Correlations in Partonic and Hadronic Interactions (CPHI-2020)
CERN, February 3-7, 2020

Recent HERMES results on polarized semi-inclusive deep-inelastic scattering

ikerbasque
Basque Foundation for Science

Gunar.Schnell @ DESY.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Correlations in Partonic and Hadronic Interactions (CPHI-2020)
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Longitudinal double-spin asymmetries in semi-inclusive DIS of electrons and positrons by protons and deuterons [PRD 99 (2019) 112001]

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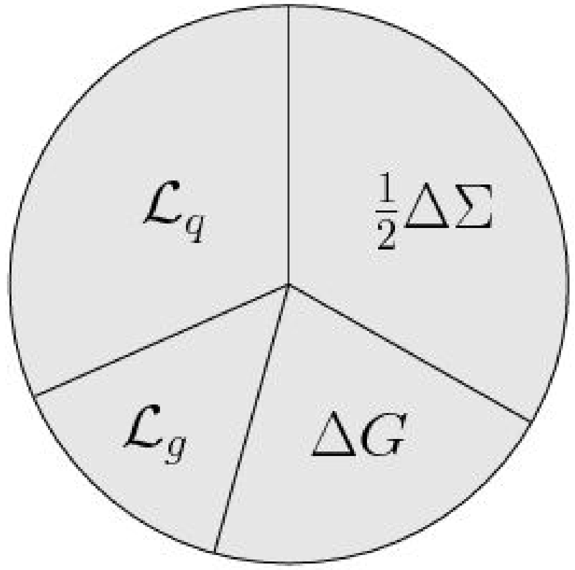
Access to angular momentum in (SI)DIS



'pizza quattro stagioni'

[M. Burkardt]

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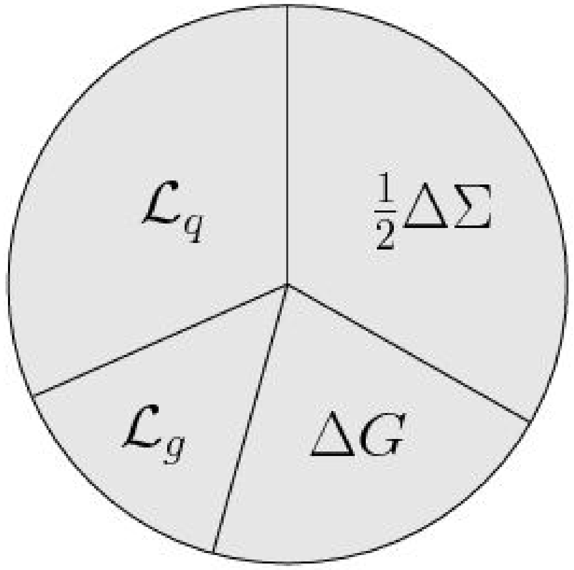

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[M. Burkardt]

evolution, high-p_T hadrons
[better: polarized pp]

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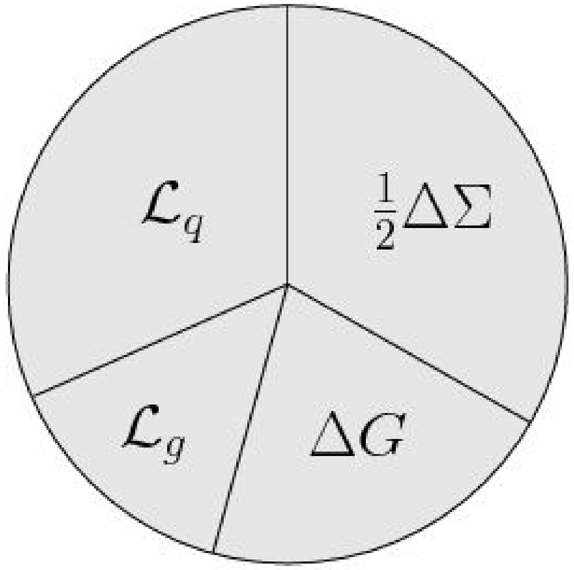


'pizza quattro stagioni'

[M. Burkardt]

(semi-)inclusive longitudinal double-spin asymmetries

evolution, high-p_T hadrons [better: polarized pp]

… other paths to the proton structure

Z. Phys. C 69, 467–474 (1996)

ZEITSCHRIFT FÜR PHYSIK C

The proton spin puzzle and Λ polarization in deep-inelastic scattering

John Ellis[1,★], Dmitri Kharzeev[1,2,★★], Aram Kotzinian[3,4,★★★]

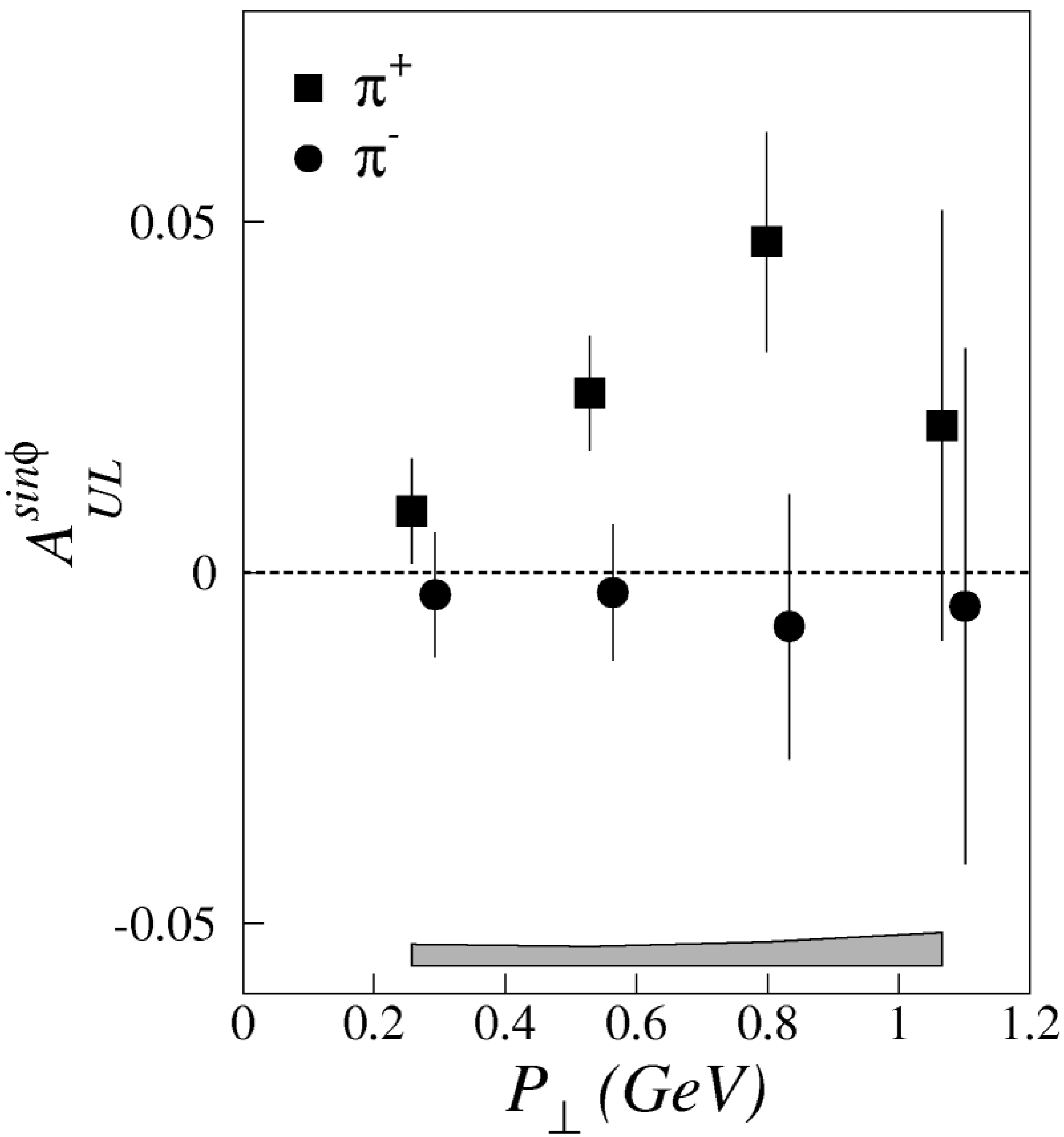
PHYSICAL REVIEW D VOLUME 54, NUMBER 1 1 JULY 1996

Longitudinal quark polarization in transversely polarized nucleons

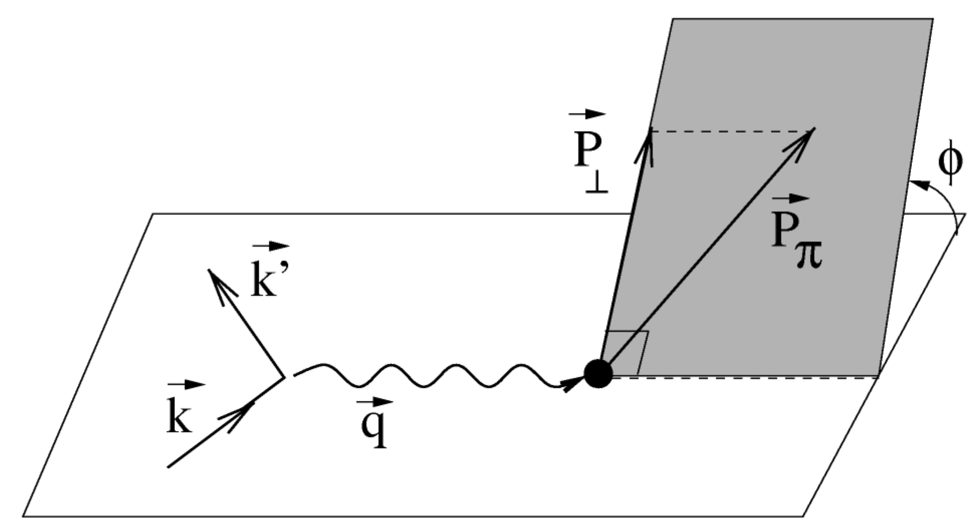
A. M. Kotzinian[*]
Yerevan Physics Institute, Alikhanian Brothers St. 2, AM-375036, Yerevan, Armenia

P. J. Mulders[†]
Department of Physics and Astronomy, Free University of Amsterdam and National Institute for Nuclear Physics and High-Energy Physics, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands

Evidence for a Single-Spin Azimuthal Asymmetry in Semi-inclusive Pion Electroproduction



$$A_{UL} = \frac{1}{|P_B|} \frac{N^{\rightarrow}(\phi) - N^{\leftarrow}(\phi)}{N^{\rightarrow}(\phi) + N^{\leftarrow}(\phi)}$$



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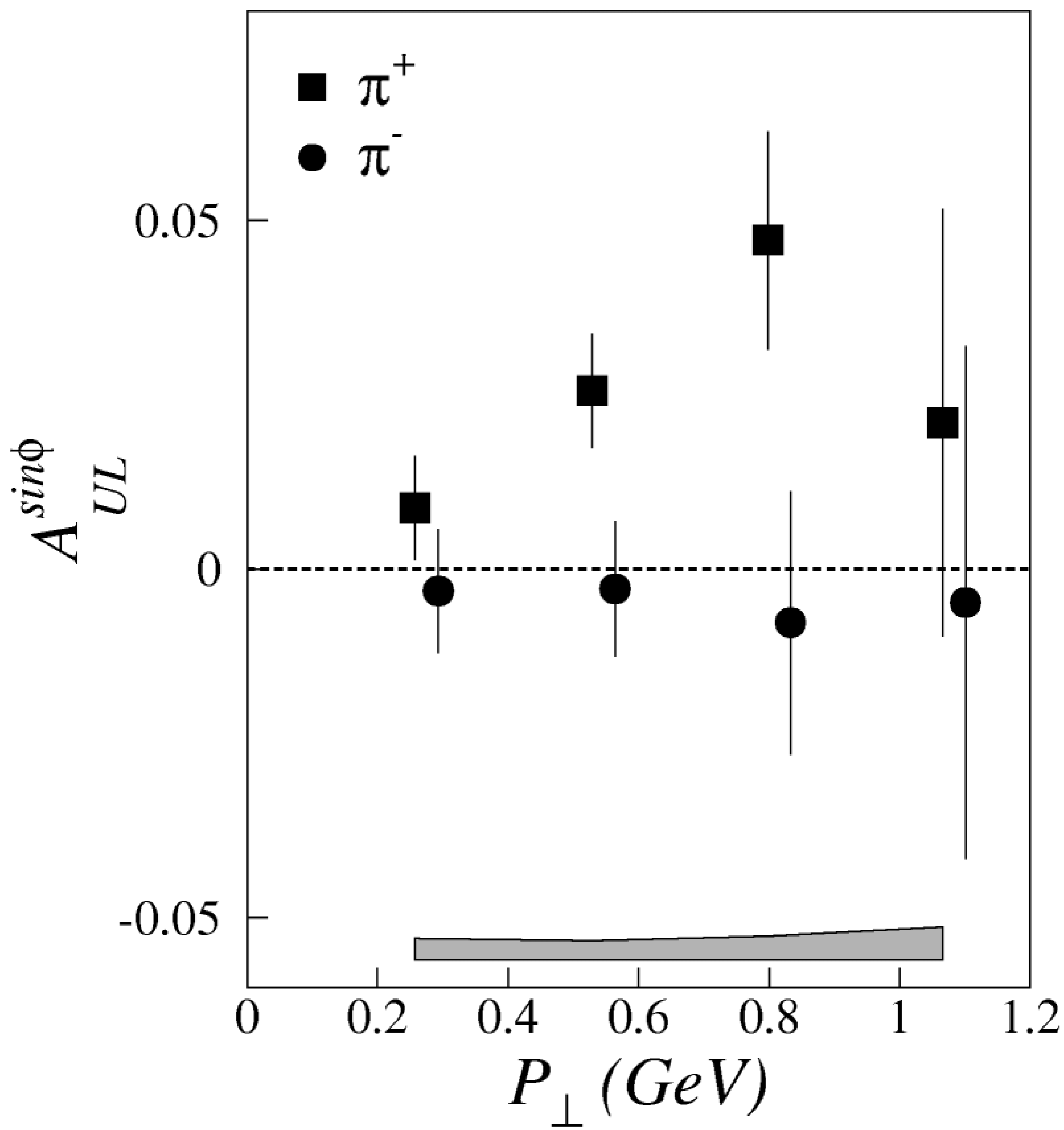

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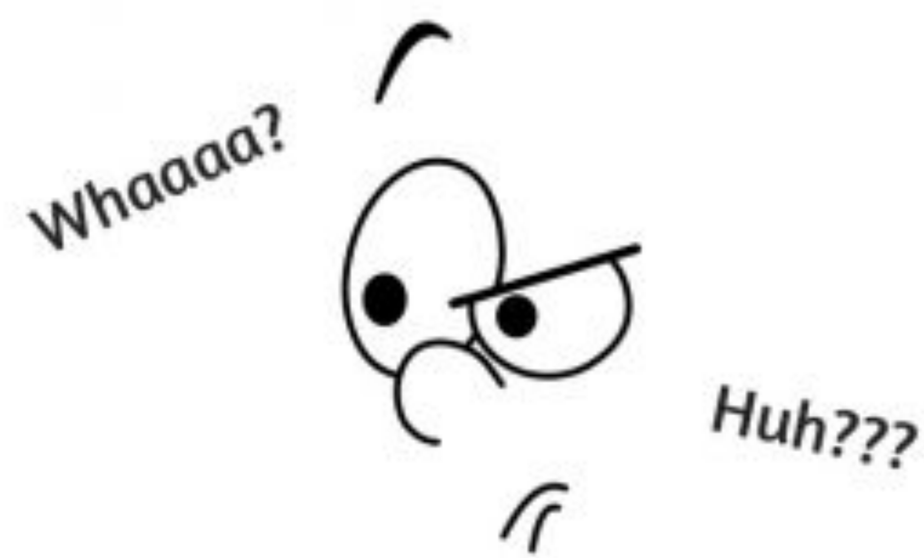
$\sim \sin\phi$?



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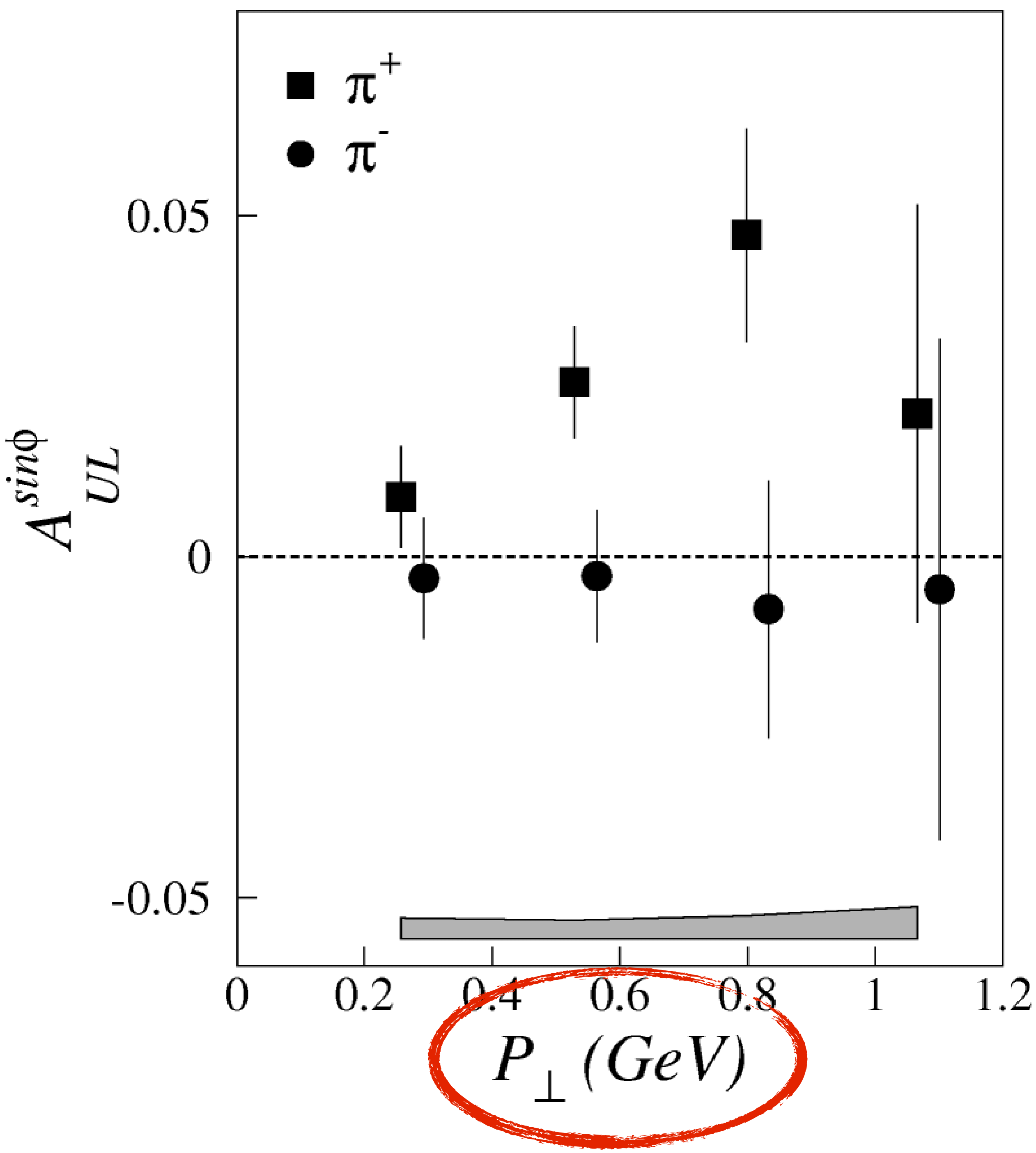

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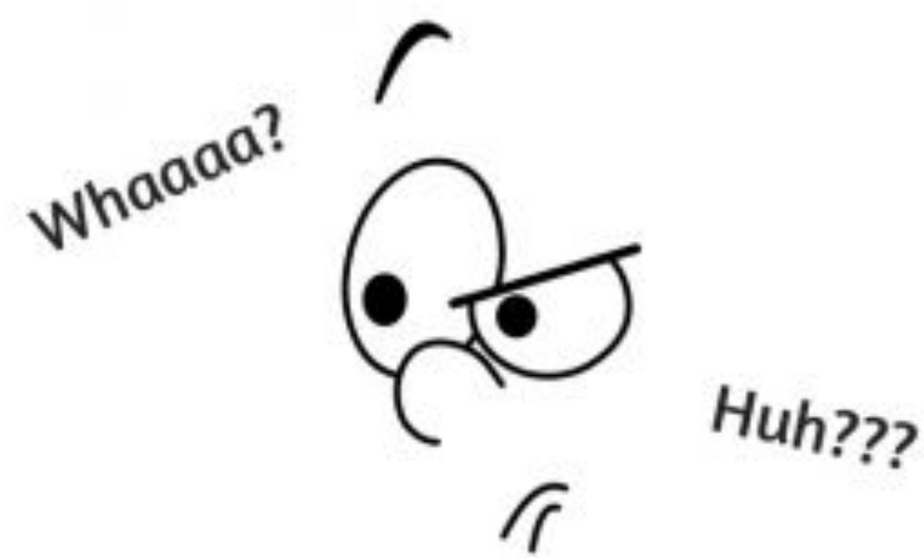

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Physics Letters B 530 (2002) 99–107

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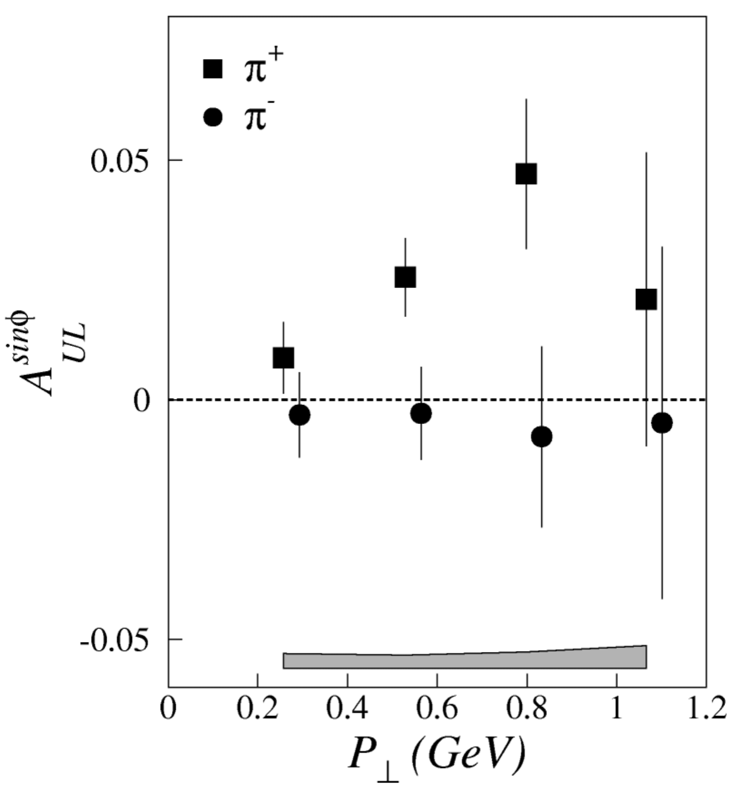
Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering ☆

Stanley J. Brodsky [a], Dae Sung Hwang [a,b], Ivan Schmidt [c]

[a] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA
[b] Department of Physics, Sejong University, Seoul 143-747, South Korea
[c] Departamento de Física, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile



Received 2 February 2002; accepted 2 February 2002

Editor: H. Georgi

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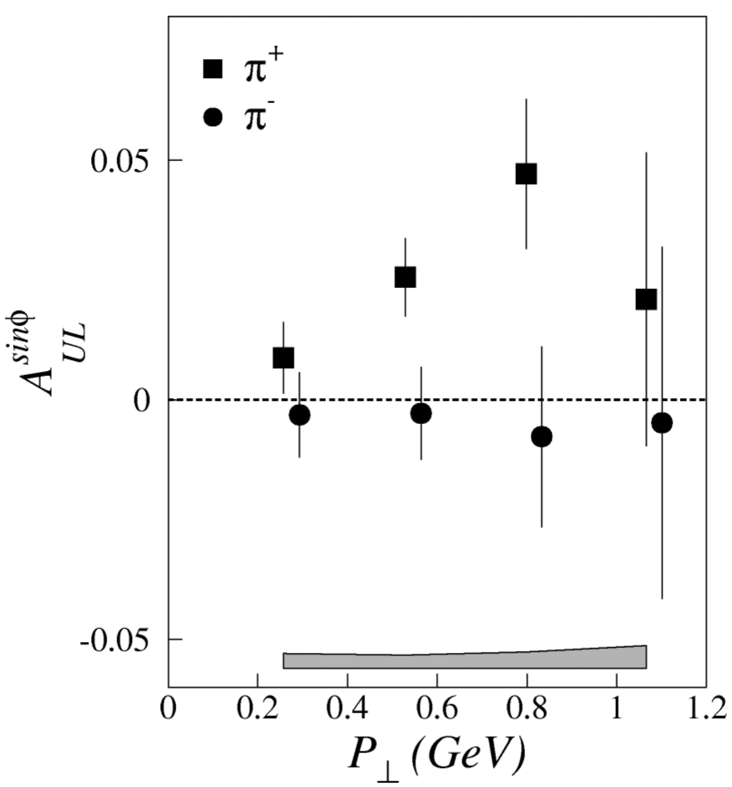

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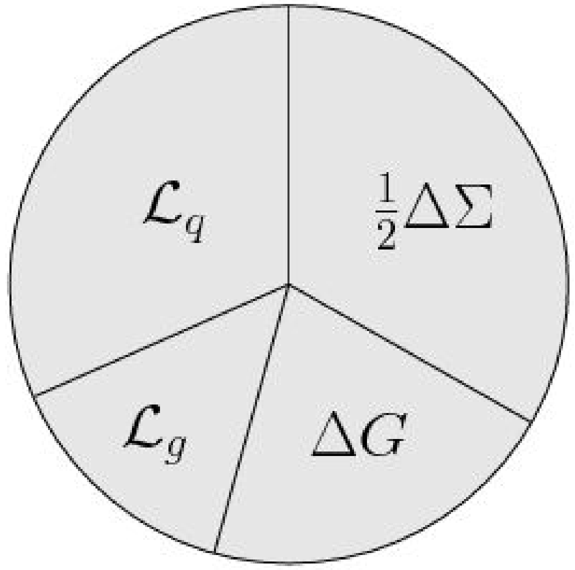


'pizza quattro stagioni'

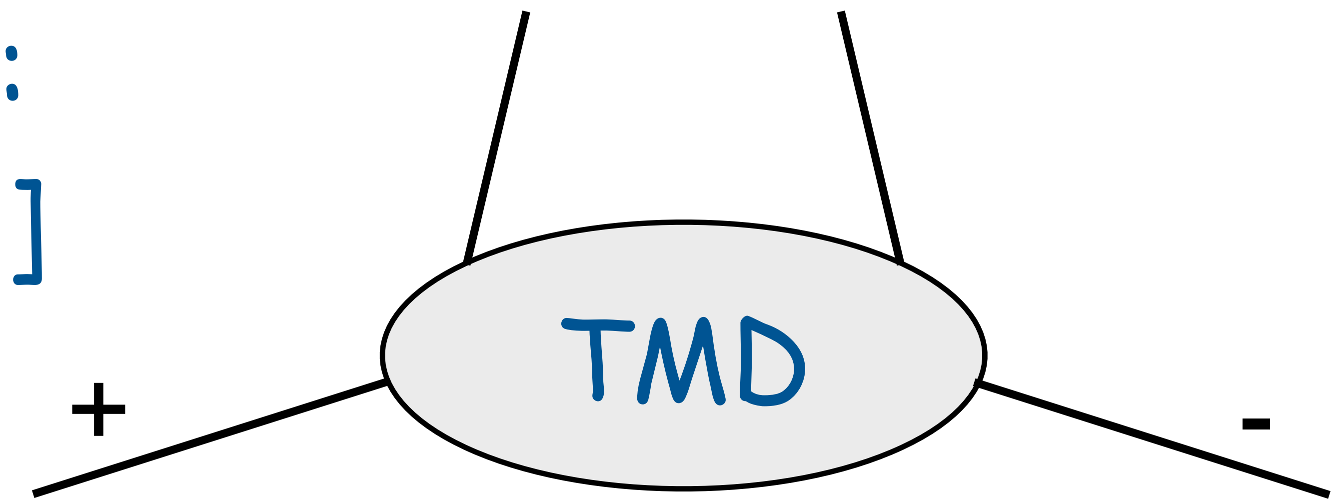
[M. Burkardt]

(semi-)inclusive longitudinal double-spin asymmetries

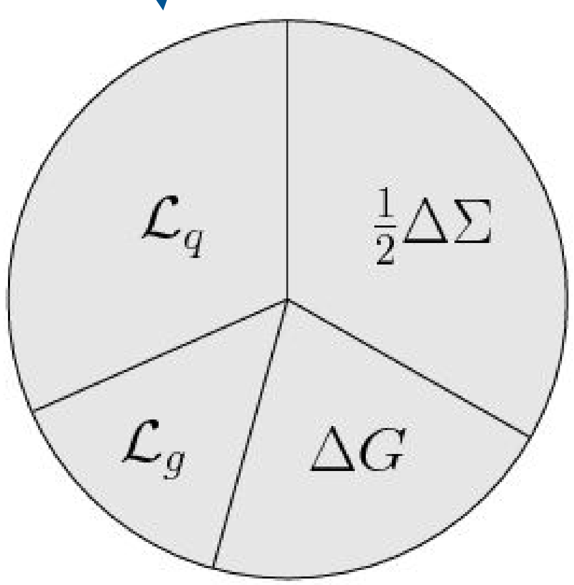
evolution, high-p_T hadrons [better: polarized pp]

Access to angular momentum in (SI)DIS

$$\Delta\mathcal{L}_q = \pm 1(\text{or } 2)$$



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



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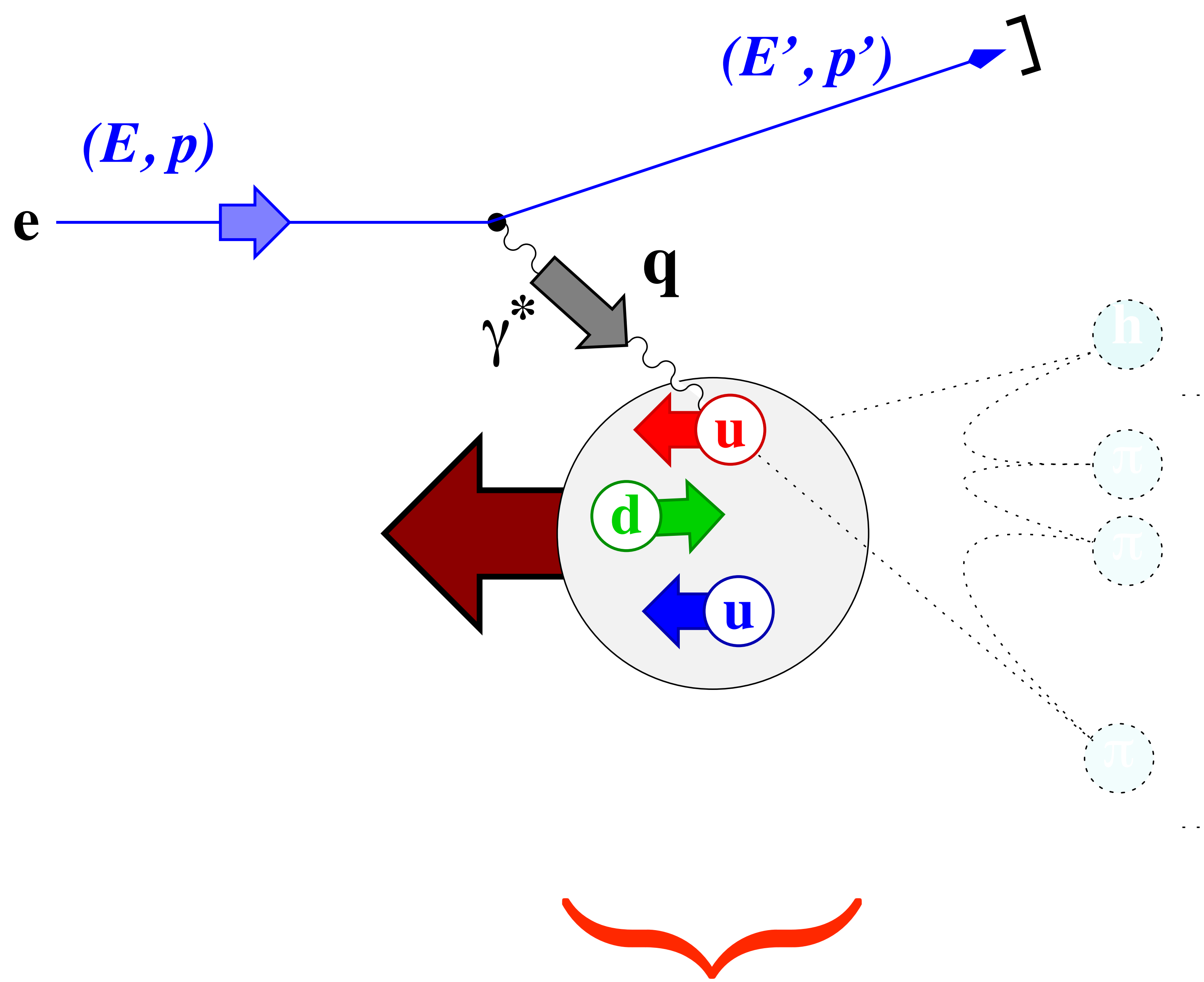
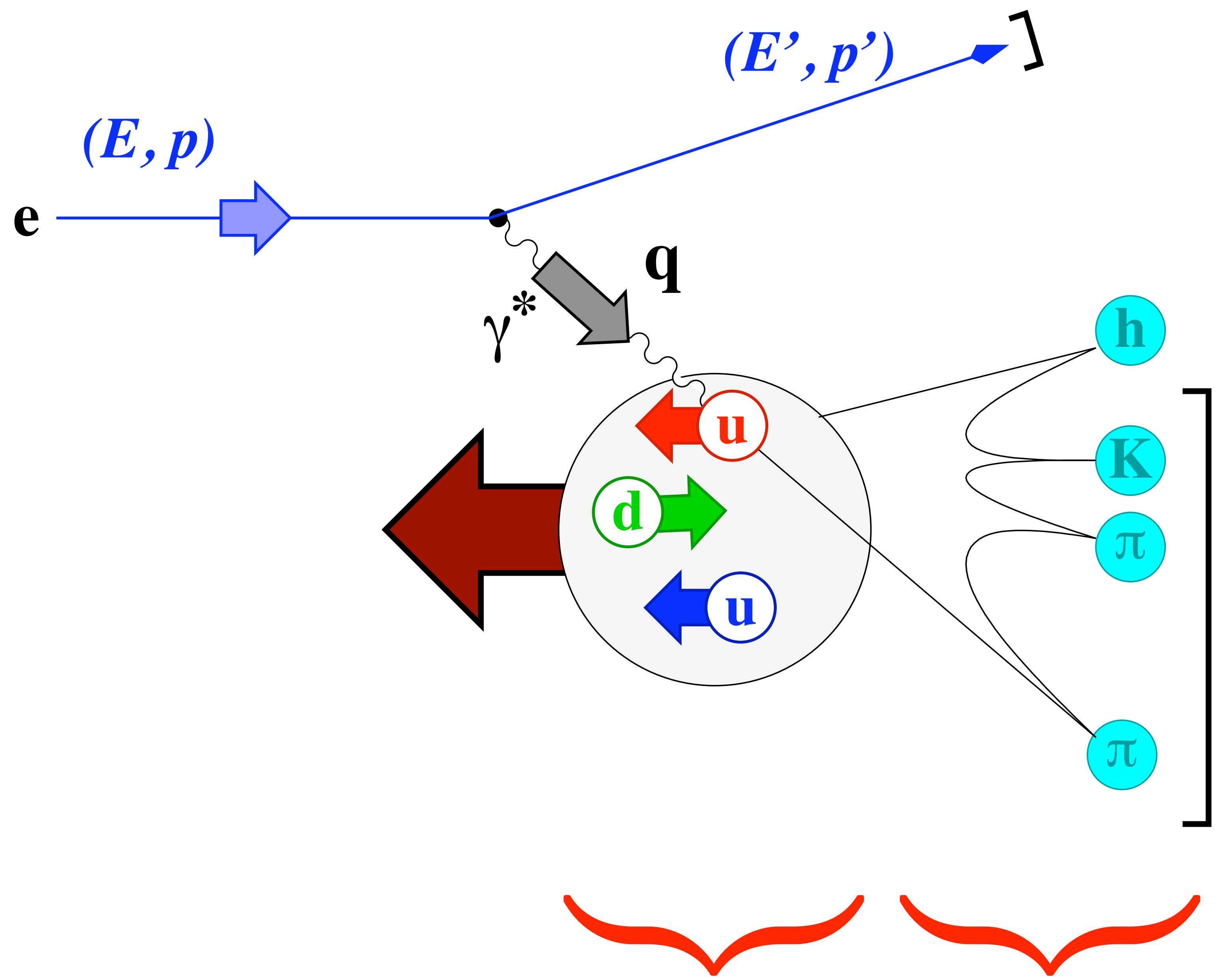
deep-inelastic scattering

inclusive



factorization: parton distributions

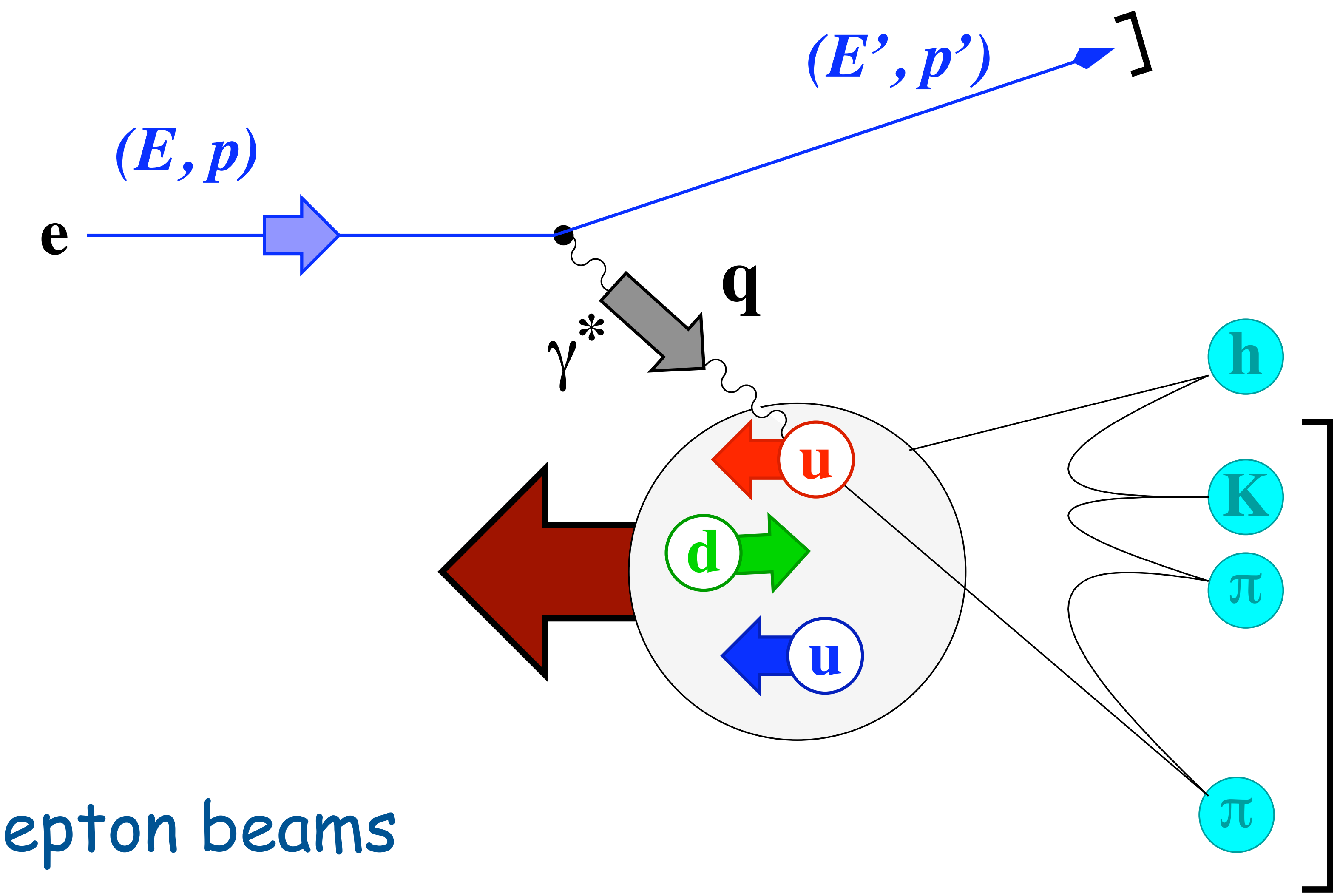
deep-inelastic scattering



semi-inclusive

factorization: parton distributions fragmentation functions

deep-inelastic scattering

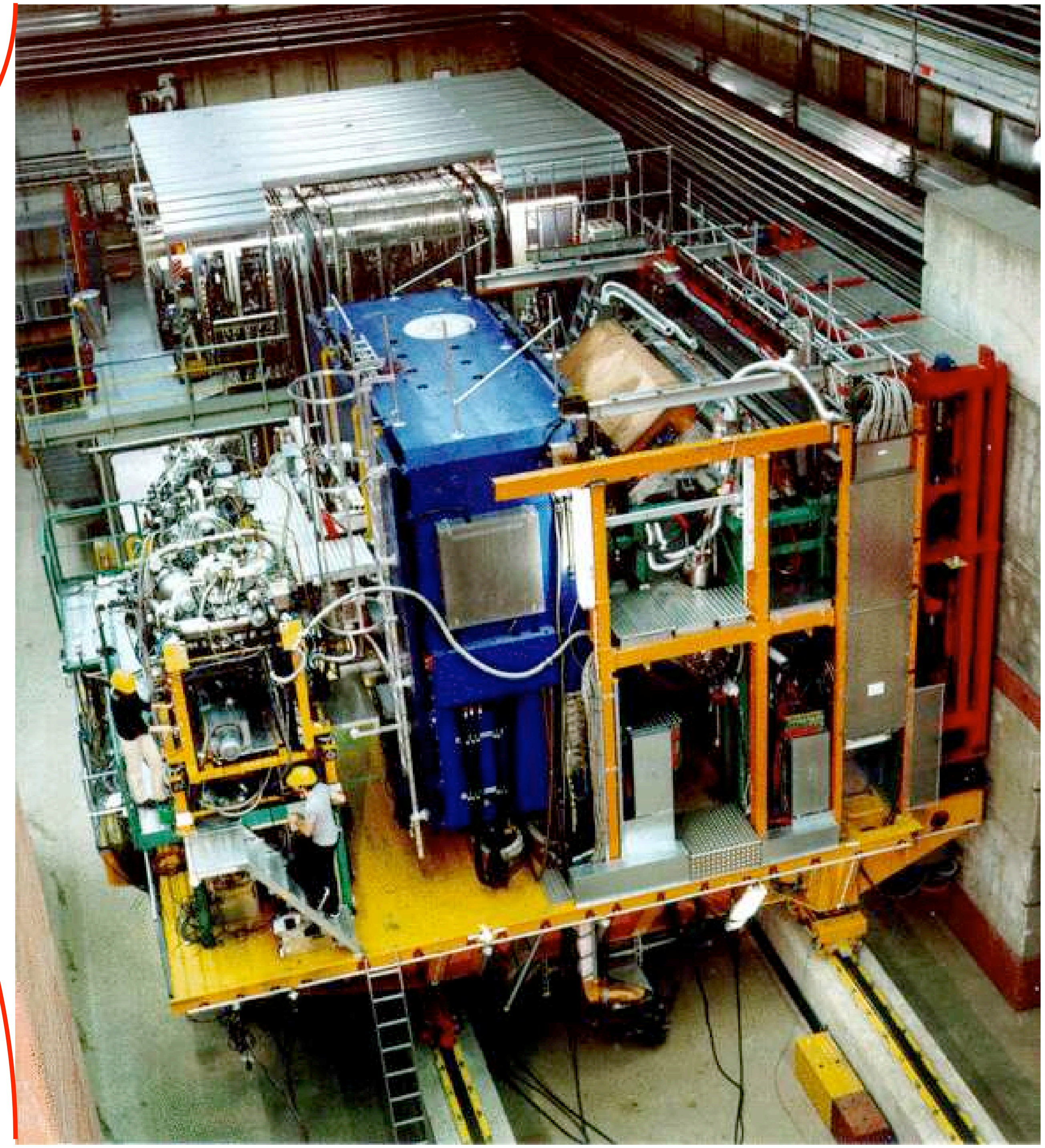


semi-inclusive

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

HERMES (†2007) @ DESY

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

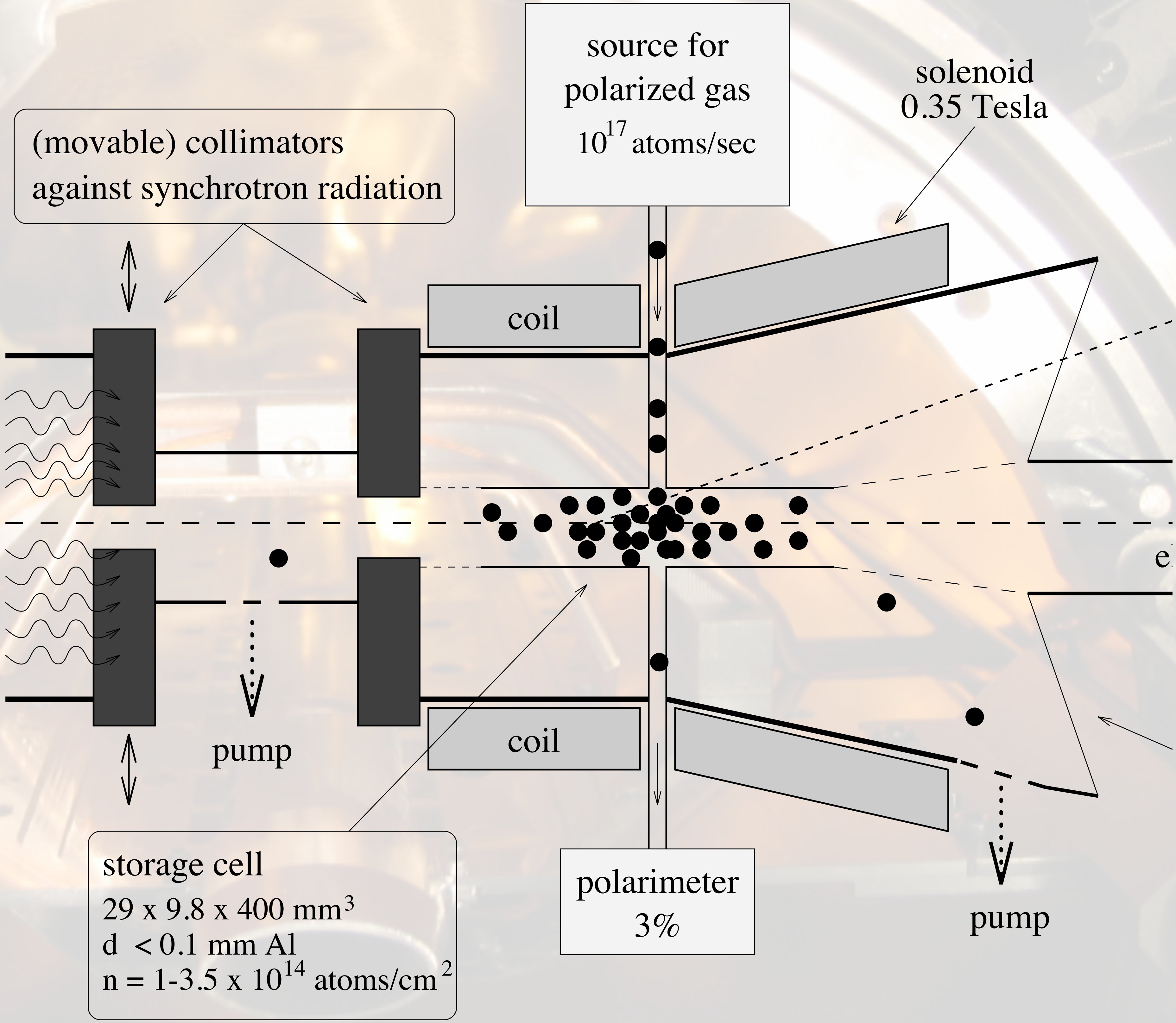


- unpolarized (H, D, He,..., Xe)
- as well as transversely (H) and **longitudinally polarized (pure) H,D & ^{3}He gas targets**

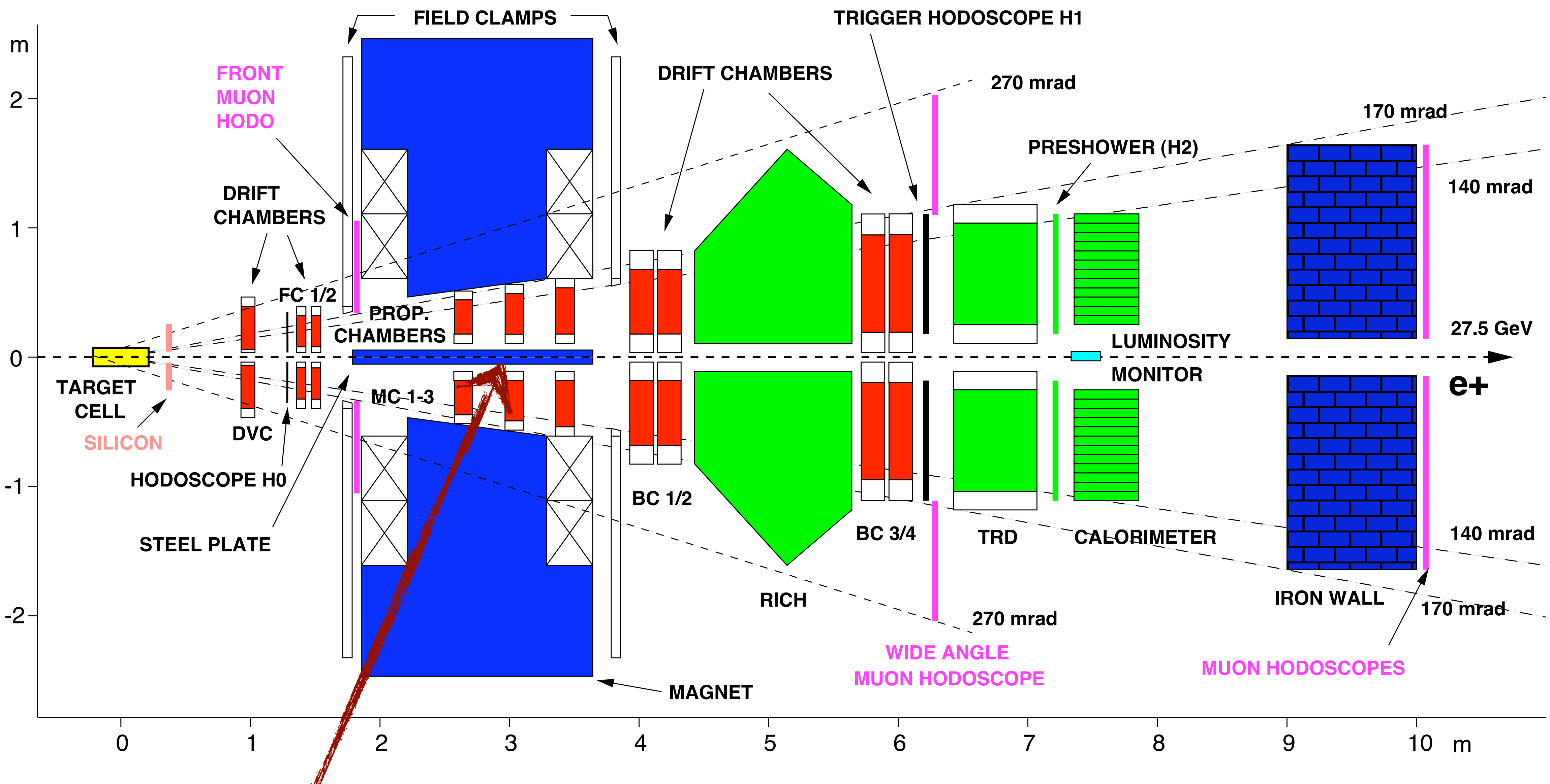
HERMES polarized target

Polarization:
longitudinal: ~85%
transversal: ~75%

fast/frequent spin reversal

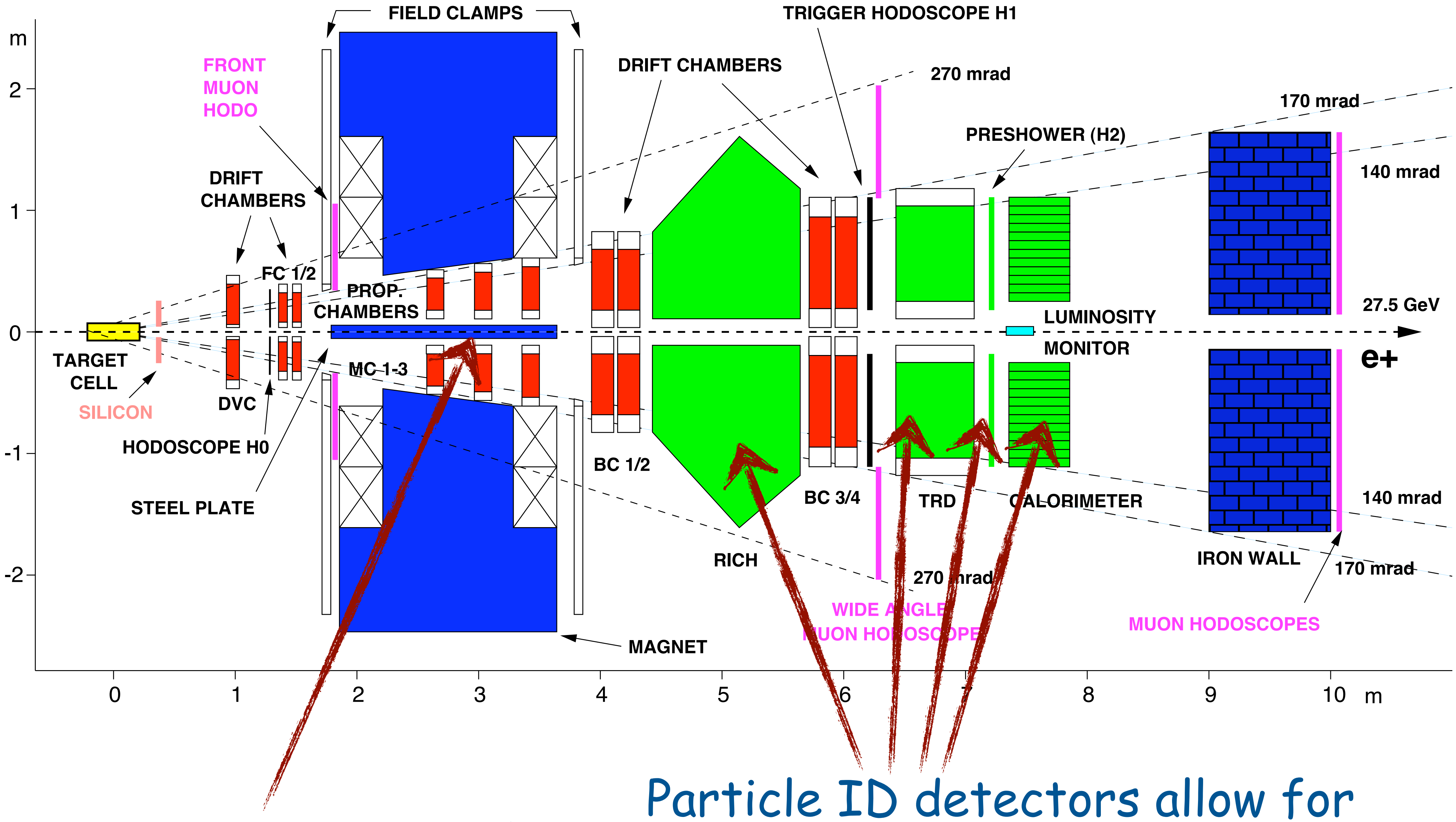


HERMES (1998-2005) schematically



two (mirror-symmetric) halves

HERMES (1998-2005) schematically

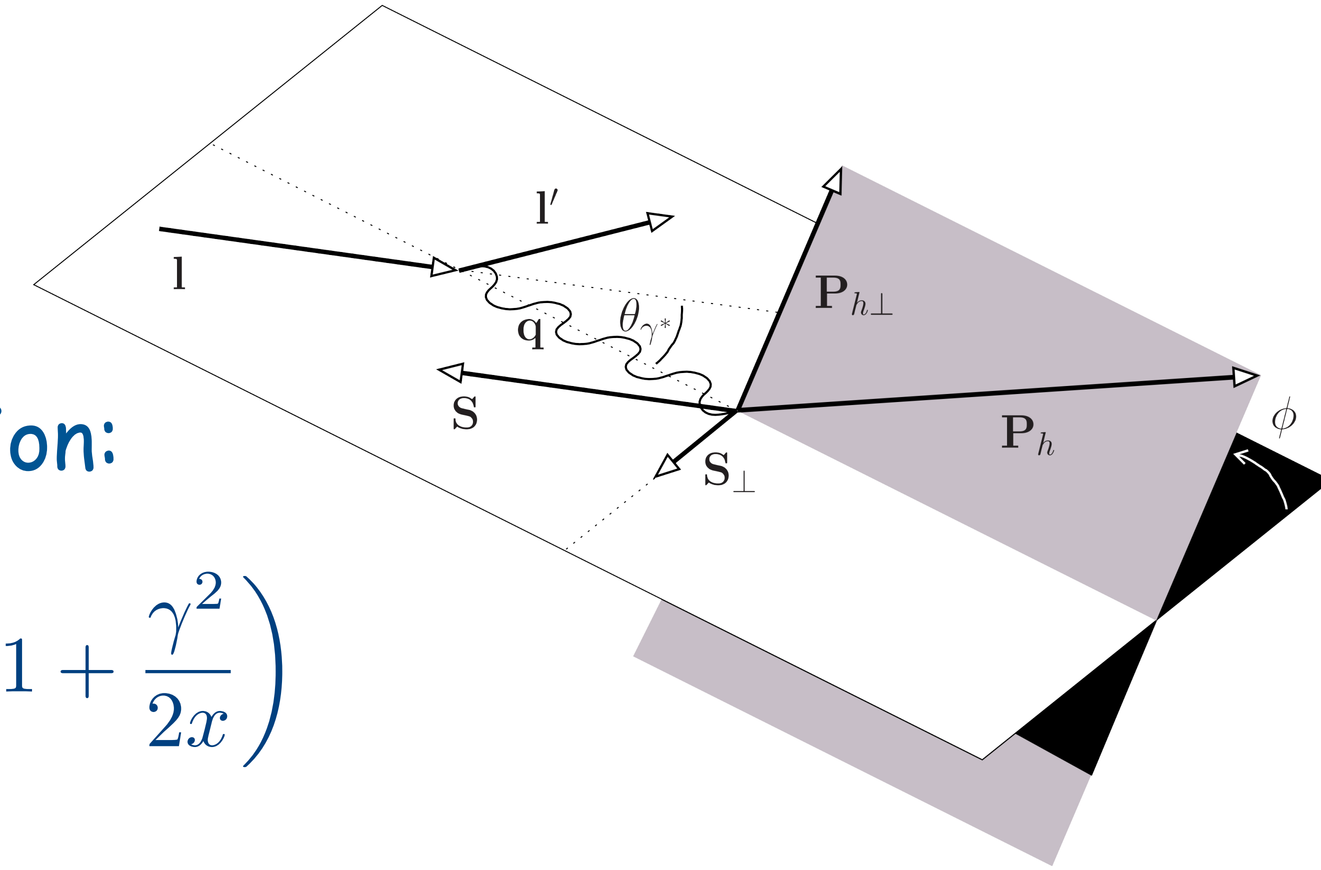


two (mirror-symmetric) halves

Particle ID detectors allow for

- lepton/hadron separation
- dual-radiator RICH: pion/kaon/proton discrimination 2 GeV < p < 15 GeV

semi-inclusive DIS



- excluding transverse polarization:

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

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

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

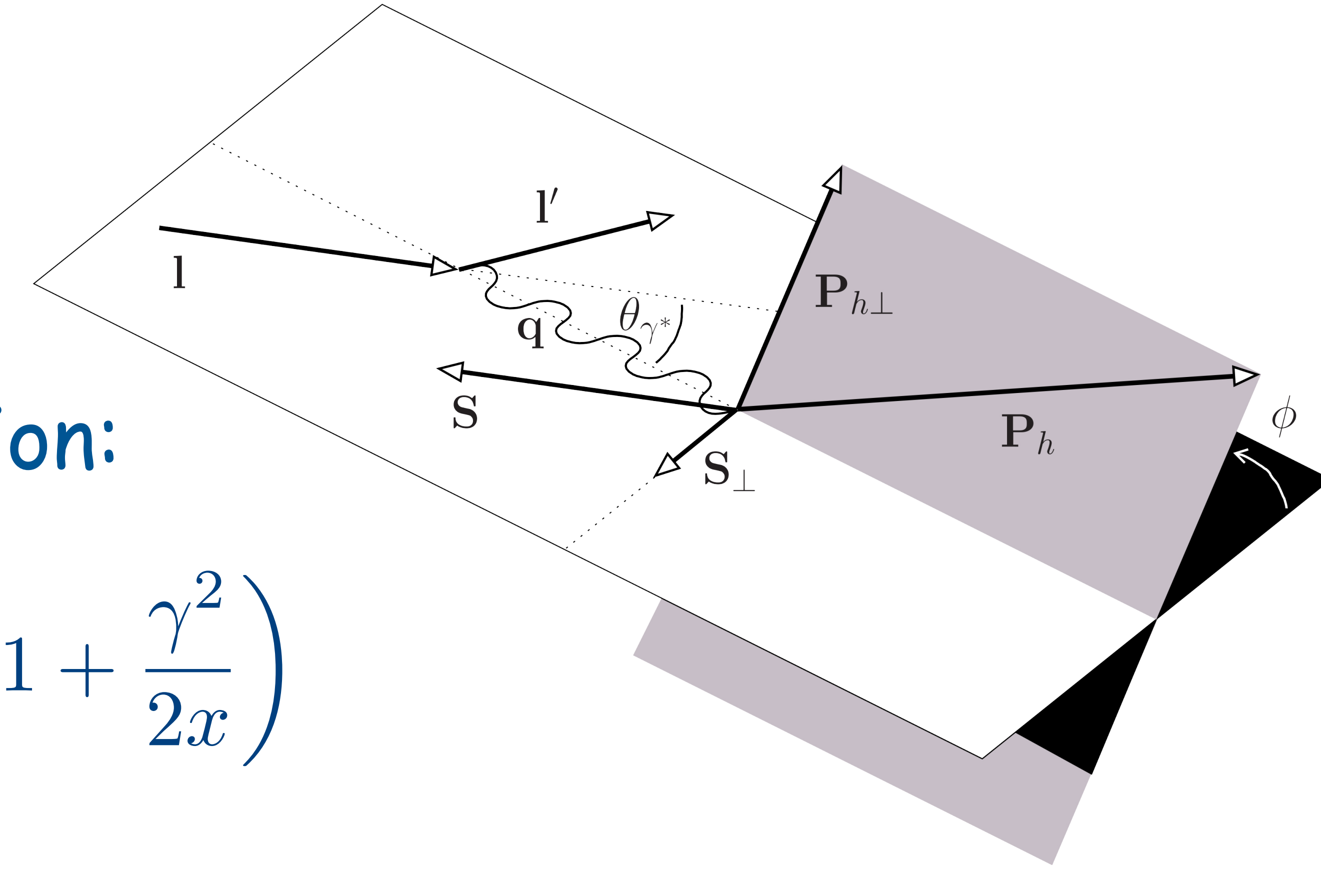
$$+\sqrt{2\epsilon}\left[\lambda\Lambda\sqrt{1-\epsilon}\,F_{LL}^{h,\cos\phi} + \sqrt{1+\epsilon}\,F_{UU}^{h,\cos\phi}\right]\cos\phi$$

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

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

Beam (λ) / Target (Λ)
helicities

semi-inclusive DIS



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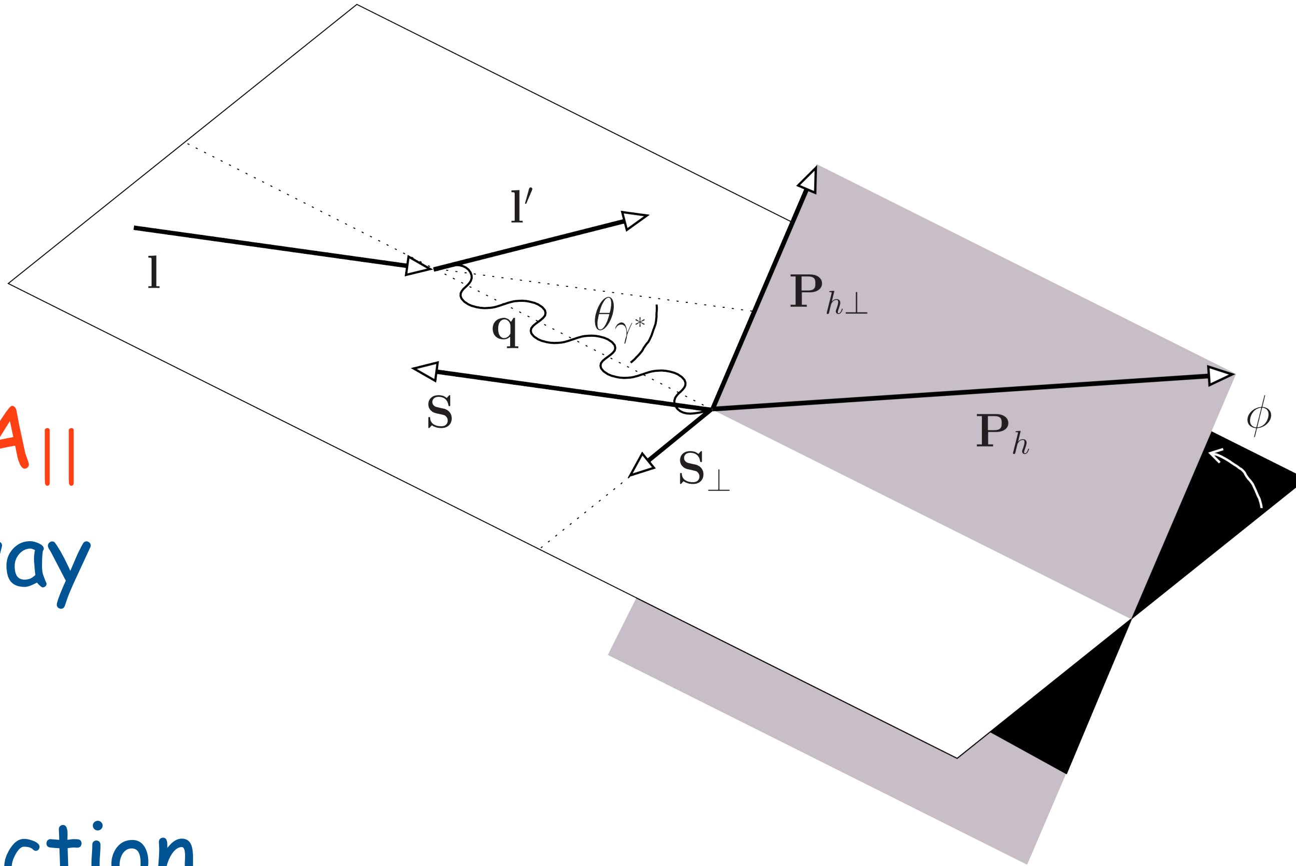
$$+\Lambda\epsilon\,F_{UL}^{h,\sin 2\phi}\sin 2\phi + \epsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi\Big\}$$

- double-spin asymmetry $\quad A_{LL}^h \equiv \dfrac{\sigma_{++}^h - \sigma_{+-}^h + \sigma_{--}^h - \sigma_{-+}^h}{\sigma_{++}^h + \sigma_{+-}^h + \sigma_{--}^h + \sigma_{-+}^h}$

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

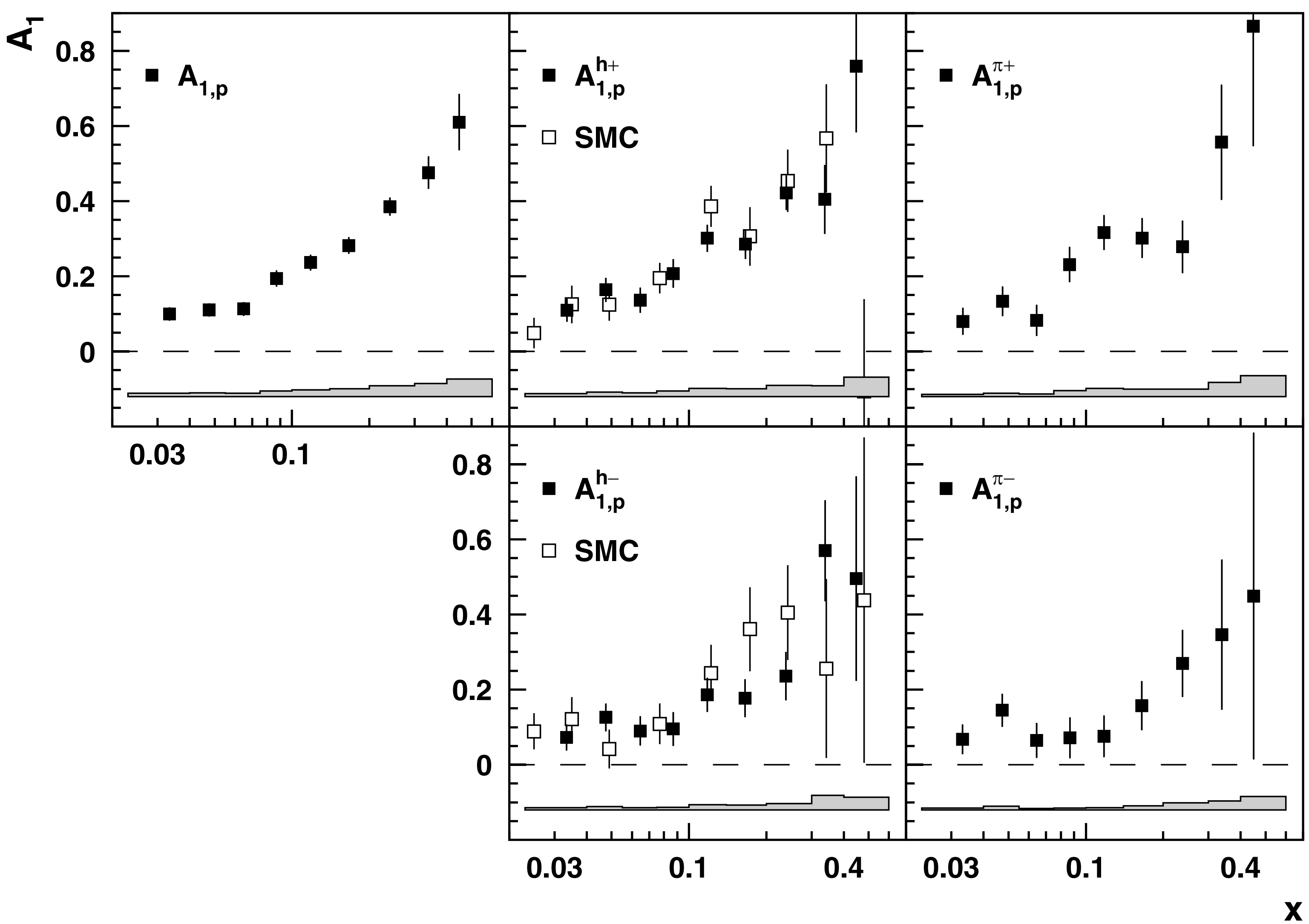
$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_{||}^h$$

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

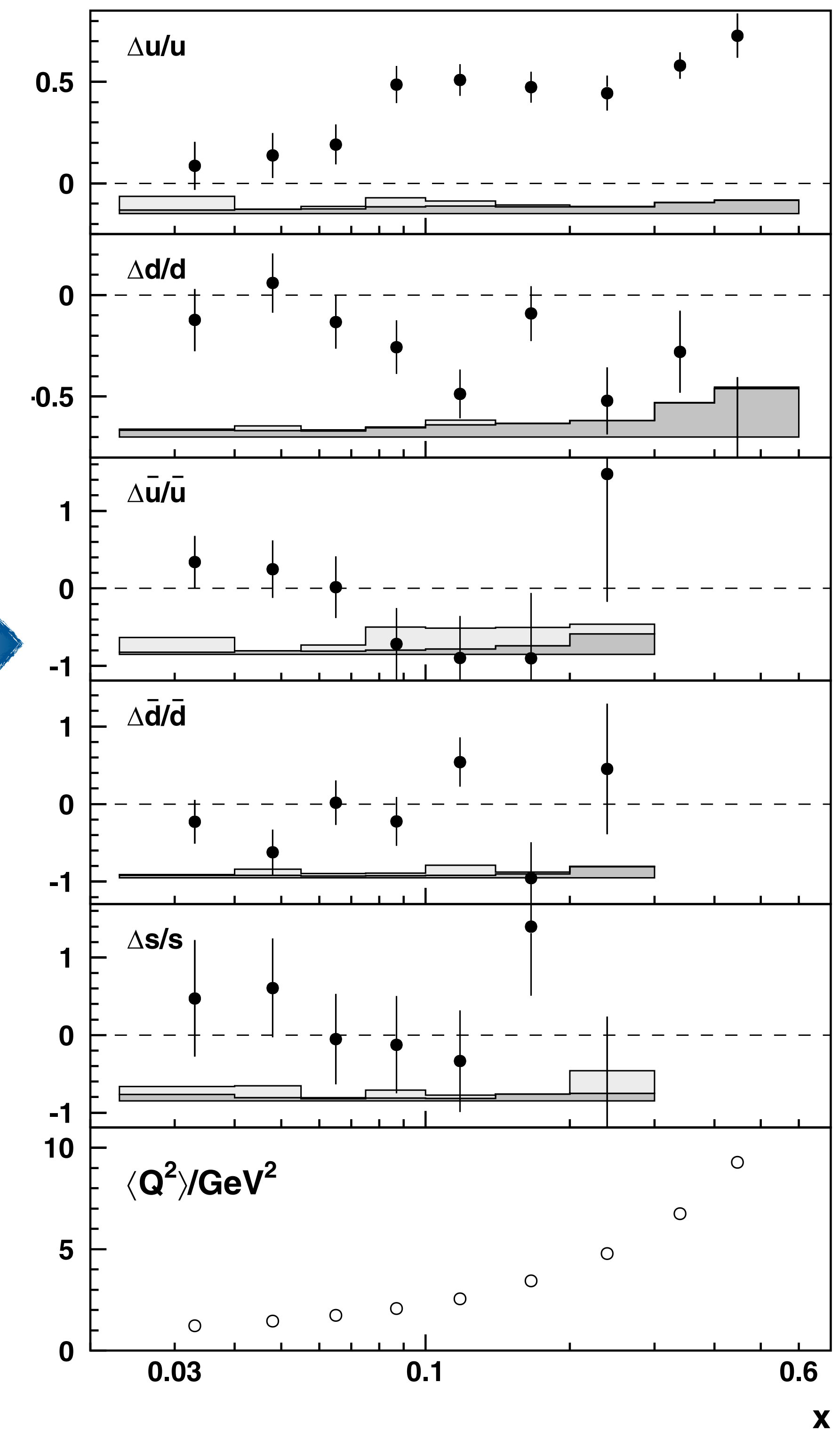
$$\eta = \frac{\epsilon\gamma y}{1-(1-y)\,\epsilon}$$

previous HERMES analysis

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



PHYSICAL REVIEW D **71,** 012003 (2005)



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

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

  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**

azimuthal-asymmetry corrections

measured

"polarized Cahn" effect etc.

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

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

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

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
- implement data-driven model for azimuthal modulations [PRD 87 (2013) 012010] into MC ☛ extract correction factor & apply to data

double-spin asymmetry $A_{||}$

$$A_{\|}^{h} \equiv \frac{C_{\phi}^{h}}{f_D}\left[\frac{L_{\rightrightarrows} N_{\rightleftarrows}^{h} - L_{\rightleftarrows} N_{\rightrightarrows}^{h}}{L_{P,\rightrightarrows} N_{\rightleftarrows}^{h} + L_{P,\rightleftarrows} N_{\rightrightarrows}^{h}}\right]_{\mathrm{B}}$$

double-spin asymmetry $A_{||}$

azimuthal
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$$A_{\parallel}^{h} \equiv \frac{C_{\phi}^{h}}{f_D}\left[\frac{L_{\rightrightarrows} N_{\rightleftarrows}^{h} - L_{\rightleftarrows} N_{\rightrightarrows}^{h}}{L_{P,\rightrightarrows} N_{\rightleftarrows}^{h} + L_{P,\rightleftarrows} N_{\rightrightarrows}^{h}}\right]_{\mathrm{B}}$$

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

double-spin asymmetry $A_{||}$

azimuthal correction

luminosities

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polarization-weighted luminosities

unfolded for QED radiation to Born level

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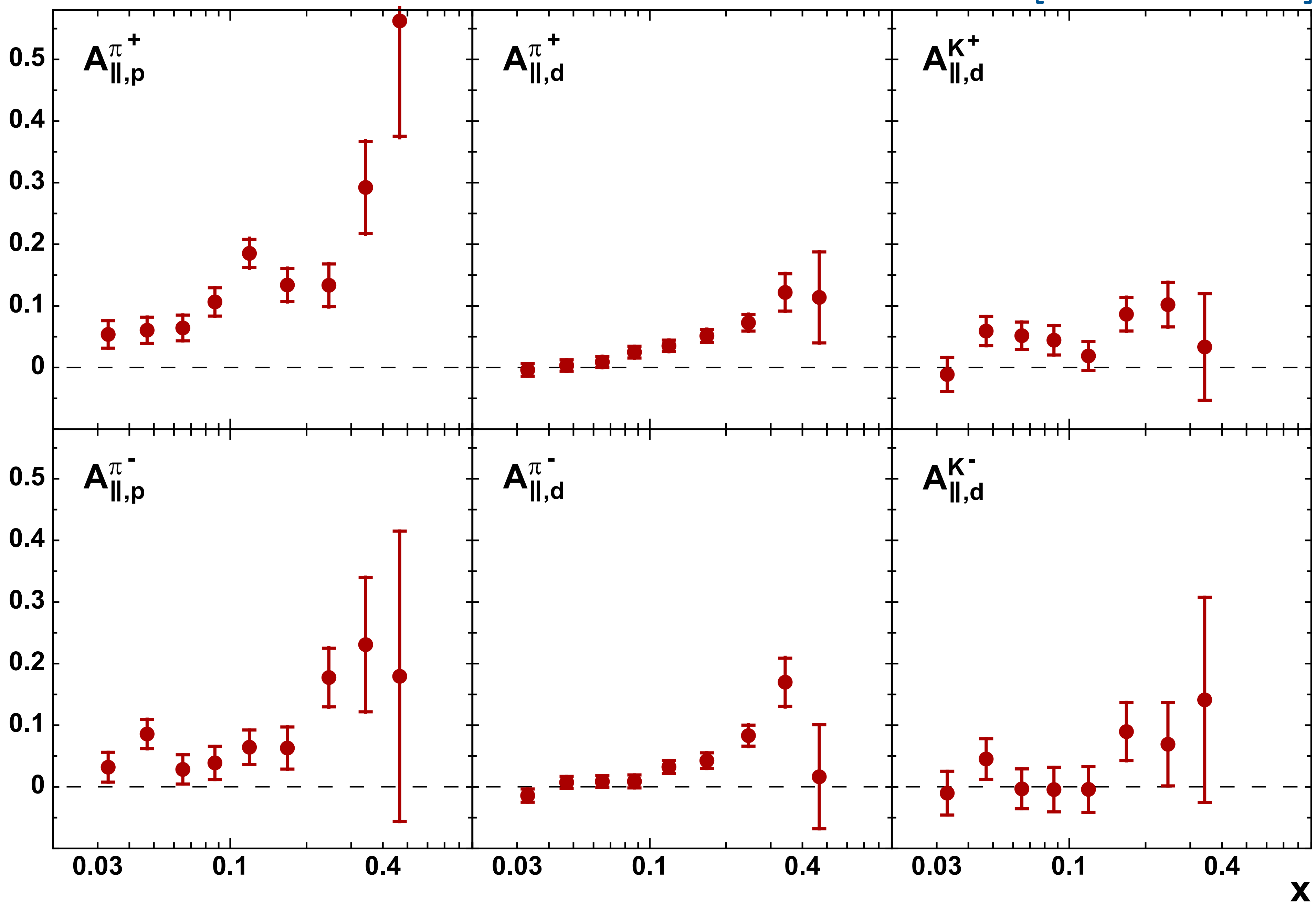
- dominated by statistical uncertainties
- main systematics arise from
  - polarization measurements [6.6% for hydrogen, 5.7% for deuterium)
  - azimuthal correction [O(few %)]

x dependence of $A_{||}$

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

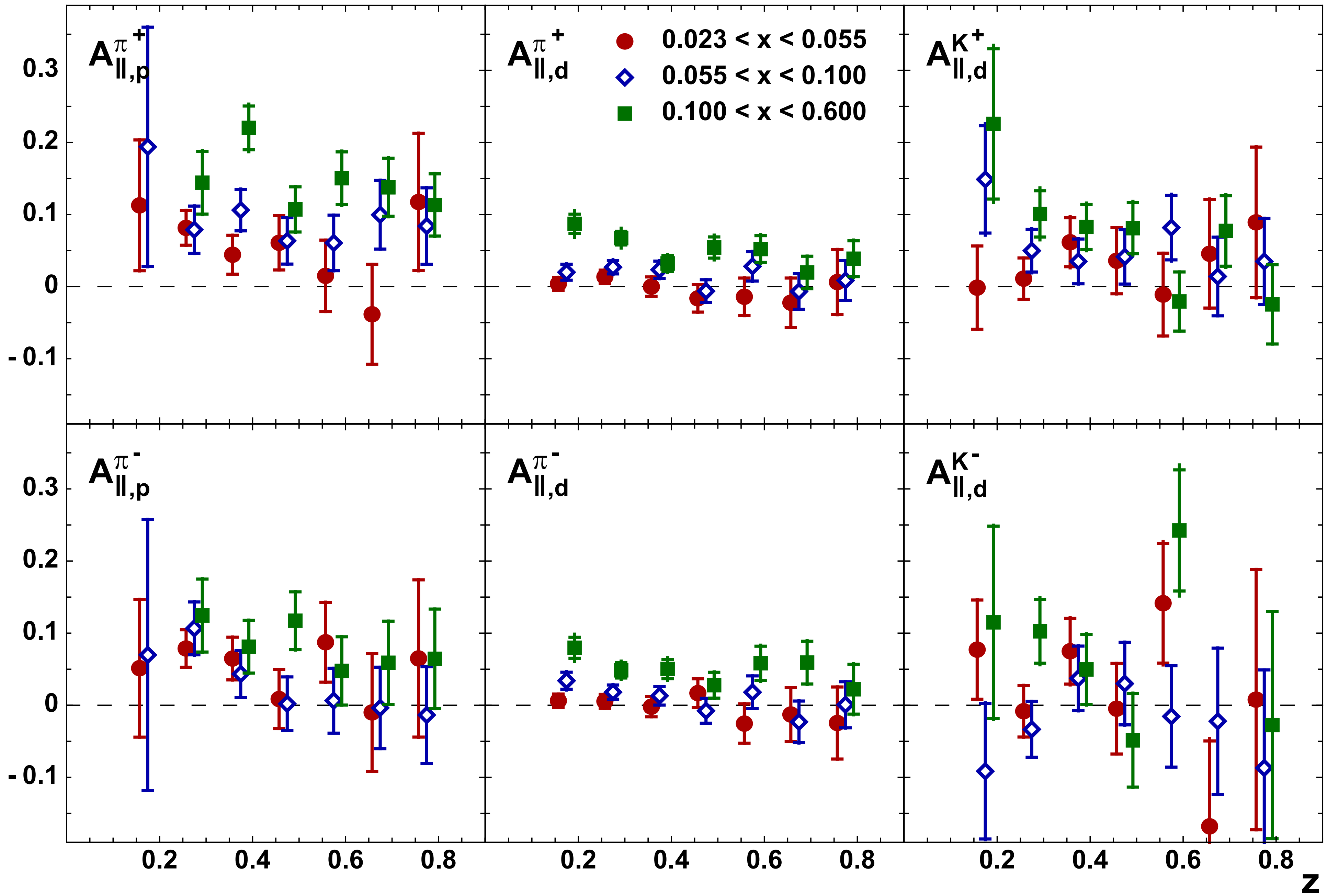
[arXiv:1810.07054]



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

- in general, no strong z-dependence visible

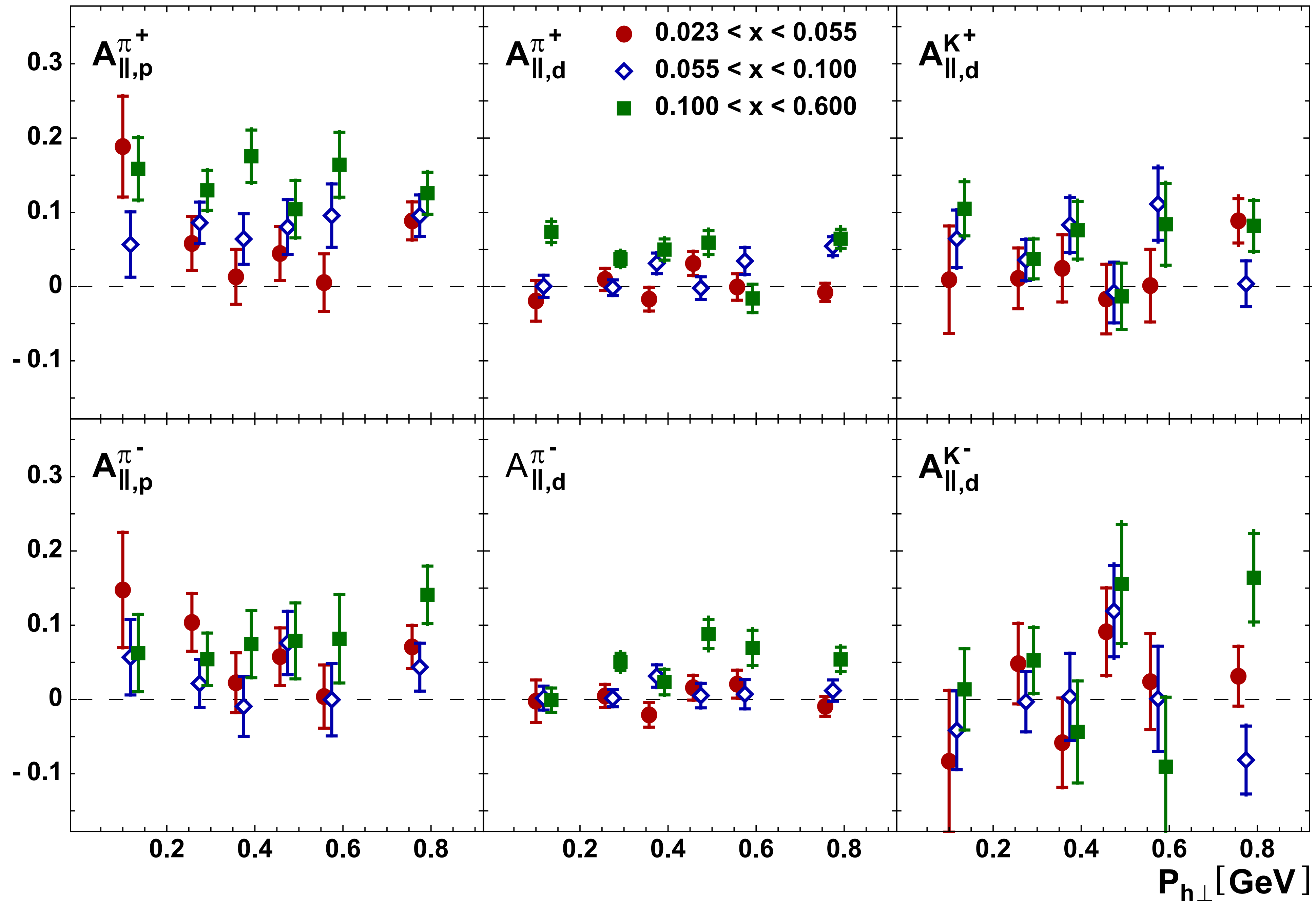
[arXiv:1810.07054]



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

- again, no strong dependence (beyond on x)

[arXiv:1810.07054]



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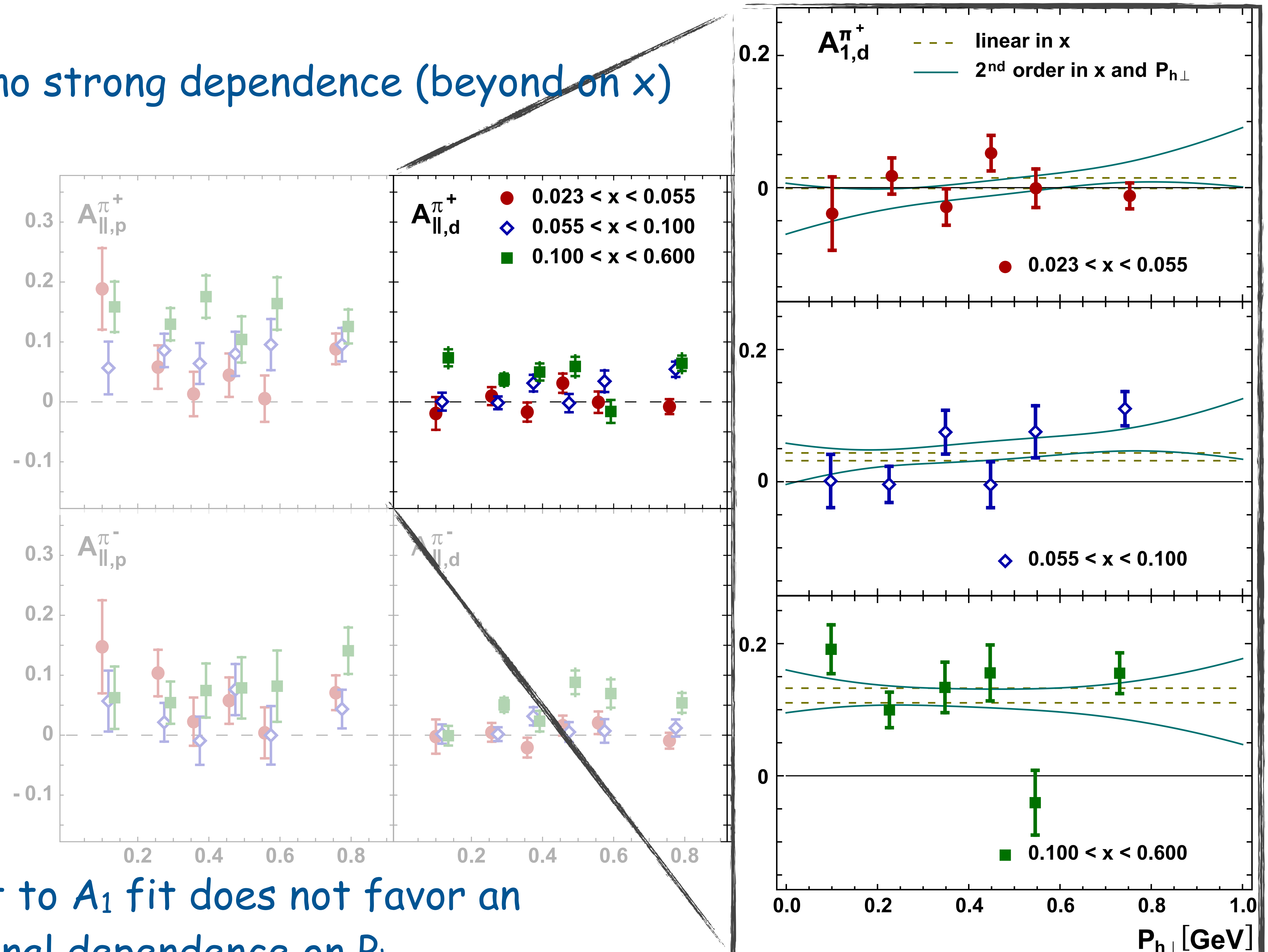

- also fit to A_1 fit does not favor an additional dependence on $P_{h\perp}$

interlude: dealing with multi-d dependences

multi-d dependences

- TMD cross sections differential in at least 5 variables
  - some easily parametrized (e.g., azimuthal dependences)
  - others mostly unknown

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- one-dimensional binning provide only glimpse of true physics
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- one-dimensional binning provide only glimpse of true physics
  - even different kinematic bins can't disentangle underlying physics dependences
  - 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

multi-d dependences

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

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

multi-d dependences

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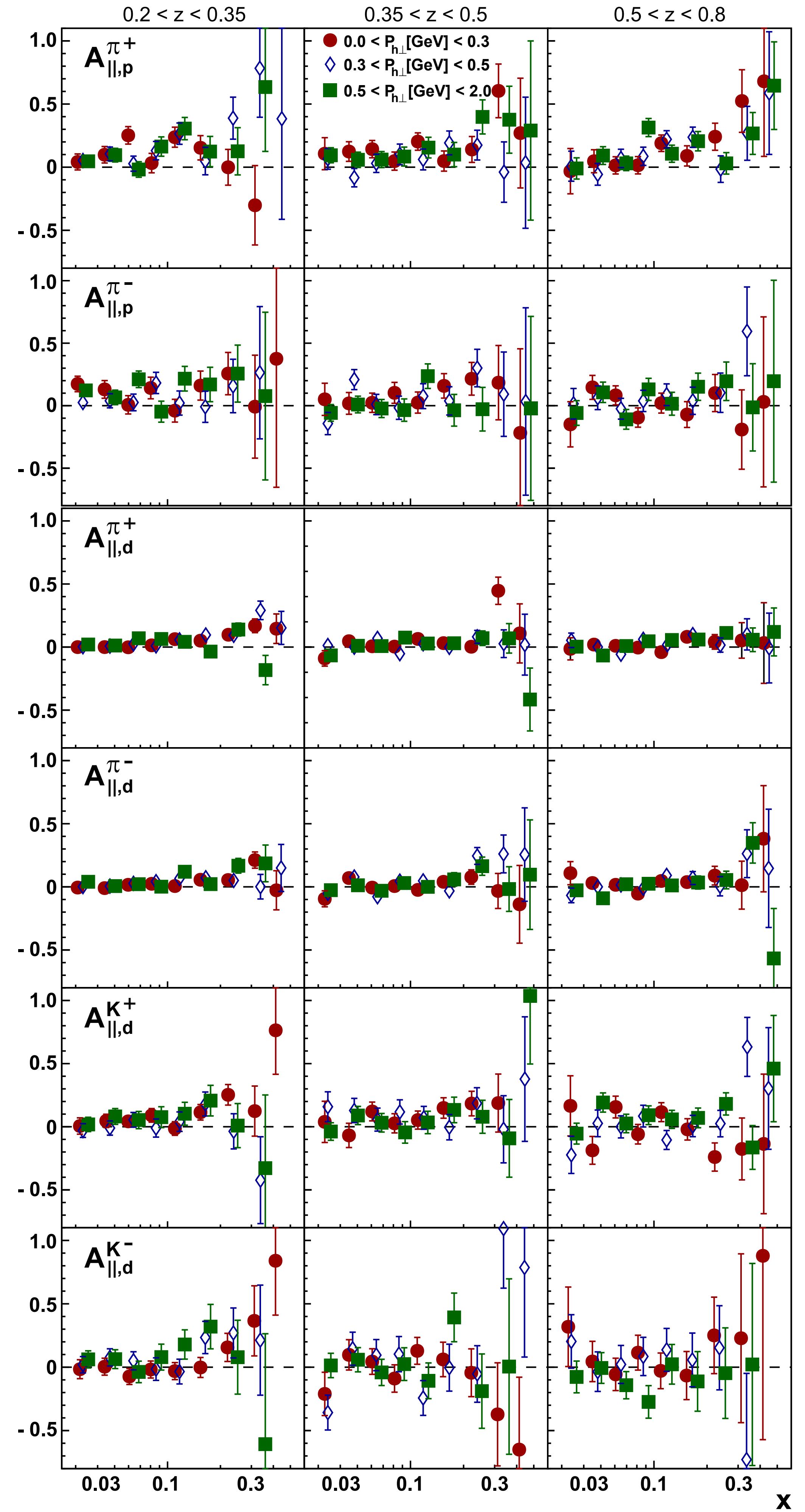
multi-d dependences

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

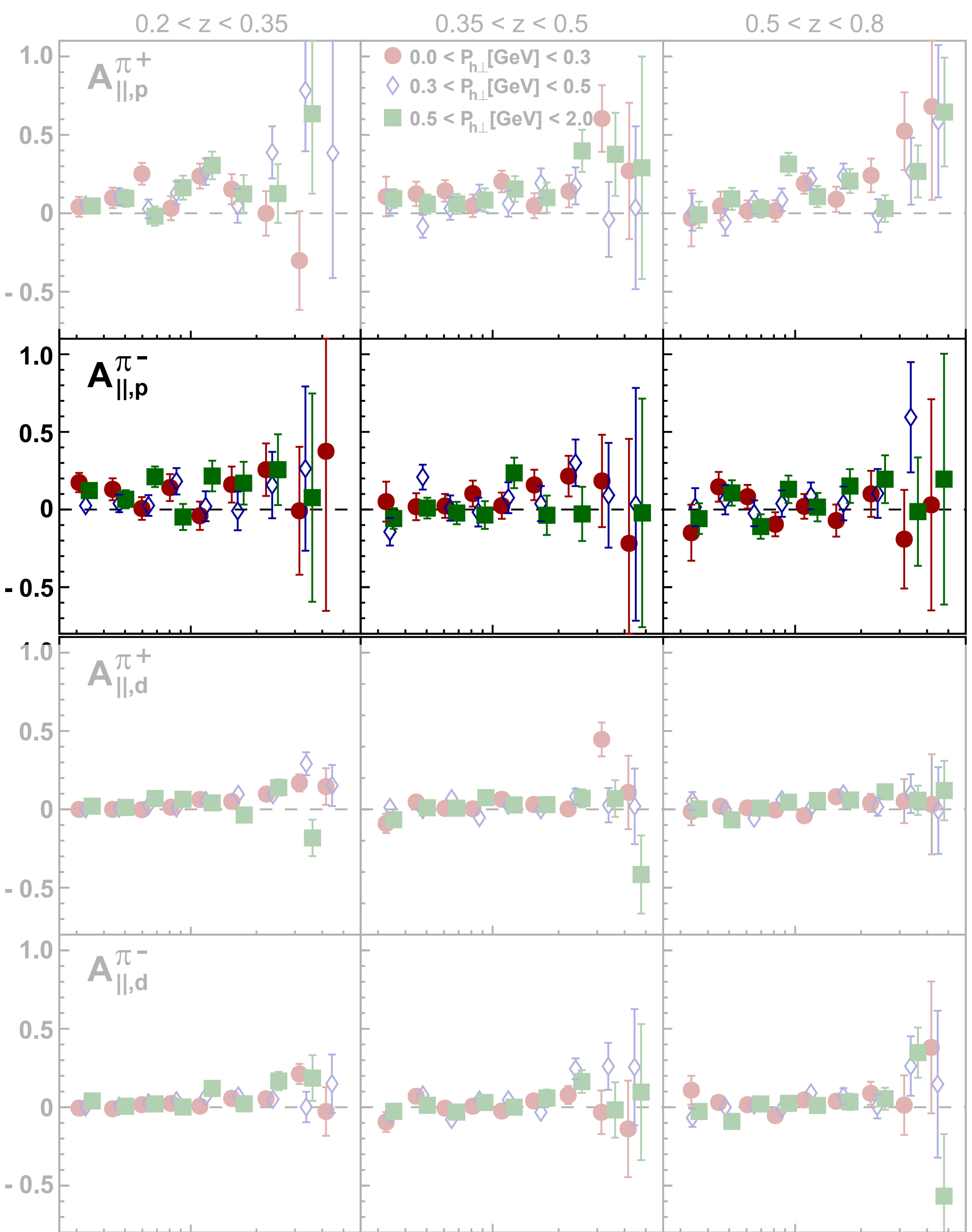
- measured cross sections / asymmetries often contain "remnants" of experimental acceptance ϵ
- difficult to evaluate precisely in absence of good physics model
  - general challenge to statistically precise data sets
  - avoid 1d binning/presentation of data
  - theorist: watch out for precise definition (if *given!*) of experimental results reported … and try not to treat data points of different projections as independent

3-dimensional binning

- 3d dependences provides transverse-momentum dependence

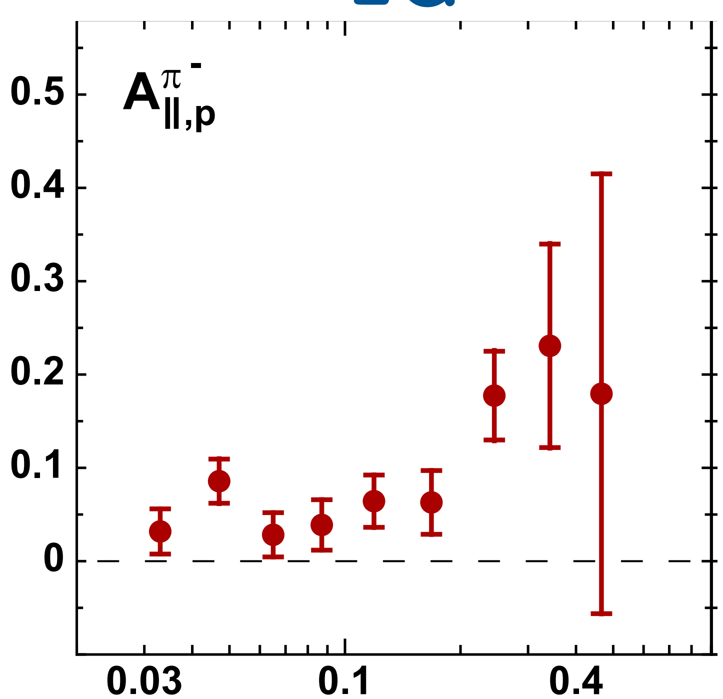


3-dimensional binning

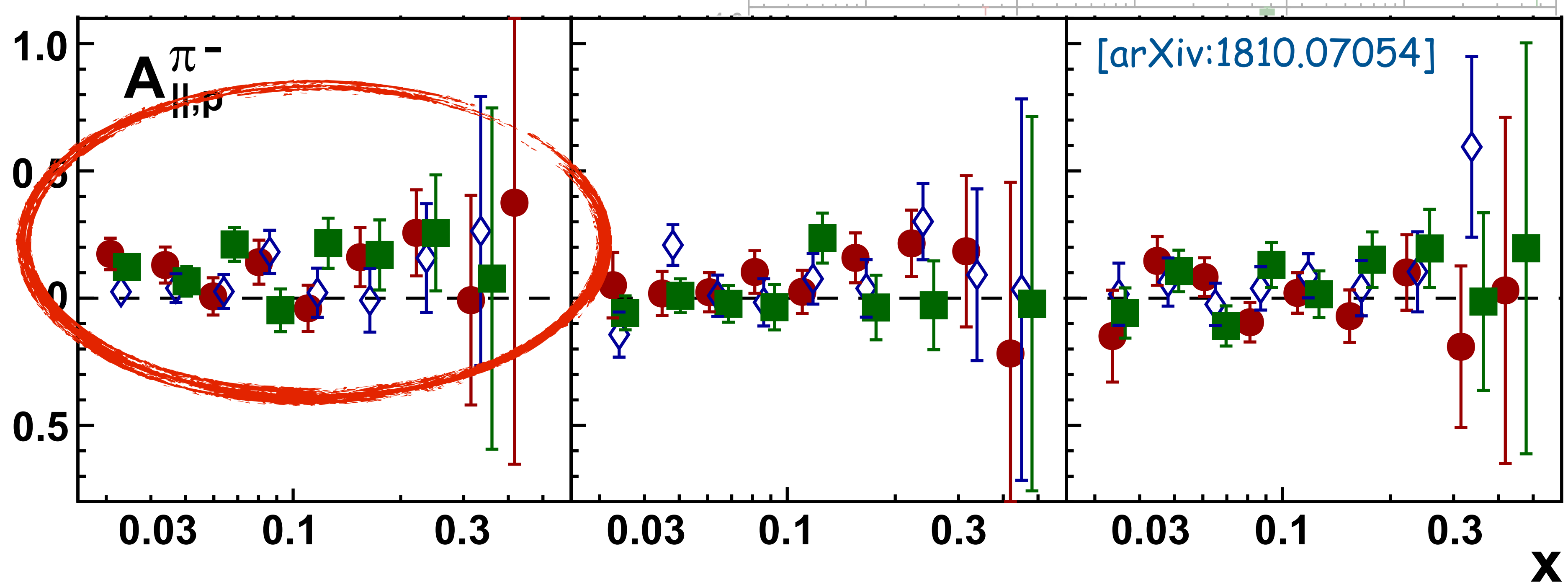


- 3d dependences provides transverse-momentum dependence
- but also extra flavor sensitivity, e.g.,
  - π^- asymmetries mainly coming from **low-z** region where **disfavored fragmentation** large and thus **sensitivity** to the large **positive up-quark polarization**

1d



3d



charge-difference asymmetries

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

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

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

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- assuming also isospin symmetry in fragmentation:

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

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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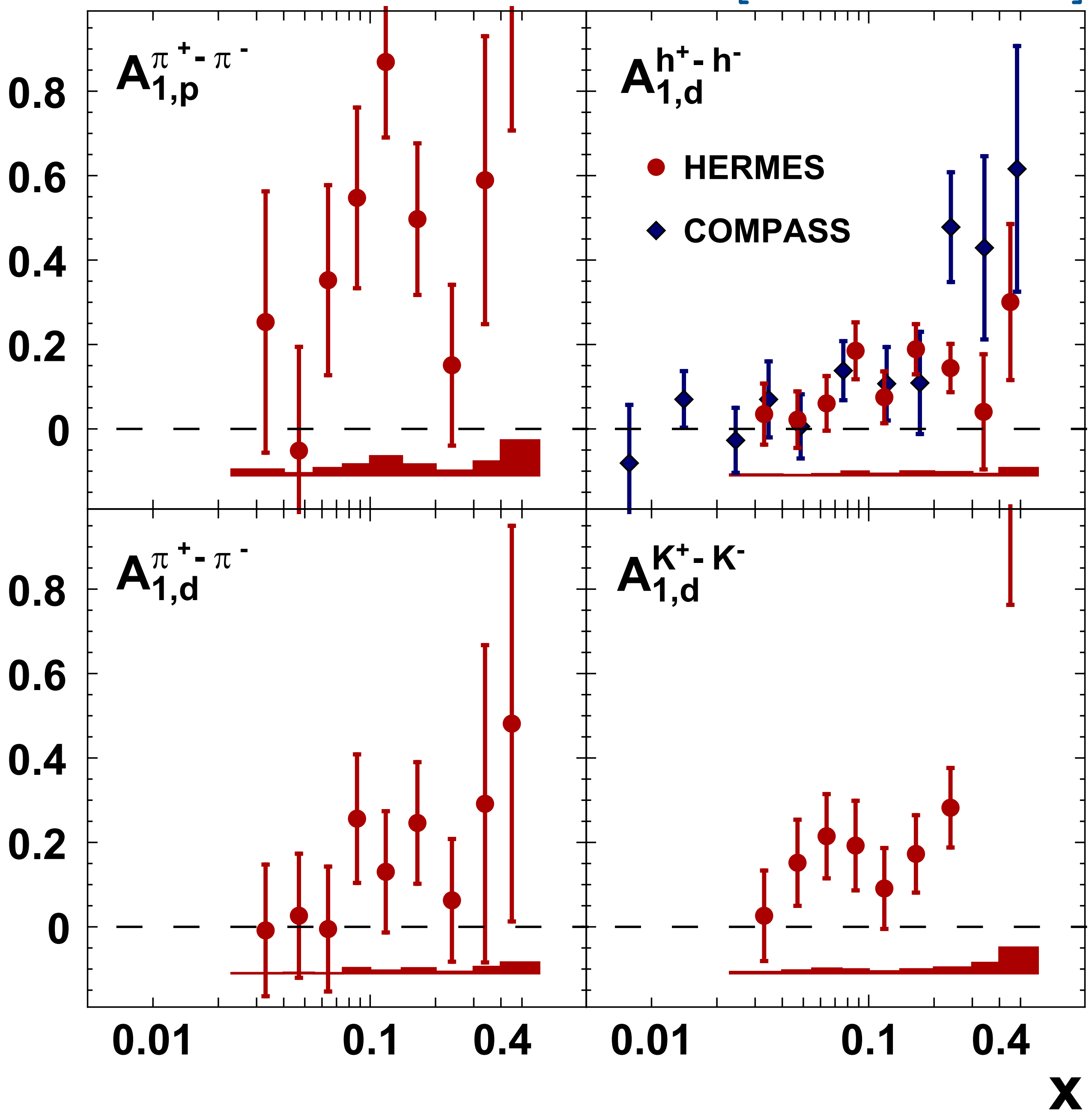
- can be used to extract valence helicity distributions

charge-difference asymmetries

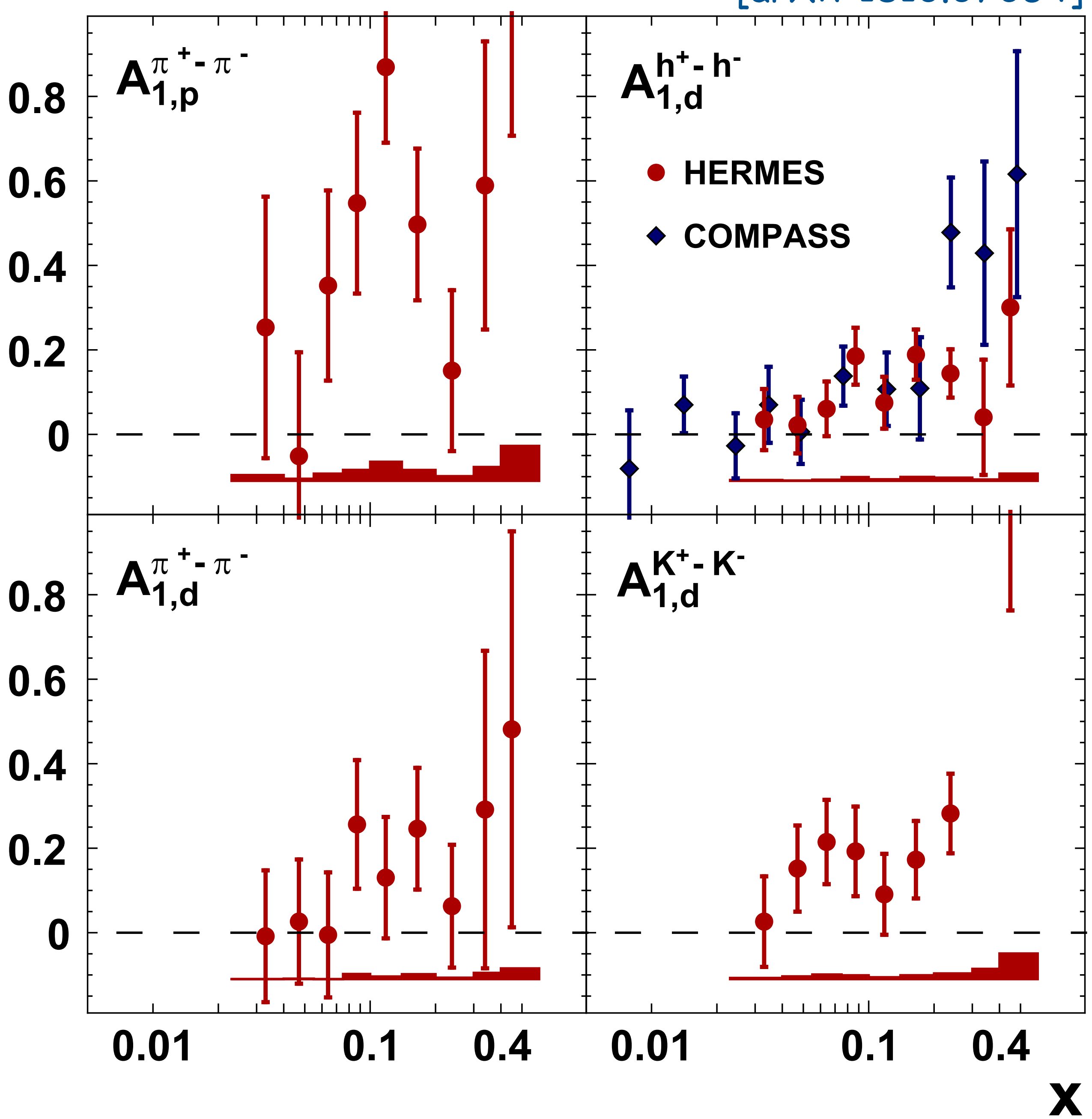
[arXiv:1810.07054]



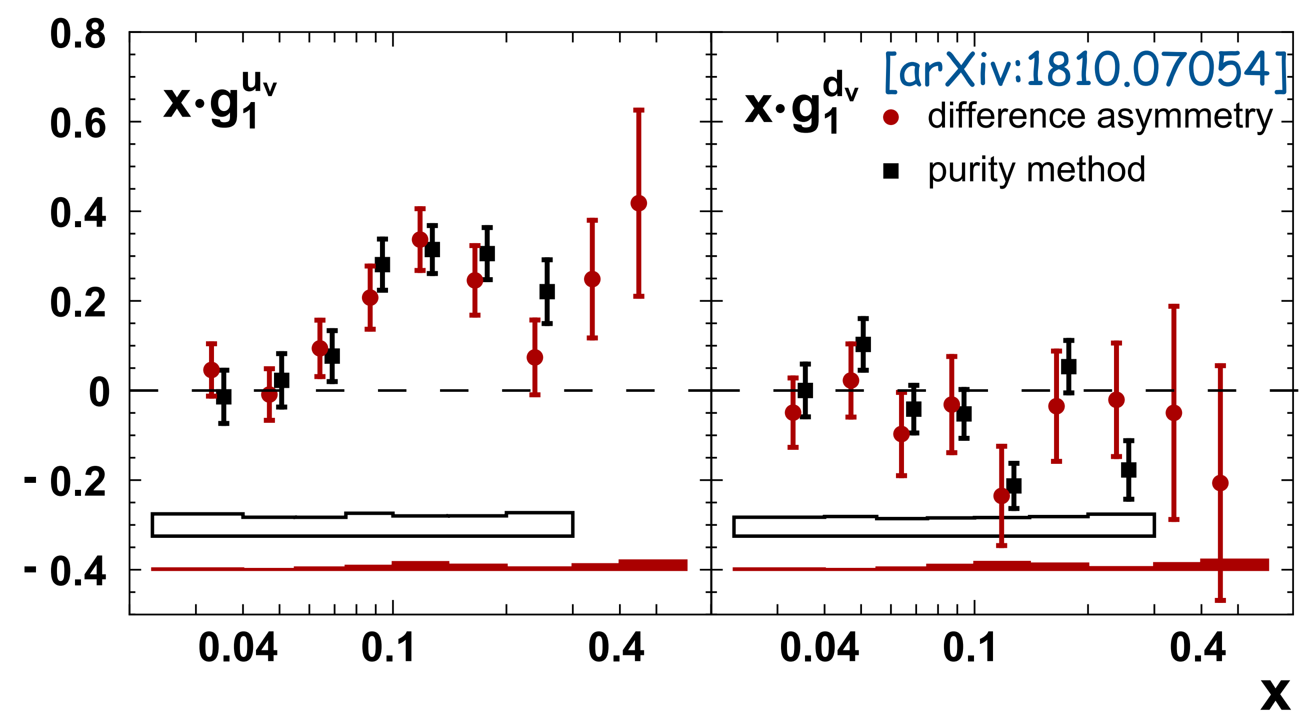
- no significant hadron-type dependence for deuterons
- deuteron results (unidentified hadrons) consistent with COMPASS

charge-difference asymmetries

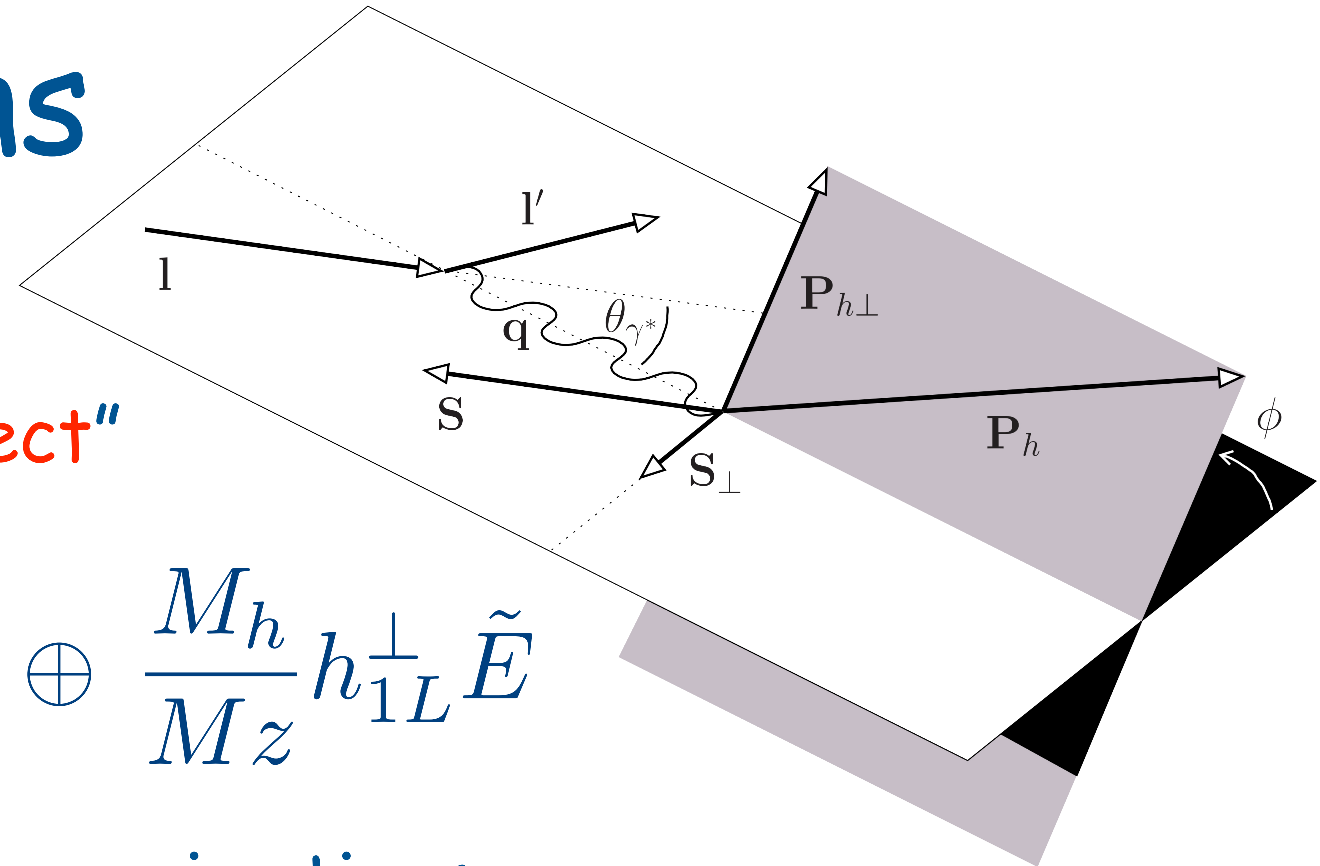
[arXiv:1810.07054]



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



azimuthal modulations



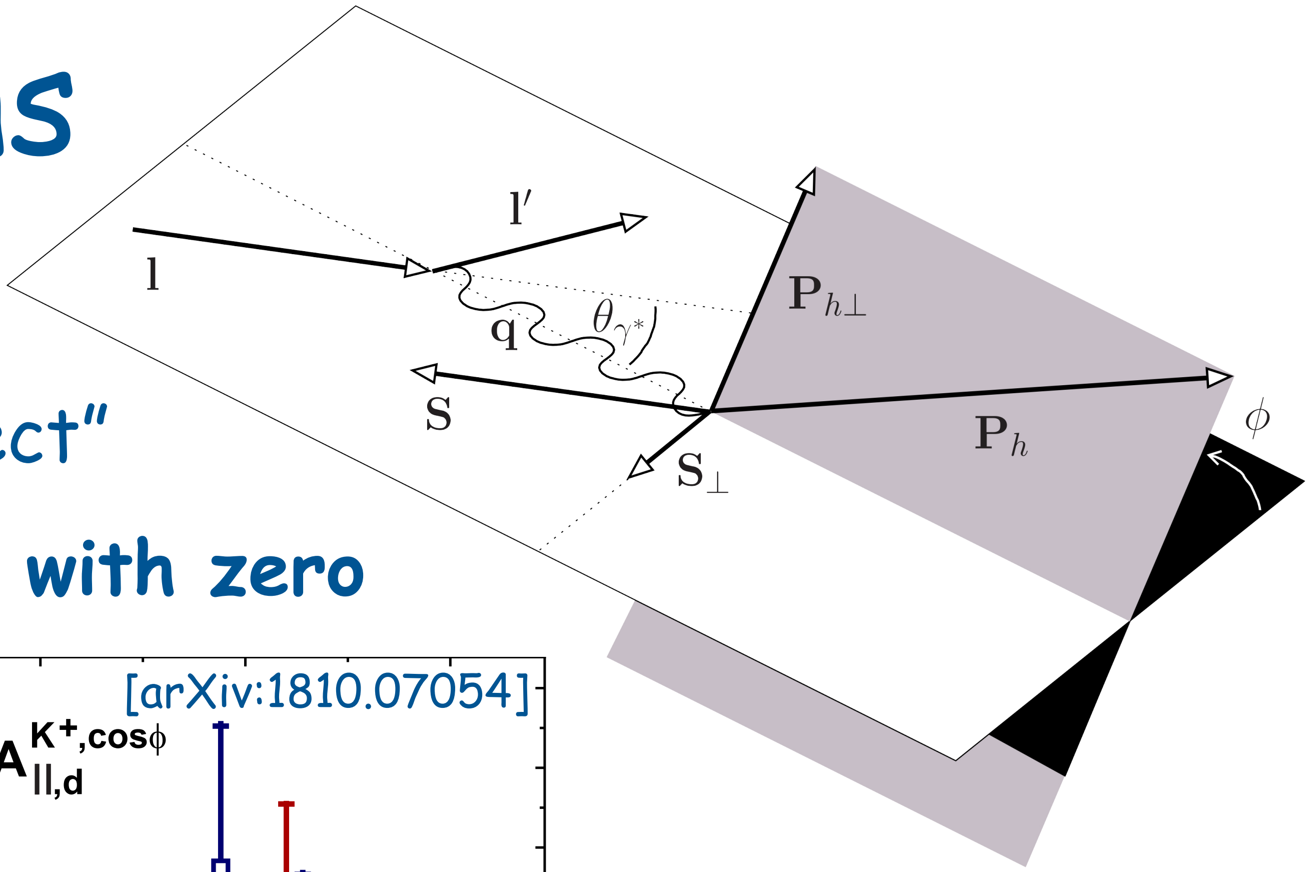
- twist-3 ☛ various contributions
- most prominent: "polarized Cahn effect"

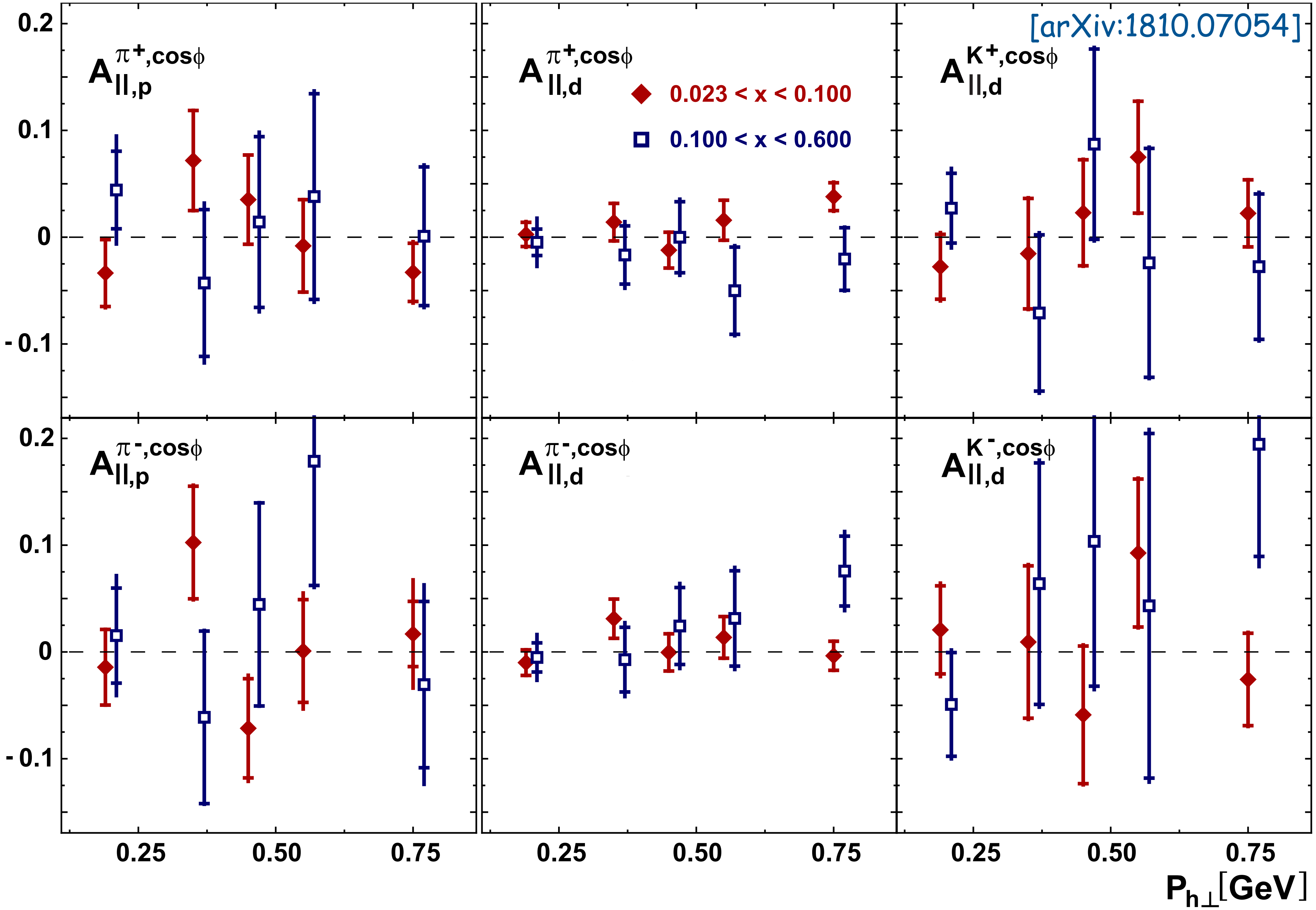
$$xg_L^{\perp}D_1 \oplus \frac{M_h}{Mz}g_1\tilde{D}^{\perp} \oplus xe_L H_1^{\perp} \oplus \frac{M_h}{Mz}h_{1L}^{\perp}\tilde{E}$$

  - the only one surviving WW-type approximations

azimuthal modulations

- twist-3 ☛ 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

data sets

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