Ringberg Workshop “New Trends in HERA Physics 2011”

On the way to a 3D picture of the nucleon structure

Recent results on GPDs from COMPASS, HERMES, and JLab

hermes

COMPASS

Hall A JLab

CLAS

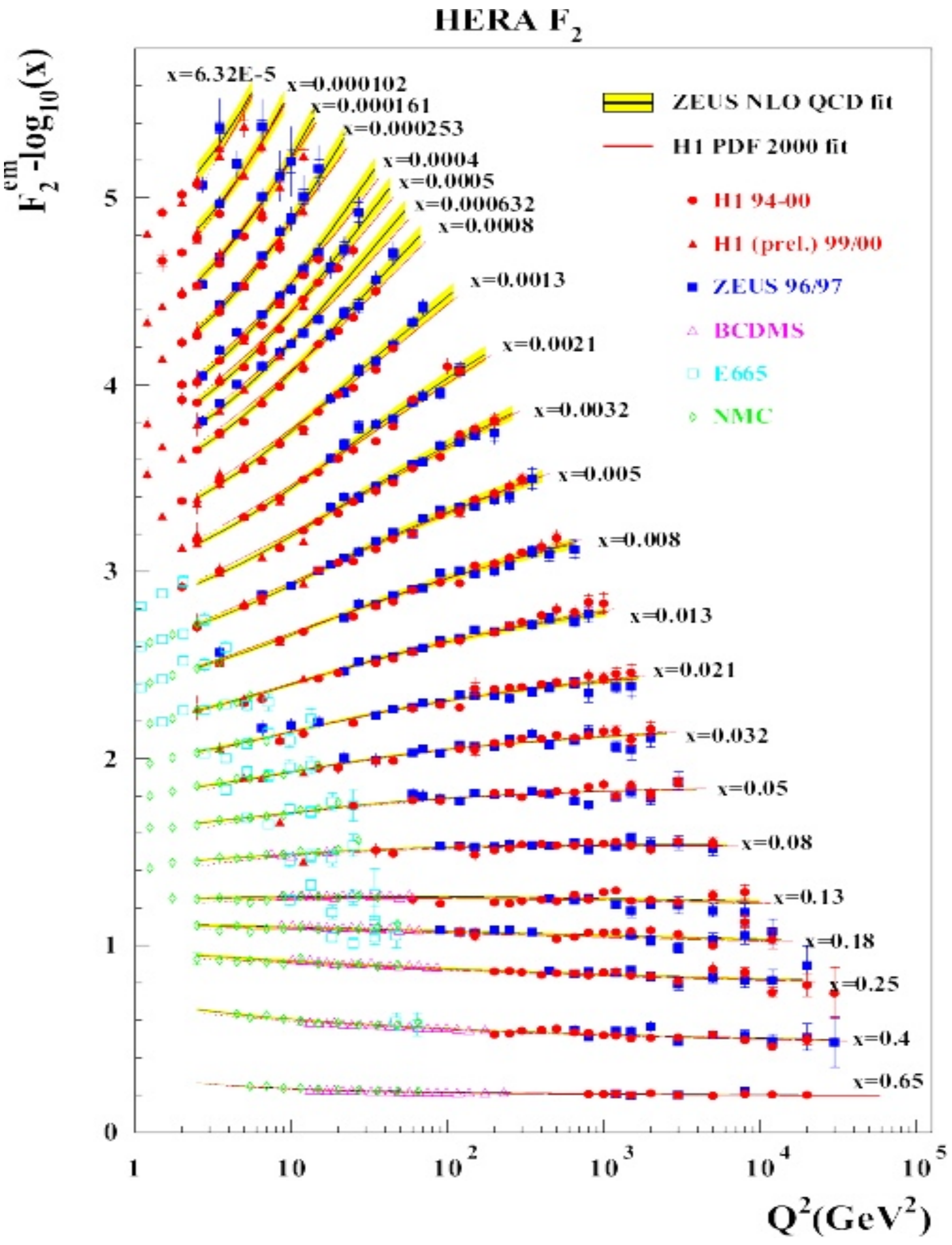
CEBAF Large Acceptance Spectrometer

Gunar.Schnell @ desy.de

ikerbasque
Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Incredible success of pQCD



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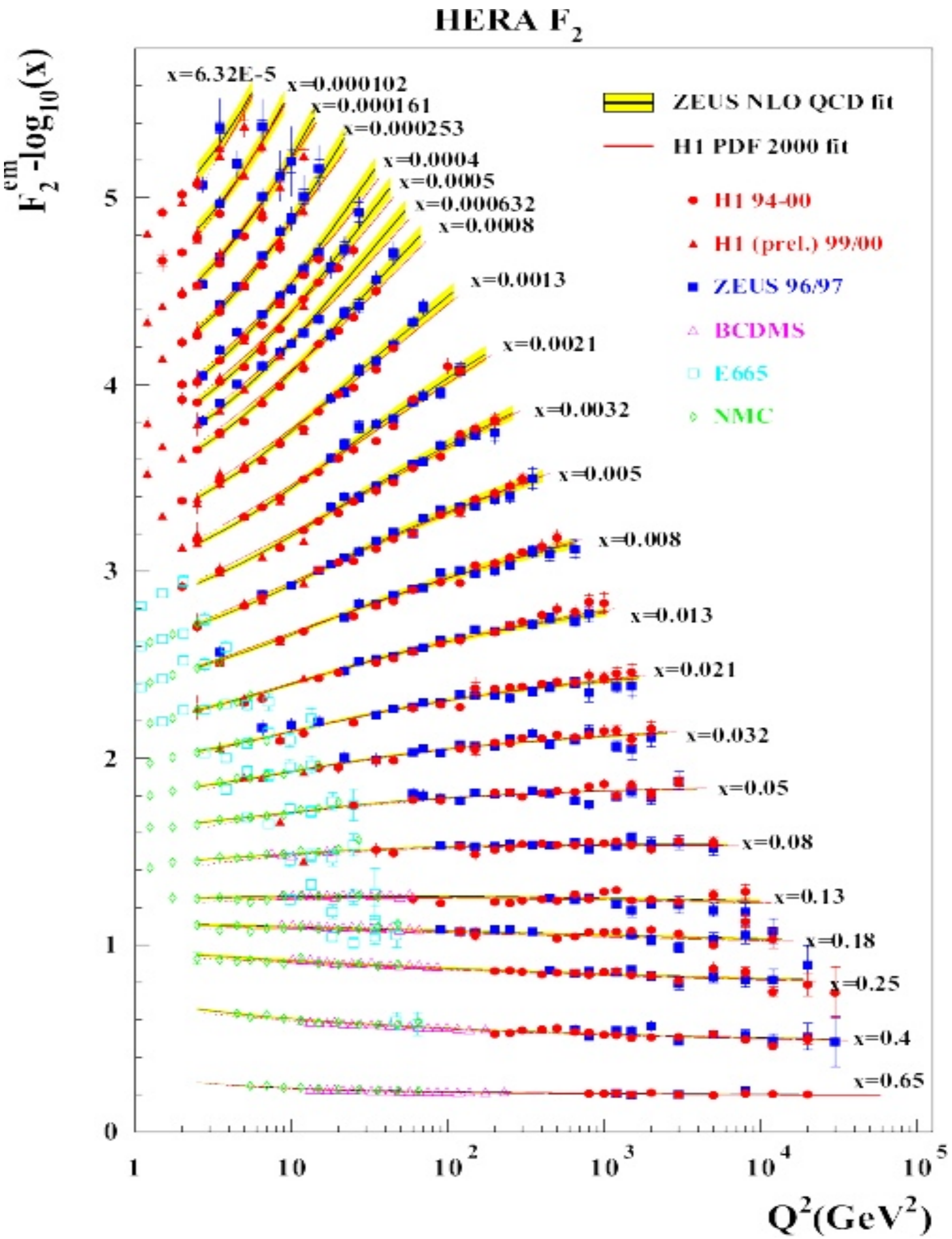

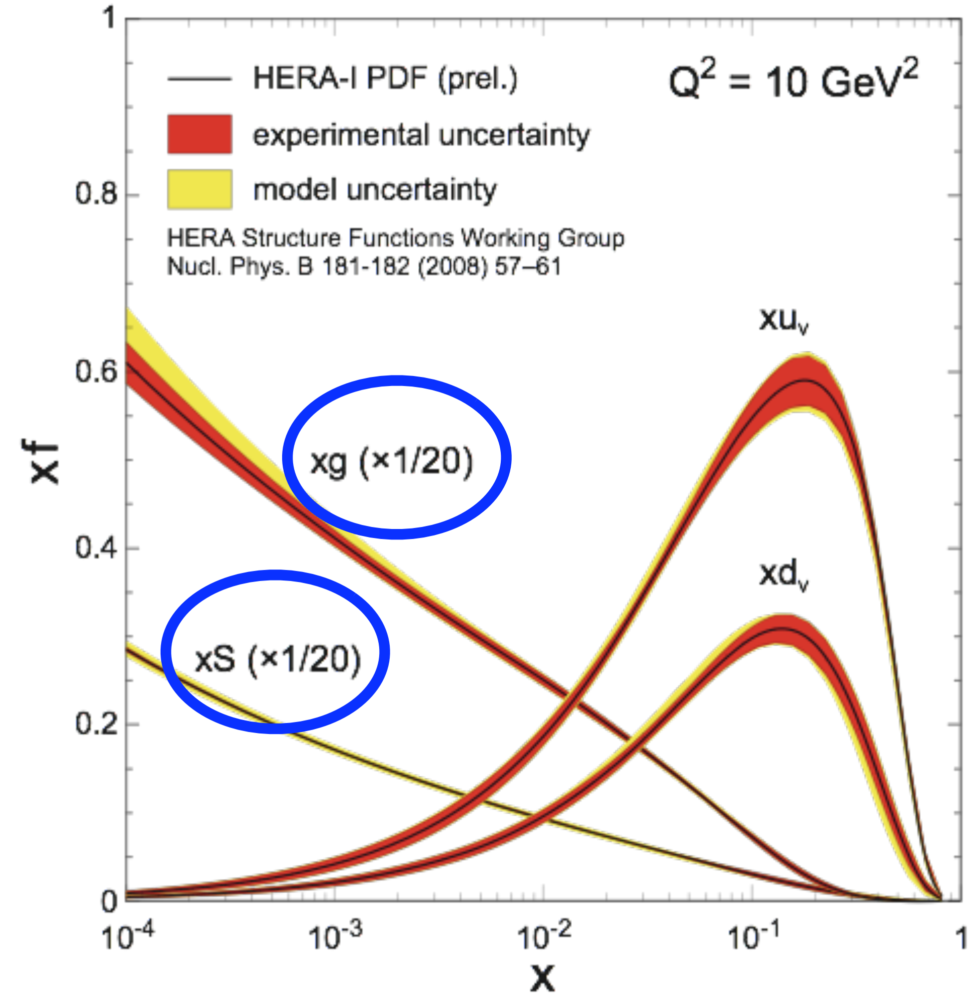

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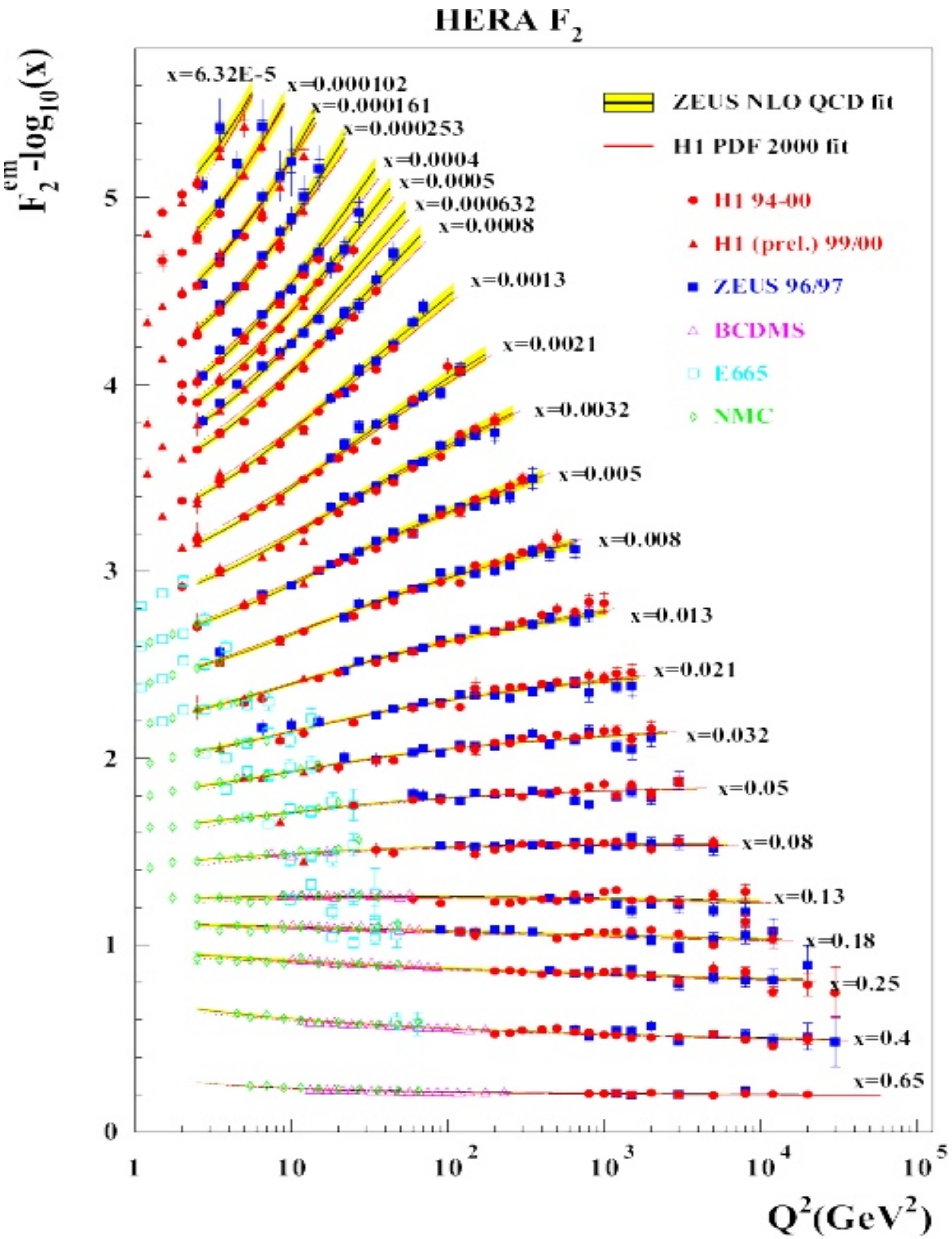

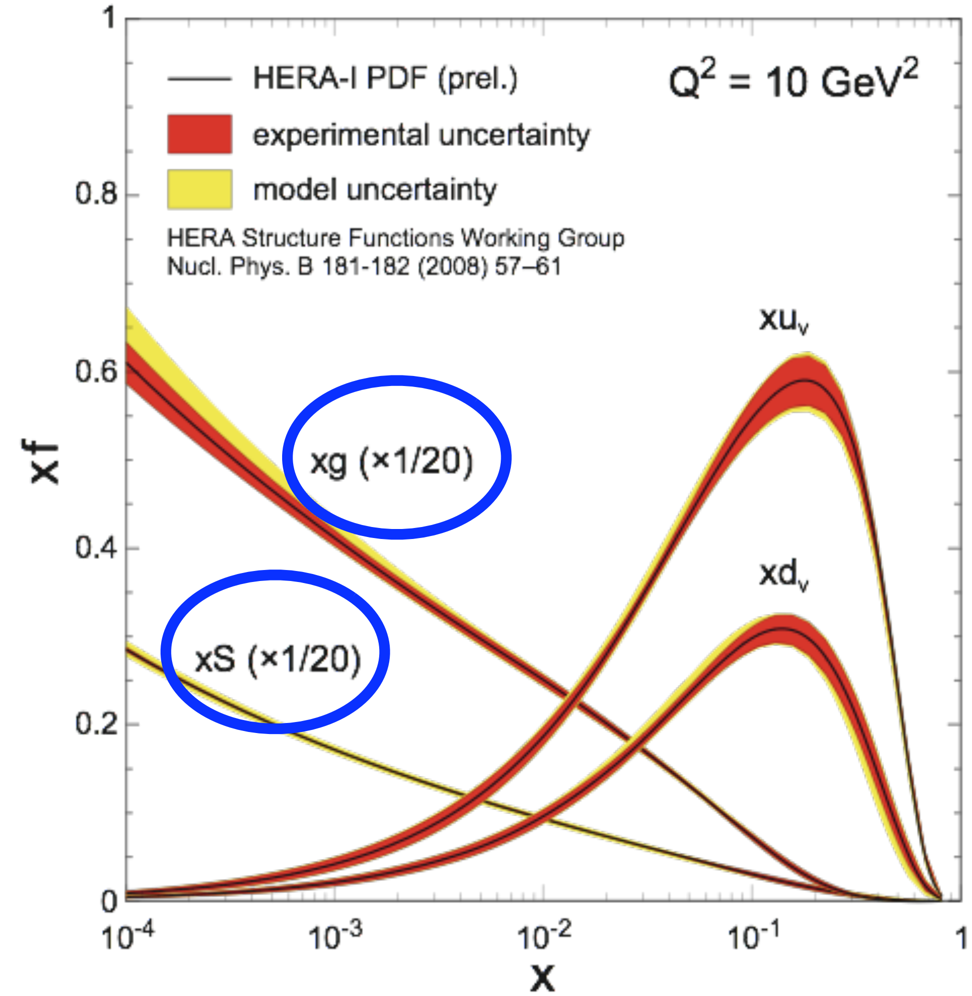

have a pretty good knowledge on how many partons (with longitudinal momentum fraction x) we have in the nucleon

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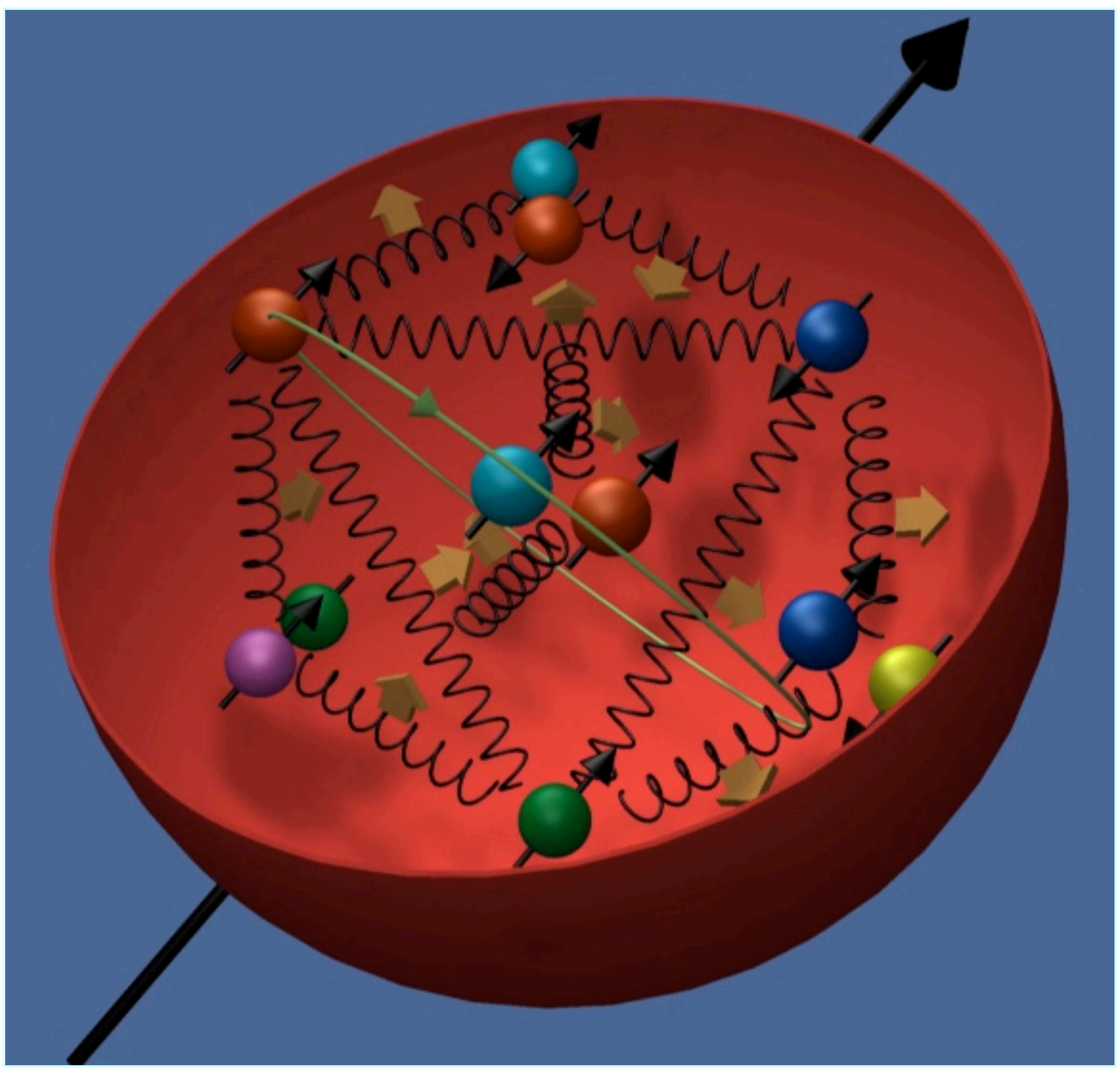
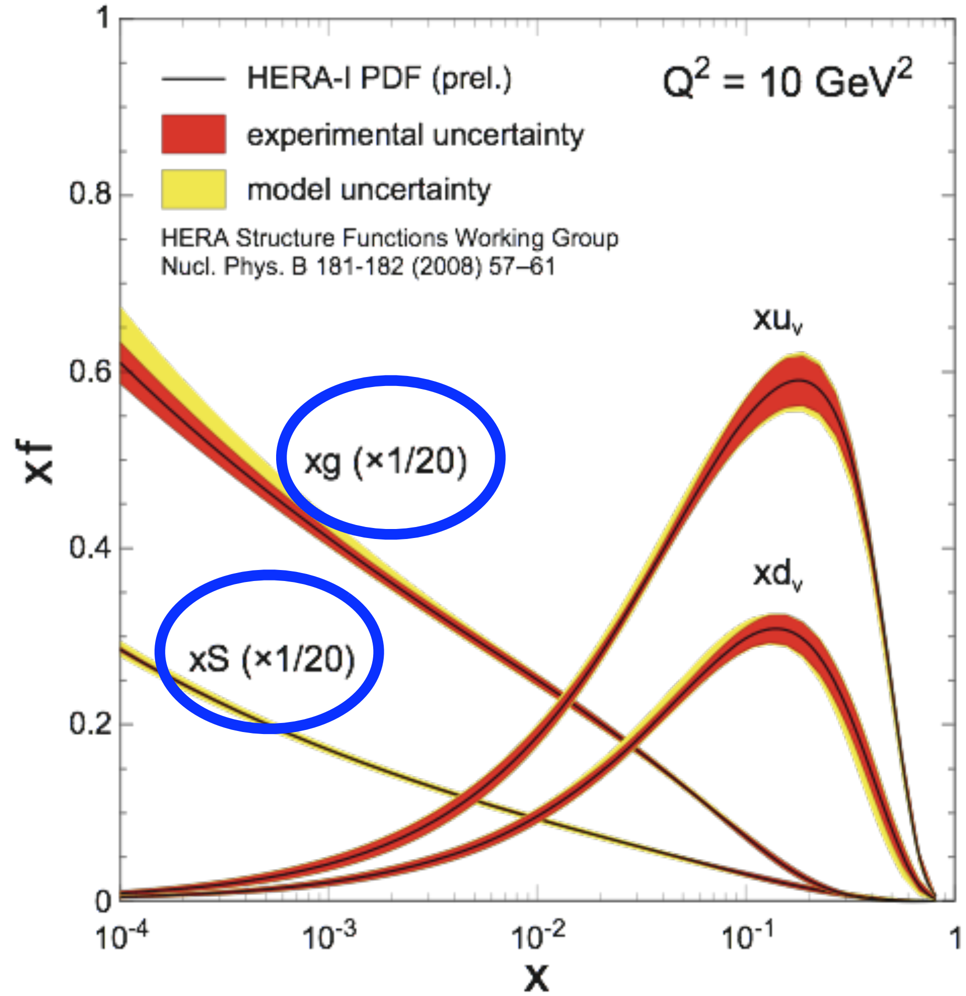
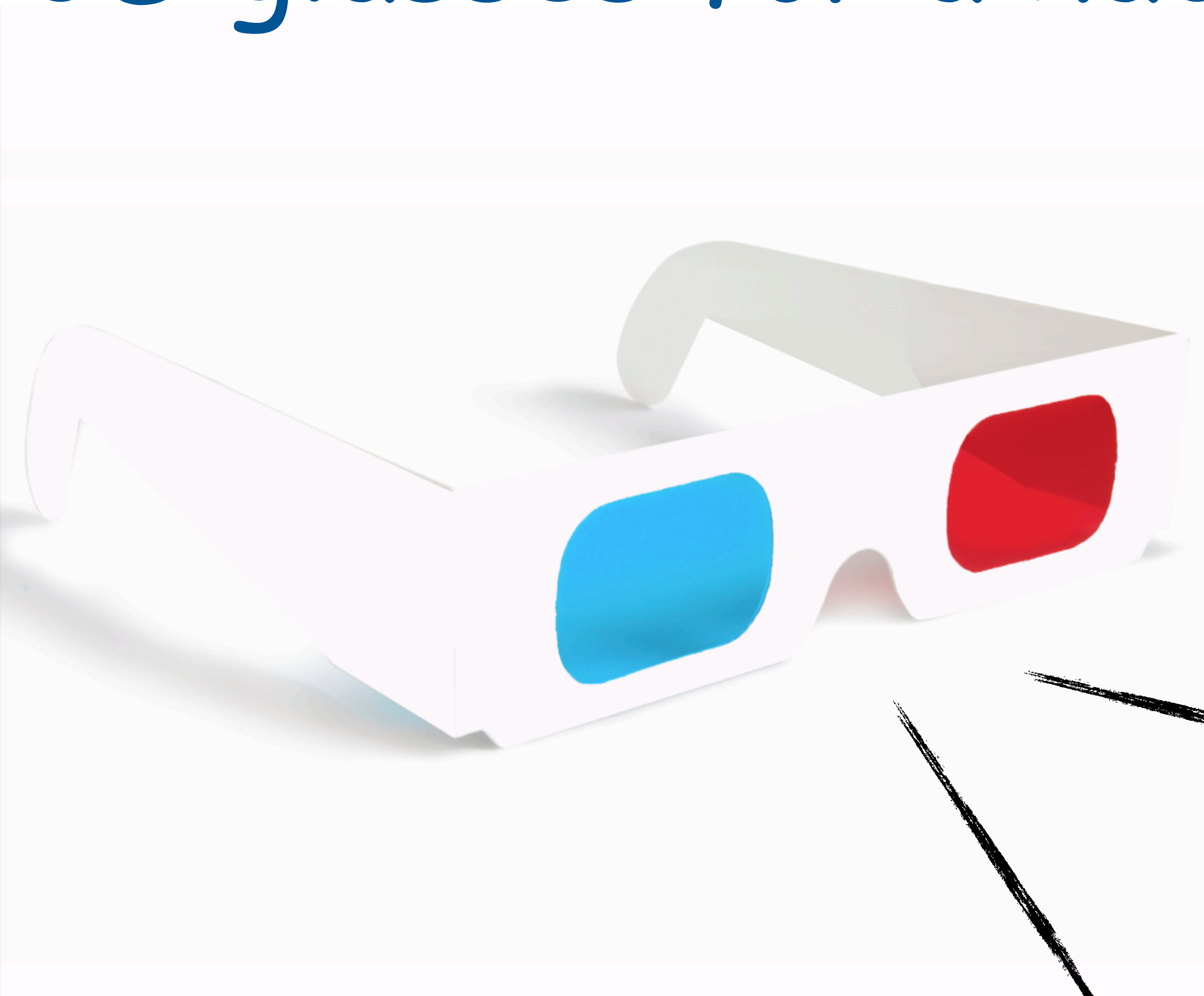




have a pretty good knowledge on how many partons (with longitudinal momentum fraction x) we have in the nucleon

BUT: **proton not a 1D object!**

3D glasses for a hadron physicist

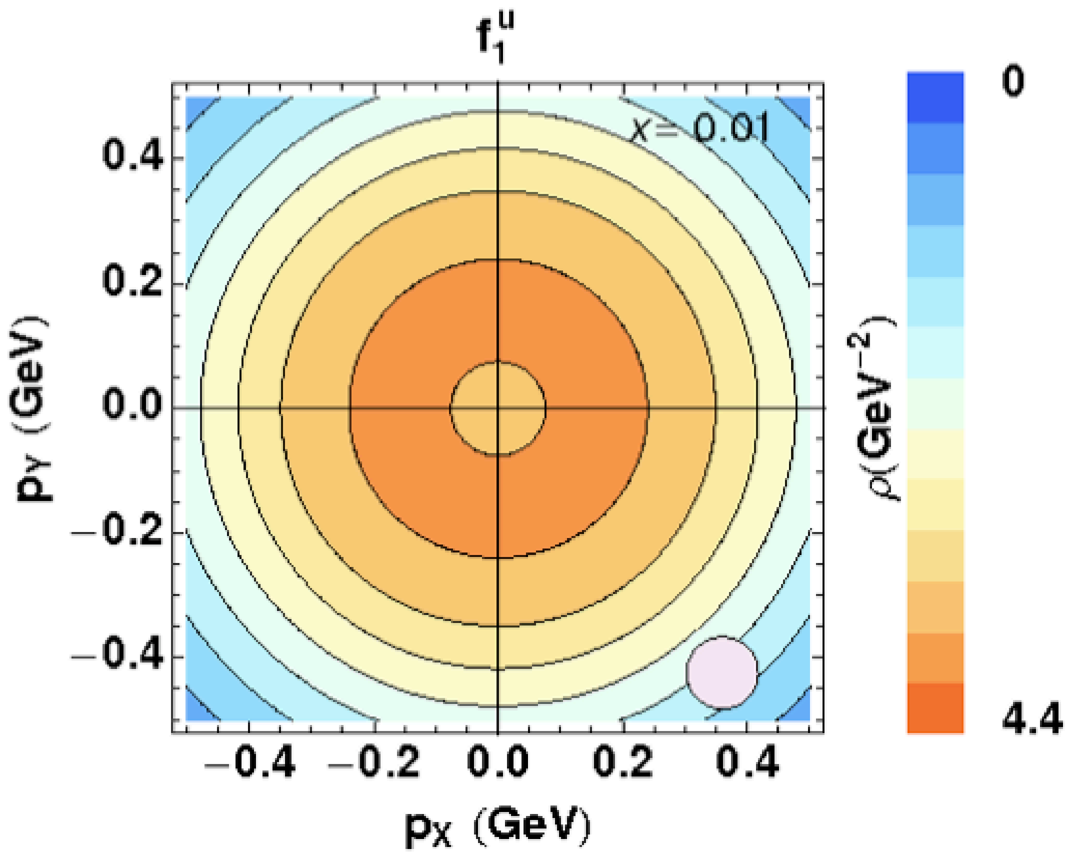


momentum space ("TMDs")

position space ("GPDs")

Is it interesting?

a slice of the proton in transverse momentum space:



[Bacchetta et al., PRD 2008]

without spin

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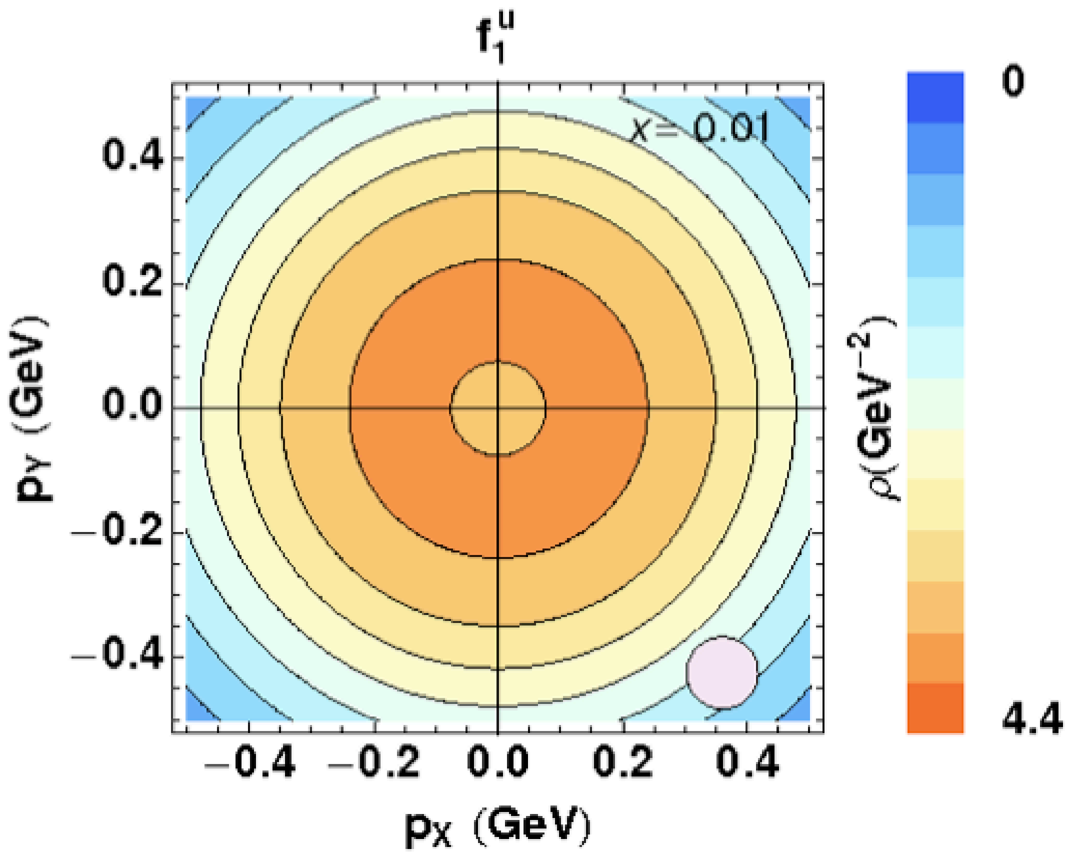

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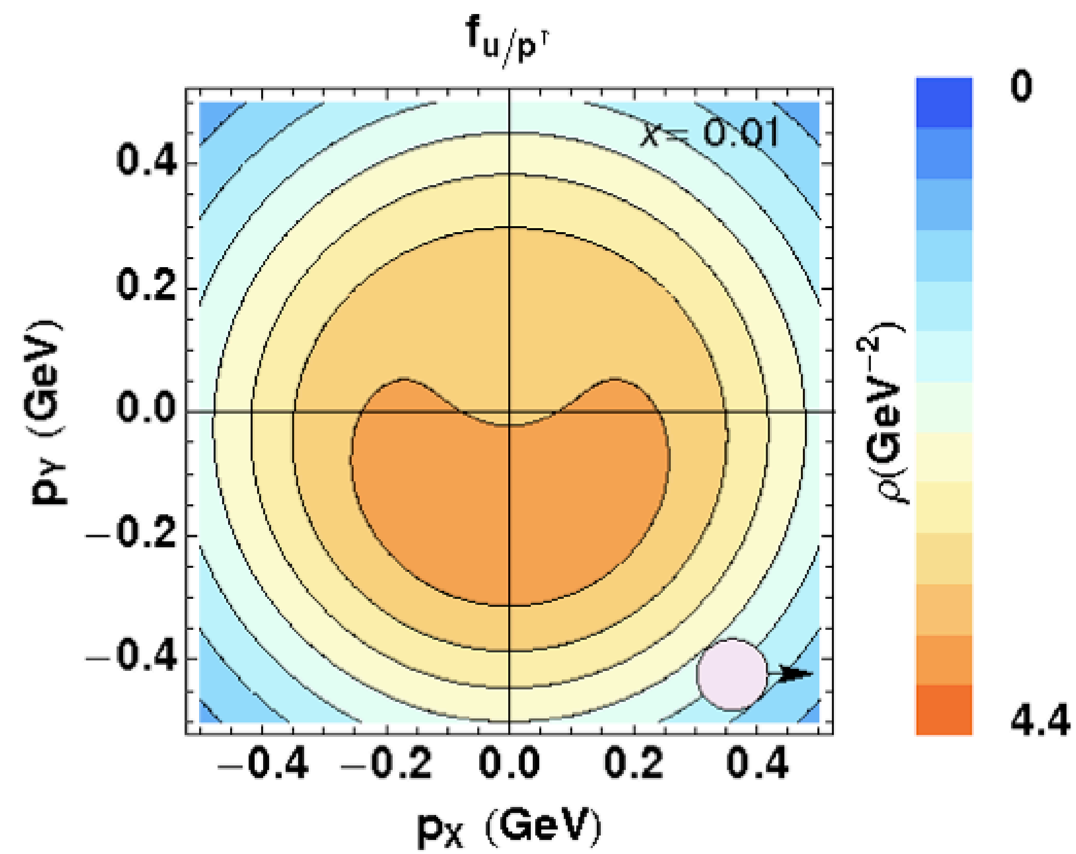

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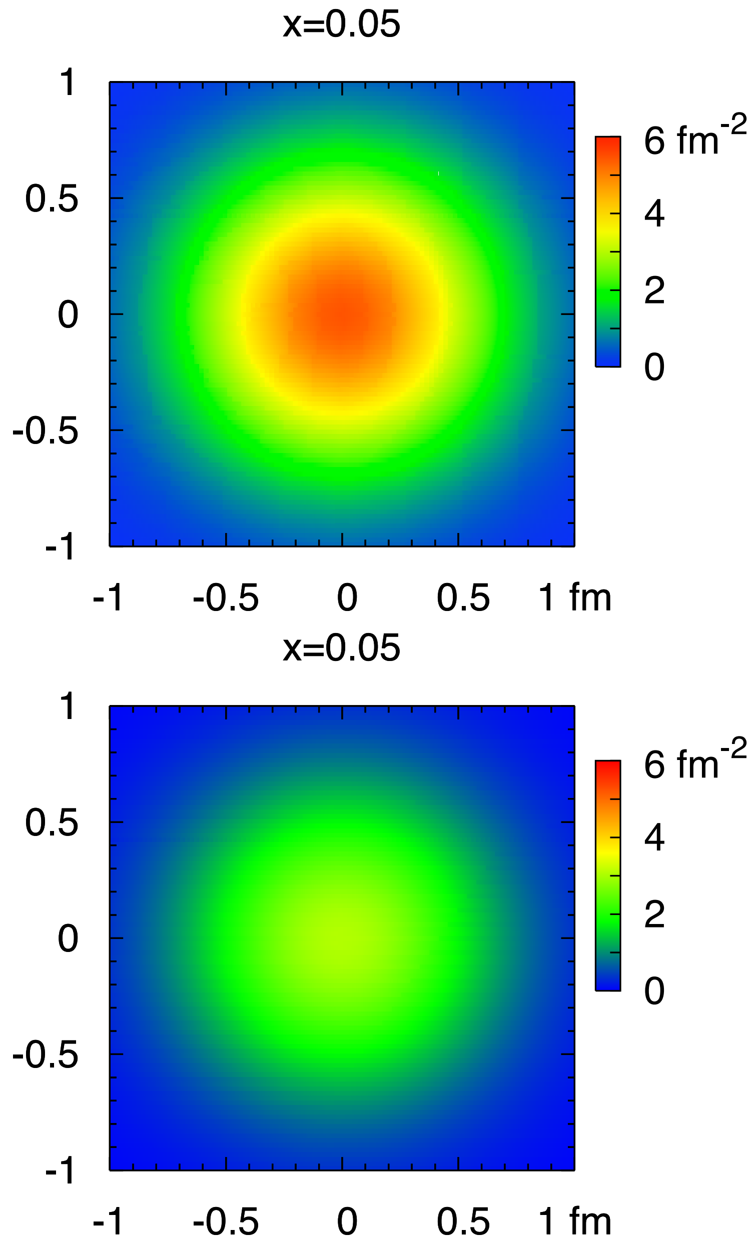
a slice of the proton in transverse position space:

[M. Diehl et al., EPJC 39 (2005) 1]



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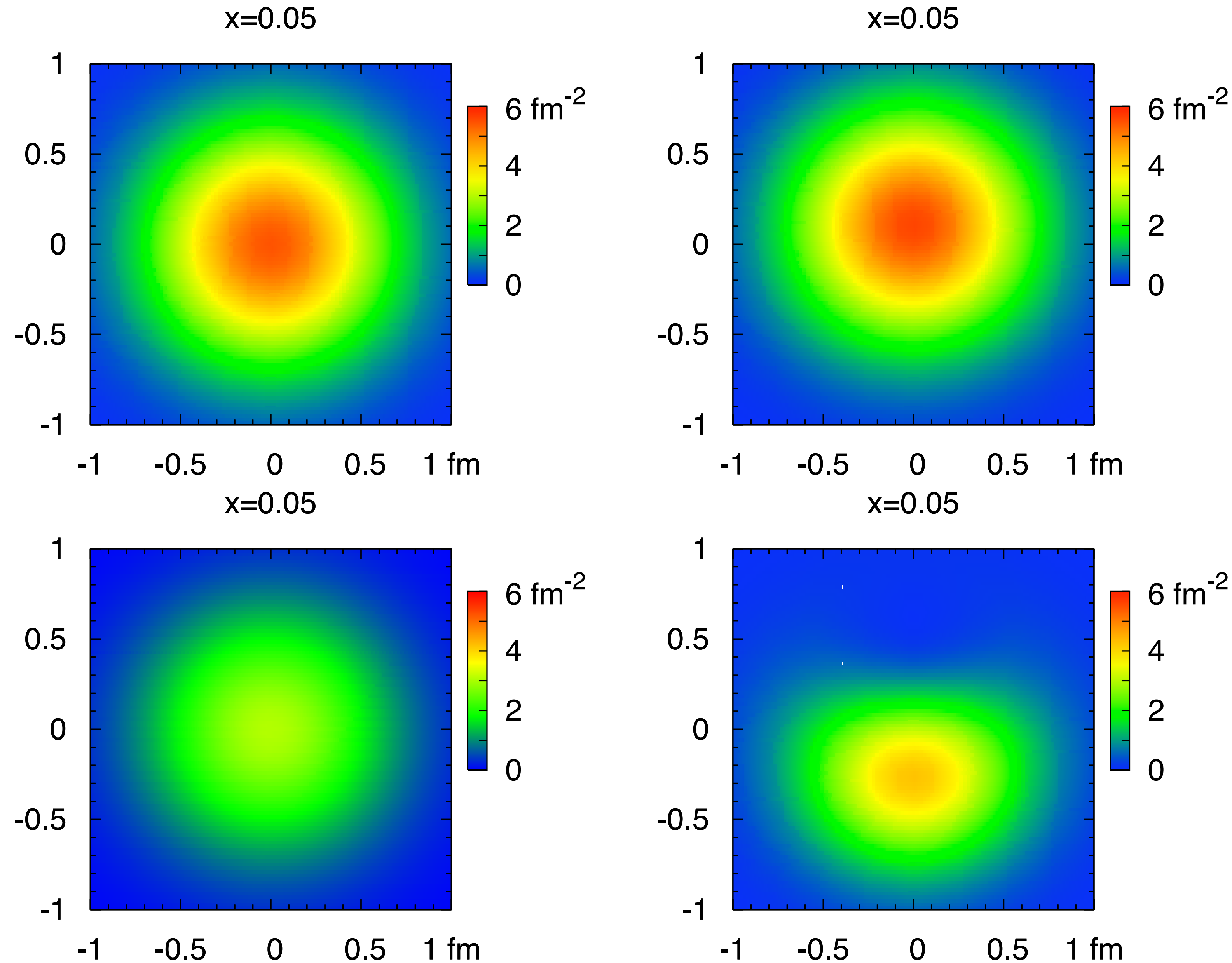


[M. Diehl et al., EPJC 39 (2005) 1]

without spin   with spin

Is it relevant?

- pQCD: single-spin asymmetries (SSA) heavily suppressed:

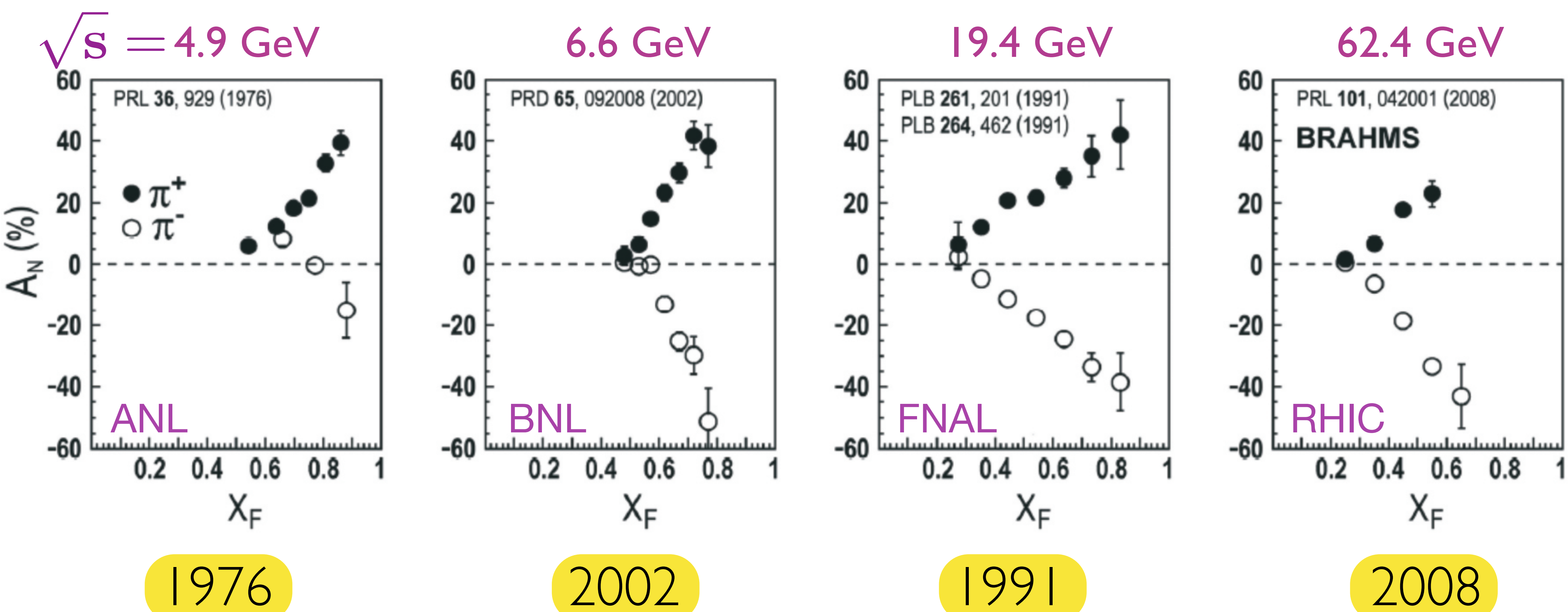
$$\mathbf{A_N} \propto \alpha_\mathbf{S} \frac{\mathbf{m_q}}{\mathbf{Q^2}}$$ [Kane, Repko, Pumplin, 1978]

Is it relevant?

- pQCD: single-spin asymmetries (SSA) heavily suppressed:

$$A_N \propto \alpha_S \frac{m_q}{Q^2}$$ [Kane, Repko, Pumplin, 1978]

- BUT: large SSA in pp collision and semi-inclusive DIS



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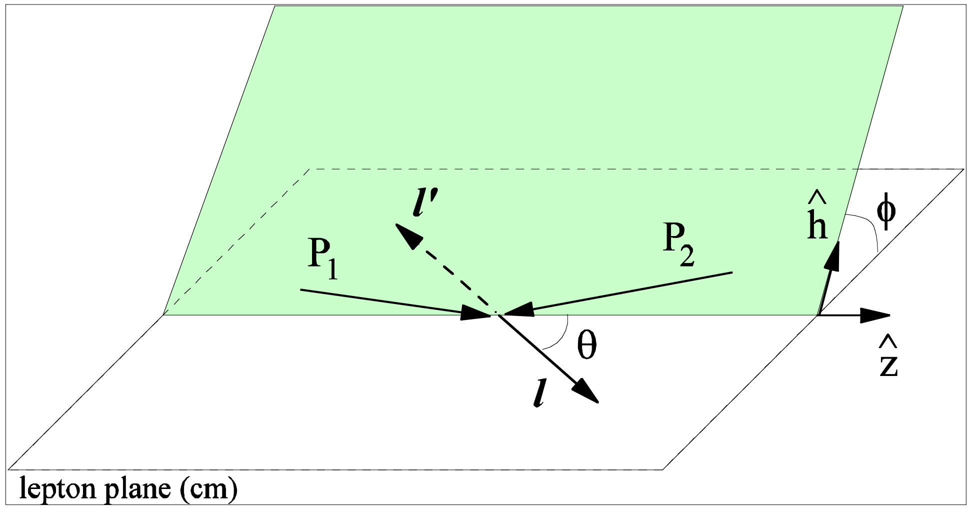
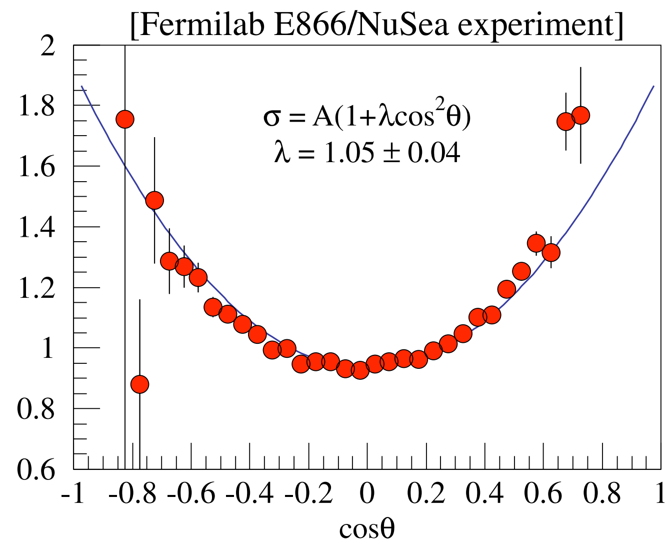


- Unpolarized Drell-Yan cross section:

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



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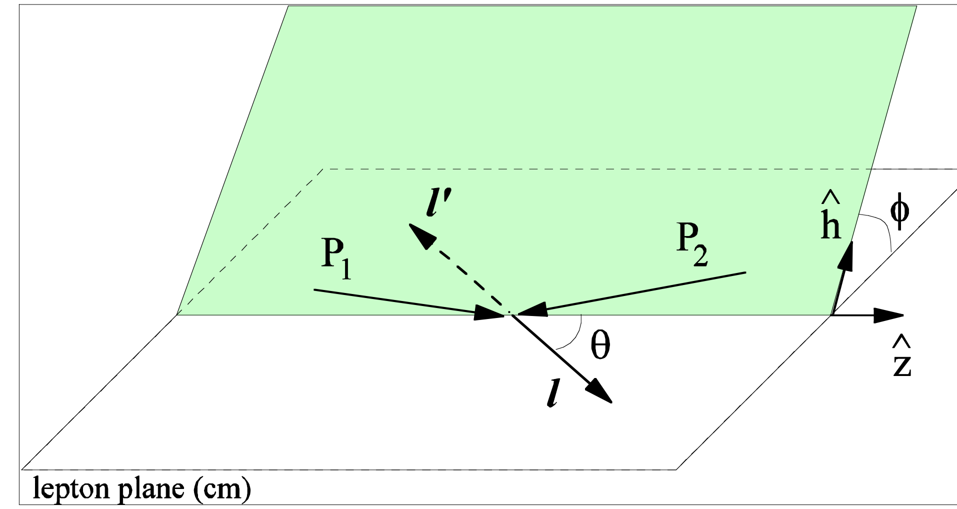

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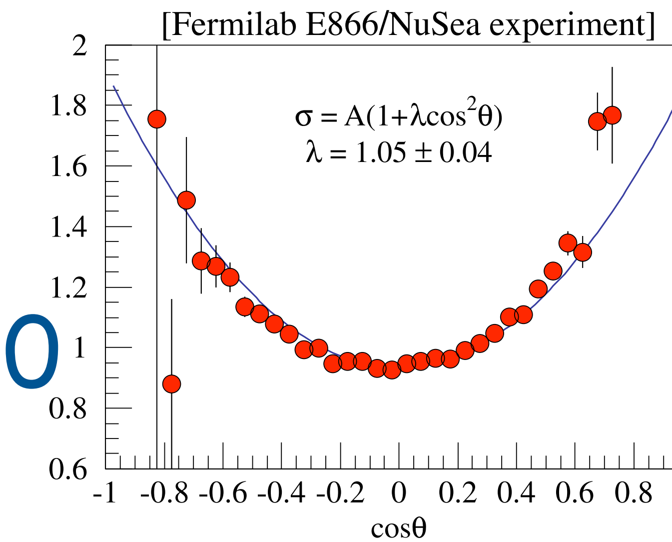

- pQCD predicts Lam-Tung relation $2\,\nu = 1-\lambda \approx 0$

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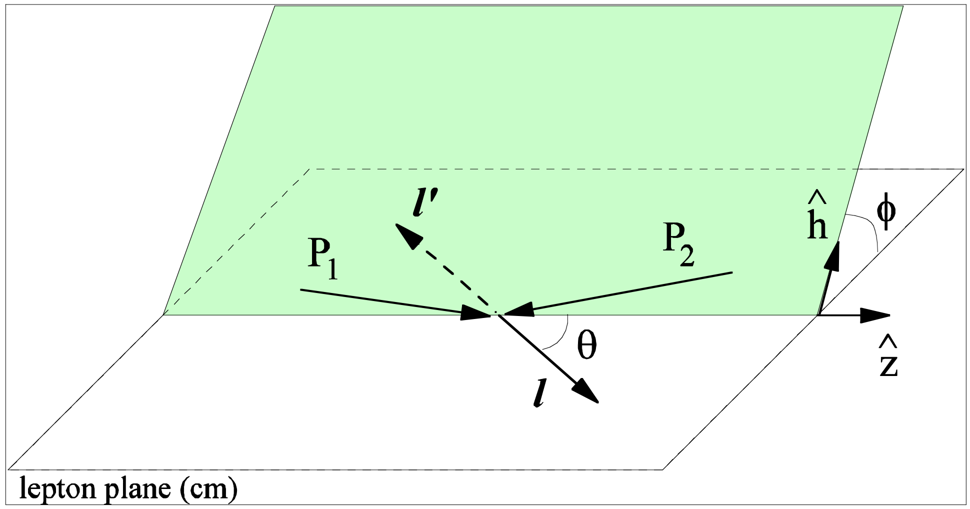

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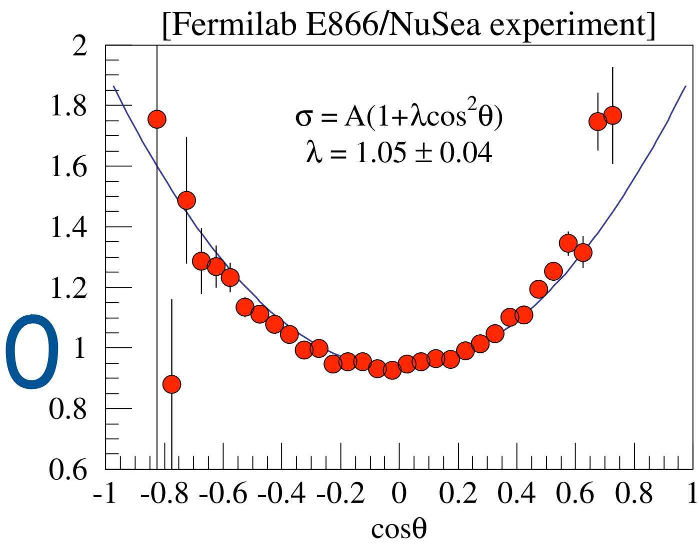
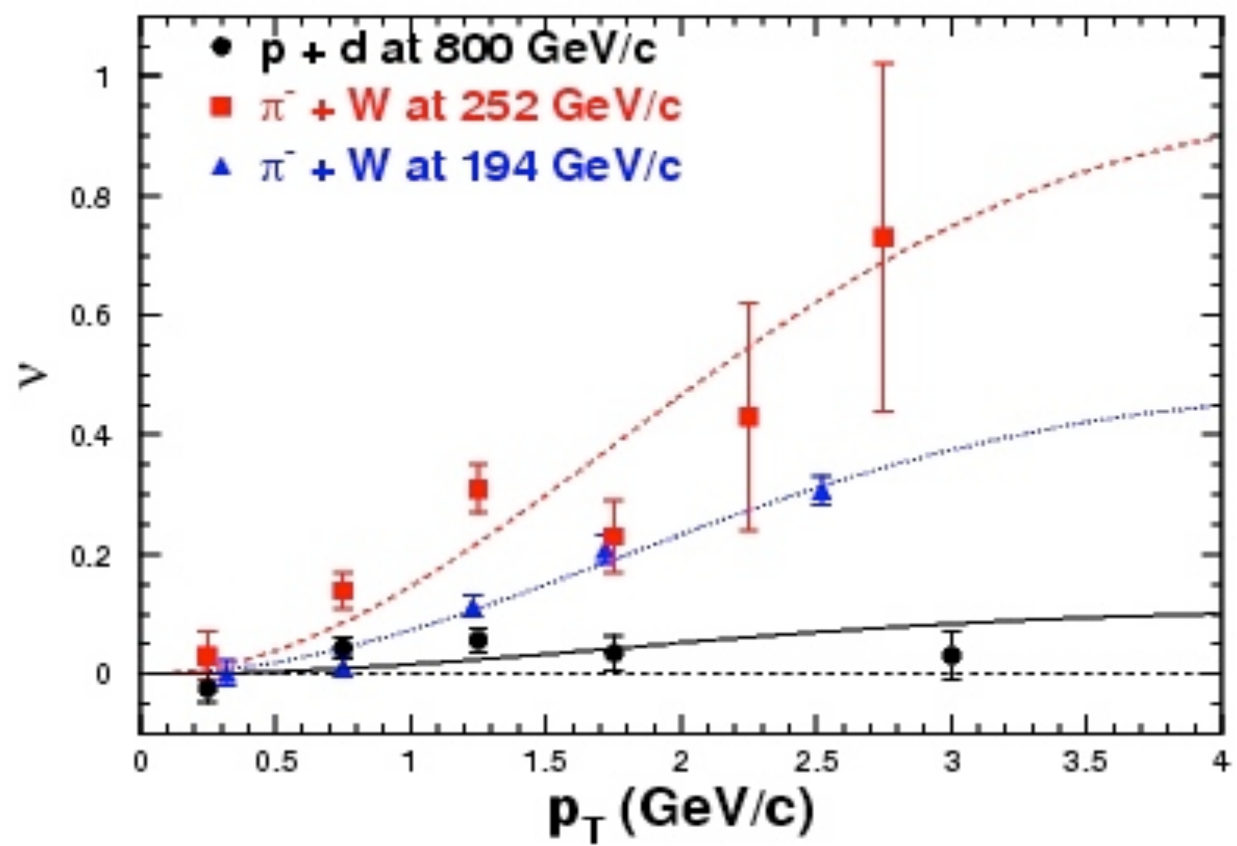


- pQCD predicts Lam-Tung relation $2\,\nu = 1-\lambda \approx 0$

- BUT: significant violations seen by Drell-Yan experiments



Is it relevant?

- spin of quarks and gluons don't sum up to give proton spin ½

$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$ ← quark spin ≈ ½ 1/3

$+ \Delta G$ ← gluon spin ≈ 0

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

Is it relevant?

- spin of quarks and gluons don't sum up to give proton spin $\frac{1}{2}$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma \quad \longleftarrow \quad \text{quark spin} \approx \tfrac{1}{2}\ 1/3$$

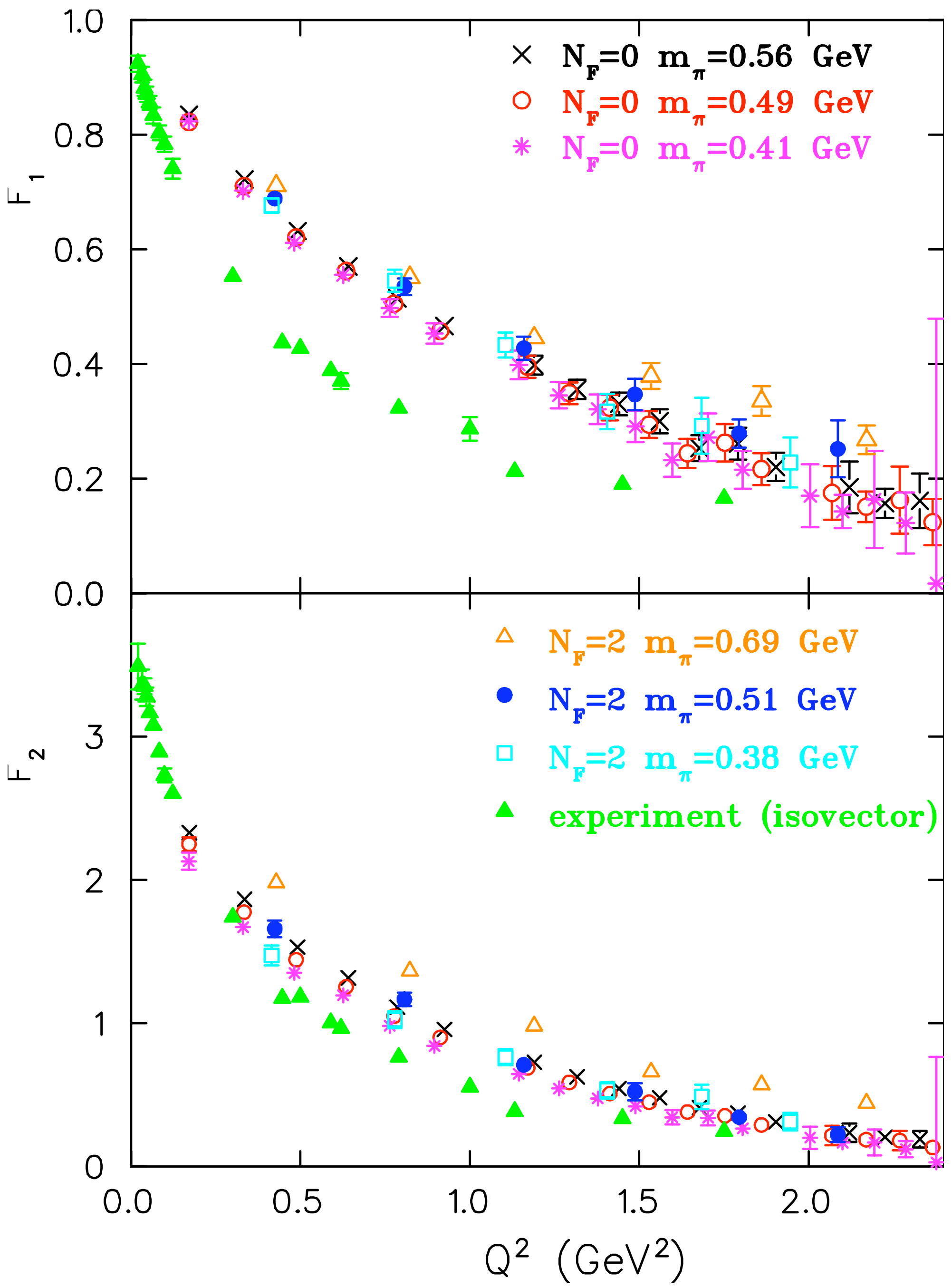
$$+\ \Delta G \quad \longleftarrow \quad \text{gluon spin} \approx 0$$

$$+\ L_q + L_g \quad \longleftarrow \quad \text{orbital angular momentum} \approx ?$$

- need orbital angular momentum (transverse space and momentum d.o.f.)

Some tradition in position-space

- decades of nucleon form factor measurements:



[Ph. Hägler, Phys. Rept 490, 49-175 (2010)]

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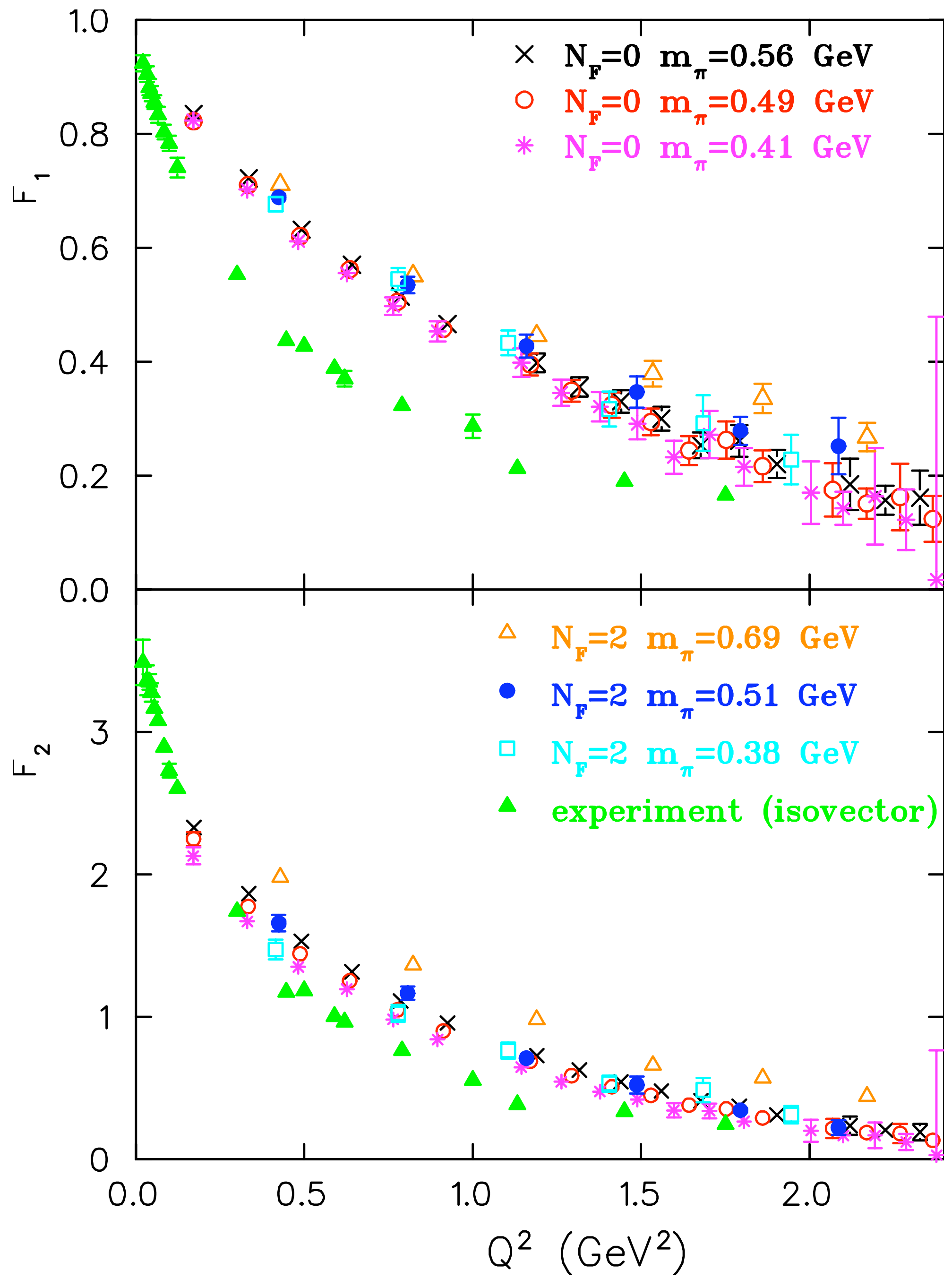

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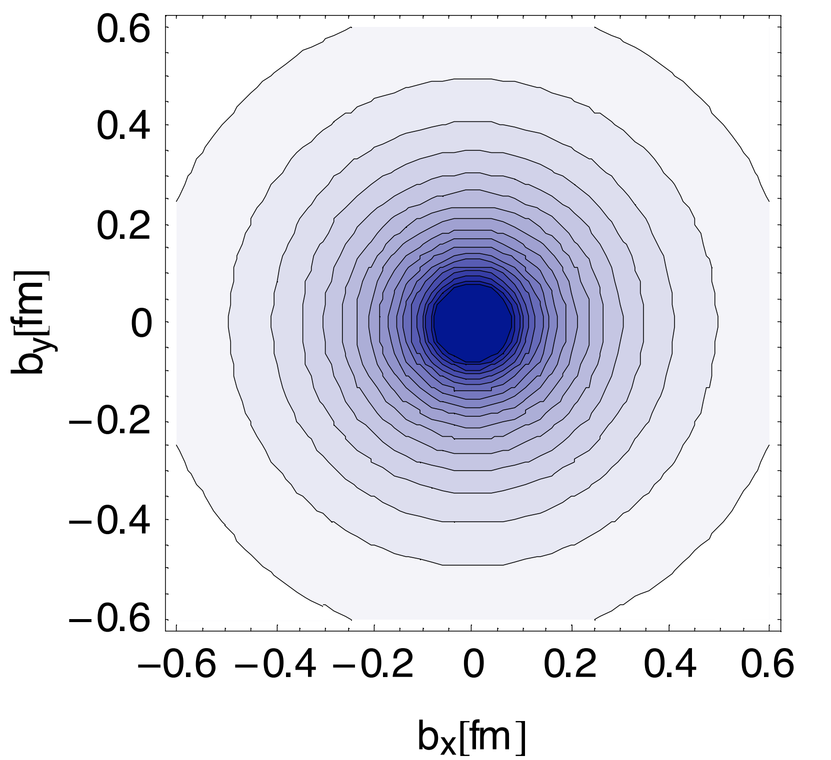
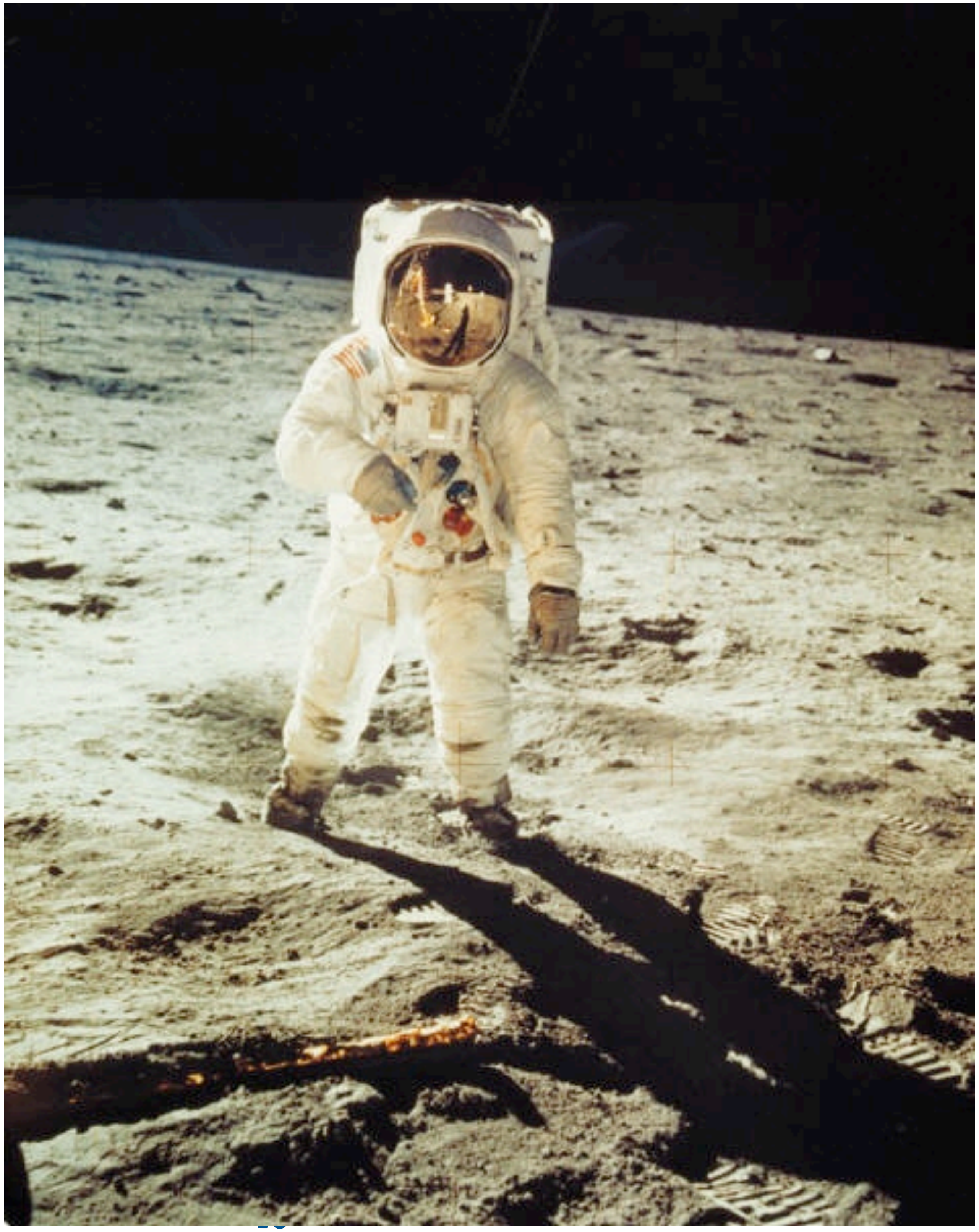


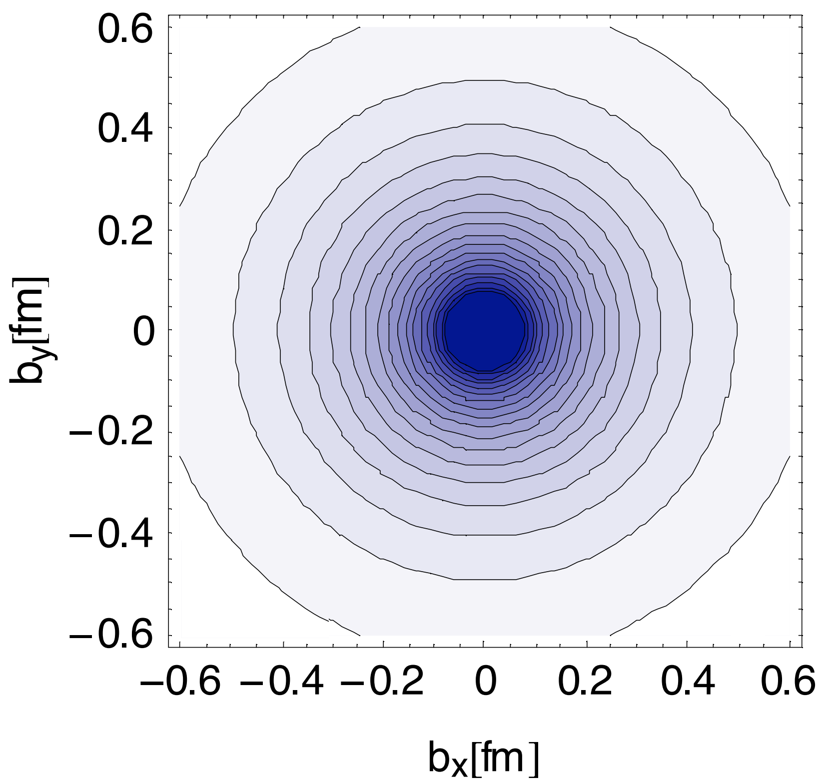
transverse size of proton

Last but not least ...

... curiosity



Towards a 3D picture of the nucleon



Form factors:
transverse distribution
of partons

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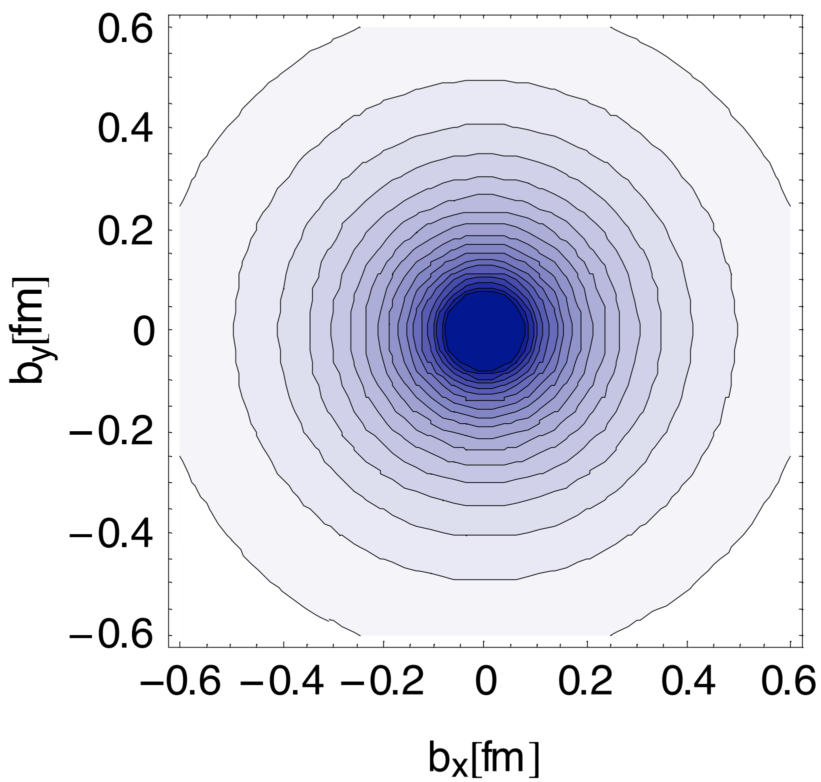

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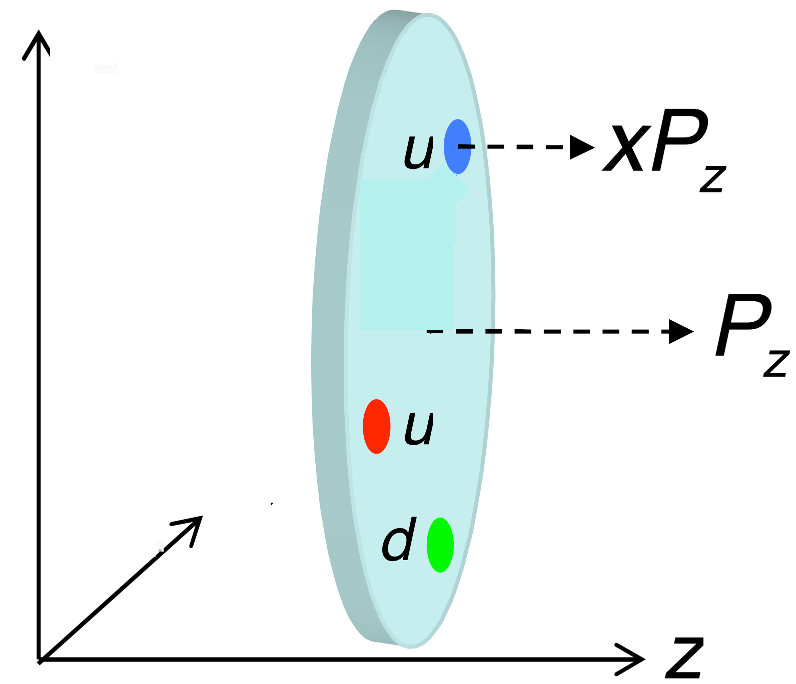
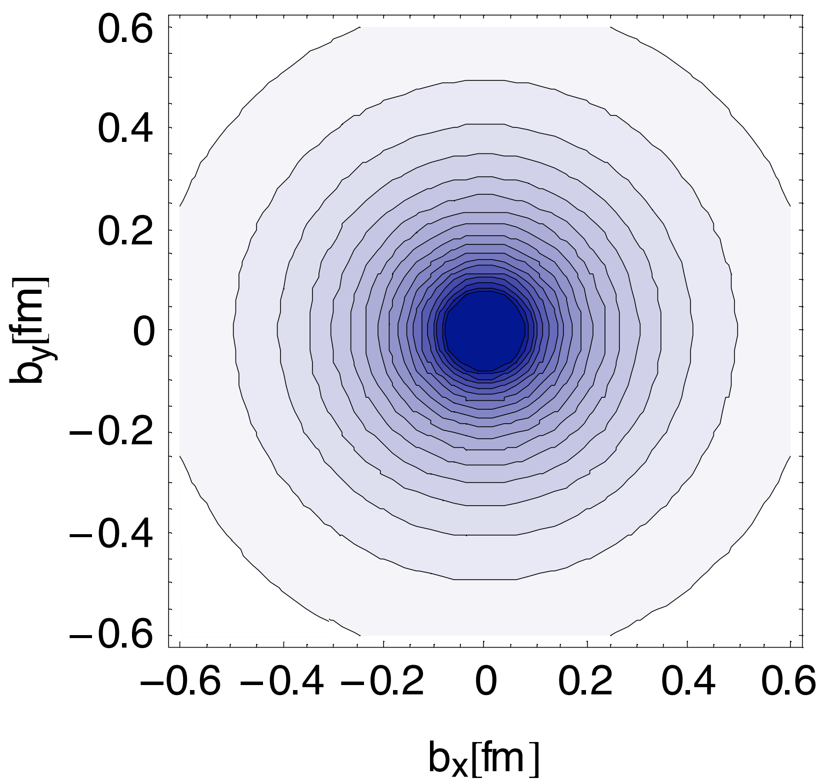


Parton distributions:
longitudinal momentum
of partons

Towards a 3D picture of the nucleon



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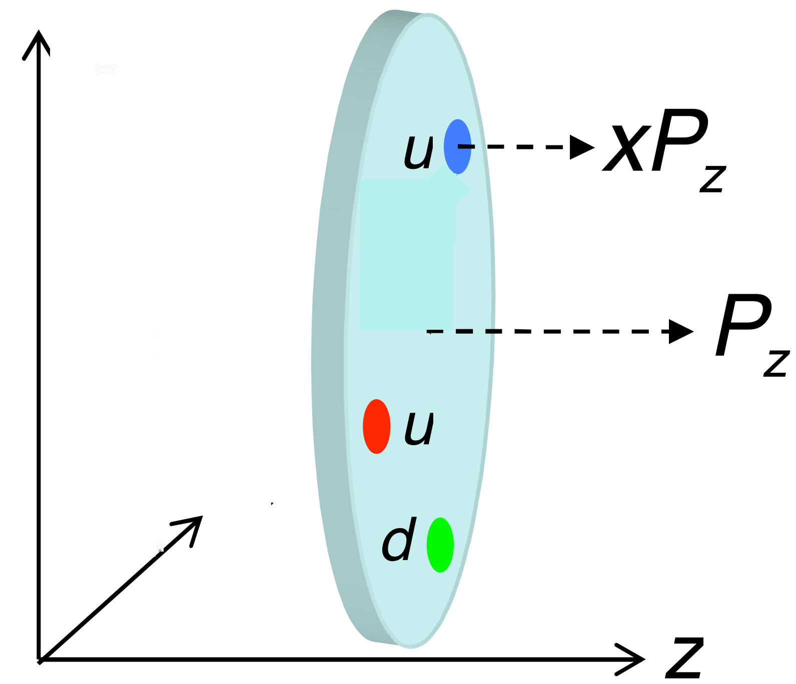

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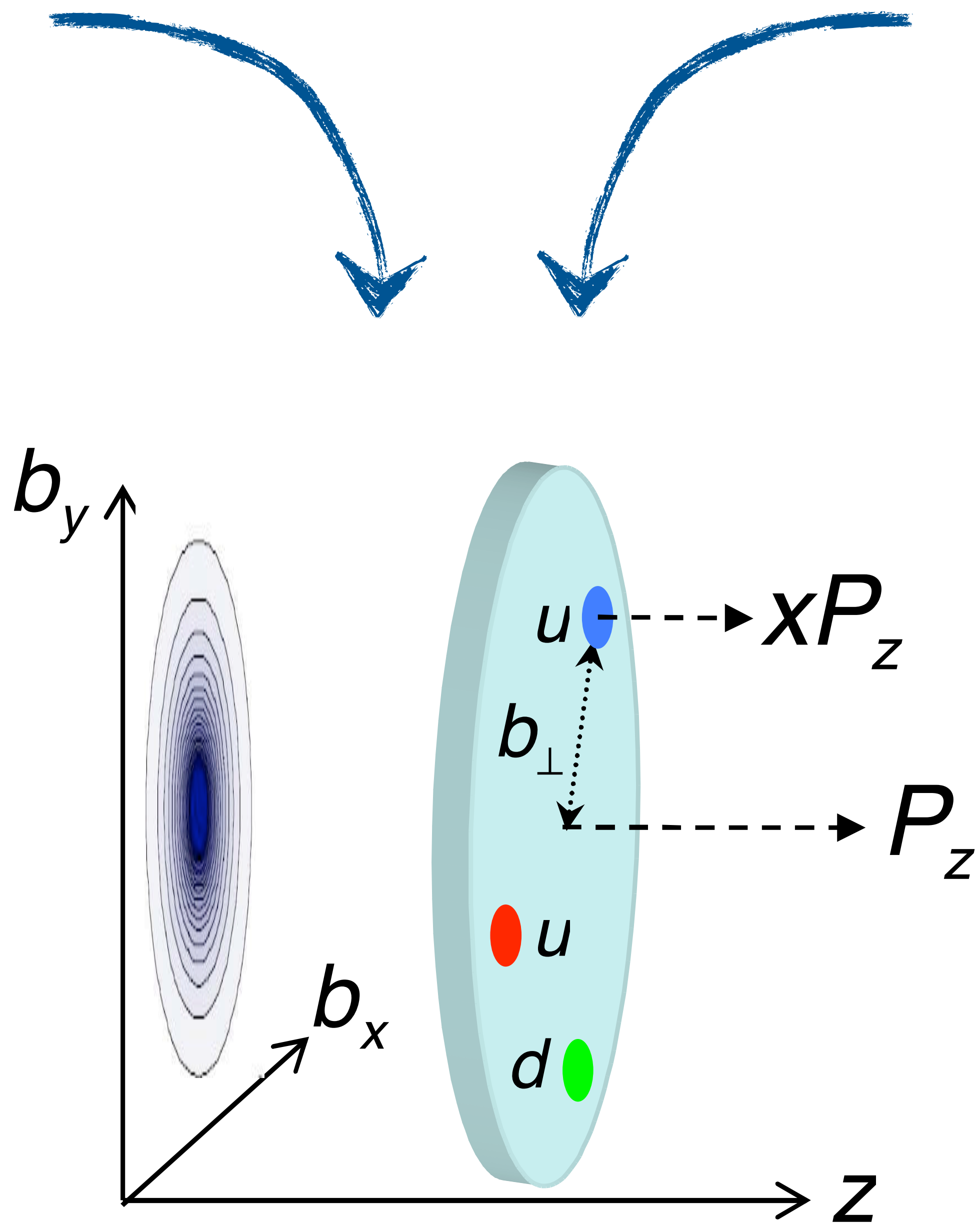
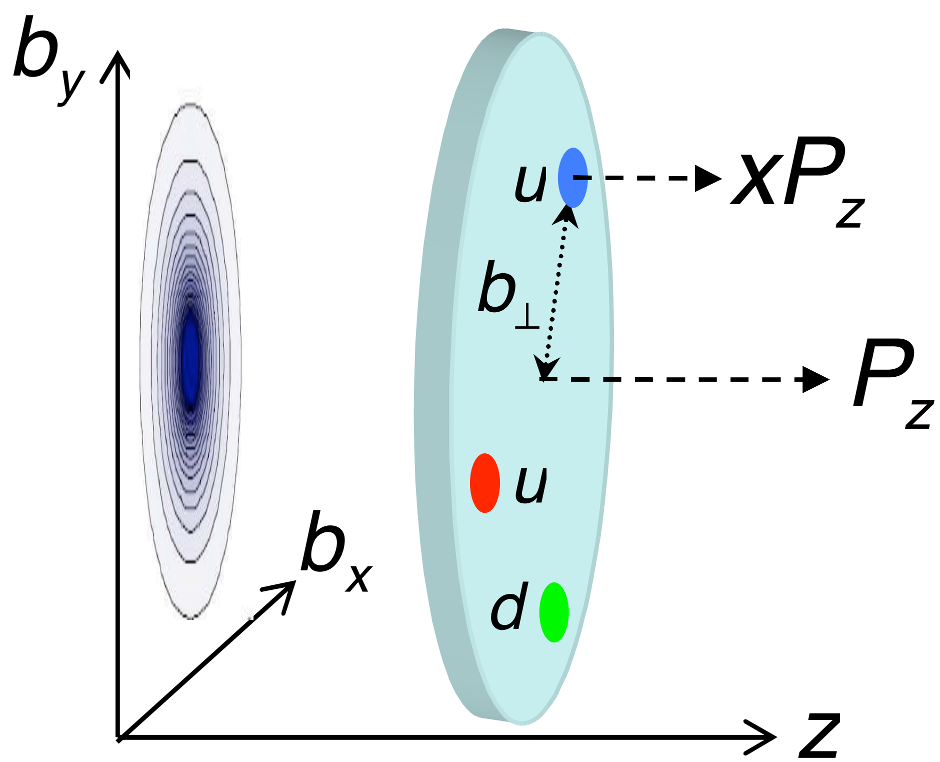
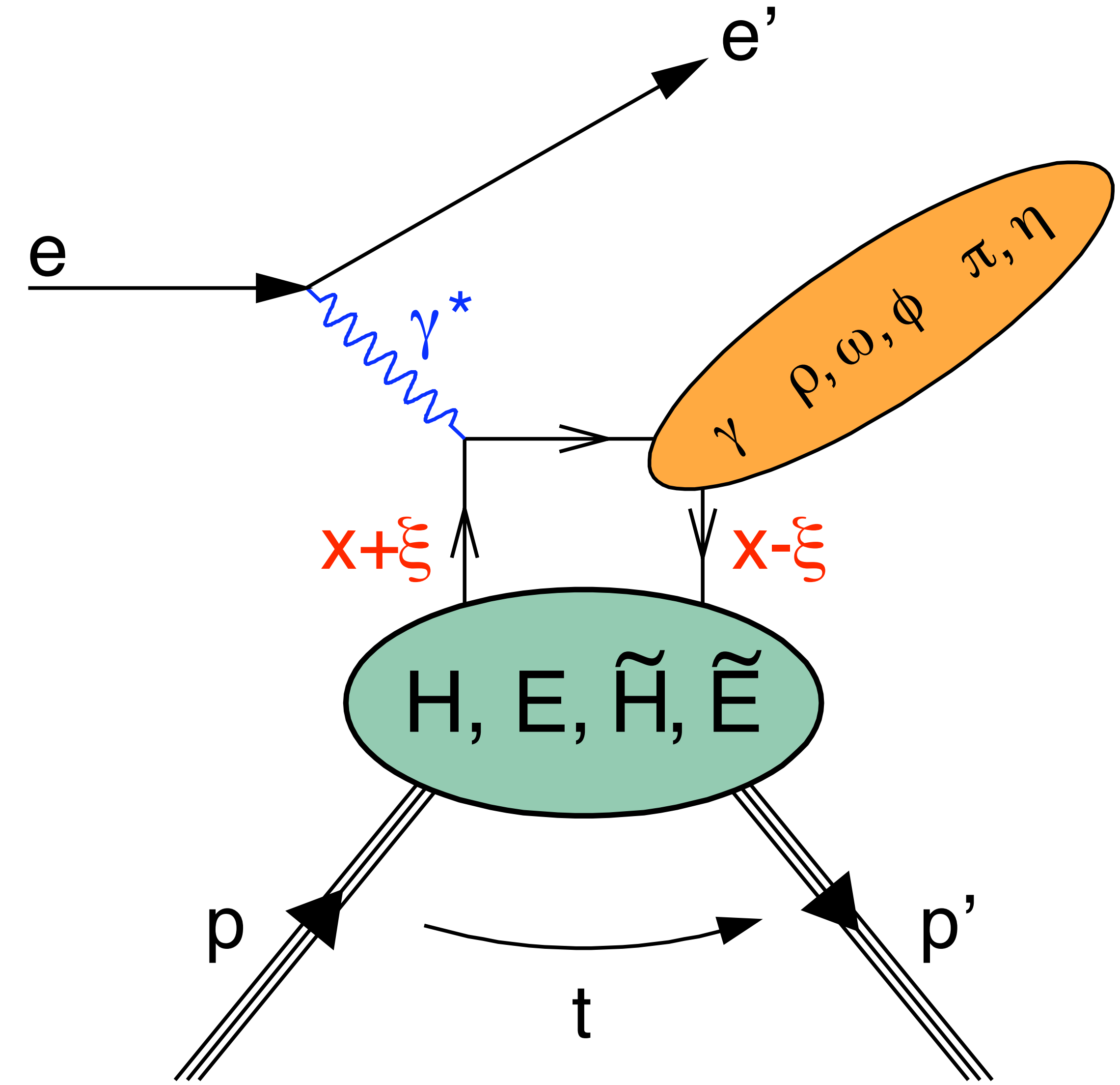


Nucleon Tomography
correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

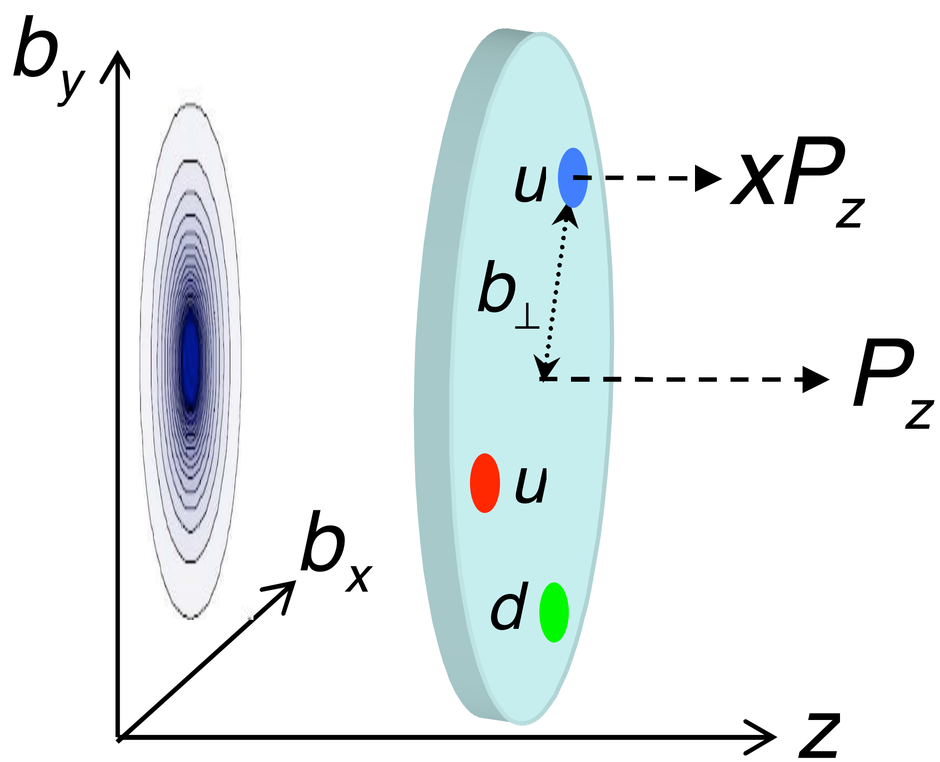


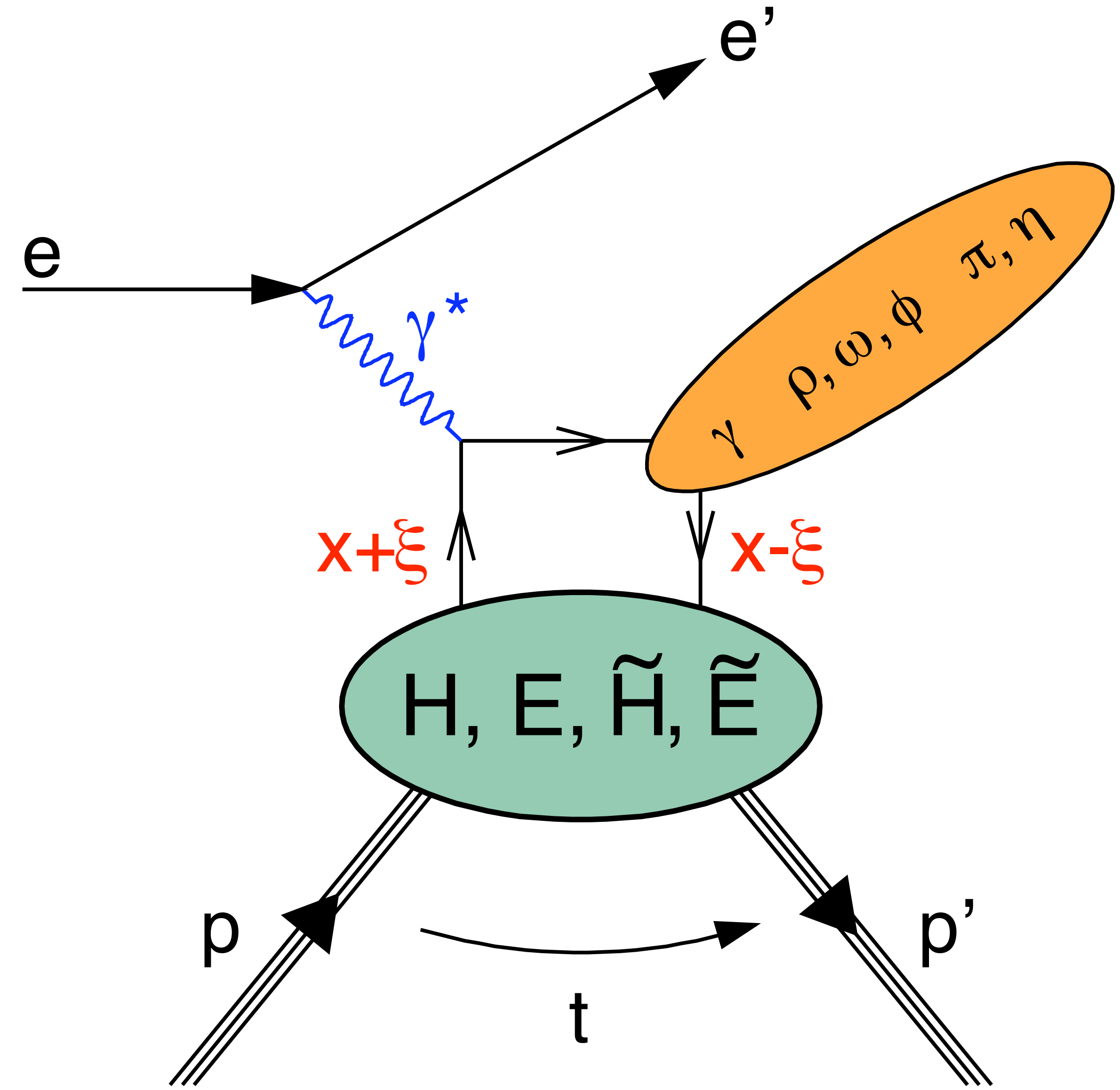


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

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

Probing GPDs in Exclusive Reactions

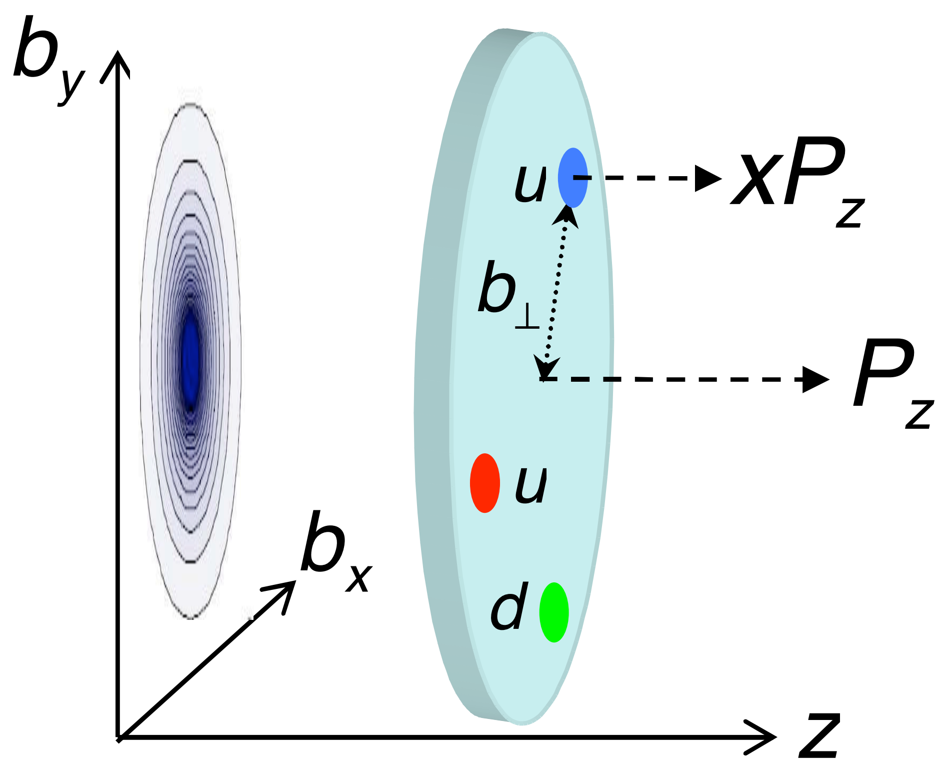


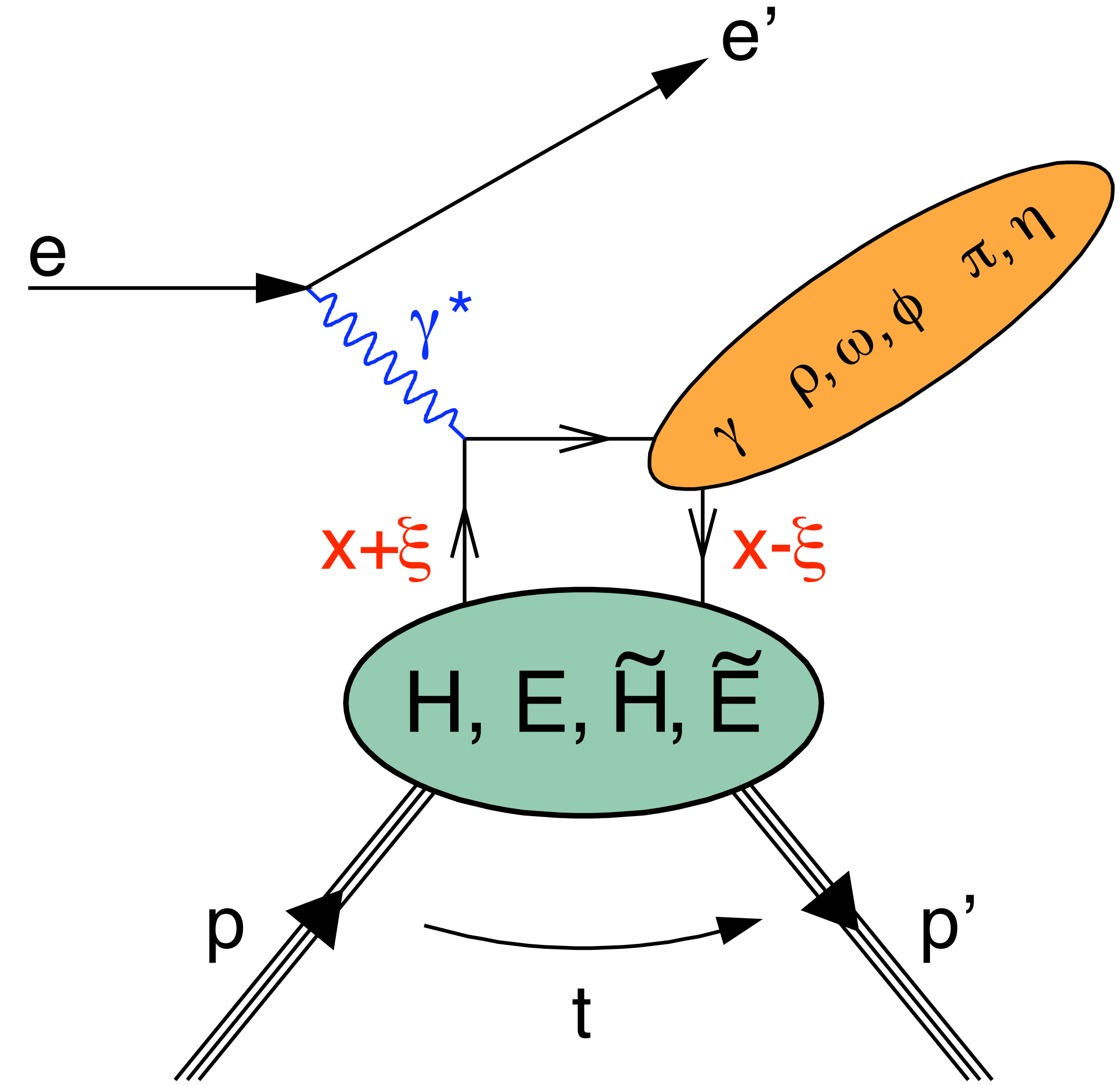


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





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

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

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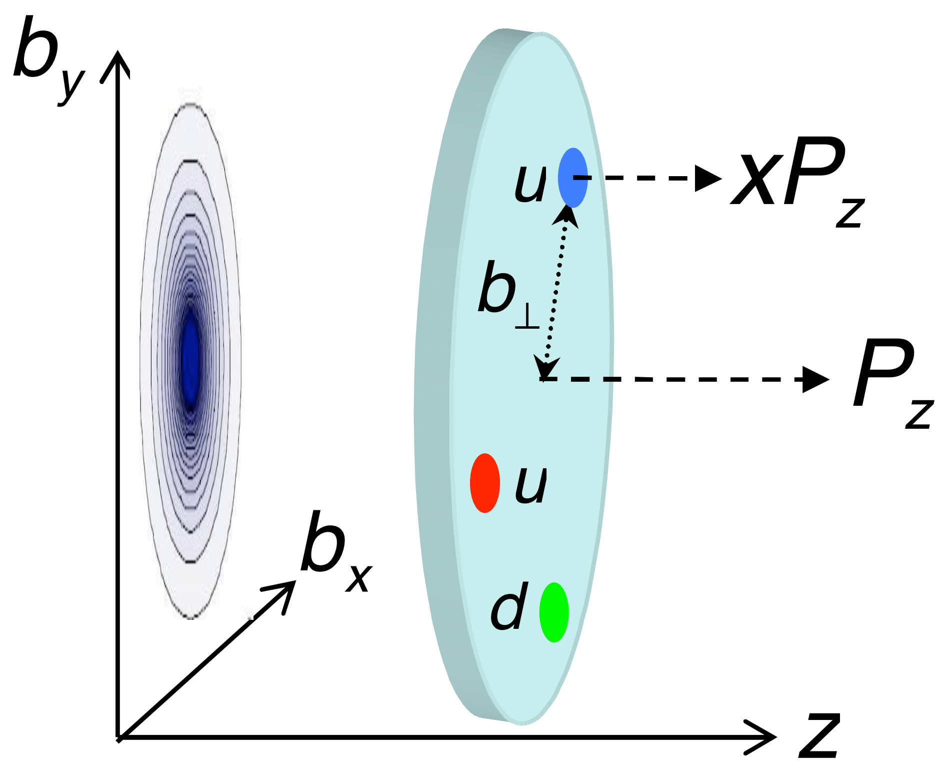

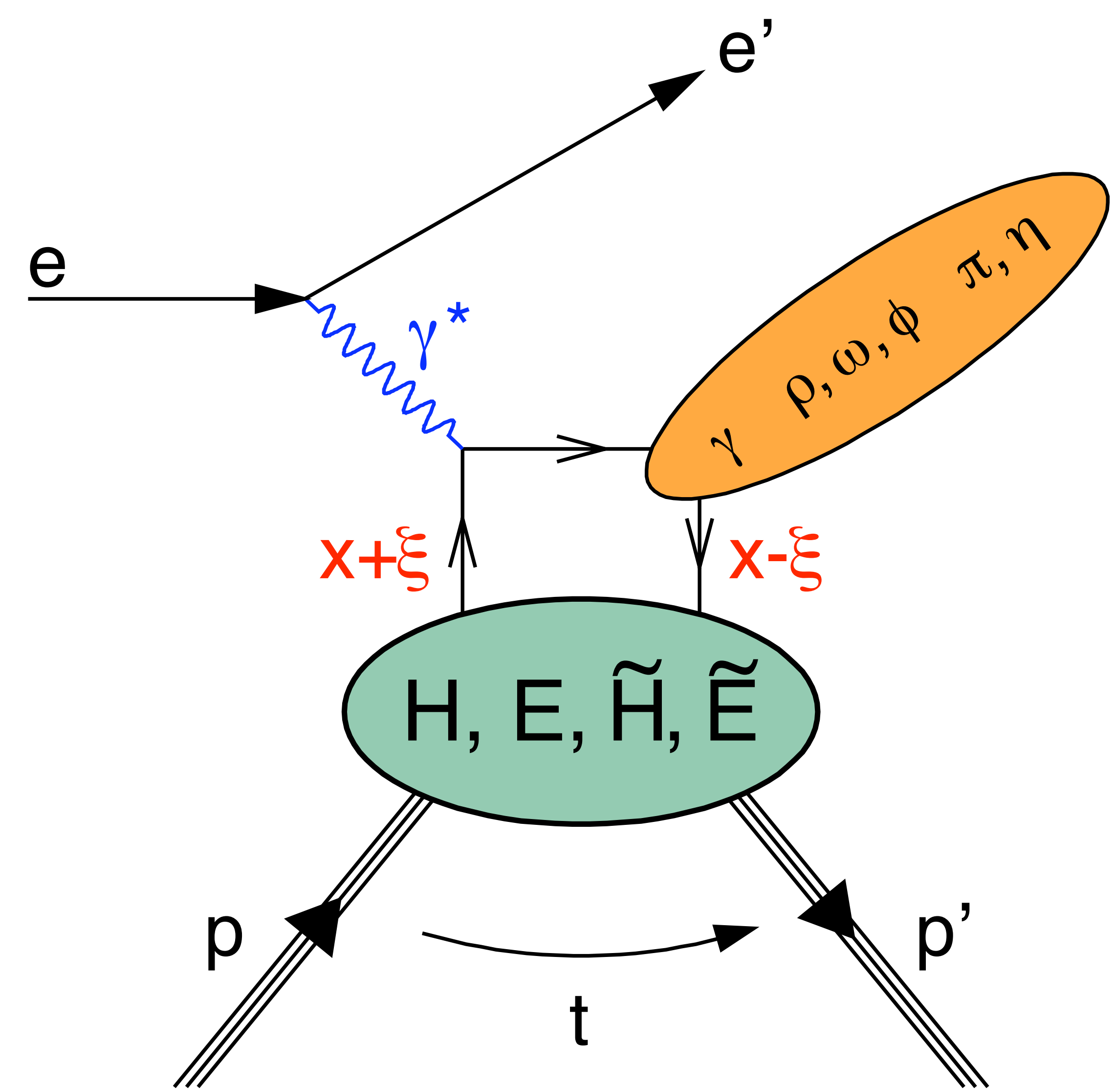

$$\int \mathrm{d}x H^q(x, \xi, t) = F_1^q(t)$$
$$\int \mathrm{d}x E^q(x, \xi, t) = F_2^q(t)$$

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

	no quark helicity flip	quark helicity flip
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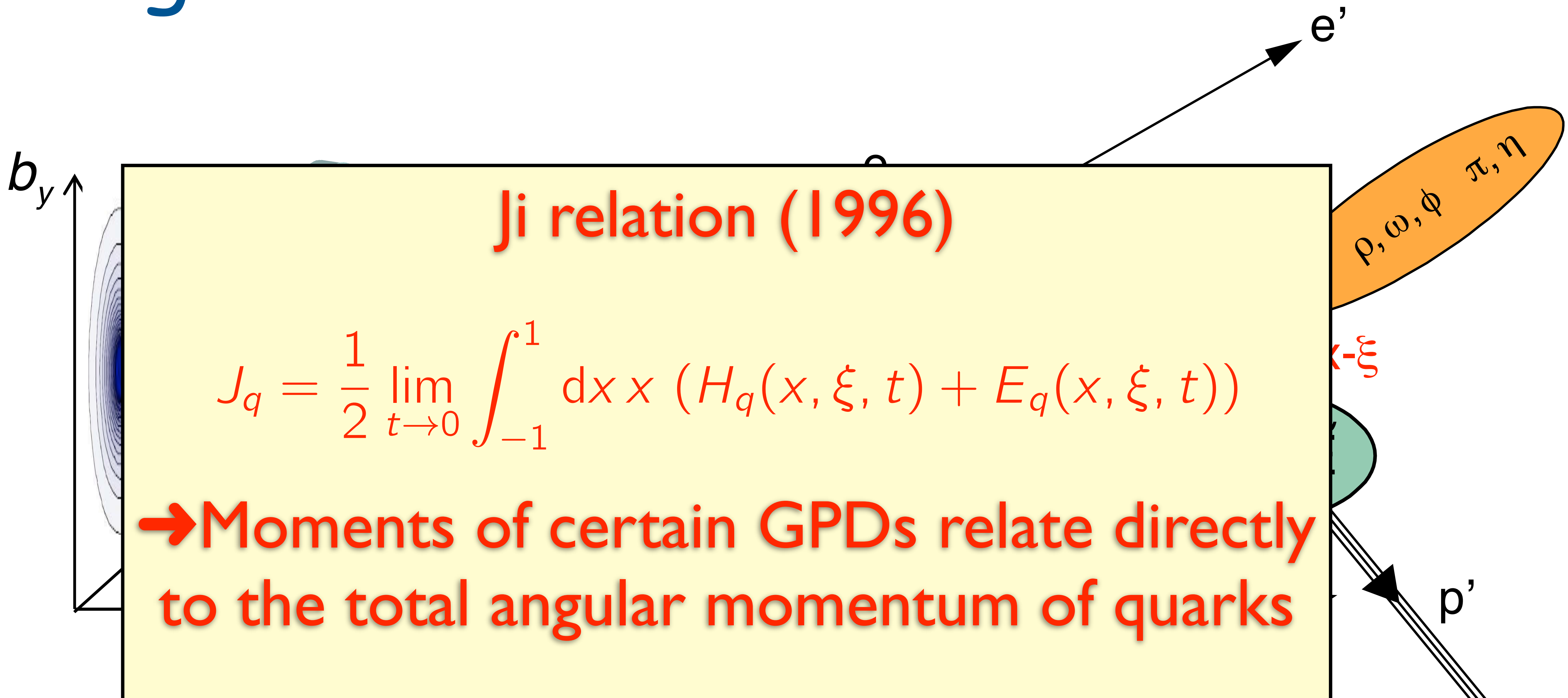

Ji relation (1996)

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

➔Moments of certain GPDs relate directly to the total angular momentum of quarks

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

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

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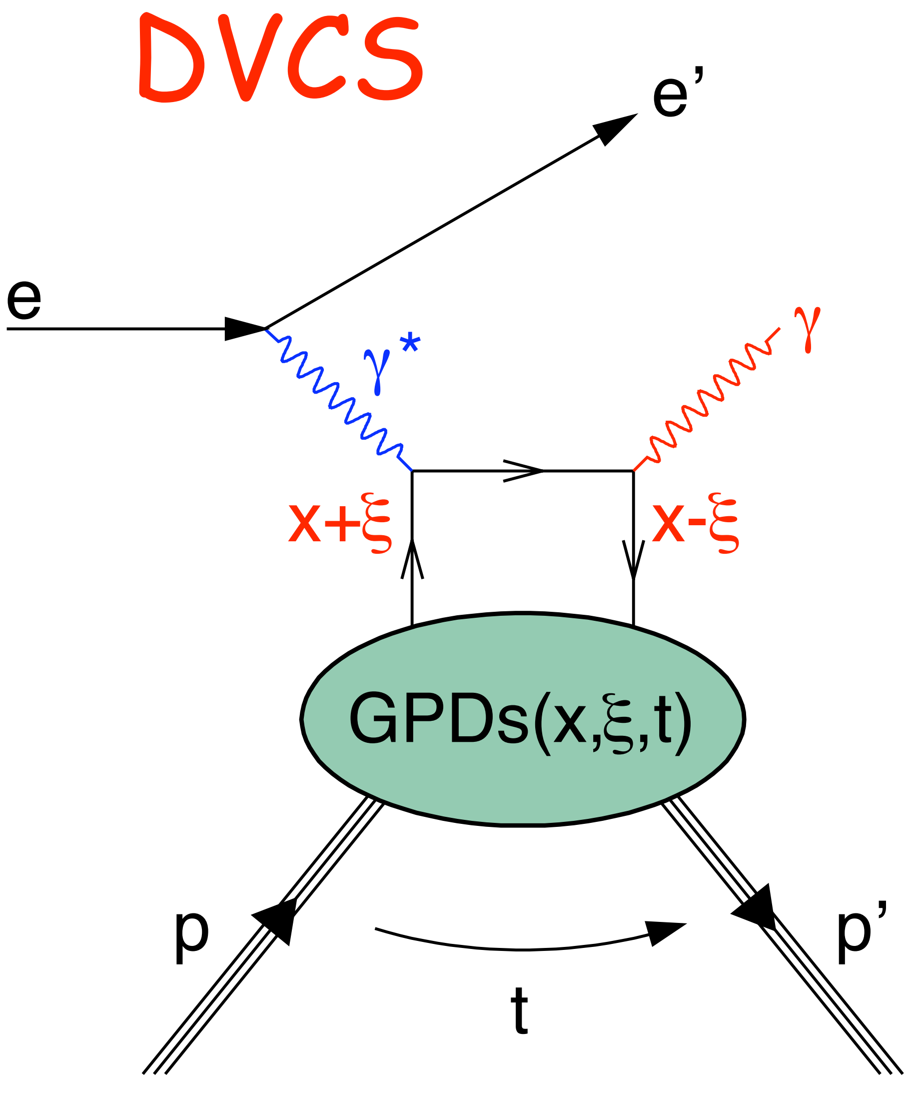
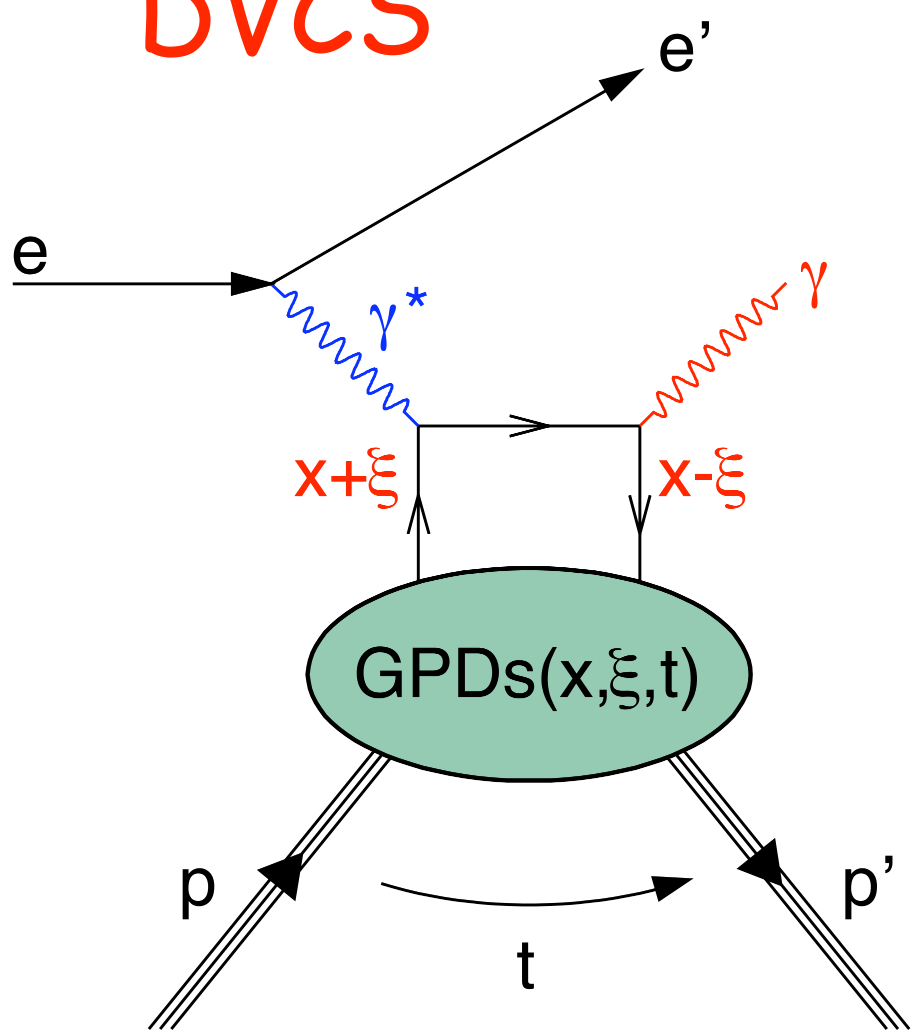
Real-photon production

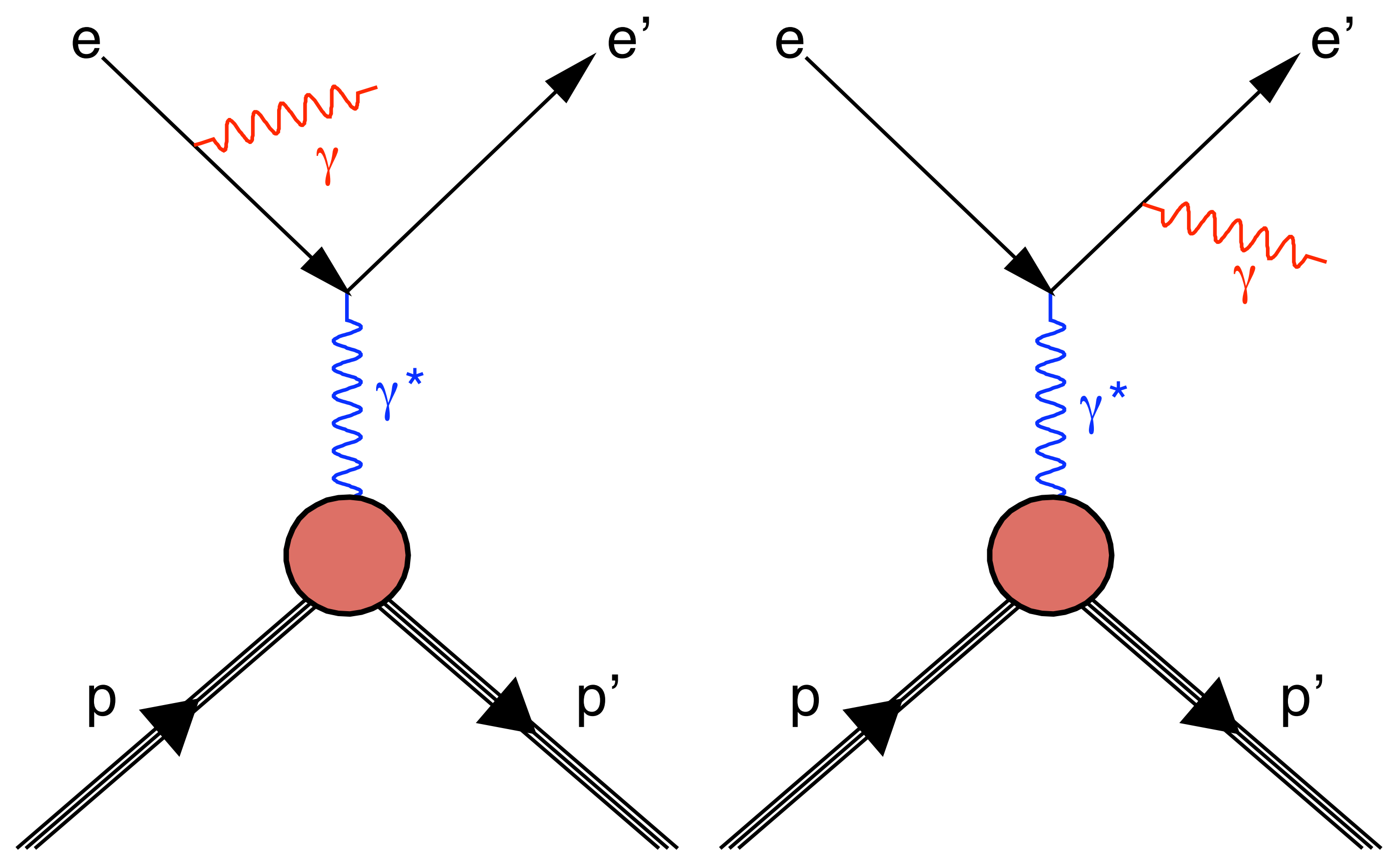


Real-photon production

DVCS



Bethe-Heitler



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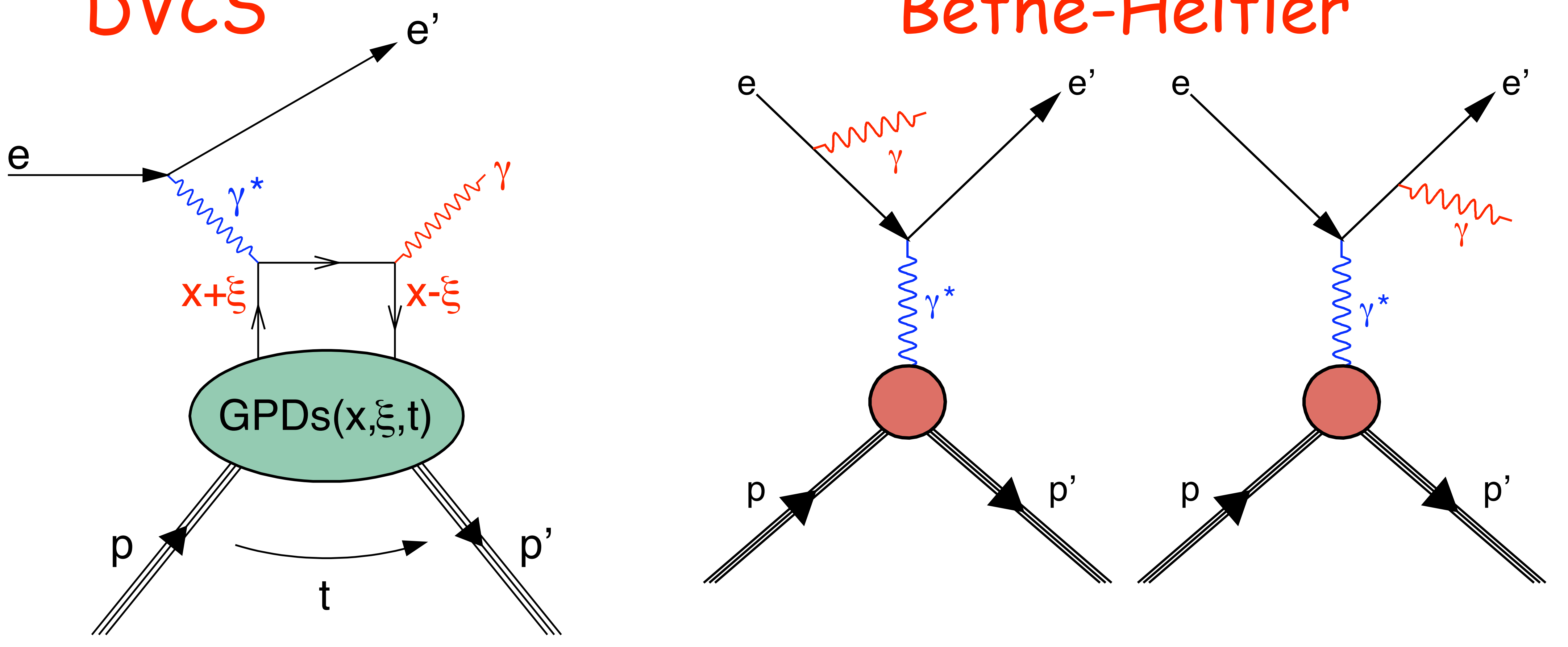
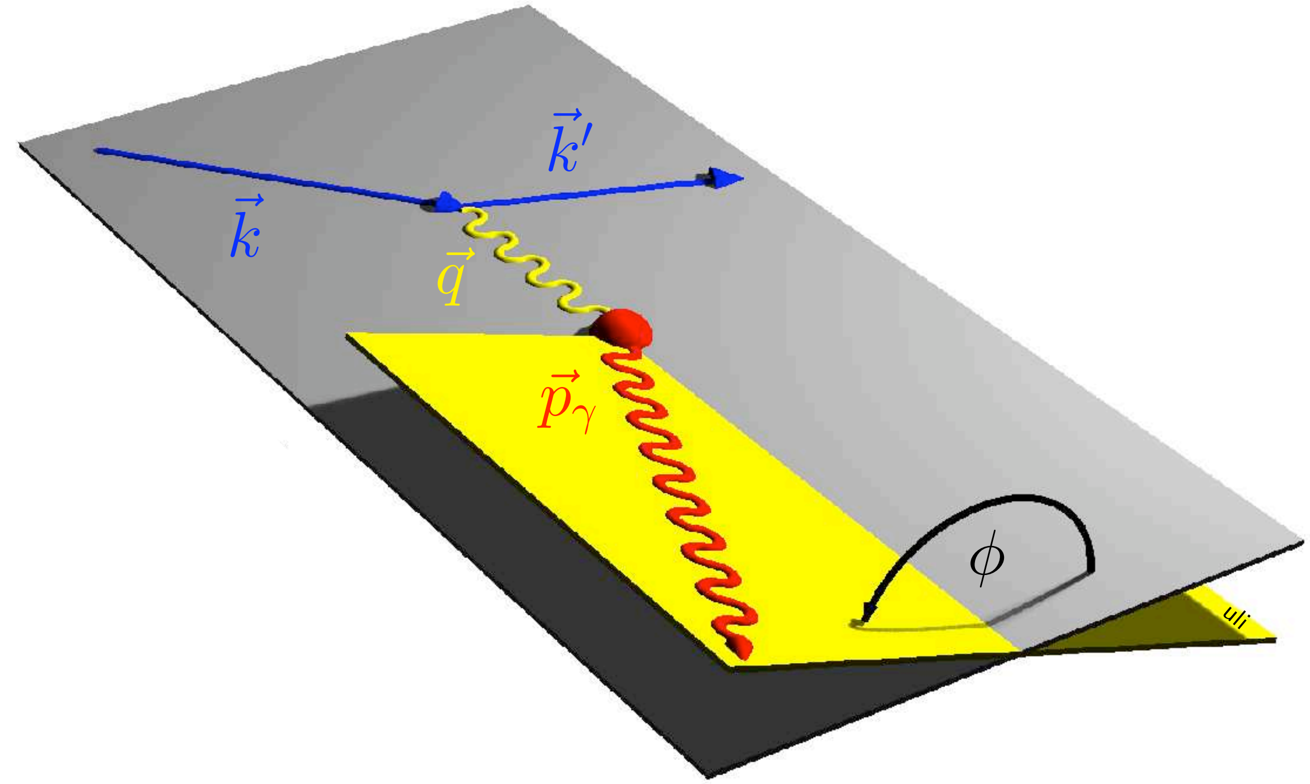


$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Azimuthal dependences in DVCS/BH

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



Fourier expansion for ϕ:

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

calculable in QED (using FF measurements)

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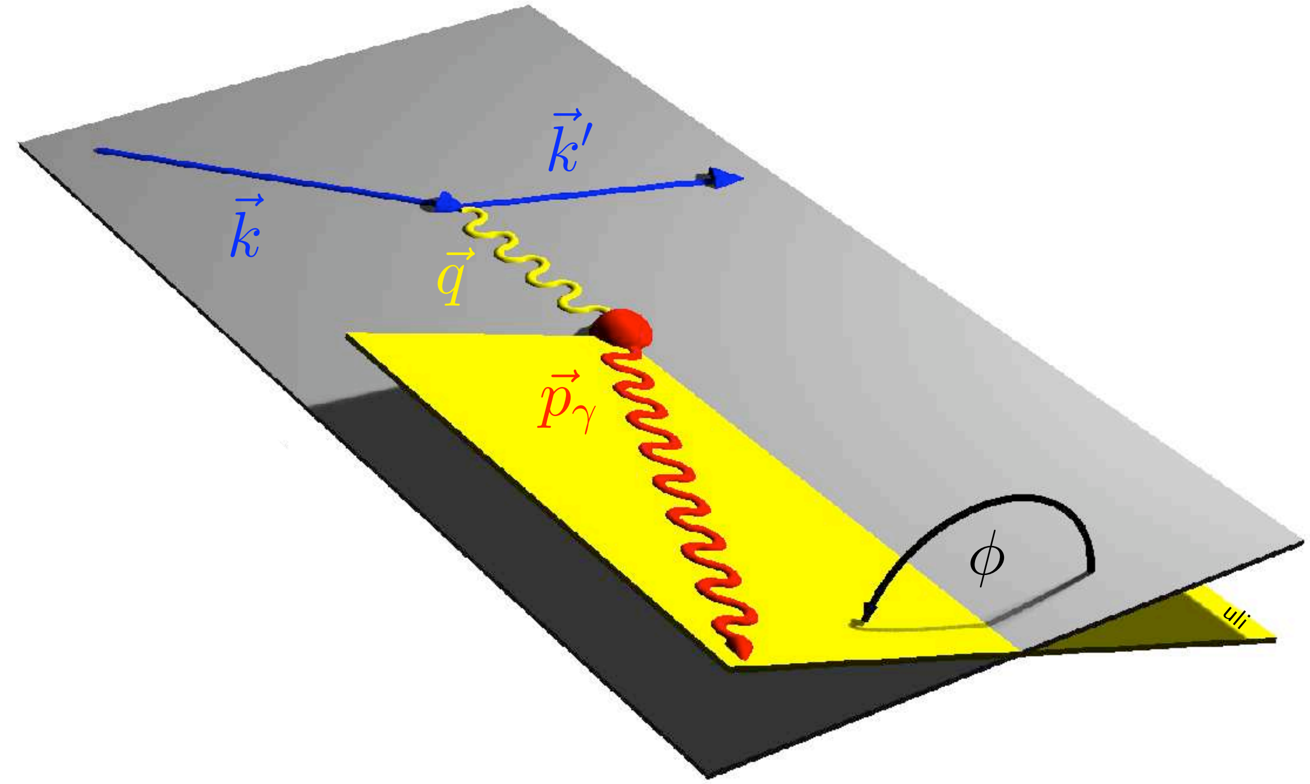

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$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

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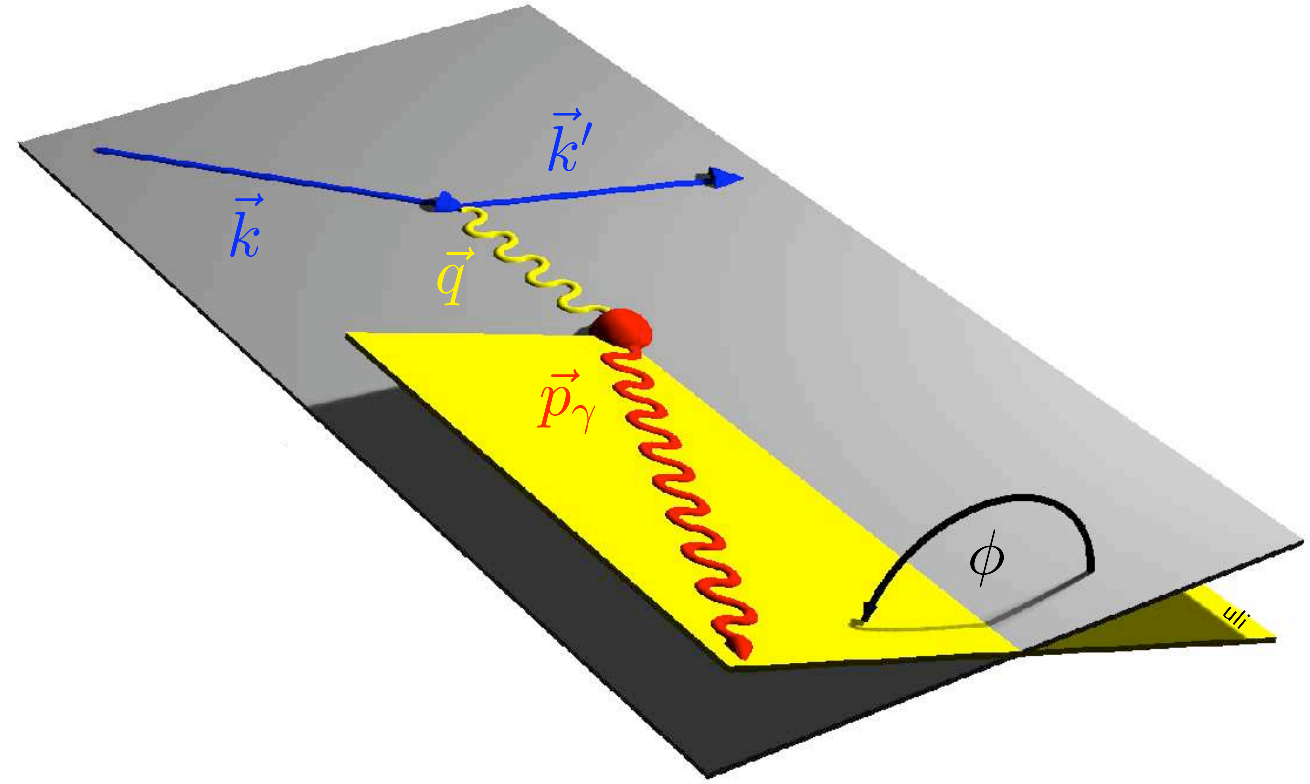

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$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

- beam polarization P_B
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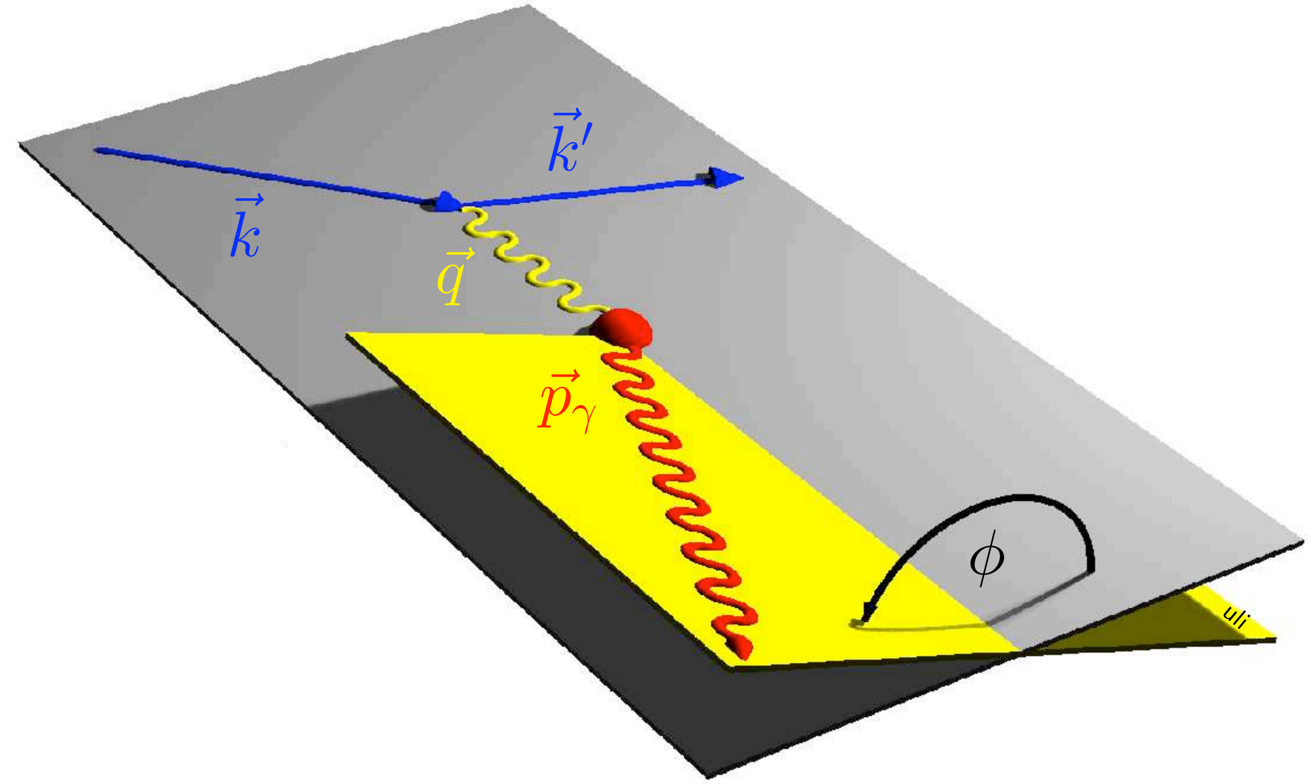

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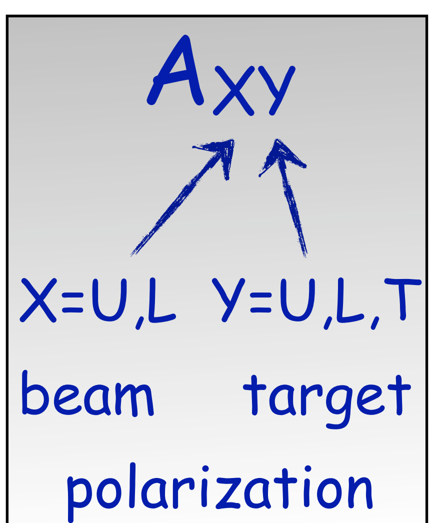
bilinear ("DVCS") or linear in GPDs

Azimuthal asymmetries in DVCS/BH

Cross section:

$$\sigma(\phi, \phi_S, P_B, C_B, P_T) = \sigma_{\mathrm{UU}}(\phi) \cdot \left[1 + P_B \mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B \mathcal{A}_{\mathrm{C}}(\phi)\right.$$



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$$|\mathcal{T}_{DVCS}|^2 = K_{DVCS}\, P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi)$$

A_{XY}

X=U,L beam

Y=U,L,T target

polarization

Azimuthal asymmetries in DVCS/BH

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$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}}\, P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi)$$

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

A_{XY}

X=U,L beam

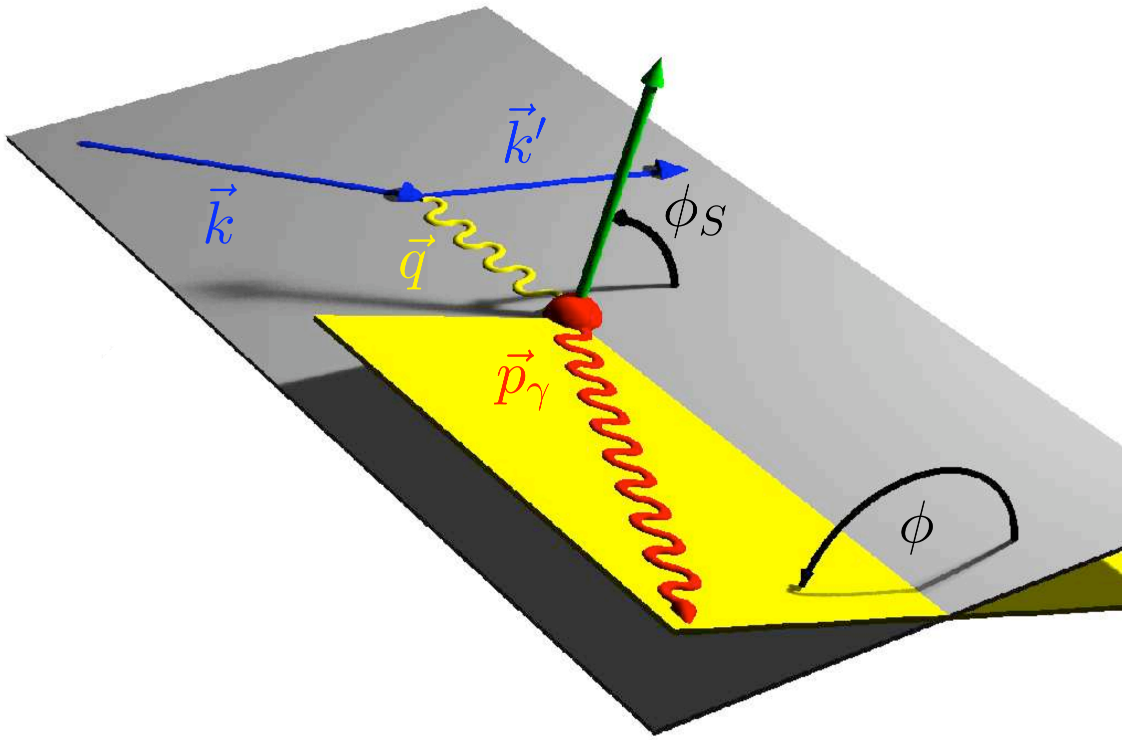
Y=U,L,T target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

$$\sigma(\phi, \phi_S, P_B, C_B, P_T) = \sigma_{\mathrm{UU}}(\phi) \cdot \left[1 + P_B \mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B \mathcal{A}_{\mathrm{C}}(\phi)\right.$$



A$_{XY}$

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beam target

polarization

Azimuthal asymmetries in DVCS/BH

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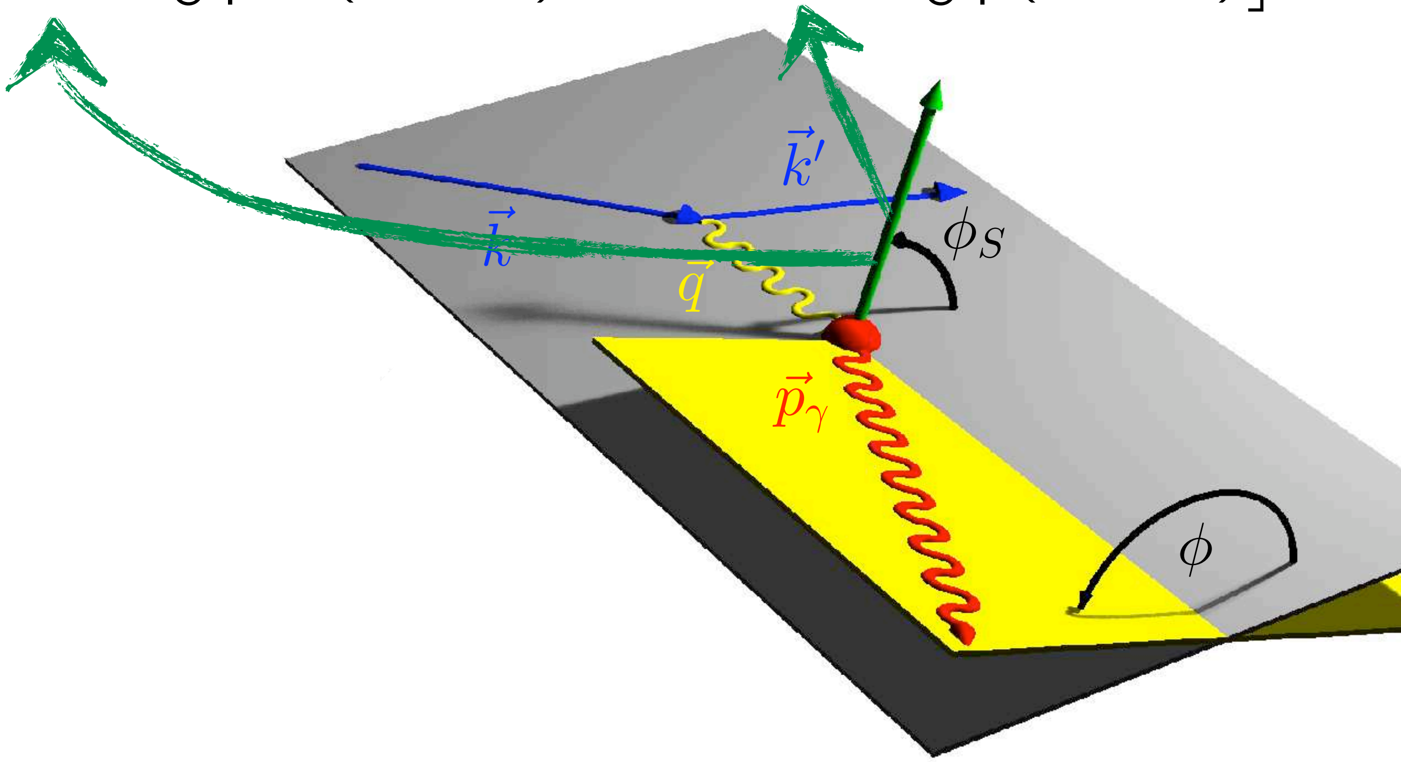
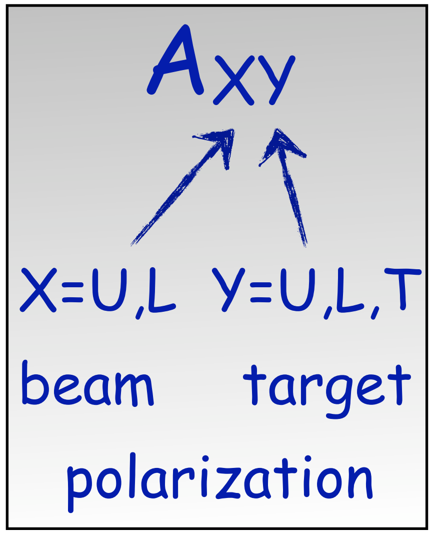


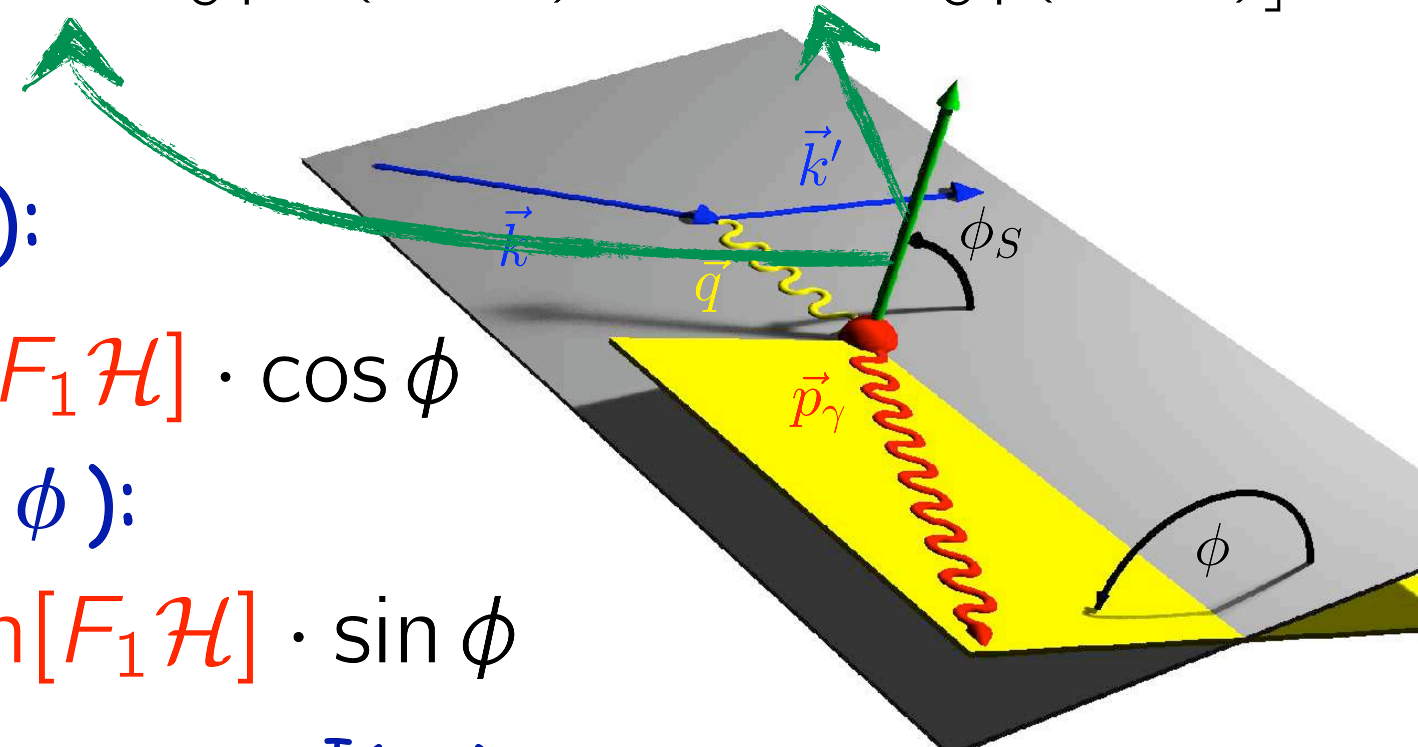


Azimuthal asymmetries in DVCS/BH

Cross section:

$$\sigma(\phi,\phi_S,P_B,C_B,P_T) = \sigma_{\mathrm{UU}}(\phi)\cdot\Big[1 + P_B\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B\mathcal{A}_{\mathrm{C}}(\phi)$$
$$+ P_T\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S) + C_B P_T \mathcal{A}_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_S)\Big]$$

Azimuthal asymmetries, e.g.,



- Beam-charge asymmetry $A_C(\phi)$:

$$d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}]\cdot\cos\phi$$

- Beam-helicity asymmetry $A_{LU}^{I}(\phi)$:

$$d\sigma(e^{\rightarrow},\phi) - d\sigma(e^{\leftarrow},\phi) \propto \mathrm{Im}[F_1\mathcal{H}]\cdot\sin\phi$$

- Transverse target-spin asymmetry $A_{UT}^{I}(\phi)$:

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\cdot\sin(\phi-\phi_S)\cos\phi$$
$$+\ \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]\cdot\cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli form factors)

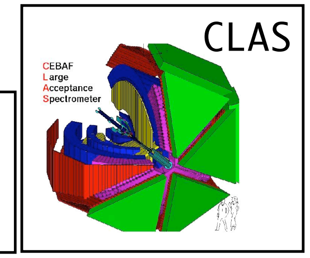
($\mathcal{H}$,$\mathcal{E}$ ... Compton form factors involving GPDs H, E, ...)

Experimental requirements

- different beam charges
- longitudinal beam polarization
- target polarization:
  - longitudinal
  - transverse
- exclusivity:
  - missing-mass technique
  - recoil-proton detection

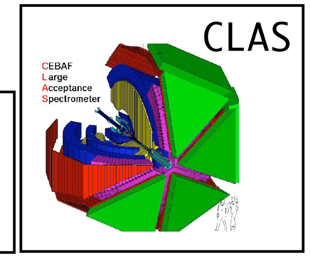
Experimental requirements

Hall A JLab



- different beam charges ☐ (planned)
- longitudinal beam polarization ☑
- target polarization:
  - longitudinal ☑
  - transverse ☐ (planned)
- exclusivity:
  - missing-mass technique ☑
  - recoil-proton detection ☐

Experimental requirements

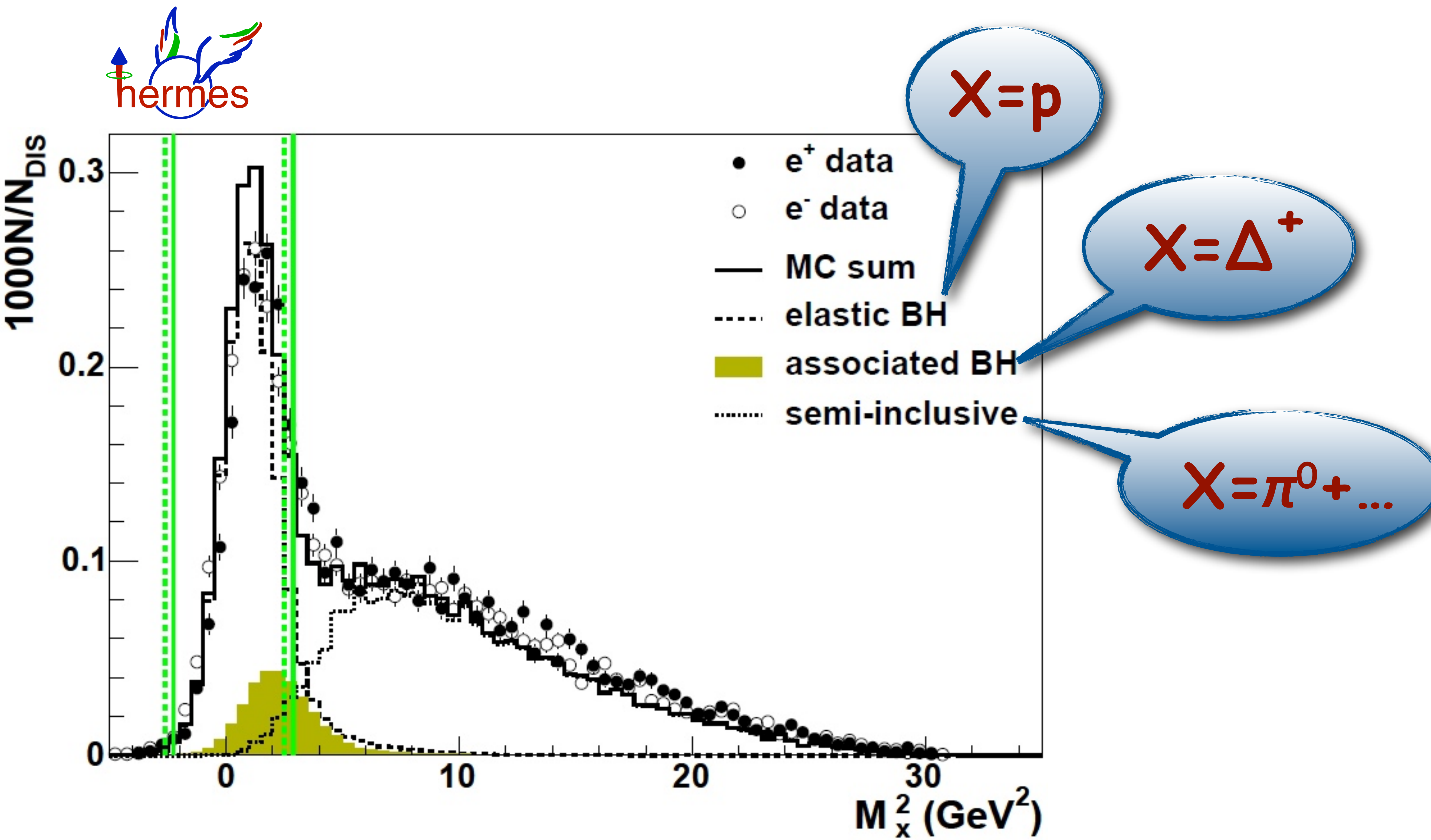


	Hall A JLab	CLAS	hermes
• different beam charges	☐	(planned)	☑
• longitudinal beam polarization	☑		☑
• target polarization:			
◦ longitudinal	☑		☑
◦ transverse	☐	(planned)	☑
• exclusivity:			
◦ missing-mass technique	☑		☑
◦ recoil-proton detection	☐		☑

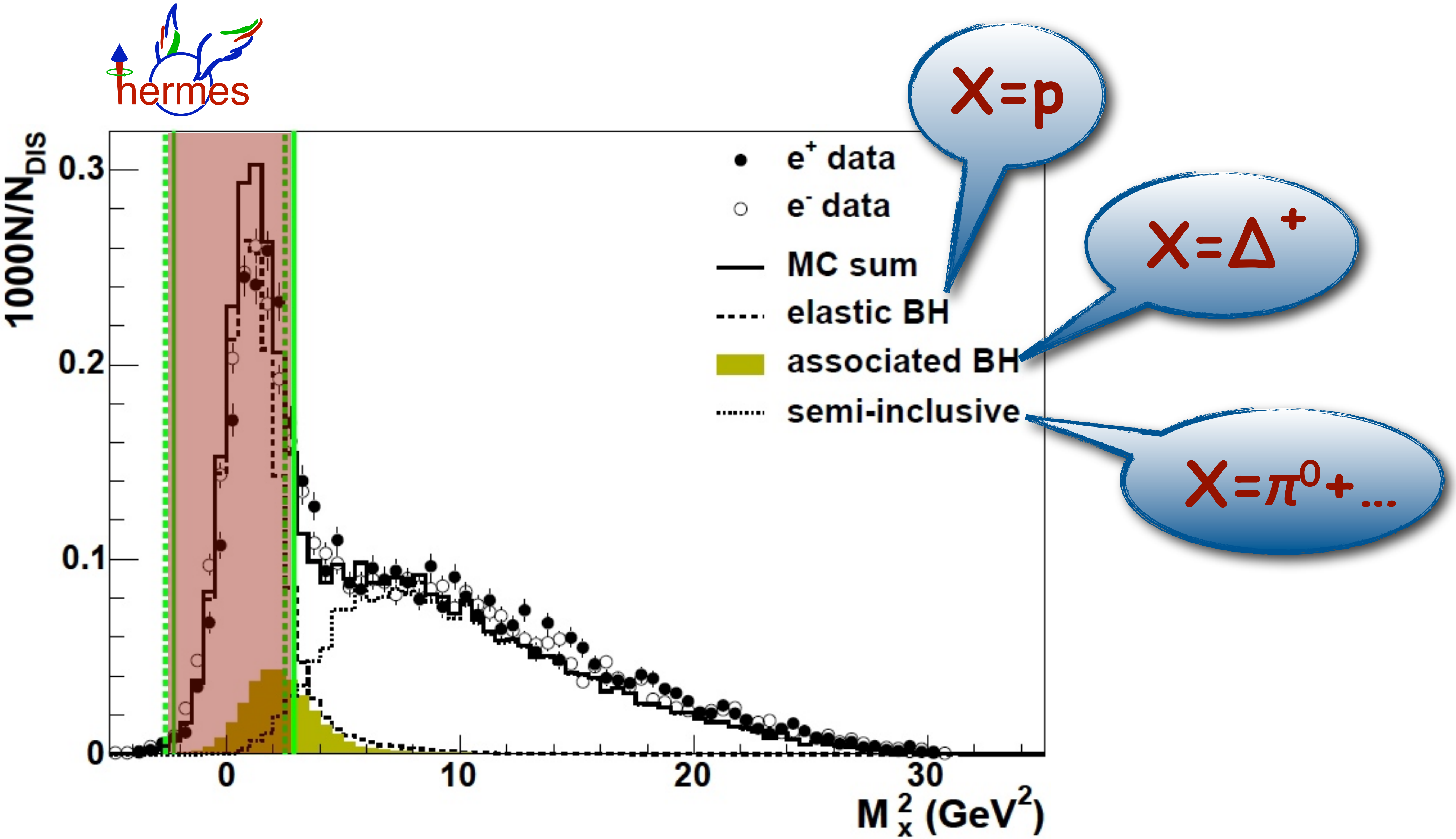
Experimental requirements

	Hall A JLab	CLAS	hermes	COMPASS (planned)
• different beam charges	☐	(planned)	☑	☑
• longitudinal beam polarization	☑		☑	☑
• target polarization:				
• longitudinal	☑		☑	☐
• transverse	☐	(planned)	☑	☑
• exclusivity:				
• missing-mass technique	☑		☑	☐
• recoil-proton detection	☐		☑	☑

Exclusivity: missing-mass technique



Exclusivity: missing-mass technique



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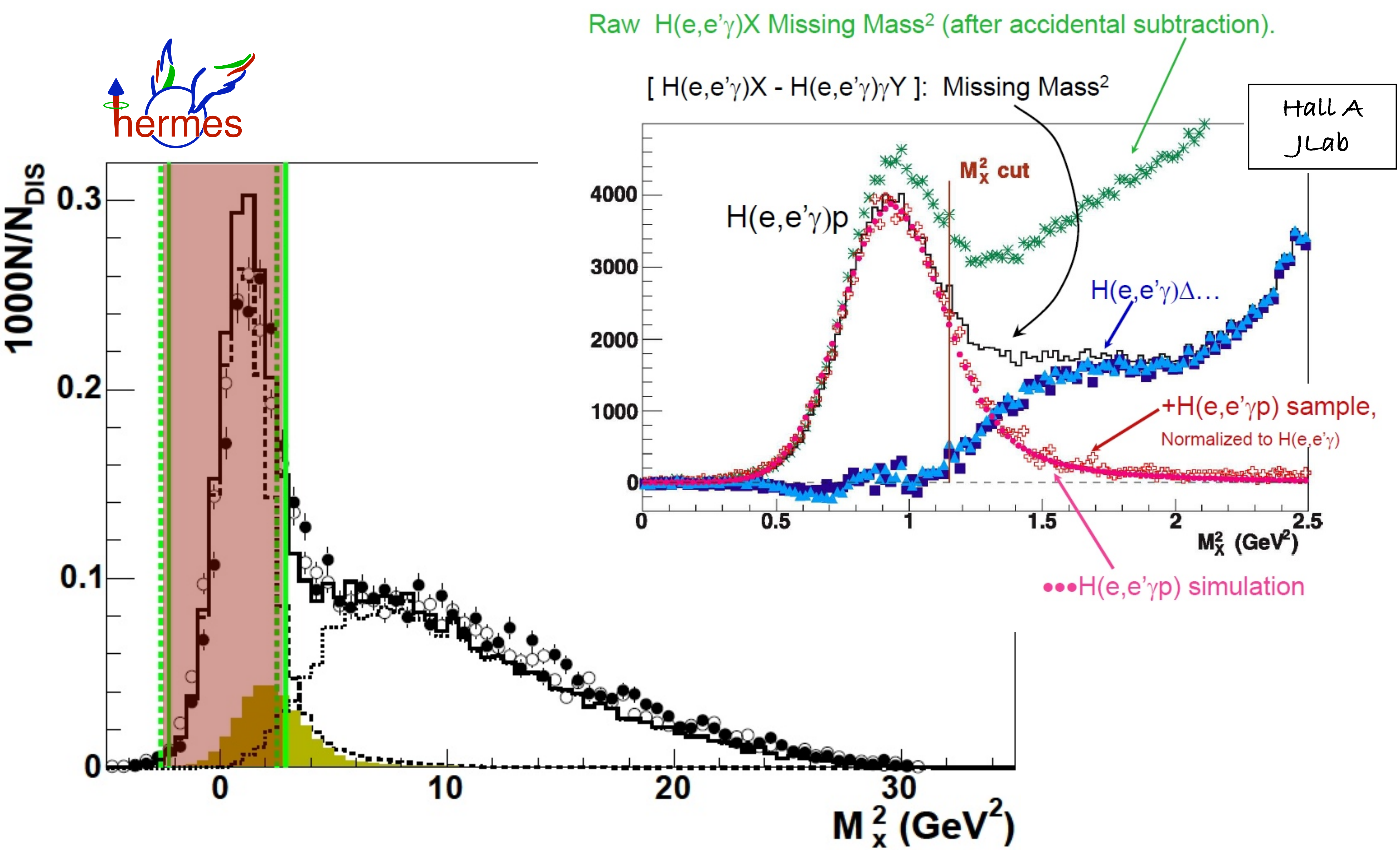
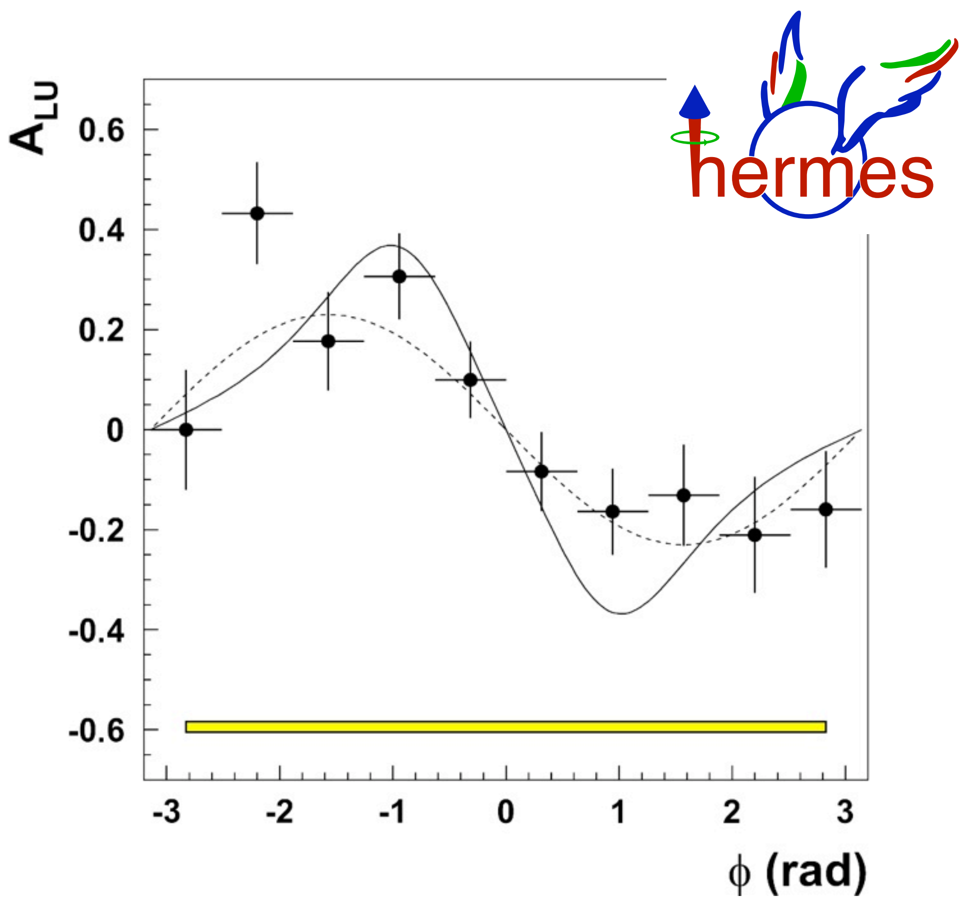
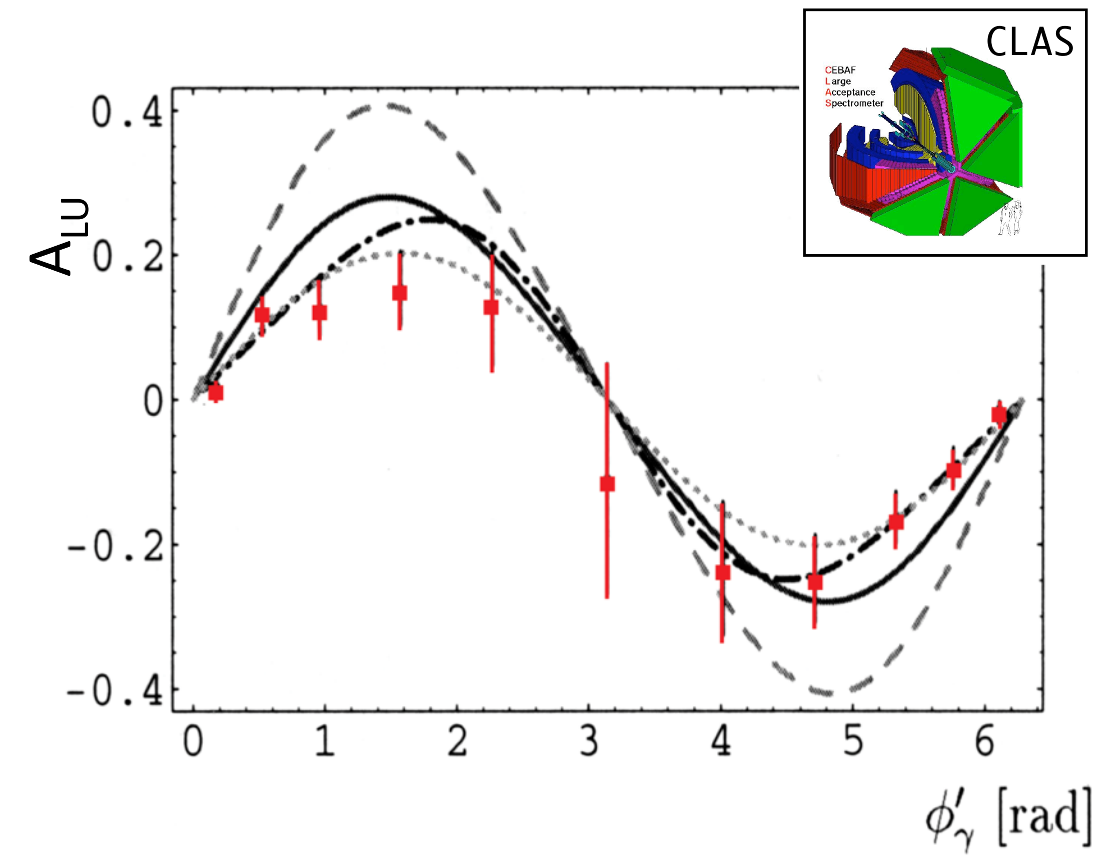


First DVCS signals ...

... from interference with BH   [PRL 87 (2001)]

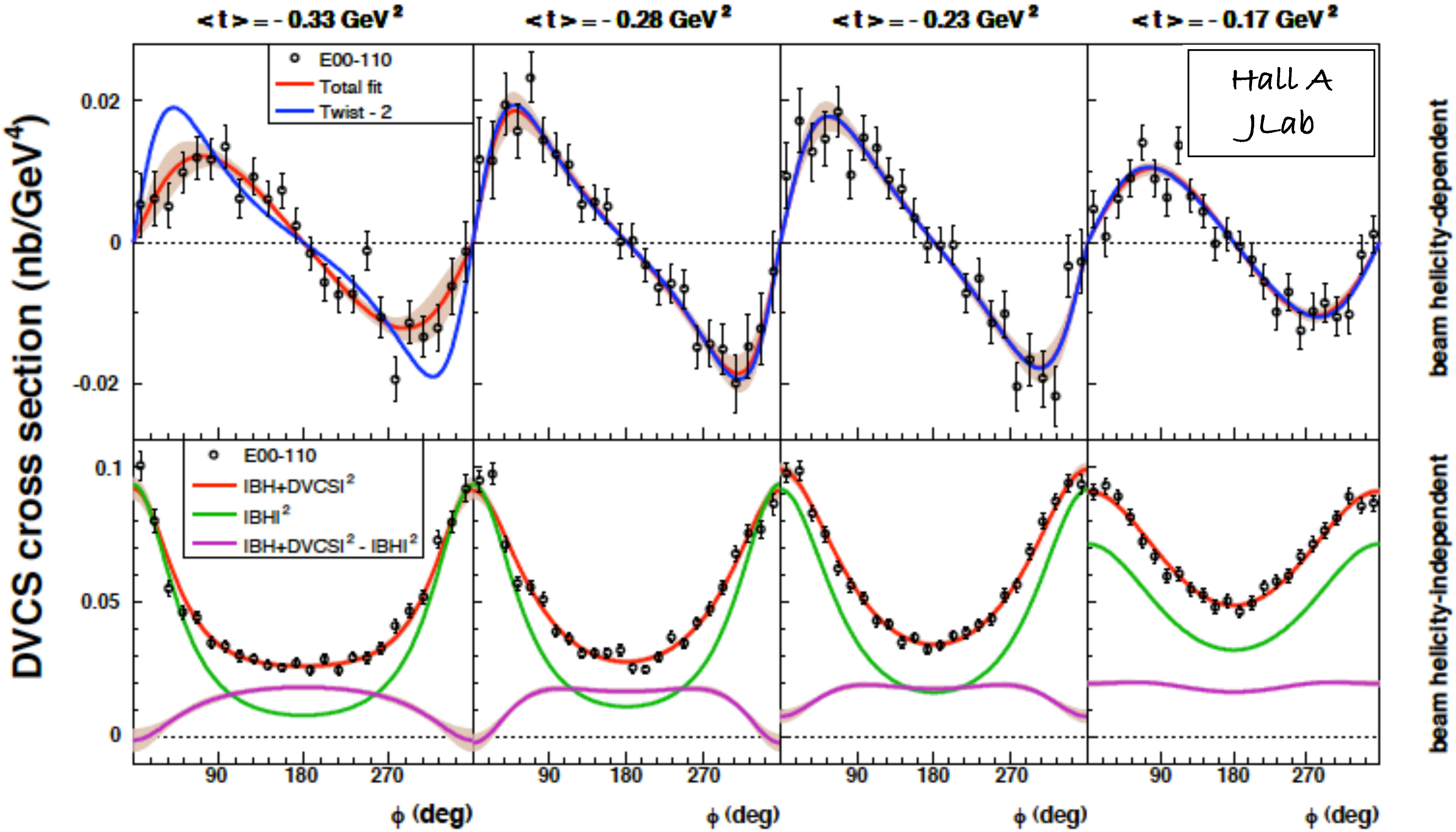




clear sinusoidal modulations

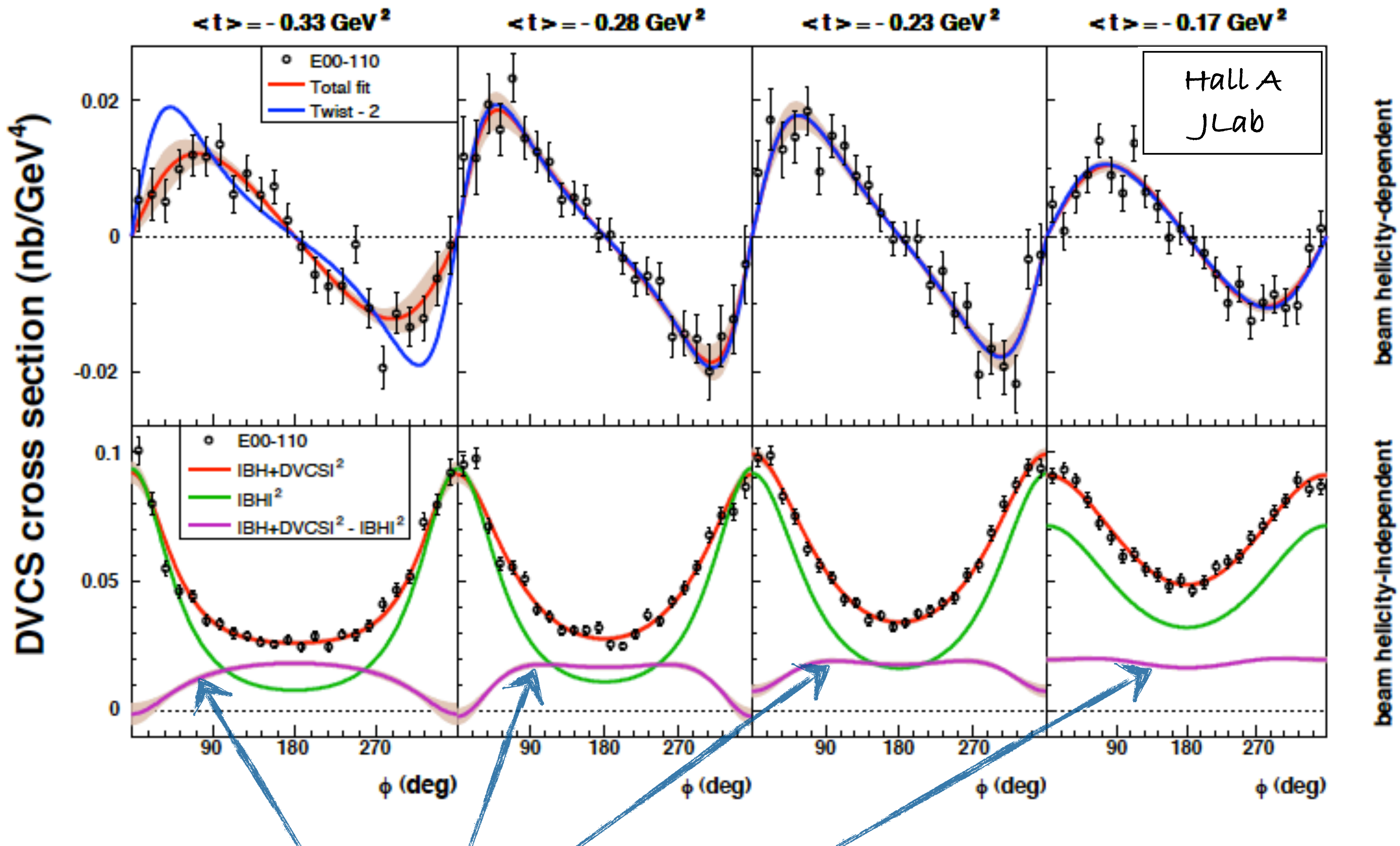
support of handbag approach

Increasing statistics ...



[V. Burkert @ Transversity 2011]

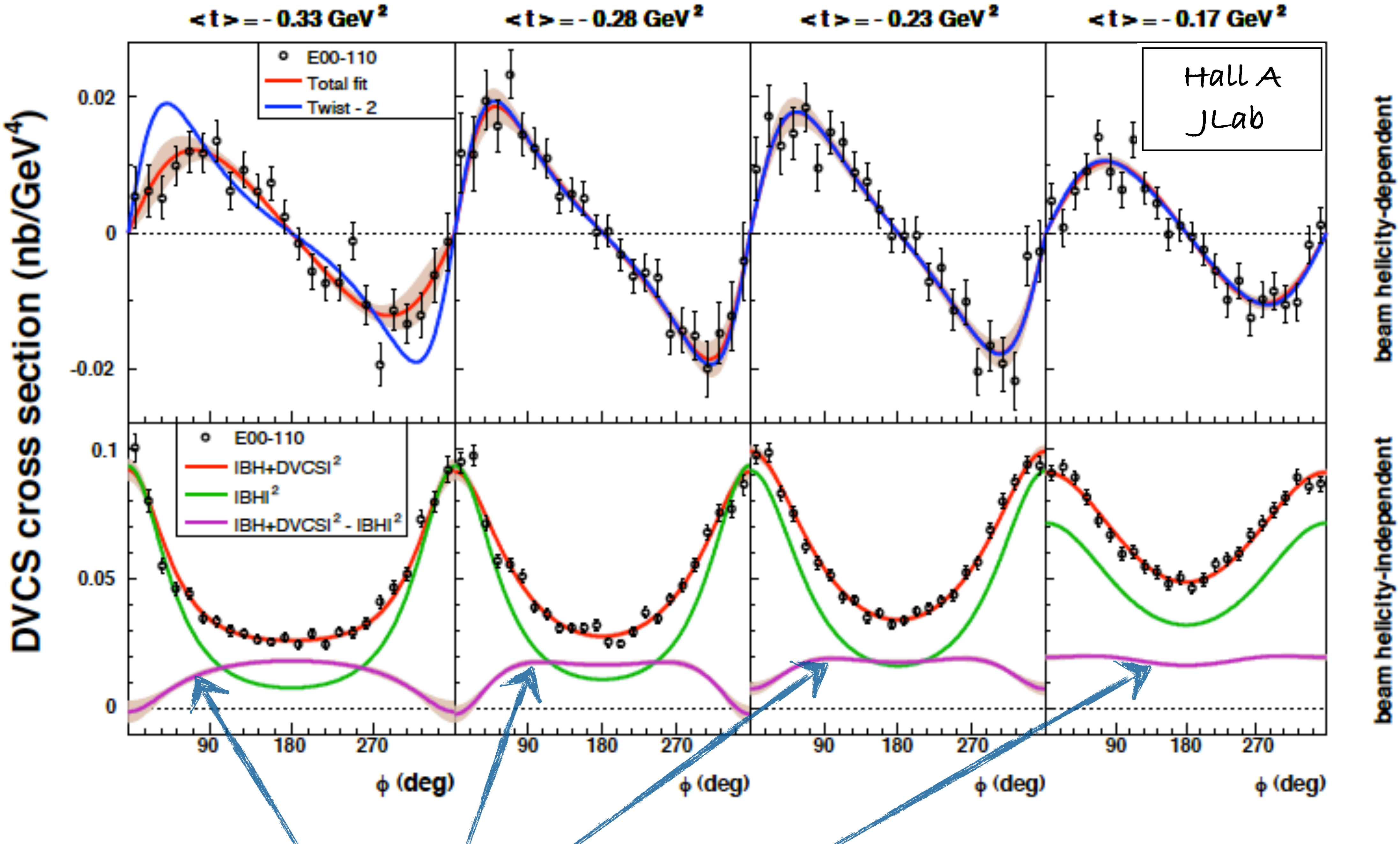
Increasing statistics ...



[V. Burkert @ Transversity 2011]

☑ Clear evidence of DVCS contribution

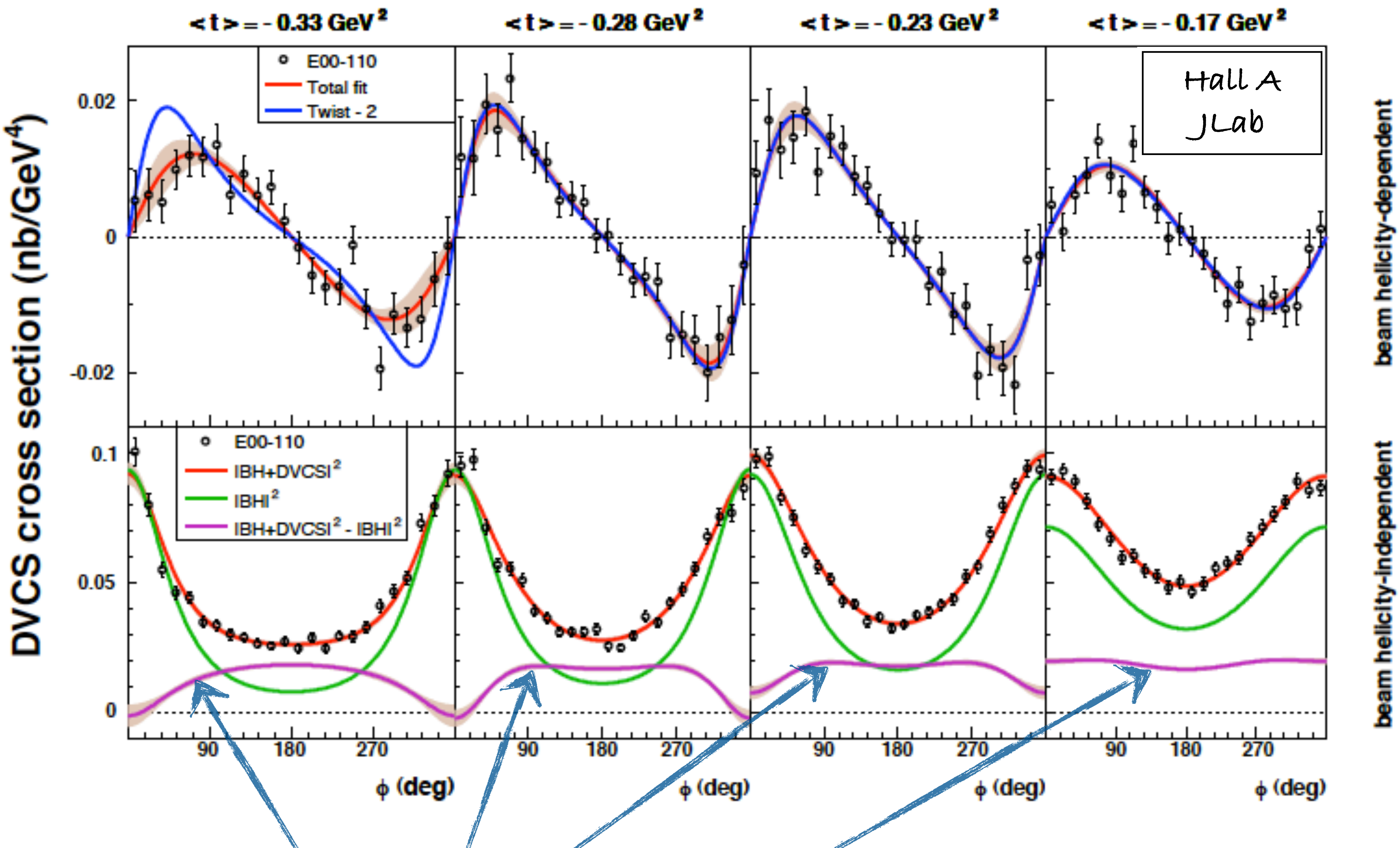
Increasing statistics ...



[V. Burkert @ Transversity 2011]

- ☑ Clear evidence of DVCS contribution
- ☑ High statistics in small range in Q^2, x_B, $-t$

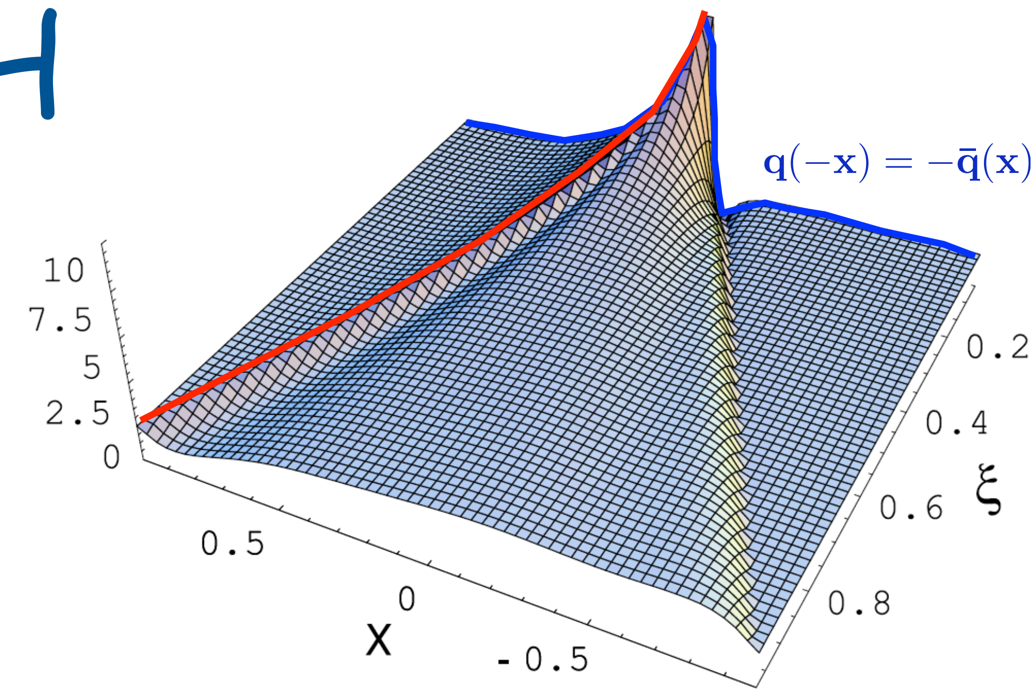
Increasing statistics …



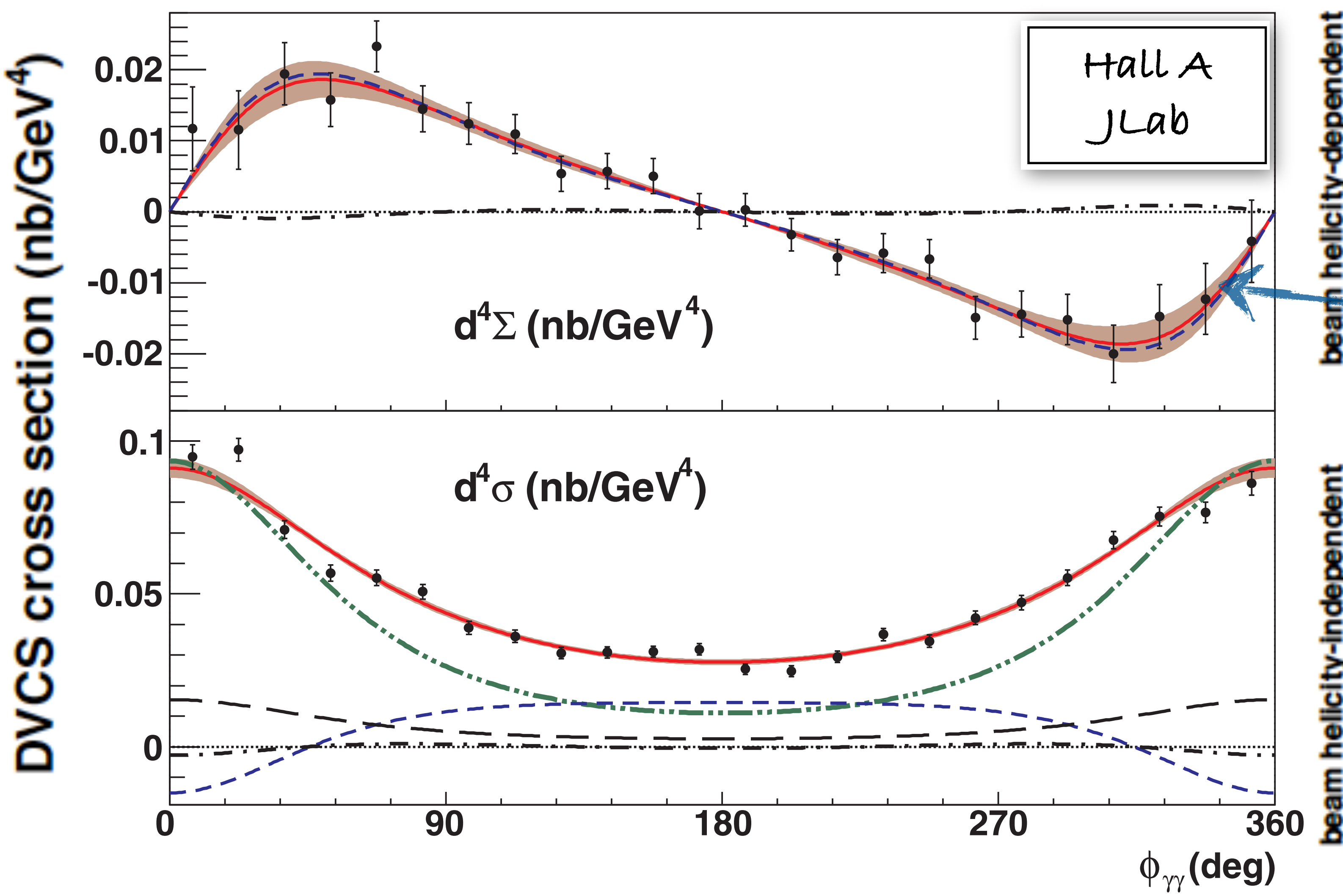
[V. Burkert @ Transversity 2011]

- Clear evidence of DVCS contribution
- High statistics in small range in Q^2, x_B, -t
- "Verified" Bjorken scaling in small Q^2 range [nucl-ex/0607029]

Information about GPD H



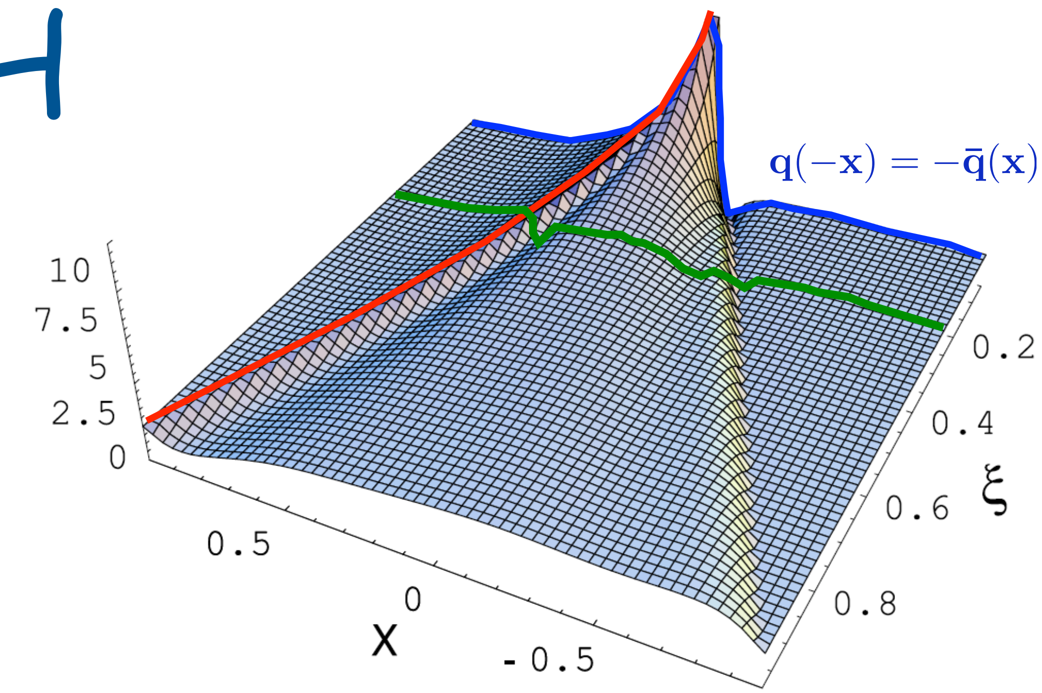
[Phys. Rev. Lett. 97 (2006) 262002]



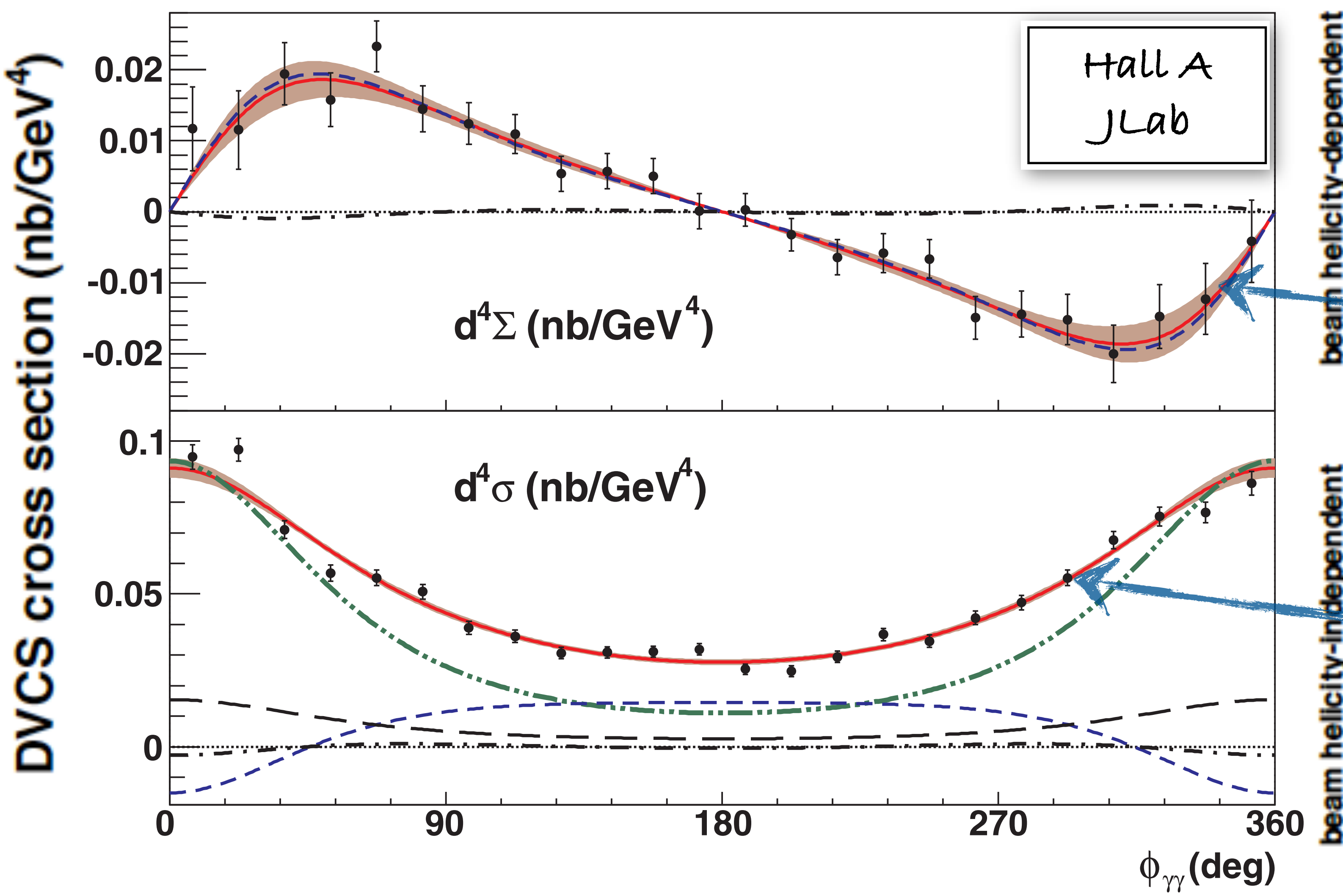
$\Im(\mathcal{T}_{\mathrm{DVCS}})$

$H(x,\xi,Q^2)$ @ $x=\xi$

Information about GPD H



[Phys. Rev. Lett. 97 (2006) 262002]



$\Im(\mathcal{T}_{\mathrm{DVCS}})$

$H(x,\xi,Q^2)$ @ $x=\xi$

$\Re(\mathcal{T}_{\mathrm{DVCS}})$

x-integral of $H(x,\xi,Q^2)$

DVCS on "neutron" (aka ^{3}He)

beam-helicity asymmetry sensitive to GPD E
-> model-dependent constraint on total angular momentum

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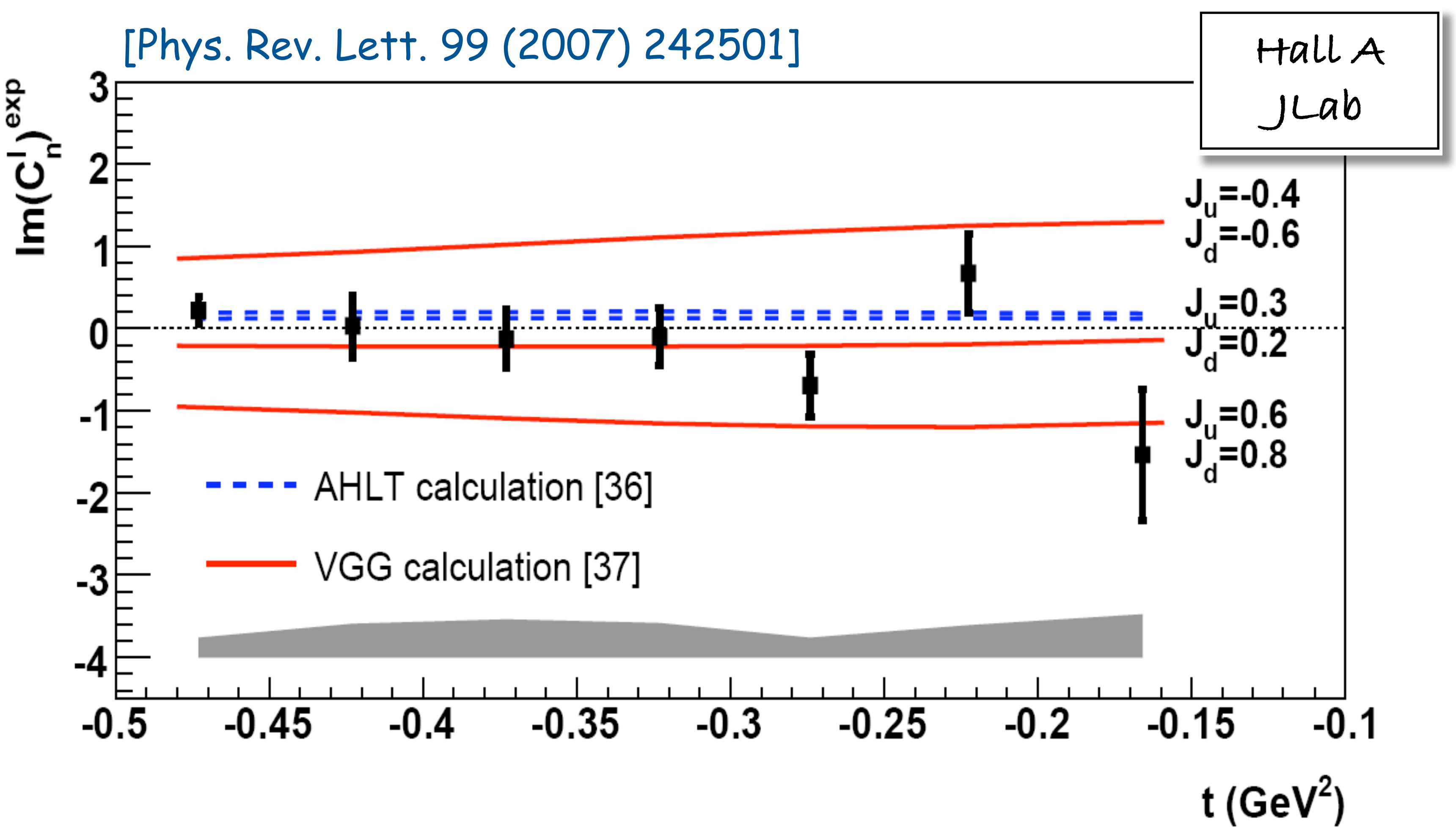
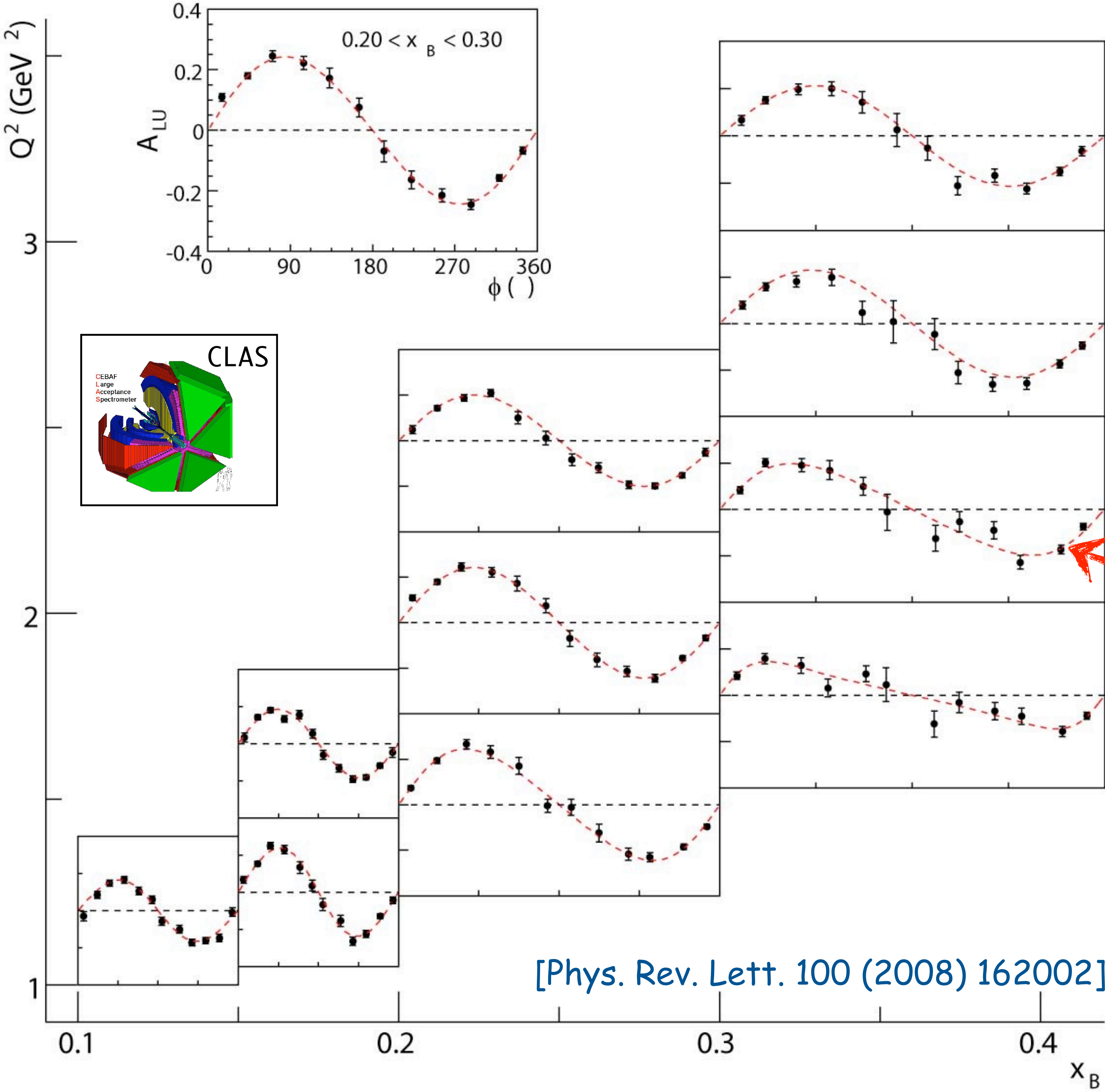


Increasing statistics ...



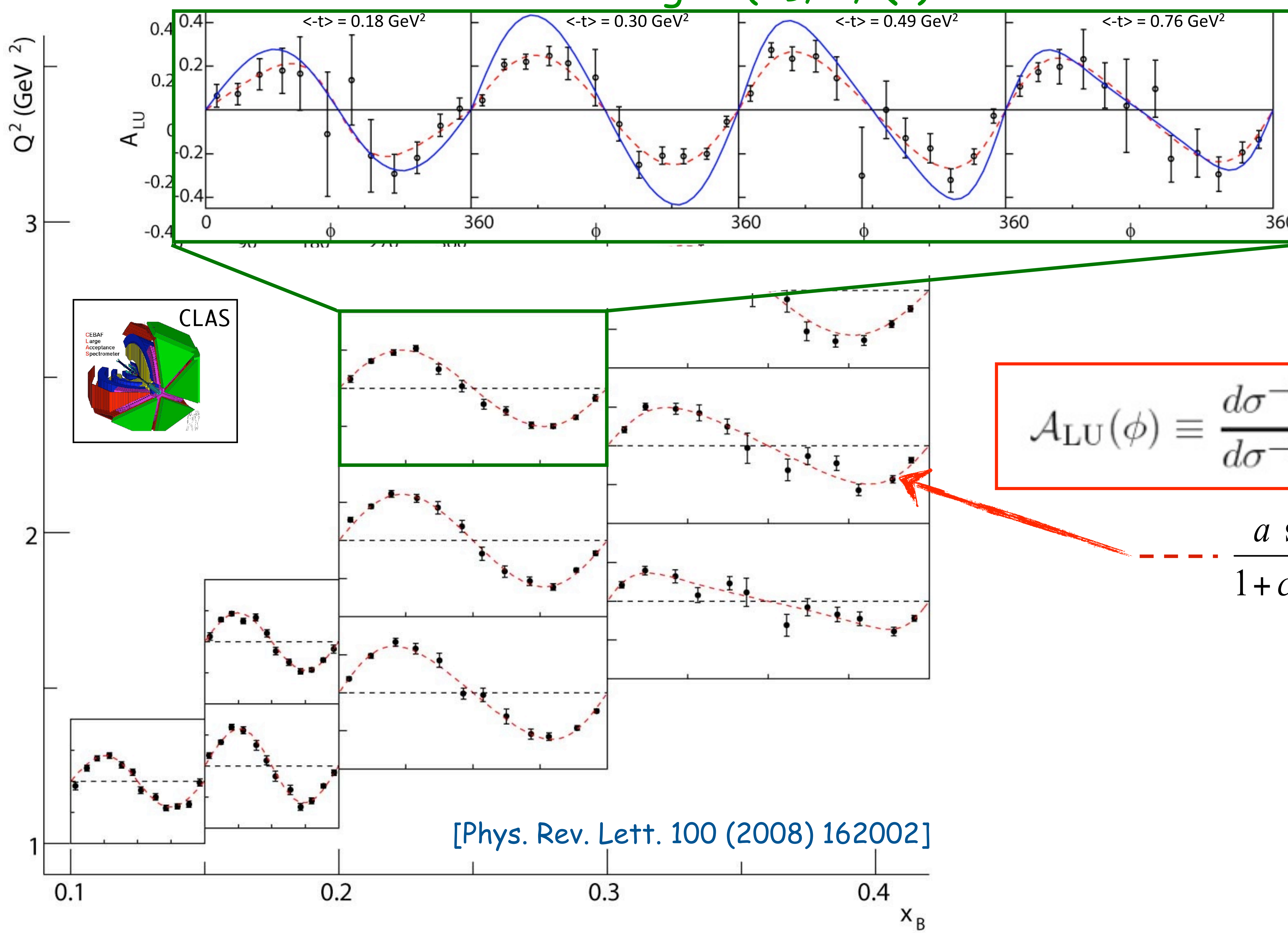
$$A_{LU}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

$$\frac{a \sin\phi}{1 + c\cos\phi}$$

[Phys. Rev. Lett. 100 (2008) 162002]

Increasing statistics ...

multi-dimensional binning in (x_B,-t,Q^2)



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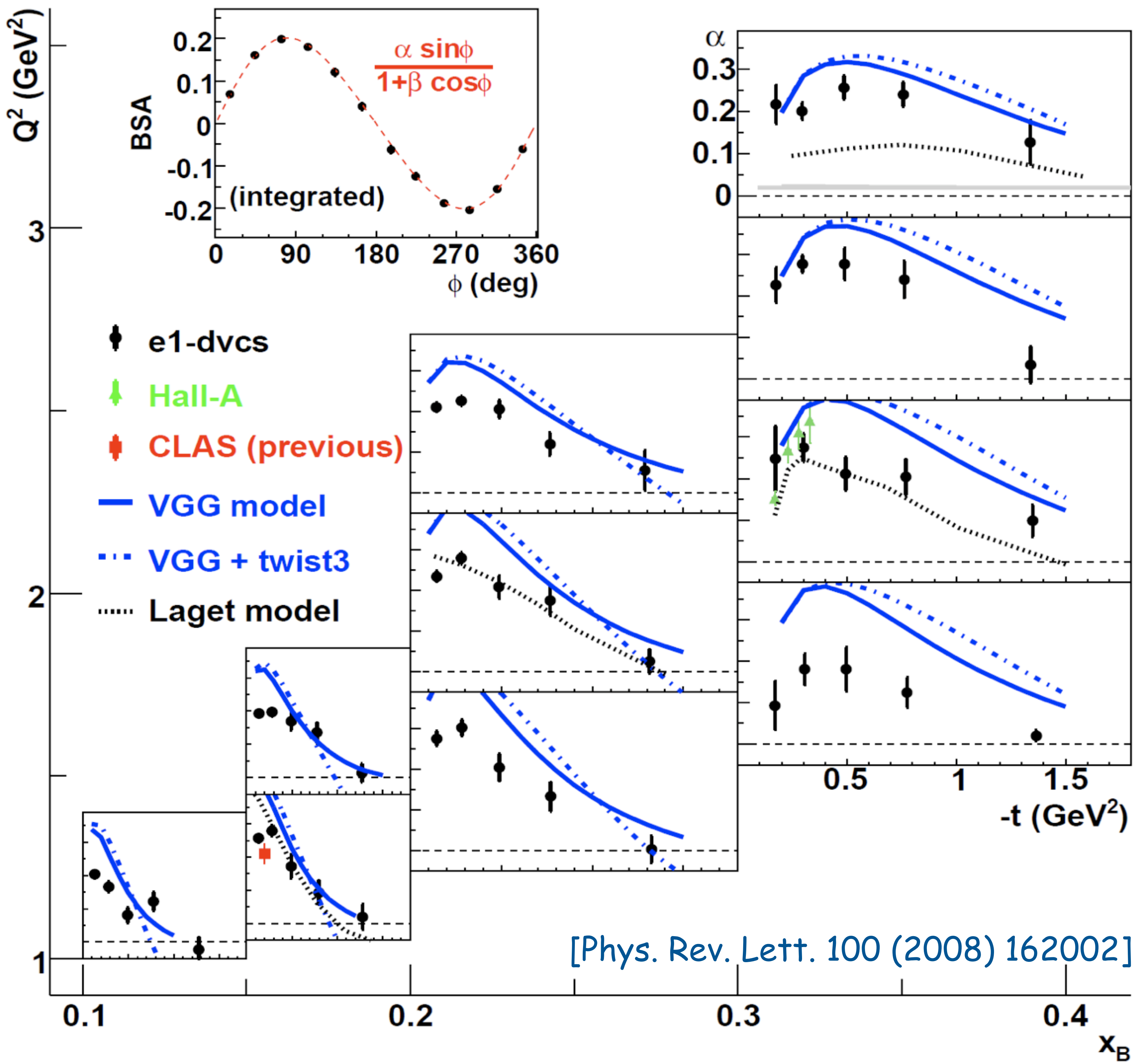

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VGG model calculations:
Phys. Rev. D60 (1999) 094017.
Prog. Nucl. Phys. 47 (2001) 401.

Increasing statistics ...

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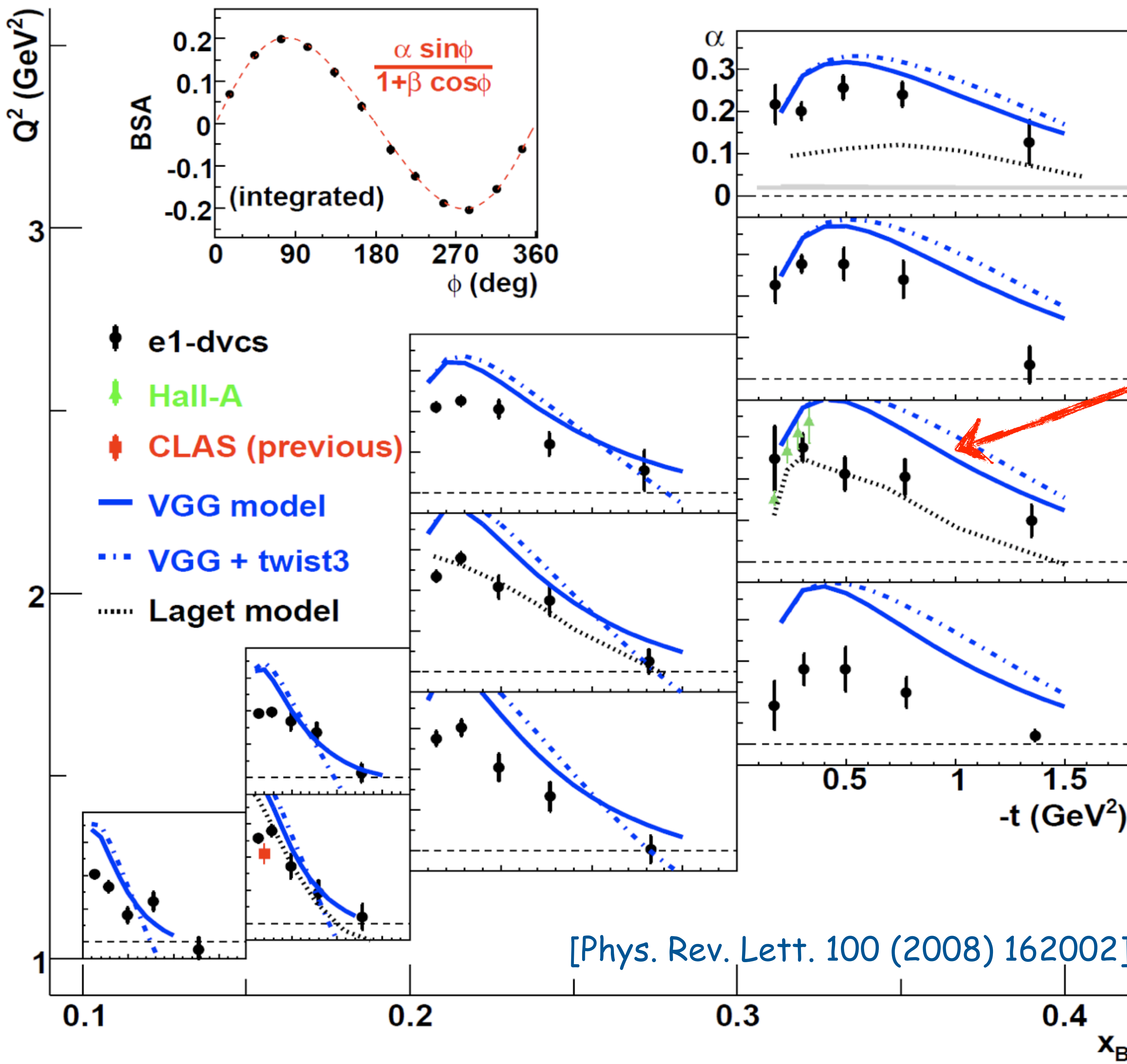

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VGG Model overshoots data (effect also observed for HERMES data)

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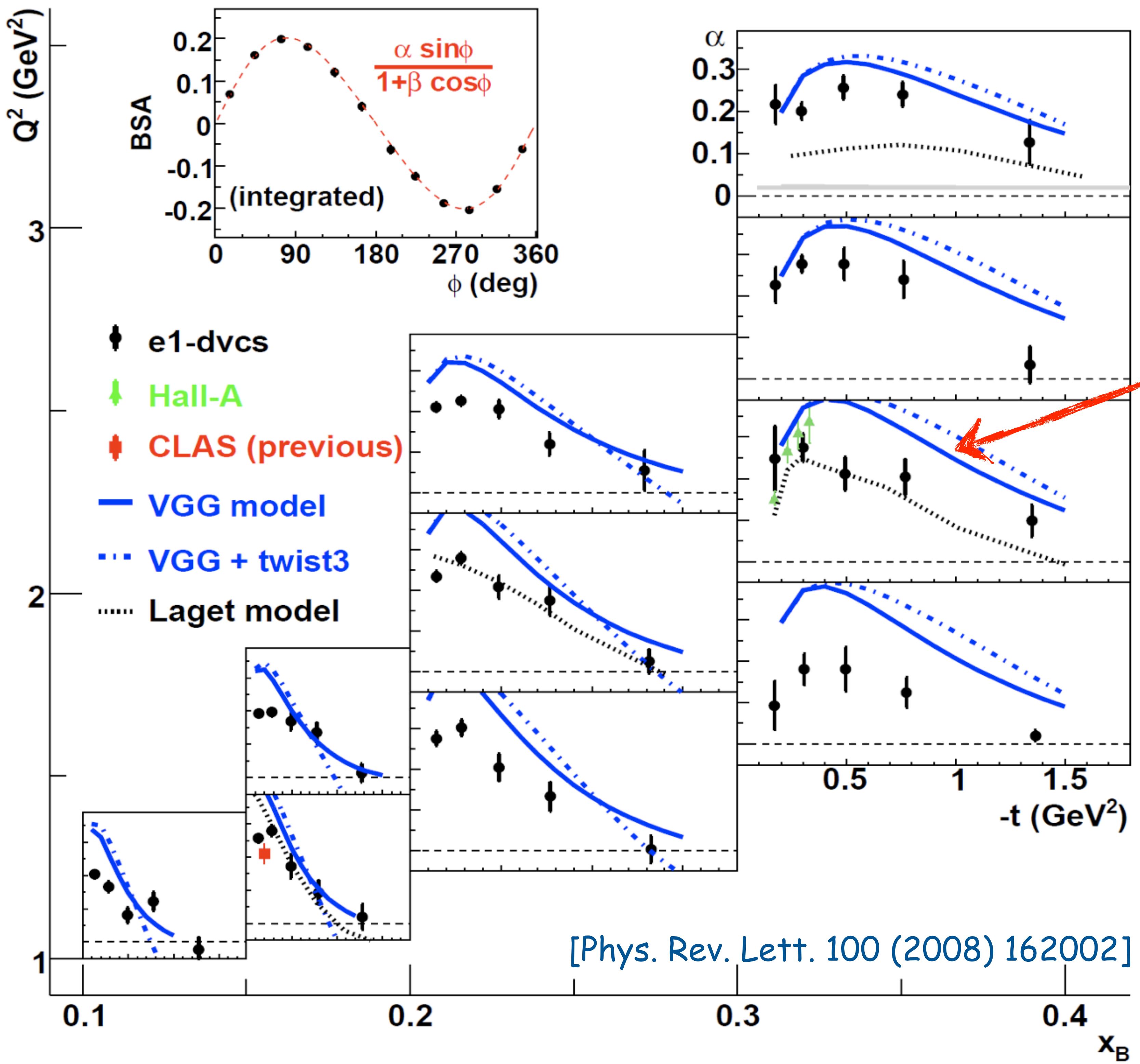

[Phys. Rev. Lett. 100 (2008) 162002]

VGG Model overshoots data (effect also observed for HERMES data)

in general no satisfactory description by models

VGG model calculations:
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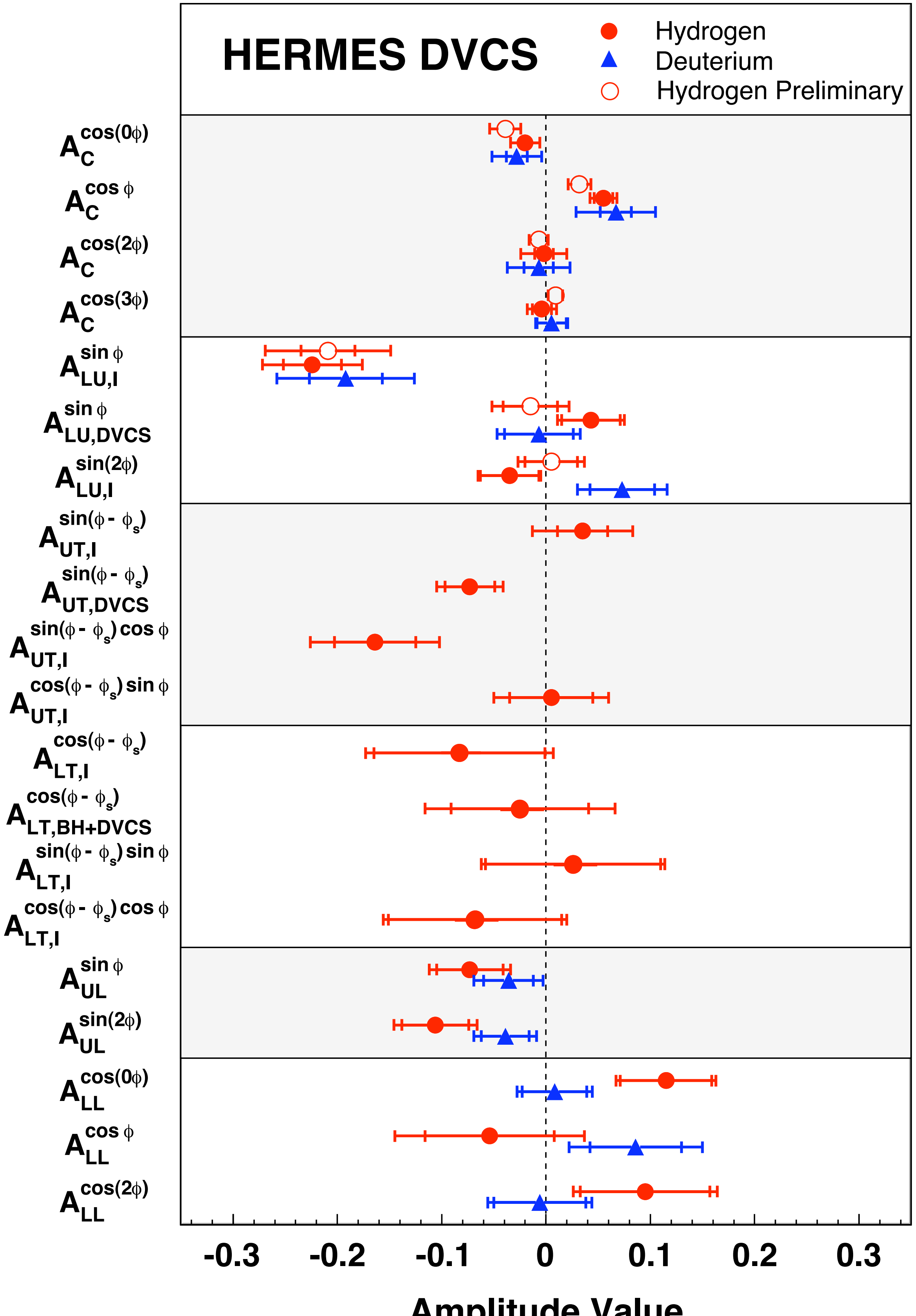
A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

Beam-helicity asymmetry:

GPD H

Transverse target spin asymmetries:

GPD E from proton target

Longitudinal target spin asymmetry:

GPD $\tilde{H}$

Double-spin asymmetry:

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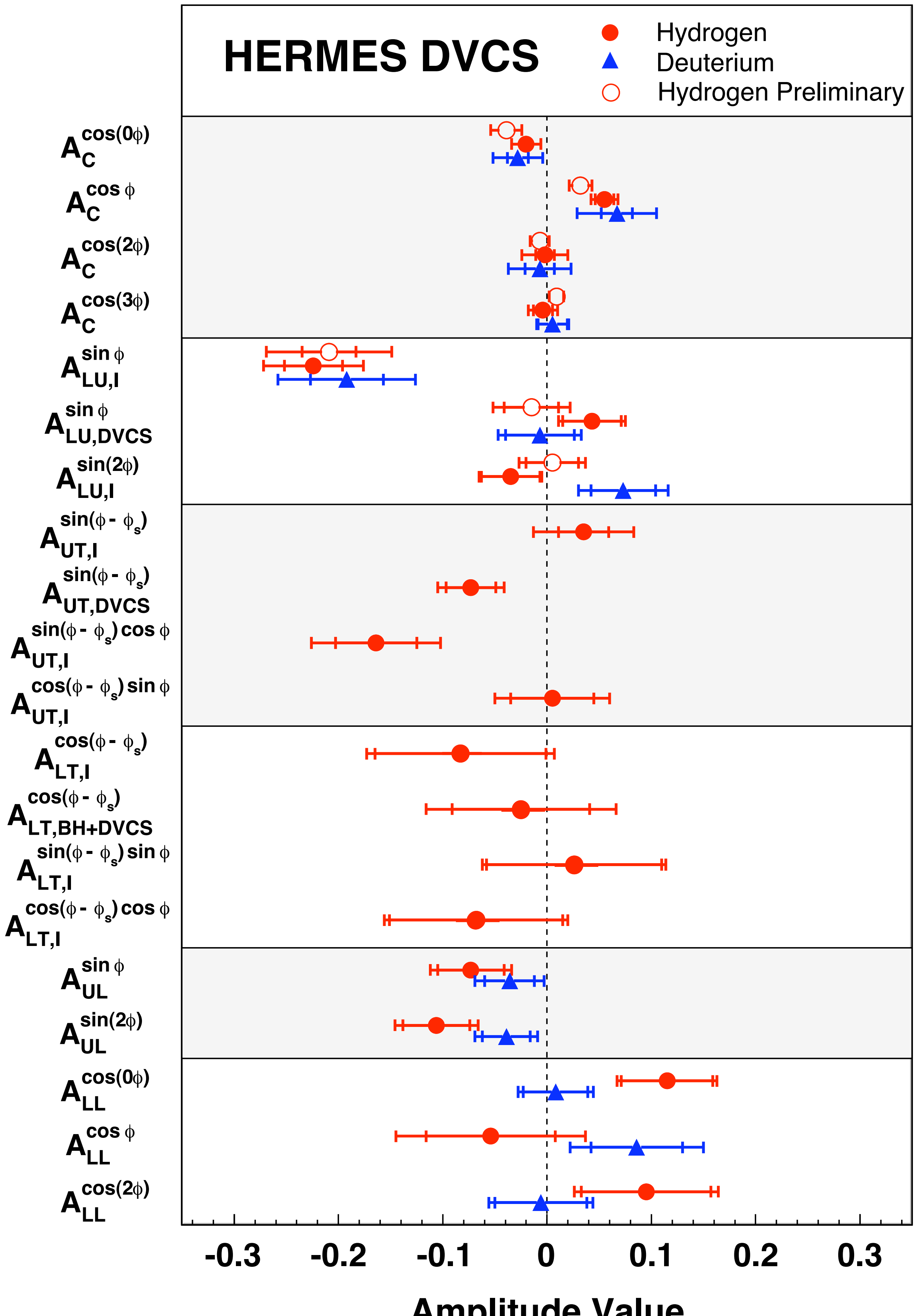
A wealth of azimuthal amplitudes



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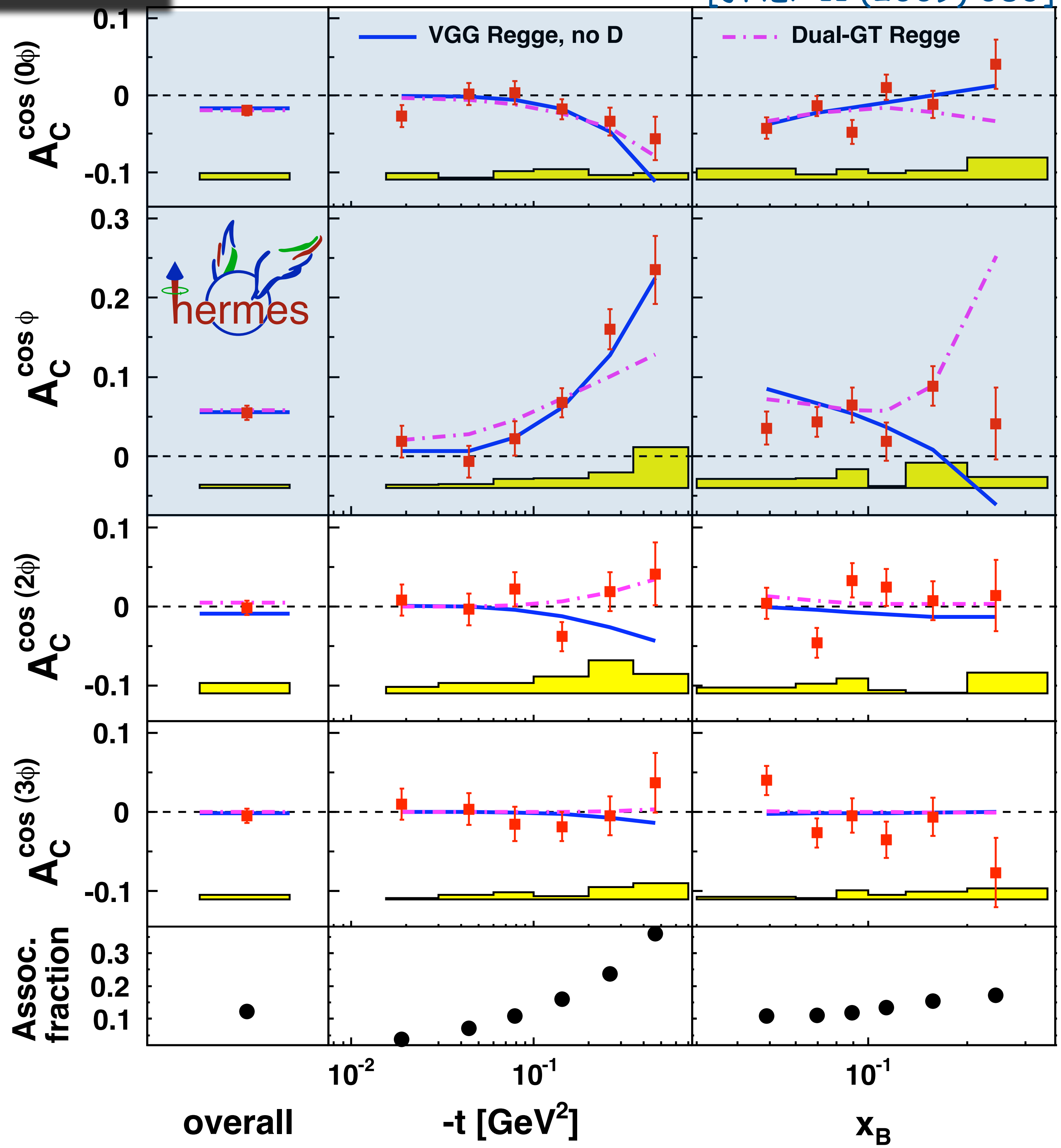
data: 1996-2005

Beam-charge asymmetry

[JHEP 11 (2009) 083]



constant term:
$\propto -A_C^{\cos\phi}$

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

[higher twist]

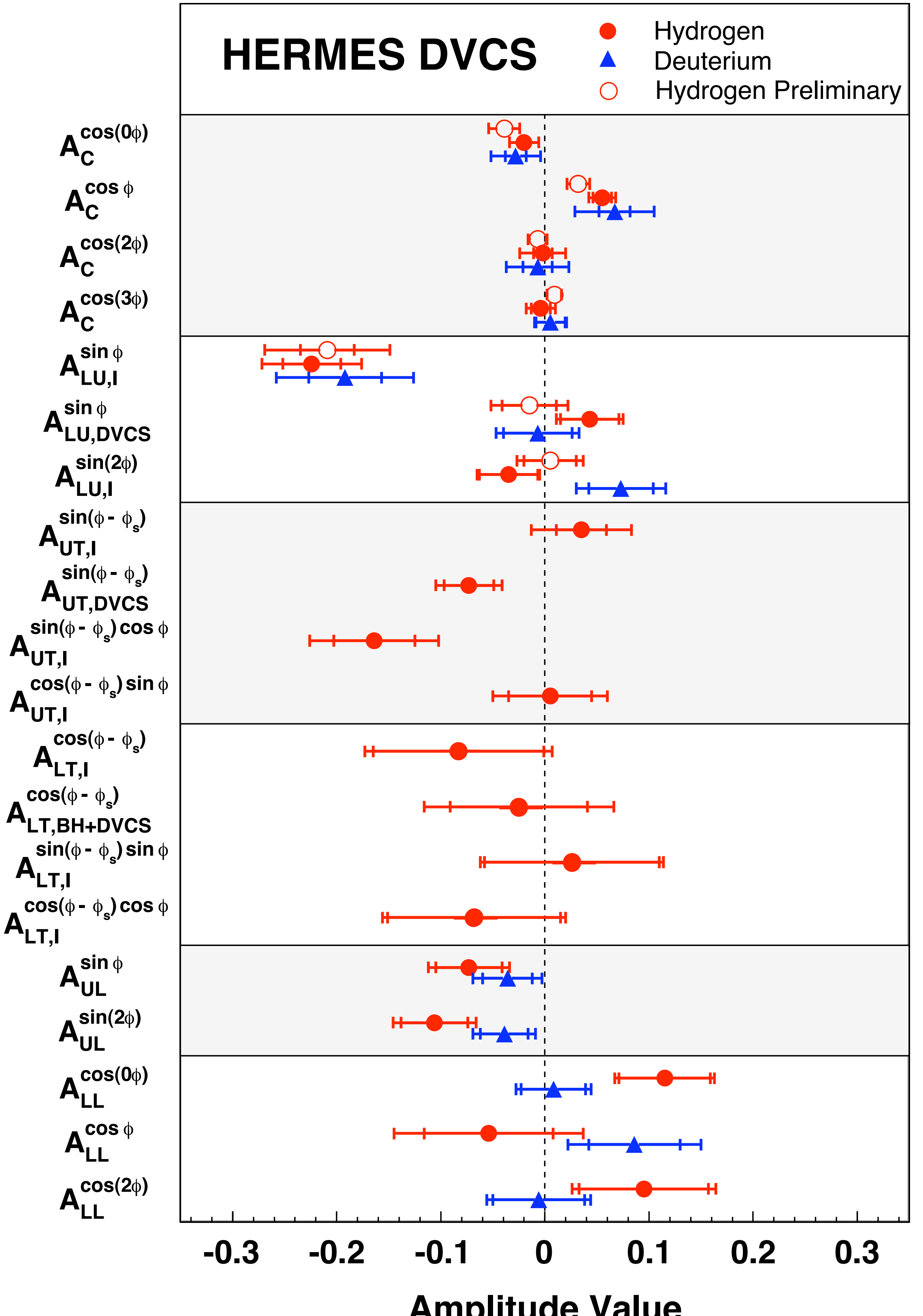
[gluon leading twist]

Resonant fraction:

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

model prediction "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

A wealth of azimuthal amplitudes



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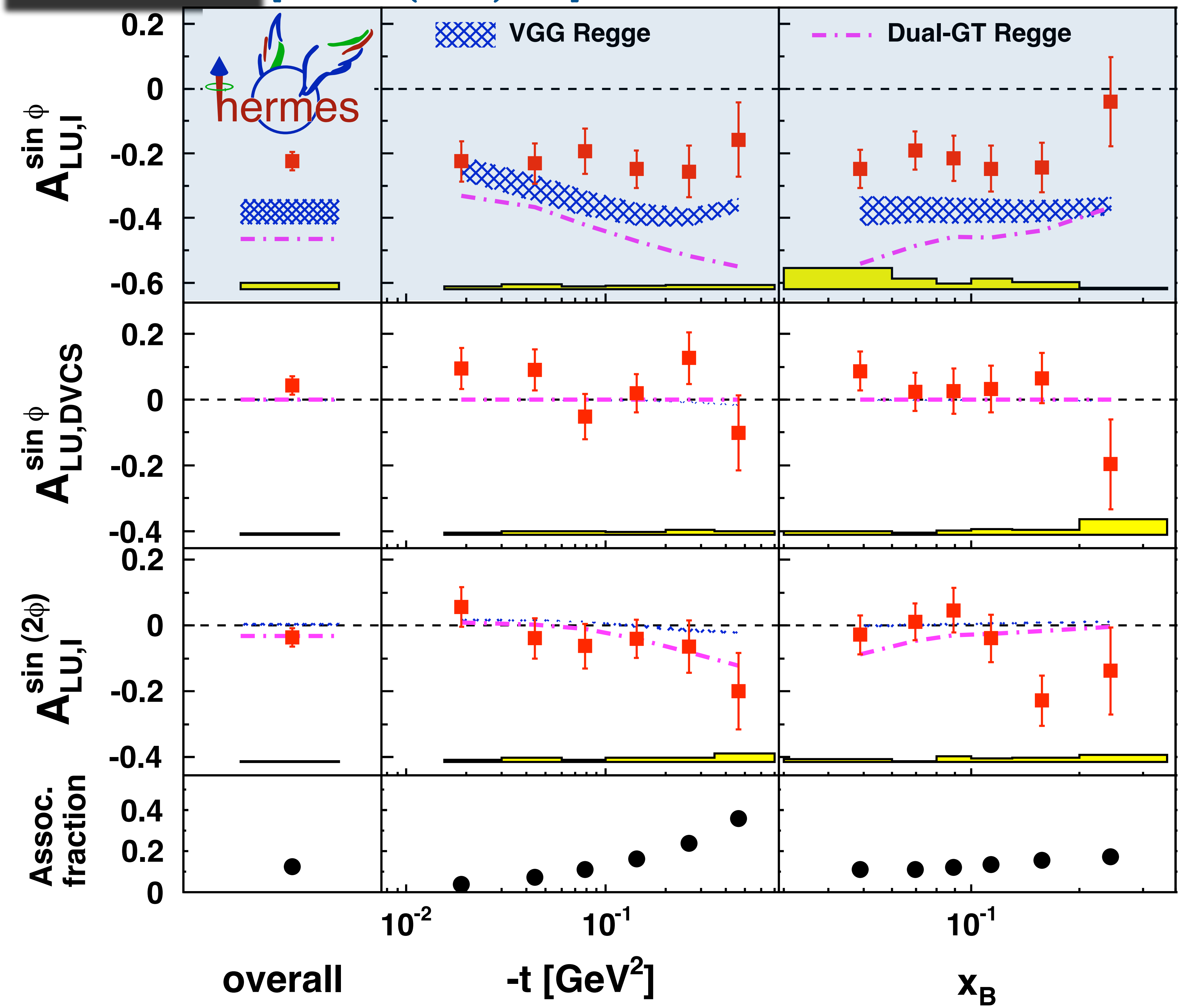

$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

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model prediction "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

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Beam-spin asymmetry

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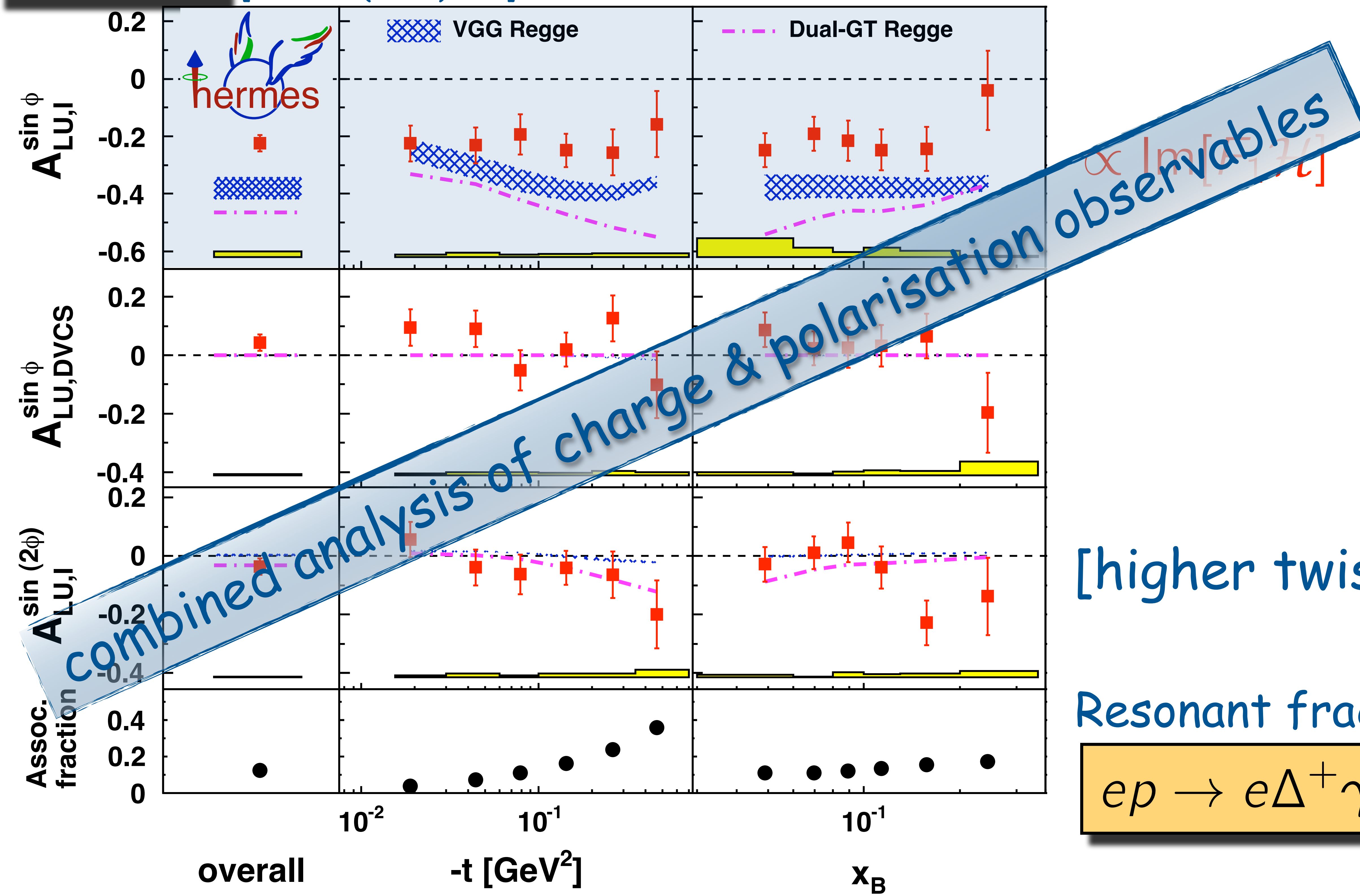

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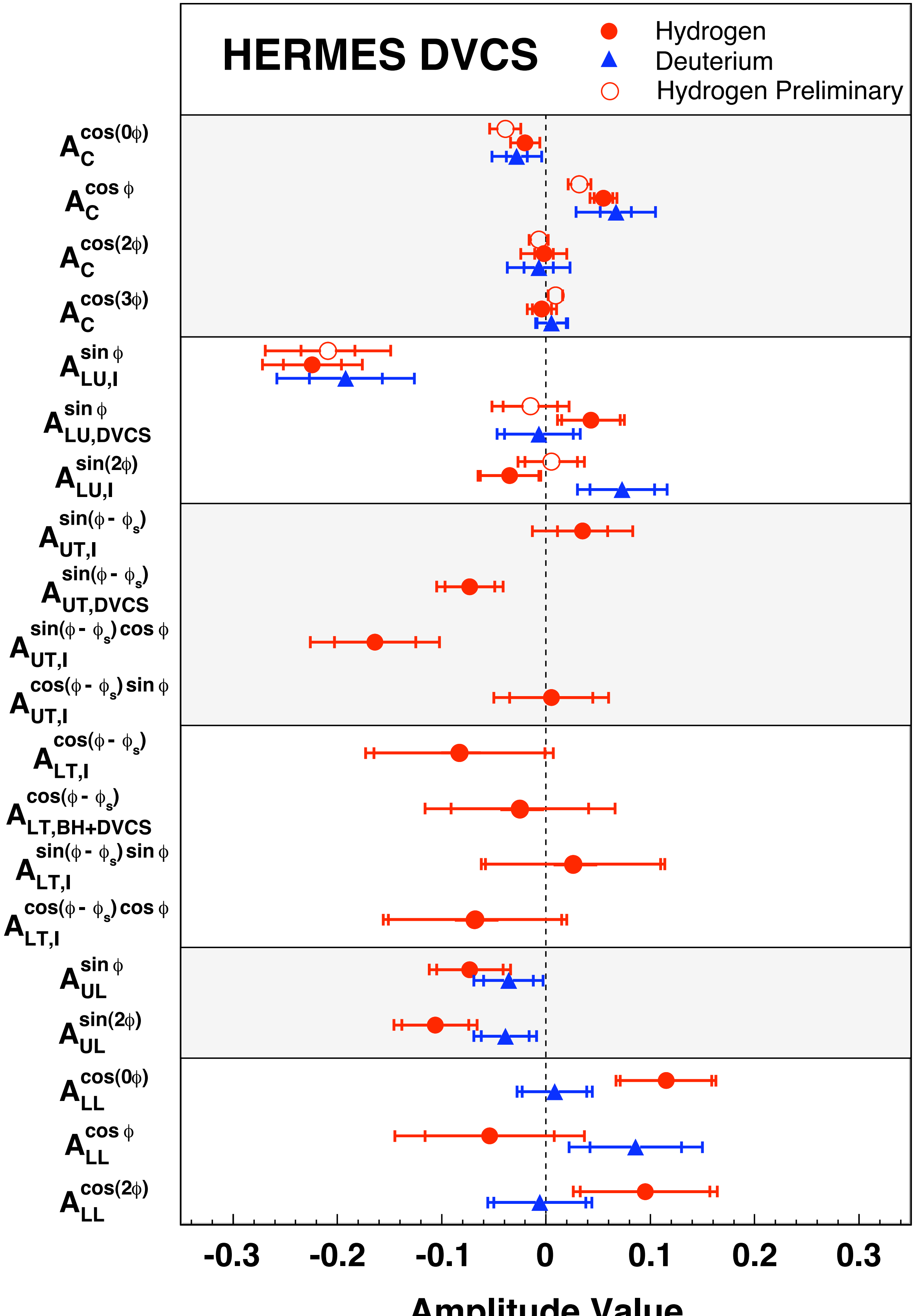

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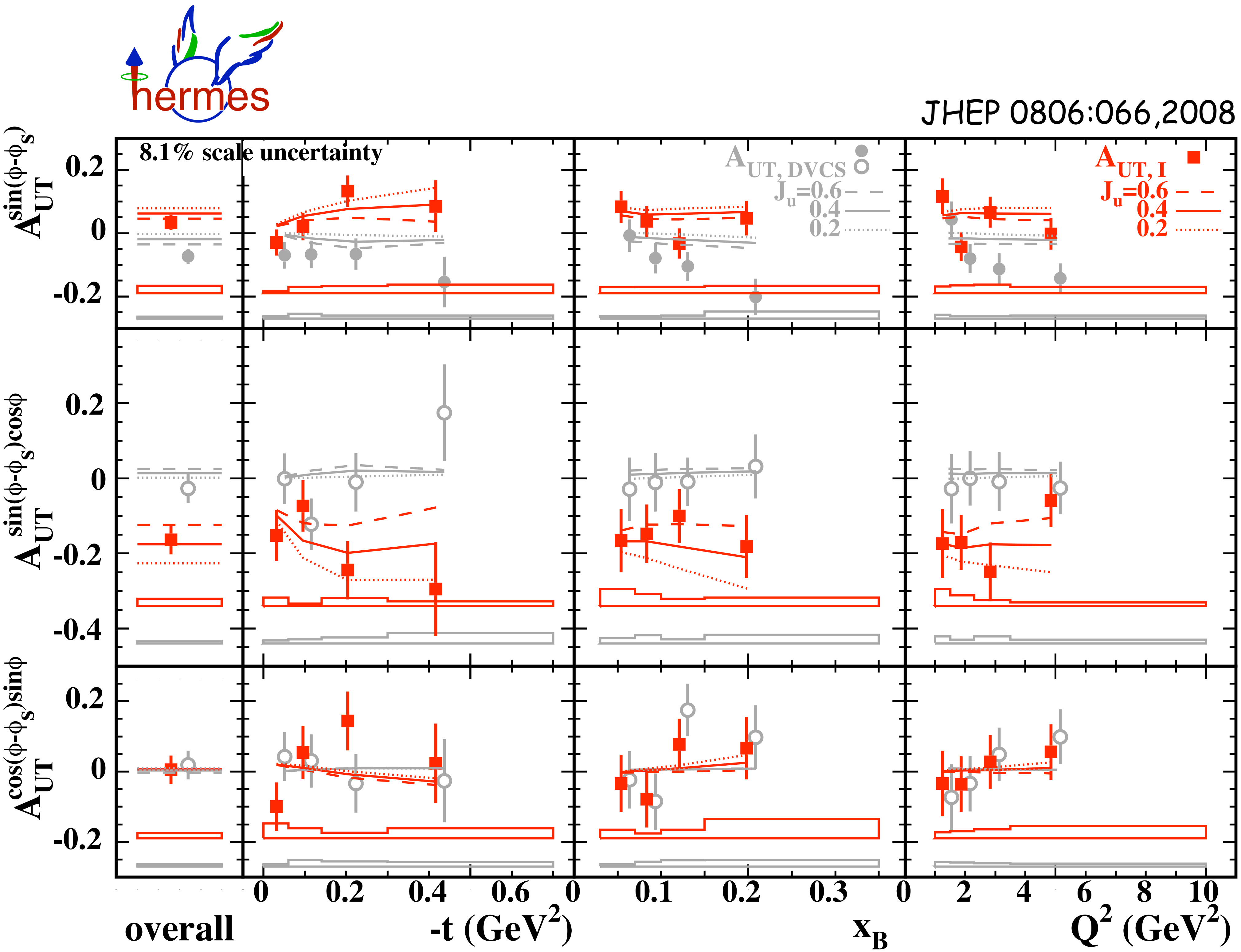
Transverse target-spin asymmetry



$\propto -A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$

$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$

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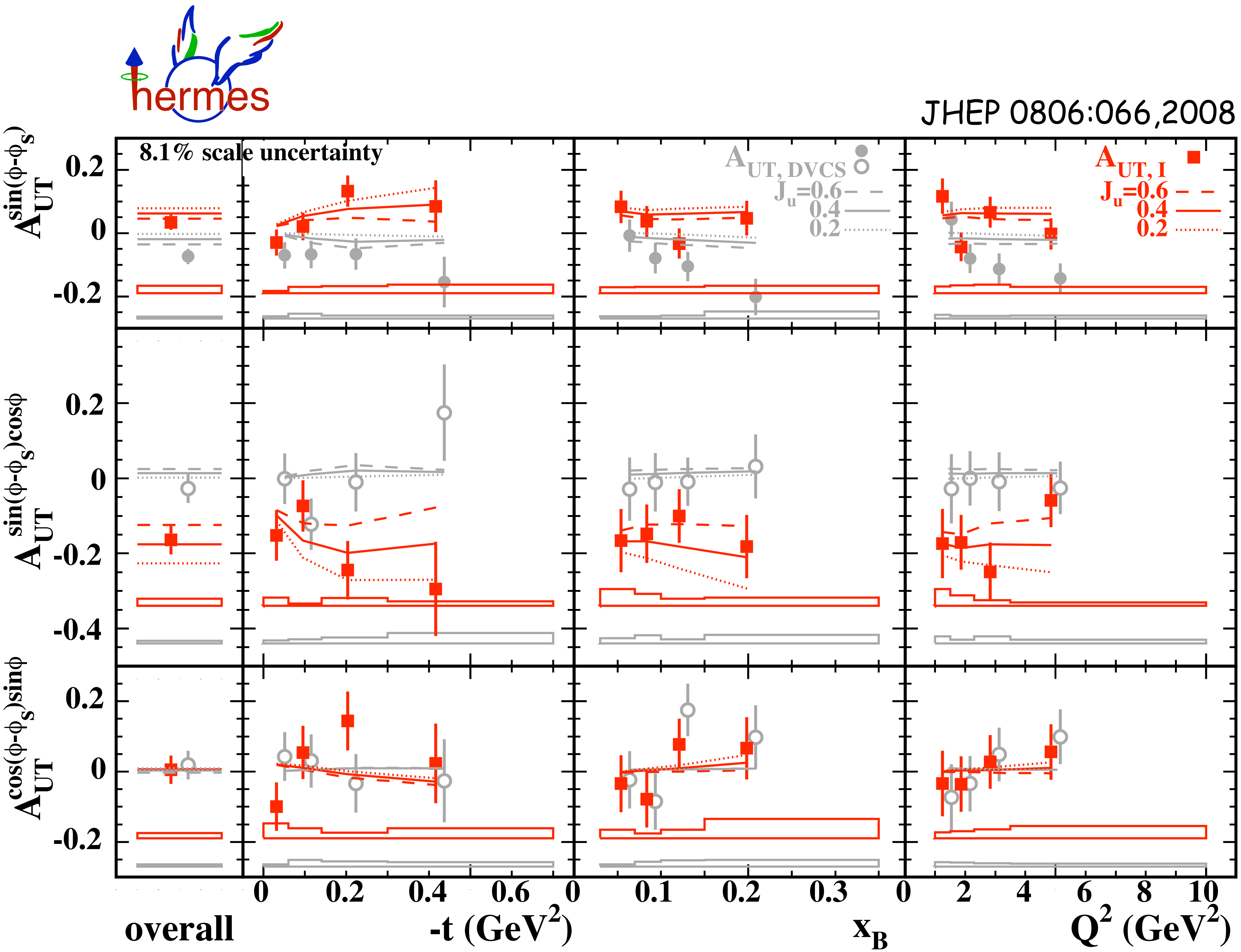
Transverse target-spin asymmetry



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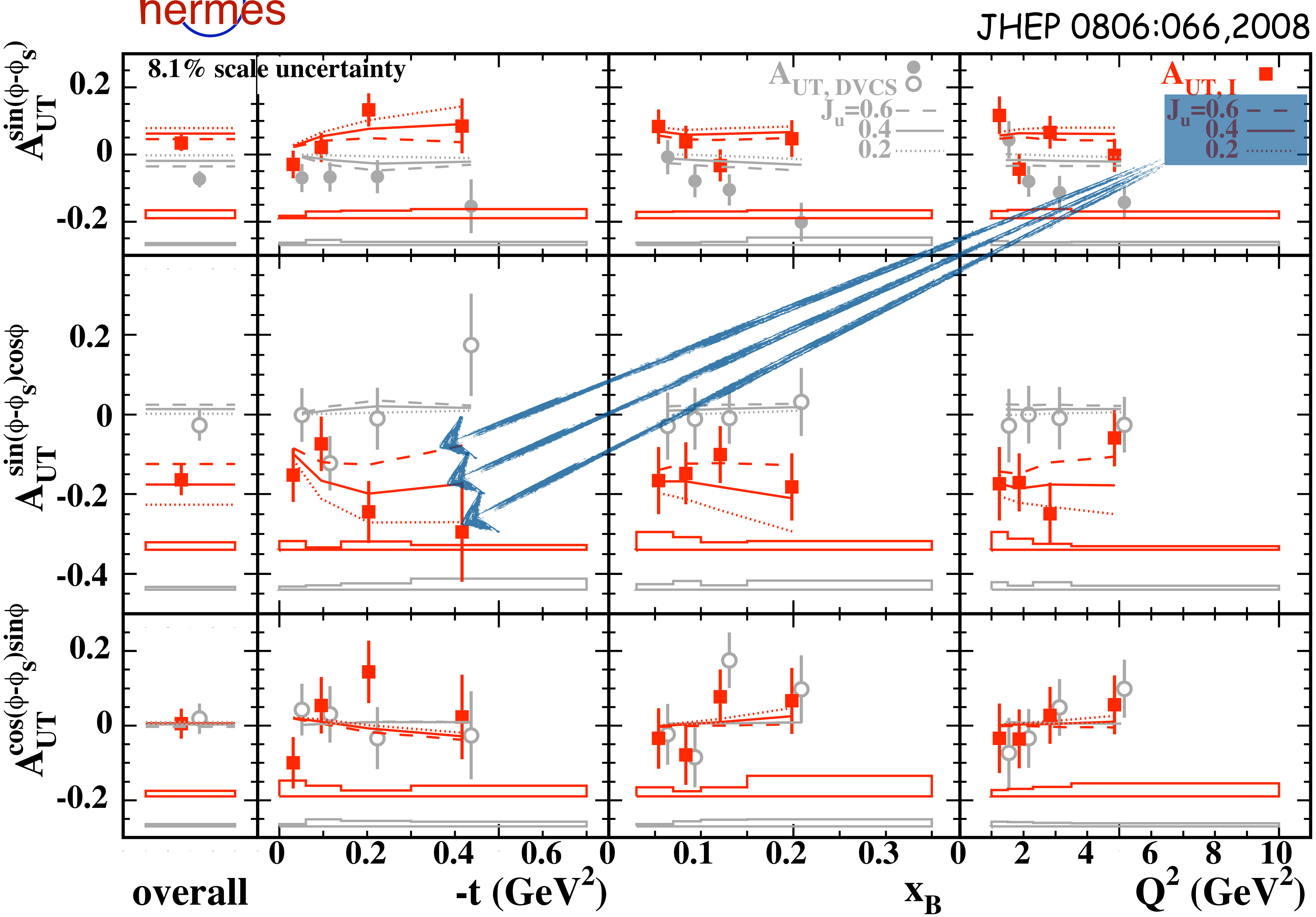

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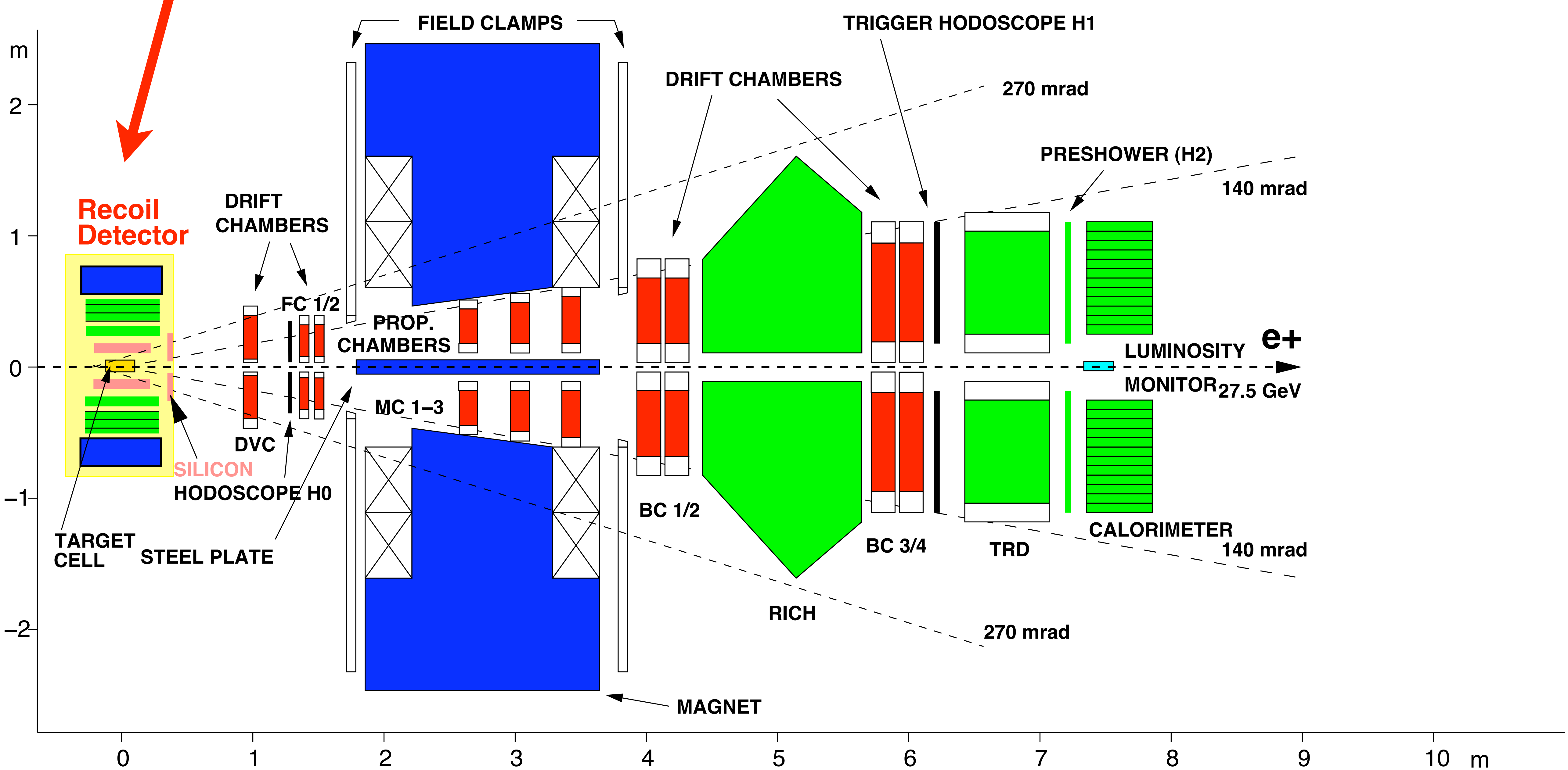
model "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

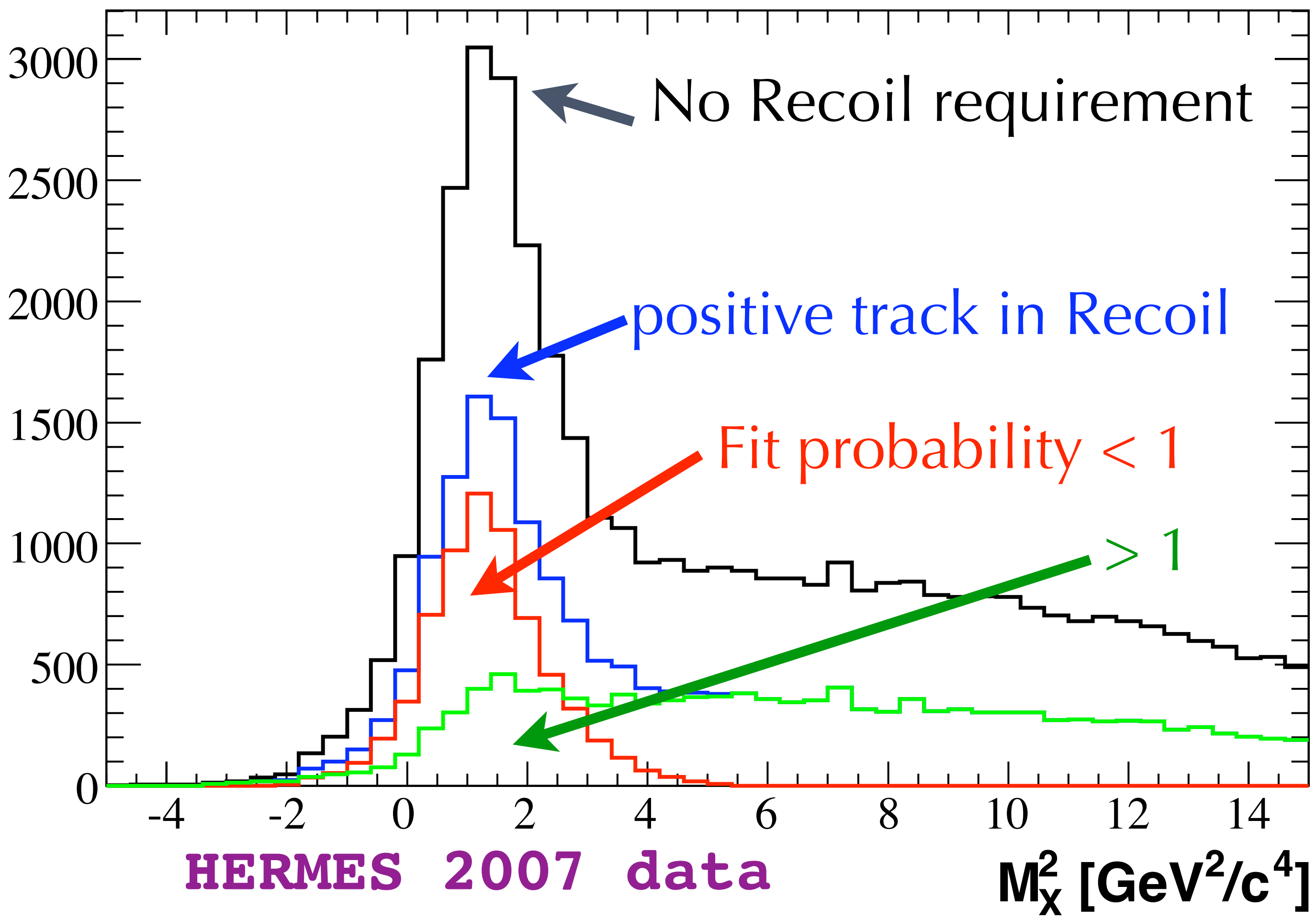
HERMES detector (2006/07)

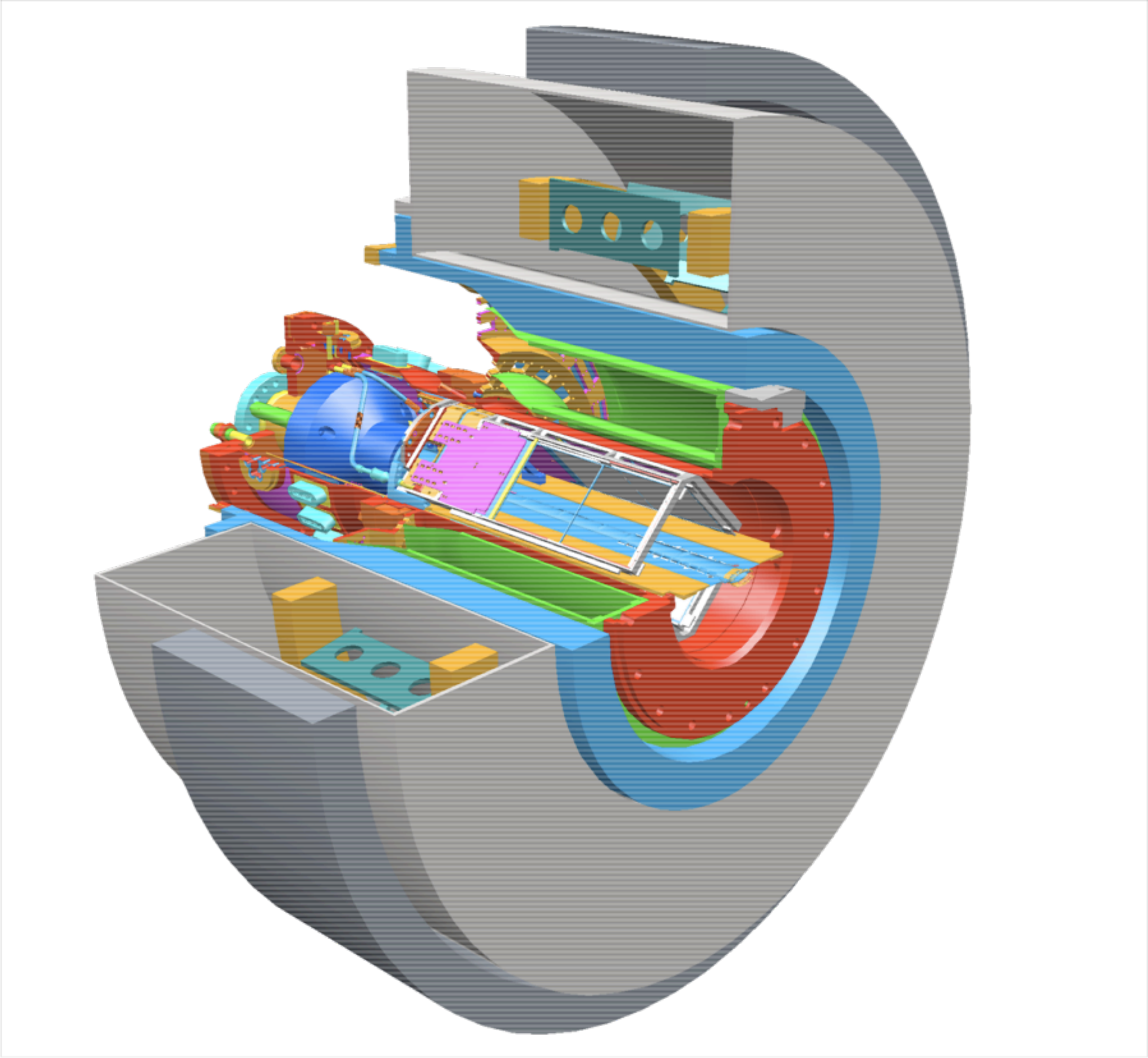
detection of
recoiling proton



HERMES detector (2006/07)

kinematic fitting





HERMES detector (2006/07)

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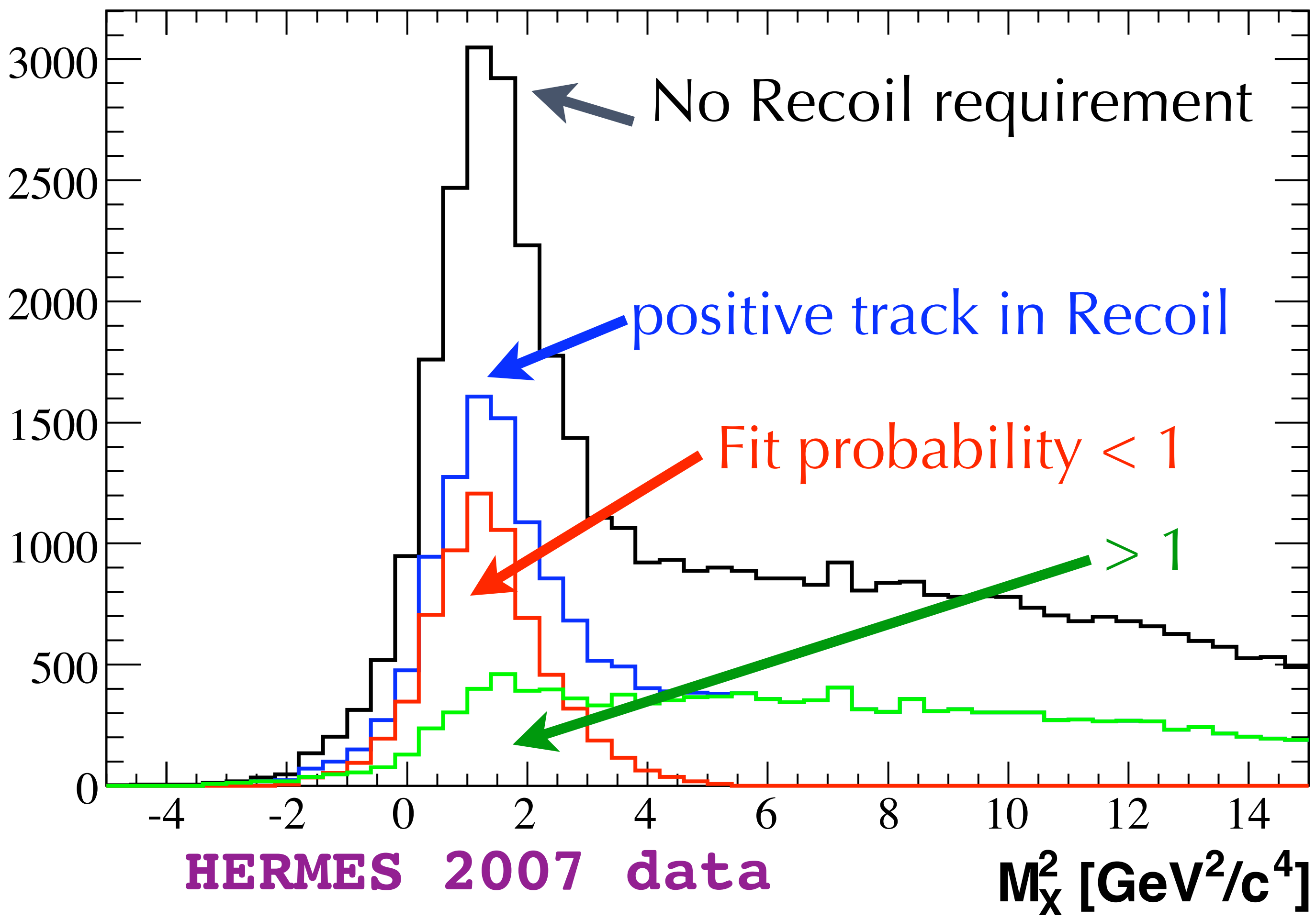
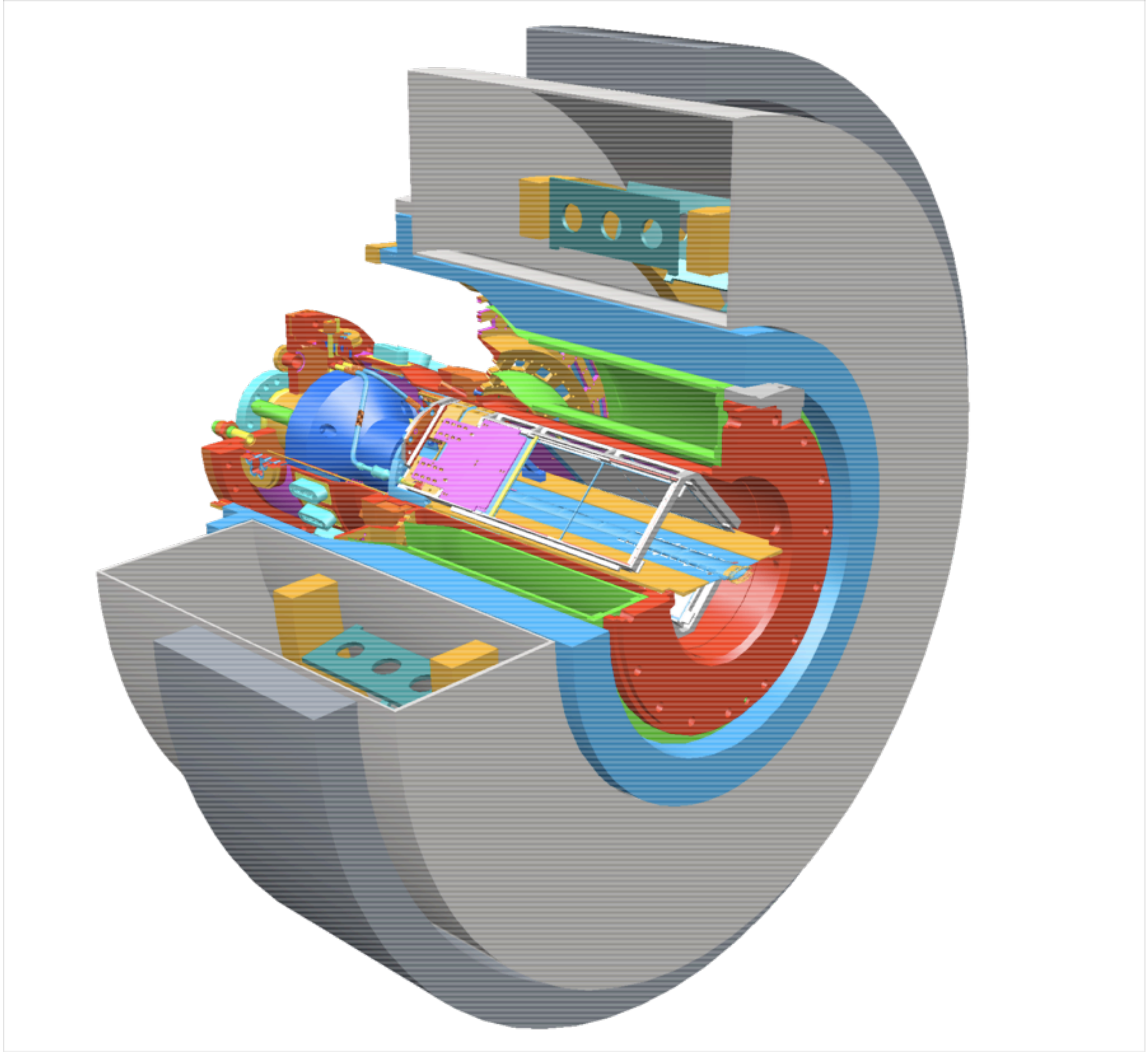




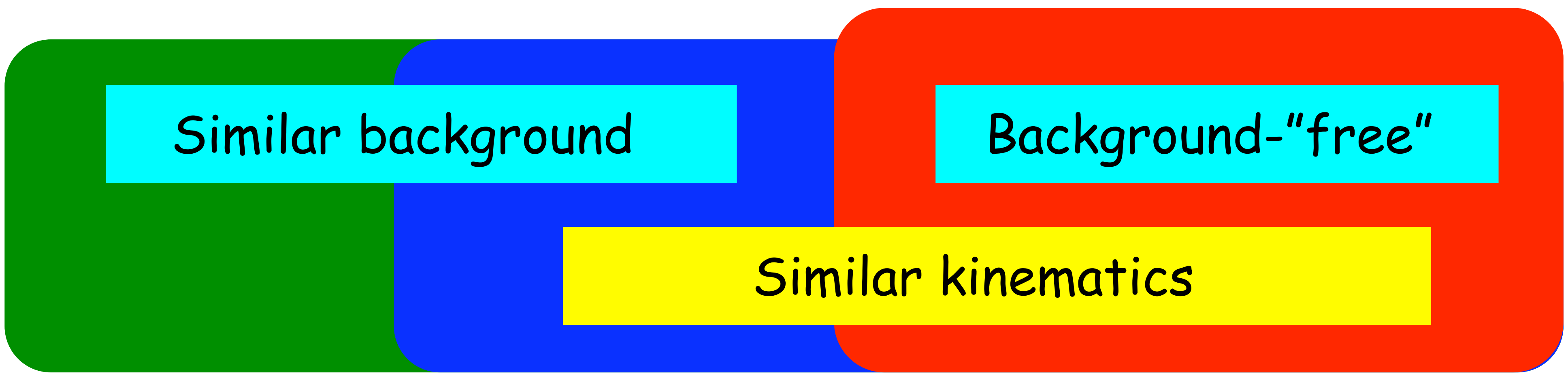
- All 3 particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS ($ep \rightarrow ep\,\gamma$) with high efficiency (~84%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (~0.1%)

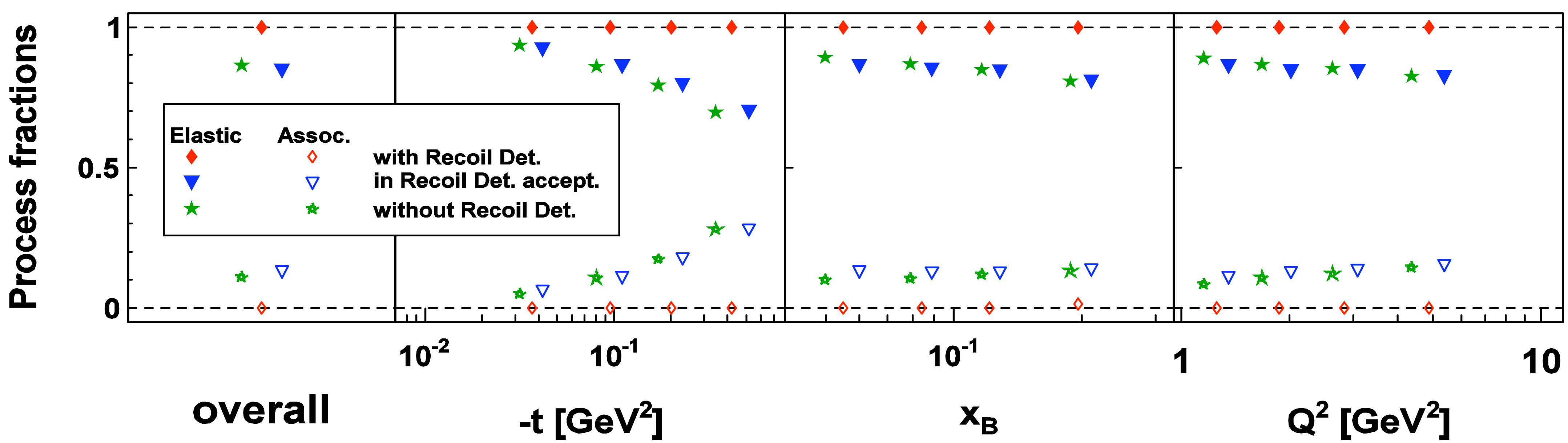
Event samples

Without Recoil Detector

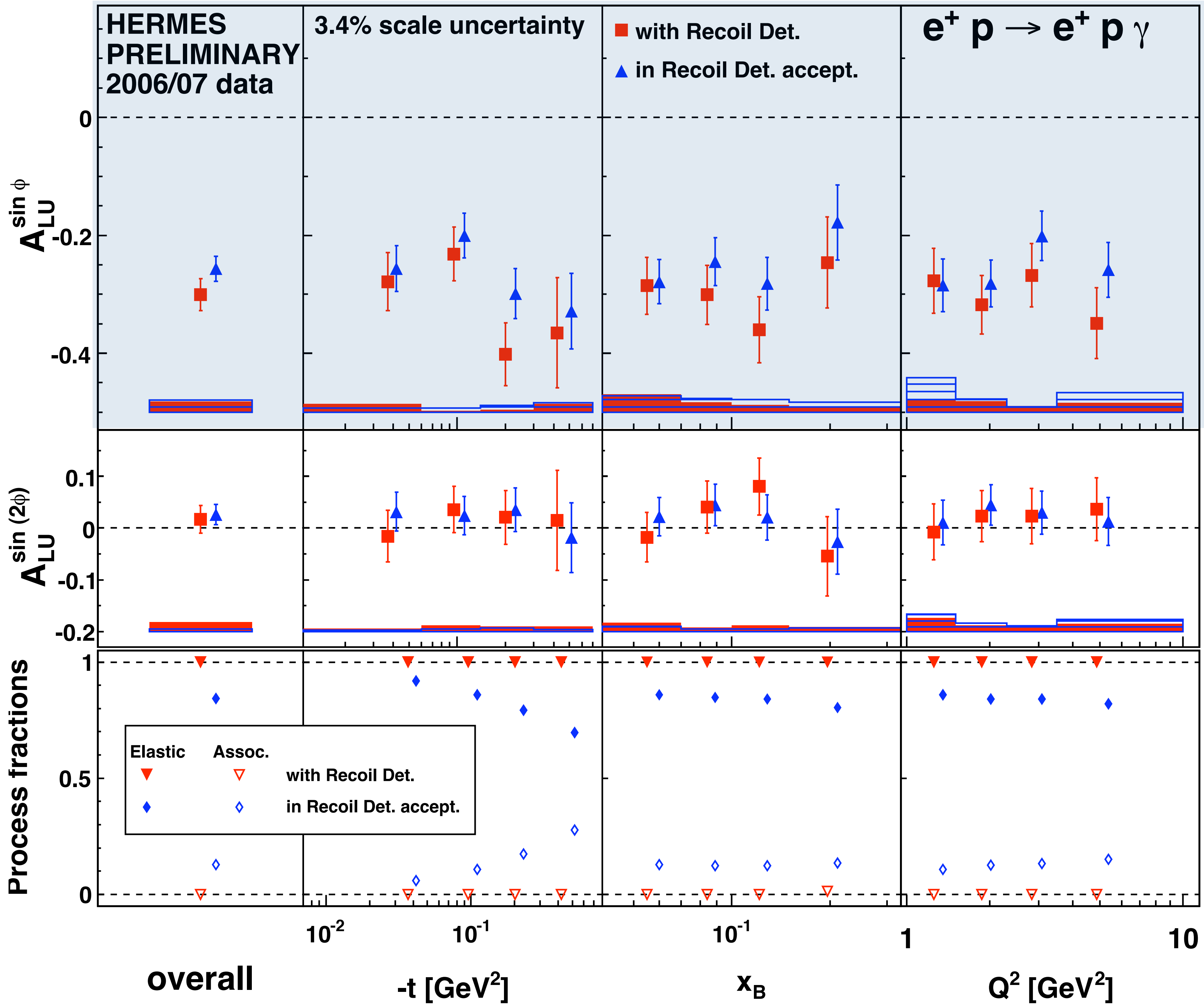
In Recoil Detector acceptance

With Recoil Detector





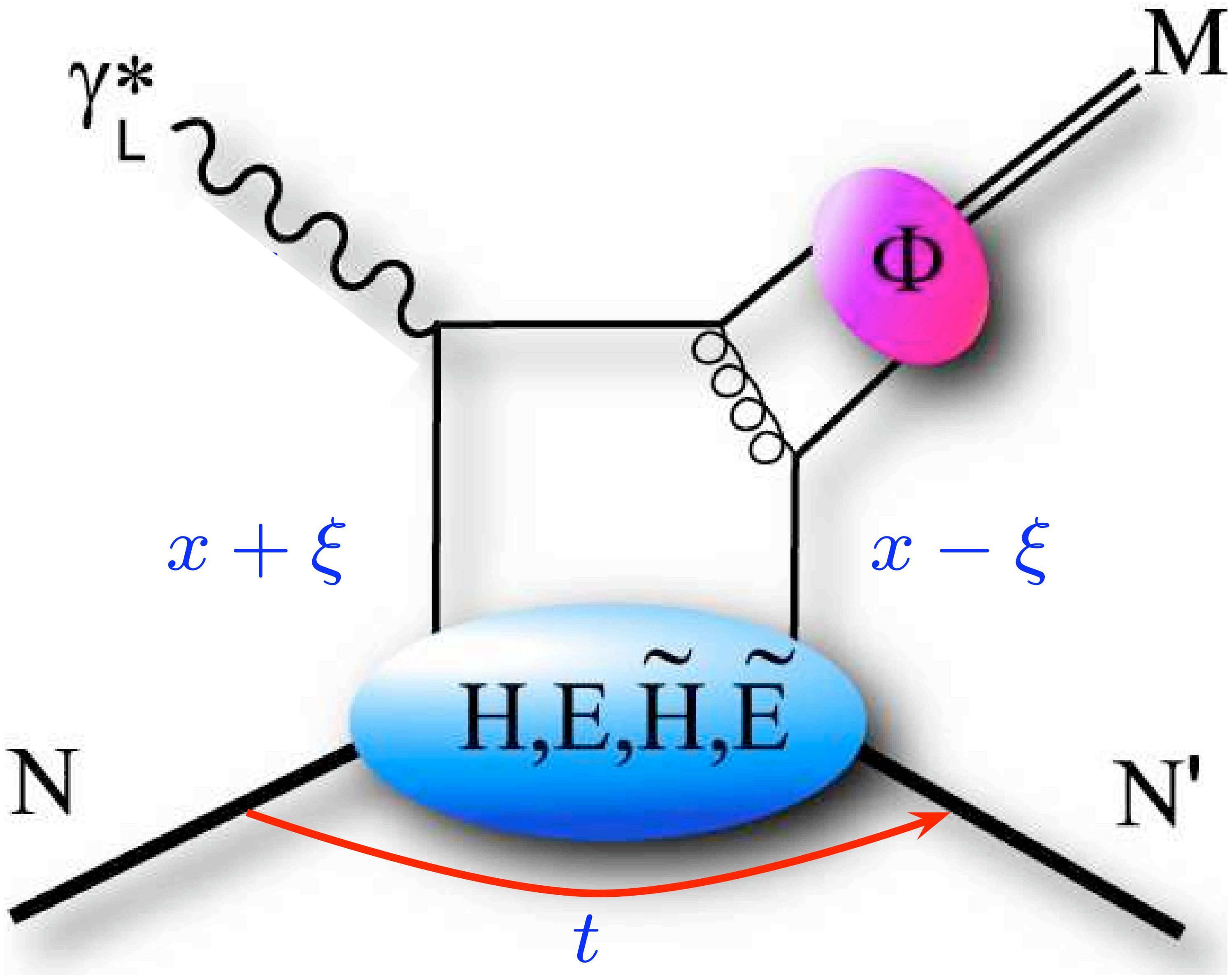
DVCS with recoil detector



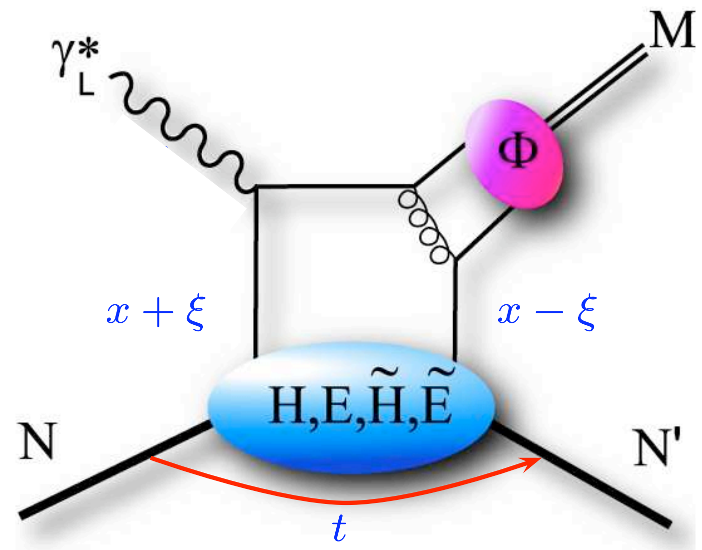
indication of larger amplitudes for pure sample

extraction of amplitudes for associated production underway

Exclusive meson production



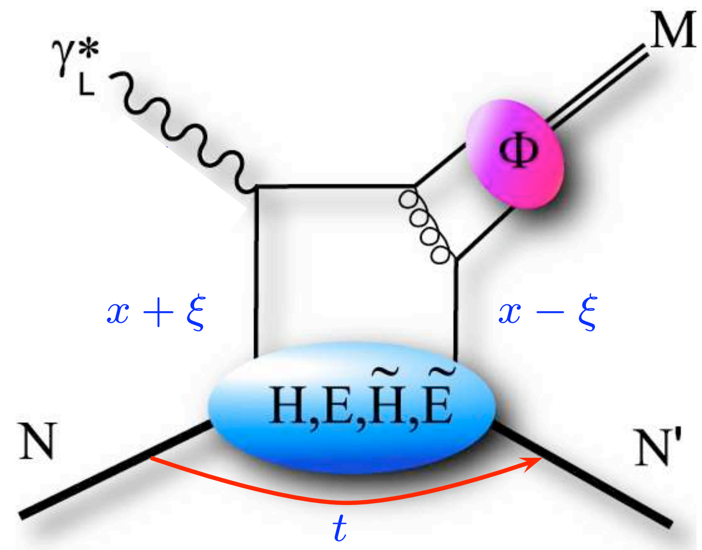
Exclusive meson production



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

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

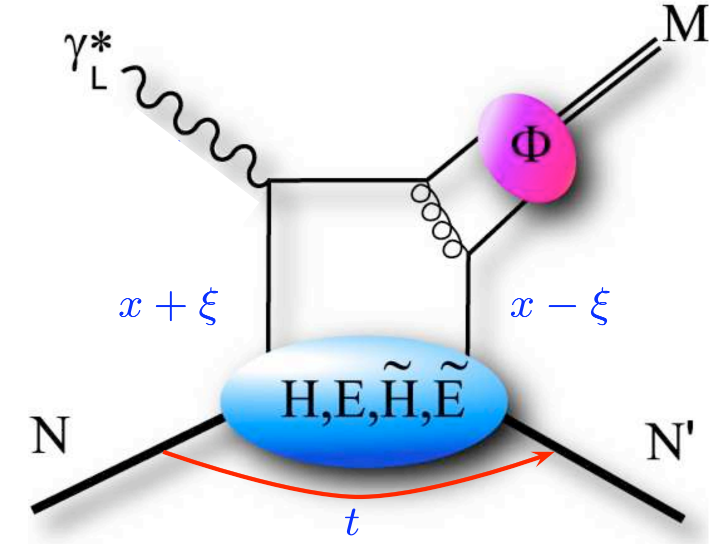
Exclusive meson production



- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons

π^0	2Δu+Δd
η	2Δu−Δd
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
φ	s, g
ρ^+	u−d
J/ψ	g

Exclusive meson production



- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- vector-meson cross section:

π^0	2Δu+Δd
η	2Δu–Δd
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

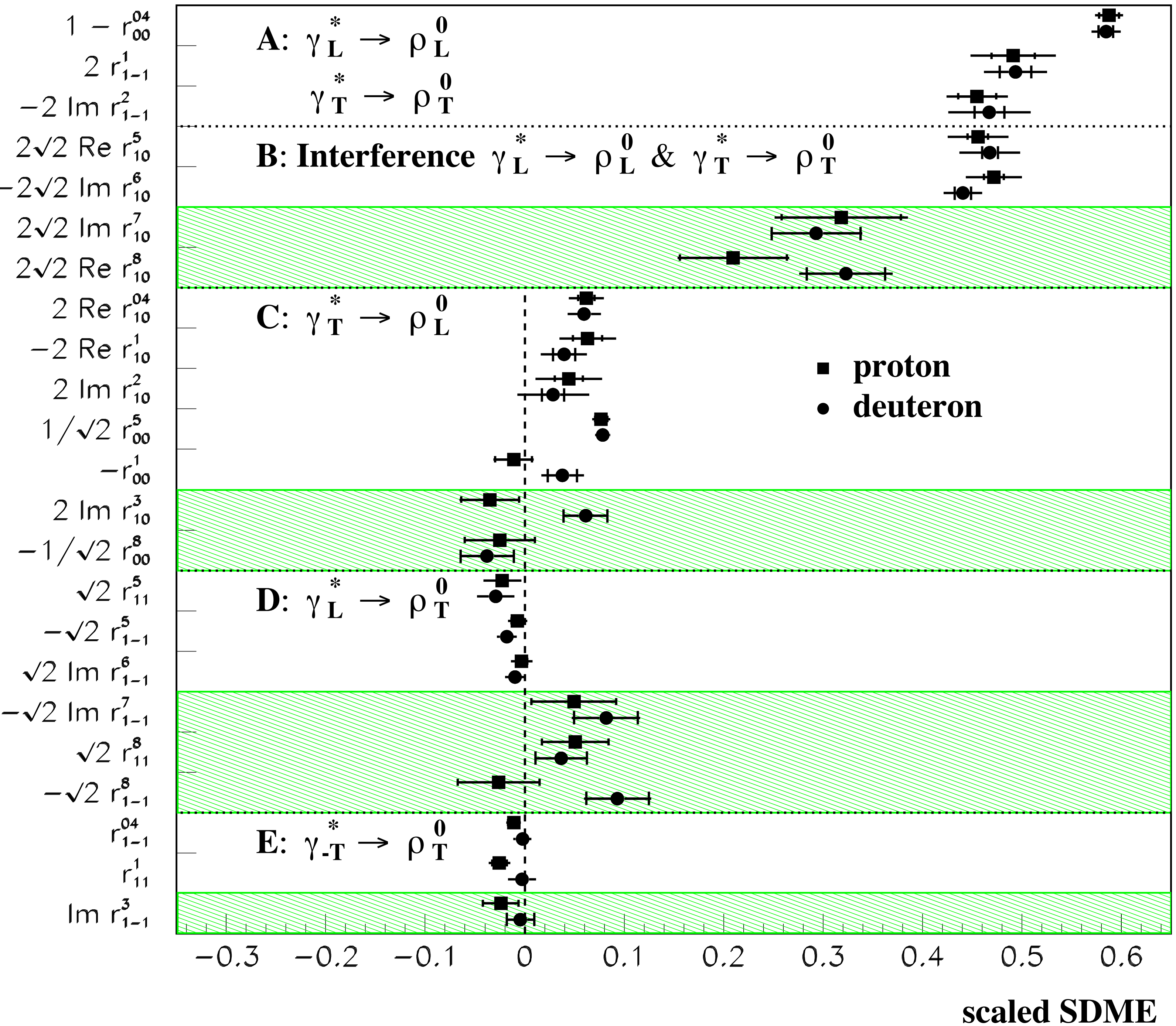
$$\frac{d\sigma}{dx_B\,dQ^2\,dt\,d\phi_S\,d\phi\,d\cos\theta\,d\varphi} = \frac{d\sigma}{dx_B\,dQ^2\,dt} W(x_B, Q^2, t, \phi_S, \phi, \cos\theta, \varphi)$$

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

look at various angular modulations to study helicity transitions (“spin-density matrix elements”)

ρ^0 SDMEs from HERMES

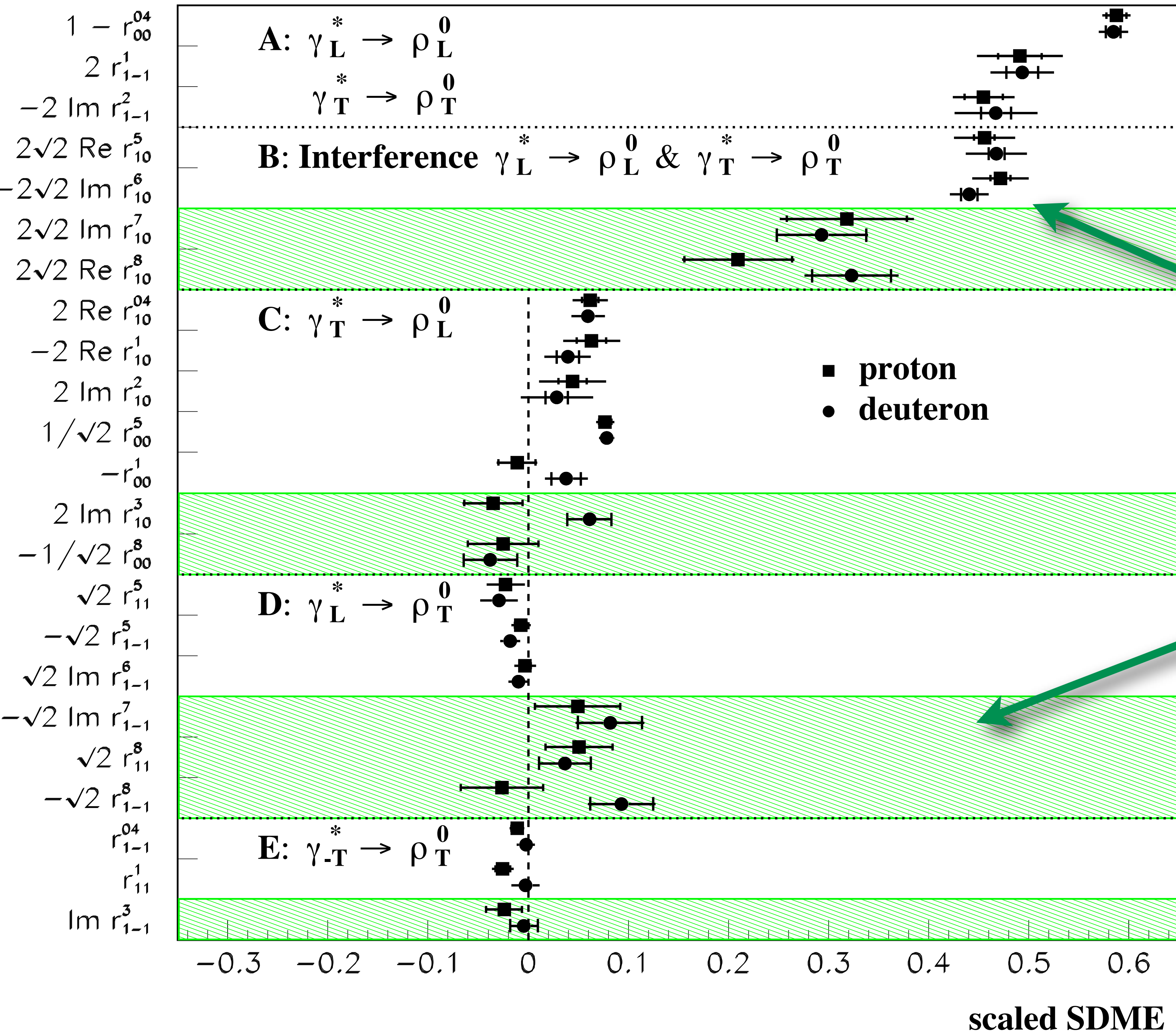
[A. Airapetian et al., arXiv:0901.0701]



target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

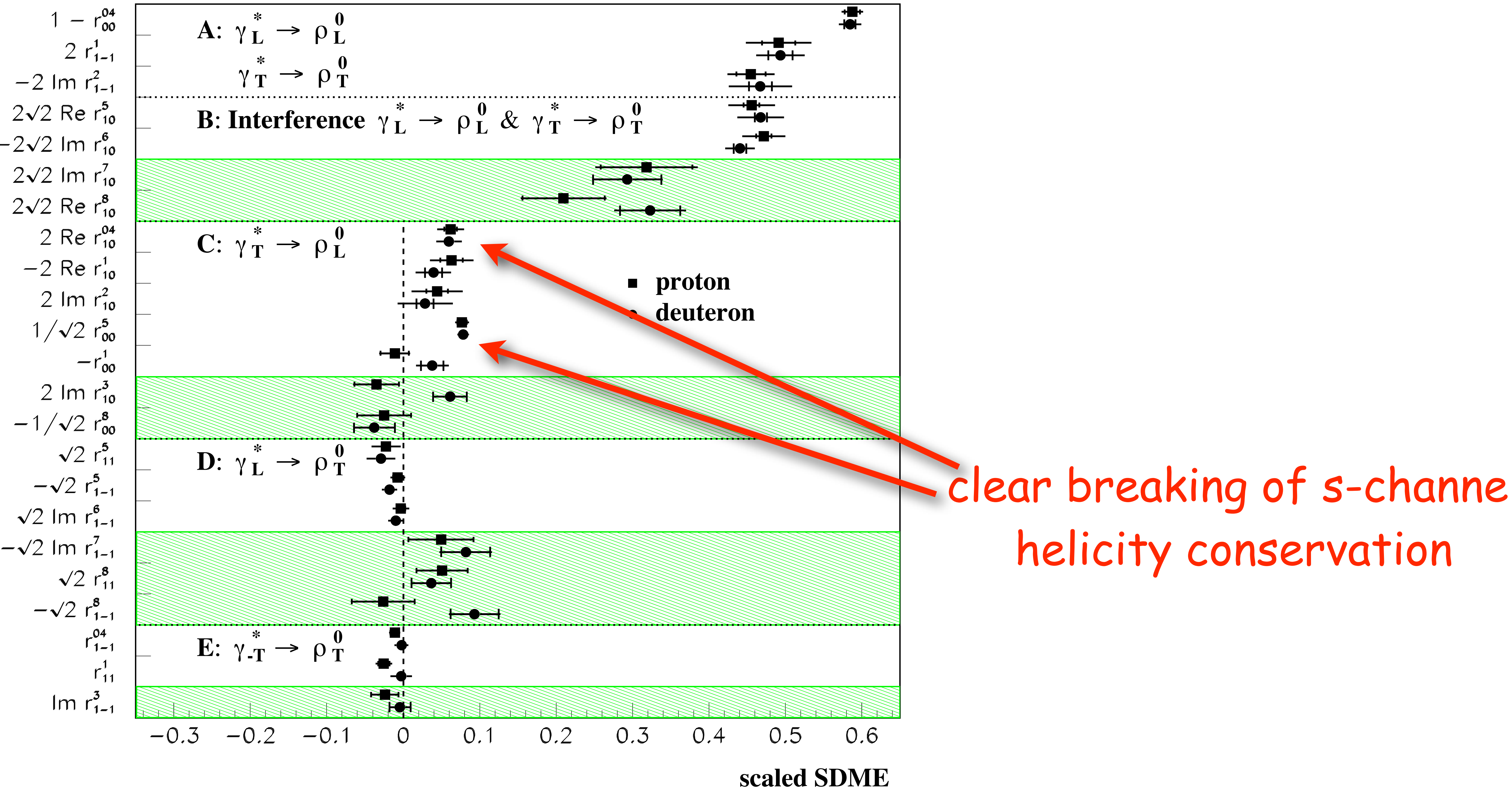


helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]



target-polarization independent SDMEs

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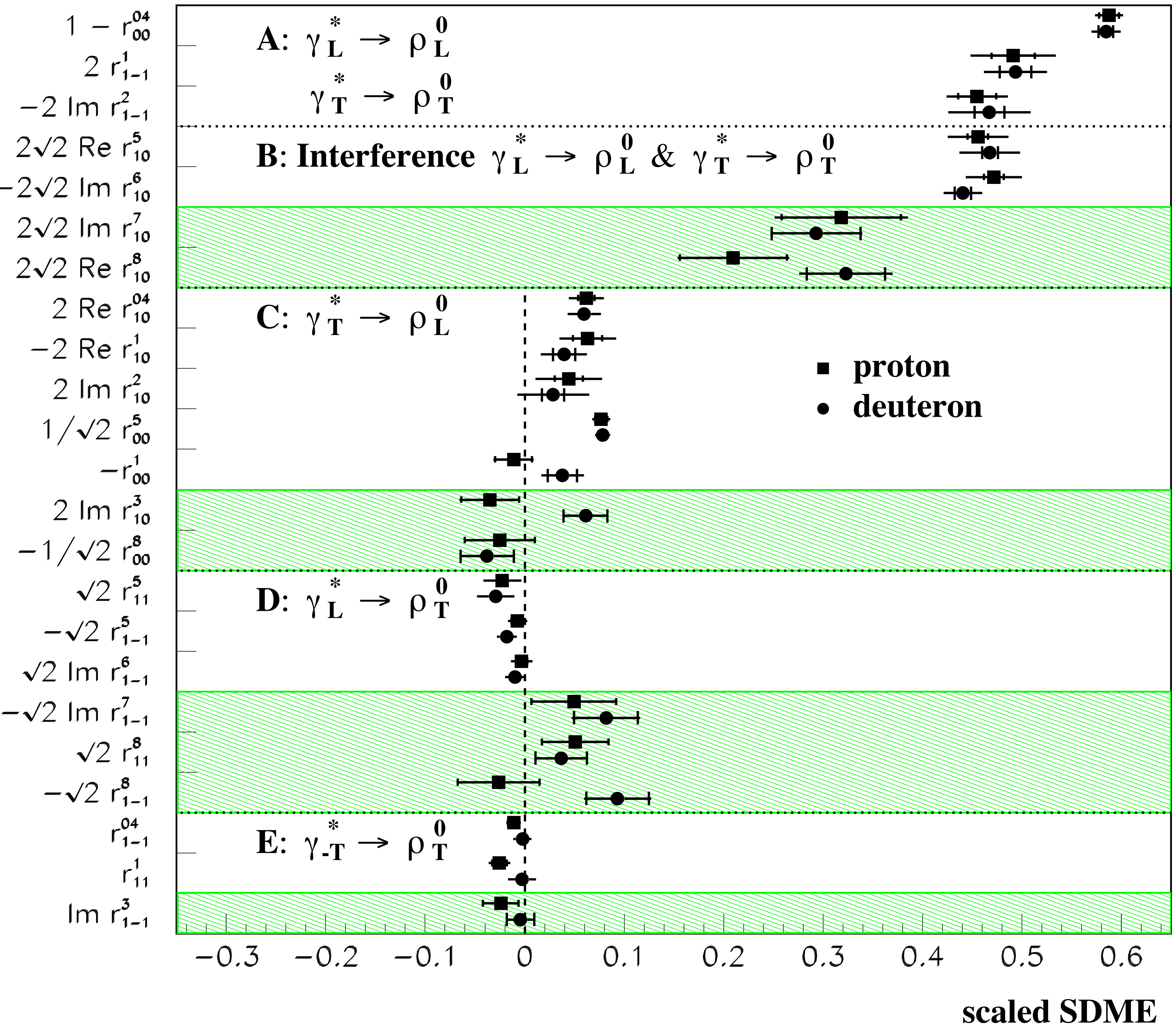
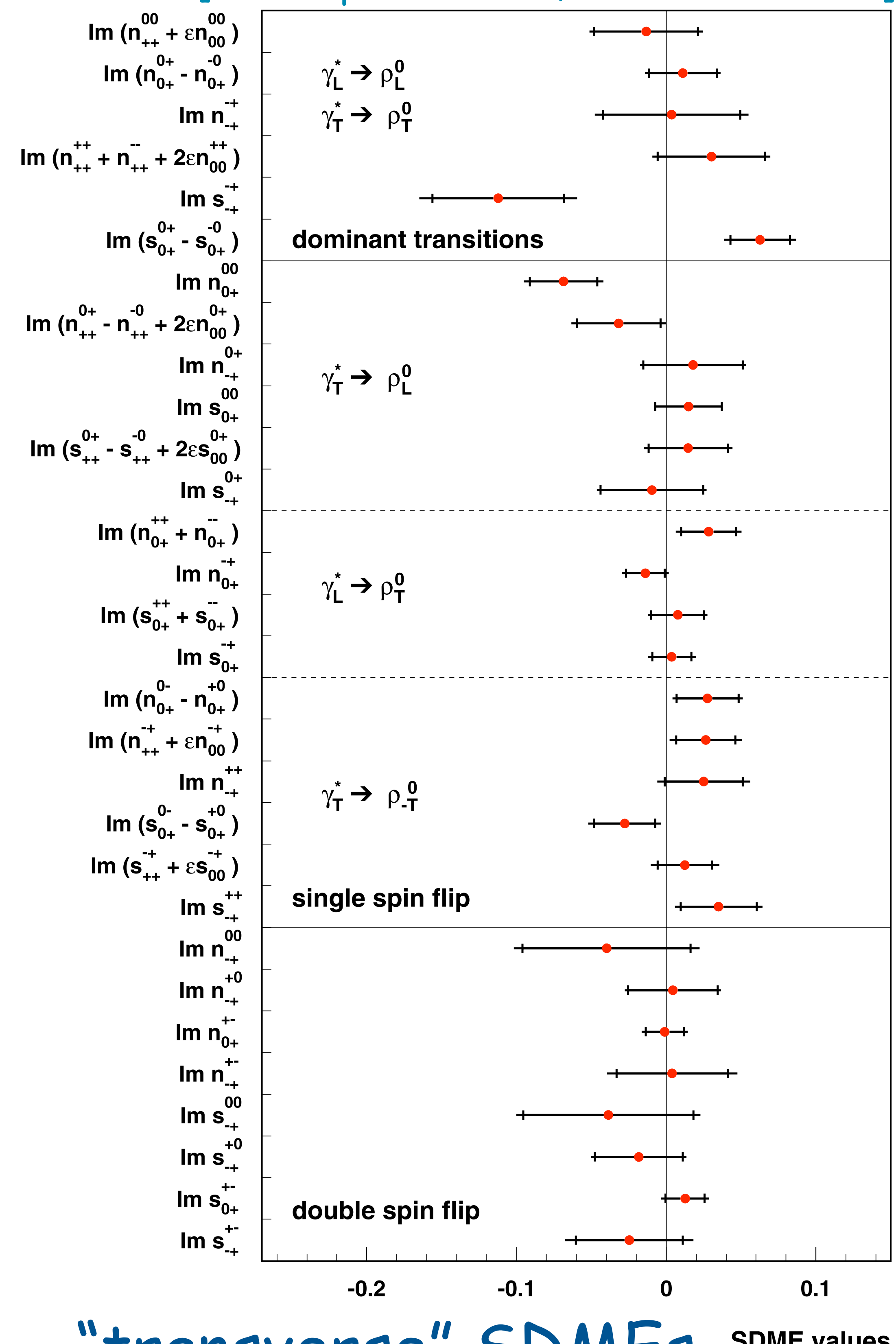


target-polarization independent SDMEs

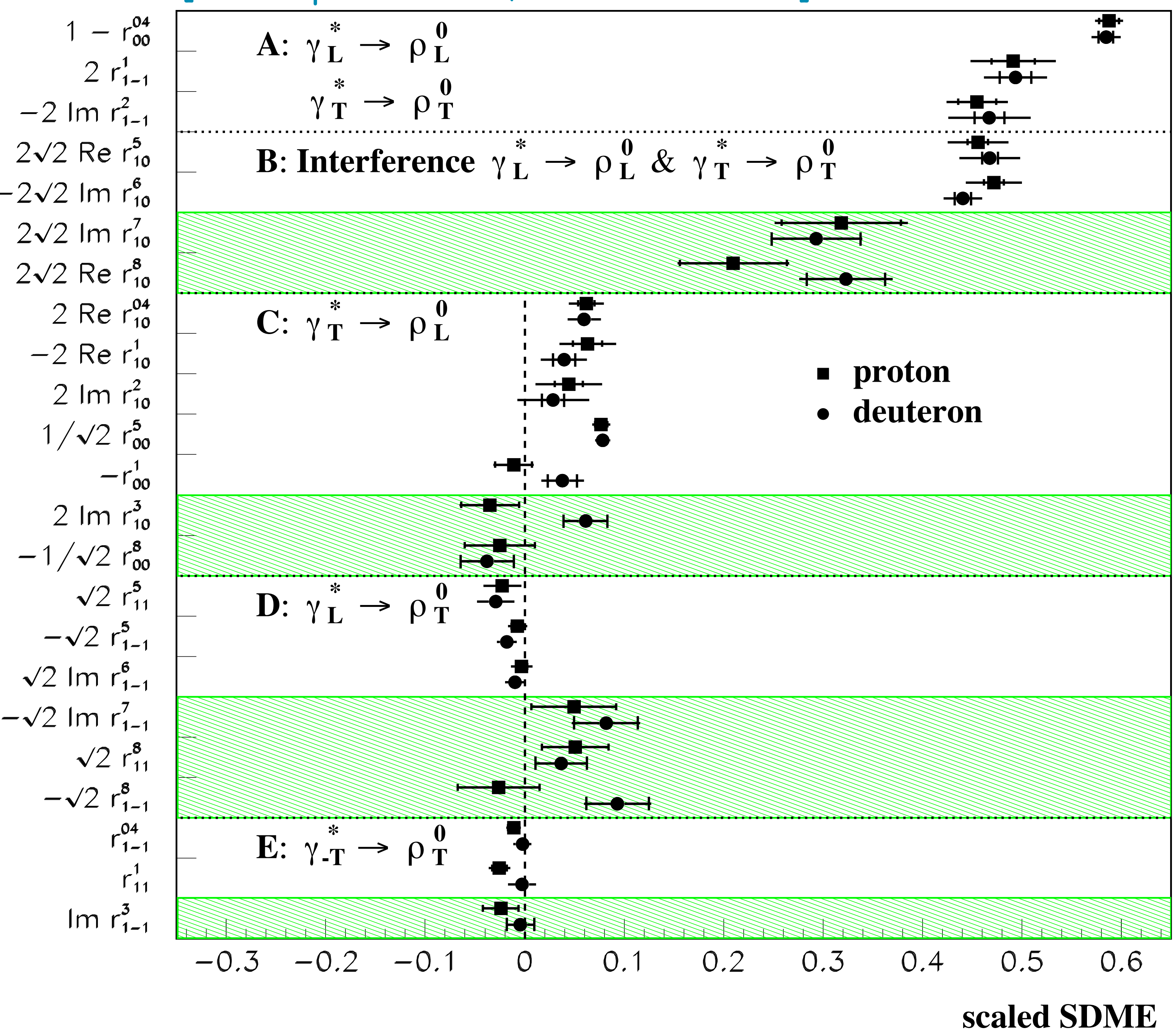
[A. Airapetian et al., arXiv:0906.5160]



"transverse" SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]



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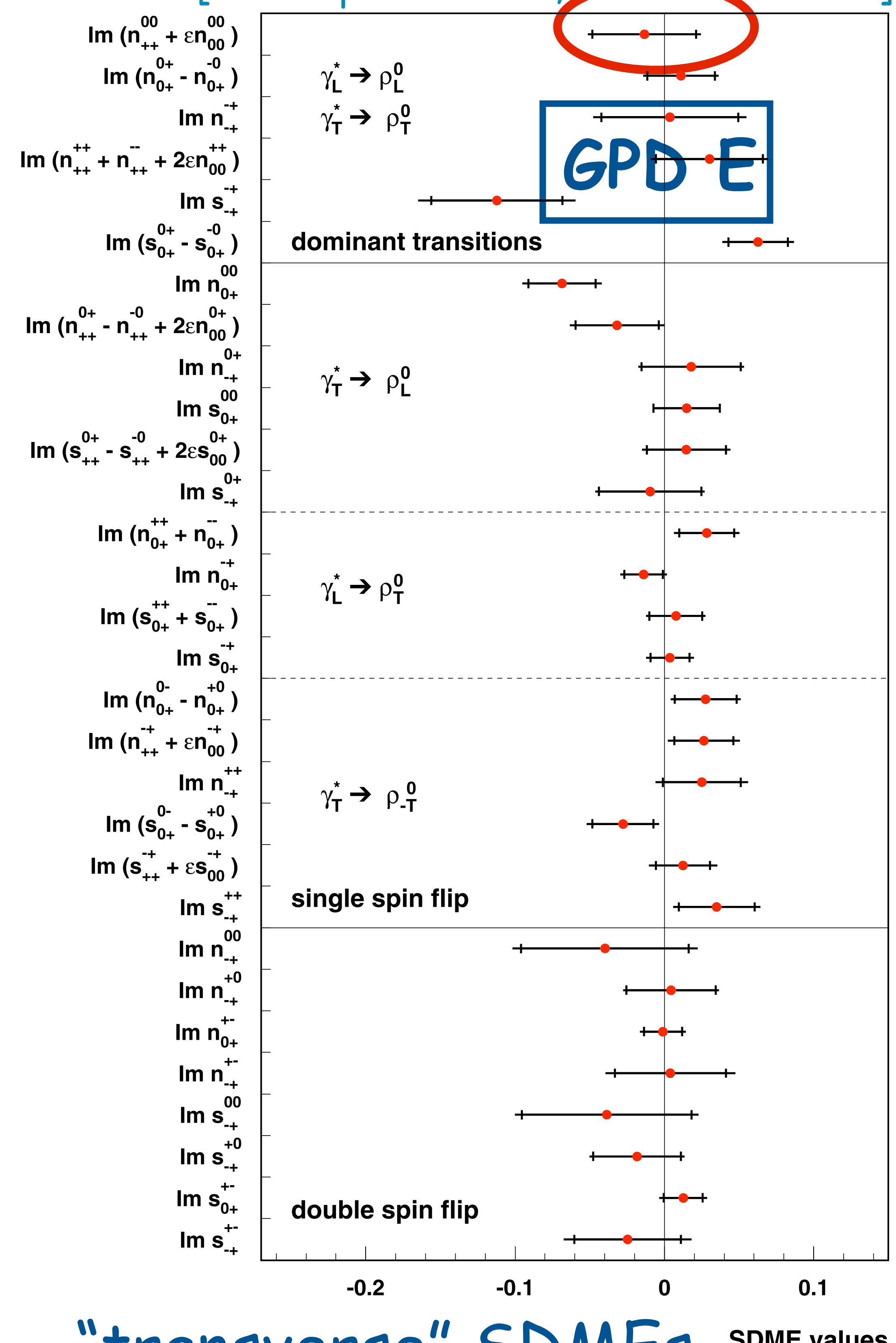

target-polarization independent SDMEs

"transverse" SDMEs

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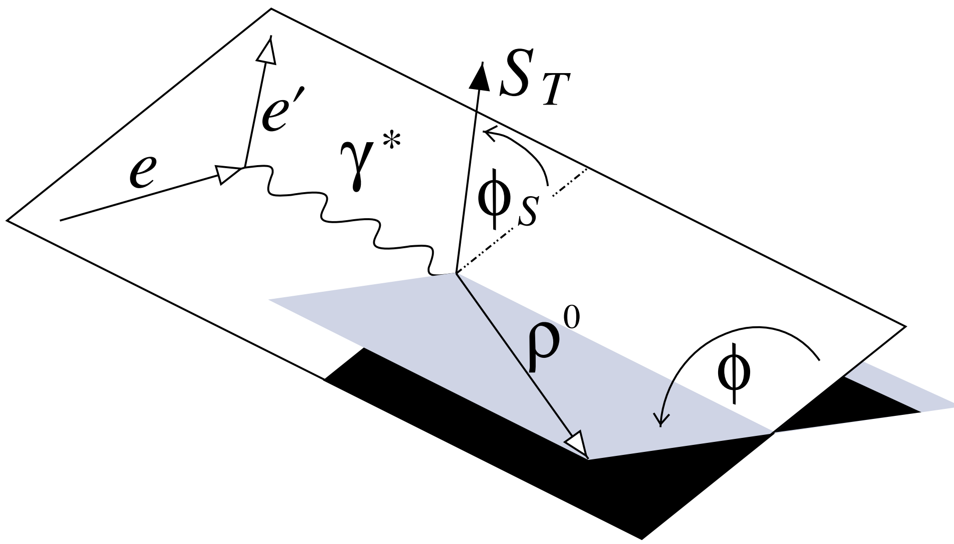
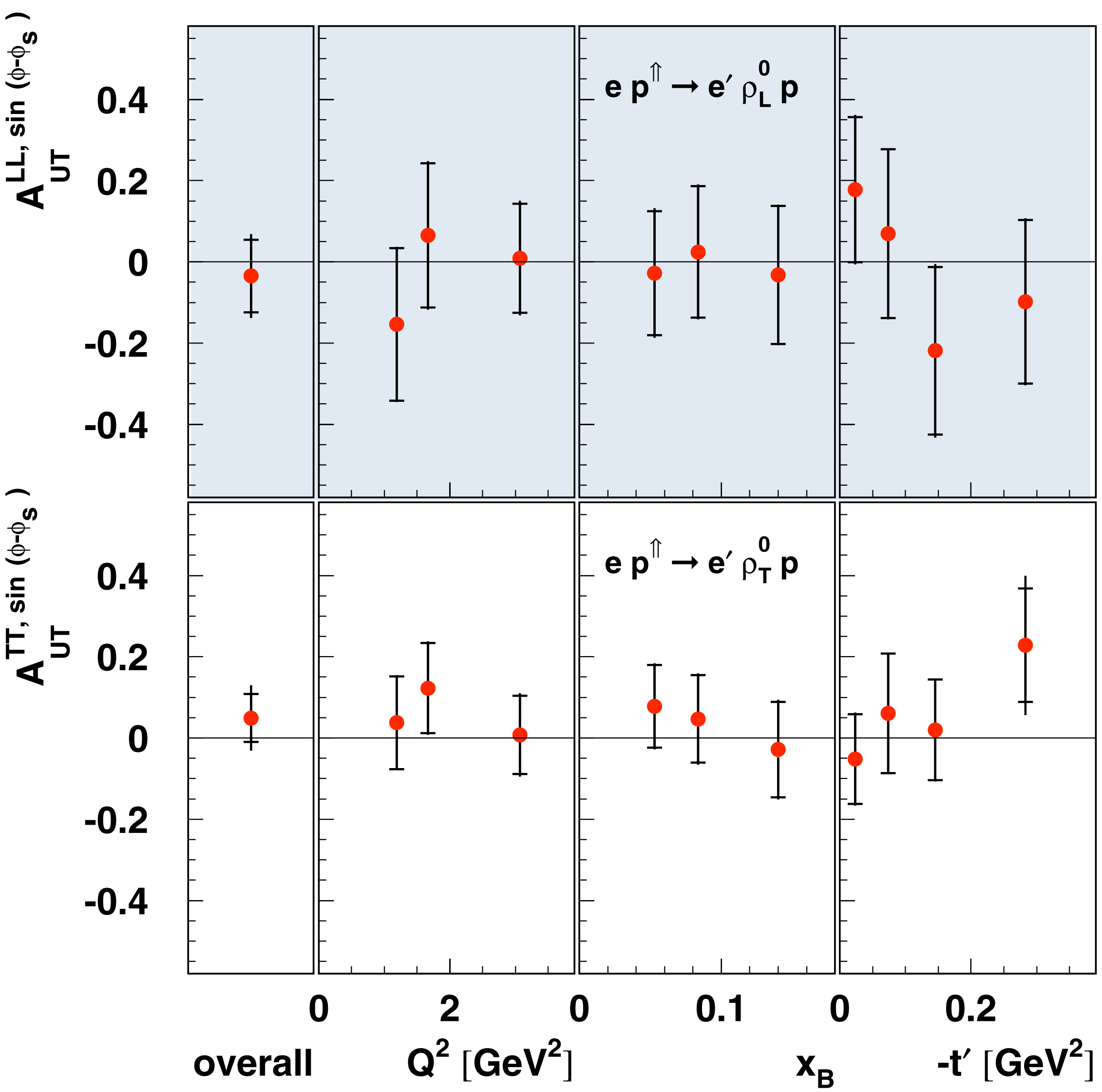
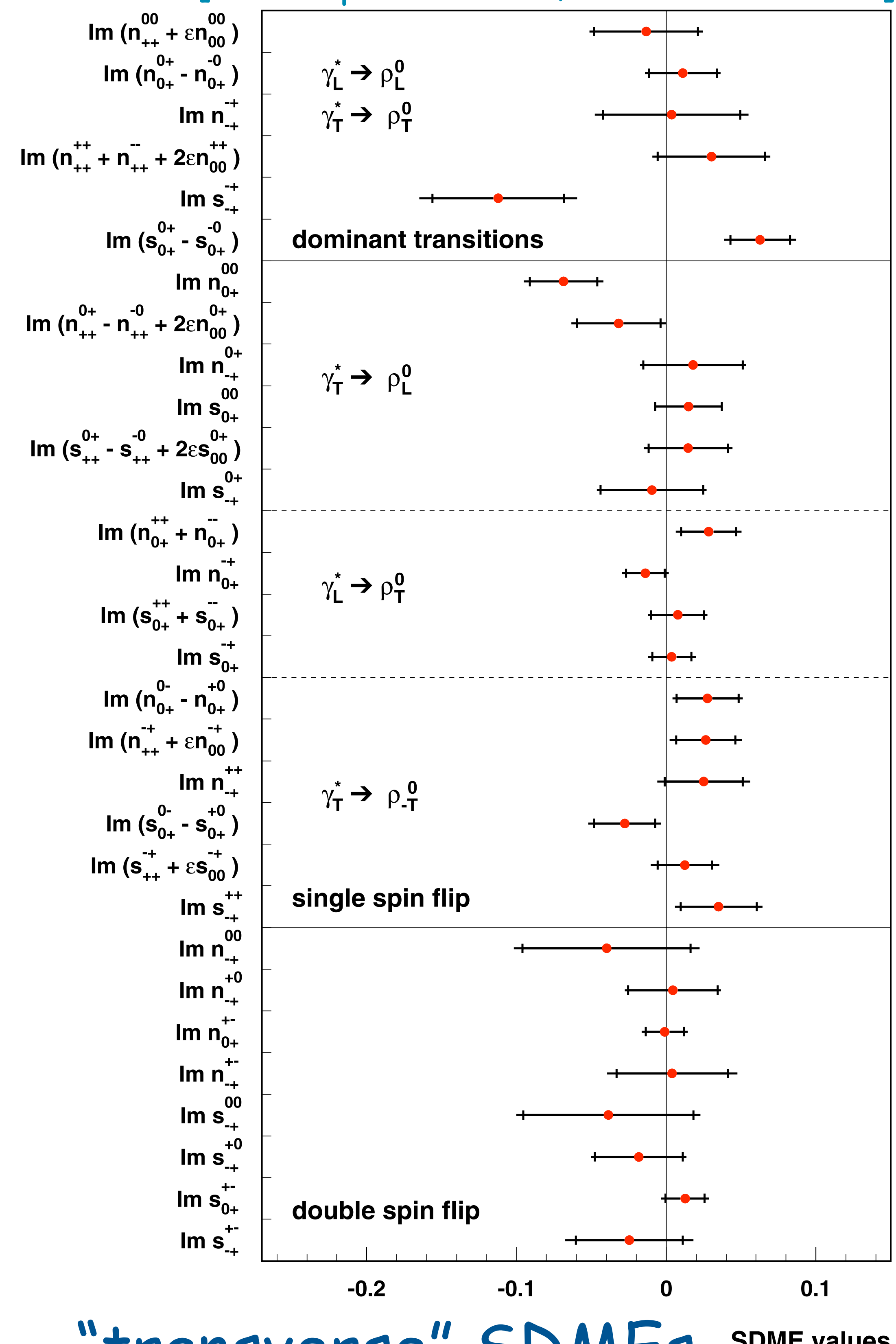
[A. Airapetian et al., arXiv:0906.5160]



longitudinal ρ^0

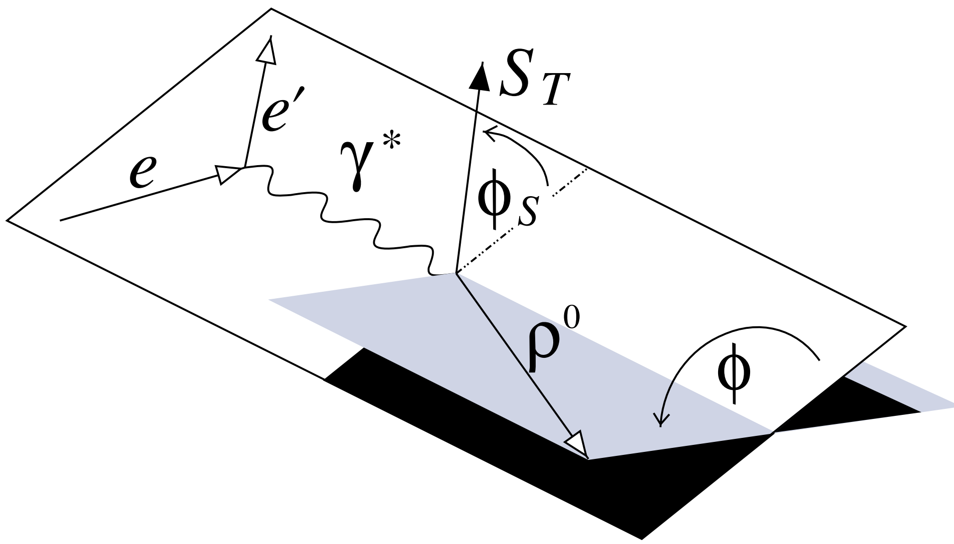
transverse ρ^0





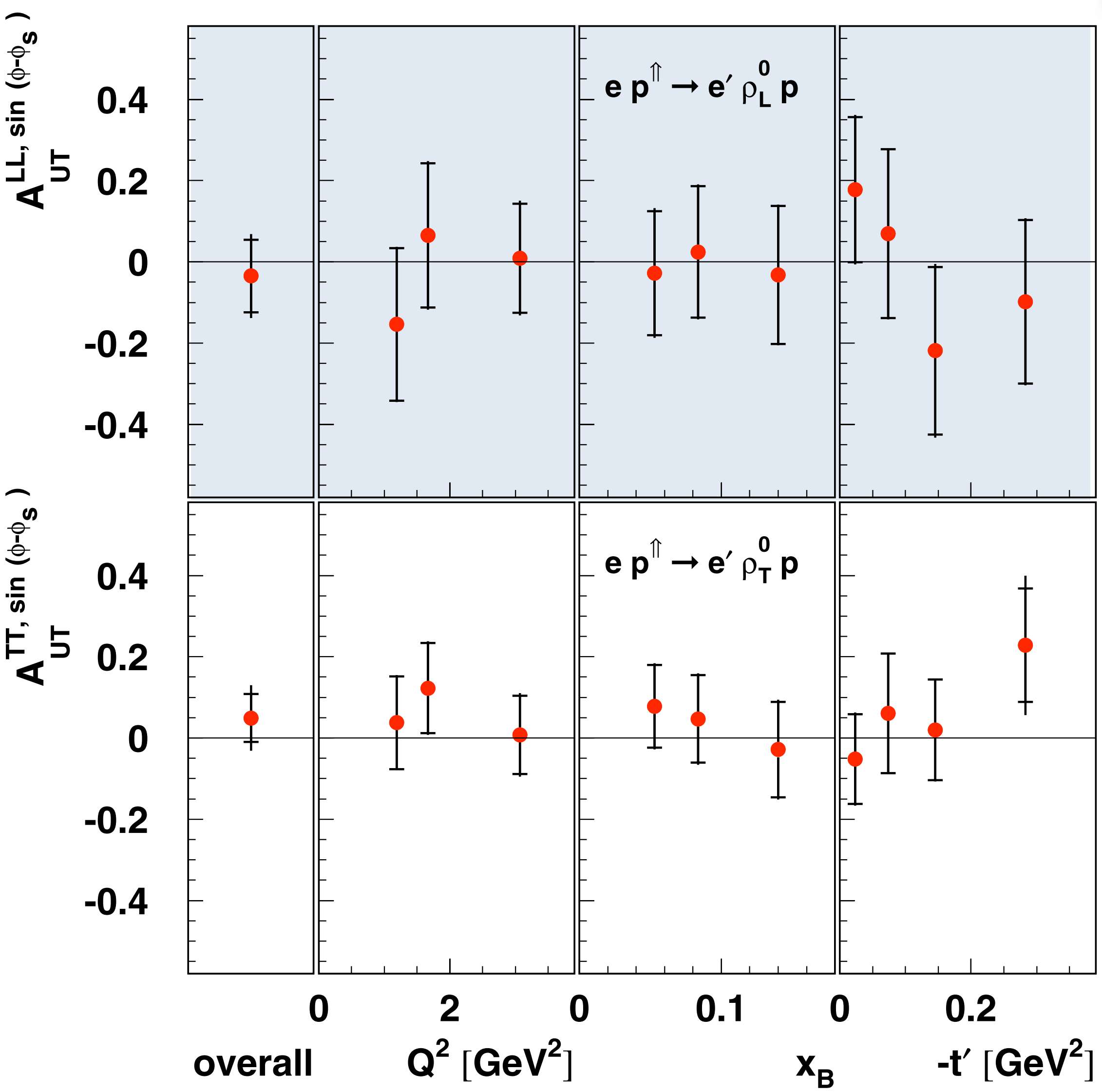
"transverse" SDMEs

ρ^0 SDMEs from HERMES



longitudinal ρ^0

transverse ρ^0



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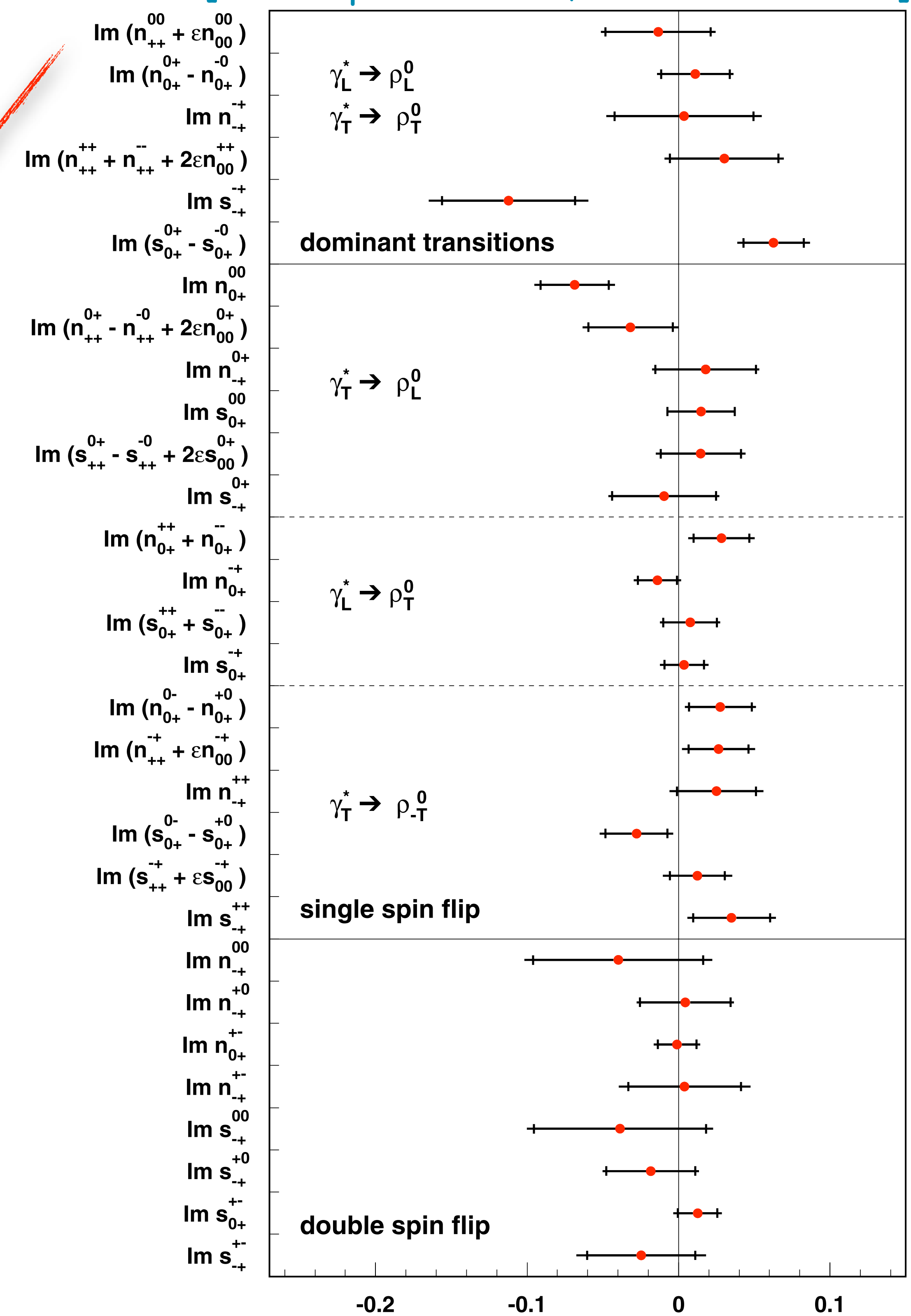
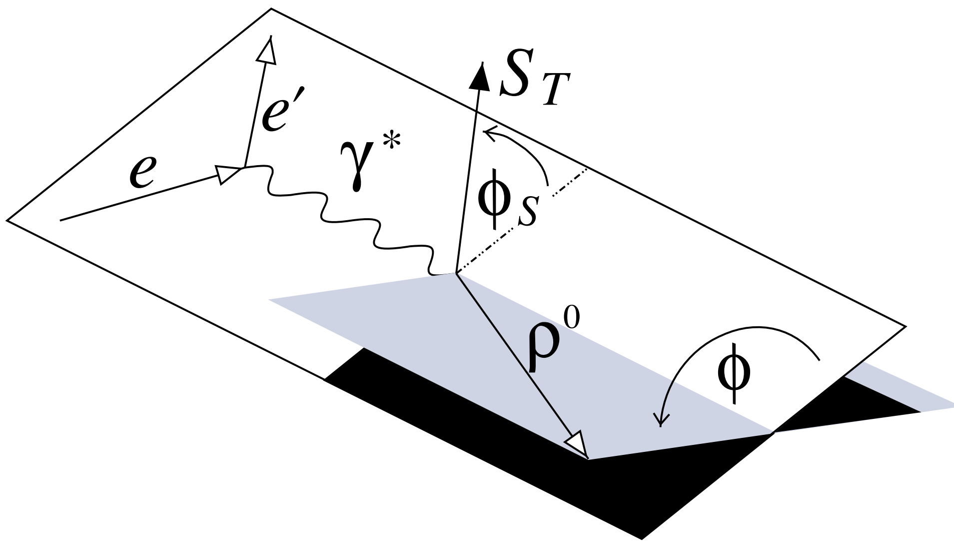


"transverse" SDMEs

ρ^0 SDMEs from HERMES



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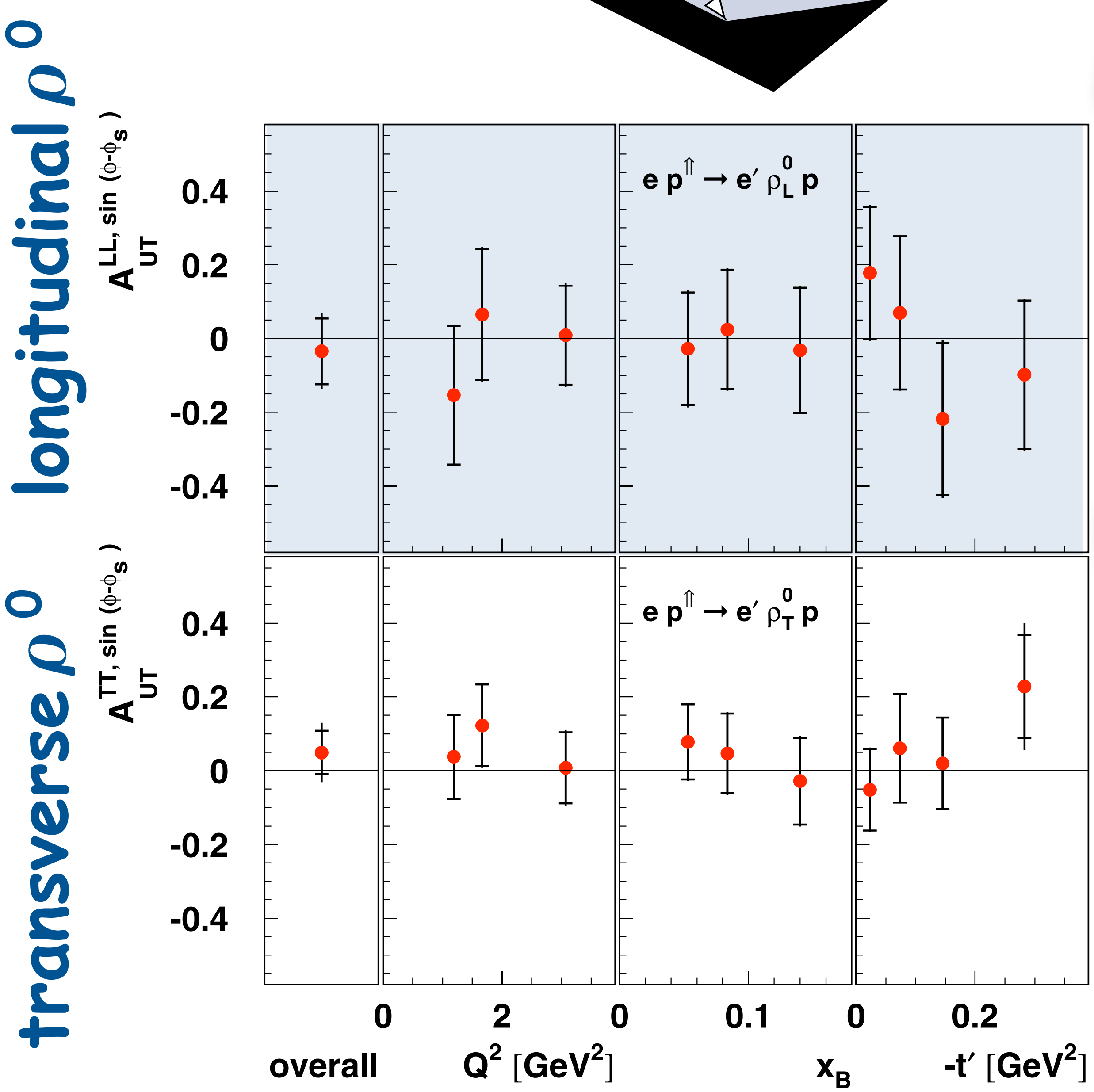
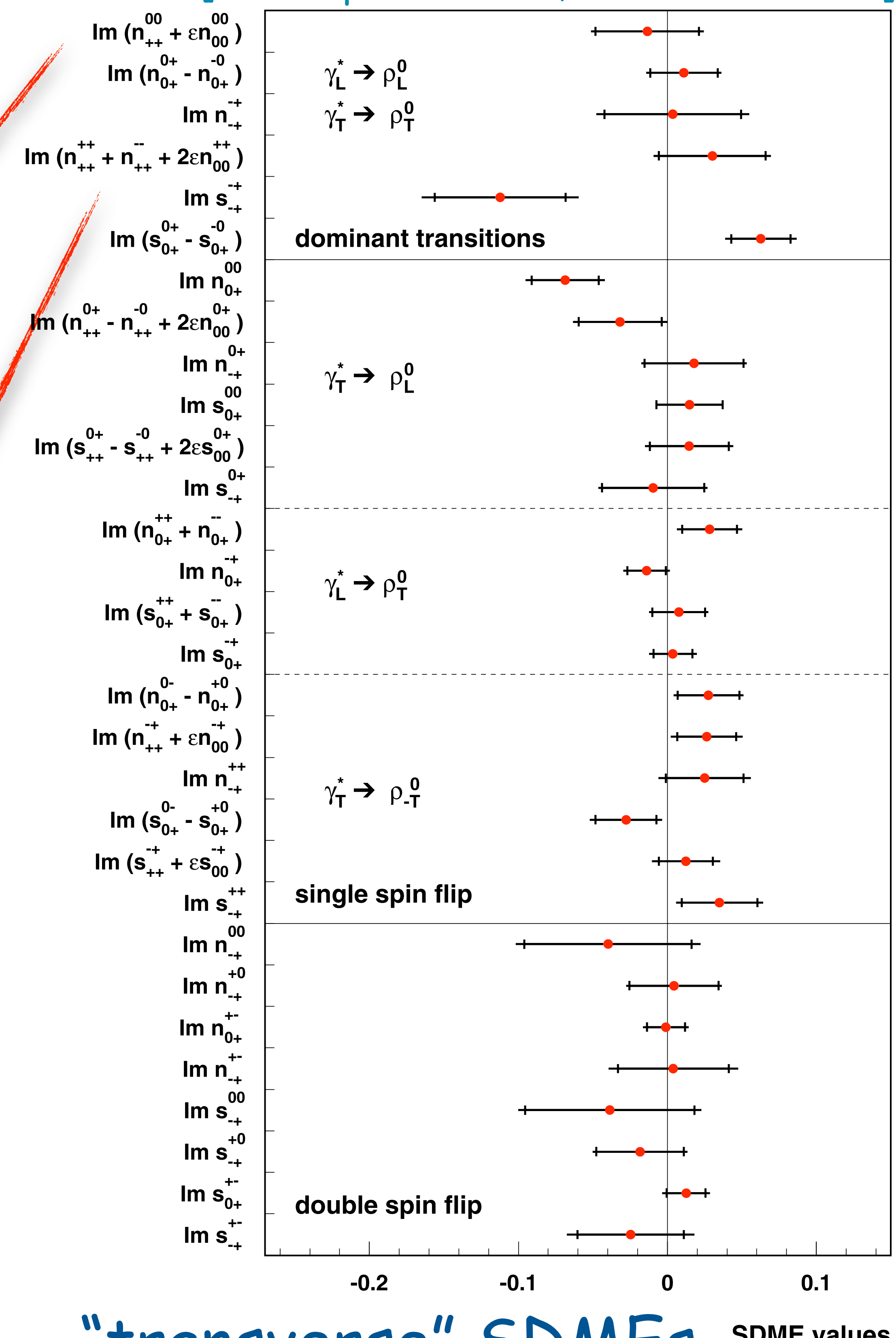
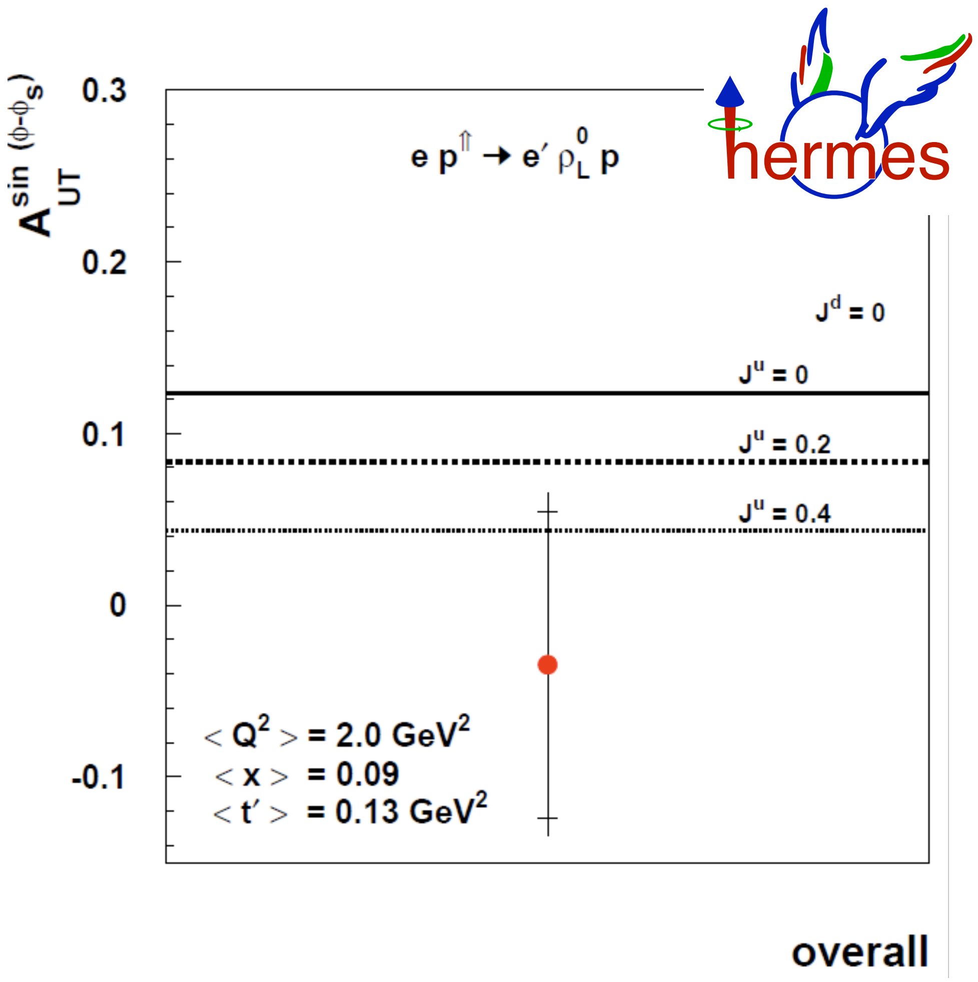
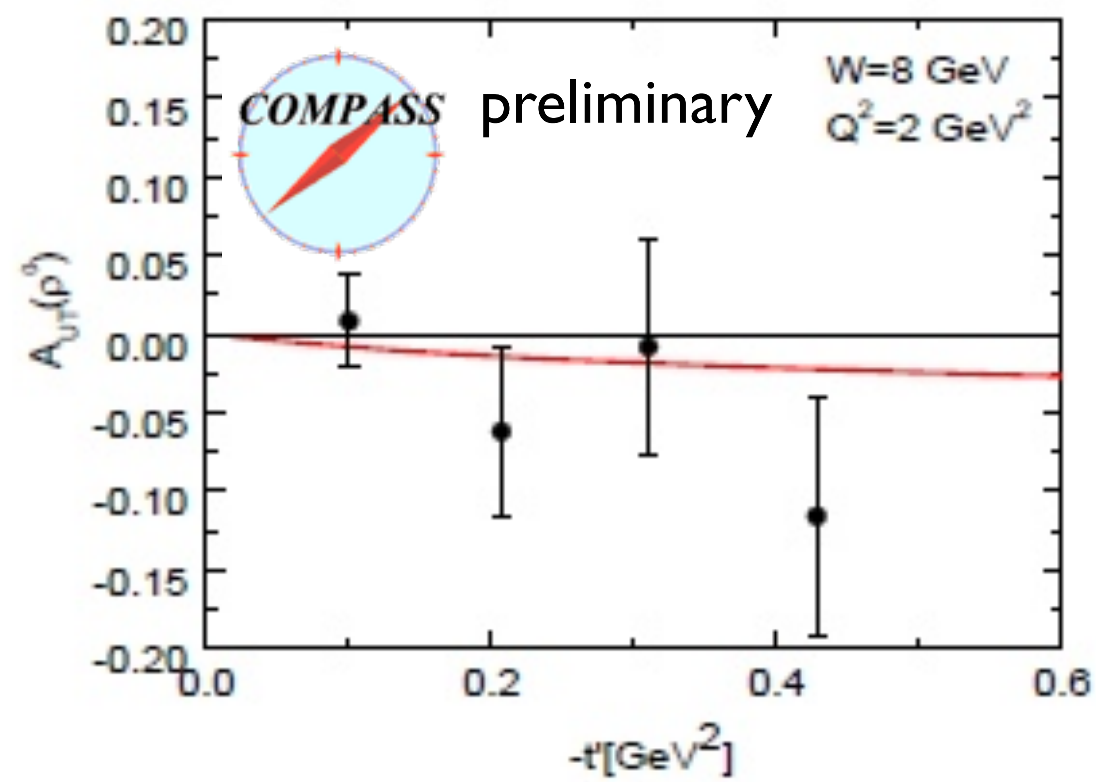




"transverse" SDMEs

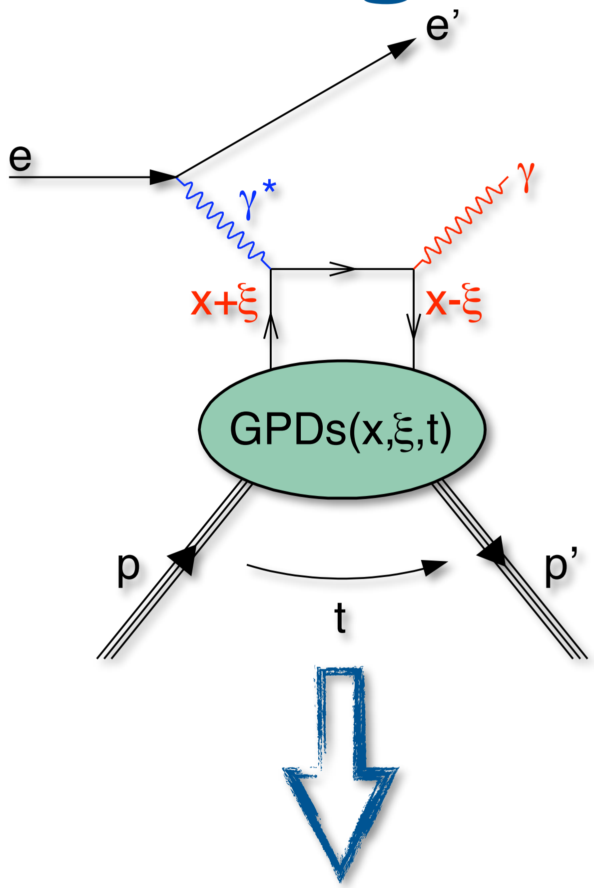
Transverse SSA

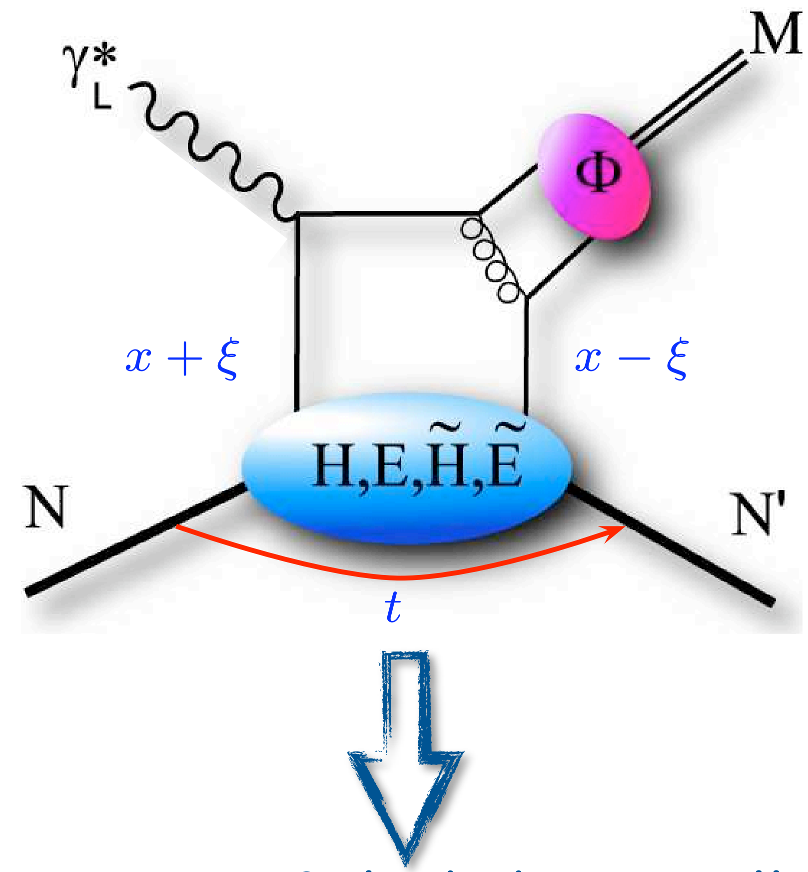




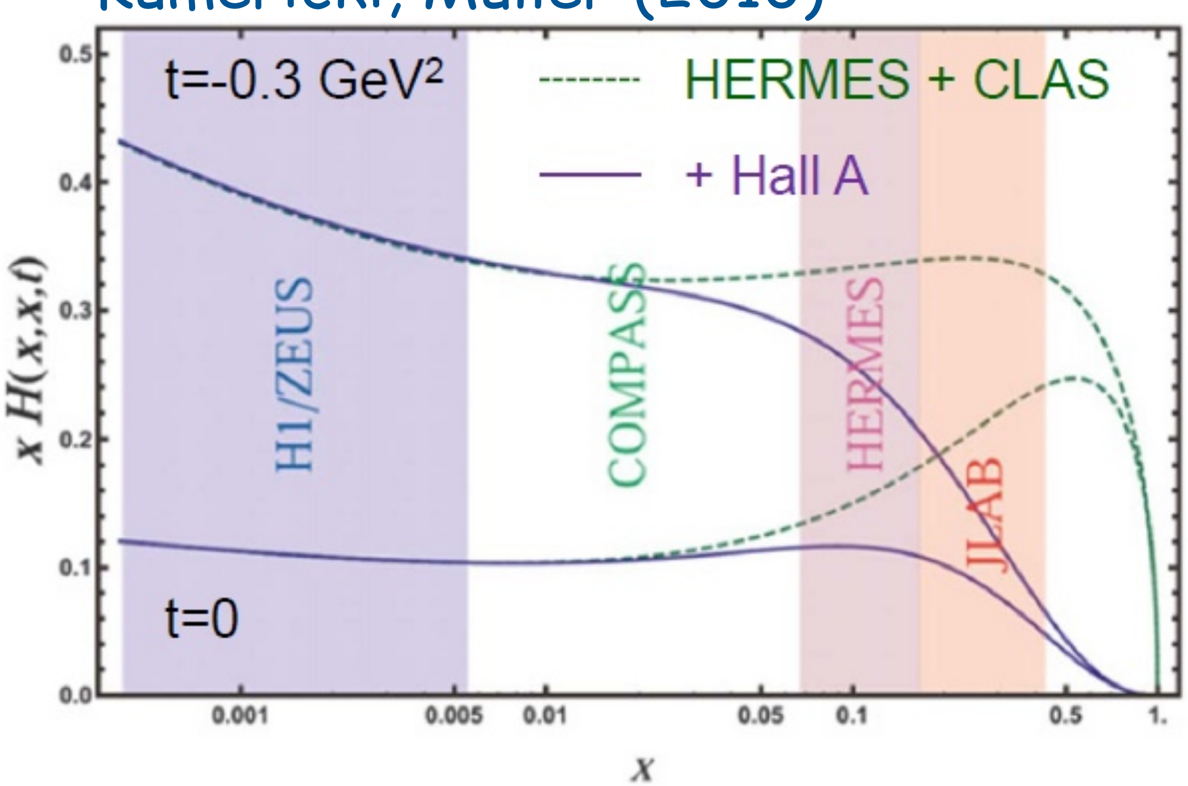
- COMPASS results: no L/T separation
- more data to come from 2010 run and future transverse DVCS program
- in principle sensitive to GPD E -> total angular momentum

Towards global GPD analyses (cf. next speaker)

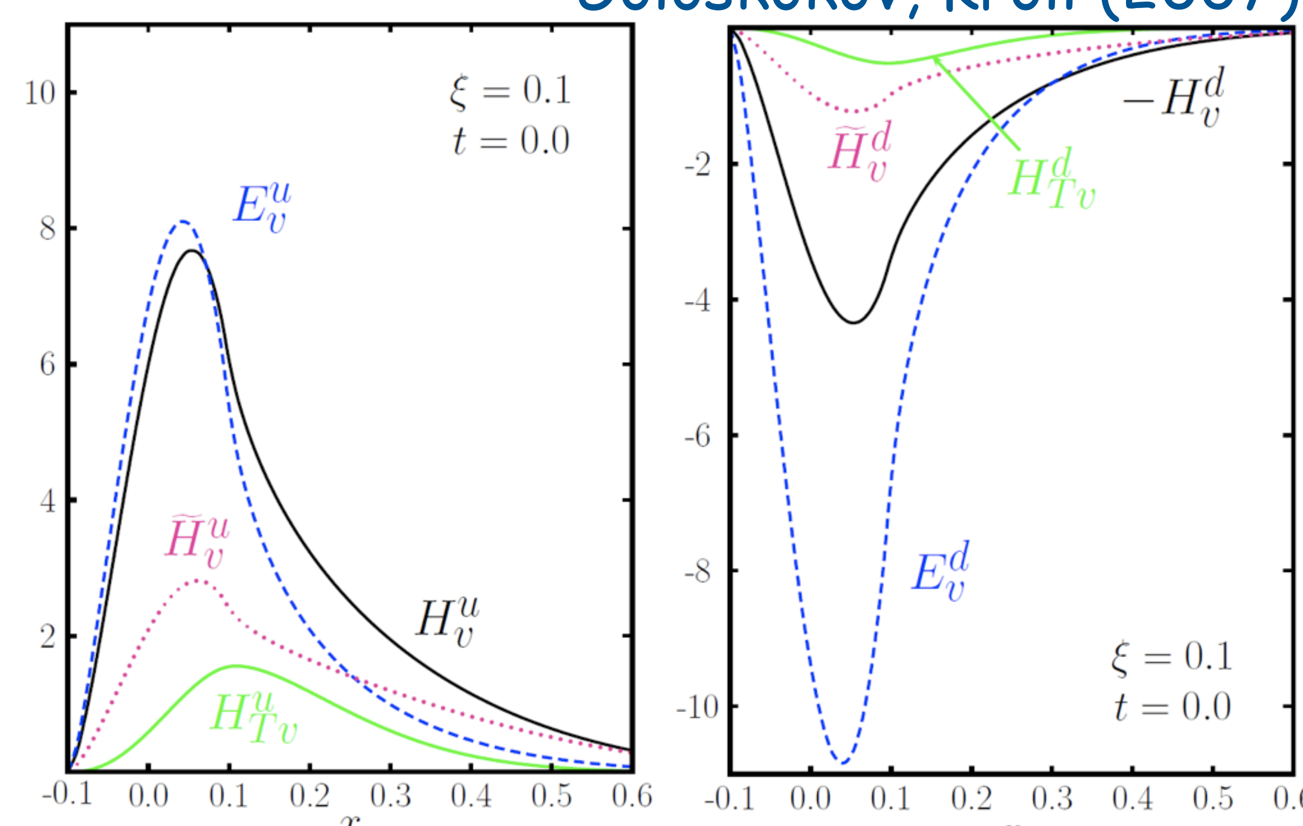




Kumericki, Müller (2010)

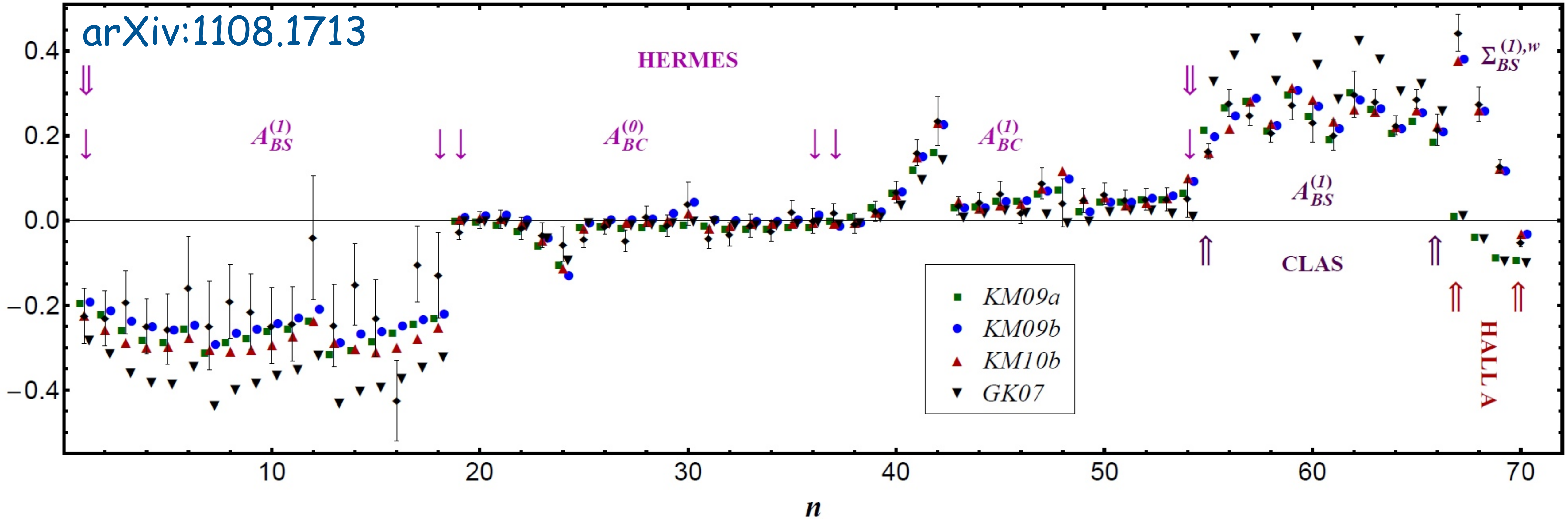


Goloskokov, Kroll (2007)



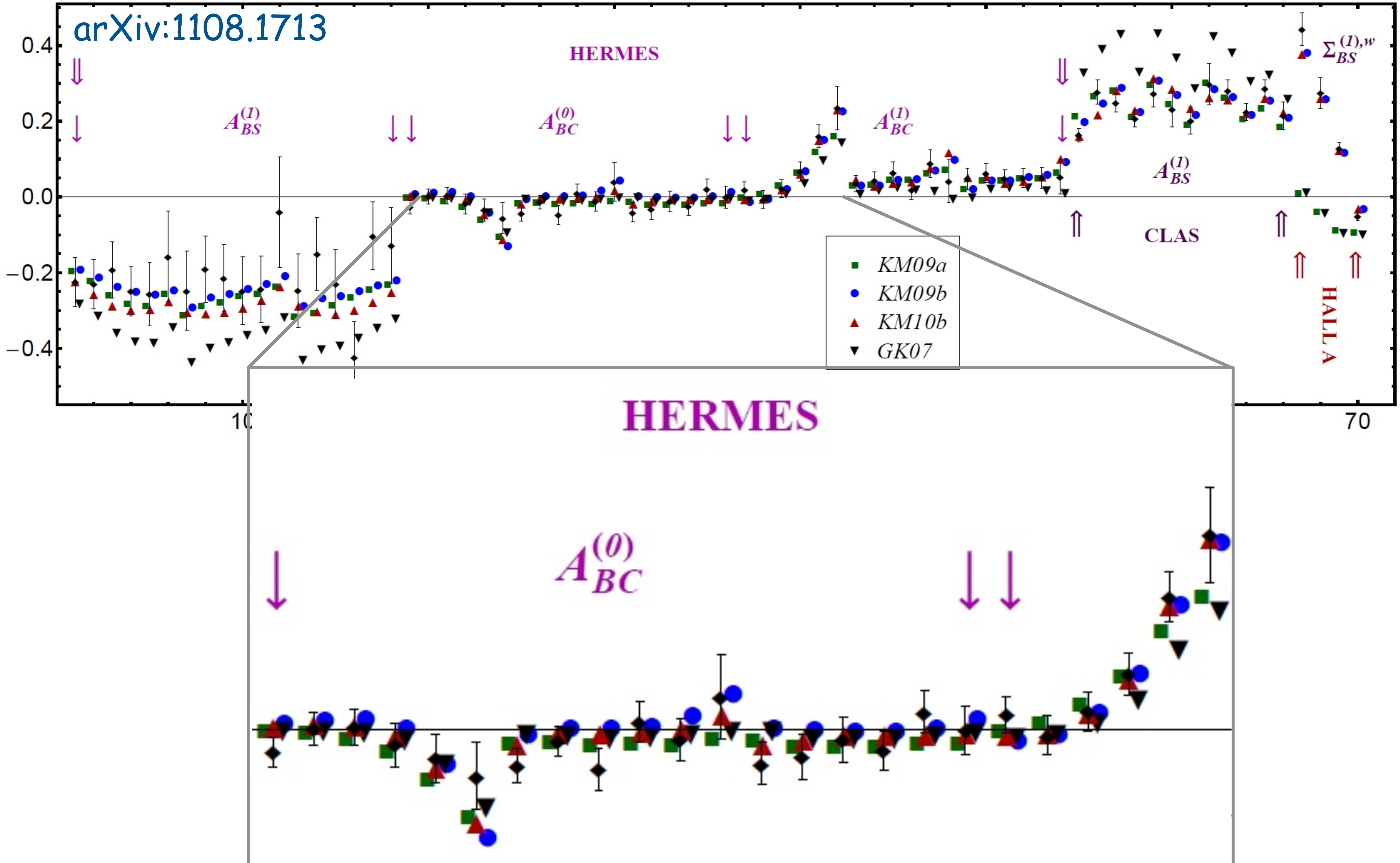
Towards global GPD analyses

➡ try out GPDs on set of DVCS azimuthal asymmetries:



Towards global GPD analyses

➡ try out GPDs on set of DVCS azimuthal asymmetries:



The proton - seen with multi-D glasses