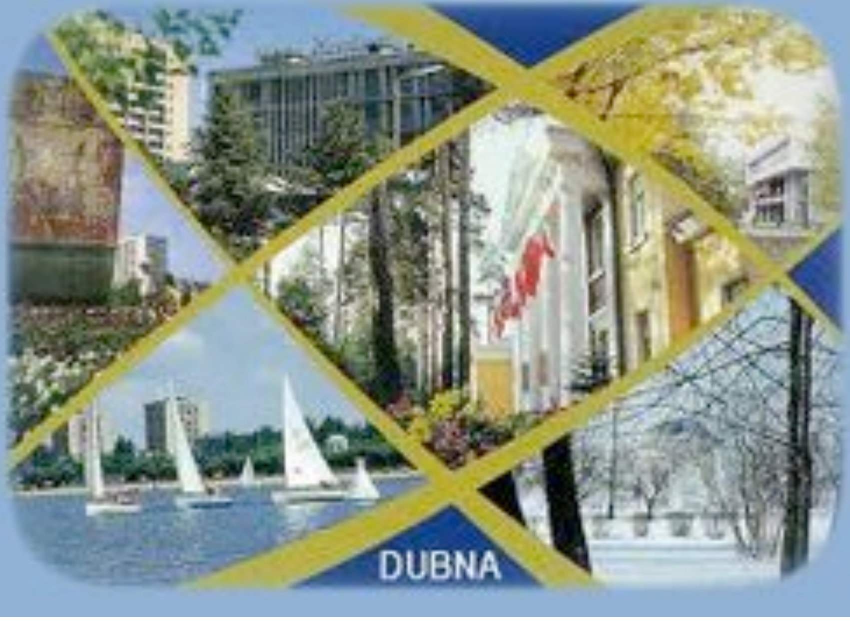

The 20th International
Spin Physics Symposium
Dubna - Sept. 17th-22nd, 2012

highlights from the hermes collaboration

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

ikerbasque
Basque Foundation for Science

Gunar.Schnell @ desy.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

20 years ago ...

20 years ago ...

- a tiny and asymmetric spin-flip amplitude in synchrotron radiation opens door for polarized DIS at HERA:

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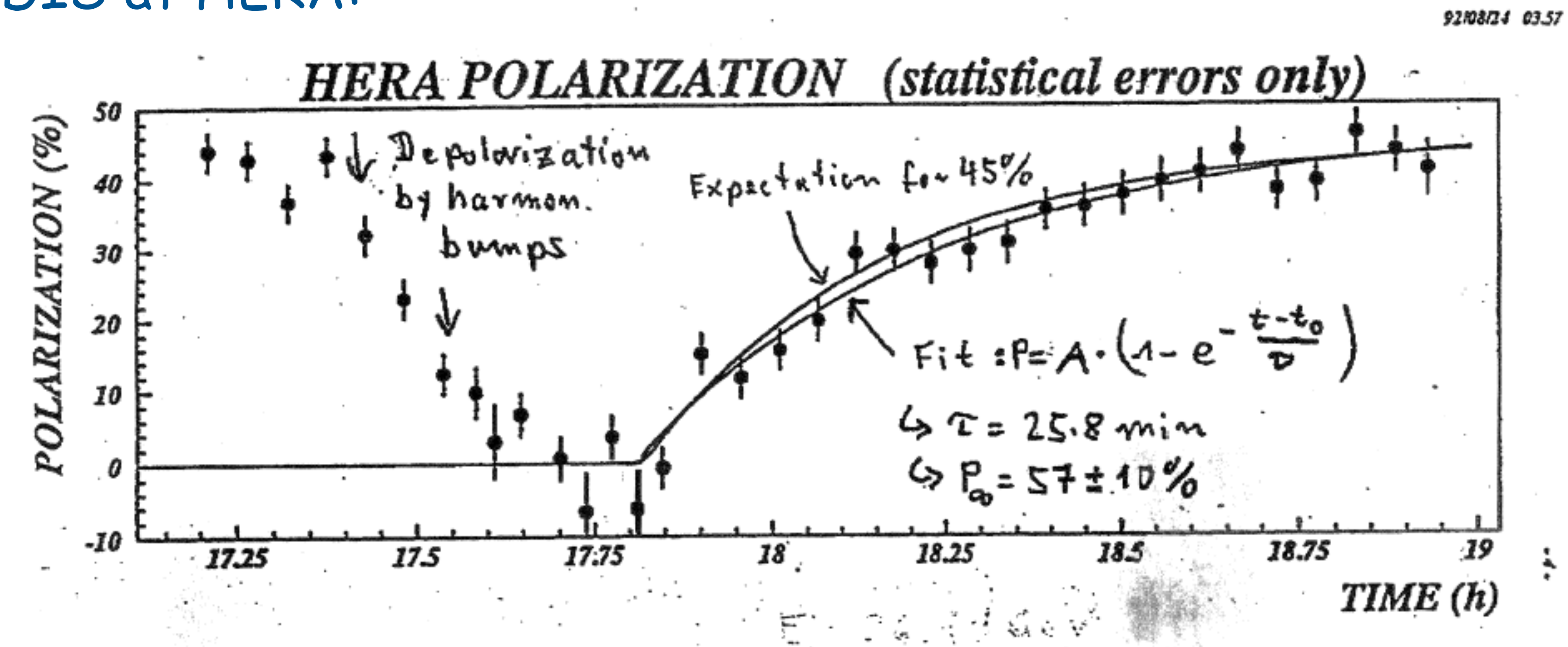

Fig. 4: Observation of rise-time at E = 26.71 GeV.

- demonstration of lepton polarization at HERA under realistic running conditions

20 years ago ...

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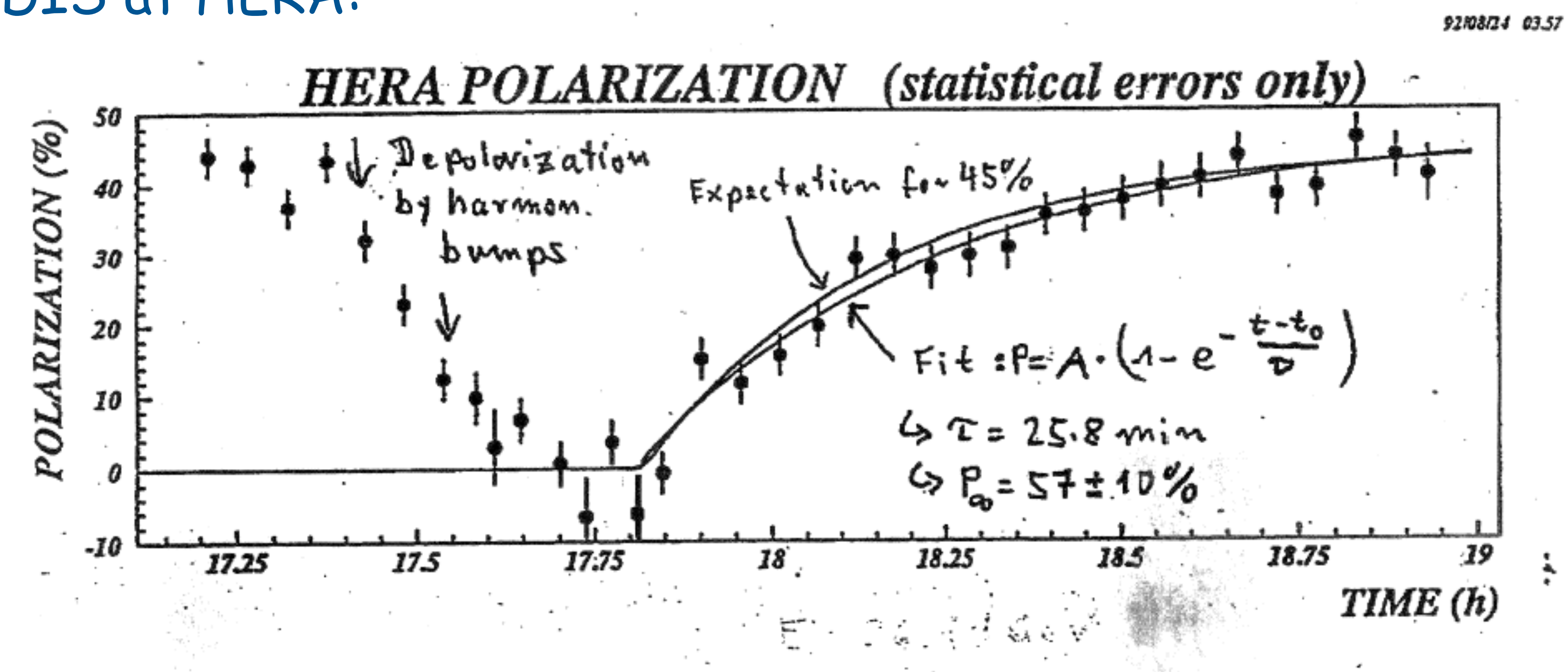


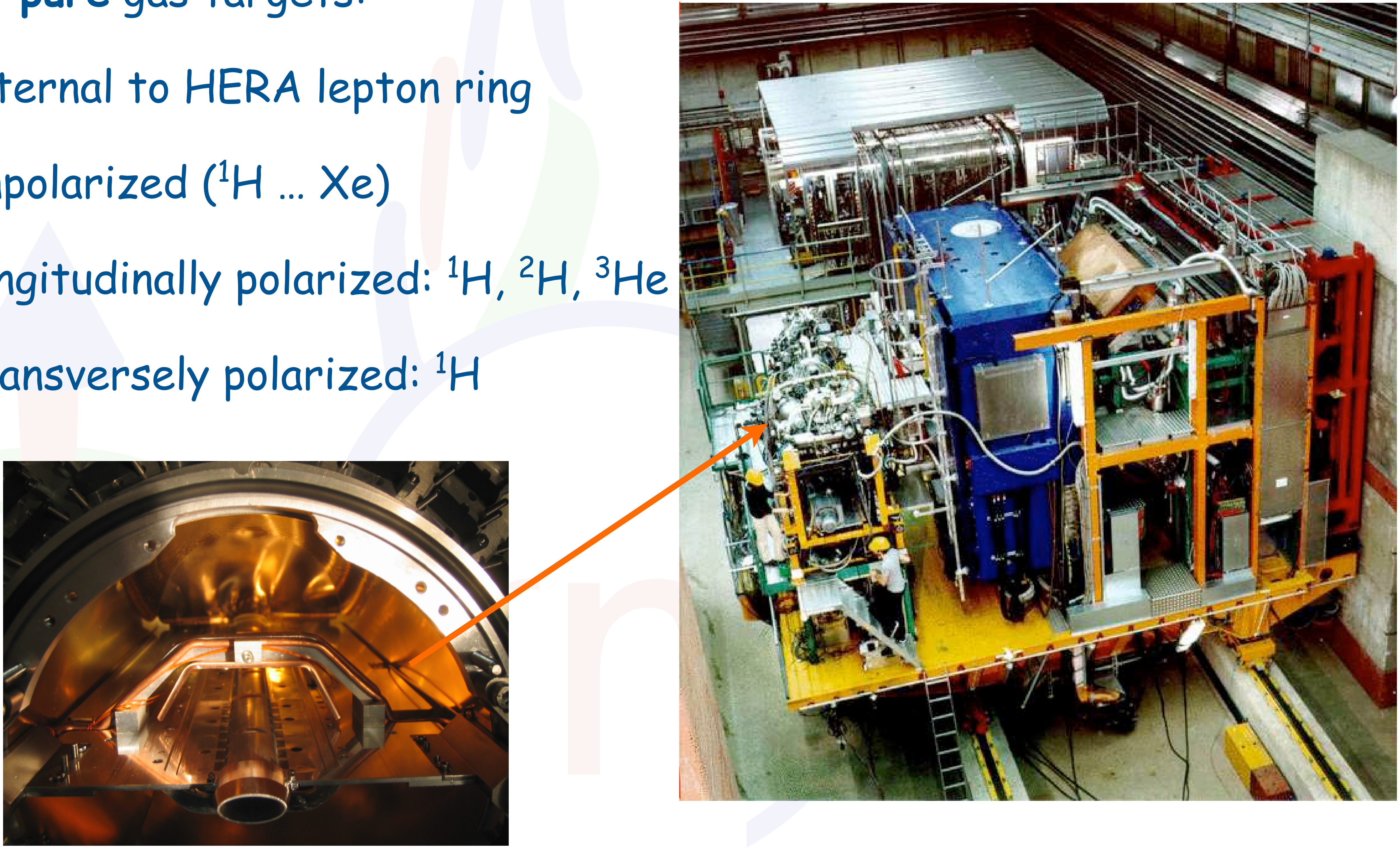
Fig. 4: Observation of rise-time at E = 26.71 GeV.

- demonstration of lepton polarization at HERA under realistic running conditions
- October 1992, PRC: "Recommend the DESY directorate to approve HERMES"
- 9 October 1992: (conditional) approval of the HERMES experiment

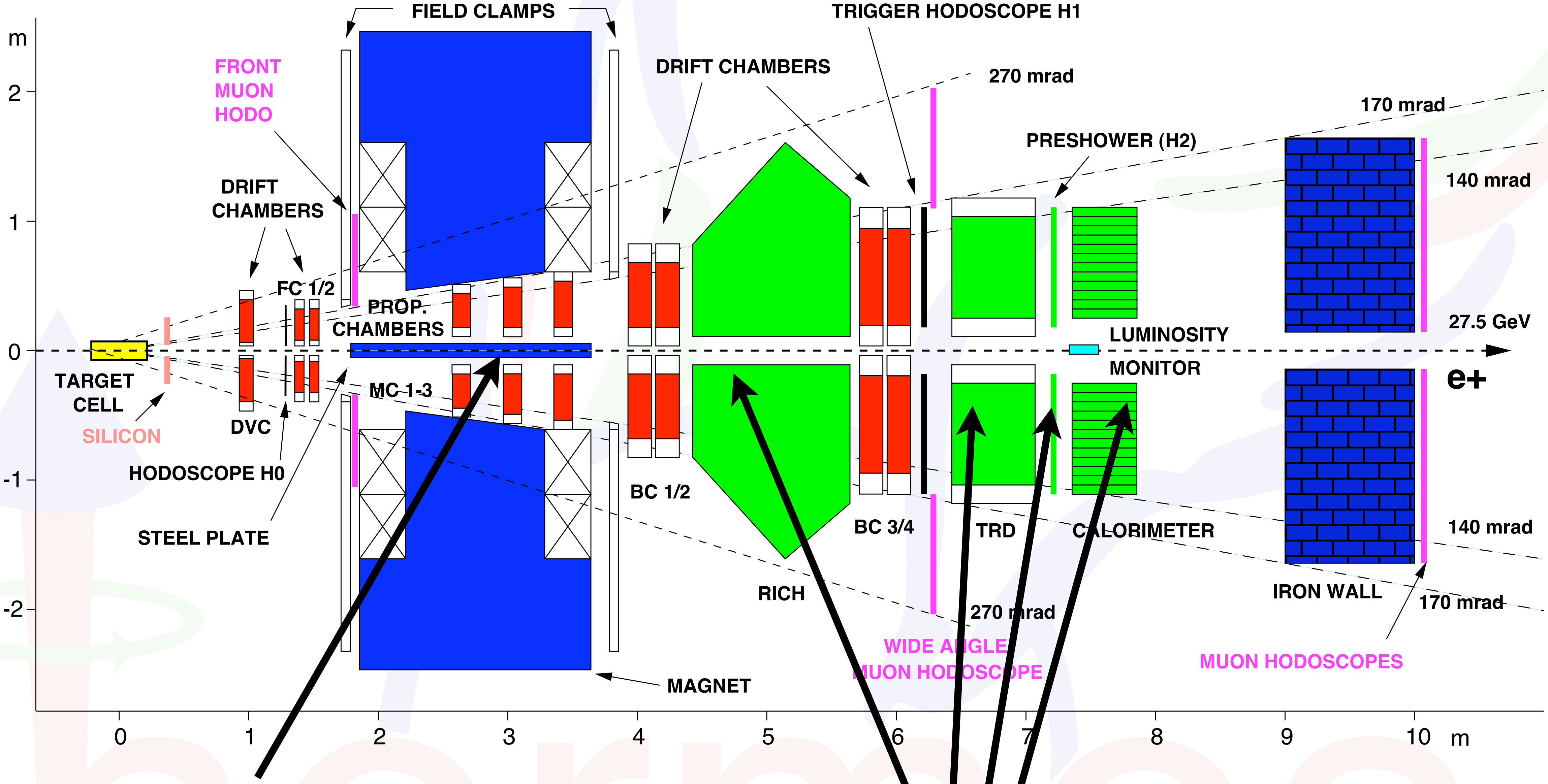
The HERMES experiment (1995-2007)

novel **pure** gas targets:

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



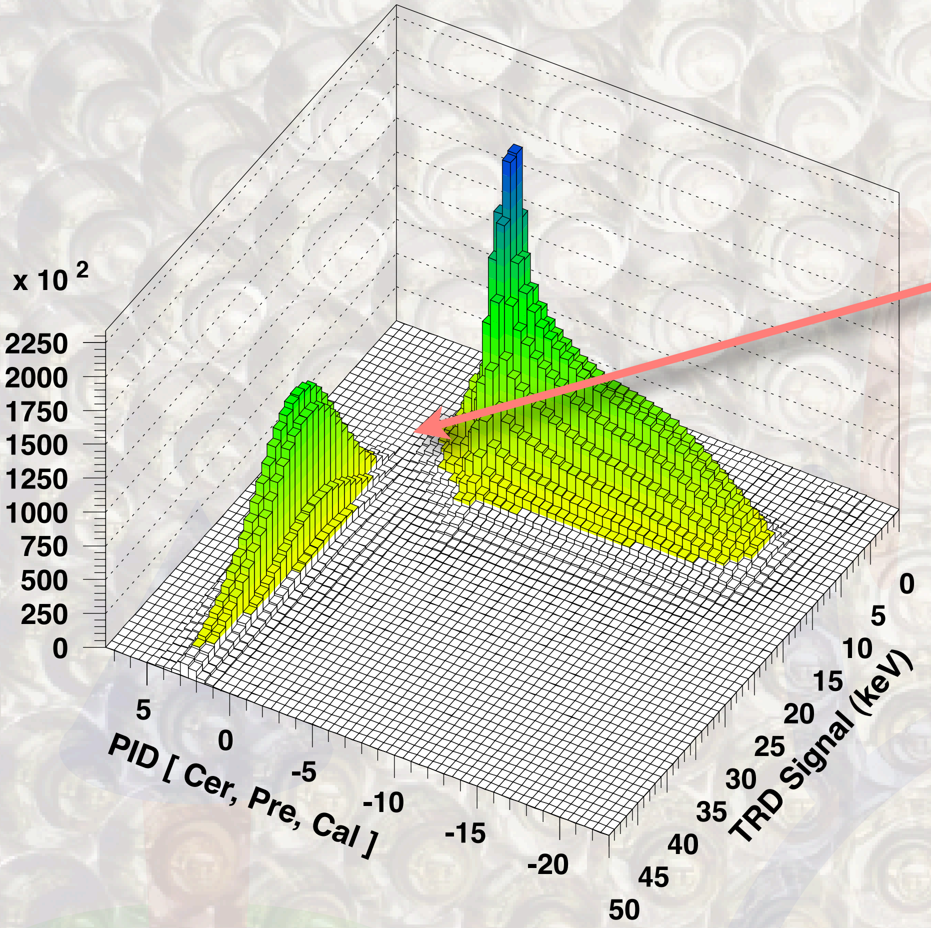
HERMES schematically



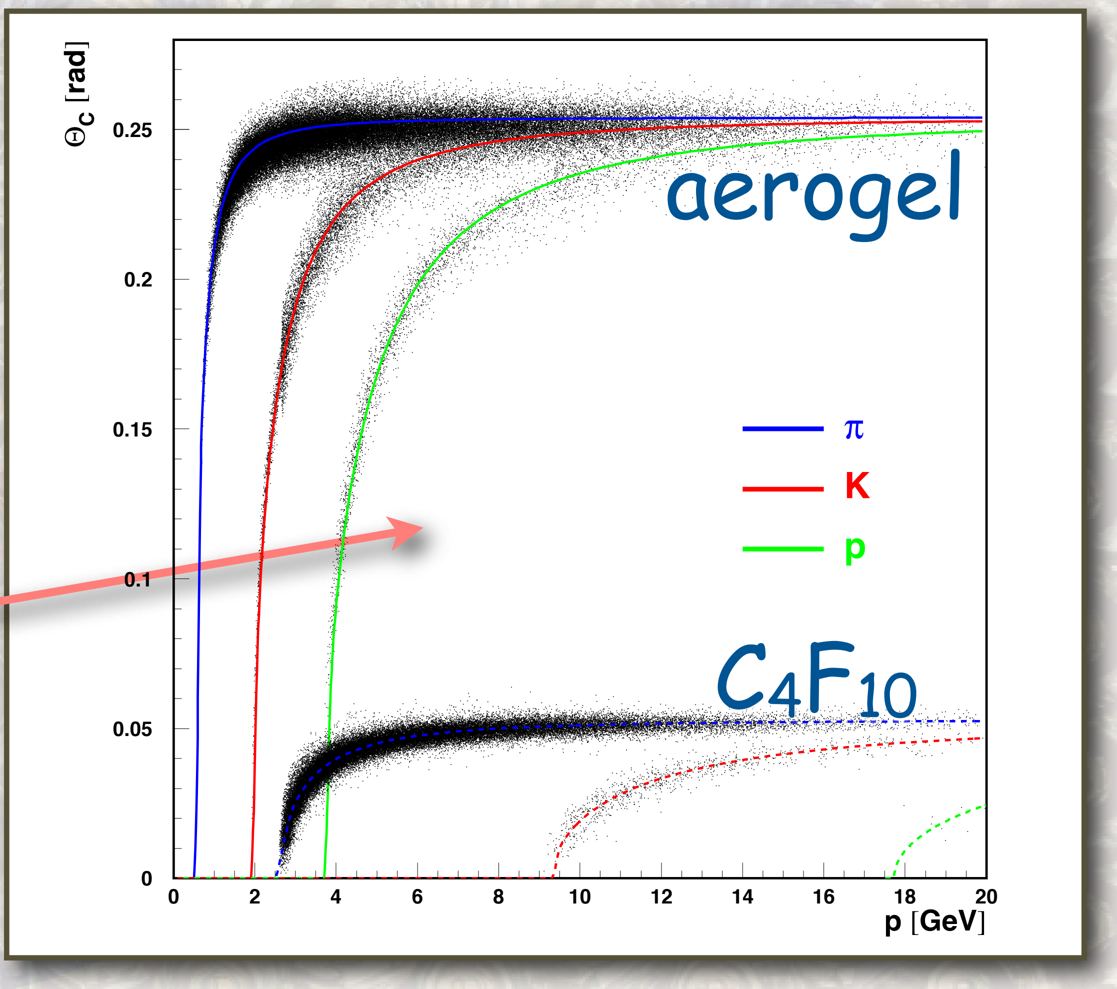
two (mirror-symmetric) halves -> no homogenous azimuthal coverage

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

Particle Identification

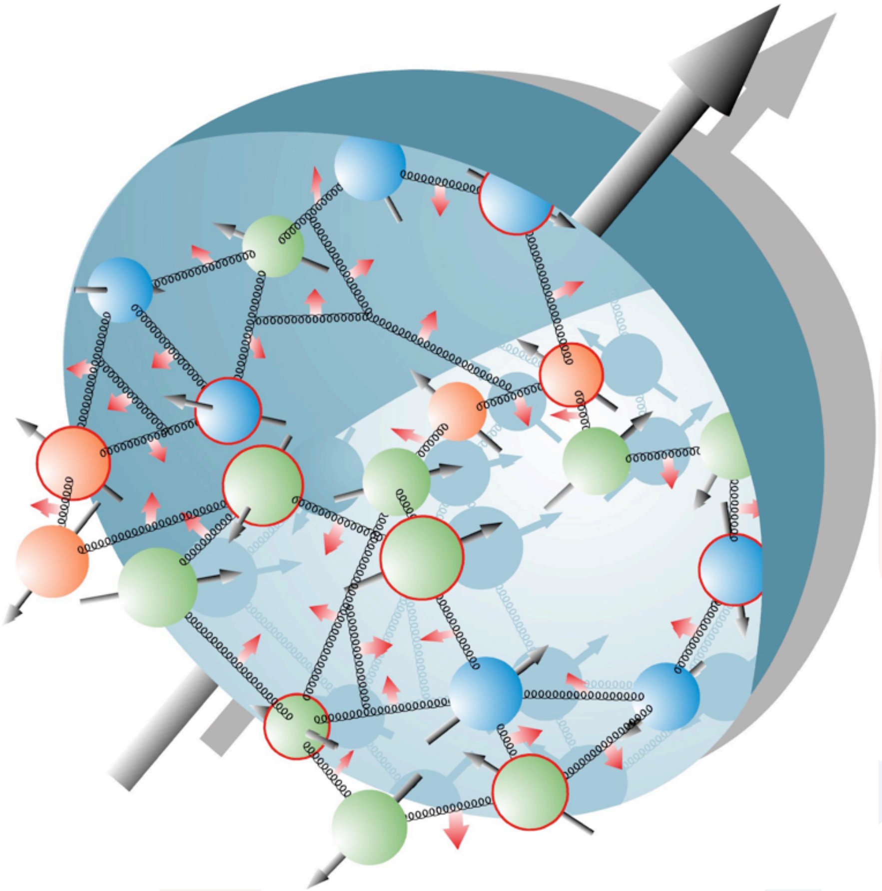


excellent lepton/hadron separation



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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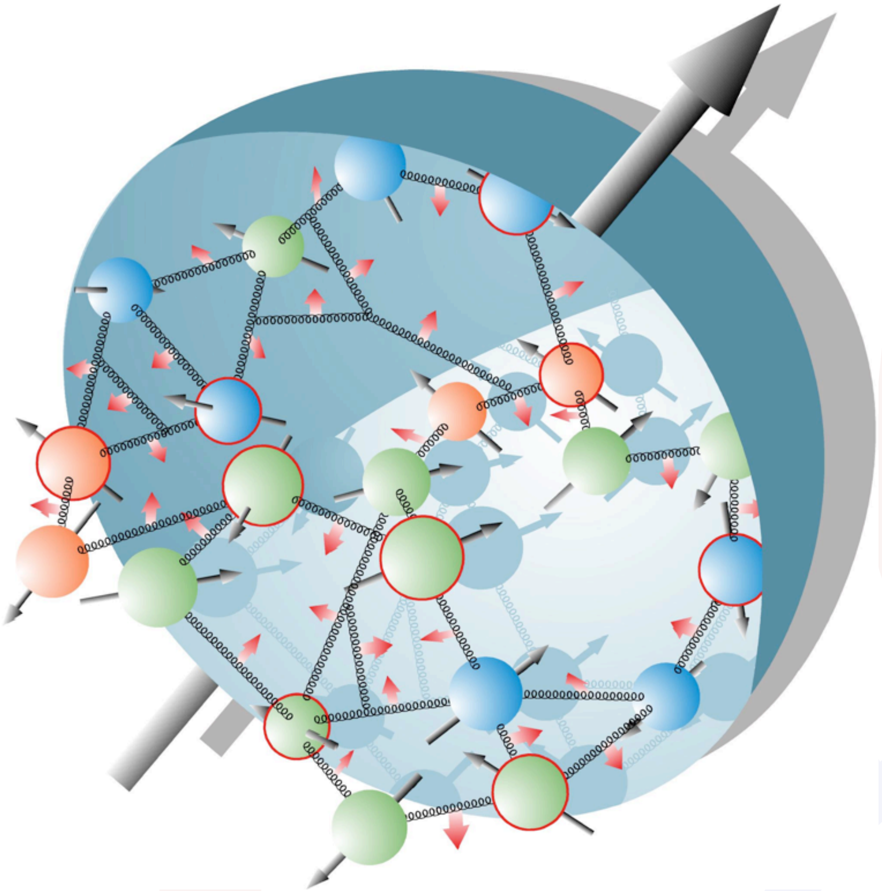

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- Inclusive DIS from longitudinally polarized Deuterium target:

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

PRD 75 (2007) 012007

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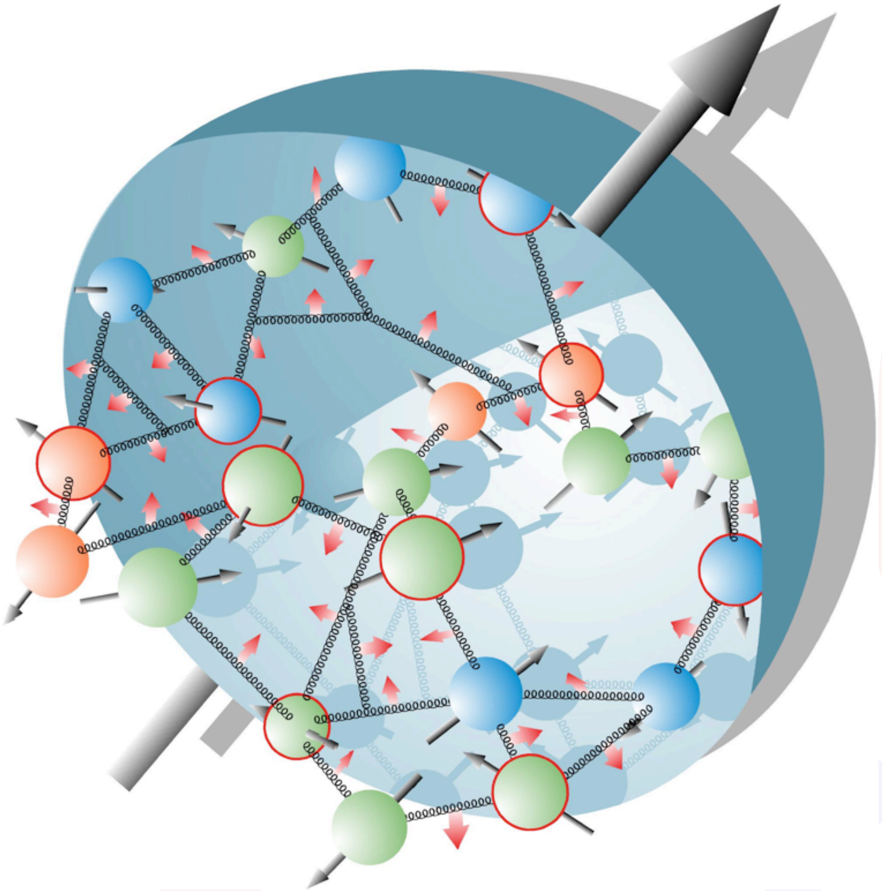

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- High-p_T hadrons at HERMES:

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

JHEP 1008 (2010) 130

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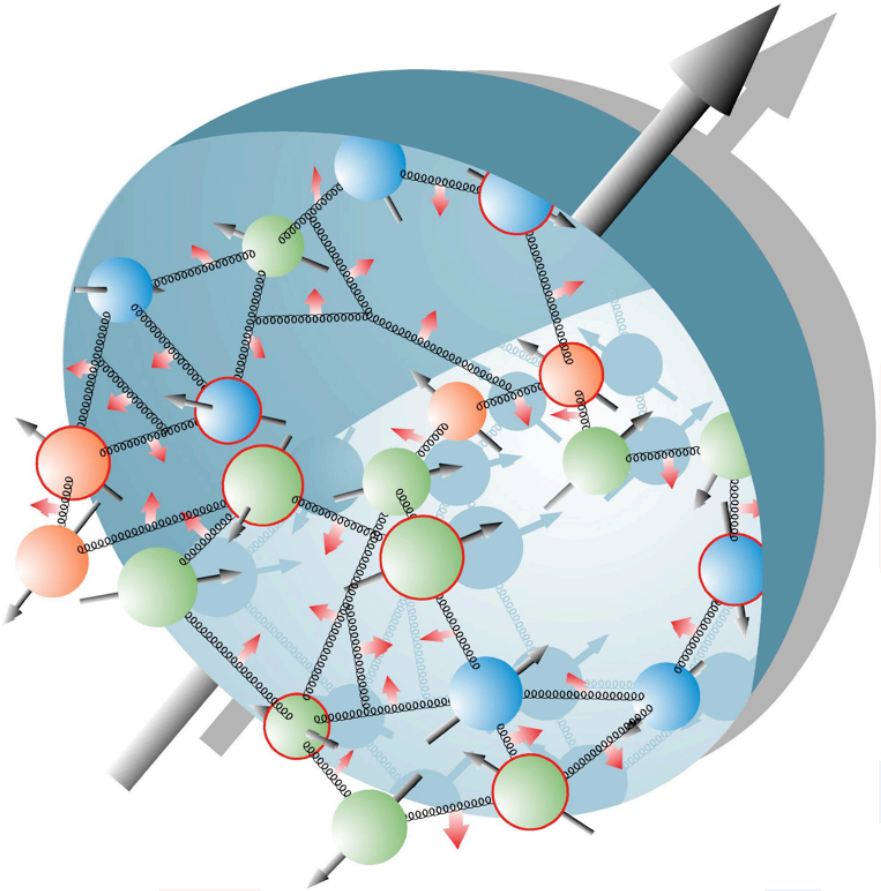

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gunar.schnell @ desy.de

HERA II - some highlights

- **transverse-target program**
  - first demonstration of Sivers effect in DIS [PRL 94 (2005) 012002] [PRL 103 (2009) 152002]
  - first clear evidence for transversity [PRL 94 (2005) 012002] [JHEP 06 (2008) 017] [PLB 693 (2010) 11]
    - involving Collins and interference fragmentation
  - sizable transverse target asymmetries in DVCS [JHEP 06 (2008) 066]
- **recoil-detector program**
  - high-statistics data set using unpolarized targets
  - measurement of DVCS with recoil-proton detection

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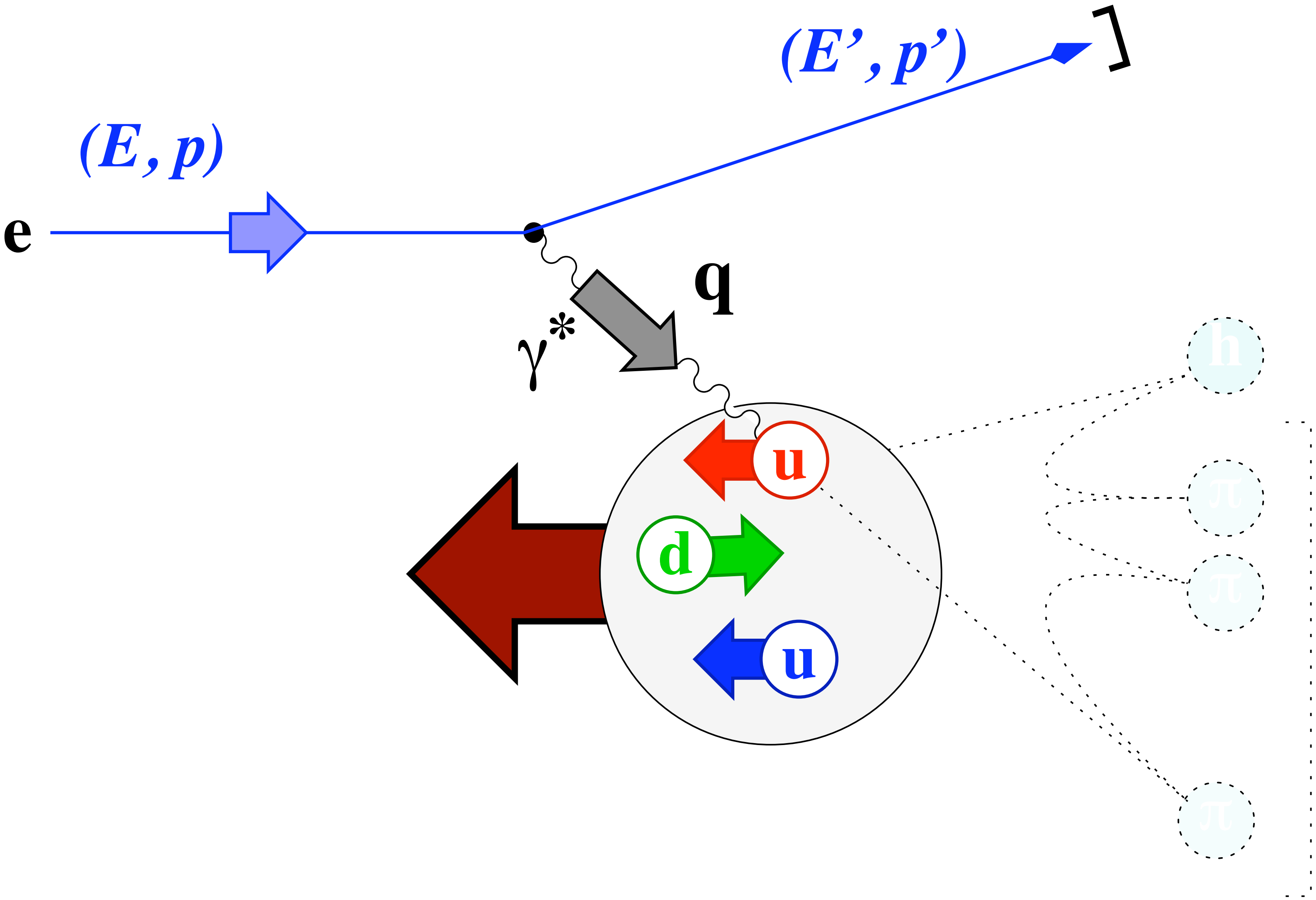
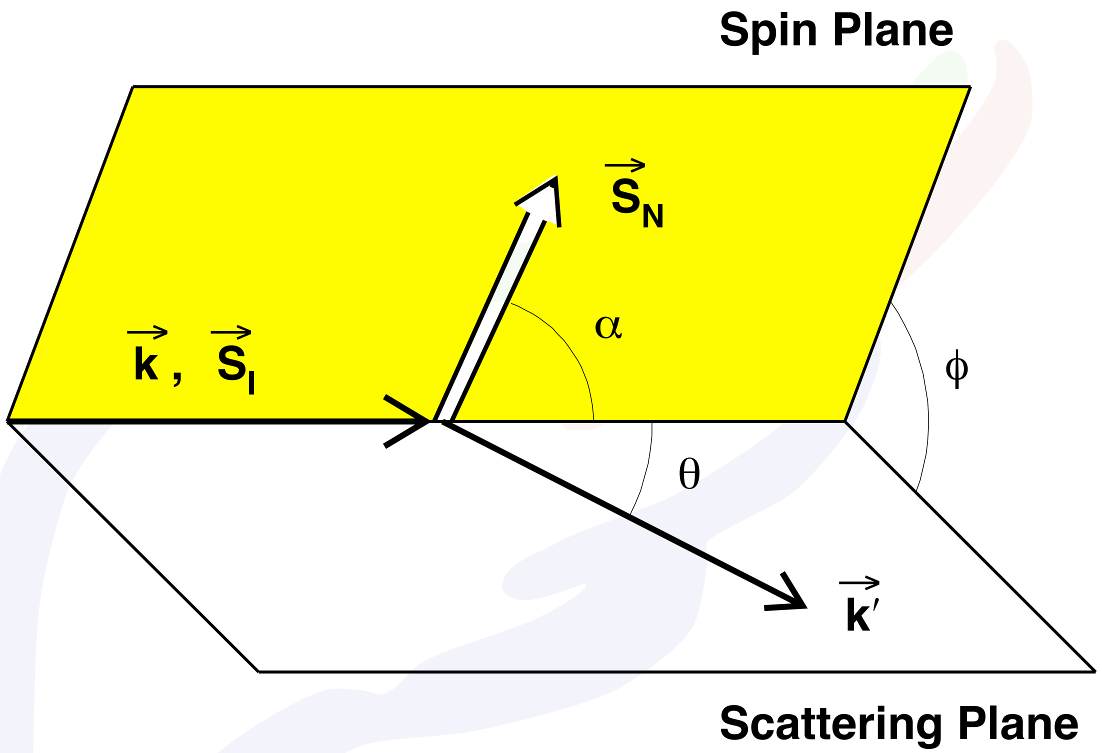
Inclusive DIS



Inclusive DIS

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



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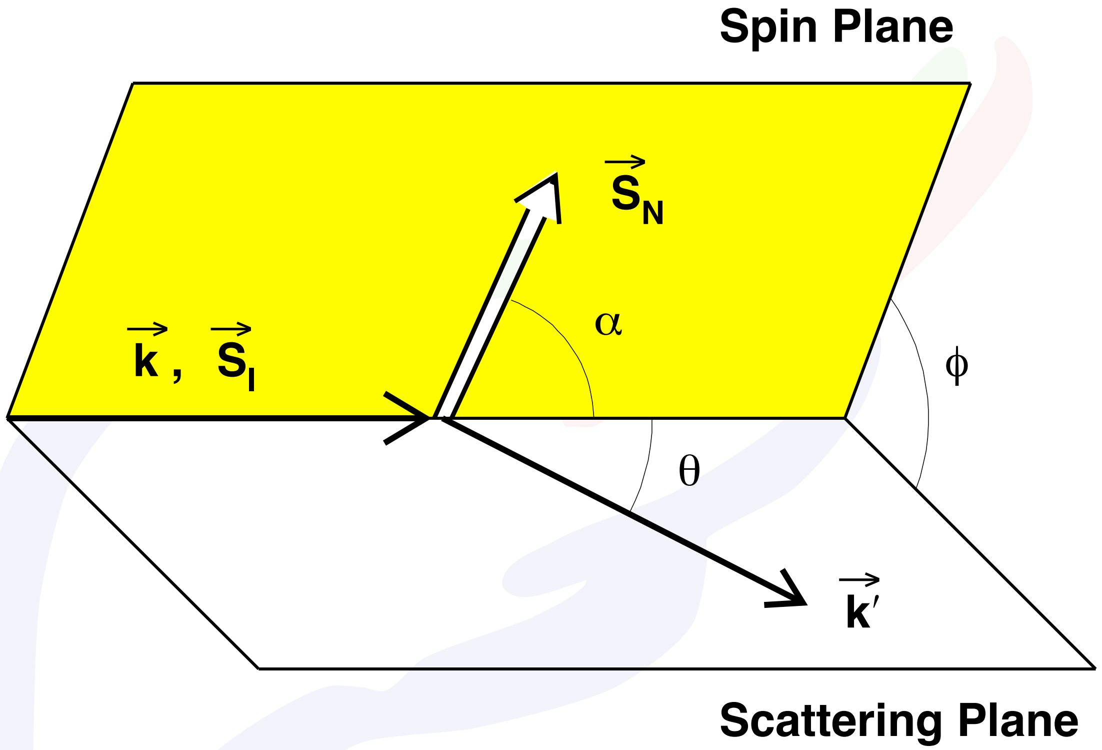
Lepton Tensor



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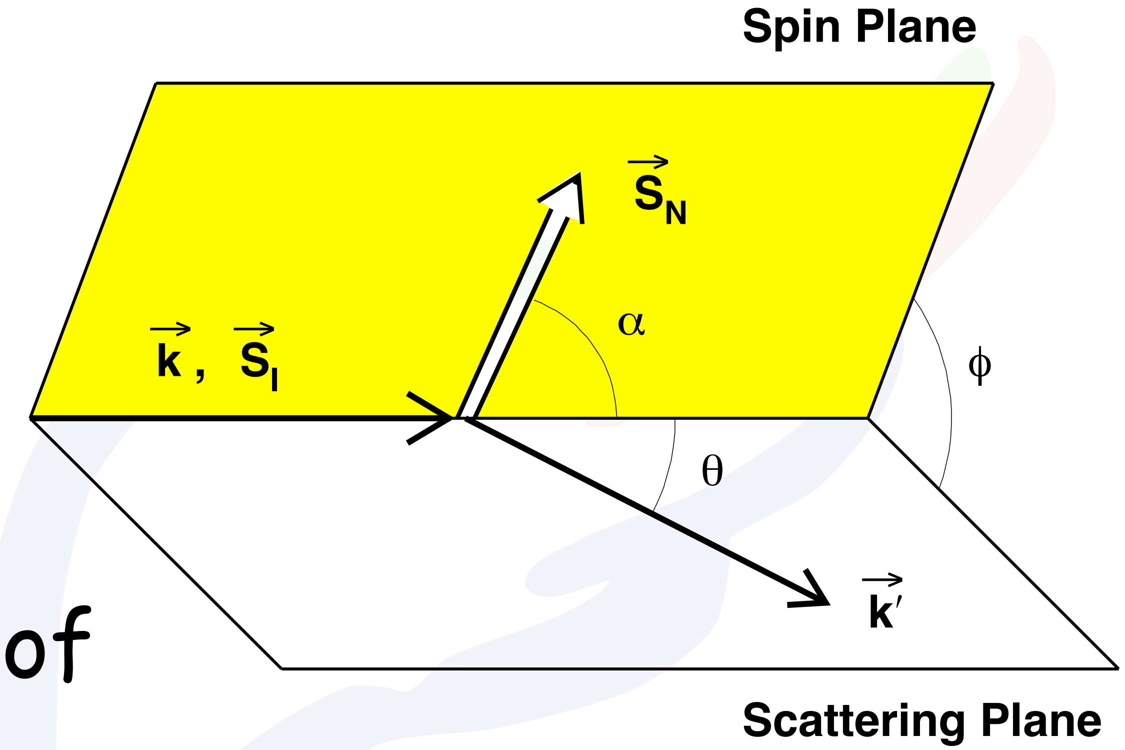
Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions



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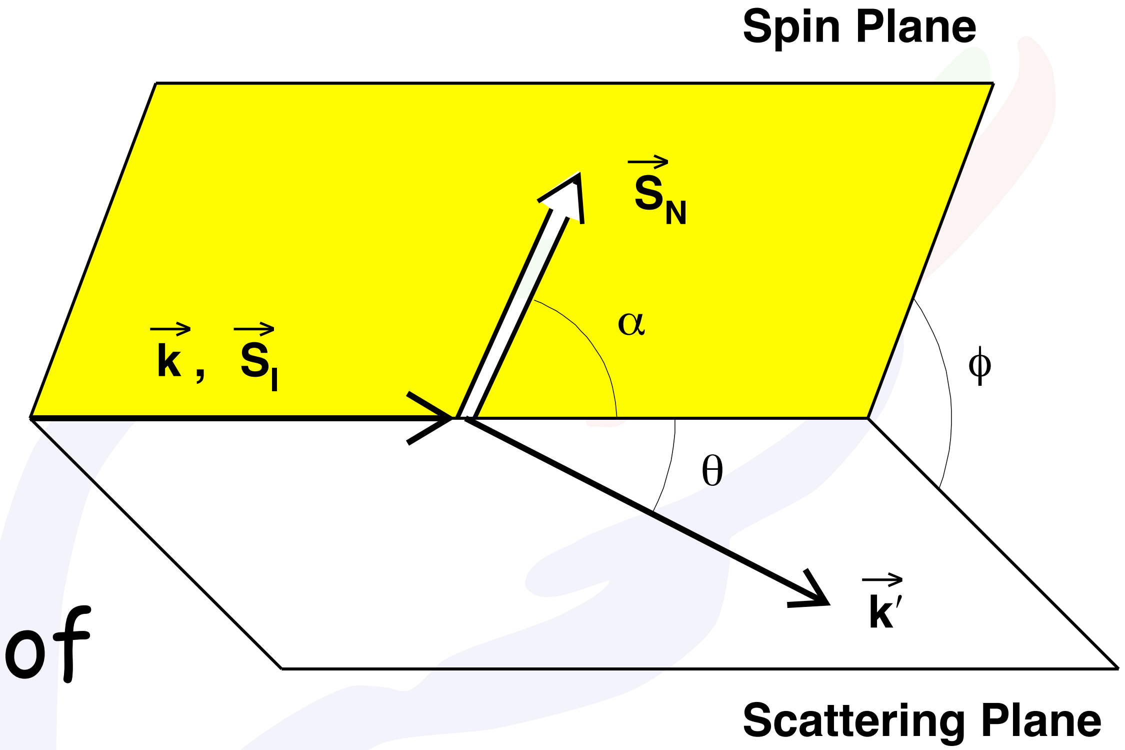


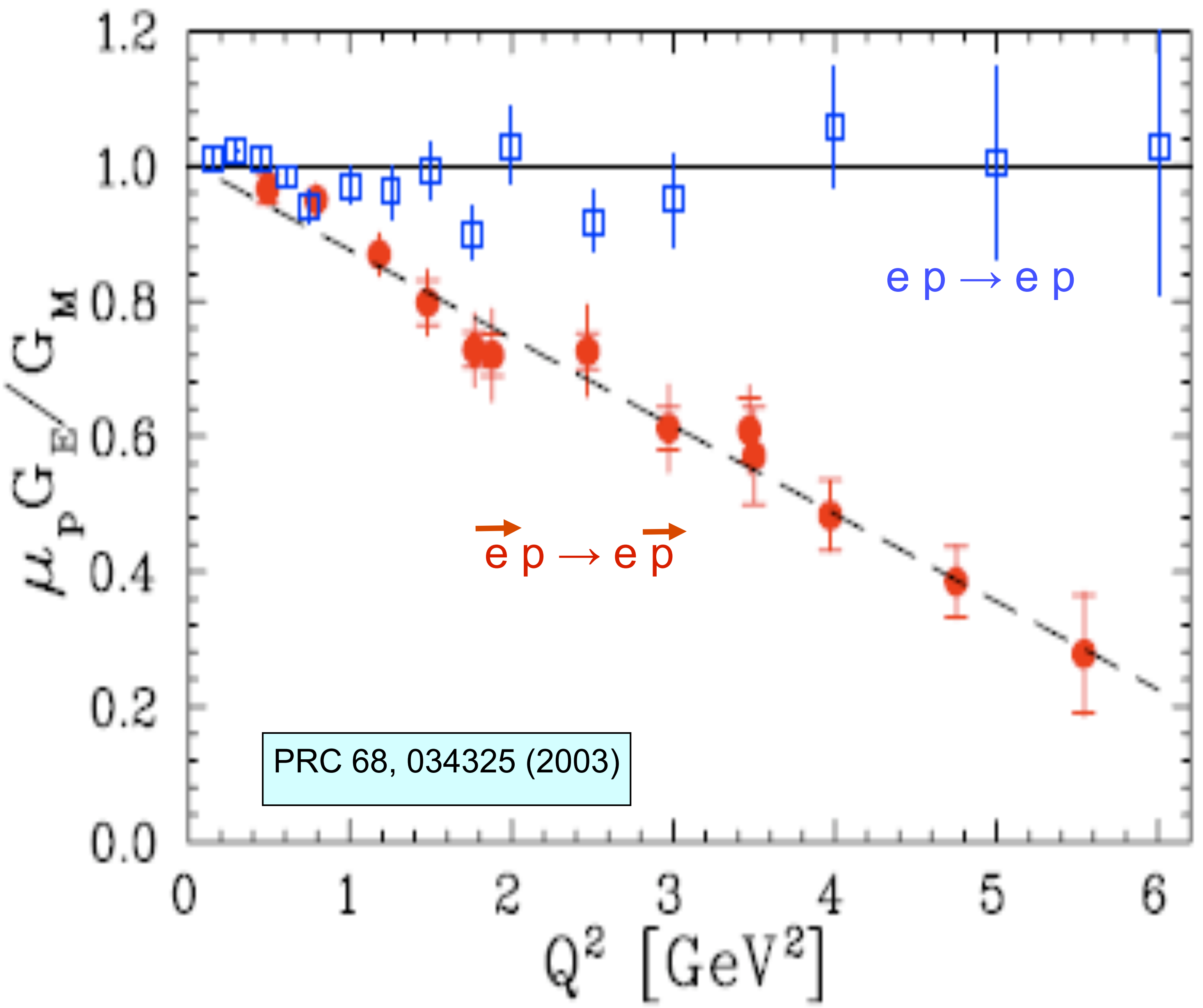
$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2 y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$

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

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

Check the details!

Check the details!

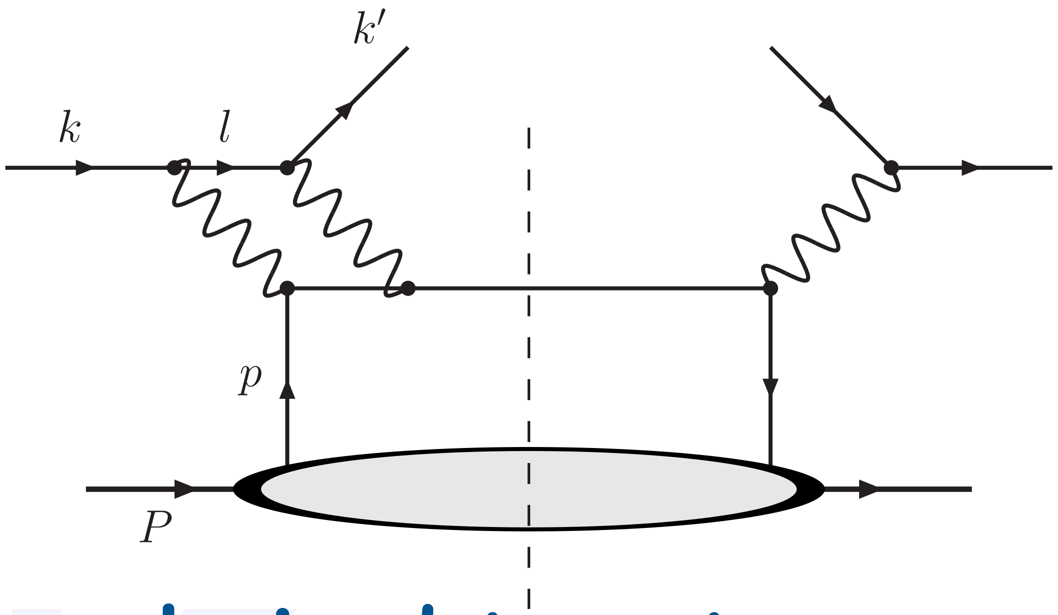


x_F

- ☛ **two-photon exchange can be important!**

Two-photon exchange

- **Candidate to explain discrepancy in form-factor measurements**



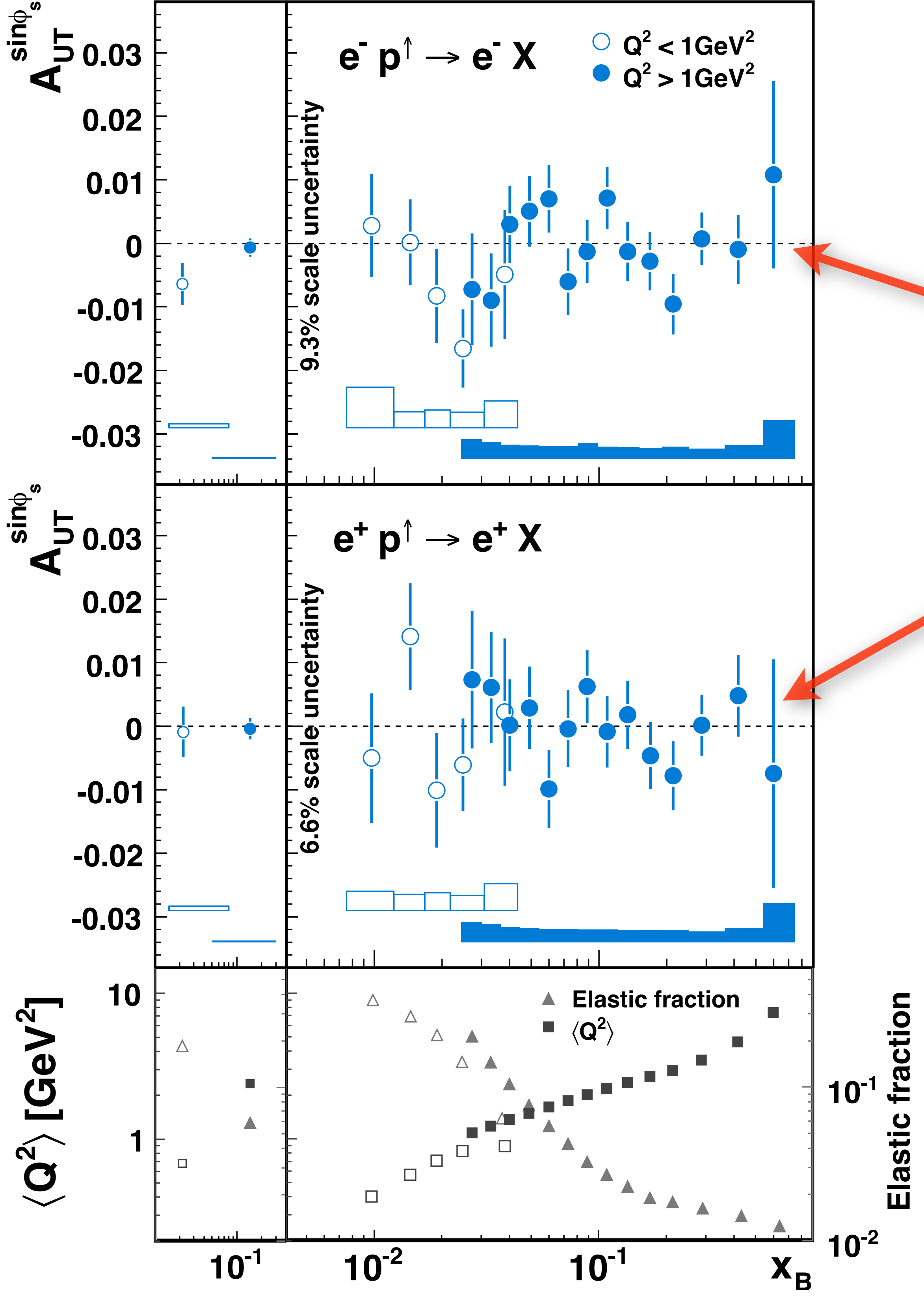
- **Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets**

- **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

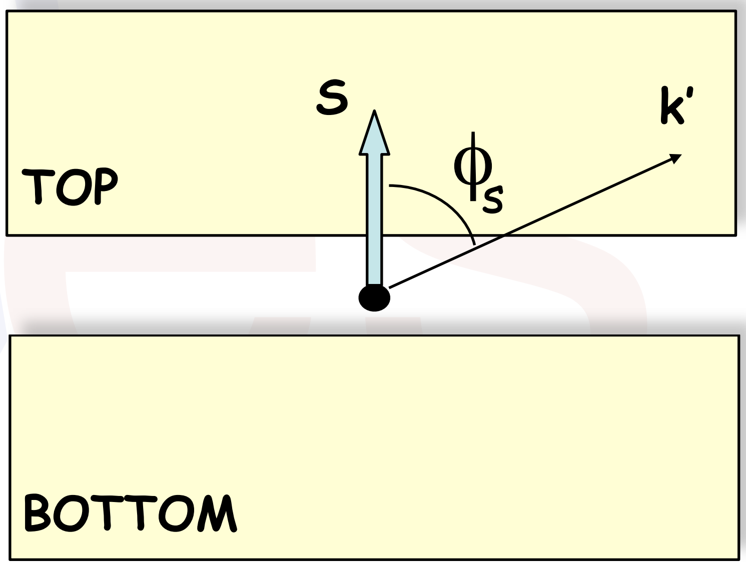
A. Airapetian et al., PLB 682 (2010) 350



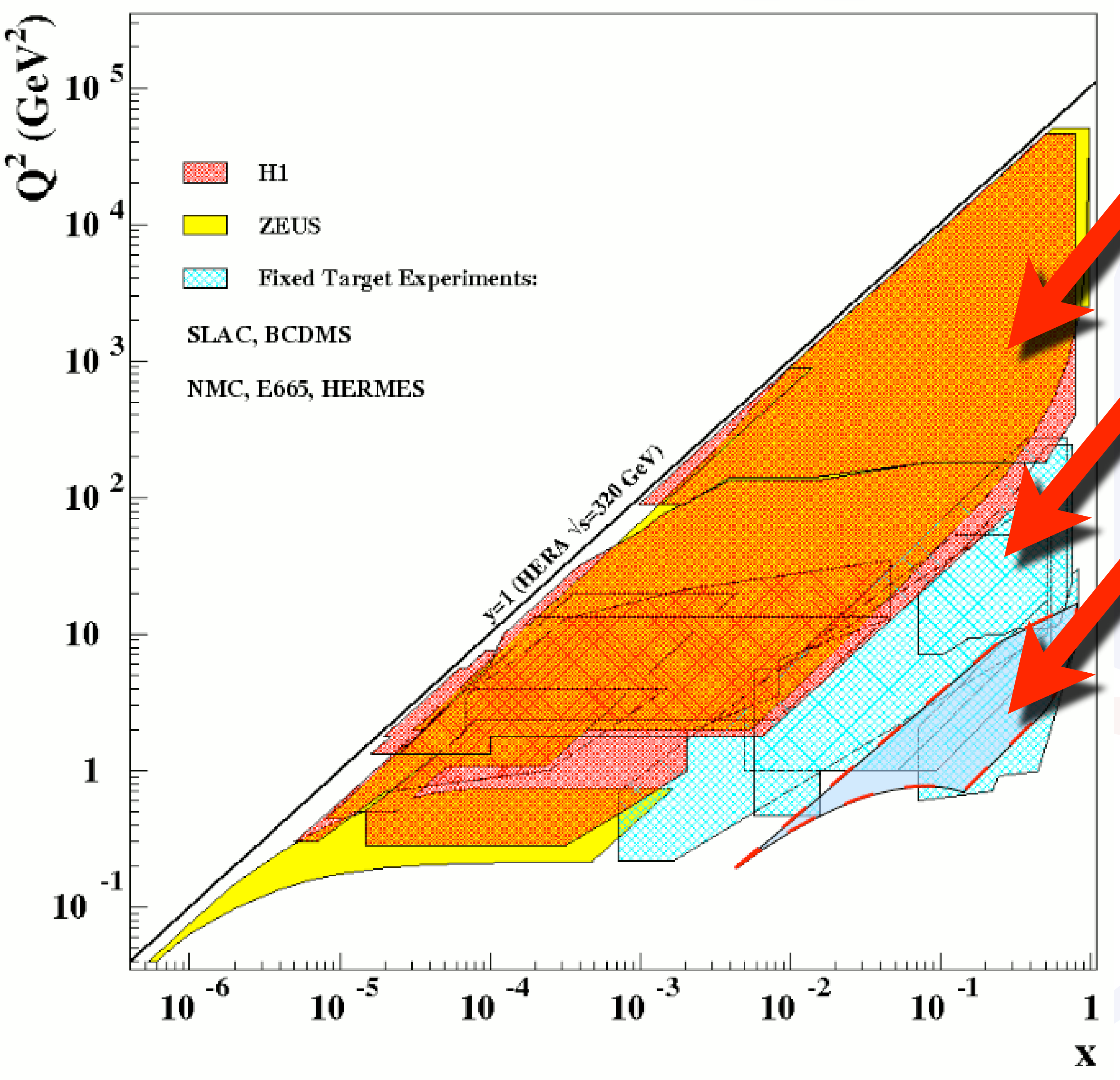
Beam	$A_{UT}^{\sin\phi_S}$ $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(stat.) $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(syst.) $\times 10^{-3}$	$\langle x_B \rangle$	$\langle Q^2 \rangle$ [GeV^2]
e^+	−0.61	3.97	0.63	0.02	0.68
e^-	−6.55	3.40	0.63		
e^+	−0.60	1.70	0.29	0.14	2.40
e^-	−0.85	1.50	0.29		

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

Front view of HERMES detector



Why measure F_2 at HERMES?



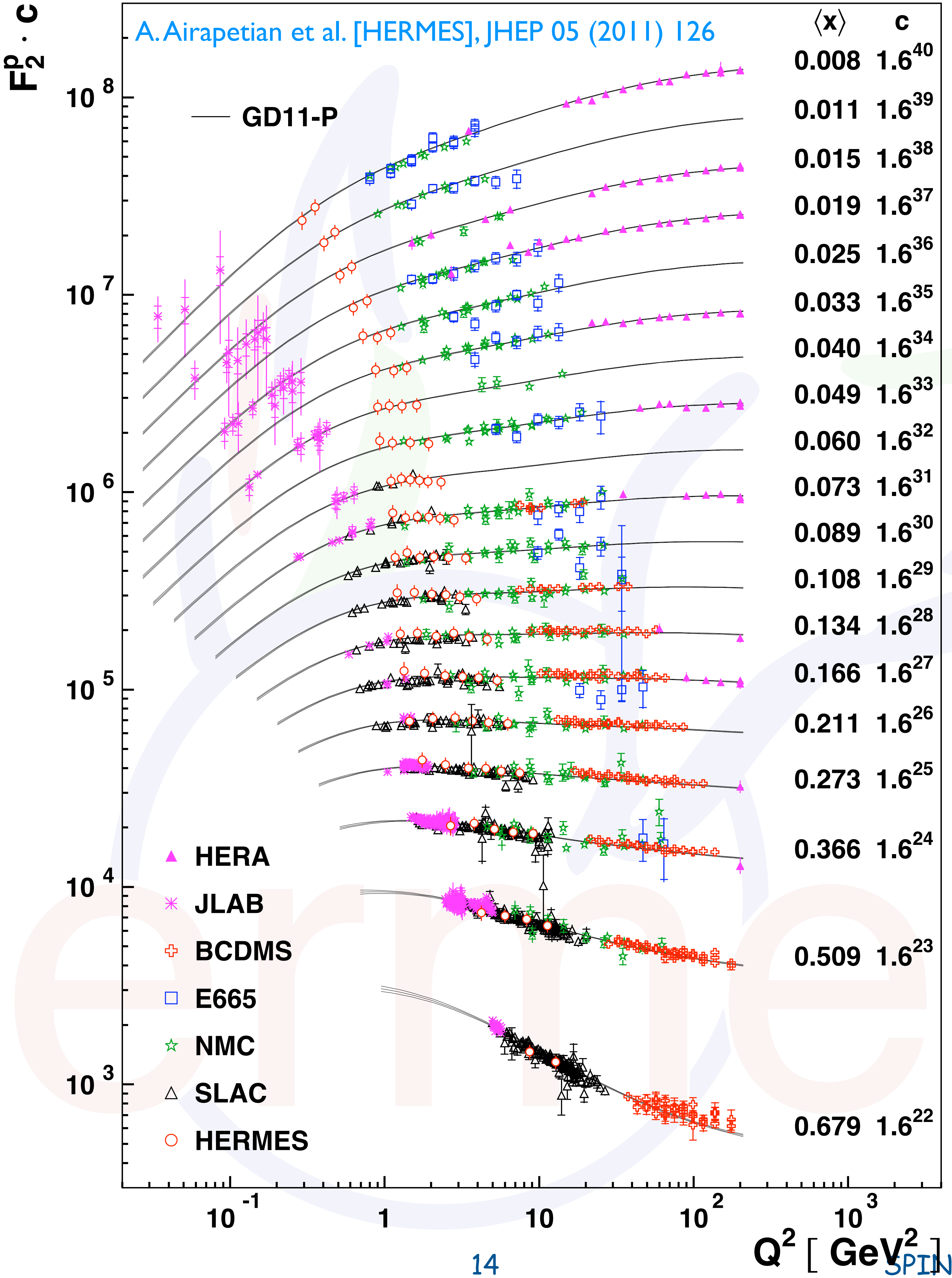
Collider experiments

Fixed target experiments

HERMES

- complementary kinematic coverage compared to colliders
- direct info at HERMES kinematics
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)

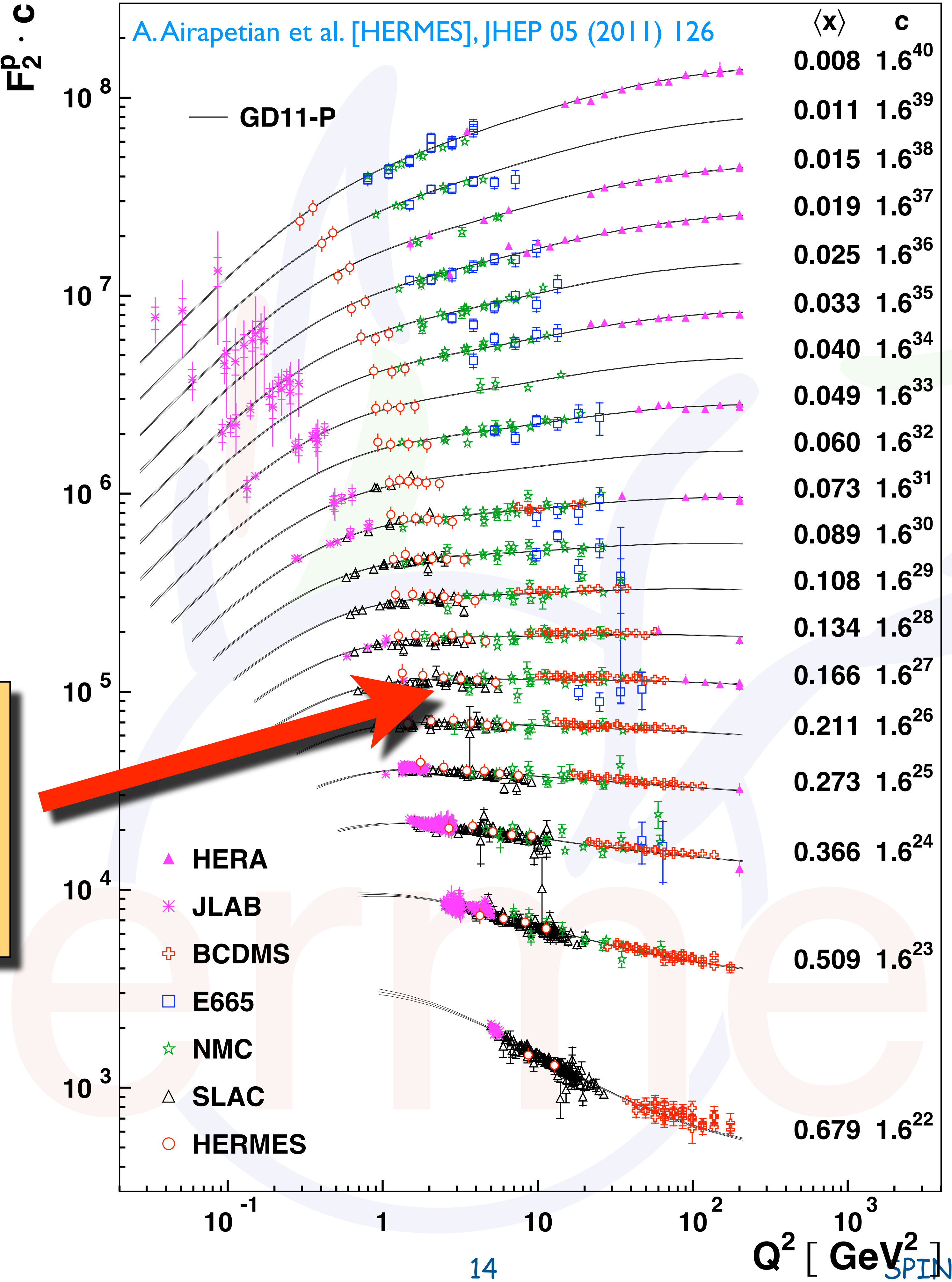
F_2 proton



GD11 - global fit

From global fit GD11:
HERMES relative normalization is
~2% for Proton and Deuteron
~0.5% for the Ratio

F_2 proton



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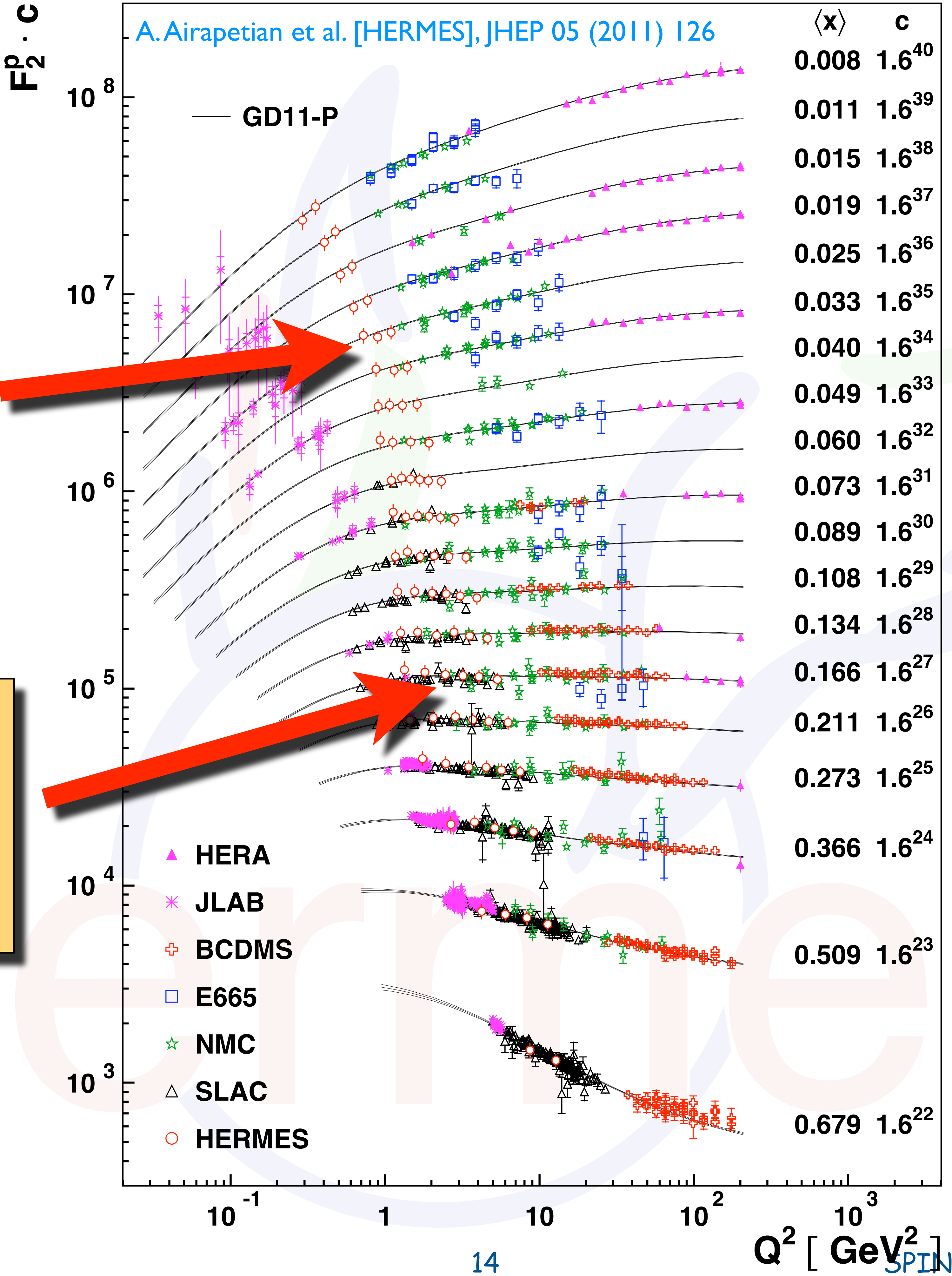
Agreement with world data in the overlap region

F_2 proton



New region covered by HERMES

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F_2 deuteron

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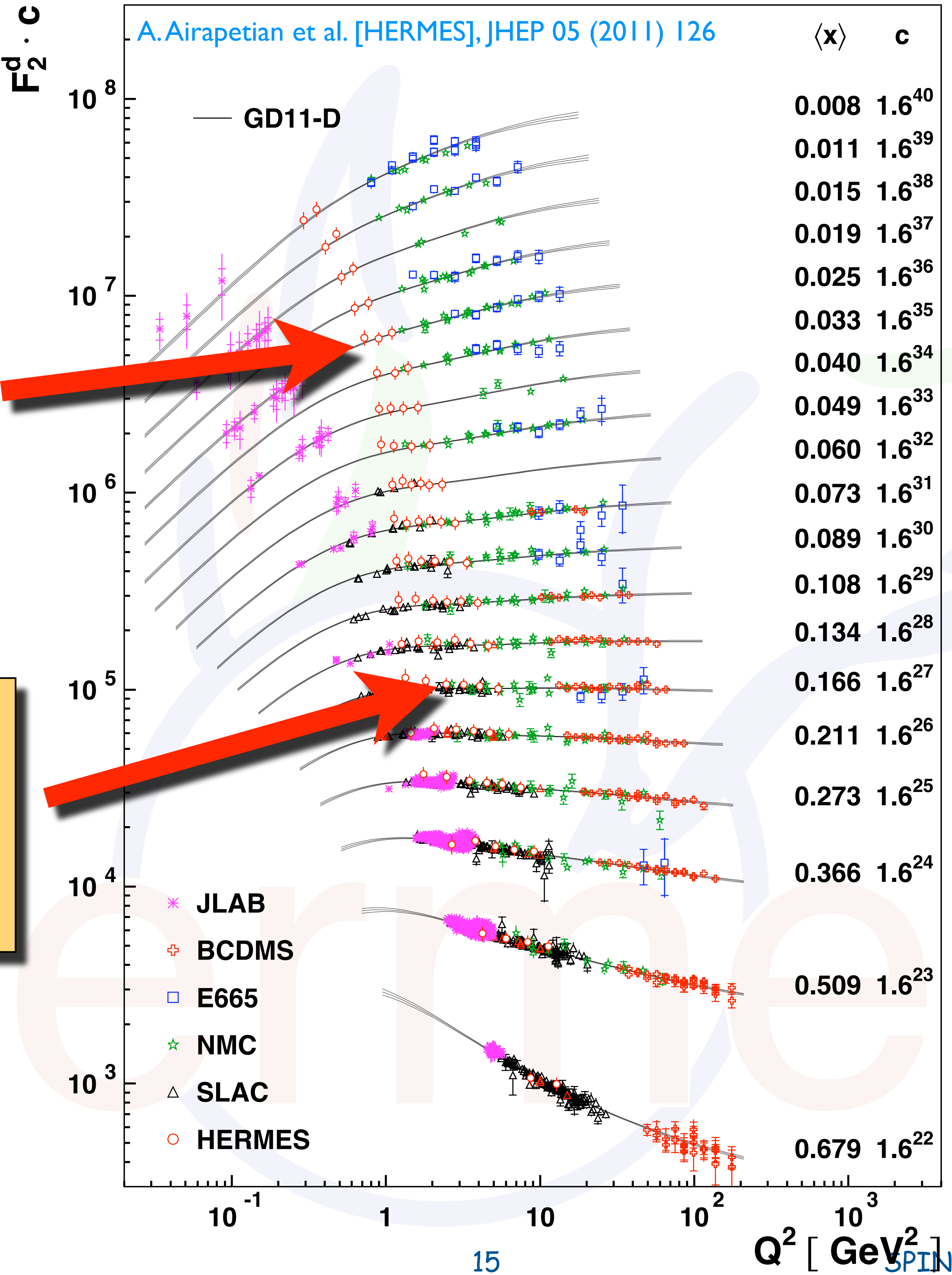

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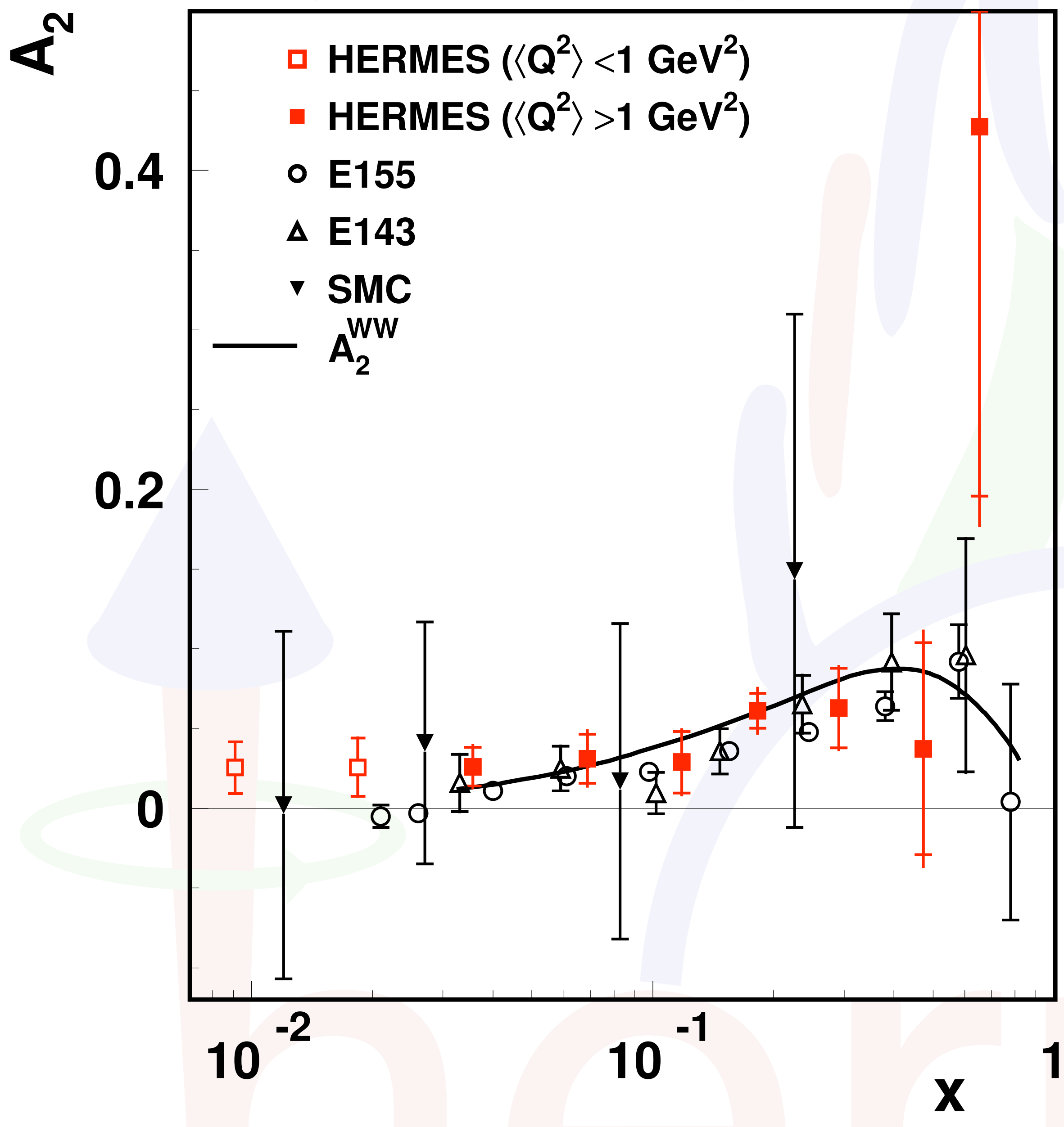
Results on A_2 and xg_2

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



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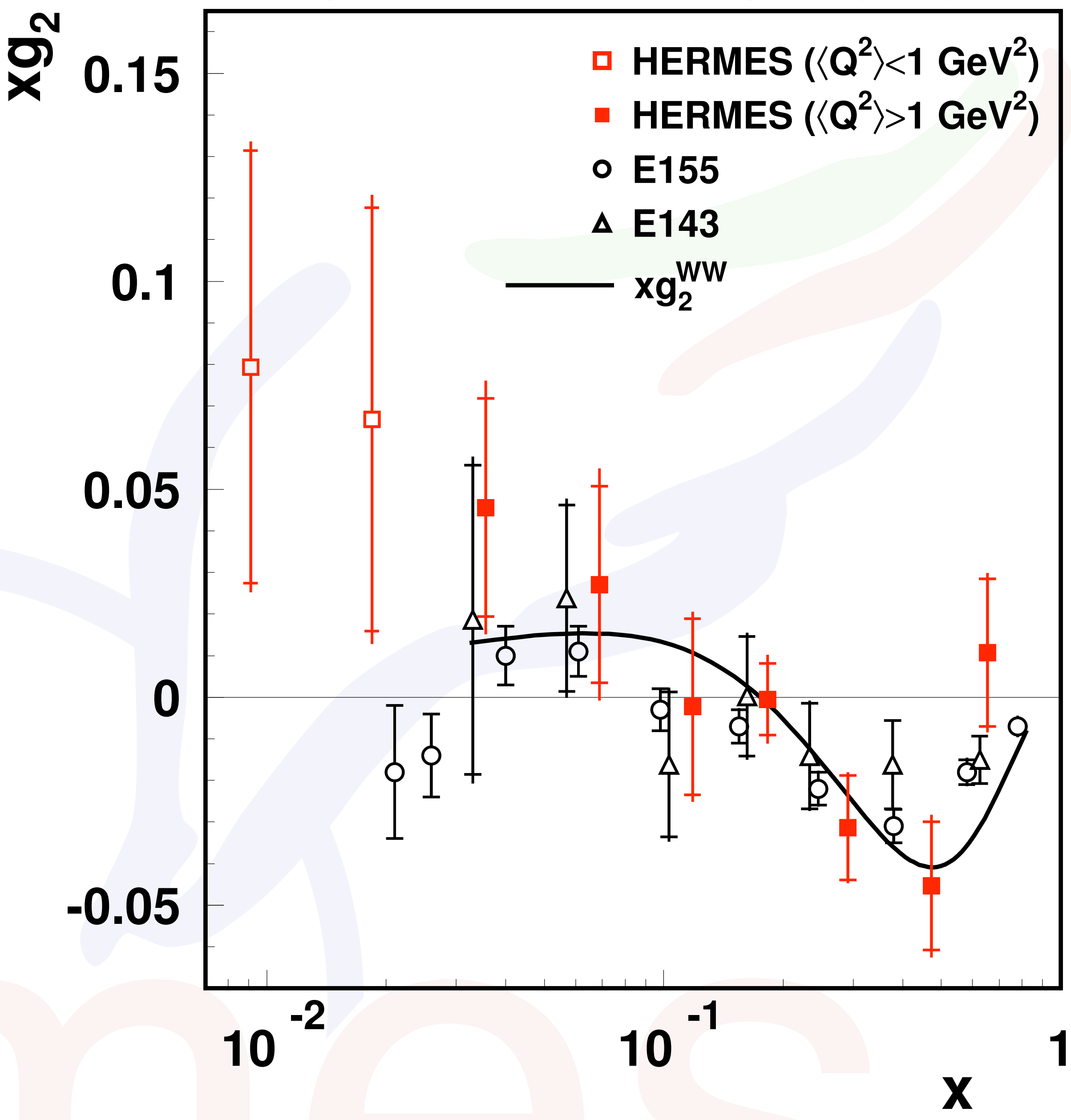

- consistent with (sparse) world data
- low beam polarization during HERA II ➥ small f.o.m.

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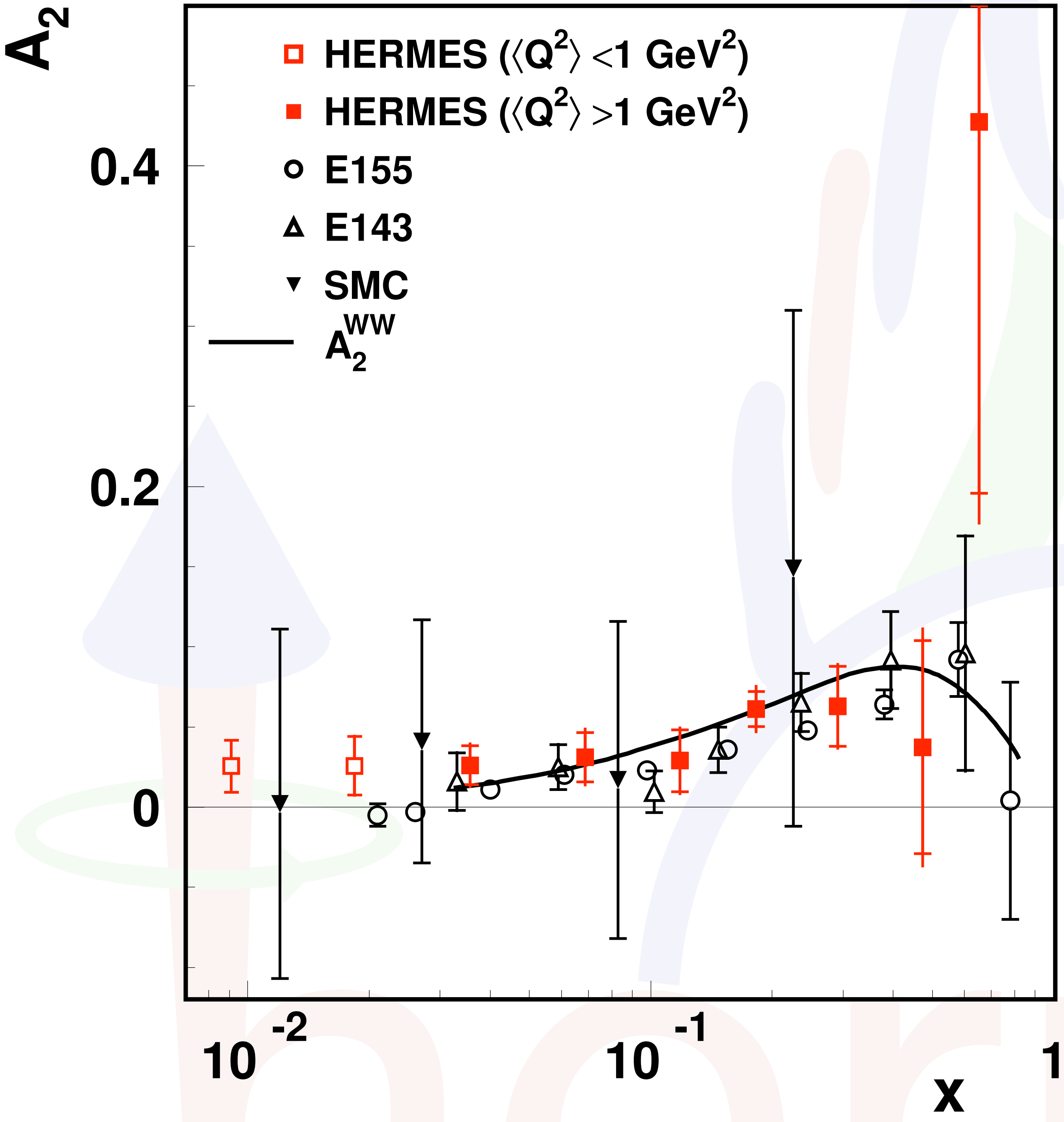

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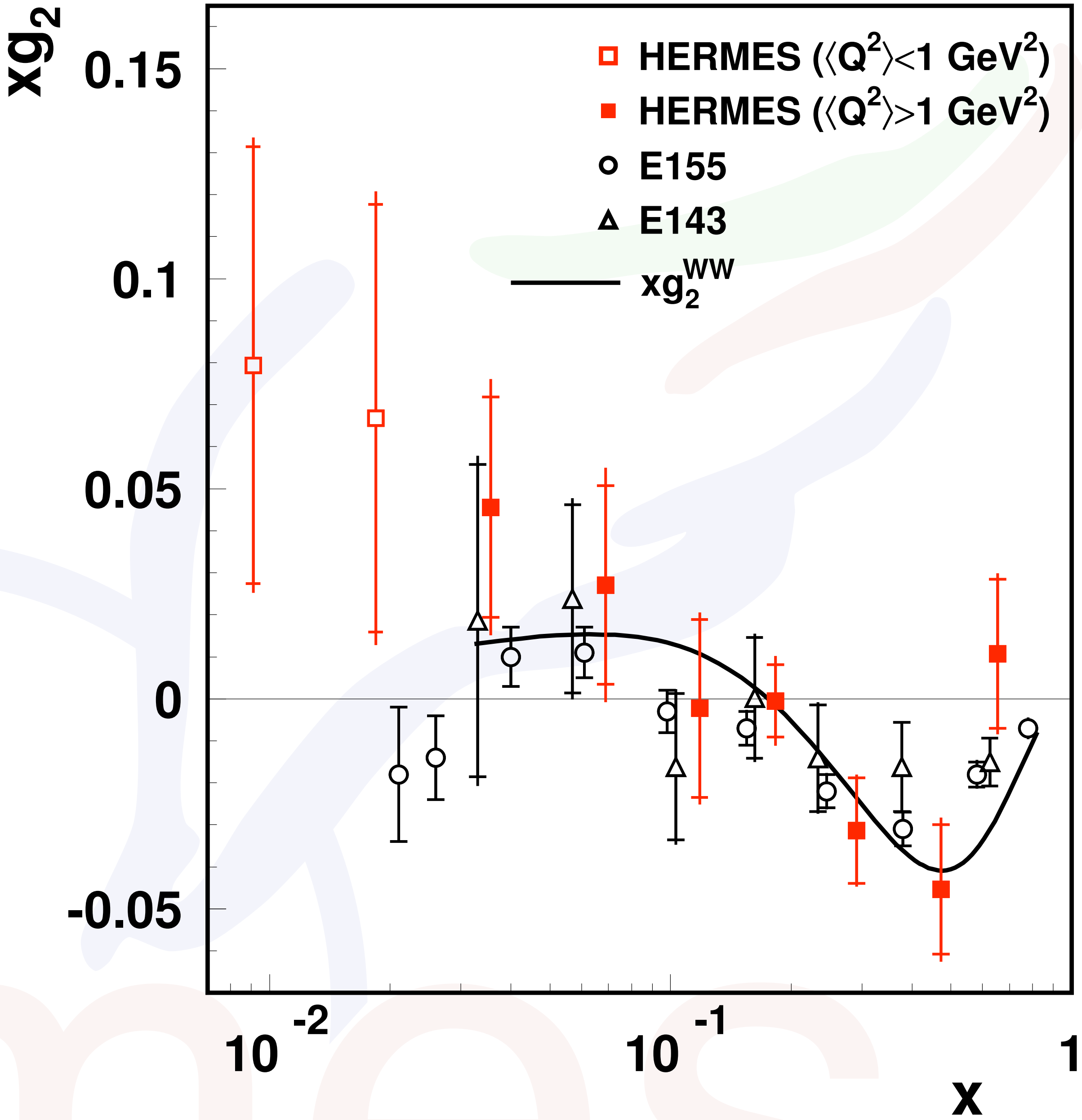

- consistent with (sparse) world data

☛ S. Korotkov (S1-VI)

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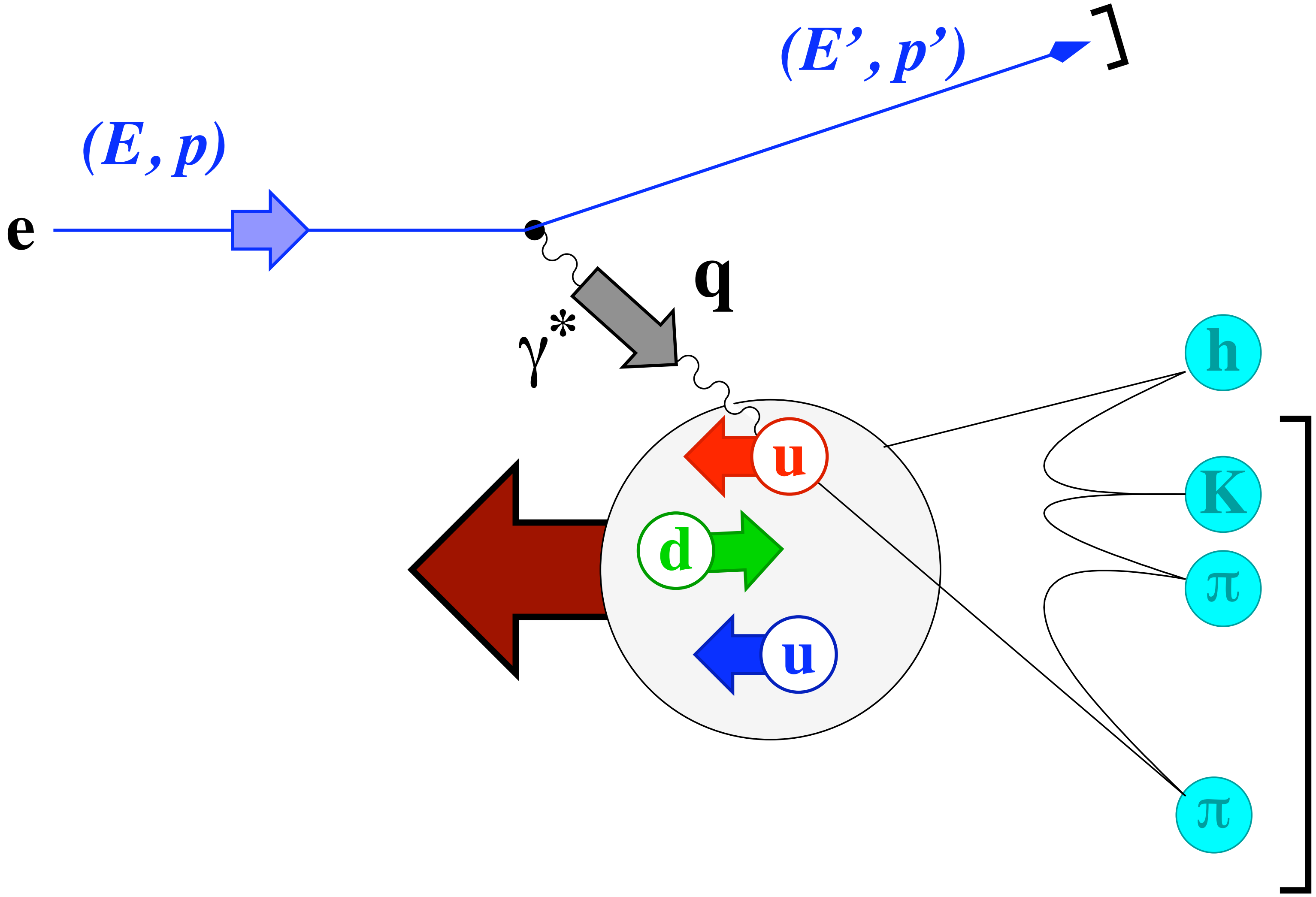
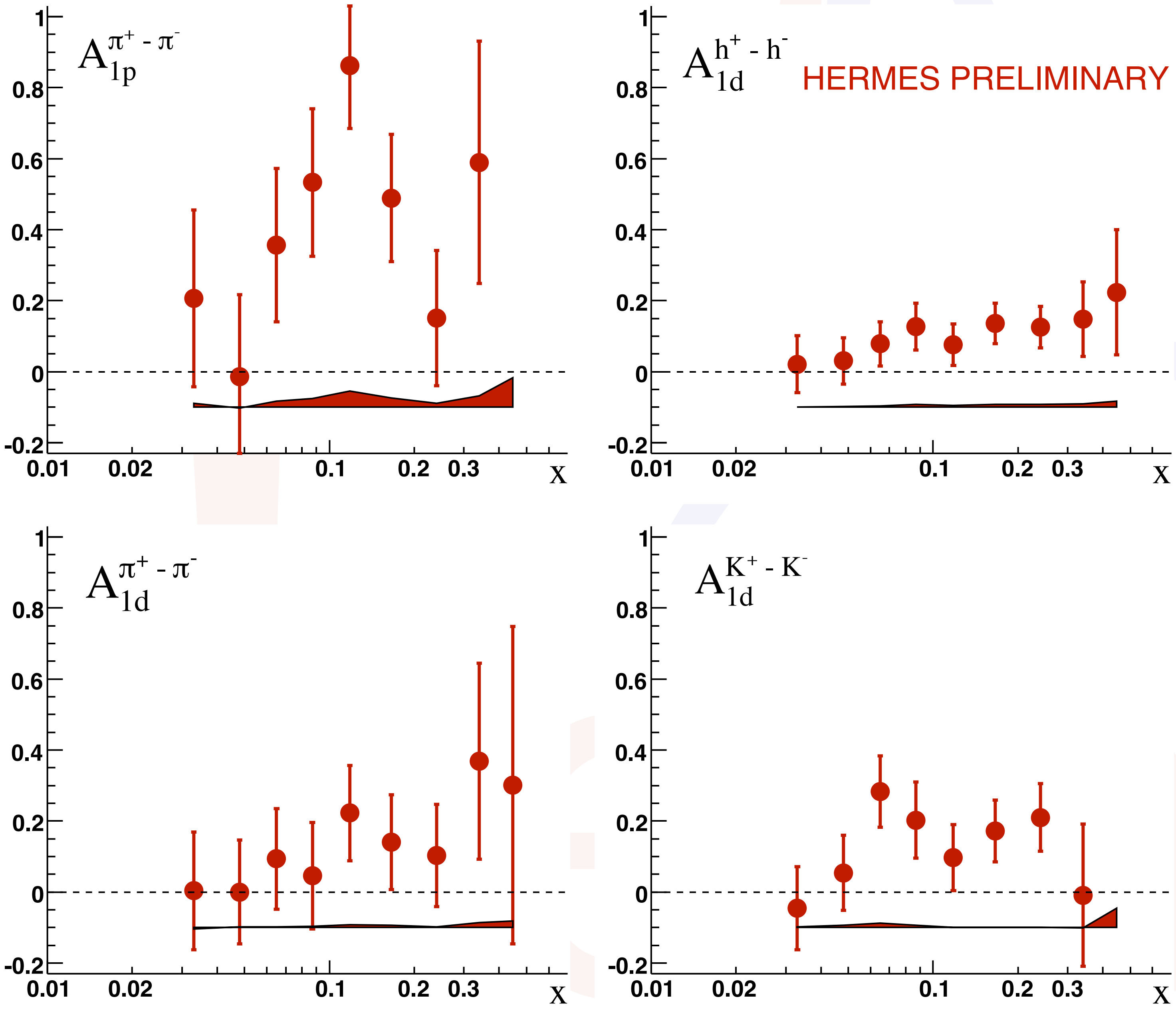
Semi-Inclusive DIS



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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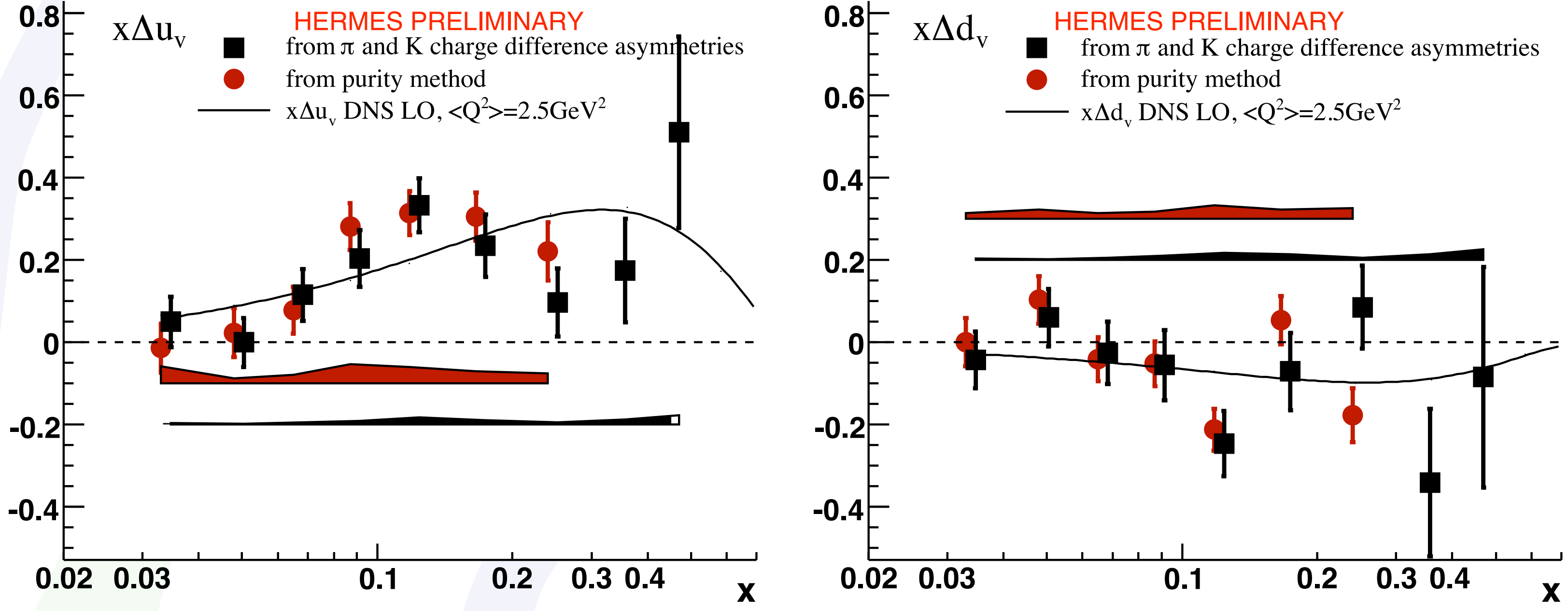
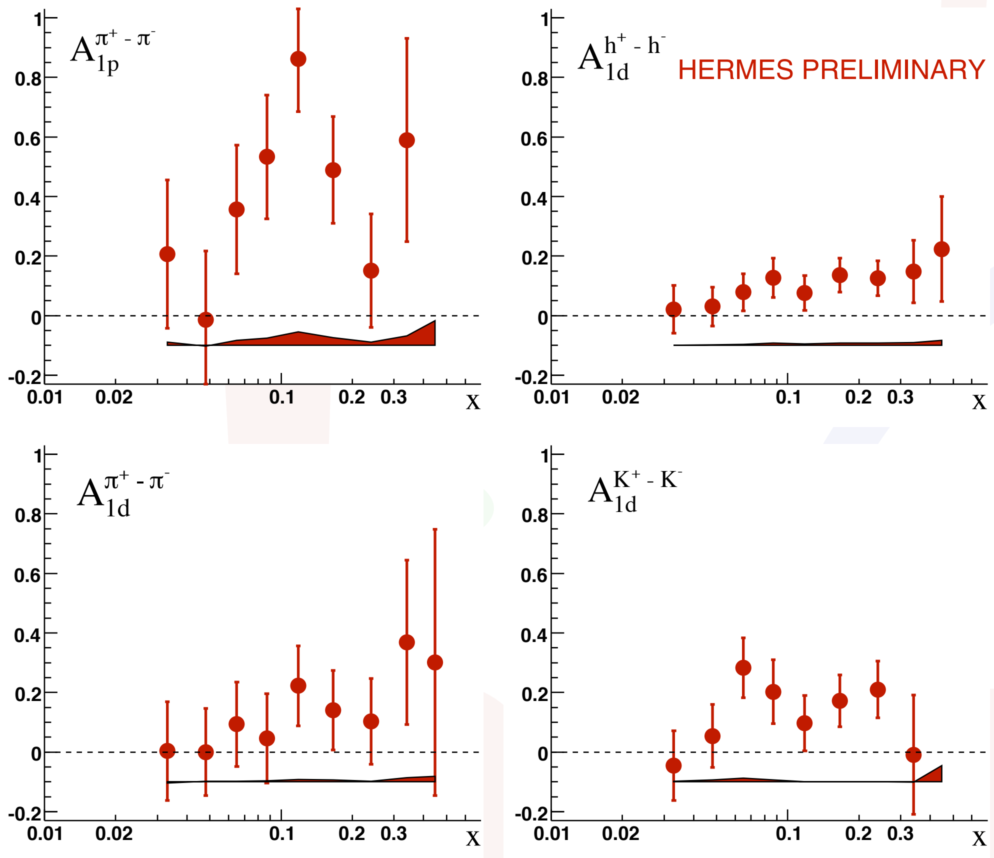




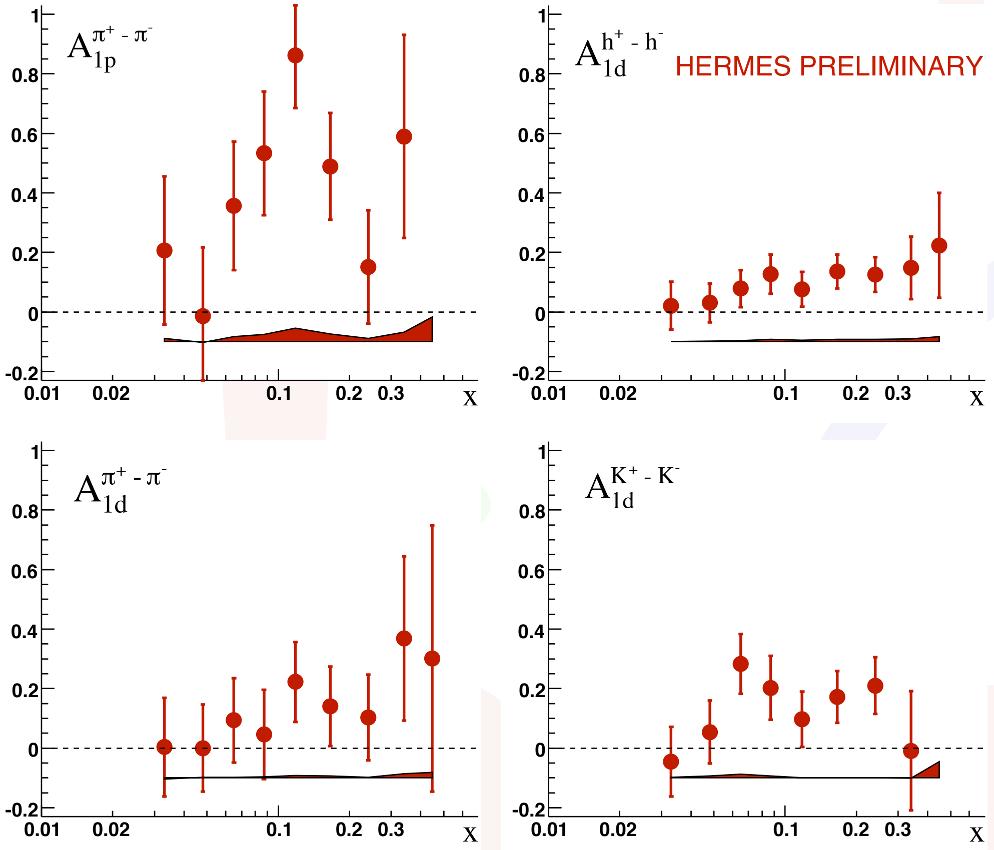
$$A_{1p}^{h^+-h^-} \cong \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}$$

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

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

Helicity density - valence quarks

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



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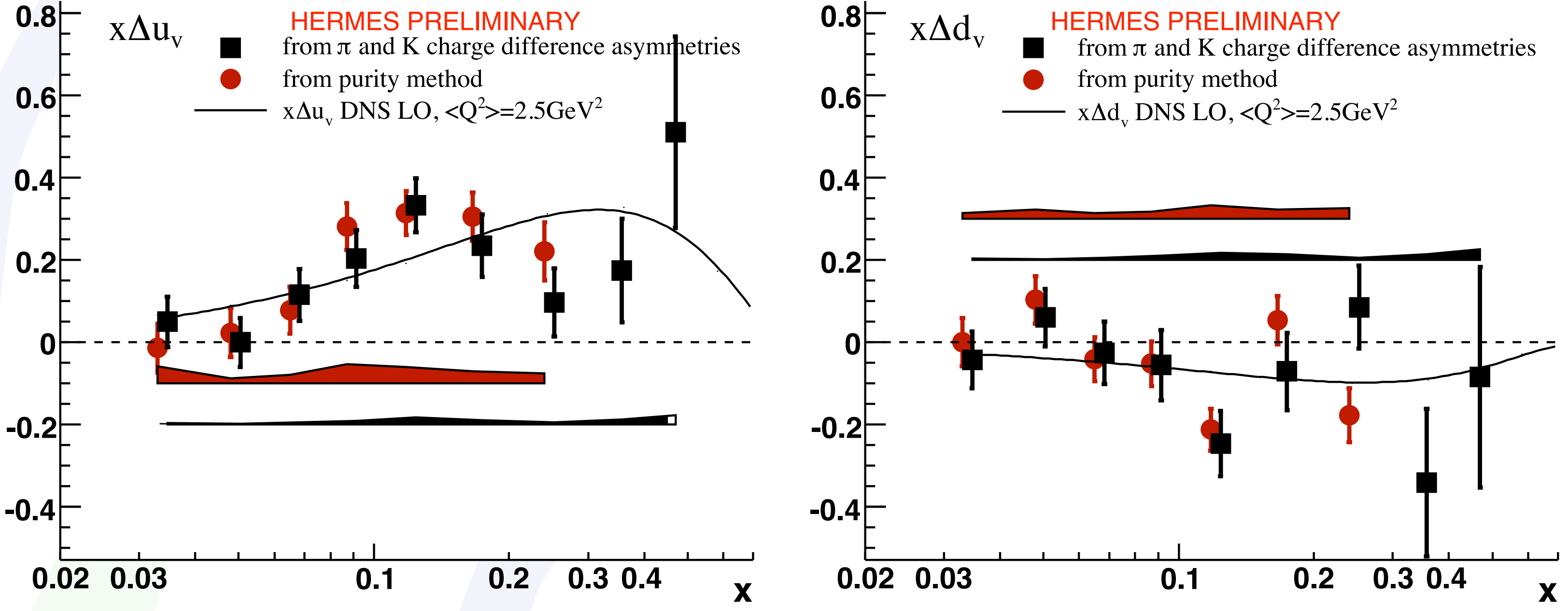

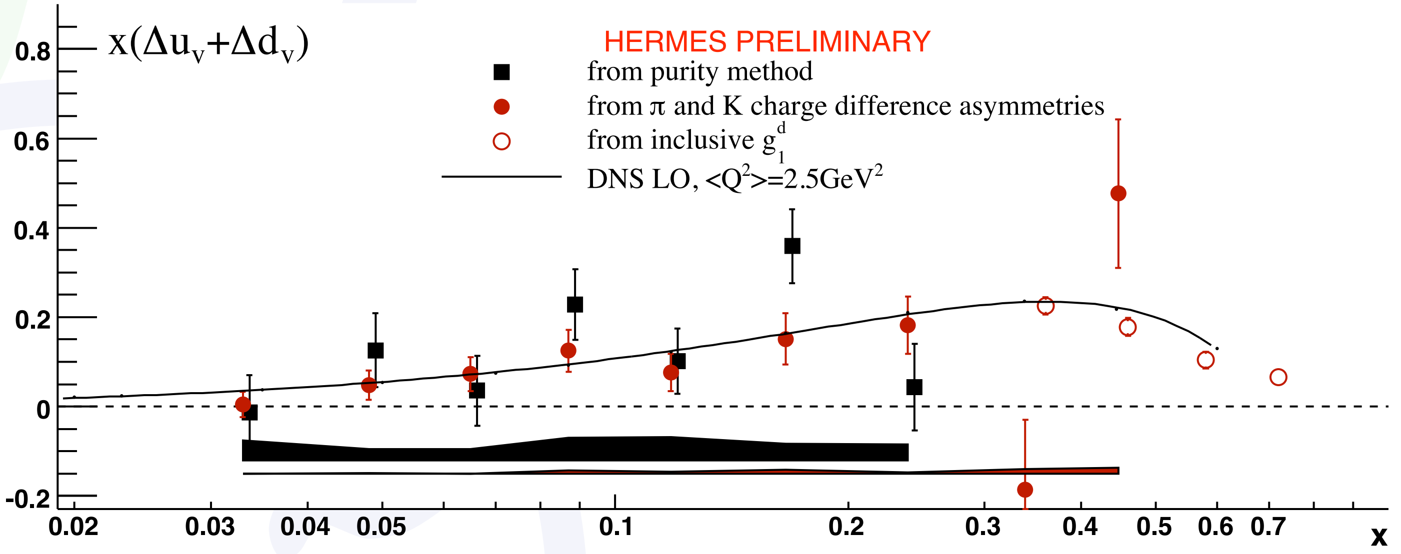

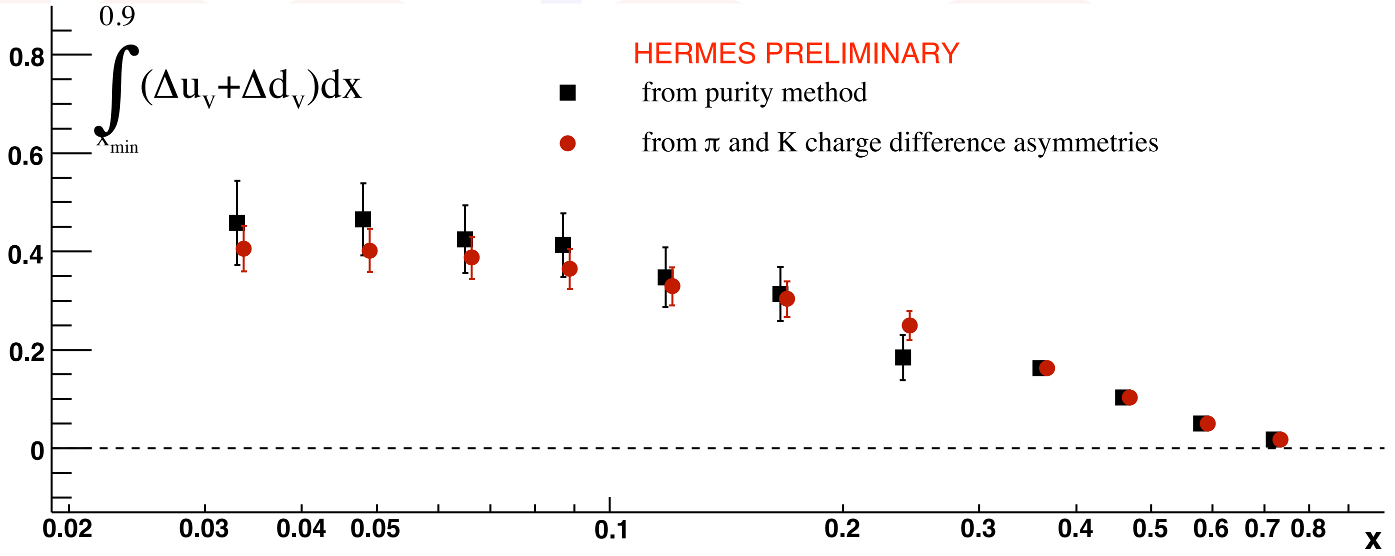

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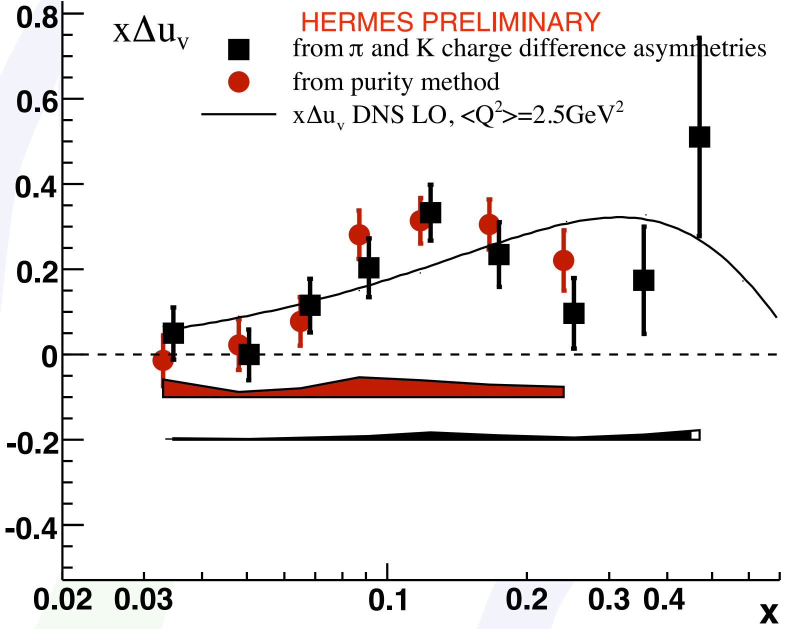

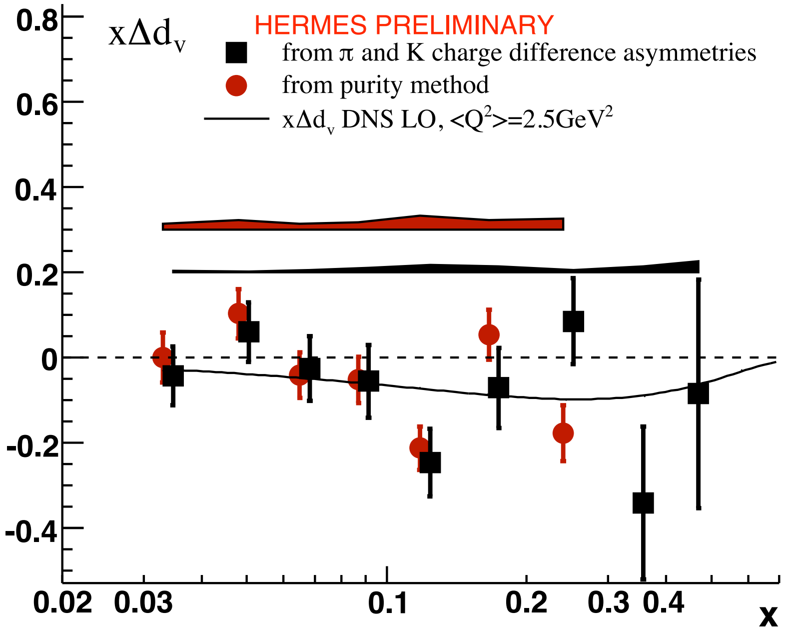

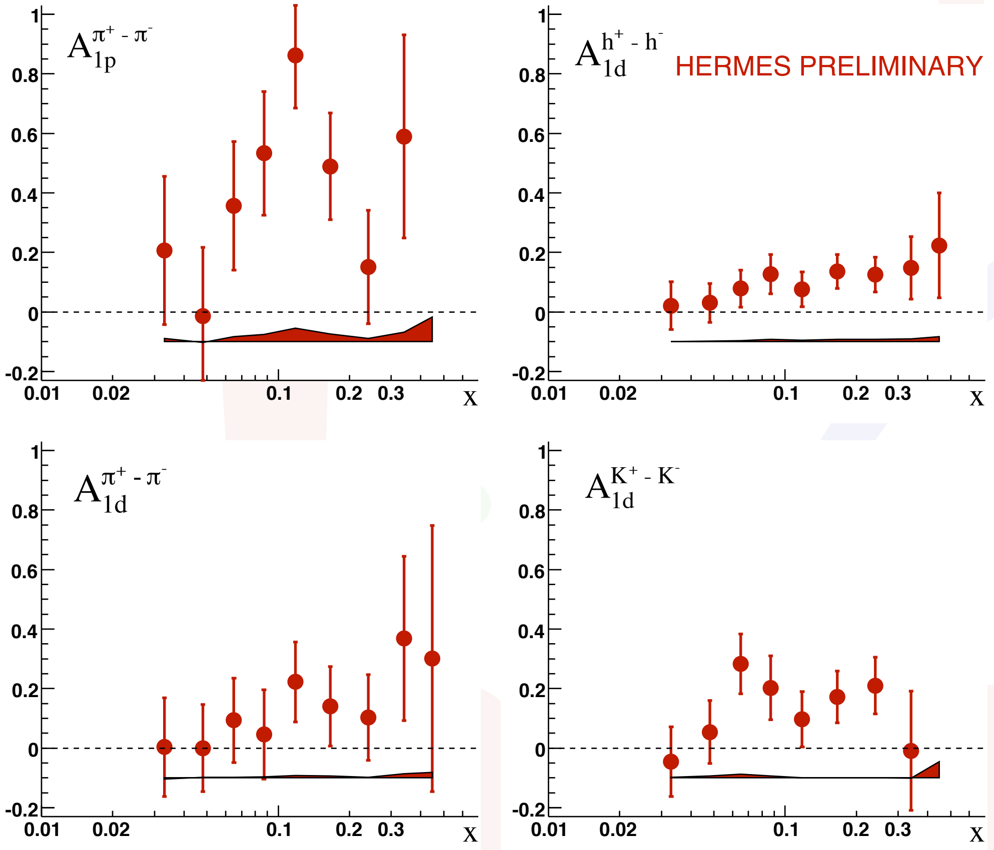

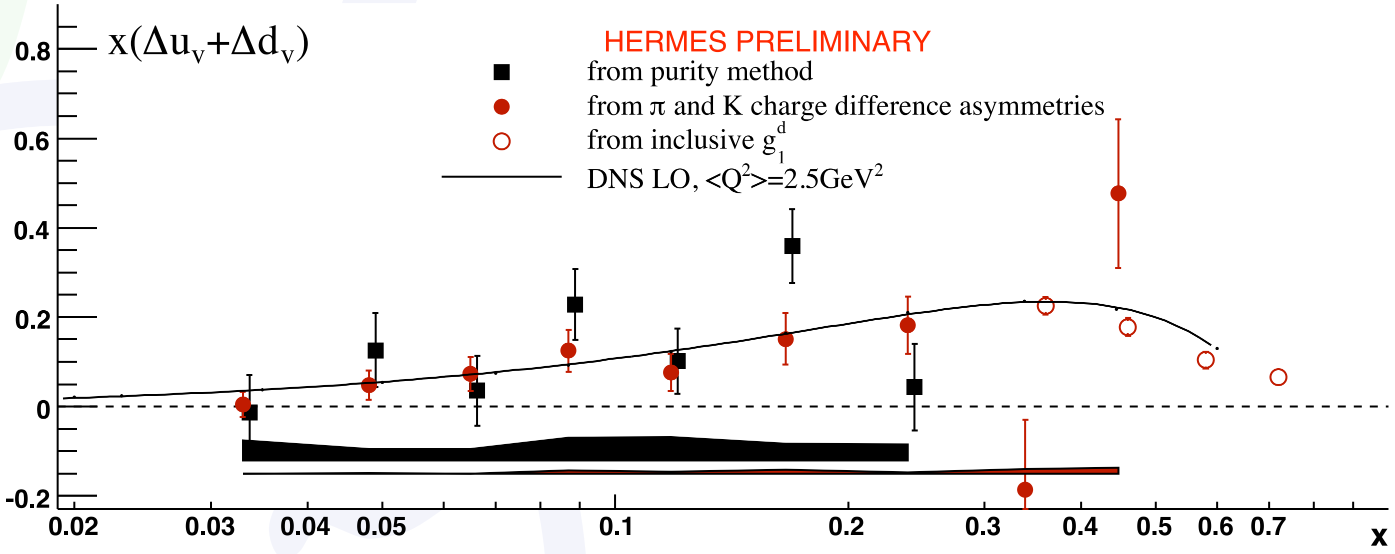

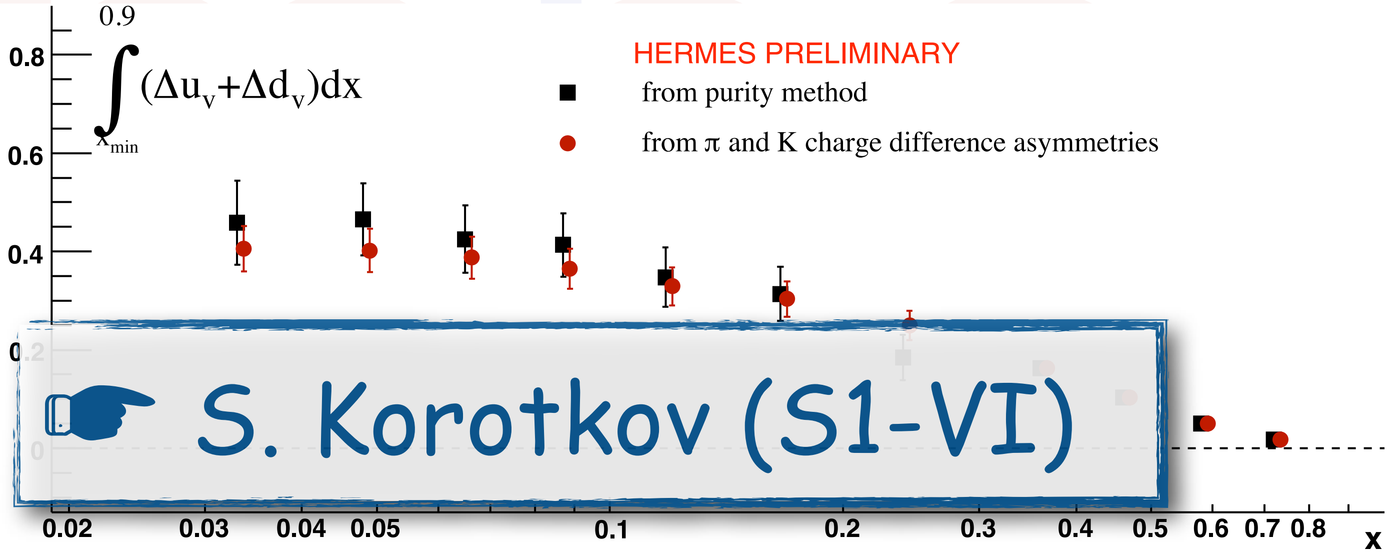

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… going 3D

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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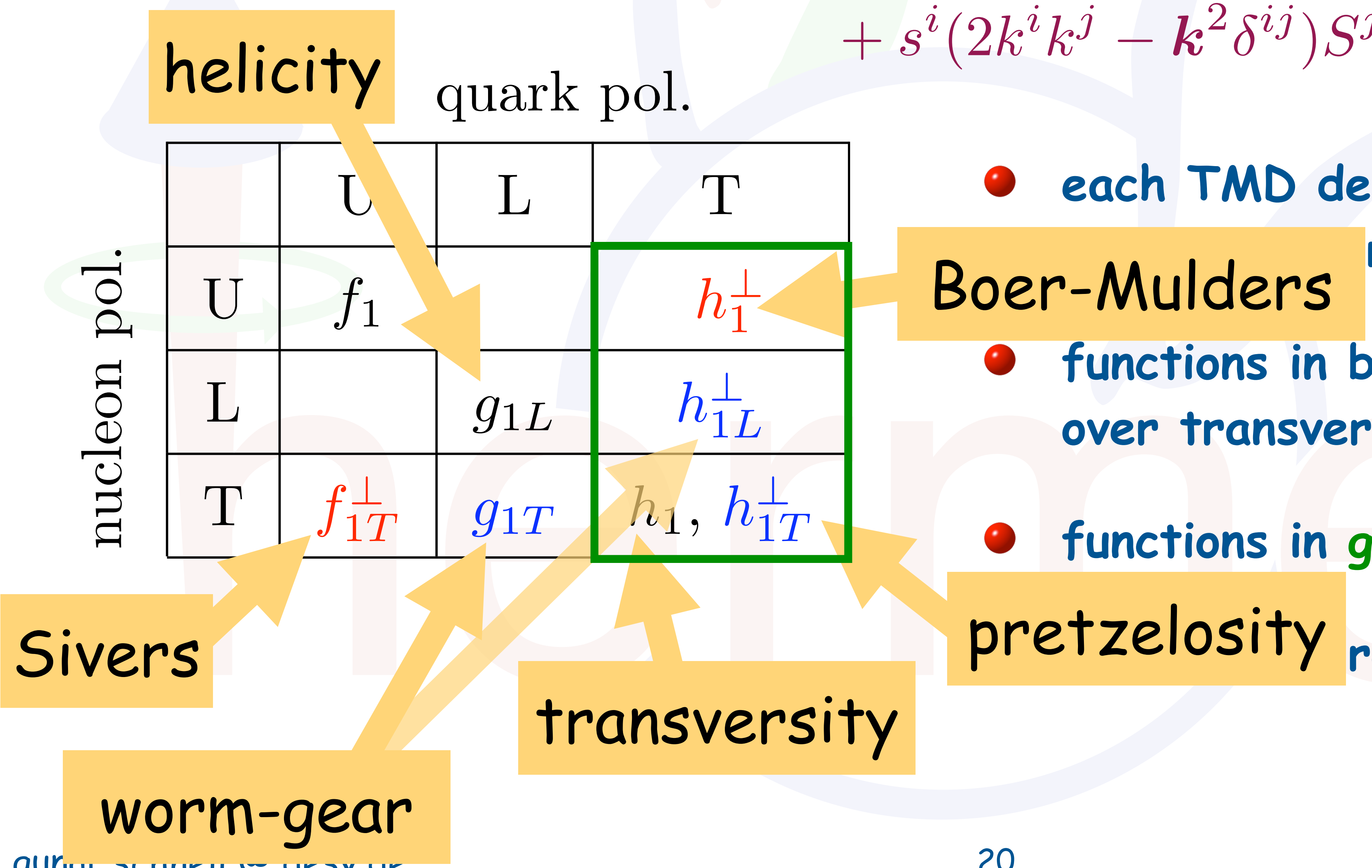

helicity

quark pol.

nucleon pol.

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Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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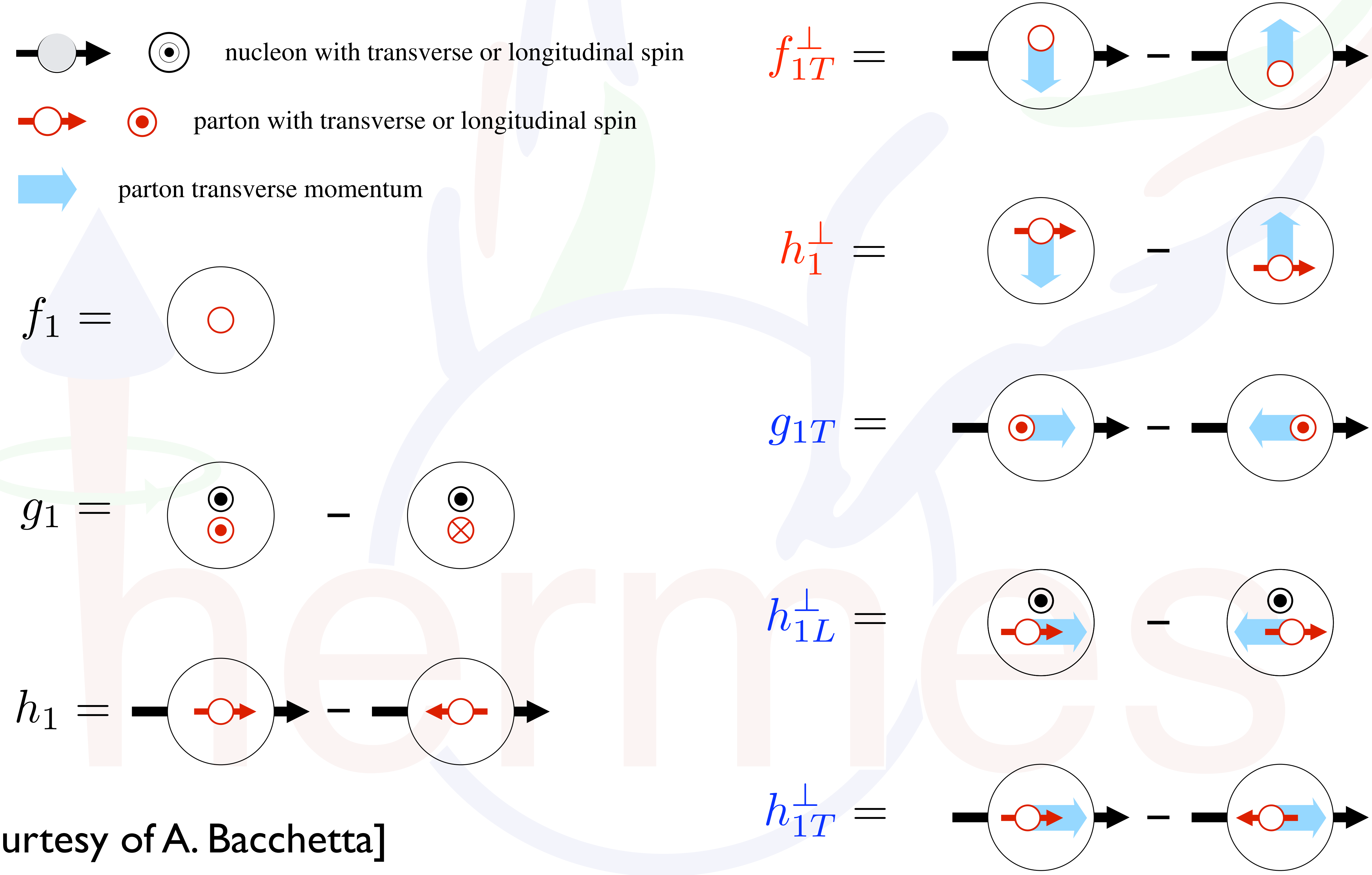
TMDs - Probabilistic interpretation

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



nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

$f_1 =$

$g_1 =$ –

$h_1 =$ –

$f_{1T}^{\perp} =$ –

$h_1^{\perp} =$ –

$g_{1T} =$ –

$h_{1L}^{\perp} =$ –

$h_{1T}^{\perp} =$ –

[courtesy of A. Bacchetta]

Probing TMDs in semi-inclusive DIS

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in SIDIS couple PDFs to:

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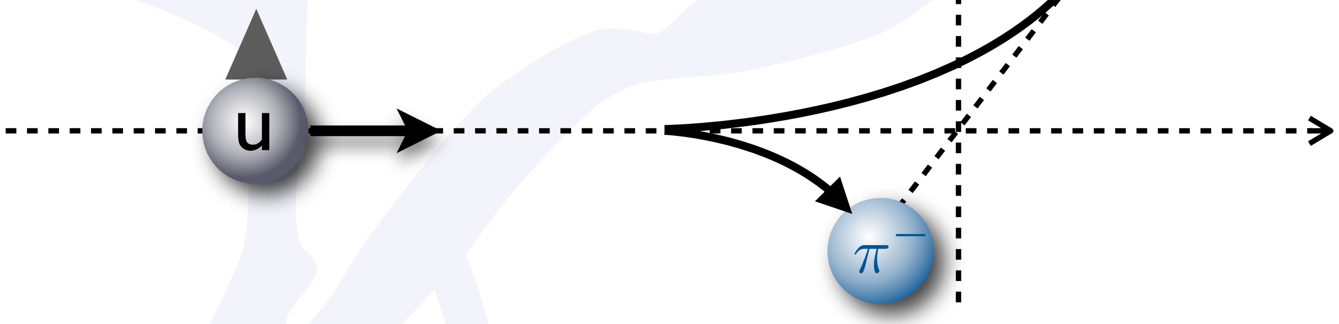
Collins FF: $H_1^{\perp,q\to h}$



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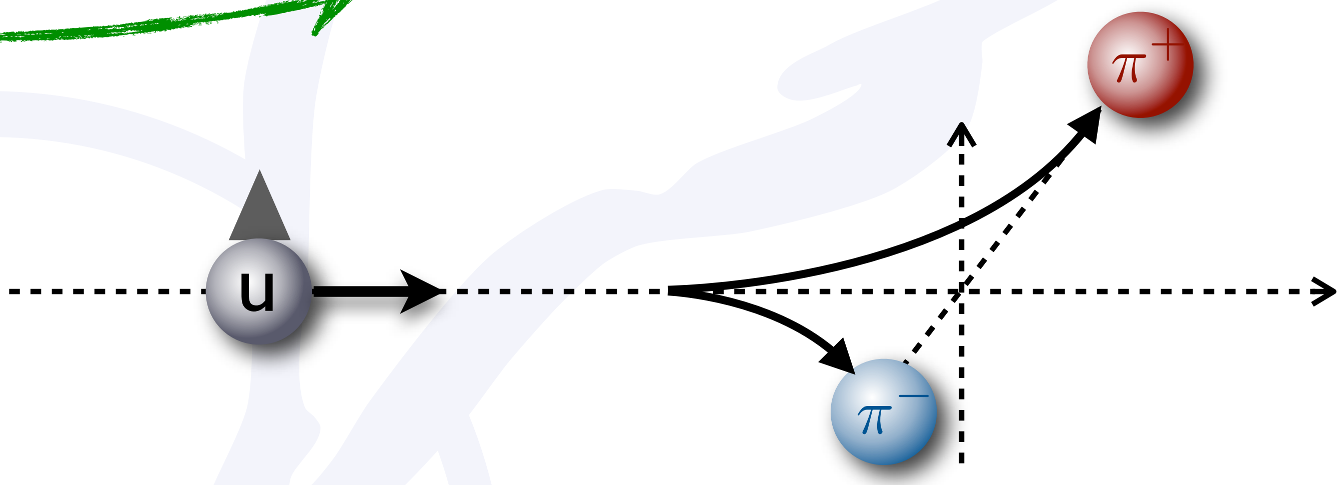

ordinary FF: $D_1^{q\to h}$

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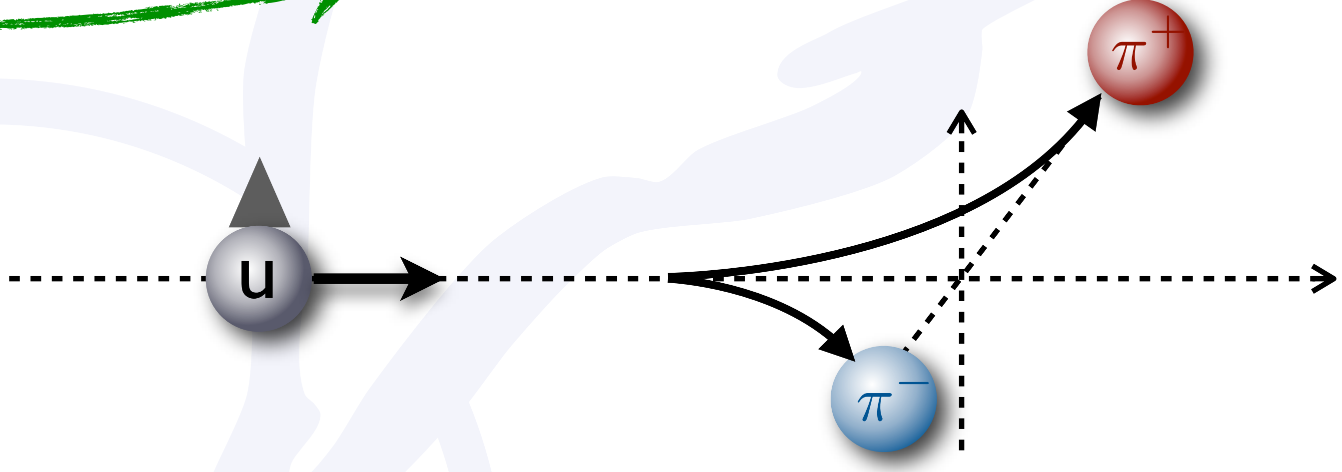


ordinary FF: $D_1^{q\rightarrow h}$

gives rise to characteristic azimuthal dependences

1-Hadron production (ep→ehX)

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

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

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

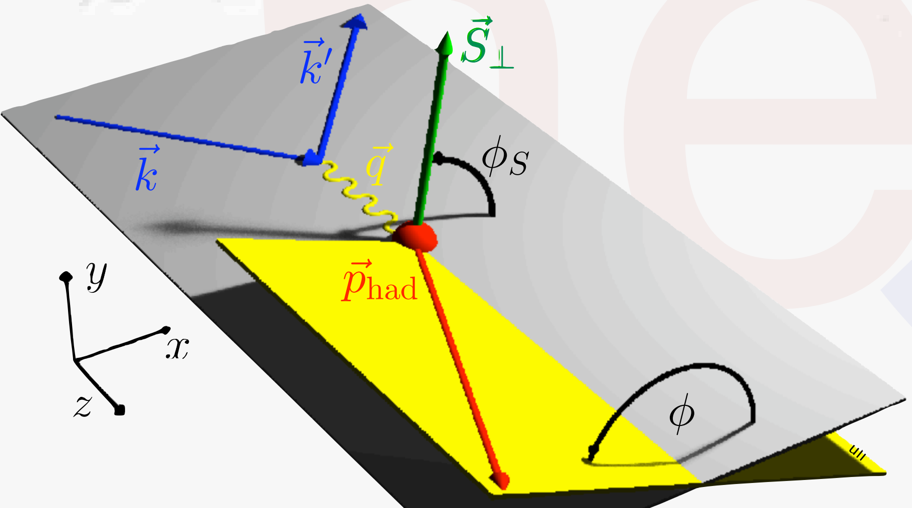
$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

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

$$\sigma_{XY}$$

Beam **Target**

Polarization



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

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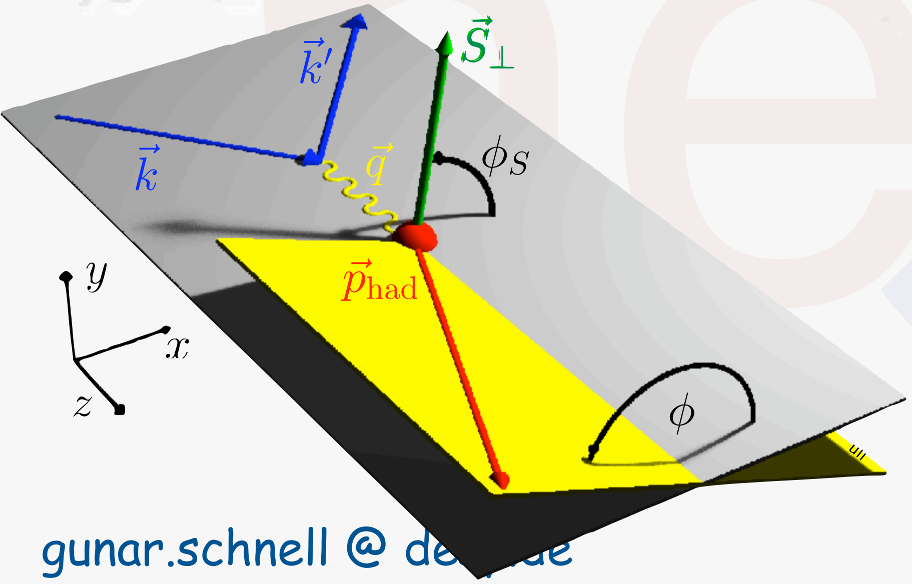
σ_{XY}

$\swarrow \quad \searrow$

Beam **Target**

Polarization



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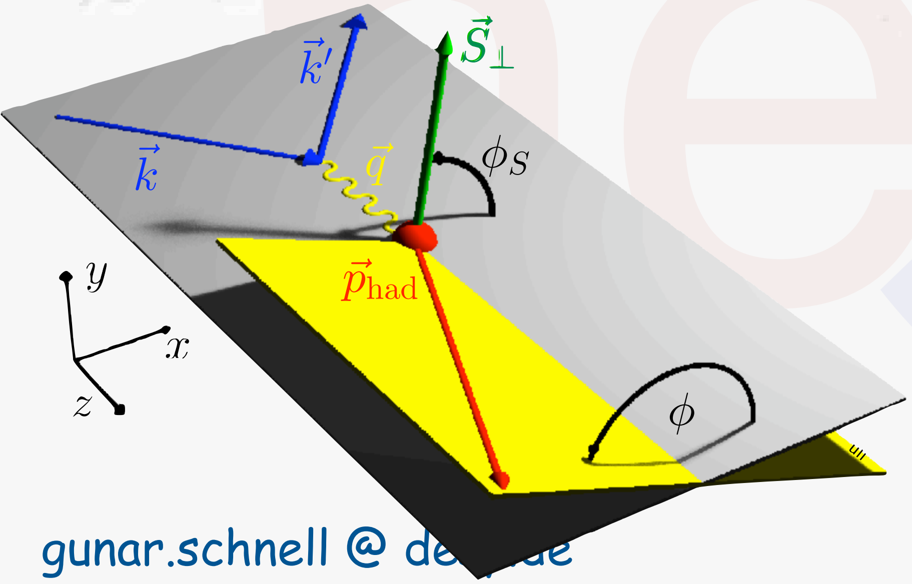

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Transversely polarized quarks?

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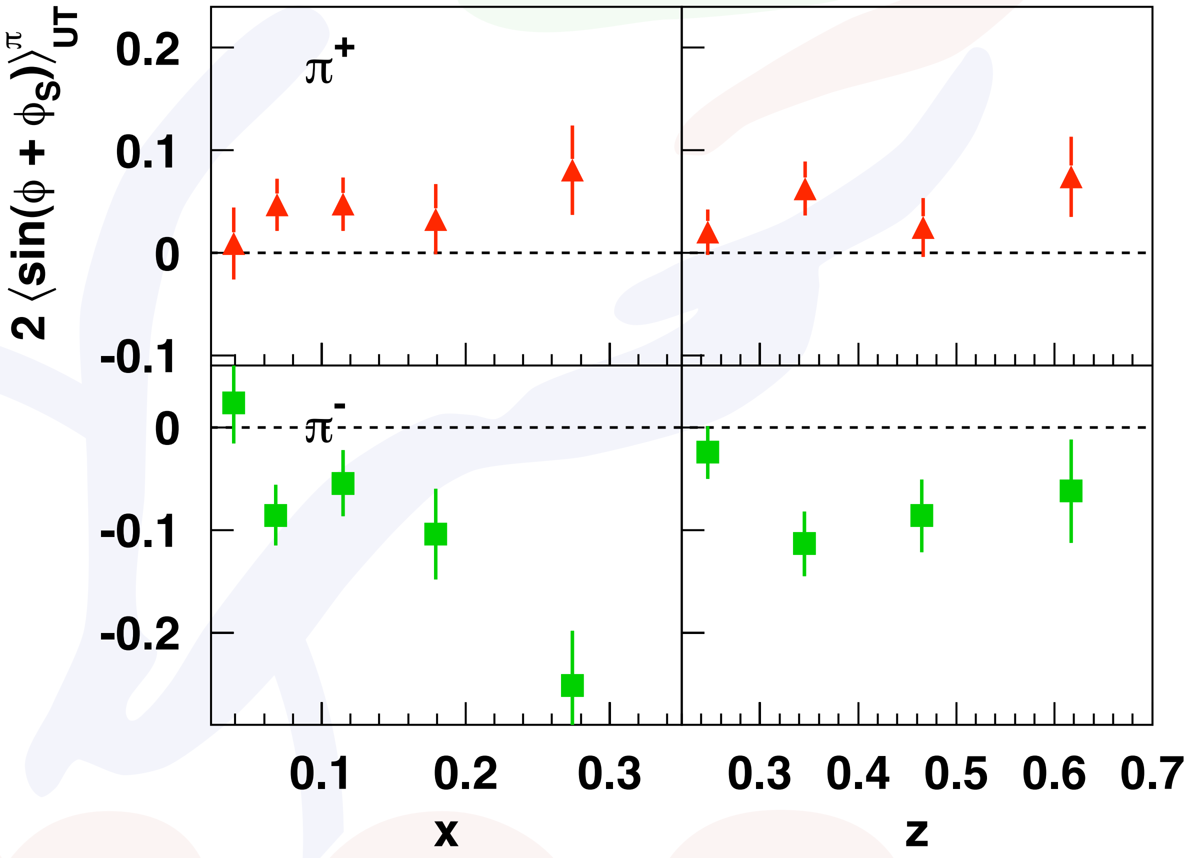
- transverse polarization of quarks leads to large effects!

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



2005: First evidence from HERMES
SIDIS on proton

Non-zero transversity
Non-zero Collins function

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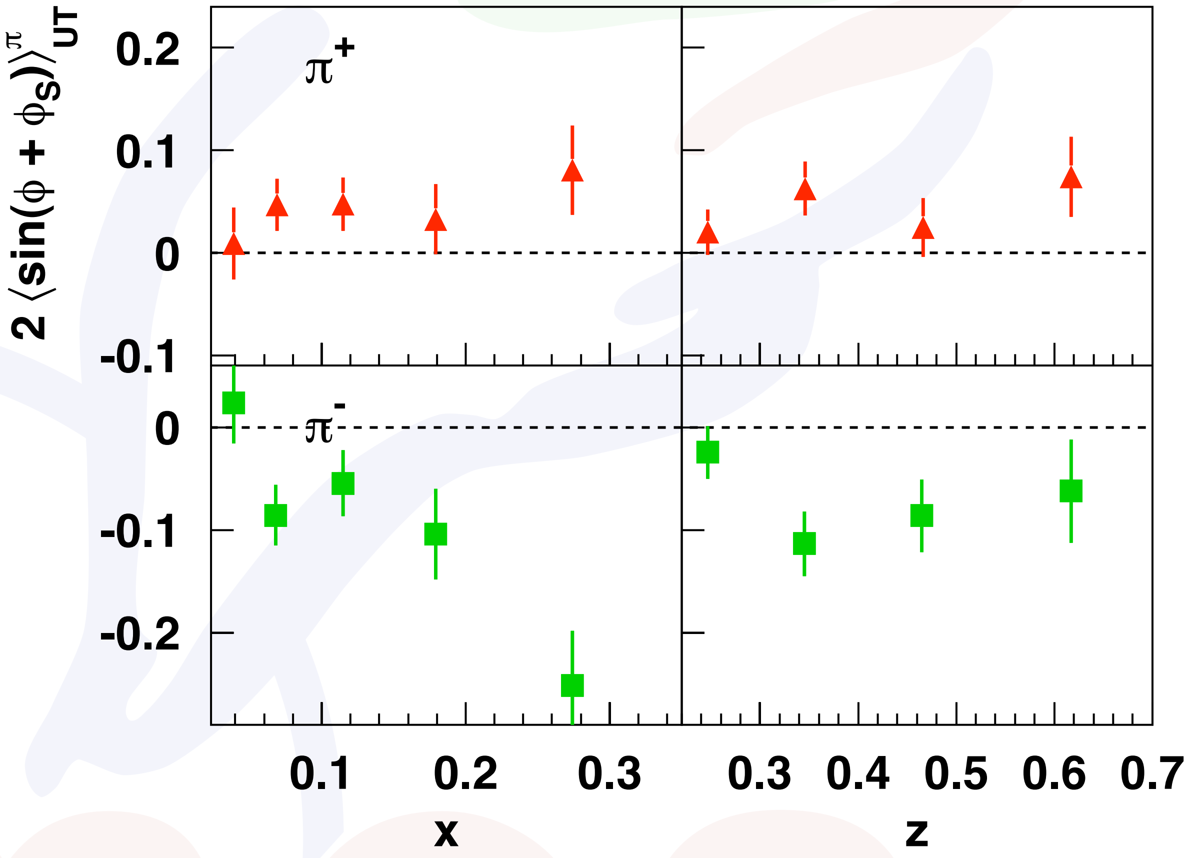

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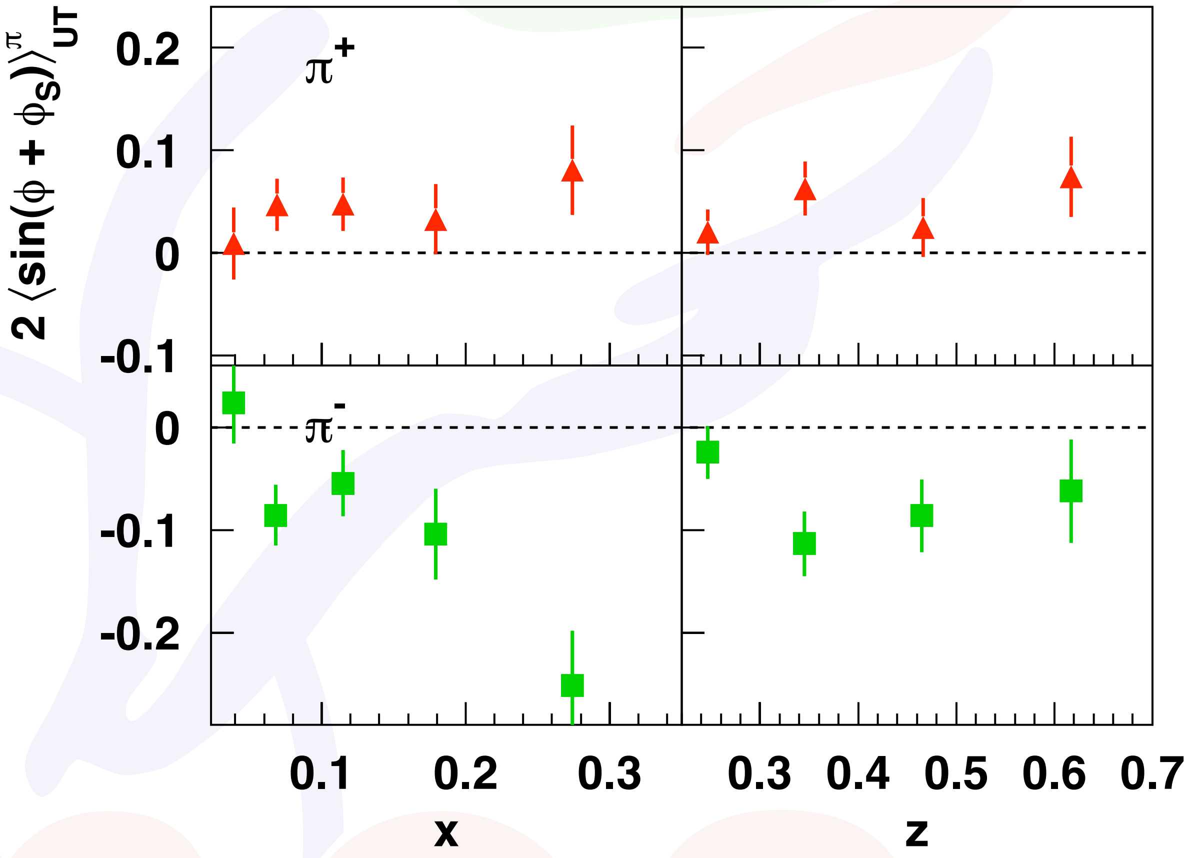

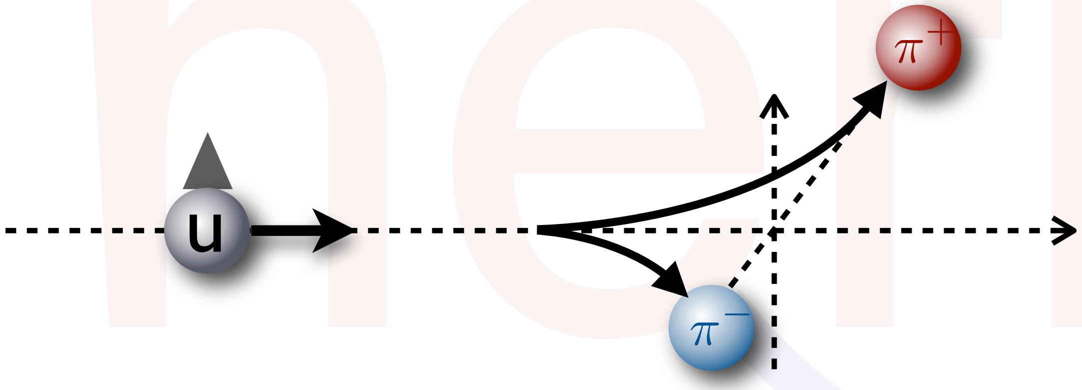

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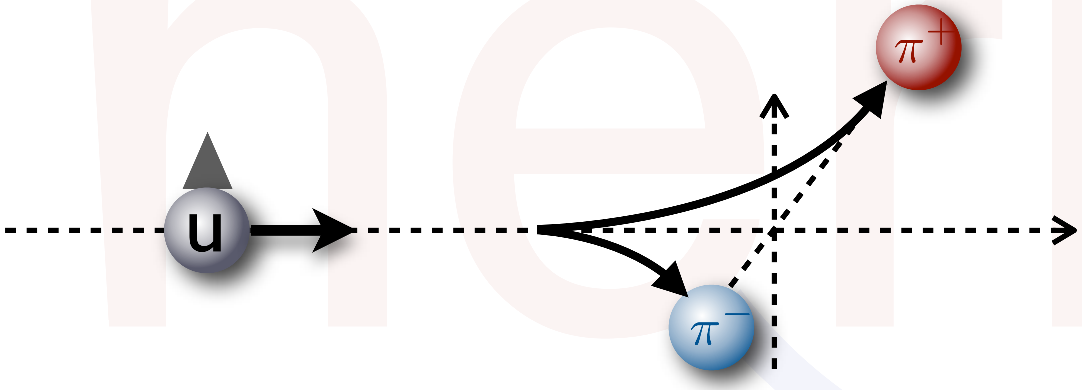
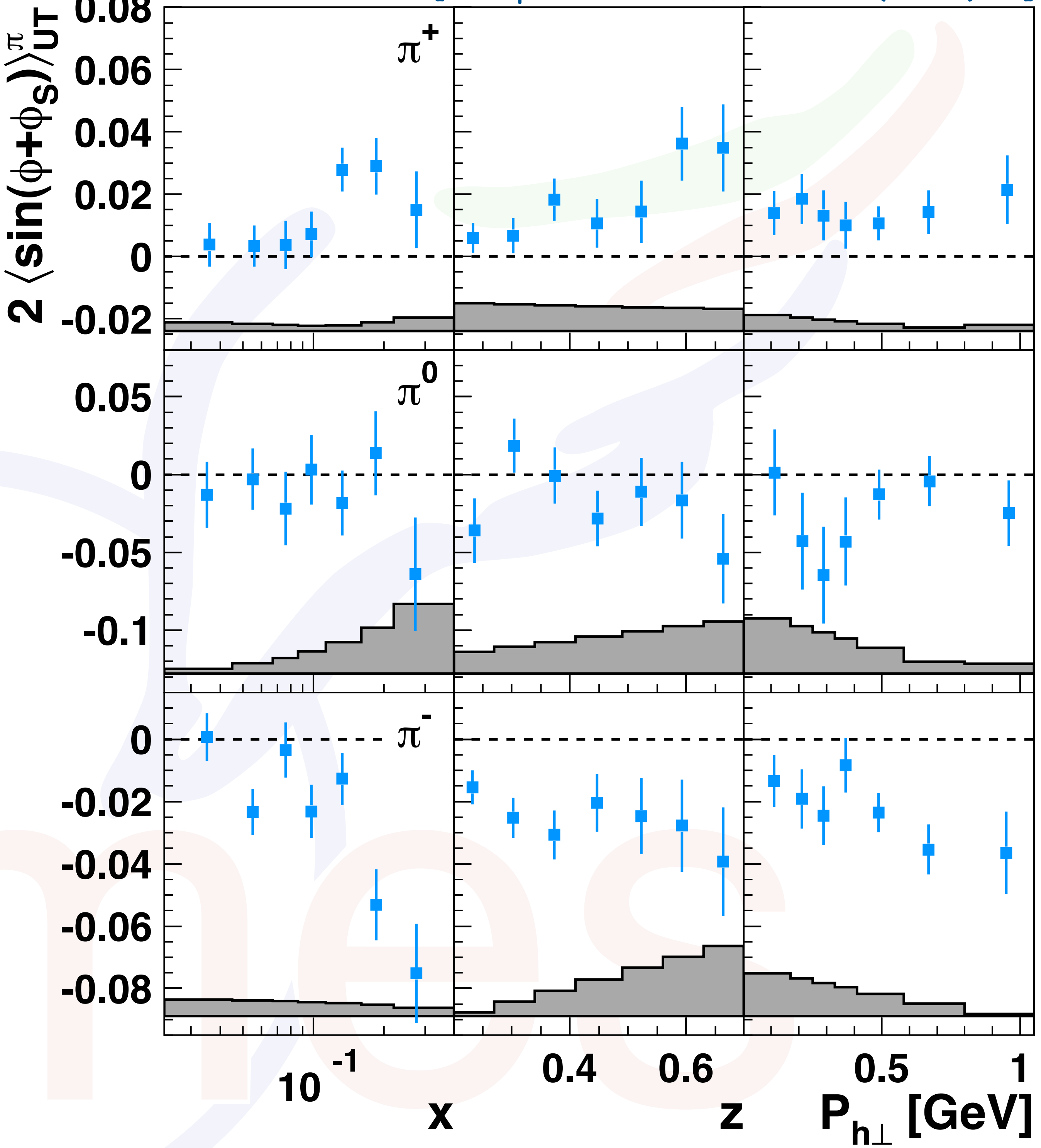


[Airapetian et al., PLB 693 (2010) 11]



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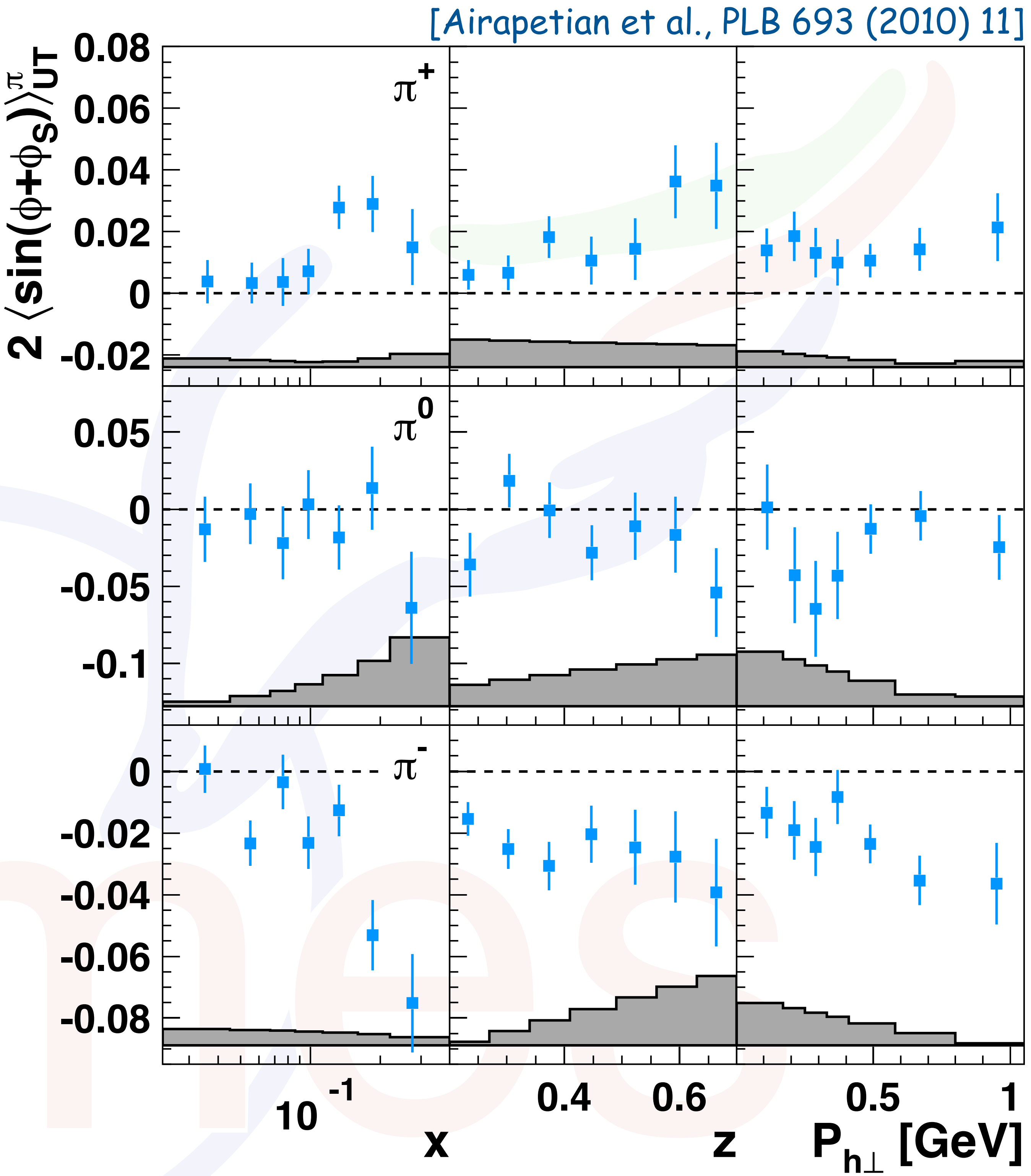
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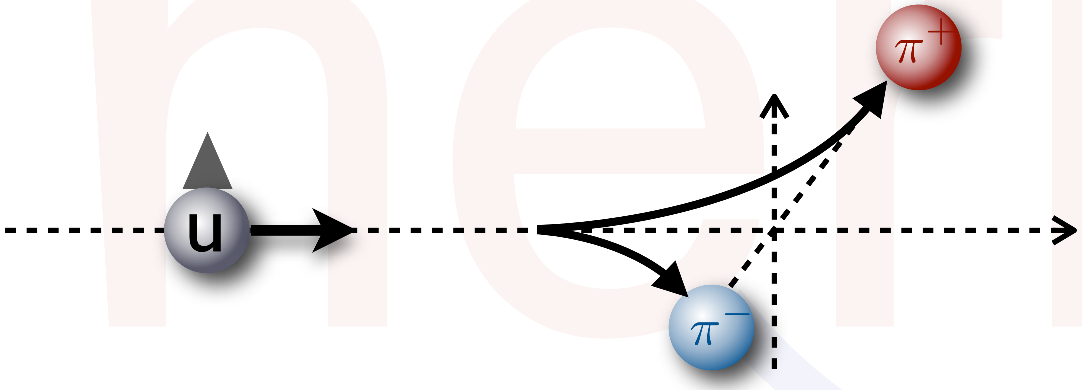
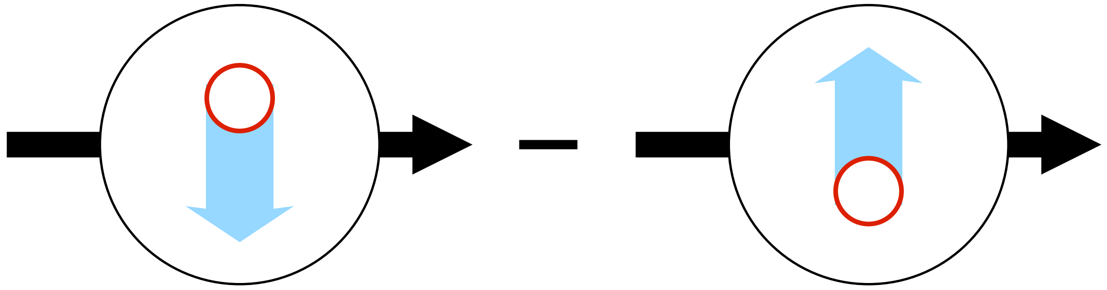


☛ L. Pappalardo (S1-VI)

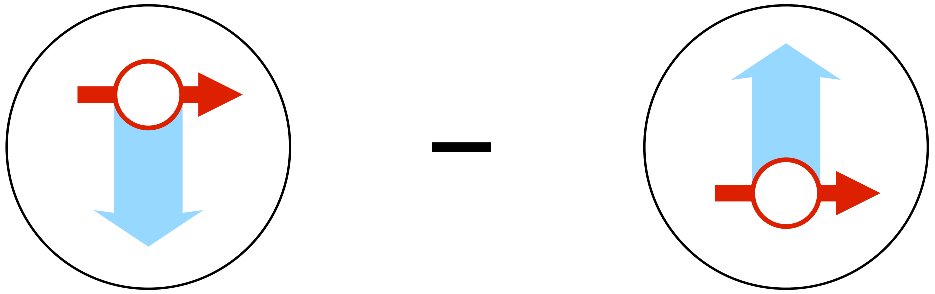


Sivers effect

naively T-odd distributions

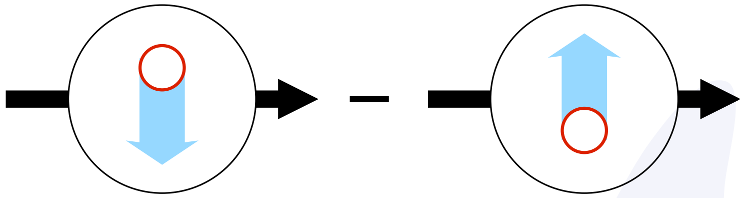
“Wilson-line physics”

Boer-Mulders effect



Sivers function

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



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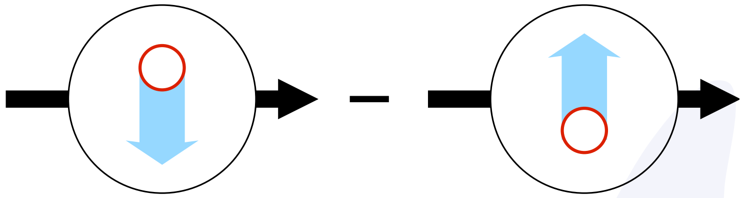

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- candidate for large (30-50%) asymmetries in p$^{\uparrow}$p->hX

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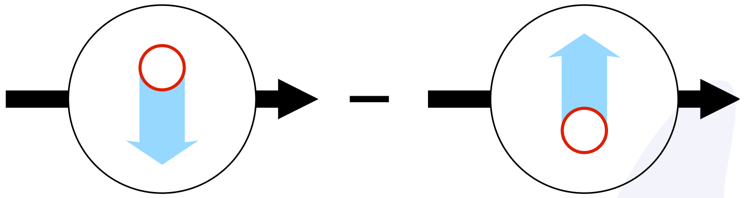

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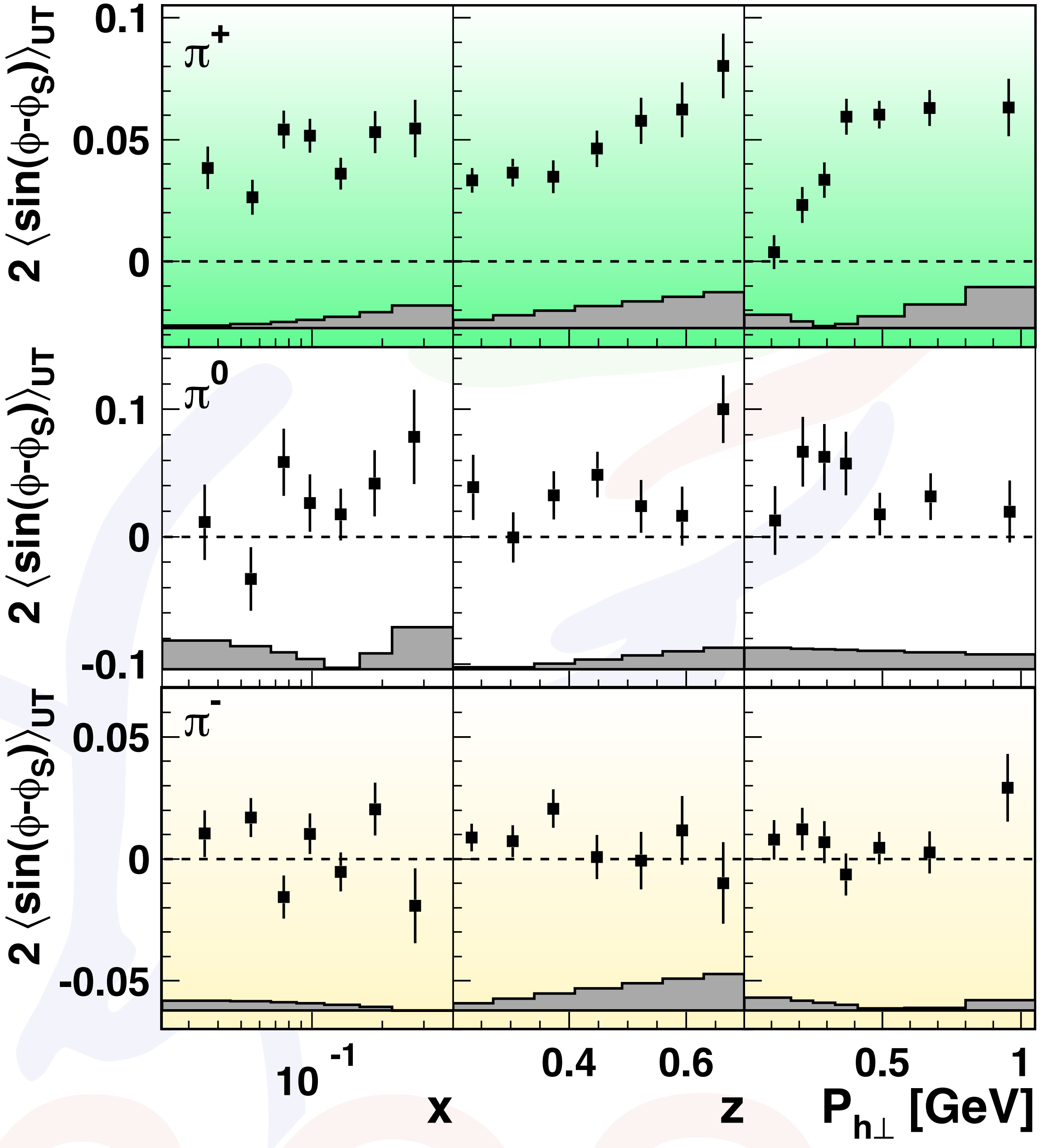

[PRL 103 (2009) 152002]

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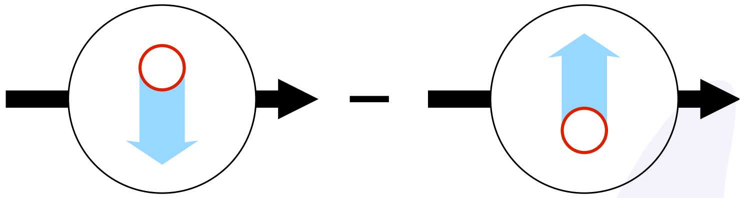

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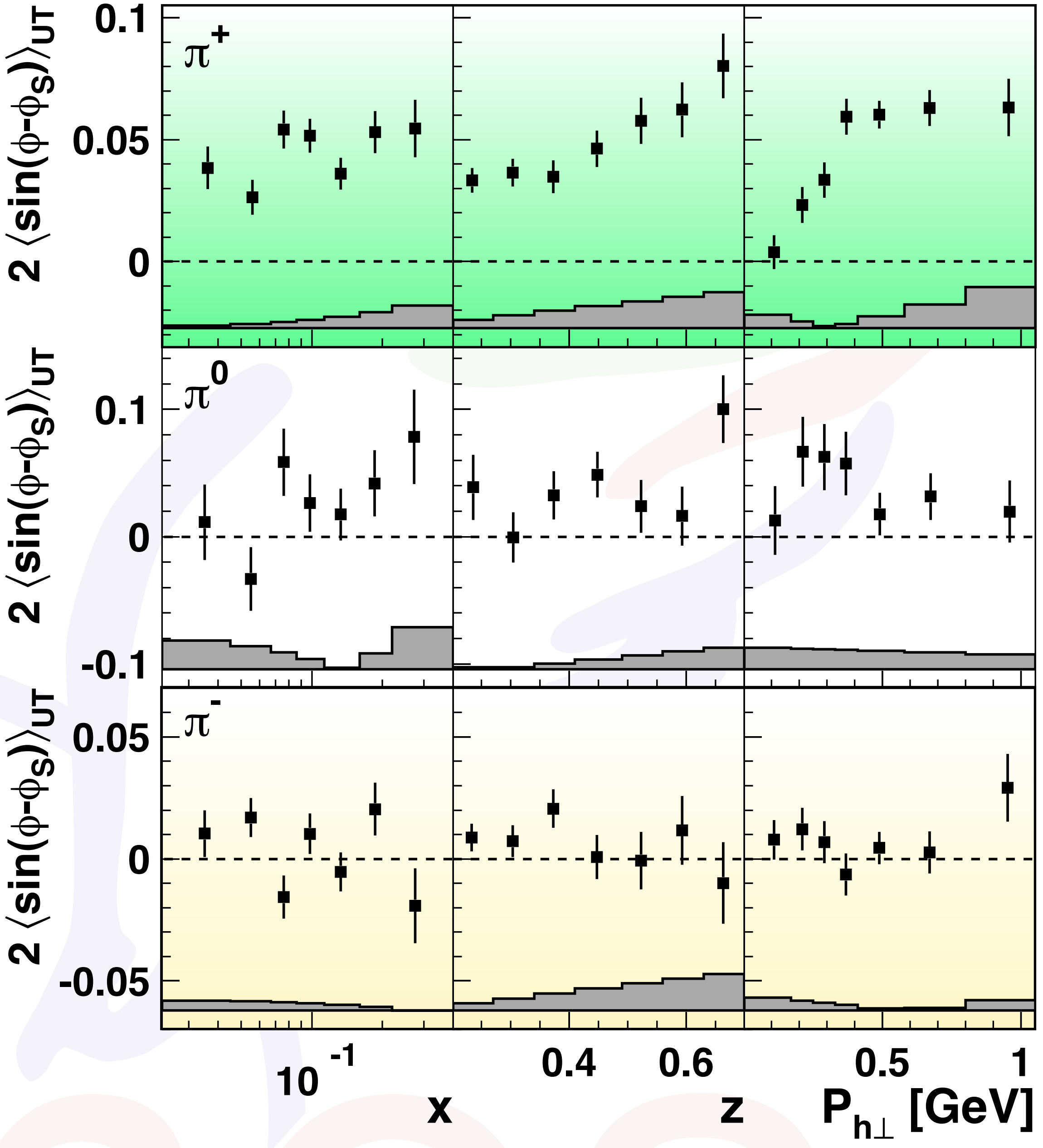

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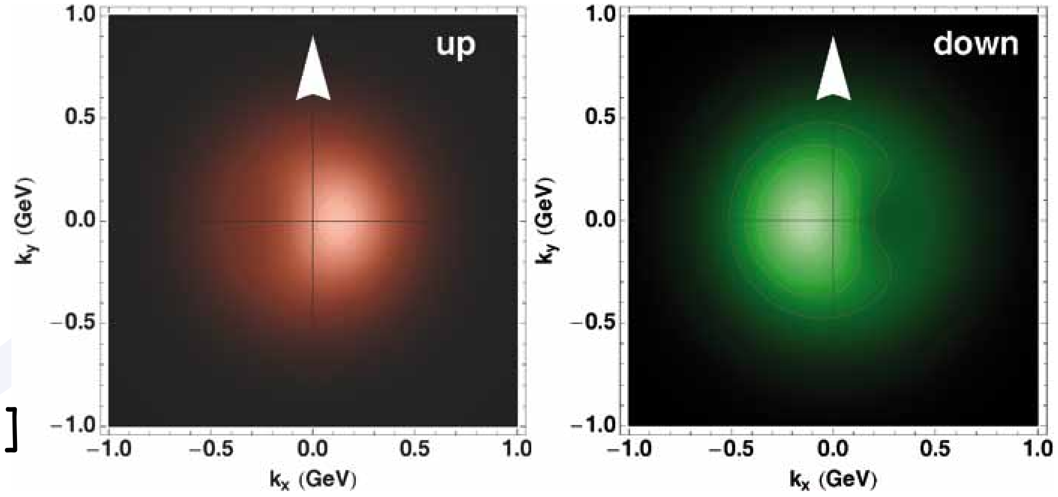

[courtesy of A. Bacchetta]

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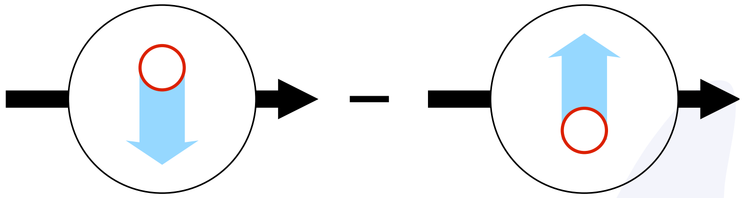
$f_{1T}^{\perp} =$ 

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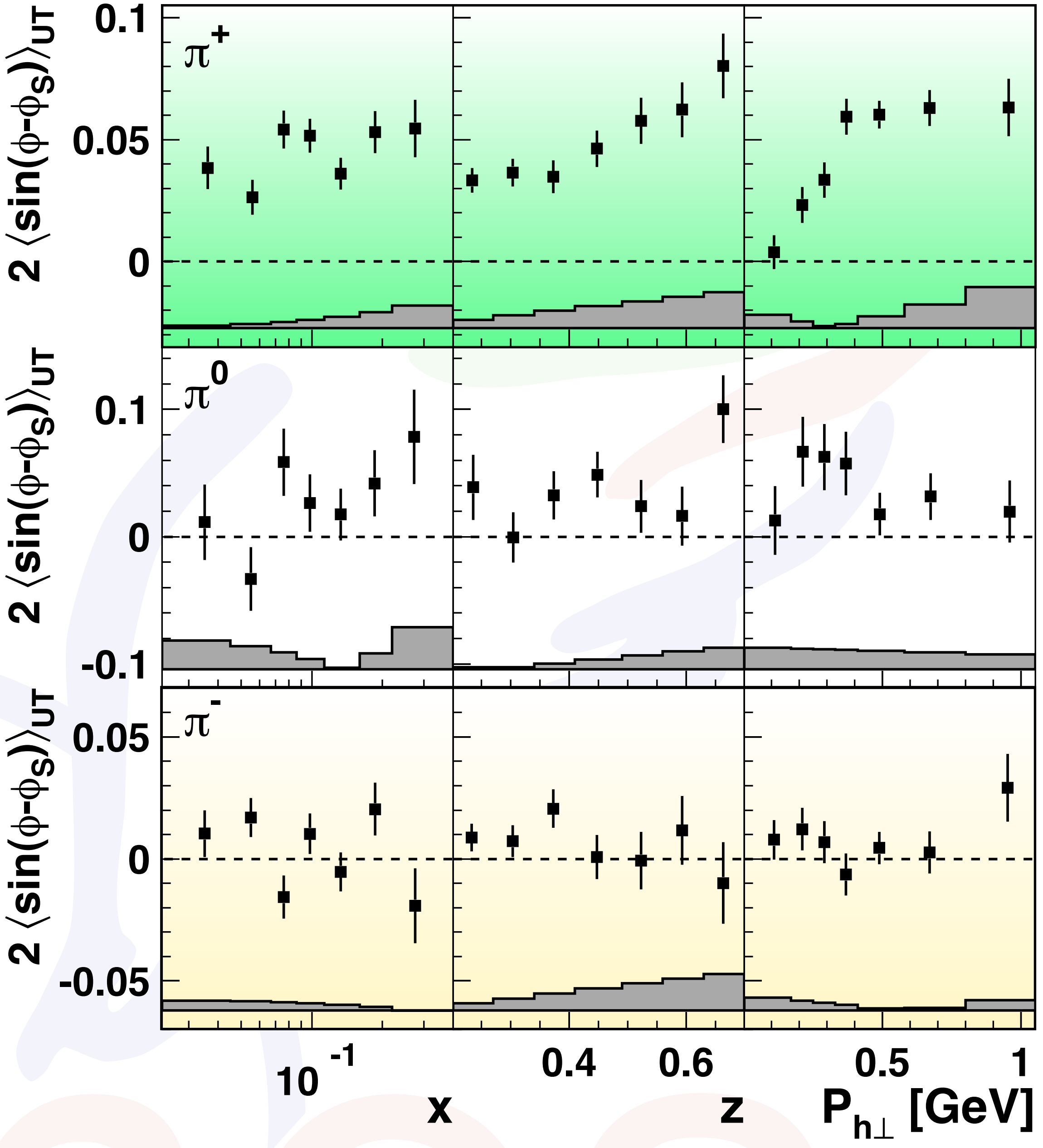

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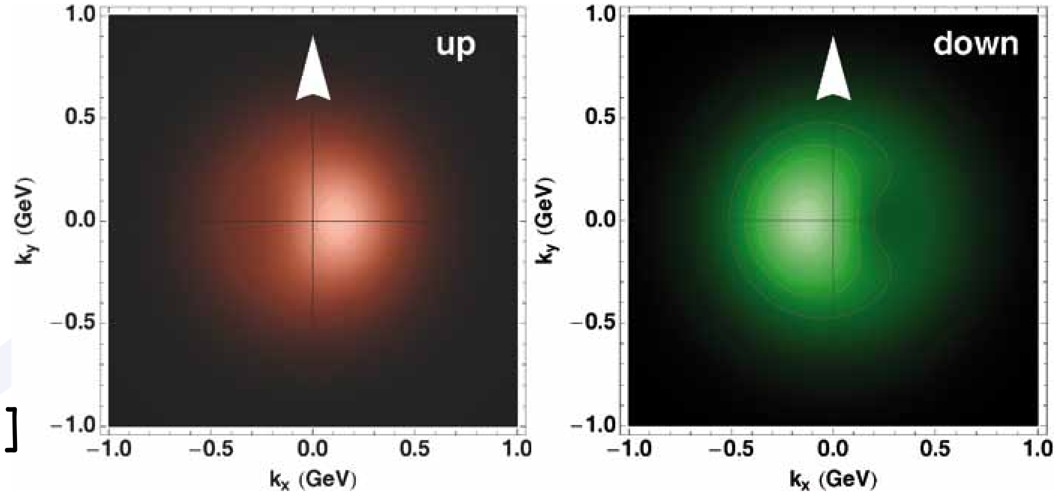

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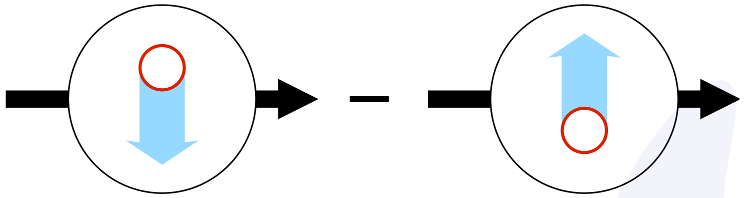

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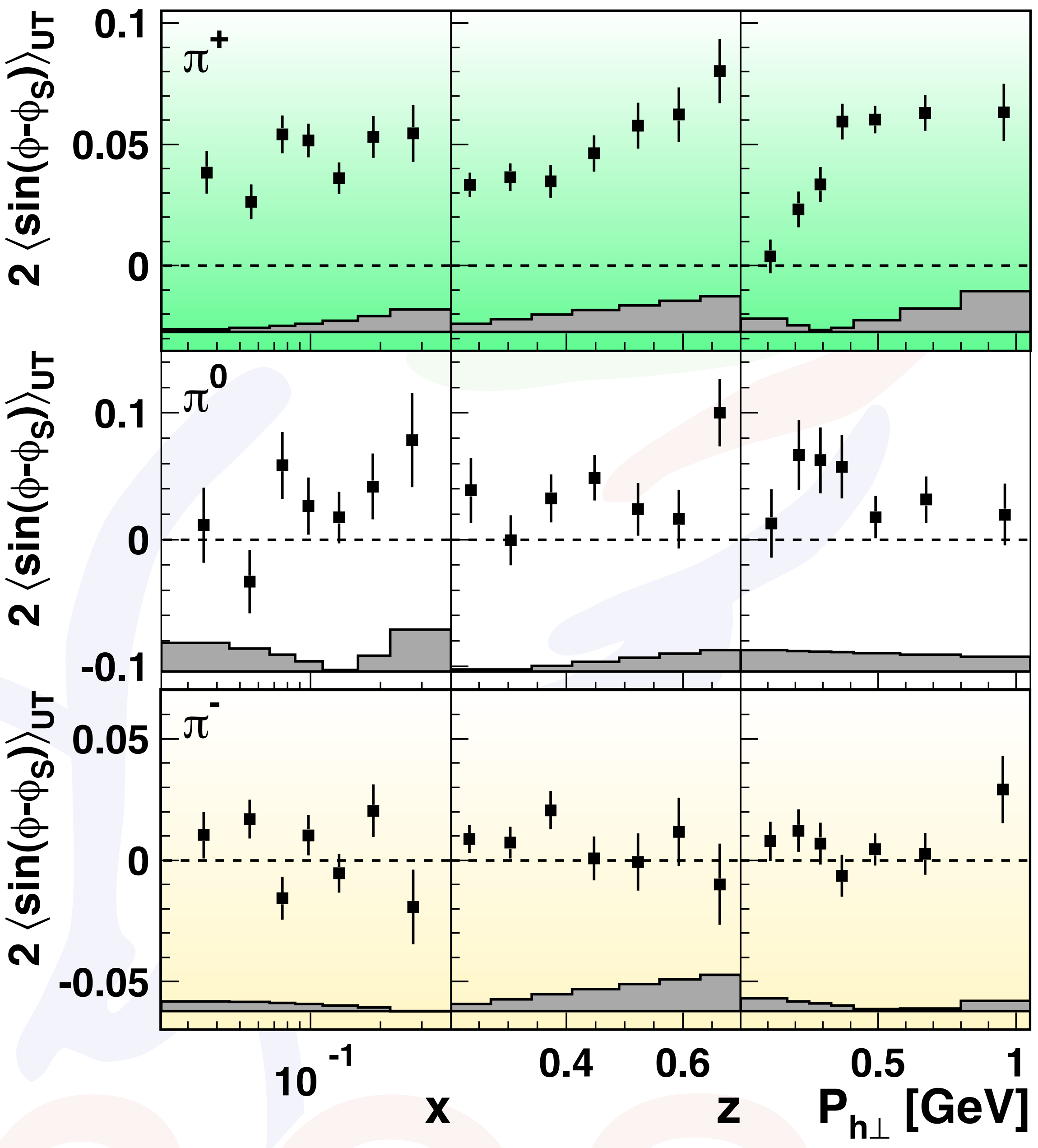
- leads to peculiar calculable universality breaking (DIS vs. Drell-Yan)



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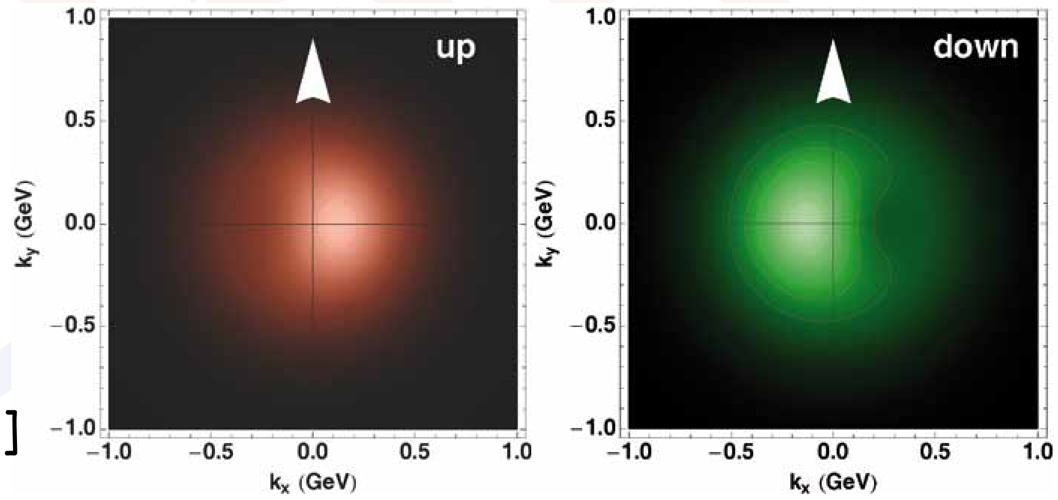
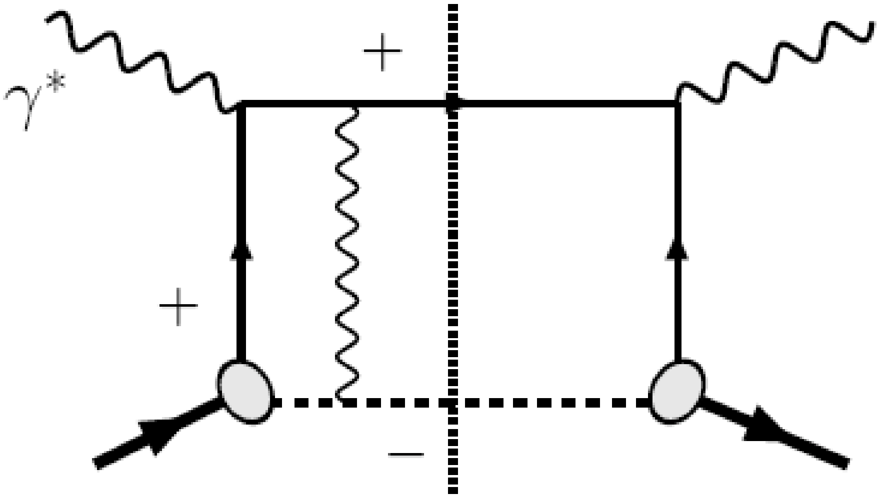


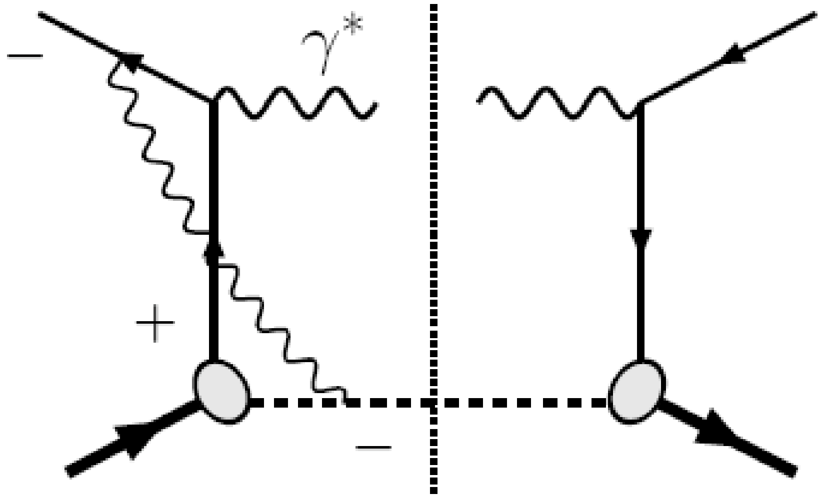
[courtesy of A. Bacchetta]

Process dependence

simple QED example



DIS: attractive



Drell-Yan: repulsive

Process dependence

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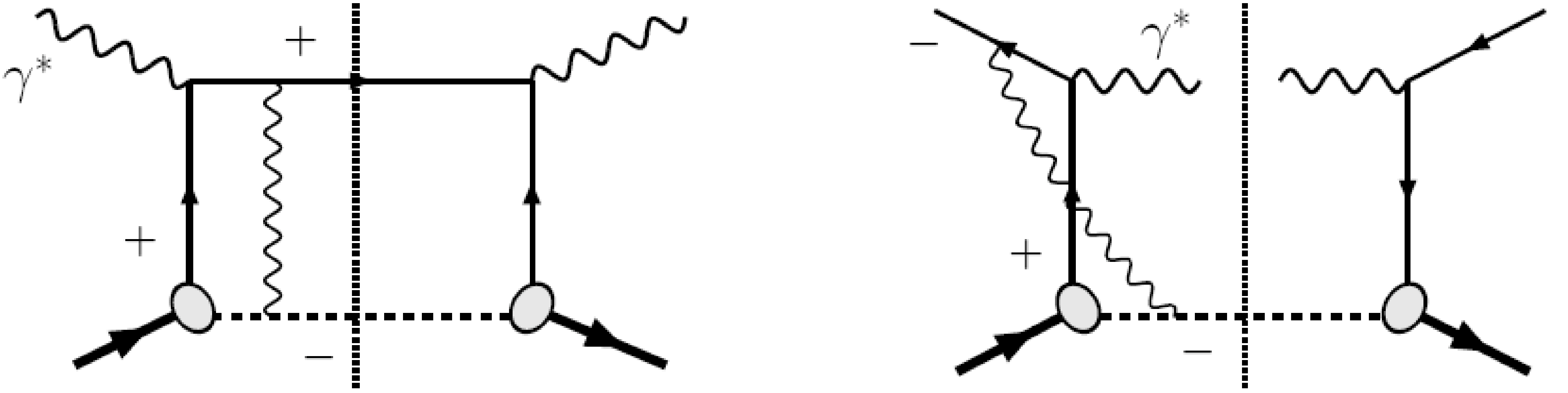
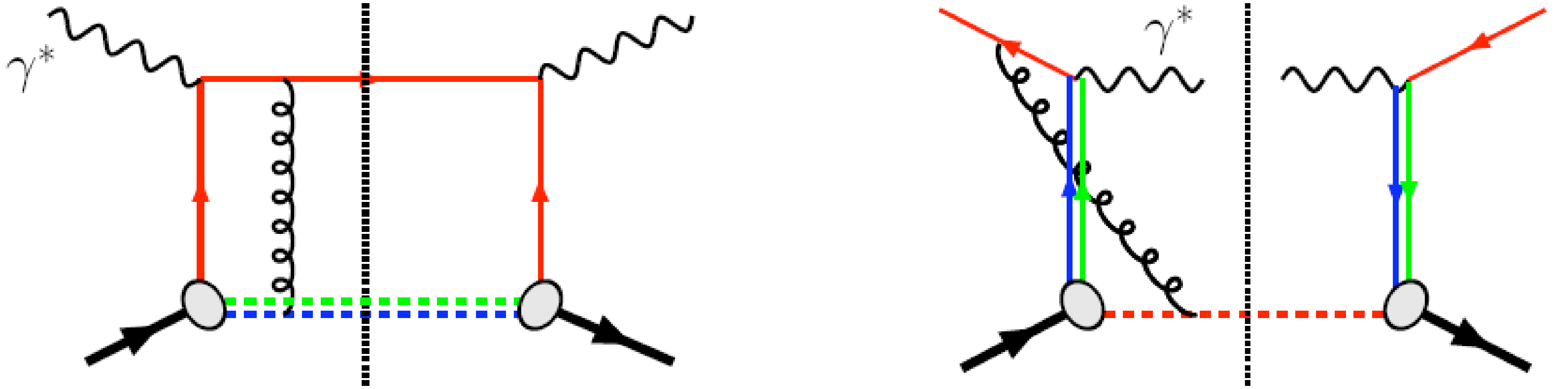


DIS: attractive

Drell-Yan: repulsive

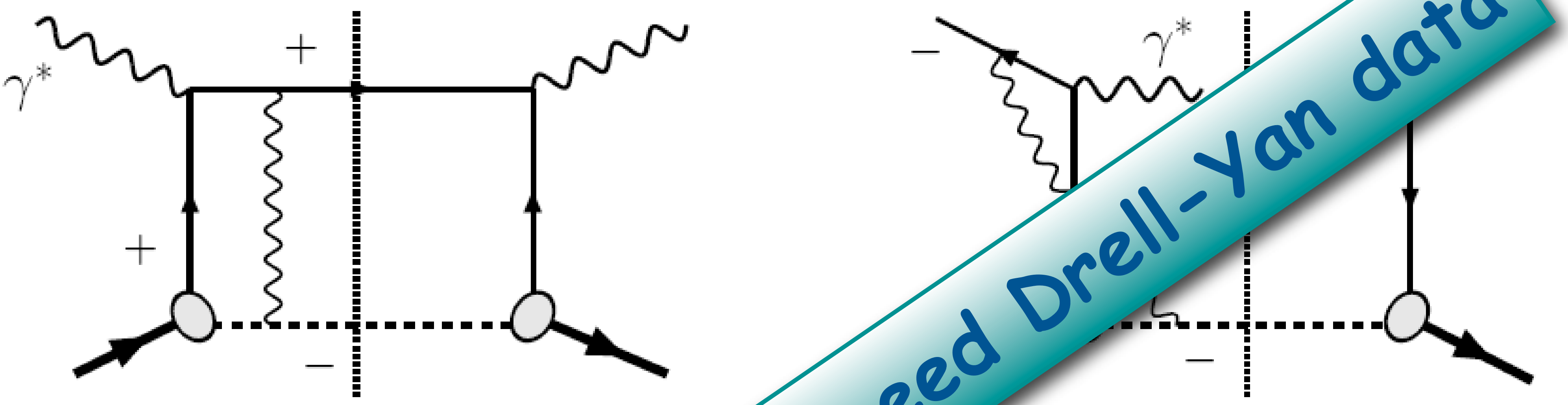
add color: QCD



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

Process dependence

simple QED example



DIS: attracti

Drell-Yan: repulsive

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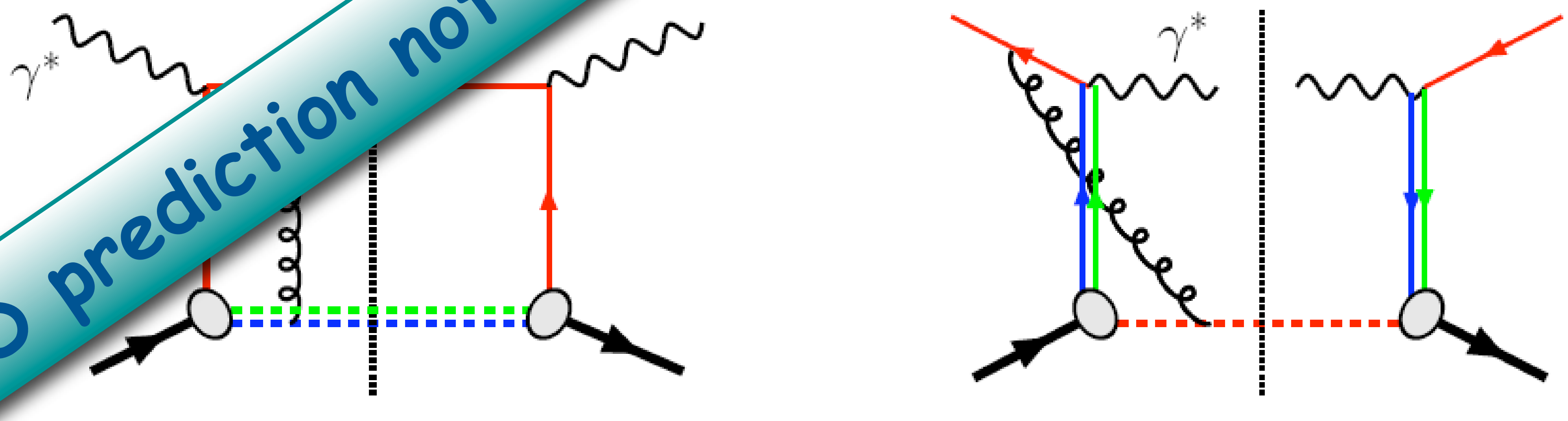
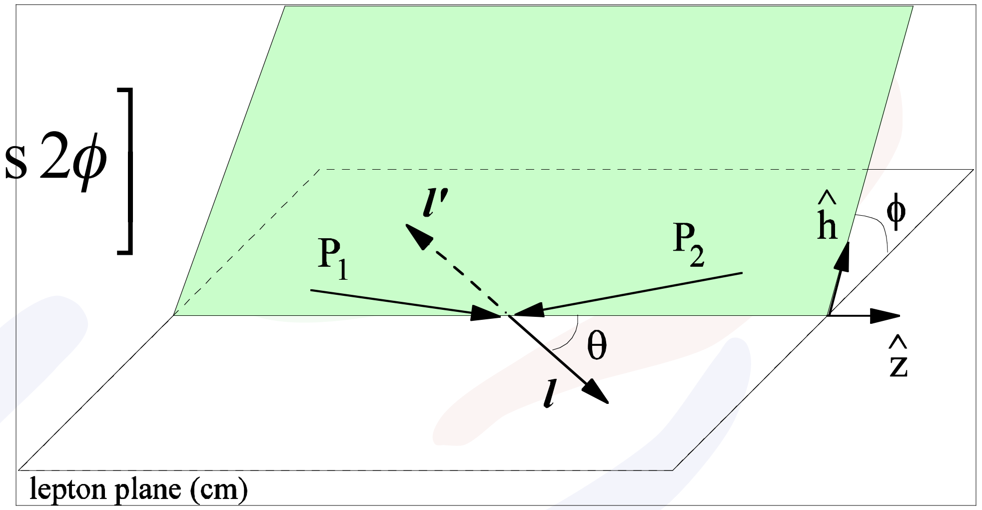


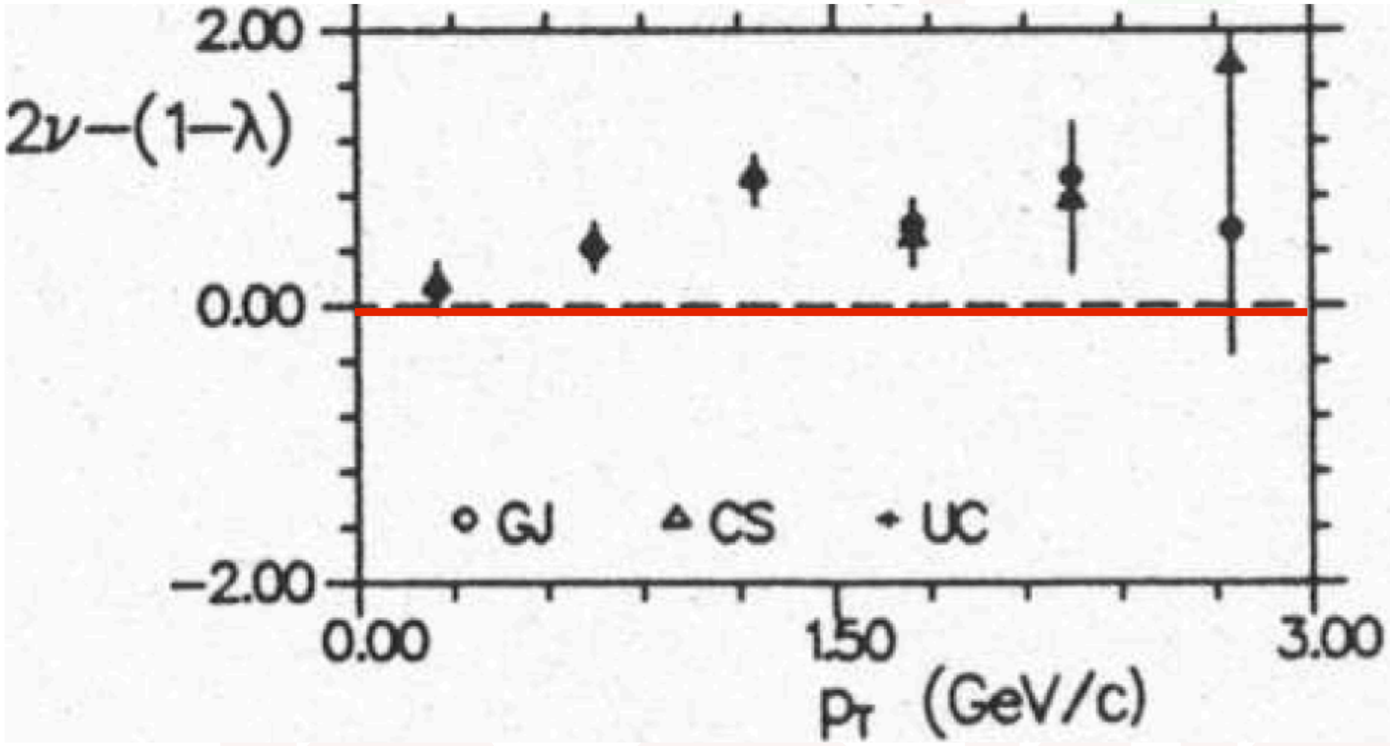
result: $\text{Sivers}|_{DIS} = - \text{Sivers}|_{DY}$

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

Unpolarized Drell-Yan

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





$$\boxed{1-\lambda-2\nu=0}$$

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

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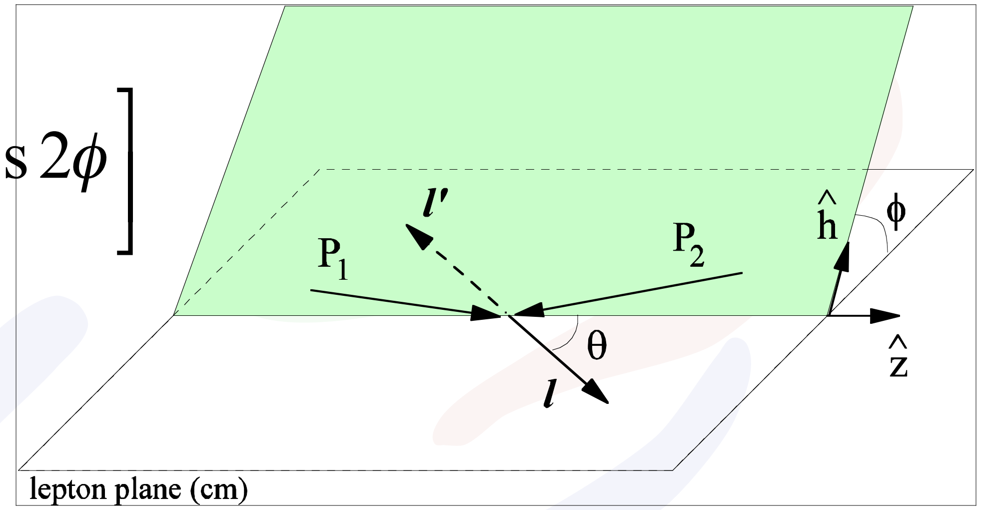

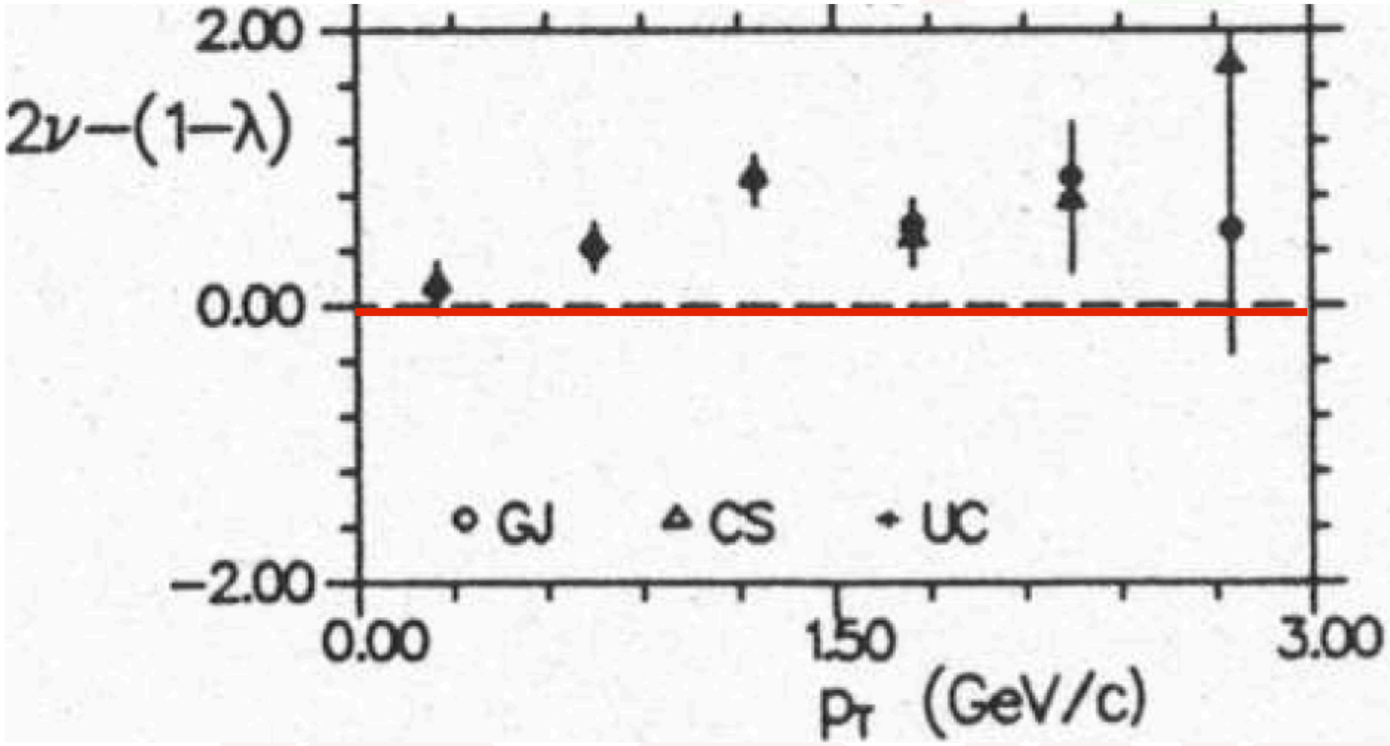

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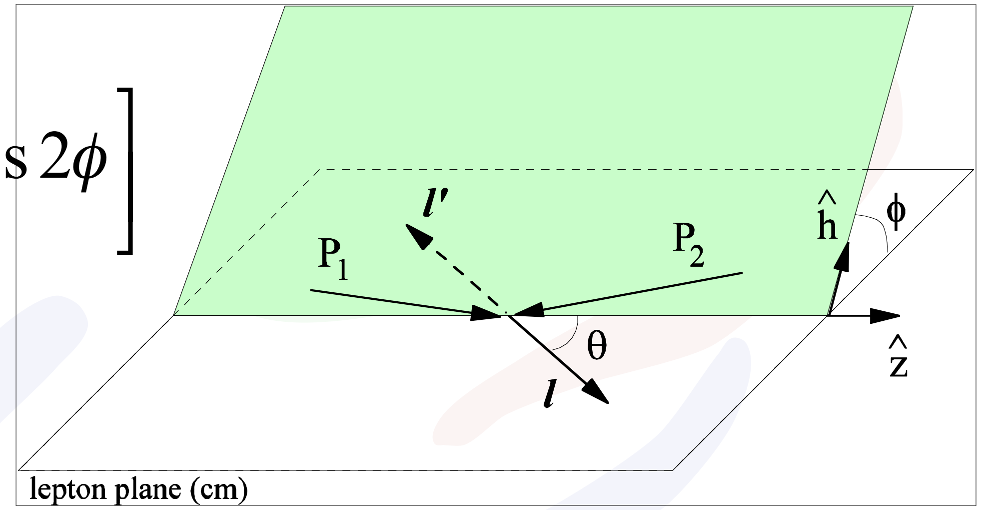

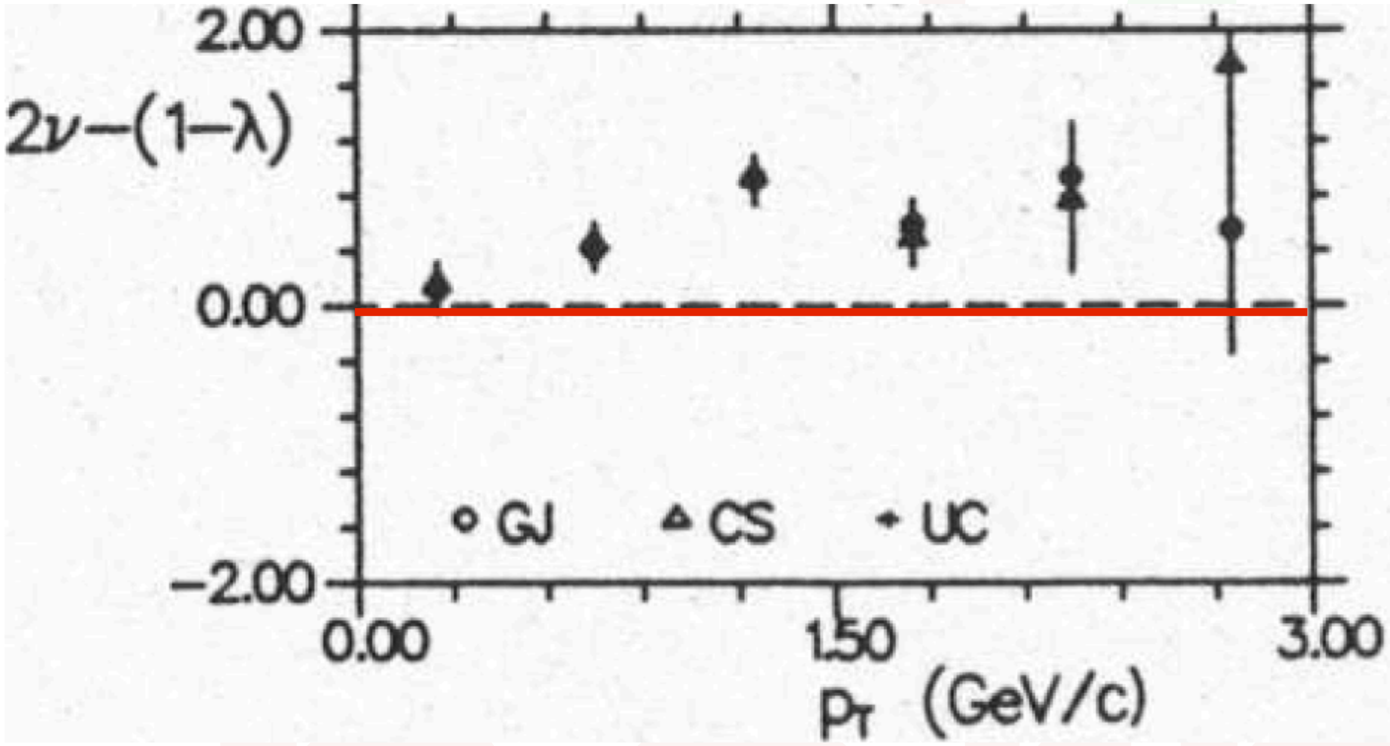

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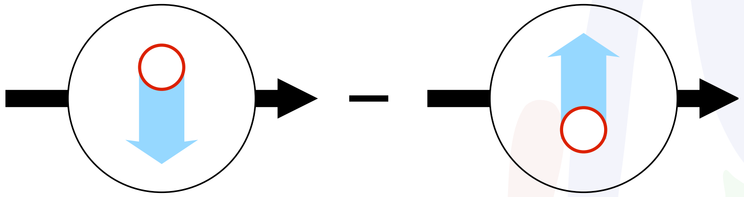
Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

- **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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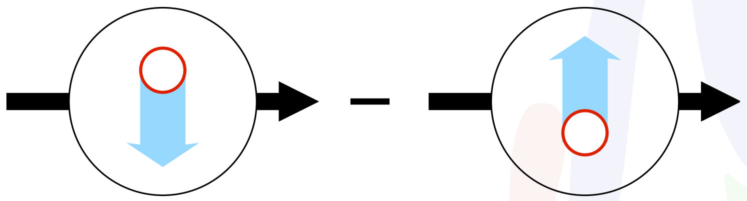

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Boer-Mulders effect

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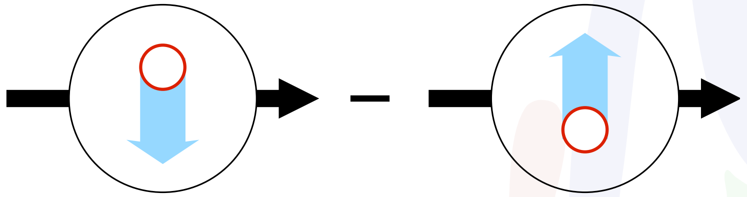

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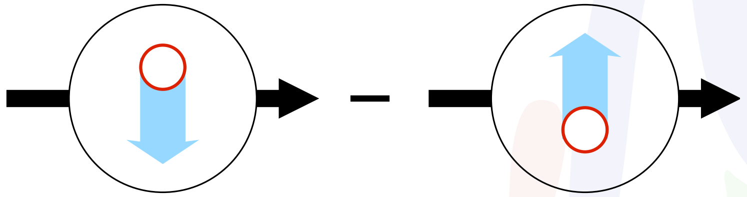

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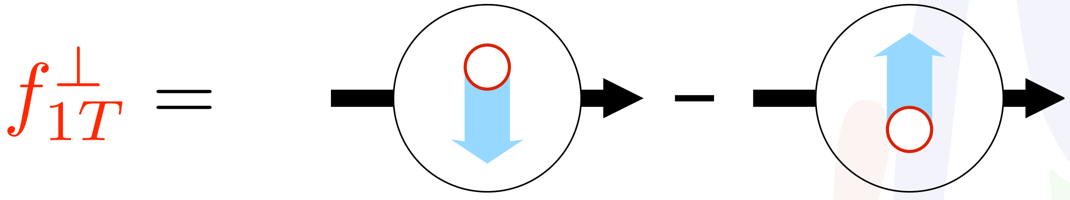

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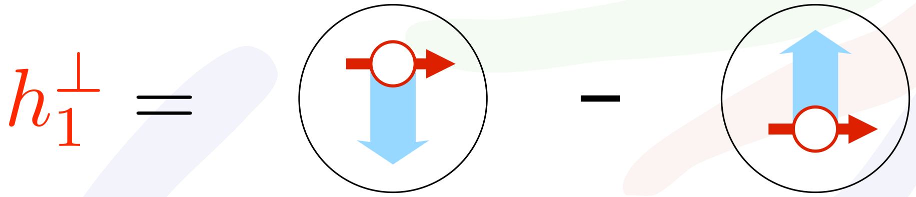

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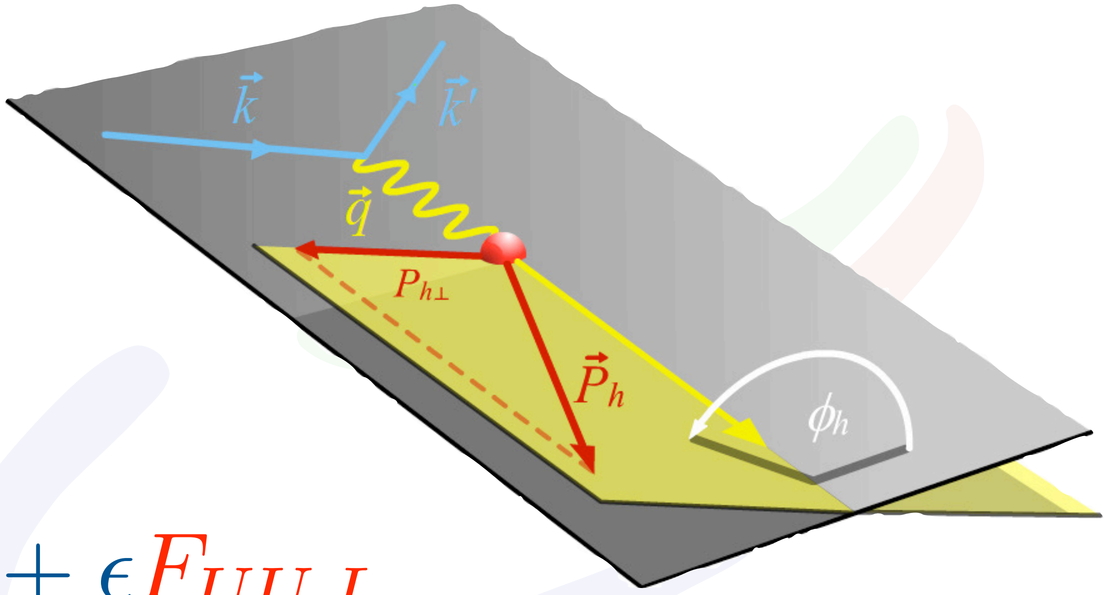
- spin-effect in **unpolarized** reactions
- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks
- QCD: sign change for DIS vs. Drell-Yan
- up to now little data from DIS

➡ HERMES with most comprehensive data set

Cross section without polarization



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

$$+\sqrt{2\epsilon(1-\epsilon)}\boxed{F_{UU}^{\cos\phi_h}}\cos\phi_h+\epsilon\boxed{F_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\}$$

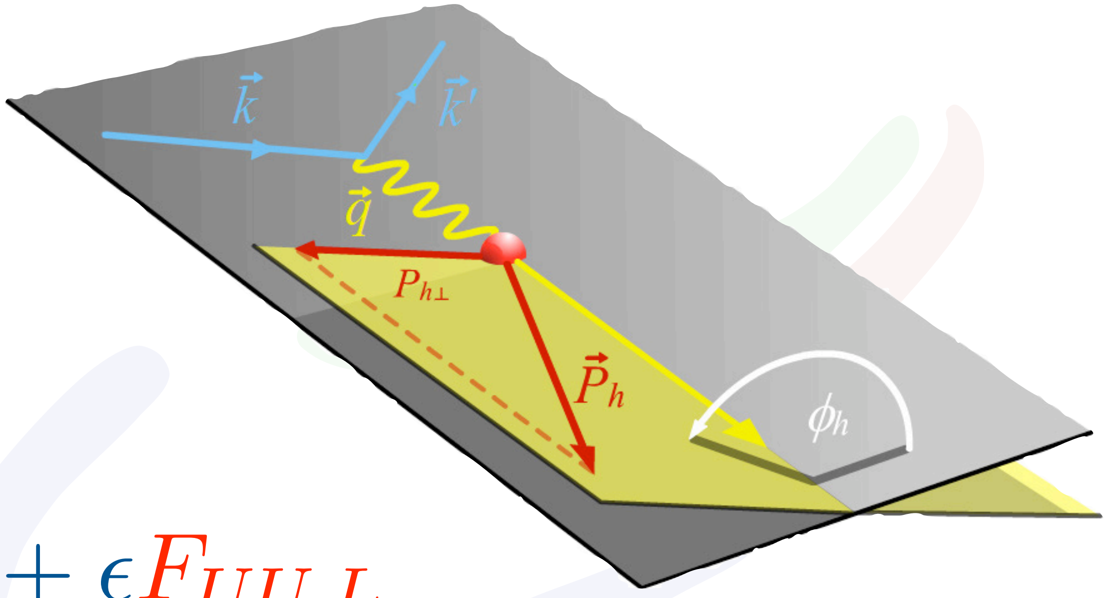
$$F_{XY,Z} = F_{\underset{\Uparrow\atop\text{beam polarization}}{X}\overset{\text{target polarization}\atop\Downarrow}{Y},\underset{\Uparrow\atop\text{virtual-photon polarization}}{Z}}(x,y,z,P_{h\perp})$$

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

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

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

Cross section without polarization



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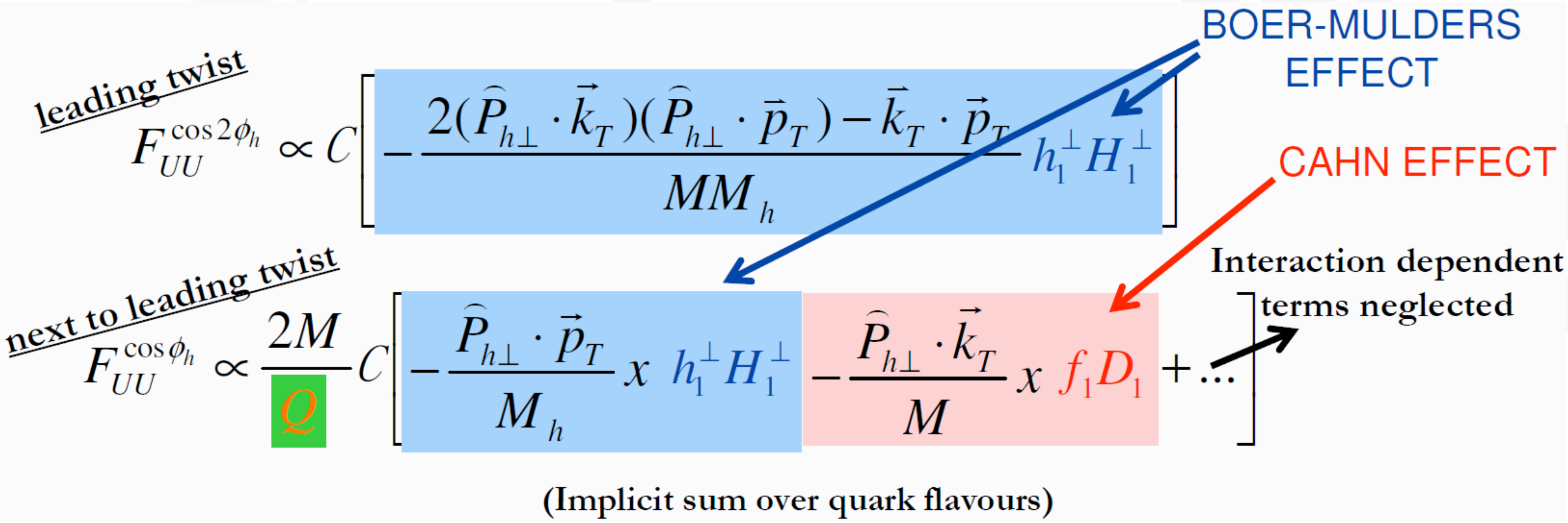

leading twist

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

next to leading twist

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

Interaction dependent terms neglected

(Implicit sum over quark flavours)

BOER-MULDERS EFFECT

CAHN EFFECT

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

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

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

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U	f_1		$h_1^\perp$
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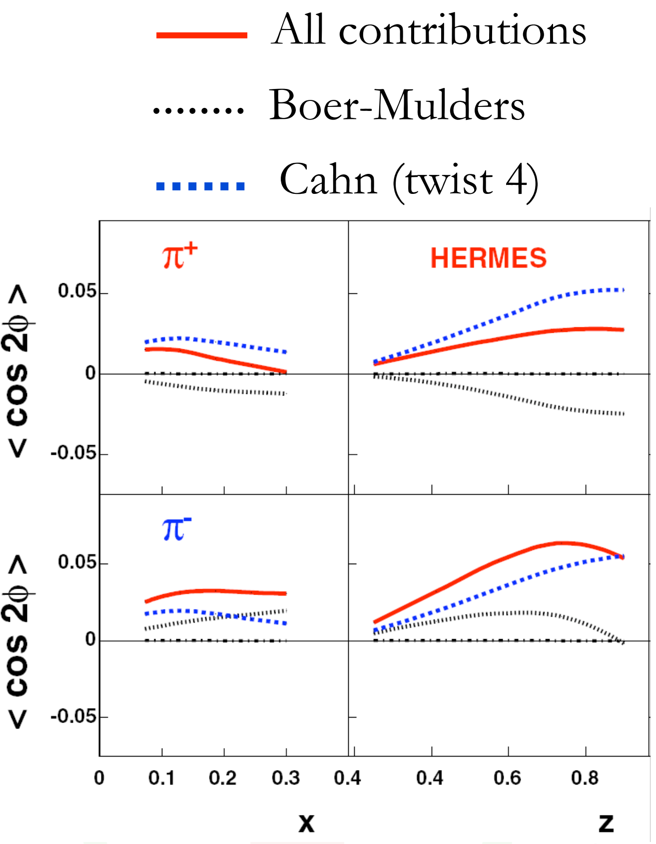
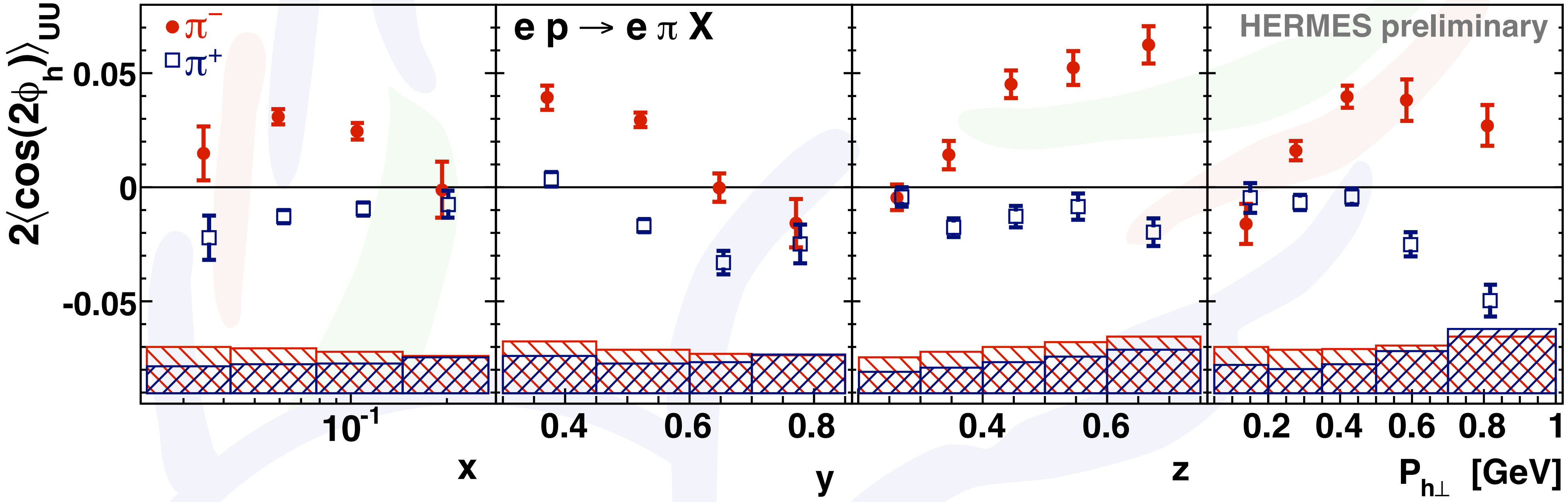
Signs of Boer-Mulders



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

[Airapetian et al., arXiv:1204.4161]



- Cahn effect only does not describe data

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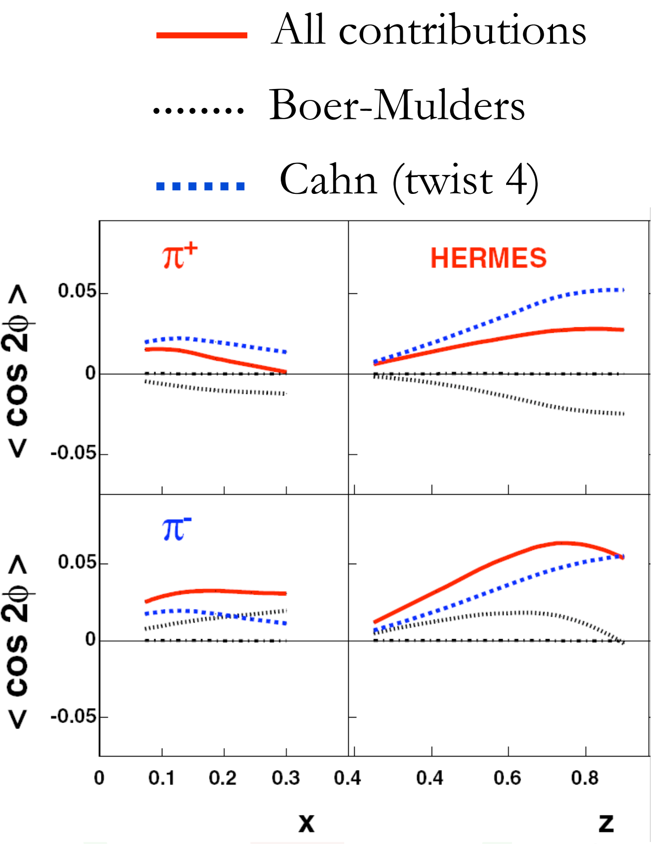

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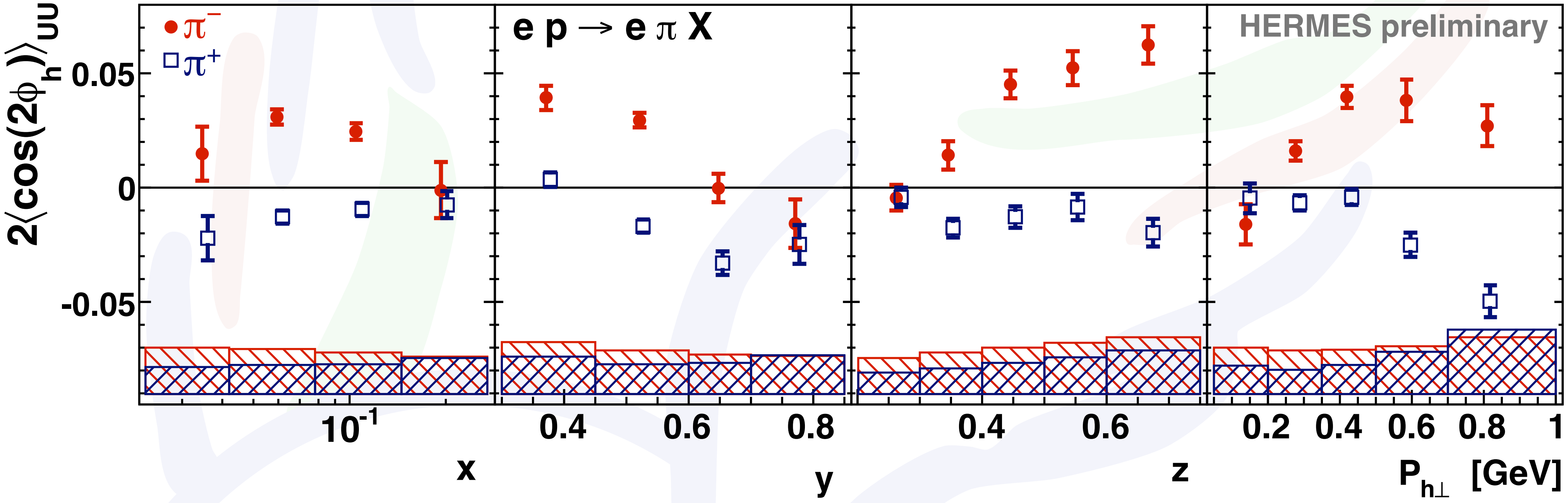

- Cahn effect only does not describe data

- opposite sign for charged pions with larger magnitude for π^- (as expected)
  -> same-sign BM-function for valence quarks

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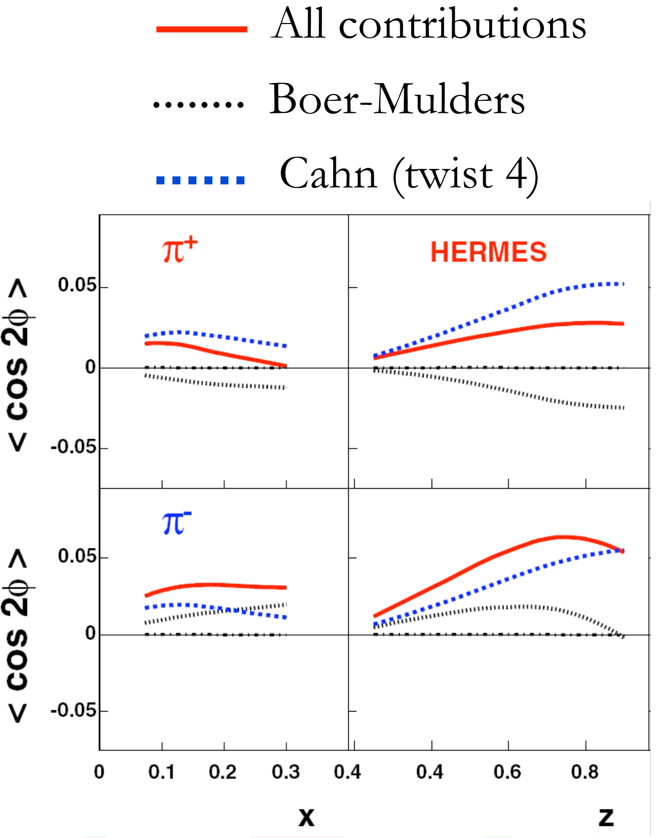

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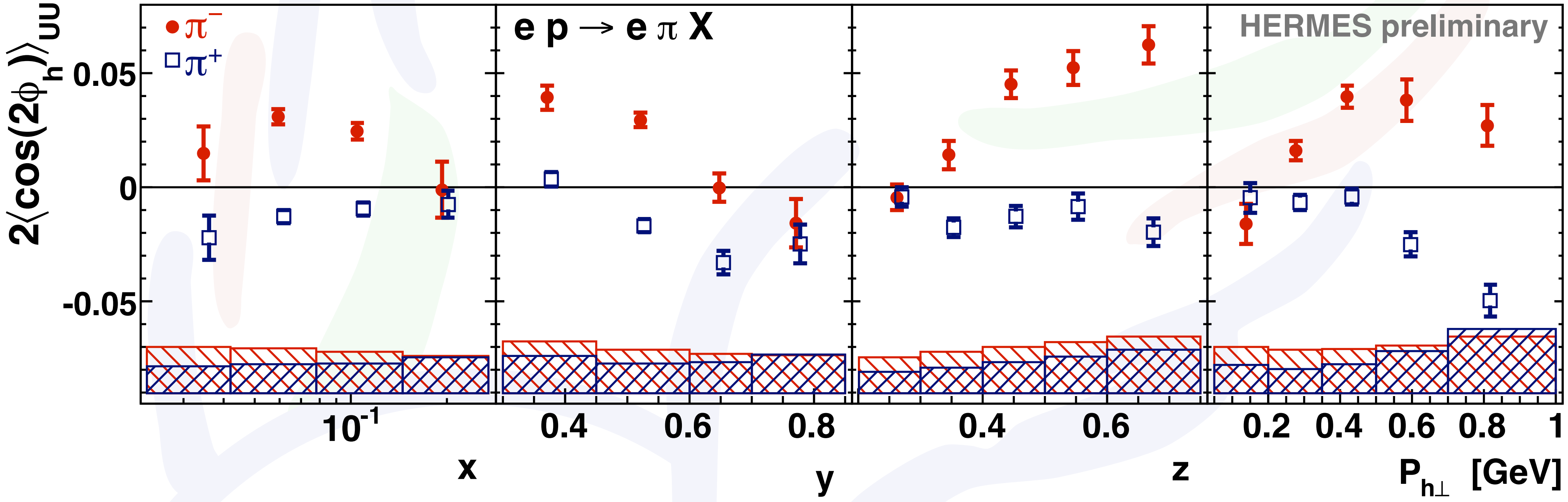

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☛ F. Giordano (S1-V)

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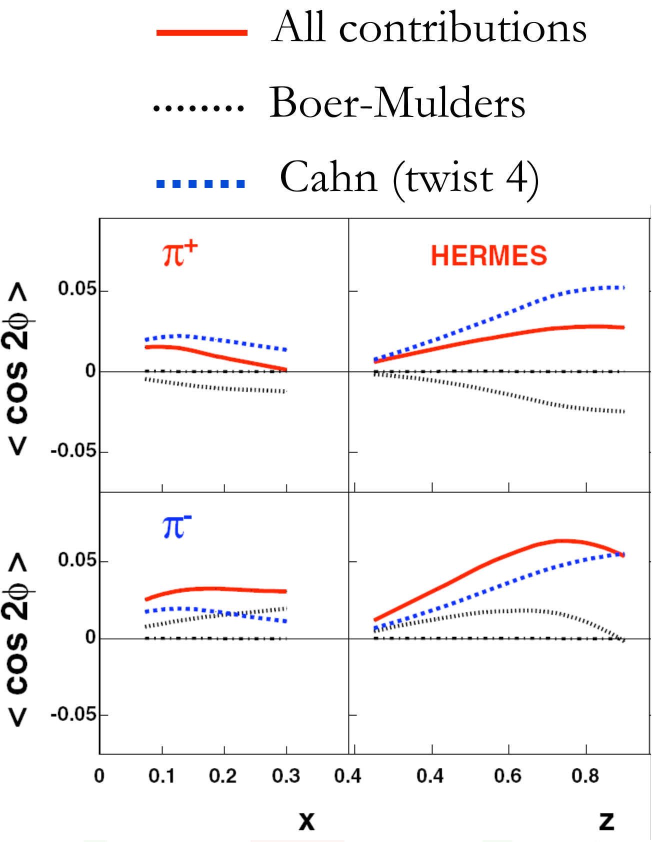

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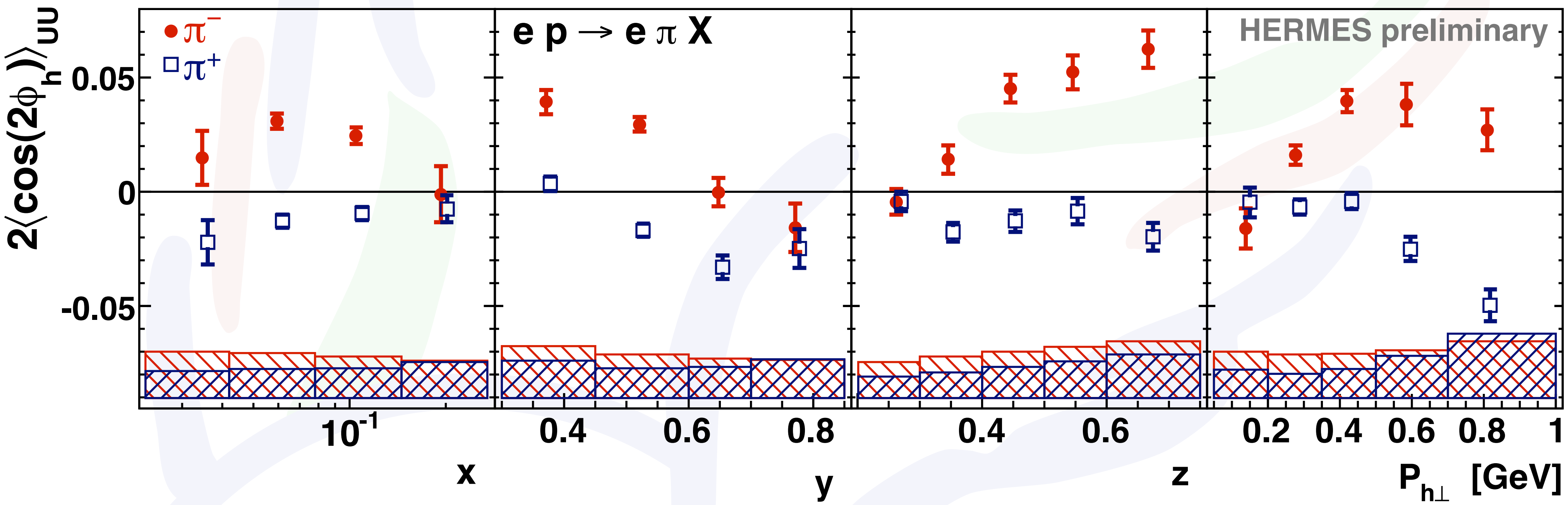

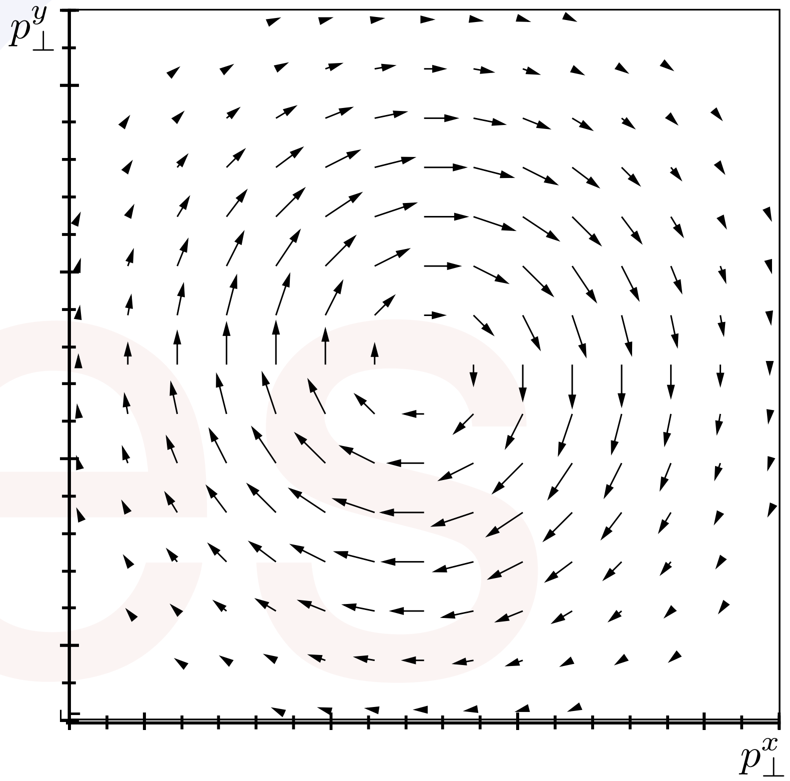

[M. Burkardt and B. Hannfious, PLB658 (2008) 130]

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☛ F. Giordano (S1-V)

Cahn effect?

BOER-MULDERS EFFECT

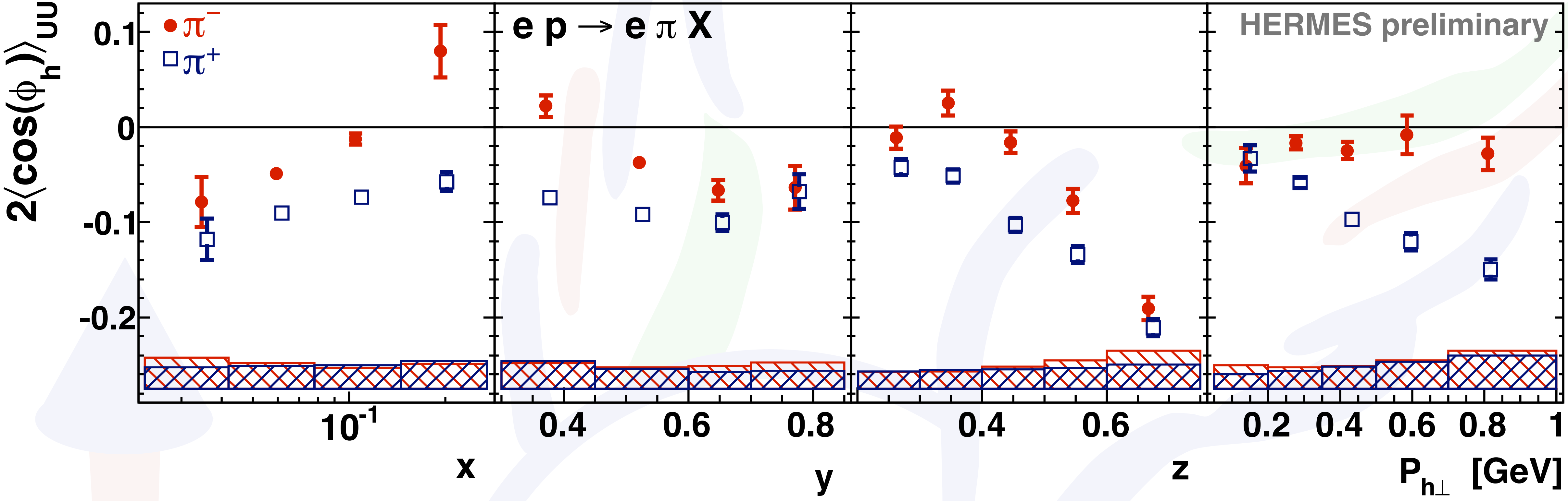
CAHN EFFECT

next to leading twist

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

Interaction dependent terms neglected

[Airapetian et al., arXiv:1204.4161]



- no dependence on hadron charge expected for Cahn effect

➡ flavor dependence of transverse momentum

➡ sign of Boer-Mulders in cosϕ modulation
(indeed, overall pattern resembles B-M modulations)

➡ additional “genuine” twist-3?

gunar.schnell @ desy.de

Cahn effect?

next to leading twist

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

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

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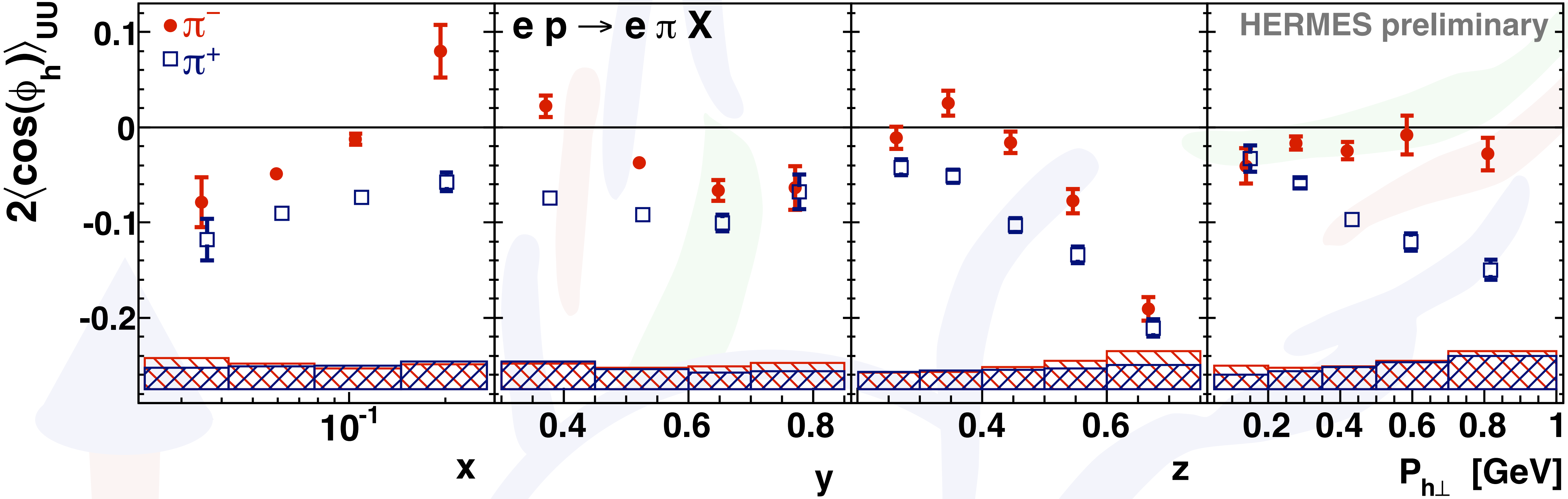

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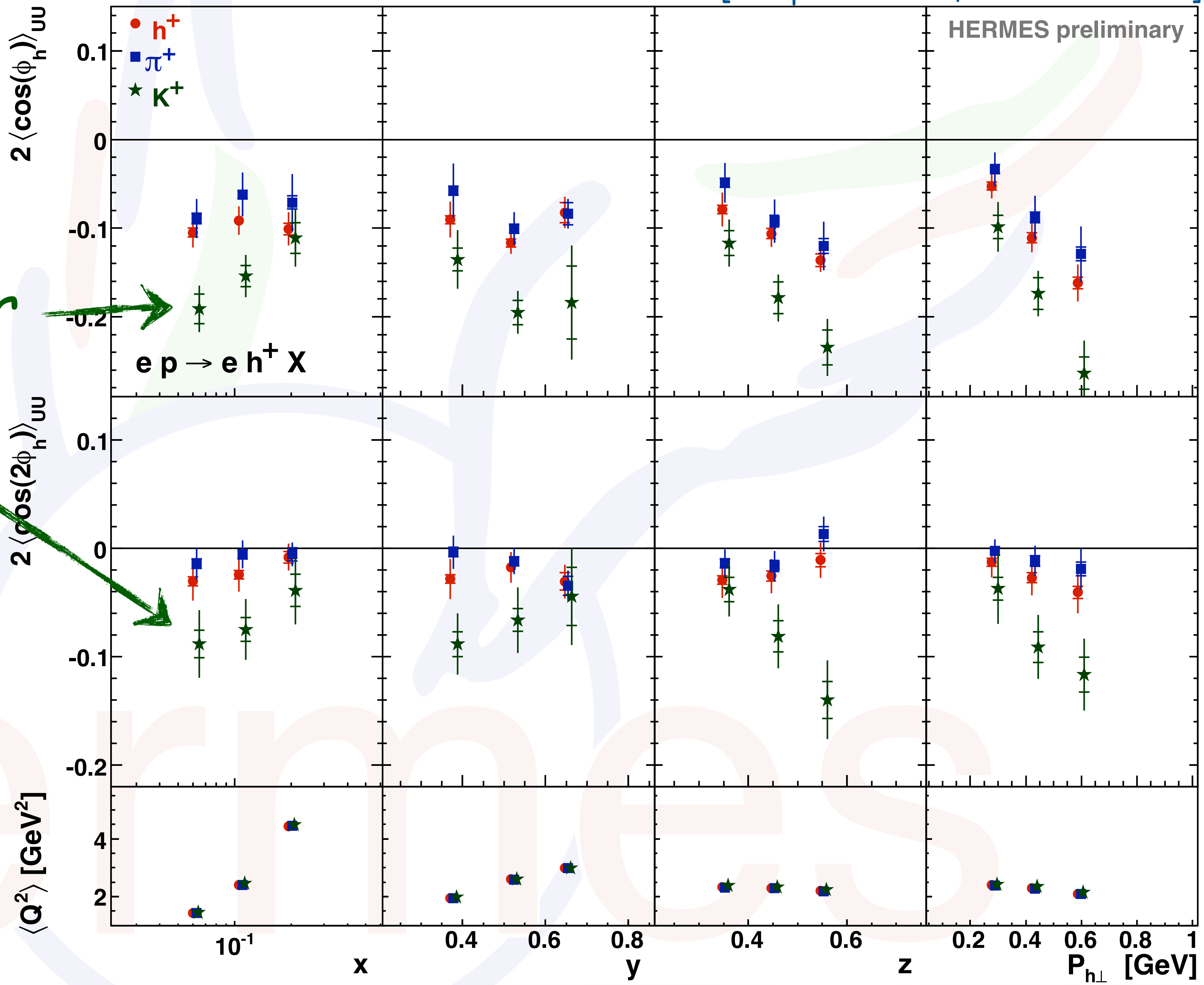
“strange” results

[Airapetian et al., arXiv:1204.4161]



intriguing behavior for kaons

☛ F. Giordano (S1-V)

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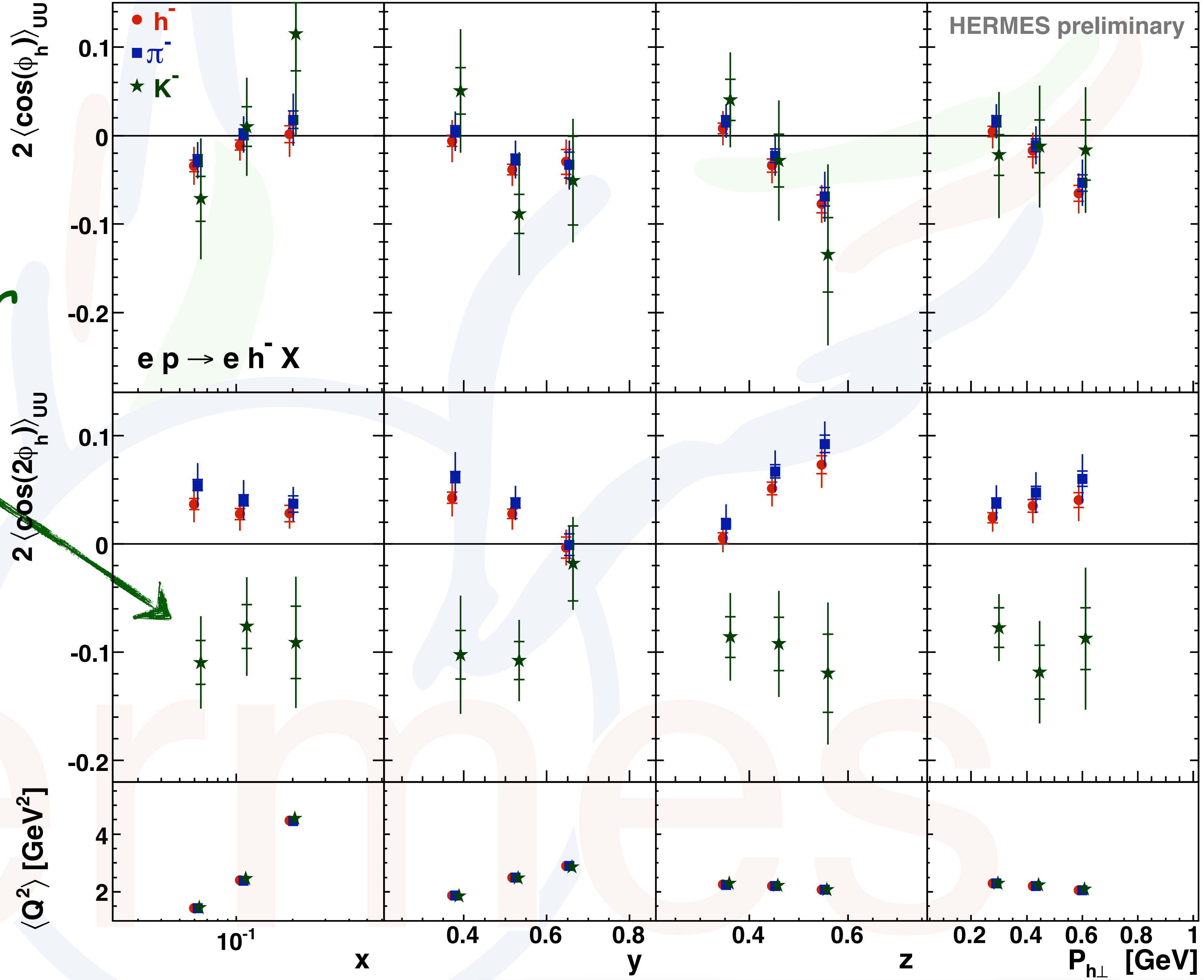

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“strange” results

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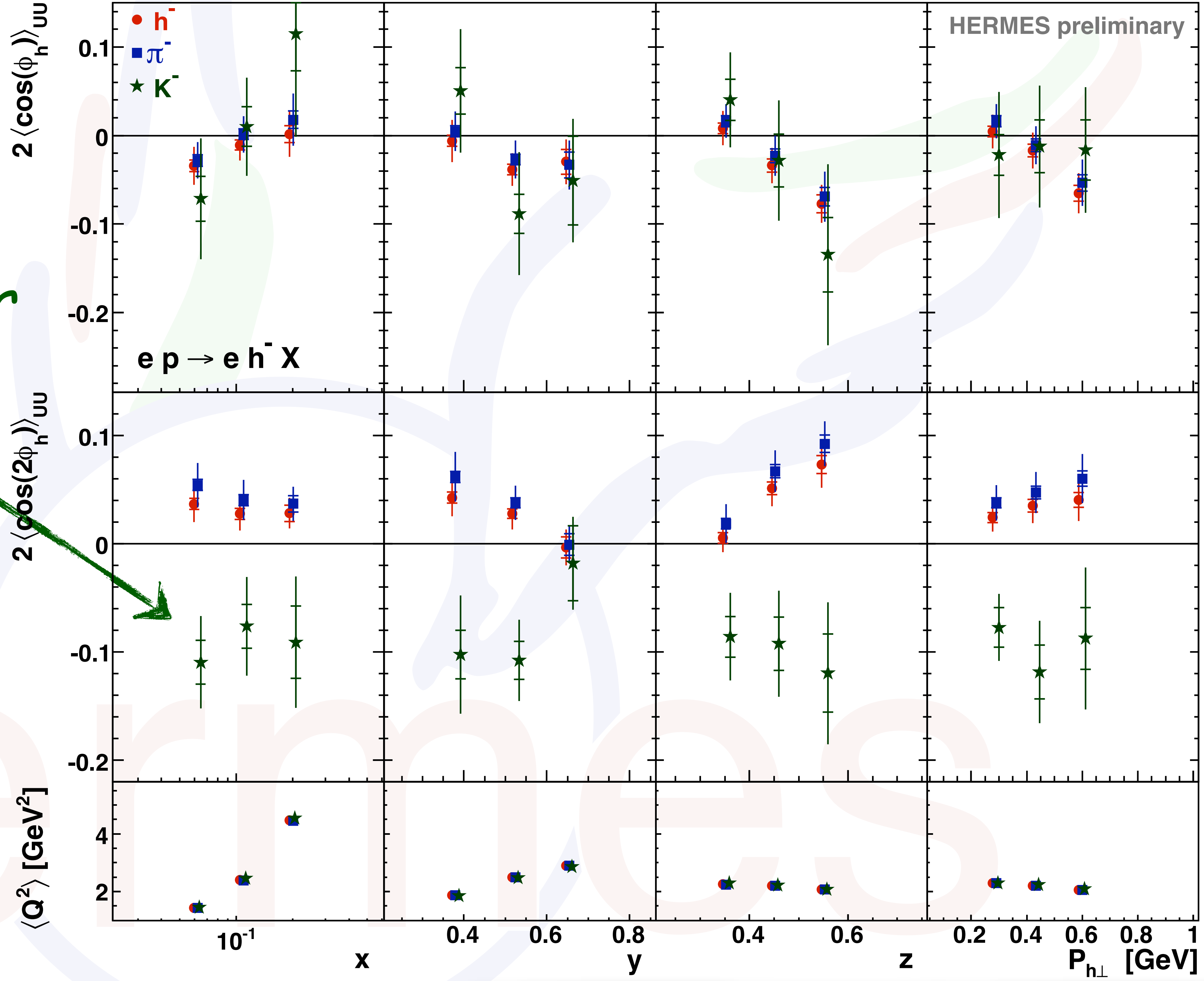

intriguing behavior for kaons

different pattern for kaon Collins function?
(cf. BRAHMS A_N and SIDIS Collins)

☛ F. Giordano (S1-V)

Hadron multiplicities in DIS

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

$$+\sqrt{2\epsilon(1-\epsilon)}\,F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

gunar.schnell @ desy.de

Hadron multiplicities in DIS

hadron multiplicity:
normalize to inclusive DIS cross section

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Hadron multiplicities in DIS

hadron multiplicity:

normalize to inclusive DIS cross section

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

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

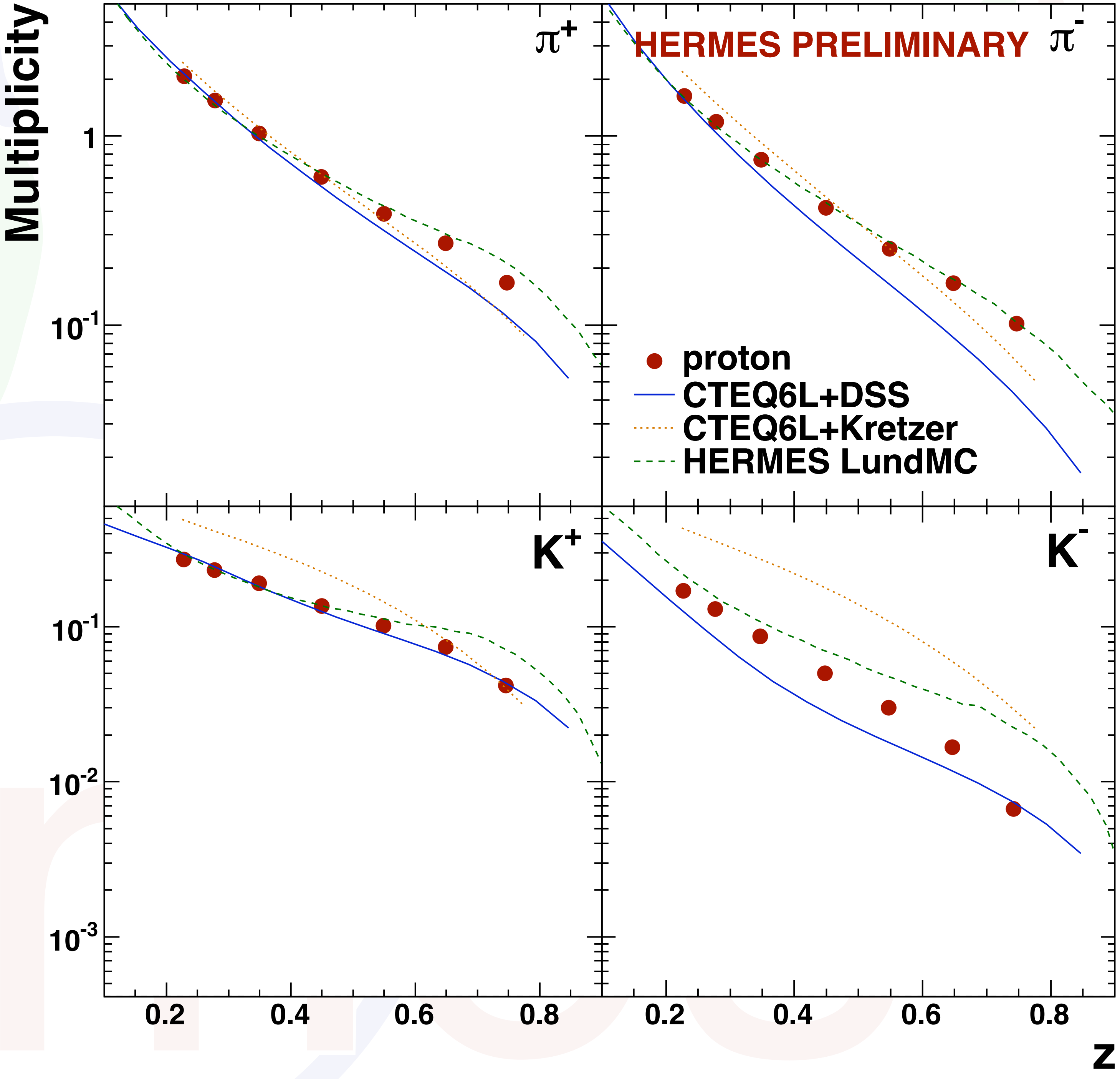
$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

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

$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

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



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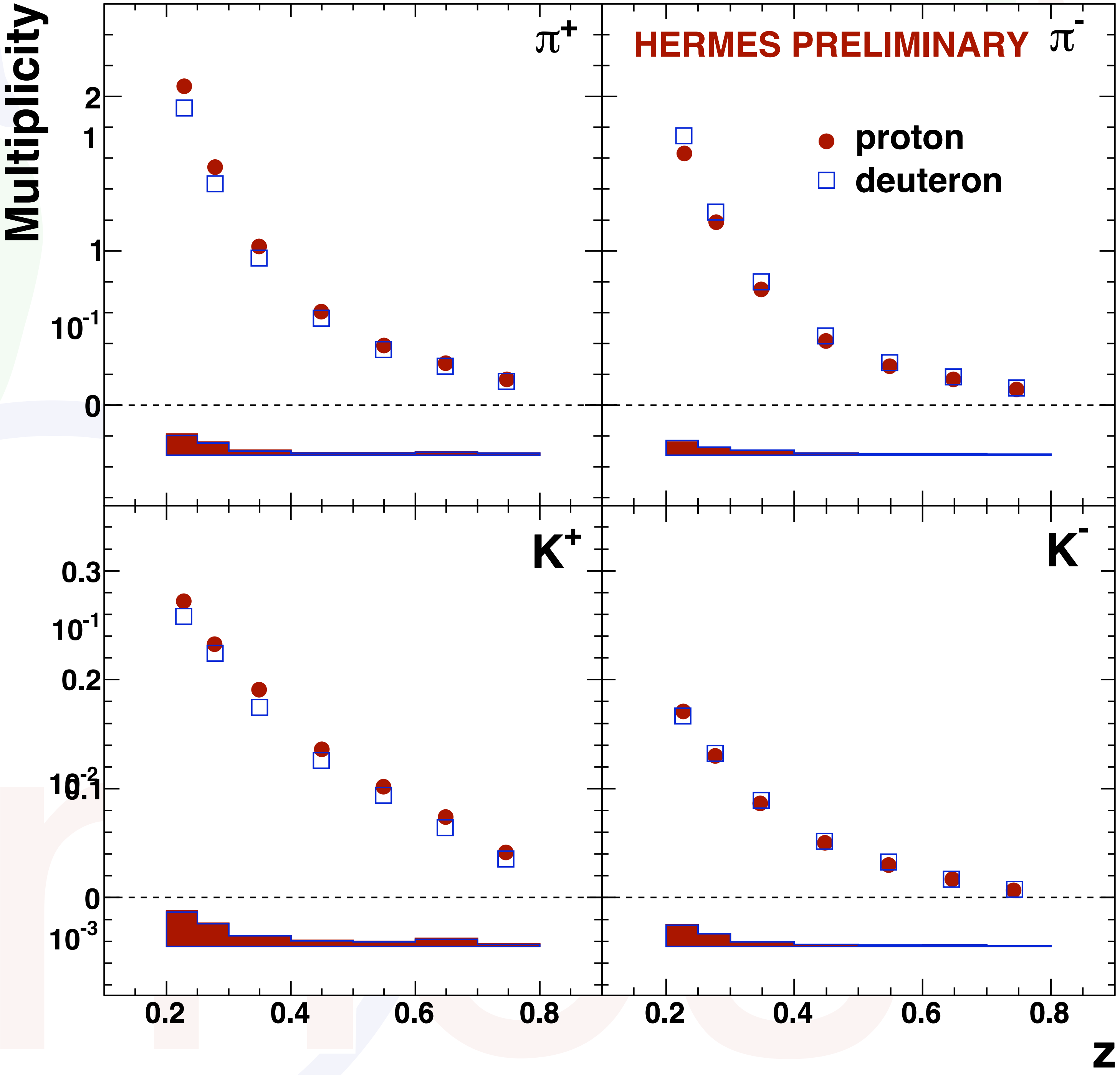
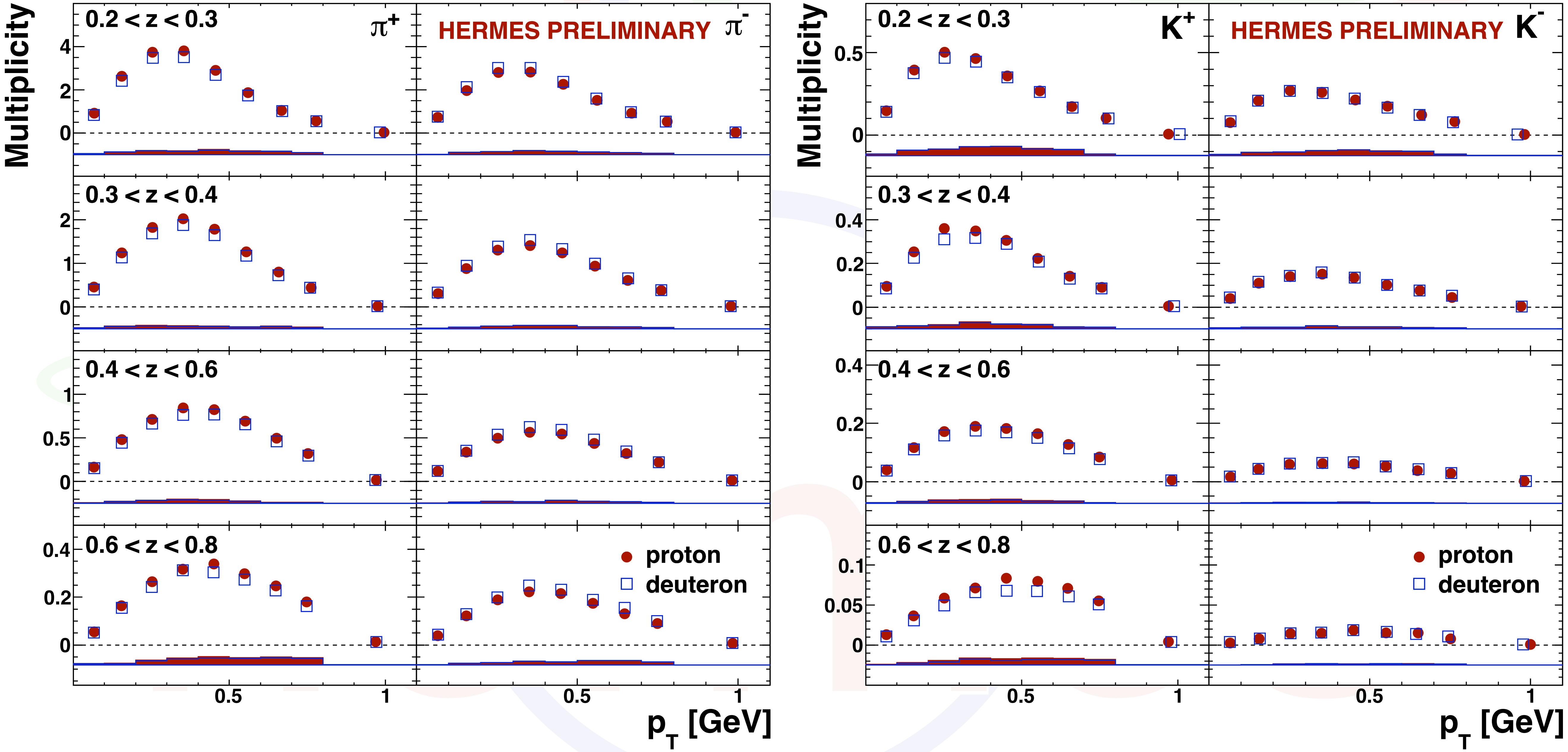


Multiplicities @ HERMES

multi-dimensional analysis allows exploration of new kinematic dependences



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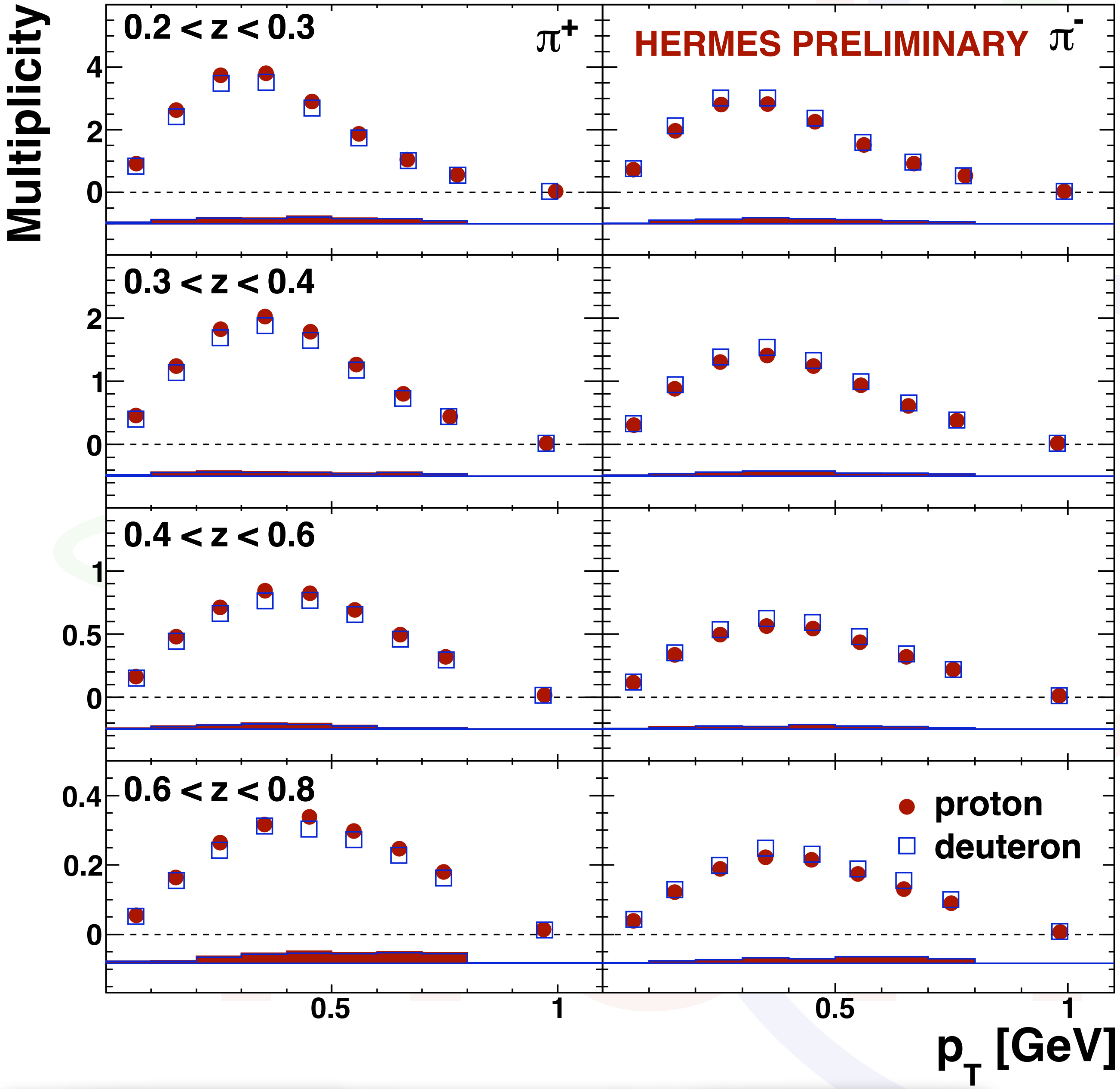
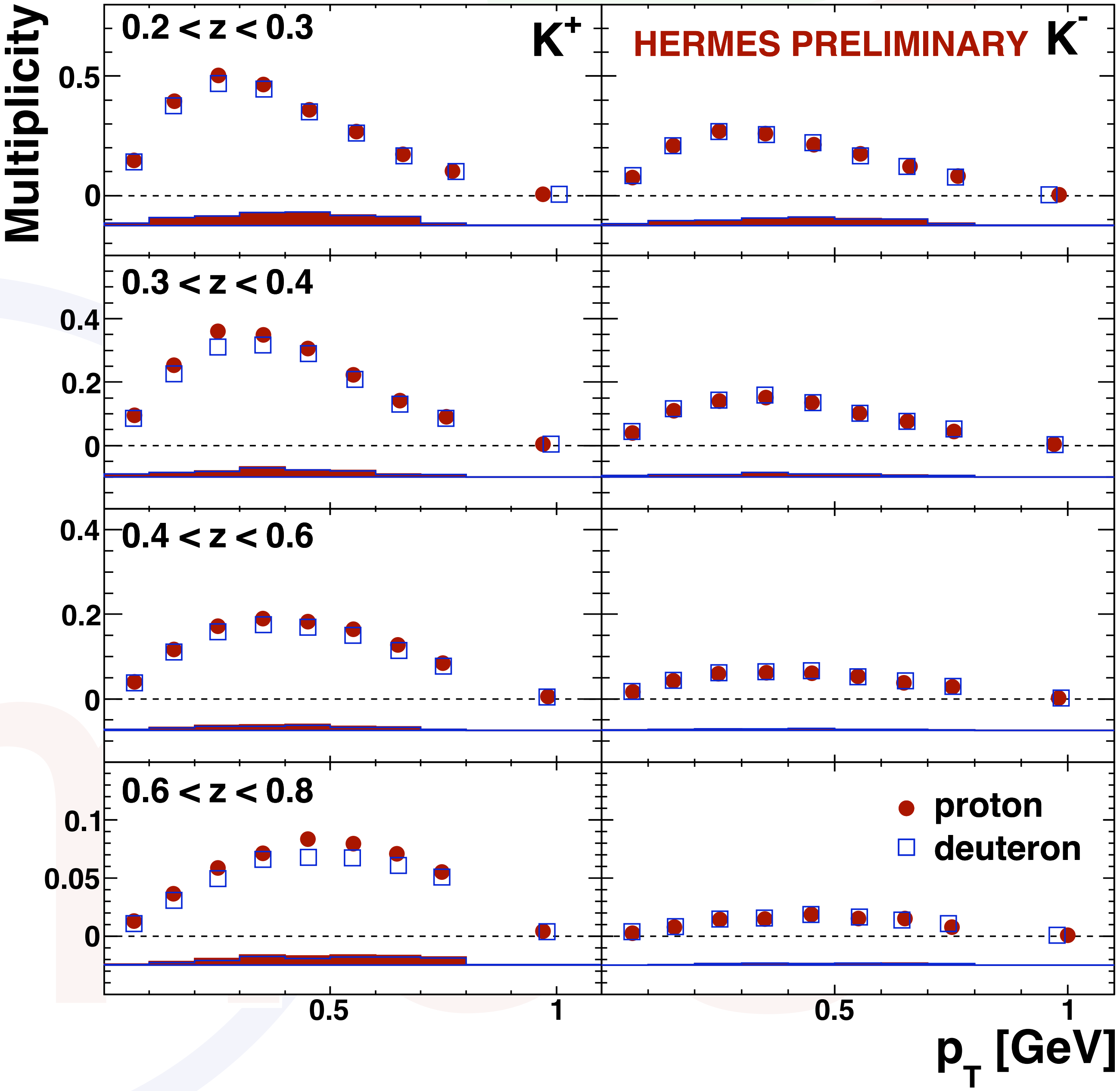
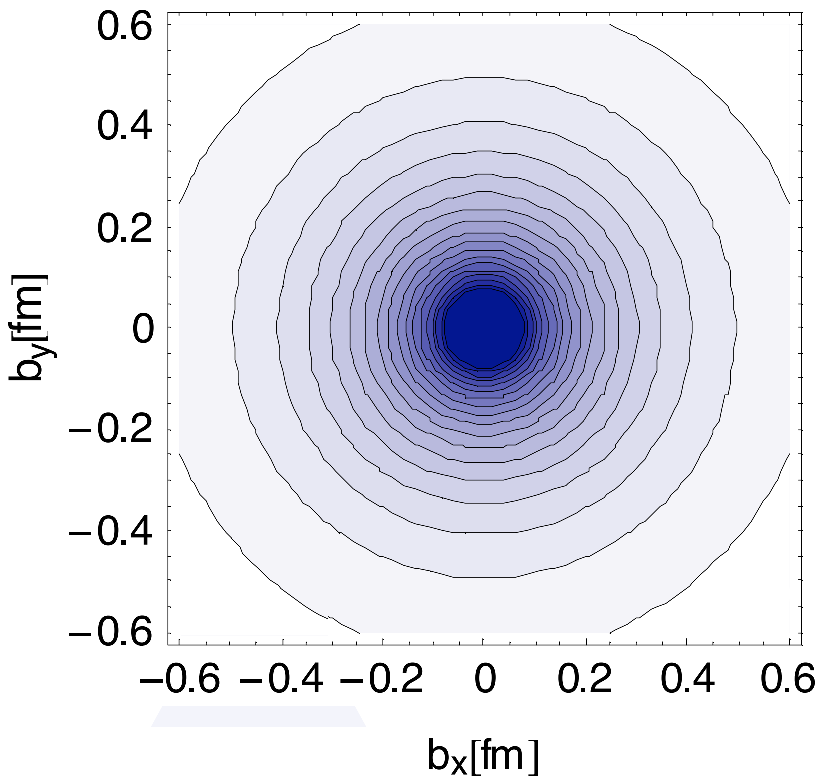




☛ G. Karyan (S2-VI)

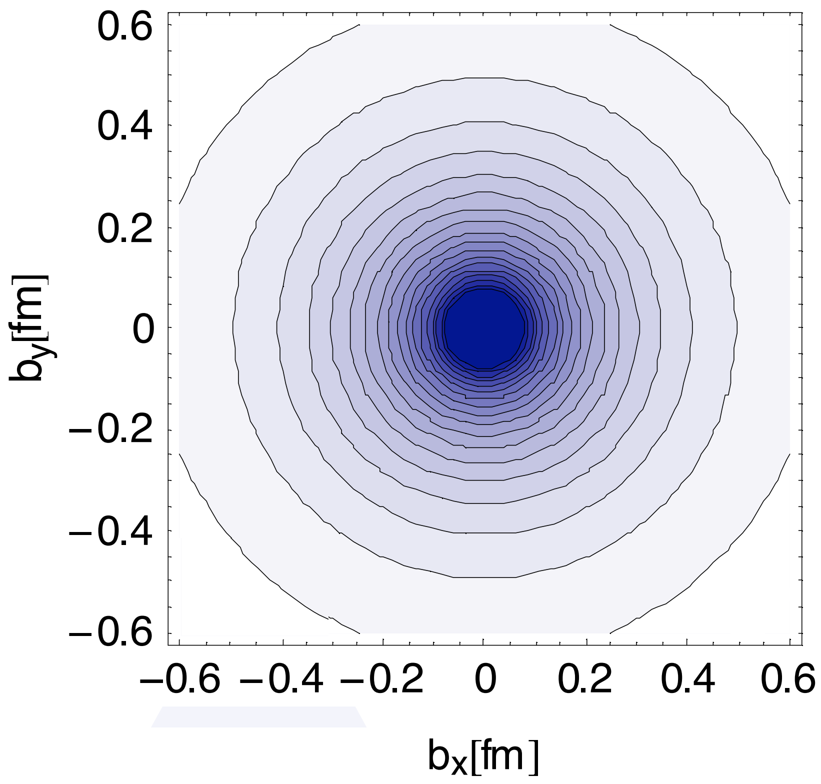
Exclusive reactions

Another 3D picture of the nucleon



Form factors:
transverse distribution
of partons

Another 3D picture of the nucleon



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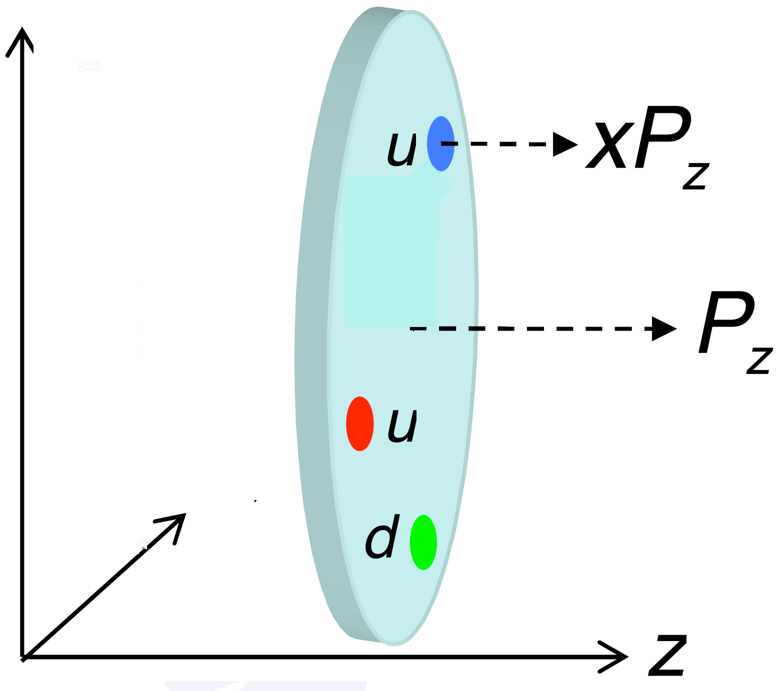
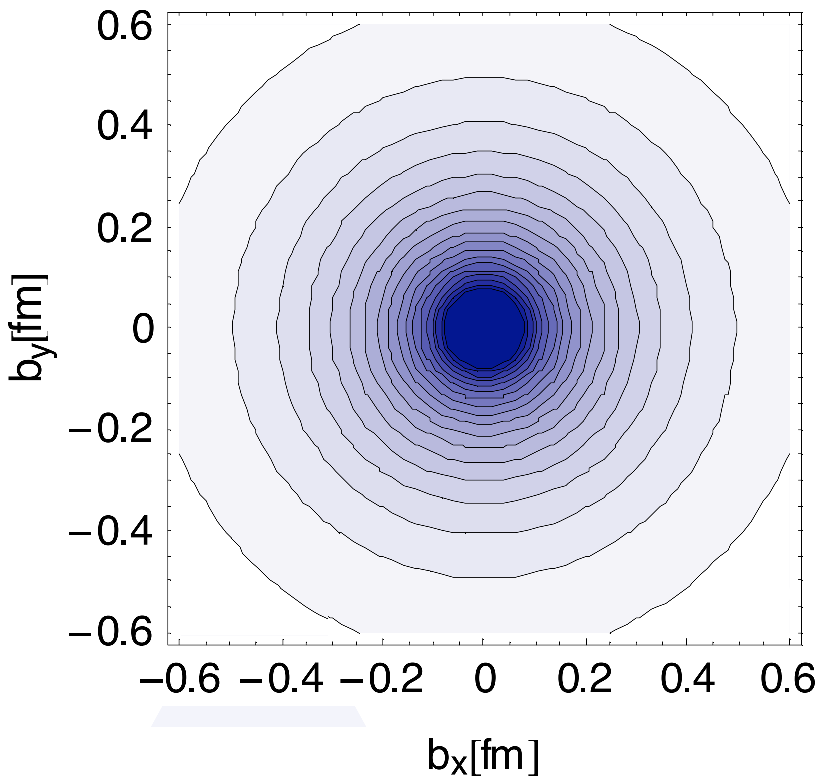


Parton distributions:
longitudinal momentum
of partons

Another 3D picture of the nucleon



Form factors:
transverse distribution
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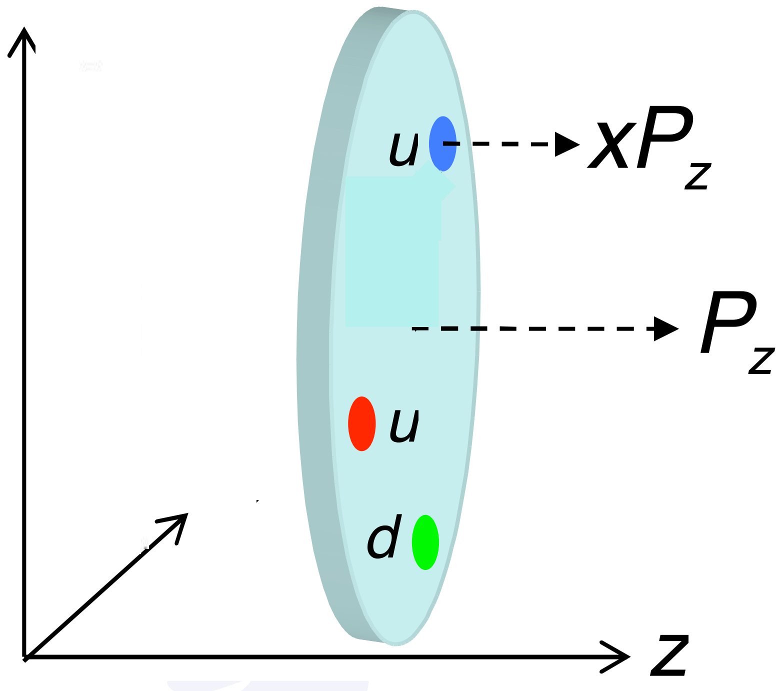

Parton distributions:
longitudinal momentum
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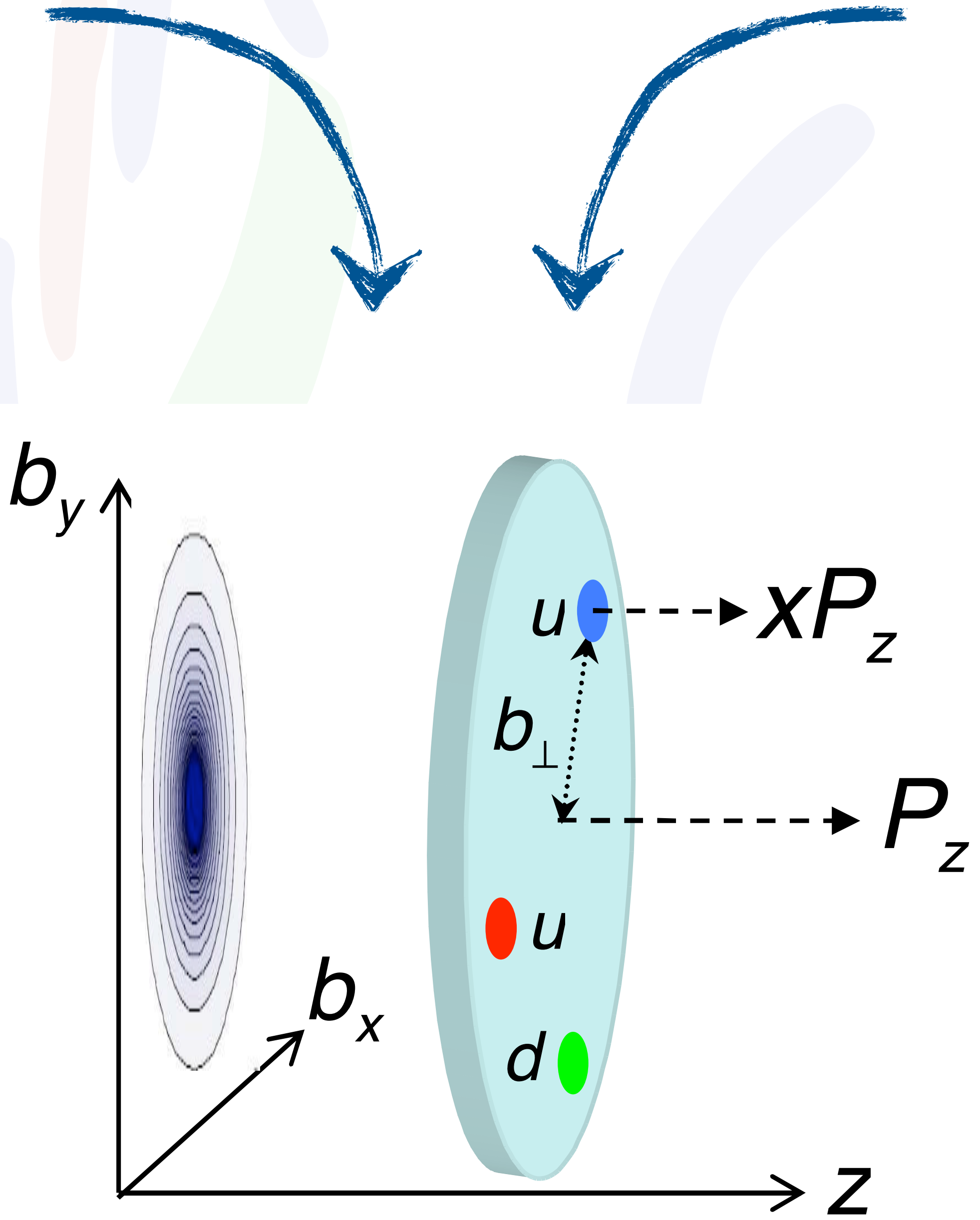
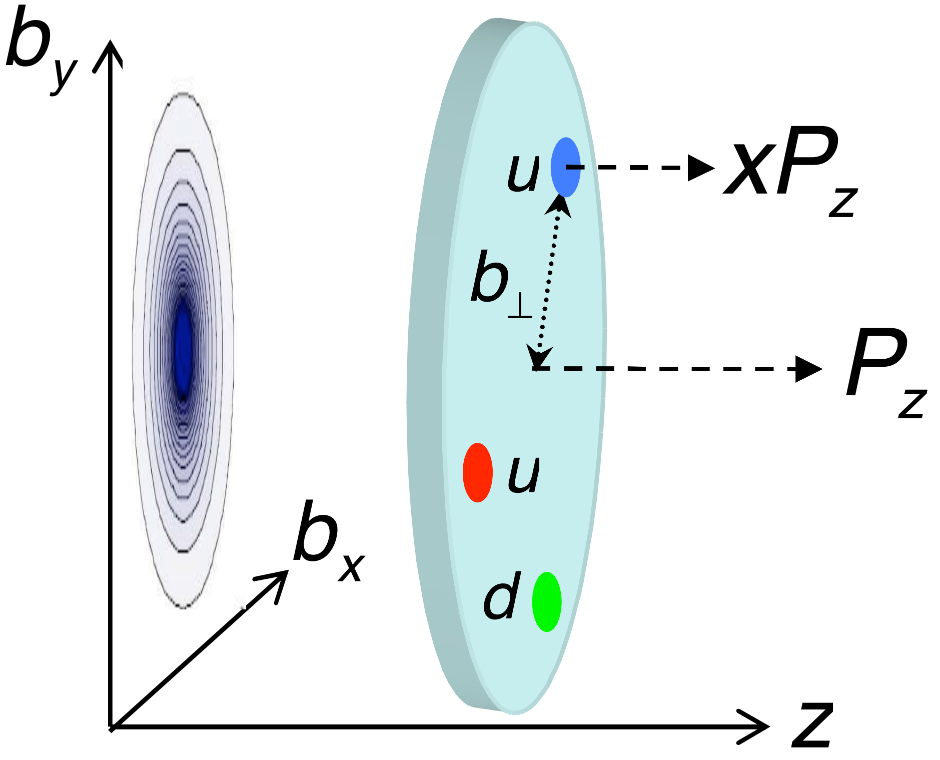
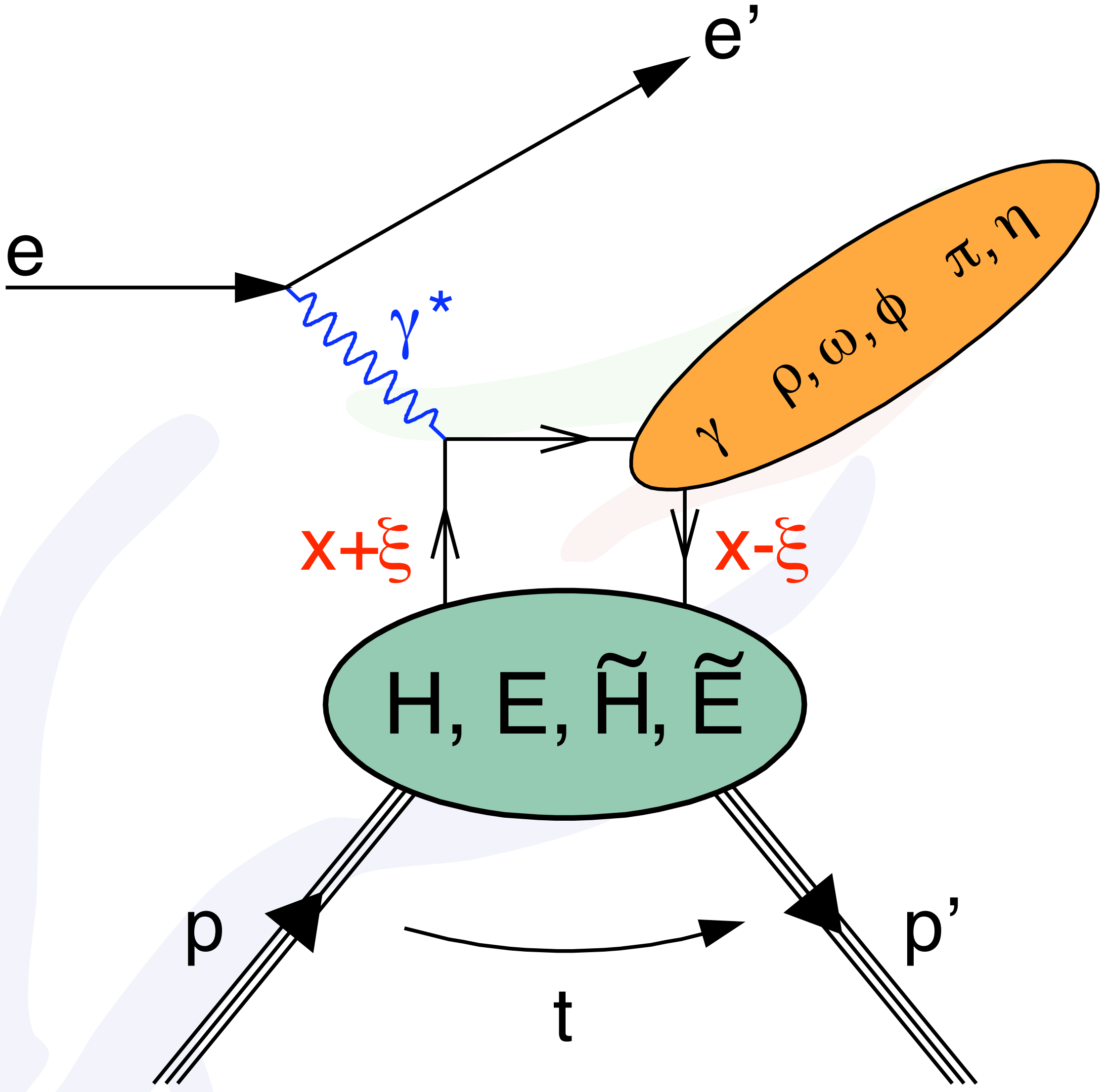


Nucleon Tomography

correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

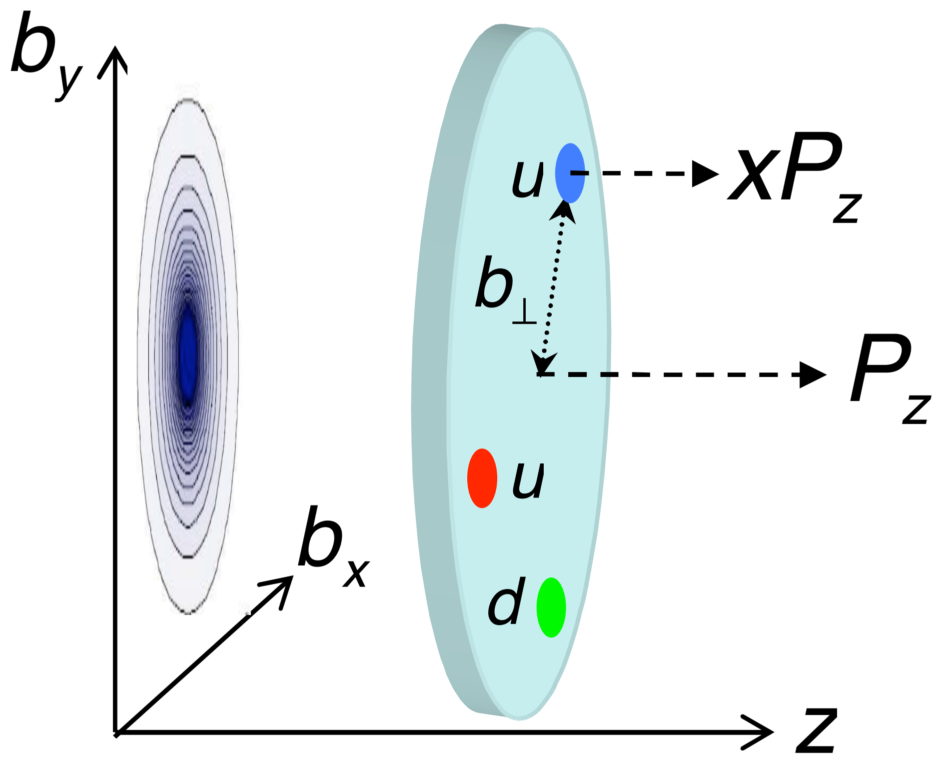


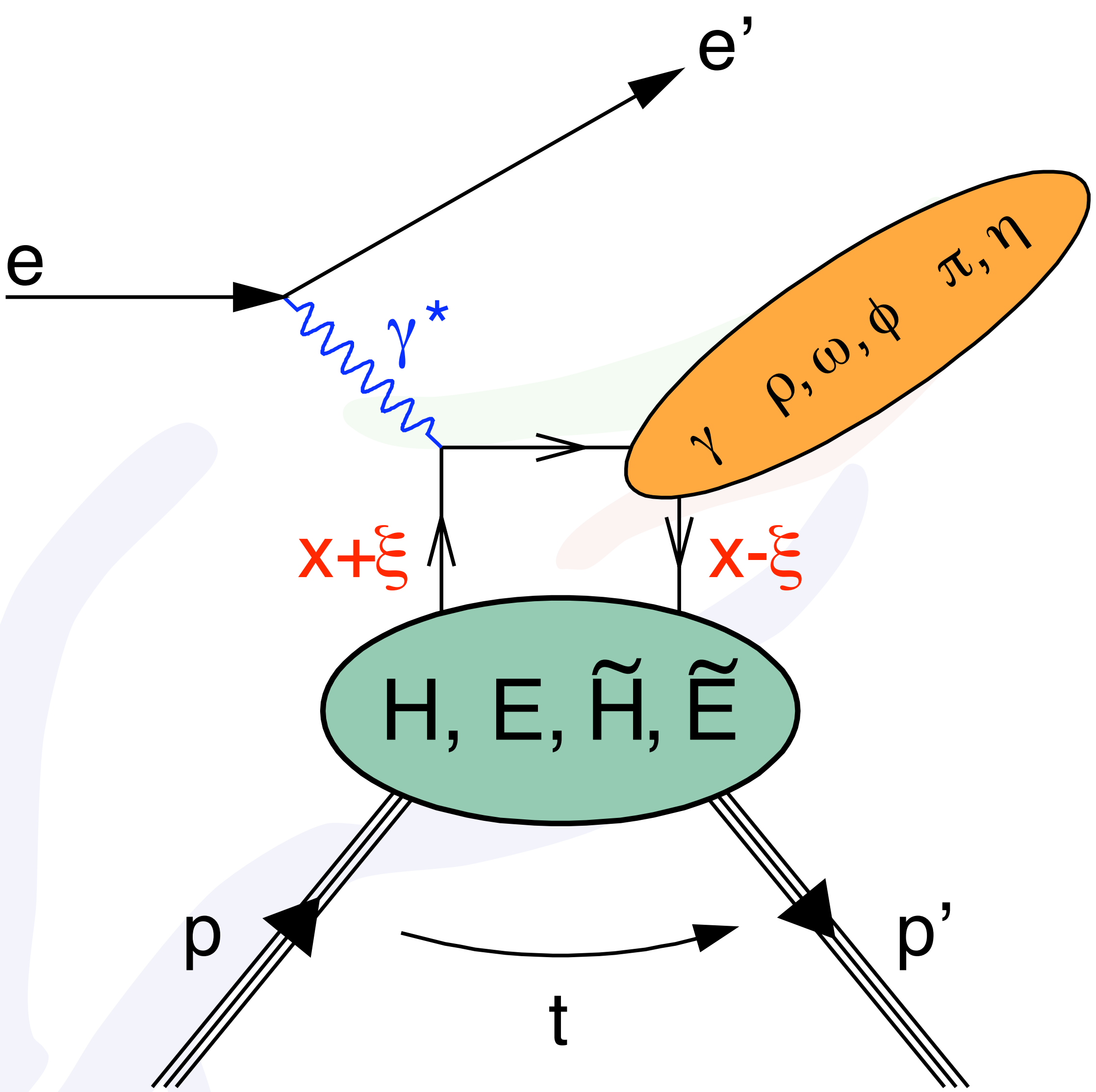


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

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

Probing GPDs in Exclusive Reactions



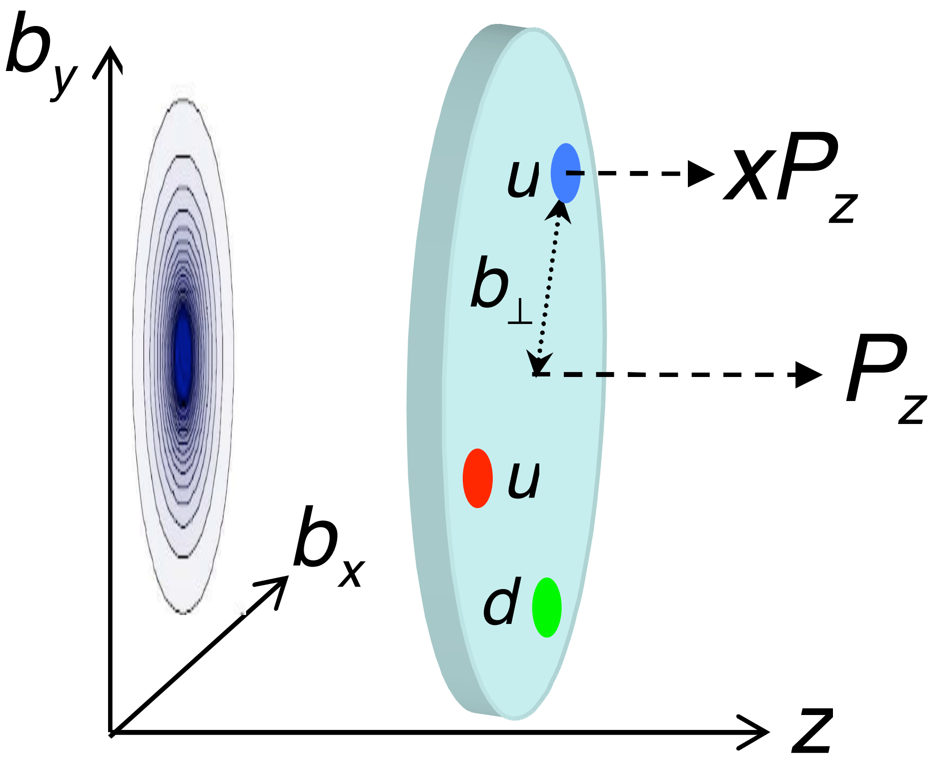


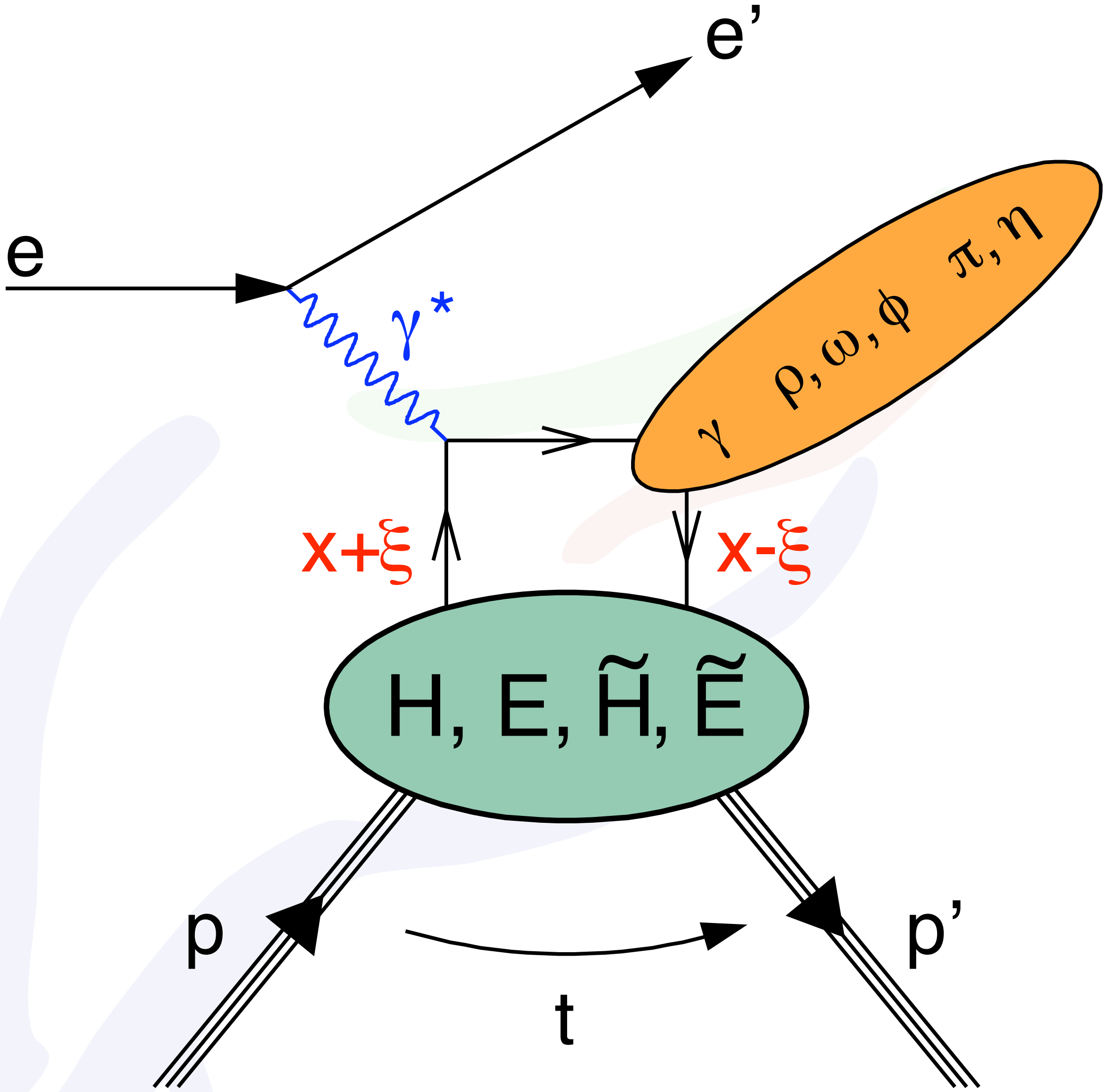
	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

gunar.schnell @ desy.de

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	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

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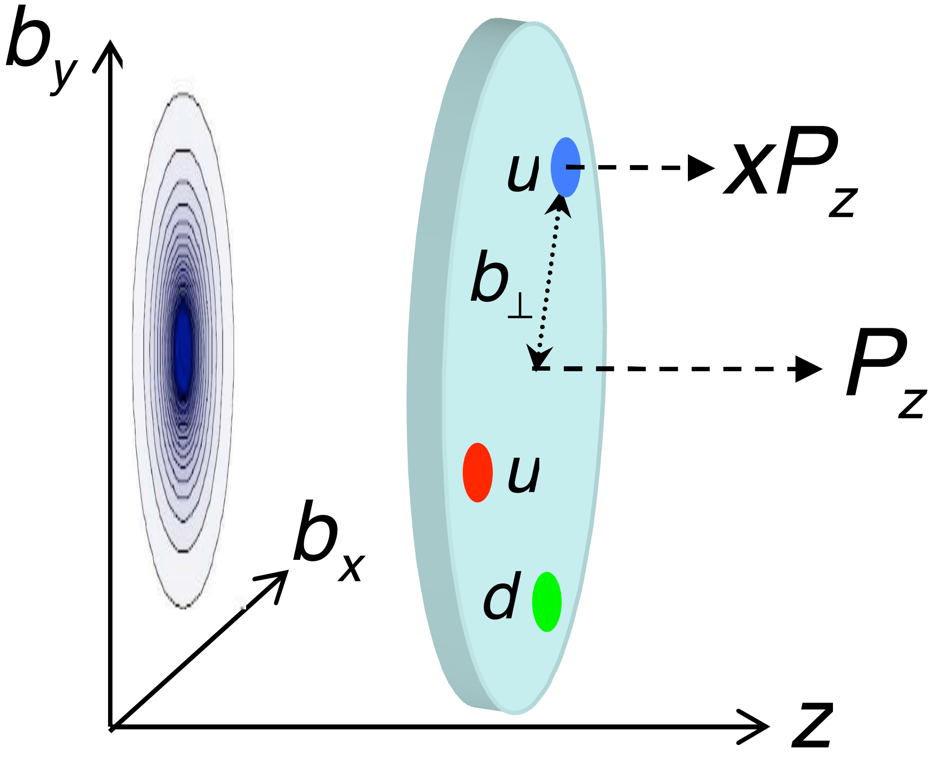
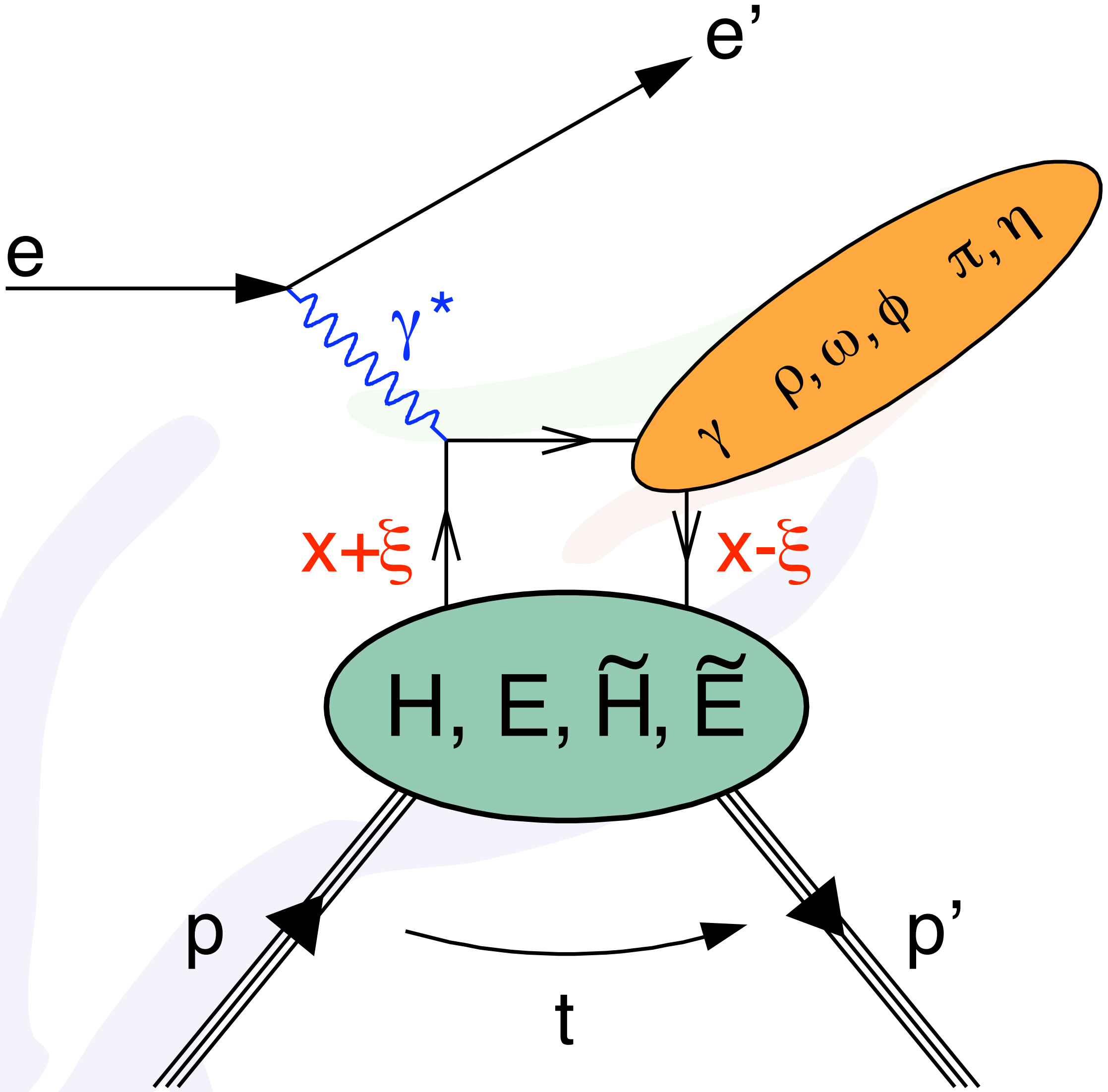
Probing GPDs in Exclusive Reactions





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

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

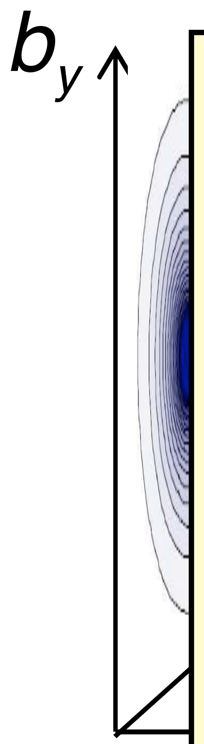
$$H^q(x,\xi=0,t=0) = q(x)$$

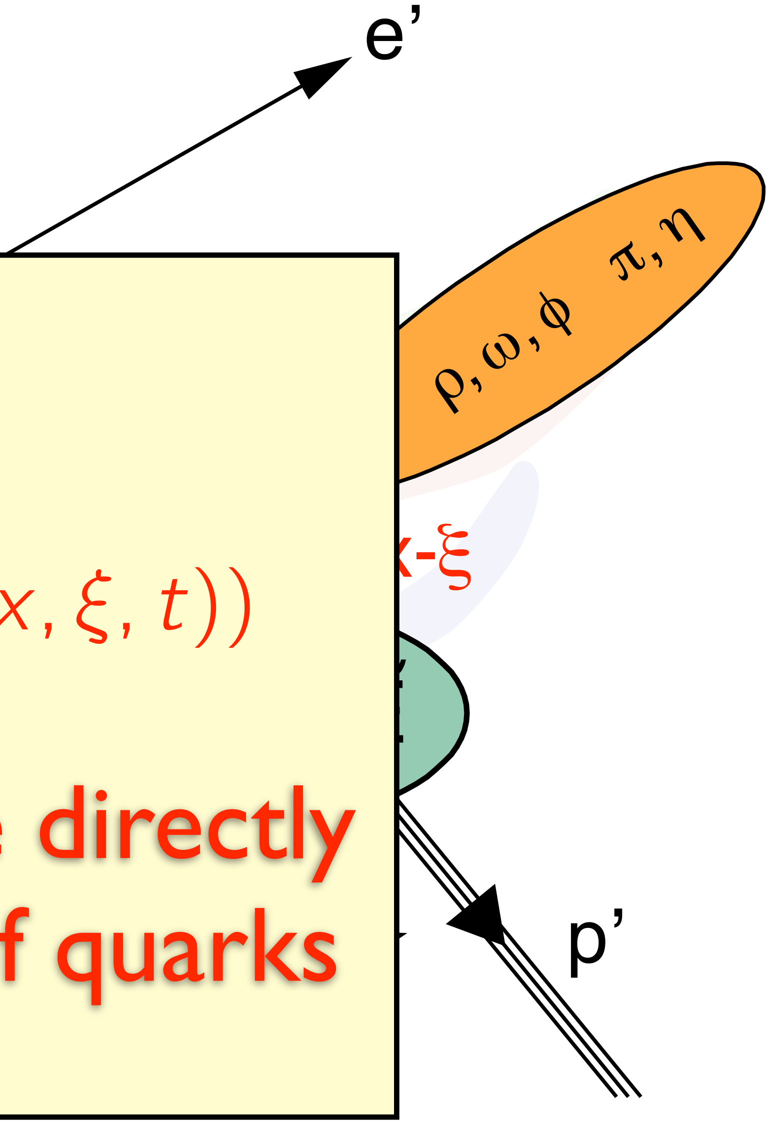
$$\widetilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

	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)

Probing GPDs in Exclusive Reactions





Ji relation (1996)

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

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

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

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

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

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

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

(+ 4 more chiral-odd functions)

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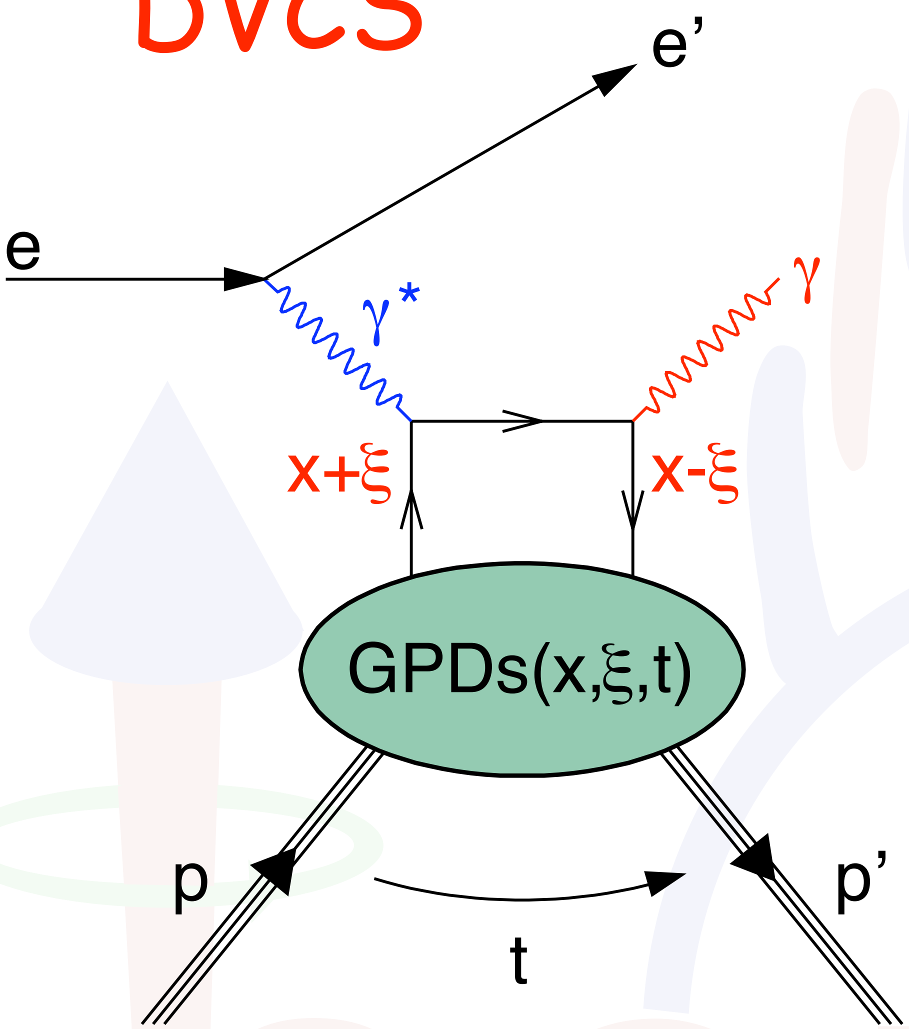
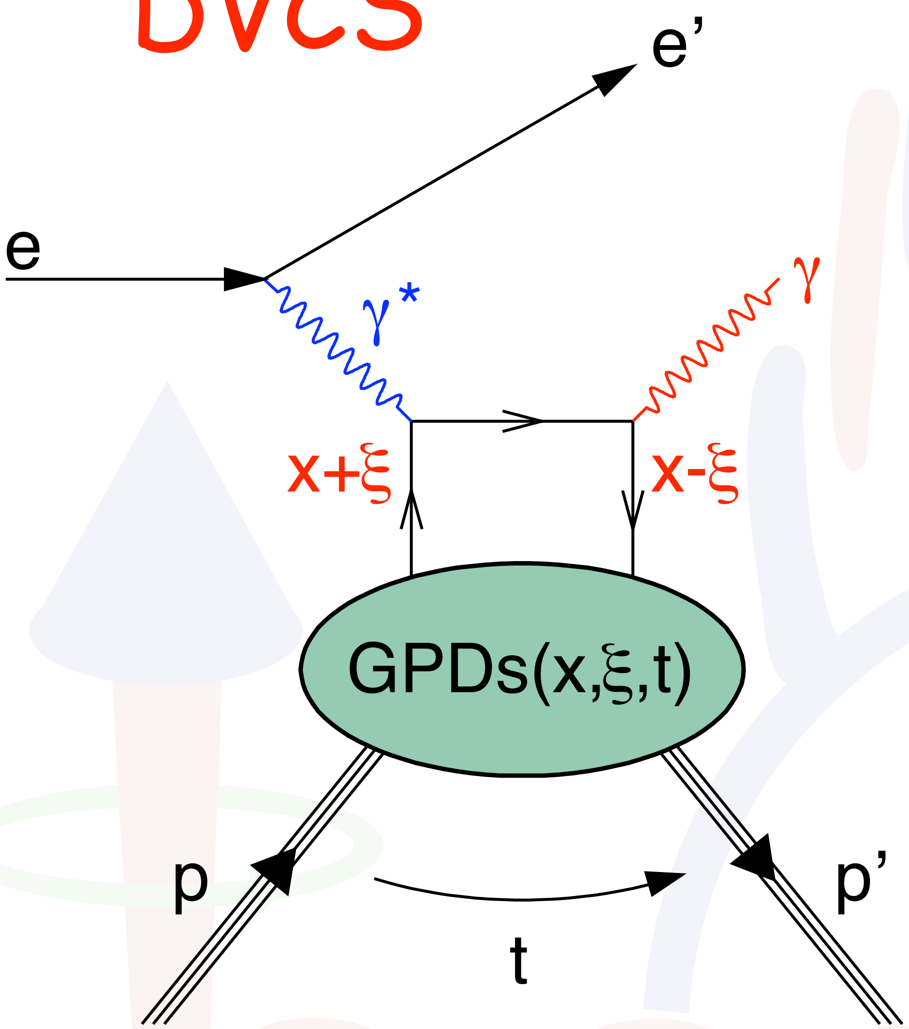
Real-photon production

DVCS

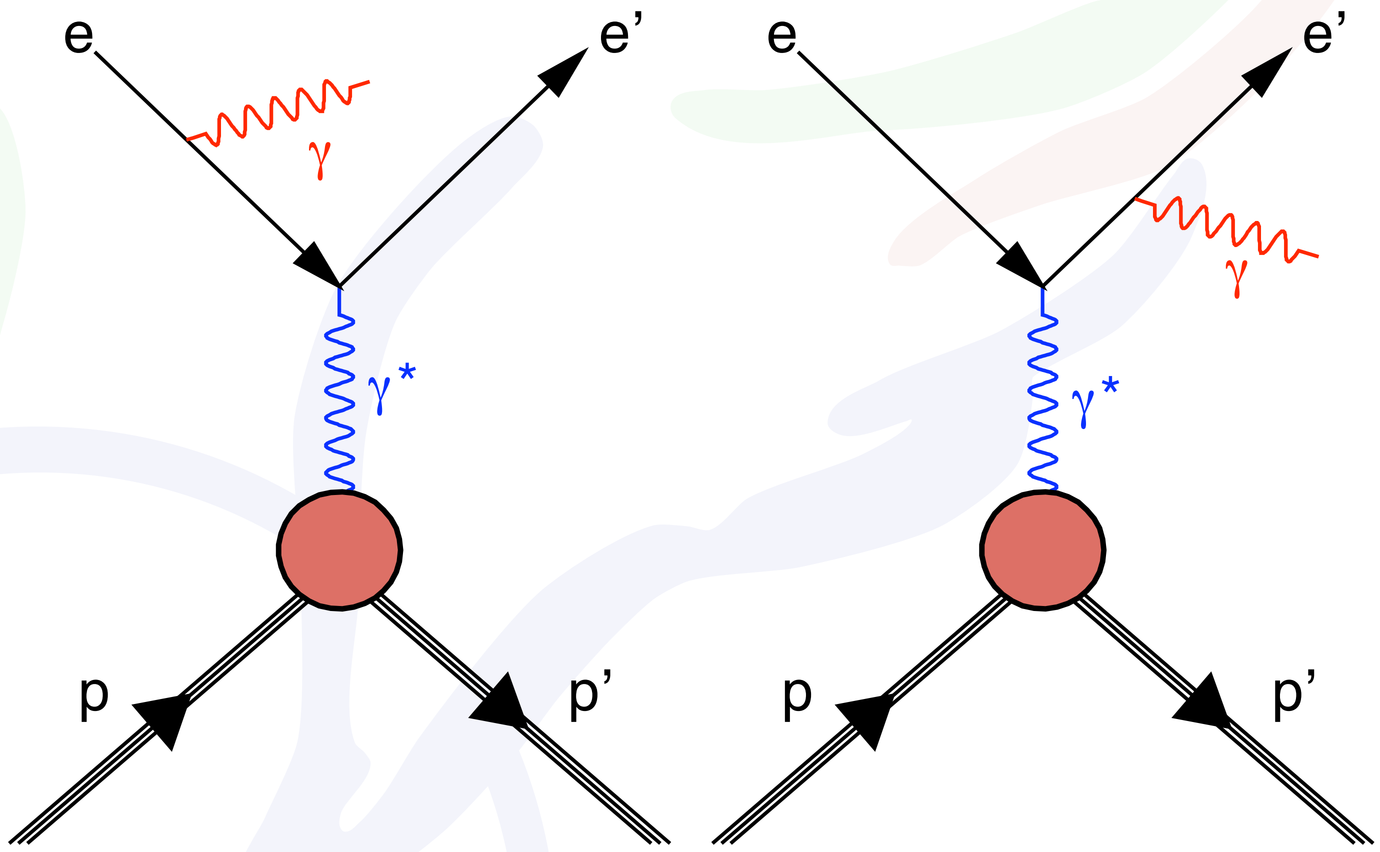


Real-photon production

DVCS



Bethe-Heitler



Real-photon production

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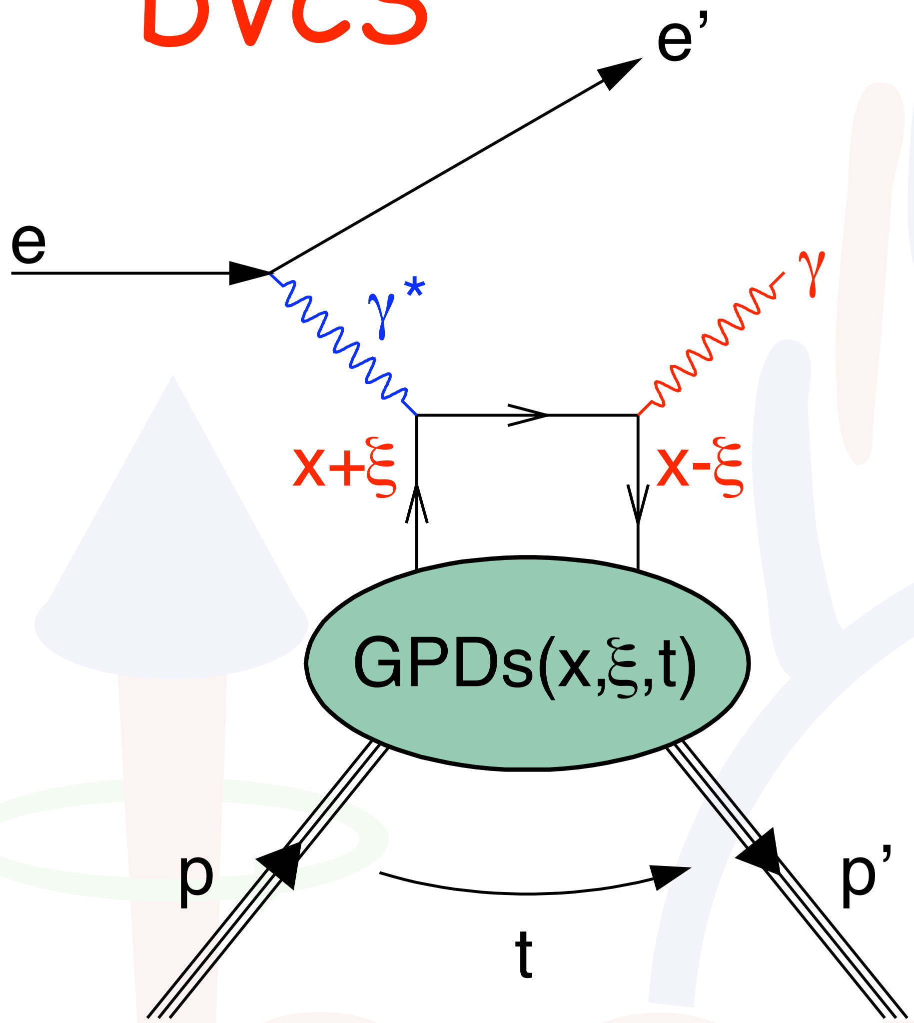

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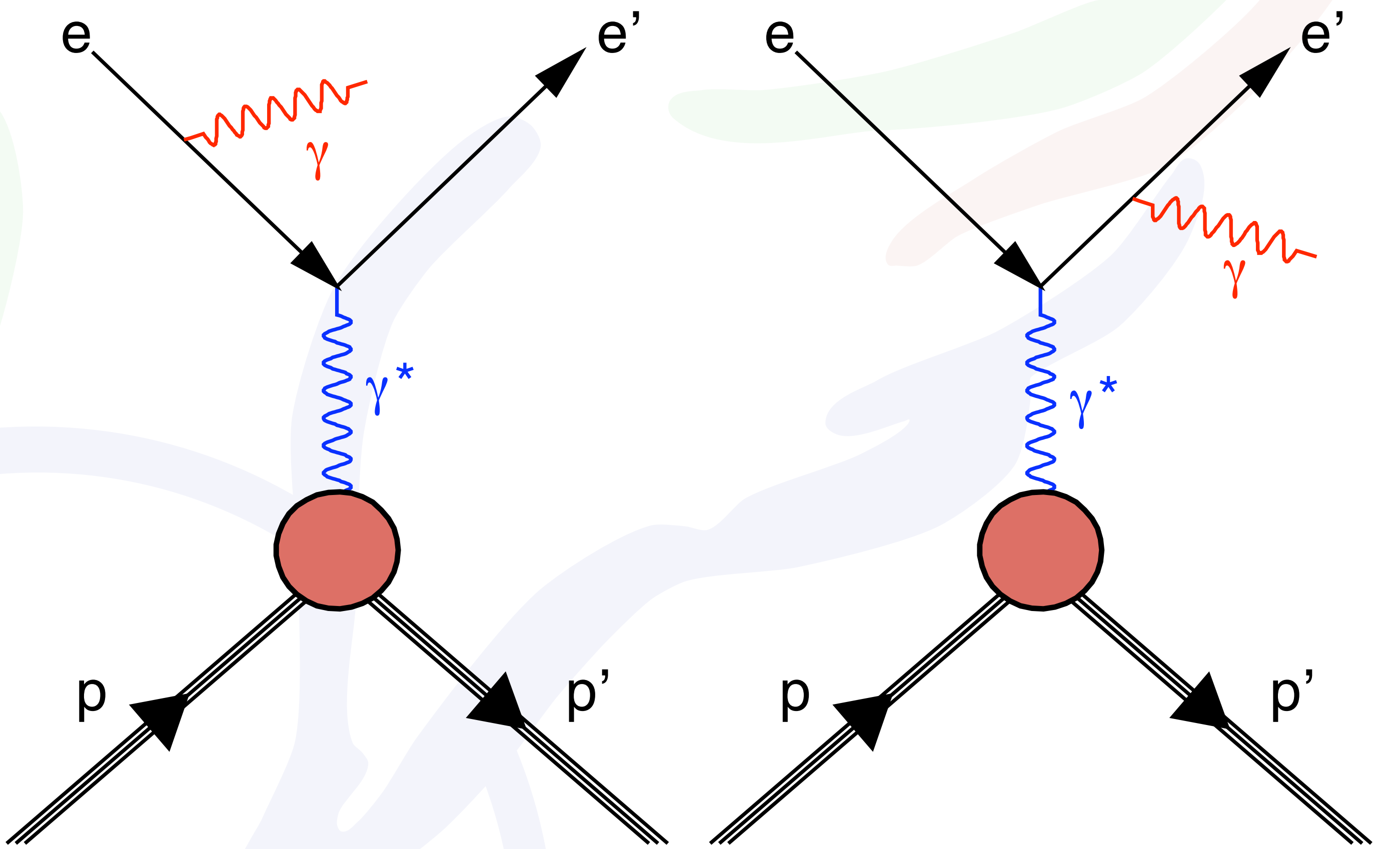
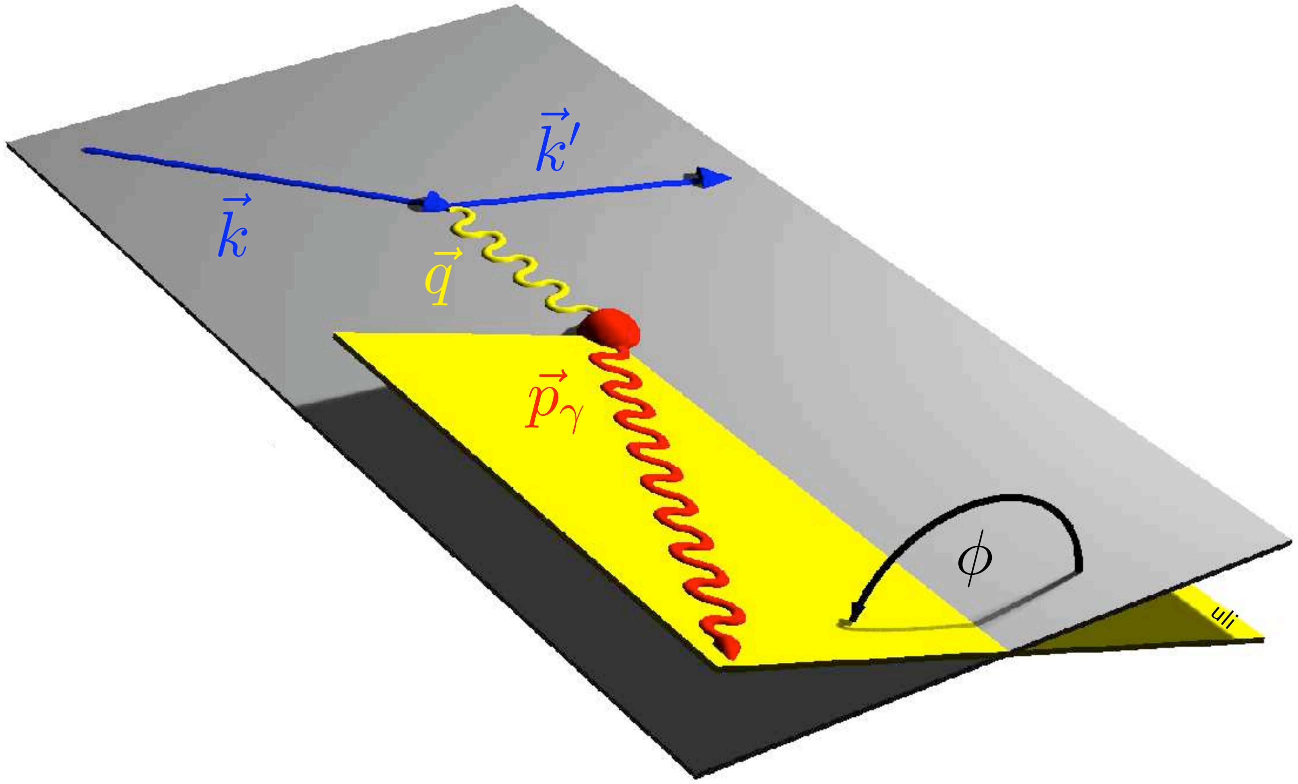


$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Azimuthal dependences in DVCS/BH

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

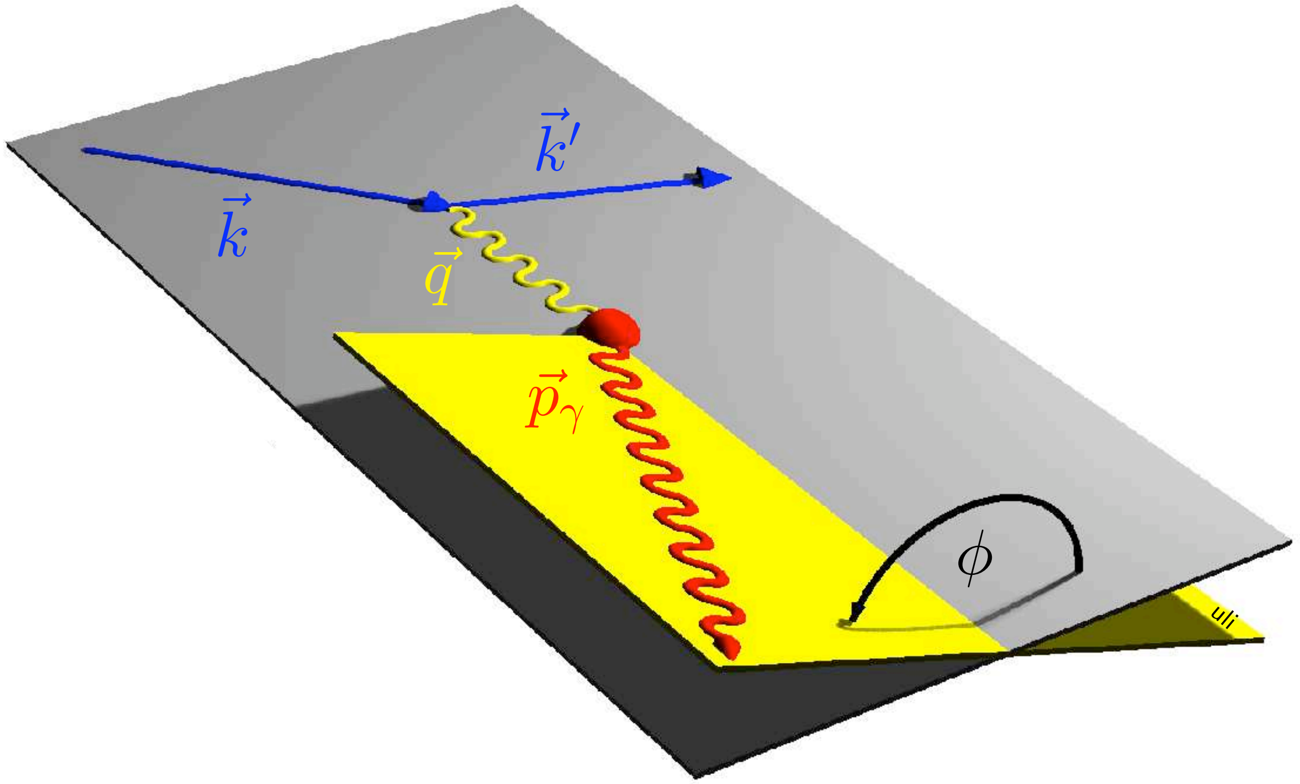


Fourier expansion for ϕ:

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

calculable in QED (using FF measurements)

Azimuthal dependences in DVCS/BH



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

Azimuthal dependences in DVCS/BH

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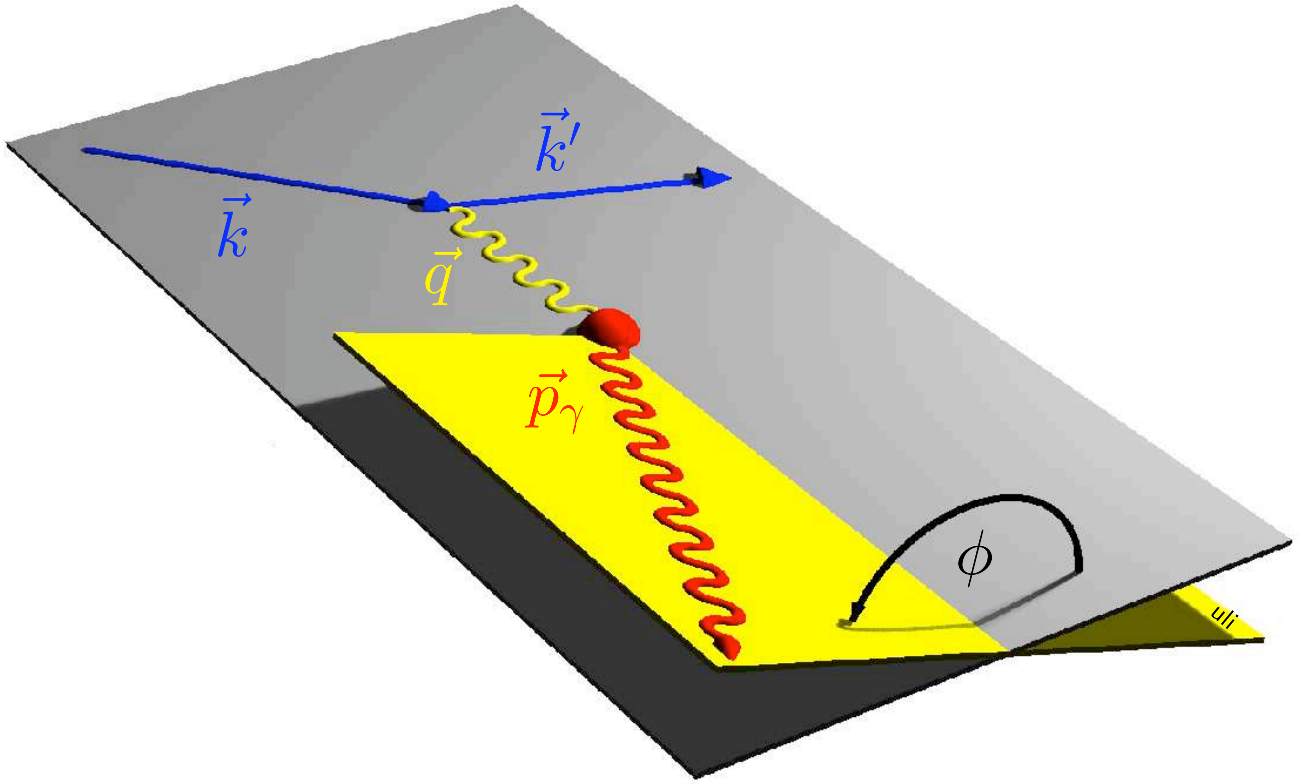

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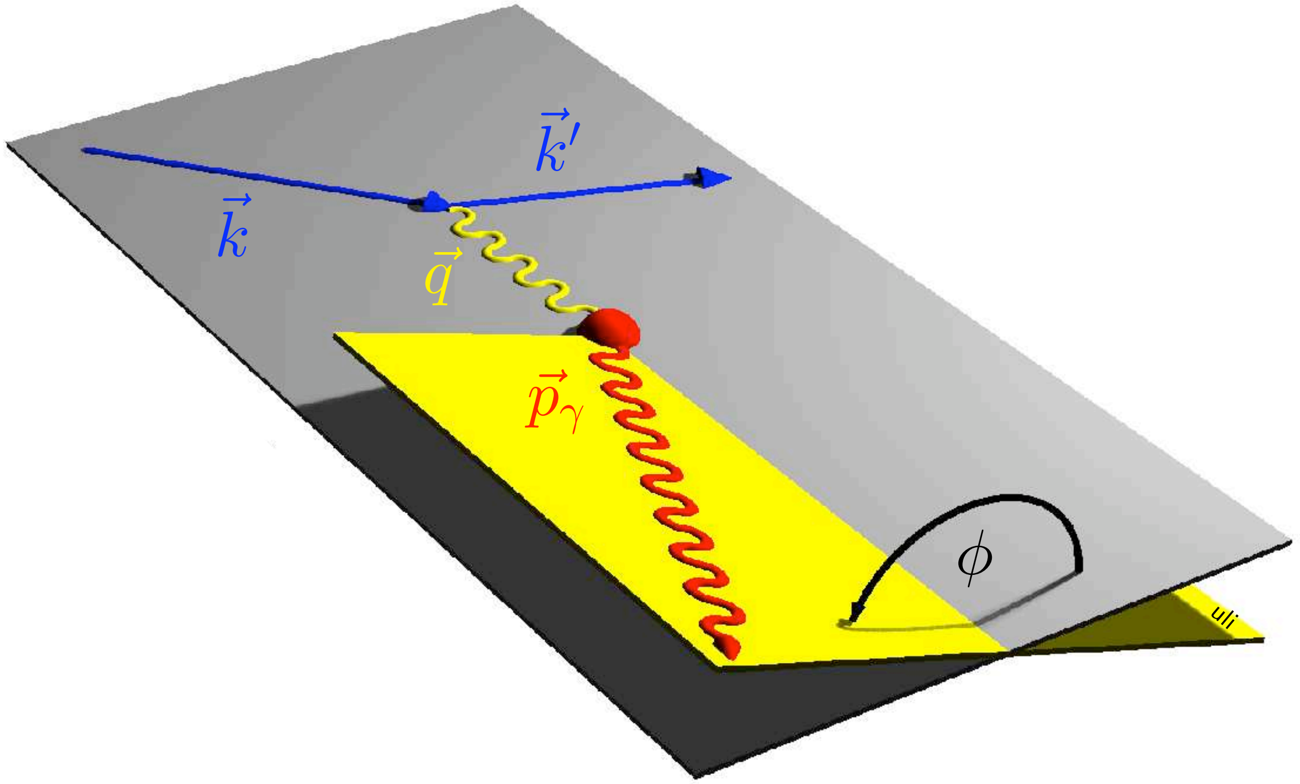
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

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



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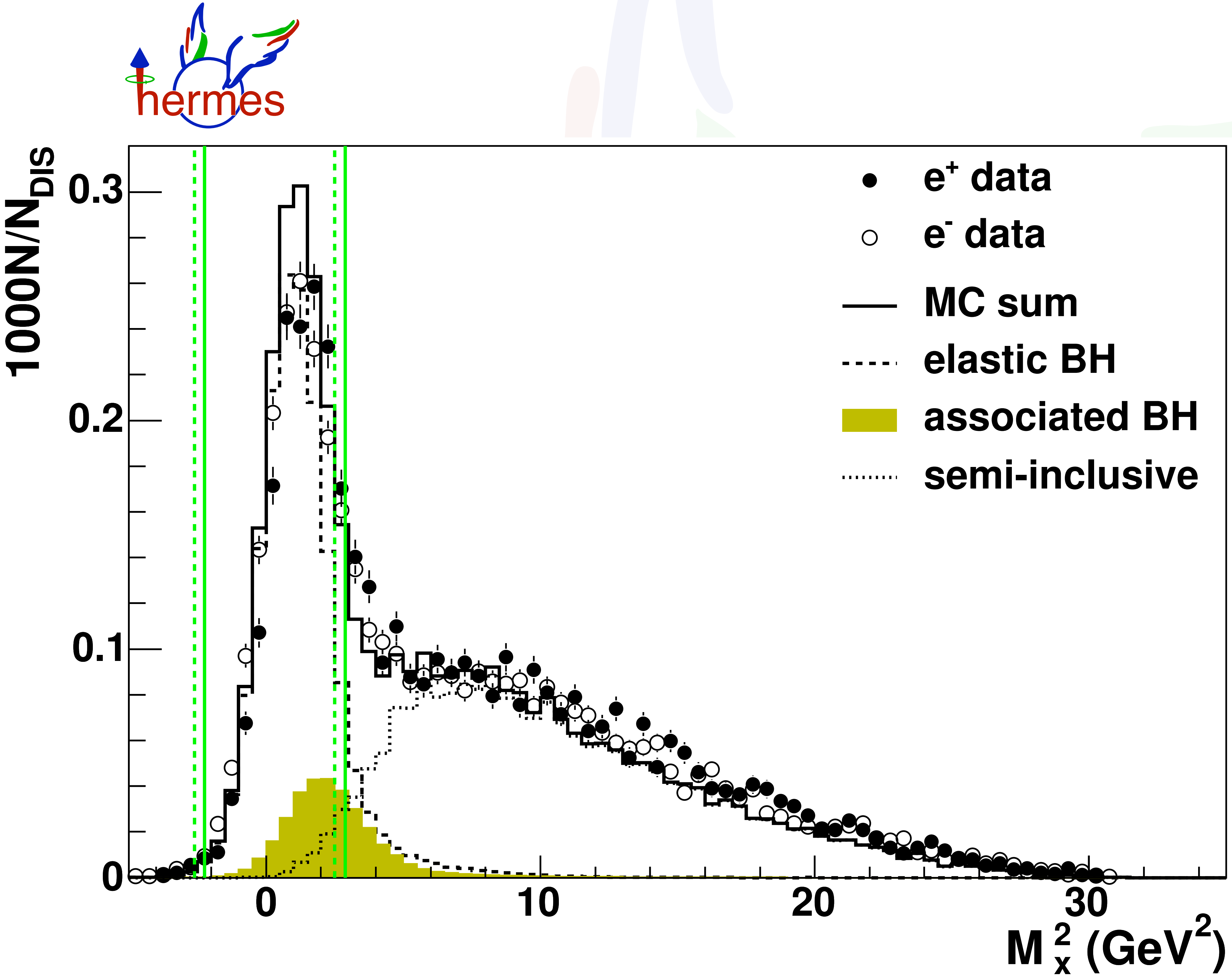
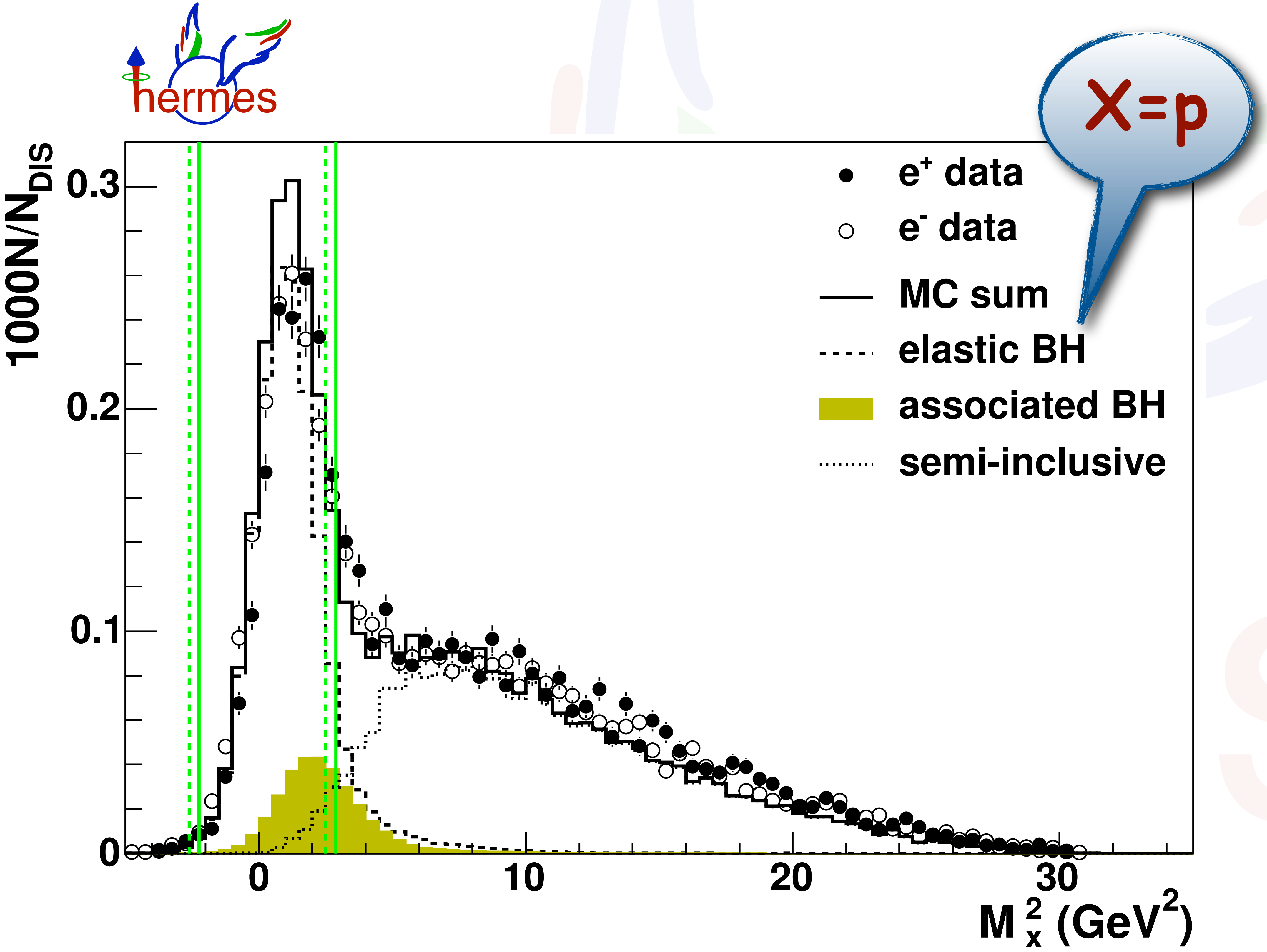
bilinear ("DVCS") or linear in GPDs

Exclusivity: missing-mass technique



Exclusivity: missing-mass technique



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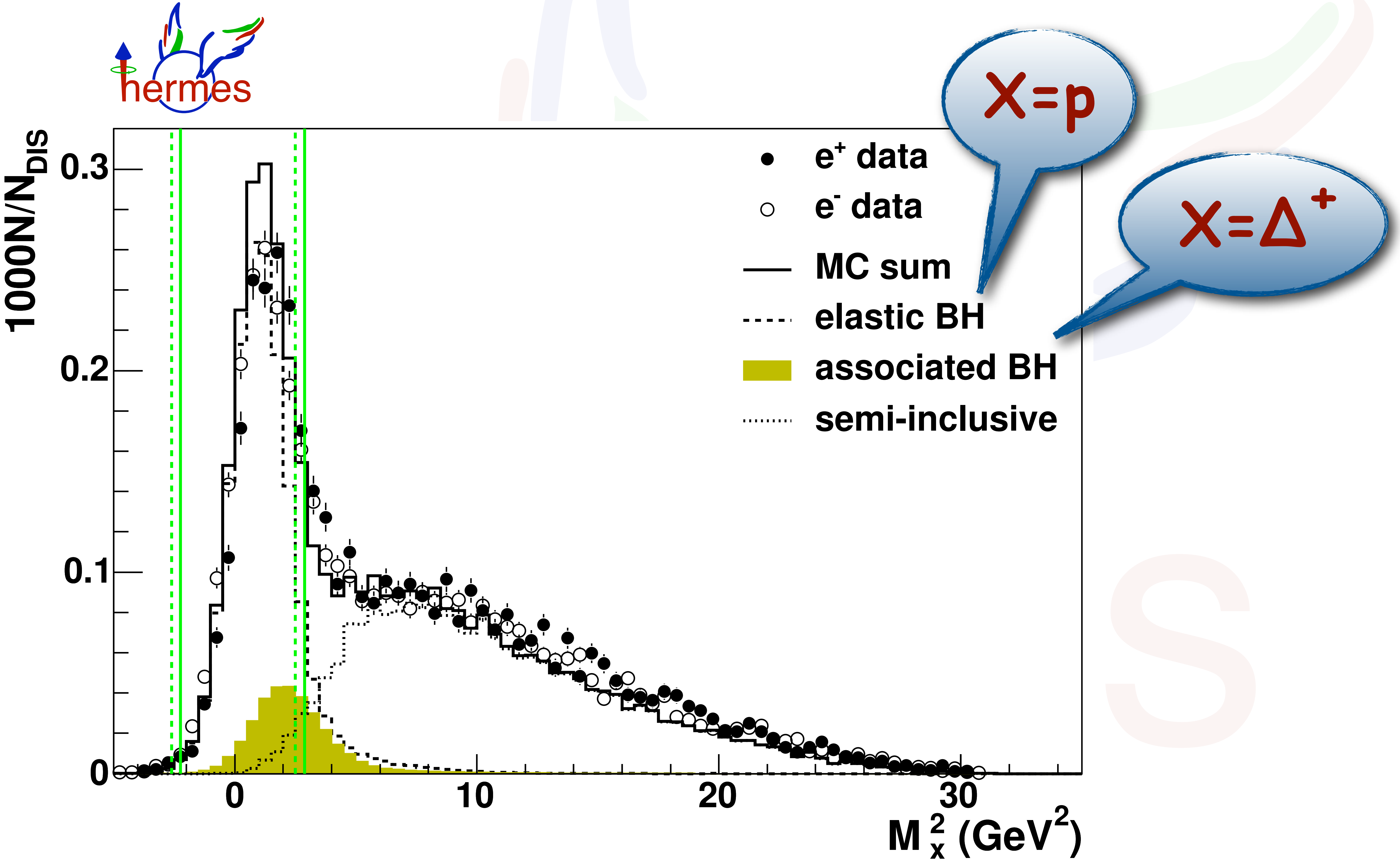

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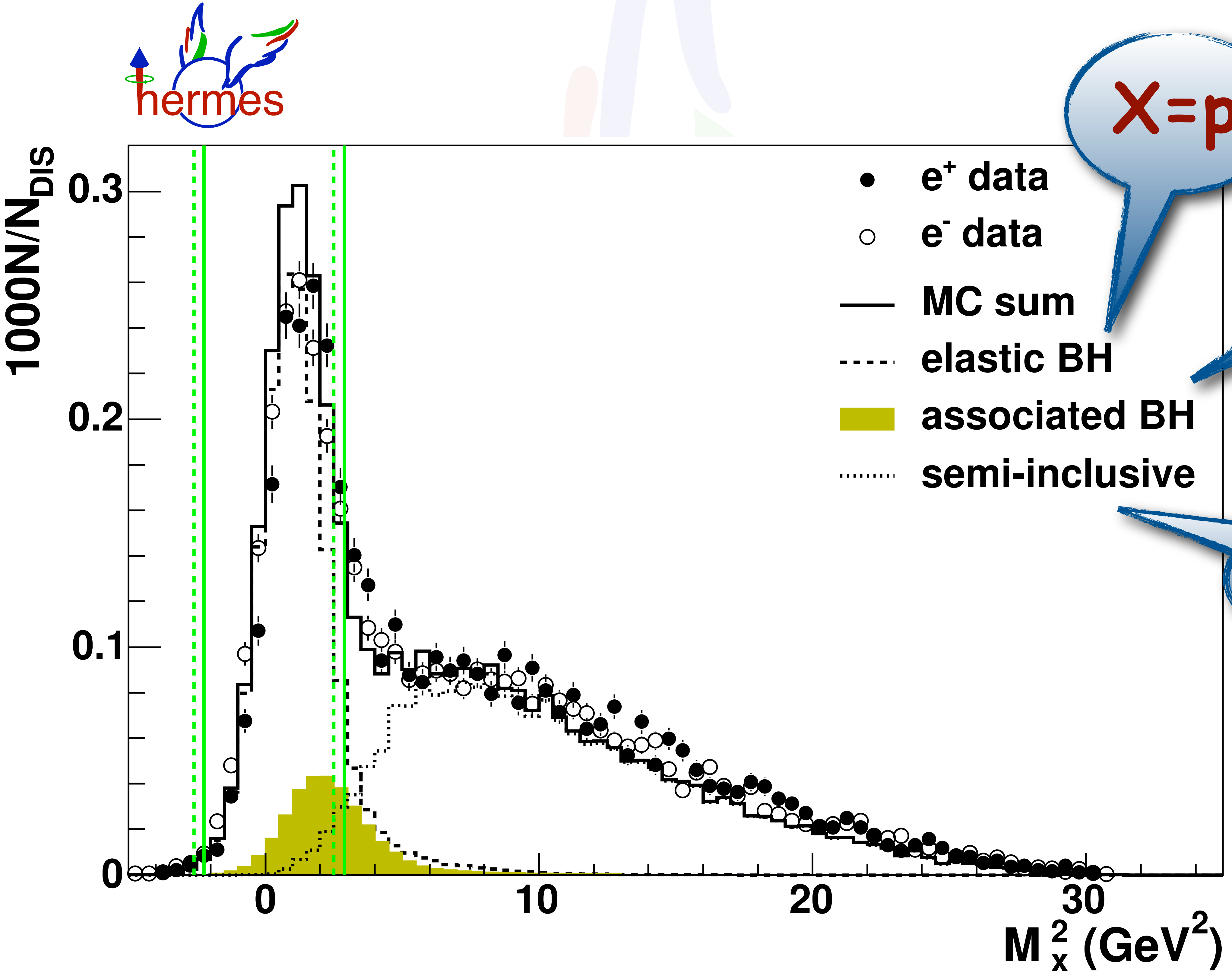
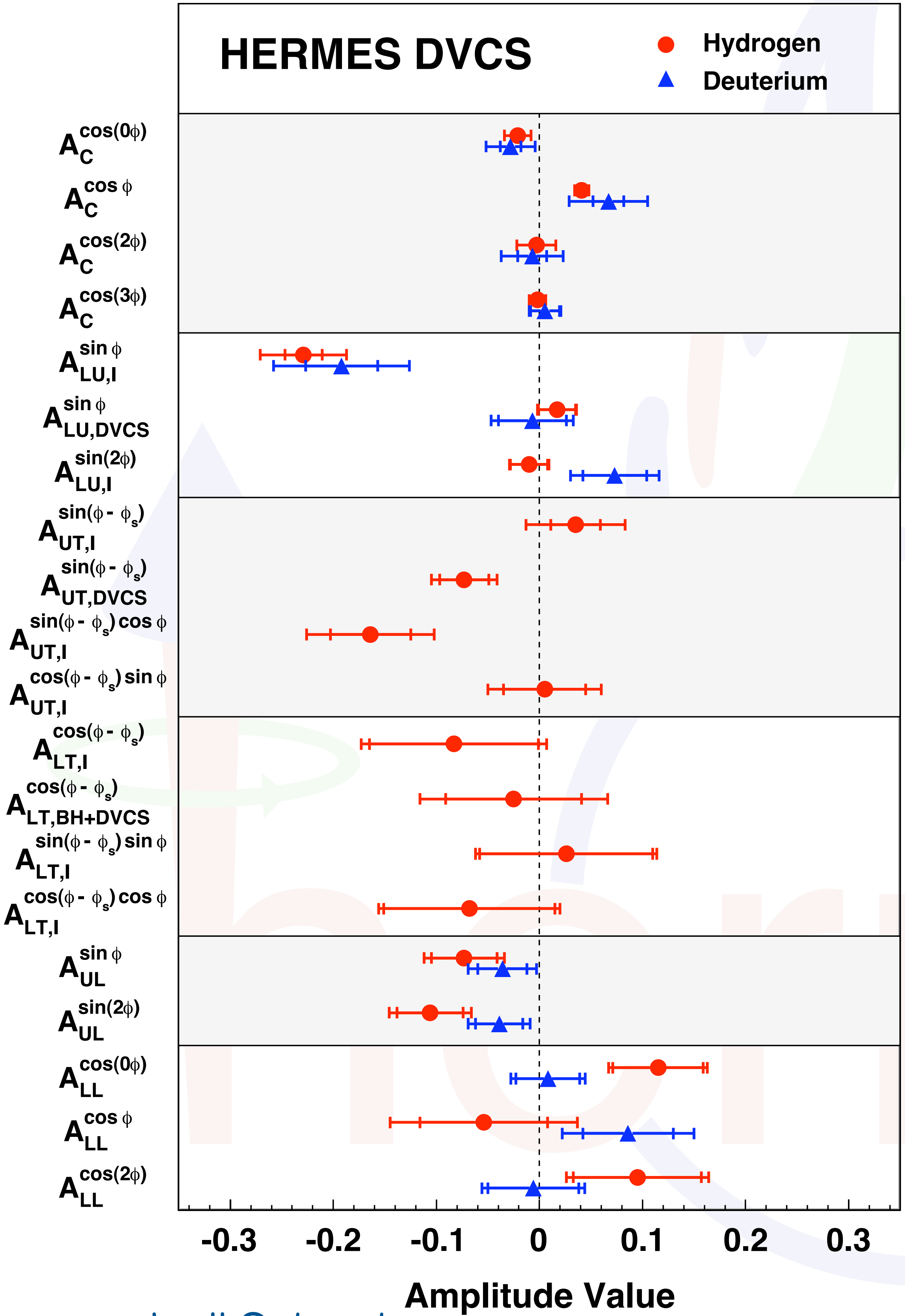


$X=p$

$X=\Delta^+$

$X=\pi^0+\ldots$

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 $\tilde{H}$

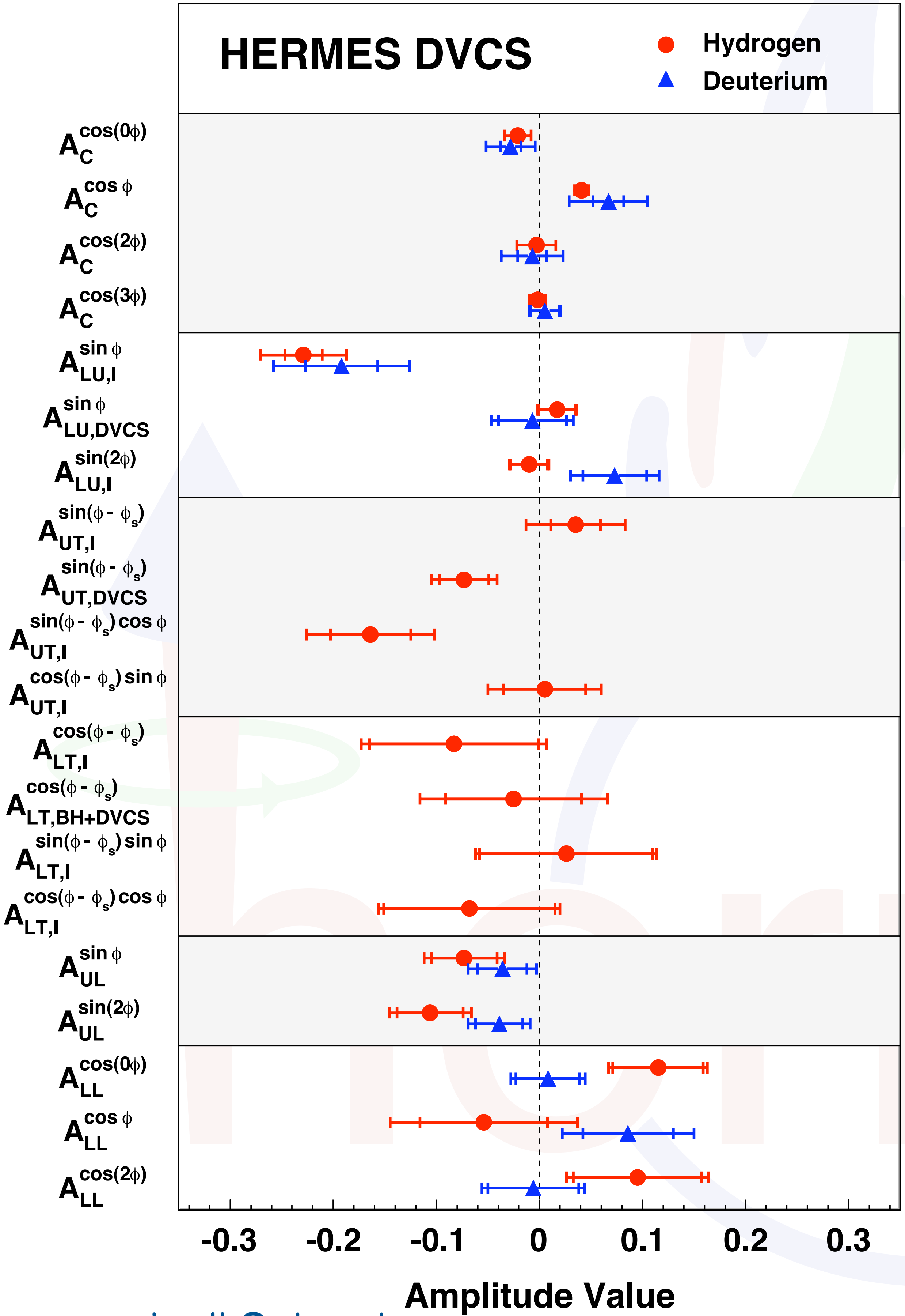
Double-spin asymmetry:

GPD $\tilde{H}$

JHEP 06 (2010) 019

NPB 842 (2011) 265

A wealth of azimuthal amplitudes



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JHEP 06 (2010) 019
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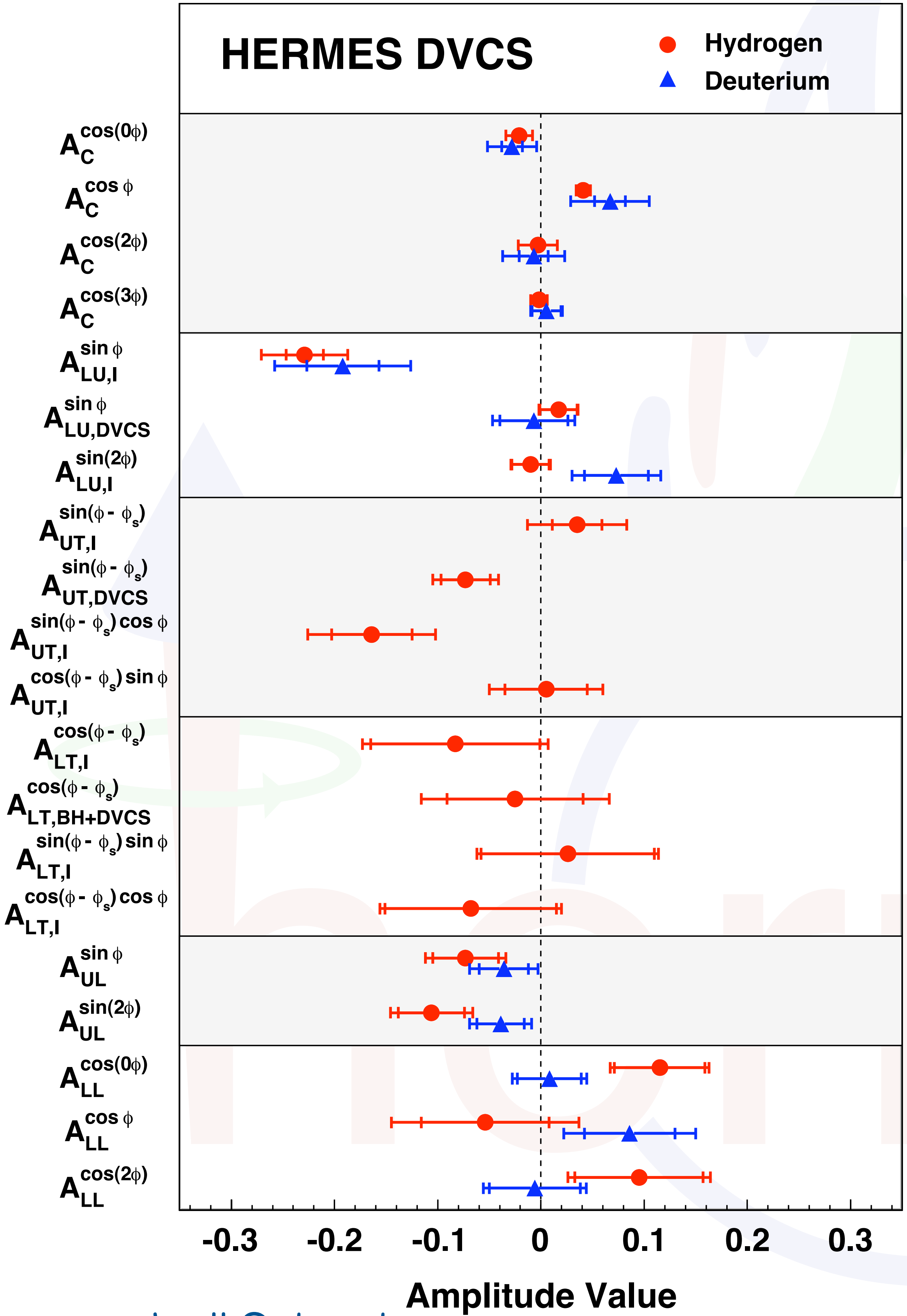
☛ M. Murray (S3-II)

A wealth of azimuthal amplitudes



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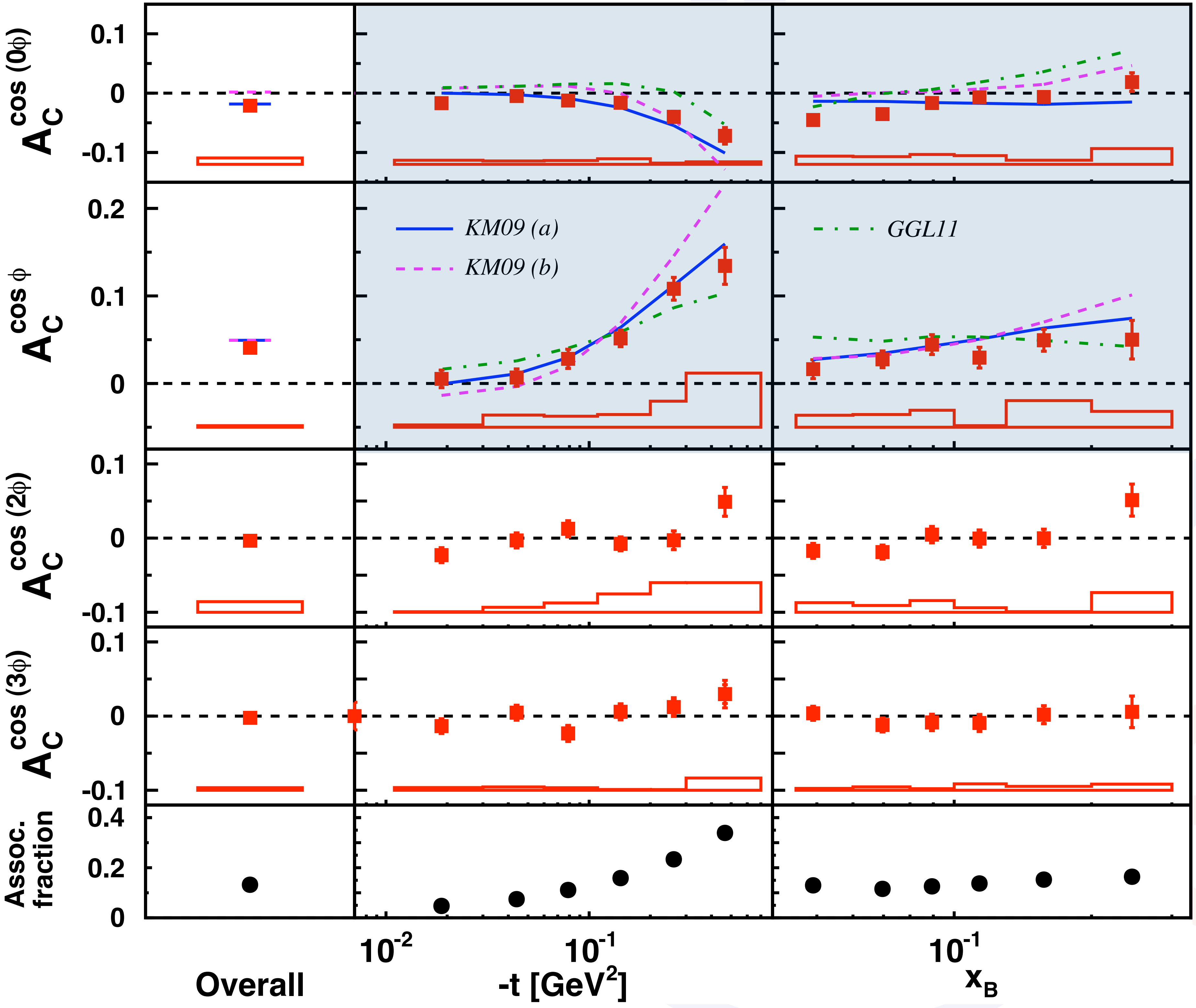
JHEP 06 (2010) 019
NPB 842 (2011) 265

☛ M. Murray (S3-II)

complete data set!

Beam-charge asymmetry

[Airapetian et al., JHEP 07 (2012) 032; arXiv:1203.6287]



constant term:

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

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

[higher twist]

[gluon leading twist]

Resonant fraction:

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

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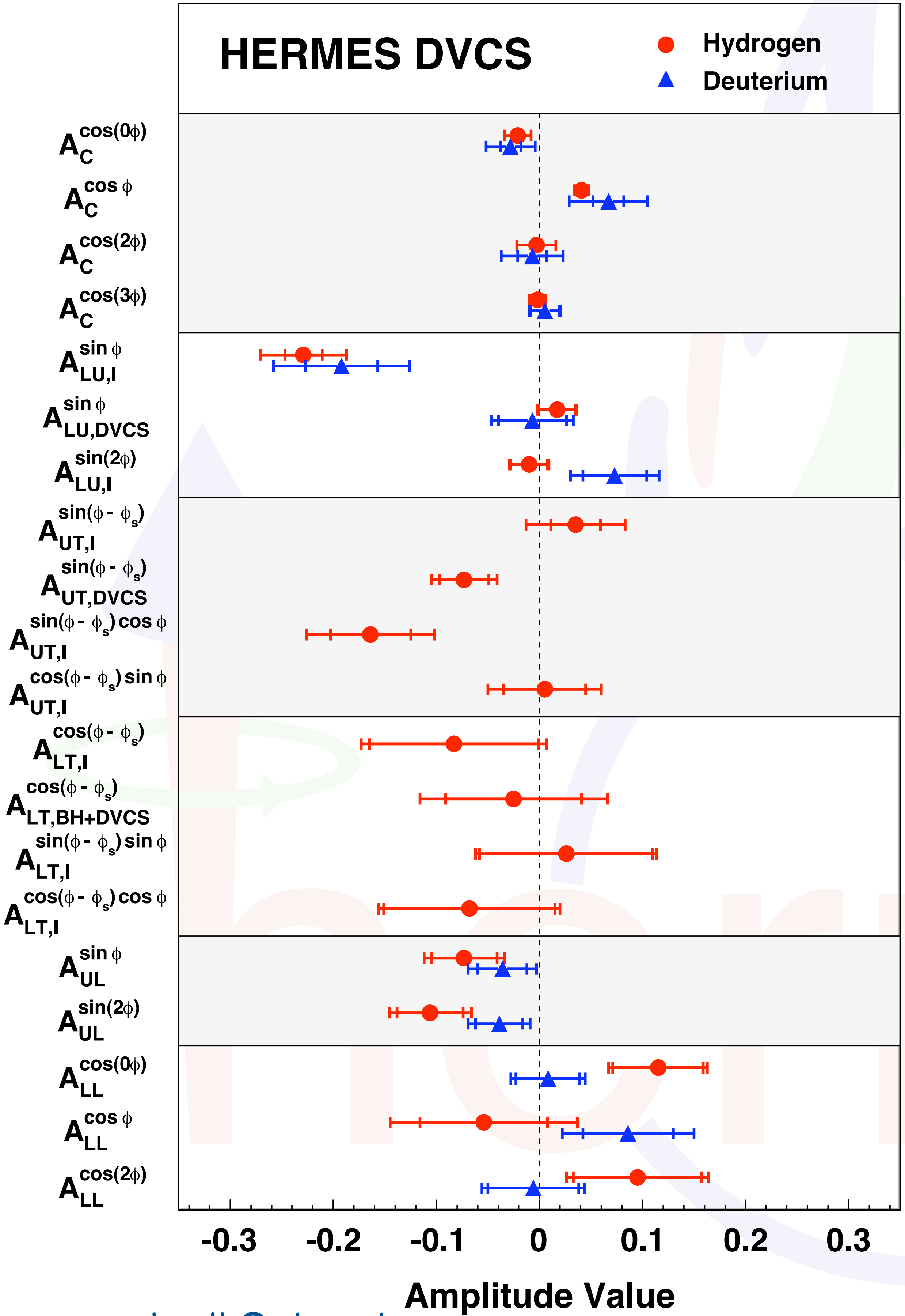
SPIN 2012 - September 21st, 2012

A wealth of azimuthal amplitudes



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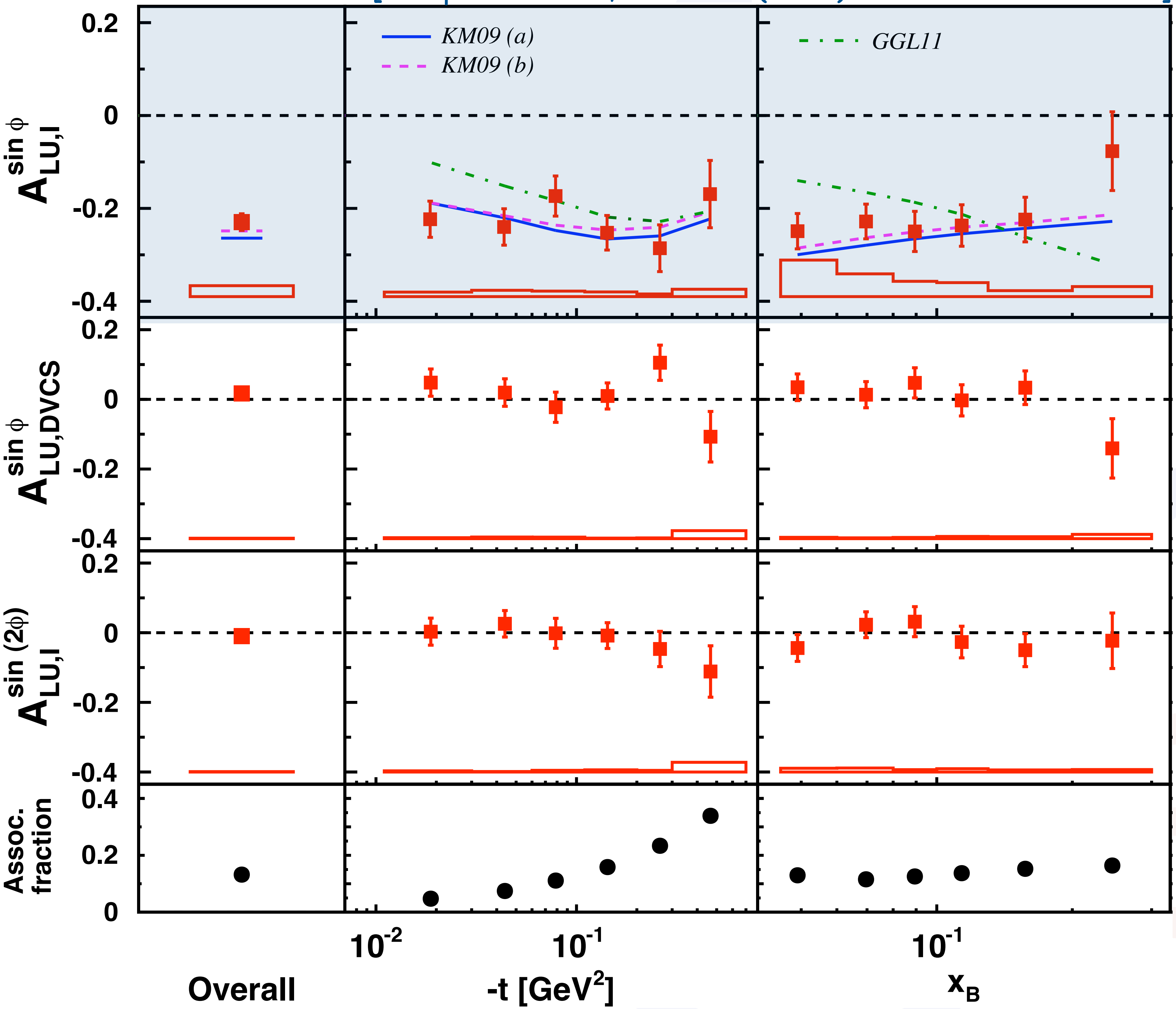


$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

Resonant fraction:

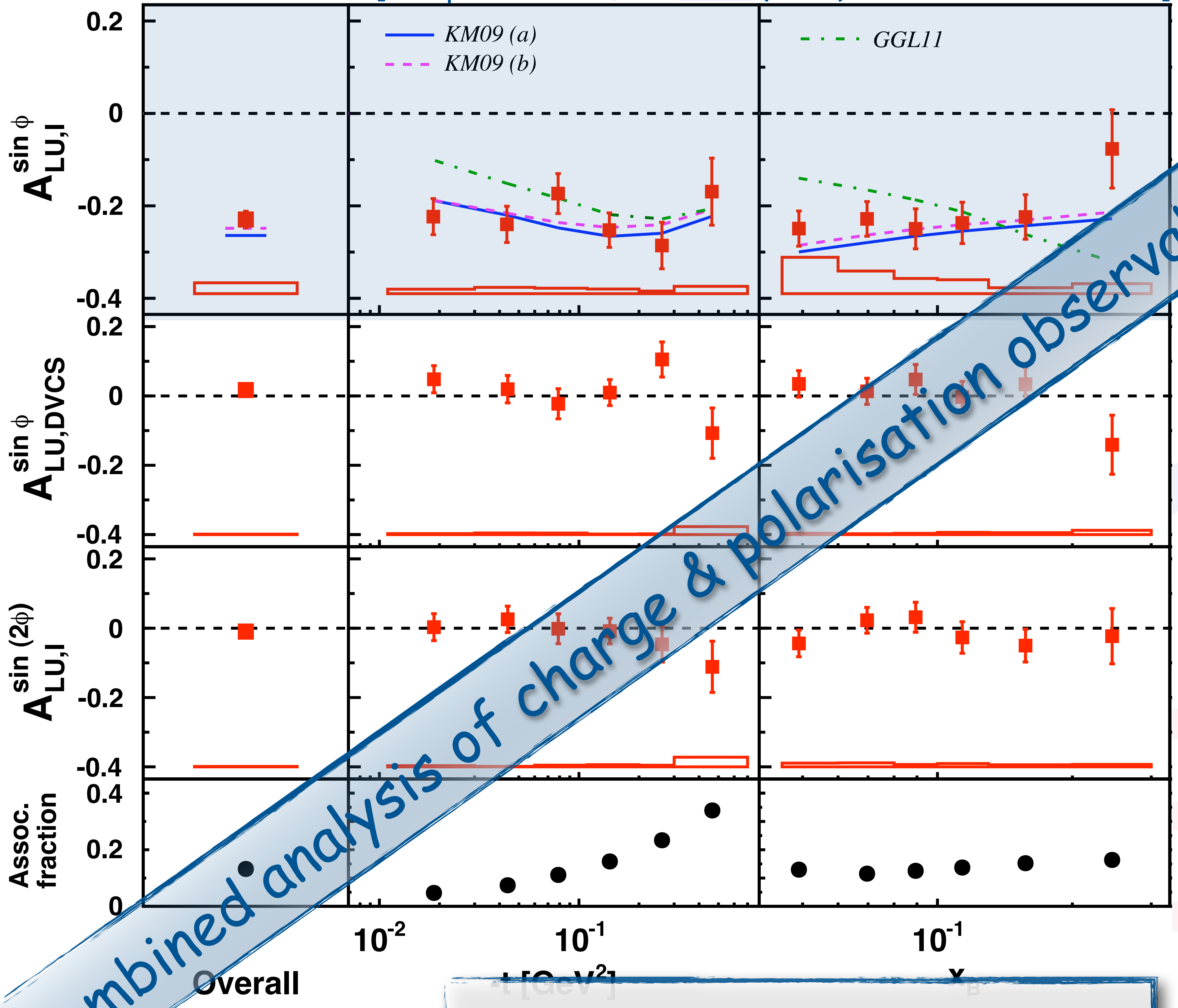
$ep \to e\Delta^+\gamma$

gunar.schnell @ desy.de

complete data set!

Beam-spin asymmetry

[Airapetian et al., JHEP 07 (2012) 032; arXiv:1203.6287]



combined analysis of charge & polarisation observables unique to HERA!

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

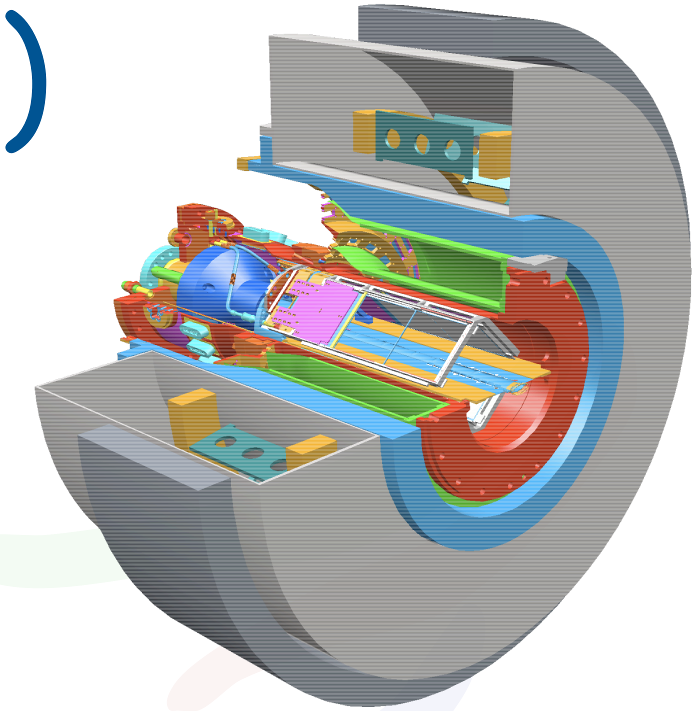
[higher twist]

Resonant fraction:

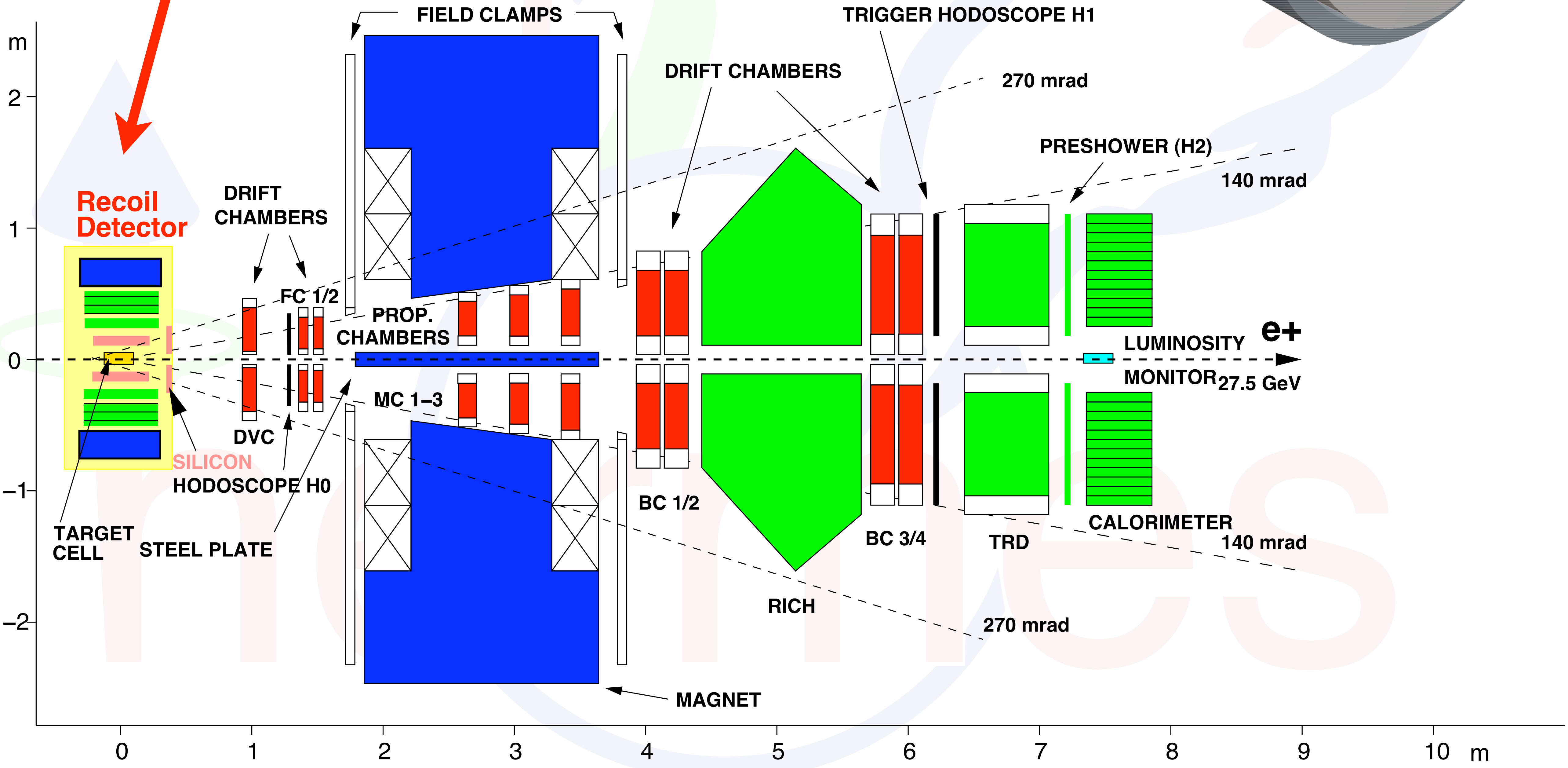
$ep \to e\Delta^+\gamma$

☛ M. Murray (S3-II)

HERMES detector (2006/07)

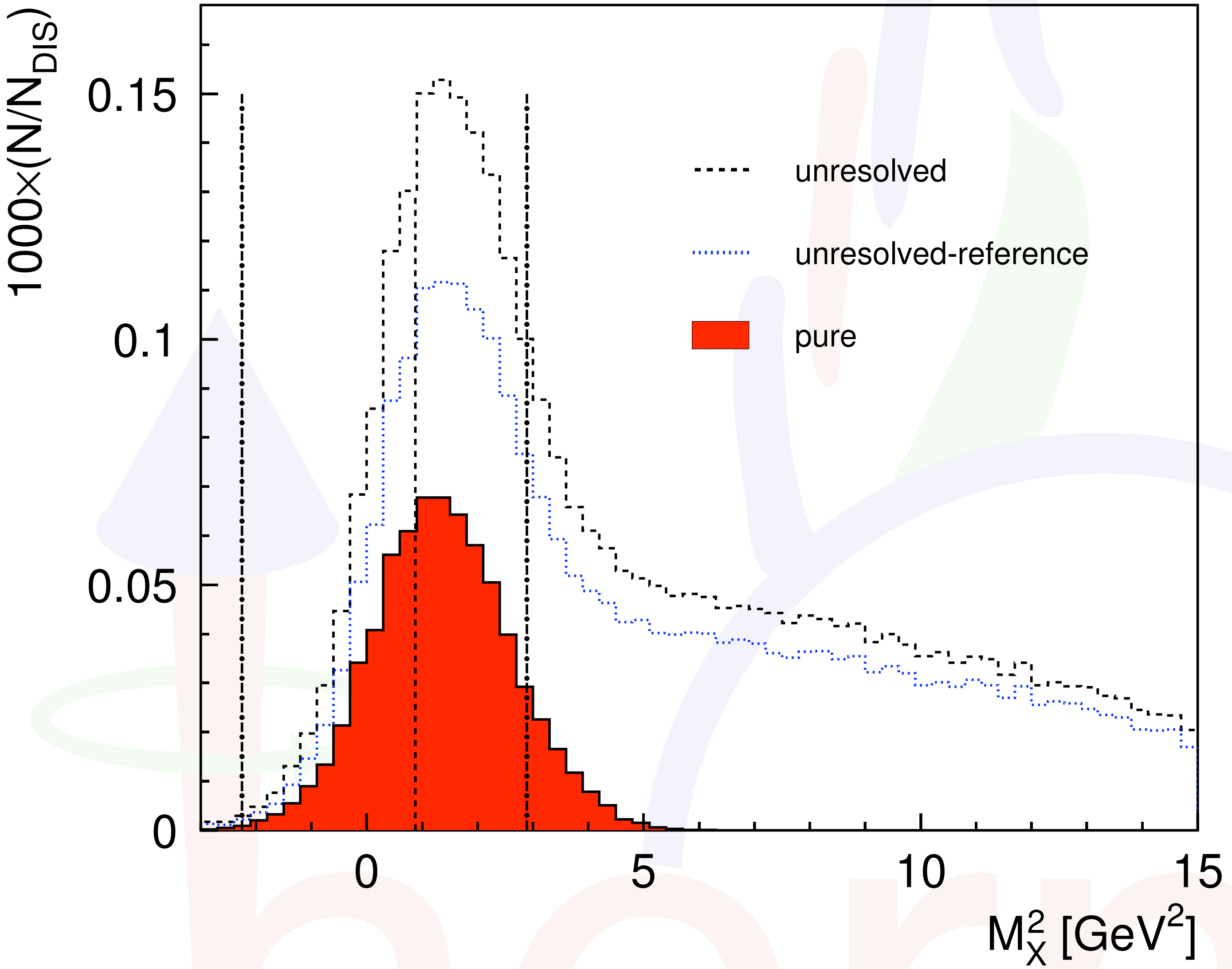


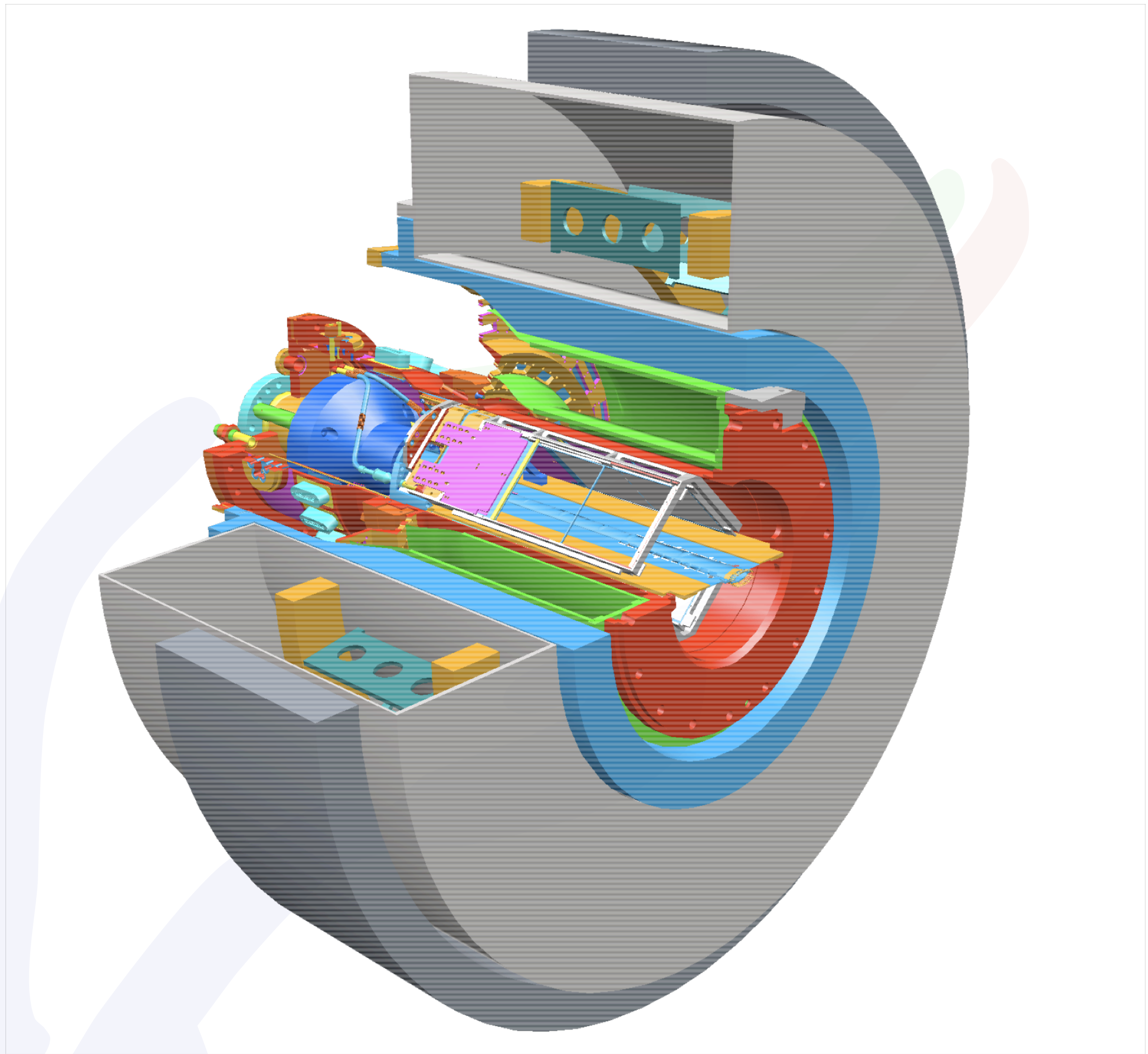
detection of recoiling proton



HERMES detector (2006/07)

kinematic fitting

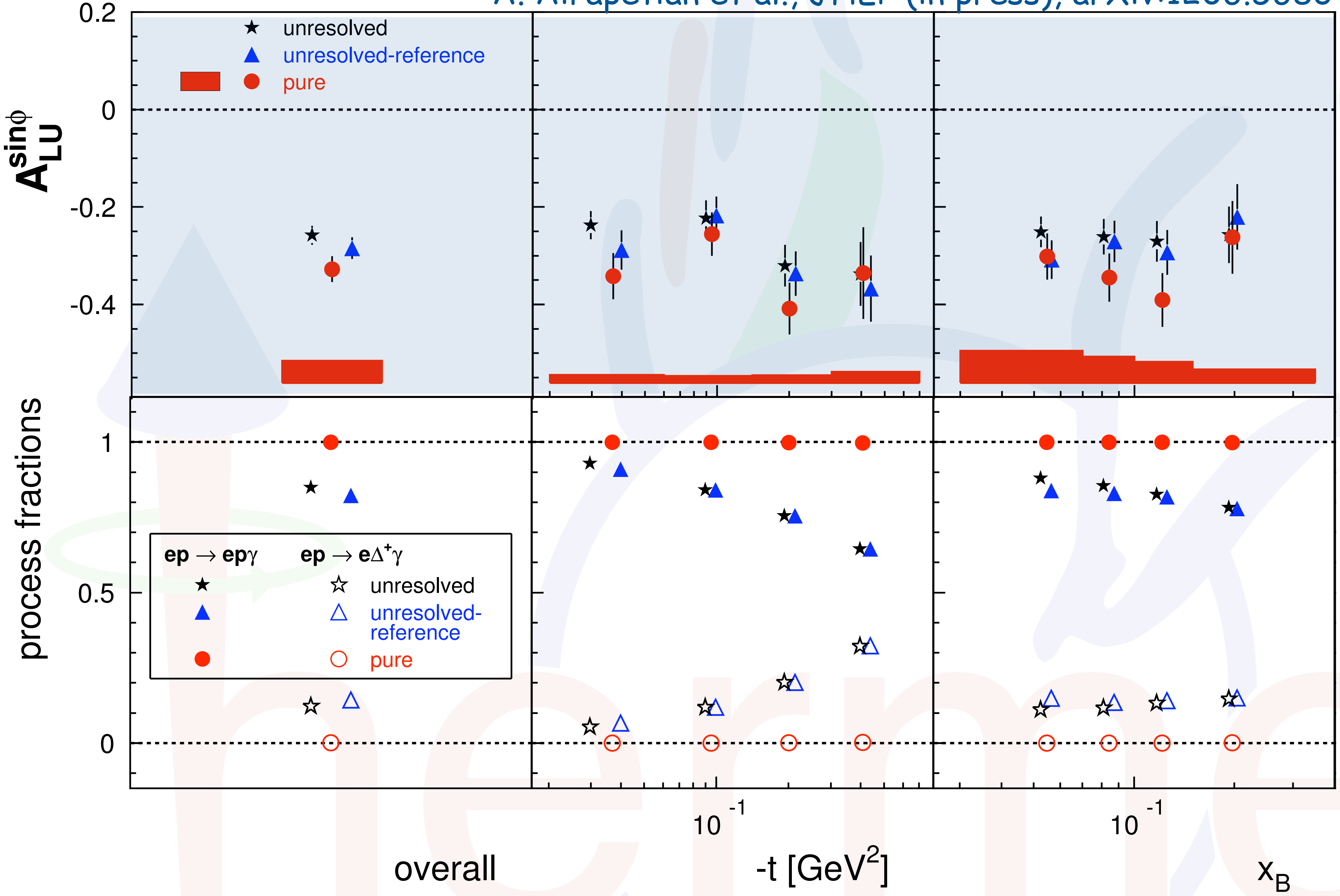




- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS (ep→ep γ) with high efficiency (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

DVCS with recoil detector

A. Airapetian et al., JHEP (in press), arXiv:1206.5683



indication of larger amplitudes for pure sample

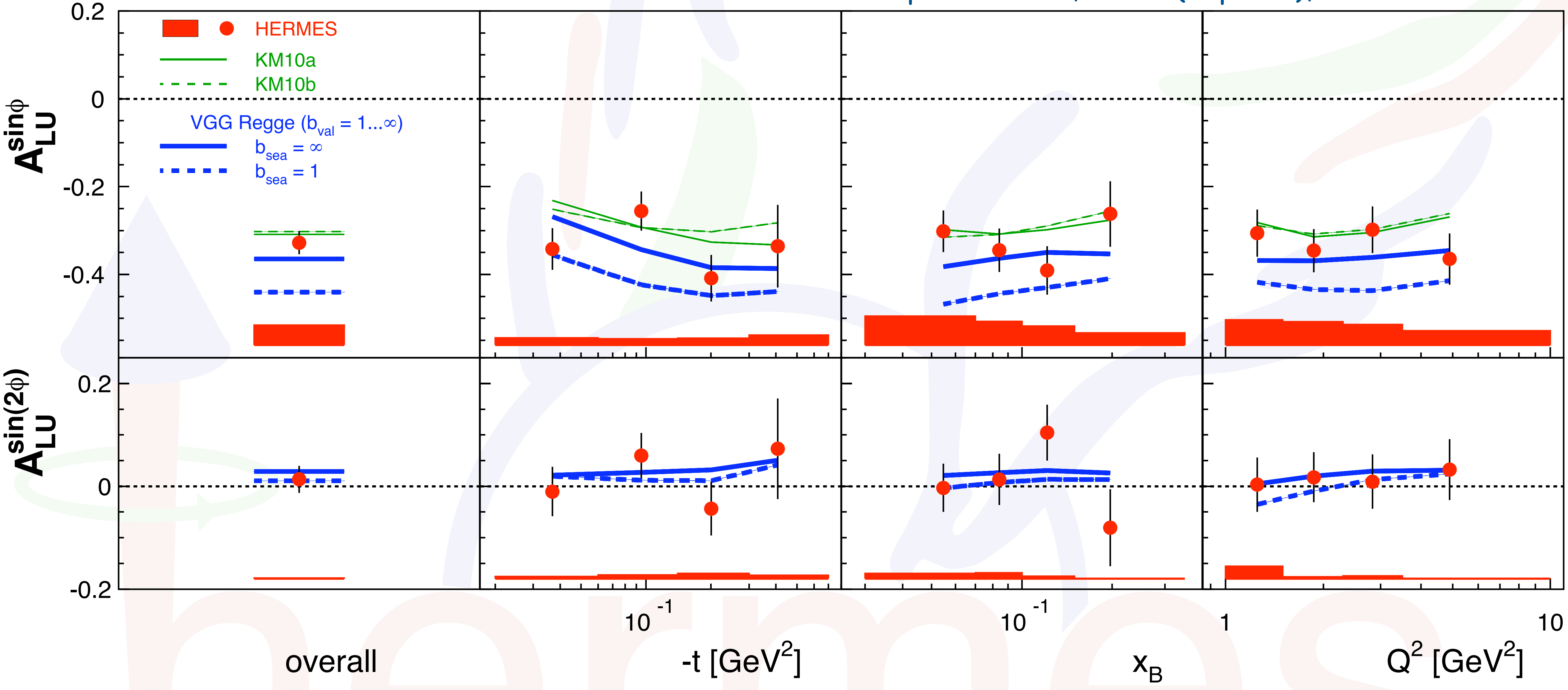
(-> assoc. in trad. analysis mainly dilution)

basically no contamination

-> clear interpretation

DVCS with recoil detector

A. Airapetian et al., JHEP (in press), arXiv:1206.5683



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

gunar.schnell @ desy.de

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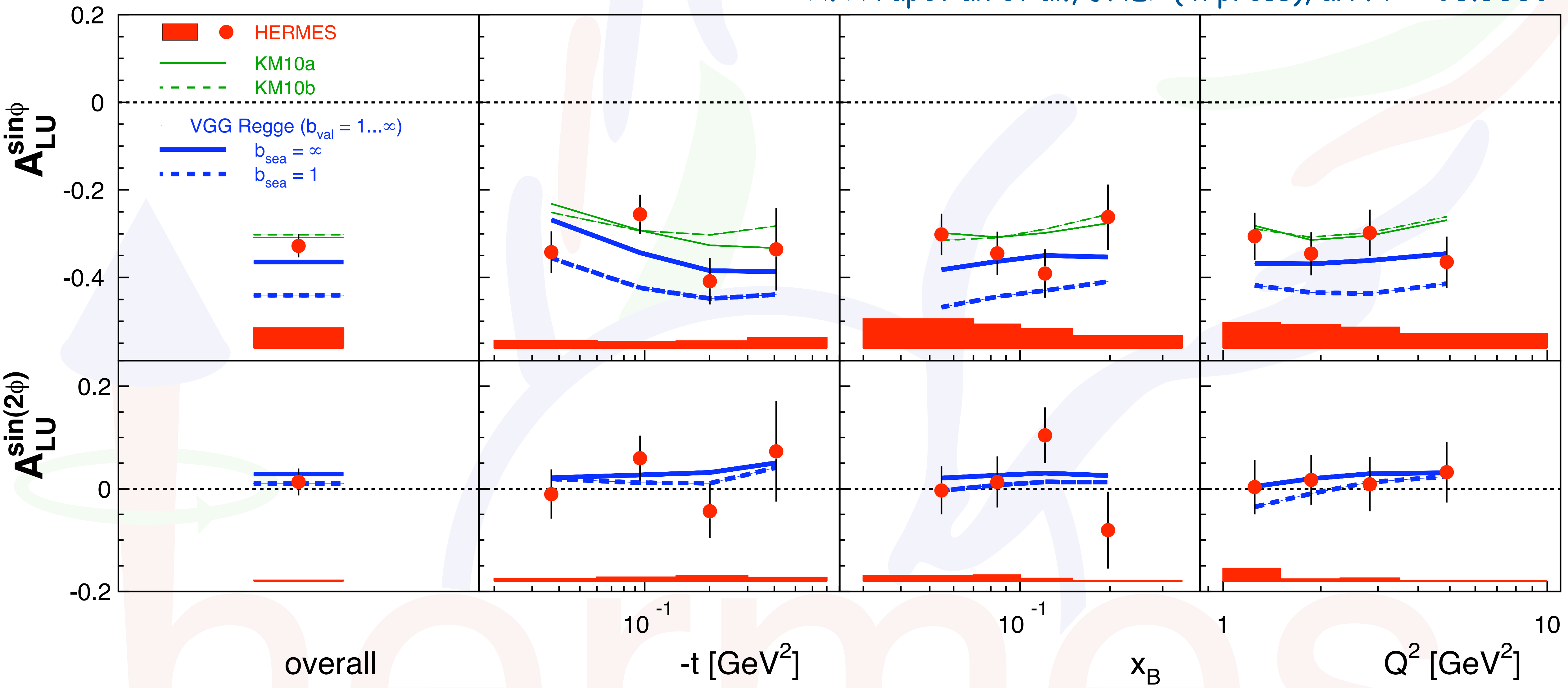

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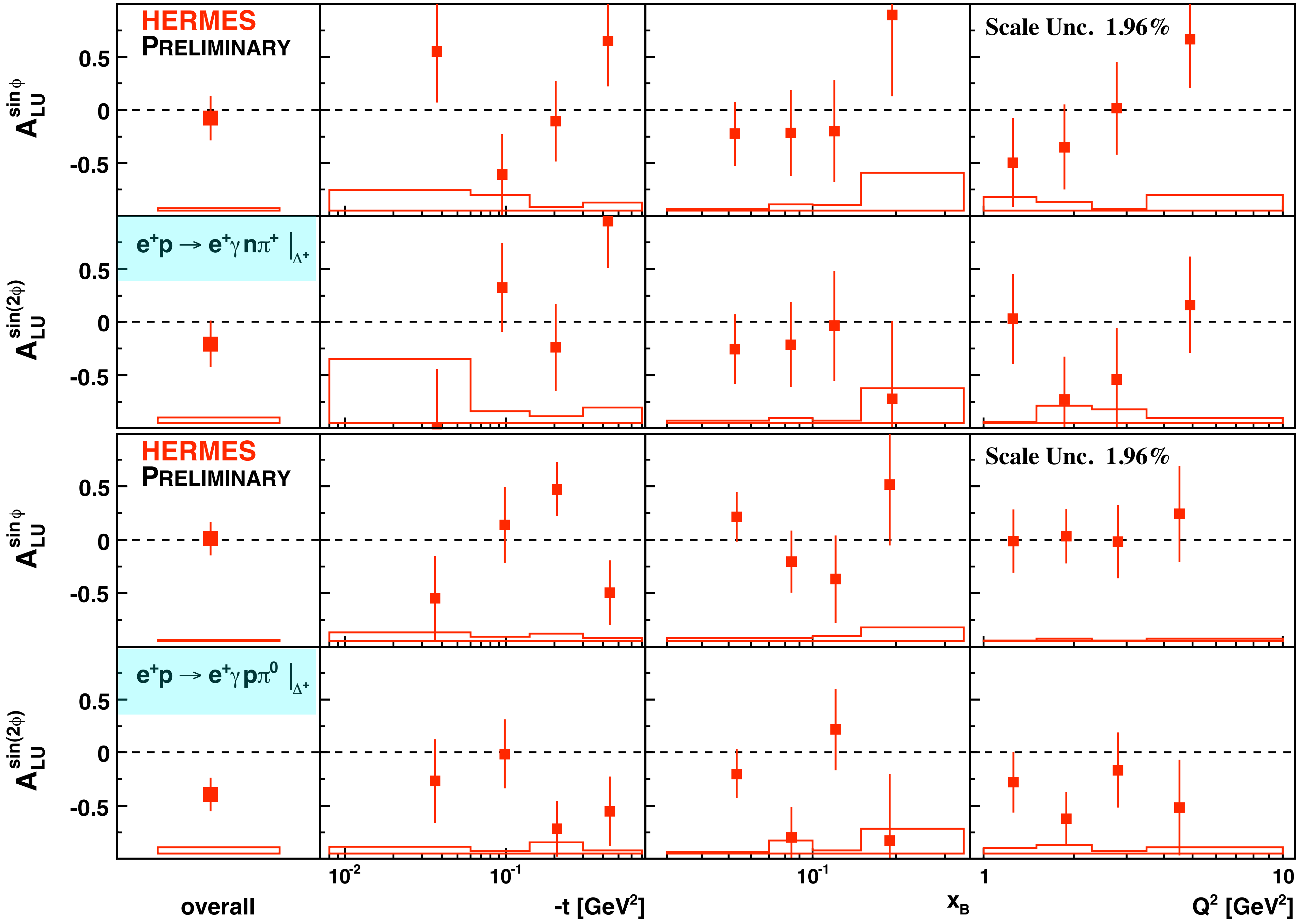
☛ S. Yaschenko (S3-II)

Associated DVCS with recoil detector

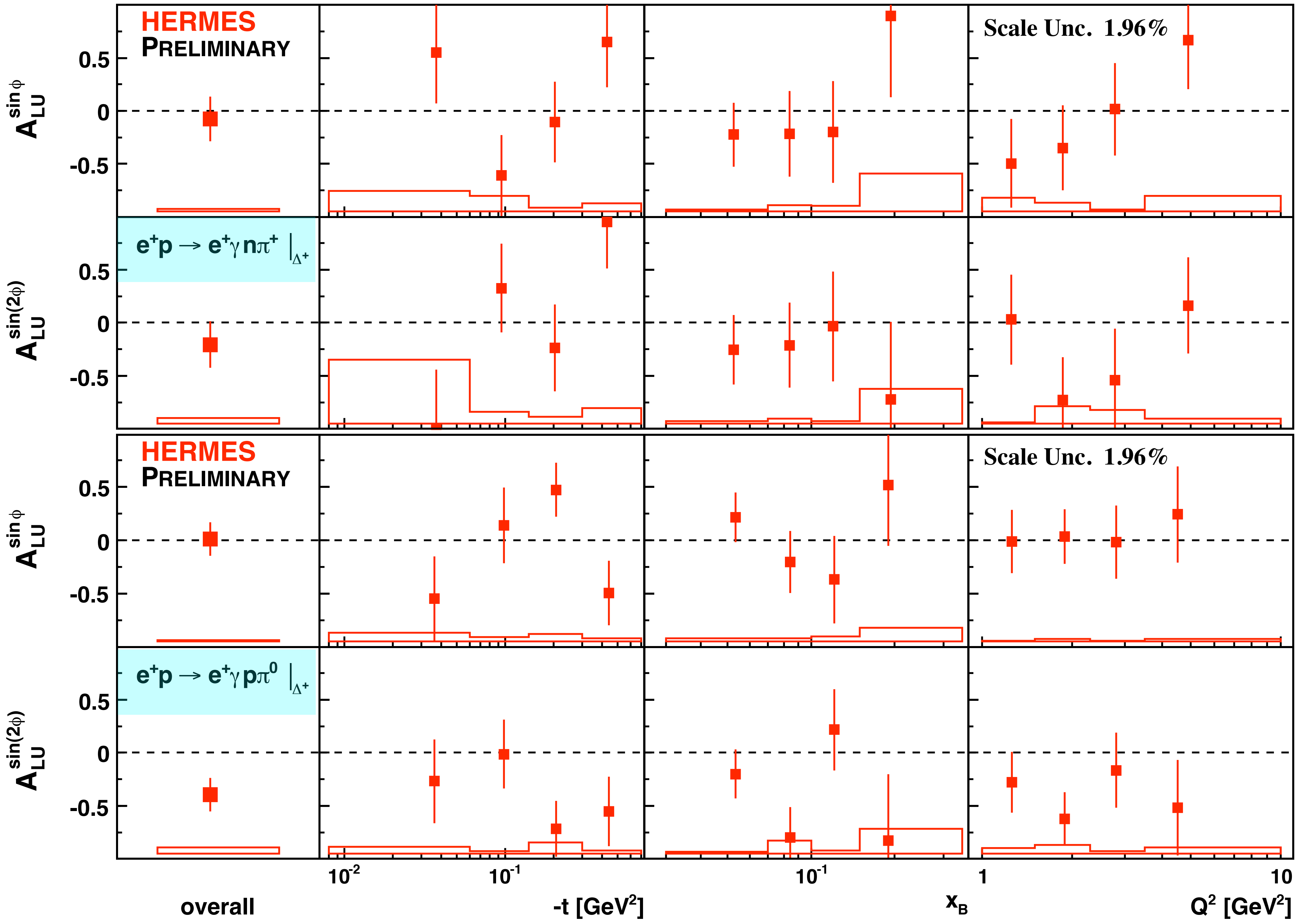
study background process for traditional analyses



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

Associated DVCS with recoil detector

study background process for traditional analyses

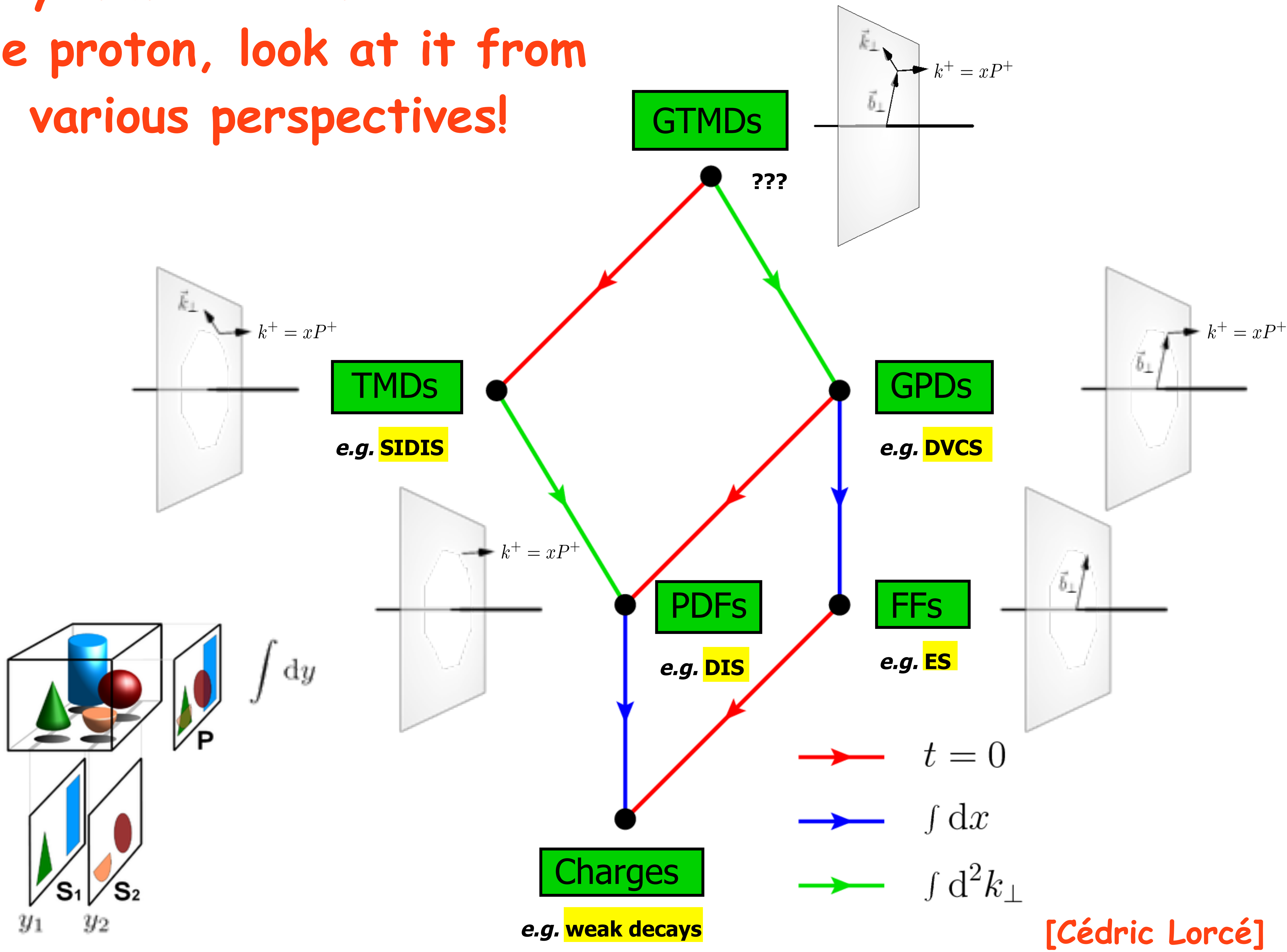


- asymmetry amplitudes consistent with zero
- consistent with pure DVCS results (e.g. dilution in traditional analysis)

☛ S. Yaschenko (S3-II)

Conclusions

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



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]

... not on today's menu

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- first observation of non-zero $\langle \sin\phi_S \rangle_{UT}$ amplitudes

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gunar.schnell @ desy.de

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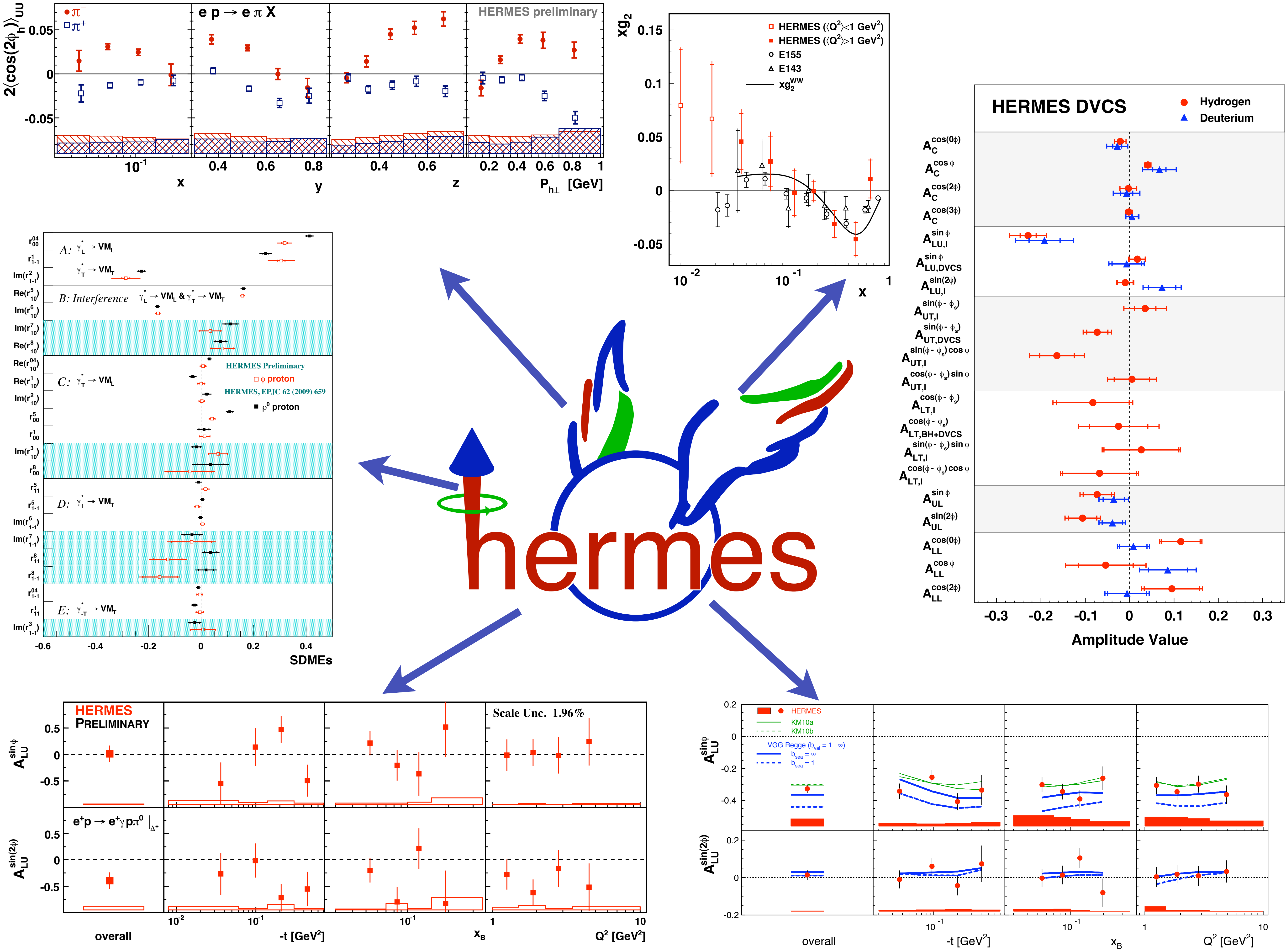
☛ M. Murray (S3-II)


hermes
HERMES preliminary
e p → e π X
$2\langle\cos(2\phi_h)\rangle_{UU}$
π^-
π^+
x
y
z
$P_{h\perp}$ [GeV]
xg_2
HERMES ($\langle Q^2\rangle$<1 GeV^2)
HERMES ($\langle Q^2\rangle$>1 GeV^2)
E155
E143
xg_2^{WW}
HERMES DVCS
Hydrogen
Deuterium
Amplitude Value
A: $\gamma^*_L \to VM_L$
$\gamma^*_T \to VM_T$
B: Interference $\gamma^*_L \to VM_L$ & $\gamma^*_T \to VM_T$
C: $\gamma^*_T \to VM_L$
D: $\gamma^*_L \to VM_T$
E: $\gamma^*_{-T} \to VM_T$
HERMES Preliminary
φ proton
HERMES, EPJC 62 (2009) 659
ρ^0 proton
SDMEs
HERMES PRELIMINARY
Scale Unc. 1.96%
$e^+p \to e^+\gamma p\pi^0 |_{\Delta^+}$
$A_{LU}^{\sin\phi}$
$A_{LU}^{\sin(2\phi)}$
overall
-t [GeV^2]
x_B
Q^2 [GeV^2]
HERMES
KM10a
KM10b
VGG Regge (b_{val} = 1...∞)
$b_{sea} = \infty$
$b_{sea} = 1$