30 years of hermes

exploiting self-polarization in storage rings at HERA

Gunar.Schnell @ desy.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

my (rather) personal review of hermes

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special thanks to R. Milner & K. Rith

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hermes

HERA measurement of spin

[C. Papanicolas (1989)]

spin can be tricky

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

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- it could have been so simple:

$$p^{\uparrow} = \sqrt{\frac{2}{3}}(u^{\uparrow}u^{\uparrow})d^{\downarrow} + \sqrt{\frac{1}{3}}(u^{\uparrow}u^{\downarrow})d^{\uparrow}$$

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- constituent quark model ($\Delta q = q^{\uparrow} - q^{\downarrow}$ ... helicity contribution):

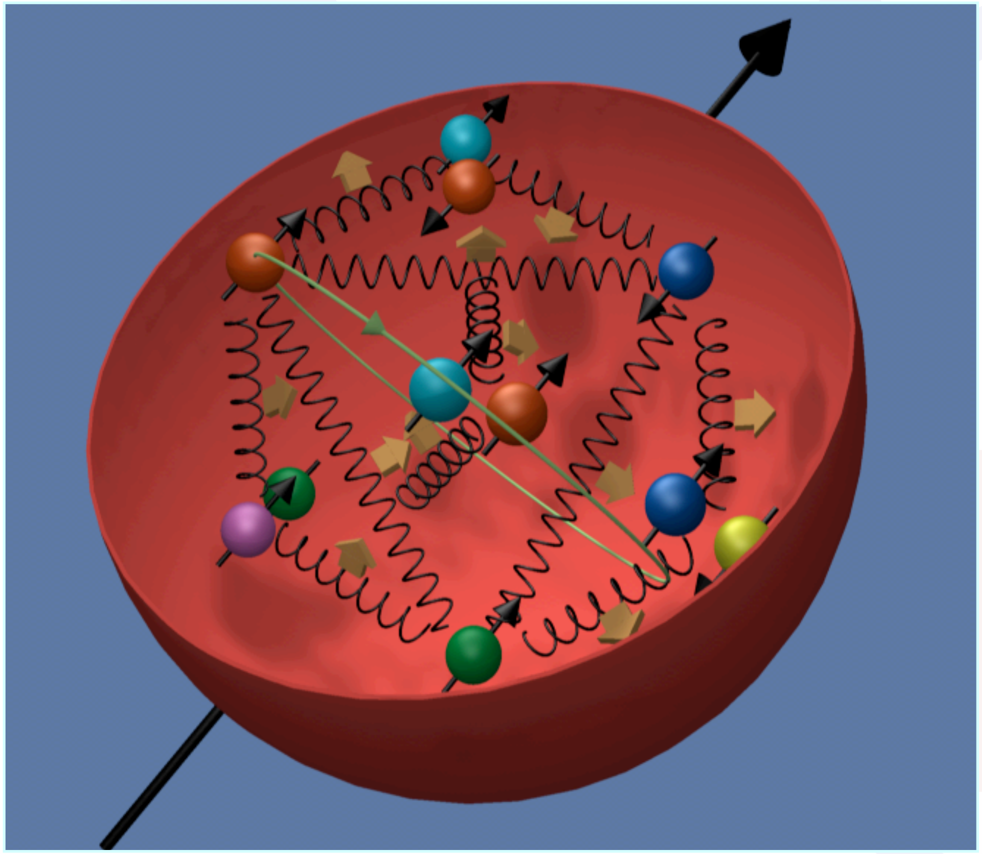
$\Delta u = 4/3$

$\Delta d = -1/3$

➡ all the proton spin coming from up and down quarks

the (original) quest: proton spin

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



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$ ← quark spin

$$+ \Delta G$$ ← gluon spin

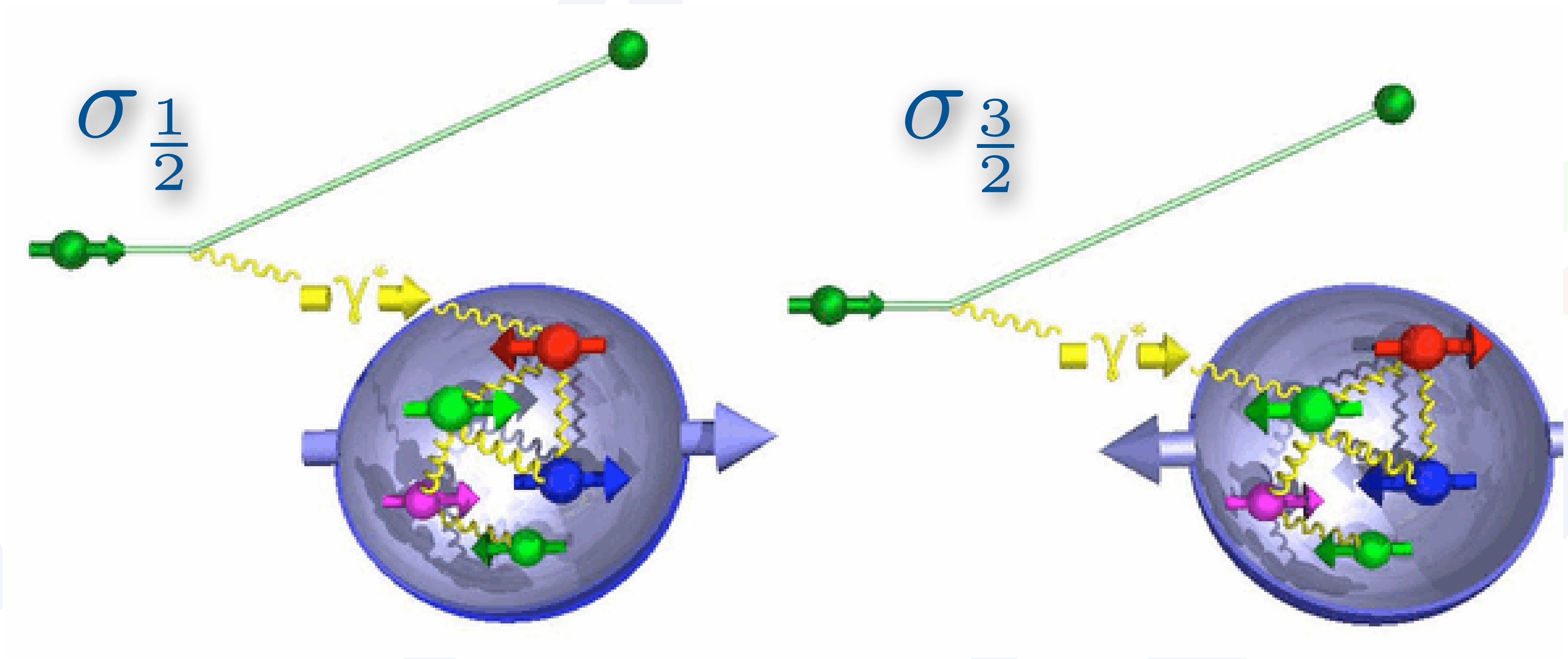
$$+ L_q + L_g$$ ← orbital angular momentum

[Jaffe & Manohar (1990)]

Deep-Inelastic Scattering

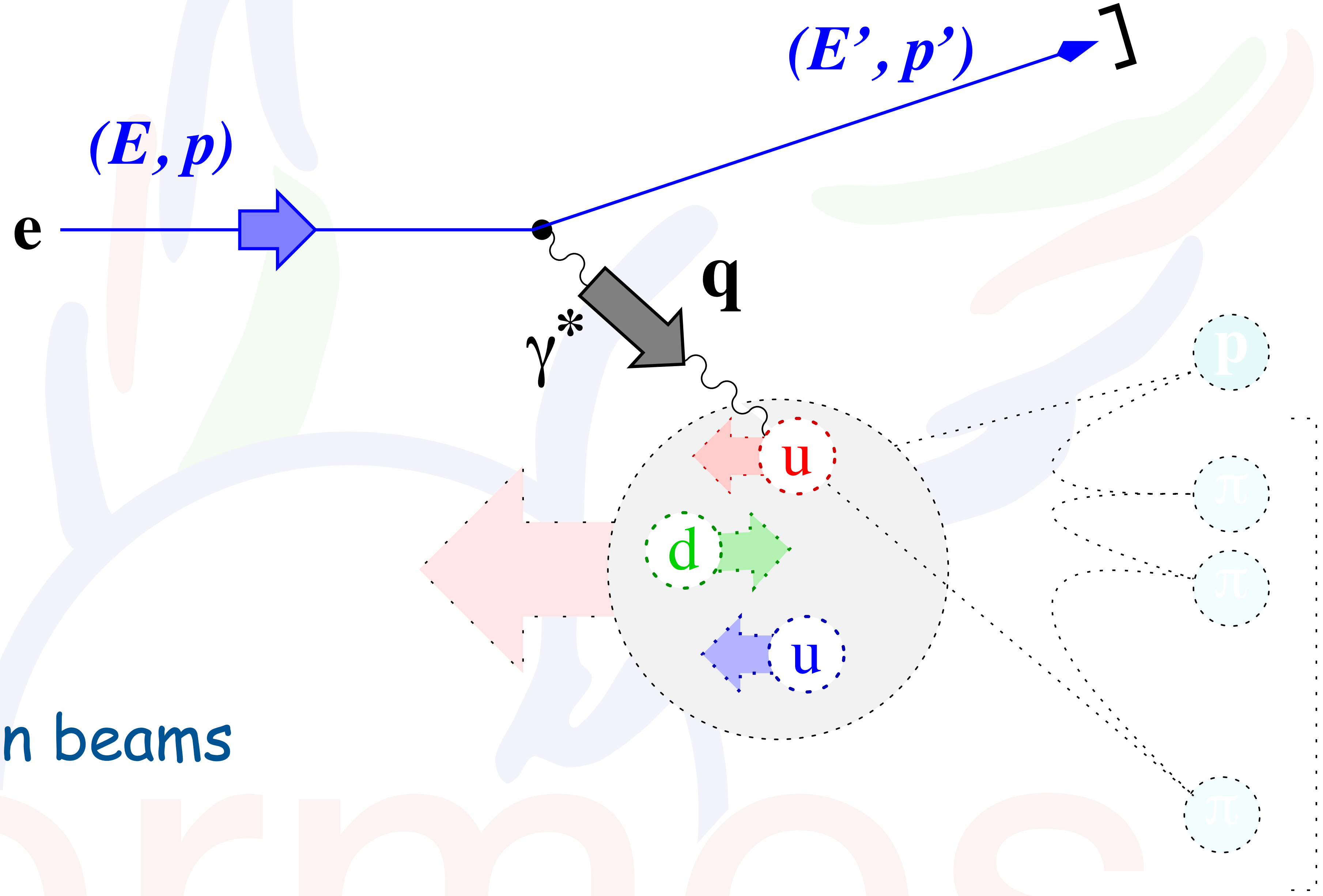
probing the structure of the nucleon

spin asymmetries



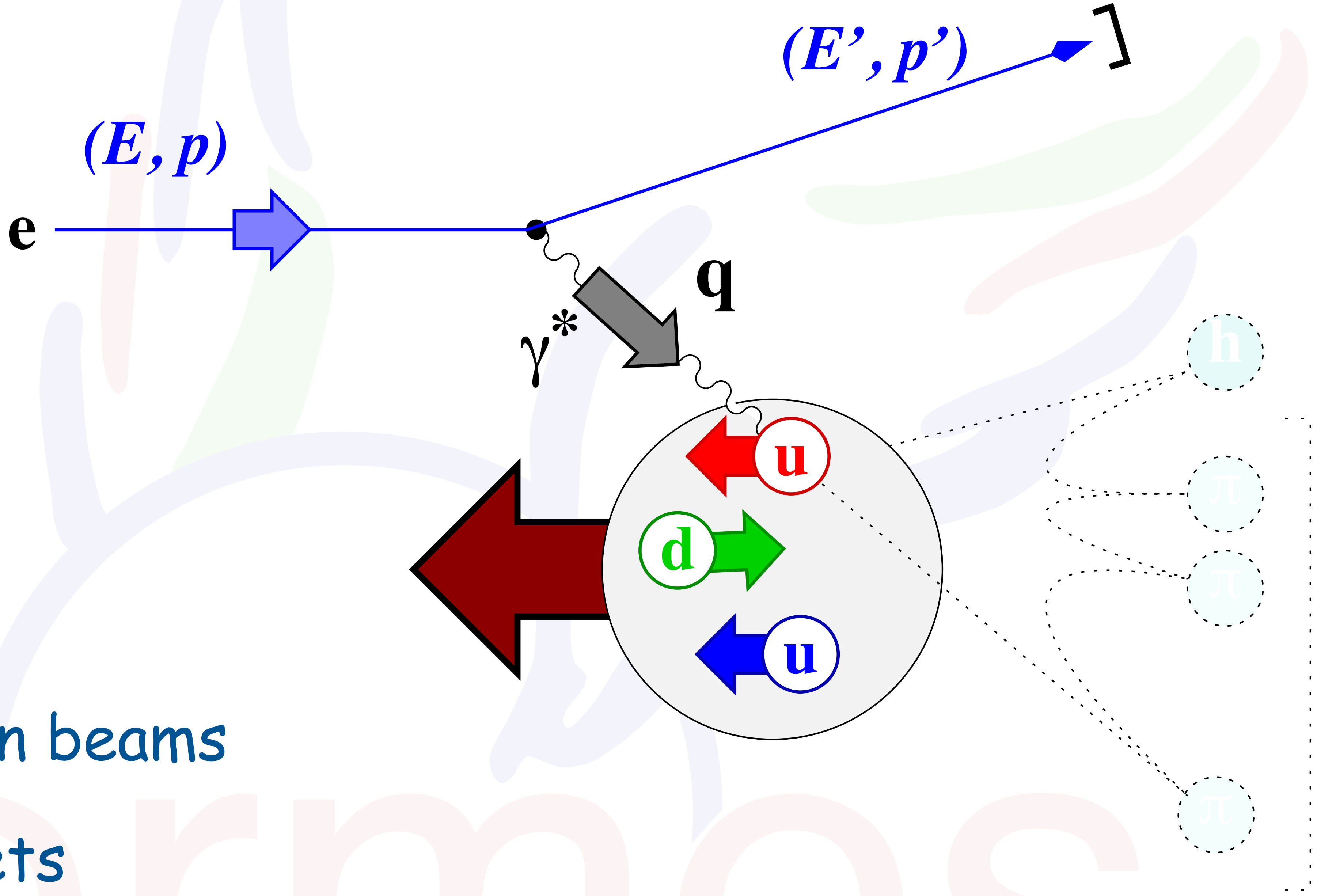
- exploit spin correlations (e.g., virtual photon couples only to spin-1/2 quarks with opposite spin)
- cross-section difference provides access to quark polarization
- in praxis form asymmetries to cancel systematics: $\frac{\sigma_{\frac{3}{2}} - \sigma_{\frac{1}{2}}}{\sigma_{\frac{3}{2}} + \sigma_{\frac{1}{2}}}$

experimental prerequisites



- polarized lepton beams

experimental prerequisites



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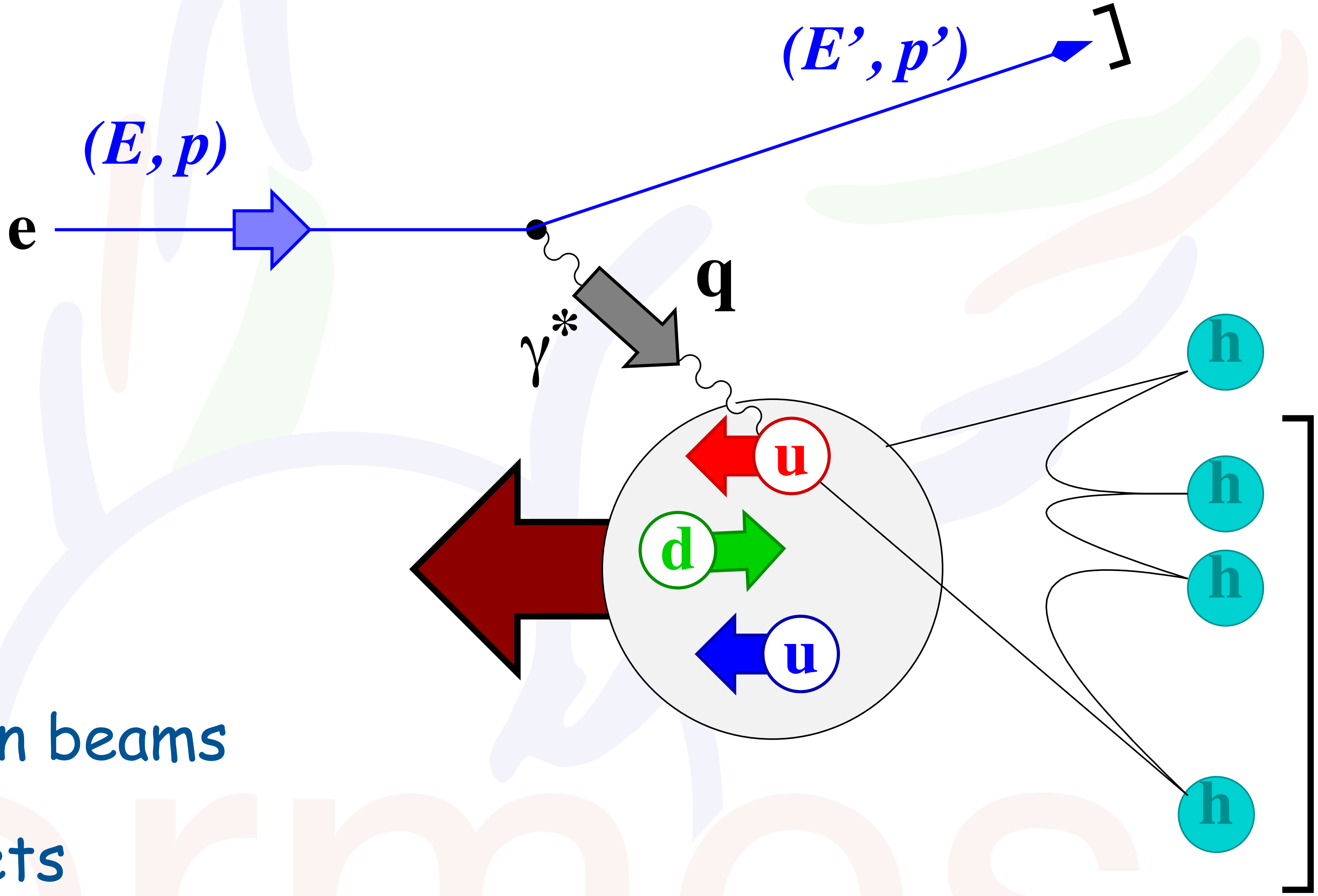

- polarized lepton beams
- polarized targets
- large-acceptance spectrometer

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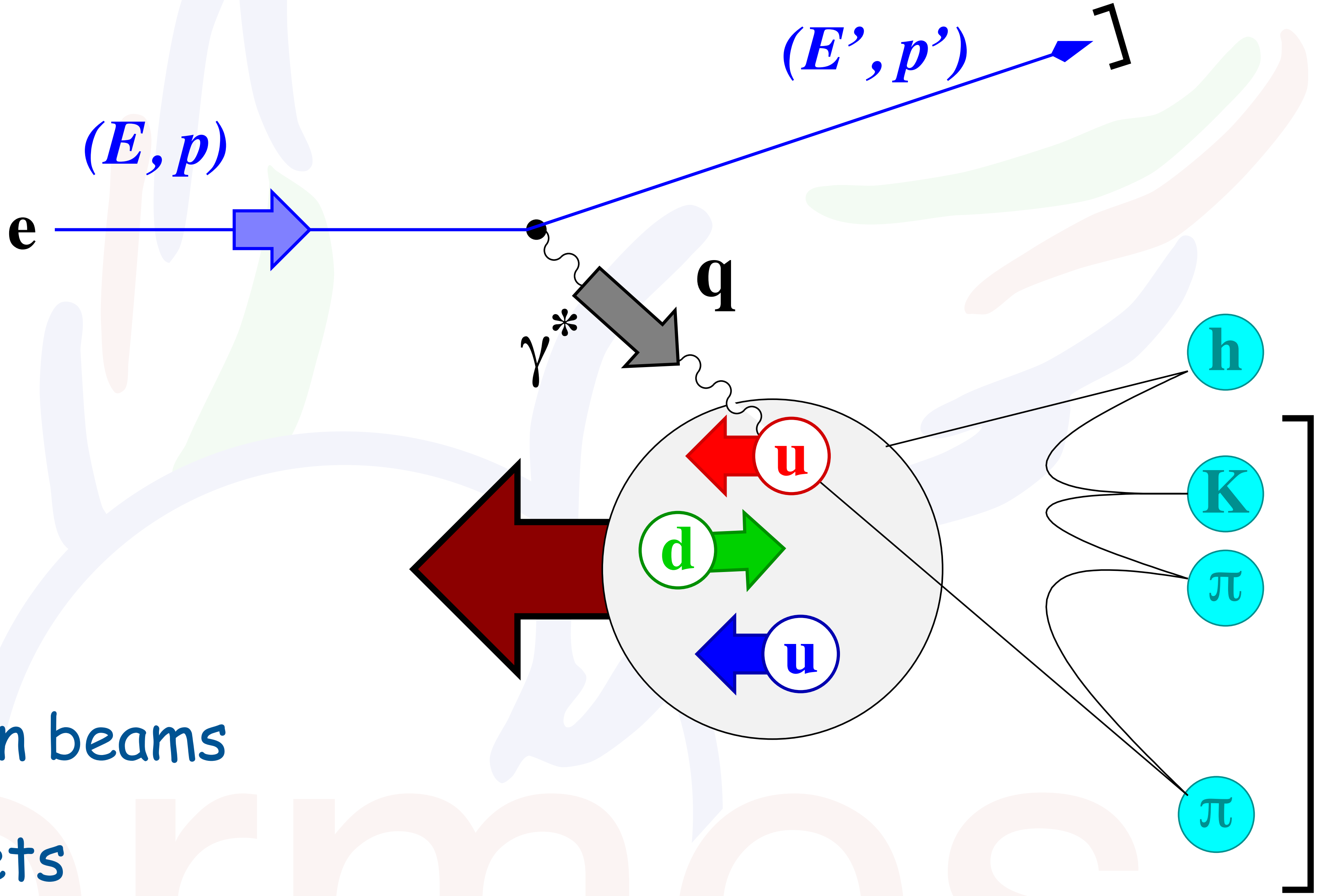

- polarized lepton beams
- polarized targets
- large-acceptance spectrometer
- good particle identification (PID)

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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- 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**)
    - heades to DESY to measure spin asymmetries at HERA
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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
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  - successful spin rotation to obtain longitudinal polarization
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- … and demonstration of storage-cell technique
- no compromises for HERA flagship colliders H1 and Zeus

beam polarization

☛ previous talk

- tiny asymmetry in spin-flip 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

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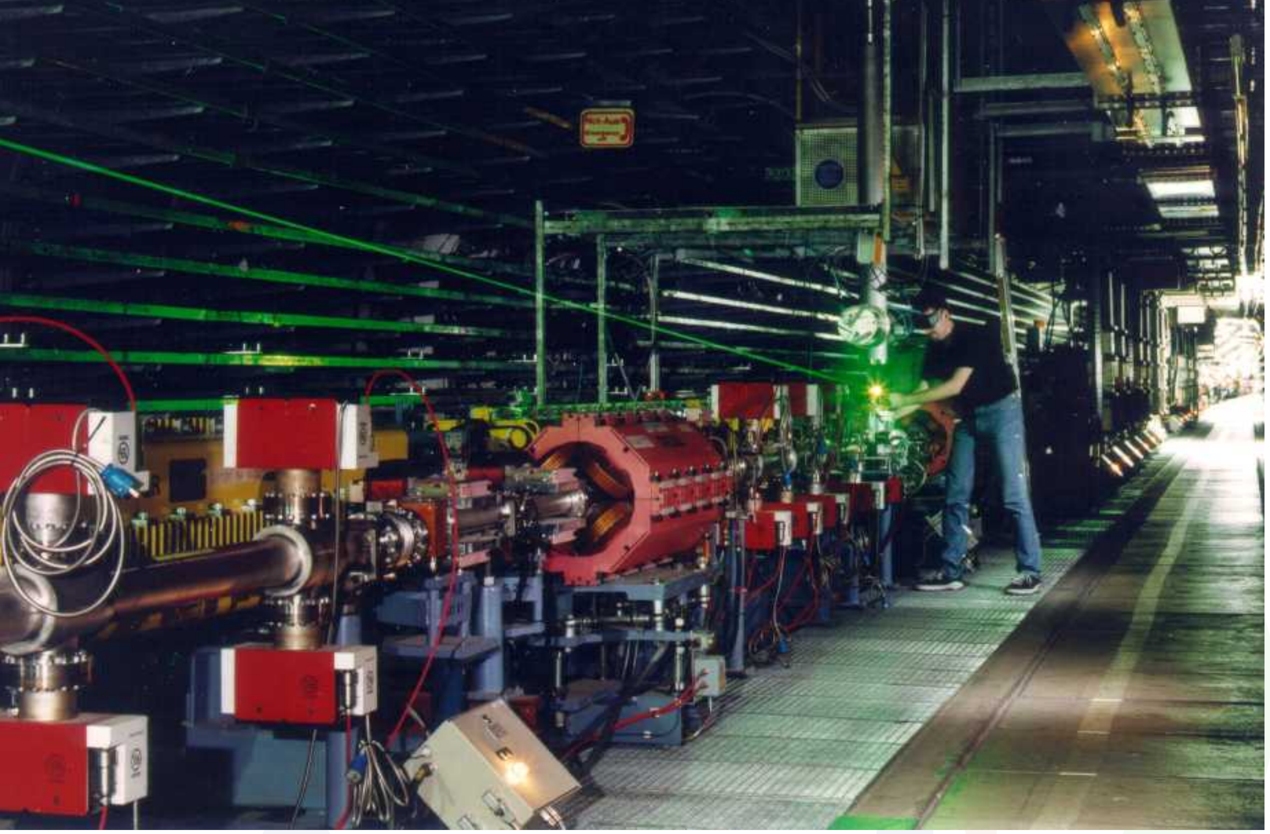
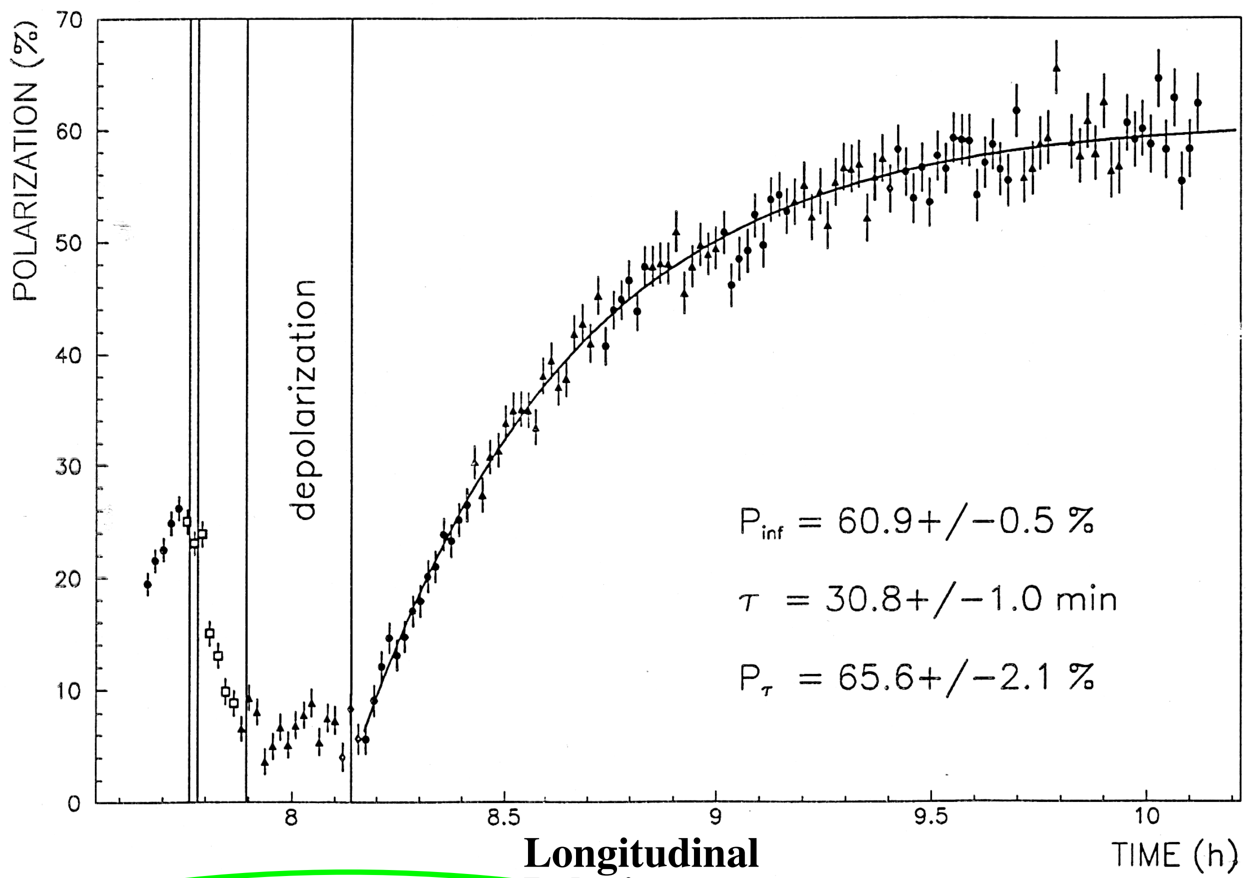
- two independent Compton polarimeters at East and West Hall





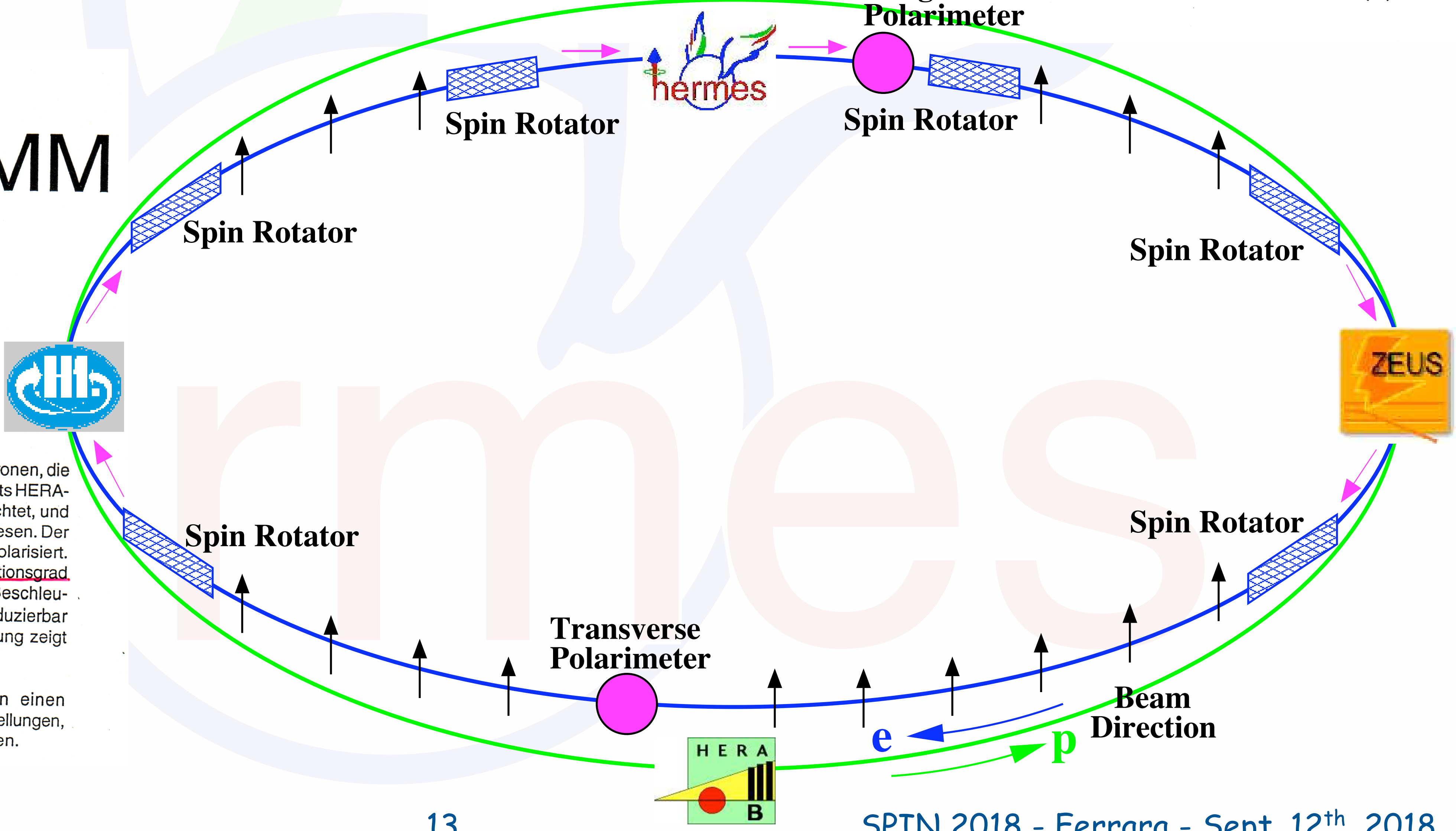
DESY TELEGRAMM

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.

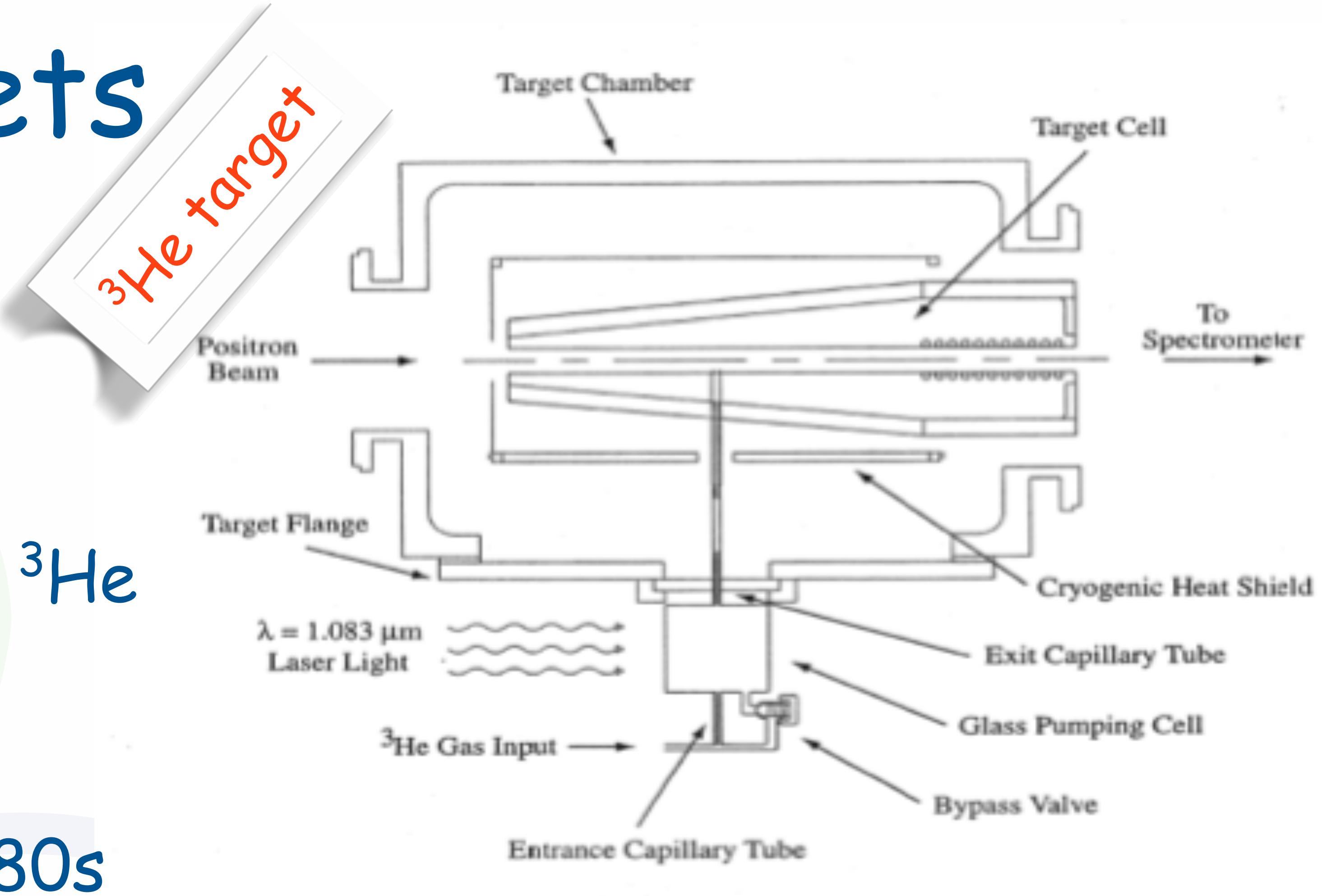
Elektronen besitzen die Eigenschaft kleiner Kreisel, sie haben einen "Eigendrehimpuls" oder "Spin". In der Teilchenphysik gibt es einige Fragestellungen, die nur mit solchen "polarisierten" Elektronen untersucht werden können.

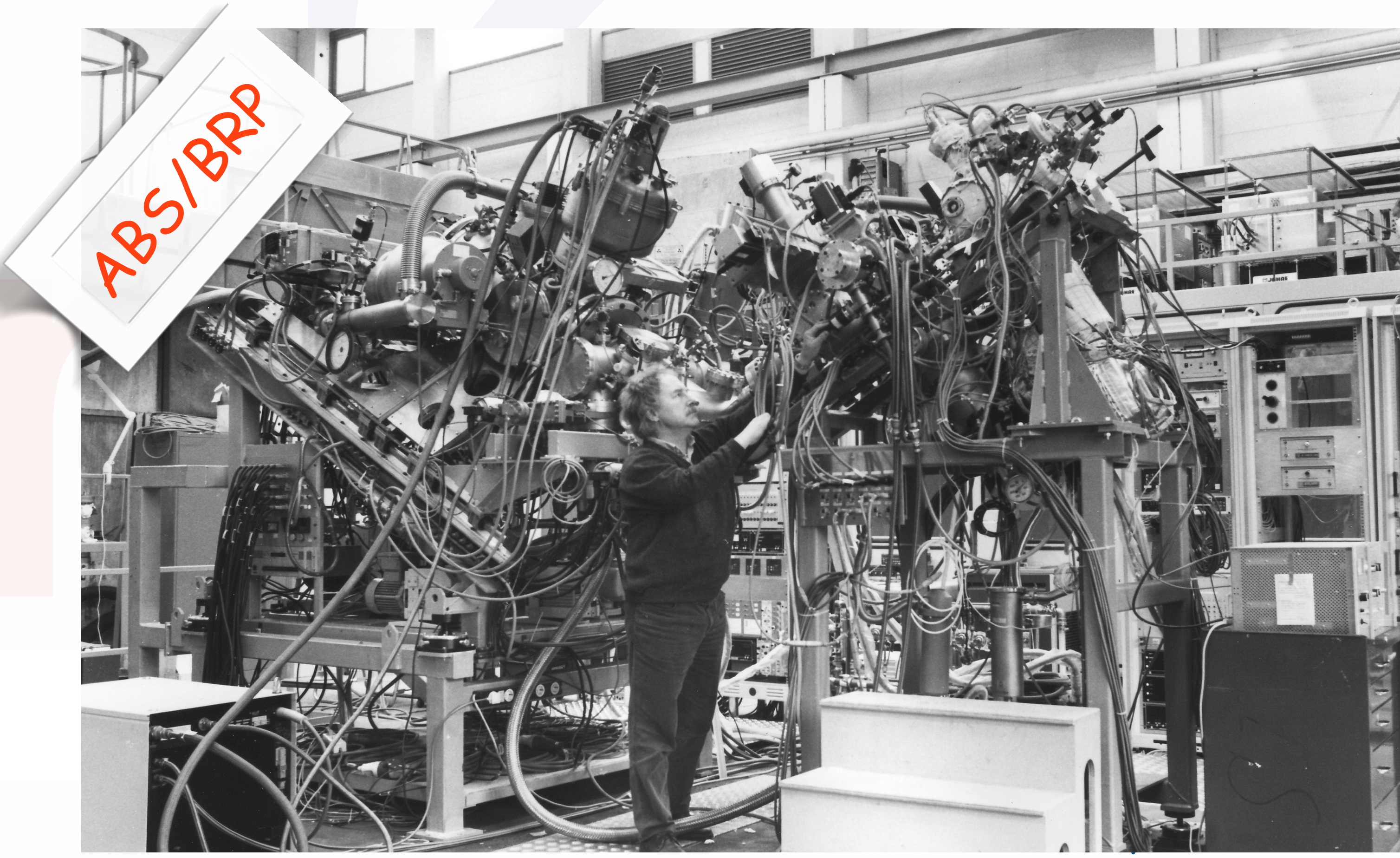


HERMES gas targets

novel **pure** gas target:

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





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☞ 1993 final approval & TDR

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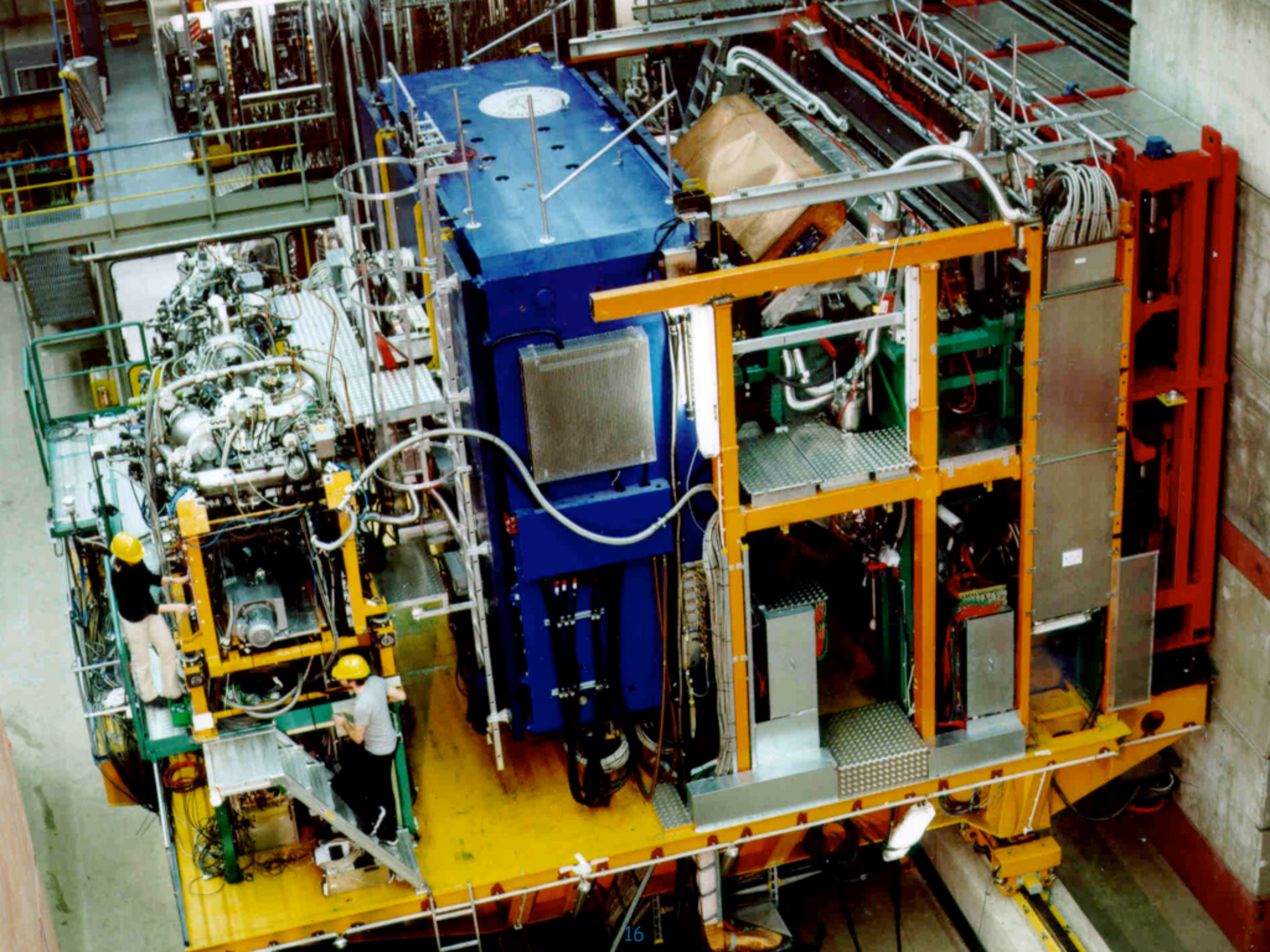
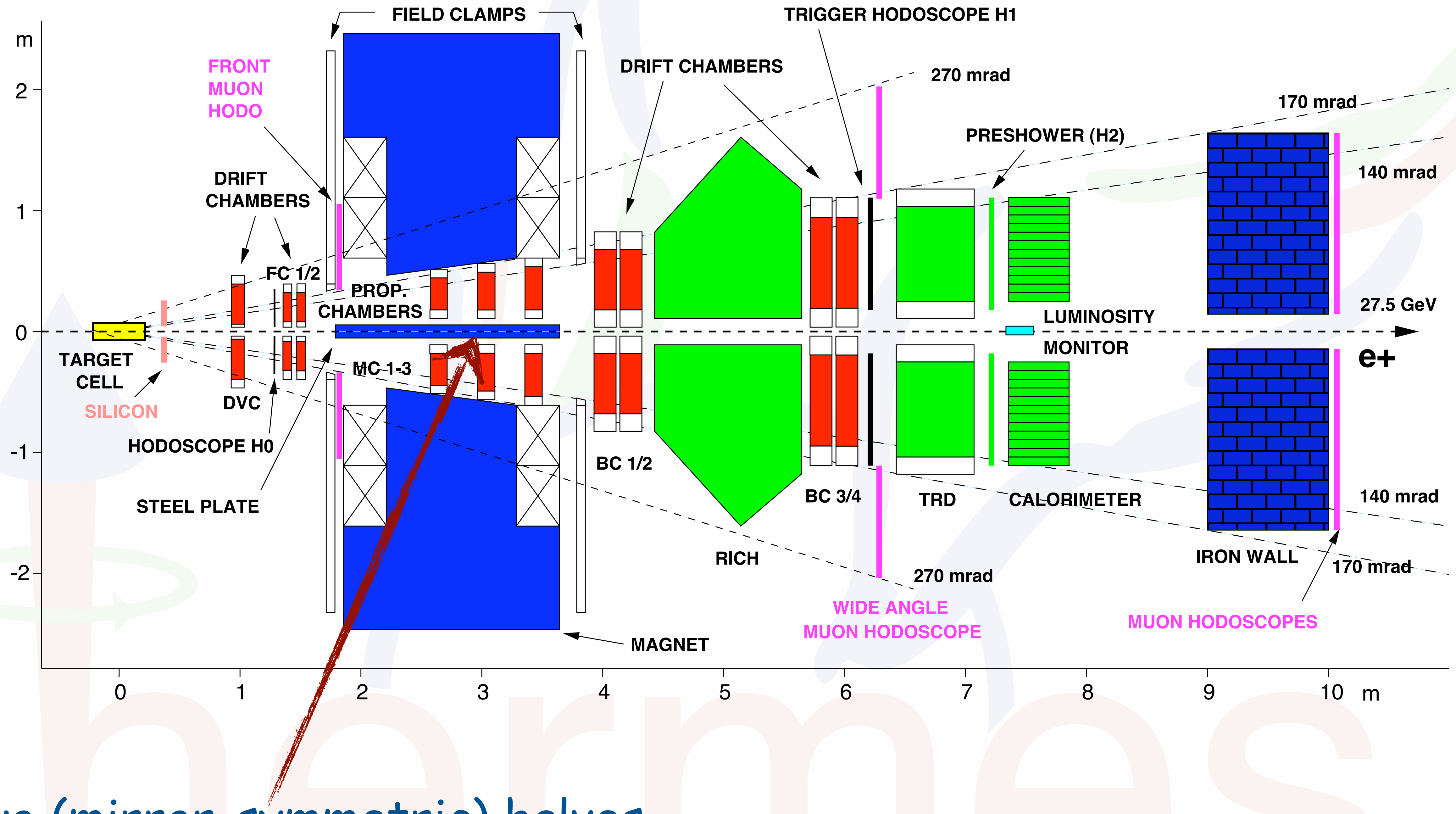
☞ 1995-2007 data taking



HERMES (1998-2005) schematically



two (mirror-symmetric) halves

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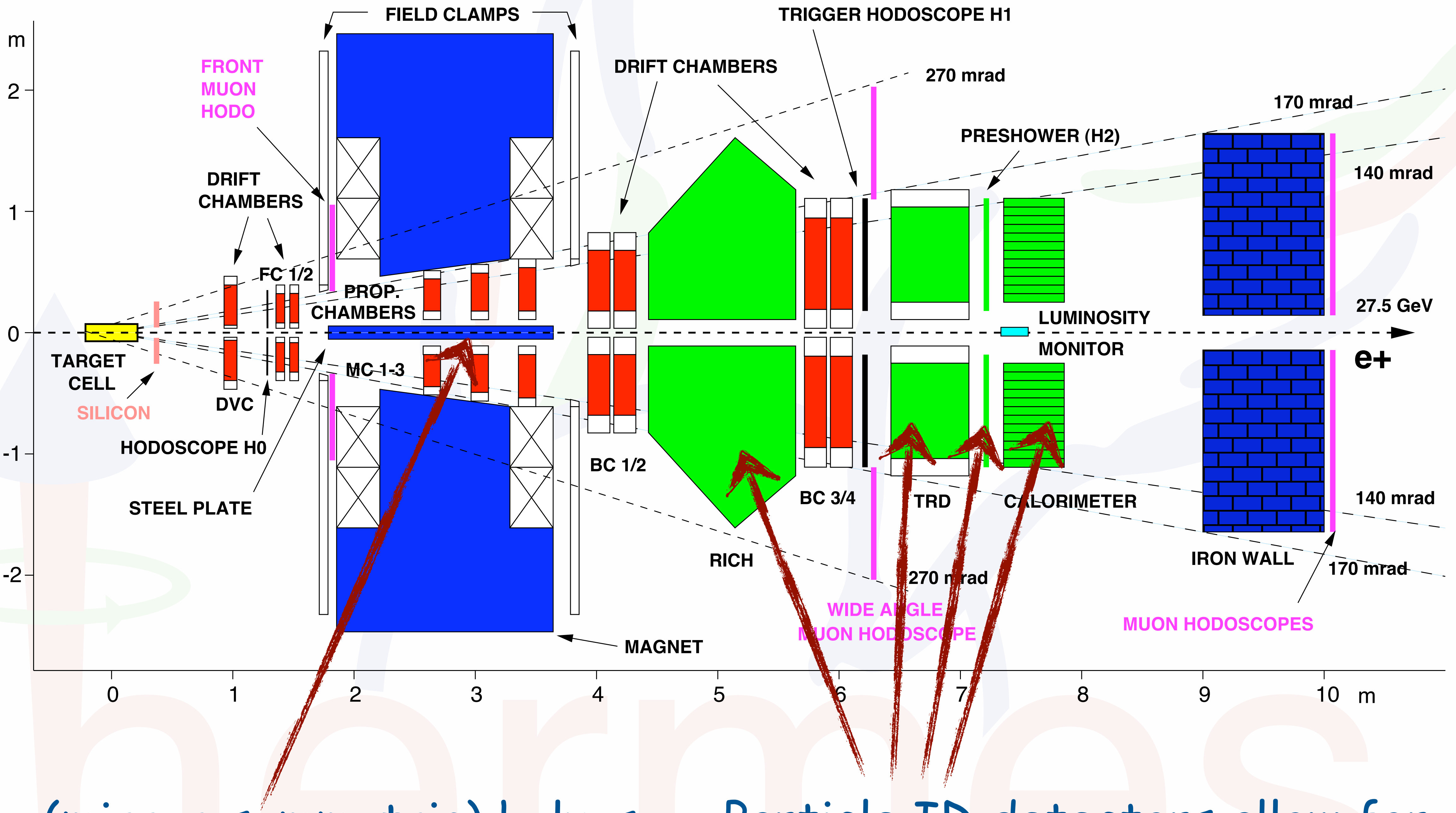
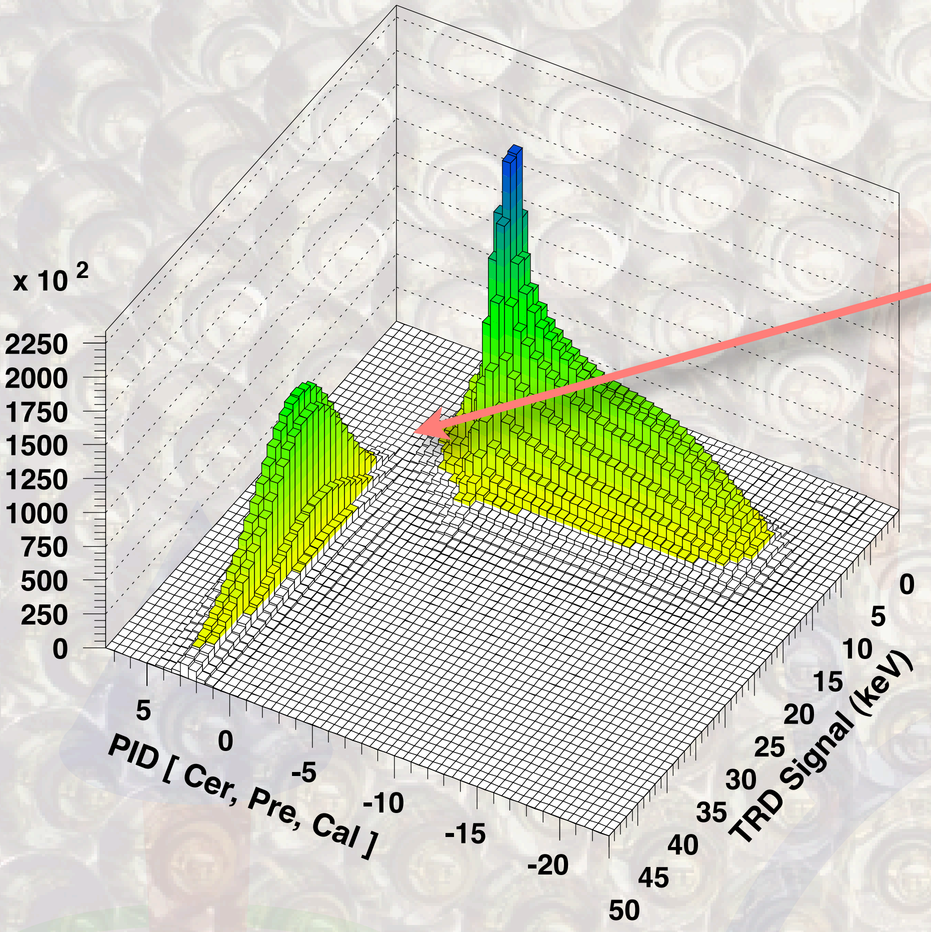


two (mirror-symmetric) halves

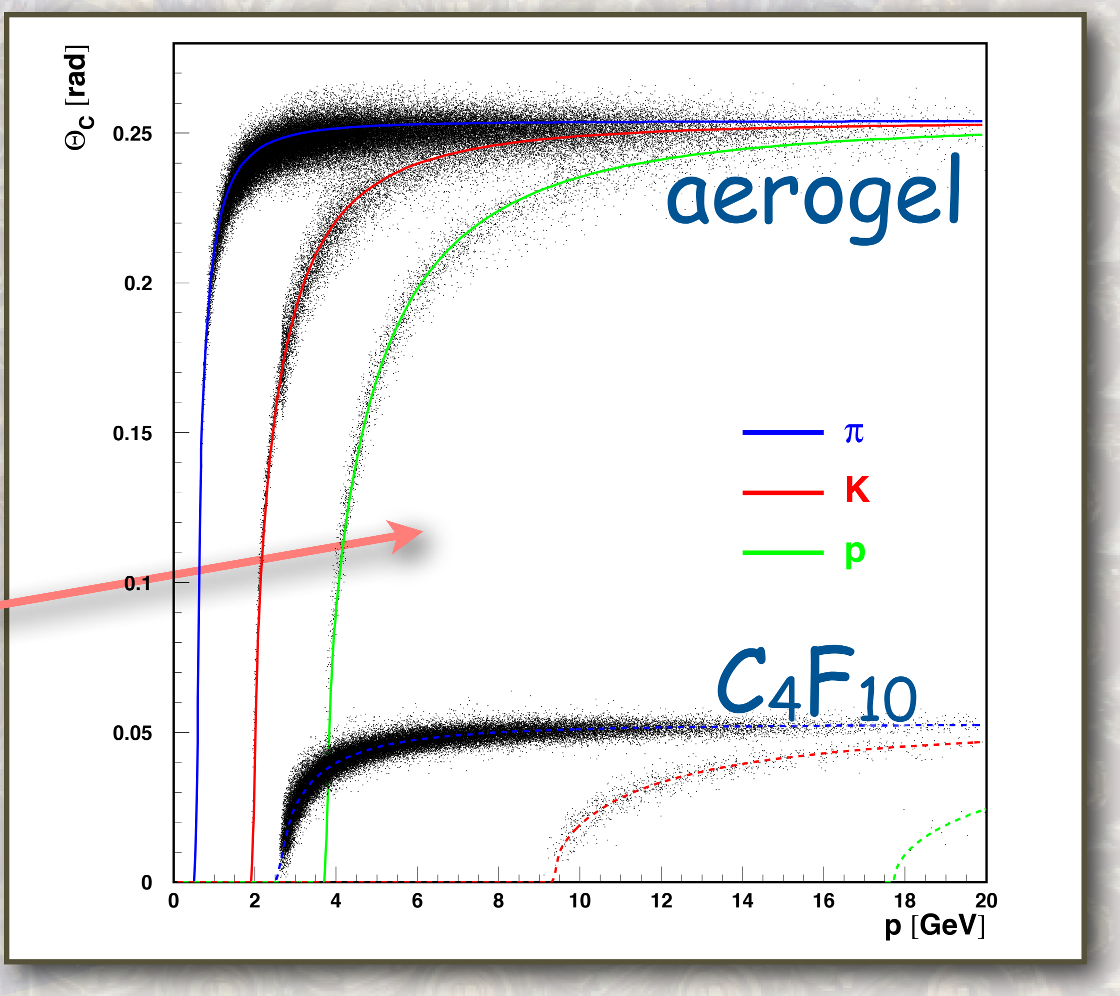
Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

Particle identification



excellent lepton/hadron separation

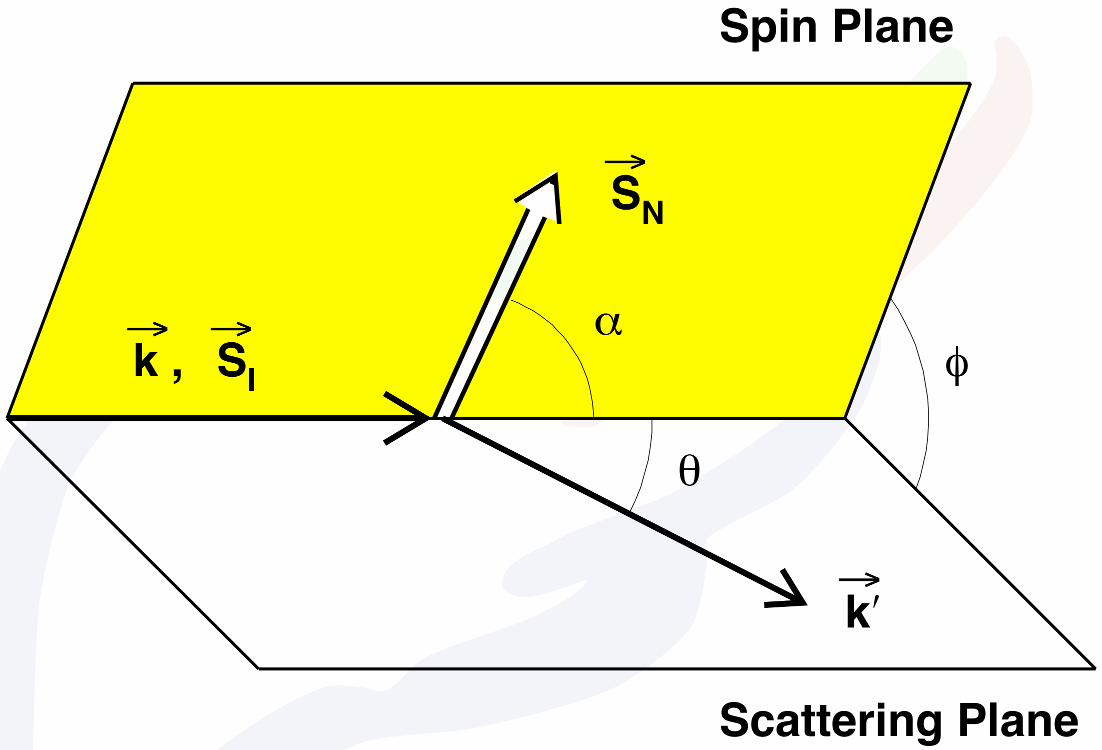
Dual-Radiator RICH hadron ID for momenta 2-15 GeV



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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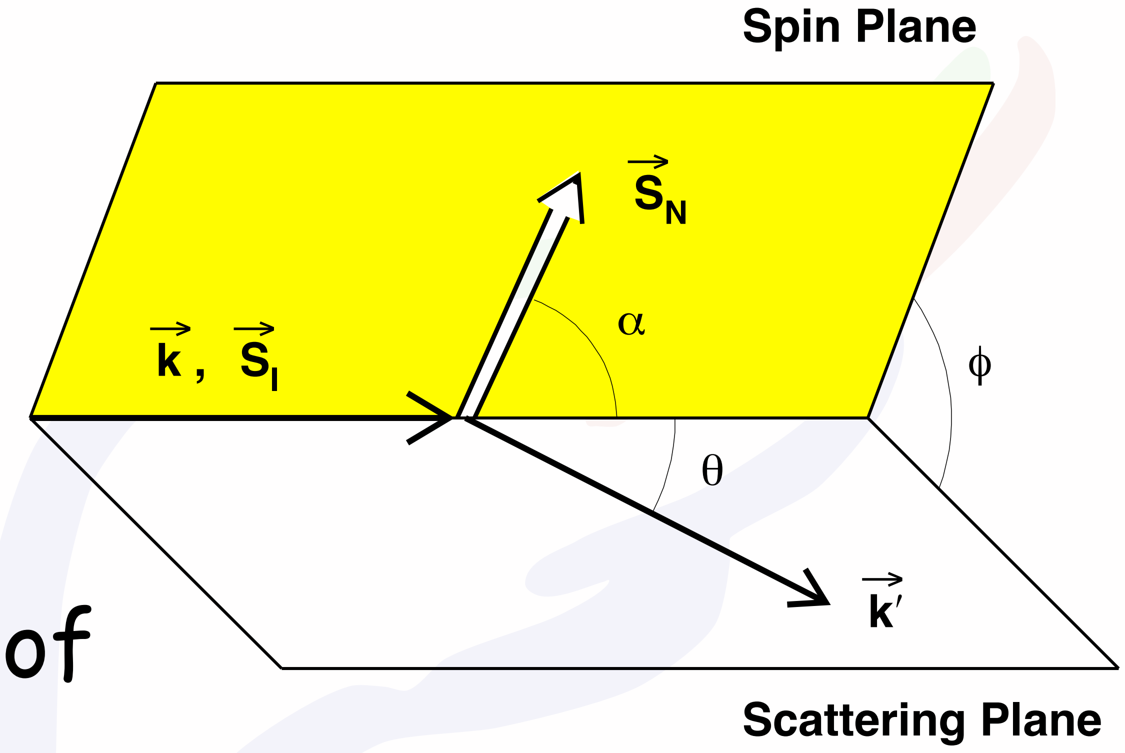
Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions



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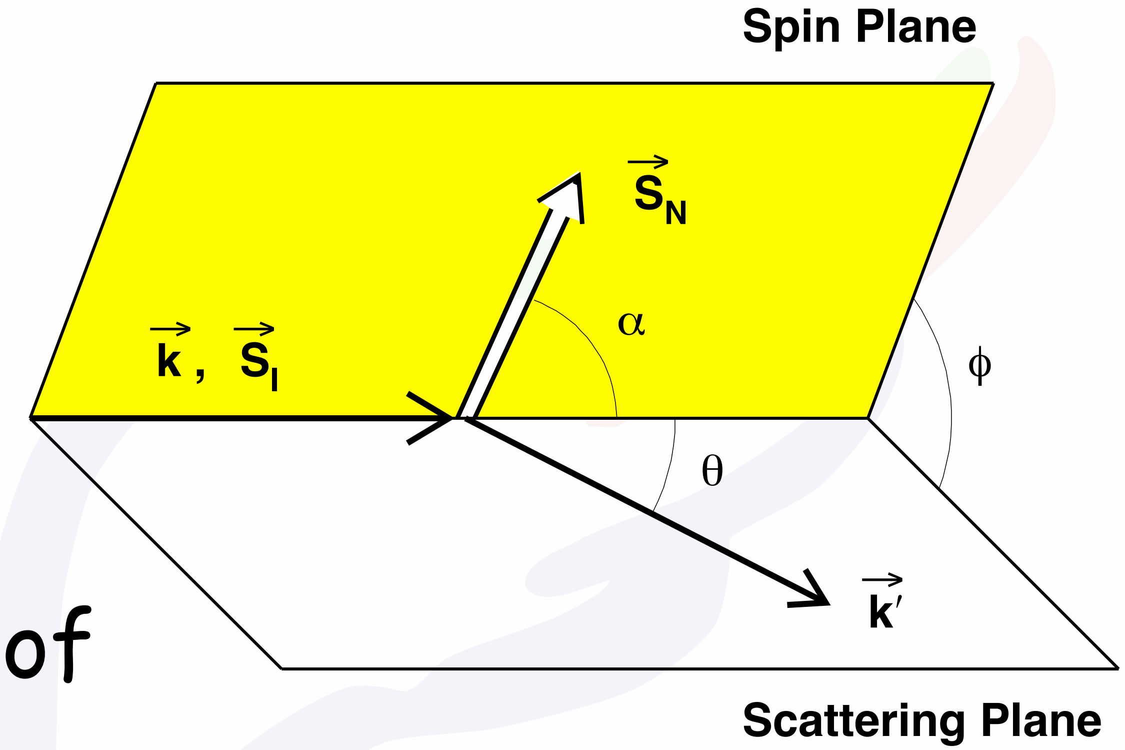
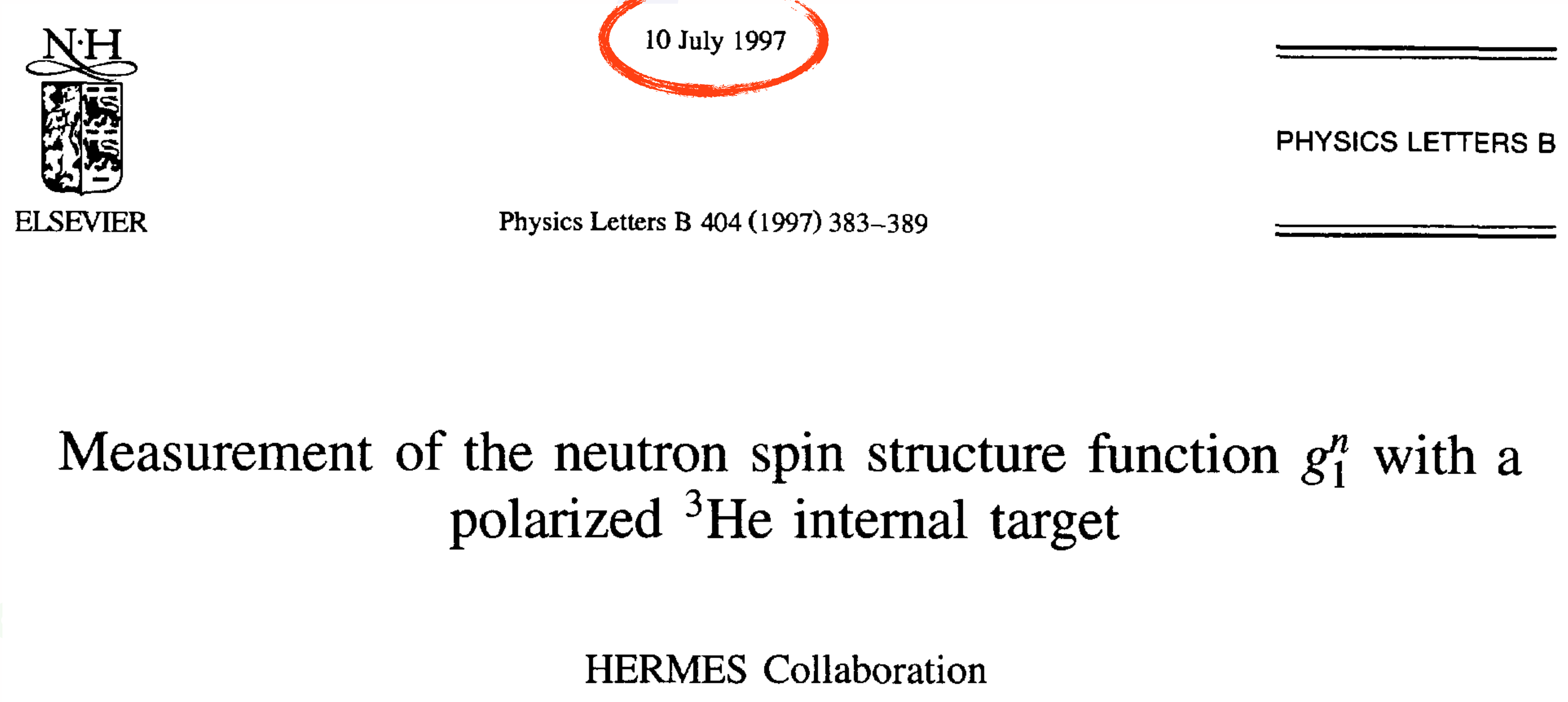


$$\frac{d^3\sigma}{dx dy d\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$

$$-S_l S_N \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{2}g_2(x,Q^2)\right]$$

$$+S_l S_N \sin\alpha\cos\phi\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

polarized structure function $g_1(x)$



10 July 1997

ELSEVIER

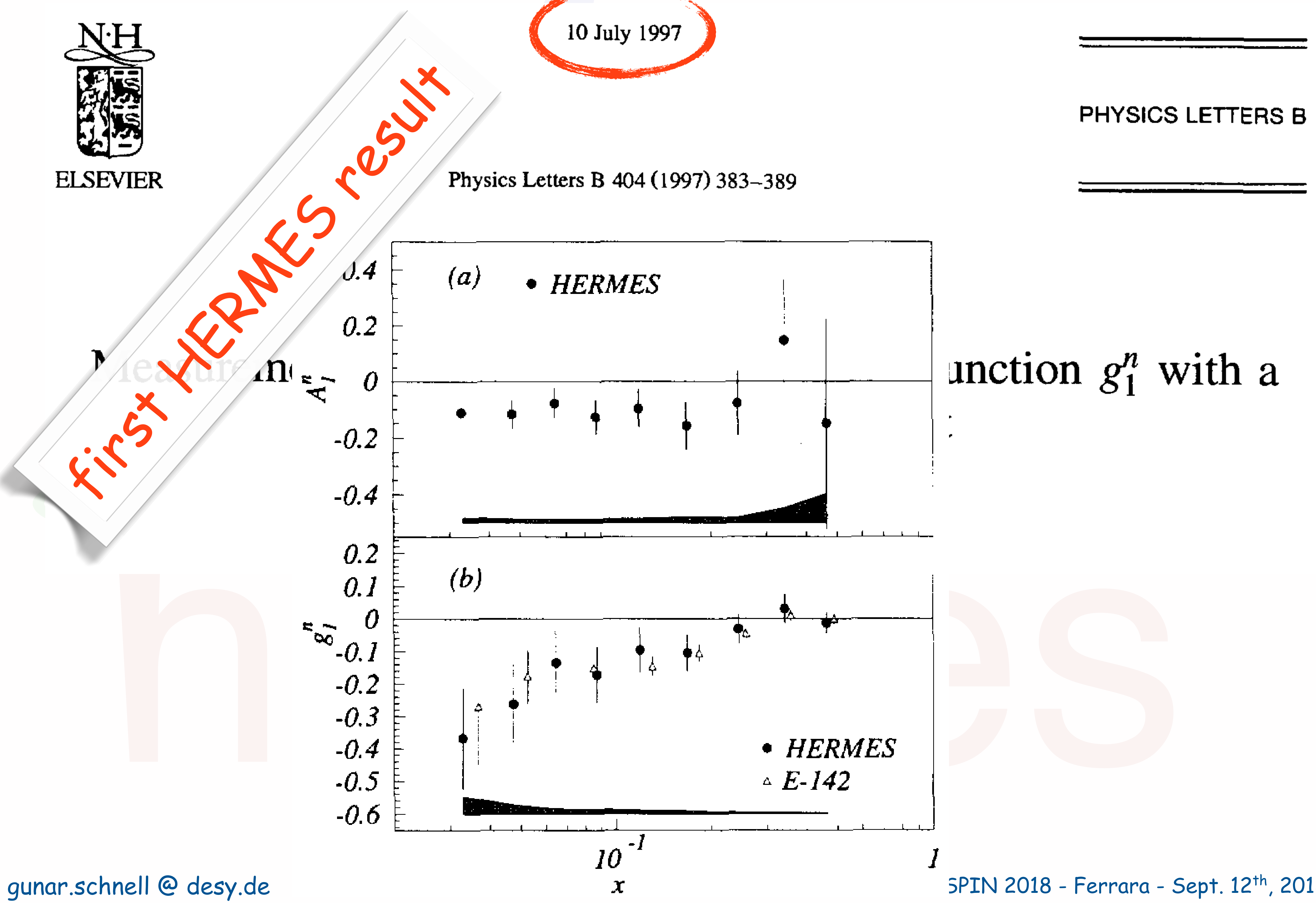
PHYSICS LETTERS B

Physics Letters B 404 (1997) 383–389

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

HERMES Collaboration

polarized structure function $g_1(x)$



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PHYSICS LETTERS B

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Measuremen

unction g_1^n with a

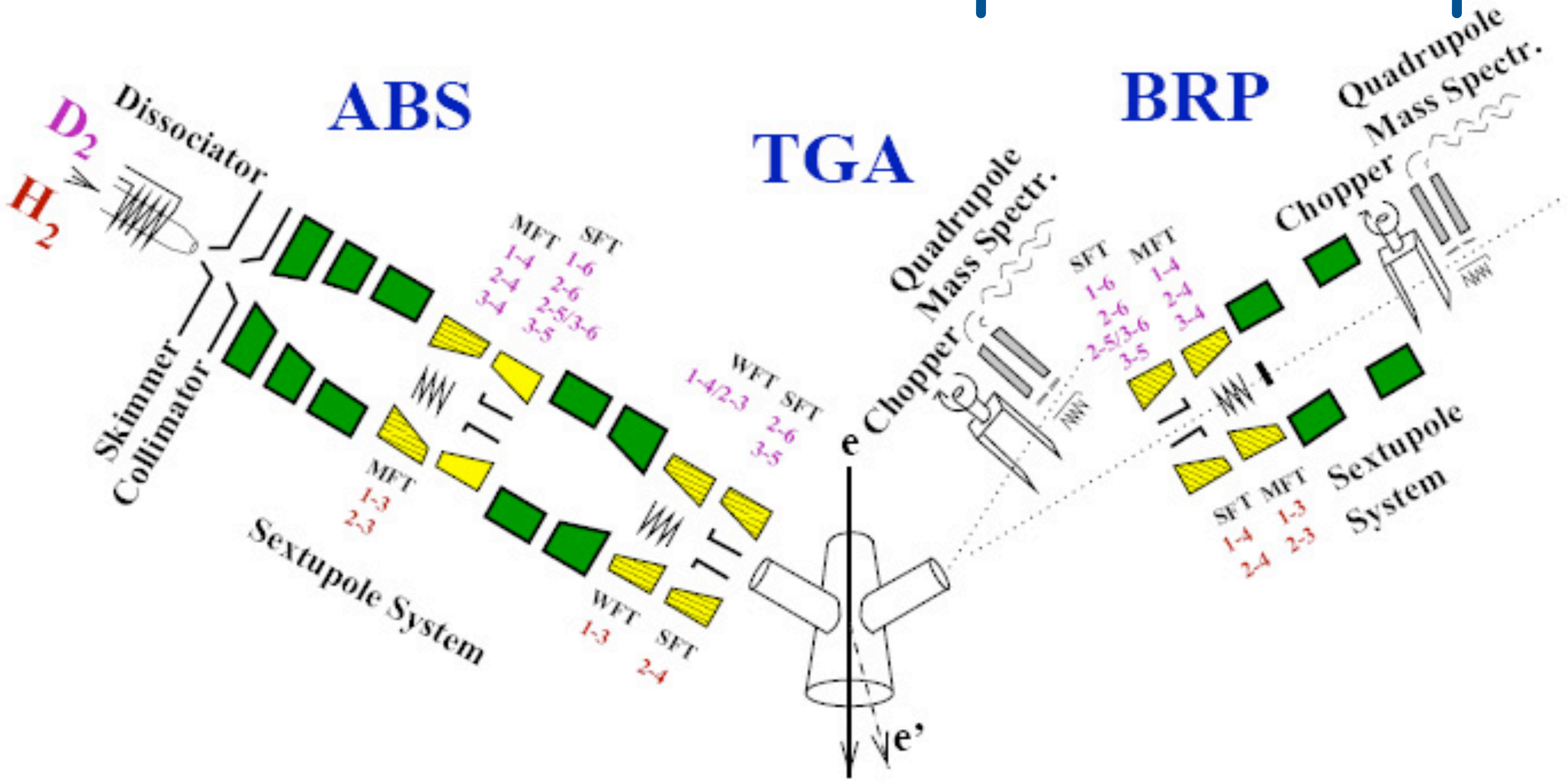
first HERMES result

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)

atomic-beam source: polarized p & d



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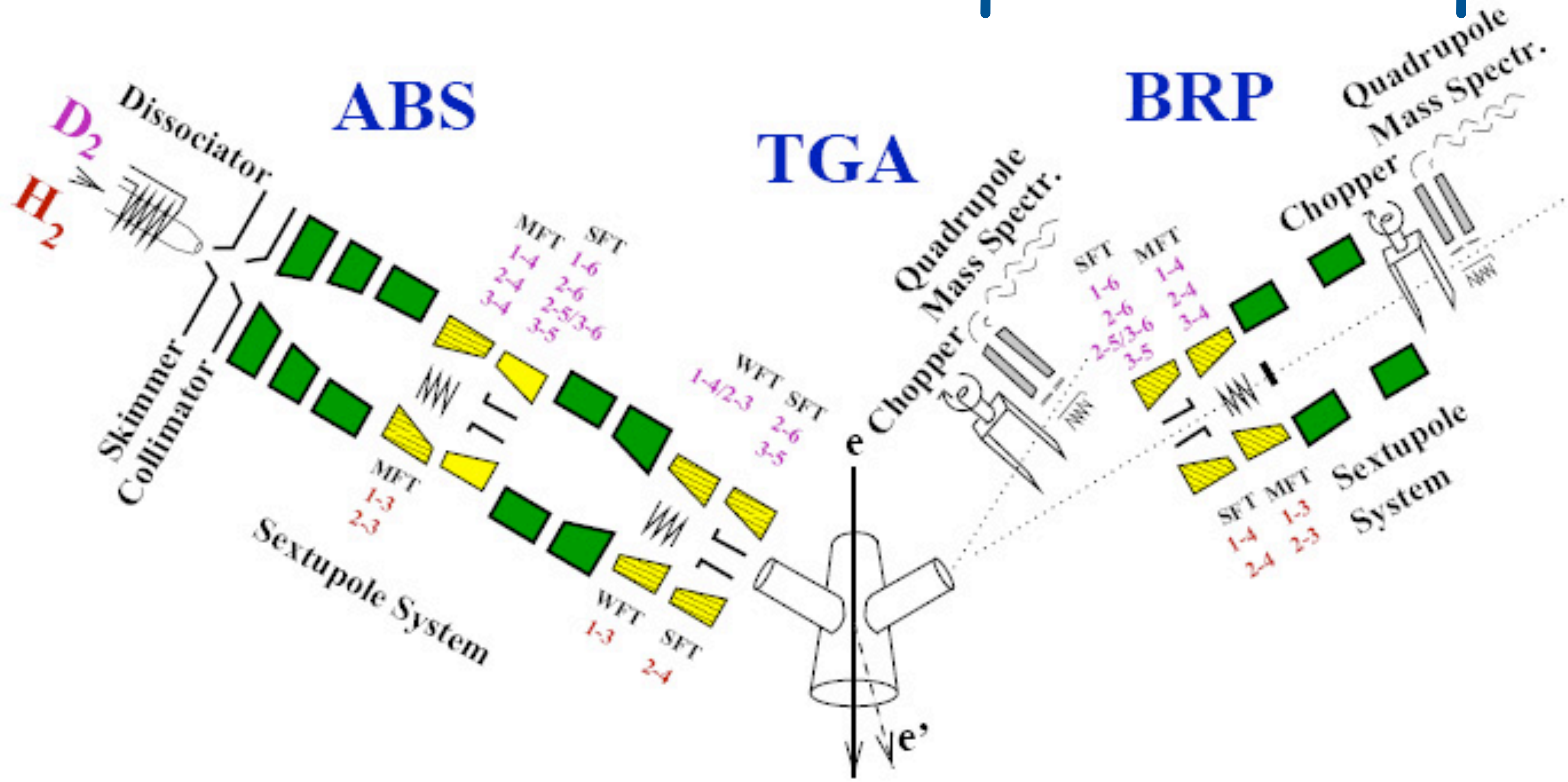
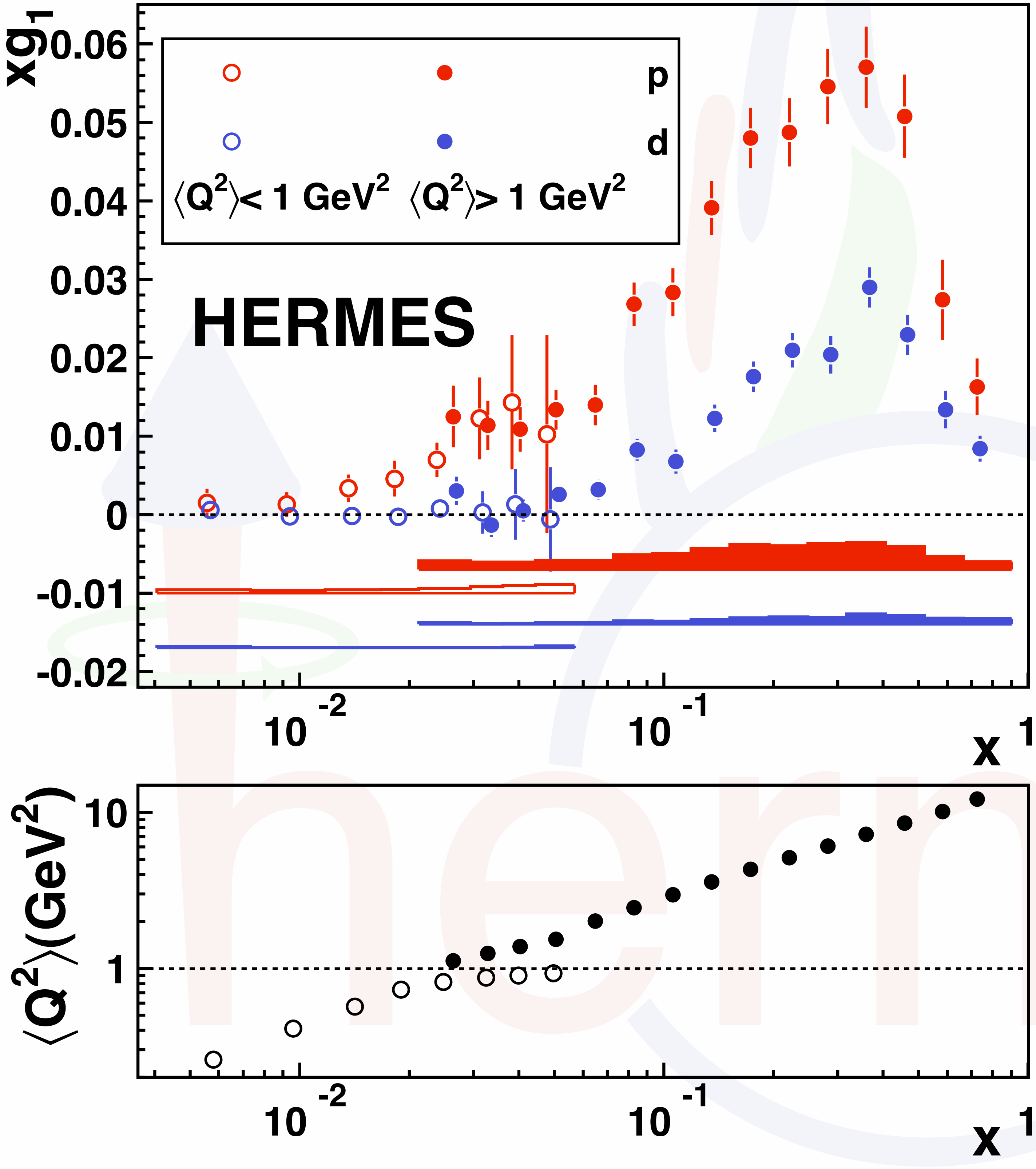


Years	Target	DIS (Milion)	Polarization
1996-1997	$H_{\|\|}$	3.5	0.851 ± 0.033
1998-2000	$D_{\|\|}$	10.2	0.845 ± 0.028
2001-2005	$H_{\perp}$	~6	0.74 ± 0.06

polarized structure function $g_1(x)$

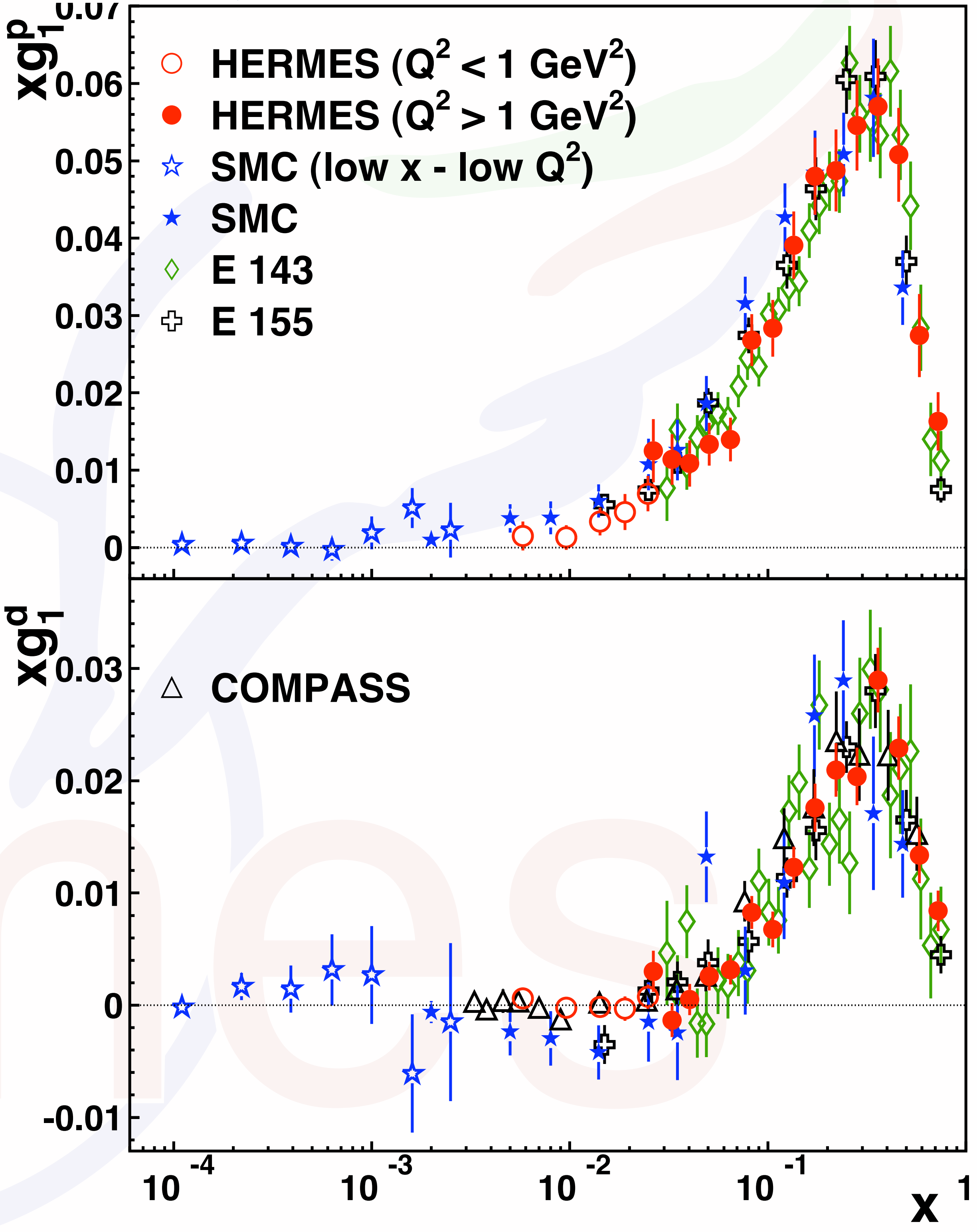
[A. Airapetian et al., PRD 75 (2007) 012007]



polarized structure function $g_1(x)$

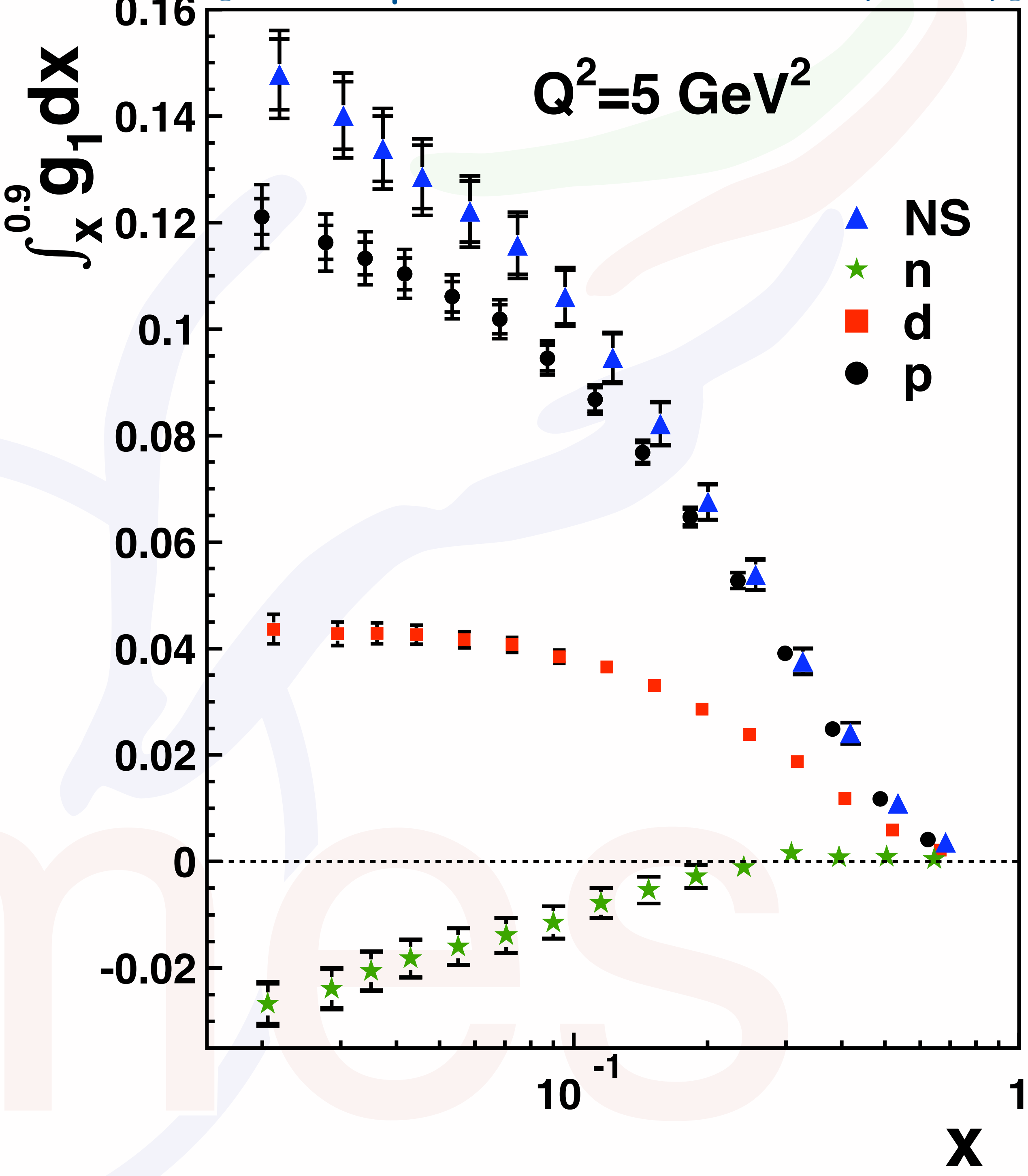
- **unfolded** for radiative and detector smearing
- unknown systematic correlations transformed into known statistical correlations
- uncertainties plotted only reflect diagonal elements of covariance -> "underestimates" statistical precision

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



Γ_1 … integral of $g_1(x)$

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



Γ_1 … integral of $g_1(x)$

Saturation

➠ close to full integral?

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

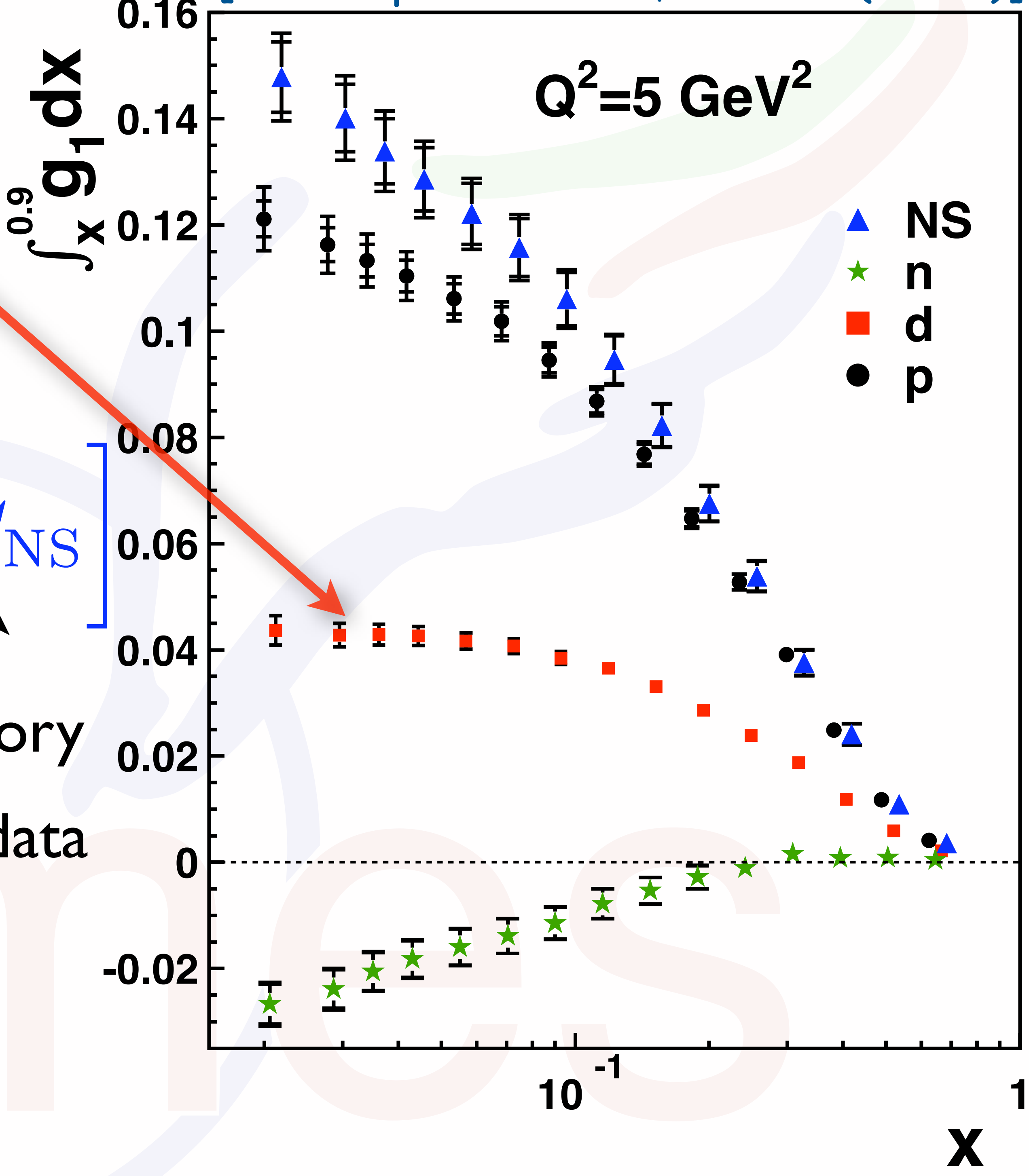
↑ theory

↑ 0.05±0.05

↑ hyperon-decay data

↑ theory

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



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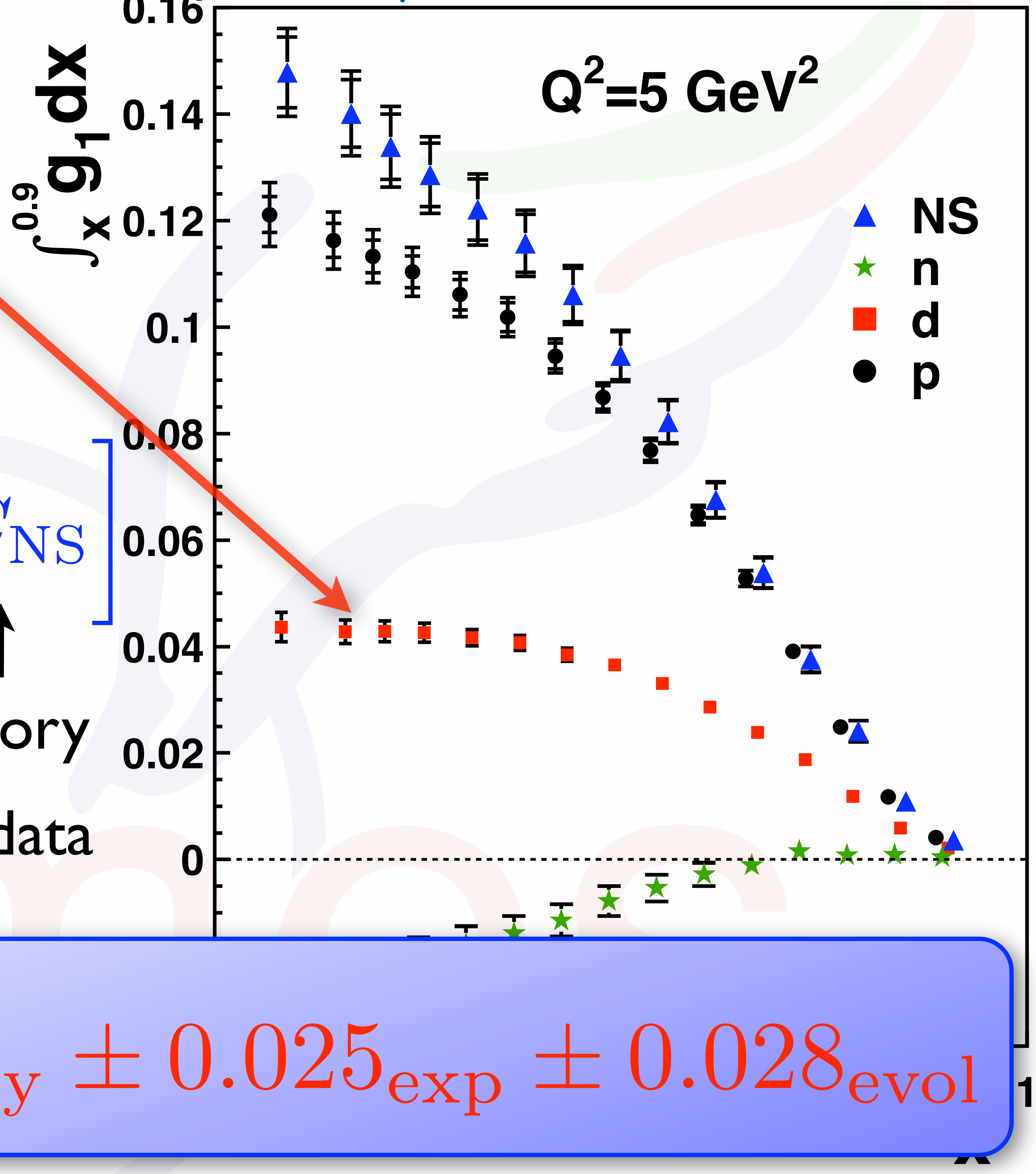

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$$\Delta\Sigma \overset{\overline{\text{MS}}}{=} 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

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

Can we do more than "just" inclusive g_1?

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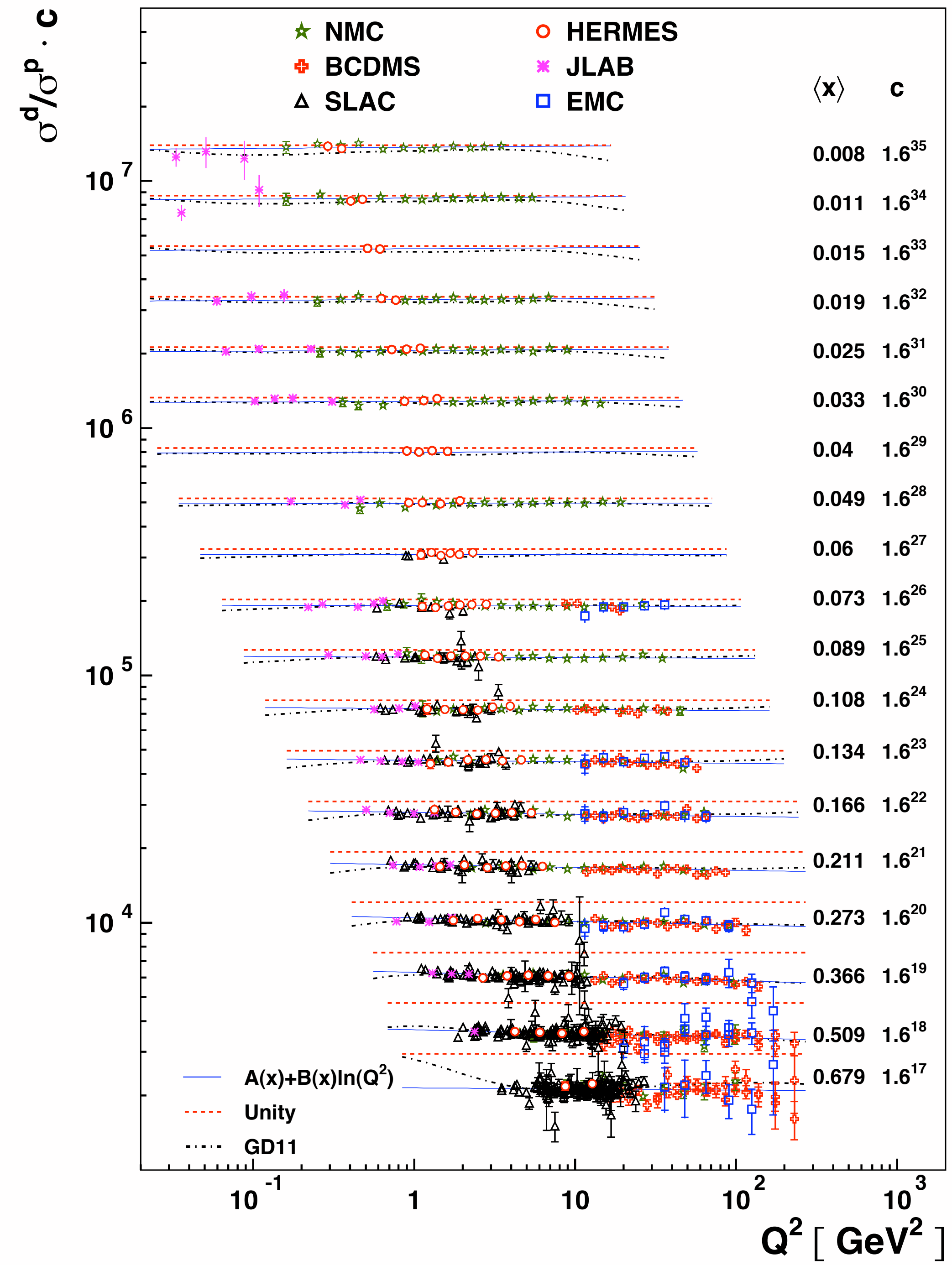
☑ unpolarized DIS: F_2 & σ^d/σ^p



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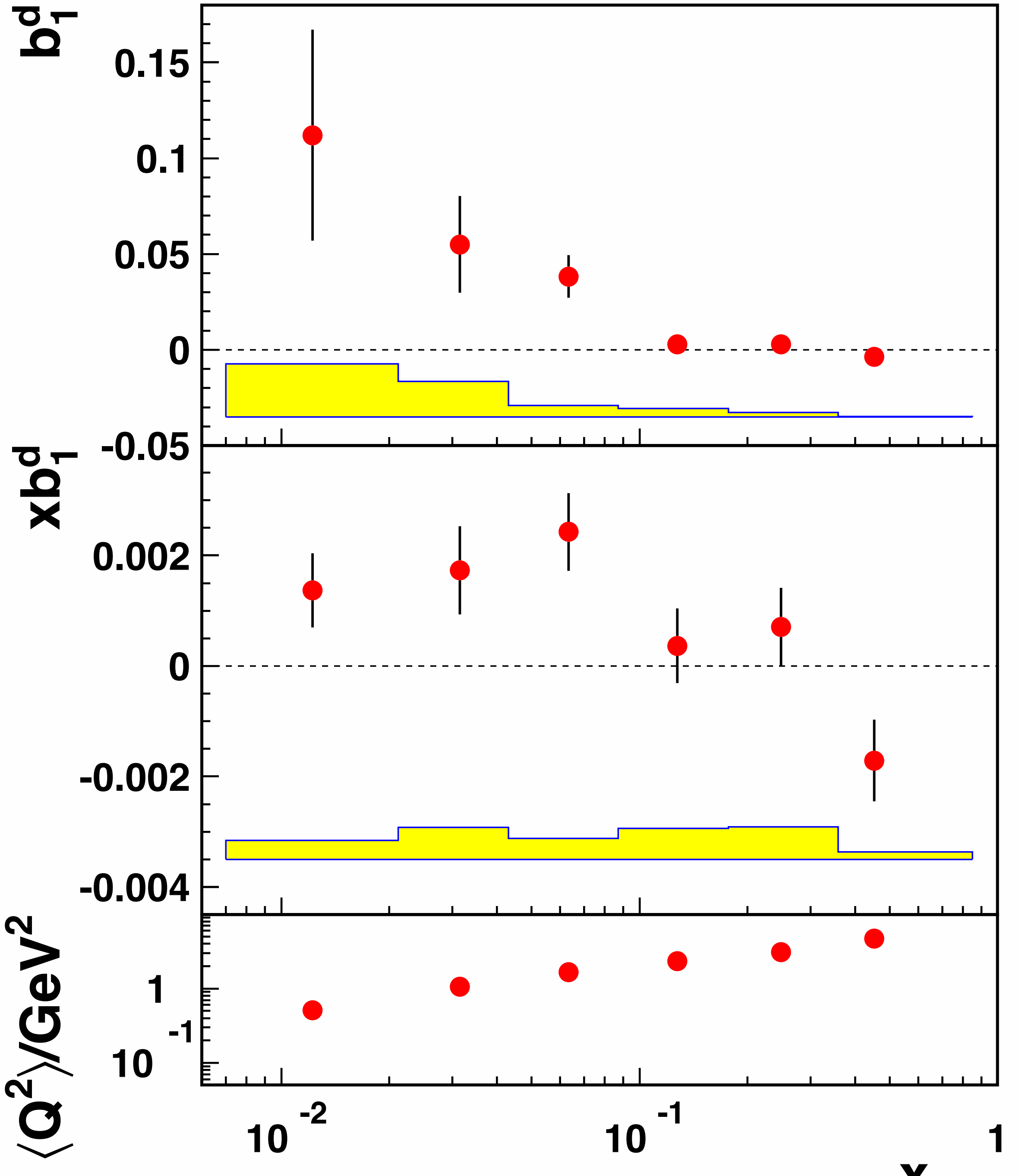
- ☑ unpolarized DIS: F_2 & σ^d/σ^p
- ☑ tensor structure function b_1



Can we do more than “just” inclusive g_1?

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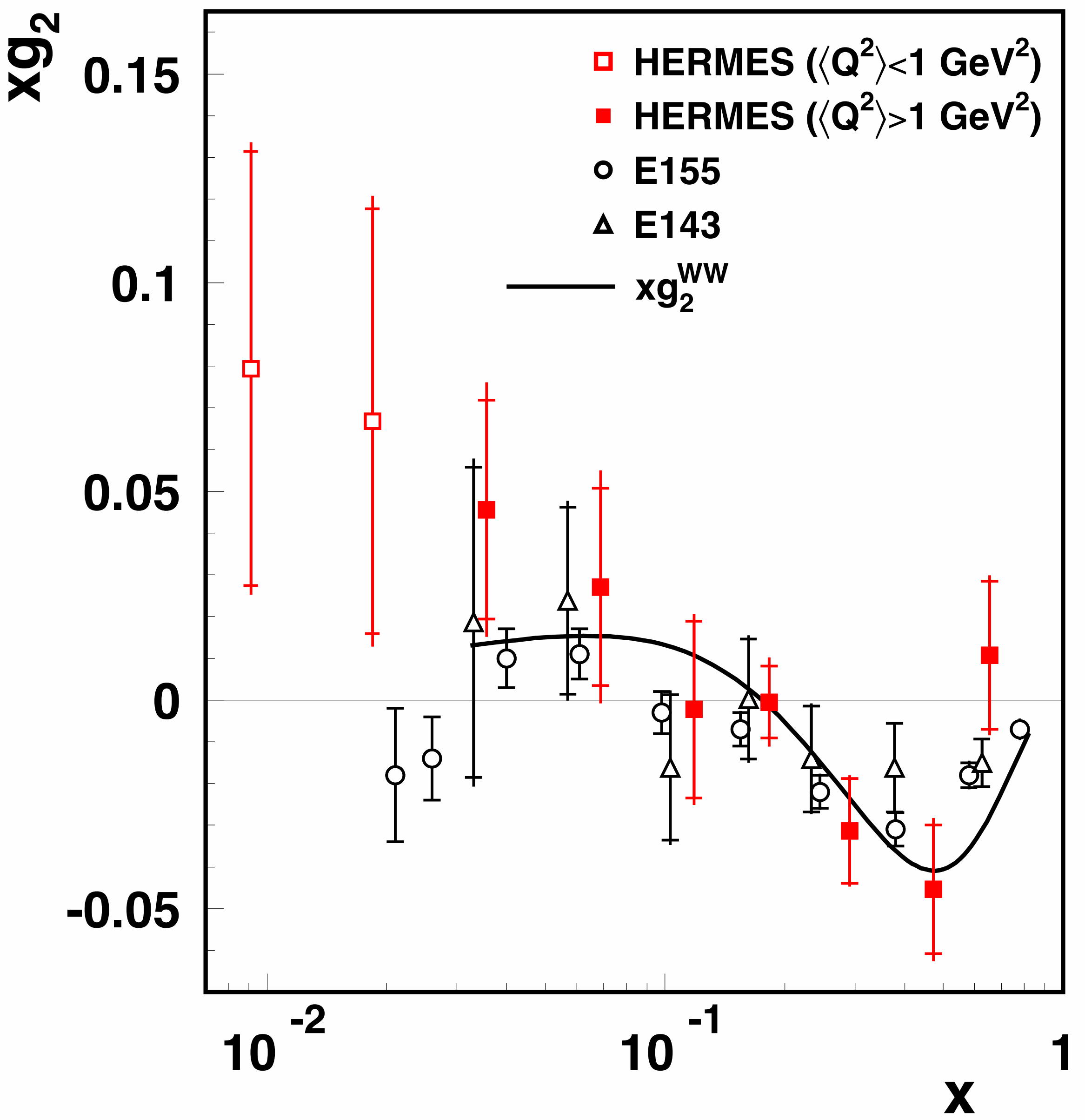
- ☑ transverse: g_2



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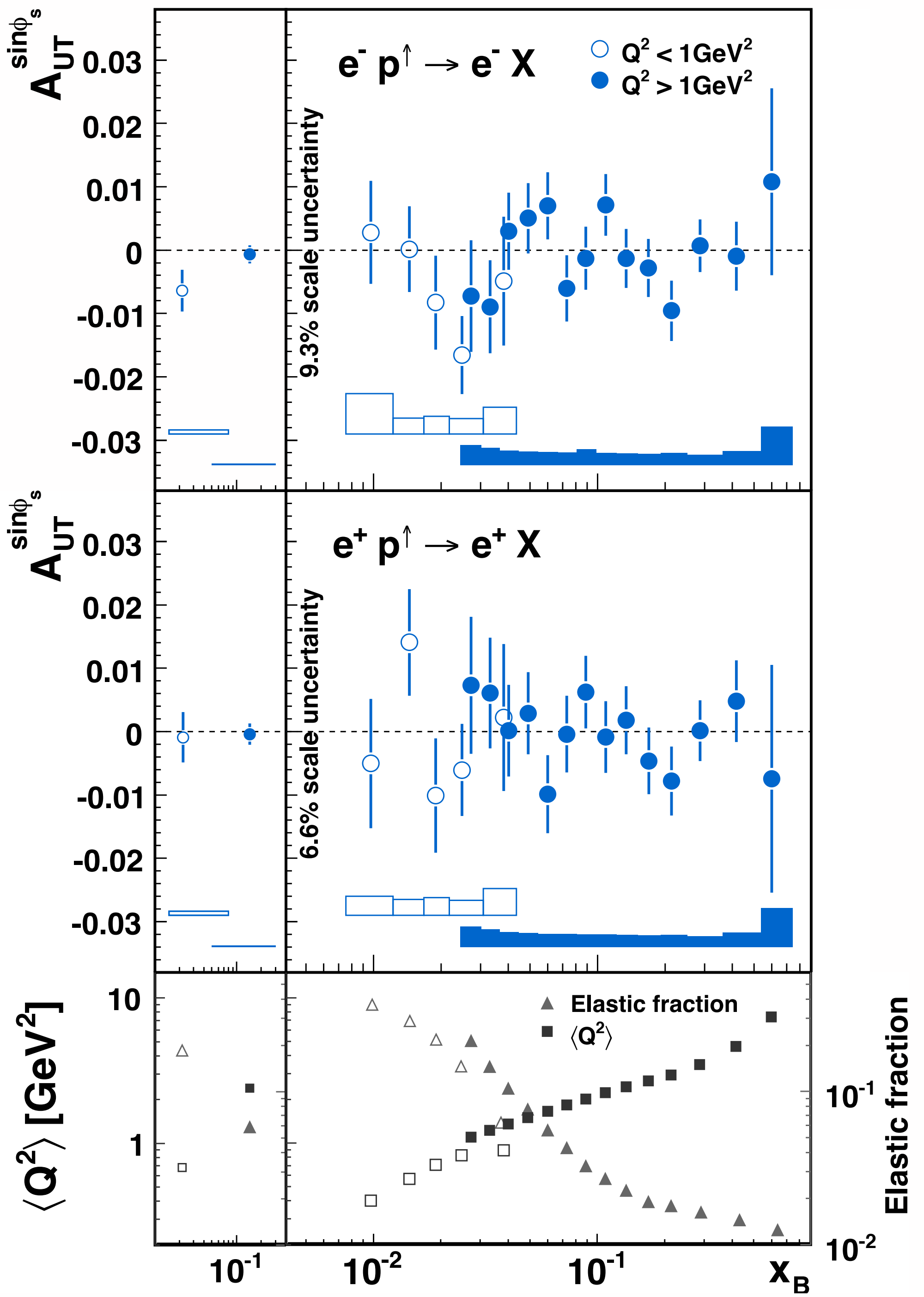
- ☑ transverse: g_2
- ☑ 2-photon exchange in incl. DIS



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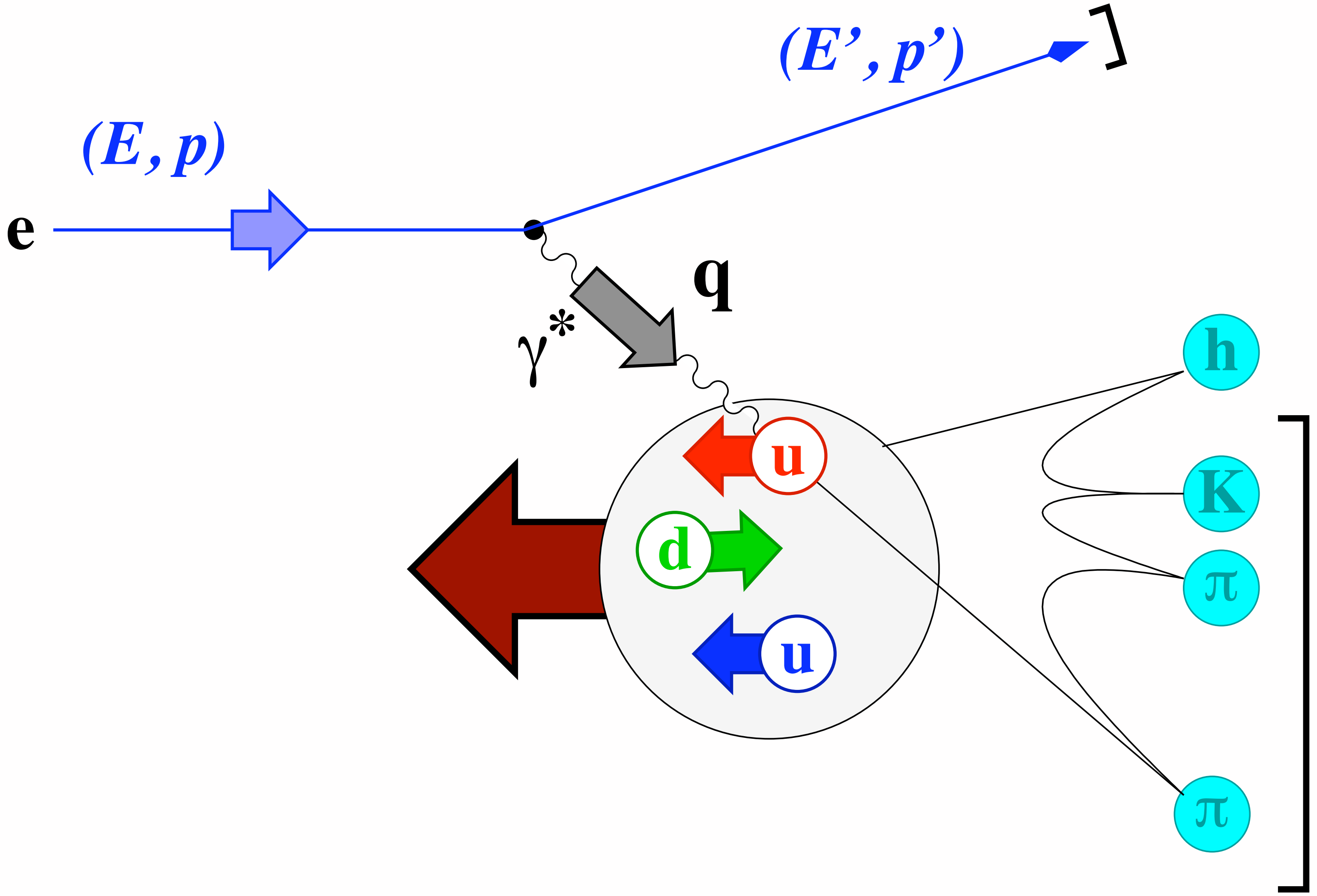
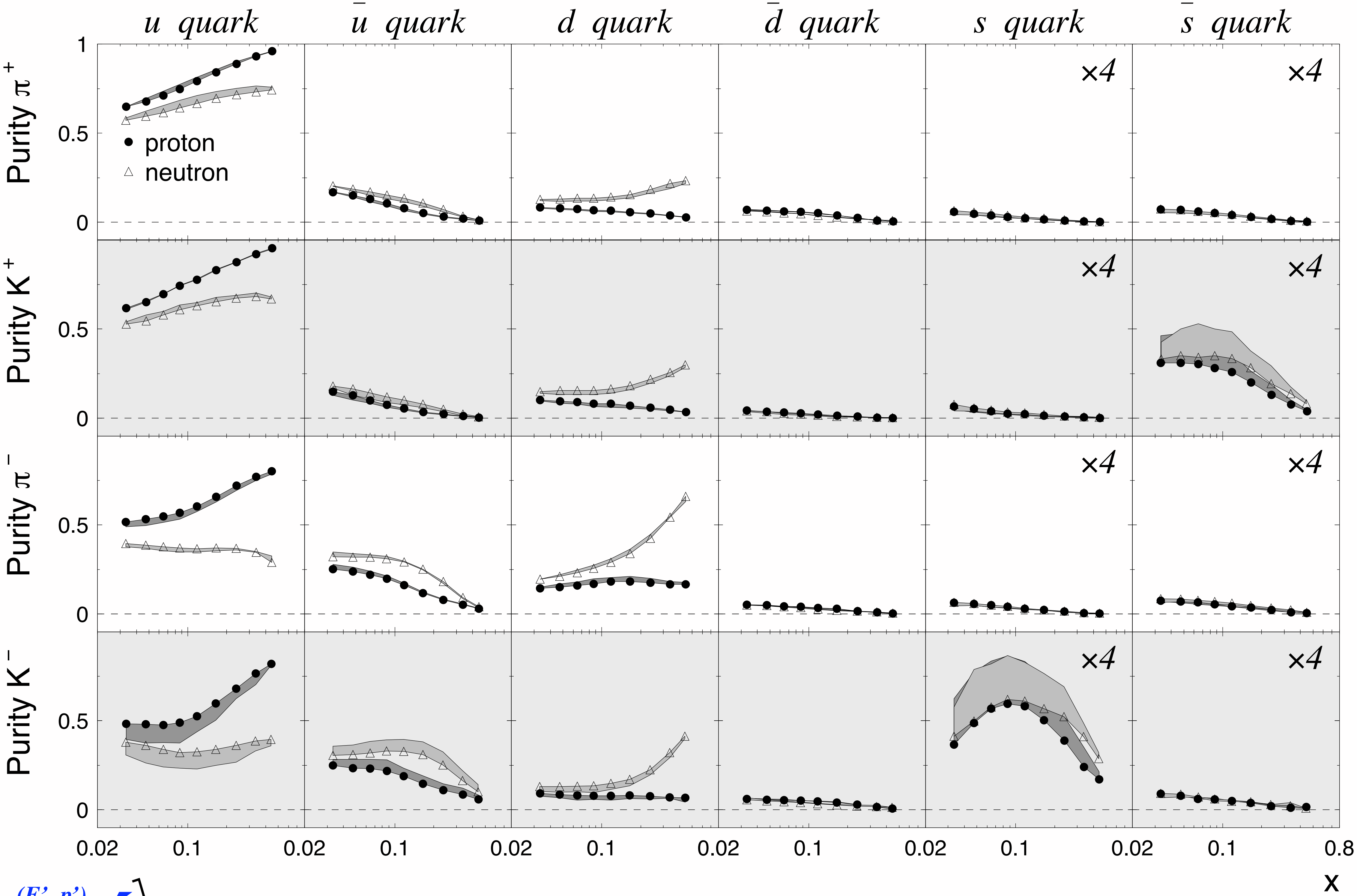
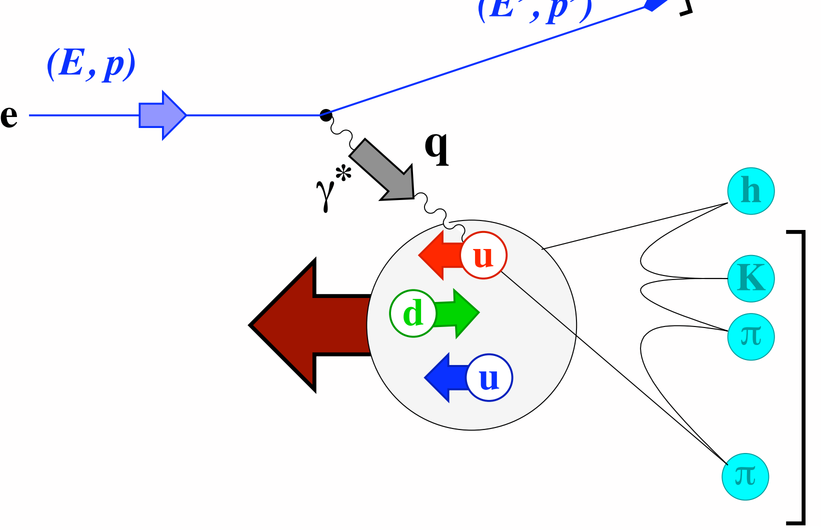
- ☑ ...

semi-inclusive DIS

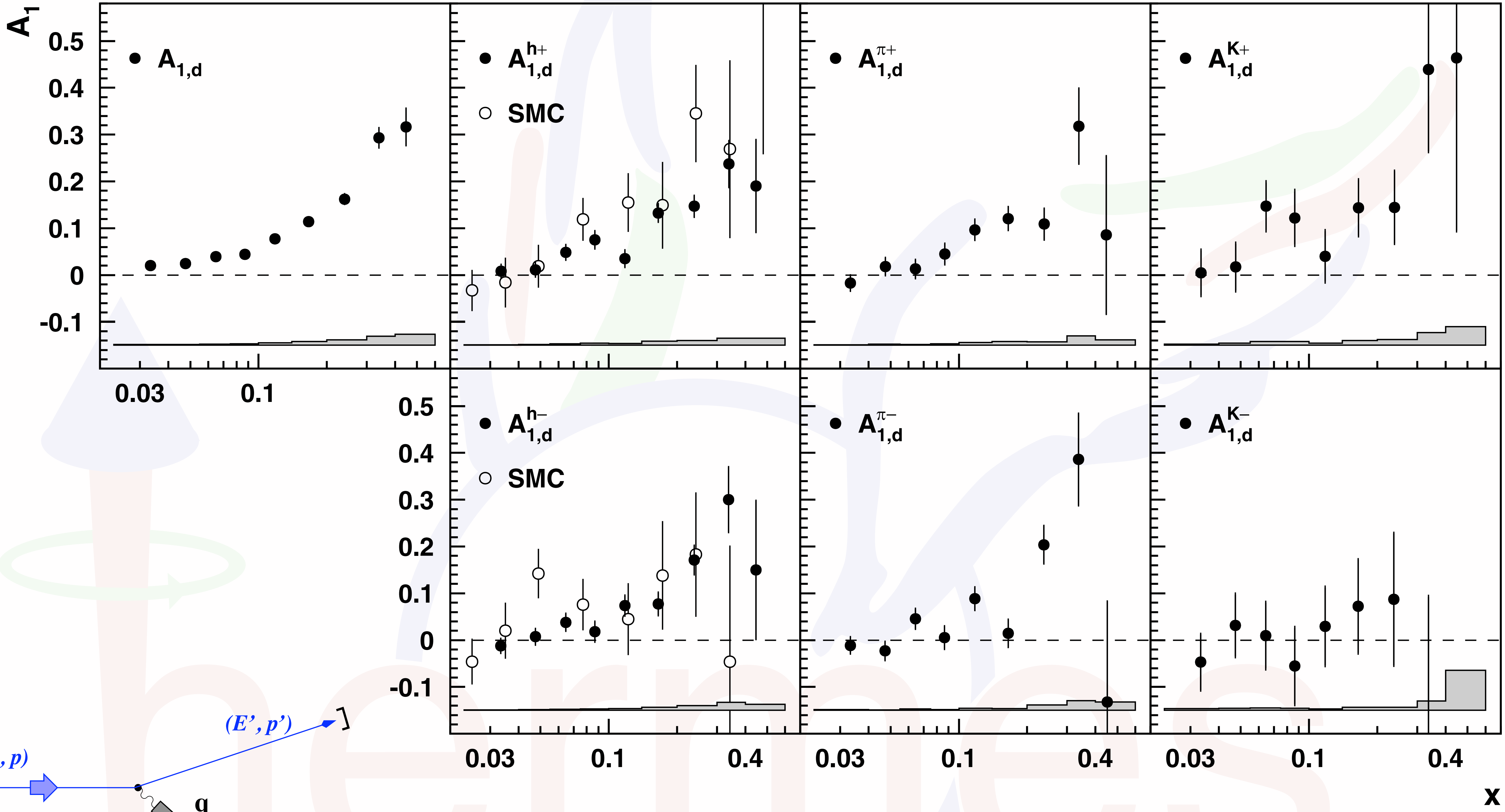


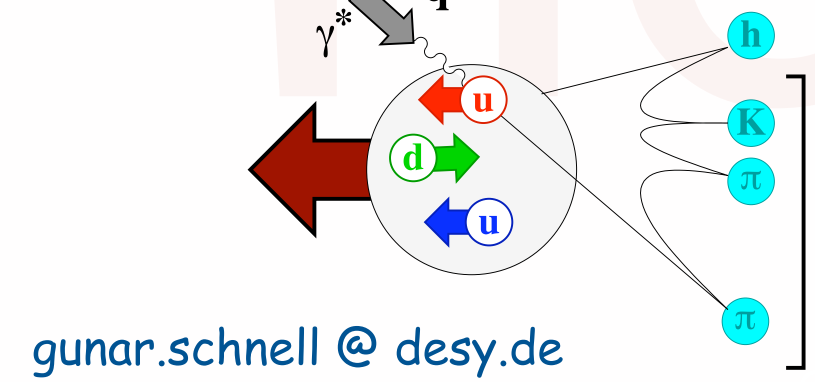




purity: $P_q^h = \dfrac{e_q f_1^q D_1^{q\rightarrow h}}{\sum_i e_i f_1^i D_1^{i\rightarrow h}}$

semi-inclusive DIS asymmetries





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

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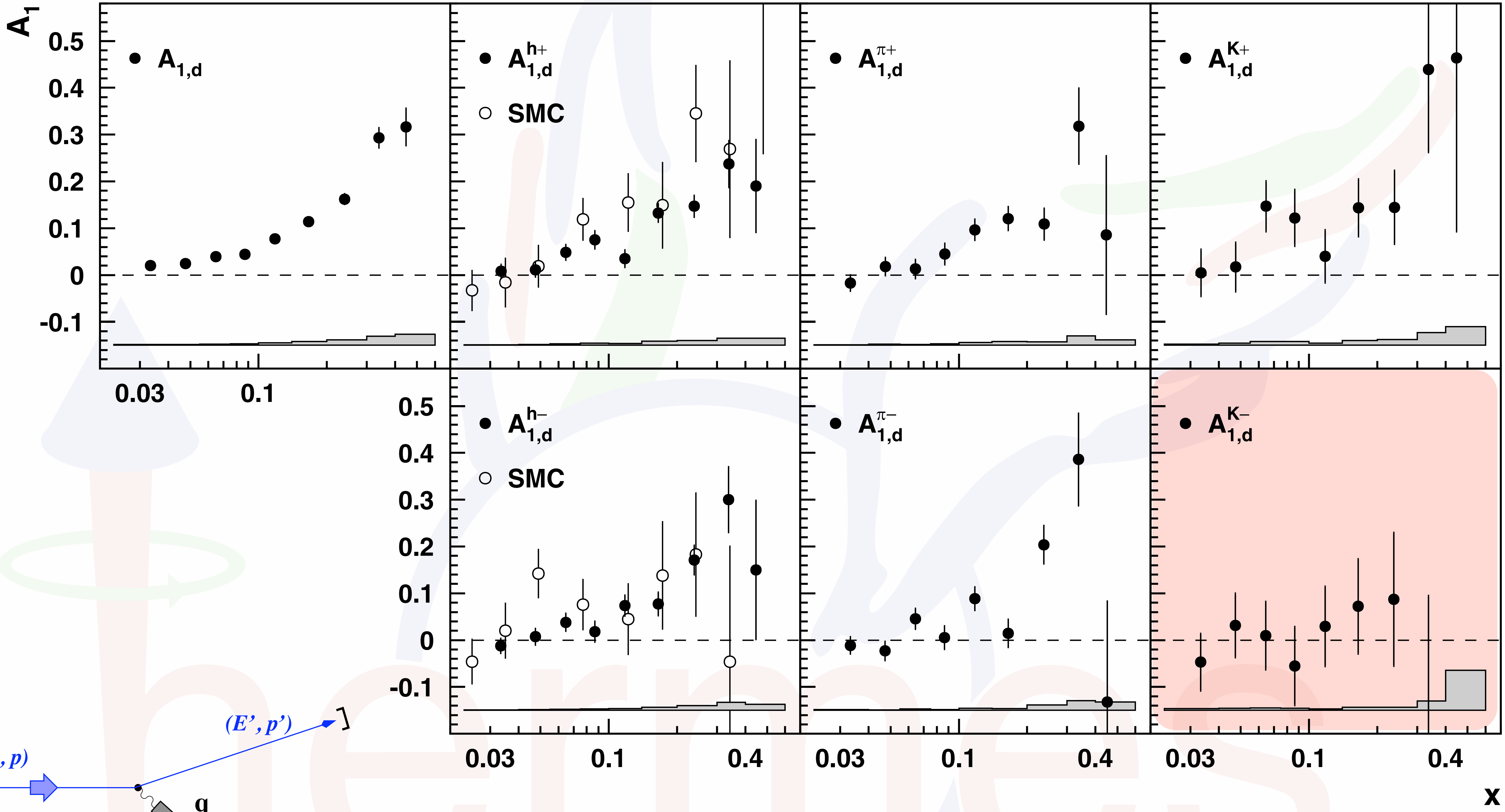

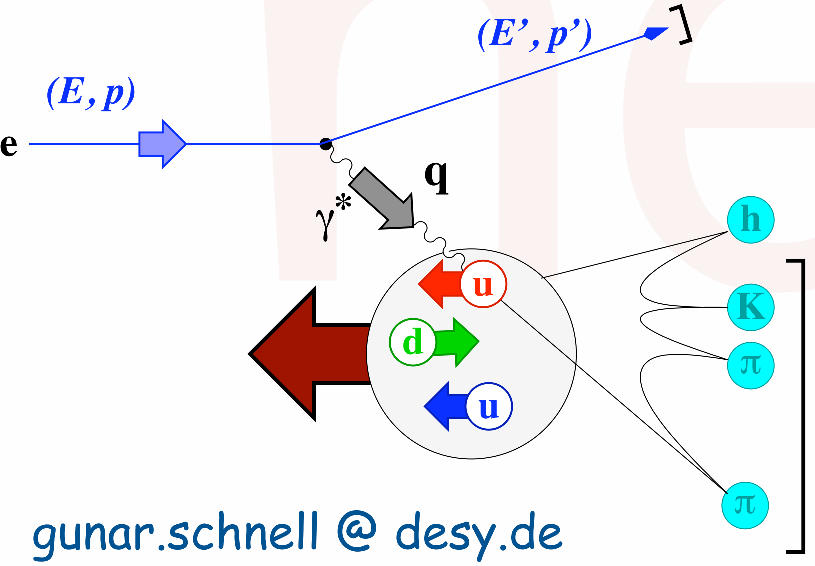

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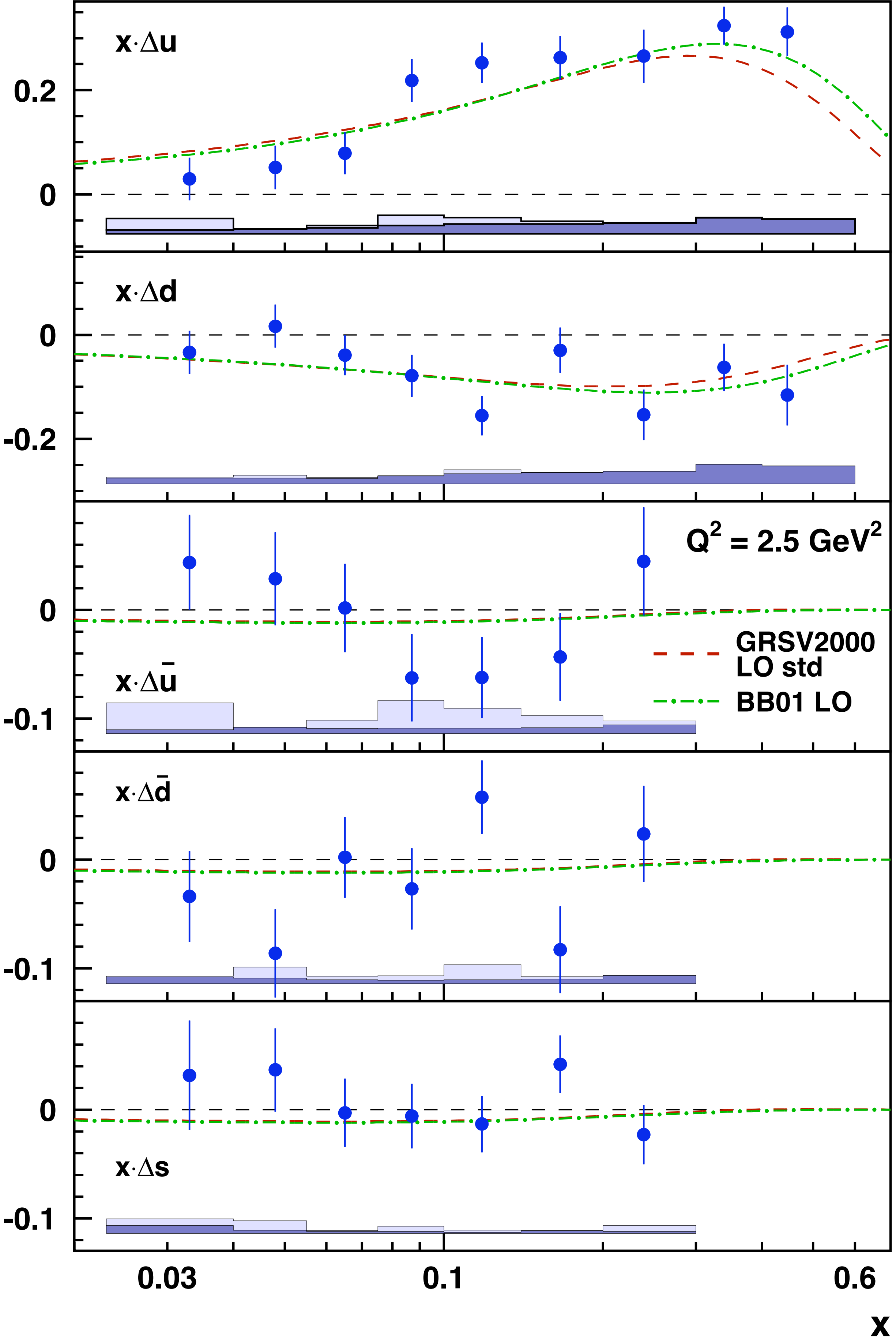
helicity density - flavor separation

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



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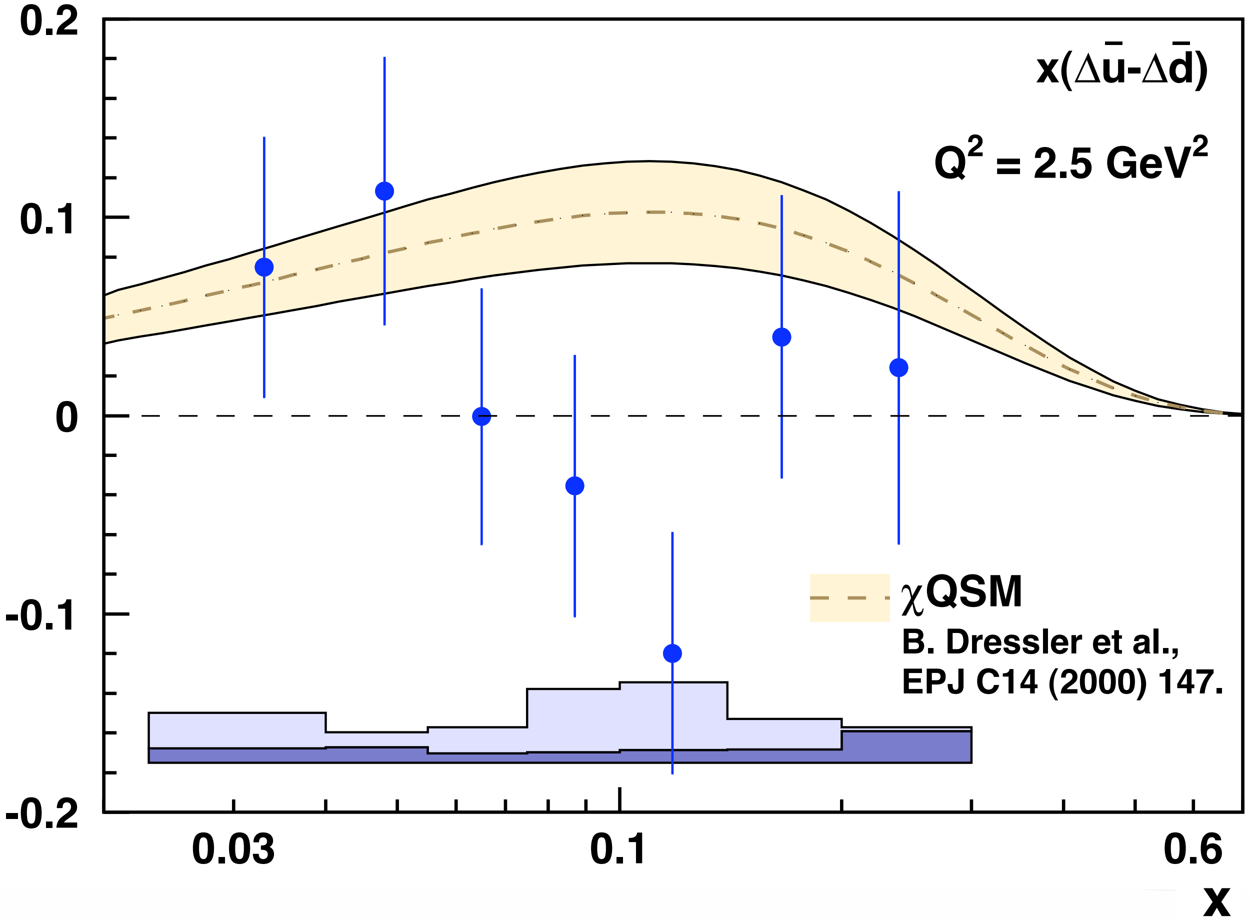
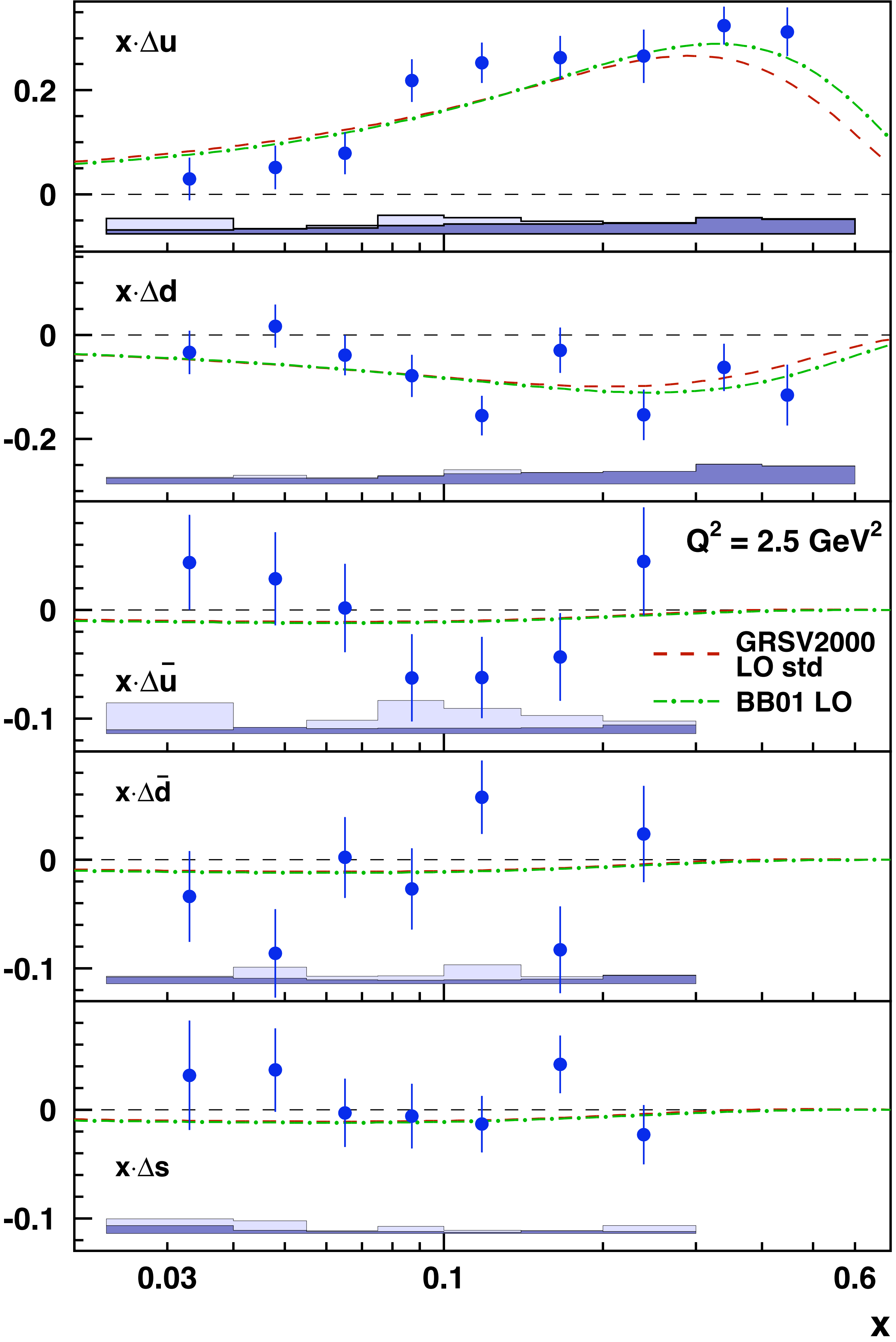
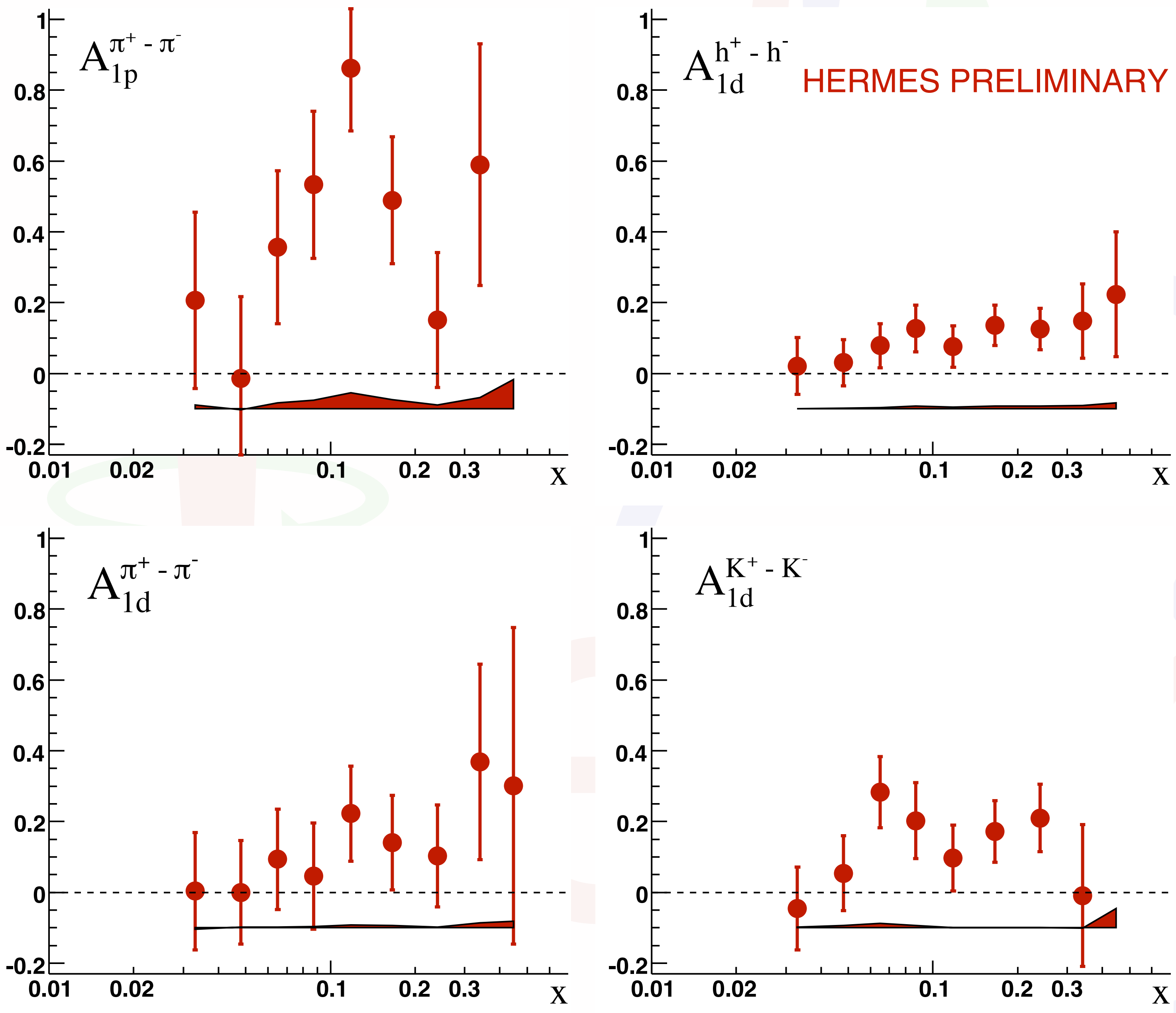




helicity density - valence quarks

$$A_1^{h^+-h^-} = \frac{(d\sigma_{h^+}^{\overset{\rightarrow}{\Leftarrow}} - d\sigma_{h^-}^{\overset{\rightarrow}{\Leftarrow}}) - (d\sigma_{h^+}^{\overset{\rightarrow}{\Rightarrow}} - d\sigma_{h^-}^{\overset{\rightarrow}{\Rightarrow}})}{(d\sigma_{h^+}^{\overset{\rightarrow}{\Leftarrow}} - d\sigma_{h^-}^{\overset{\rightarrow}{\Leftarrow}}) + (d\sigma_{h^+}^{\overset{\rightarrow}{\Rightarrow}} - d\sigma_{h^-}^{\overset{\rightarrow}{\Rightarrow}})}$$

- charge-difference double-spin asymmetries



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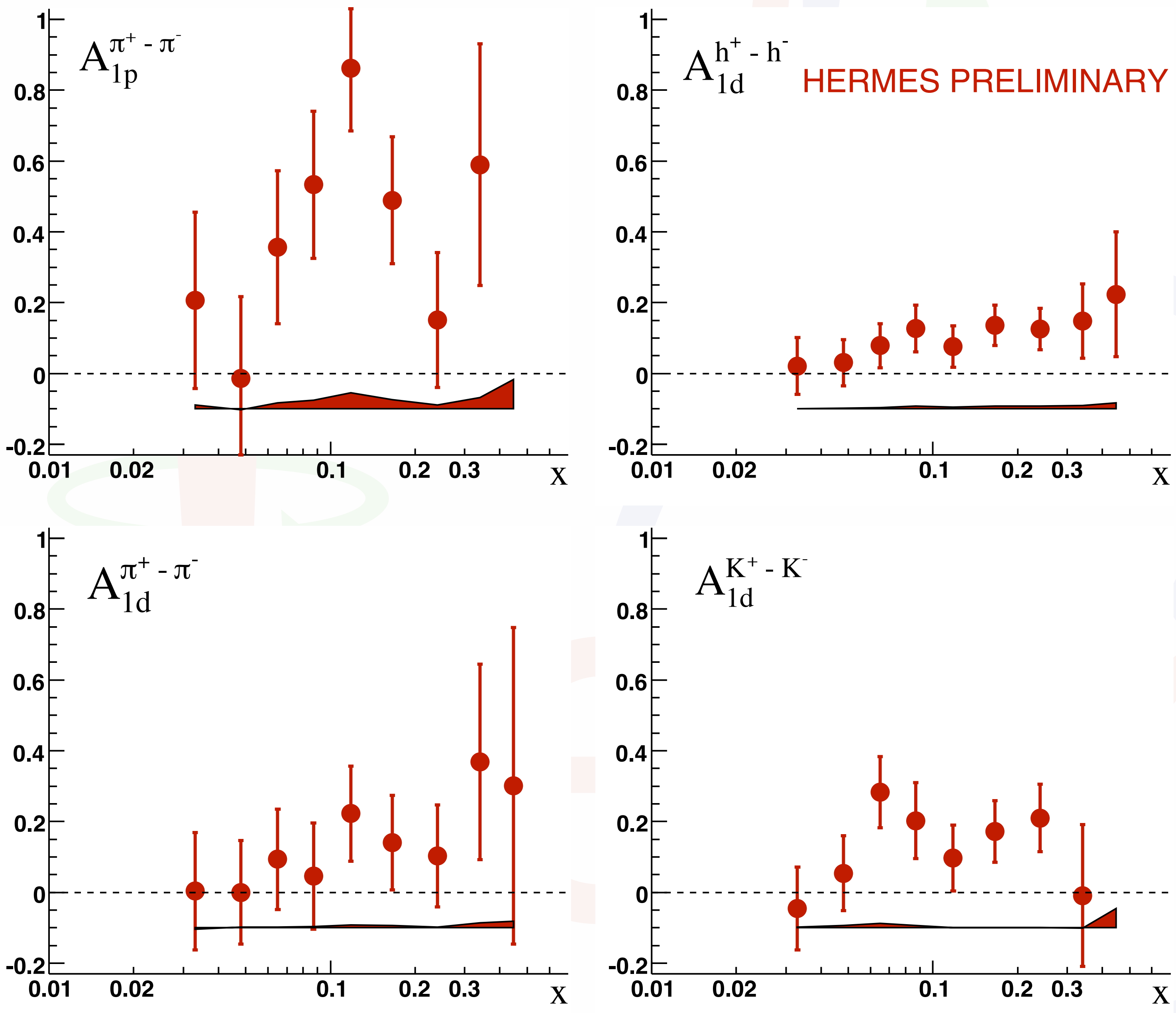

- charge-difference double-spin asymmetries
- use charge-conjugation symmetry to extract, at LO(!), valence distributions

$$A_{1p}^{h^+-h^-} \cong \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}$$

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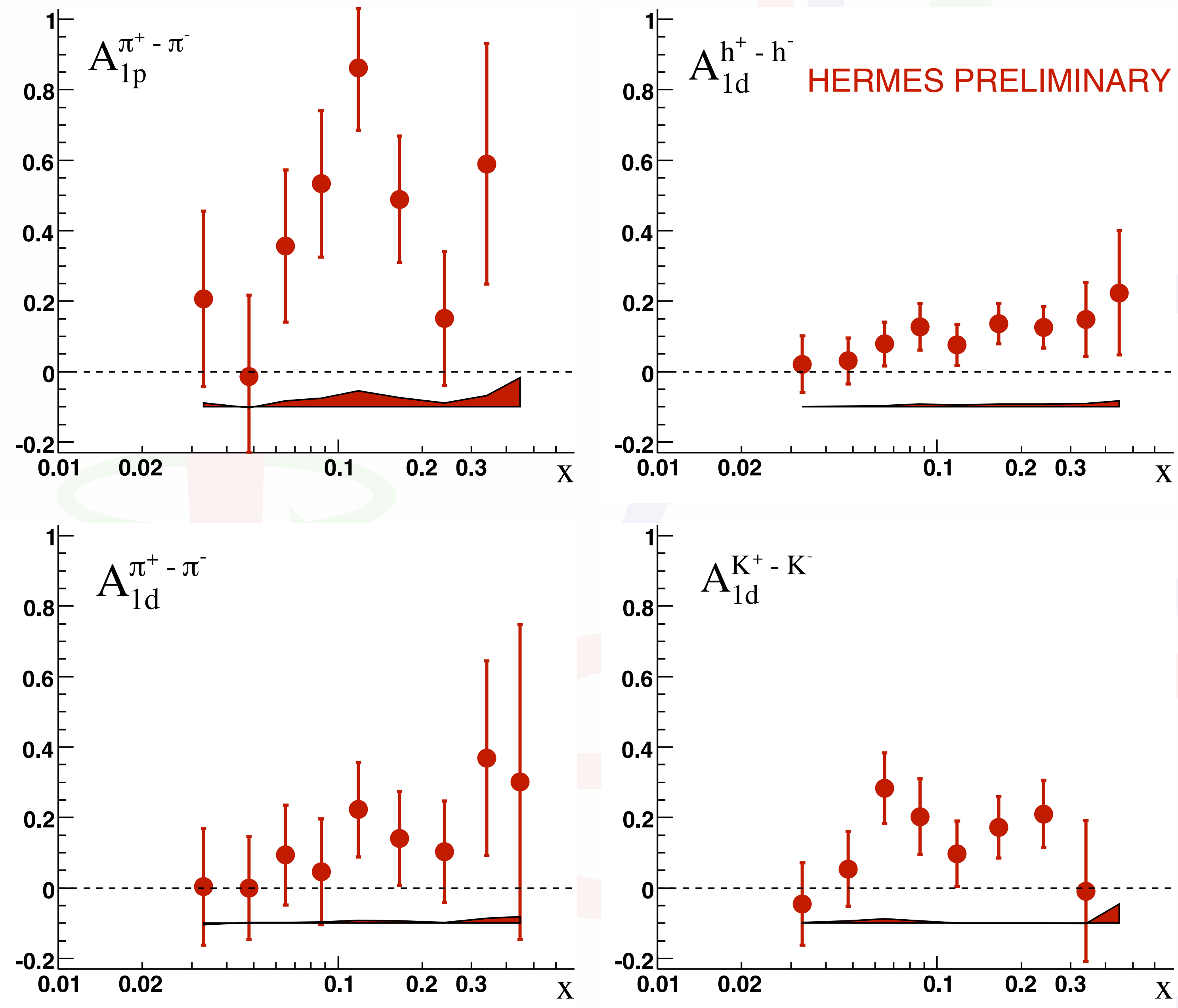
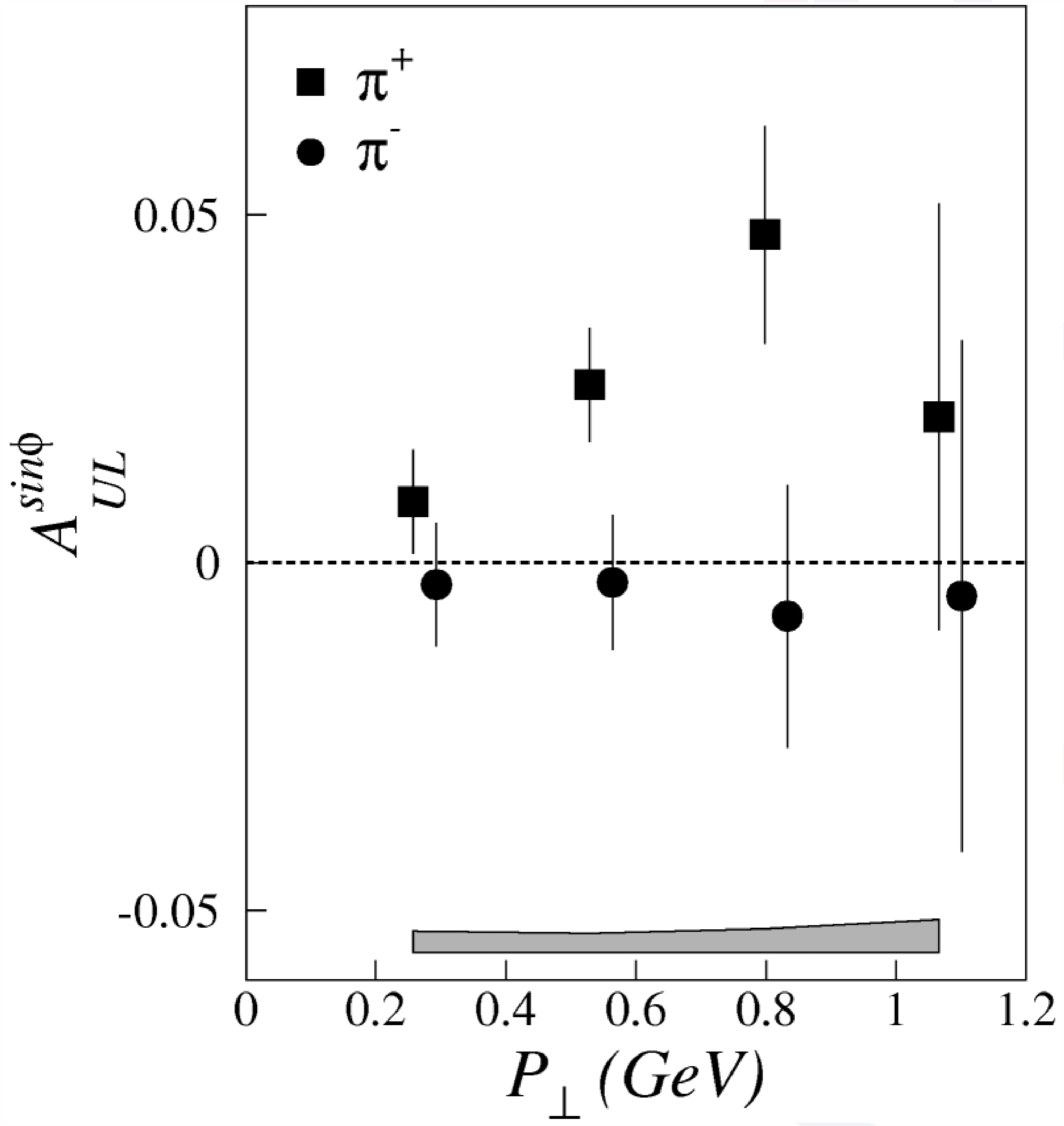


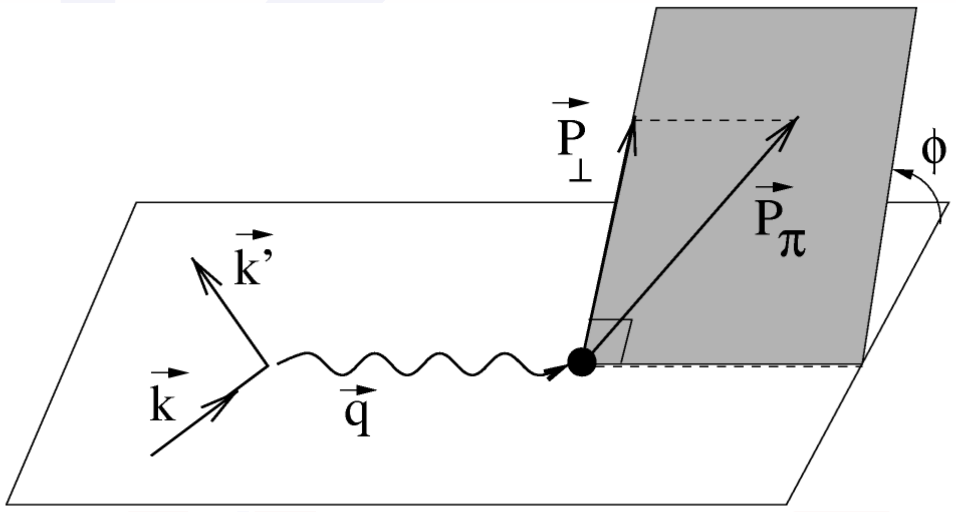
☛ P. Kravchenko

... 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

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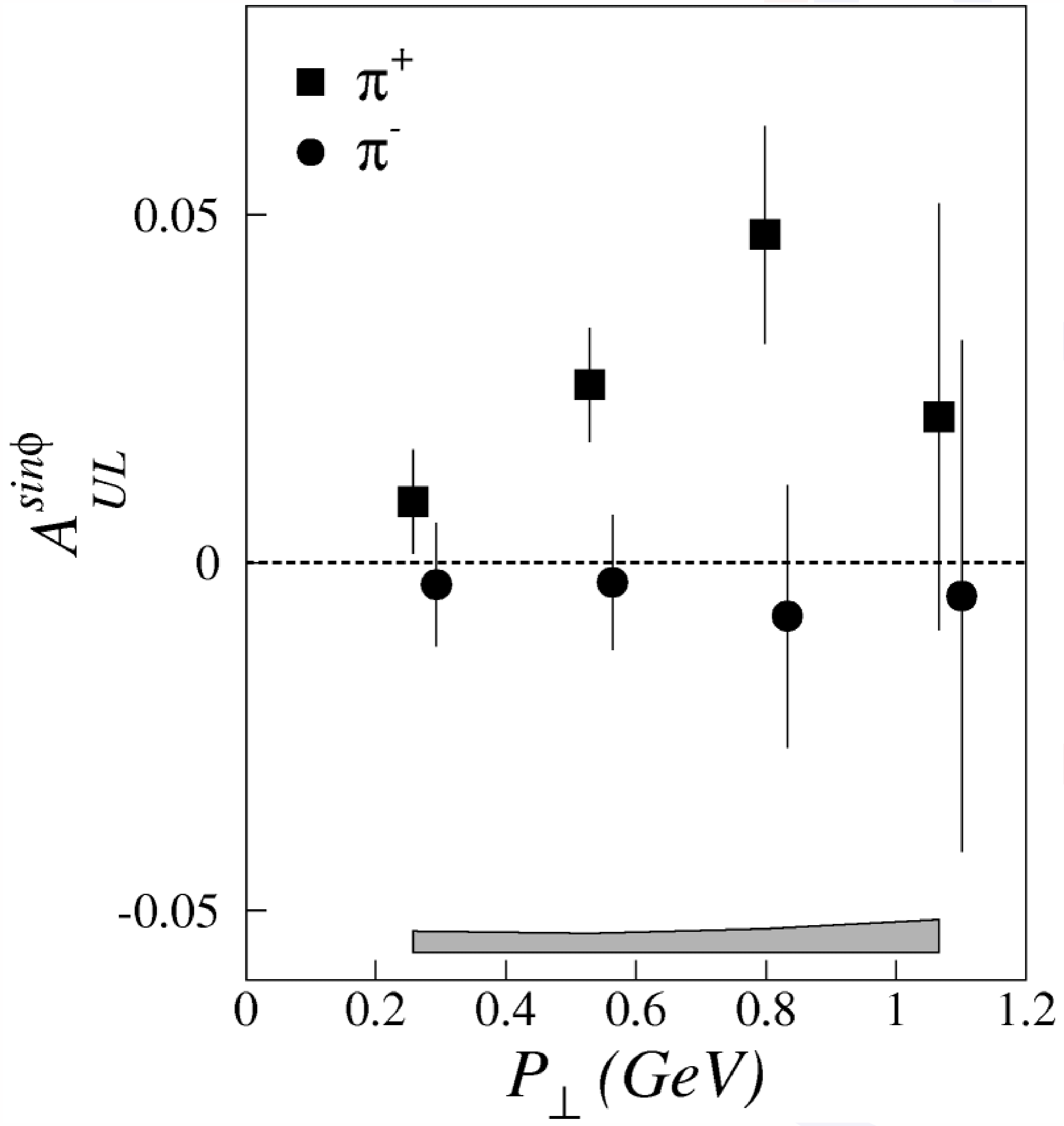

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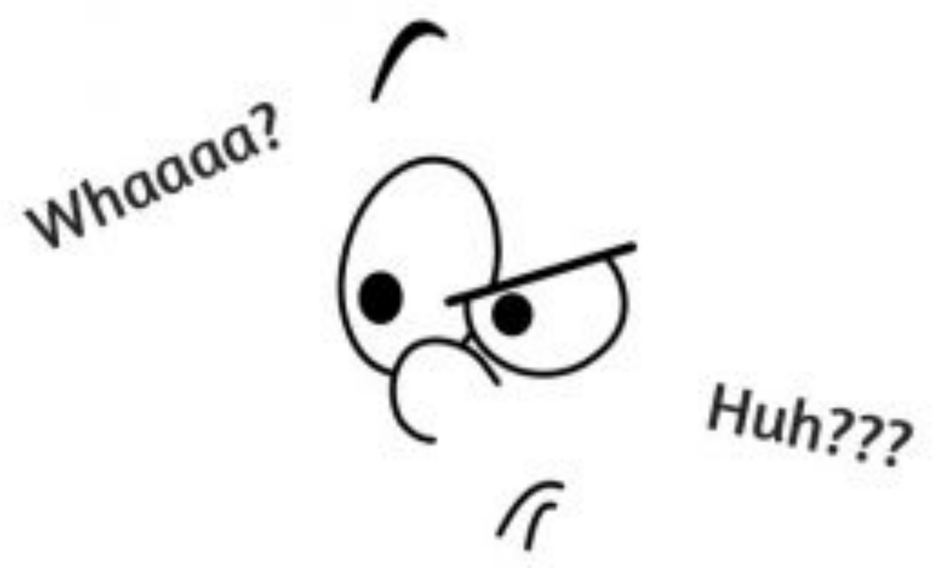

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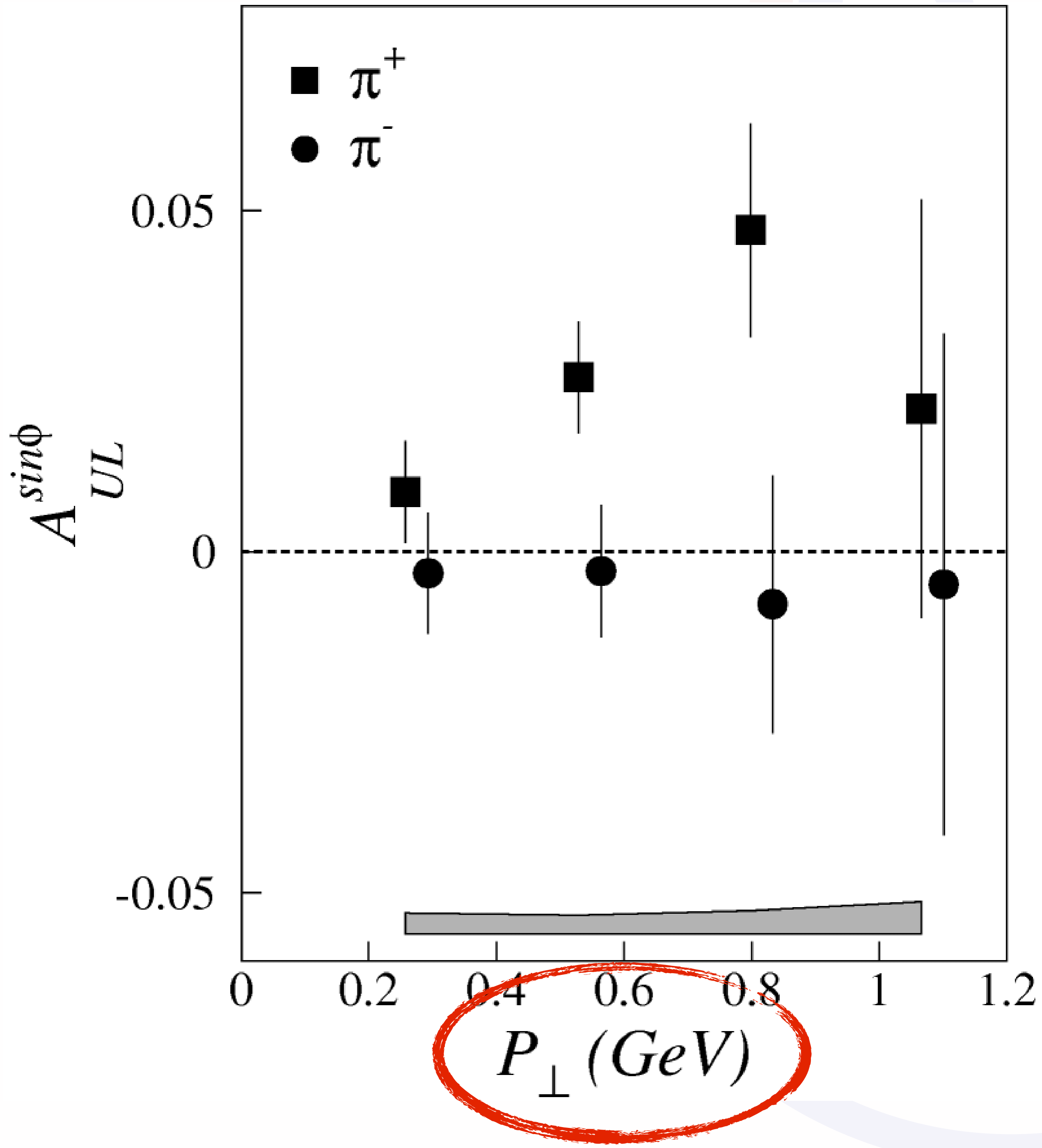

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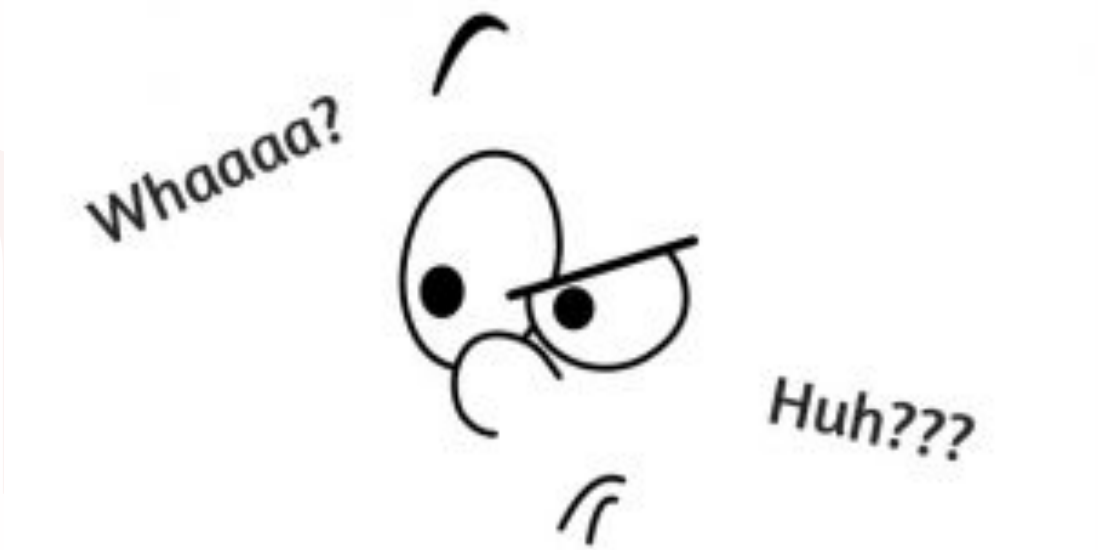

… remembering puzzling asymmetries

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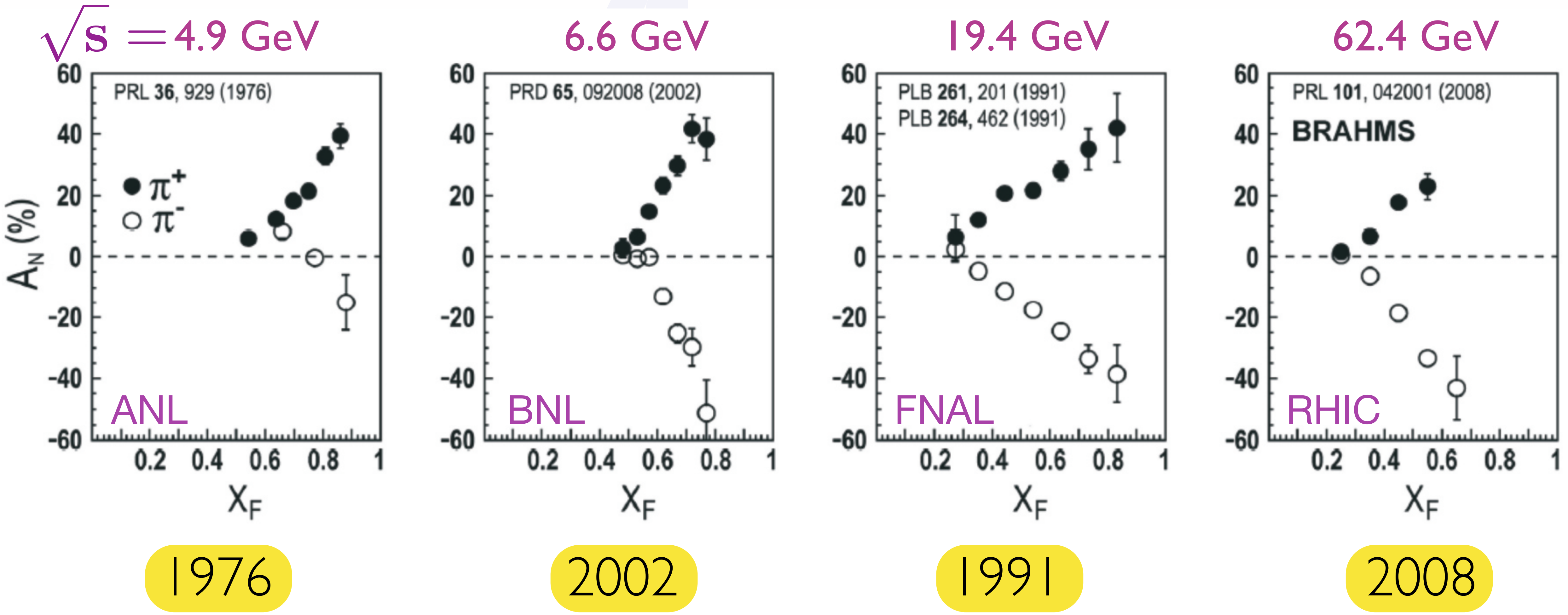
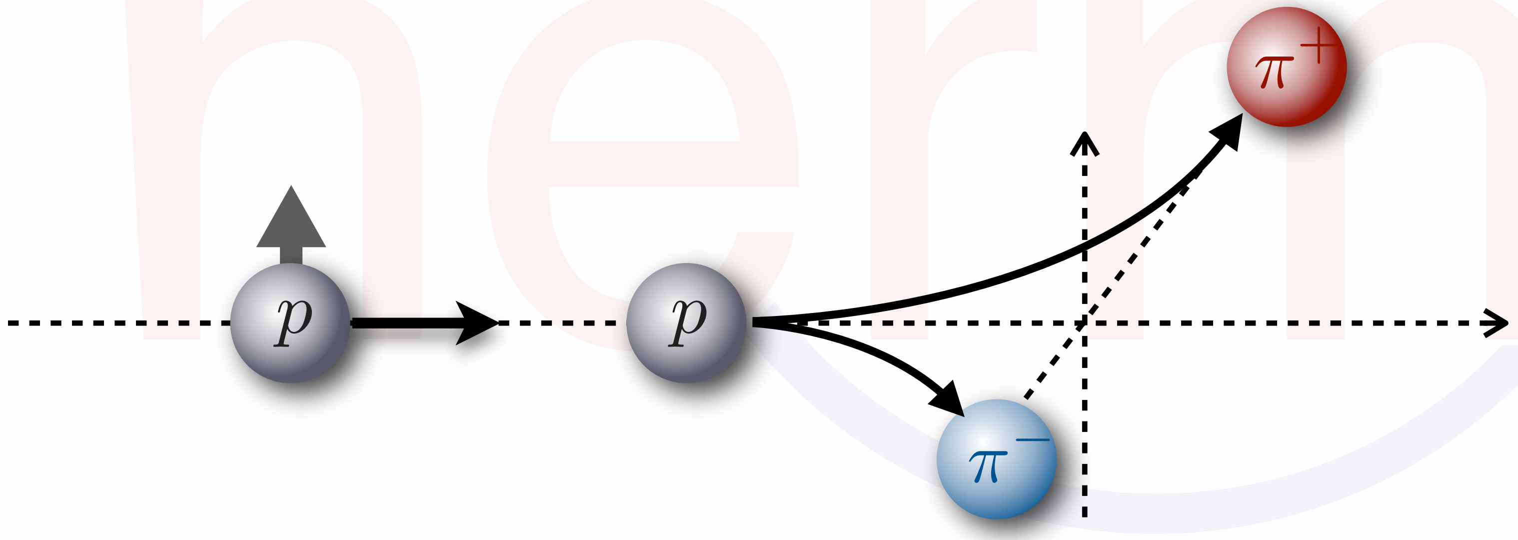
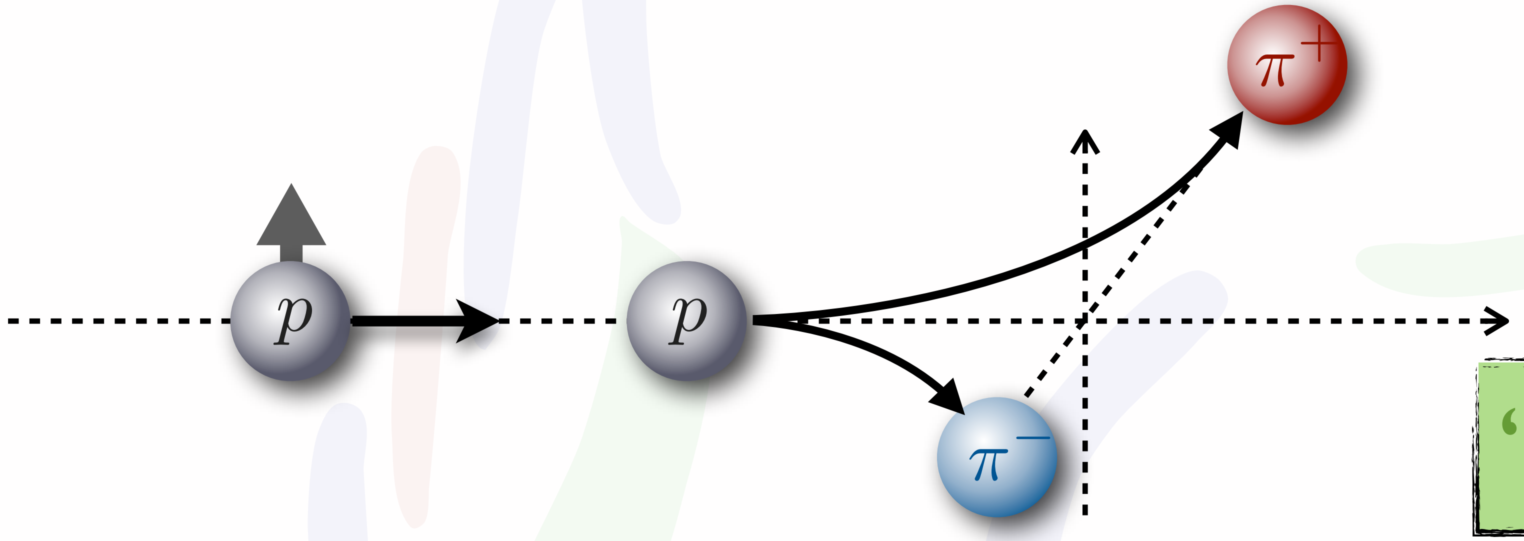




large left-right asymmetries that persist even to RHIC energies

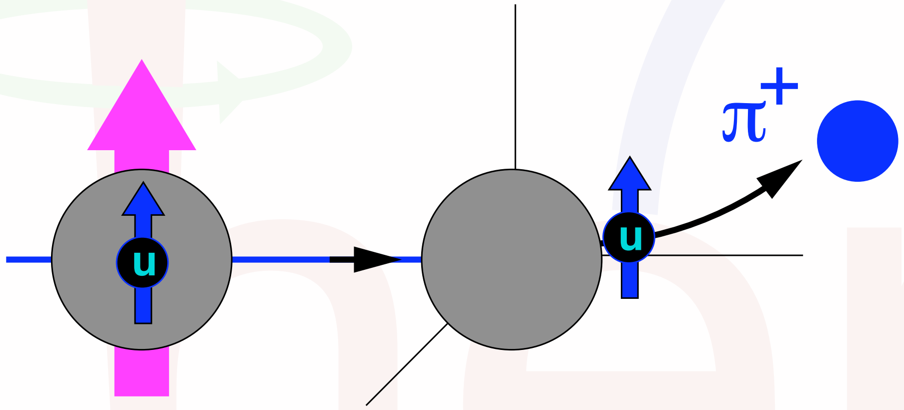
what's the origin of these SSA?



$S\cdot(P\times P_h)$

"naive T-odd"

- fragmentation effect?



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

- correlating transverse quark spin with transverse momentum

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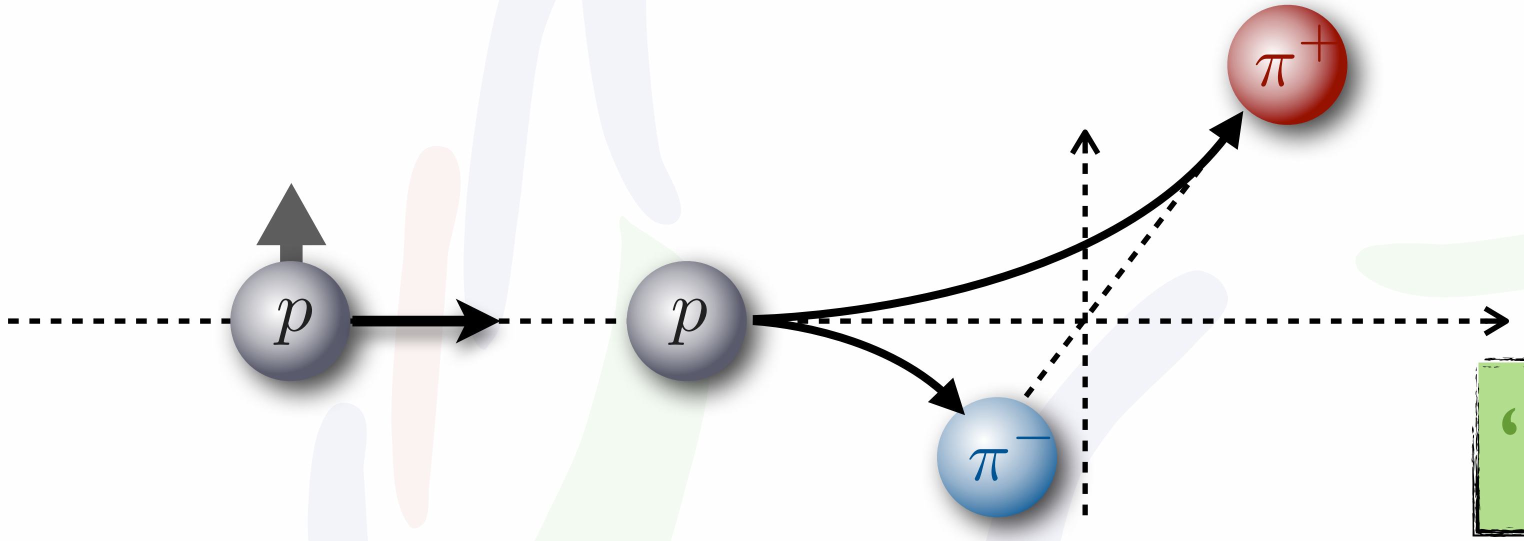

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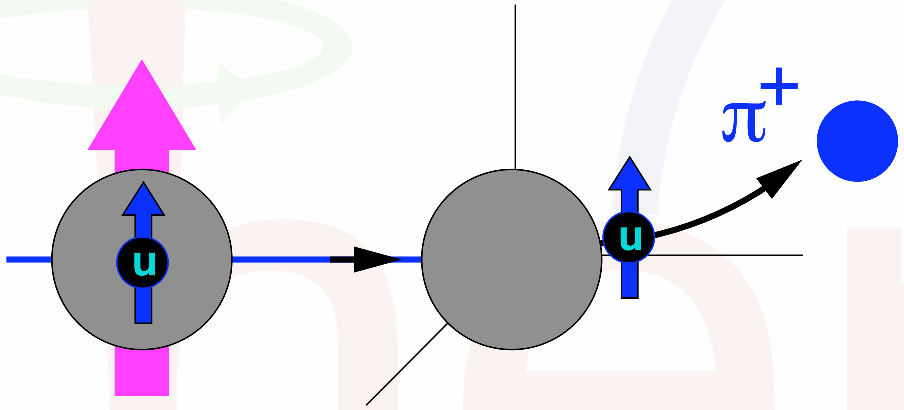
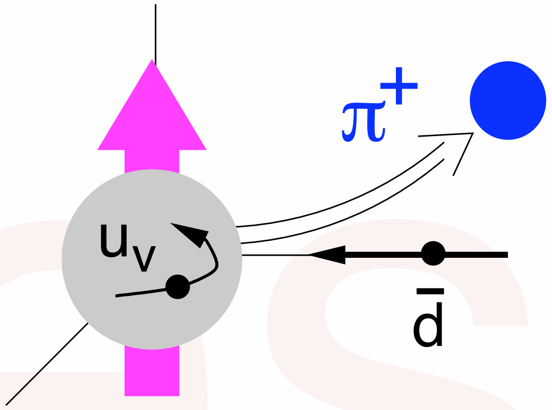


[J.C. Collins, NPB 396 (1993) 161]

- 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 introduces 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 -> BM distrib.
- 2002: Brodsky, Hwang & Schmidt: resurrection of Sivers idea

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

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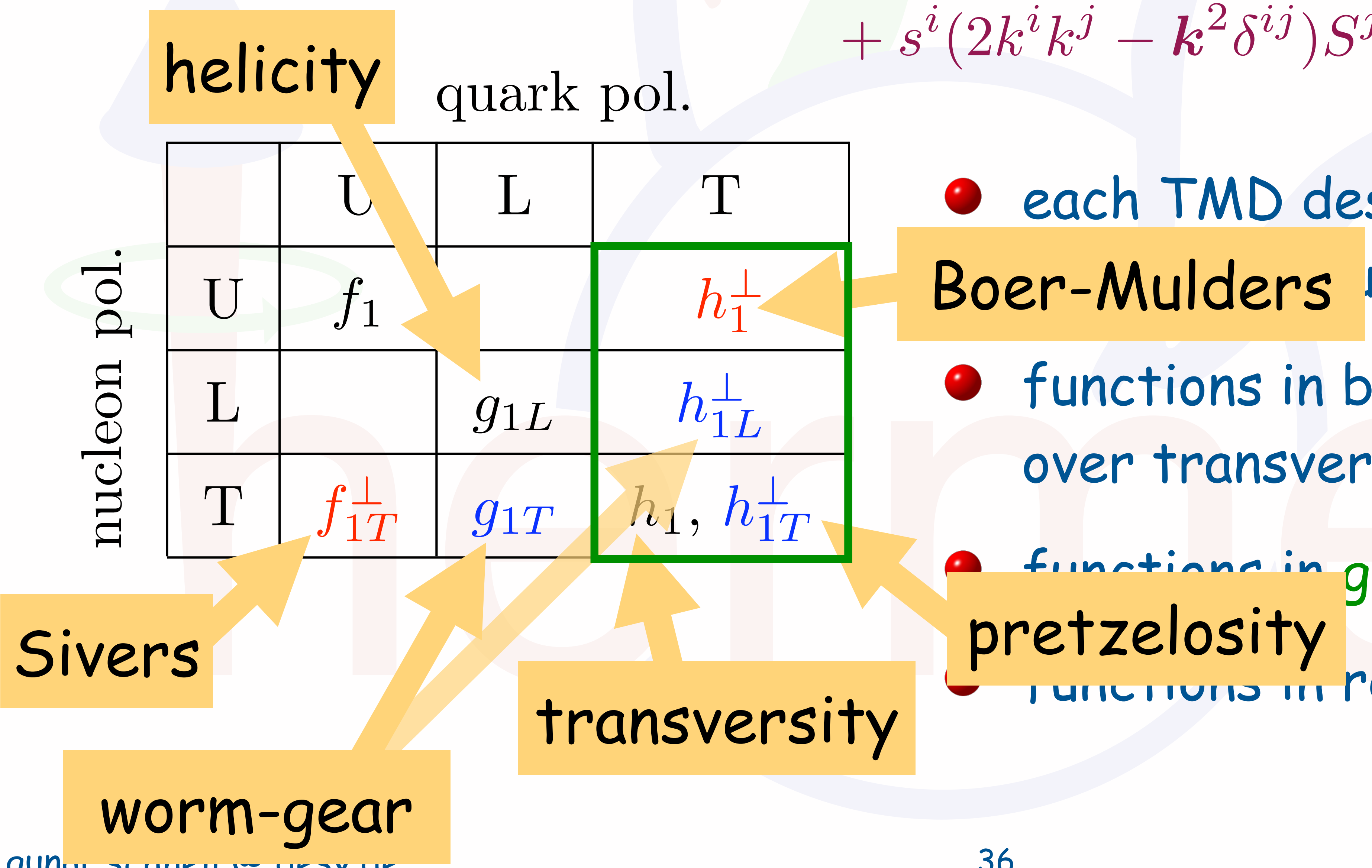

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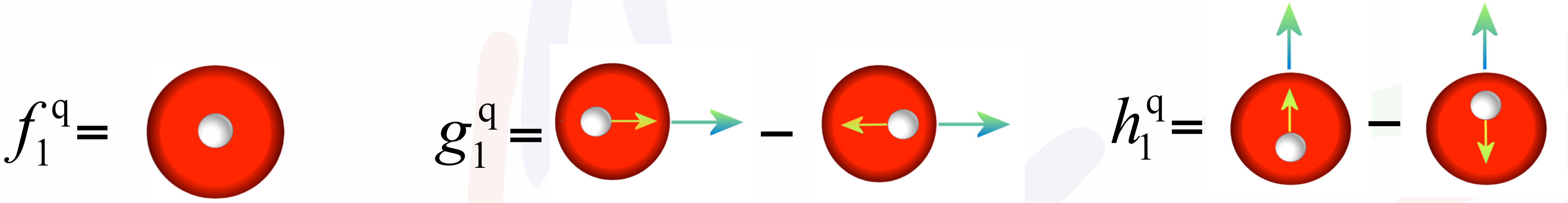
☛ A. Bressan

the “trouble” with transversity

chiral-odd transversity involves quark helicity flip



$f_1^q =$ $\quad g_1^q =$ $-$ $\quad h_1^q =$ $-$

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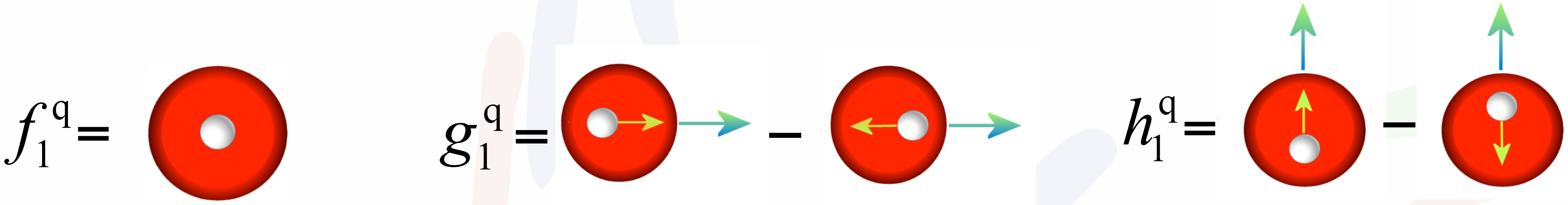

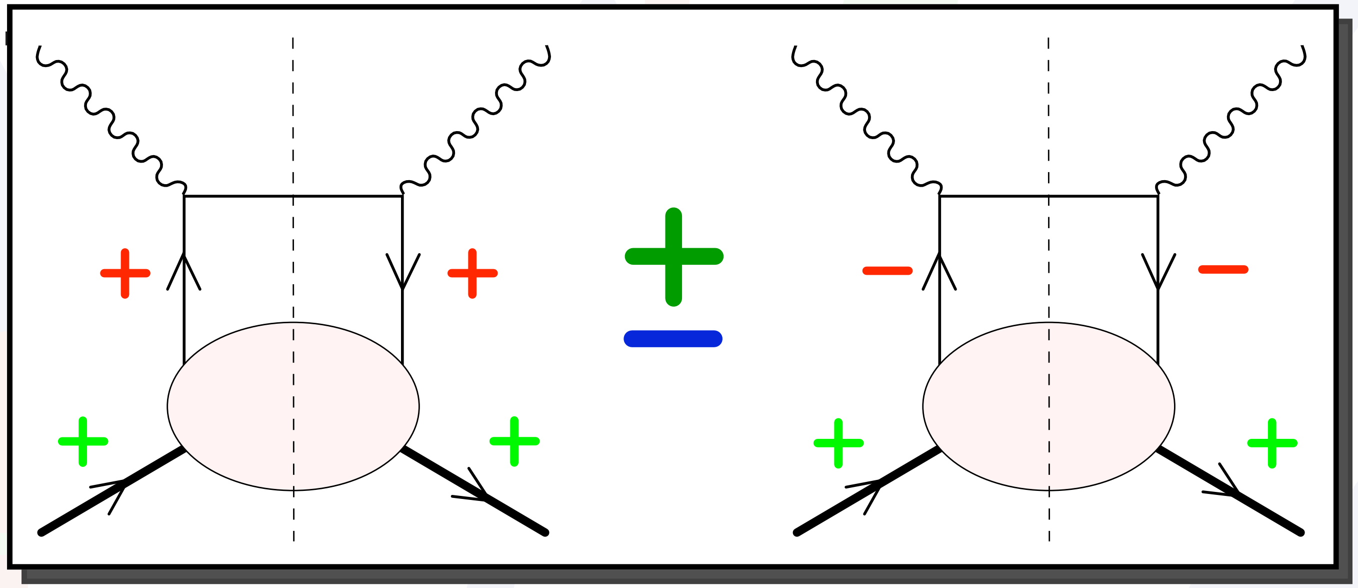

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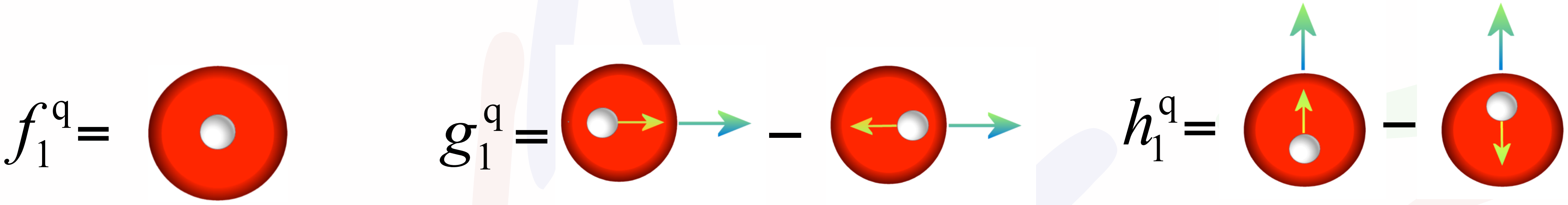

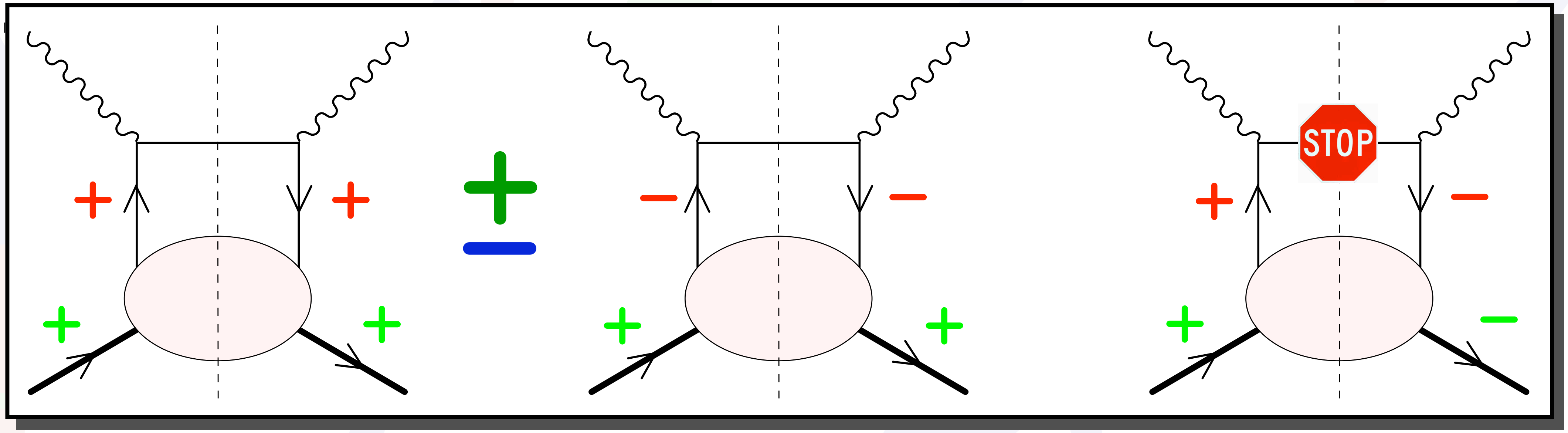

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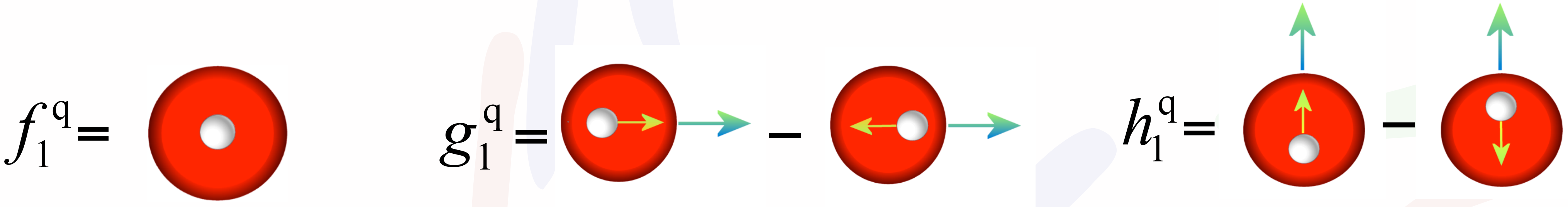

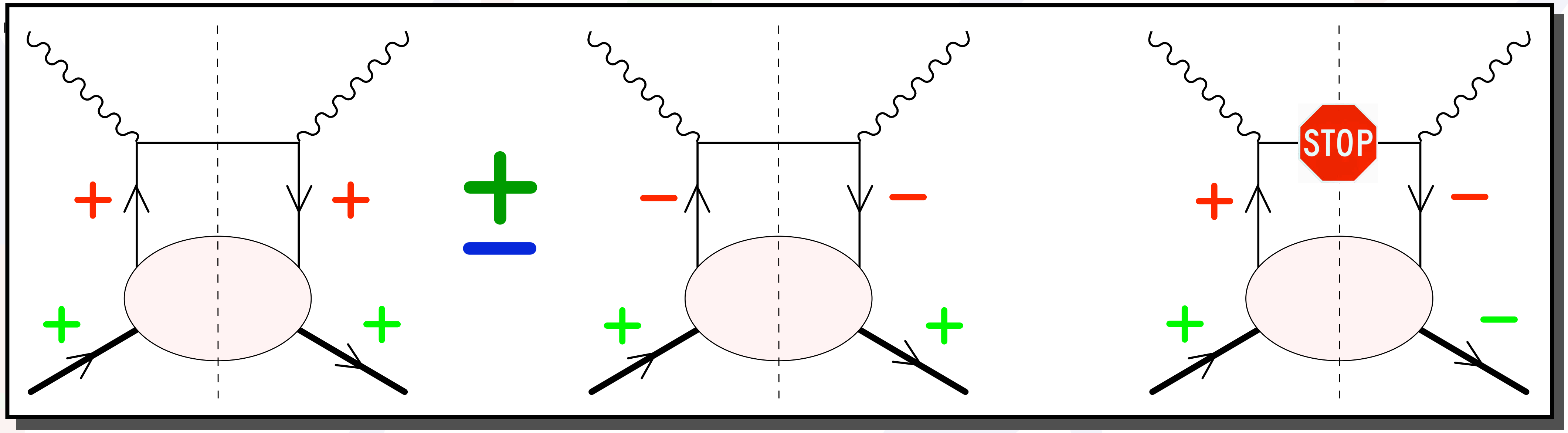

need to couple to chiral-odd fragmentation function:

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

probing TMDs in semi-inclusive DIS

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

---

*) semi-inclusive DIS with unpolarized final state

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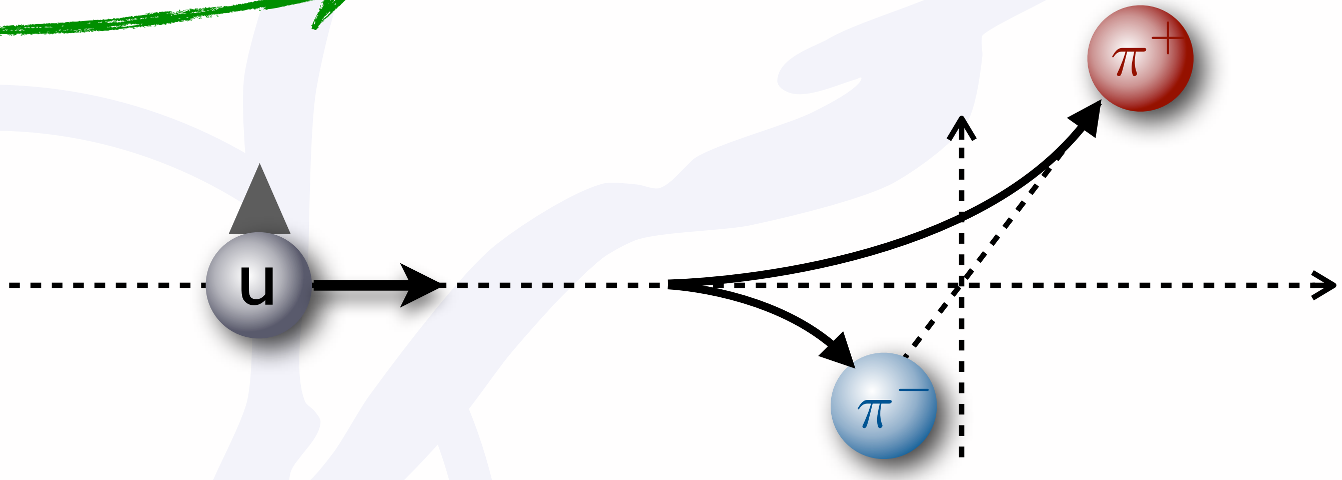

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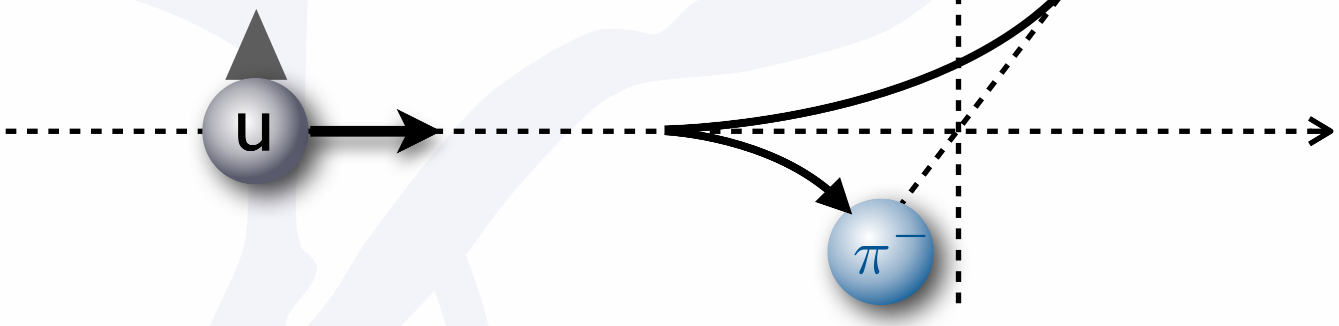

ordinary FF: $D_1^{q\rightarrow h}$

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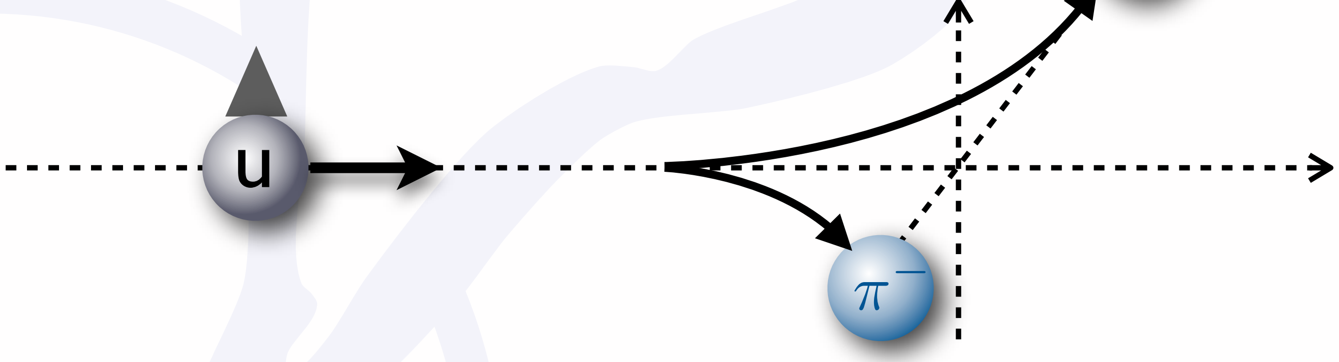


ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

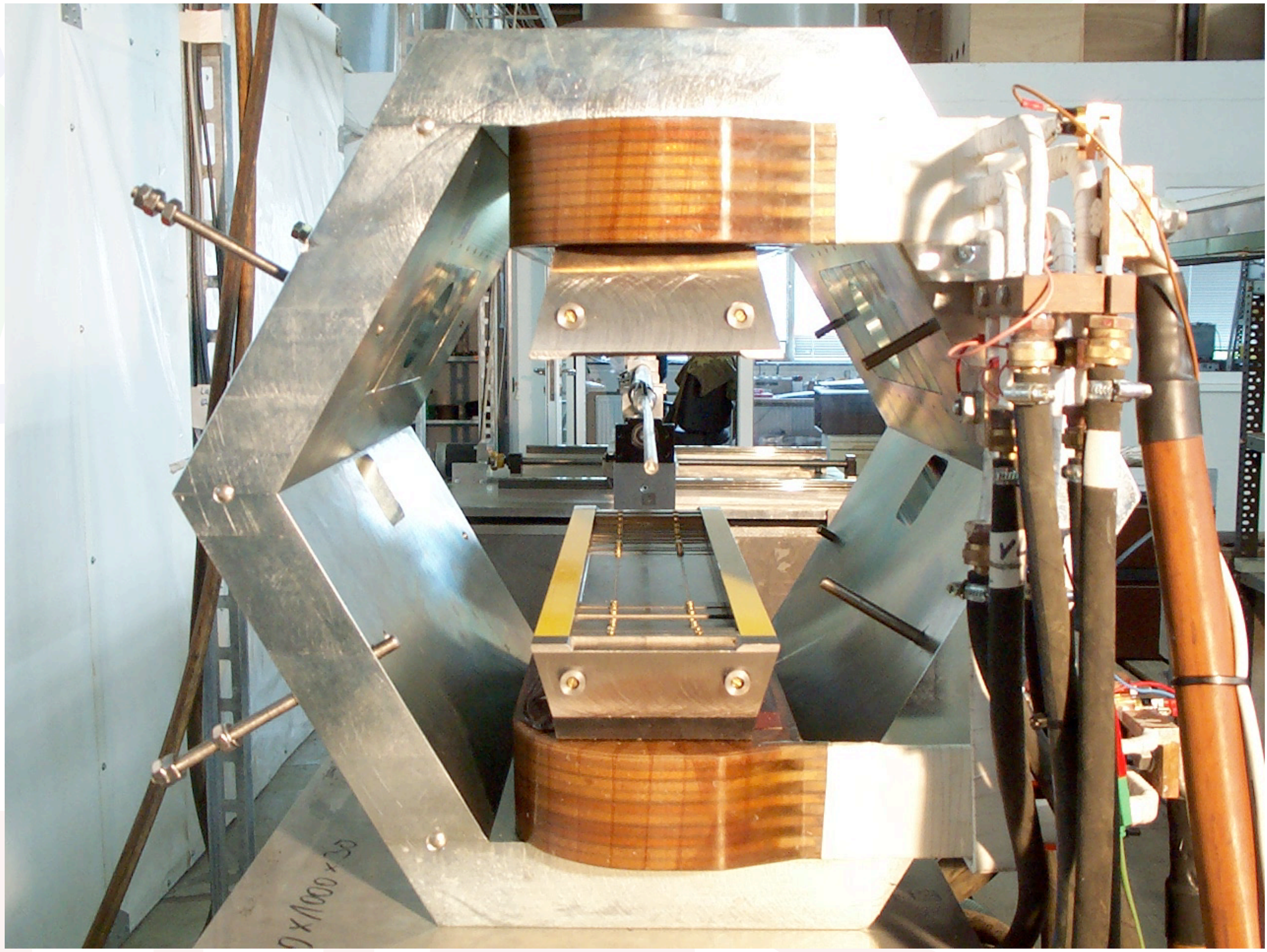
---

*) semi-inclusive DIS with unpolarized final state

HERMES: let's go transverse!

- transversely polarized protons
- $P_T \approx 74\%$
- data taking: 2002-2005
- smaller beam polarization during HERA II
  -> impact on double-spin asymmetries

transverse target magnet



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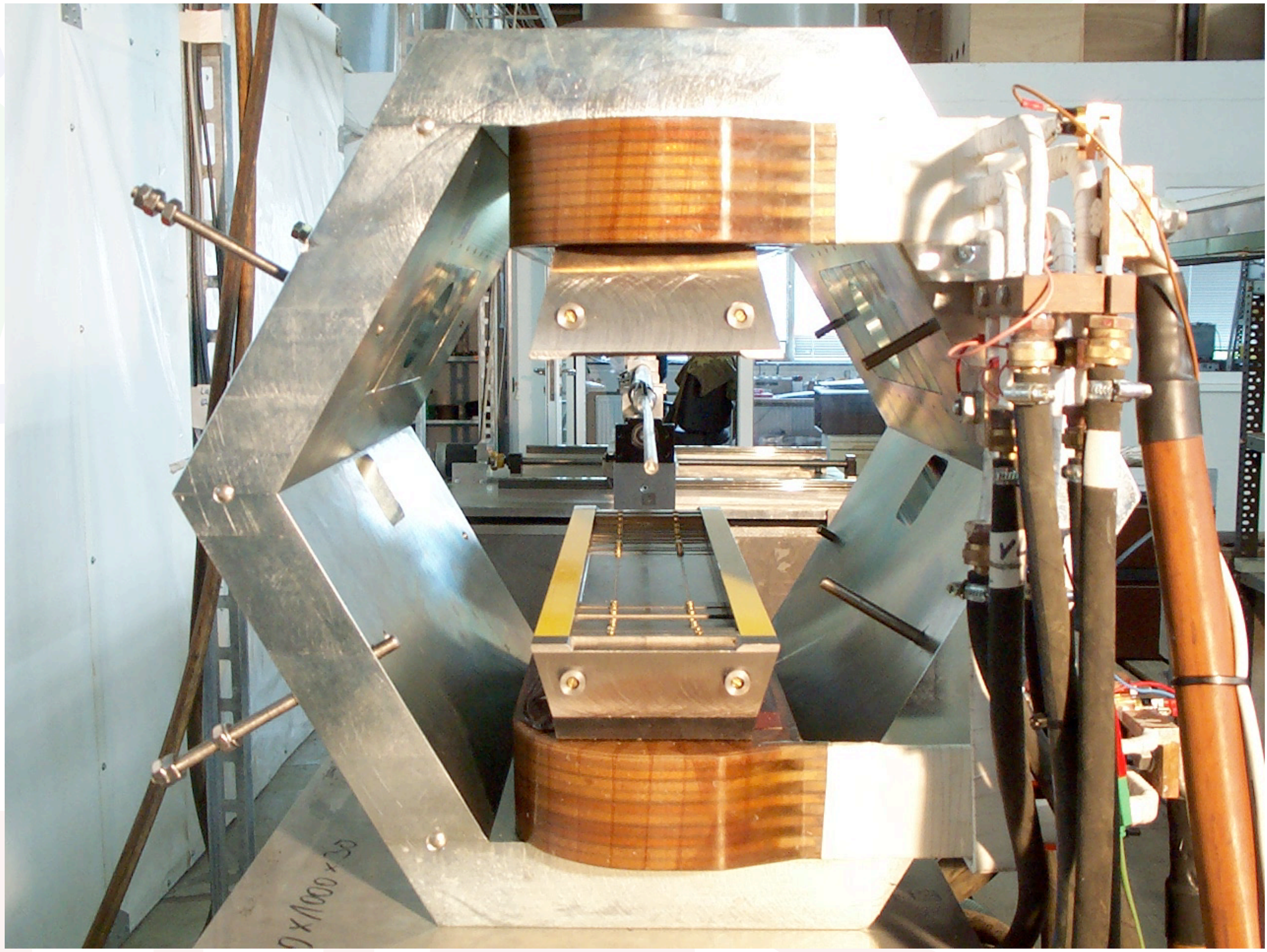

disclaimer: originally planned mainly to measure g_2

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transversely polarized quarks?

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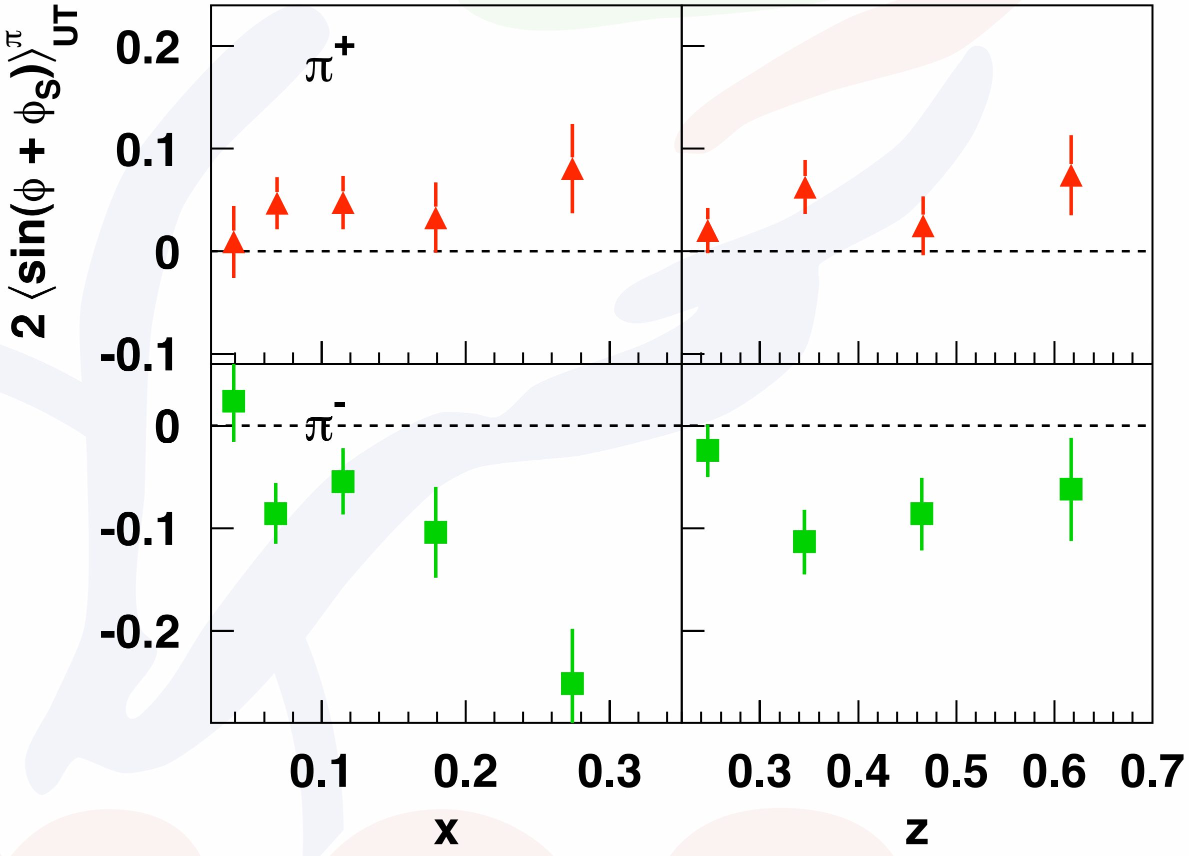
[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]

2005: First evidence from HERMES
SIDIS on proton

Non-zero transversity
Non-zero Collins function

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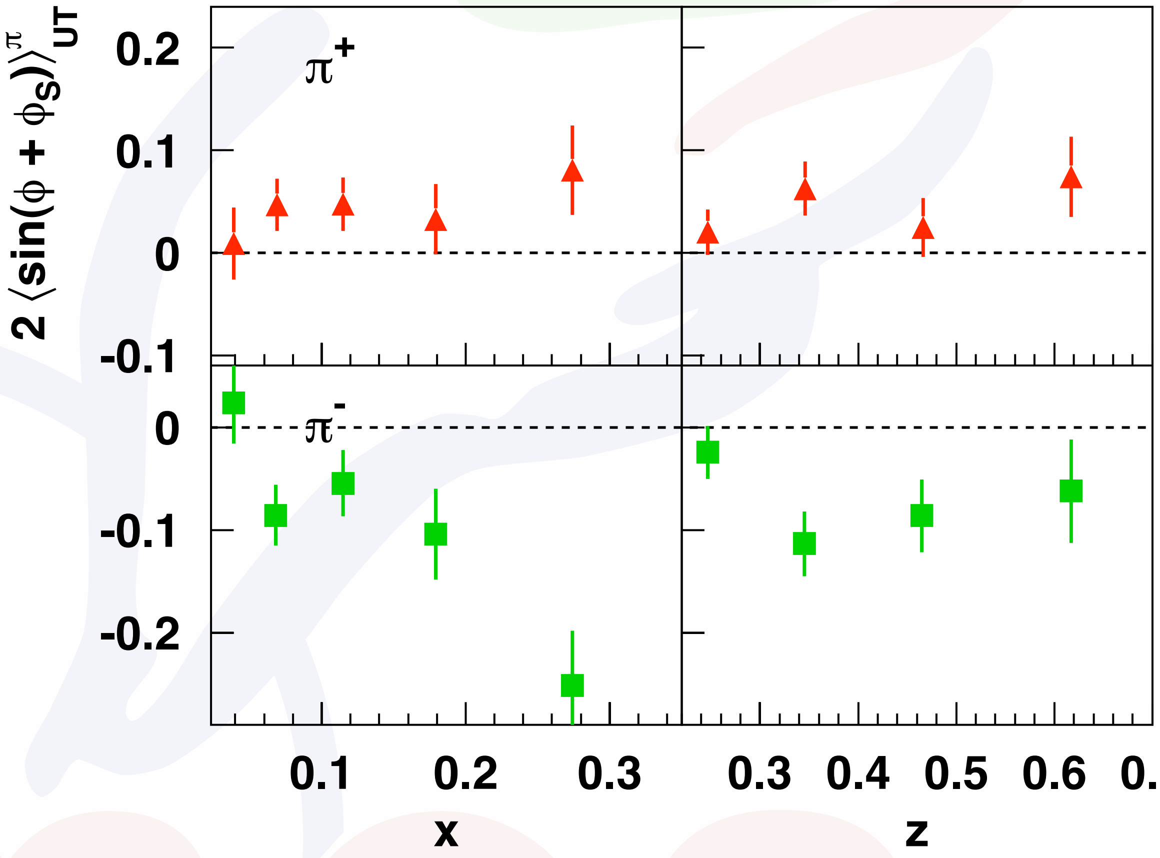

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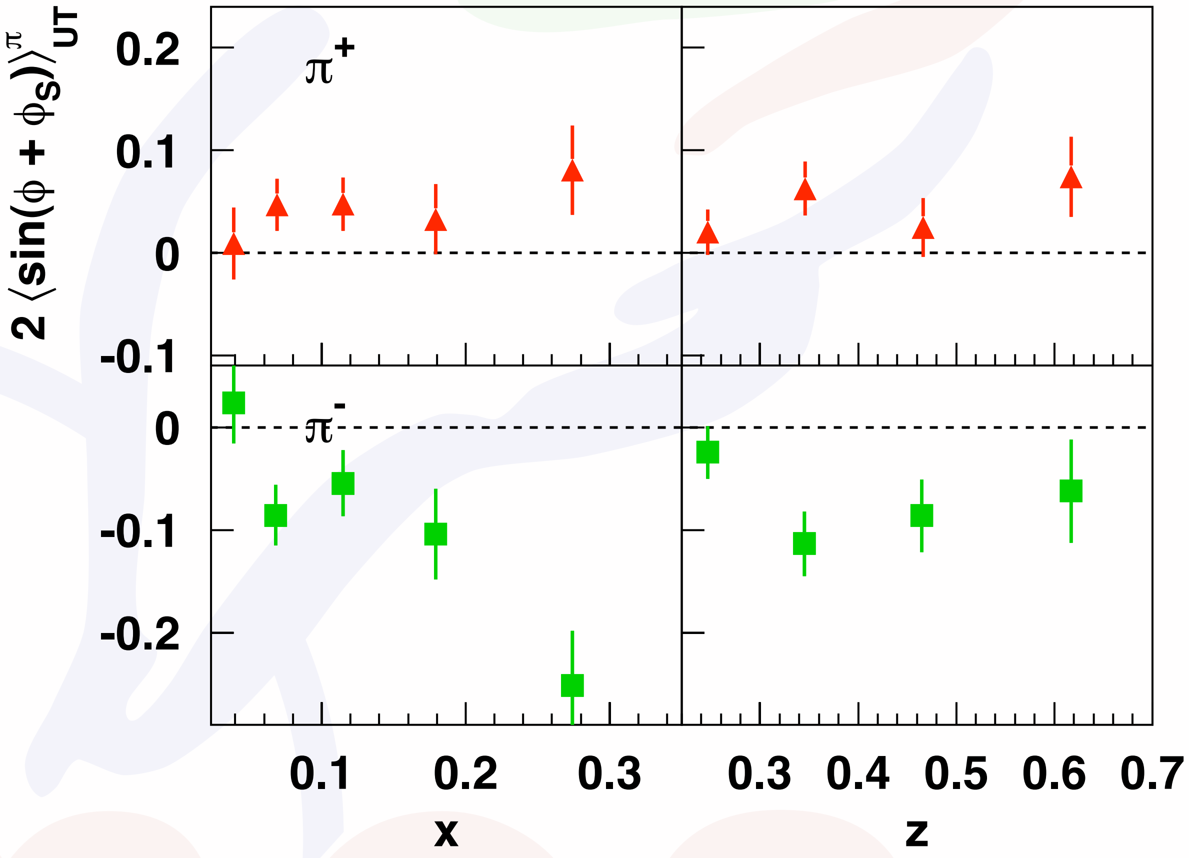

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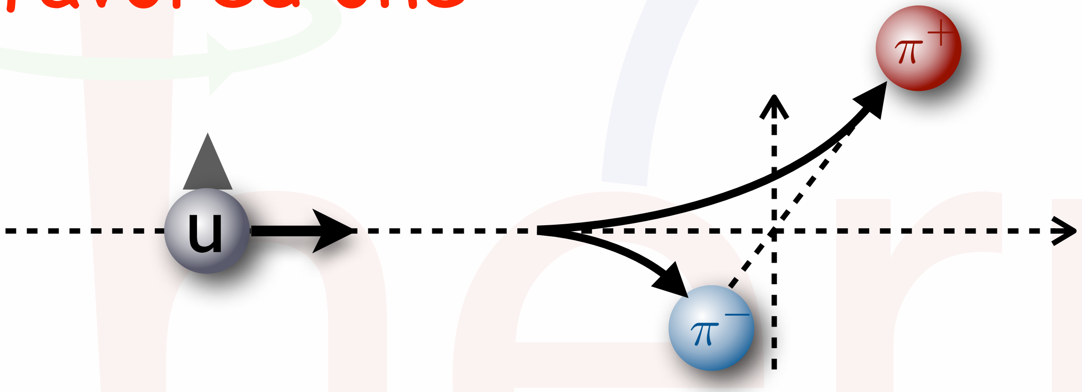

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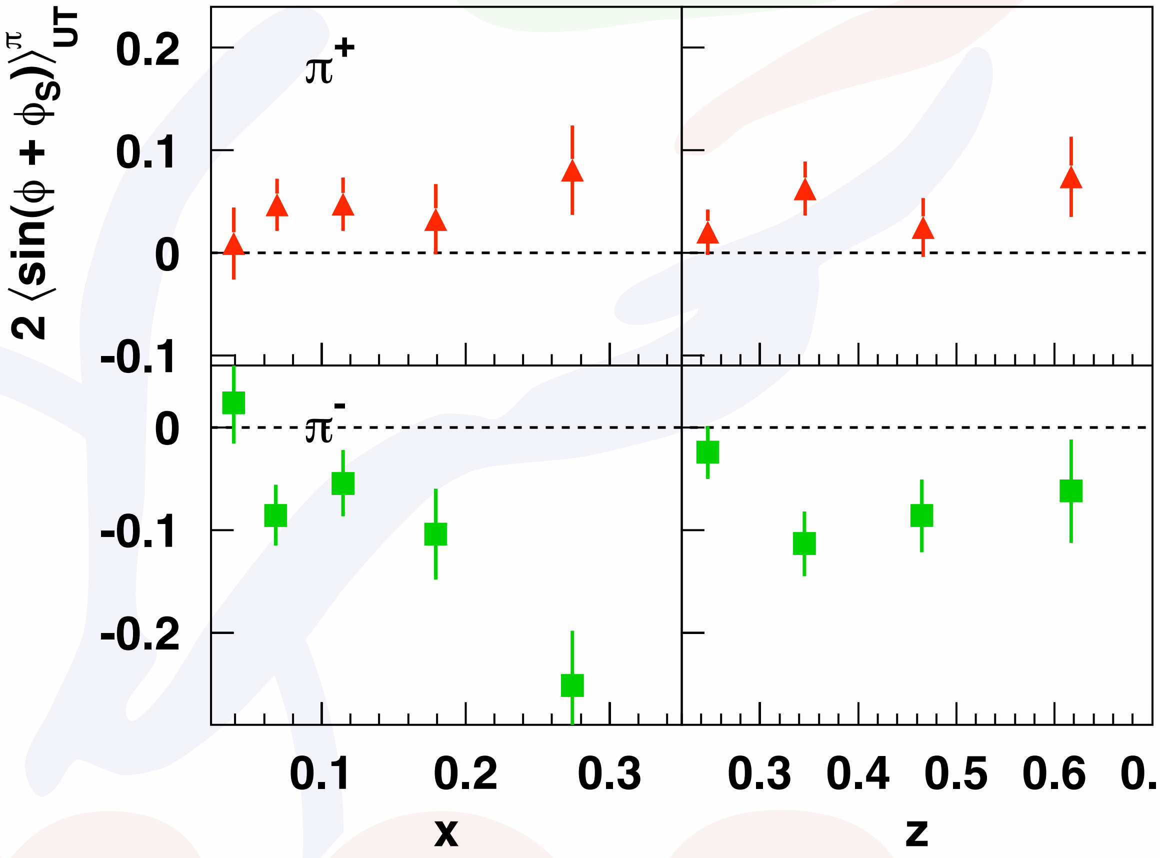

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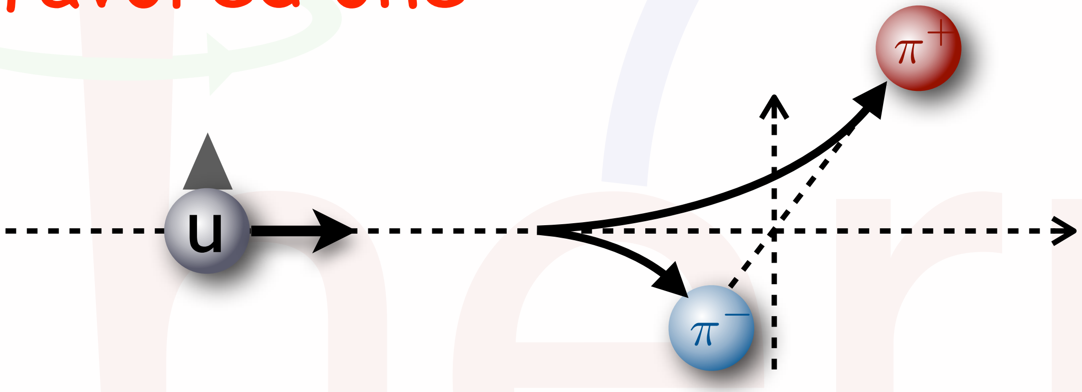
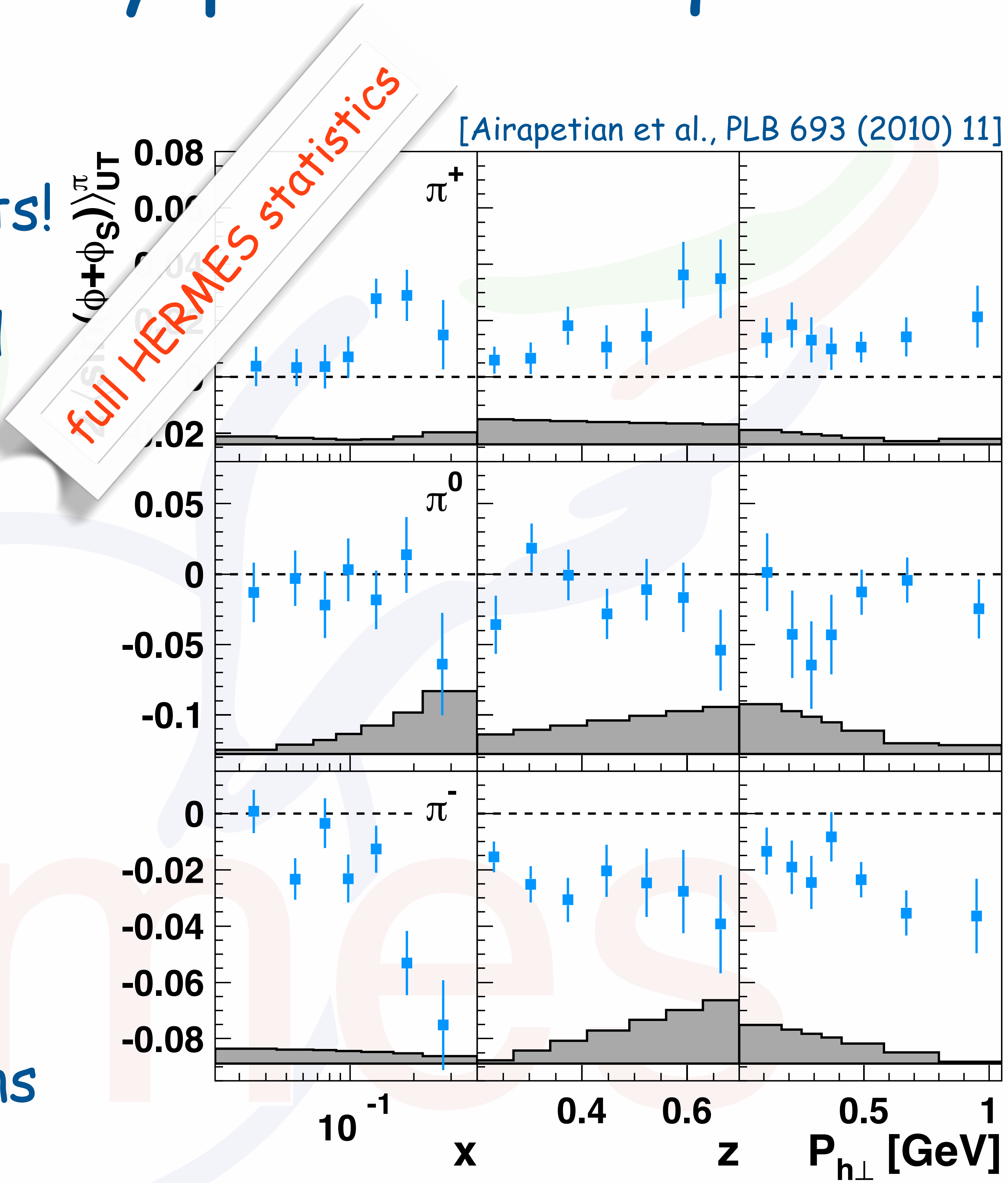
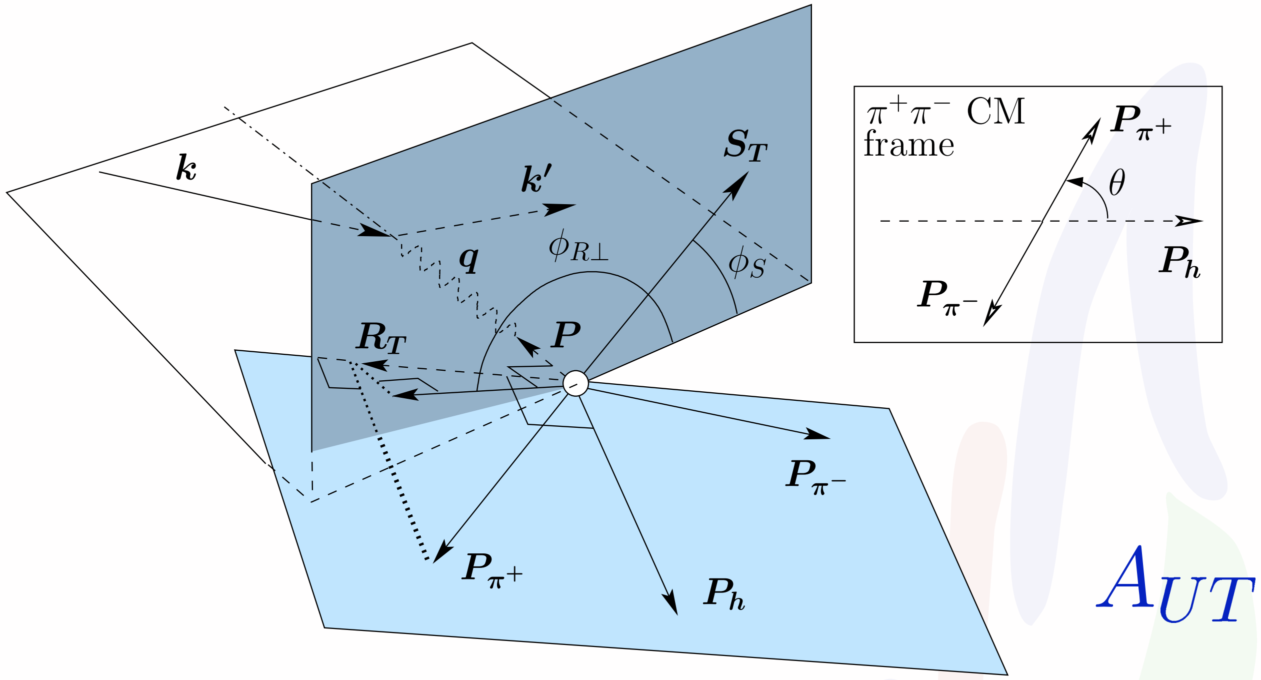


- leads to various cancellations in SSA observables

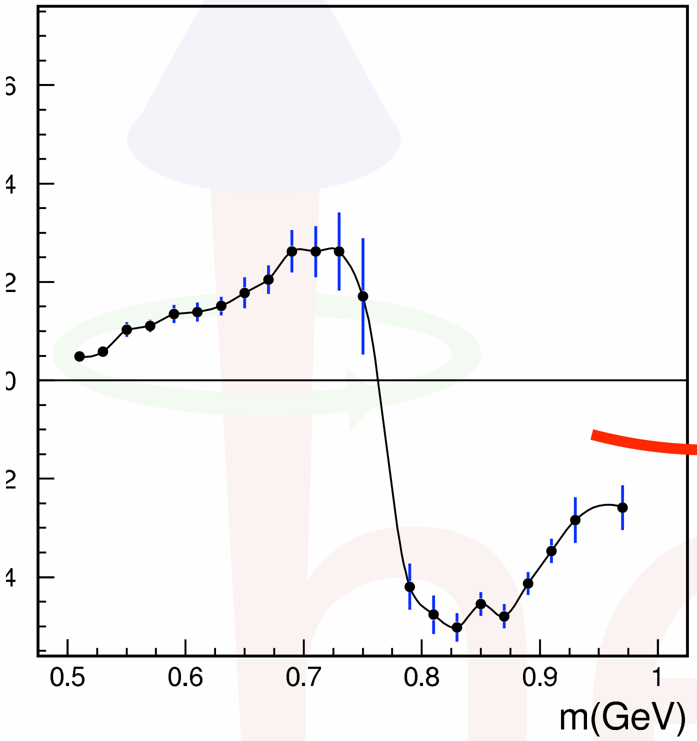

[Airapetian et al., PLB 693 (2010) 11]

full HERMES statistics

transversity (2-hadron FF)



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



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

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

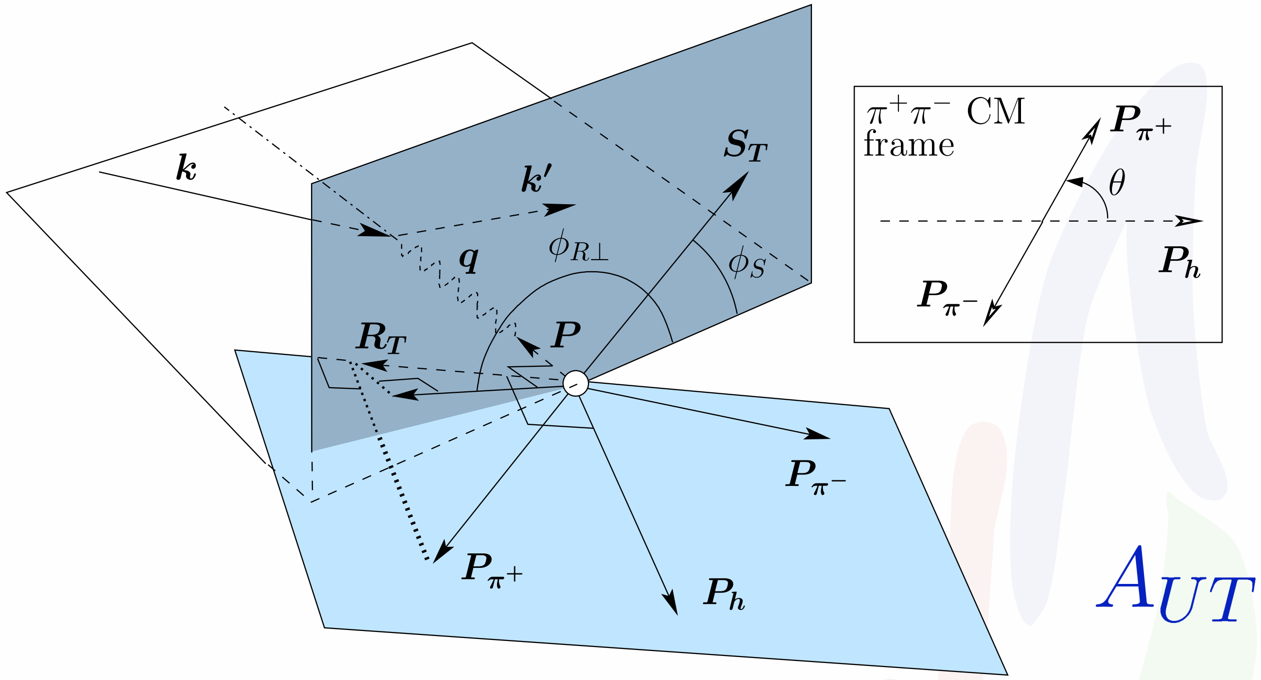
δ_0 (δ_1) → S(P)-wave phase shifts

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

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

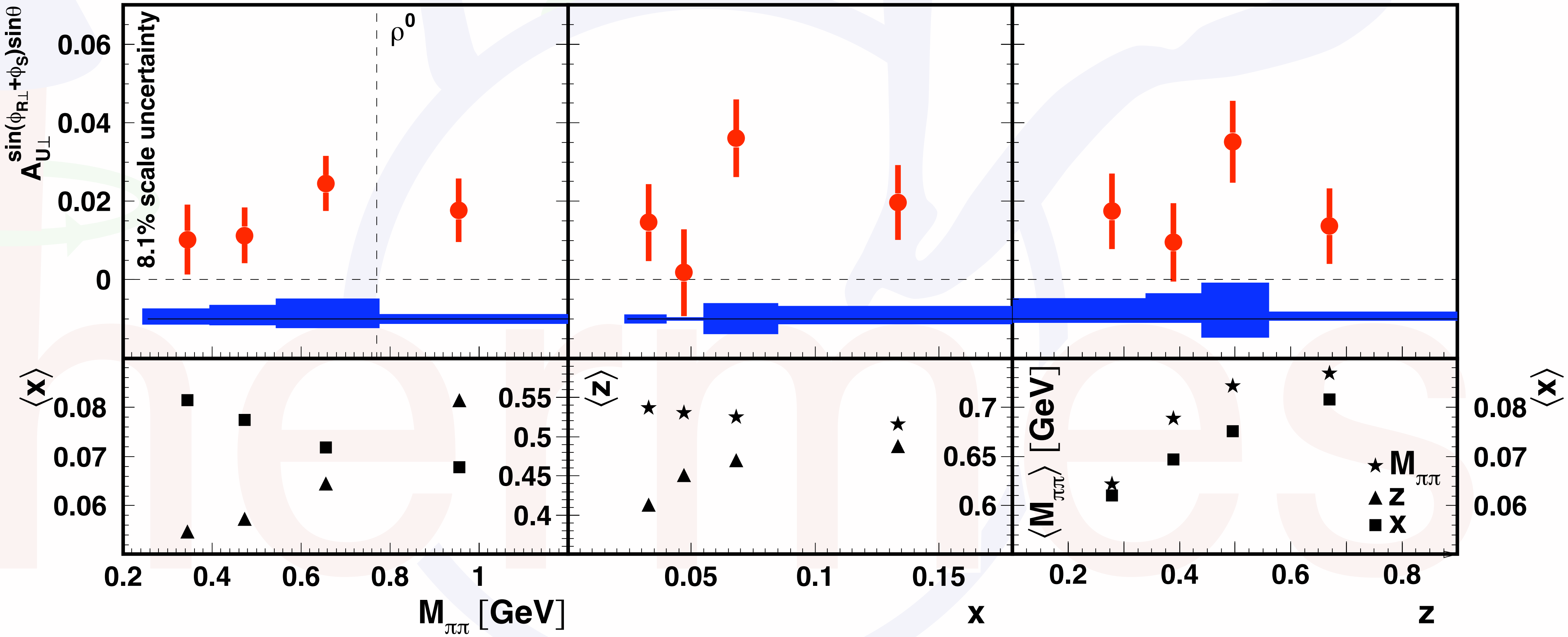
only relative transverse momentum needed -> DGLAP

transversity
(2-hadron FF)

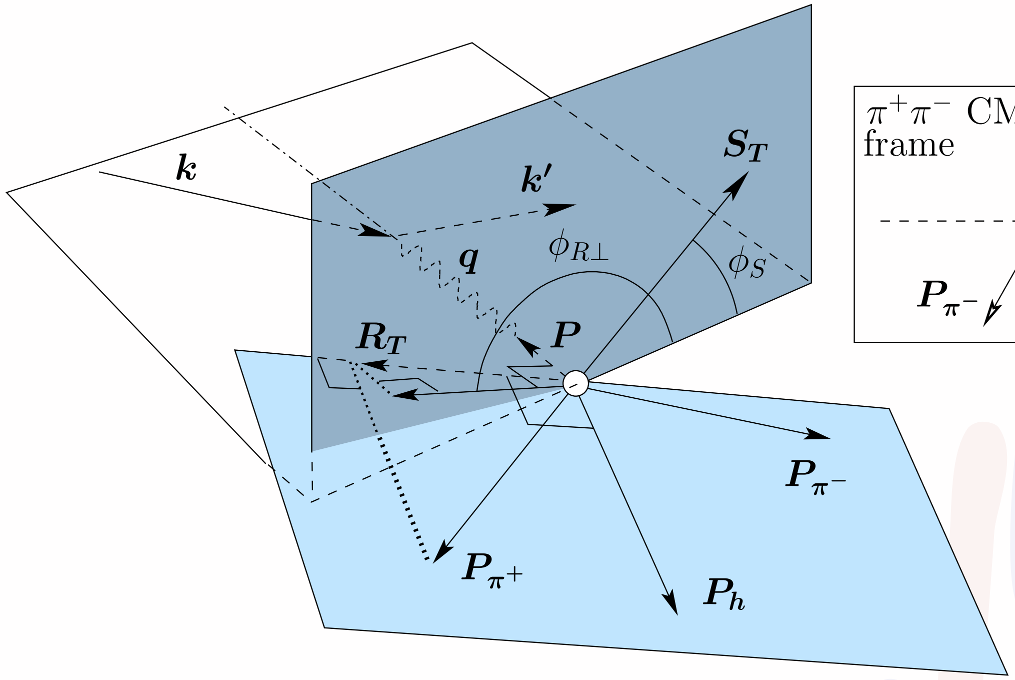


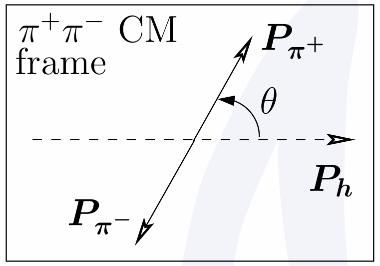
$$A_{UT} \sim \sin(\phi_{R\perp}+\phi_S)\sin\theta h_1 H_1^{\sphericalangle}$$

[A. Airapetian et al., JHEP 06 (2008) 017]



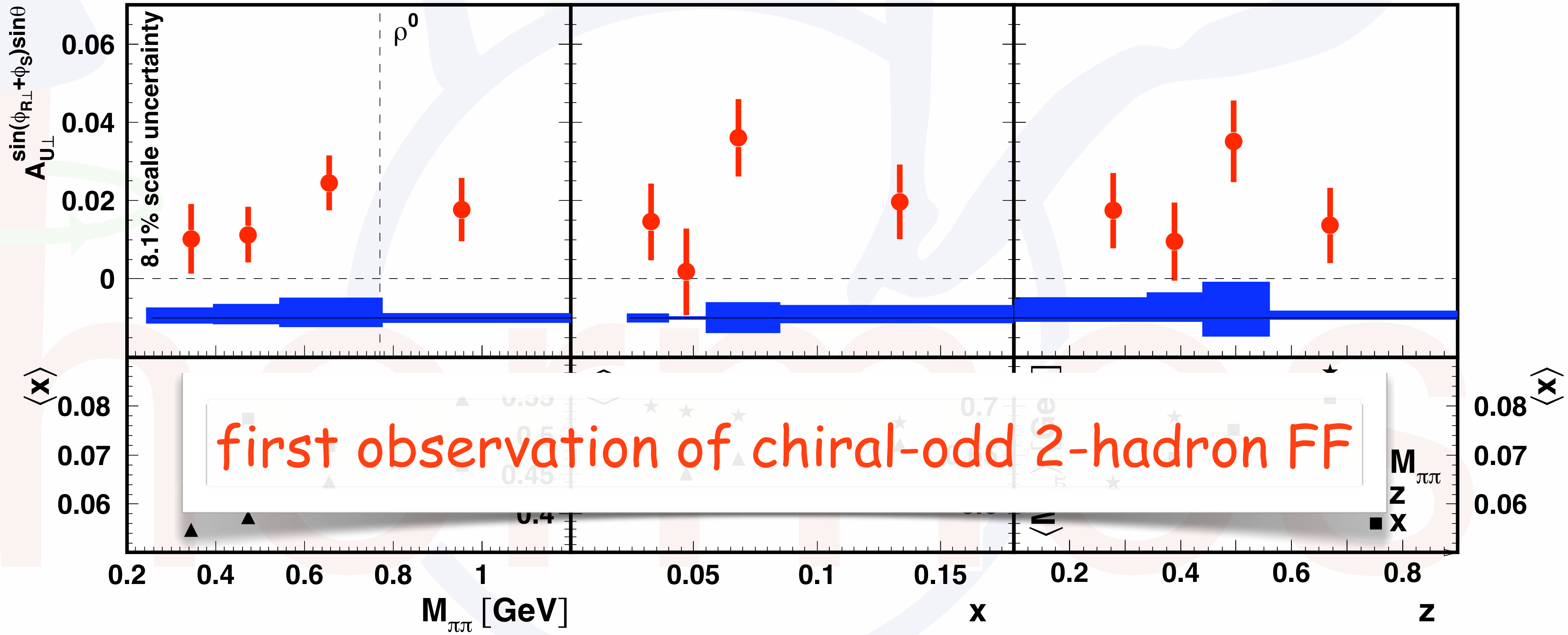
transversity (2-hadron FF)





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

[A. Airapetian et al., JHEP 06 (2008) 017]



first observation of chiral-odd 2-hadron FF

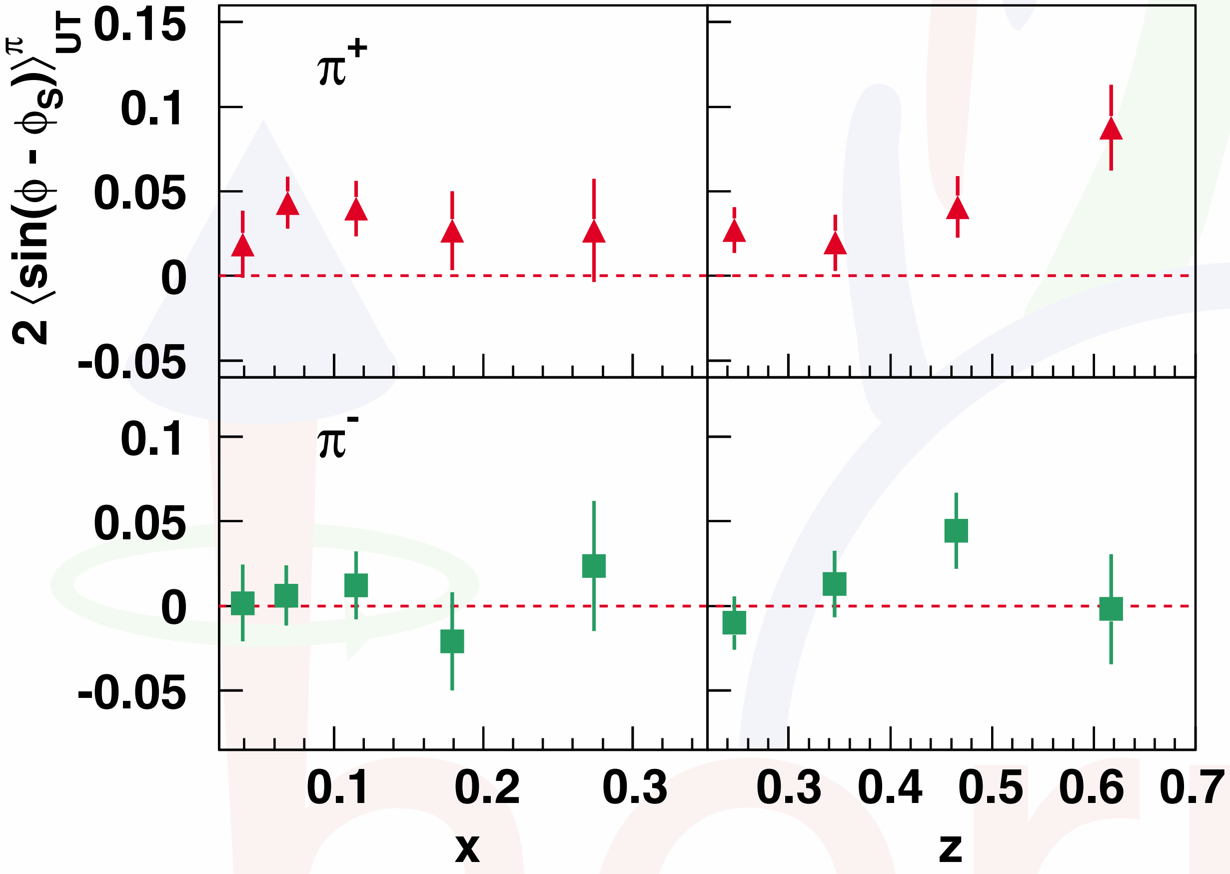
Was Collins then right about Sivers?

gunar.schnell @ desy.de

Was Collins then right about Sivers?

- no! -> first evidence of naive-T-odd Sivers function

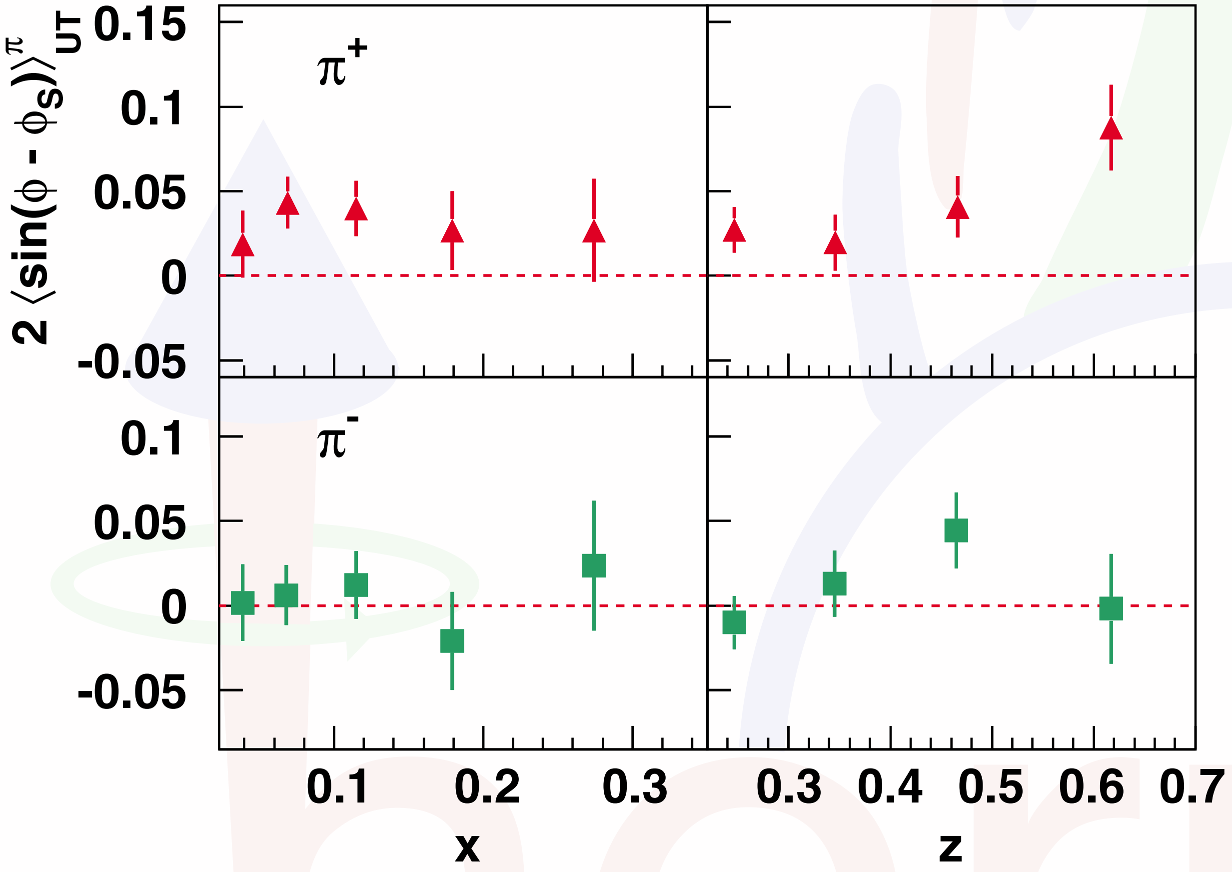
[Phys. Rev. Lett. 94 (2005) 012002]



only 2002 data!

Was Collins then right about Sivers?

[Phys. Rev. Lett. 94 (2005) 012002]



only 2002 data!

- no! -> first evidence of naive-T-odd Sivers function
- however, Sivers predicted wrong sign

Was Collins then right about Sivers?

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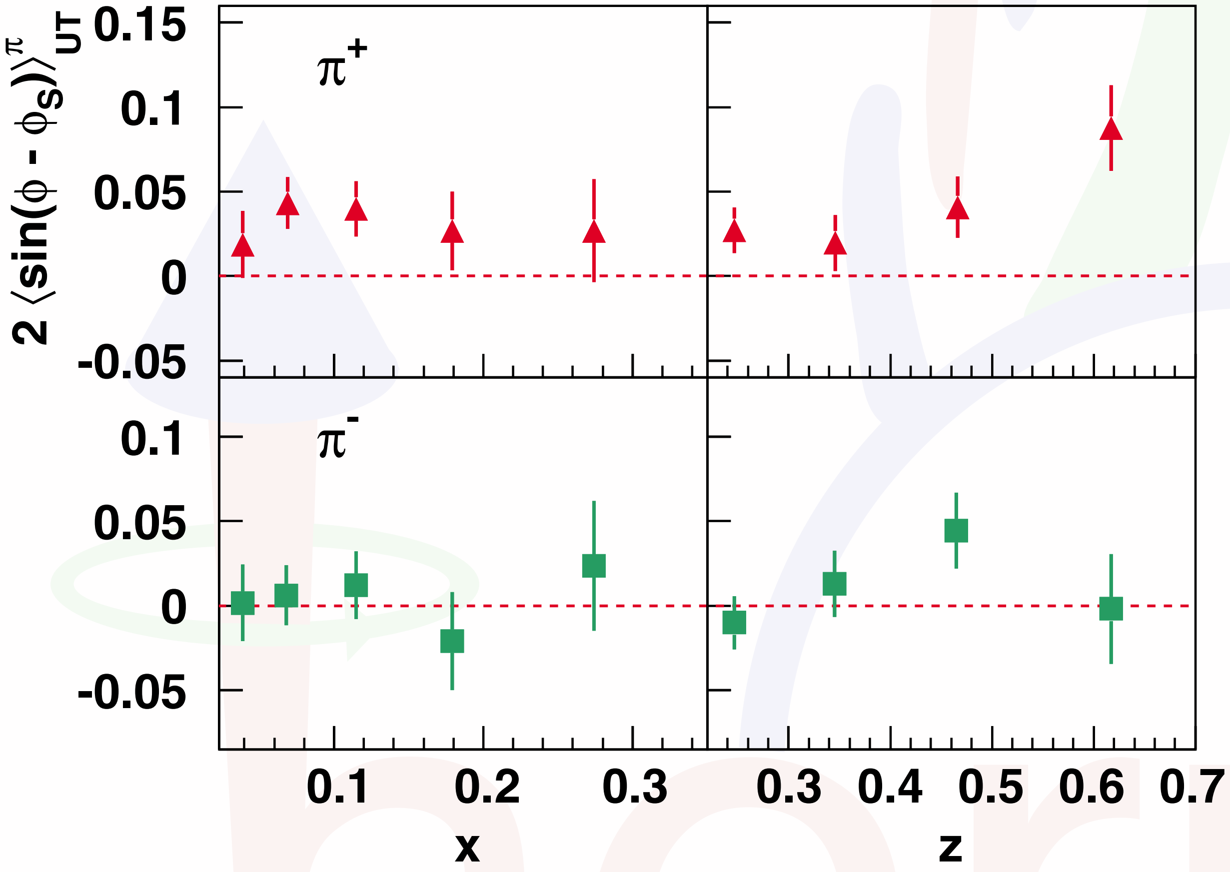
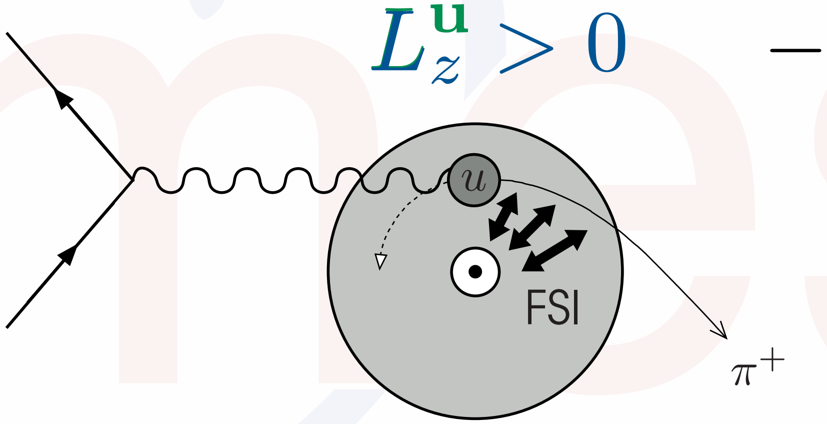


only 2002 data!

- no! -> first evidence of naive-T-odd Sivers function
- however, Sivers predicted wrong sign
- better: chromodynamic-lensing picture [M. Burkardt]

$L_z^{\mathbf{u}} > 0$ $\quad -f_{1T}^{\perp q} \sim \kappa^q$



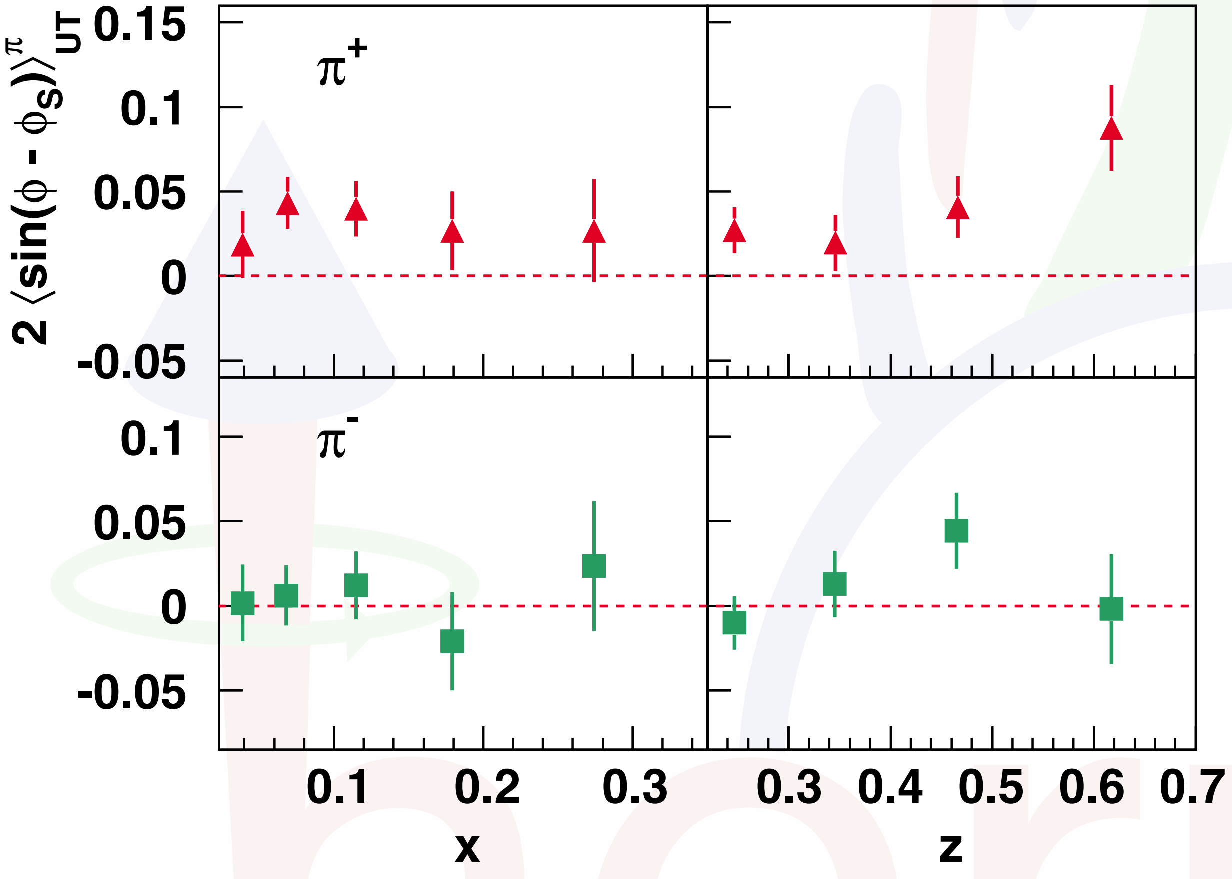
$\kappa^u = 1.67$

$\kappa^d = -2.03$

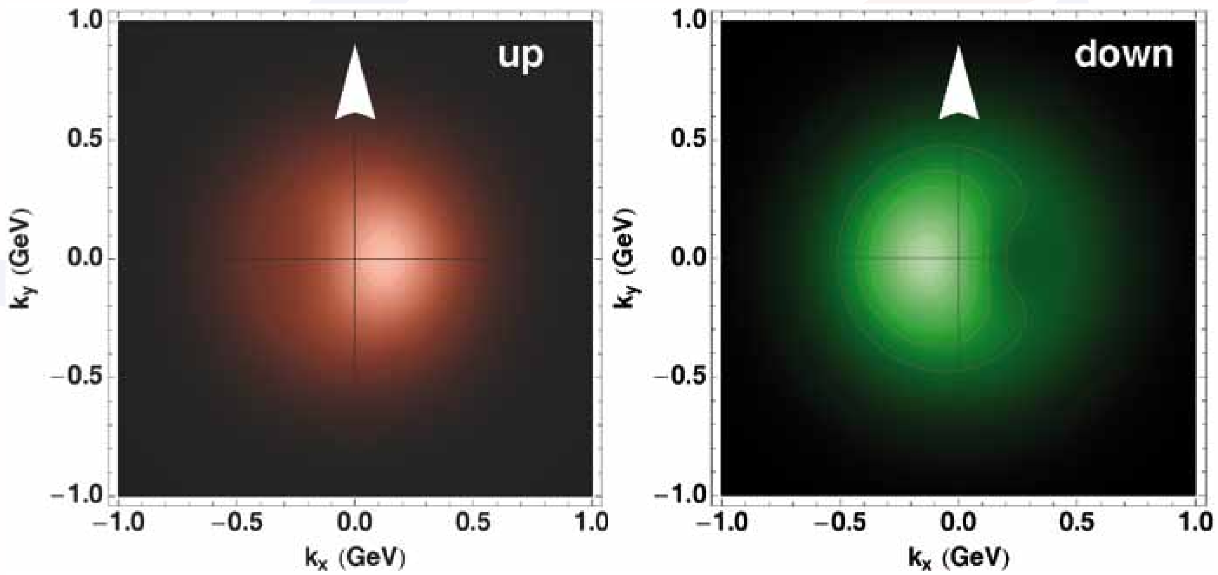
[M. Burkardt, PRD66 (2002) 014005]

Was Collins then right about Sivers?

[Phys. Rev. Lett. 94 (2005) 012002]

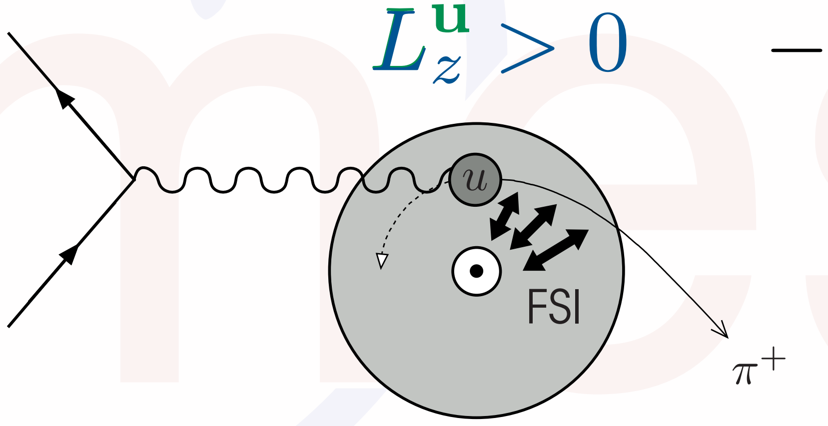


only 2002 data!



[A. Bacchetta et al.]

$$L_z^{\mathbf{u}} > 0 \qquad -f_{1T}^{\perp q} \sim \kappa^q$$



$$\kappa^u = 1.67$$

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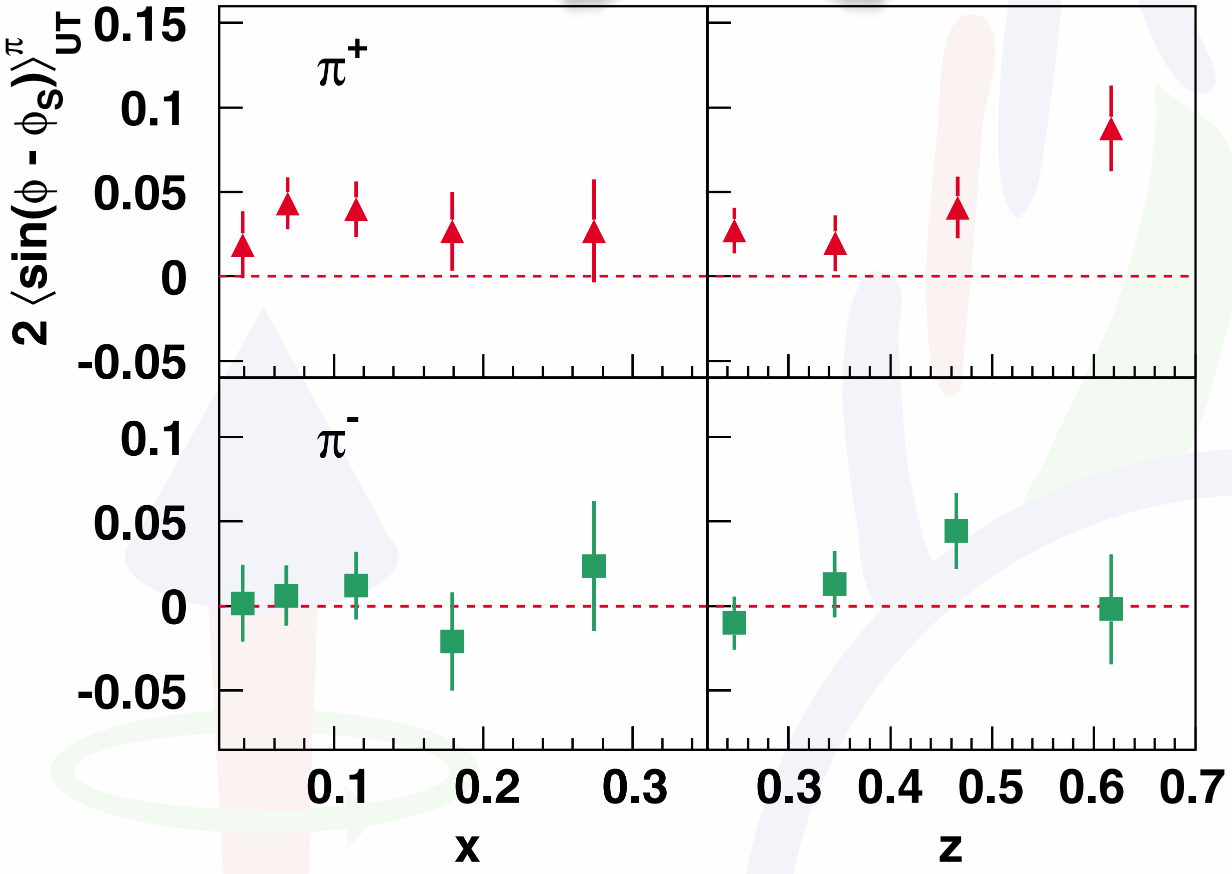
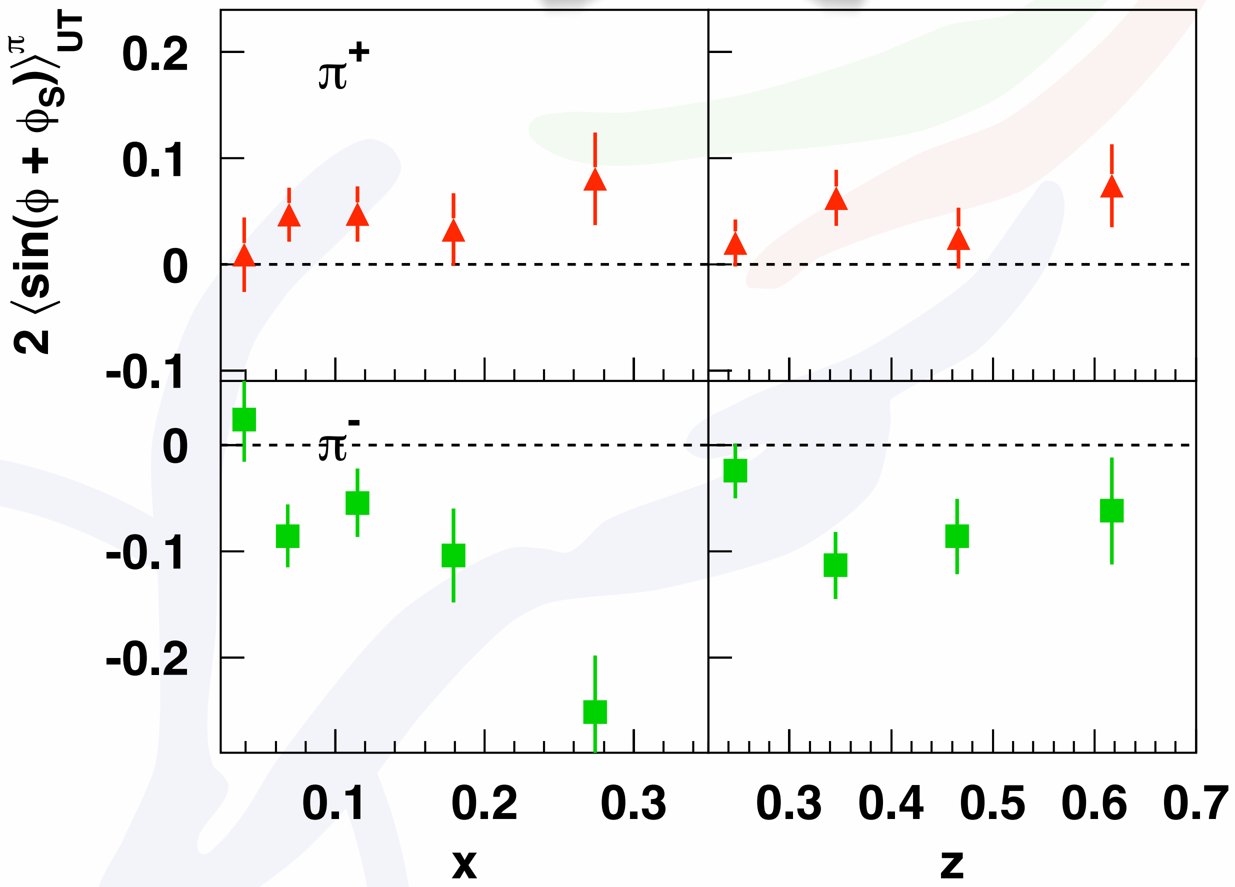
[M. Burkardt, PRD66 (2002) 014005]

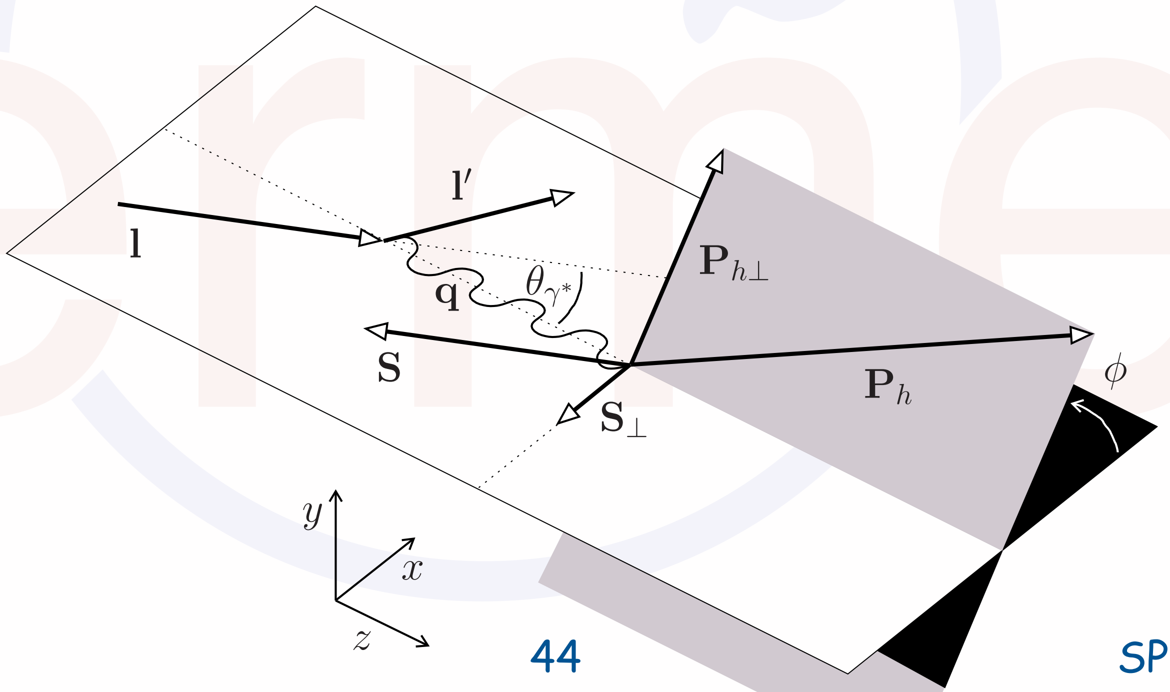
… and what about the original A_{UL}?

Sivers



Collins





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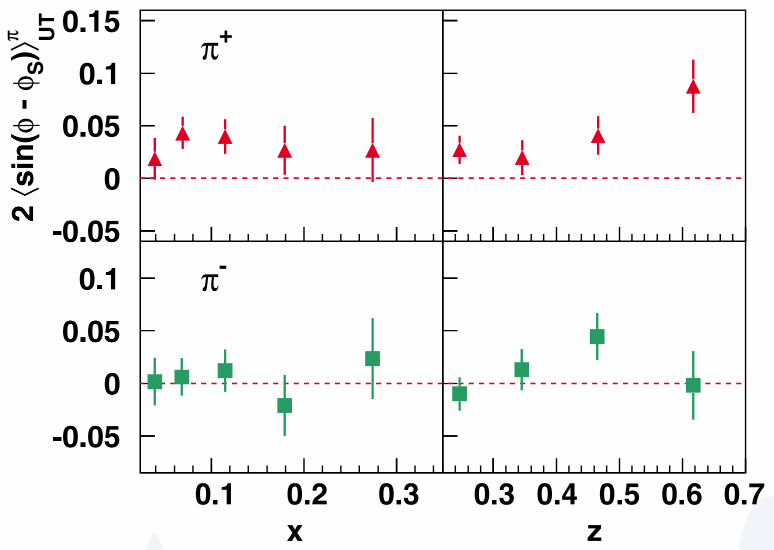
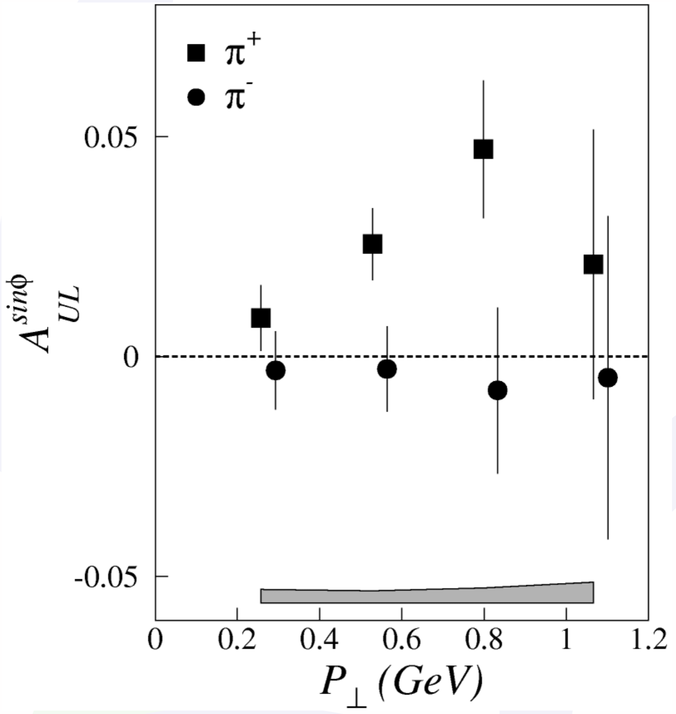
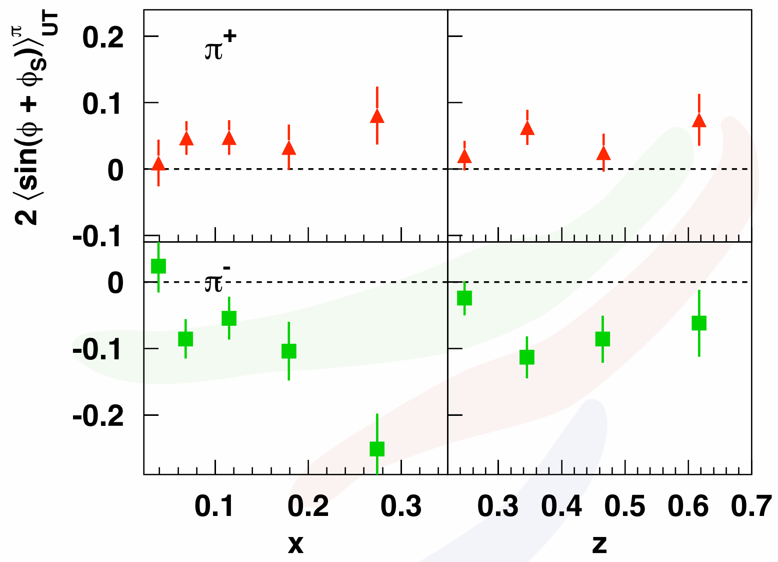
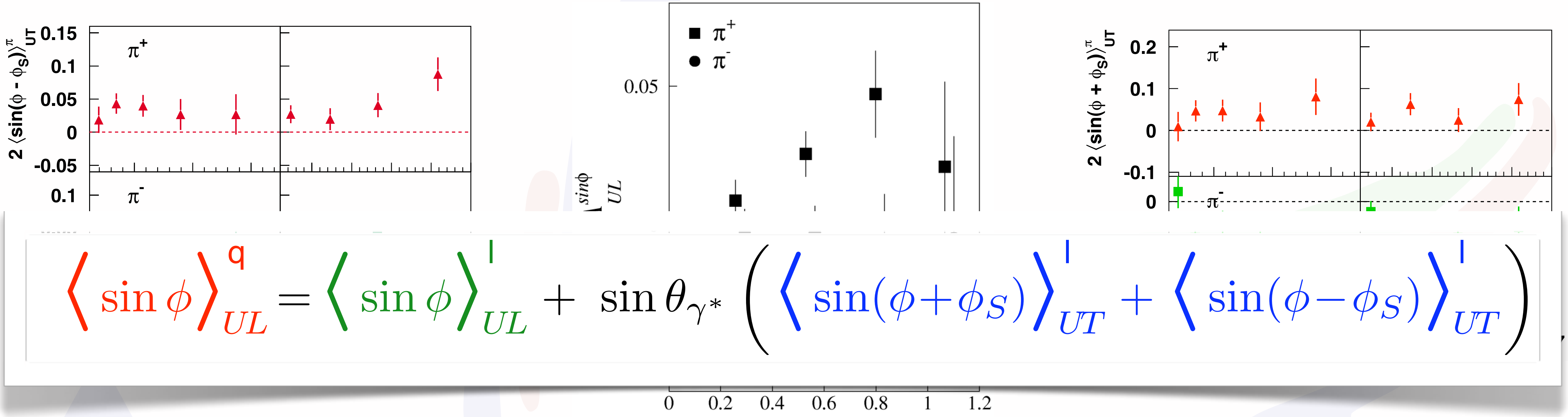


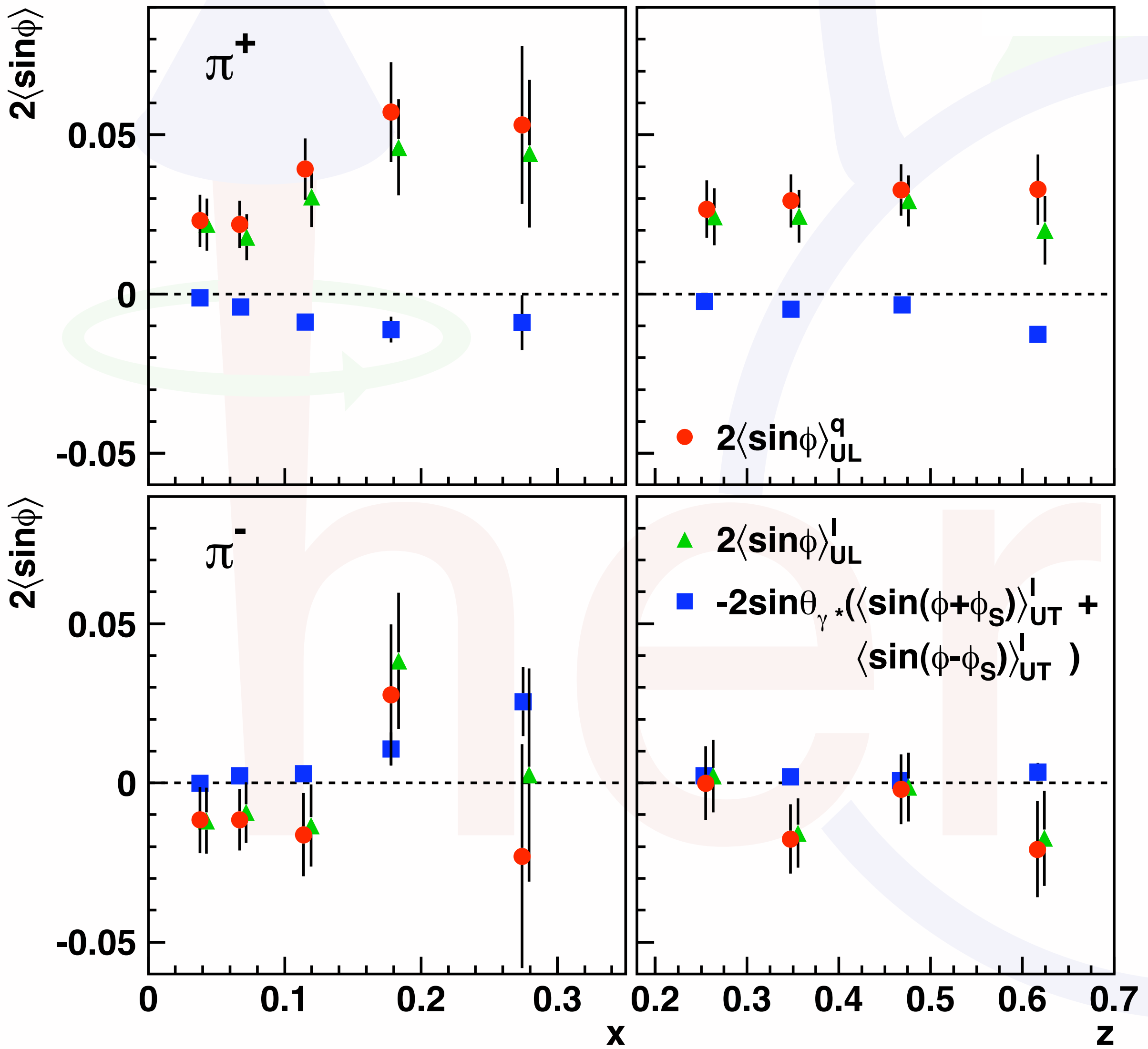




… and what about the original A_{UL}?



$$\left\langle \sin\phi \right\rangle^{q}_{UL} = \left\langle \sin\phi \right\rangle^{l}_{UL} + \sin\theta_{\gamma^*}\left(\left\langle \sin(\phi+\phi_S)\right\rangle^{l}_{UT} + \left\langle \sin(\phi-\phi_S)\right\rangle^{l}_{UT}\right)$$



☑ A_{UL} significantly positive for π^+

☑ clear evidence of twist-3 effect

… yet another sine modulations

- longitudinally polarized beam & unpolarized target ⇒ subleading-twist

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

$$\begin{aligned}\langle \sin\phi \rangle_{LU} \propto\ & \lambda_e \frac{M}{Q}\,\mathcal{I}\Big[x e(x) H_1^\perp(z) - \frac{M_h}{zM} h_1^\perp(x) E(z) \\ & + \frac{M_h}{zM} f_1(x) G^\perp(z) - x g^\perp(x) D_1(z) \\ & + \frac{m_q}{M} h_1^\perp(x) D_1(z) - \frac{m_q}{M} f_1(x) H_1^\perp(z)\Big]\end{aligned}$$

quark-mass suppressed ☞

… yet another sine modulations

- longitudinally polarized beam & unpolarized target ⇒ subleading-twist

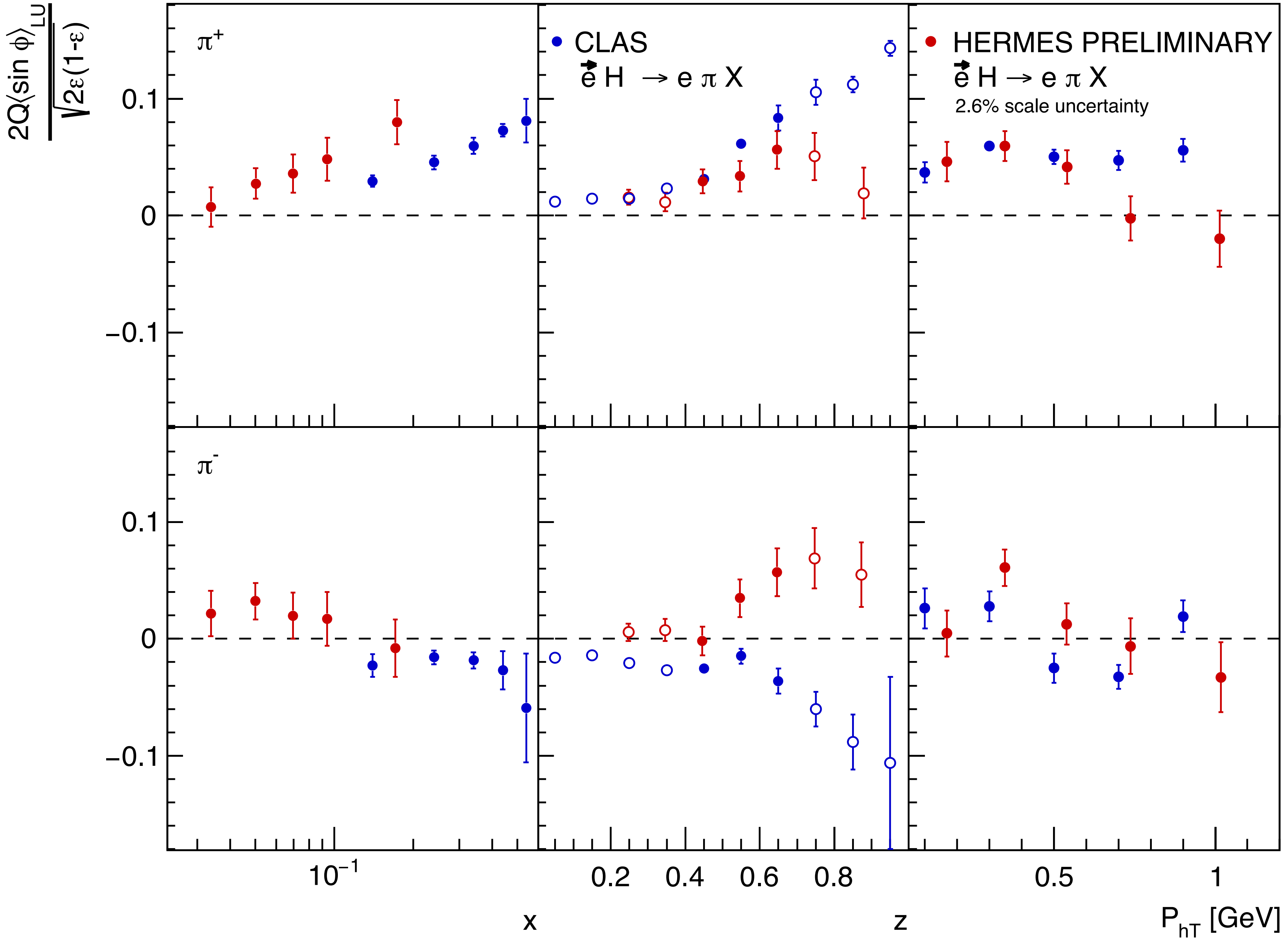
[Bacchetta et al., Phys. Lett. B 595 (2004) 309]

$$\langle \sin\phi \rangle_{LU} \propto \lambda_e \frac{M}{Q} \mathcal{I}\left[x e(x) H_1^{\perp}(z) - \frac{M_h}{zM} h_1^{\perp}(x) E(z) + \frac{M_h}{zM} f_1(x) G^{\perp}(z) - x g^{\perp}(x) D_1(z) \right]$$

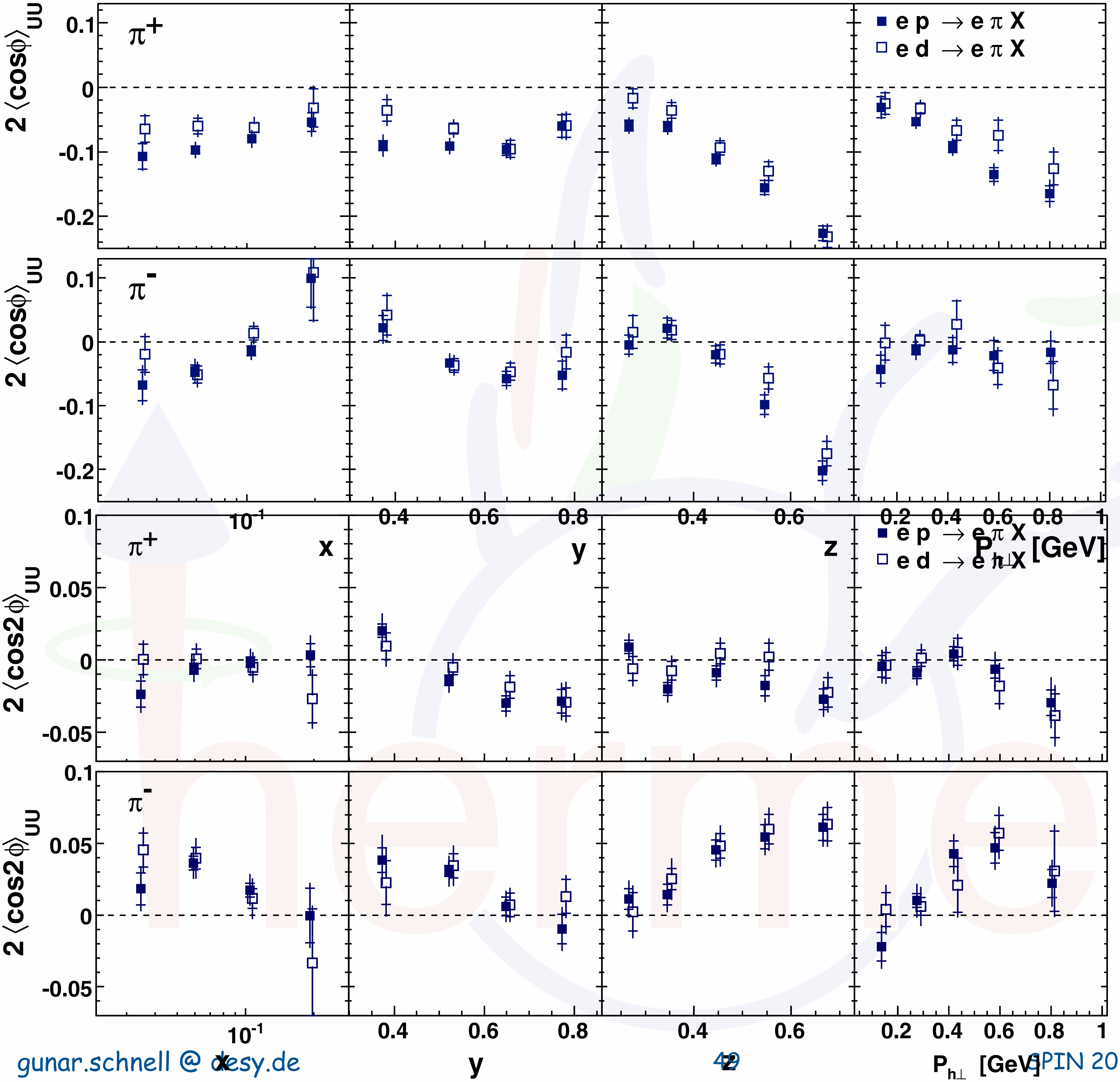
many terms contributing – difficult to separate

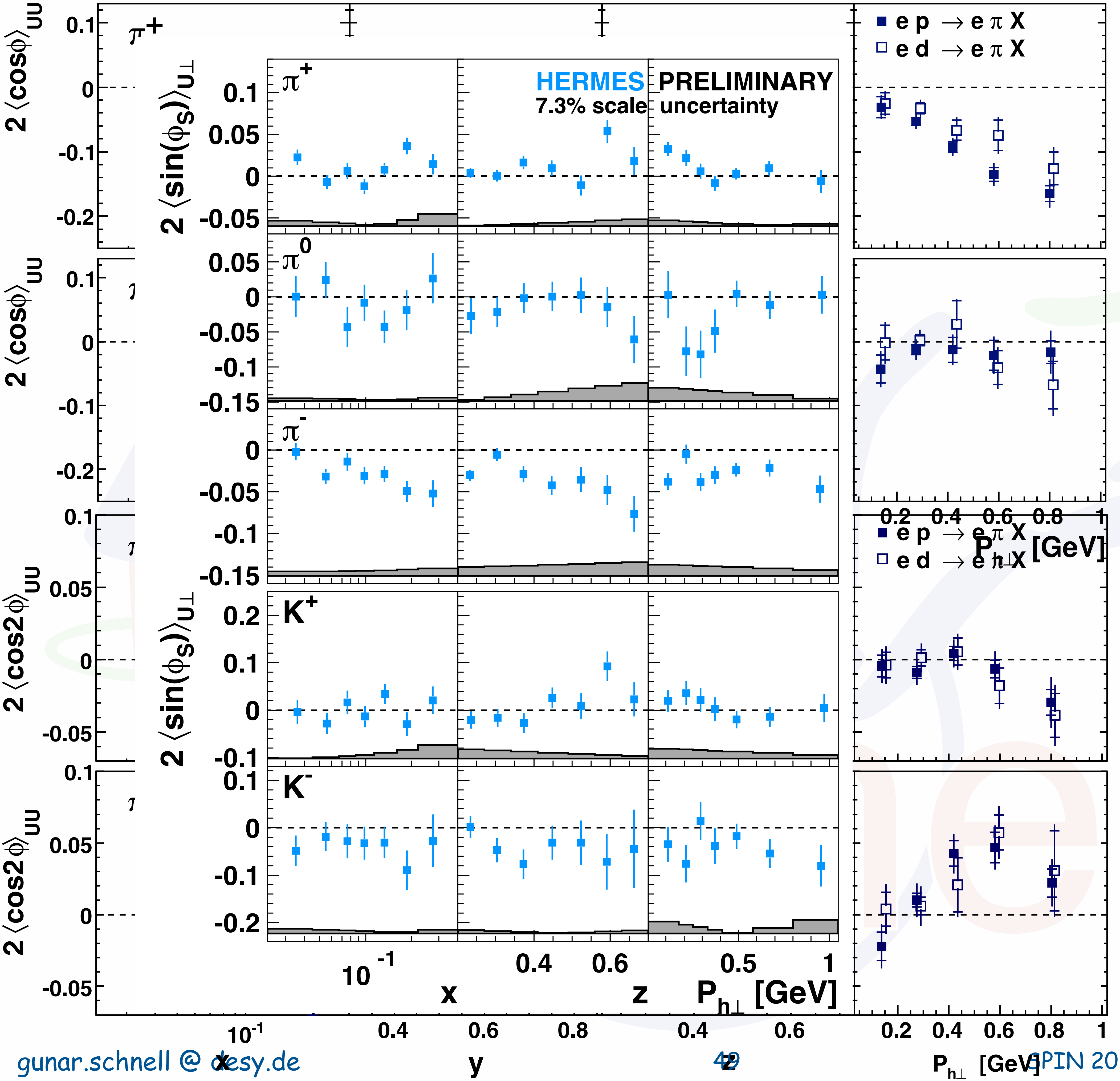
… yet another sine modulations

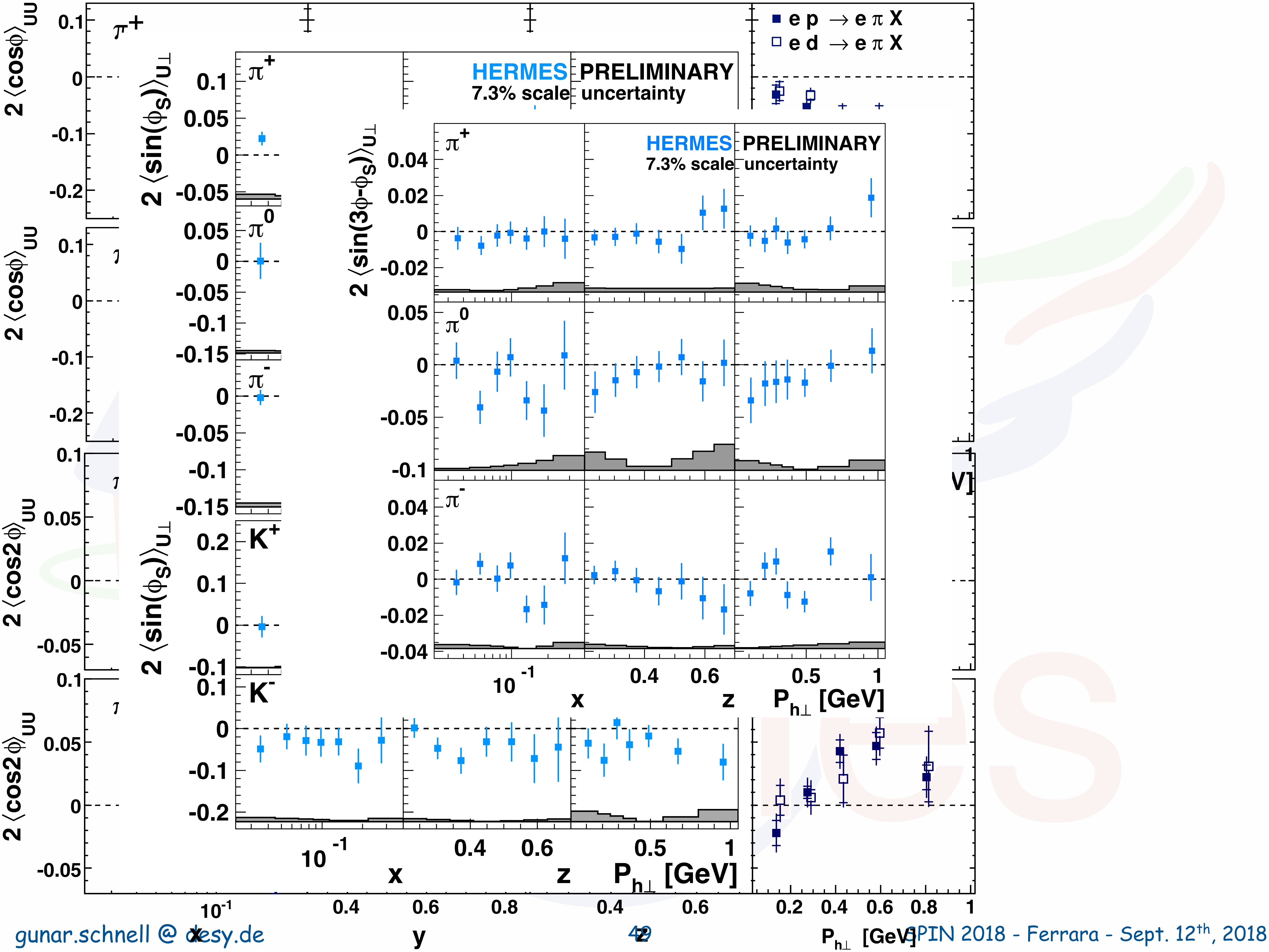
- longitudinally polarized beam & unpolarized target ⇒ subleading-twist

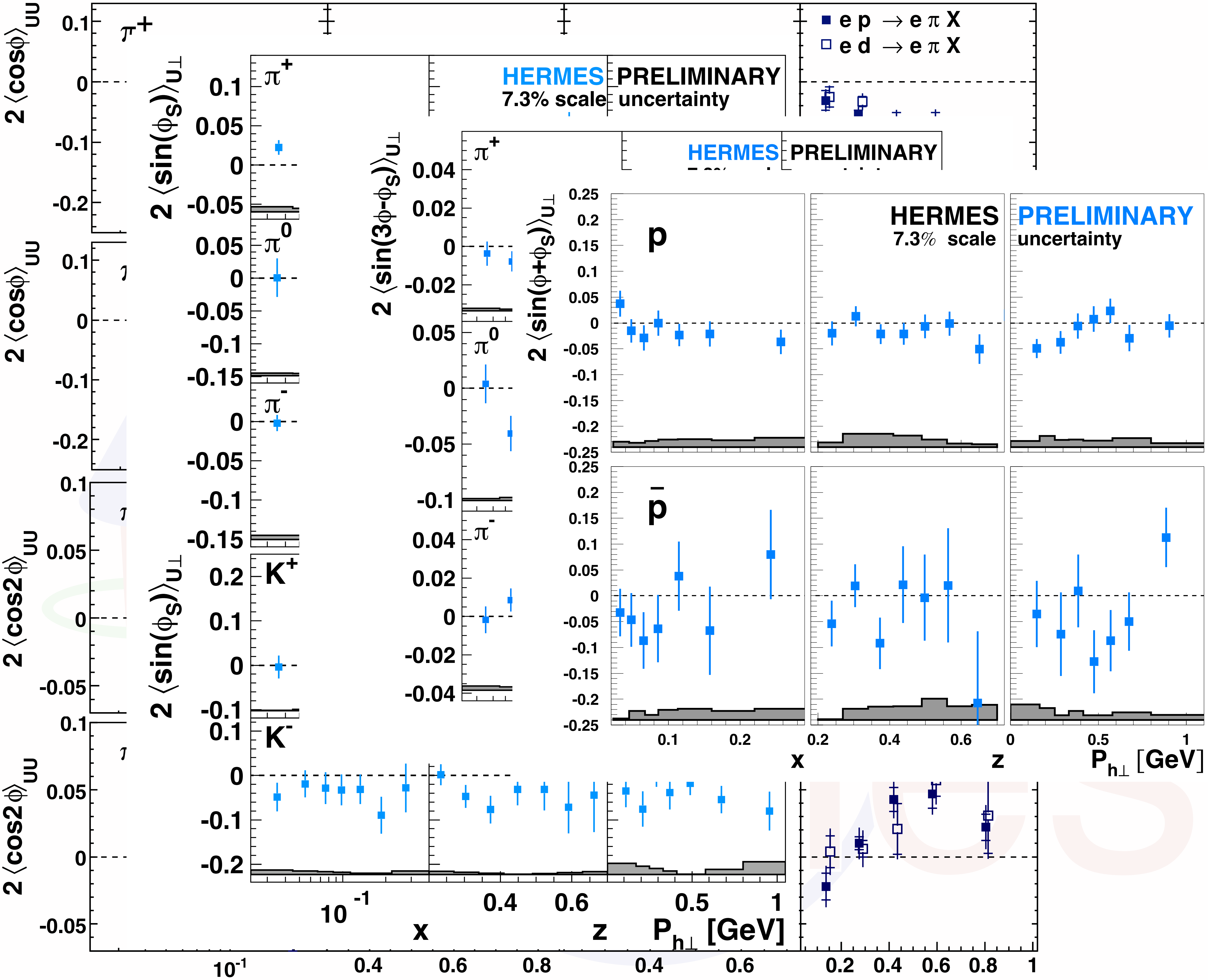


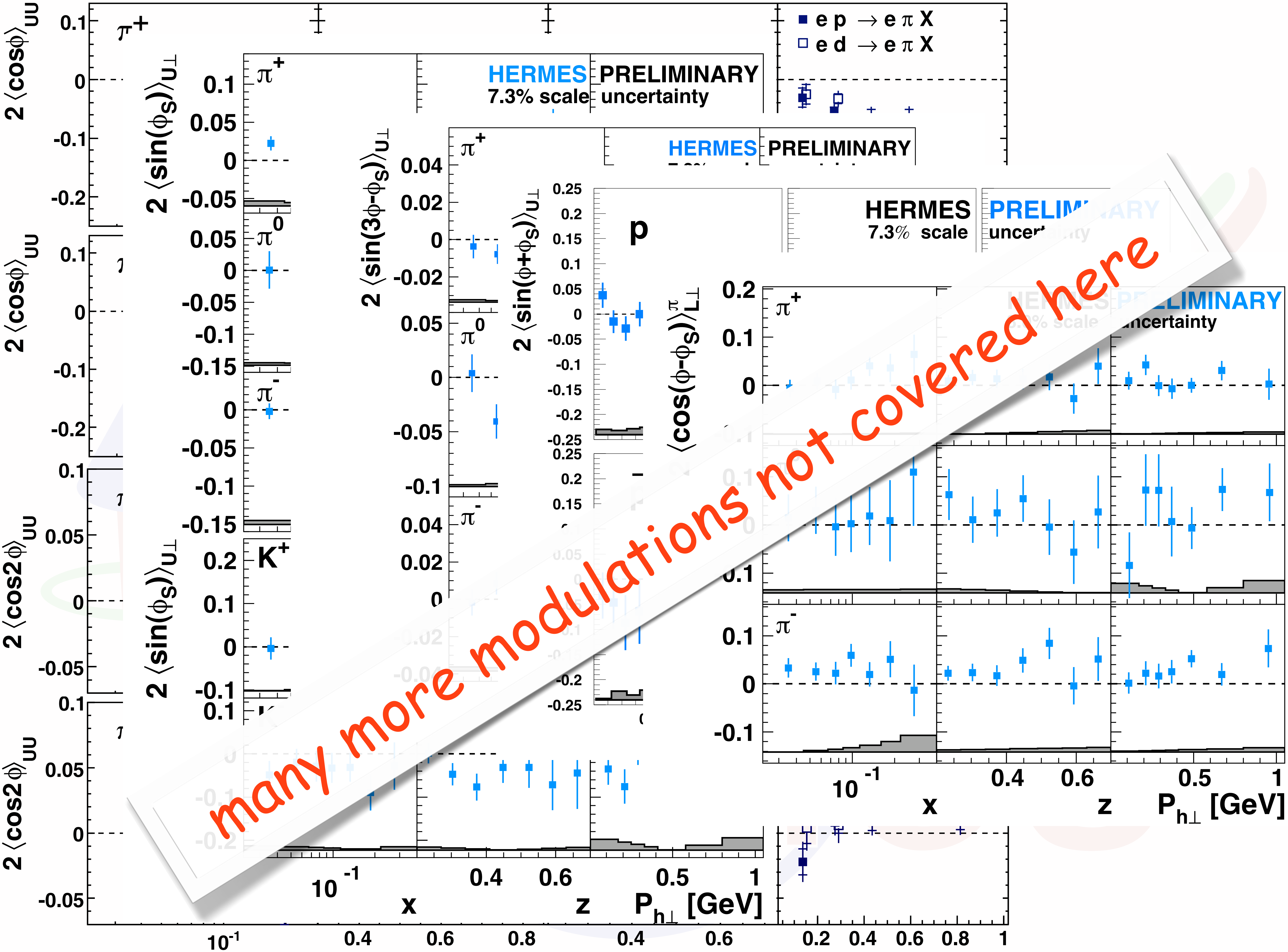
- opposite behavior at HERMES/CLAS of negative pions in z projection due to different x-range probed


2 ⟨cosφ⟩_UU
2 ⟨cos2φ⟩_UU
π+
π-
■ e p → e π X
□ e d → e π X
0.1
0
-0.1
-0.2
0.05
-0.05
10^-1
0.4
0.6
0.8
0.2
1
x
y
z
P_h⊥ [GeV]


HERMES PRELIMINARY
7.3% scale uncertainty
$2\langle\sin(\phi_S)\rangle_{U\perp}$
π^+
π^0
π^-
K^+
K^-
x
z
$P_{h\perp}$ [GeV]
10^{-1}
0.4
0.6
0.5
1
$2\langle\cos\phi\rangle_{UU}$
$2\langle\cos2\phi\rangle_{UU}$
■ e p → e π X
□ e d → e π X
■ e p → e h X
□ e d → e h X
y
$P_{h\perp}$ [GeV]
0.2
0.4
0.6
0.8
1


2 ⟨cosφ⟩_UU
2 ⟨cos2φ⟩_UU
π+
e p → e π X
e d → e π X
2 ⟨sin(φ_S)⟩_U⊥
π+
π0
π-
K+
K-
HERMES PRELIMINARY
7.3% scale uncertainty
2 ⟨sin(3φ-φ_S)⟩_U⊥
π+
π0
π-
HERMES PRELIMINARY
7.3% scale uncertainty
10^-1
x
0.4
0.6
z
0.5
1
P_h⊥ [GeV]
y
0.2
0.4
0.6
0.8
0.1
0
-0.1
-0.2
0.05
-0.05
0.04
0.02
-0.02
-0.04
-0.15

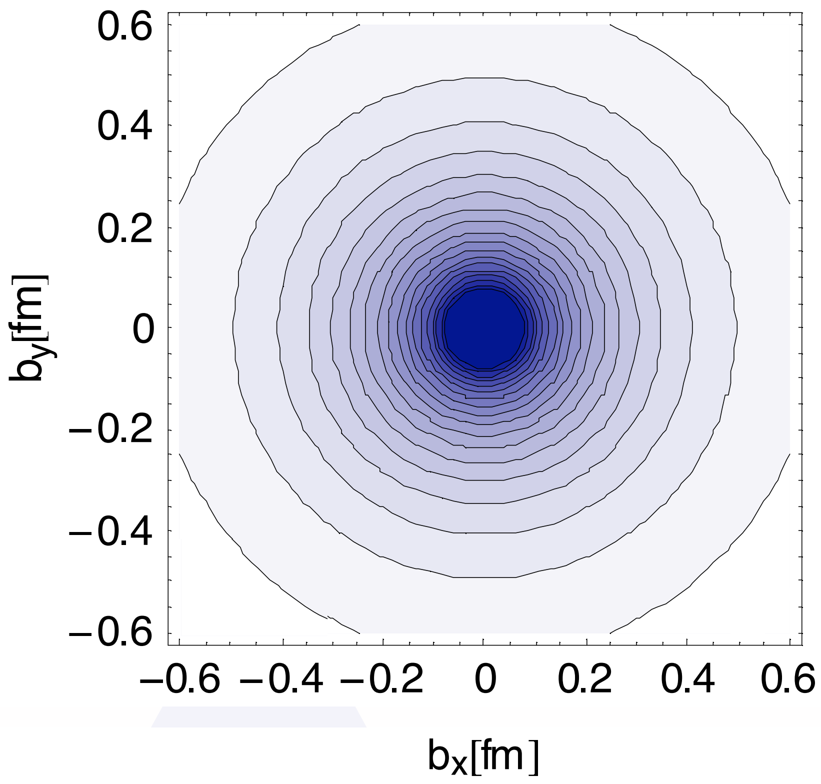

2 ⟨cosϕ⟩UU
π^+
ep → eπX
ed → eπX
2 ⟨cos2ϕ⟩UU
2 ⟨sin(ϕS)⟩U⊥
π^+
π^0
π^-
K^+
K^-
HERMES
PRELIMINARY
7.3% scale uncertainty
2 ⟨sin(3ϕ-ϕS)⟩U⊥
2 ⟨sin(ϕ+ϕS)⟩U⊥
p
$\bar{p}$
HERMES
PRELIMINARY
7.3% scale
uncertainty
x
z
Ph⊥ [GeV]
y



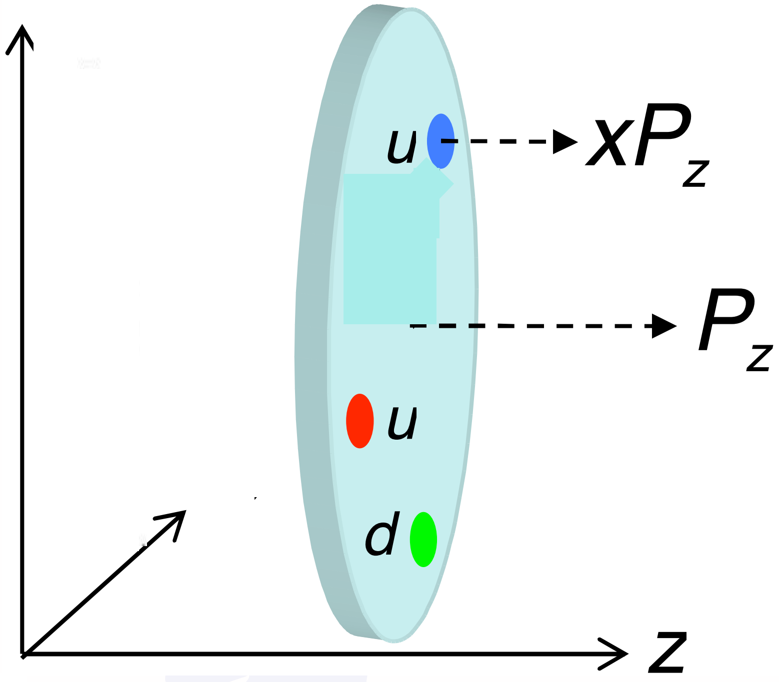
2 ⟨cosϕ⟩_UU
π+
e p → e π X
e d → e π X
2 ⟨cos2ϕ⟩_UU
2 ⟨sin(ϕ_S)⟩_U⊥
HERMES PRELIMINARY
7.3% scale uncertainty
π0
π-
K+
2 ⟨sin(3ϕ-ϕ_S)⟩_U⊥
2 ⟨sin(ϕ+ϕ_S)⟩_U⊥
p
⟨cos(ϕ-ϕ_S)⟩^π_L⊥
many more modulations not covered here
x
z
P_h⊥ [GeV]
y

exclusive reactions

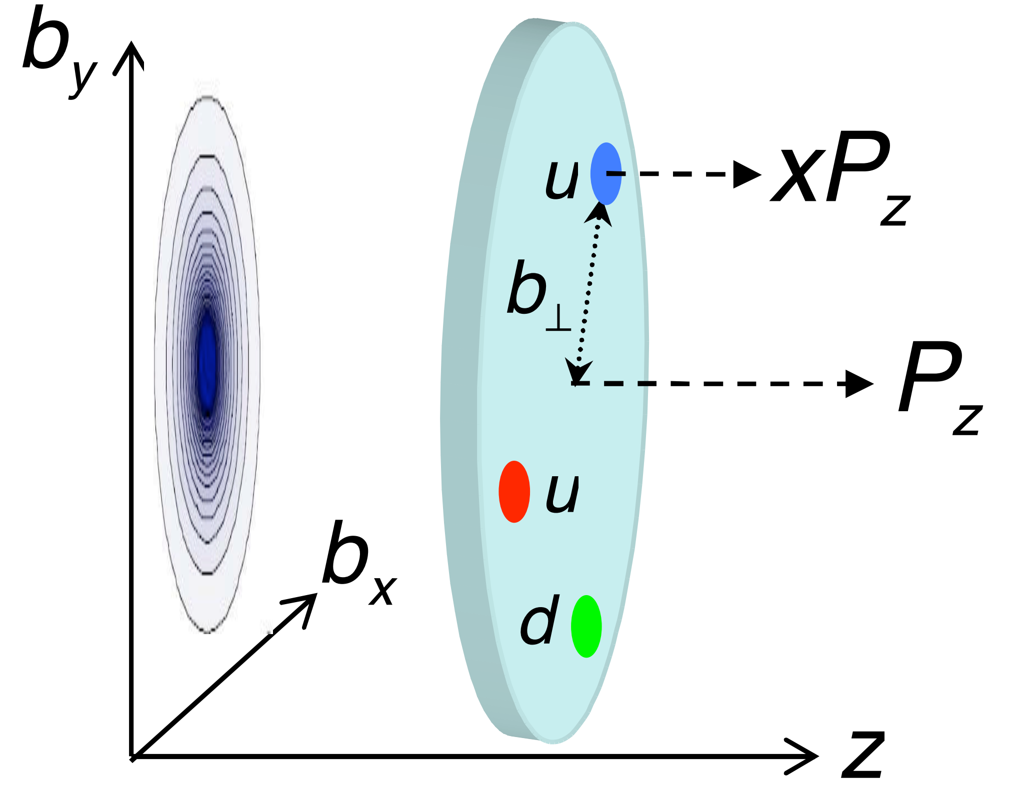
a complementary 3D picture of the nucleon



form factors:
transverse distribution
of partons



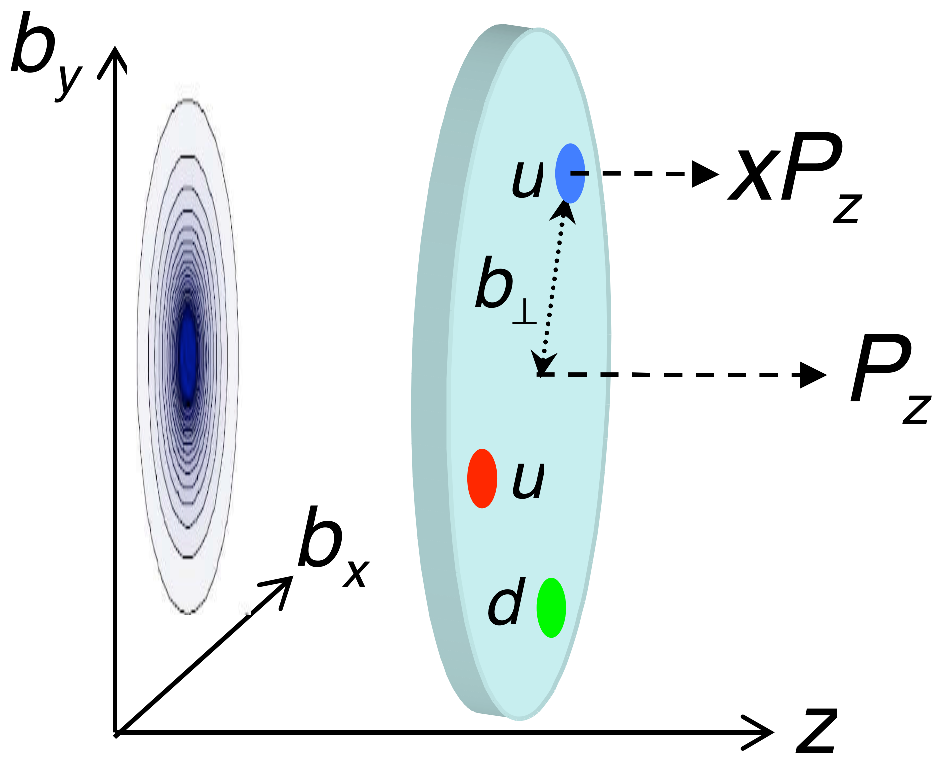
parton distributions:
longitudinal momentum
of partons

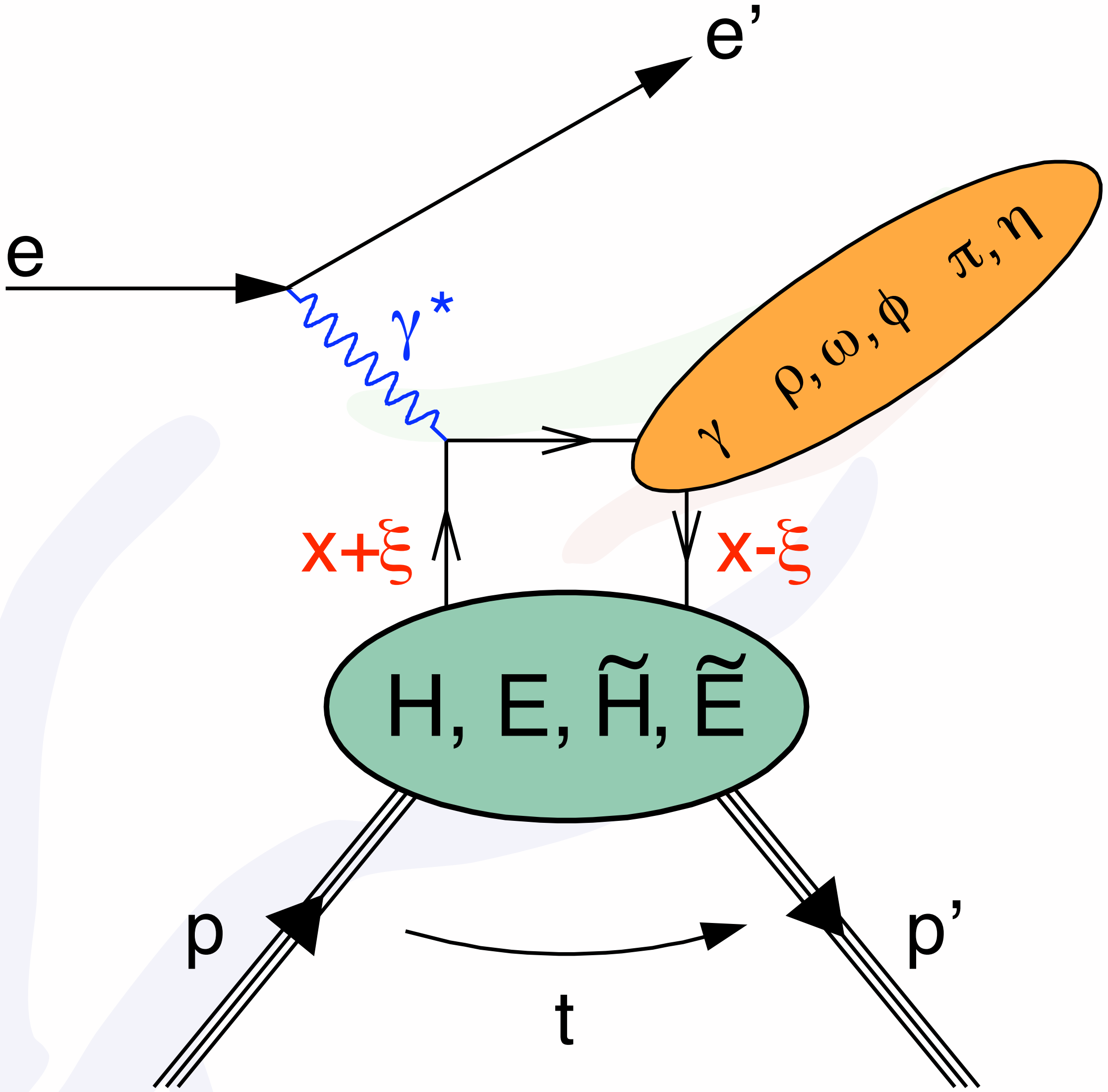


☛ S. Liuti

nucleon tomography
correlated info on transverse position and longitudinal momentum

GPDs in exclusive reactions

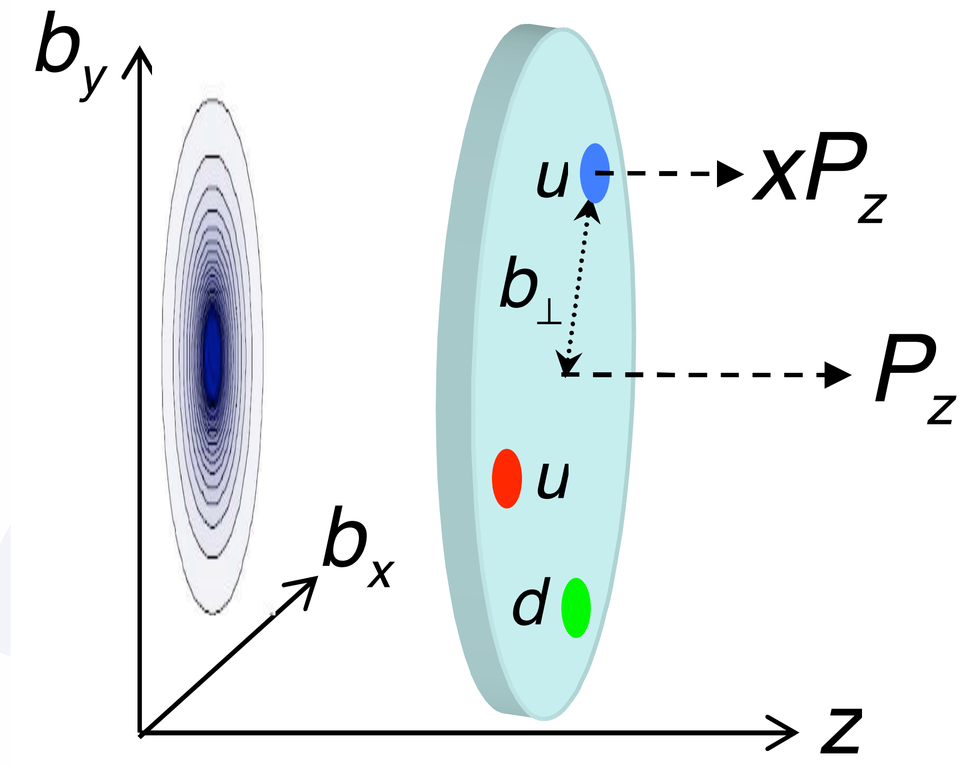


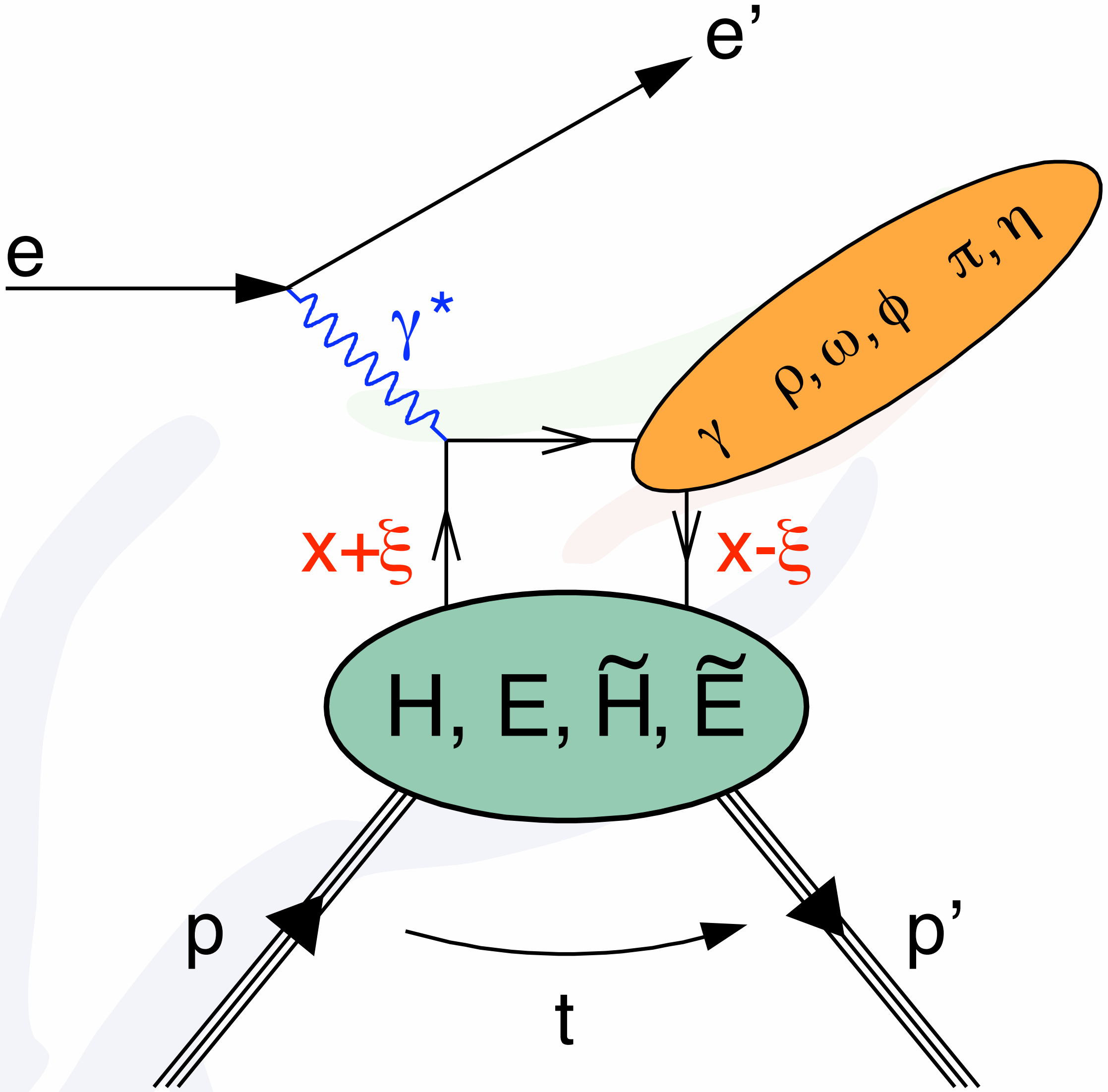


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

ξ: half the longitudinal momentum change $\approx x_B/(2-x_B)$

GPDs in exclusive reactions

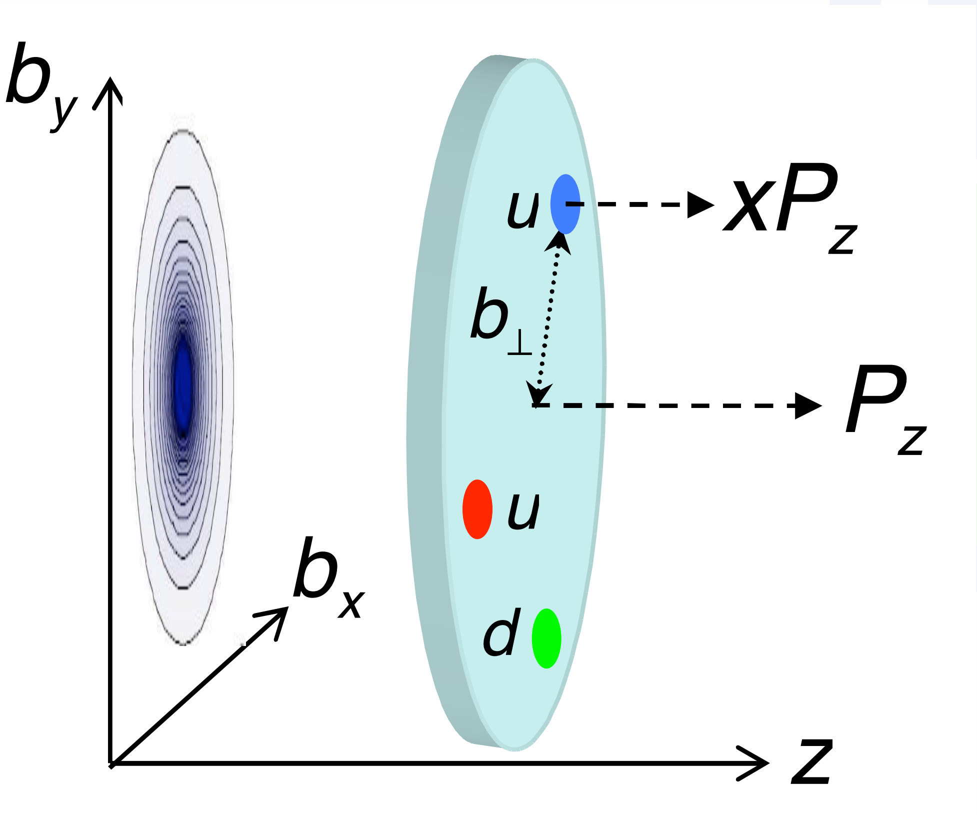


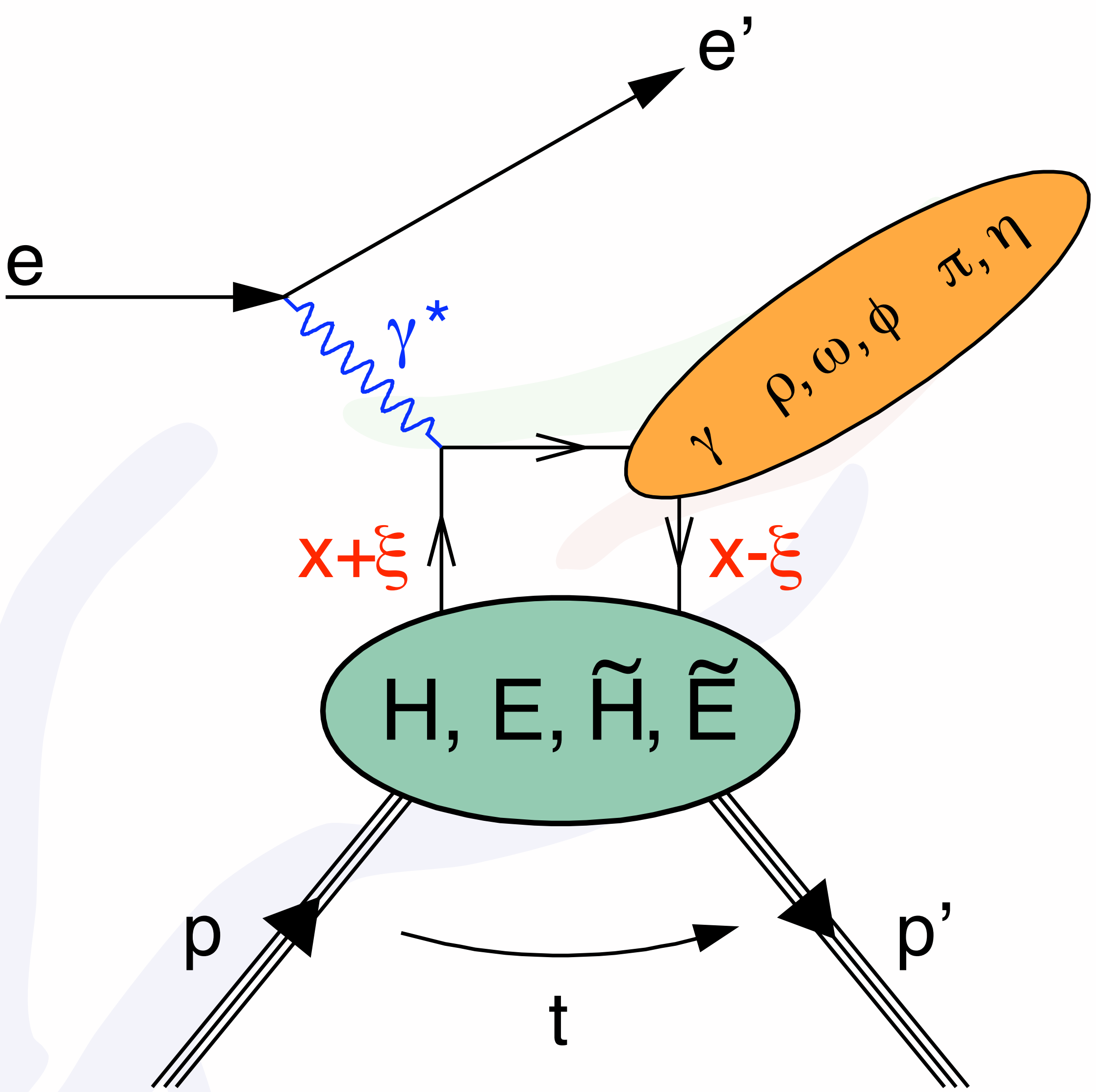


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

GPDs in exclusive reactions





	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\tilde{H}$
nucleon helicity flip	E	$\tilde{E}$

(+ 4 more chiral-odd functions)

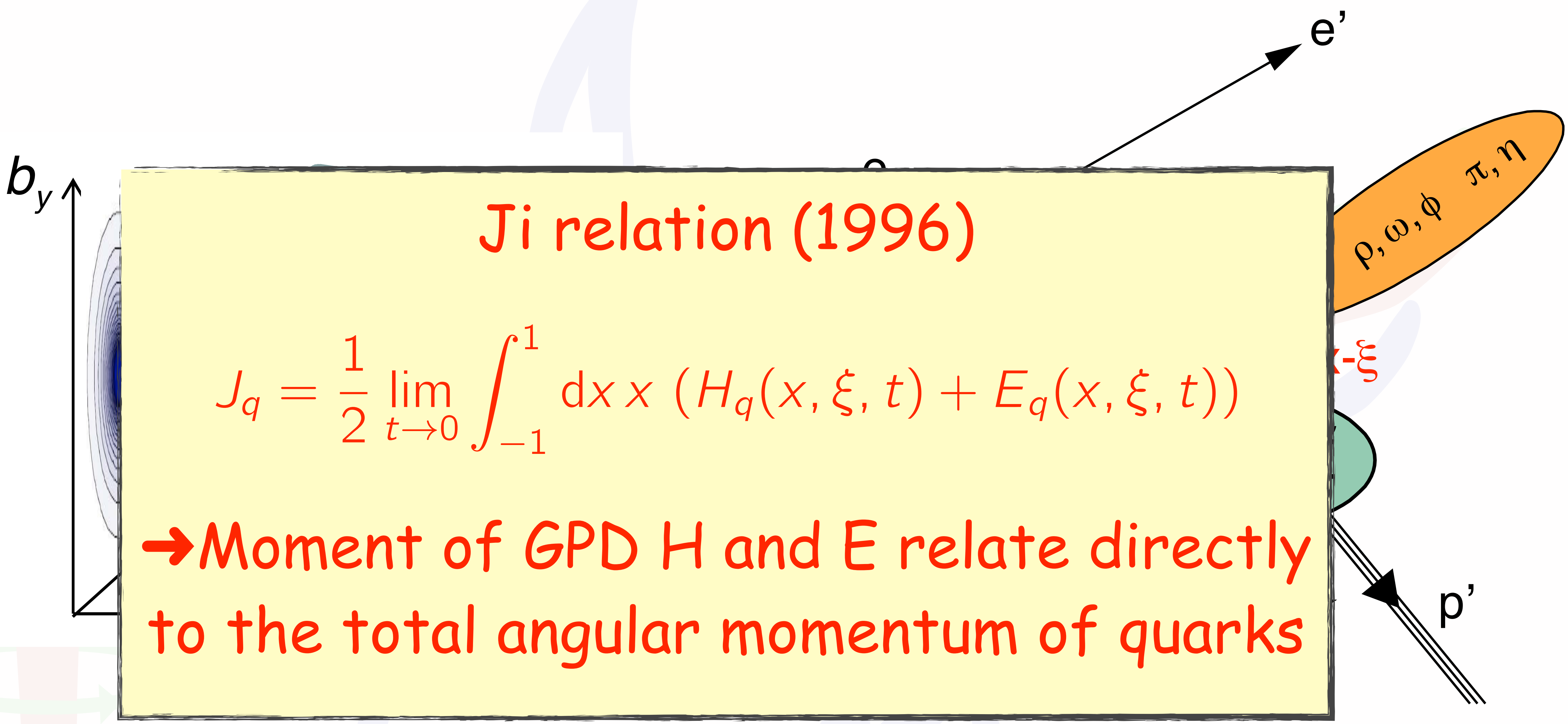
$$\int \mathrm{d}x H^q(x, \xi, t) = F_1^q(t)$$

$$\int \mathrm{d}x E^q(x, \xi, t) = F_2^q(t)$$

$$H^q(x, \xi = 0, t = 0) = q(x)$$

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

GPDs in exclusive reactions



Ji relation (1996)

$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \, (H_q(x, \xi, t) + E_q(x, \xi, t))$$

➔Moment of GPD H and E relate directly to the total angular momentum of quarks

$$\int \mathrm{d}x H^q(x, \xi, t) = F_1^q(t)$$

$$\int \mathrm{d}x E^q(x, \xi, t) = F_2^q(t)$$

$$H^q(x, \xi = 0, t = 0) = q(x)$$

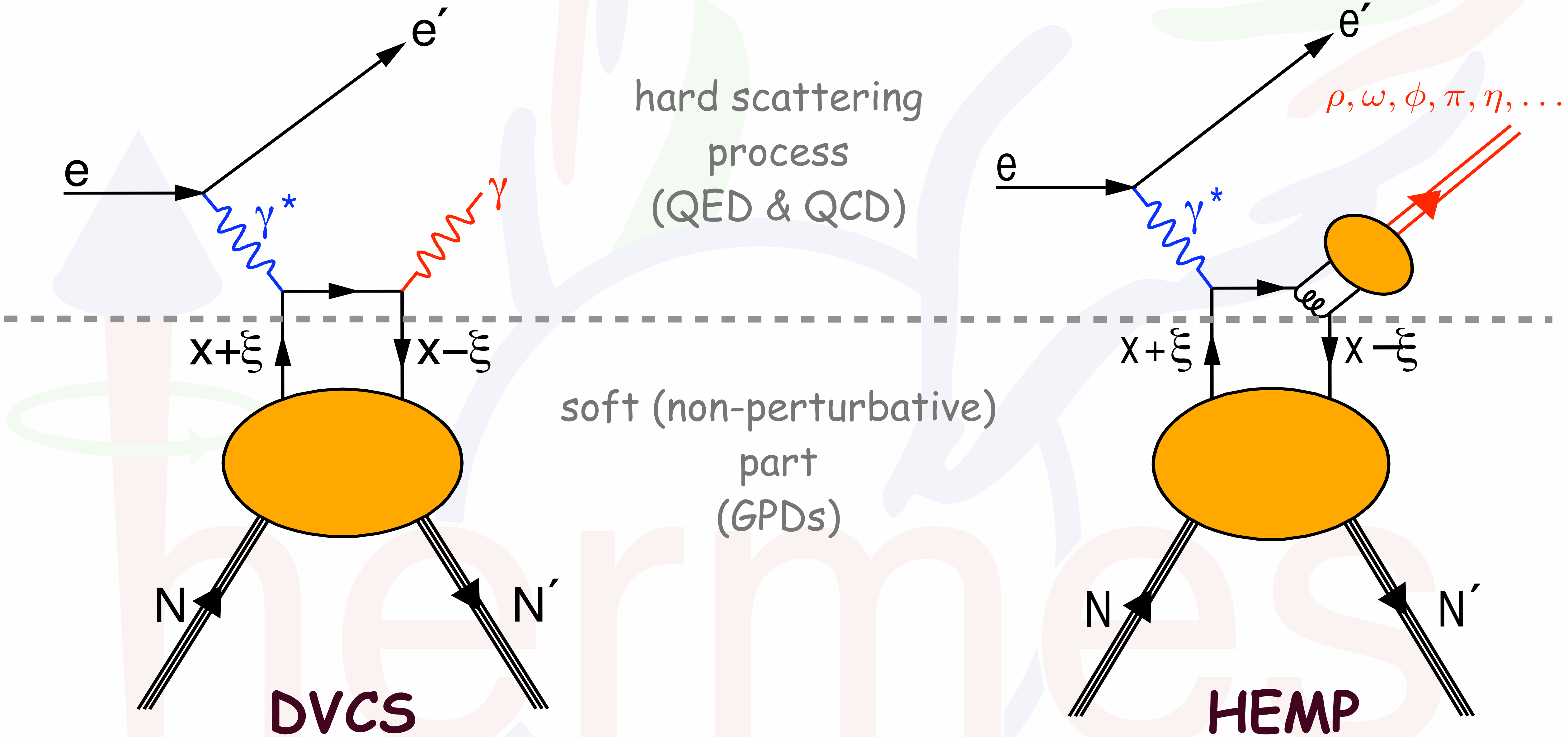
$$\widetilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

GPDs in exclusive reactions

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



hard scattering
process
(QED & QCD)

soft (non-perturbative)
part
(GPDs)

DVCS

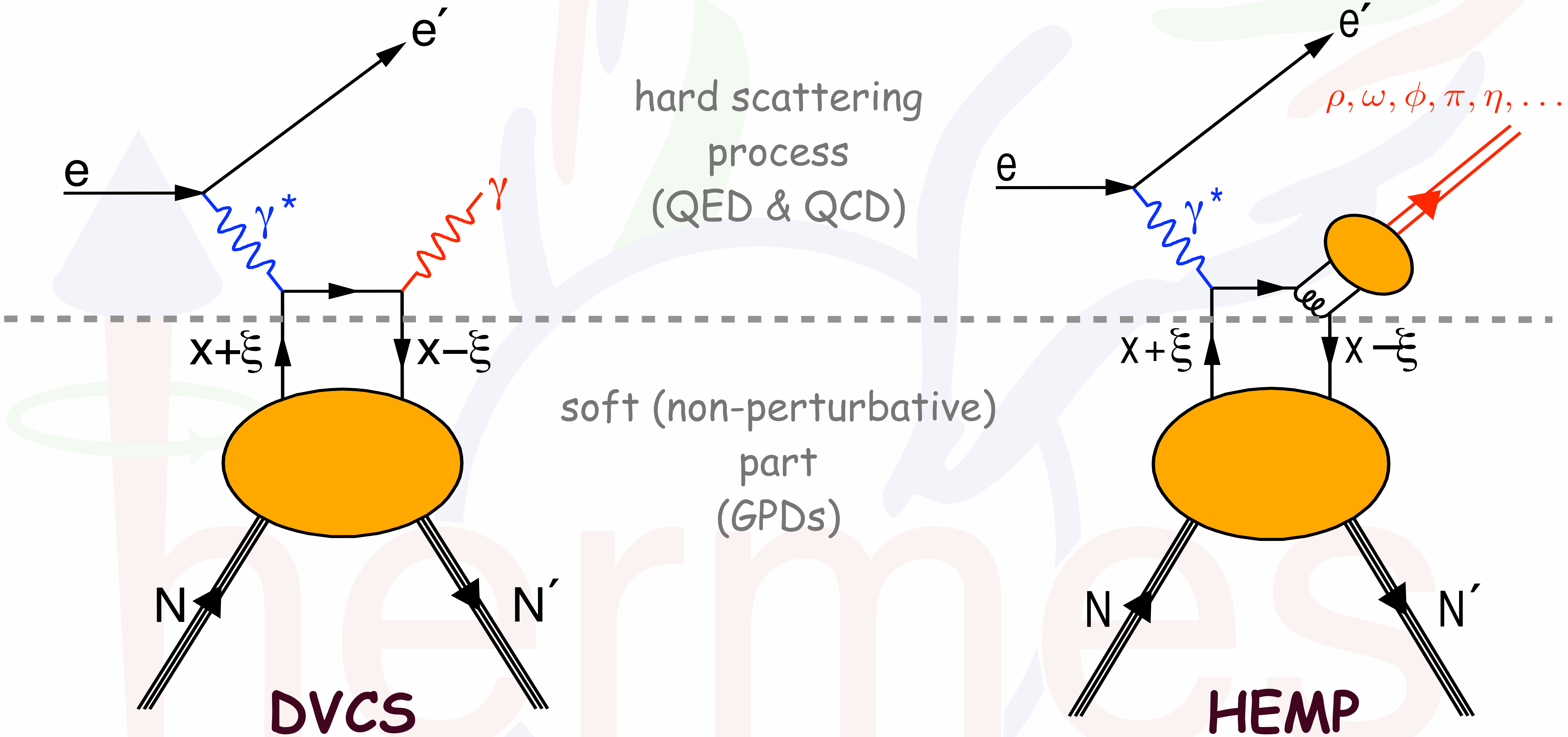
deeply virtual Compton scattering

HEMP

hard exclusive meson production

GPDs in exclusive reactions

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



hard scattering
process
(QED & QCD)

soft (non-perturbative)
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(GPDs)

DVCS

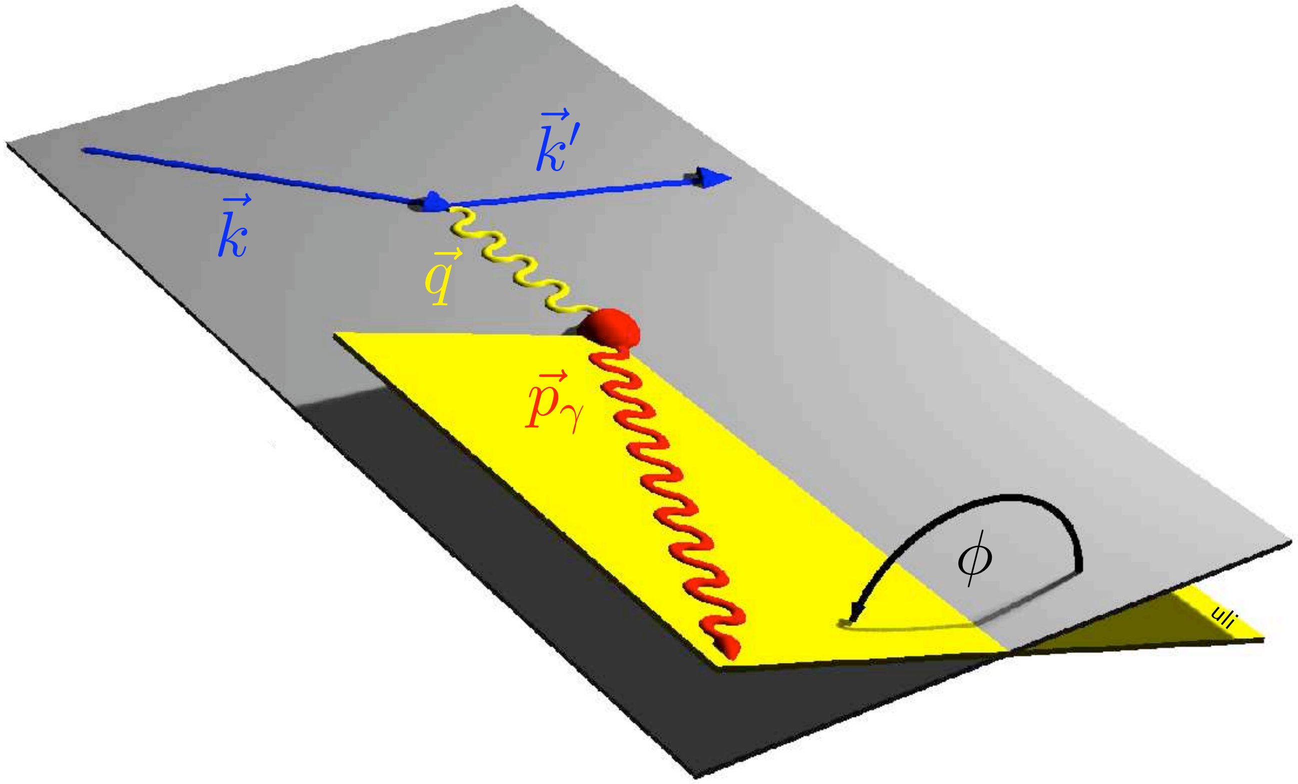
deeply virtual Compton scattering

HEMP

hard exclusive meson production

☛ GS, Tuesday

azimuthal dependences in DVCS/BH



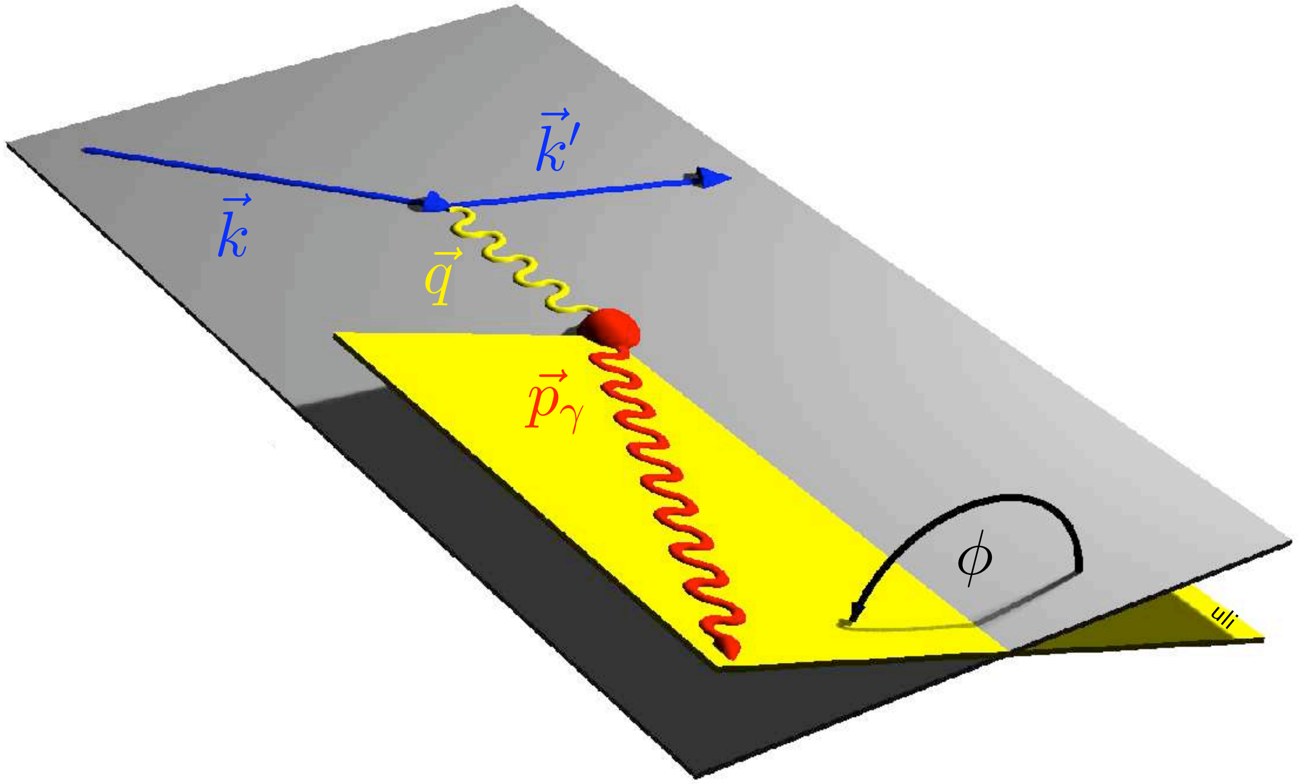
- beam polarization P_B
- beam charge C_B
- here: unpolarized target

Fourier expansion for ϕ:

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

calculable in QED
(using FF measurements)

azimuthal dependences in DVCS/BH



- beam polarization P_B
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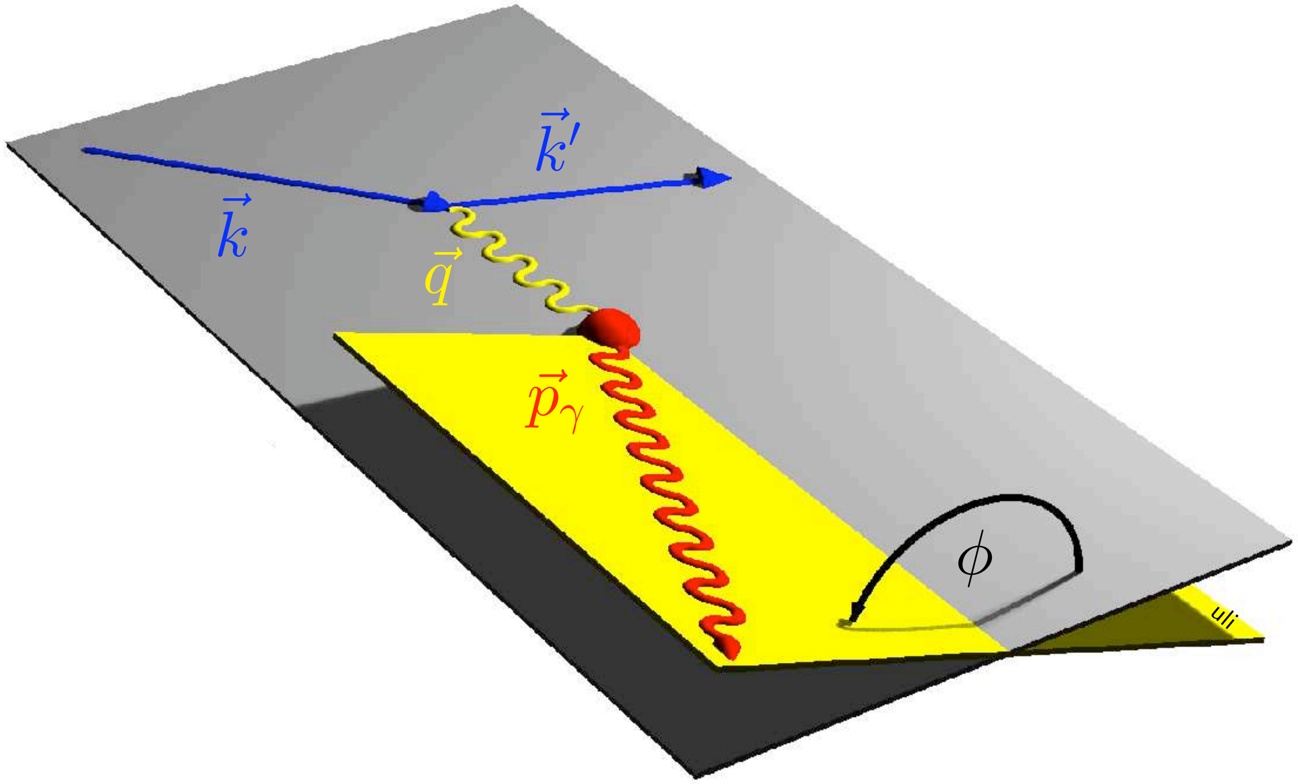
- here: unpolarized target

Fourier expansion for ϕ:

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

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

azimuthal dependences in DVCS/BH



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

Fourier expansion for ϕ:

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

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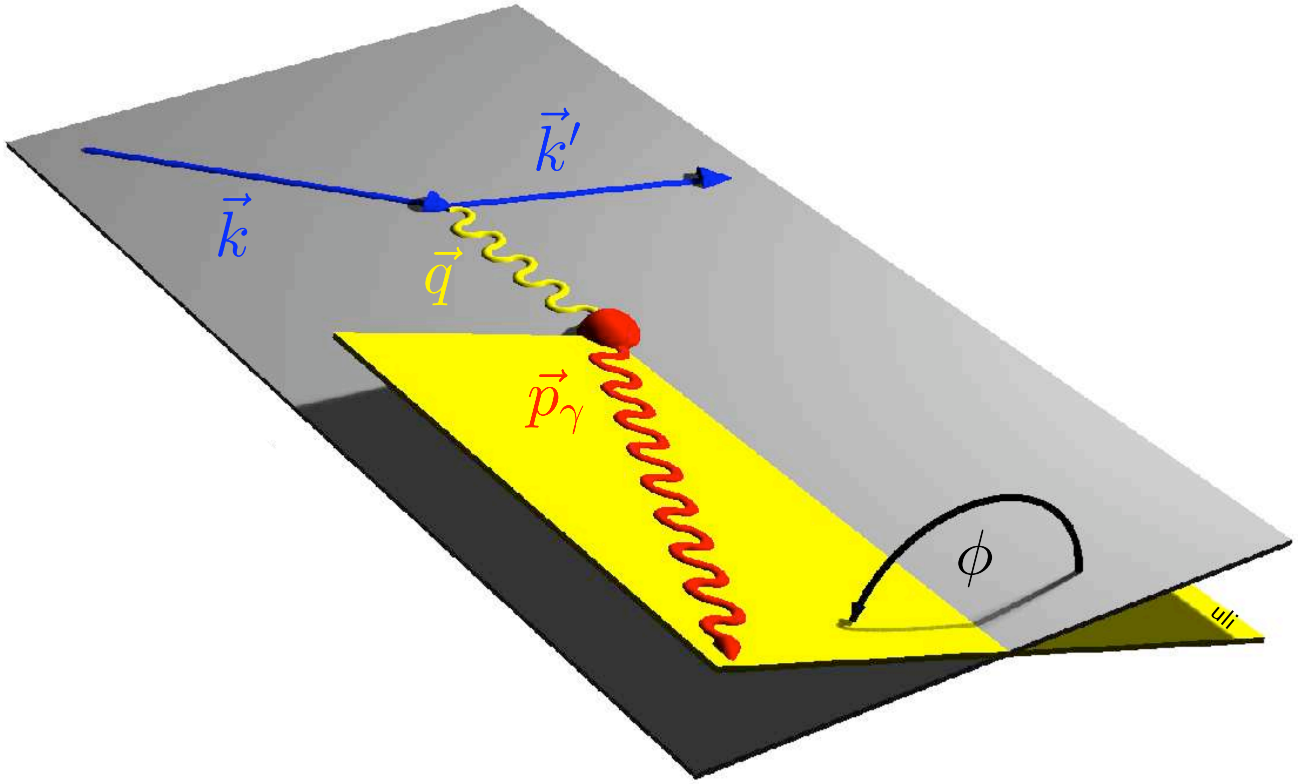
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

azimuthal dependences in DVCS/BH



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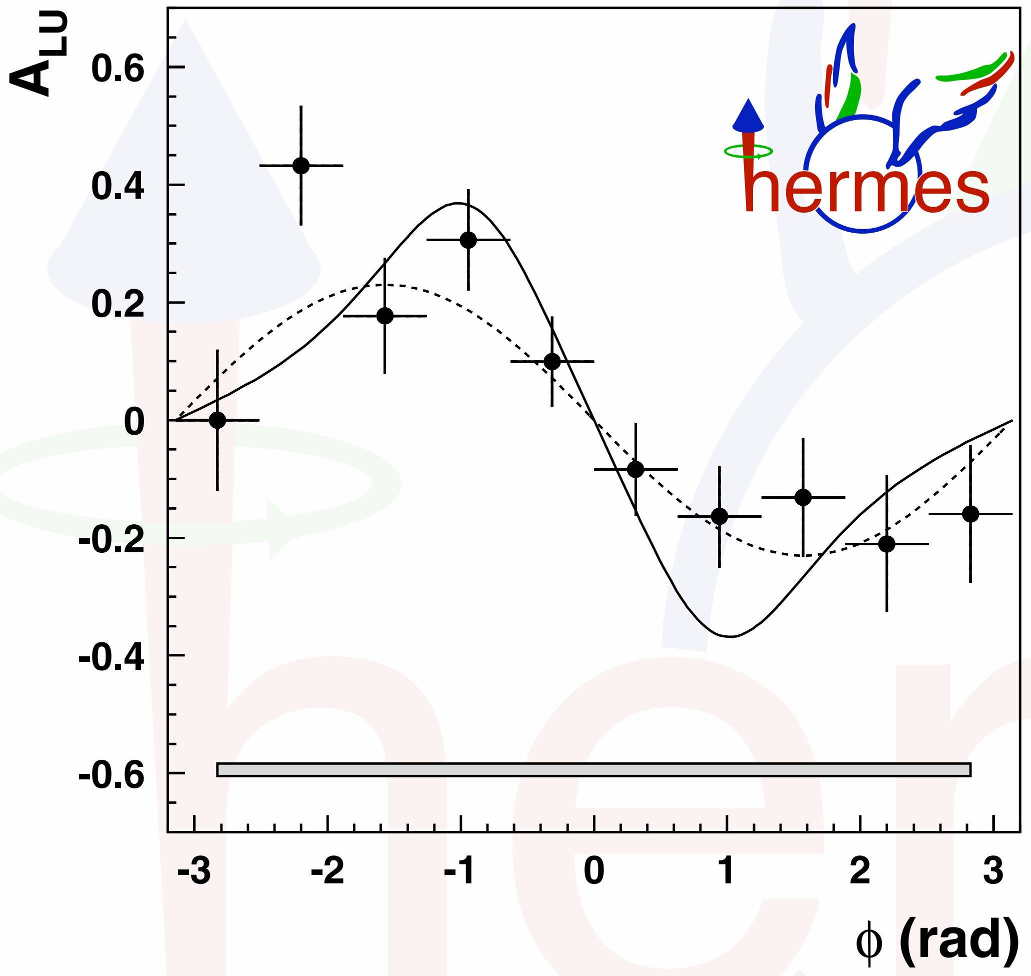
bilinear ("DVCS") or linear in GPDs

again a sine modulation ...

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



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

HERMES, PRL 87 (2001) 182001

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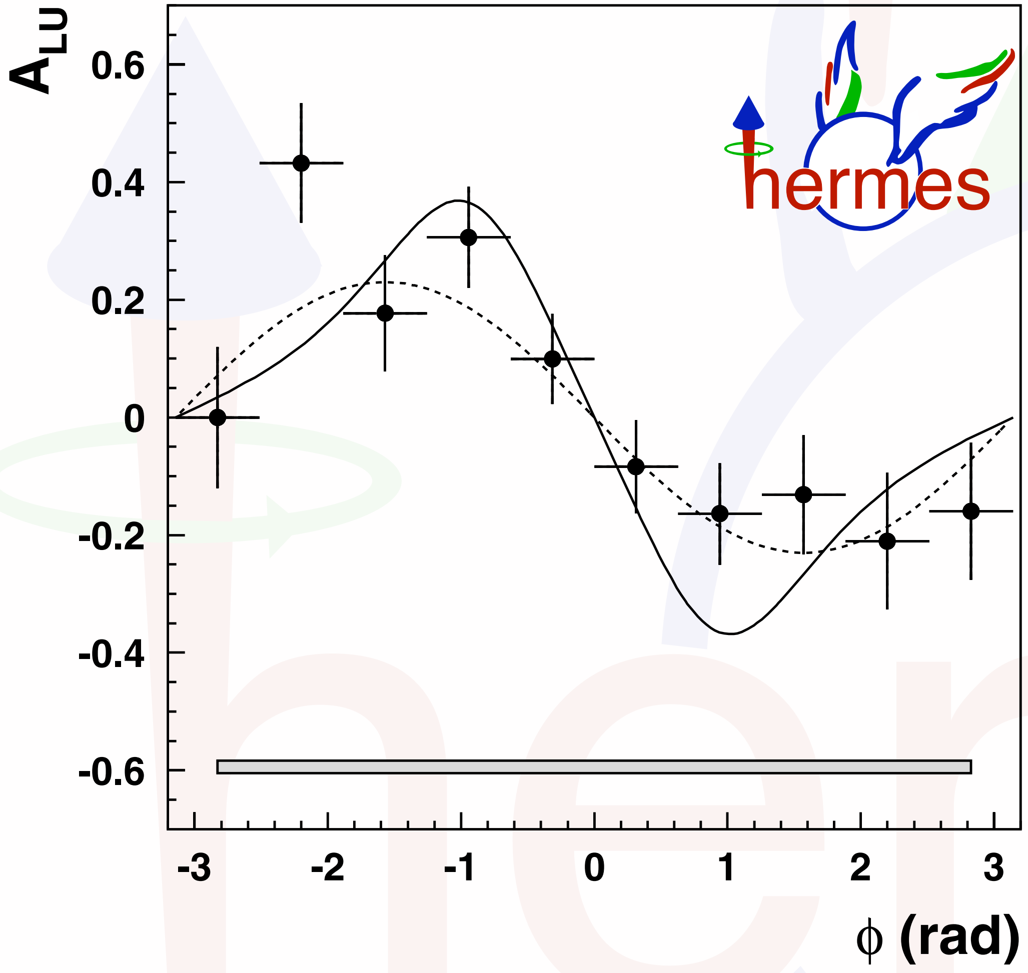
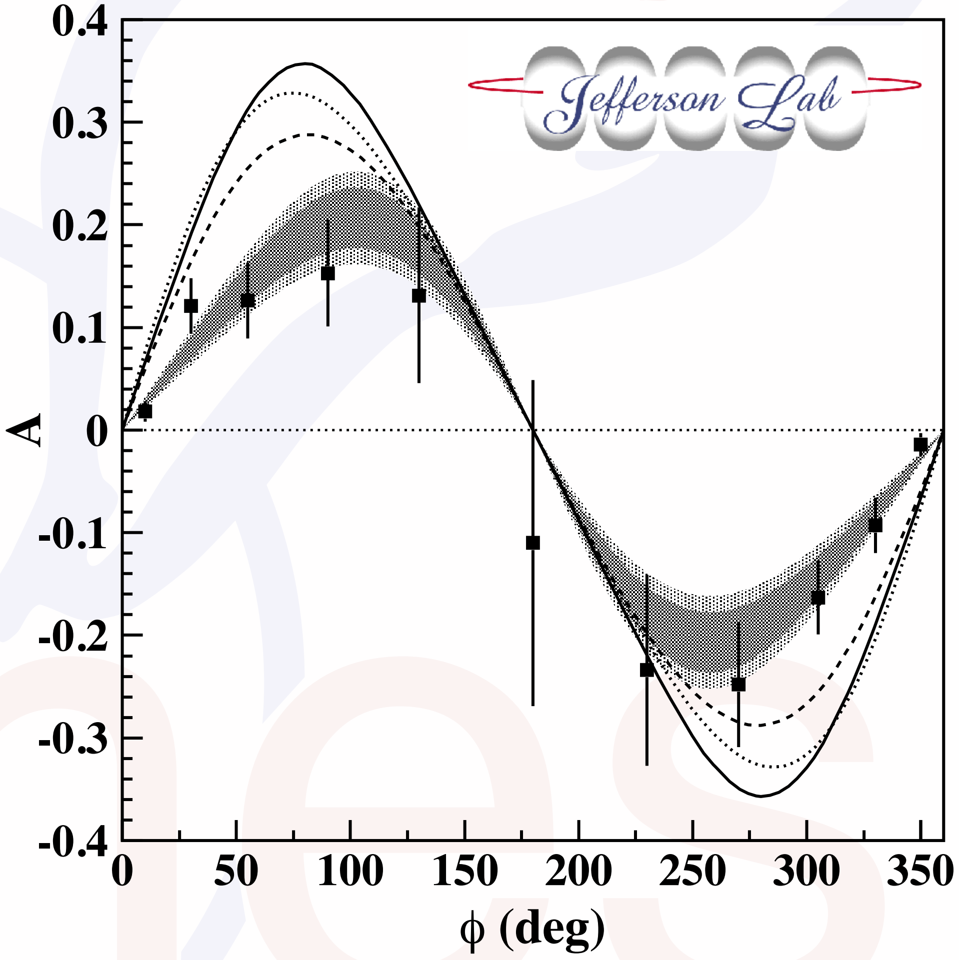


HERMES, PRL 87 (2001) 182001

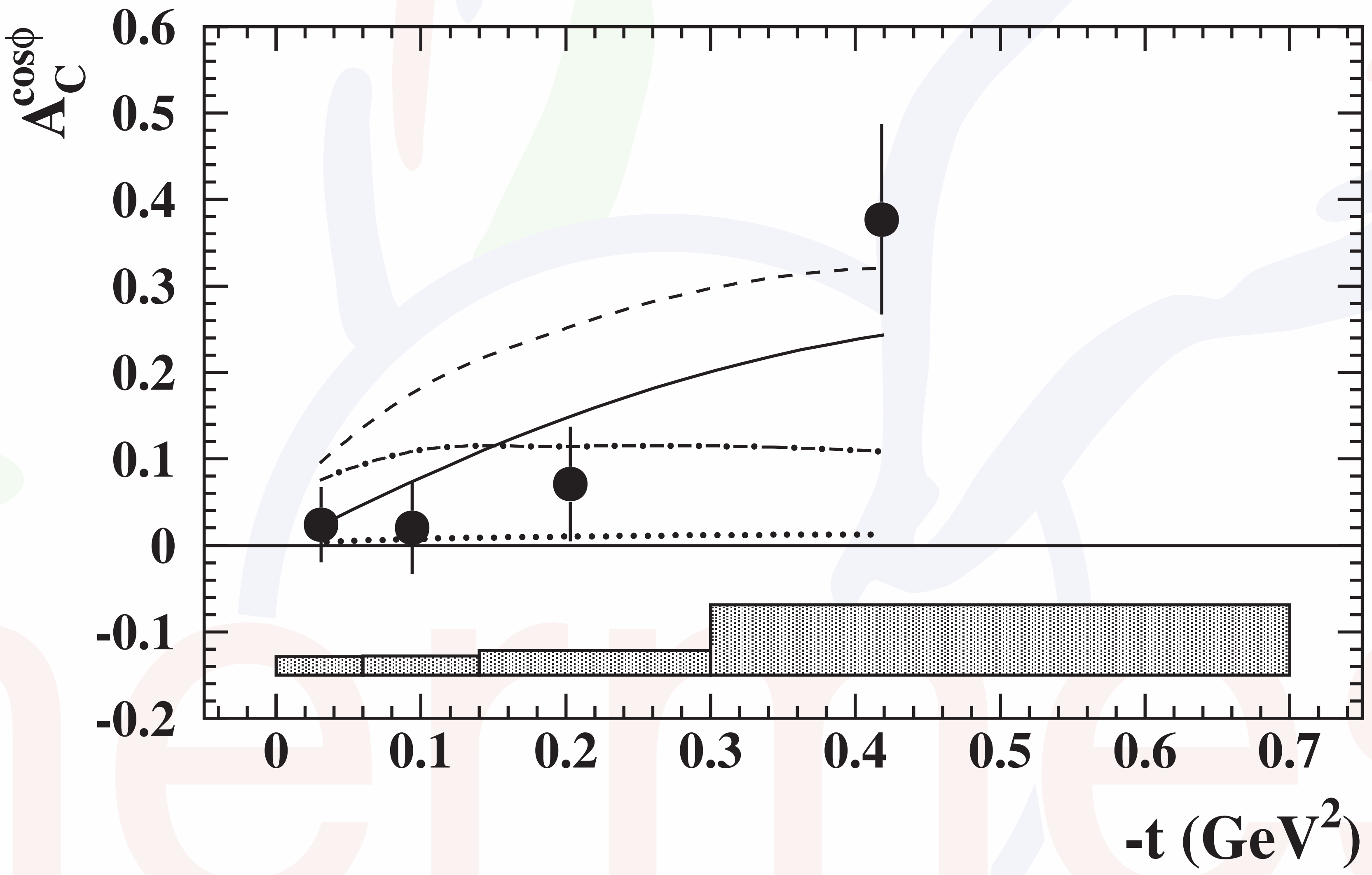


CLAS, PRL 87 (2001) 182002

still keeping “first” in the title on arXiv :-)

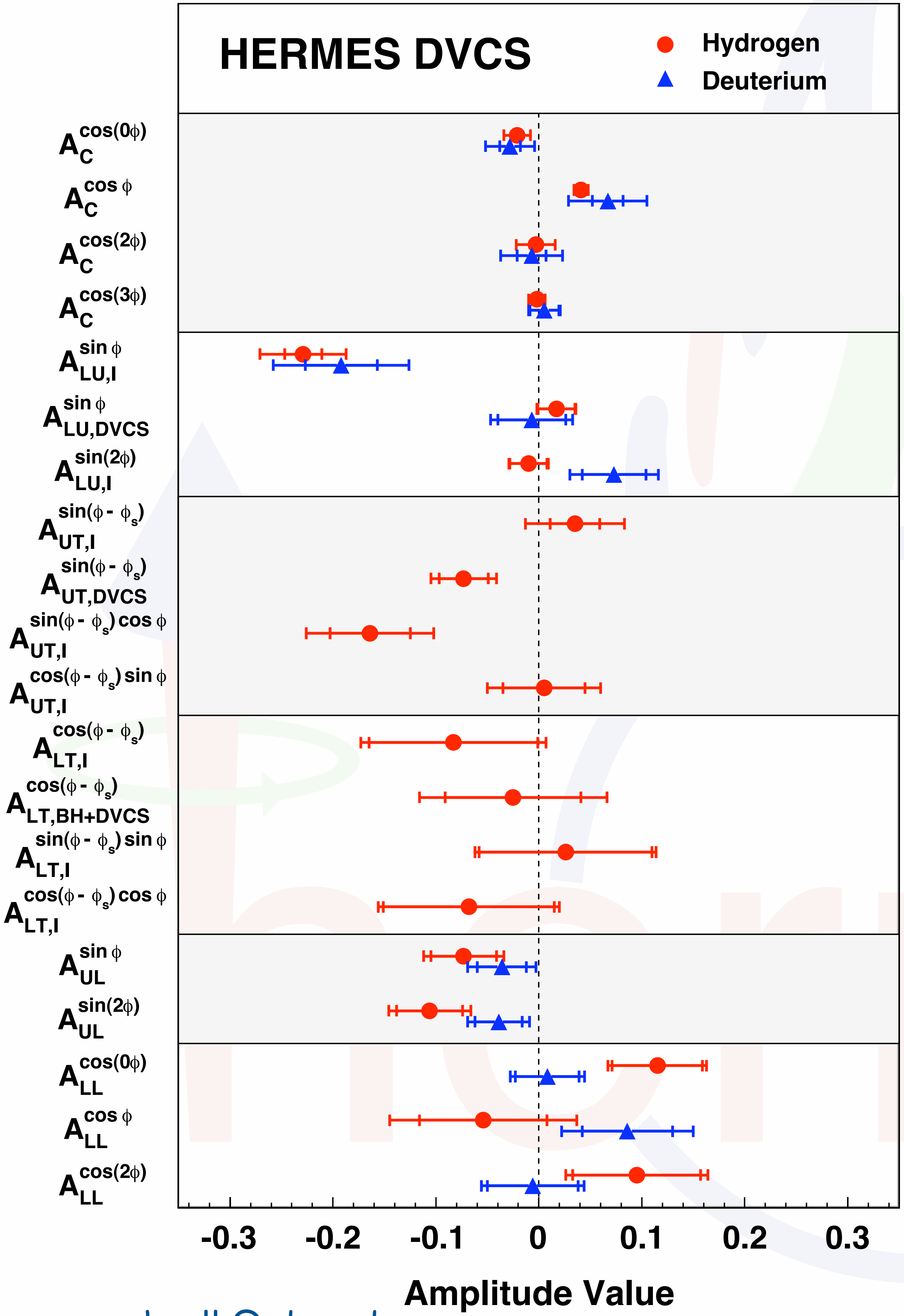
… beam-charge asymmetry …

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



- 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

Beam-helicity asymmetry:

GPD H

PRL 87 (2001) 182001
JHEP 07 (2012) 032

Transverse target spin asymmetries:

GPD E from proton target

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

Longitudinal target spin asymmetry:

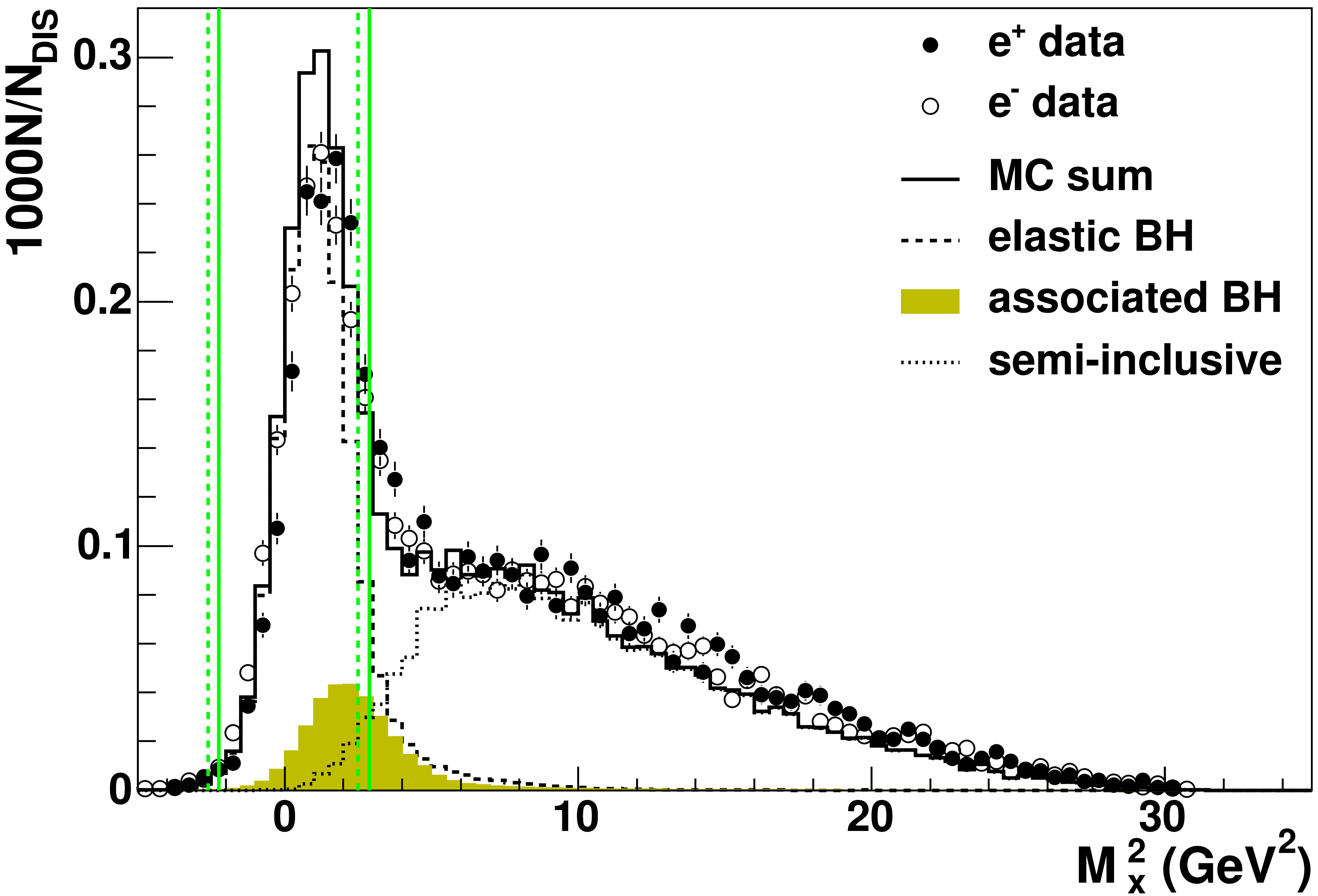
GPD $\tilde{H}$

Double-spin asymmetry:

GPD $\tilde{H}$

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

exclusivity: missing-mass technique



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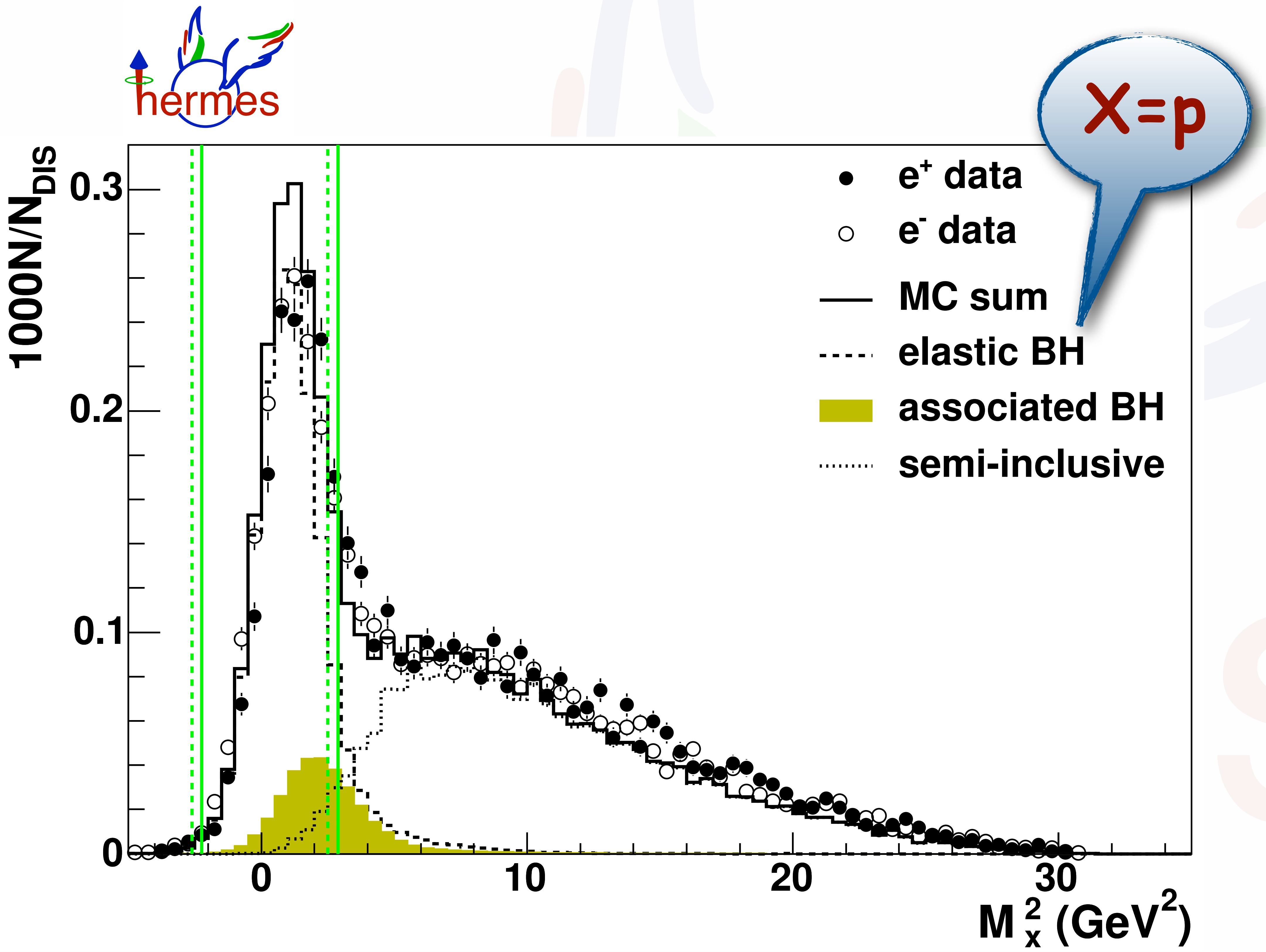

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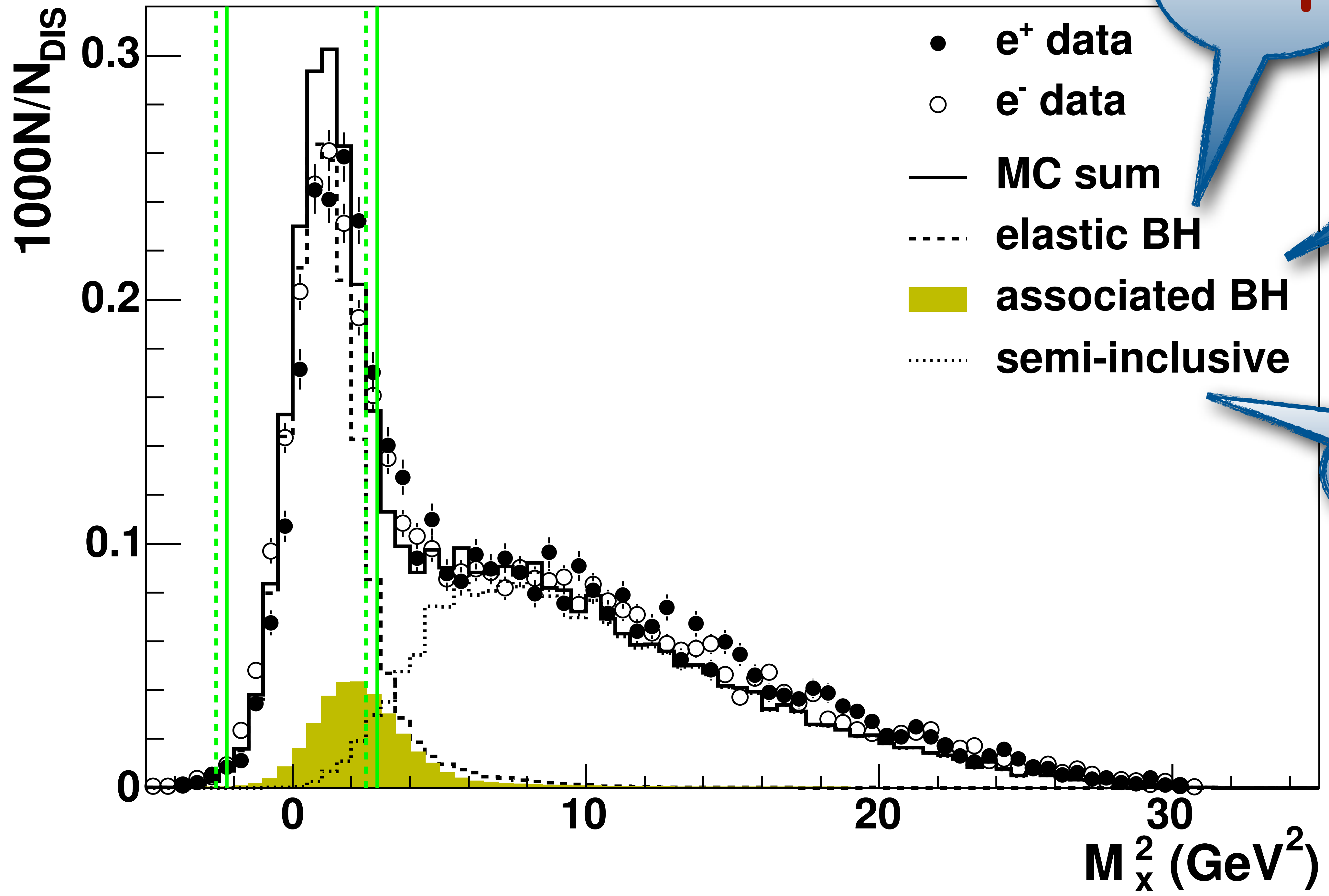
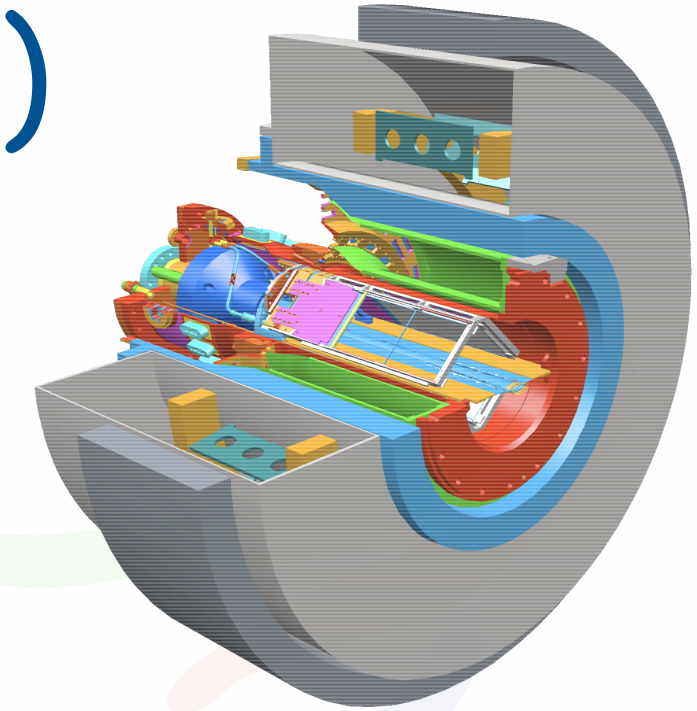


$X=p$

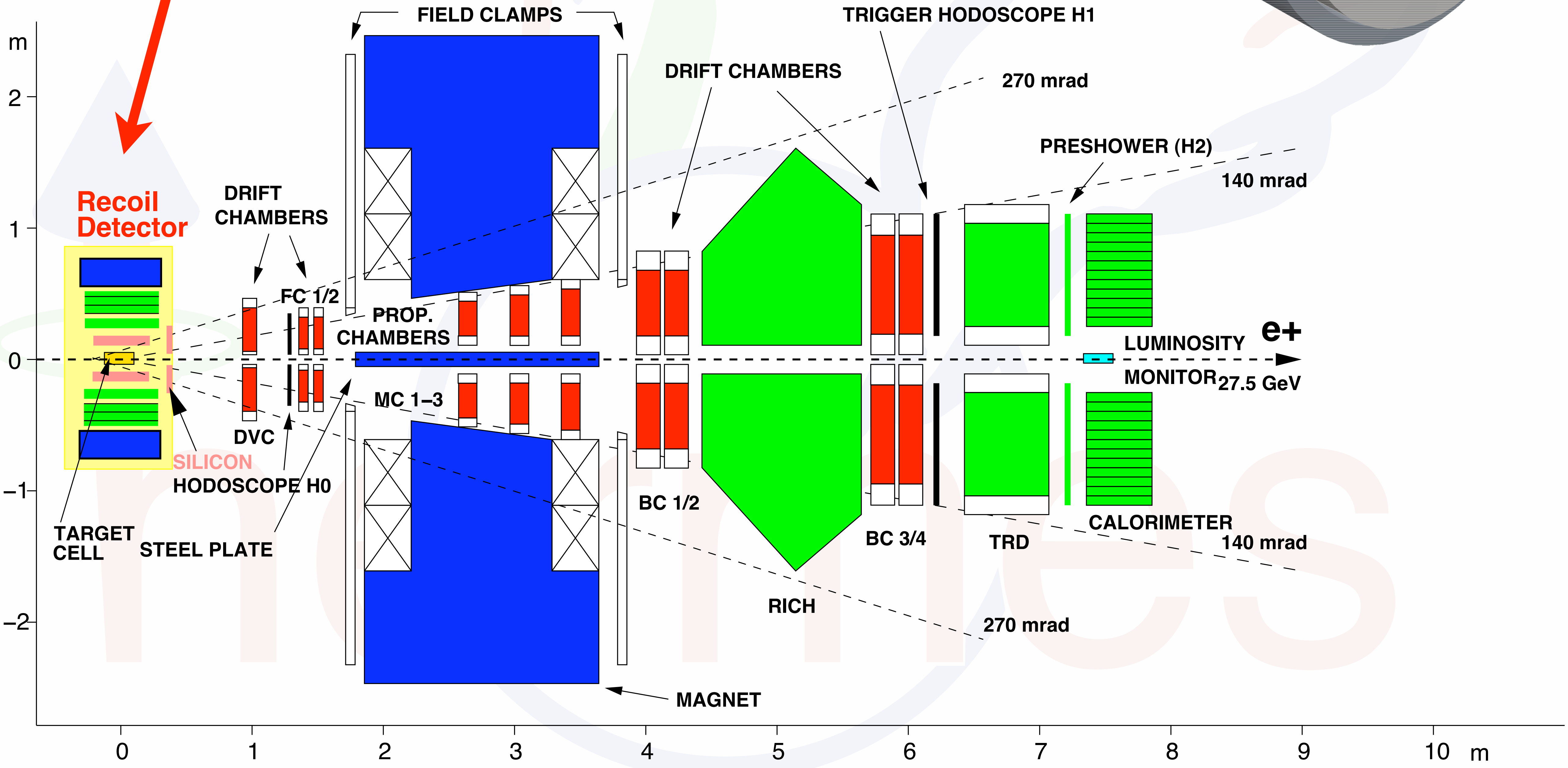
$X=\Delta^+$

$X=\pi^0+...$

HERMES detector (2006/07)

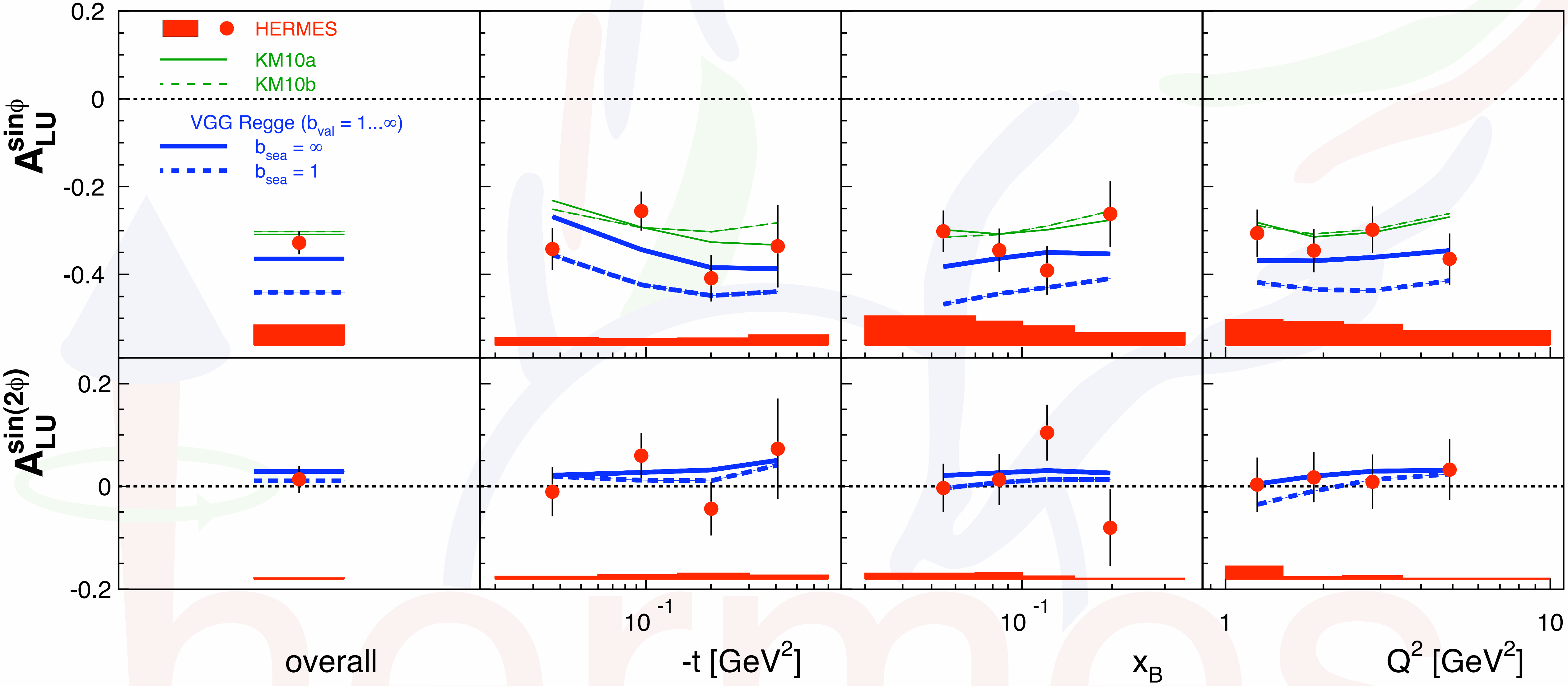


detection of recoiling proton



DVCS with recoil detector

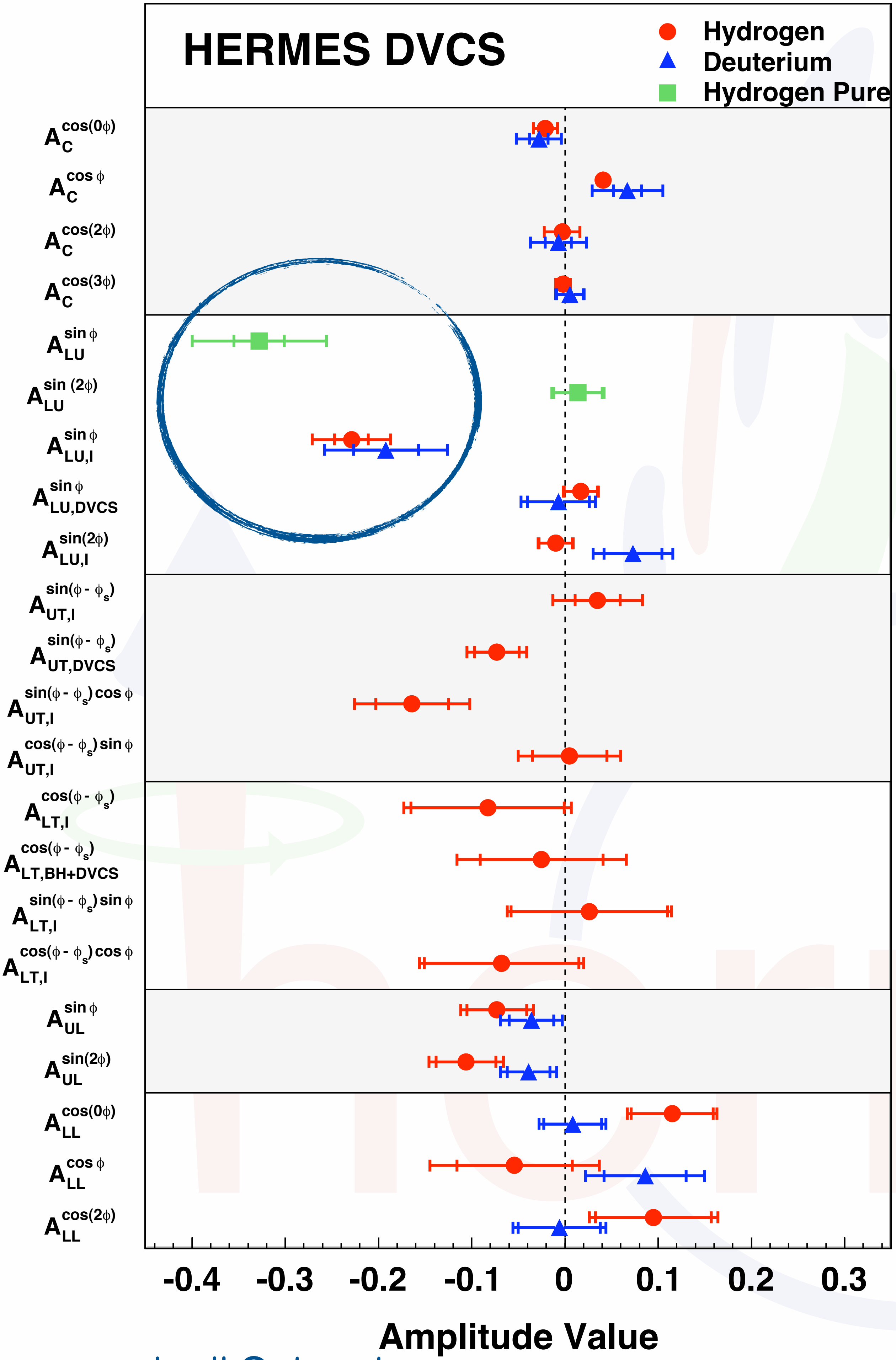
[A. Airapetian et al., JHEP 10 (2012) 042]



good agreement with models

KM10 - K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1
VGG - M. Vanderhaeghen et al., Phys. Rev. D 60 (1999) 094017

DVCS at HERMES



recoil detector:

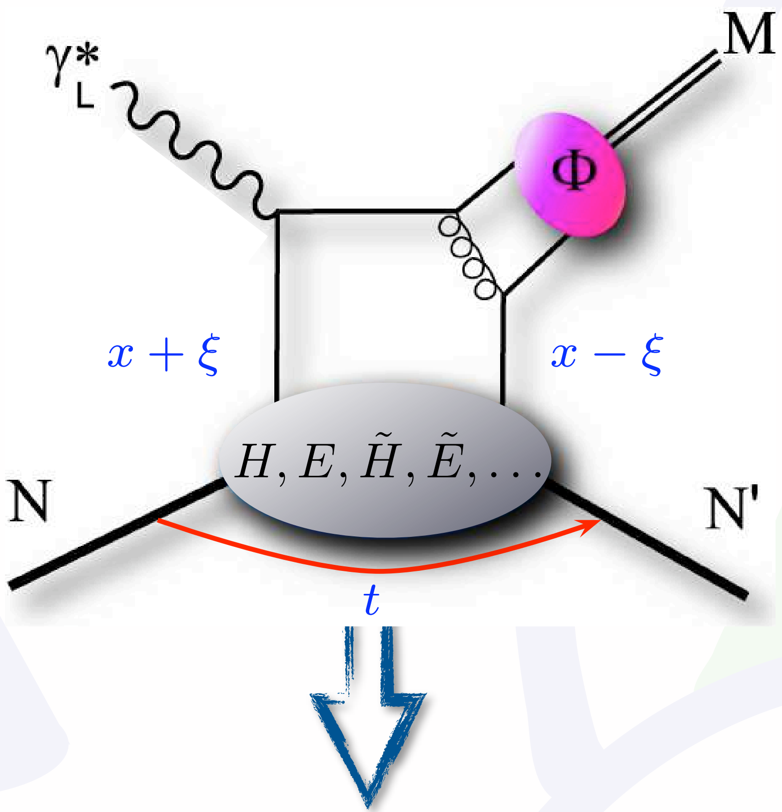
basically **no contamination**

-> clean interpretation

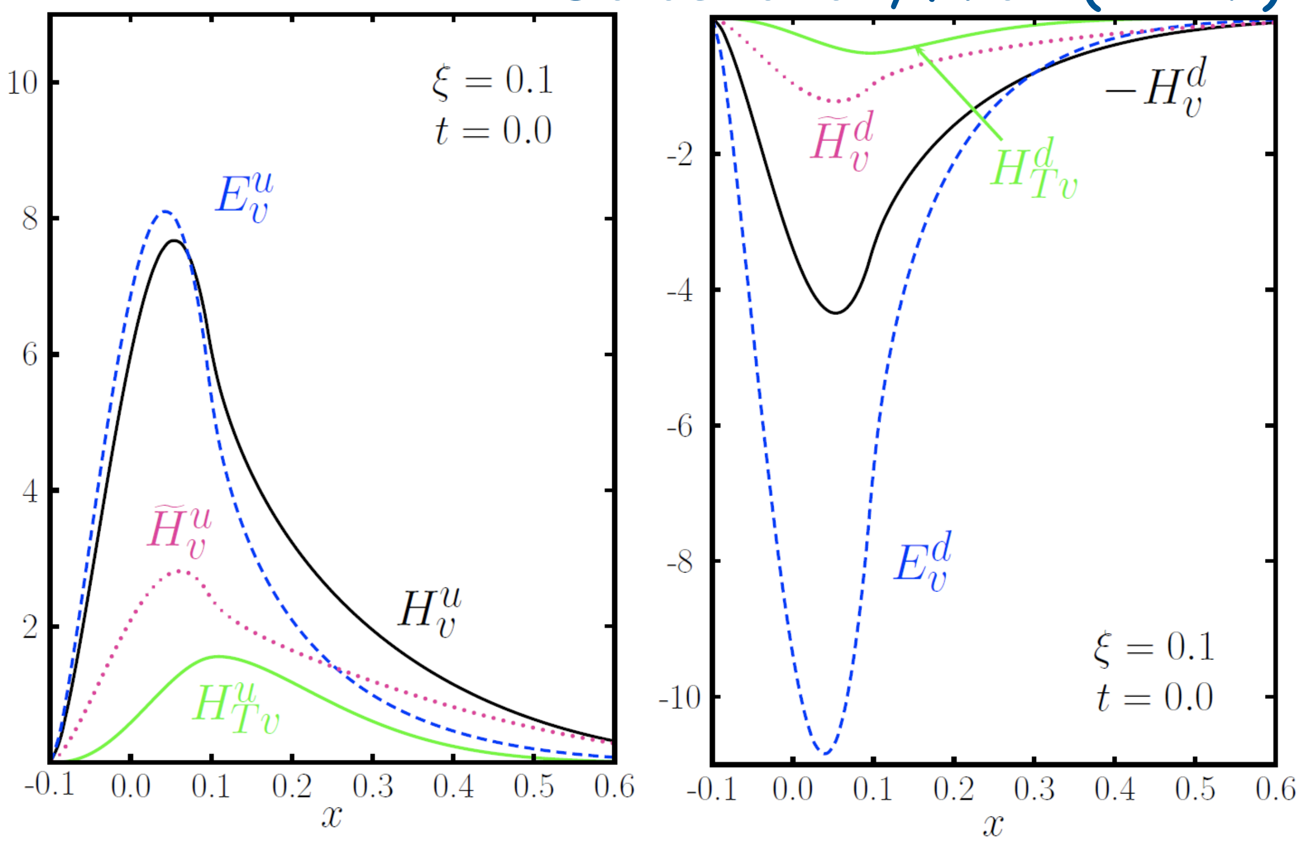
indication of **larger amplitudes for pure sample**

(-> assoc. DVCS in "traditional" analysis mainly dilution, supported by **HERMES** [JHEP 01 (2014) 077])

GPDs - a nice success story!



Goloskokov, Kroll (2007)



gunar.schnell @ desy.de

SPIN 2018 - Ferrara - Sept. 12th, 2018

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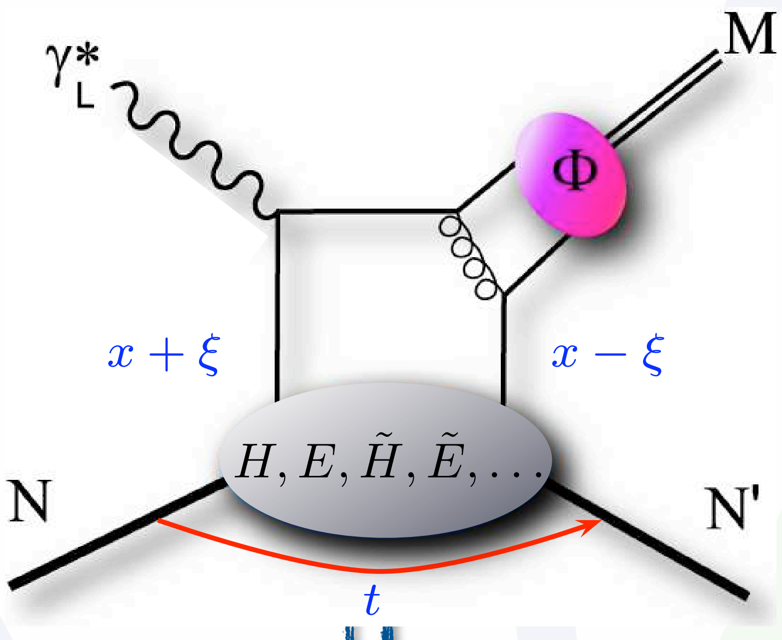

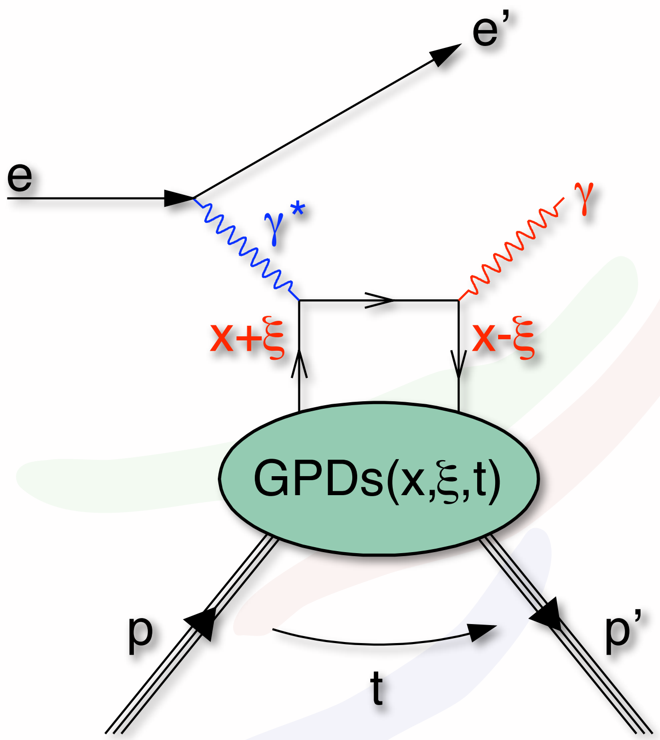

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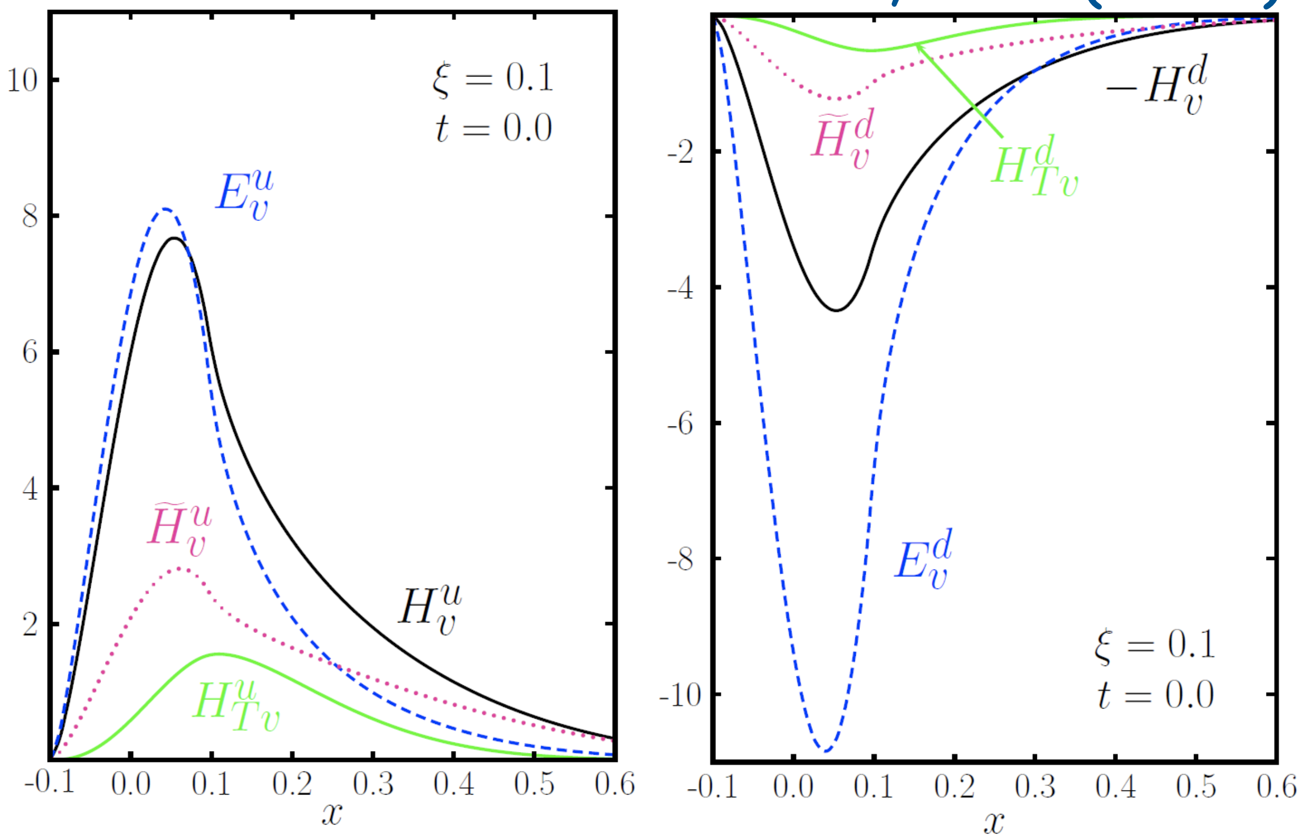
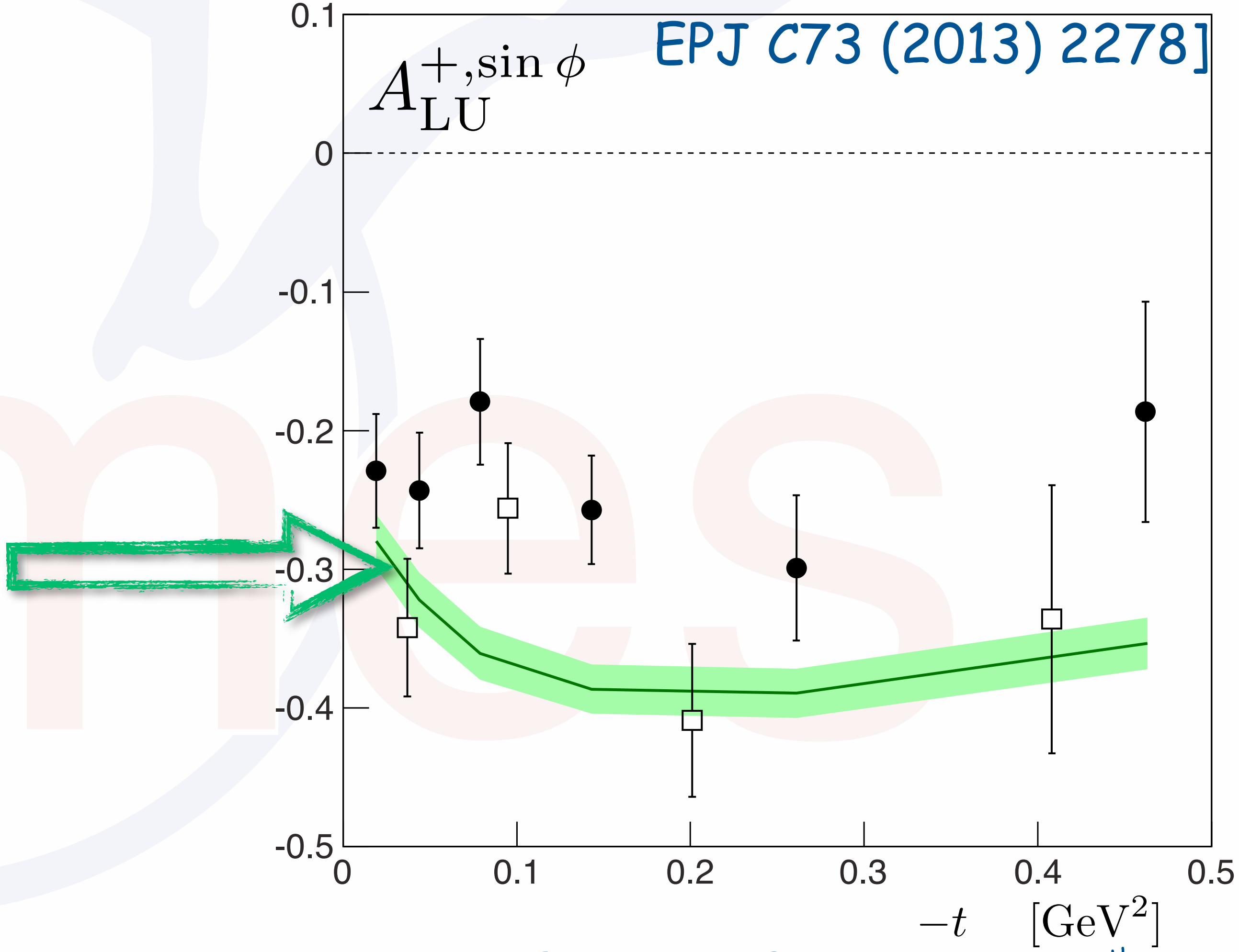


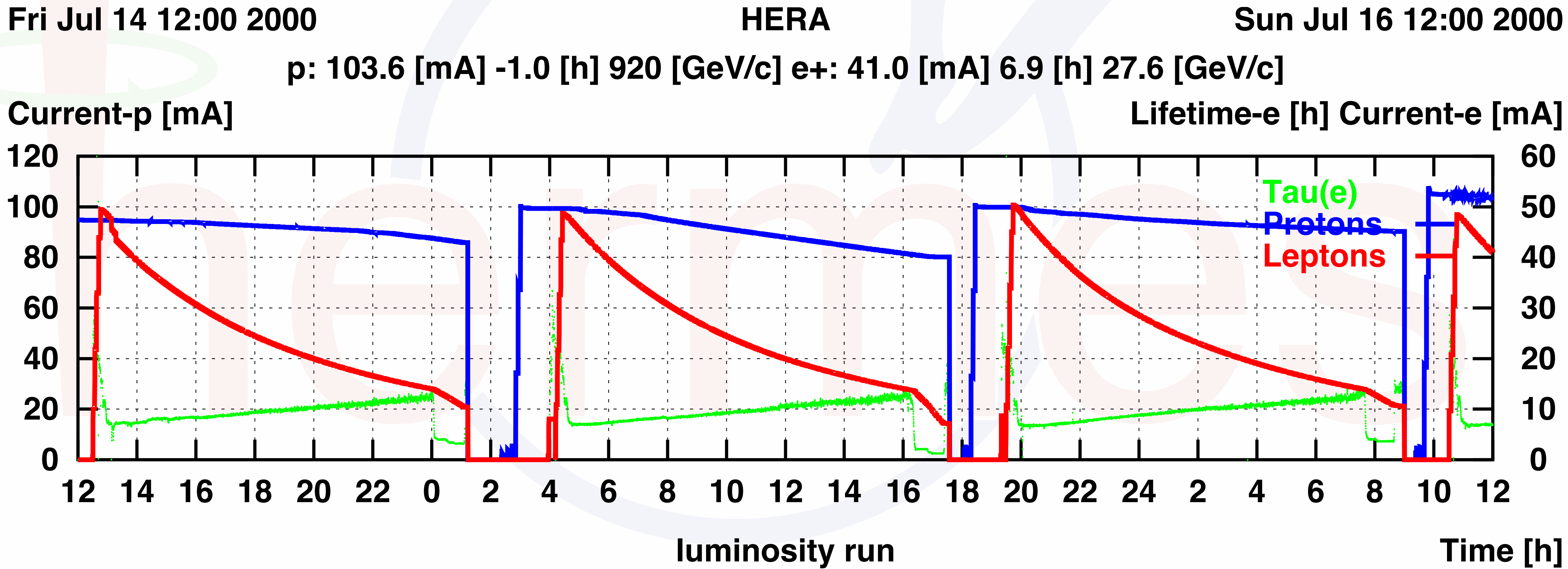
[P. Kroll, H. Moutarde, F. Sabatie, EPJ C73 (2013) 2278]



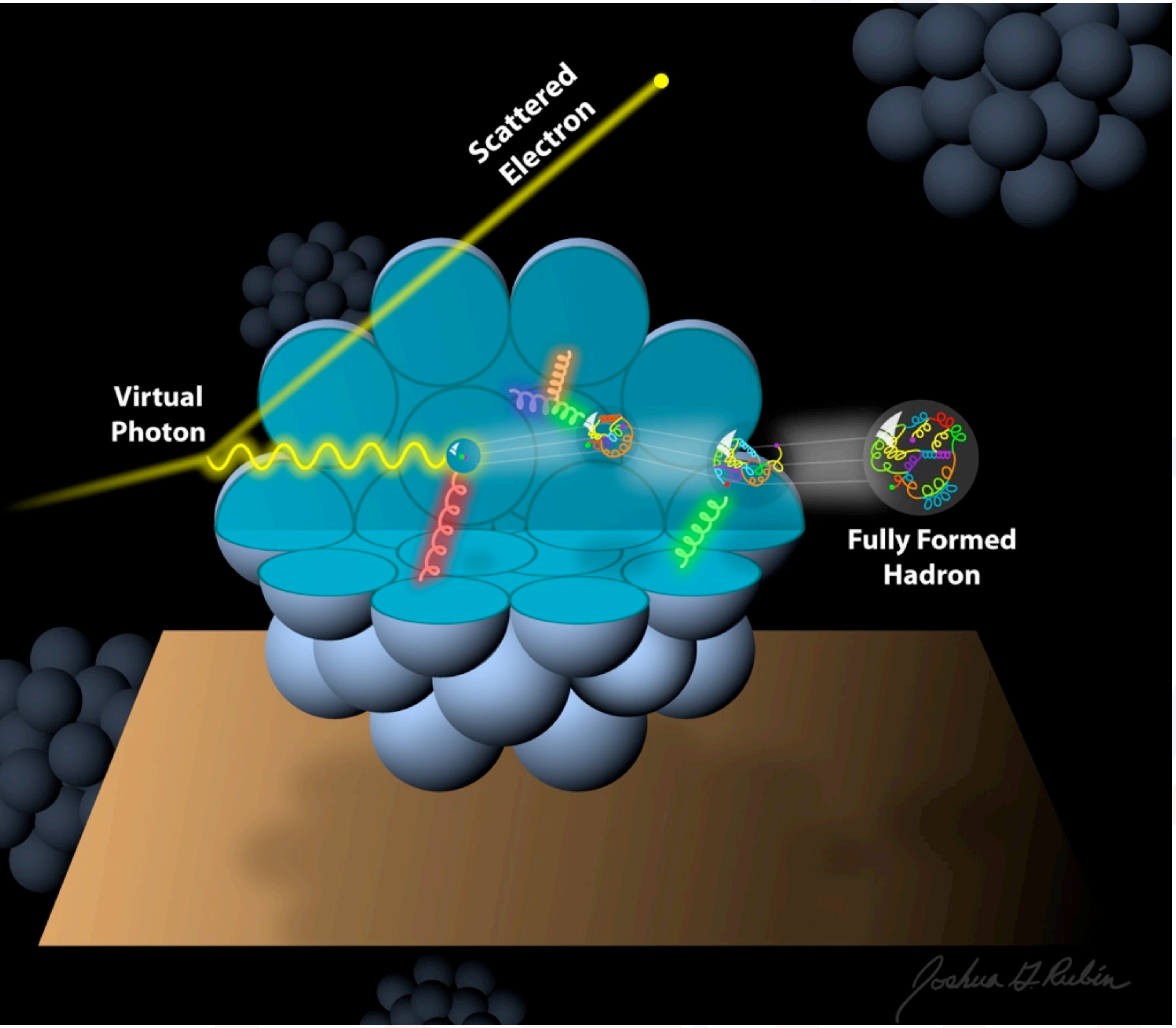
last but not least

unpolarized semi-inclusive DIS

- HERMES collected large data sets on hadron multiplicities
- no FOM boost because of dilution factor
- still benefit from large range of pure nuclear gas targets
- success story: dedicated high-density end-of-fill running



nuclei: a hadronization laboratory



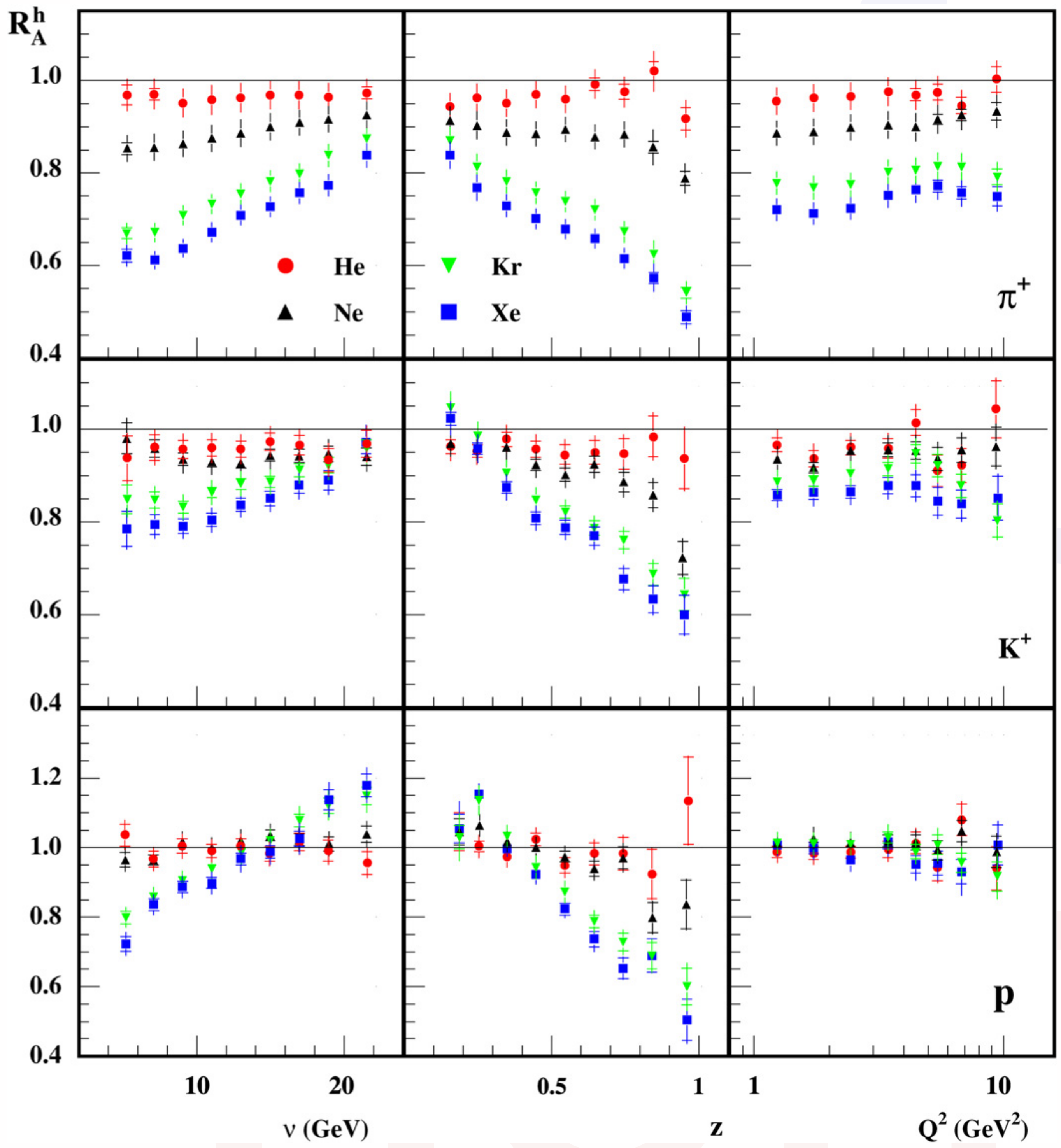
[J. Rubin]

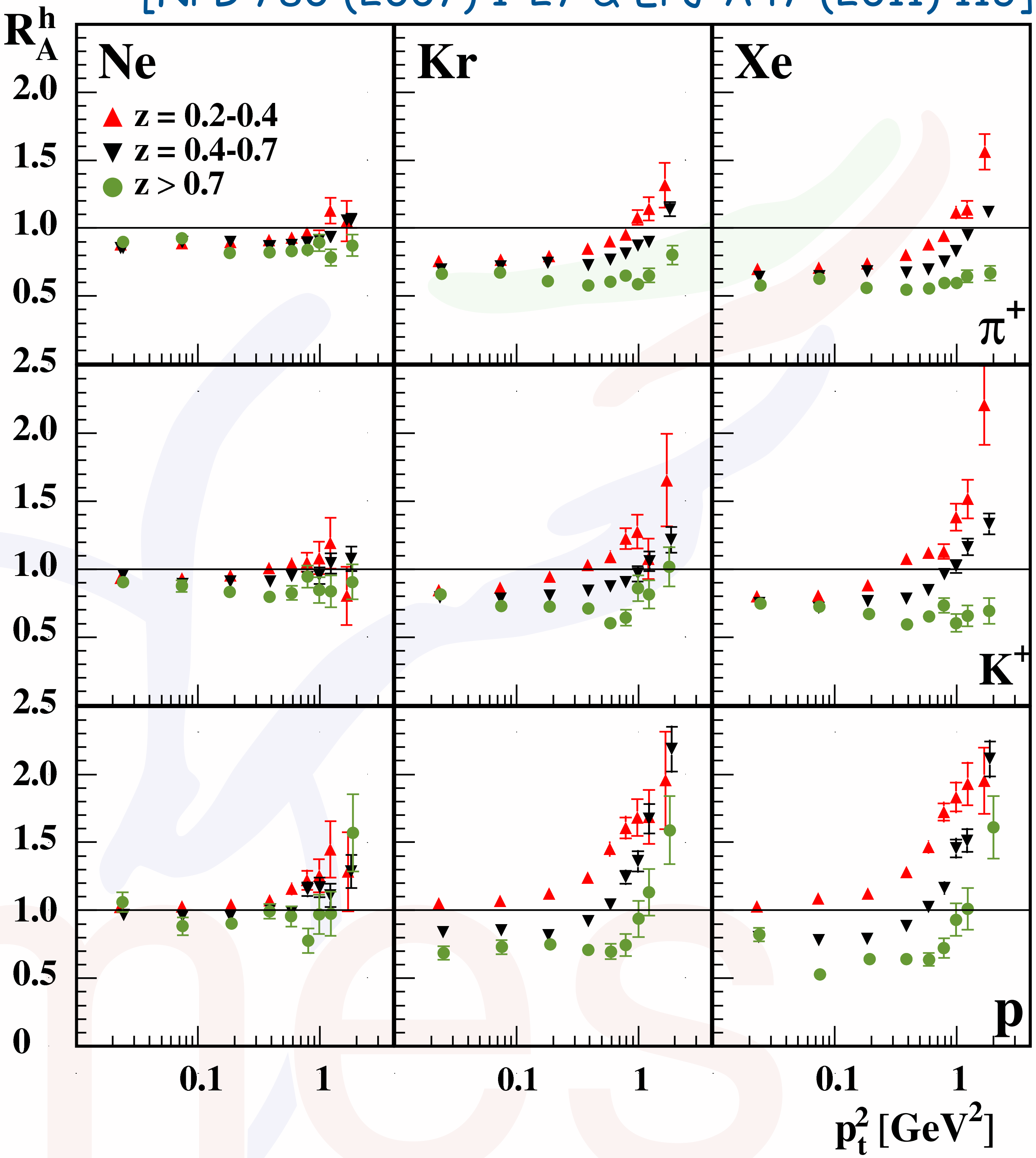
- partons in nuclear medium:
  - PDFs modified (e.g, EMC effect)
  - gluon radiation and re-scattering effects
- (pre)hadron in nuclear medium:
  - re-scattering
  - absorption
- observable: multiplicity ratios

$$\mathbf{R}_{\mathbf{A}}^{\mathbf{h}} \equiv \frac{\mathcal{M}_{\mathbf{A}}^{\mathbf{h}}}{\mathcal{M}_{\mathbf{d}}^{\mathbf{h}}}$$

nuclear attenuation

[NPB 780 (2007) 1-27 & EPJ A47 (2011) 113]

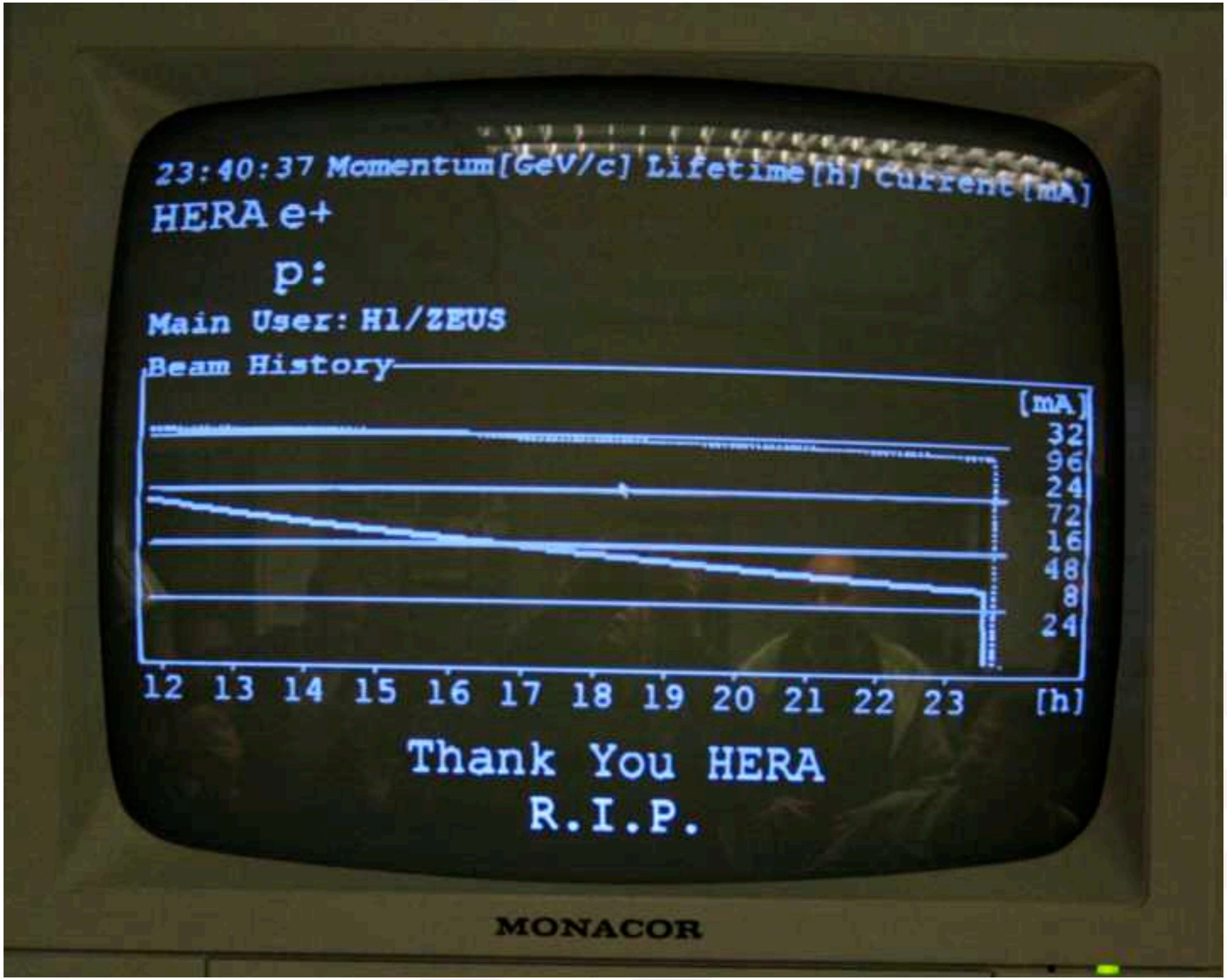




- strong mass dependence: attenuation mainly increases with *A*
- invaluable data set for hadronization models and nFFs fits

June 30th, 2007 (around midnight)

June 30th, 2007 (around midnight)



23:40:37 Momentum[GeV/c] Lifetime[h] Current[mA]

HERA e+

p:

Main User: H1/ZEUS

Beam History

Thank You HERA

R.I.P.

gunar.schnell @ desy.de

… this was not the end

- data taking finished in 2007, but work continued …

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  - final surveys, calibrations, data production

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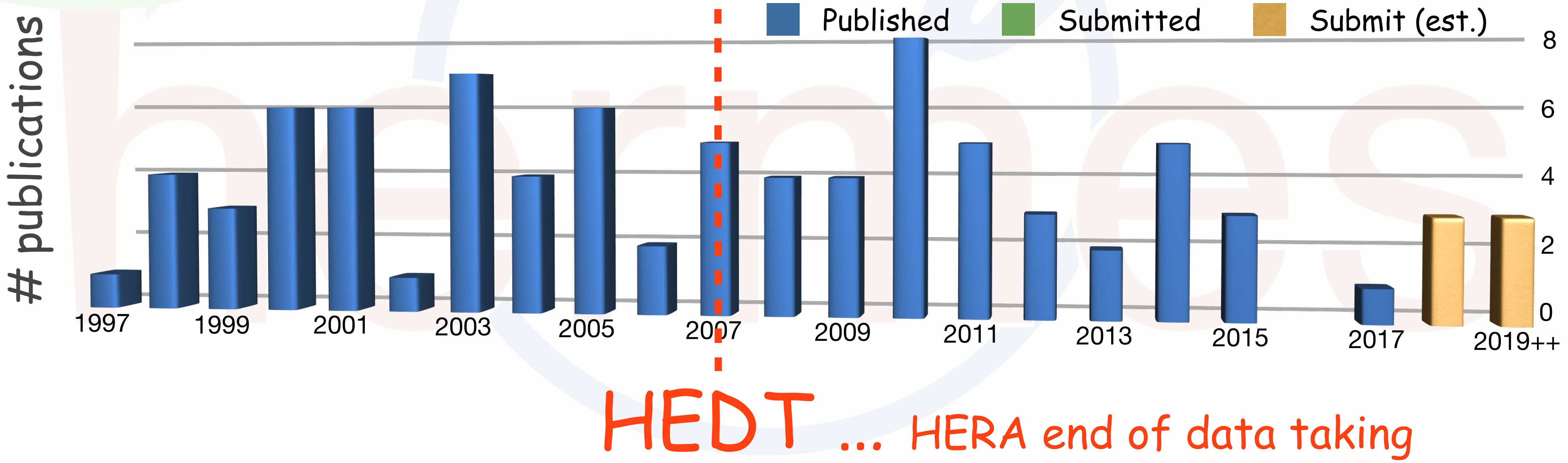
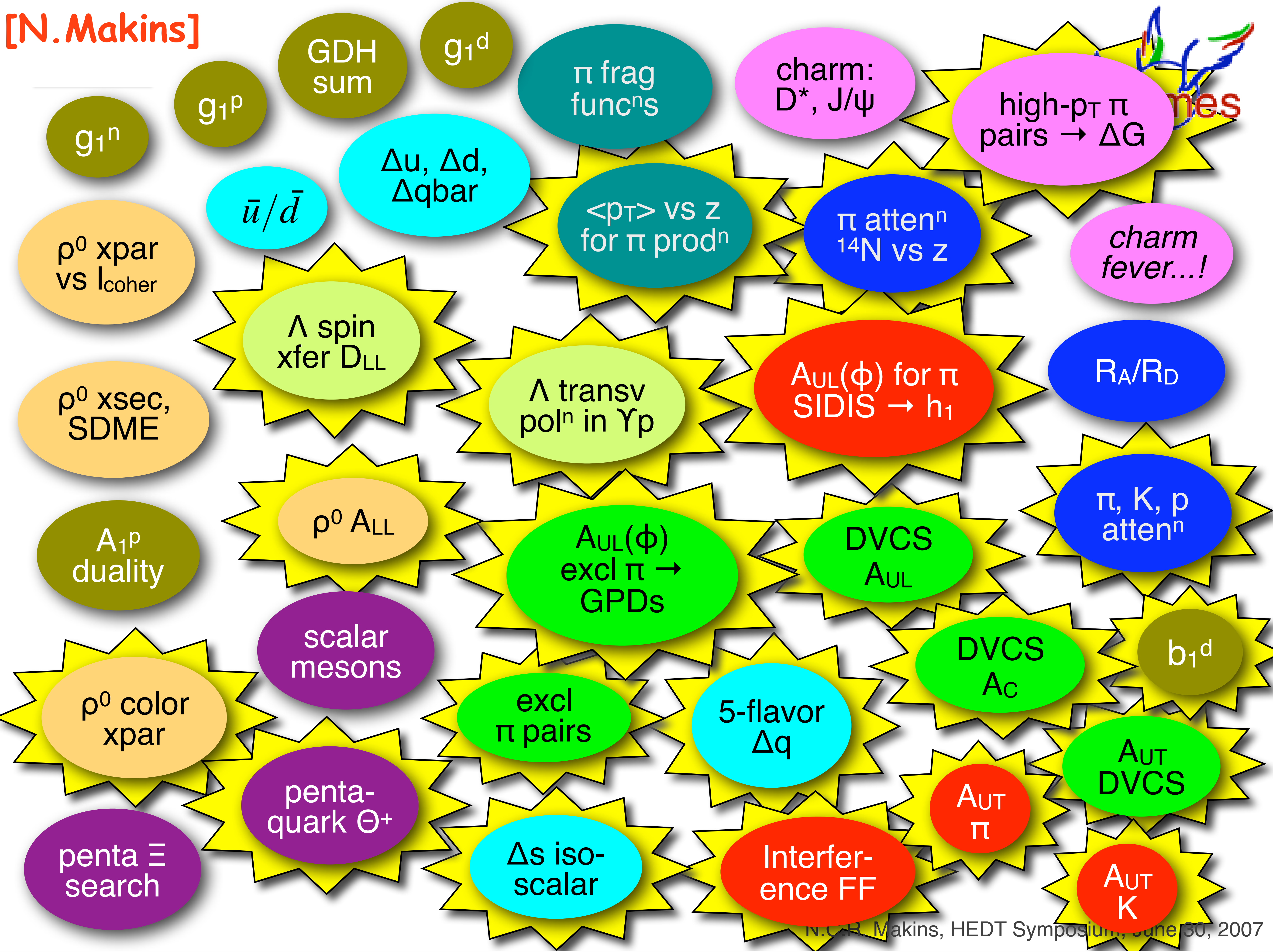
--> lesson learnt: it's never too early to start preservation!!!
  - still many analysis and publications:



[N.Makins]



g_1^n

g_1^p

GDH sum

g_1^d

π frag func^{n}s

charm: D*, J/ψ

high-p_T π pairs → ΔG

$\bar{u}/\bar{d}$

Δu, Δd, Δqbar

<p_T> vs z for π prod^n

π atten^n ^{14}N vs z

charm fever...!

ρ^0 xpar vs l_{coher}

Λ spin xfer D_{LL}

Λ transv pol^n in Υp

$A_{UL}(\phi)$ for π SIDIS → h_1

R_A/R_D

ρ^0 xsec, SDME

ρ^0 A_{LL}

π, K, p atten^n

A_1^p duality

$A_{UL}(\phi)$ excl π → GPDs

DVCS A_{UL}

scalar mesons

DVCS A_C

b_1^d

ρ^0 color xpar

excl π pairs

5-flavor Δq

A_{UT} DVCS

penta-quark Θ^+

A_{UT} π

penta Ξ search

Δs iso-scalar

Interfer-ence FF

A_{UT} K

HERMES summary

- it took quite some effort to convince a HEP lab to host a bunch of nuclear physicists … it was quite worth it!
- employed many novel techniques, e.g.
  - self-polarized lepton beam + spin rotators
  - polarized gas target with storage cell internal to lepton ring -> high polarization without dilution
  - dual-radiator RICH; recoil detector …
- plenty surprises and pioneering measurements
  - too many to cover them all here
- 80 papers / some 8700 citations / 3rd most cited HERA paper
- numerous PhDs that went on to other experiments (and elsewhere)

gunar.schnell @ desy.de

HERMES summary

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- 80 papers / so RA paper
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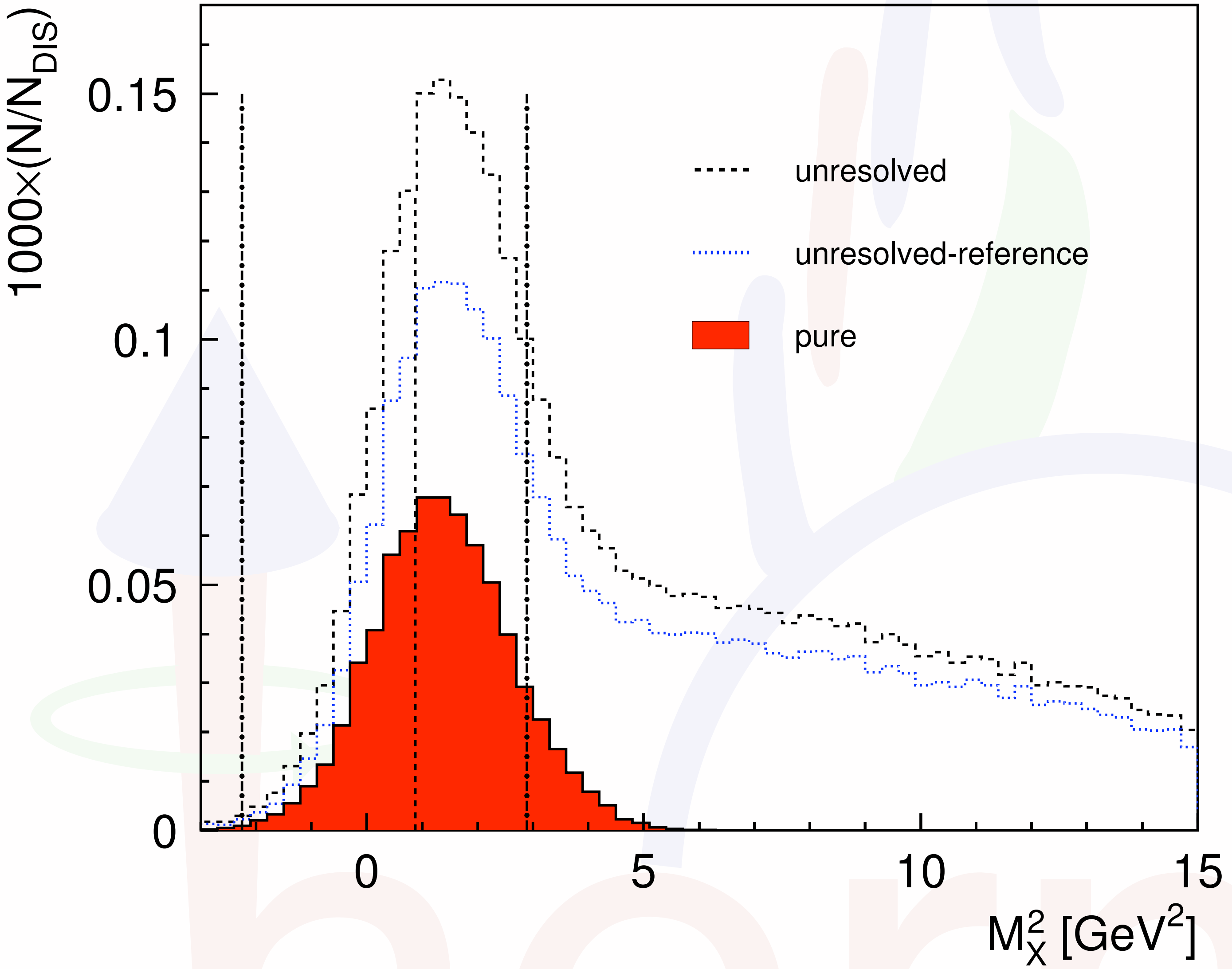
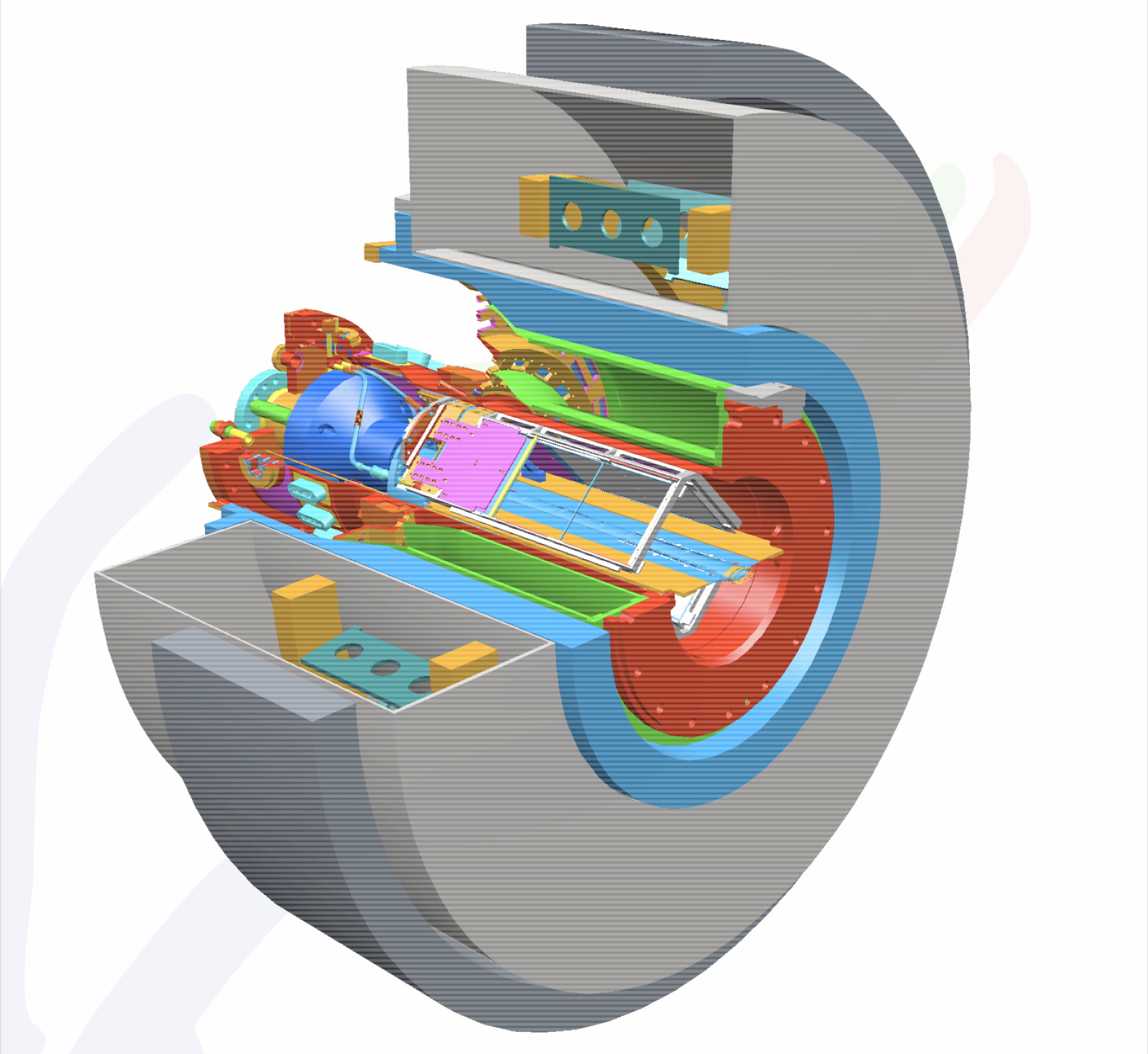
backup slides

HERMES detector (2006/07)

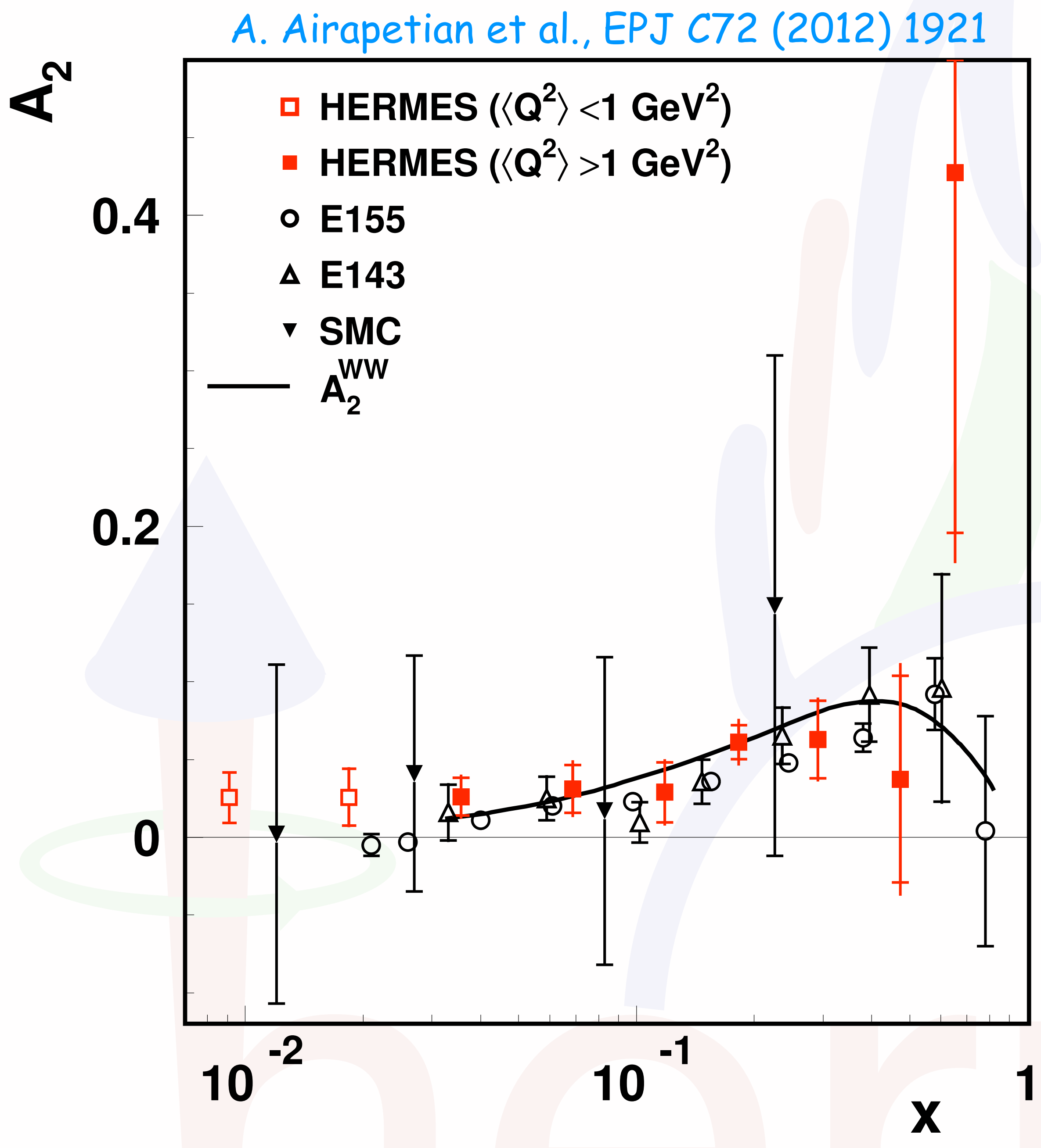
kinematic fitting

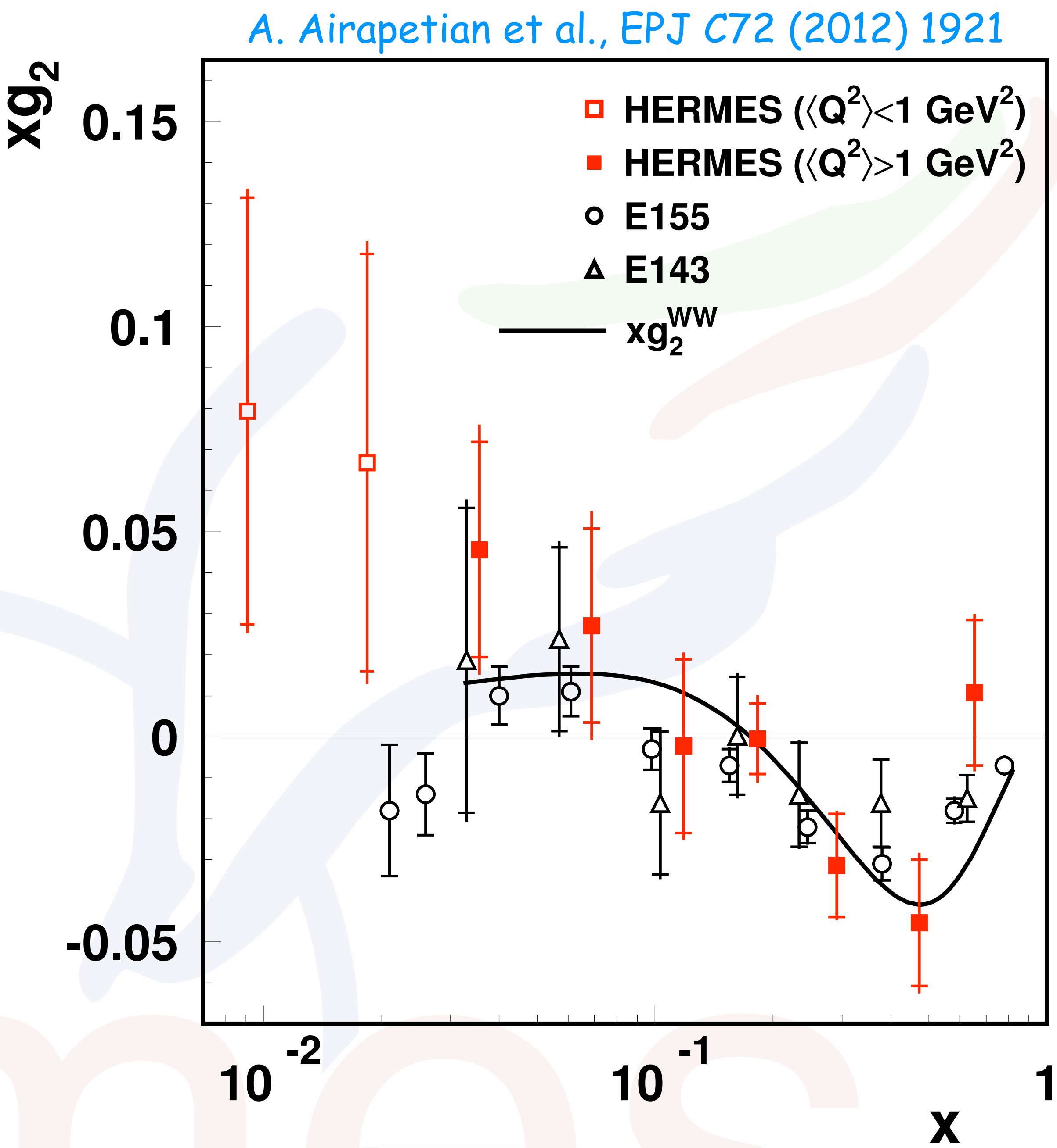




- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS ($ep \rightarrow ep \gamma$) with high efficiency (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

Results on A_2 and xg_2

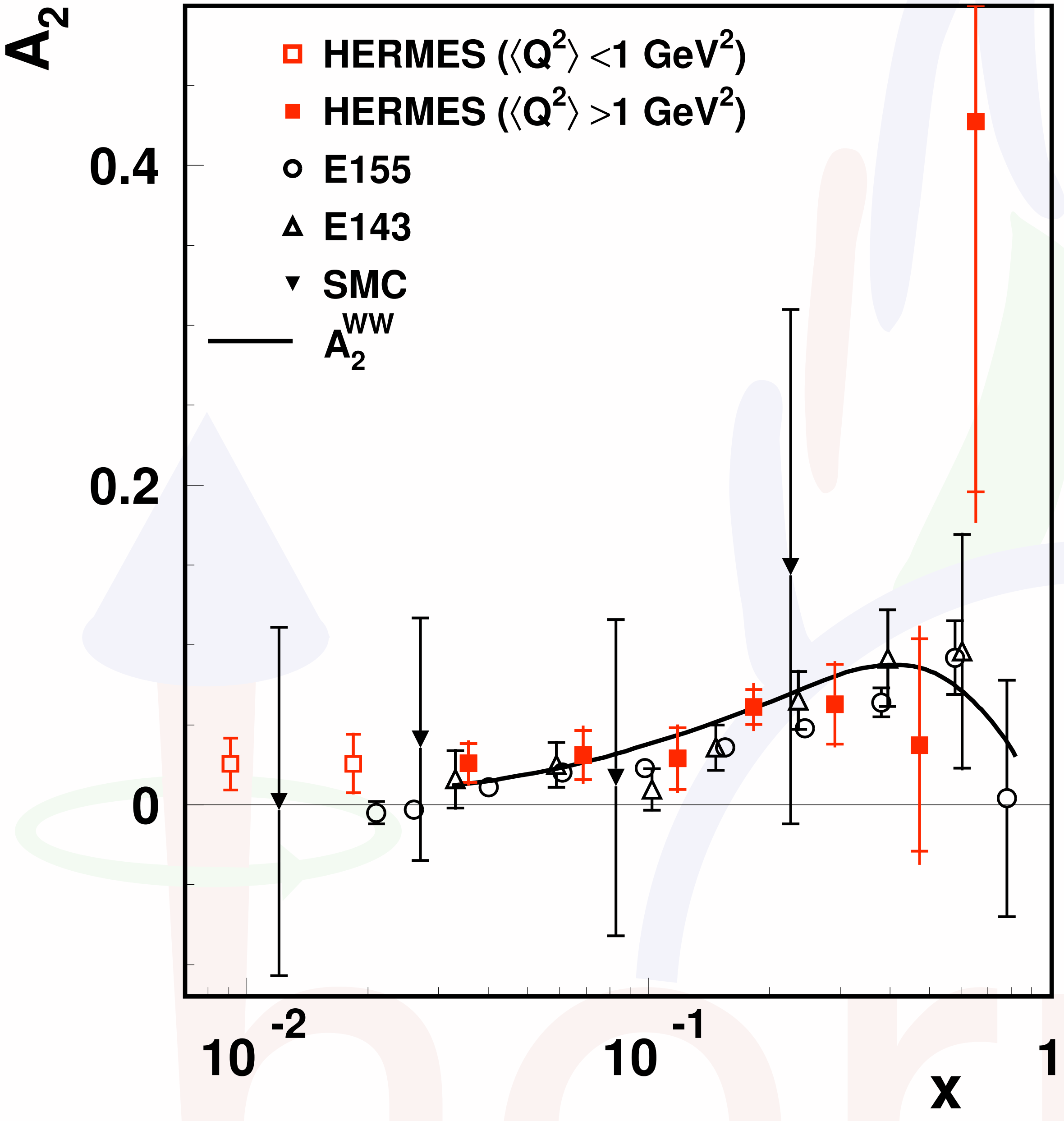

A. Airapetian et al., EPJ C72 (2012) 1921


A. Airapetian et al., EPJ C72 (2012) 1921

- consistent with (sparse) world data
- low beam polarization during HERA II ➡ small f.o.m.

Results on A_2 and xg_2

A. Airapetian et al., EPJ C72 (2012) 1921



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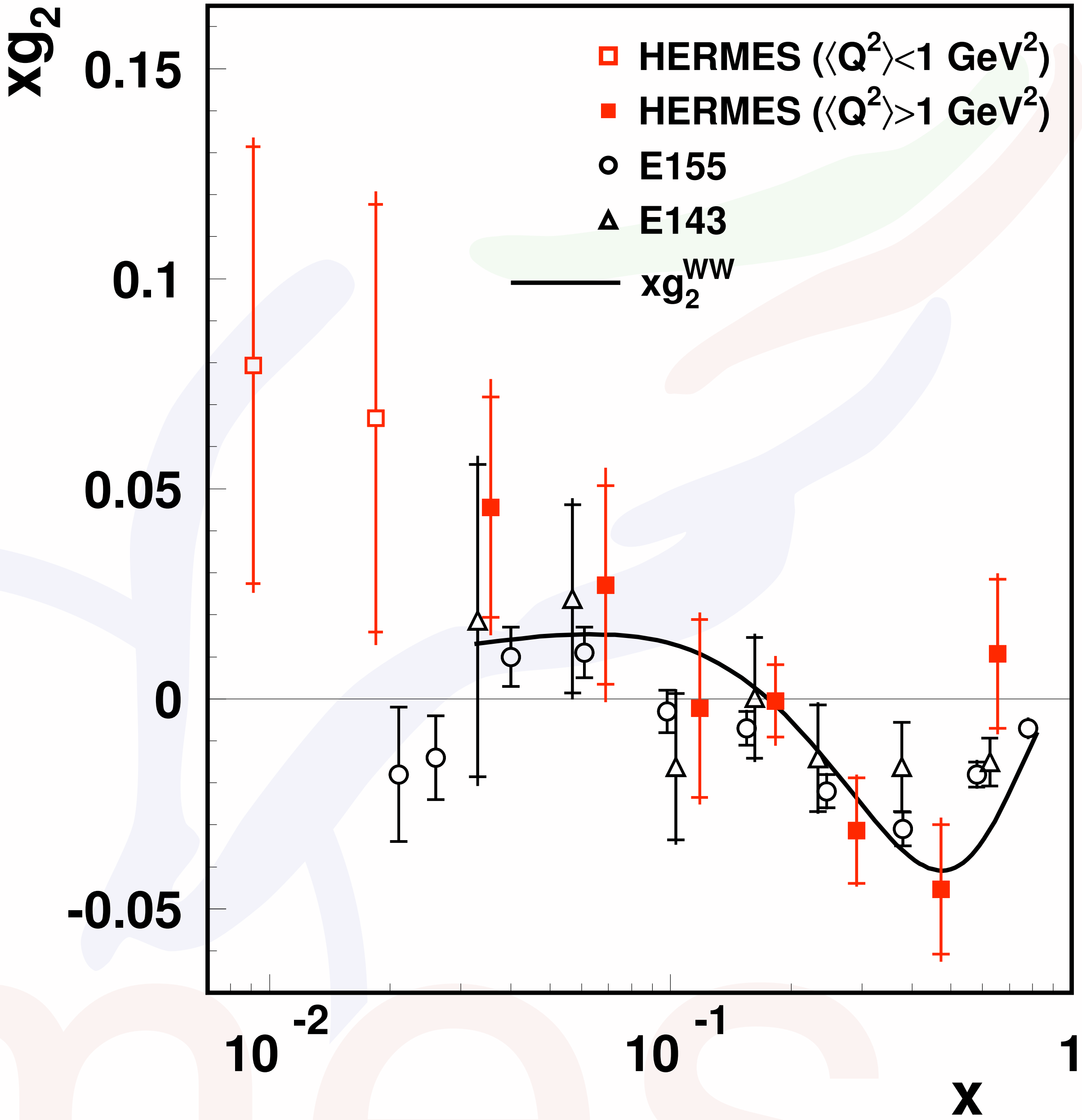

$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \mathbf{0.006} \pm \mathbf{0.024}_{\text{stat}} \pm \mathbf{0.017}_{\text{syst}}$$

$$\mathbf{d_2(Q^2)} \equiv 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx = \mathbf{0.0148} \pm \mathbf{0.0096}_{\text{stat}} \pm \mathbf{0.0048}_{\text{syst}}$$

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1-hadron production (ep→ehX)

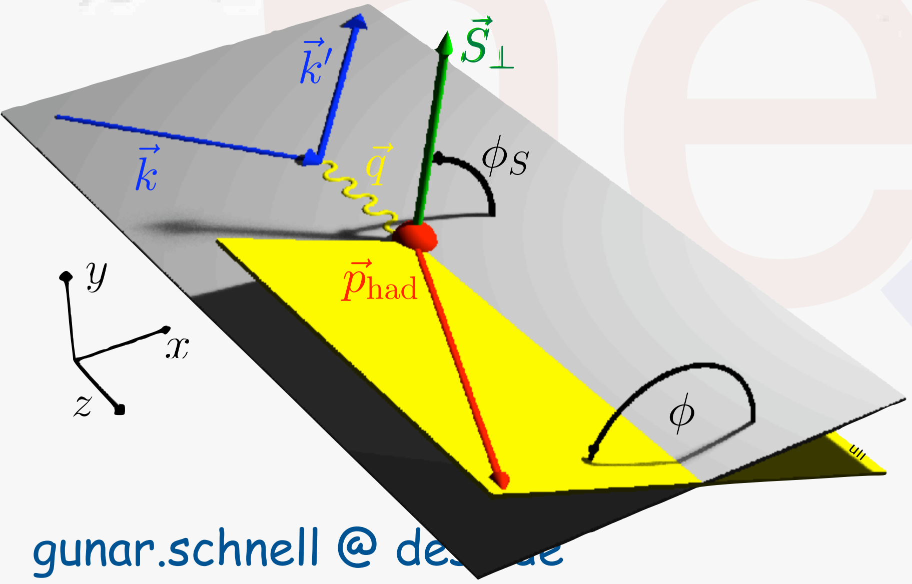
$$
\begin{aligned}
d\sigma = {} & d\sigma^{0}_{UU} + \cos 2\phi \, d\sigma^{1}_{UU} + \frac{1}{Q} \cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^{3}_{LU} \\
& + S_L \left\{ \sin 2\phi \, d\sigma^{4}_{UL} + \frac{1}{Q} \sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL}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

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

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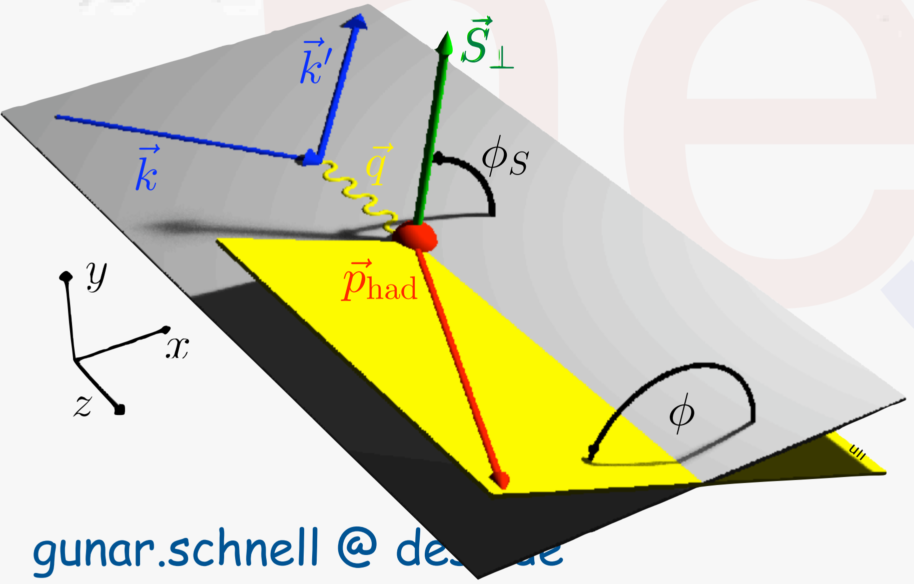
& + S_T \left\{ \boxed{\sin(\phi - \phi_S) \, d\sigma^{8}_{UT}} + \boxed{\sin(\phi + \phi_S) \, d\sigma^{9}_{UT}} + \boxed{\sin(3\phi - \phi_S) \, d\sigma^{10}_{UT}} \frac{1}{Q} \right. \\
& \qquad + \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \left. + \lambda_e \left[\boxed{\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\}
\end{aligned}
$$

σ_{XY} ↙ ↘

Beam **Target**

Polarization



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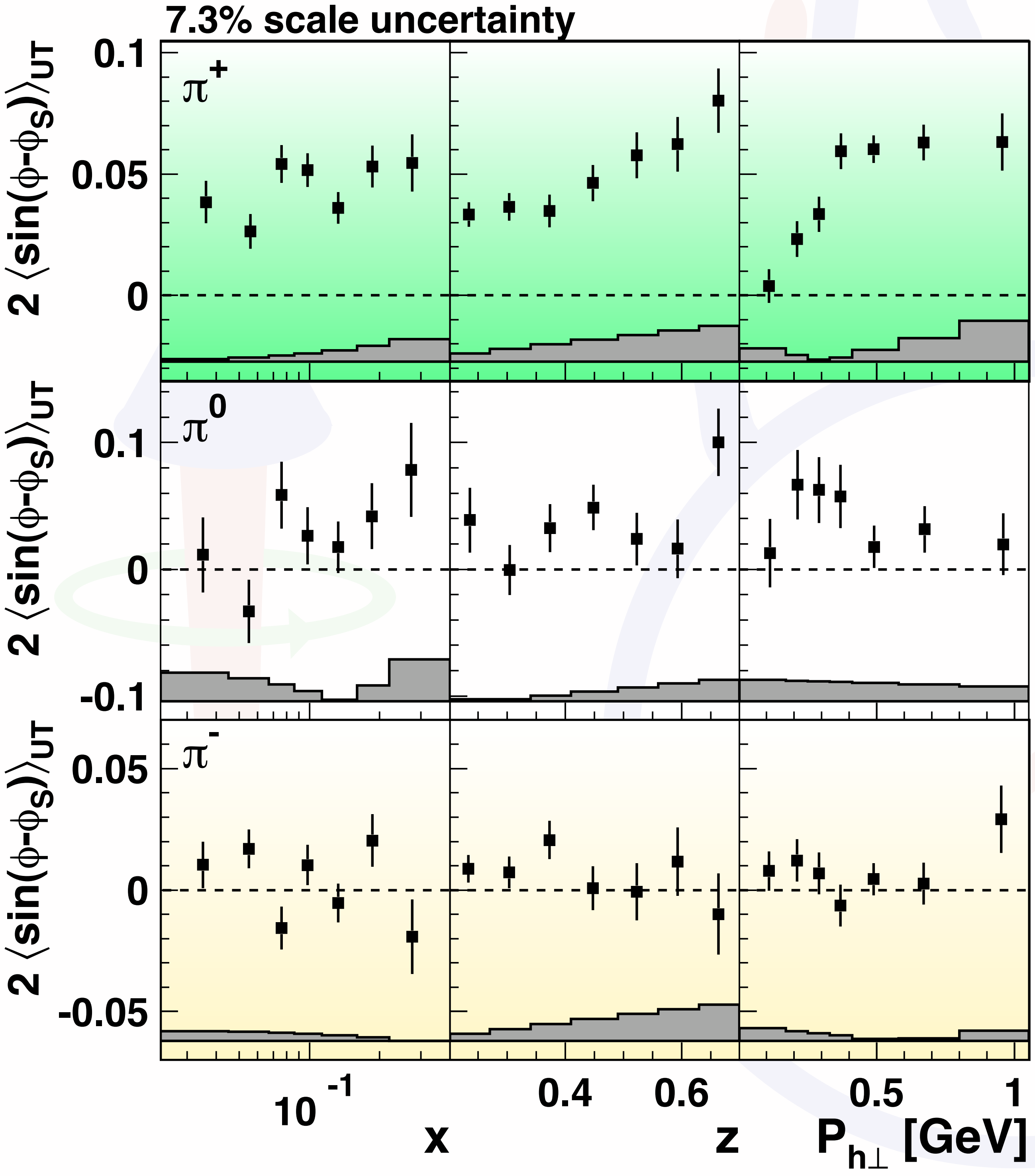
the pion Sivers amplitudes

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



π^+ dominated by u-quark scattering:

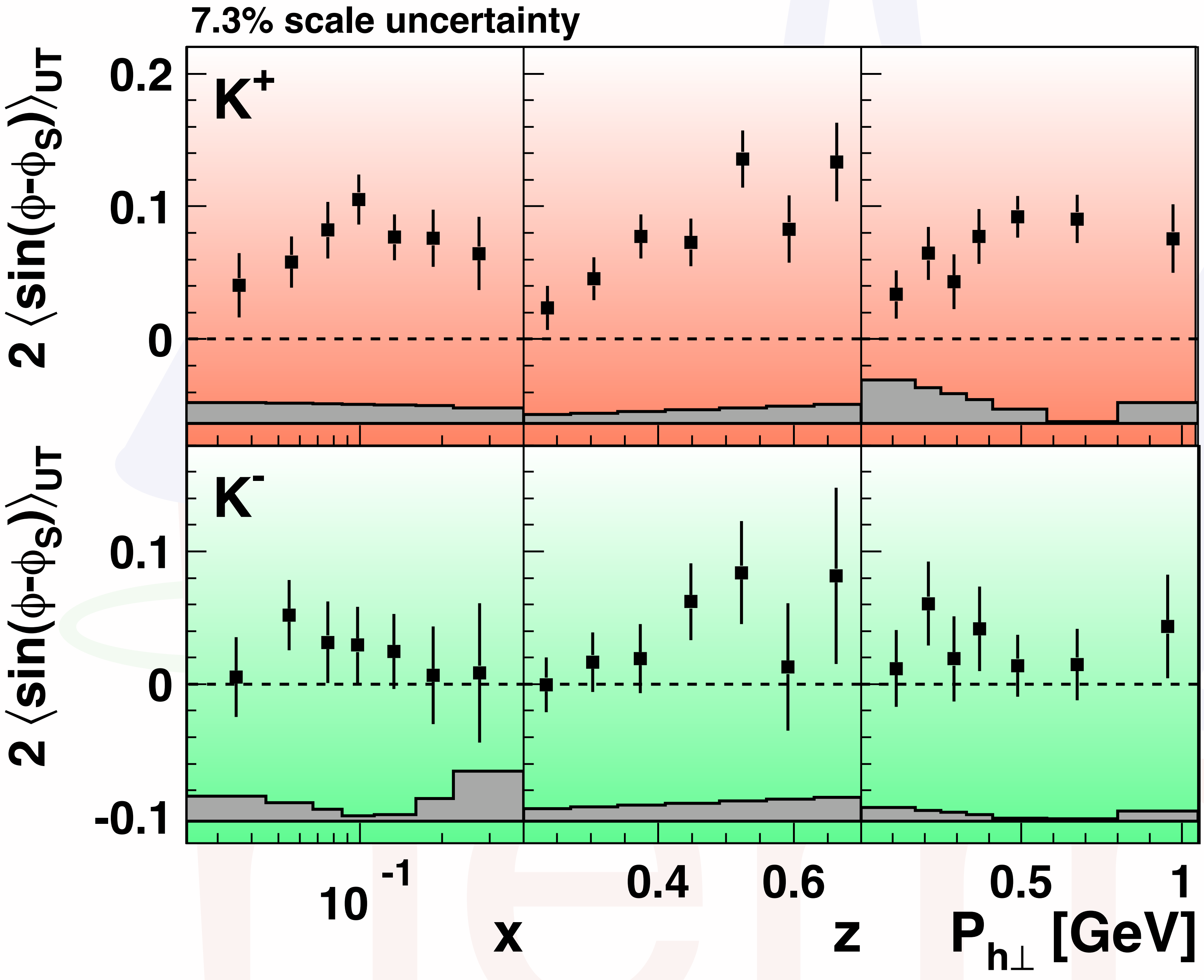
$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\ D_1^{u\to\pi^+}(z)}$$

☛ **u-quark Sivers DF < 0**

☛ **d-quark Sivers DF > 0**
(cancelation for π^-)

[*A. Airapetian et al.*, arXiv:0906.3918]

the kaon Sivers amplitudes

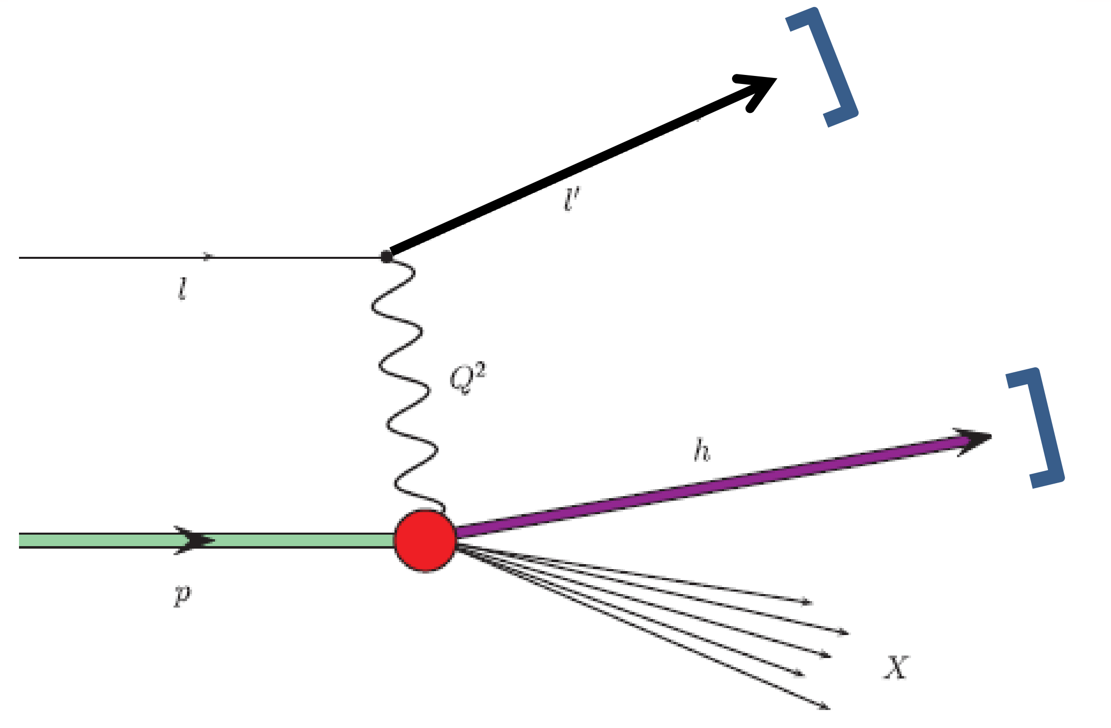


☛ large & positive

☛ slightly positive

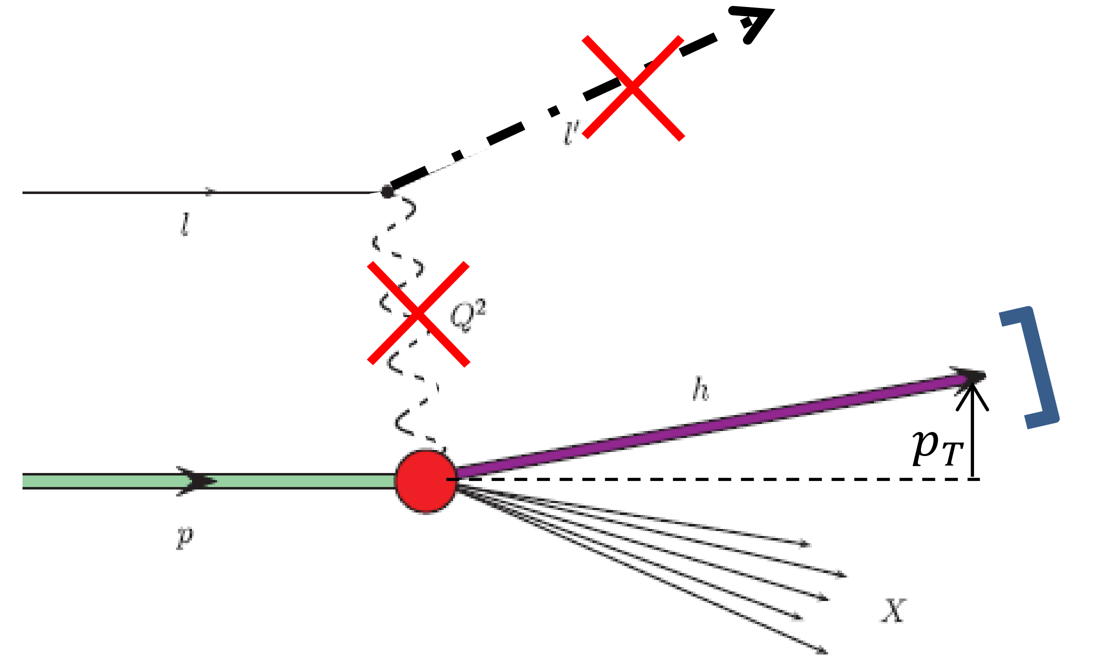
[*A. Airapetian et al.*, arXiv:0906.3918]

Semi-inclusive hadrons



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

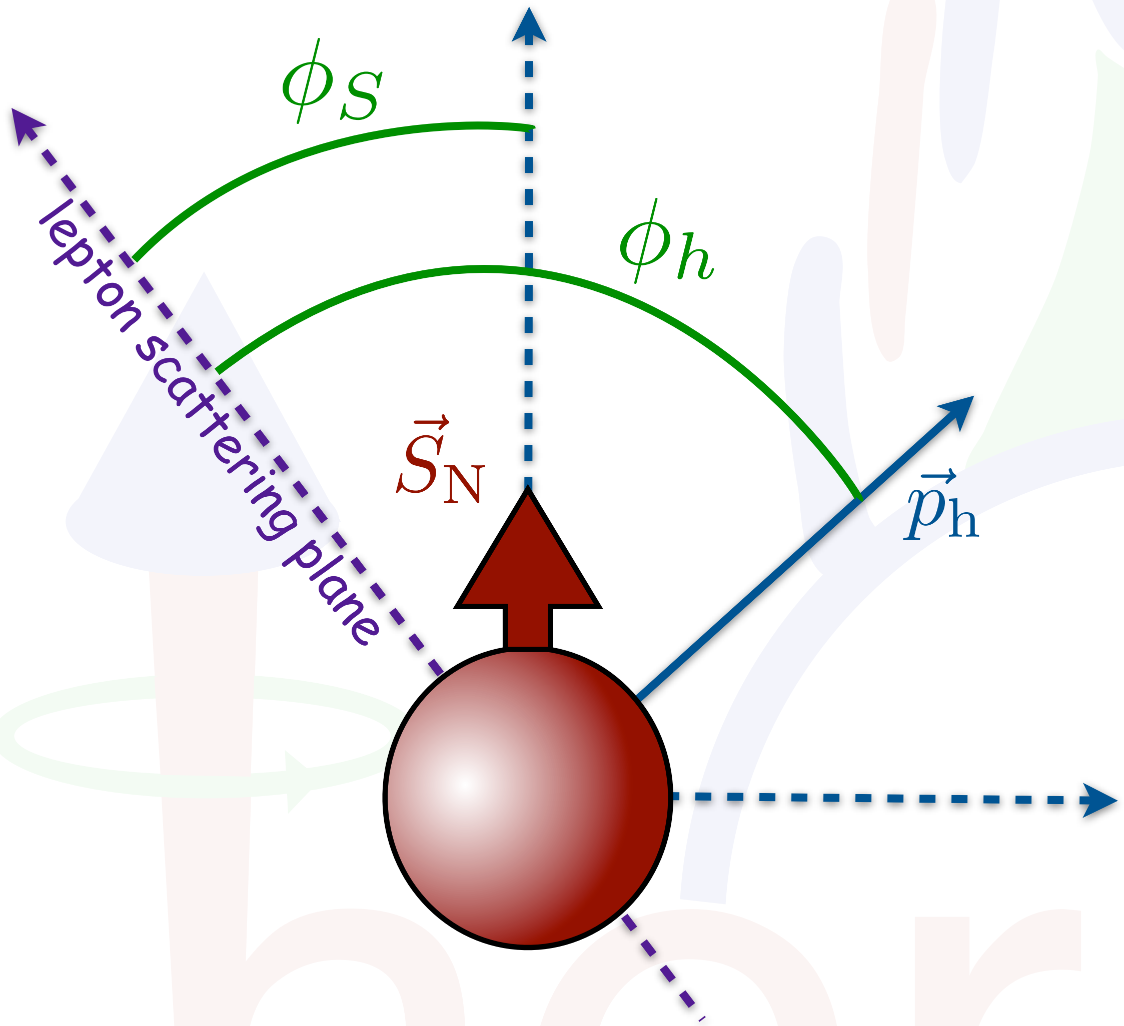
S~~e~~mi-inclusive hadrons



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

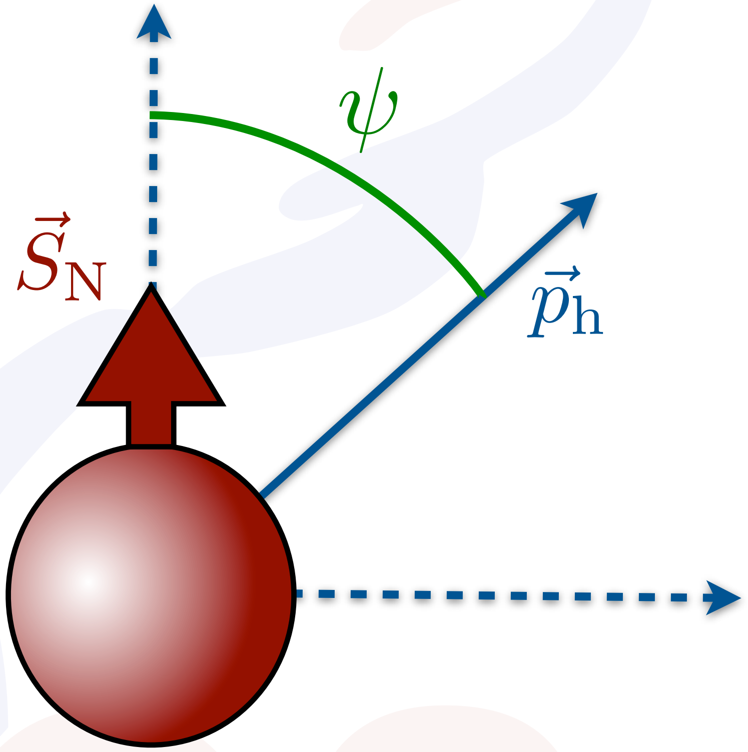
Inclusive hadron electro-production

$ep^\uparrow \rightarrow ehX$



virtual photon going into the page

$ep^\uparrow \rightarrow hX$



lepton beam going into the page

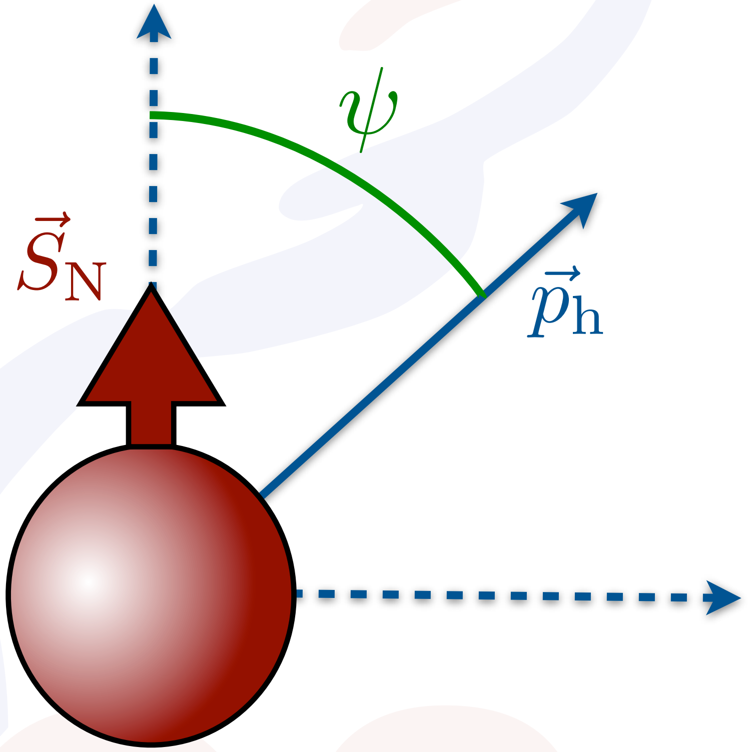
$\psi \simeq \phi_h - \phi_S$

➠ "Sivers angle"

Inclusive hadron electro-production

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

- scattered lepton undetected
  ➥ lepton kinematics unknown
- dominated by quasi-real photo-production (low Q^2)
  ➥ hadronic component of photon relevant?
- cross section proportional to S_N (k x p_h) ~ sinψ

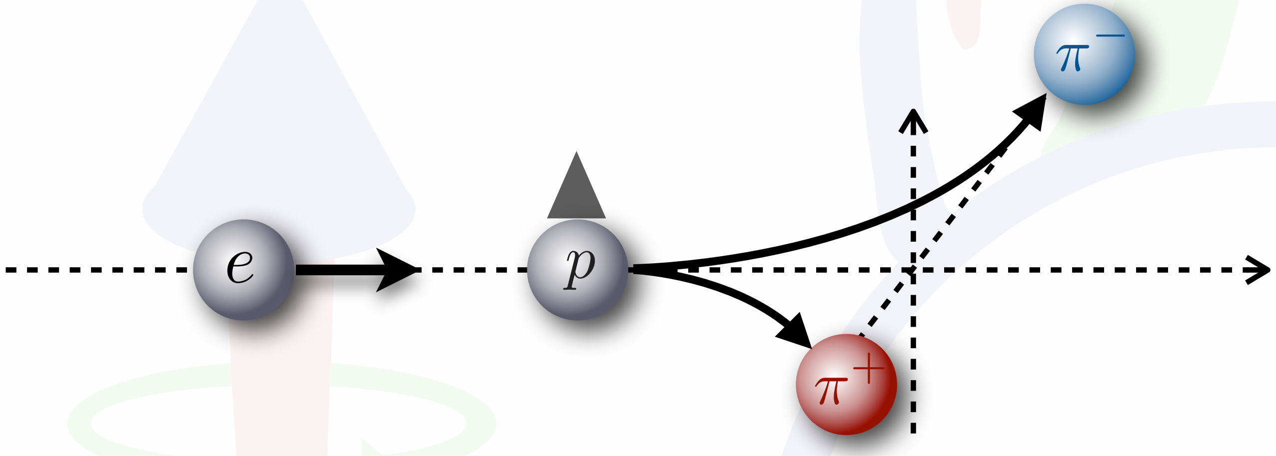


$$A_{\mathrm{UT}}(P_T, x_F, \psi) = A_{\mathrm{UT}}^{\sin\psi}(P_T, x_F)\sin\psi$$

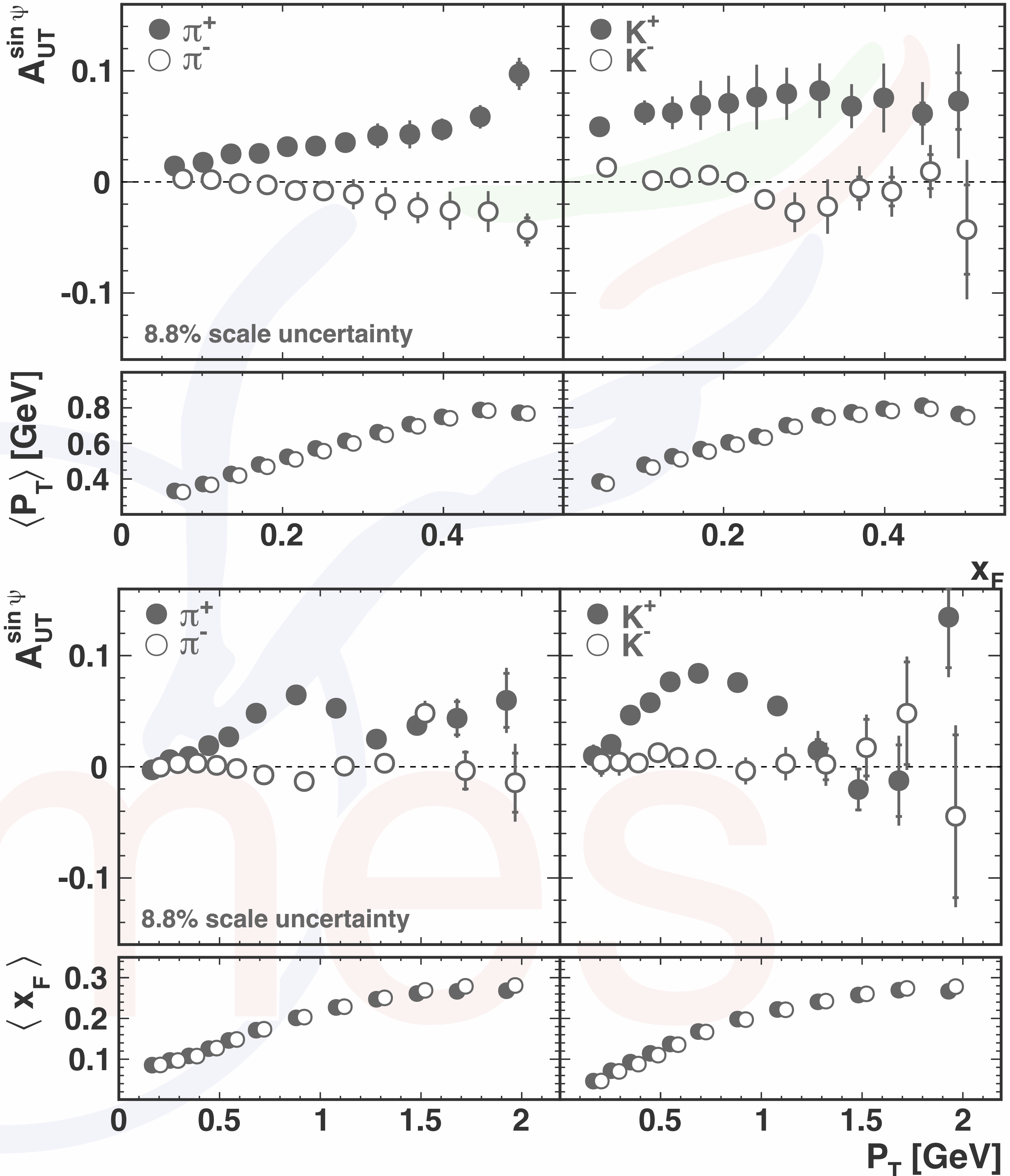
$$A_{\mathrm{N}} \equiv \frac{\int_{\pi}^{2\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UT}} \sin\psi - \int_{0}^{\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UT}} \sin\psi}{\int_{0}^{2\pi} \mathrm{d}\psi\ \sigma_{\mathrm{UU}}}$$

$$= -\frac{2}{\pi} A_{\mathrm{UT}}^{\sin\psi}$$

1D dependences of A_{UT} sinψ amplitude

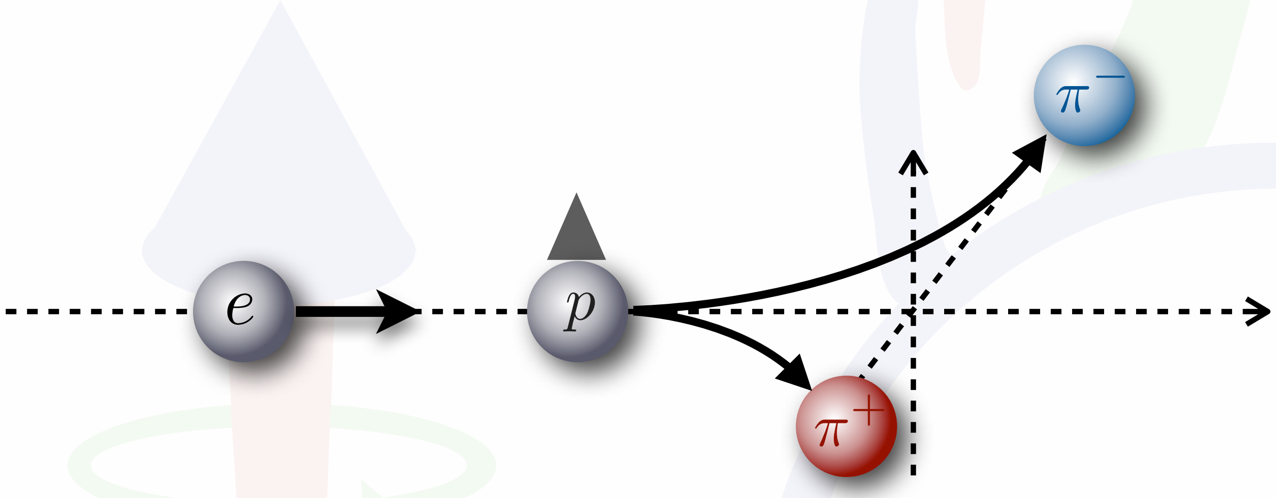


[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



1D dependences of A_{UT} sinψ amplitude

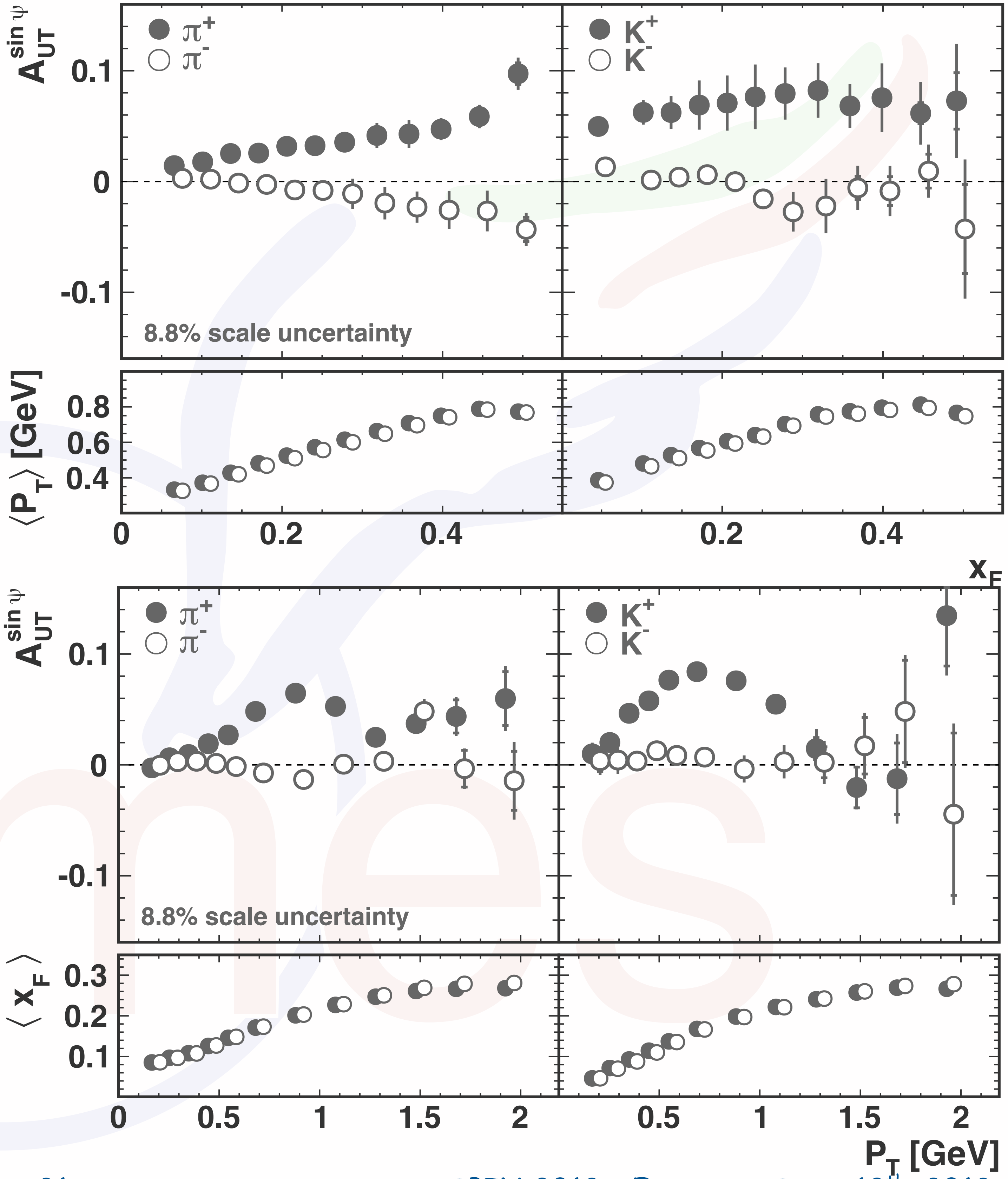
- clear left-right asymmetries for pions and positive kaons
- increasing with x_F (as in pp)



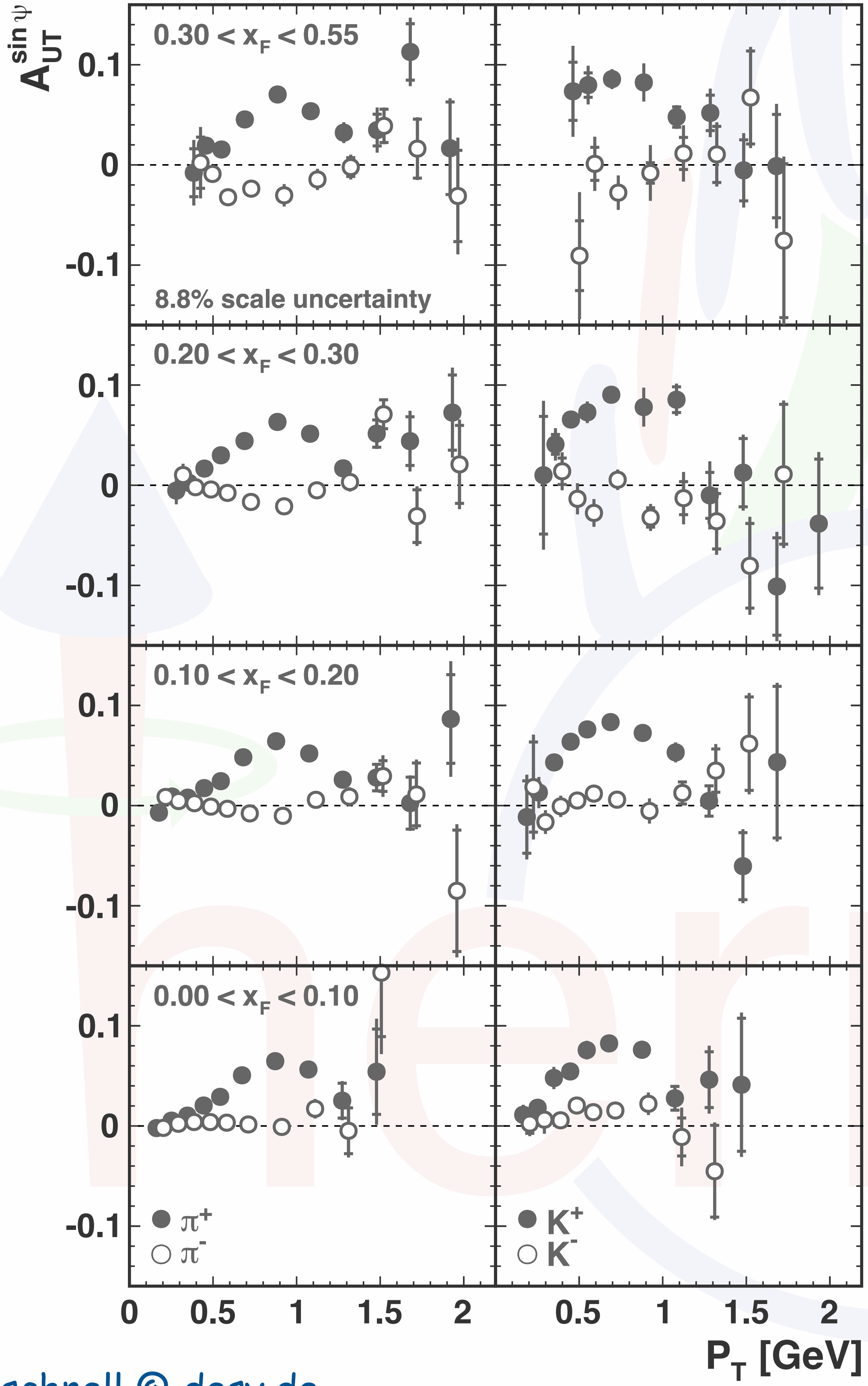
- initially increasing with P_T with a fall-off at larger P_T
- x_F and P_T correlated

➡ look at 2D dependences

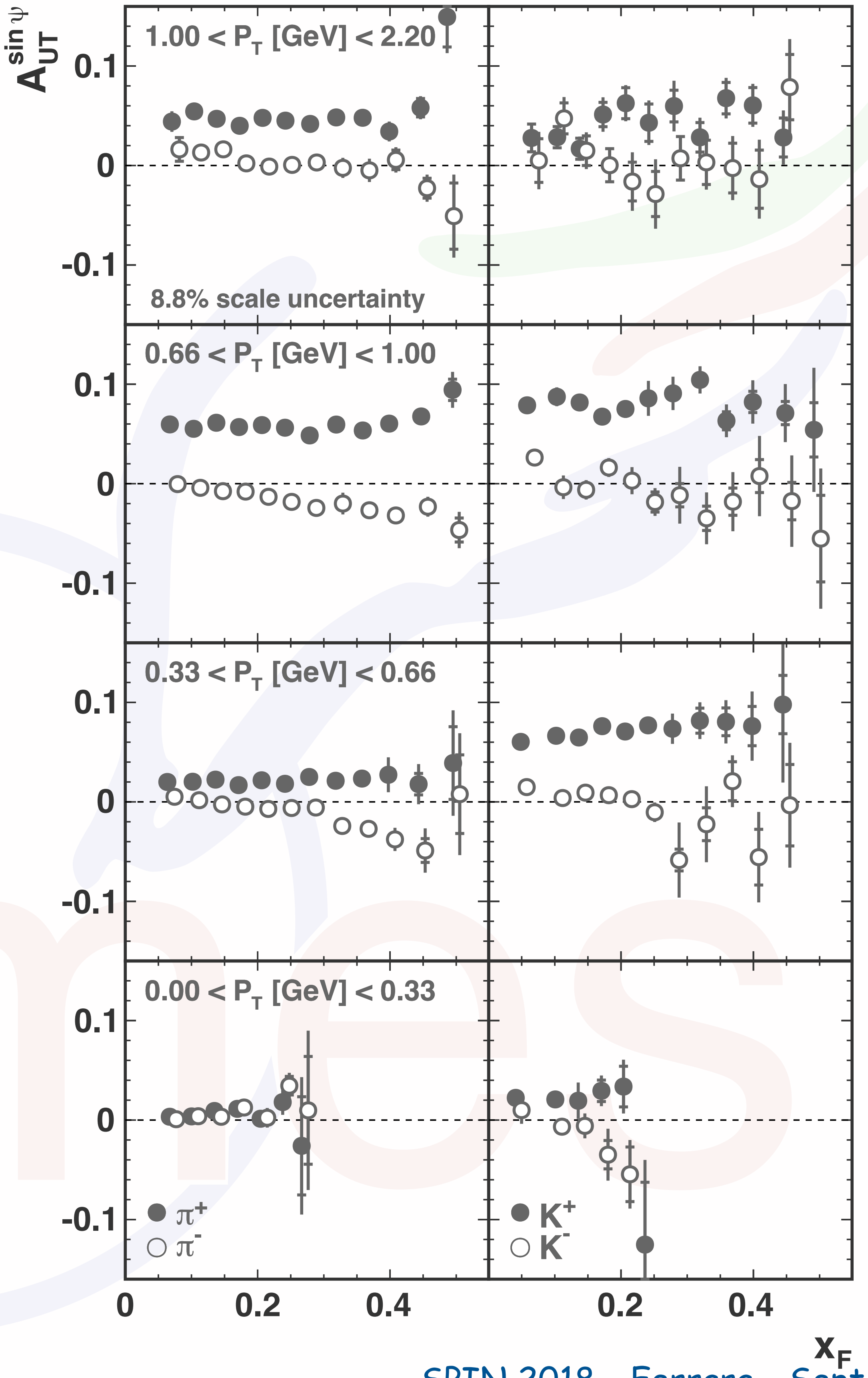
[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



Inclusive hadrons: 2D dependences

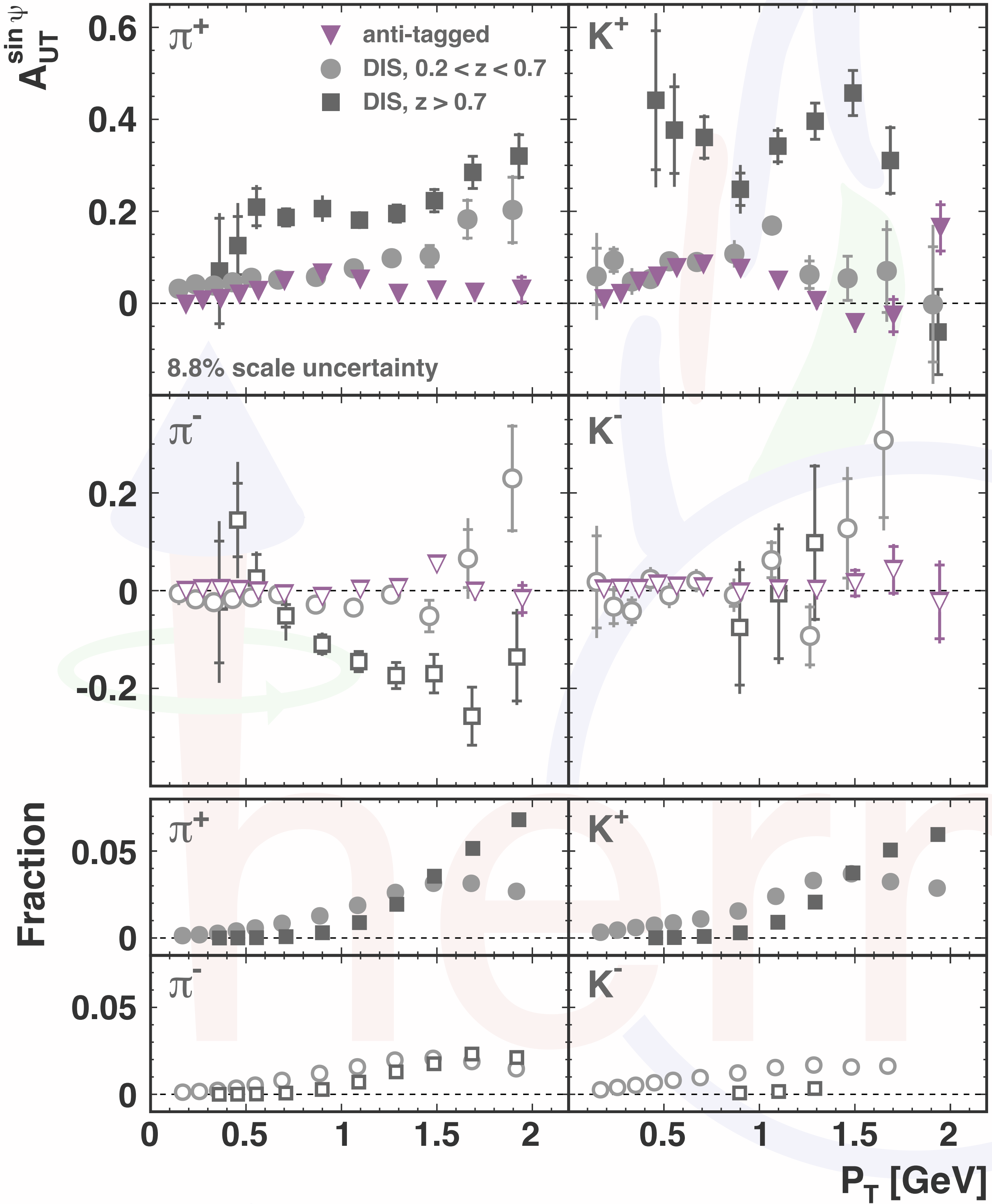


[Airapetian et al., Phys. Lett. B 728, 183-190 (2014)]



Asymmetries of subprocesses

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



"anti-tagged"

no lepton in acceptance

DIS

0.2<z<0.7

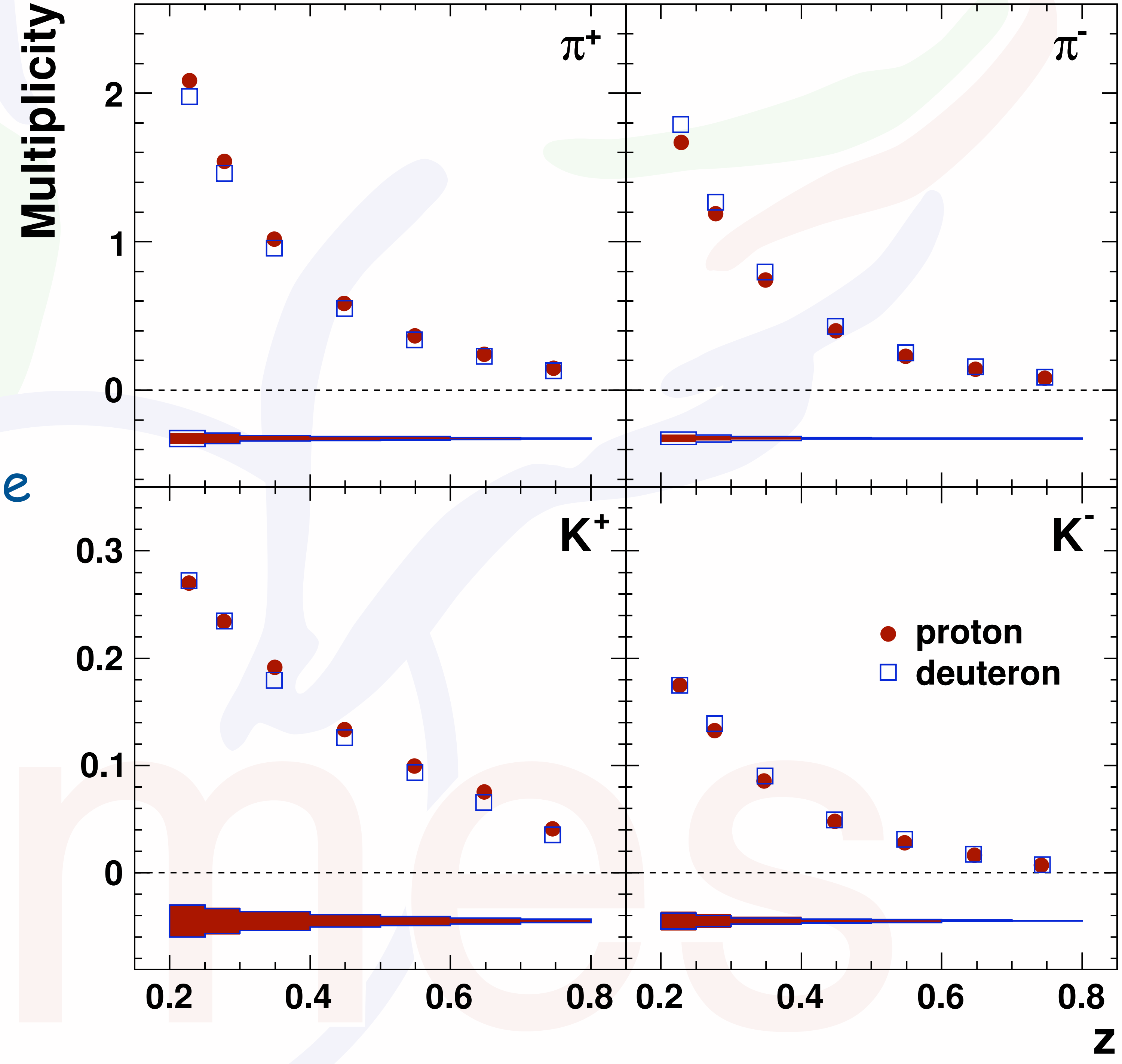
DIS z>0.7

- at large P_T significant contribution from DIS events (Q^2>1)
- asymmetries increase with larger z
- large asymmetries also for π^- in case of z>0.7

multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons http://www-hermes.desy.de/multiplicities
- extracted in a multi-dimensional unfolding procedure
- fair agreement between DSS and positive mesons
- poor description of negative mesons
- p/d differences due to flavor dependence of fragmentation

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



transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

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