Workshop on Novel Probes of the Nucleon Structure in SIDIS, e^+e^- and pp (FF2019)
Duke University - March 14-16, 2019

Fragmentation in hadron leptoproduction

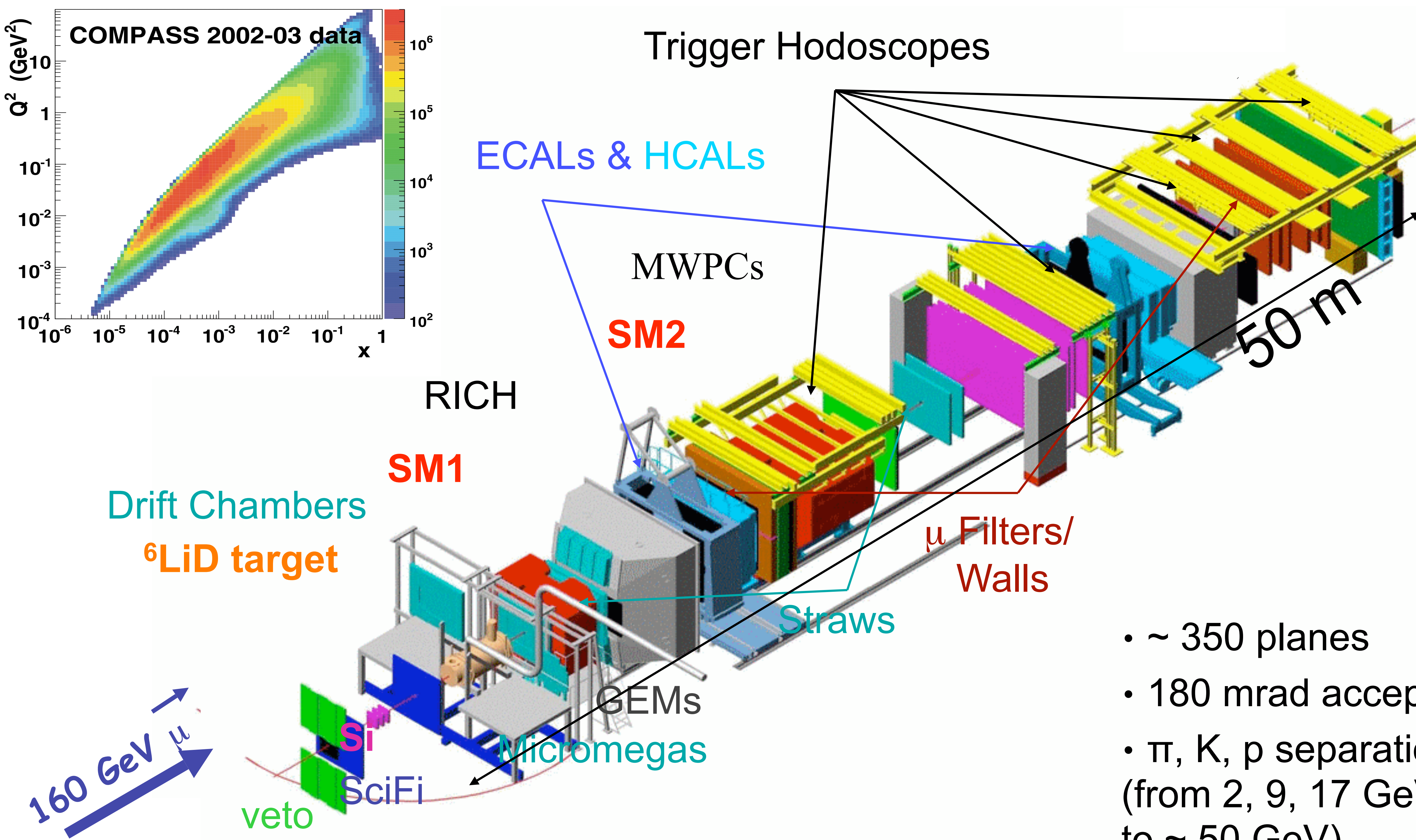
selected recent SIDIS results from COMPASS & HERMES

ikerbasque Basque Foundation for Science

Gunar.Schnell @ DESY.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

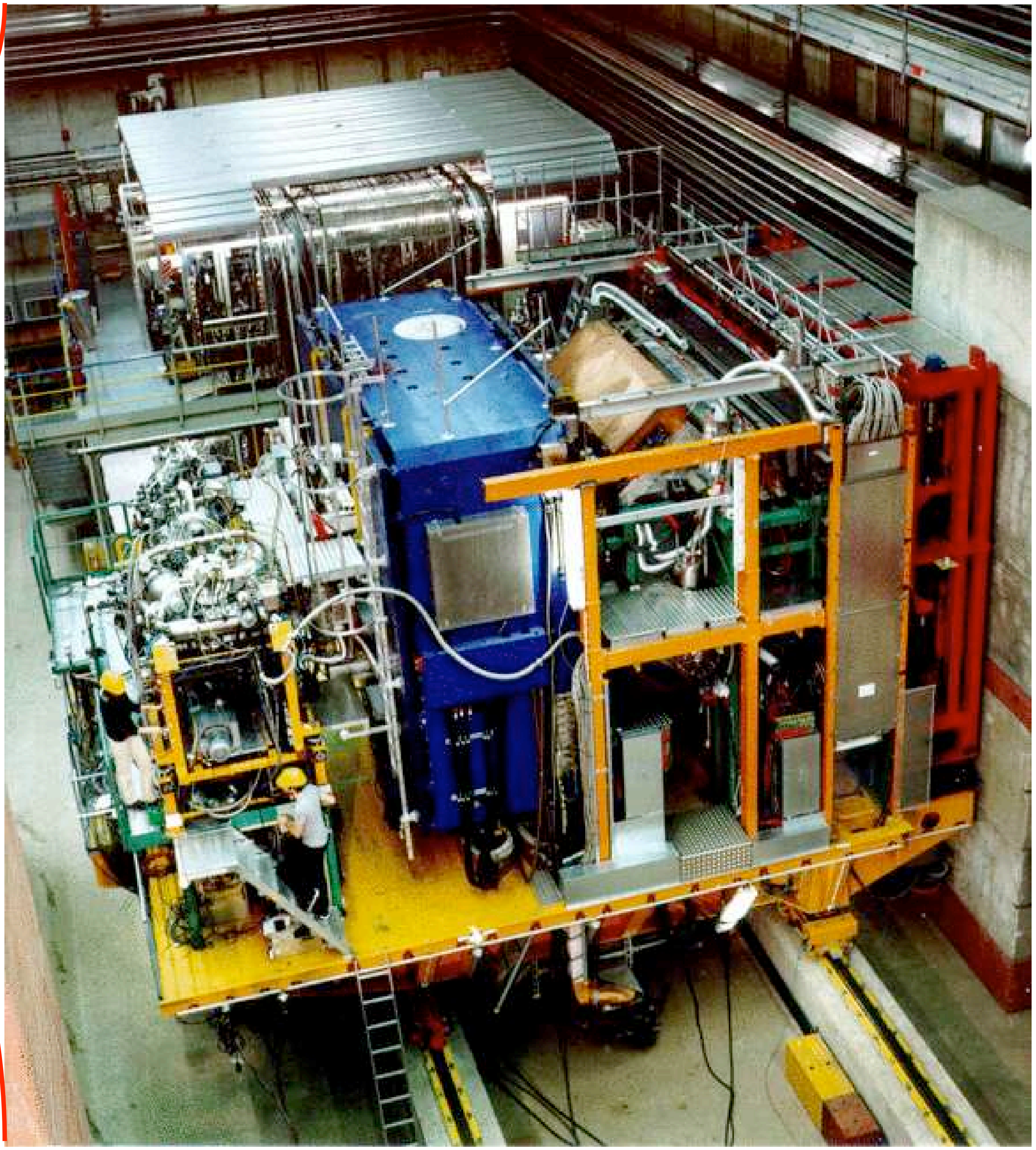
COMPASS @ CERN



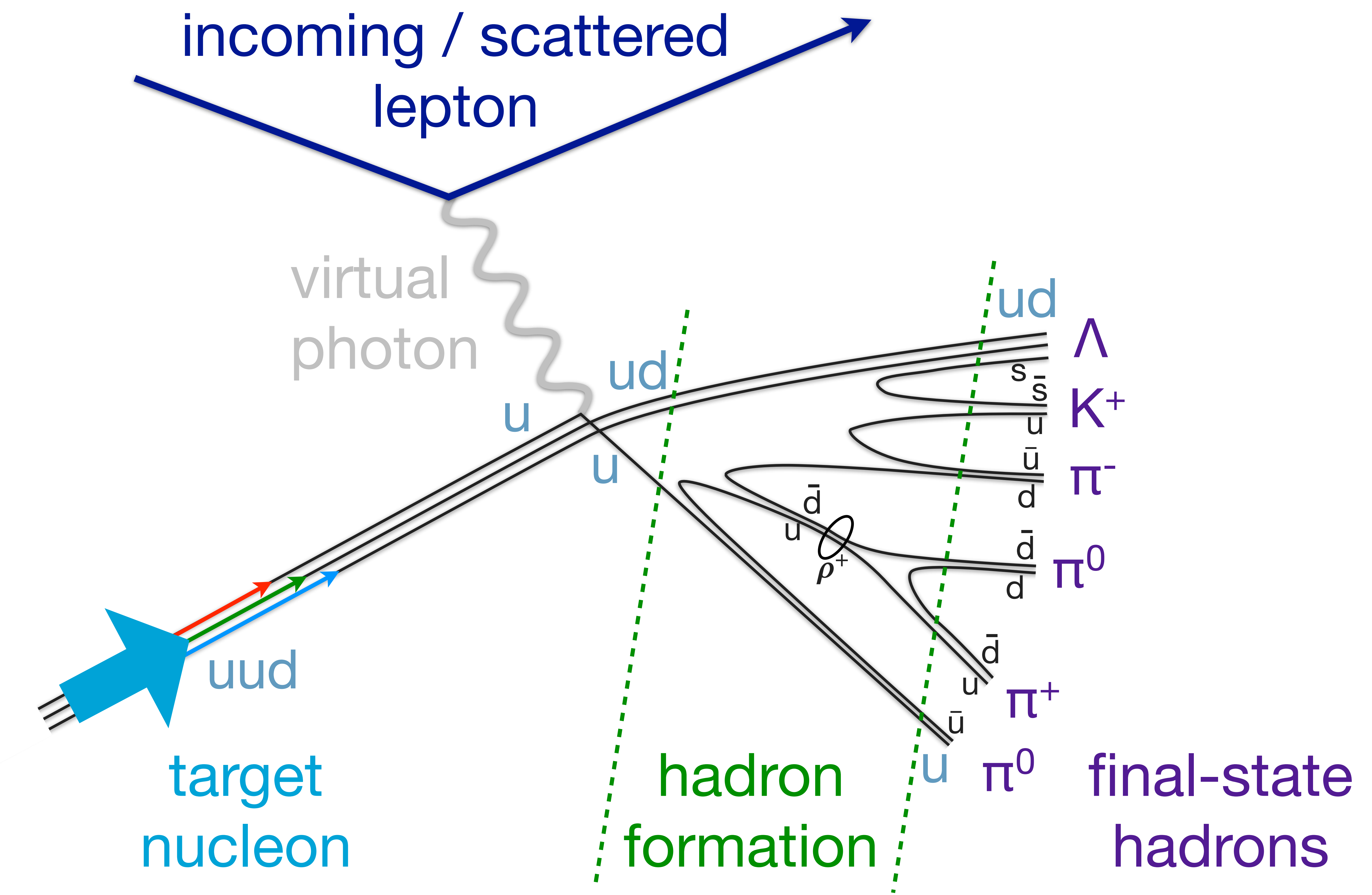
- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

HERMES (†2007) @ DESY

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

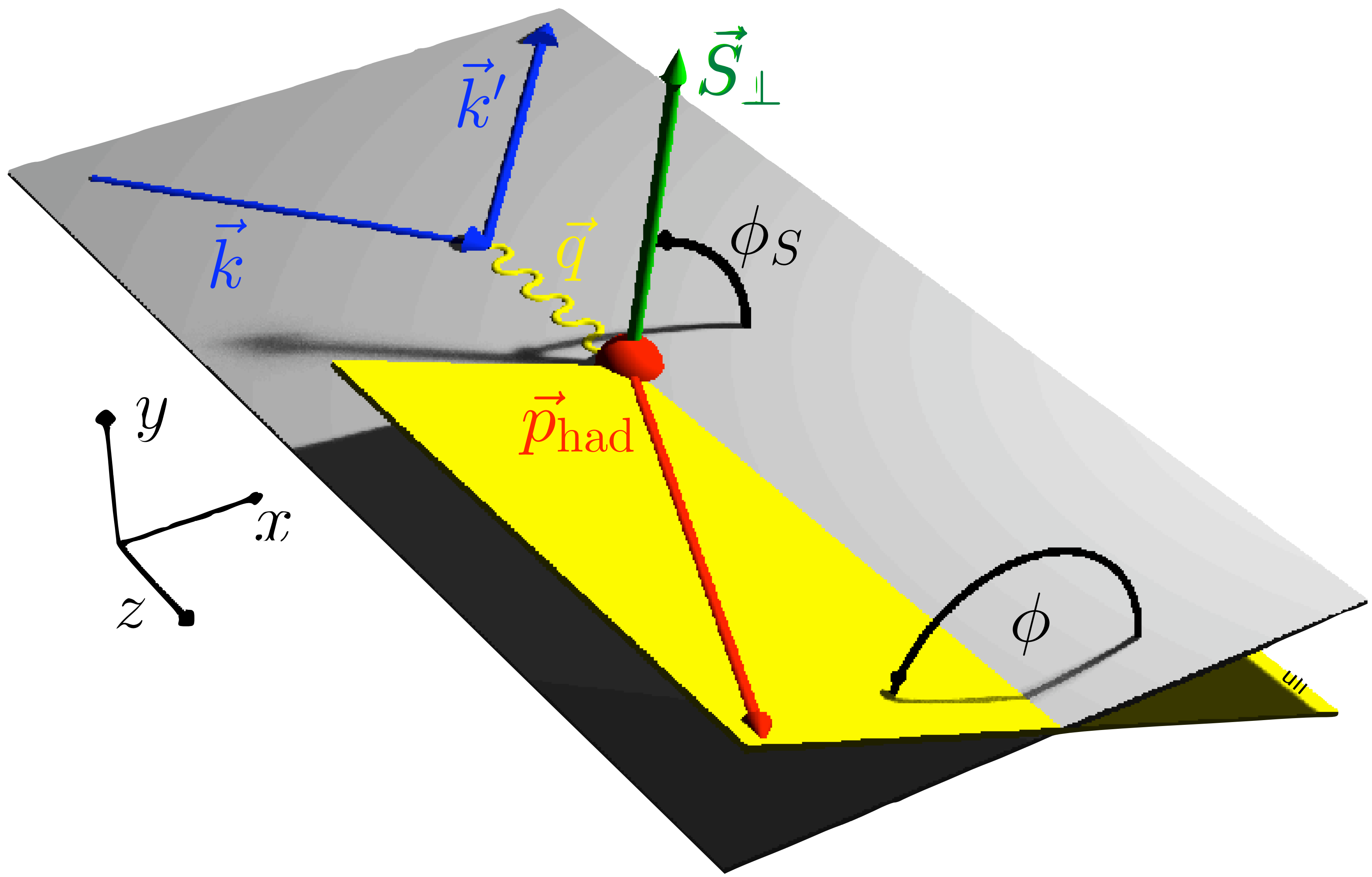


- unpolarized (H, D, He,..., Xe)
- as well as **transversely (H)** and longitudinally (H, D, He) polarized (pure) gas targets



incoming / scattered lepton
virtual photon
u
ud
u
uud
target nucleon
hadron formation
final-state hadrons
ud
Λ
s
s̄
K+
u
ū
π-
d
d̄
u
ρ+
d̄
π0
d
d̄
u
π+
ū
u
π0

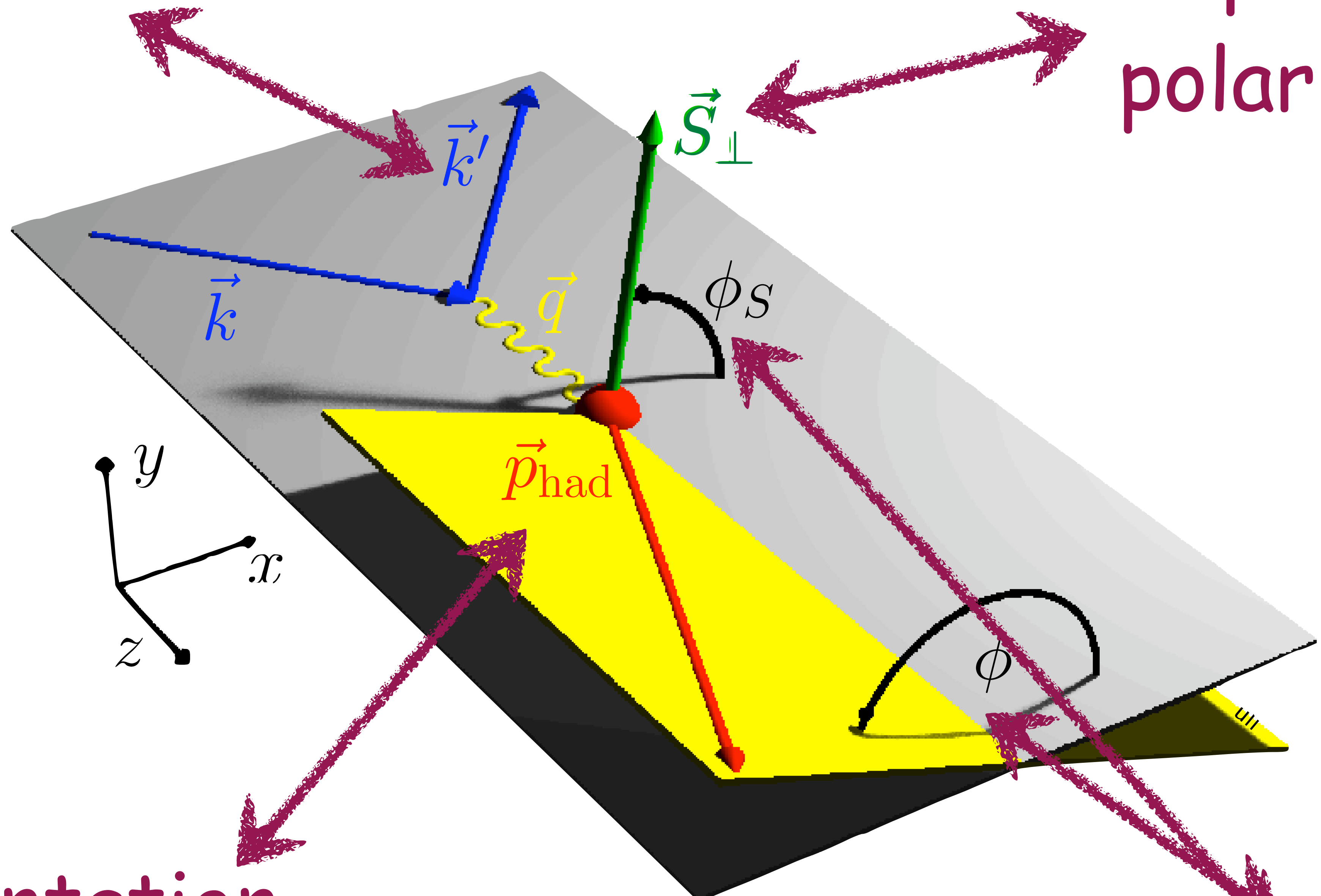
one-hadron production (ep→ehX)



one-hadron production (ep→ehX)

parton kinematics

parton polarization



fragmentation kinematics

FF selector

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

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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, $h_{1T}^\perp$

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- ... scribes a particular spin-... rrelation
- functions in black survive integration over transverse momentum
- ... green box are chirally odd
- functions in red are naive T-odd

TMDs in hadronization

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

TMDs in hadronization

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

☚ relevant for unpolarized final state

TMDs in hadronization

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

☛ relevant for unpolarized final state

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

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

TMDs in hadronization

quark pol.

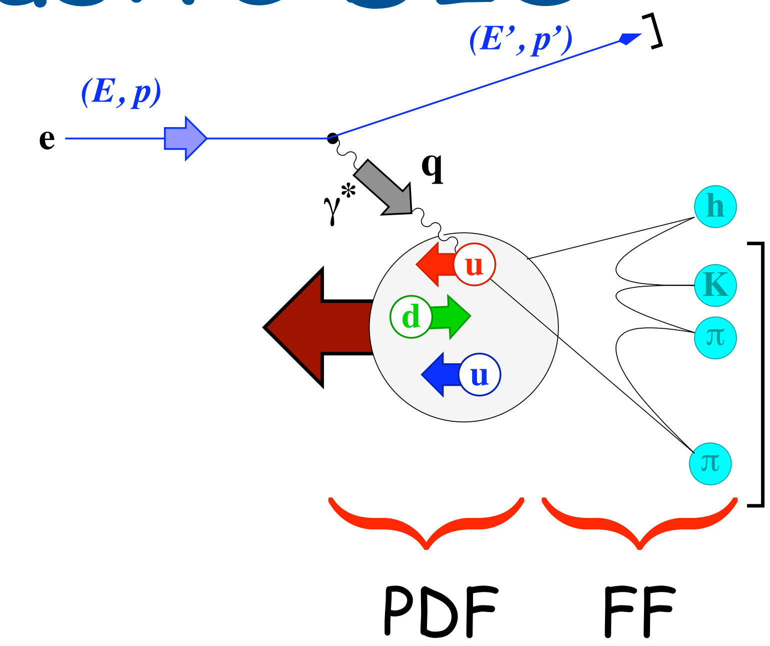
hadron pol.	U	L	T
U	$\boxed{D_1}$		$\boxed{H_1^{\perp}}$
L		G_1	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	$G_{1T}^{\perp}$	H_1 $H_{1T}^{\perp}$

relevant for unpolarized final state

polarized final-state hadrons

- 6 out of 8 require final-state polarimetry
  - most accessible: hyperons (parity-violating decay), but
  - lower production rate
  - spin structure often dominated by strange quarks
- (even) more involved: dihadron fragmentation functions

Probing TMDs in semi-inclusive DIS



quark pol.

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

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

one-hadron production (ep→ehX)

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

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

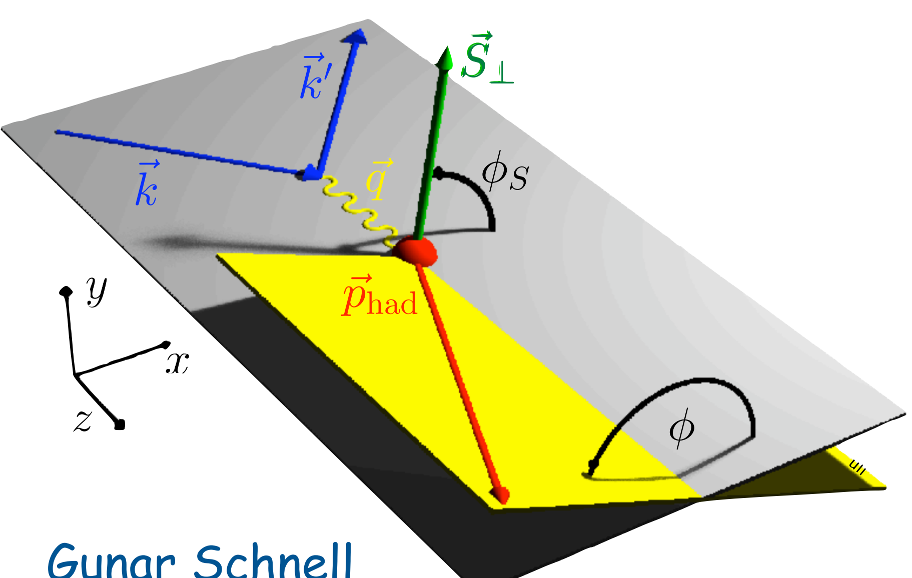
$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \right.$$

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

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

σ_{XY}

Beam **Target**
Polarization



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

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

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

Bacchetta et al., JHEP 0702 (2007) 093

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

one-hadron production (ep→ehX)

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

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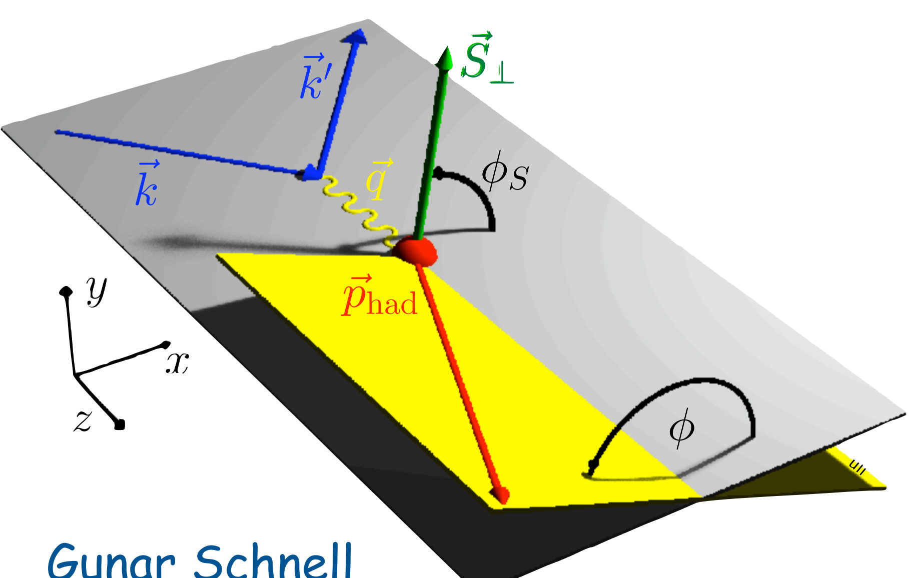
Beam **Target**

Polarization



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… possible measurements

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

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

… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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

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moments:
normalize to azimuth-independent cross-section

... possible measurements

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normalize to inclusive DIS cross section

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

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

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

moments:
normalize to azimuth-independent cross-section

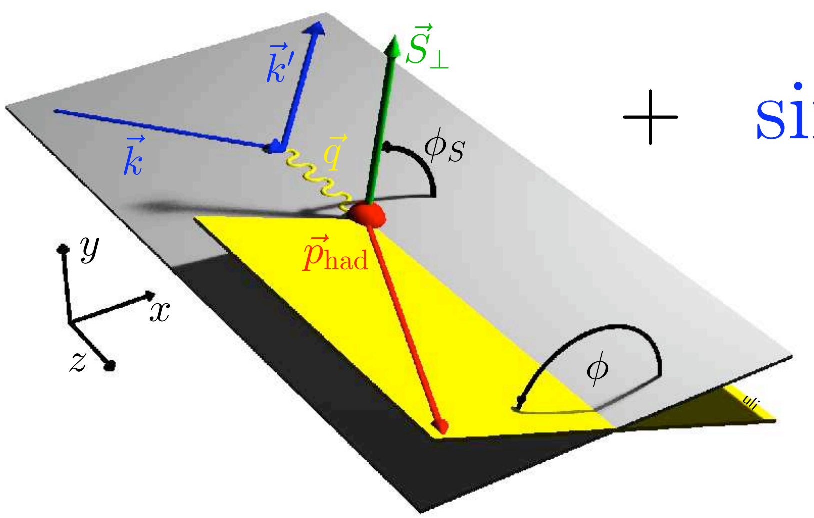
... azimuthal spin asymmetries

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^\uparrow(\phi,\phi_S) - N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S) + N_h^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\, \mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M_h} h_1^q(x,p_T^2) H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \sin(\phi-\phi_S)\sum_q e_q^2\, \mathcal{I}\left[\frac{\boldsymbol{p_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M} f_{1T}^{\perp,q}(x,p_T^2) D_1^q(z,k_T^2)\right]$$

$$+ \quad \cdots$$



$\mathcal{I}[\ldots]$: **convolution integral over initial (p_T) and final (k_T) quark transverse momenta**

fit azimuthal modulations, e.g., using maximum-likelihood method

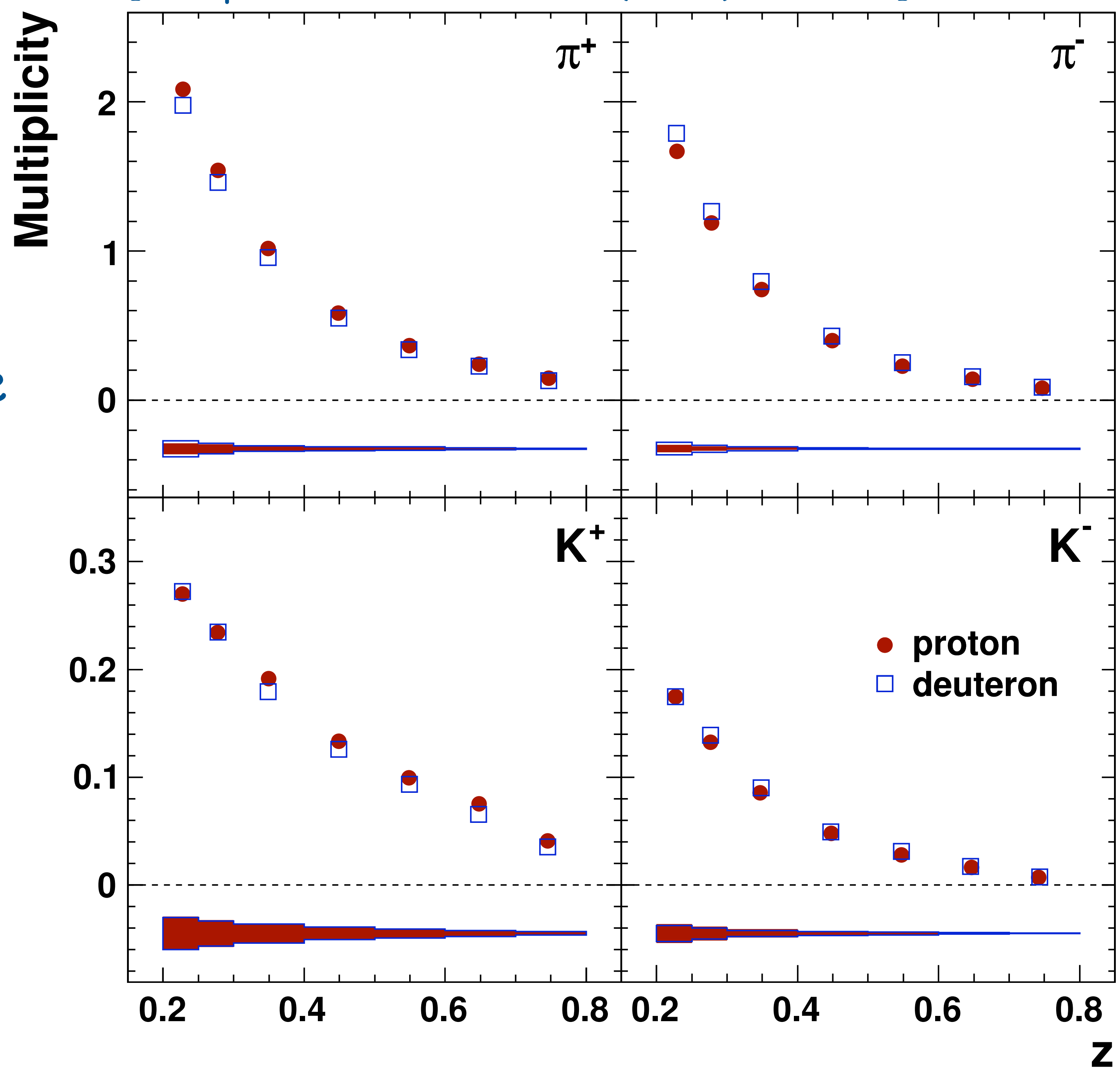
$$\boxed{PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1 + P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\sin(\phi\pm\phi_s) + \ldots)\}}$$

... results ...

multiplicities @ HERMES

- remember: M = SIDIS / DIS
- extensive data set on pure proton and deuteron targets for identified charged mesons
  - access to flavor dependence of fragmentation through different mesons & targets
- input to fragmentation function analyses
- extracted in a 3-dimensional unfolding procedure:
  - $(x, z, P_{h\perp})$
  - $(Q^2, z, P_{h\perp})$

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

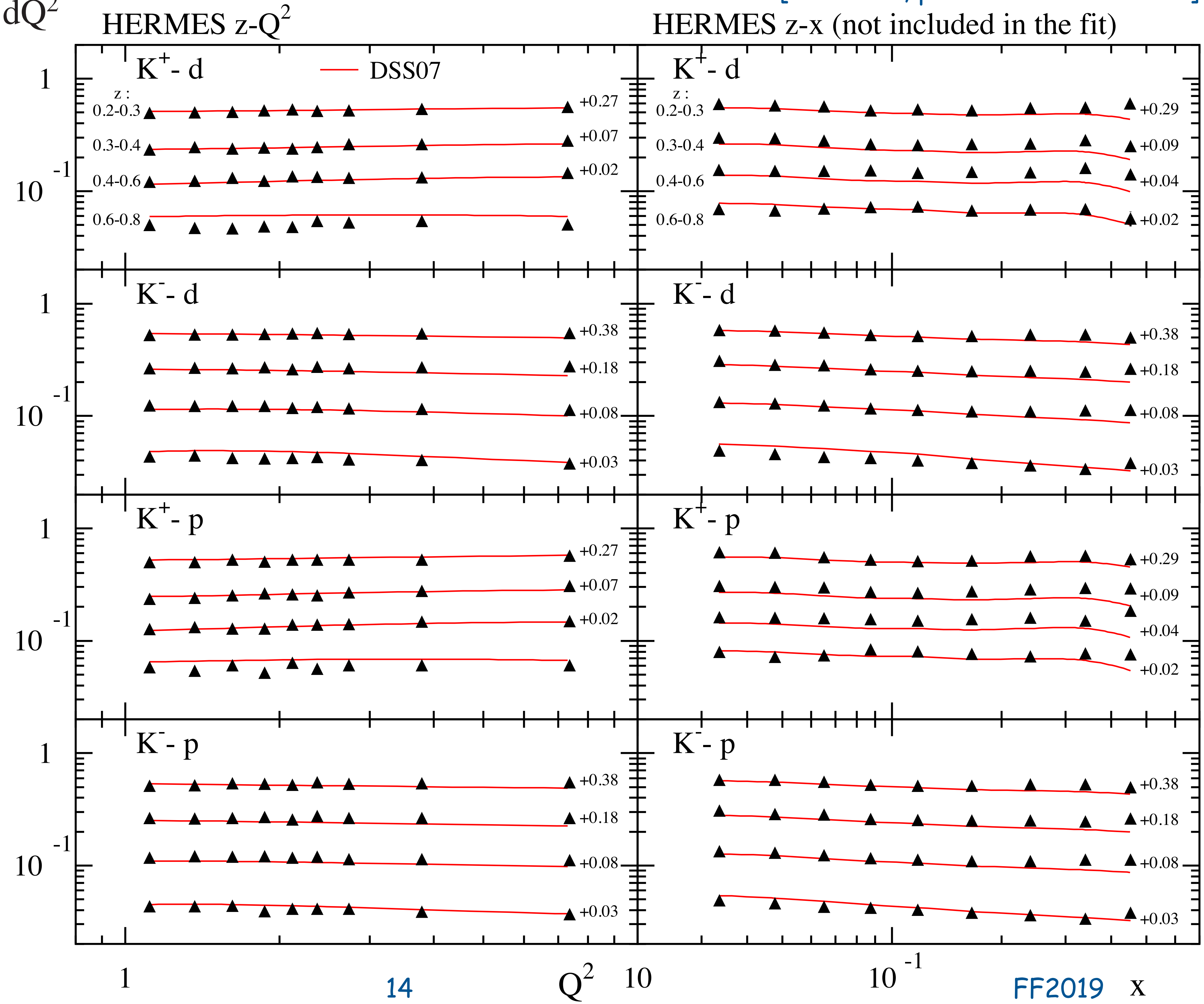


integrating vs. using average kinematics

$$\frac{\sum_q e_q^2 \int_{Q^2_{min}(x_B)}^{Q^2_{max}(x_B)} q(x_B, Q^2) D_q^{\pi}(z, Q^2) dQ^2}{\sum_q e_q^2 \int_{Q^2_{min}(x_B)}^{Q^2_{max}(x_B)} q(x_B, Q^2) dQ^2}$$

[R. Sassot, private communication]

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



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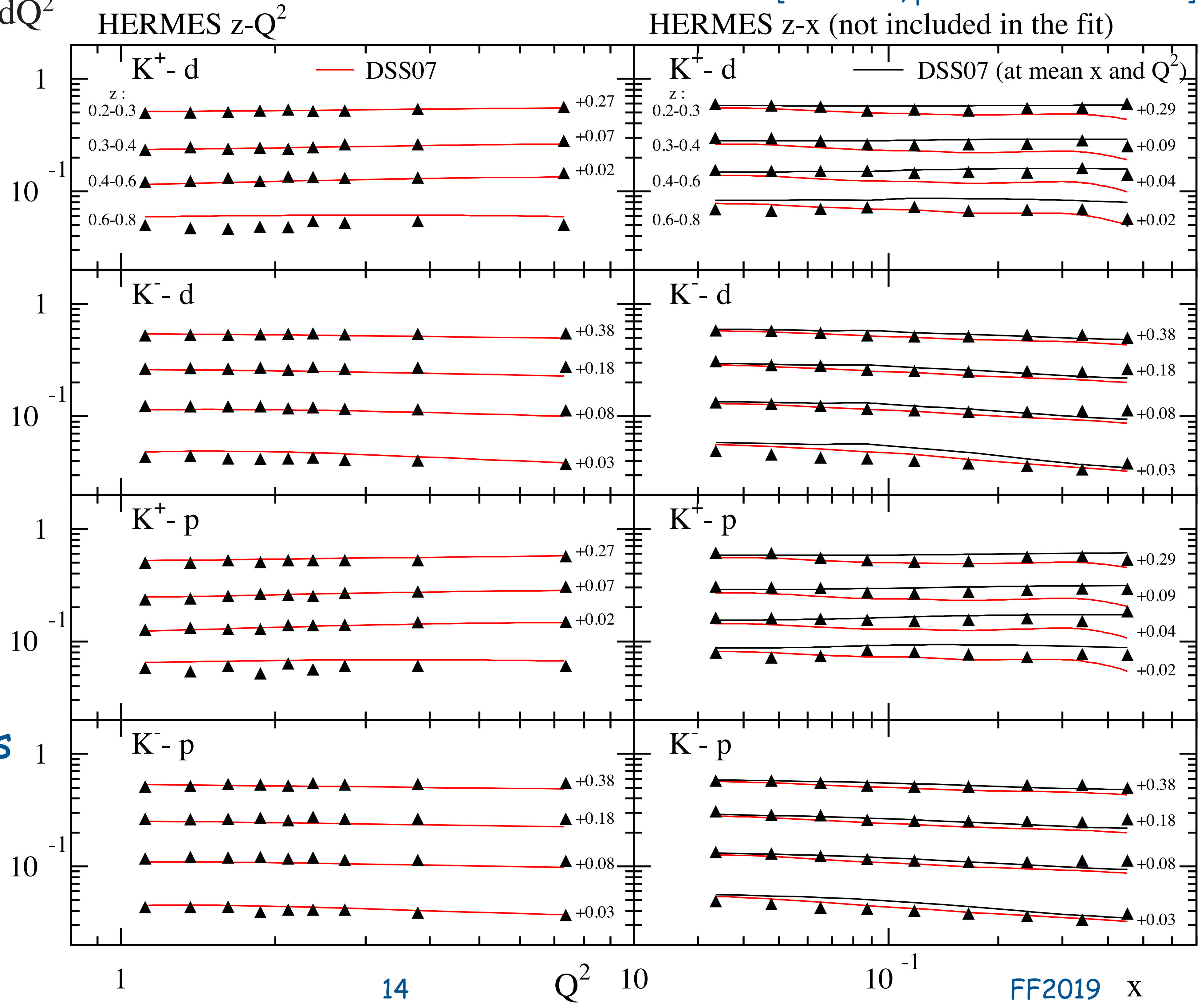
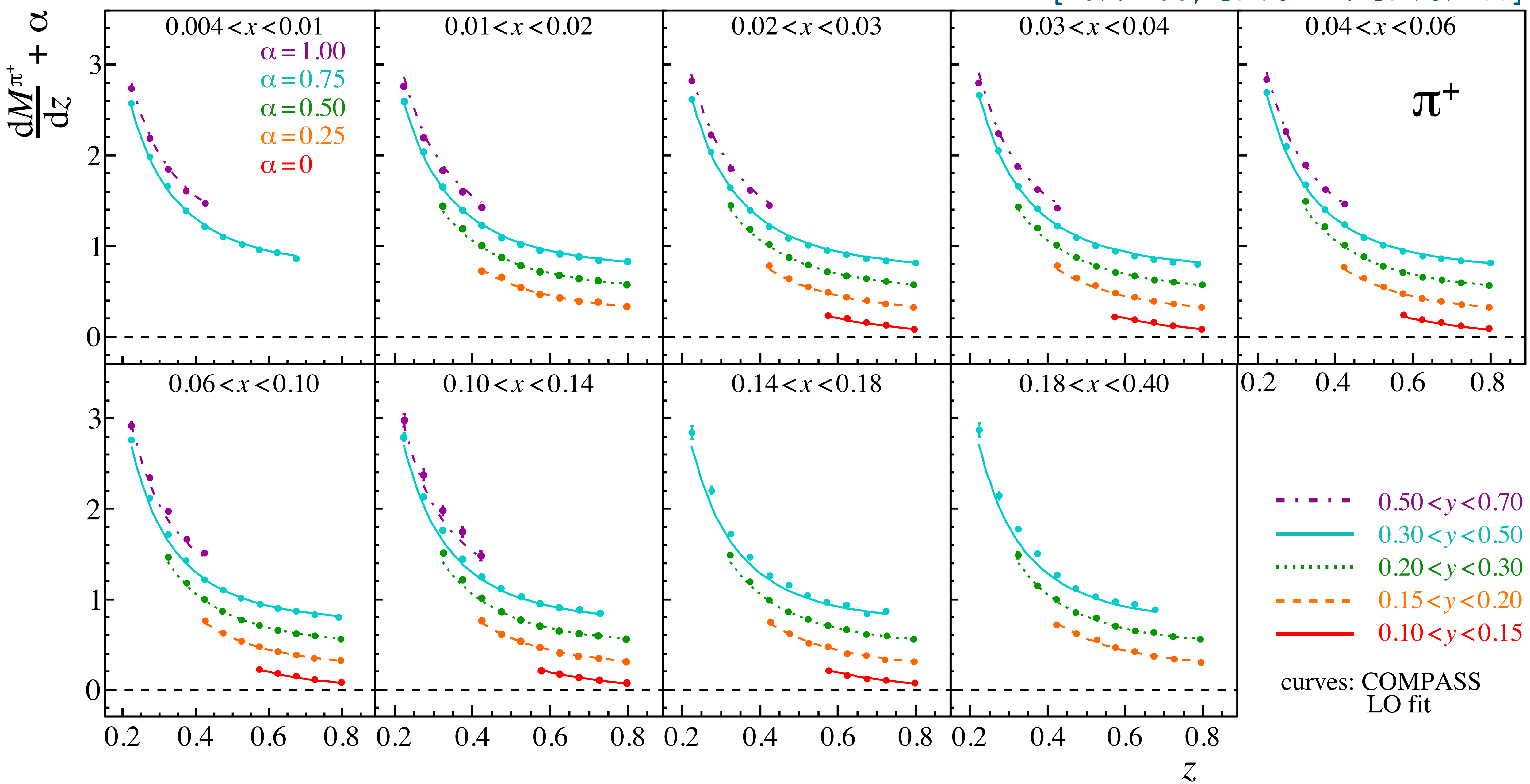
- (by now old) **DSS07** FF fit to z-Q^2 projection
- z-x "prediction" reasonable well when using **integration** over phase-space limits (red lines)
- significant changes when using **average kinematics**

[R. Sassot, private communication]



multiplicities @ COMPASS

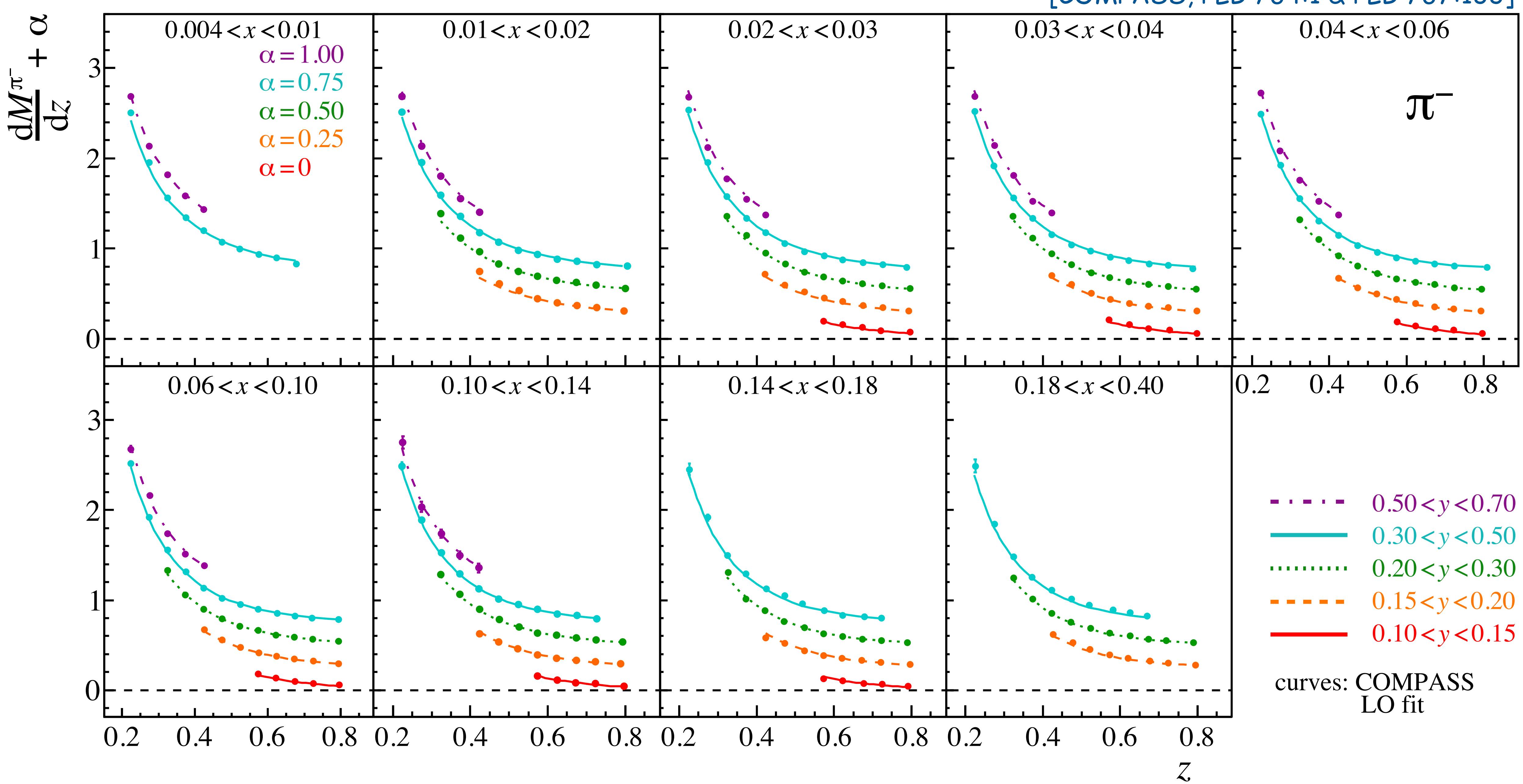
[COMPASS, PLB 764:1 & PLB 767:133]



- very precise data for pions and kaons, in a large kinematic range
- available in 3d binning in x, y, z
- follows expected hierarchy: $\pi^+ > \pi^- > K^+ > K^-$

multiplicities @ COMPASS

[COMPASS, PLB 764:1 & PLB 767:133]



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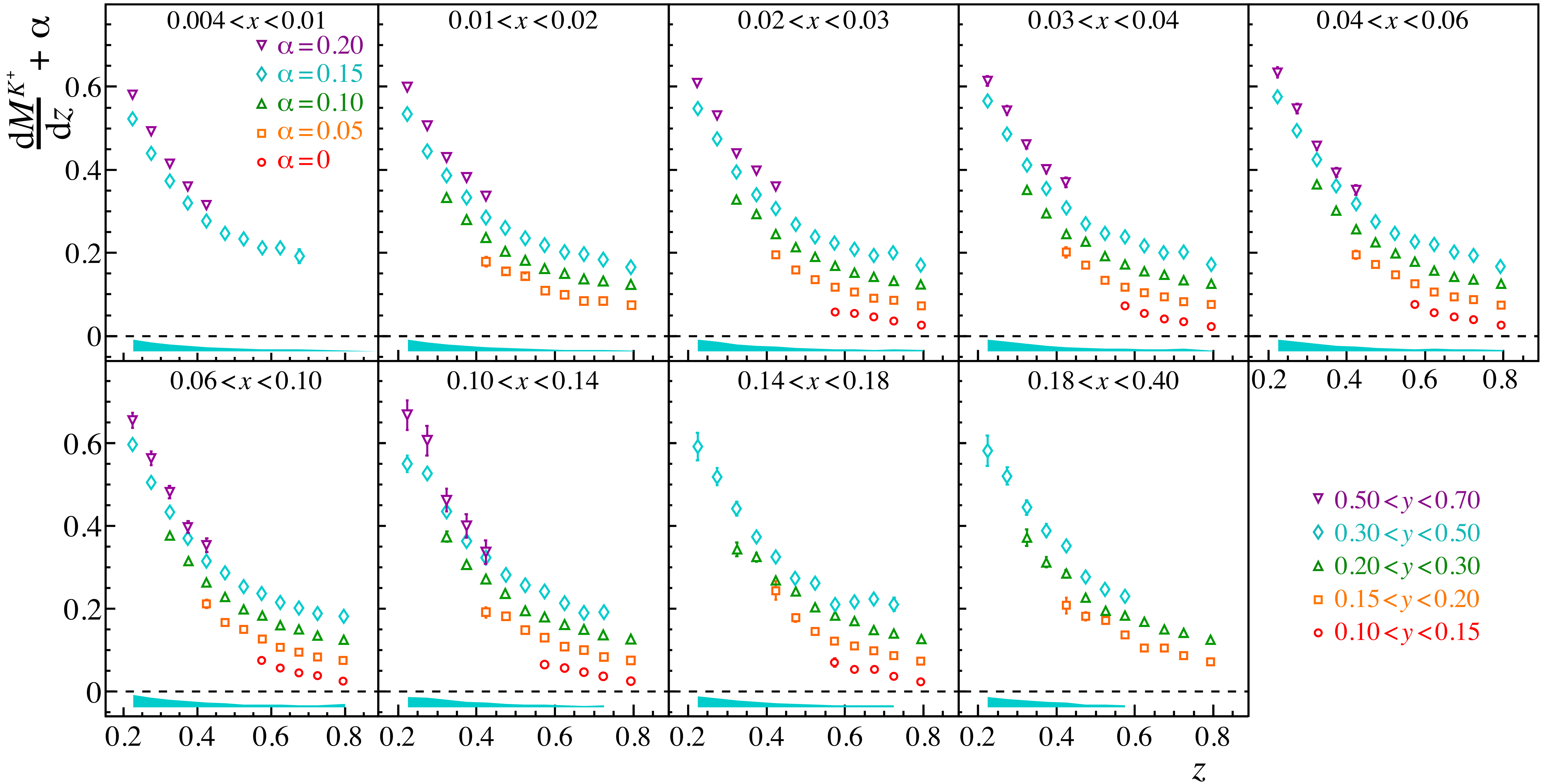

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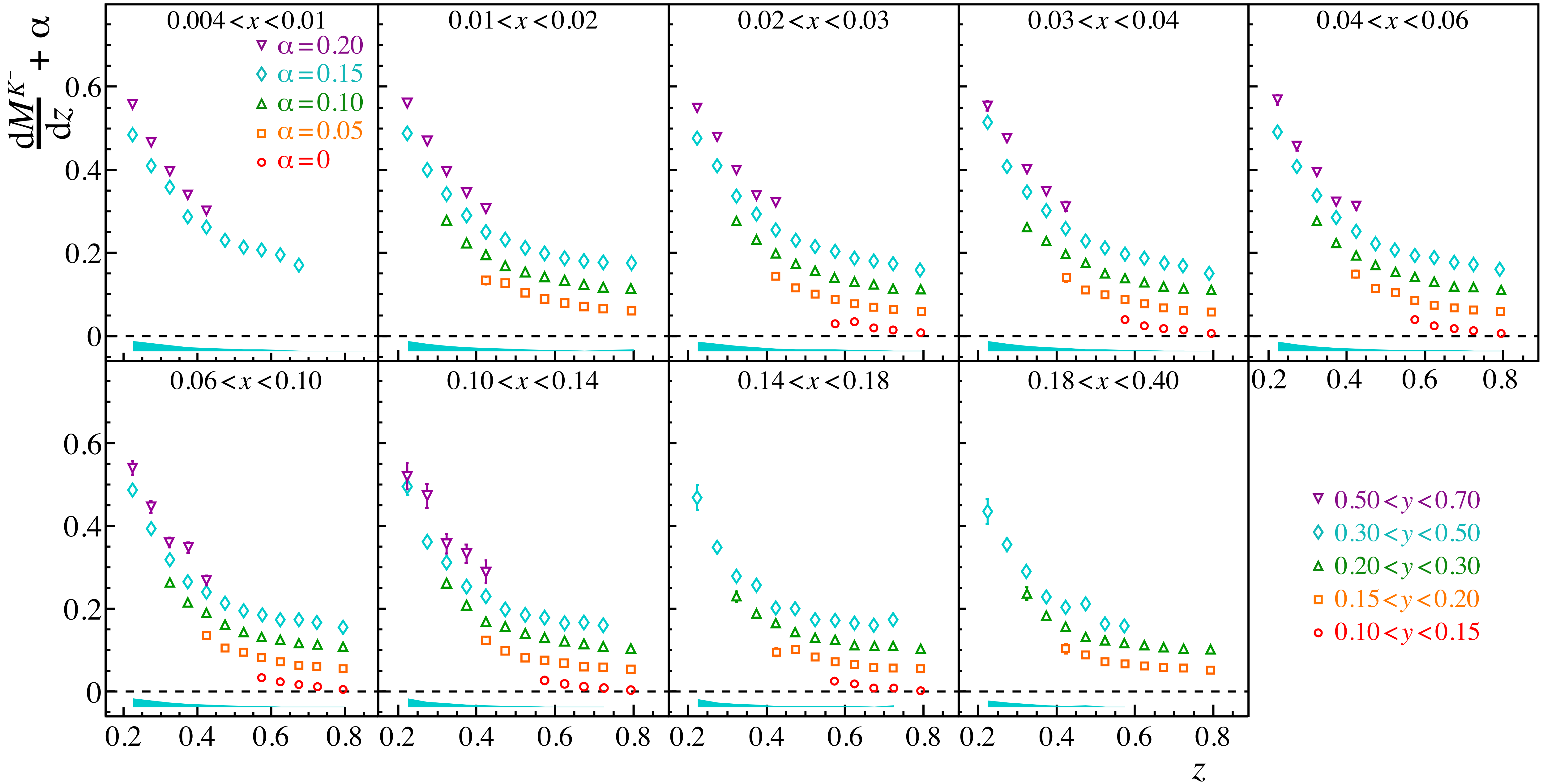

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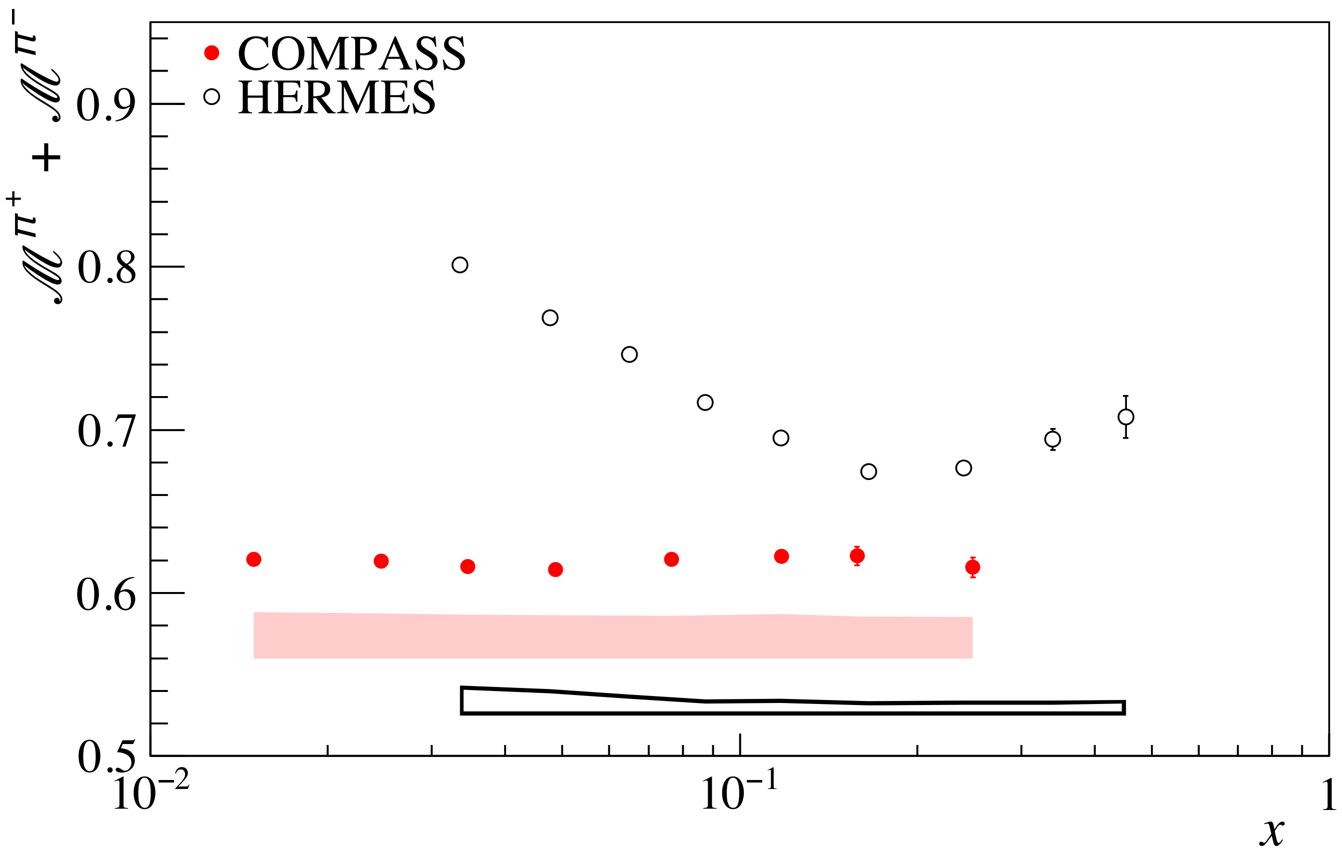
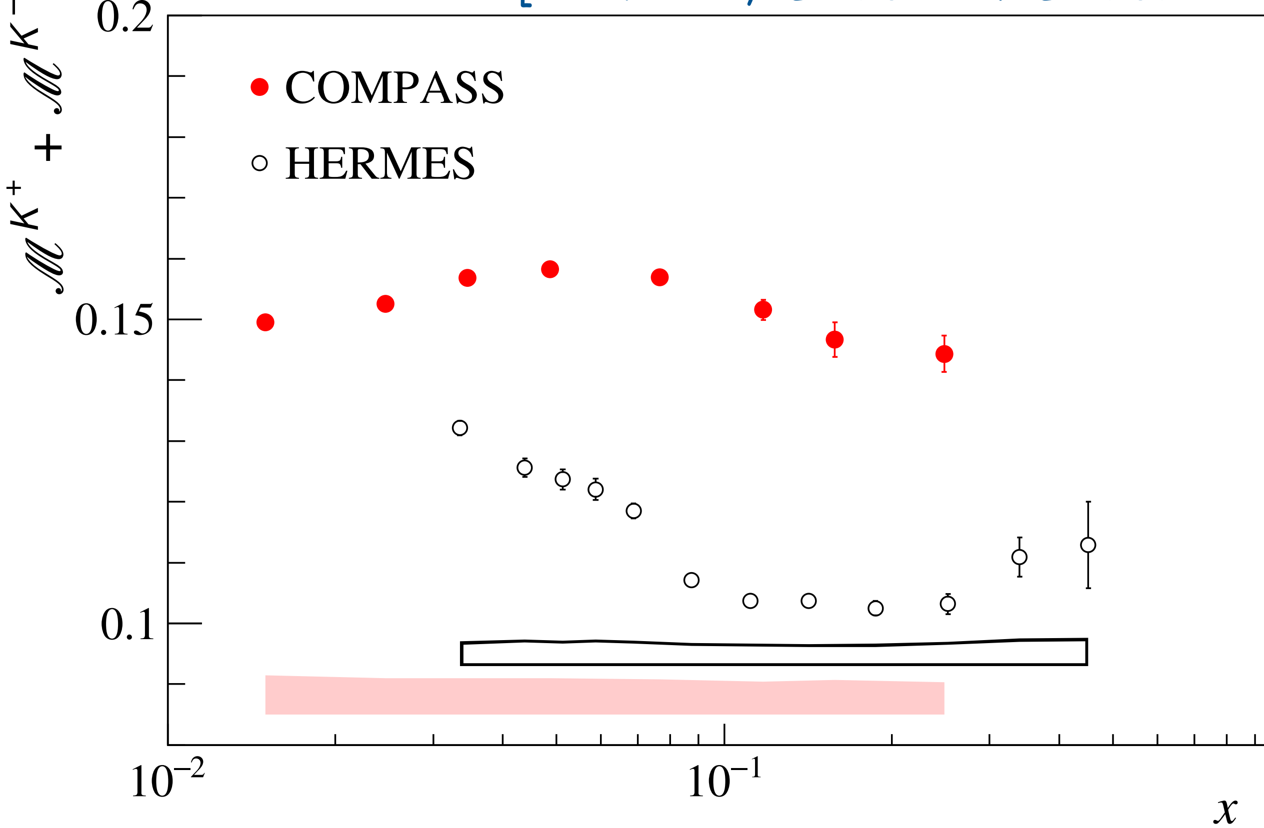


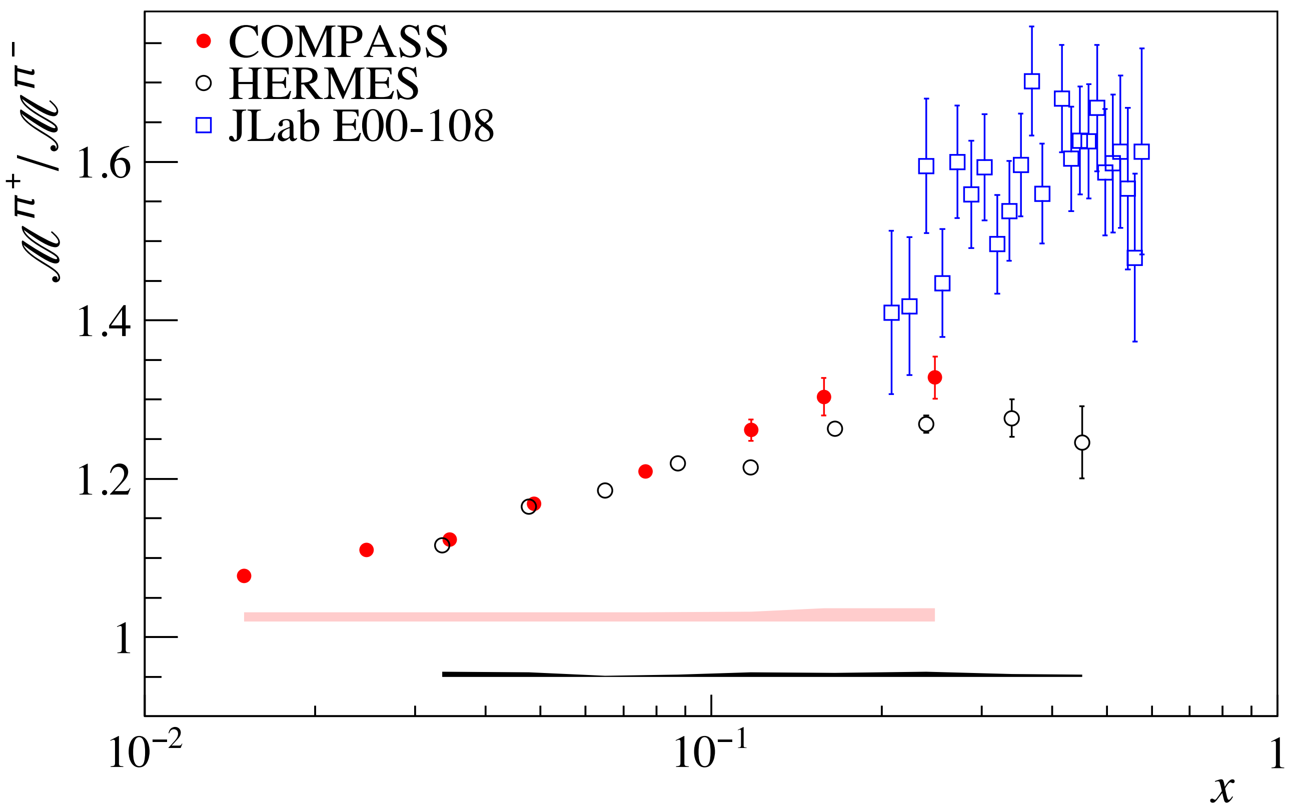


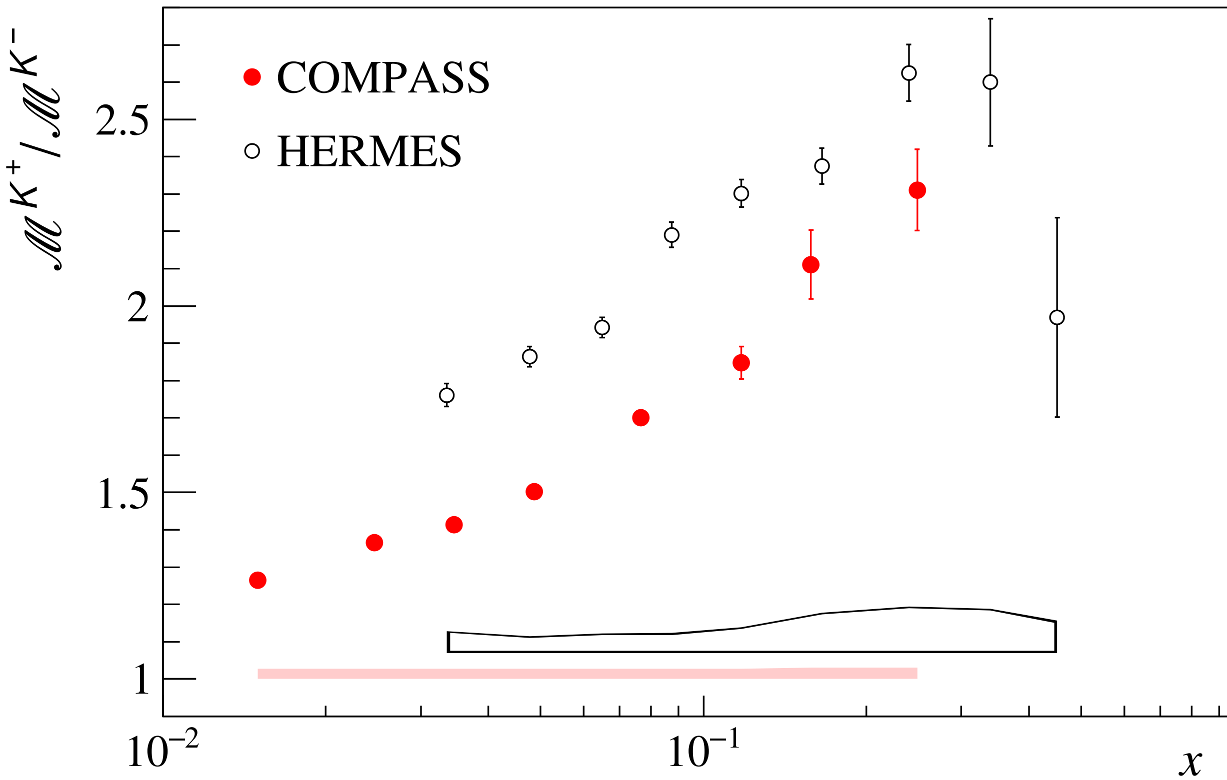
$$\mathcal{M}^{\pi^+} + \mathcal{M}^{\pi^-} \neq \mathcal{M}^{\pi^+} + \mathcal{M}^{\pi^-}$$

- COMPASS: weighted average over y
- HERMES: integral over Q^2 range of each x-bin

multiplicities @ COMPASS & HERMES

[COMPASS, PLB 764:1 & PLB 767:133]

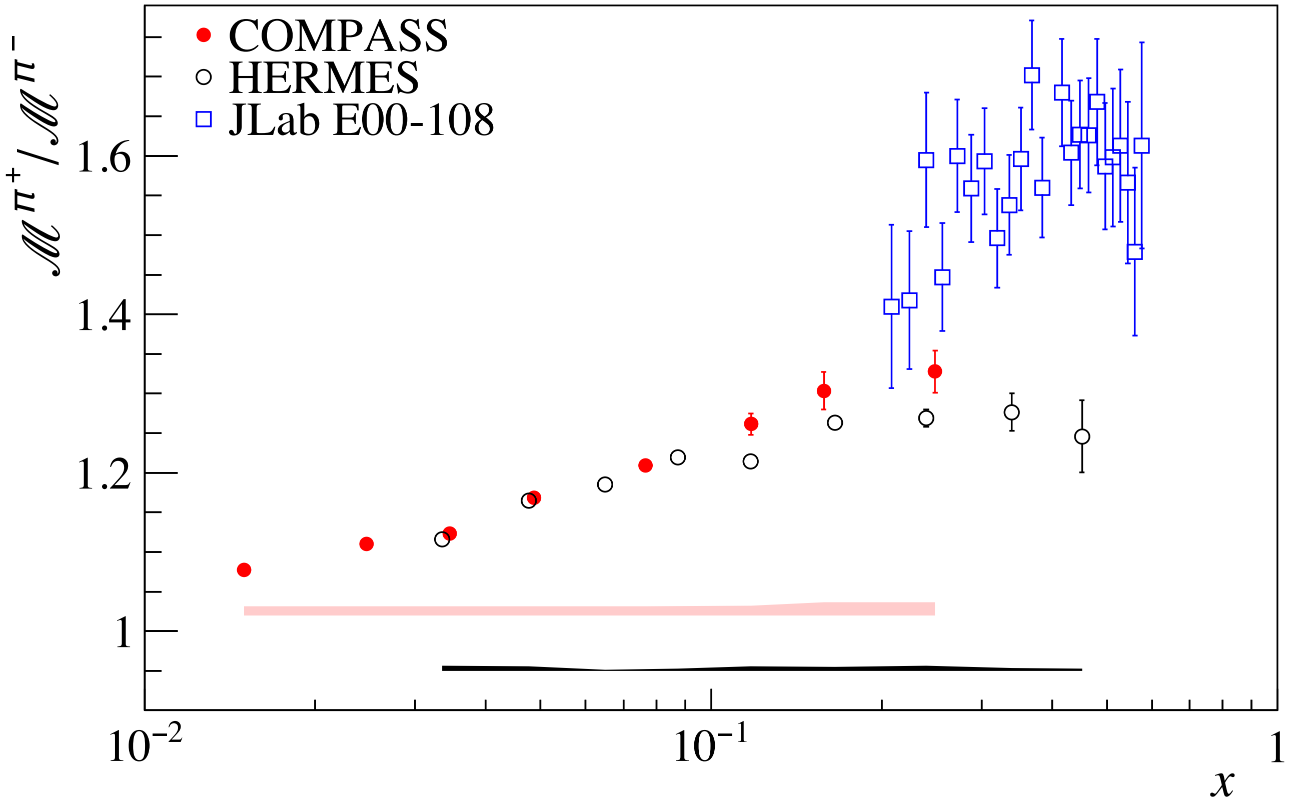


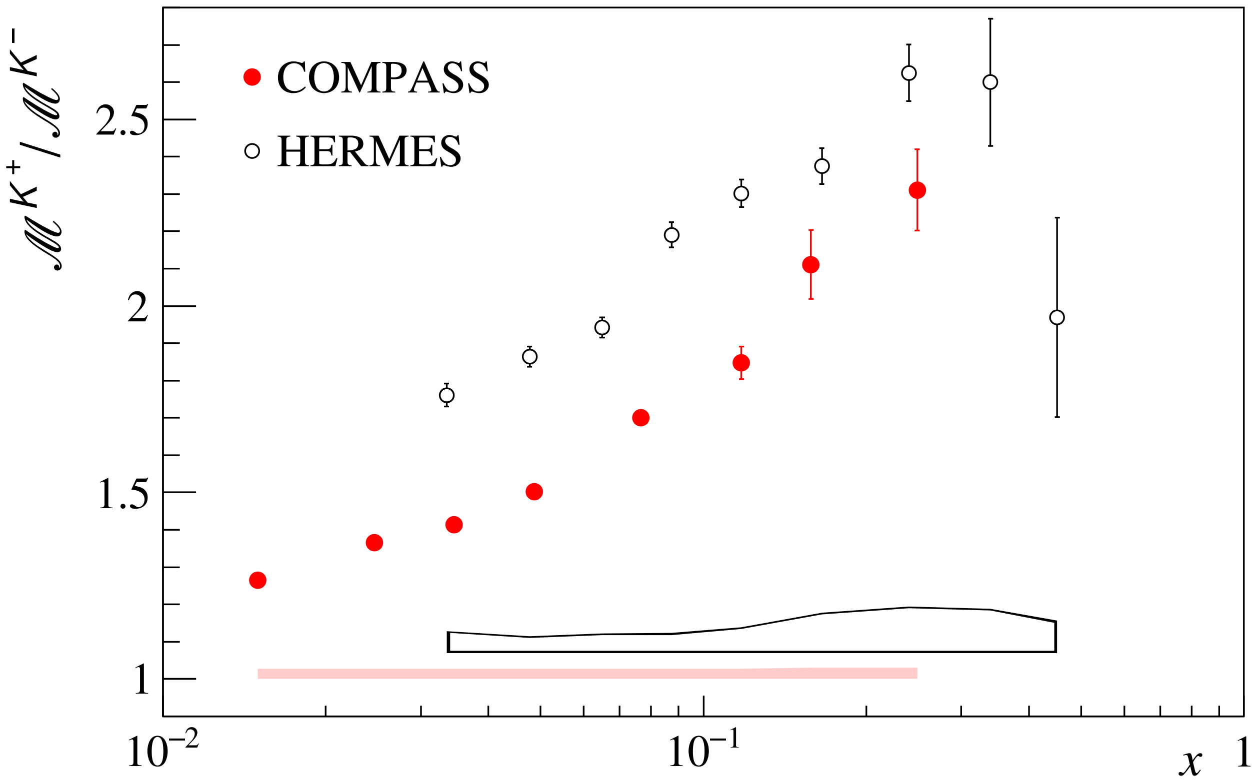


- good agreement for pions
- larger suppression of disfavored K^- production at HERMES

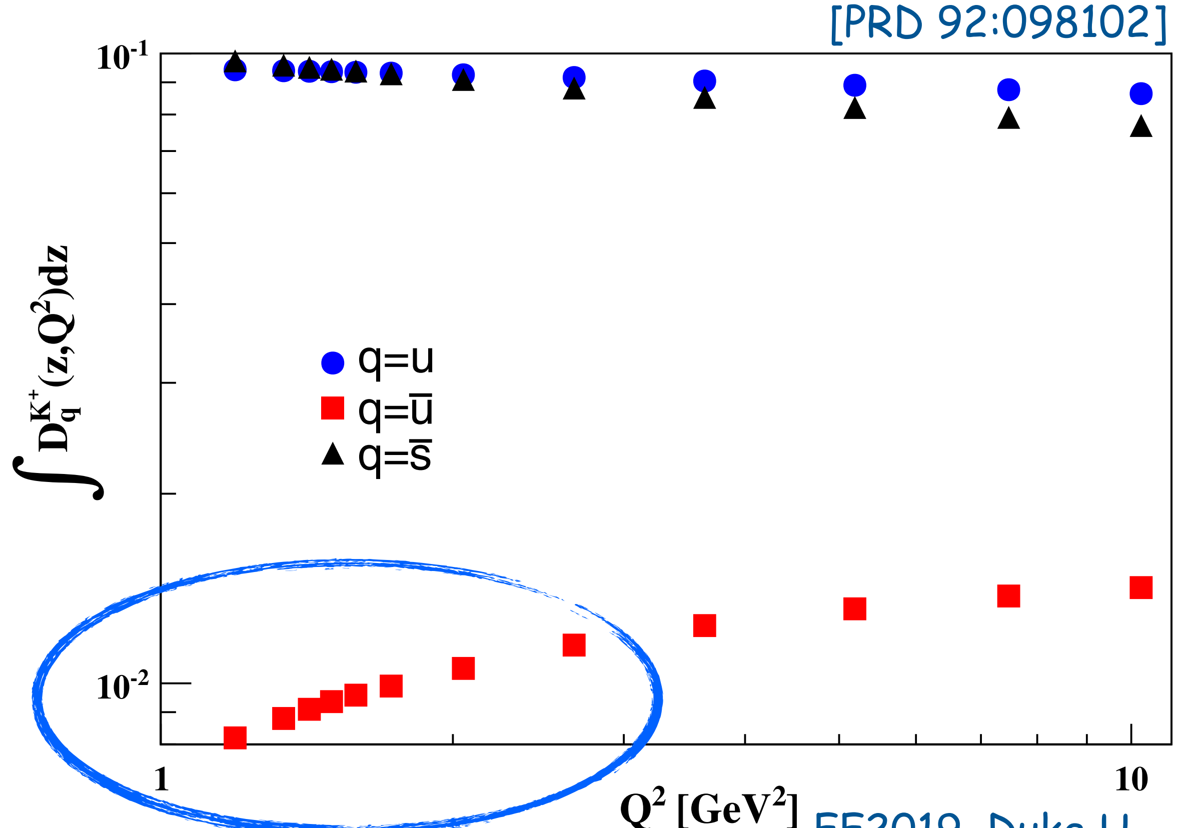
multiplicities @ COMPASS & HERMES

[PLB 764:1 & PLB 767:133]





[PRD 92:098102]



- good agreement for pions
- larger suppression of disfavored K^- production at HERMES
- large suppression of disfavored kaon FF at low Q^2 in DSS set

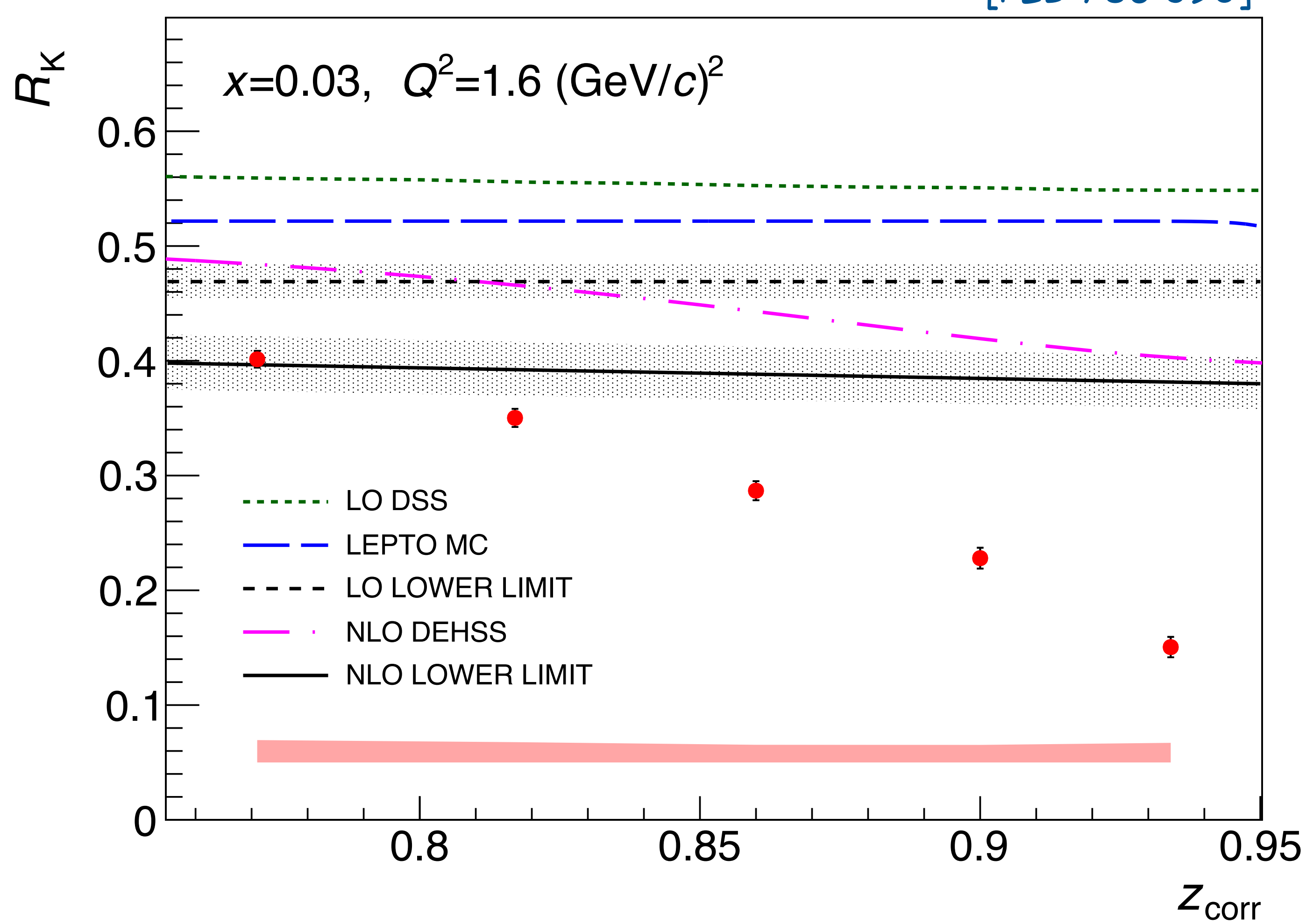
high-z multiplicities @ COMPASS

- look at kaon multiplicity ratio
- neglecting disfavored and strange fragmentation
- yields lower bound driven by light-quark PDFs:

$$R_{\mathrm{K}}(x, Q^2, z) = \frac{\mathrm{d}M^{\mathrm{K}^-}(x, Q^2, z)/\mathrm{d}z}{\mathrm{d}M^{\mathrm{K}^+}(x, Q^2, z)/\mathrm{d}z} = \frac{4(\bar{\mathrm{u}}+\bar{\mathrm{d}})D_{\mathrm{fav}} + (5\mathrm{u}+5\mathrm{d}+\bar{\mathrm{u}}+\bar{\mathrm{d}}+2\bar{\mathrm{s}})D_{\mathrm{unf}} + 2\mathrm{s}D_{\mathrm{str}}}{4(\mathrm{u}+\mathrm{d})D_{\mathrm{fav}} + (5\bar{\mathrm{u}}+5\bar{\mathrm{d}}+\mathrm{u}+\mathrm{d}+2\mathrm{s})D_{\mathrm{unf}} + 2\bar{\mathrm{s}}D_{\mathrm{str}}}$$

$$R_{\mathrm{K}} > \frac{\bar{\mathrm{u}}+\bar{\mathrm{d}}}{\mathrm{u}+\mathrm{d}}$$

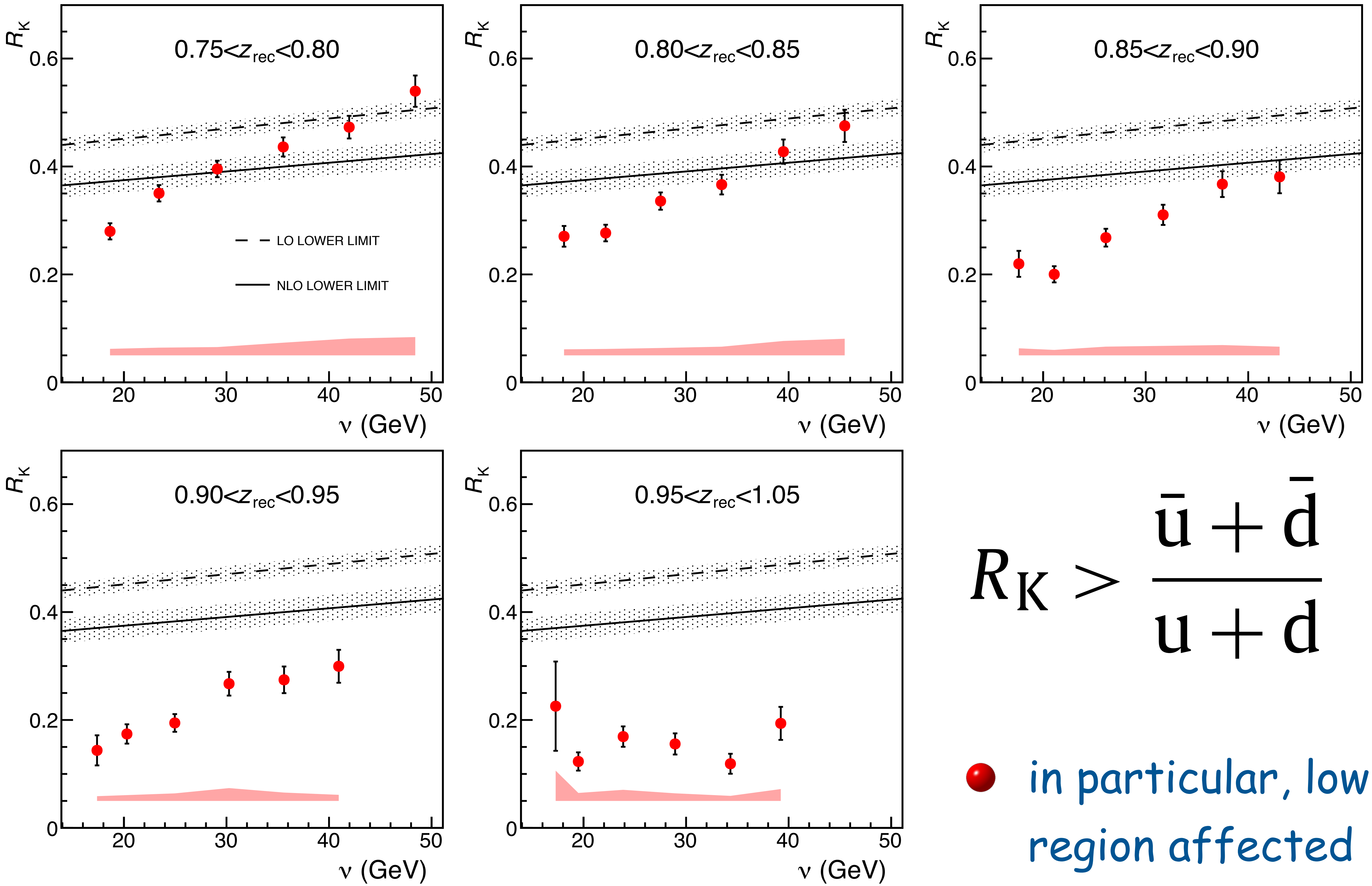
[PLB 786:390]



- … in variance with data

high-z multiplicities @ COMPASS

[PLB 786:390]

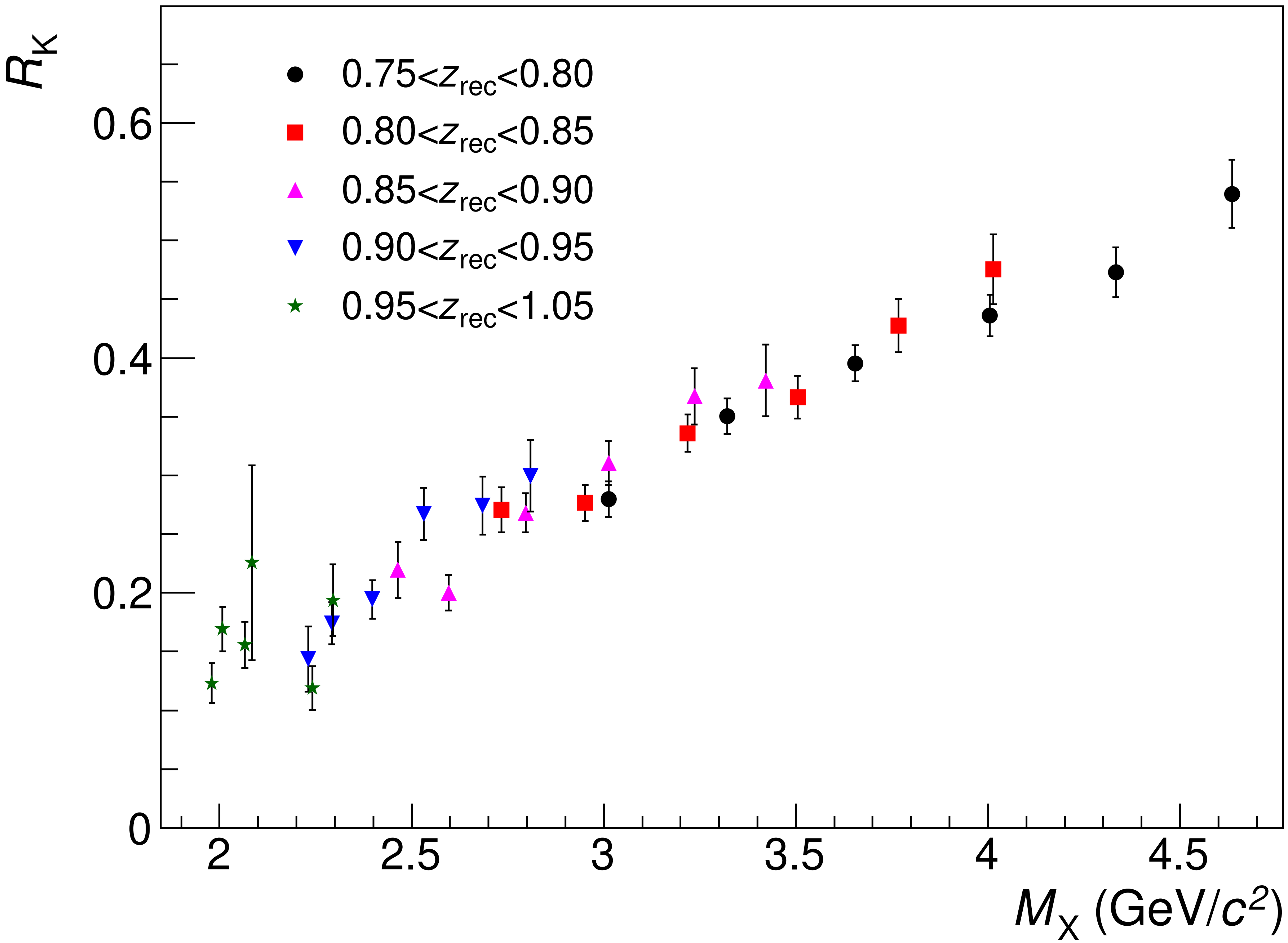


$$R_K > \frac{\bar{u}+\bar{d}}{u+d}$$

- in particular, low-ν region affected

high-z multiplicities @ COMPASS

[PLB 786:390]



- not so surprising: strong suppression mainly at low missing mass, where phase space for "independent" fragmentation tight

$P_{h\perp}$-multiplicity landscape

	EMC [11]	HERMES [15]	JLAB [31]	COMPASS [16]	COMPASS (This paper)
Target	p/d	p/d	d	d	d
Beam energy (GeV)	100–280	27.6	5.479	160	160
Hadron type	$h^{\pm}$	$\pi^{\pm}$, $K^{\pm}$	$\pi^{\pm}$	$h^{\pm}$	$h^{\pm}$
Observable	$M^{h^{+}+h^{-}}$	M^{h}	σ^{h}	M^{h}	M^{h}
Q^2_{min} $(\mathrm{GeV}/c)^2$	2/3/4/5	1	2	1	1
W^2_{min} $(\mathrm{GeV}/c^2)^2$	-	10	4	25	25
y range	[0.2,0.8]	[0.1,0.85]	[0.1,0.9]	[0.1,0.9]	[0.1,0.9]
x range	[0.01,1]	[0.023,0.6]	[0.2,0.6]	[0.004,0.12]	[0.003,0.4]
P^2_{hT} range $(\mathrm{GeV}/c)^2$	[0.081, 15.8]	[0.0047,0.9]	[0.004,0.196]	[0.02,0.72]	[0.02,3]

[11] J. Ashman et al. (EMC), Z. Phys.C 52, 361 (1991).

[15] A. Airapetian et al. (HERMES), Phys. Rev. D87, 074029 (2013).

[16] C. Adolph et al. (COMPASS), Eur. Phys. J. C73, 2531 (2013); 75, 94(E) (2015).

[31] R. Asaturyan et al., Phys. Rev. C 85, 015202 (2012).

["This paper"] M. Aghasyan et al. (COMPASS), Phys. Rev. D 97, 032006 (2018).

… as well as more limited measurements by H1 and Zeus

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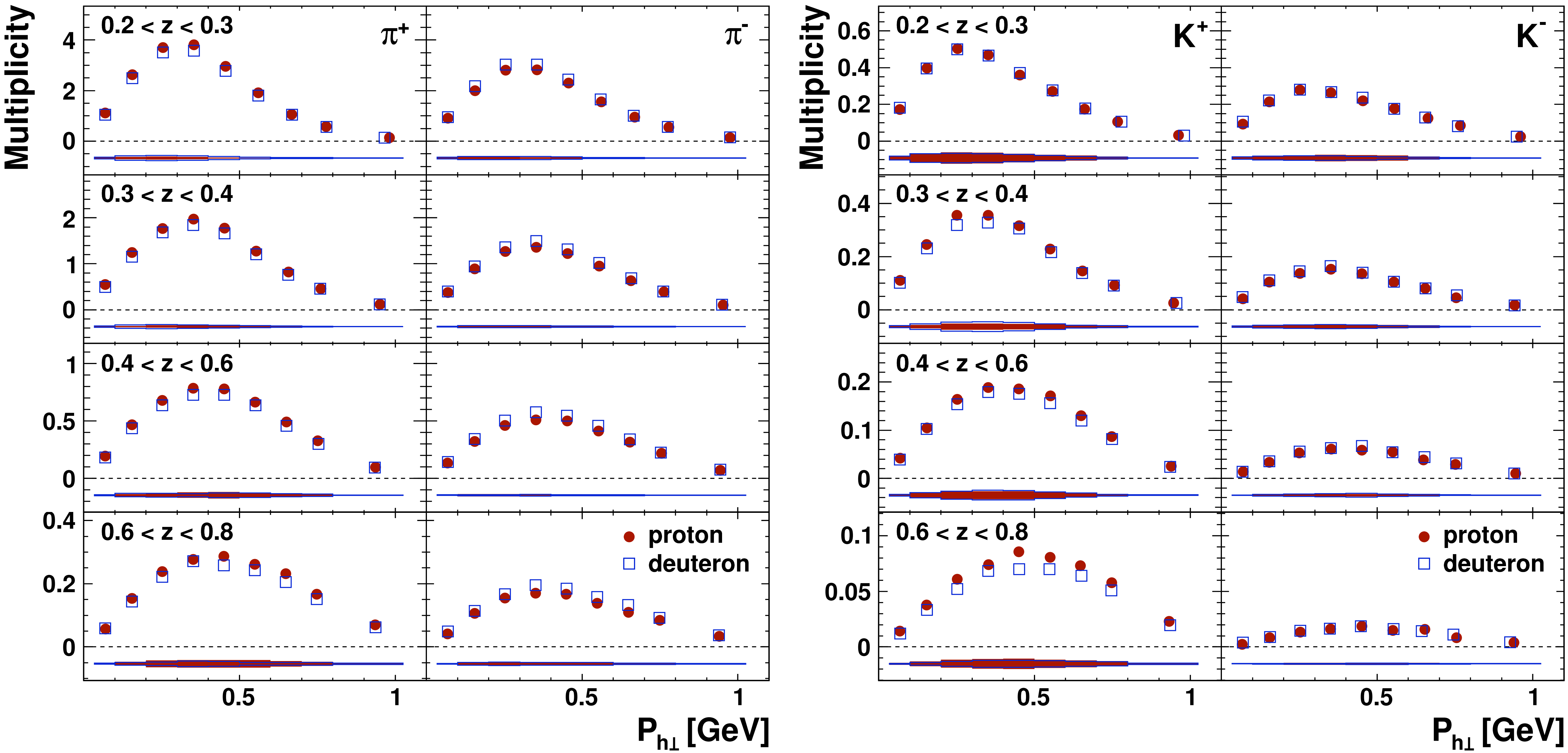
multiplicities: $P_{h\perp}$ dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target/hadron variation, e.g. [A. Signori et al., JHEP 11(2013)194]

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



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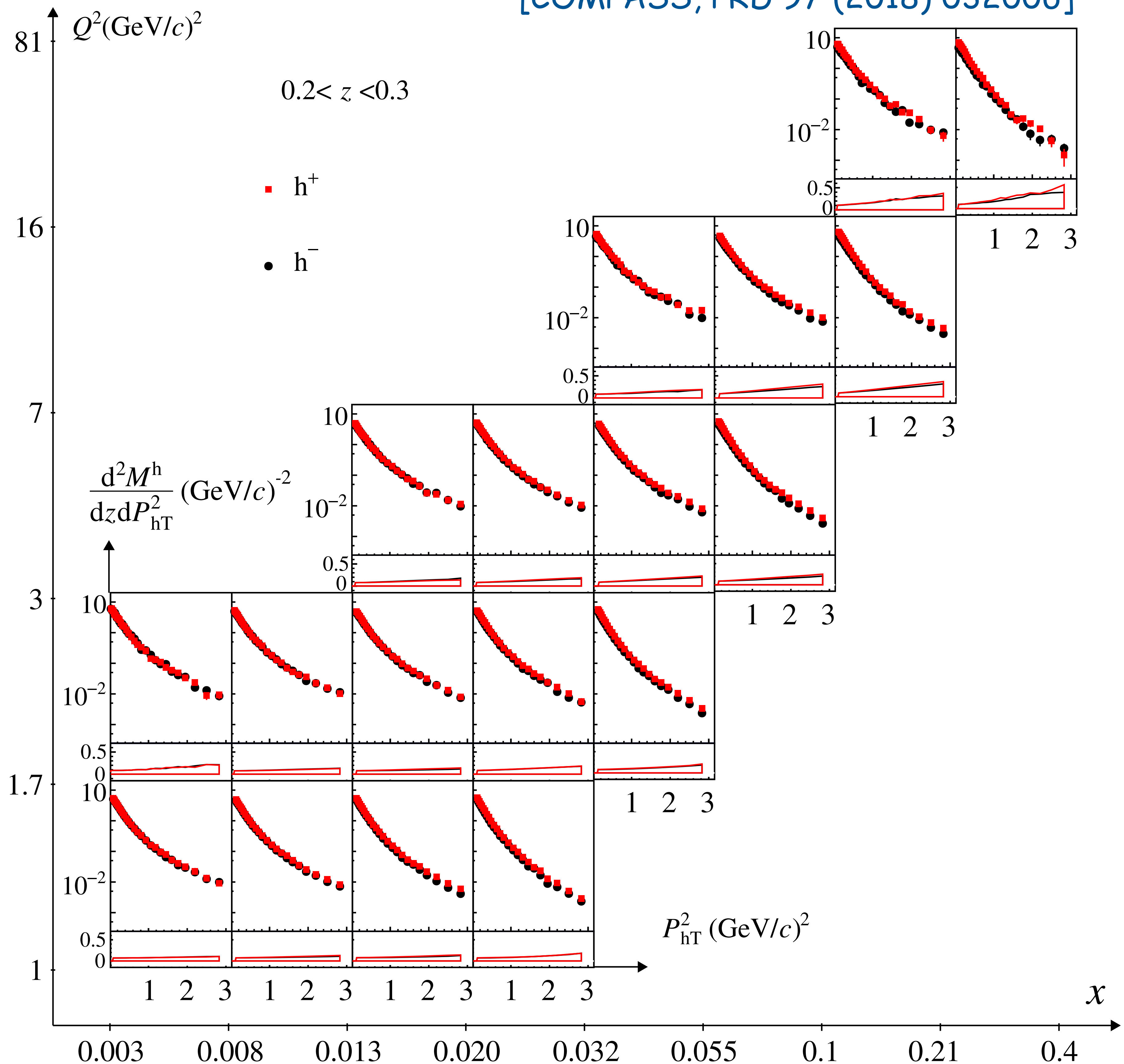
… as well as more limited measurements by H1 and Zeus

$P_{h\perp}$ dependence

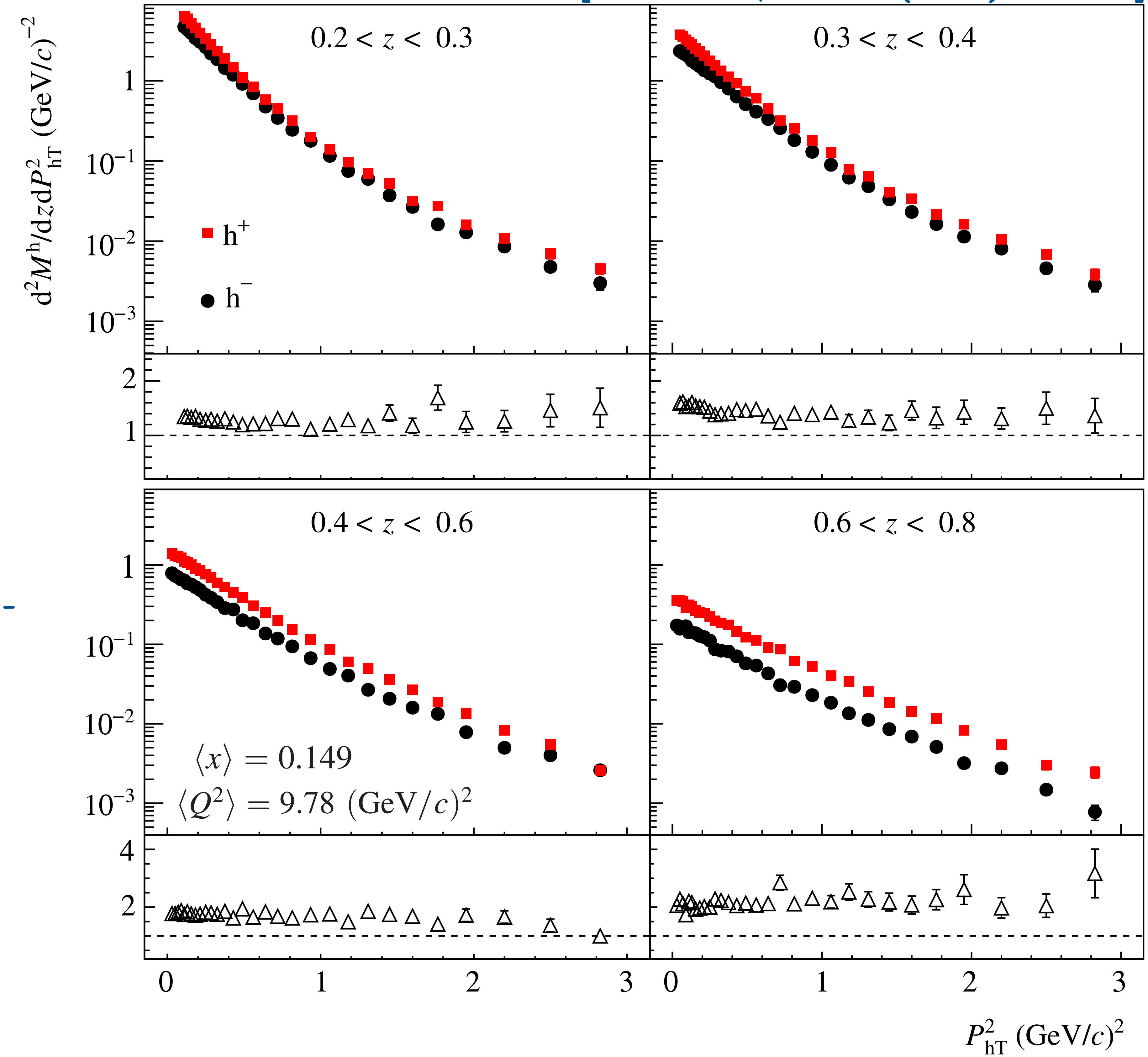
[COMPASS, PRD 97 (2018) 032006]

- data on LiD target
- differential in x, z, Q^2, $P_{h\perp}{}^2$
- one(!) example (lowest z bin)
- high statistical precision allows for more detailed studies



$P_{h\perp}$ dependence

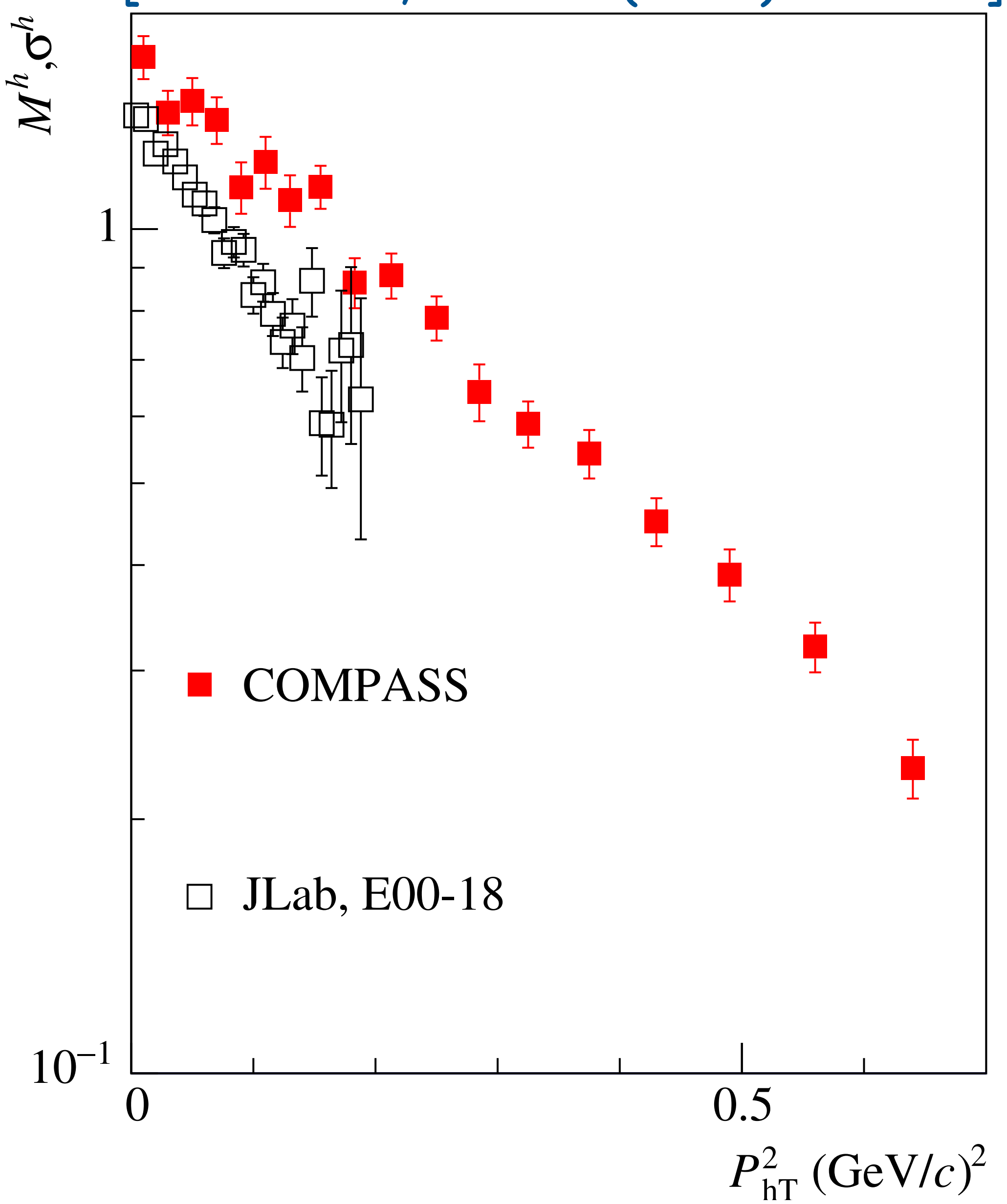
[COMPASS, PRD 97 (2018) 032006]



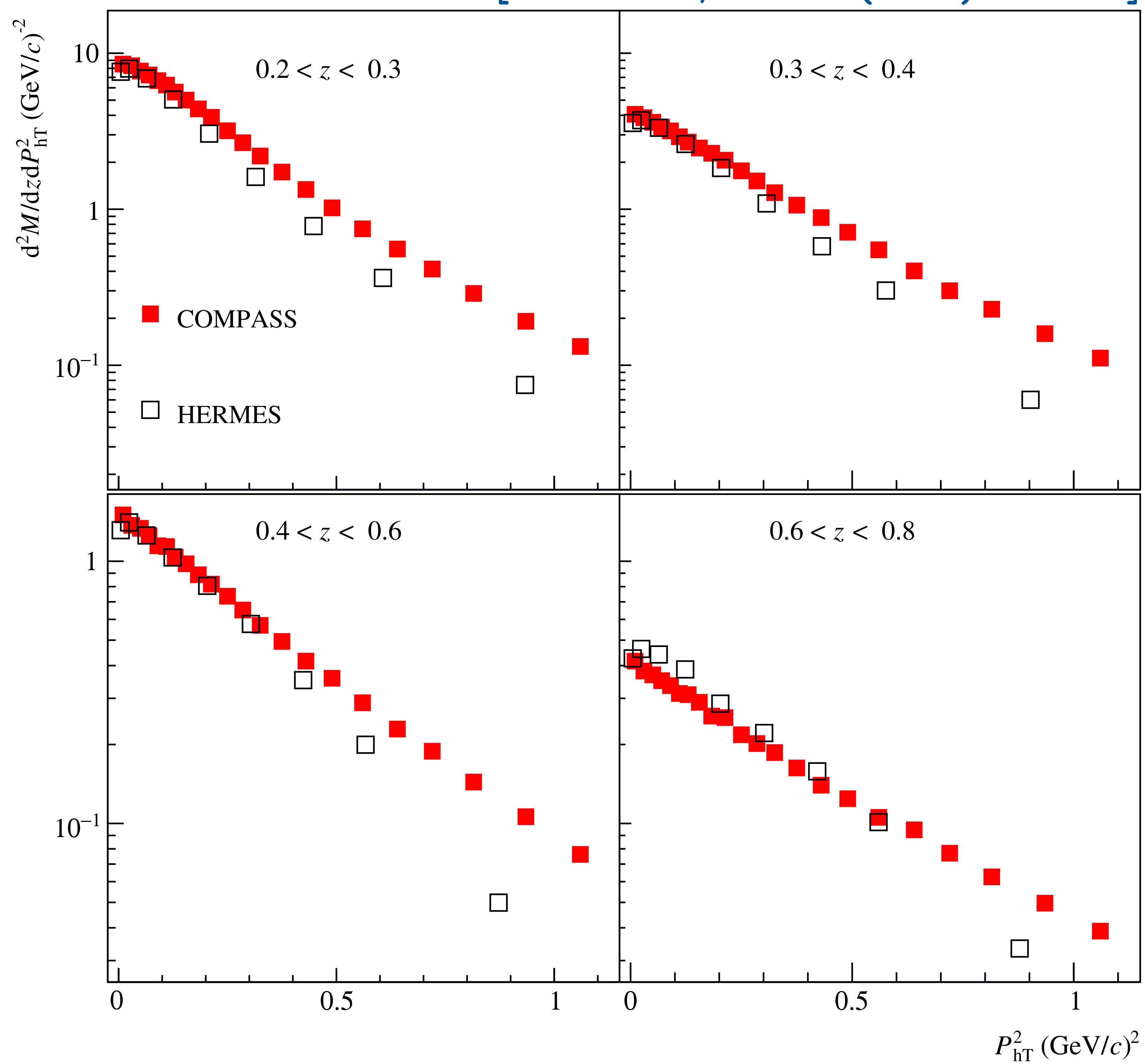
- differences between h+ and h- increase with z

COMPASS vs. JLab & HERMES

[COMPASS, PRD 97 (2018) 032006]

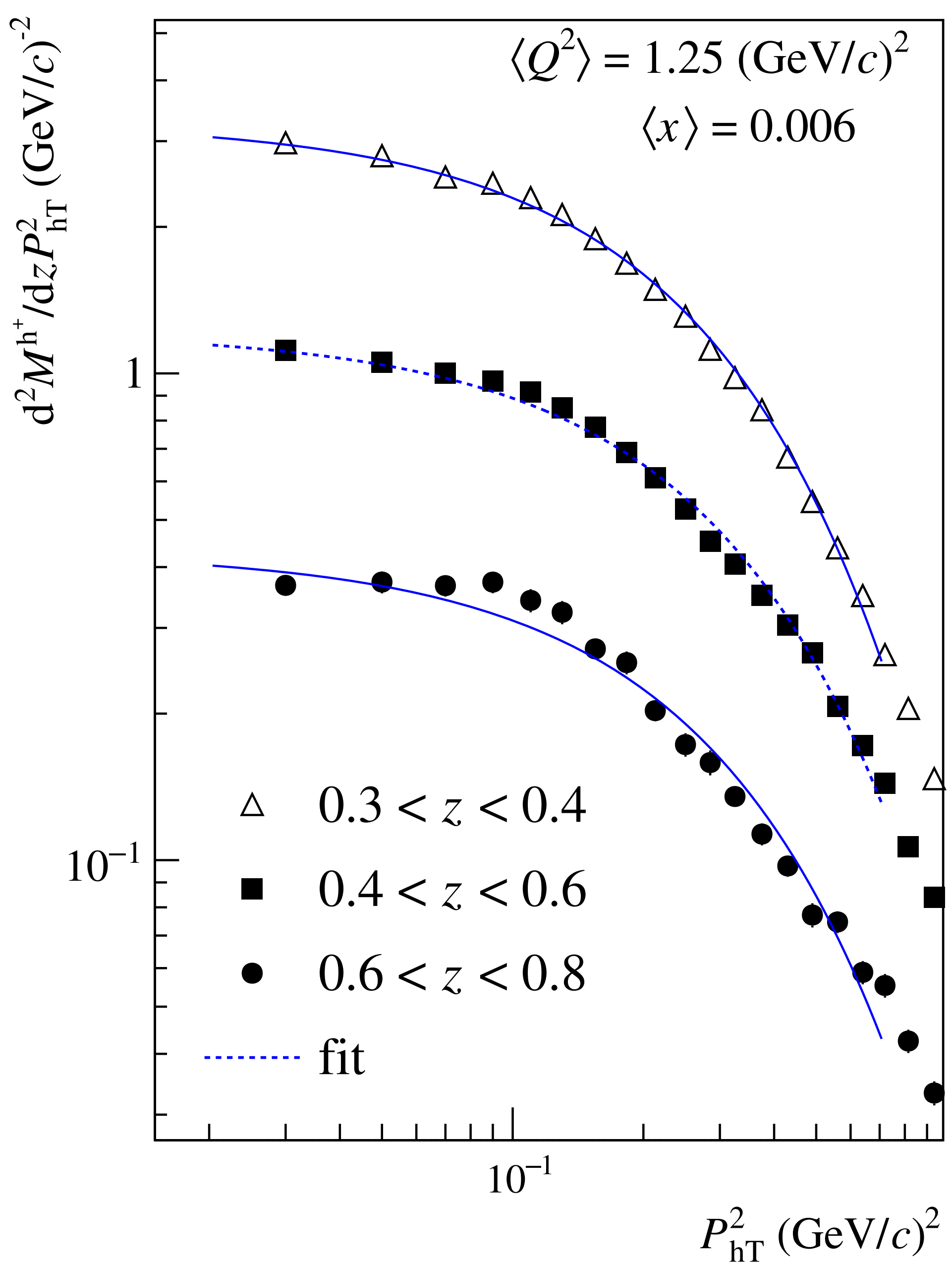


[COMPASS, PRD 97 (2018) 032006]

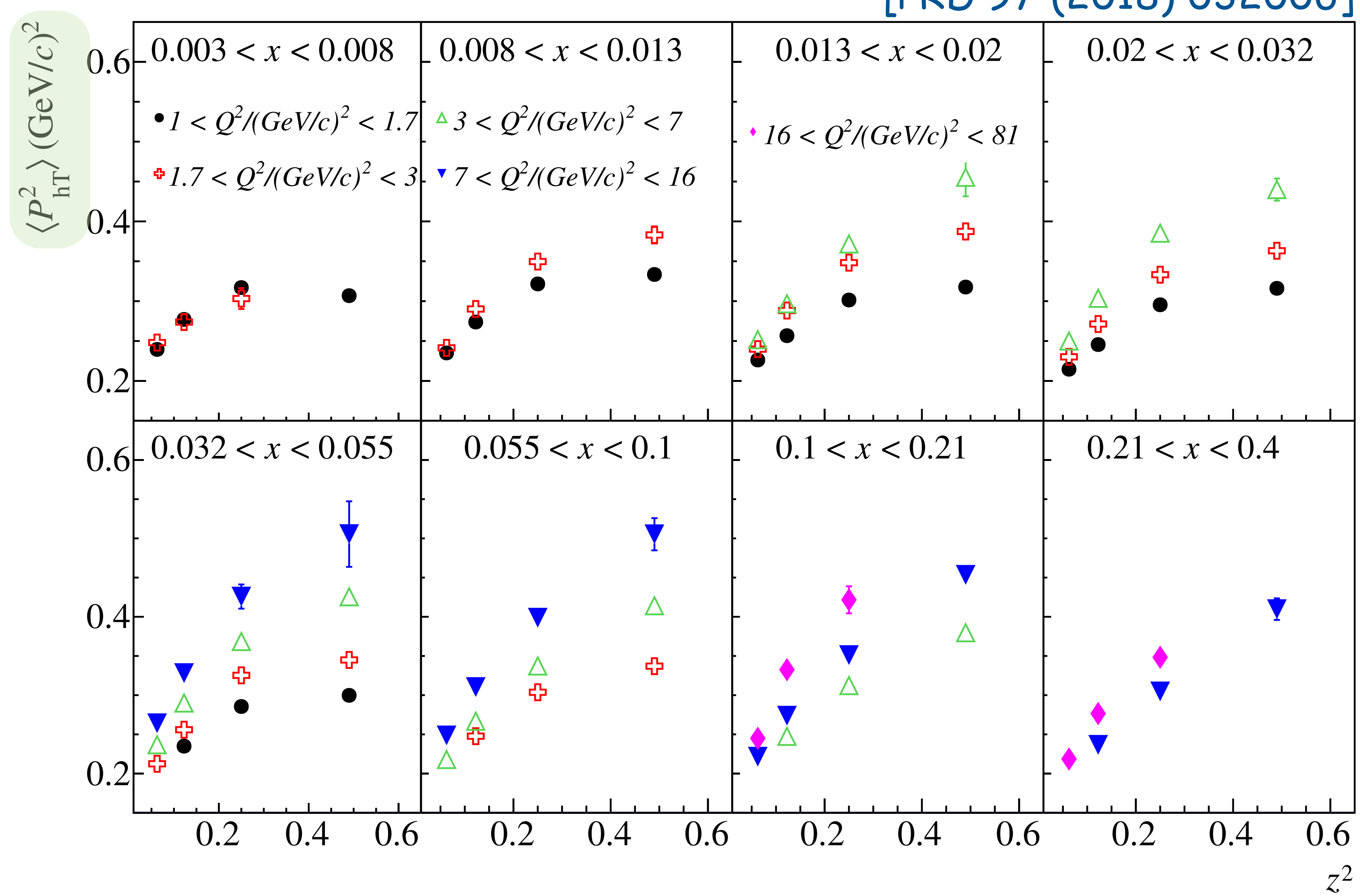


fitting the $P_{h\perp}$ dependence

$$\frac{d^2 M^h(x, Q^2; z)}{dz\, dP_{hT}^2} = \frac{N}{\langle P_{hT}^2 \rangle} \exp\left(- \frac{P_{hT}^2}{\langle P_{hT}^2 \rangle} \right)$$



[PRD 97 (2018) 032006]

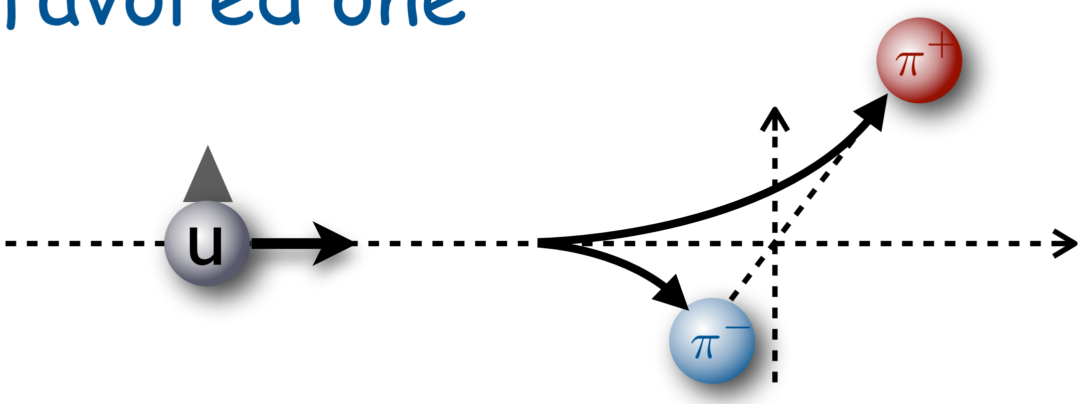


$\left\langle P_{h\perp}^2(z) \right\rangle = z^2 \left\langle p_T^2 \right\rangle + \left\langle K_T^2 \right\rangle$ does not work!

chiral-odd fragmentation

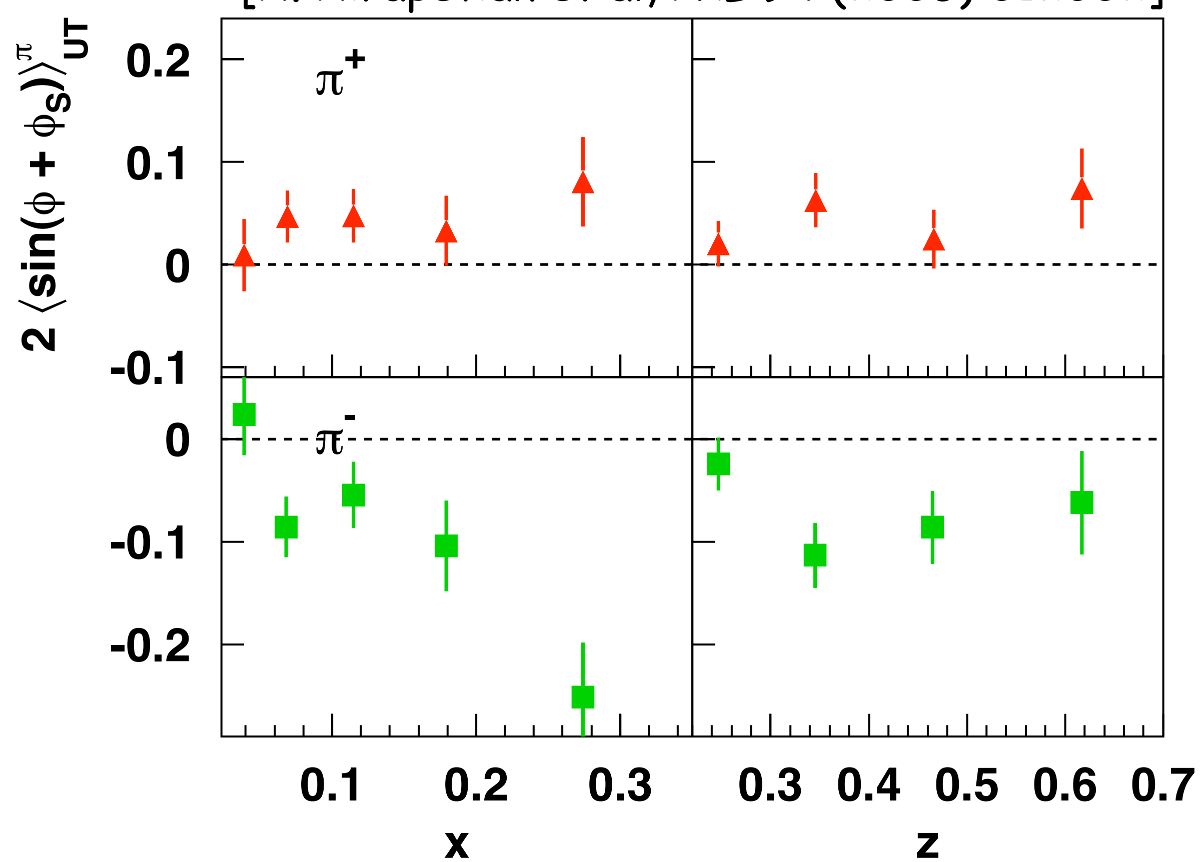
Collins amplitudes

- significant in size and opposite in sign for charged pions
- **disfavored** Collins FF **large** and **opposite in sign** to favored one



- leads to various cancellations in SSA observables

[A. Airapetian et al, PRL 94 (2005) 012002]



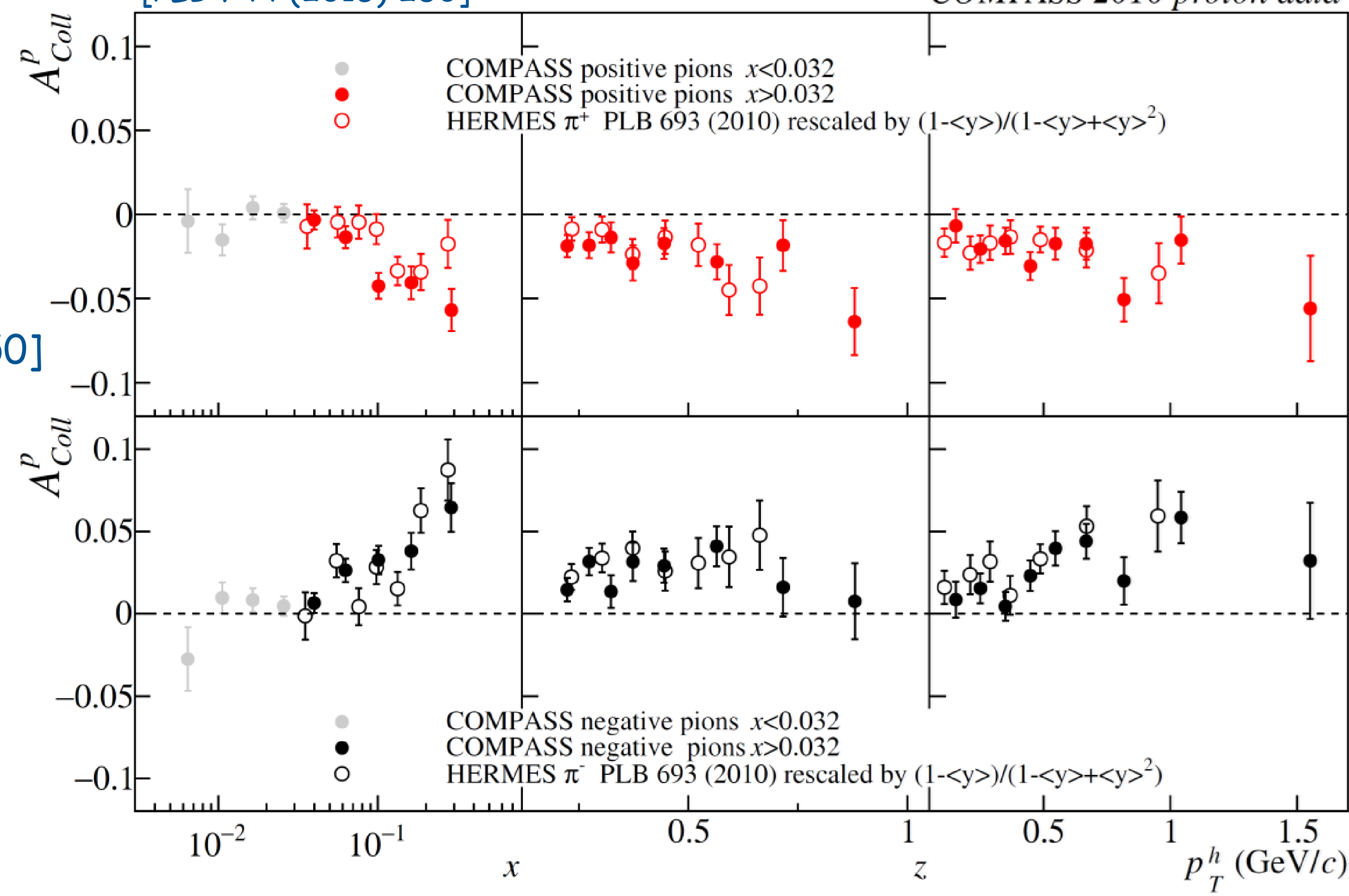
2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

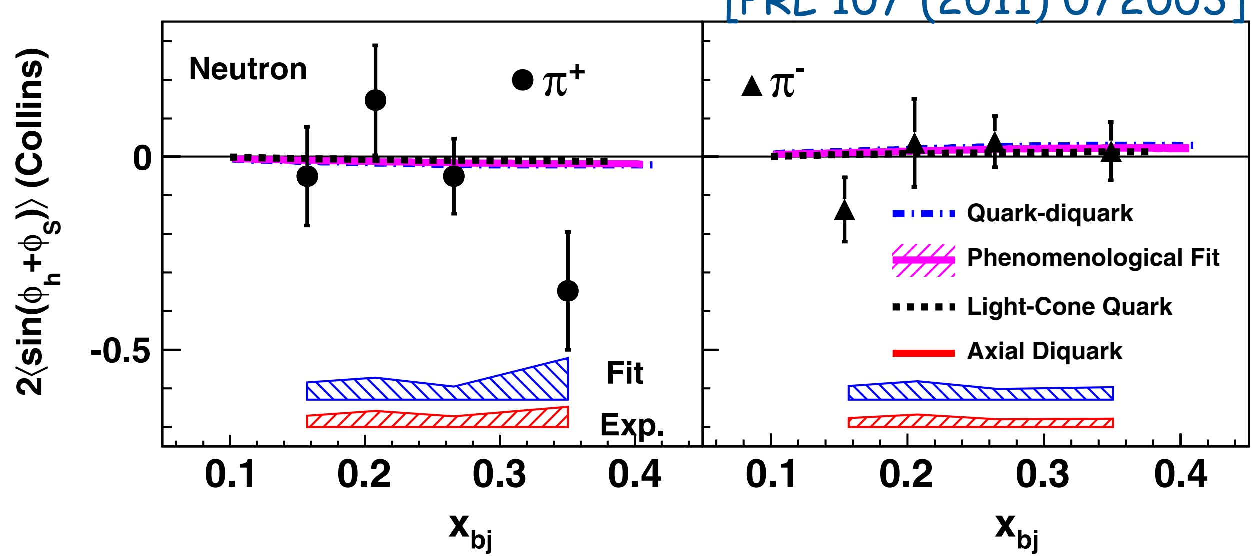
Collins amplitudes

- since those early days, a wealth of new results:
  - COMPASS
    [PLB 692 (2010) 240,
    PLB 717 (2012) 376, PLB 744 (2015) 250]
  - HERMES
    [PLB 693 (2010) 11]
  - Jefferson Lab
    [PRL 107 (2011) 072003]

[PLB 744 (2015) 250]



[PRL 107 (2011) 072003]



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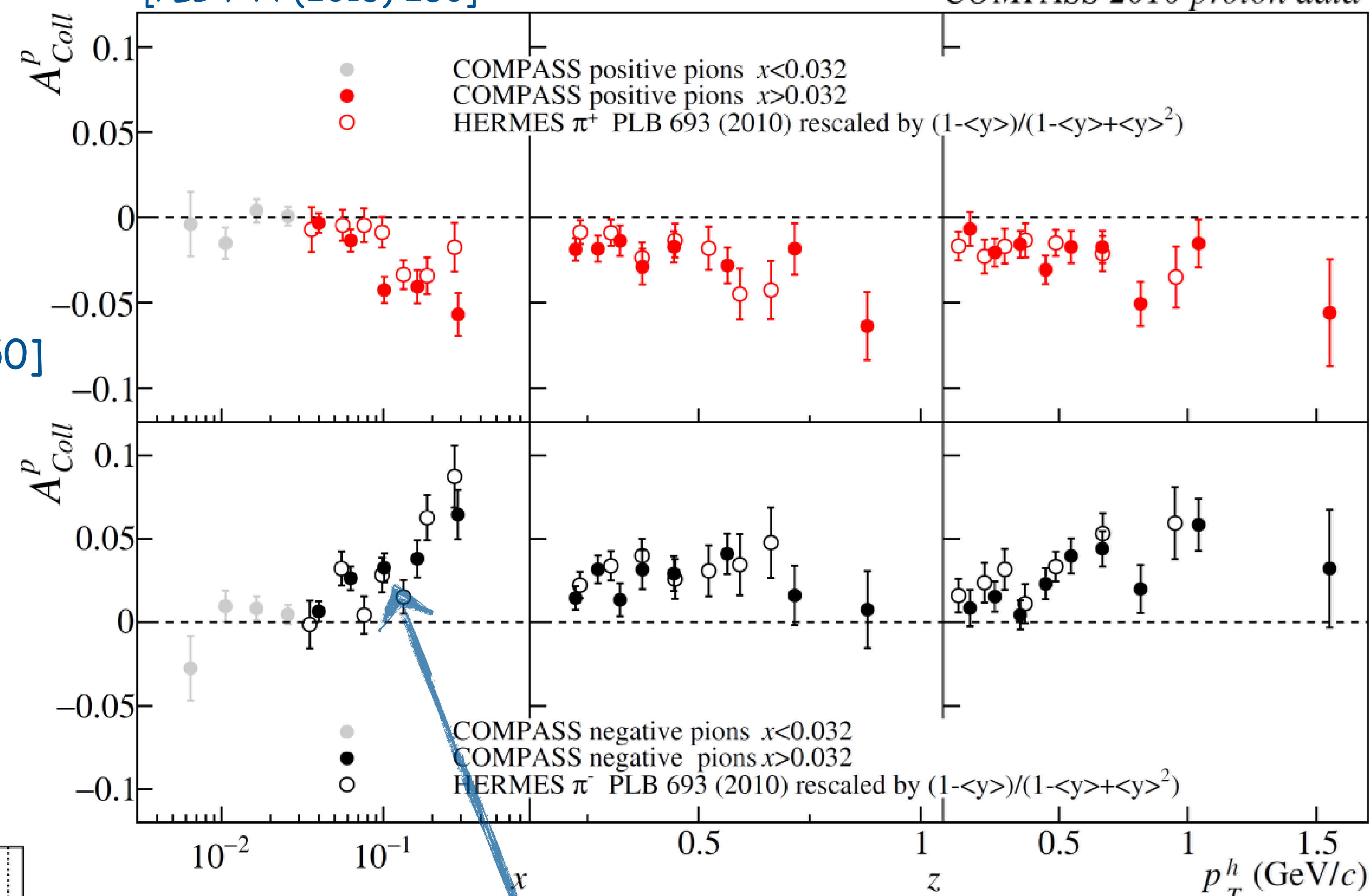
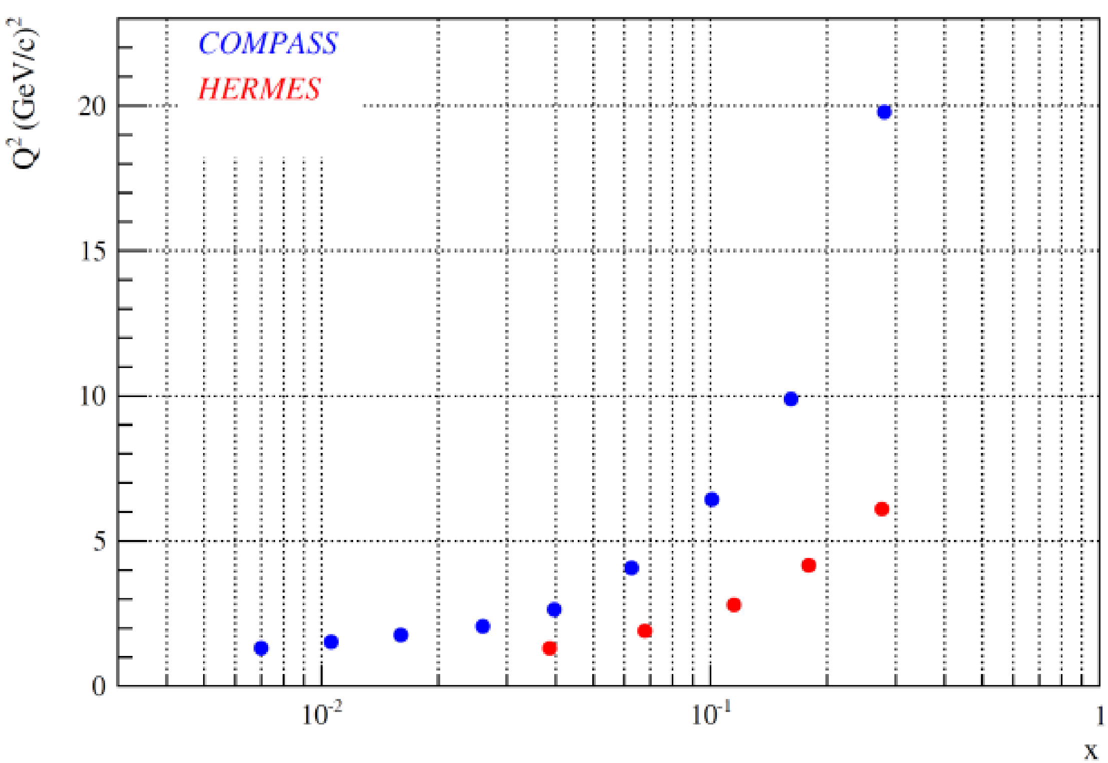




- excellent agreement of various proton data, also with neutron results
- no indication of strong evolution effects

the "Collins trap"

$$H_{1,\mathrm{fav}}^{\perp} \simeq -H_{1,\mathrm{dis}}^{\perp}$$

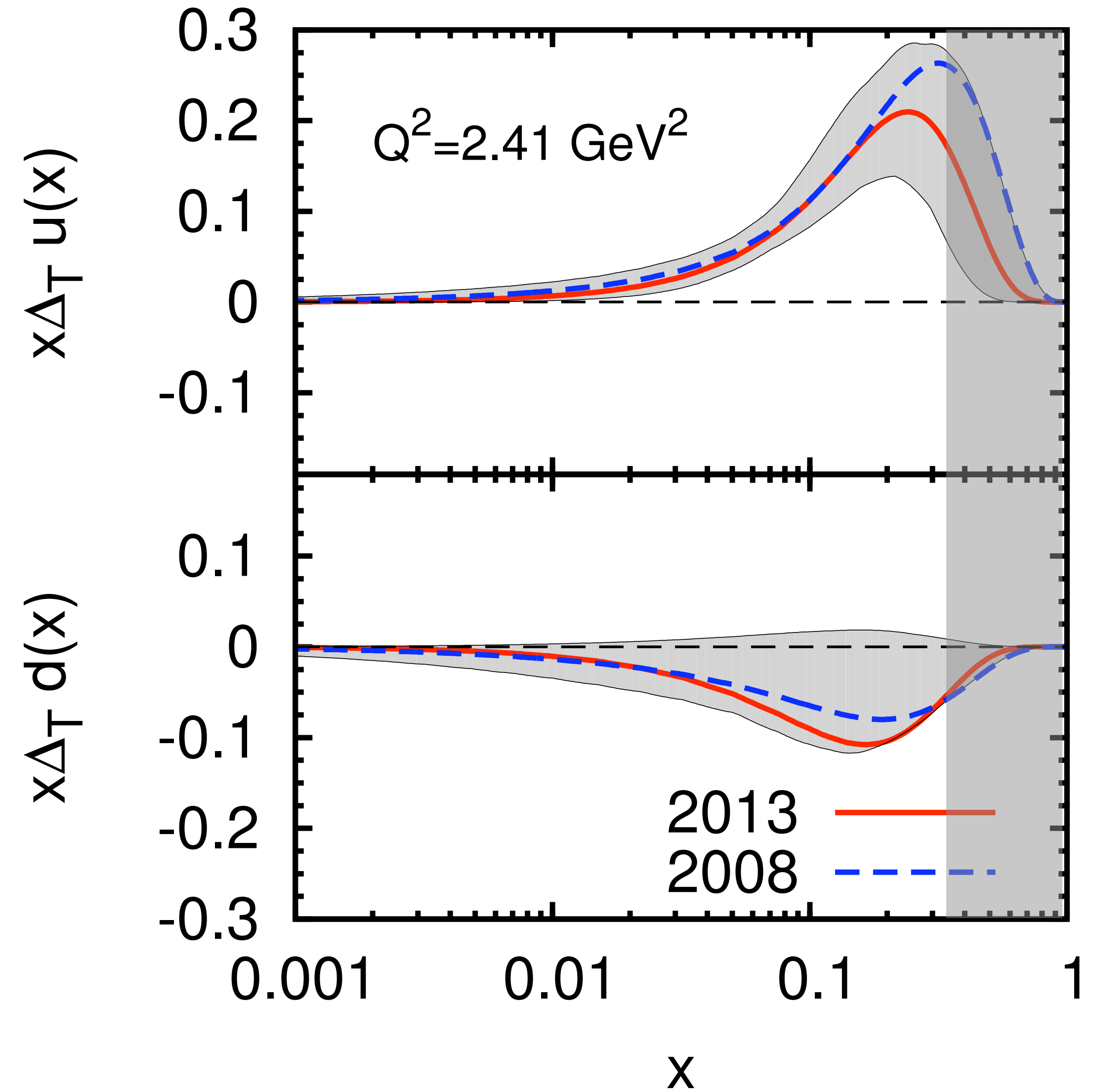
thus

$$\langle \sin(\phi+\phi_S)\rangle_{UT}^{\pi^+} \sim \left(4h_1^u - h_1^d\right) H_{1,\mathrm{fav}}^{\perp}$$

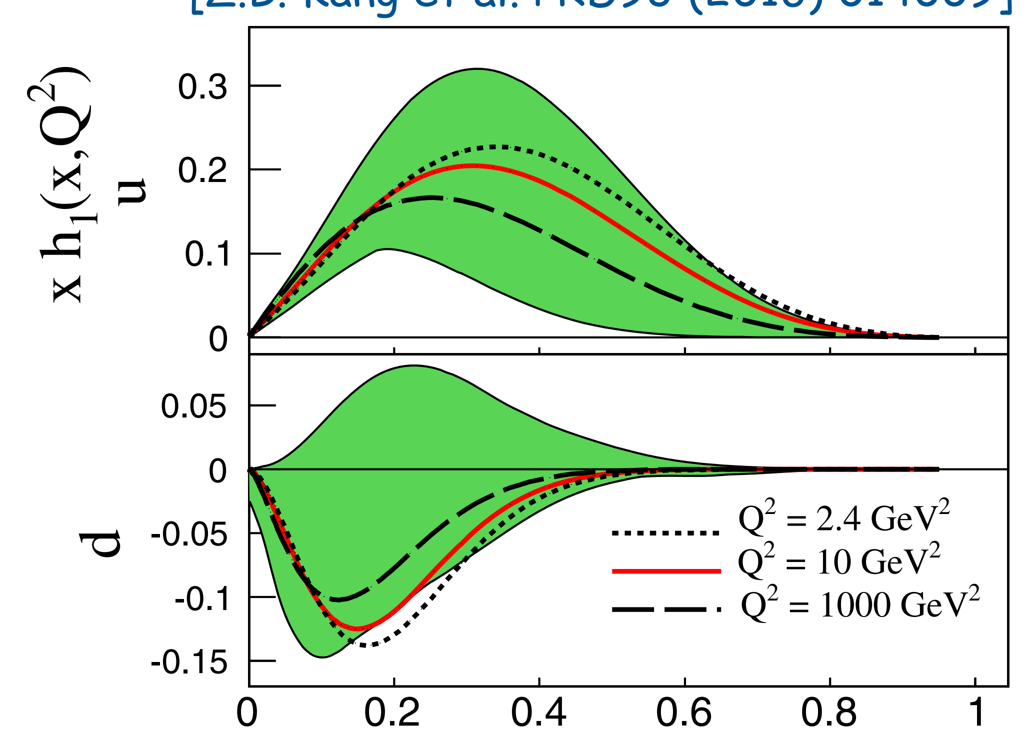
$$\langle \sin(\phi+\phi_S)\rangle_{UT}^{\pi^-} \sim -\left(4h_1^u - h_1^d\right) H_{1,\mathrm{fav}}^{\perp}$$

"impossible" to disentangle u/d transversity -> current limits driven mainly by Soffer bound?

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



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



the "Collins trap"

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

thus

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

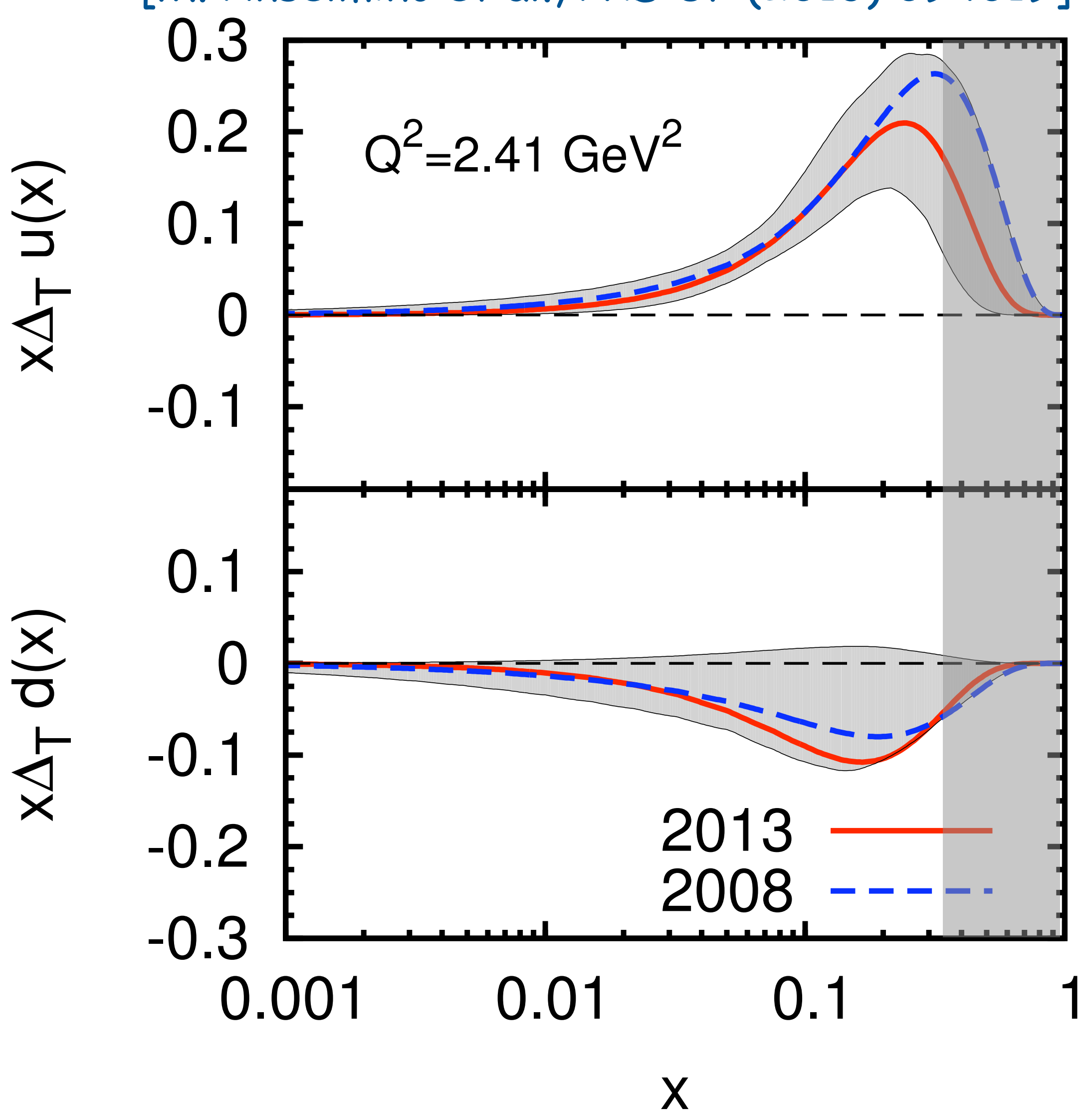
$$\langle \sin(\phi+\phi_S)\rangle^{\pi^-}_{UT} \sim -\left(4h_1^u - h_1^d\right) H^{\perp}_{1,\text{fav}}$$

"impossible" to disentangle u/d transversity -> current limits driven mainly by Soffer bound?

clearly need precise data from "neutron" target(s), e.g., COMPASS d, and later JLab12 & EIC

(valid for all chiral-odd TMDs)

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



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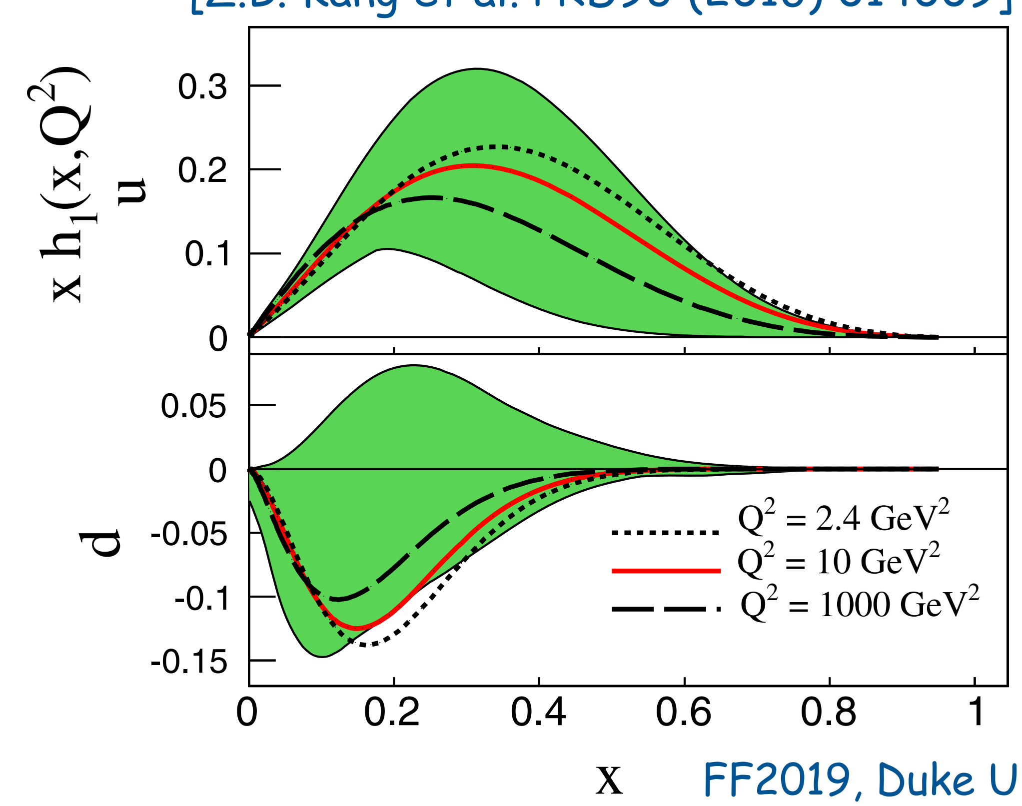
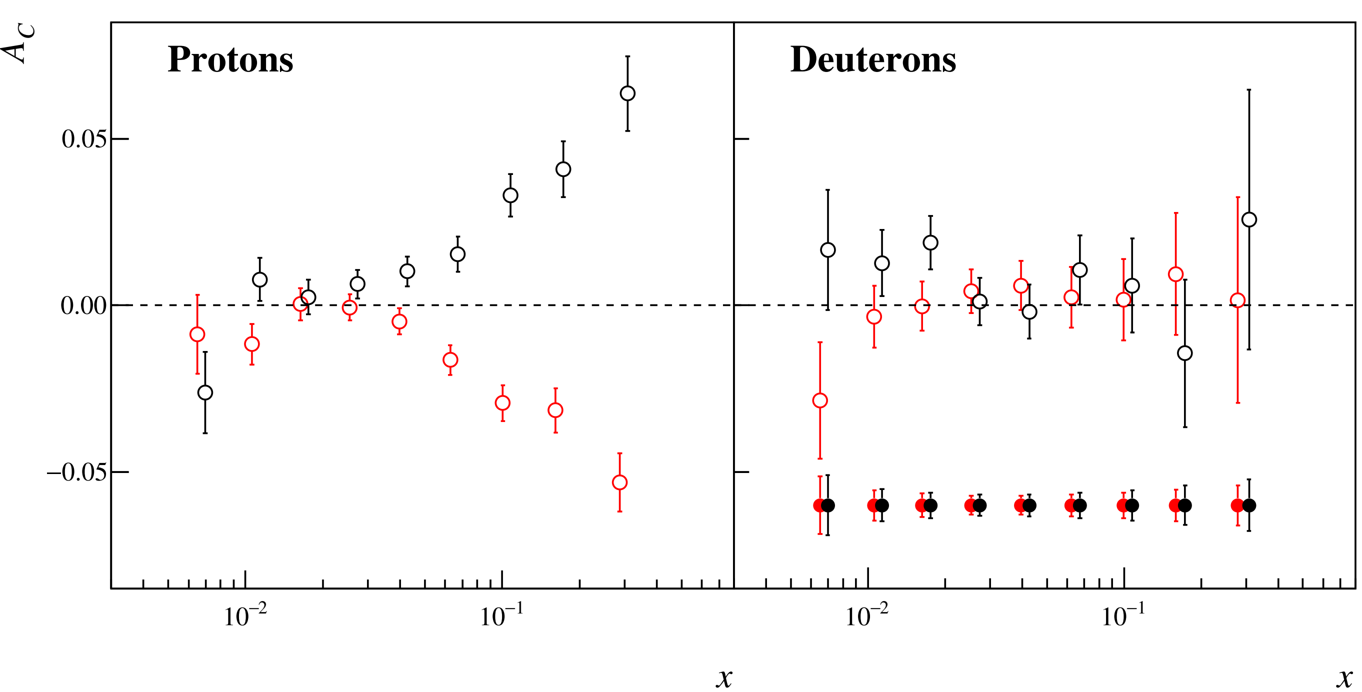
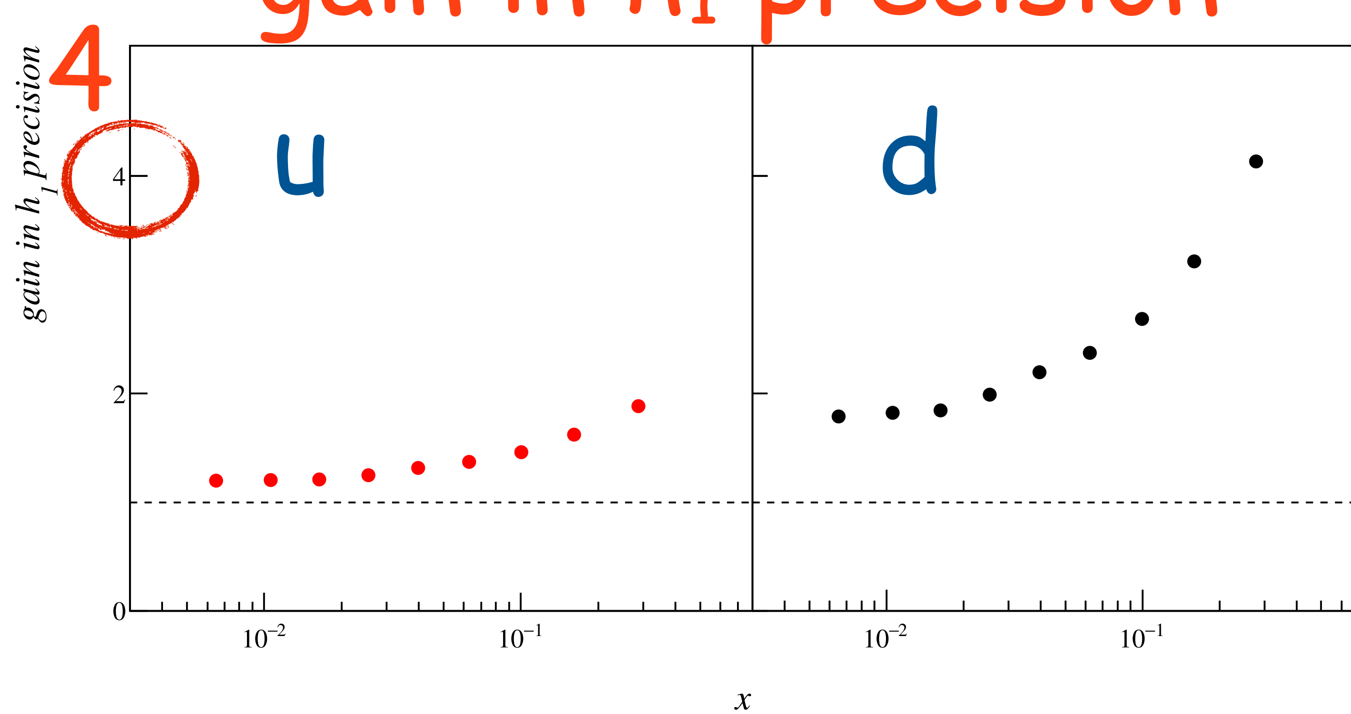


d-transversity running at COMPASS

- currently much more p than d data available
- add another year of d running after CERN LS2 (2021)
  - large impact on d-transversity
  - reduced correlations between u and d transversity (note, correlations important in tensor-charge calculation)



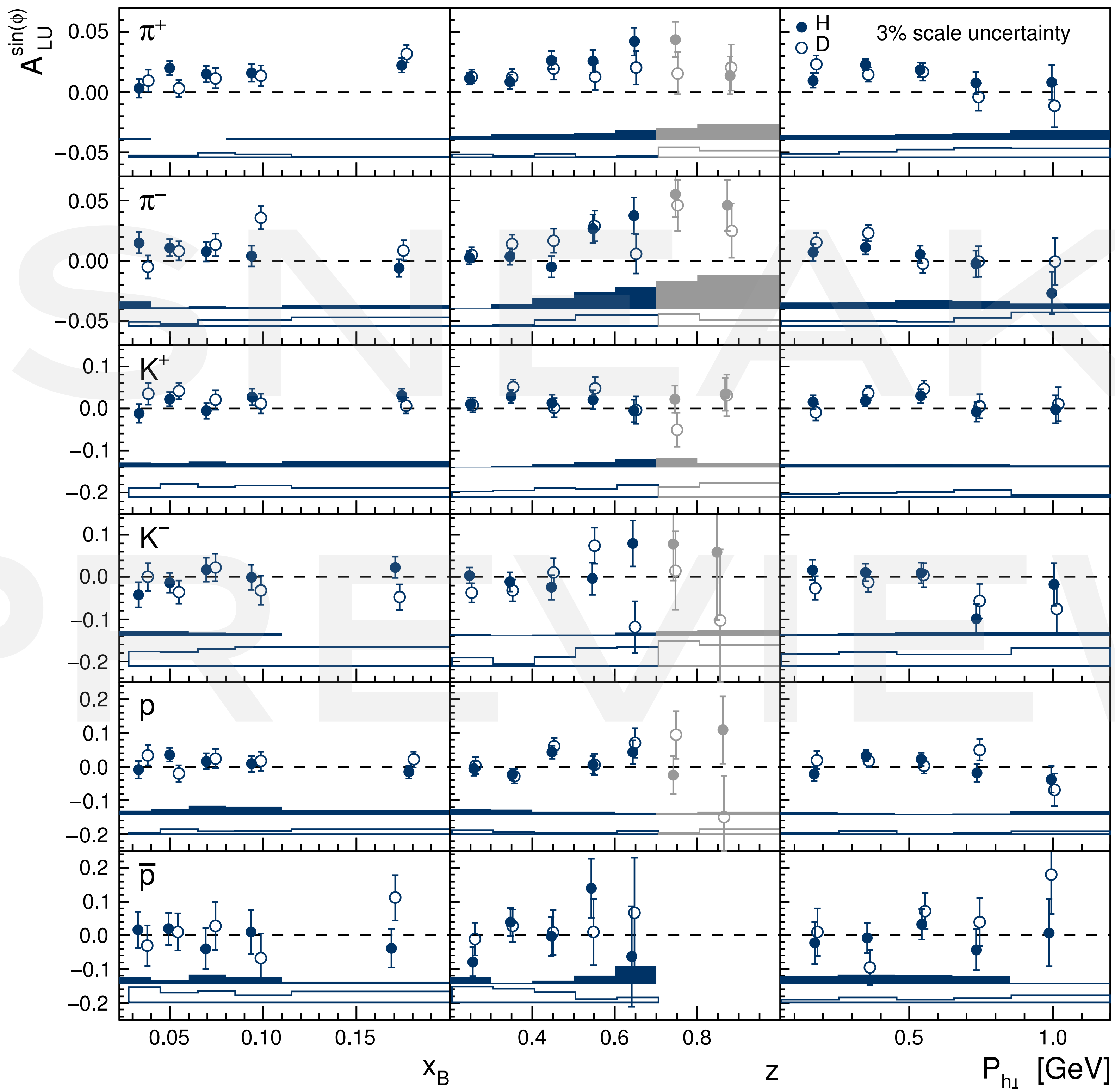
gain in h_1 precision



non-vanishing twist-3

beam-helicity asymmetry (twist-3)

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



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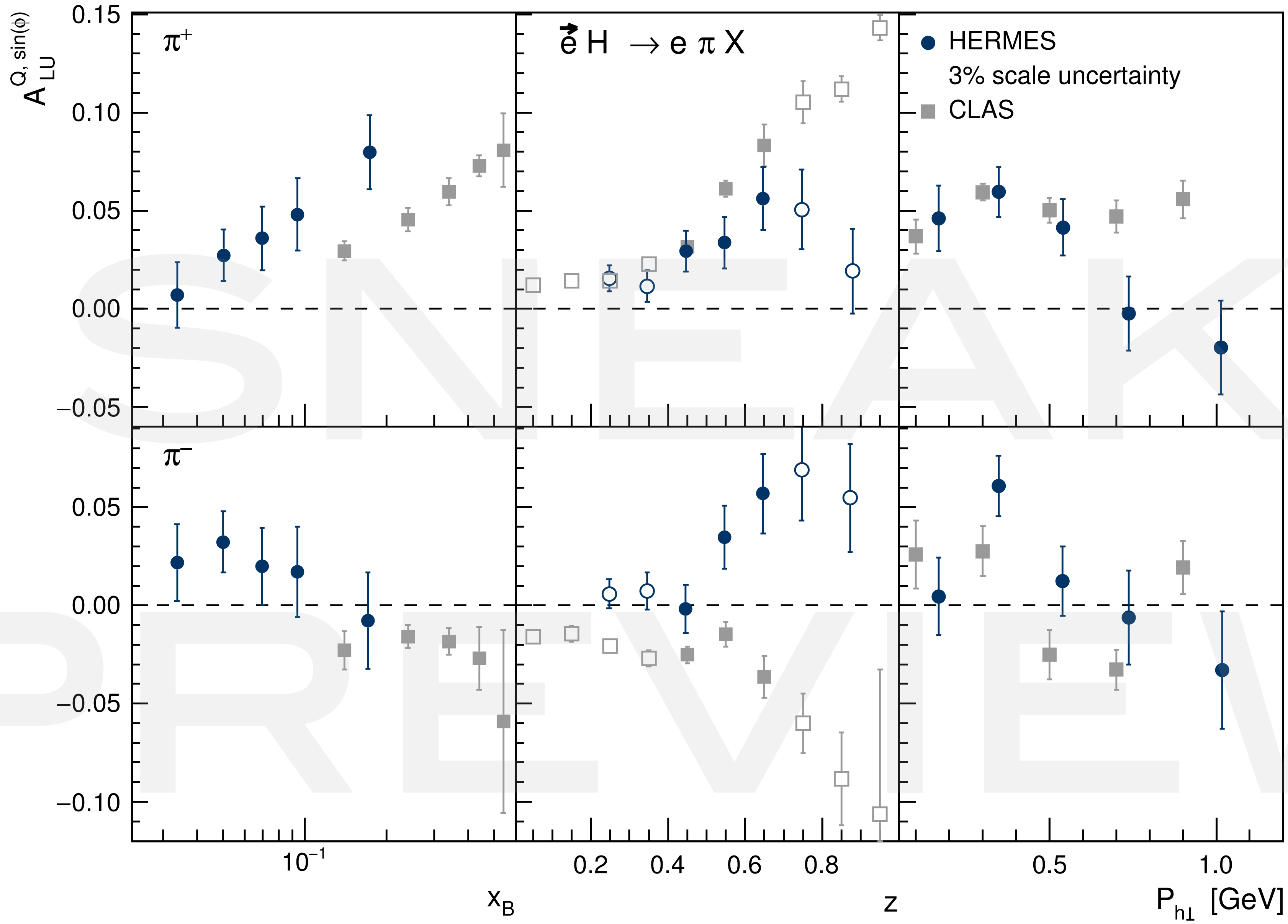
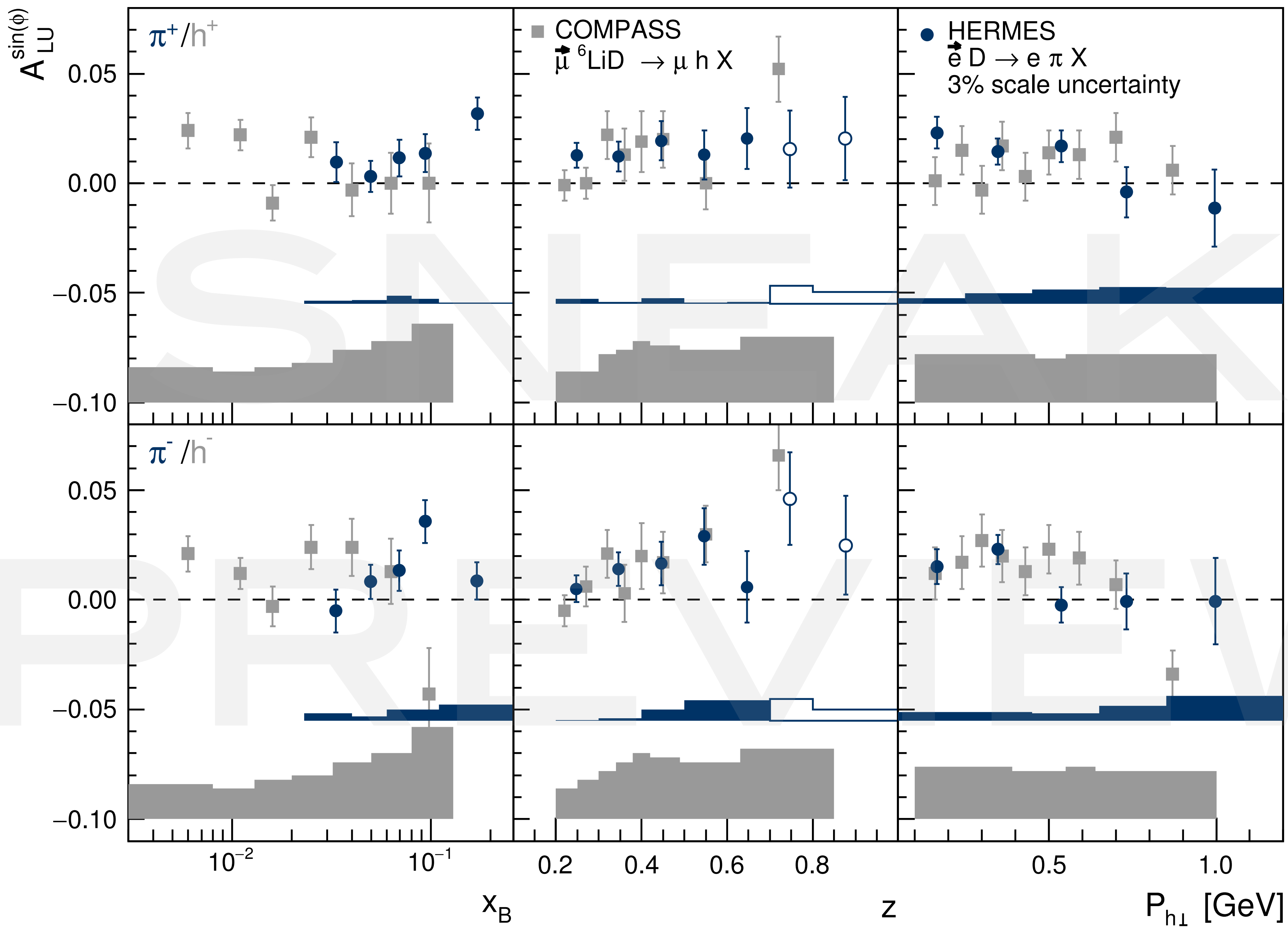


- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed
- CLAS more sensitive to e(x)Collins term due to higher x probed?

beam-helicity asymmetry (twist-3)

$$\frac{M_h}{Mz} h_1^{\perp} E \oplus x g^{\perp} D_1 \oplus \frac{M_h}{Mz} f_1 G^{\perp} \oplus xeH_1^{\perp}$$



- consistent behavior for charged pions / hadrons at HERMES / COMPASS for isoscalar targets back to the roots

longitudinal double-spin asymmetries

- flagship observable for extraction of proton's quark helicity dist.'s
- revisited at HERMES to
  - exploit slightly larger data set
  - provide $A_{||}$ in addition to A_1

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

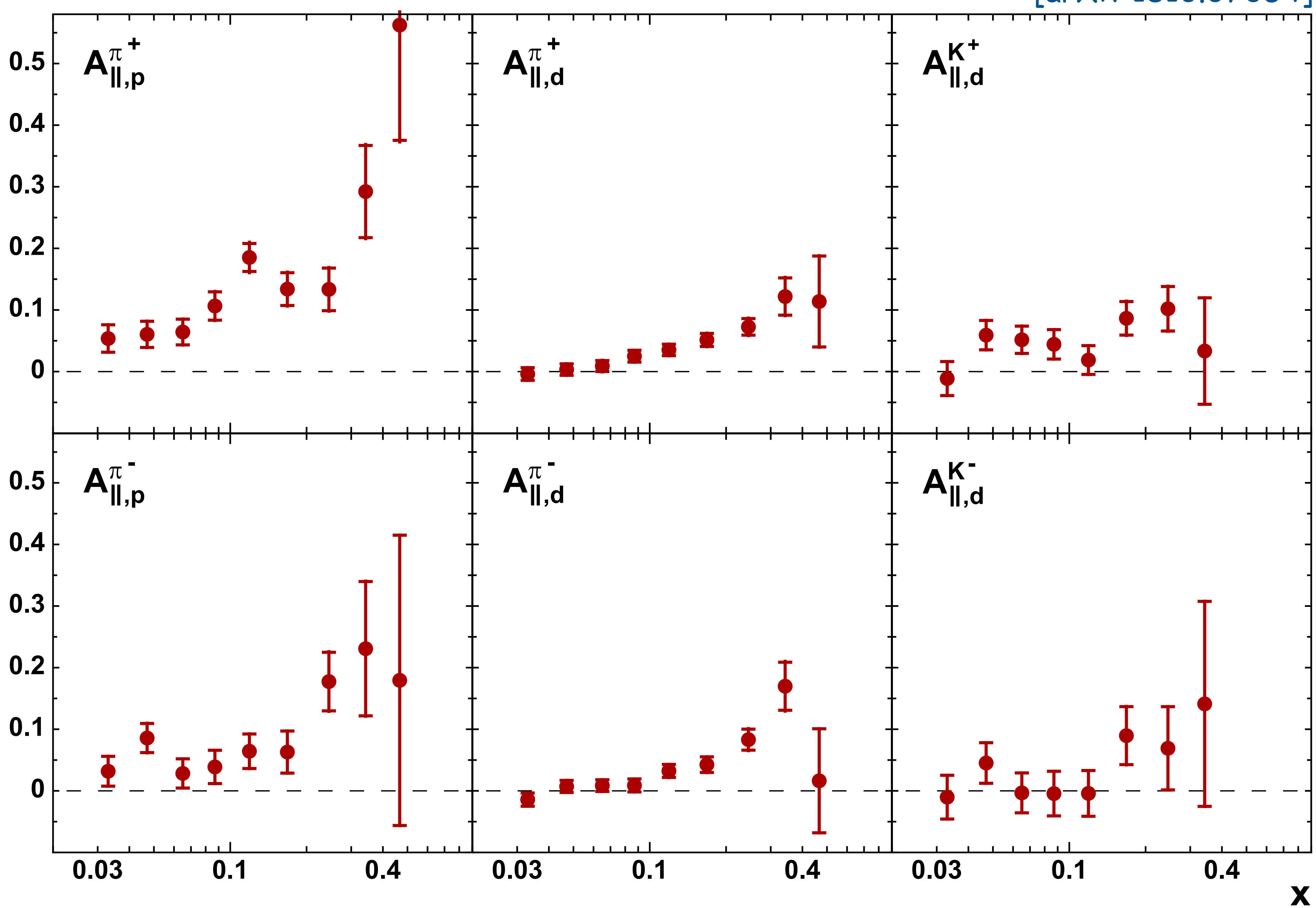
  R (ratio of longitudinal-to-transverse cross section) to be measured [only available for inclusive DIS data, e.g., used in g_1 SF measurements]

  - look at multi-dimensional dependences
  - extract twist-3 cosine modulations

longitudinal double-spin asymmetries

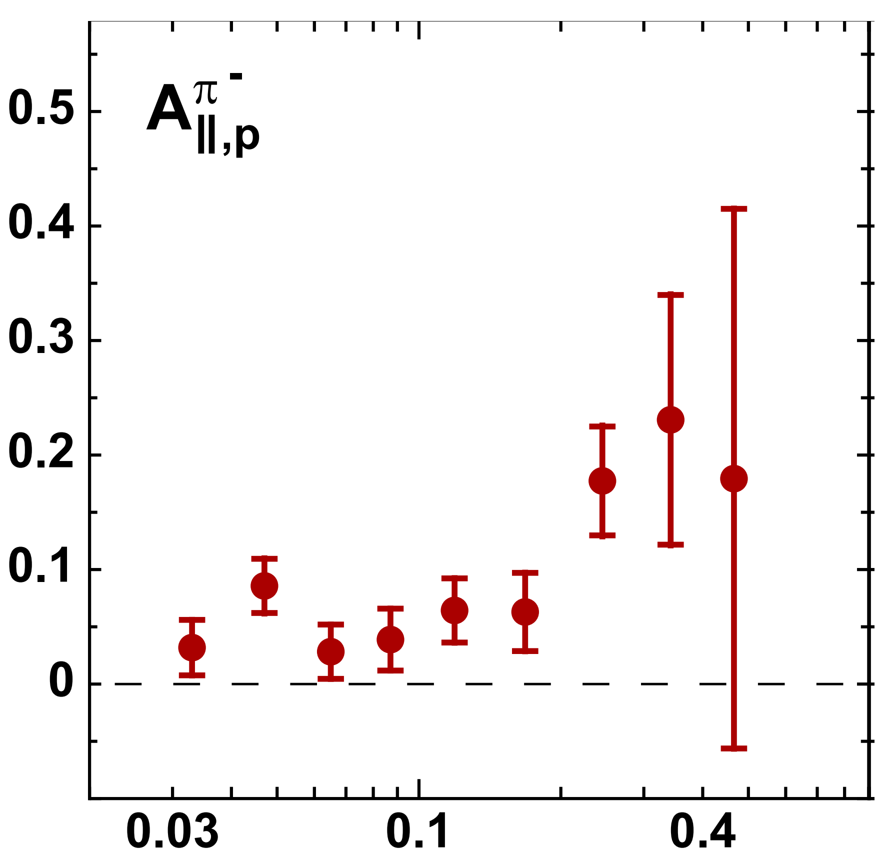
- x dependence of $A_{||}$ (consistent with previous HERMES publication)

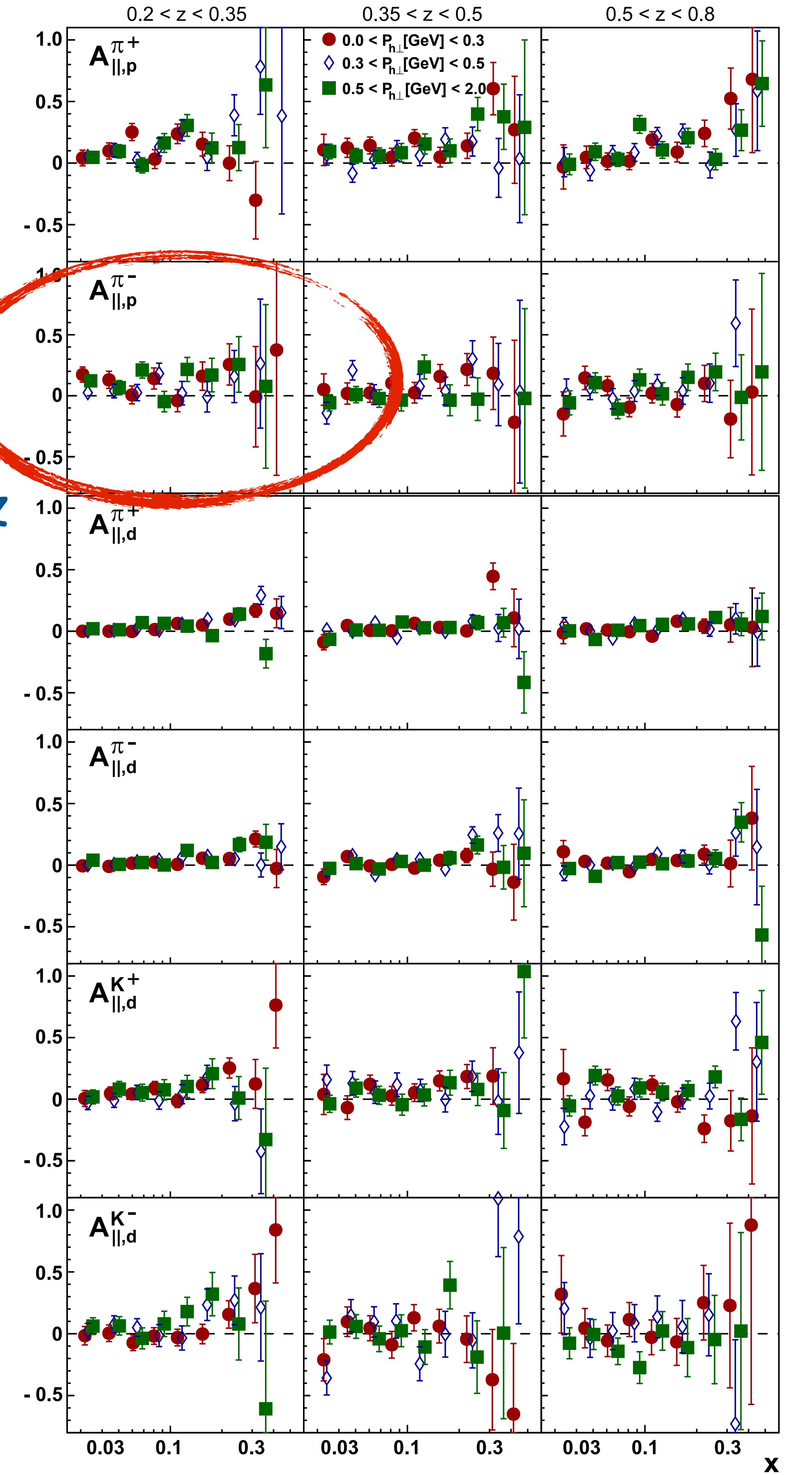
[arXiv:1810.07054]



longitudinal DSA

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

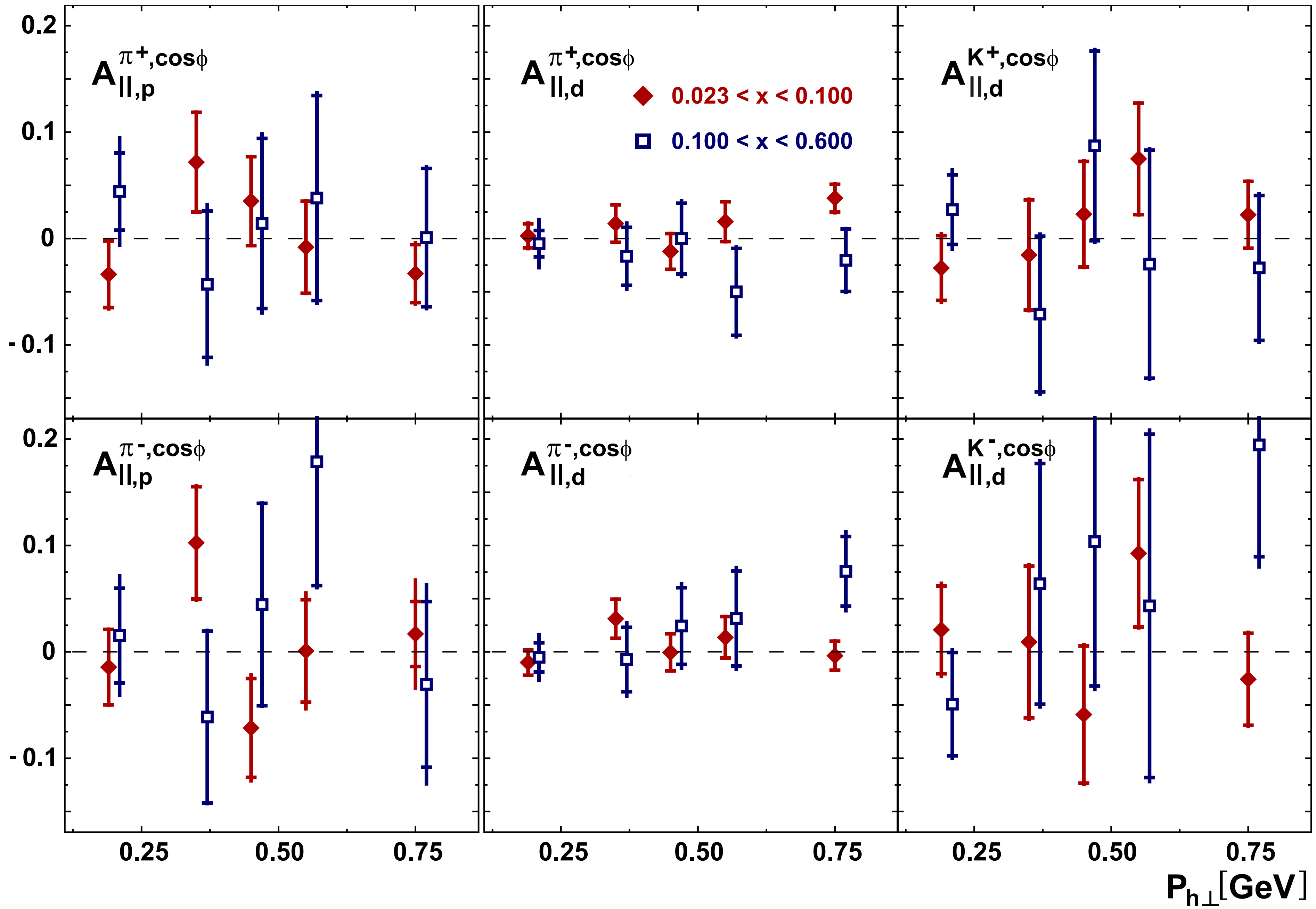




longitudinal DSA - cosine moments

- "polarized Cahn effect"
- twist-3 effect, thus various other contributions
- largely consistent with zero at HERMES

[arXiv:1810.07054]

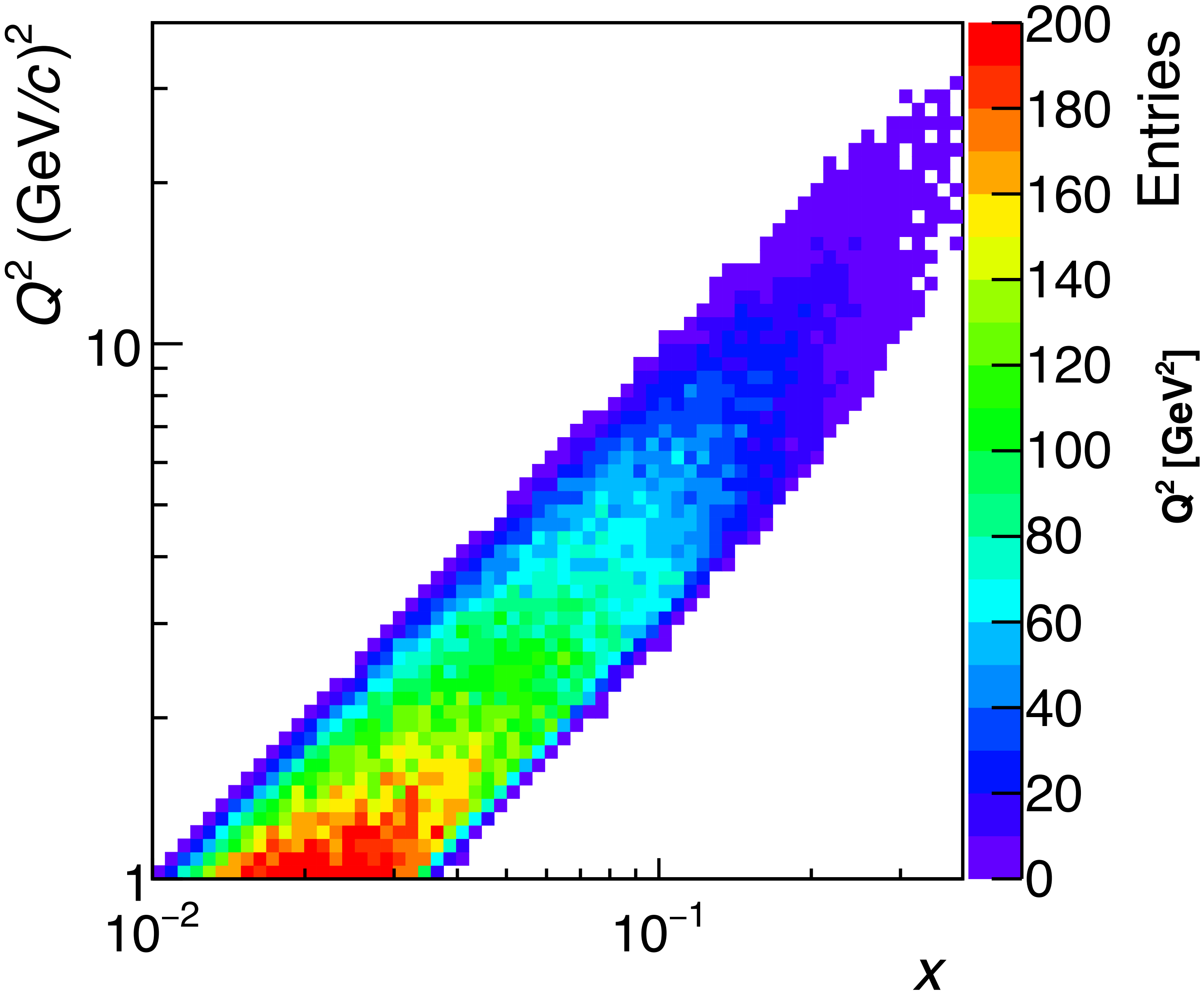


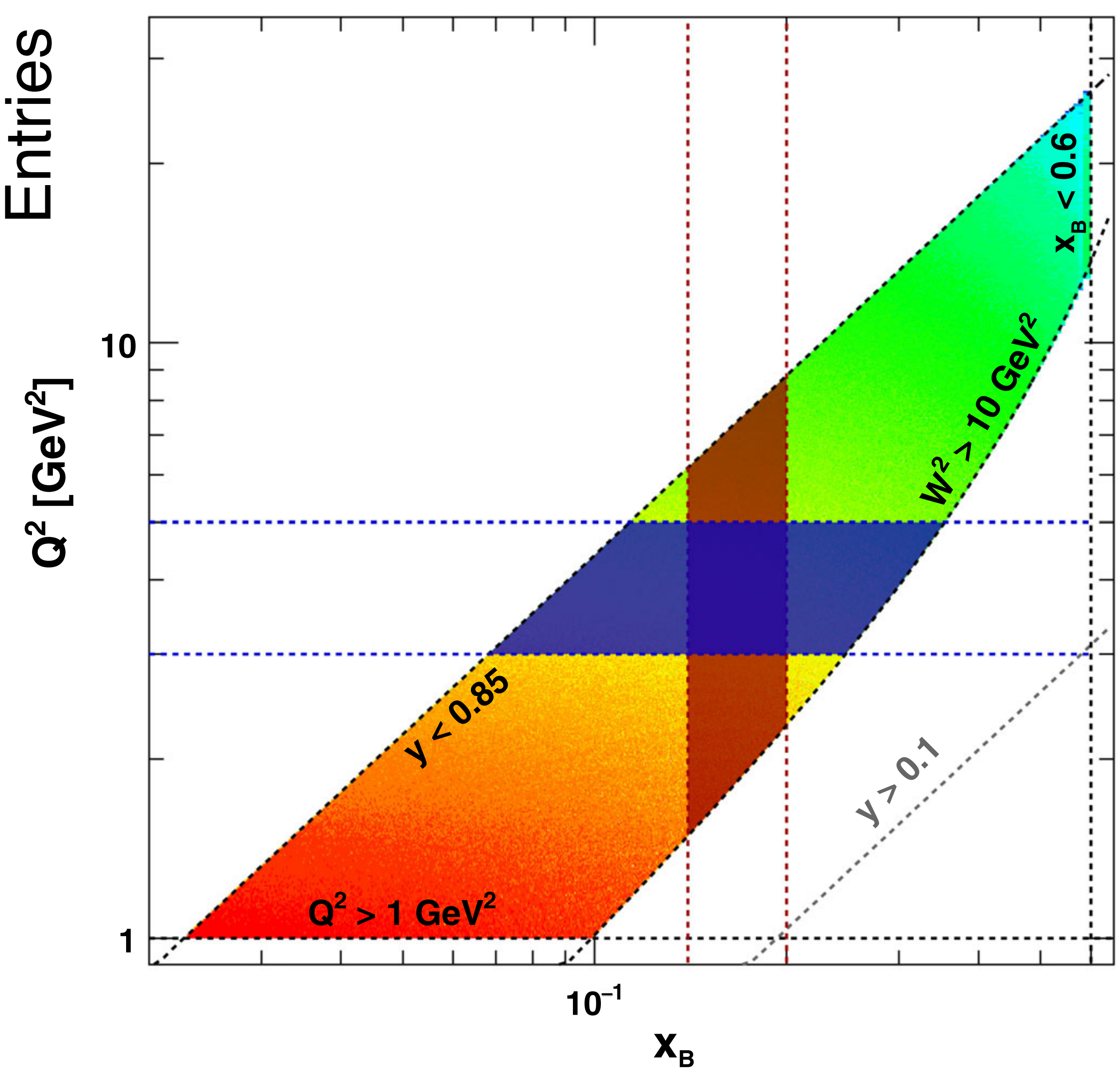
conclusions

- SIDIS provides important input to the study of FFs
  - flavor dependence of collinear FFs
  - pushing theory description in corner places of kinematics
  - transverse-momentum dependent multiplicities clearly indicate z-dependent transverse-momentum Gaussian width of FFs
- access to chiral-odd FF through azimuthal modulations
  - also here: easier flavor decomposition of FFs
  - d-quark transversity difficult to access with only proton targets
  - additional deuteron data to come from COMPASS
- non-zero beam-helicity asymmetries
  - sizable twist-3 effects
  - intriguing kinematic dependences might shed light at different roles of the various terms contributing
- COMPASS and HERMES continue producing results

backup

kinematic coverage

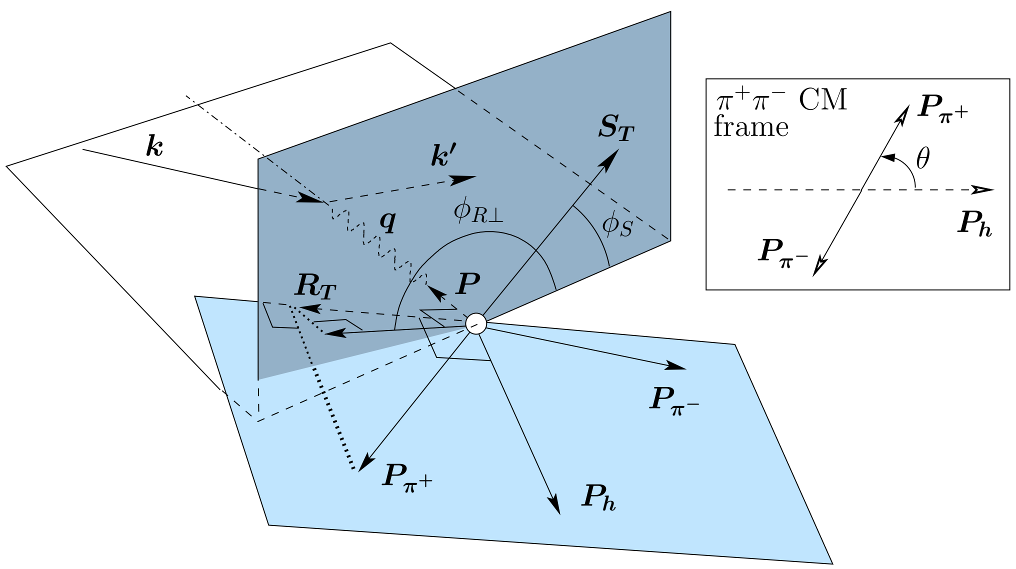




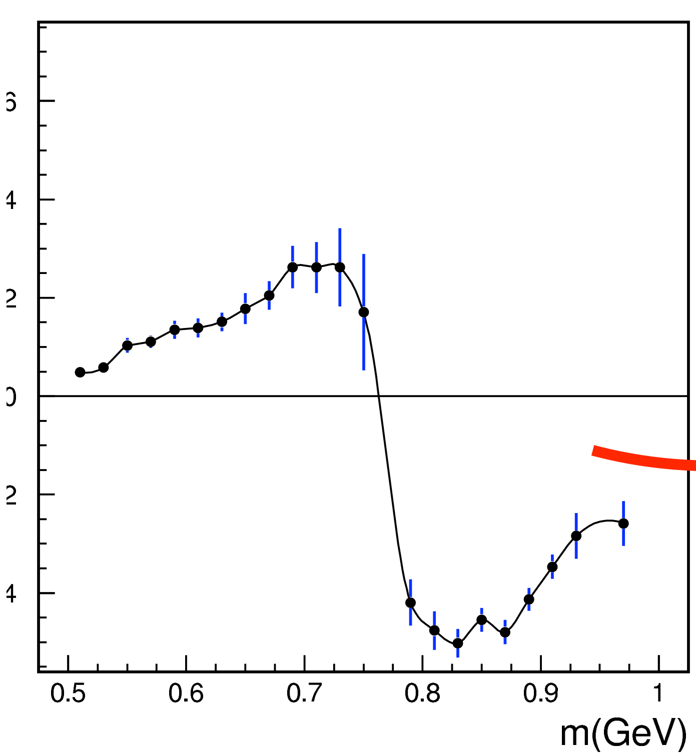
- COMPASS
- HERMES

	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 (2-hadron fragmentation)



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



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

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

δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

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

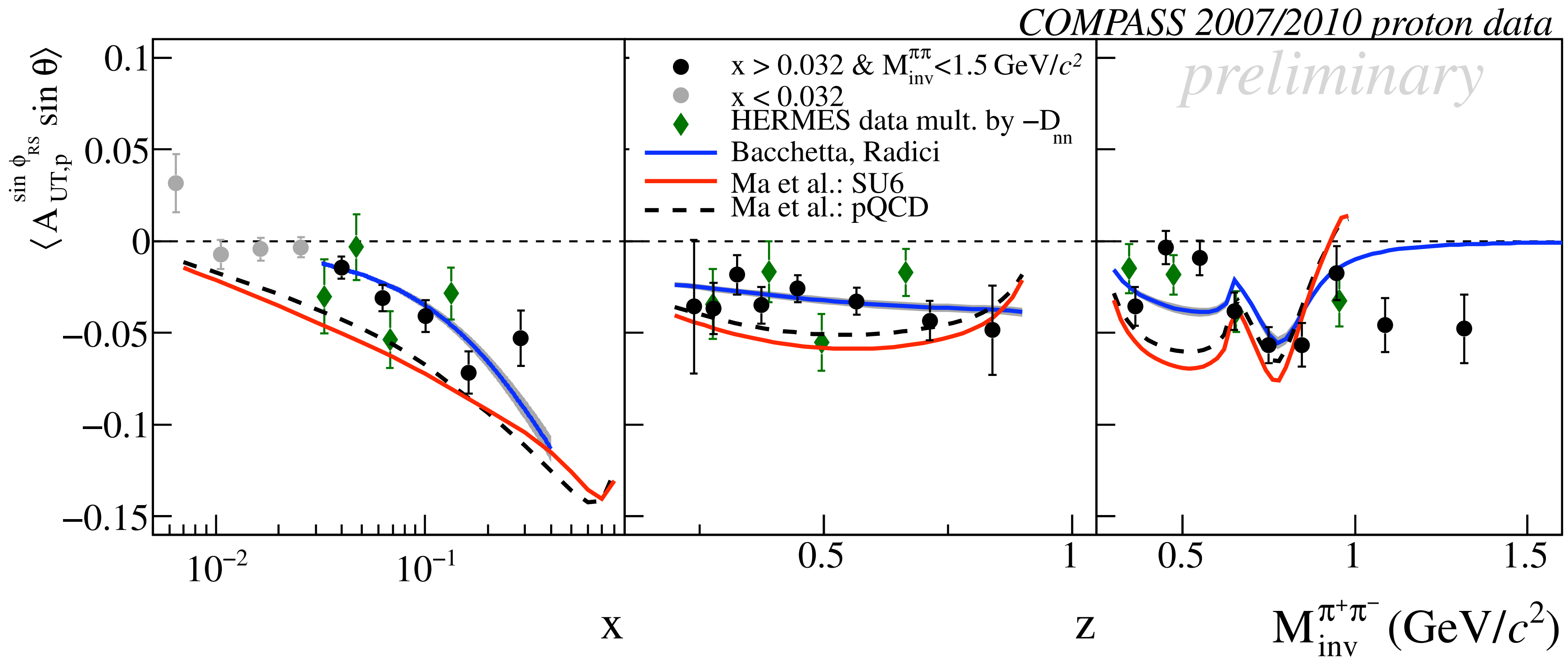
$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

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

Transversity (2-hadron fragmentation)

- HERMES, COMPASS: for comparison scaled HERMES data by depolarization factor and changed sign
- ^{2}H results consistent with zero

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



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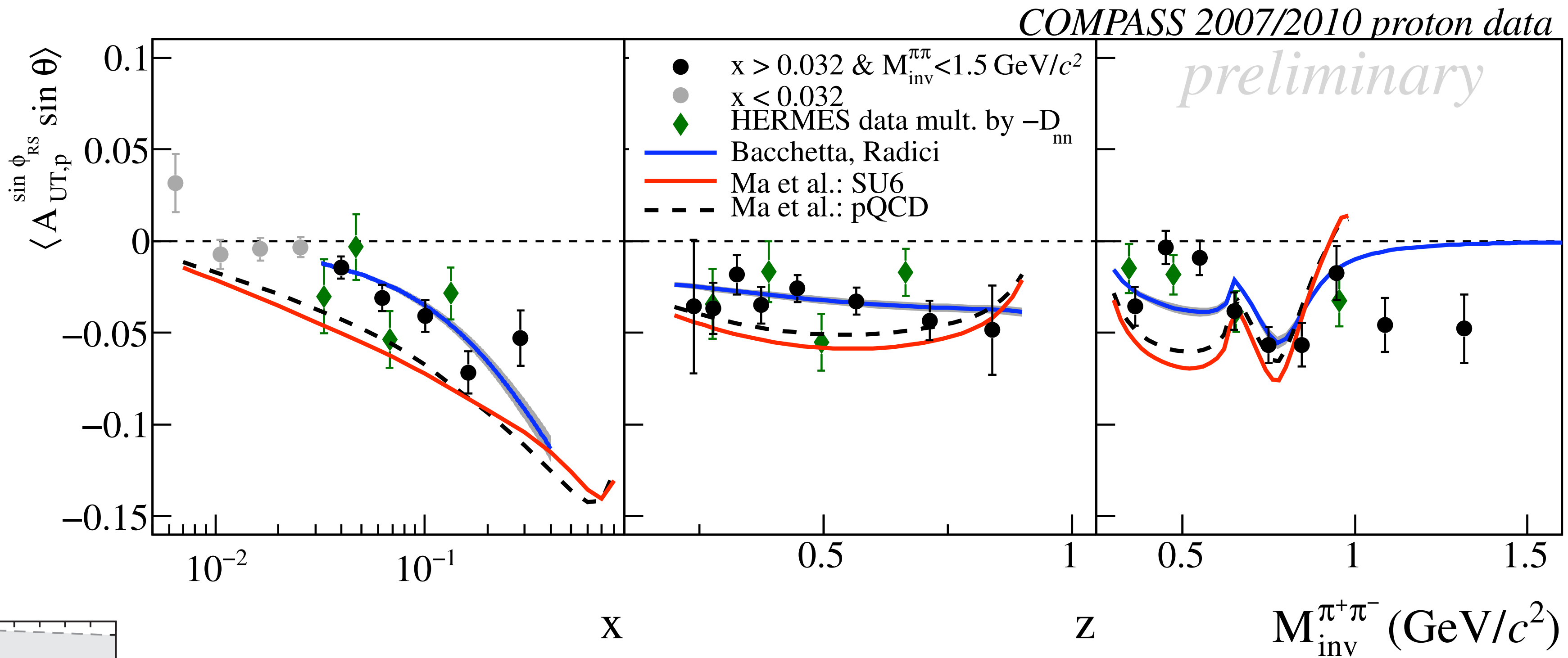
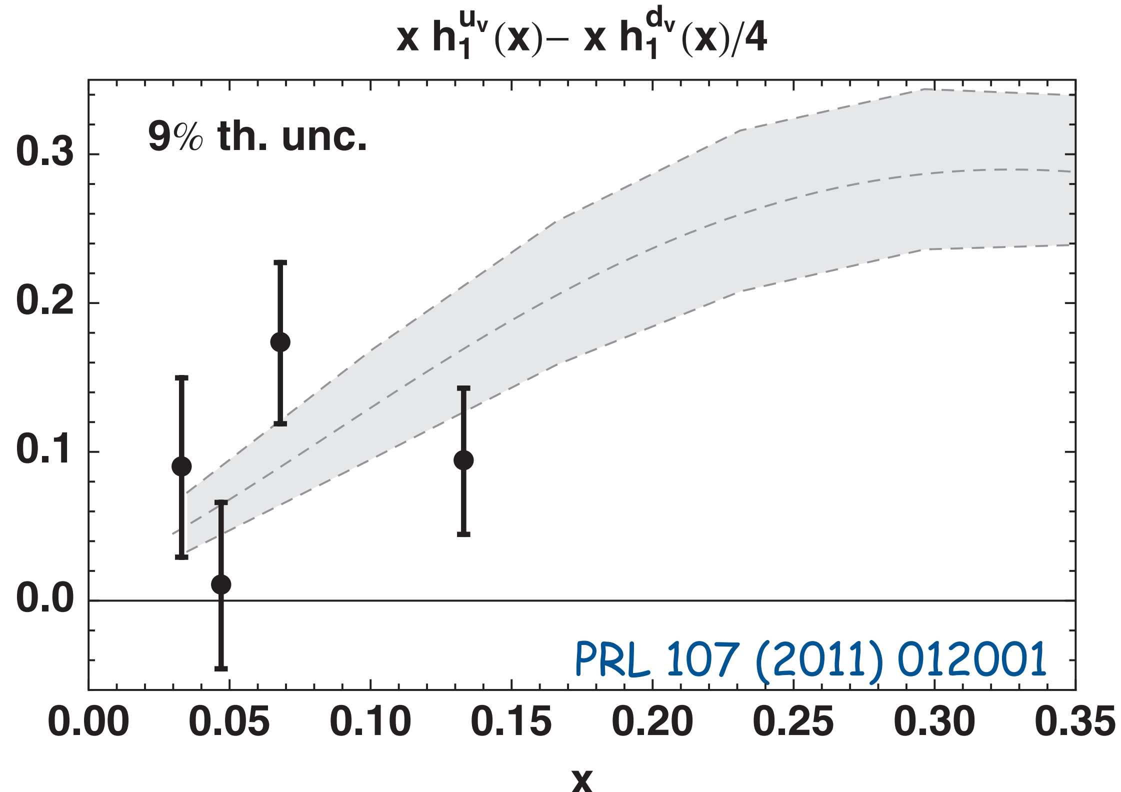
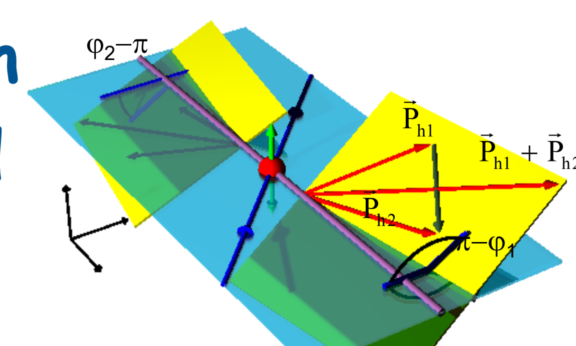




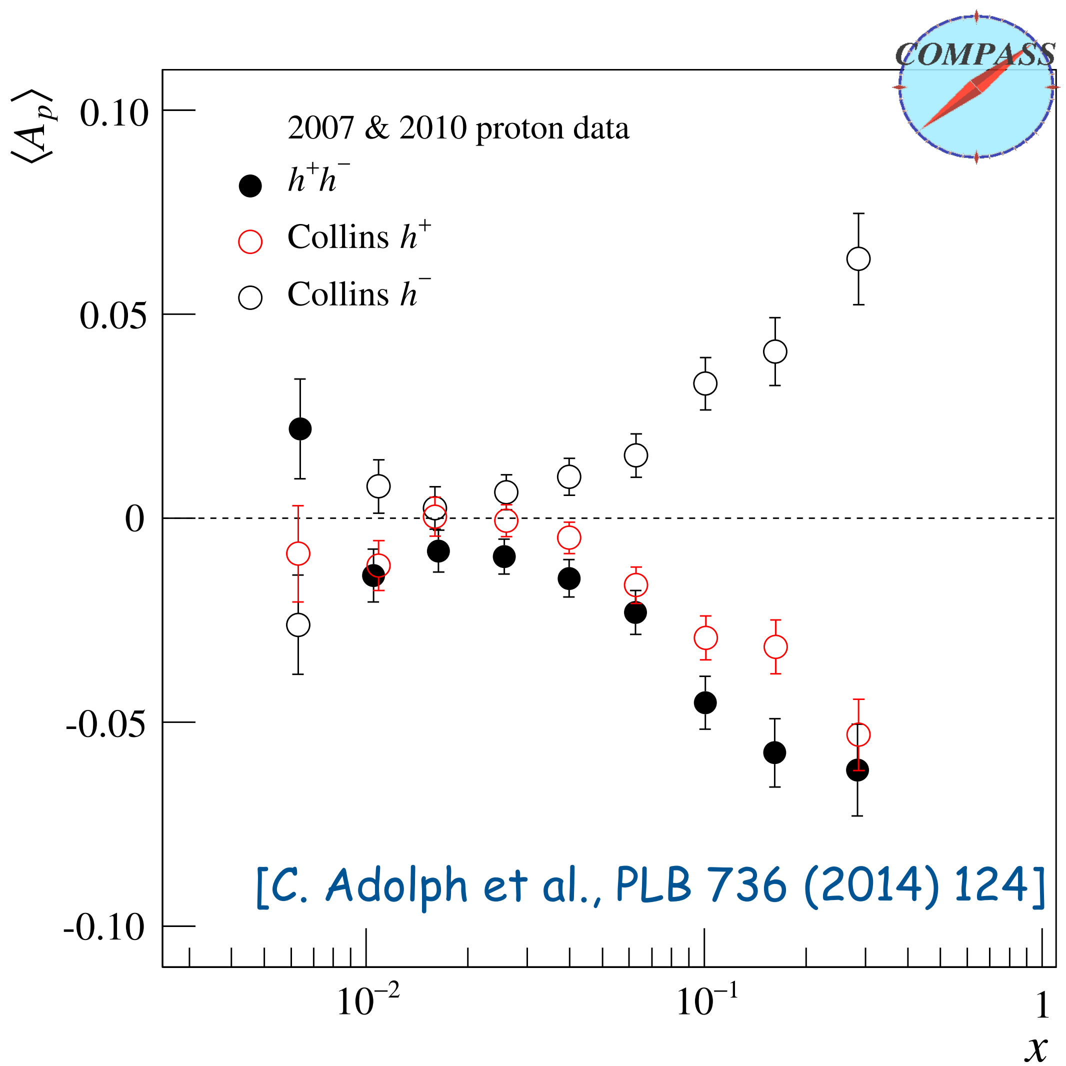
- data from e^+e^- by BELLE allow **first (collinear) extraction of transversity** (compared to Anselmino et al.)

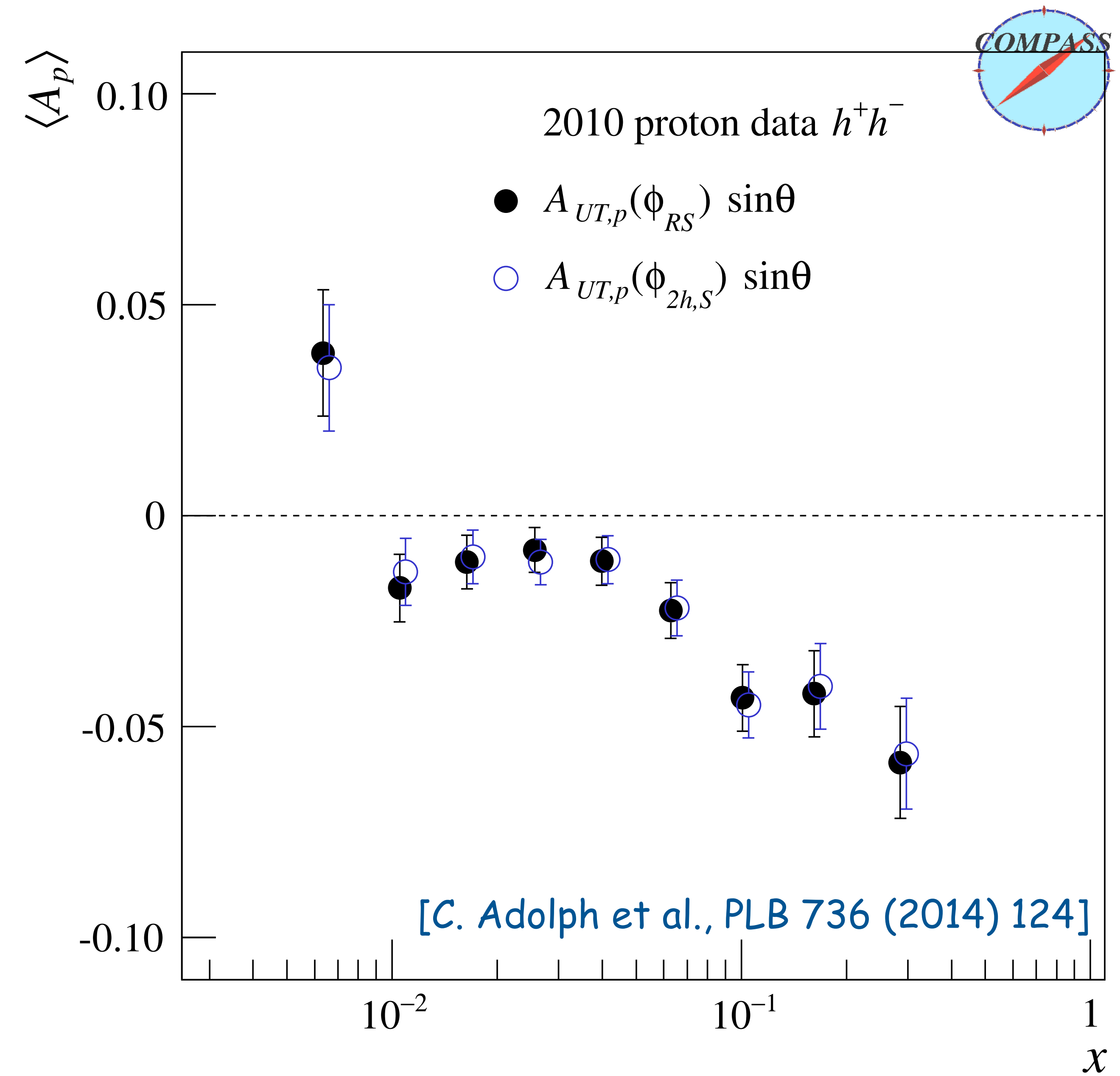


- updated analysis available (incl. COMPASS)

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

Di-hadron vs. Collins fragmentation





- apparent similarity of Collins and di-hadron asymmetries
- suggested common origin of Collins and di-hadron FF in PLB 736 (2014) 124

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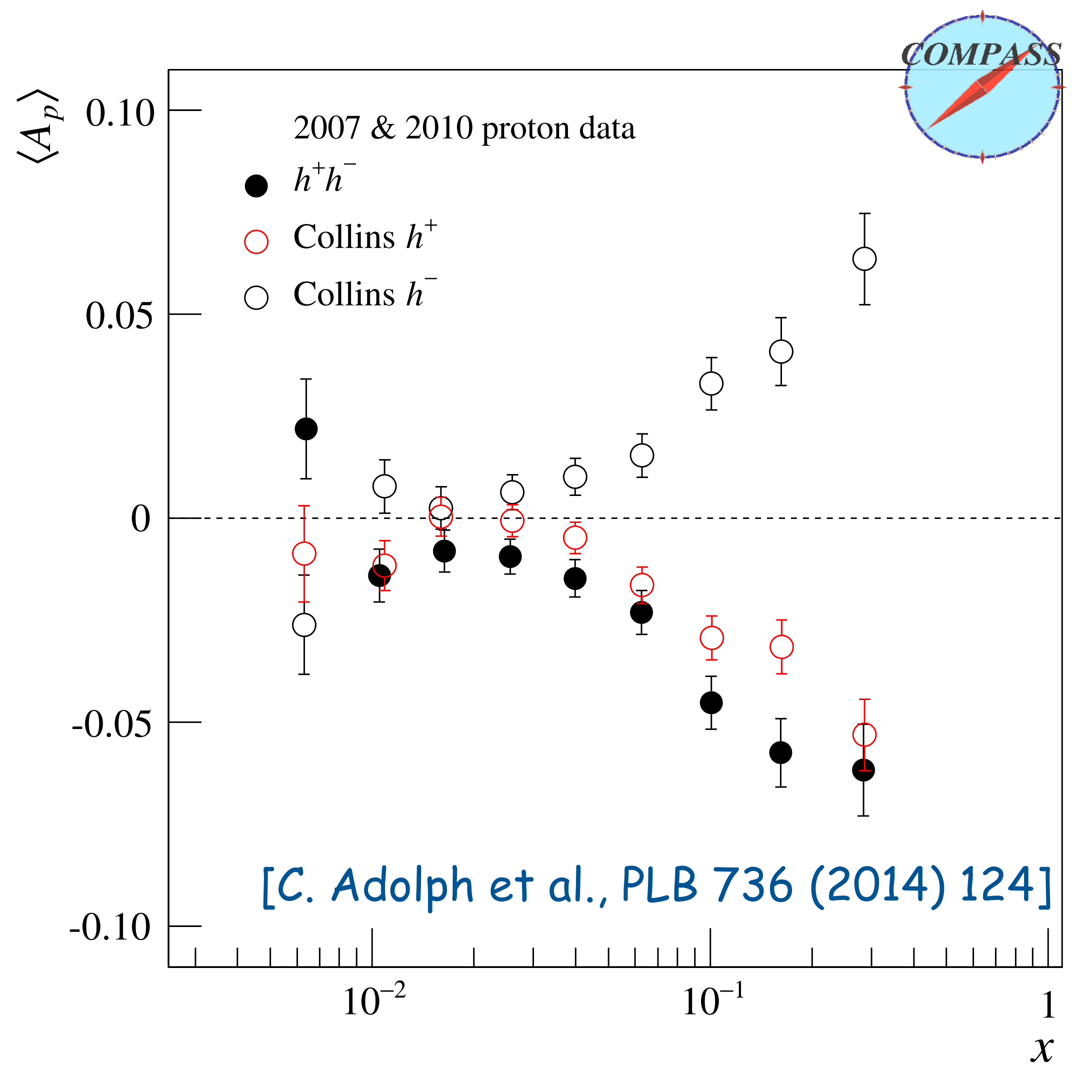

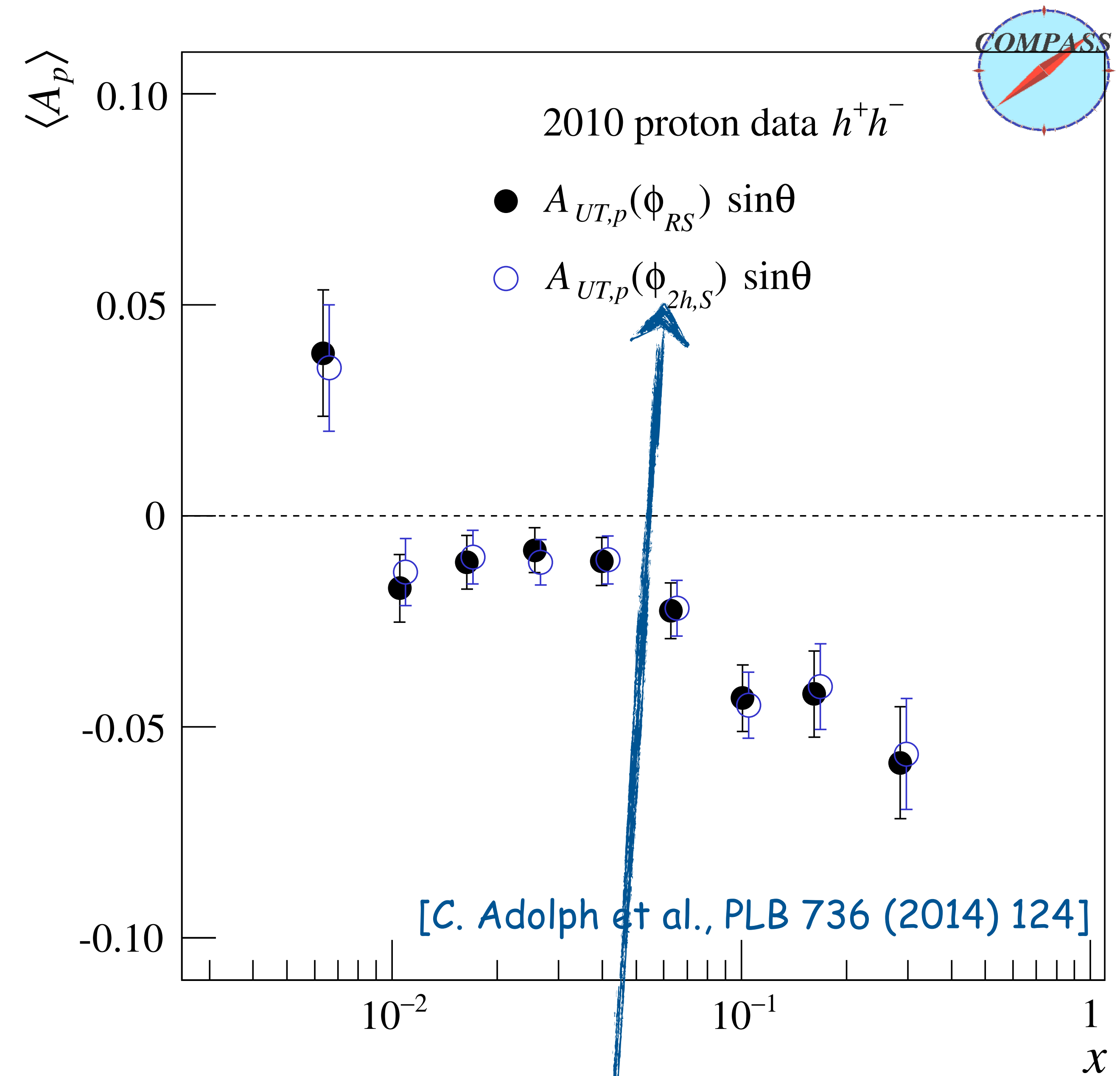

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"Collins angle" of $\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$

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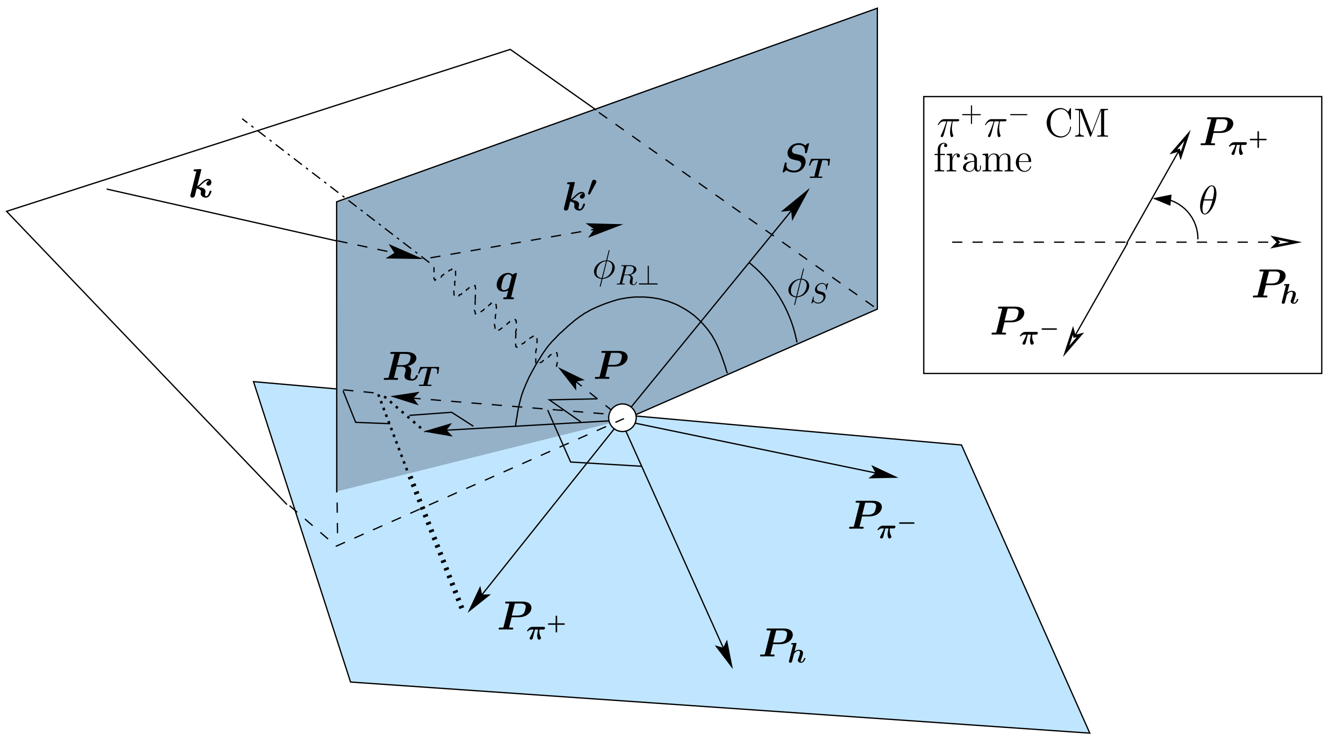
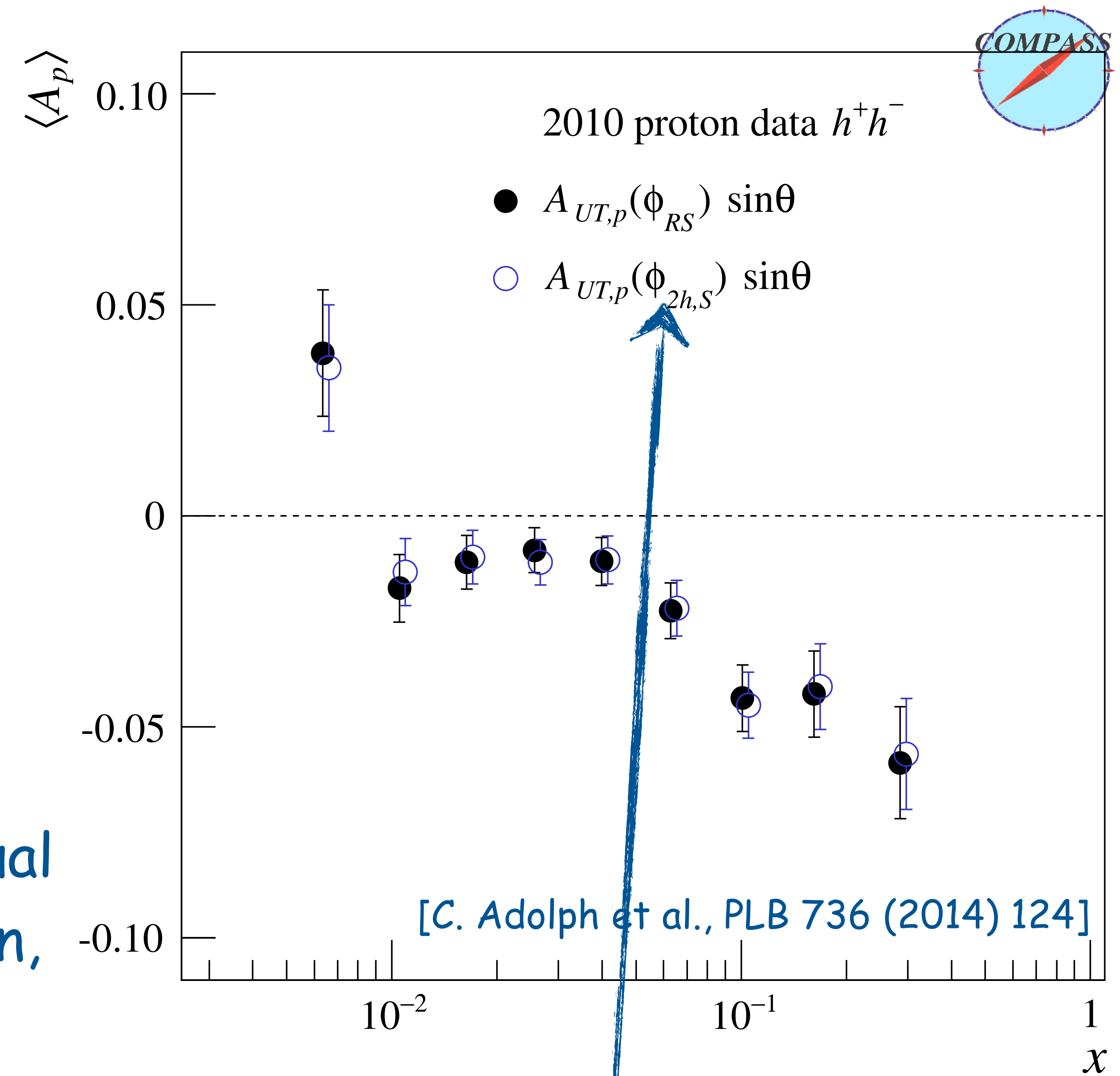
Di-hadron vs. Collins fragmentation





- in the limit of collinear P_h (w.r.t. virtual photon), e.g., in collinear factorization, $\phi_{2h,S}$ reduces just to ϕ_{RS}

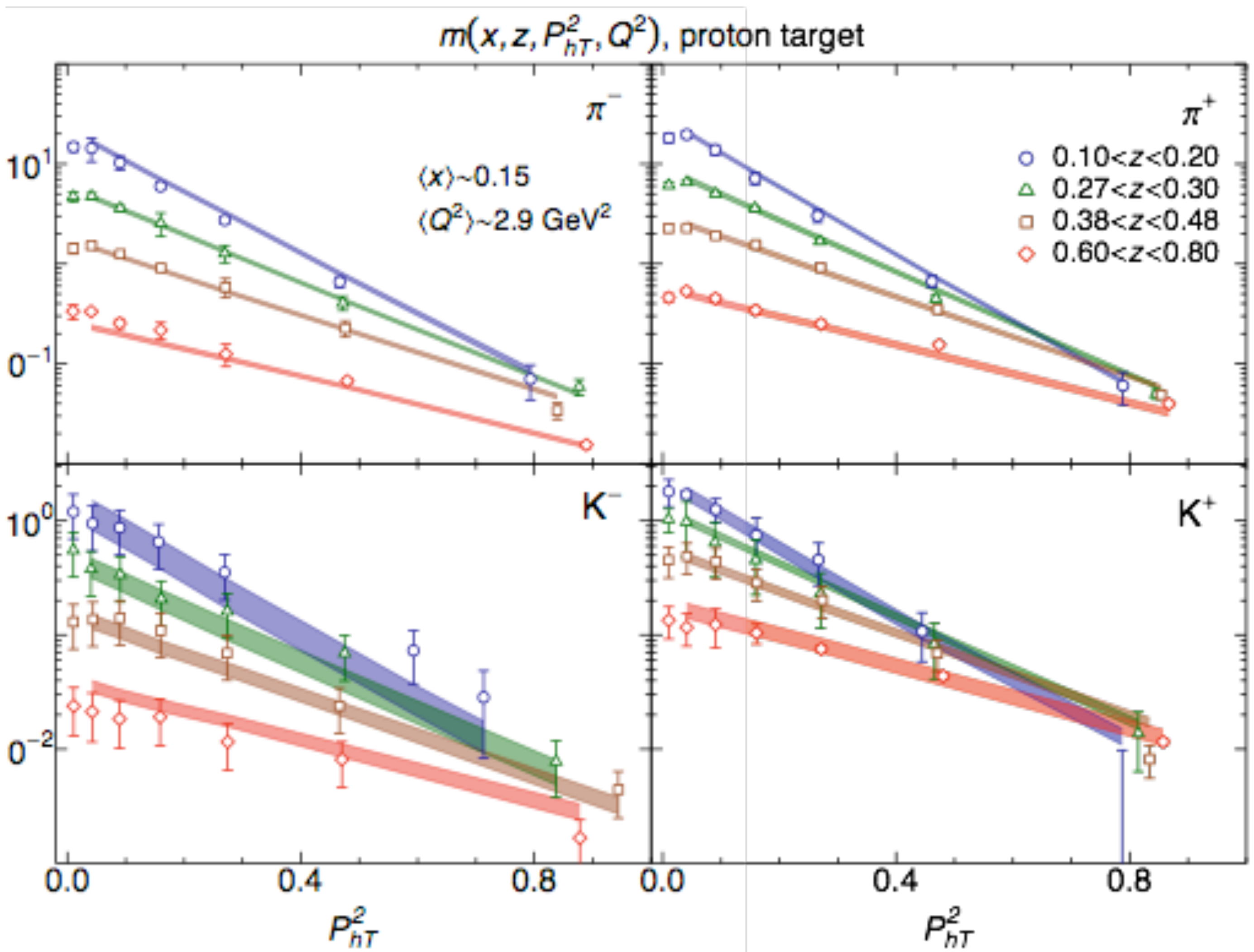
"Collins angle" of $\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$

➡ no big surprise that those two asymmetries are very similar?

FF TMD flavor dependence

- fit to HERMES multiplicity data:

$$m_N^h(x,z,\boldsymbol{P}_{hT}^2;Q^2) = \frac{\pi}{\sum_q e_q^2\, f_1^q(x;Q^2)} \sum_q e_q^2\, f_1^q(x;Q^2)\; D_1^{q\to h}(z;Q^2)\; \frac{e^{-\boldsymbol{P}_{hT}^2/\langle \boldsymbol{P}_{hT,q}^2\rangle}}{\pi\,\langle \boldsymbol{P}_{hT,q}^2\rangle}$$



$$f_1^q(x,\boldsymbol{k}_\perp^2;Q^2) = f_1^q(x;Q^2)\; \frac{e^{-\boldsymbol{k}_\perp^2/\langle \boldsymbol{k}_{\perp,q}^2\rangle}}{\pi\langle \boldsymbol{k}_{\perp,q}^2\rangle}$$

$$D_1^{q\to h}(z,\boldsymbol{P}_\perp^2;Q^2) = D_1^{q\to h}(z;Q^2)\; \frac{e^{-\boldsymbol{P}_\perp^2/\langle \boldsymbol{P}_{\perp,q\to h}^2\rangle}}{\pi\langle \boldsymbol{P}_{\perp,q\to h}^2\rangle}$$

$$\langle \boldsymbol{P}_{hT,q}^2\rangle = z^2\langle \boldsymbol{k}_{\perp,q}^2\rangle + \langle \boldsymbol{P}_{\perp,q\to h}^2\rangle$$

[A. Signori, A. Bacchetta, M. Radici and GS, JHEP 11(2013)194]

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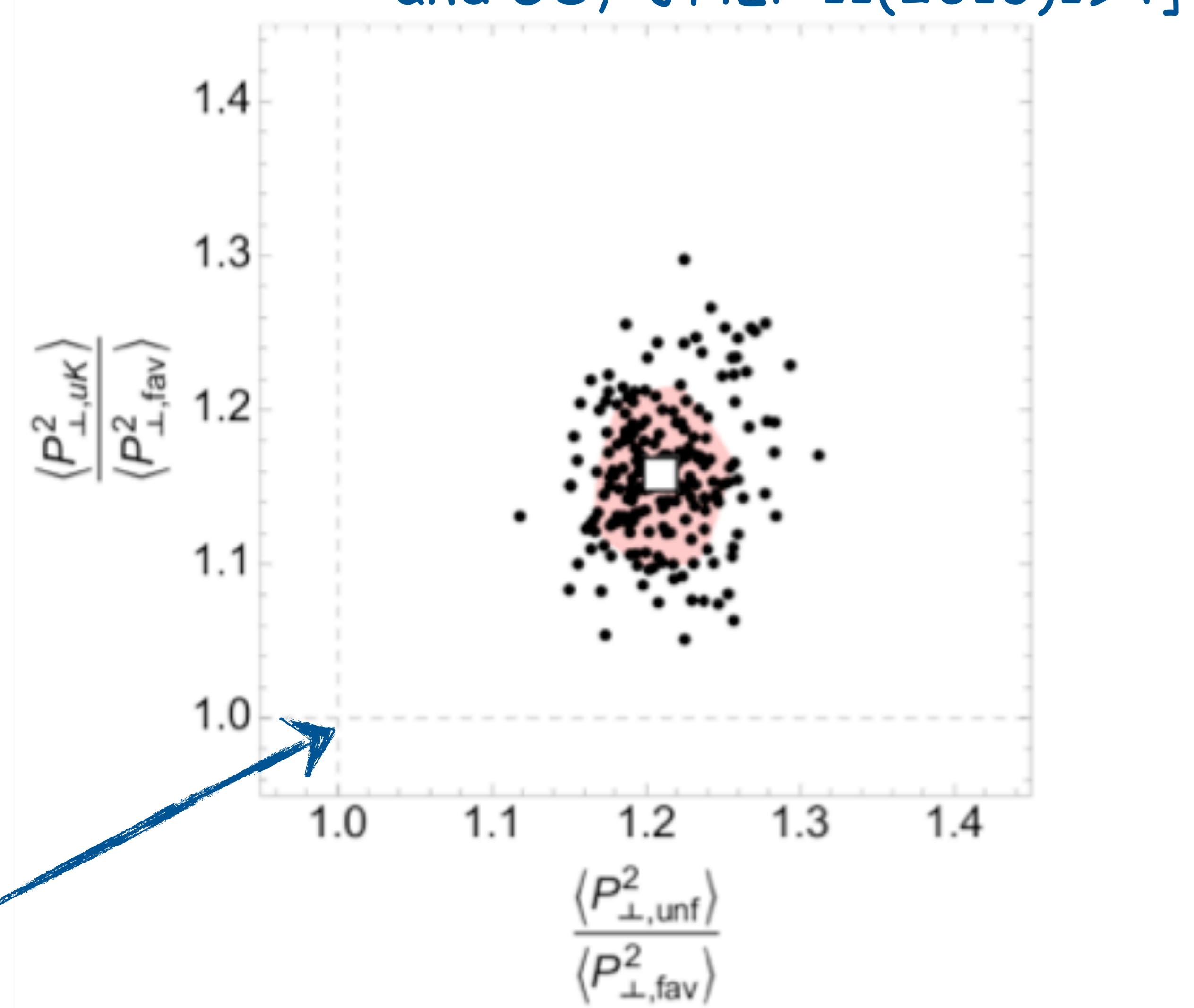
q→π favored width
<
q→K favored width

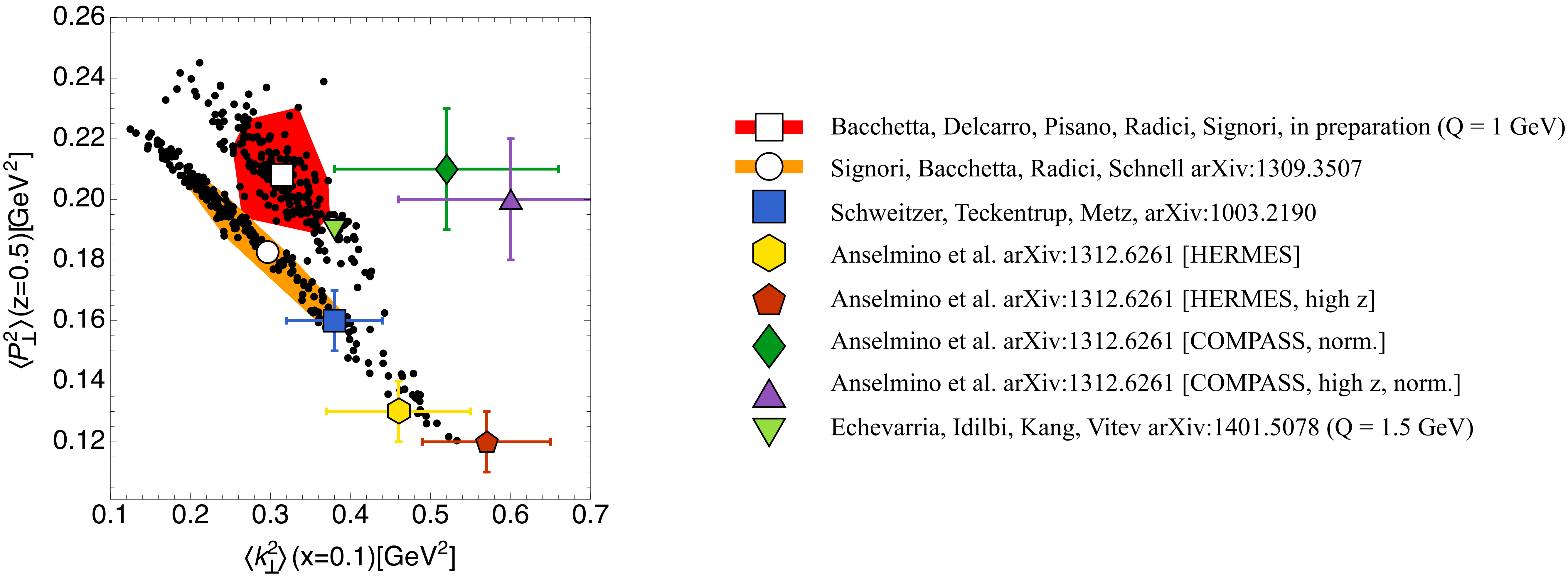


point of
no flavor dep.

q→π favored width < unfavored

FF TMD flavor dependence

- fit to SIDIS, DY & Z boson production: JHEP 06 (2017) 081



- fit to e^+e^- data: PLB 772 (2017) 78-86

- new data: COMPASS arXiv:1709.07374