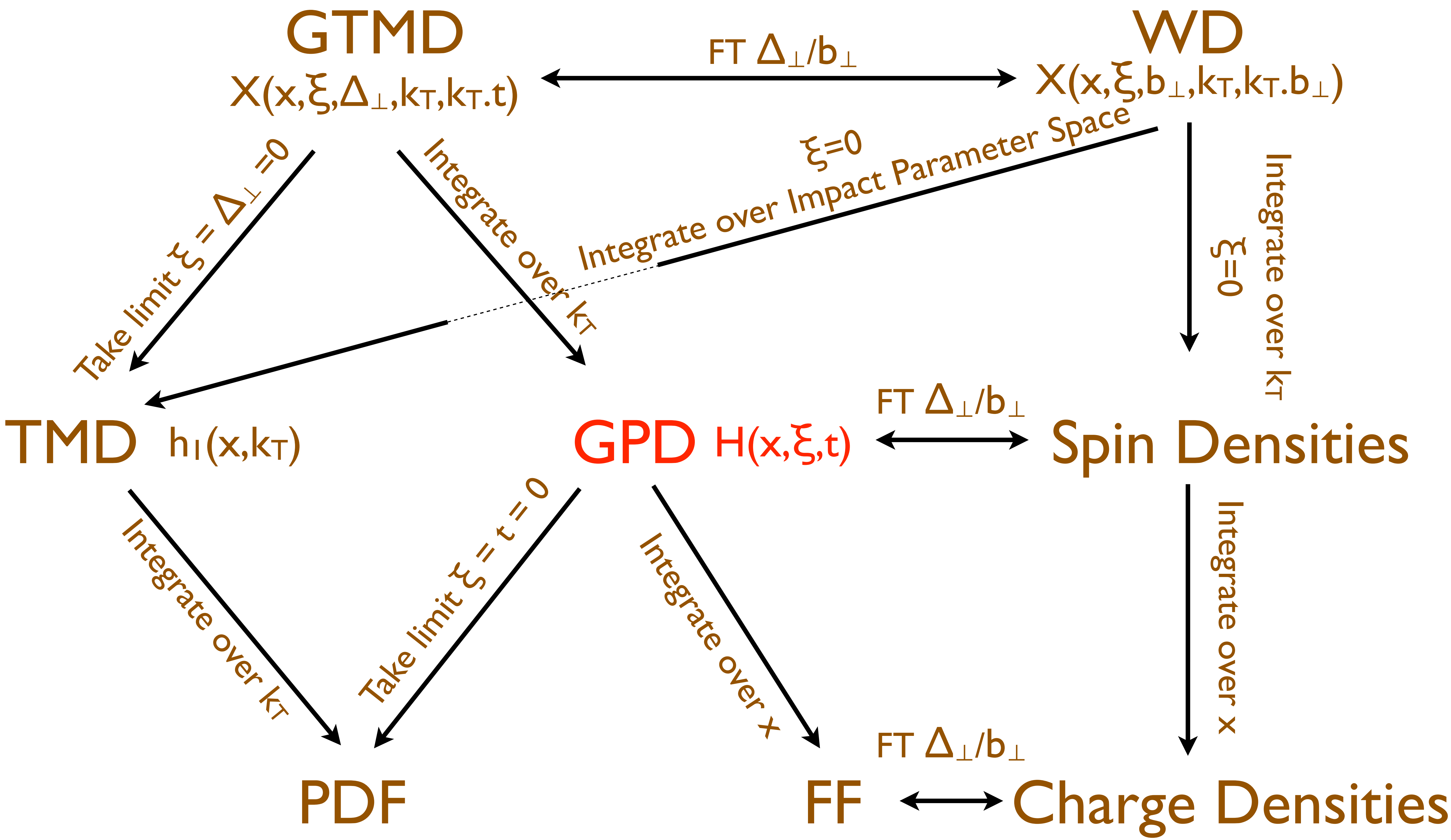
# DVCS @ HERMES

M. MURRAY, UNIVERSITY OF GLASGOW

SPIN 2012

# Distribution Graph



# GPD Physics

GPDs describe only the soft part of the interaction

Accessed via cross-sections and asymmetries: requires convolution with a hard scattering kernel

$H \rightarrow \mathcal{H}$ $\tilde{H} \rightarrow \tilde{\mathcal{H}}$ $E \rightarrow \mathcal{E}$ $\tilde{E} \rightarrow \tilde{\mathcal{E}}$

Results in "Compton Form Factors" accessible through DVCS, which have real and imaginary parts

# GPD Physics

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Accessed via cross-sections and asymmetries:
requires convolution with a hard scattering kernel

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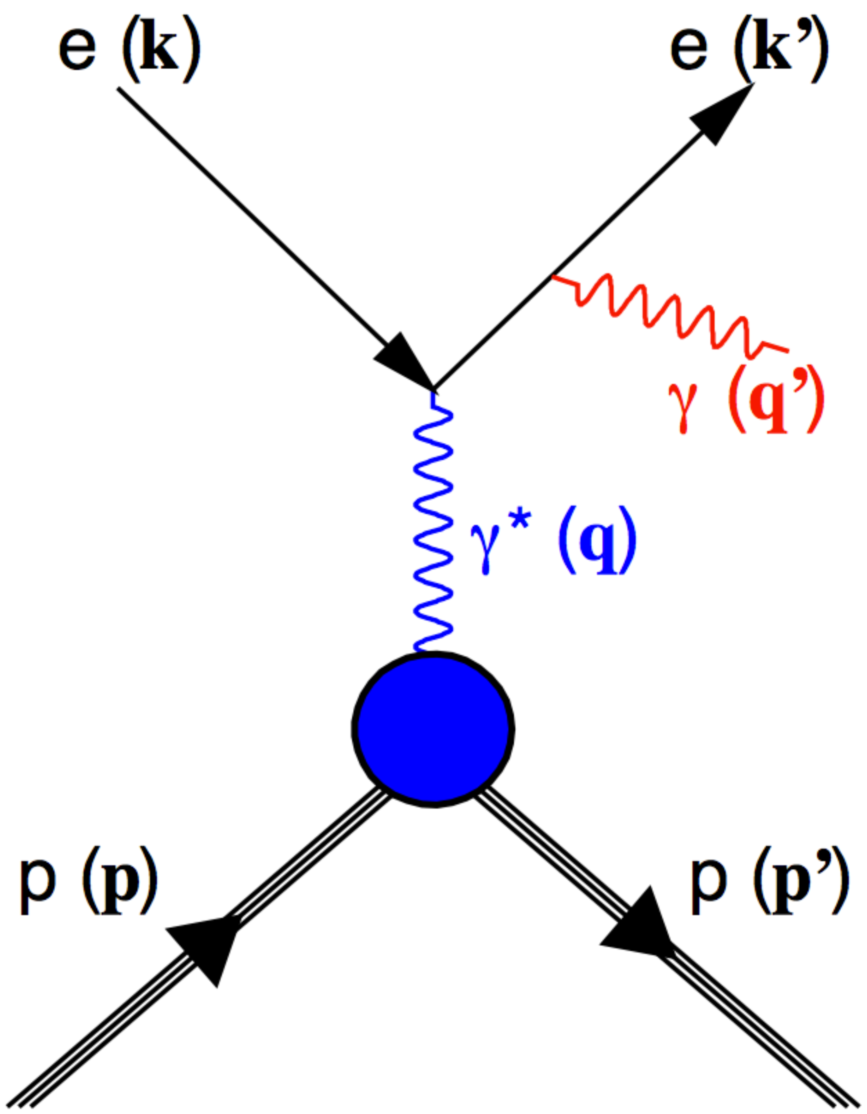
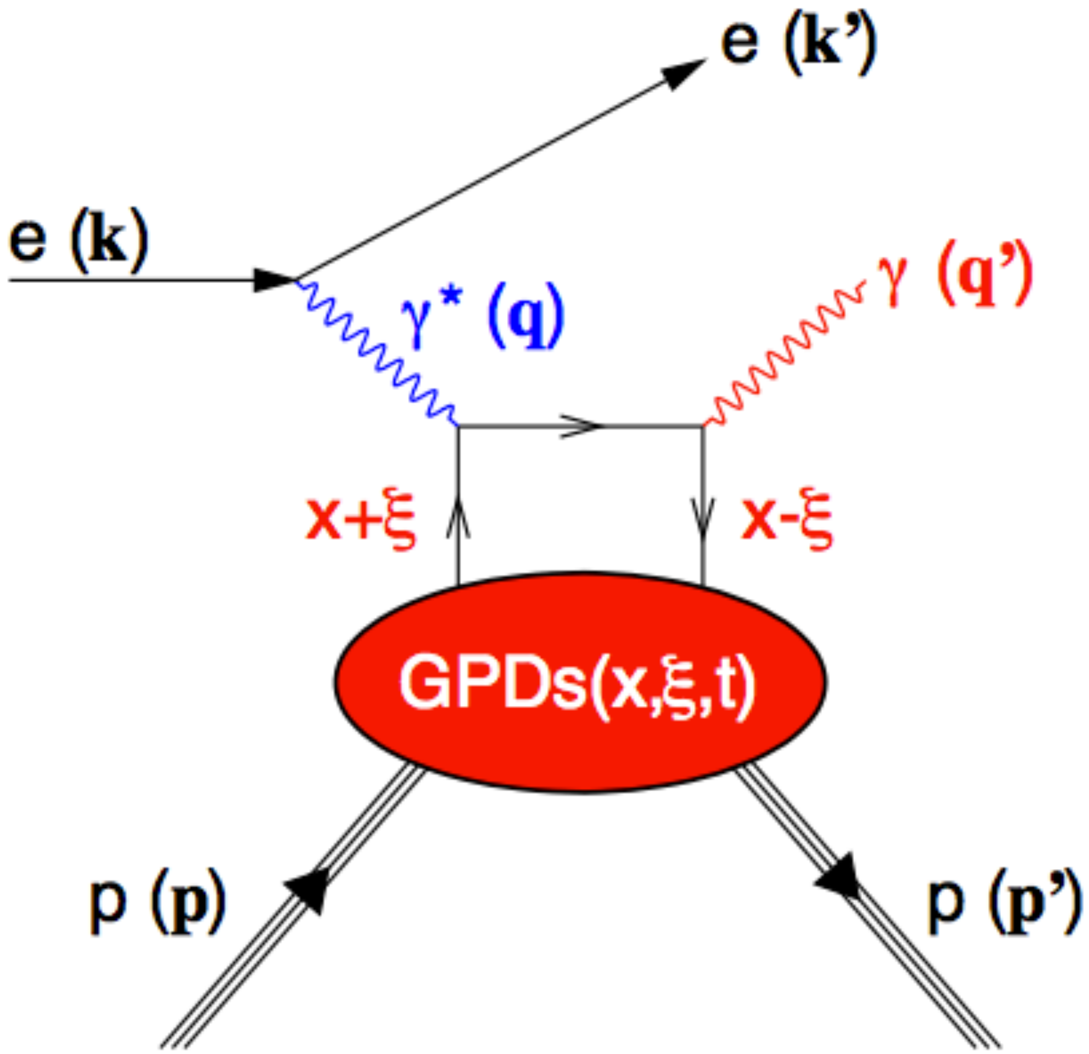
$$\begin{aligned} \Im m\, \mathcal{F}(\xi, t) &= F(\xi, \xi, t) \pm F(-\xi, \xi, t)\,, \\ \Re e\, \mathcal{F}(\xi, t) &= \mathcal{P}_{\mathrm{C}} \int_{-1}^{1} \frac{F(x, \xi, t)}{x - \xi} \pm \frac{F(x, \xi, t)}{x + \xi}\, dx \end{aligned}$$

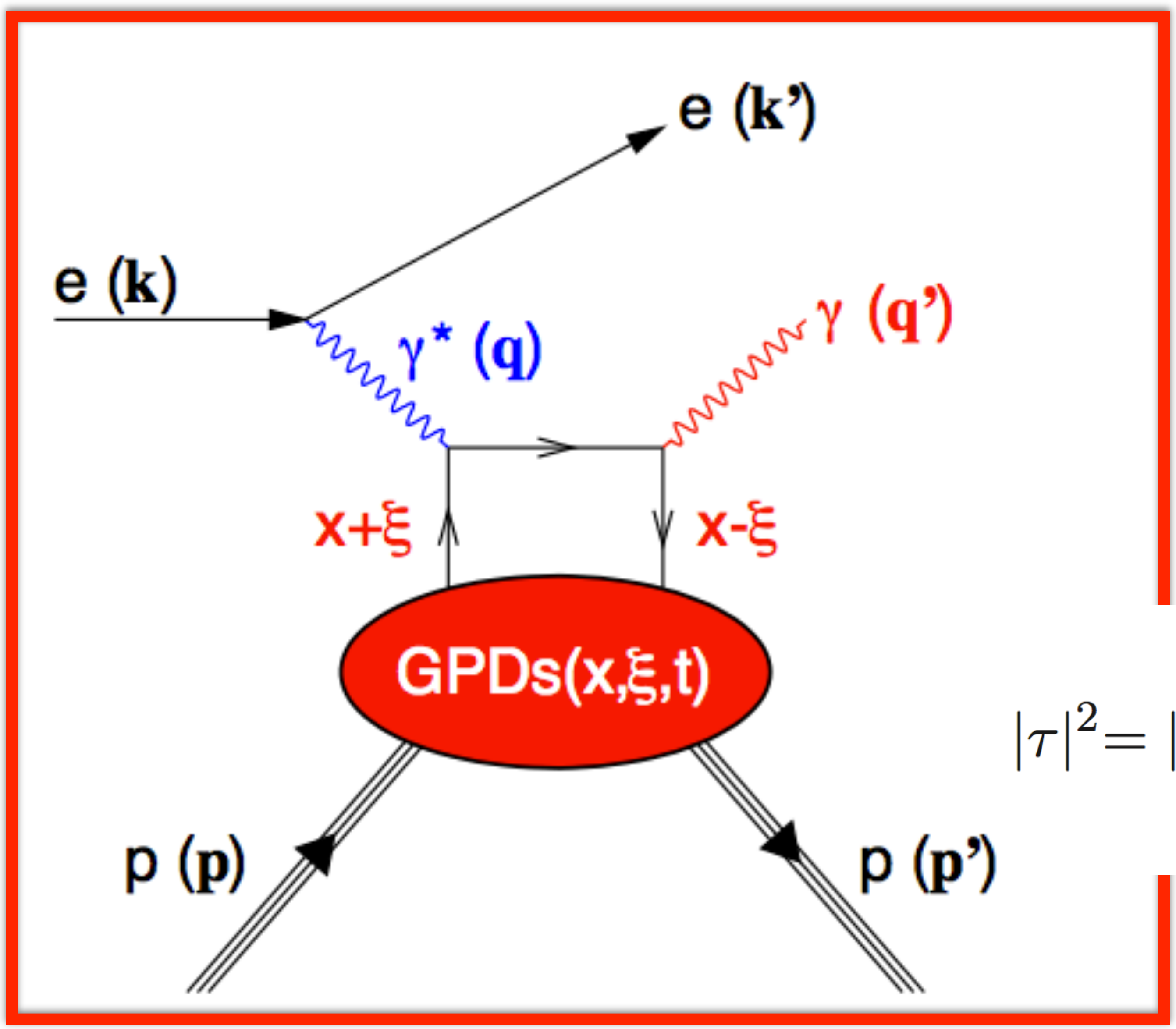
# Deeply Virtual Compton Scattering

e p → e p γ



# Deeply Virtual Compton Scattering




$$\frac{d\sigma}{dx_B\, dQ^2\, d|t|\, d\phi} = \frac{x_B\, e^6\, |\tau|^2}{32(2\pi)^4\, Q^4\, \sqrt{1+\epsilon^2}}$$

$$|\tau|^2 = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \overbrace{\tau_{BH}\tau_{DVCS}^* + \tau_{BH}^*\tau_{DVCS}}^{\mathcal{I}}$$

# DVCS @ HERMES

$$\mathcal{A}_C(\phi) \equiv \frac{\mathrm{d}\sigma^+(\phi) - \mathrm{d}\sigma^-(\phi)}{\mathrm{d}\sigma^+(\phi) + \mathrm{d}\sigma^-(\phi)} \quad \overset{\sim}{\propto} \quad \mathrm{Re}(\mathcal{H})$$

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) \equiv \frac{(\mathrm{d}\sigma(\phi)^{+\rightarrow} - \mathrm{d}\sigma(\phi)^{+\leftarrow}) - (\mathrm{d}\sigma(\phi)^{-\rightarrow} - \mathrm{d}\sigma(\phi)^{-\leftarrow})}{(\mathrm{d}\sigma(\phi)^{+\rightarrow} + \mathrm{d}\sigma(\phi)^{+\leftarrow}) + (\mathrm{d}\sigma(\phi)^{-\rightarrow} + \mathrm{d}\sigma(\phi)^{-\leftarrow})} \quad \overset{\sim}{\propto} \quad \mathrm{Im}(\mathcal{H})$$

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) \equiv \frac{(\mathrm{d}\sigma(\phi)^{+\rightarrow} + \mathrm{d}\sigma(\phi)^{-\rightarrow}) - (\mathrm{d}\sigma(\phi)^{+\leftarrow} + \mathrm{d}\sigma(\phi)^{-\leftarrow})}{(\mathrm{d}\sigma(\phi)^{+\rightarrow} + \mathrm{d}\sigma(\phi)^{-\rightarrow}) + (\mathrm{d}\sigma(\phi)^{+\leftarrow} + \mathrm{d}\sigma(\phi)^{-\leftarrow})} \quad \overset{\sim}{\propto} \quad \mathrm{Im}[\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$$

$$\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi, \phi_S) \equiv \frac{d\sigma^+(\phi,\phi_S) - d\sigma^+(\phi,\phi_S+\pi) - d\sigma^-(\phi,\phi_S) + d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S) + d\sigma^+(\phi,\phi_S+\pi) + d\sigma^-(\phi,\phi_S) + d\sigma^-(\phi,\phi_S+\pi)} \quad \overset{\sim}{\propto} \quad \mathrm{Im}(\mathcal{E})$$

$$\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi, \phi_S) \equiv \frac{d\sigma^+(\phi,\phi_S) - d\sigma^+(\phi,\phi_S+\pi) + d\sigma^-(\phi,\phi_S) - d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S) + d\sigma^+(\phi,\phi_S+\pi) + d\sigma^-(\phi,\phi_S) + d\sigma^-(\phi,\phi_S+\pi)} \quad \overset{\sim}{\propto} \quad \mathrm{Im}(\mathcal{E})$$

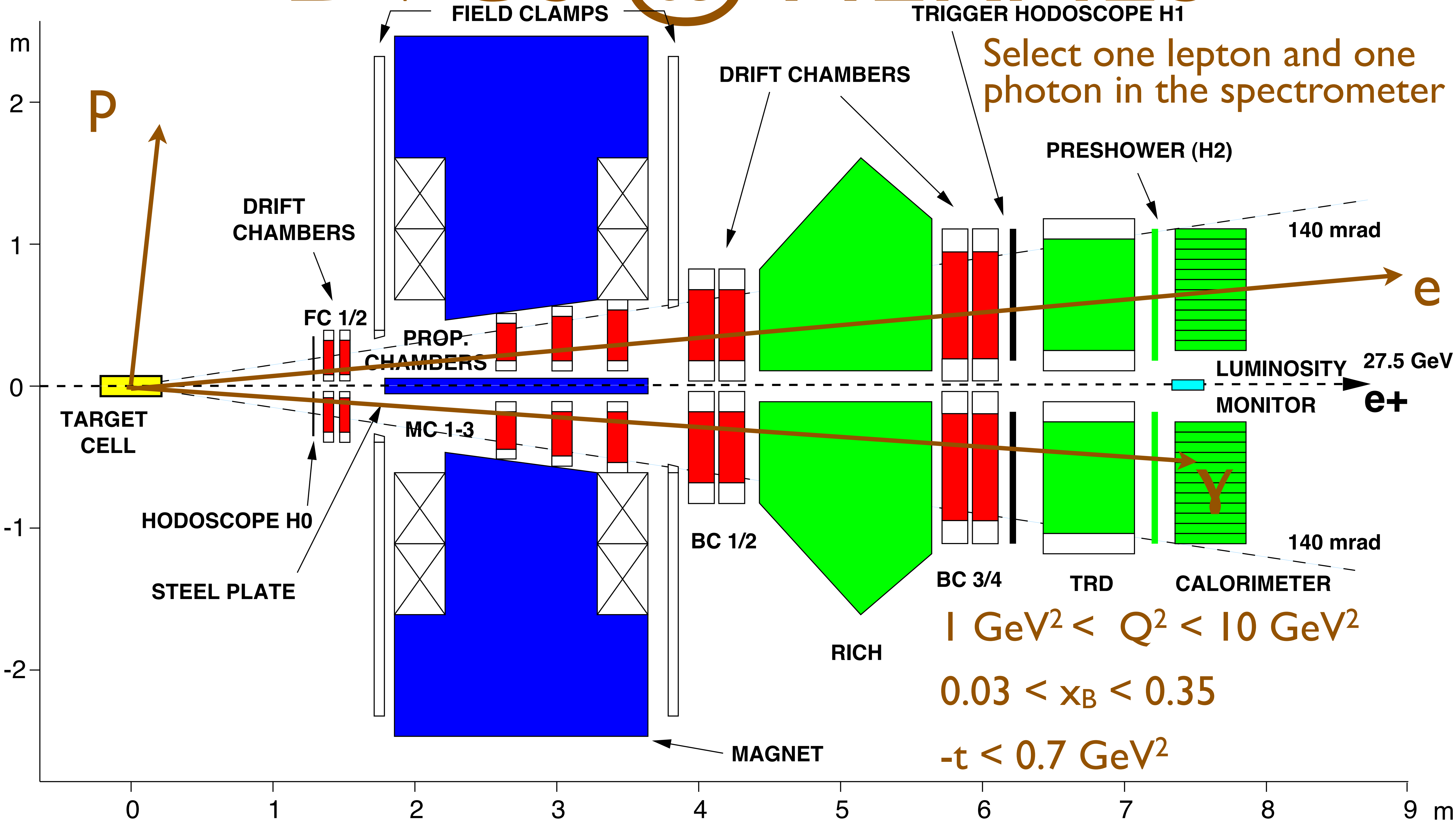
$$\mathcal{A}_{\mathrm{LT}}^{\mathrm{BH+DVCS}}(\phi, \phi_S) \equiv \frac{1}{8 d\sigma_{\mathrm{UU}}}\left[(d\overrightarrow{\sigma}^{+\uparrow} - d\overrightarrow{\sigma}^{+\downarrow} - d\overleftarrow{\sigma}^{+\uparrow} + d\overleftarrow{\sigma}^{+\downarrow}) + (d\overrightarrow{\sigma}^{-\uparrow} - d\overrightarrow{\sigma}^{-\downarrow} - d\overleftarrow{\sigma}^{-\uparrow} + d\overleftarrow{\sigma}^{-\downarrow})\right] \quad \overset{\sim}{\propto} \quad \mathrm{Re}(\mathcal{H}+\mathcal{E})$$

$$\mathcal{A}_{\mathrm{LT}}^{\mathrm{I}}(\phi, \phi_S) \equiv \frac{1}{8 d\sigma_{\mathrm{UU}}}\left[(d\overrightarrow{\sigma}^{+\uparrow} - d\overrightarrow{\sigma}^{+\downarrow} - d\overleftarrow{\sigma}^{+\uparrow} + d\overleftarrow{\sigma}^{+\downarrow}) - (d\overrightarrow{\sigma}^{-\uparrow} - d\overrightarrow{\sigma}^{-\downarrow} - d\overleftarrow{\sigma}^{-\uparrow} + d\overleftarrow{\sigma}^{-\downarrow})\right] \quad \overset{\sim}{\propto} \quad \mathrm{Re}(\mathcal{H})$$

$$\mathcal{A}_{\mathrm{UL}}(\phi) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] - [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]}{[\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] + [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]} \quad \overset{\sim}{\propto} \quad \mathrm{Im}(\widetilde{\mathcal{H}})$$

$$\mathcal{A}_{\mathrm{LL}}(\phi) \equiv \frac{[\sigma^{\rightarrow\Rightarrow}(\phi) + \sigma^{\leftarrow\Leftarrow}(\phi)] - [\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]}{[\sigma^{\rightarrow\Rightarrow}(\phi) + \sigma^{\leftarrow\Leftarrow}(\phi)] + [\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]} \quad \overset{\sim}{\propto} \quad \mathrm{Re}(\widetilde{\mathcal{H}})$$

# DVCS @ HERMES




Select one lepton and one photon in the spectrometer

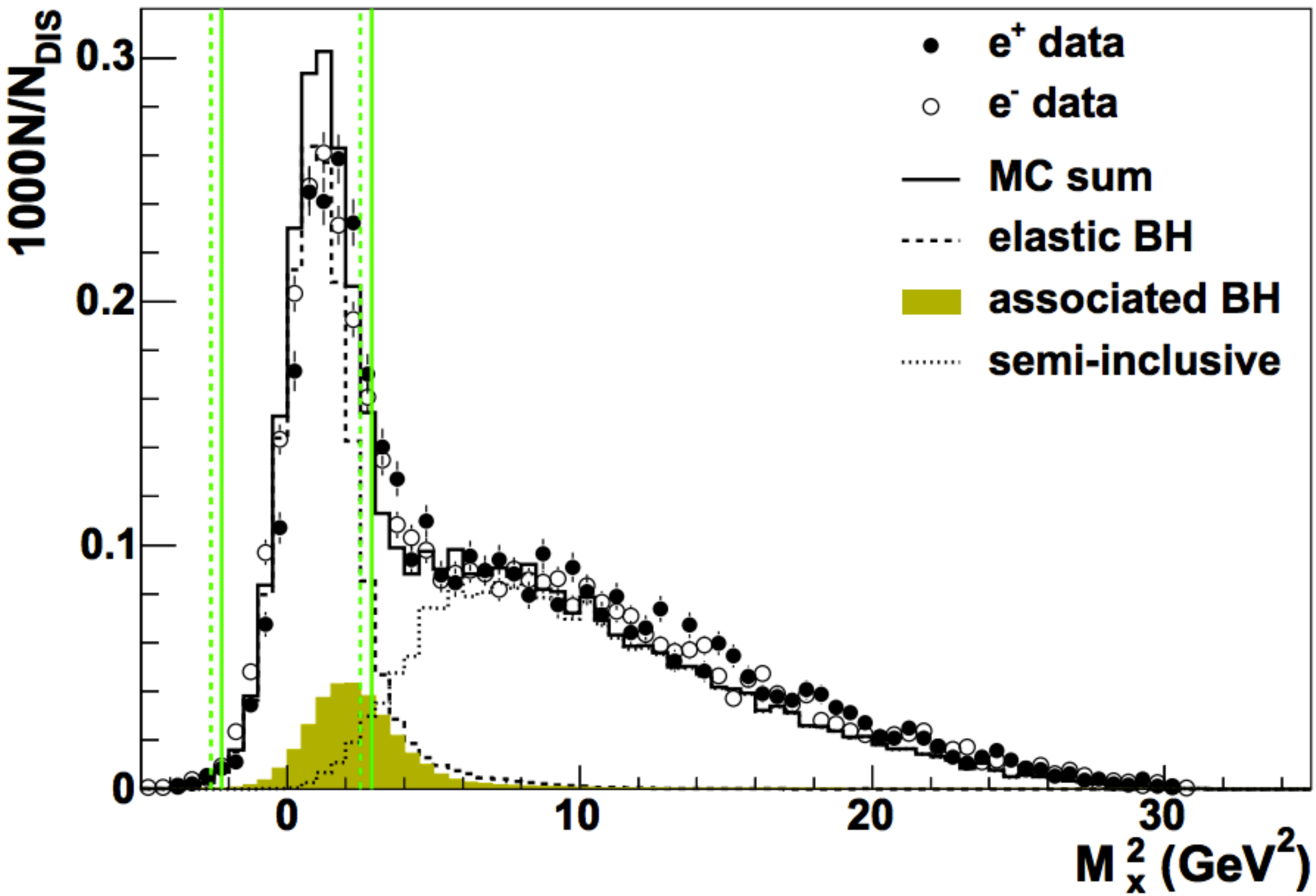
$1\ \text{GeV}^2 < Q^2 < 10\ \text{GeV}^2$

$0.03 < x_B < 0.35$

$-t < 0.7\ \text{GeV}^2$

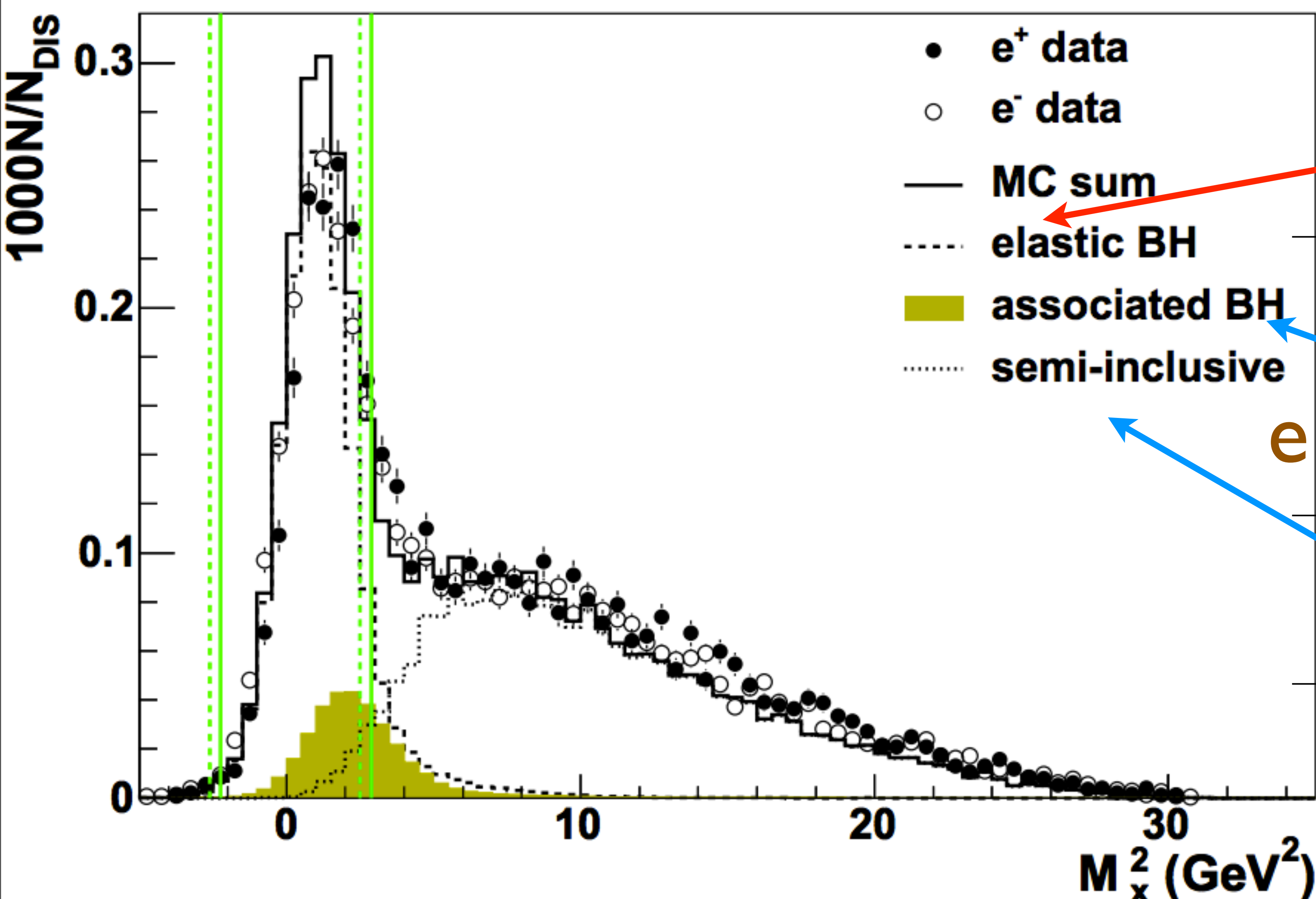
$\langle Q^2 \rangle \cong 2.4\ \text{GeV}^2$ $\langle x_B \rangle \cong 0.1$ $\langle -t \rangle \cong 0.1\ \text{GeV}^2$

# DVCS @ HERMES



$1000N/N_{DIS}$
0.3
0.2
0.1
0
0
10
20
30
$M_x^2$ (GeV$^2$)
$e^+$ data
$e^-$ data
MC sum
elastic BH
associated BH
semi-inclusive

# DVCS @ HERMES




Wanted Signal

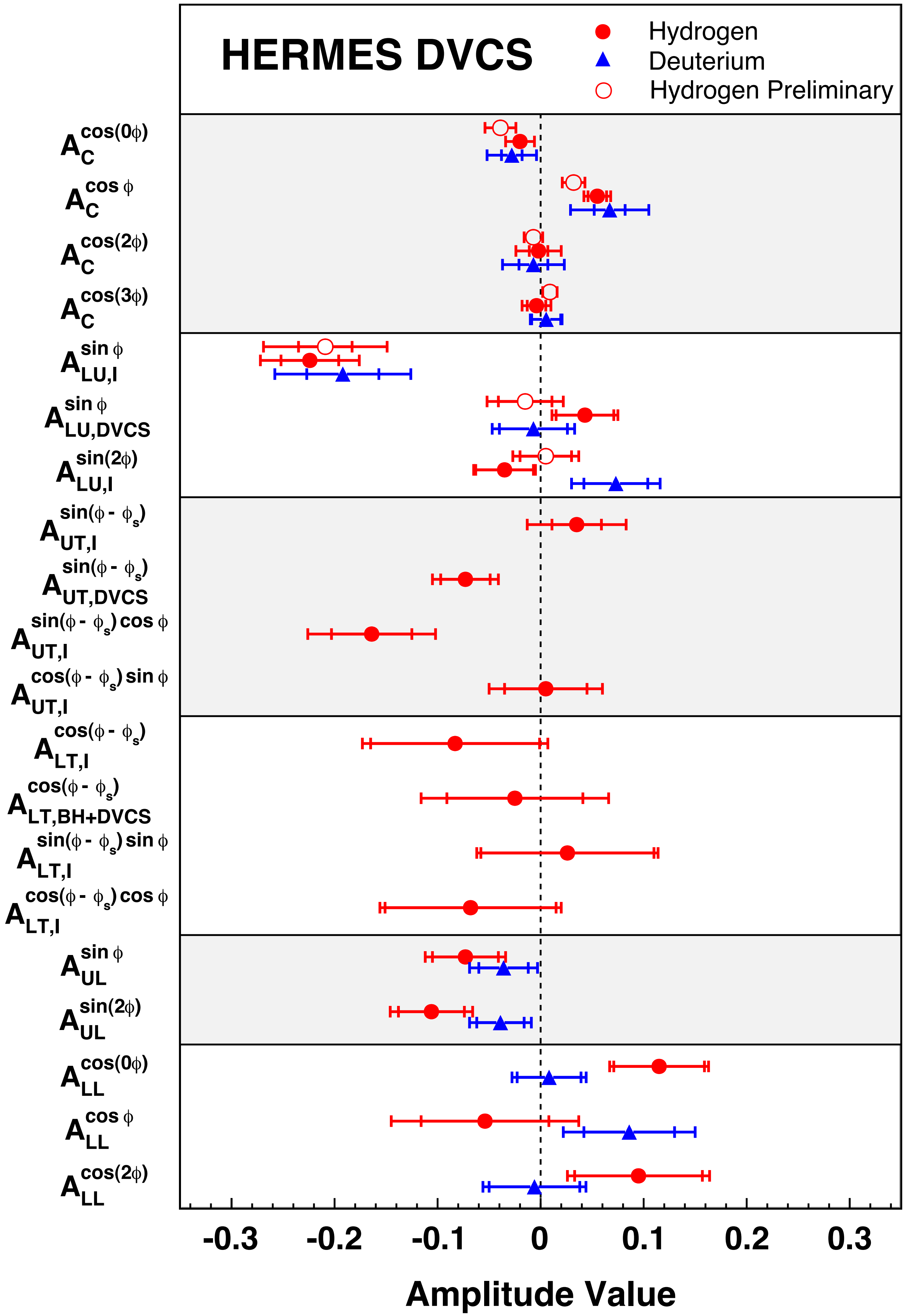
BH from Δ, e.g

$e\,\Delta \rightarrow e\,\gamma\,\Delta \rightarrow e\gamma p\,\pi^0$

$e\,p \rightarrow e\,X\,\gamma$

$e\,p \rightarrow e\,p\,\pi^0$

DVCS @

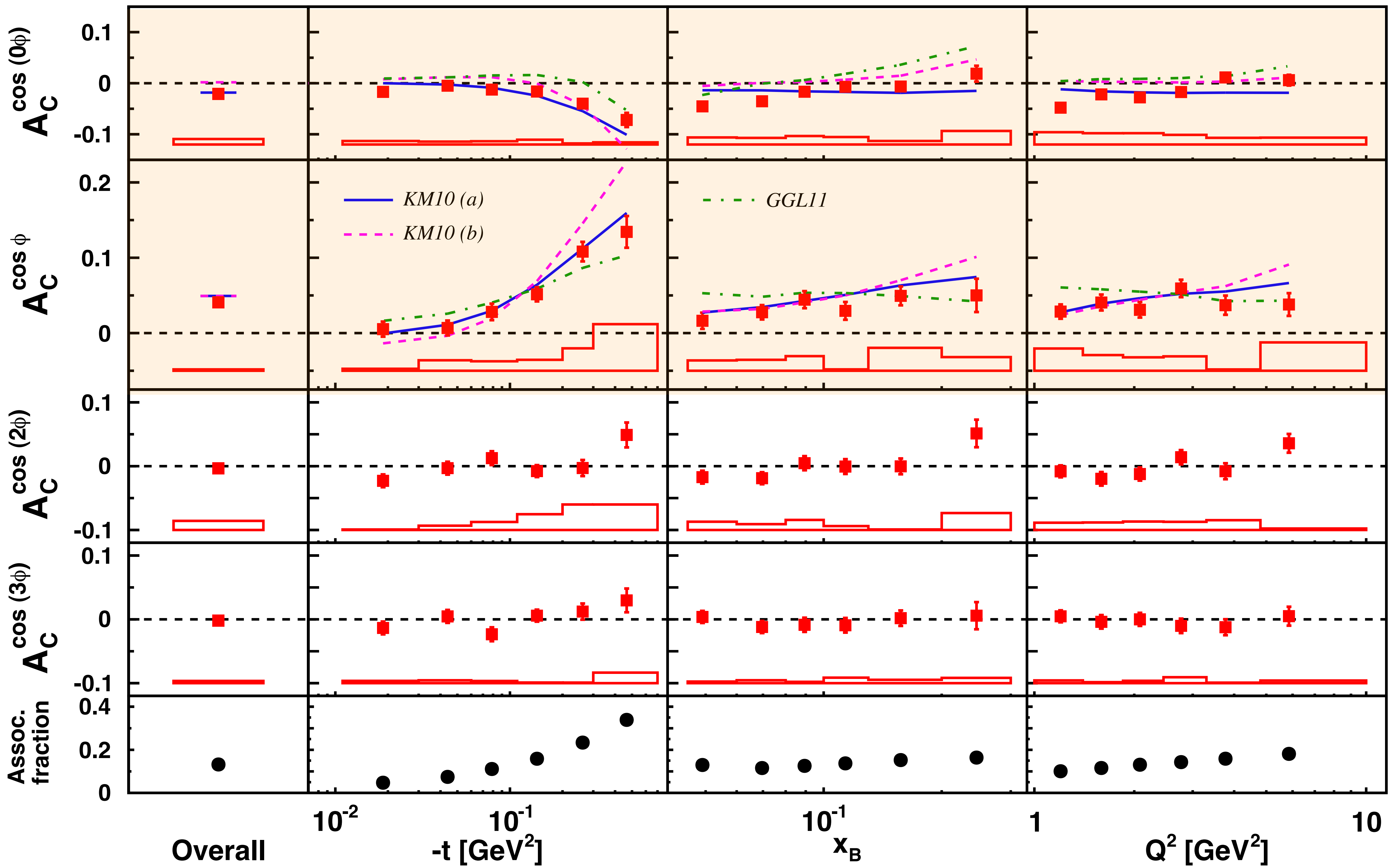


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Preliminary
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value


HERMES

# Beam-Charge Asymmetries

*A. Airapetian et al, JHEP 07 (2012) 032* http://arxiv.org/abs/1203.6287



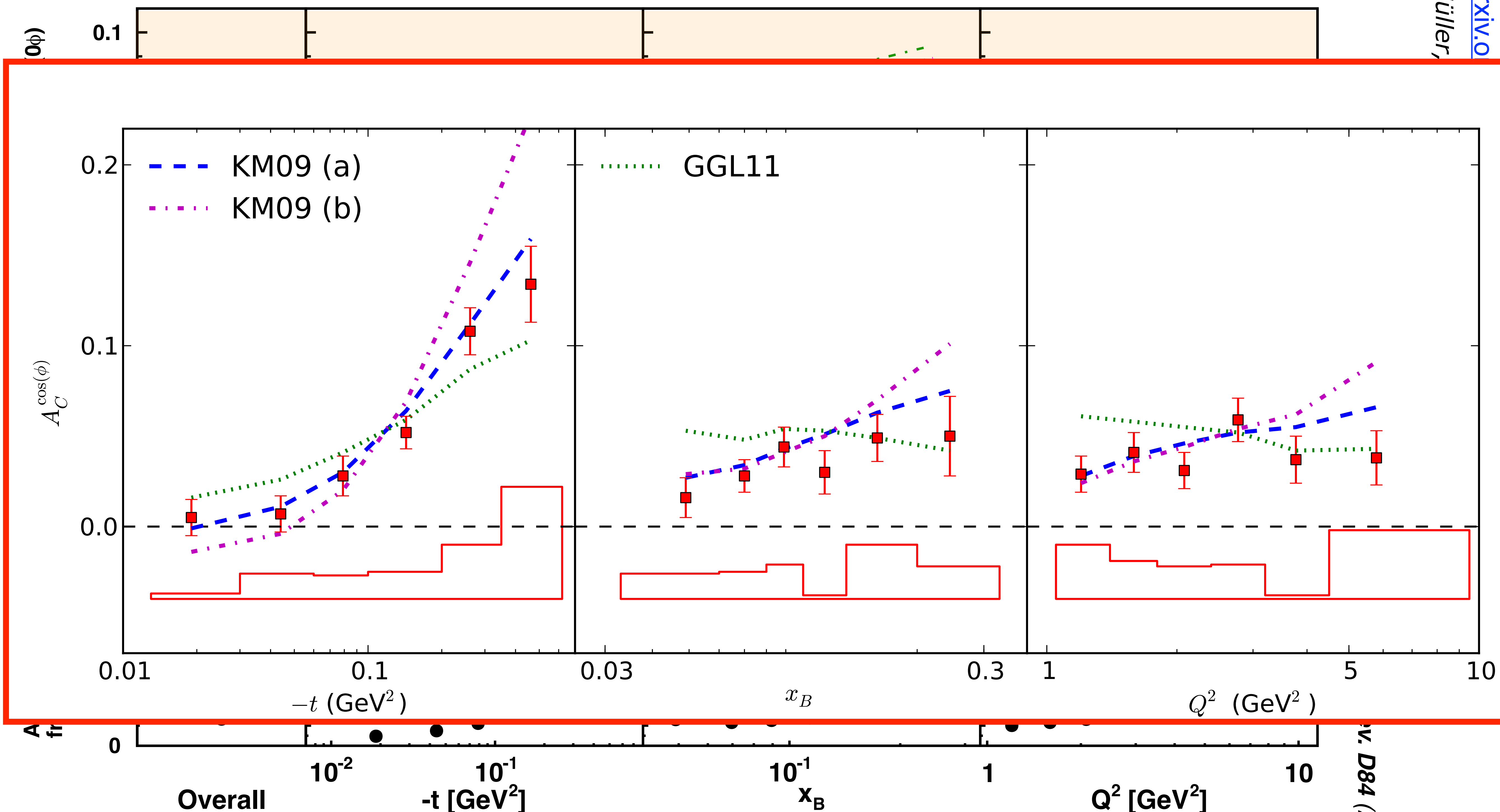

Beam Charge Asymmetries access Re($\mathcal{H}$)

*Kumerički and Müller, Nucl. Phys.* ***B841*** *(2010)* http://arxiv.org/abs/0904.0458

*G. Goldstein, J. Hernandez and S. Liuti,* ***Phys. Rev. D84*** *(2011)* http://arxiv.org/abs/1012.3776

# Beam-Charge Asymmetries

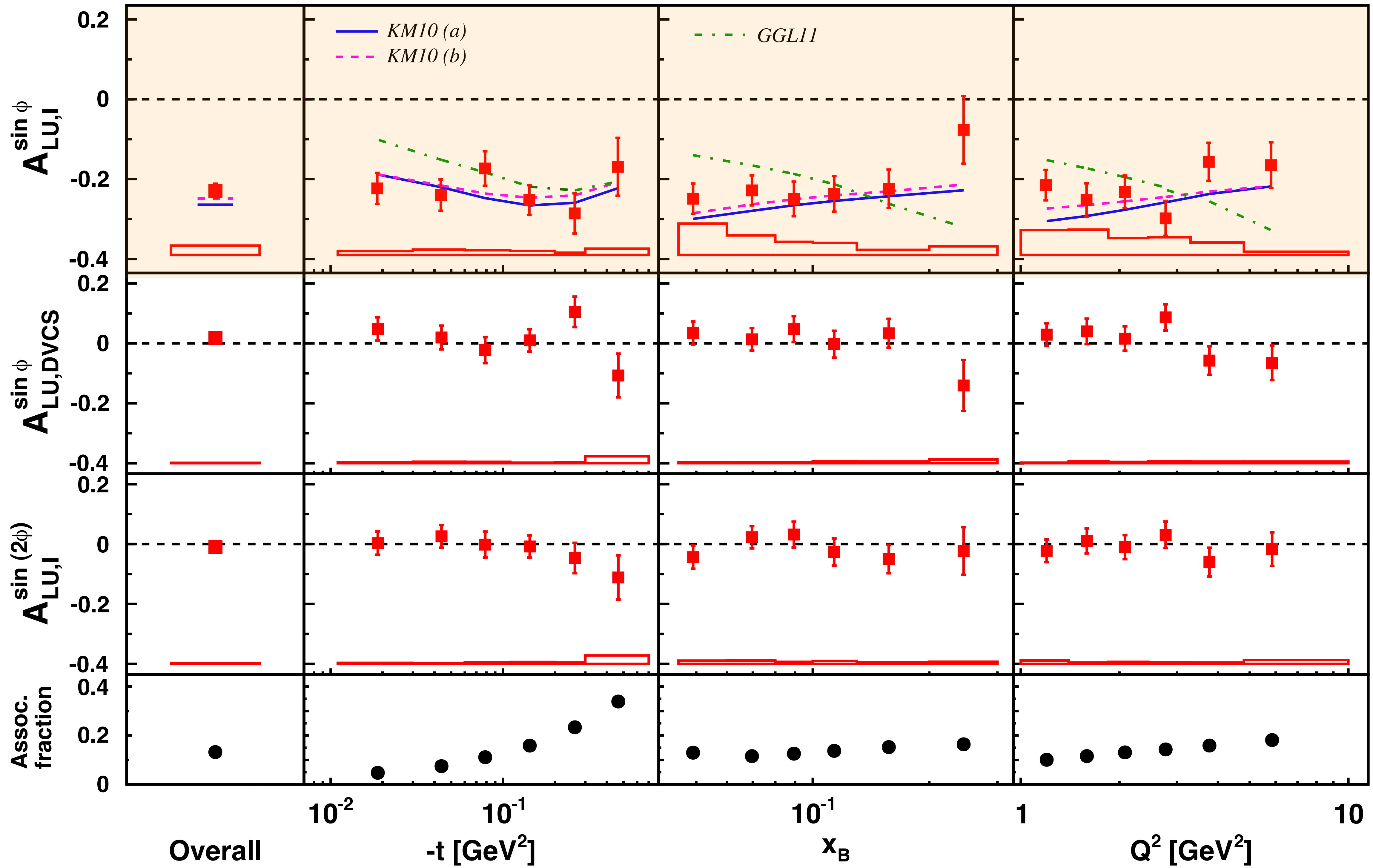
http://arxiv.org/abs/1203.6287




Beam Charge Asymmetries access Re($\mathcal{H}$)

# Beam-Spin Asymmetries

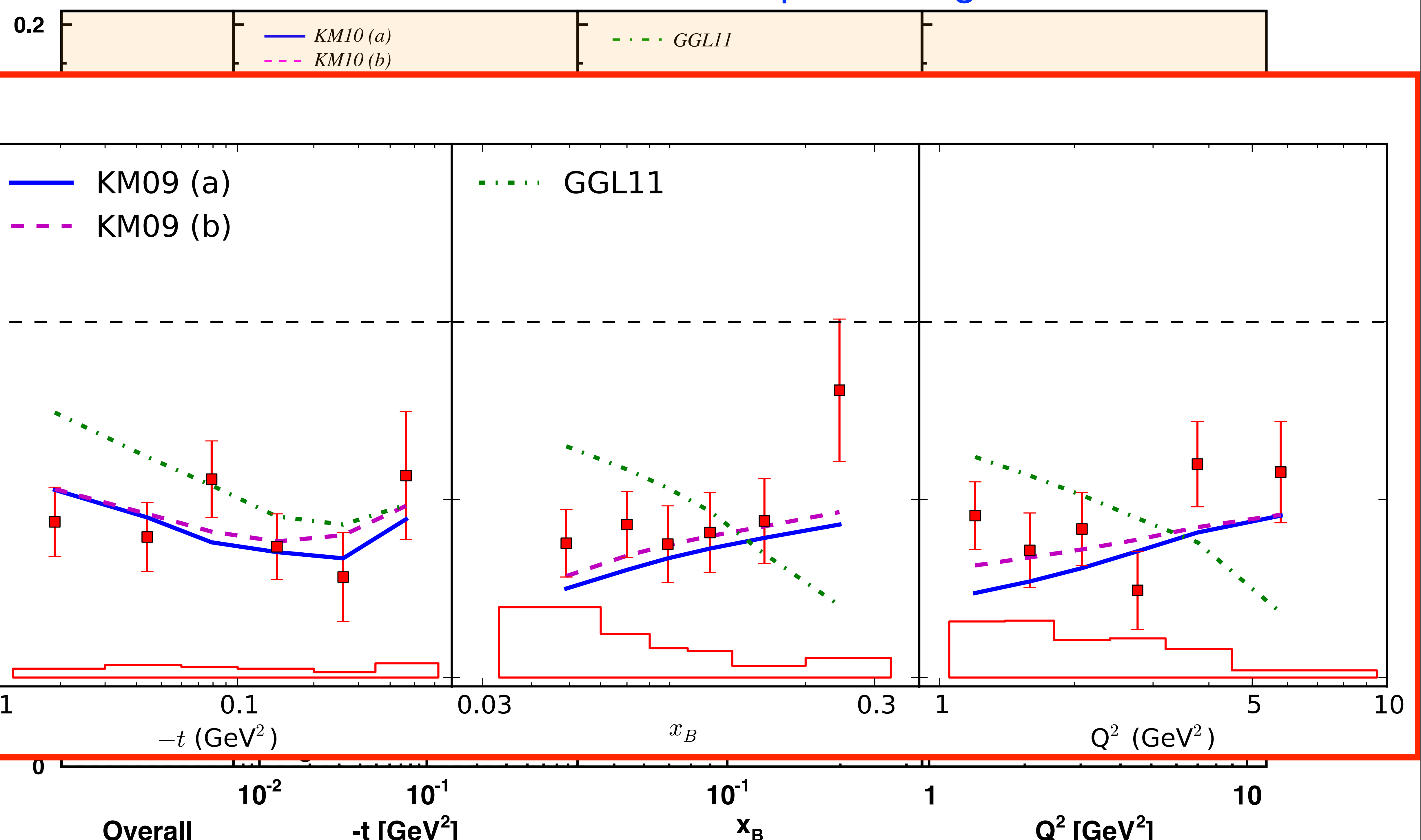
*A. Airapetian et al, JHEP 07 (2012) 032* http://arxiv.org/abs/1203.6287




Beam Helicity Asymmetries access Im($\mathcal{H}$)

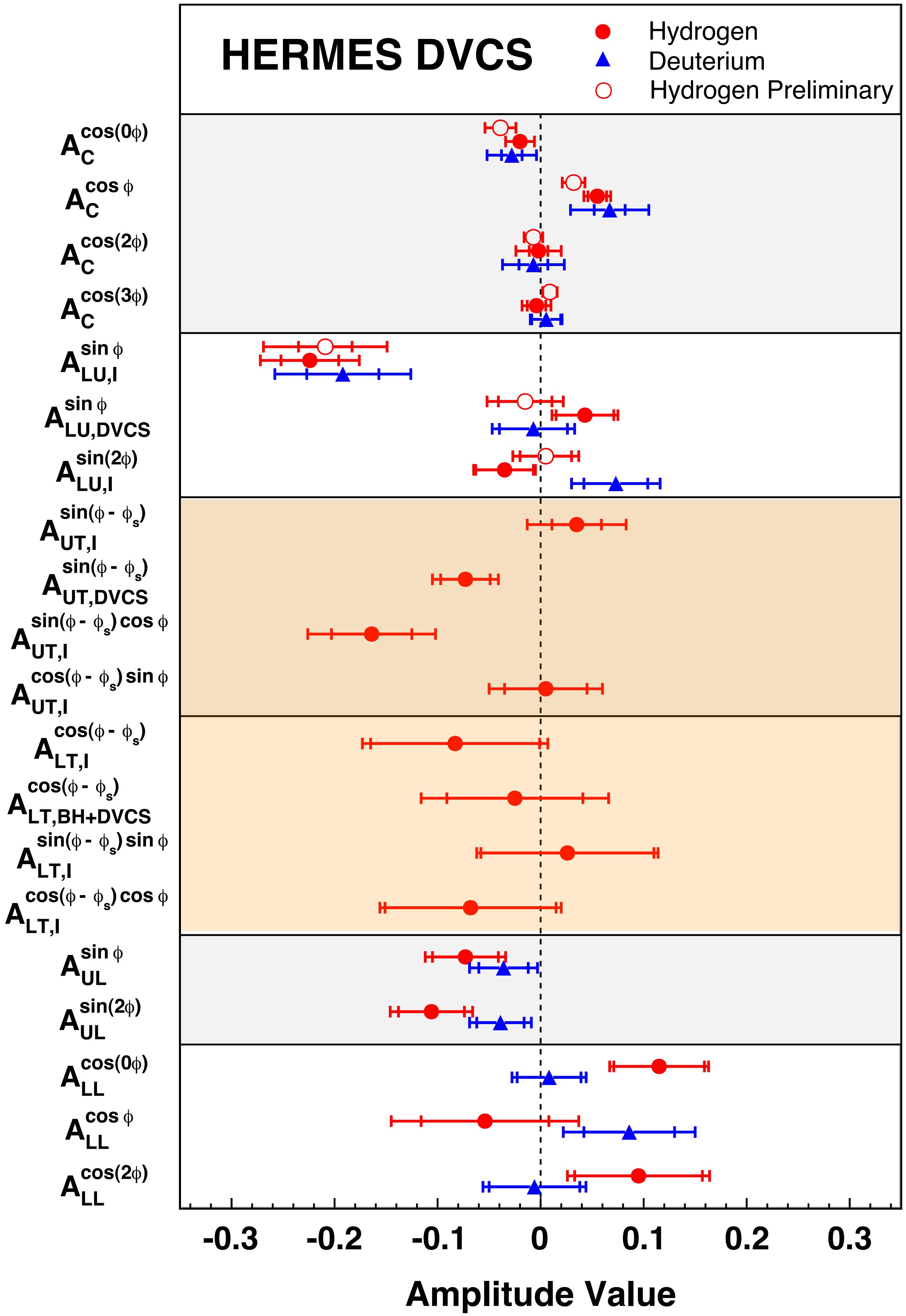
# Beam-Spin Asymmetries

http://arxiv.org/abs/1203.6287



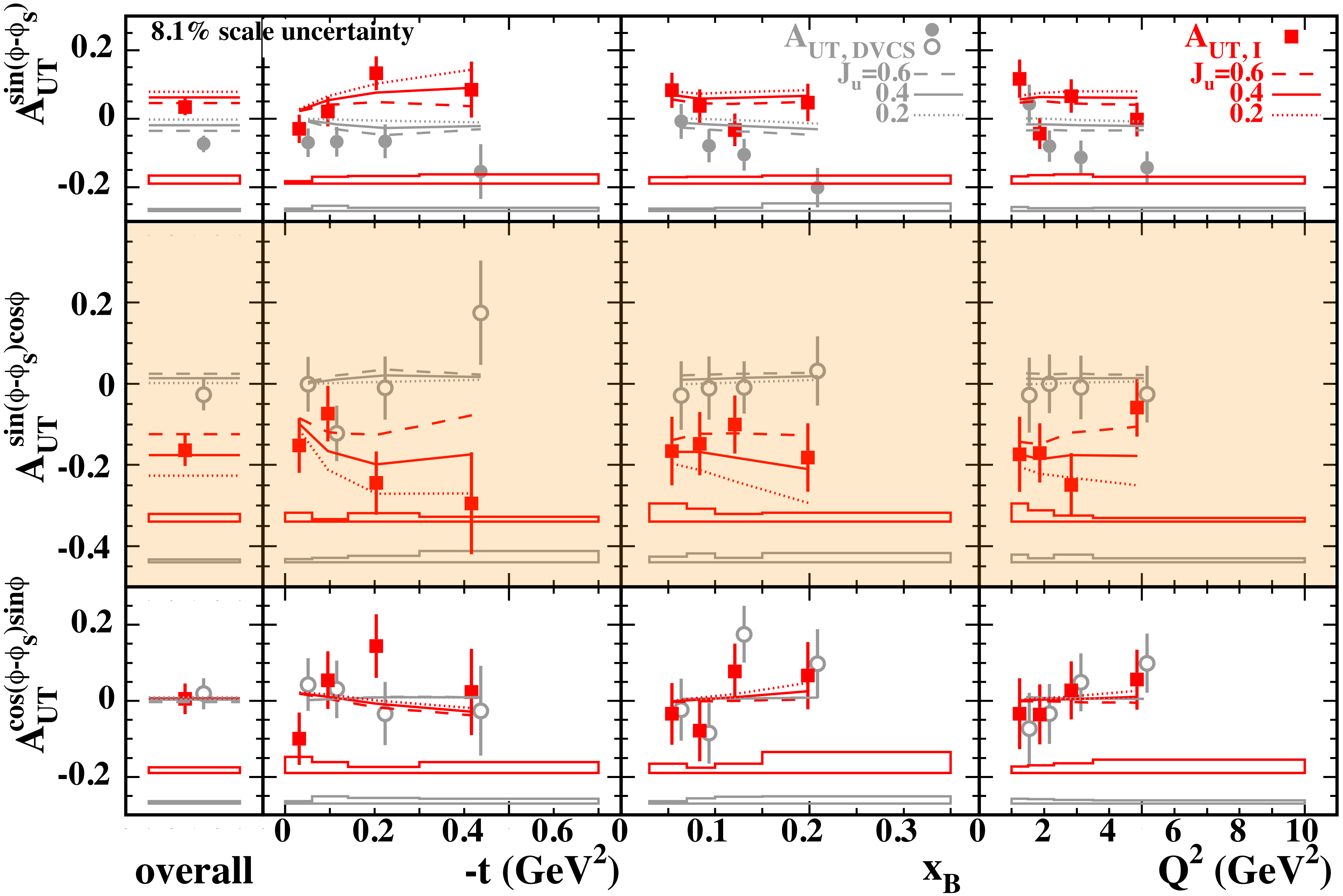

Beam Helicity Asymmetries access Im($\mathcal{H}$)

DVCS @


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Preliminary
$A_C^{\cos(0\phi)}$
$A_C^{\cos\phi}$
$A_C^{\cos(2\phi)}$
$A_C^{\cos(3\phi)}$
$A_{LU,I}^{\sin\phi}$
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value

HERMES

# Transverse-Target Asymmetries




DVCS amplitude involves transversity GPDs

Transverse Target Asymmetries can access E?

Pioneering measurement to be repeated at CLAS12 and the EIC

VGG Model:

http://arxiv.org/abs/hep-ph/9905372

*Phys.Rev. D60 (1999) 094017*

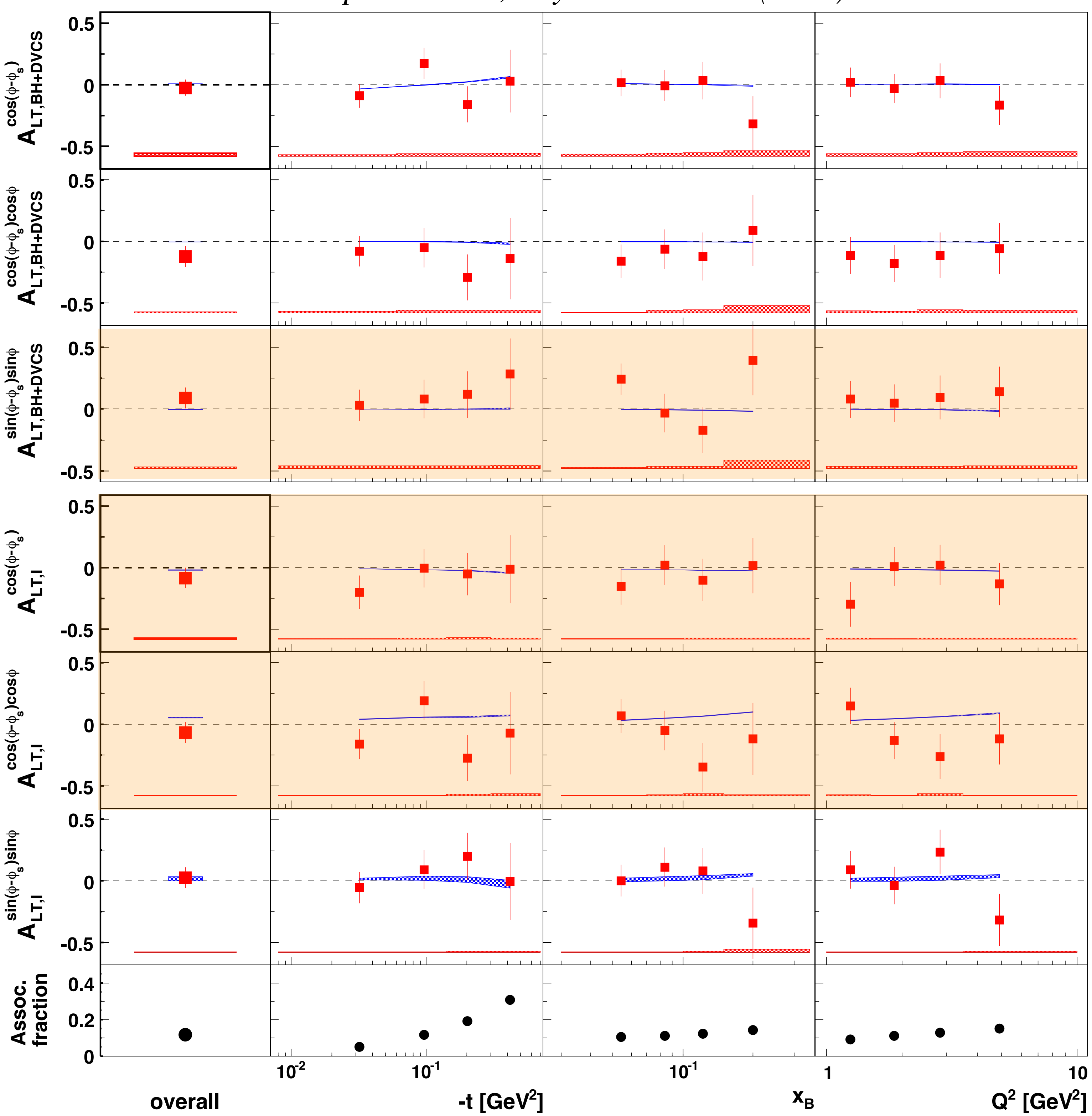
HERMES Data:

http://arxiv.org/abs/0802.2499

*A. Airapetian et al, JHEP 06 (2008) 066, 24pp*

# Double-Spin Asymmetries

*A. Airapetian et al, Phys. Lett. B 704 (2011) 15-23*



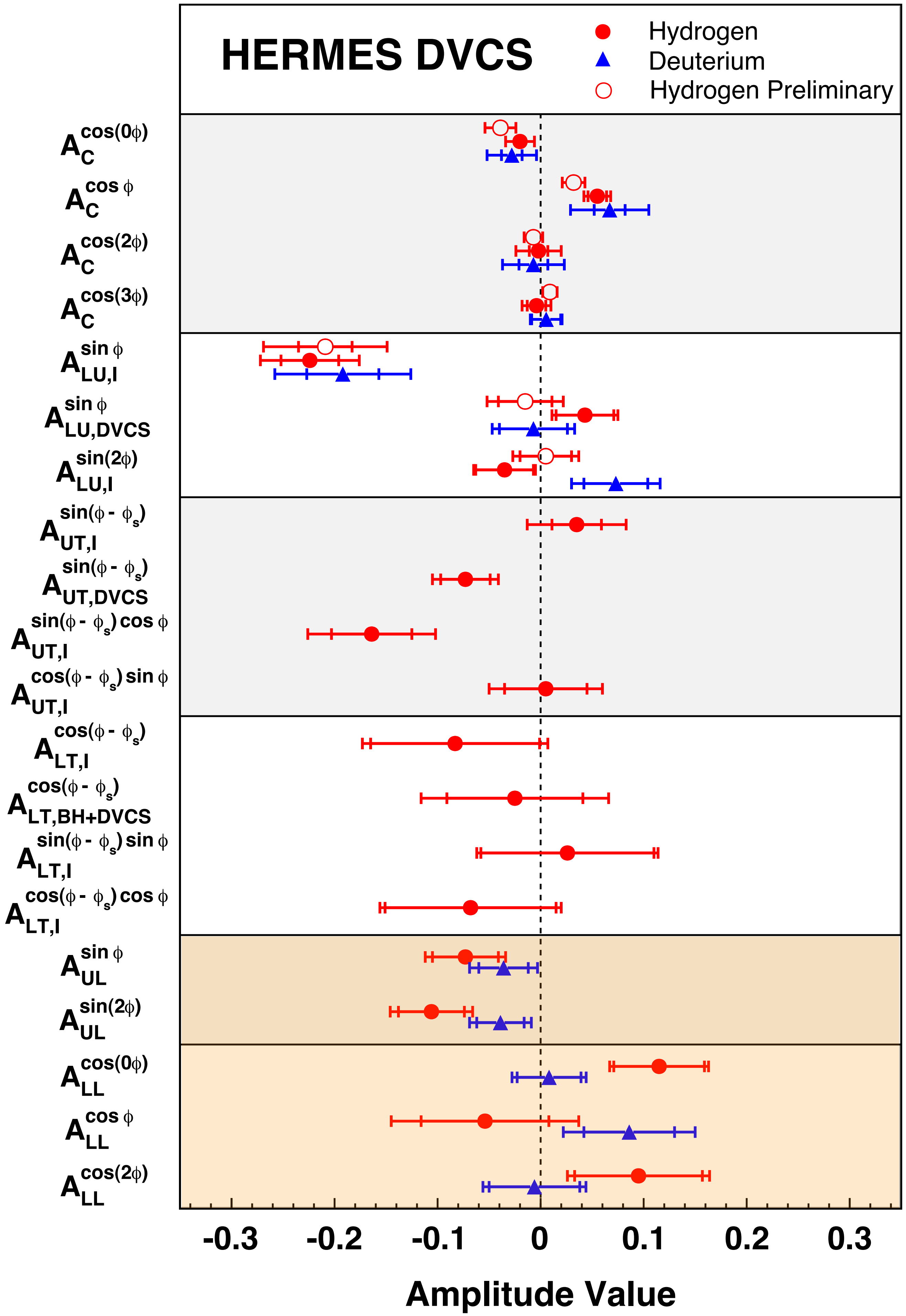

Tran. Pol. target / Long. Pol. Beam

Real parts of $\mathcal{H}$ and $\mathcal{E}$

Extracted to be 0; compatible with VGG predictions.

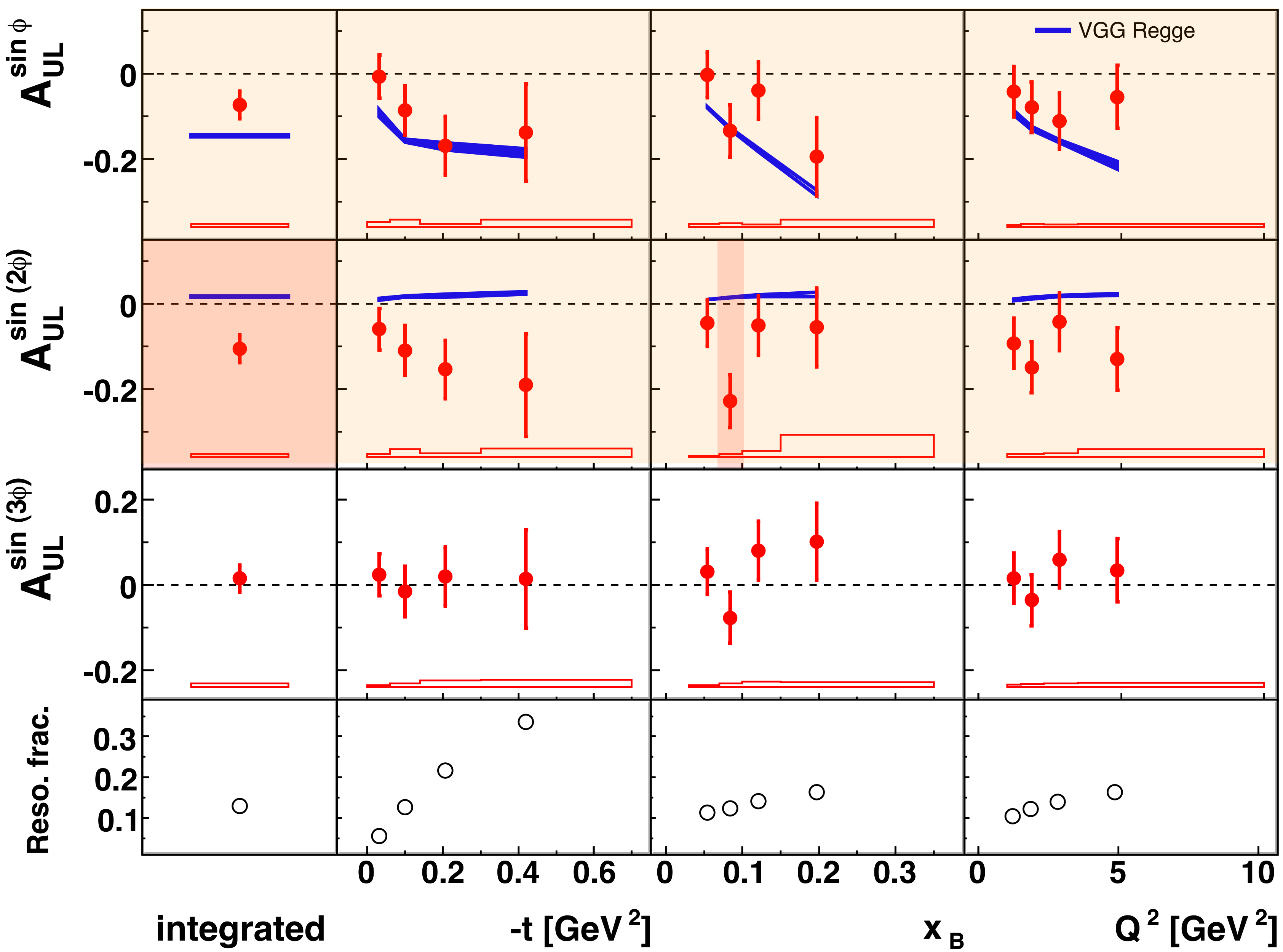
http://arxiv.org/abs/1106.2990

DVCS @


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Preliminary
$A_C^{\cos(0\phi)}$
$A_C^{\cos\phi}$
$A_C^{\cos(2\phi)}$
$A_C^{\cos(3\phi)}$
$A_{LU,I}^{\sin\phi}$
$A_{LU,DVCS}^{\sin\phi}$
$A_{LU,I}^{\sin(2\phi)}$
$A_{UT,I}^{\sin(\phi-\phi_s)}$
$A_{UT,DVCS}^{\sin(\phi-\phi_s)}$
$A_{UT,I}^{\sin(\phi-\phi_s)\cos\phi}$
$A_{UT,I}^{\cos(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)}$
$A_{LT,BH+DVCS}^{\cos(\phi-\phi_s)}$
$A_{LT,I}^{\sin(\phi-\phi_s)\sin\phi}$
$A_{LT,I}^{\cos(\phi-\phi_s)\cos\phi}$
$A_{UL}^{\sin\phi}$
$A_{UL}^{\sin(2\phi)}$
$A_{LL}^{\cos(0\phi)}$
$A_{LL}^{\cos\phi}$
$A_{LL}^{\cos(2\phi)}$
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Amplitude Value

HERMES

# Longitudinal-Target Asymmetries




Long. Pol. target asymmetries access Im($\widetilde{\mathcal{H}}$)

http://arxiv.org/abs/1004.0177

*A. Airapetian et al, JHEP 06 (2010) 019*

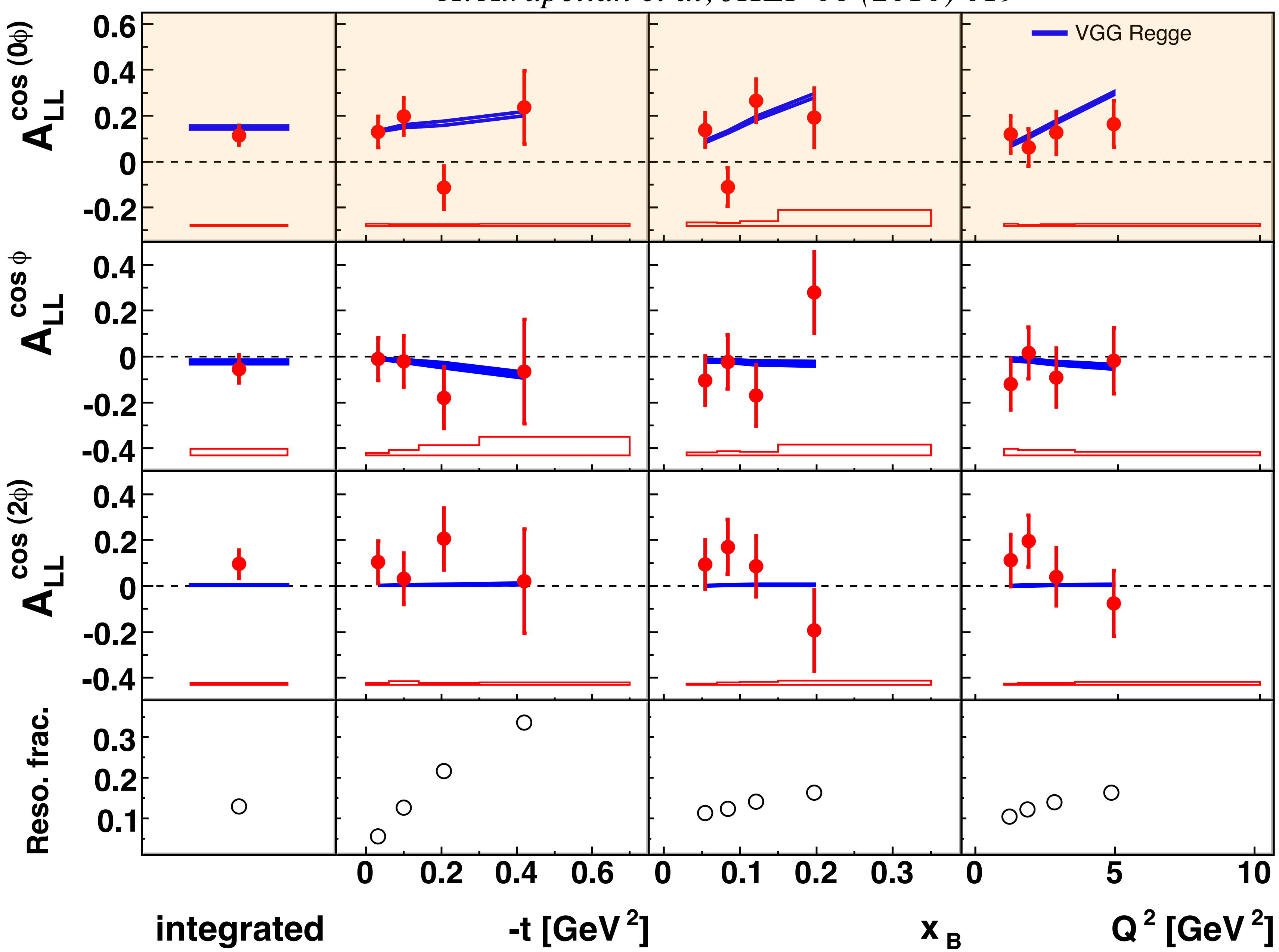
VGG Model:

http://arxiv.org/abs/hep-ph/9905372

*Phys.Rev. D60 (1999) 094017*

# Double-Spin Asymmetries

*A. Airapetian et al, JHEP 06 (2010) 019*

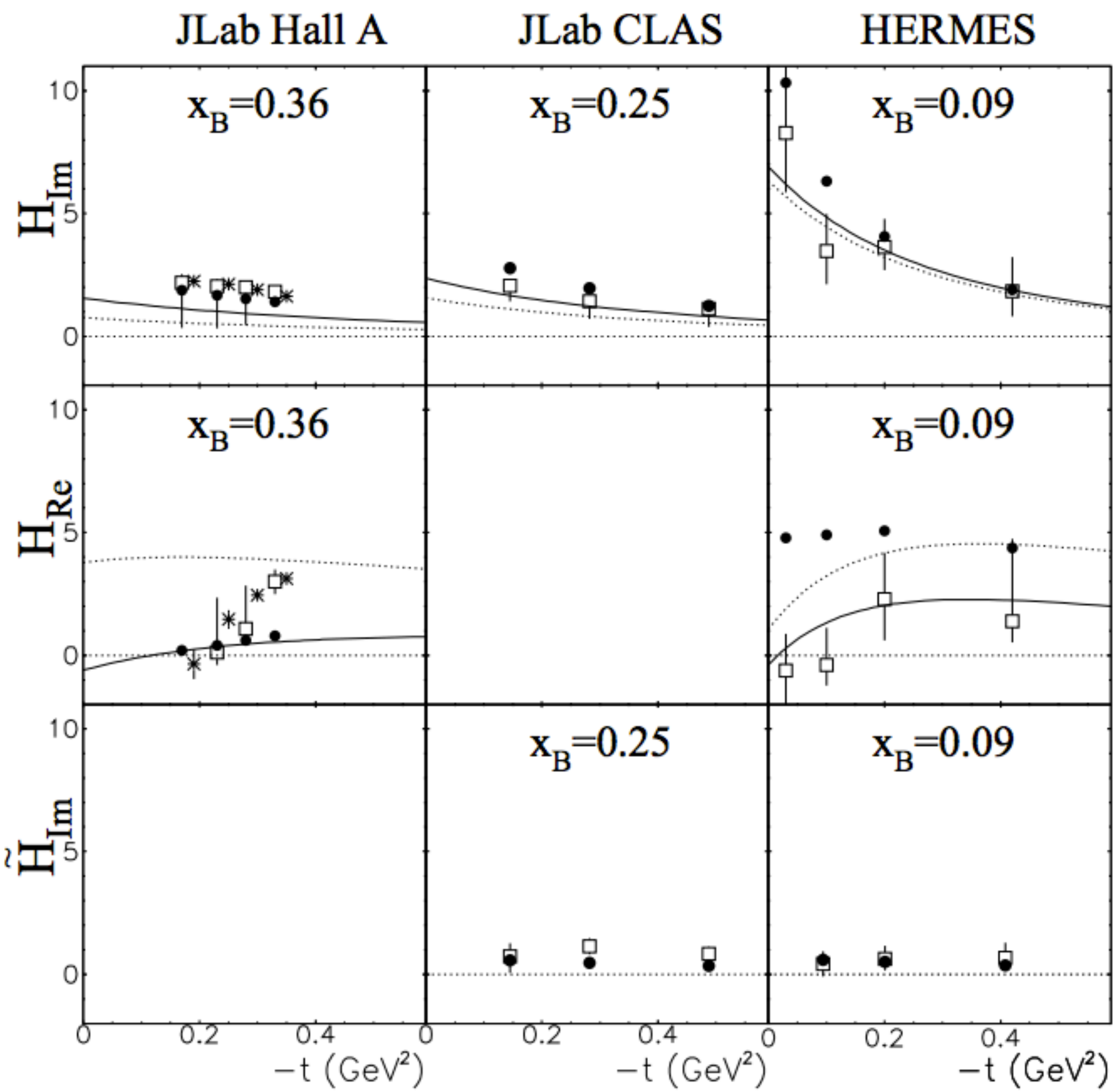



Long. Pol. target / Long. Pol. Beam access Re($\widetilde{\mathcal{H}}$)

Caveat! Relatively large BH contribution to these asymmetries!

http://arxiv.org/abs/1004.0177

# GPD Extraction



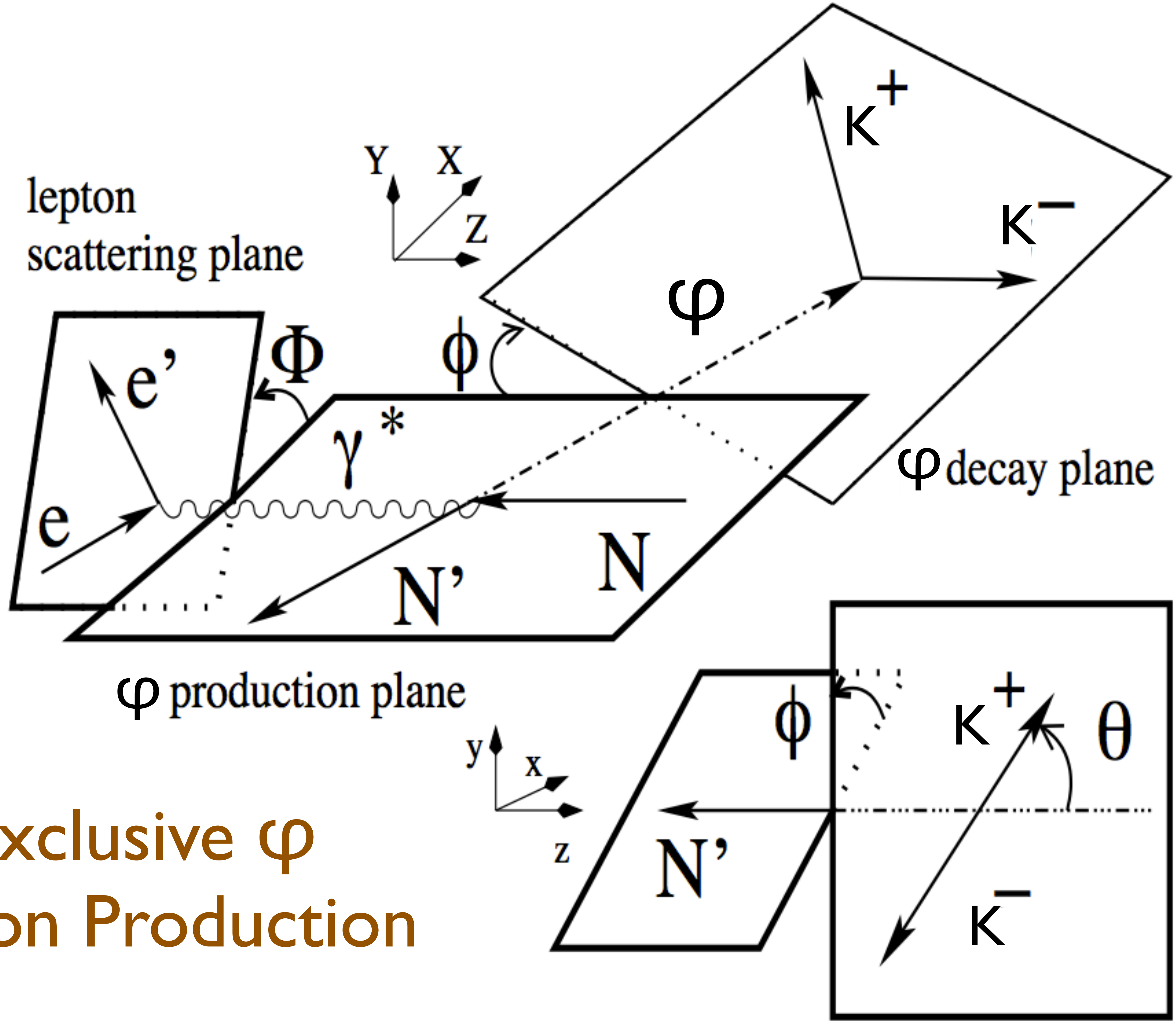

Even for H, VGG model GPDs are shown not to be consistent with experimental measurements when CFFs are extracted from data.

http://arxiv.org/abs/1011.4195
*Guidal, **ICHEP Procs.** (2010)*

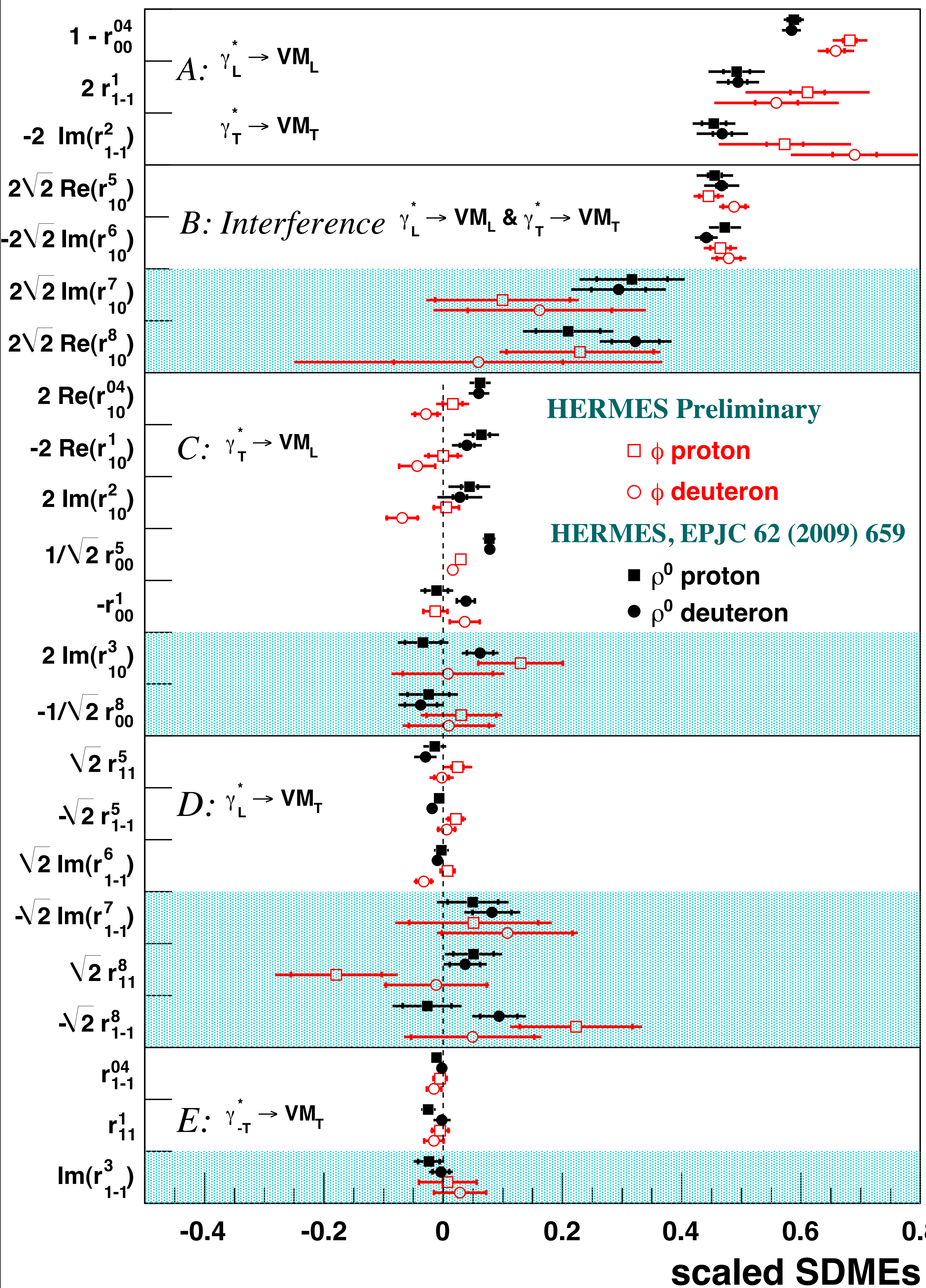
http://arxiv.org/abs/0904.1648
*H. Moutarde, **Phys. Rev. D79** (2009)*

http://arxiv.org/abs/0904.0458
*Kumerički and Müller, Nucl. Phys. **B841** (2010)*

# Other Data?




# Exclusive φ Meson Production

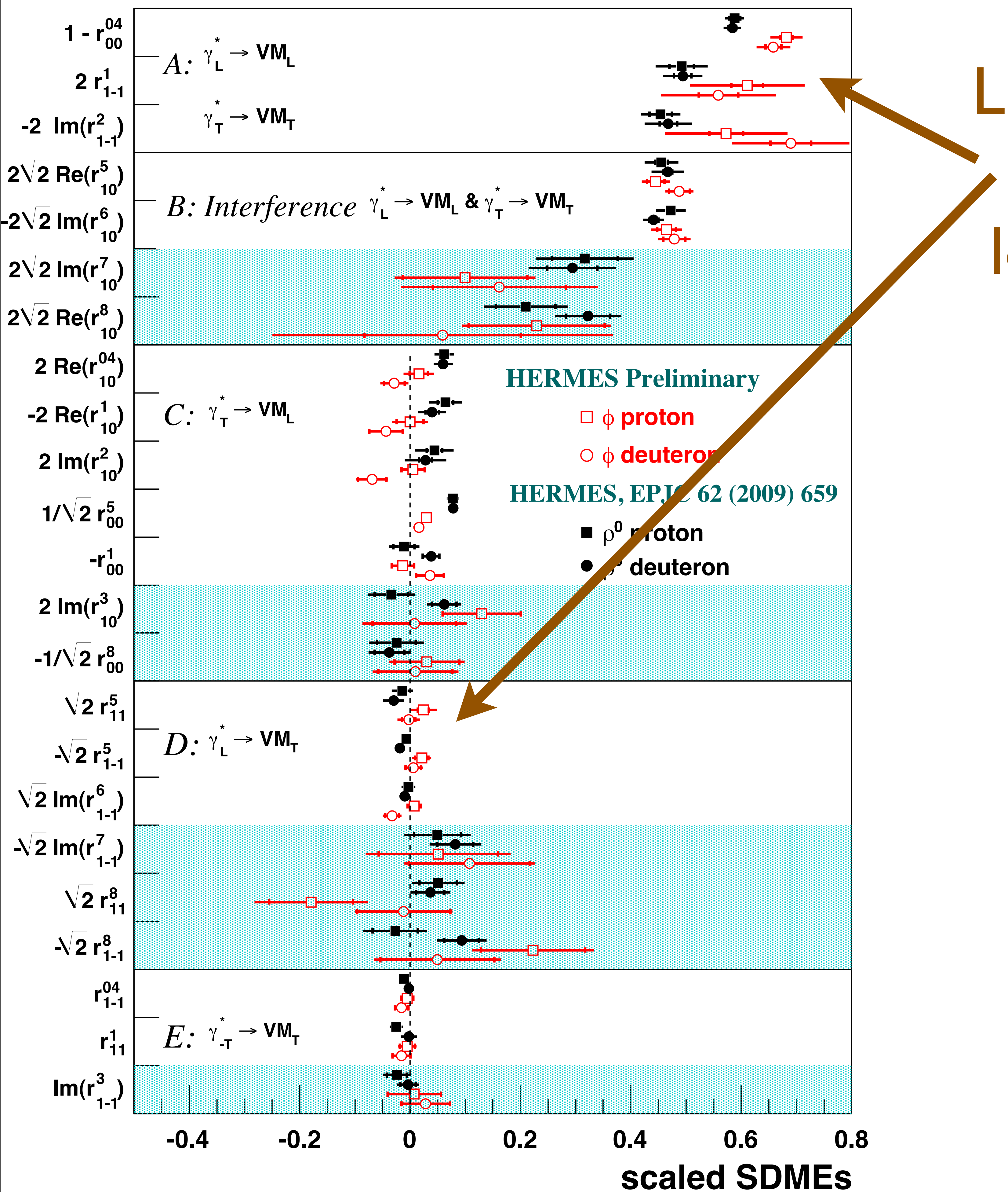



# Exclusive Meson Production

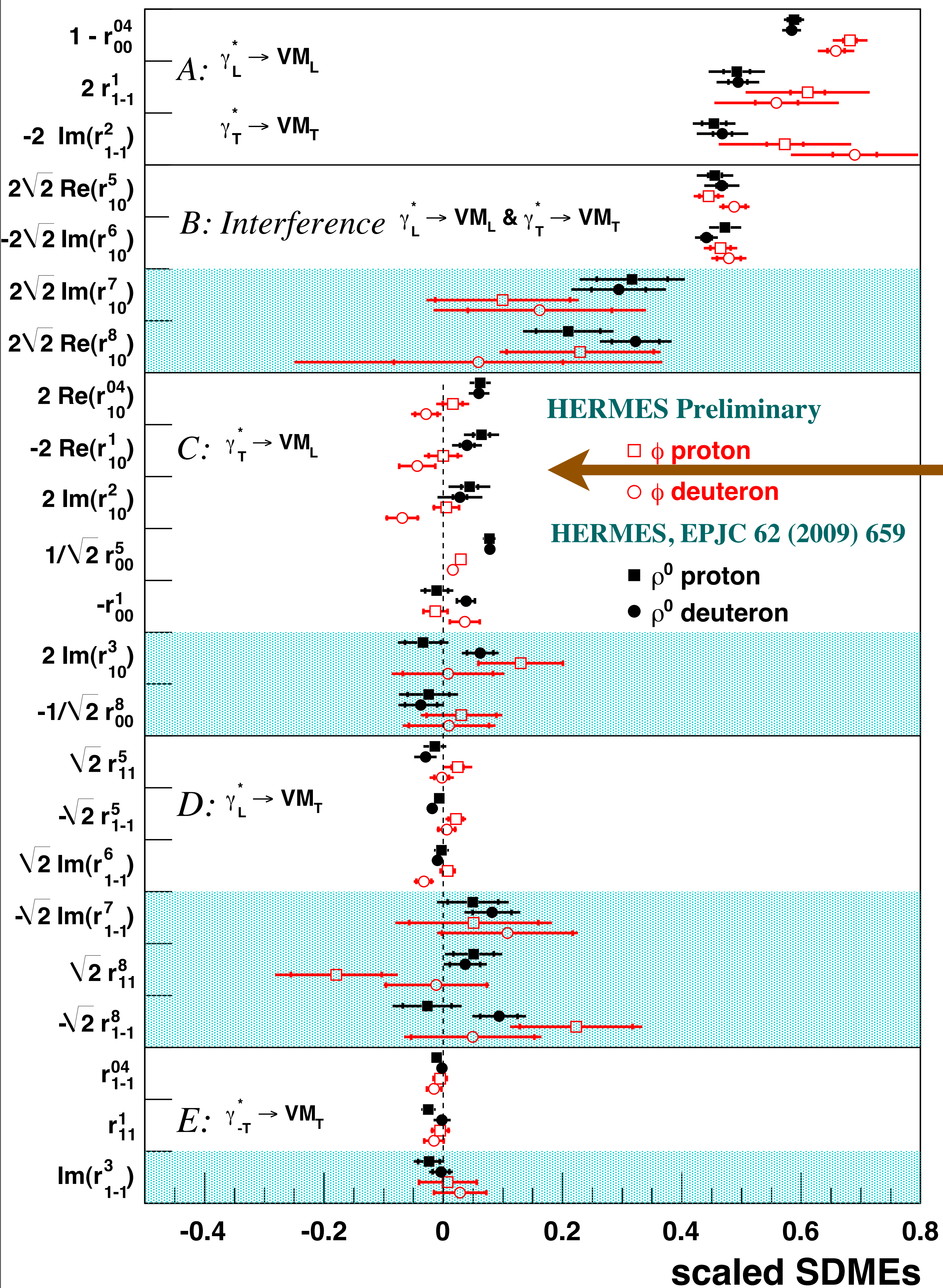
Results taken from measurement of $ep \rightarrow eX\varphi$.

No measured distinction between proton and deuteron data.

Leading-twist transitions are typically larger than the $\rho^0$-equivalent.

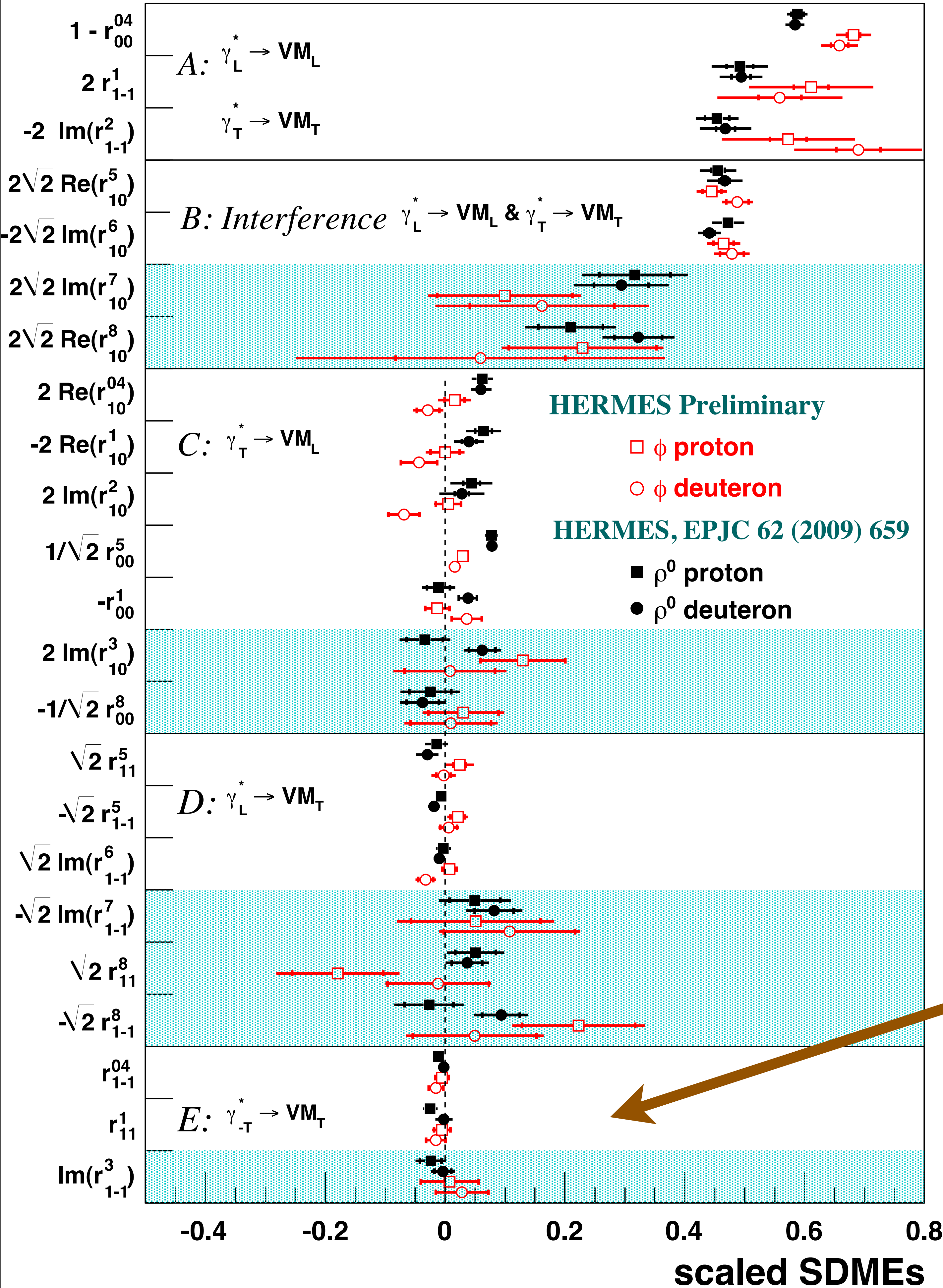



# Longitudinal photons mostly produce longitudinal mesons




Longitudinal photons mostly produce longitudinal mesons

Some small indication that transverse photons can produce longitudinal mesons

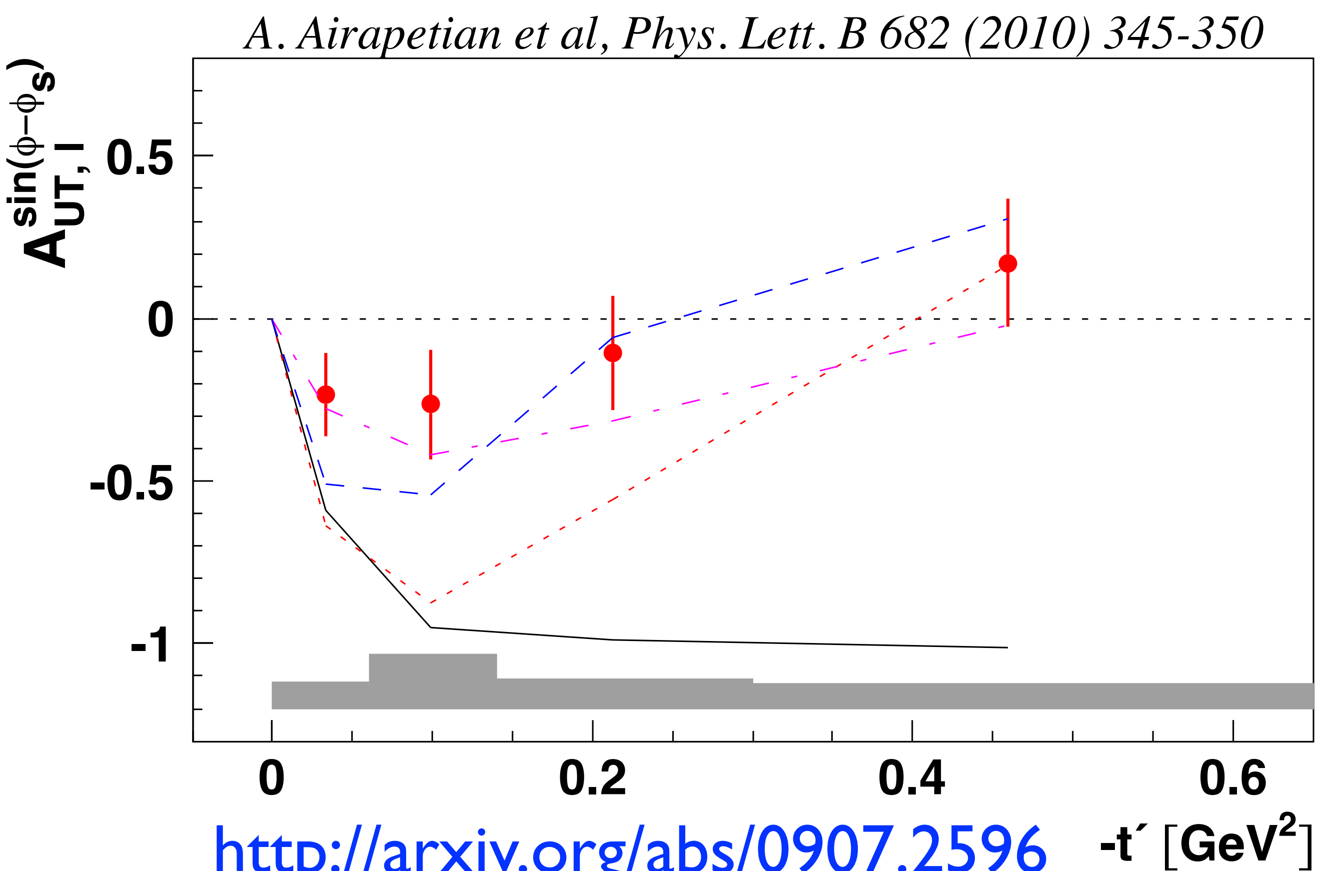



Longitudinal photons mostly produce longitudinal mesons

Some small indication that transverse photons can produce longitudinal mesons

Zero indication of two units of angular momentum change (-T γ makes +T φ)

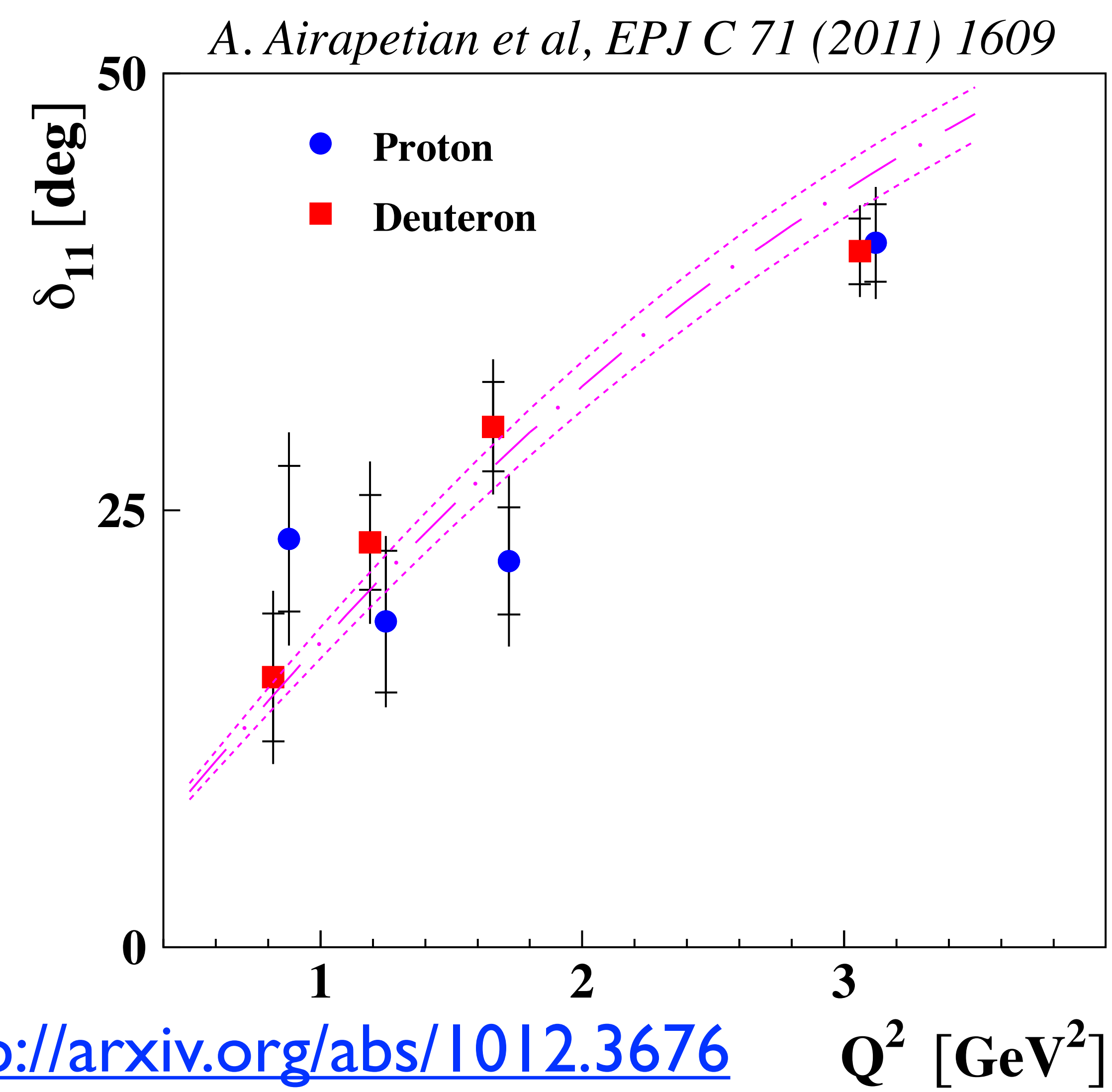
# Other Data?




http://arxiv.org/abs/0907.2596

Meson data can also play a vital role in accessing GPDs - especially the "polarised" GPDs $\tilde{H}$ and $\tilde{E}$!

Extraction of SDMES and Helicity Amplitude Ratios at HERMES for ρ mesons have shown that the handbag approximation is insufficient!




http://arxiv.org/abs/1012.3676

# Conclusions - What did we learn at HERMES?

- DVCS can be used to access information on Generalised Parton Distributions
- HERMES has the most diverse DVCS measurements of any experiment.
- Polarised target experiments are essential for the extraction of GPDs; should be seen as a fundamental experimental priority!

# Conclusions - What did we learn at HERMES?

- Lack of data means that nuclear effects on GPDs are not quantified! Incentive for new experiments at JLab, COMPASS and the EIC!
- Already, GPDs can be constrained - but there is much left to do!
- What effects do chiral-odd GPDs or higher-twist distributions have?

Nuclear

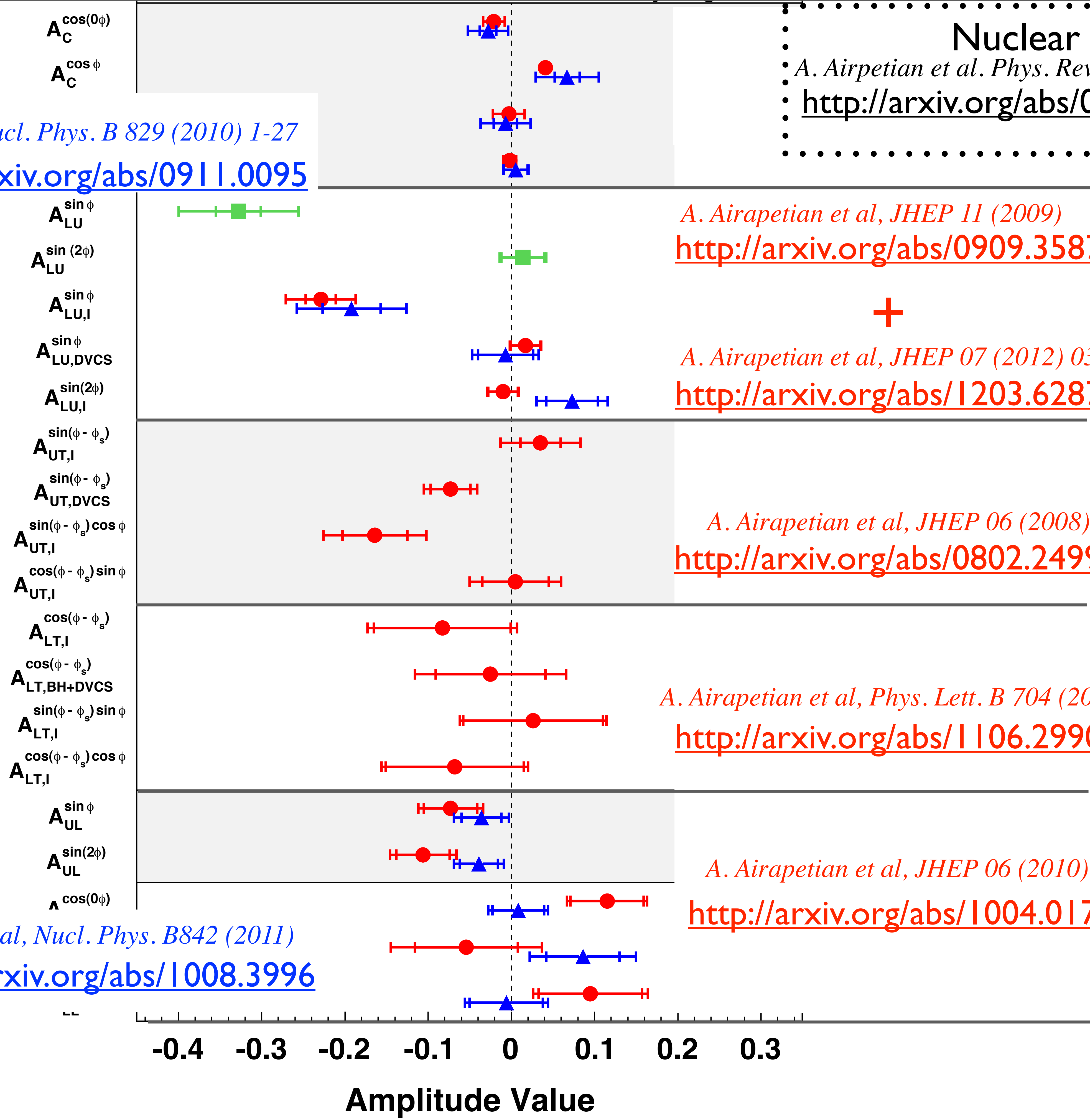
*A. Airpetian et al. Phys. Rev. C 81 (2010)*

http://arxiv.org/abs/0911.0091

*A. Airapetian et al, Nucl. Phys. B 829 (2010) 1-27*

http://www.arxiv.org/abs/0911.0095

DVCS @ HERMES




*A. Airapetian et al, JHEP 11 (2009)*

http://arxiv.org/abs/0909.3587

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*A. Airapetian et al, JHEP 07 (2012) 032*

http://arxiv.org/abs/1203.6287

*A. Airapetian et al, JHEP 06 (2008)*

http://arxiv.org/abs/0802.2499

*A. Airapetian et al, Phys. Lett. B 704 (2011)*

http://arxiv.org/abs/1106.2990

*A. Airapetian et al, JHEP 06 (2010)*

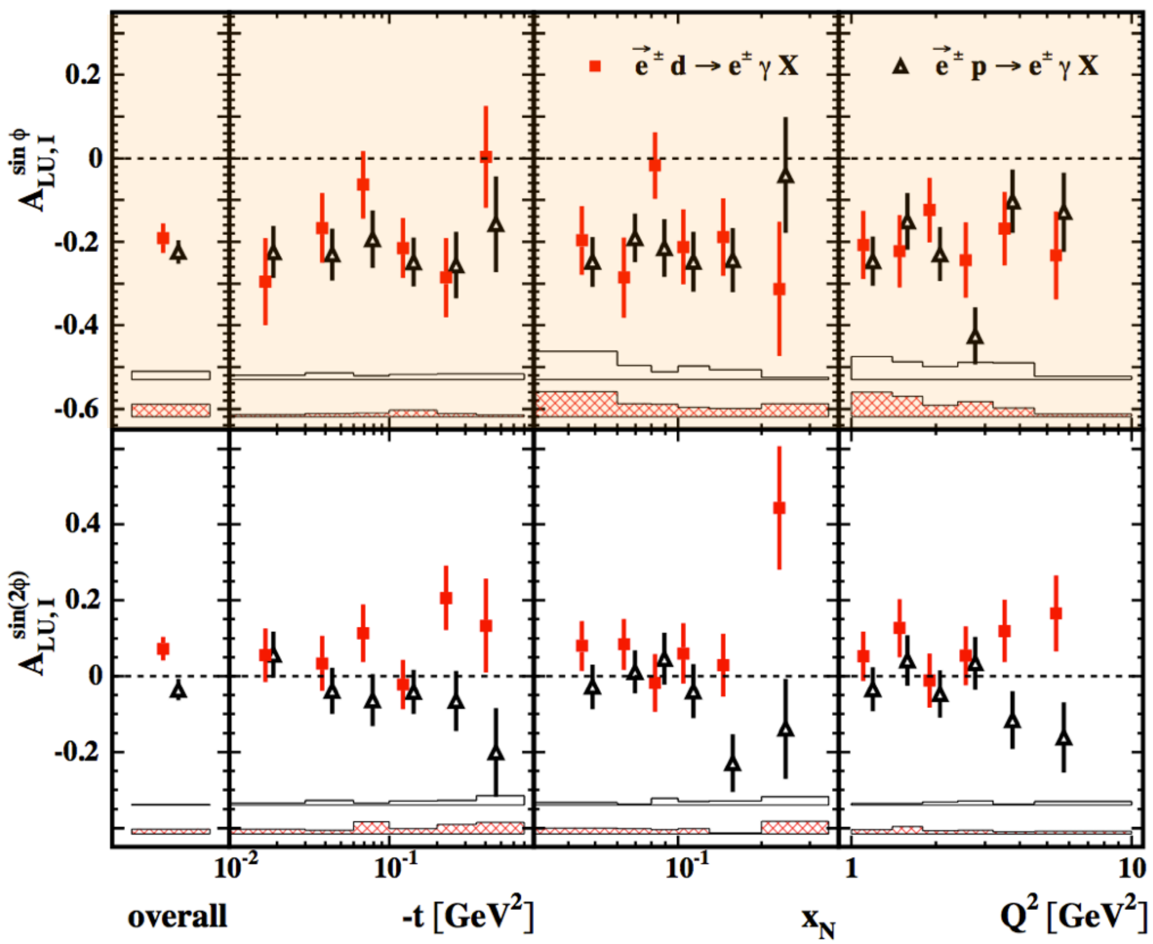
http://arxiv.org/abs/1004.0177

*A. Airapetian et al, Nucl. Phys. B842 (2011)*

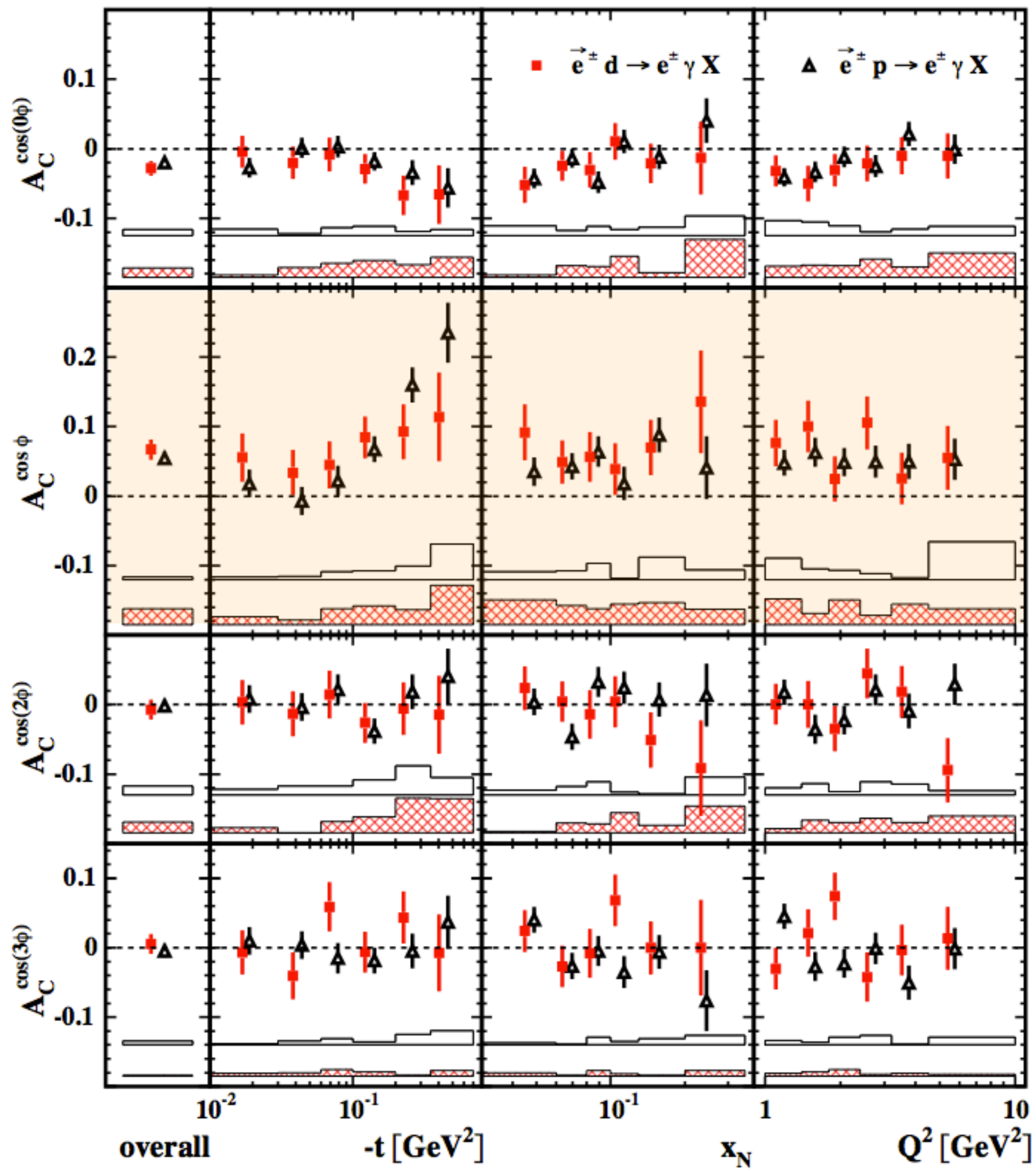
http://www.arxiv.org/abs/1008.3996

# Deuterium Beam-Asymmetries

*A. Airapetian et al, Nucl. Phys. B 829 (2010) 1-27*



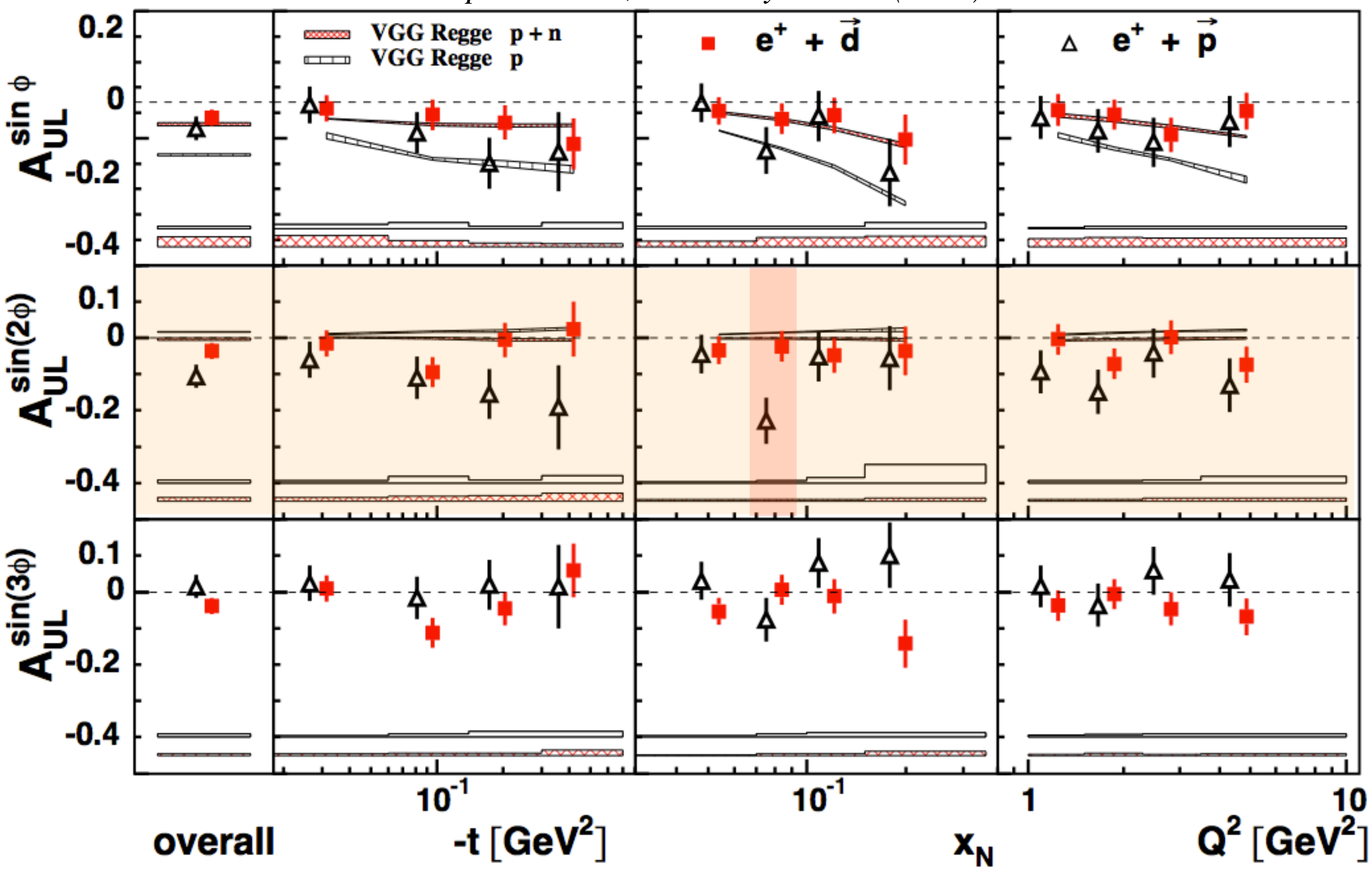

http://arxiv.org/abs/0911.0095




Deuterium is governed by different GPDs - but the asymmetry data is not *so* different even at low *t*!

# Deuterium-Target Asymmetries

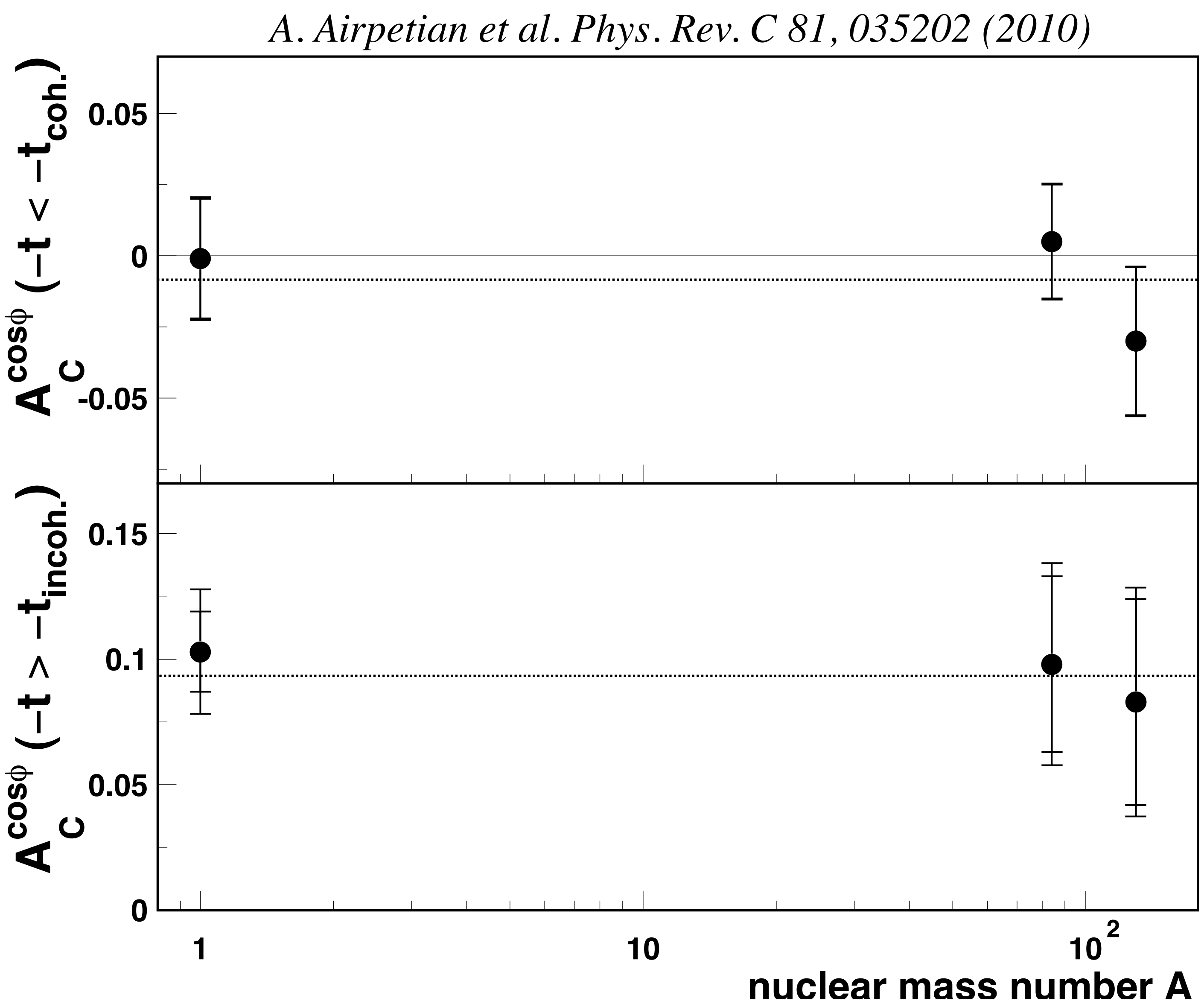
*A. Airapetian et al, Nucl. Phys. B842 (2011) 265-298*




No good idea how to model long. pol. deuterium GPDs. Currently use a proton/ neutron hybrid

http://arxiv.org/abs/1008.3996

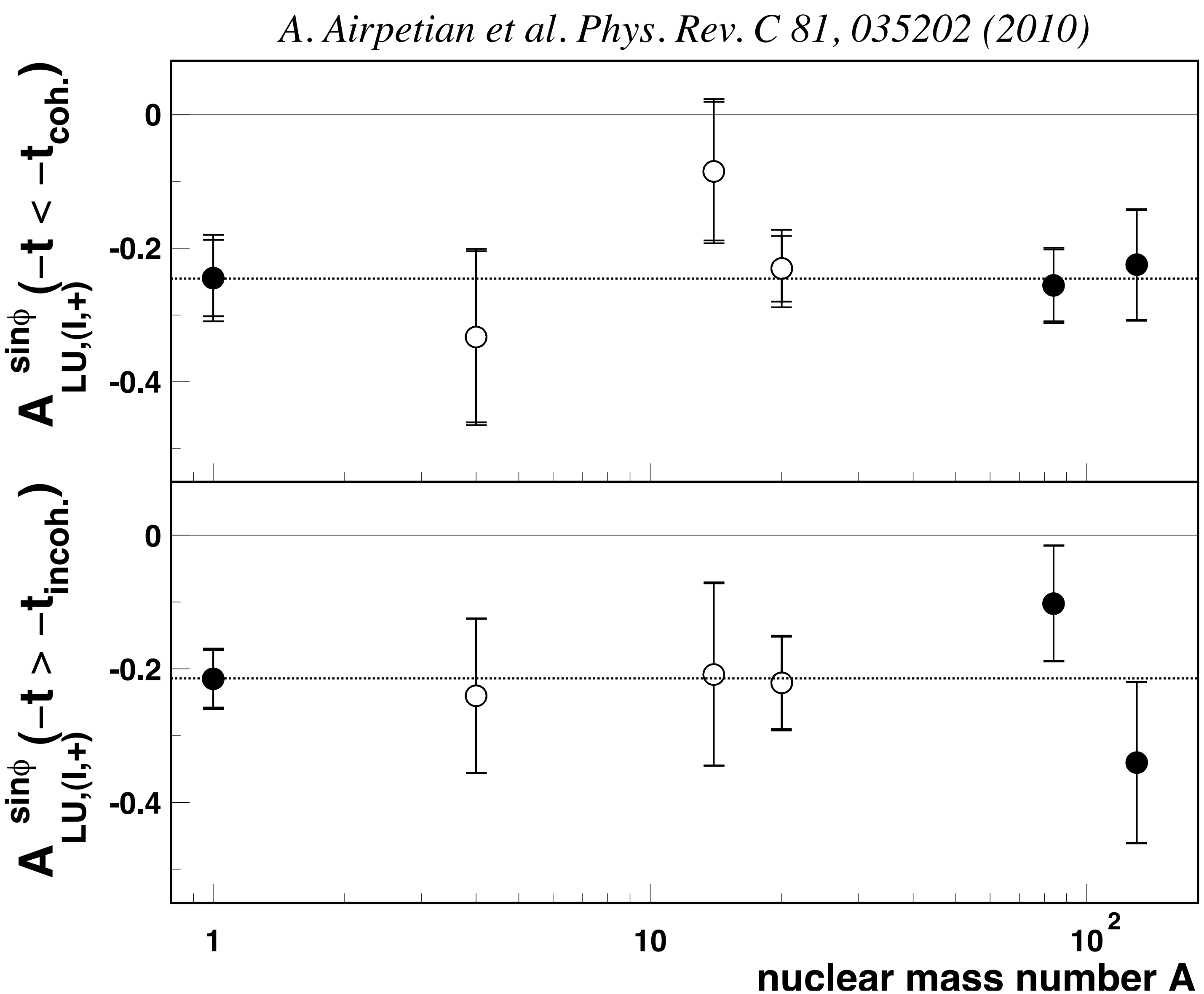
# Nuclear Mass Dependence




Nuclear-Binding models expected the DVCS asymmetry for nuclear targets to be 160-180% of the Hydrogen asymmetry.

http://arxiv.org/abs/0911.0091

# Nuclear Mass Dependence

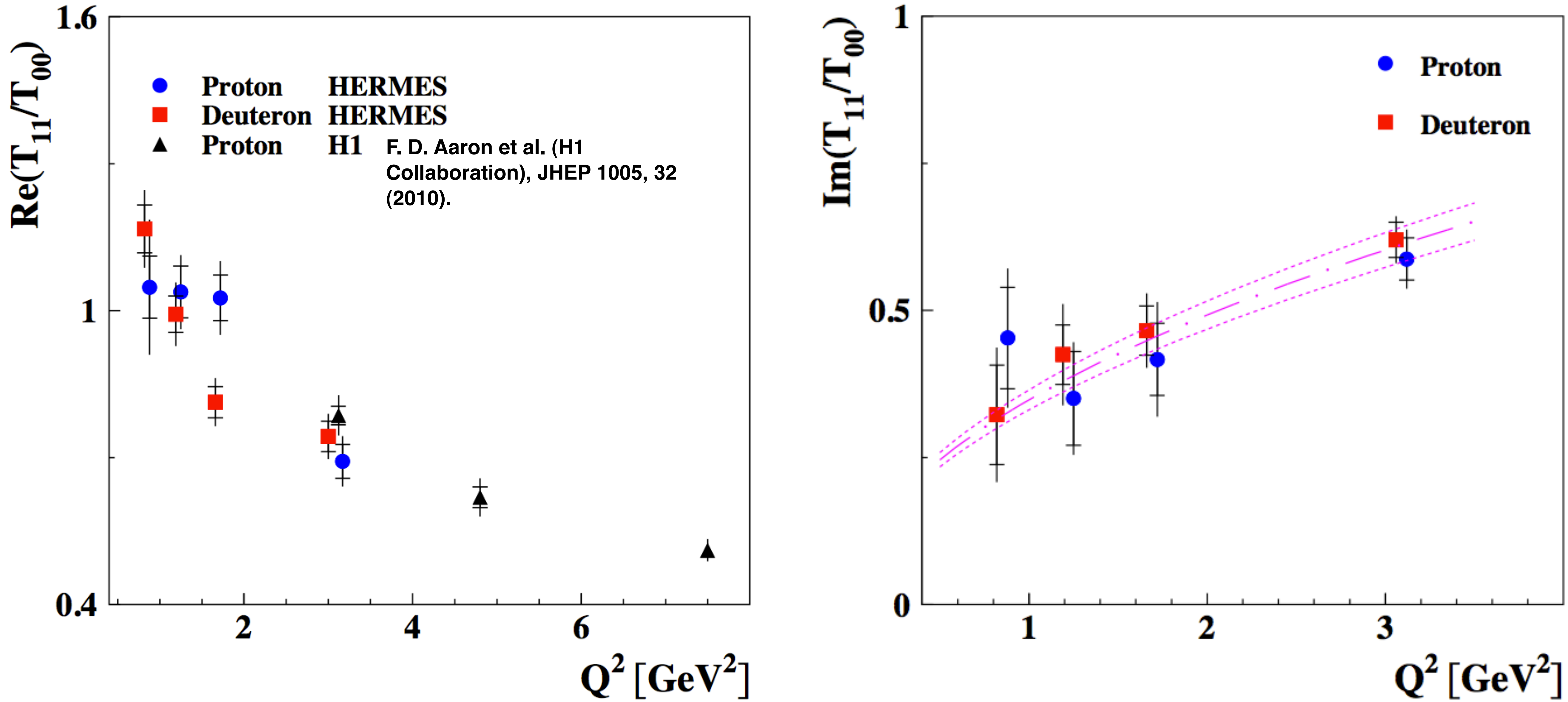



● spin ½

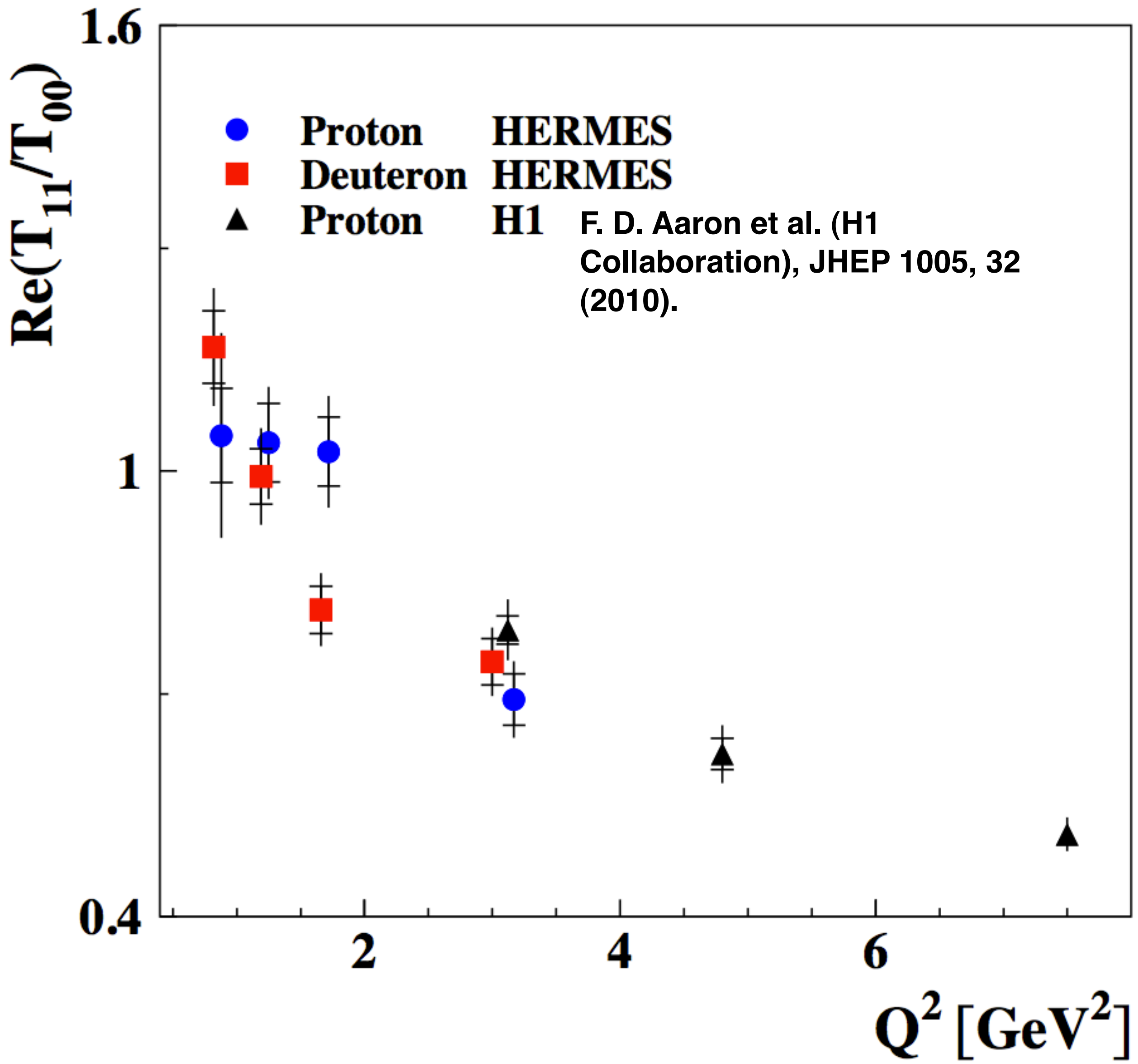
○ spin 1

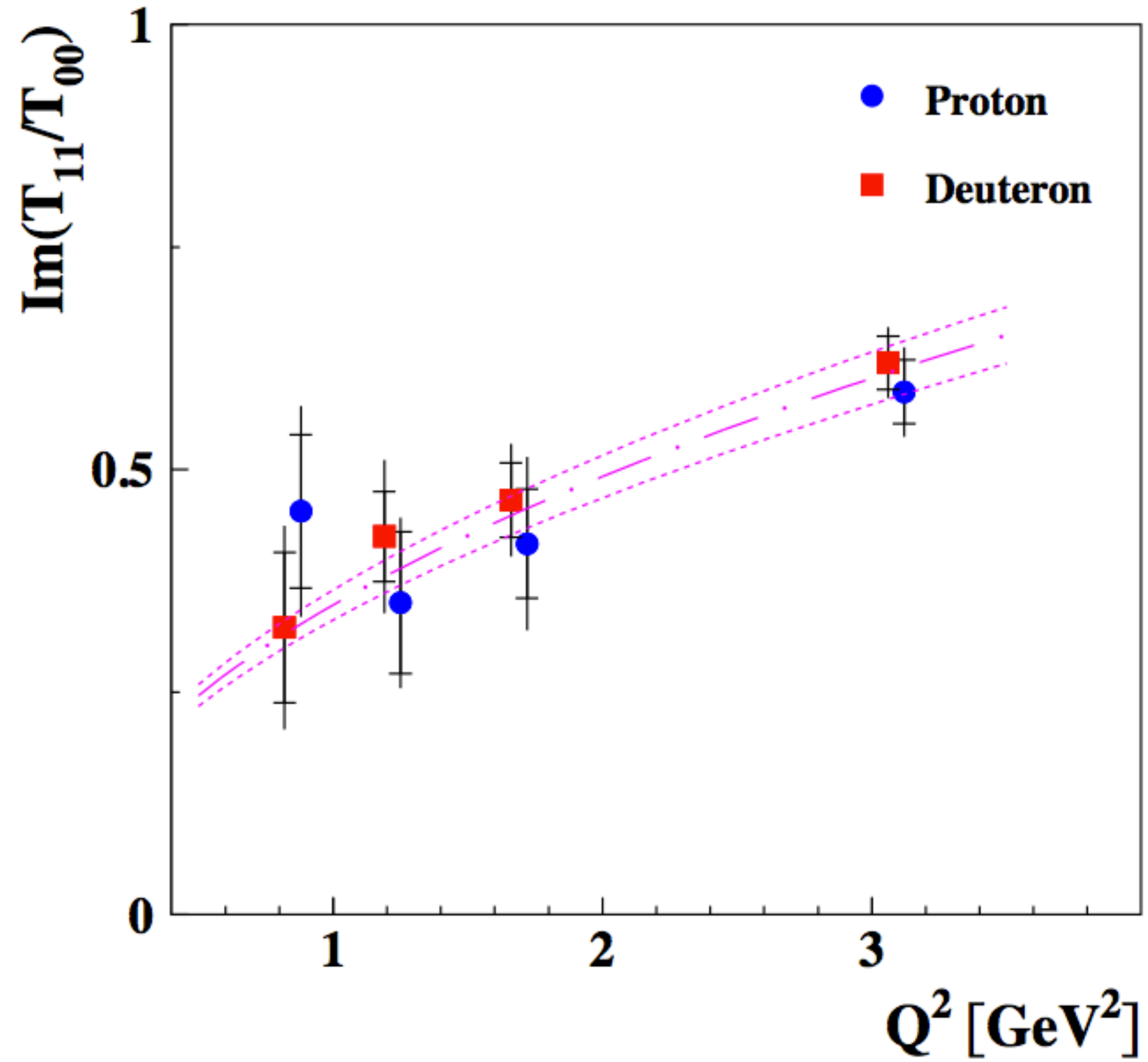
The data shows no significant difference between coherent and incoherent DVCS processes

http://arxiv.org/abs/0911.0091




# Kinematic Dependence of $t_{11}$




Real Part follows a/Q with a=1.11±0.03GeV as expected!

Imaginary Part follows bQ with b=0.34±0.02GeV$^{-1}$ (fit has no basis in theory)

# Phase Differences of HARs

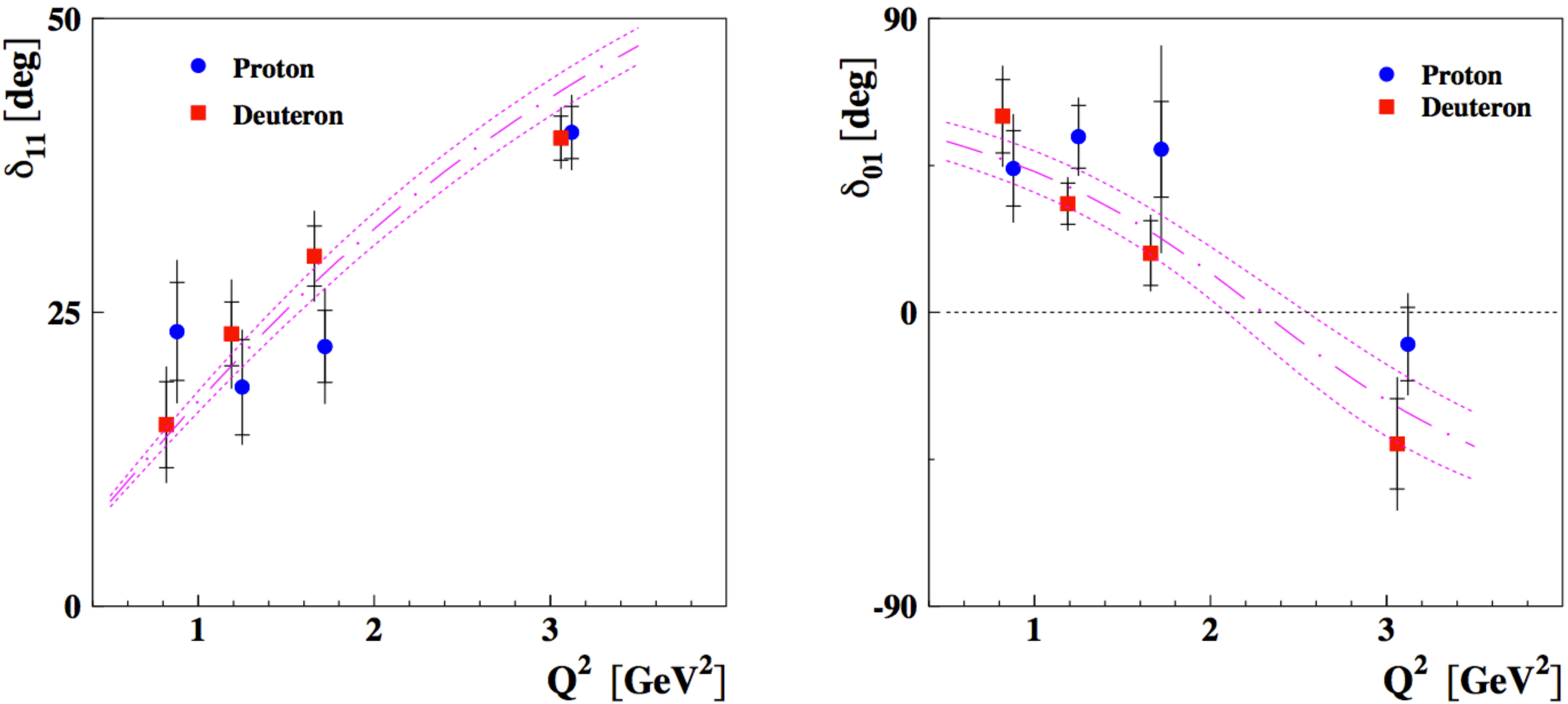
- GPD model predicts small phase difference for $\tan(\delta_{11})=\mathrm{Im}(t_{11})/\mathrm{Re}(t_{11})$

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C 53, 367 (2008)

- $t_{01}$ is expected to be the largest SCHC-violating amplitude and $\delta_{01}$ should be constant

D. Yu. Ivanov and R. Kirschner, Phys. Rev. D 58, 114026 (1998)

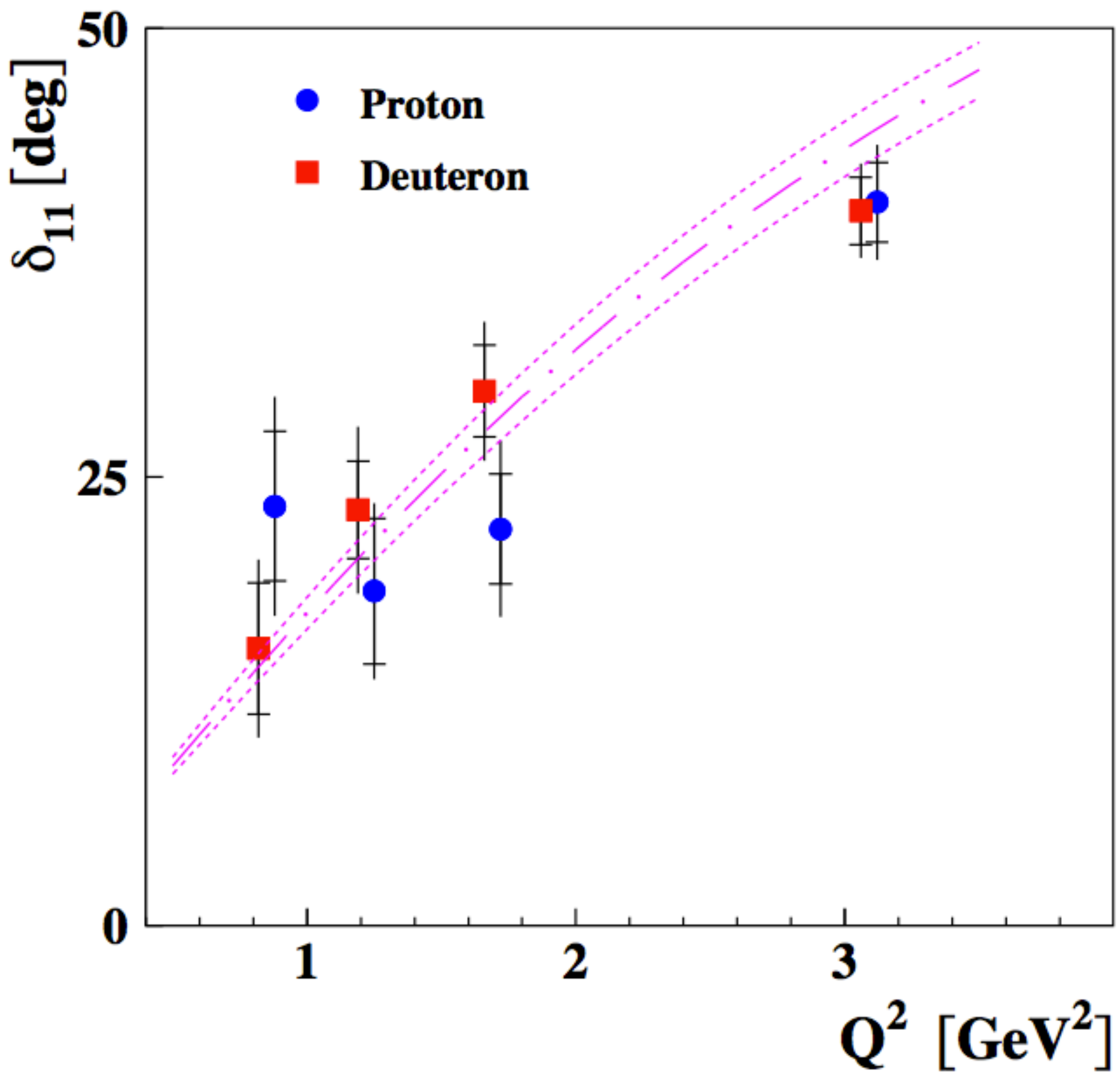
# Phase Differences of HARs

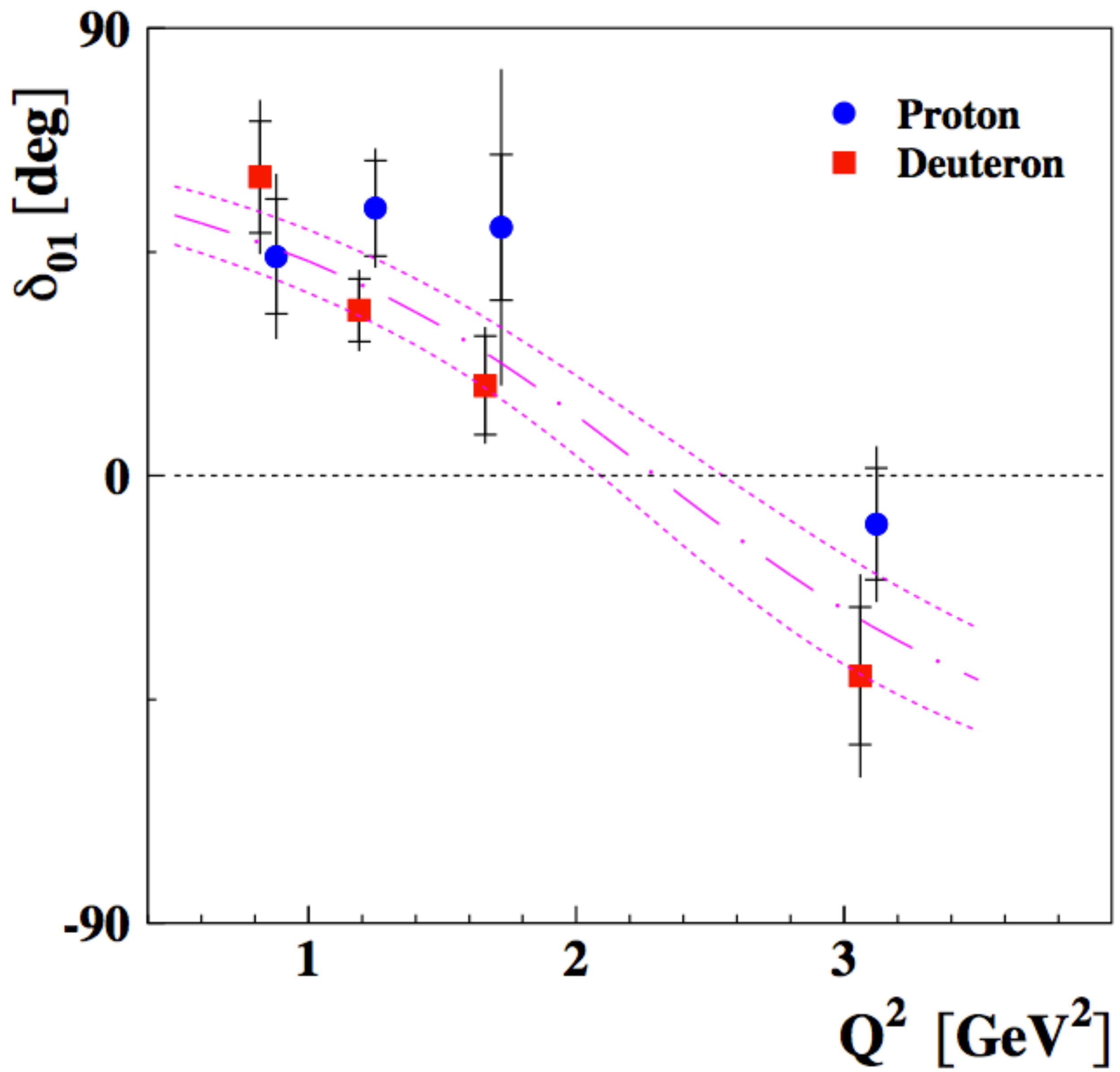


Large value contradicts GPD-based models

Should be a constant

(Neither Re($t_{01}$) nor Im($t_{01}$) follow theoretical dependence predictions!!!)




N.B: Fits have no basis in theory

# Helicity Amplitude Hierarchy

Behaviour of UPE

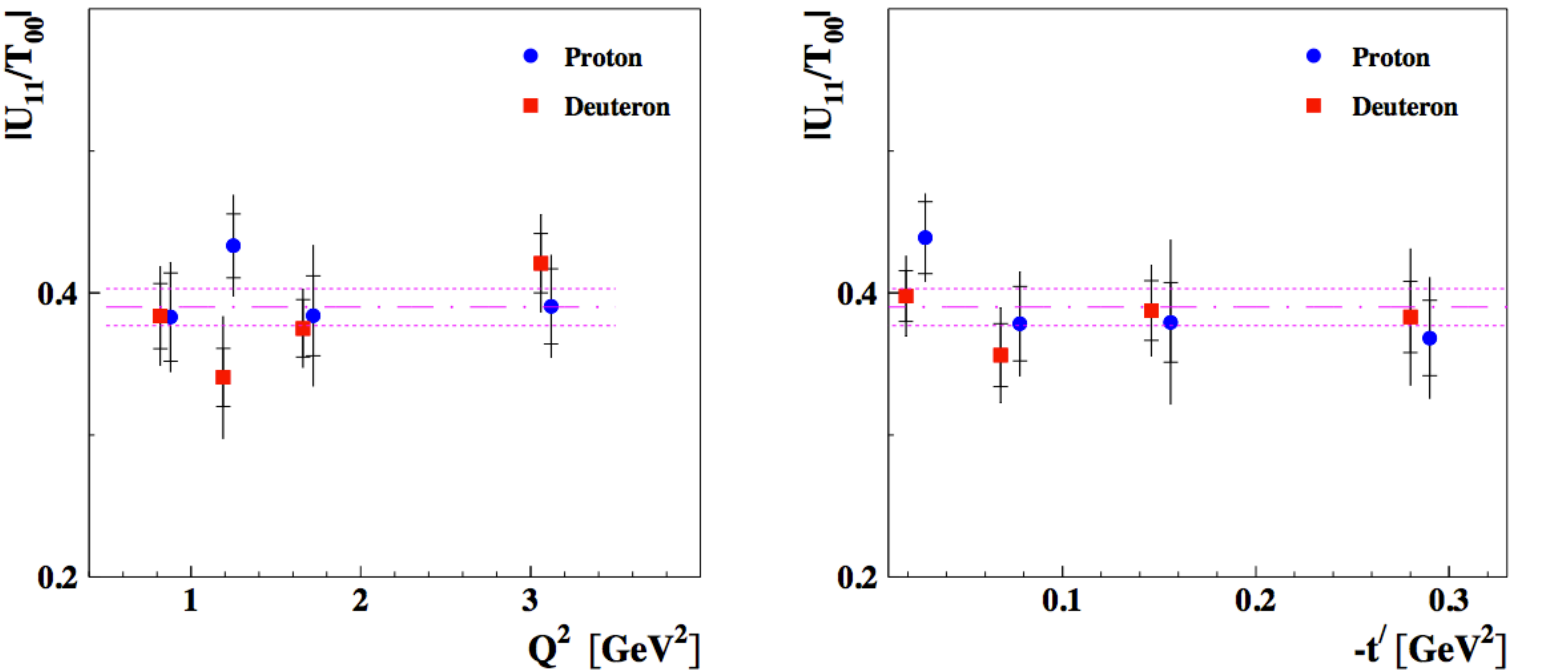
$$|T_{00}|^2 \approx |T_{11}|^2 >> |U_{11}|^2 > |T_{01}|^2 >> |T_{10}|^2 \ldots$$

- $u_{11} = |U_{11}|/|T_{00}|$ should be small ($u_{11} \approx 0.2$) but visible (only) for $\rho^0$ at HERMES!

- May naively expect a $1/Q$ dependence in $u_{11}$

- UPE is one-pion exchange => may also see some influence of the pion-pole at small *t?*

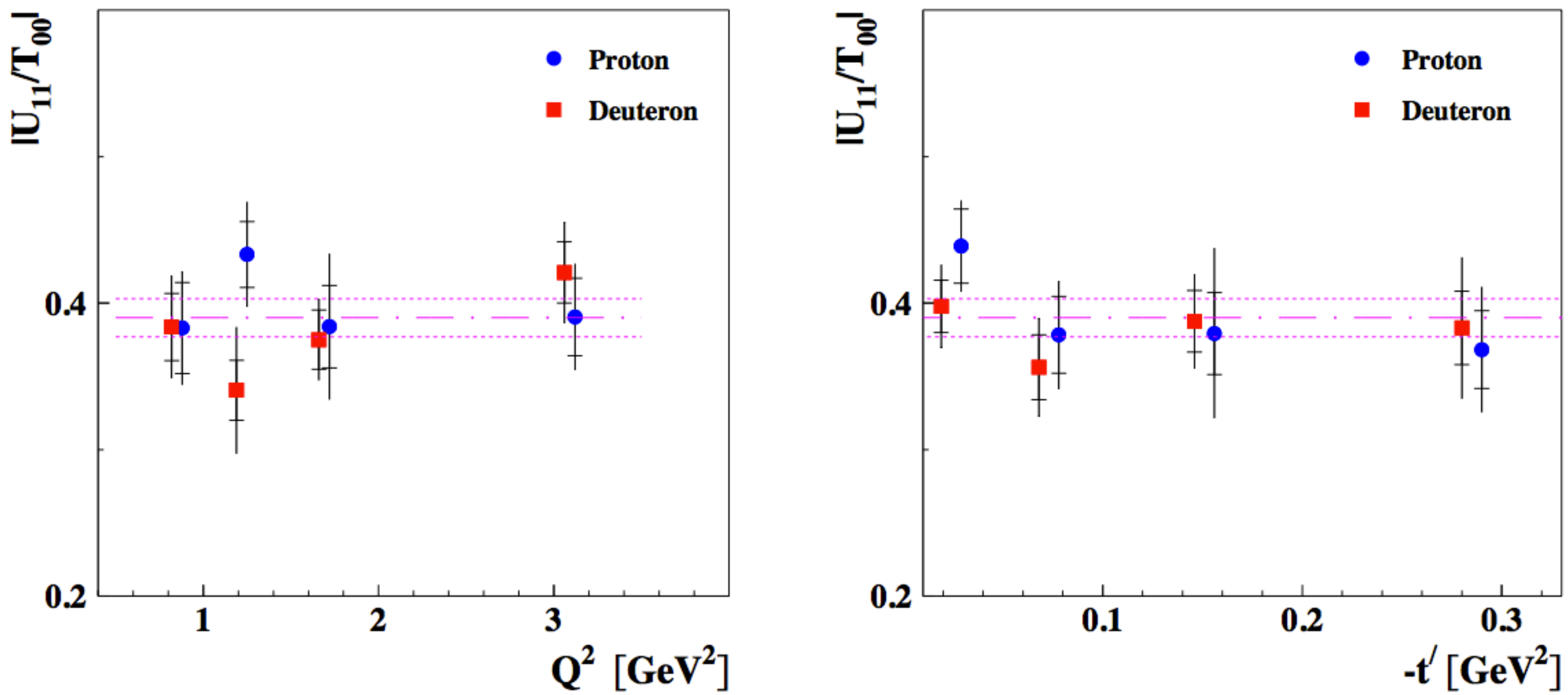
# Unnatural Parity Exchange



# Unnatural Parity Exchange

No dependence on $Q^2$!

No dependence on t′!




Existence established to 20σ (integrated extraction)

Magnitude of $U_{11}$ is 2.5x smaller than $T_{00}$

# Unnatural Parity Exchange

- No dependence on $Q^2$ may be because HERMES is far from the asymptotic region ?

- No dependence on $t'$

➡ Too far from pion-pole ?

➡ $U_{11}$ not dominated by one-pion exchange ?

➡ An underlying dependence of $T_{00}$ on $t'$ ?