20 years of DIS @HERA - June 19th, 2012

The spin-momentum structure of the nucleon

--highlights from the hermes collaboration--

Gunar.Schnell @ desy.de

ikerbasque
Basque Foundation for Science

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Euskal Herriko Unibertsitatea

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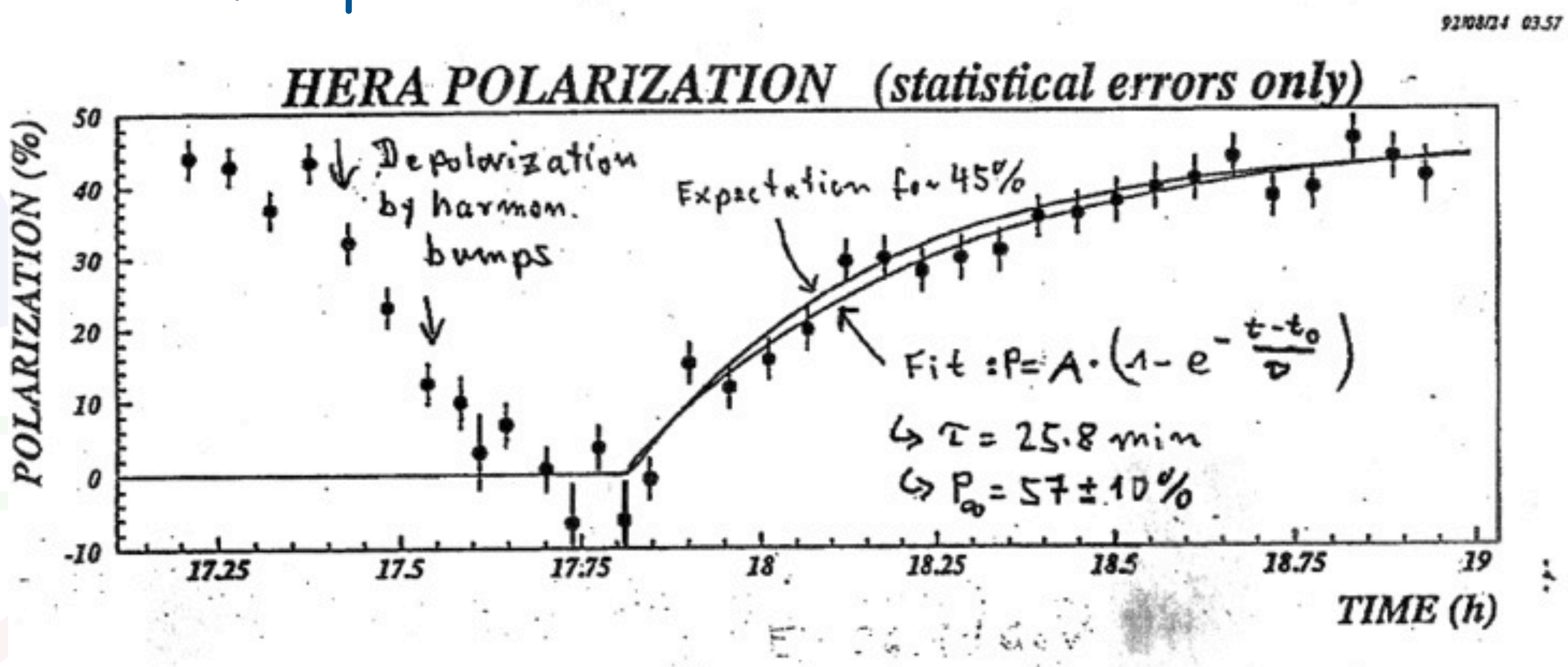

Fig. 4: Observation of rise-time at E = 26.71 GeV.

- demonstration of lepton polarization at HERA under realistic running conditions

HERMES

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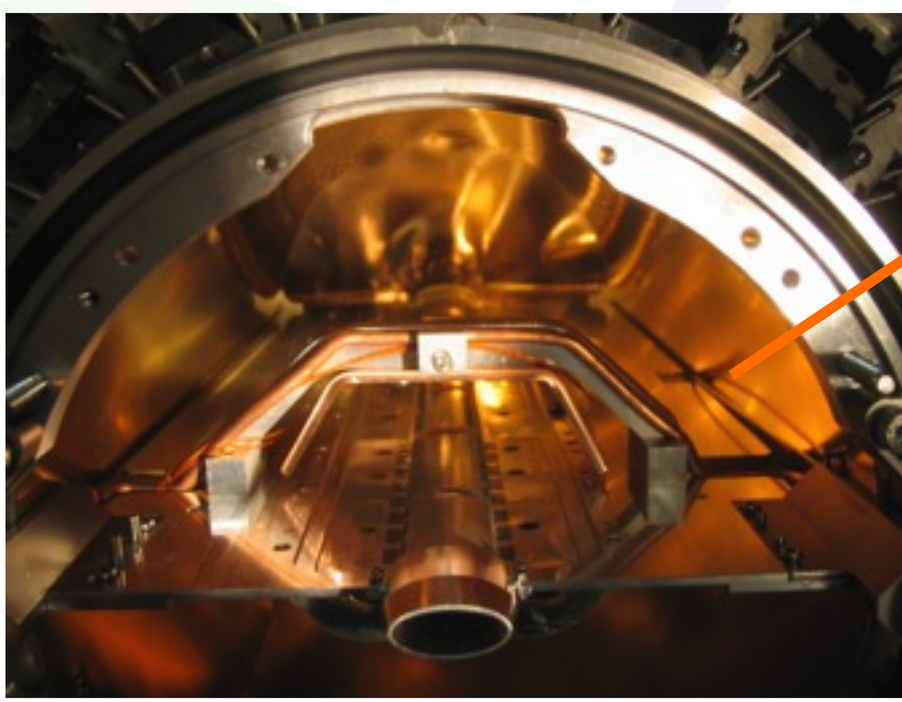
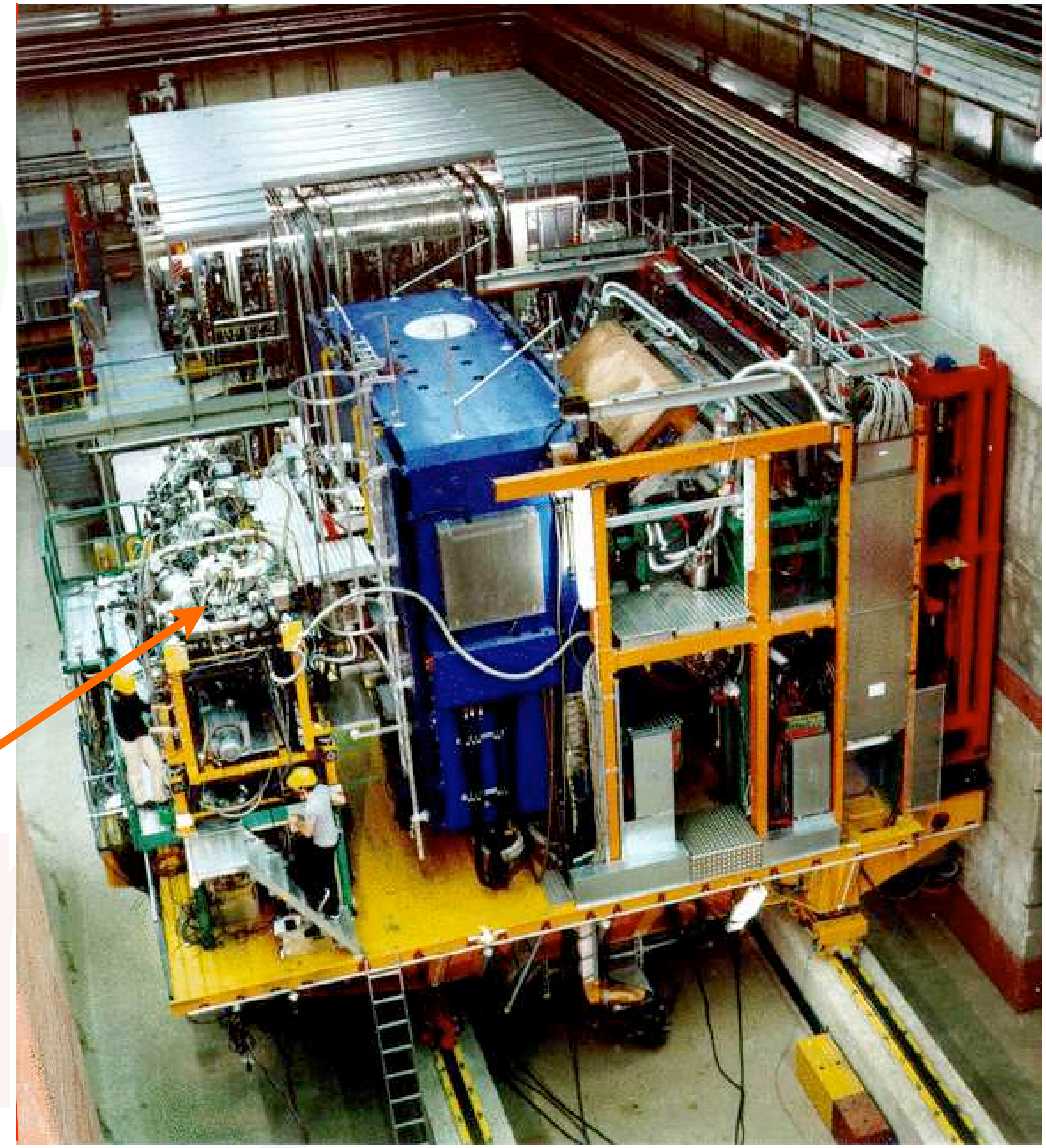
- November 1992, Scientific Council
  - "Parallel running of ep and HERMES?"
- June 15, 1993
  - full approval of HERMES
- March 31, 1995
  - HERMES interlock set

The HERMES experiment

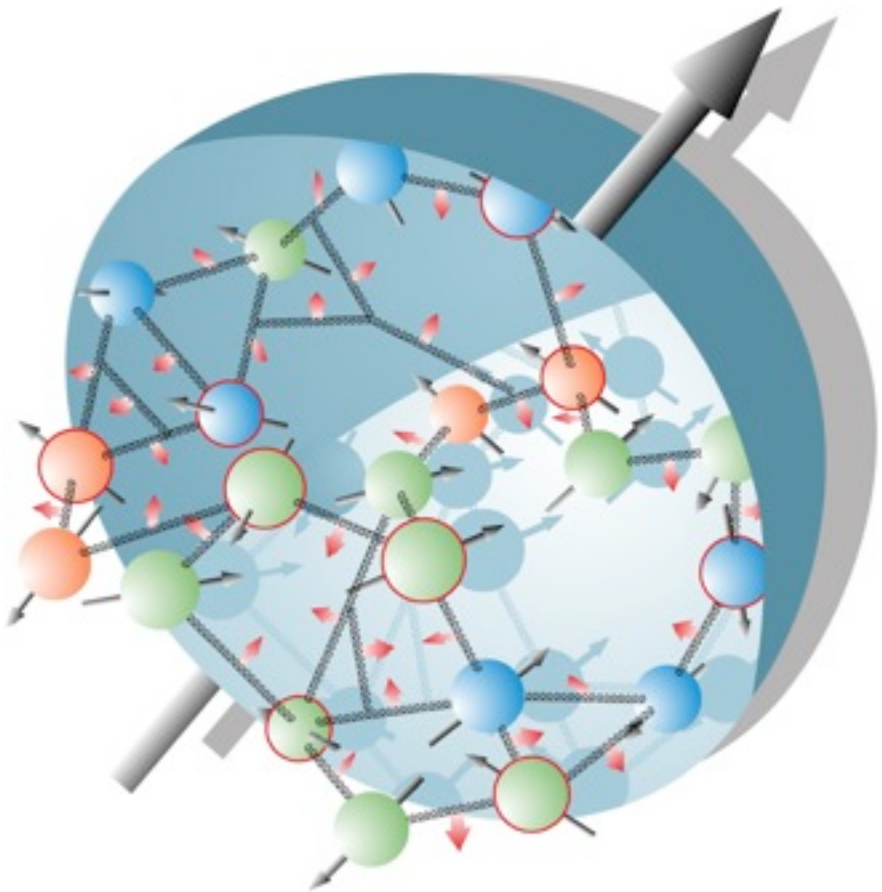
pure gas targets:

- internal to lepton ring
- unpolarized (^1H … Xe)
- longitudinally polarized: ^1H, ^2H
- transversely polarized: ^1H





The HERA-I harvest



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

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- ΔG ← gluon spin
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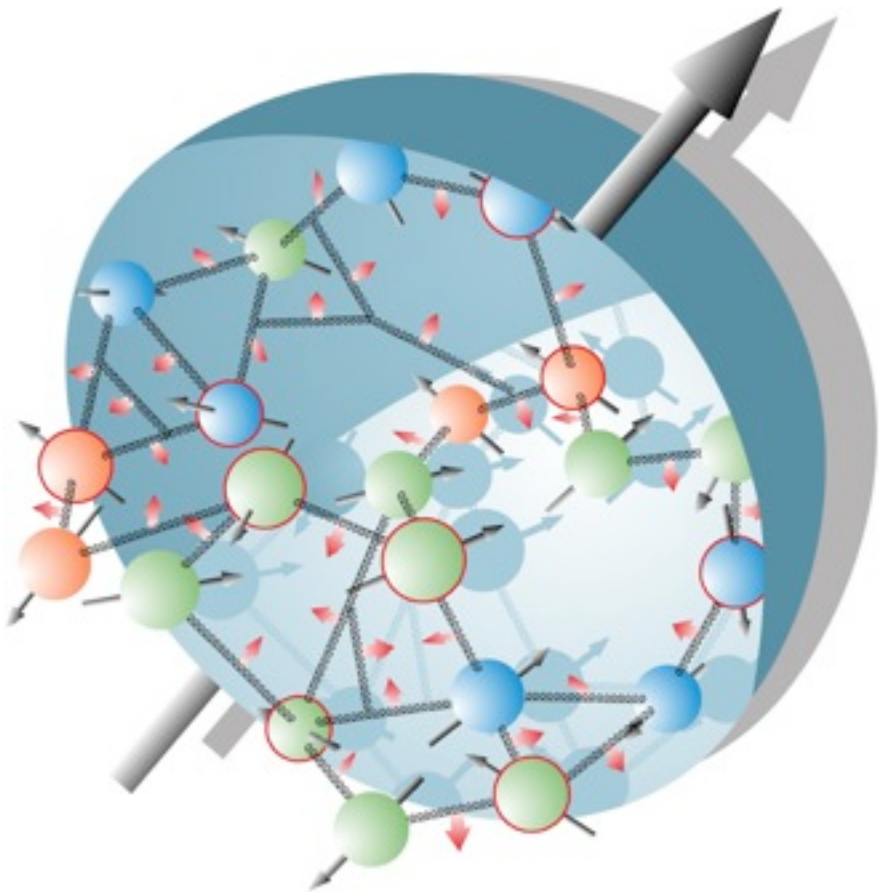

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$\Delta\Sigma = 0.330 \pm 0.025^{\text{(exp.)}} \pm 0.011^{\text{(theory)}} \pm 0.028^{\text{(evol.)}}$

PRD 75 (2007) 012007

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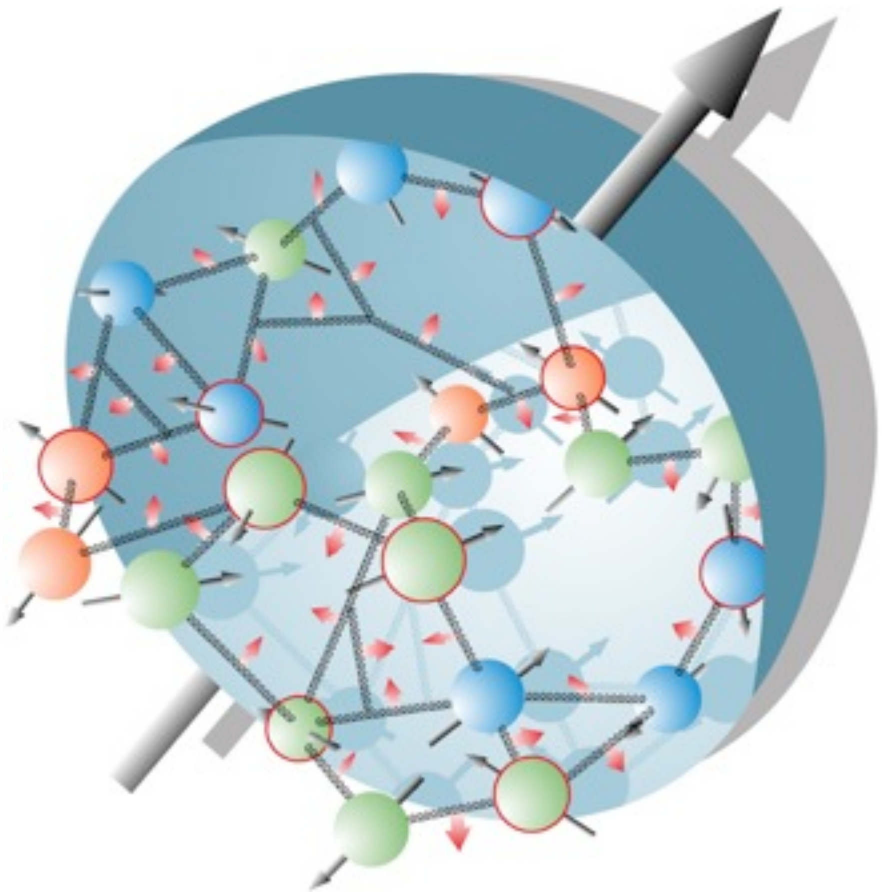

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JHEP 1008 (2010) 130

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

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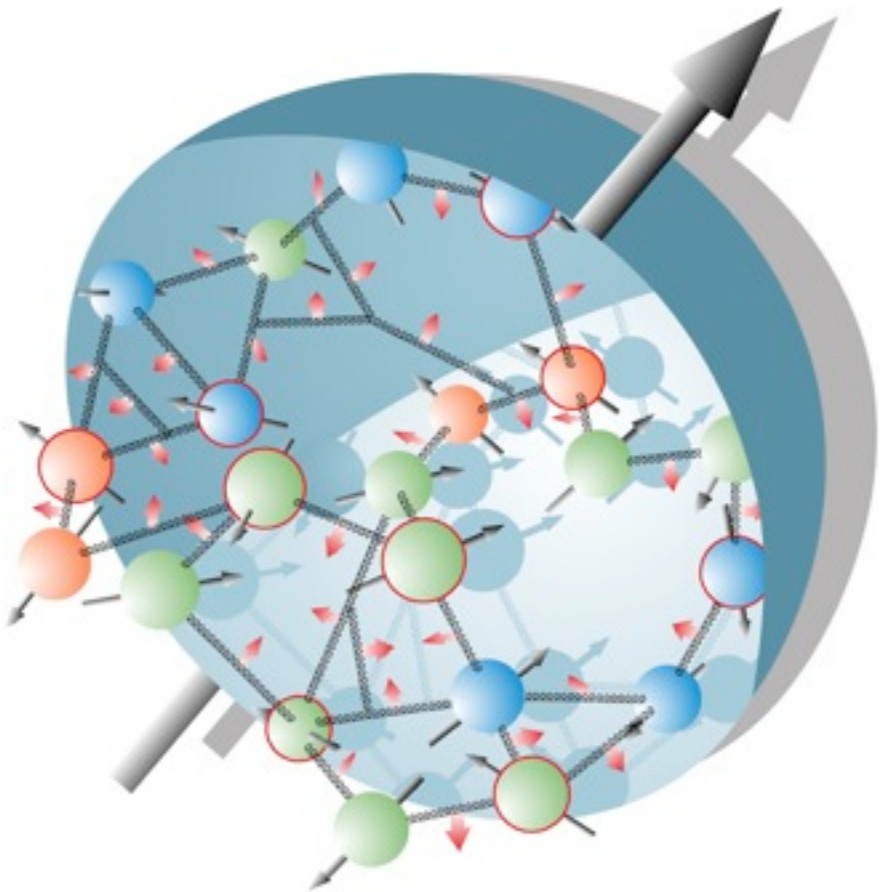

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  - transversity?
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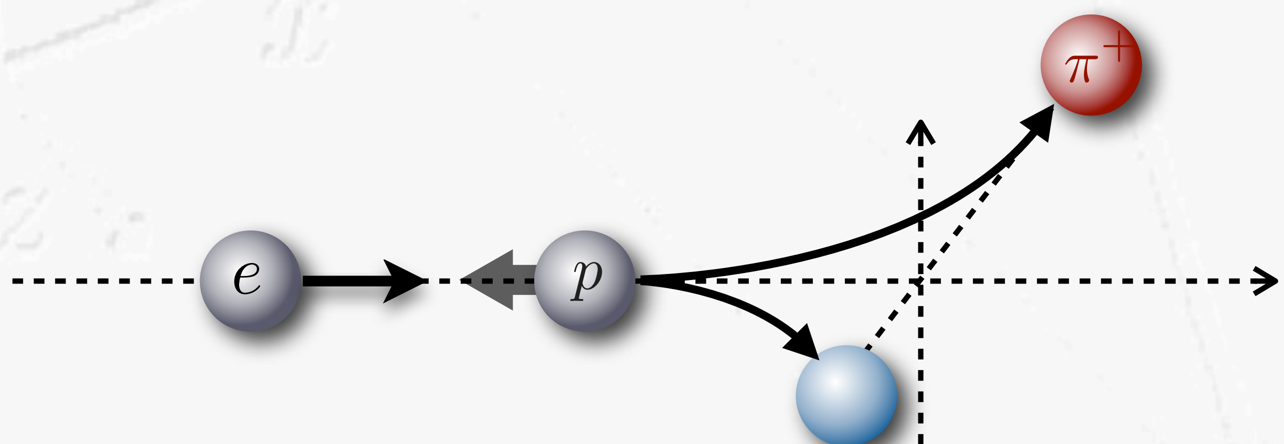

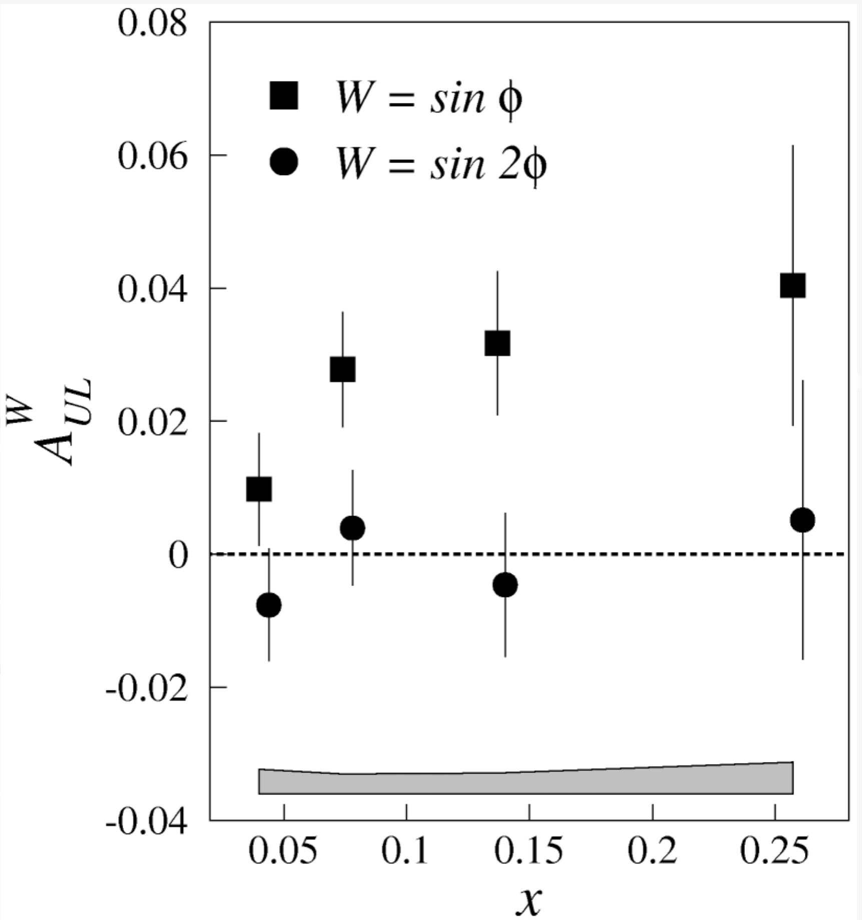

[1] PRL 84 (2000) 4047

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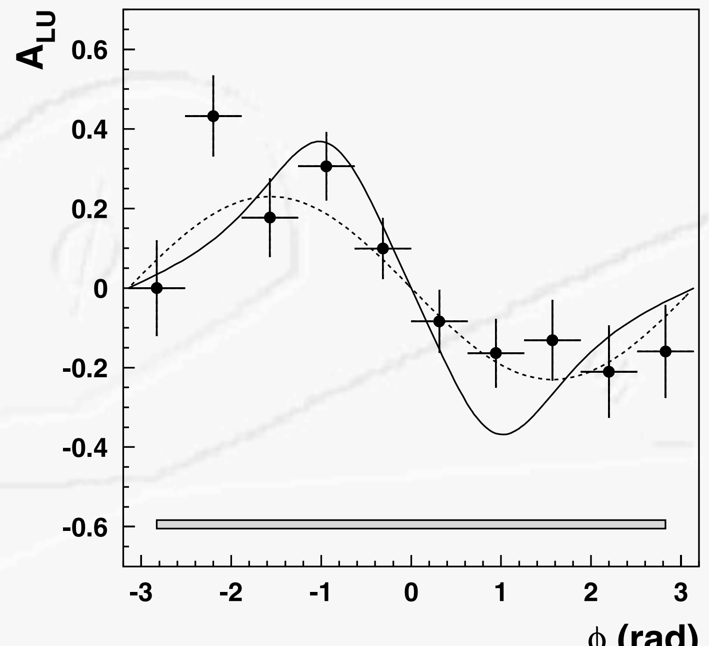
- Ji (1997): relates moments of GPDs*) to total angular momentum
  - accessible in DVCS
  - HERMES measures A_{LU} in DVCS [2]



[1] PRL 84 (2000) 4047
[2] PRL 87 (2001) 182001

*) GPDs=generalized parton distributions

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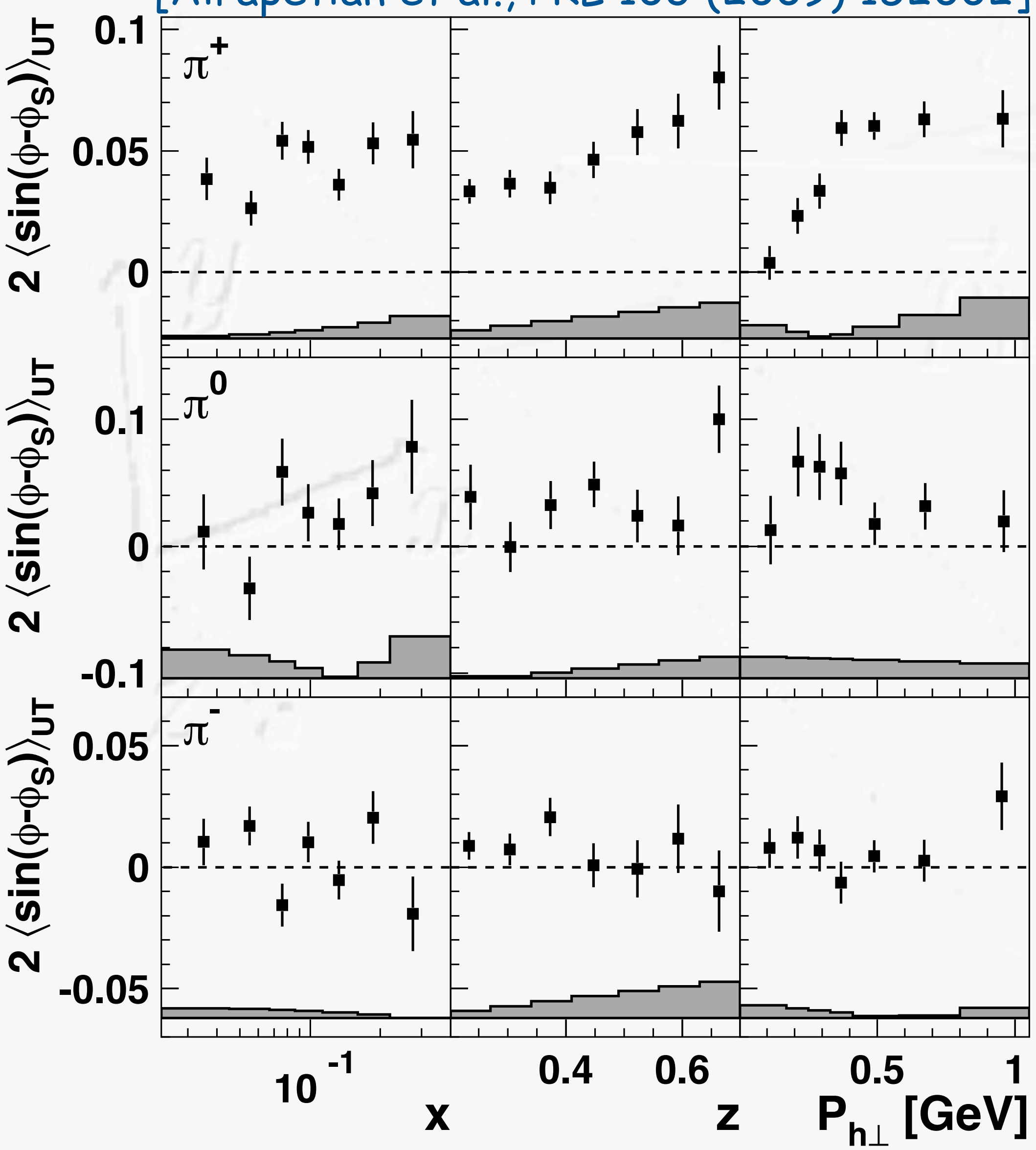
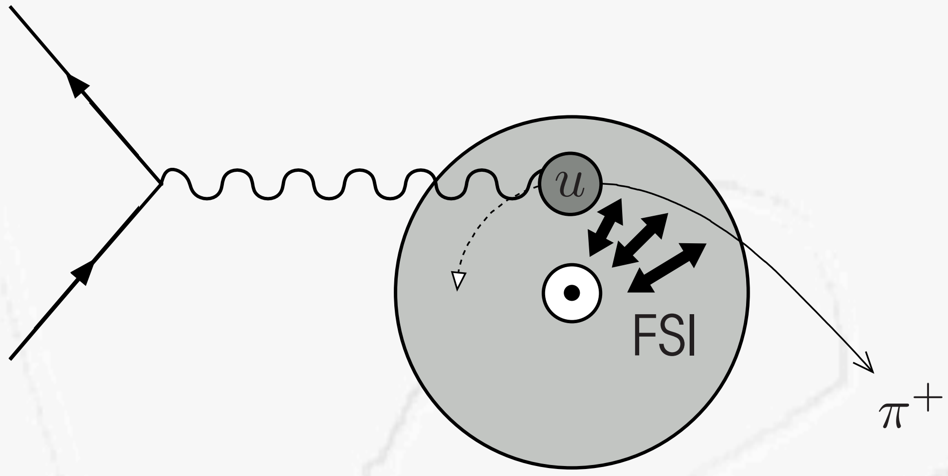
- confirm existence of Sivers effect -> asymmetry in transverse-momentum distribution of partons in nucleon

[Airapetian et al., PRL 103 (2009) 152002]





[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]

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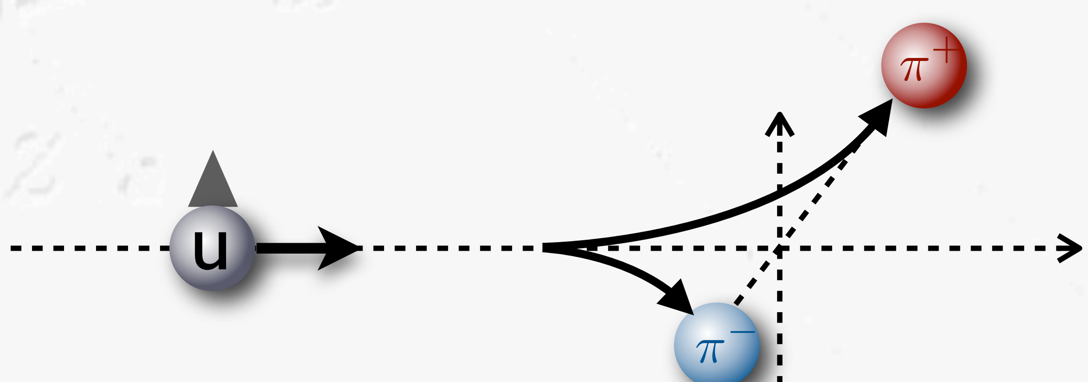
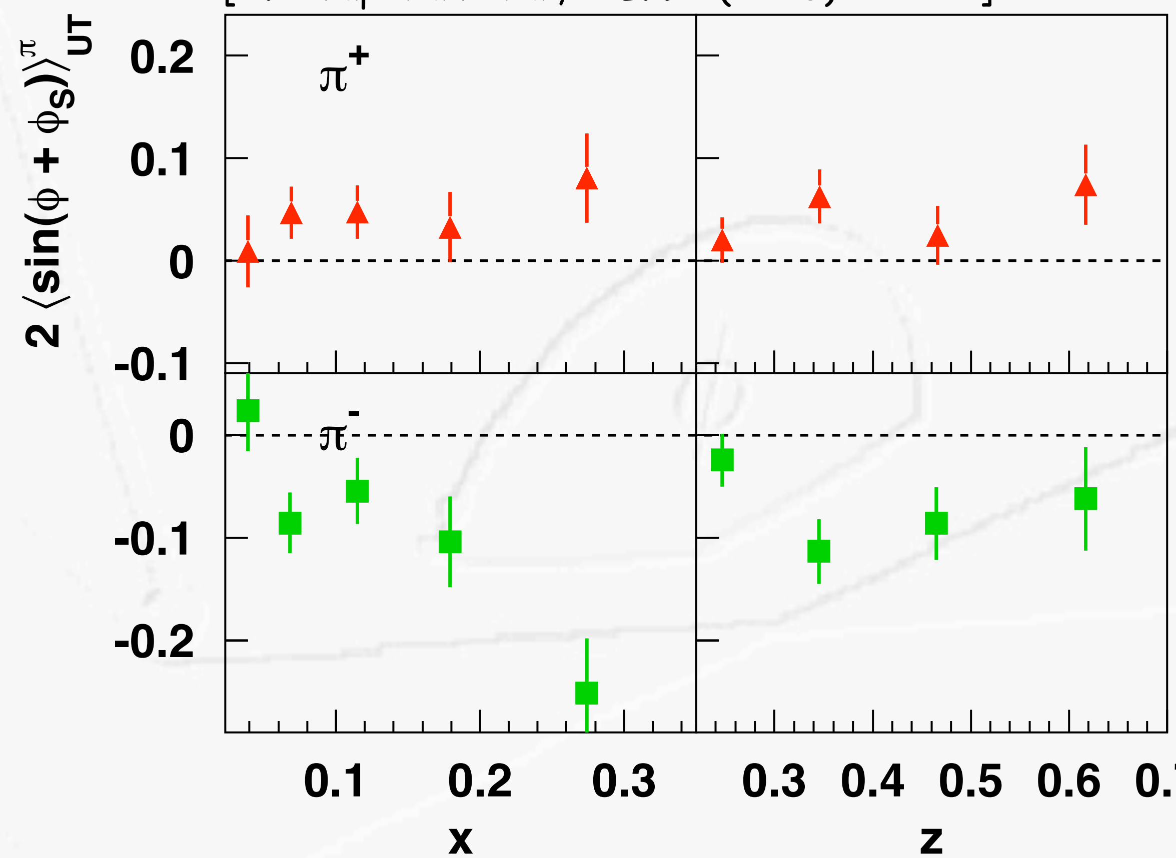


[A. Airapetian et al, PRL. 94 (2005) 012002]



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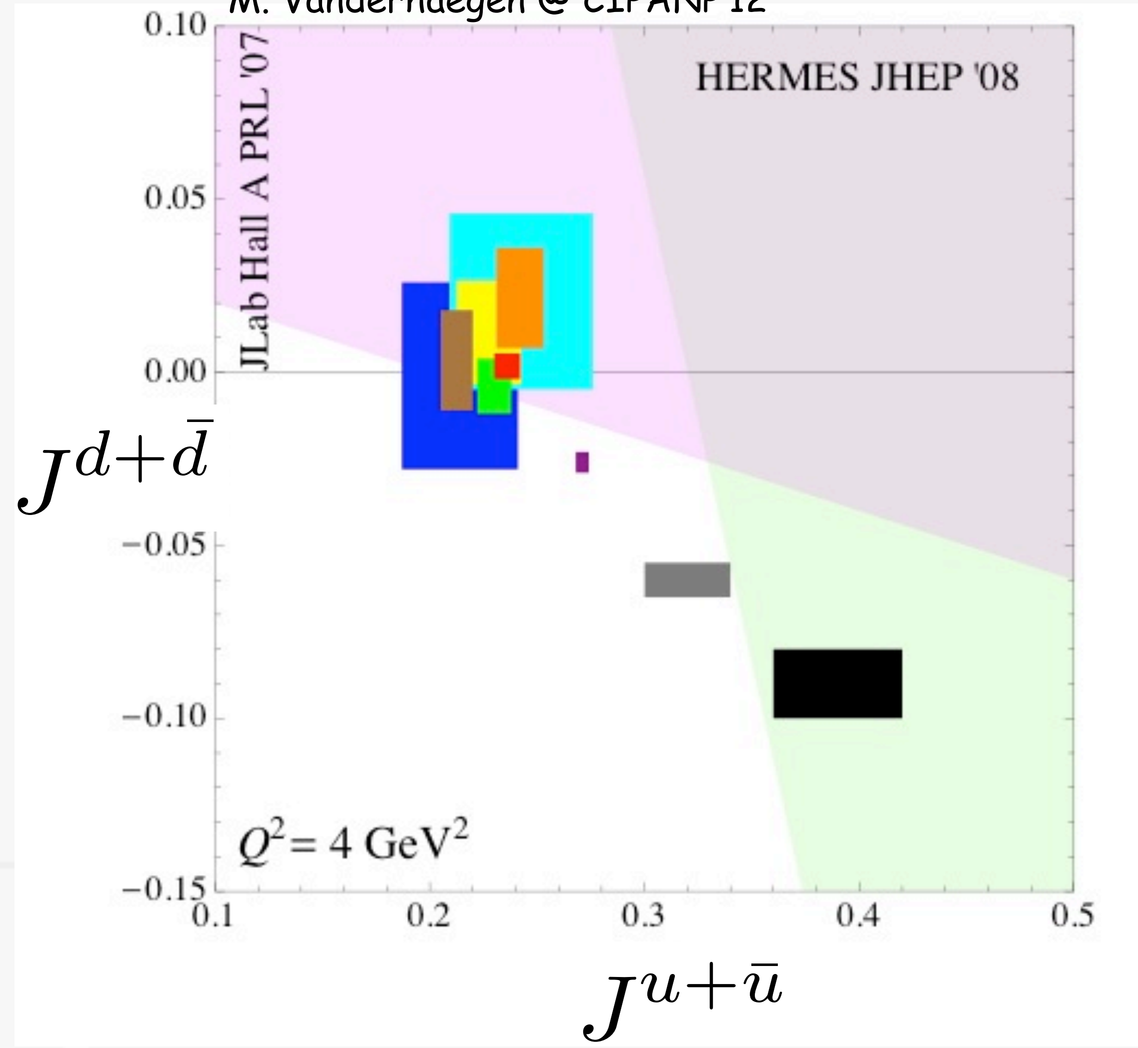
M. Vanderhaegen @ CIPANP'12



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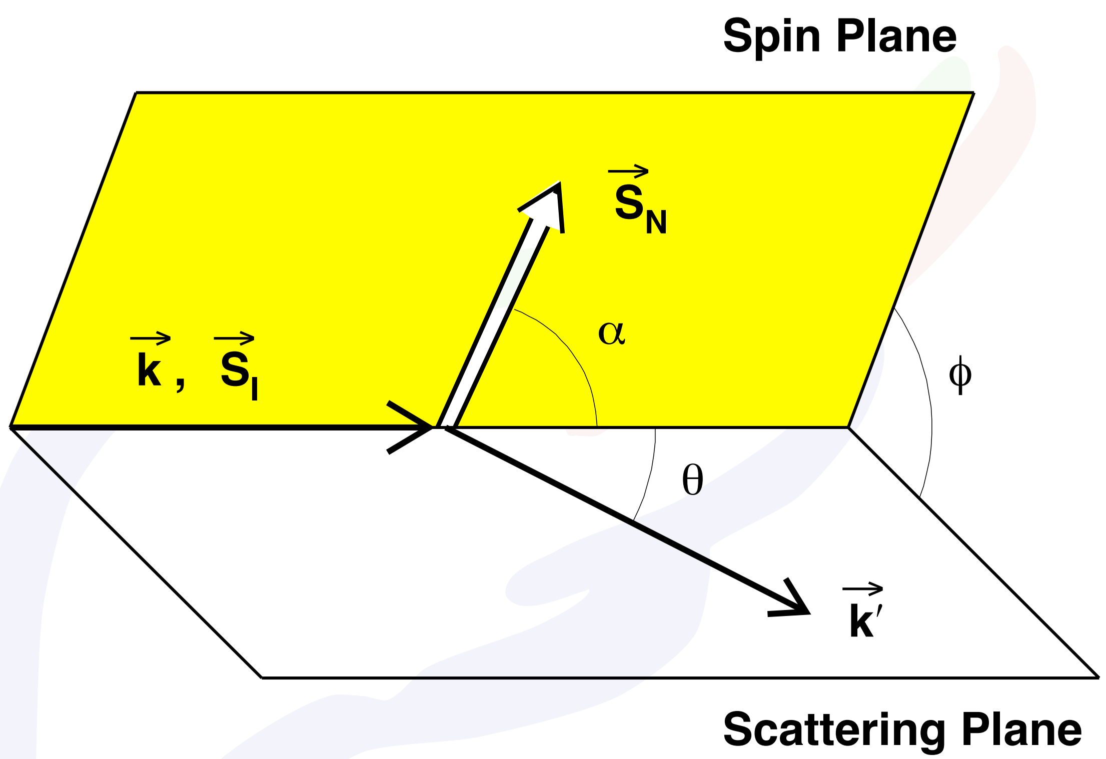
- add one more piece to the structure-function landscape: g_2

Inclusive DIS

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



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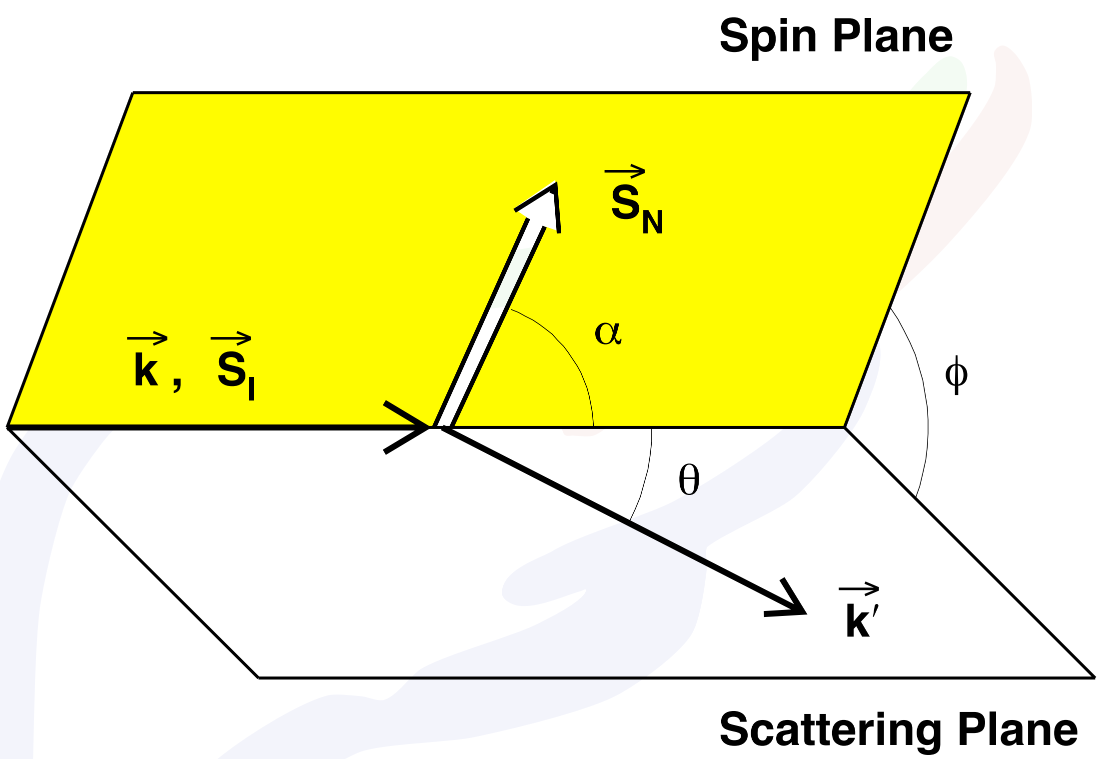
Lepton Tensor



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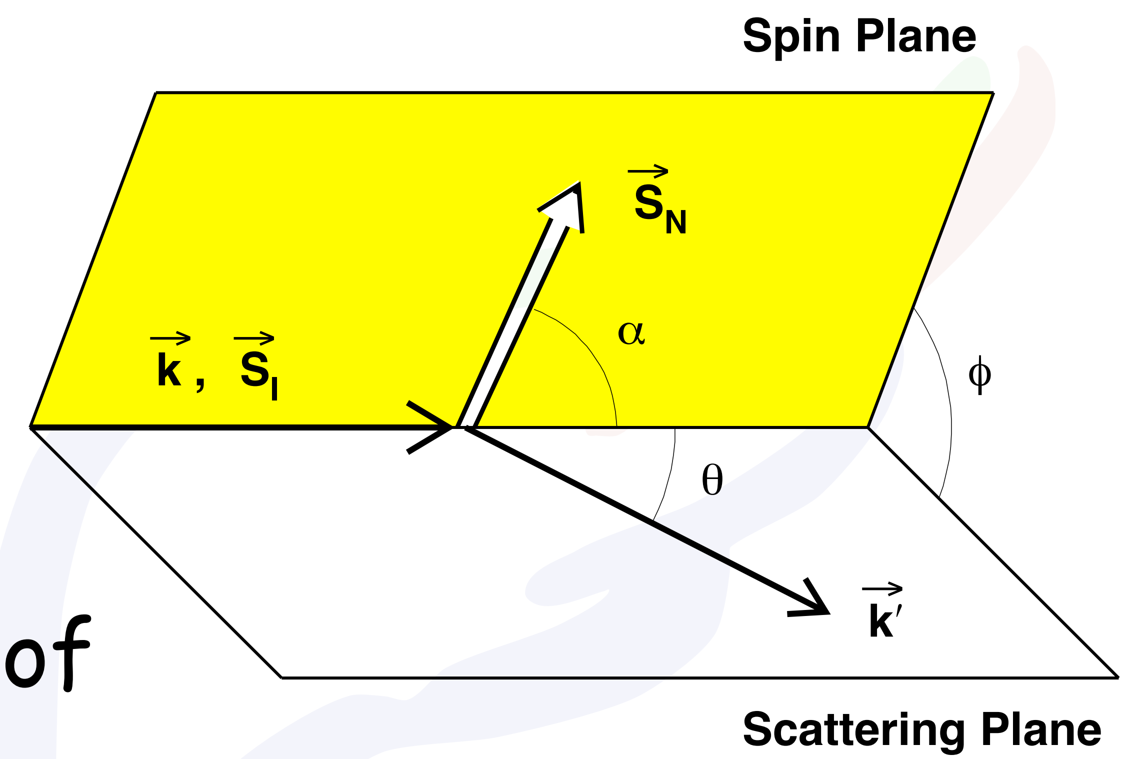
Hadron Tensor parametrized in terms of Structure Functions



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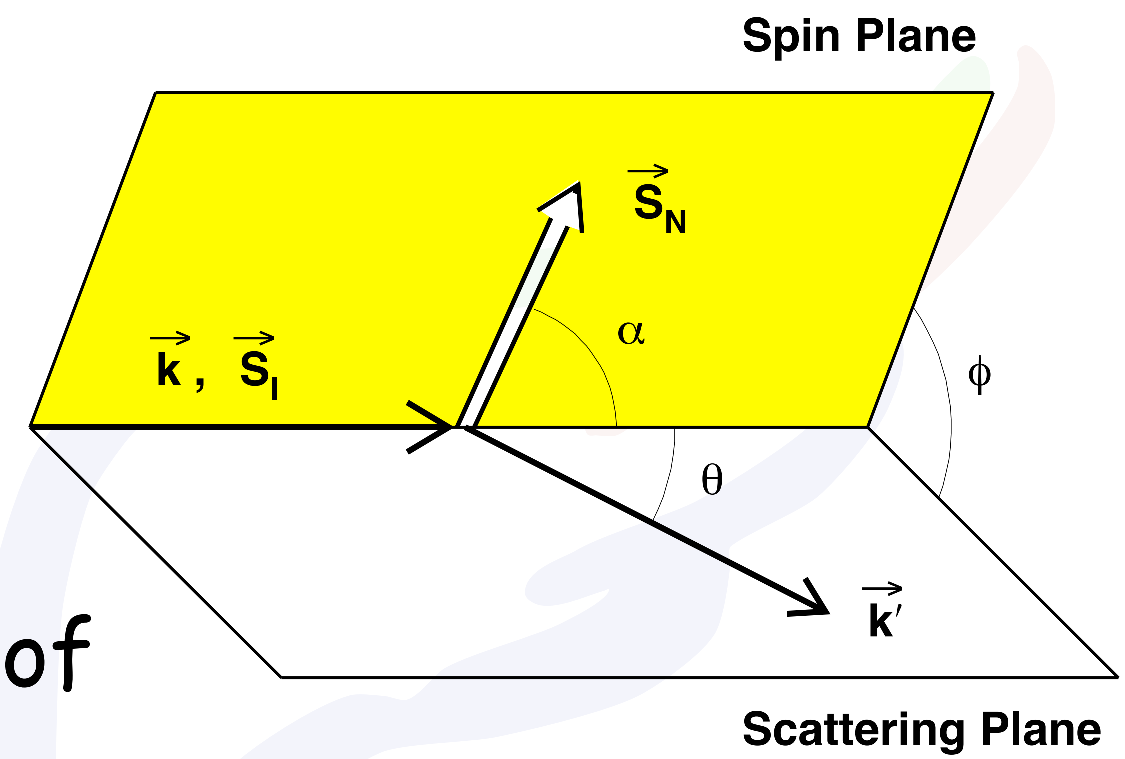
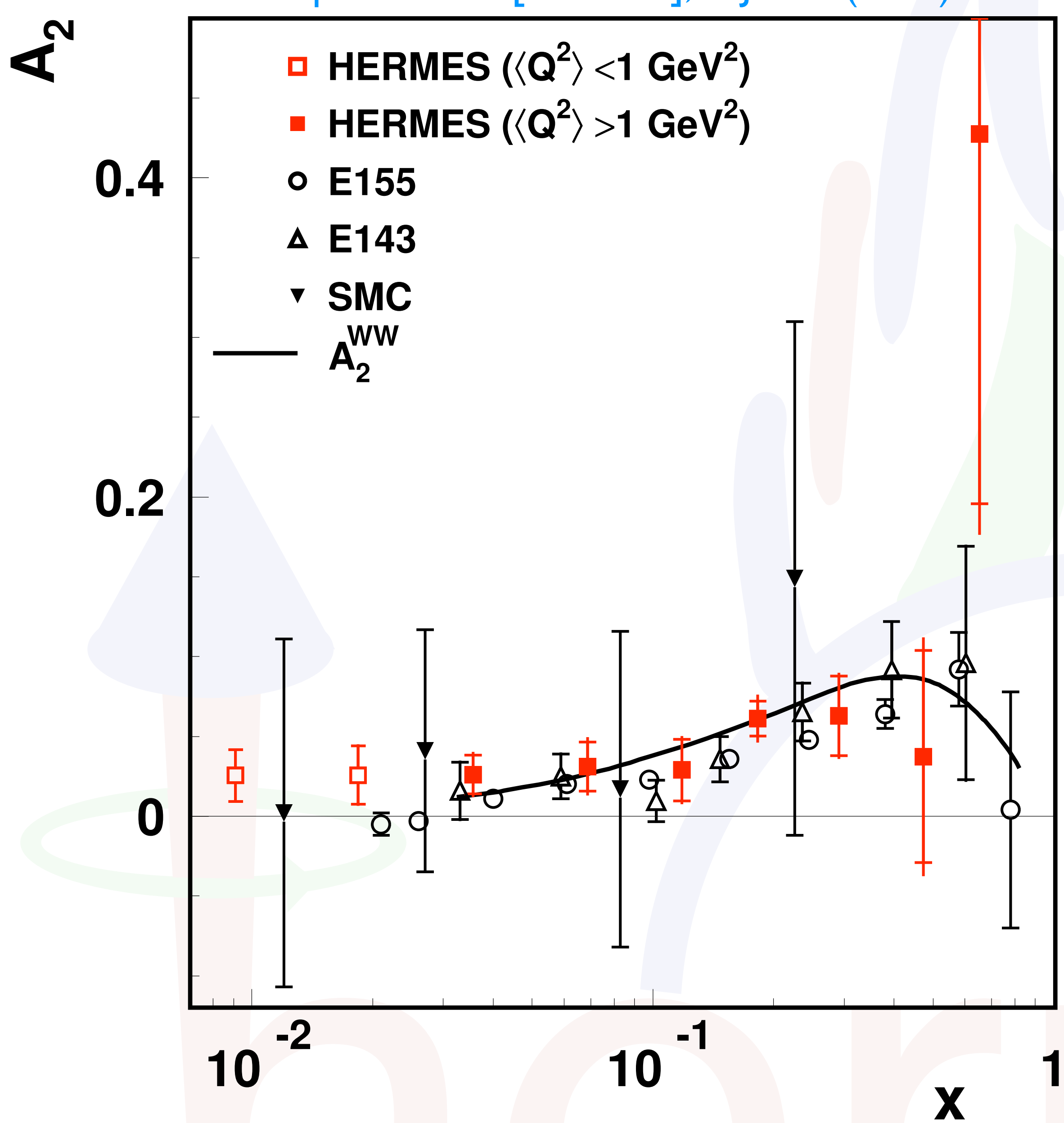
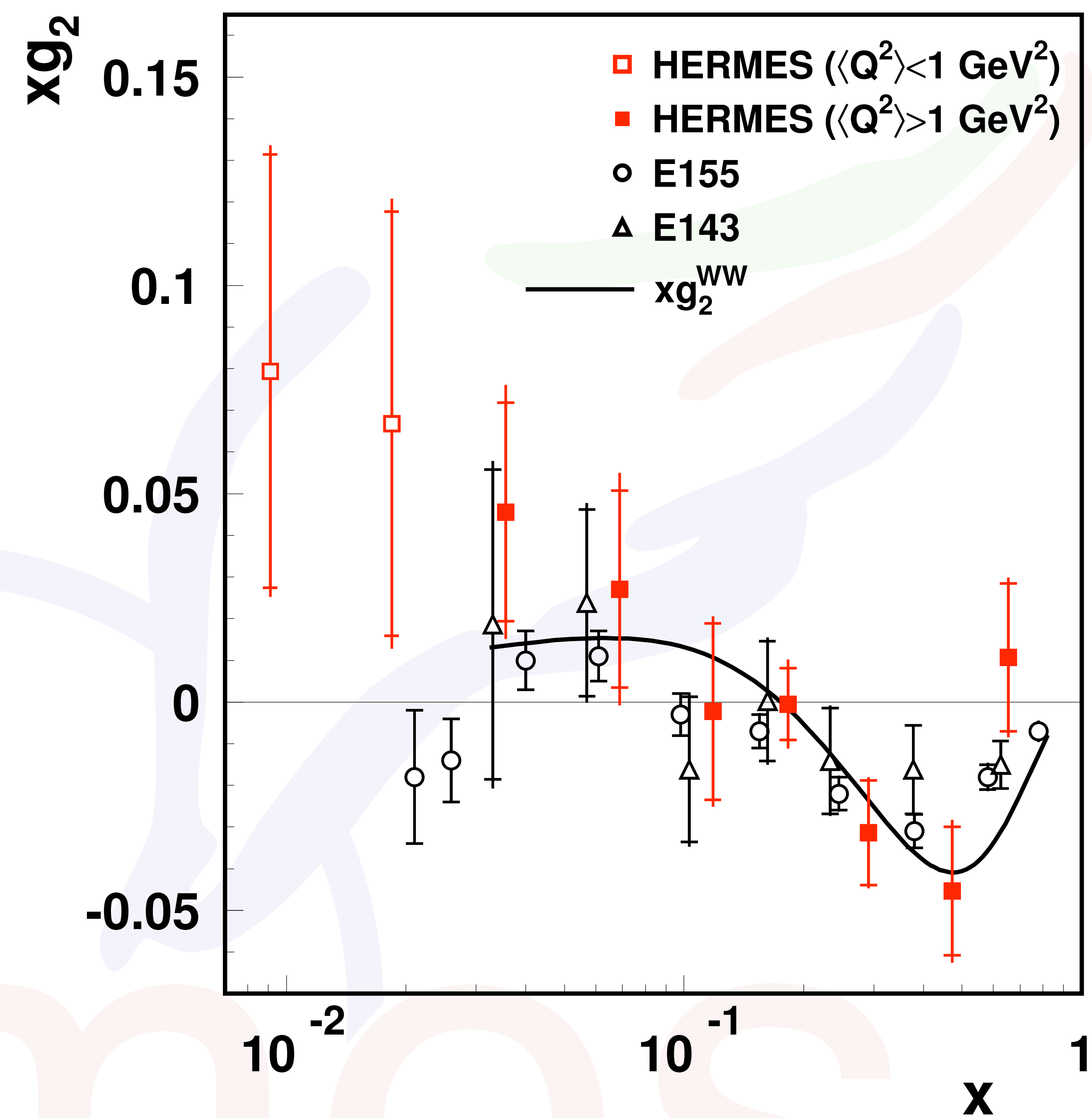


$$\frac{d^3\sigma}{dxdyd\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$
$$-S_l S_N \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)\boxed{g_1(x,Q^2)} - \frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right]$$
$$+S_l S_N \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}\boxed{g_1(x,Q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

Results on A_2 and xg_2

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





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

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

... going 3D

Spin-Momentum Structure of the Nucleon

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

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

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

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

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

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helicity

quark pol.

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

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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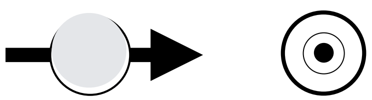
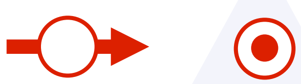
Probabilistic interpretation

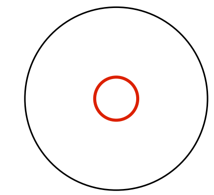
Proton goes out of the screen/
photon goes into the screen

 nucleon with transverse or longitudinal spin

 parton with transverse or longitudinal spin

 parton transverse momentum

[courtesy of A. Bacchetta, Pavia]

$f_1 =$ 

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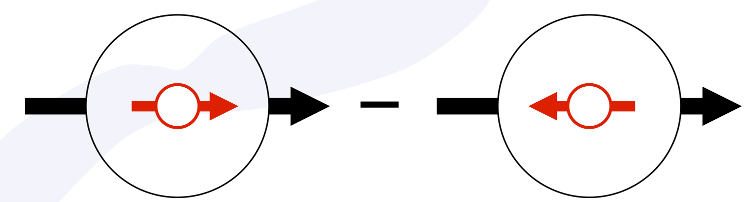
$h_1 =$ 

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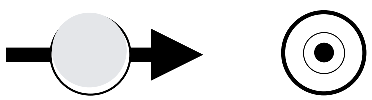
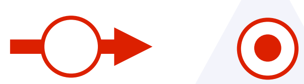
 nucleon with transverse or longitudinal spin

 parton with transverse or longitudinal spin

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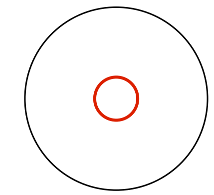
$f_1 =$ 

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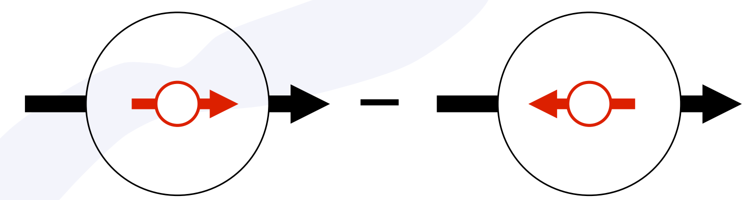
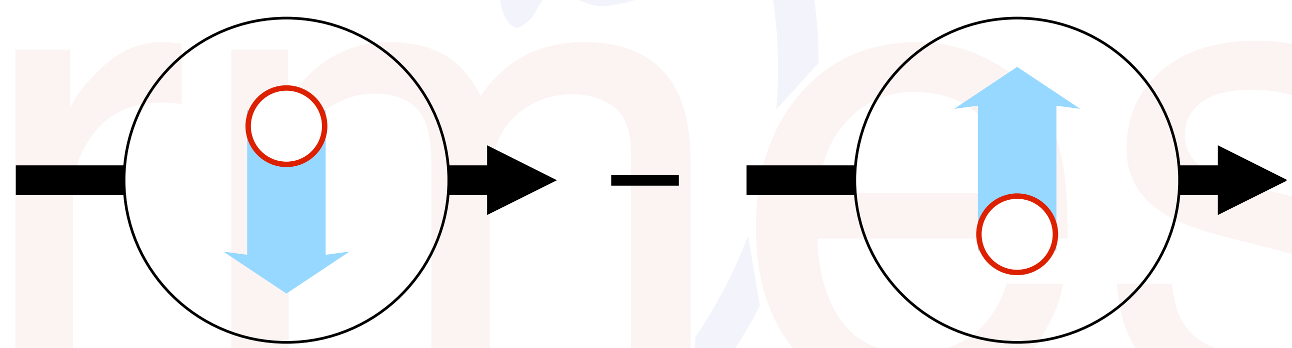
$h_1 =$ 

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

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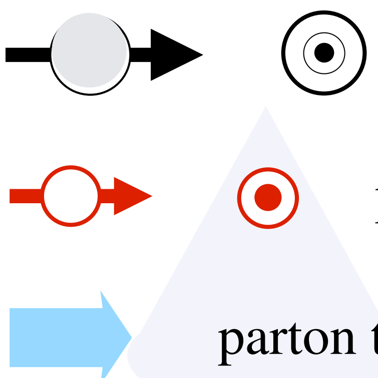

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

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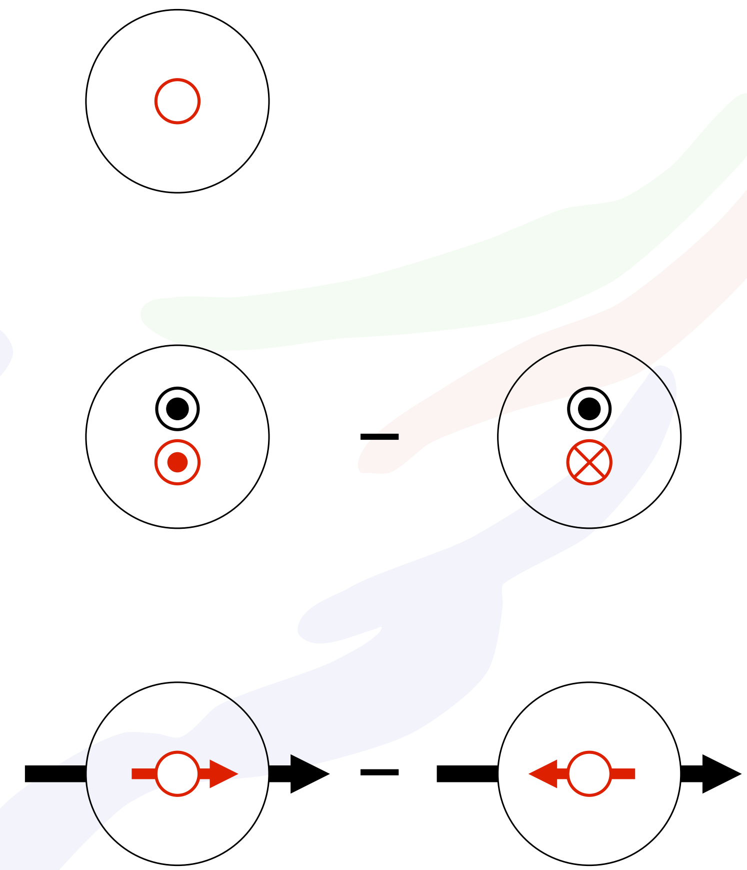

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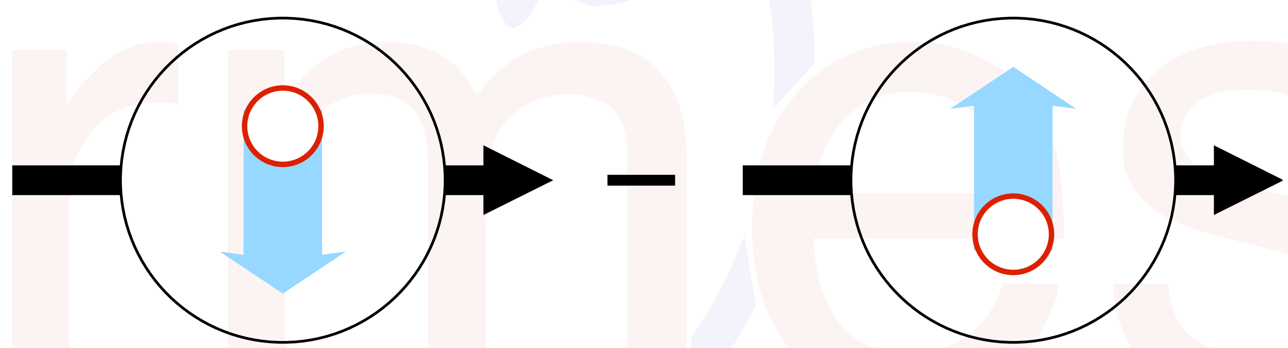
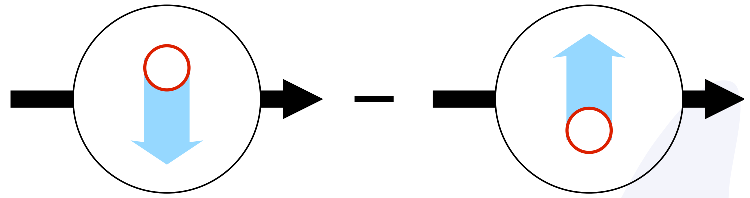


correlates transverse momentum & spin

Sivers function

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

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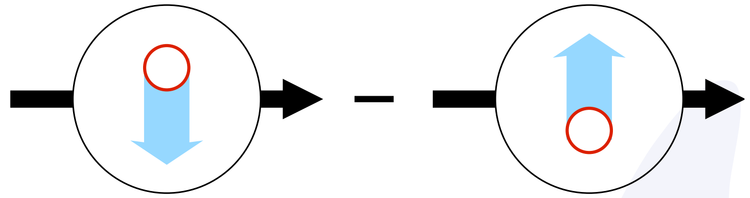
$f_{1T}^{\perp} =$ 

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

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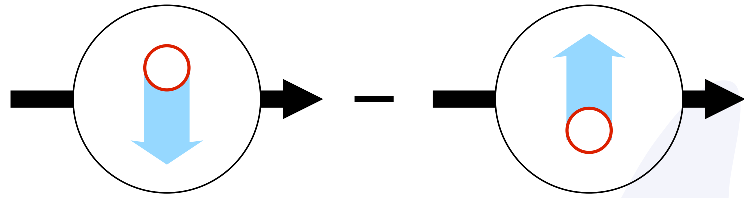
$f_{1T}^{\perp} =$ 

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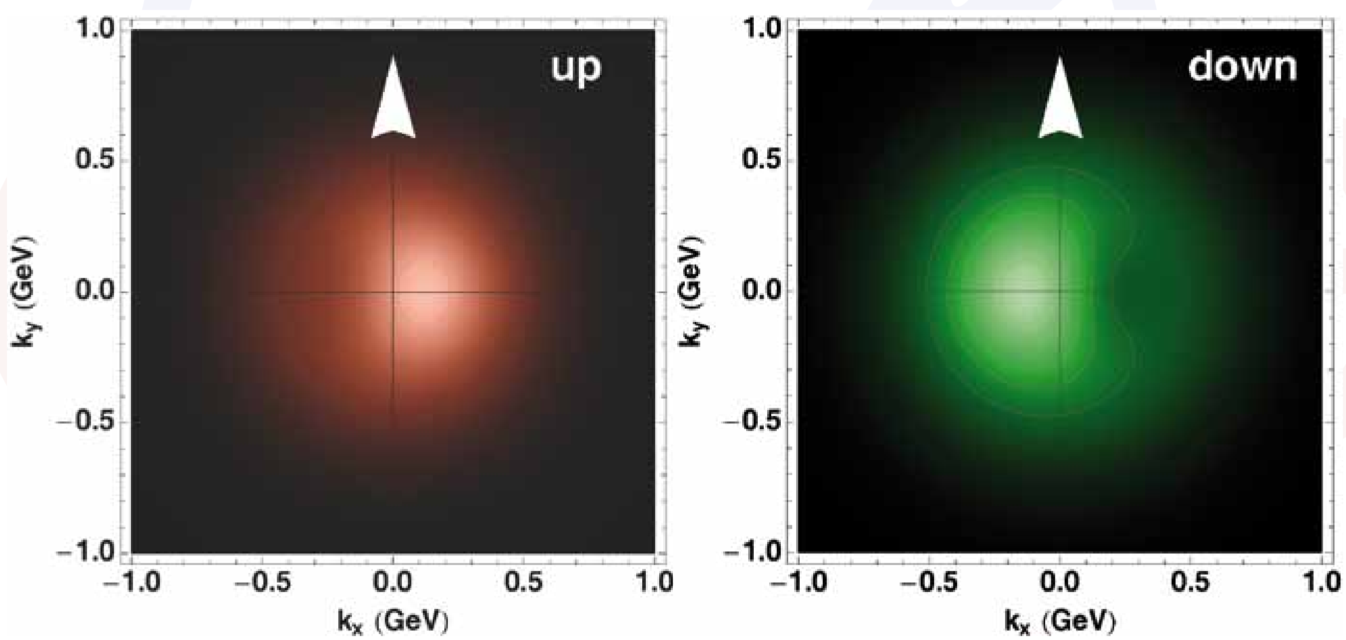

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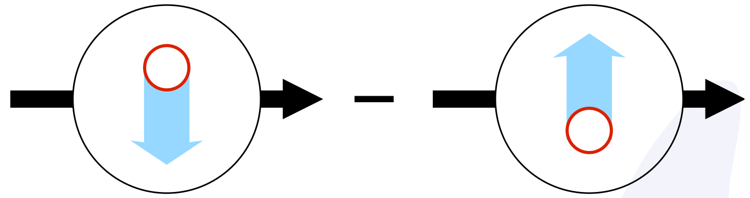
$f_{1T}^{\perp} =$ 

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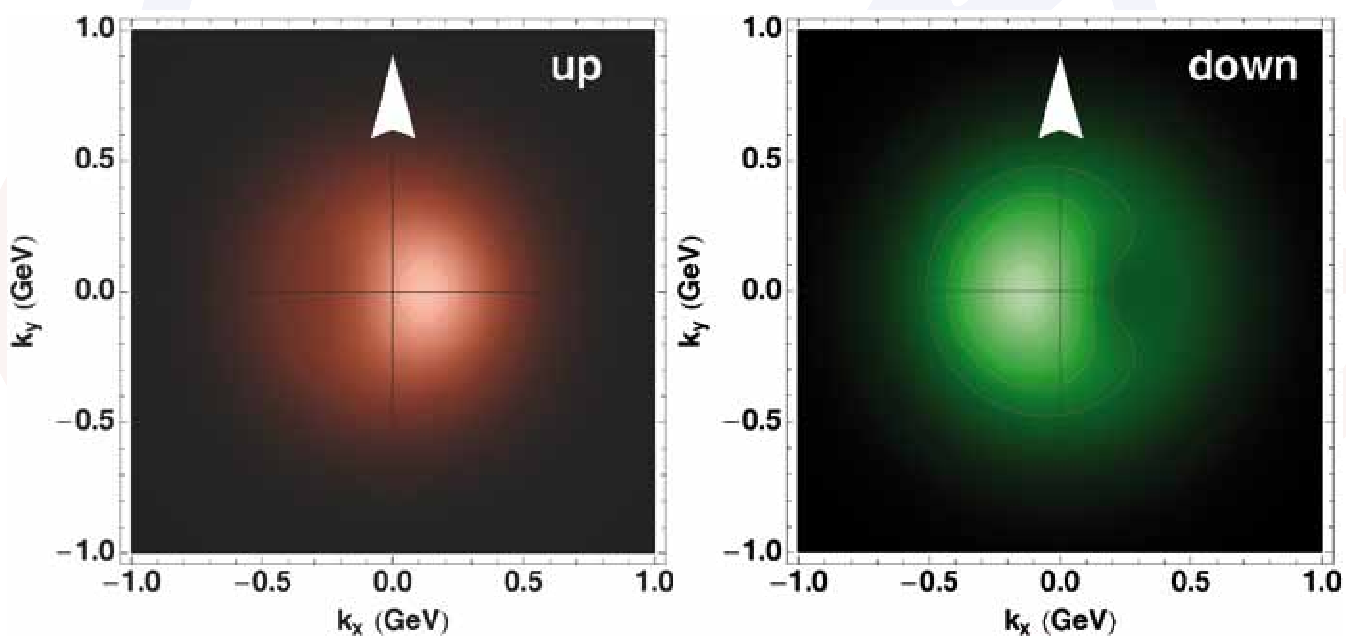
- (naive) T-odd structure: $S_N \cdot (p_\perp \times P_N)$ -- requires ISI/FSI
- leads to peculiar calculable universality breaking (DIS vs. Drell-Yan)



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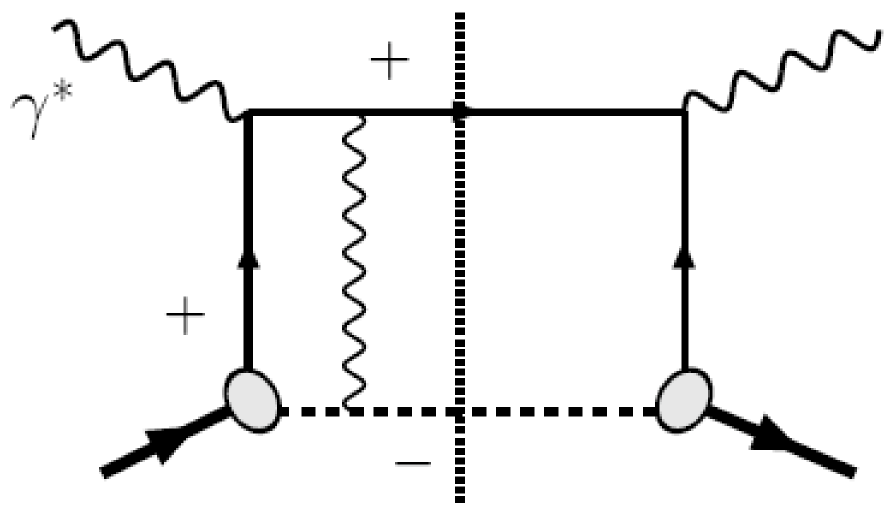
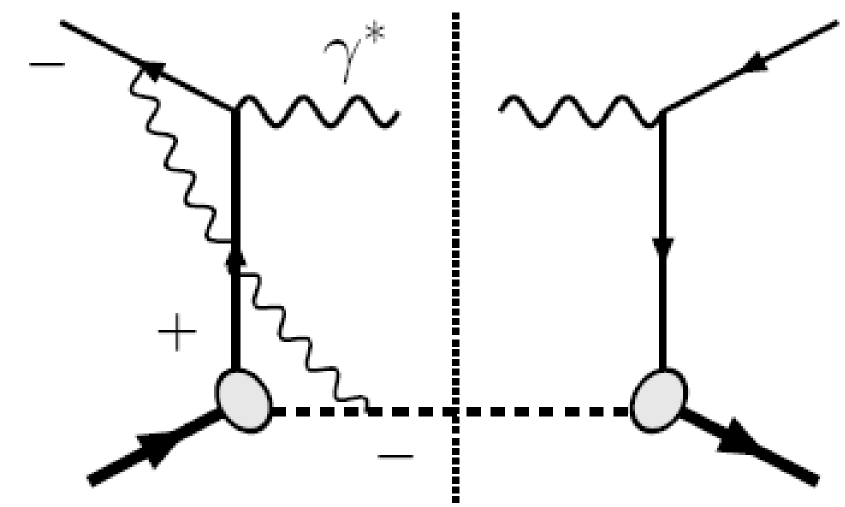
Process dependence

simple QED example



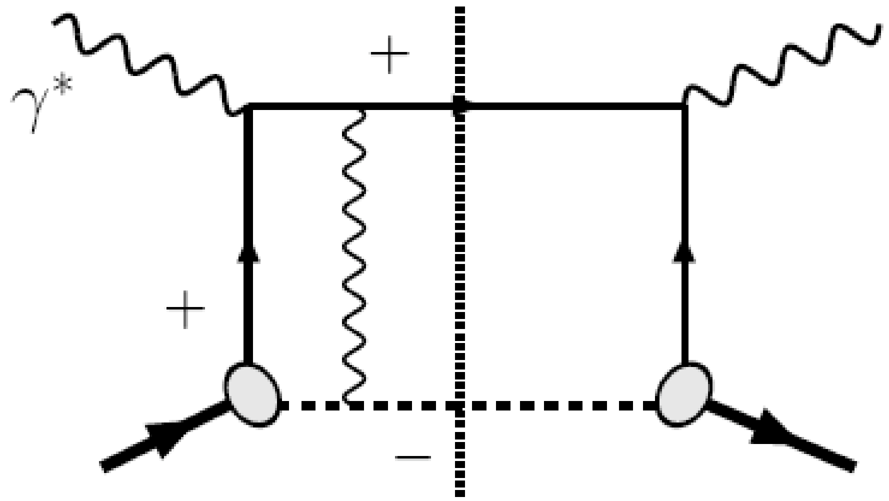


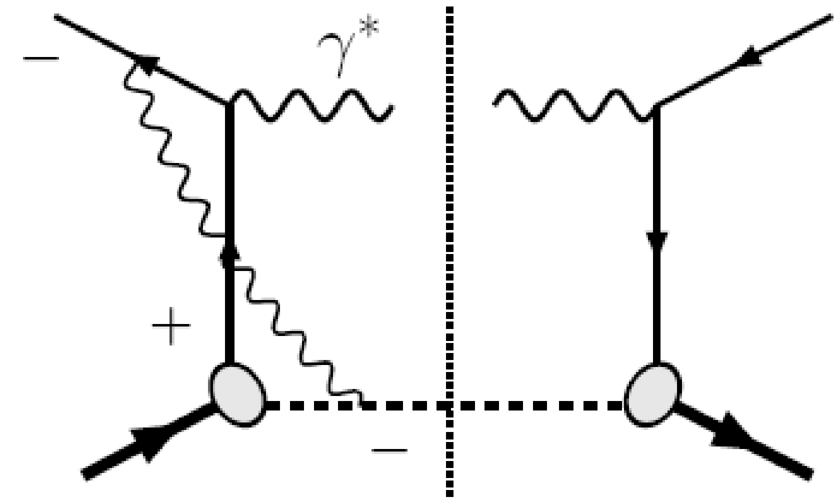
DIS: attractive

Drell-Yan: repulsive

Process dependence

simple QED example

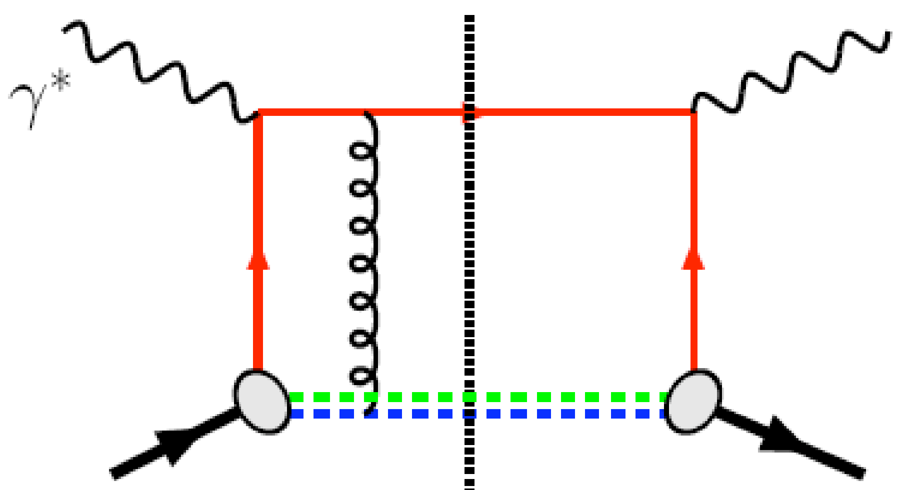


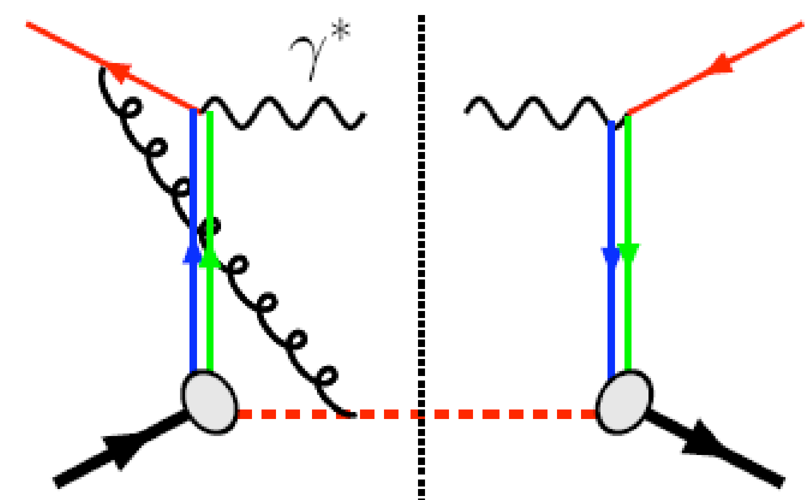


DIS: attractive

Drell-Yan: repulsive

add color: QCD

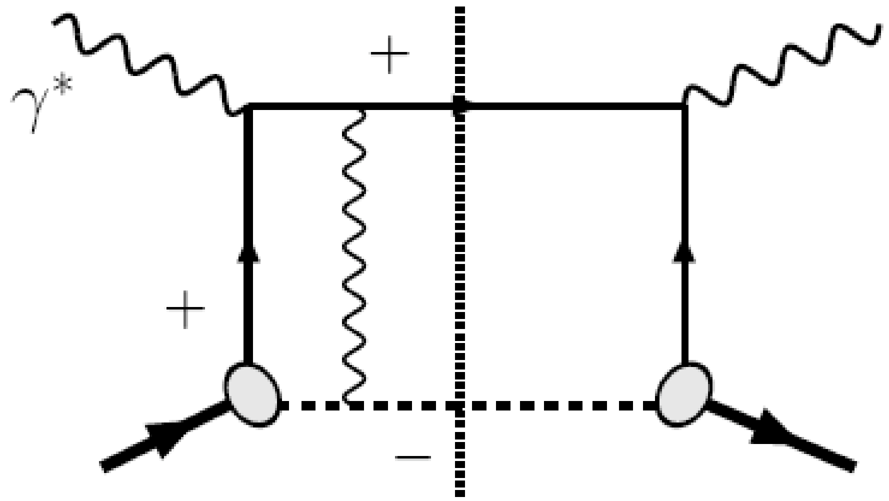


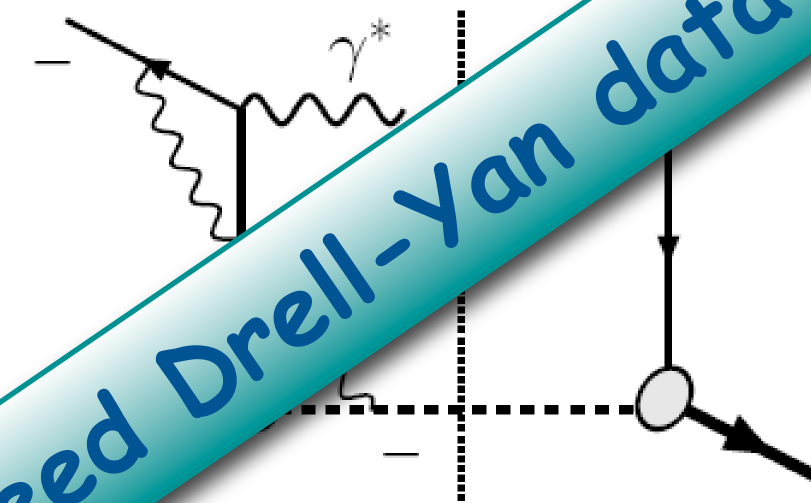


result: $\text{Sivers}|_{\text{DIS}} = - \text{Sivers}|_{\text{DY}}$

Process dependence

simple QED example





DIS: attracti

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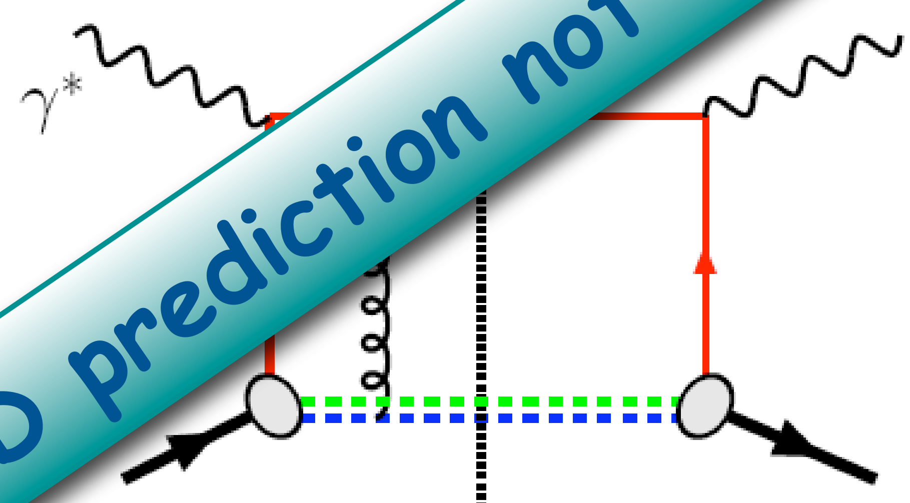
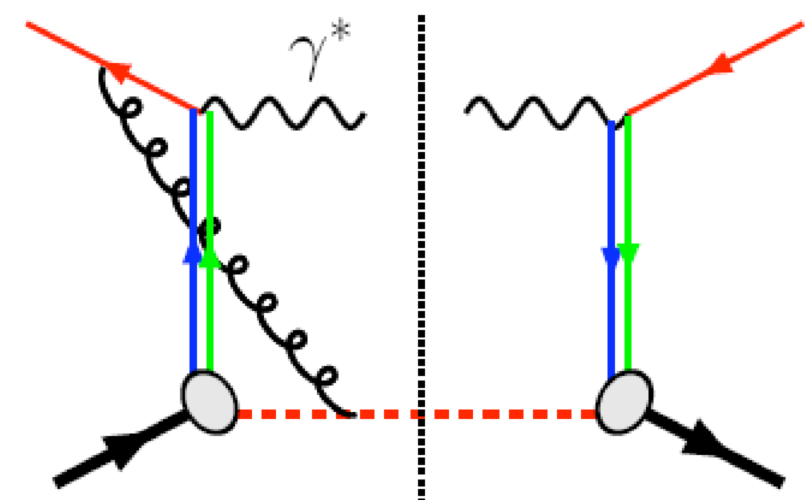
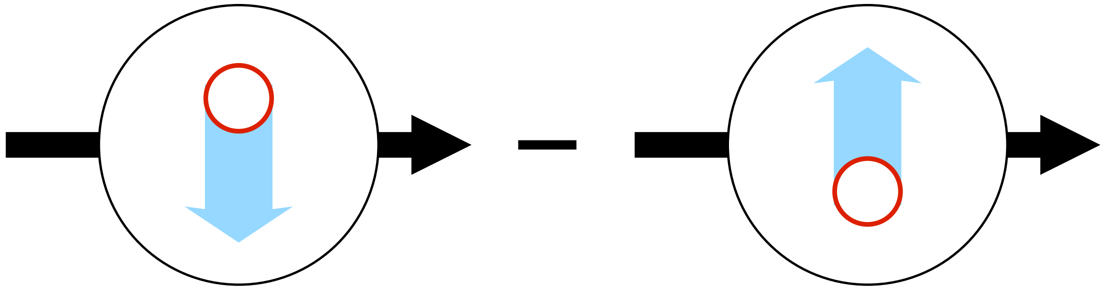




result: Sivers$|_{DIS}$ = - Sivers$|_{DY}$

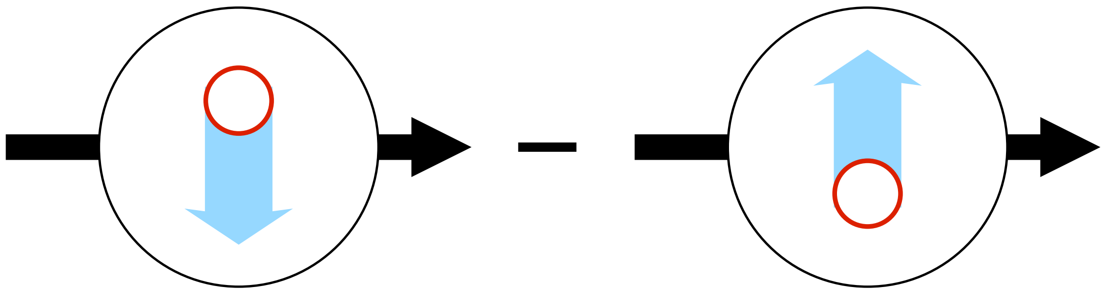
rigorous QCD prediction not tested!! - need Drell-Yan data



Sivers effect

naively T-odd distributions

“Wilson-line physics”



Sivers effect

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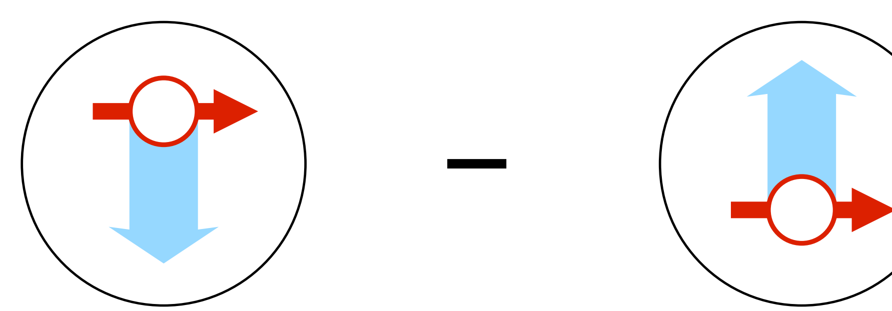
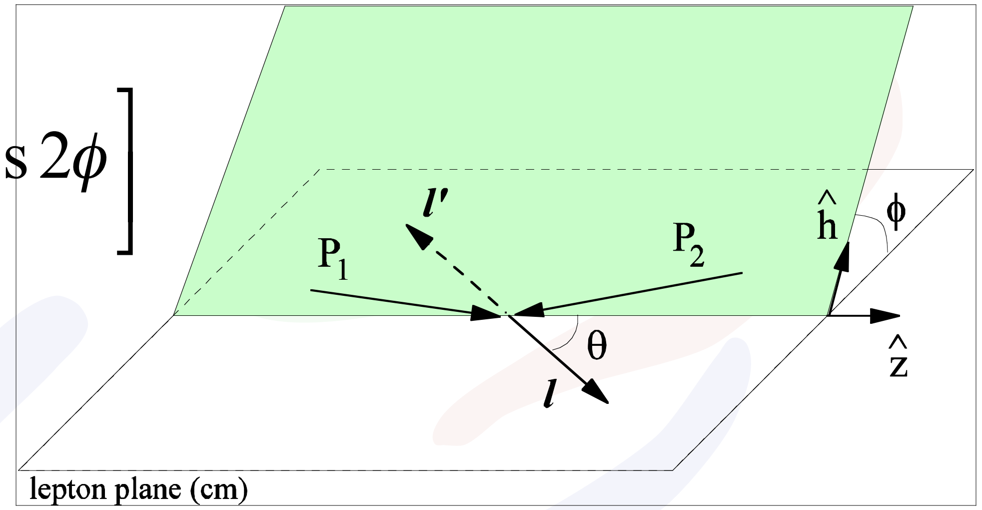
"Wilson-line physics"

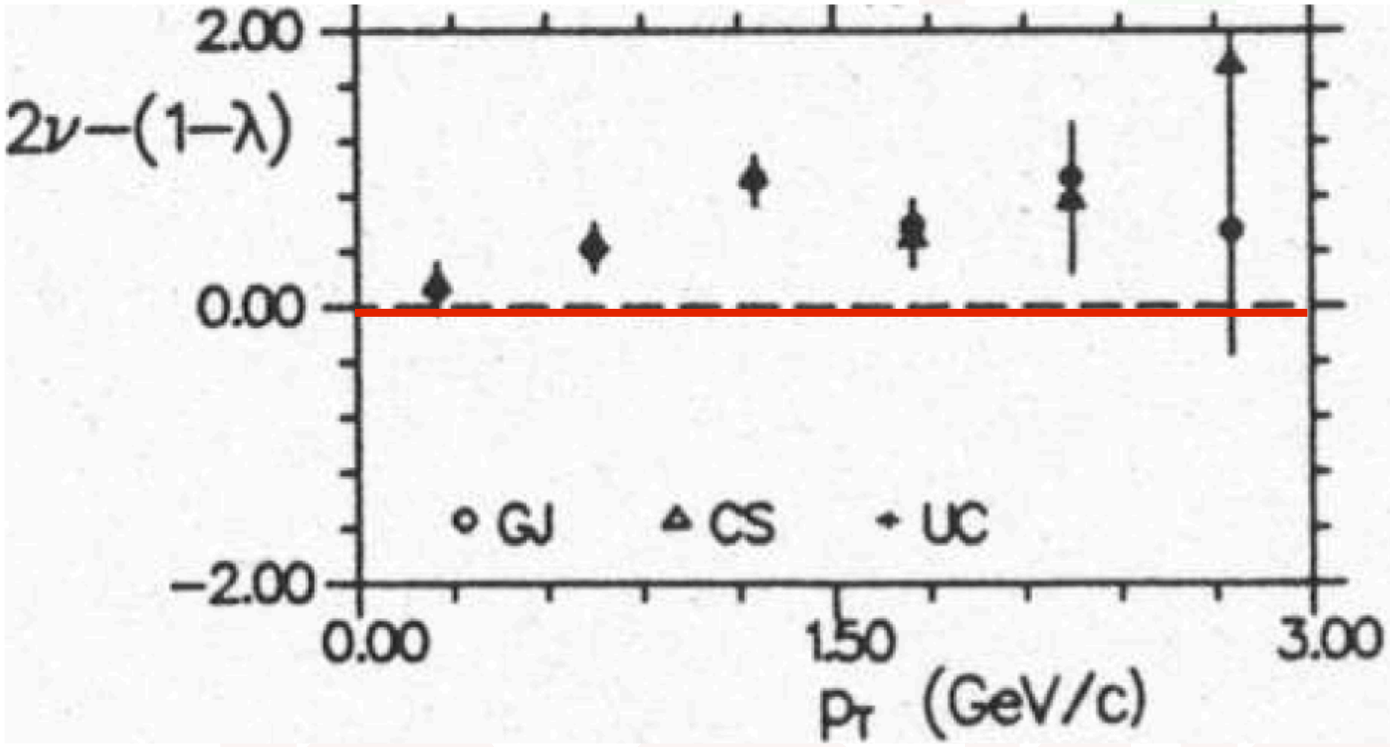
Boer-Mulders effect



Unpolarized Drell-Yan

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



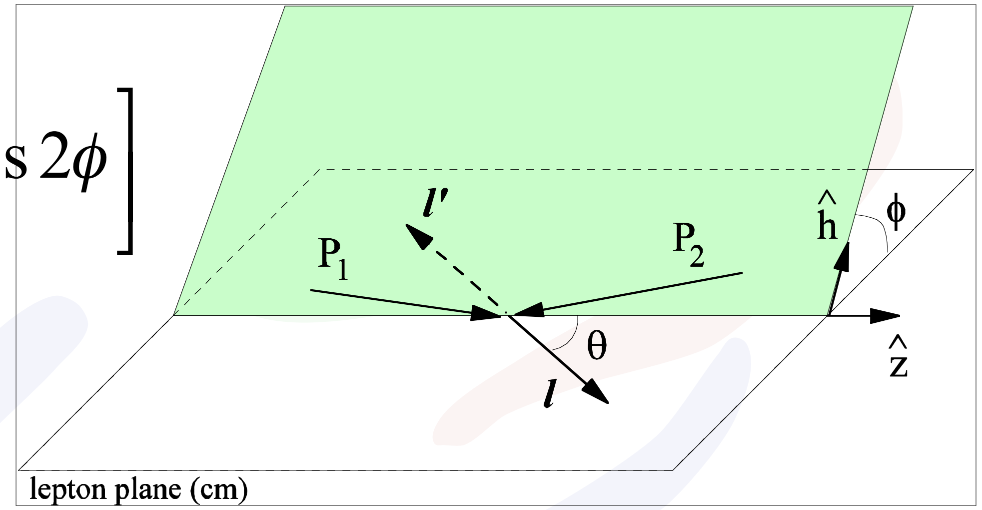


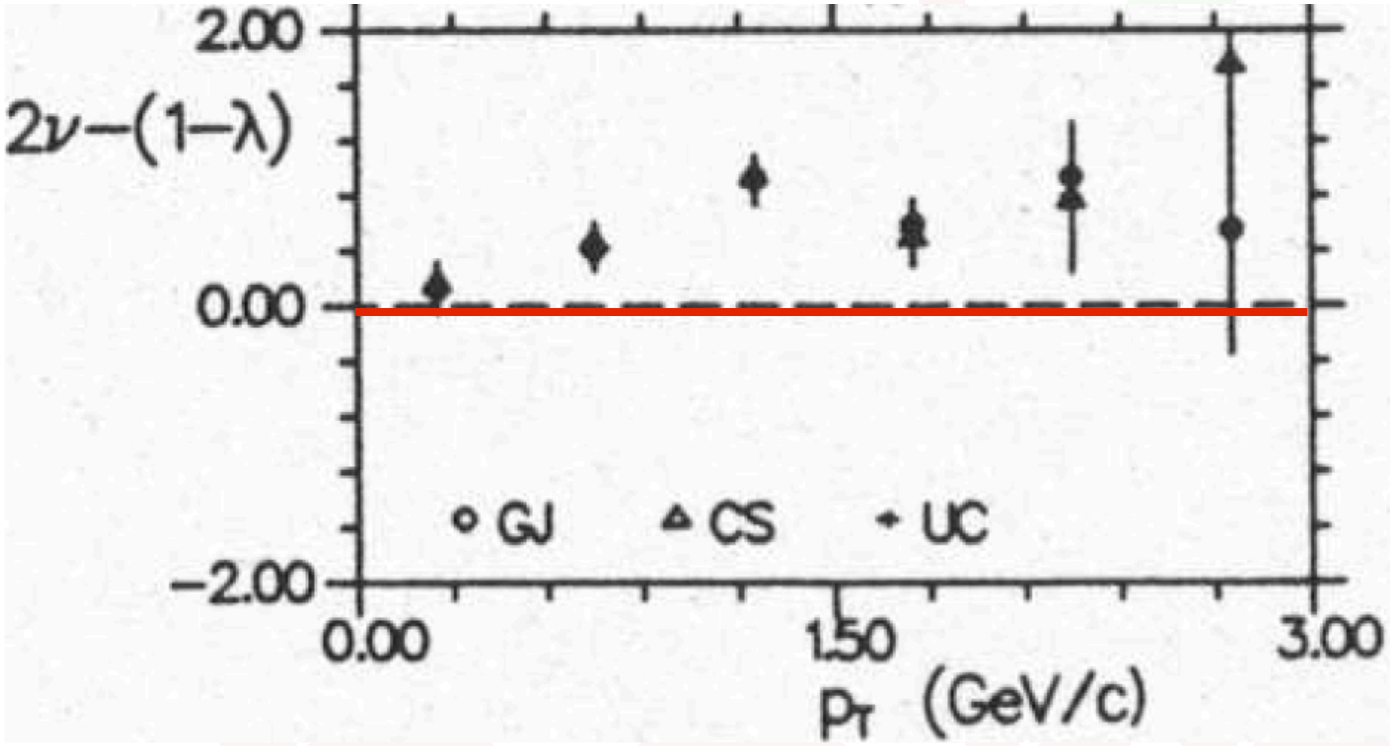
$$1-\lambda-2\nu=0$$

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

- **failure of collinear pQCD**

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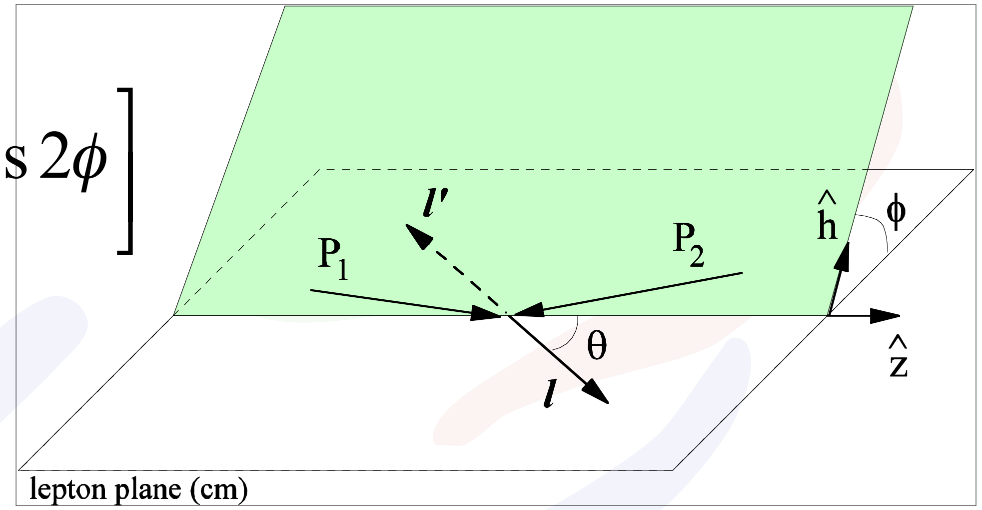
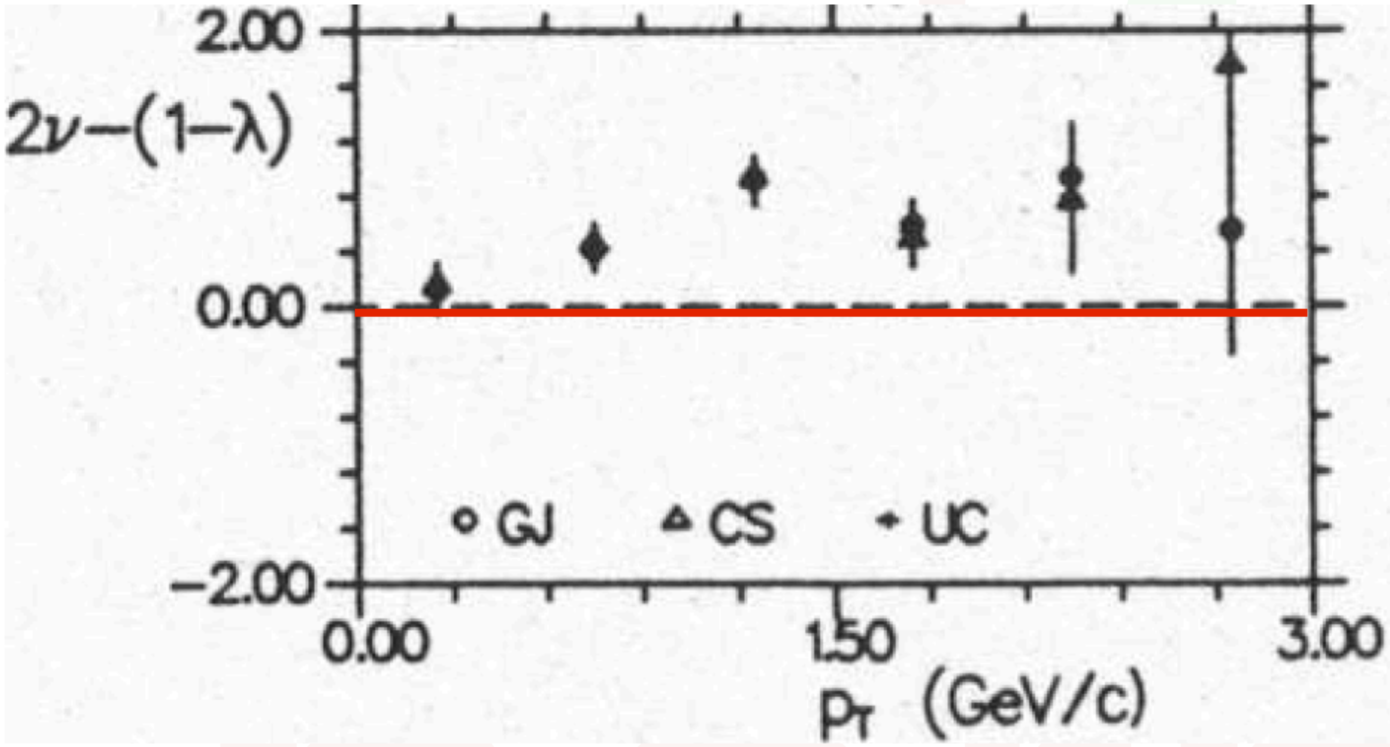




$$1-\lambda-2\nu=0$$

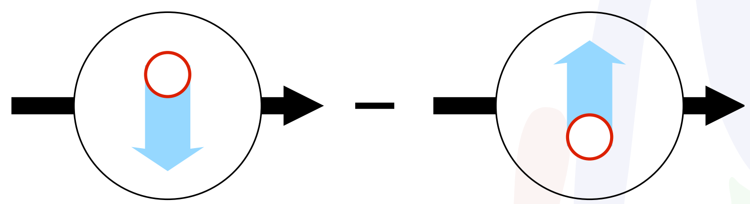
Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

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

Boer-Mulders effect

Sivers effect:

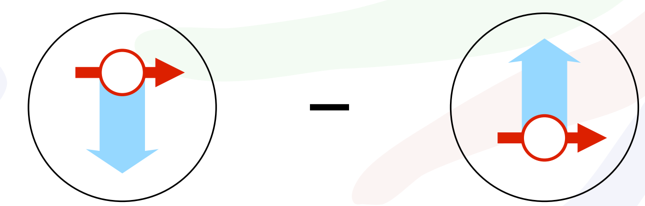
$f_{1T}^{\perp} =$



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

Boer-Mulders effect:

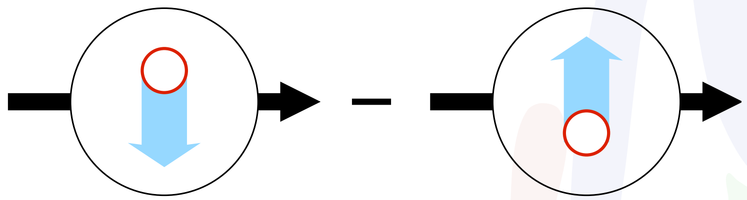
$h_1^{\perp} =$



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

Boer-Mulders effect

Sivers effect:

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

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

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$h_1^{\perp} =$ 

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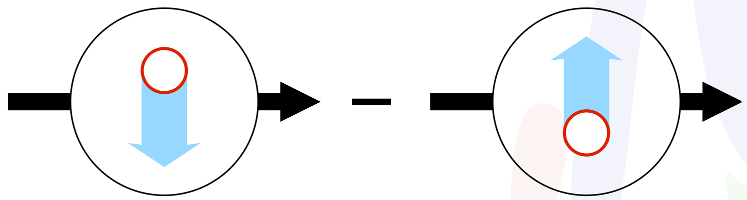
- spin-effect in **unpolarized** reactions

Boer-Mulders effect

Sivers effect:

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

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- spin-effect in **unpolarized** reactions
- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks

Boer-Mulders effect

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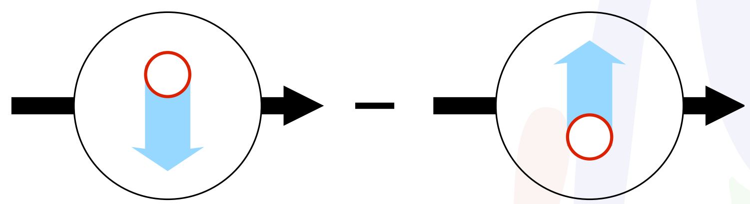
$f_{1T}^{\perp} =$ 

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- spin-effect in **unpolarized** reactions
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Boer-Mulders effect

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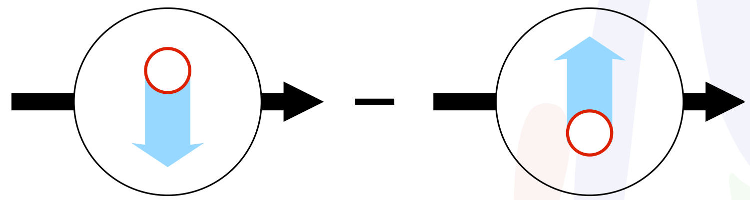
$f_{1T}^{\perp} =$ 

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

Boer-Mulders effect:

$h_1^{\perp} =$ 

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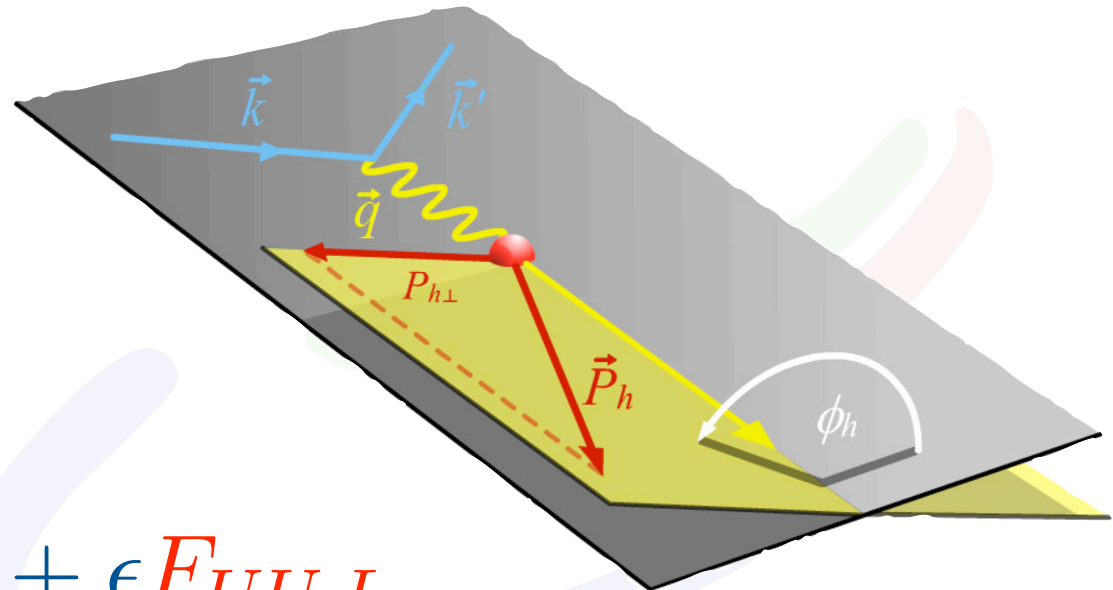
- spin-effect in **unpolarized** reactions
- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks
- QCD: sign change for DIS vs. Drell-Yan
- up to now little data from DIS

➡ HERMES with most comprehensive data set

Cross section without polarization



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

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

target polarization

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

beam polarization

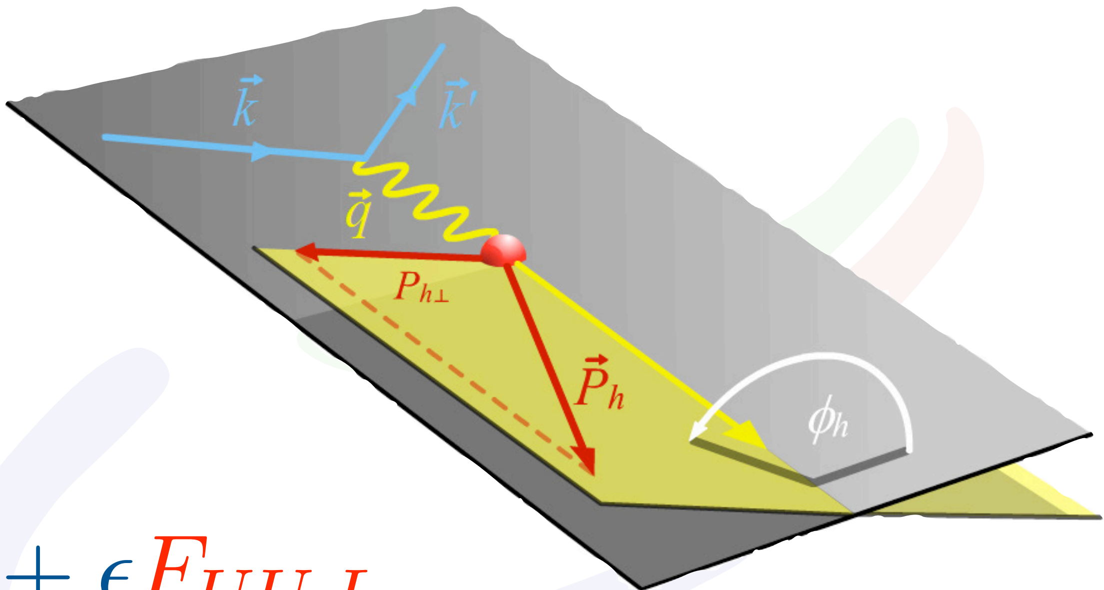
virtual-photon polarization

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

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

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

Cross section without polarization



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

BOER-MULDERS EFFECT

leading twist

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

CAHN EFFECT

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)

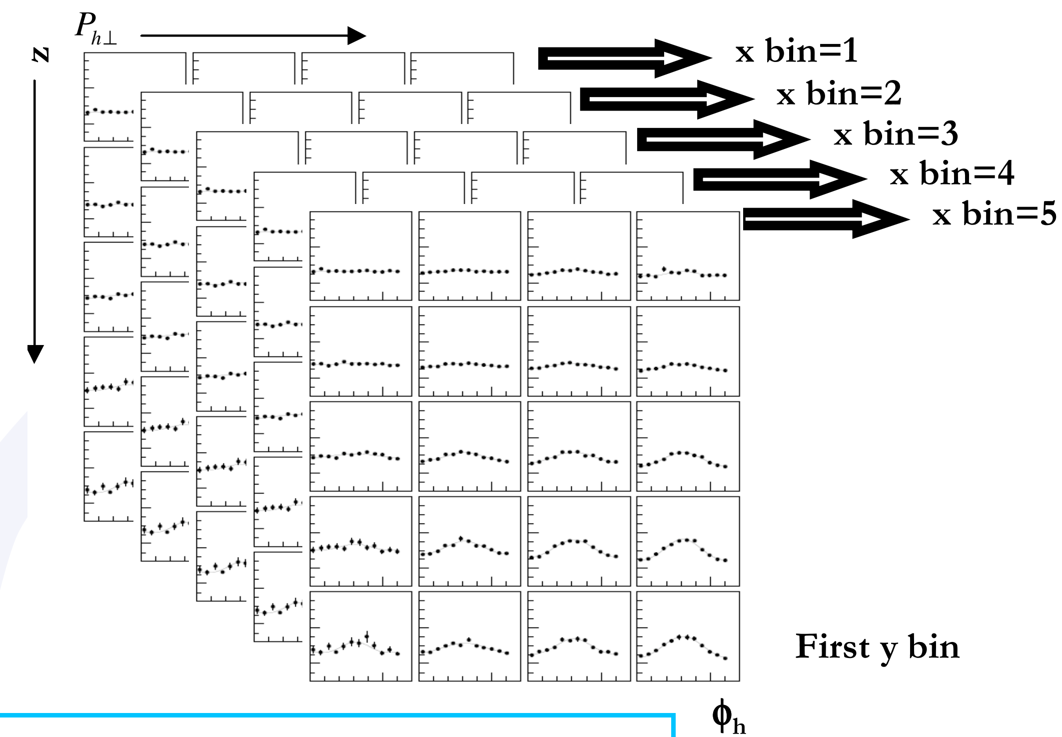
$$\gamma=\frac{2Mx}{Q}$$

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

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

Extraction of cosine modulations

- **Fully differential analysis in $(x,y,z,P_{h\perp},\phi)$**



- **Multi-dimensional unfolding: correction for finite acceptance, QED radiation, kinematic smearing, detector resolution**

probability that an event generated with a certain kinematics is measured with a different kinematics

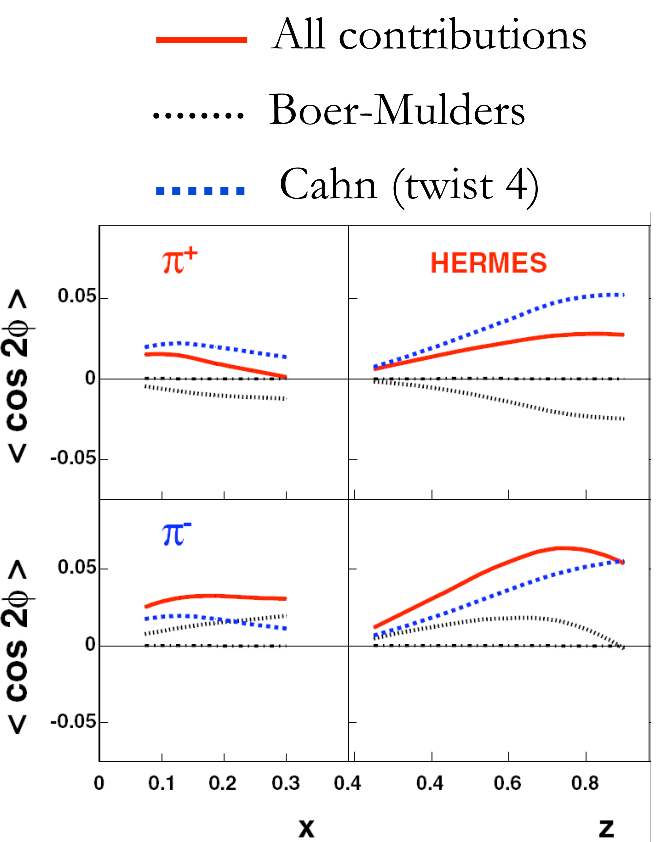
$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

includes the events smeared into the acceptance

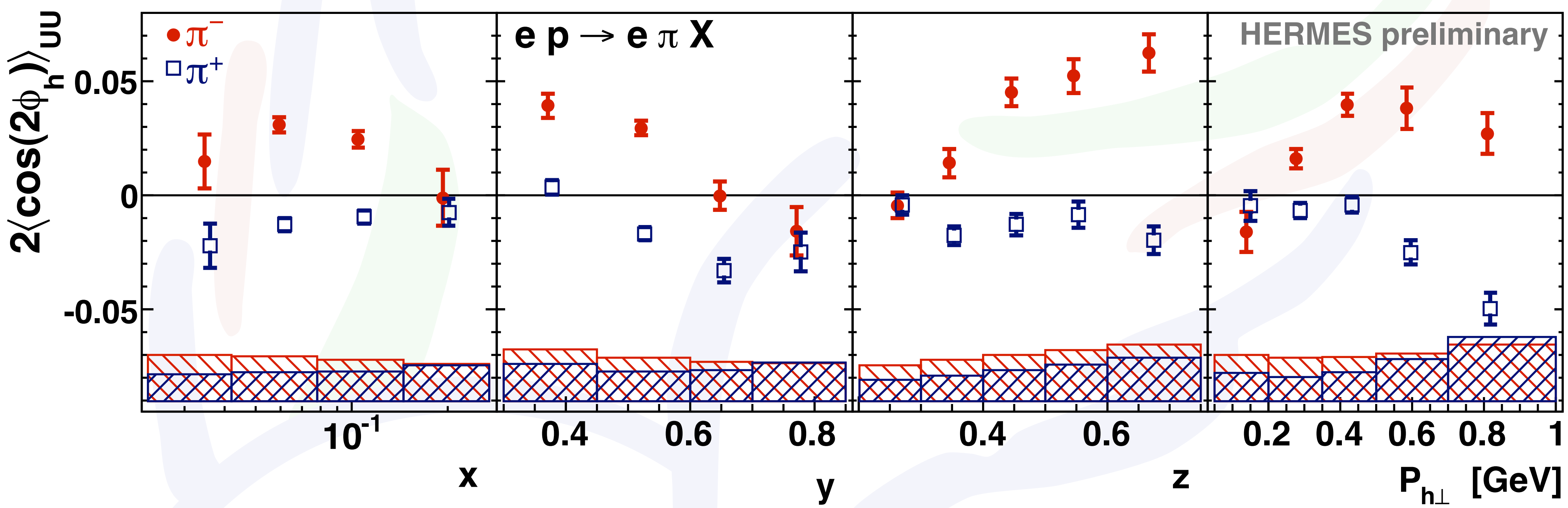
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

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

Signs of Boer-Mulders

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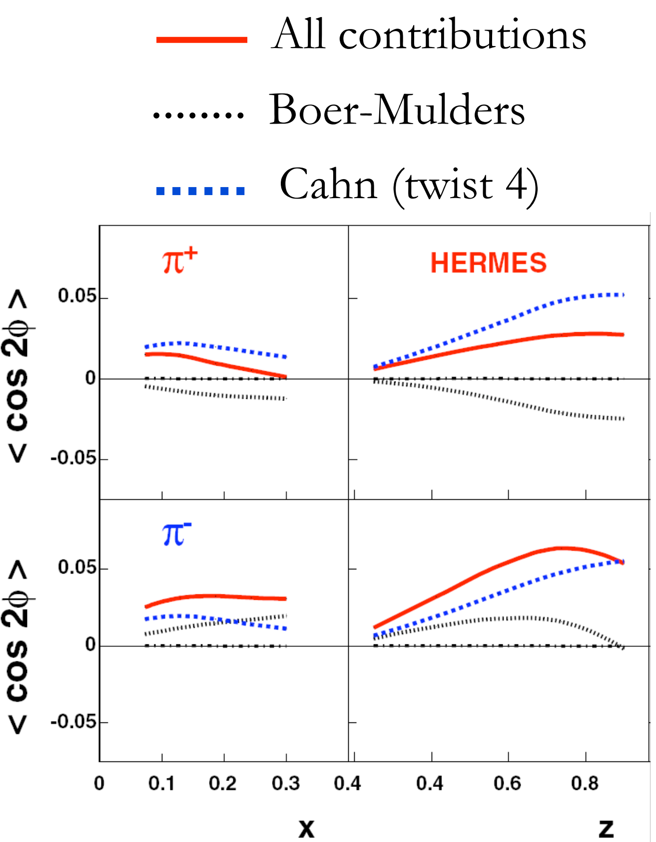
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$



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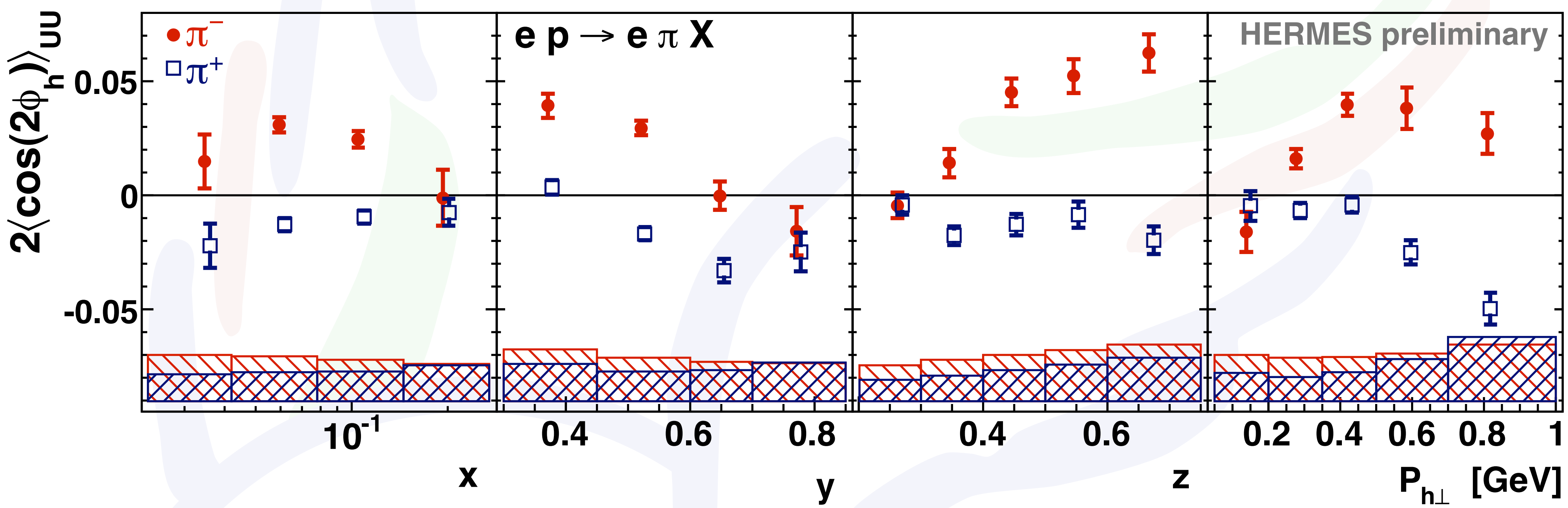
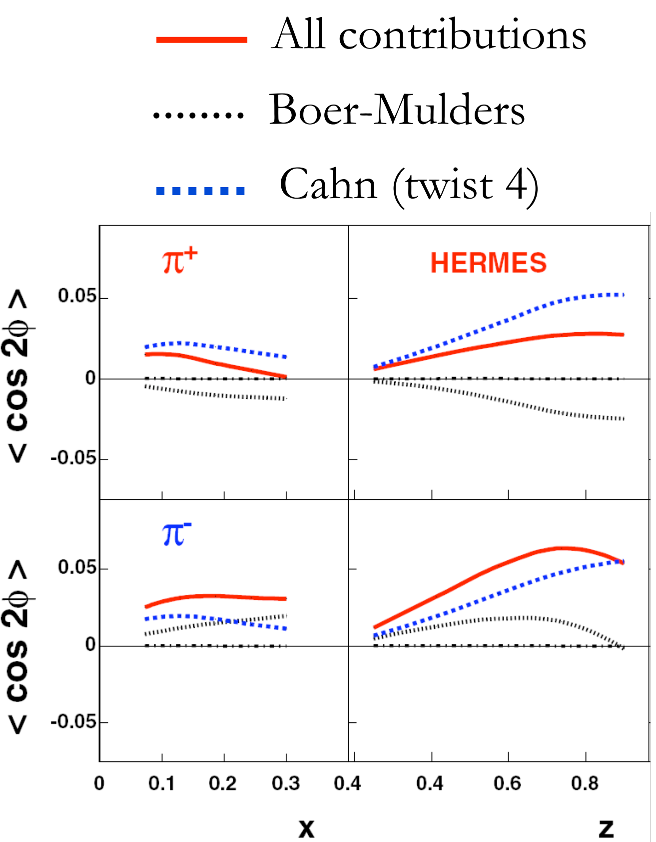


- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for π^- (as expected)

  -> same-sign BM-function for valence quarks

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

Signs of Boer-Mulders



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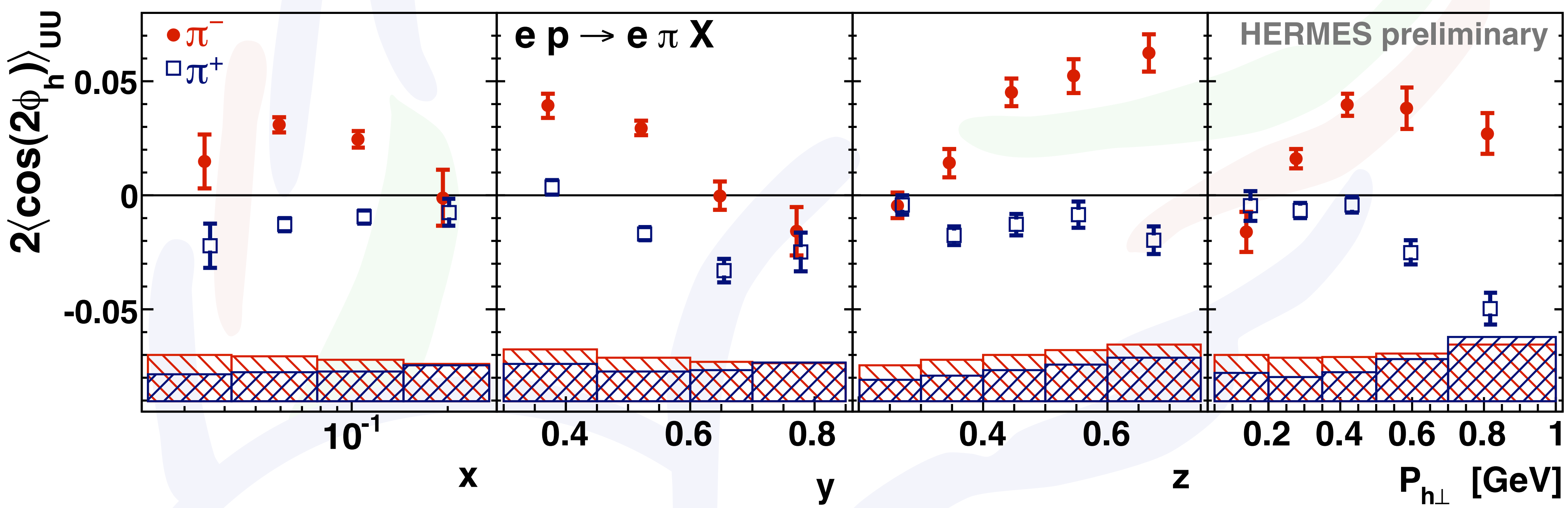
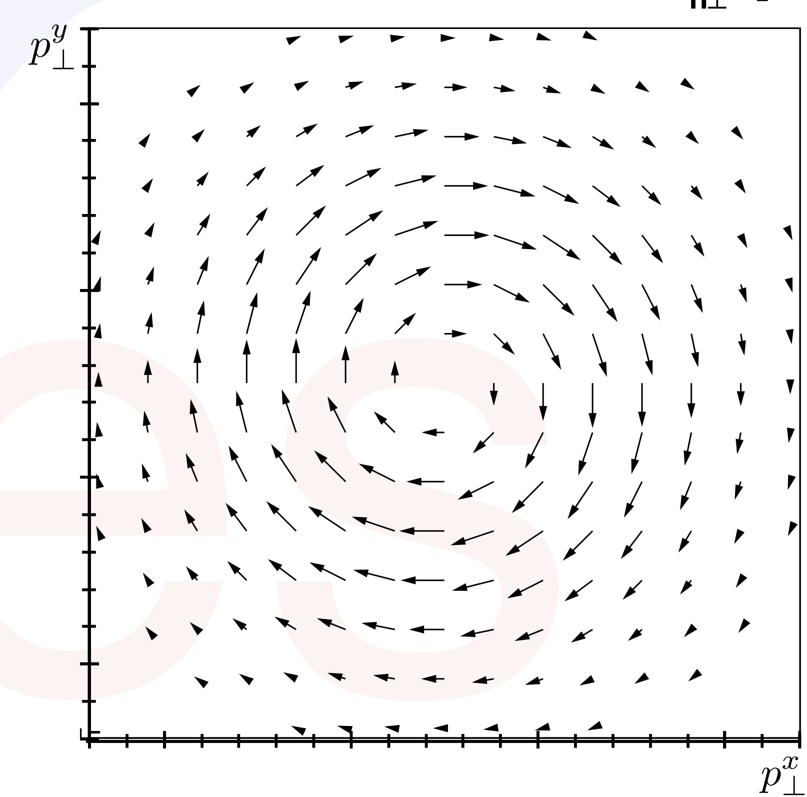




[M. Burkardt and B. Hannfious, PLB658 (2008) 130]

- 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

Cahn effect?

BOER-MULDERS EFFECT

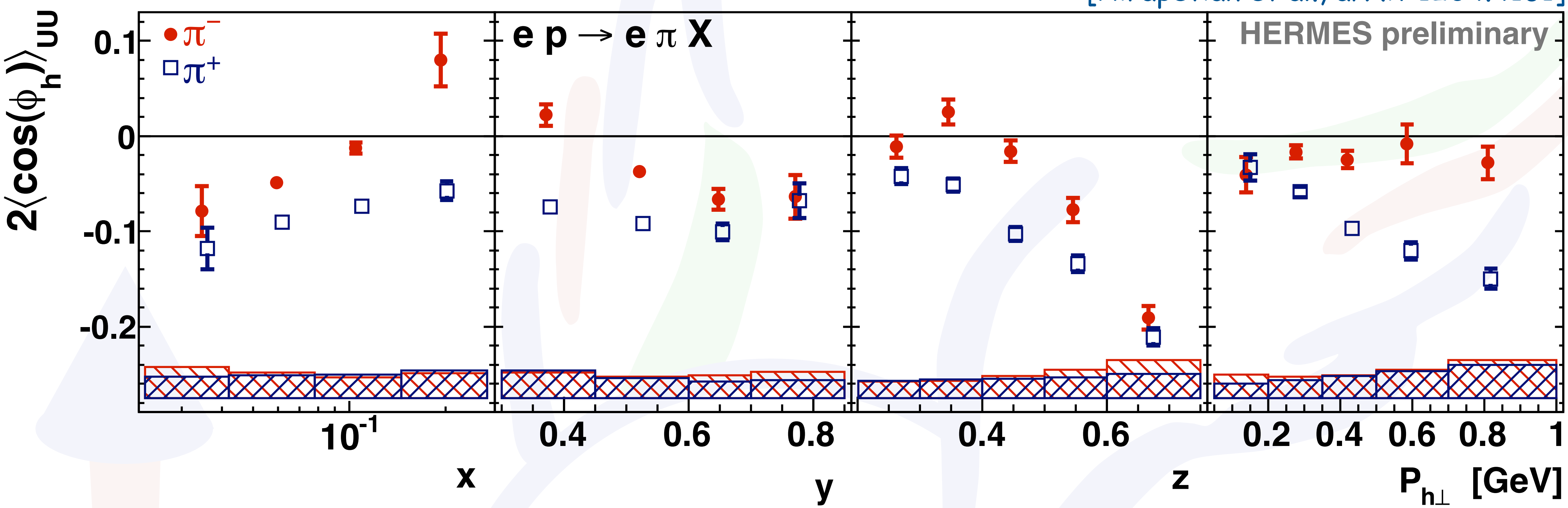
CAHN EFFECT

next to leading twist

Interaction dependent terms neglected

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

[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 $\cos\phi$ modulation
(indeed, overall pattern resembles B-M modulations)

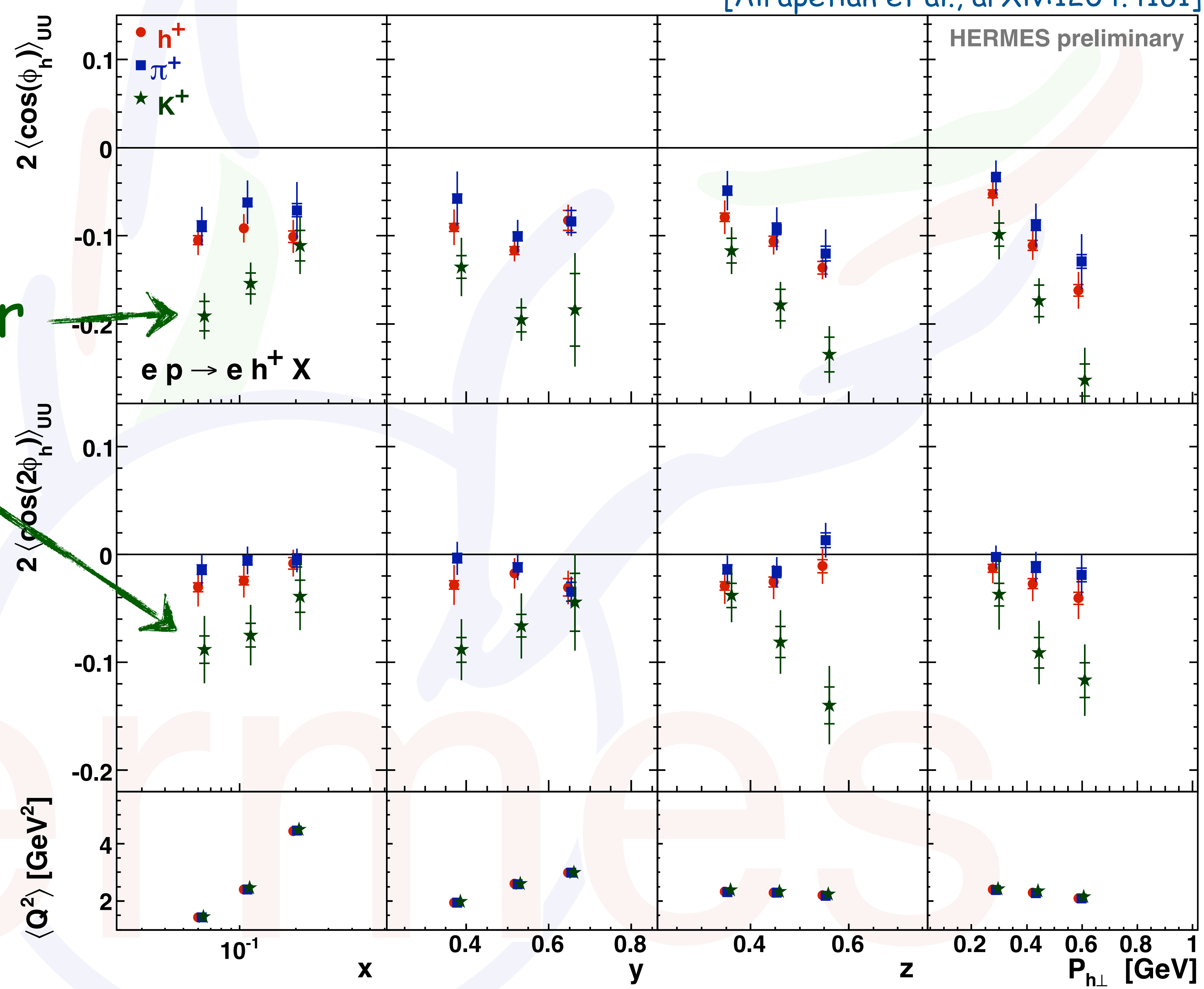
➡ additional "genuine" twist-3?

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

"strange" results

[Airapetian et al., arXiv:1204.4161]

intriguing behavior for kaons



	U	L	T
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L		g_{1L}	$h_{1L}^\perp$
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"strange" results

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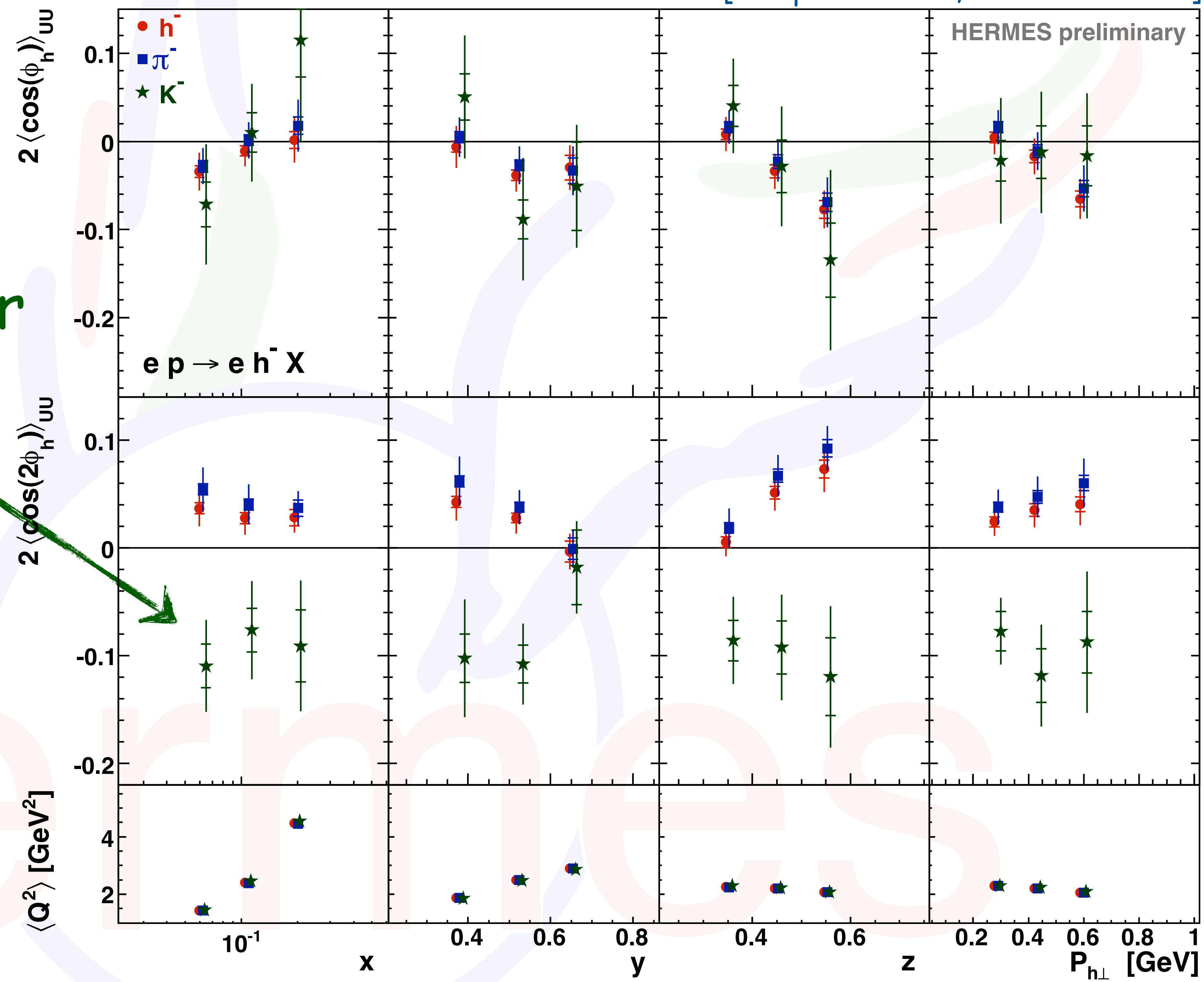

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

"strange" results

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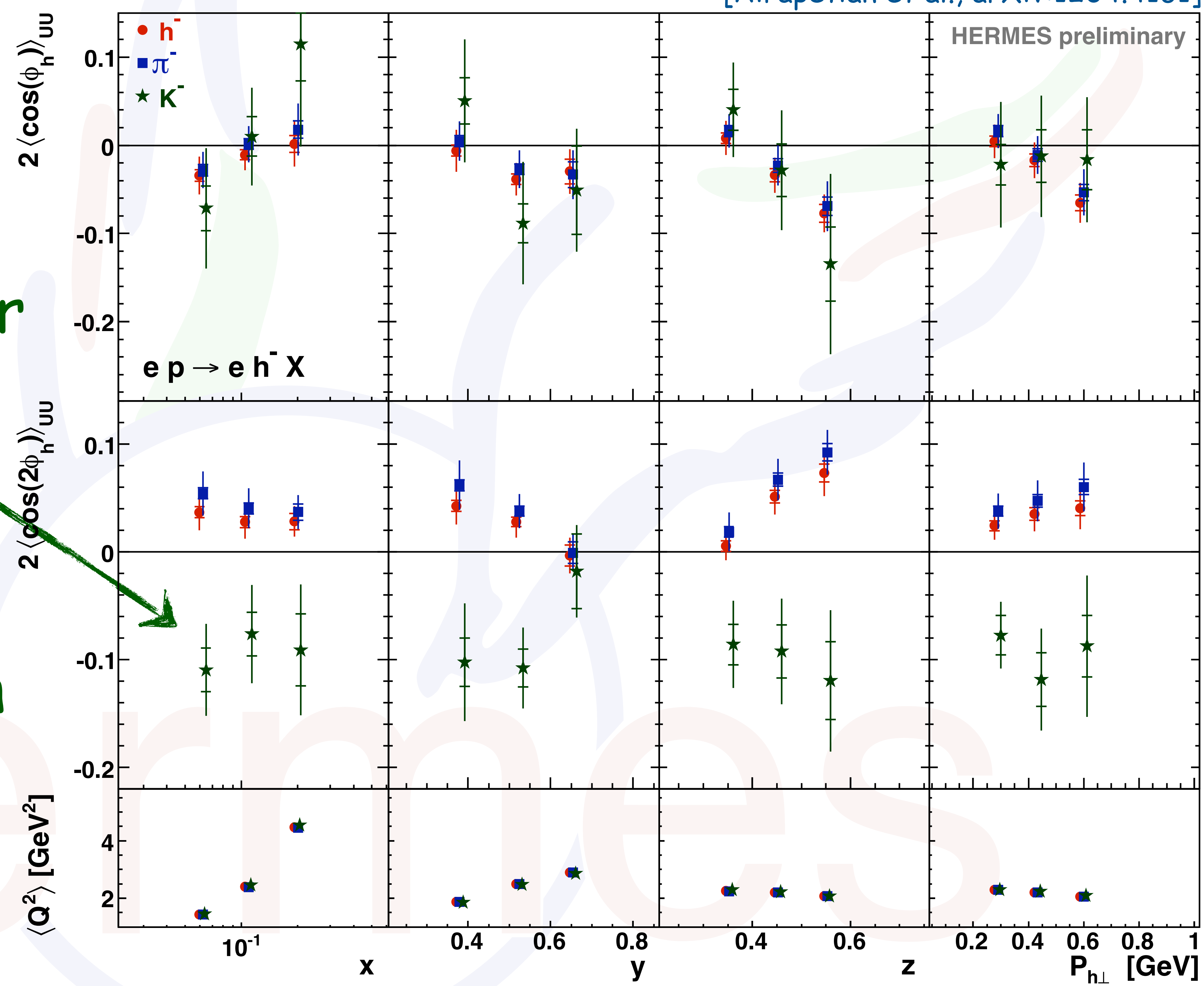
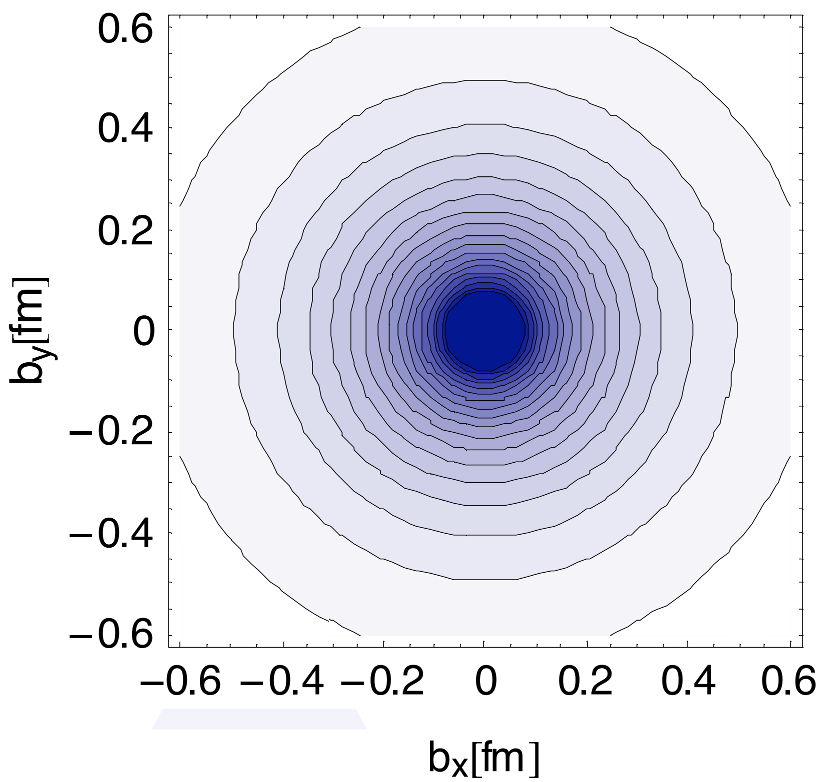


intriguing behavior for kaons

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

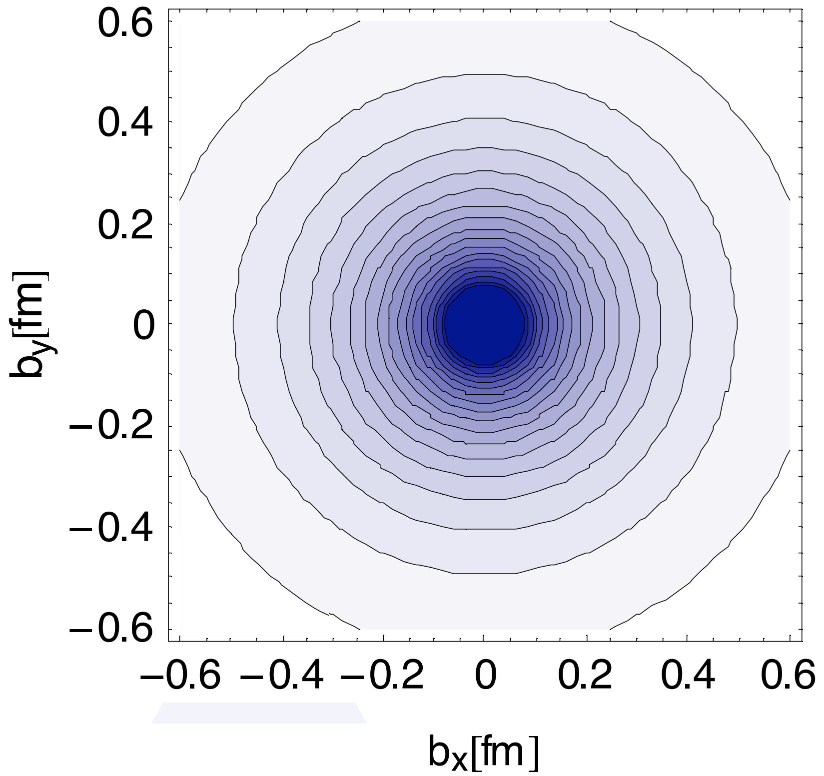
Exclusive reactions

Another 3D picture of the nucleon



Form factors:
transverse distribution
of partons

Another 3D picture of the nucleon



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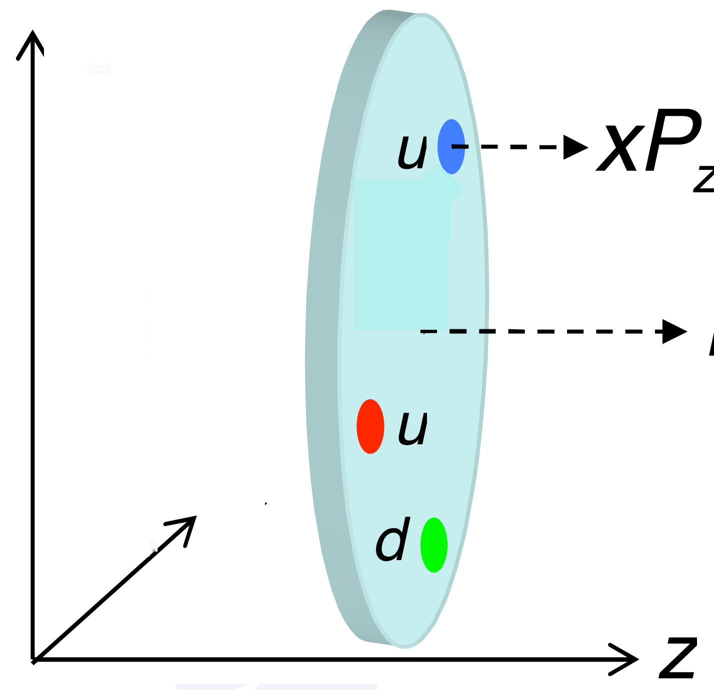
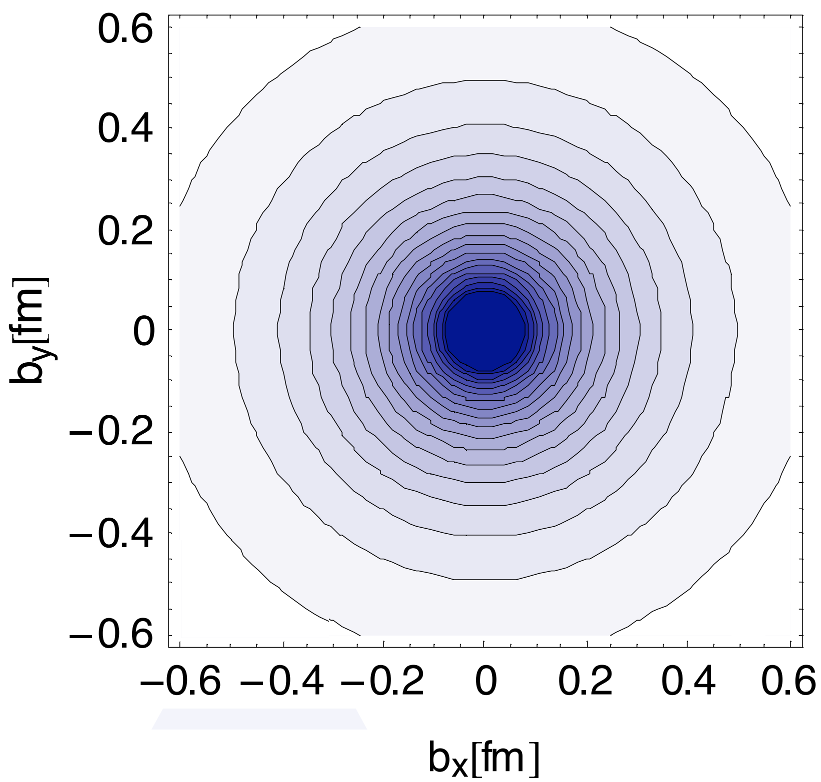


Parton distributions:
longitudinal momentum
of partons

Another 3D picture of the nucleon



Form factors:
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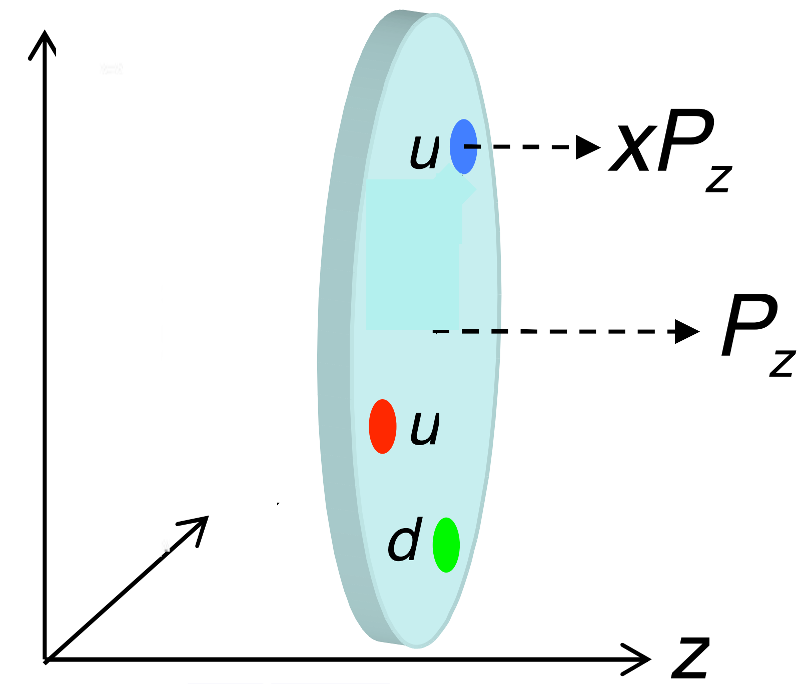

Parton distributions:
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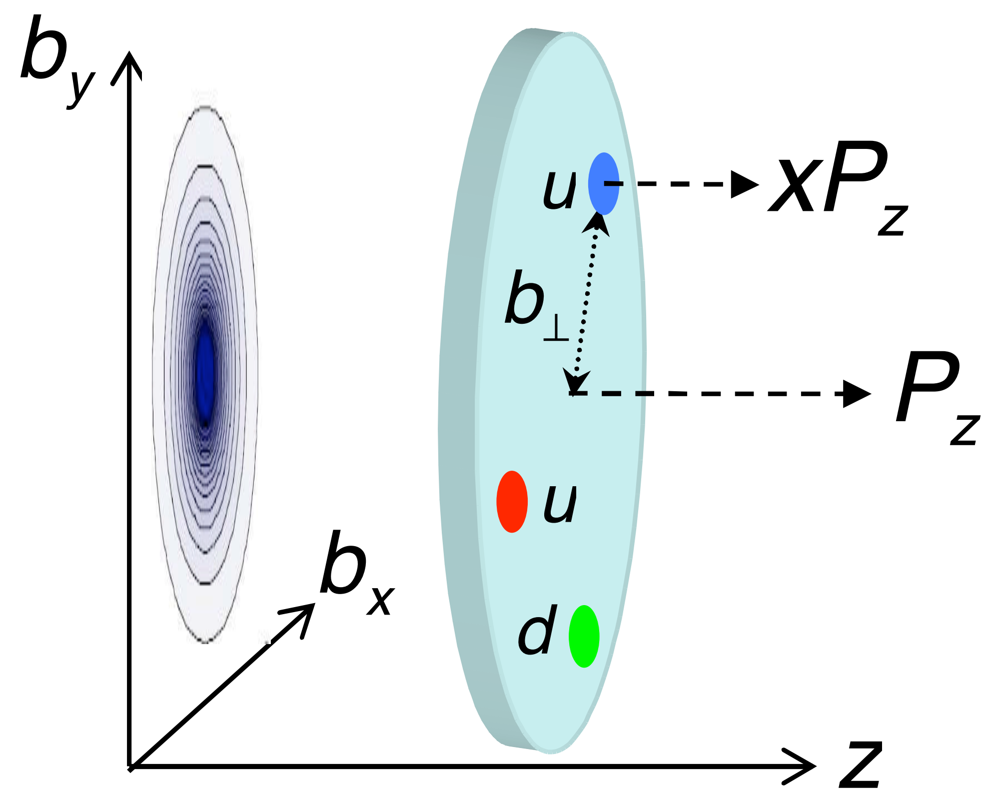
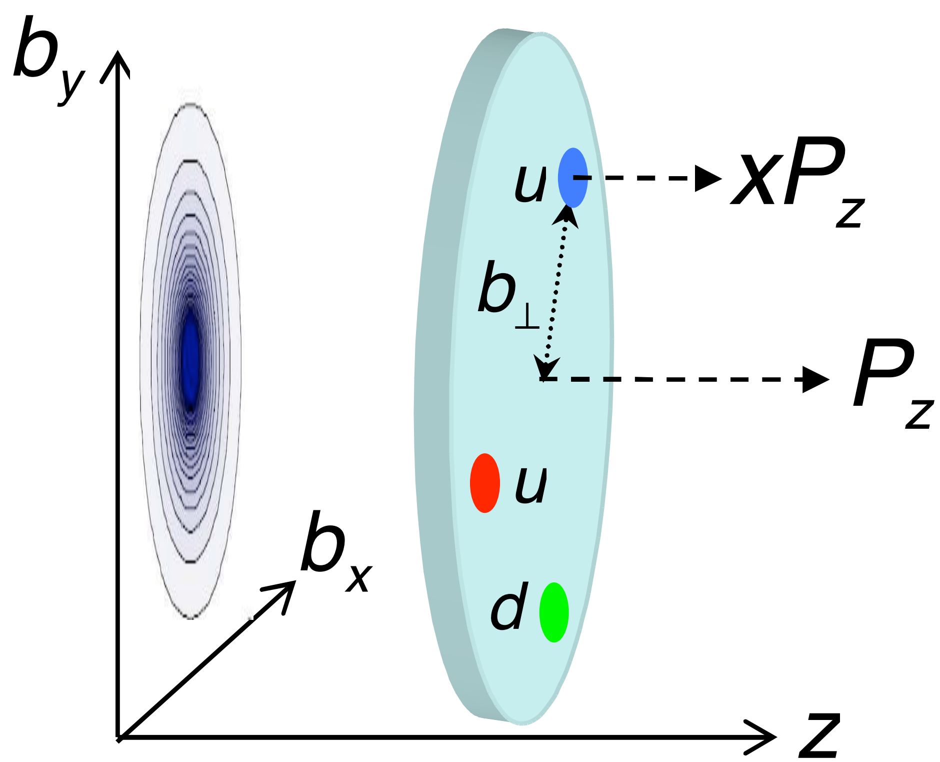
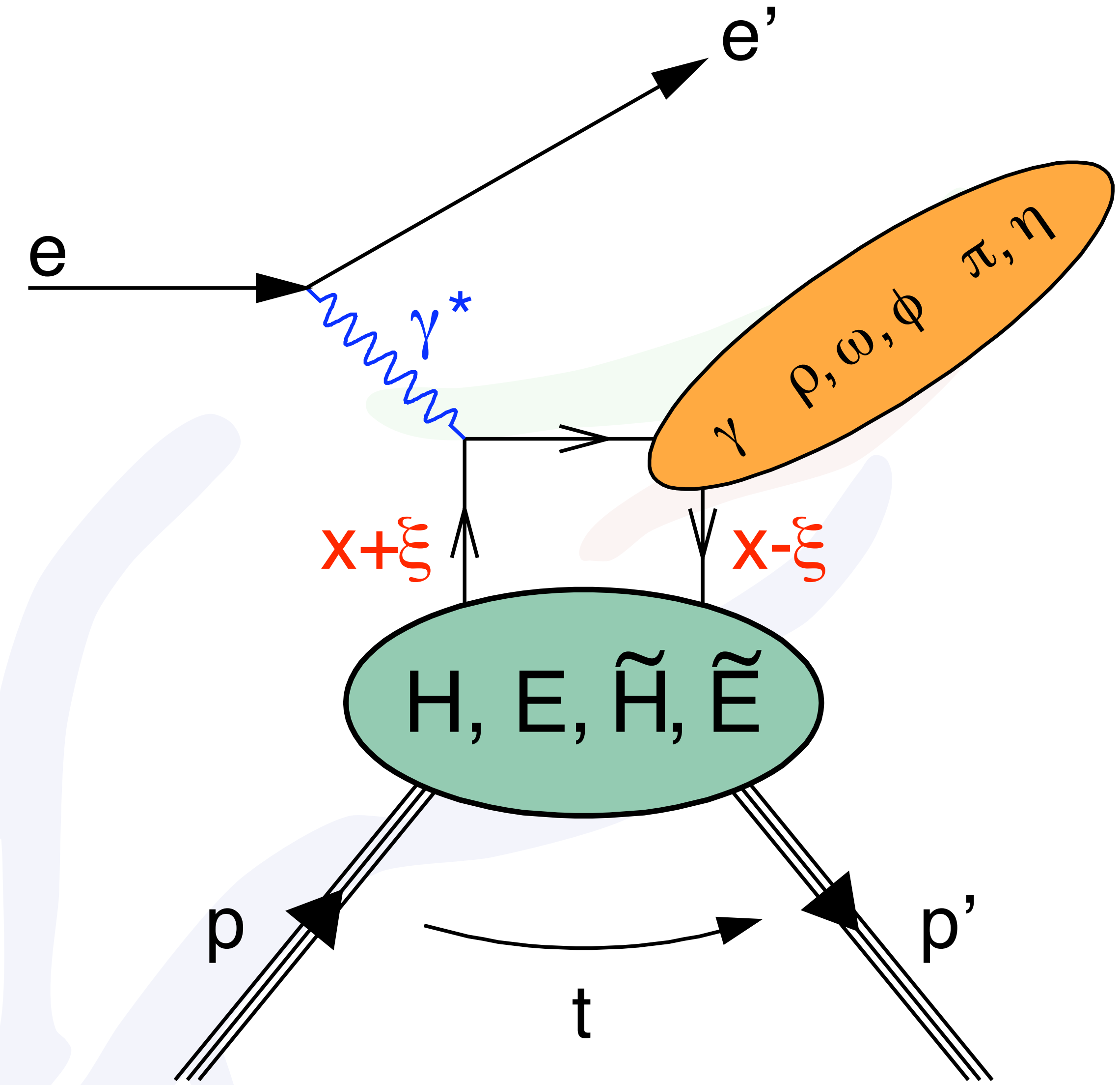


Nucleon Tomography
correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

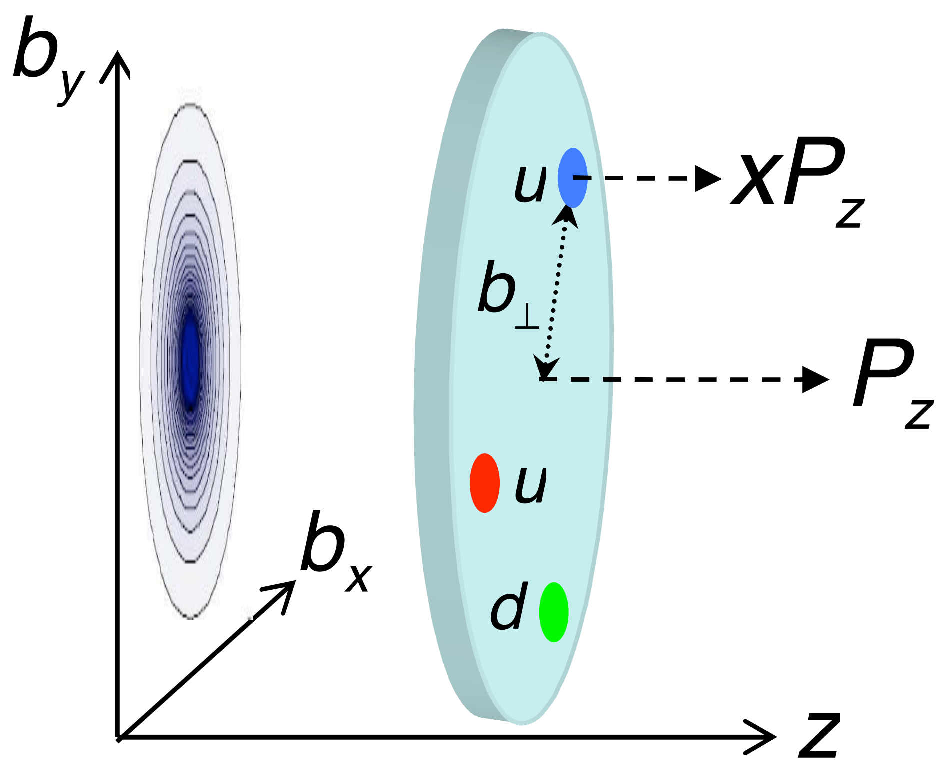


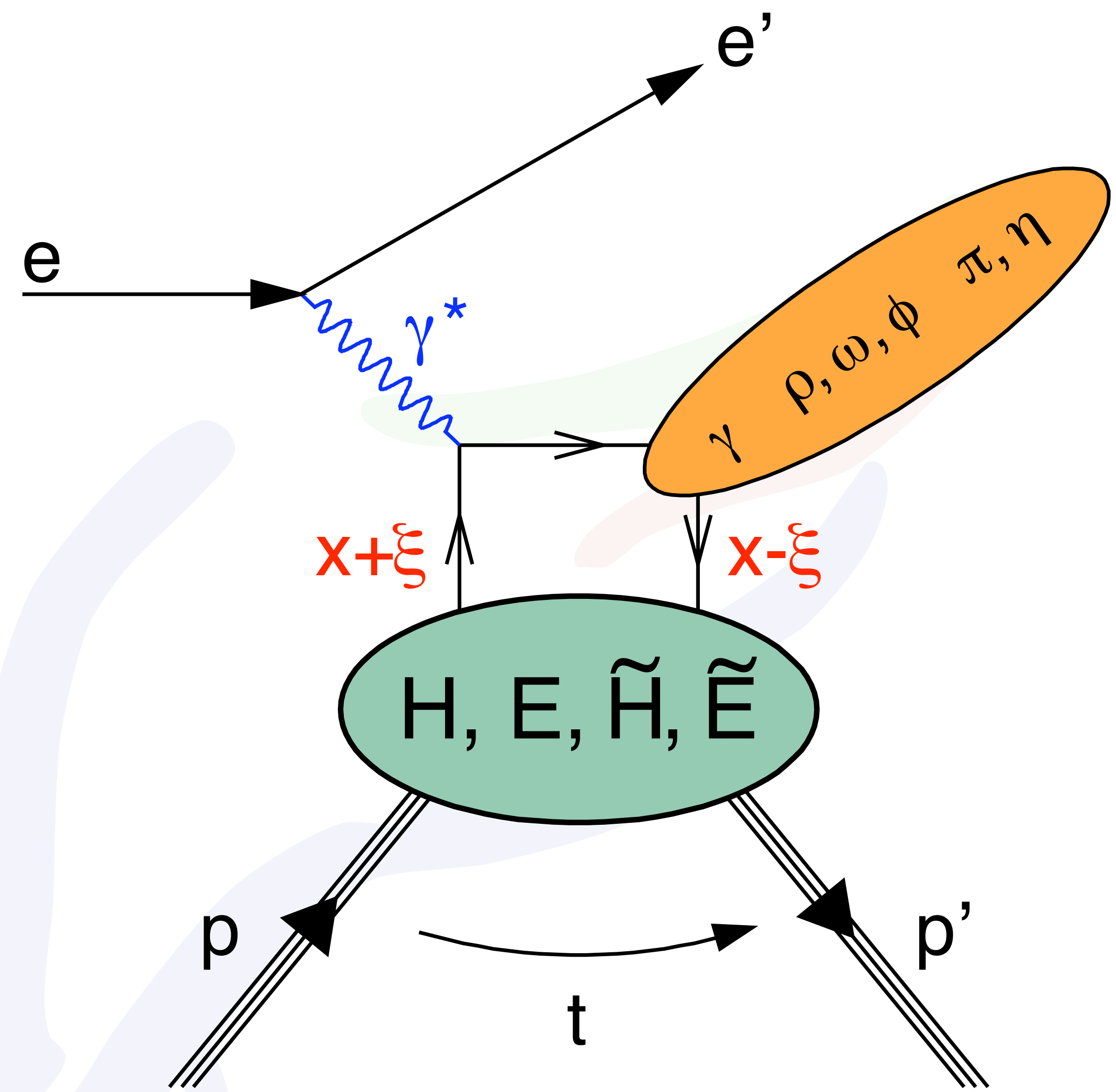


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

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

Probing GPDs in Exclusive Reactions

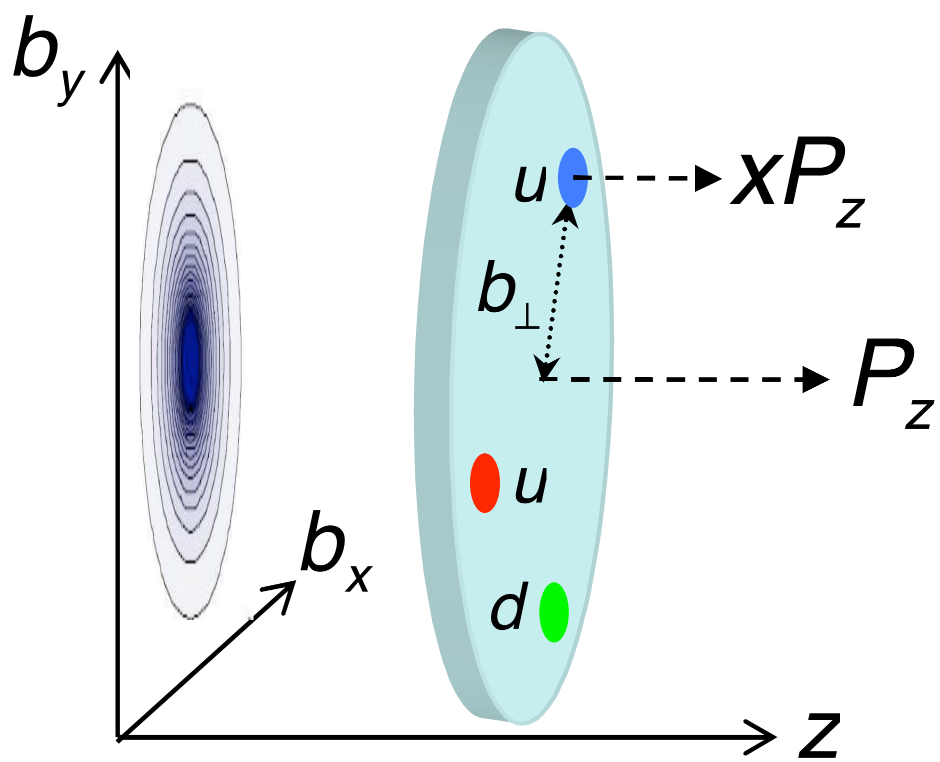


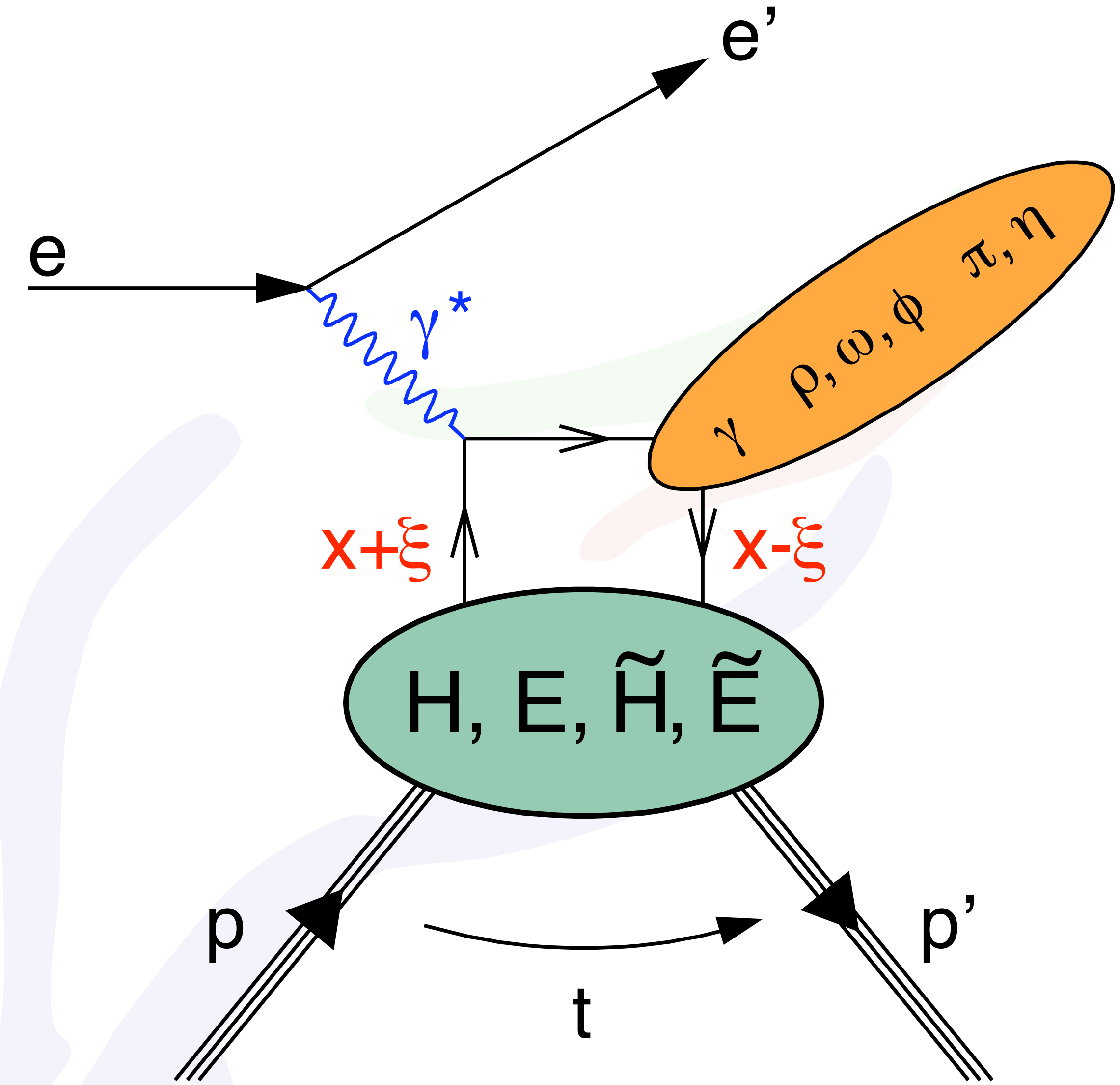


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\tilde{H}$
nucleon helicity flip	E	$\tilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





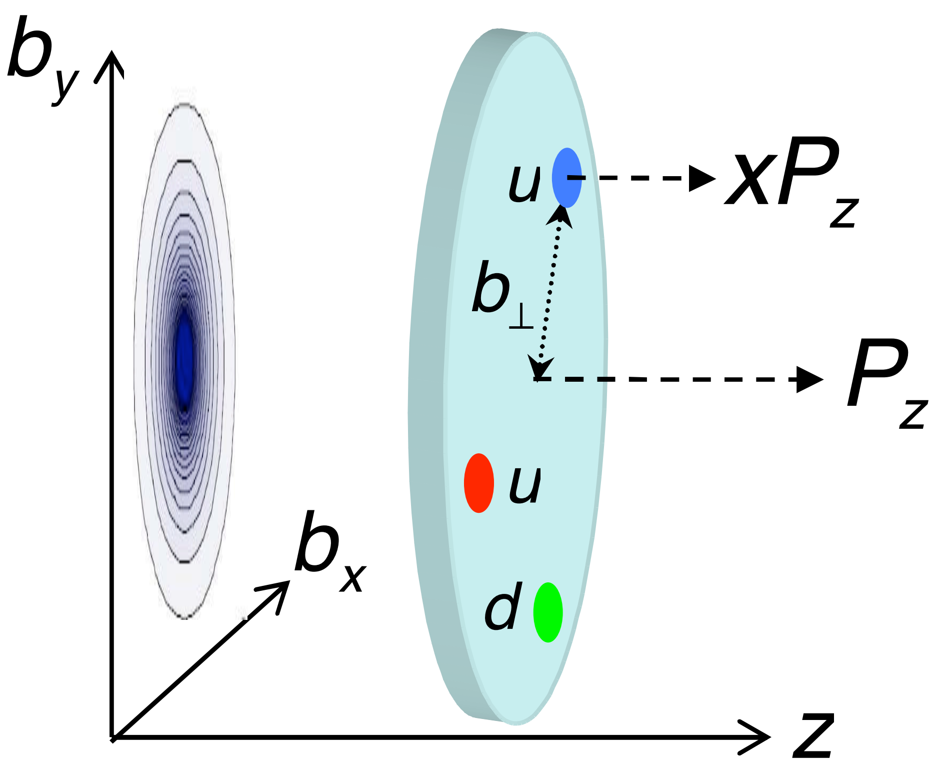
$$\int dx H^q(x, \xi, t) = F_1^q(t)$$

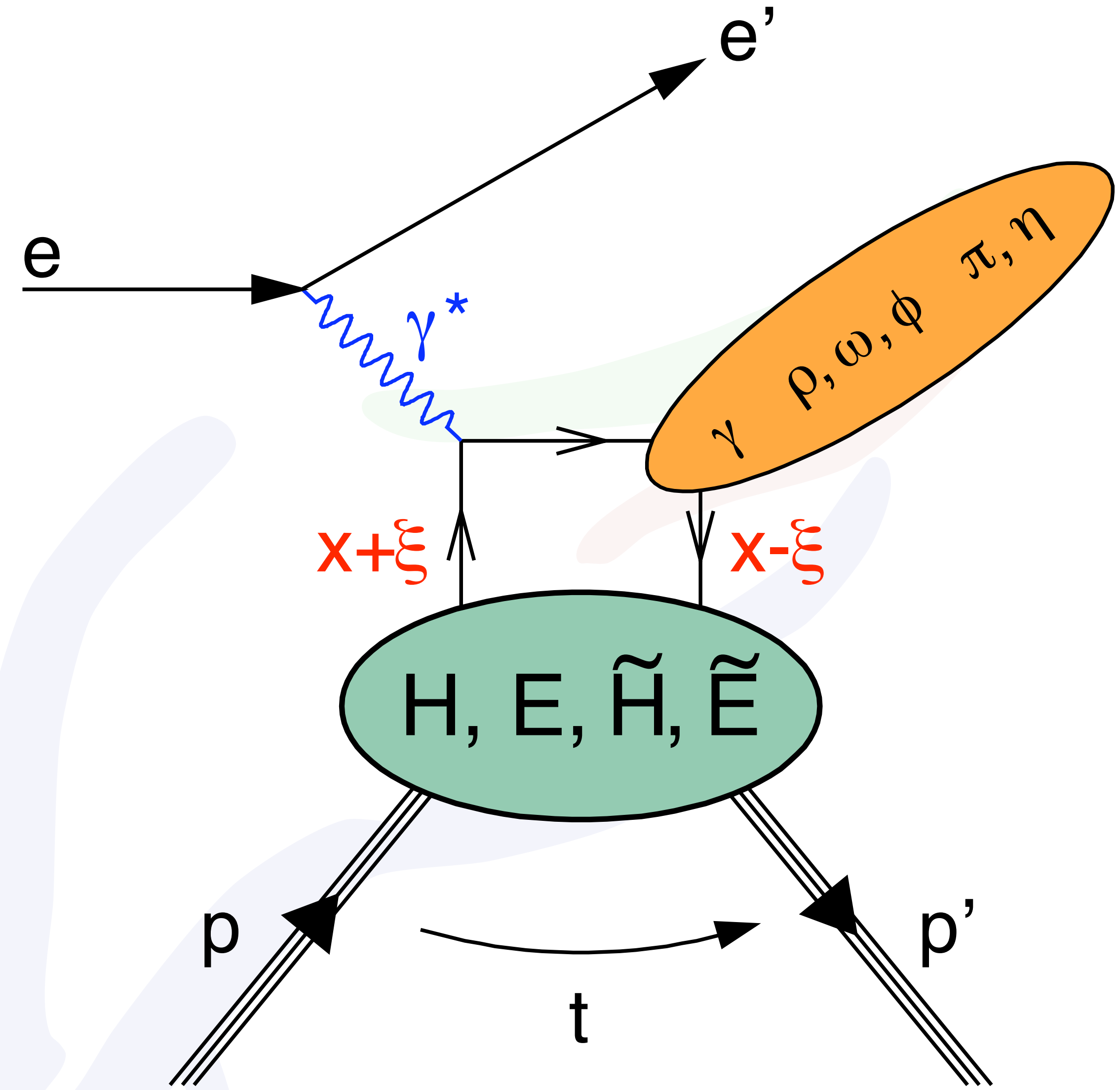
$$\int dx E^q(x, \xi, t) = F_2^q(t)$$

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

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





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

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

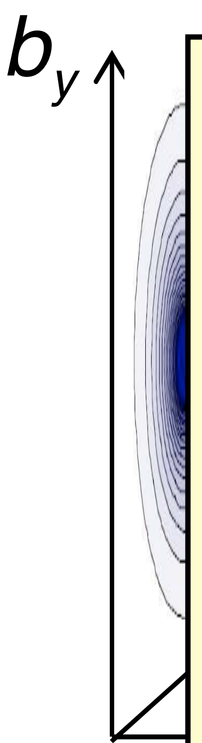
$$H^q(x,\xi=0,t=0) = q(x)$$

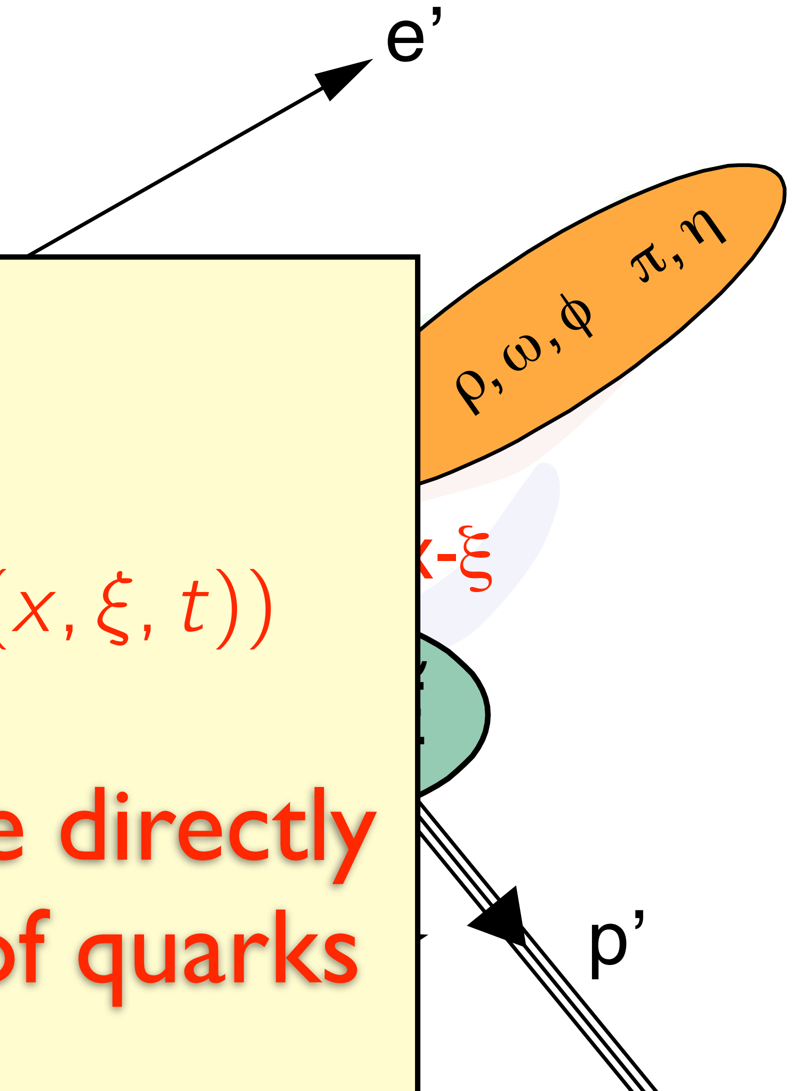
$$\widetilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

	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)

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

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

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

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

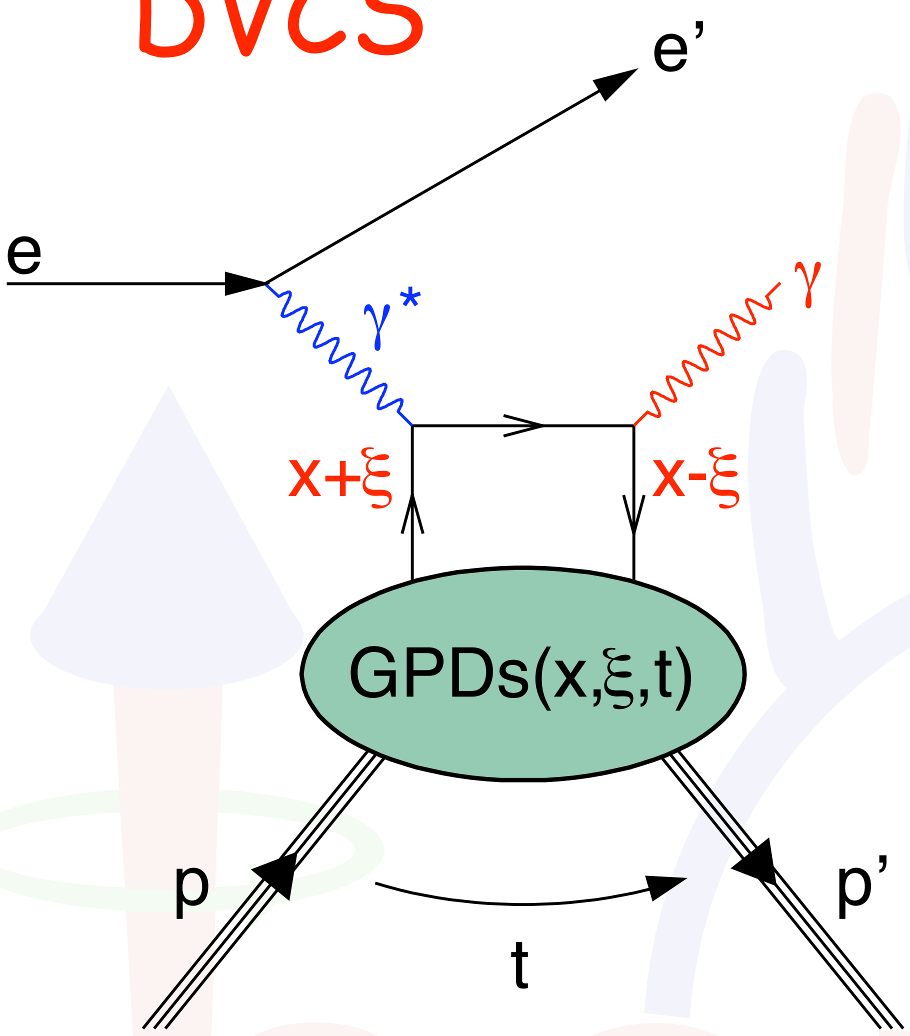
$$\widetilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

	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)

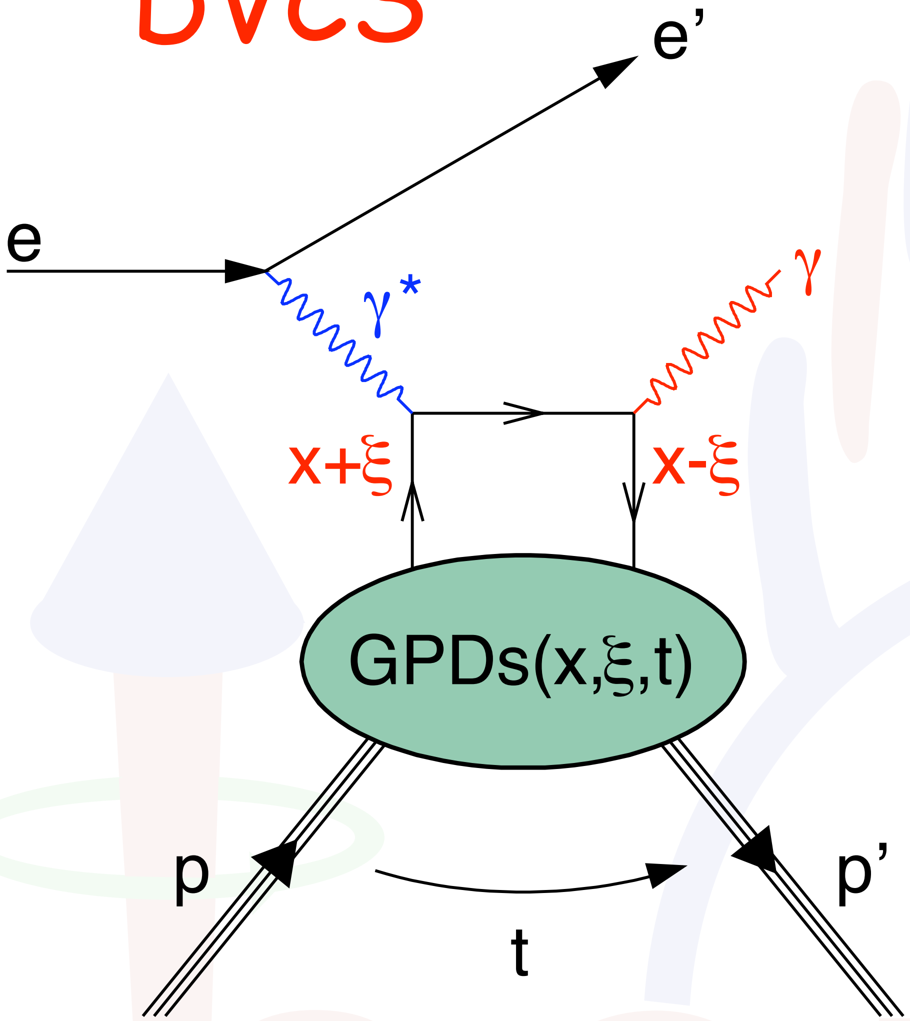
Real-photon production

DVCS

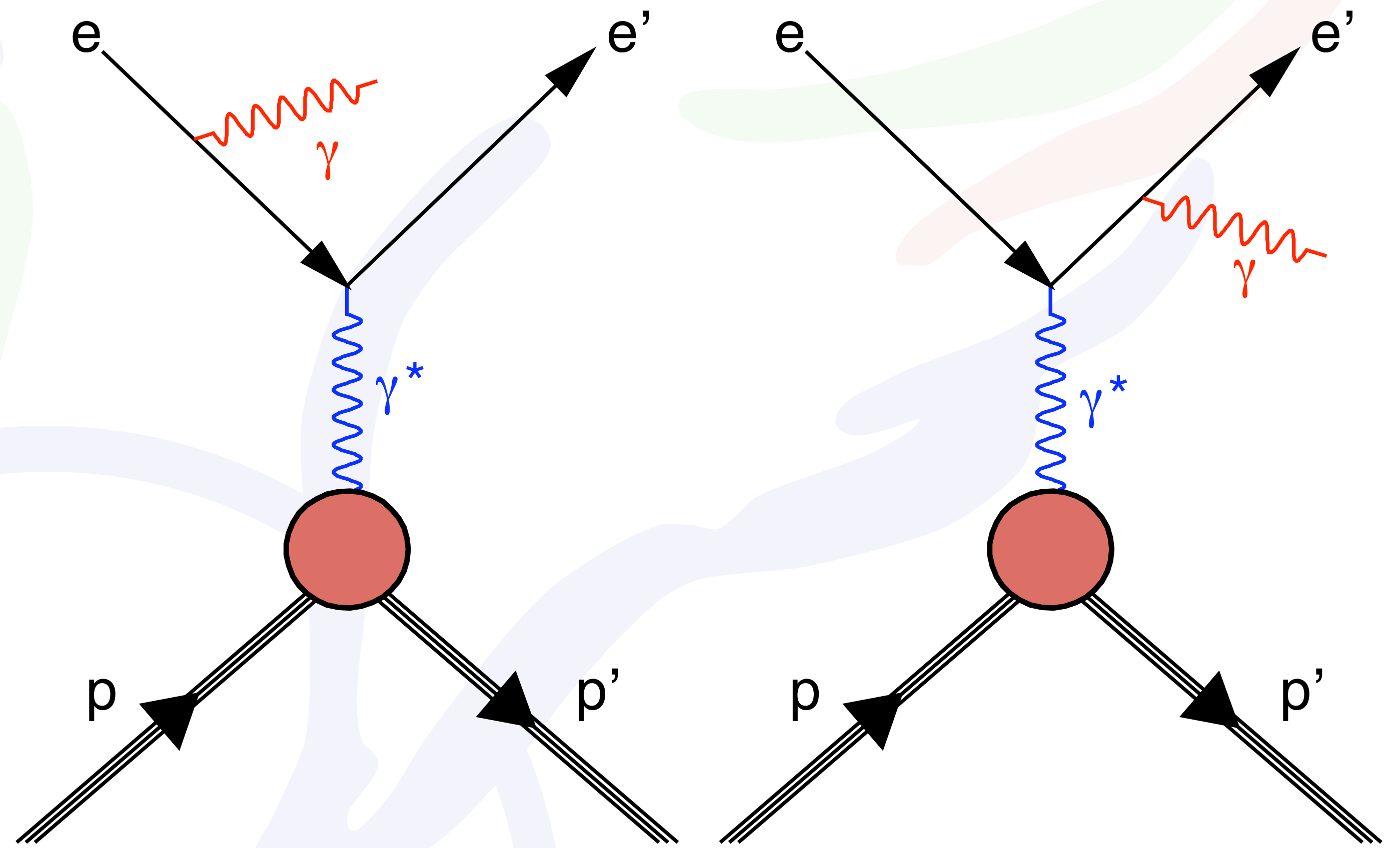


Real-photon production

DVCS

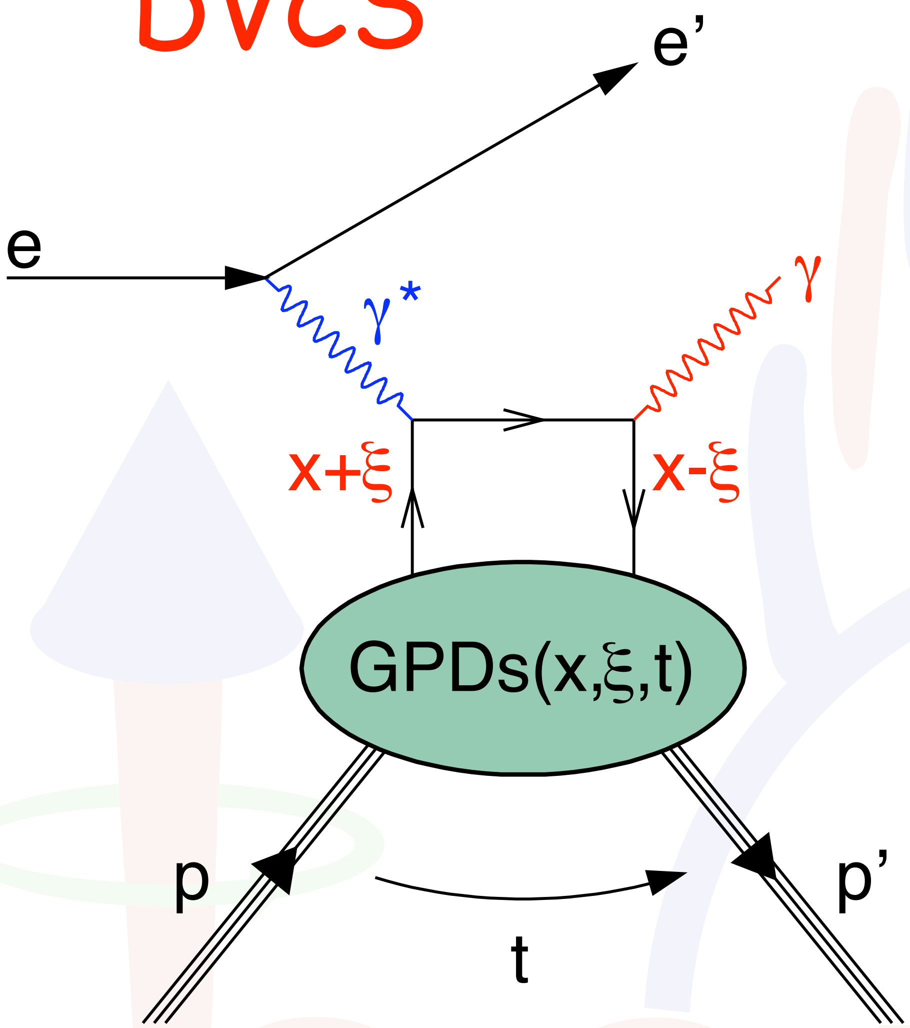


Bethe-Heitler

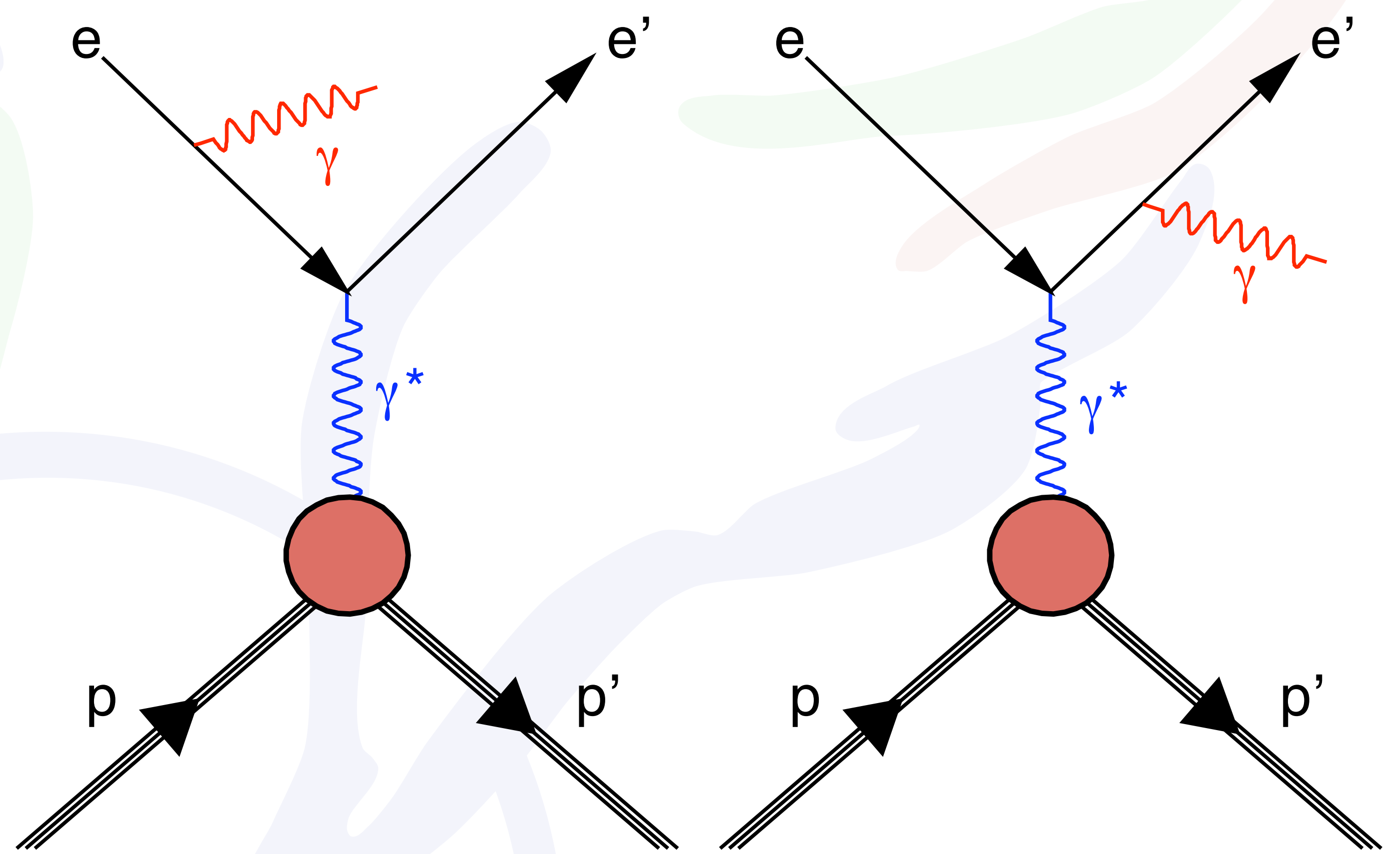


Real-photon production

DVCS

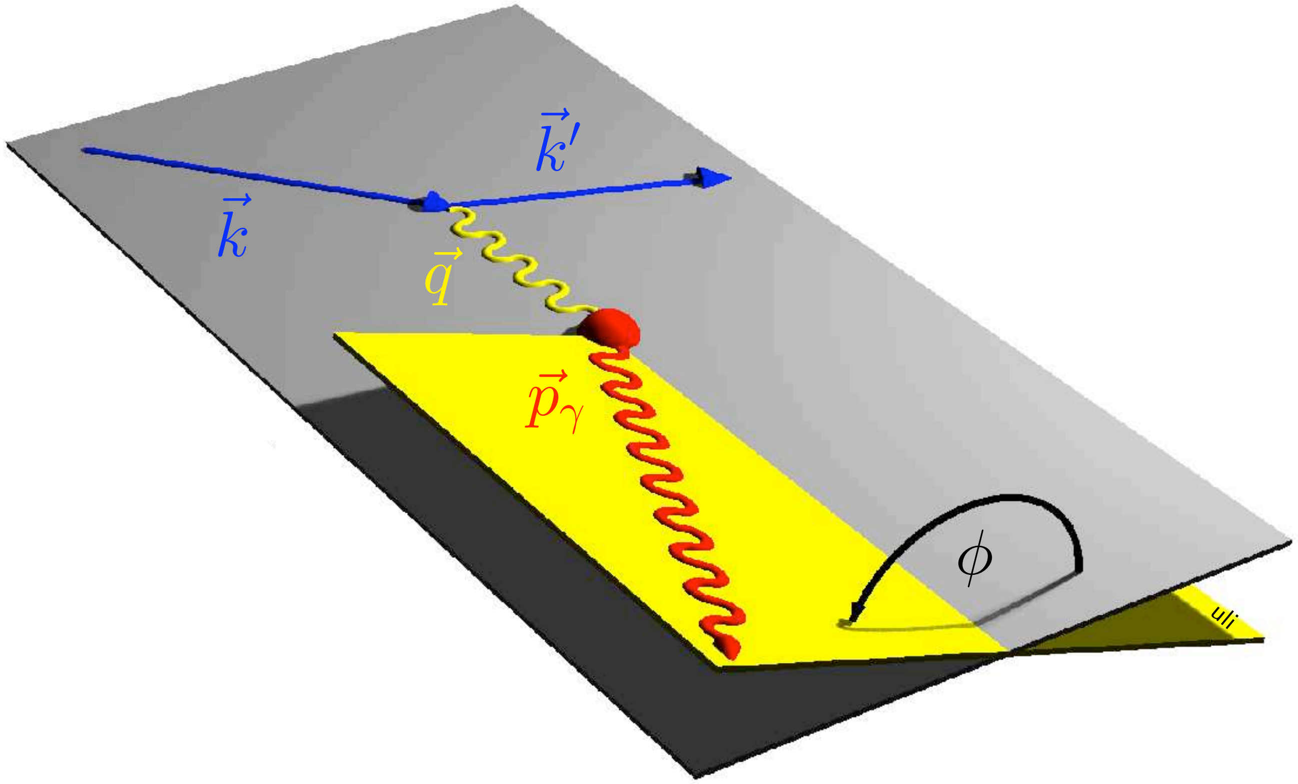


Bethe-Heitler



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

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

- beam polarization P_B
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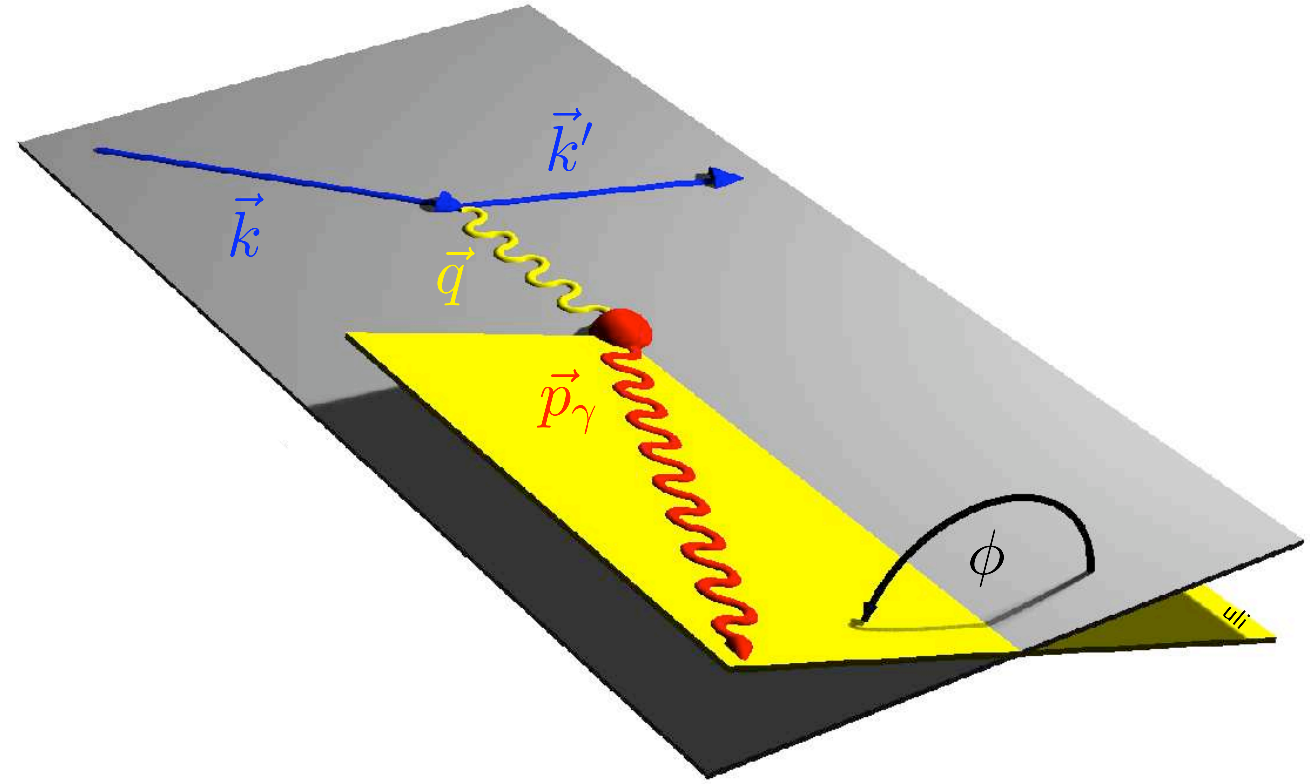
- here: unpolarized target



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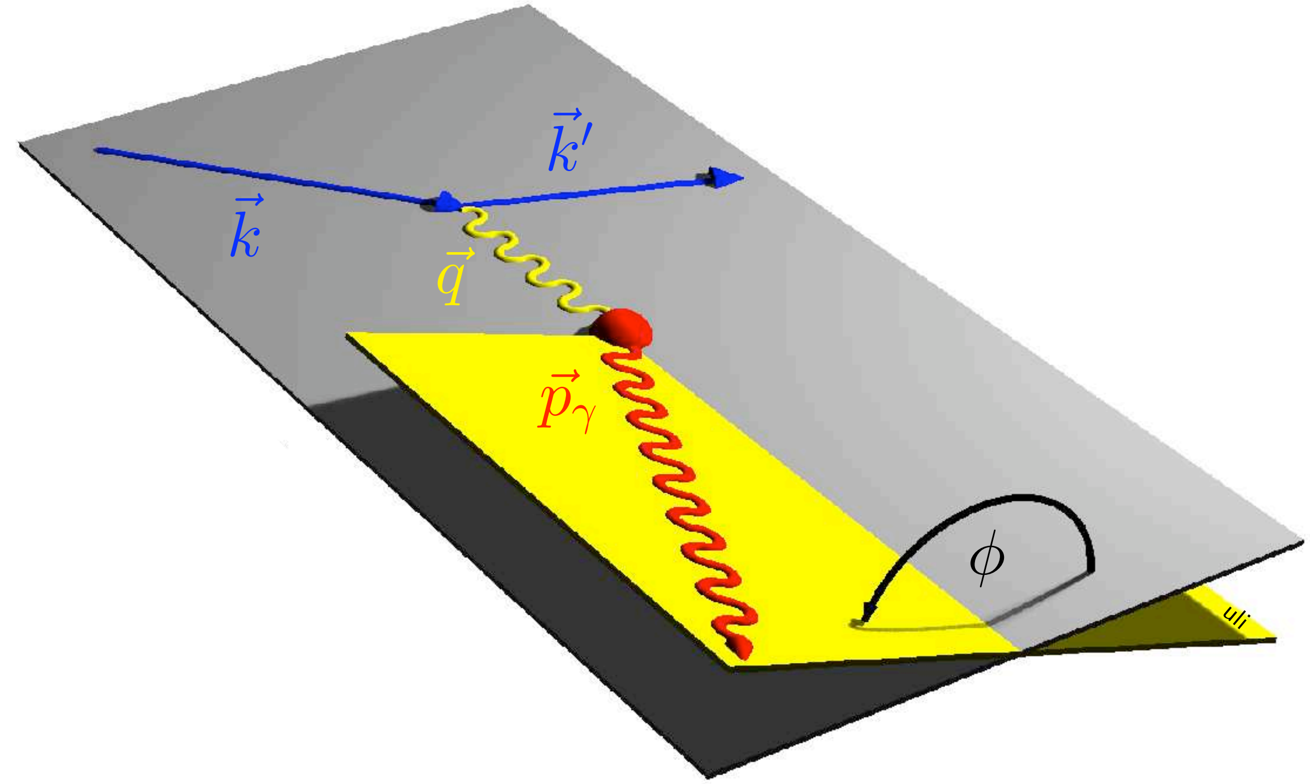
$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH



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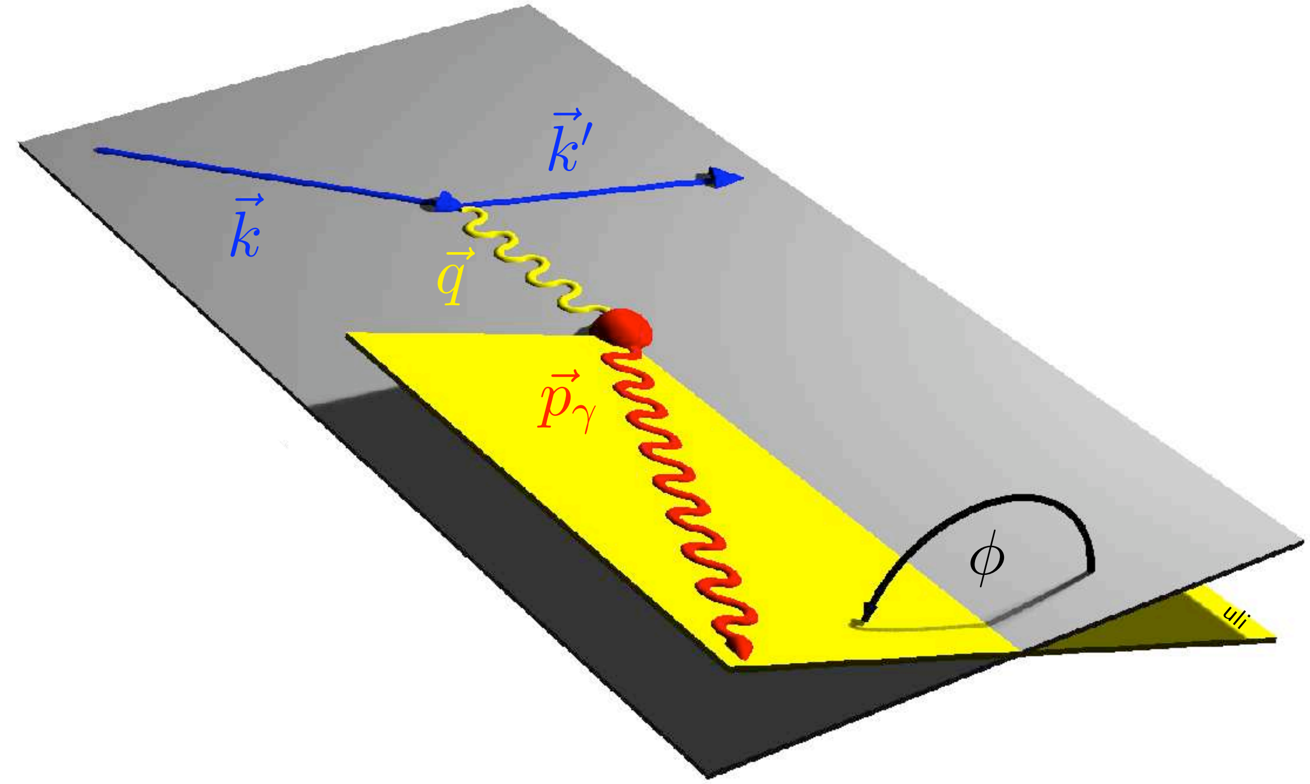
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH



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

Fourier expansion for ϕ:

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

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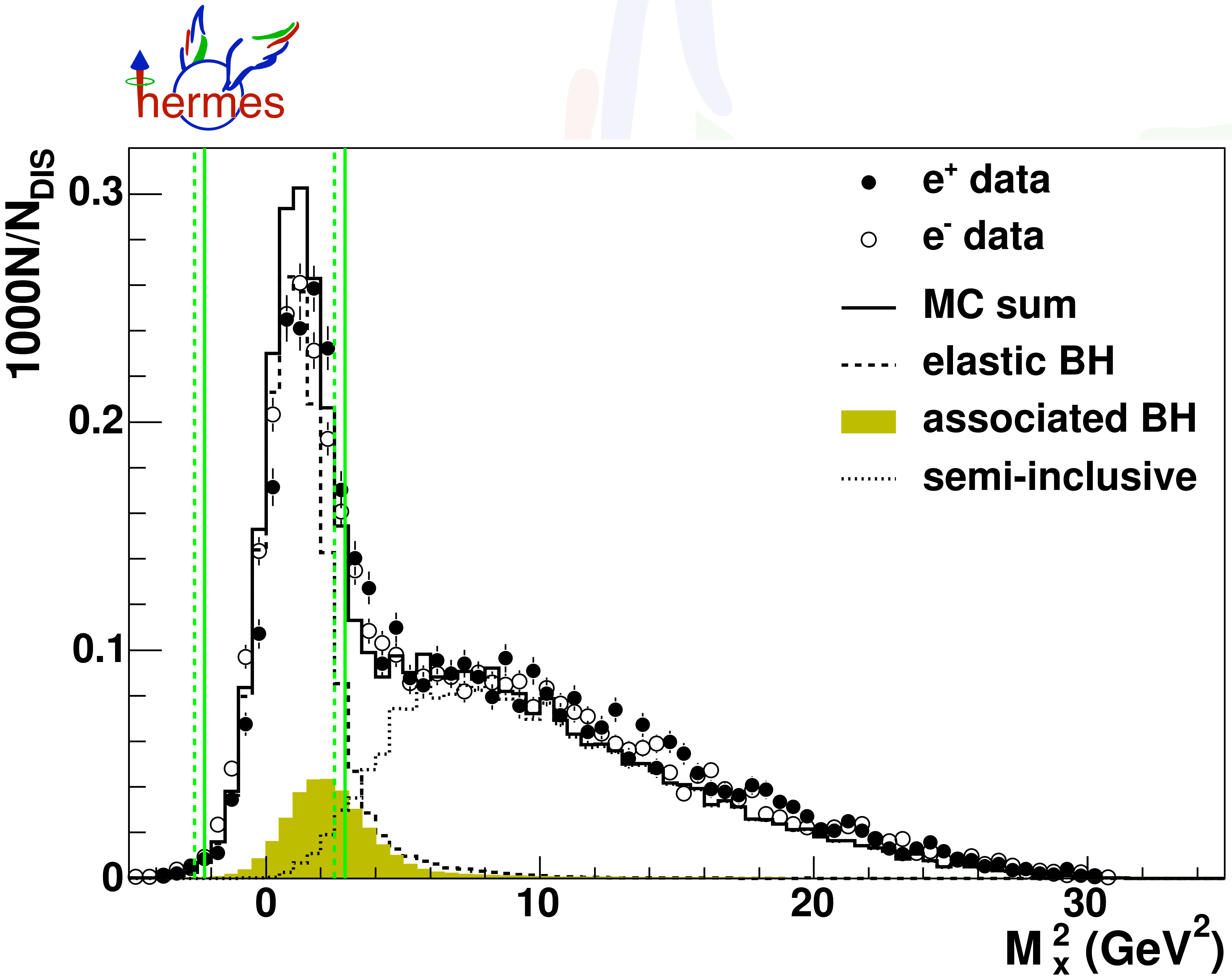
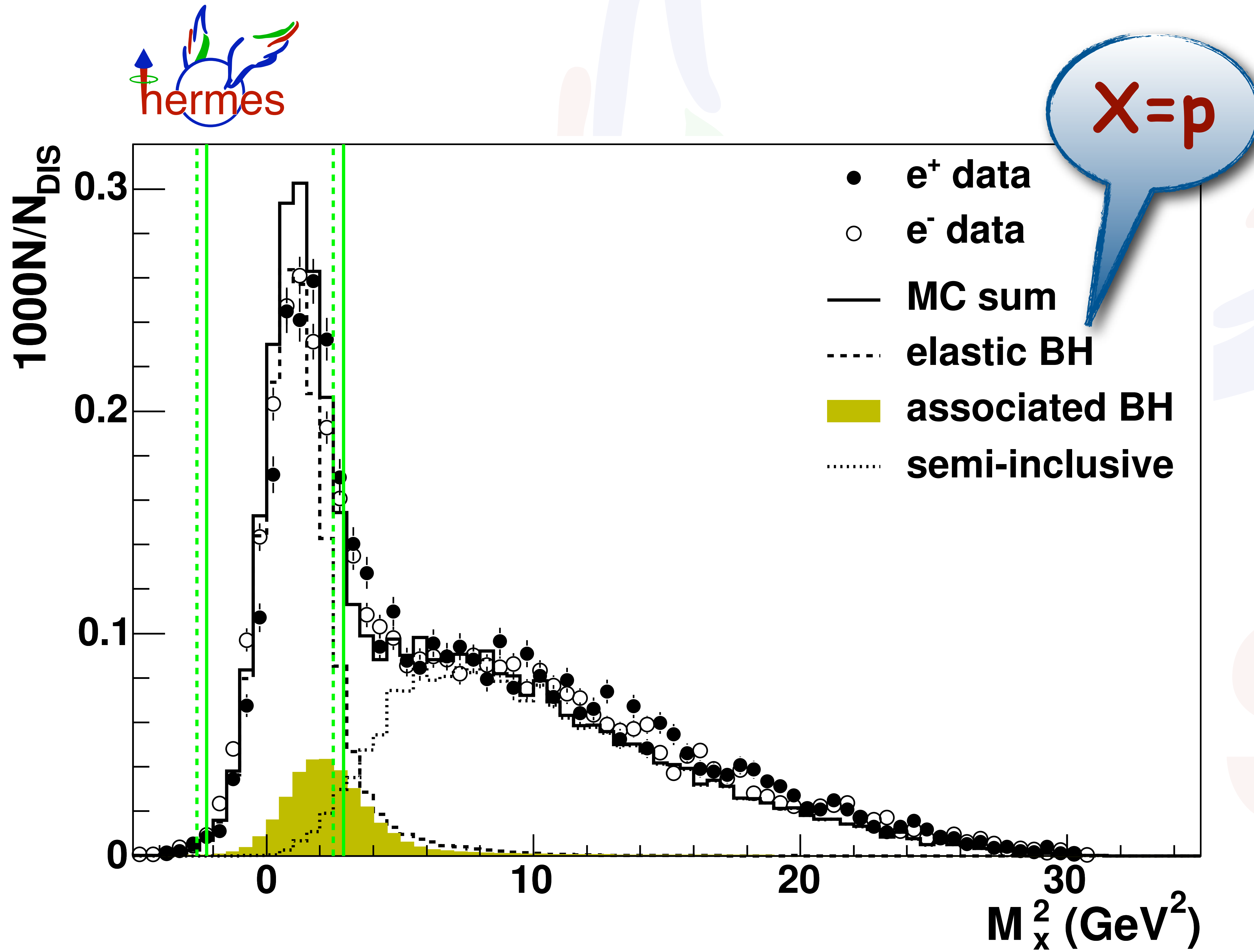
bilinear (“DVCS”) or linear in GPDs

Exclusivity: missing-mass technique



Exclusivity: missing-mass technique



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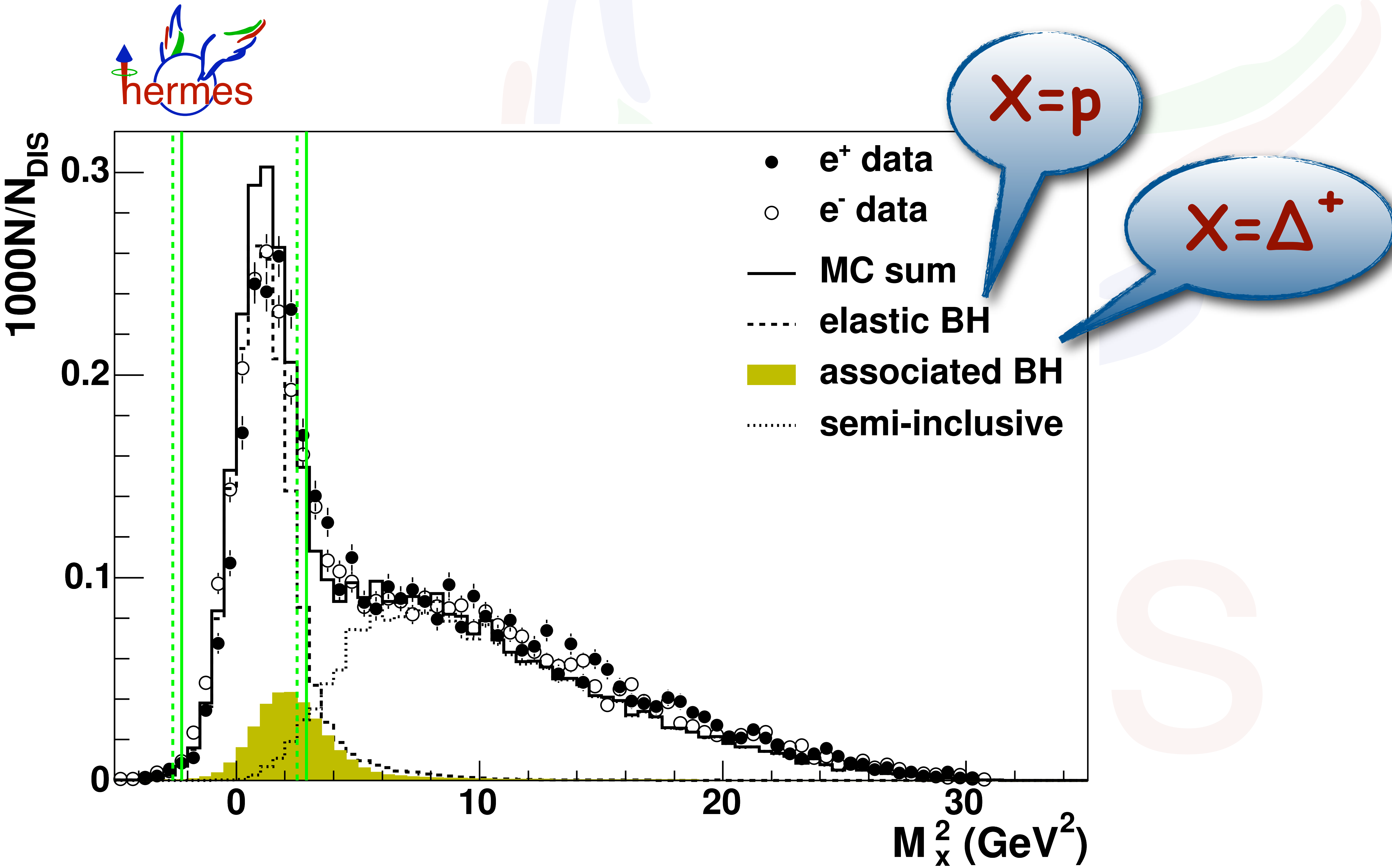

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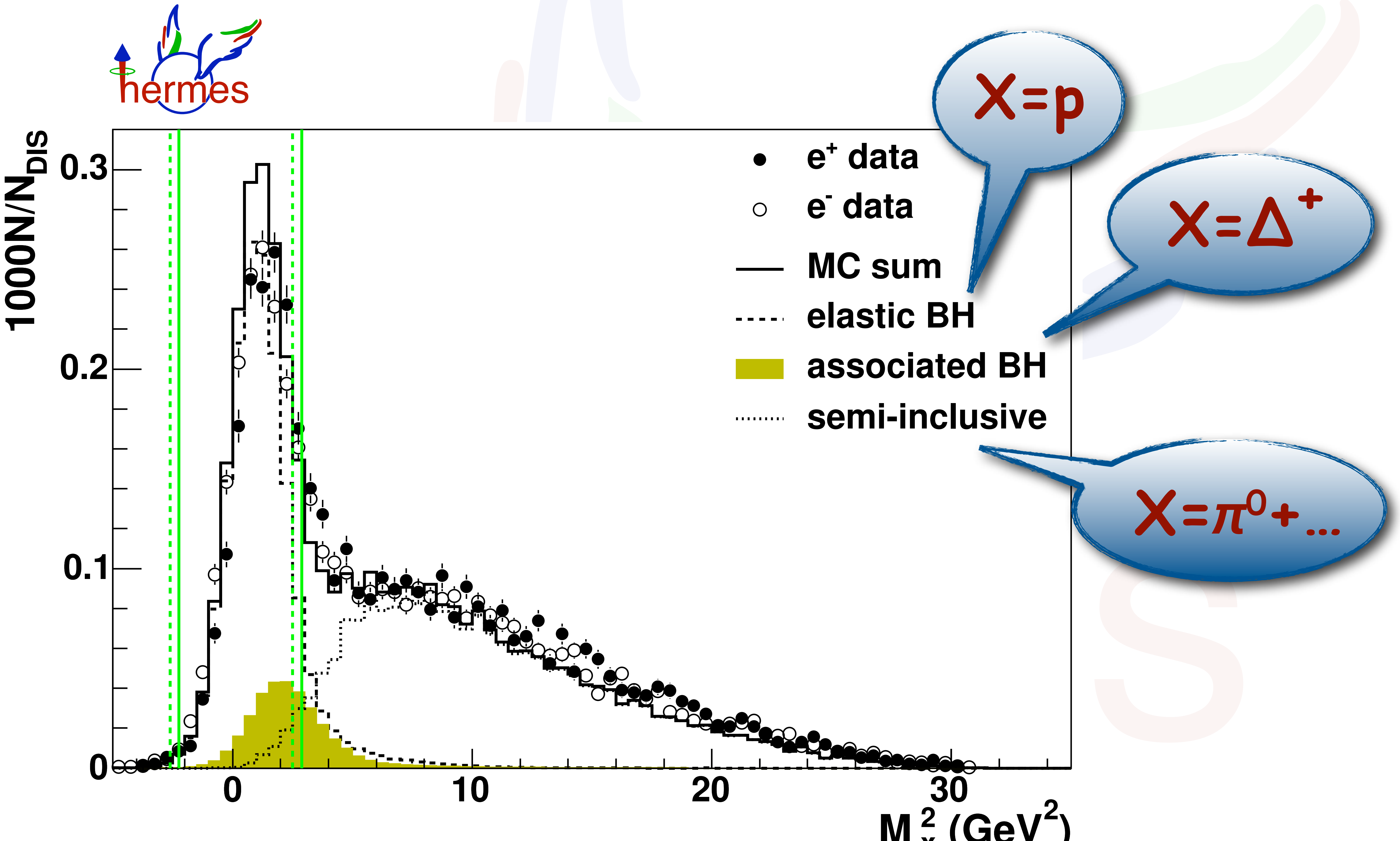
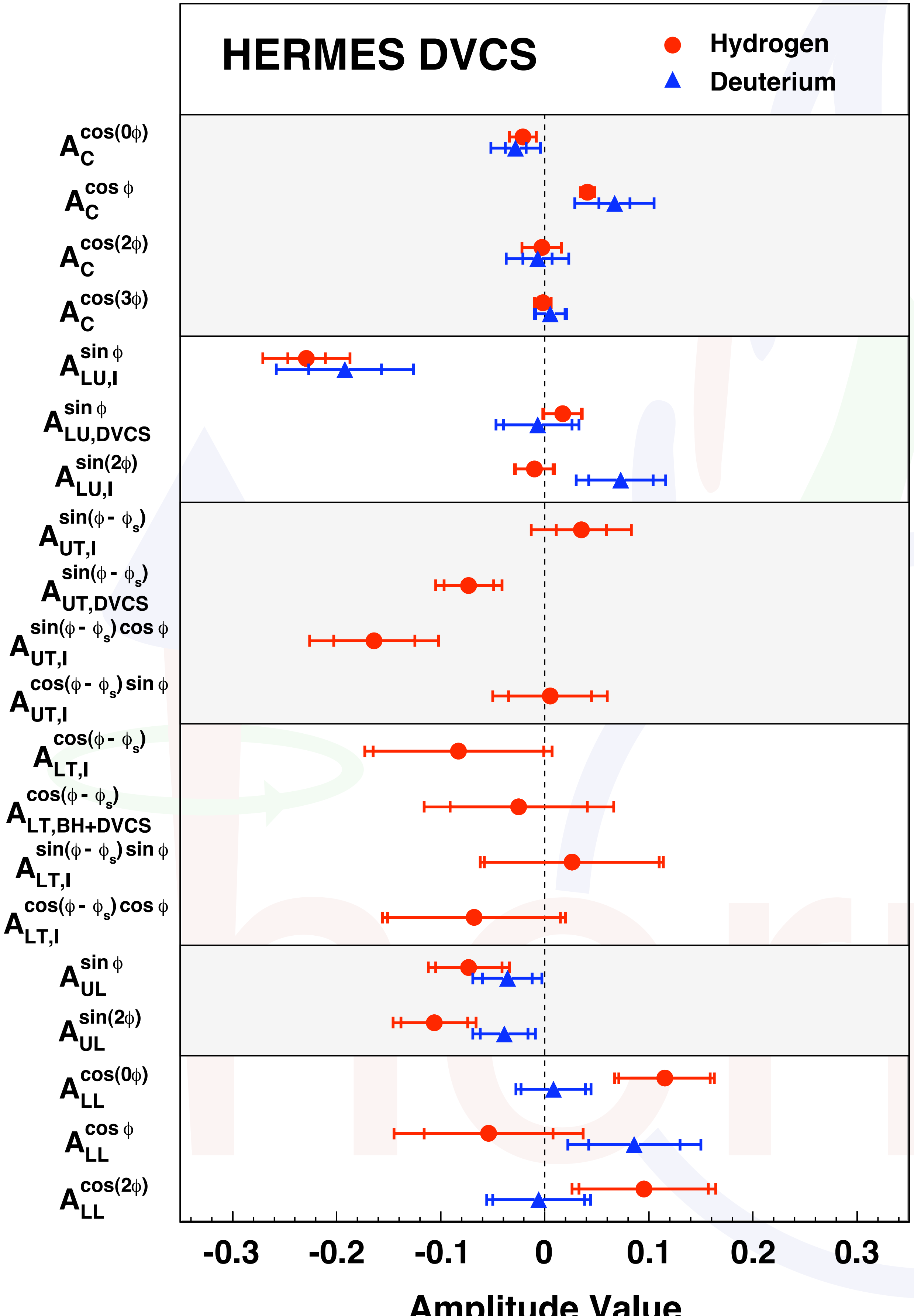


A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

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

Beam-helicity asymmetry:

GPD H

Transverse target spin asymmetries:

GPD E from proton target

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

Longitudinal target spin asymmetry:

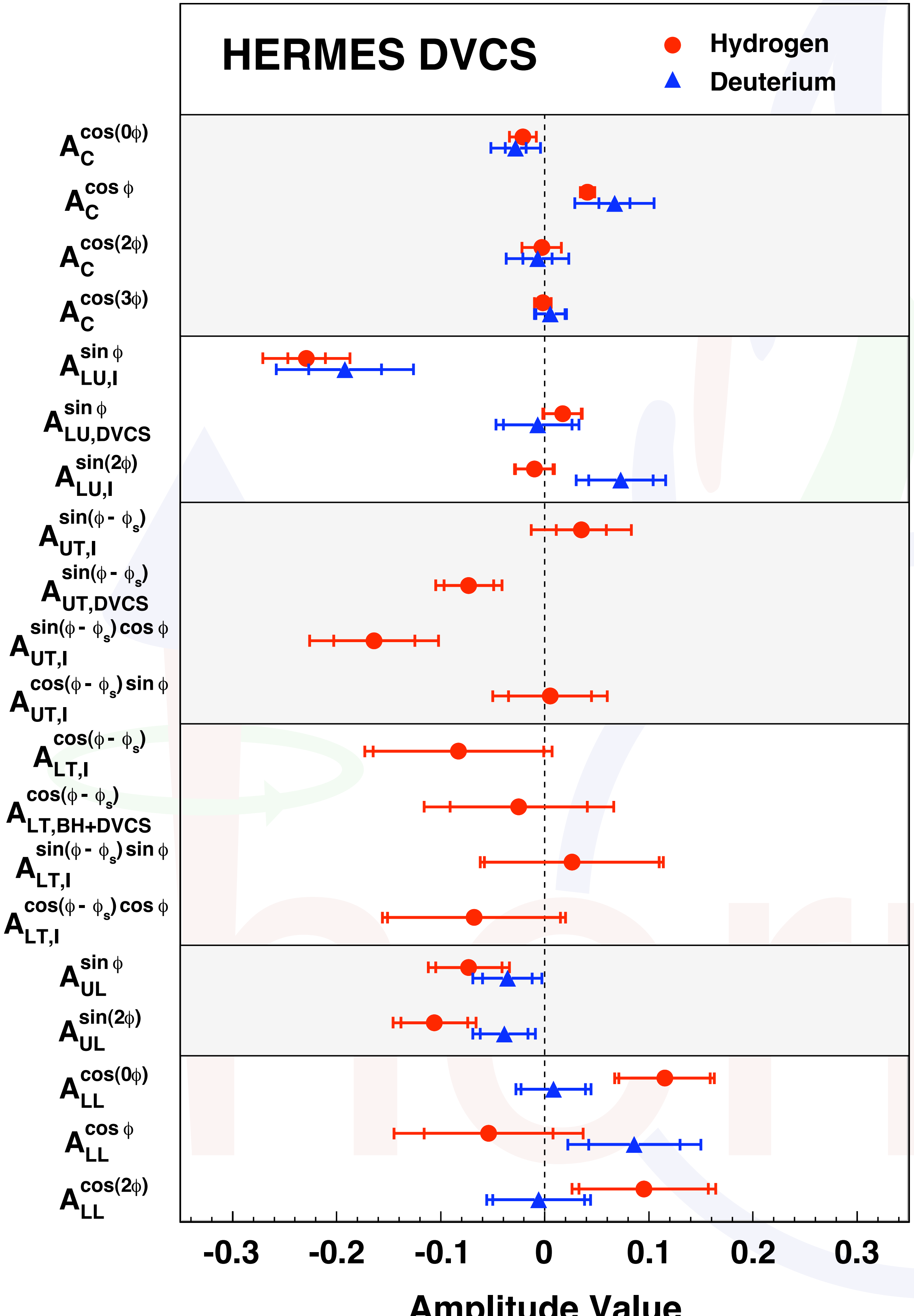
GPD $\tilde{H}$

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

Double-spin asymmetry:

GPD $\tilde{H}$

A wealth of azimuthal amplitudes



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NPB 842 (2011) 265

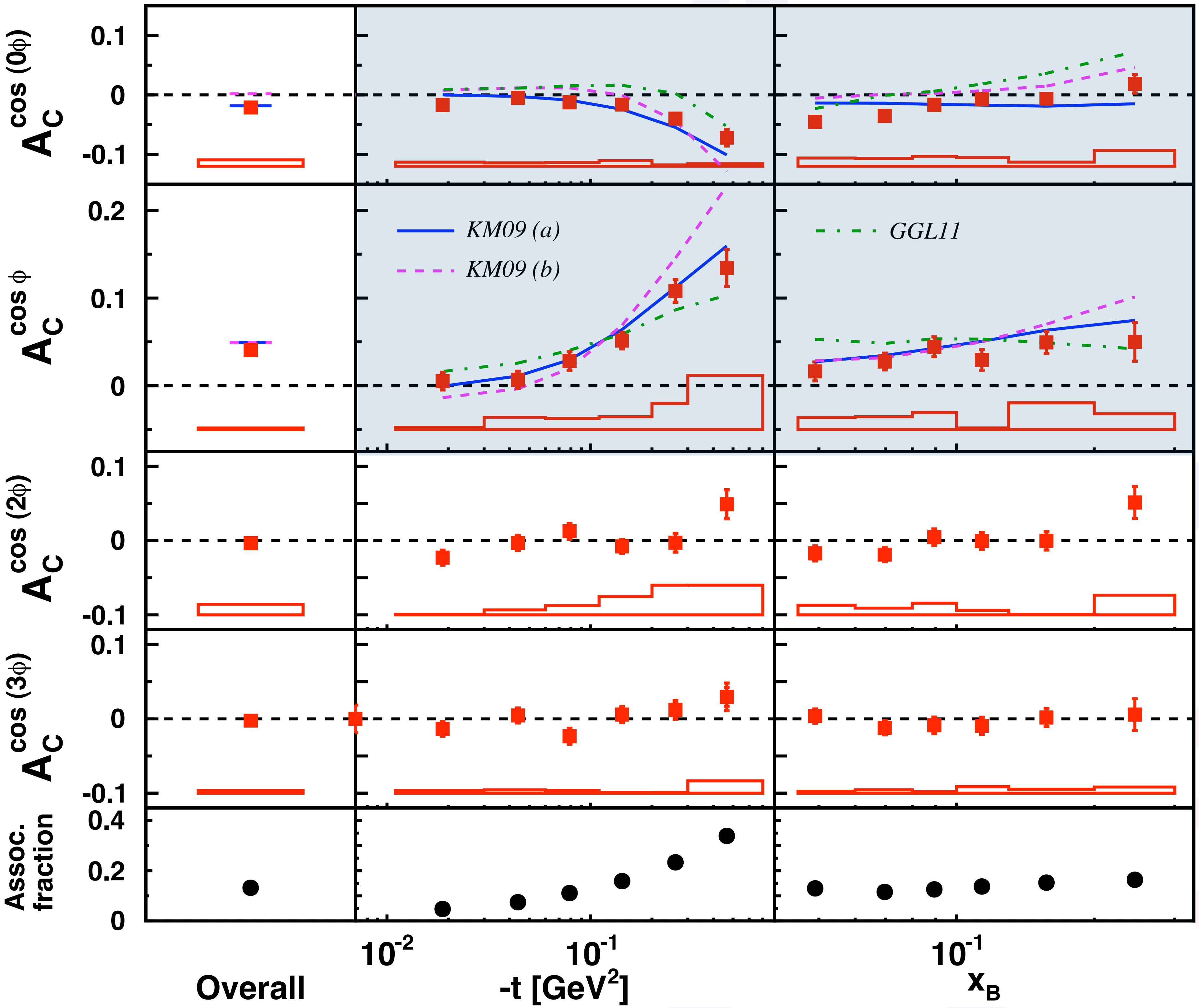
Double-spin asymmetry:

GPD $\tilde{H}$

complete data set!

Beam-charge asymmetry

[Airapetian et al., accept. by JHEP; arXiv:1203.6287]



constant term:

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

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

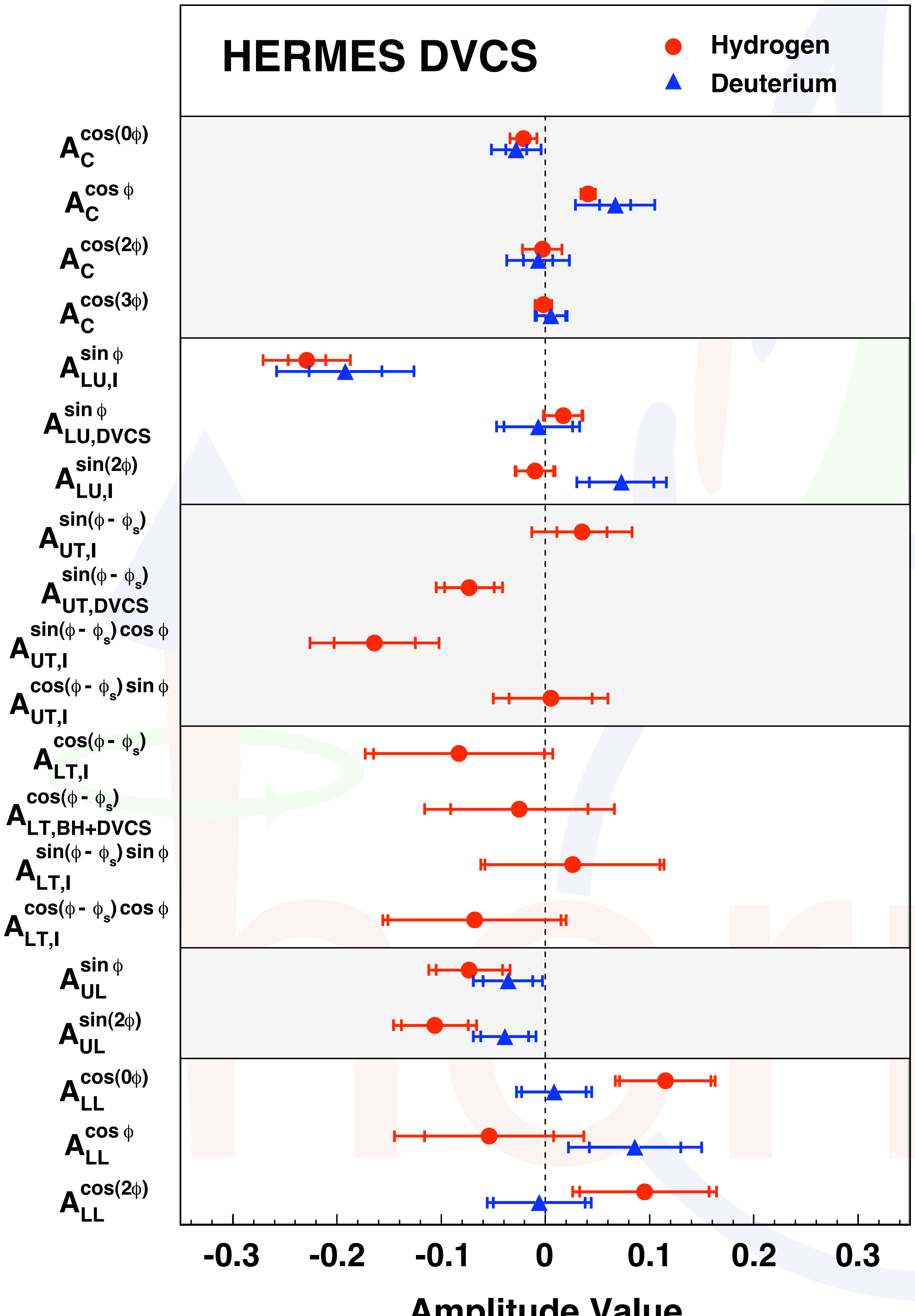
[higher twist]

[gluon leading twist]

Resonant fraction:

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

A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103

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GPD $\tilde{H}$

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complete data set!

Beam-spin asymmetry

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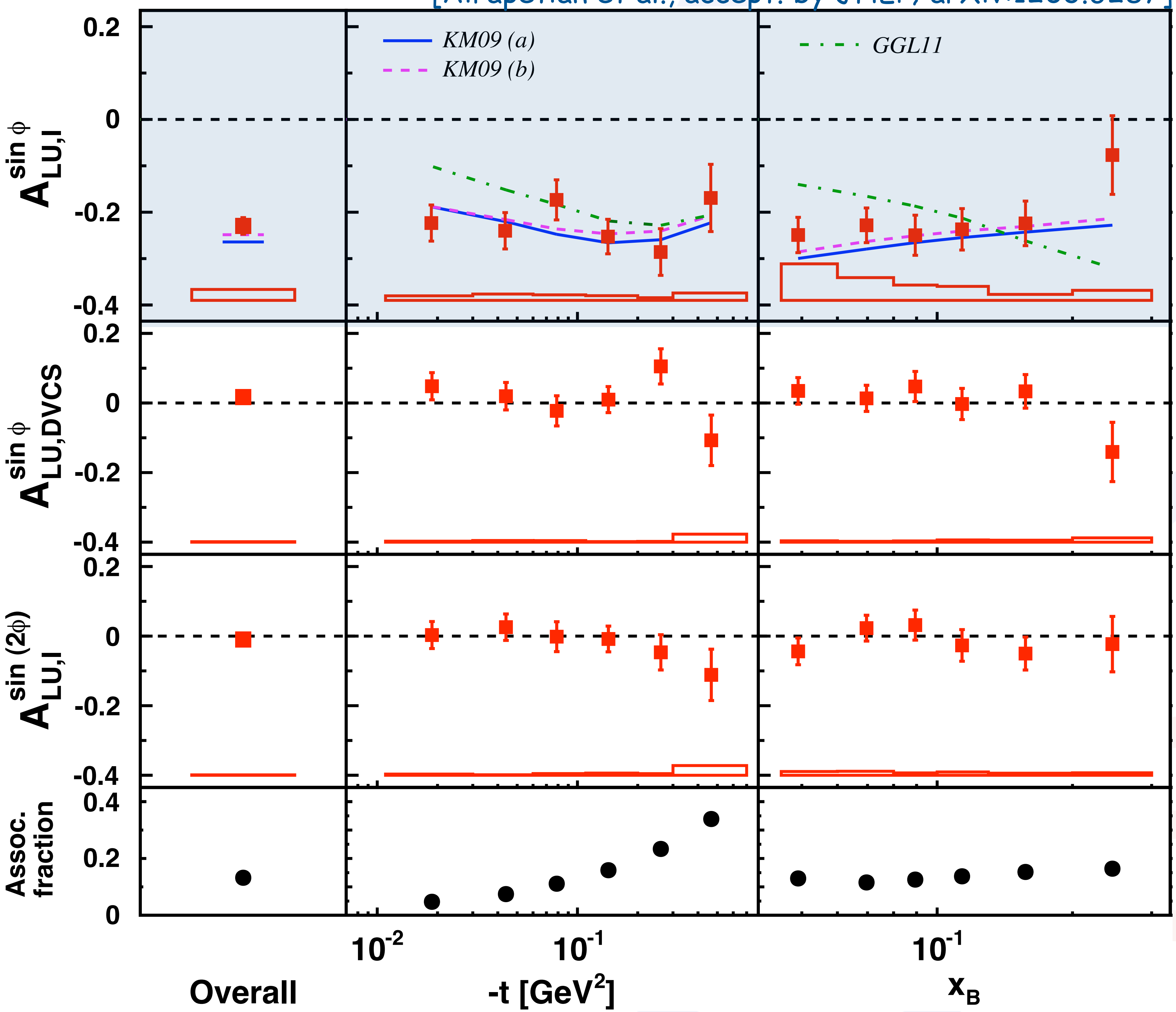


$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

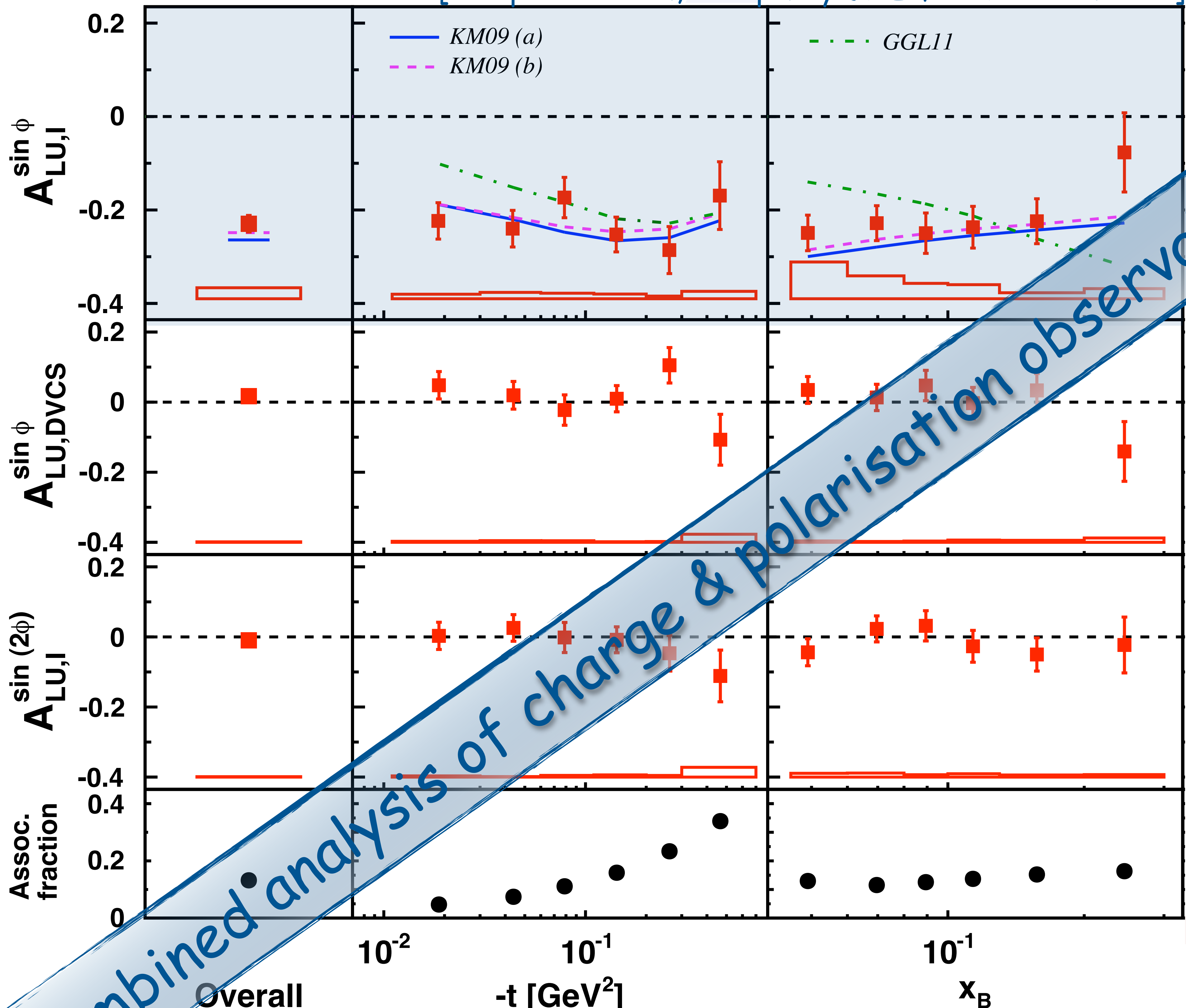
Resonant fraction:

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

complete data set!

Beam-spin asymmetry

[Airapetian et al., accept. by JHEP; arXiv:1203.6287]



combined analysis of charge & polarisation observables unique to HERA!

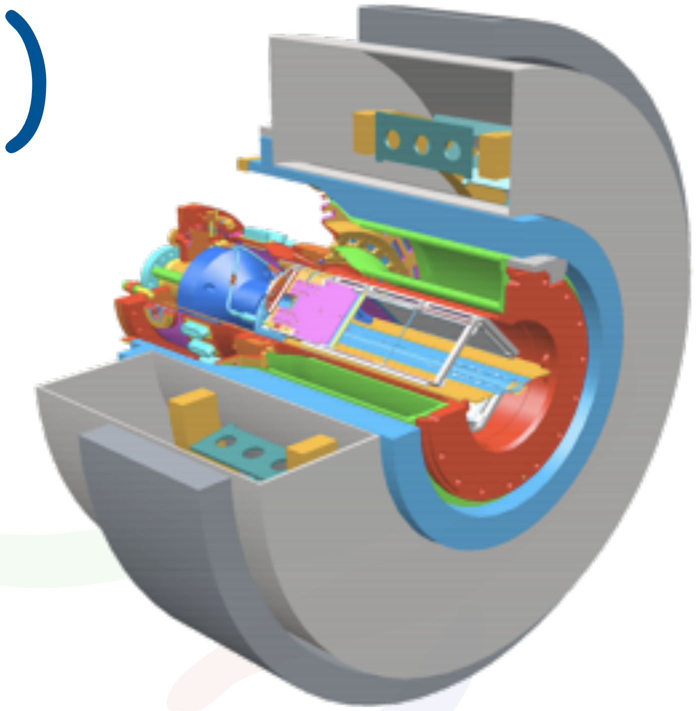
$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

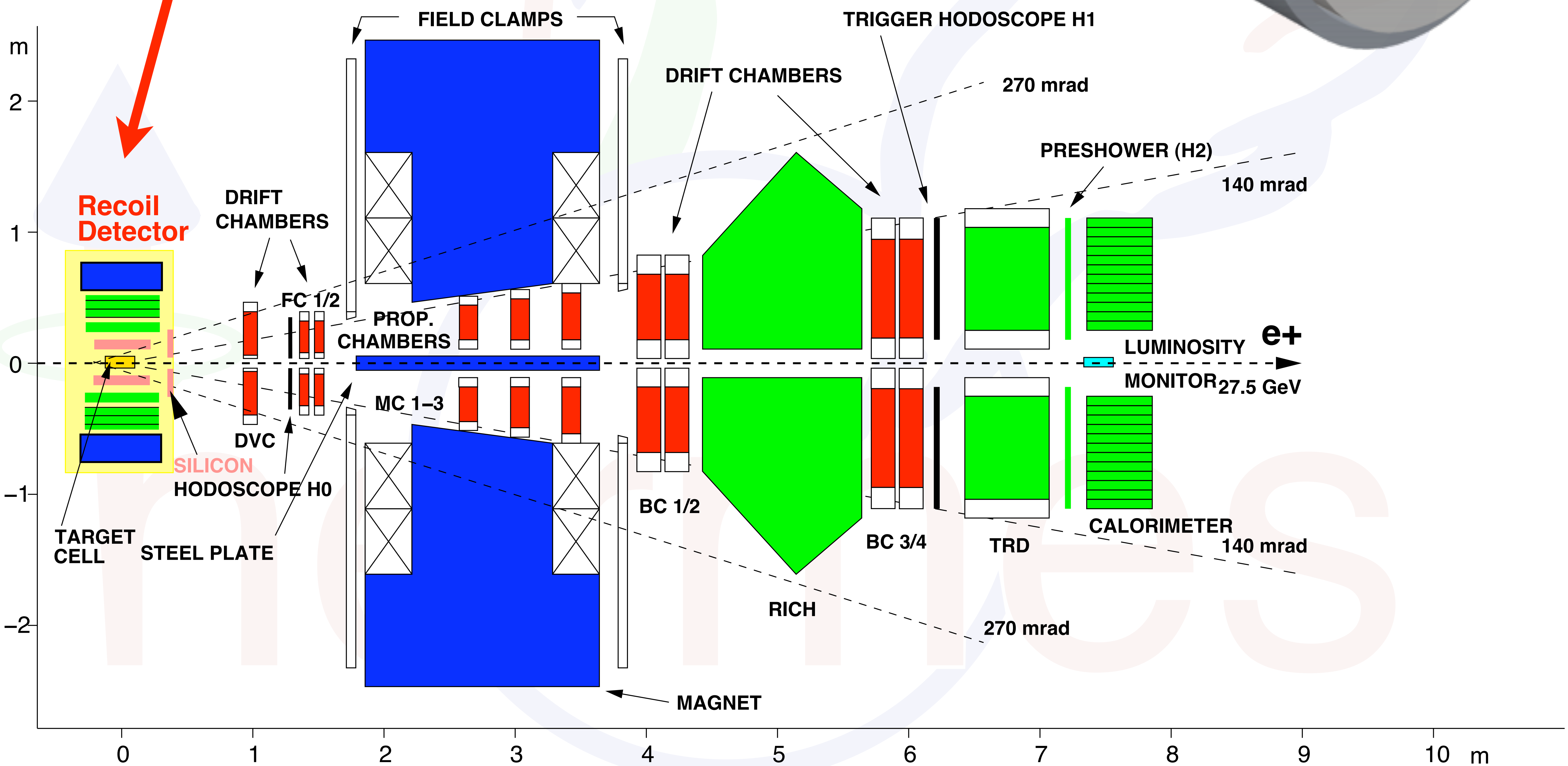
Resonant fraction:

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

HERMES detector (2006/07)

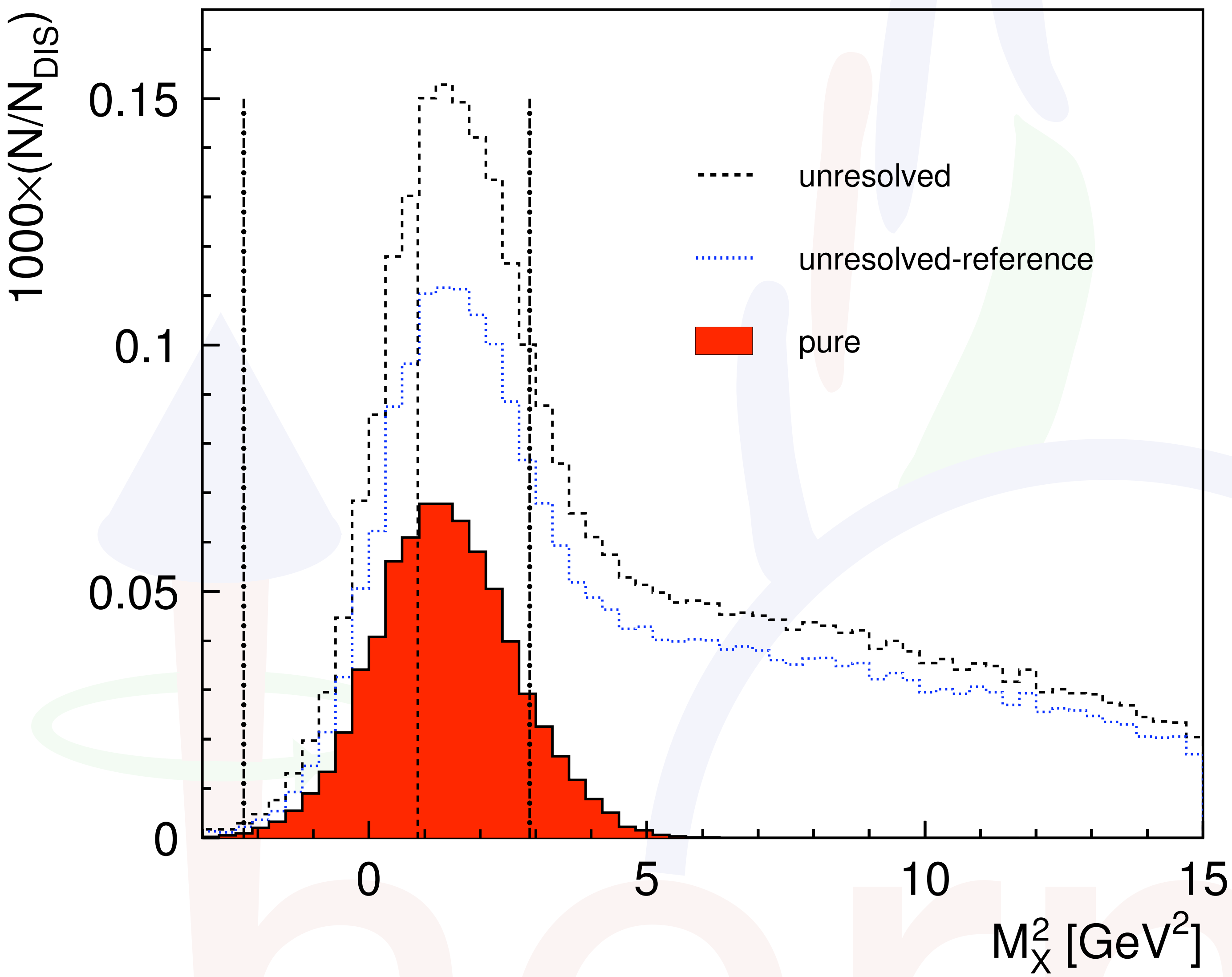


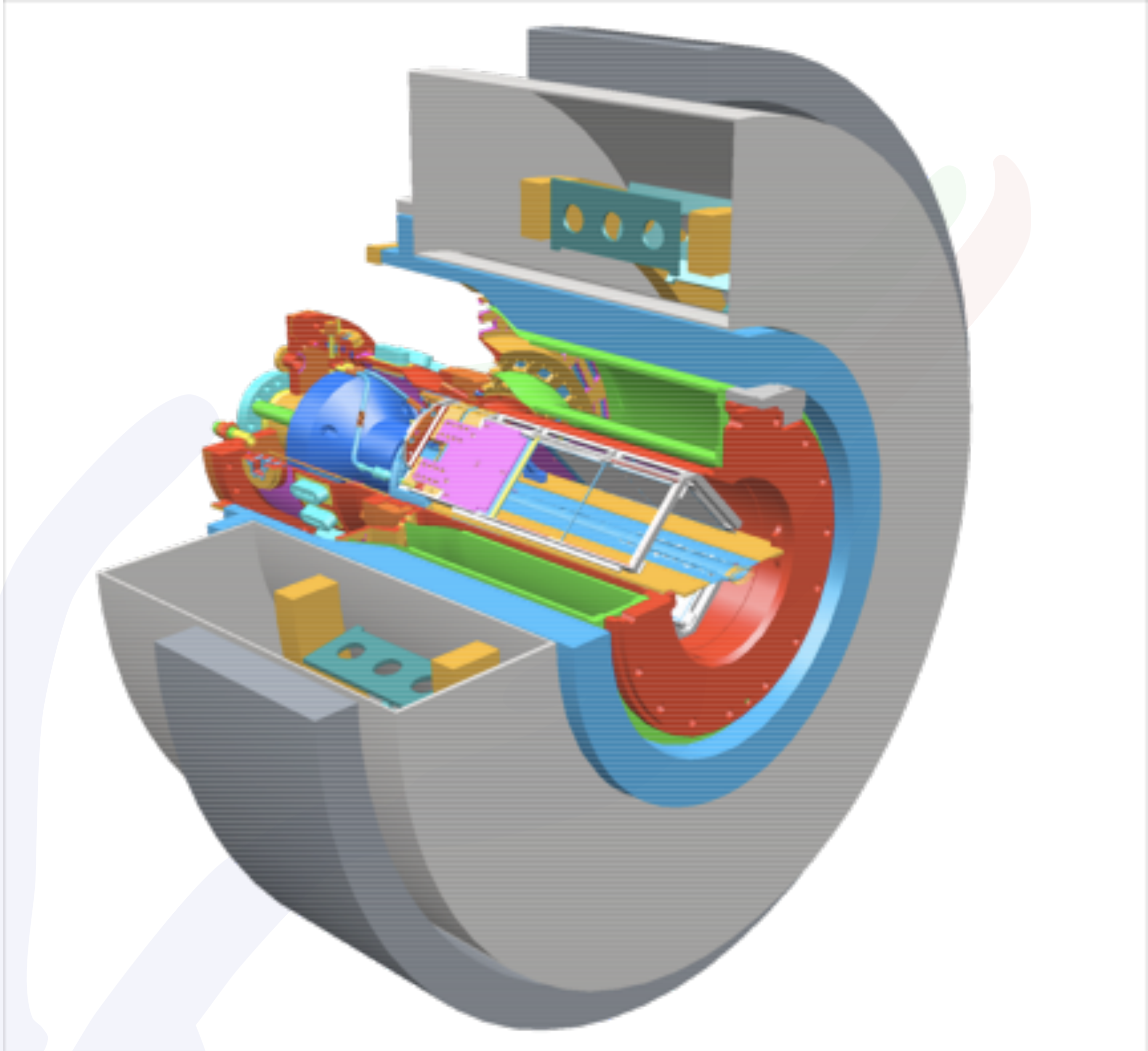
detection of
recoiling proton



HERMES detector (2006/07)

kinematic fitting

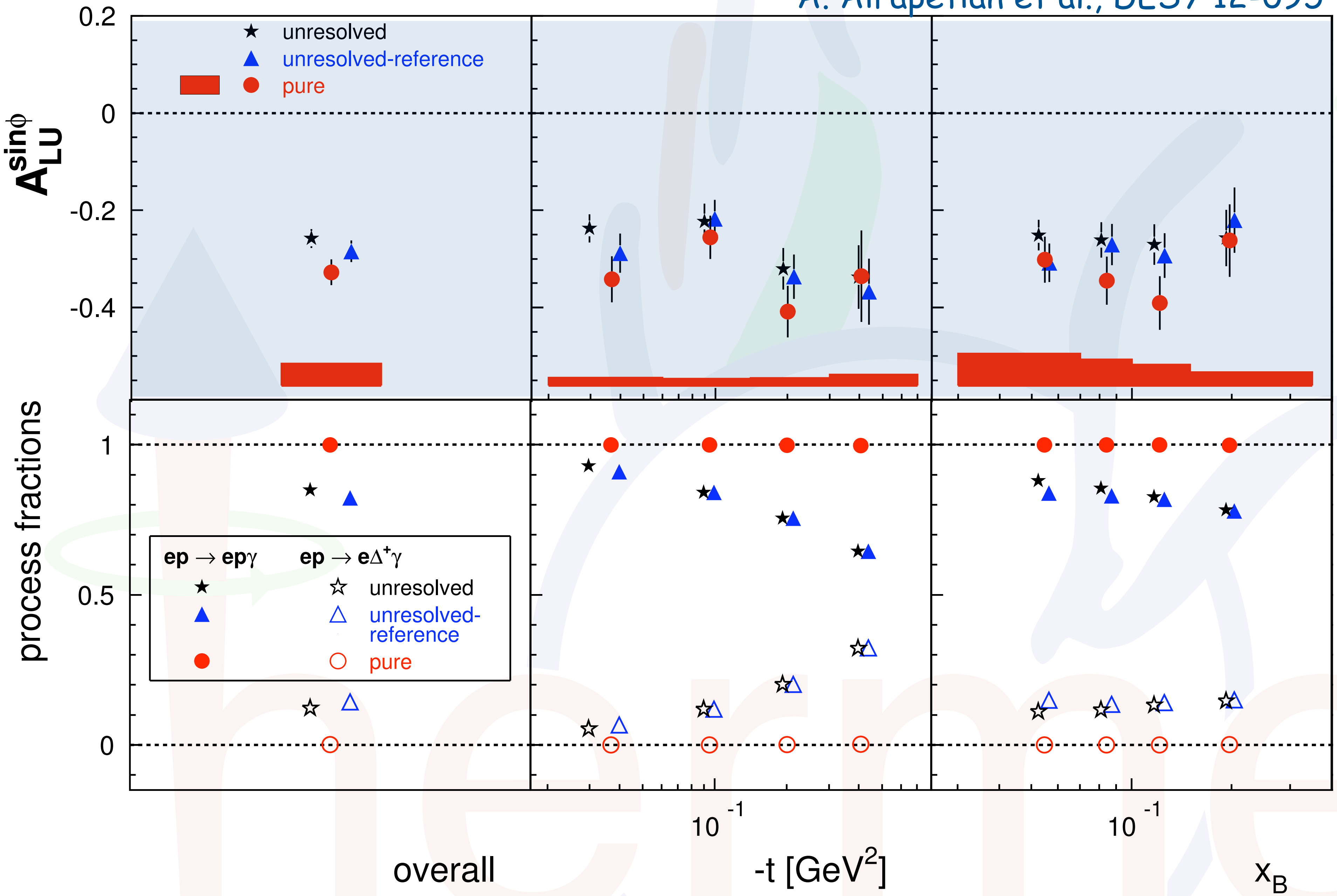




- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS ($ep \rightarrow ep\gamma$) with high efficiency (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

DVCS with recoil detector

A. Airapetian et al., DESY 12-095



indication of larger amplitudes for pure sample

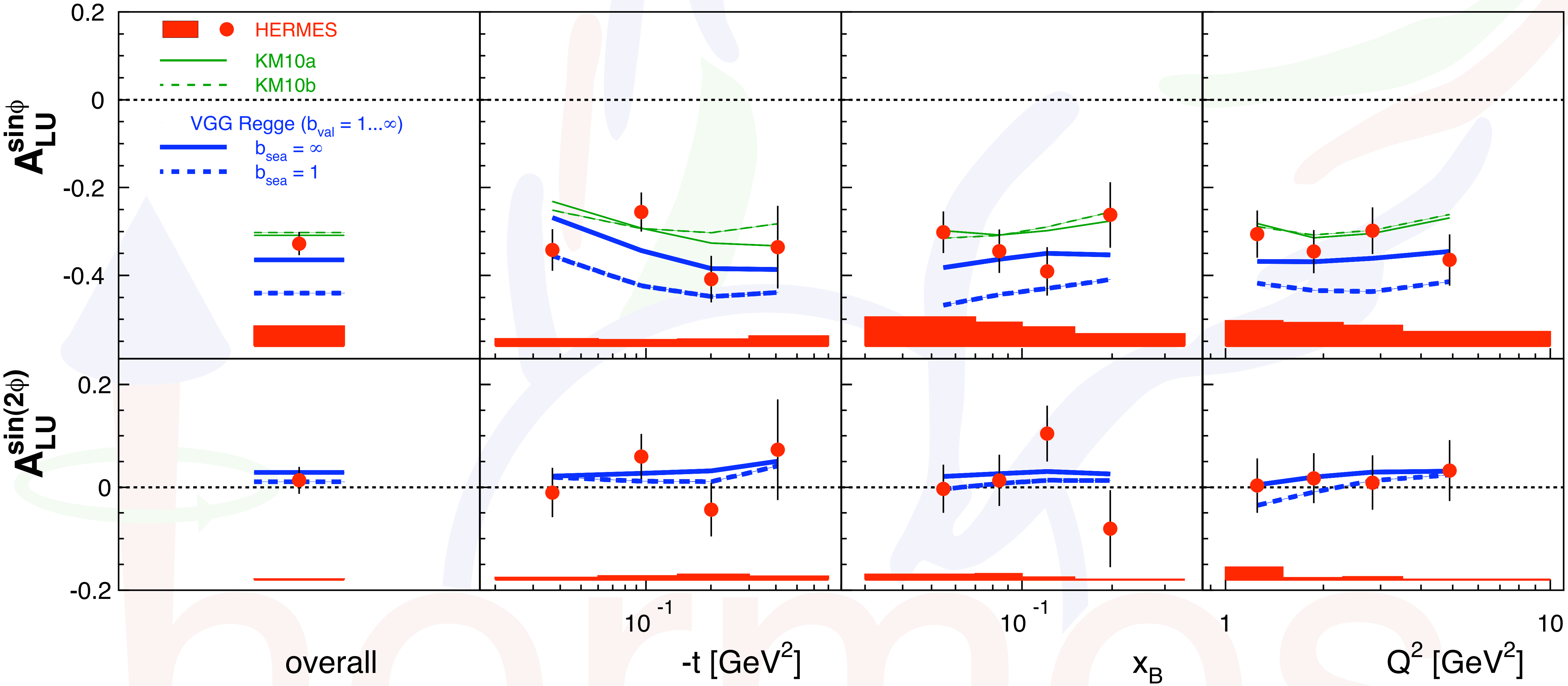
(-> assoc. in trad. analysis mainly dilution)

basically no contamination

-> clear interpretation

DVCS with recoil detector

A. Airapetian et al., DESY 12-095



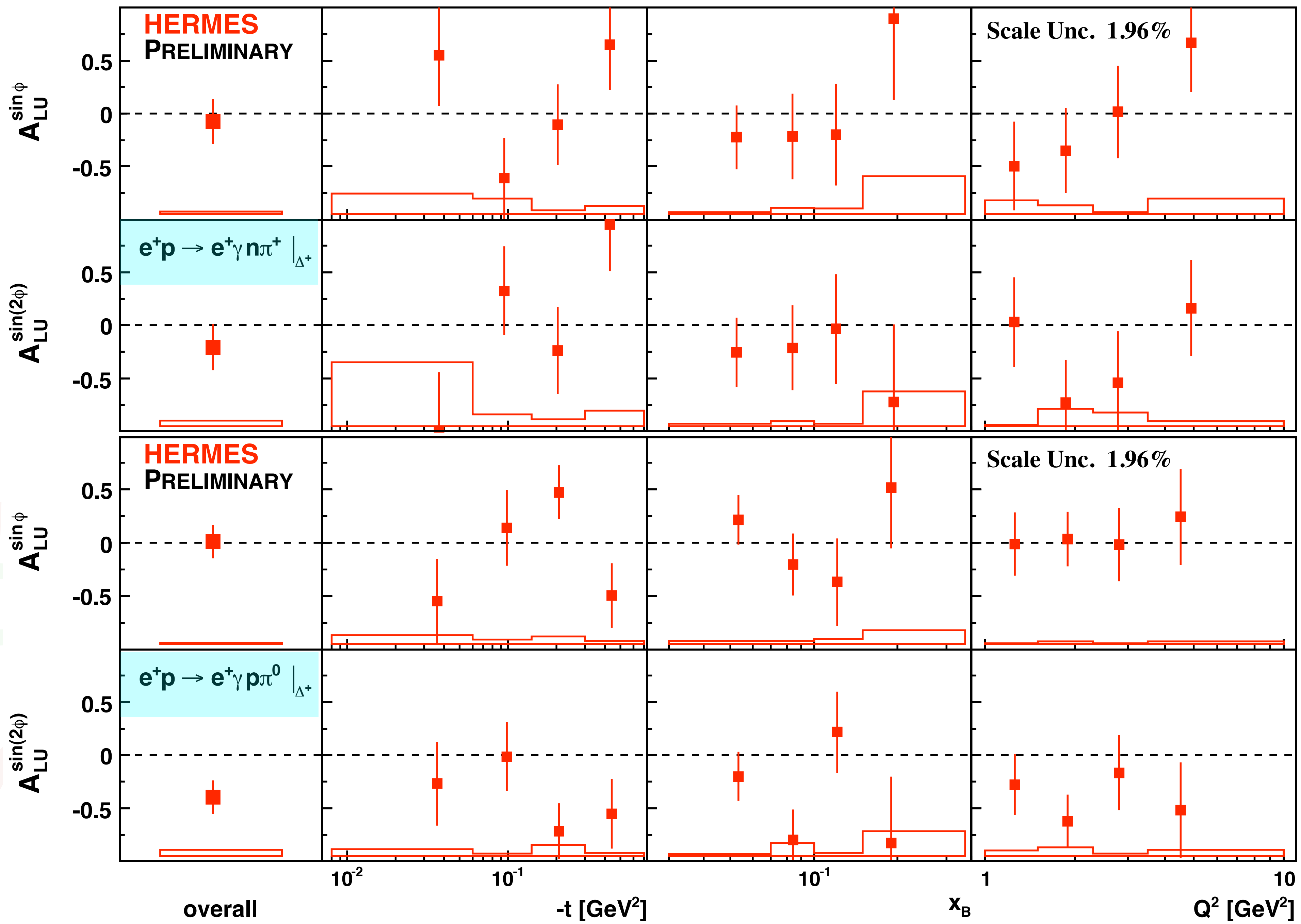
good agreement with models

KM10 - K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

VGG - M. Vanderhaeghen et al., Phys. Rev. D 60 (1999) 094017

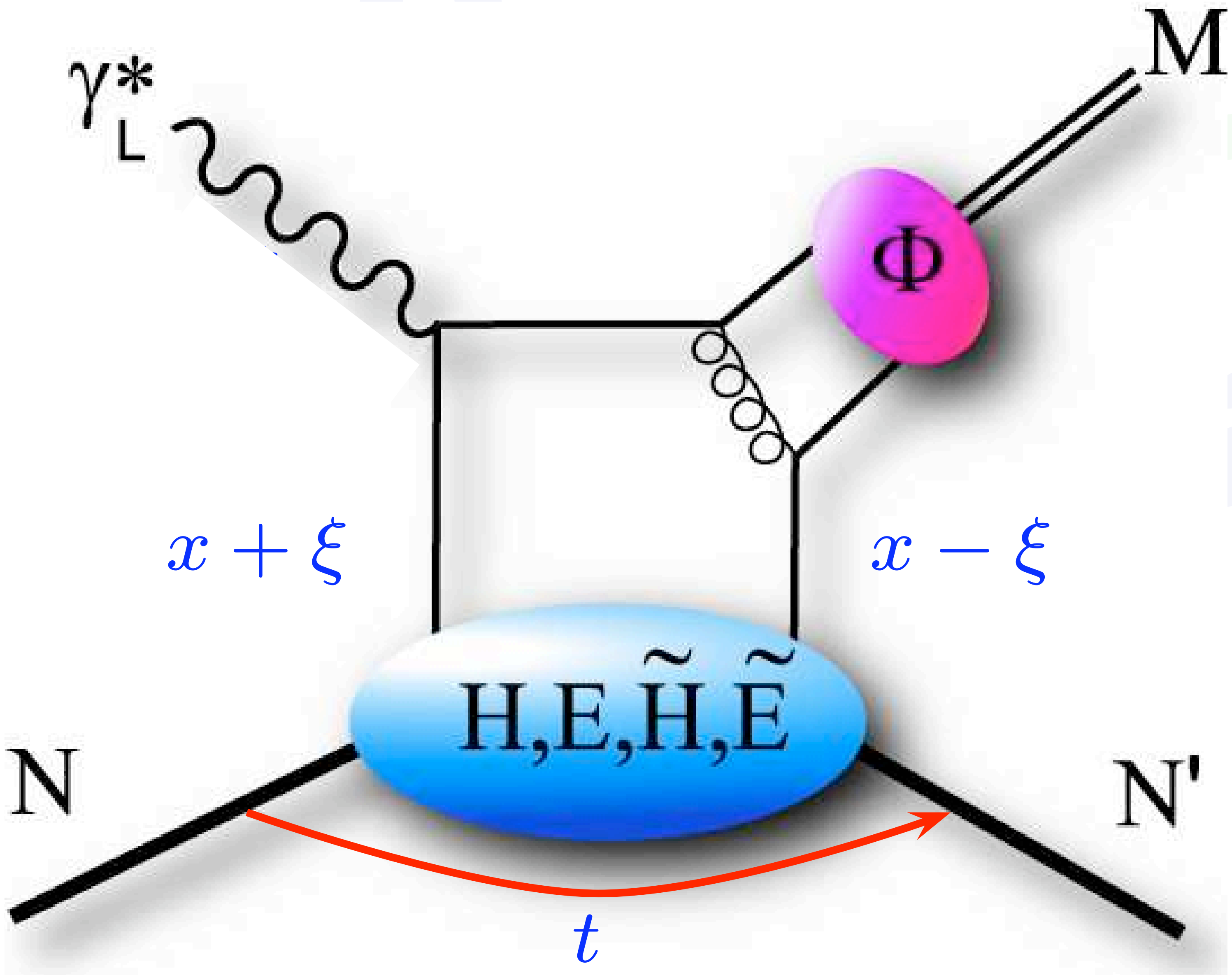
Associated DVCS with recoil detector

study background process for traditional analyses

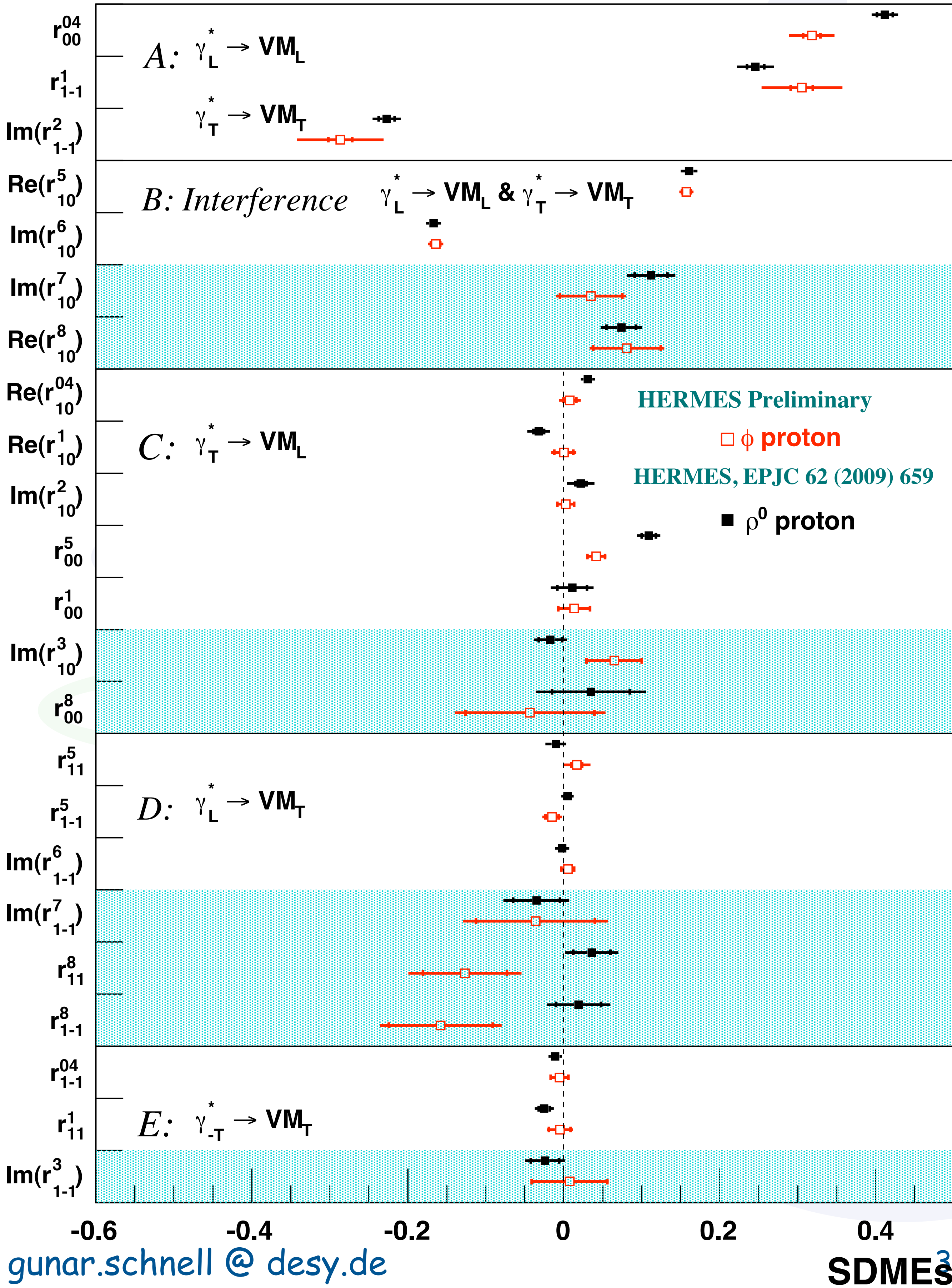


- asymmetry amplitudes consistent with zero
- consistent with pure DVCS results (e.g., dilution in traditional analysis)

Exclusive meson production

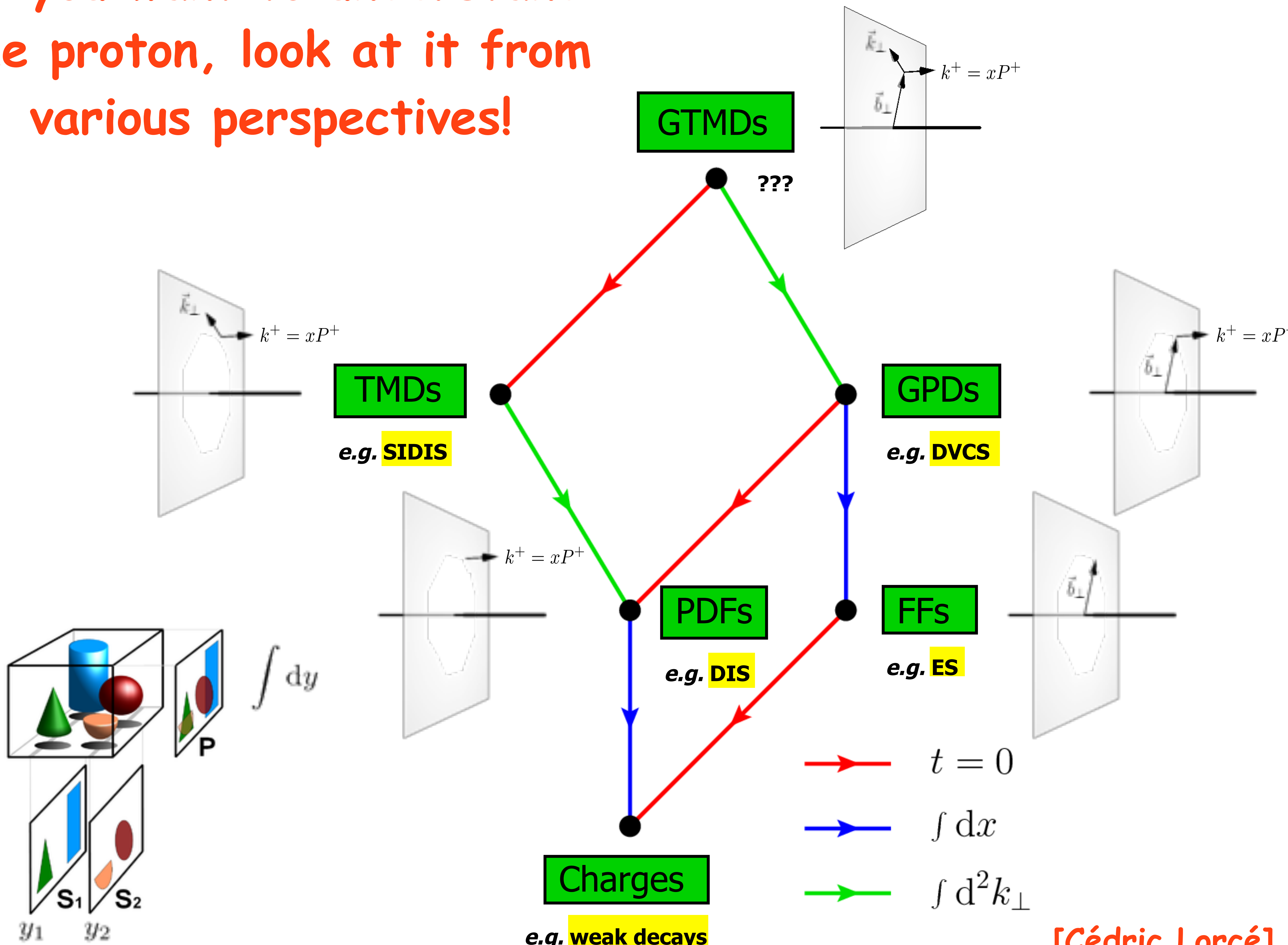


SDMEs for phi production

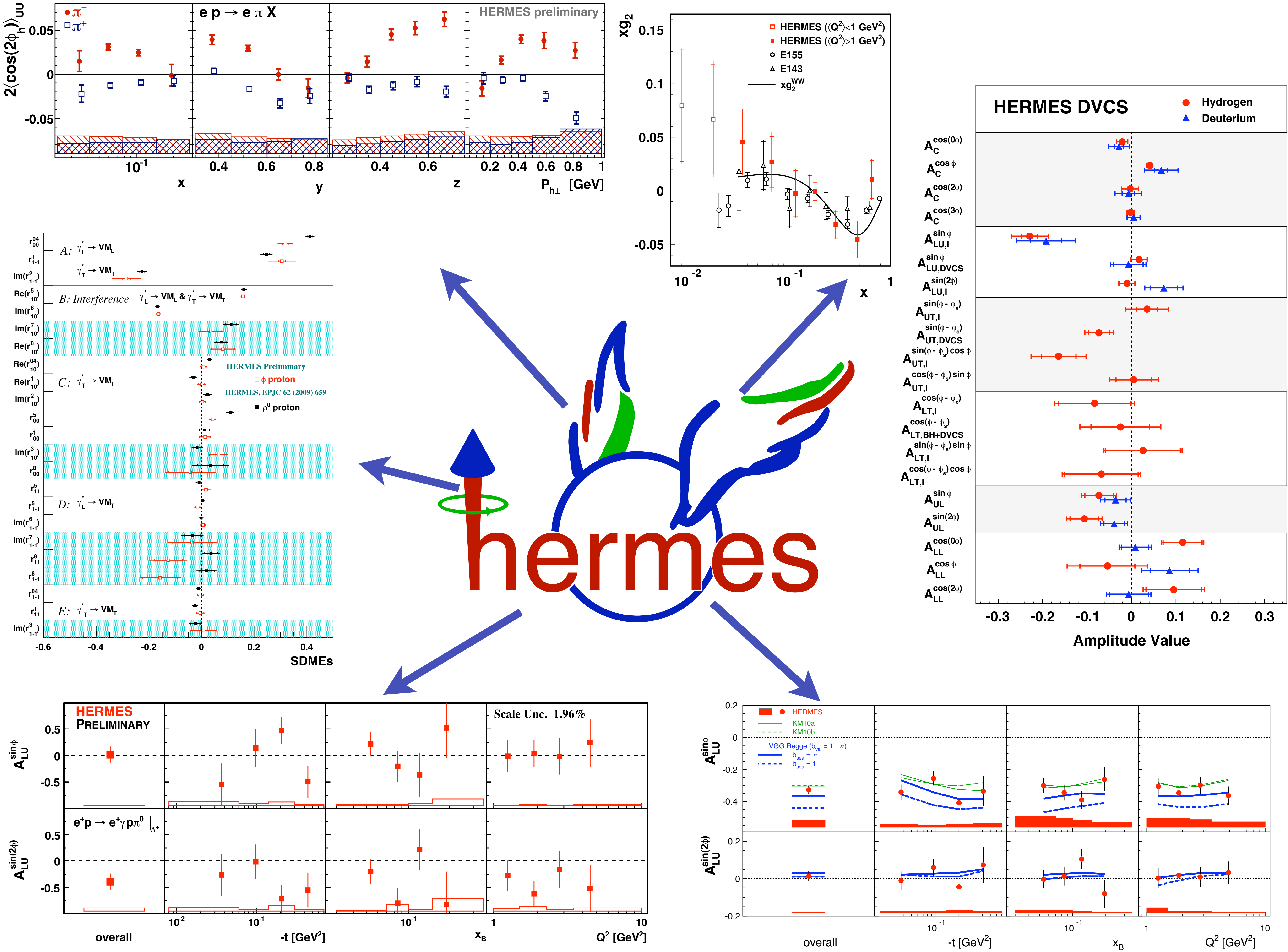


- (decay) angular distributions reveal helicity transitions
- similar to rho production: helicity-conserving SDMEs dominate
- hardly any violation of SCHC observed for phi

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



[Cédric Lorcé]



HERMES preliminary
e p → e π X
x
y
z
P_h⊥ [GeV]
HERMES (⟨Q²⟩<1 GeV²)
HERMES (⟨Q²⟩>1 GeV²)
E155
E143
x
HERMES DVCS
Hydrogen
Deuterium
Amplitude Value
A: γ*_L → VM_L
B: Interference
C: γ*_T → VM_L
D: γ*_L → VM_T
E: γ*_T → VM_T
HERMES Preliminary
φ proton
HERMES, EPJC 62 (2009) 659
ρ⁰ proton
SDMEs
hermes
HERMES
PRELIMINARY
Scale Unc. 1.96%
e⁺p → e⁺γpπ⁰ |Δ⁺
overall
-t [GeV²]
x_B
Q² [GeV²]
HERMES
KM10a
KM10b
VGG Regge (b_val = 1...∞)
b_sea = ∞
b_sea = 1
overall
-t [GeV²]
x_B
Q² [GeV²]