Overview of HERMES Results on Exclusive Processes

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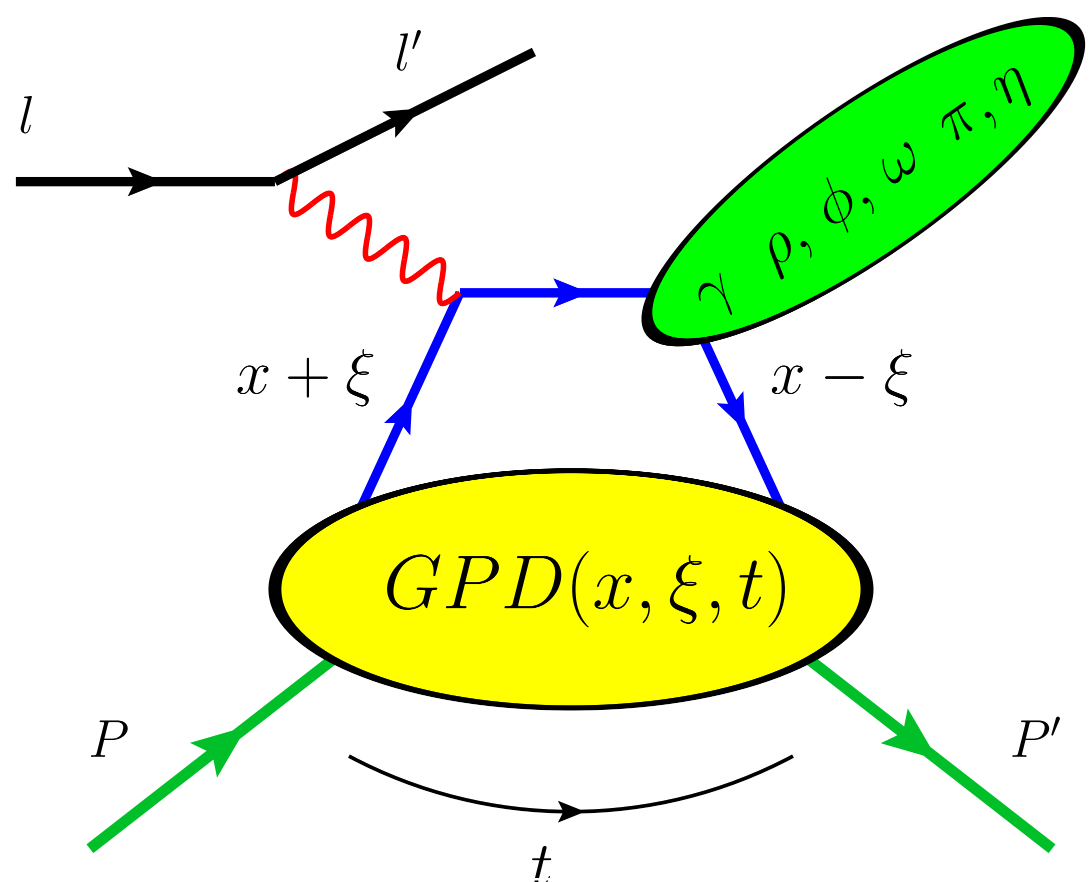
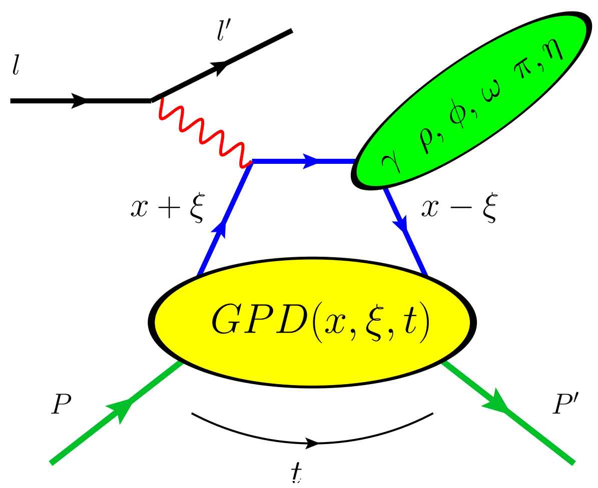
for the HERMES collaboration
Transversity 2014

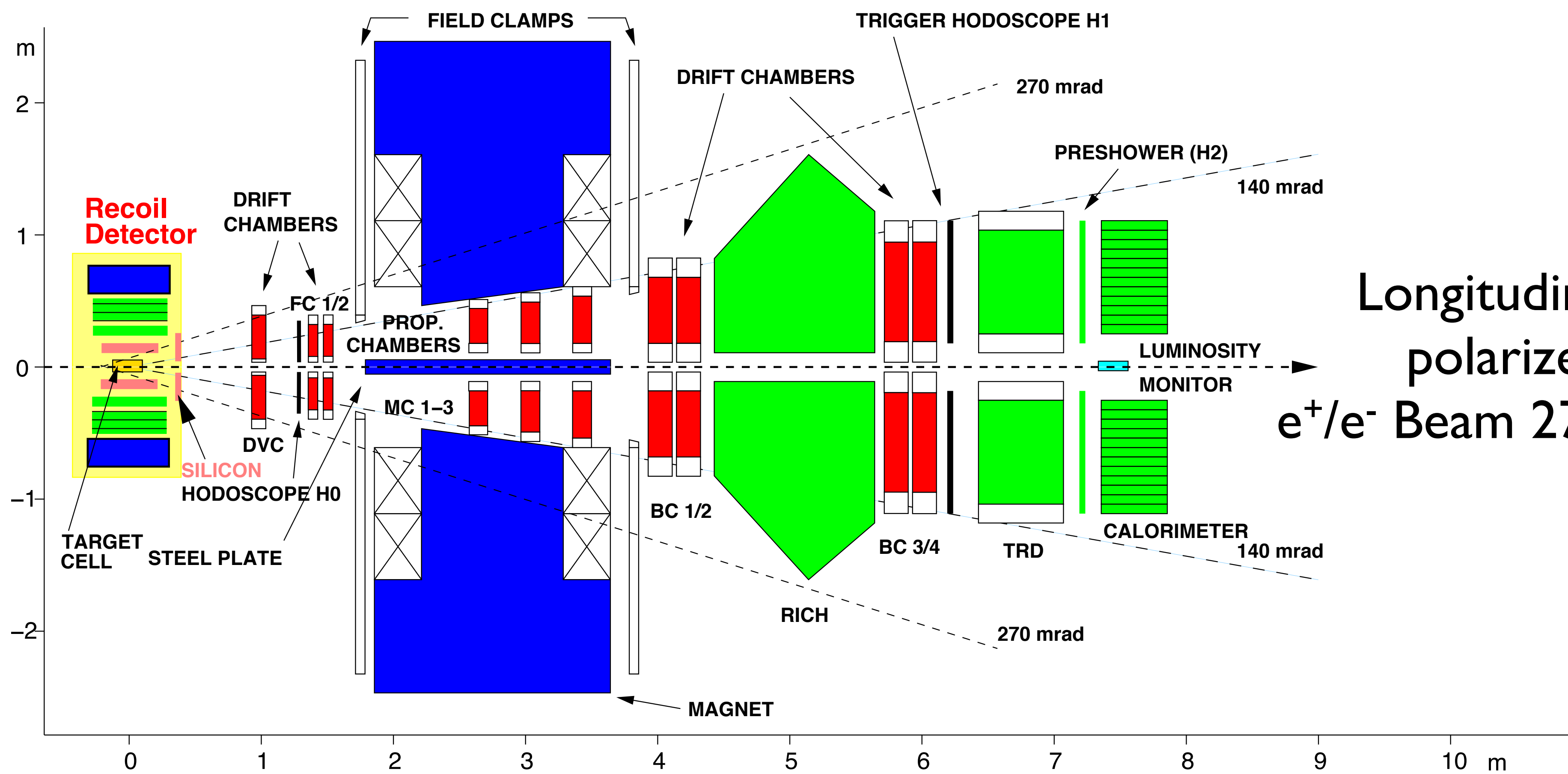
Introduction

Experimental probe of GPDs ⟶ Hard exclusive Processes



Experimental probe of GPDs ⟶ Hard exclusive Processes





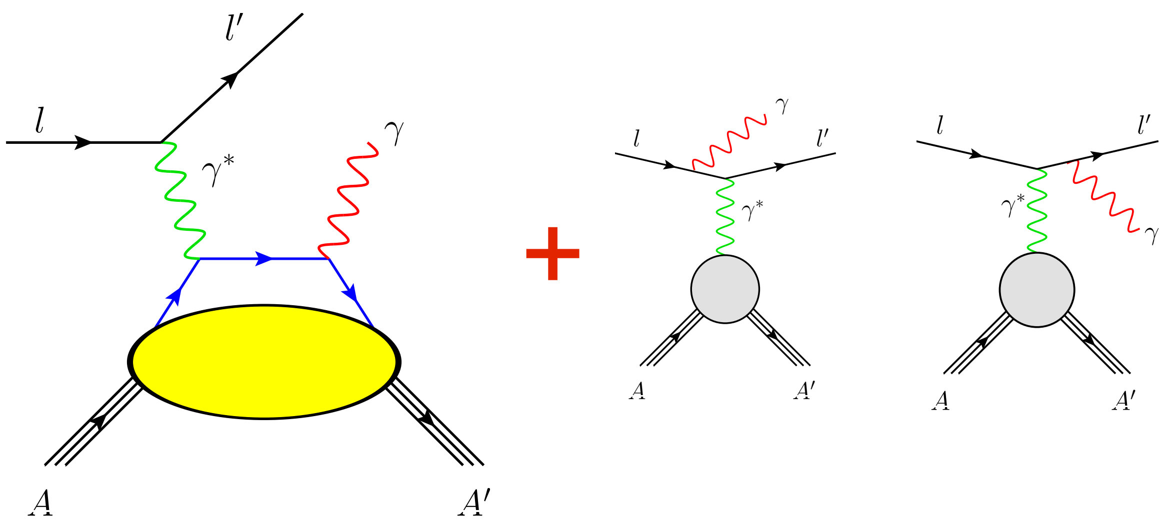
Longitudinally polarized e^+/e^- Beam 27.6 GeV

- Data Taking: 1995-2007
- Reconstruction: δp/p<2%, δΘ<1 mrad
- Internal gas targets: *unpol* H, D, He, N, Ne, Kr, Xe, *Lpol* He, H, D, *Tpol* H
- Particle ID: TRD, Preshower, Calorimeter, RICH

lepton-hadron separation > 99 % efficiency

- In 2006-2007 : Data Taking with Recoil Detector

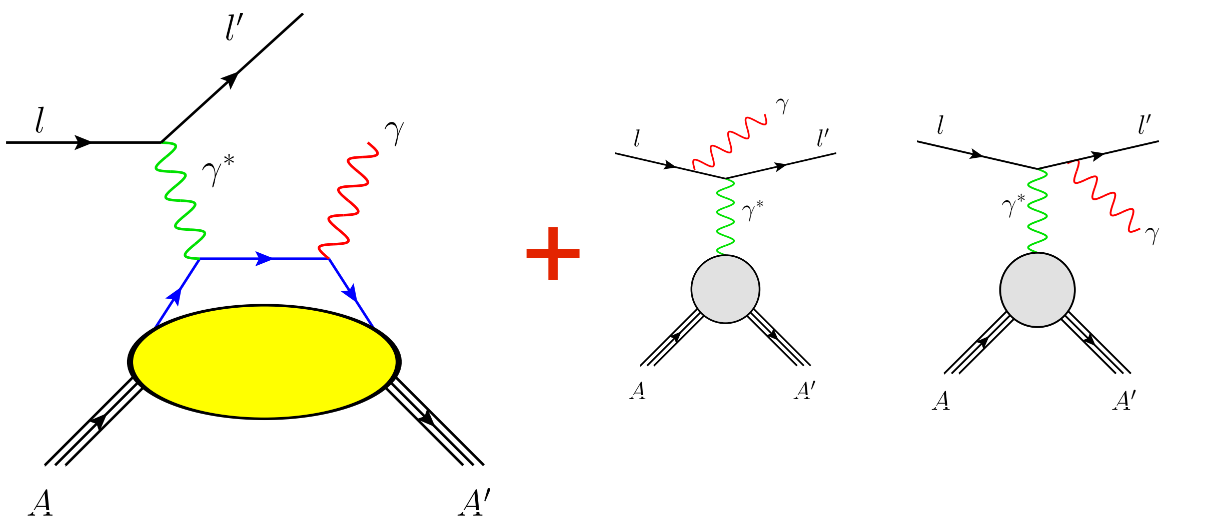
Experimental probe of GPDs ⟶ Hard exclusive Processes



Deeply Virtual Compton Scattering

- Theoretically the cleanest probe of GPDs
- Theoretical accuracy at NNLO
- GPDs are accessed through convolution integrals with hard scattering amplitude
- Experimental observables: Azimuthal asymmetries, cross sections, cross section differences.
- Amplitudes depend on all GPDs $H, E, \widetilde{H}, \widetilde{E}$

Experimental probe of GPDs ⟶ Hard exclusive Processes



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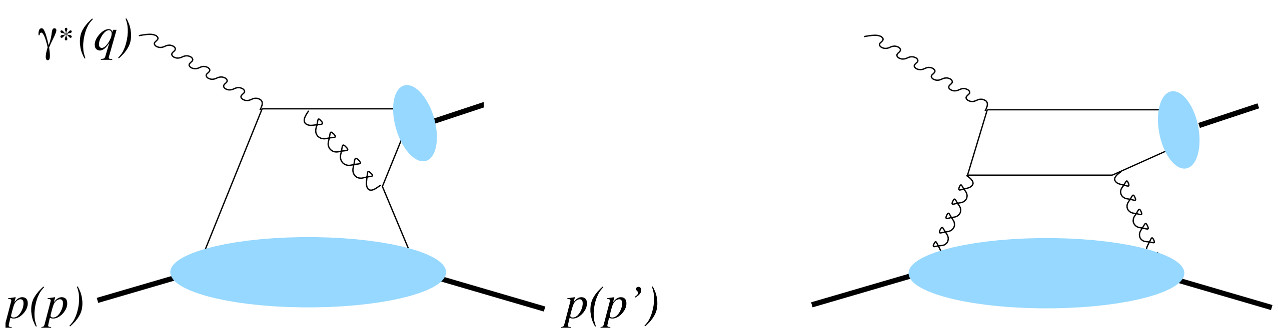


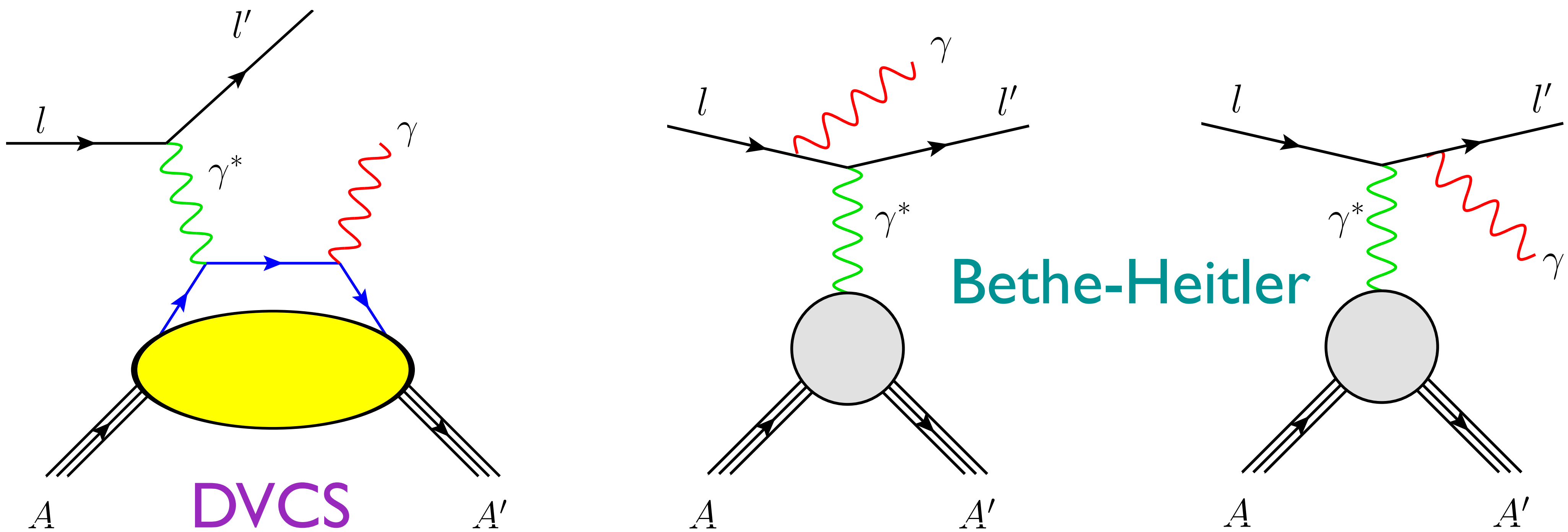
Vector Mesons

- Factorization for σ_L (to ρ_L, ϕ_L, ω_L) only
- σ_L to σ_T suppressed by 1/Q
- σ_T suppressed by $1/Q^2$
- Experimental observables: cross sections, SDMEs, azimuthal asymmetries, Helicity amplitude ratios
- At leading twist → sensitive to GPDs H and E
- Observables for different mesons provide a possibility of flavor tagging.

Pseudoscalar mesons

- Experimental observables: Cross sections, azimuthal asymmetries
- At leading twist → sensitive to GPDs $\widetilde{H}$ and $\widetilde{E}$

Deeply Virtual Compton Scattering



DVCS and Bethe-Heitler $\Rightarrow$ Same final state $\Rightarrow$ Interference

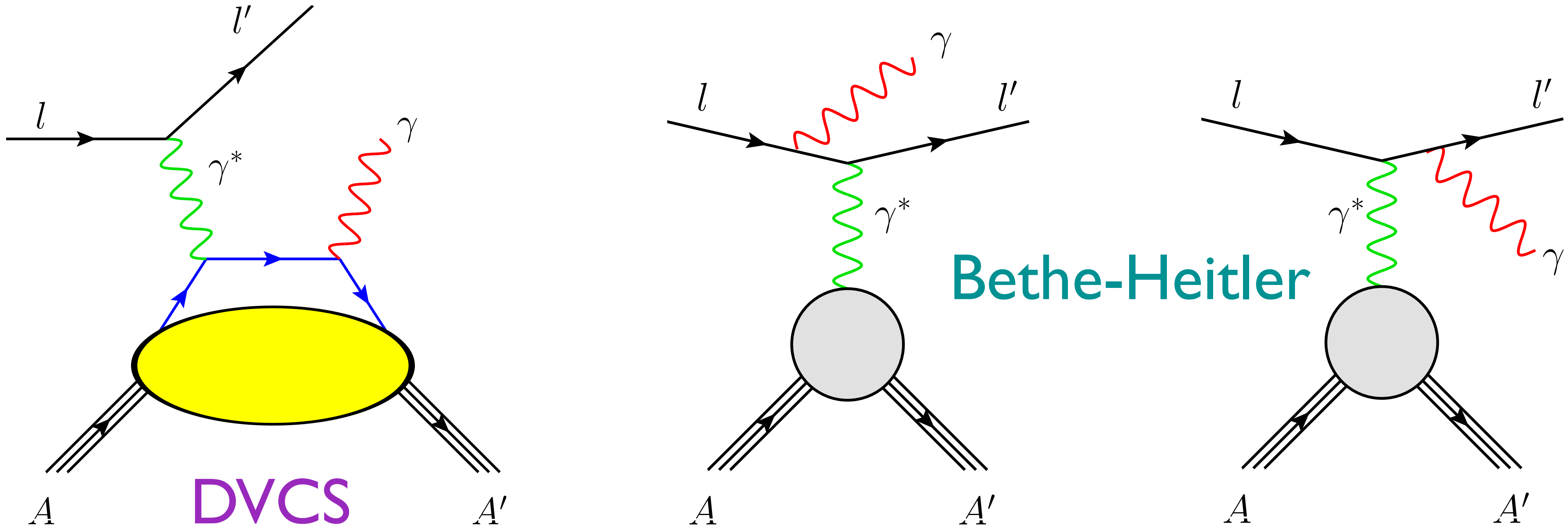
$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS}}_{I}$$

At HERMES kinematics $|\mathcal{T}_{DVCS}|^2 << |\mathcal{T}_{BH}|^2$

DVCS amplitudes can be accessed trough Interference

Interference $\Rightarrow$ non-zero azimuthal asymmetries

Deeply Virtual Compton Scattering



$$\frac{d\sigma}{dx_B dQ^2 d|t| d\phi} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{DVCS}\mathcal{T}^*_{BH} + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS}}_{I}$$

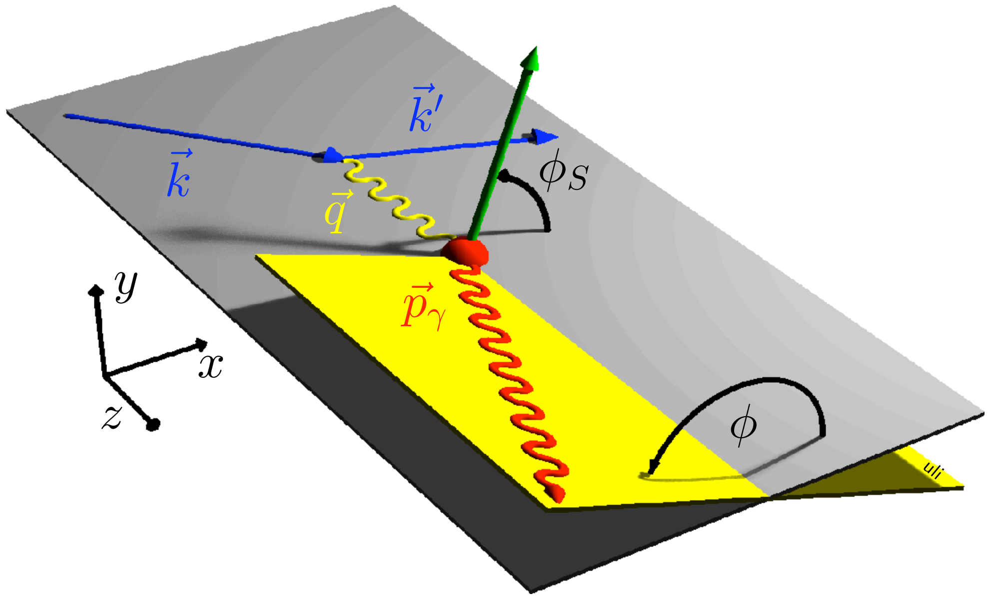
Bethe-Heitler is parametrized in terms of electromagnetic Form-Factors

DVCS is parametrized in terms of Compton Form-Factors

CFFs = convolutions of hard scattering amplitudes and GPD's

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} dx C_q(\xi,x) F^q(x,\xi,t)$$

Access to GPDs



$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\}$$

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

$$\mathcal{I} = -\frac{K_{\rm I} e_\ell}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\rm I} \cos(n\phi) + \sum_{n=1}^{3} s_n^{\rm I} \sin(n\phi) \right\}$$

- Beam-Charge asymmetry
  $$\sigma(e^+,\phi) - \sigma(e^-,\phi) \propto Re[F_1\mathcal{H}]$$
- Beam-Spin Asymmetry
  $$\sigma(\overrightarrow{e},\phi) - \sigma(\overleftarrow{e},\phi) \propto Im[F_1\mathcal{H}]$$
- Longitudinal Target-Spin Asymmetry
  $$\sigma(\overset{\Rightarrow}{P},\phi) - \sigma(\overset{\Leftarrow}{P},\phi) \propto Im[F_1\widetilde{\mathcal{H}}]$$
- Longitudinal Double-Spin Asymmetry
  $$\sigma(\overset{\Rightarrow}{P},\overrightarrow{e},\phi) - \sigma(\overset{\Rightarrow}{P},\overleftarrow{e},\phi) \propto Re[F_1\widetilde{\mathcal{H}}]$$
- Transverse Target-Spin Asymmetry
  $$\sigma(\phi,\phi_S) - \sigma(\phi,\phi_S+\pi) \propto Im[F_2\mathcal{H} - F_1\mathcal{E}]$$
- Transverse Double-Spin Asymmetry
  $$\sigma(\overrightarrow{e},\phi,\phi_S) - \sigma(\overleftarrow{e},\phi,\phi_S+\pi) \propto Re[F_2\mathcal{H} - F_1\mathcal{E}]$$

Longitudinally polarized target:

$$c_n = c_{n,unp} + \lambda\Lambda c_{n,LP}$$
$$s_n = \lambda s_{n,unp} + \Lambda s_{n,LP}$$

Transversely polarized target:

$$c_n = c_{n,unp} + \Lambda c_{n,UT} + \lambda\Lambda c_{n,LT}$$
$$s_n = \lambda s_{n,unp} + \Lambda s_{n,UT} + \lambda\Lambda s_{n,LT}$$

λ - Beam helicity

Λ - Target spin projection

e_ℓ - Beam charge

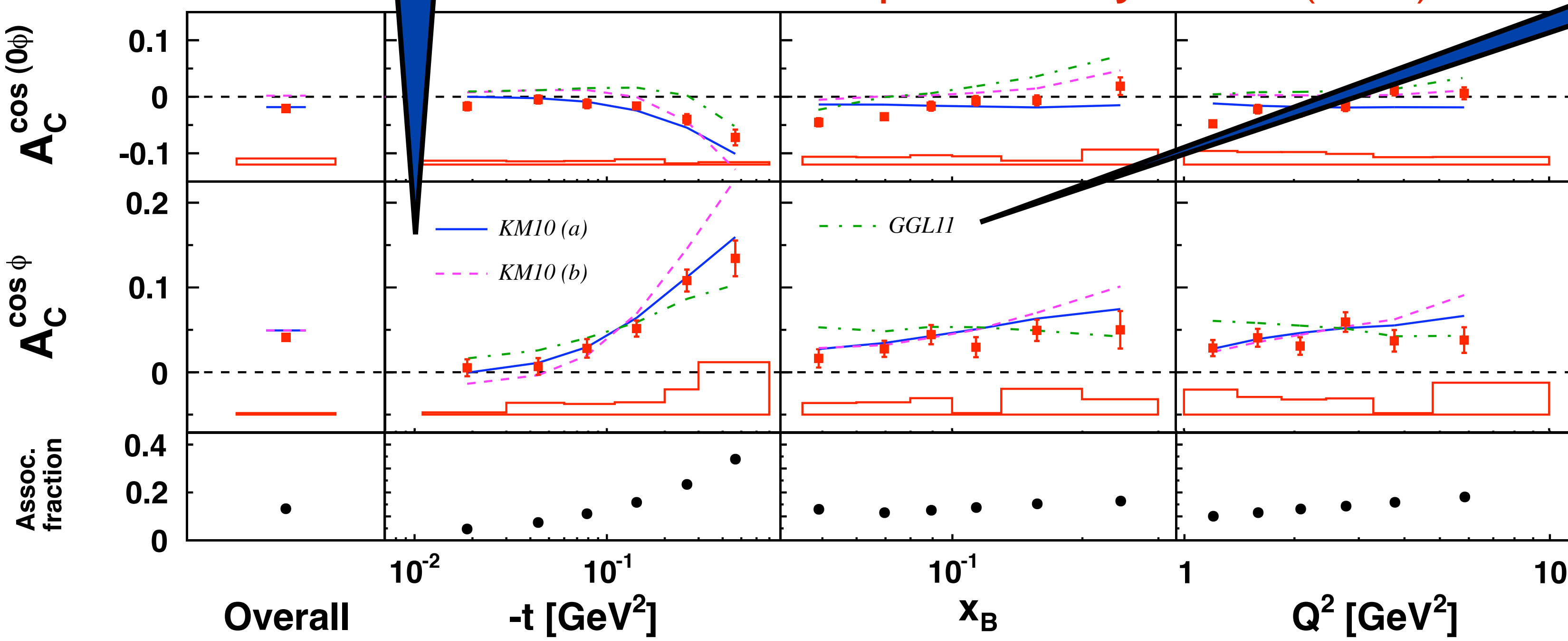
Beam-Charge & Beam-Helicity Asymmetries

KM10: Global fit
K. Kumericki, D. Muller
Nucl.Phys.B 841(2010) 1

$$\mathcal{A}_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{+\leftarrow})}$$

Airapetian el al. JHEP 07 (2012) 032

GGL11: Model calculation
G. Goldstein, S. Liuti,
J. Hernandez
Phys.Rev.D 84 034007 (2011)



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

Beam charge asymmetry
- non-zero leading amplitude
- strong -t dependence
- no x_B and Q^2 dependencies

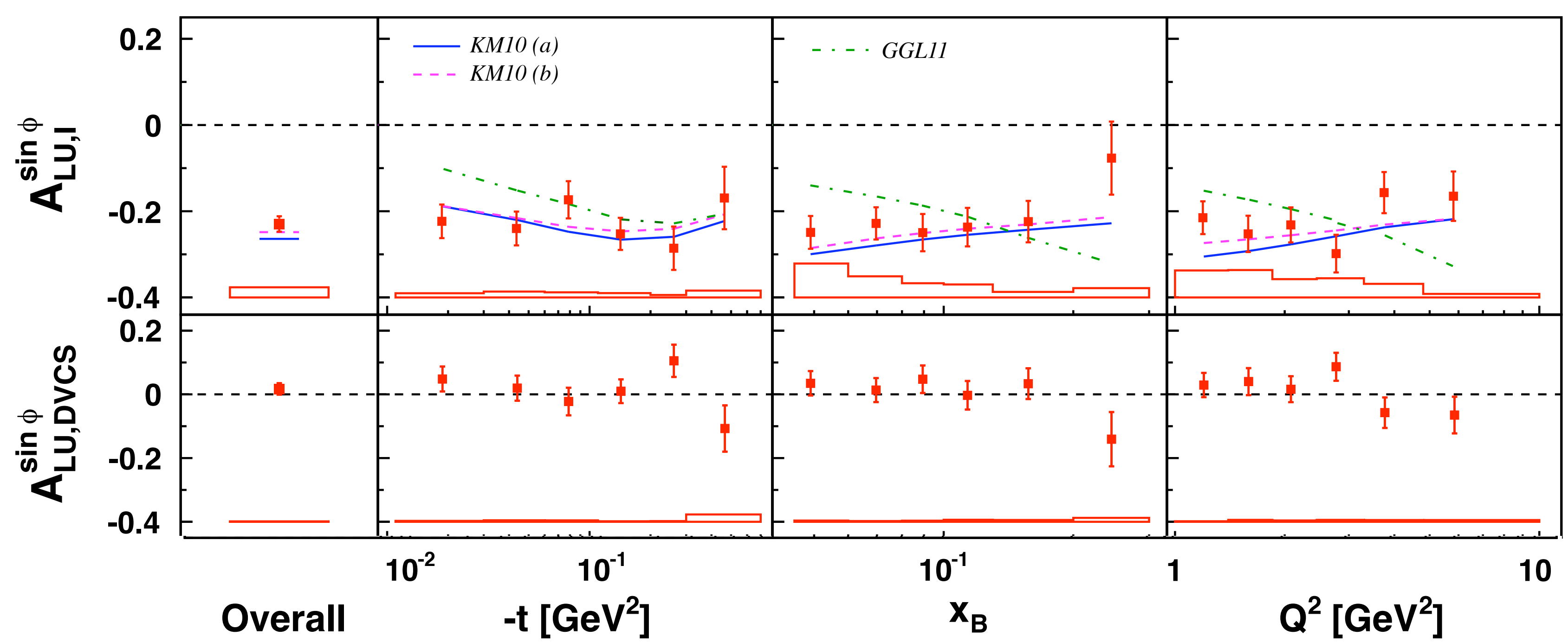
$\propto \mathcal{R}e[F_1\mathcal{H}]$

Fractions of associated process from MC

$$\mathcal{A}_{LU}^{I,DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) \pm (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}$$

Charge-difference beam-helicity asymmetry
- significant negative value of the leading amplitude
- no kinematic dependencies

$\propto \mathcal{I}m[F_1\mathcal{H}]$



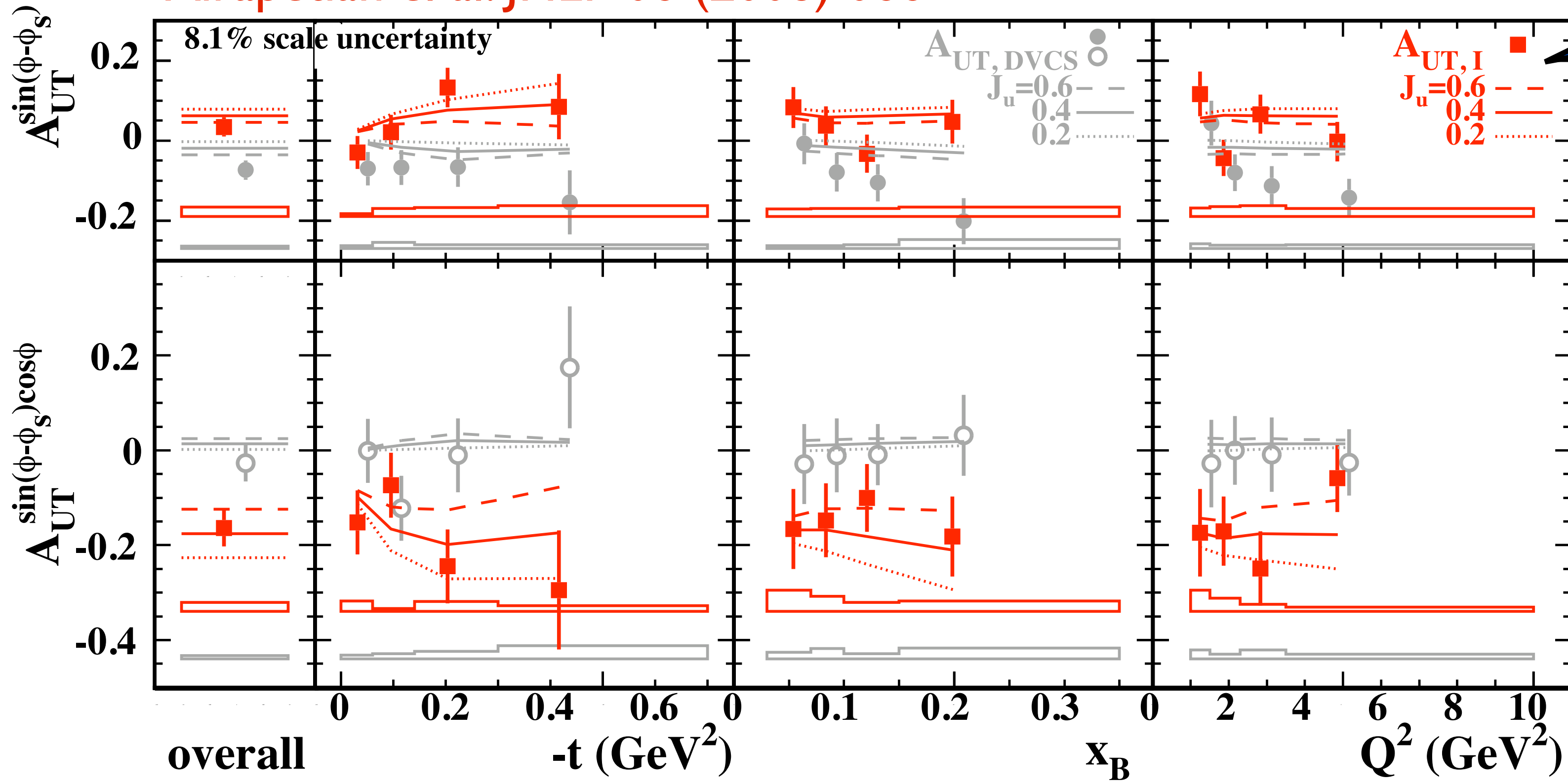
Charge-averaged beam-helicity asymmetry
- consistent with zero

$\propto \mathcal{I}m[\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$

Transverse Target-Spin Asymmetries

$$\mathcal{A}_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow} - \sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow} - \sigma^{-\Downarrow})}{(\sigma^{+\Uparrow} + \sigma^{+\Downarrow}) + (\sigma^{-\Uparrow} + \sigma^{-\Downarrow})}$$

Airapetian el al. JHEP 06 (2008) 066



VGG: Model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

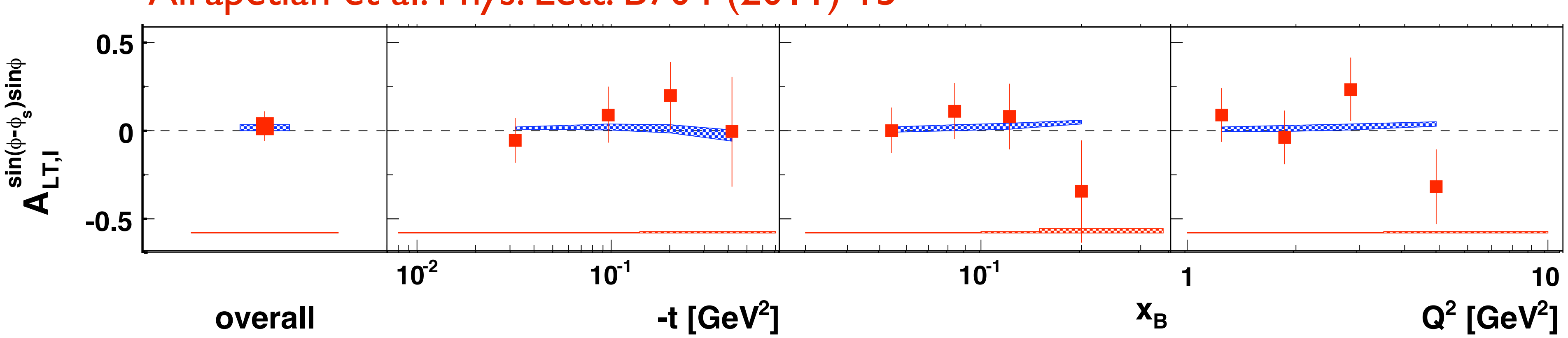
Charge-difference Transverse Target-Spin asymmetry
- Non-zero leading cos(nϕ) amplitudes.

$$\propto \begin{array}{l} \mathcal{I}m\left[F_2\mathcal{H} - F_1\mathcal{E}\right] \\ \mathcal{I}m\left[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* - \xi(\widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^* - \widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*)\right] \end{array}$$

Leading cos(ϕ) amplitude of charge difference target-spin asymmetry A^I_{UT} is sensitive to CFF $\mathcal{E}$, therefore J_u.

$$\mathcal{A}_{LT}^{I}(\phi,\phi_S) = \frac{(\overrightarrow{\sigma}^{+\Uparrow} + \overleftarrow{\sigma}^{+\Downarrow} - \overrightarrow{\sigma}^{+\Downarrow} - \overleftarrow{\sigma}^{+\Uparrow}) - (\overrightarrow{\sigma}^{-\Uparrow} + \overleftarrow{\sigma}^{-\Downarrow} - \overrightarrow{\sigma}^{-\Downarrow} - \overleftarrow{\sigma}^{-\Uparrow})}{(\overrightarrow{\sigma}^{+\Uparrow} + \overleftarrow{\sigma}^{+\Downarrow} + \overrightarrow{\sigma}^{+\Downarrow} + \overleftarrow{\sigma}^{+\Uparrow}) + (\overrightarrow{\sigma}^{+\Uparrow} + \overleftarrow{\sigma}^{+\Downarrow} + \overrightarrow{\sigma}^{+\Downarrow} + \overleftarrow{\sigma}^{+\Uparrow})}$$

Airapetian et al. Phys. Lett. B704 (2011) 15

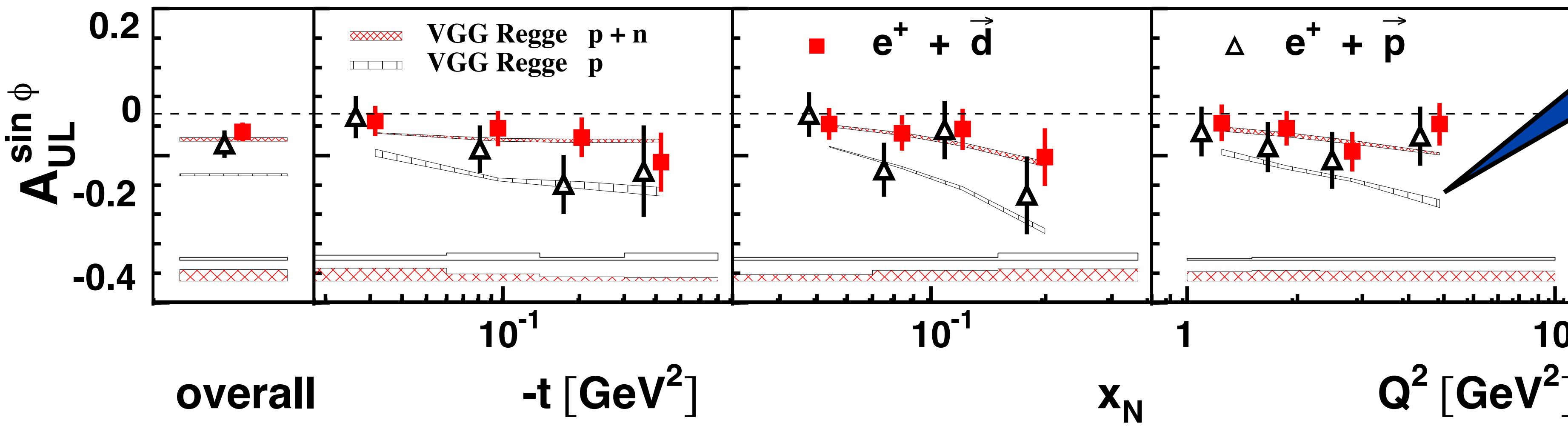


Charge-difference Transverse Double-Spin asymmetry
- leading amplitudes are consistent with zero
- sensitivity to J_u is suppressed by kinematic pre- factor

$$\propto \mathcal{R}e\left[F_2\mathcal{H} - F_1\mathcal{E}\right]$$

Longitudinal Target-Spin Asymmetries

$$\mathcal{A}_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$



VGG: Model calculation
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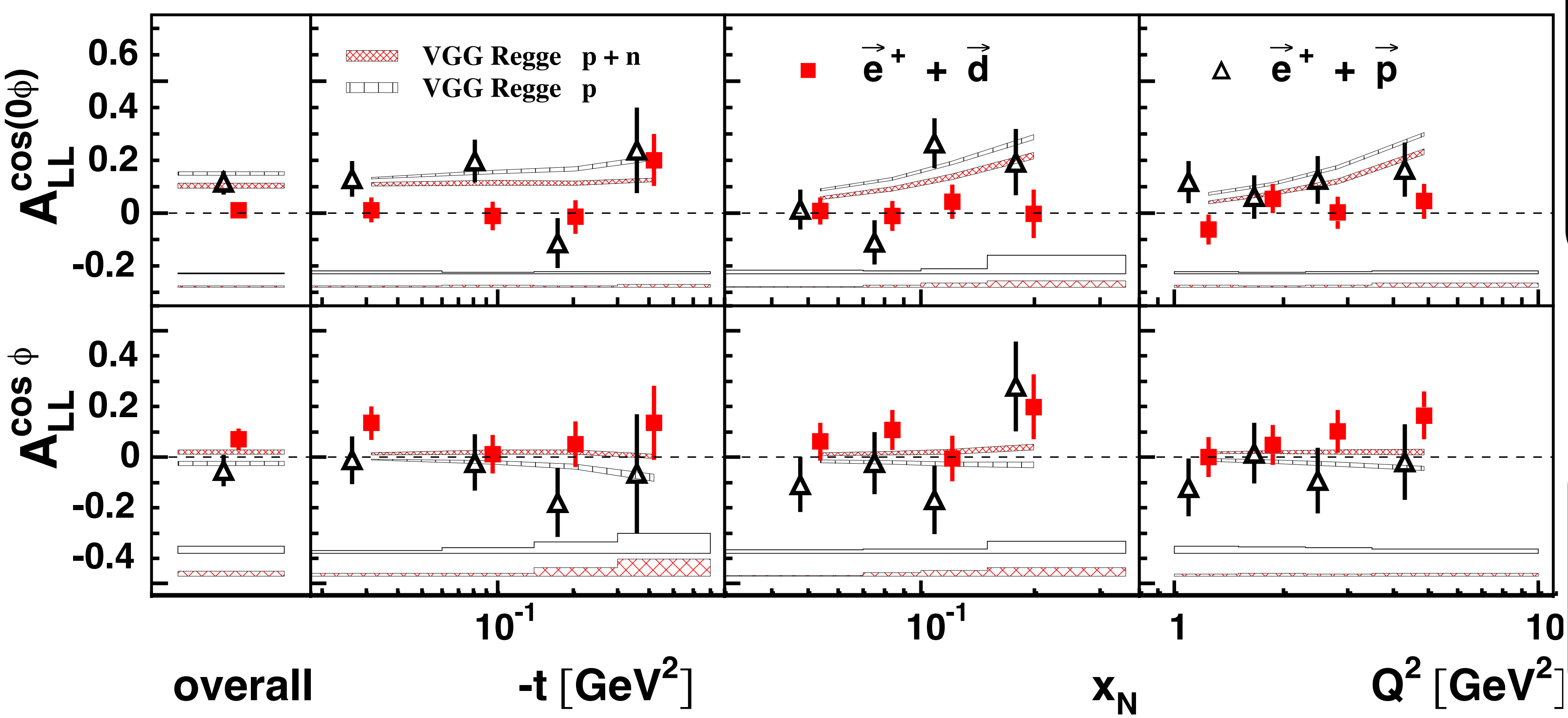
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

$\propto \mathcal{I}m[F_1\widetilde{\mathcal{H}}]$

$$\mathcal{A}_{LL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}$$



Longitudinal Target-Spin asymmetry

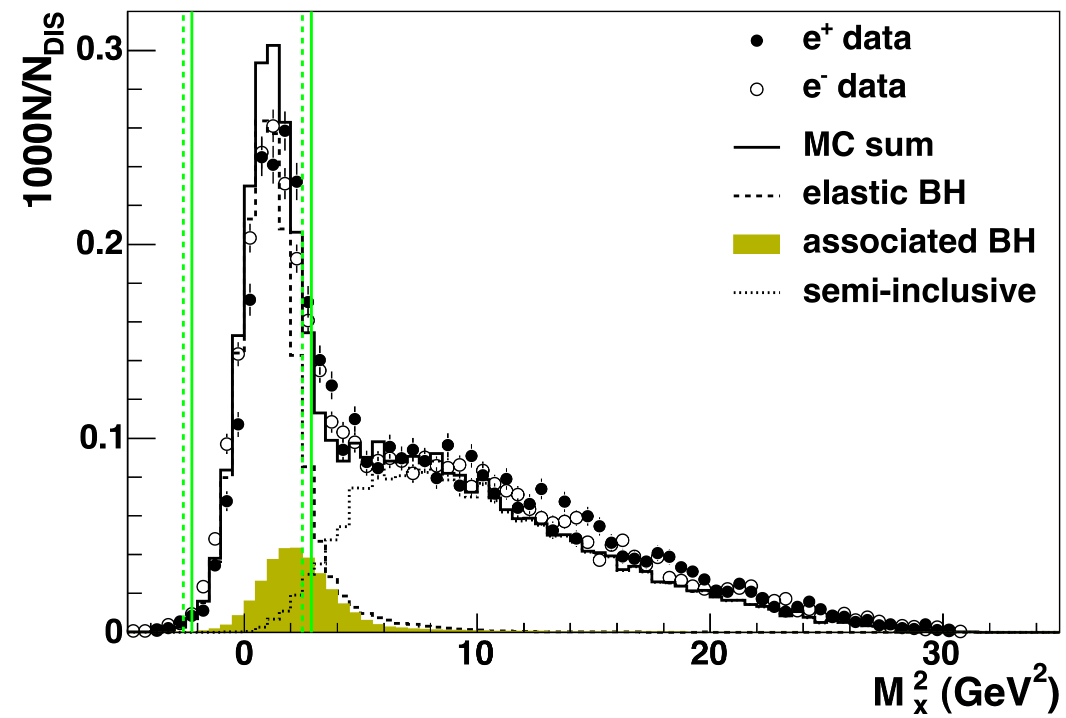
- Non-zero negative value of leading sin(ϕ) amplitude on both targets.
- Results on deuteron neither support nor disfavor large contribution from neutron, predicted by the model.
- Results on proton and deuteron targets are compatible.

$\propto \mathcal{R}e[F_1\widetilde{\mathcal{H}}]$

Asymmetry amplitudes are attributed not only to squared DVCS and Interference terms but also to squared BH term

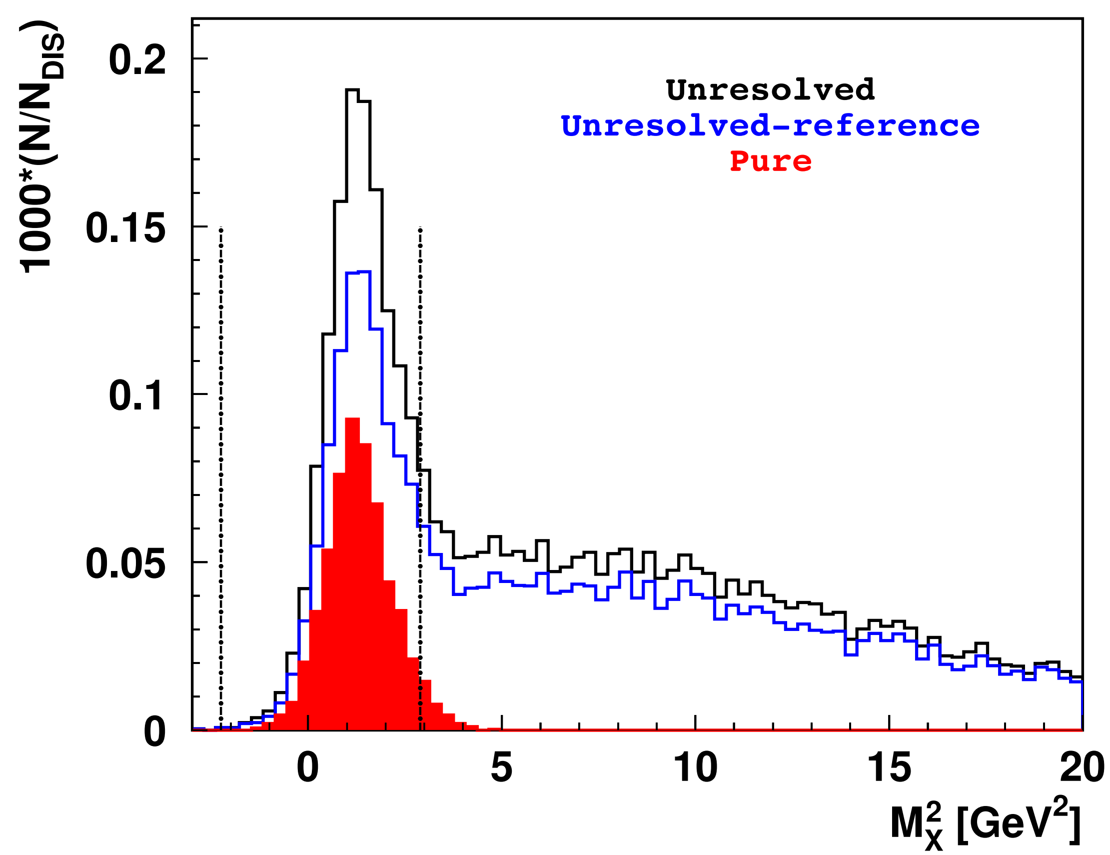
Measurements with Recoil Detection

- Events with one DIS lepton and one trackless cluster in the calorimeter.
- "***Unresolved***" for associated process $ep \rightarrow e\Delta^{+}\gamma$ ≈12 %



- "***Unresolved reference***" sample.
- "Hypothetical" proton required in the Recoil Detector acceptance.

- "***Pure Elastic***" sample.
- Kinematic event fitting technique. Allows to achieve purity > 99.9 %

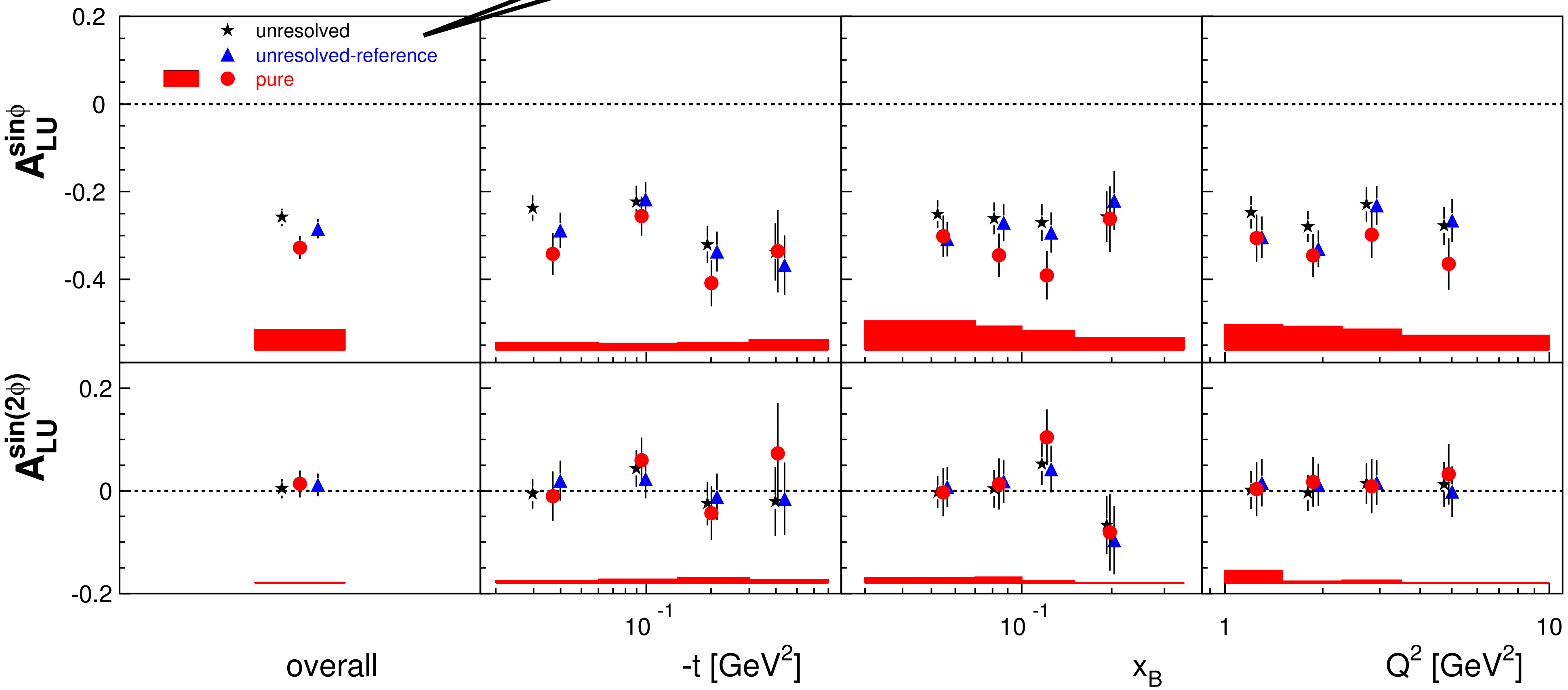


Beam-Helicity Asymmetry (Recoil Measurement)

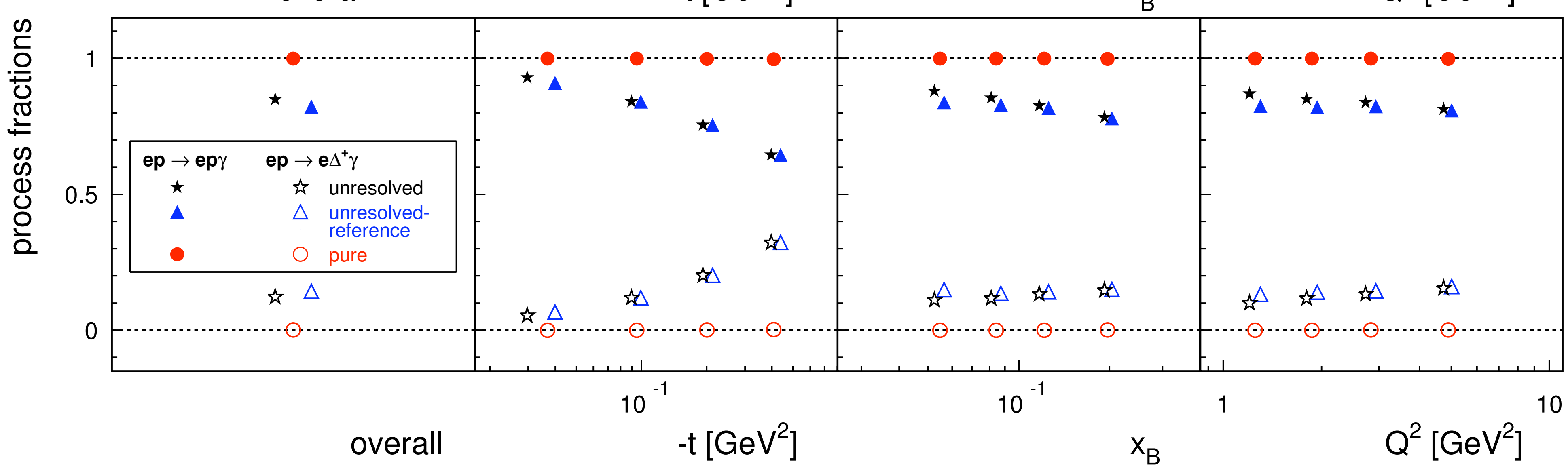
$$\mathcal{A}_{LU}(\phi) = \frac{\sigma^{+\rightarrow} - \sigma^{+\leftarrow}}{\sigma^{+\rightarrow} + \sigma^{+\leftarrow}}$$

Unresolved
Unresolved Reference
Pure Elastic

Airapetian el al. JHEP 10 (2014) 042



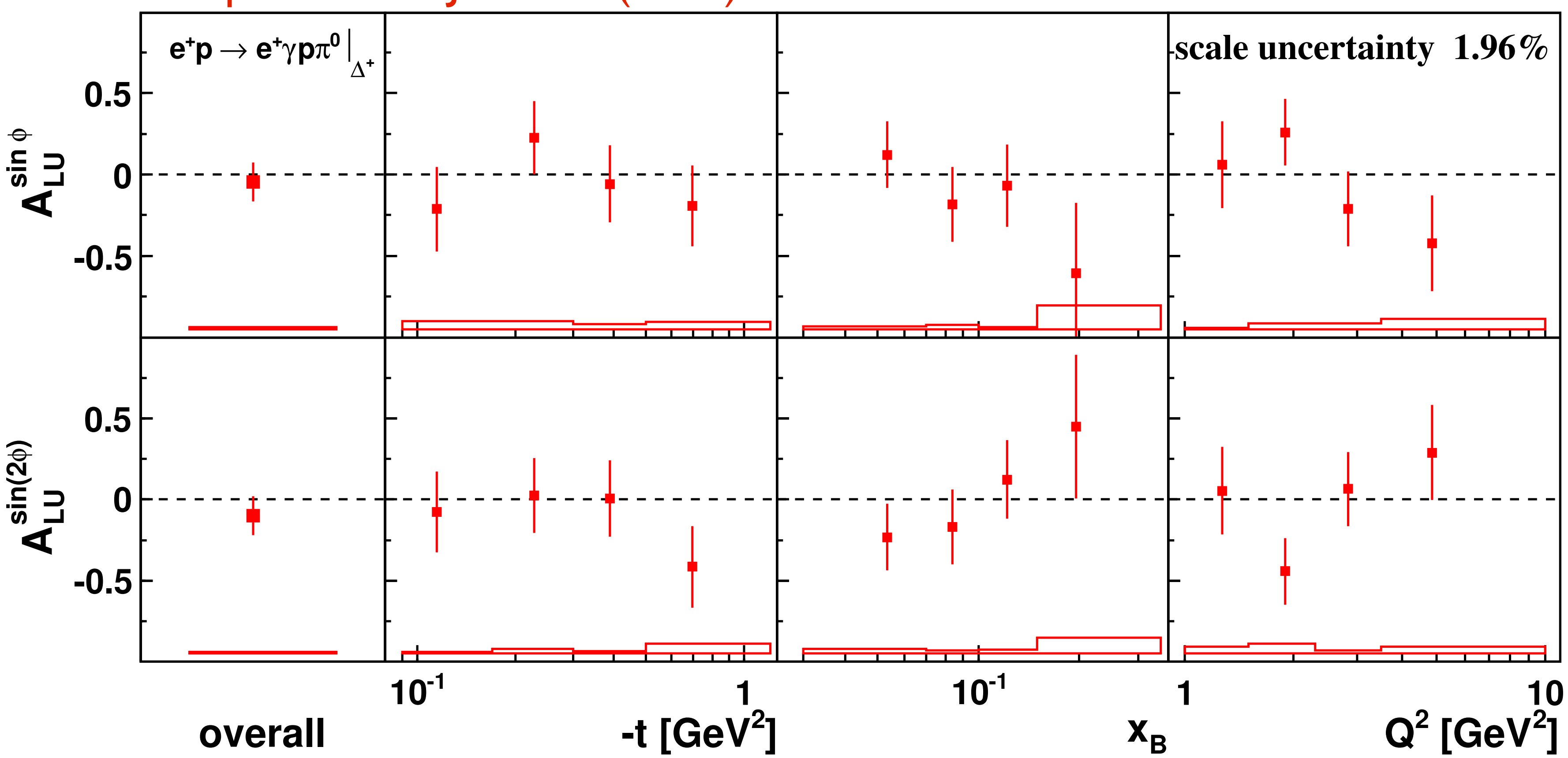
Indication of slightly larger magnitude of leading amplitude for pure elastic sample compared with reference sample

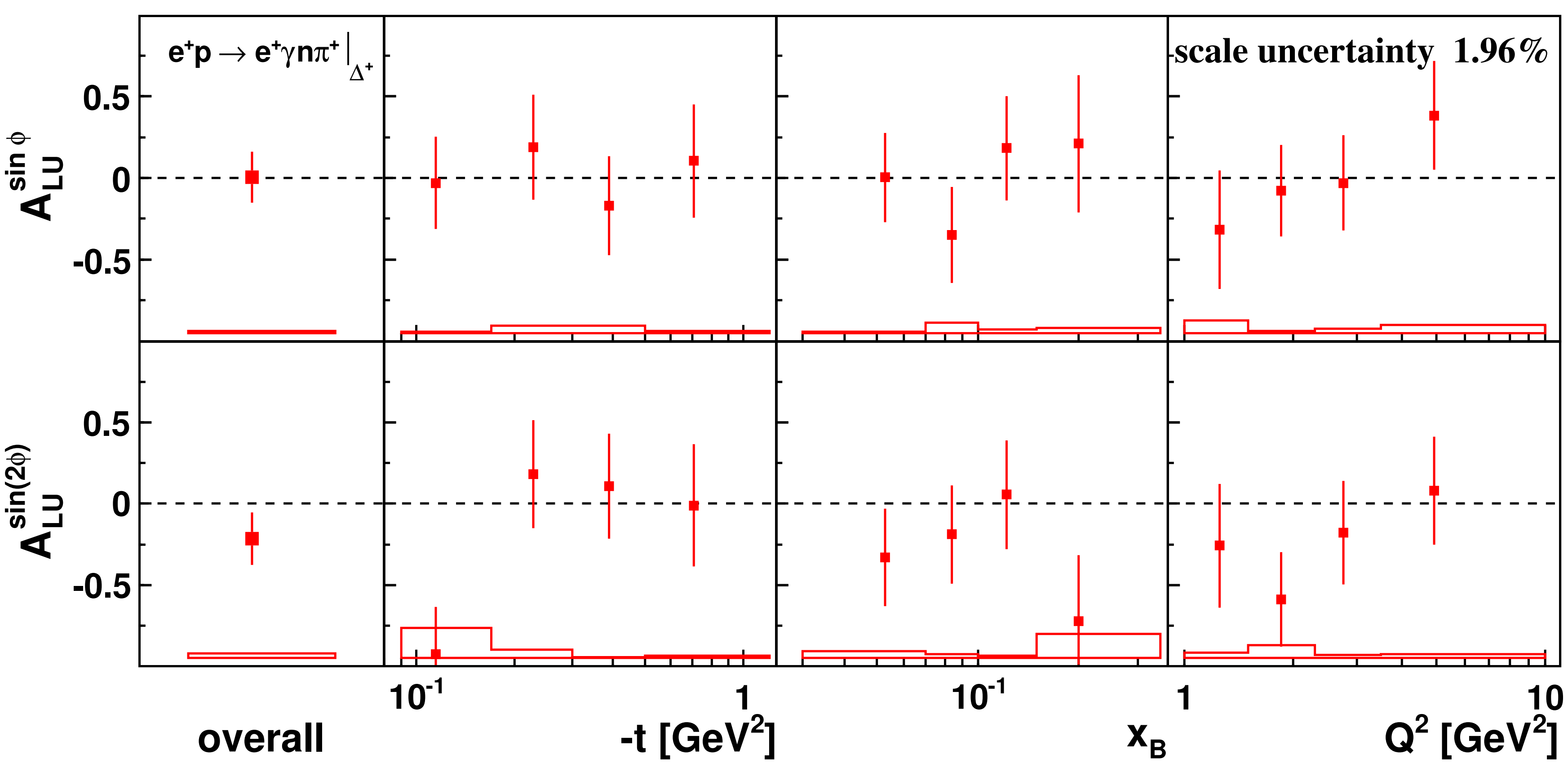


Fractional contributions of elastic and associated processes for different samples

Associated Process $e^+p \rightarrow e^+\gamma\Delta^+$

Airapetian el al. JHEP 01 (2014) 077





$$\mathcal{A}_{LU}(\phi) = \frac{\sigma^{+\rightarrow} - \sigma^{+\leftarrow}}{\sigma^{+\rightarrow} + \sigma^{+\leftarrow}}$$

$$e^+p \rightarrow e^+\gamma p\pi^0|_{\Delta^+}$$

Fractional contributions

- Associated DVCS/BH - 85 ± 1%
- Elastic DVCS/BH - 4.6 ± 0.1 %
- SIDIS - 11 ± 1 %

Asymmetry amplitudes are consistent with zero for both channels.

$$e^+p \rightarrow e^+\gamma n\pi^+|_{\Delta^+}$$

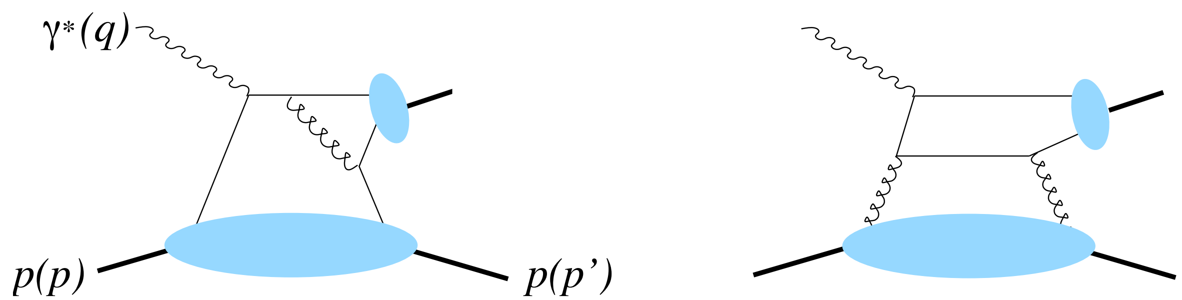
Fractional contributions

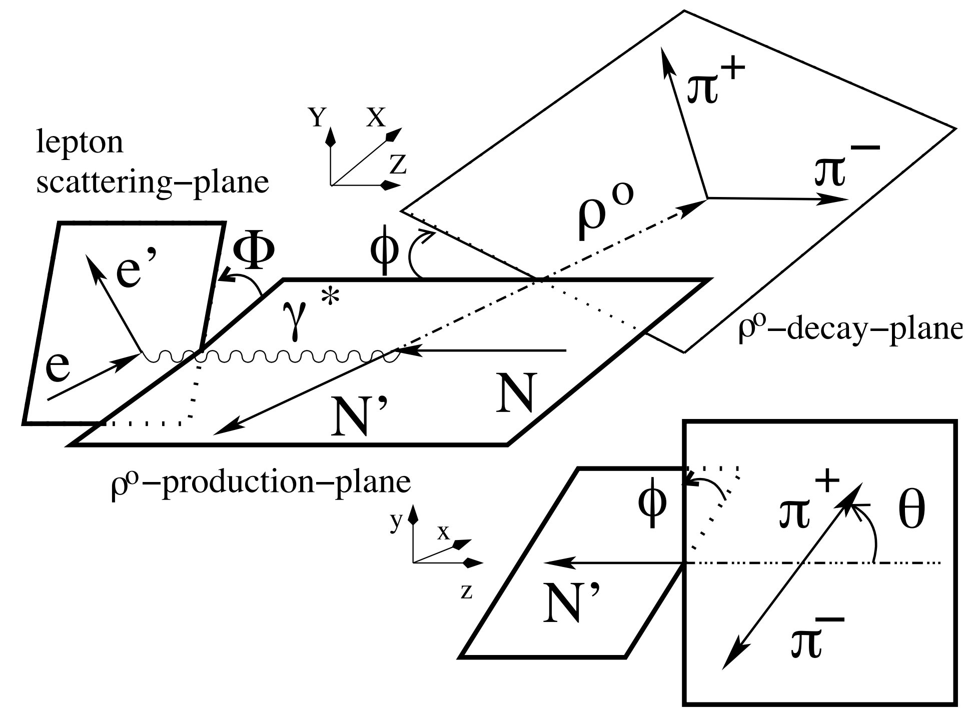
- Associated DVCS/BH - 77 ± 2%
- Elastic DVCS/BH - 0.2 ± 0.1 %
- SIDIS - 23 ± 3 %

Exclusive Vector Meson Production

pQCD description of the process.

I) dissociation of the virtual photon into quark-antiquark pair
II) scattering of a pair on a nucleon
III) formation of the observed vector meson





UPE GPDs $\widetilde{H}, \widetilde{E}$

NPE GPDs H, E

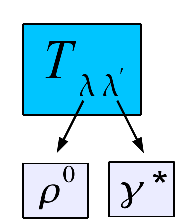
Cross Section

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

production and decay angular distribution: W decomposition

$$W = W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT}$$

parameterization in terms of helicity amplitudes

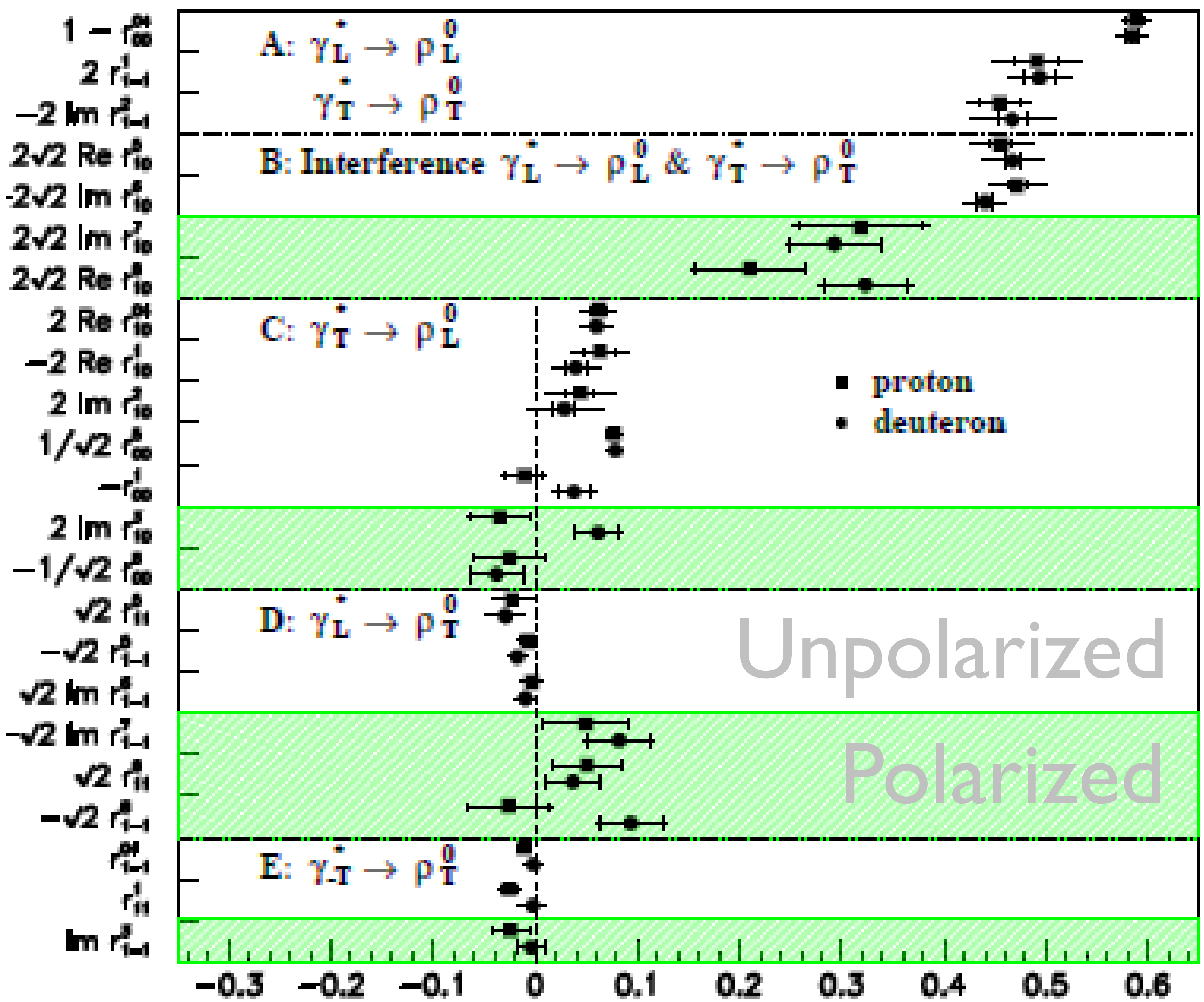


or SDMEs

-Schilling, Wolf (1973)
-Diehl (2007)

SDMEs ρ^0

$$|T_{00}| \sim |T_{11}| \gg |T_{01}| > |T_{10}| \geq |T_{1-1}|$$



- Selected hierarchy of NPE helicity amplitudes is confirmed
- No differences between proton and deuteron

$\gamma^*_L \to V_L$ && $\gamma^*_T \to V_T$ (Class A & B)

- SDMEs are significantly different from zero
- SDMEs of Class B are smaller than SDMEs of Class A

$\gamma^*_T \to V_L$ (Class C)

- some SDMEs are significantly different from zero (up to 10σ)
- Violation from SCHC

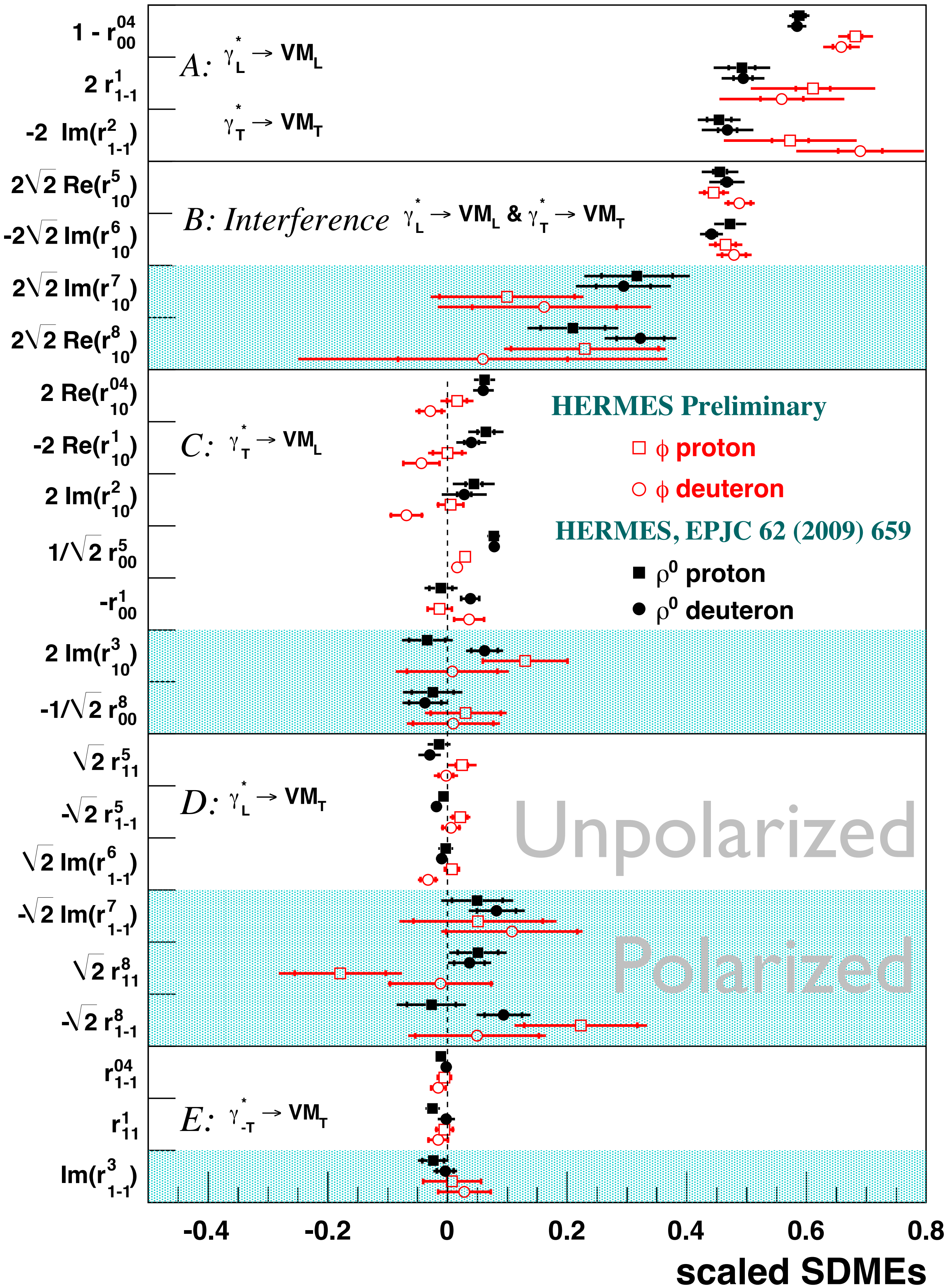
$\gamma^*_L \to V_T$ (Class D)

- Unpolarized SDMEs are slightly negative
- Polarized SDMEs are slightly positive

$\gamma^*_{-T} \to V_T$ (Class E)

- SDMEs on Deuteron are consistent with zero
- Small deviation from zero for SDMEs on hydrogen

SDMEs Φ



- Selected hierarchy of NPE helicity amplitudes is confirmed
- No significant differences between proton and deuteron

$\gamma^*_L \rightarrow V_L$ & $\gamma^*_T \rightarrow V_T$ (Class A & B)

- SDMEs are significantly different from zero
- 10-20% difference between ρ and ϕ SDMEs

$\gamma^*_T \rightarrow V_L$ (Class C)

- SDMEs are consistent with zero
- SDMEs on deuteron are slightly negative
- No strong indication of violation from SCHC

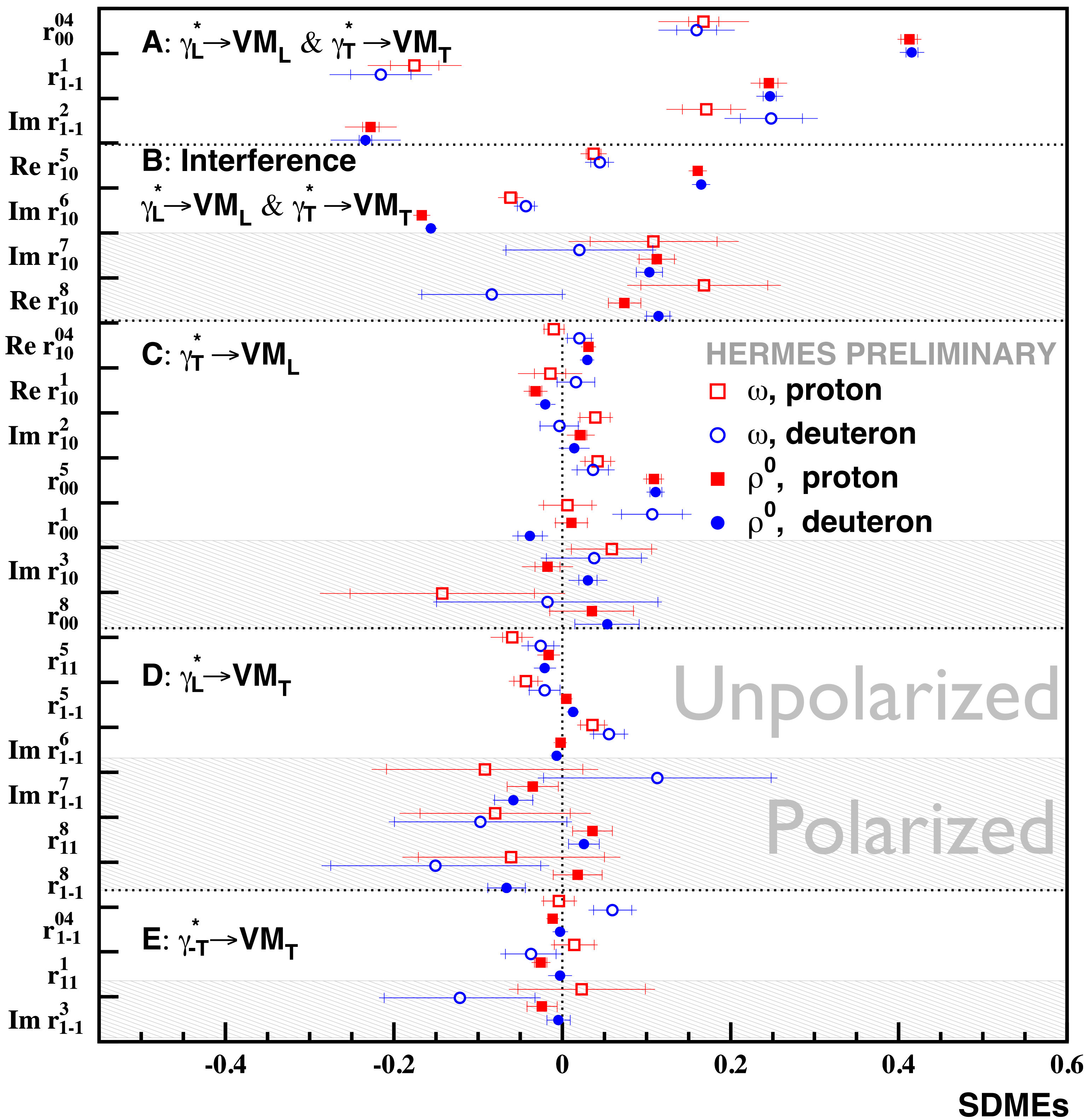
$\gamma^*_L \rightarrow V_T$ (Class D)

- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

$\gamma^*_{-T} \rightarrow V_T$ (Class E)

- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

SDMEs ω



- Selected hierarchy of NPE helicity amplitudes is not confirmed
- No differences between proton and deuteron

$\gamma^*_L \to V_L$ & $\gamma^*_T \to V_T$ (Class A & B)

- SDMEs are significantly different from zero
- Significant differences between ρ and ω SDMEs

$\gamma^*_T \to V_L$ (Class C)

- SDMEs are consistent with zero on both targets

$\gamma^*_L \to V_T$ (Class D)

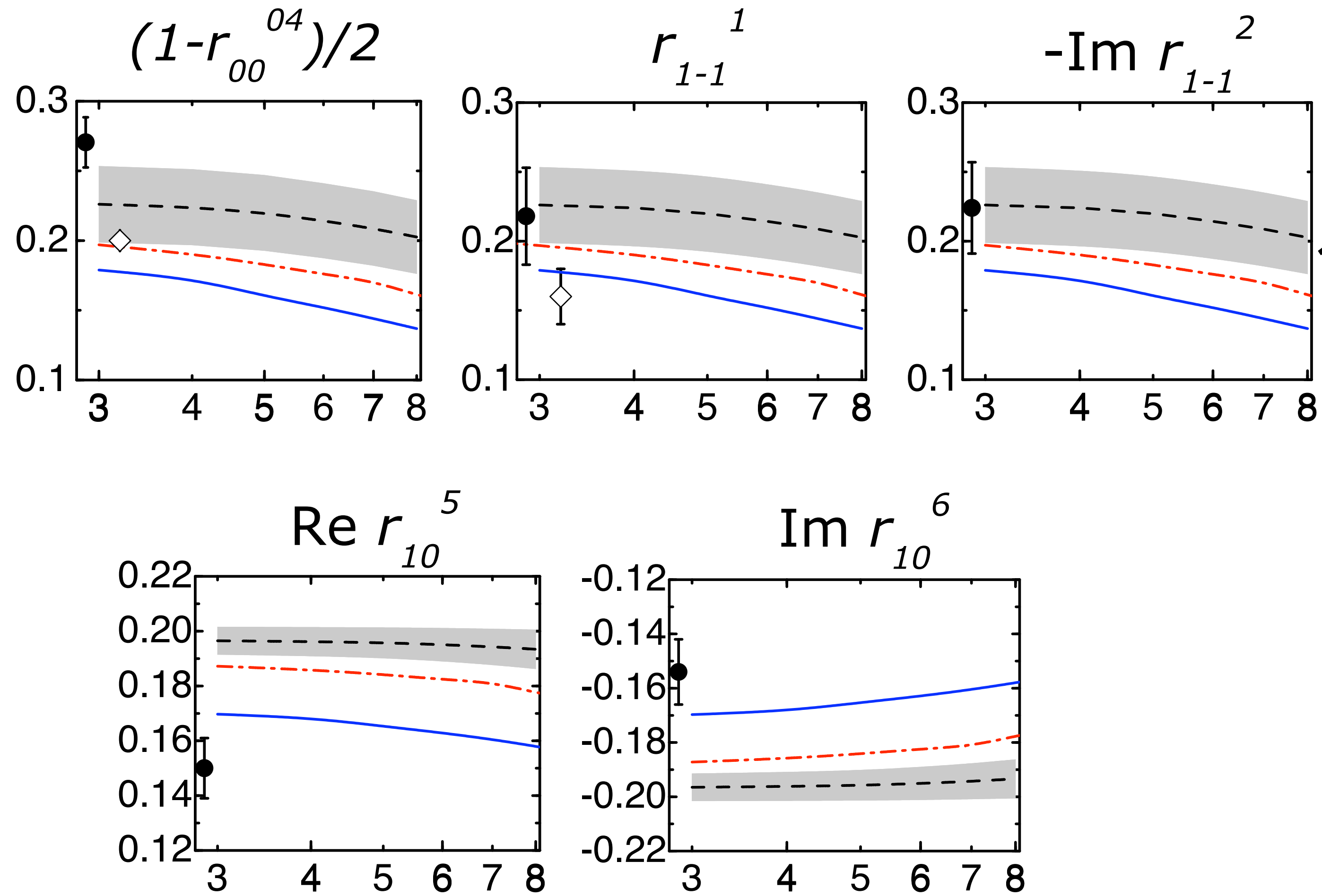
- Unpolarized SDMEs differ from zero
- Small evidence for violation from SCHC

$\gamma^*_{-T} \to V_T$ (Class E)

- Unpolarized and Polarized SDMEs are consistent with zero for both hydrogen and deuteron

Comparison with GPD models

GPD model: S.Goloskokov, P. Kroll (2008)



W=5 GeV (HERMES)
W=10 GeV (COMPASS)
W=90 GeV (H1,ZEUS)

$\gamma^*_L \to \rho^0_L$ & $\gamma^*_T \to \rho^0_T$

$$1 - r^{04}_{00}, r^1_{1-1}, -Imr^2_{1-1} \propto T_{11}$$

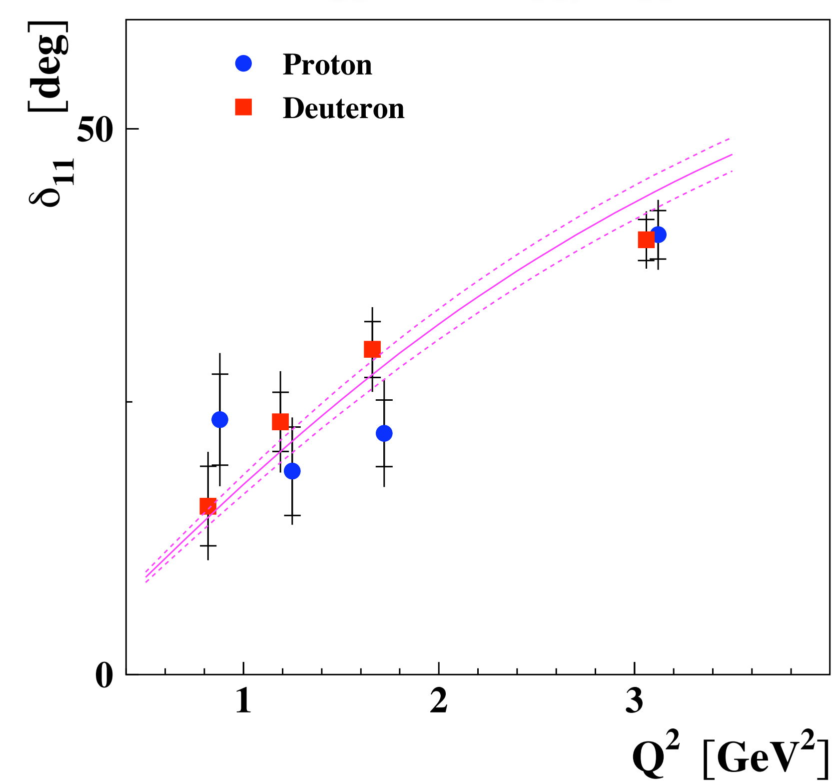
model is in agreement with data

interference $\gamma^*_L \to \rho^0_L$ & $\gamma^*_T \to \rho^0_T$

model dose not describe the data

model uses phase difference between T_{00} and T_{11}, δ_{11}=3.1 deg.

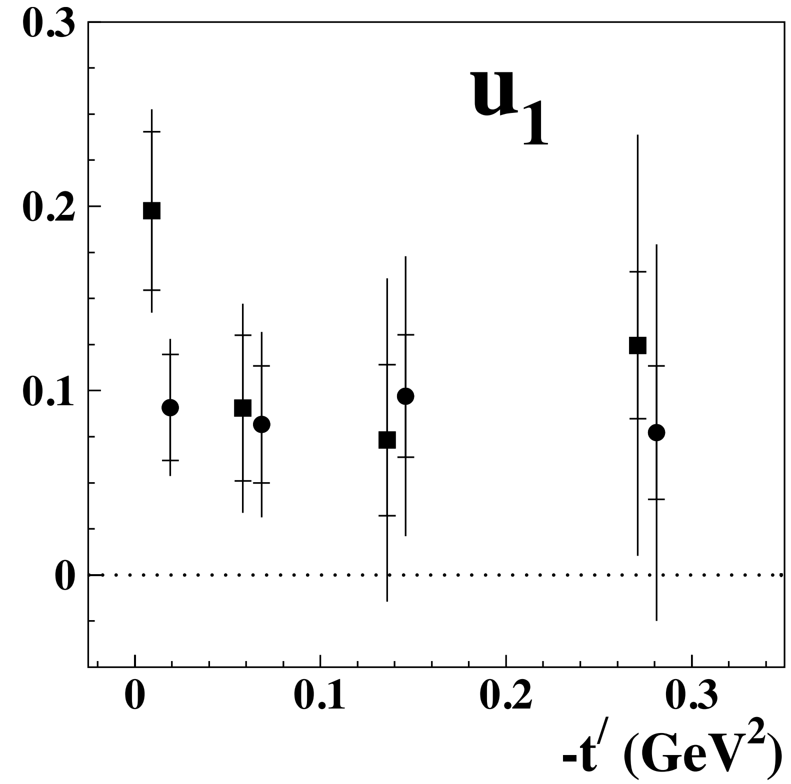
$$tan\,\delta_{11} = \frac{Im(T_{11}/T_{00})}{Re(T_{11}/T_{00})}$$



HERMES result δ_{11}=31.5 ± 1.4 deg.

Large phase difference was observed also by H1 (δ_{11}=20)

UPE Contribution ρ^0



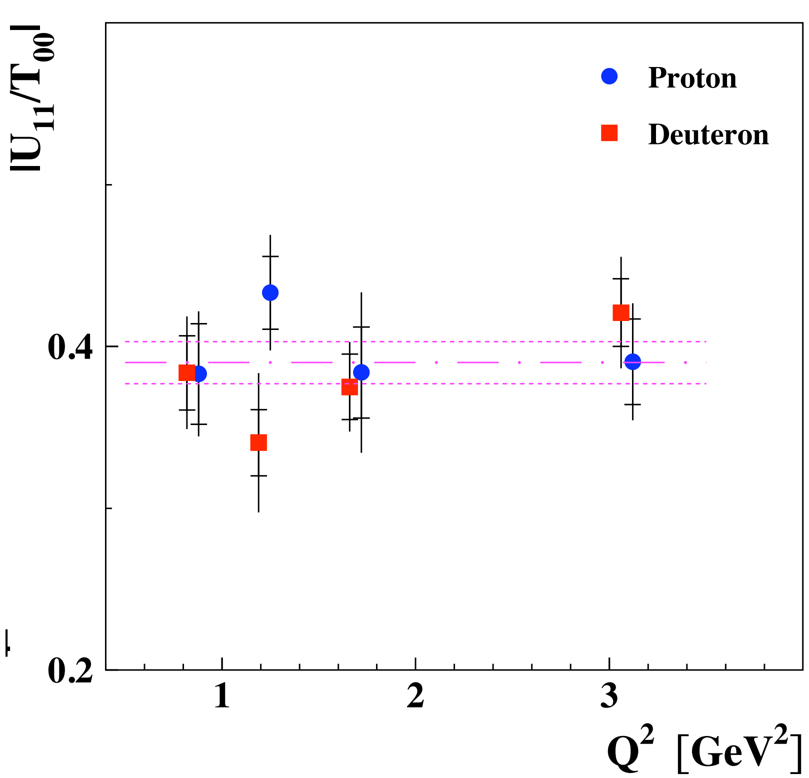
At large W^2 and Q^2 the transition should be suppressed by M/Q

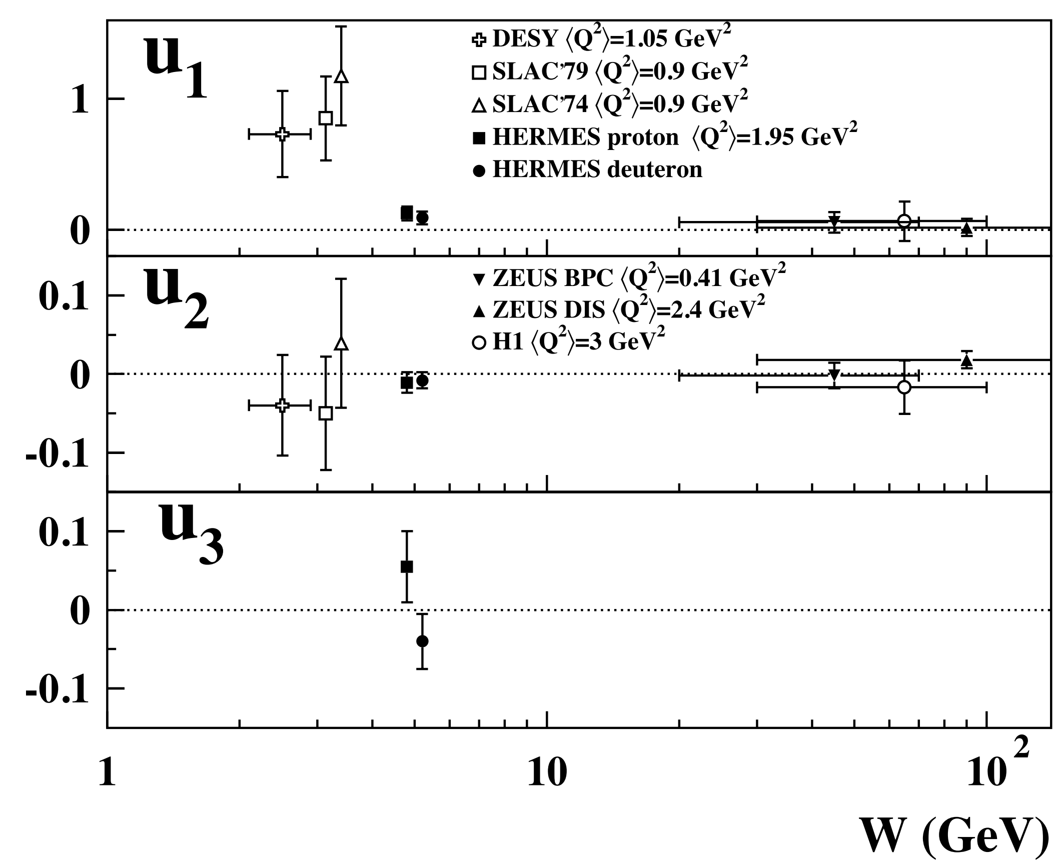
- direct helicity amplitude ratio analysis: U_{11}/T_{00}
- the combination of SDMEs is expected to be zero in case of NPE

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$$

$$u_2 = r^{5}_{11} + r^{5}_{1-1}$$

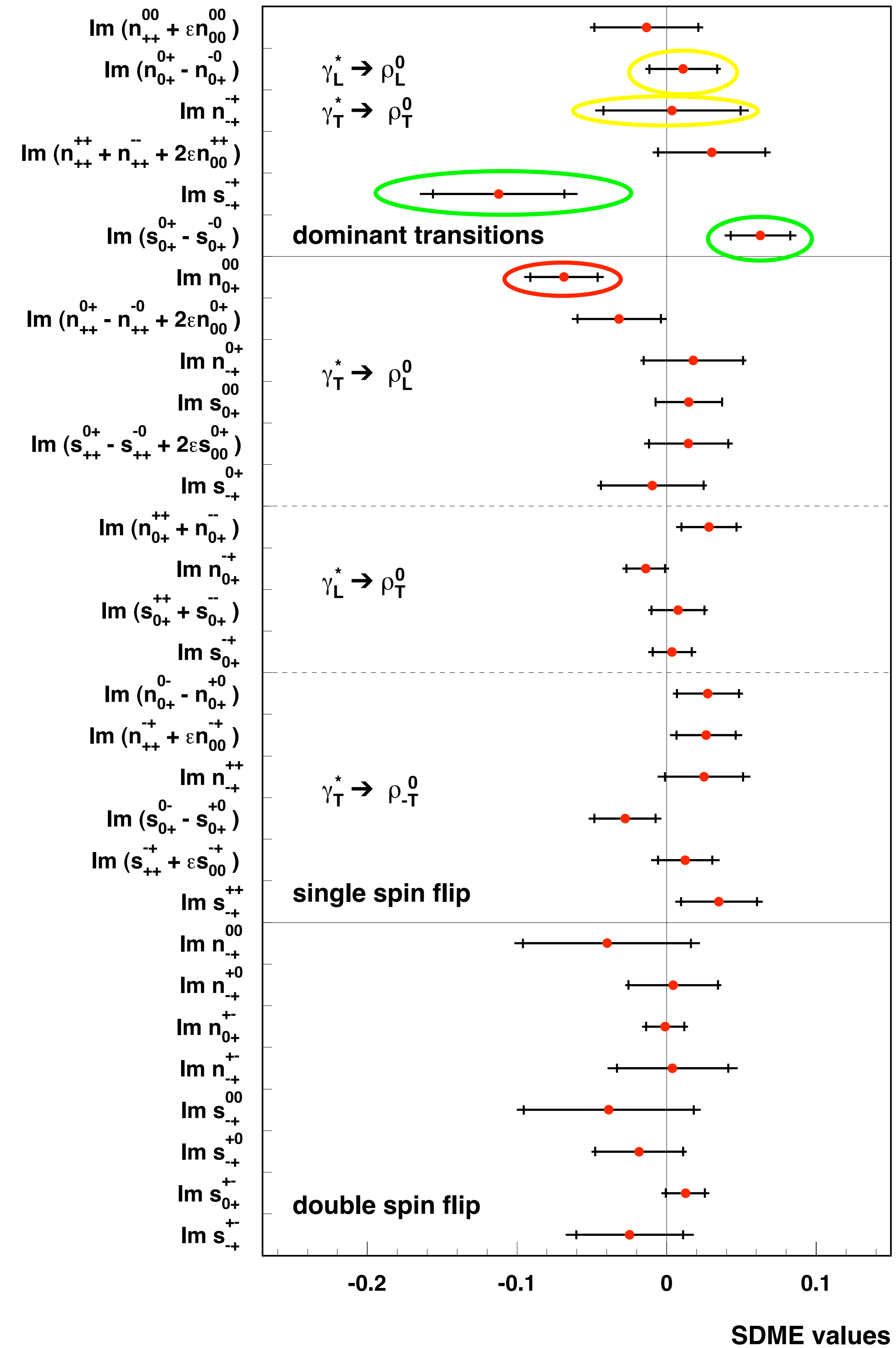
$$u_3 = r^{8}_{11} + r^{8}_{1-1}$$





Transverse SDMEs of ρ^0

- Most of the SDMEs are consistent with zero within 1.5σ
- SDMEs $\mathrm{Im}\,(s^{0+}_{0+} - s^{-0}_{0+})$, $\mathrm{Im}\,s^{-+}_{-+}$ and $\mathrm{Im}\,n^{00}_{0+}$ differ form zero by 2.5σ
- Non - zero value for SDME $\mathrm{Im}\,n^{00}_{0+}$ - violation from SCHC
- In case of NPE - expected $s^{\nu\nu'}_{\mu\mu'} < n^{\nu\nu'}_{\mu\mu'}$
- Non - zero values for SDMEs $\mathrm{Im}\,(s^{0+}_{0+} - s^{-0}_{0+})$ and $\mathrm{Im}\,s^{-+}_{-+}$ indicate a large contribution of UPE



Transverse SDMEs of ρ^0

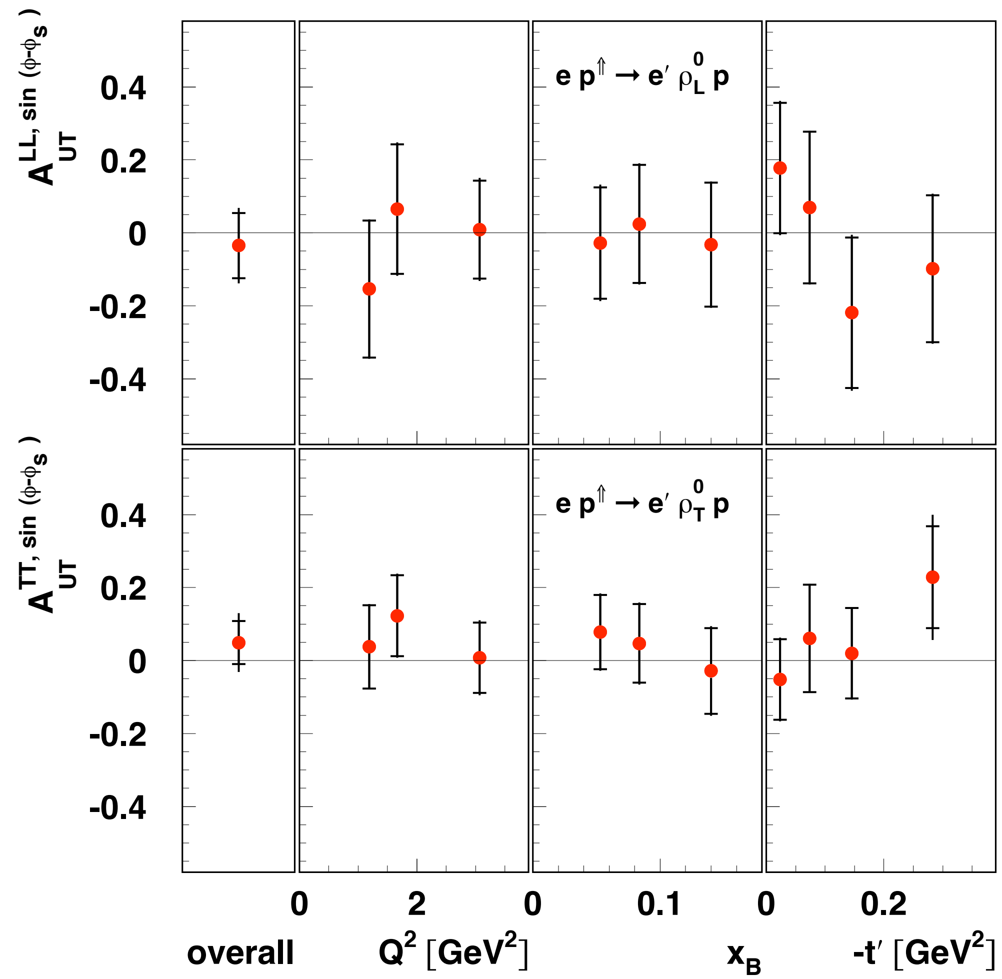
Transverse Target-Spin Asymmetry : ~ GPD E

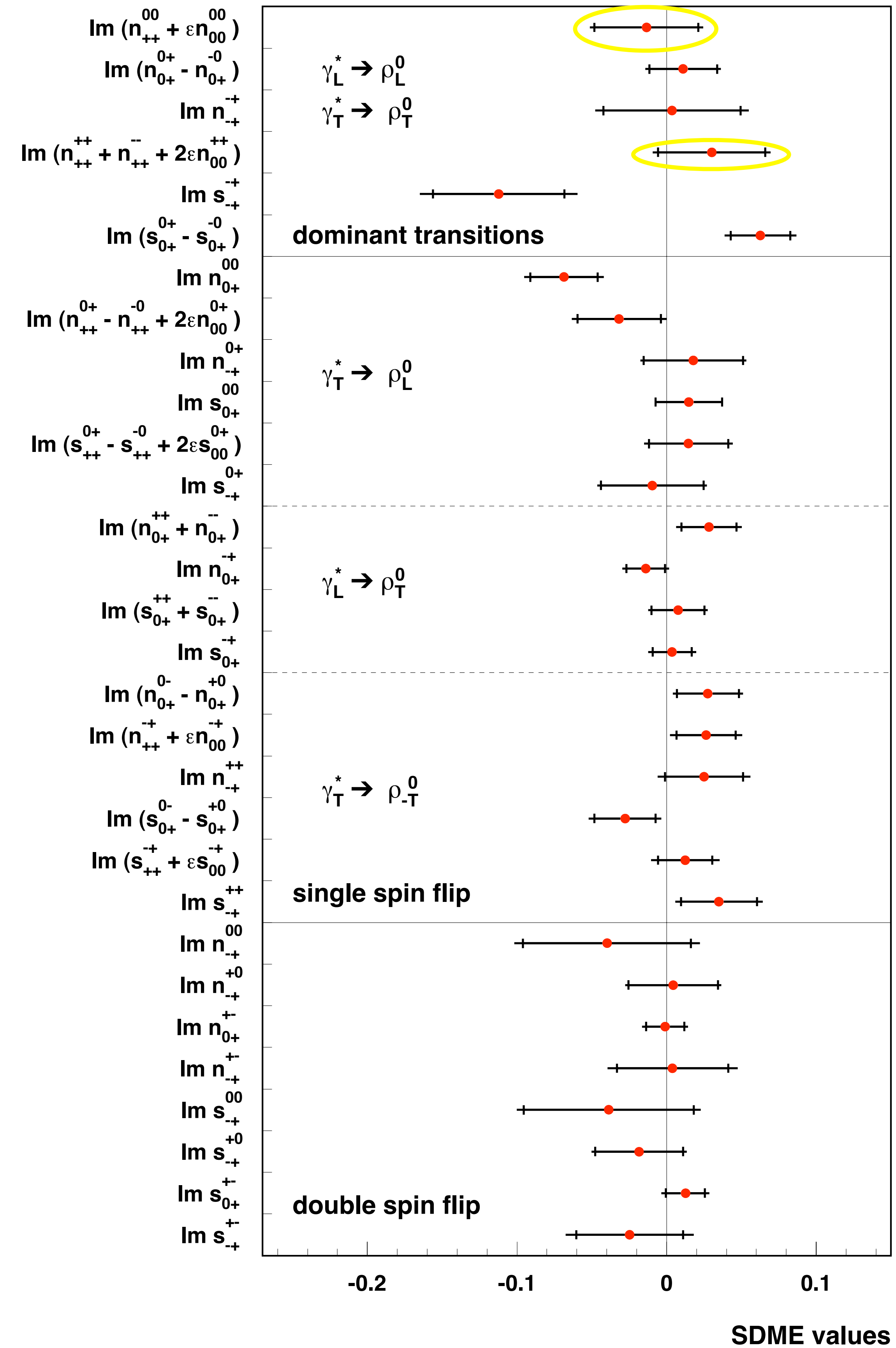
for L - L

$$A_{UT}^{LL,\sin(\phi-\phi_s)} = \frac{\mathbf{Im}(n_{00}^{++} + \epsilon n_{00}^{00})}{u_{++}^{00} + \epsilon u_{00}^{00}}$$

and T - T

$$A_{UT}^{TT,\sin(\phi-\phi_s)} = \frac{\mathbf{Im}(n_{++}^{++} + n_{++}^{--} + 2\epsilon n_{00}^{++})}{1 - (u_{++}^{00} + \epsilon u_{00}^{00})}$$





Results for R

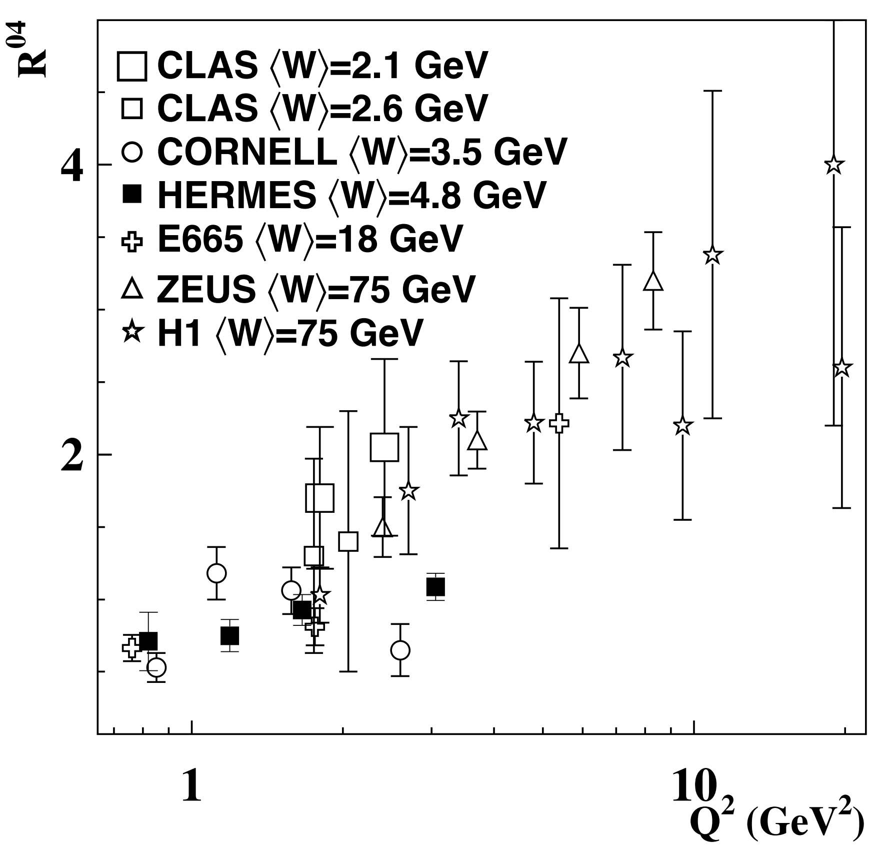
Commonly used observable $R^{04} = \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$

In case of SCHC and NPE $R^{04} = R = \sigma_L / \sigma_T$

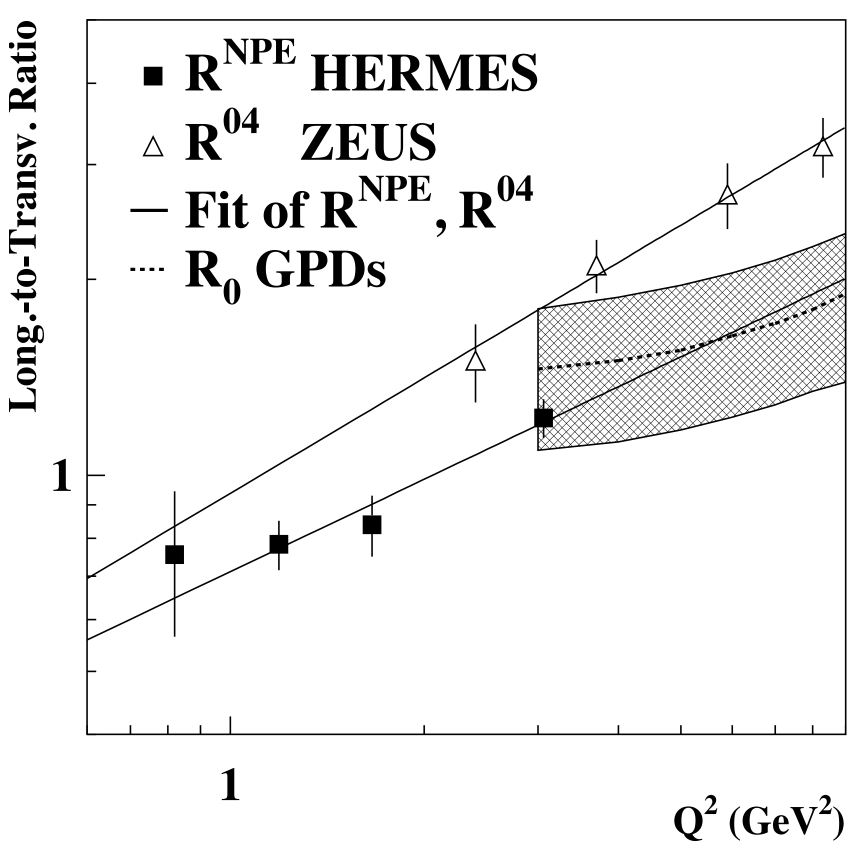
Strong W dependence for both - UPE contribution and ratio R

W dependence of the Q^2 slope can be studied $R(Q^2) = c_0 (\frac{Q^2}{M_V^2})^{c_1}$

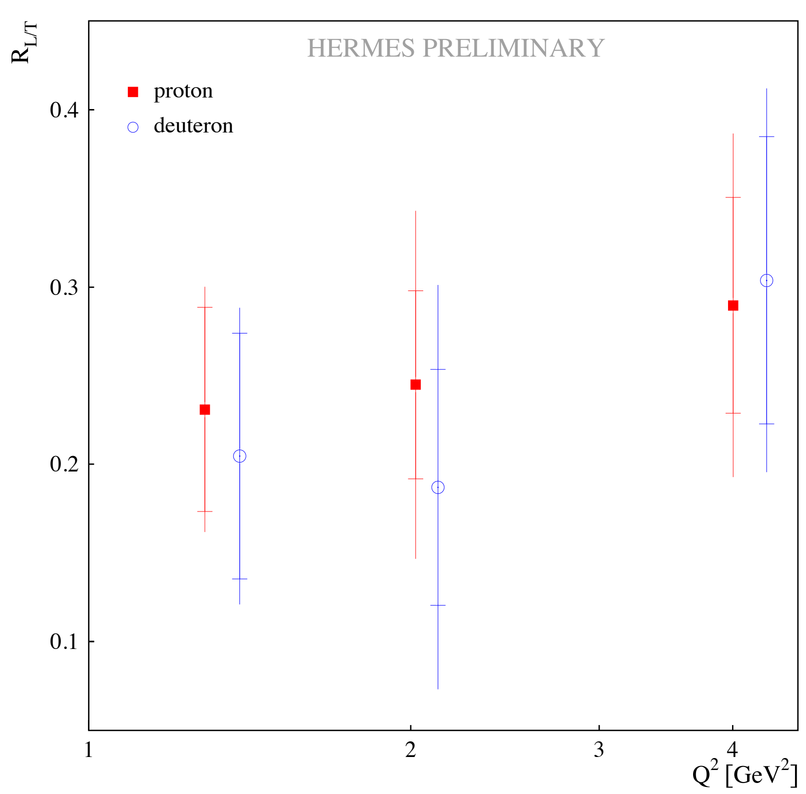
ρ^0



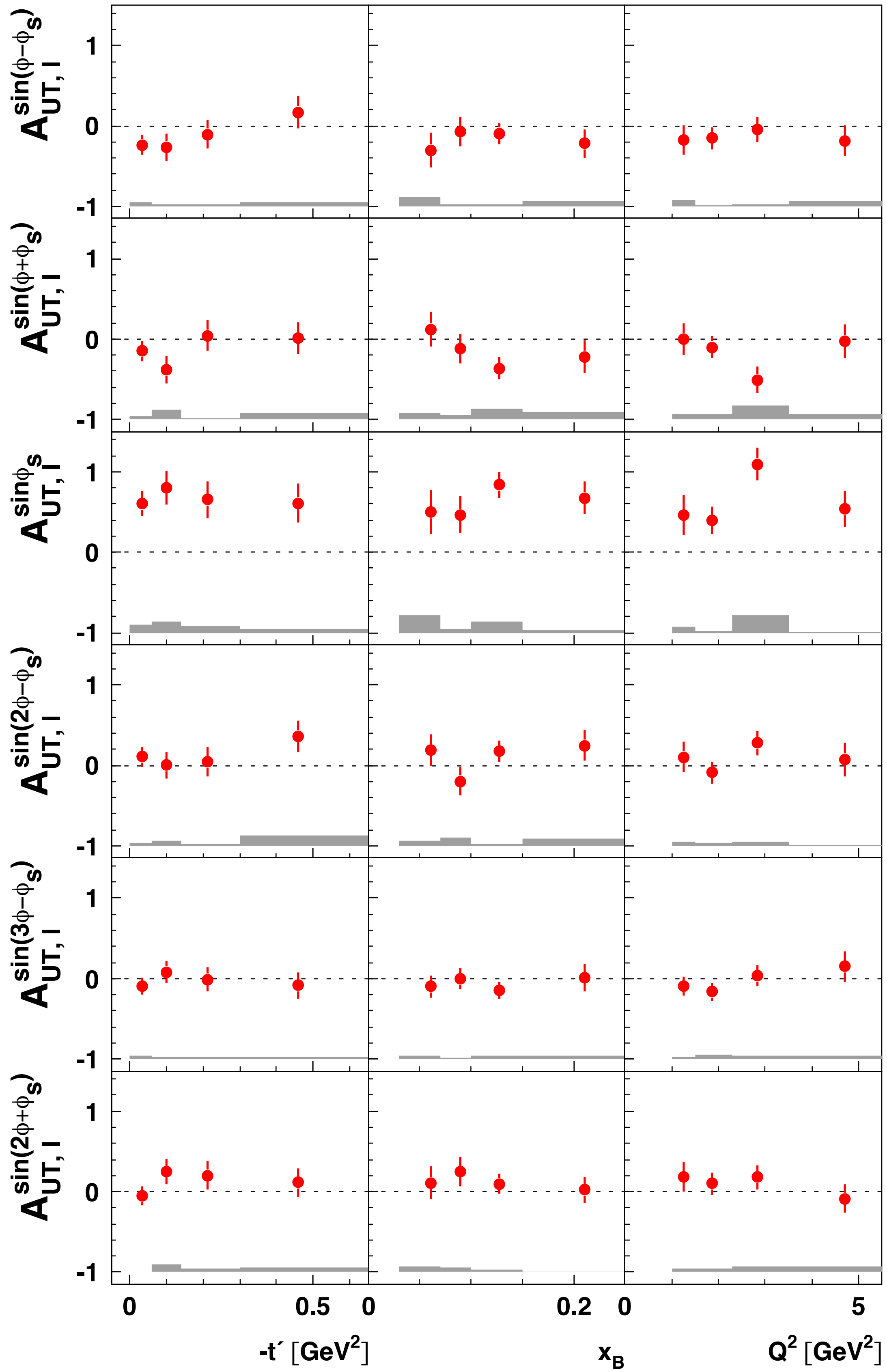
ρ^0



ω



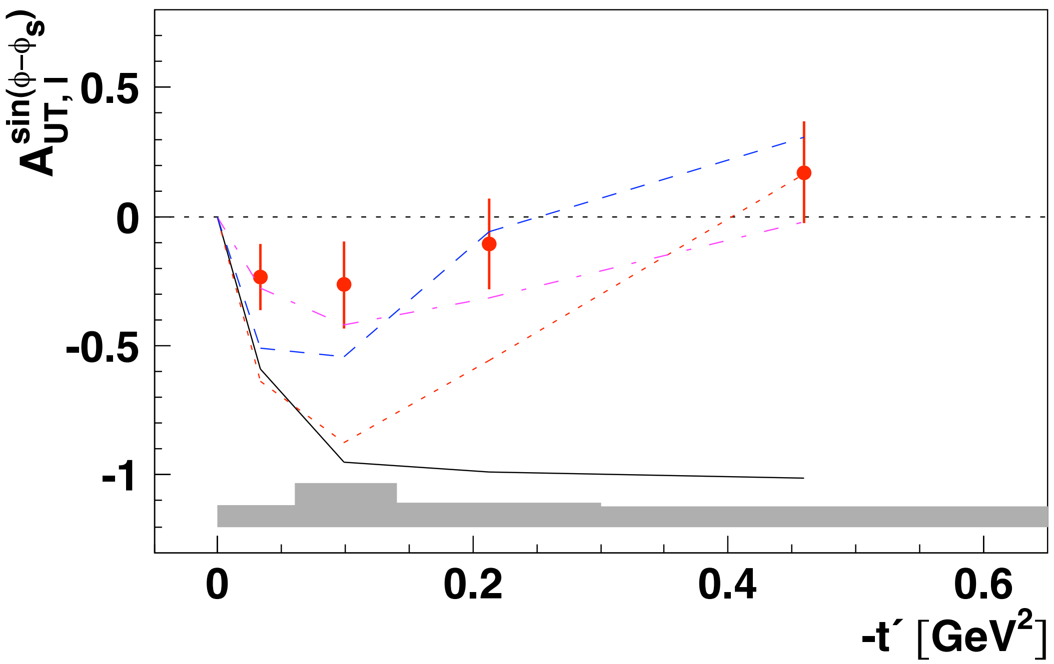
Exclusive π⁺ Production



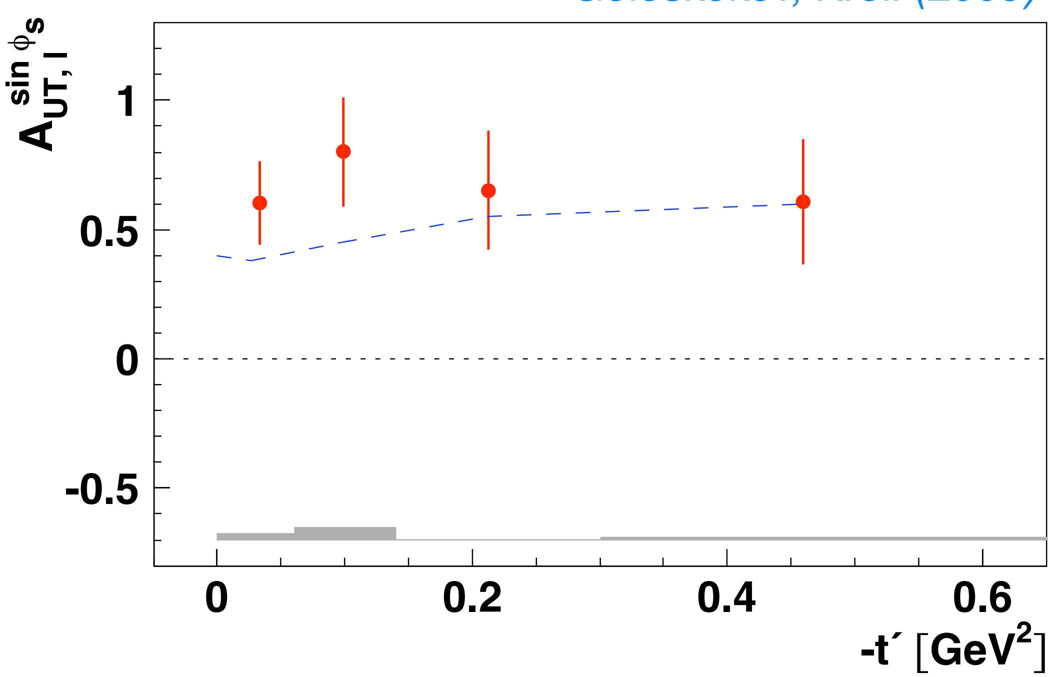
$$\mathcal{A}_{UT}(\phi,\phi_S) = \frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

- 6 azimuthal asymmetry amplitudes are measured
- no L/T separation
- small overall value for the leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_S)}$
- unexpectedly large value for the asymmetry amplitude $A_{UT}^{\sin(\phi_S)}$
- other amplitudes are consistent with zero
- evidence for contribution from transversally polarized photons

Exclusive π^+ Production



-Goloskokov, Kroll (2009)-



Leading amplitude $A_{UT}^{\sin(\phi-\phi_S)}$

- small asymmetry with possible sign change
- $A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\widetilde{\mathcal{E}} * \widetilde{\mathcal{H}})$
- theoretical expectation:

large negative value *Frankfurt et.al. (2001)*
Belitsky, Muller (2001)

- difference could be due the γ^*_T .

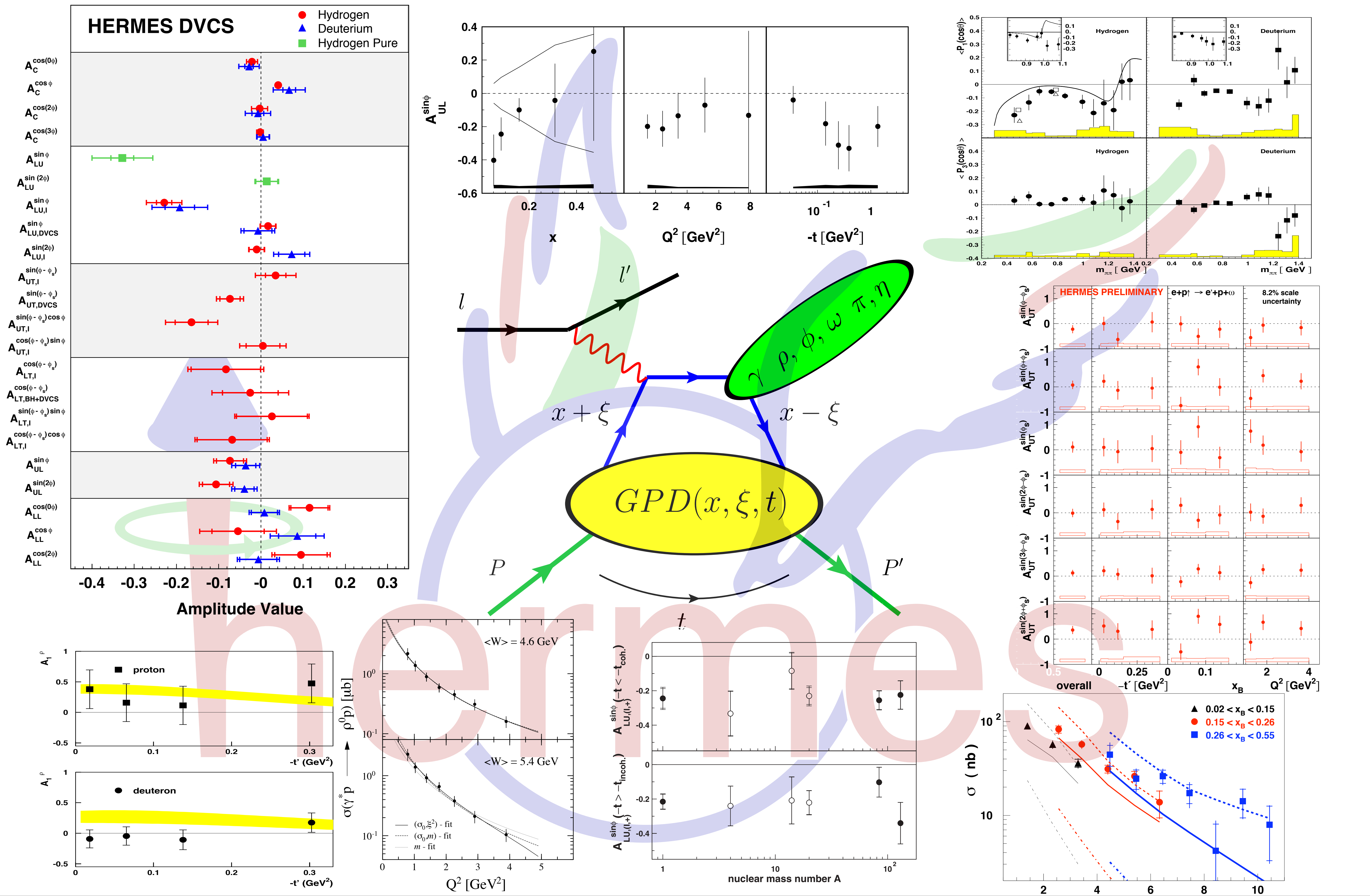
Goloskokov, Kroll (2009)
Bechler, Muller (2009)

amplitude $A_{UT}^{\sin(\phi_S)}$

- large positive value
- mild t' dependence
- does not vanish at -t'=0
- can be explained by a sizable interference

between contributions from γ^*_L and γ^*_T.

Summary


HERMES DVCS
Hydrogen
Deuterium
Hydrogen Pure
Amplitude Value
x
Q2 [GeV2]
-t [GeV2]
GPD(x, ξ, t)
γ ρ, φ, ω π, η
x + ξ
x − ξ
P
P′
t
Hydrogen
Deuterium
HERMES PRELIMINARY
e+p↑ → e′+p+ω
8.2% scale uncertainty
overall
−t′ [GeV2]
xB
proton
deuteron
<W> = 4.6 GeV
<W> = 5.4 GeV
nuclear mass number A
0.02 < xB < 0.15
0.15 < xB < 0.26
0.26 < xB < 0.55
hermes

Backup

No recoil detection

Small missing energy

$$\Delta E = \frac{M_x^2 - M^2}{2M} \approx 0$$

Small energy transfer to the target nucleon

$$t = (q - v)^2$$

Kinematic requirements

$$1 < Q^2 < 7 \quad GeV^2$$

$$-t' < 0.4 \quad GeV^2$$

$$3 < W < 6.3\, GeV$$

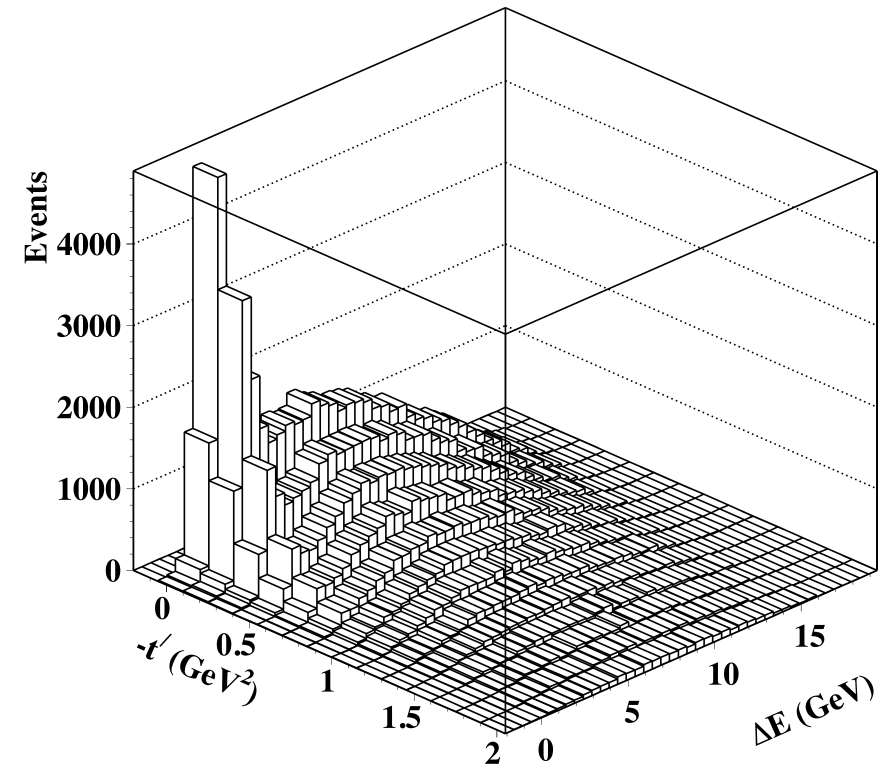
$$-1.0 < \Delta E < 0.6 \quad GeV$$

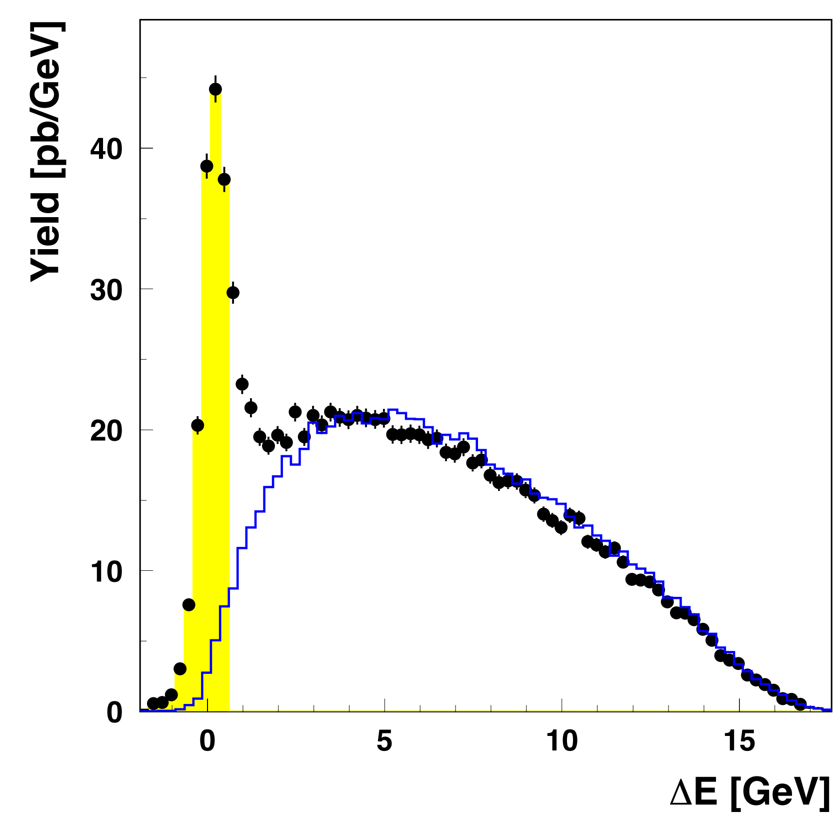
Invariant mass of hadronic system

ρ⁰ $0.6 < M_{\pi\pi} < 1.0\, GeV$

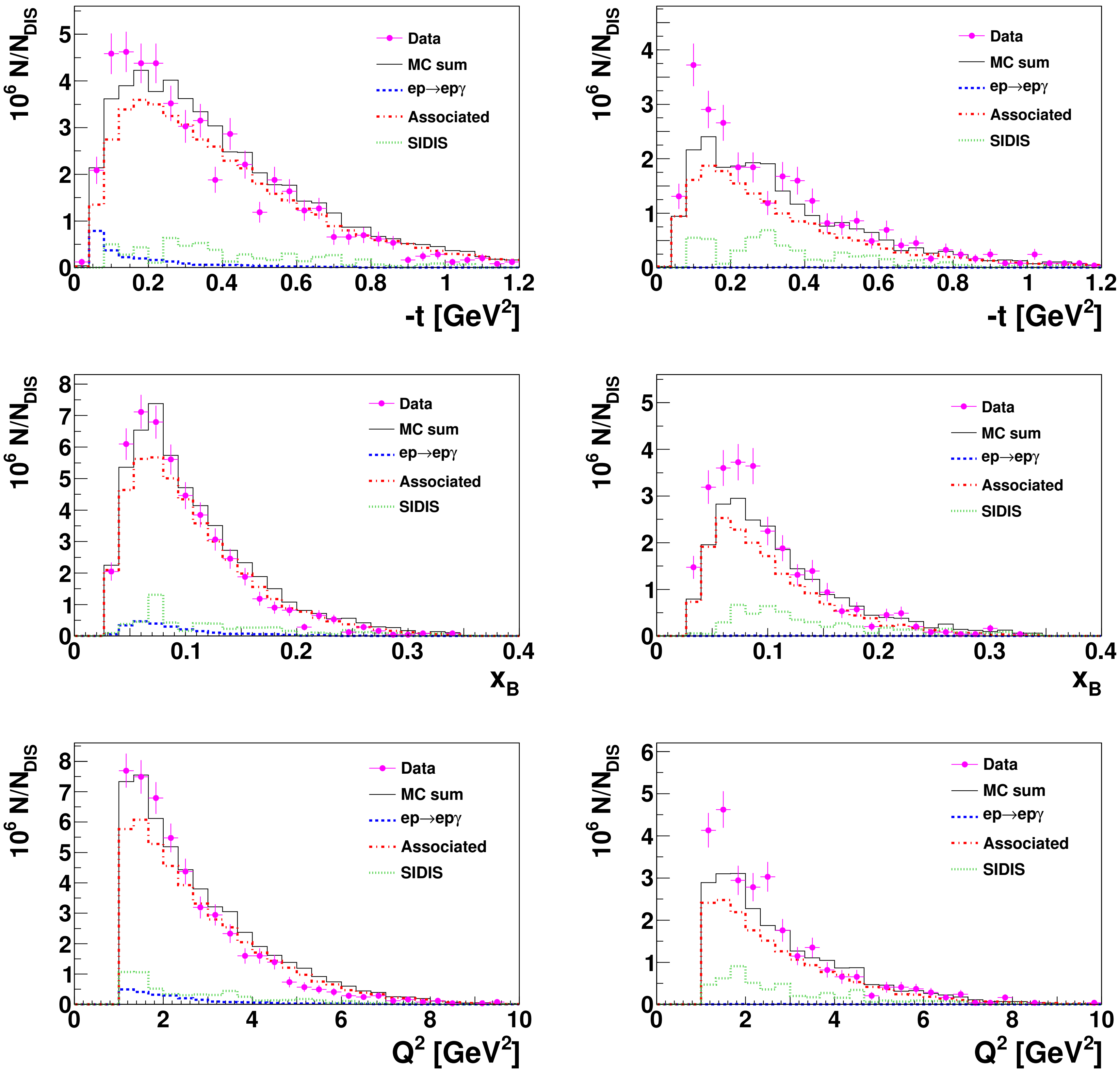
Φ $1.012 < M_{KK} < 1.028\, GeV$

ω $0.71 < M_{\pi\pi\pi} < 0.87\, GeV$





Data-MC Comparison



UPE Contribution Φ and ω

- u values are consistent with zero.
- Process dynamics is dominated by two-gluon exchange mechanism.

- Significantly large value for u_1
- Process dynamics is dominated by quark exchange mechanism.