QCD on and off the lattice [aka Schäfer Fest]

Sep 18 – 20, 2023
Universität Regensburg

the physics of hermes

a selective review

Gunar.Schnell @ desy.de

G.S. acknowledges support by the EU via STRONG-2020 (grant No. 824093) and the QuantERA project T-NiSQ (grant PCI2022-132984), as well as the Spanish Ministry of Science and Innovation (grant PID2022-136510NB-C33).

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Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

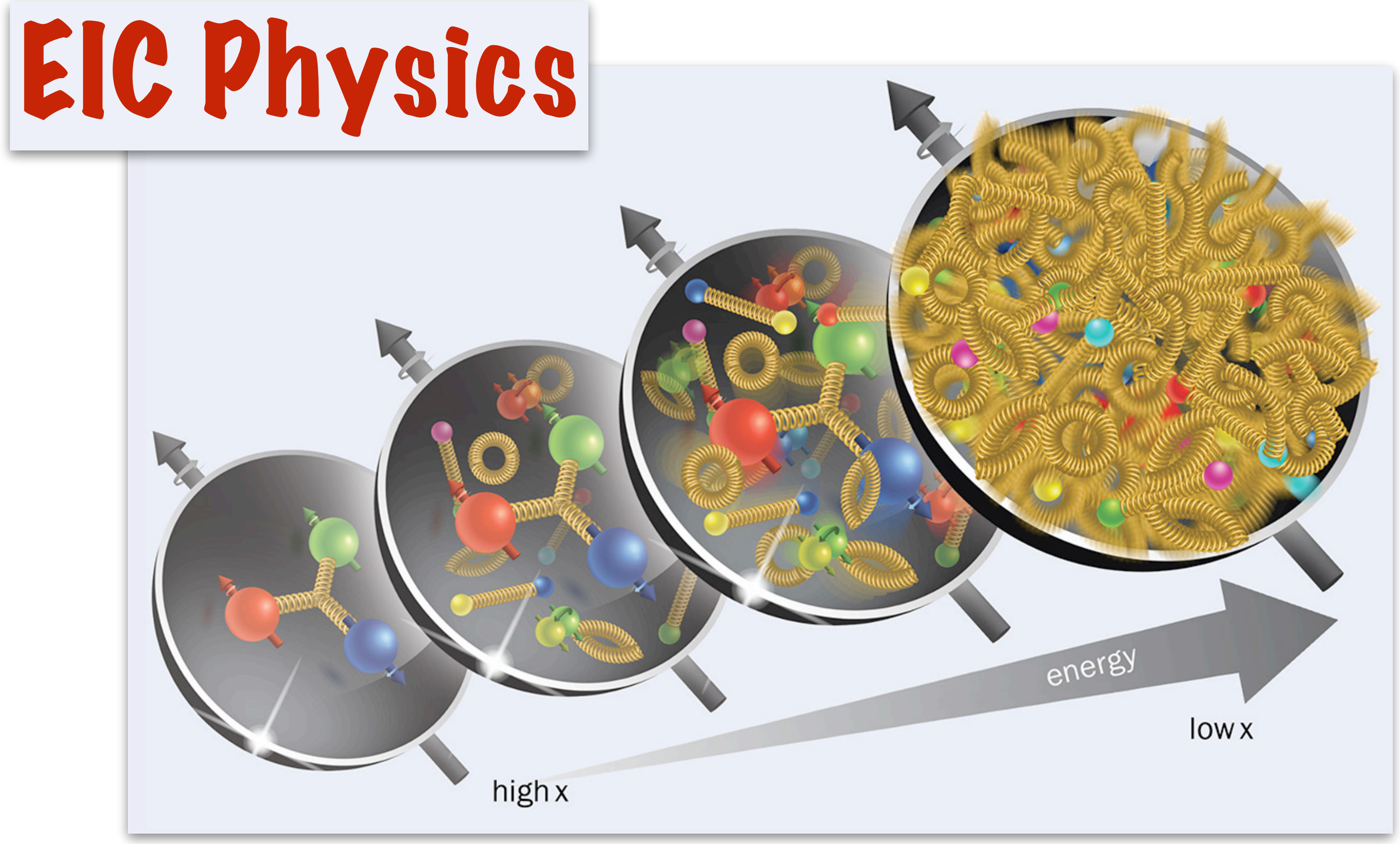
Connecting hadron/nuclear community with Lattice QCD

"Lattice Forum" (LatFor) Initiative (2001–2006)

- Procure significant computing resources for hadron and particle physics in Germany
- Hardware platforms under discussion: QCDOC, apeNEXT, PC clusters
- Several meetings involving the lattice, hadron and nuclear communities
- Strong link to FAIR: PANDA, CBM

Nucleon Structure in Lattice QCD (1997 — …)

- Structure functions
- Nucleon spin
- Strangeness in the nucleon
- Form factors, charges
- Generalised Parton Distributions
- Large-momentum Effective Theory — LaMET



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hermes

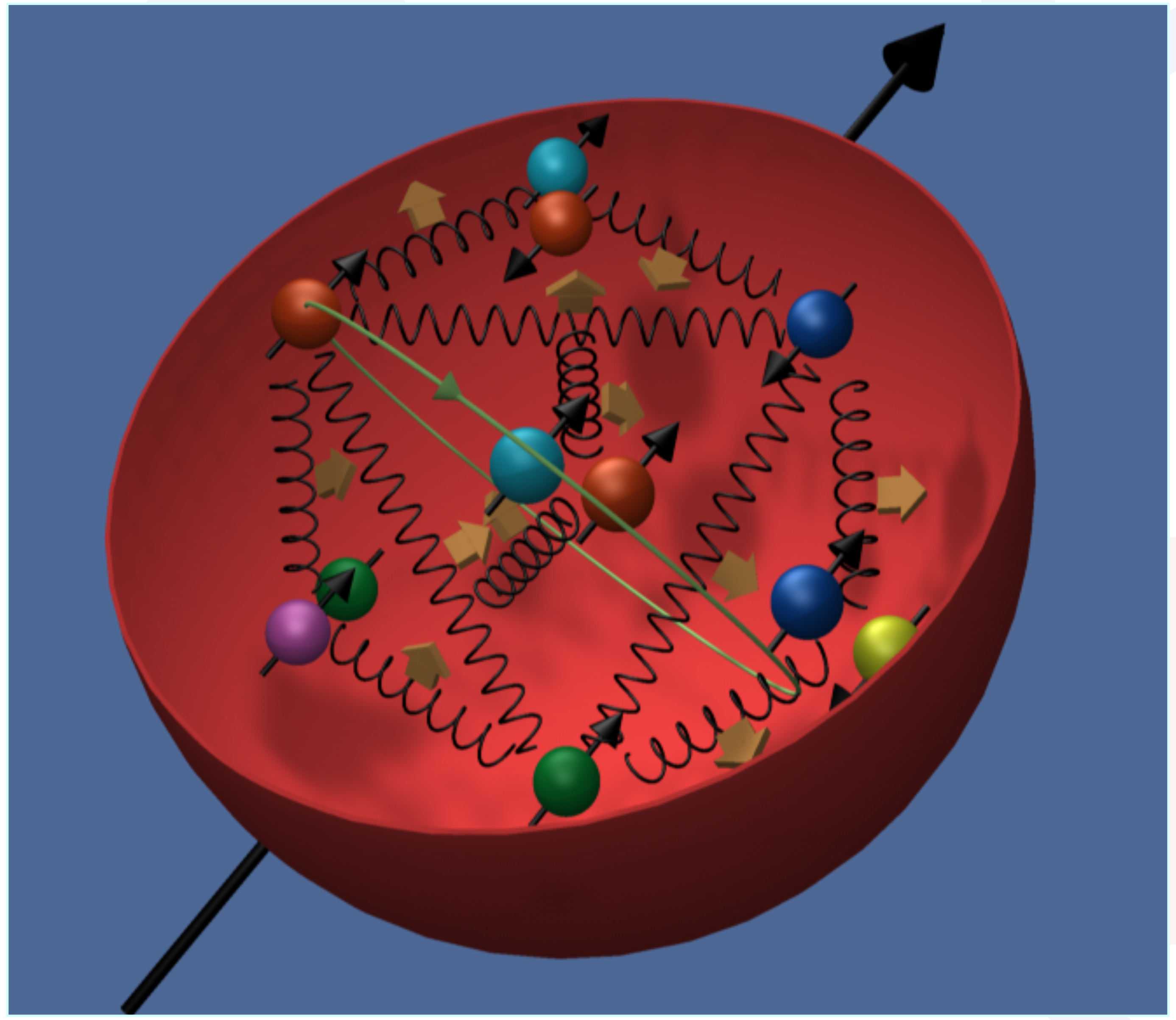
HERA measurement of spin

[C. Papanicolas (1989)]

the (original) quest: proton spin

"You think you understand something? Now add spin …" [Jaffe]

The understanding of the proton changed dramatically with the finding of EMC that the proton spin hardly comes from spin of quarks.



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

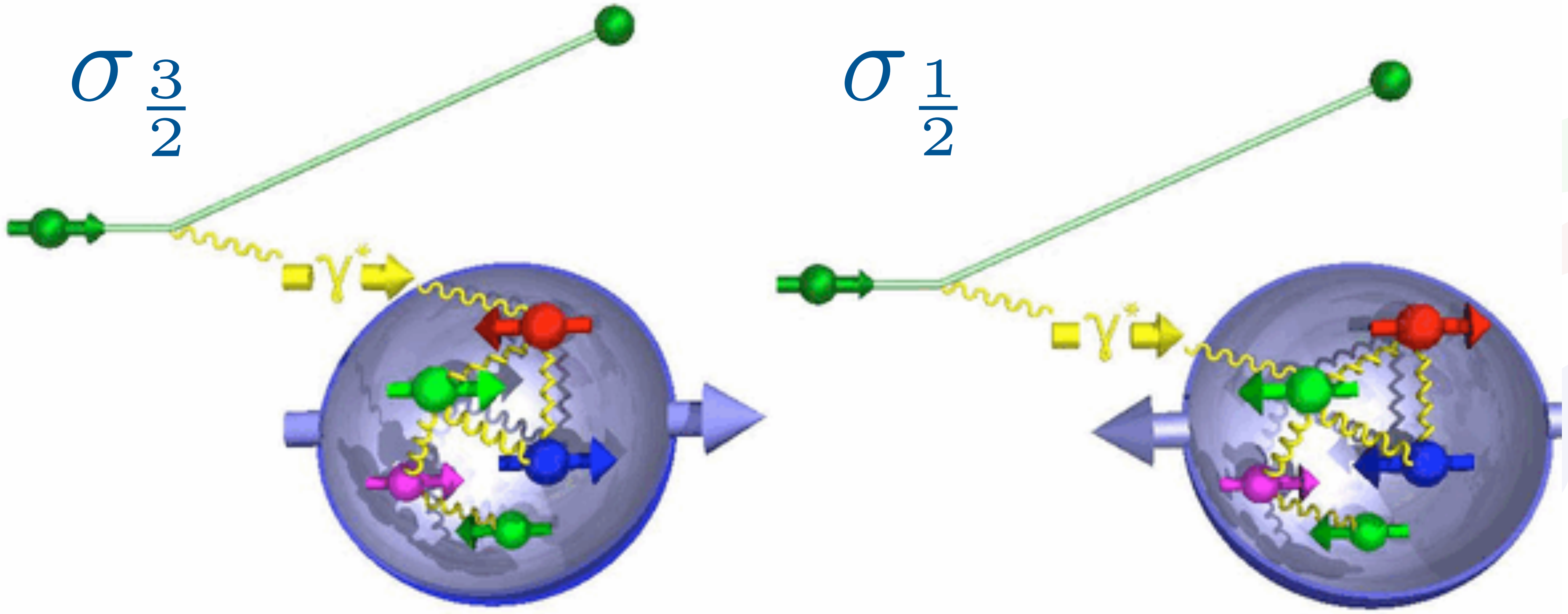
- $\frac{1}{2}\Delta\Sigma$ ⟵ quark spin
- ΔG ⟵ gluon spin
- $L_q + L_g$ ⟵ orbital angular momentum

[Jaffe & Manohar (1990)]

Deep-Inelastic Scattering

probing the structure of the nucleon

spin asymmetries



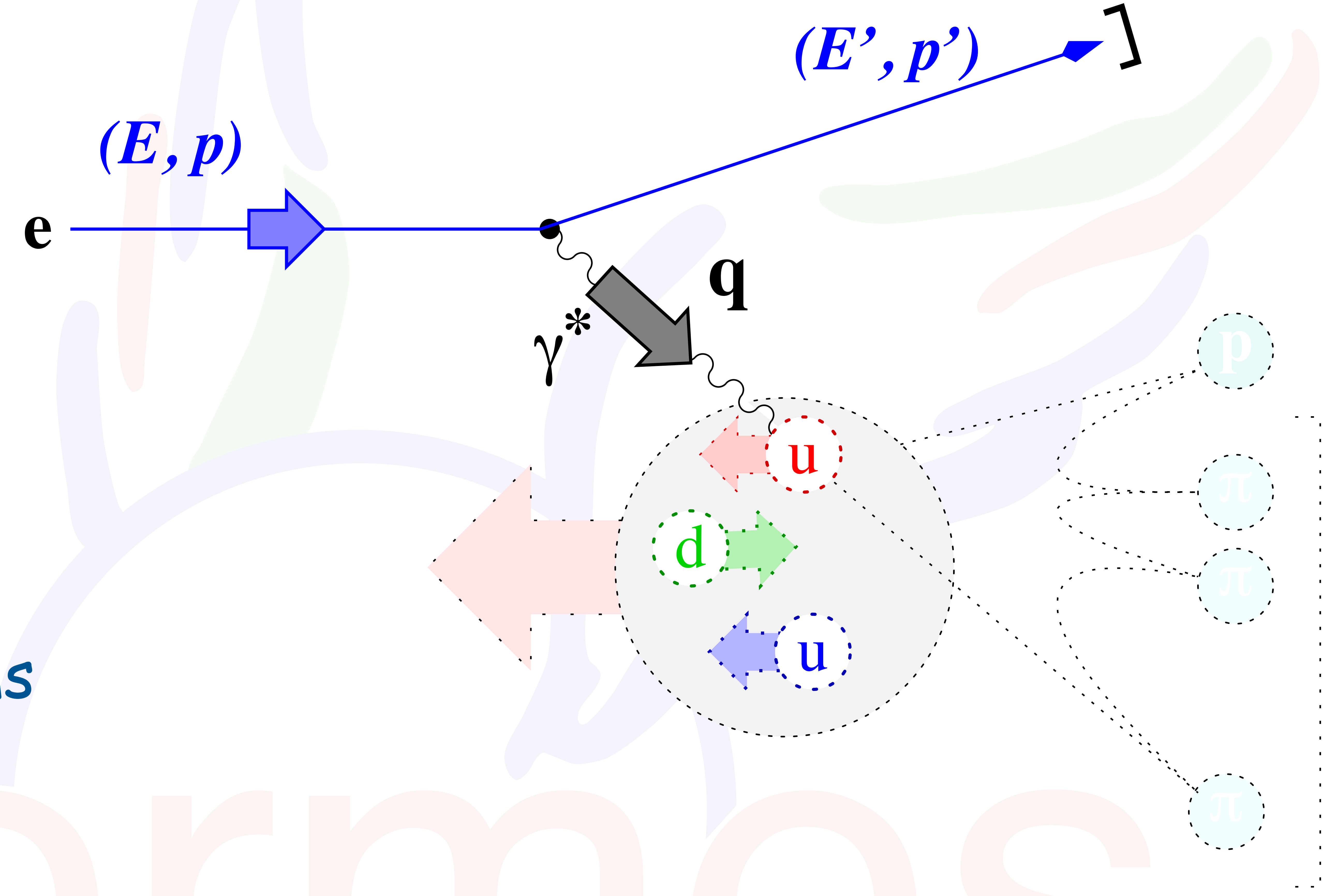
- exploit spin correlations (e.g., virtual photon couples only to spin-1/2 quarks with opposite spin)

- cross-section difference provides access to quark polarization

- in praxis form asymmetries to cancel systematics:

$$\frac{\sigma_{\frac{3}{2}} - \sigma_{\frac{1}{2}}}{\sigma_{\frac{3}{2}} + \sigma_{\frac{1}{2}}}$$

experimental prerequisites



- polarized lepton beams

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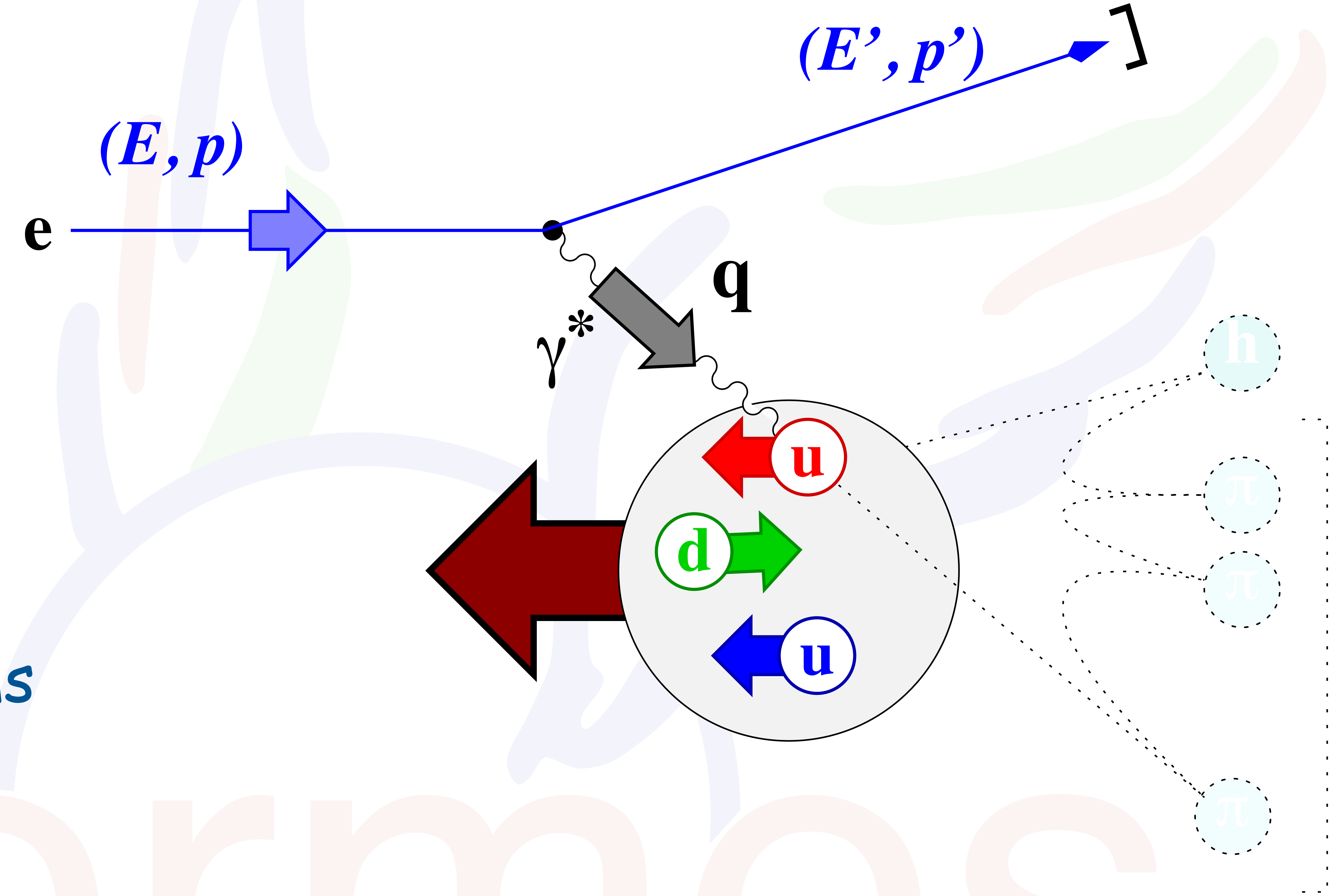

- polarized lepton beams
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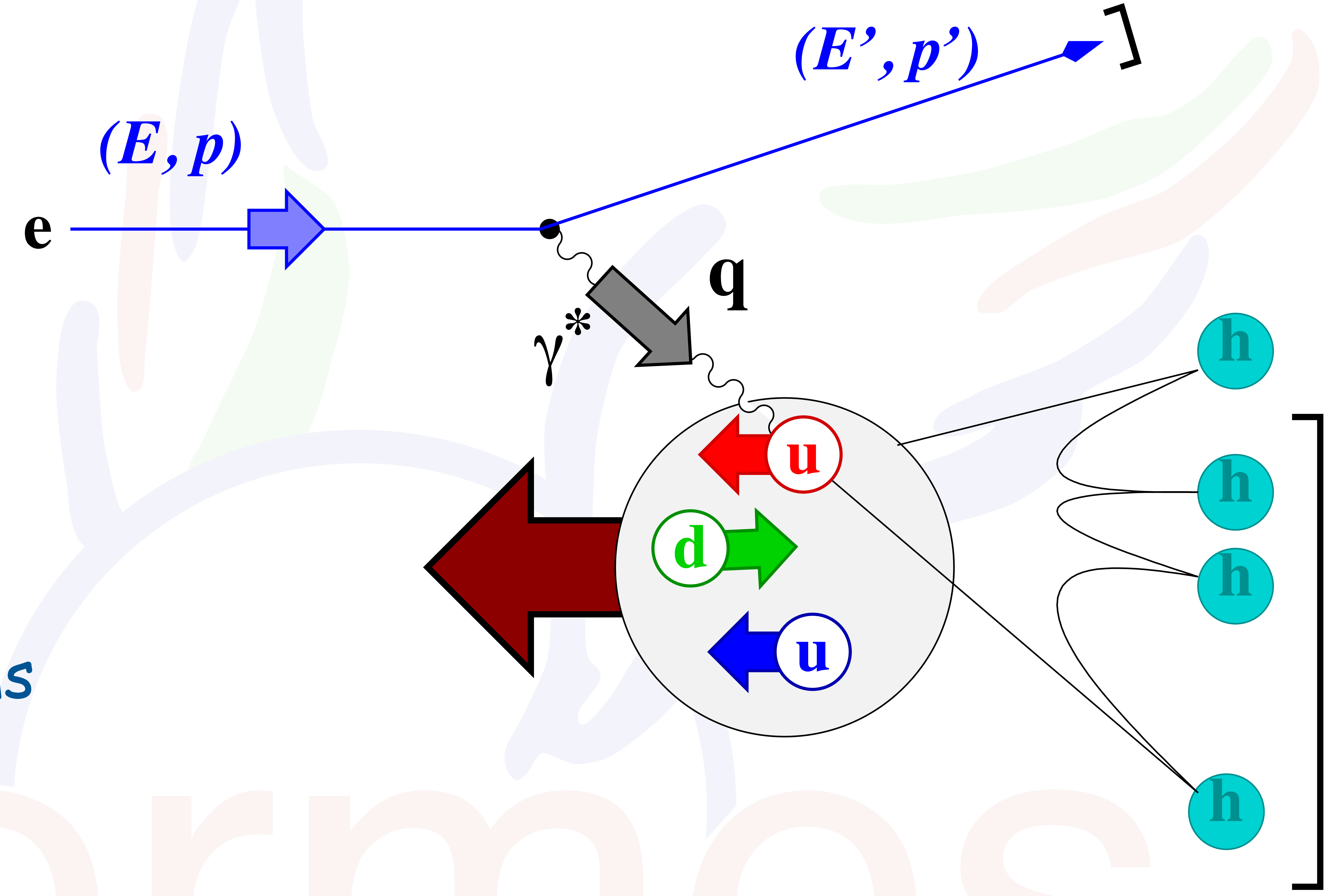

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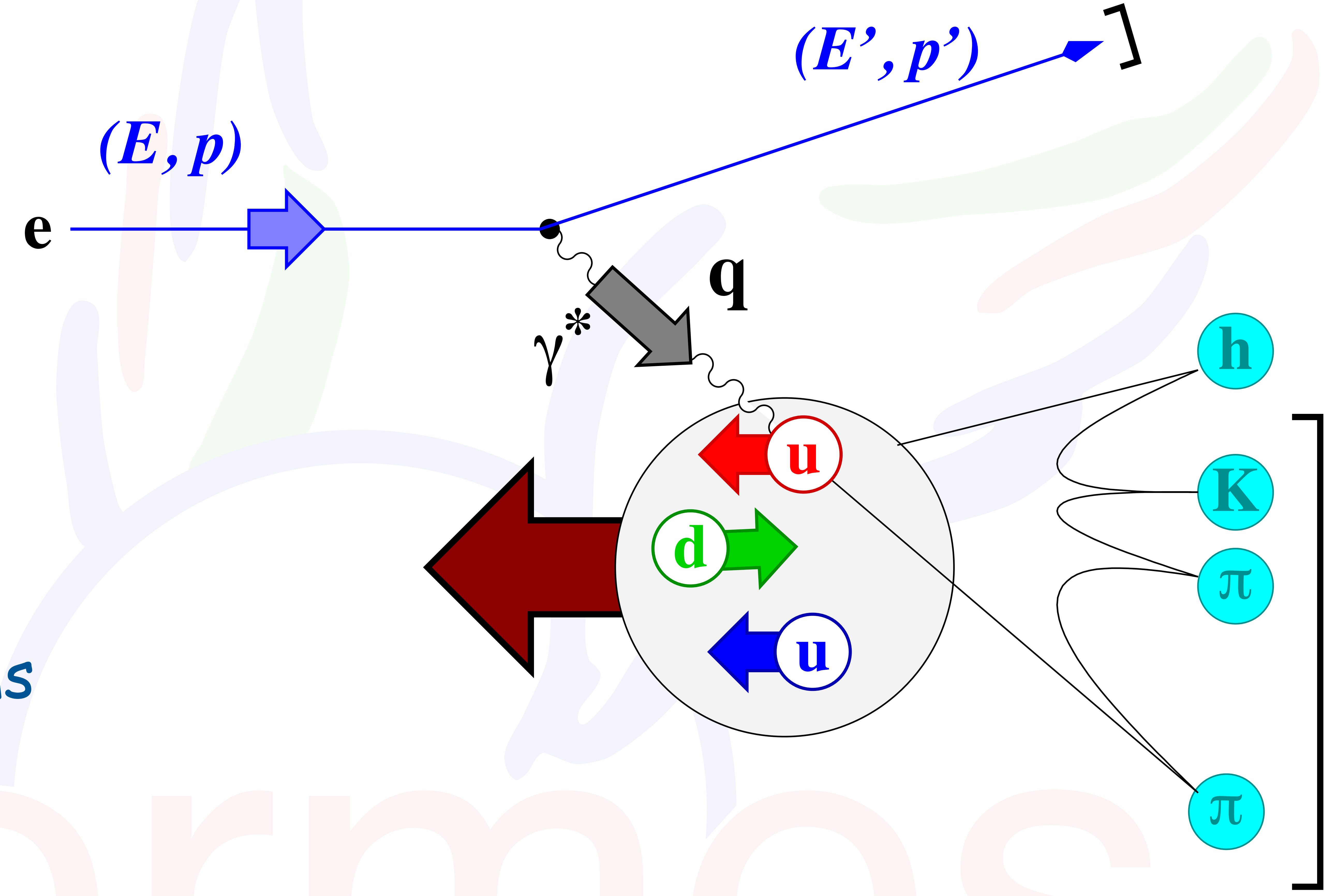

- polarized lepton beams
- polarized targets
- large-acceptance spectrometer
- good particle identification (PID)

experimental situation in the 1980s

- polarized beams
  - polarized electron beam at SLAC
    - polarized at source; high intensity
  - tertiary polarized muon beam at NA of SPS at CERN
    - highly polarized (weak meson decays); low intensity

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  - solid (e.g. NH_3) targets -> high density, but large dilution
- statistical precision: $\sim \frac{1}{f P_B P_T} \frac{1}{\sqrt{N}}$ (f… dilution factor)
  - solid targets f≈0.2 -> directly scales uncertainties (as do P_B & P_T)

new developments

self-polarized leptons in storage rings -> HERA

highly polarized gas targets

- why not combine for double-polarization experiment with excellent figure of merit?

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- 1987: two groups with similar ideas (North America … **R. Milner** & Europe … **K. Rith**)
  - head to DESY to measure spin asymmetries at HERA
  - two separate LOIs beginning of 1988

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- DESY management sympathetic, but …
  - common effort -> 12/1988 common collaboration 1990 proposal) and …

… conditions for approval

- demonstration of high longitudinal electron beam polarization
  - demonstration of transverse self-polarization of HERA $e^{\pm}$
  - successful spin rotation to obtain longitudinal polarization
- demonstration of high flux with high polarization from polarized sources …
- … and demonstration of storage-cell technique
- no compromises for HERA flagship colliders H1 and Zeus

beam polarization

- tiny asymmetry in spin-flip amplitude by emission of synchrotron radiation
  -> build-up of self polarization
  - degree of transverse polarization depends critically on machine energy and magnet alignment
  - longitudinal polarization through (movable) spin rotators in front / behind experiment (installed winter 1993/94) -> both helicities

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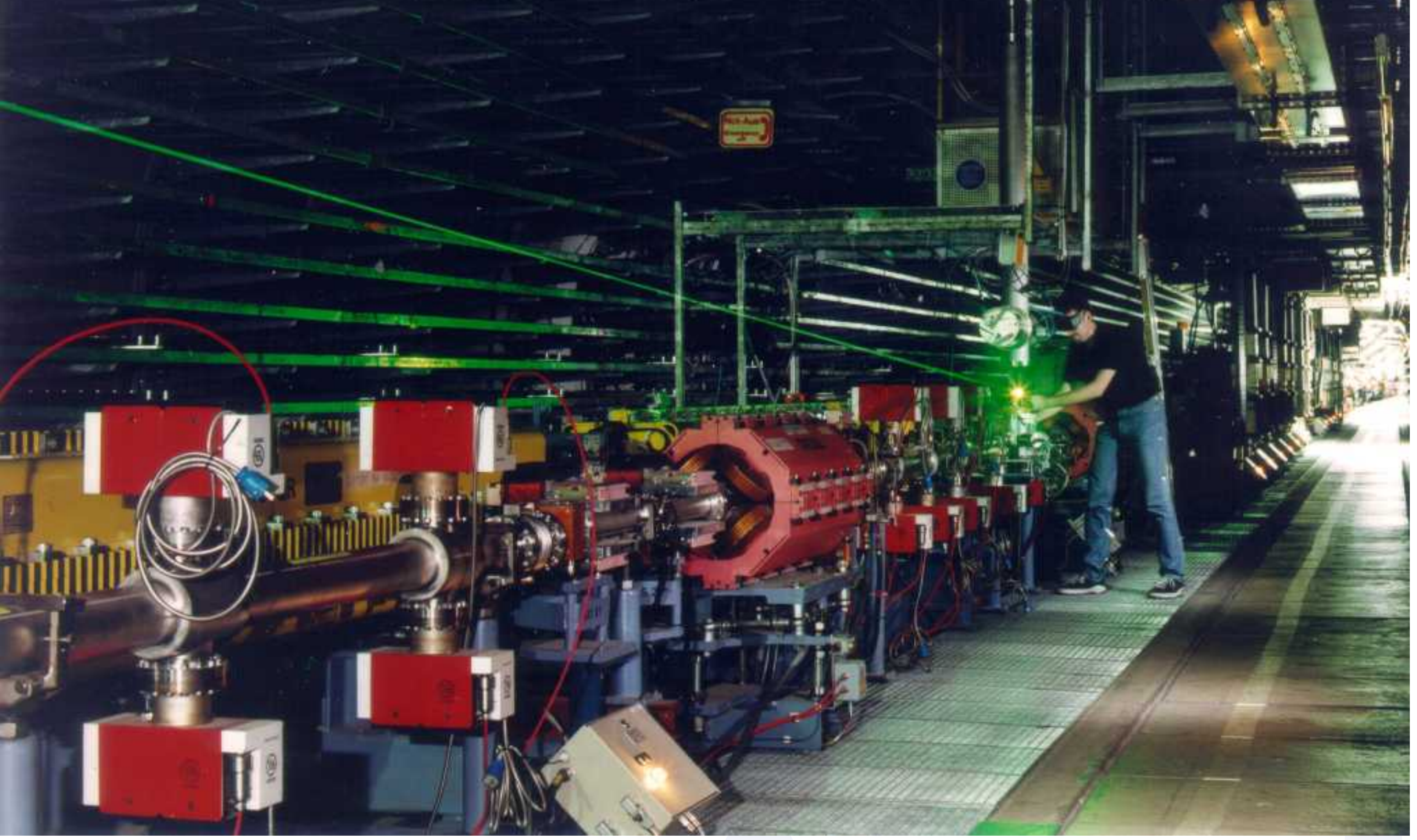
- HERA polarization
  - 11/1991: 8% ... first demonstration of self-polarization at HERA
  - 9/1992: 60% ... polarization sufficient for HERMES
  - 5/1994: 60% longitudinal polarization
- two independent Compton polarimeters at East and West Hall



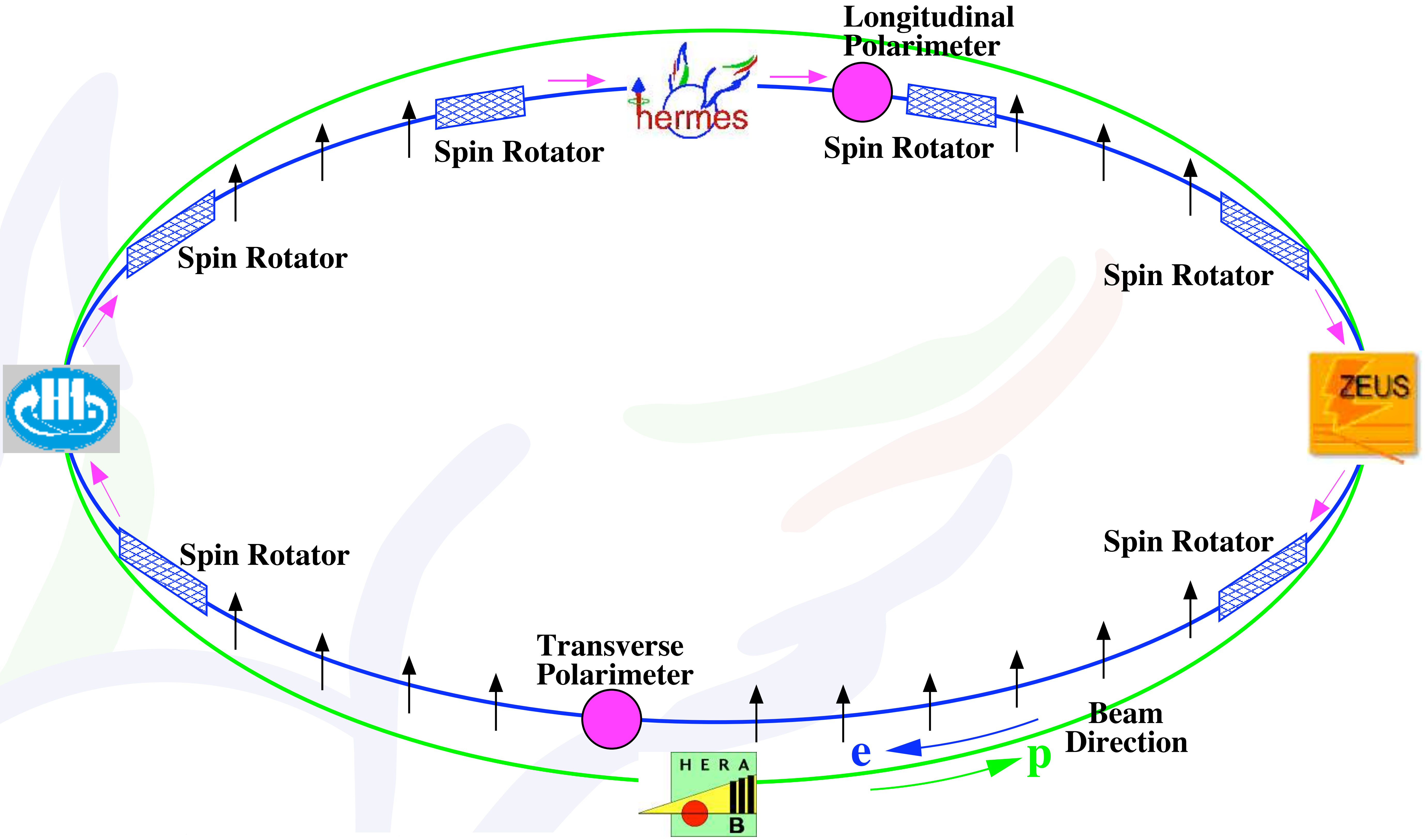
DESY TELEGRAMM

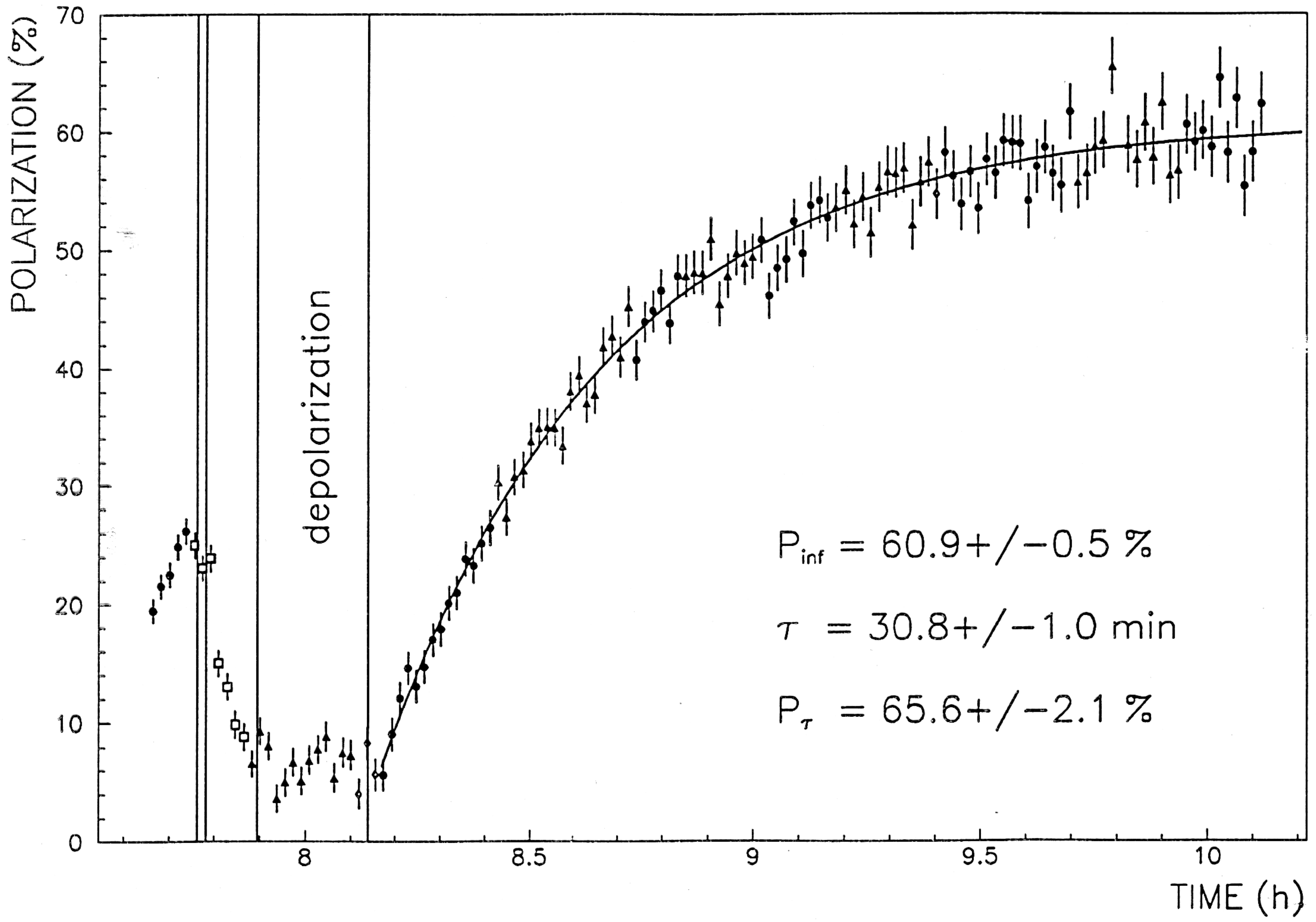
vom 24. November 1991

Erste Messung von Polarisation der Elektronen in HERA

Letzte Woche wurde in HERA zum ersten Mal die Polarisation von Elektronen, die Ausrichtung ihrer "Spins", beobachtet. Im Bereich des geraden Abschnitts HERA-West wurde dazu ein Laserstrahl auf die umlaufenden Elektronen gerichtet, und es wurden die an den Elektronen zurückgestreuten Photonen nachgewiesen. Der Laserstrahl war im Wechsel (90mal in der Sekunde) links und rechts polarisiert. Bei einer Strahlenergie von 26,67 GeV wurde auf diese Weise ein Polarisationsgrad der Elektronen von etwa 8% gemessen. Durch die Veränderung der Beschleunigungsspannung in HERA konnte ihre Polarisation gezielt und reproduzierbar variiert werden. Eine in 10MeV-Energieschritten durchgeführte Messung zeigt Strukturen, die von Depolarisationsresonanzen herrühren.

Elektronen besitzen die Eigenschaft kleiner Kreisel, sie haben einen "Eigendrehimpuls" oder "Spin". In der Teilchenphysik gibt es einige Fragestellungen, die nur mit solchen "polarisierten" Elektronen untersucht werden können.

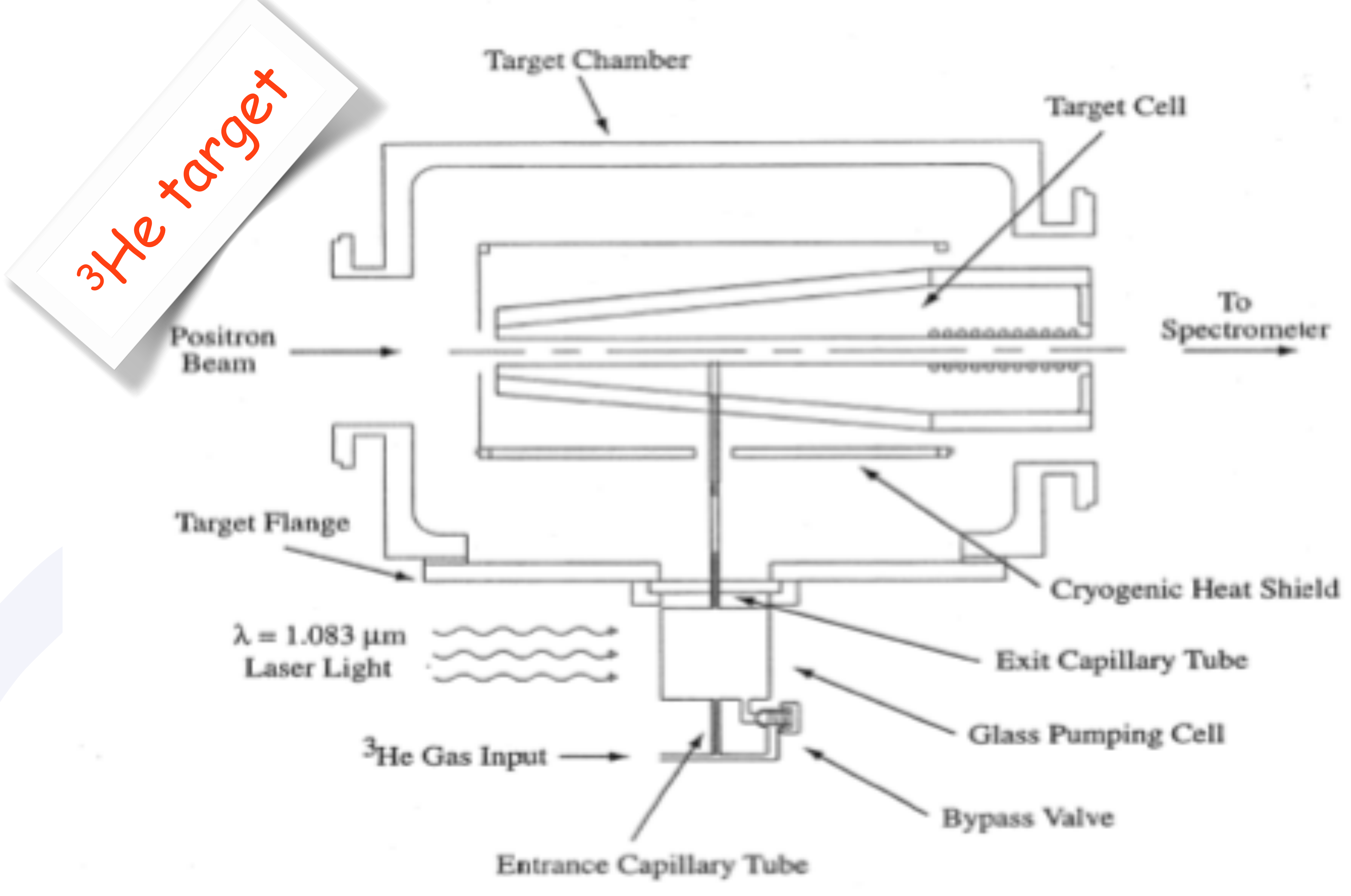


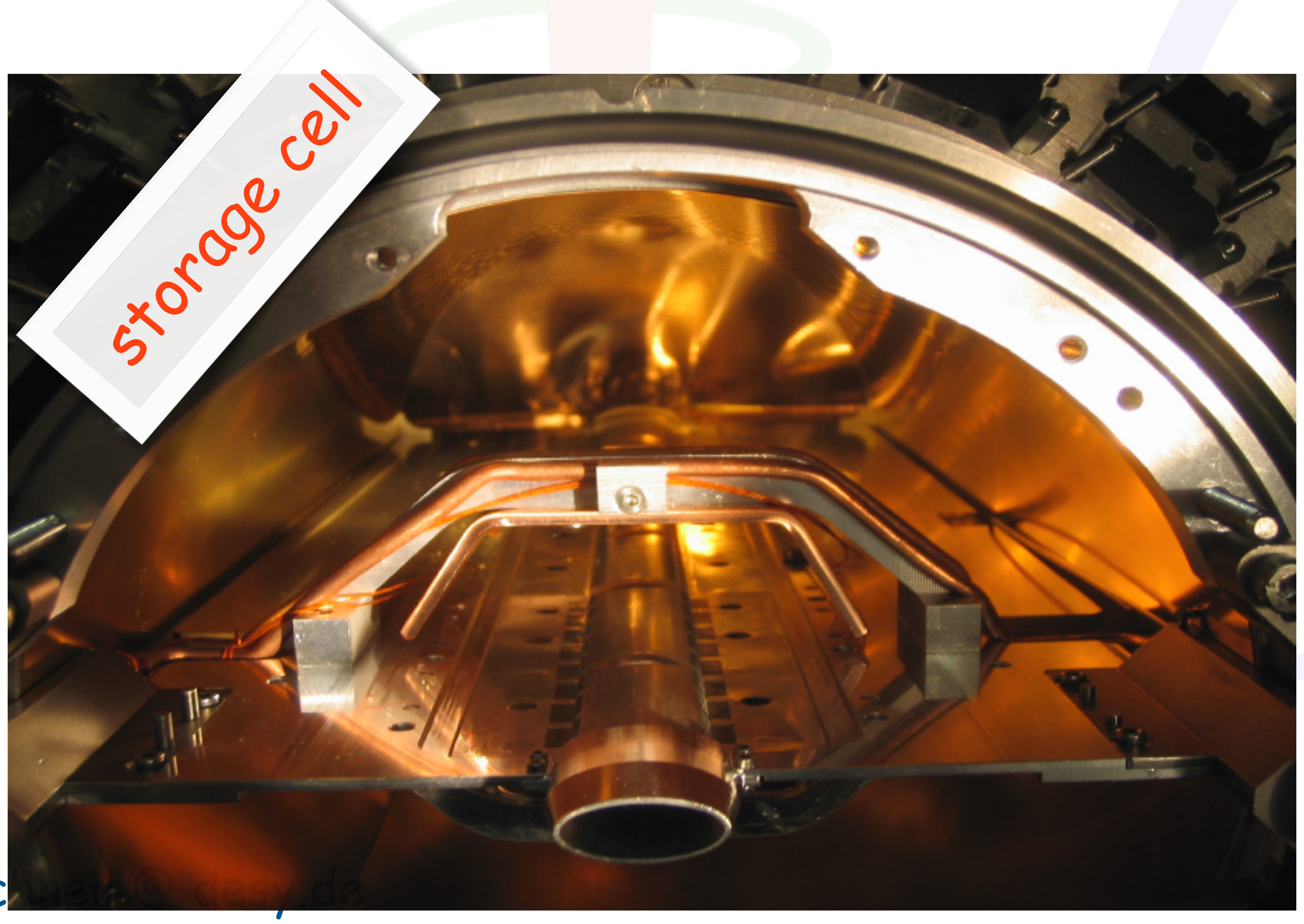


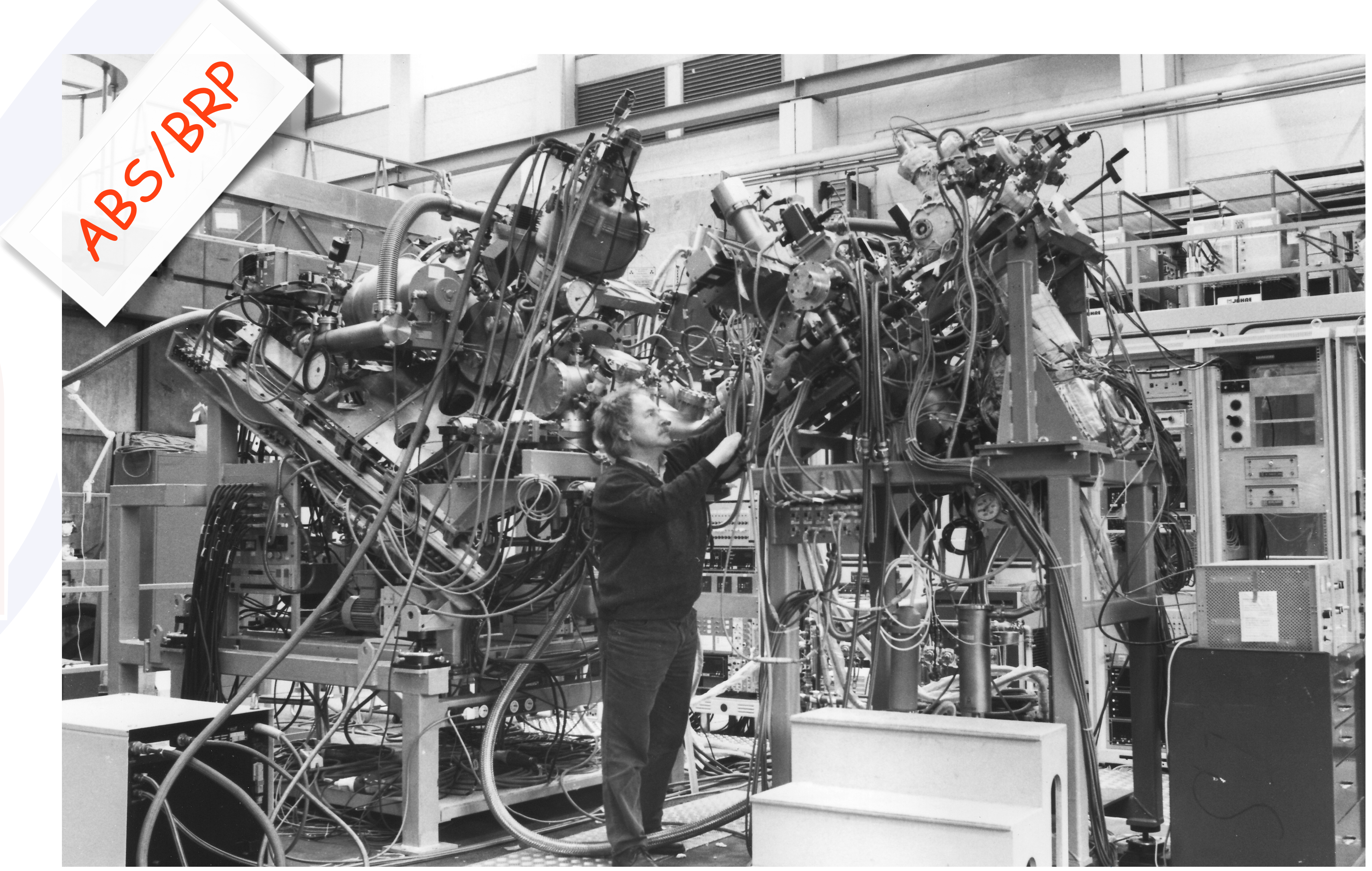
HERMES gas targets

novel **pure** gas target:

- internal to HERA lepton ring
- longitudinally polarized: ^1H, ^2H, ^3He
- transversely polarized: ^1H
- rapid spin reversal every 60...180s
- unpolarized (^1H ... Xe)







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☛ 1993 final approval & TDR

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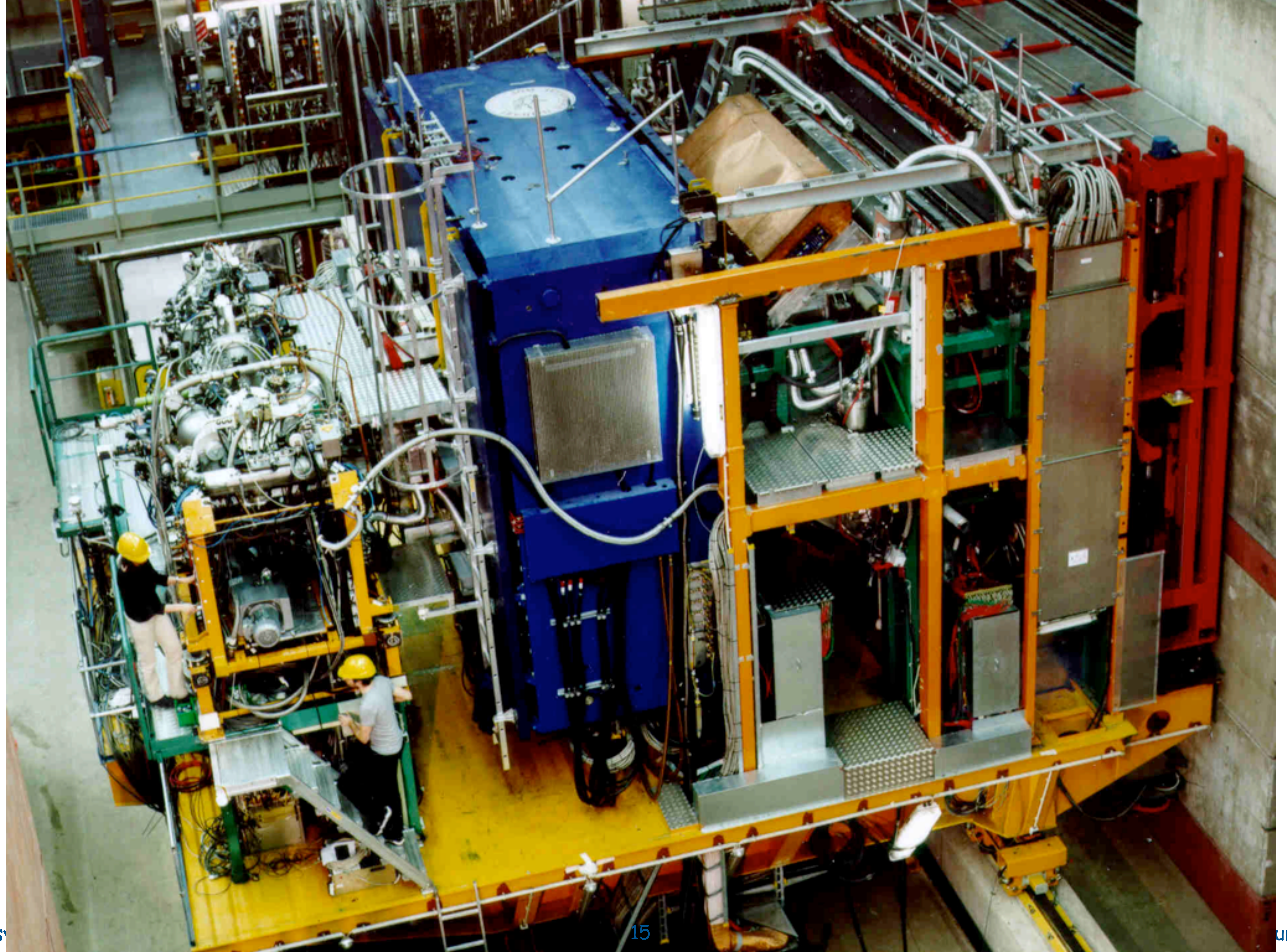
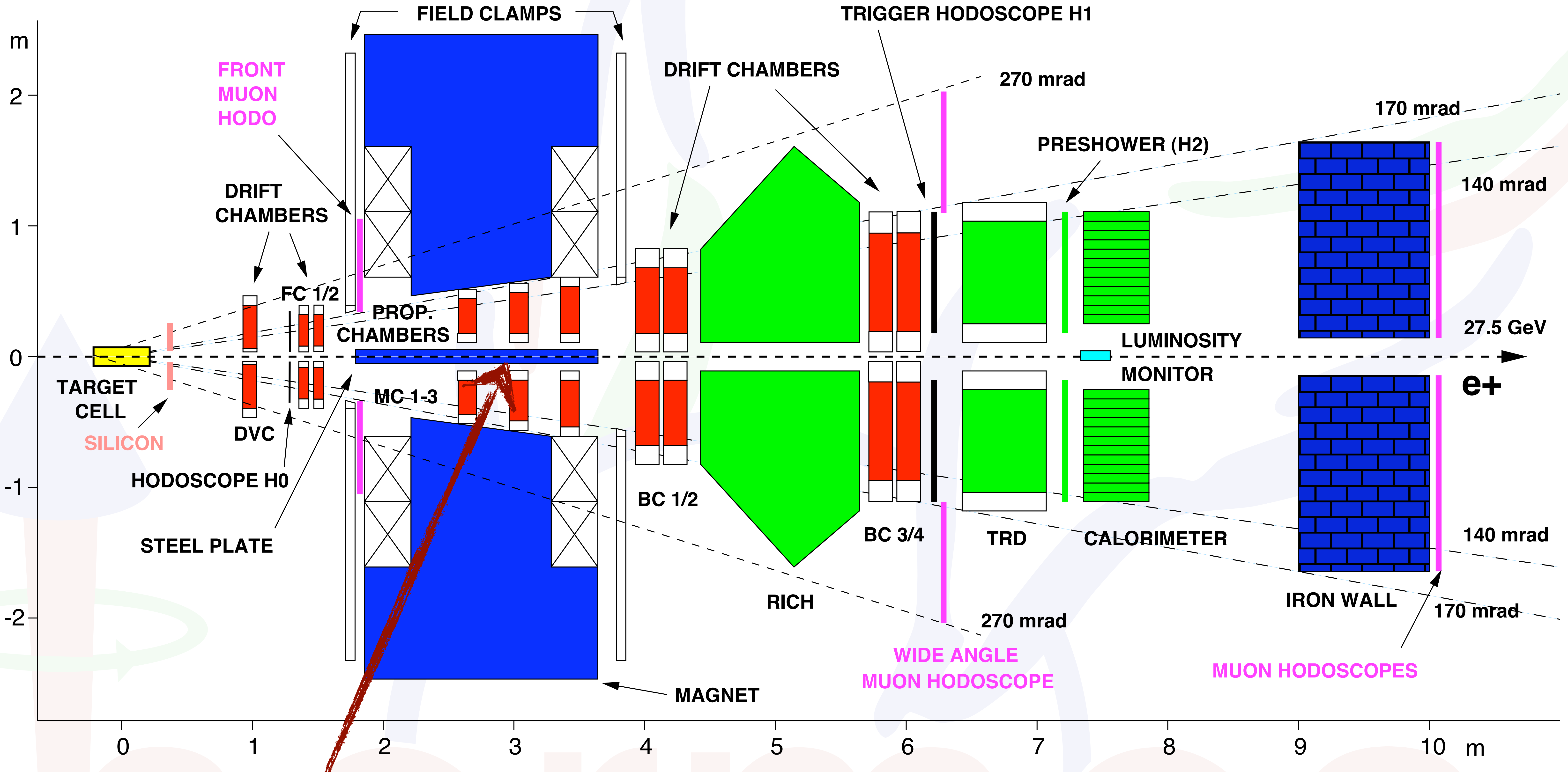
☛ 1995-2007 data taking



HERMES (1998-2005) schematically



two (mirror-symmetric) halves

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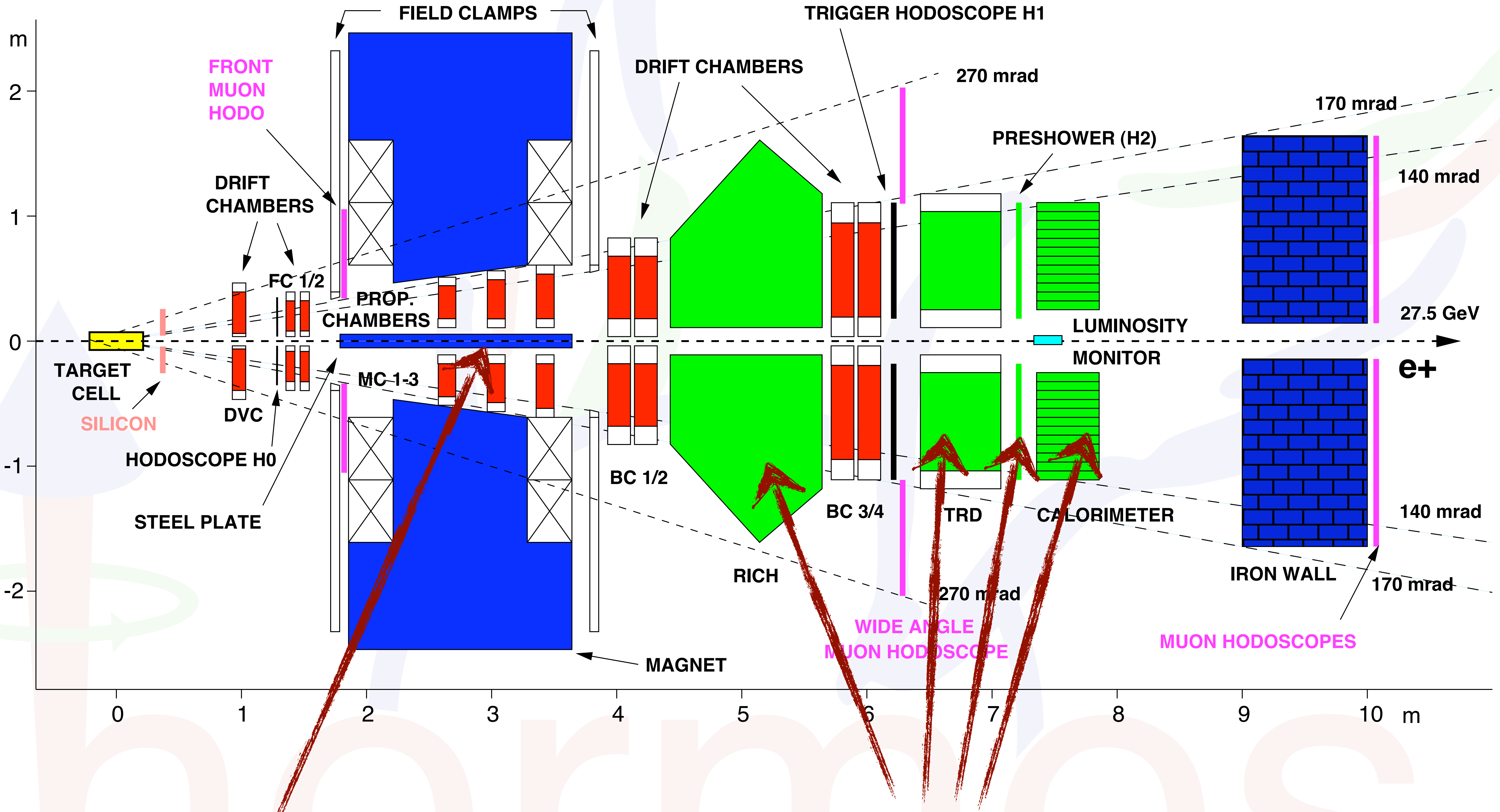


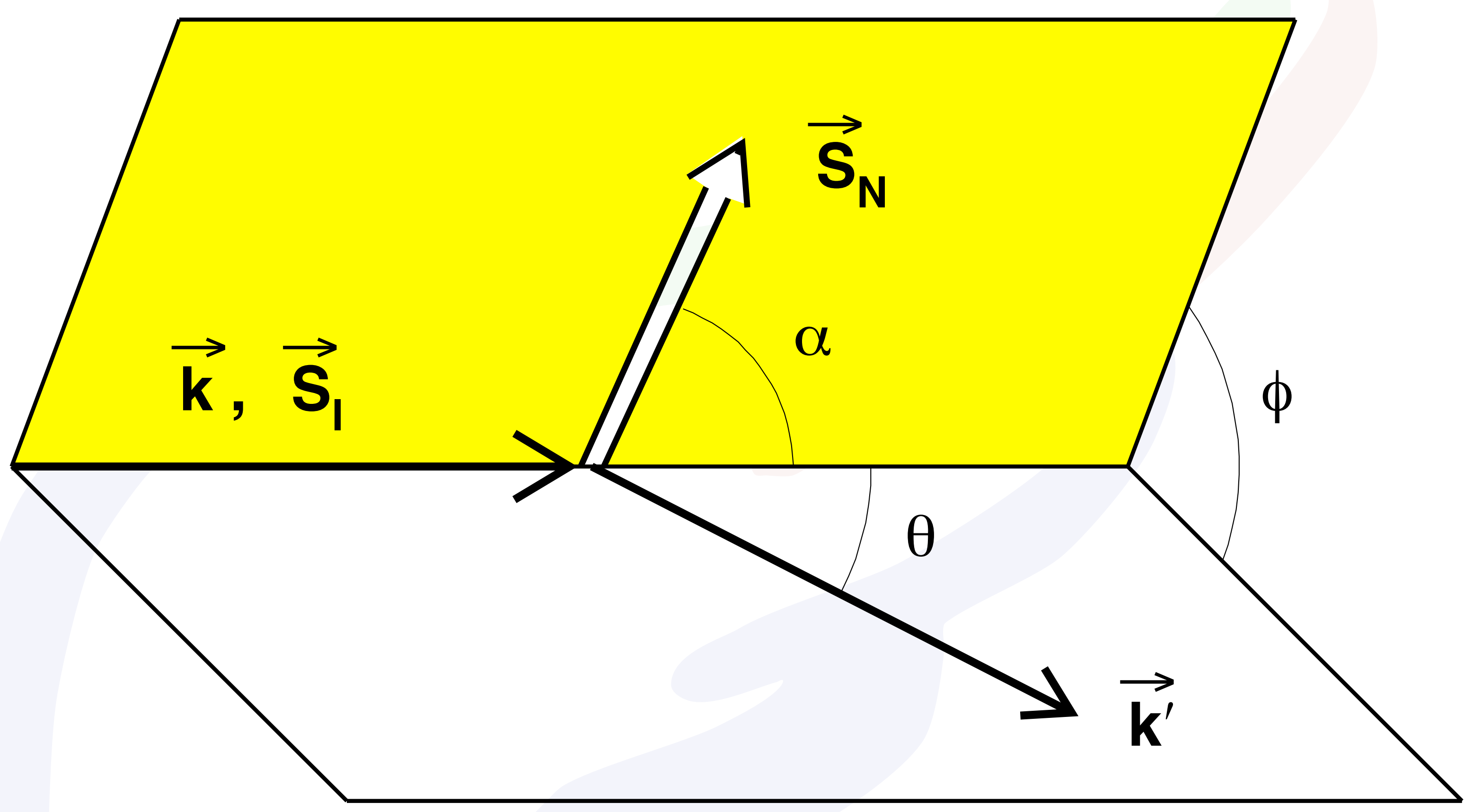
two (mirror-symmetric) halves

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination in momentum range of 2 GeV < p < 15 GeV

bread & butter physics

inclusive DIS (one-photon exchange)

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



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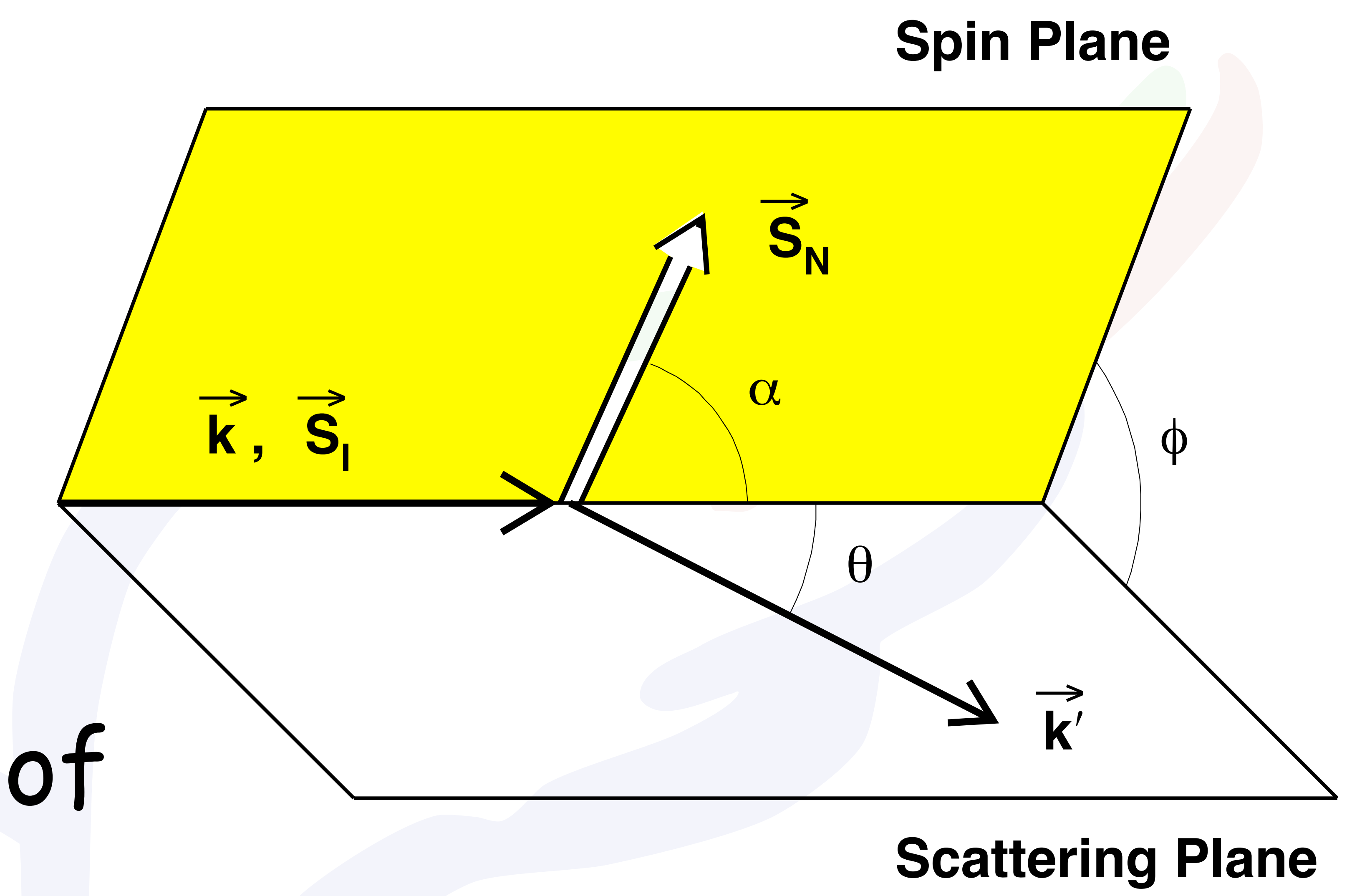
Lepton Tensor

Hadron Tensor parametrized in terms of Structure Functions



$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$
$$-S_l S_N \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{2}g_2(x,Q^2)\right]$$
$$+S_l S_N \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

polarized structure function $g_1(x)$

N·H
ELSEVIER

10 July 1997

Physics Letters B 404 (1997) 383–389

PHYSICS LETTERS B

Measurement of the neutron spin structure function g_1^n with a polarized ^{3}He internal target

HERMES Collaboration

, Y. Sakemi [ab], I. Savin [g], K.P. Schüler [e],

polarized structure function $g_1(x)$

first HERMES result

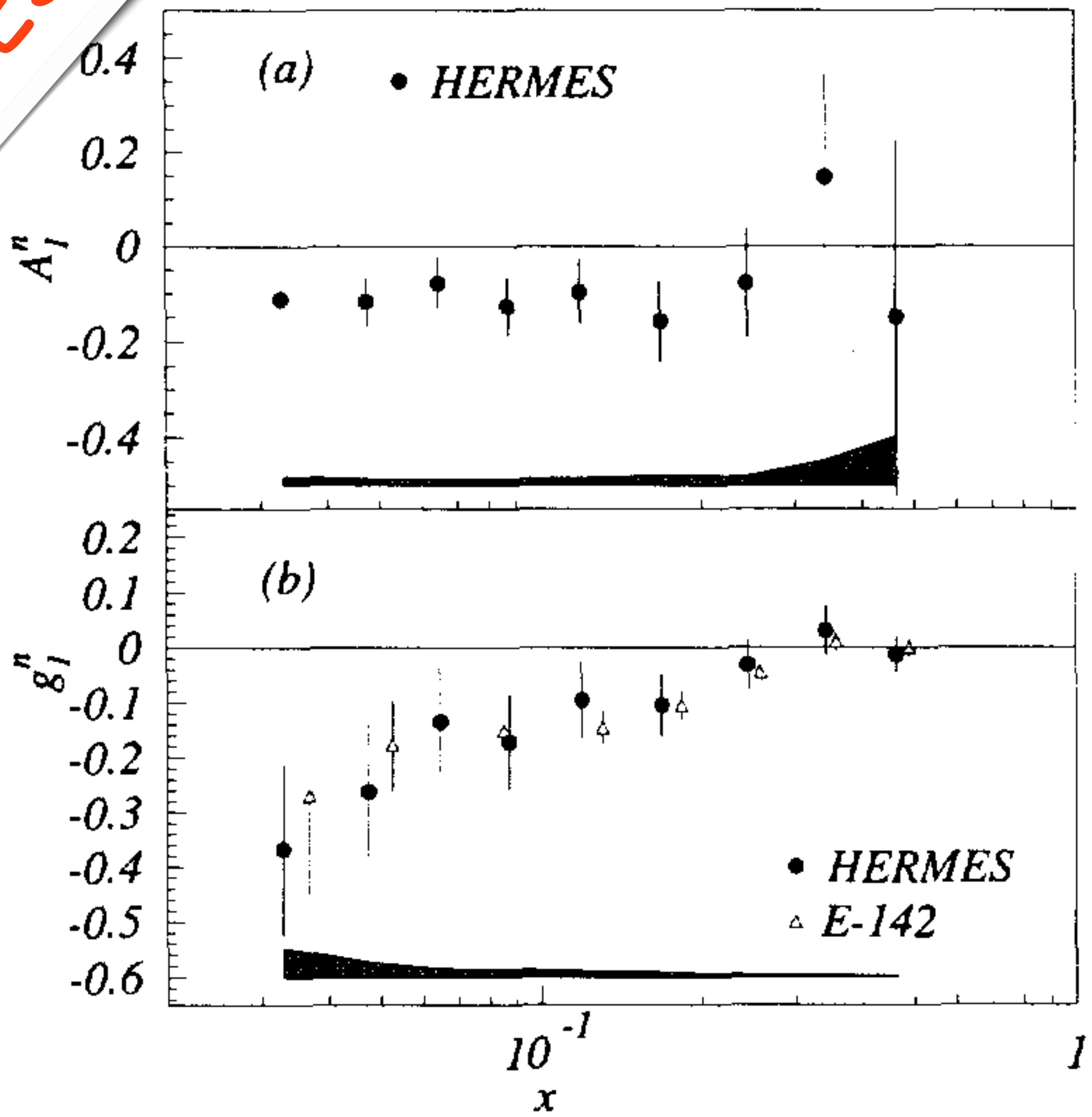
10 July 1997

ELSEVIER

Physics Letters B 404 (1997) 383–389

PHYSICS LETTERS B

M... ...unction g_1^n with a



on $g_1(x)$

The hermes Soccer Team

Top row: Bruce Bray, Kalen Martens, Richard Milner, Marc Beckmann, Mike Vetterli, Wolfgang Lorenzon, Eric Belz
Bottom row: Ralf Kaiser, Johan Blouw, Greg Rakness, Michael Spengos, Armand Simon, Gunnar Schnell, Erhard Steffens

HERMES vs. SLAC E154: 3 – 2 (Caltech, May 1996)

Andreas & HERMES

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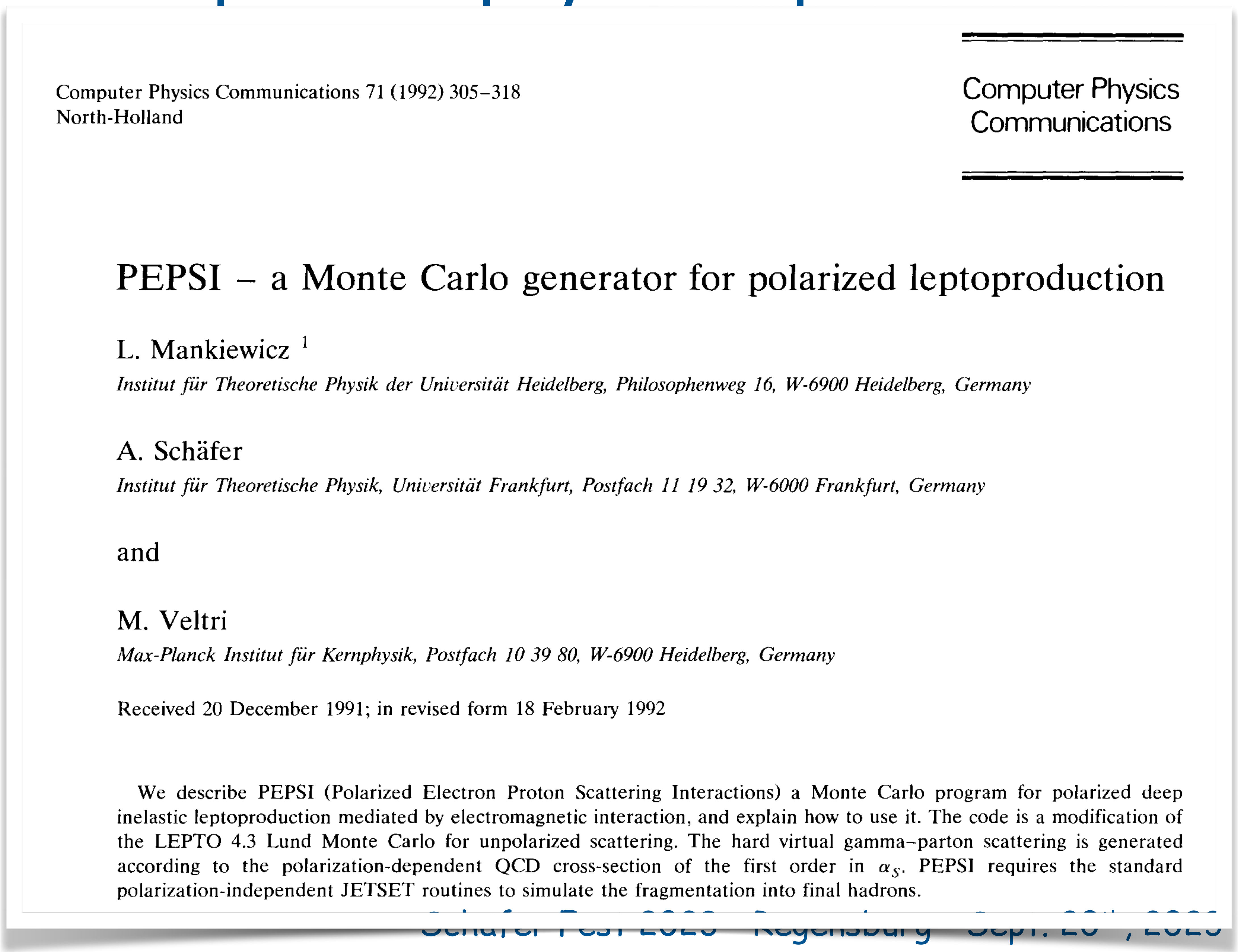

Computer Physics Communications 71 (1992) 305–318
North-Holland

Computer Physics Communications

PEPSI – a Monte Carlo generator for polarized leptoproduction

L. Mankiewicz [1]
Institut für Theoretische Physik der Universität Heidelberg, Philosophenweg 16, W-6900 Heidelberg, Germany

A. Schäfer
Institut für Theoretische Physik, Universität Frankfurt, Postfach 11 19 32, W-6000 Frankfurt, Germany

and

M. Veltri
Max-Planck Institut für Kernphysik, Postfach 10 39 80, W-6900 Heidelberg, Germany

Received 20 December 1991; in revised form 18 February 1992

We describe PEPSI (Polarized Electron Proton Scattering Interactions) a Monte Carlo program for polarized deep inelastic leptoproduction mediated by electromagnetic interaction, and explain how to use it. The code is a modification of the LEPTO 4.3 Lund Monte Carlo for unpolarized scattering. The hard virtual gamma–parton scattering is generated according to the polarization-dependent QCD cross-section of the first order in α_S. PEPSI requires the standard polarization-independent JETSET routines to simulate the fragmentation into final hadrons.

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- a look at the HERMES author data base reveals:

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schaefer  regensburg [join Jan 99] [dq] [hipt] [azim] [f2] [gdhr]
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- co-authored 67 HERMES papers

Andreas & HERMES

Andreas Schäfer (Regensburg U.) iD

hep-th | nucl-th

Author Identifier: A.Schafer.1

Advisor: Berndt Muller

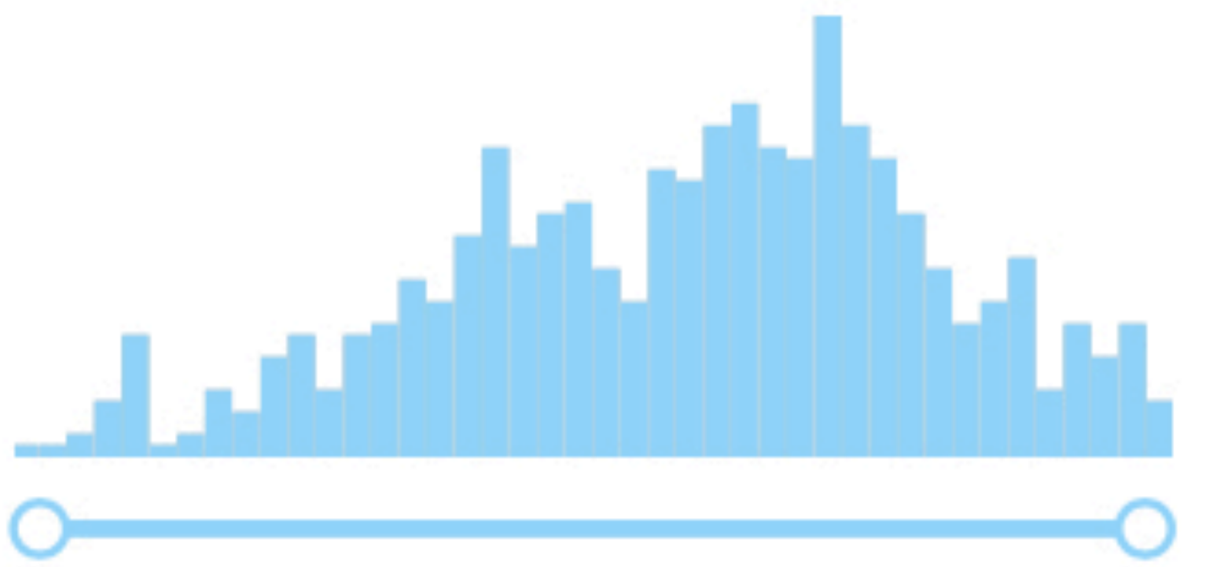
present
STAFF, Regensburg U.

edit

Updated on Sep 14, 2023

Research works (647) | Cited By

Date of paper



647 results | cite all | claim

Citation Summary | Most Cited

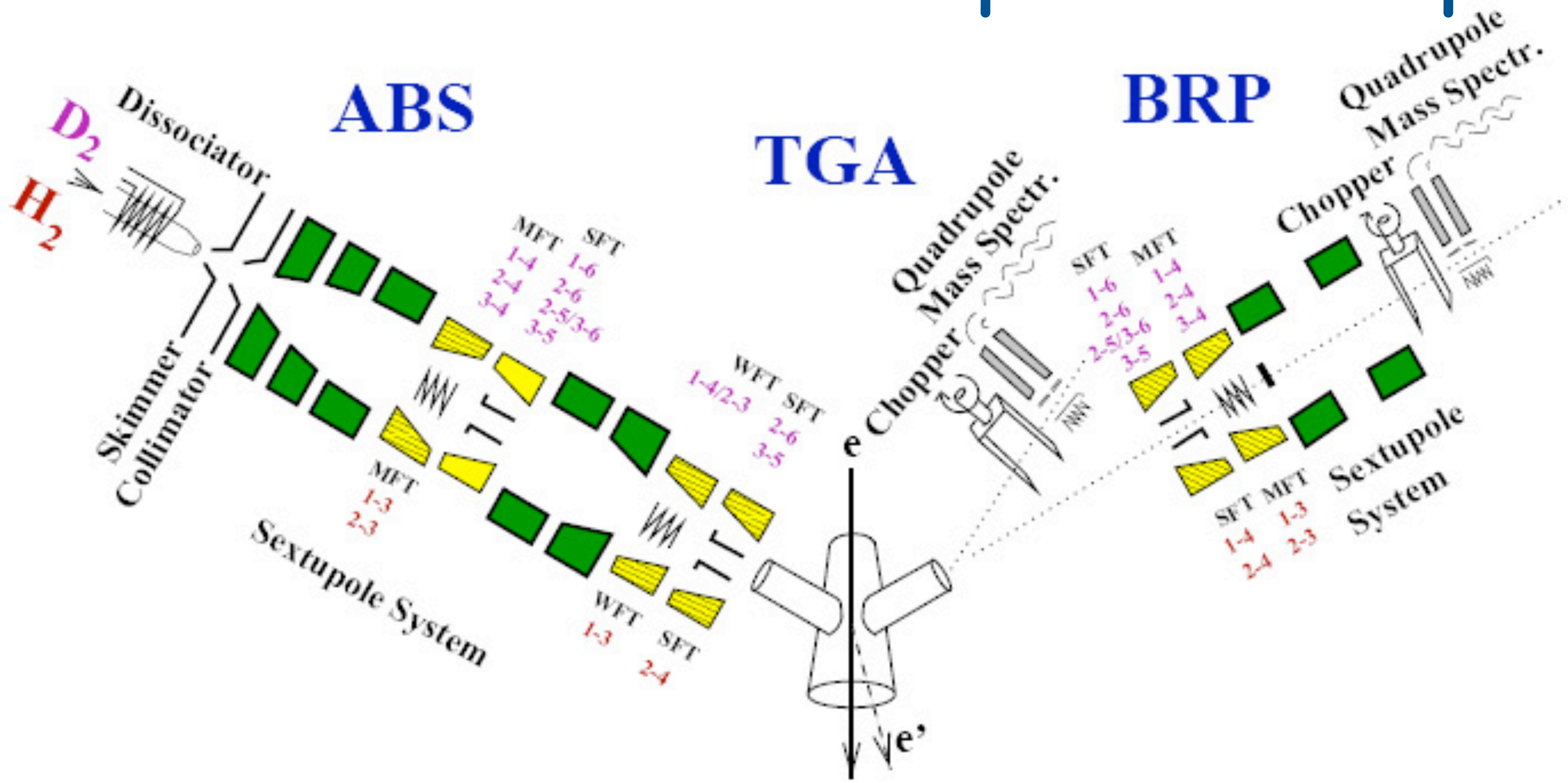
Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target #1

HERMES Collaboration • A. Airapetian (Michigan U.) et al. (Aug, 2004)

Published in: *Phys.Rev.Lett.* 94 (2005) 012002 • e-Print: hep-ex/0408013 [hep-ex]

pdf | DOI | cite | claim | reference search | 774 citations

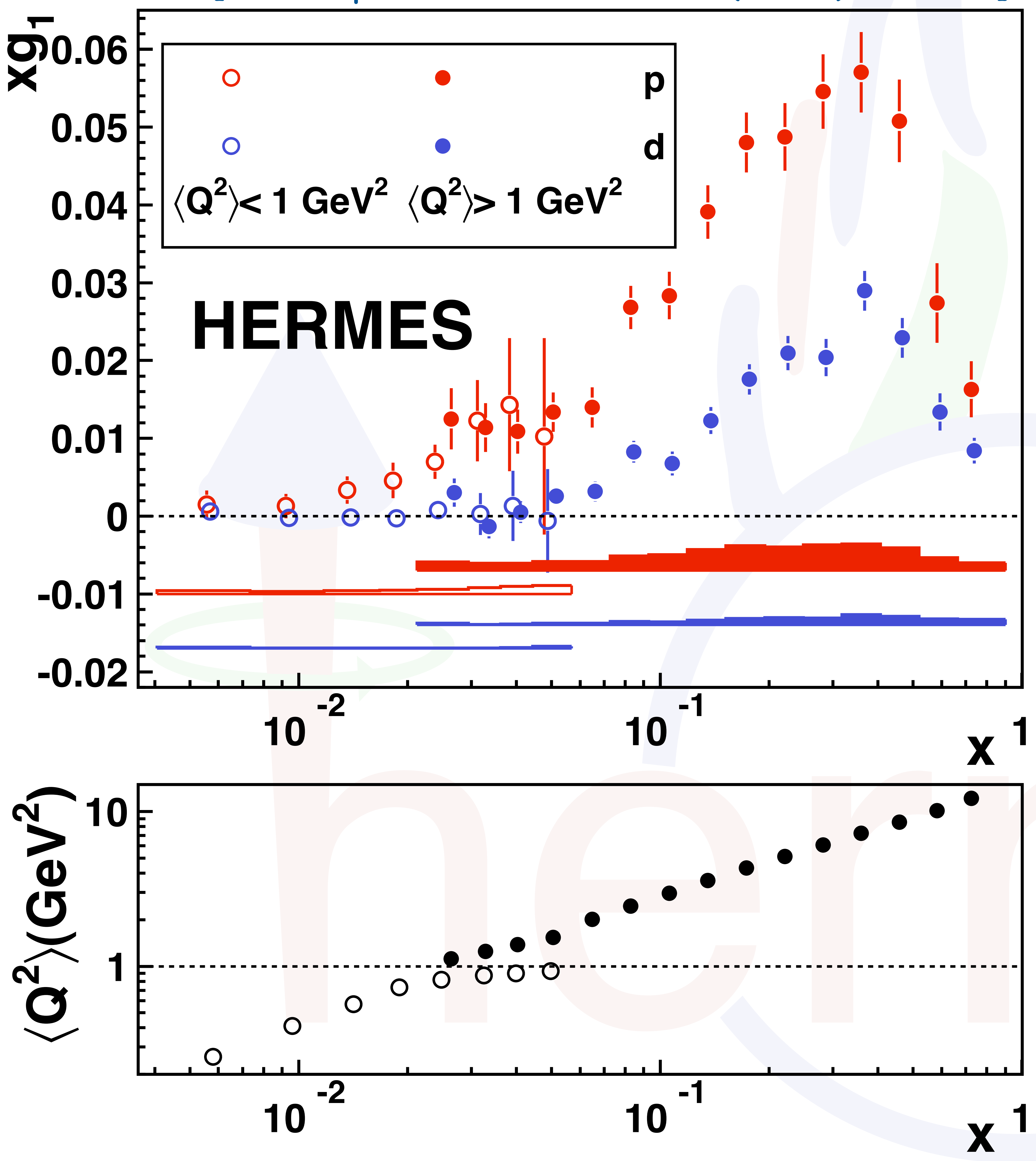
atomic-beam source: polarized p & d



Years	Target	DIS (Milion)	Polarization
1996-1997	$H_{\|\|}$	3.5	0.851 ± 0.033
1998-2000	$D_{\|\|}$	10.2	0.845 ± 0.028
2001-2005	$H_{\perp}$	~6	0.74 ± 0.06

polarized structure function $g_1(x)$

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



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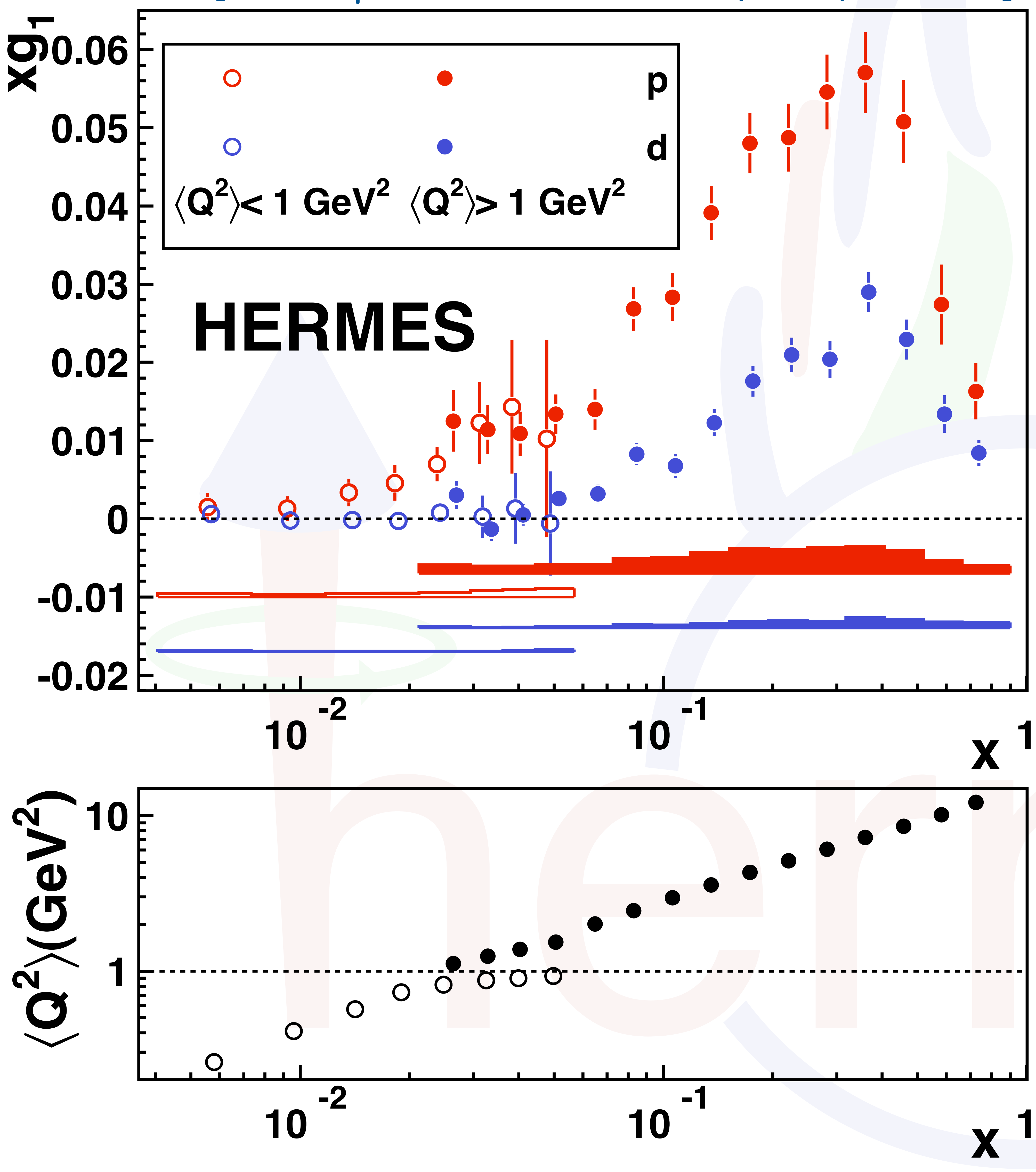

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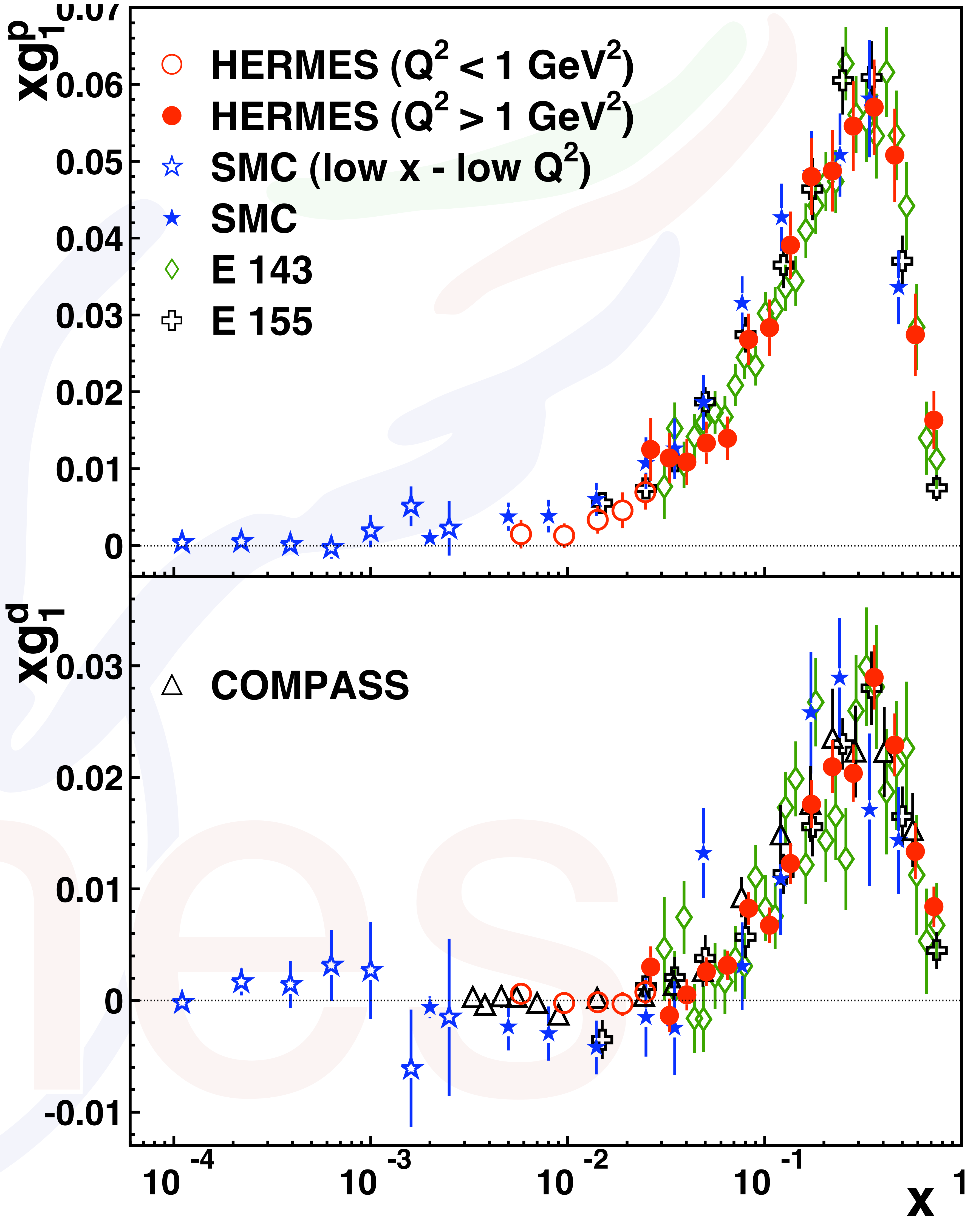

Γ_1 ... integral of $g_1(x)$

Saturation

➠ close to full integral?

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

↑ theory (for ΔC_{S})

↑ 0.05±0.05 (for ω_D)

↑ hyperon-decay data (for a_8)

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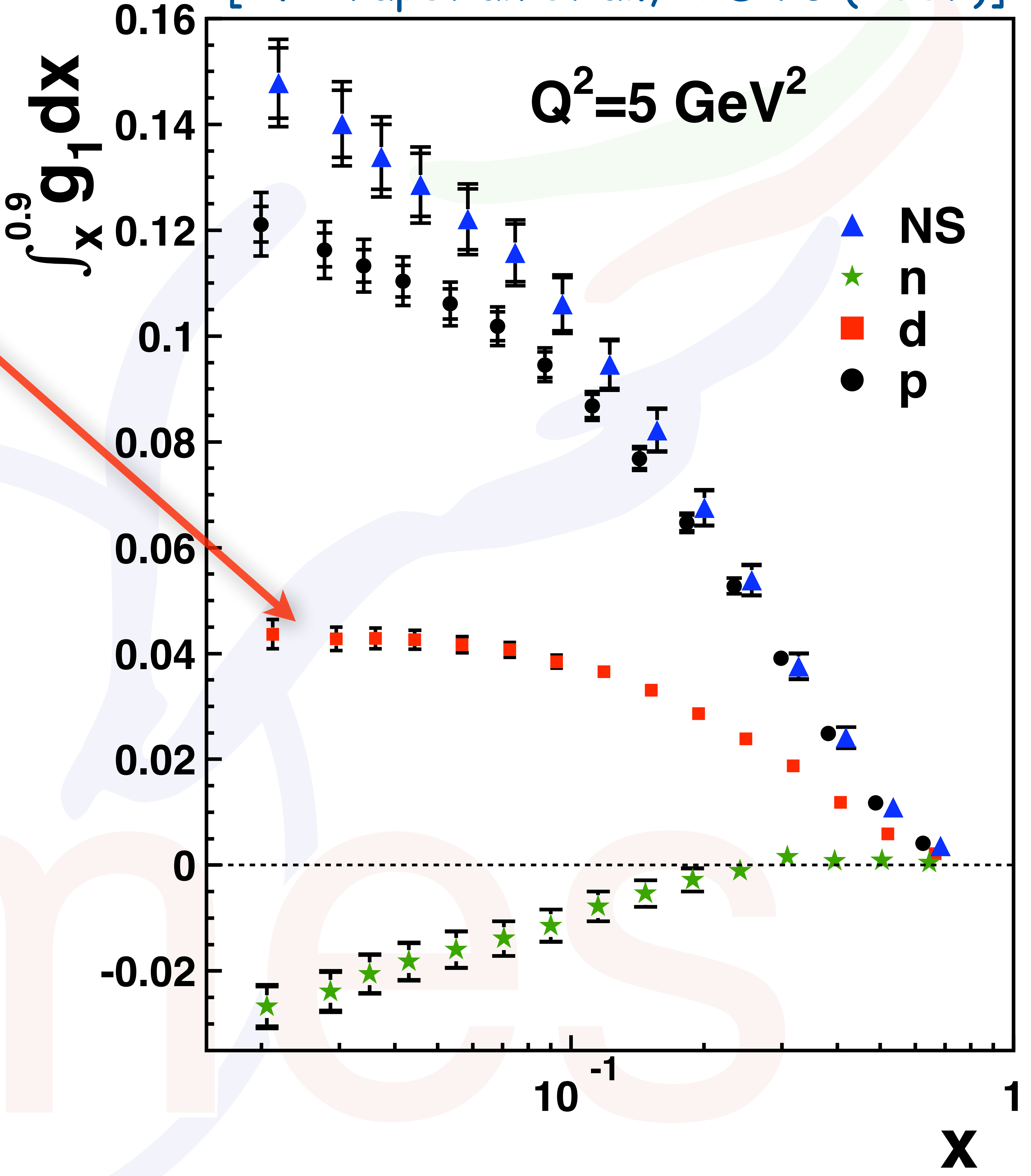
[A. Airapetian et al., PRD 75 (2007)]



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0.05±0.05 (ω_D)

hyperon-decay data (a_8)

theory (ΔC_{NS})

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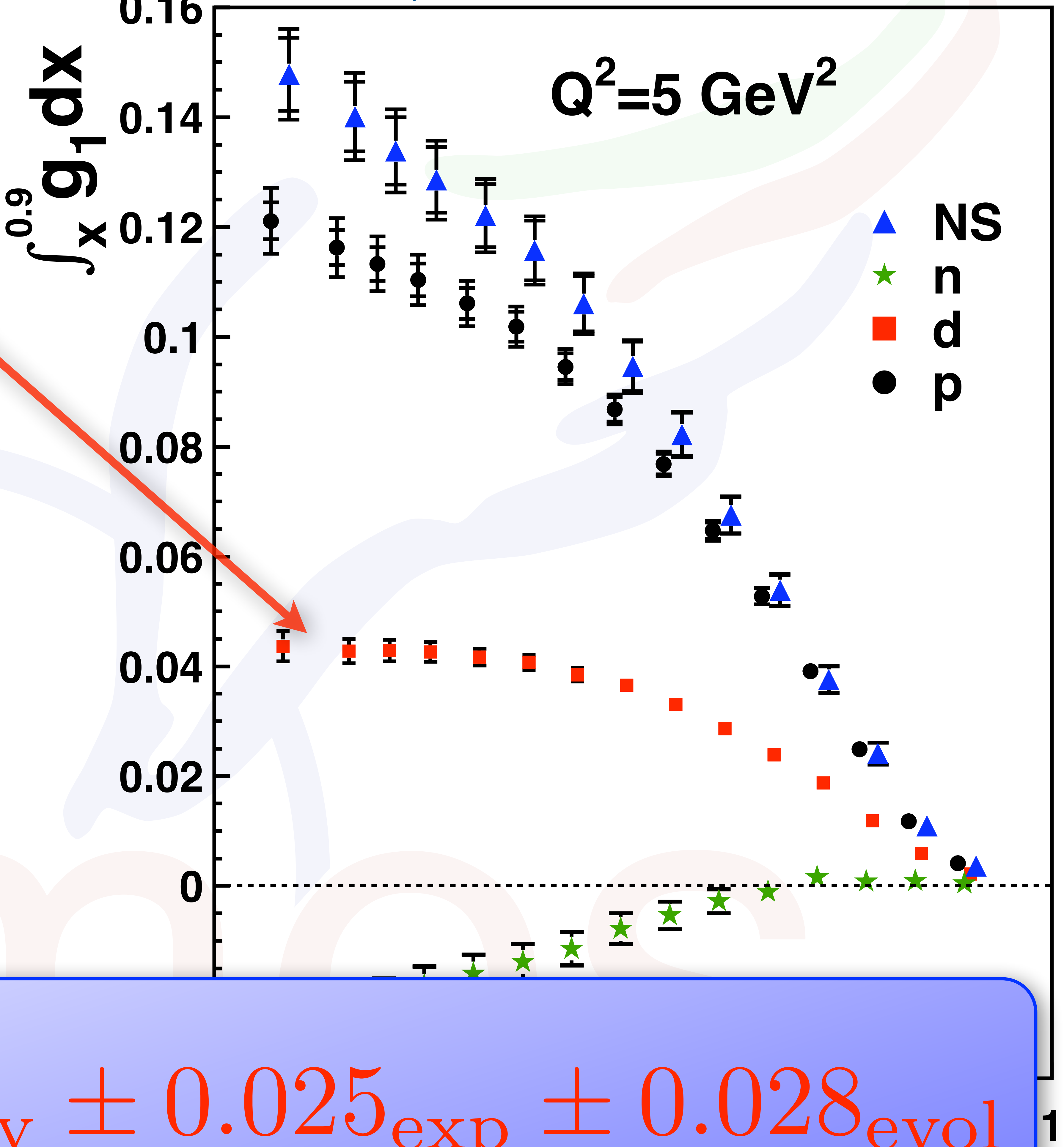

$$\Delta\Sigma \overset{\overline{\text{MS}}}{=} 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

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

Can HERMES do more than “just” inclusive g_1?

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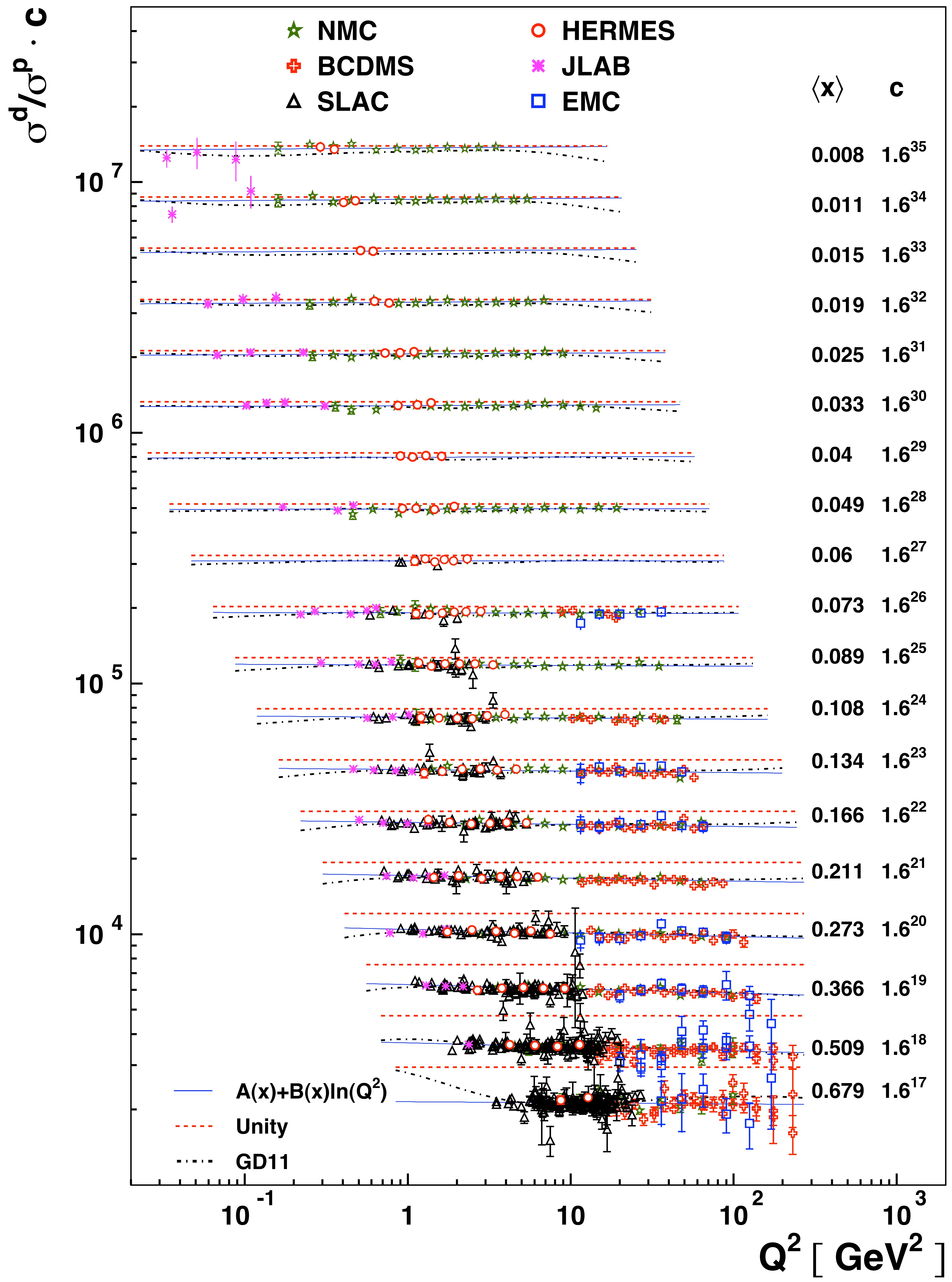
☑ unpolarized DIS: F_2 & σ^d/σ^p



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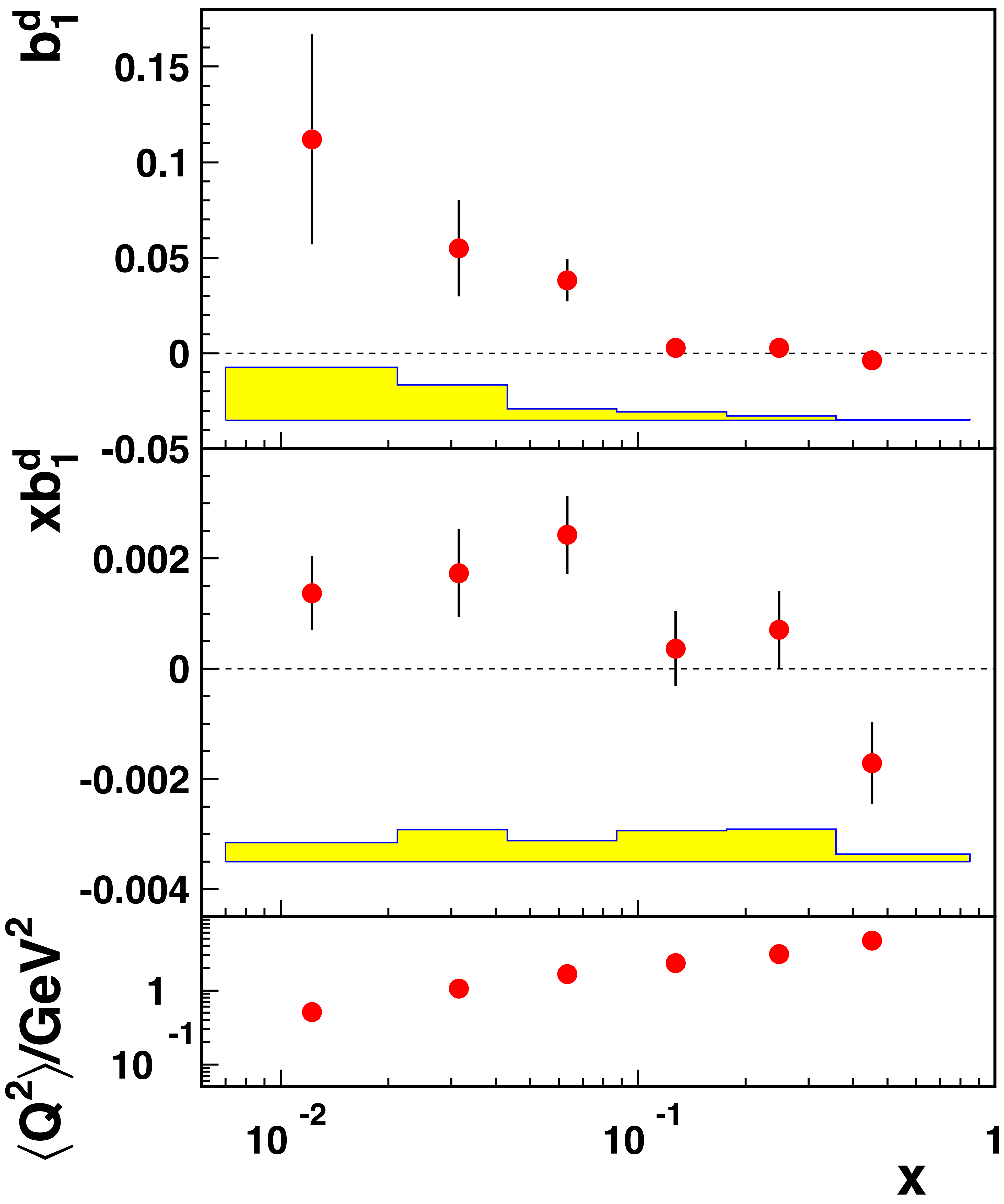
- ☑ tensor structure function b_1



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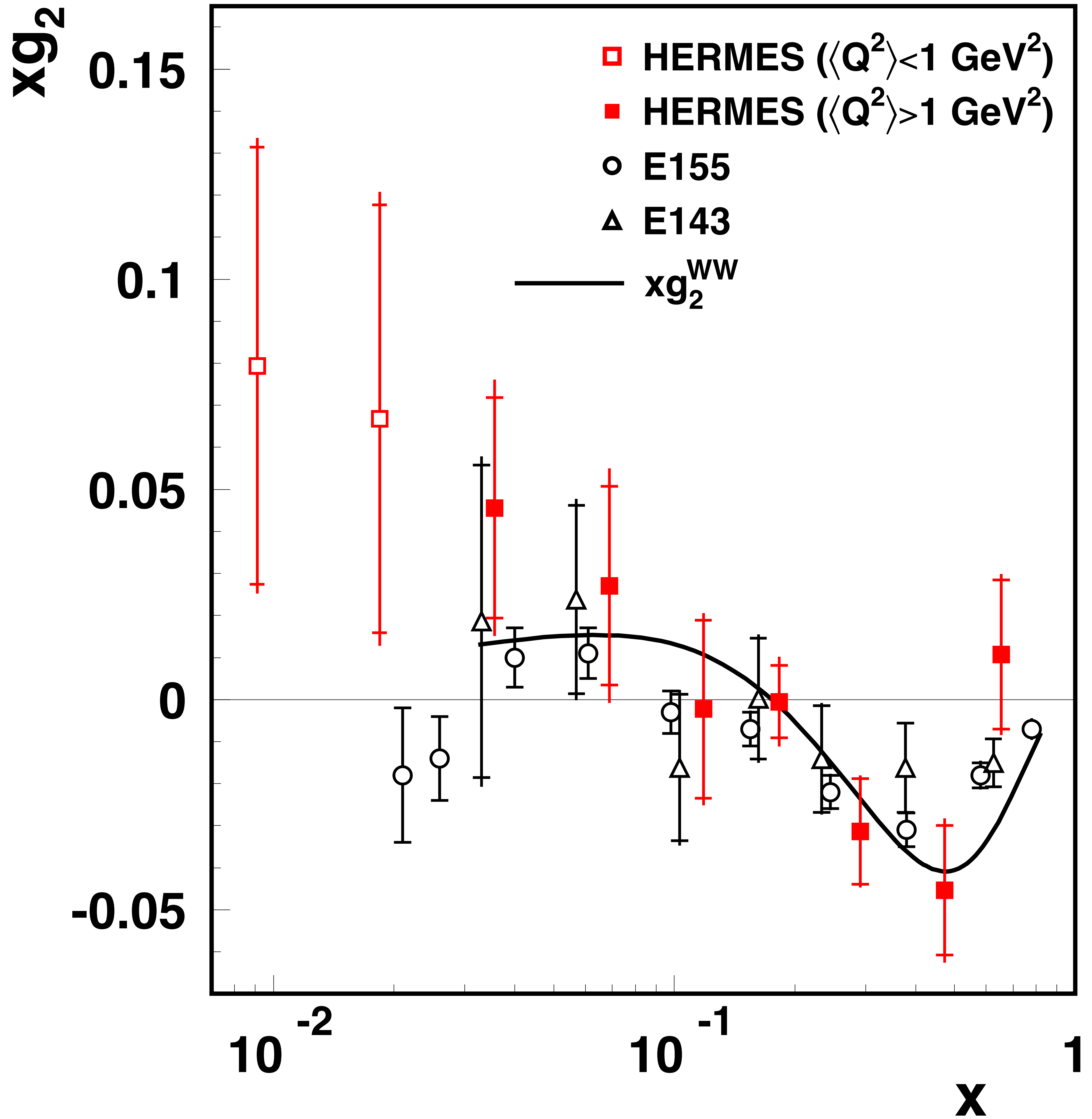
- ☑ transverse: g_2



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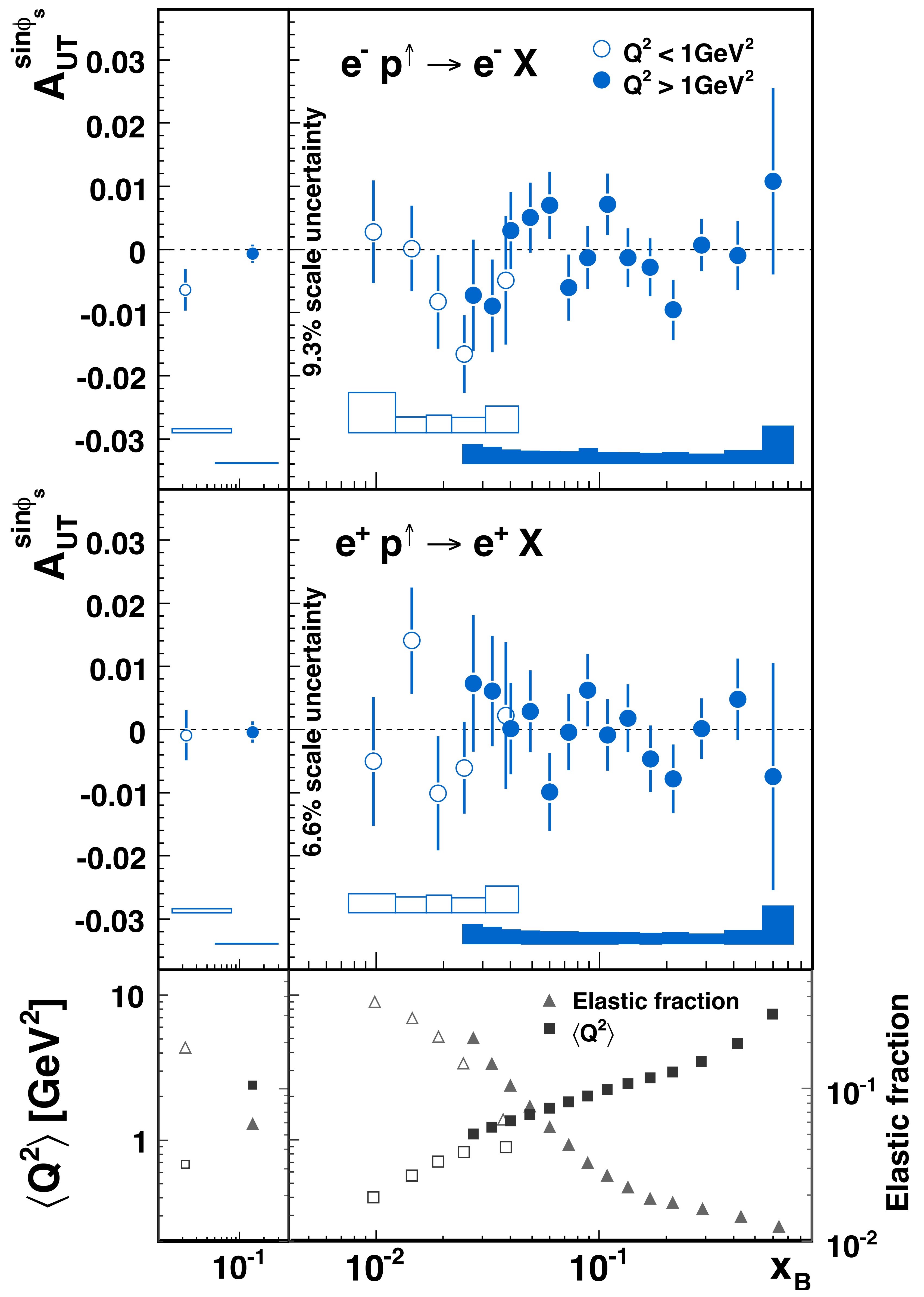
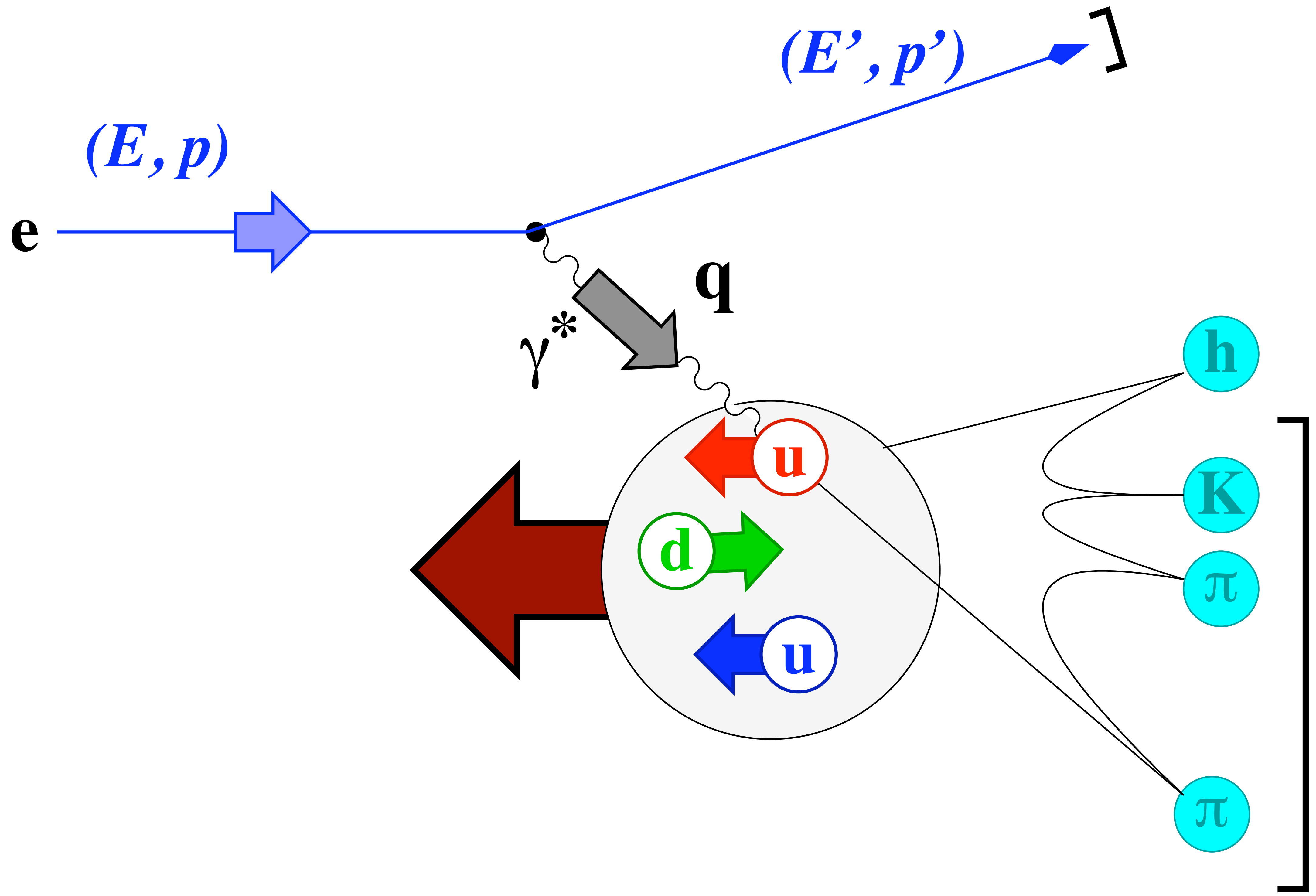
- ☑ tensor structure function b_1
- ☑ transverse: g_2
- ☑ 2-photon exchange in incl. DIS

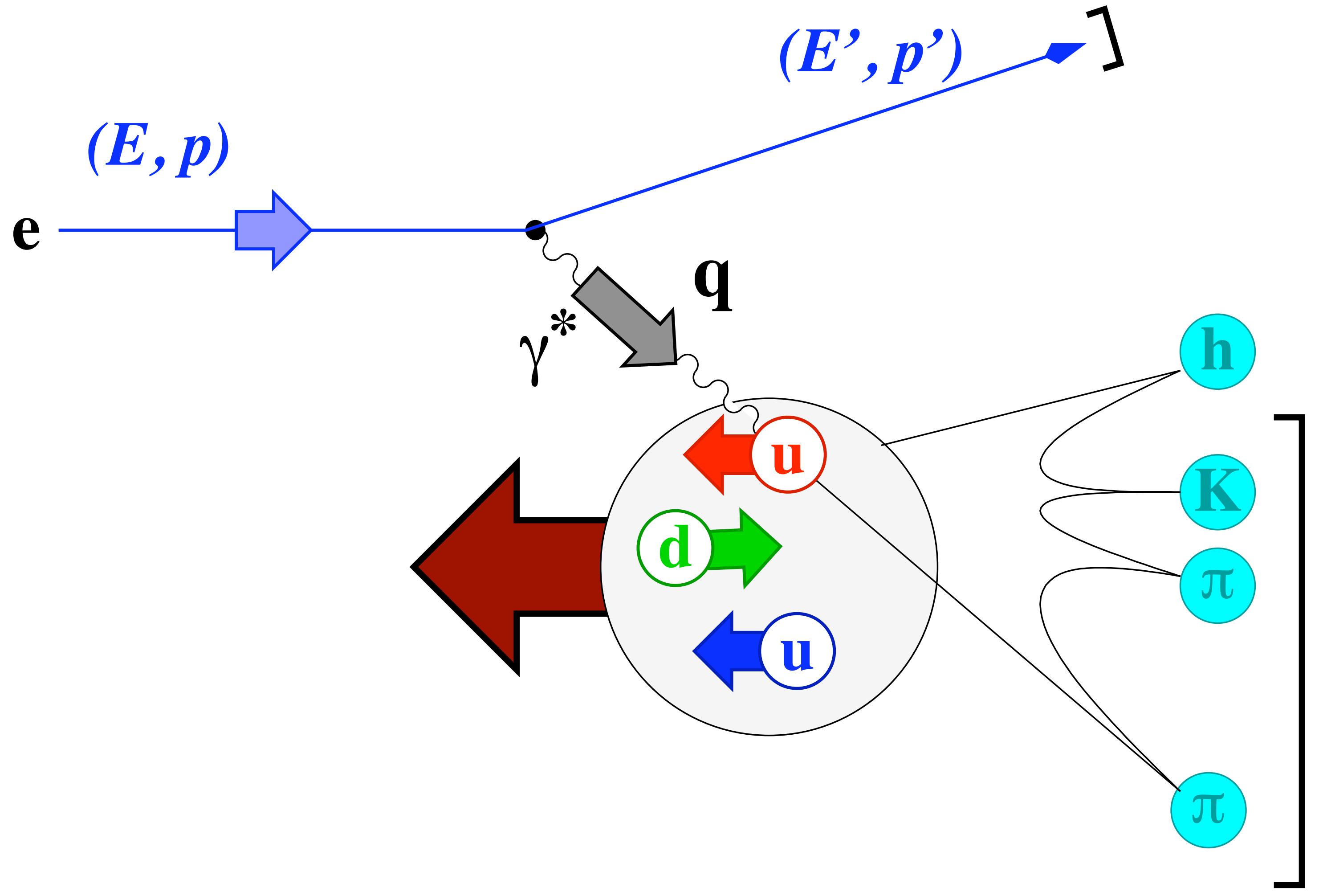


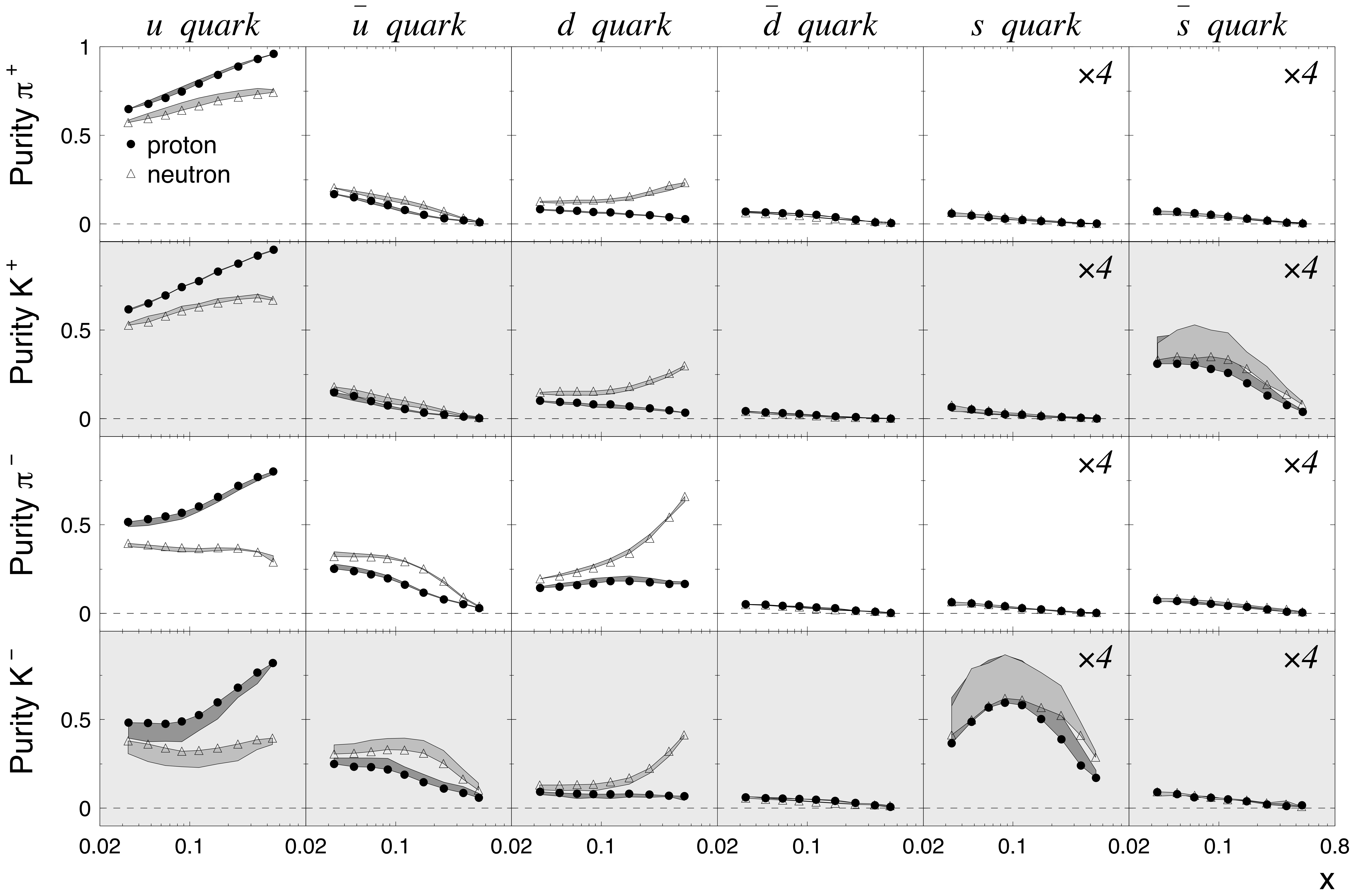
Can HERMES do more than "just" inclusive g_1?

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

semi-inclusive DIS

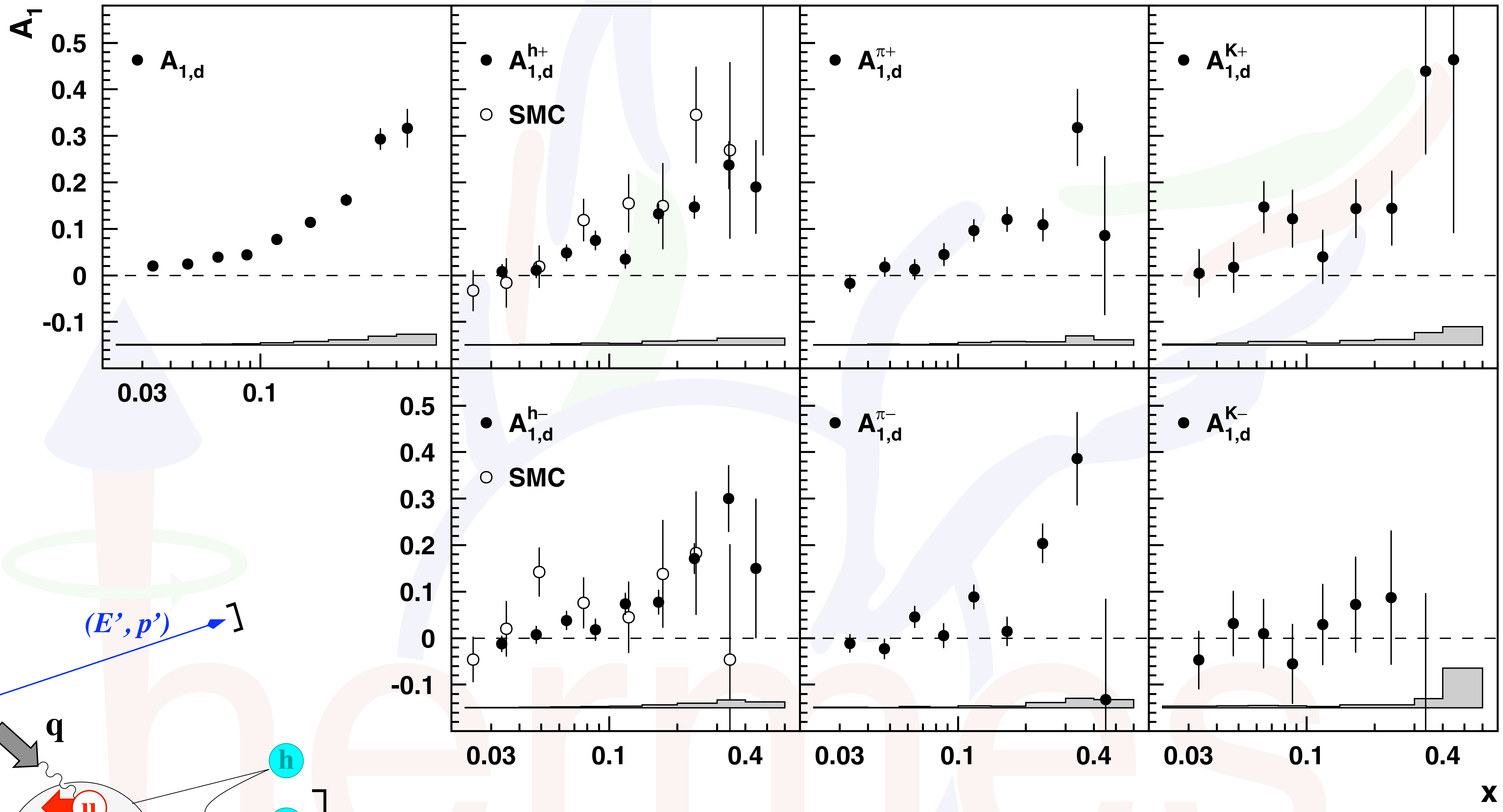


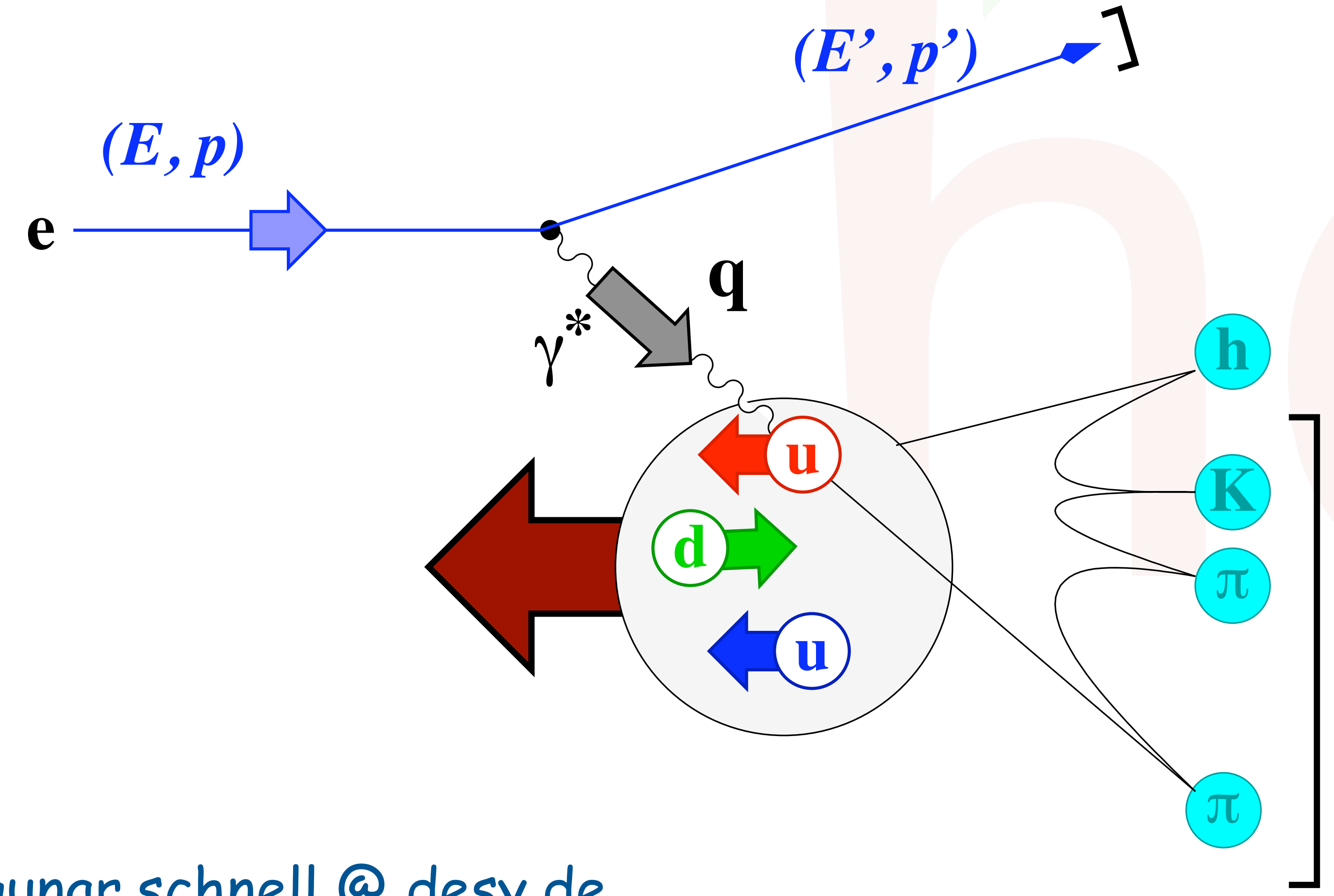




purity: $$P_q^h = \frac{e_q f_1^q D_1^{q\to h}}{\sum_i e_i f_1^i D_1^{i\to h}}$$

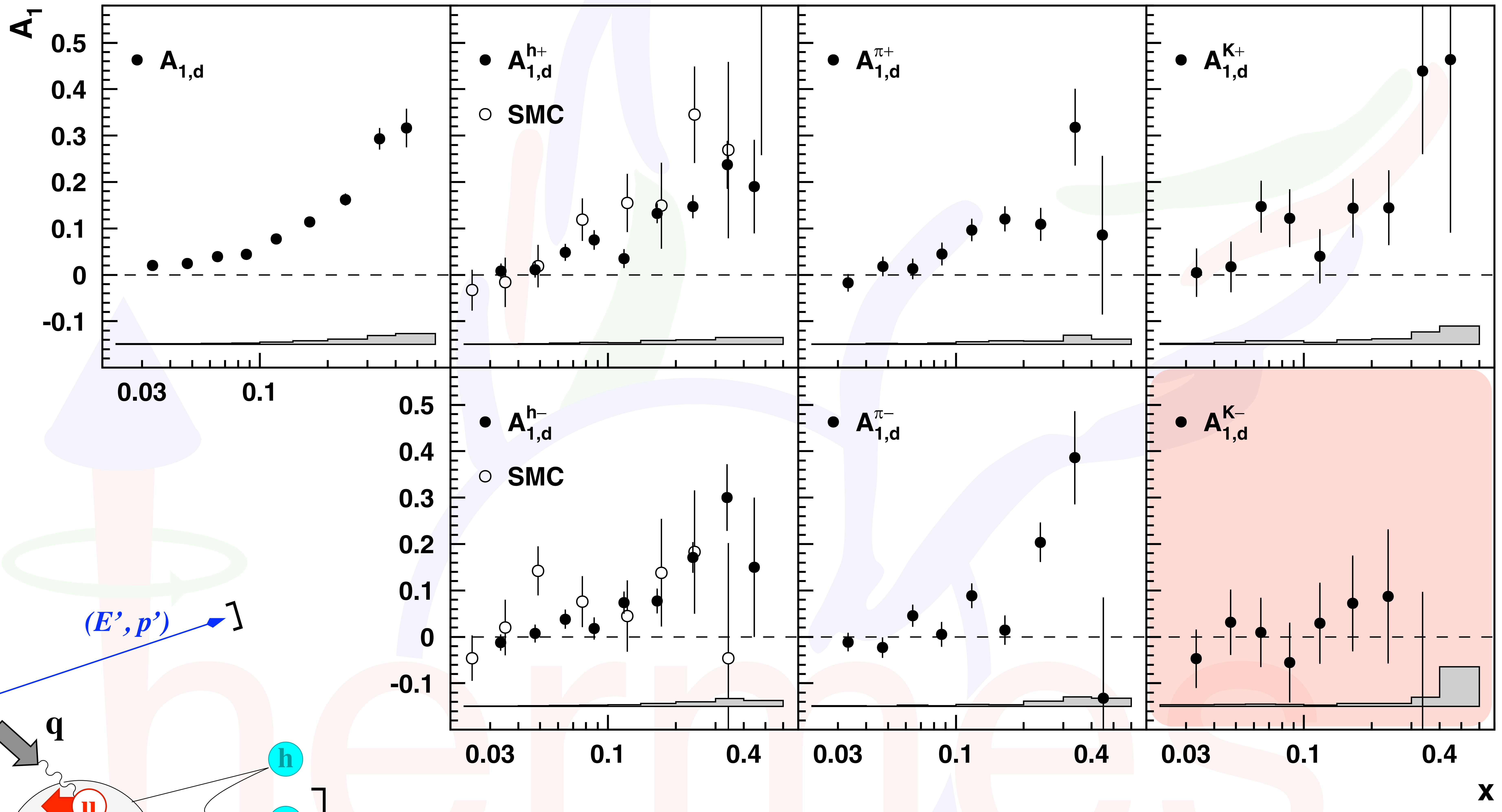
semi-inclusive DIS asymmetries

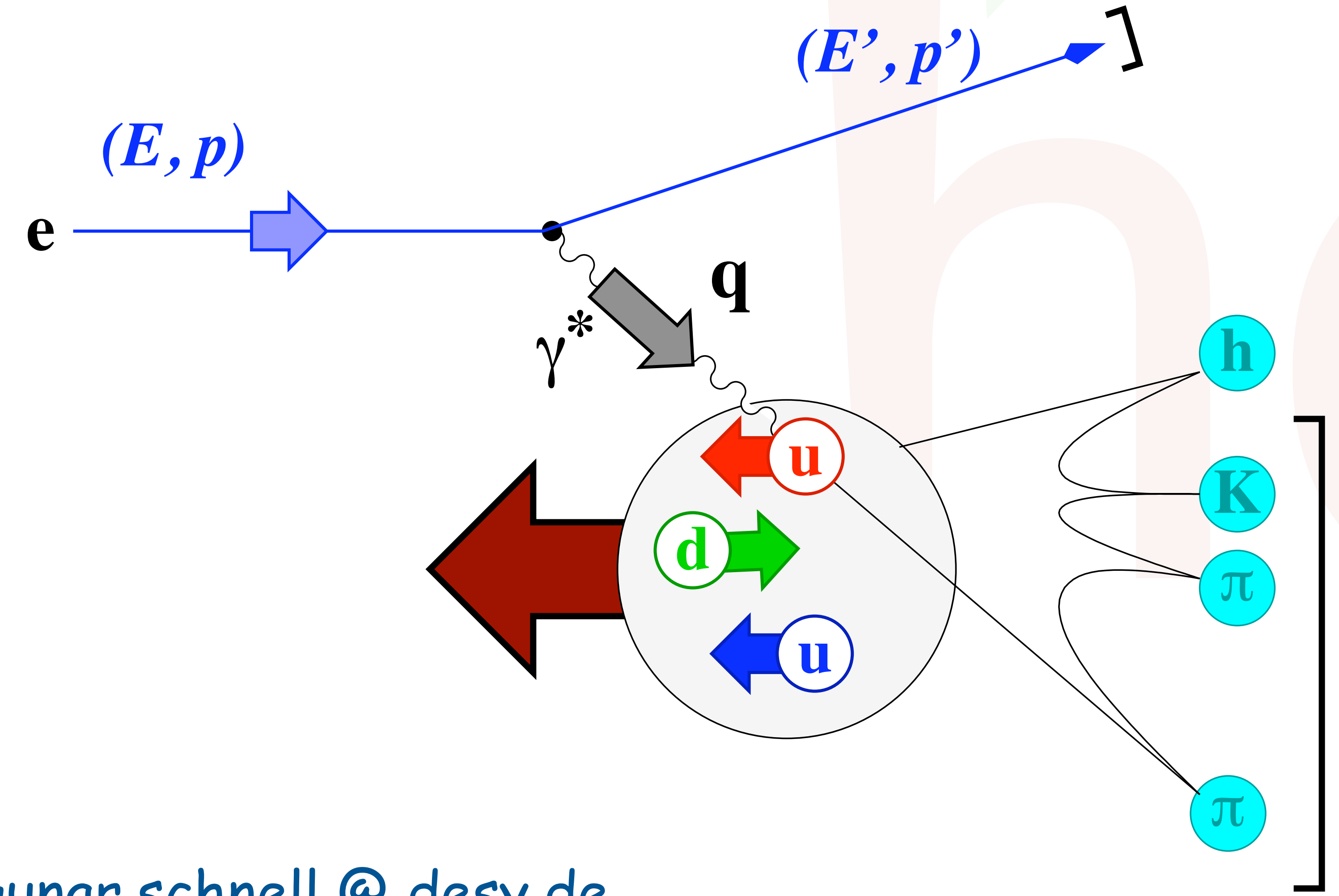




$$A_1^h = \sum_i P_i^h \frac{g_1^i}{f_1^i}$$

semi-inclusive DIS asymmetries





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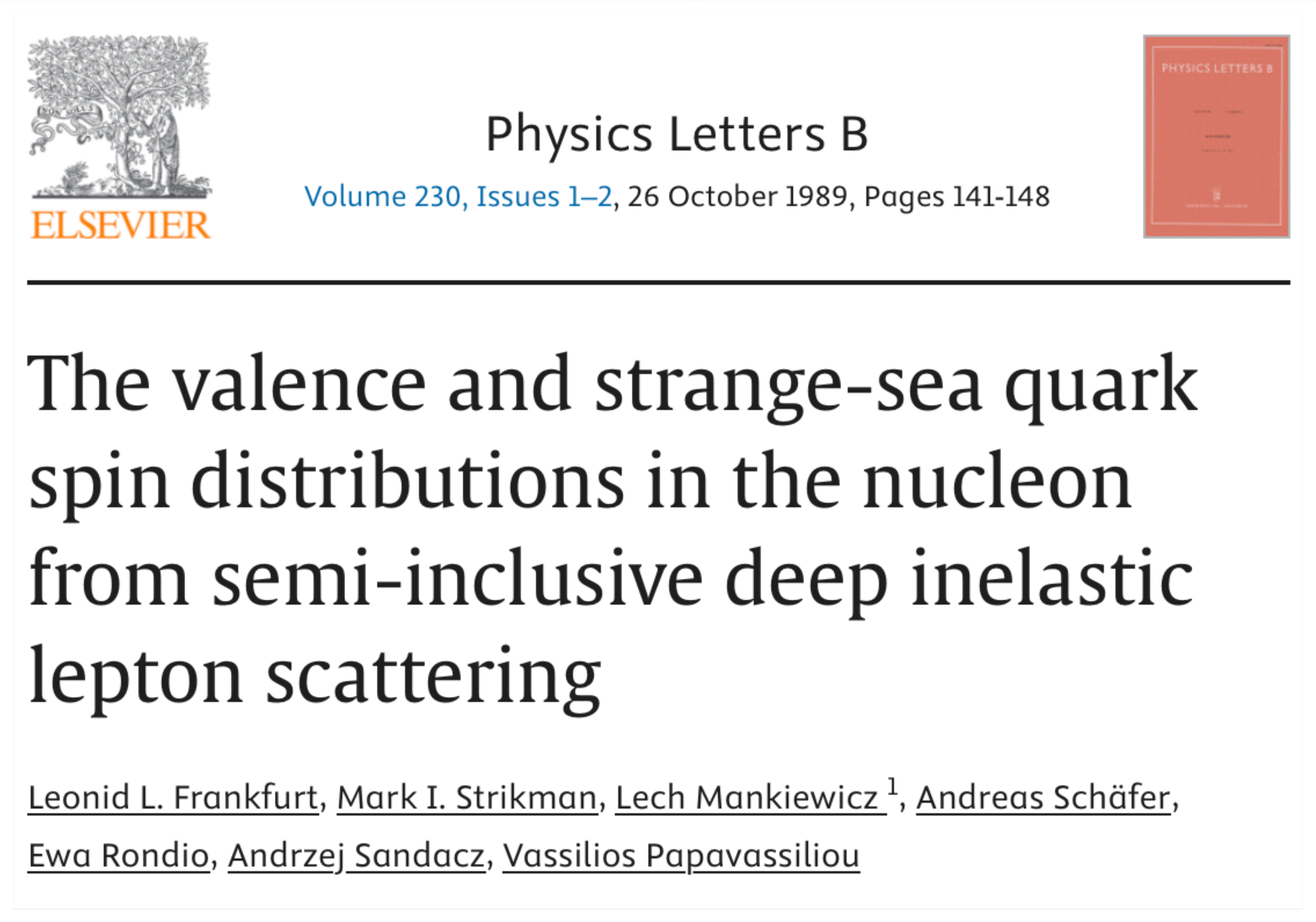
helicity density - flavor separation

- first 5-flavor extraction of Δq



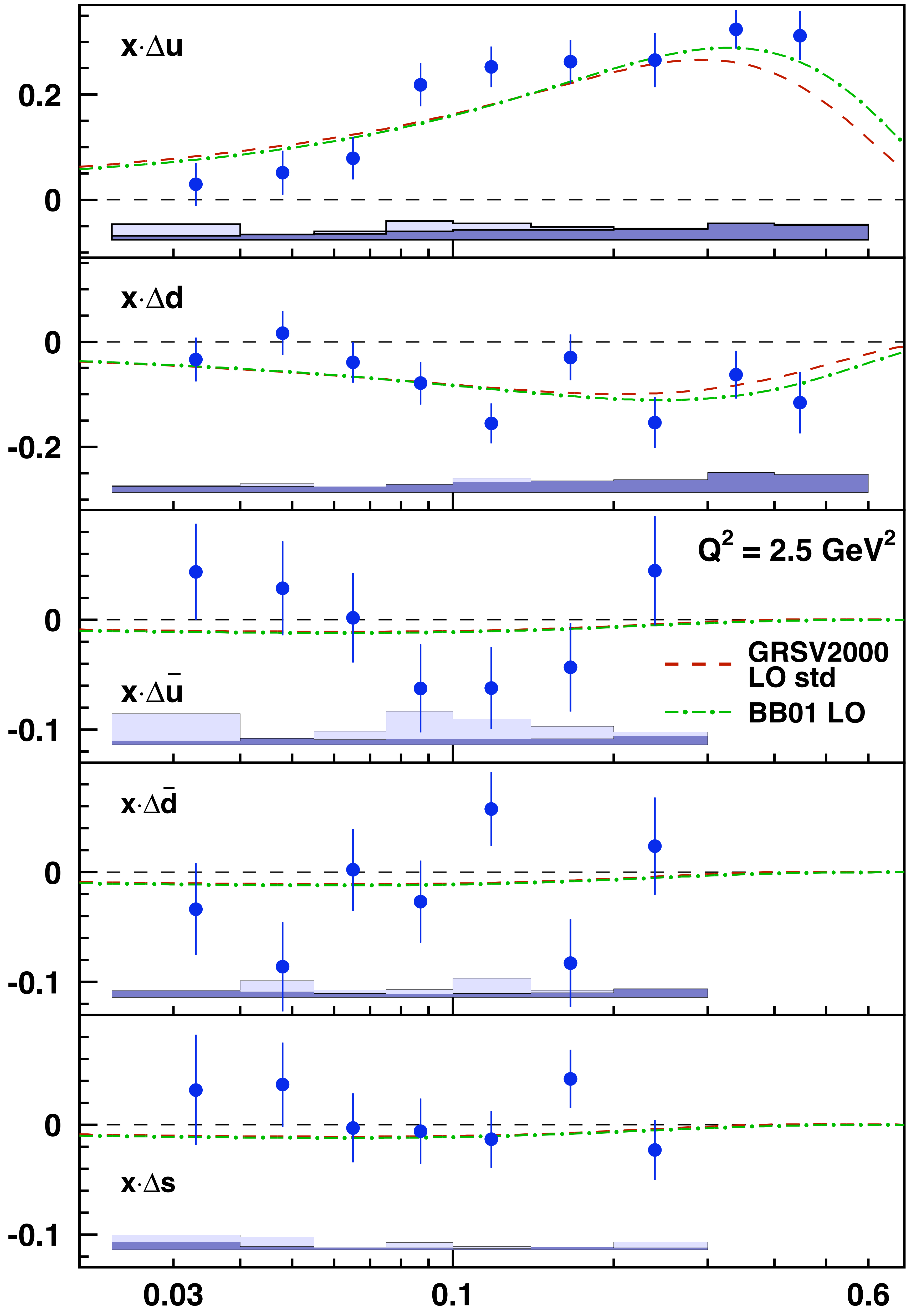
Physics Letters B

Volume 230, Issues 1–2, 26 October 1989, Pages 141-148

ELSEVIER

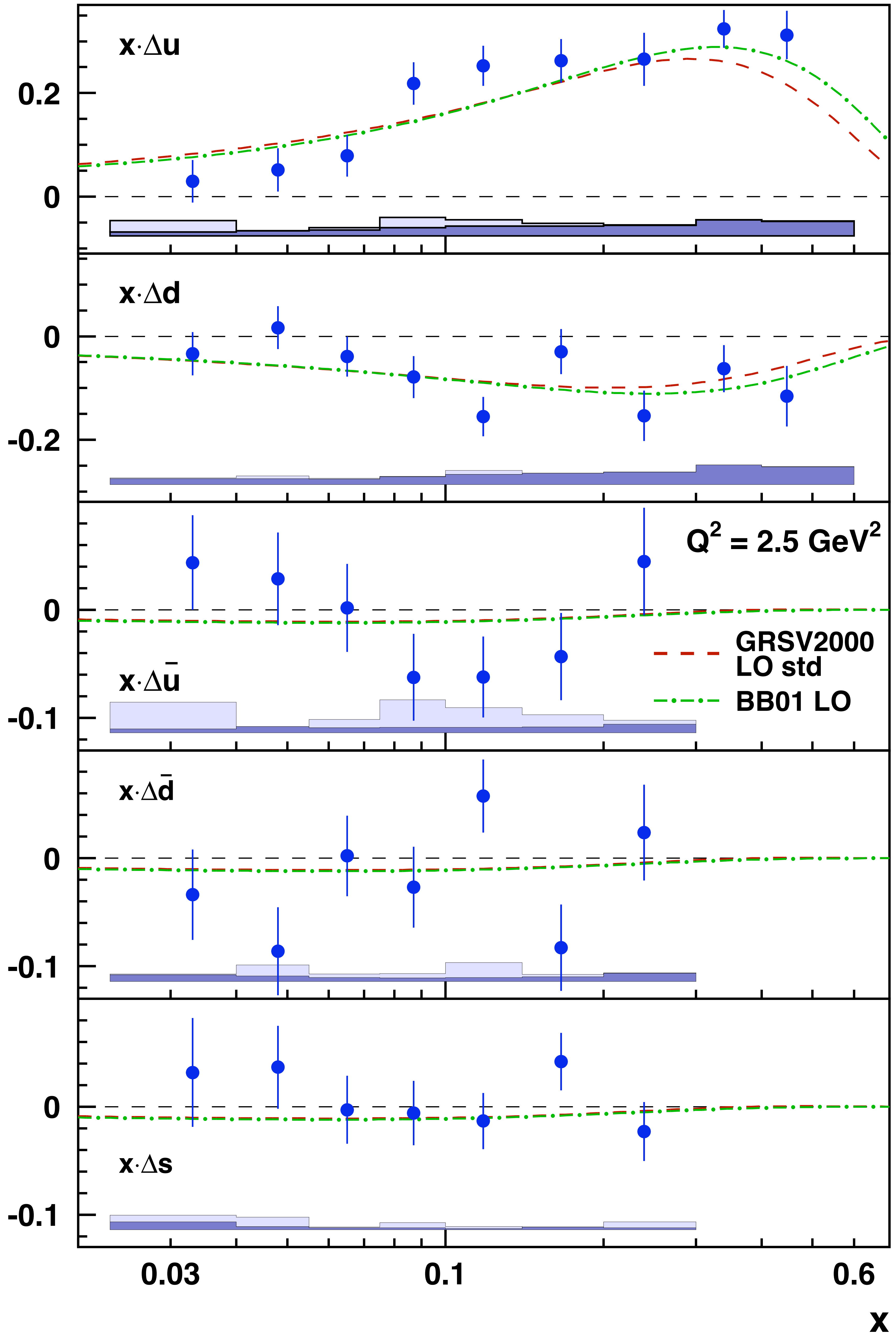
The valence and strange-sea quark spin distributions in the nucleon from semi-inclusive deep inelastic lepton scattering

Leonid L. Frankfurt, Mark I. Strikman, Lech Mankiewicz [1], Andreas Schäfer, Ewa Rondio, Andrzej Sandacz, Vassilios Papavassiliou



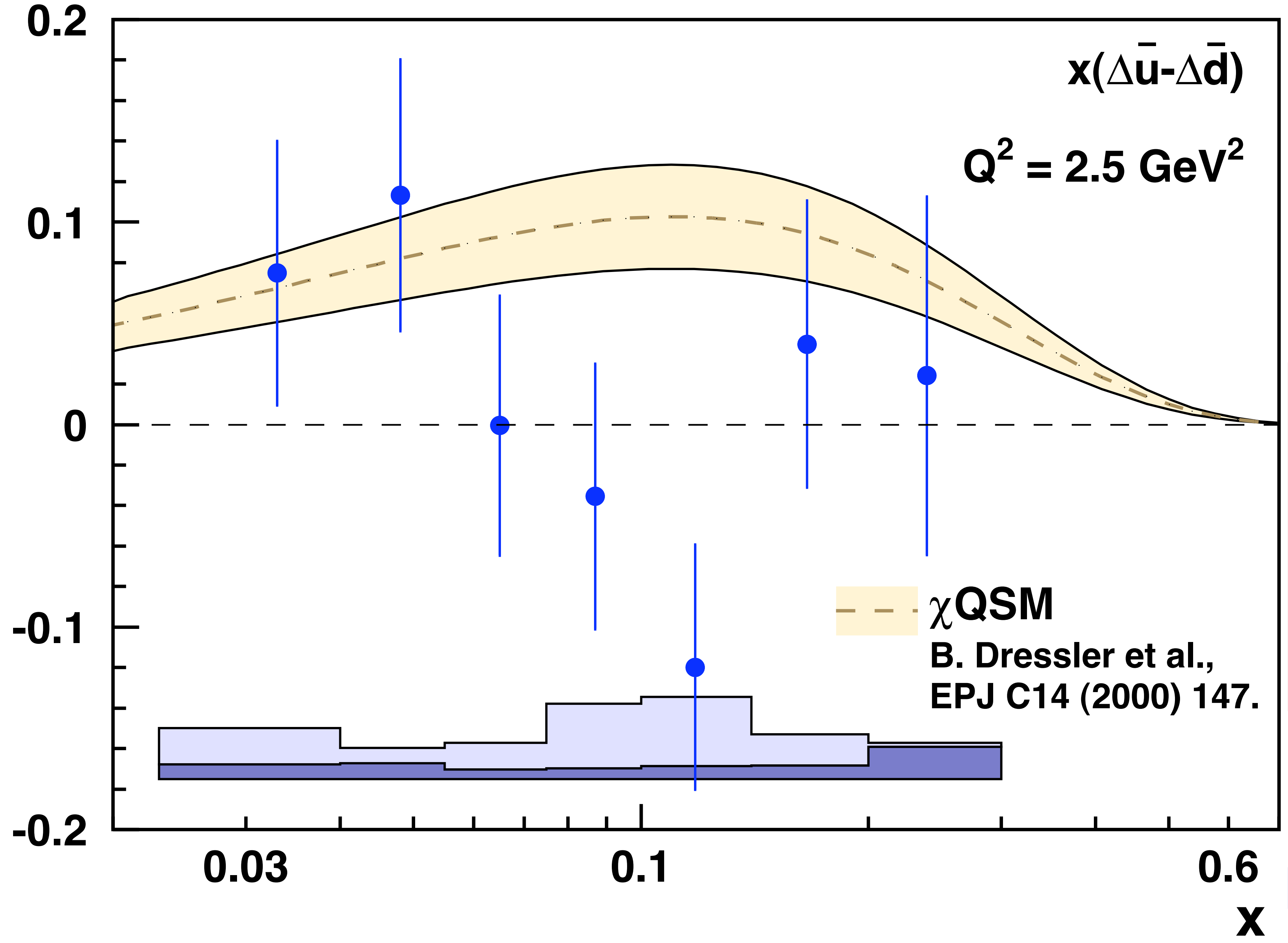
helicity density - flavor separation

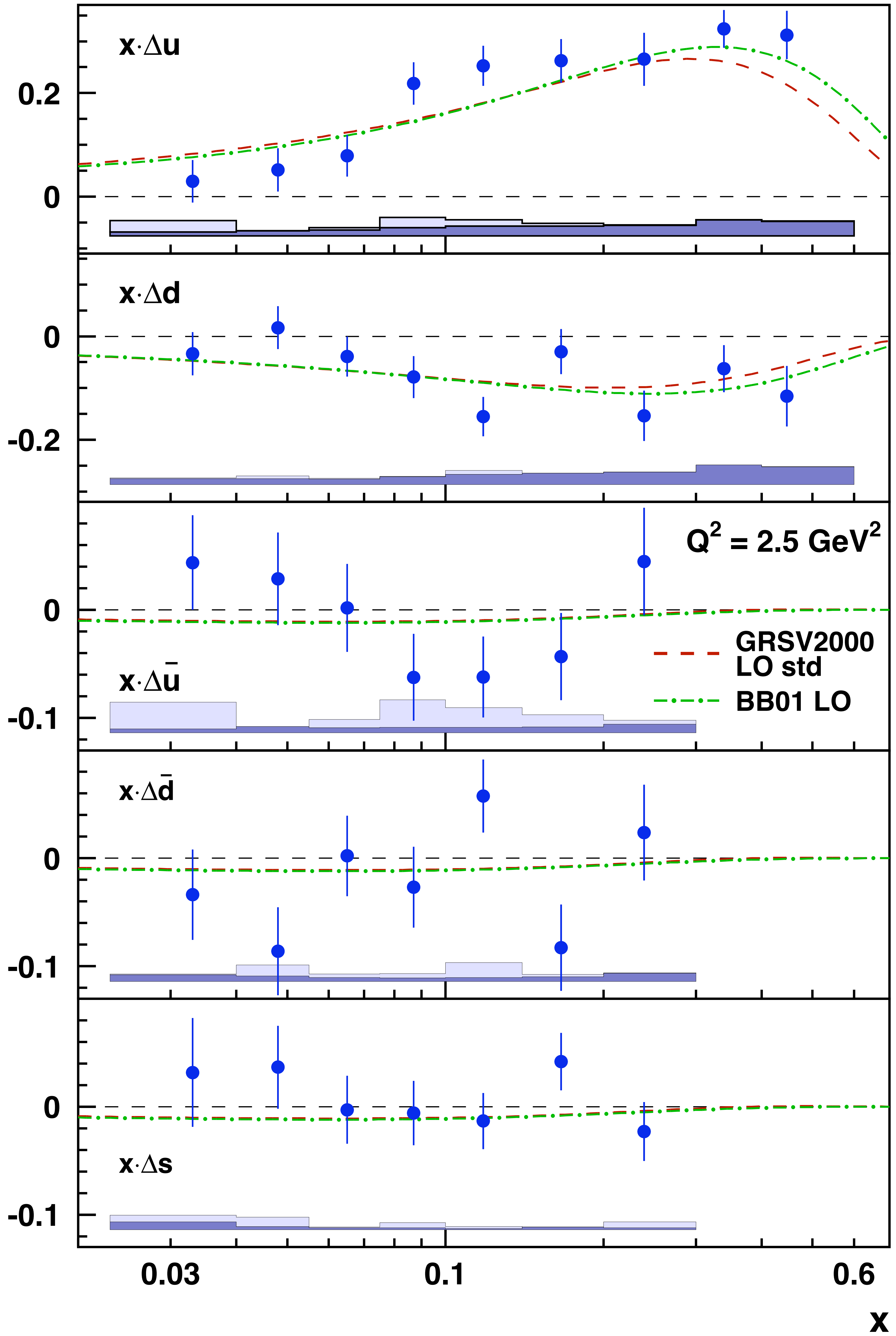
- first 5-flavor extraction of Δq
- no hint for sea quark pol's
  -> in contrast to incl. DIS



helicity density - flavor separation

- first 5-flavor extraction of Δq
- no hint for sea quark pol's
  -> in contrast to incl. DIS
- no significant flavor asymmetry of sea

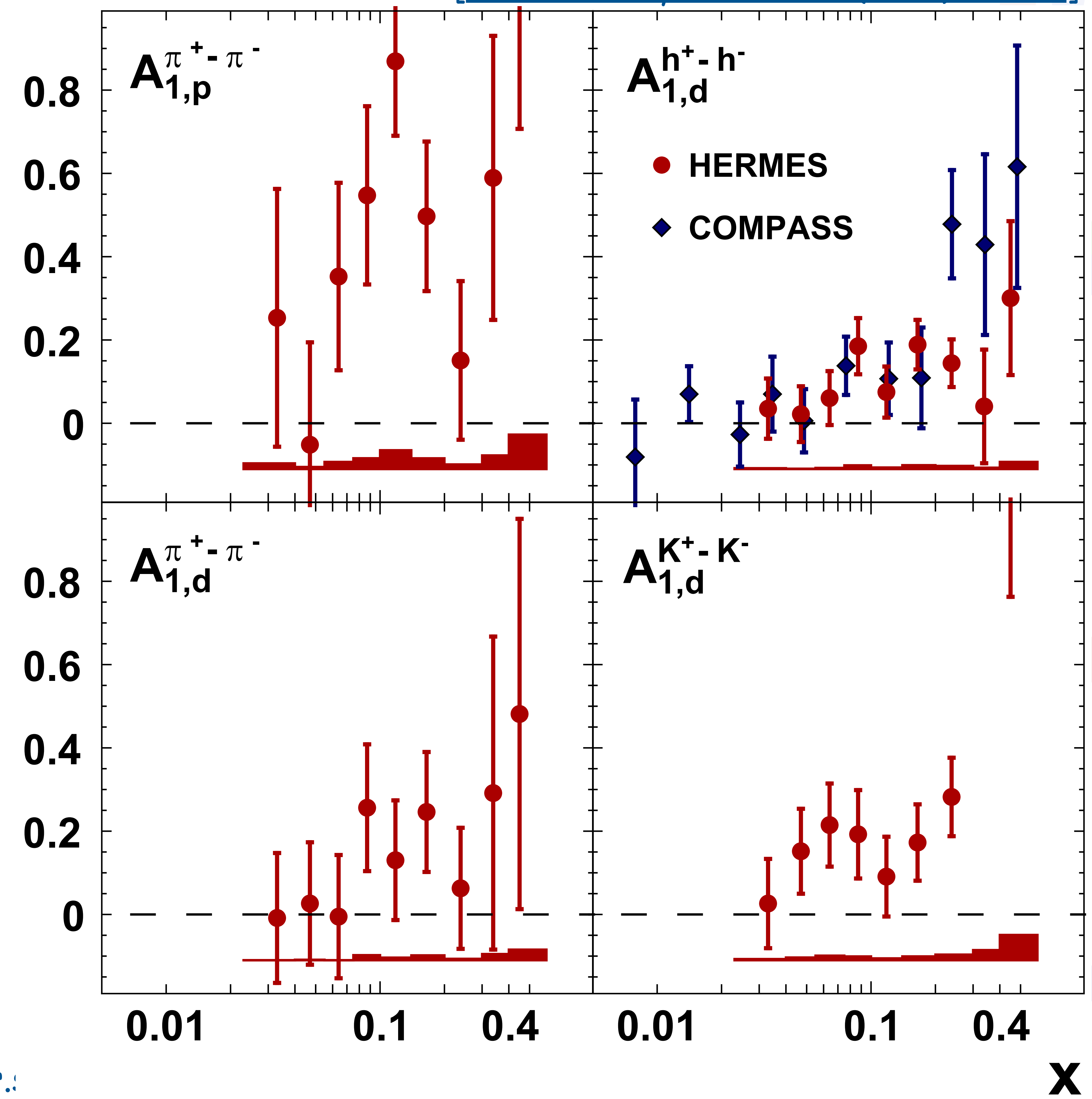




helicity density - valence quarks

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

[HERMES, Phys. Rev. D99 (2019) 112001]



- charge-difference double-spin asymmetries
- use charge-conjugation symmetry to extract, at LO(!), valence distributions

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

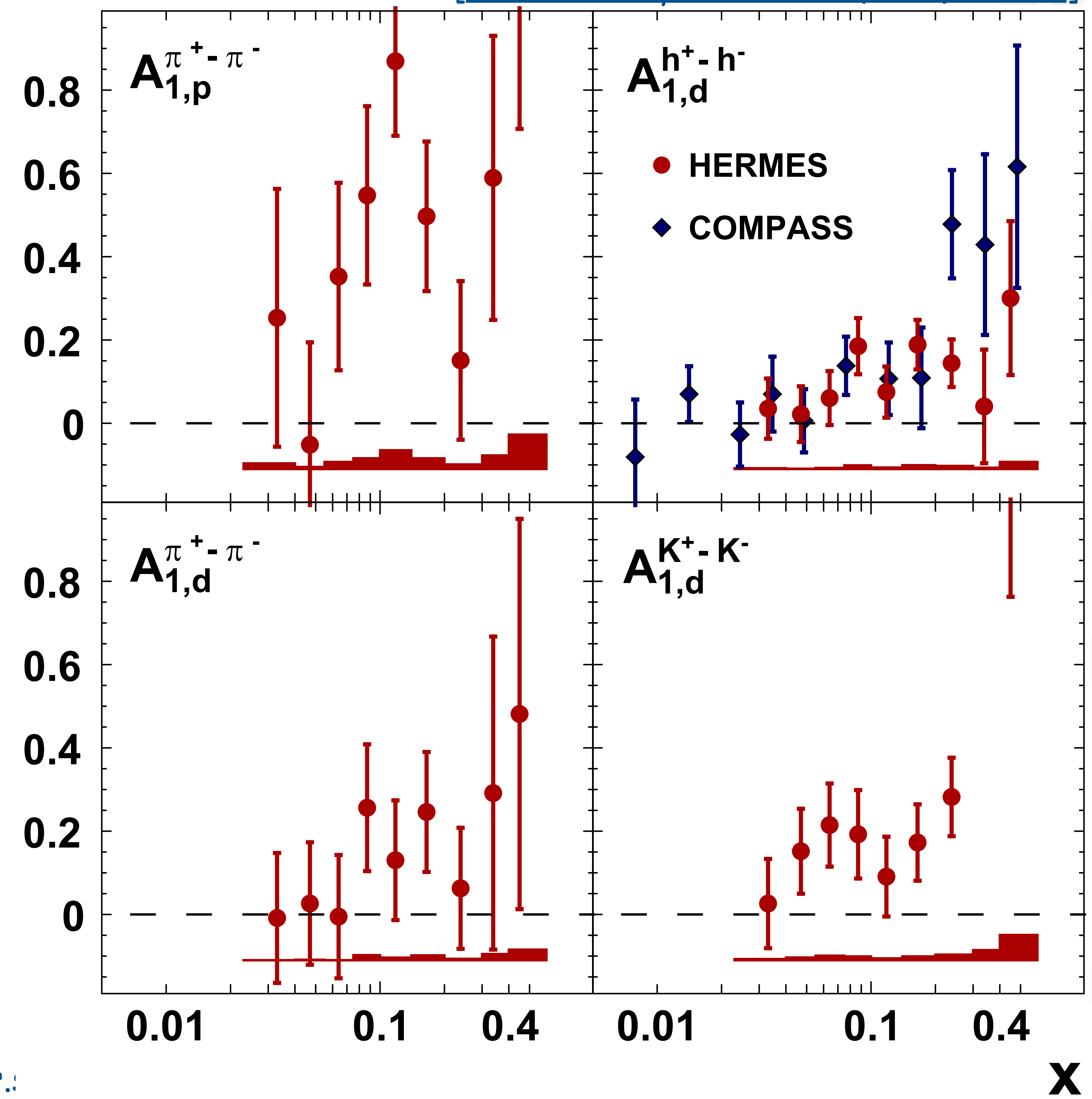
$$A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

helicity density - valence quarks

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

- charge-difference double-spin asymmetries
- use charge-conjugation symmetry to extract, at LO(!), valence distributions
- valence distributions consistent with JETSET-based extraction:

[HERMES, Phys. Rev. D99 (2019) 112001]



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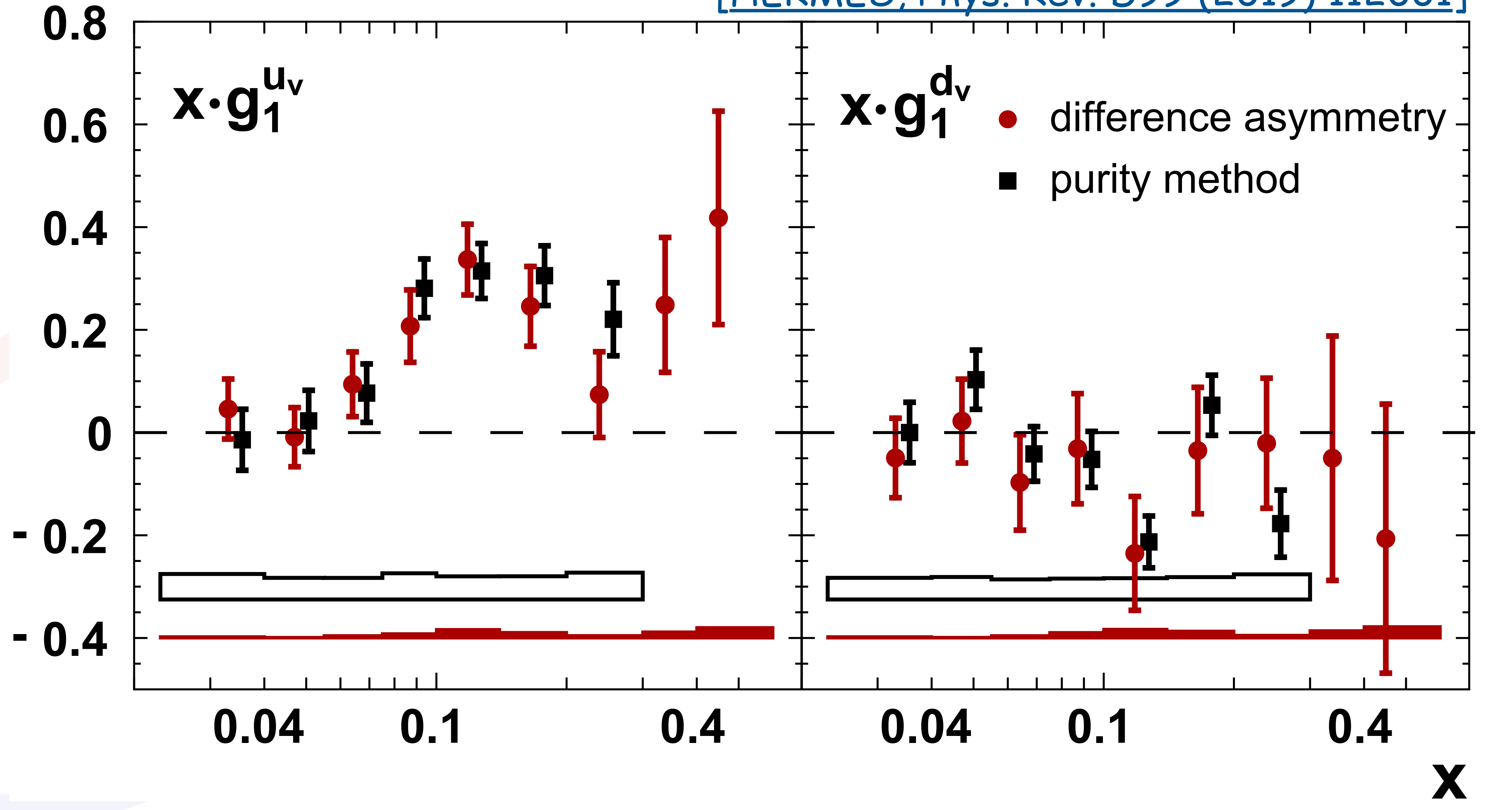
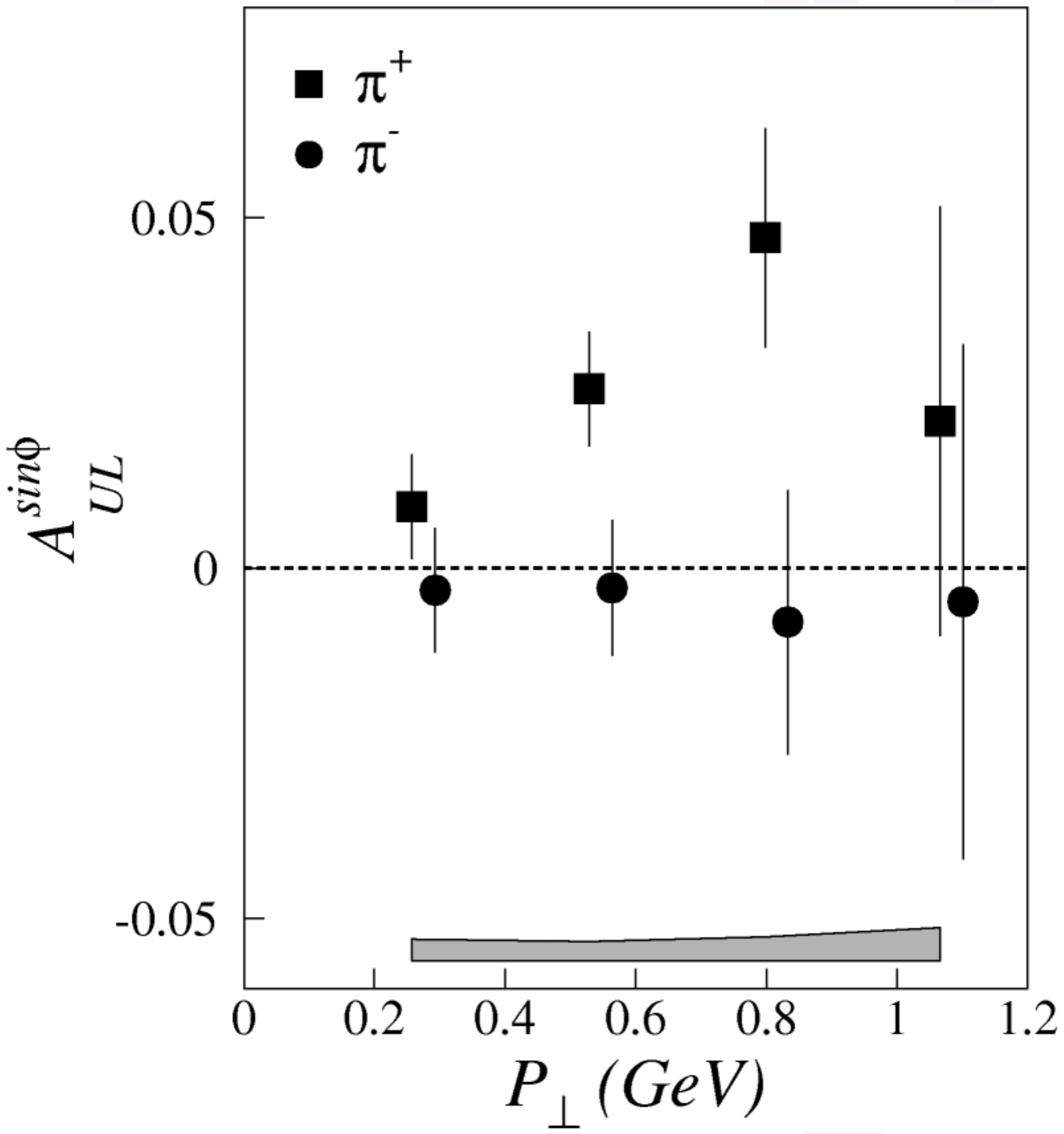
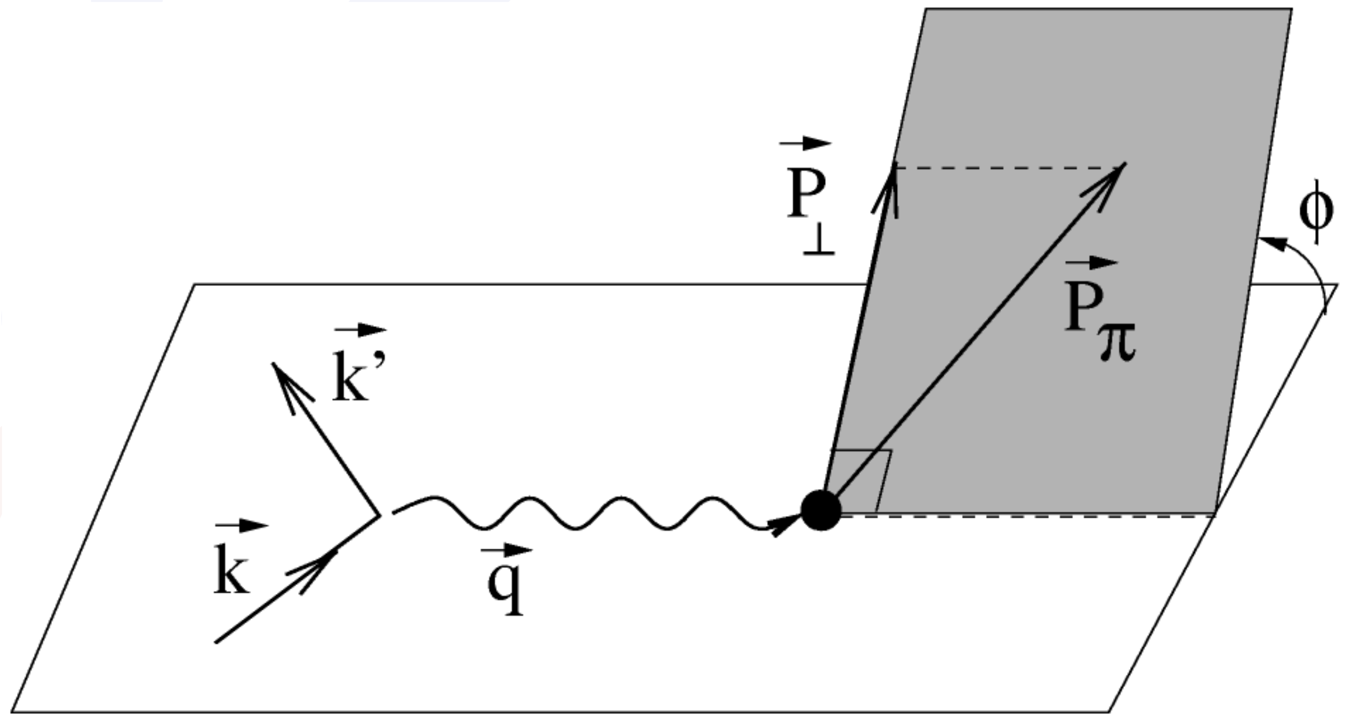


... going 3D

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

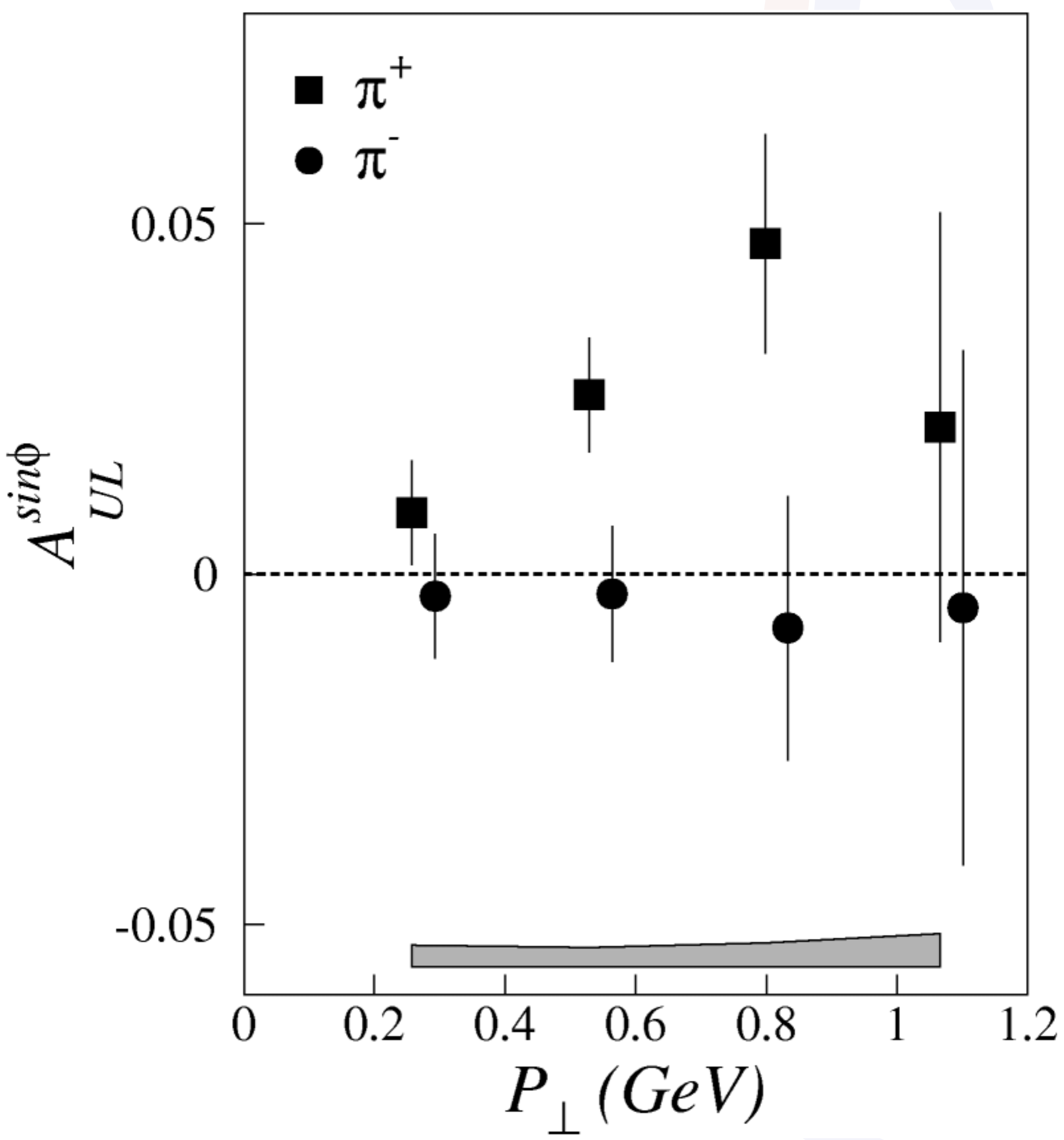


$$A_{UL} = \frac{1}{|P_B|}\frac{N^{\rightarrow}(\phi) - N^{\leftarrow}(\phi)}{N^{\rightarrow}(\phi) + N^{\leftarrow}(\phi)}$$



Volume 84, Number 18 PHYSICAL REVIEW LETTERS 1 May 2000

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



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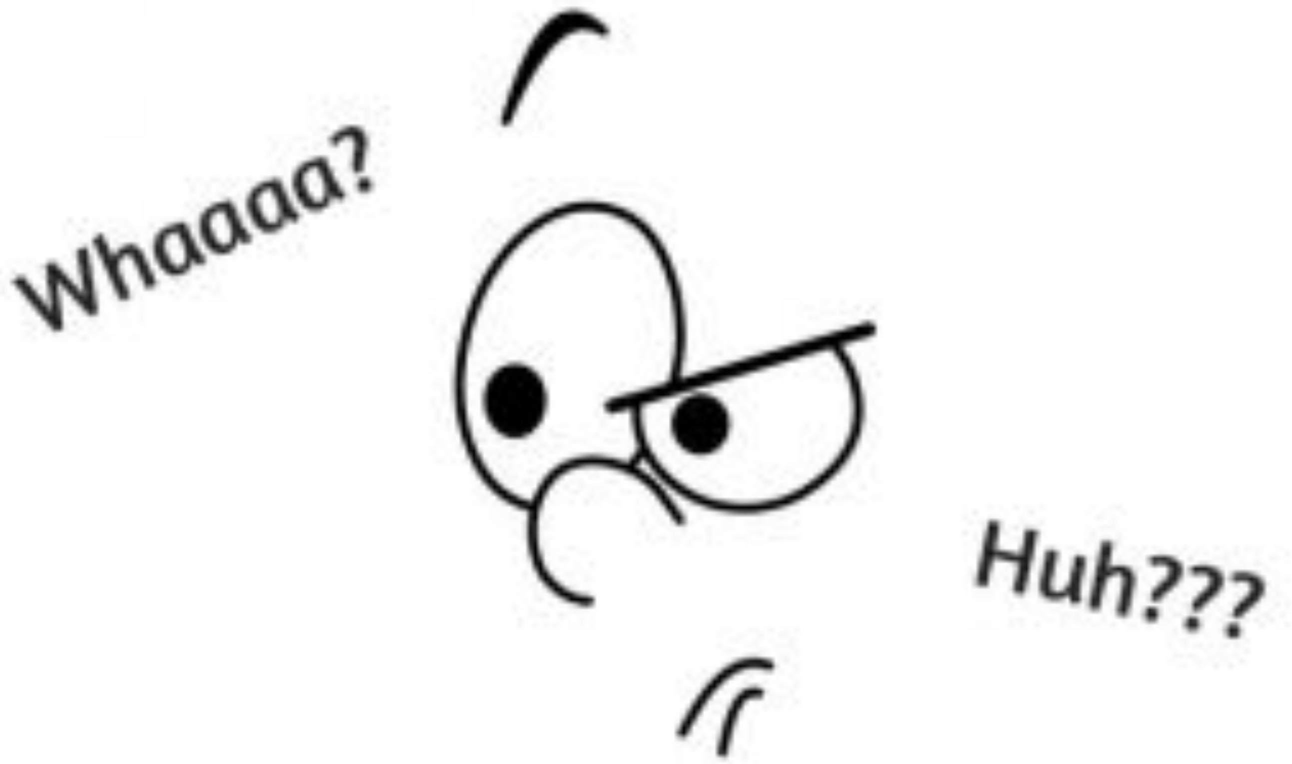
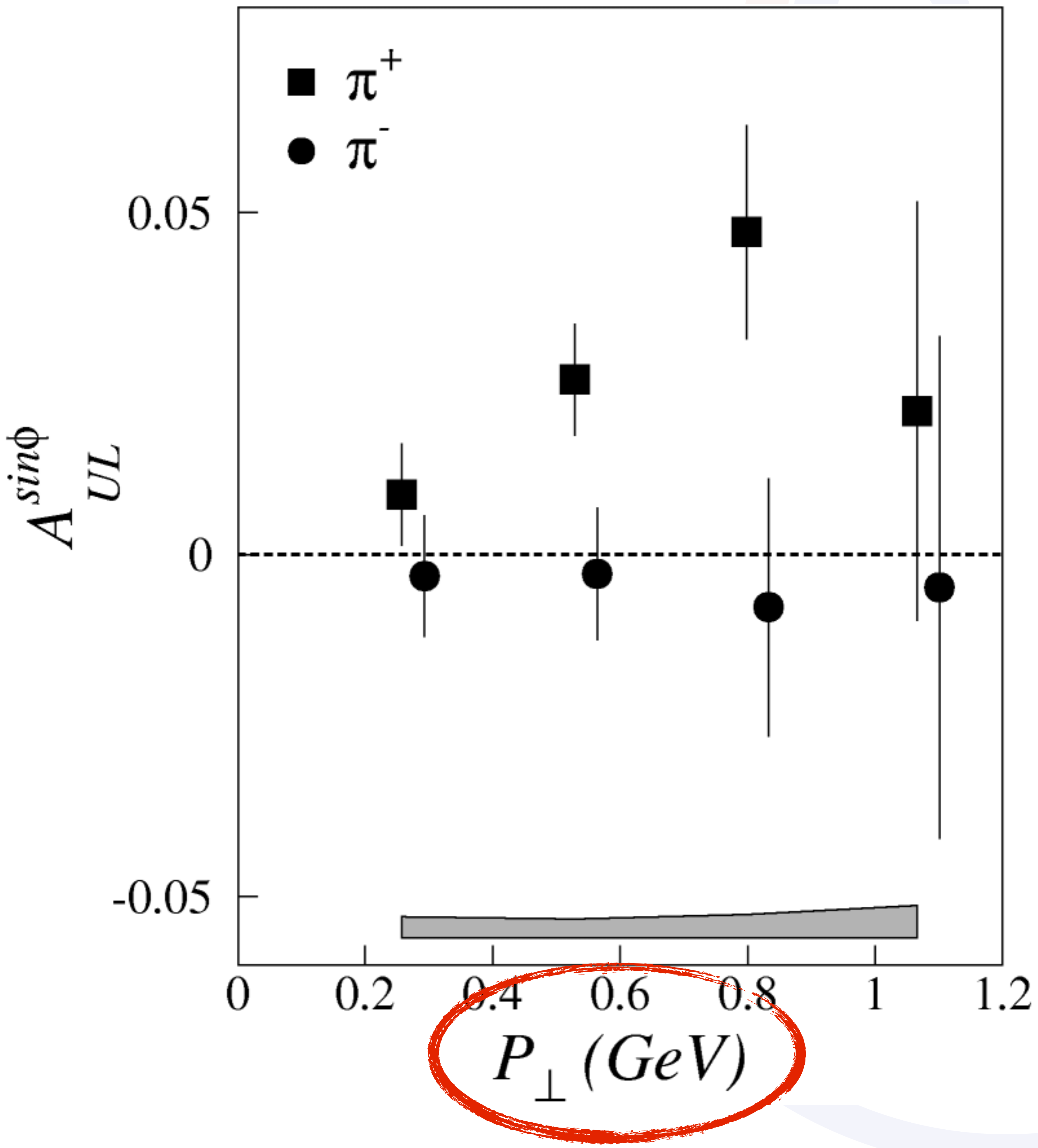
$\sim \sin\phi$?



VOLUME 84, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 2000

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



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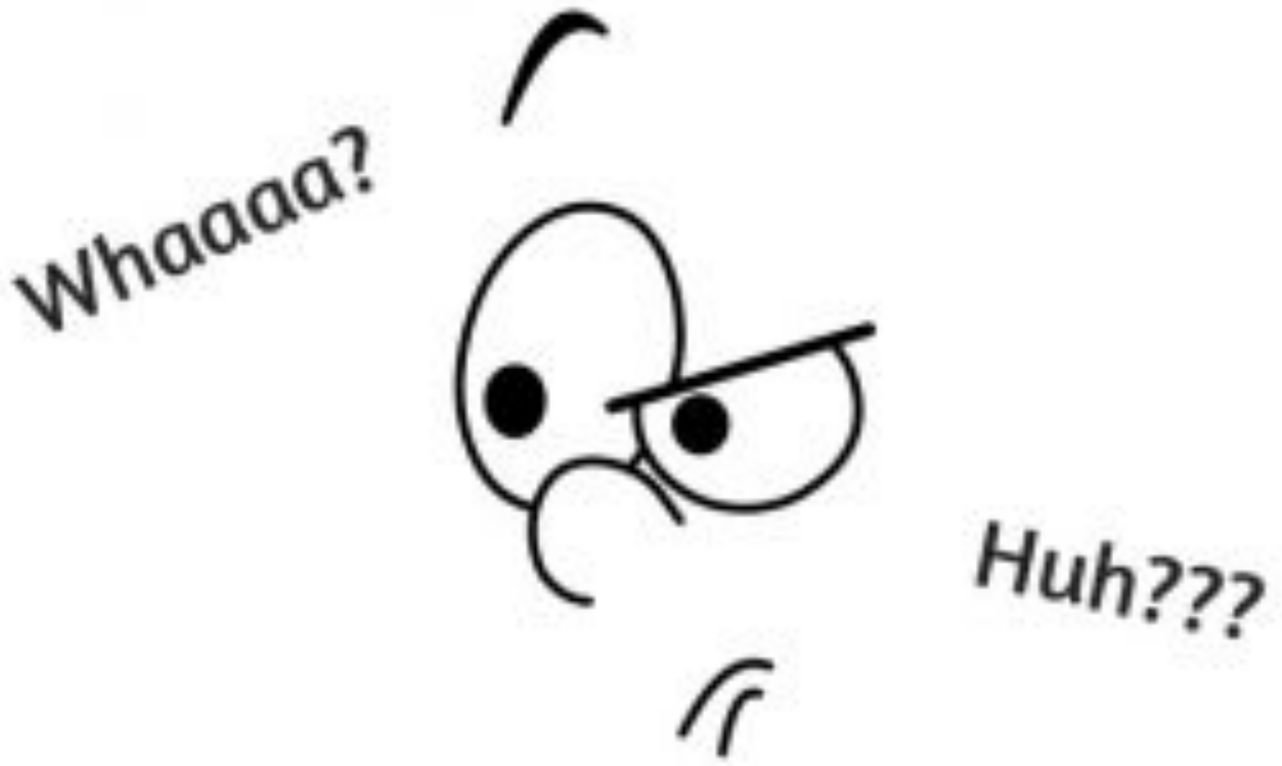
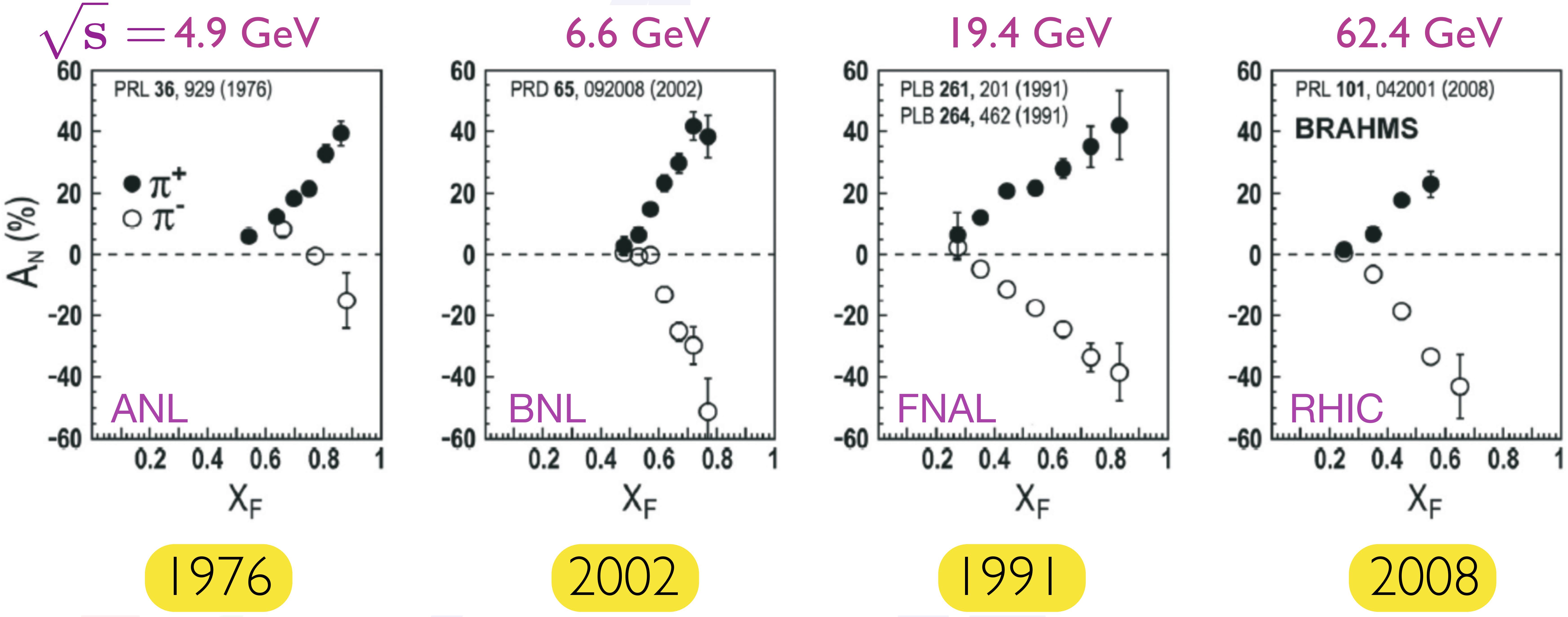
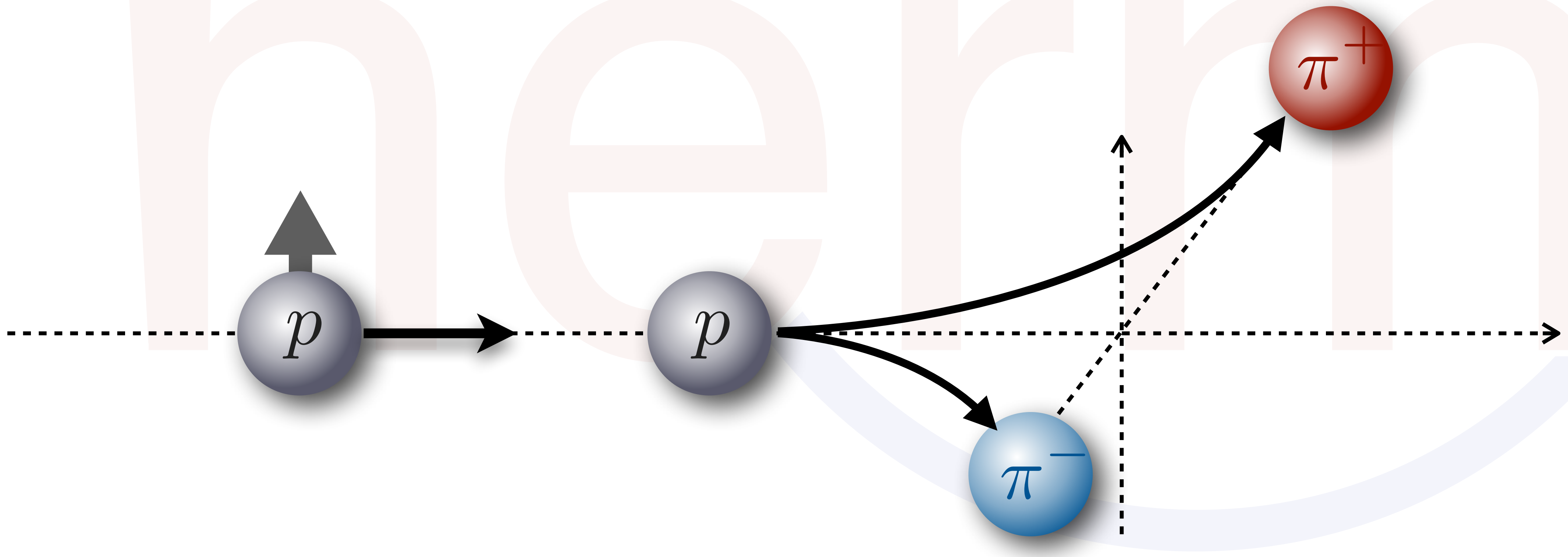


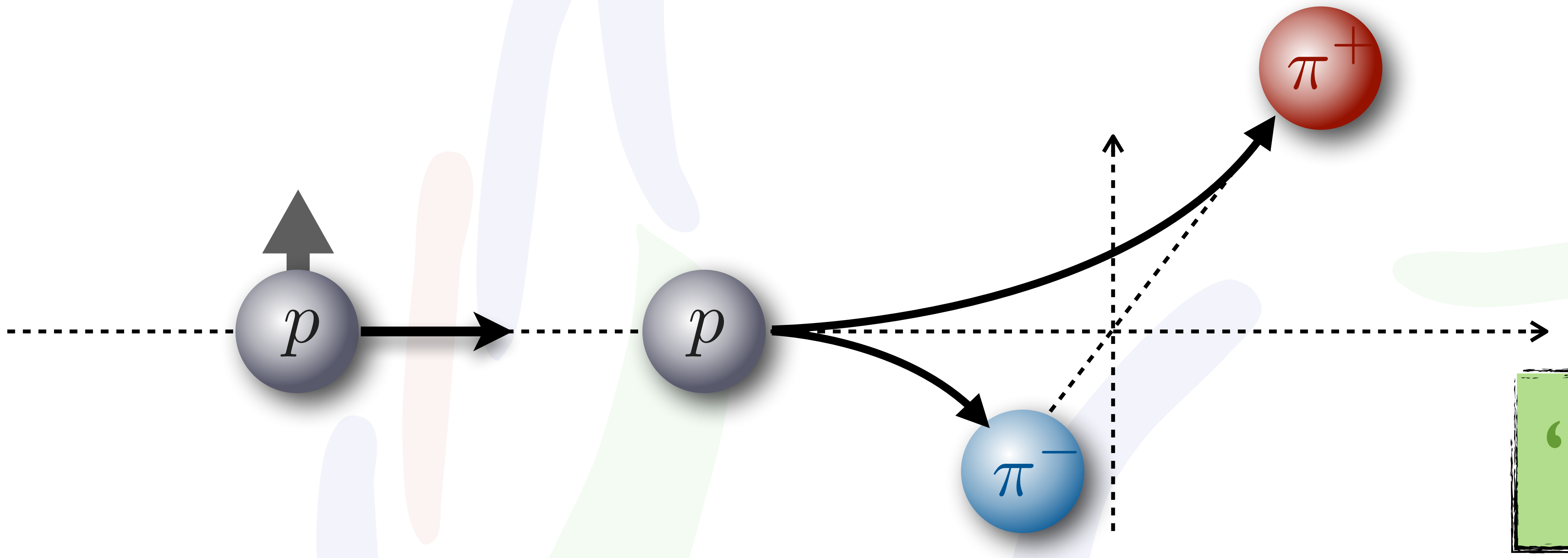
… remembering puzzling asymmetries





large left-right asymmetries that persist even to RHIC energies

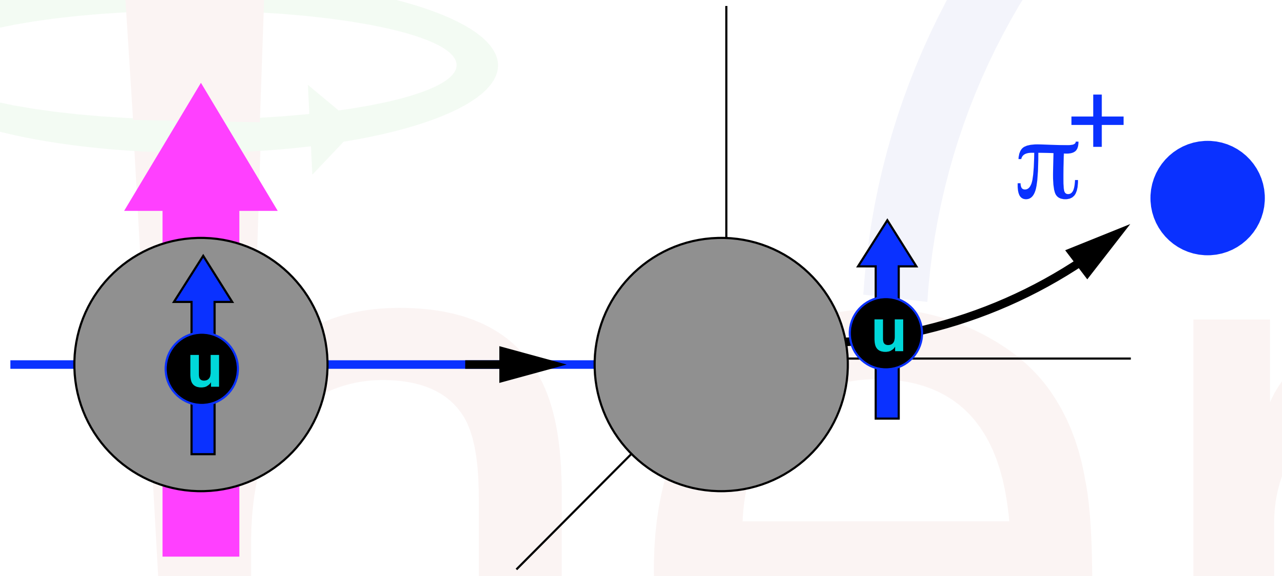
what's the origin of these SSA?



$S \cdot (P \times P_h)$

"naive T-odd"

- fragmentation effect?



[J.C. Collins, NPB 396 (1993) 161]

- correlating transverse quark spin with transverse momentum

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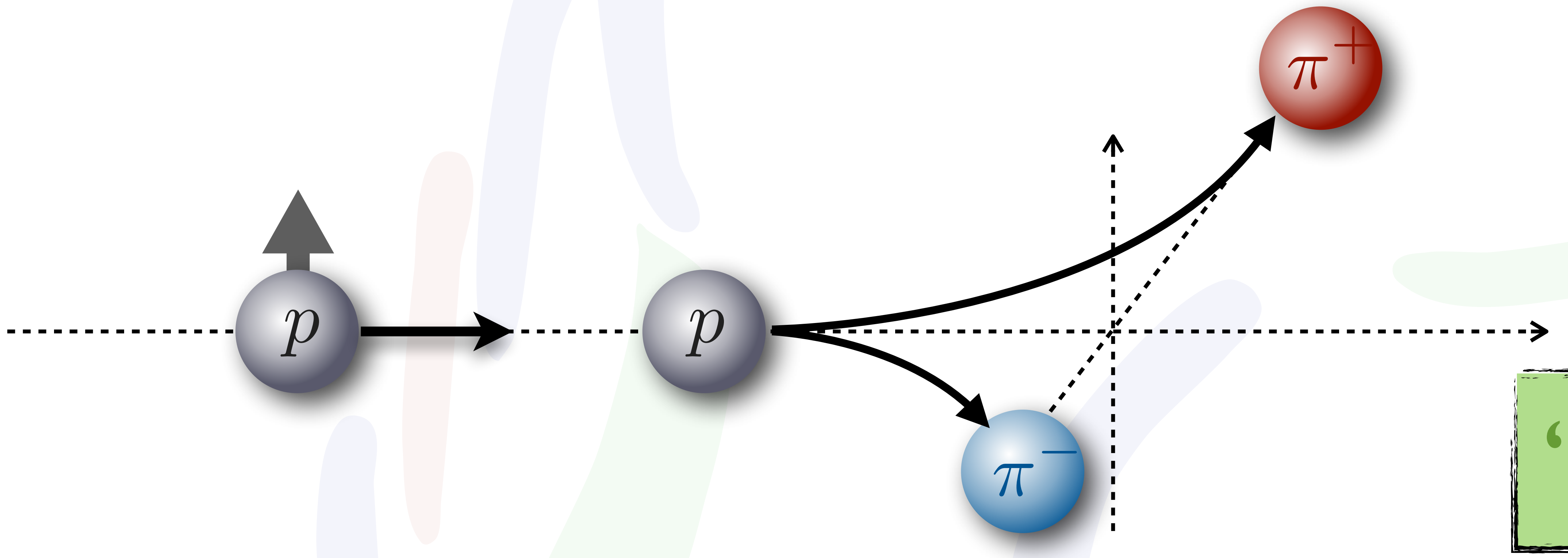

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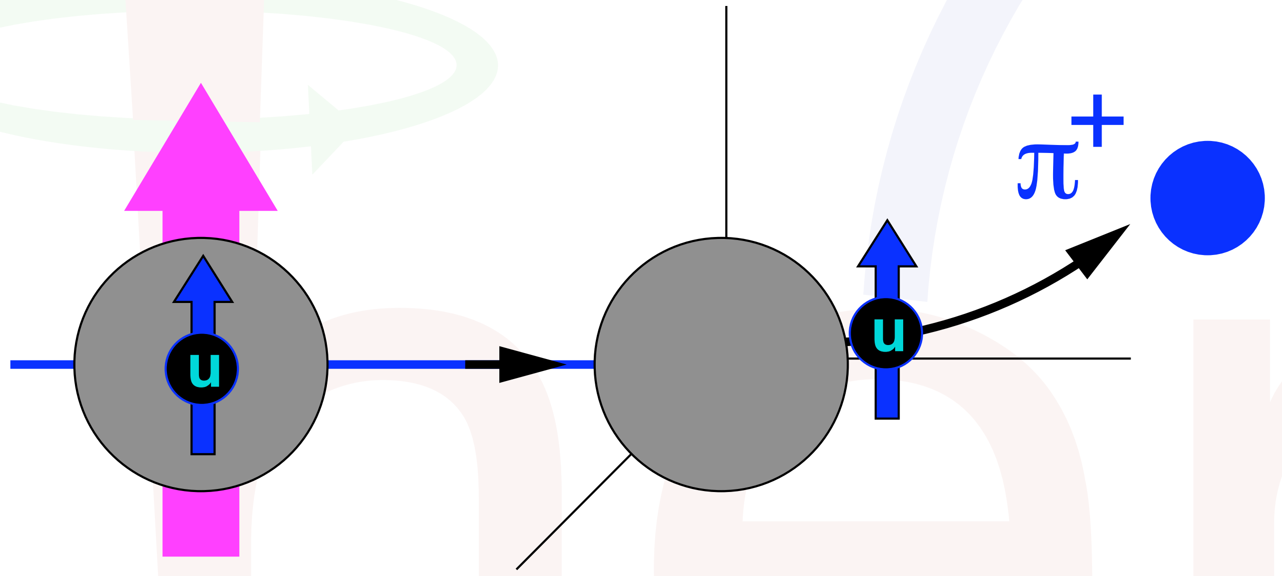
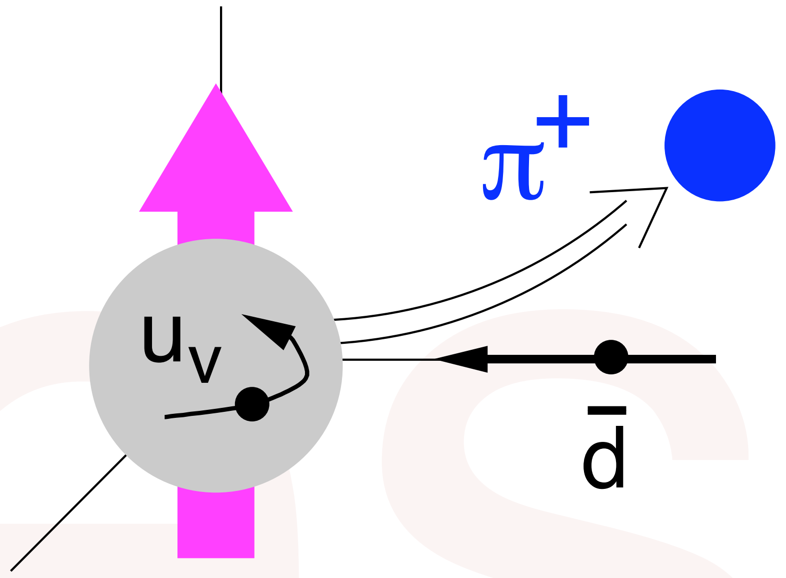


[J.C. Collins, NPB 396 (1993) 161]

- correlating transverse quark spin with transverse momentum

- quark-distribution effect?



[D.W. Sivers, PRD 41 (1990) 83]

- correlating transverse quark momentum with transverse spin of nucleon

a short history of naive time reversal

- 1978: Kane, Pumplin & Repko: transverse-spin asymmetries suppressed in pQCD
- 1990: Sivers proposes transverse spin-momentum correlation for quark distributions
- 1993: Collins dislikes (& disproves) idea, introduces similar correlation in fragmentation
- 1996: Mulders&Tangerman: compendium of azimuthal asymmetries
- 1998: Boer&Mulders: naive T-odd observables -> Boer-Mulders distribution
- 2002: Brodsky, Hwang & Schmidt: resurrection of Sivers idea

a short history of naive time reversal

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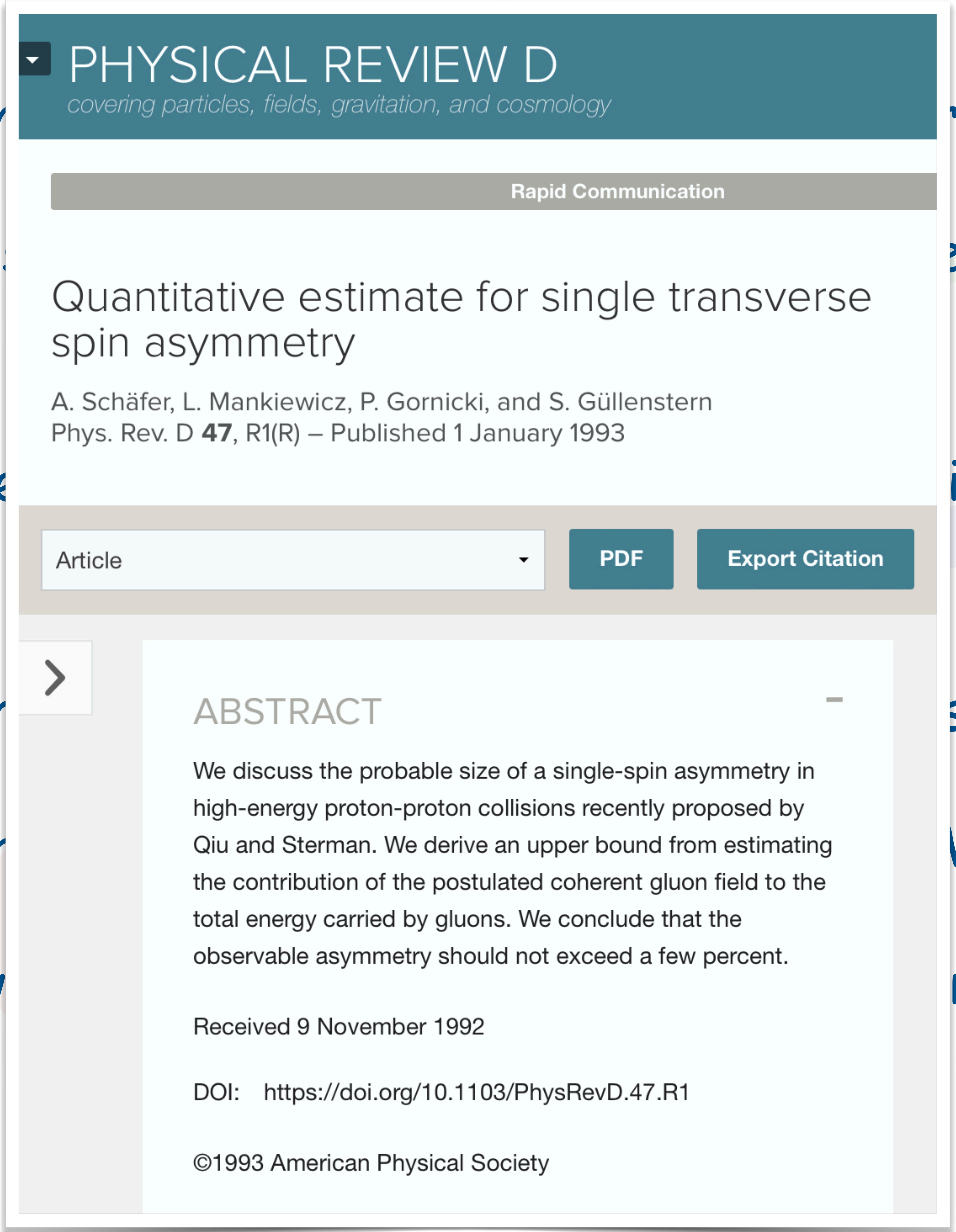

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Rapid Communication

Quantitative estimate for single transverse spin asymmetry

A. Schäfer, L. Mankiewicz, P. Gornicki, and S. Güllenstern

Phys. Rev. D **47**, R1(R) – Published 1 January 1993

Article | PDF | Export Citation

ABSTRACT

We discuss the probable size of a single-spin asymmetry in high-energy proton-proton collisions recently proposed by Qiu and Sterman. We derive an upper bound from estimating the contribution of the postulated coherent gluon field to the total energy carried by gluons. We conclude that the observable asymmetry should not exceed a few percent.

Received 9 November 1992

DOI: https://doi.org/10.1103/PhysRevD.47.R1

Spin-momentum structure of the nucleon

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

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

$$+ s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Big],$$

quark pol. (columns) / nucleon pol. (rows)

	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 chiral-odd
- functions in red are naive T-odd

Spin-momentum structure of the nucleon

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$$+\,s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Big],$$

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helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- each TMD describes a particular spin-momentum tion
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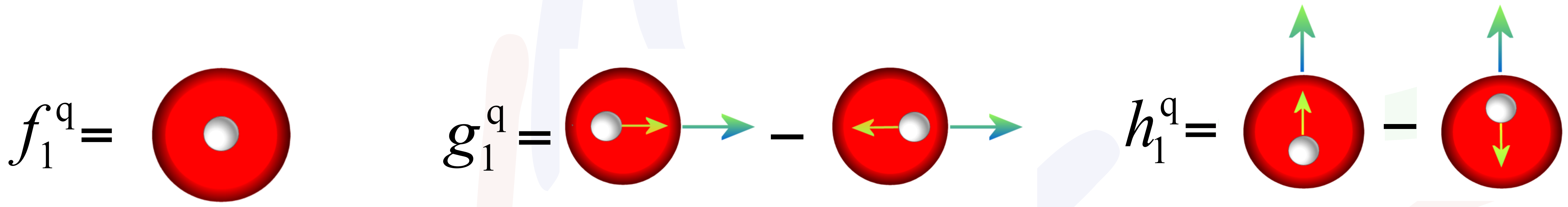
the "trouble" with transversity

chiral-odd transversity involves quark helicity flip



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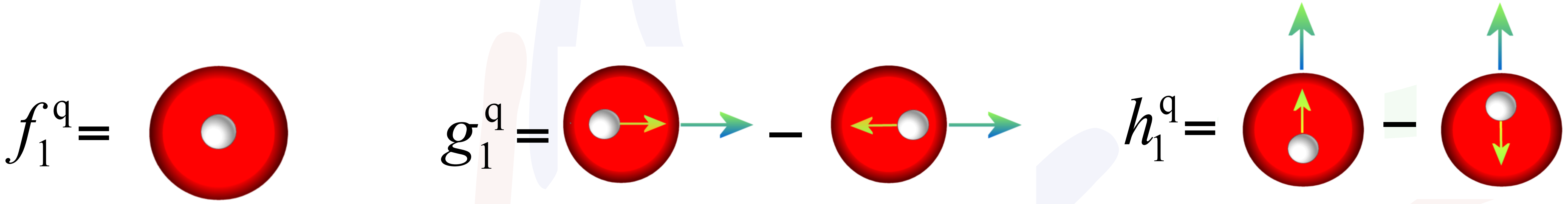

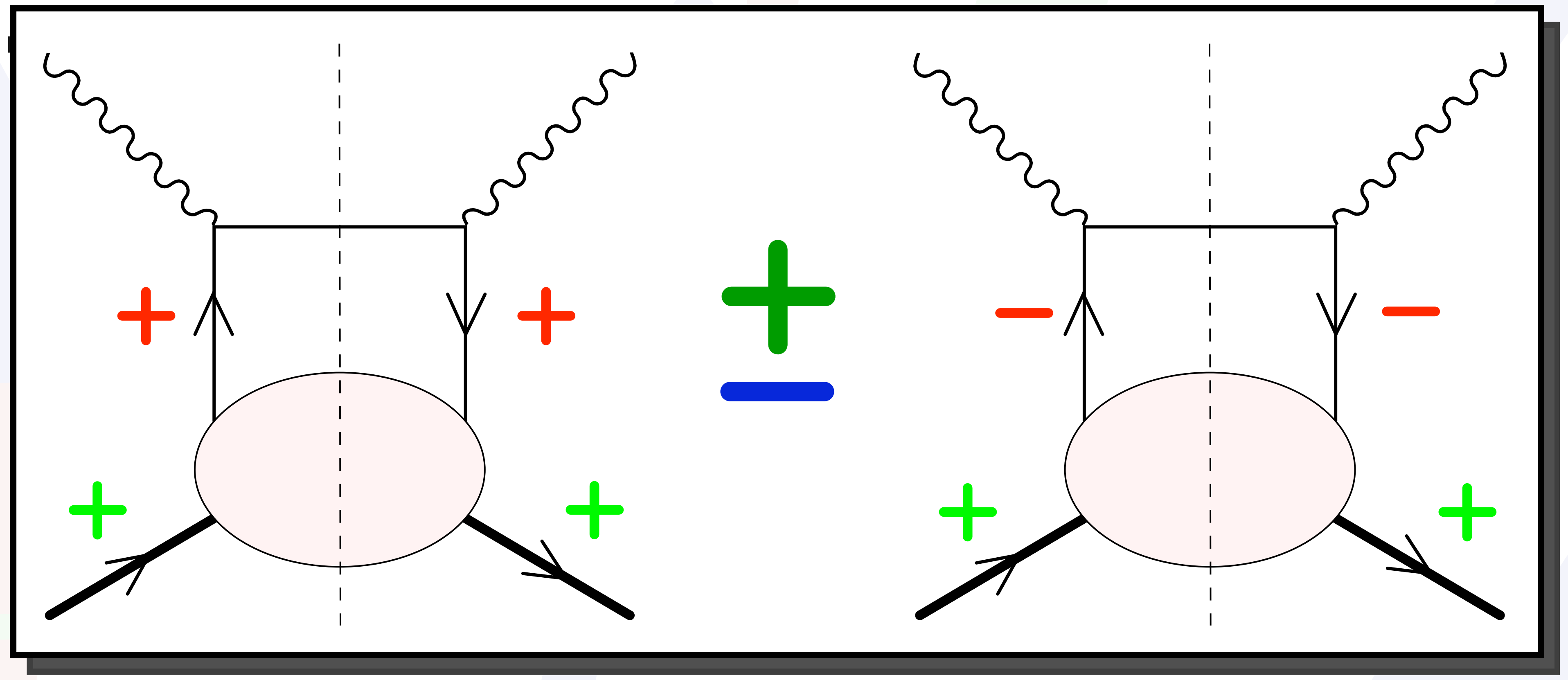

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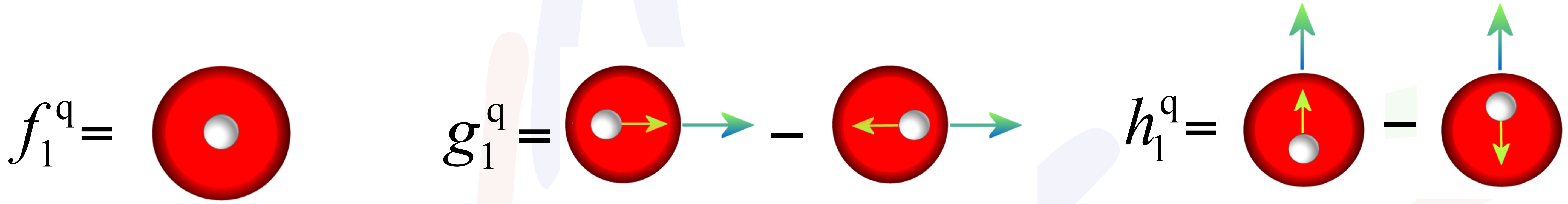

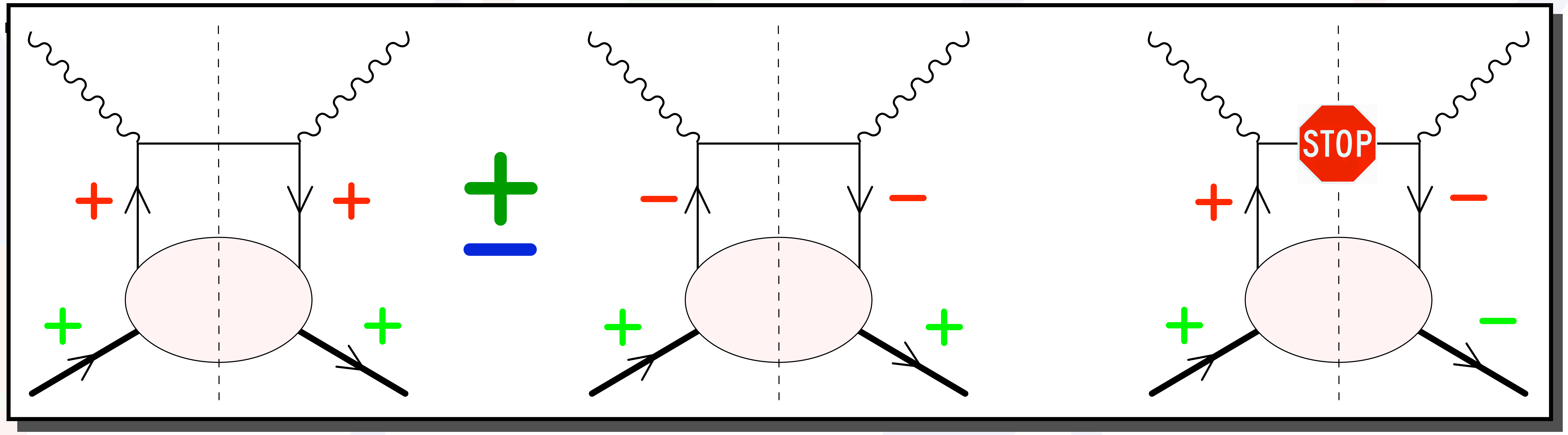

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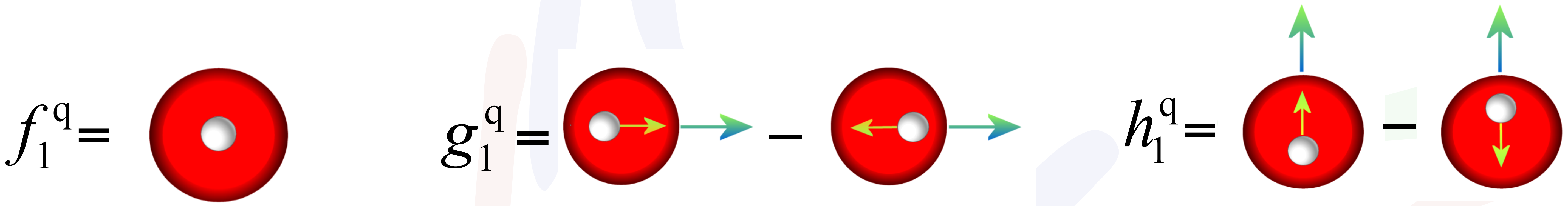
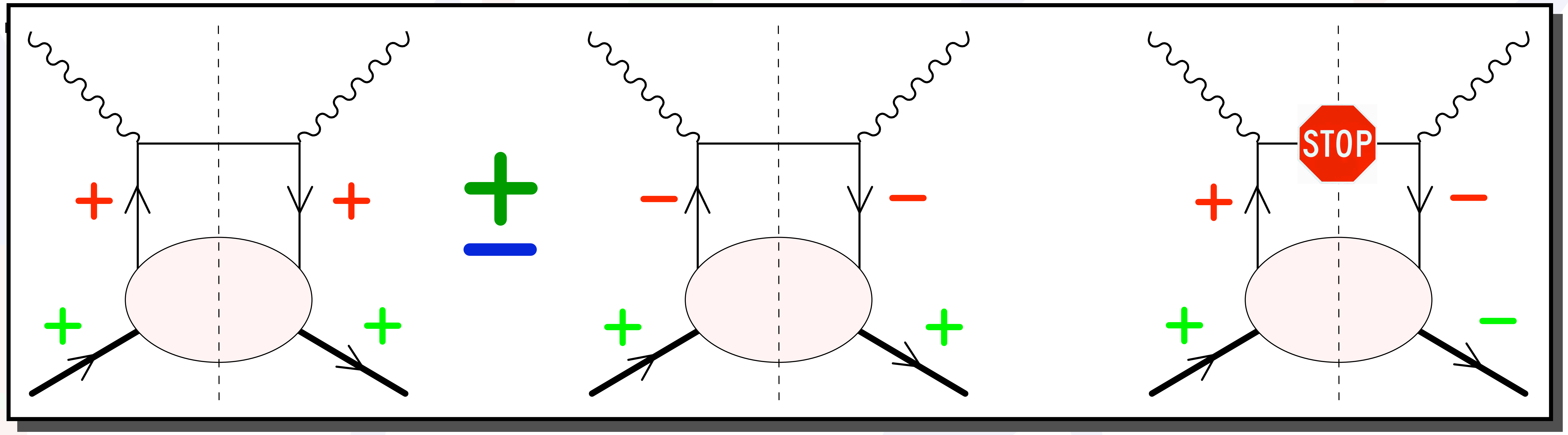




need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- 2-hadron fragmentation
- Collins fragmentation

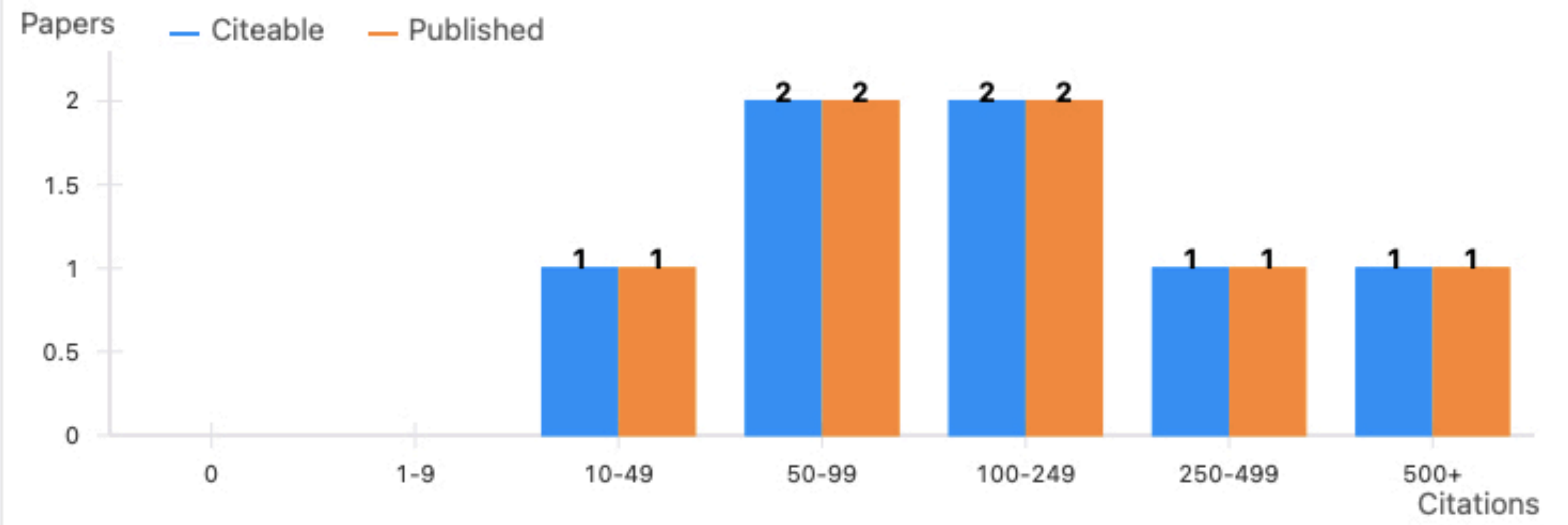
A. & A.

- in 2002, Alessandro Bacchetta joins Andreas' group as a young researcher and later AvH Fellow
- beginning of a remarkably successful program on transverse-spin physics at HERMES

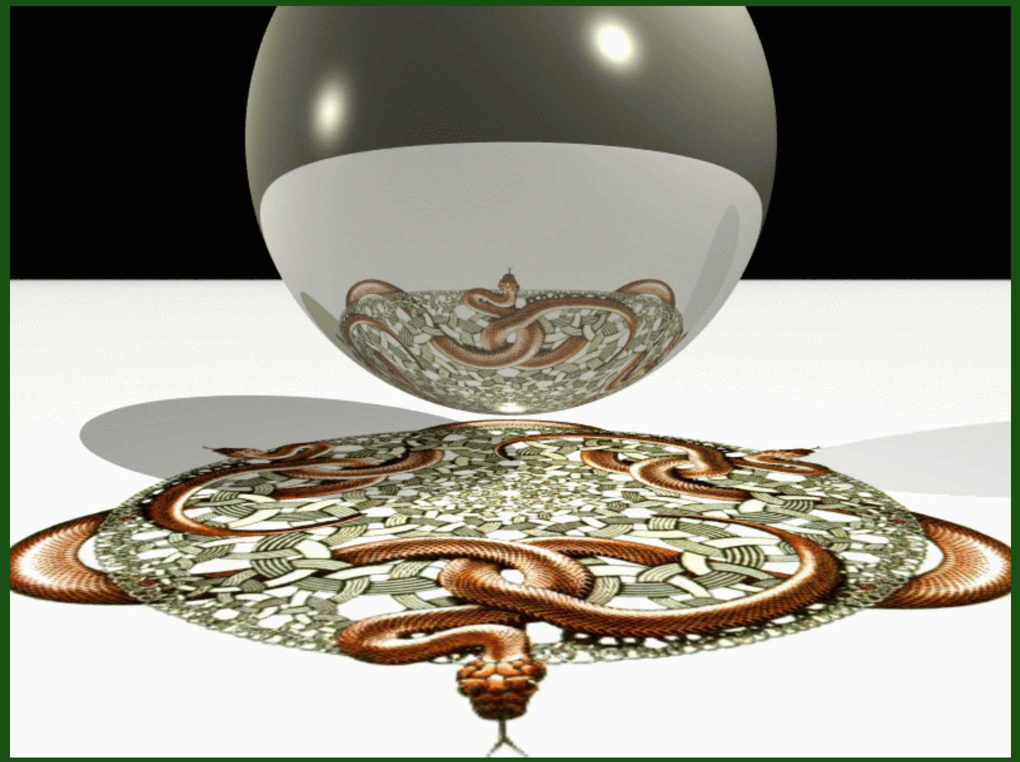
literature | a Schäfer and a Bacchetta and cn HERMES

☐ Exclude self-citations

	Citeable	Published
Papers	7	7
Citations	1,762	1,762
h-index	7	7
Citations/paper (avg)	251.7	251.7



Probing the transverse spin of quarks in deep inelastic scattering



Alessandro Bacchetta

probing TMDs in semi-inclusive DIS

quark pol. (columns) / nucleon pol. (rows)

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

in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

probing TMDs in semi-inclusive DIS

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
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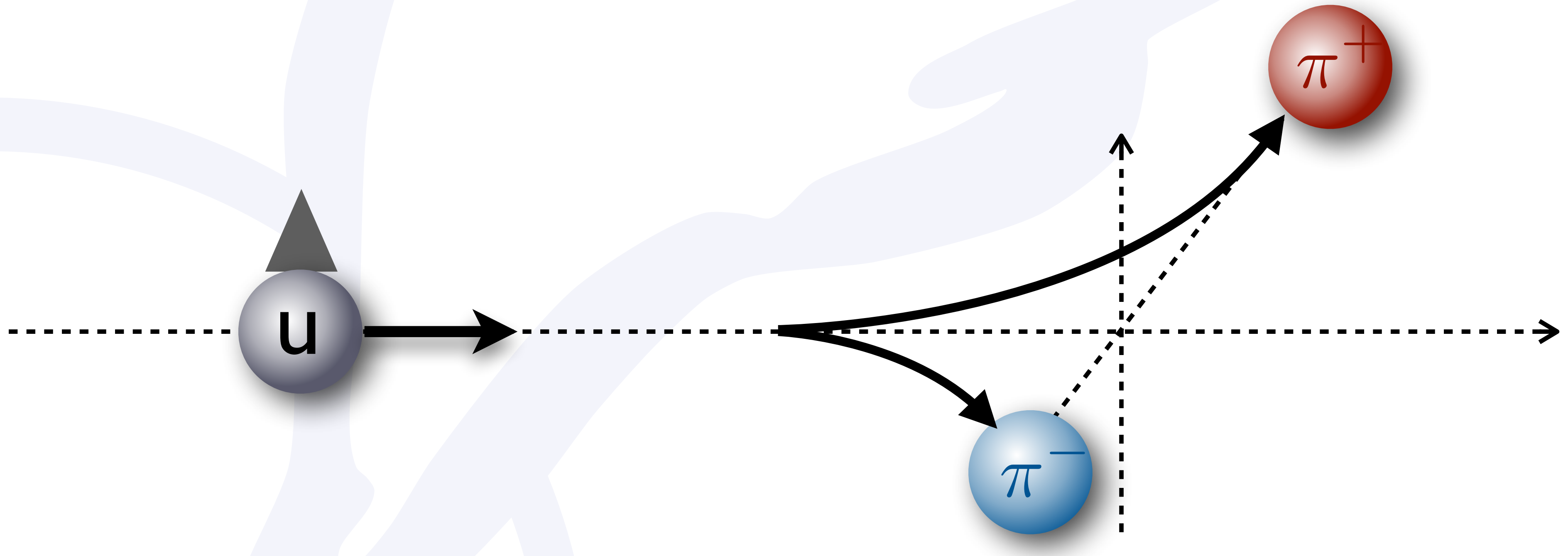
in SIDIS*) couple PDFs to:

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



*) semi-inclusive DIS with unpolarized final state

probing TMDs in semi-inclusive DIS

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

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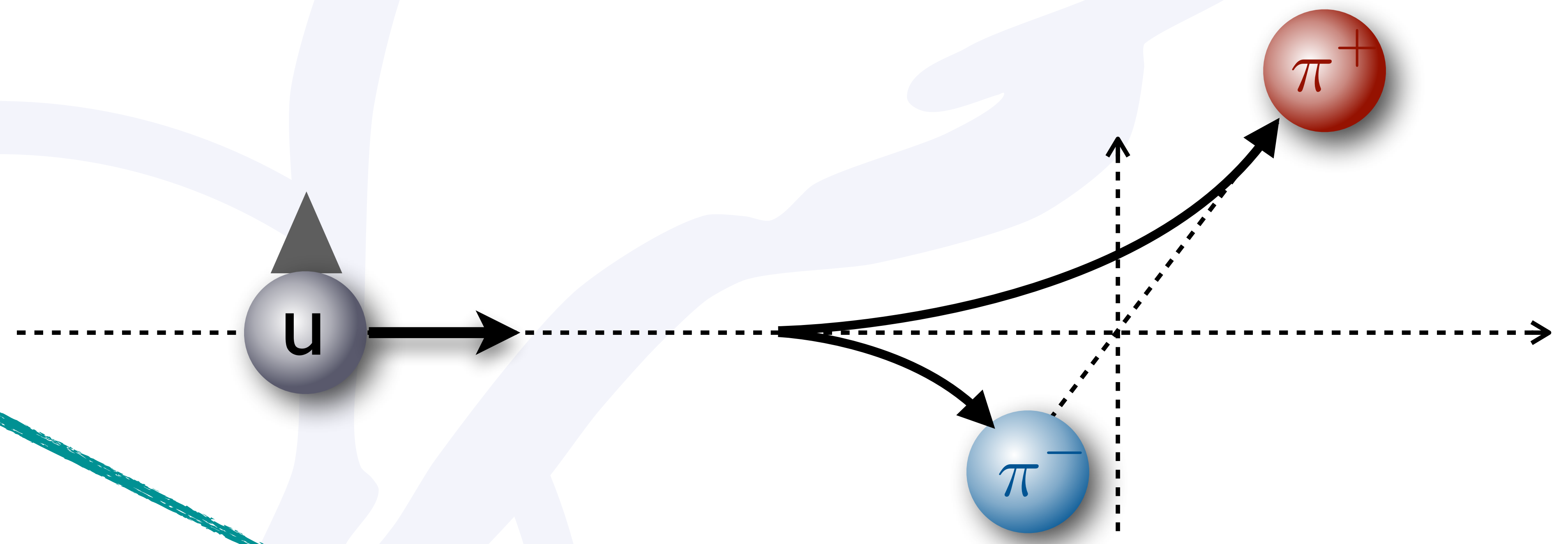


ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

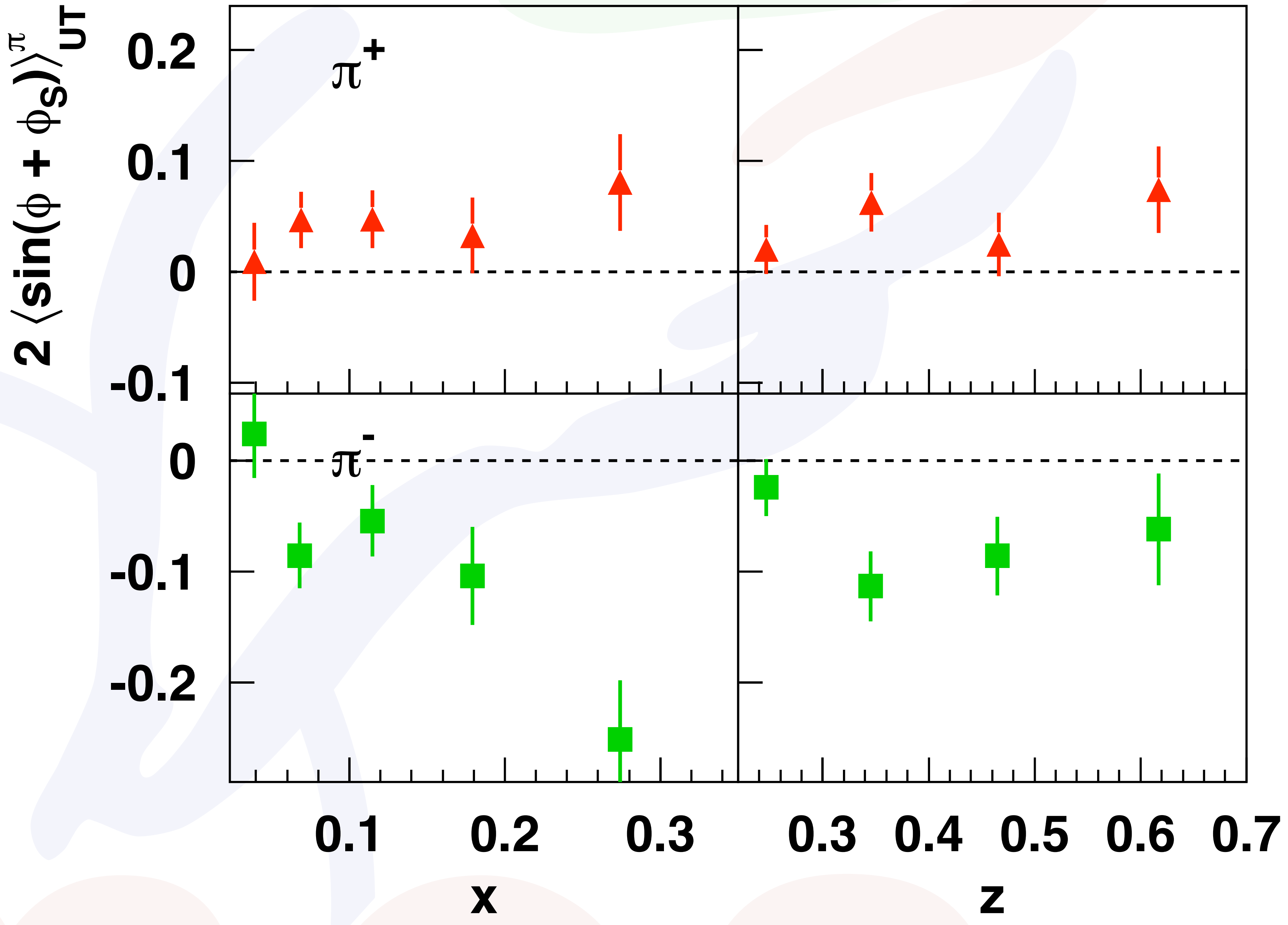
*) semi-inclusive DIS with unpolarized final state

transversely polarized quarks?

transversely polarized quarks?

- transverse polarization of quarks leads to large effects!

[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

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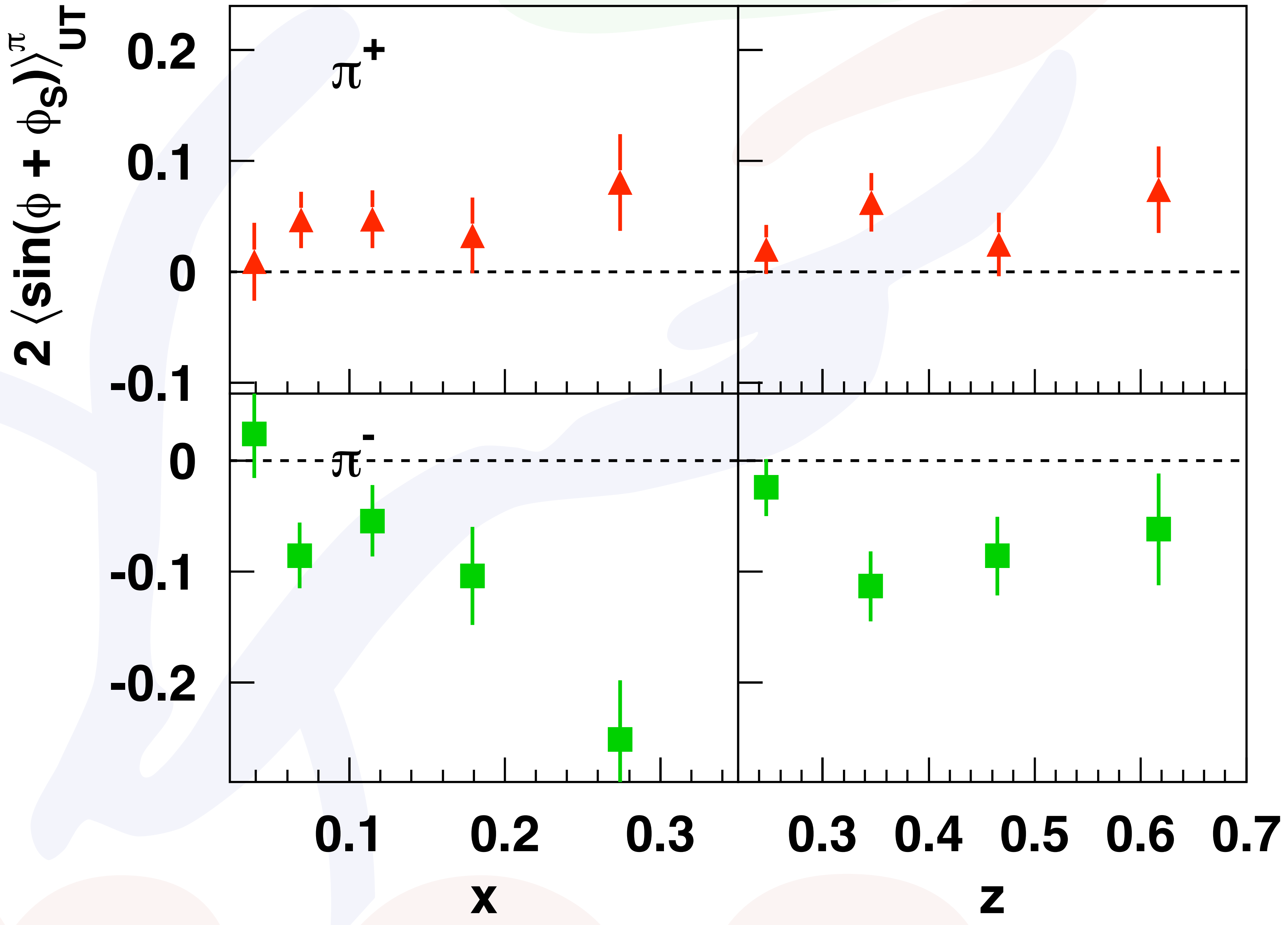
- opposite in sign for charged pions

[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]

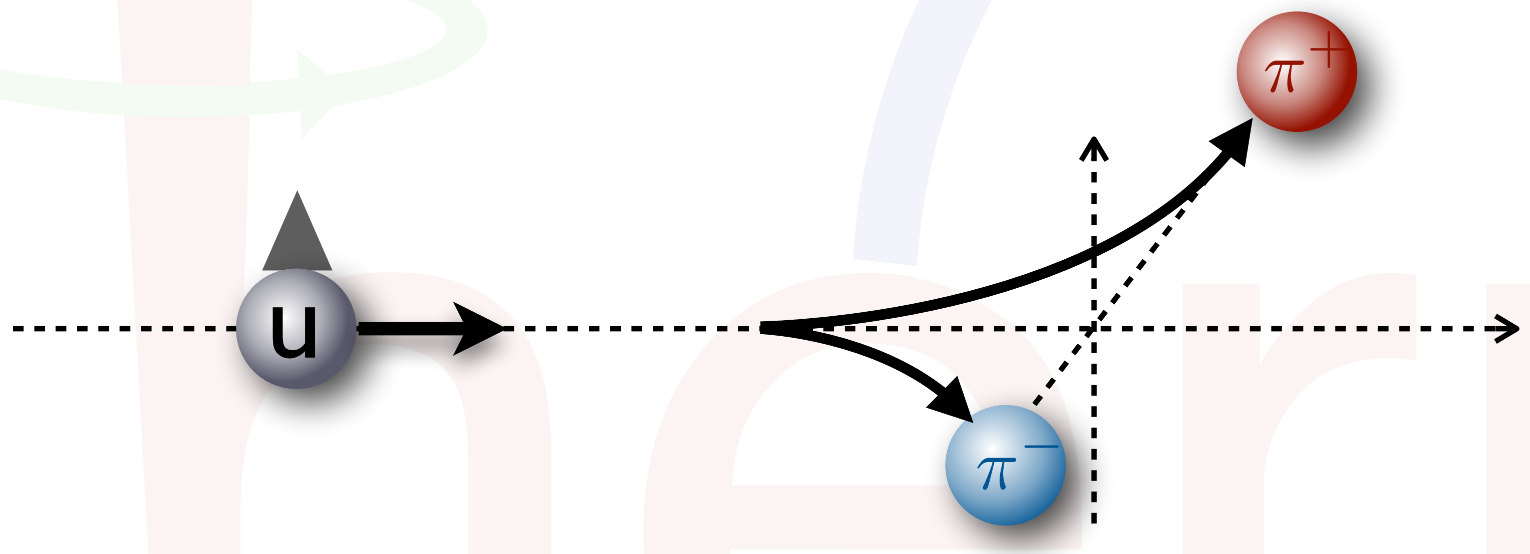


2005: First evidence from HERMES SIDIS on proton

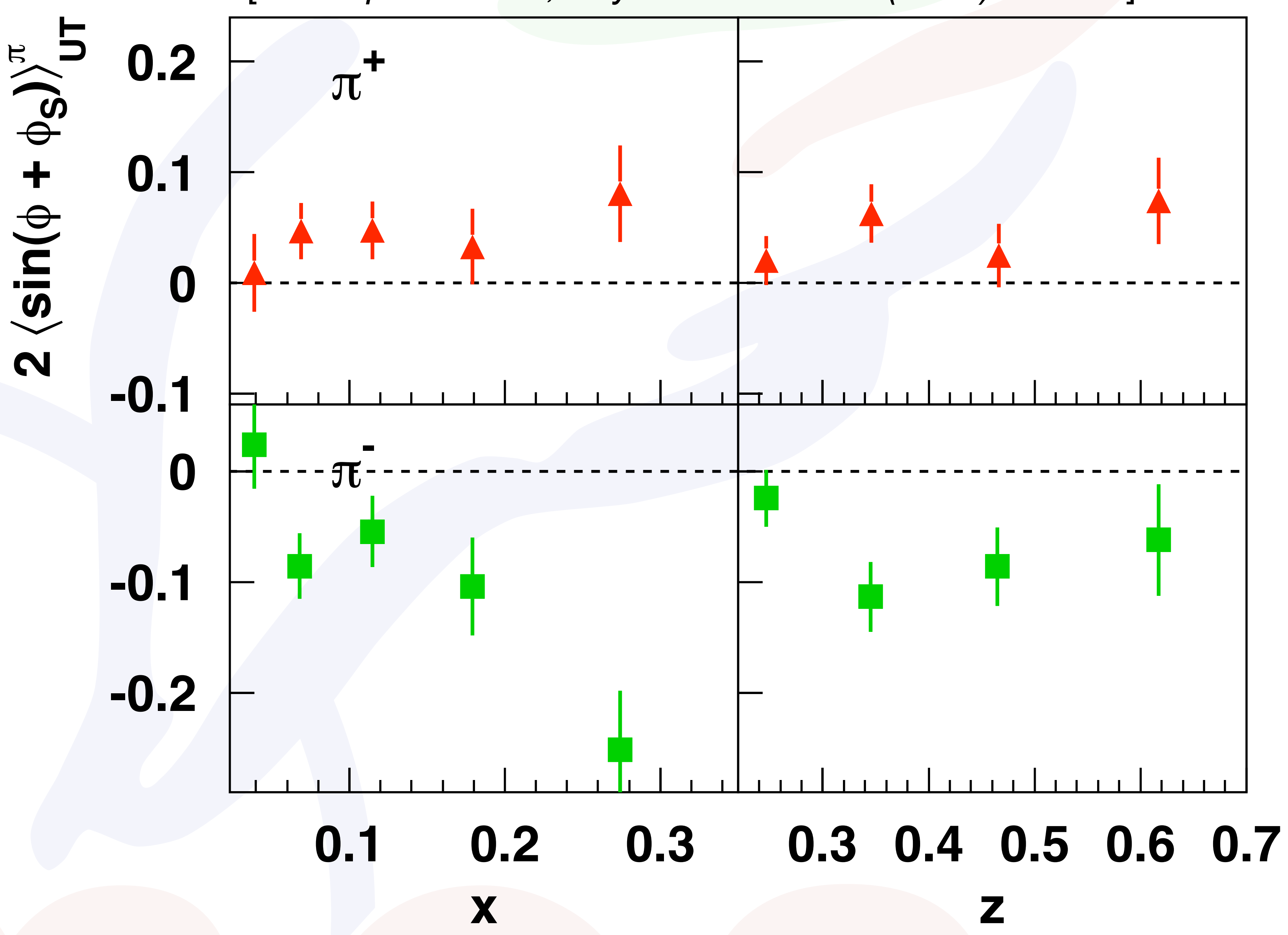
Non-zero transversity
Non-zero Collins function

transversely polarized quarks?

- transverse polarization of quarks leads to large effects!
- opposite in sign for charged pions
- disfavored Collins FF large and **opposite in sign** to favored one



[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

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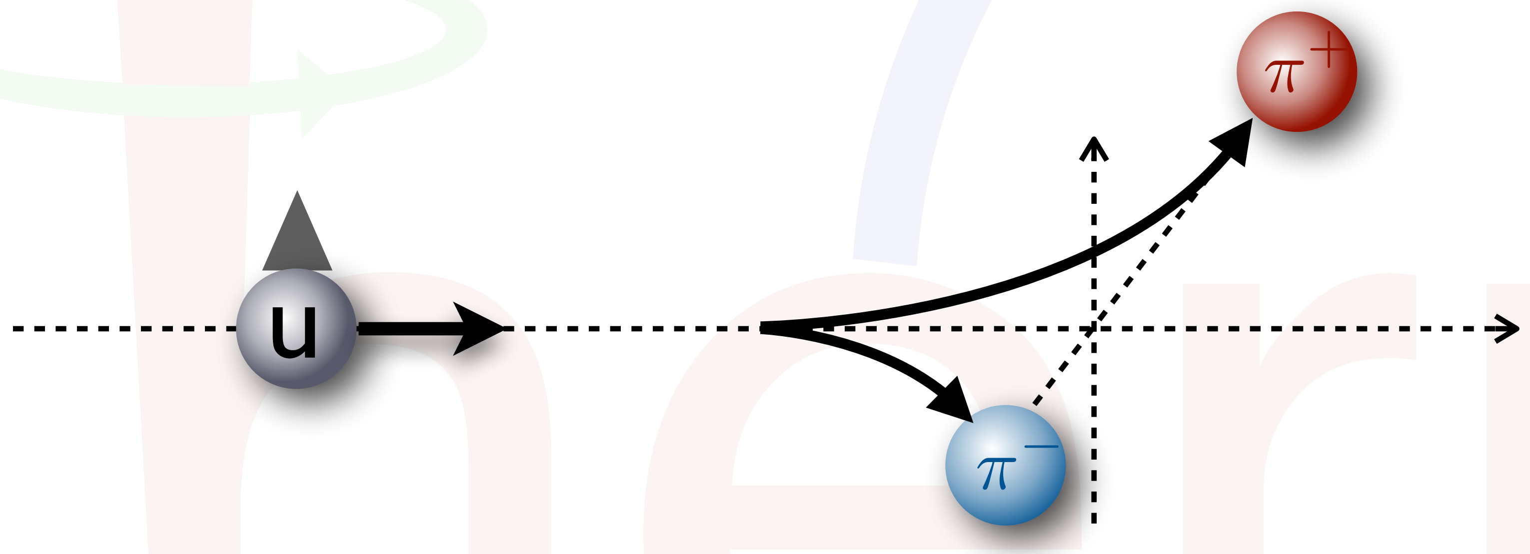

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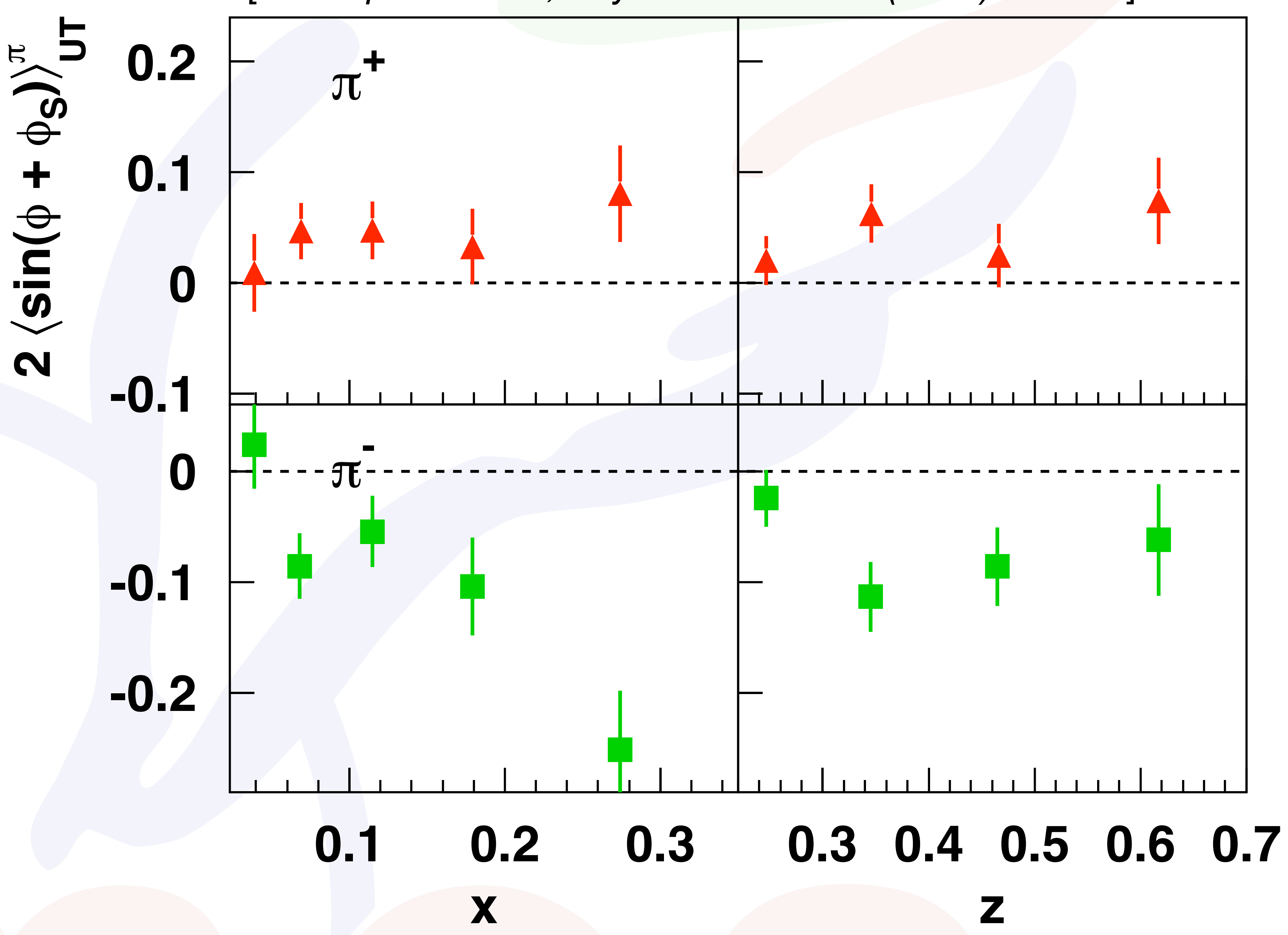

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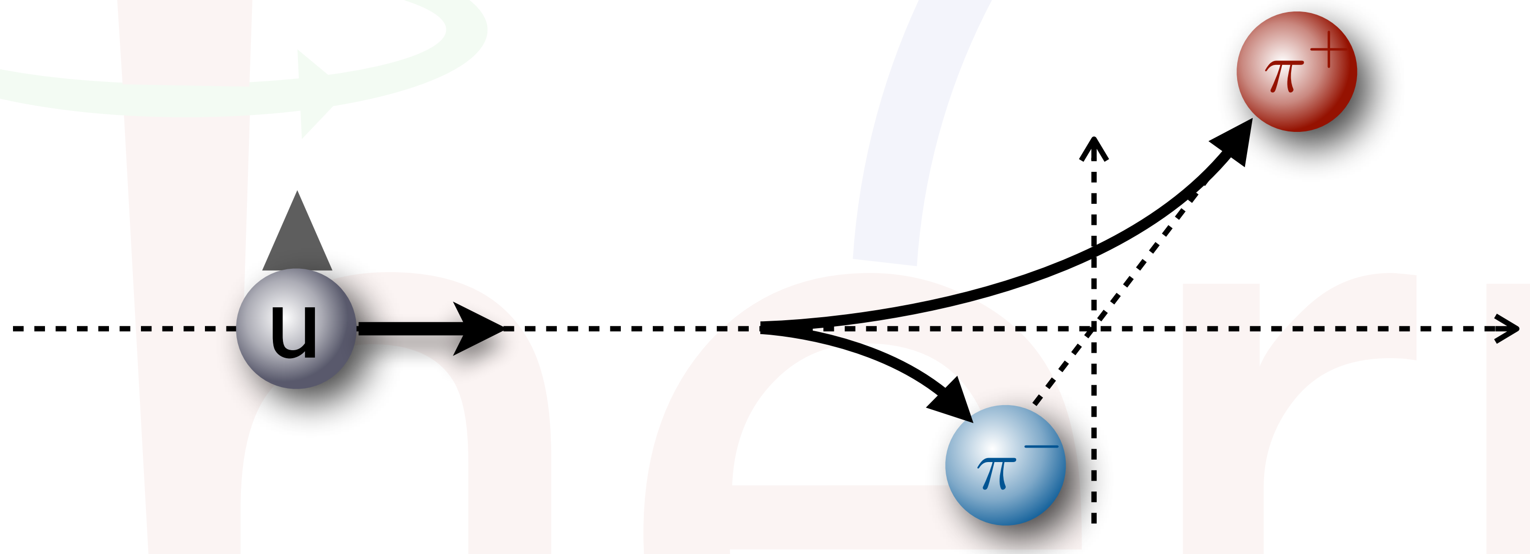

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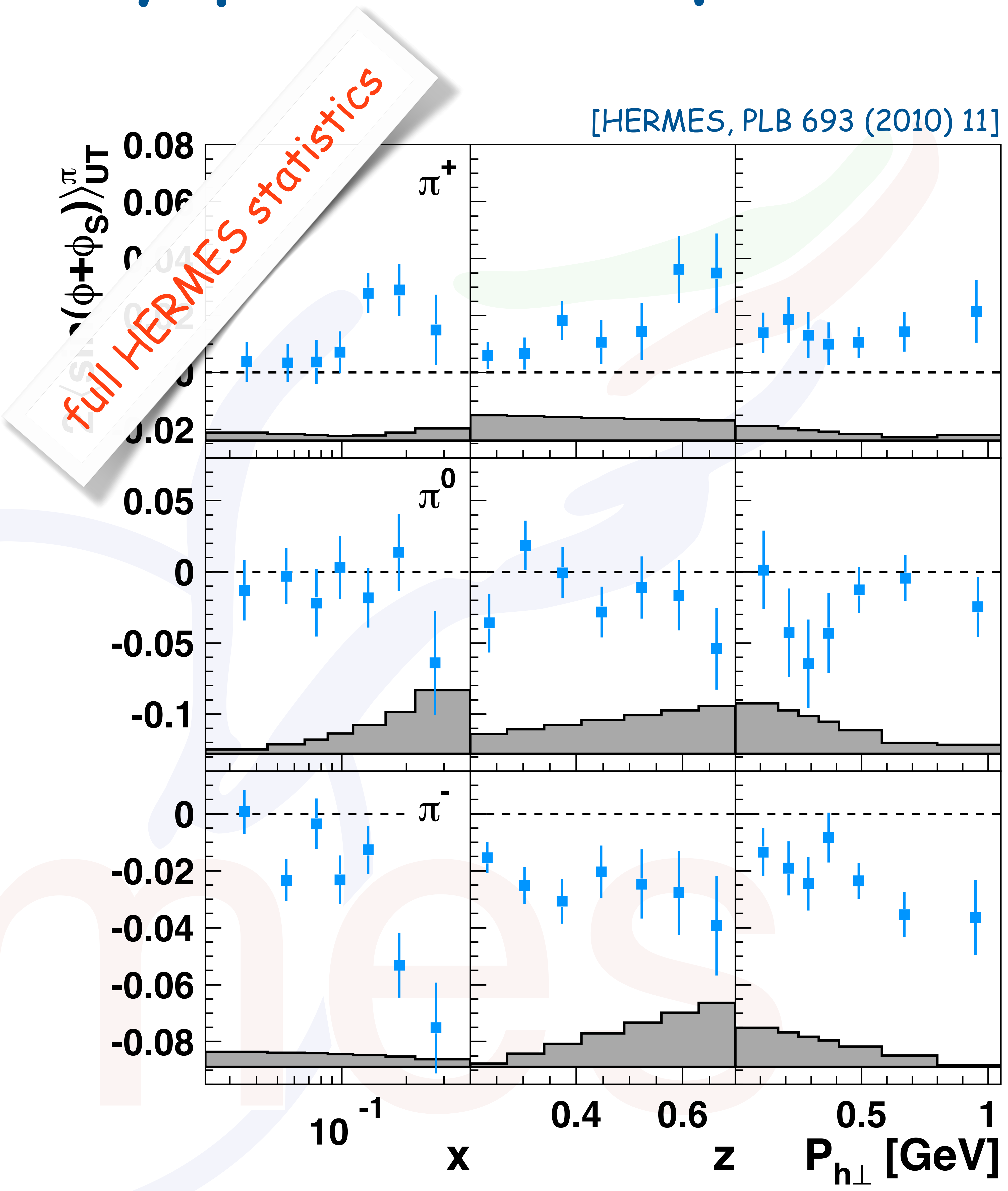
[HERMES, PLB 693 (2010) 11]



Was Collins then right about Sivers?

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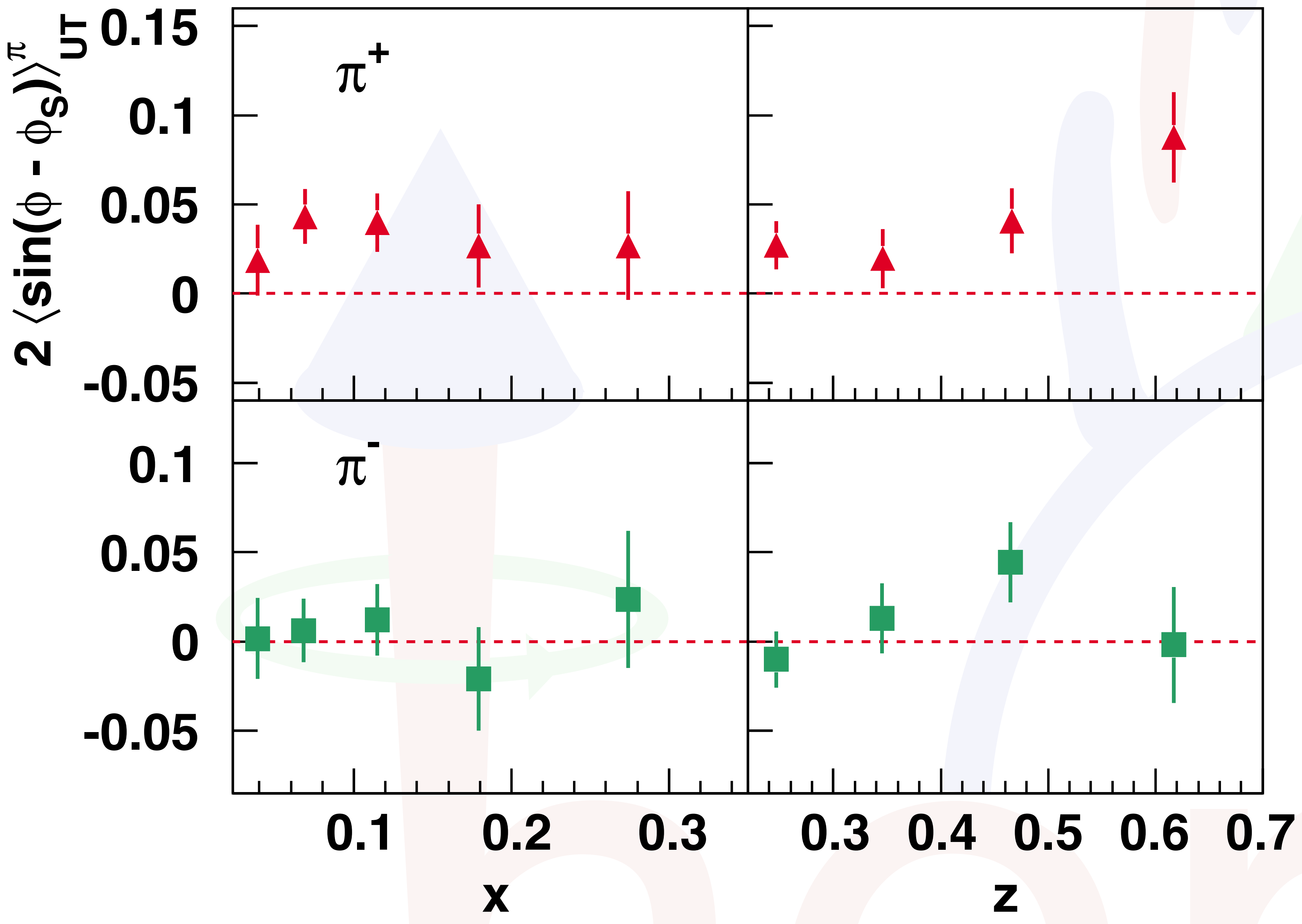

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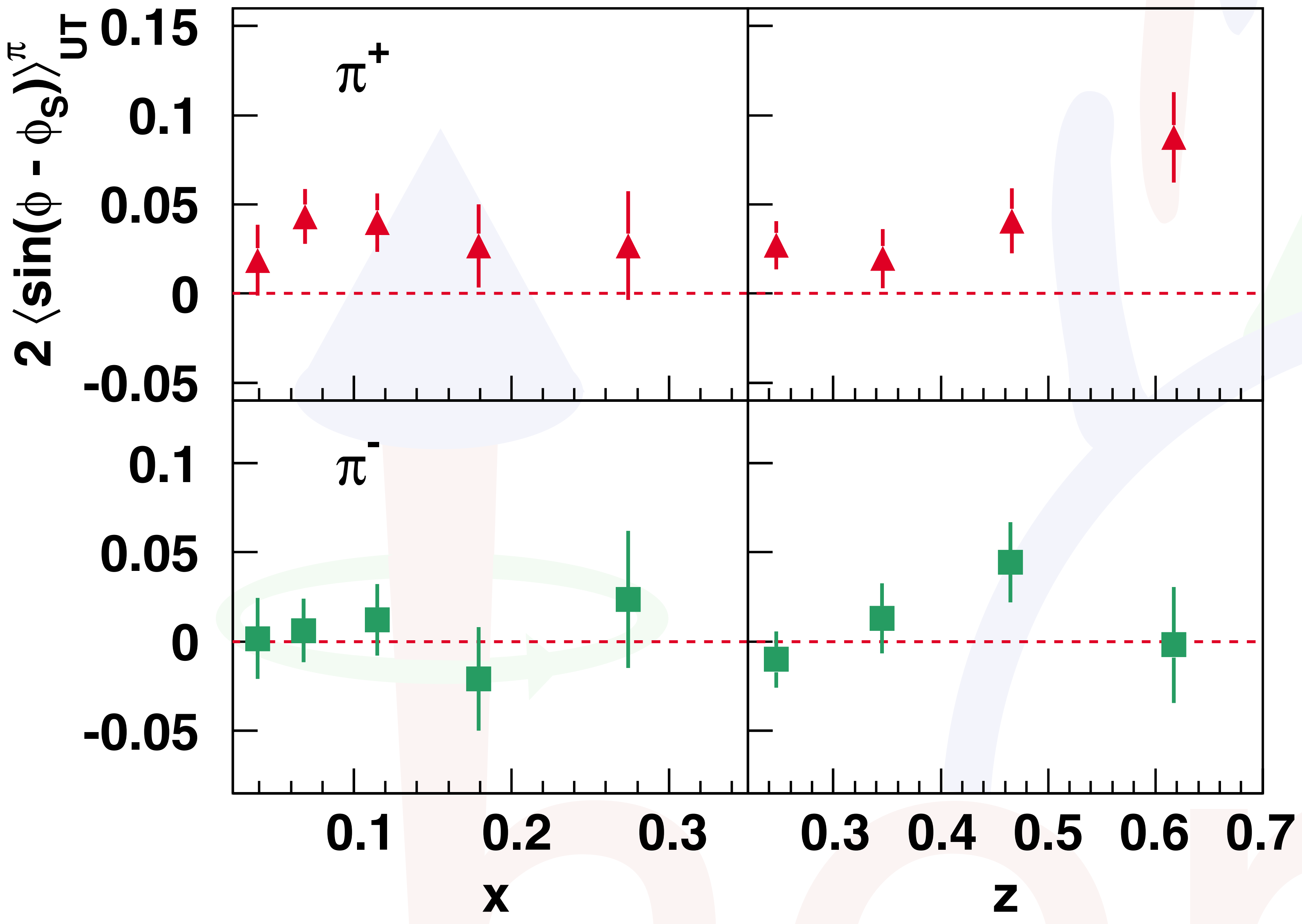

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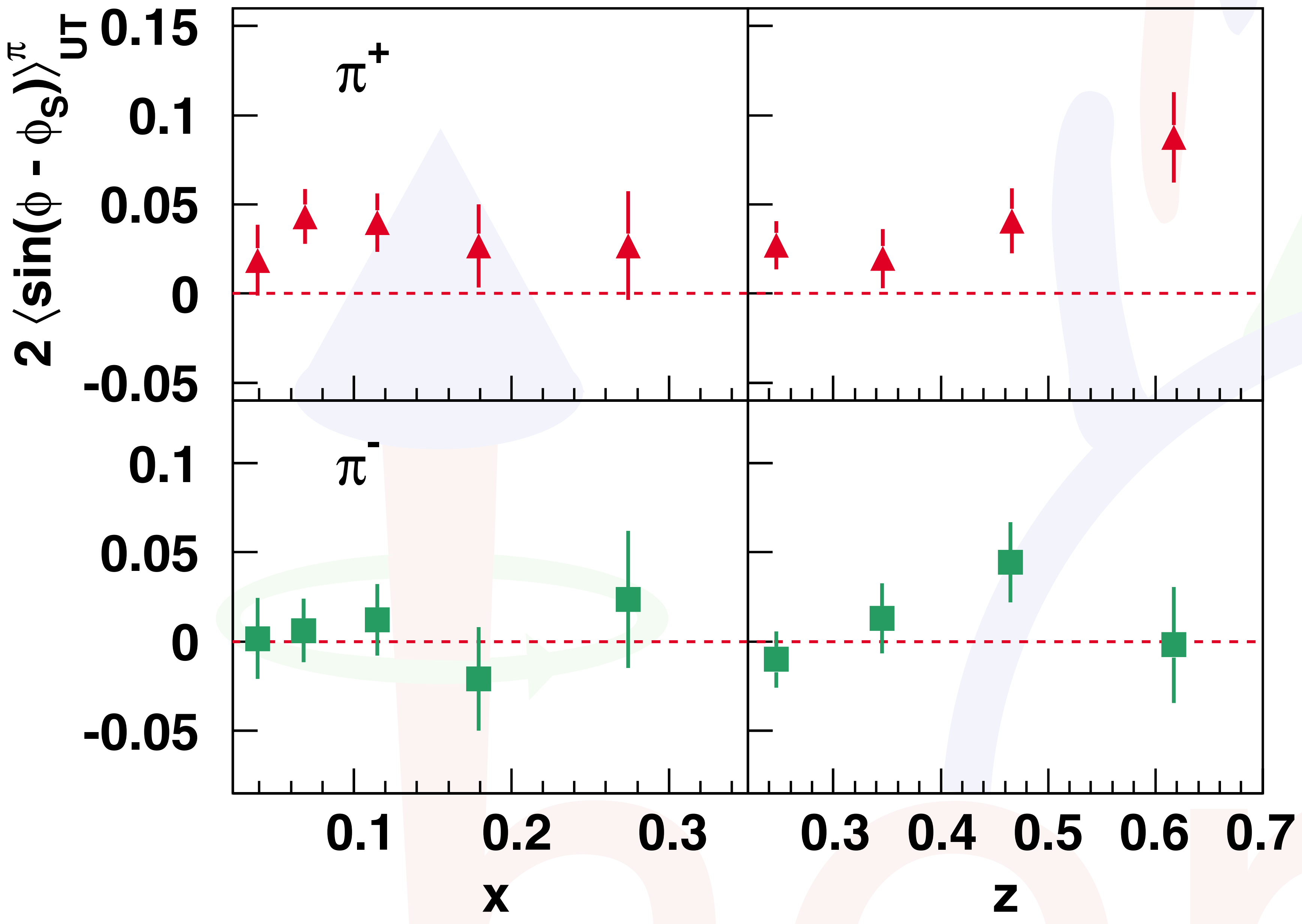

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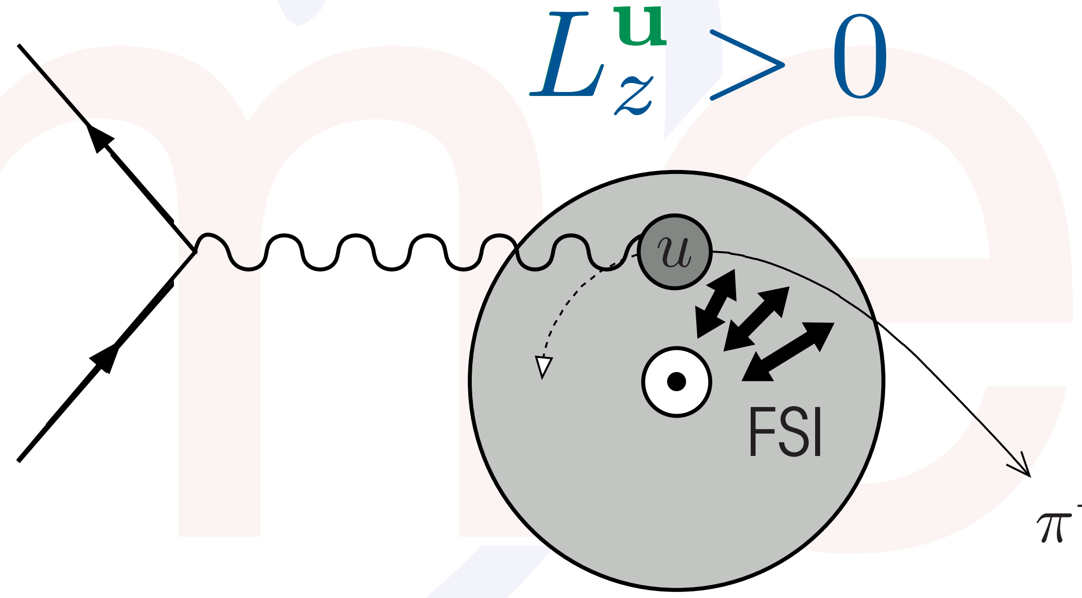
- however, Sivers predicted wrong sign
- better: chromodynamic-lensing picture [M. Burkardt]



$$-f_{1T}^{\perp q} \sim \kappa^q$$

$$\kappa^u = 1.67$$

$$\kappa^d = -2.03$$

[M. Burkardt, PRD66 (2002) 014005]

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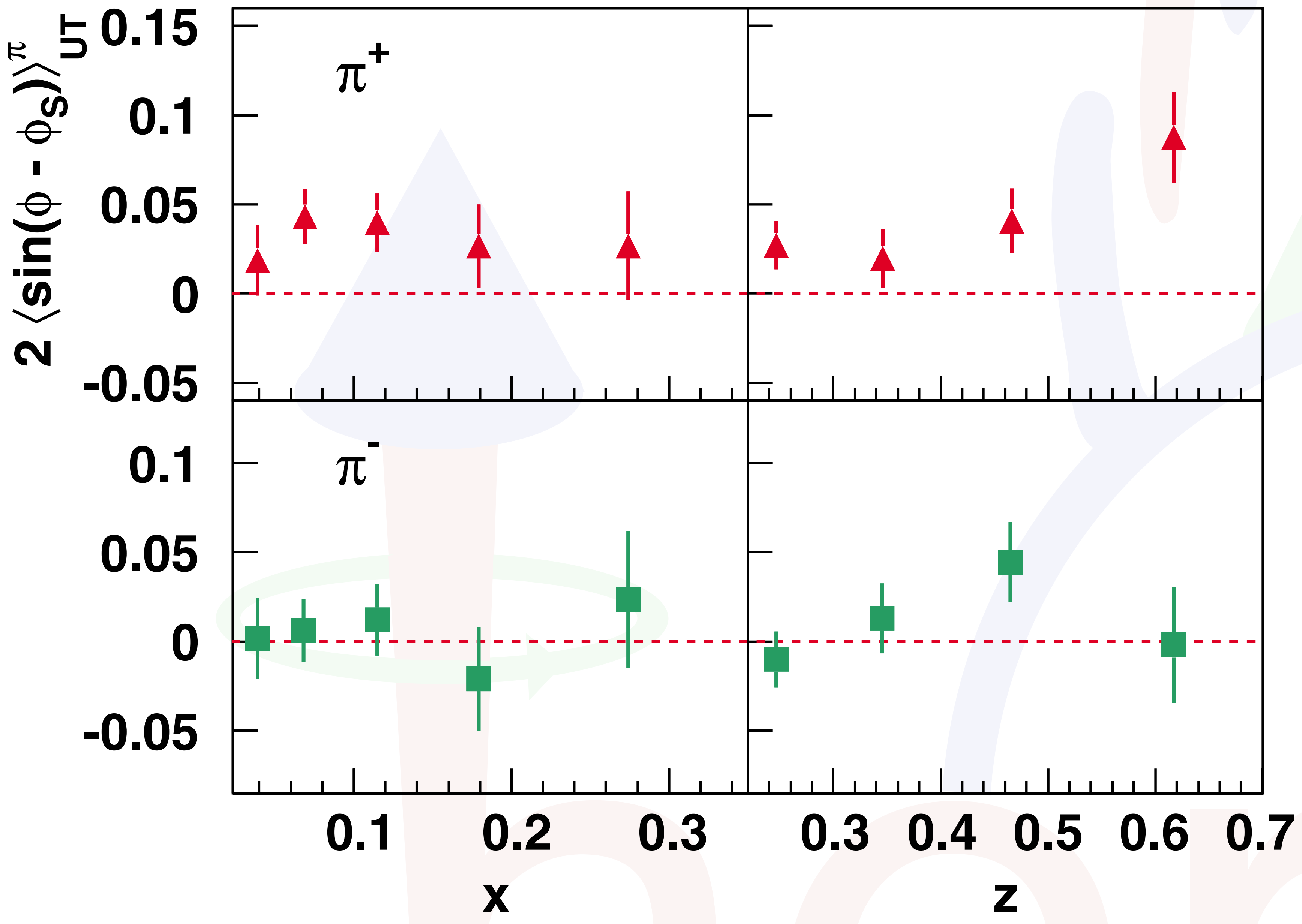

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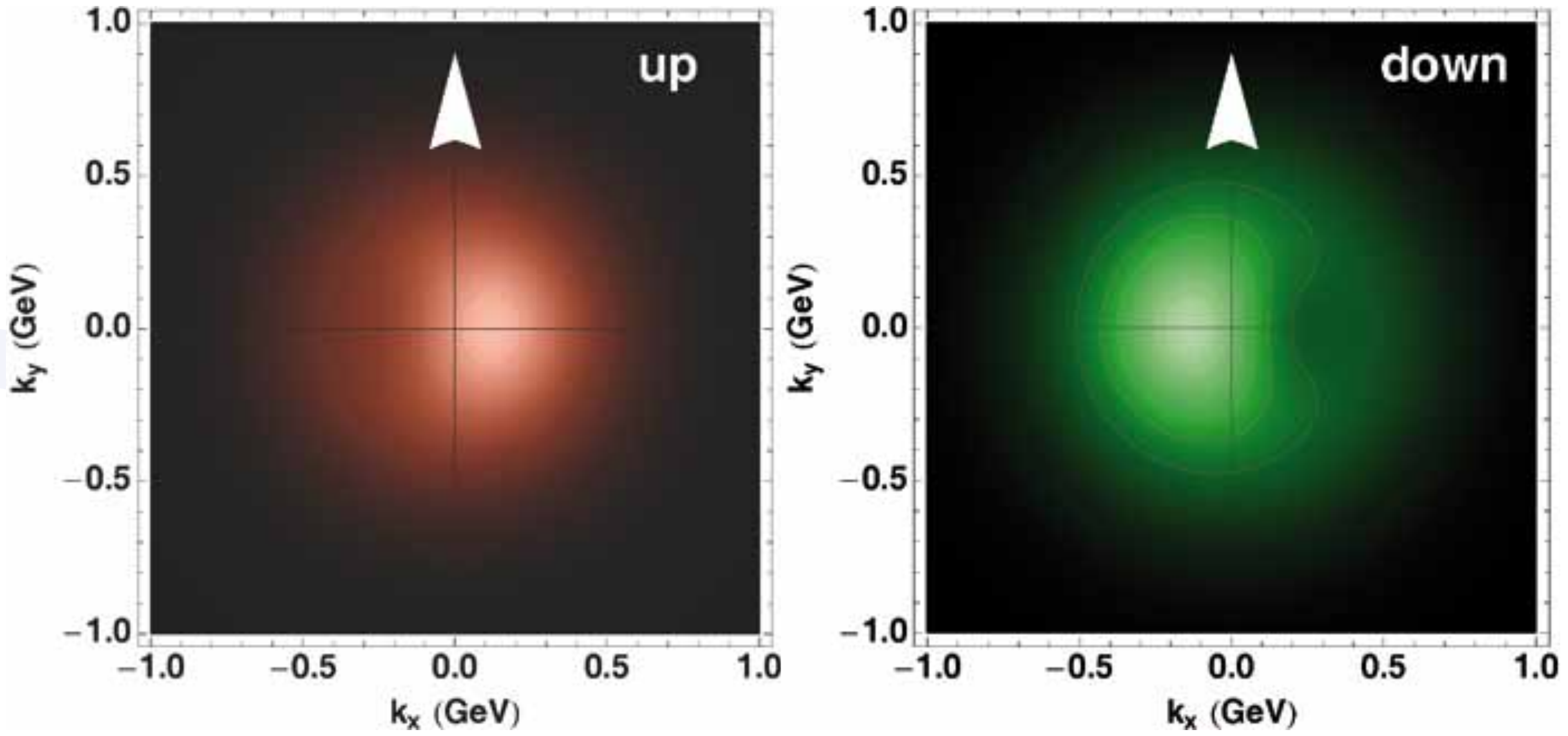

[A. Bacchetta et al.]

$L_z^{\mathbf{u}} > 0$

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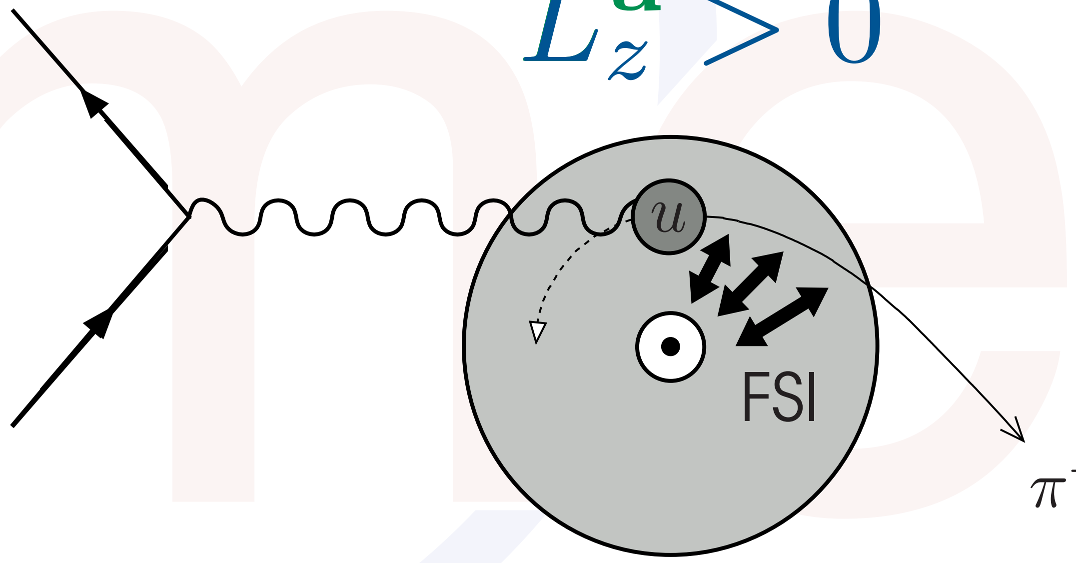

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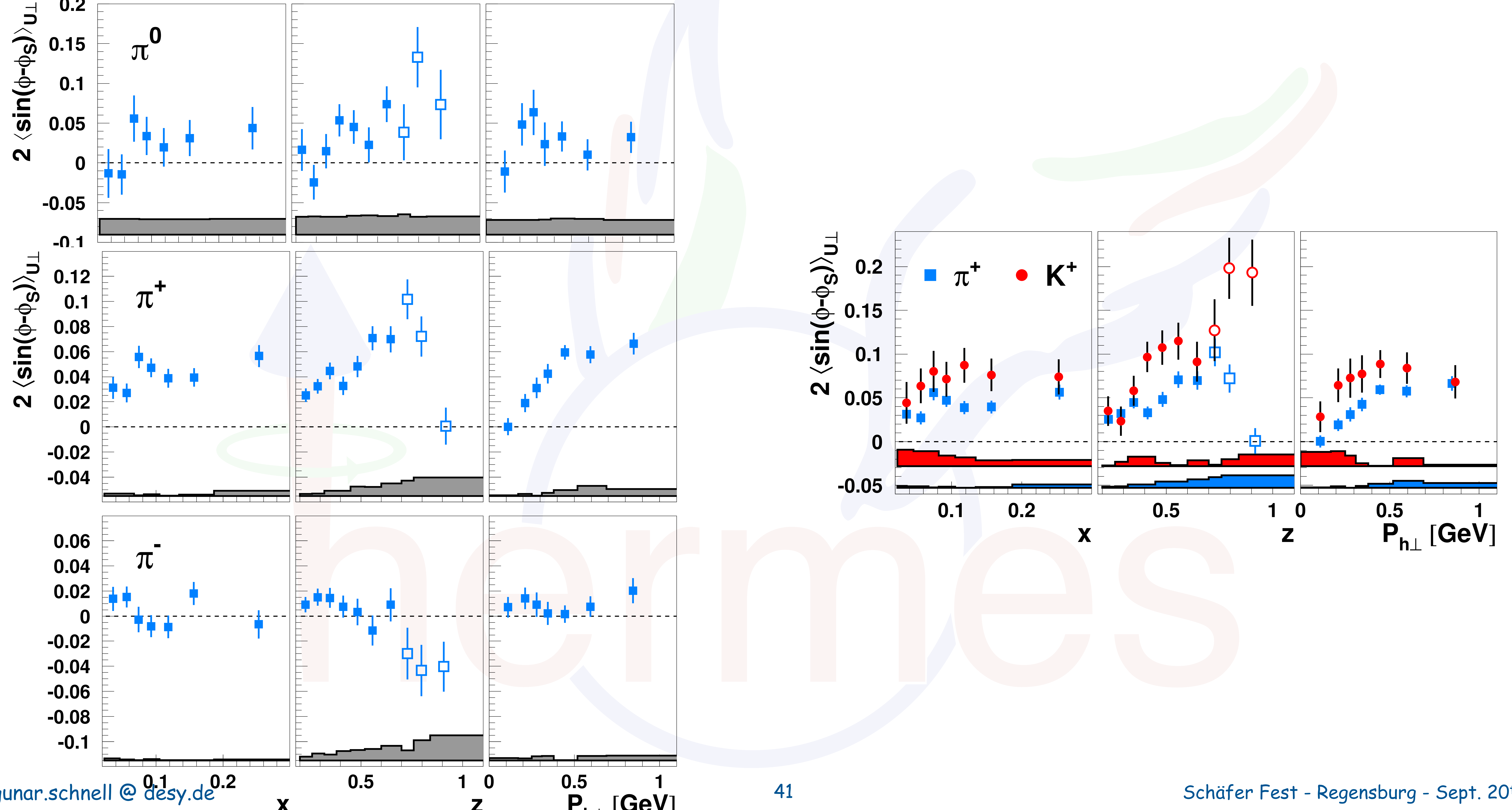
[HERMES, JHEP12(2020)010]



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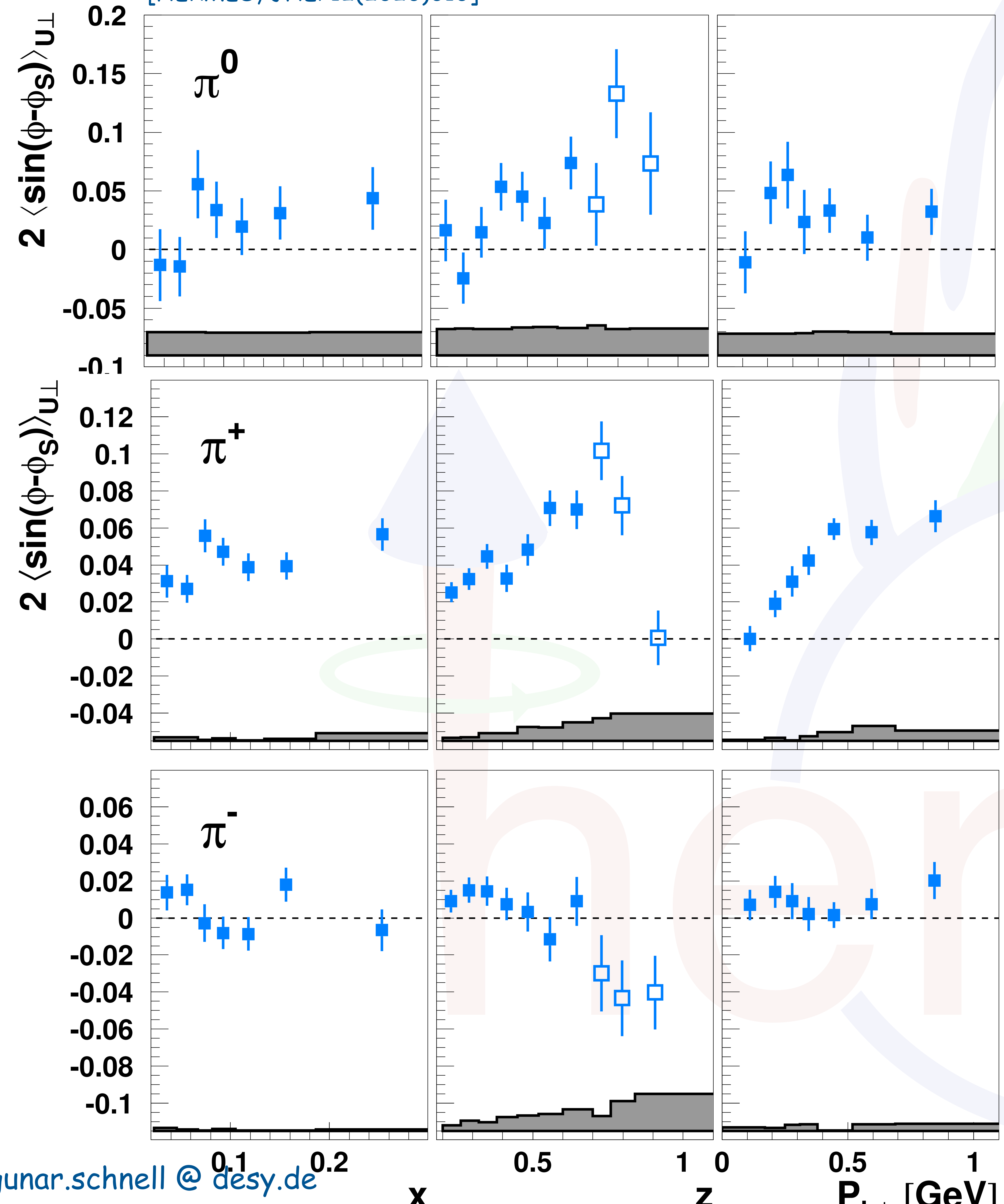

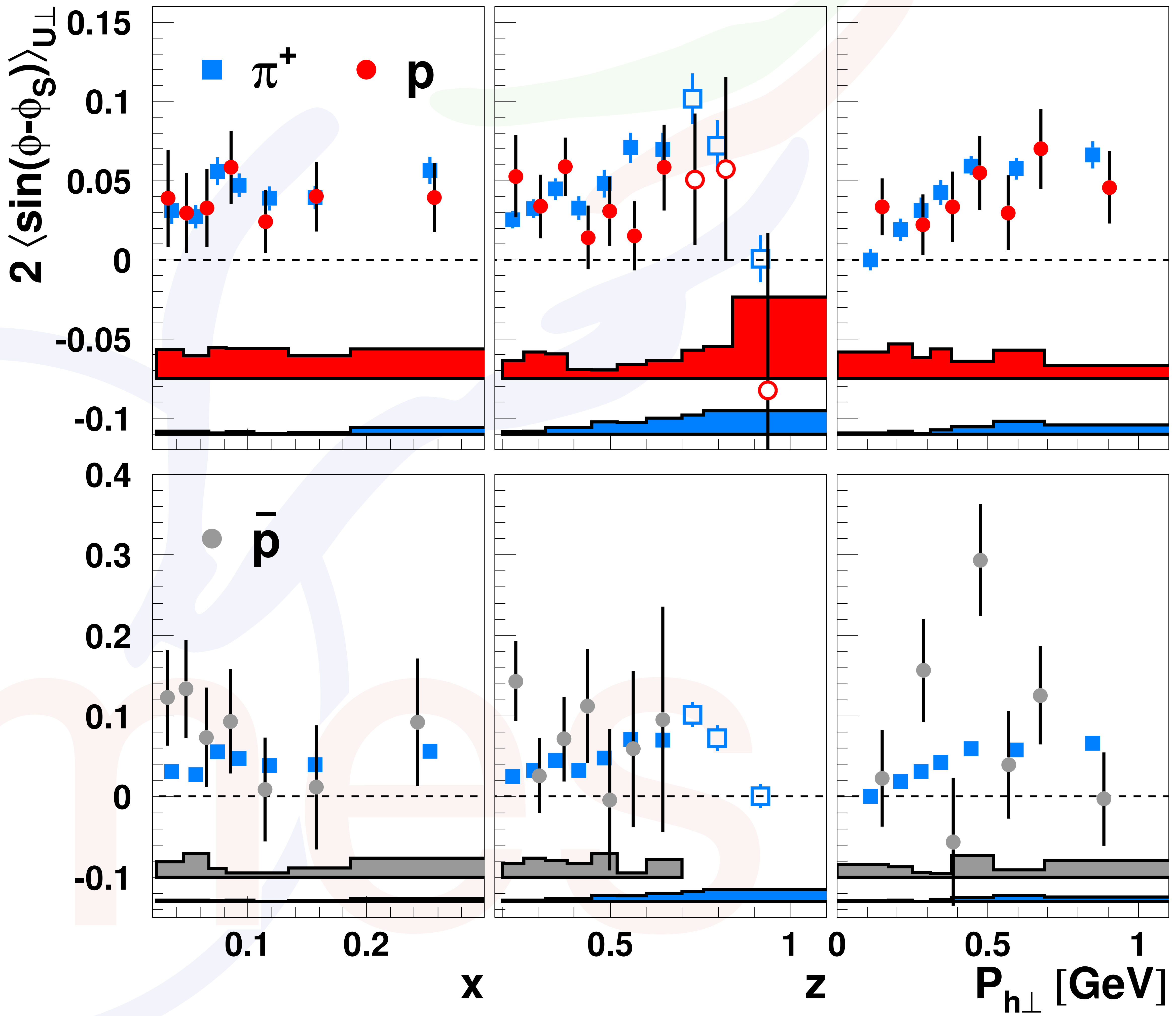

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JHEP12(2020)010

hermes

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[a] Deceased.

https://doi.org/10.1007/JHEP12(2020)010

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

90%

95%

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3d 1d

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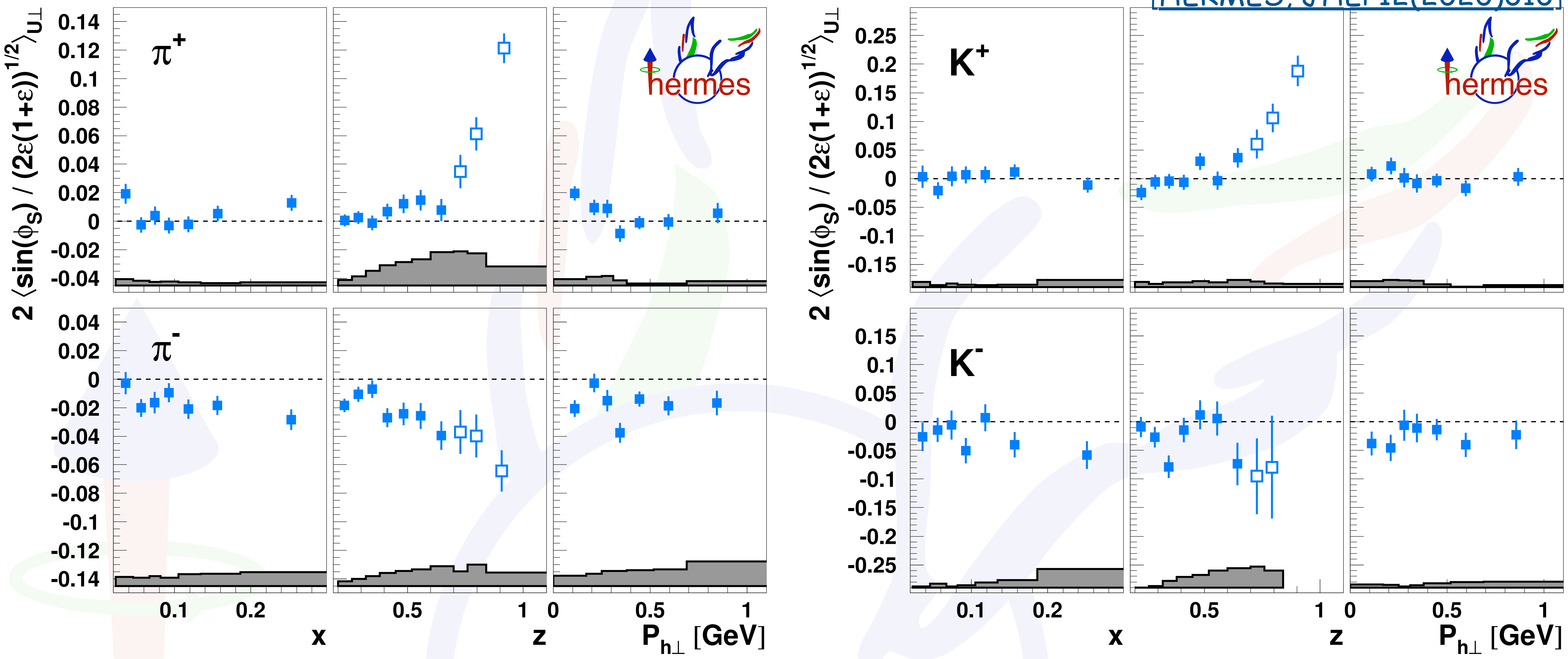
$\sin(2\phi+\phi_S)$				✓				
$\cos(\phi-\phi_S)$	[Worm-gear]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

90%

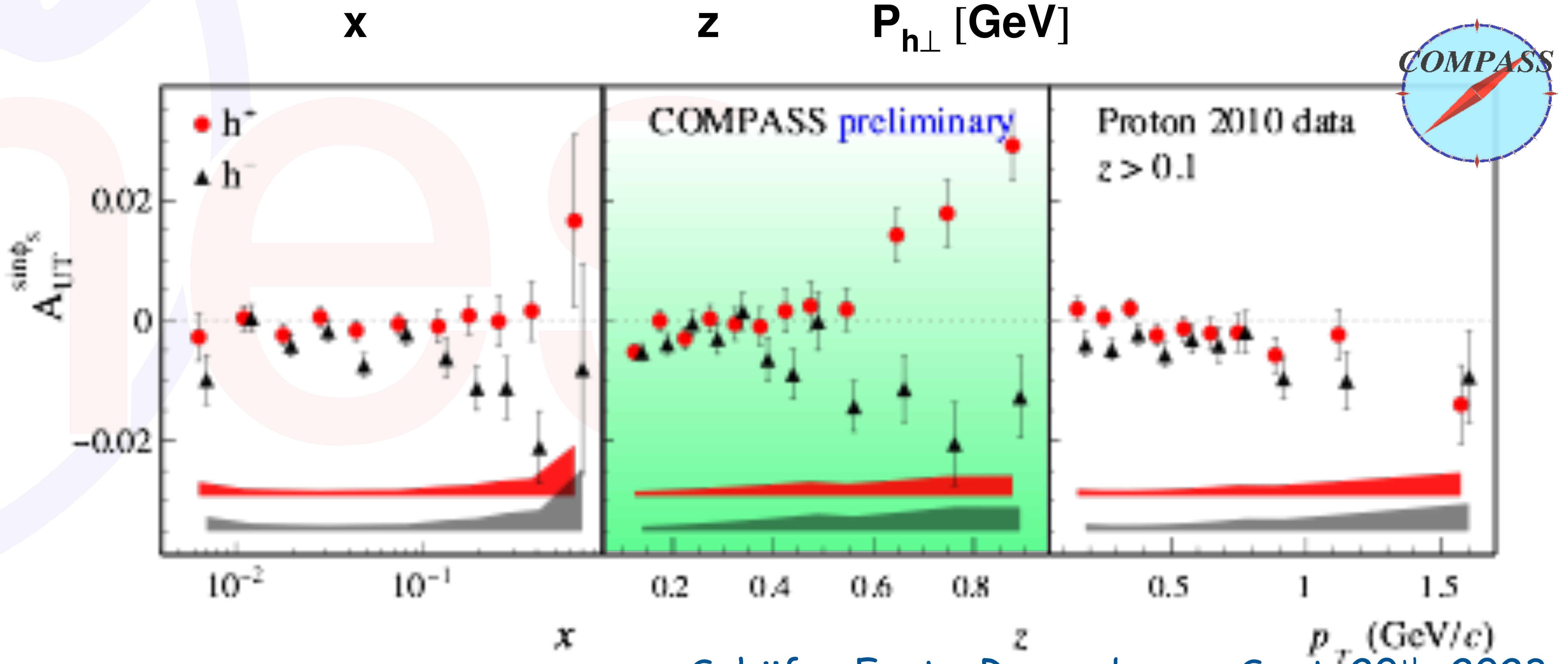
95%

sub-leading twist!

[HERMES, JHEP12(2020)010]

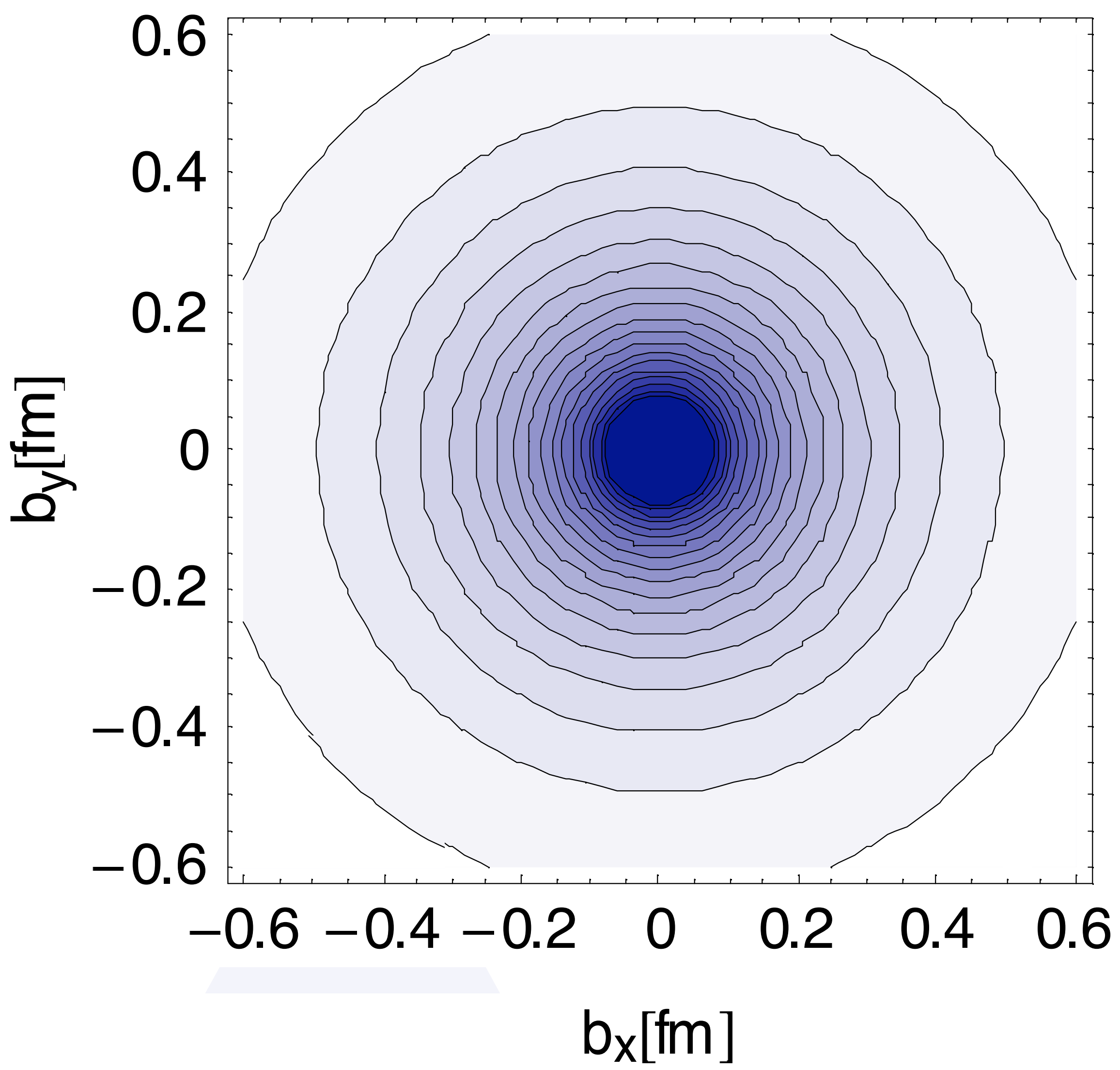


- clearly non-zero asymmetries
- opposite sign for pions (Collins-like behavior)
- striking z dependence and in particular magnitude
- similar observation at COMPASS



exclusive reactions

a complementary 3D picture of the nucleon



form factors: transverse distribution of partons

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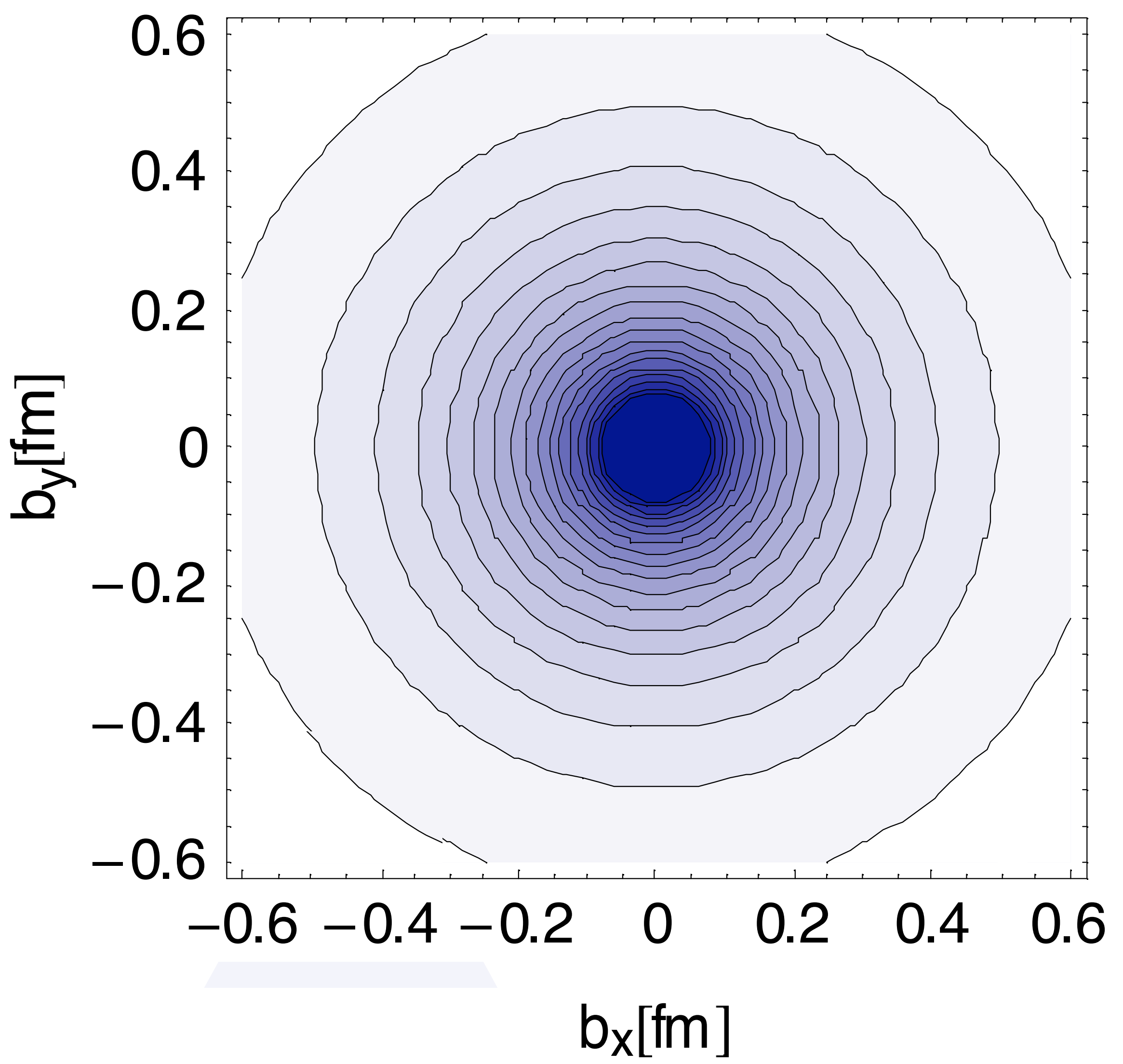

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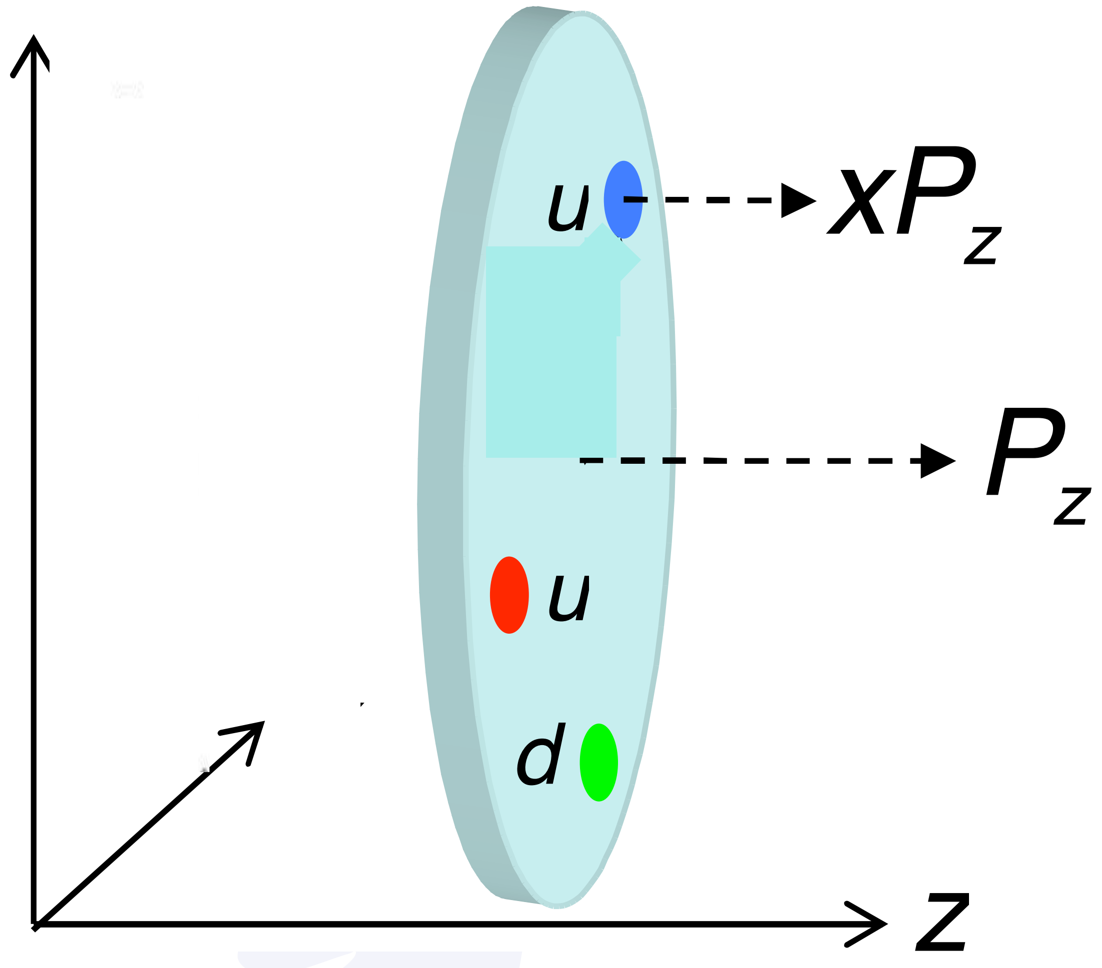

parton distributions: longitudinal momentum of partons

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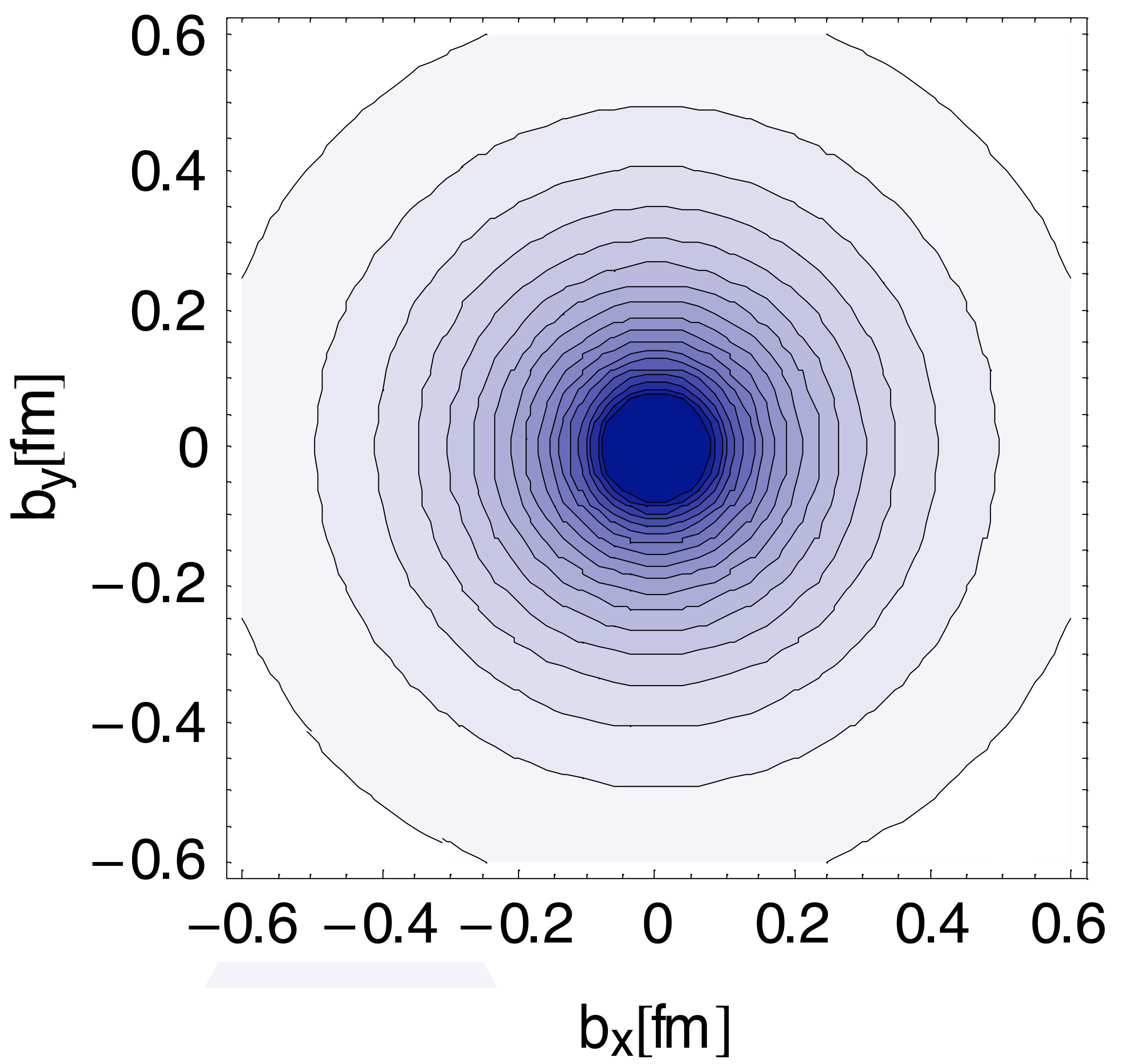

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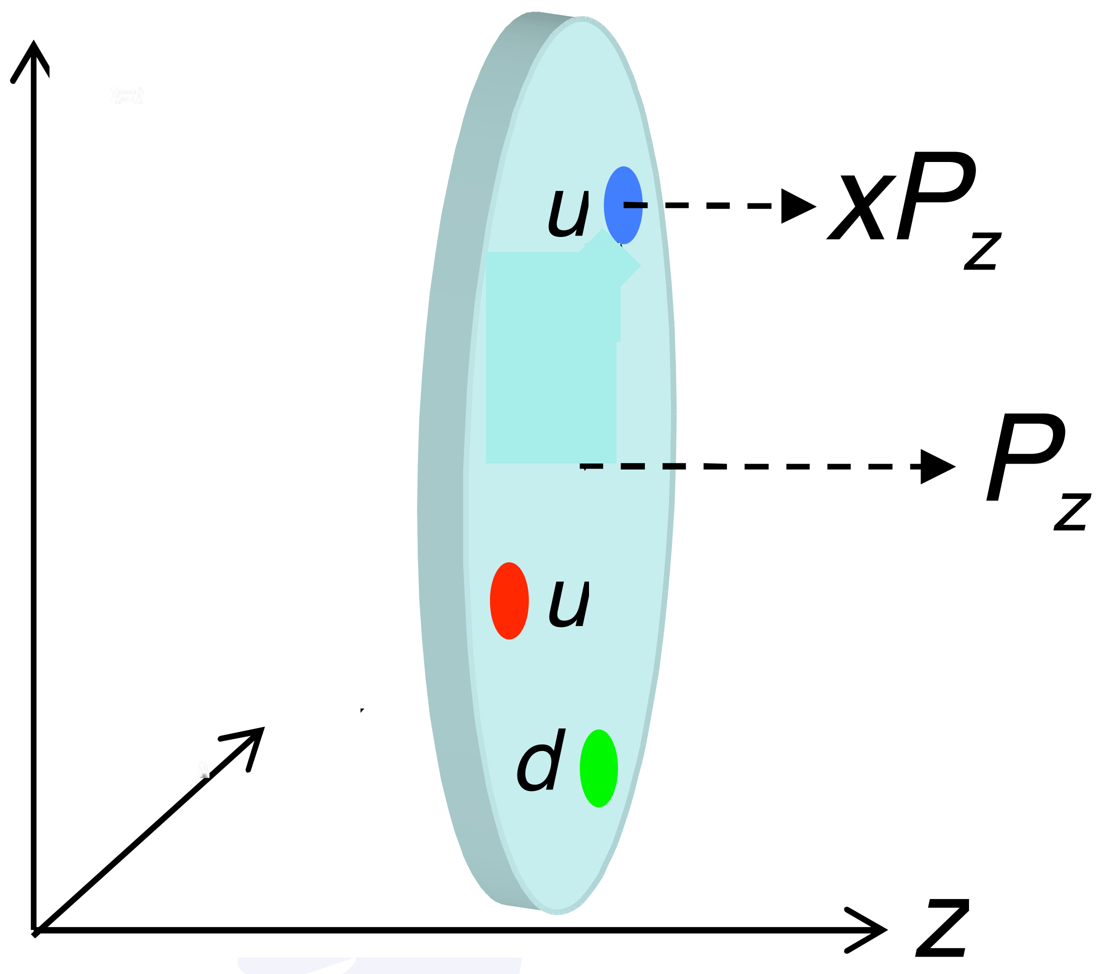

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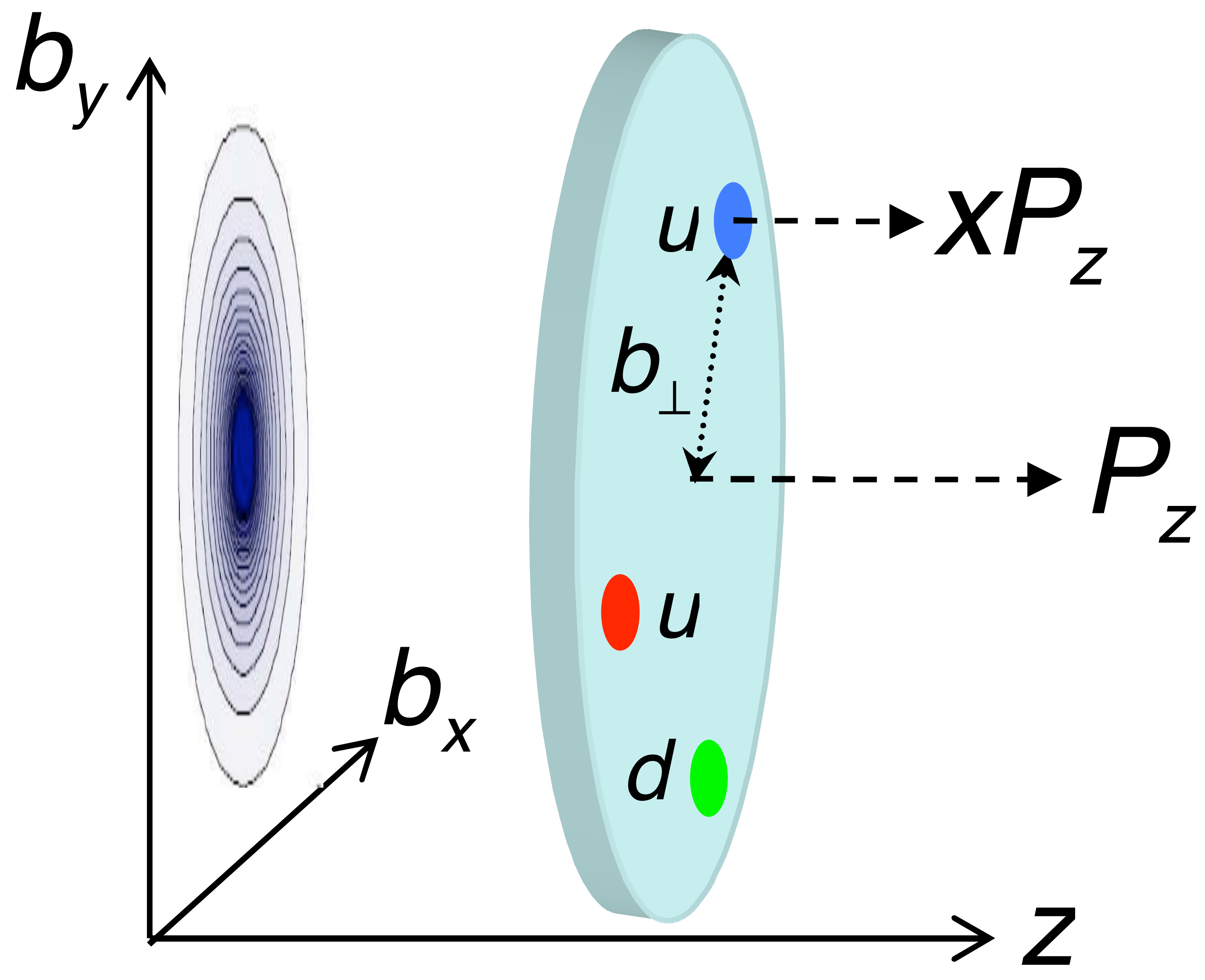
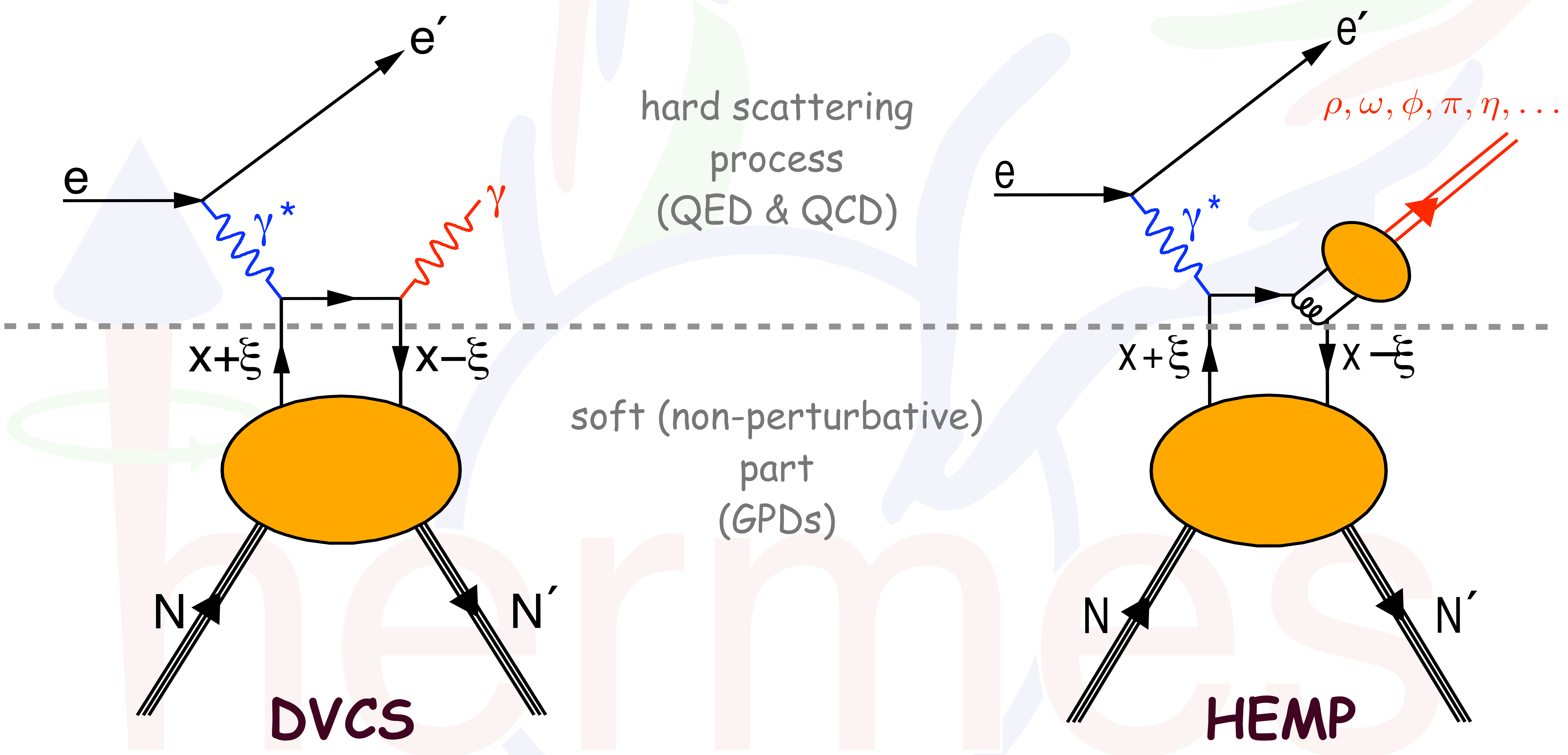


nucleon tomography

correlated info on transverse position and longitudinal momentum

GPDs in exclusive reactions

GPDs can be accessed through
measurements of hard exclusive lepton-nucleon scattering processes.

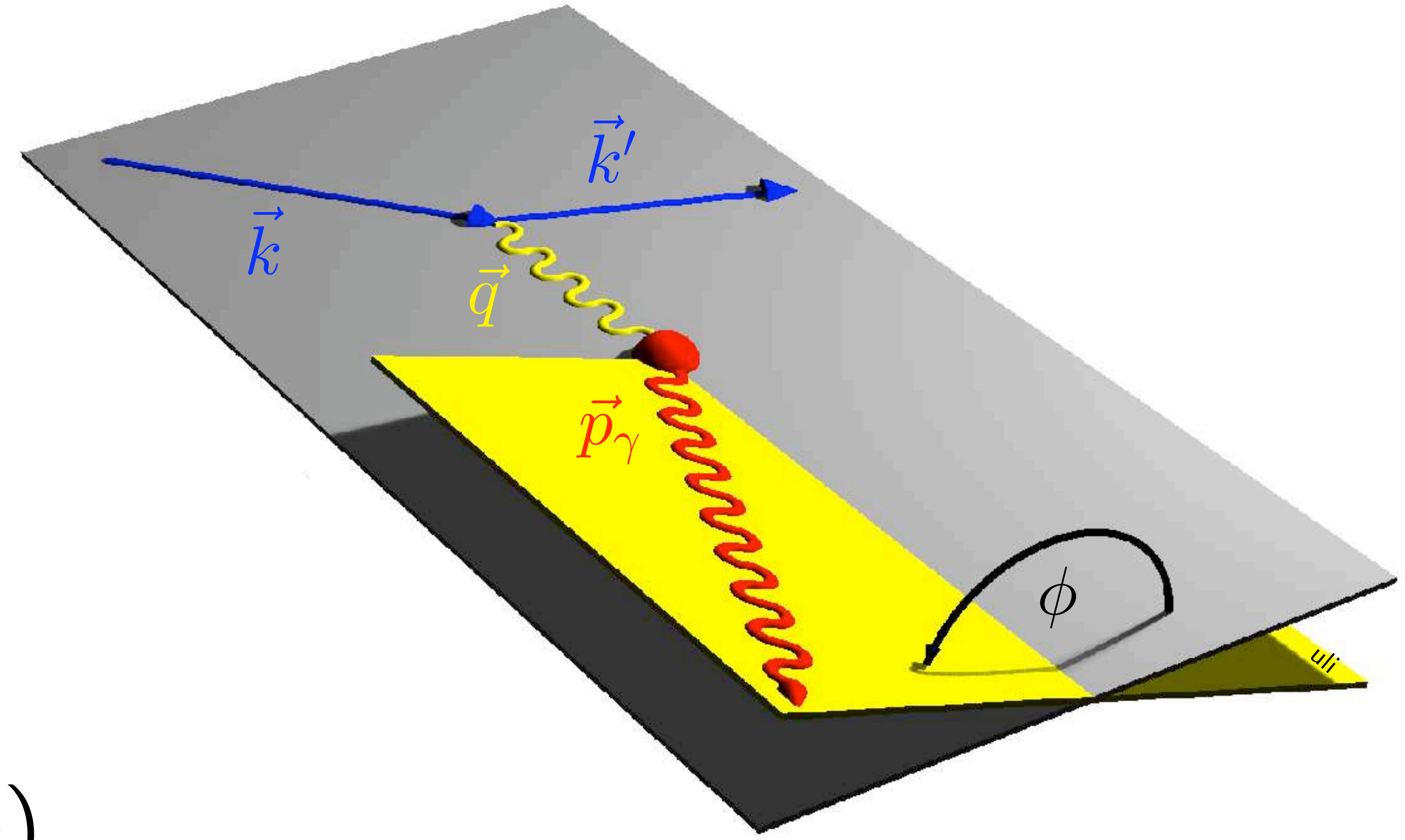


deeply virtual Compton scattering

hard exclusive meson production

azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



Fourier expansion for ϕ:

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

calculable in QED
(using FF measurements)

azimuthal dependences in DVCS/BH

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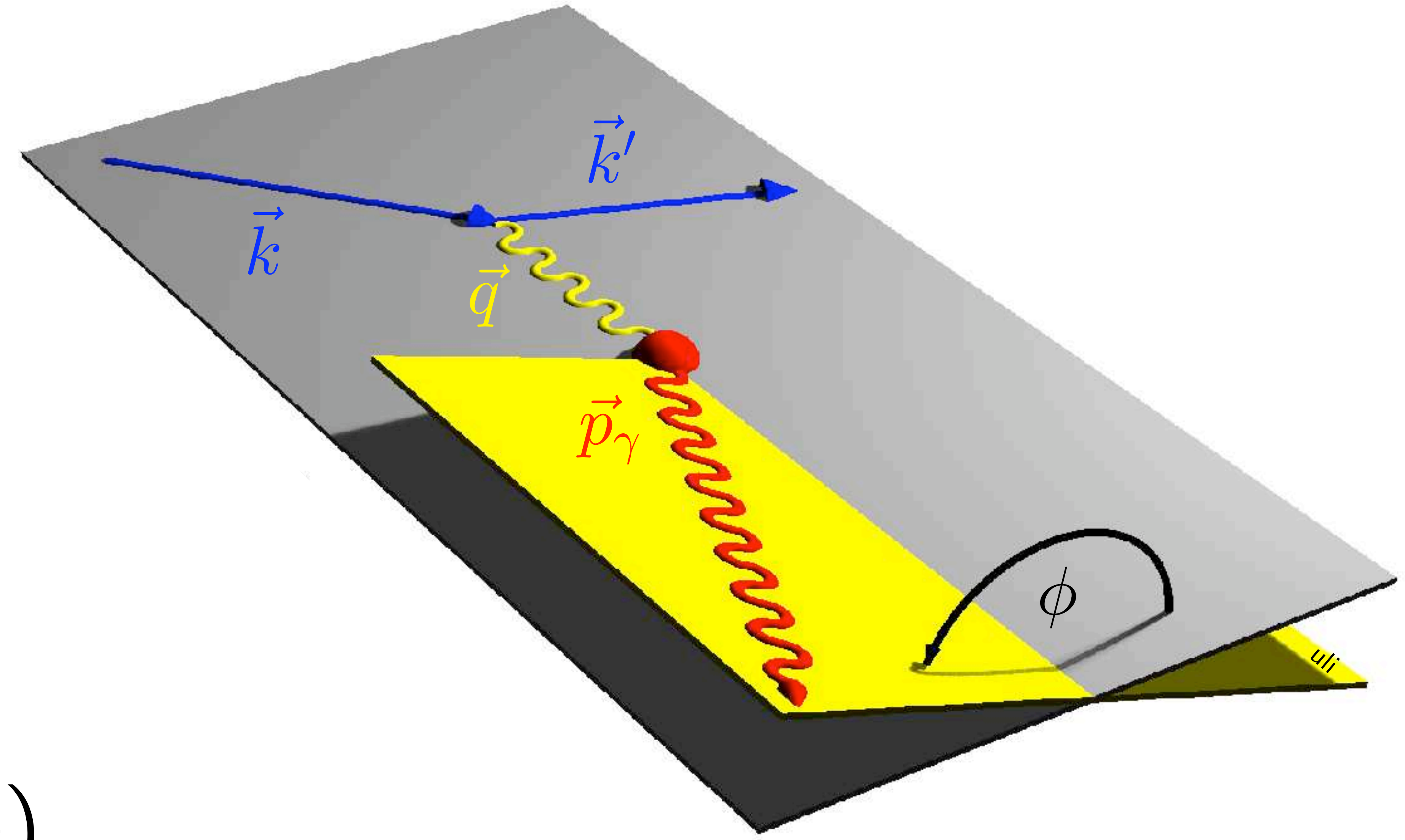

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azimuthal dependences in DVCS/BH

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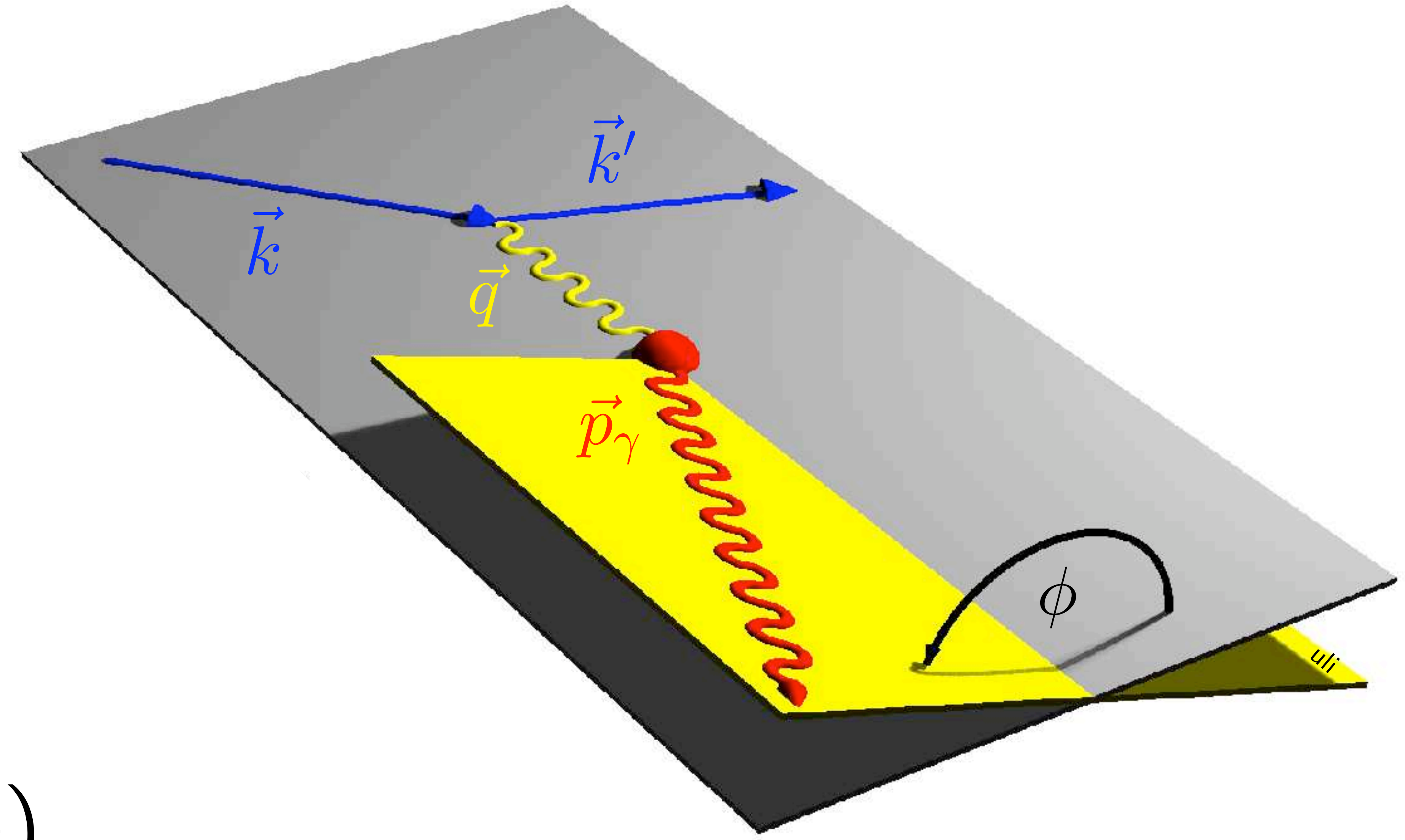

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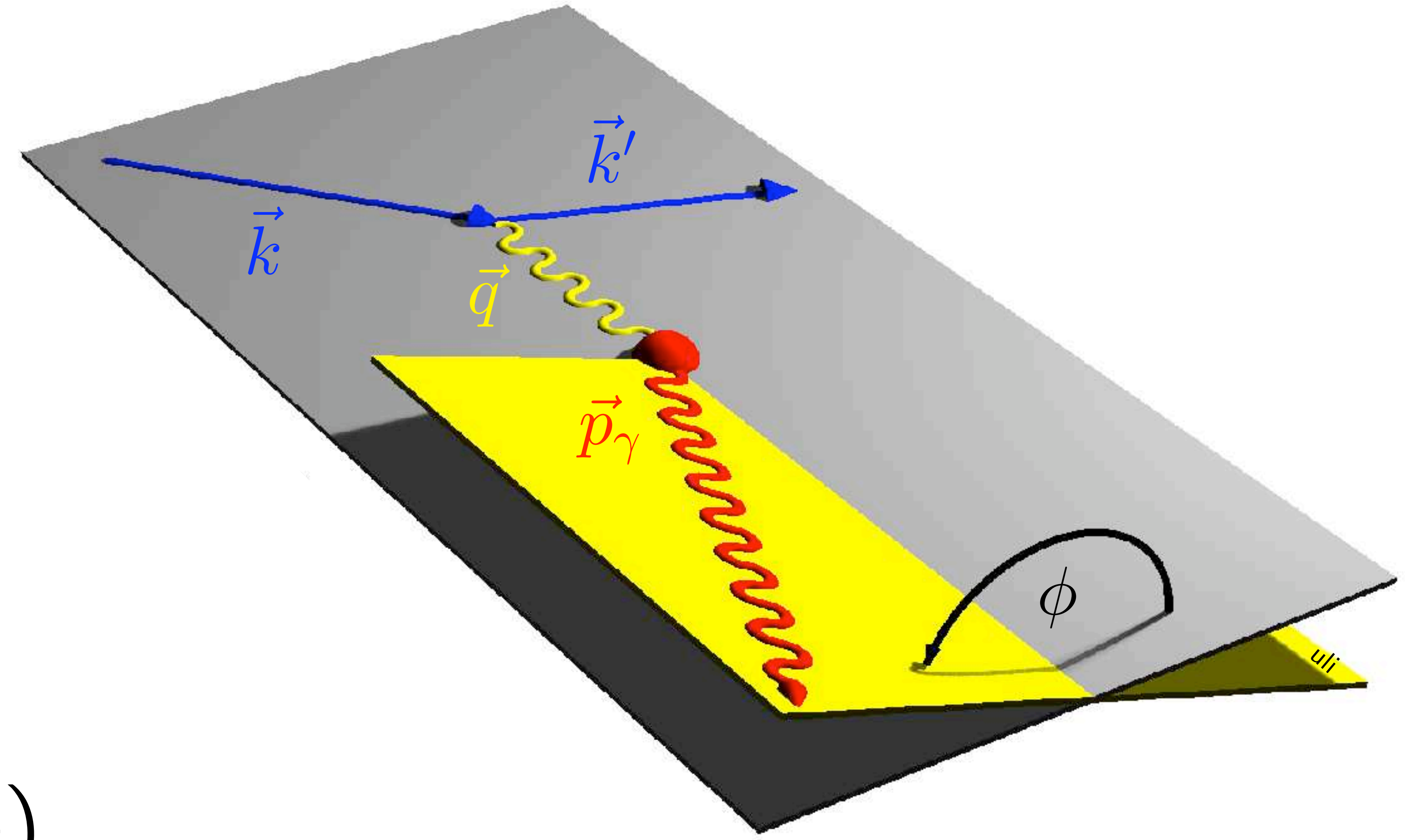
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



Fourier expansion for ϕ:

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

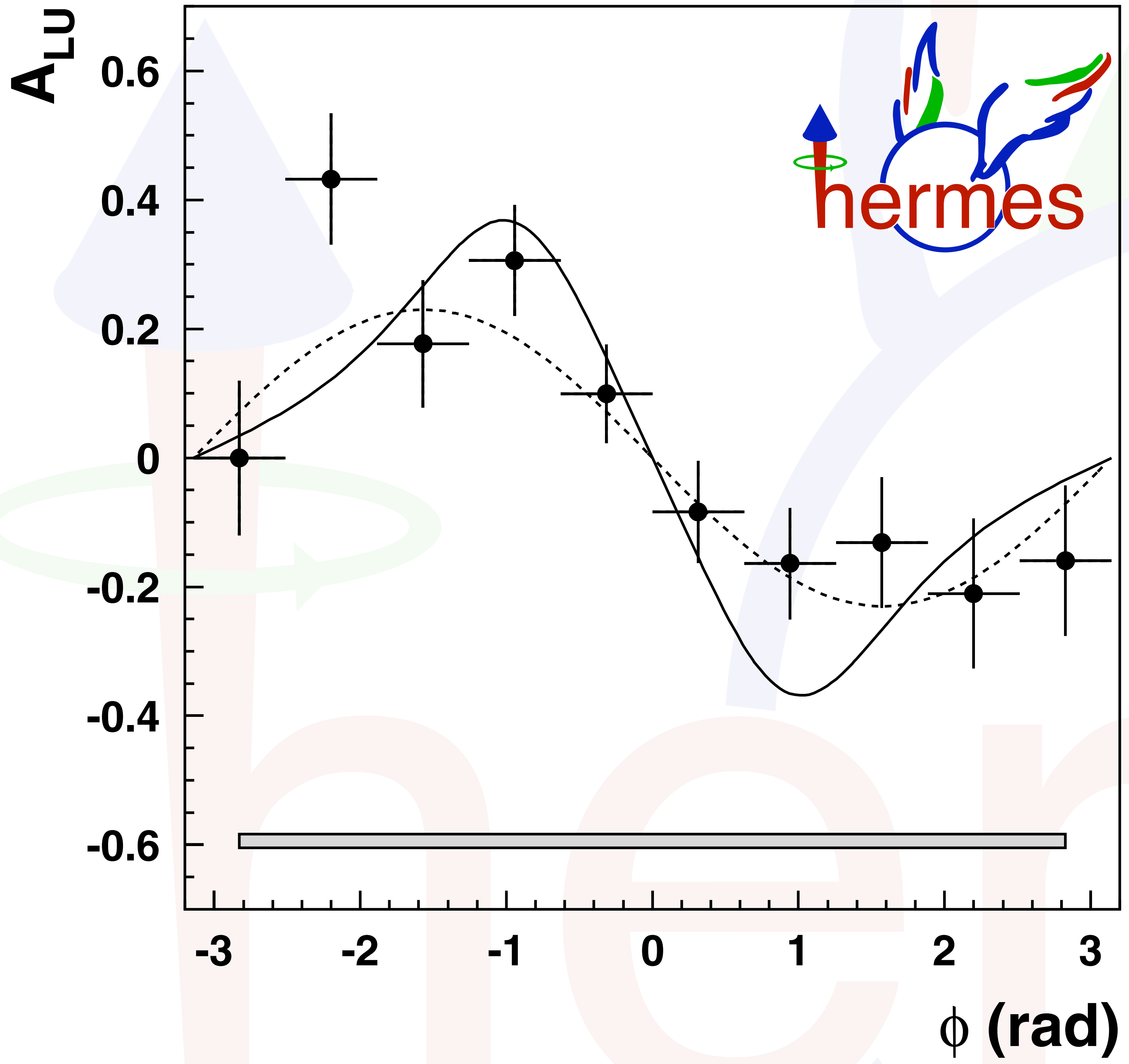
$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

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

bilinear ("DVCS") or linear in GPDs

again a sine modulation ...

- exploit HERA beam-helicity reversal for beam-spin asymmetry
- Bethe Heitler has no beam-spin asymmetry -> DVCS!!!



HERMES, PRL 87 (2001) 182001

$$A_{LU}(\phi) = \frac{1}{\langle|P_l|\rangle} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

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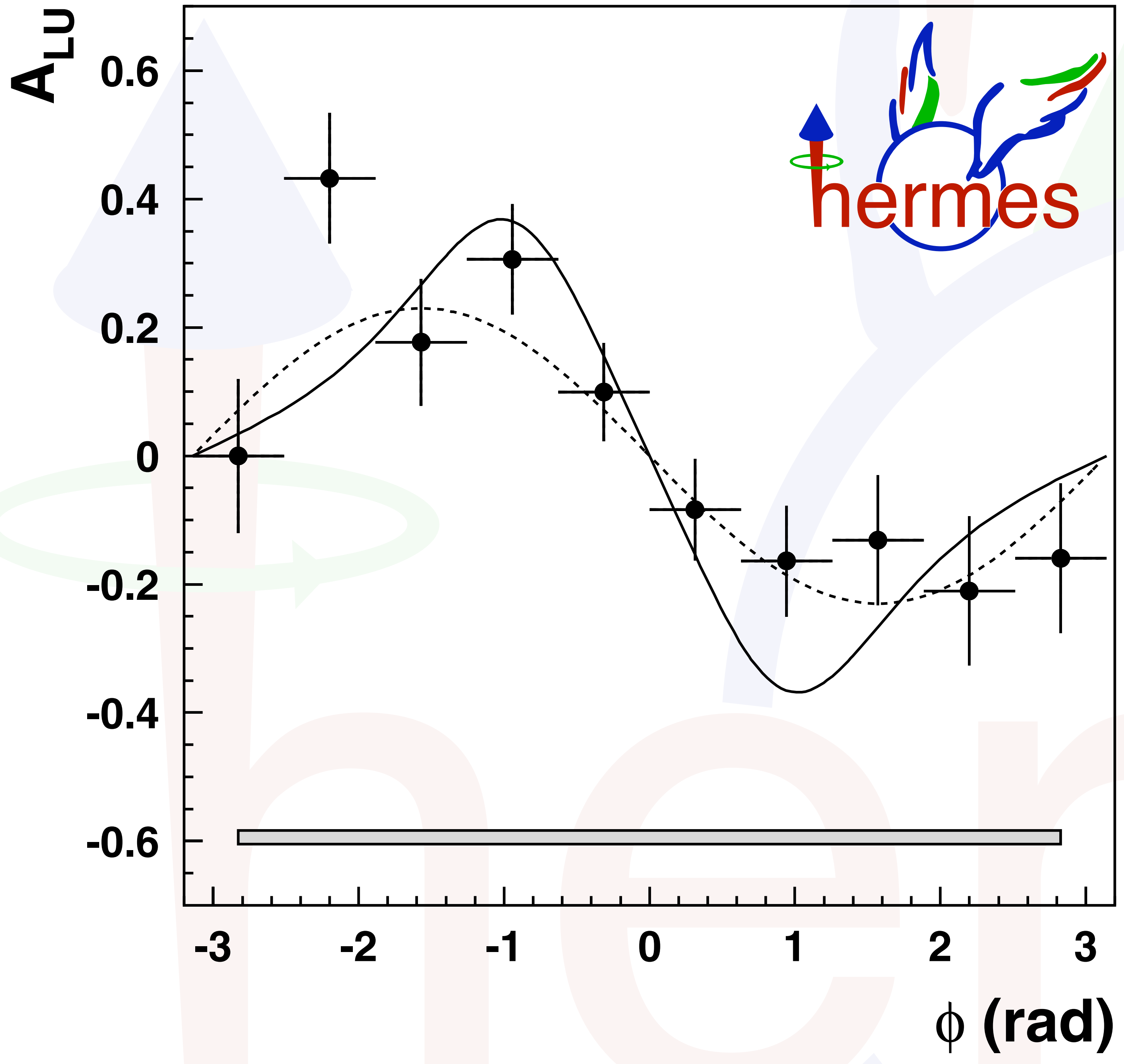
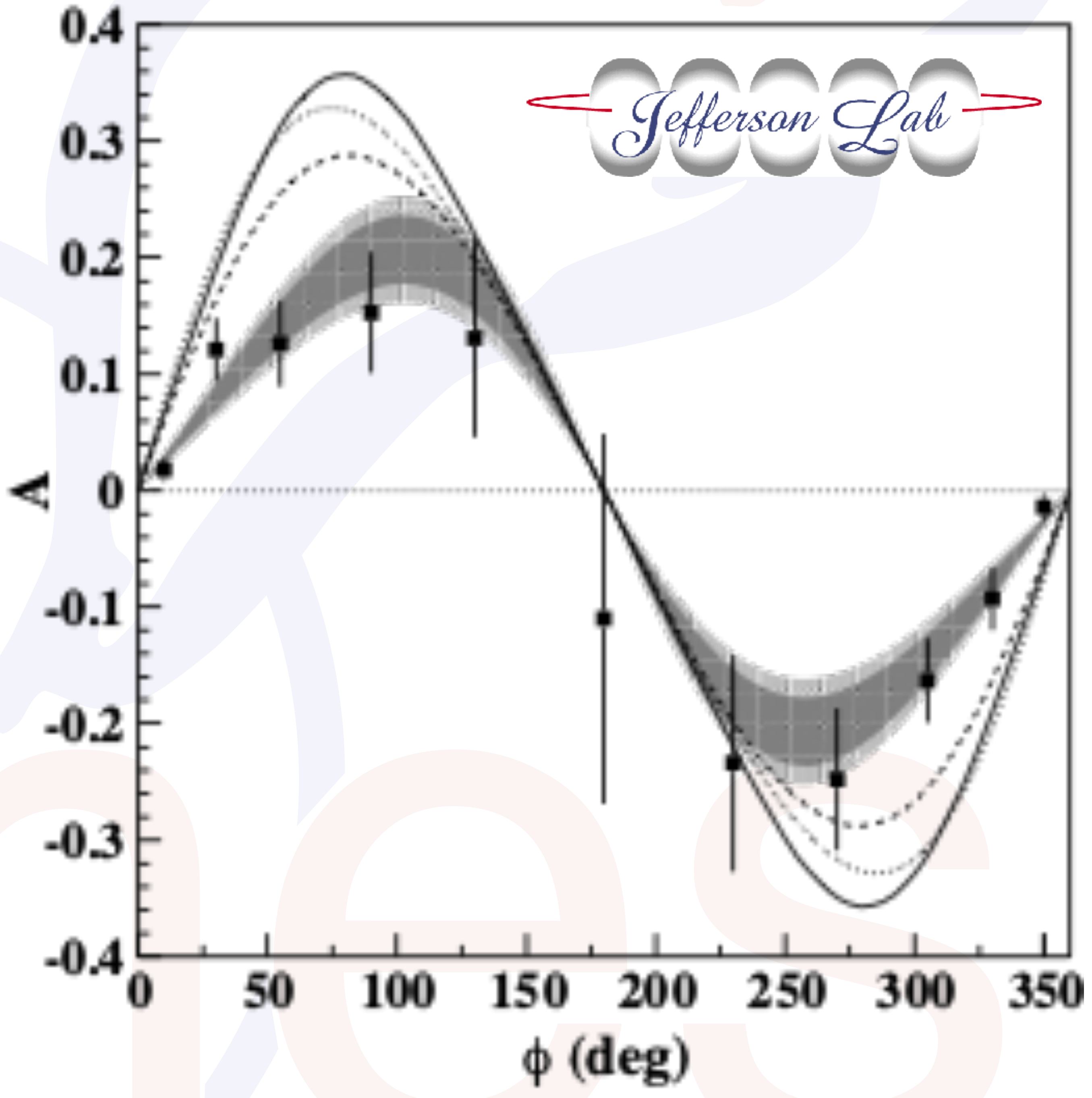


HERMES, PRL 87 (2001) 182001

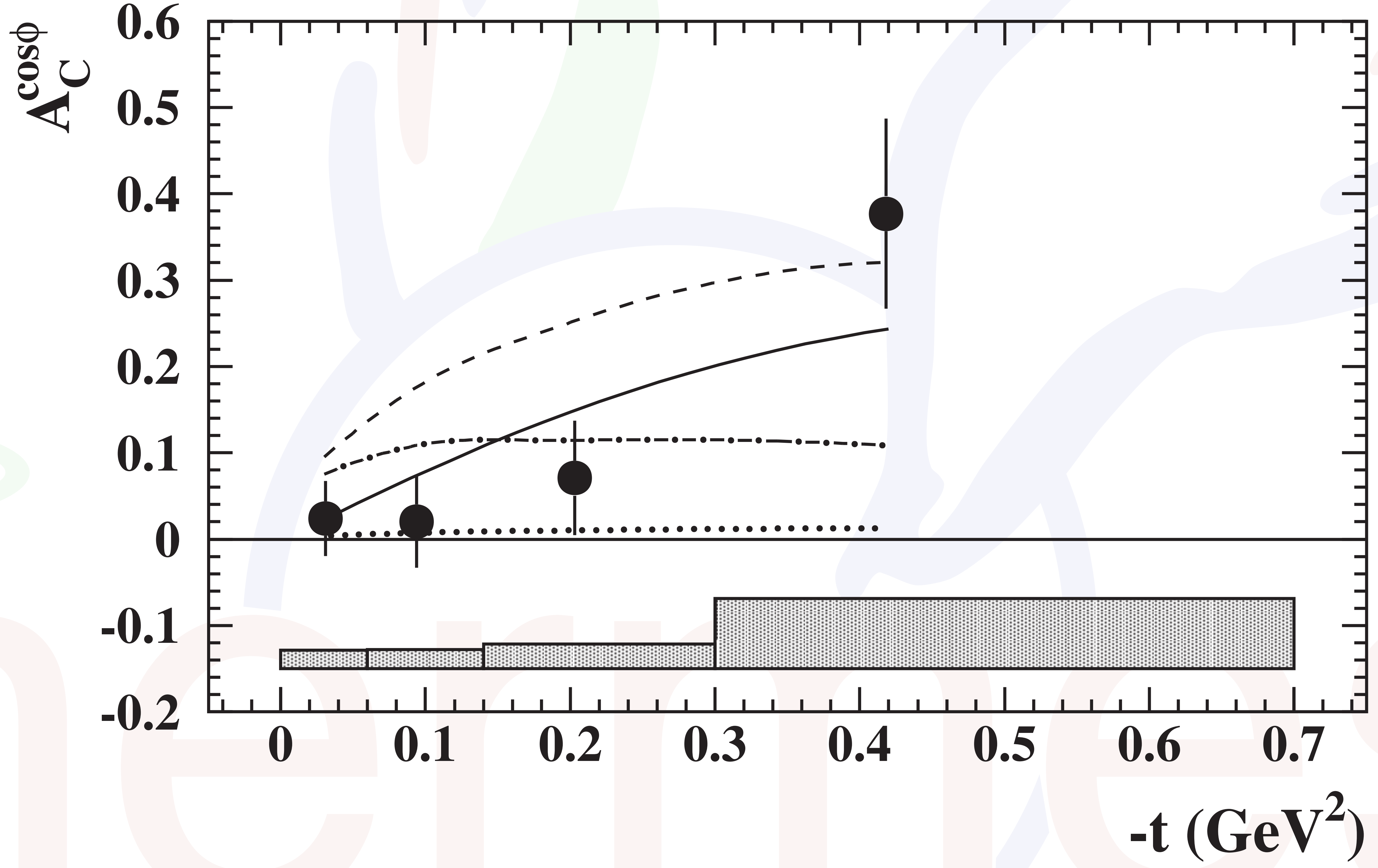


CLAS, PRL 87 (2001) 182002

still keeping "first" in the title on arXiv :-)

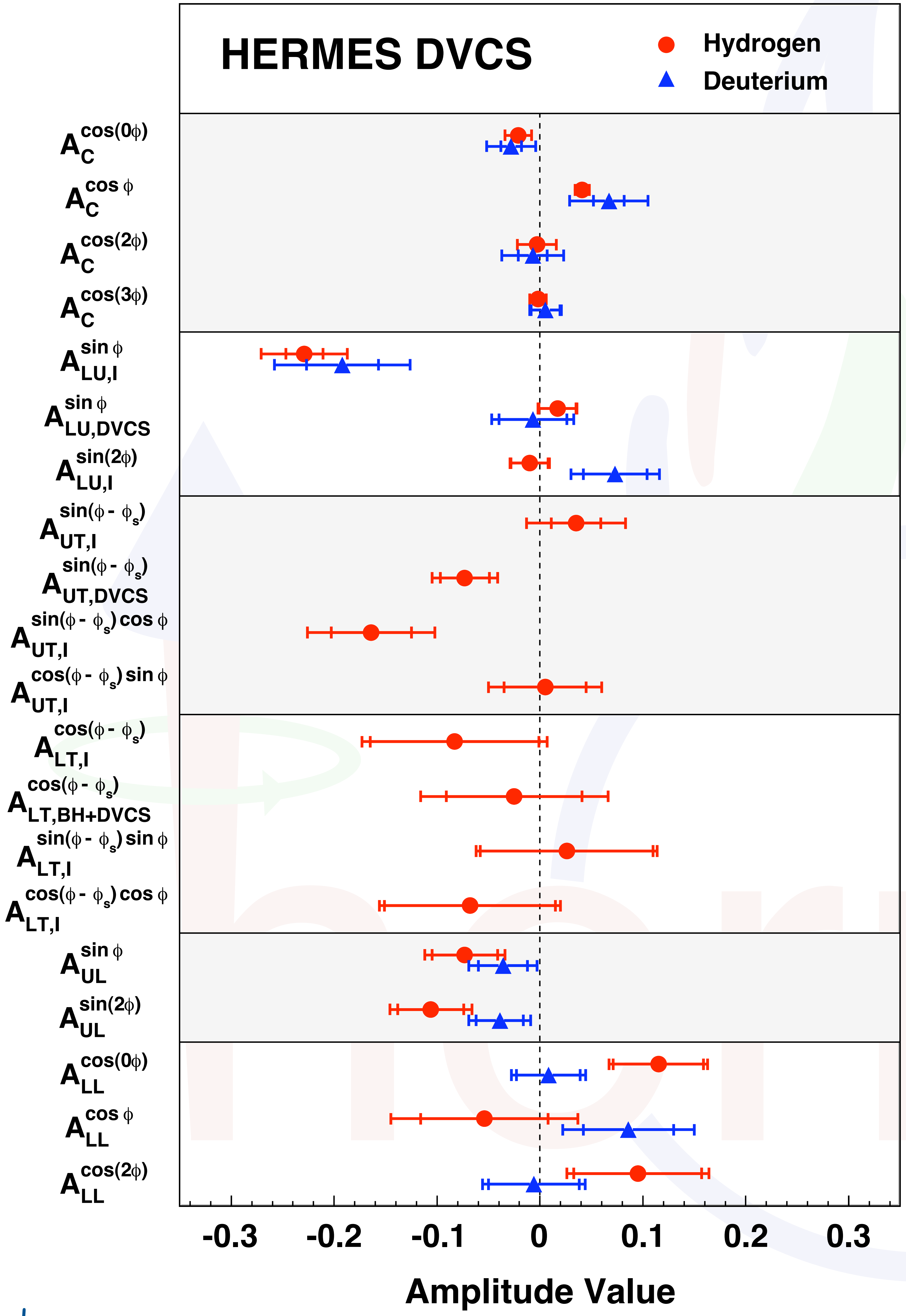
… beam-charge asymmetry …

- unique to HERA: $$\frac{d\sigma(e^+) - d\sigma(e^-)}{d\sigma(e^+) + d\sigma(e^-)}$$



- sensitive to the real part of the Compton form factor $\mathcal{H}$

… a wealth of azimuthal amplitudes



Beam-charge asymmetry:
GPD H

PRD 75 (2007) 011103
NPB 829 (2010) 1
JHEP 11 (2009) 083
PRC 81 (2010) 035202
PRL 87 (2001) 182001
JHEP 07 (2012) 032

Beam-helicity asymmetry:
GPD H

Transverse target spin asymmetries:
GPD E from proton target

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

Longitudinal target spin asymmetry:
GPD $\tilde{H}$

Double-spin asymmetry:
GPD $\tilde{H}$

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

June 30th, 2007 (around midnight)

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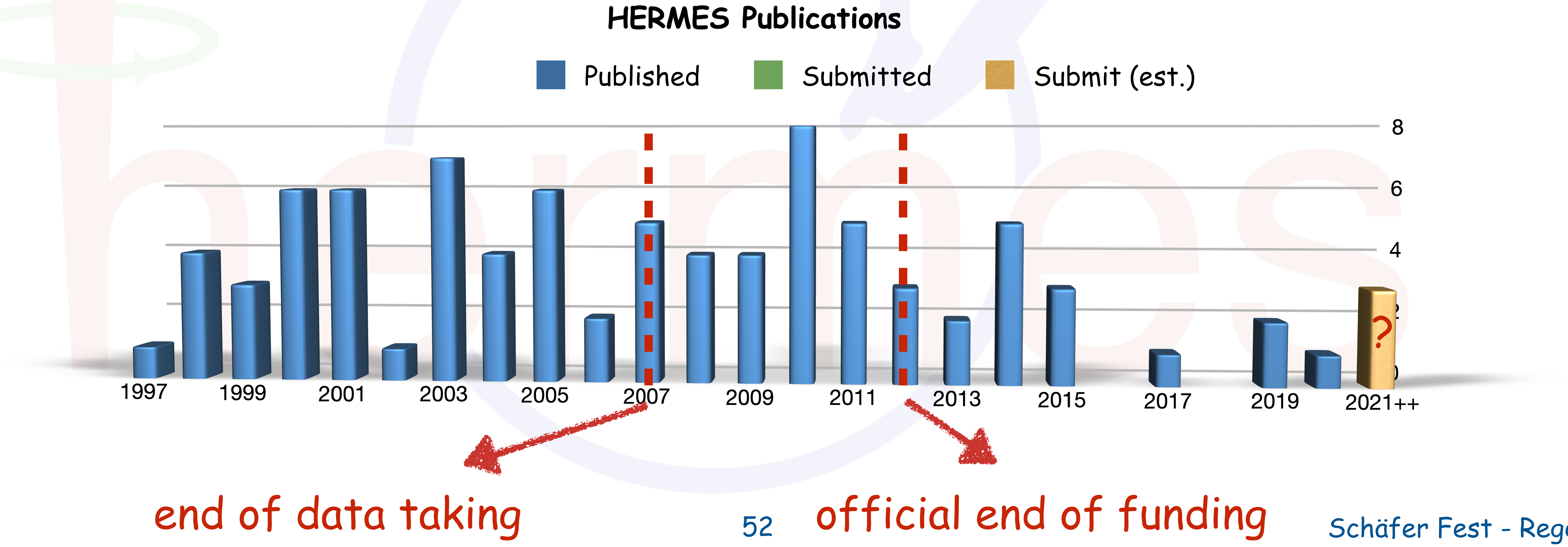
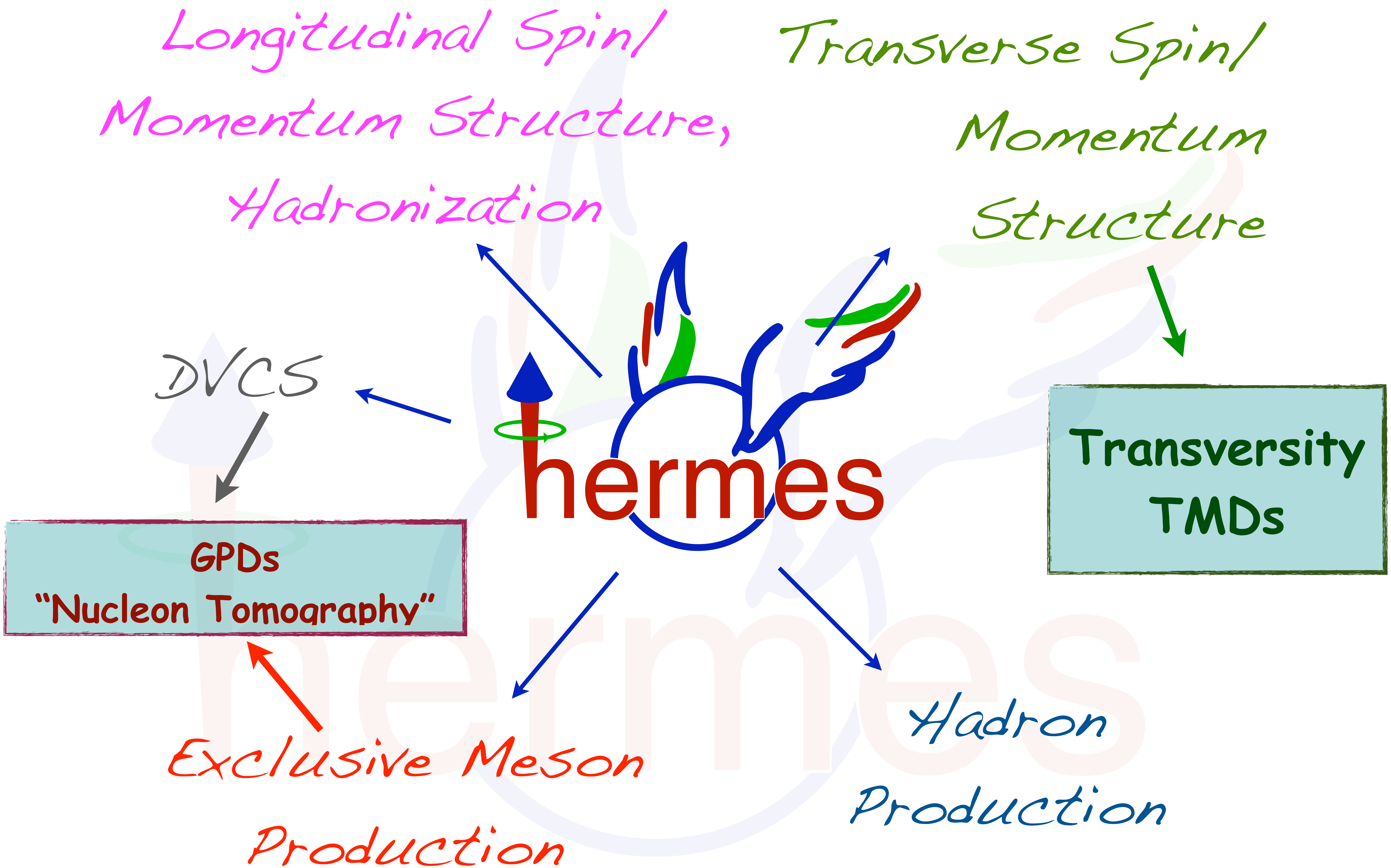
  - still many analysis and publications:




Longitudinal Spin/
Momentum Structure,
Hadronization
Transverse Spin/
Momentum
Structure
DVCS
GPDs
"Nucleon Tomography"
hermes
Transversity
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Production
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Longitudinal Spin/ Momentum Structure, Hadronization

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