POETIC 2013

Physics Opportunities at an ElecTron Ion Collider

highlights from the hermes collaboration

- the HERMES experiment
- inclusive DIS
- semi-inclusive DIS
- 3D structure via TMDs and GPDs

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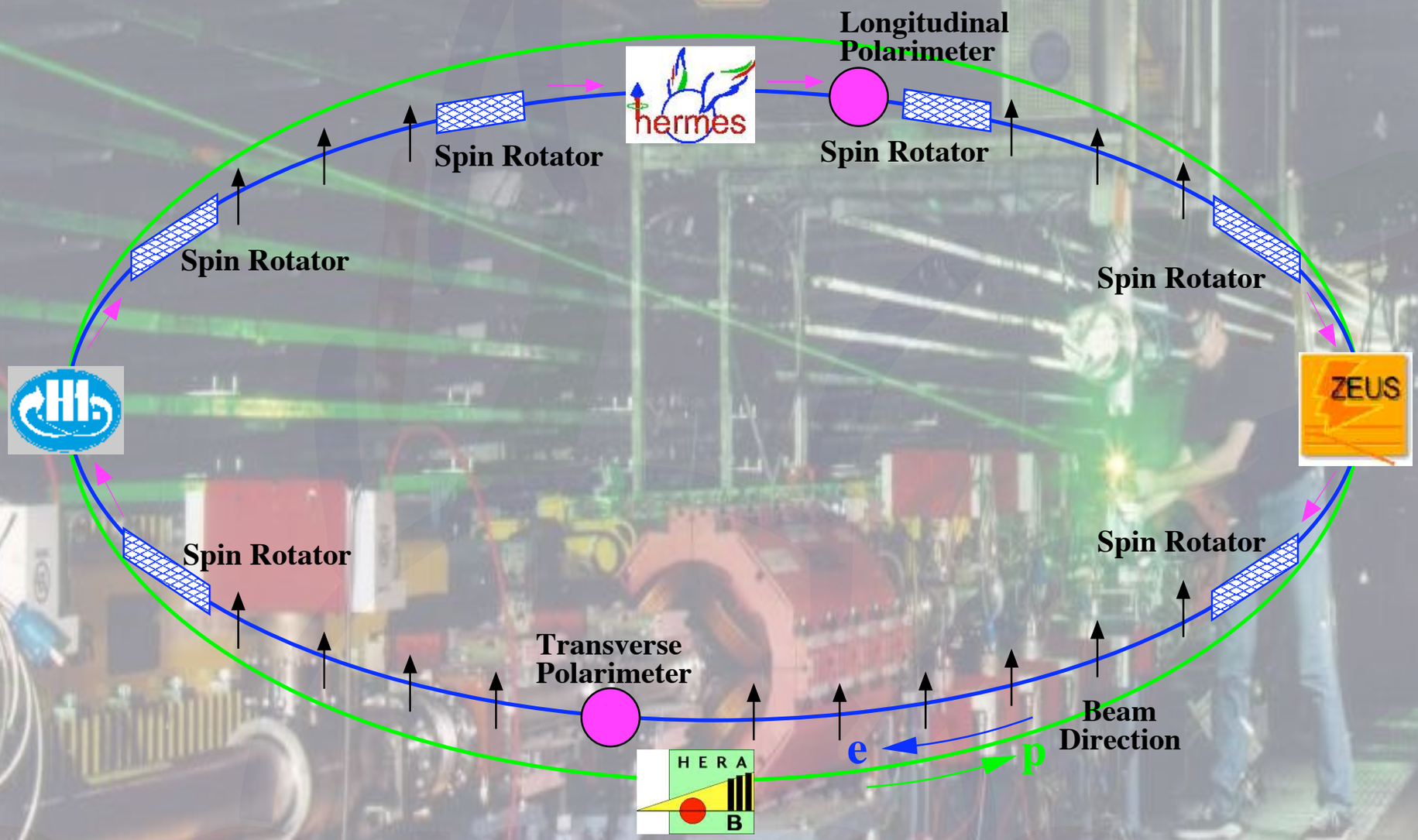
Beam polarization at HERA



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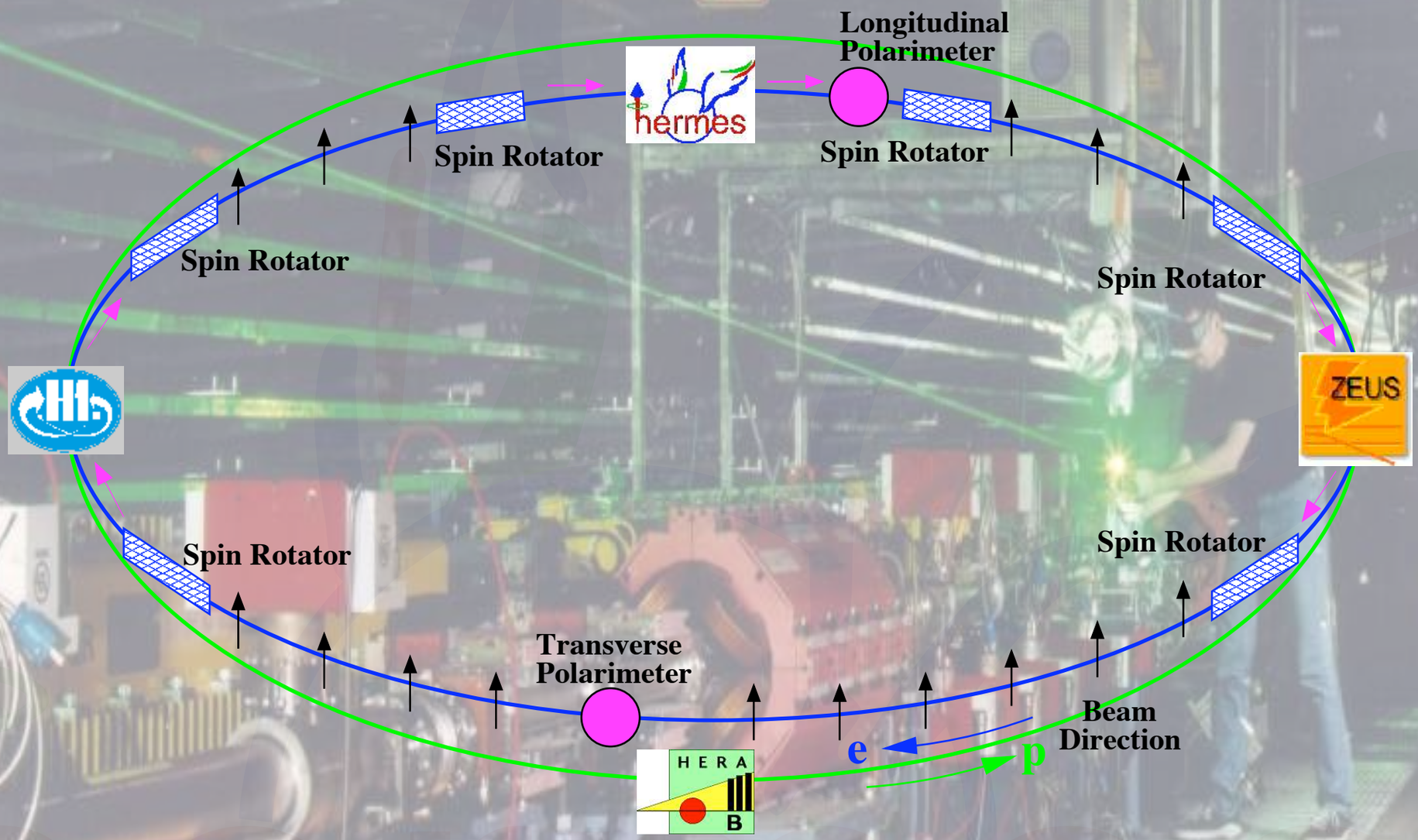

- 27.5 GeV electron/positron beam

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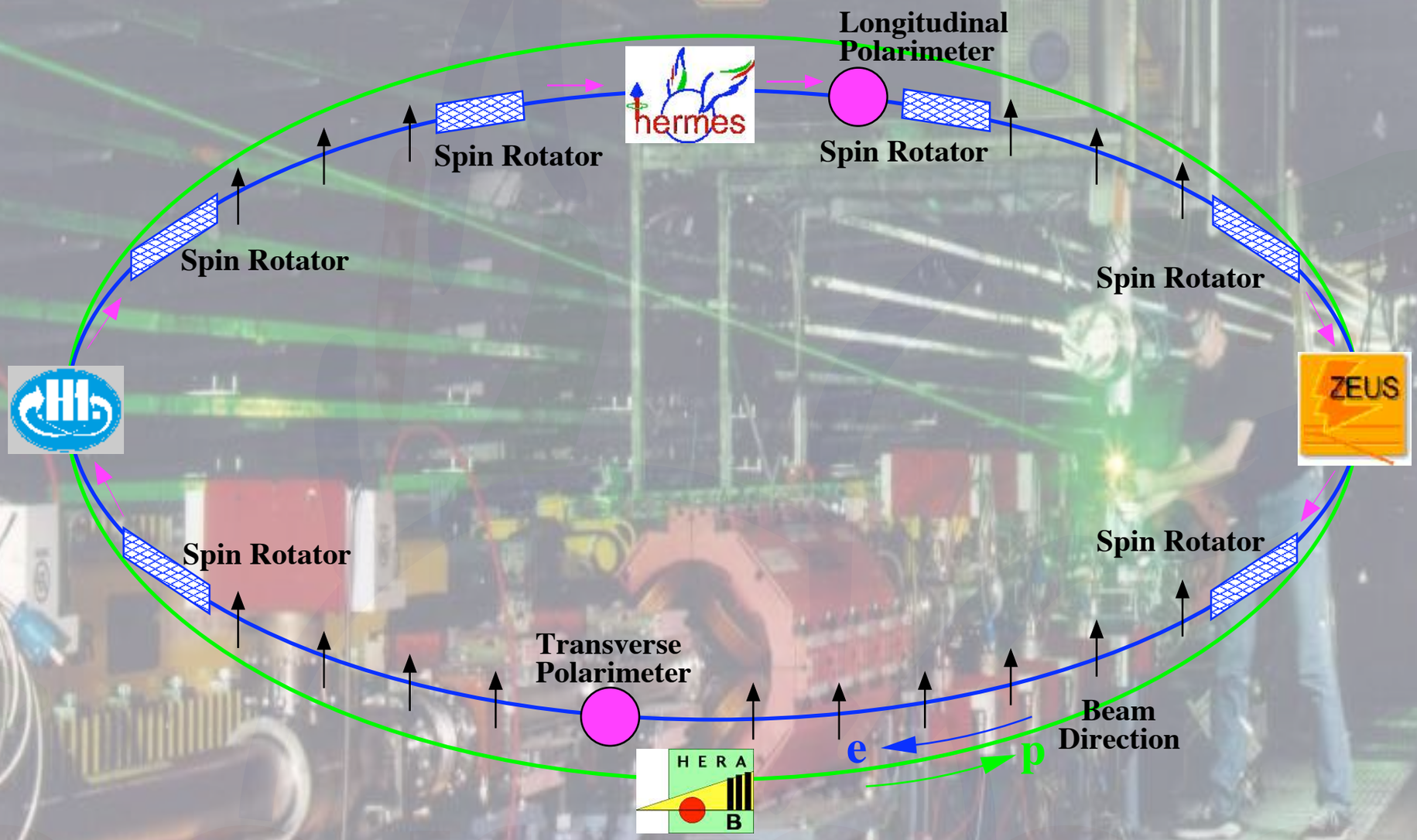
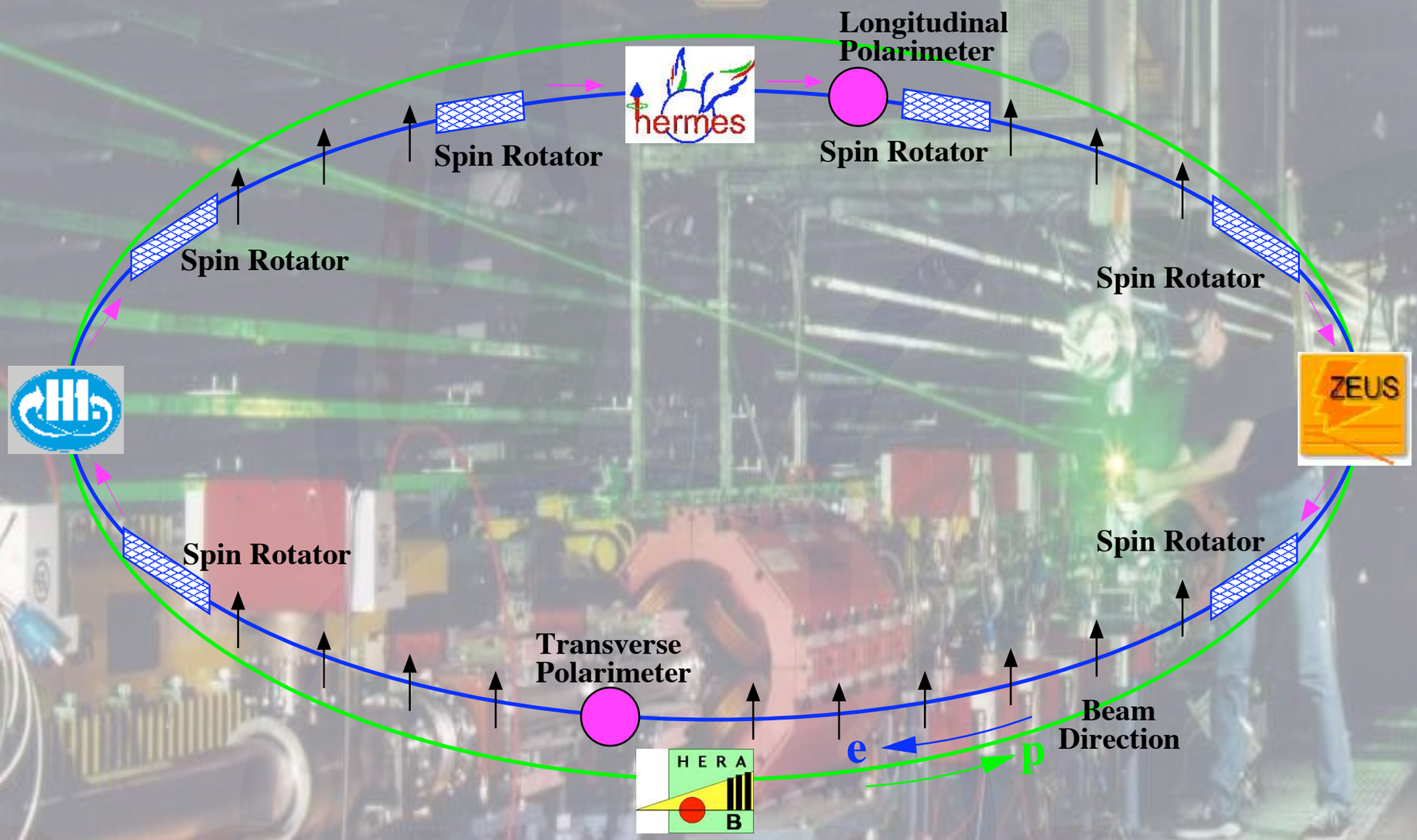


- 27.5 GeV electron/positron beam
- transversely polarized through Sokolov-Ternov effect

Beam polarization at HERA

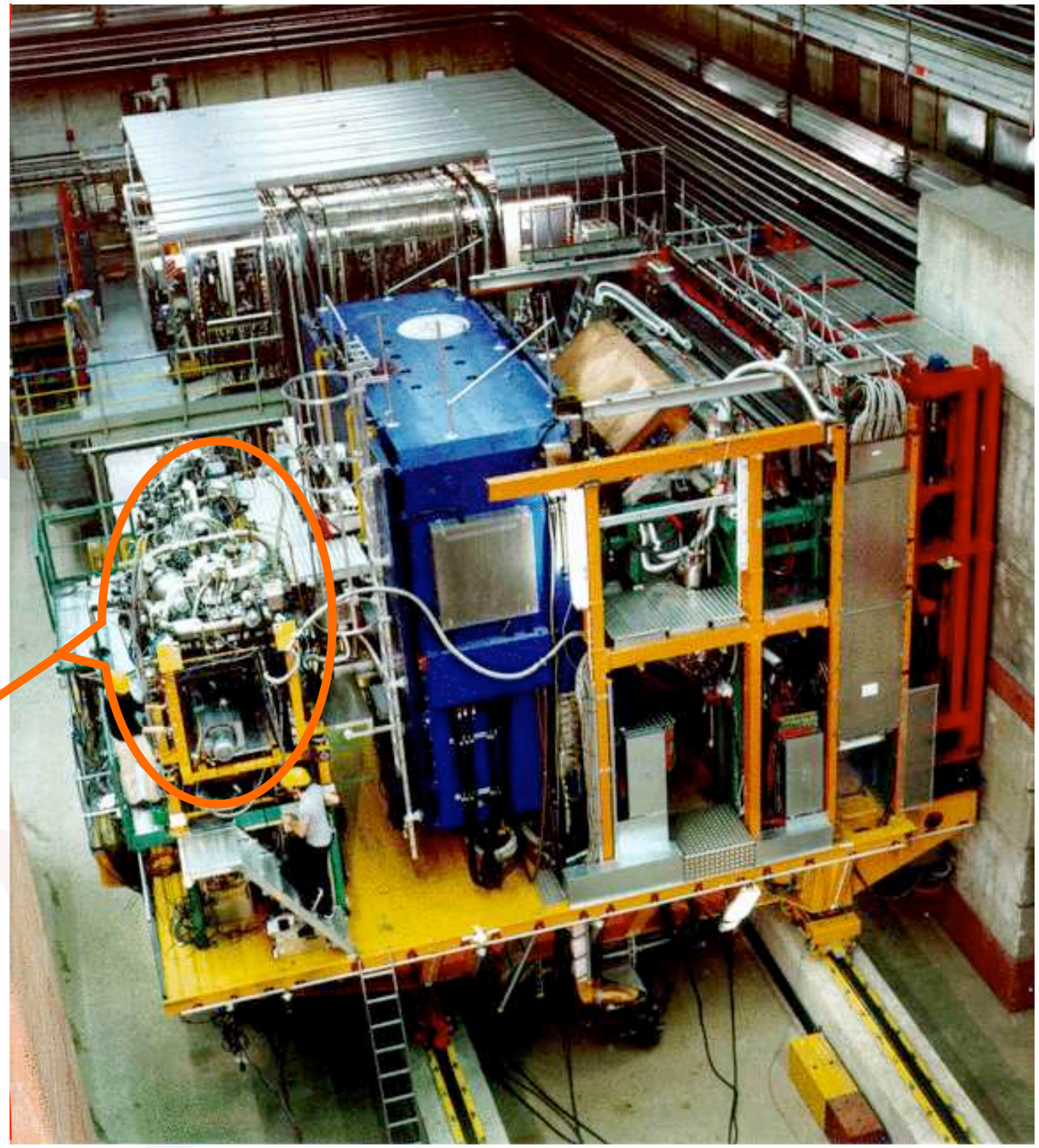


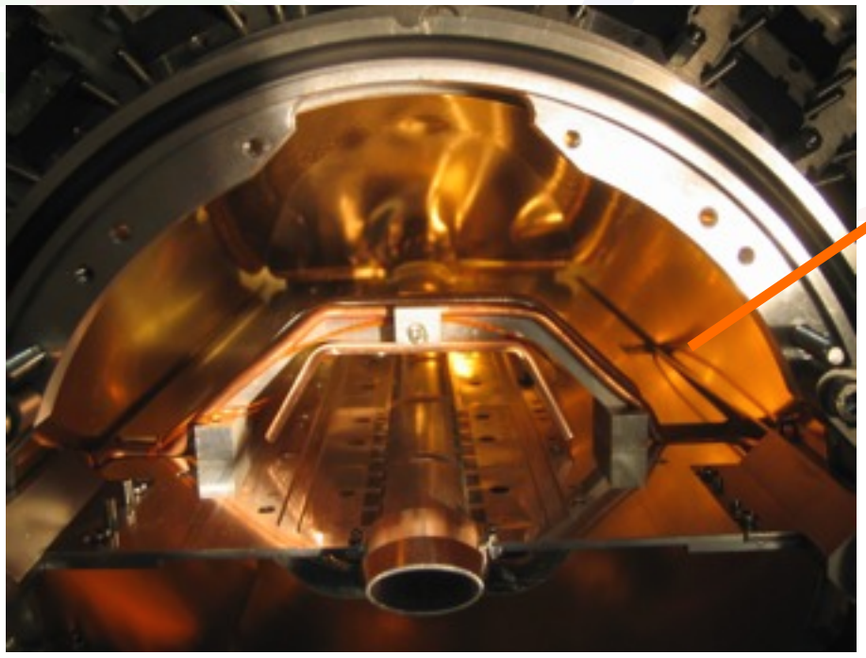
- 27.5 GeV electron/positron beam
- transversely polarized through Sokolov-Ternov effect
- average beam polarization up to 55%

The HERMES experiment (1995-2007)

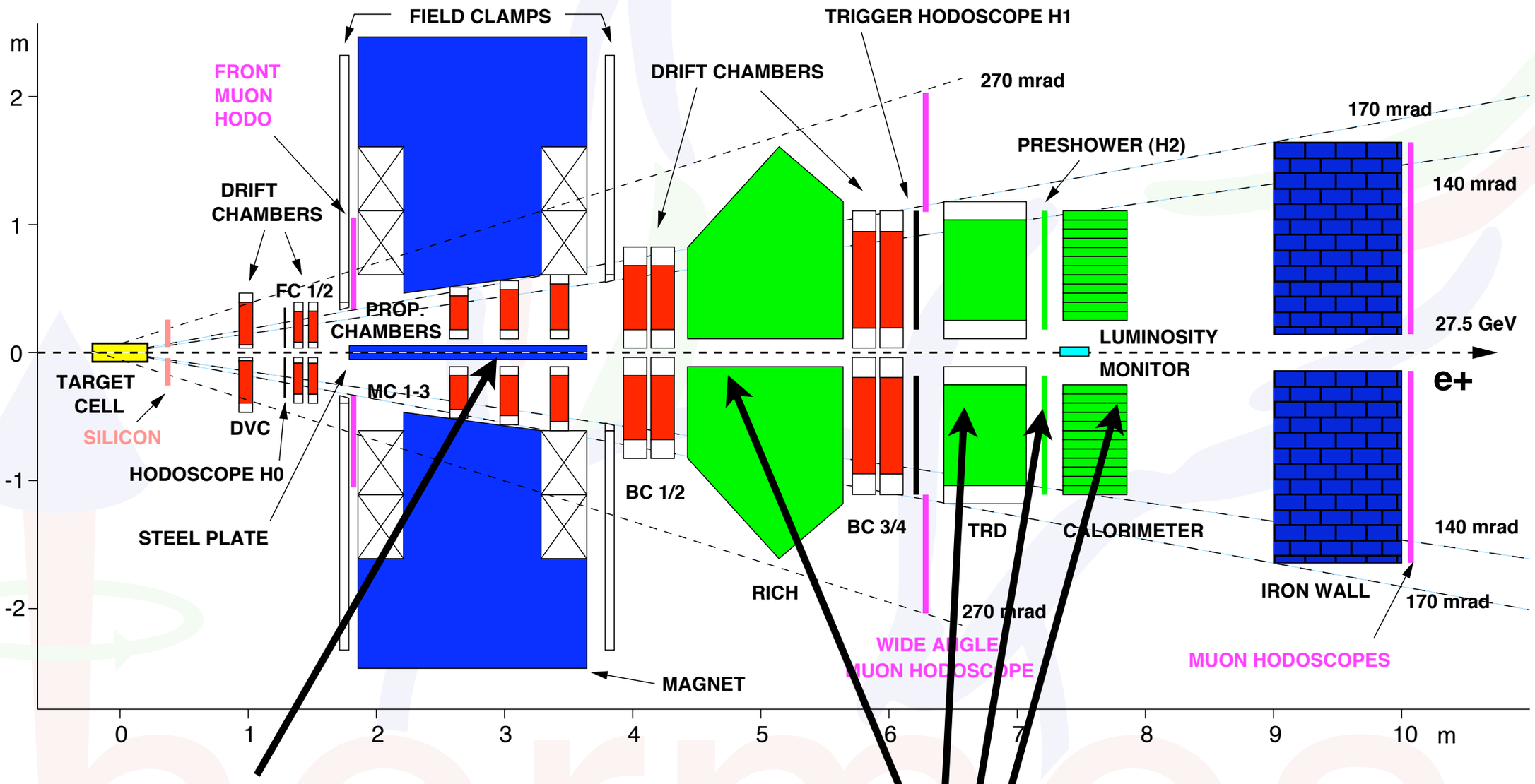
novel **pure** gas target:

- internal to HERA lepton ring
- unpolarized (^{1}H … Xe)
- longitudinally polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H





HERMES schematically

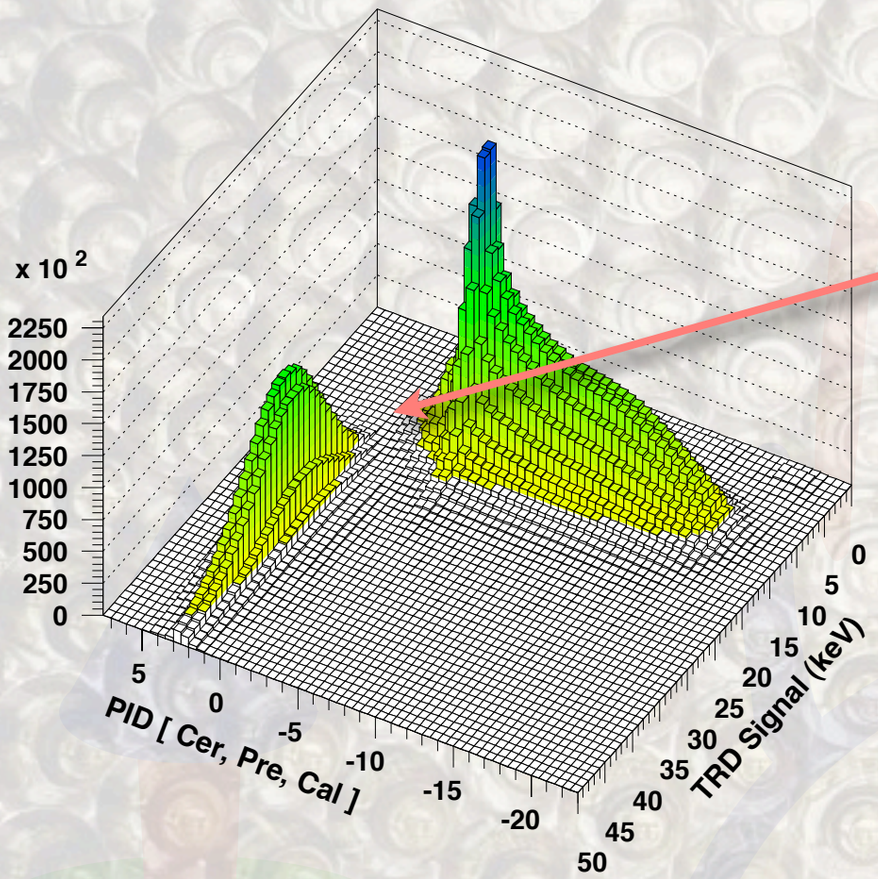


two (mirror-symmetric) halves
-> no homogenous azimuthal coverage

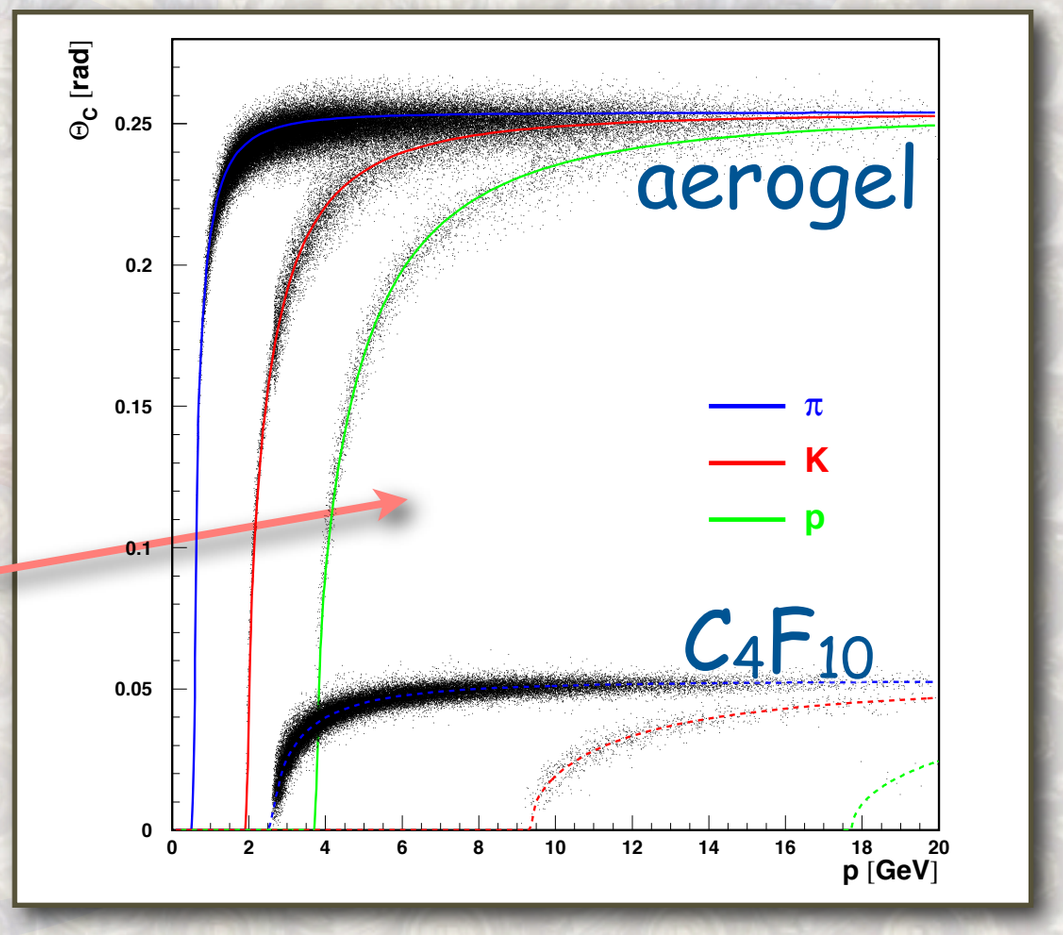
Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

Particle identification

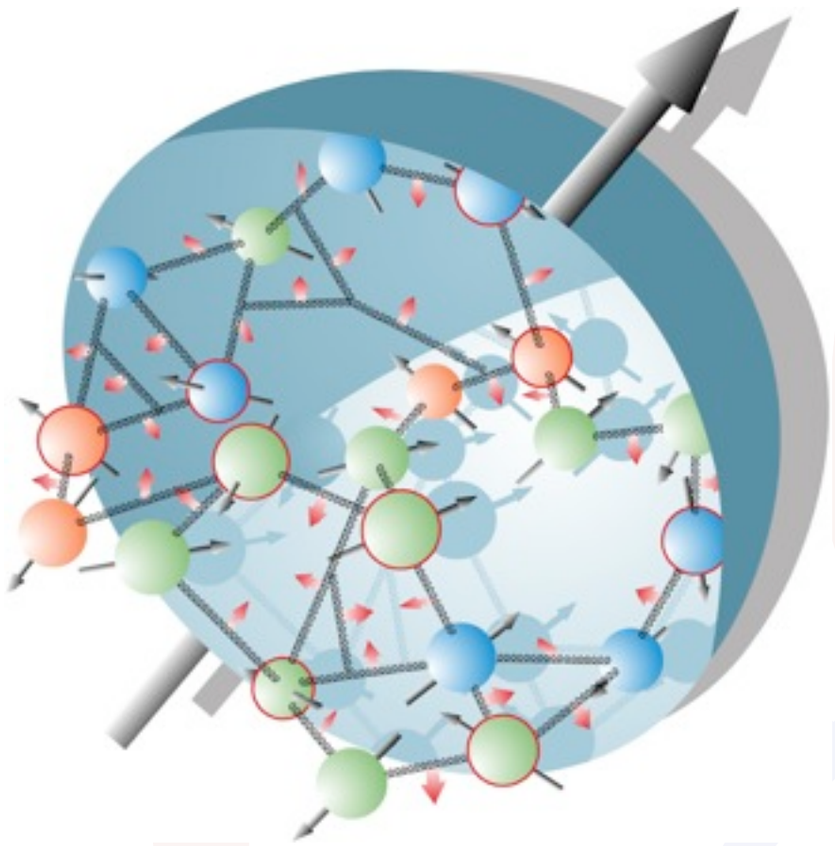
excellent lepton/hadron separation



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



The HERA-I (1995-2000) harvest



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

$+ \Delta G$ ← gluon spin

$+ L_q + L_g$ ← orbital angular momentum

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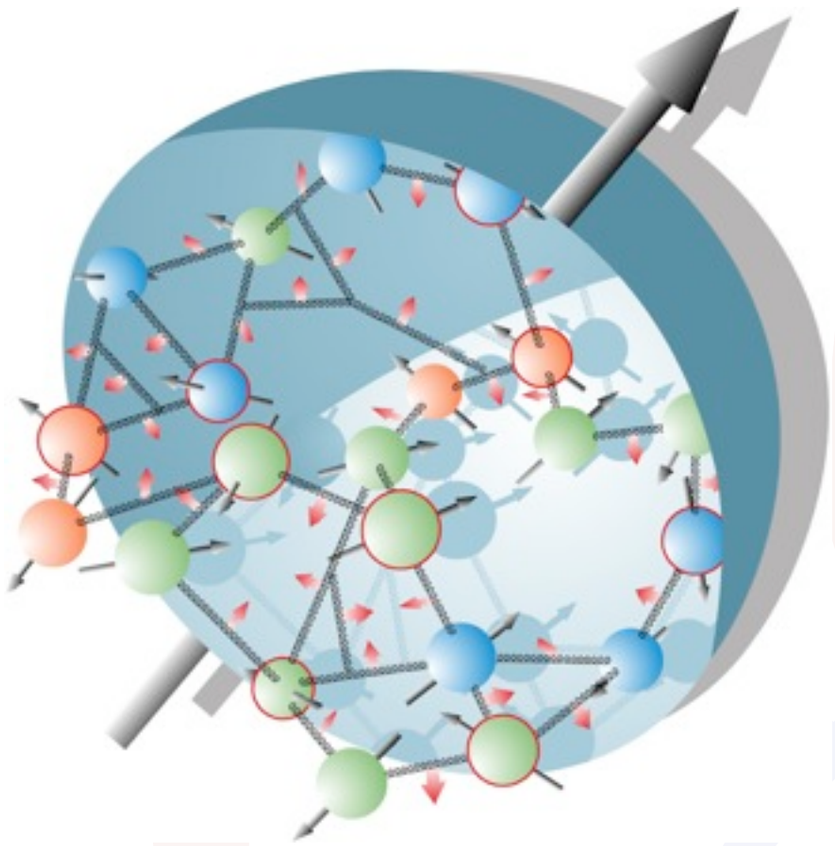

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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- ΔG ← gluon spin
- $L_q + L_g$ ← orbital angular momentum

- Inclusive DIS from longitudinally polarized deuterium target:

$$\Delta\Sigma = 0.330 \pm 0.025\ ^{(exp.)} \pm 0.011\ ^{(theory)} \pm 0.028\ ^{(evol.)}$$

PRD 75 (2007) 012007

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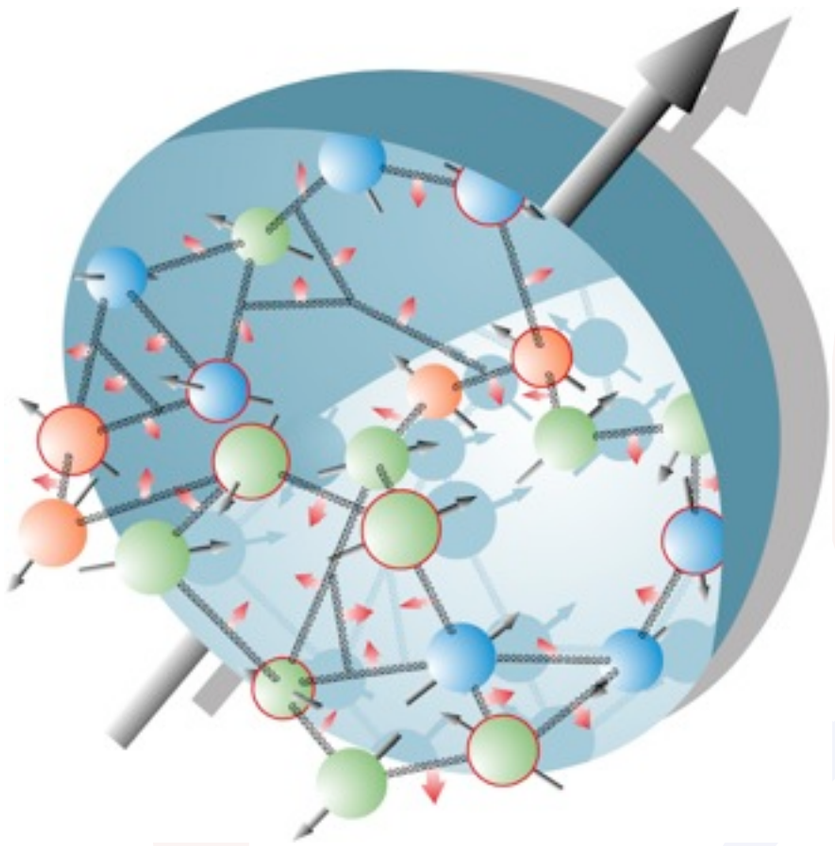

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- High-p_T hadrons at HERMES:

$$\Delta G/G = 0.071 \pm 0.034^{(stat)} \pm 0.010\,^{(sys\text{-}exp)}\ {}^{+0.127}_{-0.105}\,^{(sys\text{-}model)}$$

JHEP 1008 (2010) 130

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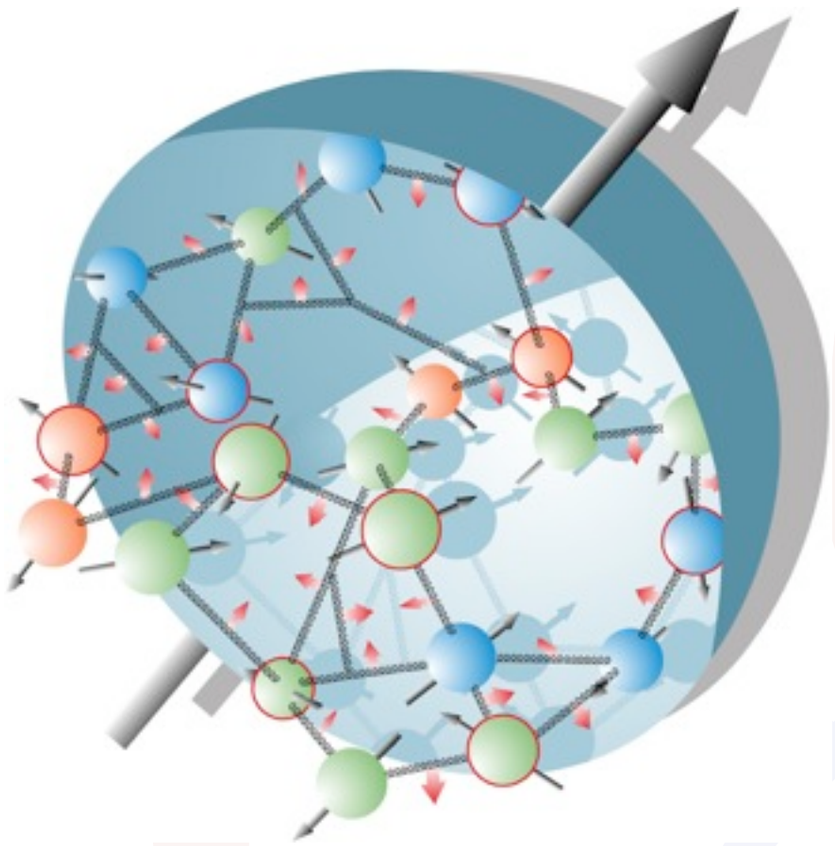

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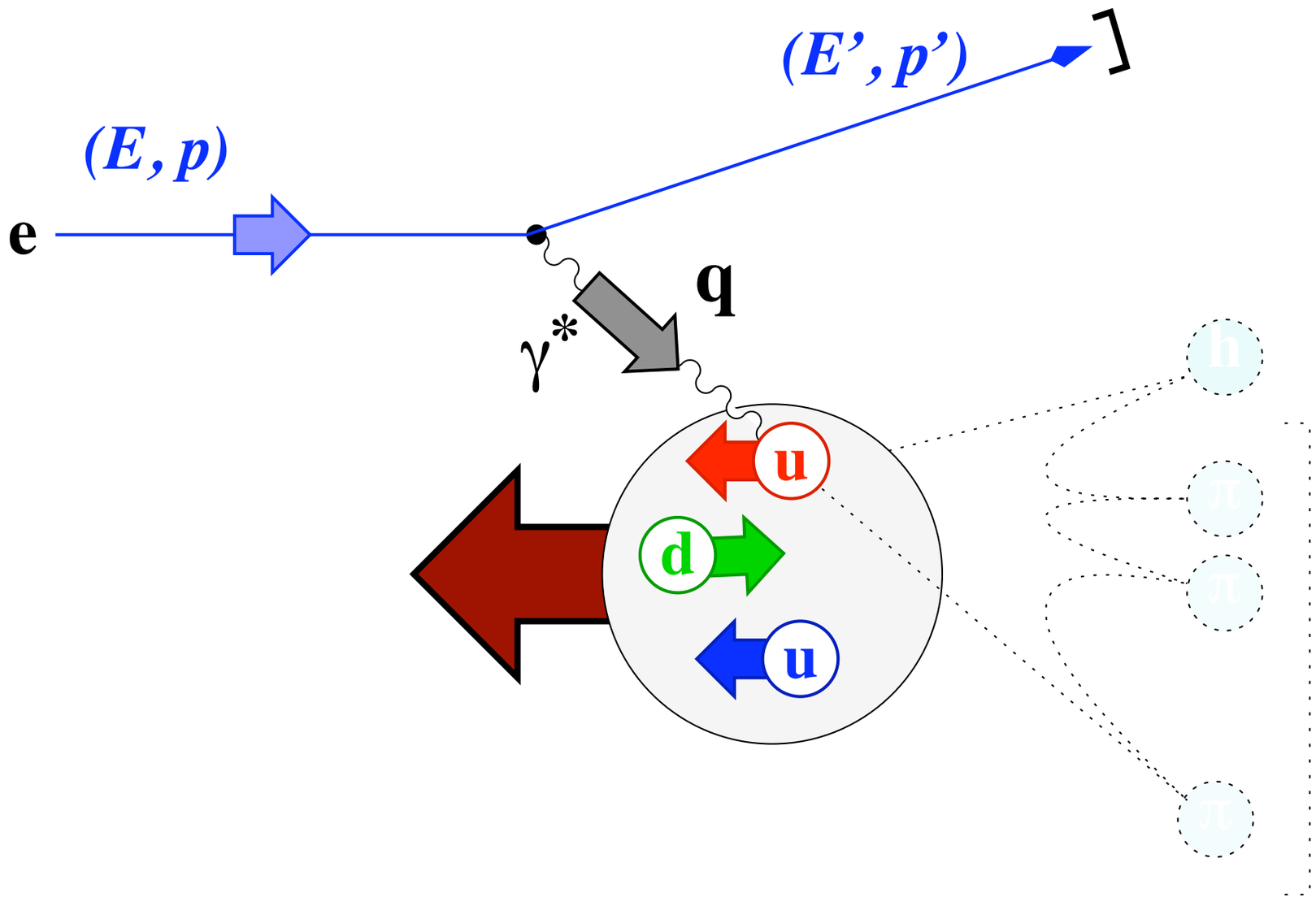
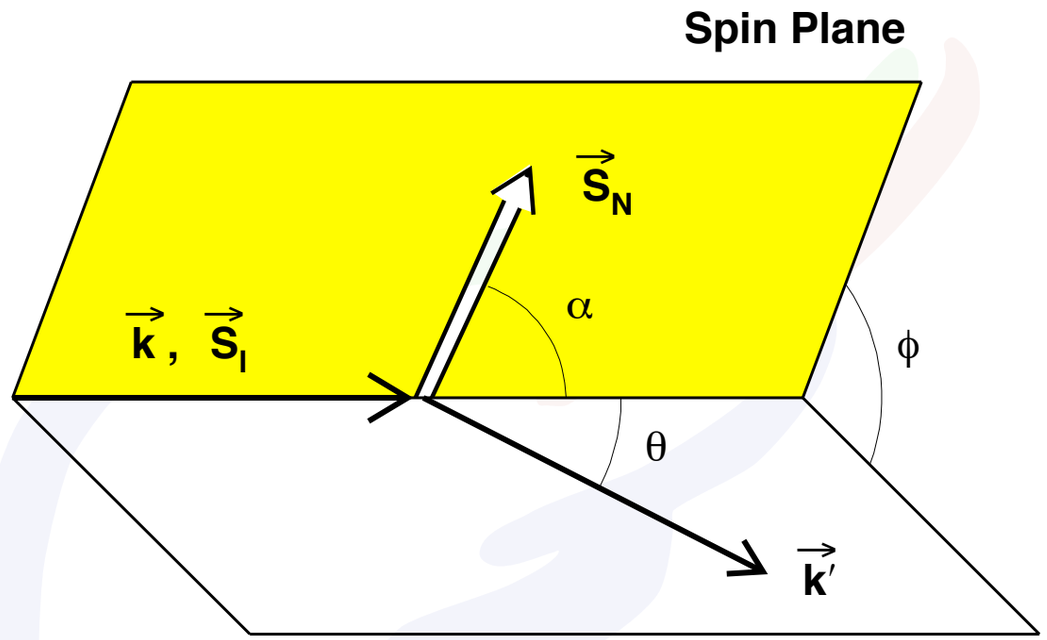
Inclusive DIS



Inclusive DIS (one-photon exchange)

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



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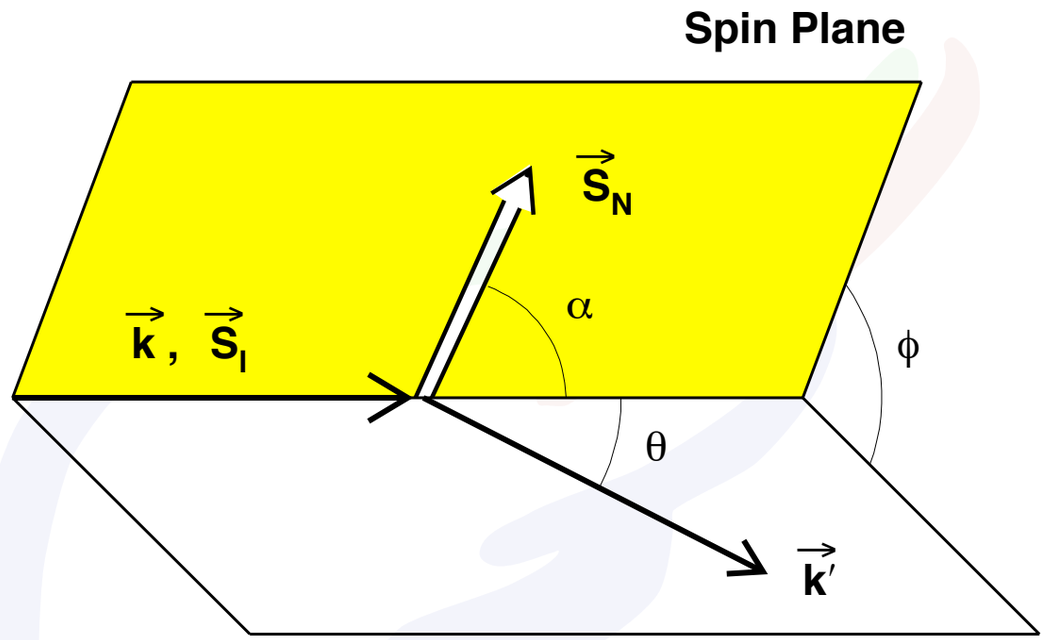
Lepton Tensor



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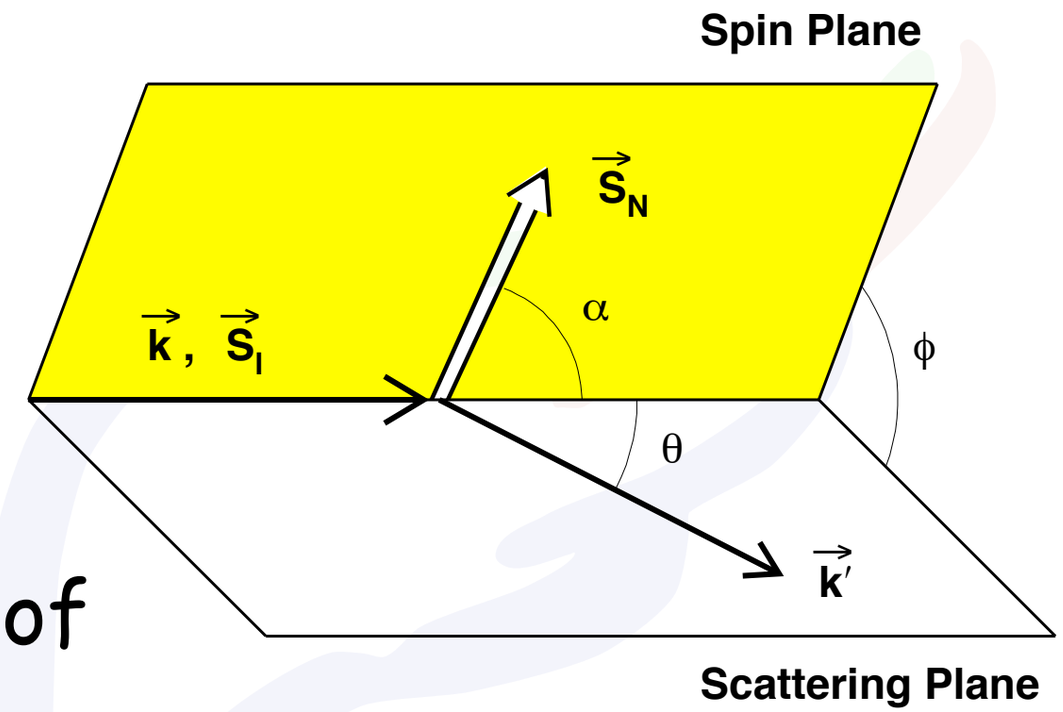
Lepton Tensor

Hadron Tensor parametrized in terms of Structure Functions



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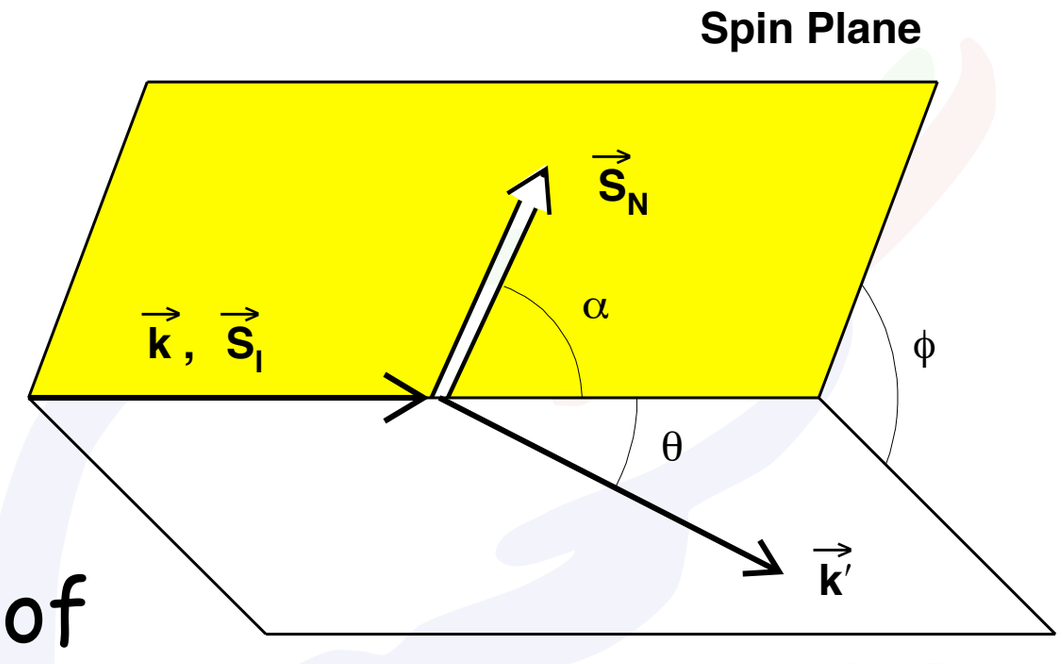
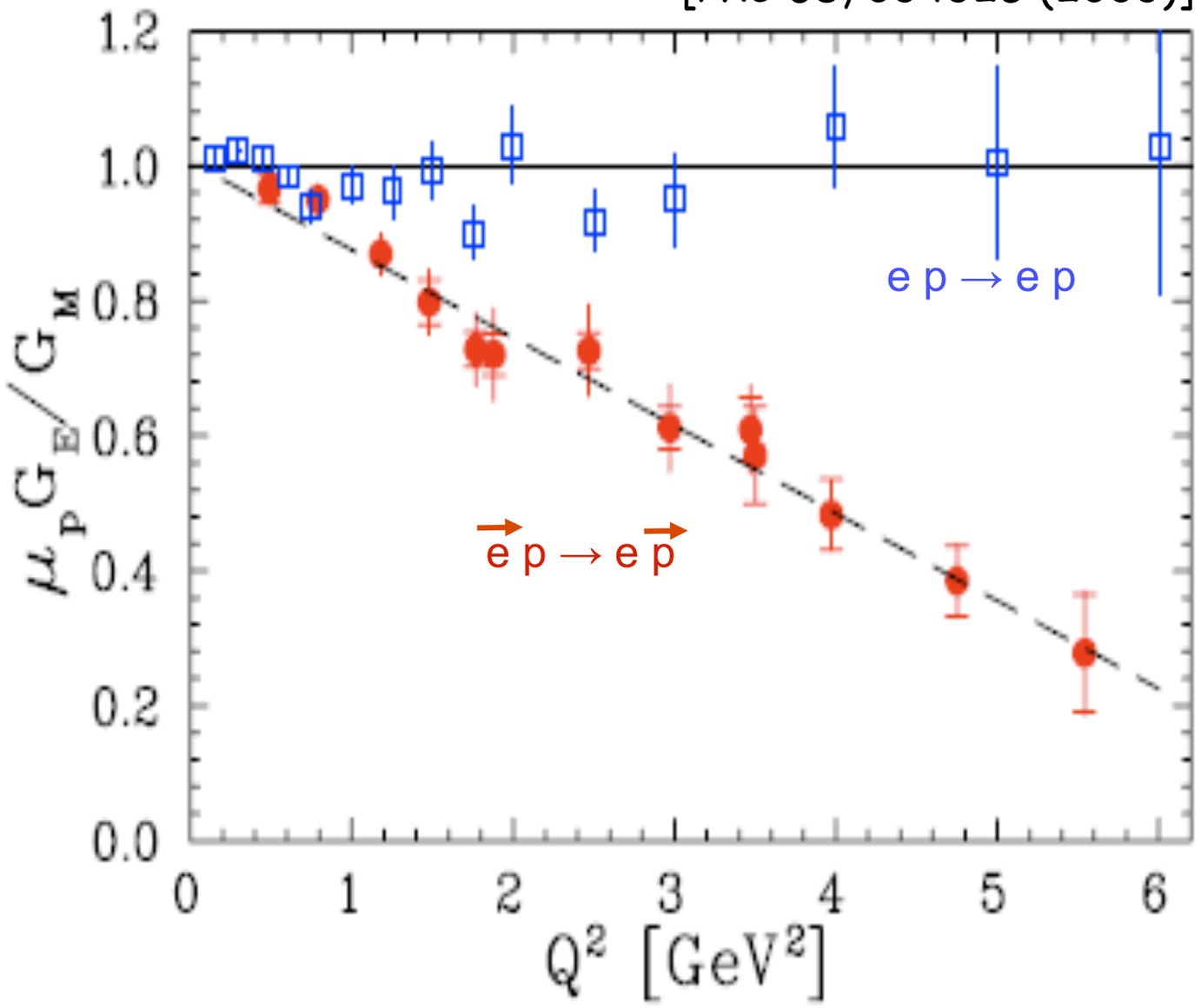


$$\frac{d^3\sigma}{dxdyd\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$
$$-S_lS_N\cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{2}g_2(x,Q^2)\right]$$
$$+S_lS_N\sin\alpha\cos\phi\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

Check the details!

Check the details!

[PRC 68, 034325 (2003)]

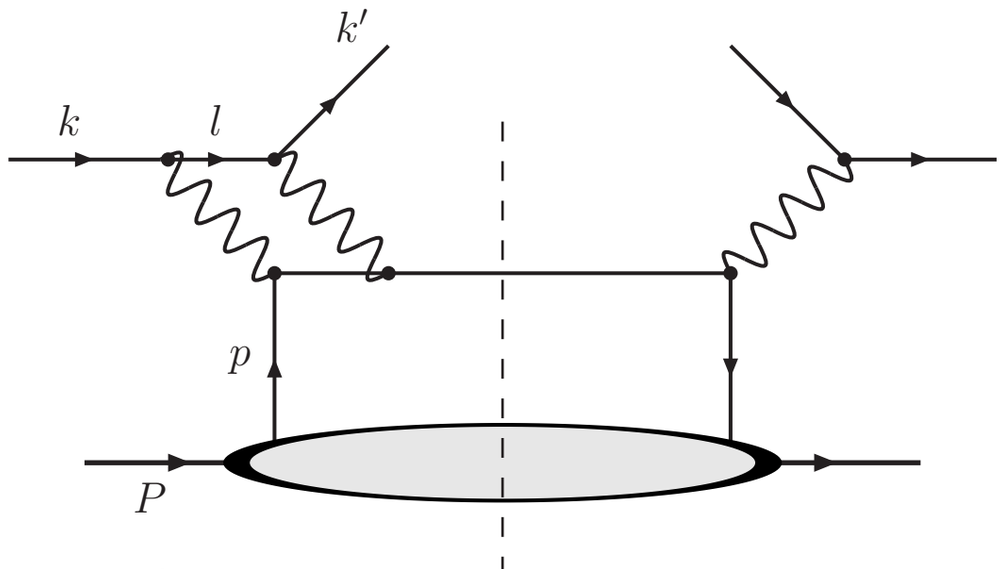


☛ two-photon exchange can be important!

x_F

Two-photon exchange

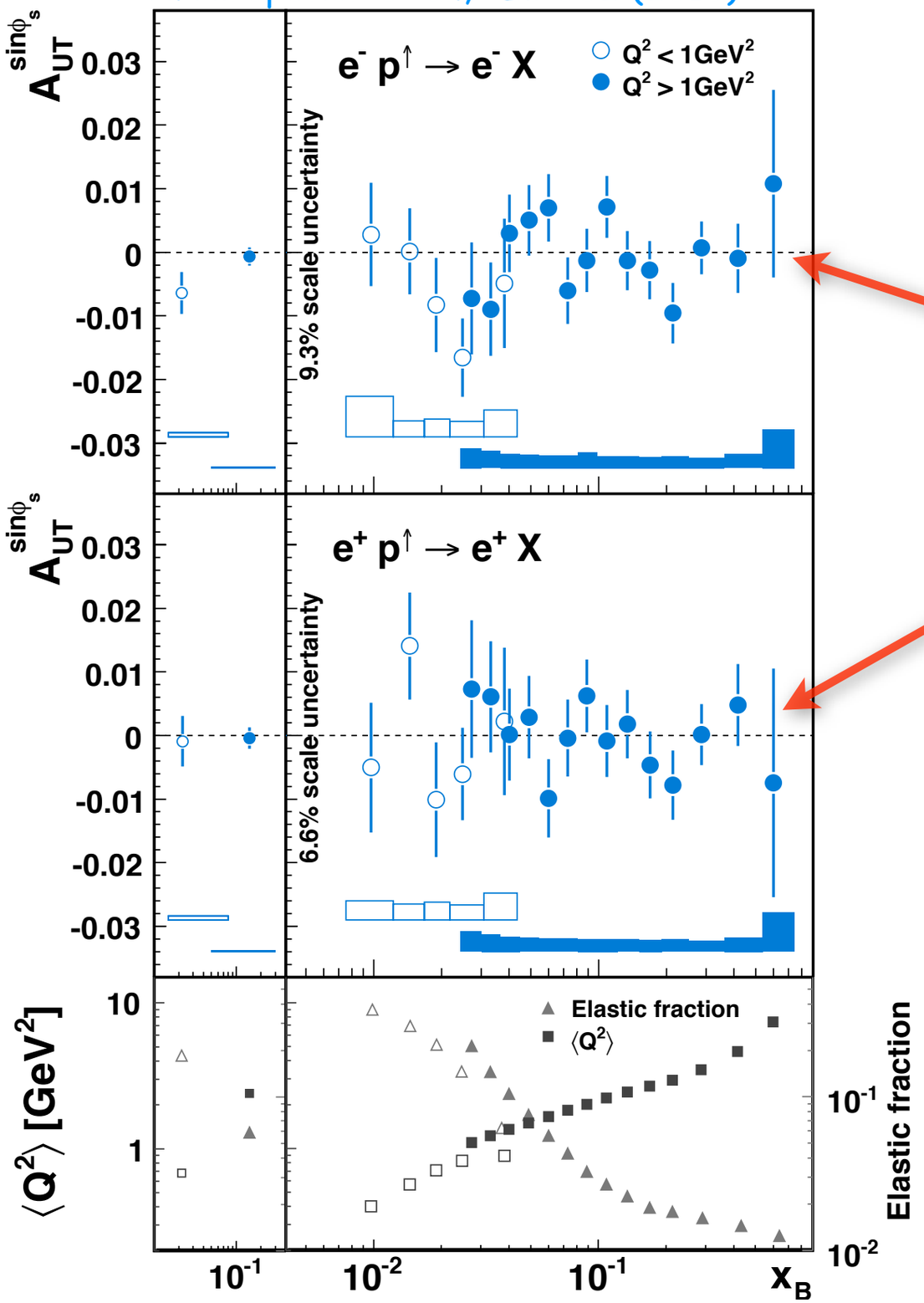
- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets



- cross section proportional to S(kxk') - either measure left-right asymmetries or sine modulation
- sensitive to beam charge due to odd number of e.m. couplings to beam

No sign of two-photon exchange

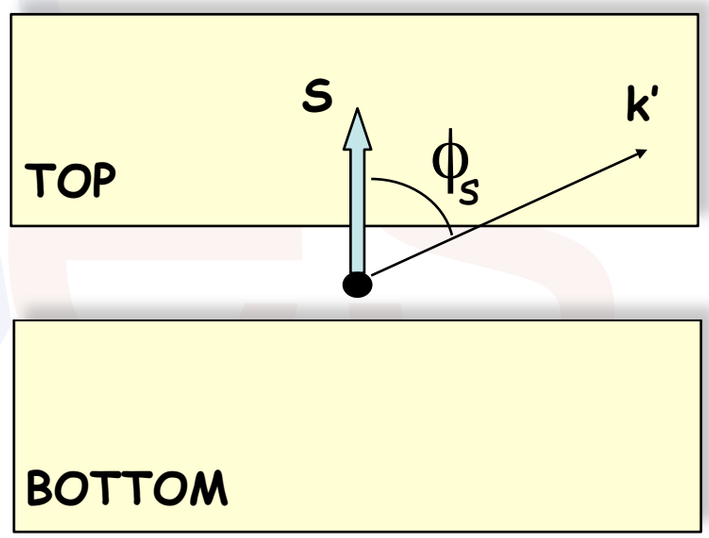
A. Airapetian et al., PLB 682 (2010) 350



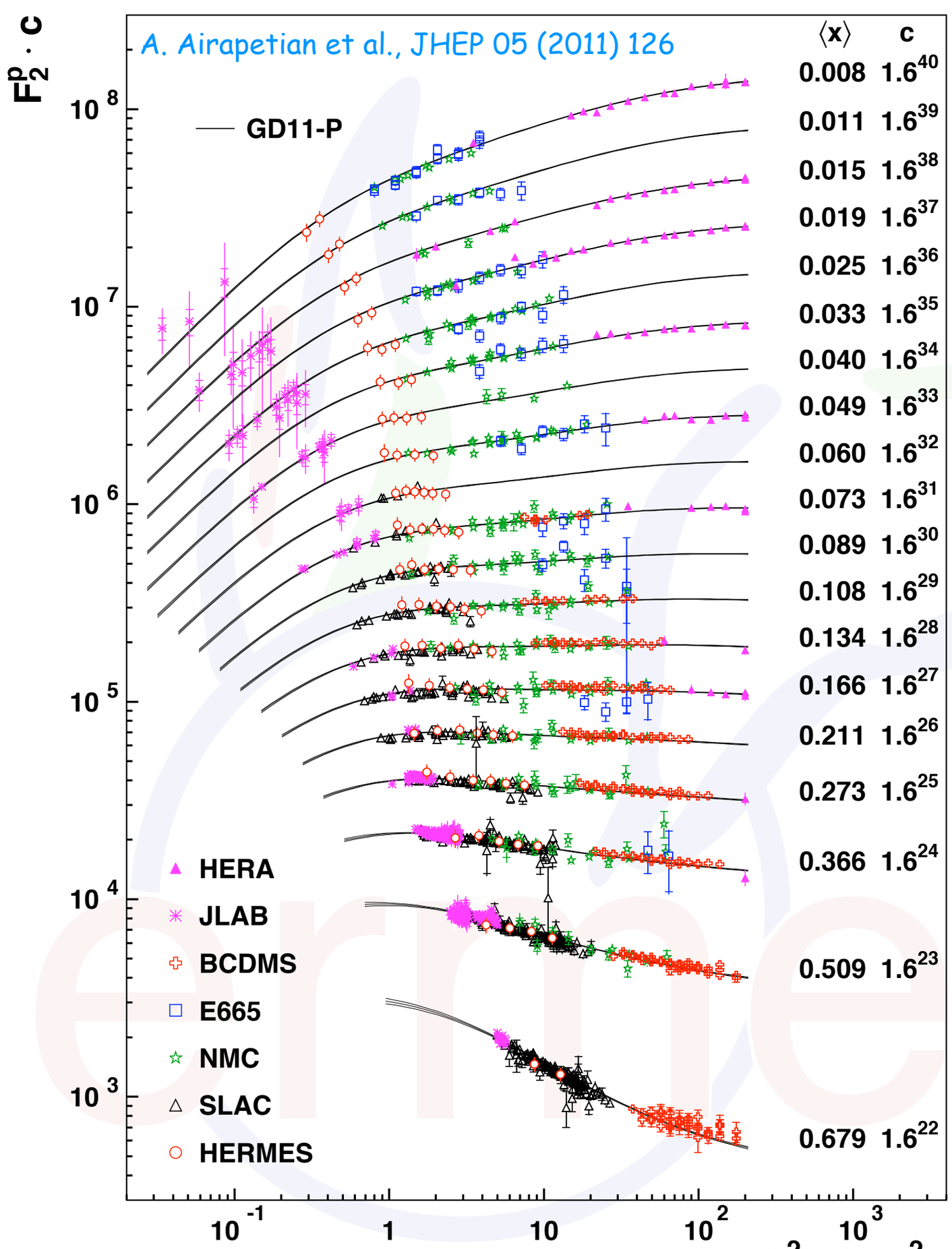
Beam	$A_{UT}^{\sin\phi_S} \times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(stat.) $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(syst.) $\times 10^{-3}$	$\langle x_B \rangle$	$\langle Q^2 \rangle$ [GeV^2]
e^+	−0.61	3.97	0.63	0.02	0.68
e^-	−6.55	3.40	0.63		
e^+	−0.60	1.70	0.29	0.14	2.40
e^-	−0.85	1.50	0.29		

consistent with zero for both e^+/e^-

Front view of HERMES detector



F_2 proton

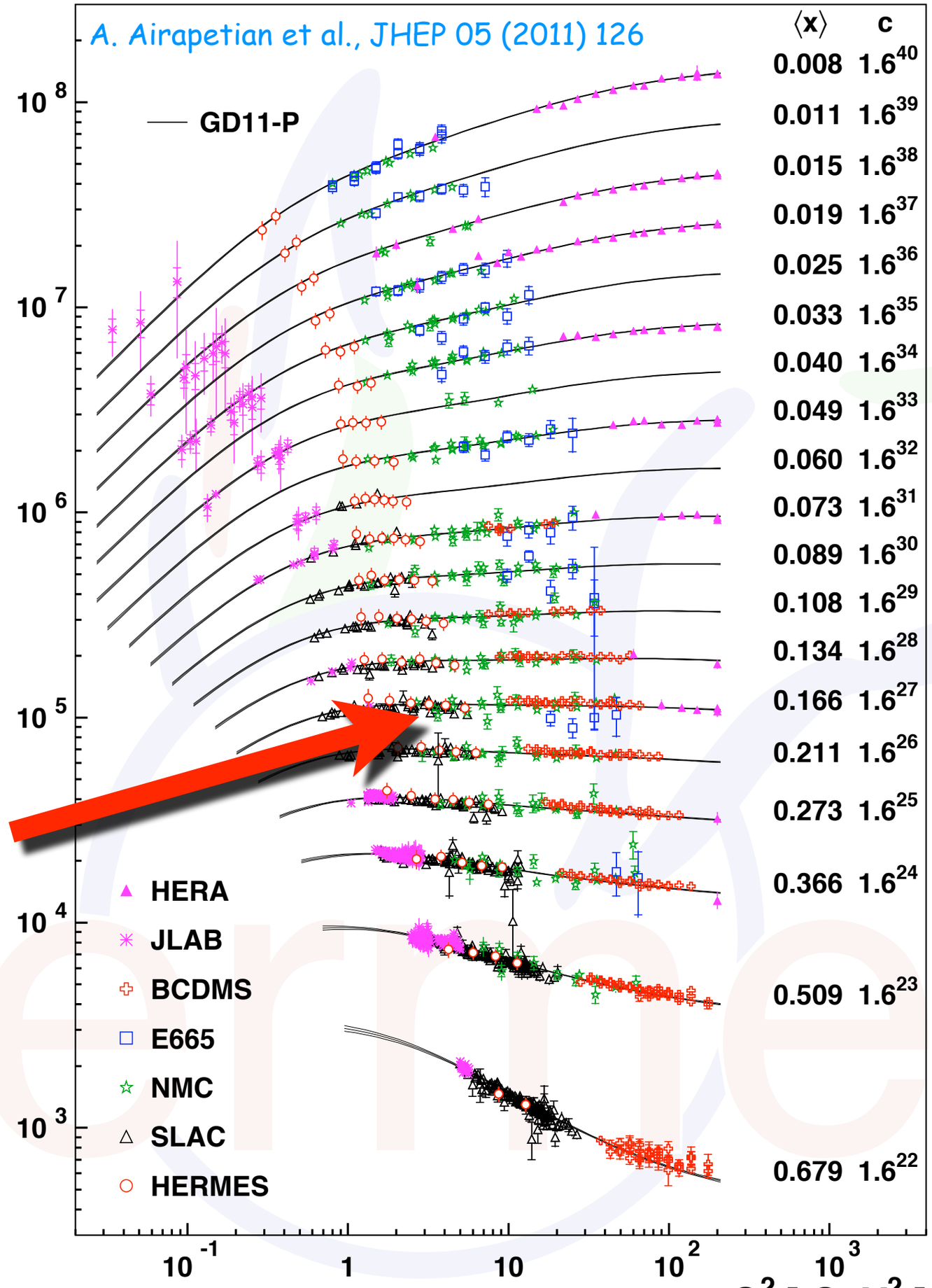


GD11 - global fit

From global fit GD11:
HERMES relative normalization
~2% for proton and deuteron

~0.5% for their ratio

F_2 proton



Agreement with world data in the overlap region

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New region covered by HERMES

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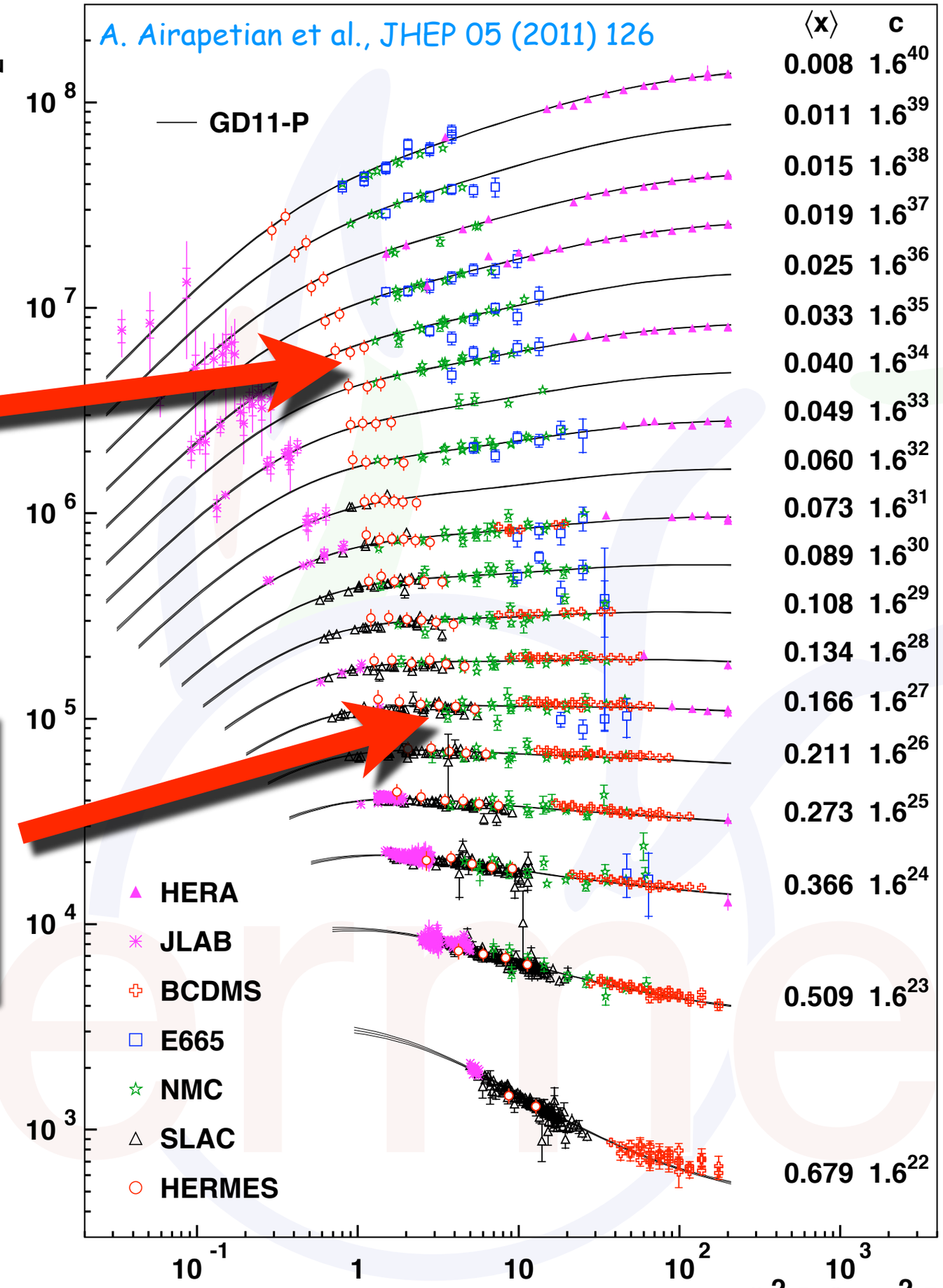

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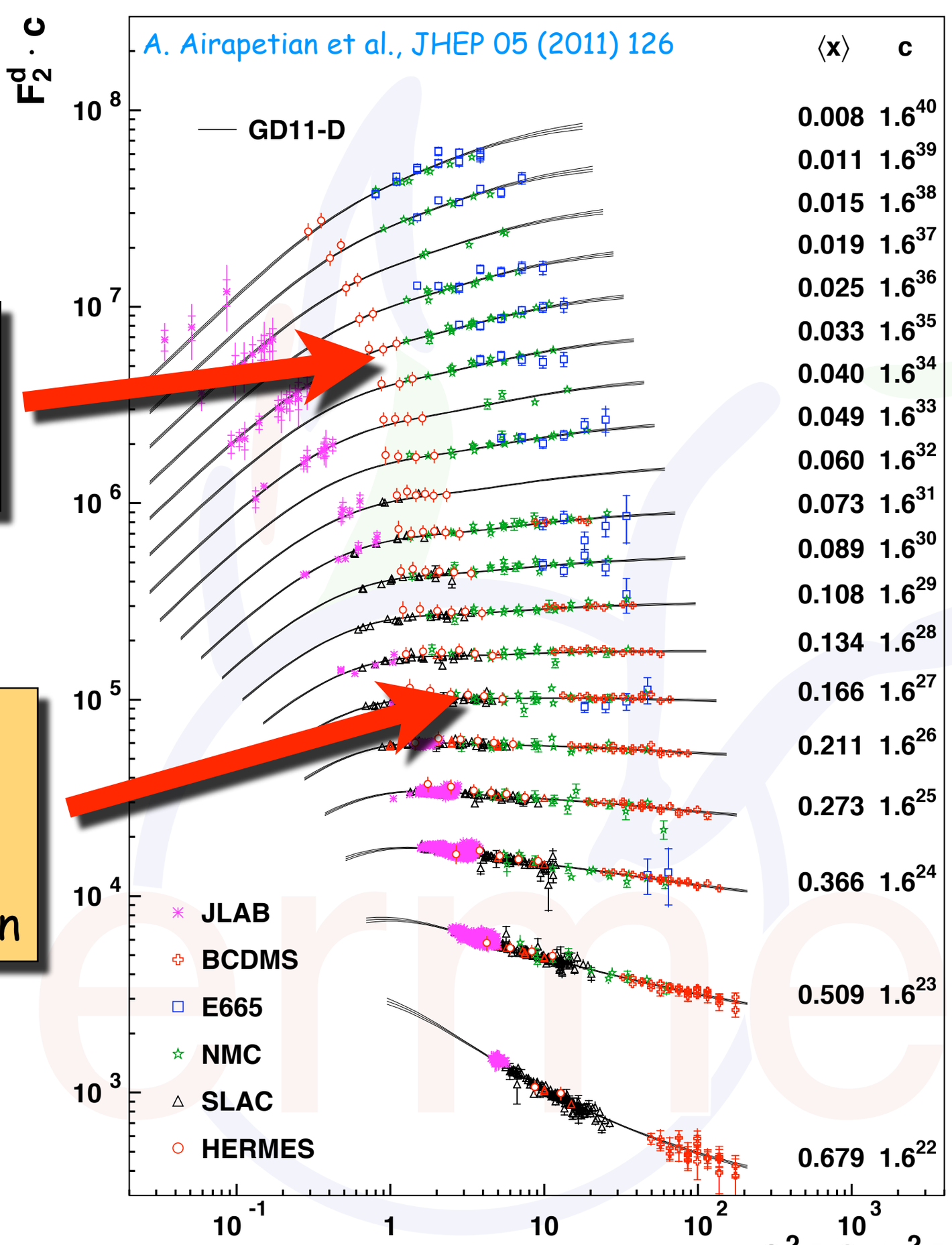

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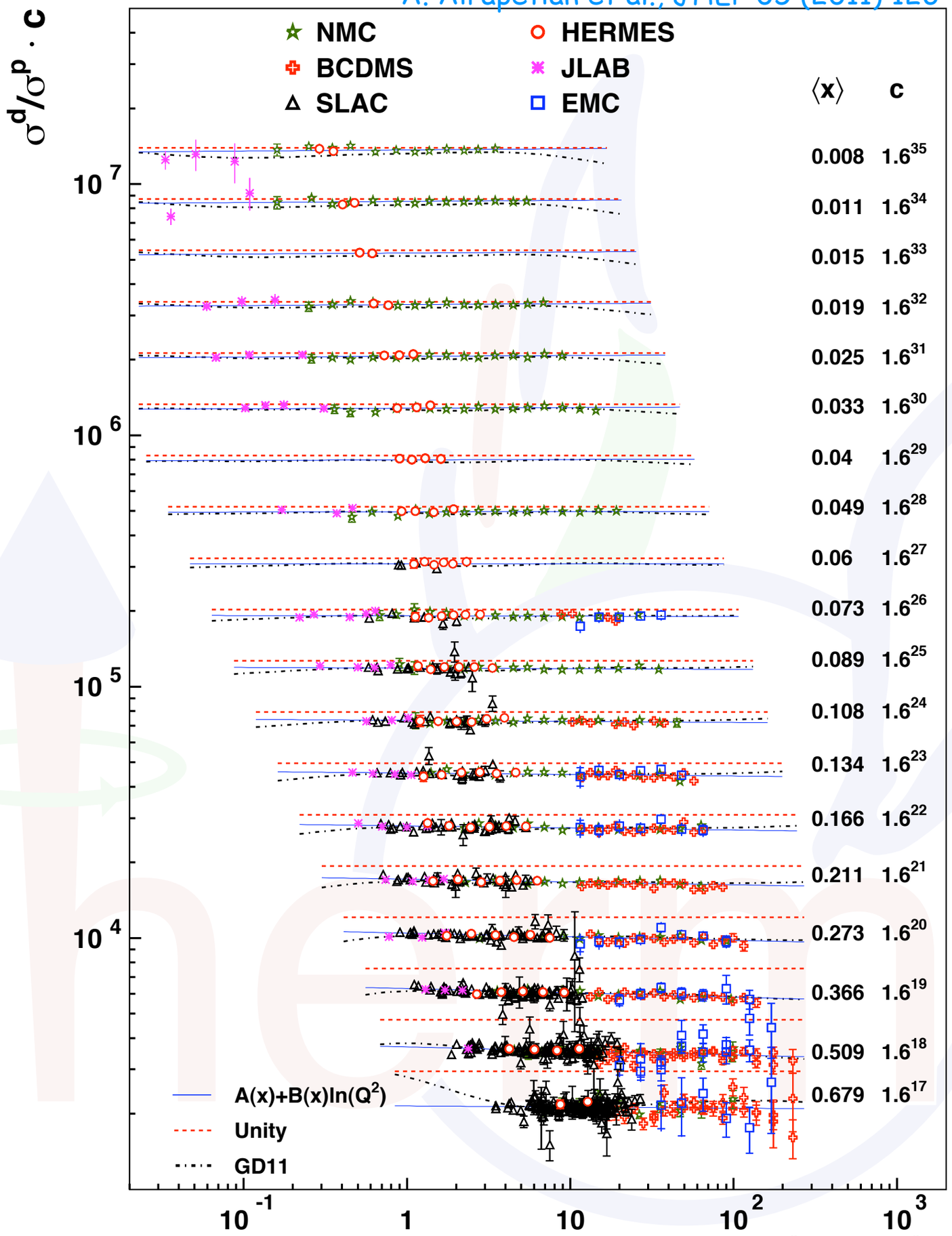
A. Airapetian et al., JHEP 05 (2011) 126

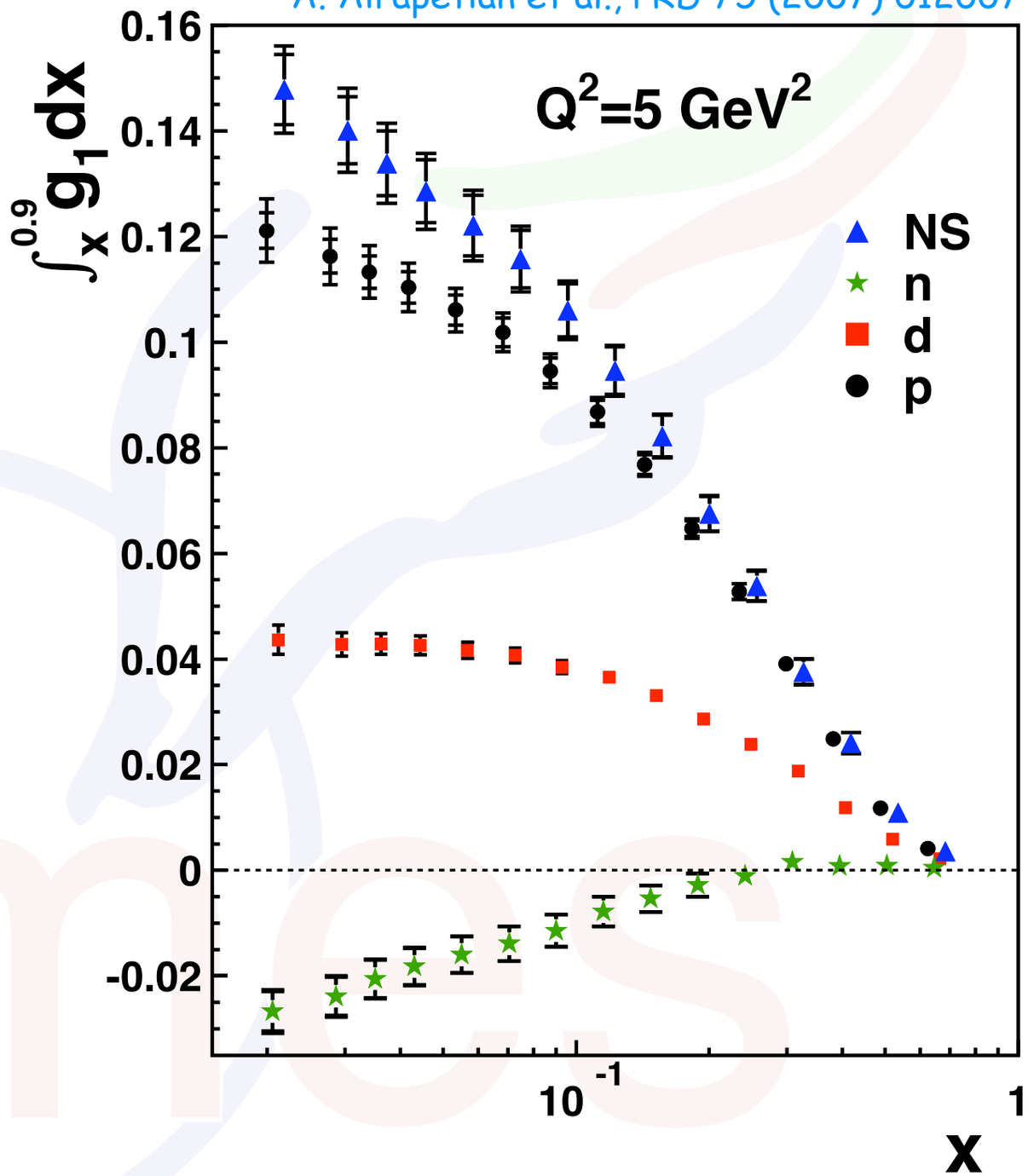
σ^d/σ^p



Many systematic errors common to proton and deuteron cross sections cancel in ratio

Polarized structure function g_1

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



Polarized structure function g_1

Saturation

➠ **close to full integral?**

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

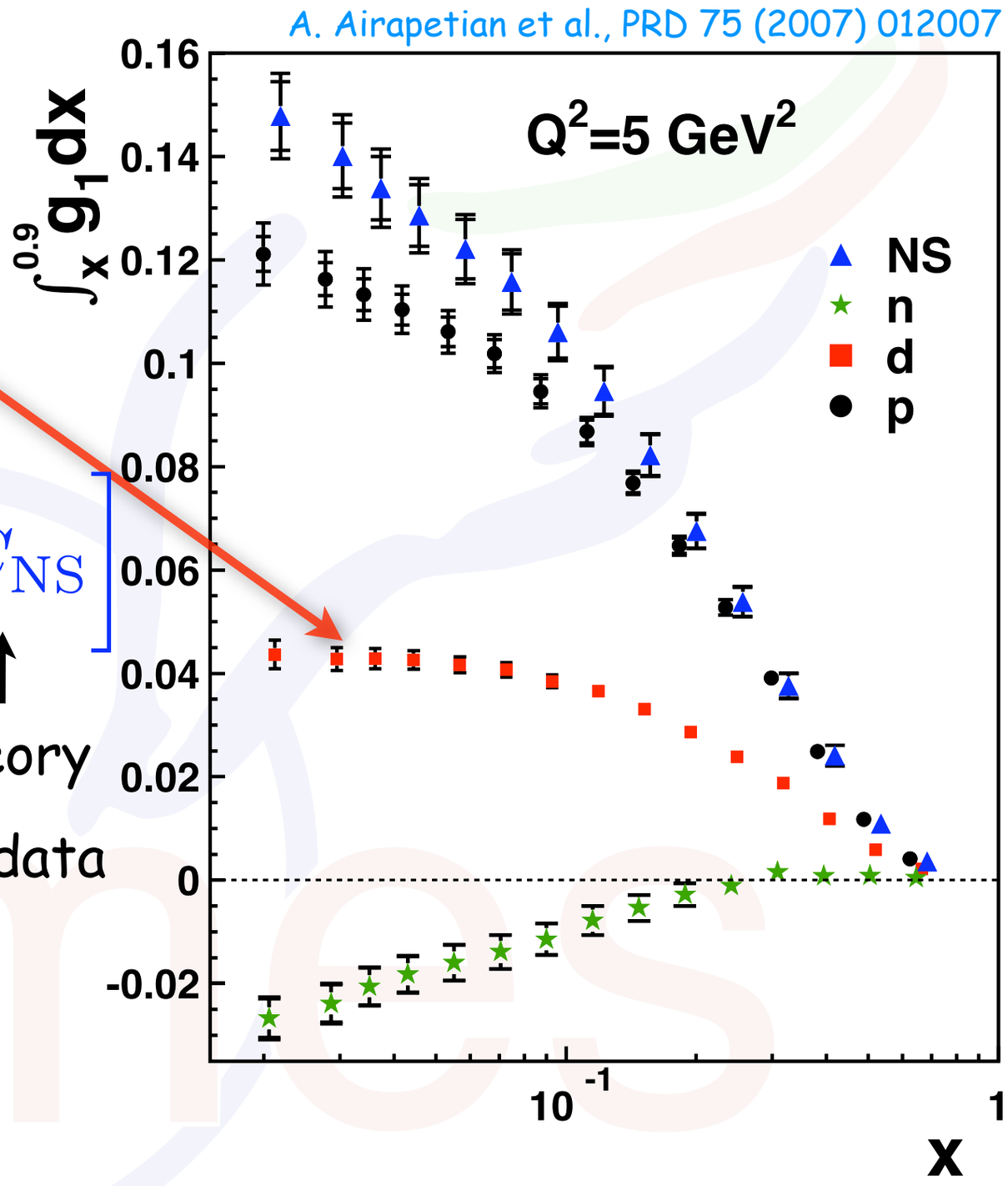
theory: $\frac{1}{\Delta C_{\rm S}}$

$\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D}$: 0.05 ± 0.05

a_8: hyperon-decay data

$\Delta C_{\rm NS}$: theory

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



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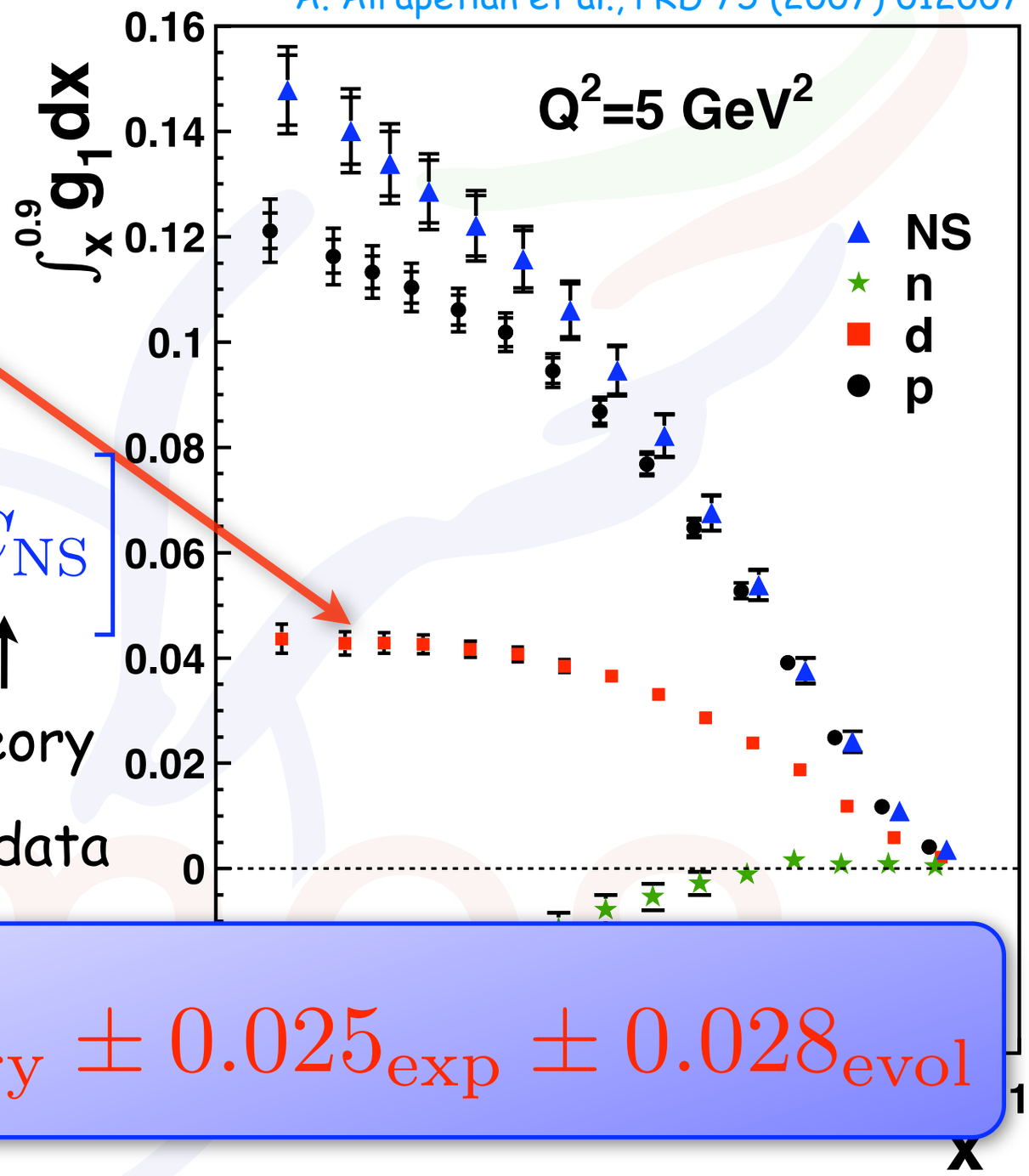

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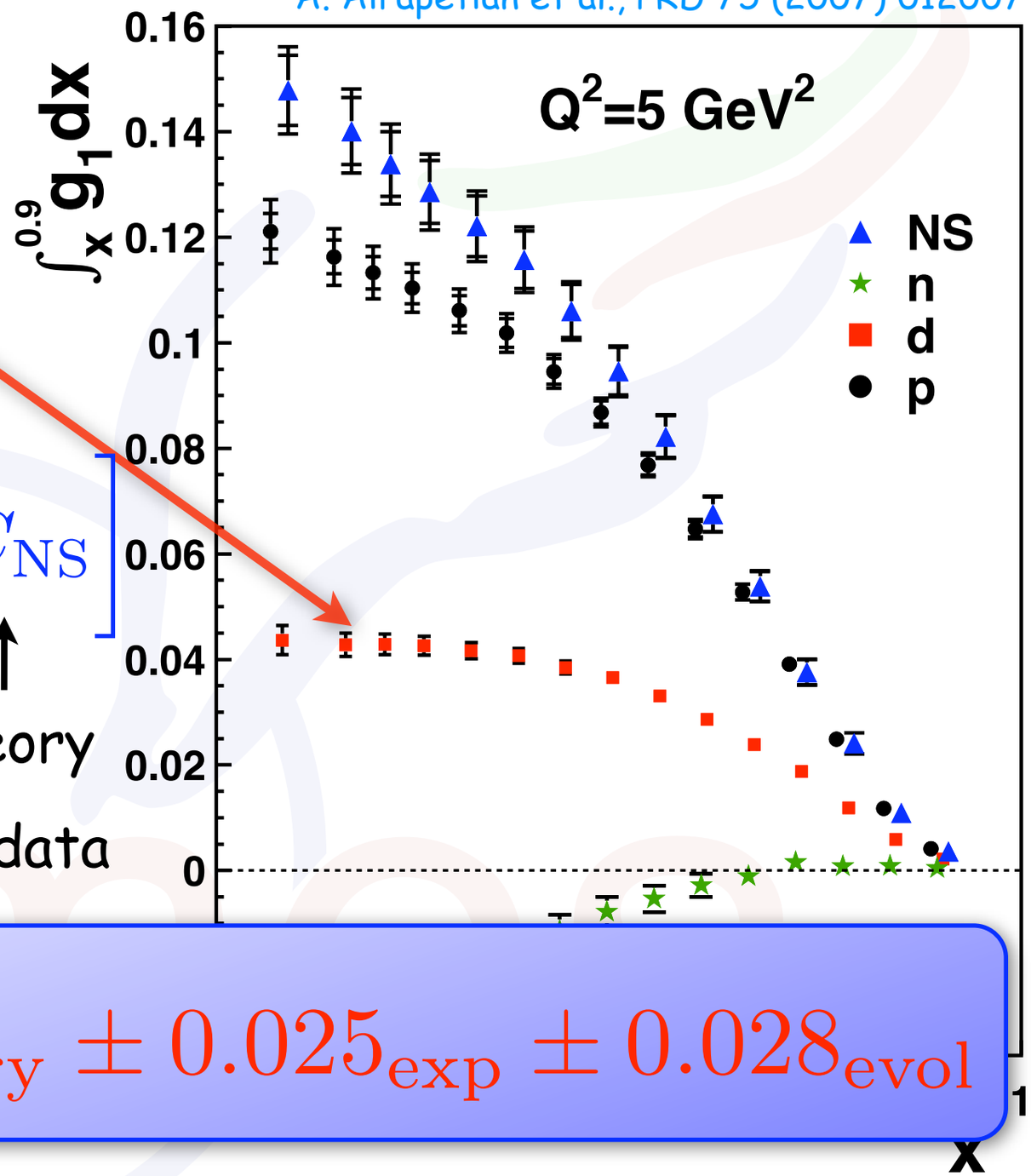
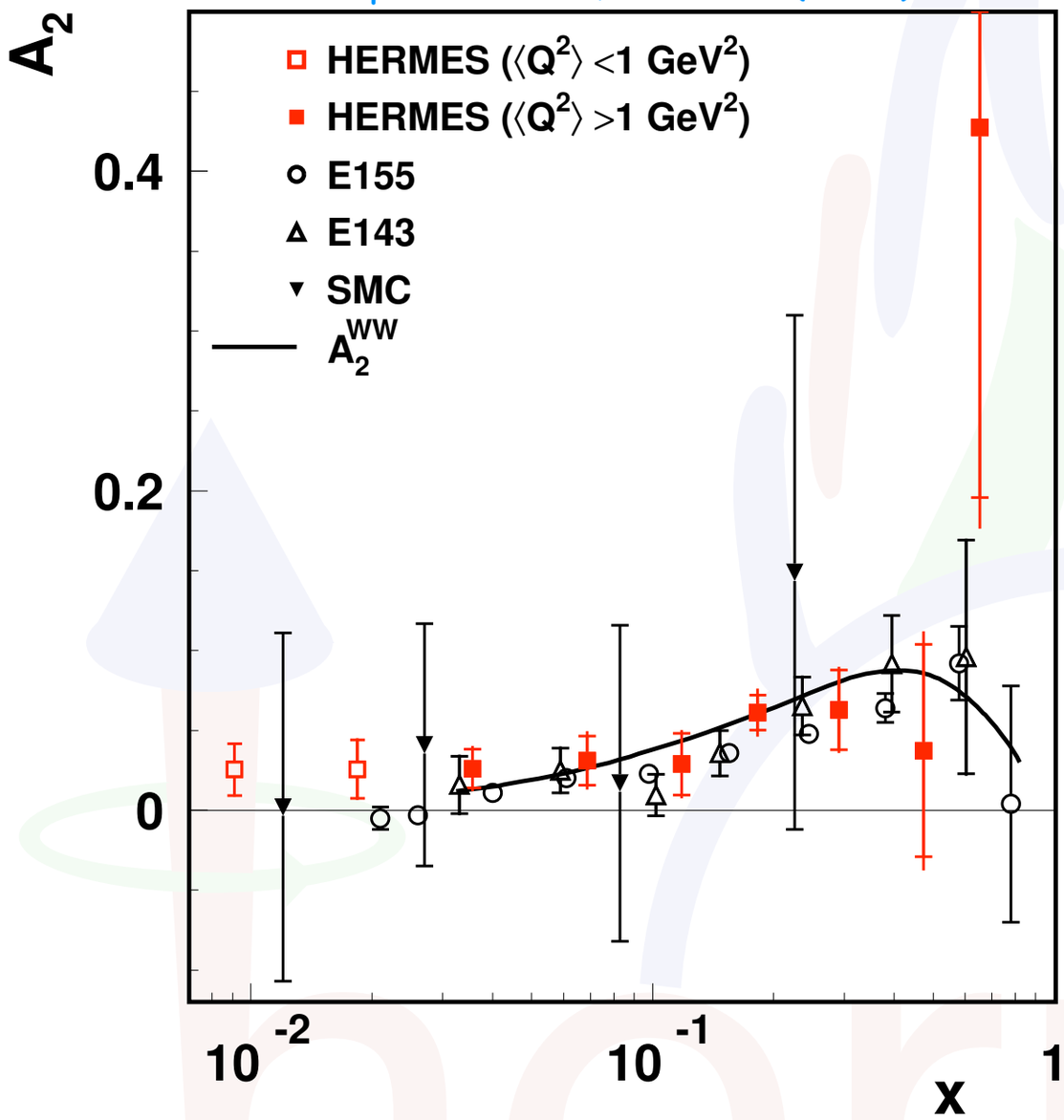


$$\Delta\Sigma \overset{\overline{\rm MS}}{=} 0.330 \pm 0.011_{\rm theory} \pm 0.025_{\rm exp} \pm 0.028_{\rm evol}$$

most precise result; only 1/3 of nucleon spin from quarks

Results on A_2 and xg_2

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



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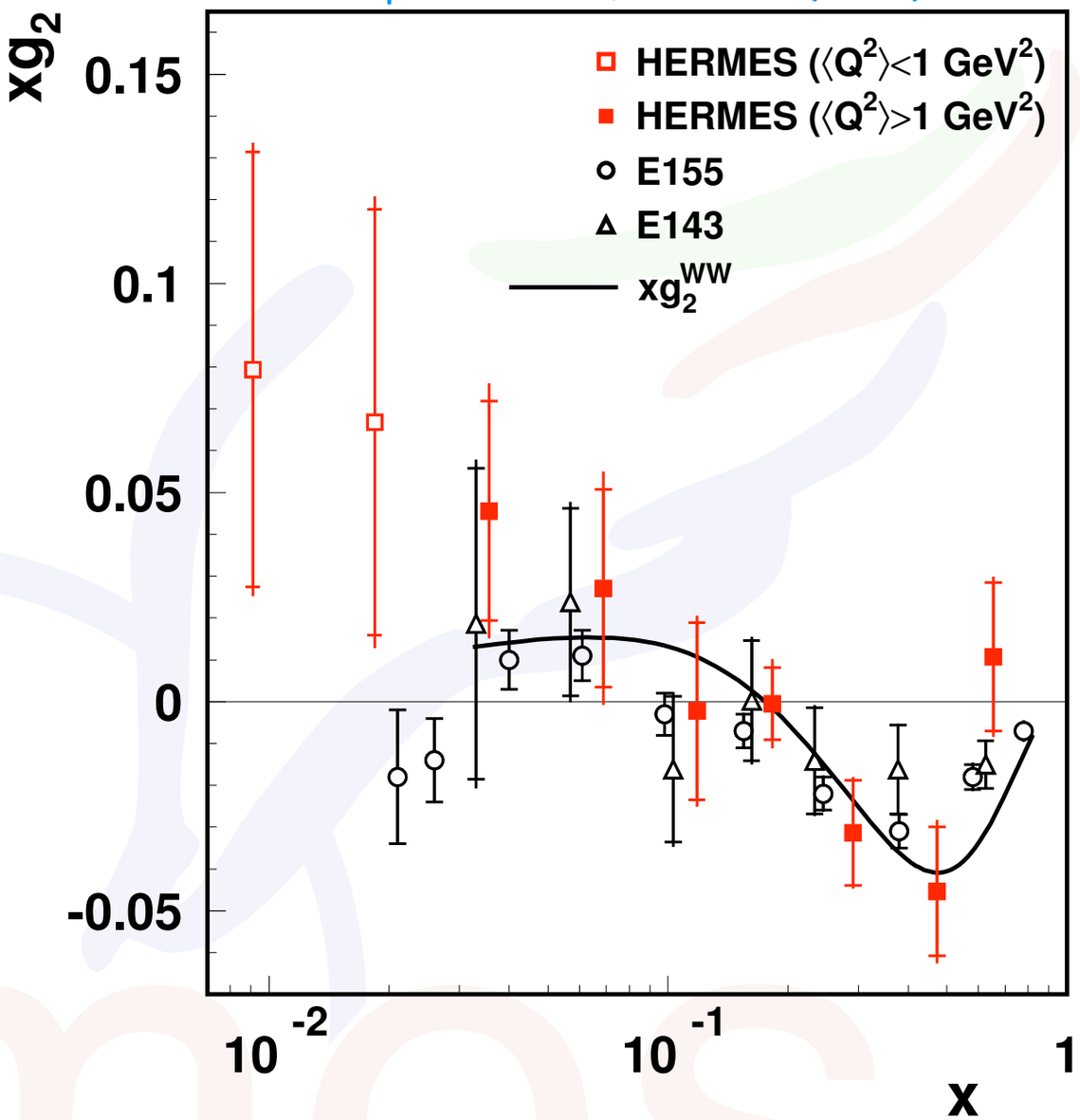

- consistent with (sparse) world data
- low beam polarization during HERA II ➥ small f.o.m.

Results on A_2 and xg_2

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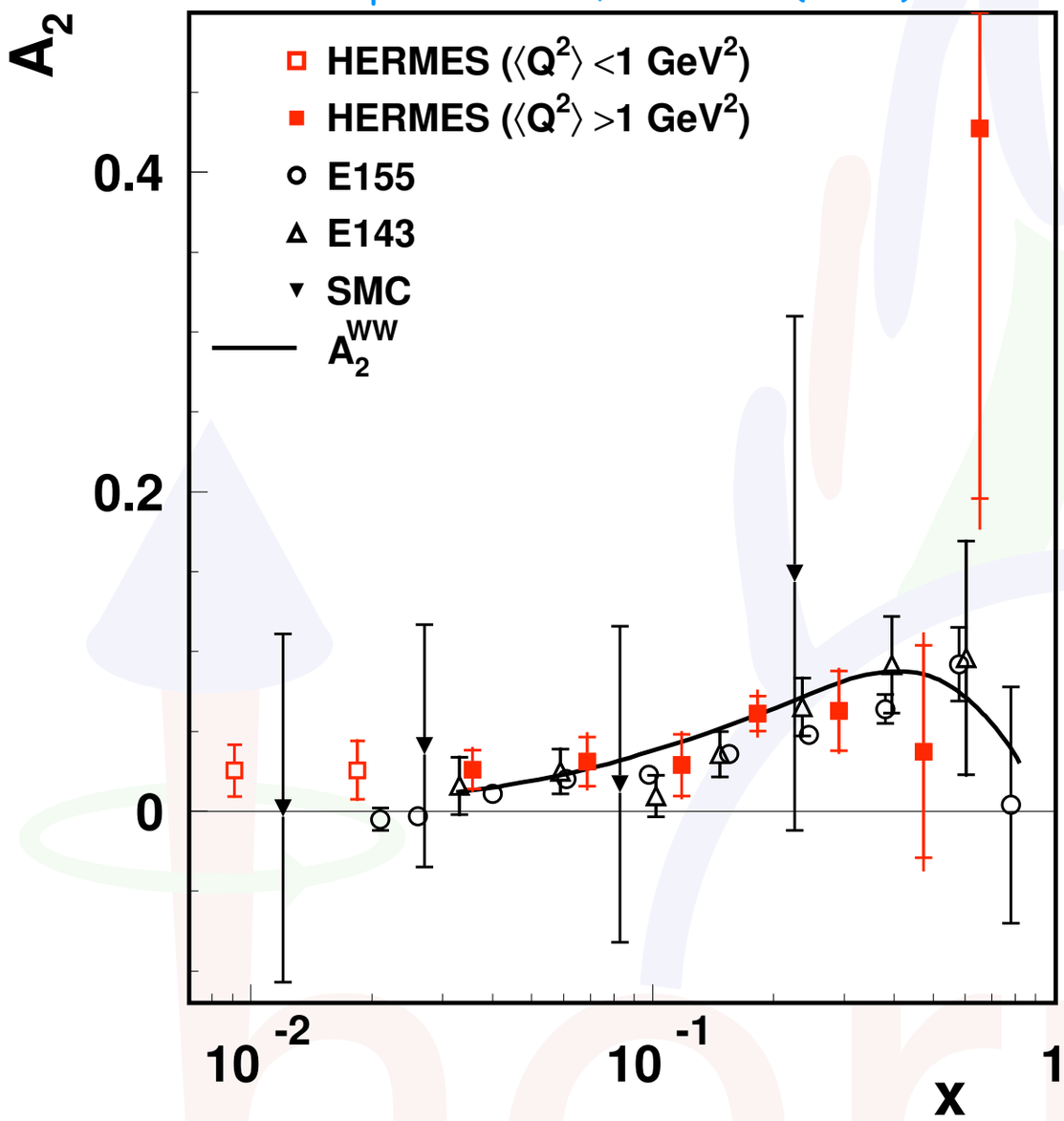

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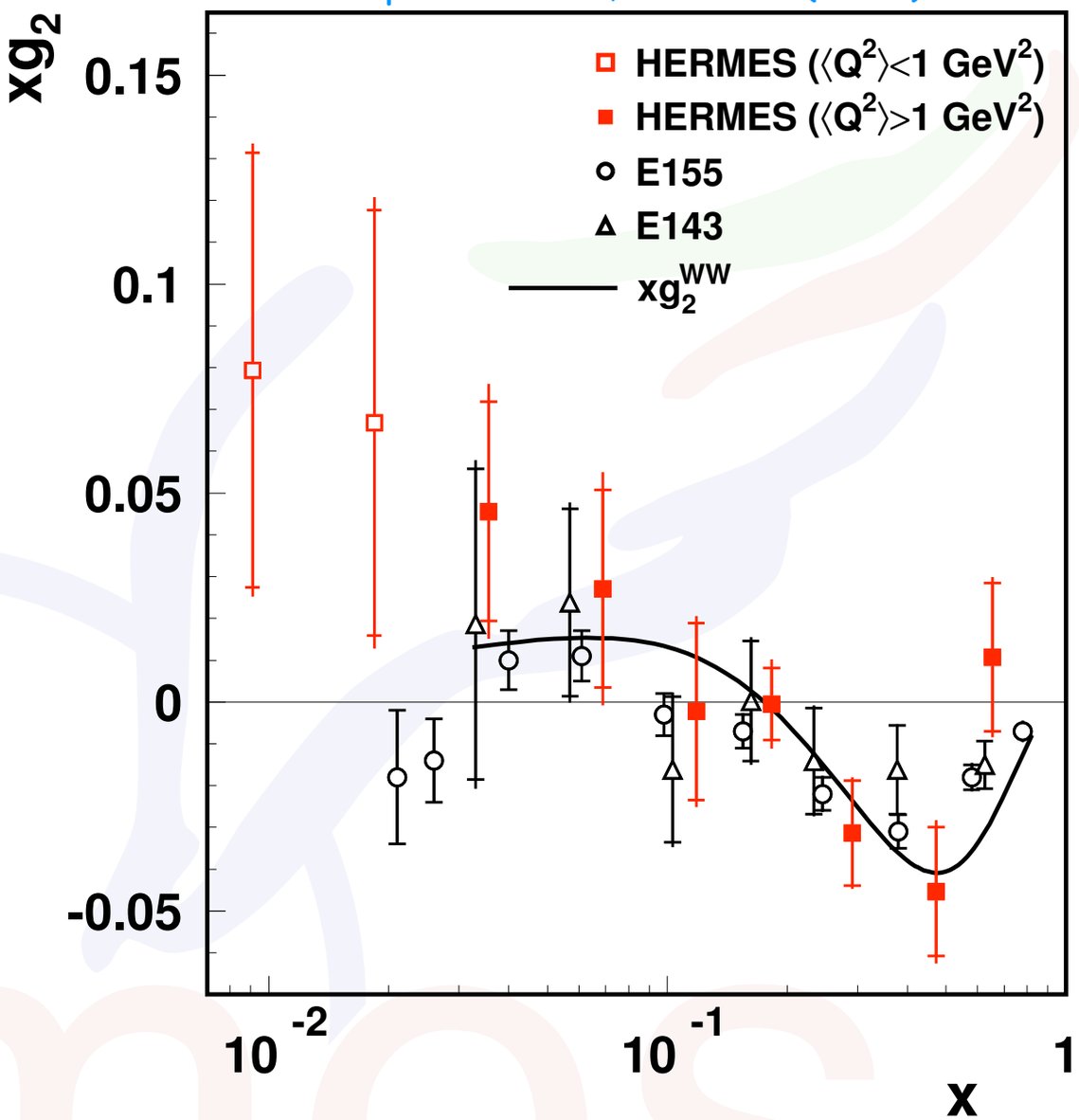
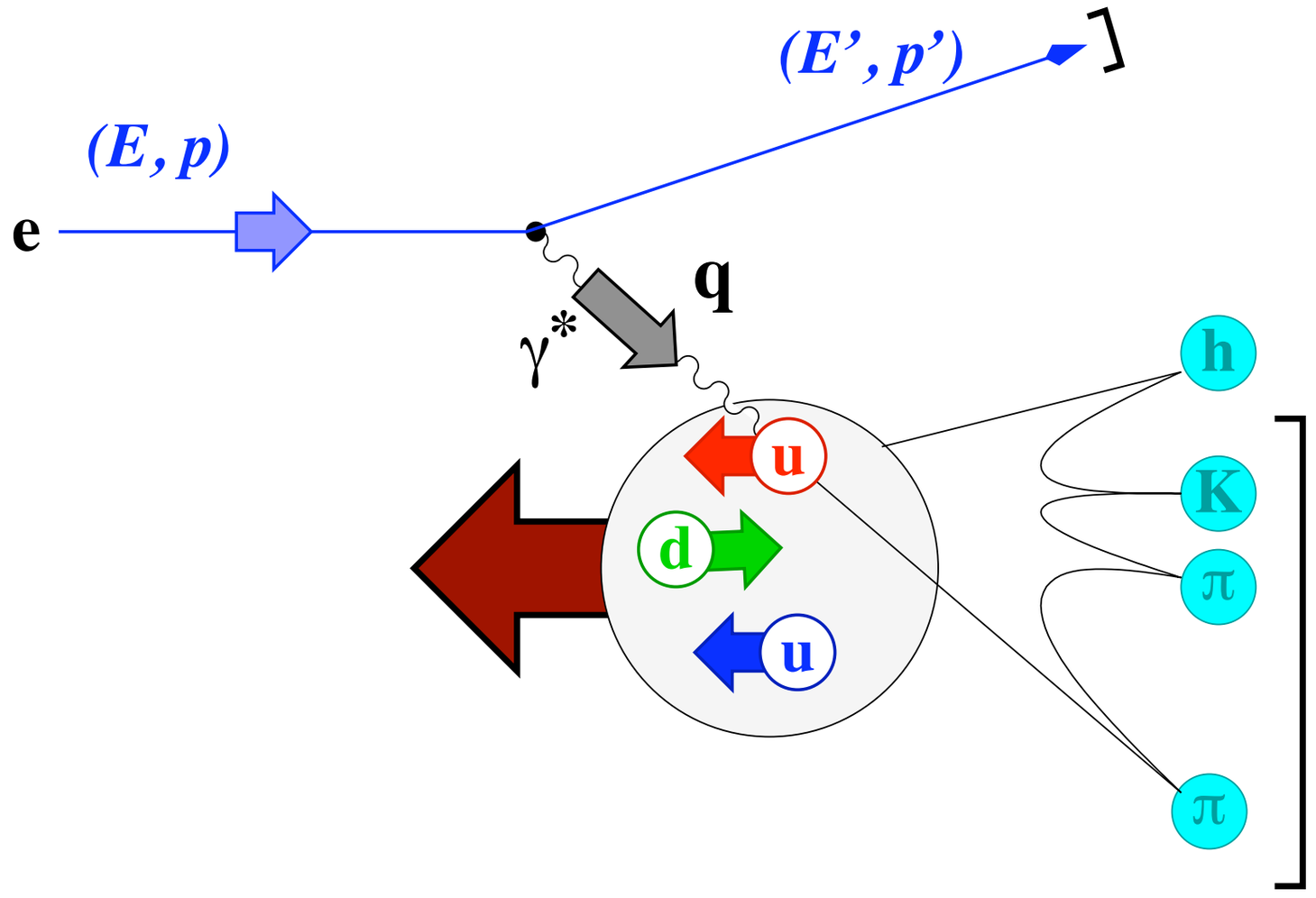


$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \mathbf{0.006 \pm 0.024_{stat} \pm 0.017_{syst}}$$

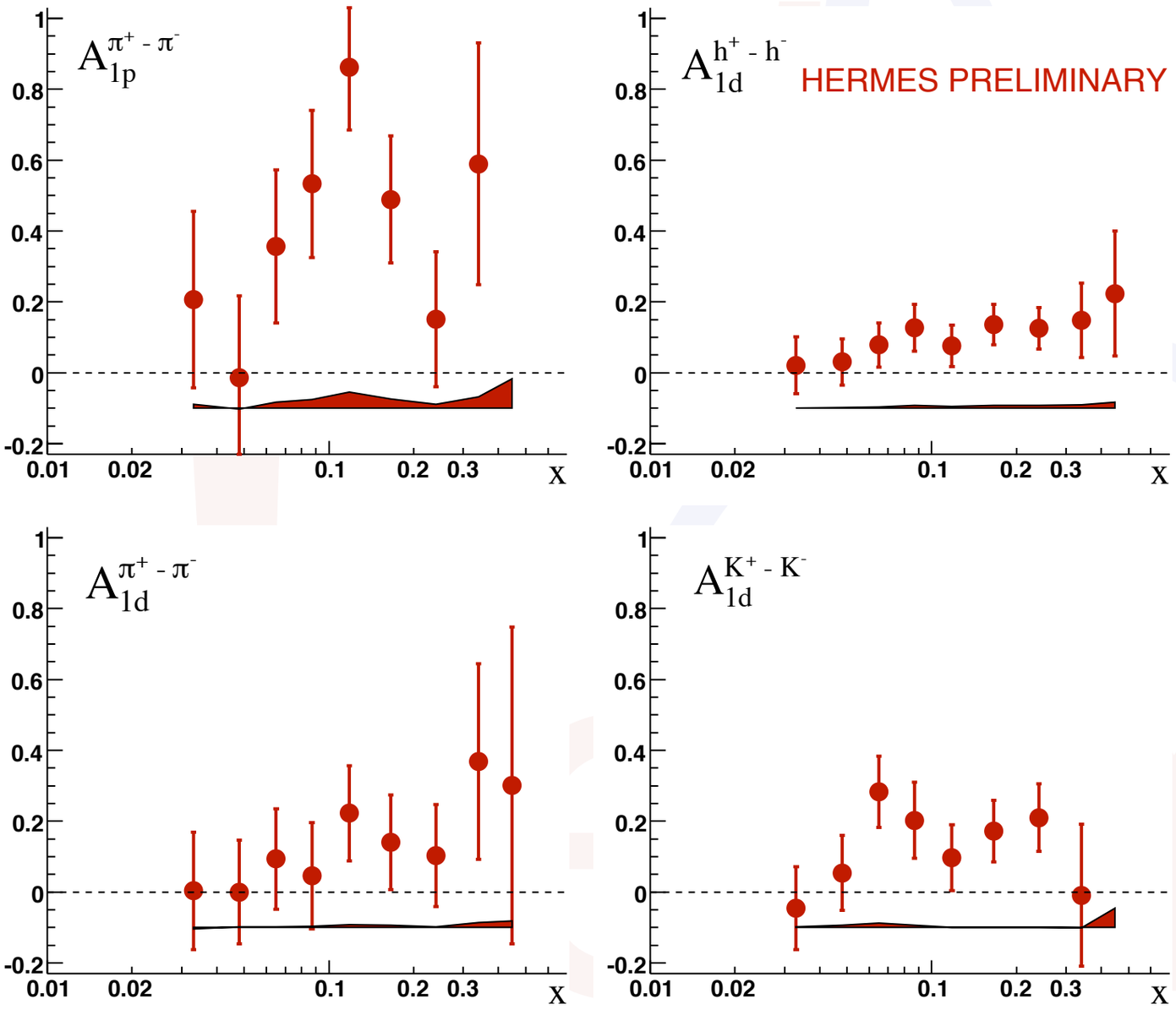
$$\mathbf{d_2(Q^2)} \equiv 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx = \mathbf{0.0148 \pm 0.0096_{stat} \pm 0.0048_{syst}}$$

Semi-Inclusive DIS



Helicity density - valence quarks

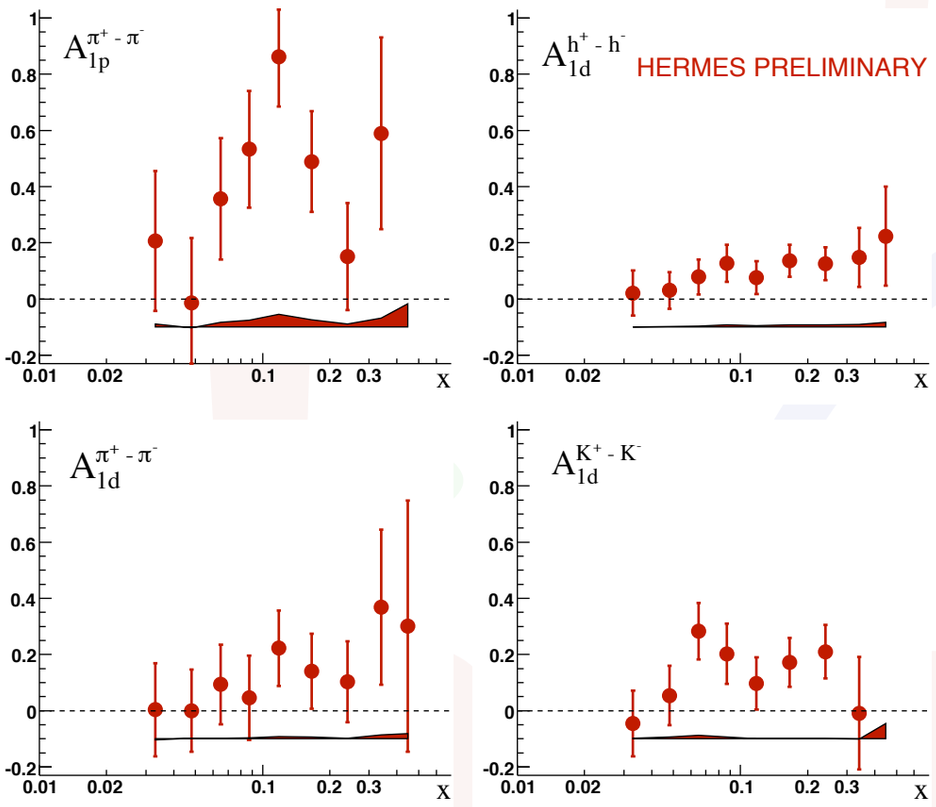
$$A_1^{h^+-h^-} = \frac{(d\sigma^{\rightarrow}_{h^+\Leftarrow} - d\sigma^{\rightarrow}_{h^-\Leftarrow}) - (d\sigma^{\rightarrow}_{h^+\Rightarrow} - d\sigma^{\rightarrow}_{h^-\Rightarrow})}{(d\sigma^{\rightarrow}_{h^+\Leftarrow} - d\sigma^{\rightarrow}_{h^-\Leftarrow}) + (d\sigma^{\rightarrow}_{h^+\Rightarrow}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

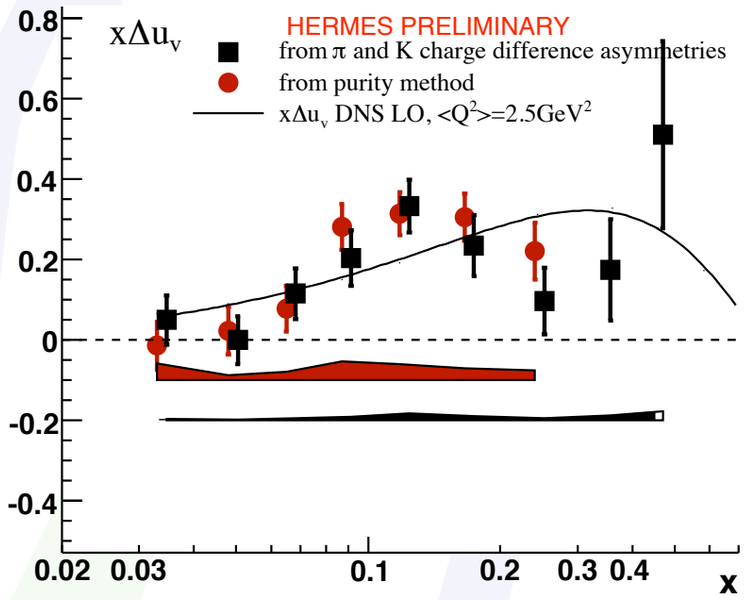


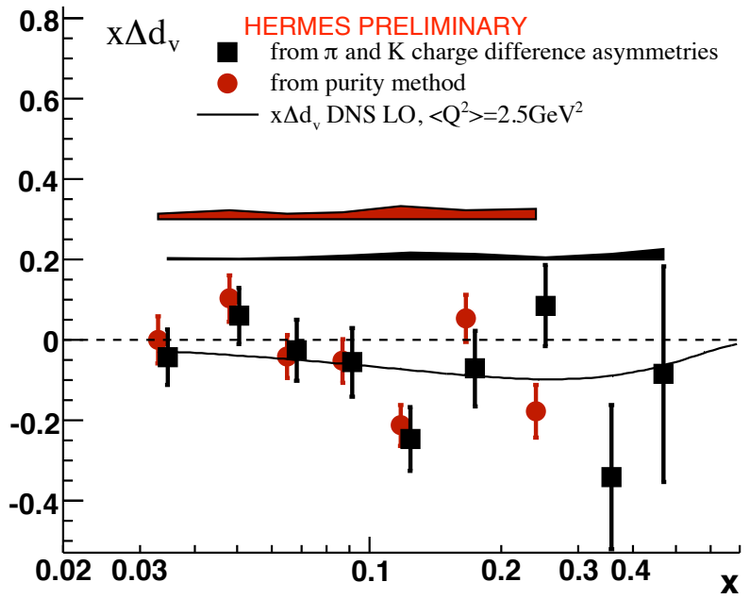
- charge-difference double-spin asymmetries

Helicity density - valence quarks

$$A_1^{h^+-h^-} = \frac{(d\sigma^{\rightarrow}_{h^+} - d\sigma^{\rightarrow}_{h^-}) - (d\sigma^{\rightarrow}_{h^+} - d\sigma^{\rightarrow}_{h^-})}{(d\sigma^{\rightarrow}_{h^+} - d\sigma^{\rightarrow}_{h^-}) + (d\sigma^{\rightarrow}_{h^+} - d\sigma^{\rightarrow}_{h^-})}$$







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

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

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

… going 3D

Spin-momentum structure of the nucleon

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

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

quark pol.

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

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

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helicity

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Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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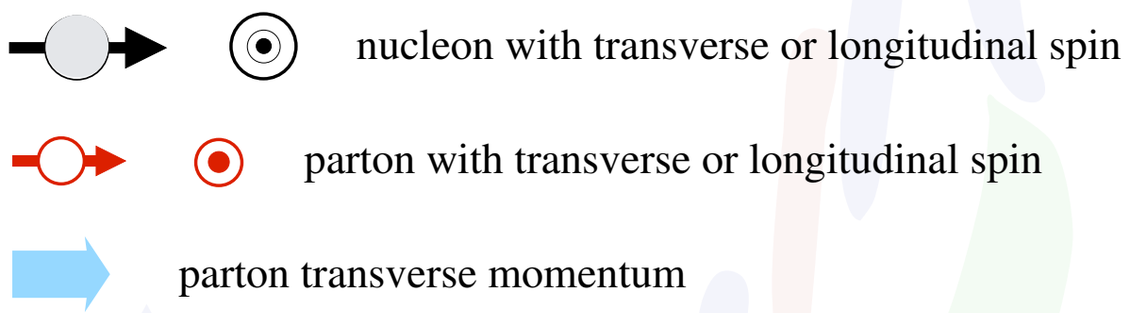
TMDs - probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen



$f_1 =$

$g_1 =$ –

$h_1 =$ –

$f_{1T}^{\perp} =$ –

$h_1^{\perp} =$ –

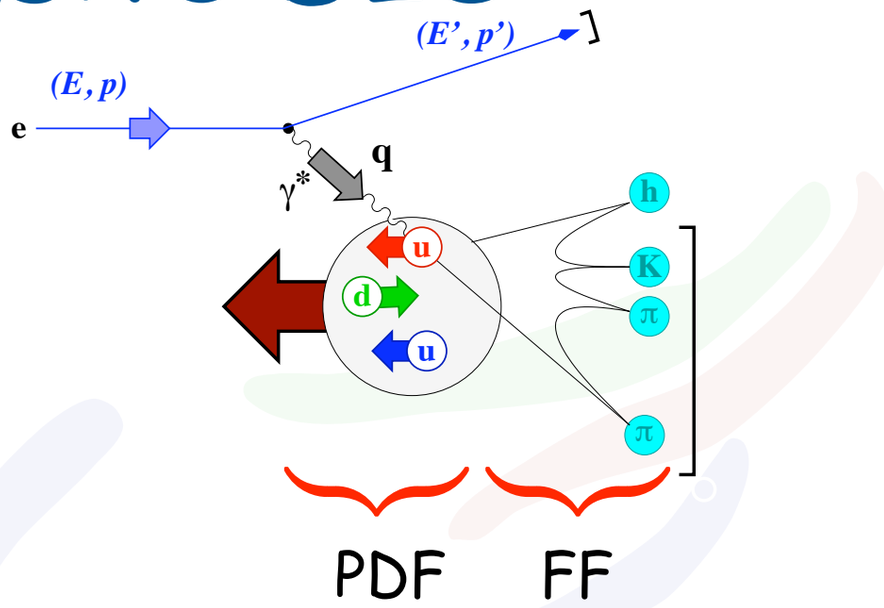
$g_{1T} =$ –

$h_{1L}^{\perp} =$ –

$h_{1T}^{\perp} =$ –

[courtesy of A. Bacchetta]

Probing TMDs in semi-inclusive DIS



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in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

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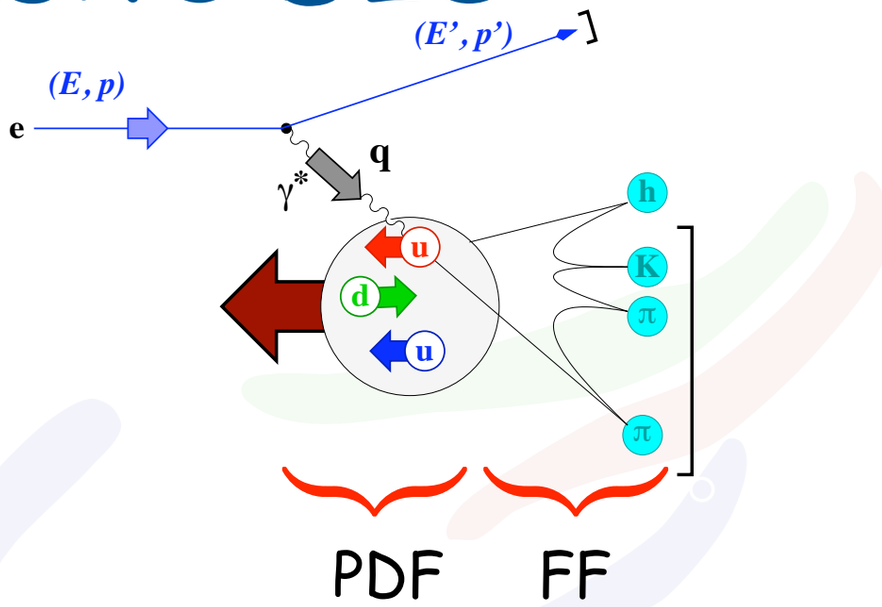

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→ Collins FF: $H_1^{\perp, q\to h}$

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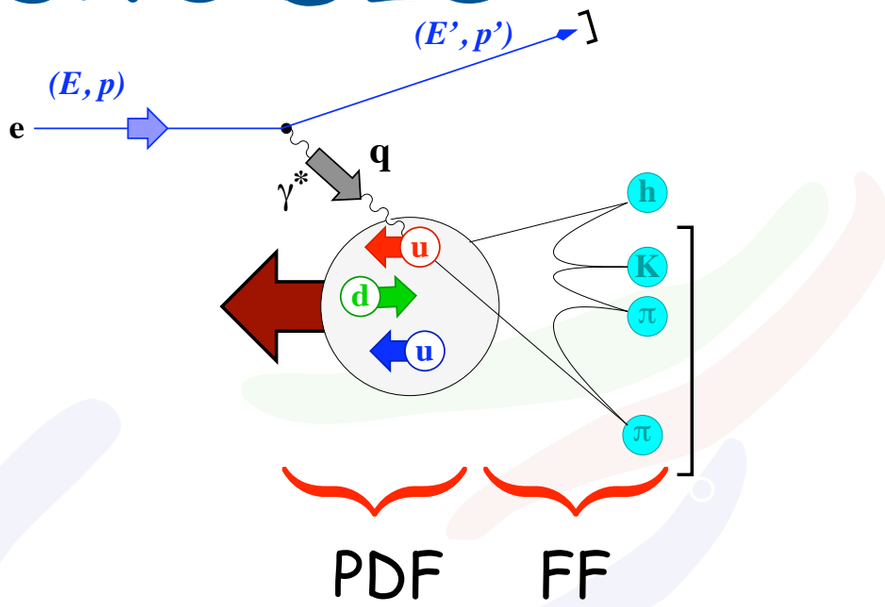

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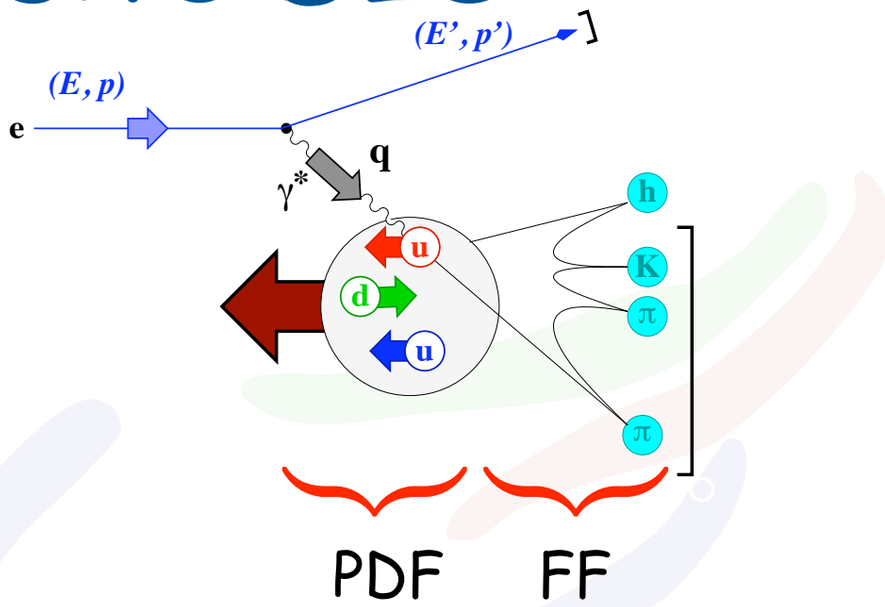

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➟ gives rise to characteristic azimuthal dependences

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1-Hadron production (ep→ehX)

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

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

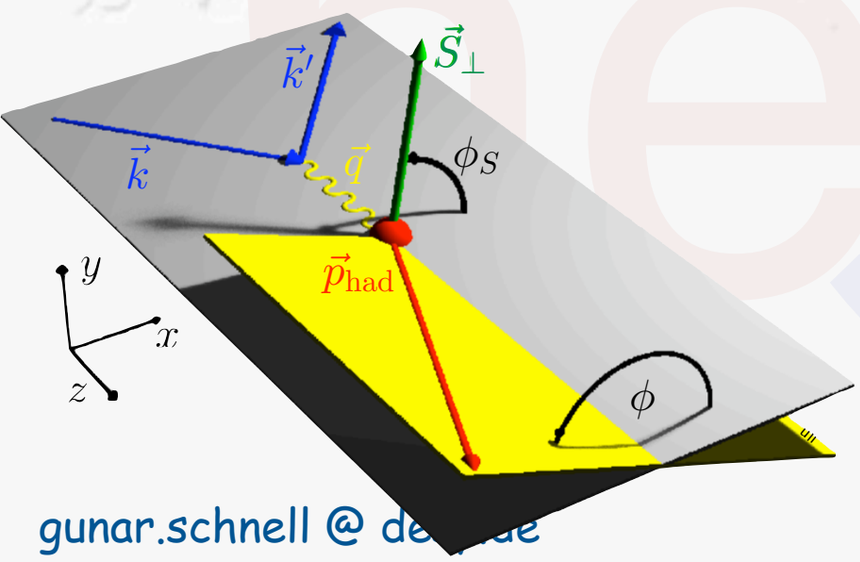
$$+S_T \left\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \right.$$

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

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

σ_{XY}

Beam Target Polarization



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

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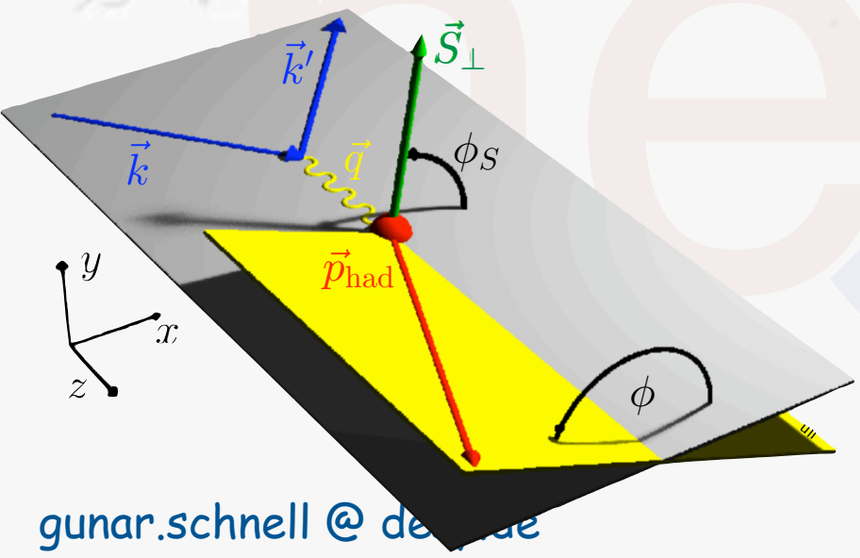
σ_{XY}

Beam Target
Polarization



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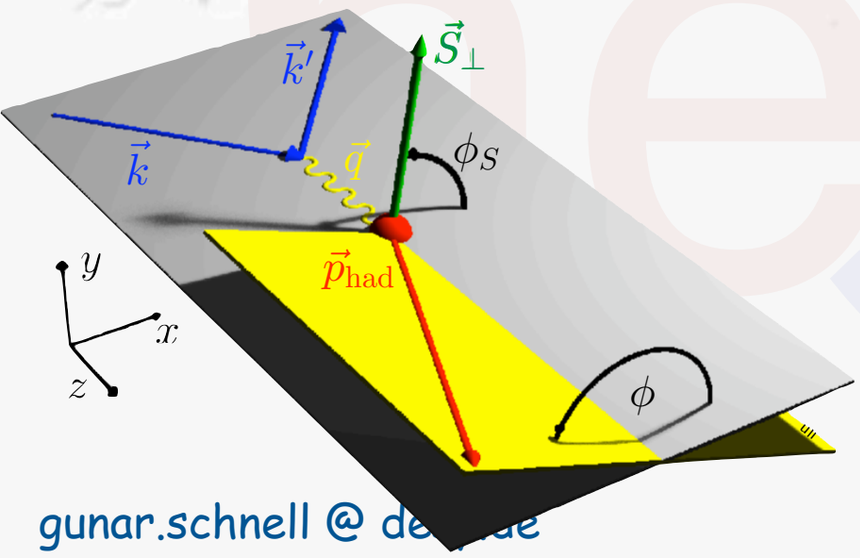

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Hadron multiplicities in DIS

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

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$$F_{XY,Z} = F_{XY,Z}(x,y,z,P_{h\perp})$$

target polarization; beam polarization; virtual-photon polarization

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

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hadron multiplicity:
normalize to inclusive DIS cross section

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Hadron multiplicities in DIS

hadron multiplicity:
normalize to inclusive DIS cross section

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

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

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

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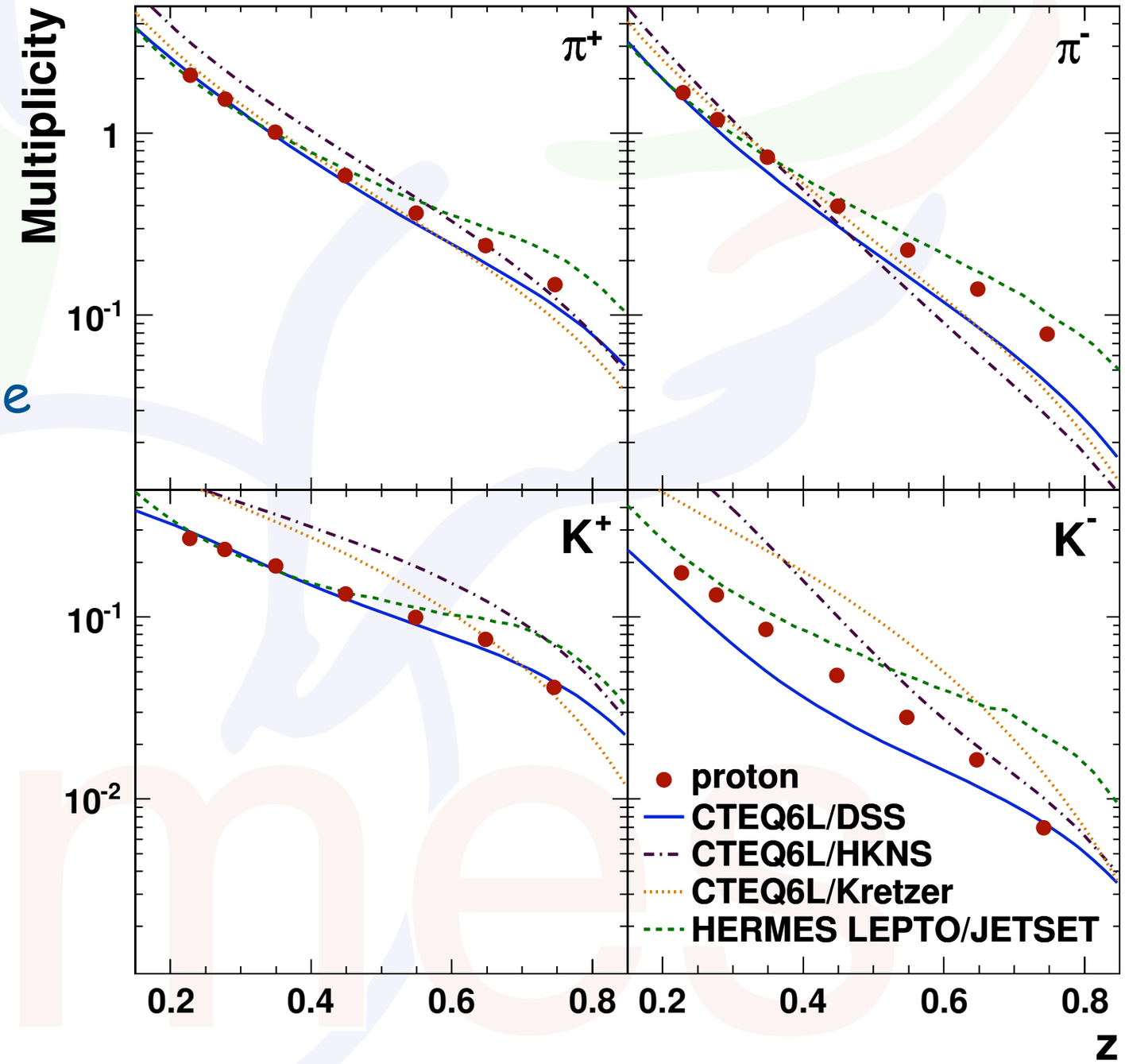
Multiplicities @ HERMES

- extensive data set on pure proton and deuteron targets for identified charged mesons
- 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., arXiv:1212.5407]



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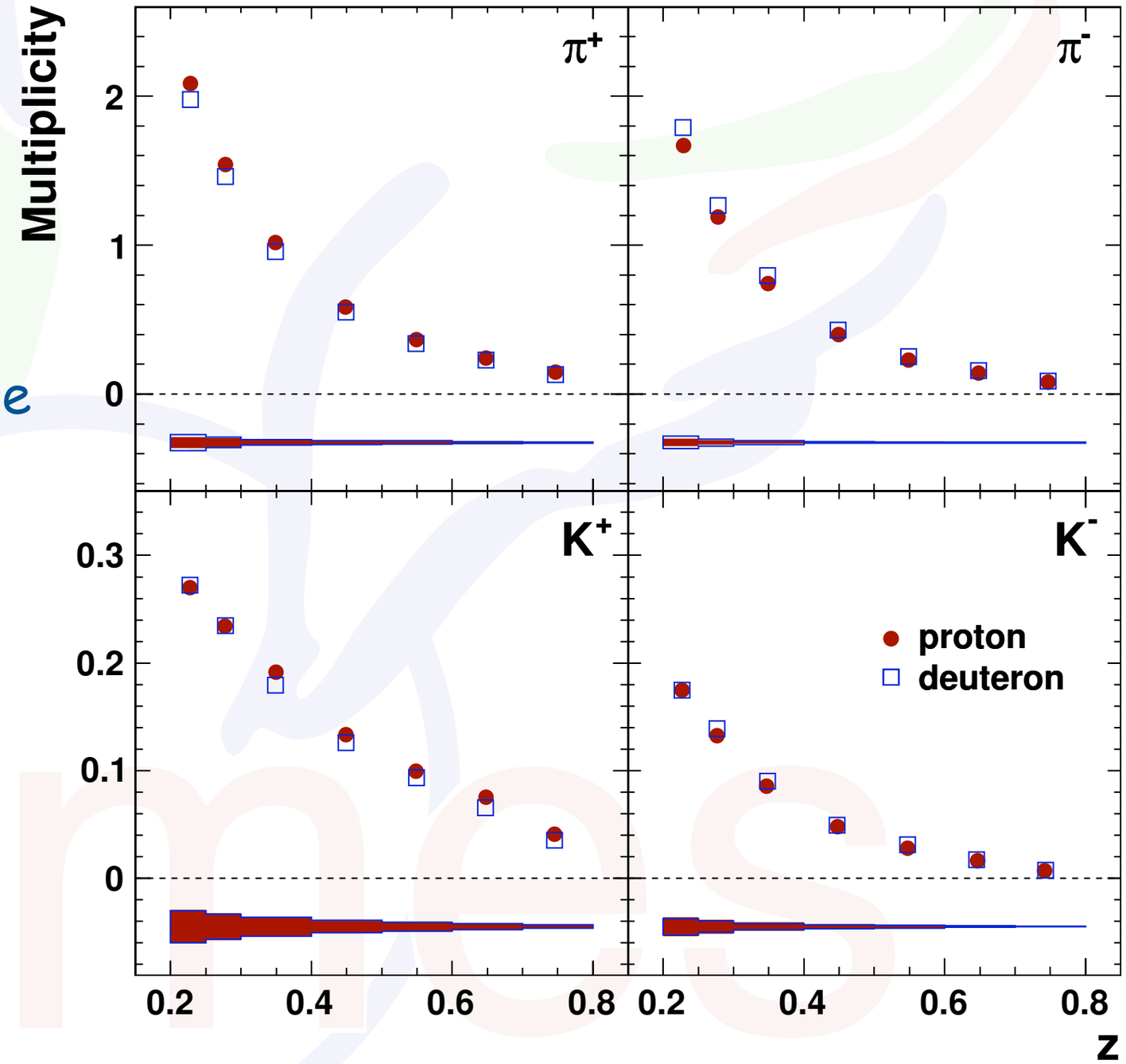
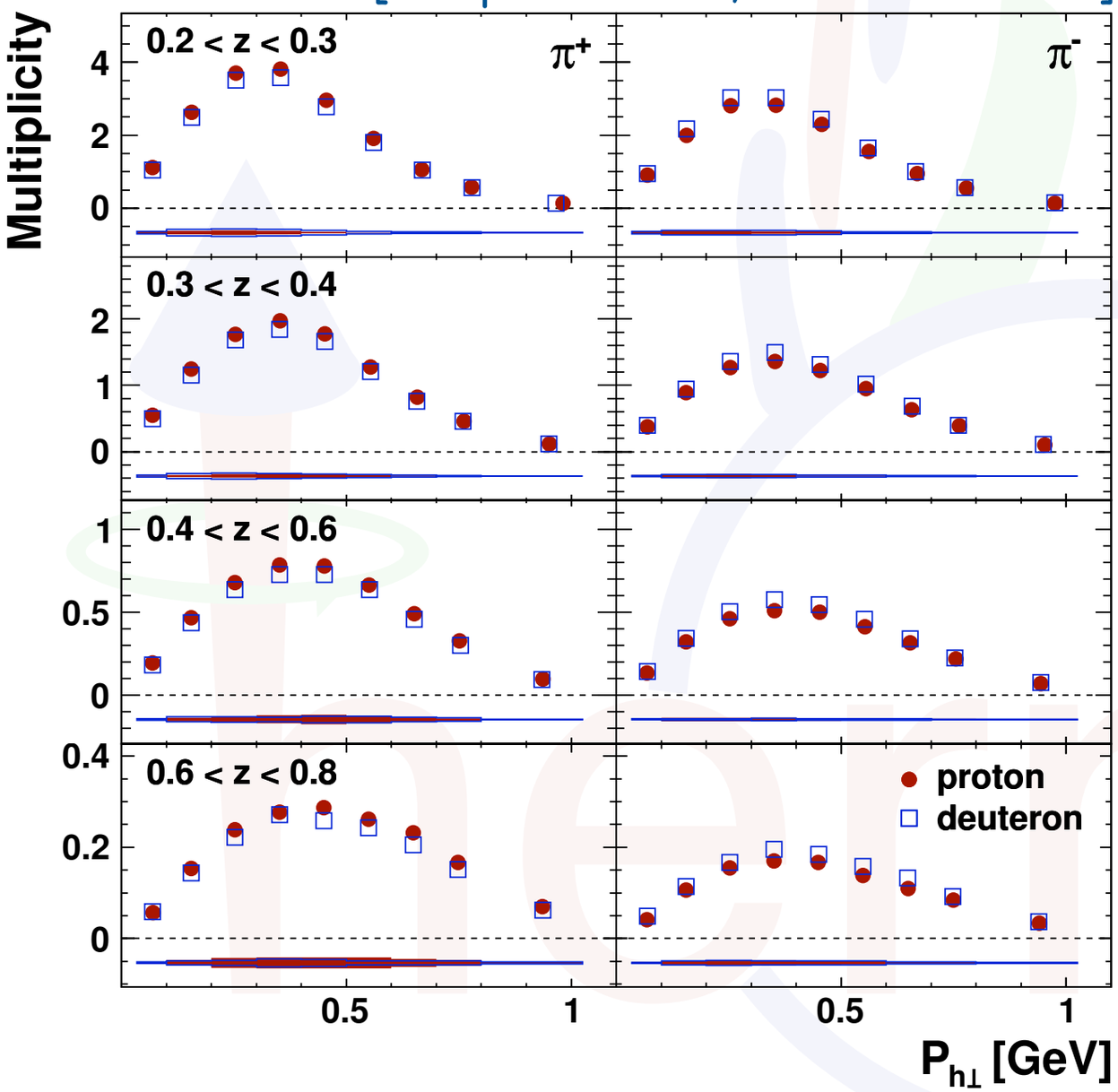


Multiplicities @ HERMES

multi-dimensional analysis allows exploration of new kinematic dependences

[Airapetian et al., arXiv:1212.5407]



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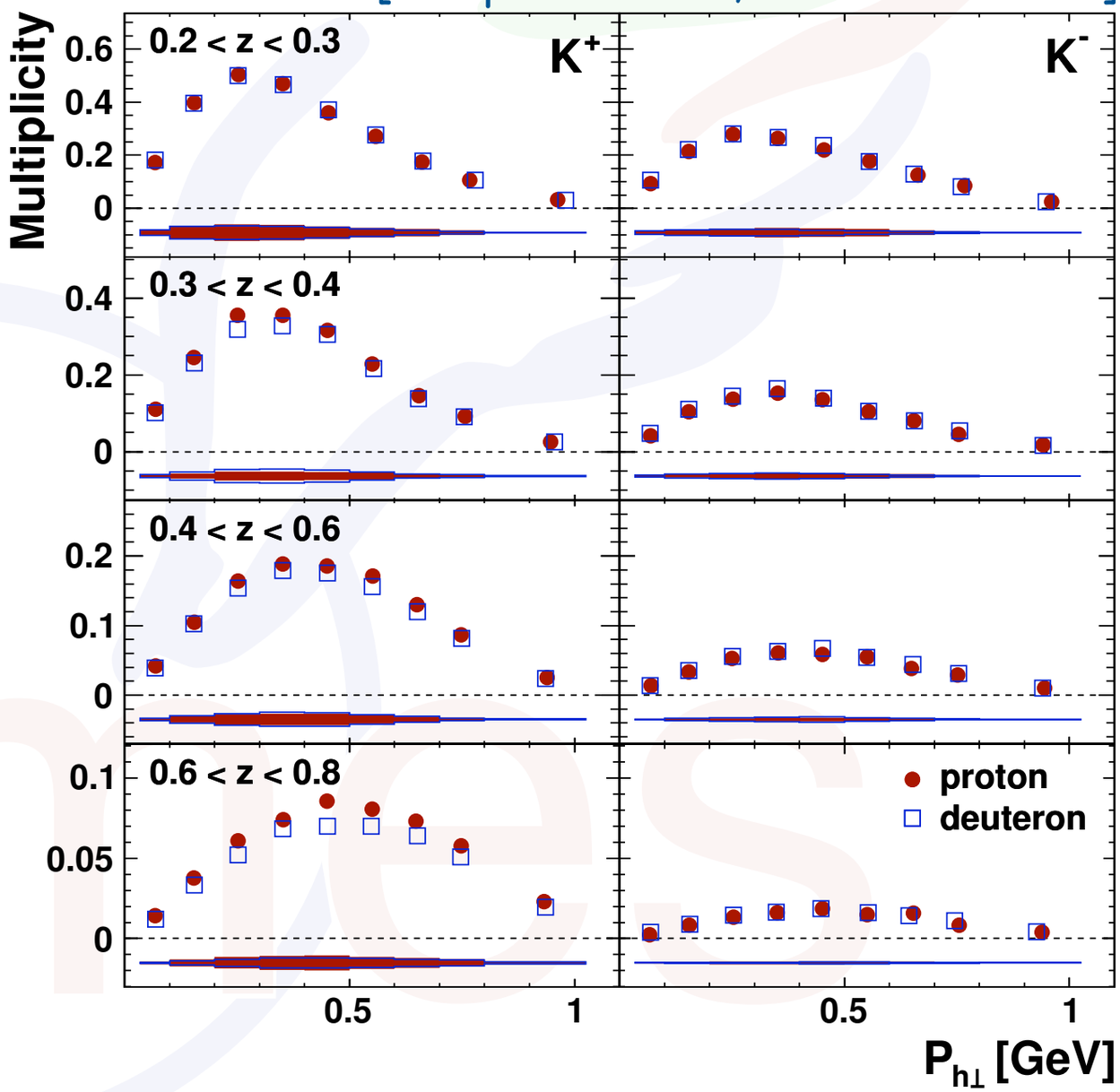

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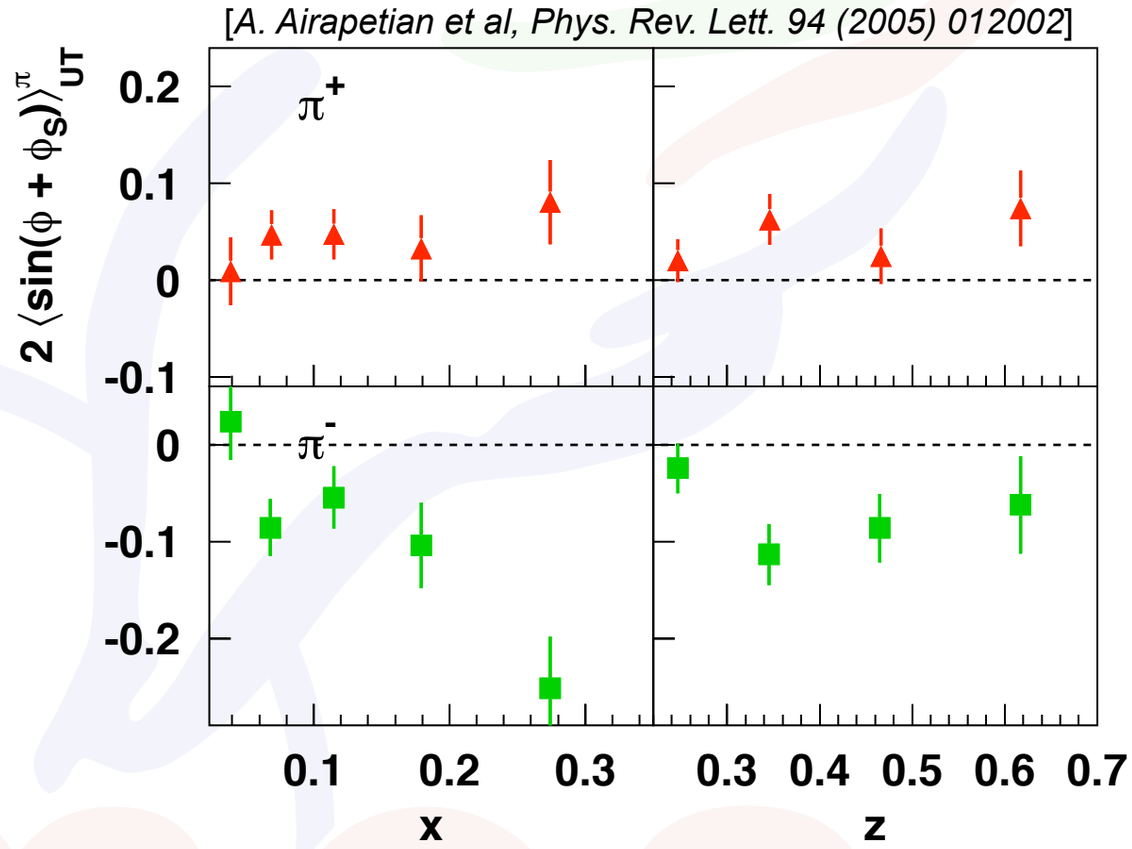
Transversely polarized quarks?

- transverse polarization of quarks leads to large effects!



2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

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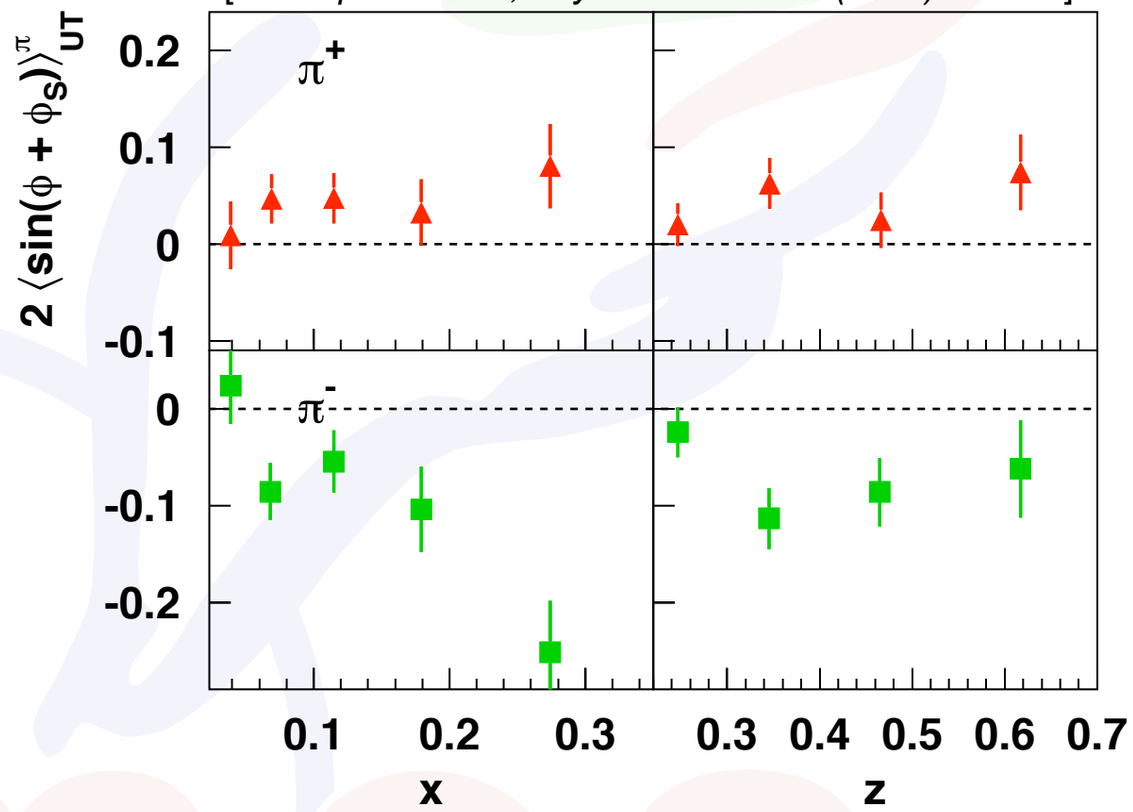

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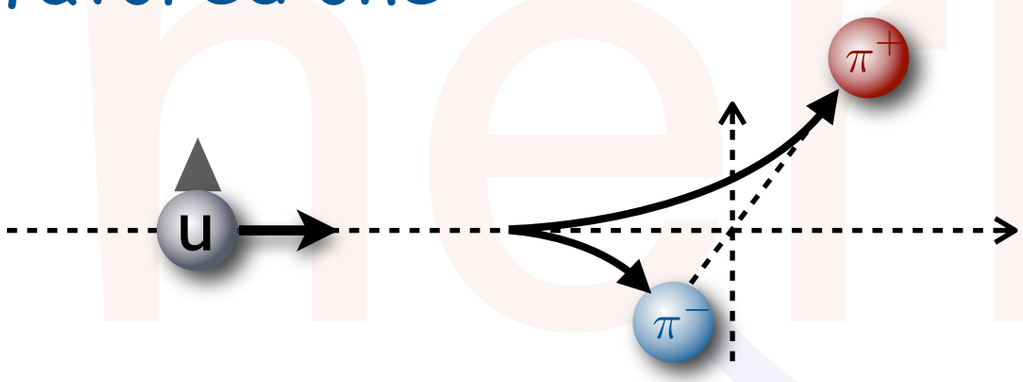

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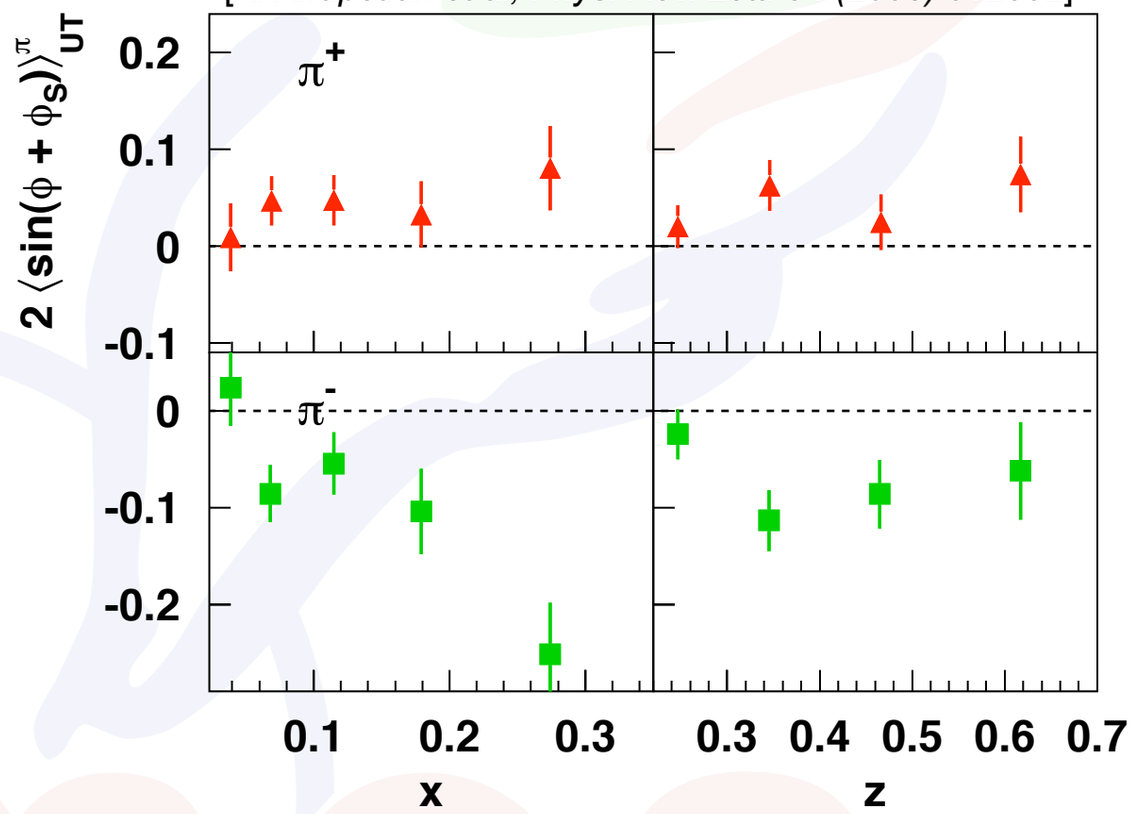

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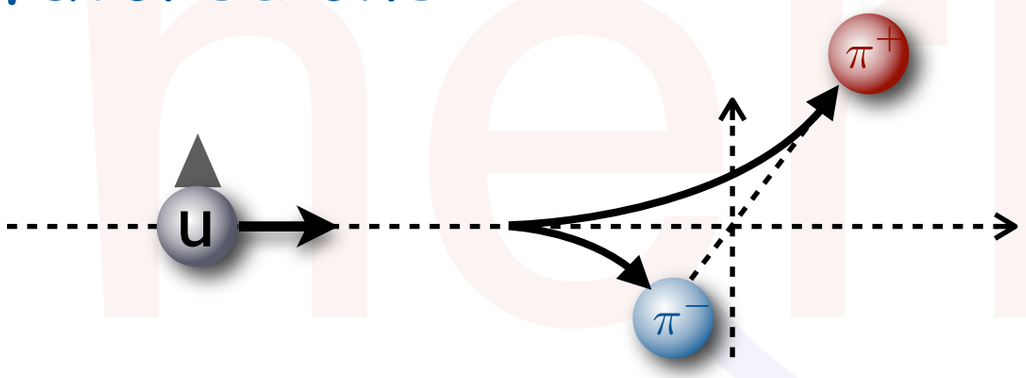
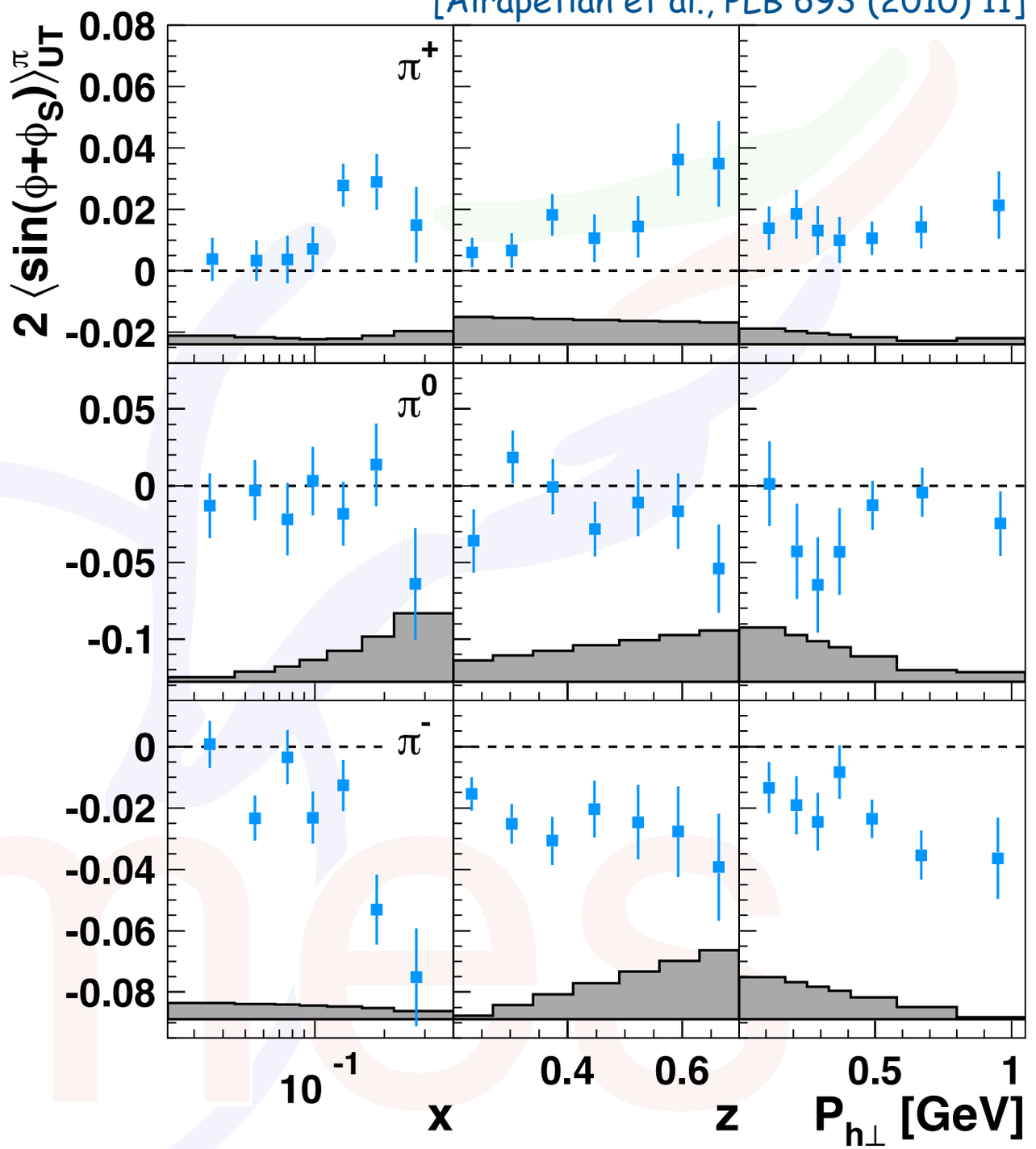
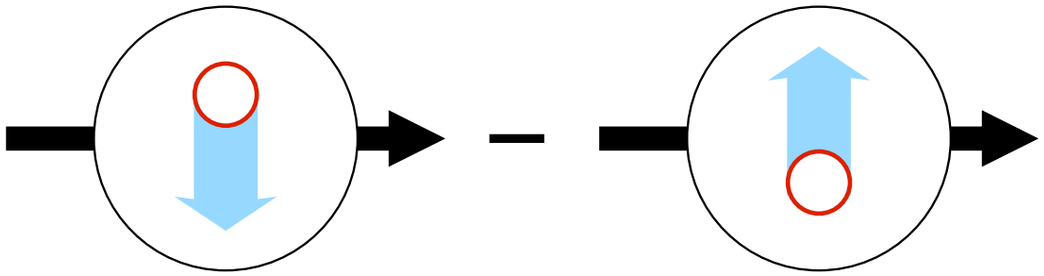


[Airapetian et al., PLB 693 (2010) 11]



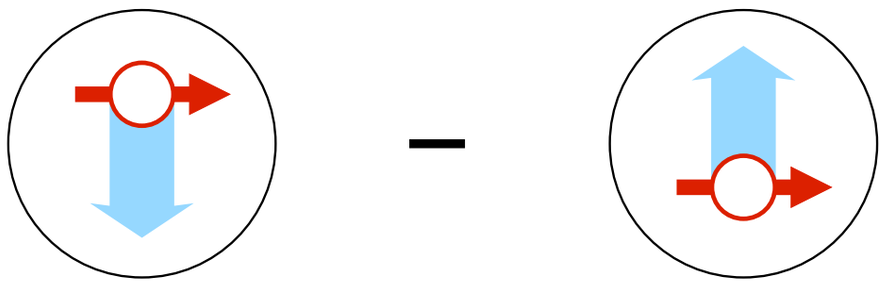


Sivers effect

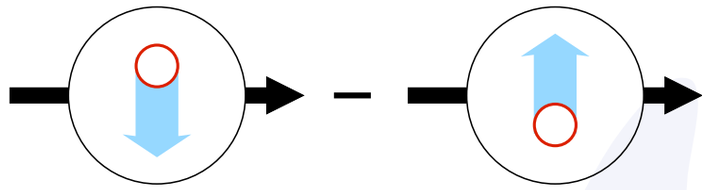
naively T-odd distributions

"Wilson-line physics"

Boer-Mulders effect



Sivers function

$f_{1T}^{\perp} =$ 

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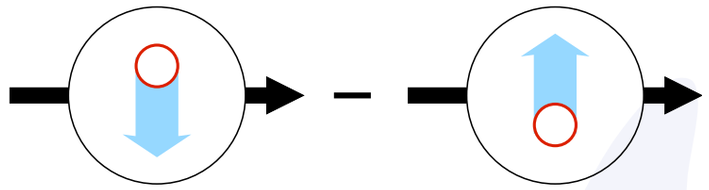
$f_{1T}^{\perp} =$ 

- correlates transverse momentum of quarks with transverse spin of proton
- candidate for large (30-50%) asymmetries in $p^{\uparrow}p \to hX$

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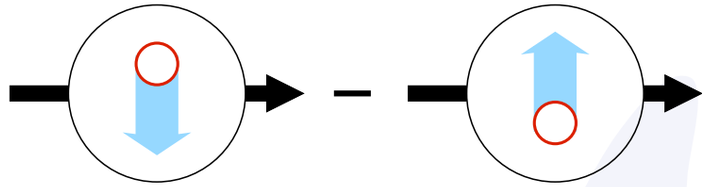
$f_{1T}^{\perp} =$ 

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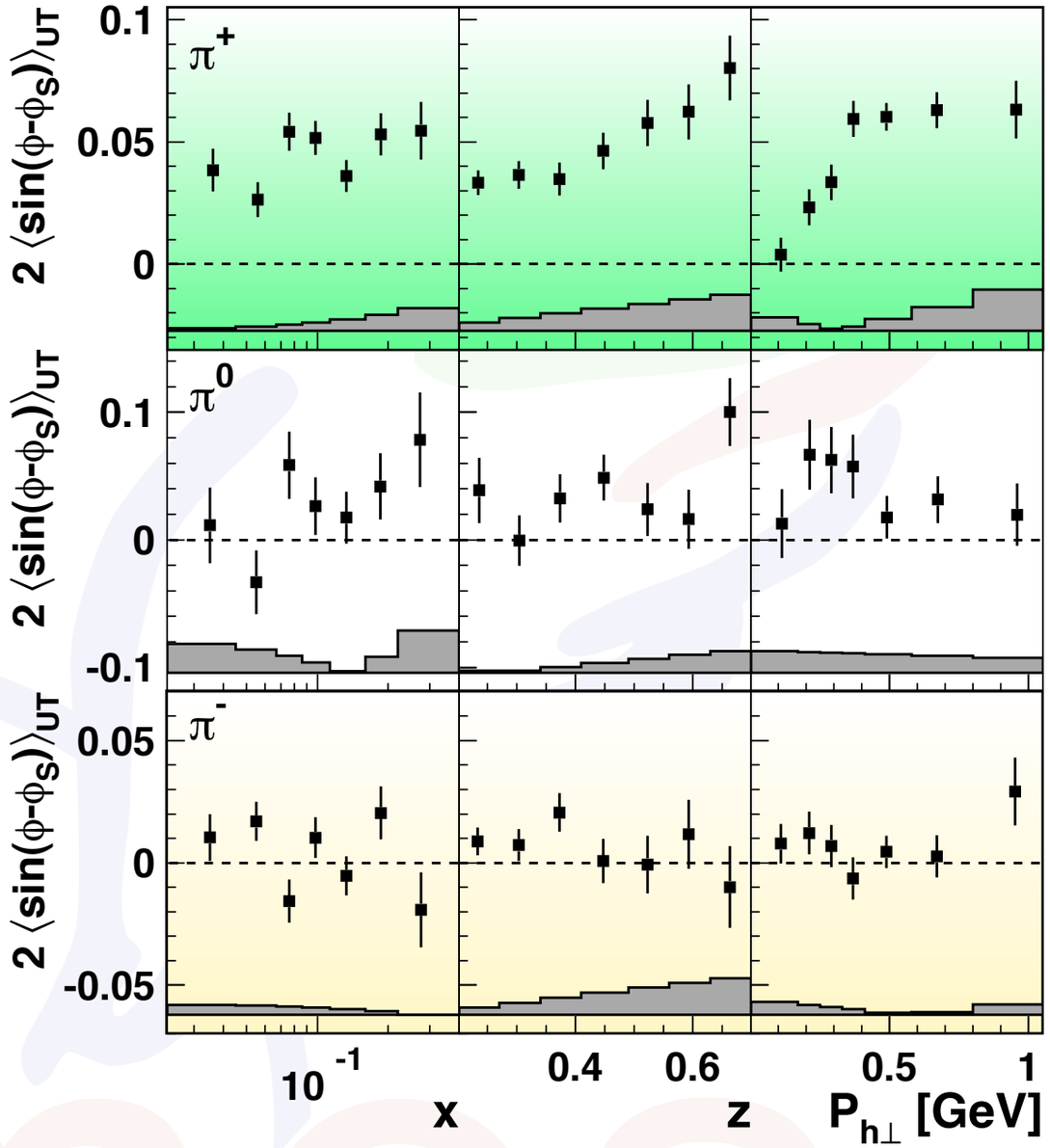
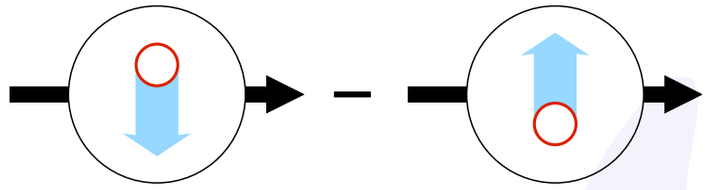


[PRL 103 (2009) 152002]

Sivers function

$f_{1T}^{\perp} =$ 

- correlates transverse momentum of quarks with transverse spin of proton
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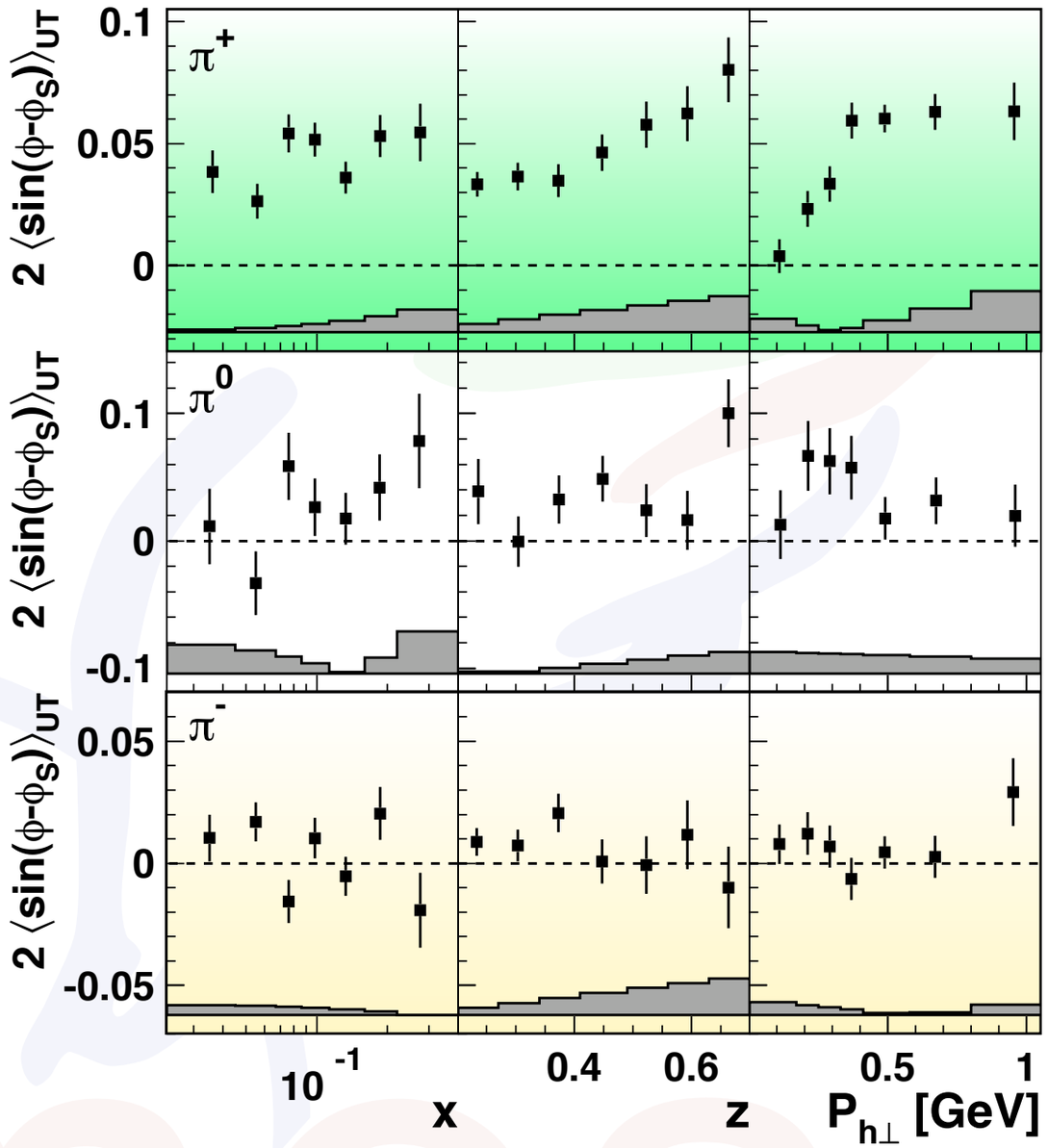
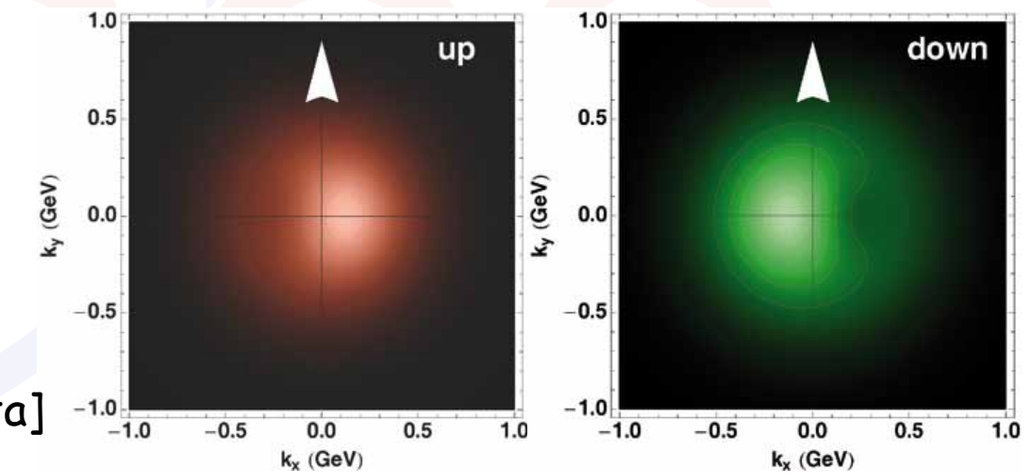
- HERMES: u-quark and d-quark Sivers have opposite signs
- (naive) T-odd structure: $S_N \cdot (p_\perp \times P_N)$ -- requires ISI/FSI

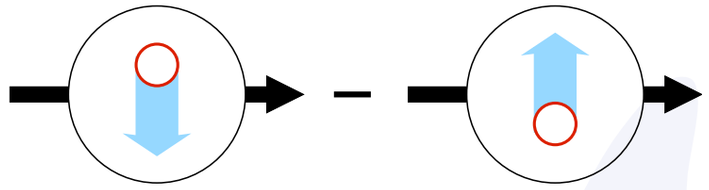


[PRL 103 (2009) 152002]



[courtesy of A. Bacchetta]

Sivers function

$f_{1T}^{\perp} =$ 

- correlates transverse momentum of quarks with transverse spin of proton
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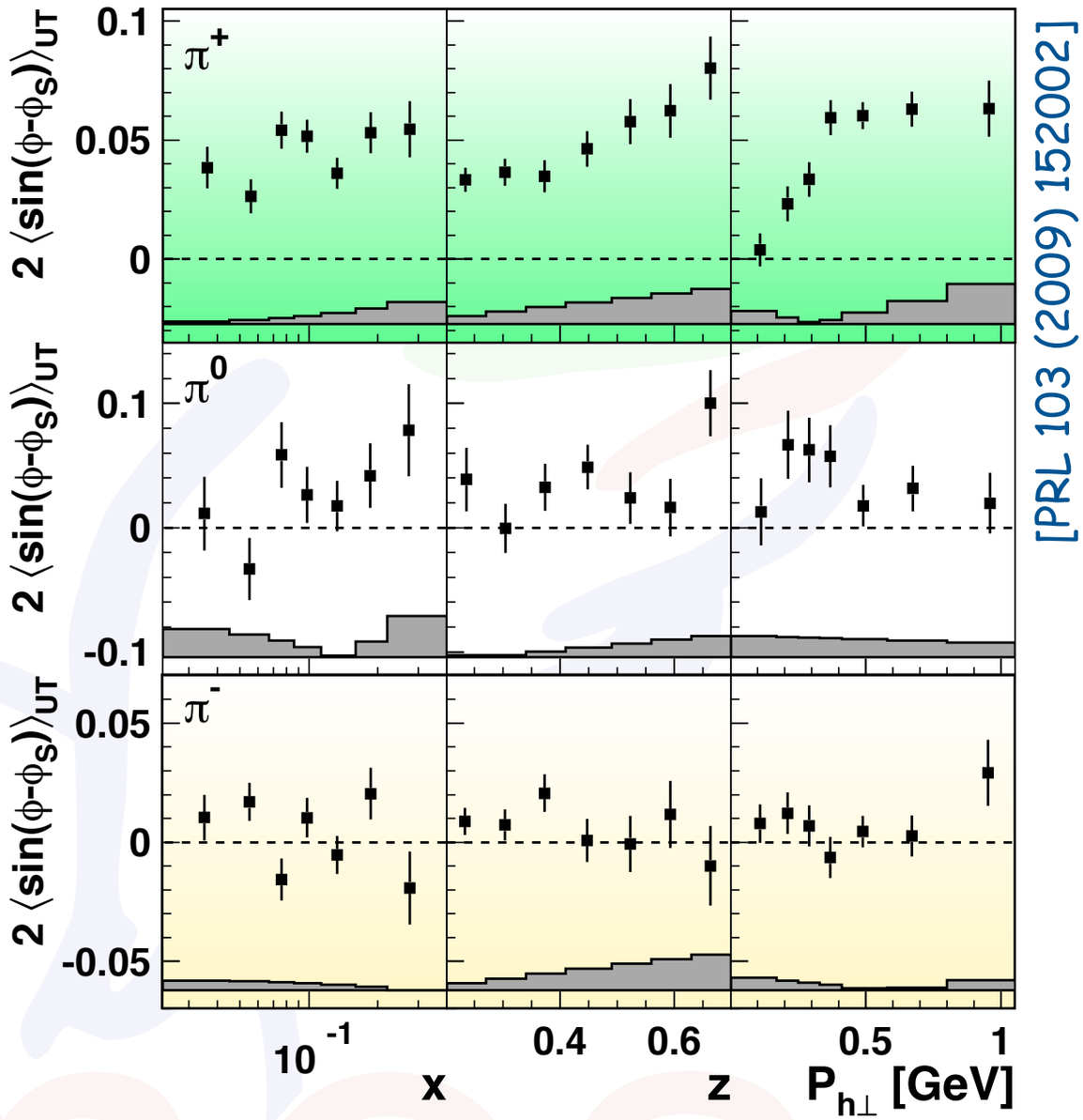
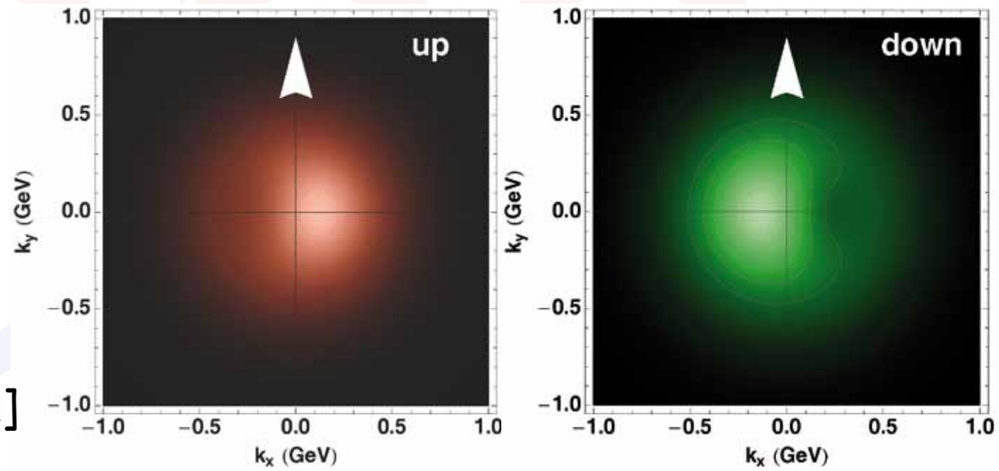
- HERMES: u-quark and d-quark Sivers have opposite signs
- (naive) T-odd structure: $S_N \cdot (p_\perp \times P_N)$ -- requires ISI/FSI
- leads to peculiar calculable universality breaking (DIS vs. Drell-Yan)



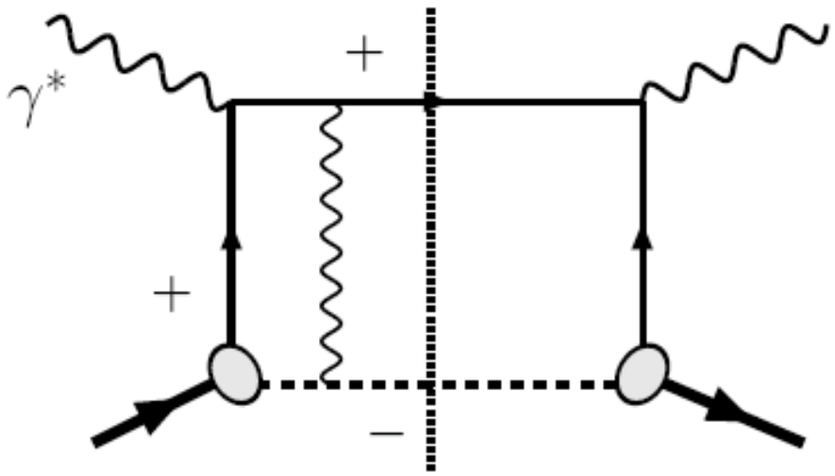
[PRL 103 (2009) 152002]

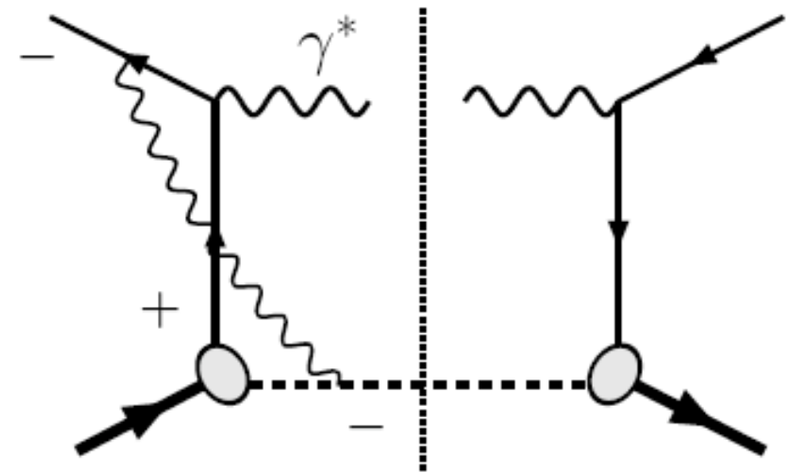


[courtesy of A. Bacchetta]

Process dependence

simple QED example



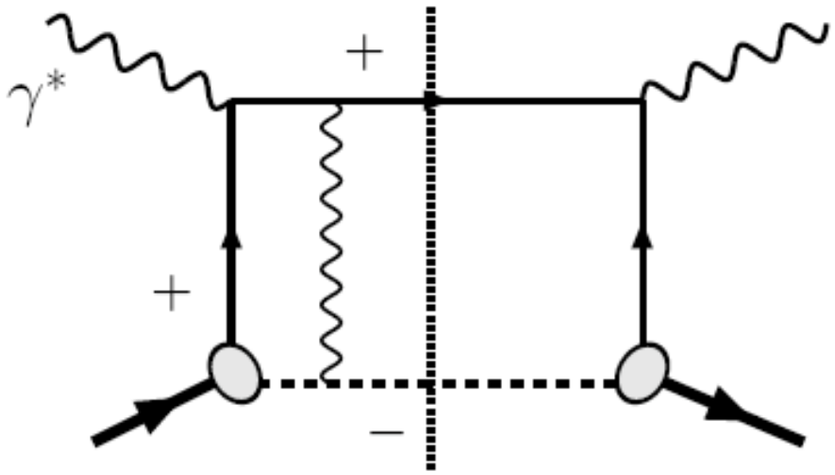


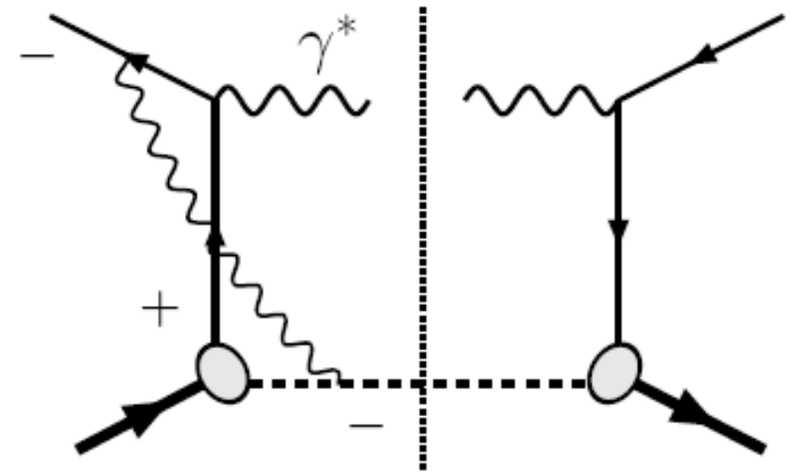
DIS: attractive

Drell-Yan: repulsive

Process dependence

simple QED example

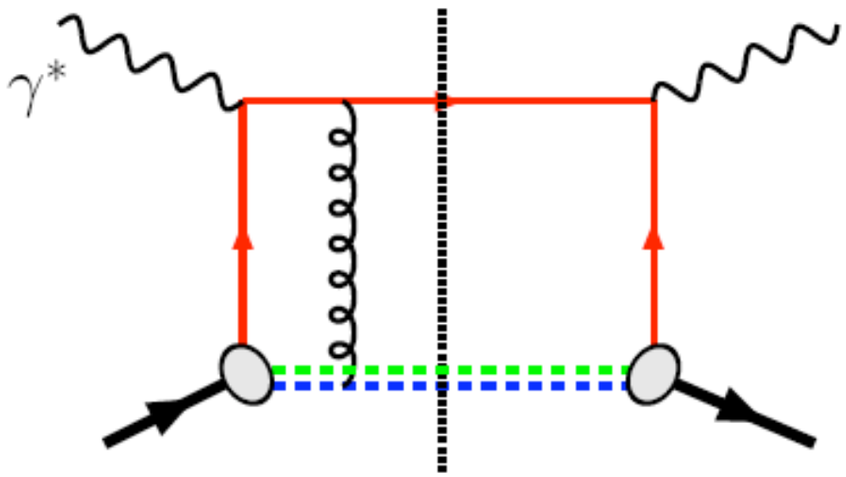


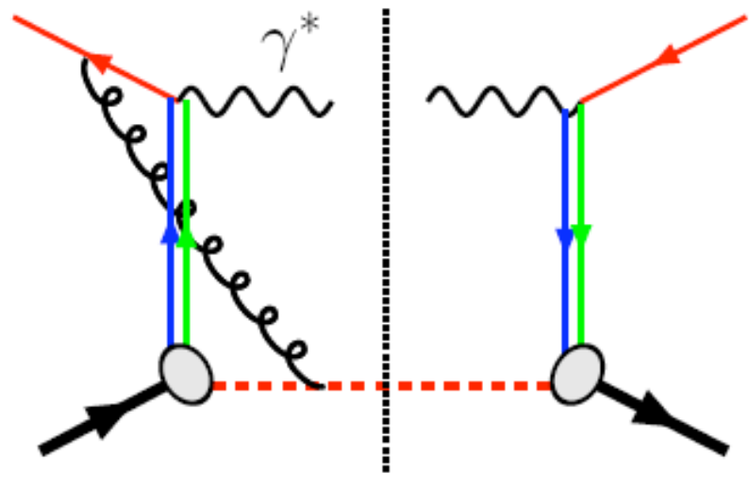


DIS: attractive

Drell-Yan: repulsive

add color: QCD

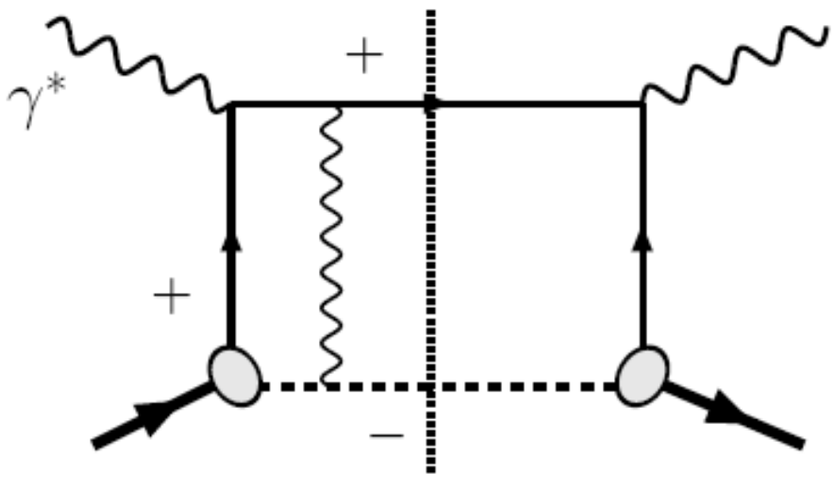


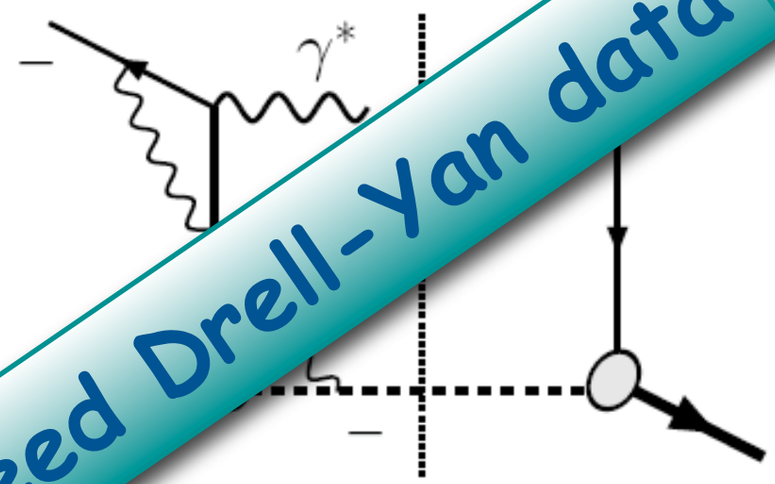


result: $\text{Sivers}|_{DIS} = -\ \text{Sivers}|_{DY}$

Process dependence

simple QED example





DIS: attracti

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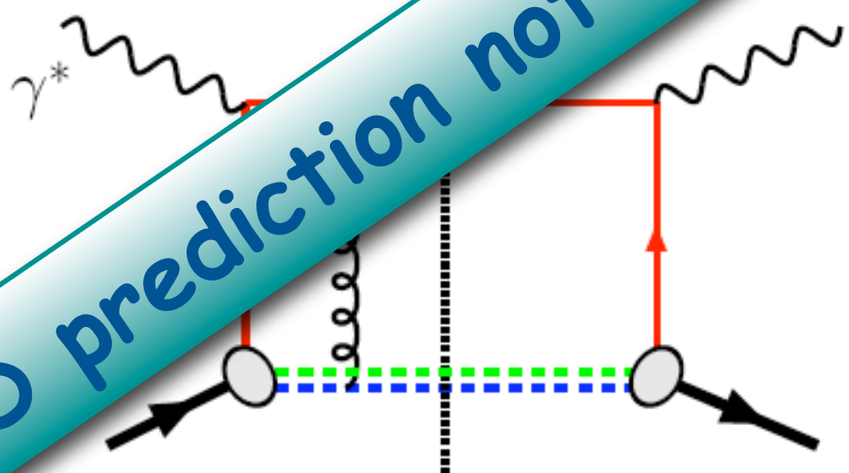
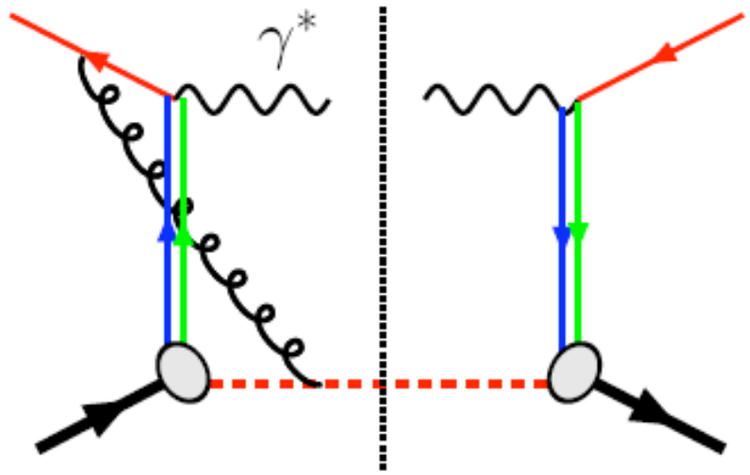
QCD



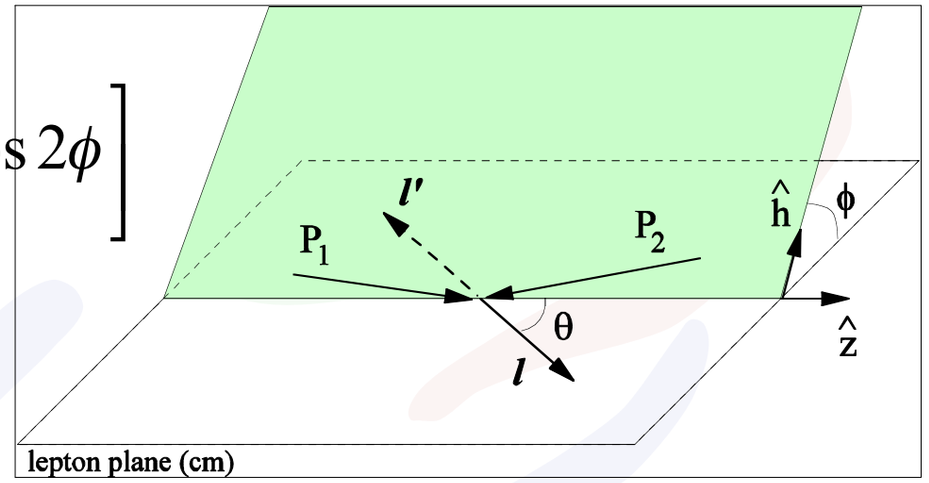


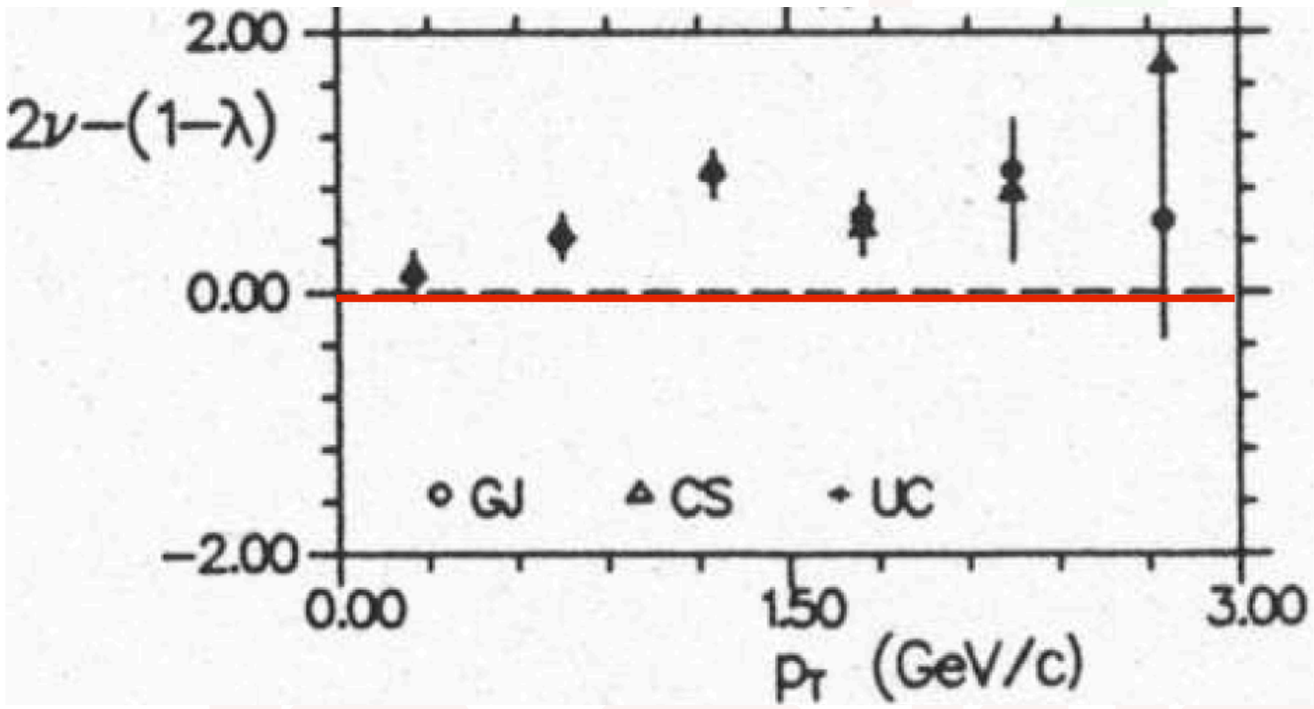
rigorous QCD prediction not tested!! – need Drell-Yan data

result: Sivers$|_{DIS}$ = - Sivers$|_{DY}$

Unpolarized Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



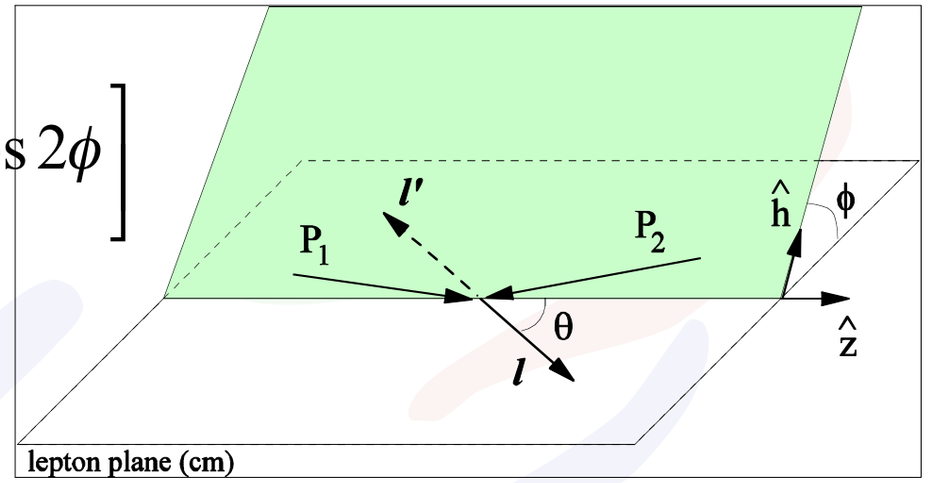


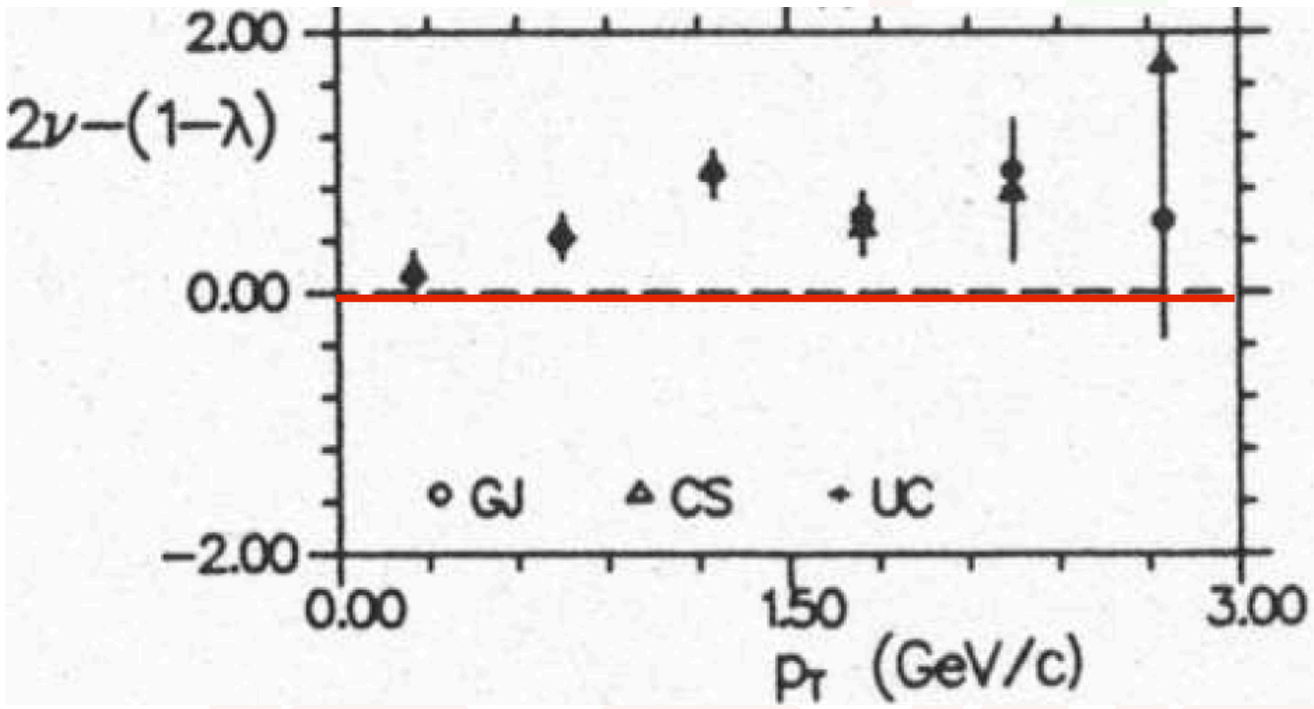
$$1 - \lambda - 2\nu = 0$$

Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

Unpolarized Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$





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[NA10 ('86/'88) & E615 ('89)]

- **"failure" of collinear pQCD**

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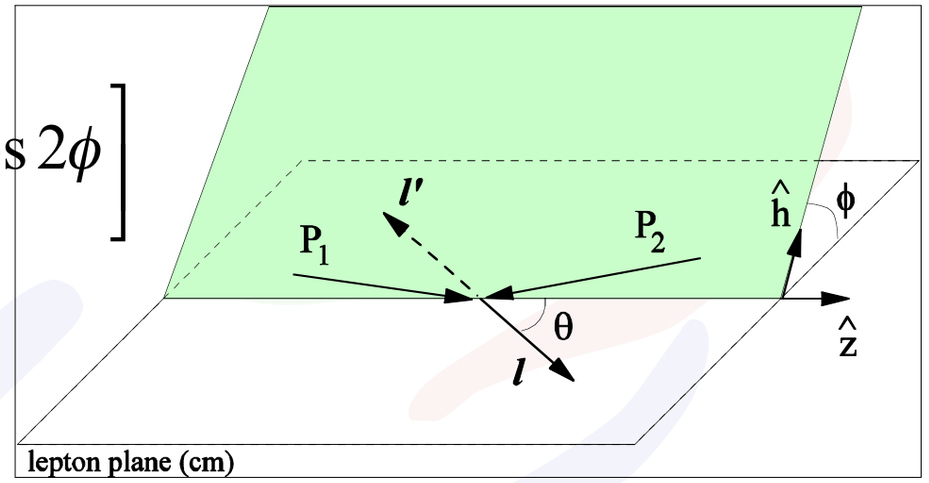
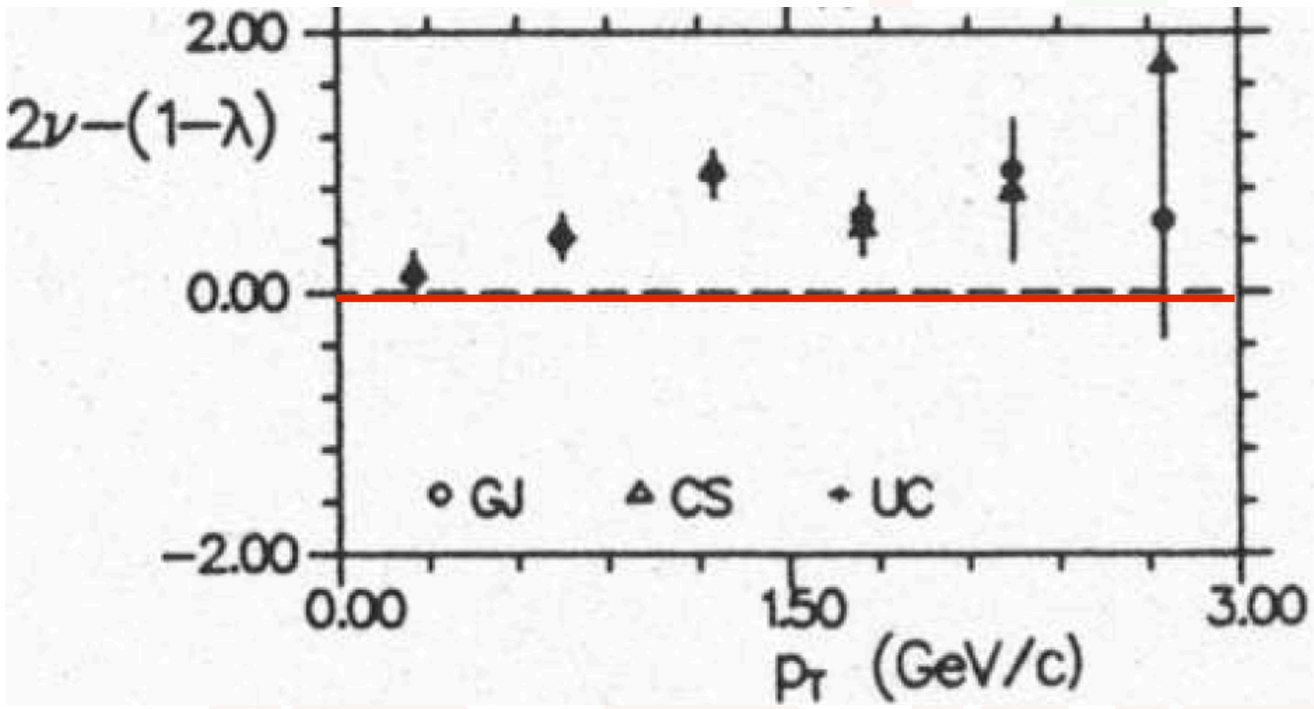




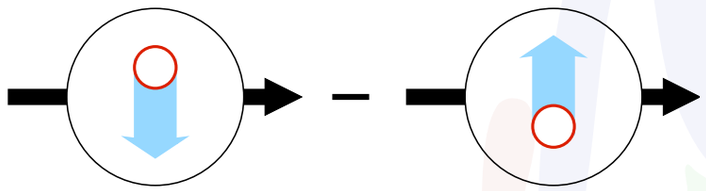
$$1 - \lambda - 2\nu = 0$$

Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

- "failure" of collinear pQCD
- possible source: Boer-Mulders effect

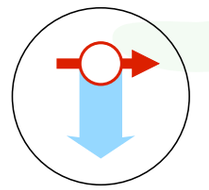
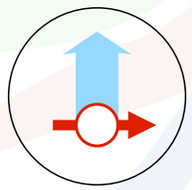
Boer-Mulders effect

Sivers effect:

$f_{1T}^{\perp} =$  −

$S_N \cdot (p_\perp \times P_N)$

Boer-Mulders effect:

$h_1^{\perp} =$  − 

$S_q \cdot (p_\perp \times P_N)$

Boer-Mulders effect

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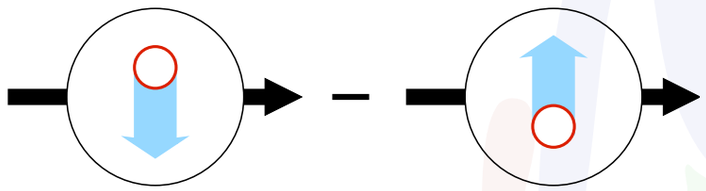
$f_{1T}^{\perp} =$  –

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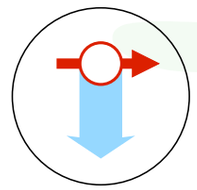
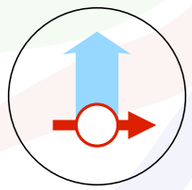
$h_1^{\perp} =$  – 

$S_q \cdot (p_\perp \times P_N)$

- spin-effect in **unpolarized** reactions

Boer-Mulders effect

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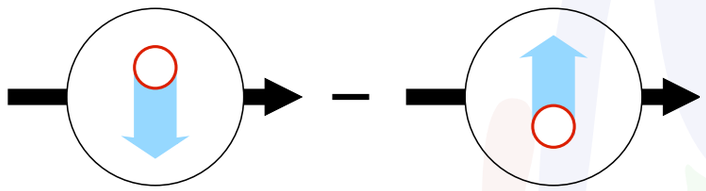
$f_{1T}^{\perp} =$ 

$S_N \cdot (p_\perp \times P_N)$

Boer-Mulders effect:

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- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks

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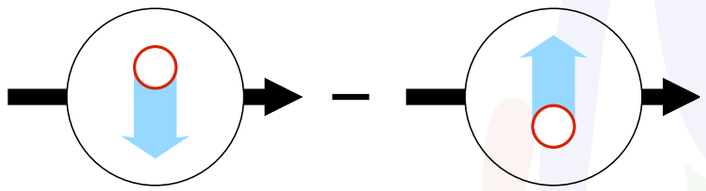
$f_{1T}^{\perp} =$ 

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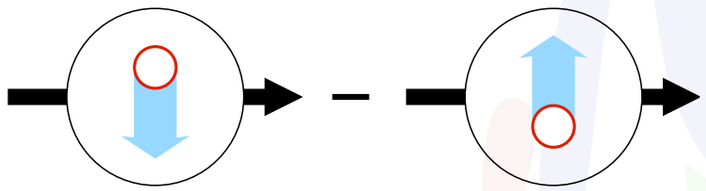
$f_{1T}^{\perp} =$ 

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Boer-Mulders effect:

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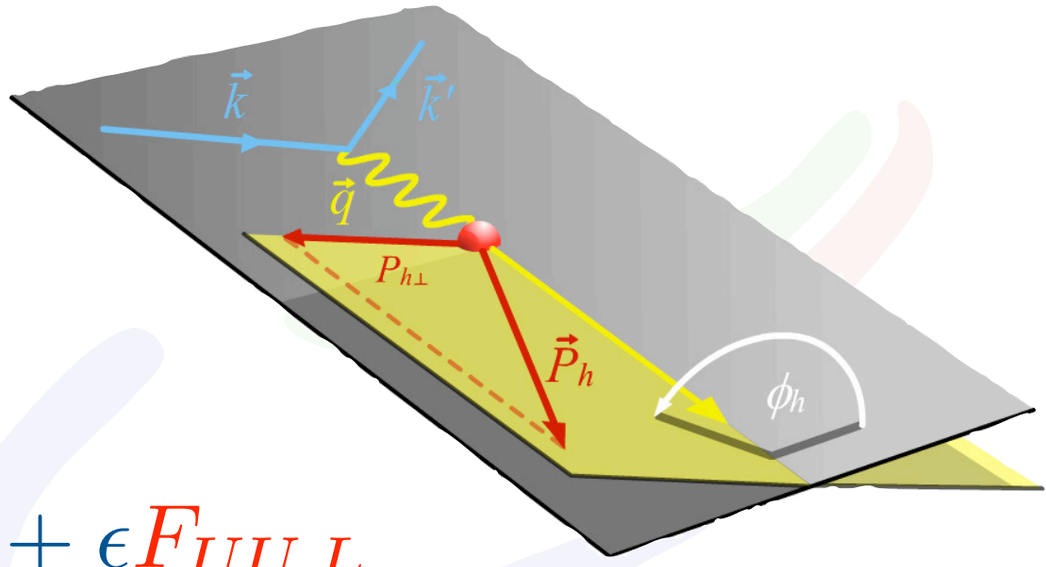
- spin-effect in **unpolarized** reactions
- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks
- QCD: sign change for DIS vs. Drell-Yan
- up to now little data from DIS

➡ HERMES with most comprehensive data set

Cross section without polarization



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

$$F_{XY,Z} = F_{XY,Z}(x,y,z,P_{h\perp})$$

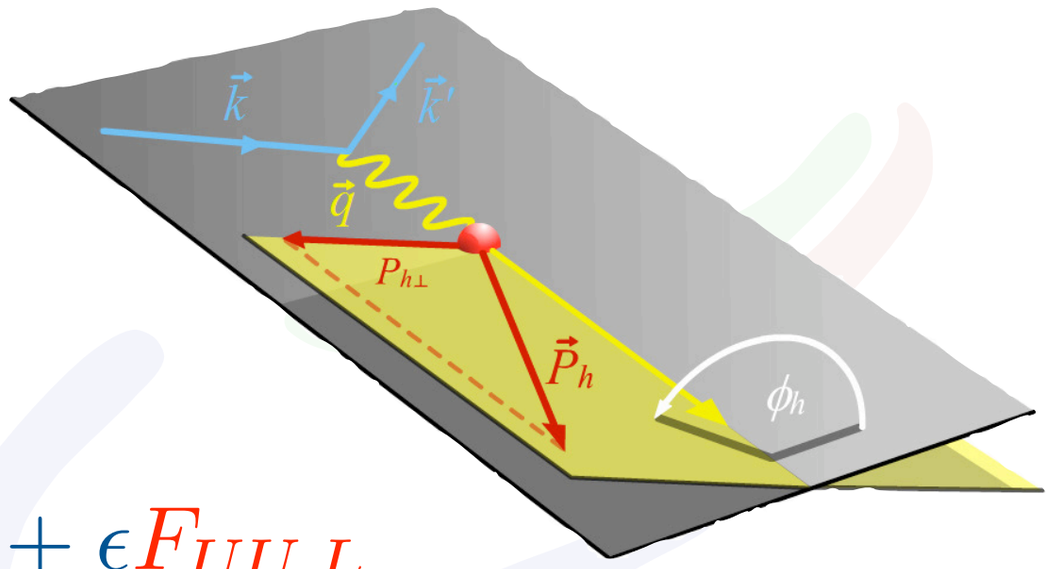
target polarization ⇩ | beam polarization ⇧ | virtual-photon polarization ⇧

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

Cross section without polarization



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BOER-MULDERS EFFECT

CAHN EFFECT

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}\,h_1^\perp H_1^\perp\right]$$

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\,x\,h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\,x\,f_1 D_1 + \ldots\right]$$

Interaction dependent terms neglected

(Implicit sum over quark flavours)

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]

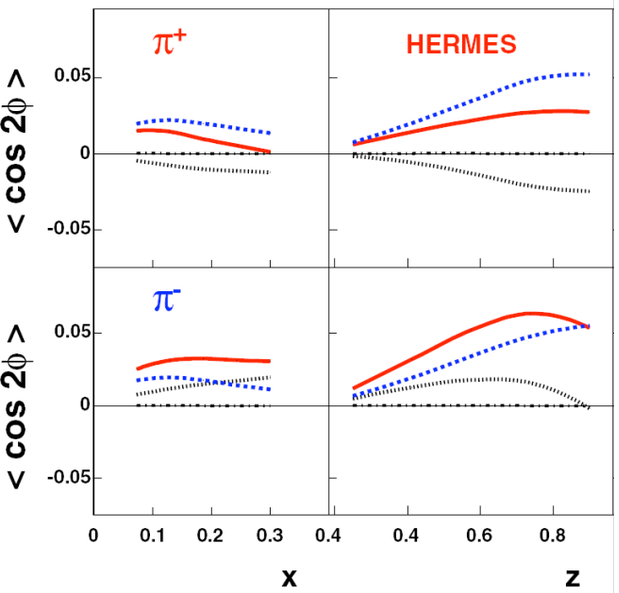
Signs of Boer-Mulders

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

All contributions

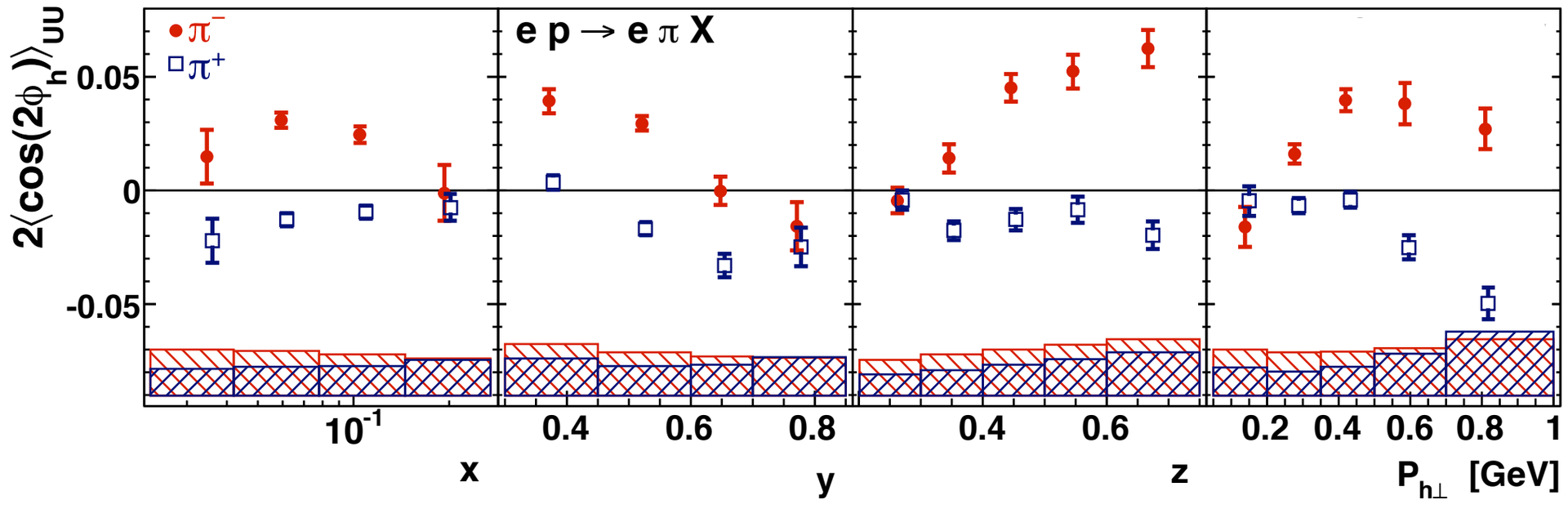
Boer-Mulders

Cahn (twist 4)



[V. Barone et al., Phys. Rev.D78 (2008) 045022]

[Airapetian et al., PRD 87 (2013) 012010]



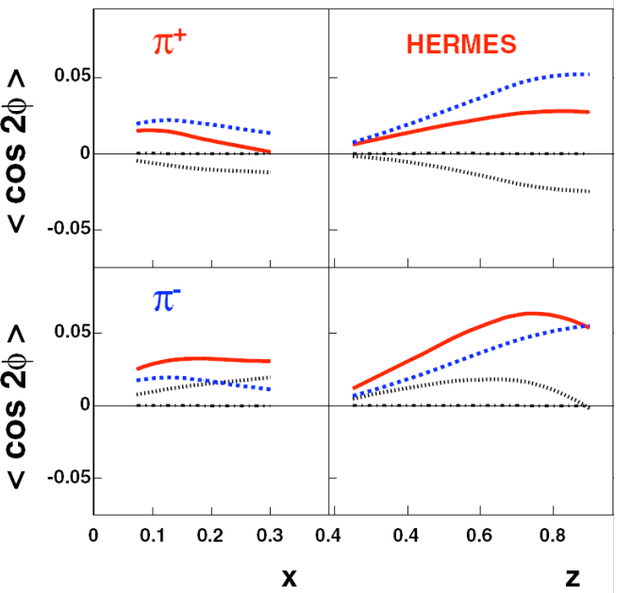
Signs of Boer-Mulders

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

All contributions

Boer-Mulders

Cahn (twist 4)



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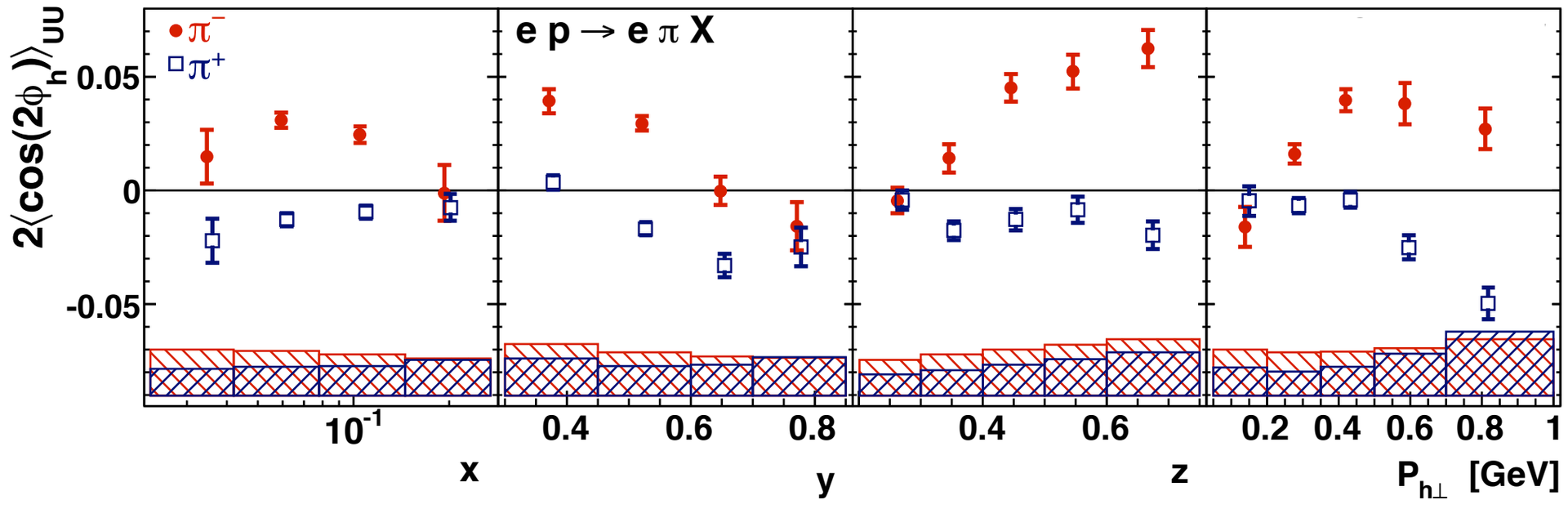
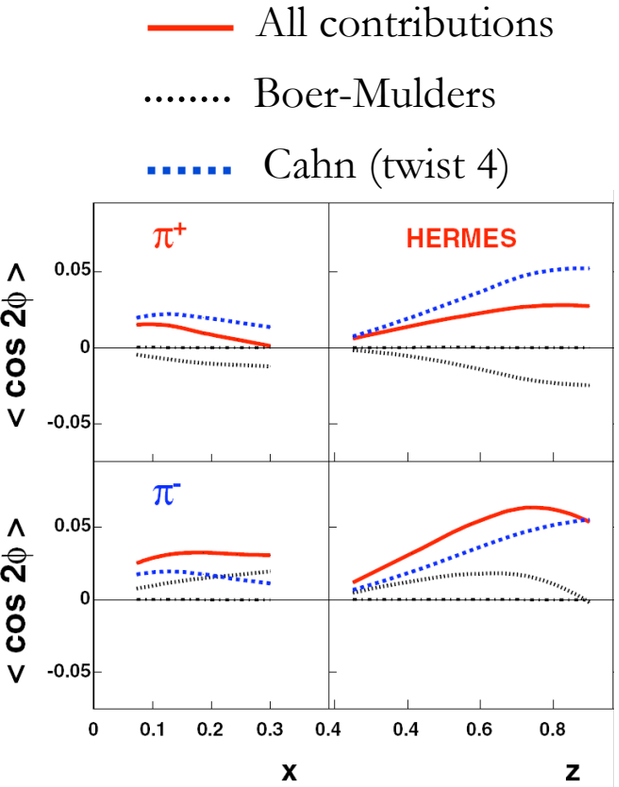


- Cahn effect only does not describe data

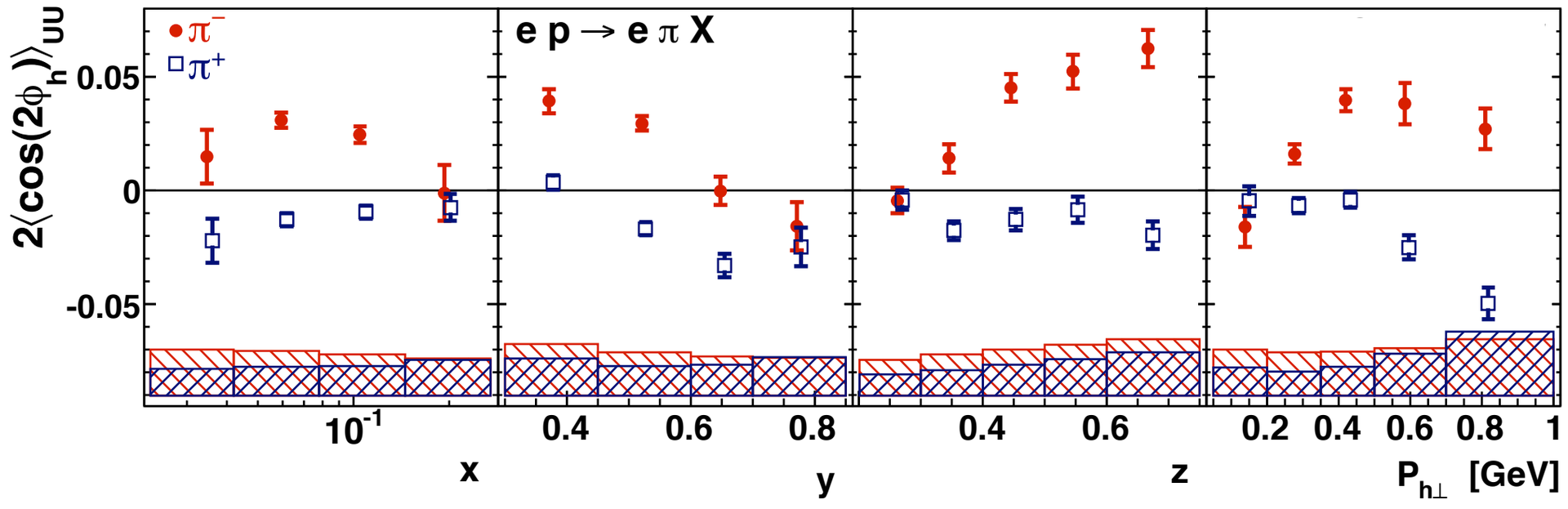
Signs of Boer-Mulders

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



[V. Barone et al., Phys. Rev.D78 (2008) 045022]

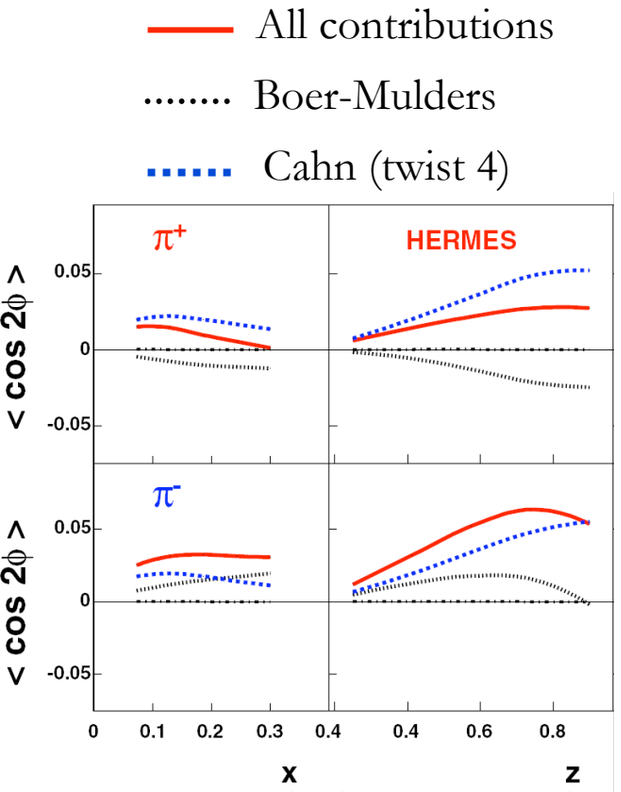
[Airapetian et al., PRD 87 (2013) 012010]



- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for π^- (as expected)
  -> same-sign BM-function for valence quarks

Signs of Boer-Mulders

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



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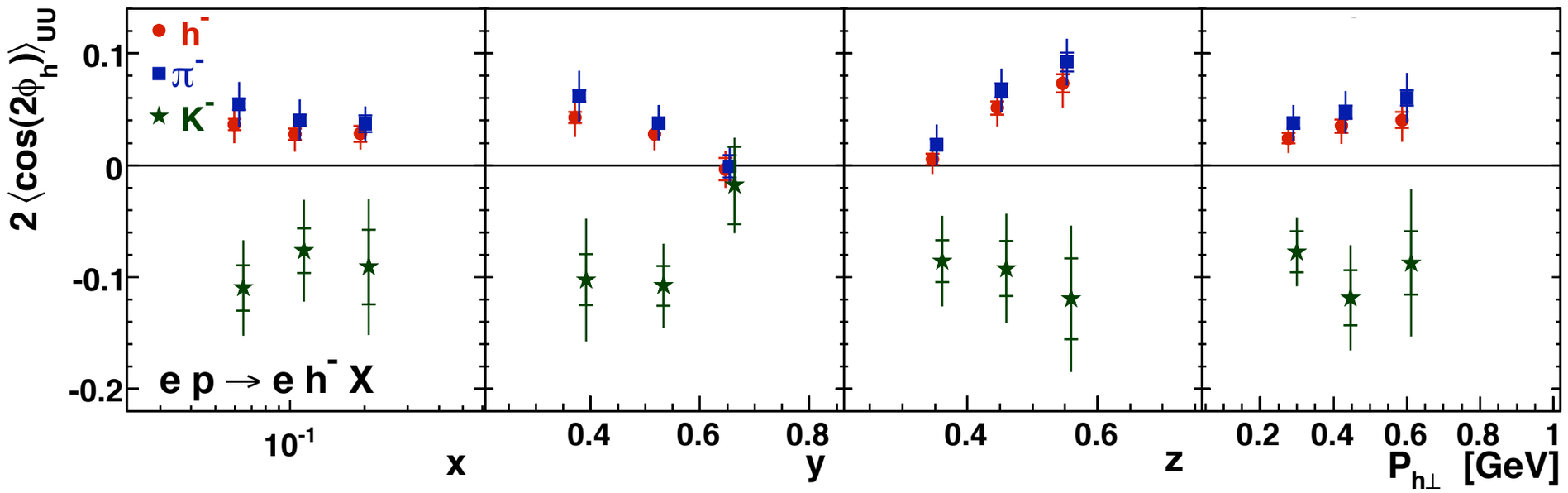


- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for π^- (as expected)
  -> same-sign BM-function for valence quarks
- intriguing behavior for kaons

Cahn effect?

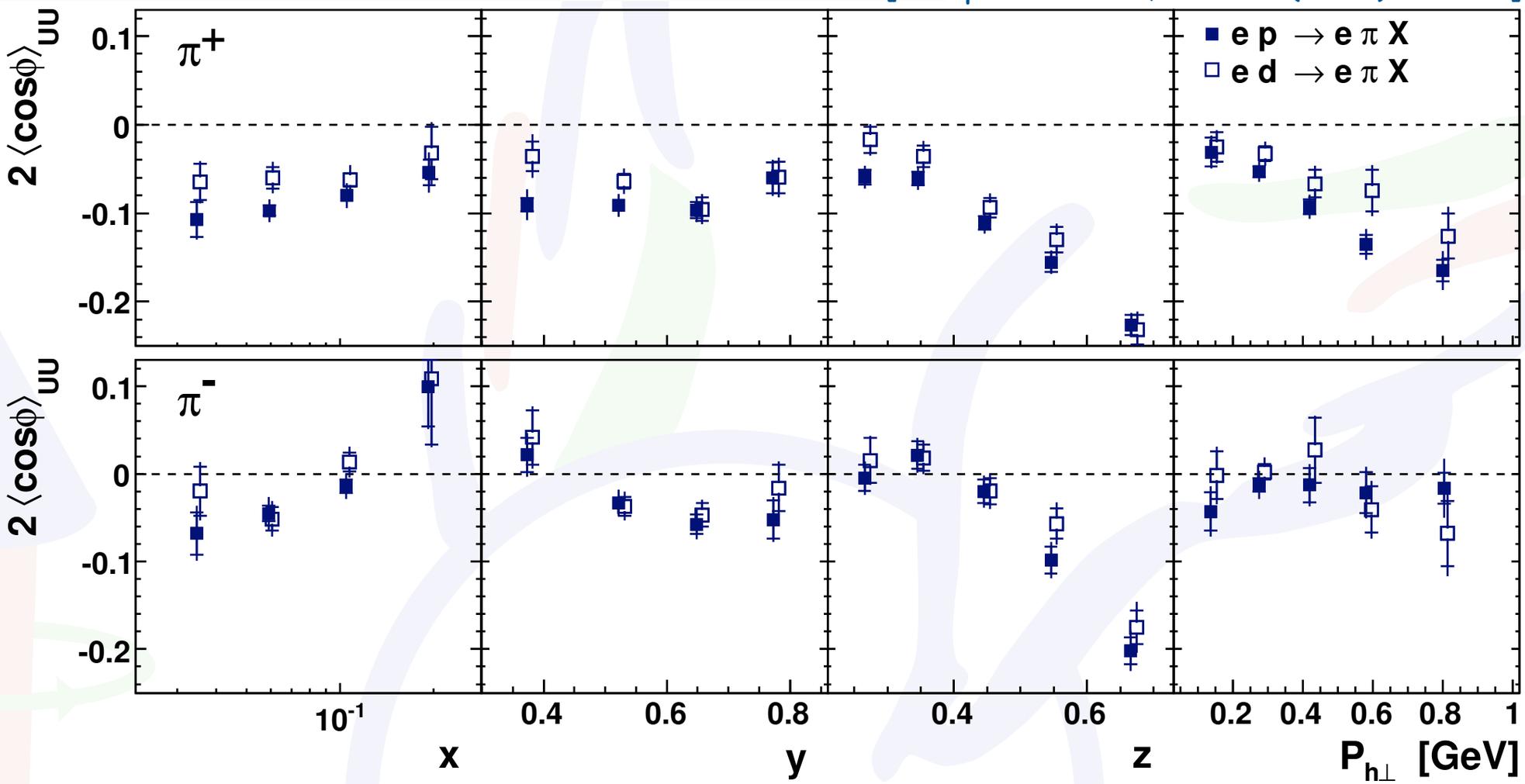
BOER-MULDERS EFFECT

CAHN EFFECT

$$\text{next to leading twist}\quad F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\widehat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\, x\, h_1^{\perp} H_1^{\perp} - \frac{\widehat{P}_{h\perp}\cdot\vec{k}_T}{M}\, x\, f_1 D_1 + \dots \right]$$

Interaction dependent terms neglected

[Airapetian et al., PRD 87 (2013) 012010]



- no dependence on hadron charge expected for Cahn effect

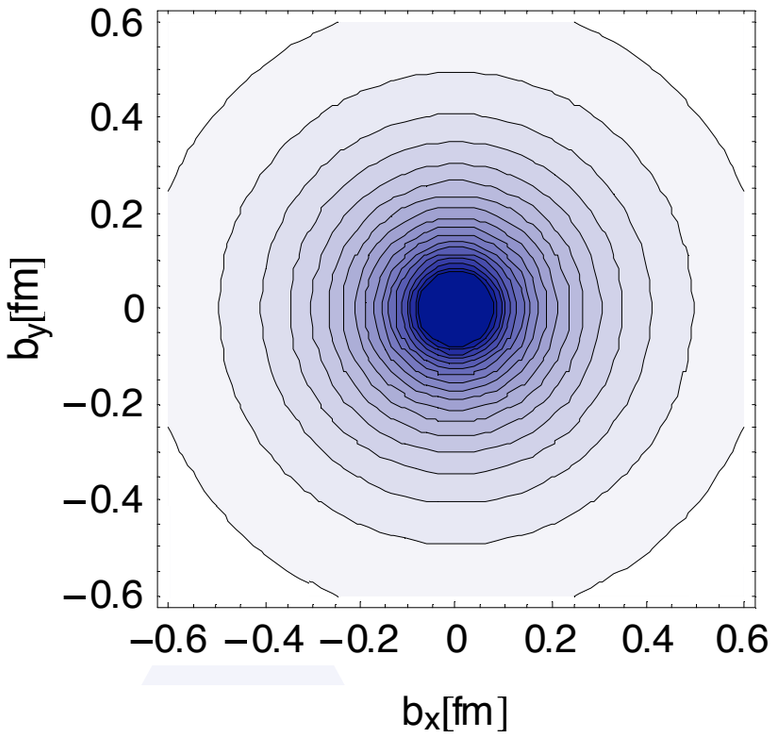
➡ flavor dependence of transverse momentum

➡ sign of Boer-Mulders in $\cos\phi$ modulation
(indeed, overall pattern resembles B-M modulations)

➡ additional "genuine" twist-3?

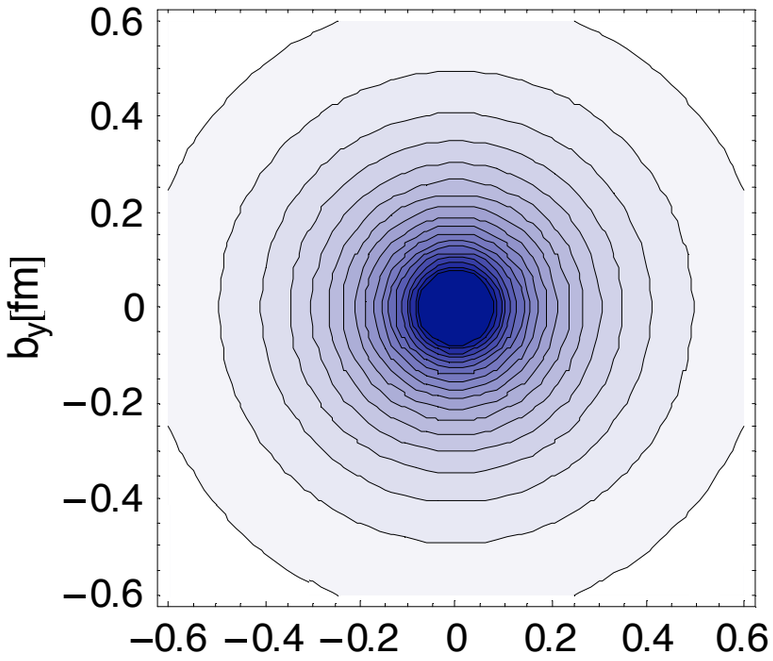
Exclusive reactions

A complementary 3D picture of the nucleon



Form factors:
transverse distribution
of partons

A complementary 3D picture of the nucleon



Form factors:
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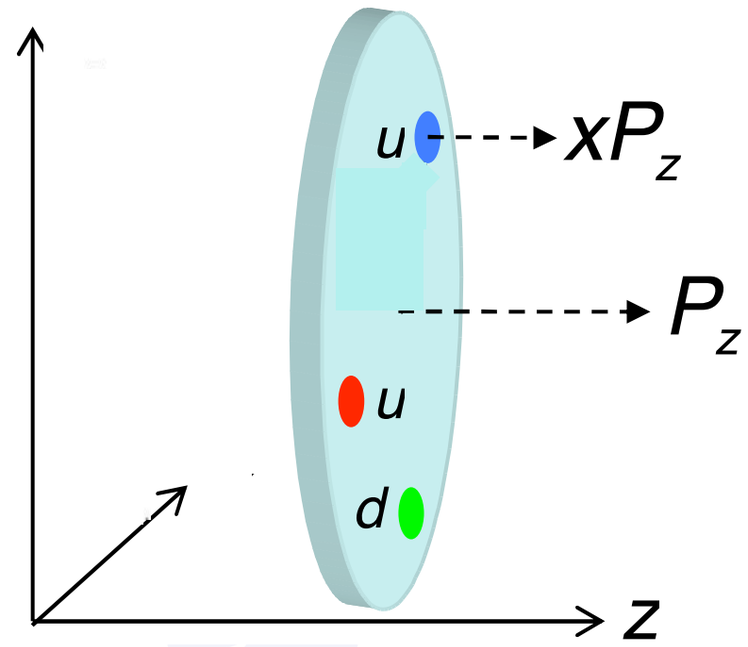
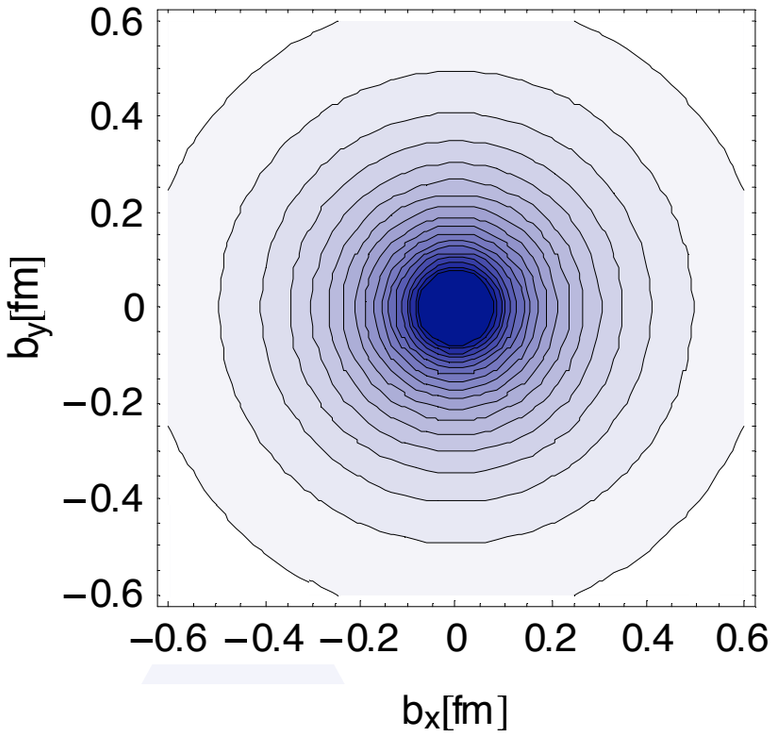


Parton distributions:
longitudinal momentum of partons

A complementary 3D picture of the nucleon



Form factors:
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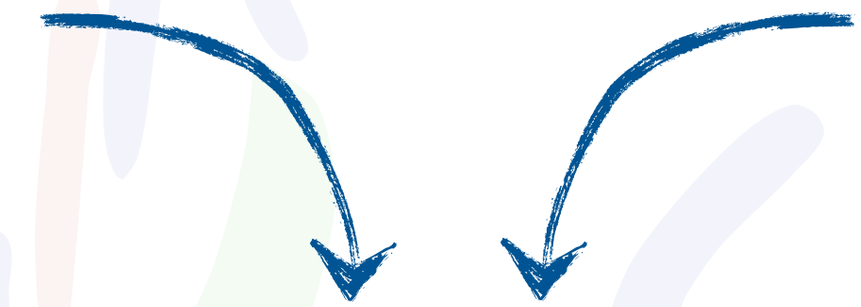

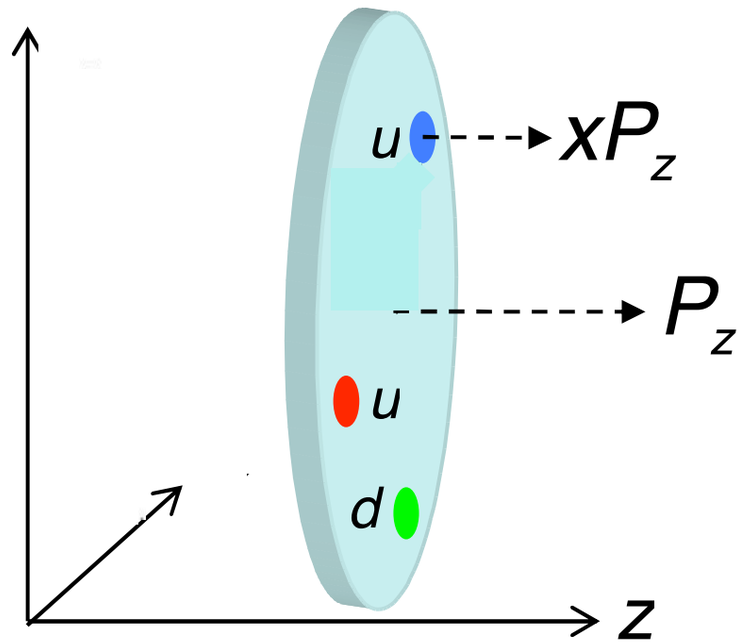

Parton distributions:
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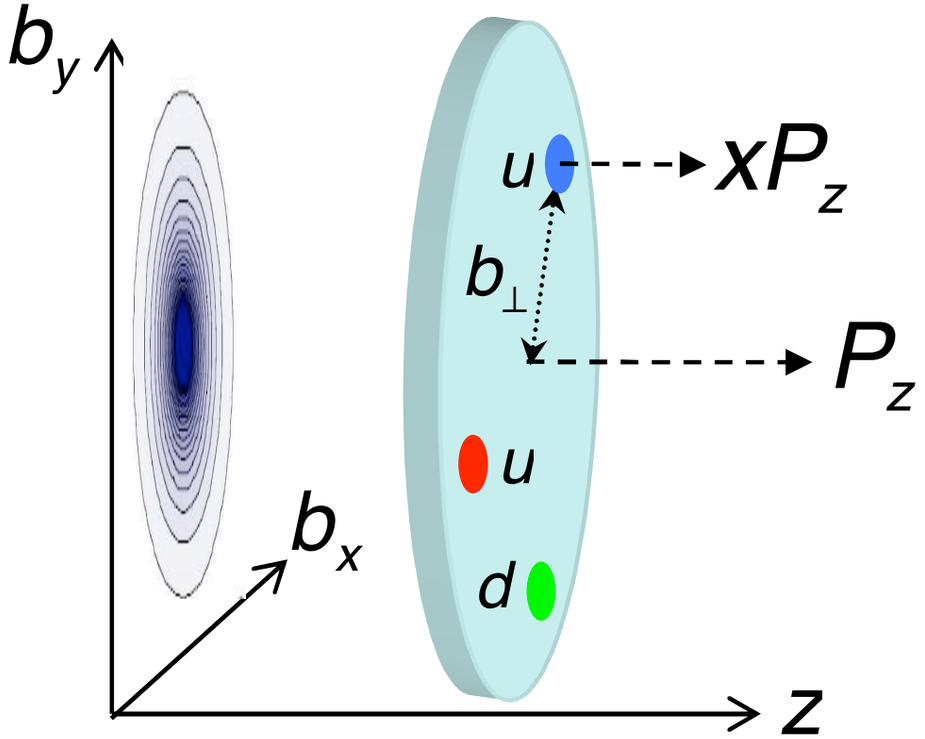
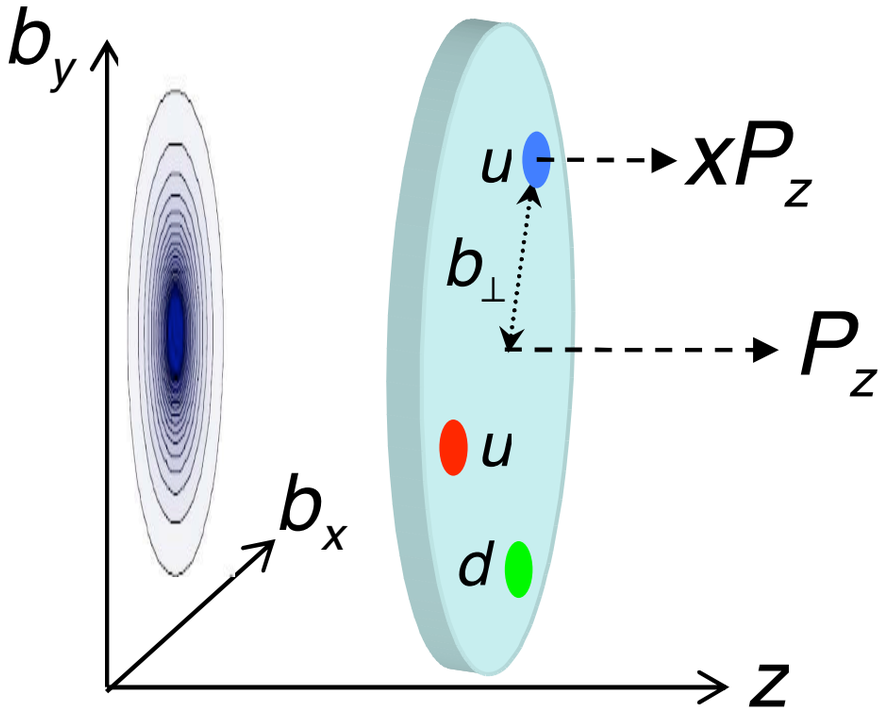
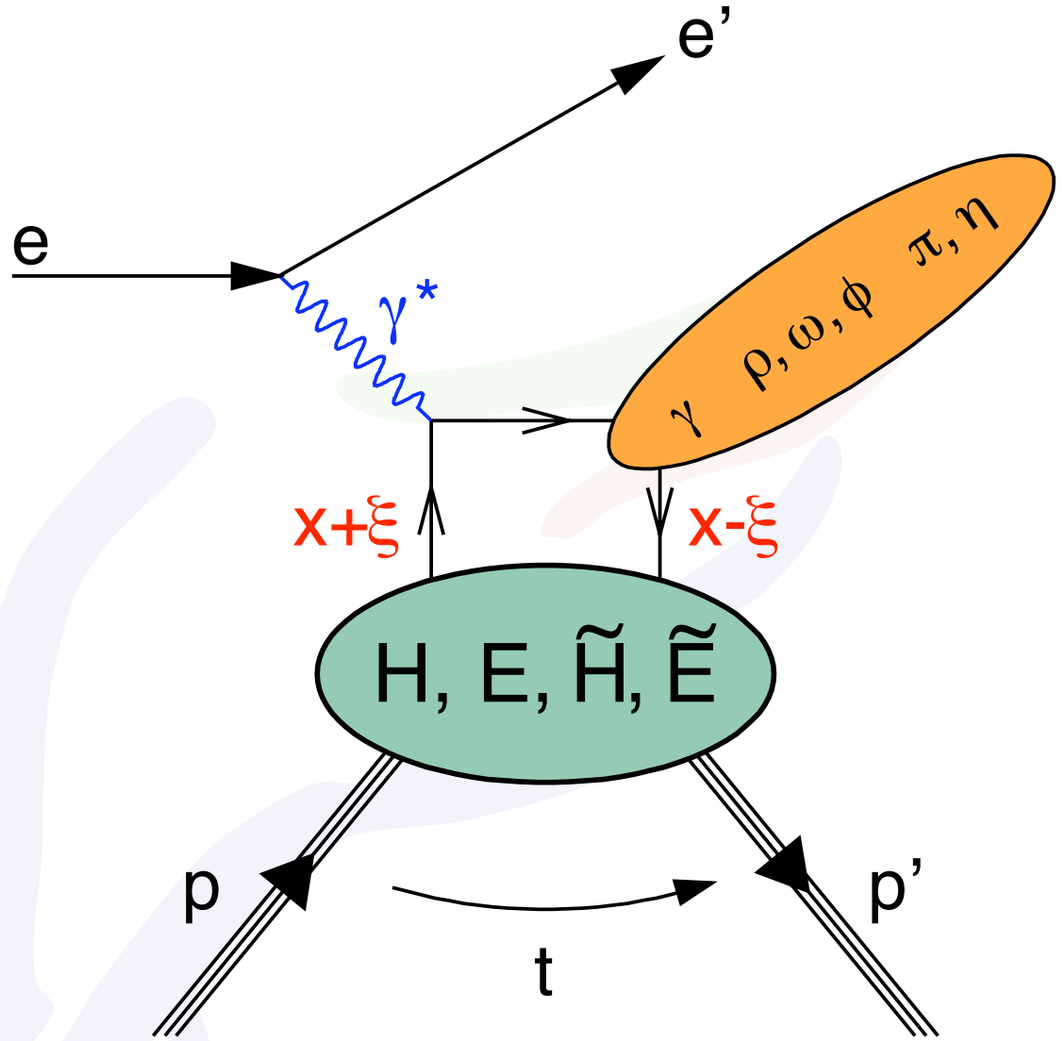


Nucleon Tomography
correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

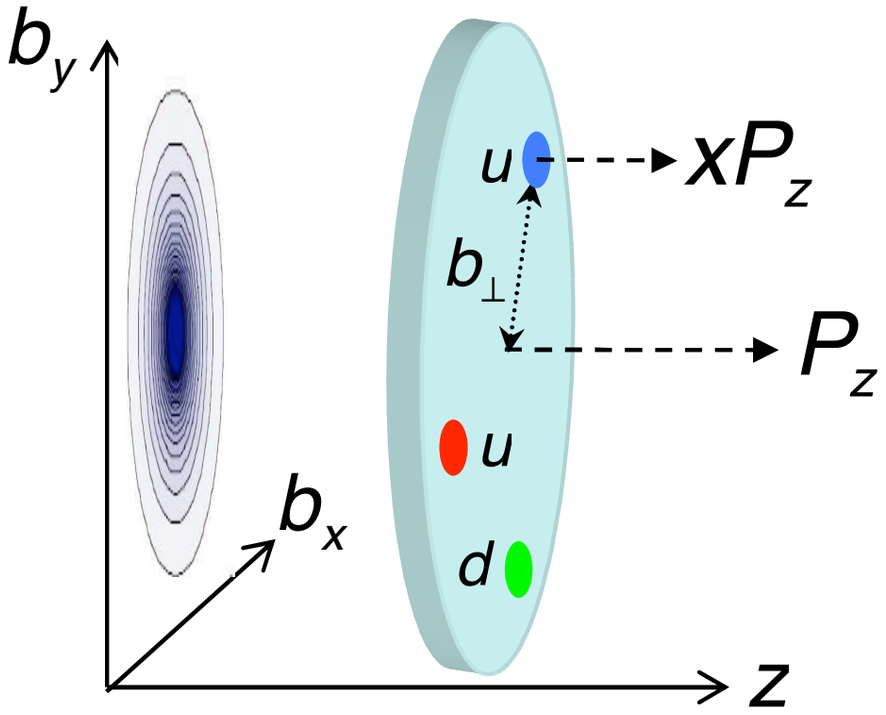


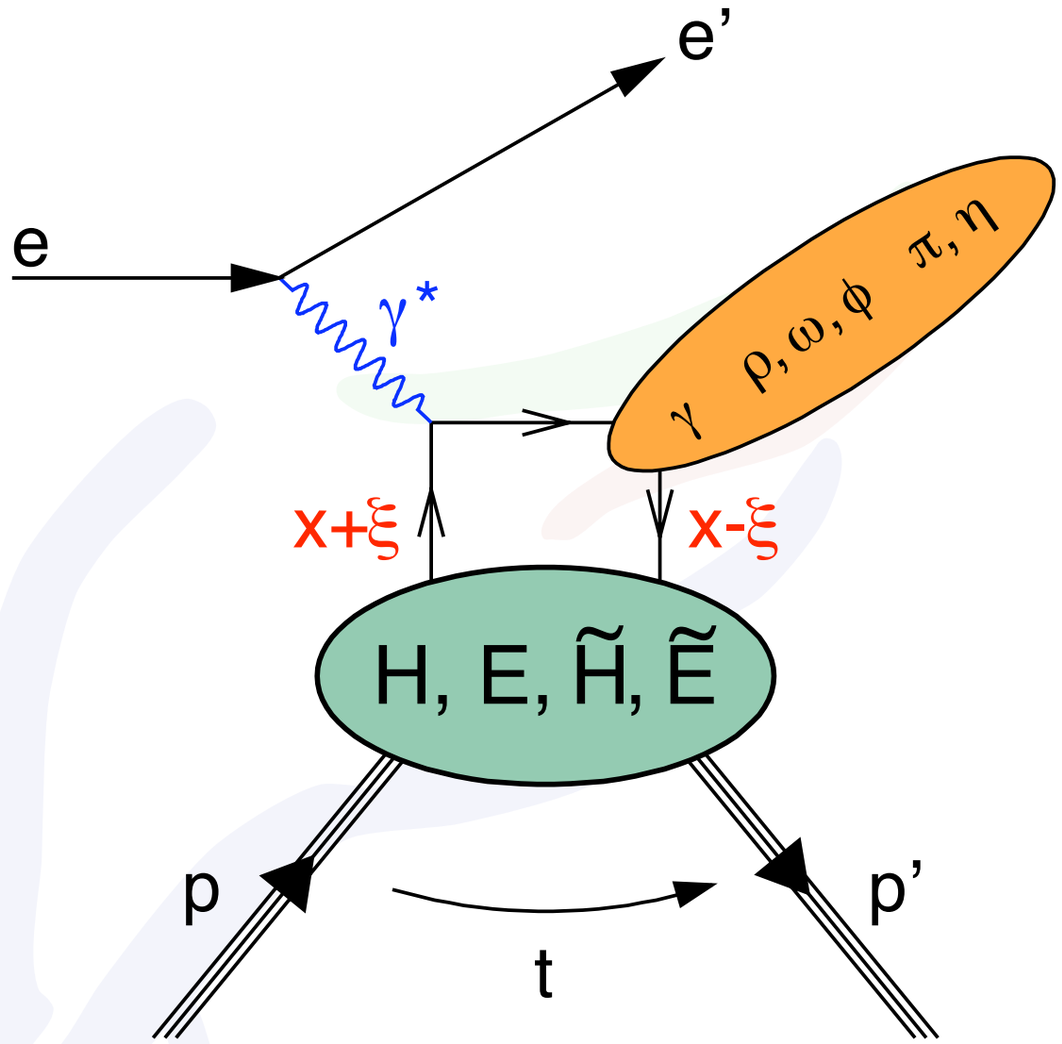


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

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

Probing GPDs in Exclusive Reactions

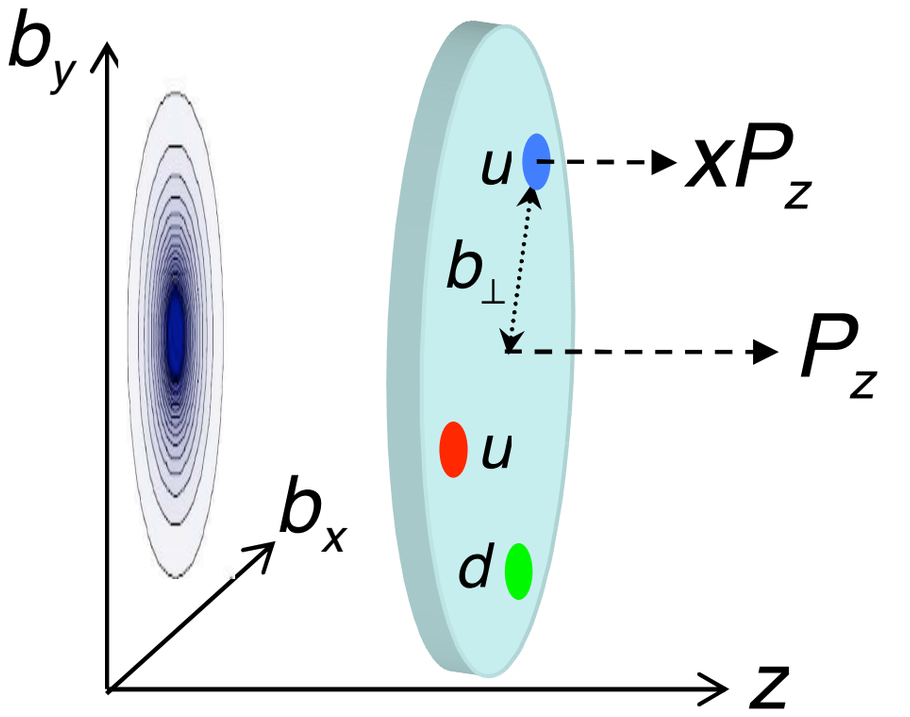


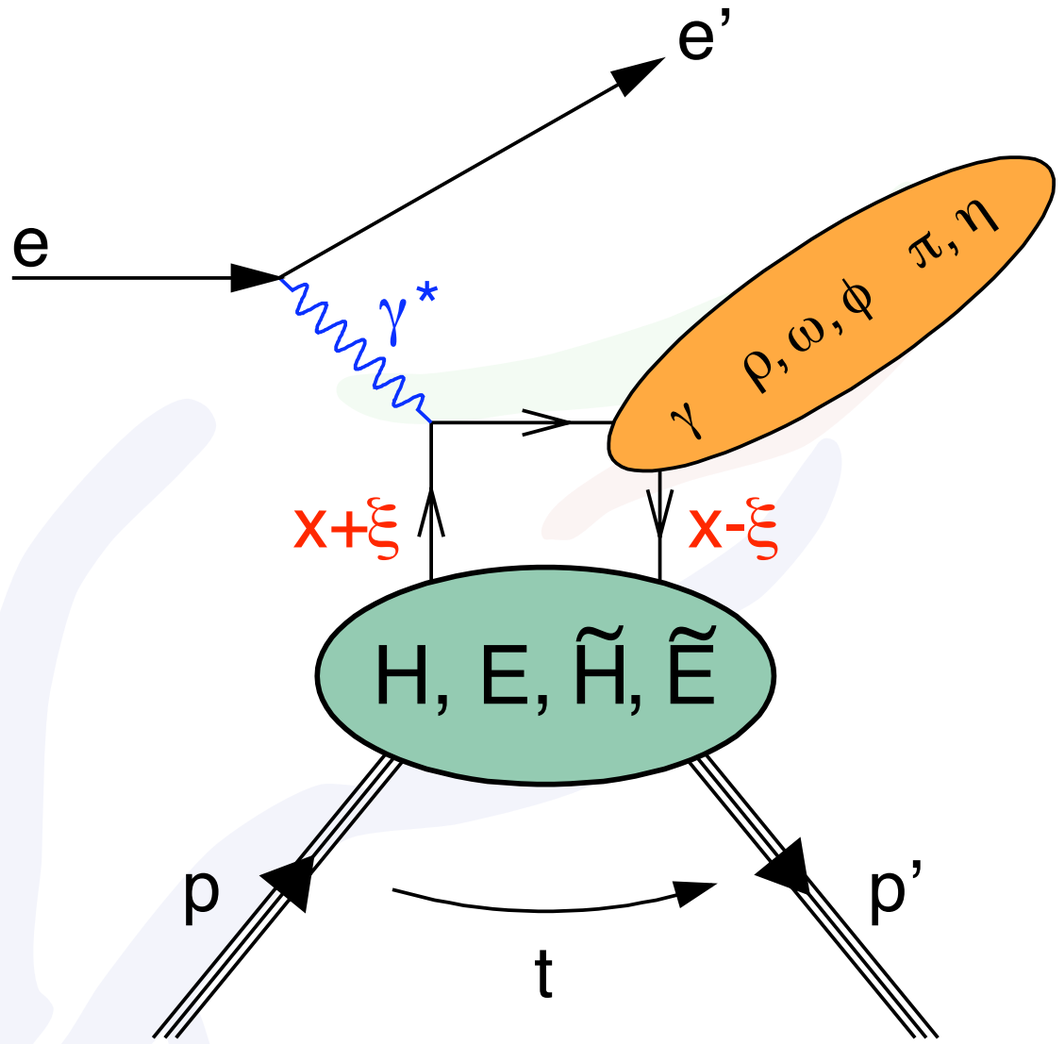


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\tilde{H}$
nucleon helicity flip	E	$\tilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





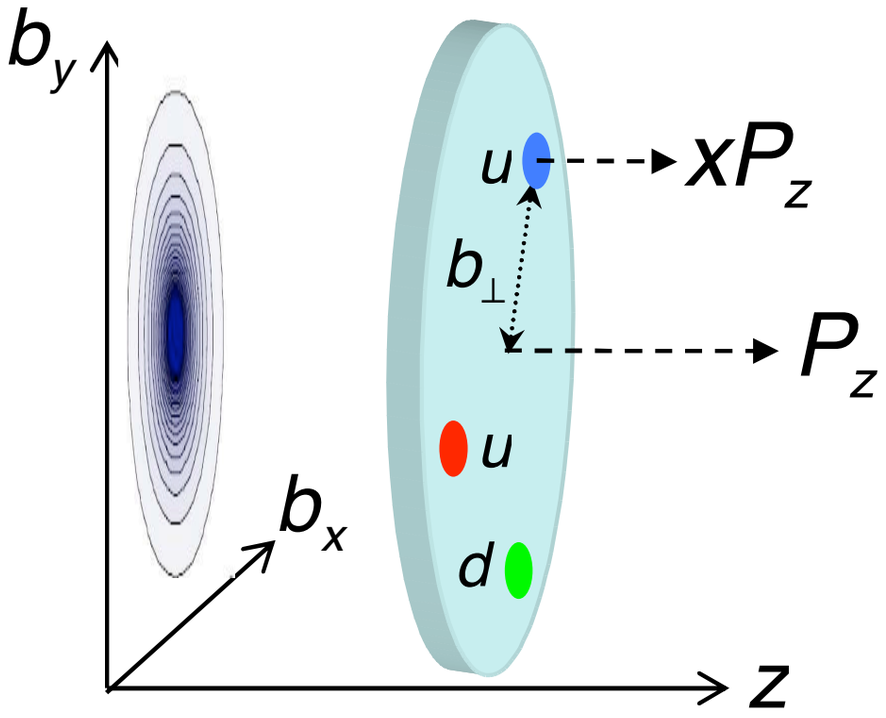
$$\int \mathrm{d}x H^q(x,\xi,t) = F_1^q(t)$$

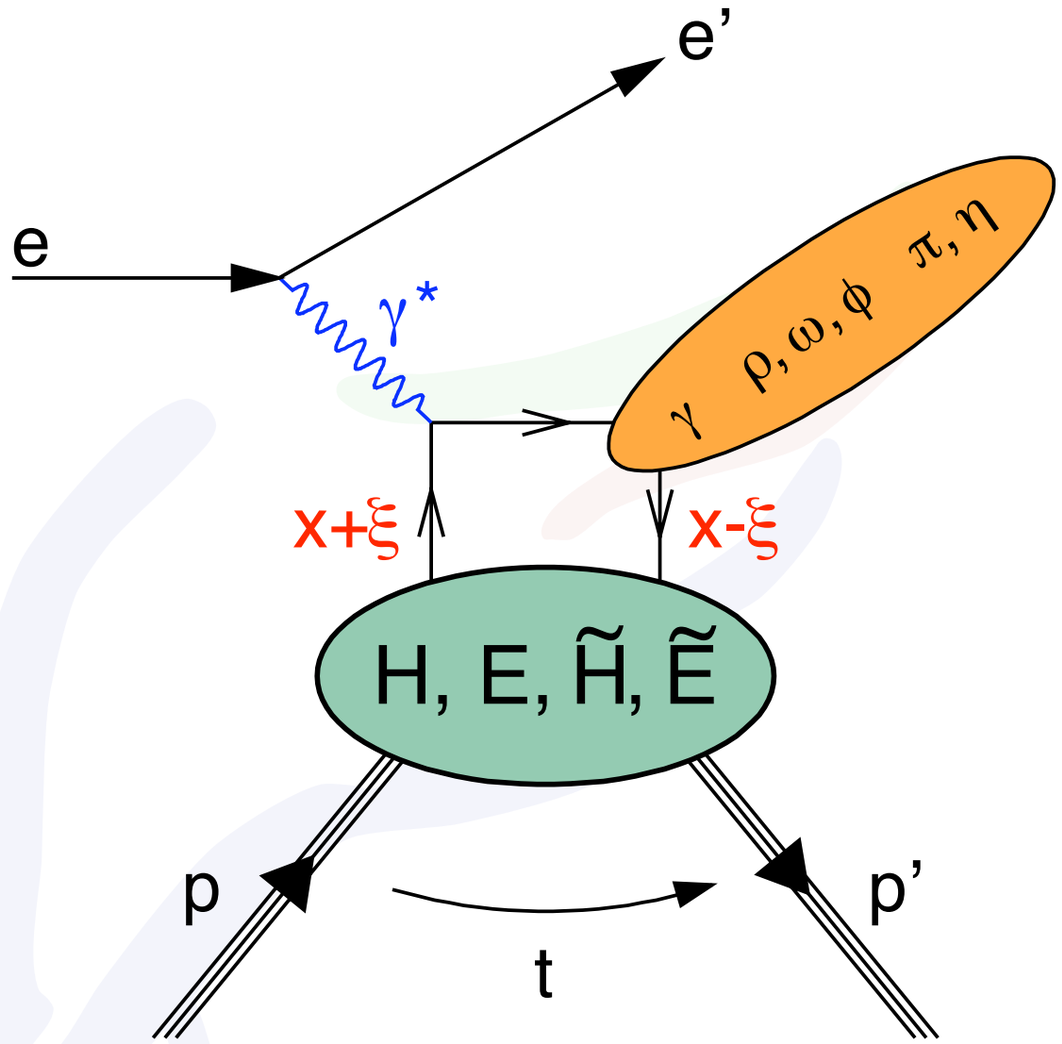
$$\int \mathrm{d}x E^q(x,\xi,t) = F_2^q(t)$$

	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)

Probing GPDs in Exclusive Reactions





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

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

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

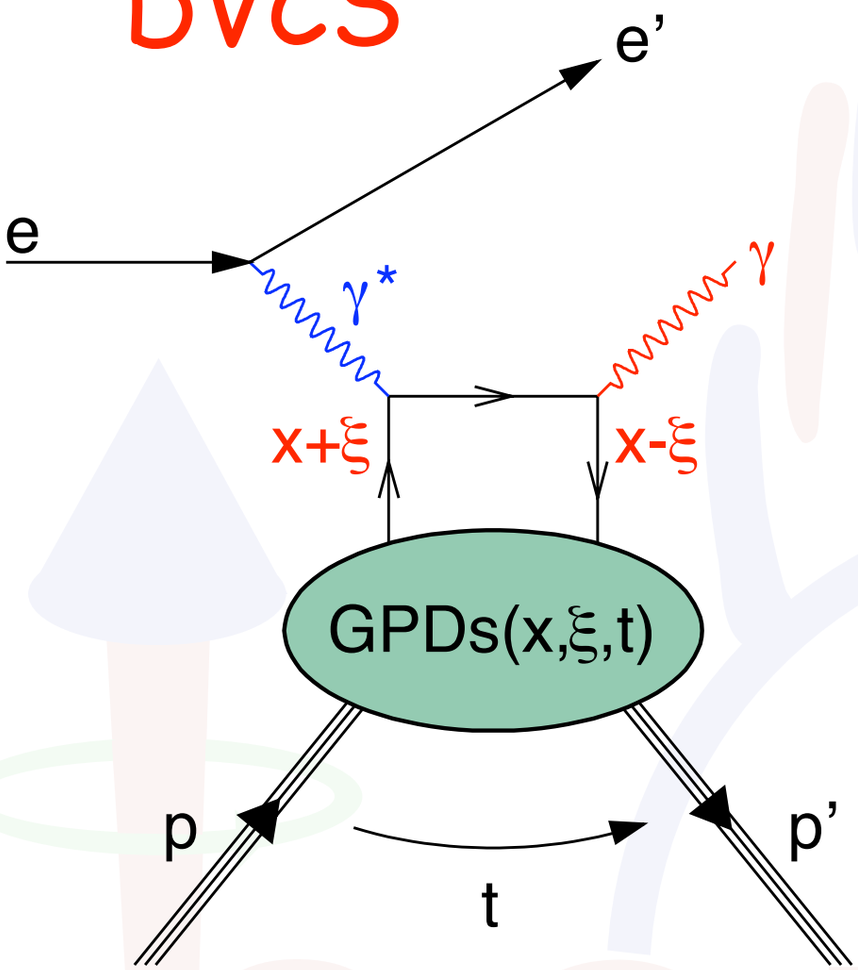
$$\widetilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

	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)

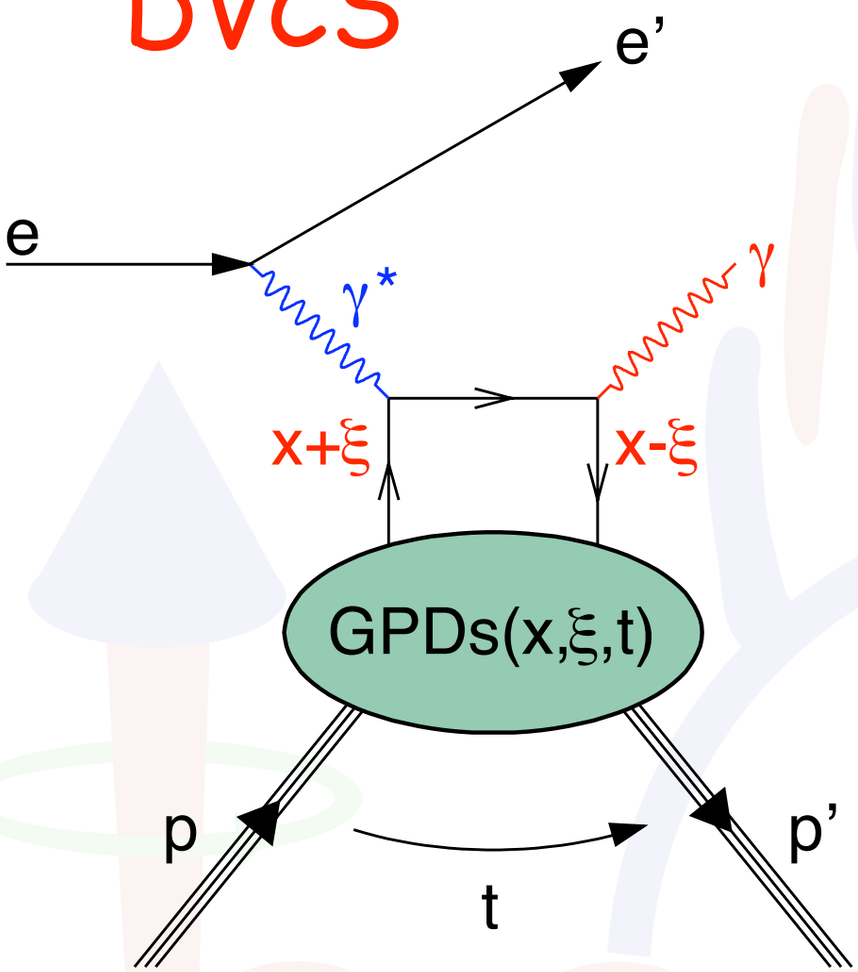
Real-photon production

DVCS

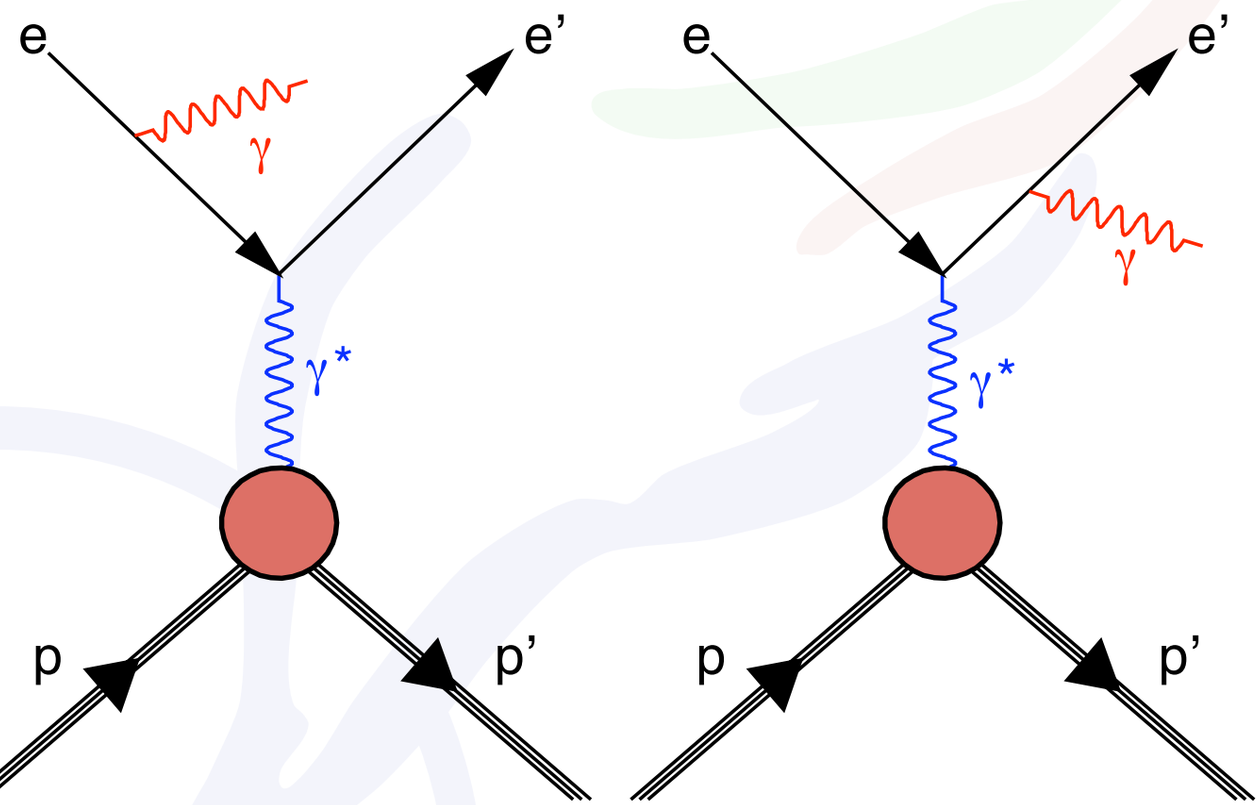


Real-photon production

DVCS



Bethe-Heitler



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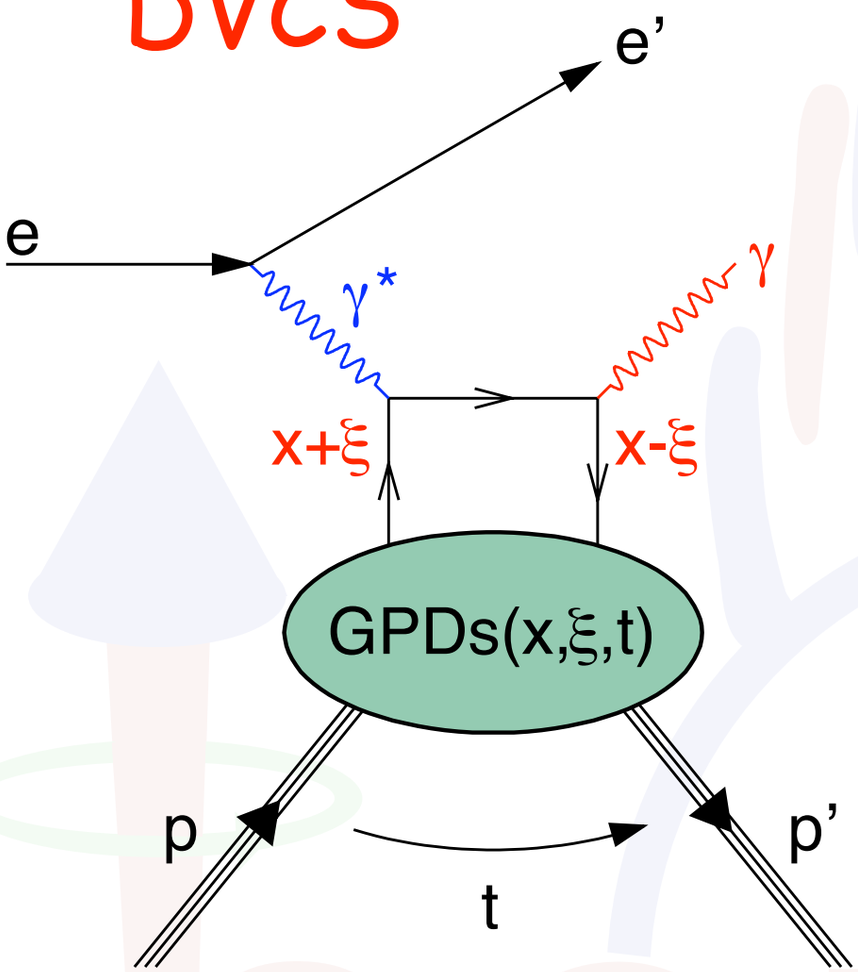

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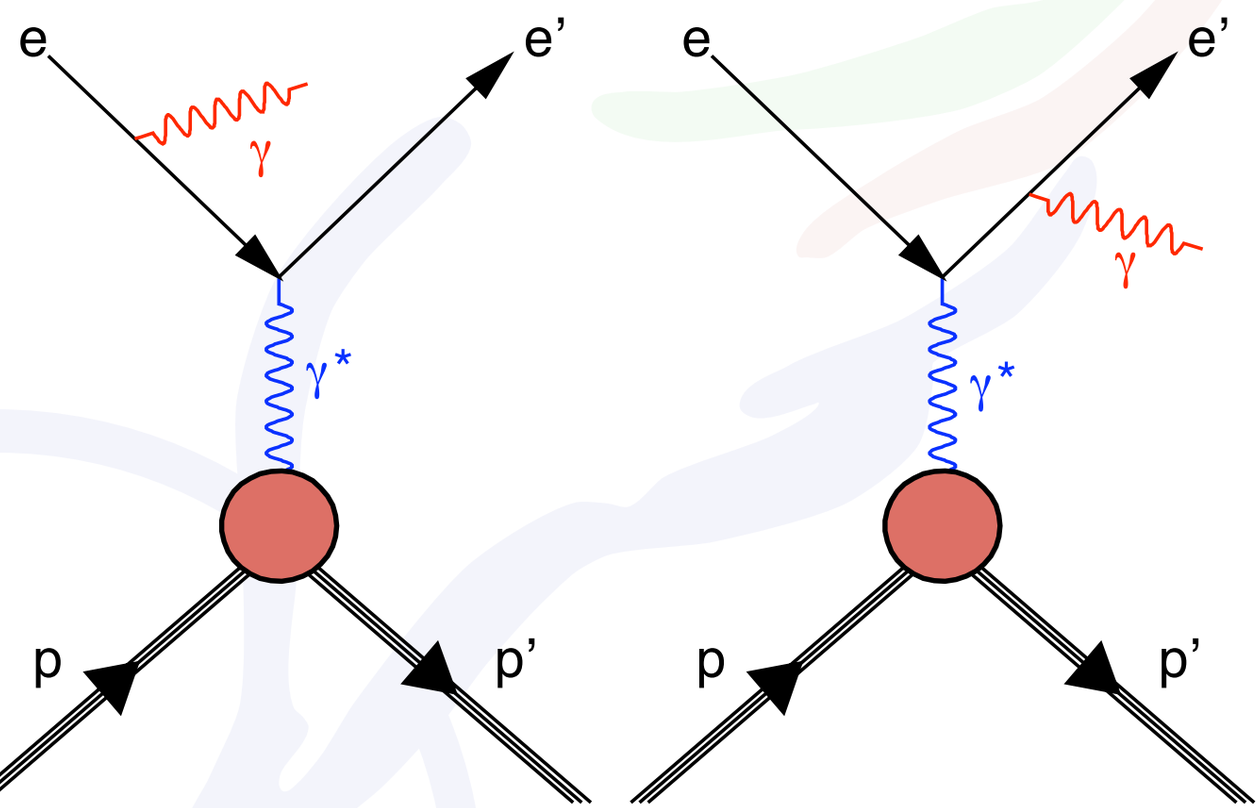
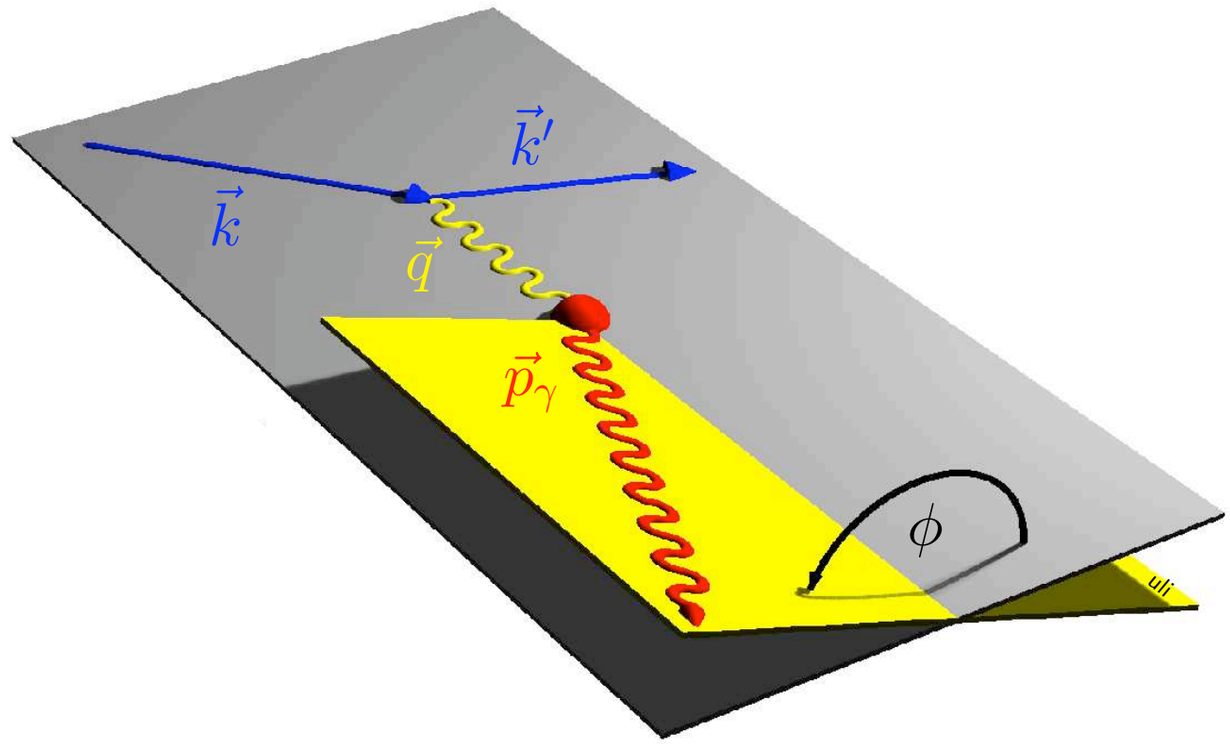


$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2+|\mathcal{T}_{\mathrm{BH}}|^2+\mathcal{I}\right)$$

Azimuthal dependences in DVCS/BH

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



Fourier expansion for ϕ:

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

calculable in QED
(using FF measurements)

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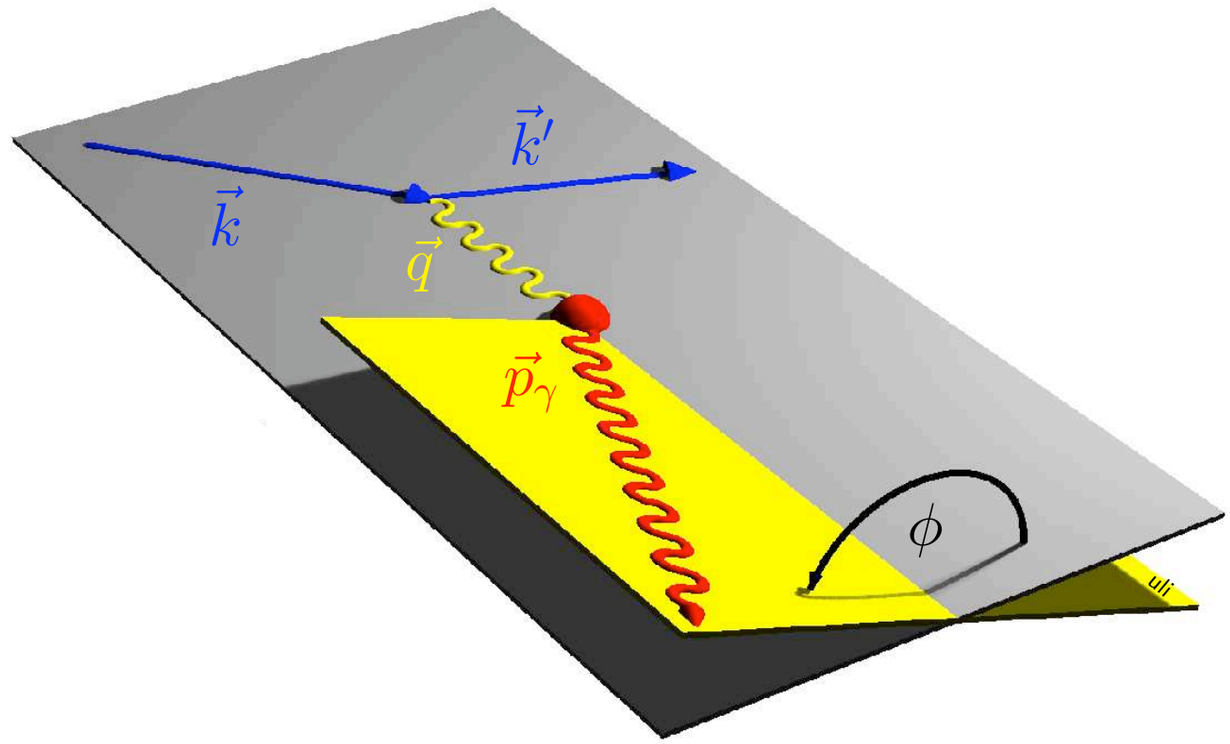

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$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

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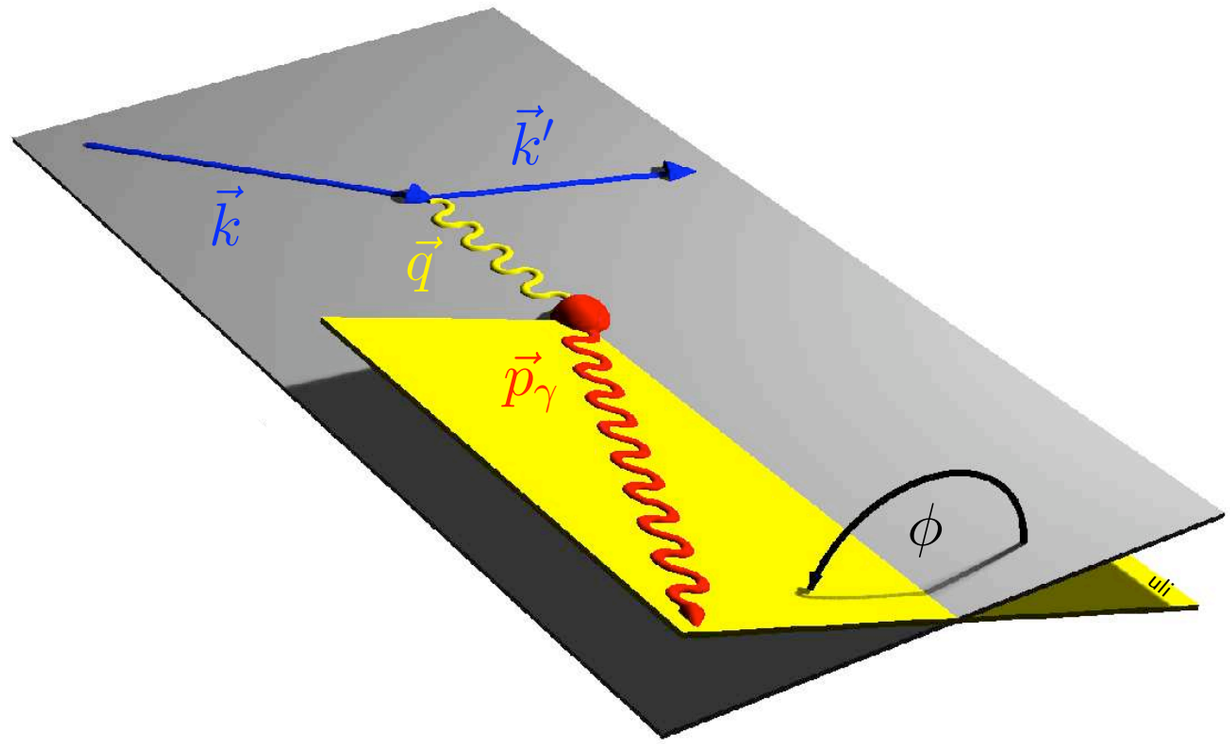

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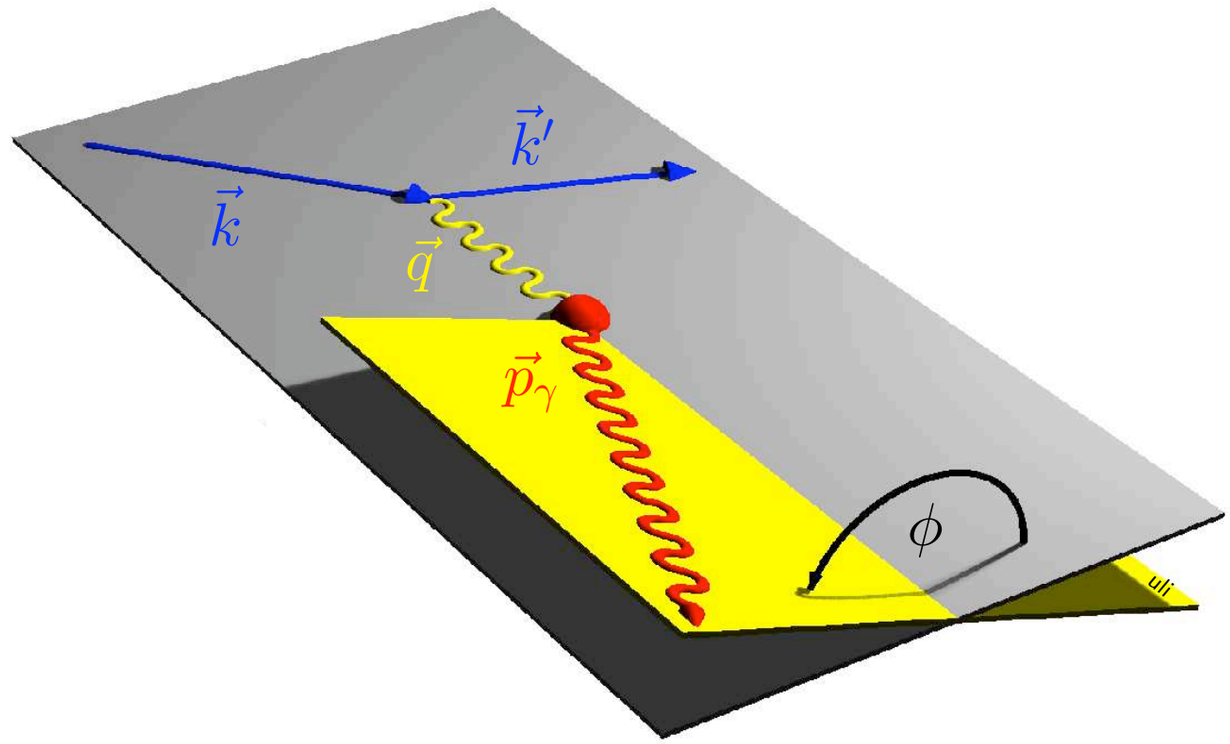
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

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



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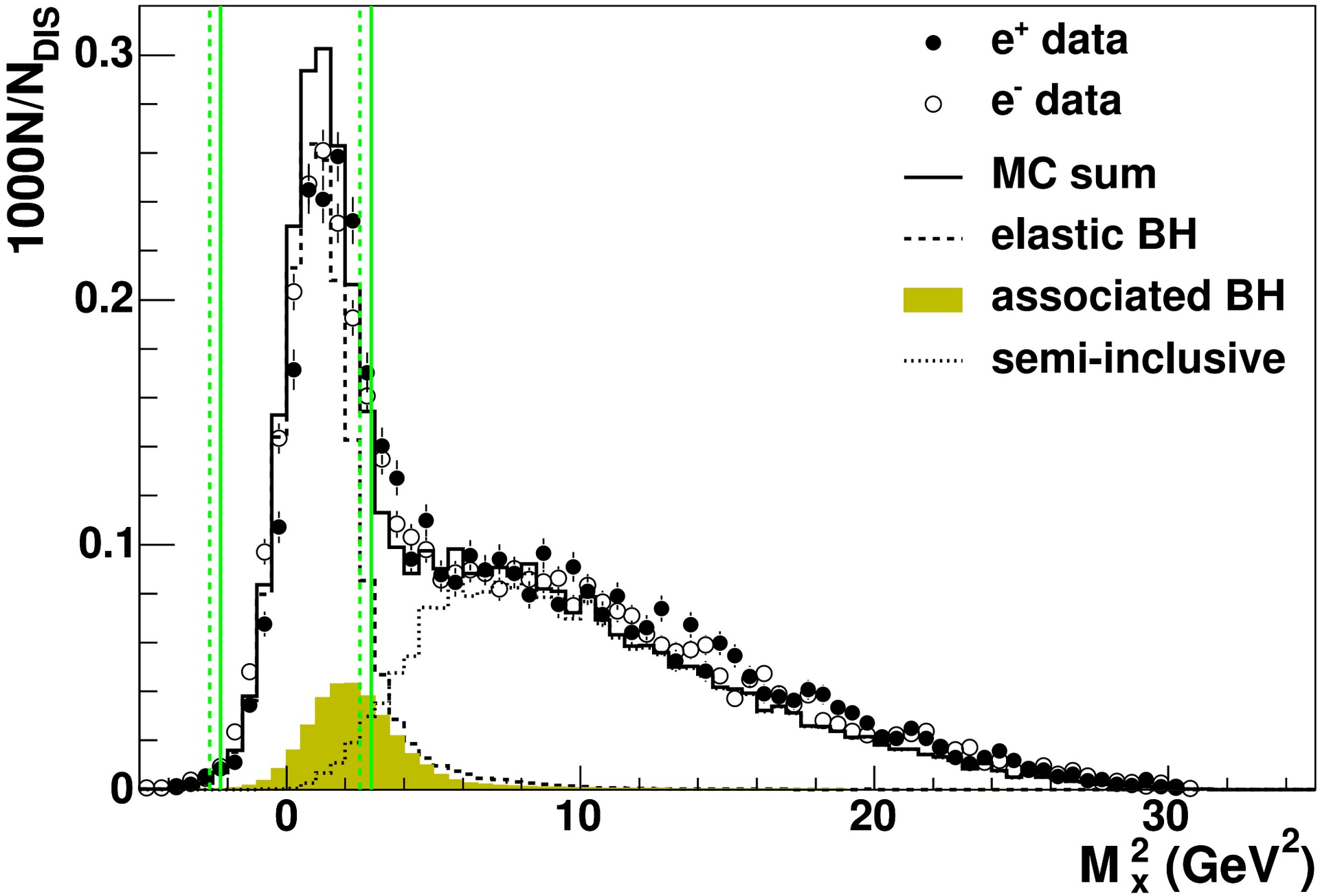
bilinear ("DVCS") or linear in GPDs

Exclusivity: missing-mass technique



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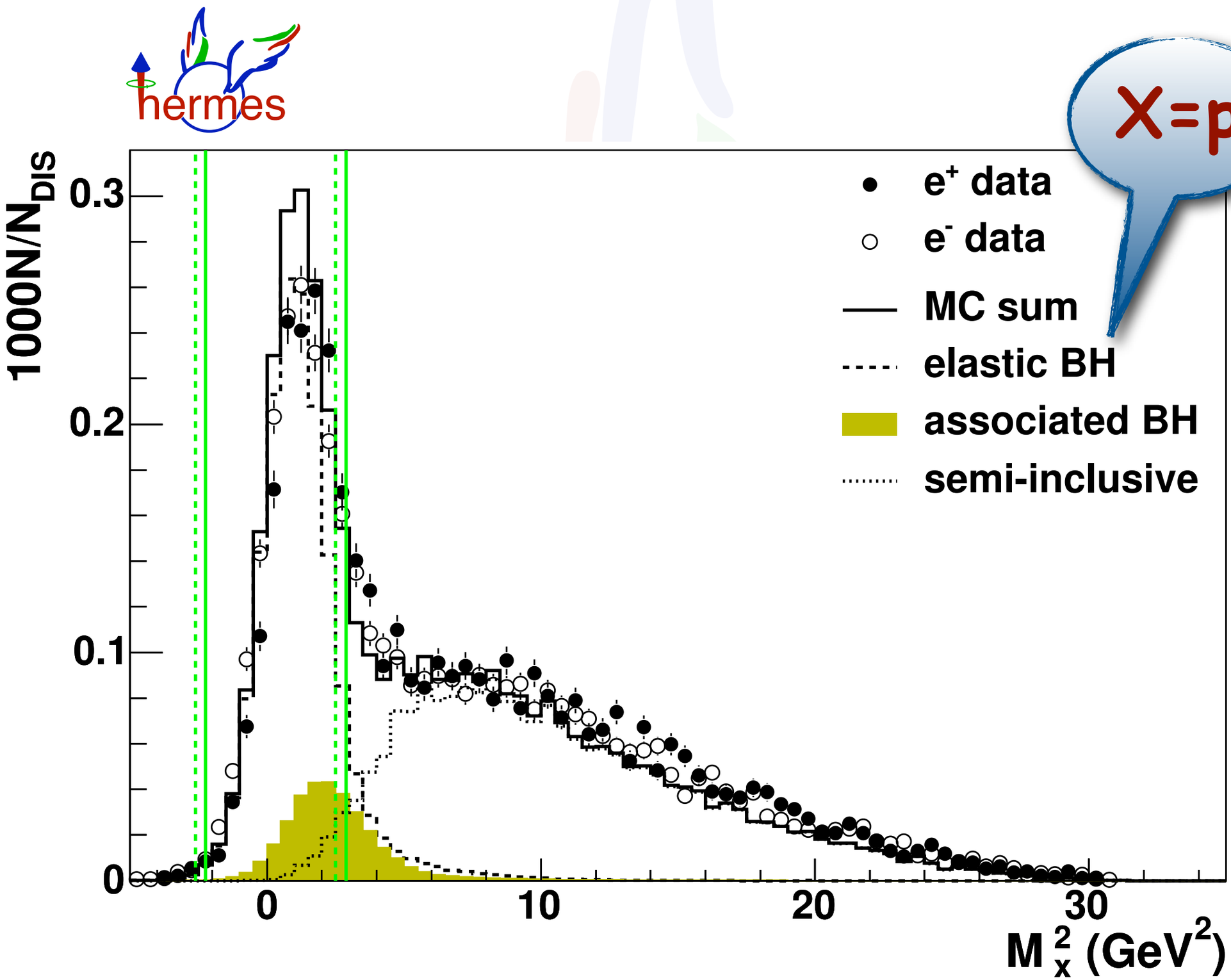

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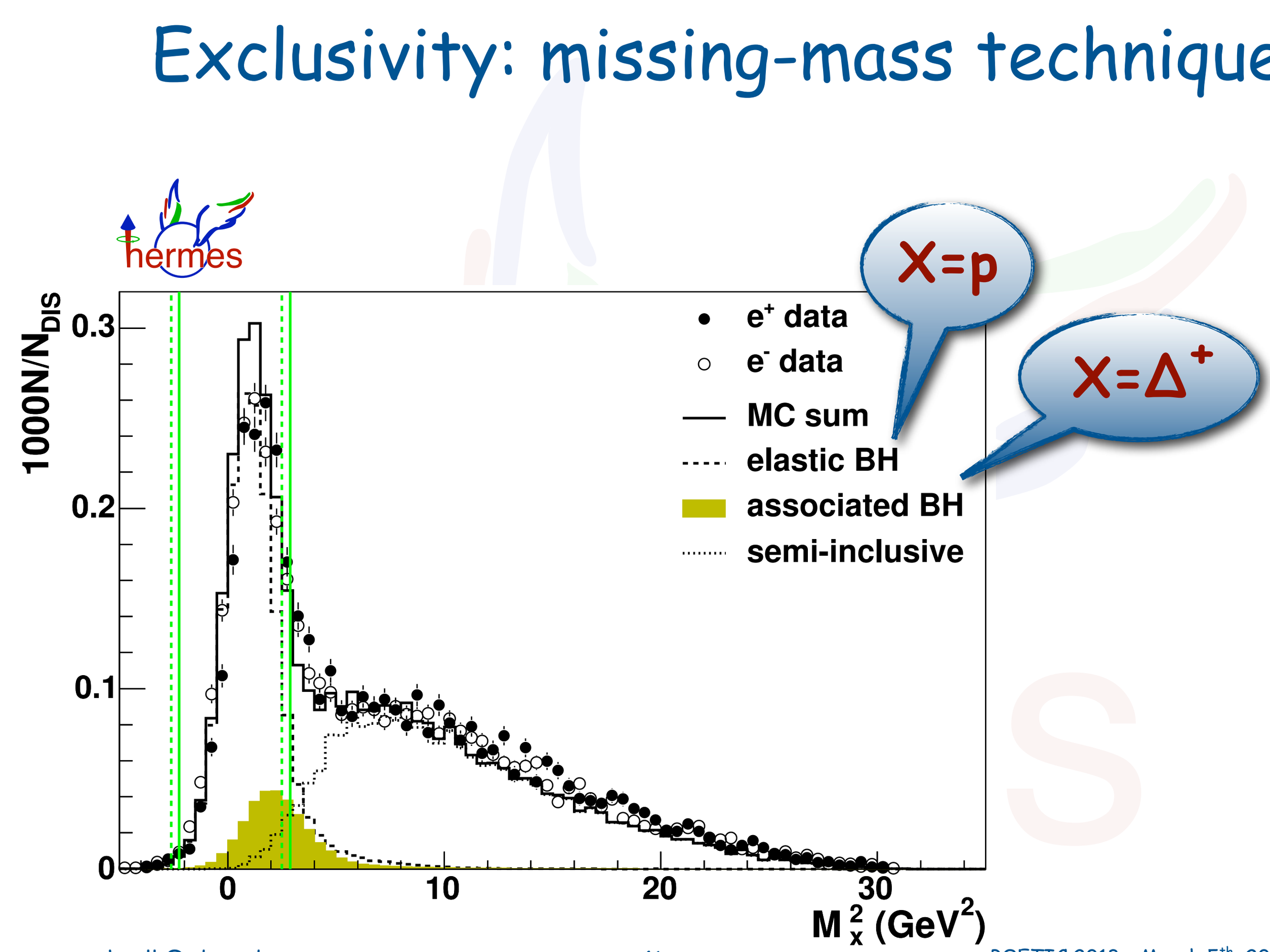

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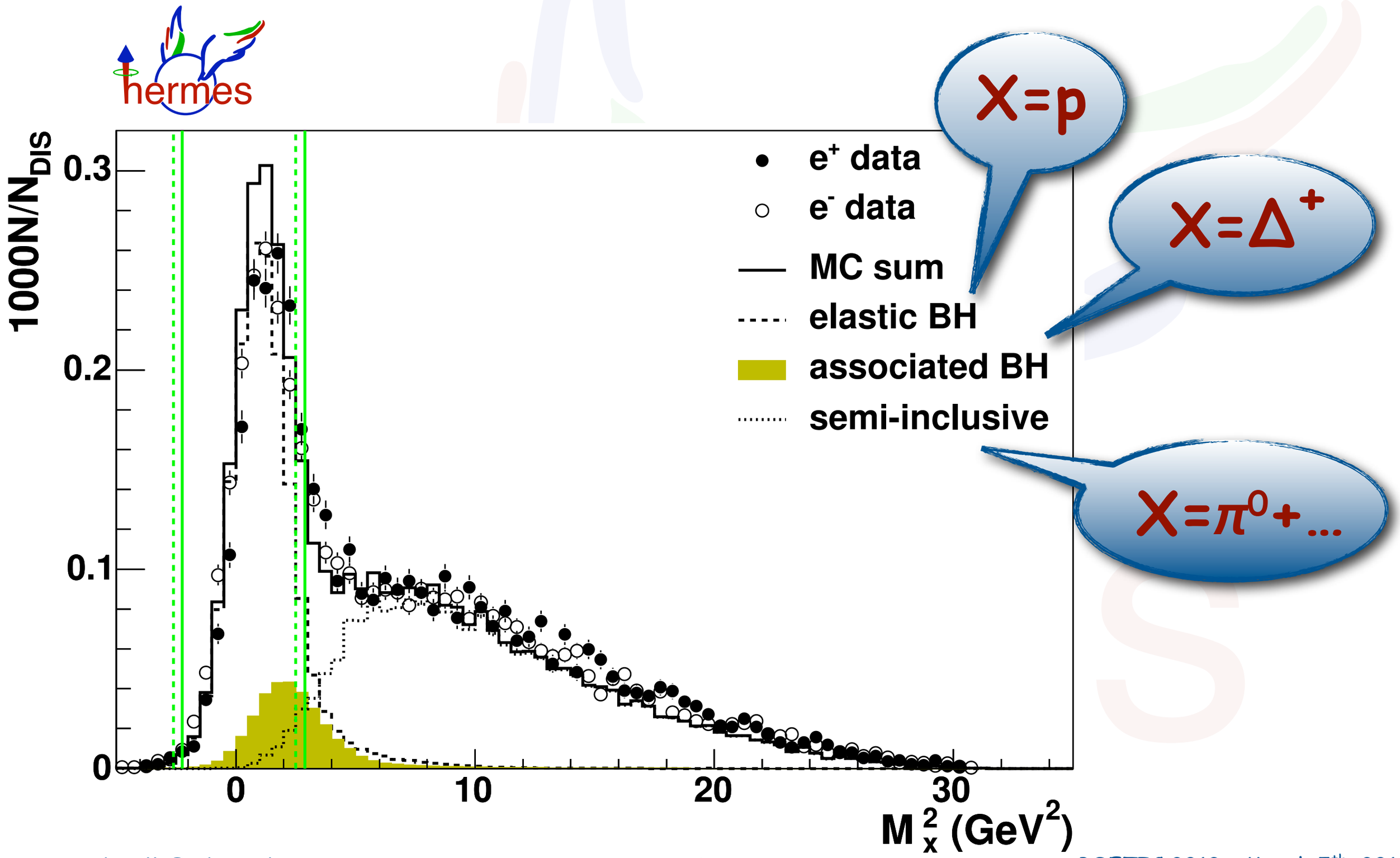
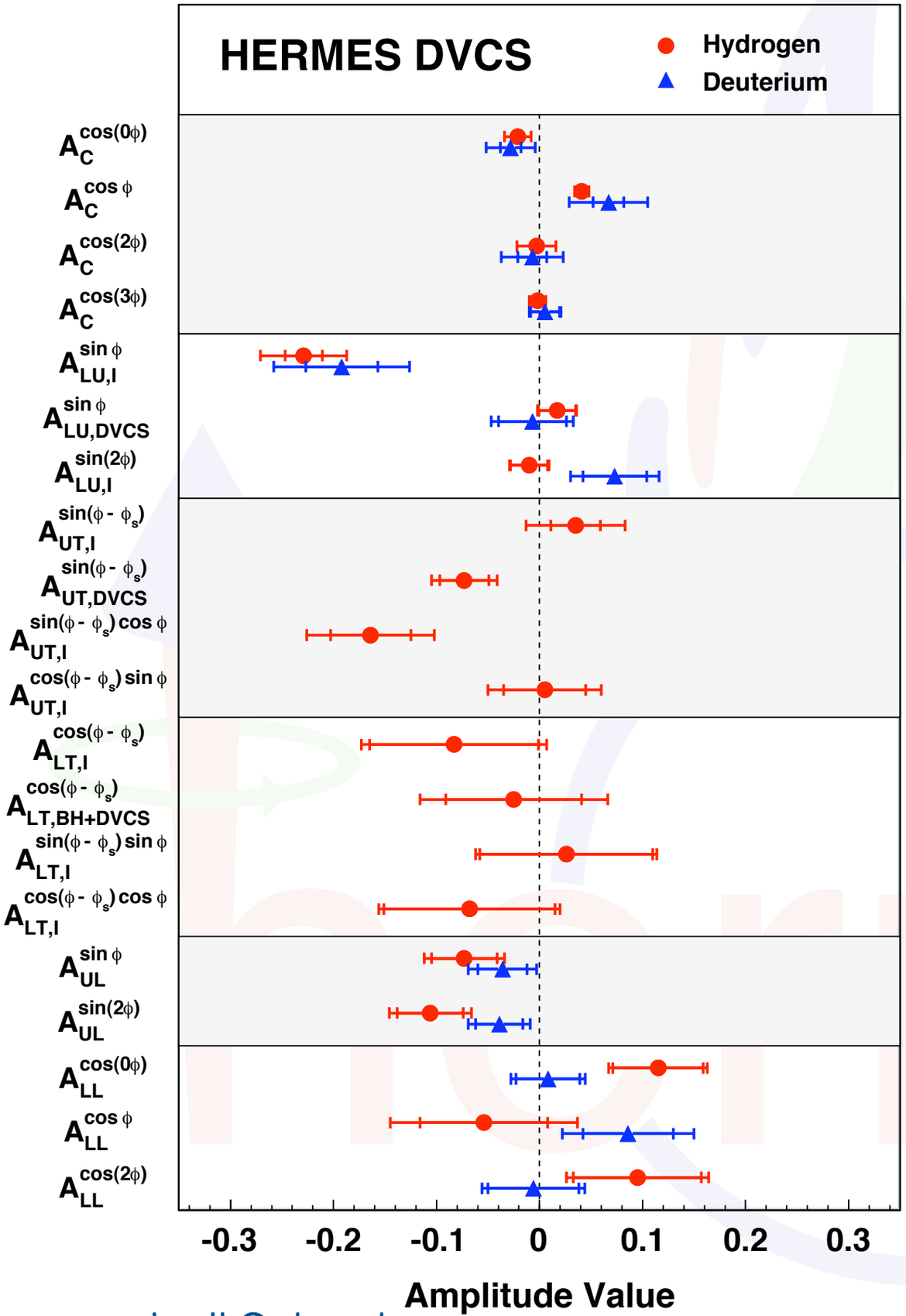


A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103
NPB 829 (2010) 1
JHEP 11 (2009) 083

Beam-helicity asymmetry:

GPD H

PRC 81 (2010) 035202
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 $\tilde{H}$

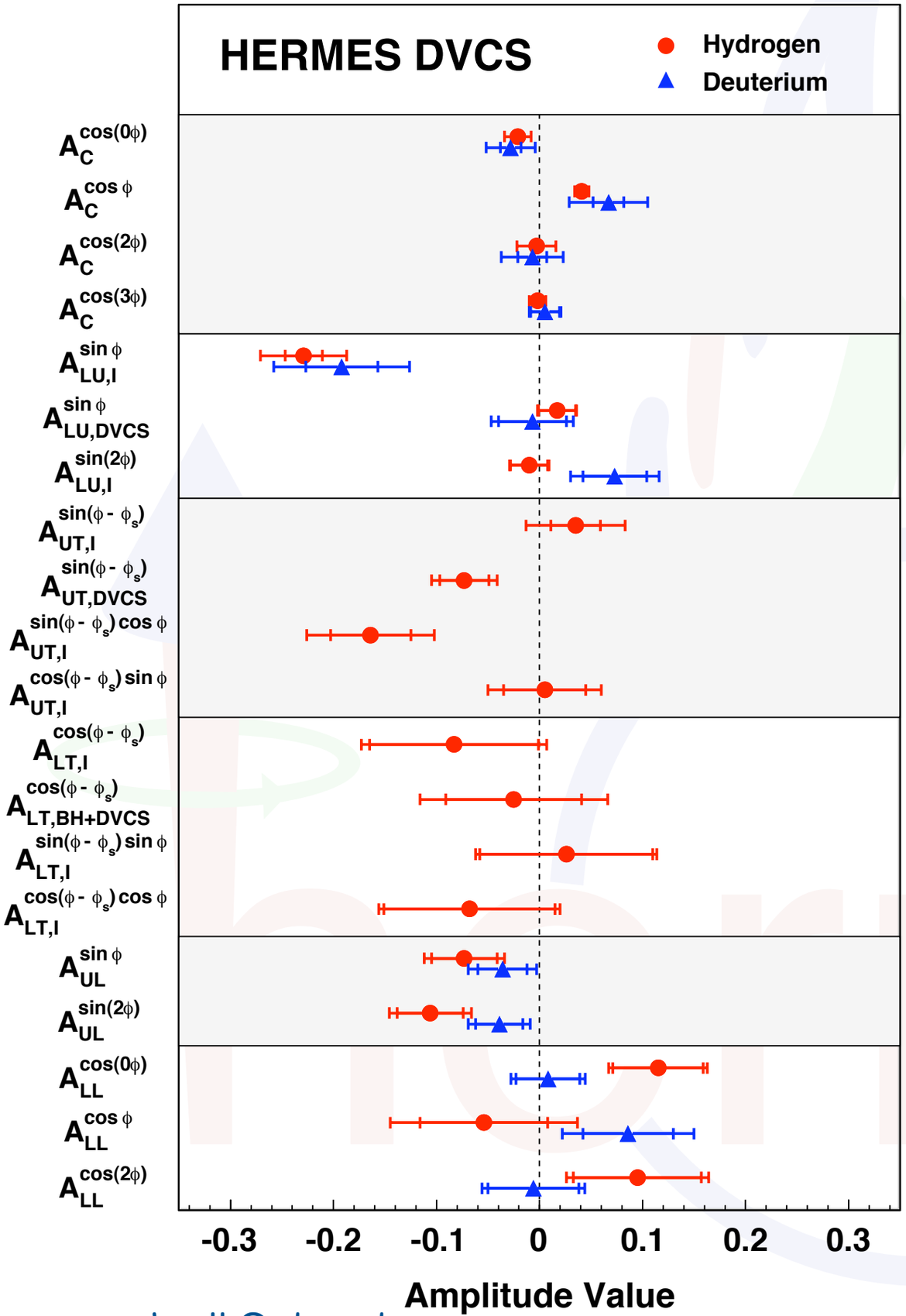
JHEP 06 (2010) 019

Double-spin asymmetry:

GPD $\tilde{H}$

NPB 842 (2011) 265

A wealth of azimuthal amplitudes



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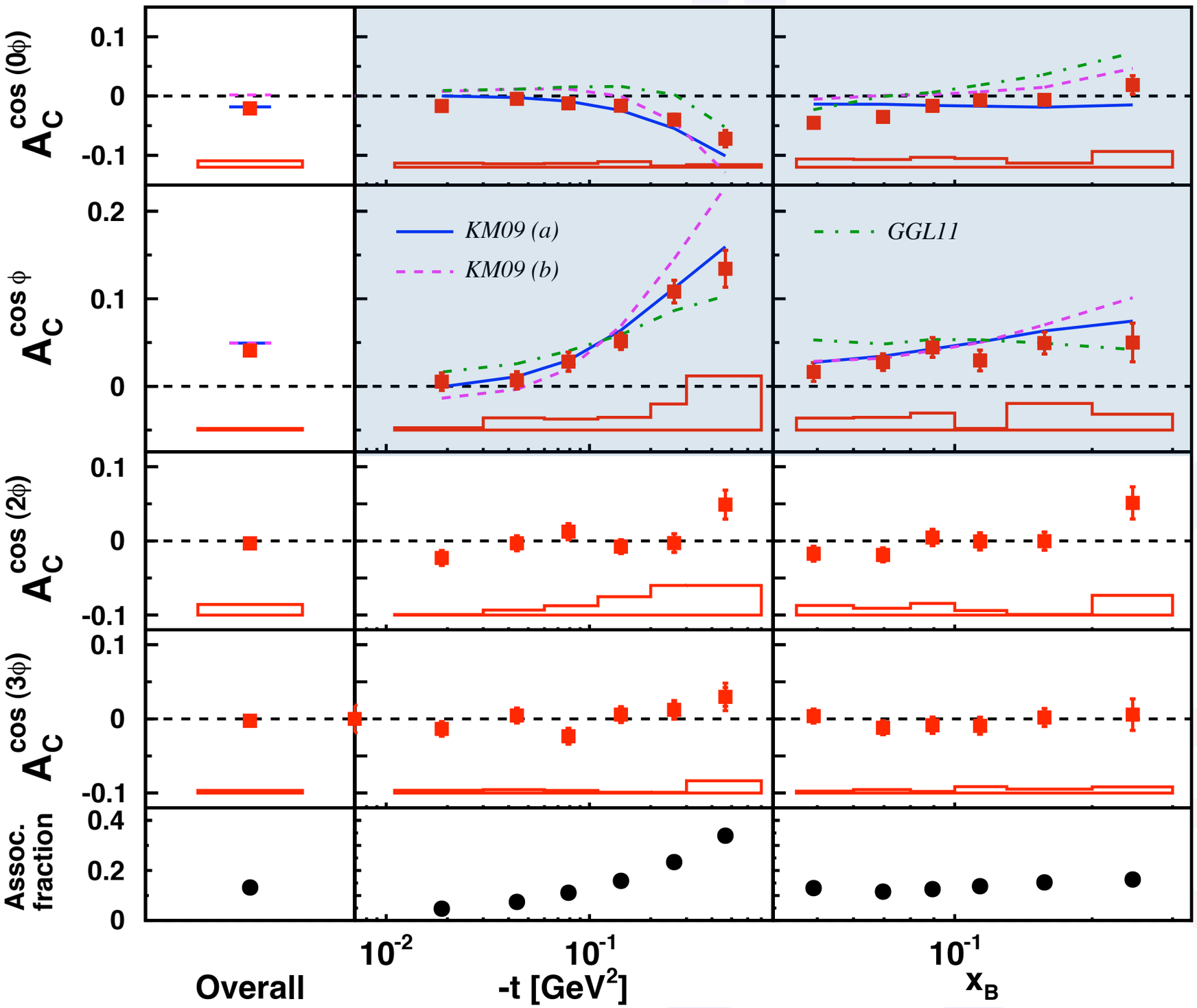
NPB 842 (2011) 265

complete data set!

Beam-charge asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



constant term:

$$\propto -A_C^{\cos\phi}$$

$$\propto \mathrm{Re}[F_1\mathcal{H}]$$

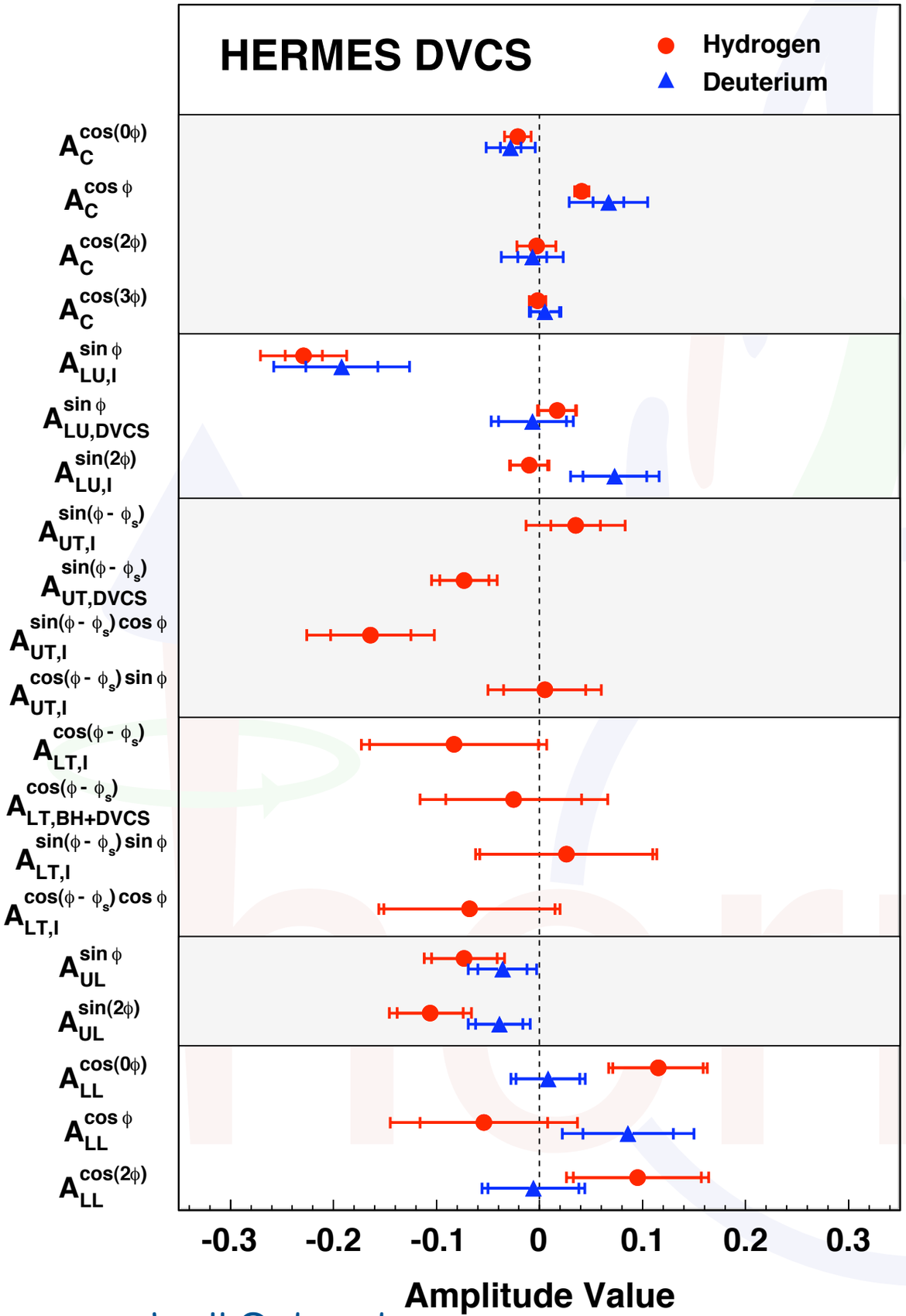
[higher twist]

[gluon leading twist]

Resonant fraction:

$$ep \to e\Delta^+\gamma$$

A wealth of azimuthal amplitudes



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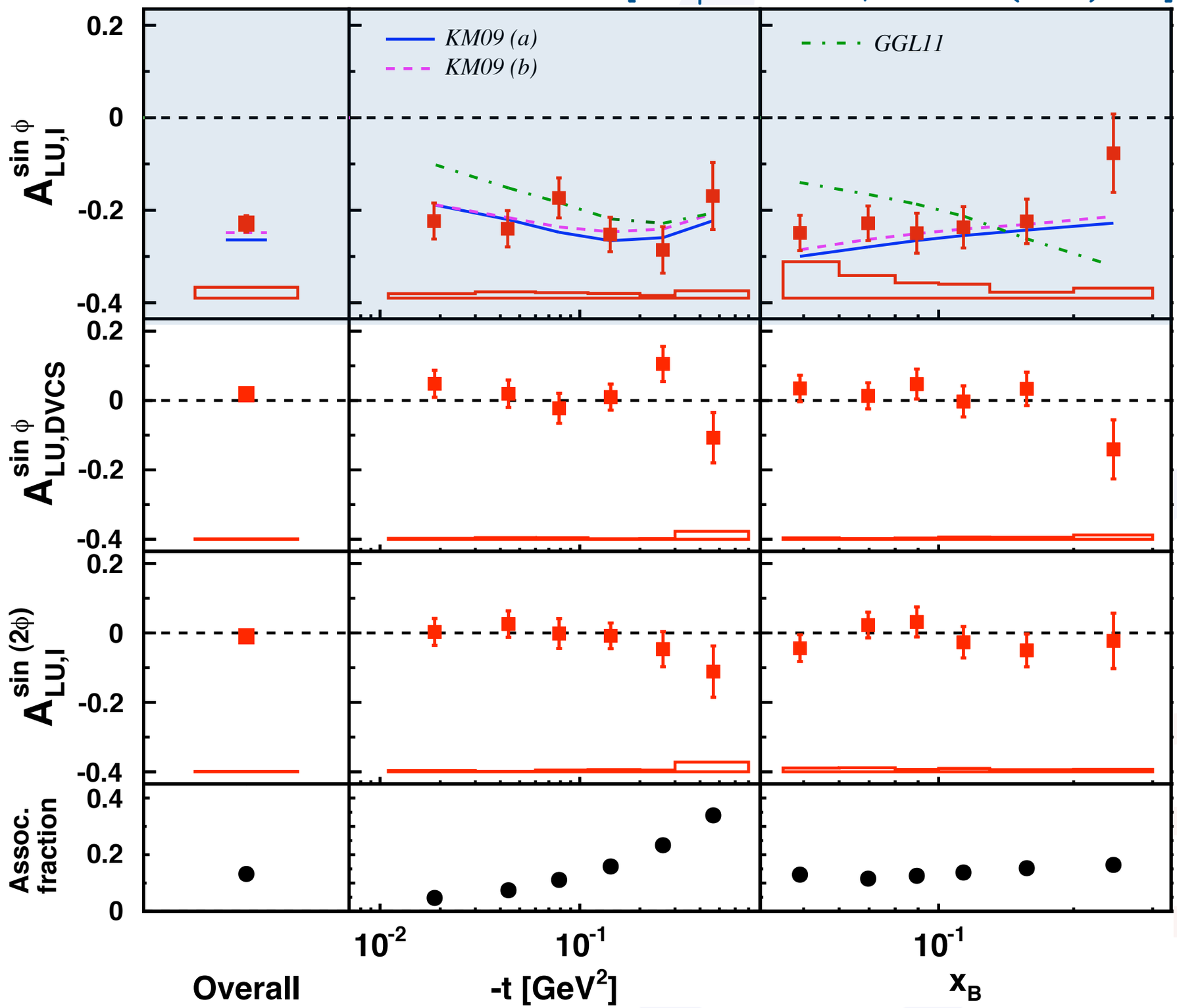


$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

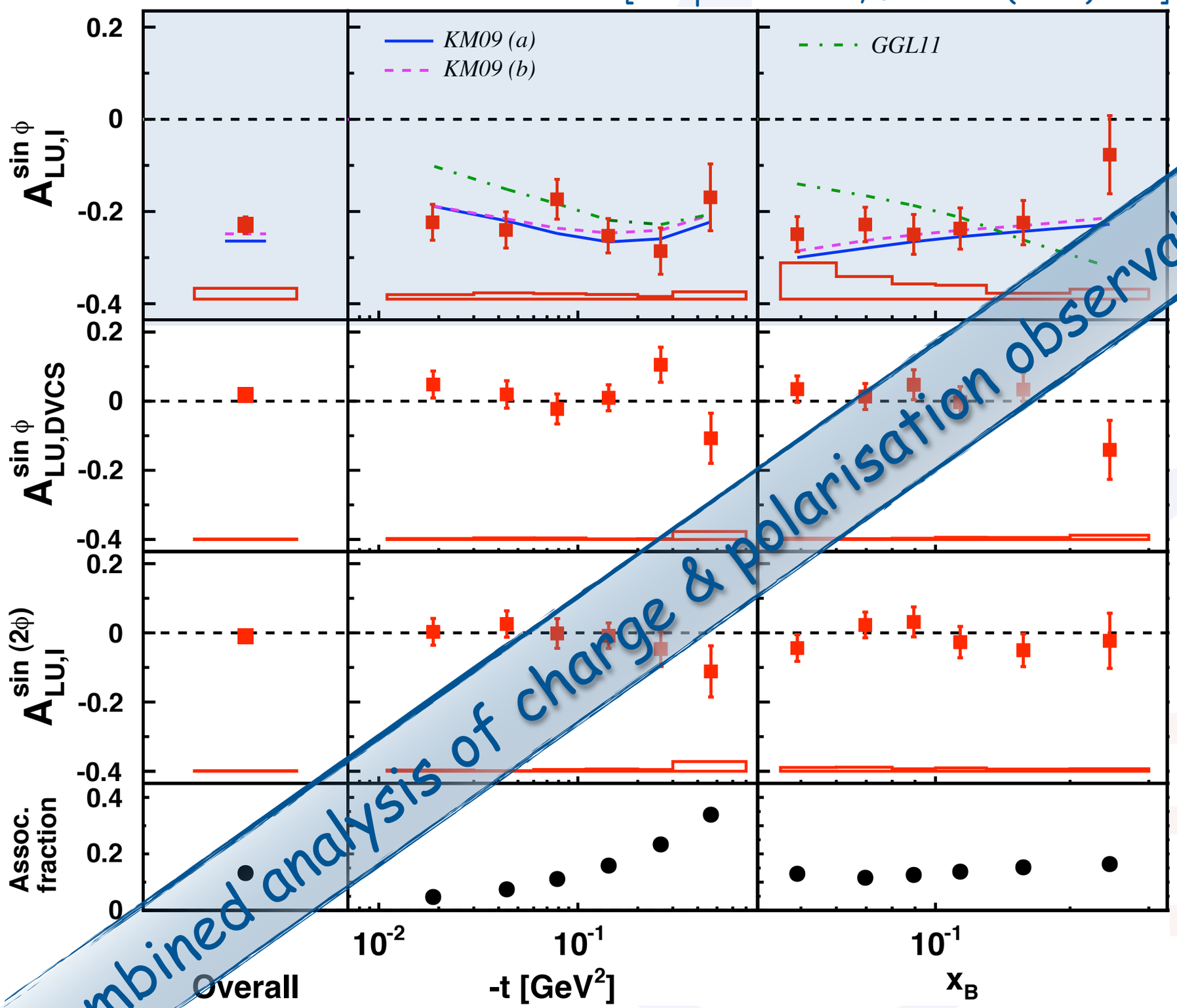
Resonant fraction:

$ep \to e\Delta^+\gamma$

complete data set!

Beam-spin asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



combined analysis of charge & polarisation observables unique to HERA!

$\propto \mathrm{Im}[F_1\mathcal{H}]$

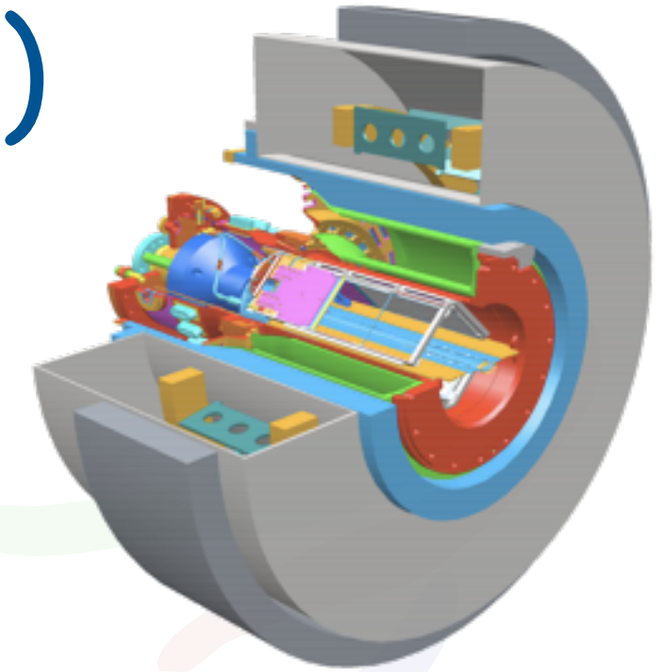
[higher twist]

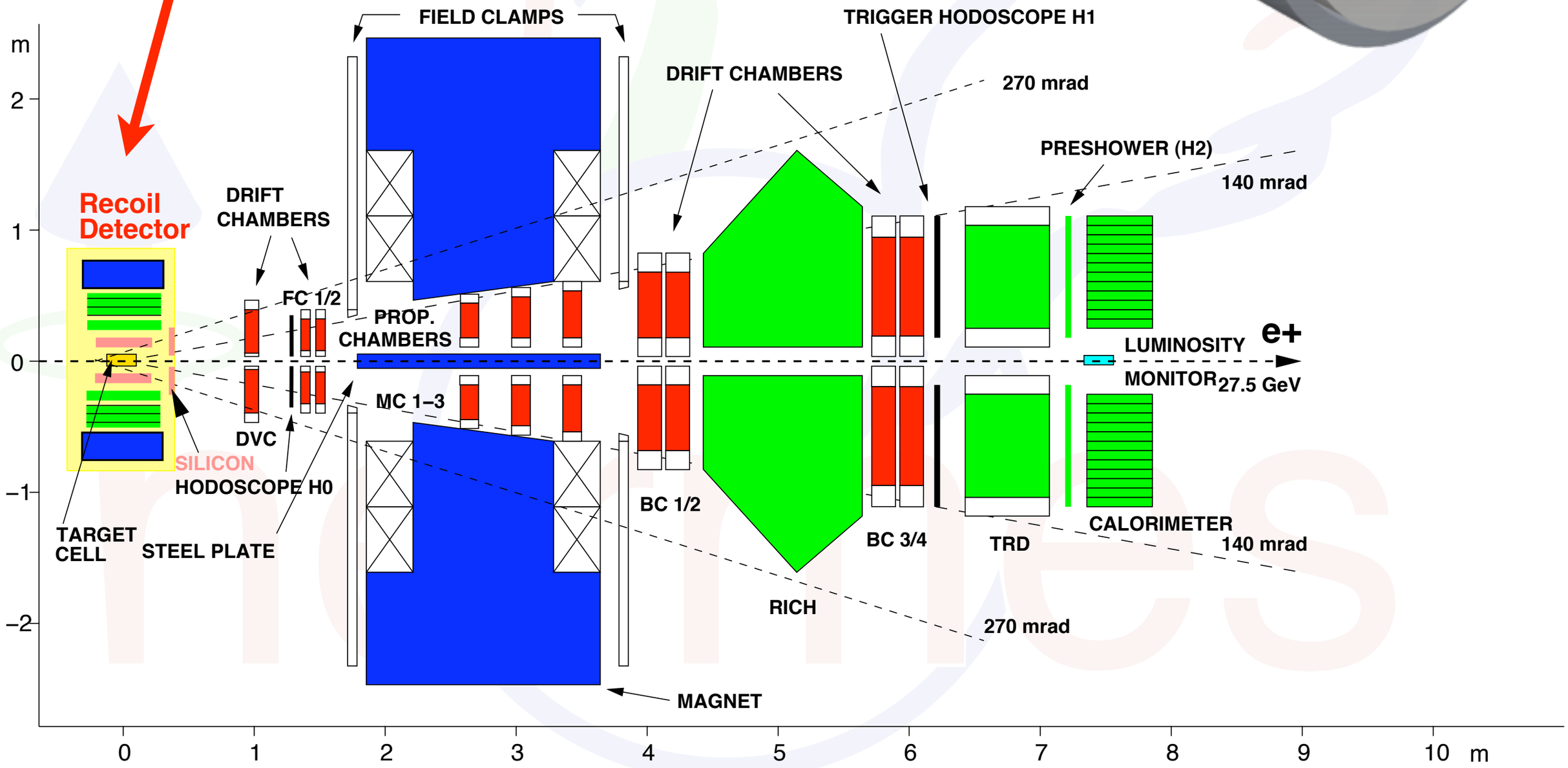
Resonant fraction:

$$ep \to e\Delta^+\gamma$$

HERMES detector (2006/07)

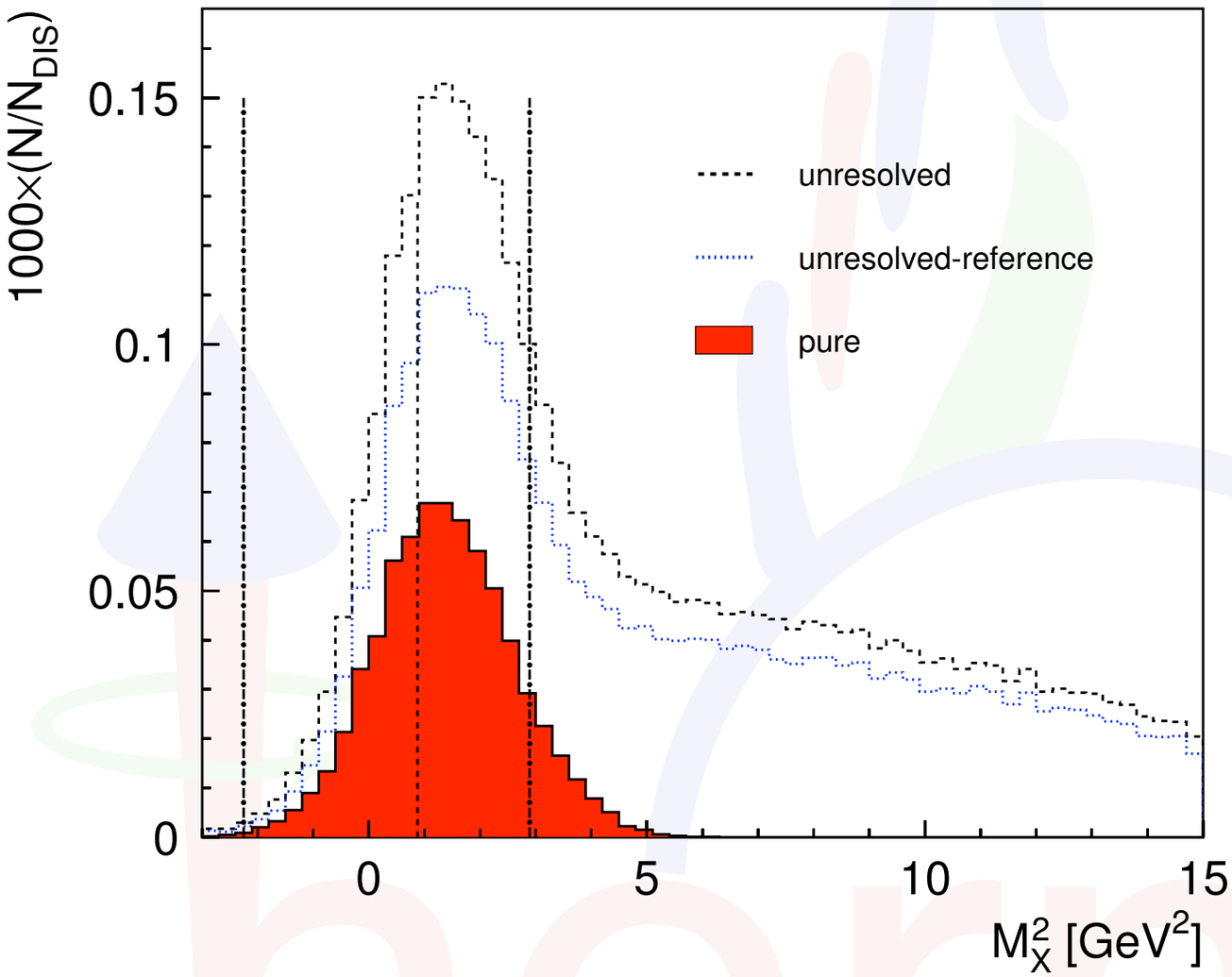
detection of
recoiling proton

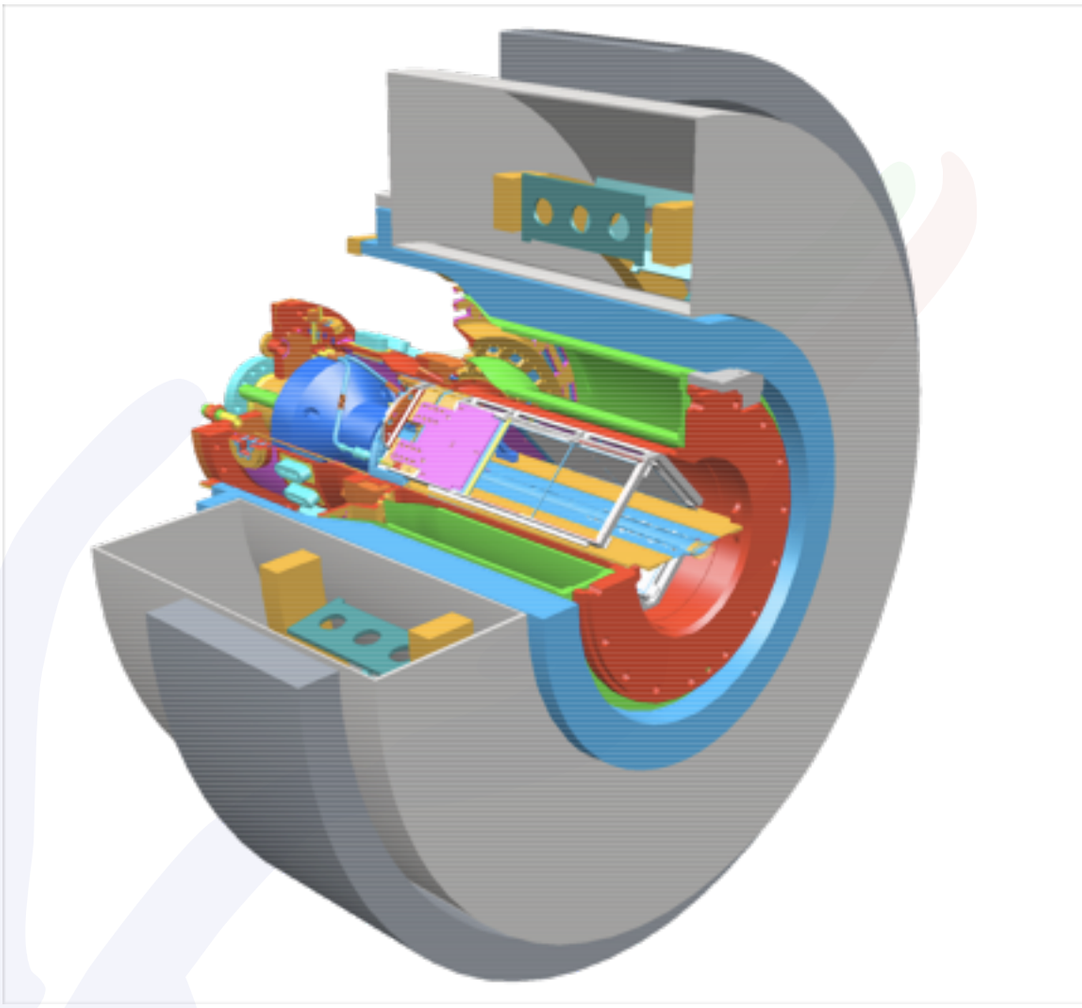




HERMES detector (2006/07)

kinematic fitting

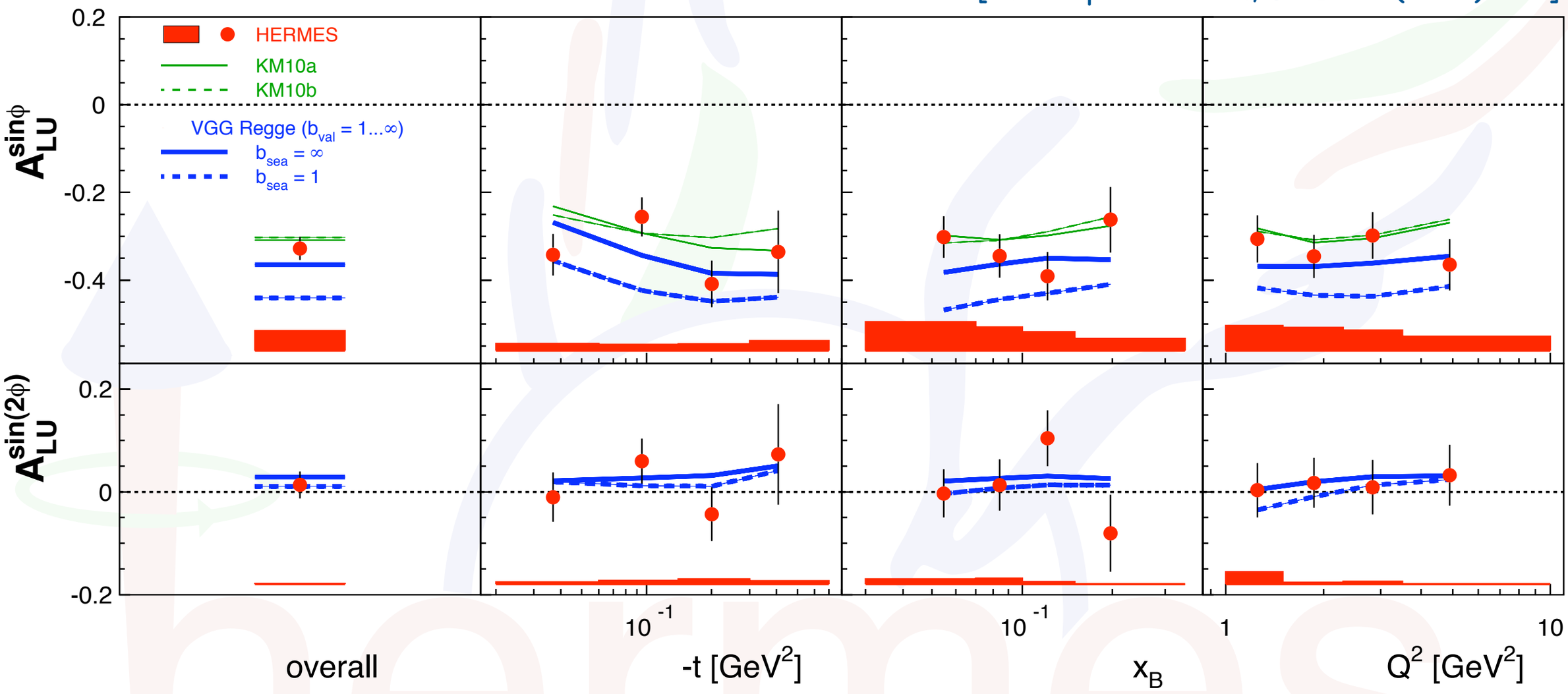




- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS ($ep \to ep\gamma$) with high efficiency (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

DVCS with recoil detector

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

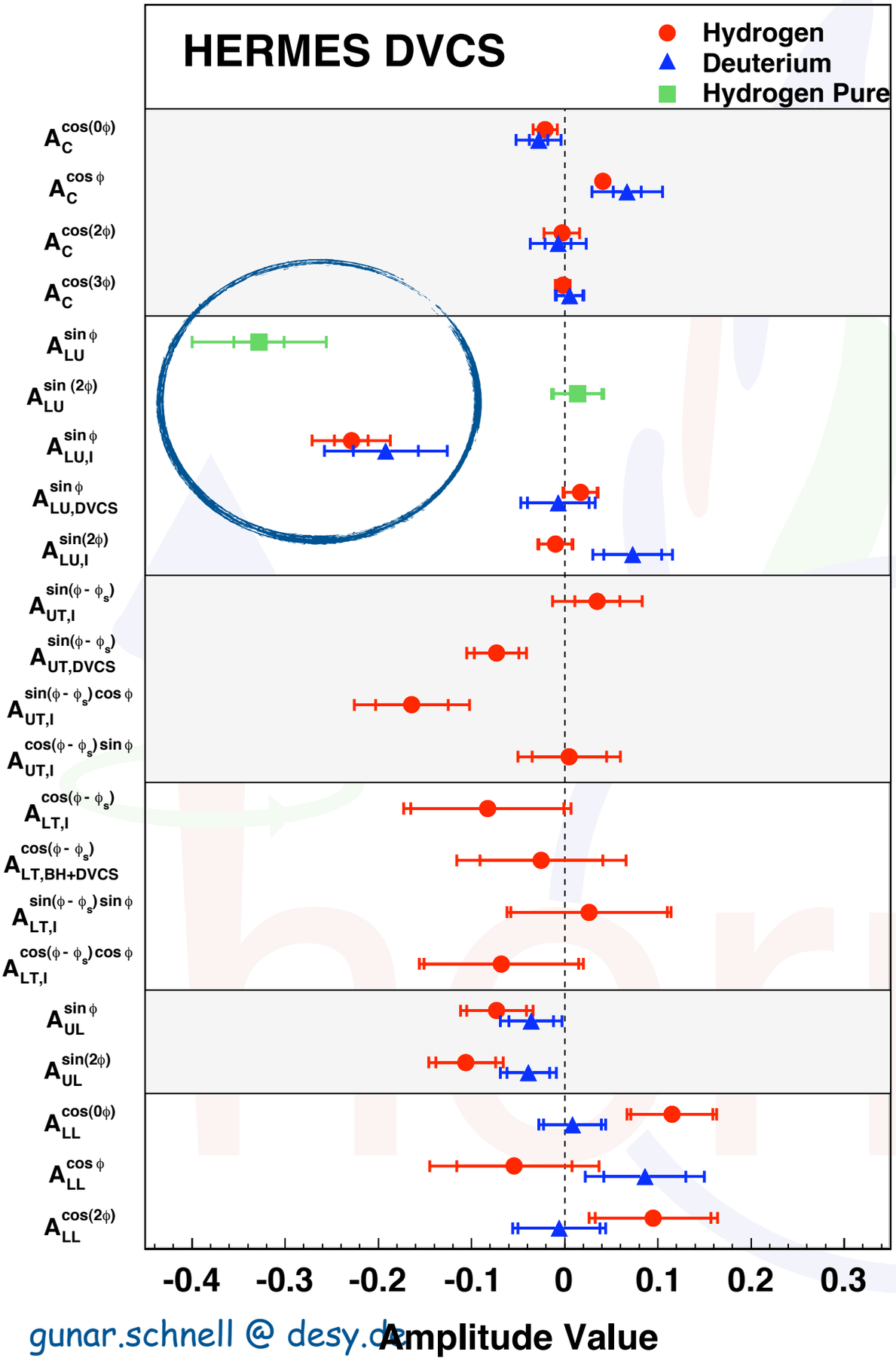


good agreement with models

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

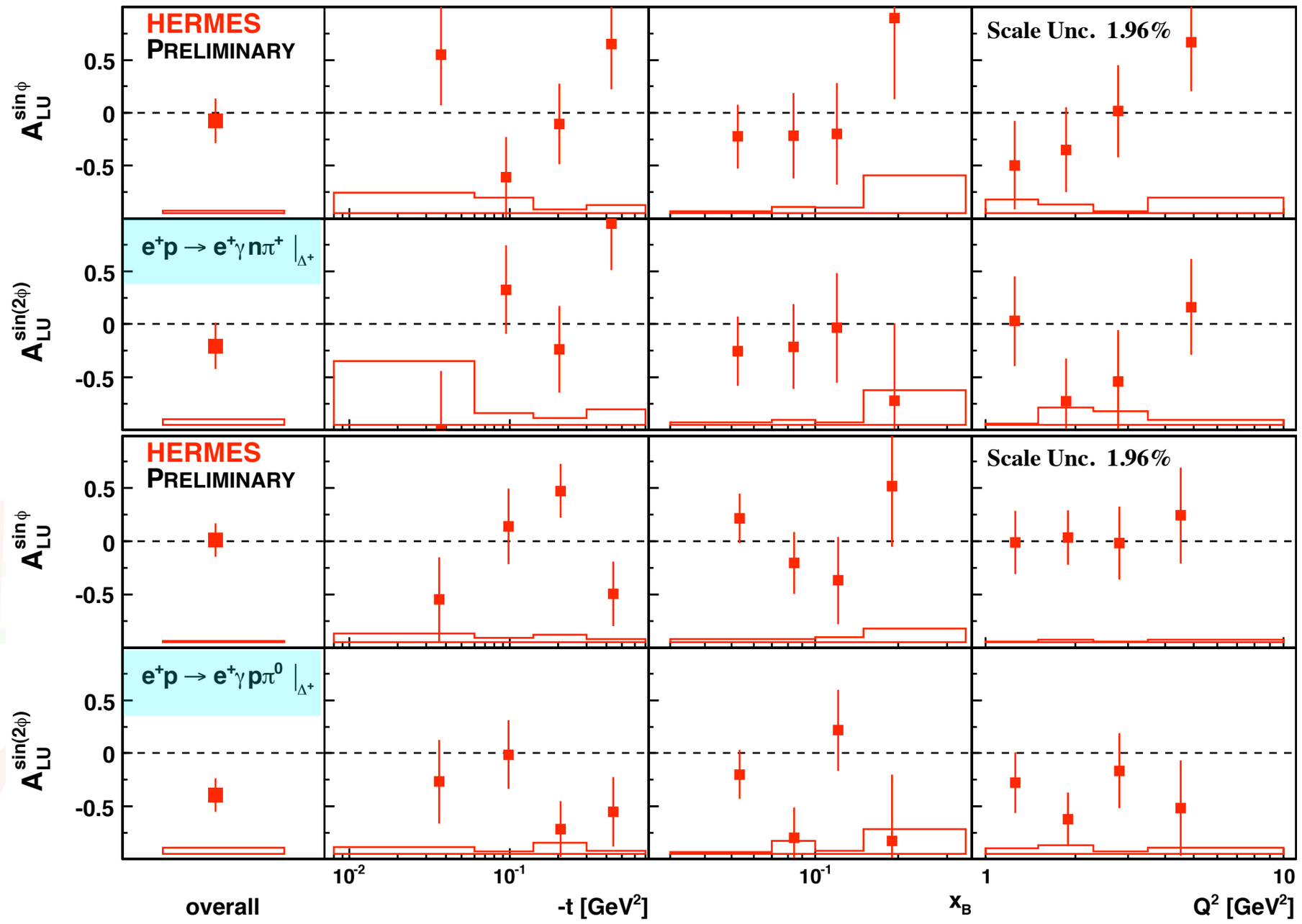


indication of larger amplitudes for pure sample

(-> assoc. DVCS in "traditional" analysis mainly dilution)

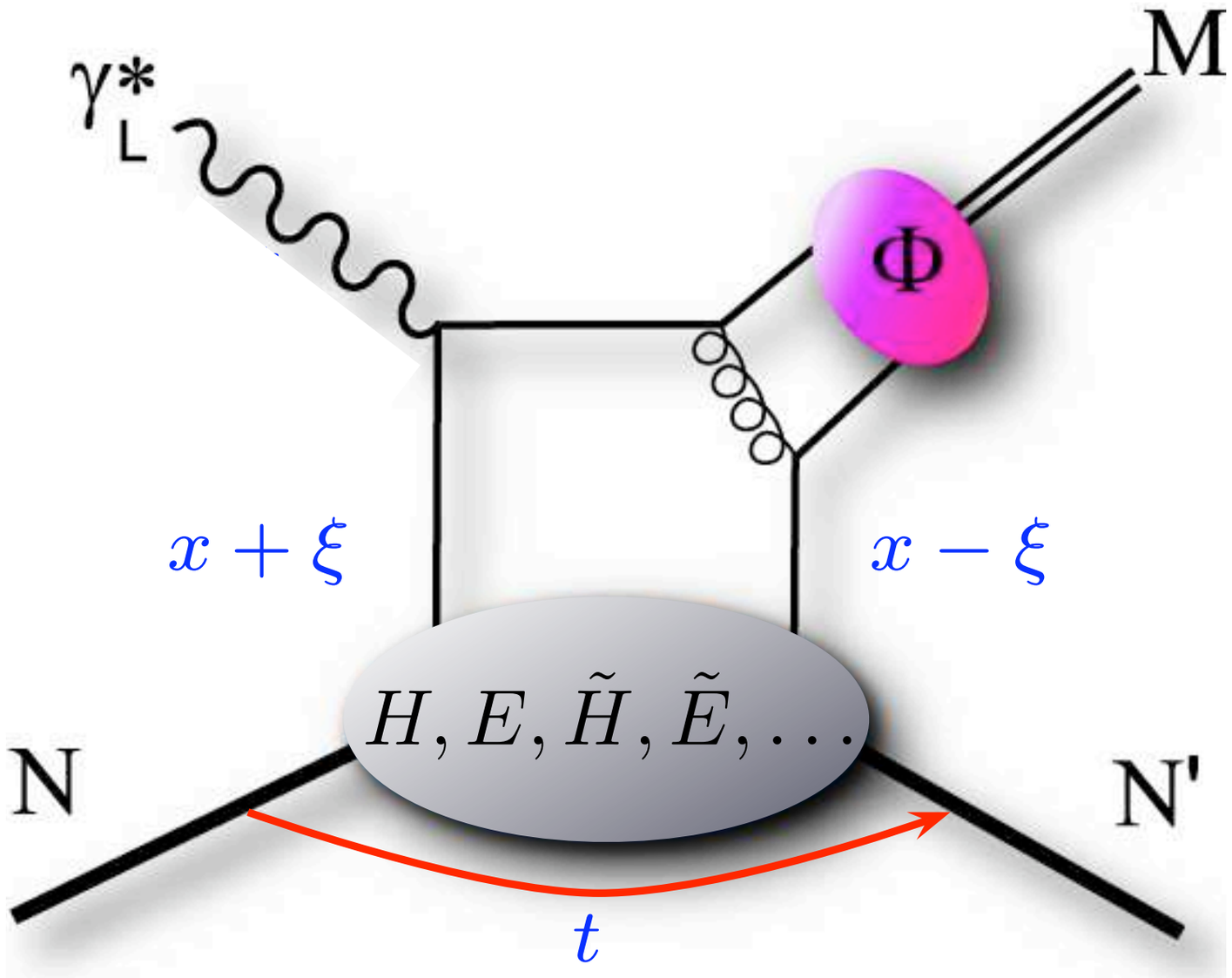
basically no contamination
-> clean interpretation

Associated DVCS with recoil detector



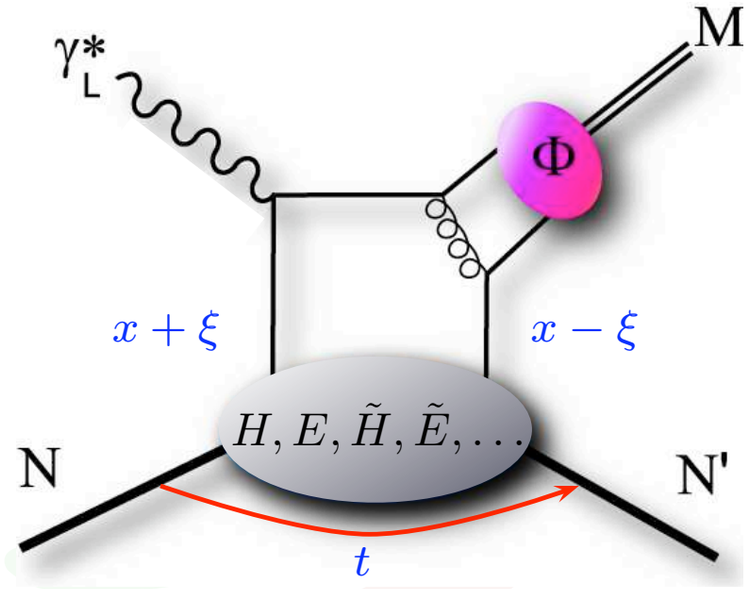
- asymmetry amplitudes consistent with zero
- consistent with pure DVCS results (e.g., dilution in traditional analysis)

Exclusive meson production



Exclusive meson production

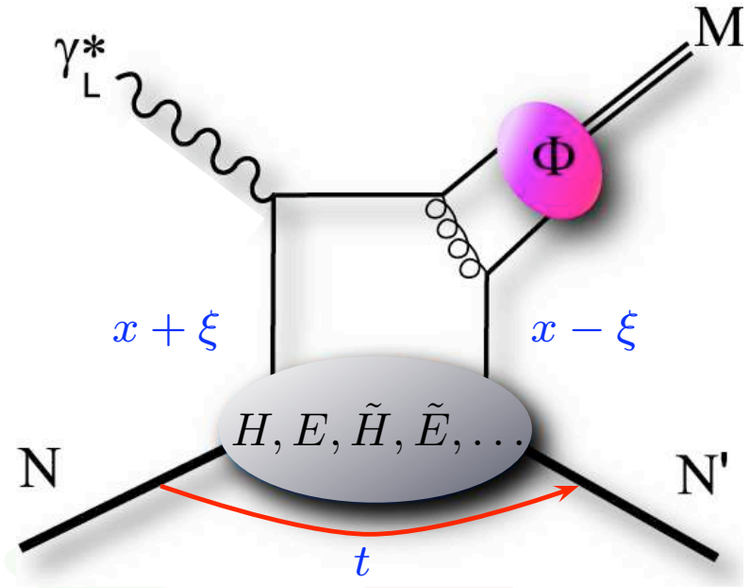
- GPDs convoluted with meson amplitude



π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

Exclusive meson production

- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations



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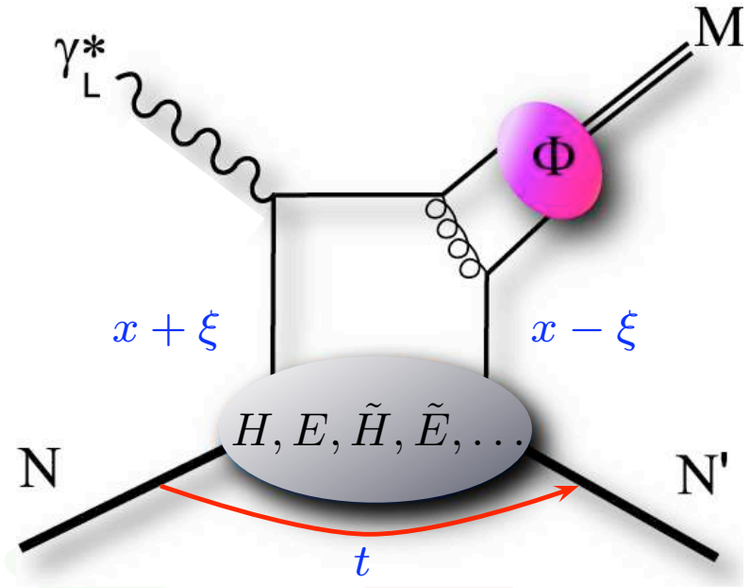

- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
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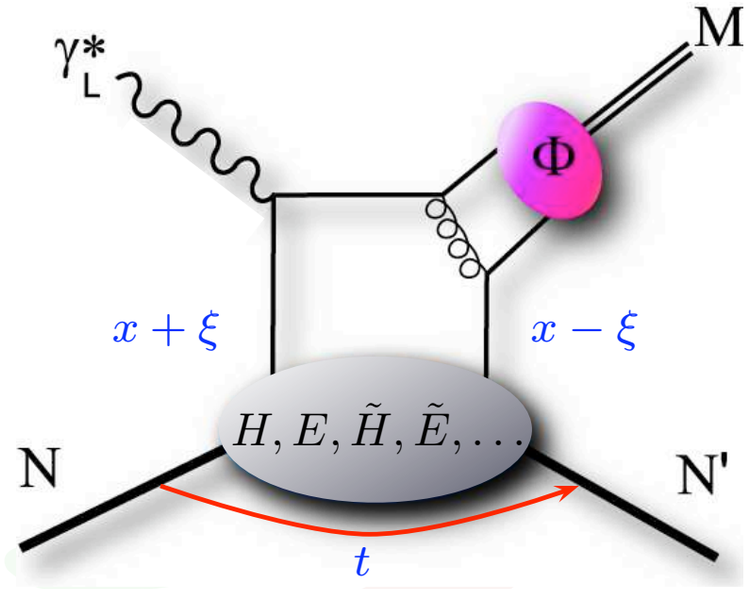

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J/ψ	g

- vector-meson cross section:

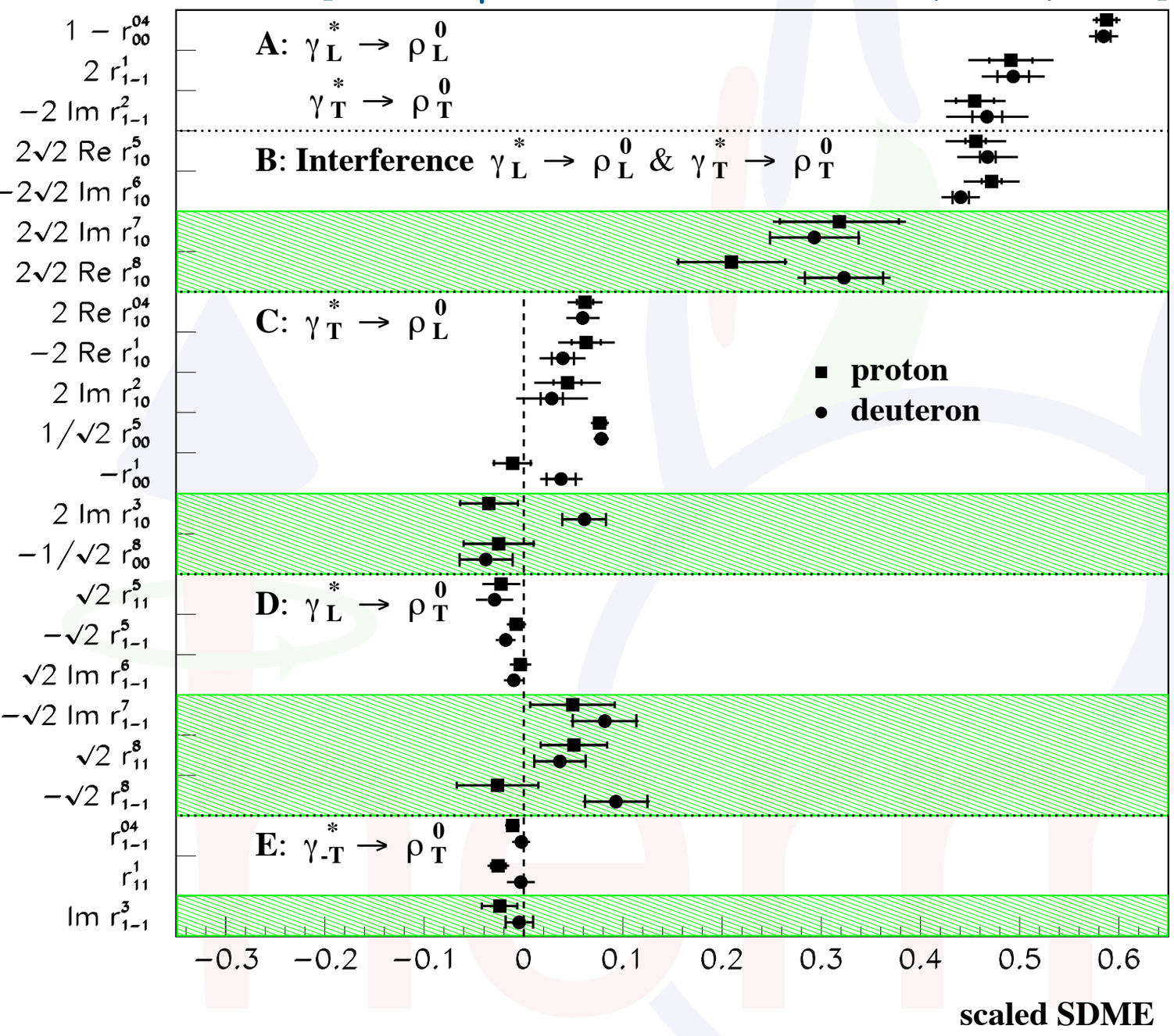
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi_S\,\mathrm{d}\phi\,\mathrm{d}\cos\theta\,\mathrm{d}\varphi} = \frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t} W(x_B, Q^2, t, \phi_S, \phi, \cos\theta, \varphi)$$

$$W = W_{UU} + P_B W_{LU} + S_L W_{UL} + P_B S_L W_{LL} + S_T W_{UT} + P_B S_T W_{LT}$$

look at various angular (decay) distributions to study helicity transitions ("spin-density matrix elements")

ρ^0 SDMEs from HERMES

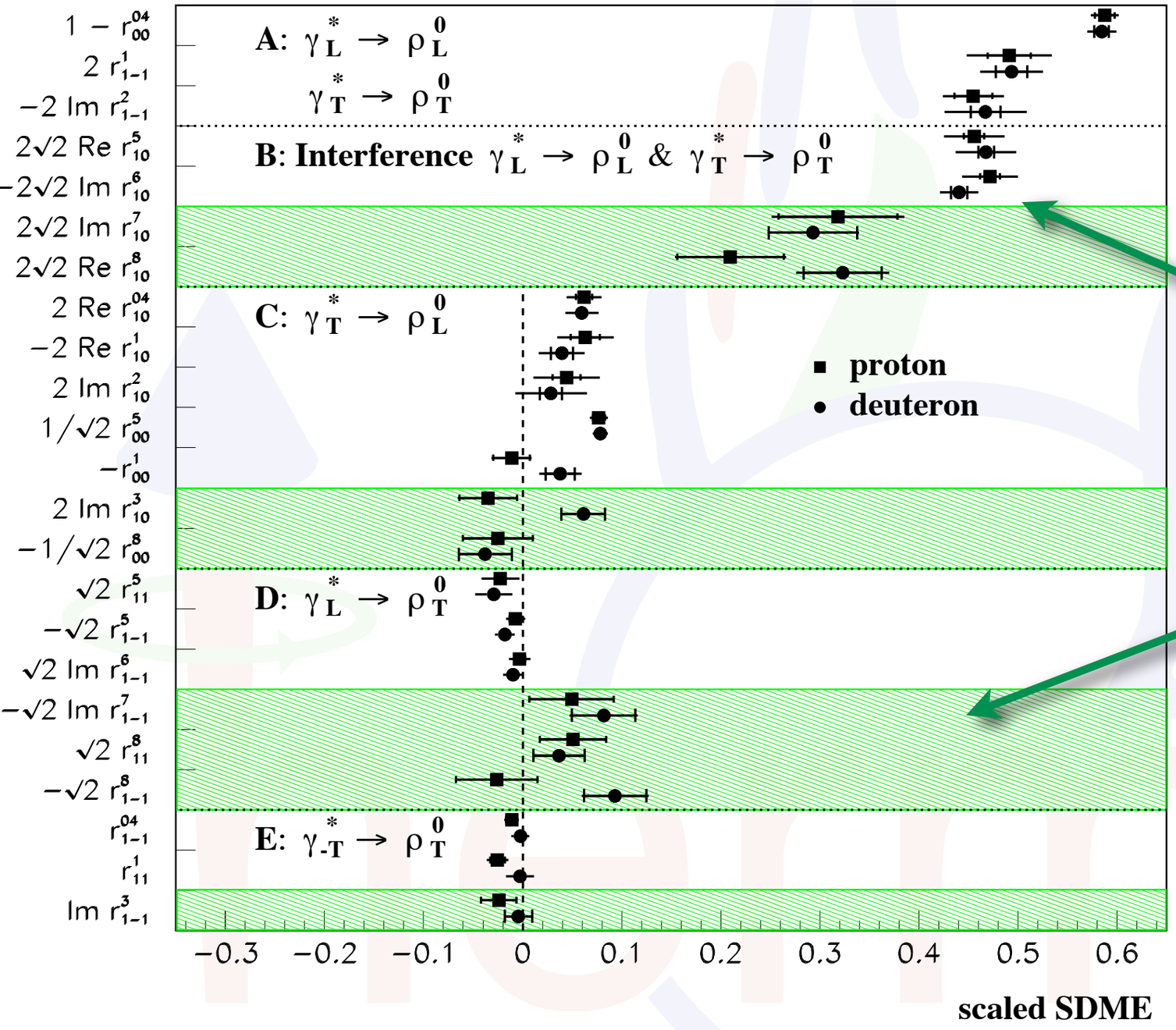
[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]

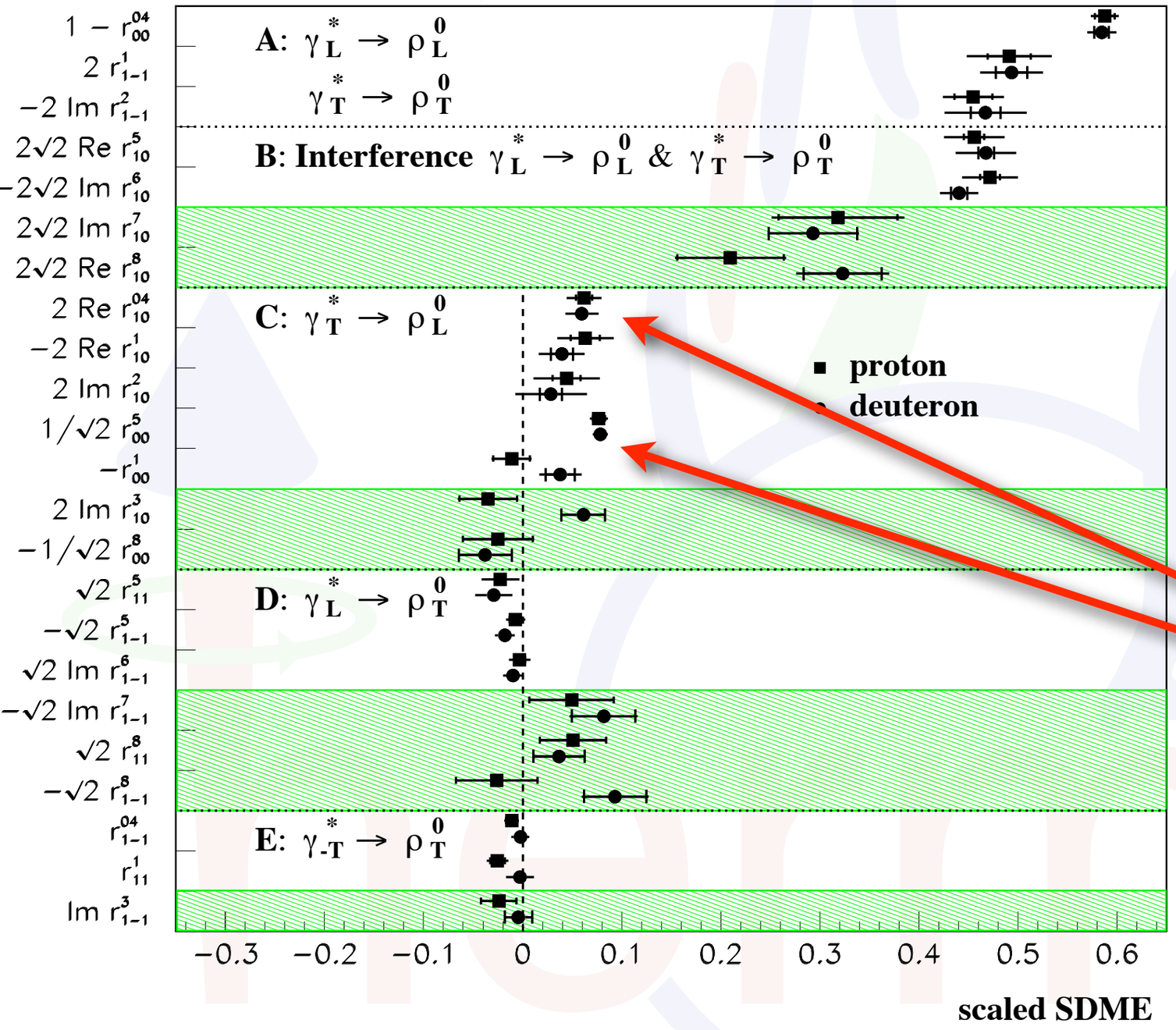


helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]

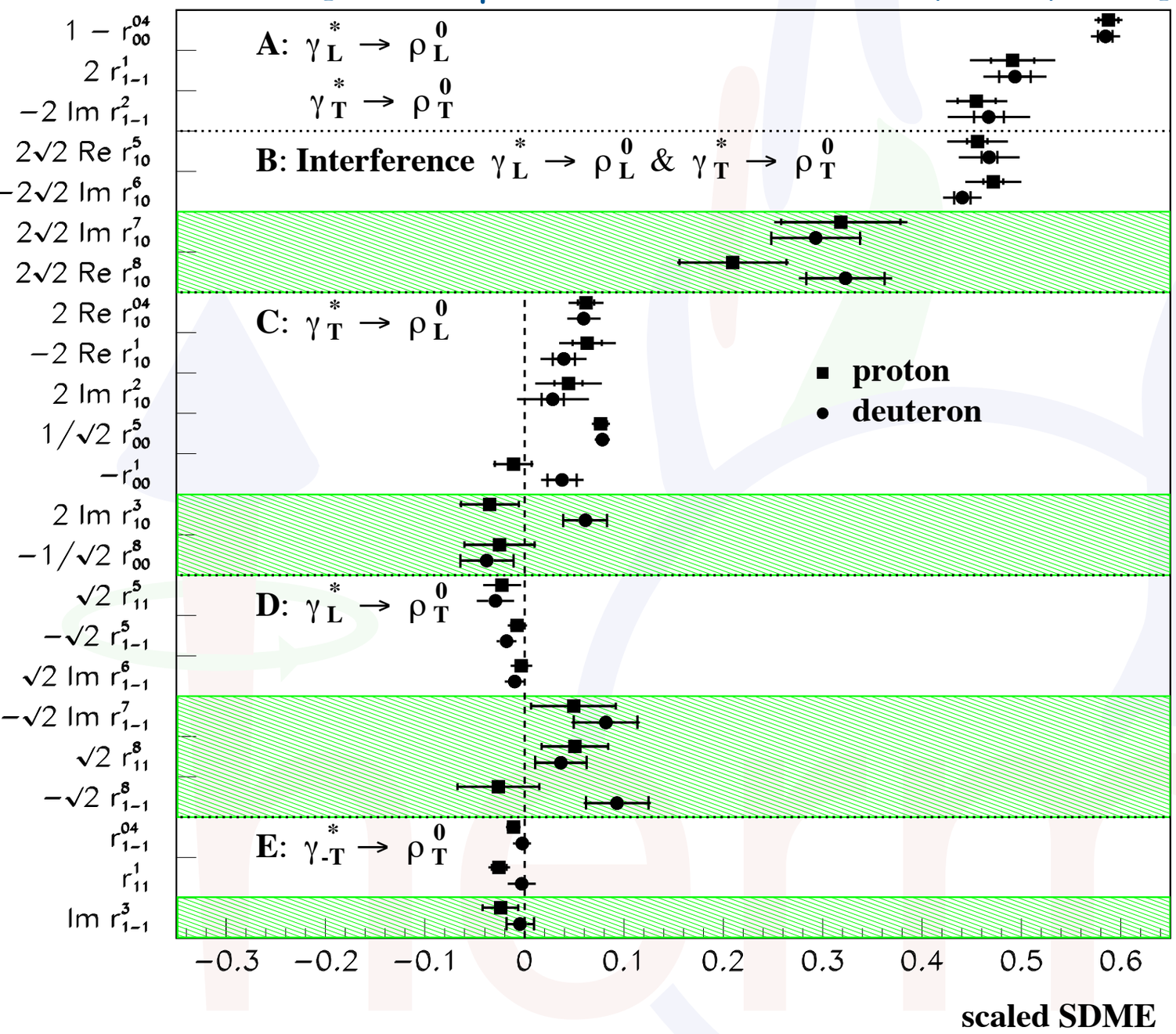


clear breaking of s-channel helicity conservation

target-polarization independent SDMEs

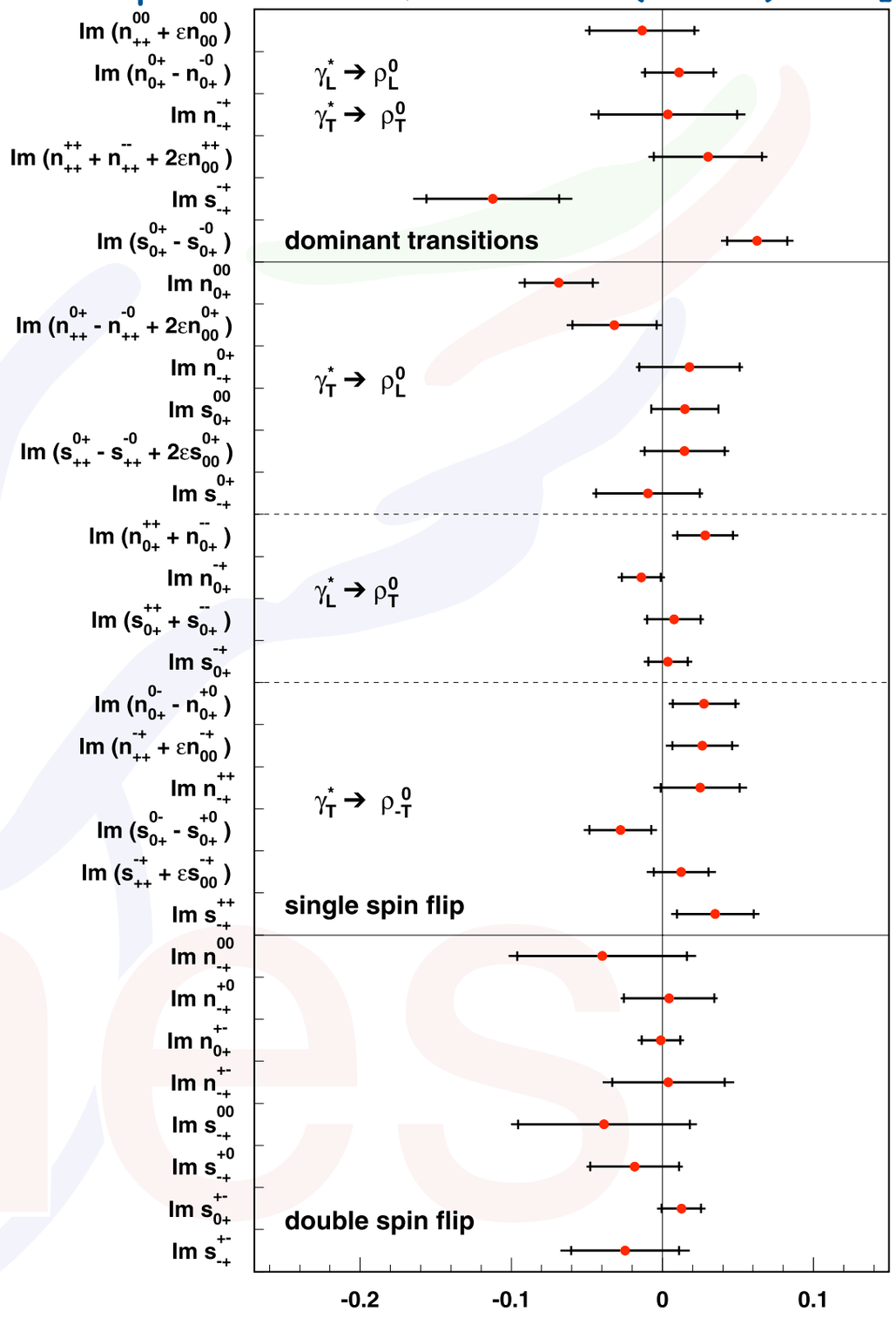
ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

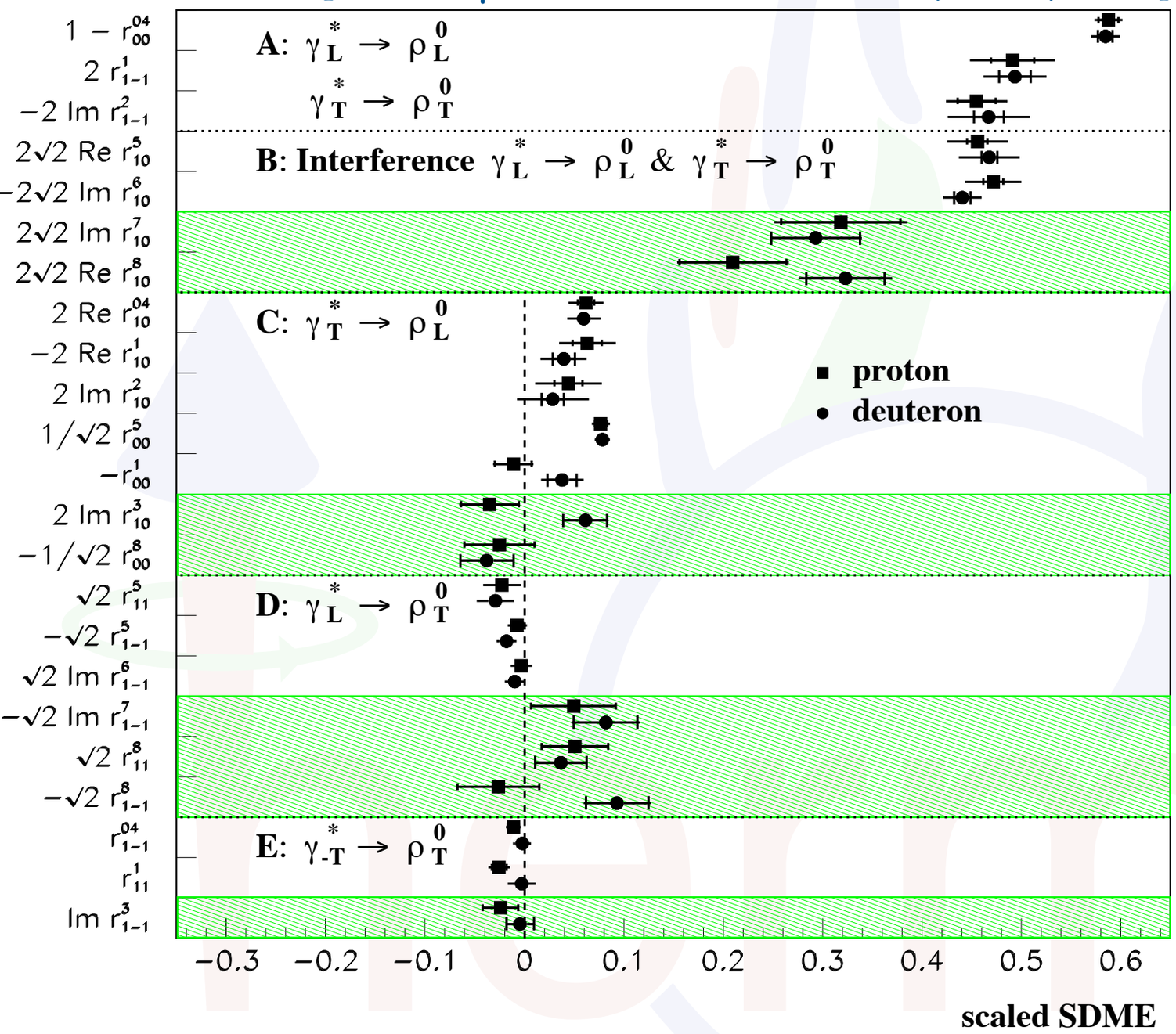
[A. Airapetian et al., PLB 679 (2009) 100]



"transverse" SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]



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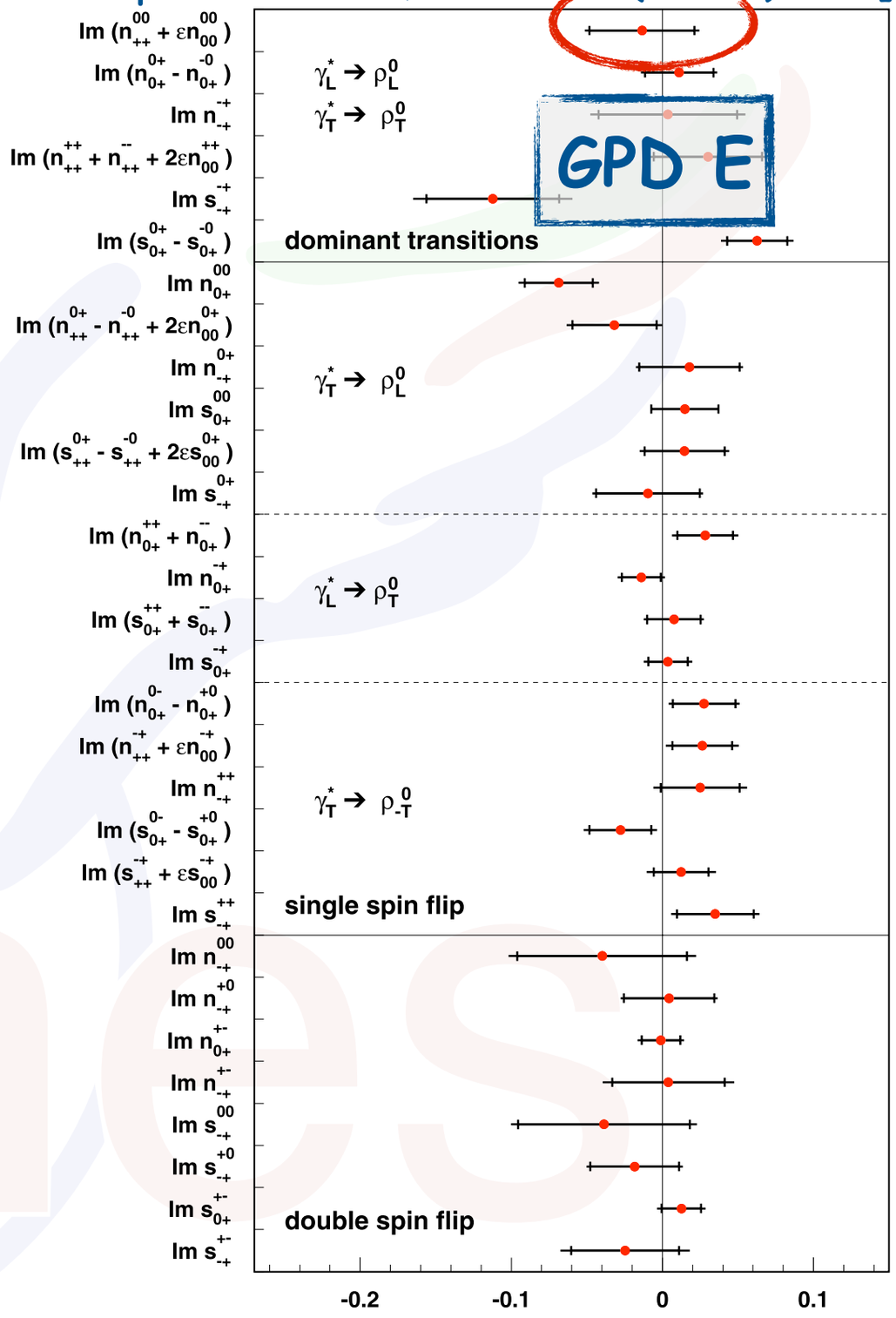
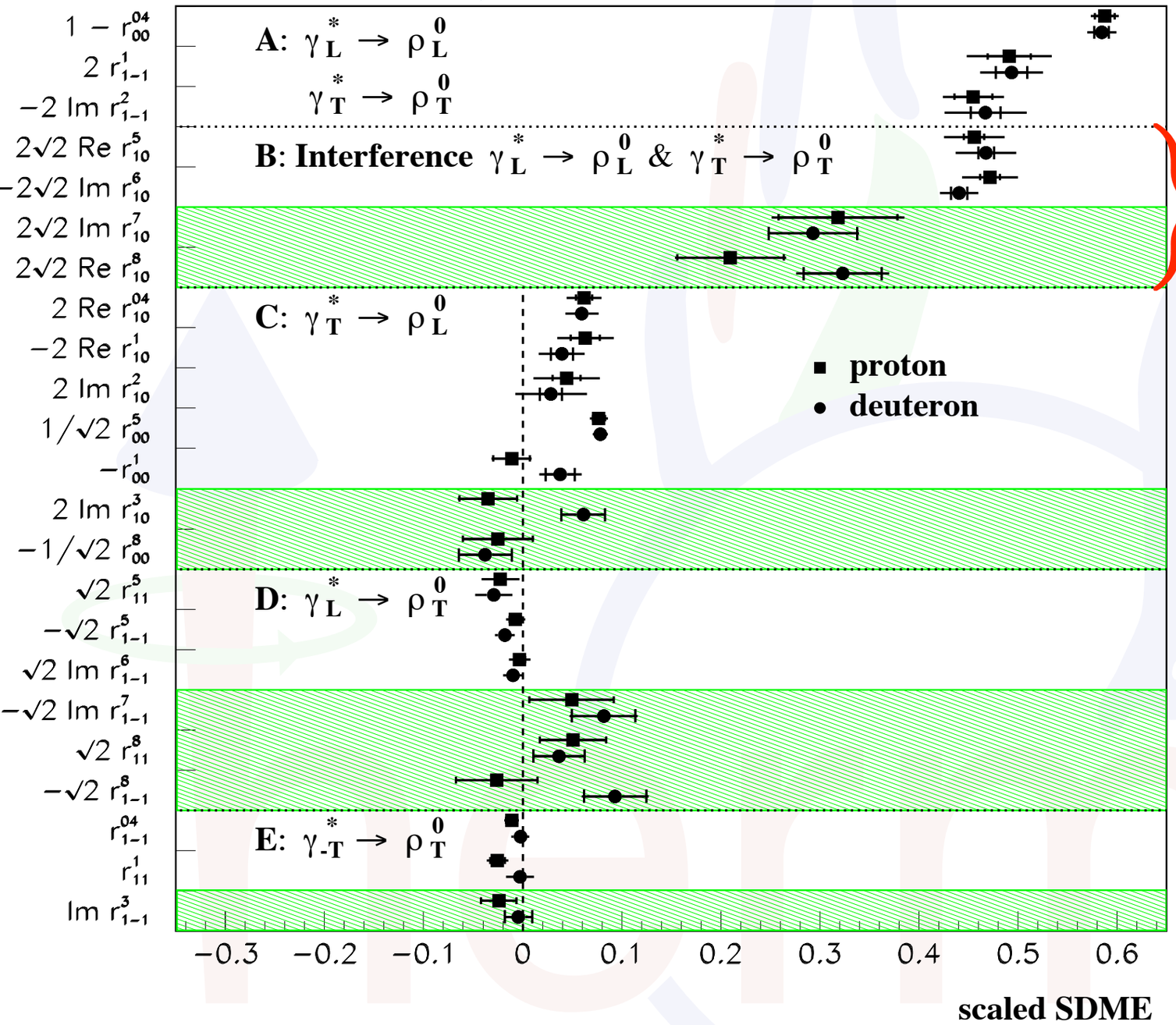
[A. Airapetian et al., PLB 679 (2009) 100]



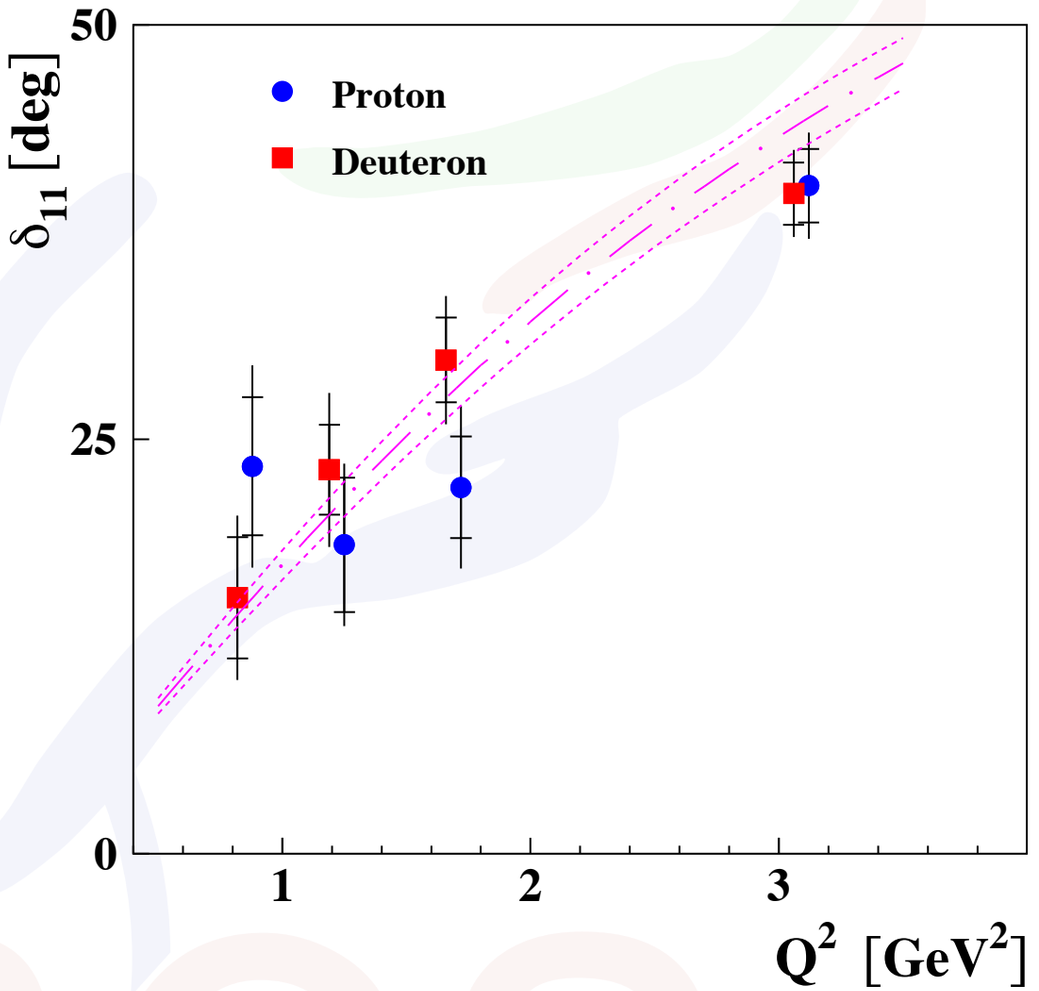
"transverse" SDMEs

ρ^0 SDMEs from HERMES: challenges

[A. Airapetian et al., EPJ C62 (2009) 659]

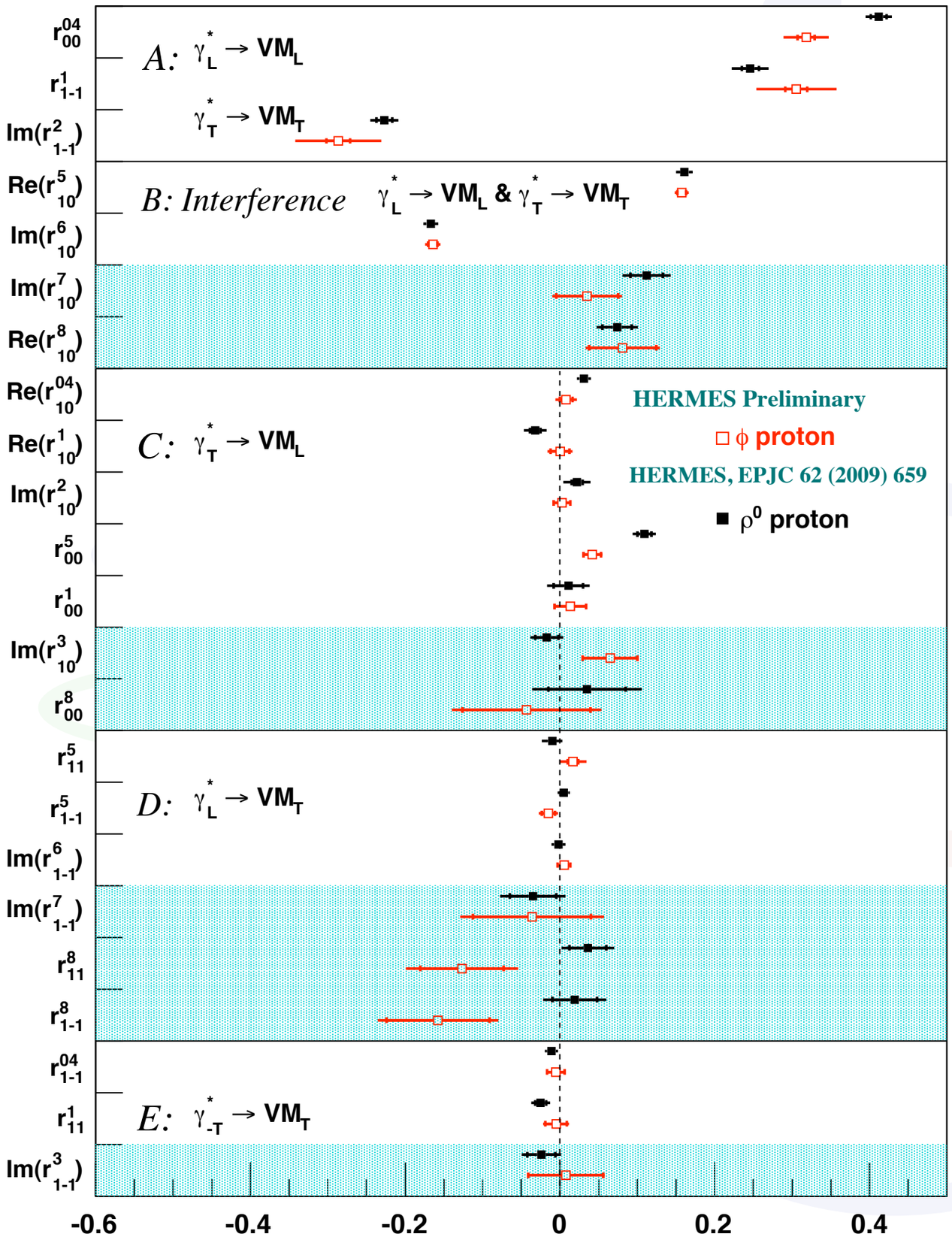


[A. Airapetian et al, EPJ C71 (2011) 1609]



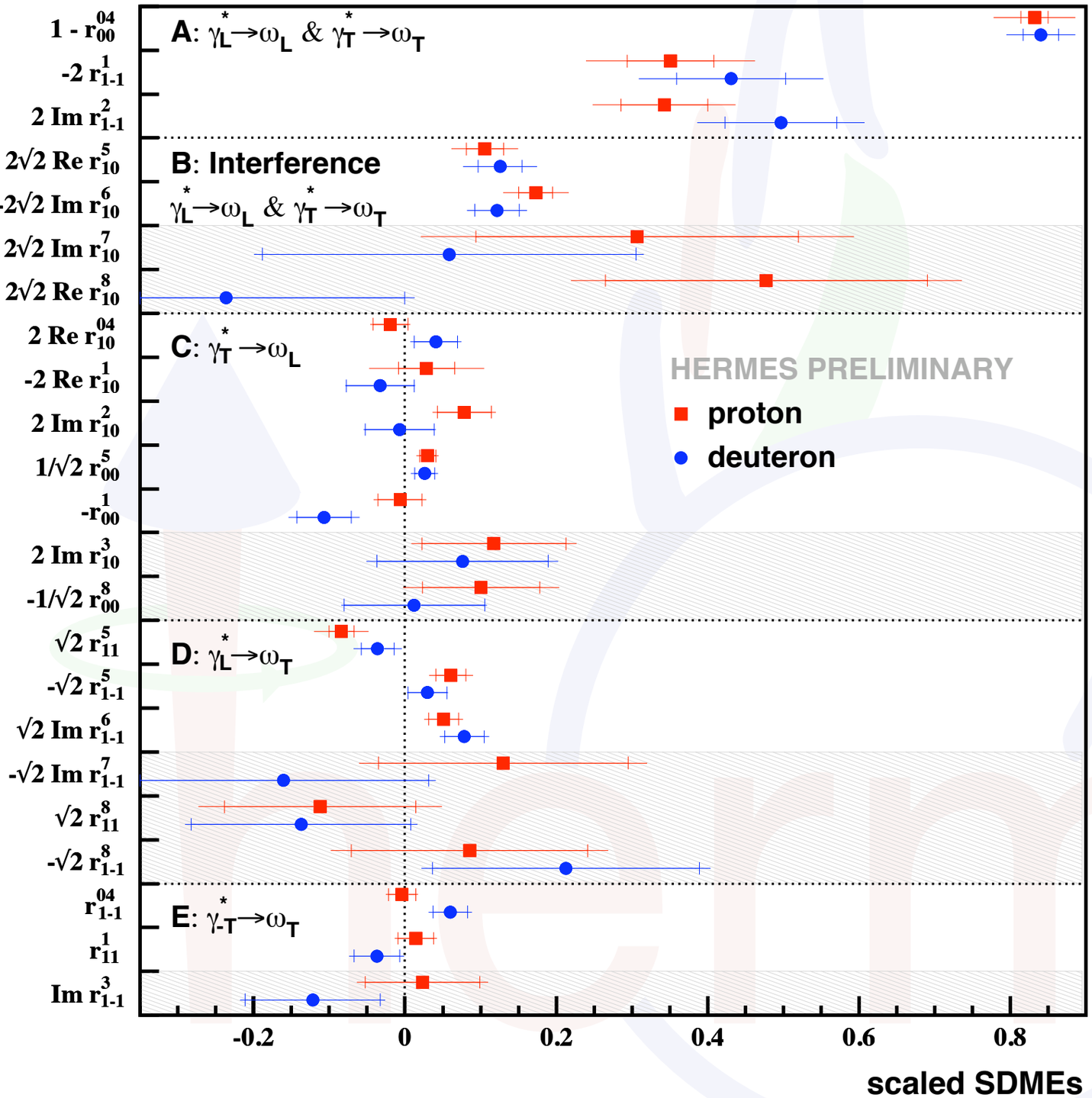
Extraction of SDMEs and helicity amplitude ratios at HERMES for ρ mesons challenges GPD-based calculations (giving small values)

ρ^0 and ϕ production



- similar for both phi and rho production: helicity-conserving SDMEs dominate
- hardly any violation of SCHC observed for phi while some indication for rho production
- also here: large interference effects

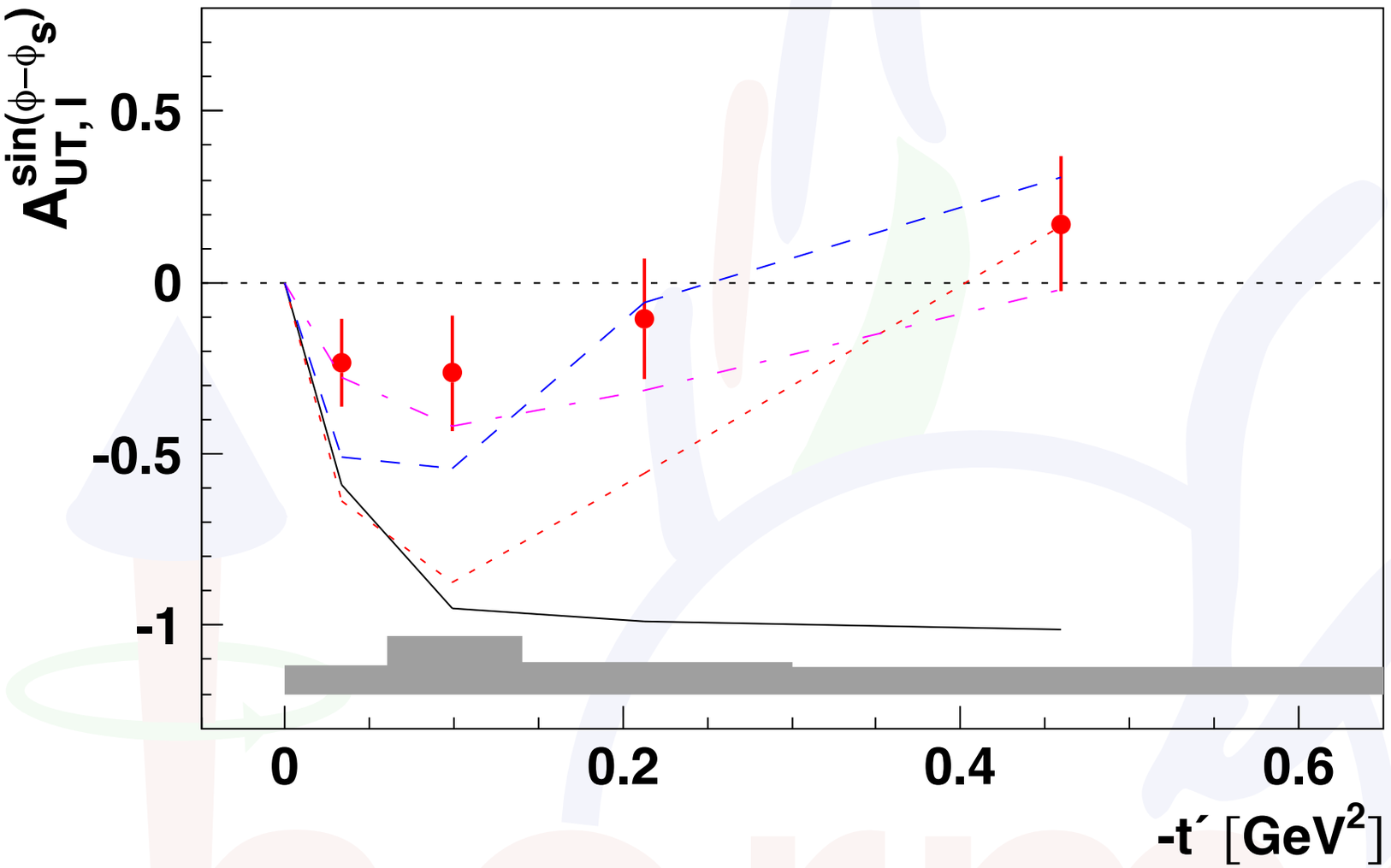
… ω production



- helicity-conserving SDMEs dominate
- hardly any violation of SCHC
- interference smaller than for phi and rho

Exclusive π^+ production

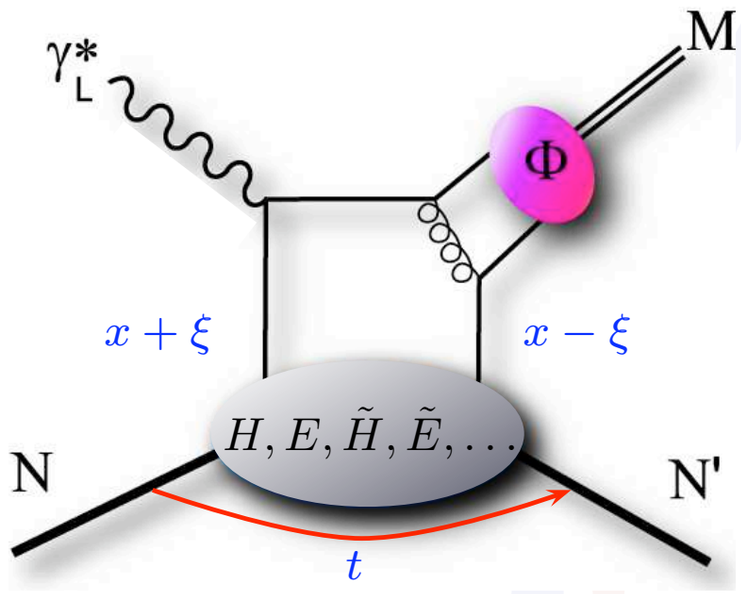
[A. Airapetian et al, PLB 682 (2010) 345]



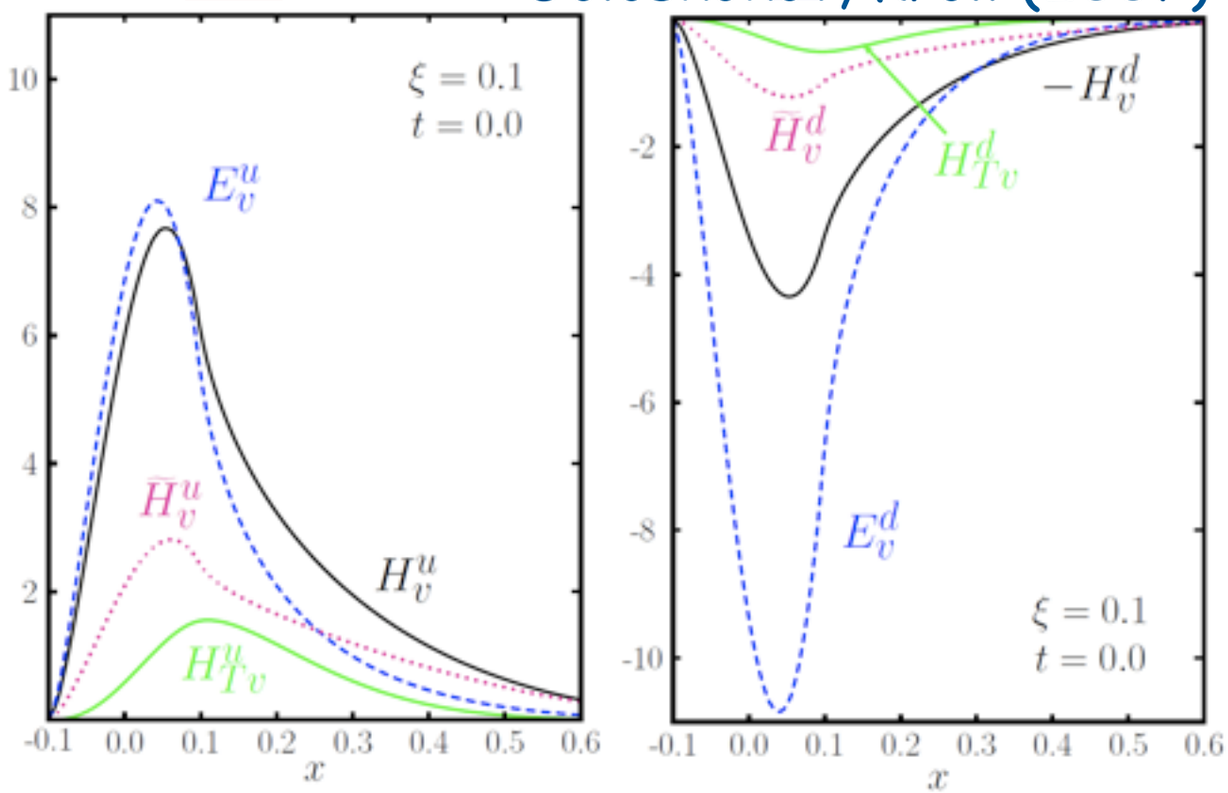
transverse target spin asymmetry

meson data can also play a vital role in accessing the "polarised" GPDs, e.g., $\tilde{H}$ and $\tilde{E}$

GPDs - a nice success story!



Goloskokov, Kroll (2007)



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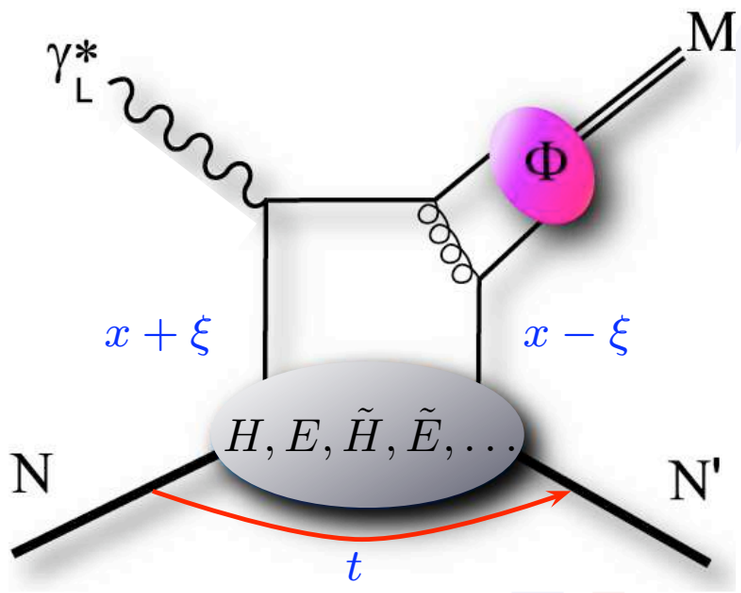
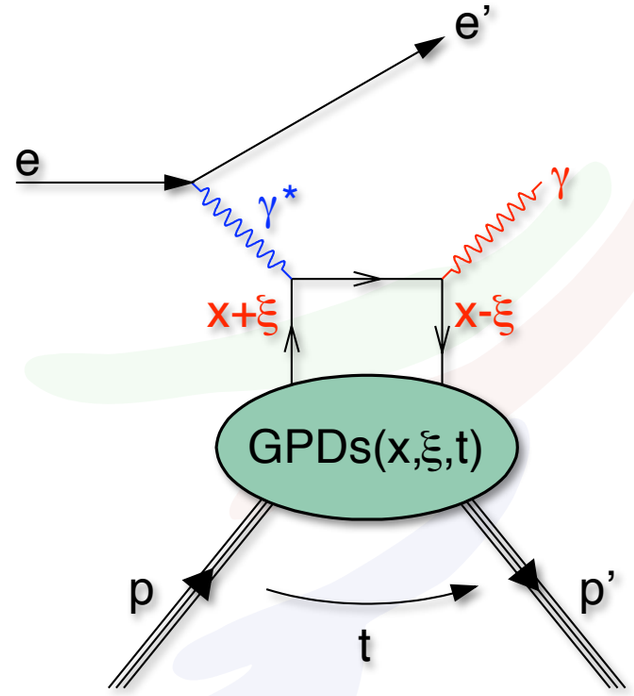
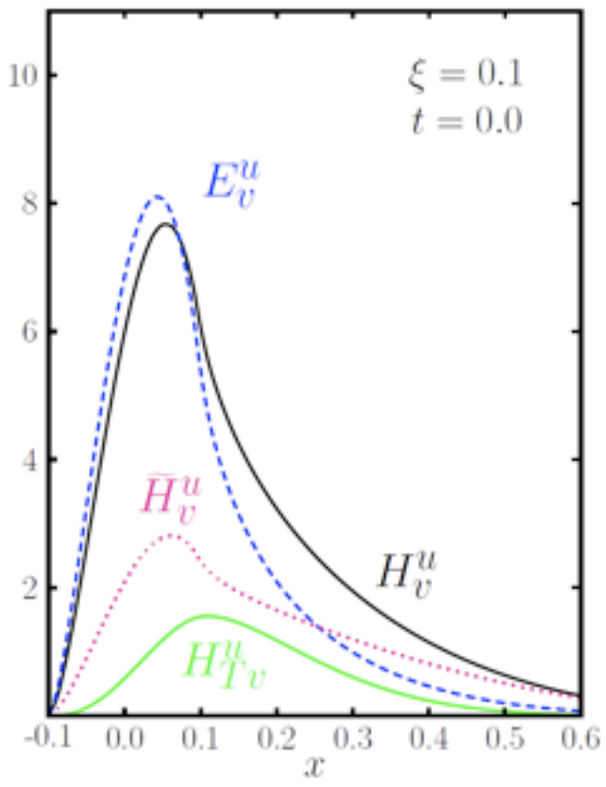
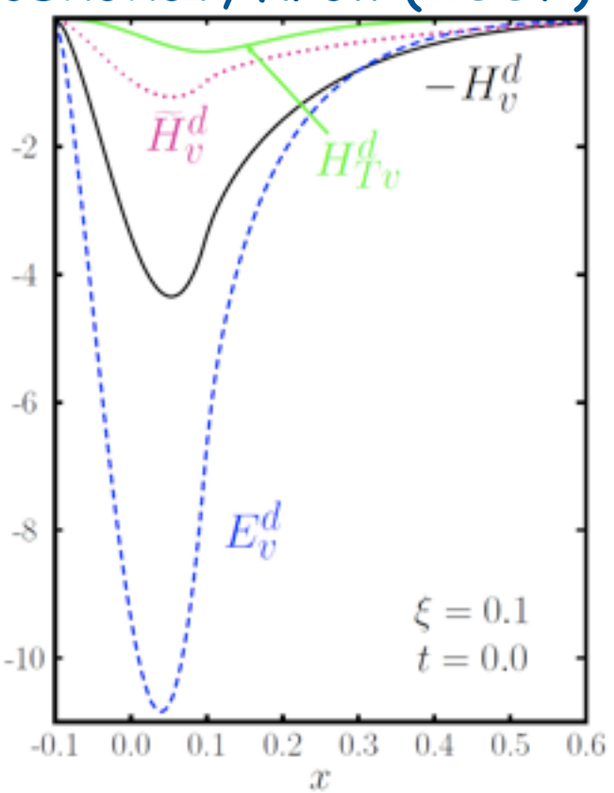


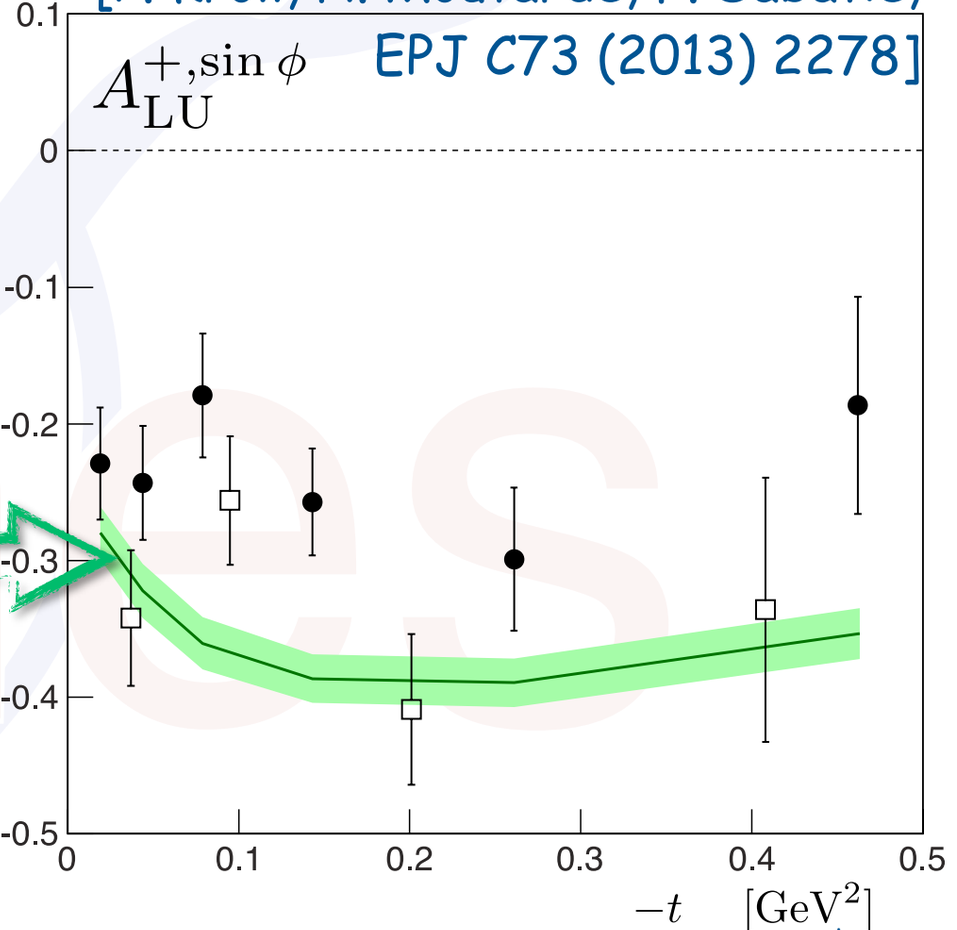


[P. Kroll, H. Moutarde, F. Sabatie, EPJ C73 (2013) 2278]

Goloskokov, Kroll (2007)

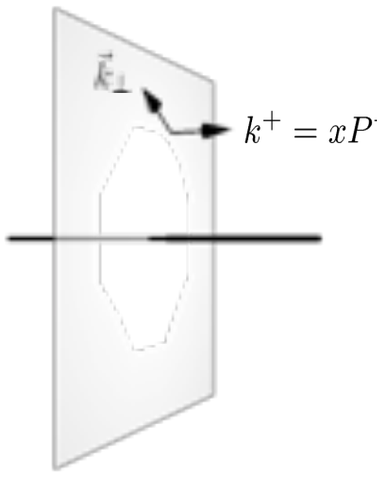


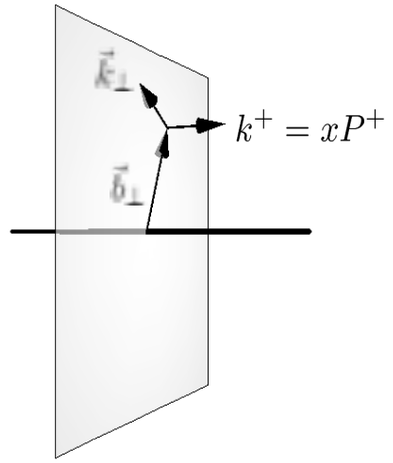


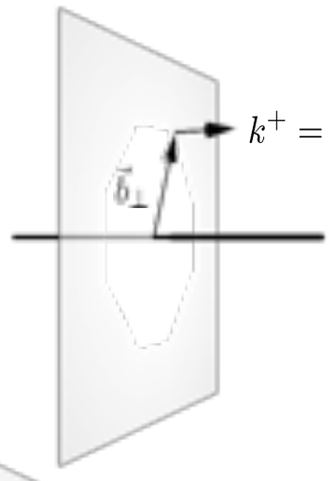


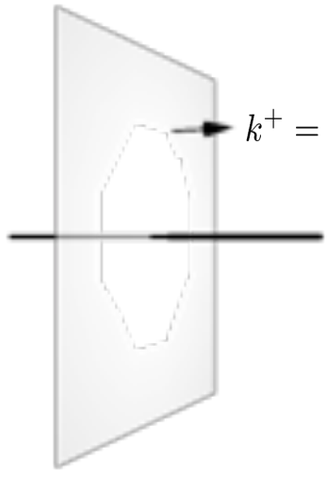
Conclusions

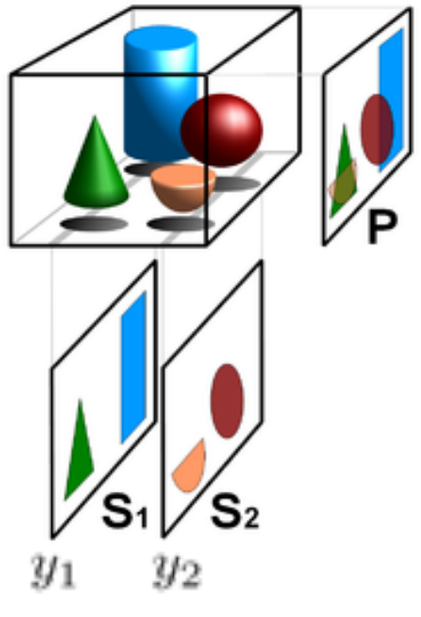
If you want to understand the proton, look at it deeply from various perspectives!











$\int \mathrm{d}y$

GTMDs

???

TMDs

e.g. **SIDIS**

GPDs

e.g. **DVCS**

PDFs

e.g. **DIS**

FFs

e.g. **ES**

Charges

e.g. **weak decays**

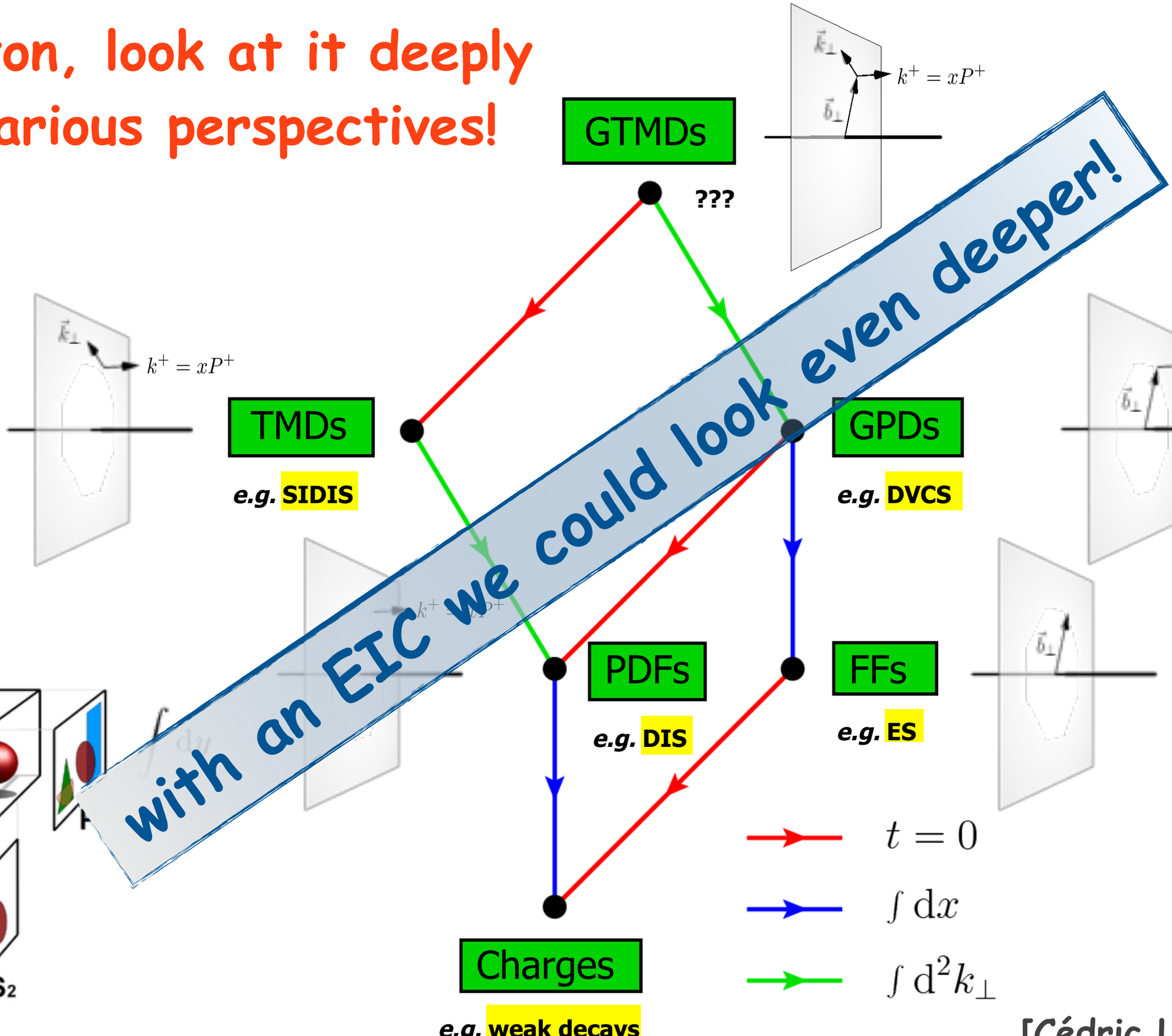
$t = 0$

$\int \mathrm{d}x$

$\int \mathrm{d}^2 k_\perp$

[Cédric Lorcé]

If you want to understand the proton, look at it deeply from various perspectives!



[Cédric Lorcé]