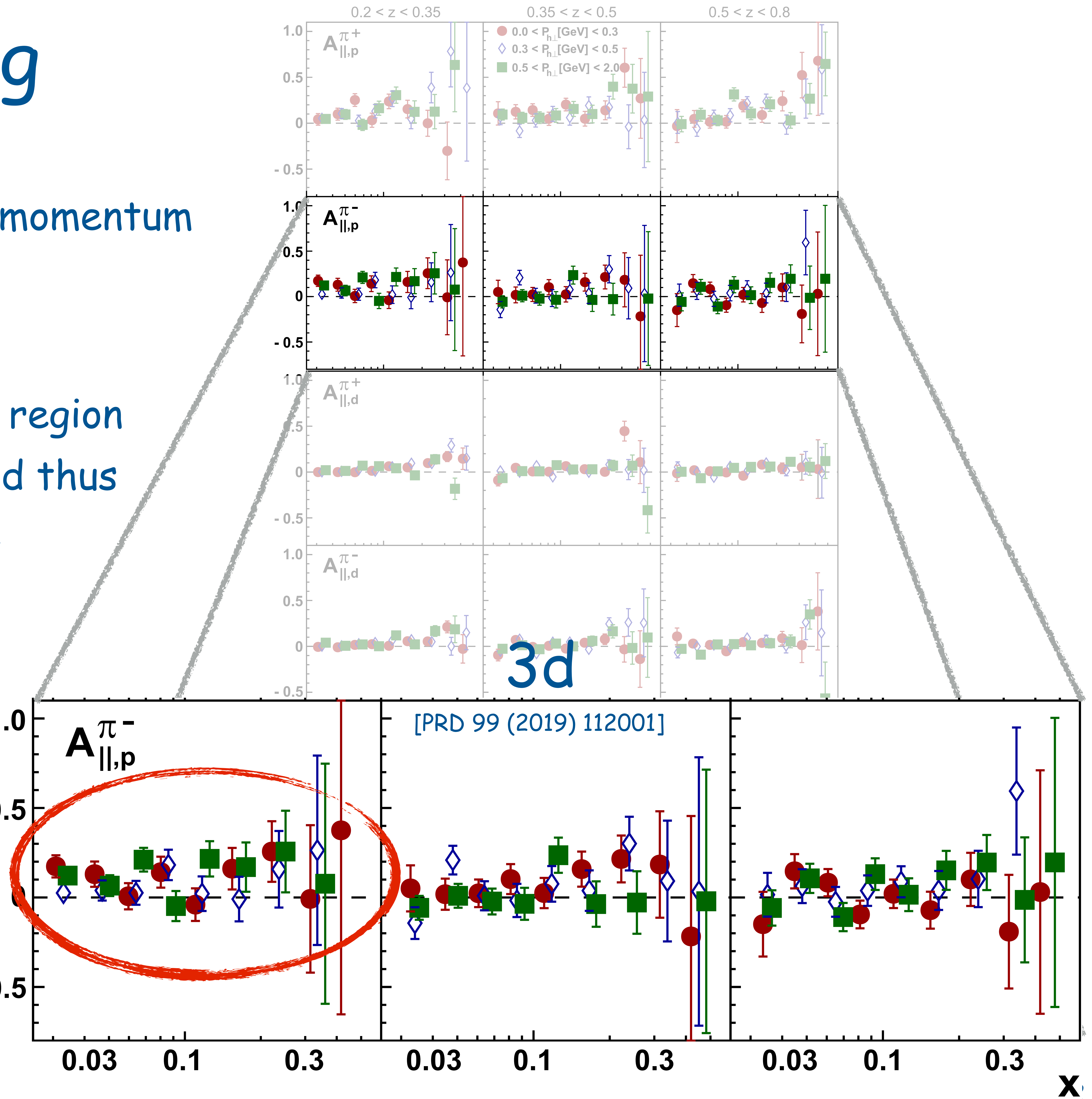


3-dimensional binning

- **first-ever 3d binning** provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - π^- asymmetries mainly coming from **low-z** region where **disfavored fragmentation** large and thus **sensitivity** to the large **positive up-quark polarization**

1d





JHEP

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Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons

hermes

The HERMES Collaboration

A. Airapetian,[13,16] N. Akopov,[26] Z. Akopov,[6] E.C. Aschenauer,[7] W. Augustyniak,[25] R. Avakian,[26,a] A. Bacchetta,[21] S. Belostotski,[19,a] V. Bryzgalov,[20] G.P. Capitani,[11] E. Cisbani,[22] G. Ciullo,[10] M. Contalbrigo,[10] W. Deconinck,[6] R. De Leo,[2] E. De Sanctis,[11] M. Diefenthaler,[9] P. Di Nezza,[11] M. Düren,[13] G. Elbakian,[26] F. Ellinghaus,[5] A. Fantoni,[11] L. Felawka,[23] G. Gavrilov,[6,19,23] V. Gharibyan,[26] D. Hasch,[11] Y. Holler,[6] A. Ivanilov,[20] H.E. Jackson,[1,a] S. Joosten,[12] R. Kaiser,[14] G. Karyan,[6,26] E. Kinney,[5] A. Kisselev,[19] V. Kozlov,[17] P. Kravchenko,[9,19] L. Lagamba,[2] L. Lapikás,[18] I. Lehmann,[14] P. Lenisa,[10] W. Lorenzon,[16] S.I. Manaenkov,[19] B. Marianski,[25,a] H. Marukyan,[26] Y. Miyachi,[24] A. Movsisyan,[10,26] V. Muccifora,[11] Y. Naryshkin,[19] A. Nass,[9] G. Nazaryan,[26] W.-D. Nowak,[7] L.L. Pappalardo,[10] P.E. Reimer,[1] A.R. Reolon,[11] C. Riedl,[7,15] K. Rith,[9] G. Rosner,[14] A. Rostomyan,[6] J. Rubin,[15] D. Ryckbosch,[12] A. Schäfer,[21] G. Schnell,[3,4,12] B. Seitz,[14] T.-A. Shibata,[24] V. Shutov,[8] M. Statera,[10] A. Terkulov,[17] M. Tytgat,[12] Y. Van Haarlem,[12] C. Van Hulse,[12] D. Veretennikov,[3,19] I. Vilardi,[2] S. Yaschenko,[9] D. Zeiler,[9] B. Zihlmann[6] and P. Zupranski[25]

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[a] Deceased.

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3d

1d

Azimuthal modulation		Significant non-vanishing Fourier amplitude π^+	π^-	K^+	K^-	p	π^0	$\bar{p}$
$\sin(\phi+\phi_S)$	[Collins]	✓	✓	✓		✓		
$\sin(\phi-\phi_S)$	[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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

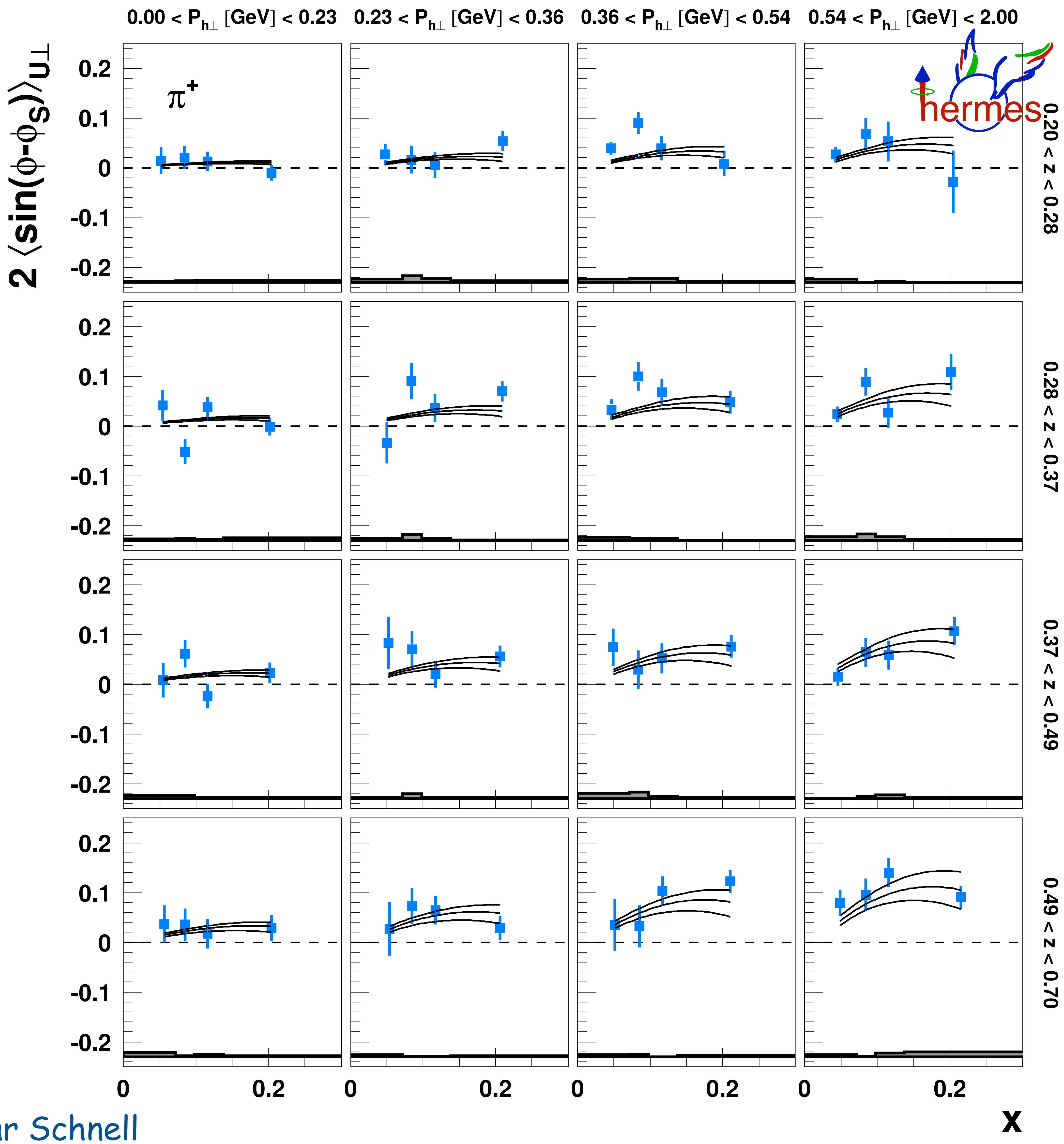
90%

95%

	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]

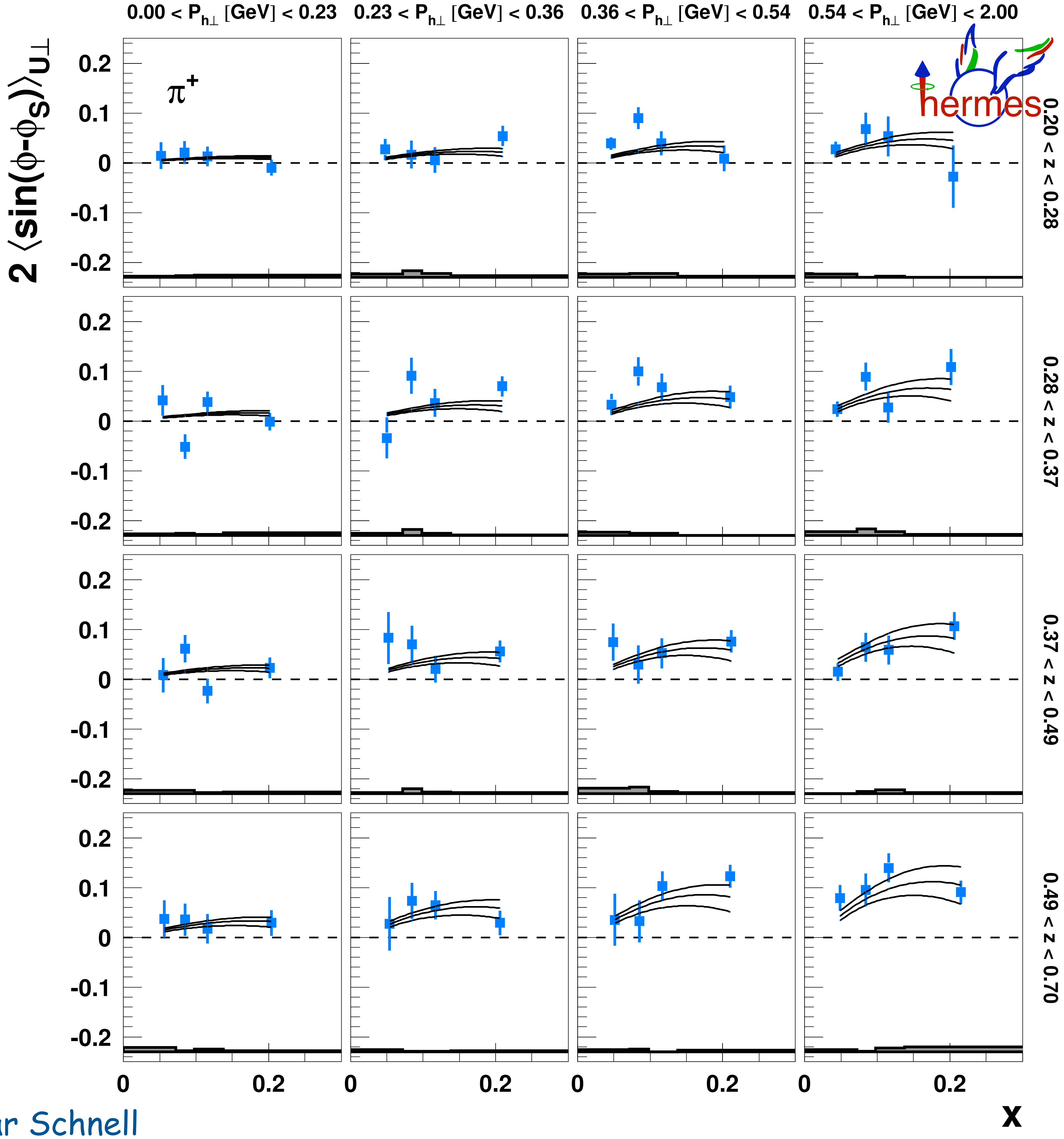


- 3d analysis: 4x4x4 bins in $(x, z, P_{h\perp})$
- reduced systematics
- disentangle correlations
- isolate phase-space region with large signal strength
- allows more detailed comparison with calculations
- accompanied by kinematic distribution to guide phenomenology

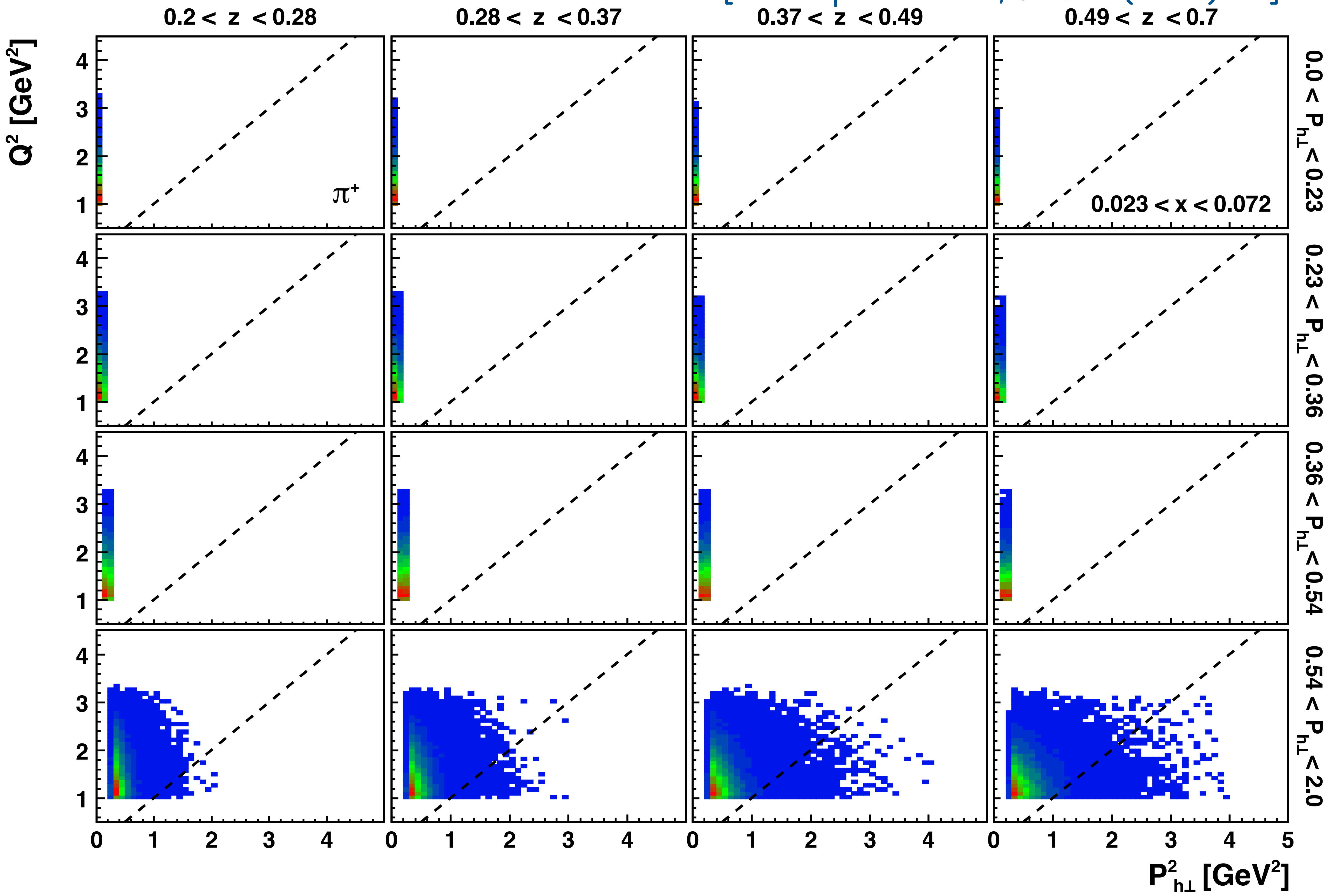
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes
multi-dimensional analysis

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

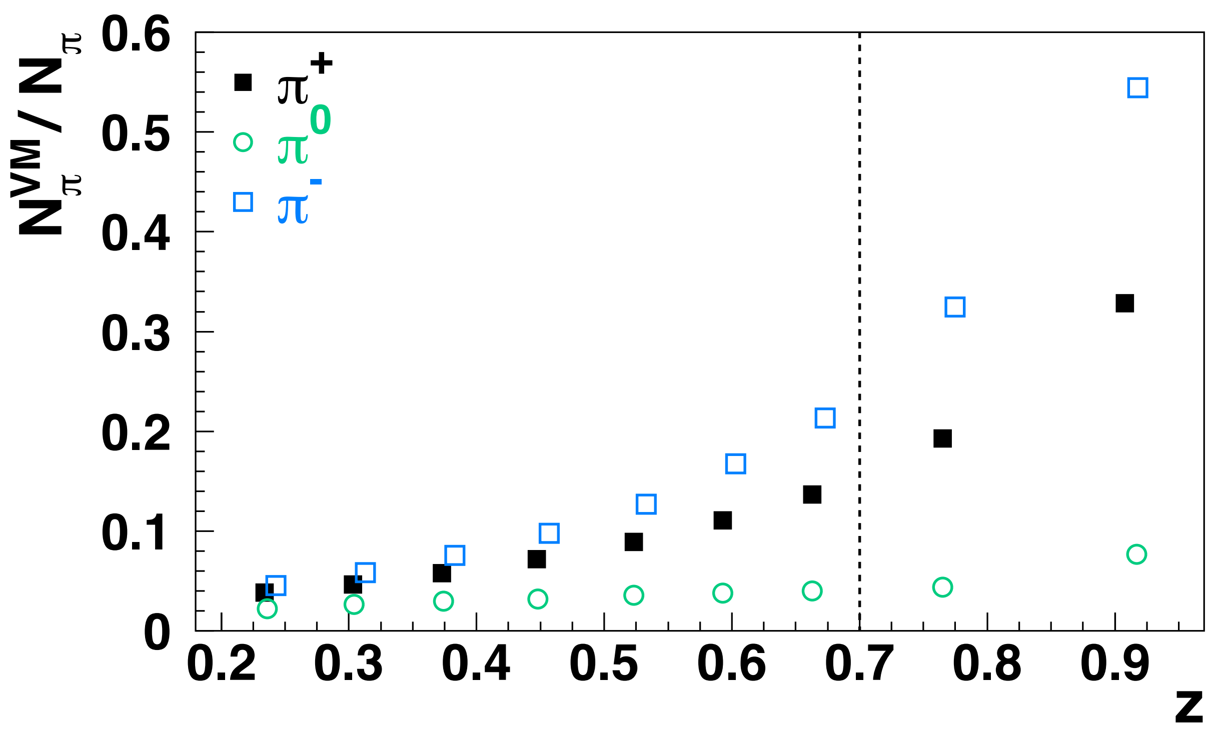


[A. Airapetian et al., JHEP12(2020)010]



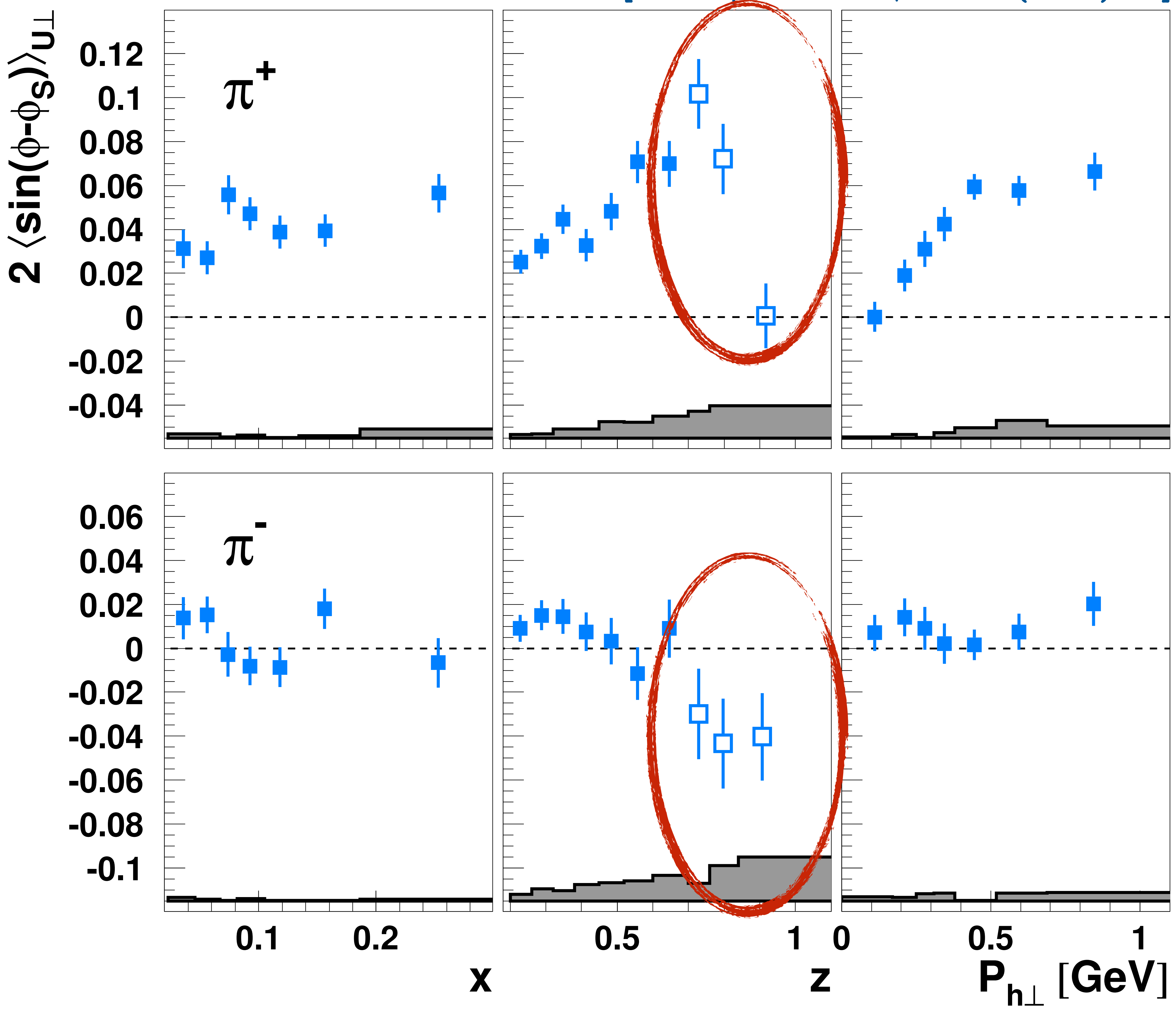
multi-d dependence and kinematical distribution should facilitate analyses within TMD formalism

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

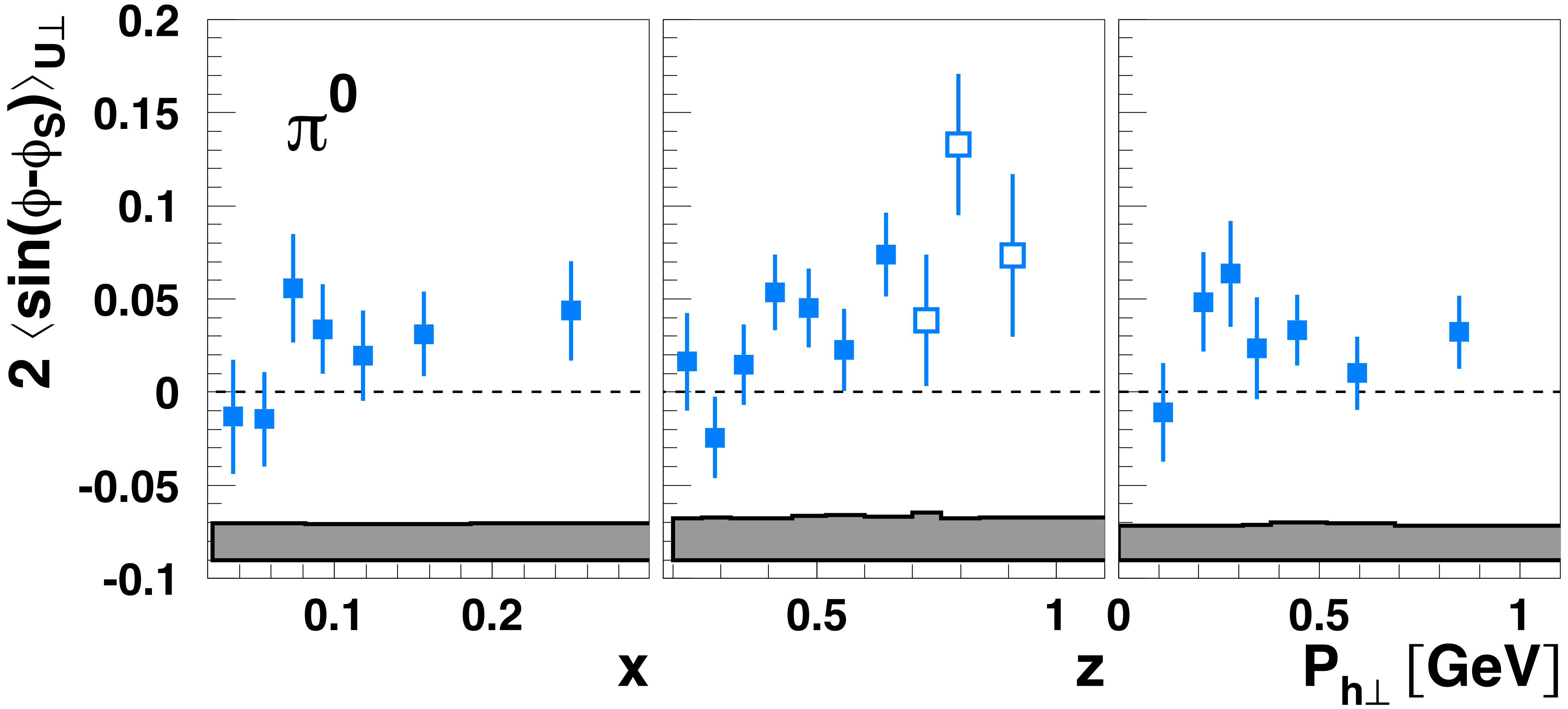


Sivers amplitudes for pions

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



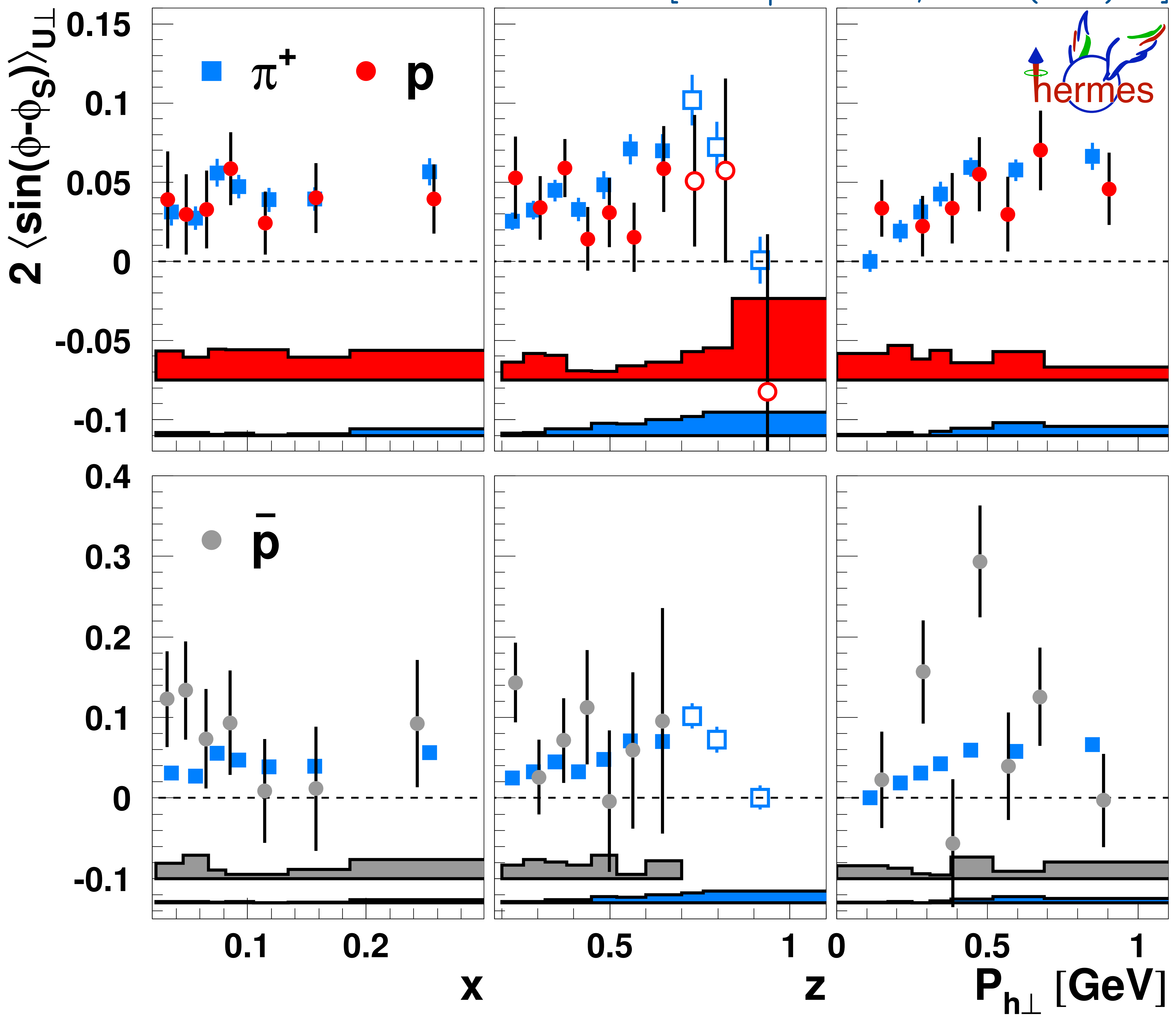
- **high-z data** probes region of **increased flavor sensitivity** to struck quark (but also where contributions from exclusive vector-meson production becomes significant)
  - only last z bin shows indication of sizable ρ^0 contribution (decaying into charged pions)



	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 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?

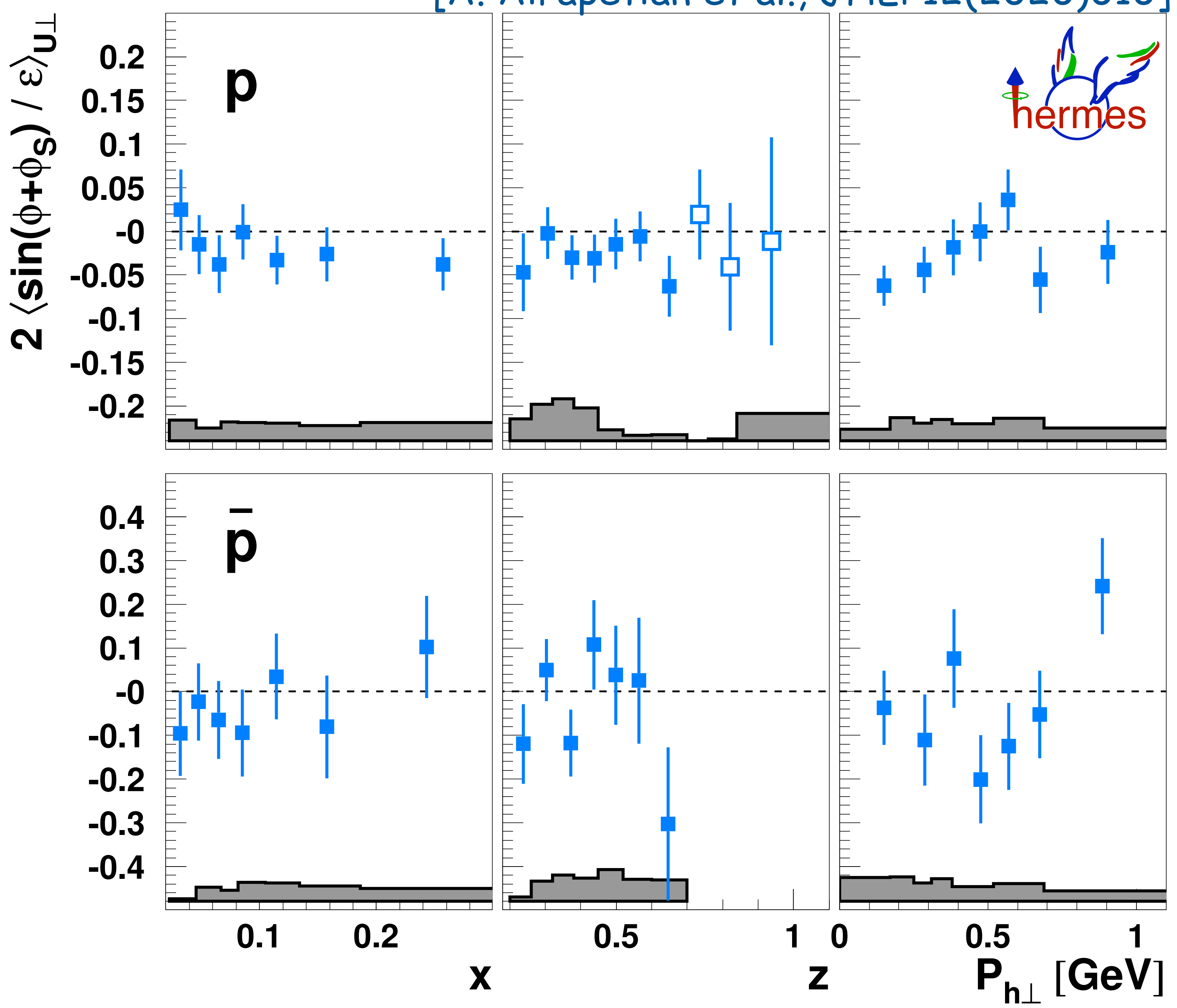
$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

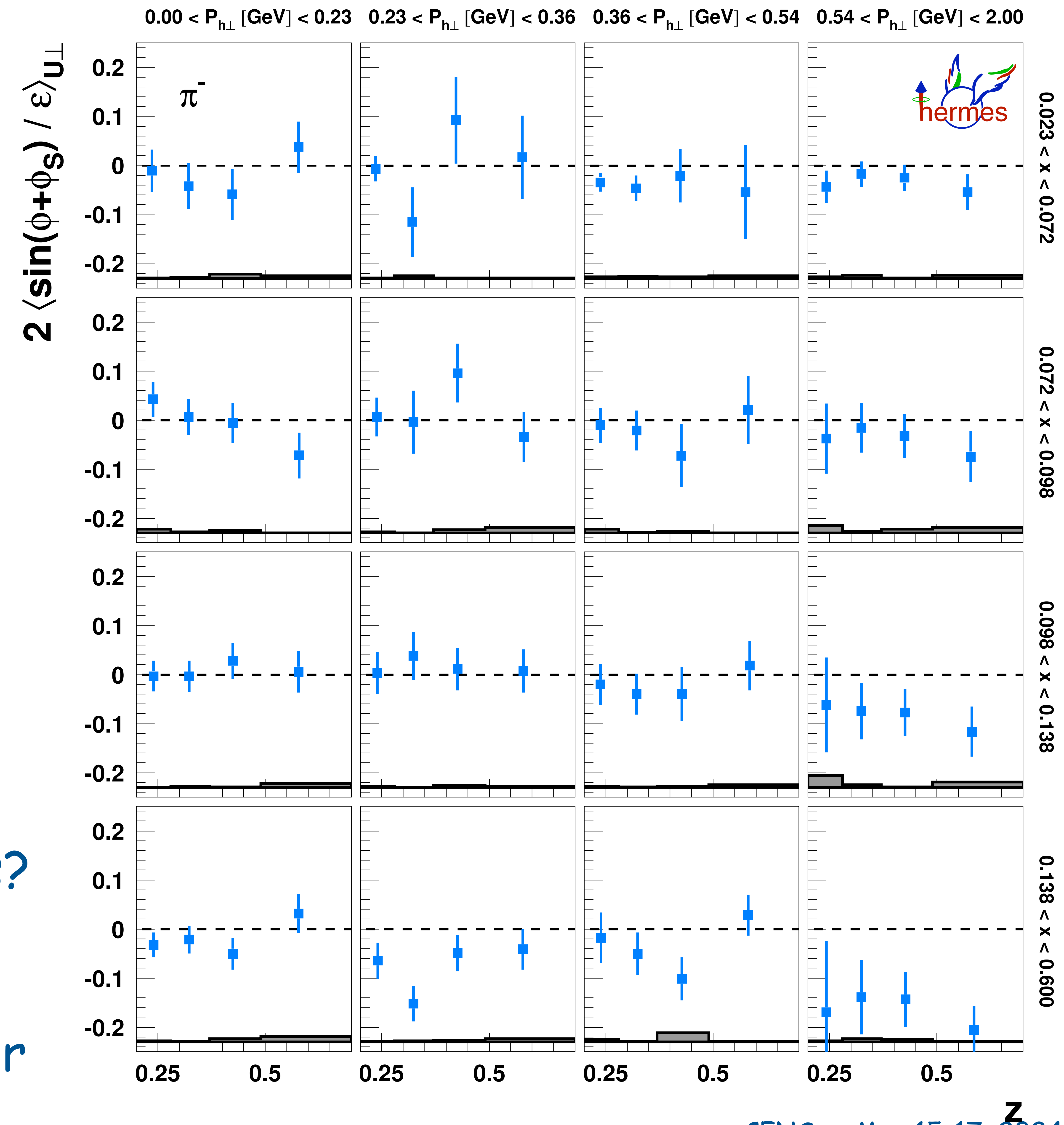
$$\approx -\mathcal{C}\,\frac{f_{1T}^{\perp,u}(x,p_T^2)}{f_1^u(x,p_T^2)}$$

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

new HERMES results on Collins amplitudes

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

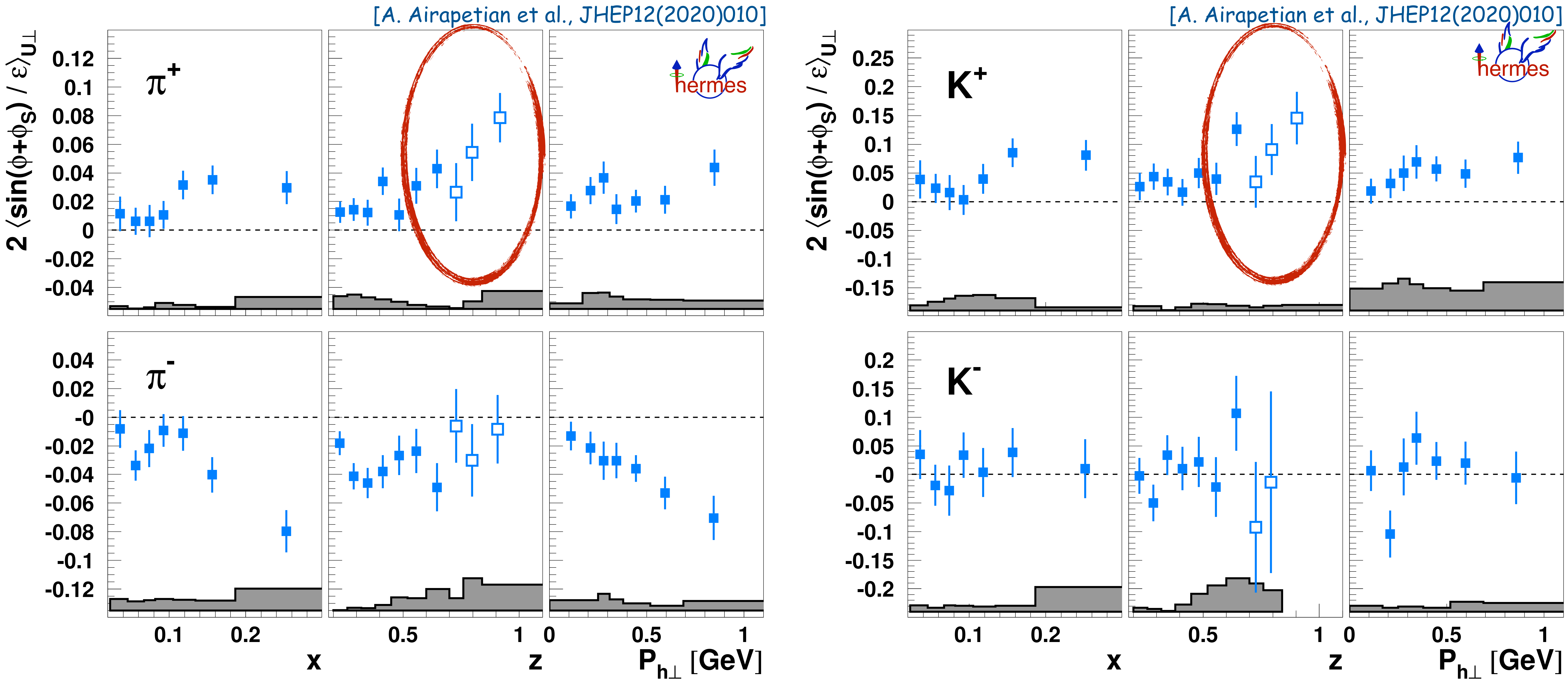




- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic "depolarization" prefactor

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

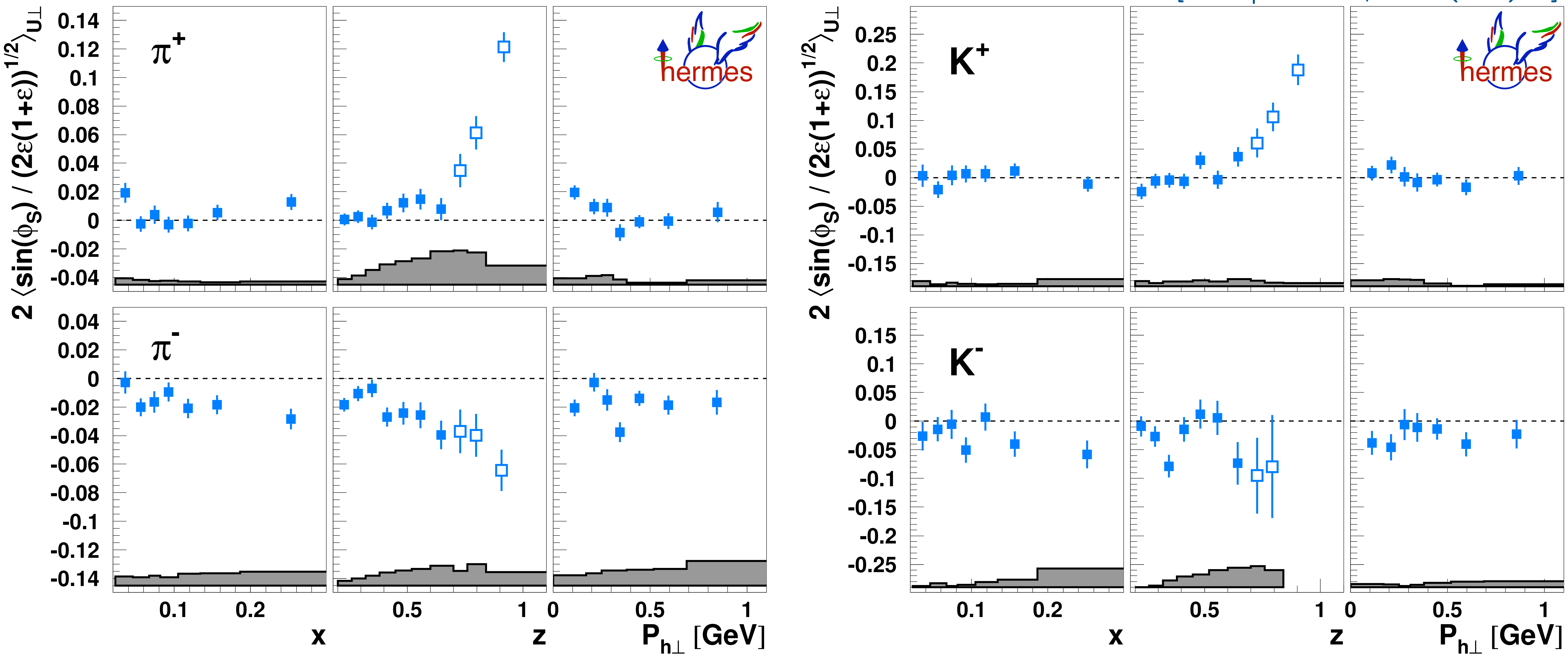
new HERMES results on Collins amplitudes



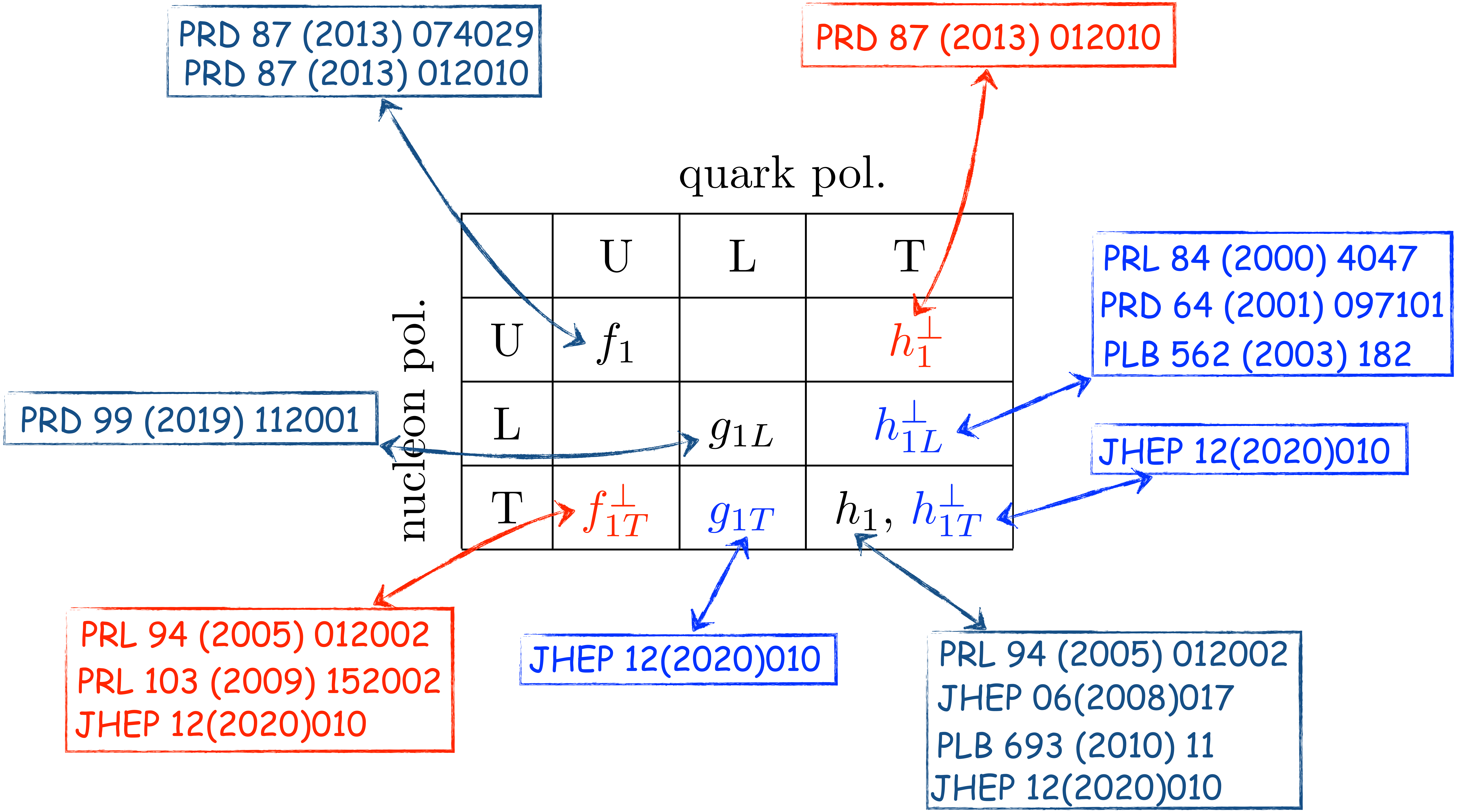
- first-ever results for **(anti-)protons** consistent with zero
  ➥ vanishing Collins effect for (spin-1/2) baryons?
- analysis now **performed in 3d**, both including or not including kinematic “depolarization” prefactor
- **high-z region** with larger quark-flavour sensitivity, with **increasing amplitudes** for positive pions and kaons

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



PRD 87 (2013) 074029
PRD 87 (2013) 012010
PRD 87 (2013) 012010
quark pol.
nucleon pol.
U
L
T
U
L
T
f_1
$h_1^\perp$
g_{1L}
$h_{1L}^\perp$
$f_{1T}^\perp$
g_{1T}
h_1, $h_{1T}^\perp$
PRL 84 (2000) 4047
PRD 64 (2001) 097101
PLB 562 (2003) 182
PRD 99 (2019) 112001
JHEP 12(2020)010
PRL 94 (2005) 012002
PRL 103 (2009) 152002
JHEP 12(2020)010
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