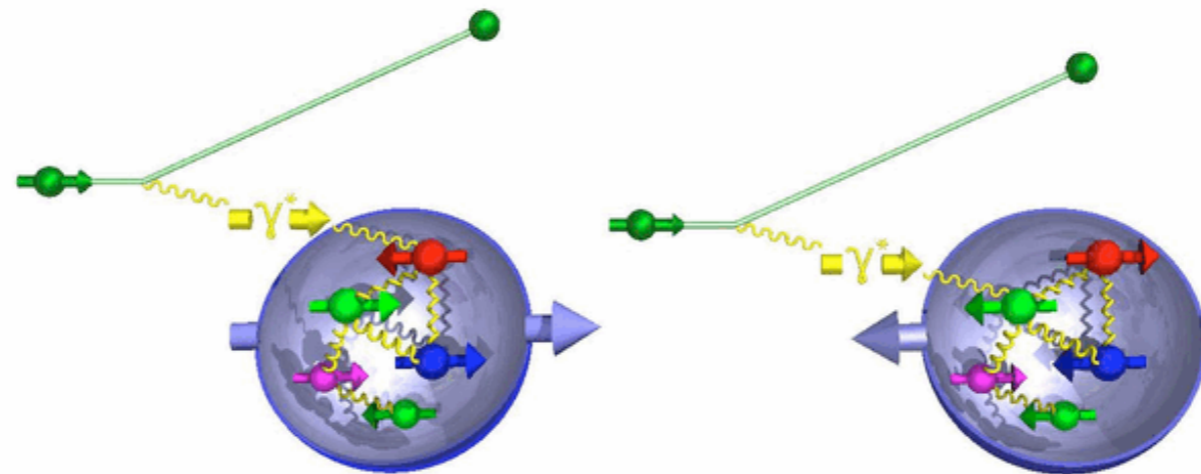


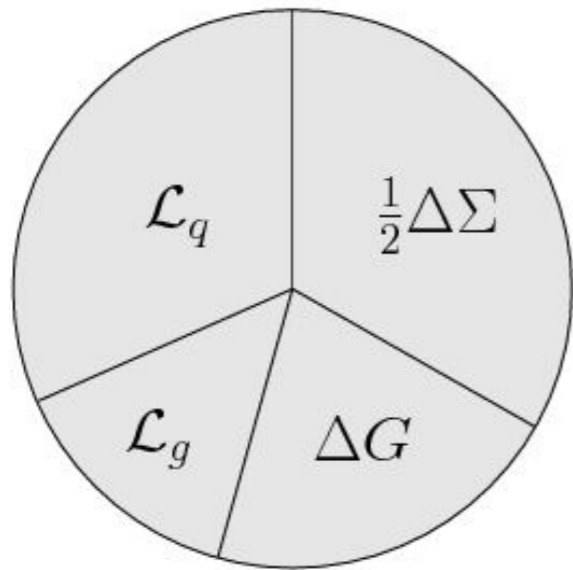
27th International Workshop on Deep-Inelastic Scattering and Related Subjects



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



Access to angular momentum in (SI)DIS

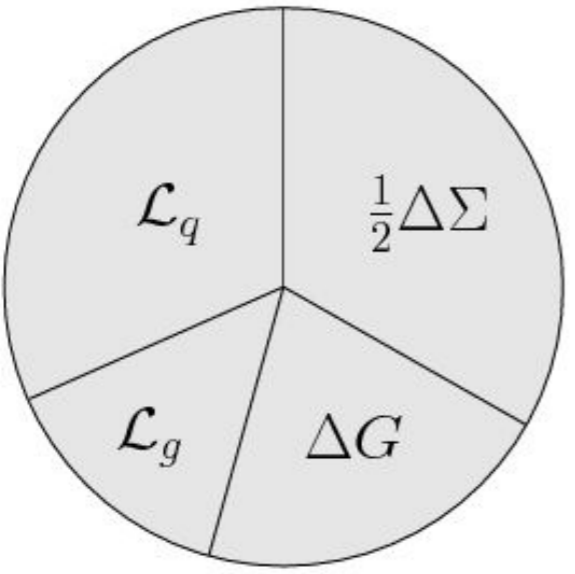


‘pizza quattro stagioni’

[M. Burkardt]

➔ A. Bacchetta (Mo)

Access to angular momentum in (SI)DIS



'pizza quattro stagioni'

[M. Burkardt]

A. Bacchetta (Mo)

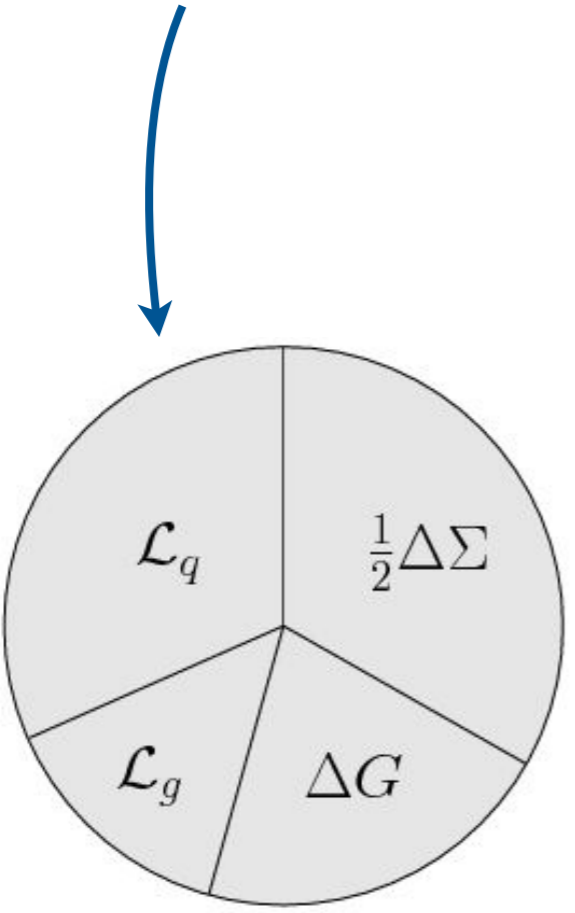


evolution

[better: polarized pp]

Access to angular momentum in (SI)DIS

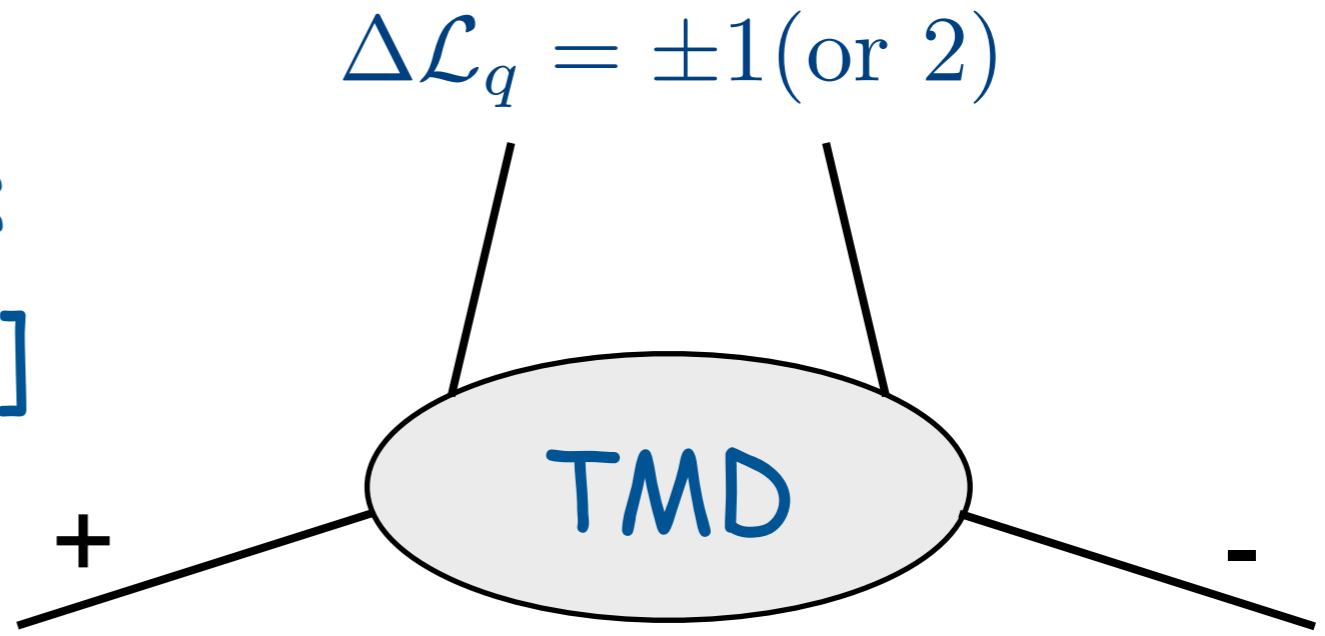
TMDs? (SIDIS):
[better(?): GPDs]



'pizza quattro stagioni'

[M. Burkardt]

➔ A. Bacchetta (Mo)

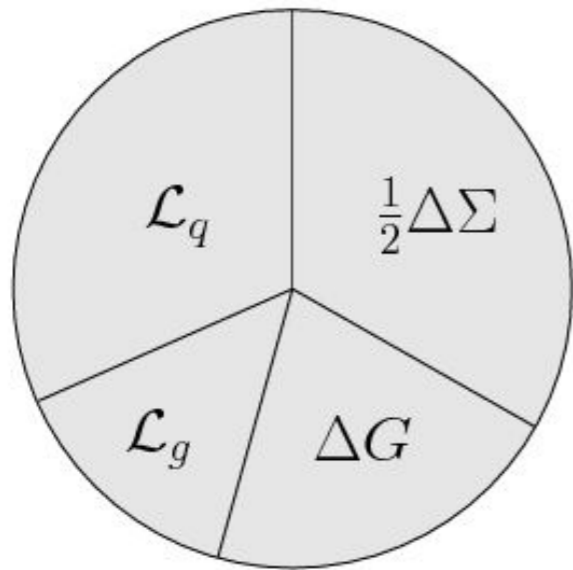
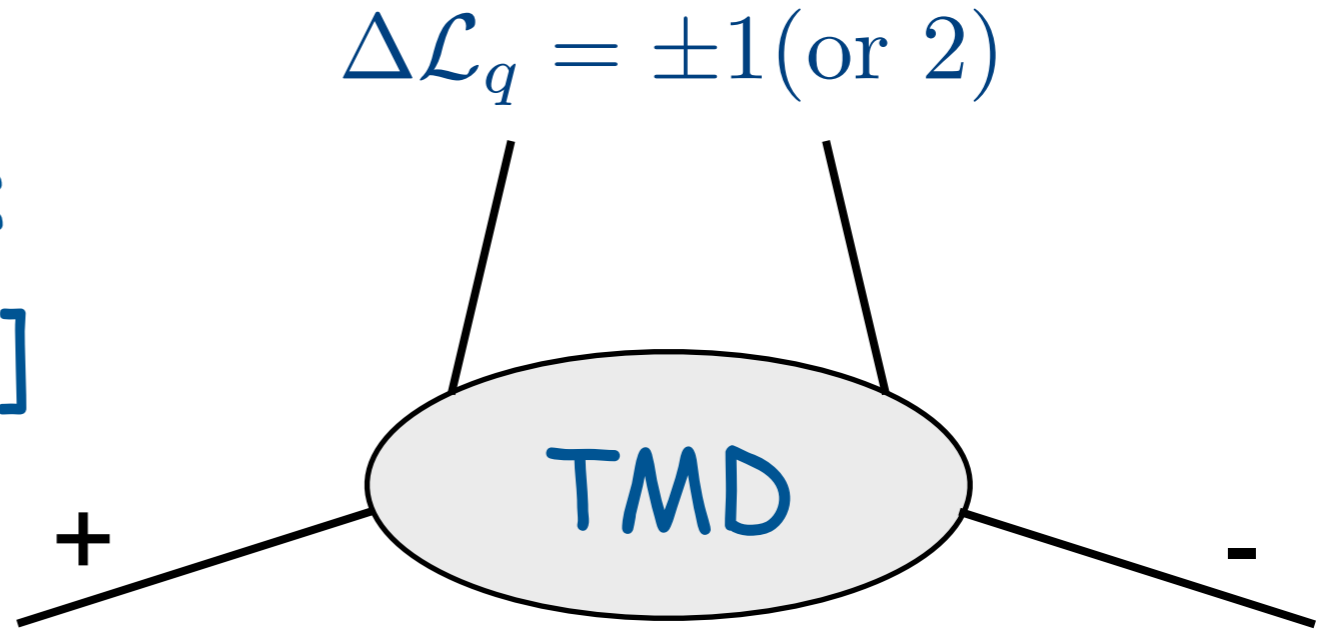


evolution

[better: polarized pp]

Access to angular momentum in (SI)DIS

TMDs? (SIDIS):
[better(?): GPDs]



'pizza quattro stagioni'

[M. Burkardt]

→ A. Bacchetta (Mo)

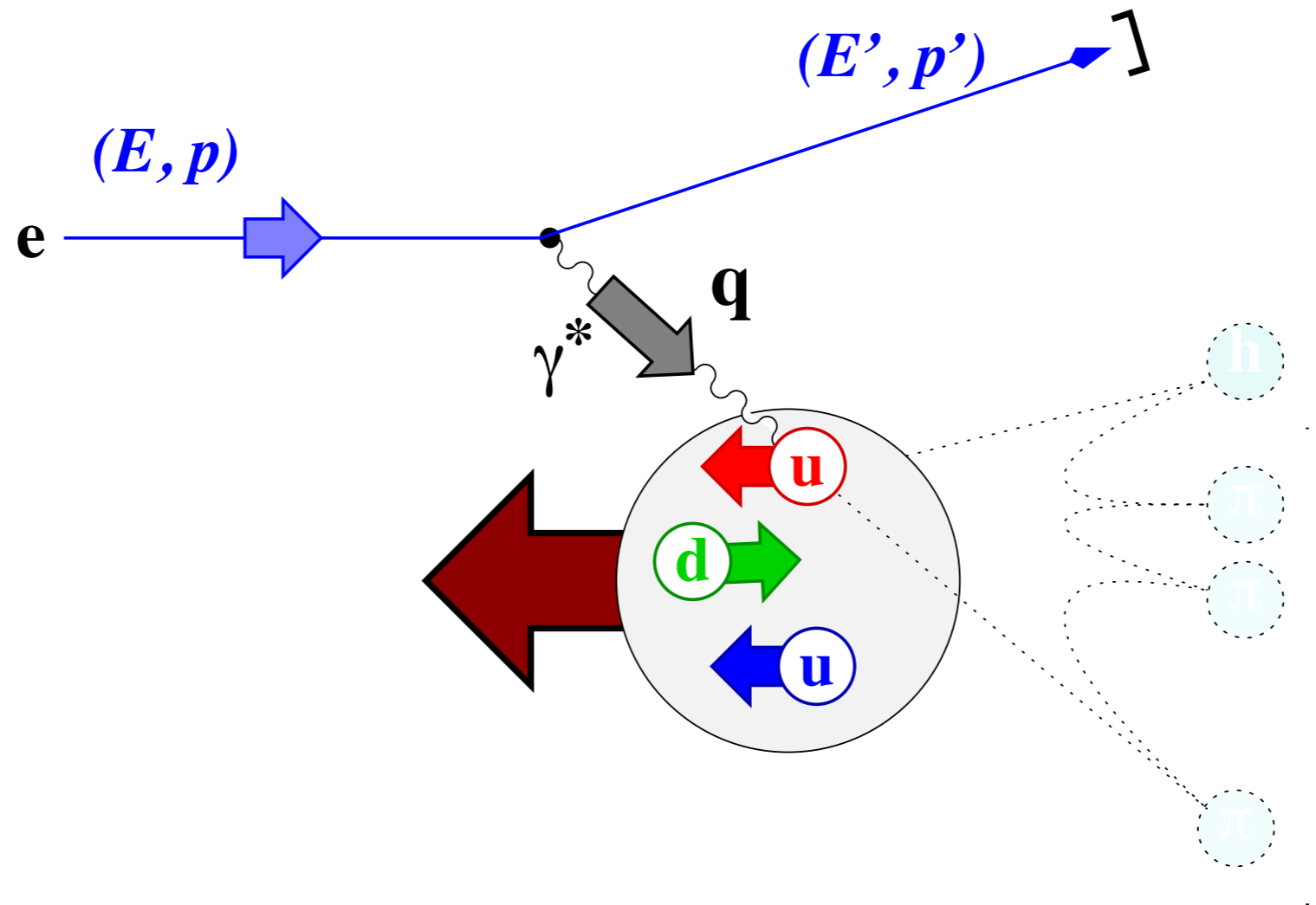
(semi-)inclusive
longitudinal double-spin
asymmetries

evolution

[better: polarized pp]

deep-inelastic scattering

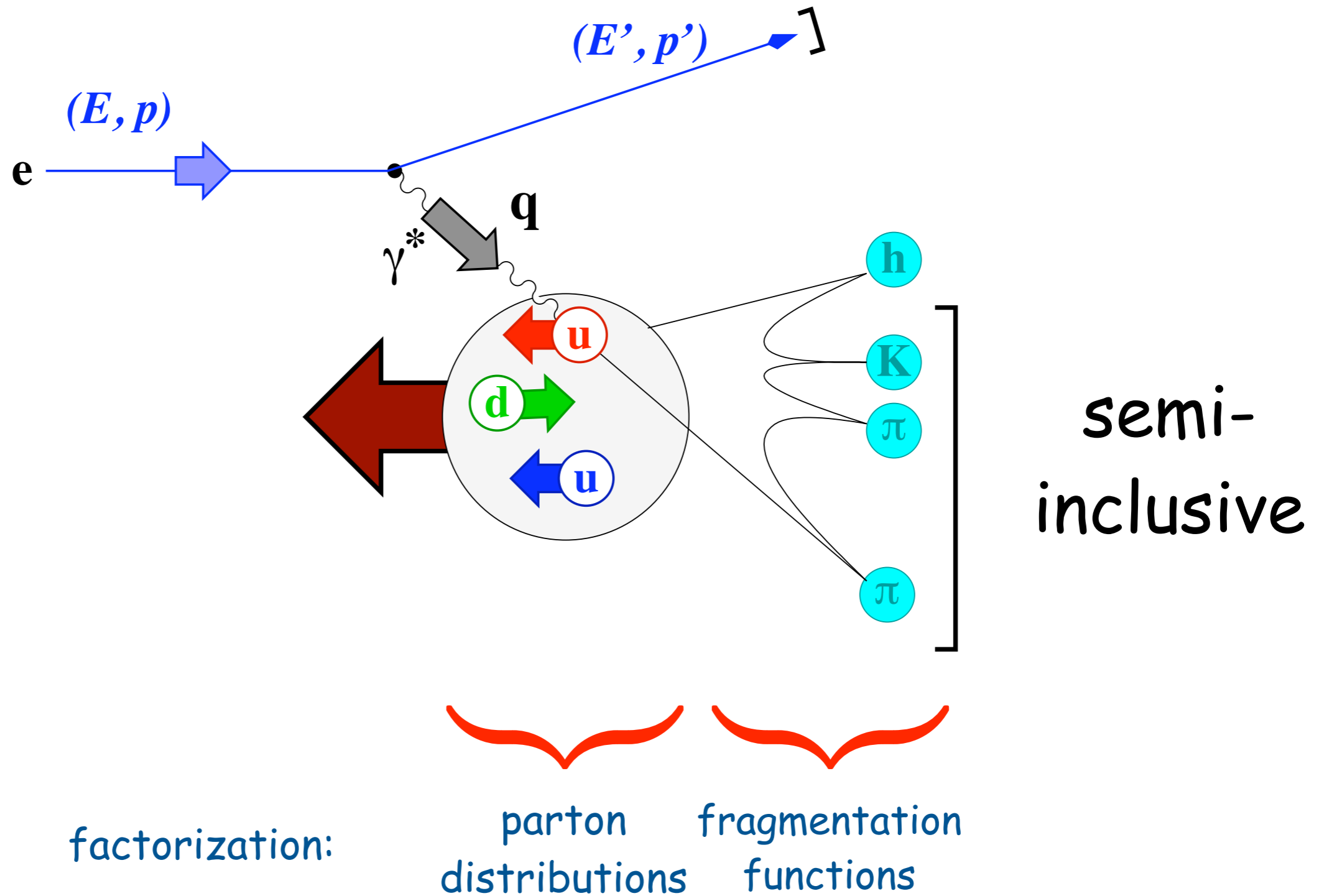
inclusive



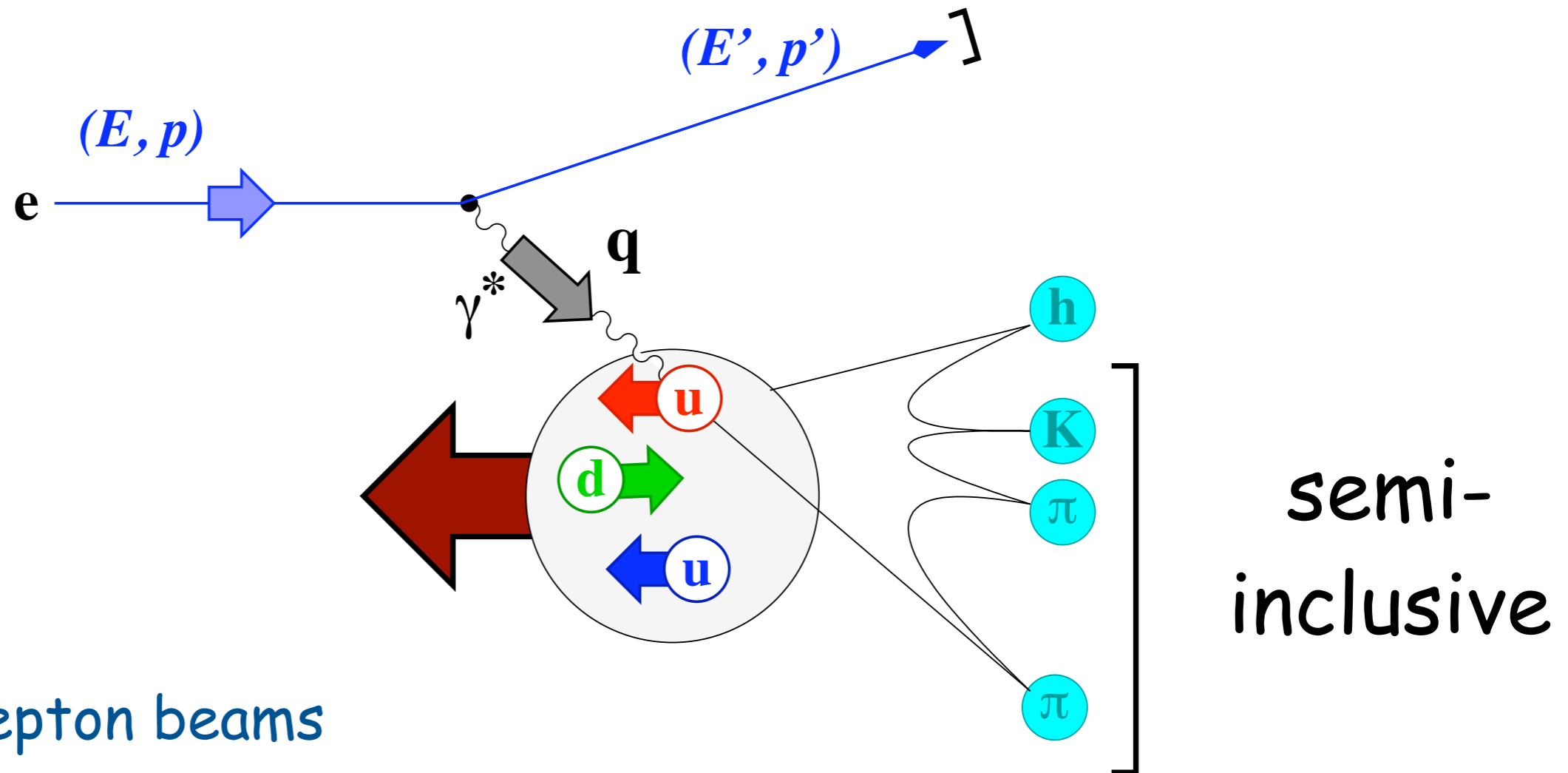
factorization:

parton
distributions

deep-inelastic scattering



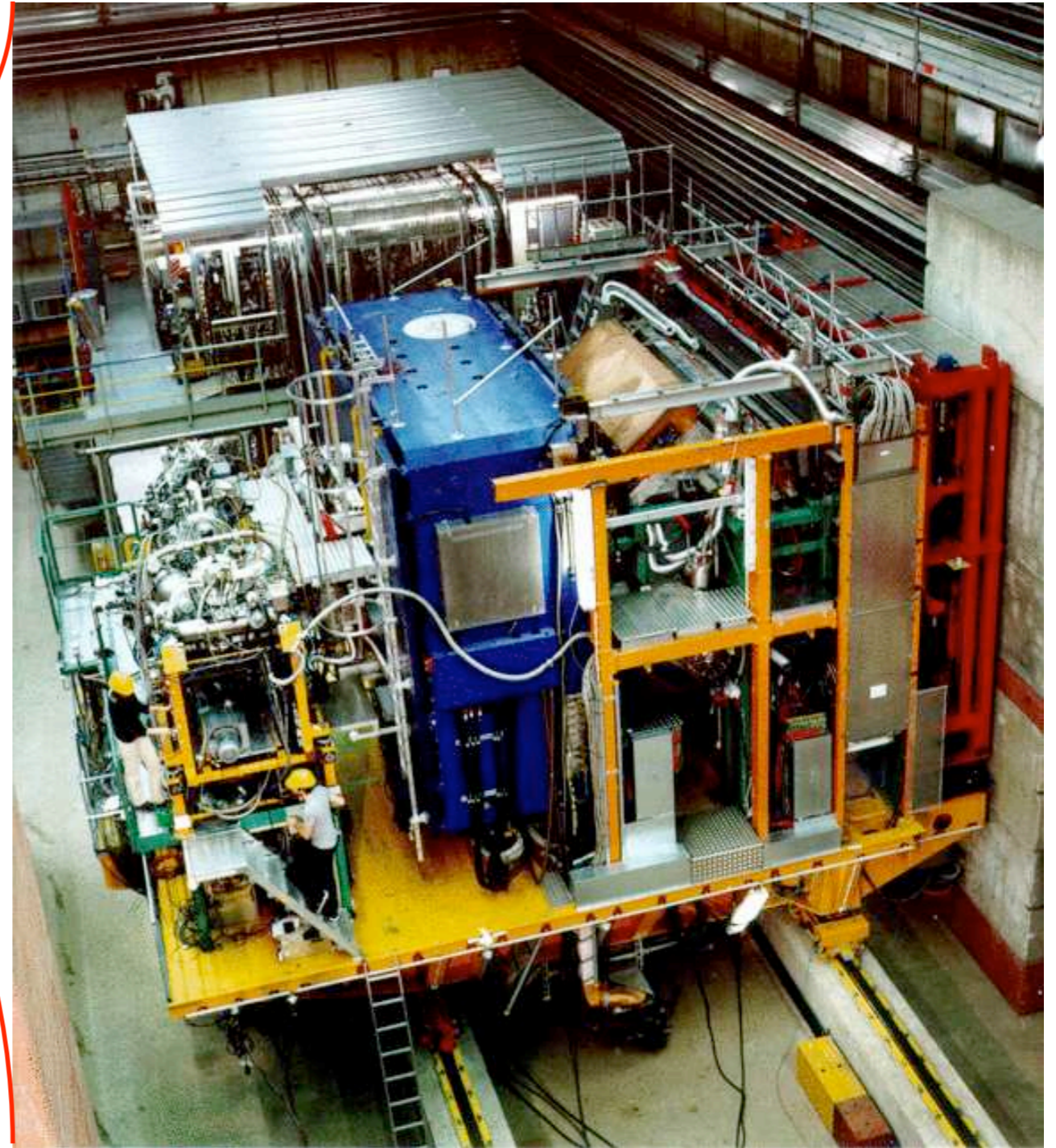
deep-inelastic scattering



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

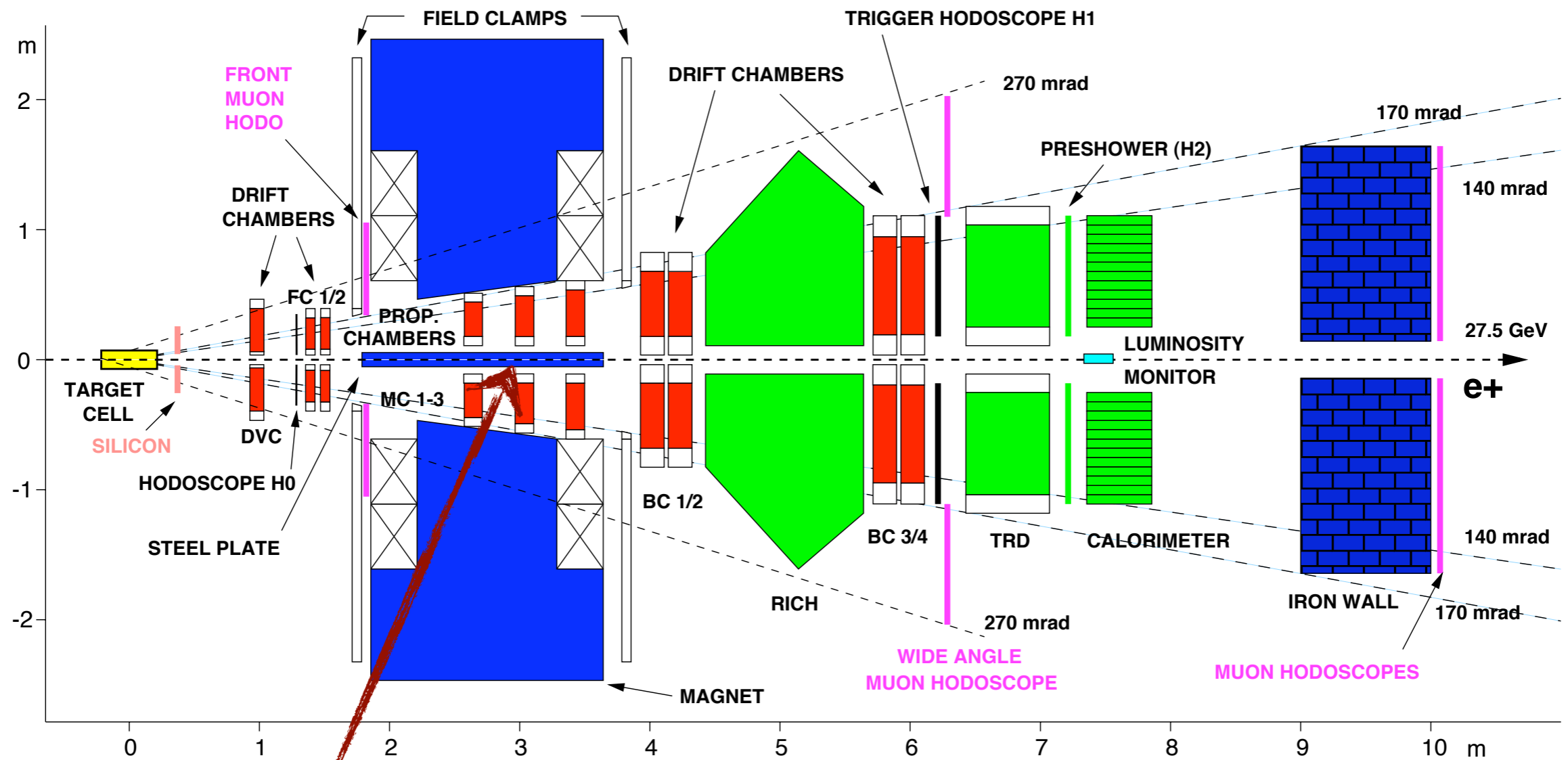
HERMES (†2007) @ DESY

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



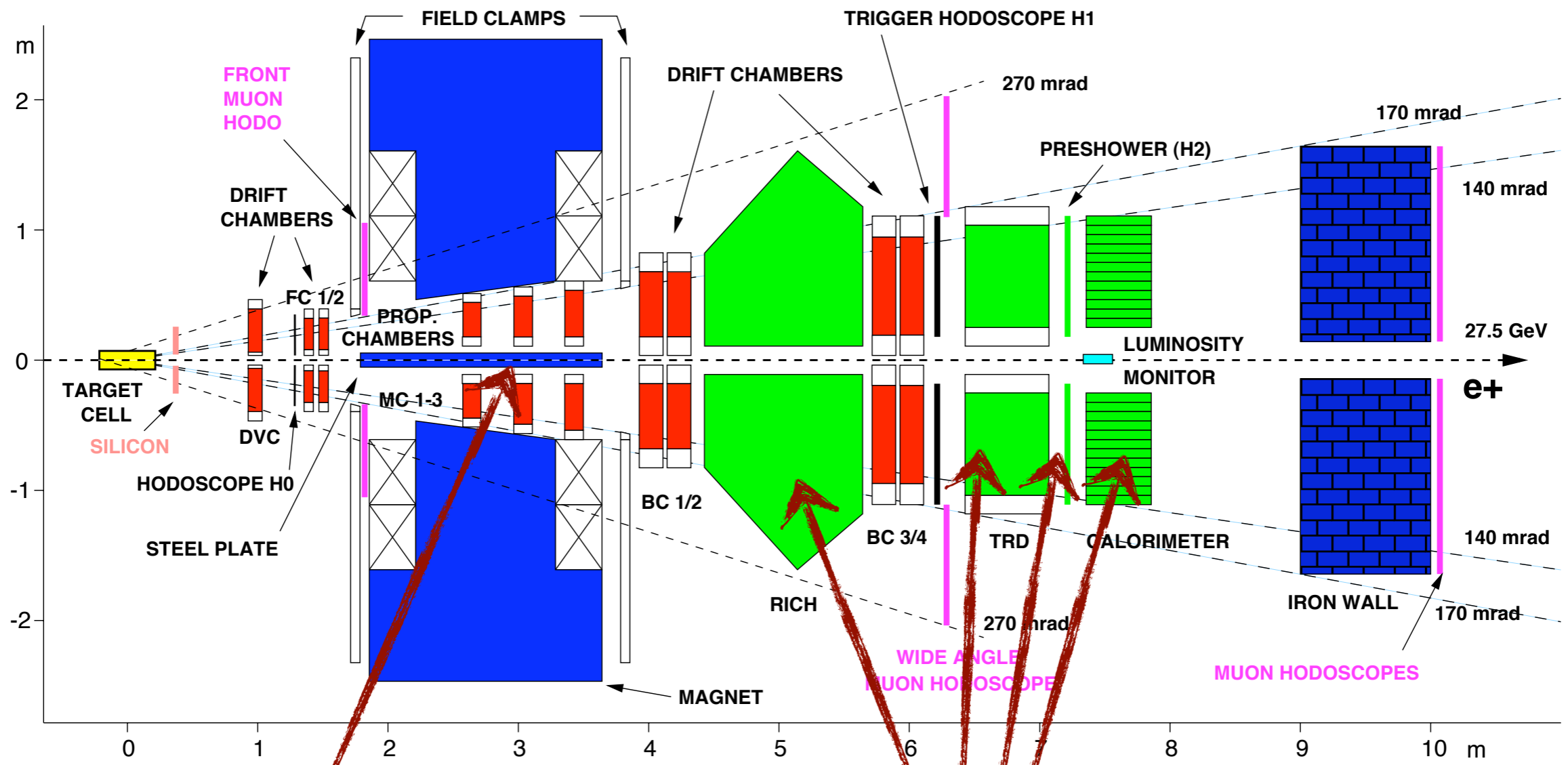
- unpolarized (H, D, He, ..., Xe)
- as well as transversely (H) and longitudinally polarized (pure) H, D & ^3He gas targets

HERMES (1998-2005) schematically



two (mirror-symmetric) halves

HERMES (1998-2005) schematically



two (mirror-symmetric) halves

Particle ID detectors allow for

- lepton/hadron separation
- dual-radiator RICH: pion/kaon/proton discrimination $2 \text{ GeV} < p < 15 \text{ GeV}$

semi-inclusive DIS

- excluding transverse polarization:

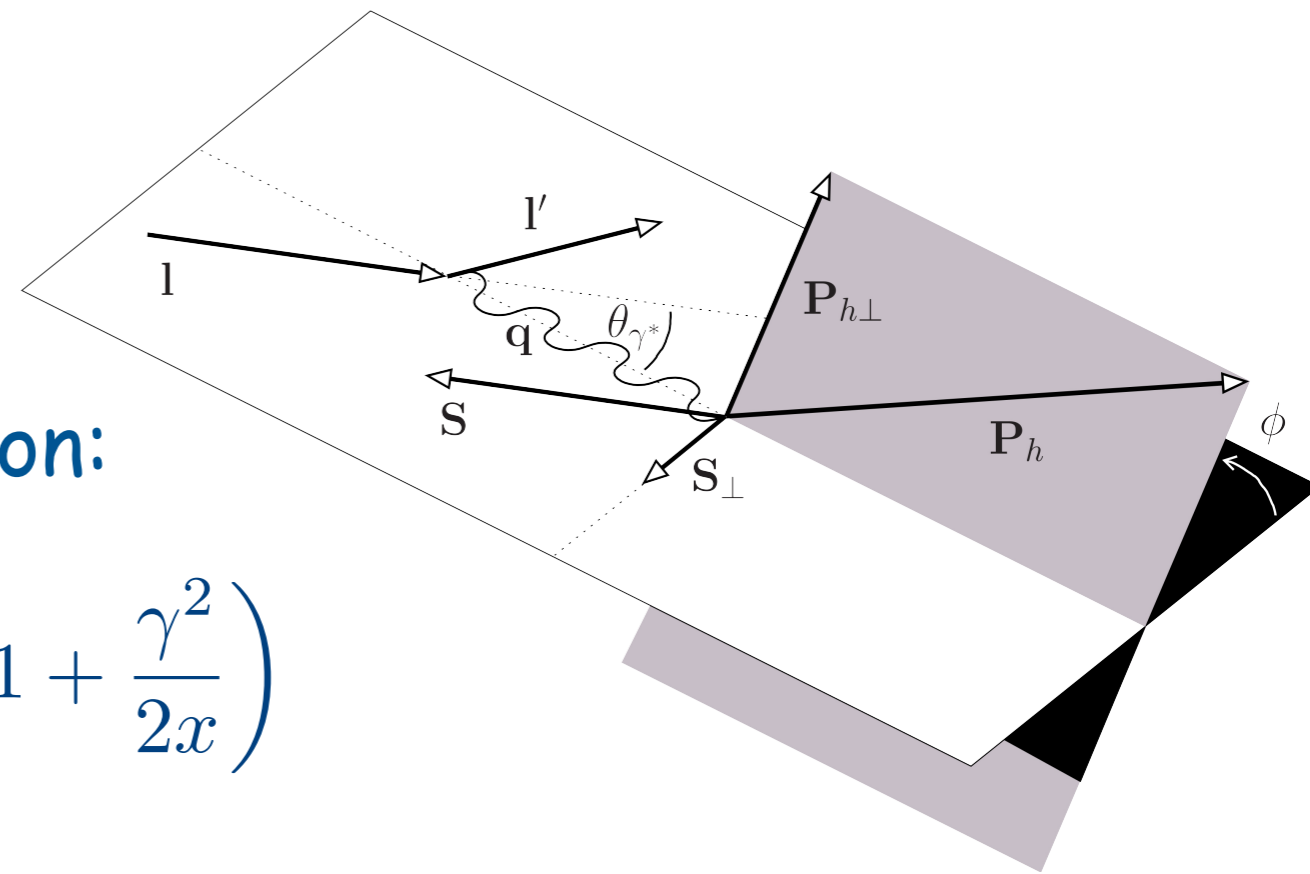
$$\frac{d\sigma^h}{dx dy dz dP_{h\perp}^2 d\phi} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x} \right)$$

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

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

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

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



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

Beam (λ) / Target (Λ)
helicities

semi-inclusive DIS

- excluding transverse polarization:

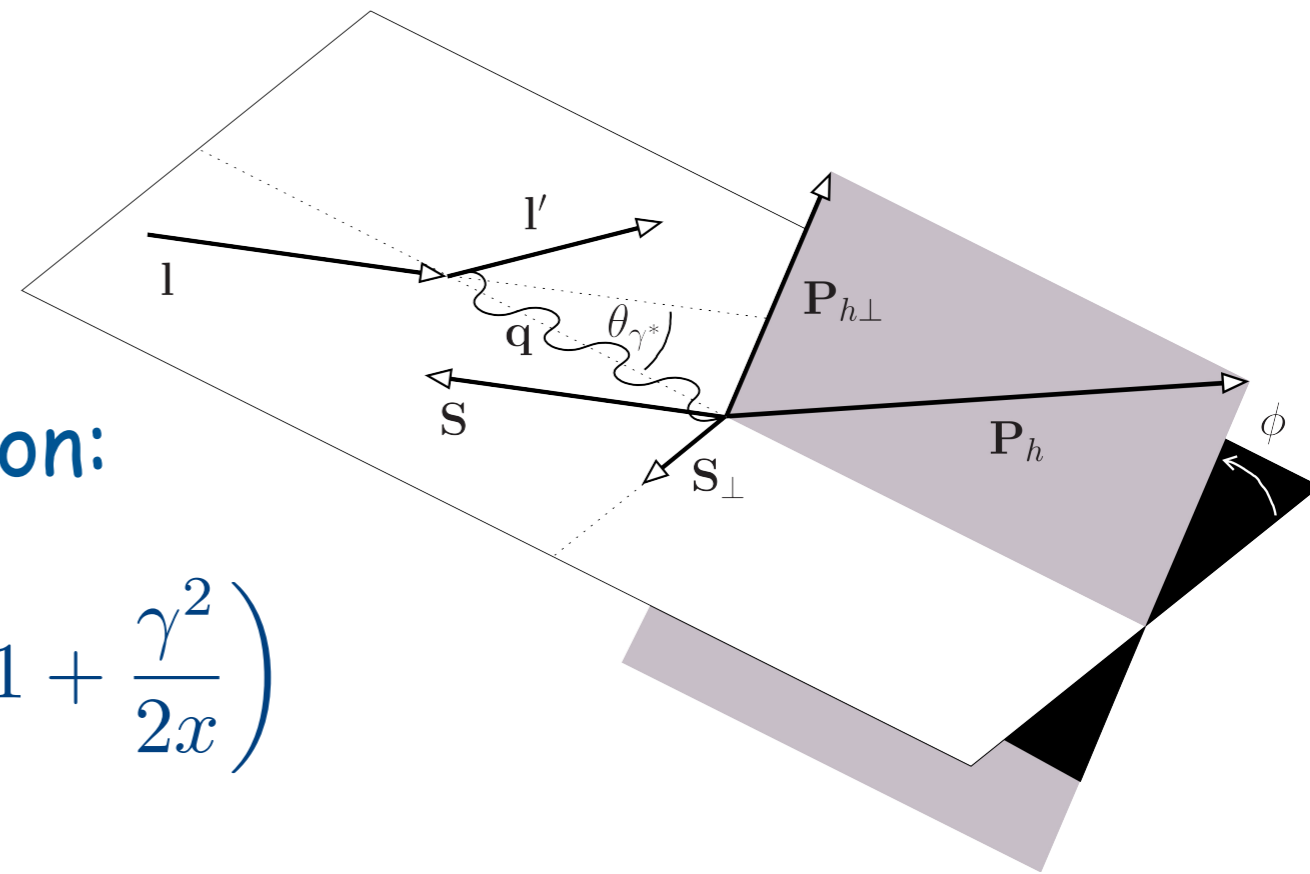
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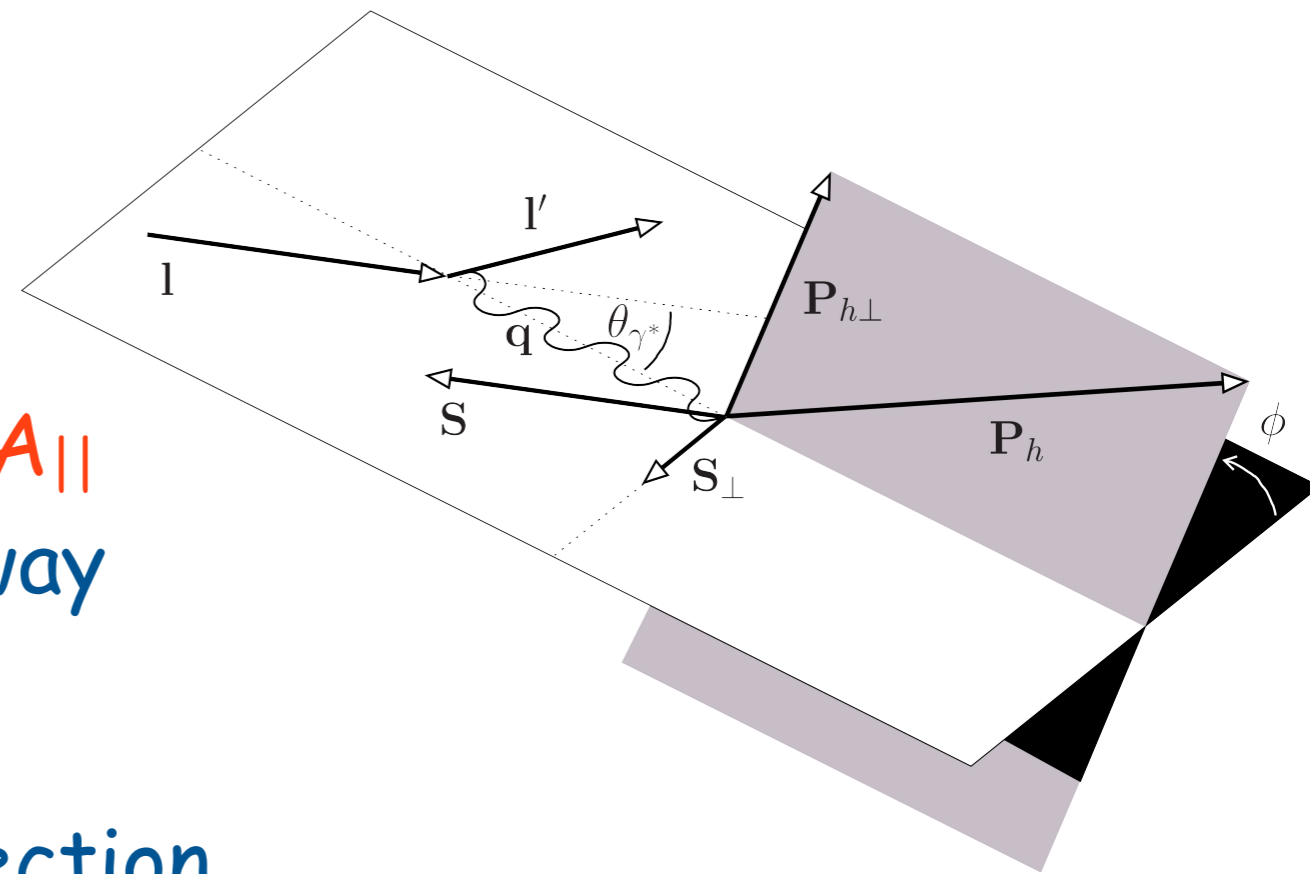
$$\left. + \Lambda\epsilon F_{UL}^{h,\sin 2\phi} \sin 2\phi + \epsilon F_{UU}^{h,\cos 2\phi} \cos 2\phi \right\}$$



- 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



- in experiment extract instead $A_{||}$ which differs from A_{LL} in the way the polarization is measured:
- A_{LL} : along virtual-photon direction
- $A_{||}$: along beam direction (results in small admixture of transverse target polarization and thus contributions from A_{LT})
- $A_{||}$ related to virtual-photon-nucleon asymmetry A_1

$$A_1^h = \frac{1}{D(1 + \eta\gamma)} A_{||}^h$$

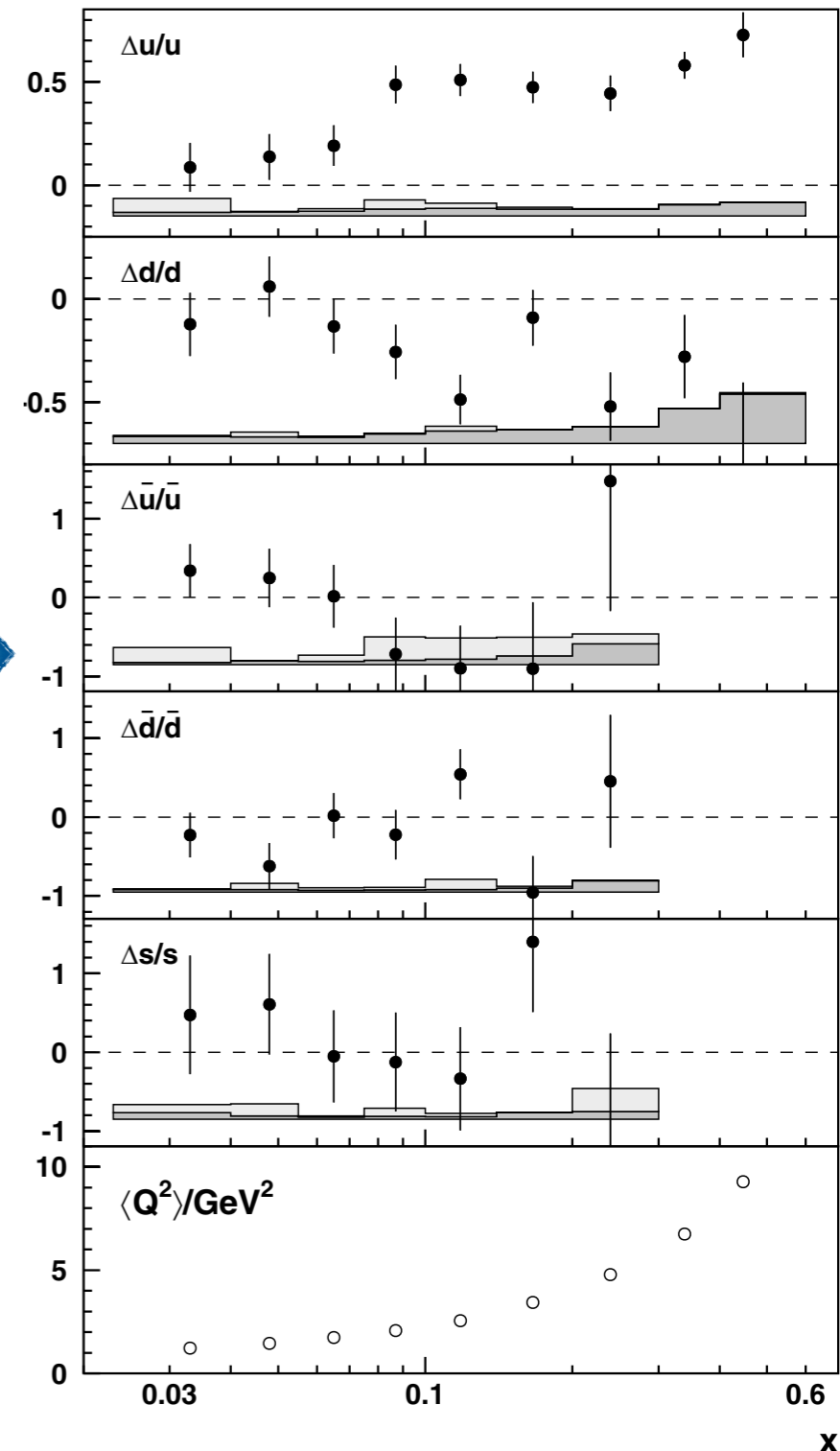
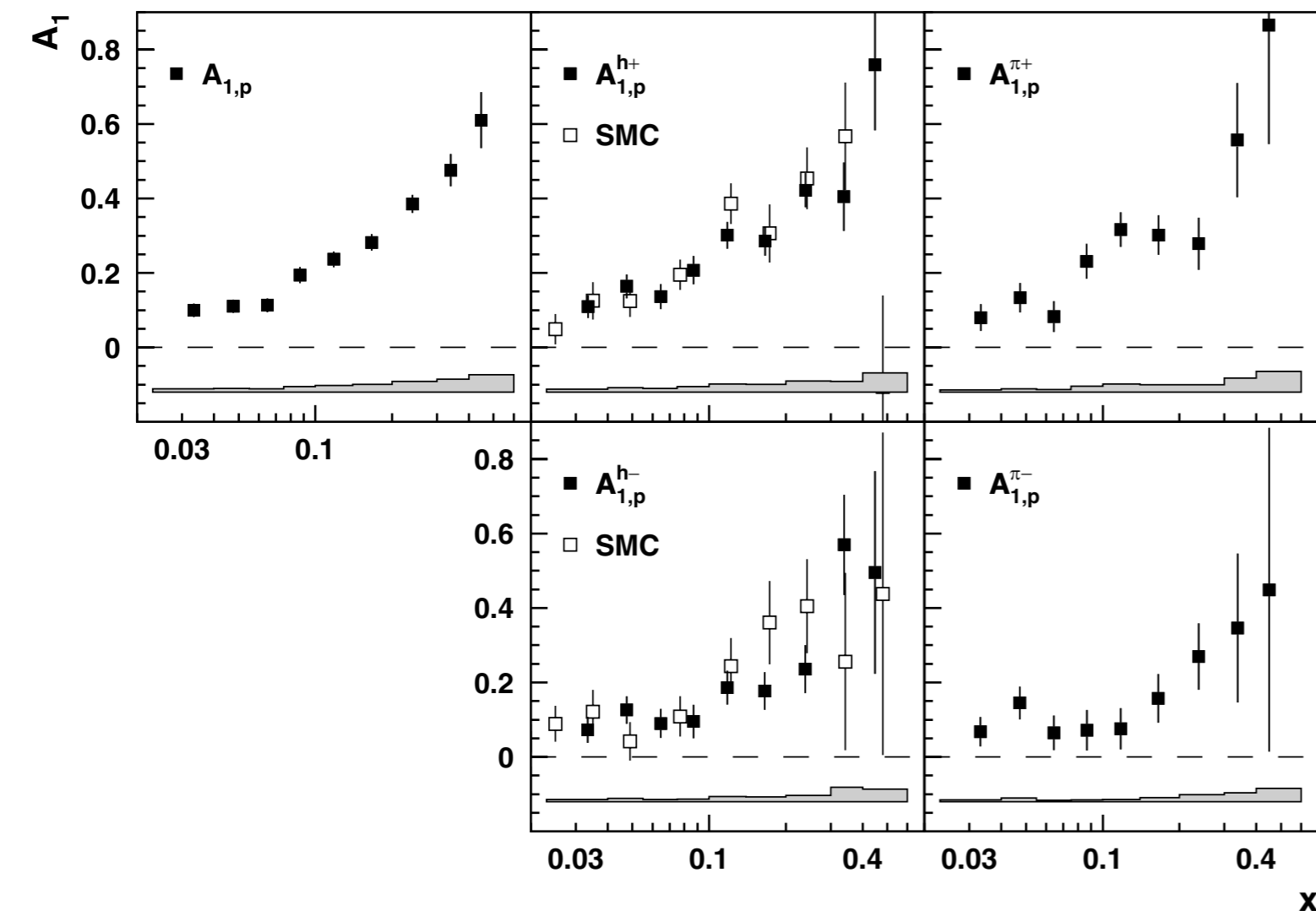
$$D = \frac{1 - (1 - y)\epsilon}{1 + \epsilon R}$$

$$\eta = \frac{\epsilon\gamma y}{1 - (1 - y)\epsilon}$$

previous HERMES analysis

- (semi-) inclusive asymmetries used for LO extraction of helicity PDFs

PHYSICAL REVIEW D 71, 012003 (2005)



x

re-analysis of 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

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

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

azimuthal-asymmetry corrections

measured

"polarized Cahn" effect etc.

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

Boer-Mulders and Cahn effects etc.

azimuthal acceptance

- both numerator and in particular denominator ϕ dependent
- in theory integrated out
- in praxis, detector acceptance also ϕ dependent
- convolution of physics & acceptance leads to bias in normalization of asymmetries

azimuthal-asymmetry corrections

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azimuthal acceptance

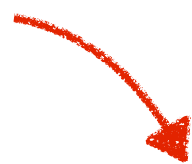
- both numerator and in particular denominator ϕ dependent
 - in theory integrated out
 - in praxis, detector acceptance also ϕ dependent
 - convolution of physics & acceptance leads to bias in normalization of asymmetries
- implement data-driven model for azimuthal modulations [PRD 87 (2013) 012010] into MC → extract correction factor & apply to data

double-spin asymmetry $A_{||}$

$$A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

double-spin asymmetry $A_{||}$

azimuthal
correction


$$A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

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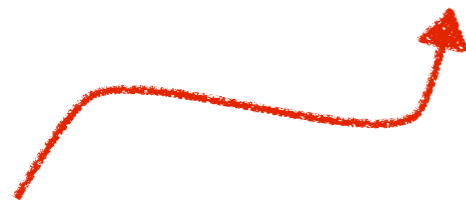
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nucleon-in-nucleus
depolarization factor
(0.926 for deuteron due
to D-state admixture)

double-spin asymmetry $A_{||}$

azimuthal
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$$A_{||}^h \equiv \frac{C_{\phi}^h}{f_D}$$



nucleon-in-nucleus
depolarization factor
(0.926 for deuteron due
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luminosities

$$\left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

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polarization-weighted
luminosities

double-spin asymmetry $A_{||}$

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$$\left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

nucleon-in-nucleus
depolarization factor
(0.926 for deuteron due
to D-state admixture)

polarization-weighted
luminosities

unfolded for
QED radiation
to Born level

double-spin asymmetry $A_{||}$

$$A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

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- dominated by statistical uncertainties

double-spin asymmetry $A_{||}$

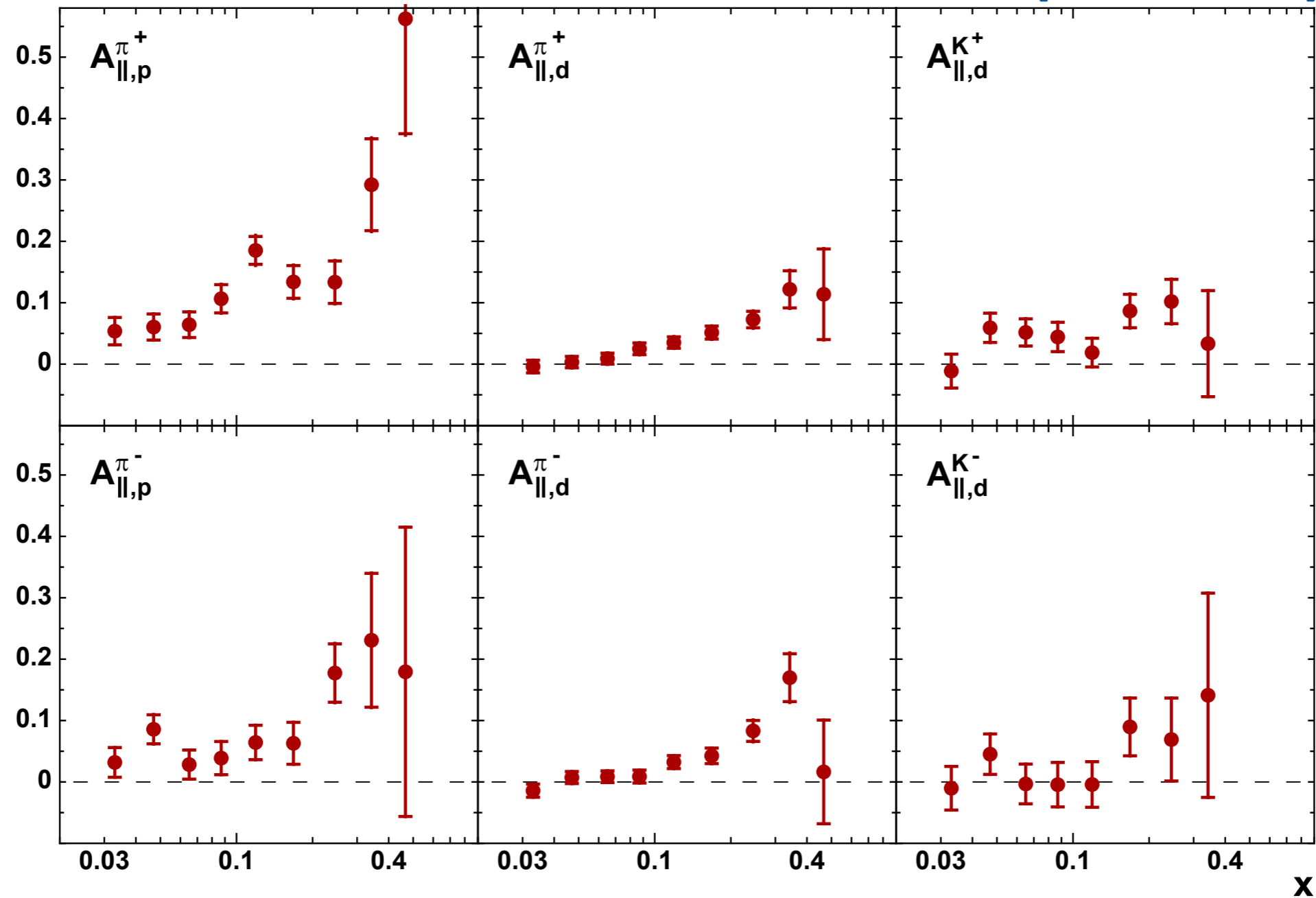
$$A_{||}^h \equiv \frac{C_{\phi}^h}{f_D} \left[\frac{L_{\Rightarrow} N_{\Leftarrow}^h - L_{\Leftarrow} N_{\Rightarrow}^h}{L_{P,\Rightarrow} N_{\Leftarrow}^h + L_{P,\Leftarrow} N_{\Rightarrow}^h} \right]_B$$

- dominated by statistical uncertainties
- main systematics arise from
 - polarization measurements [6.6% for hydrogen, 5.7% for deuterium]
 - azimuthal correction [O(few %)]

x dependence of $A_{||}$

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

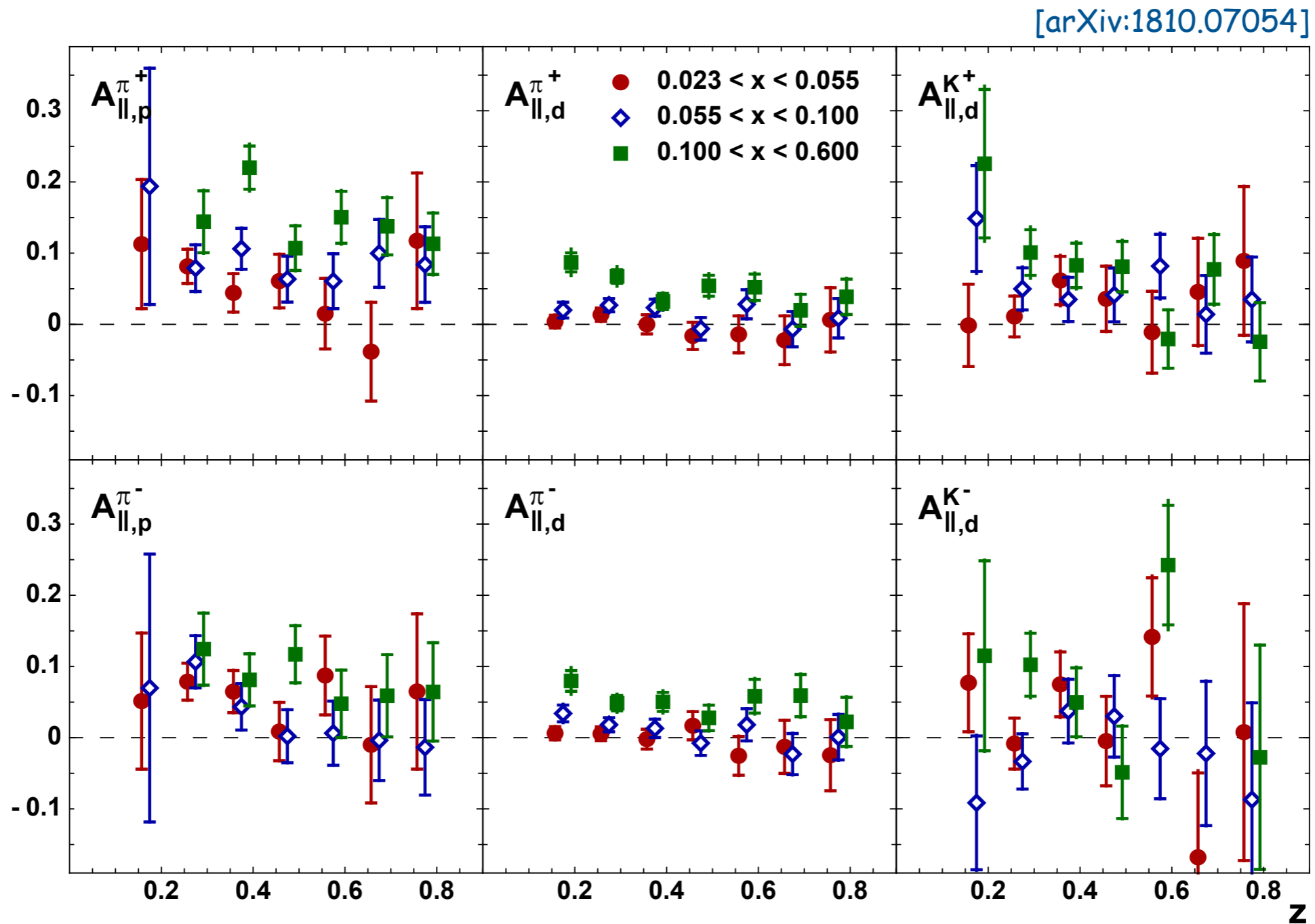
[arXiv:1810.07054]



x

z dependence of $A_{||}$ (three x ranges)

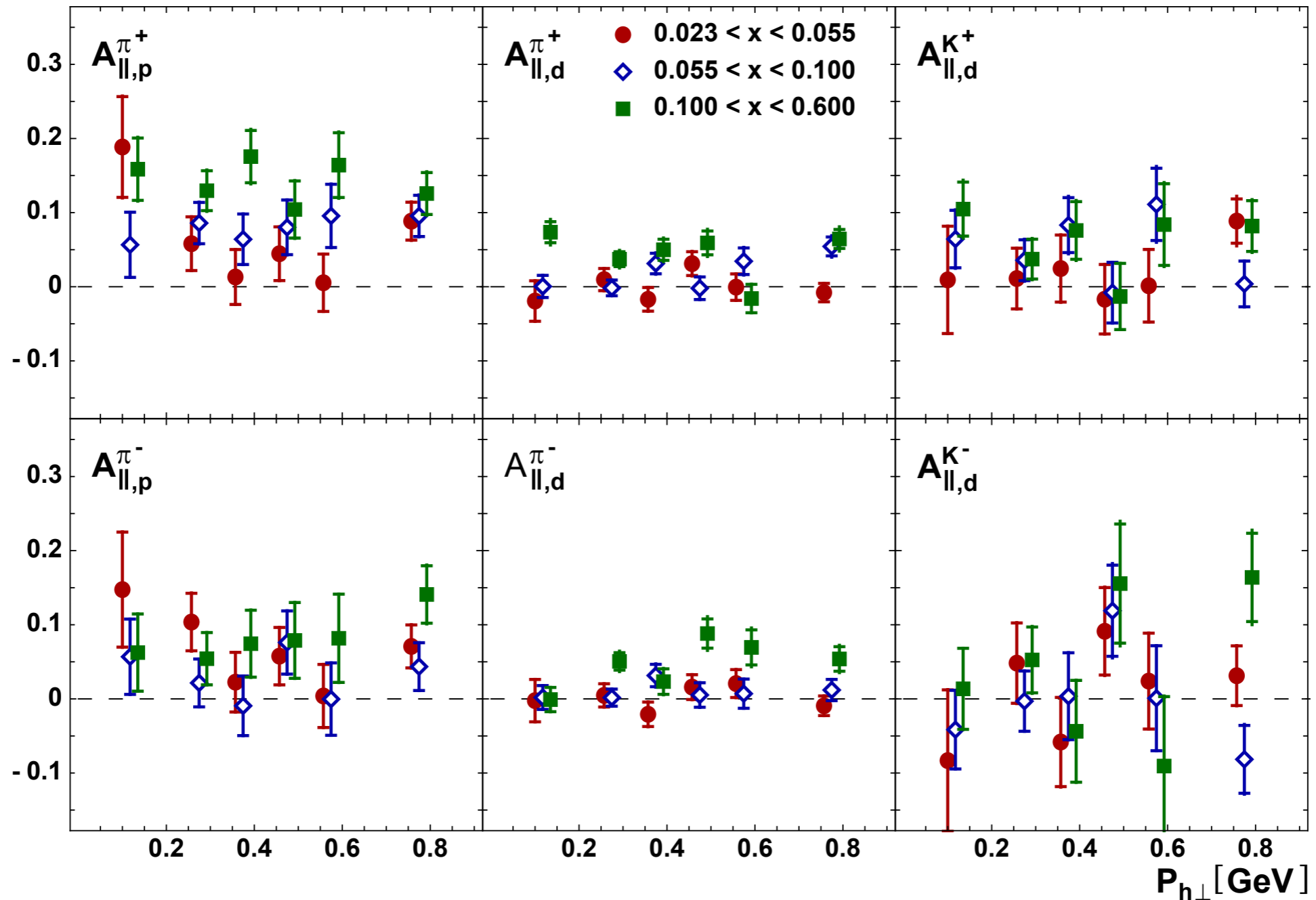
- in general, no strong z-dependence visible



$P_{h\perp}$ dependence of $A_{||}$ (three x ranges)

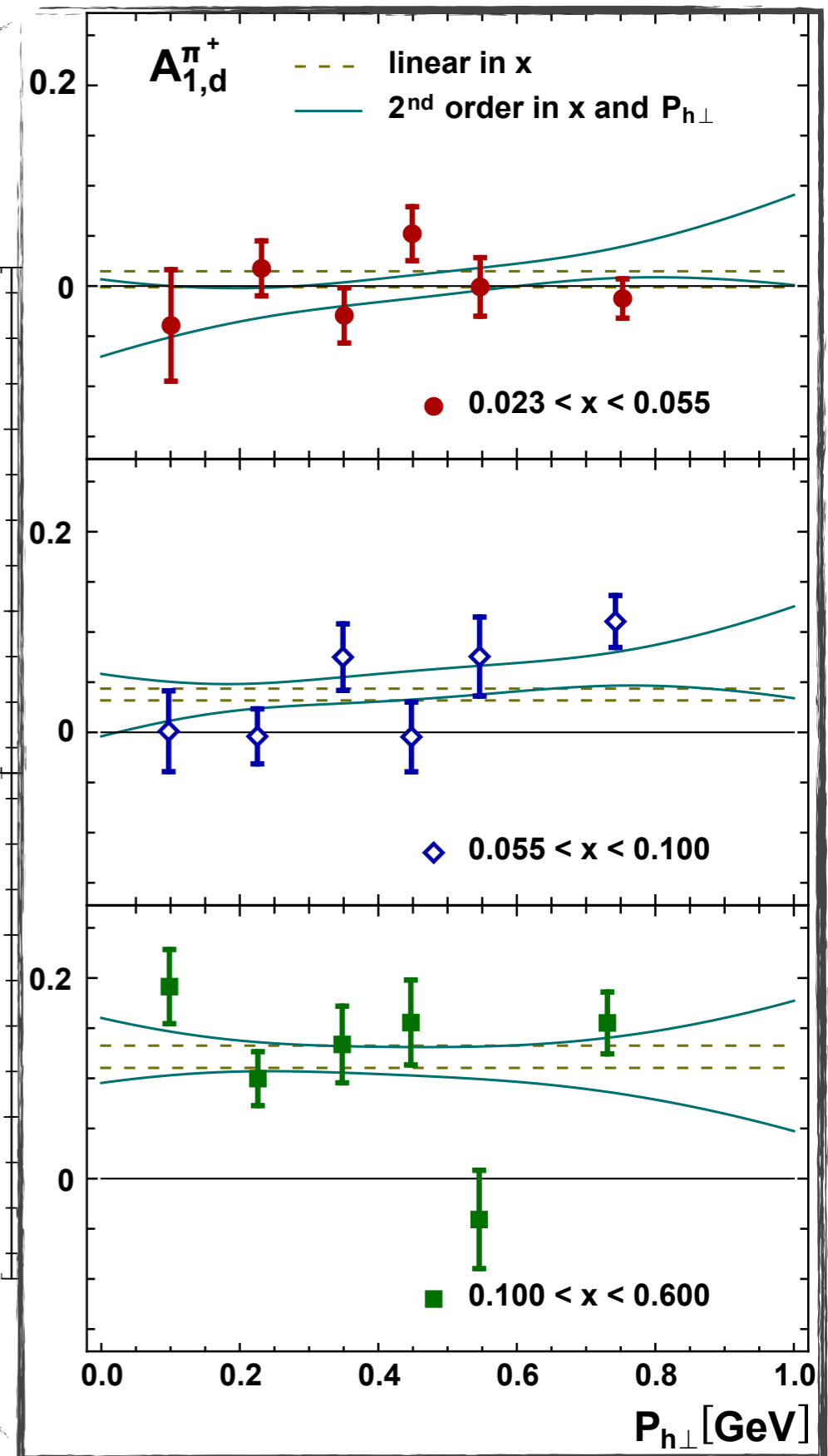
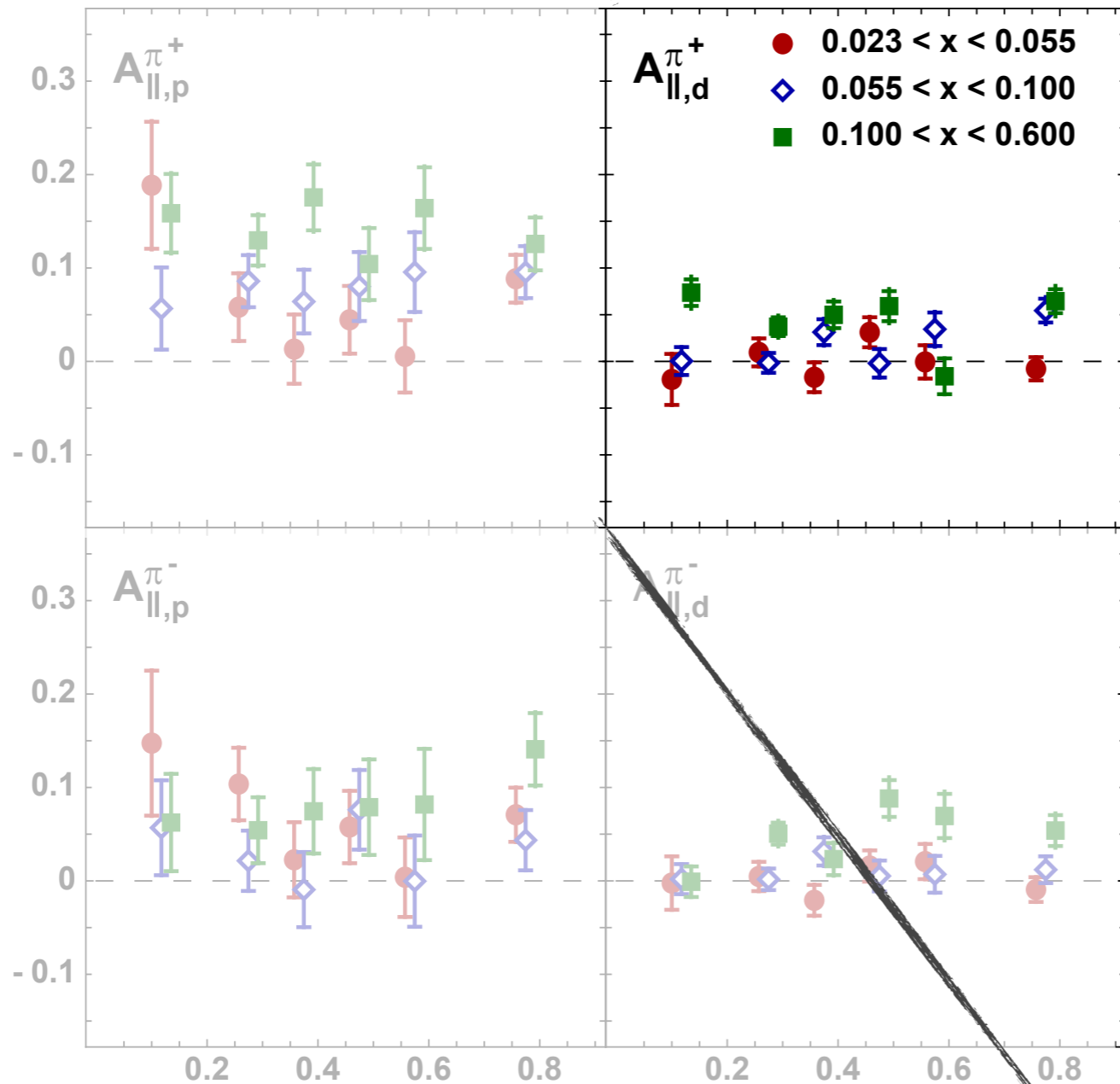
- again, no strong dependence (beyond on x)

[arXiv:1810.07054]



$P_{h\perp}$ dependence of $A_{||}$ (three x ranges)

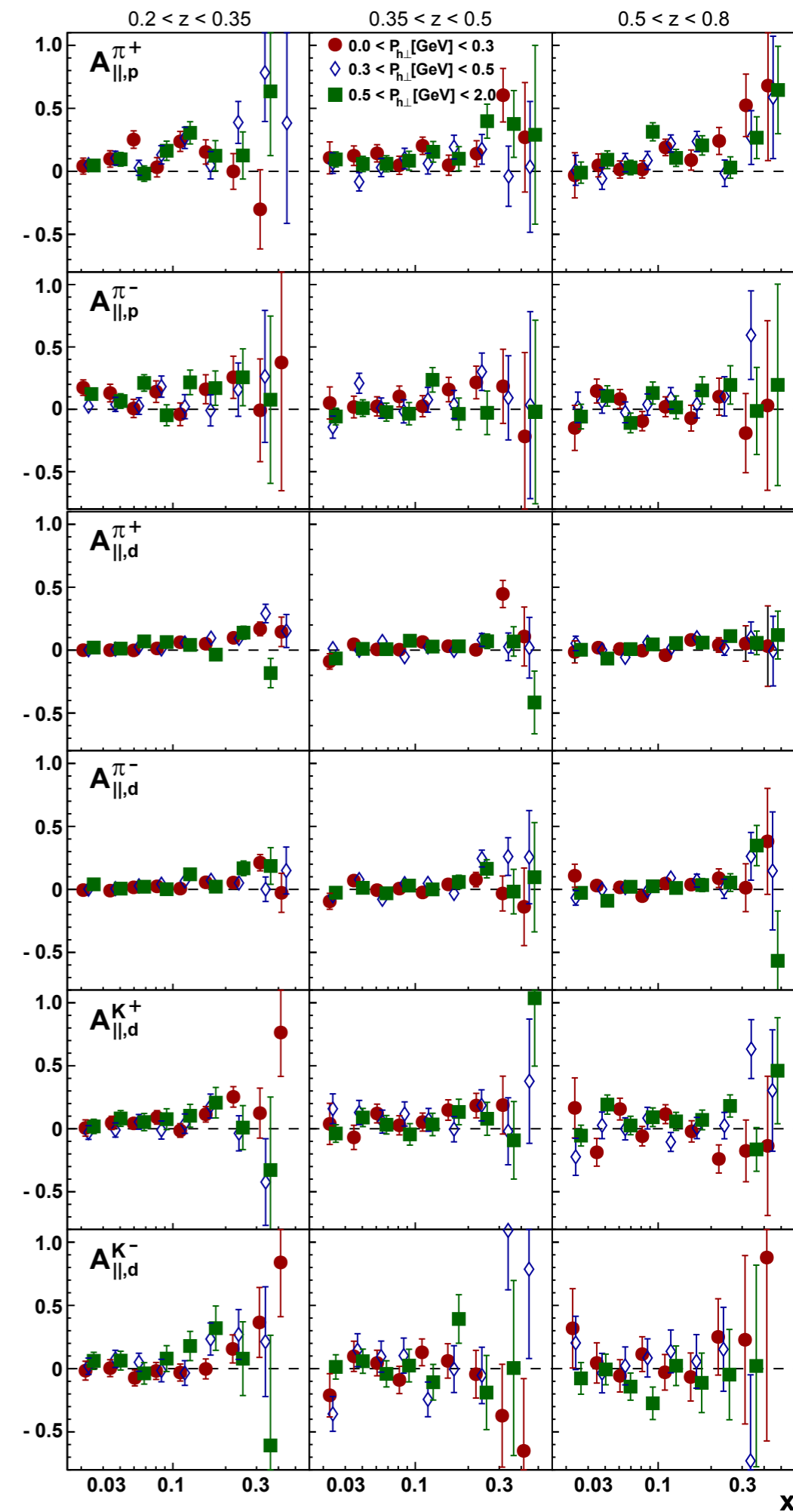
- again, no strong dependence (beyond on x)



- also fit to A_1 fit does not favor an additional dependence on $P_{h\perp}$

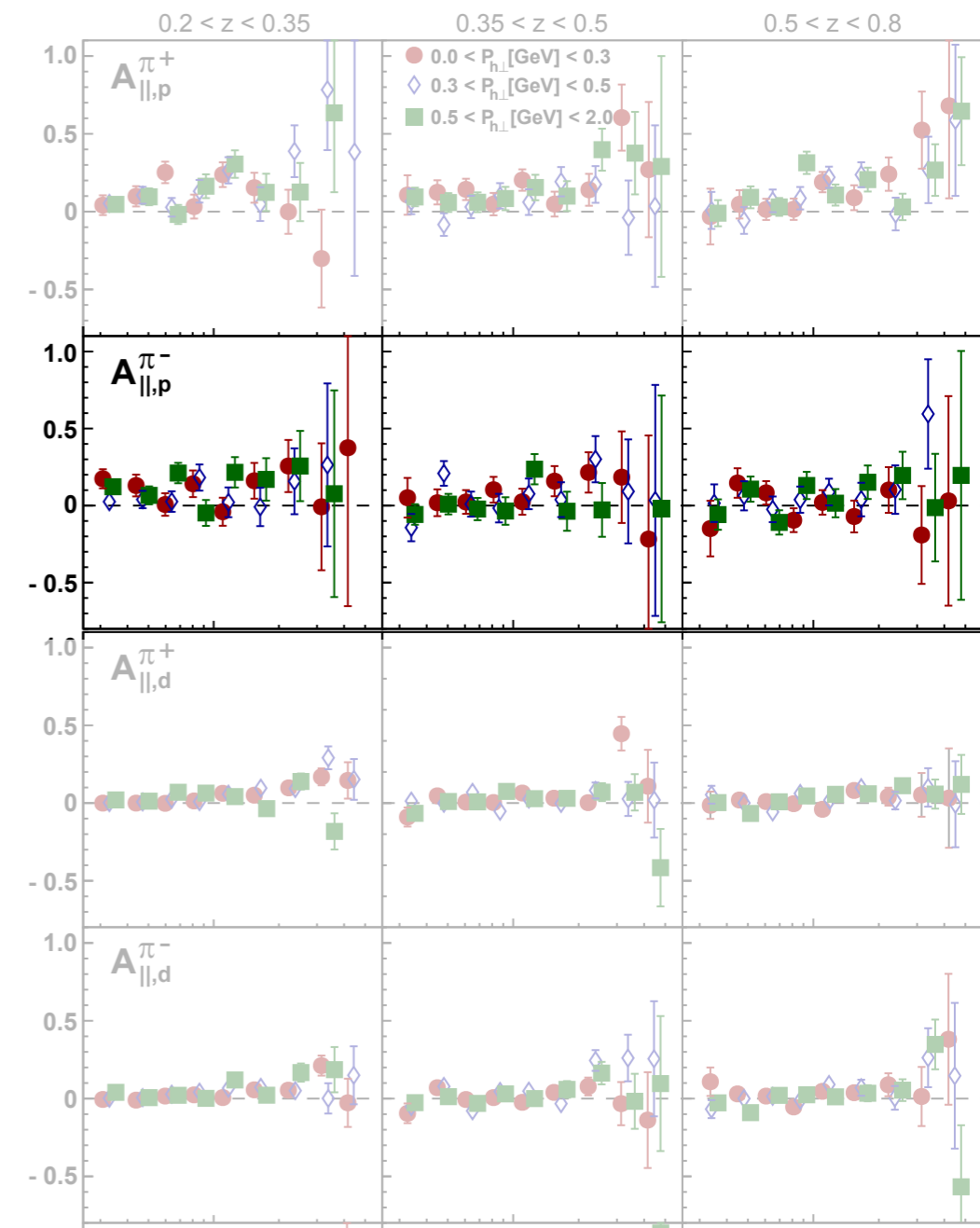
3-dimensional binning

- 3d dependences provides transverse-momentum dependence

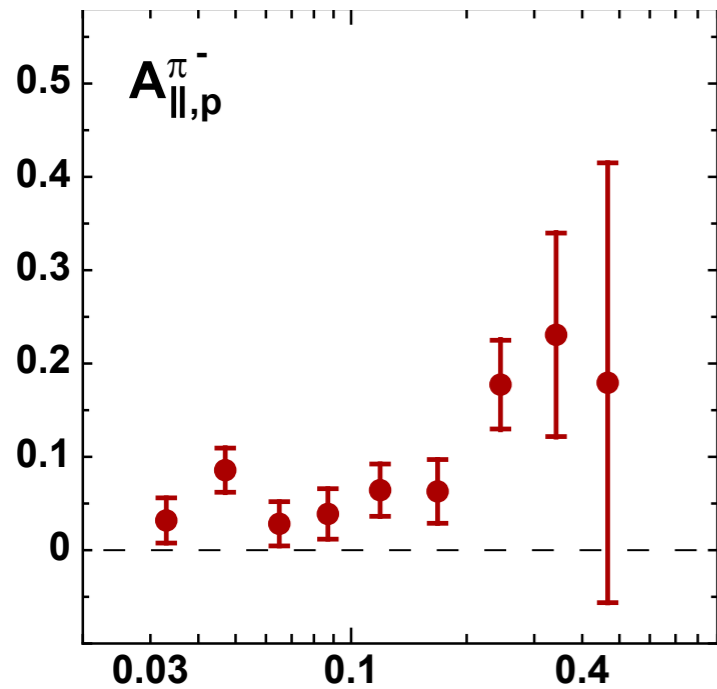


3-dimensional binning

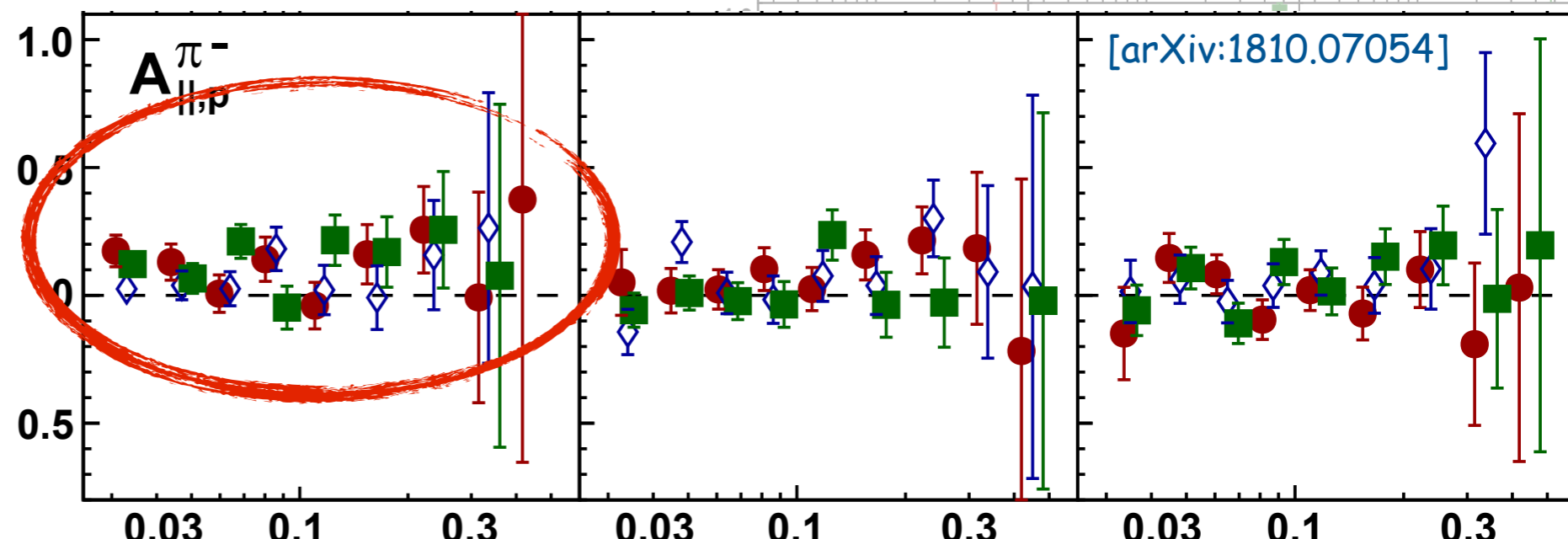
- 3d dependences provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
 - π^- asymmetries mainly coming from **low- z** region where **disfavored fragmentation** large and thus **sensitivity to the large positive up-quark polarization**



1d



3d



charge-difference asymmetries

$$A_1^{h^+ - h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$

charge-difference asymmetries

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- at leading-order and leading-twist, assuming charge conjugation symmetry for fragmentation functions:

$$A_{1,d}^{h^+ - h^-} \stackrel{\text{LO LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}$$

charge-difference asymmetries

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- assuming also isospin symmetry in fragmentation:

$$A_{1,p}^{h^+ - h^-} \stackrel{\text{LO}_{\text{LT}}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

charge-difference asymmetries

$$A_1^{h^+ - h^-}(x) \equiv \frac{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) - \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}{\left(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}\right) + \left(\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-}\right)}$$

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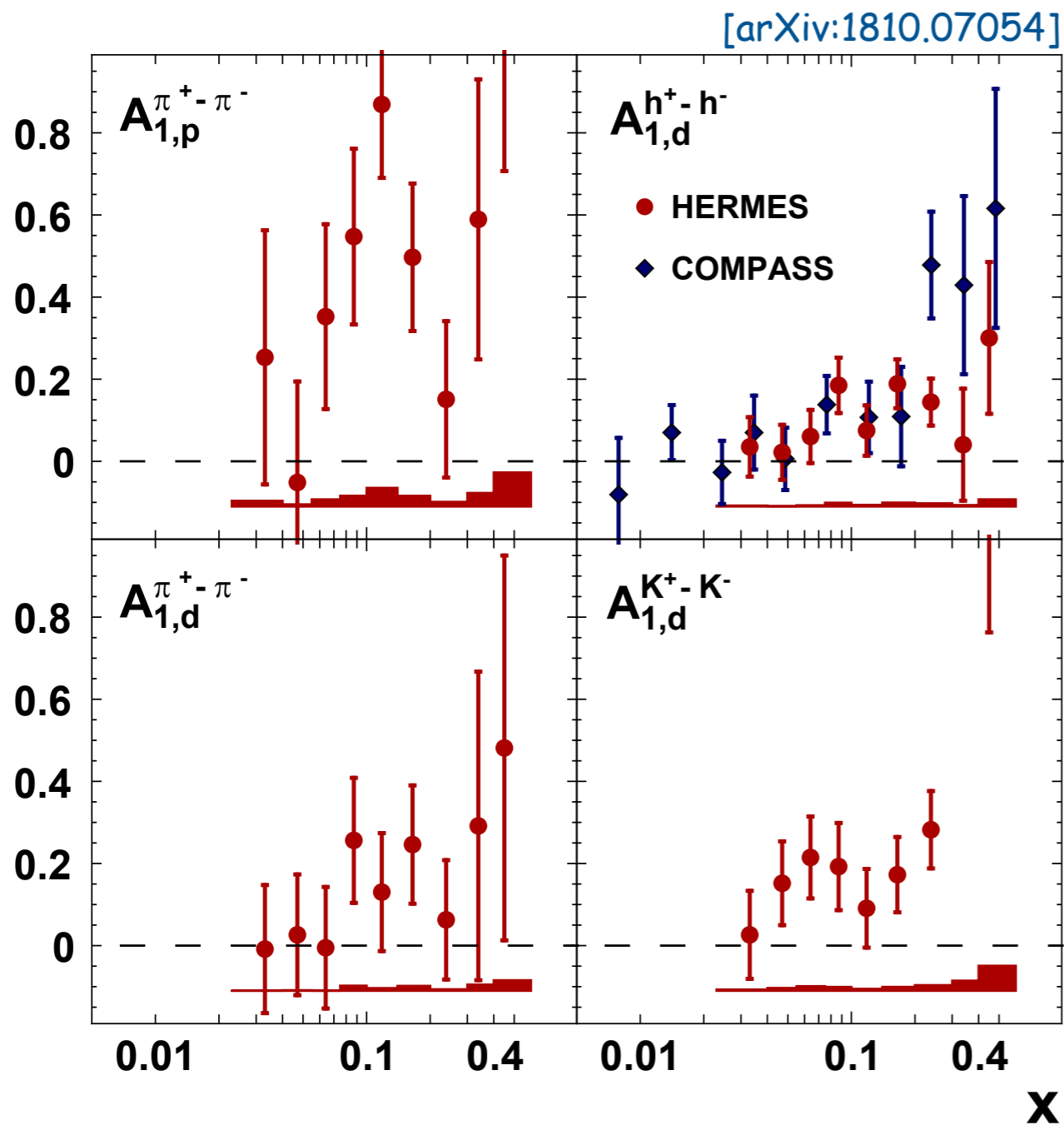
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- can be used to extract valence helicity distributions

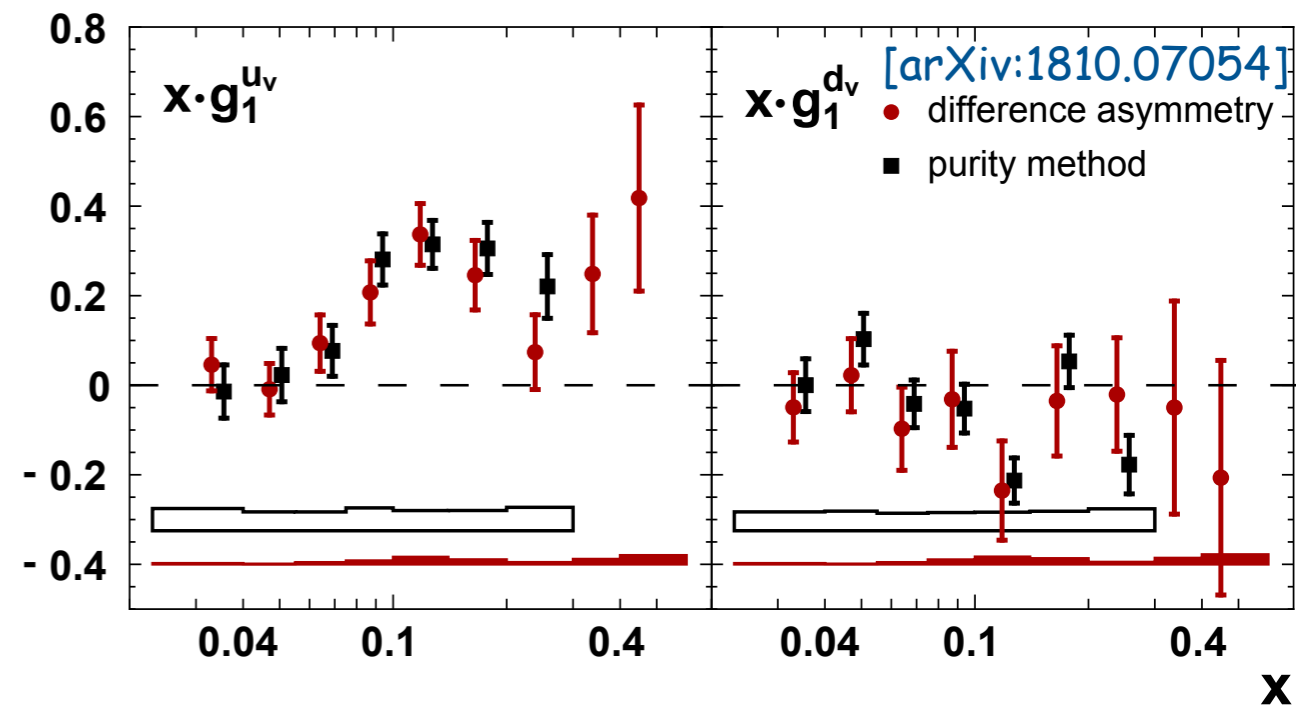
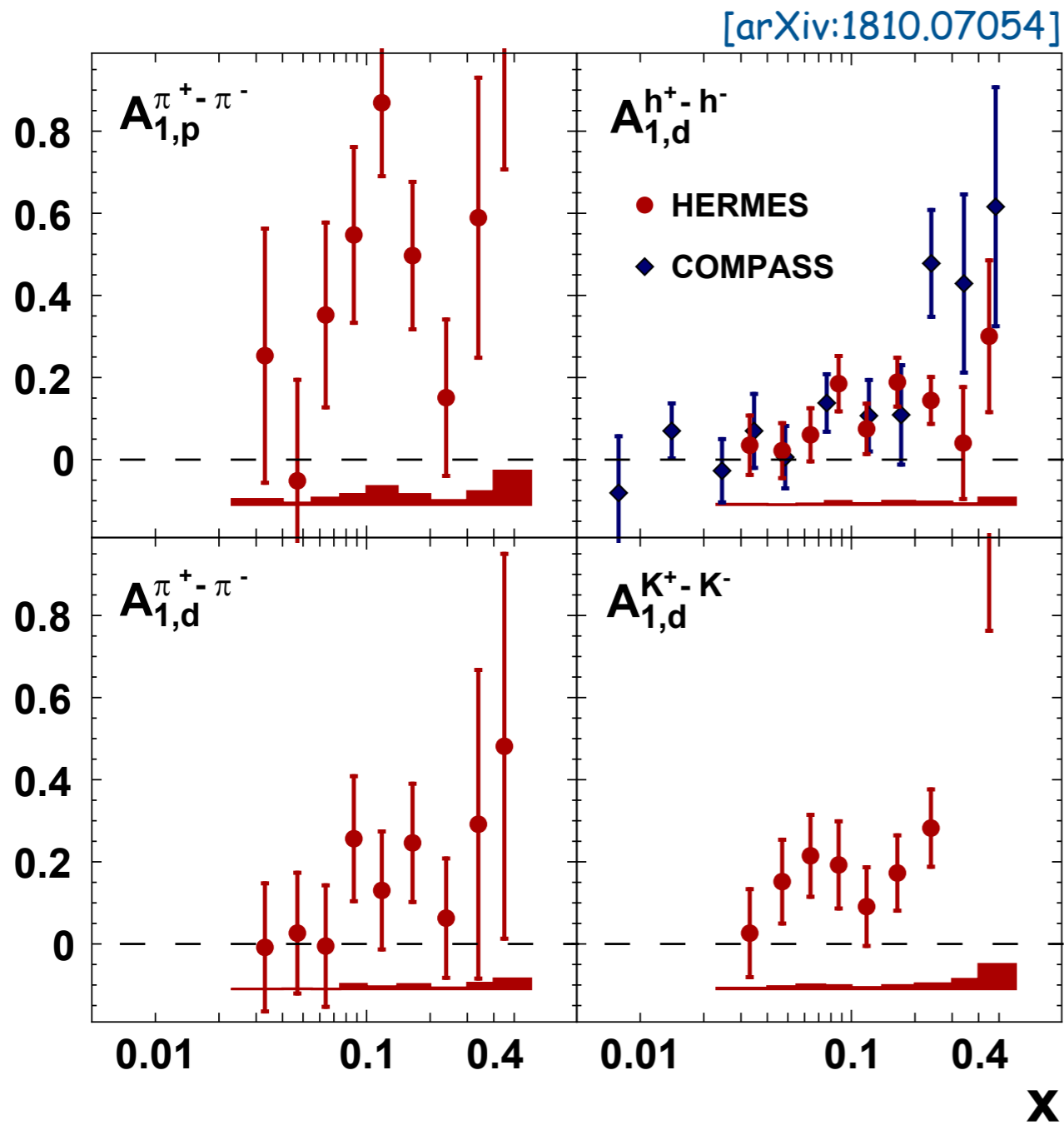
charge-difference asymmetries

- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with *COMPASS*



charge-difference asymmetries

- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with *COMPASS*
- valence distributions consistent with *JETSET*-based extraction:



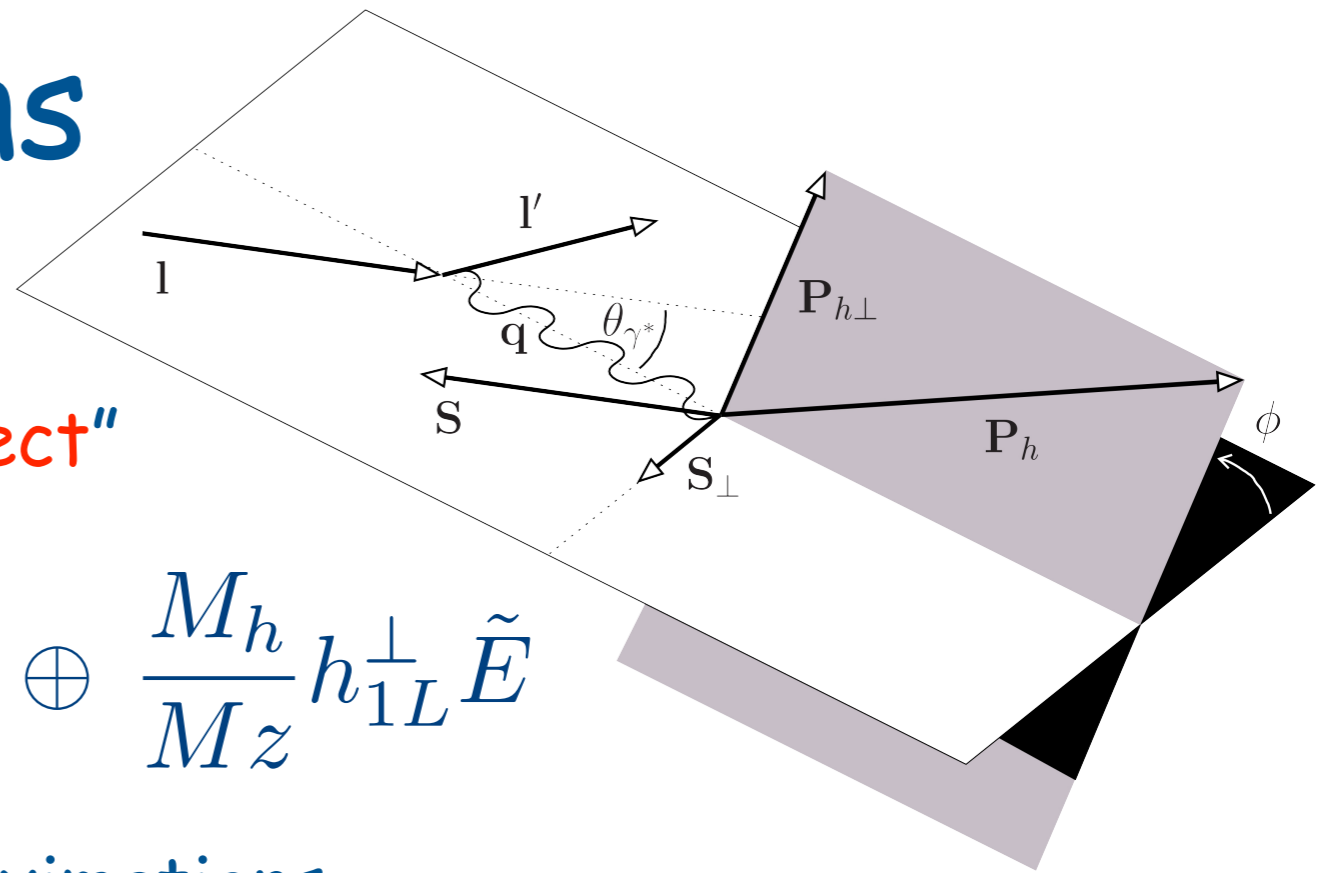
azimuthal modulations

- twist-3 → various contributions
- most prominent: "polarized Cahn effect"

$$xg_L^\perp D_1 \oplus \frac{M_h}{M_z} g_1 \tilde{D}^\perp \oplus xe_L H_1^\perp \oplus \frac{M_h}{M_z} h_{1L}^\perp \tilde{E}$$

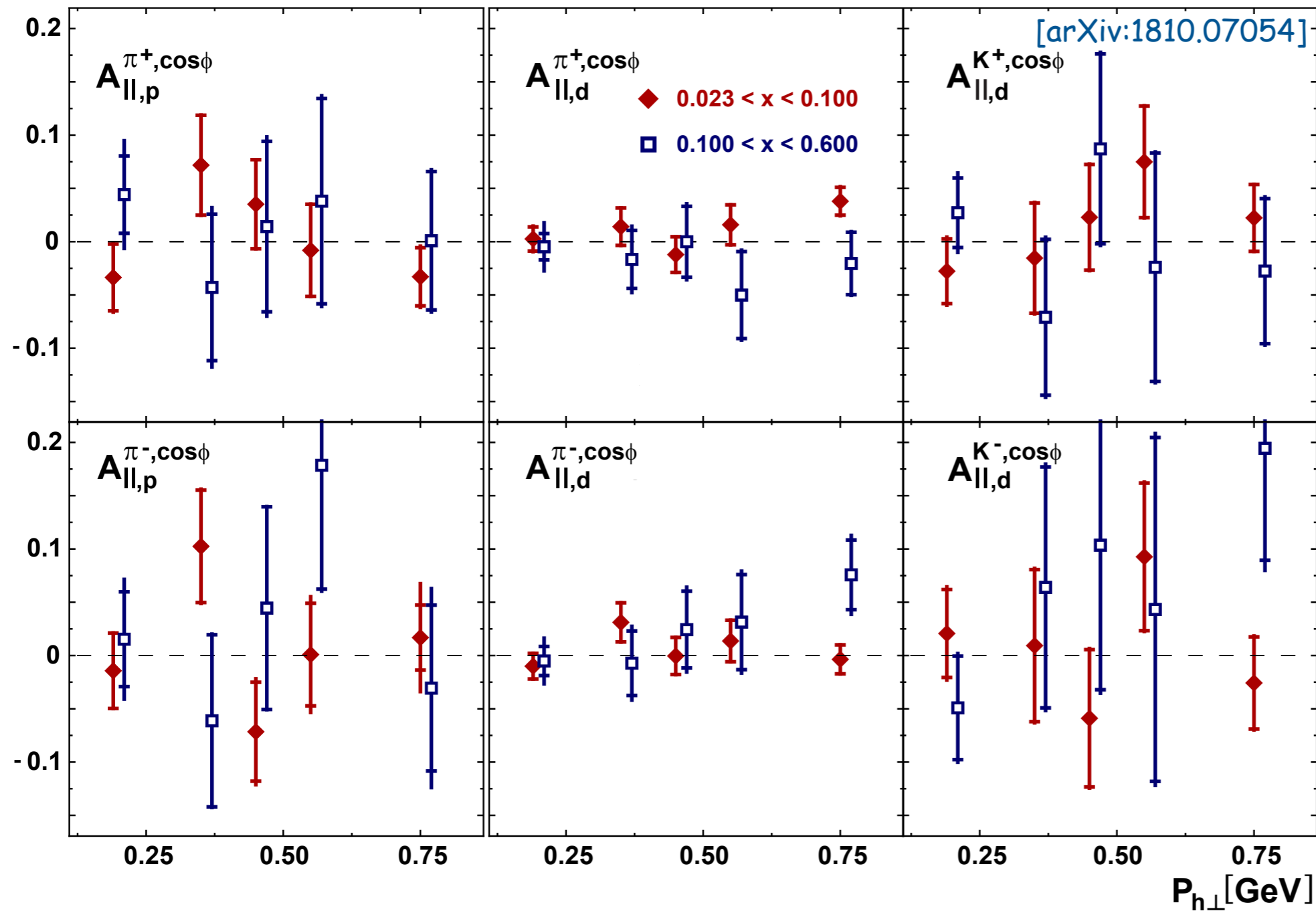
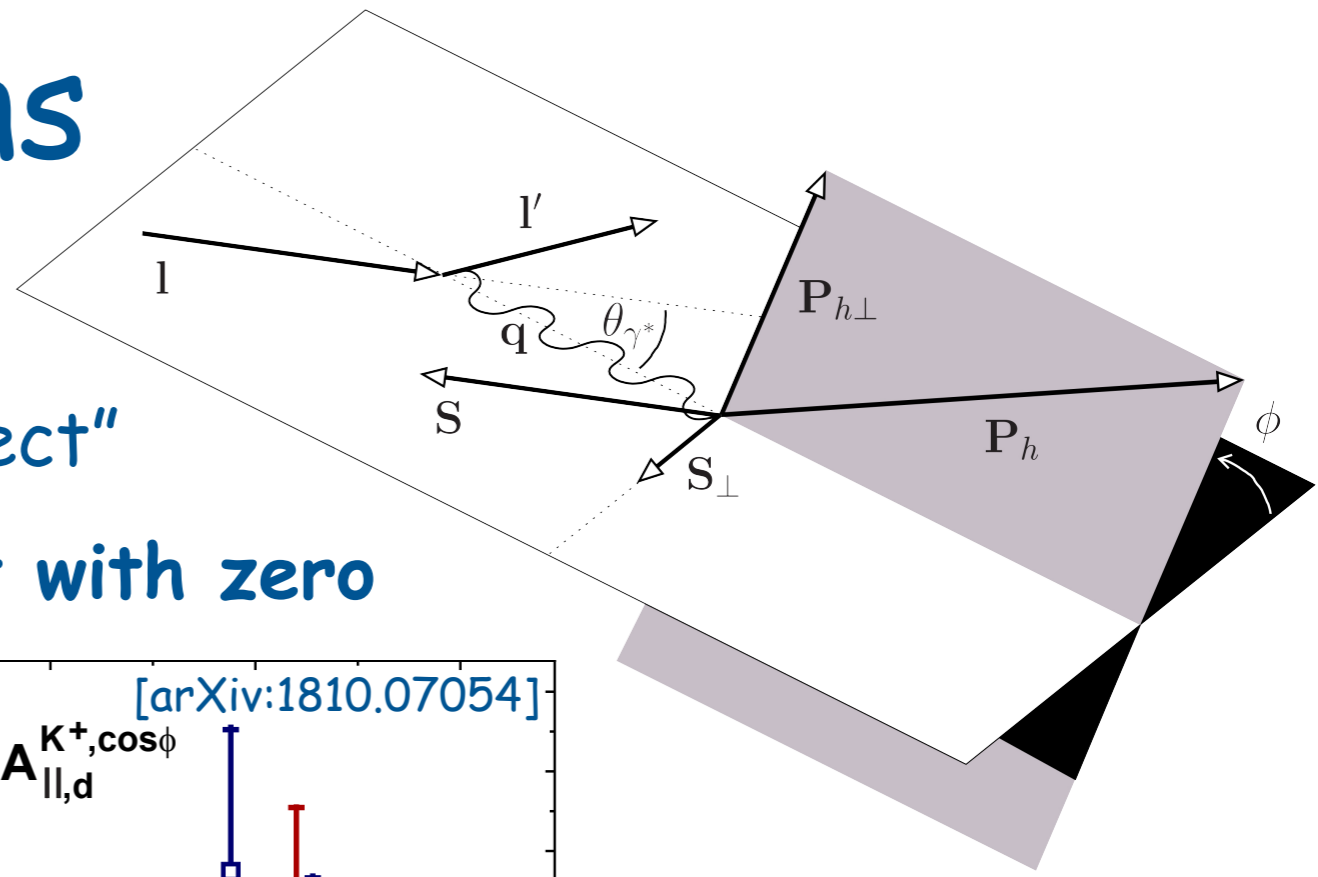
- only one surviving WW-type approximations

→ K. Tezgin (We, WG-6)



azimuthal modulations

- twist-3 \rightarrow various contributions
- most prominent: "polarized Cahn effect"
- cosine modulations largely consistent with zero



summary

- several longitudinal double-spin asymmetries in SIDIS have been presented that
 - extend the analysis of previous HERMES publications to include also transverse-momentum dependence and for the first time also a 3d binning
 - provide $A_{||}$ in addition to A_1
- within precision of the measurements, the virtual-photon-nucleon asymmetries display no significant dependence on z and $P_{h\perp}$
- hadron-charge difference asymmetries in agreement with COMPASS
 - used for LO, leading-twist extraction of valence helicity PDFs
- $\cos \phi$ moments of semi-inclusive double-spin asymmetry compatible with zero

backup

Year	Beam Type	Target Gas	Hadron Type	Hadron Momentum P_h
1996	e^+	H	π^\pm	4–13.8 GeV
1997	e^+	H	π^\pm	4–13.8 GeV
1998	e^-	D	π^\pm, K^\pm	2–15 GeV
1999	e^+	D	π^\pm, K^\pm	2–15 GeV
2000	e^+	D	π^\pm, K^\pm	2–15 GeV