GPD's @ HERMES

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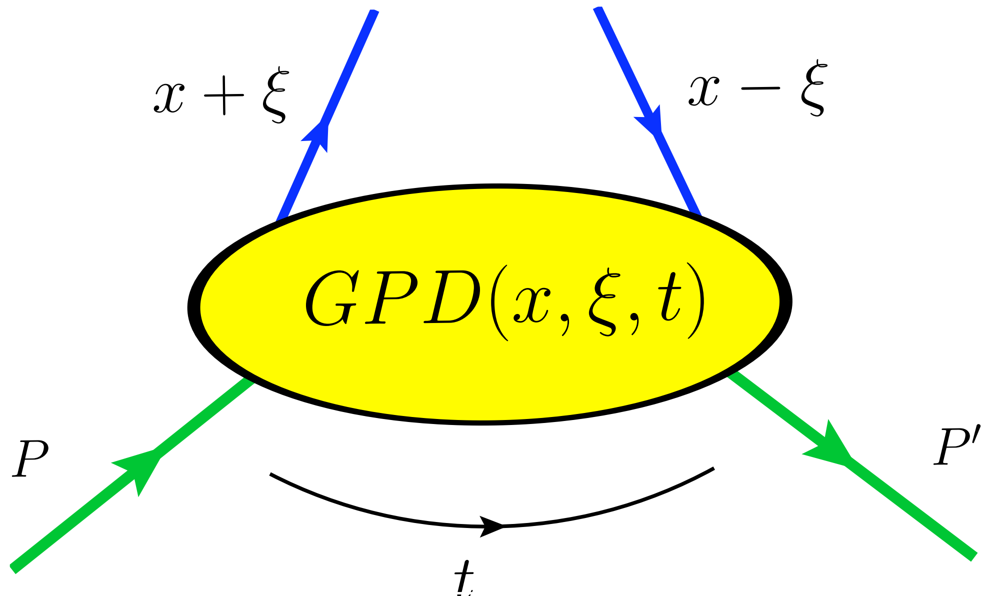
GPDs describe the nucleon structure in terms of quark and gluon degrees of freedom

Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon



Relation to total angular momentum (Ji relation):

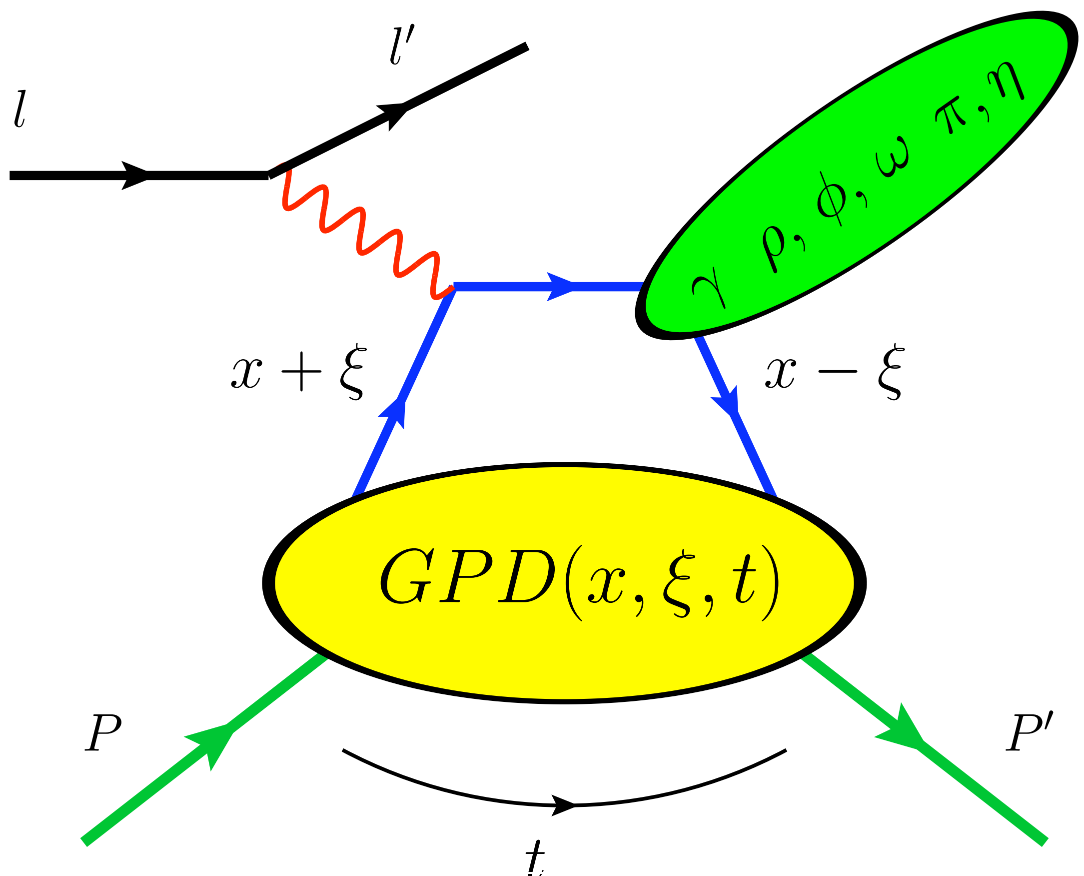
$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,(H_q(x,\xi,t)+E_q(x,\xi,t))$$

leading-twist, quark chirality conserving		
spin-1/2	unpolarized	polarized
no nucleon hel. flip	H	$\widetilde{H}$
nucleon hel. flip	E	$\widetilde{E}$

Form Factors:
Transverse distribution of quarks in space coordinate.
F(t)=∫dx*GPD(x, ξ, t)

PDFs:
Quark longitudinal momentum fraction in the nucleon.
q(x)=GPD(x, ξ=0, t=0)

Hard Exclusive Processes.



Deeply Virtual Compton Scattering

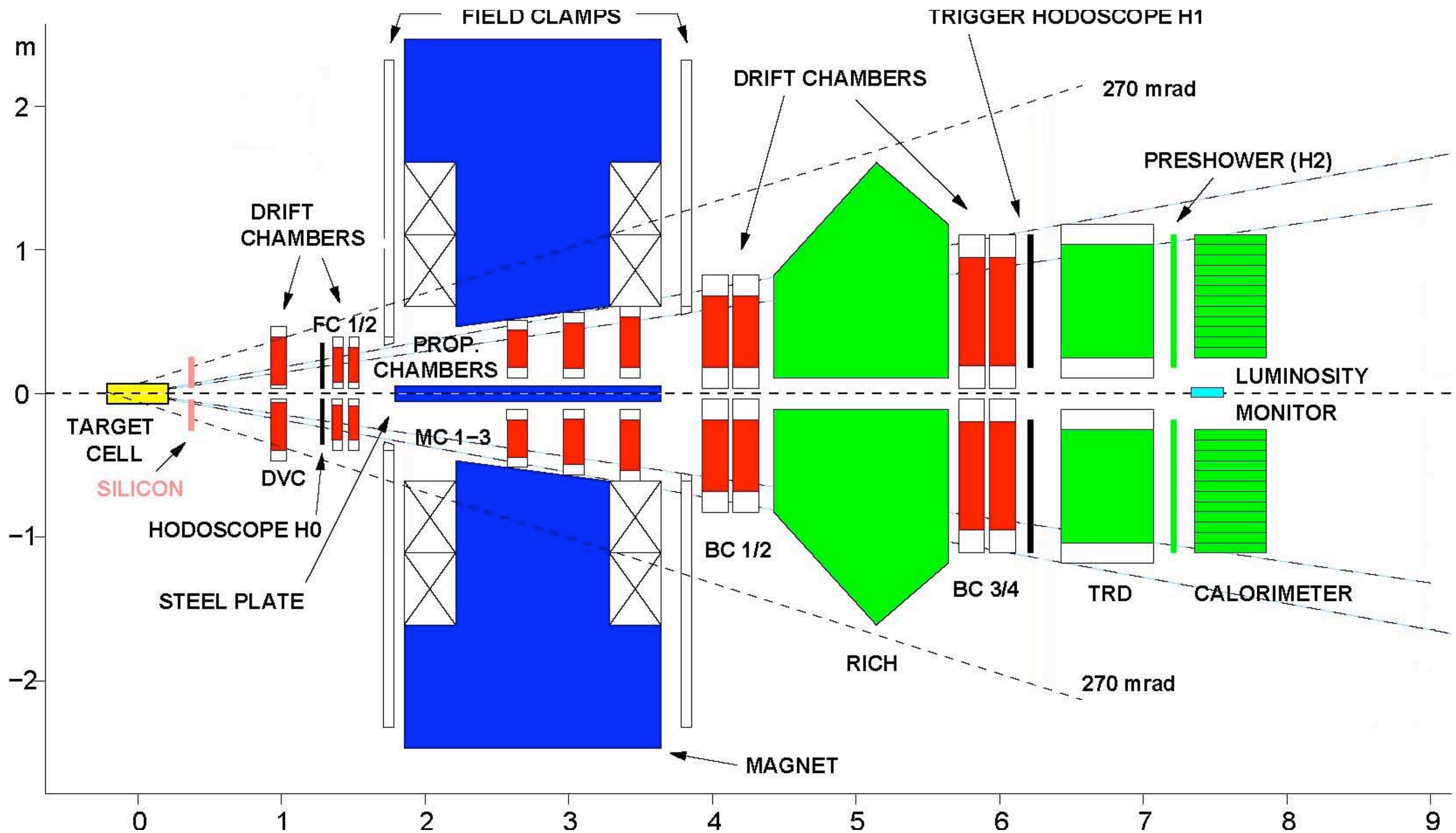
- Theoretically the cleanest probe of GPDs
- Theoretical accuracy at NNLO
- GPDs are accessed through convolution integrals with hard scattering amplitude
- Experimental observables: Azimuthal asymmetries
- GPDs $H, E, \widetilde{H}, \widetilde{E}$ are accessed

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: SDMEs, Transverse target spin asymmetries, Helicity amplitude rations
- At leading twist → sensitive to GPDs H and E

Pseudoscalar mesons

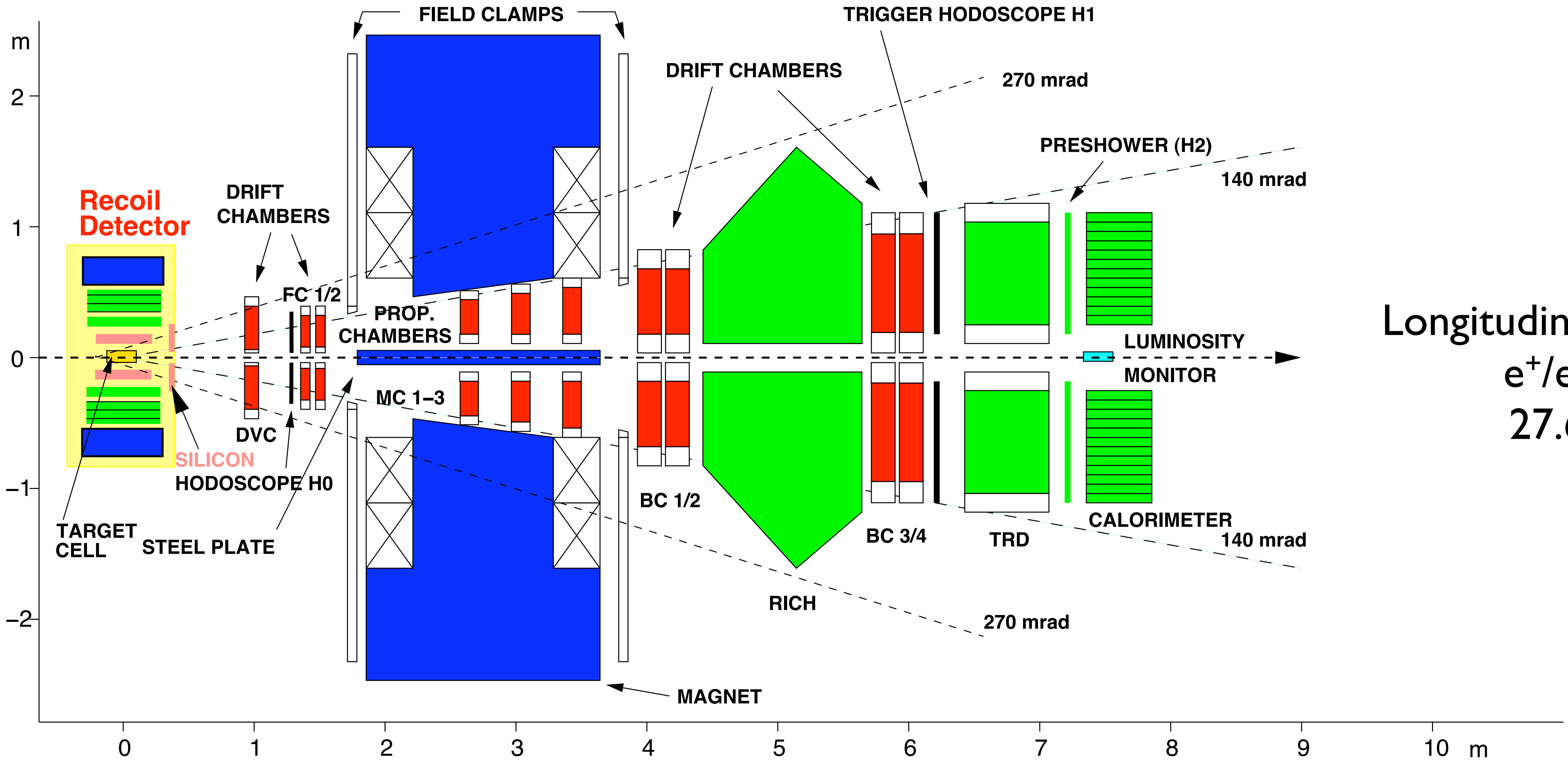
- Experimental observables: Cross sections, Transverse Target Spin Asymmetries
- At leading twist → sensitive to GPDs $\widetilde{H}$ and $\widetilde{E}$



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

- Data Taking: 1995-2007
- Reconstruction: $\delta p/p<2\%$, $\delta\Theta<1$ 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



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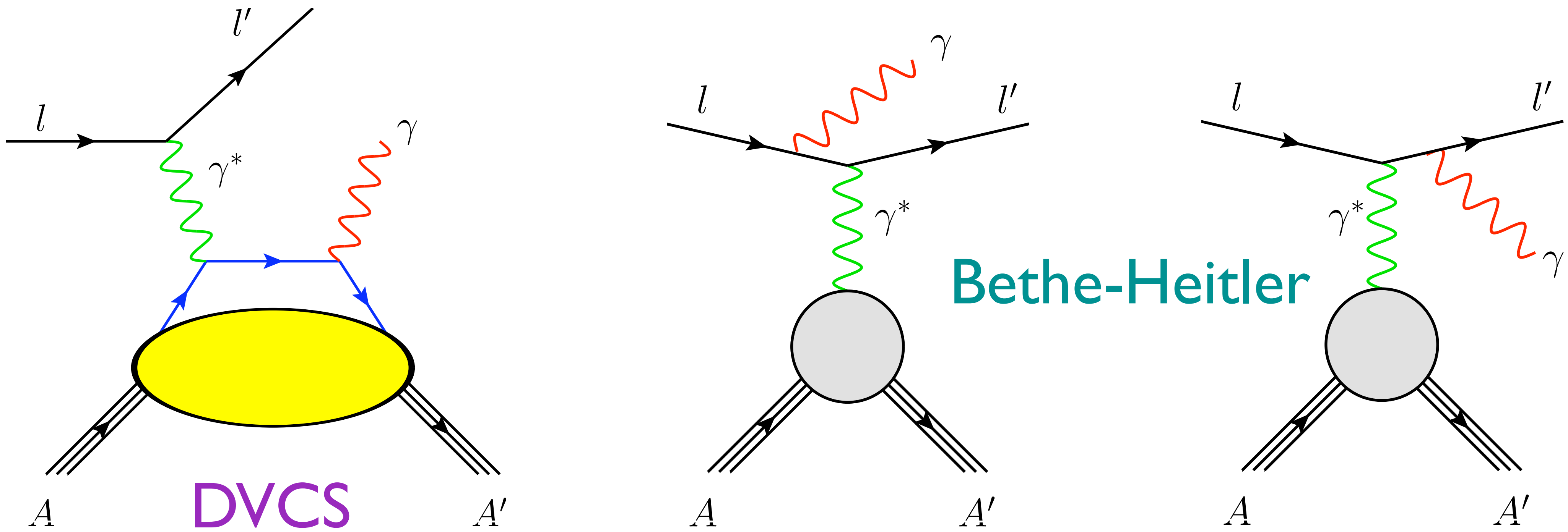
lepton-hadron separation > 99 % efficiency

- In 2006-2007 : Data Taking with Recoil Detector



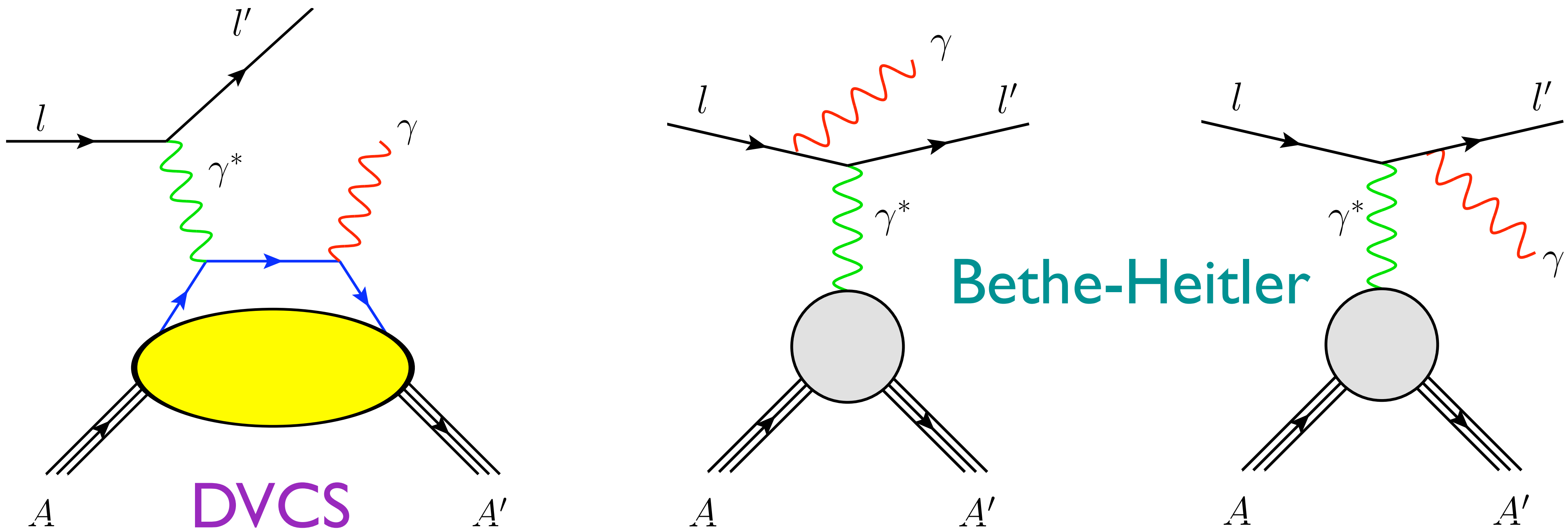
DVCS and Bethe-Heitler ⇒ Same final state ⇒ Interference

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

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

DVCS amplitudes can be accessed trough Interference

Interference ⇒ non-zero azimuthal asymmetries



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

Bethe-Heitler is parametrized in terms of electromagnetic Form-Factors $F_1,\ F_2$

DVCS is parametrized in terms of Compton Form-Factors $\mathcal{H},\ \mathcal{E},\ \widetilde{\mathcal{H}},\ \widetilde{\mathcal{E}}$

CFFs = convolutions of hard scattering amplitudes and GPD's

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

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

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

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

- Beam-Charge asymmetry

  $\sigma(e^+,\phi) - \sigma(e^-,\phi) \propto Re[F_1\mathcal{H}]$
- Beam-Spin Asymmetry

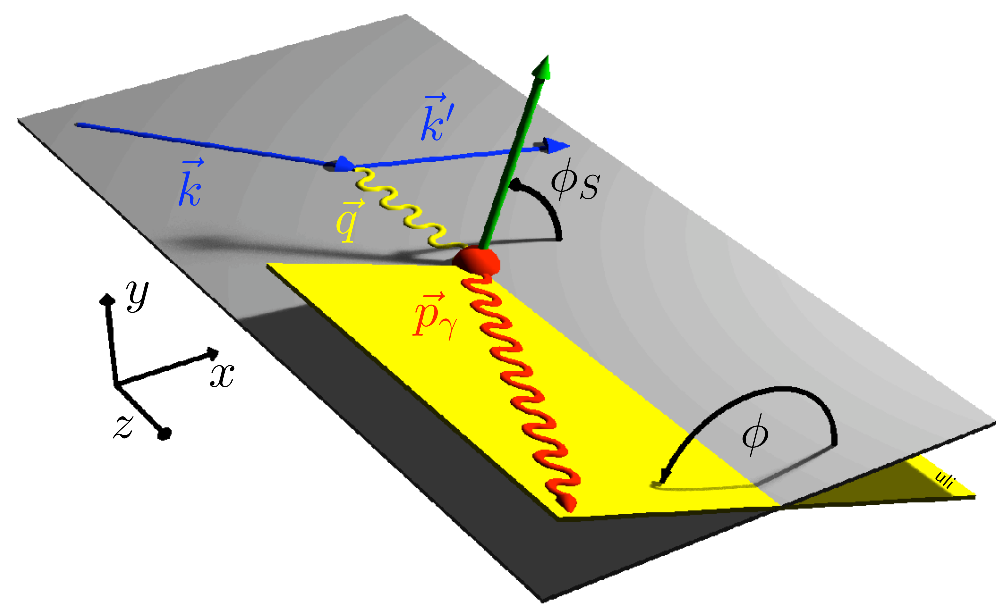
  $\sigma(\overrightarrow{e},\phi) - \sigma(\overleftarrow{e},\phi) \propto Im[F_1\mathcal{H}]$
- Longitudinal Target-Spin Asymmetry

  $\sigma(\overset{\Rightarrow}{P},\phi) - \sigma(\overset{\Leftarrow}{P},\phi) \propto Im[F_1\widetilde{\mathcal{H}}]$
- 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

  $\sigma(\overrightarrow{e},\phi,\phi_S) - \sigma(\overleftarrow{e},\phi,\phi_S+\pi) \propto Re[F_2\mathcal{H} - F_1\mathcal{E}]$



Event Selection w/o Recoil Detector

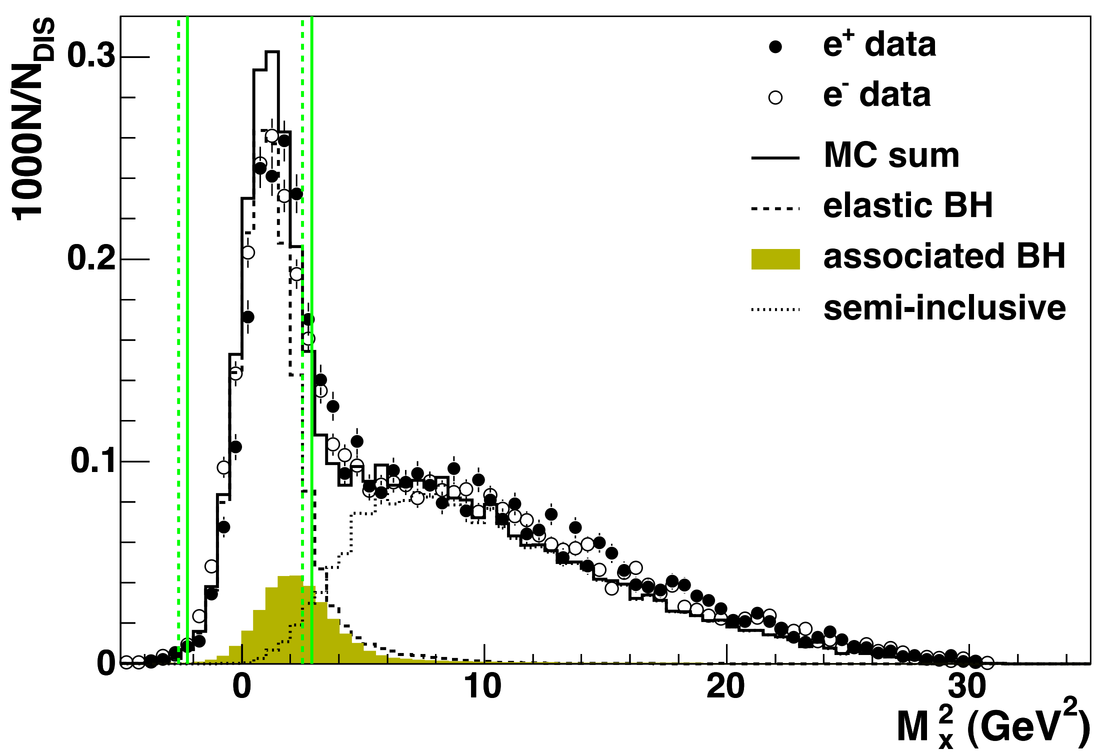
- Events with one DIS lepton and one trackless cluster in the calorimeter.
- Recoiling nucleon was not detected

$\Longrightarrow$ Exclusivity via missing mass technique: $M_x^2 = (P + q - q')^2$

$$W^2 > 9\,GeV^2, \quad \nu < 22\,GeV$$

$$0.03 < x_B < 0.35,\ 1 < Q^2 < 10\,GeV^2$$

$$-t < 0.7\,GeV^2, \quad E_\gamma > 5\,GeV$$



Proton:
- Elastic; $ep \rightarrow ep\gamma$
- Associated; mainly $ep \rightarrow e\Delta^+\gamma$
- SIDIS; mainly $ep \rightarrow e\pi^0 X$ ≈4%

SIDIS background correction:

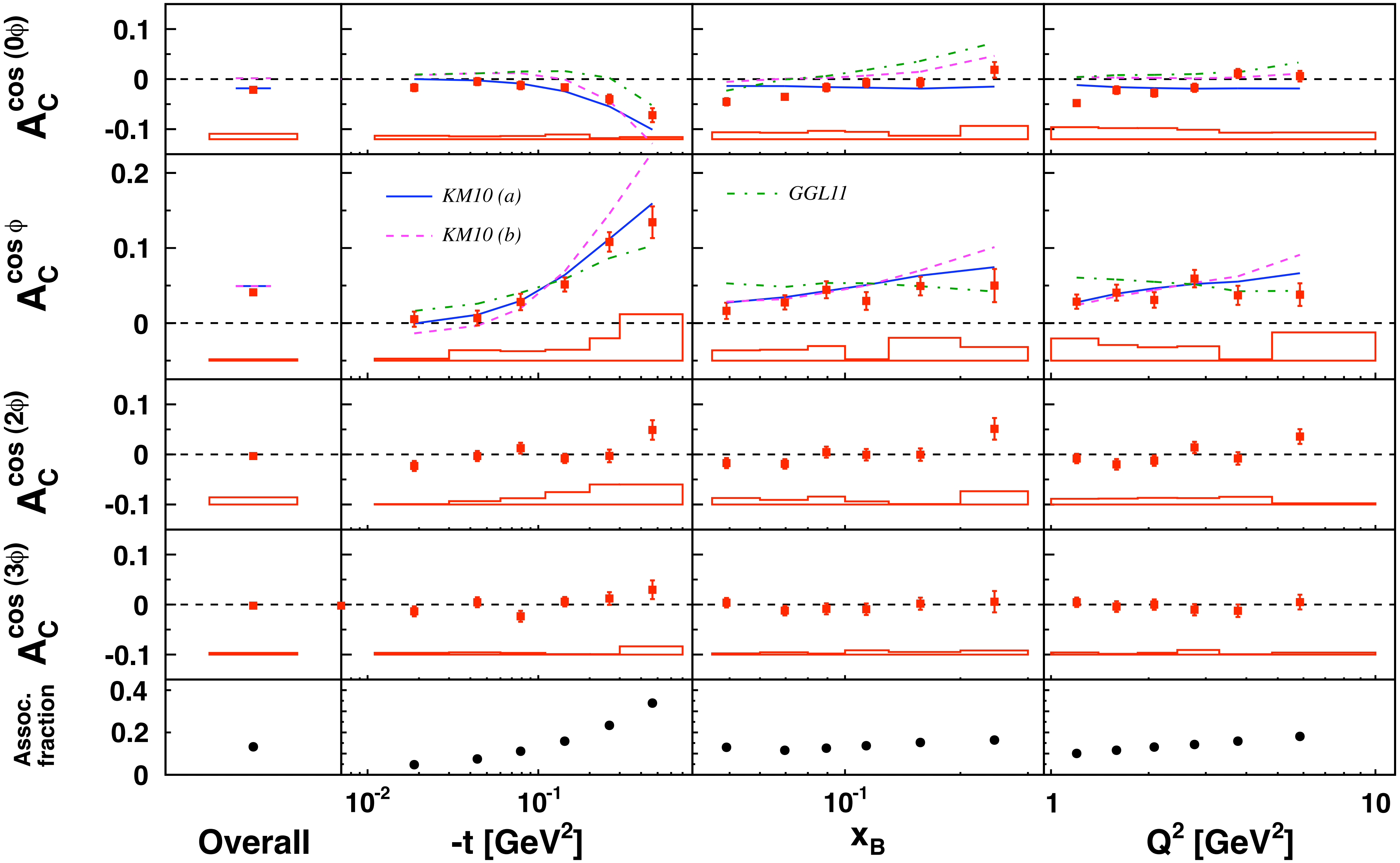
$$A_{excl.} = \frac{1}{1 - f_{BG}}[A_{meas.} - f_{BG}A_{BG}]$$

$$-2.25\,GeV^2 < M_x^2 < 2.89\,GeV^2$$

Associated cannot be resolved $\longrightarrow$ defined as a part of signal.

Beam-charge asymmetry

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



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

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

Beam charge asymmetry
- non-zero leading amplitude
- strong -t dependence
- no x_B and Q^2 dependencies
- good agreement with model predictions

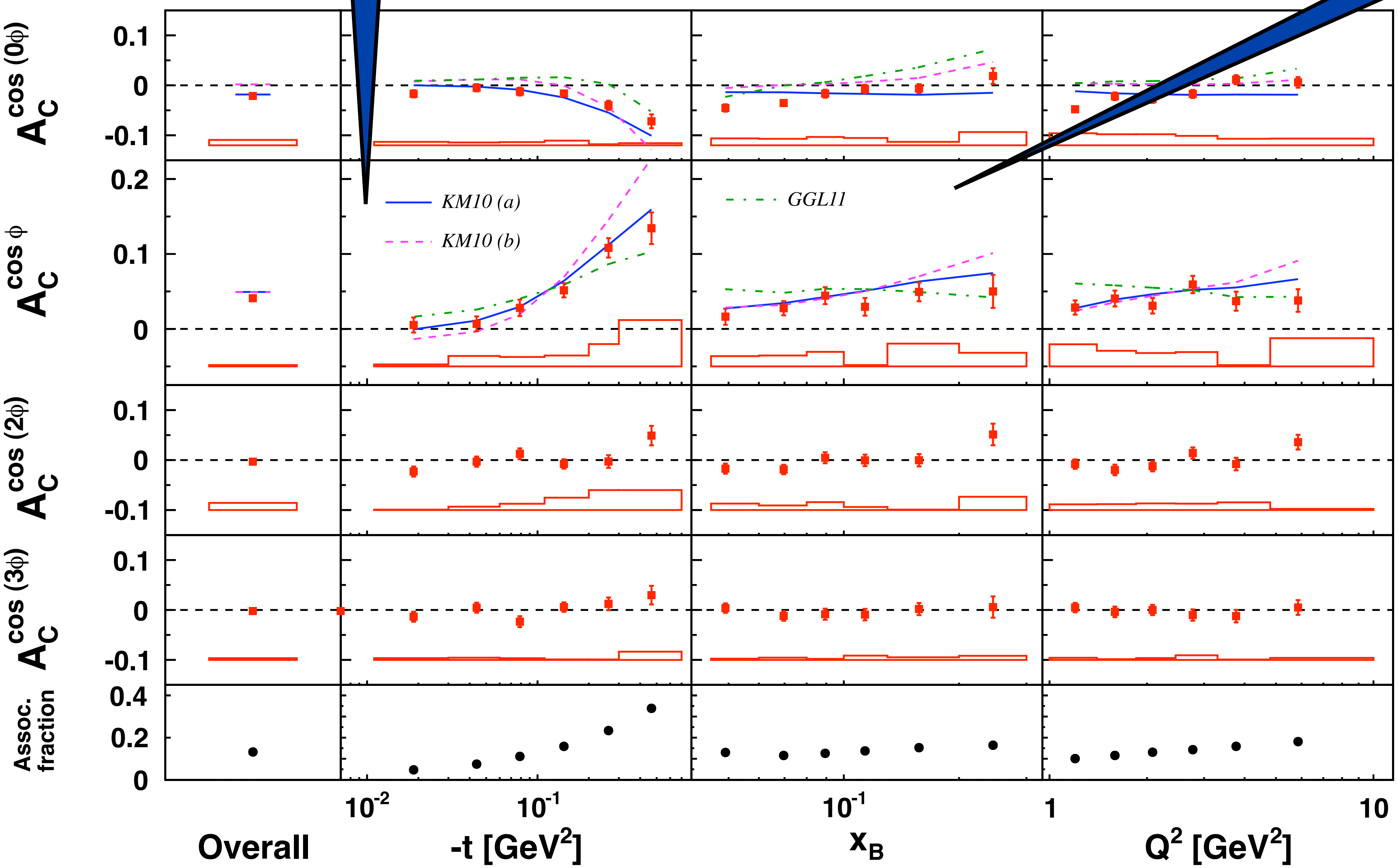
Fractions of associated process from MC

Beam-charge asymmetry

KM10: Global fit including data from JLab, HERMES and HERA
K. Kumericki, D. Muller
Nucl.Phys.B 841(2010) 1

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

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



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

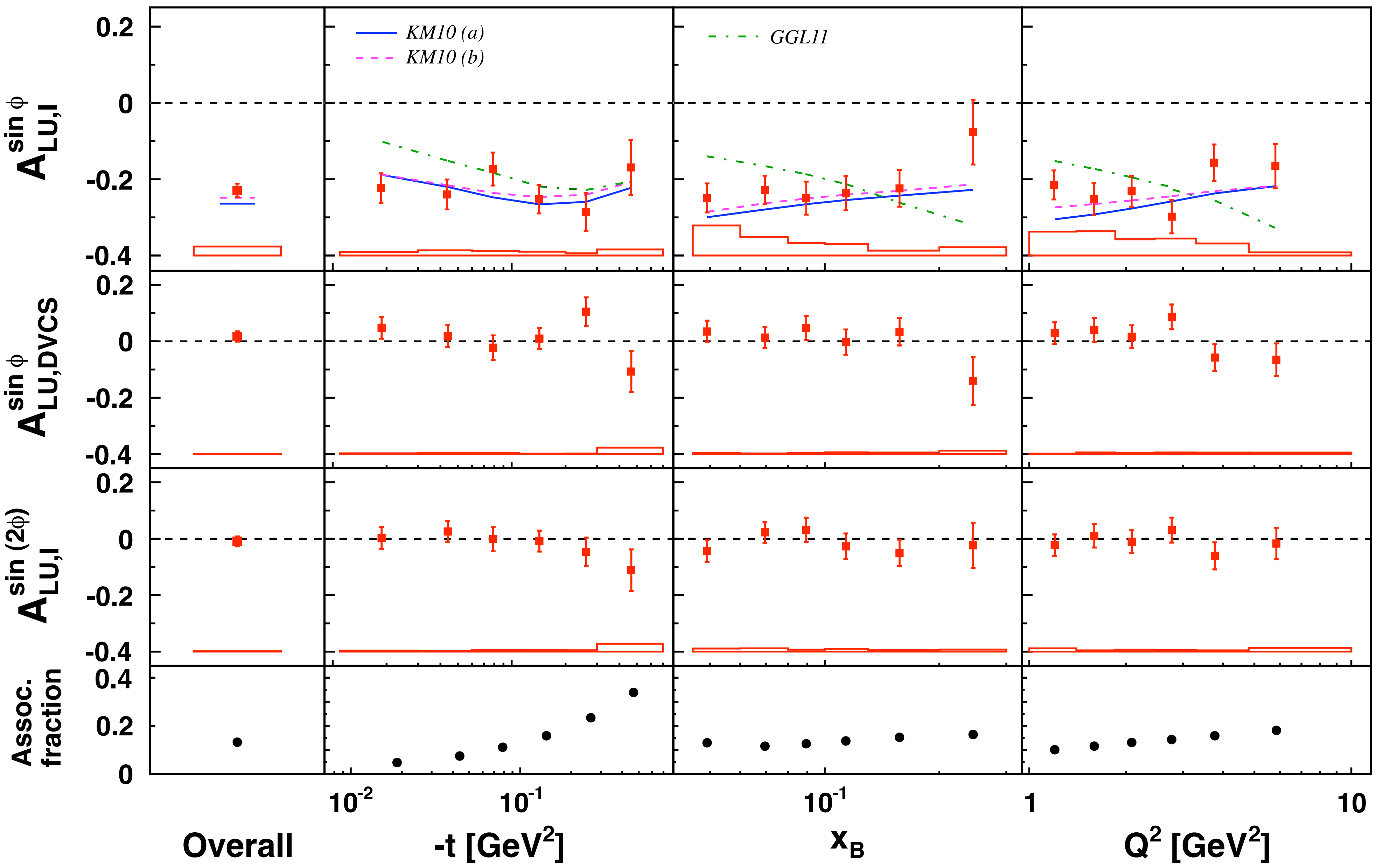
$\propto \mathcal{R}e[F_1\mathcal{H}]$

Beam charge asymmetry
- non-zero leading amplitude
- strong -t dependence
- no x_B and Q^2 dependencies
- good agreement with model predictions

Fractions of associated process from MC

Beam-helicity asymmetries

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



Charge-difference beam-helicity asymmetry
- significant negative value of the leading amplitude
- no kinematic dependencies
- non leading amplitudes are consistent with zero

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

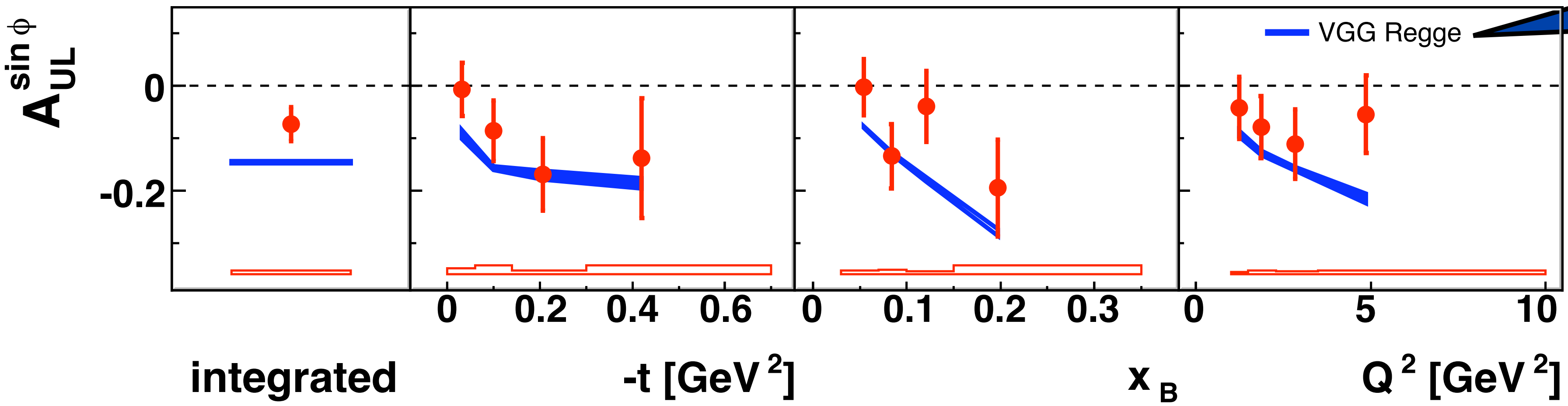
$\propto \mathcal{I}m\left[\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right]$

Charge-averaged beam-helicity asymmetry
- consistent with zero

Fractions of associated process from MC

Longitudinal Single Target-Spin and Double-Spin asymmetries

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

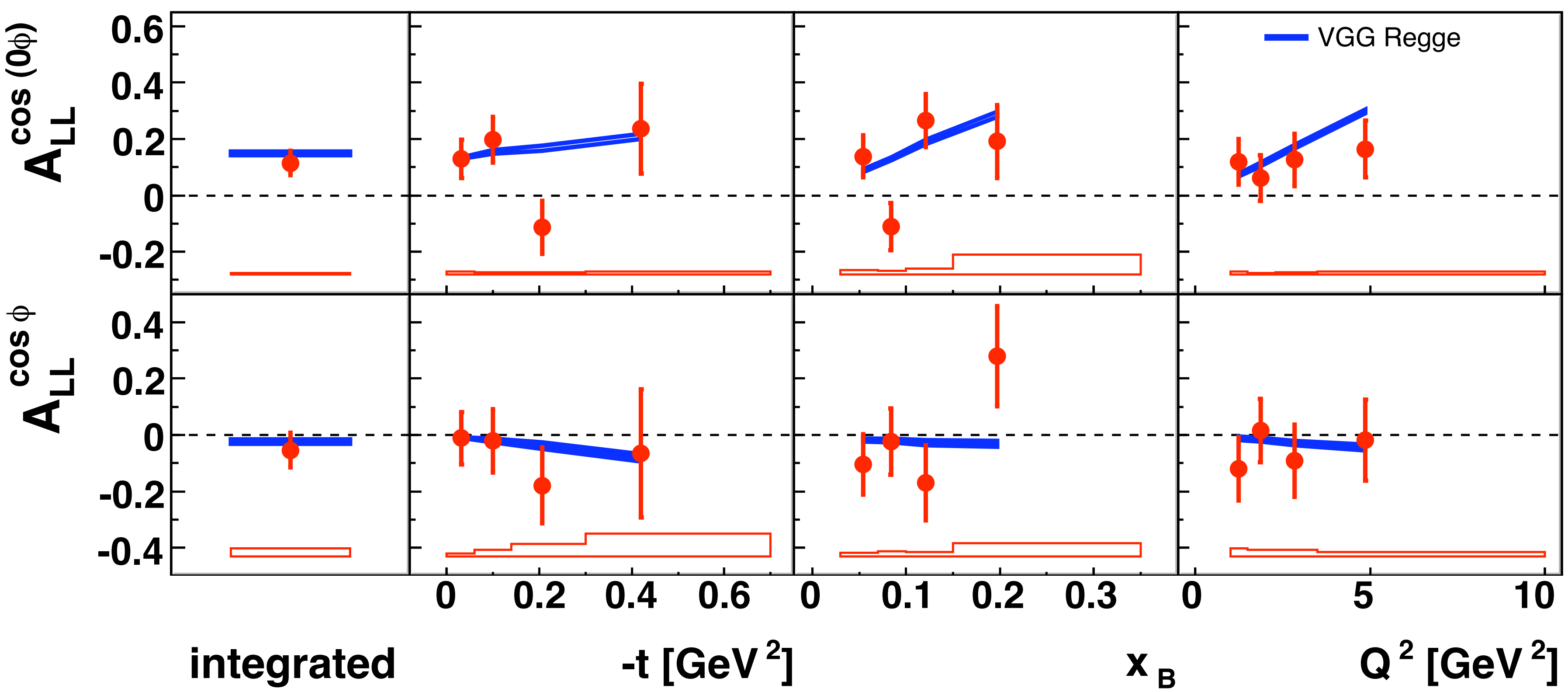


VGG: Model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

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

Longitudinal Target Spin Asymmetry
- non-zero negative value of the leading sin(ϕ) amplitude
- mild kinematic dependence

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



Longitudinal Double-Spin Asymmetry
- constant term is positive
- leading cos(ϕ) amplitude is consistent with zero

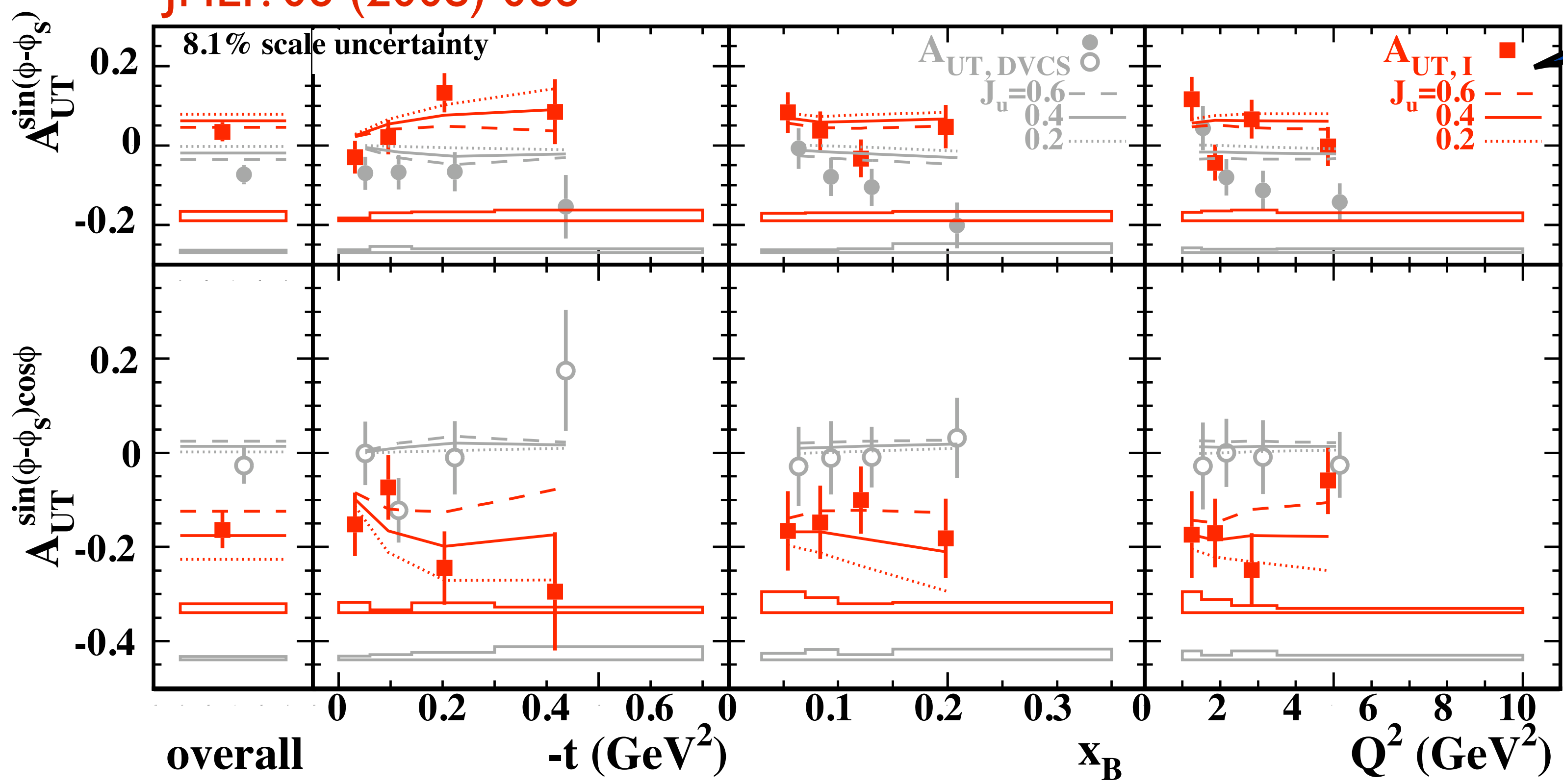
$$\propto \mathcal{R}e\left[F_1\widetilde{\mathcal{H}}\right]$$

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

Transverse Single Target-Spin and Double-Spin asymmetries

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

JHEP. 06 (2008) 066



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Charge-difference Transverse Target-Spin asymmetry

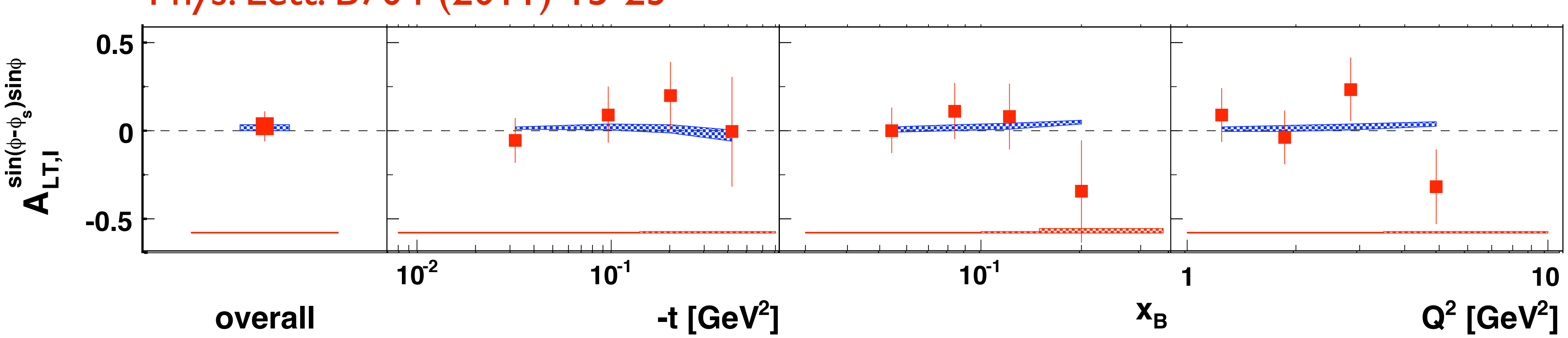
- Non-zero leading cos(nϕ) amplitudes.

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

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

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

Phys. Lett. B704 (2011) 15-23



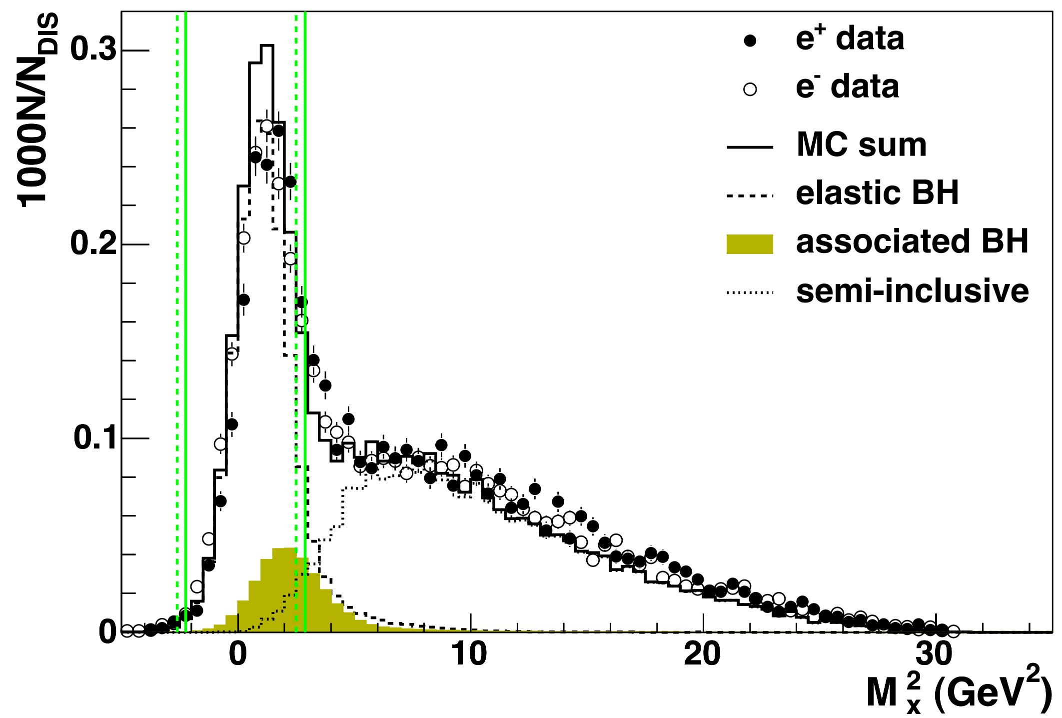
Charge-difference Transverse Double-Spin asymmetry

- leading amplitudes are consistent with zero
- sensitivity to is suppressed J_u is suppressed by kinematic pre-factor

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

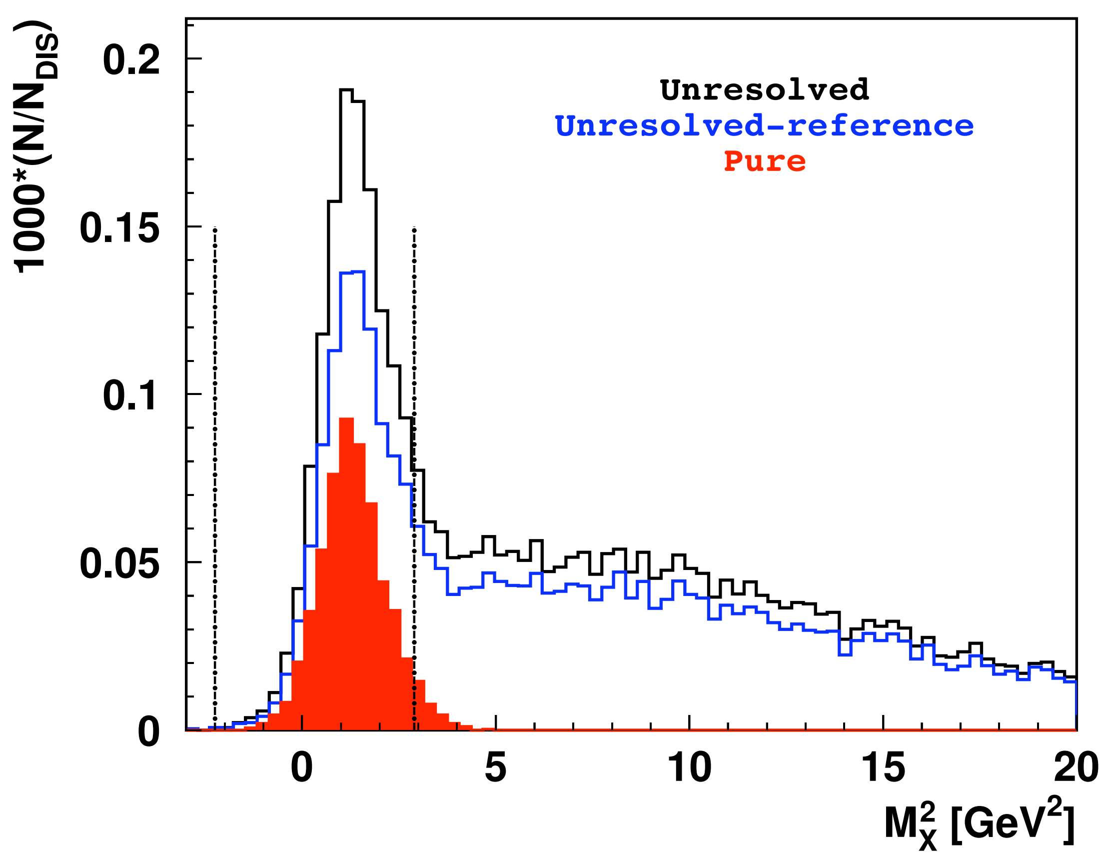
Event Selection with Recoil Detector

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

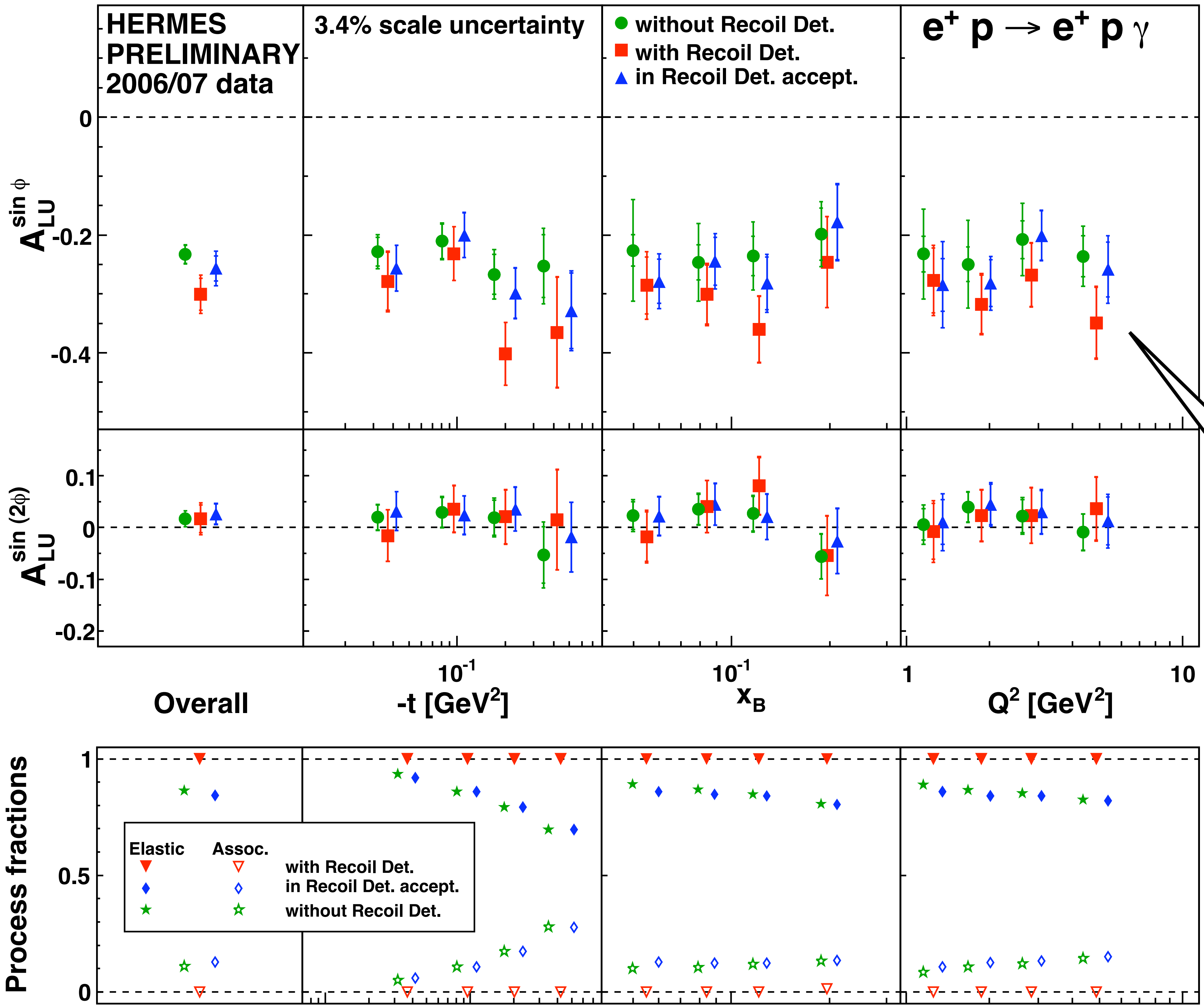


- "***Unresolved reference***" sample.
- "Hypothetical" proton required in the Recoil Detector acceptance.

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



Beam-Spin asymmetry with Recoil



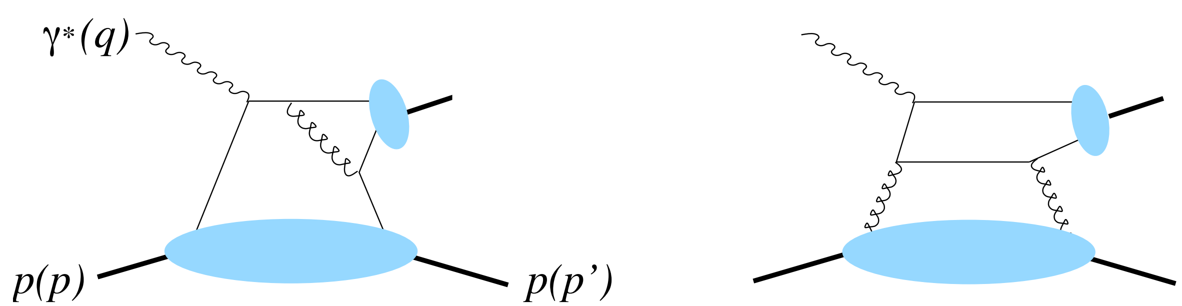
$$\mathcal{A}_{LU}(\phi) = \frac{\sigma^{+\rightarrow} - \sigma^{+\leftarrow}}{\sigma^{+\rightarrow} + \sigma^{+\leftarrow}}$$

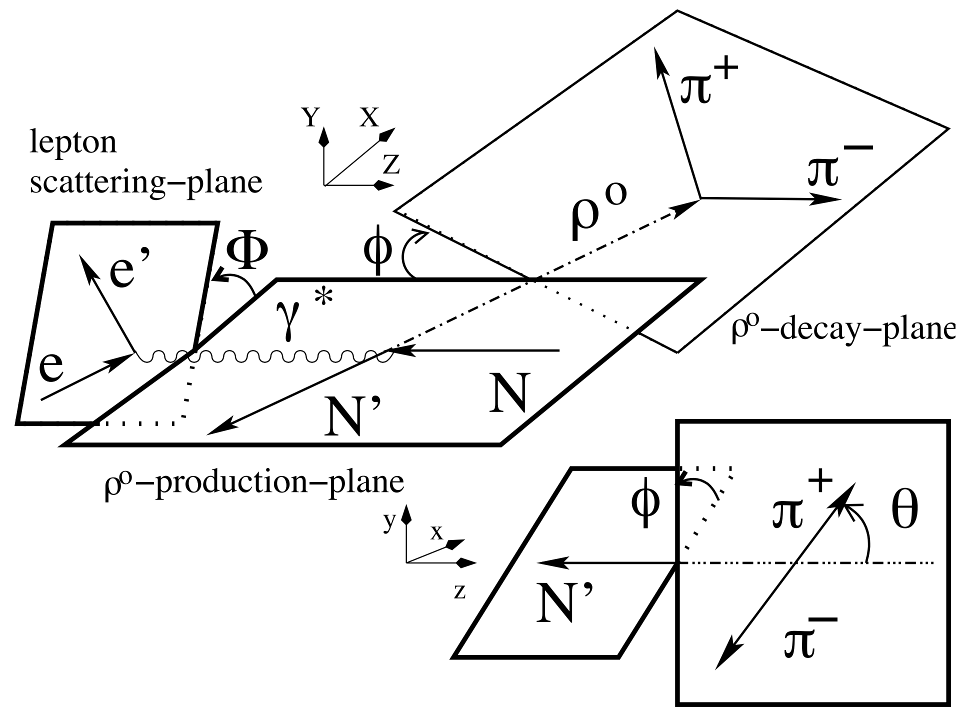
Indication of slightly larger magnitude of leading amplitude for pure elastic sample compared with reference sample

Unresolved
Unresolved Reference
Pure Elastic

Fractional contributions of elastic and associated processes for different samples 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

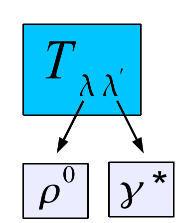
Cross Section

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

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

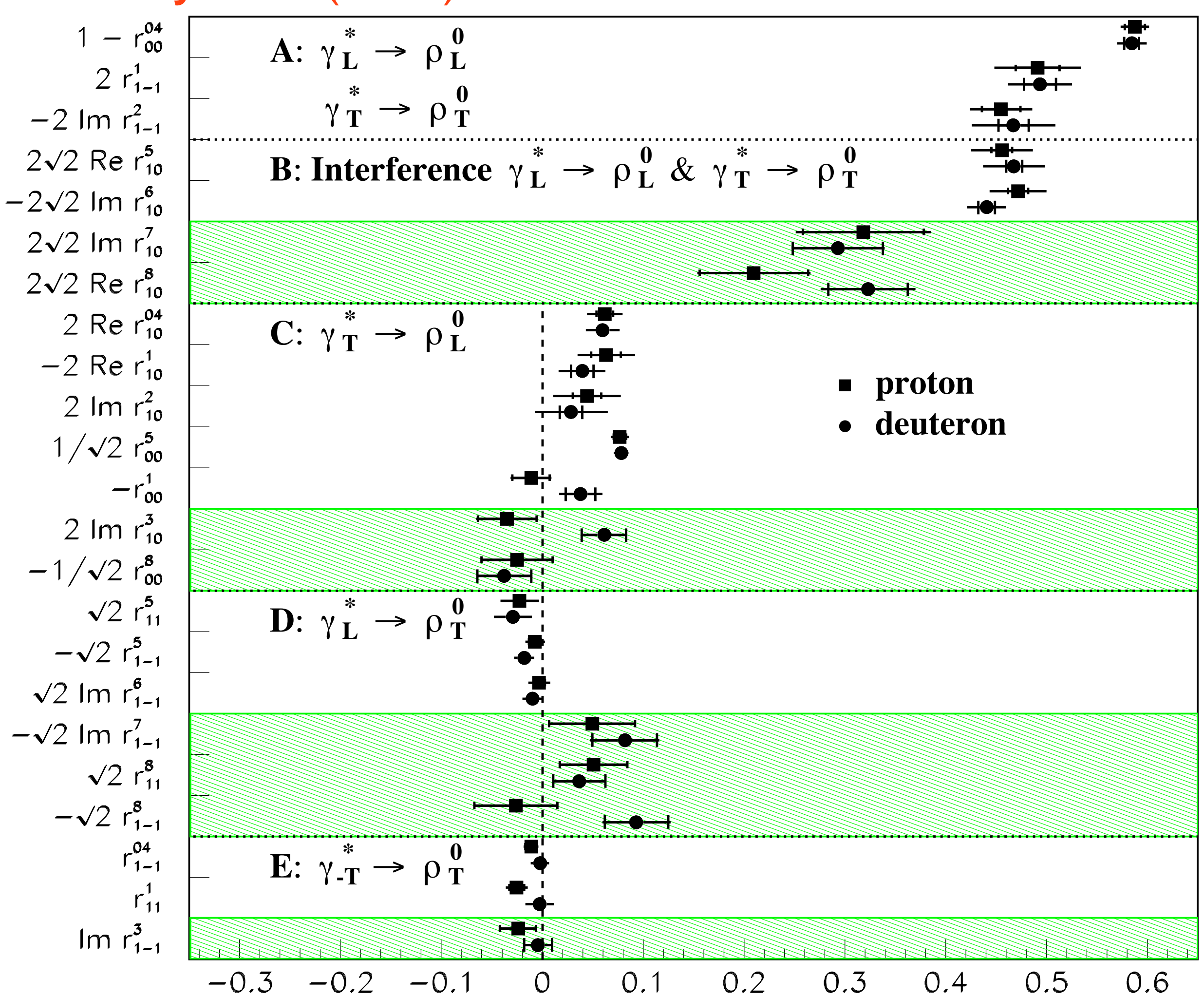


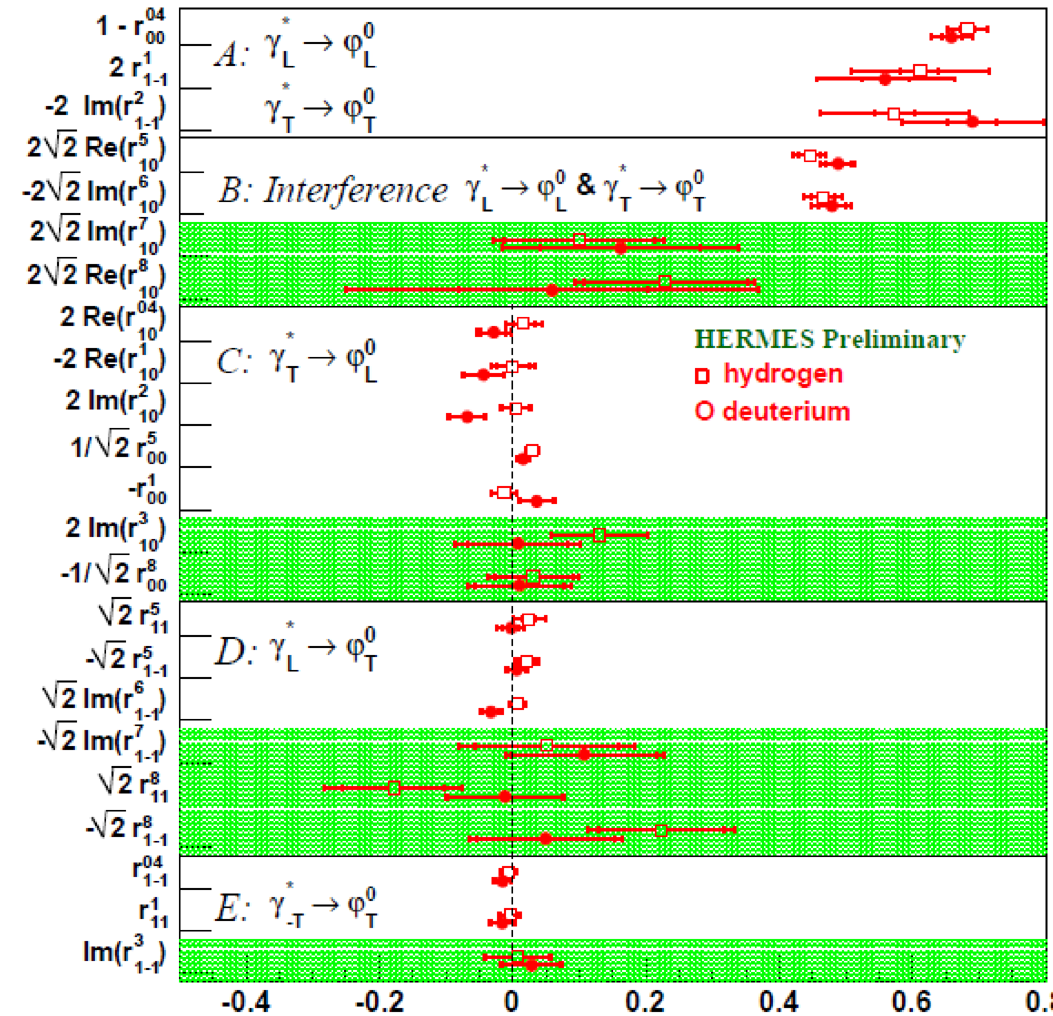
or SDMEs

ρ^0 and ϕ SDMEs on an unpolarized target

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

EPJ C 62 (2009) 659-694





$\gamma^*_L \rightarrow V_L$ & $\gamma^*_T \rightarrow V_T$
- SDMEs are significantly different from zero
- 10-20% difference between ρ and ϕ SDMEs

$\gamma^*_T \rightarrow V_L$
- pronounced difference between ρ and ϕ SDMEs
- 2-10 σ level violation from SCHC for ρ

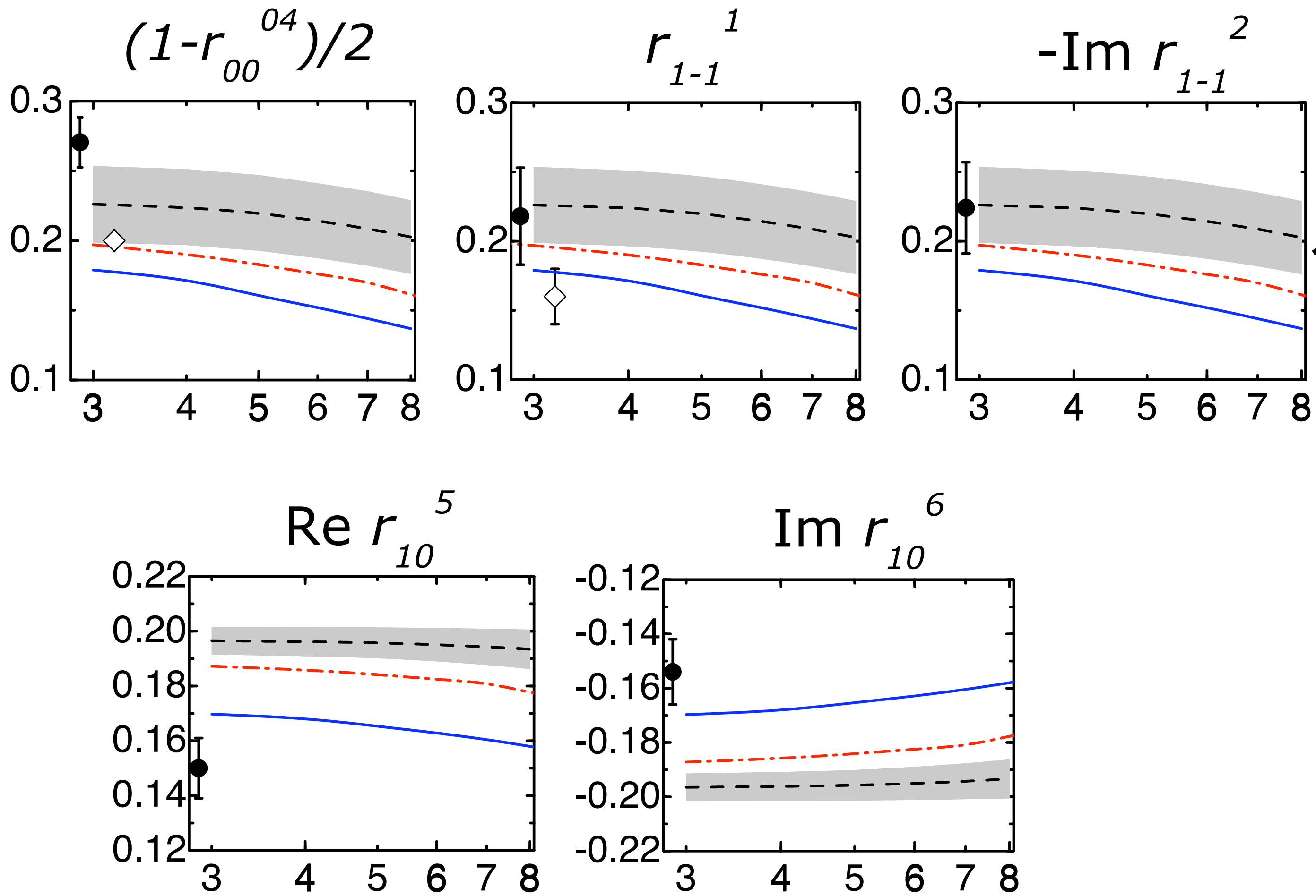
$\gamma^*_L \rightarrow V_T$ & $\gamma^*_{-T} \rightarrow V_T$
- SDMEs are consistent with zero

- Selected hierarchy is confirmed
- No differences between proton and deuteron

Comparison of ρ^0 SDMEs to GPD model

GPD model: S.Goloskokov, P. Kroll (2007)

W=5 GeV (HERMES)
W=10 GeV (COMPASS)
W=75 GeV (H1,ZEUS)



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

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

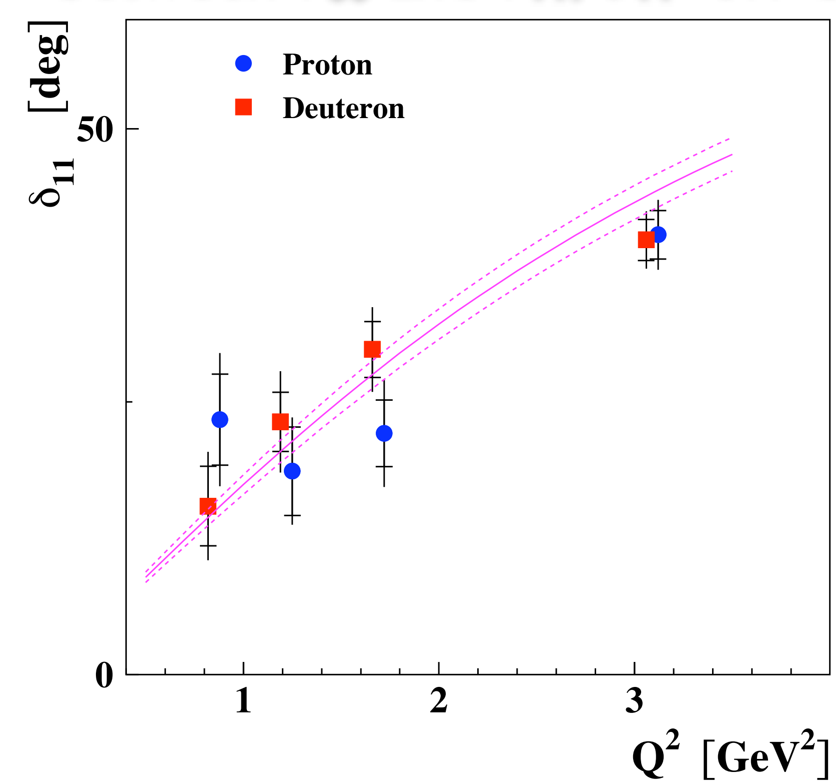
model is in an agreement with data

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

model dose not describe the data

model predicts 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)

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

$$u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{1} - 2r_{1-1}^{1} \qquad u_2 = r_{11}^{5} + r_{1-1}^{5} \qquad u_3 = r_{11}^{8} + r_{1-1}^{8}$$

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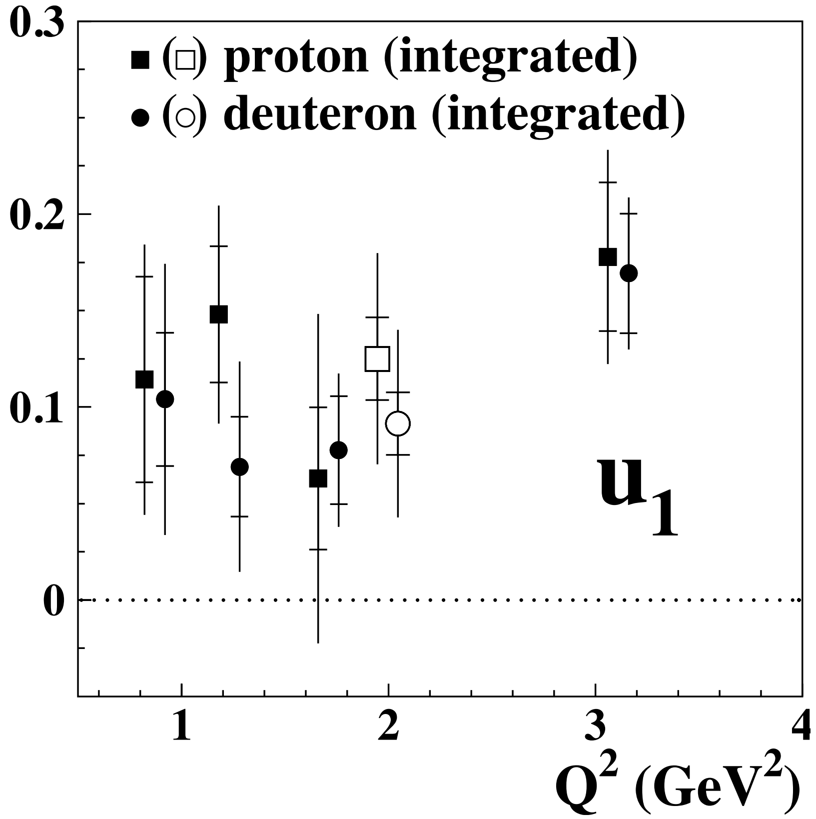
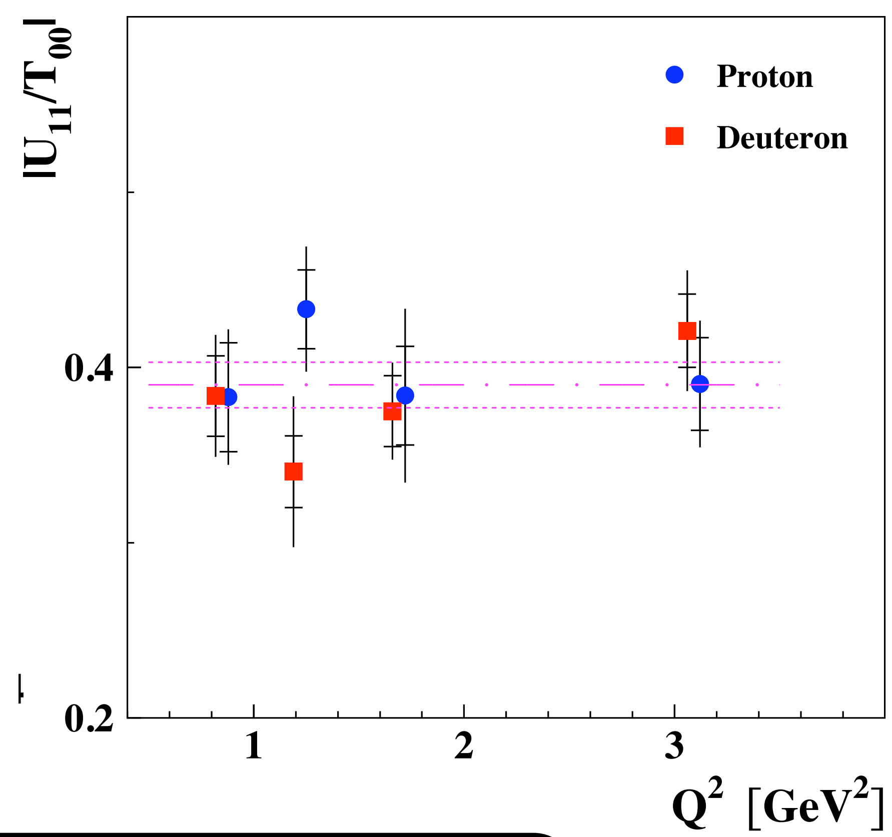
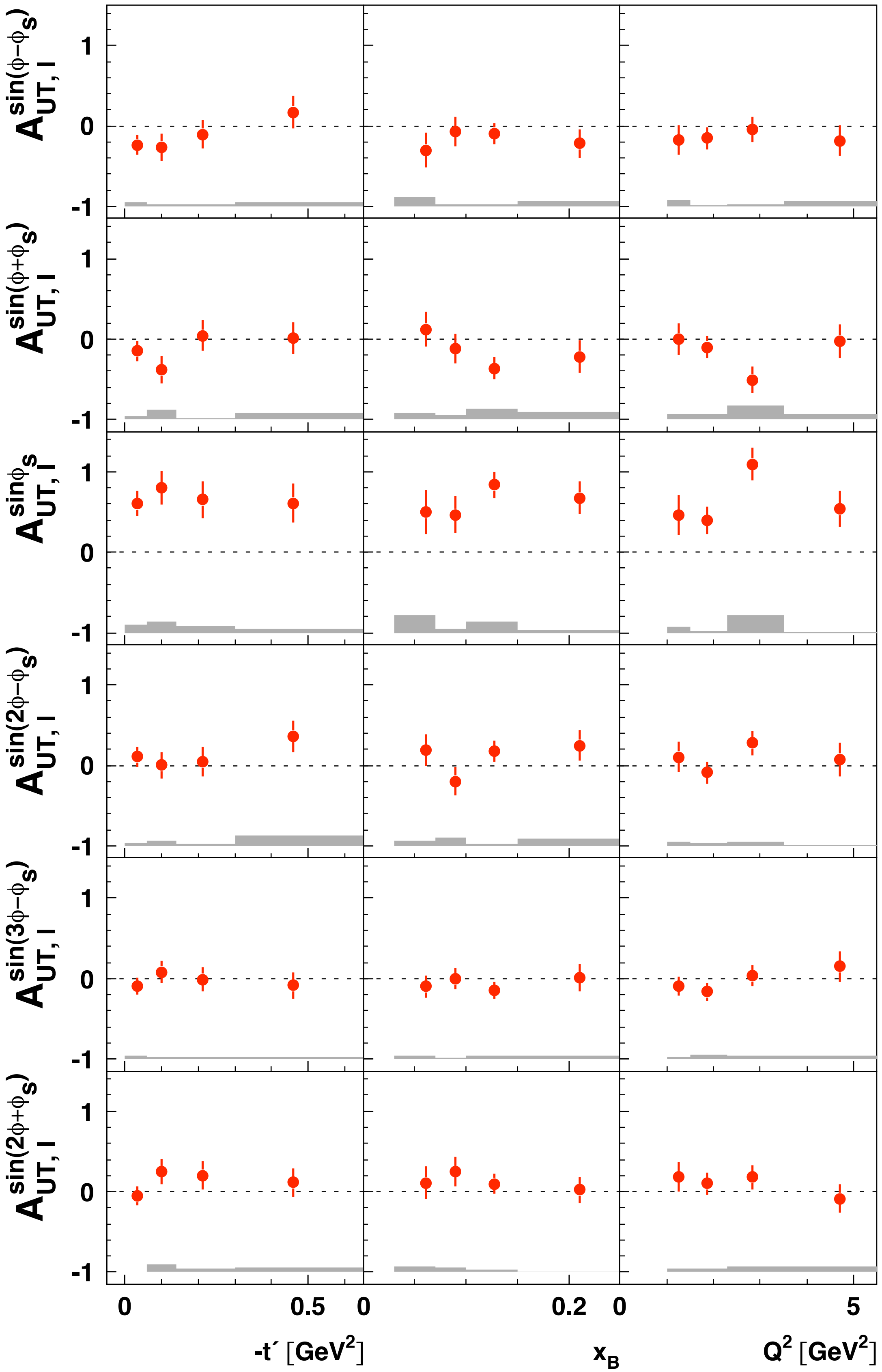


EPJ C 71 (2011) 1609



- Significant UPE contribution for ρ^0
  Sensitivity to GPD $\widetilde{H}$
- No signal of UPE contribution for ϕ

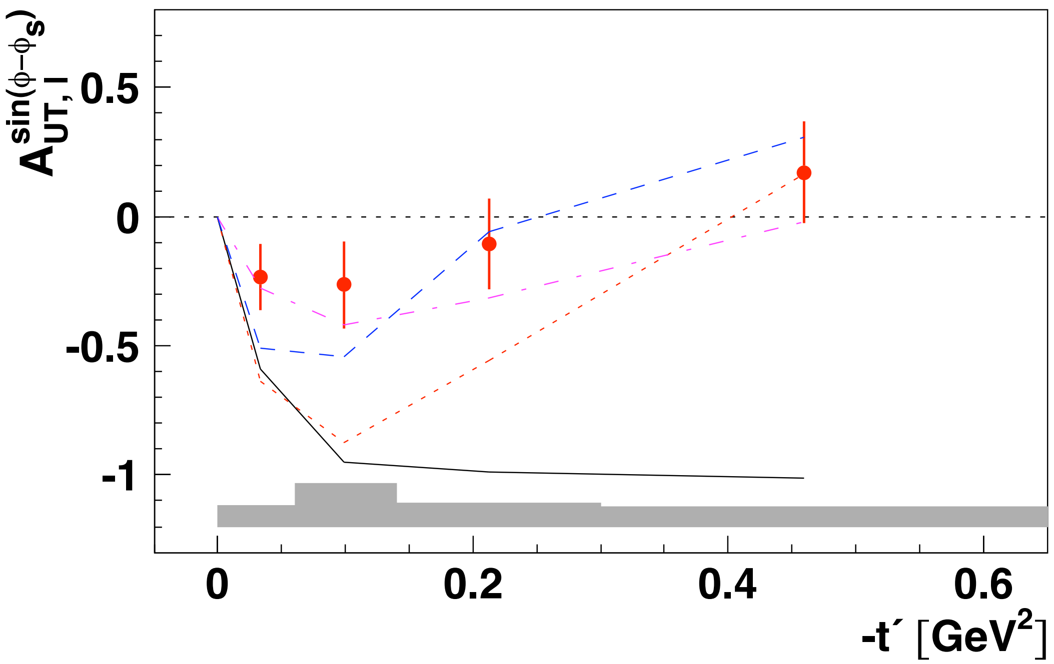
Exclusive π^+ production



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

- 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



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)*

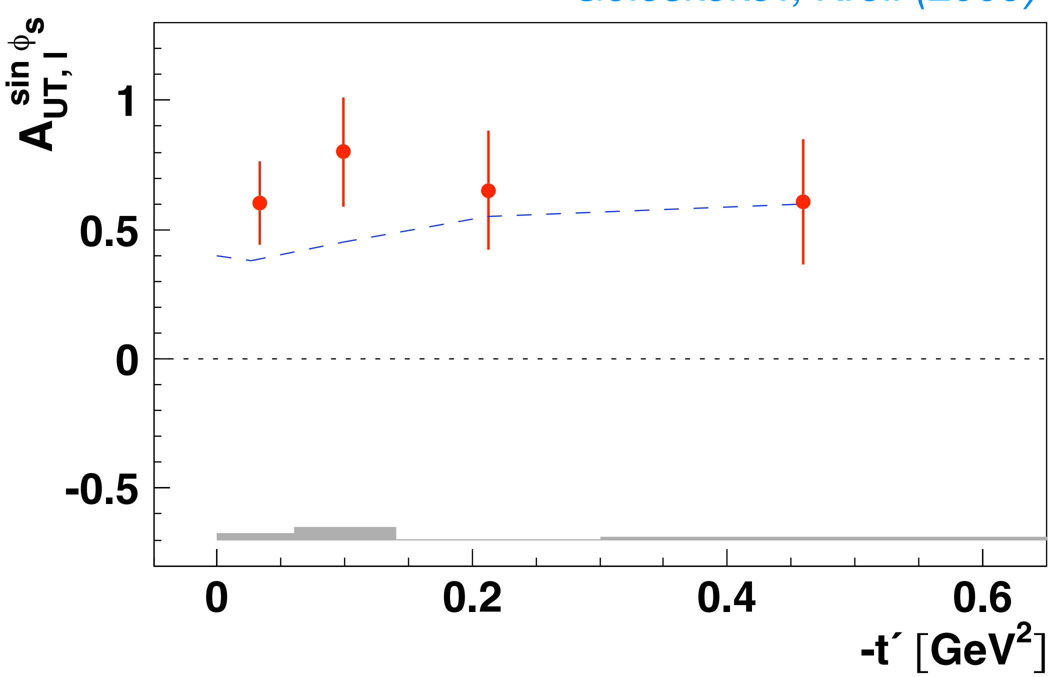
Belitsky, Muller (2001)

- difference could be due the γ^*_T .

Goloskokov, Kroll (2009)

Bechler, Muller (2009)

-Goloskokov, Kroll (2009)-

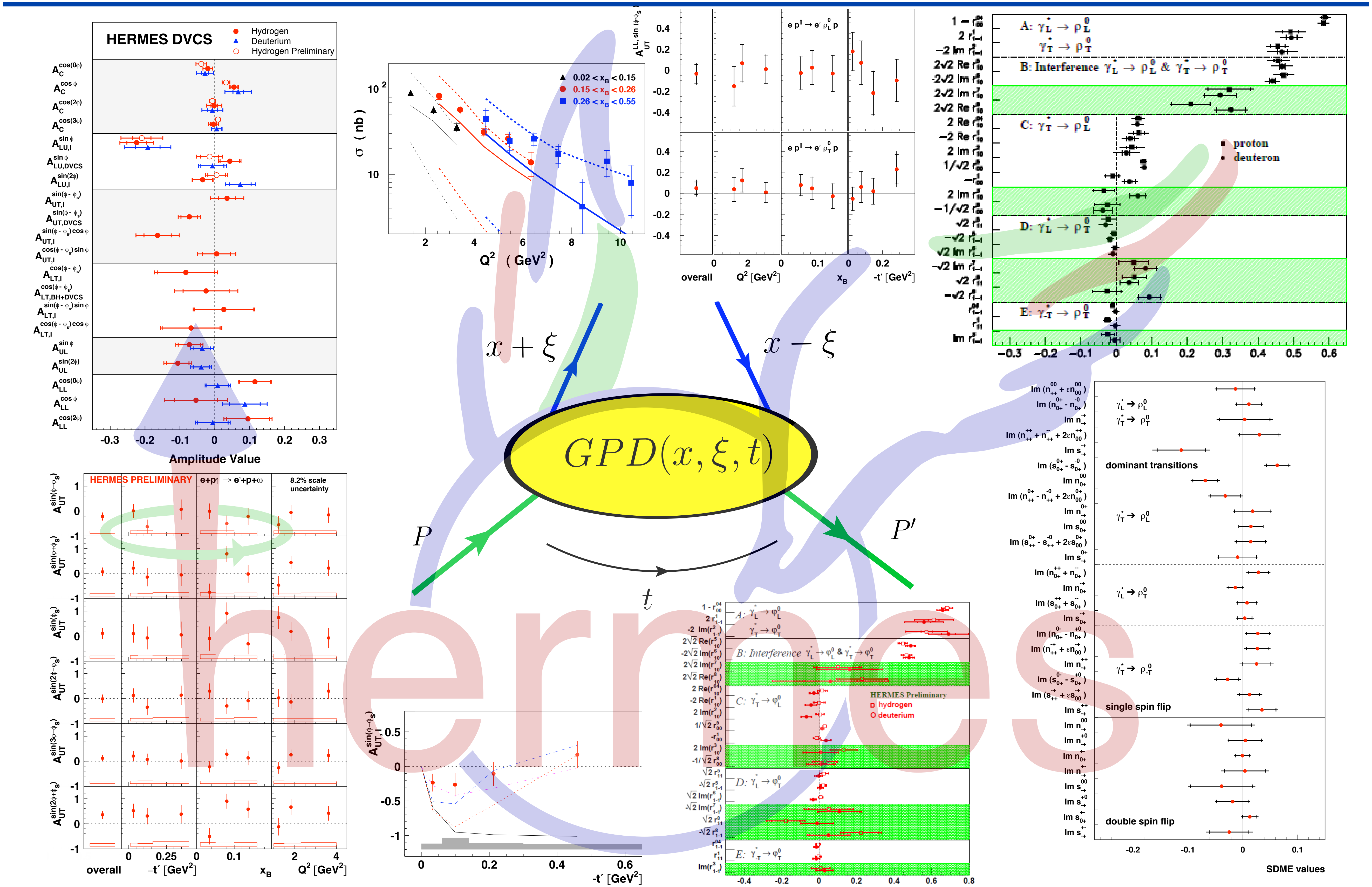


amplitude $A_{UT}^{\sin(\phi_S)}$

- 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 Preliminary
Amplitude Value
HERMES PRELIMINARY
8.2% scale uncertainty
overall
Q² (GeV²)
σ (nb)
0.02 < x_B < 0.15
0.15 < x_B < 0.26
0.26 < x_B < 0.55
A: γ*_L → ρ⁰_L
γ*_T → ρ⁰_T
B: Interference γ*_L → ρ⁰_L & γ*_T → ρ⁰_T
C: γ*_T → ρ⁰_L
D: γ*_L → ρ⁰_T
E: γ*_T → ρ⁰_T
proton
deuteron
x + ξ
x − ξ
GPD(x, ξ, t)
P
P′
t
dominant transitions
single spin flip
double spin flip
SDME values
HERMES Preliminary
hydrogen
deuterium
-t′ [GeV²]
hermes