Study of GPDs at HERMES

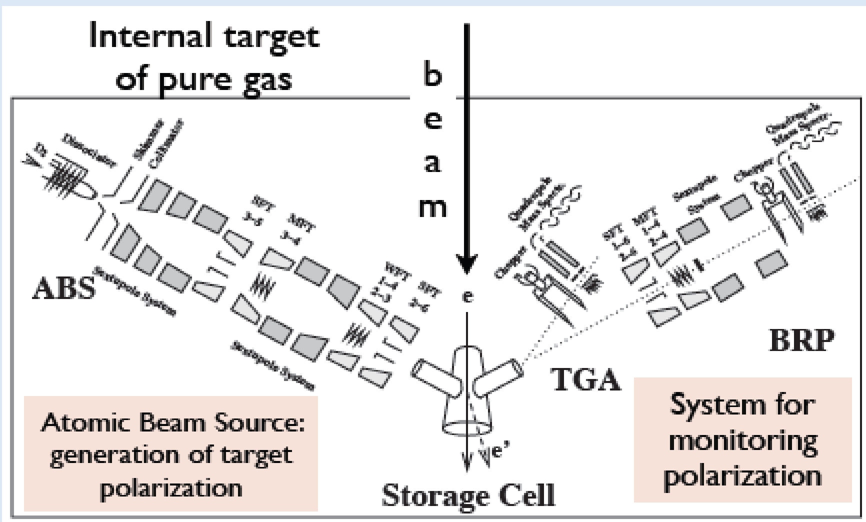
Hrachya Marukyan
AANL (Yerevan Physics Institute)
(on behalf of the HERMES Collaboration)

Correlations in Partonic and Hadronic Interactions 2020 (CPHI-20)
CERN, Geneva, Switzerland, Feb. 3-7, 2020

- HERMES experiment at HERA
- Exclusive reactions and GPDs
- DVCS: measurement of azimuthal asymmetries at HERMES
- Measurements of BSAs: use of Recoil Detector information
- Exclusive meson production and GPDs
- Summary

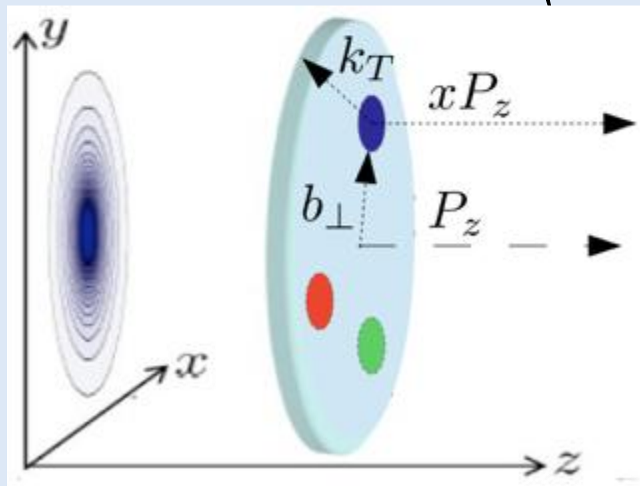
HERMES at DESY

Self-polarized e^+ and e^- beams
27.6 GeV
Helicity switched every few months



Polarized hydrogen (Long.,Trans.), deuterium (Long.)
Polarization flipped at 60-180 s time interval
Unpolarized *He,N,Ne,Kr,Xe*

Wigner distributions $W\left(x, \vec{k}_T, \vec{b}_\perp\right)$



$\int d^2 \vec{b}_\perp$

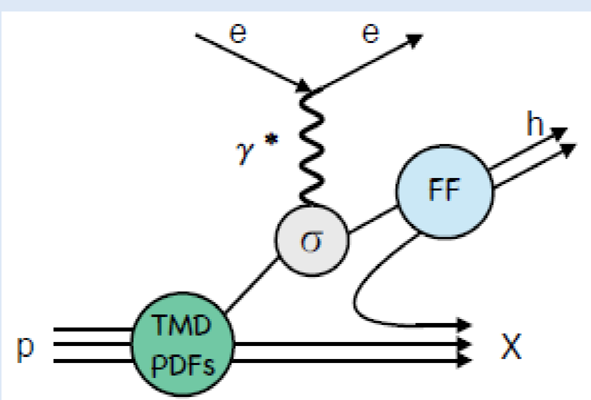
$\int d^2 \vec{k}_T$

TMD PDFs: $f_p^q(x, k_T)$,…

GPDs: $H_p^q(x, \xi, t)$, …

Semi-inclusive measurements
Direct info about momentum distribution

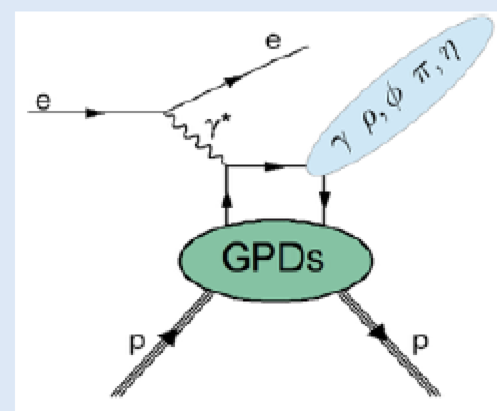
Exclusive Measurements
Direct info about spatial distribution



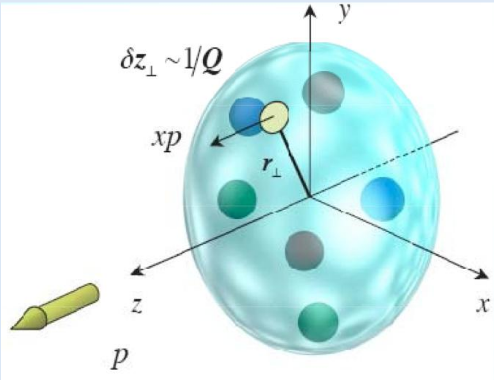
$\int d^2 \vec{k}_T$

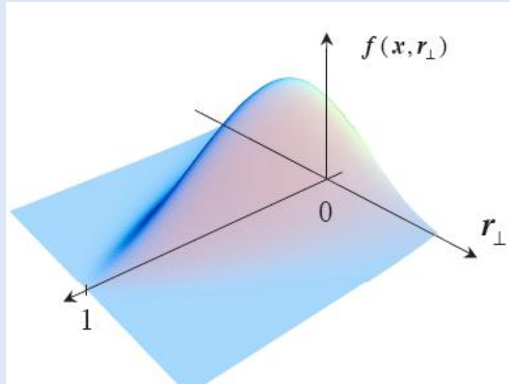
ξ=0, t=0

PDFs $f_p^q(x)$,…



Exclusive reactions & GPDs





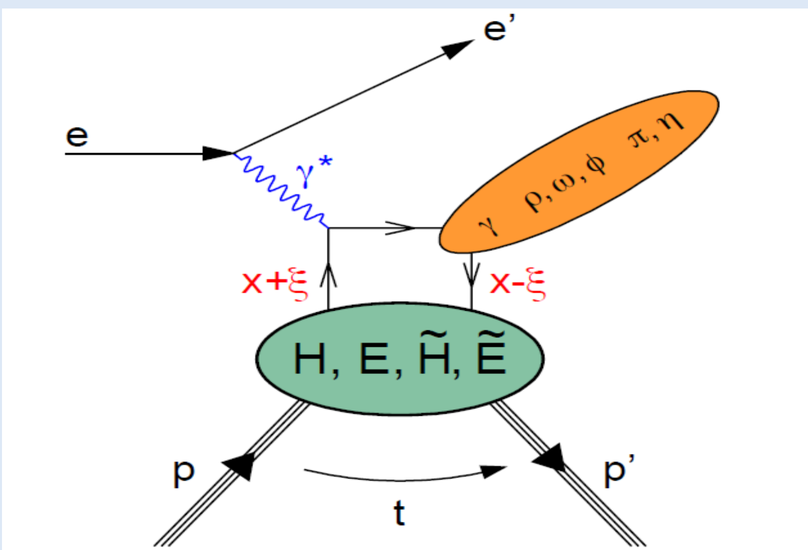
Ji sum rule ⟹ access OAM

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\,x[H^q(x,\xi,t)+E^q(x,\xi,t)]$$

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

Correlated information about longitudinal momentum xp and transverse spatial position $r_\perp$

H^q and E^q : quark Generalized Parton Distributions (GPDs)



Spin-½ target: 4 chiral-even leading-twist quark GPDs $H, E, \widetilde{H}, \widetilde{E}$

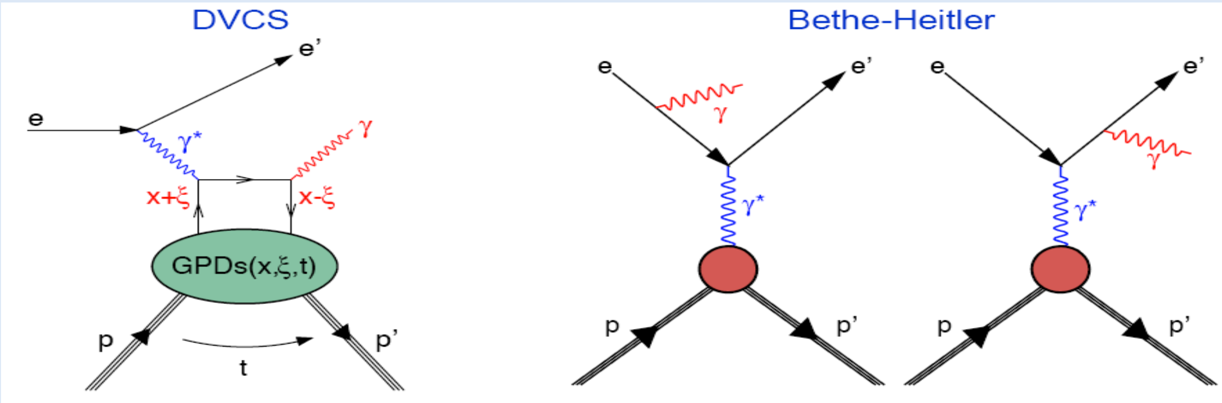
Final state sensitive to different GPDs

DVCS (γ) $H, E, \widetilde{H}, \widetilde{E}$

Vector mesons (ρ, ω, ϕ) $H, E,$

Pseudoscalar mesons (π,η) $\widetilde{H}, \widetilde{E}$

Deeply virtual Compton scattering & GPDs



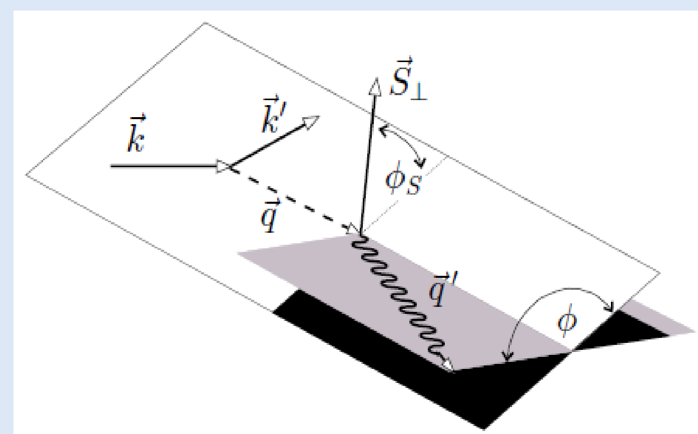
- Theoretically cleanest way to access GPDs
- Interference between DVCS and Bethe-Heitler amplitude
- $|\tau_{DVCS}| \ll |\tau_{BH}|$ at HERMES

Access to GPD combinations through azimuthal asymmetries

A_{XY} — X: beam, Y: target

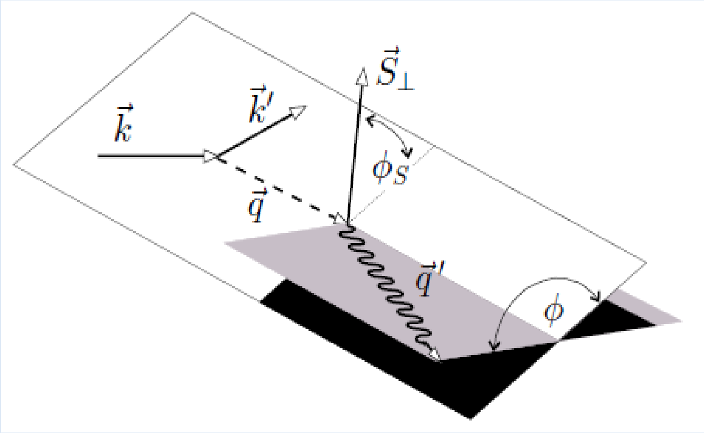
HERMES: Complete set of asymmetries

- Both beam charges
- Both beam helicities
- Unpolarized ^1H, ^2H, and also nuclear targets
- Longitudinally polarized ^1H and ^2H targets
- Transversely polarized ^1H target
- Recoil detector: unpolarized ^1H and ^2H



Accessing GPDs in DVCS

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



Compton Form Factors: convolutions of GPDs with hard scattering kernels

$$\mathcal{F}(\xi,t)=\sum_q\int_{-1}^{1}\mathrm{d}x\,C_q^{\mp}(\xi,x)F^q(x,\xi,t)$$ → GPD

DVCS without recoil detector

- Event with exactly one DIS–lepton and exactly one trackless cluster in the calorimeter.
- No recoil detection ➡ Exclusivity via missing mass: $M_X^2=(q + P - q')^2$

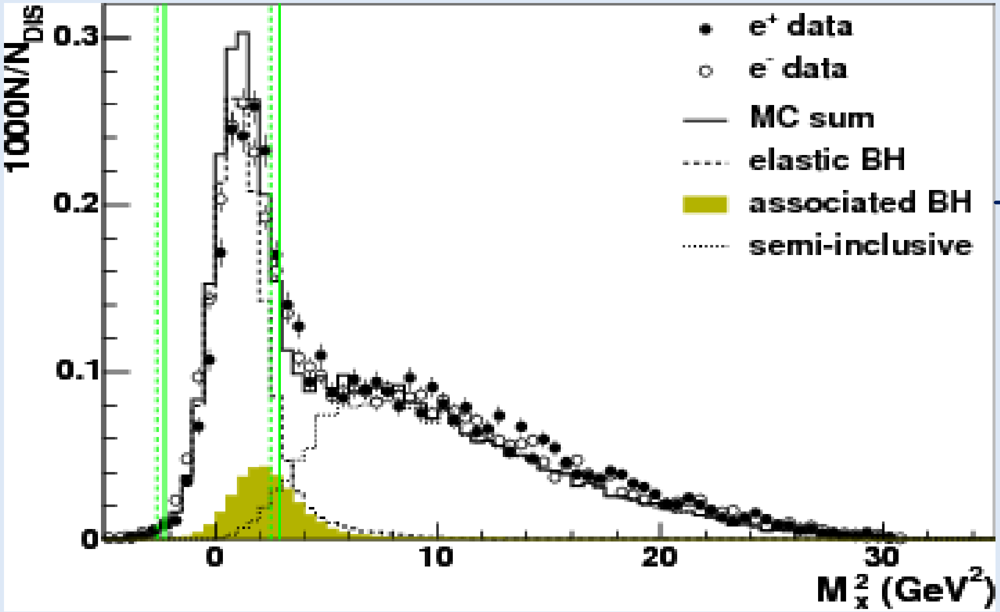
$5 < \Theta_{\gamma^*\gamma} < 45$ mrad

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

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

$W > 3$ GeV, $\nu < 22$ GeV

MC for background and cuts, systematic uncertainty



$e\ p \rightarrow e'\ X\ \gamma$

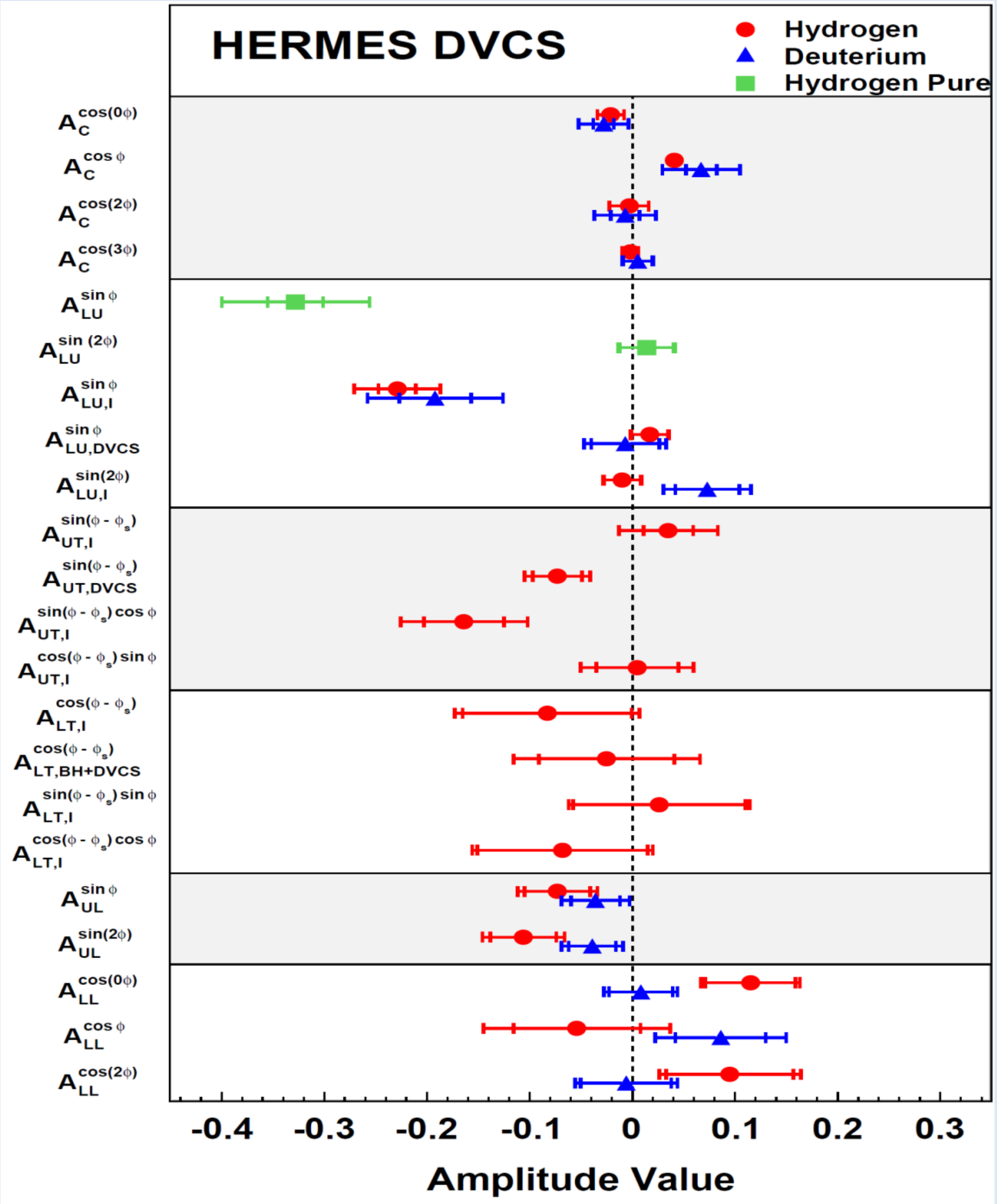
- $e\ p \rightarrow e'\ p\ \gamma$; elastic BH
- $e\ p \rightarrow e'\ \Delta^+\ \gamma$; associated BH
- $e\ p \rightarrow e'\ \pi^0\ X$; semi-inclusive

Correction; π^0 background ($\approx$ 3%)

Associated ($\approx$ 12%) ; part of signal

➡ Exclusive bin ($-(1.5)^2 < M_X^2 < (1.7)^2$ GeV^2)

DVCS asymmetries at HERMES



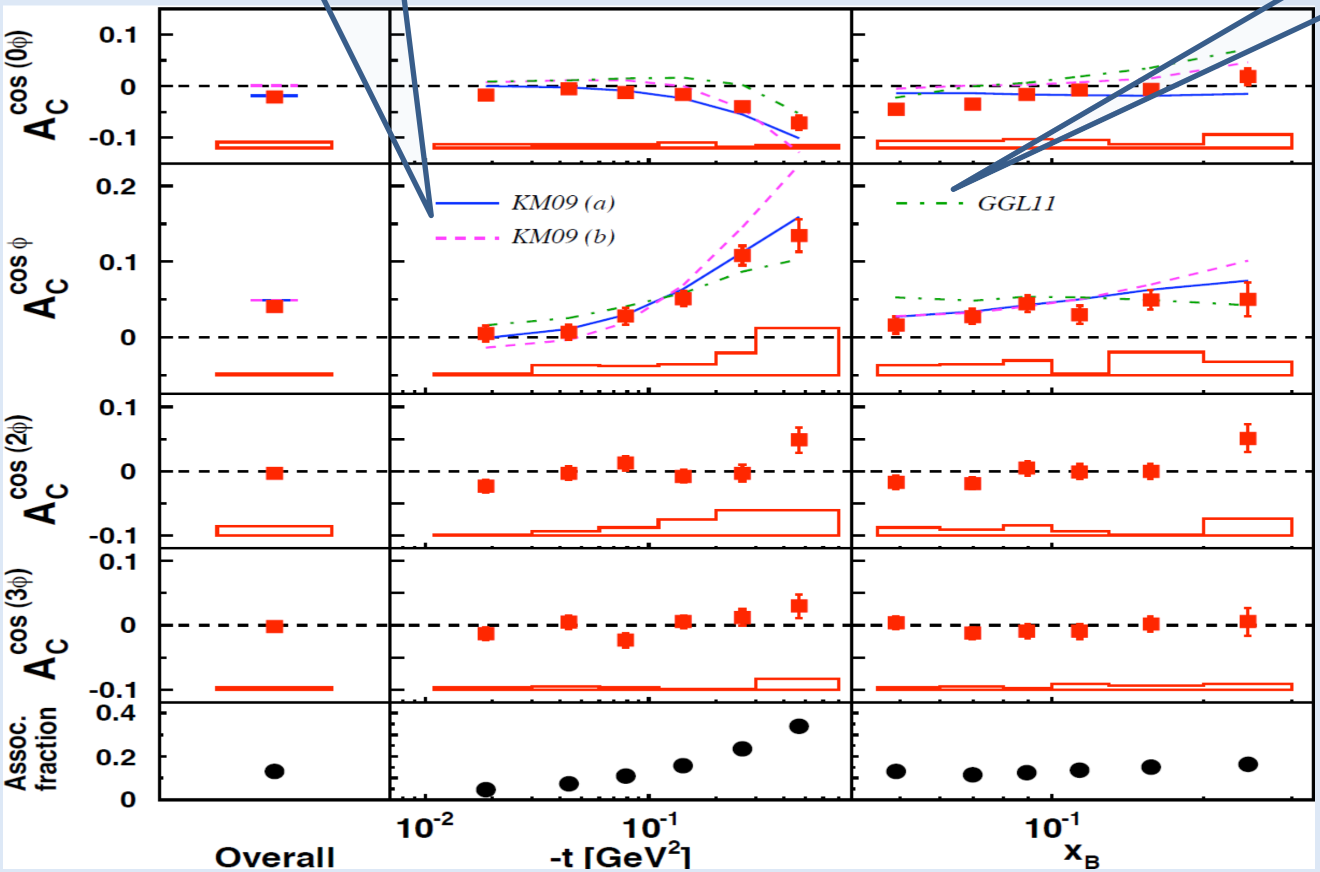
- Beam-charge asymmetry
  GPD H H: PRL 87 (2001) 182001
  PRD 75 (2007) 011103
  JHEP 11 (2009) 083
  JHEP 07 (2012) 032 JHEP 10 (2012) 042
  D: Nucl. Phys. B 829 (2010)1
- Beam-spin asymmetry
  GPD H
- Transverse target-spin asymmetry
  GPD E H: JHEP 06 (2008) 066
- Transverse double-spin asymmetry
  GPD E H: Phys. Lett. B 704 (2011) 15
- Longitudinal target spin asymmetry
  GPD $\tilde{H}$ H: JHEP 06 (2010) 019
  D: Nucl. Phys. B 842 (2011) 265
- Longitudinal double spin asymmetry
  GPD $\tilde{H}$

Beam-charge asymmetry A_C

KM09:global fit
Including data from HERA
HERMES and Jlab
K. Kumerički, D. Müller
Nucl. Phys. **B 84** (2010) 1

JHEP 07 (2012) 032, arXiv:1203.6287

GGL11:model calculation
G. Goldstein, S. Liuti,
J. Hernandez
Phys. Rev. **D 84** 034007 (2010)



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

$\propto \Re e\,[F_1\mathcal{H}]$

Higher twist

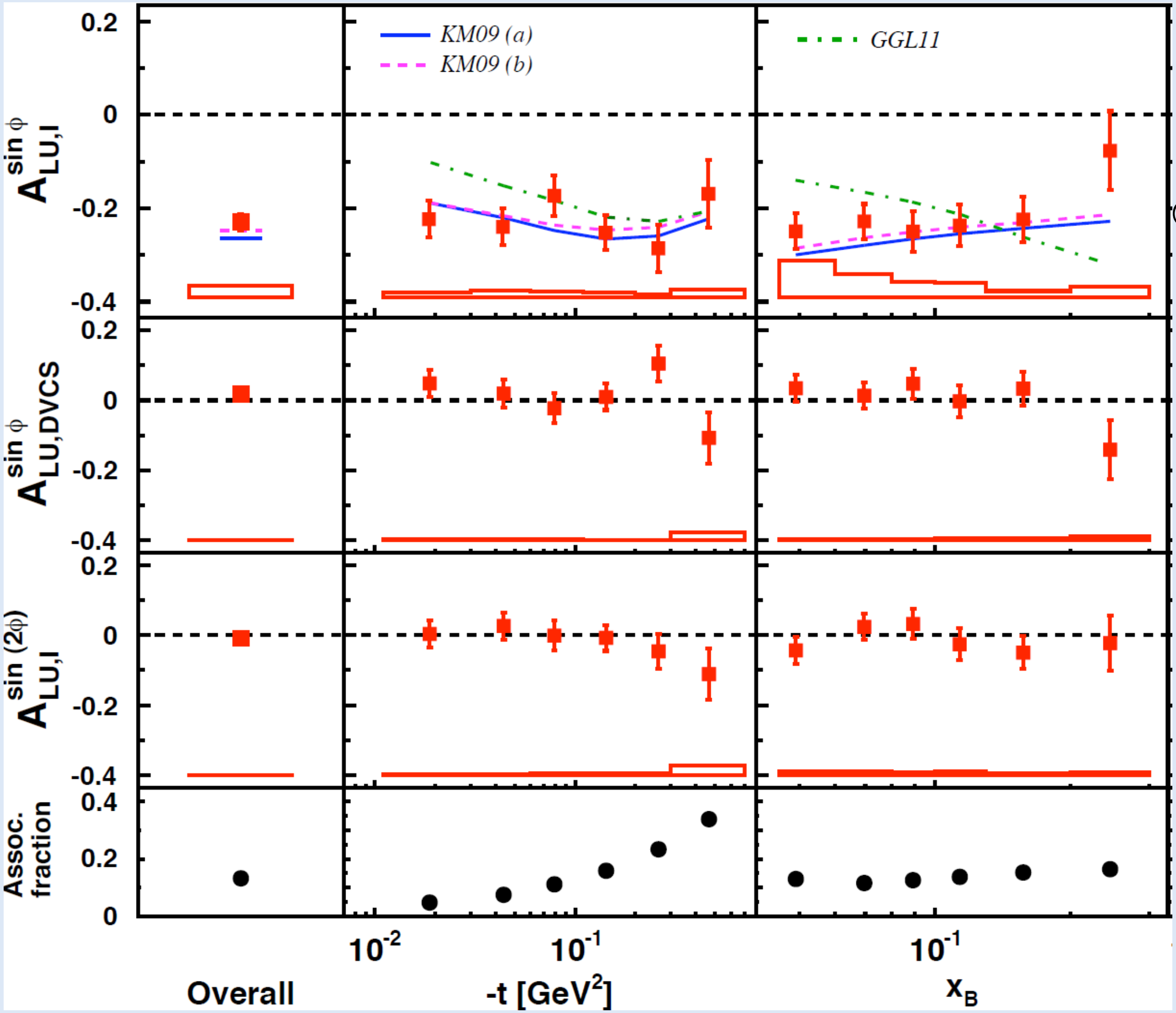
Gluon leading twist

Fractions of associated process from MC

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

Beam-charge-separated asymmetries $A_{LU,I}$ & $A_{LU,DVCS}$

JHEP 07 (2012) 032, arXiv:1203.6287



$\propto \Im m\,[F_1\mathcal{H}]$

$\propto \Im m\,[\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*]$

Higher twist

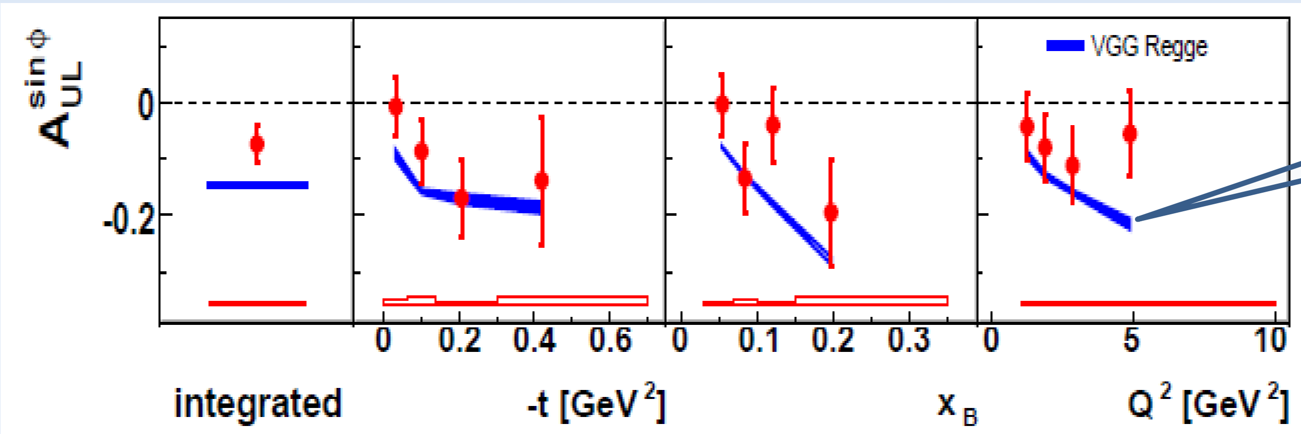
Fractions of associated process from MC

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

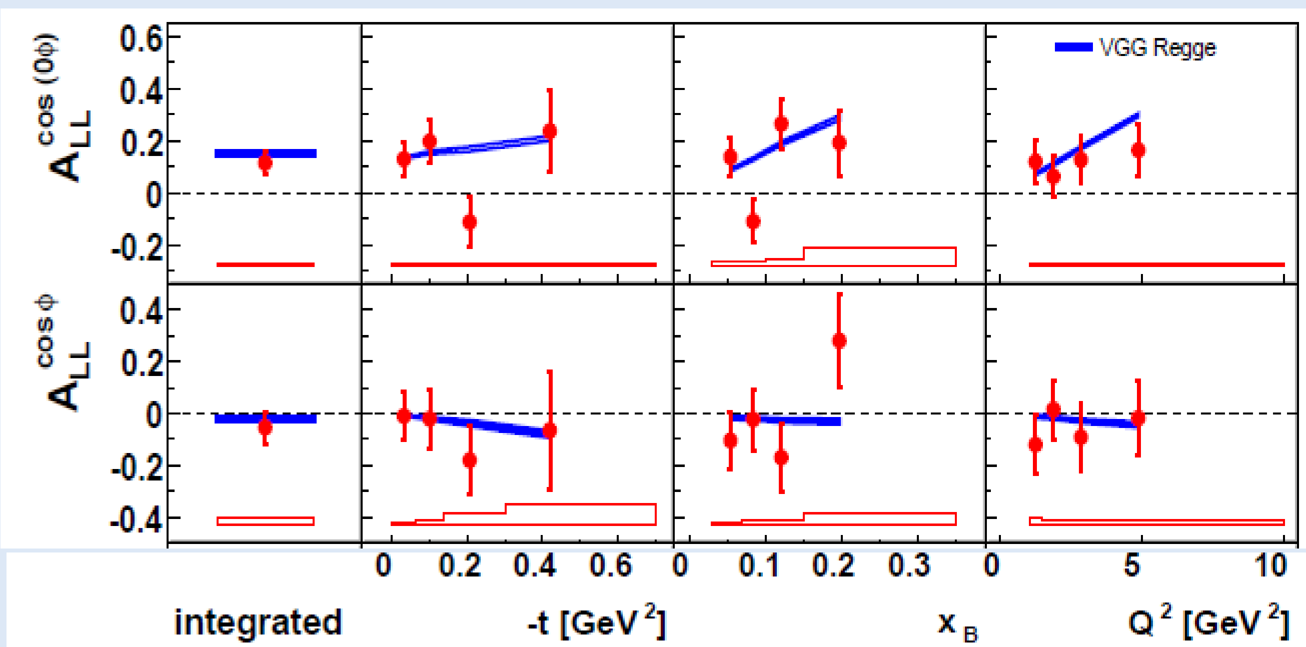
Longitudinal single- and double-spin asymmetries $A_{U(L)L}$

JHEP 06 (2010) 019, arXiv:1004.0177

VGG: model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys. Rev. **D60** (1999) 0940177
Prog. Nucl. Phys. **47** (2001) 401



$$\propto \Im m\,[F_1\tilde{\mathcal{H}}]$$

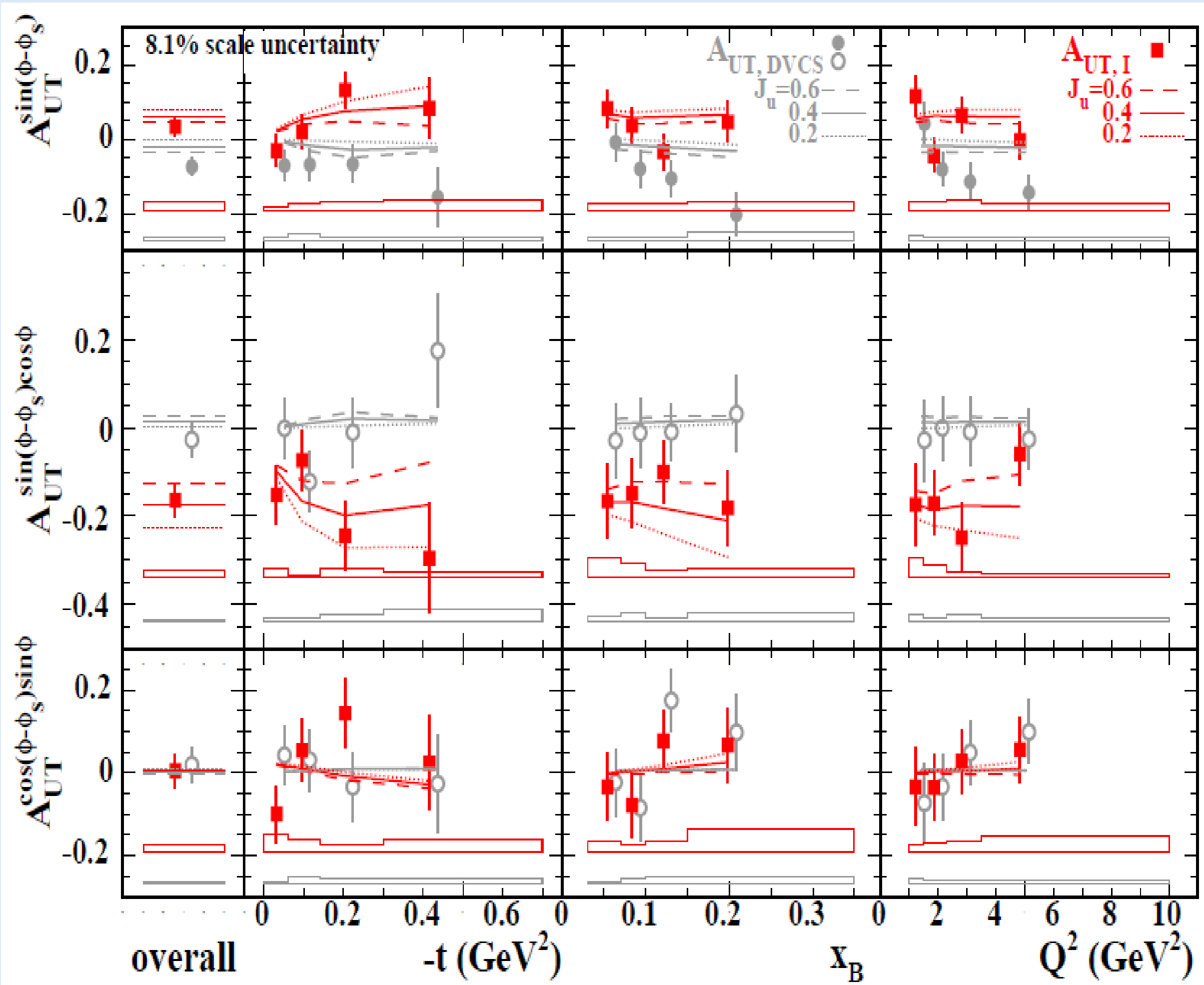


Relatively large BH contribution to these asymmetries

$$\propto \Re e\,[F_1\tilde{\mathcal{H}}]$$

DVCS: Transverse target-spin asymmetry A_{UT}

Sensitive to GPD E JHEP 06 (2008) 066, arXiv:0802.2499



Sensitive to J_u

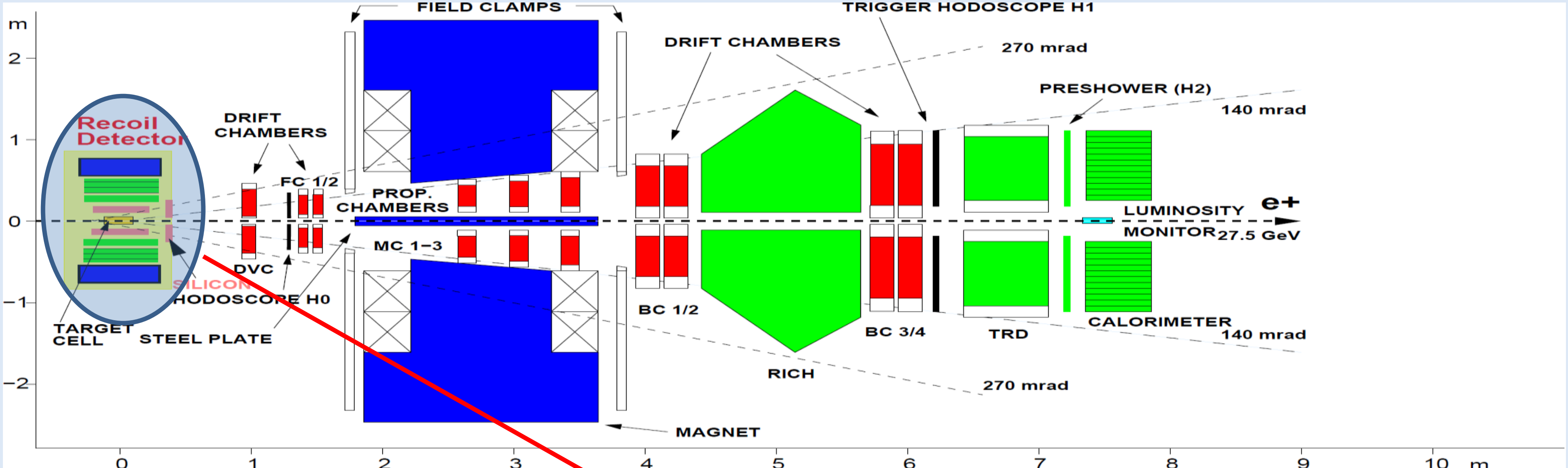
$$\propto \Im m\,[F_2\mathcal{H} - F_1\mathcal{E}]$$

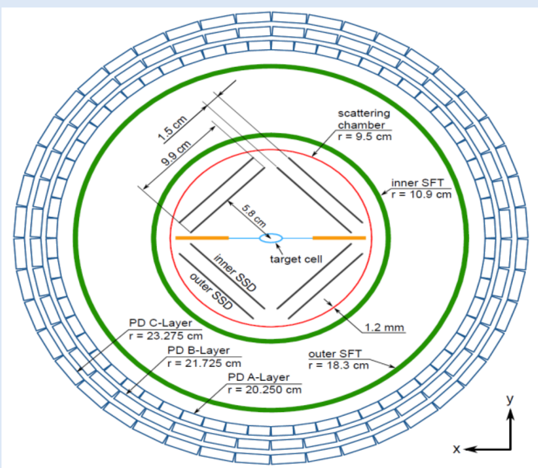
Not sensitive to J_u

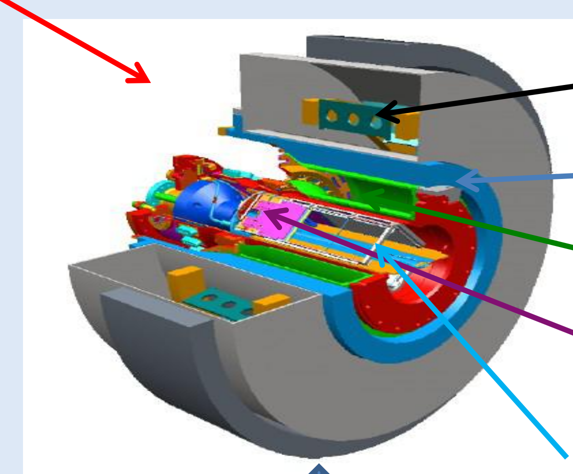
$$\propto \Im m\,[F_2\tilde{\mathcal{H}} - (F_1 + \xi F_2)\tilde{\mathcal{E}}]$$

Model: VGG with variation of J_u, while J_d=0

DVCS with recoil detector





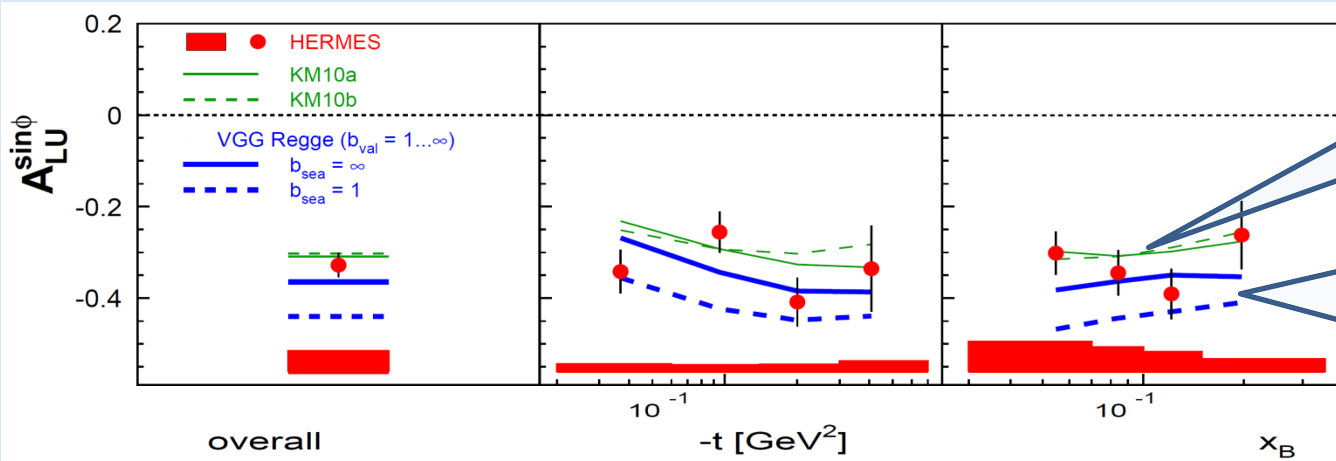


Recoil Detector to tag exclusivity

A. Airapetian et al., JINST B (2013) P05012

Pure elastic DVCS

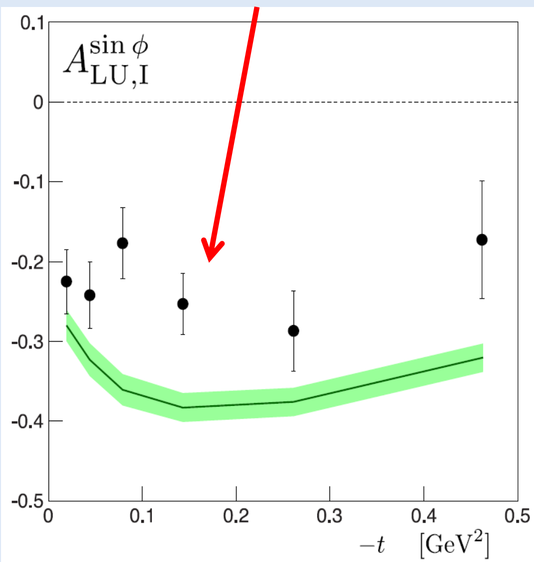
JHEP 10 (2012) 042, arXiv:1206.5683



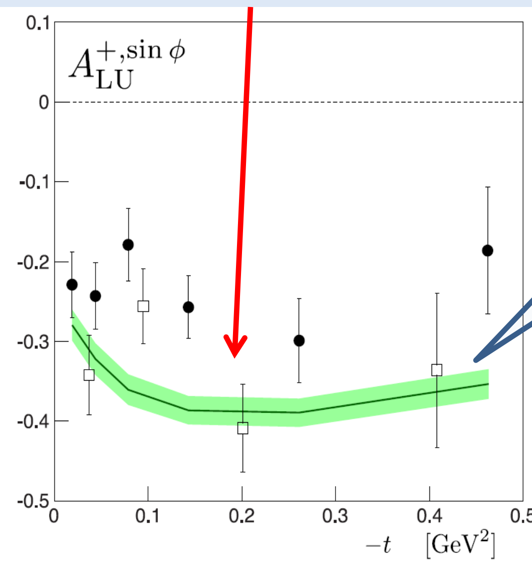
KM10:global fit
Including data from HERA
HERMES and Jlab
K. Kumerički, D. Müller
Nucl. Phys. **B 84** (2010) 1

VGG: model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys. Rev. **D60** (1999) 0940177
Prog. Nucl. Phys. **47** (2001) 401

JHEP 07 (2012) 032



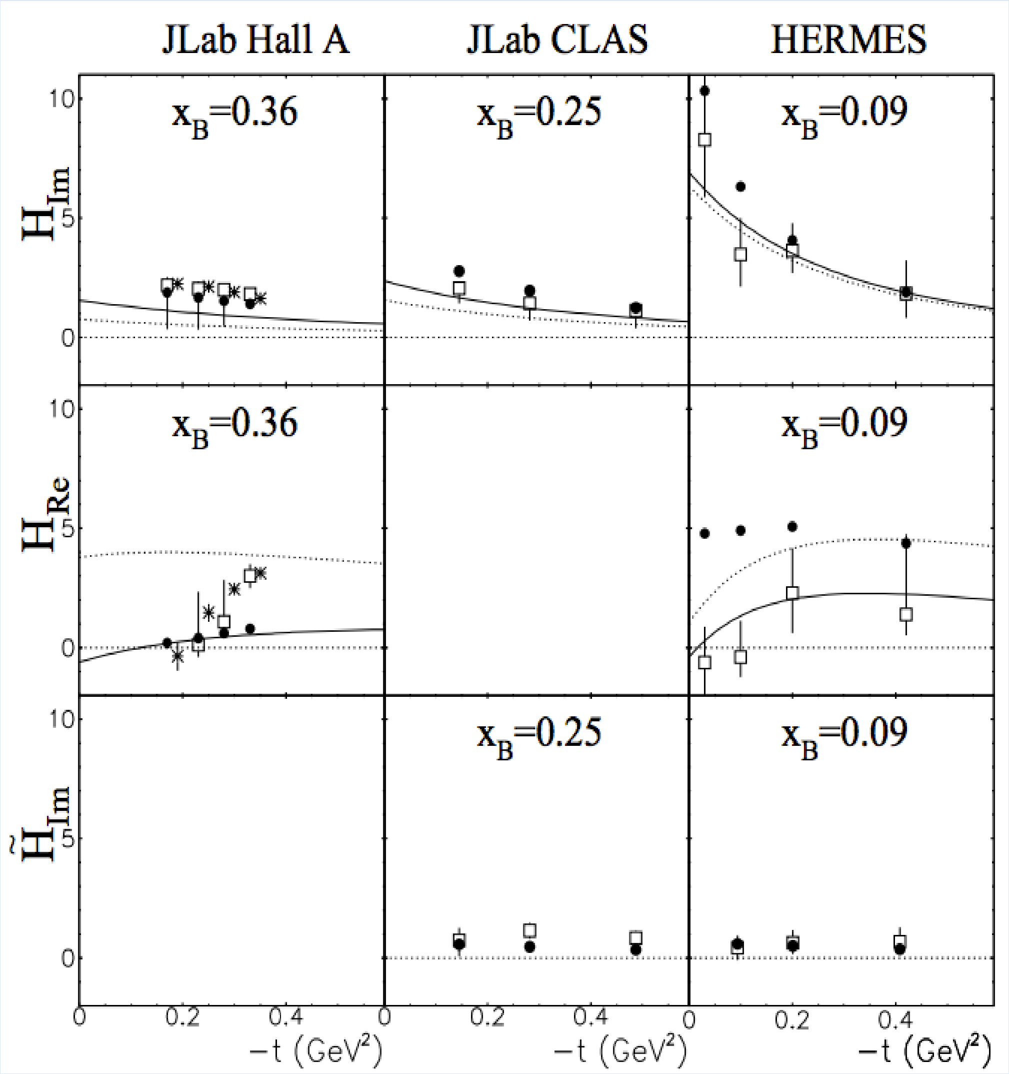
JHEP 10 (2012) 042



KMS: model calculation
GPDs are extracted from HEMP.
P. Kroll, H Moutarde, F. Sabatie,
Eur. Phys. J. C **73** (2001) 2278

The leading amplitude for pure elastic process is well described by recent fits to previously published data and by KMS model fit to exclusive meson data.

M. Guidal ICHEP Proc. (2010) 148



CFFs are extracted from experimental measurements

- VGG model:
  GPD H in this model is not consistent with experimental results.

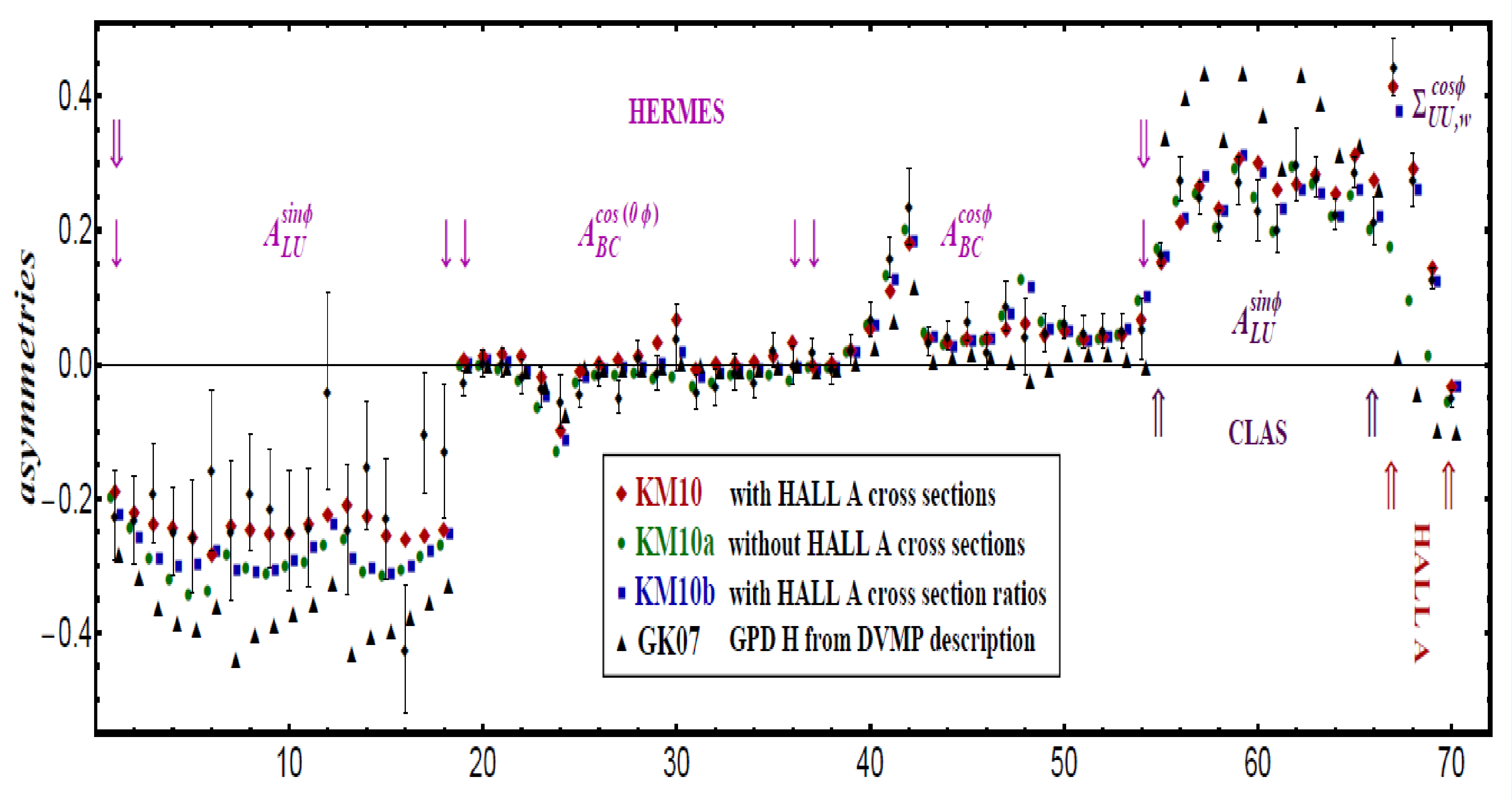
❑ M. Guidal, ICHEP Proc. (2010) 148

⋆ H. Moutarde, Phys. Rev. **D** 79 (2009)

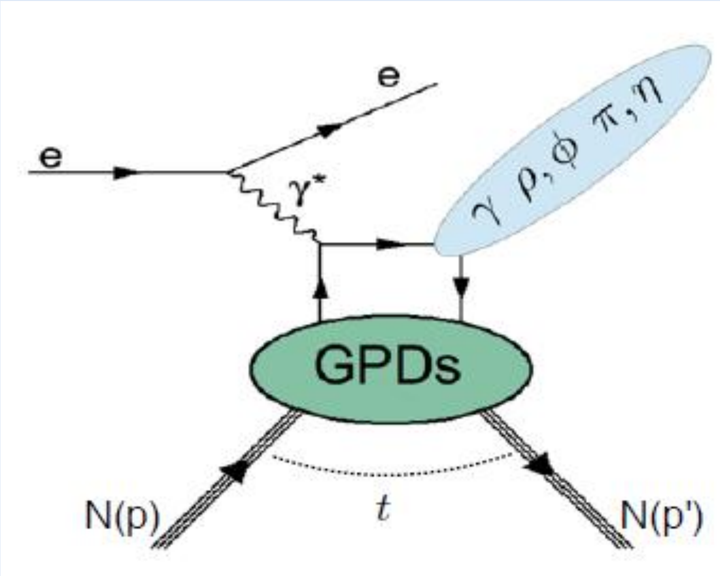
<u>Curves:</u>
K. Kumericki, D. Muller
Nucl. Phys. **B** 841 (2010)

Results of different fits

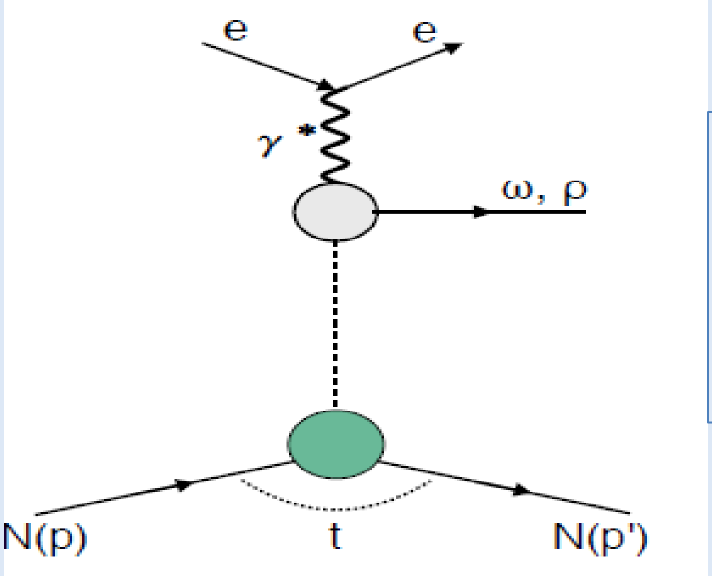
D. Müller: Few Body Syst. 55 (2014) 317-337



Exclusive meson production



- Probes various types of GPDs with different sensitivity and different flavour combinations
- Complementary to DVCS process
- Unpolarized target:
  nucleon-helicity-non-flip GPDs $H, \tilde{H}$ and
  $\bar{E}_T = 2\tilde{H}_T + E_T$.
- Transversely polarized target:
  nucleon-helicity-flip GPDs $E, \tilde{E}$ and H_T.



NPE ($J^P = 0^+, 1^-, 2^+ \ldots$) (two-gluon exchange = pomeron, ρ, ω, f_2, a_2, ... reggeons = $\bar{q}q$ exchange):
GPDs H and E

UPE ($J^P = 0^-, 1^+, \ldots$) (π, a_1, b_1,...reggeons = $\bar{q}q$ exchange):
GPDs $\tilde{H}$ and $\tilde{E}$

Angular distribution and extraction of SDMEs

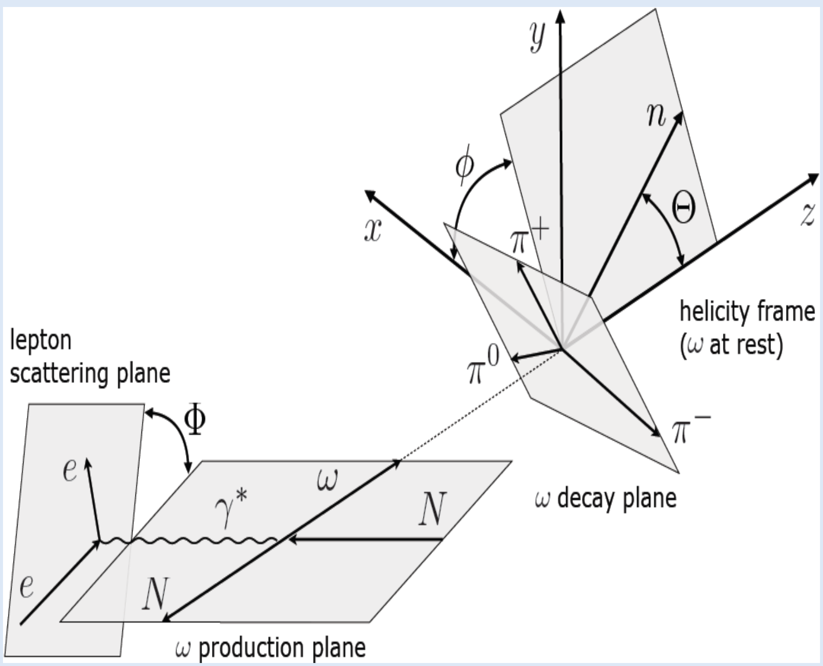
Three-dimensional angular distribution $W^{U+L}(\Phi, \phi, \cos\Theta)$ depends linearly on SDMEs – $r^{\alpha}_{\lambda_V \lambda'_V}$ and beam polarization P_b

$$r^{\alpha}_{\lambda_V \lambda'_V} \sim \rho_{\lambda_V \lambda'_V} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\alpha}_{\lambda_\gamma \lambda'_\gamma} F^{*}_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

$\gamma^* (\lambda_\gamma) + N (\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N)$

Photon SDMEs

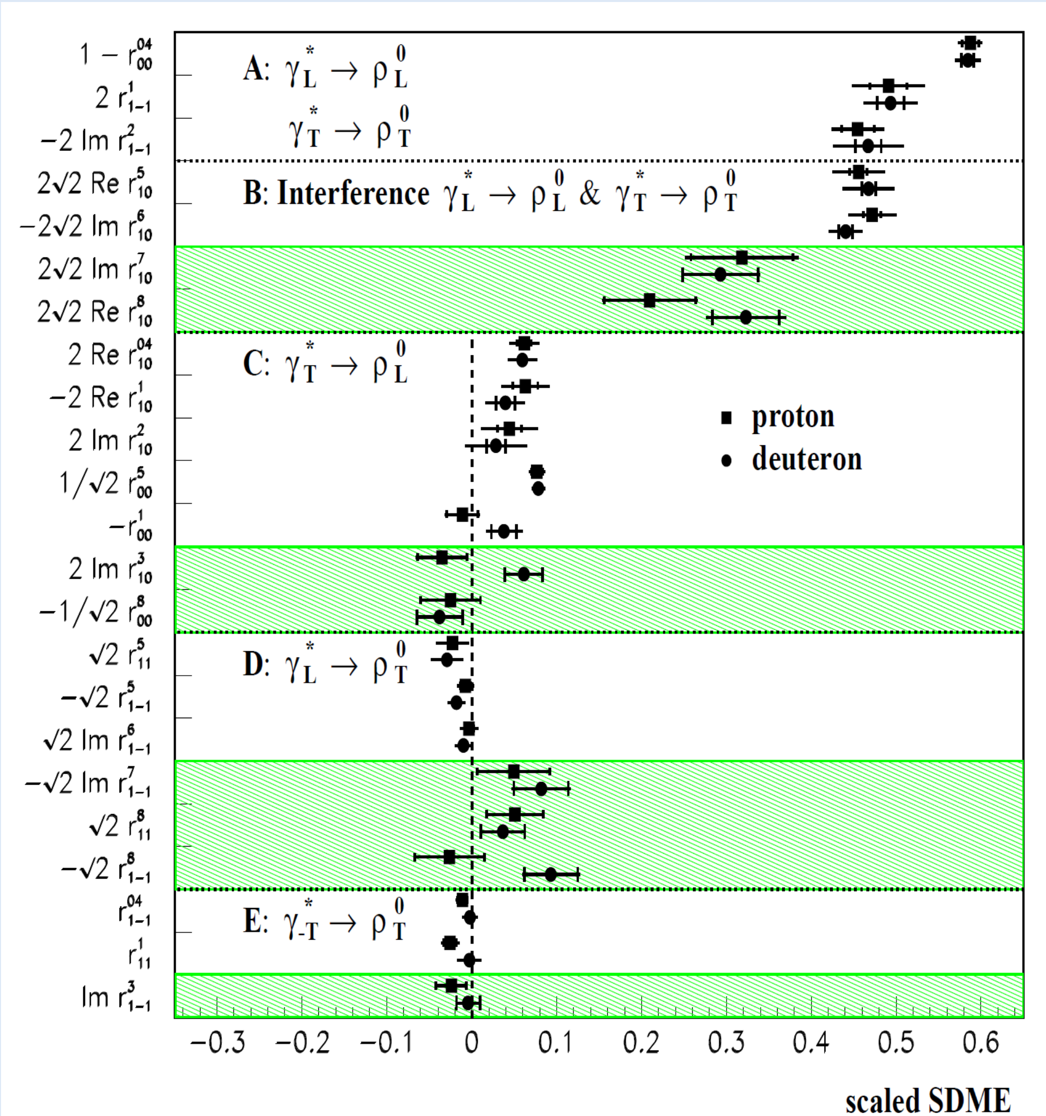
Helicity amplitudes



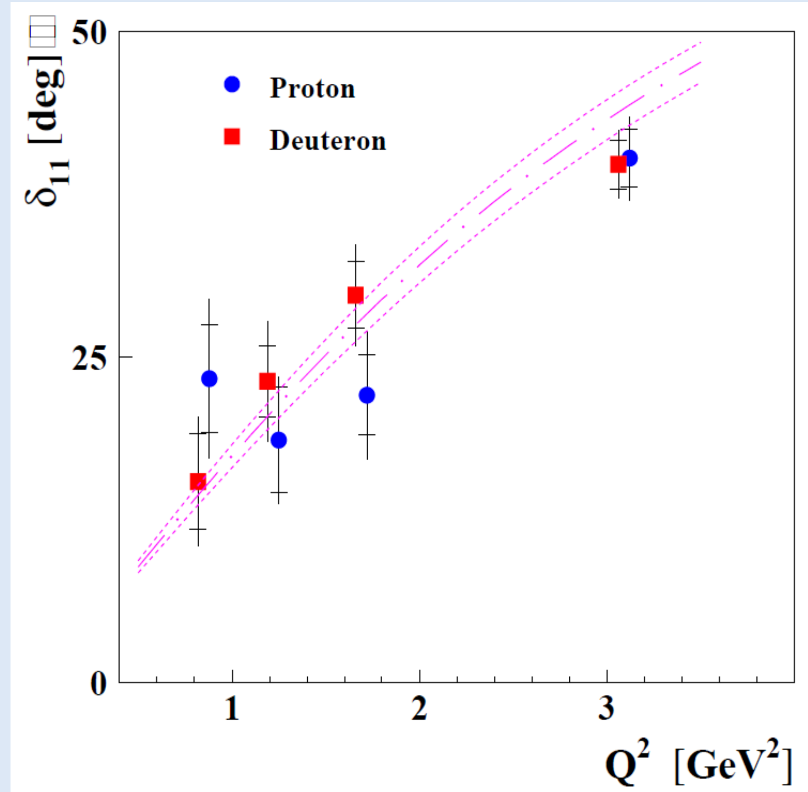
- Helicity amplitudes are the fundamental quantities to be compared with theory.
- They form a basis for the SDMEs.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs: 15 unpolarized and 8 polarized.
- The SDMEs are extracted by fitting the angular distribution $W^{U+L}(\Phi, \phi, \cos\Theta)$ to the experimental angular distribution of pions from ω - decay using unbinned Maximum Likelihood method.

ρ^0 – meson production: SDMEs

Eur. Phys. J. C 62 (2009) 659



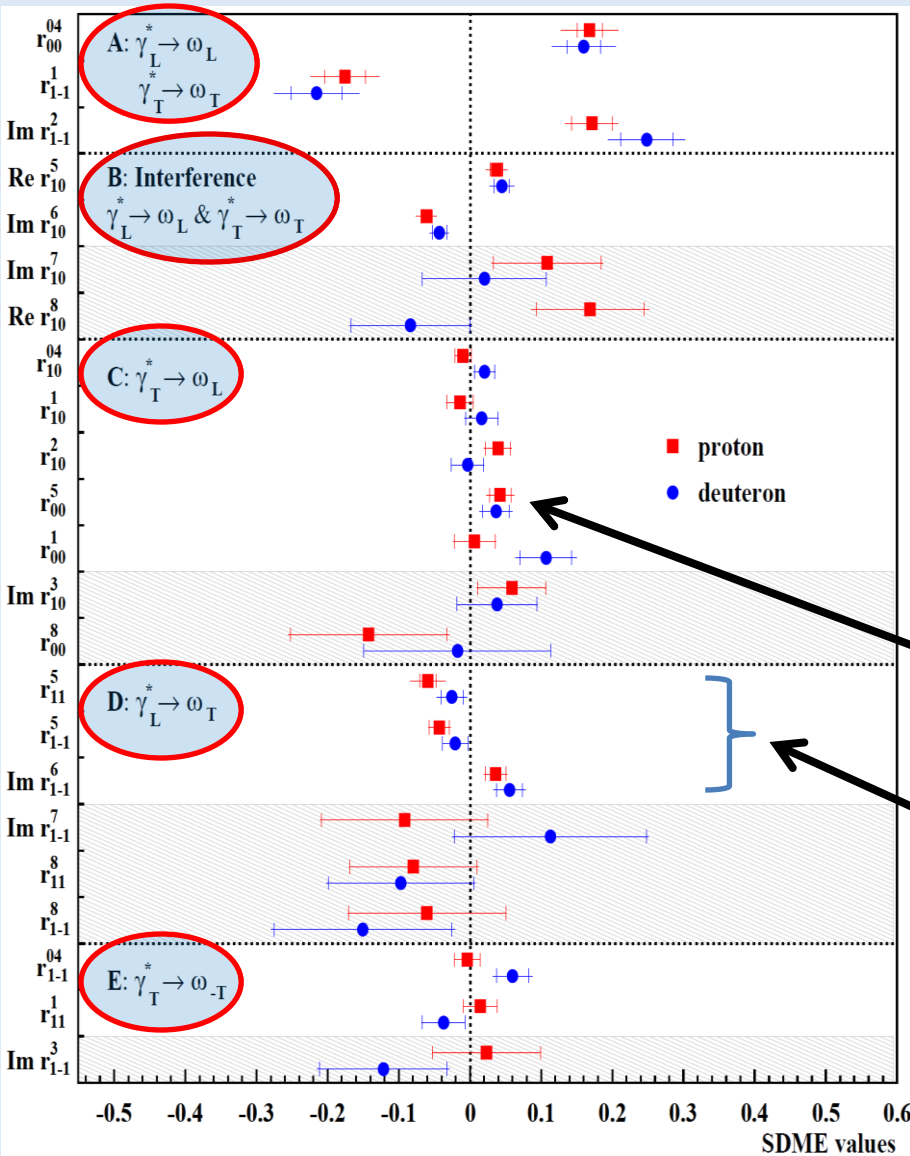
Eur. Phys. J. C 71 (2011) 1609



Extraction of SDMEs and helicity amplitude ratios at HERMES for ρ^0 – mesons challenges GPD-based calculations (giving small values).

SDMEs in exclusive ω production

Eur. Phys. J. C 74 (2014) 3110



- 5 classes of SDMEs
- Unpolarized and polarized SDMEs
- Similar magnitudes of SDMEs on proton & deuteron
- SCHC (S-Channel Helicity Conservation): holds for class – A & class – B SDMEs:

$$\begin{cases} r^1_{1-1} = -\mathrm{Im}\, r^2_{1-1} \\ \mathrm{Re}\, r^5_{10} = -\mathrm{Im}\, r^6_{10} \\ \mathrm{Im}\, r^7_{10} = \mathrm{Re}\, r^8_{10} \end{cases}$$

- SCHC: slightly violated for class – C

$r^5_{00} \neq 0$ by 3(2) σ for p(d)

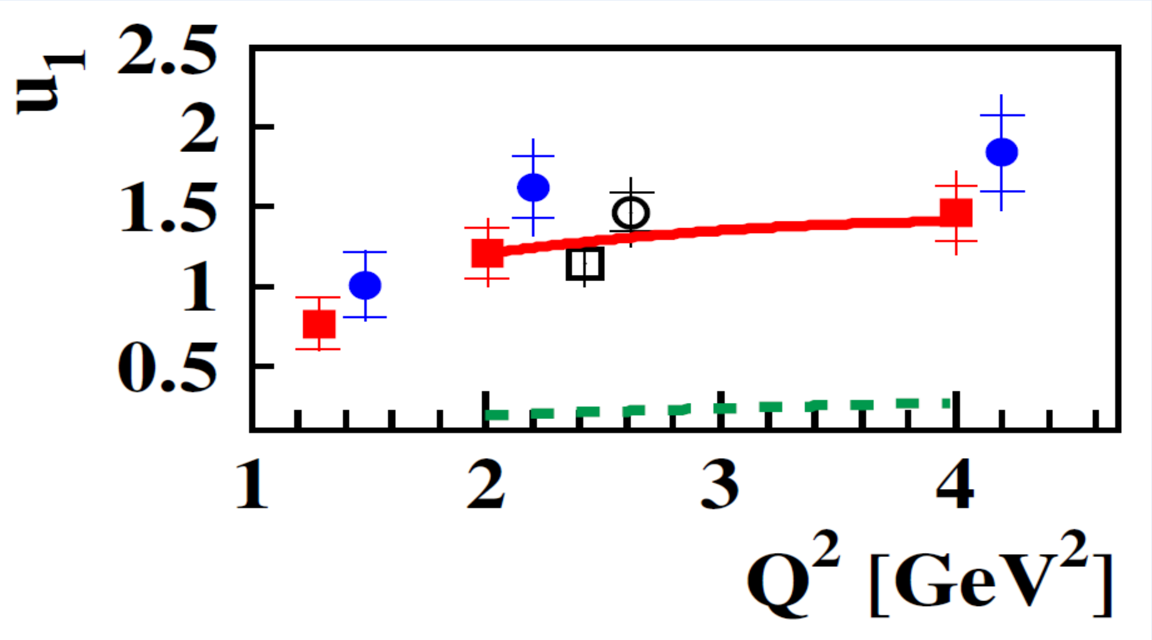
- SCHC: slightly violated for class – D

$r^5_{11} + r^5_{1-1} - \mathrm{Im}\, r^6_{1-1} \neq 0$ by 3(2.5) σ for p(d)

Extraction of πω transition form factor

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

Eur. Phys. J. C 74 (2014) 3110



GK model
S. Goloskokov & P. Kroll,
Eur. Phys. J. A 50 (2014) 146

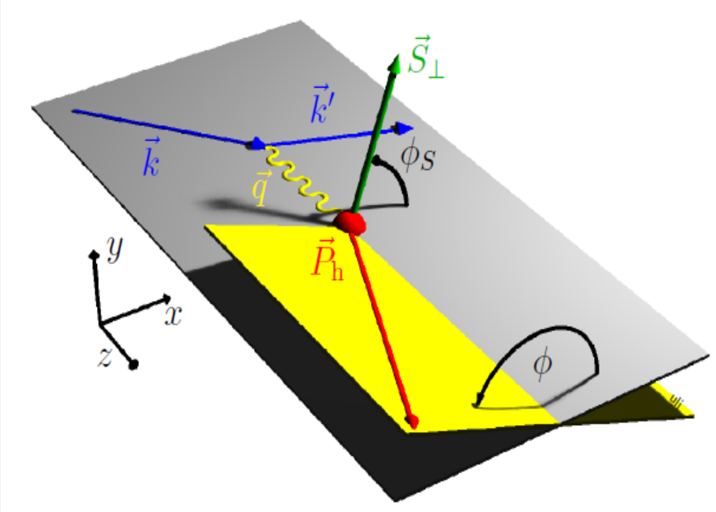
Only the magnitude of the πω transition form factor (not the sign) can be evaluated.

- The solid line show the calculation of the GK model with pion-pole contribution
  Dashed line are the model results without the pion-pole.
- The pion-pole contribution seems to account completely for UPE.

Exclusive ω - meson production: A_{UT} asymmetry

$e(k) + N(p) \to e(k') + N(p') + \omega$

$\omega \to \pi^+ \ \pi^- \ \pi^0, \ \pi^0 \to 2\gamma$



Angular dependent part

$$w(\phi,\phi_S) = 1 + A_{UU}^{\cos(\phi)}\cos(\phi) + A_{UU}^{\cos(2\phi)}\cos(2\phi)$$
$$+ S_\perp\Big[A_{UT}^{\sin(\phi+\phi_S)}\sin(\phi+\phi_S) + A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S)$$
$$+ A_{UT}^{\sin(\phi_S)}\sin(\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S) + A_{UT}^{\sin(3\phi-\phi_S)}\sin(3\phi-\phi_S)\Big]$$

$$w(\phi,\phi_S,\theta) = \frac{3}{2}r_{00}^{04}\cos^2(\theta)\,w_L(\phi,\phi_S) + \frac{3}{4}\left(1-r_{00}^{04}\right)\sin^2(\theta)\,w_T(\phi,\phi_S)$$

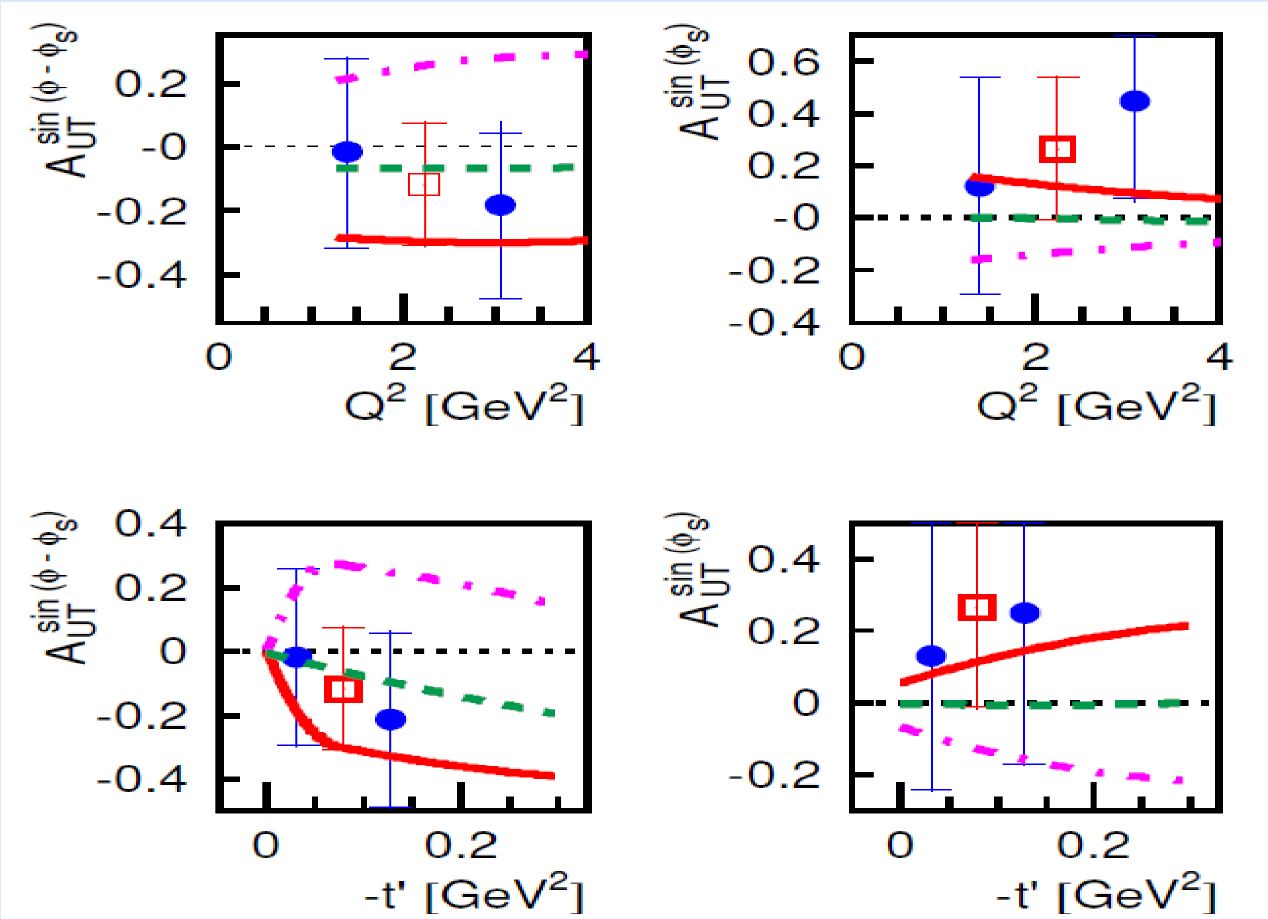
$$w_L(\phi,\phi_S) = 1 + A_{UU,L}(\phi) + S_\perp A_{UT,L}(\phi,\phi_S)$$

$$w_T(\phi,\phi_S) = 1 + A_{UU,T}(\phi) + S_\perp A_{UT,T}(\phi,\phi_S)$$

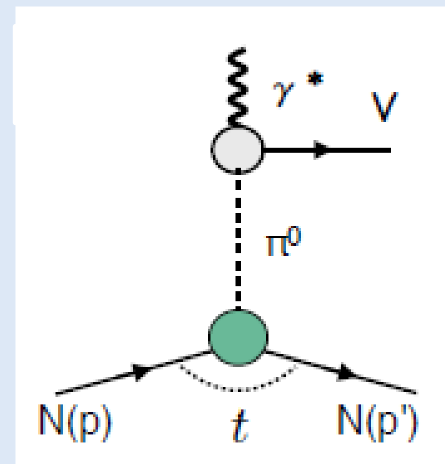
Fit angular distributions of ω–decay pions

Exclusive ω - meson production: amplitudes of A_{UT}

Eur. Phys. J. C 75 (2015) 600



GK model
S. Goloskokov & P. Kroll,
Eur. Phys. J. A 50 (2014) 146



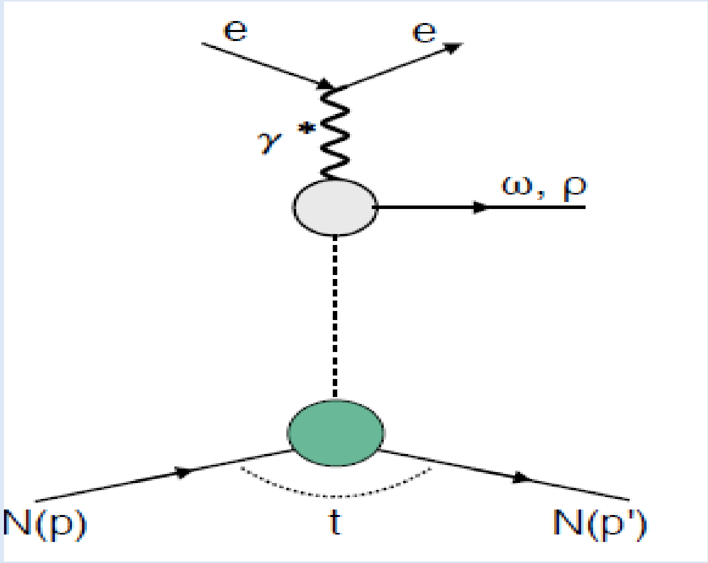
Pion pole

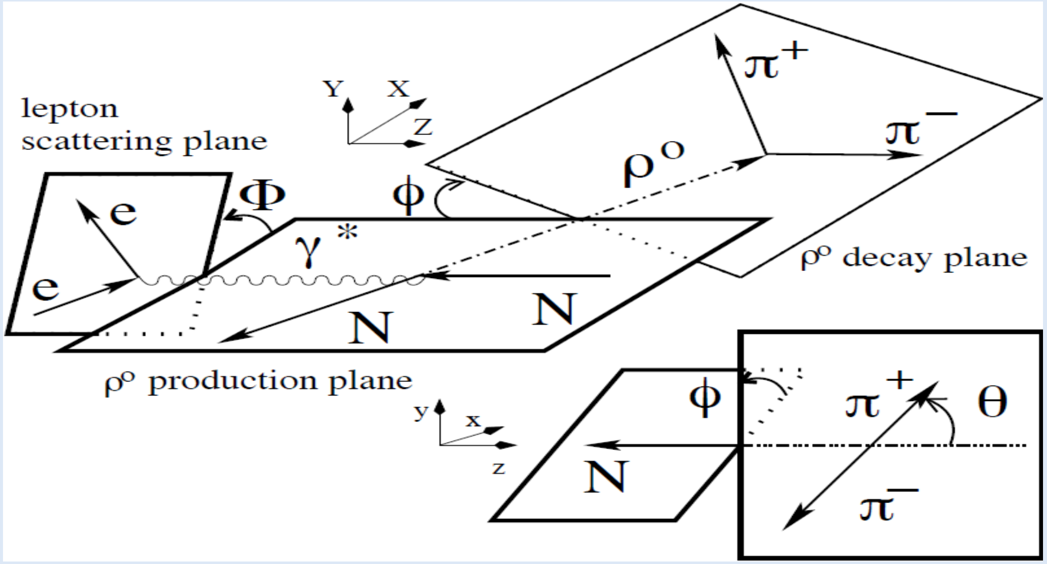
$$\left(\propto \frac{1}{t - m_{\pi}^{2}} \right)$$

- The solid (dash-dotted) lines show the calculation of the GK model for a positive (negative) $\pi\omega$ transition form factor
- Dashed lines are the model results without the pion pole.

Exclusive ρ^0 – meson production: helicity ratios

$$e(k) + N(p) \dashrightarrow e(k') + N(p') + \rho^0$$
$$\rho^0 \dashrightarrow \pi^+ \ \pi^-$$





$\gamma^* (\lambda_\gamma) + N (\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

Helicity amplitude ratios:

$$t^{(n)}_{\lambda_V \lambda_\gamma} = T^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$
$$u^{(n)}_{\lambda_V \lambda_\gamma} = U^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

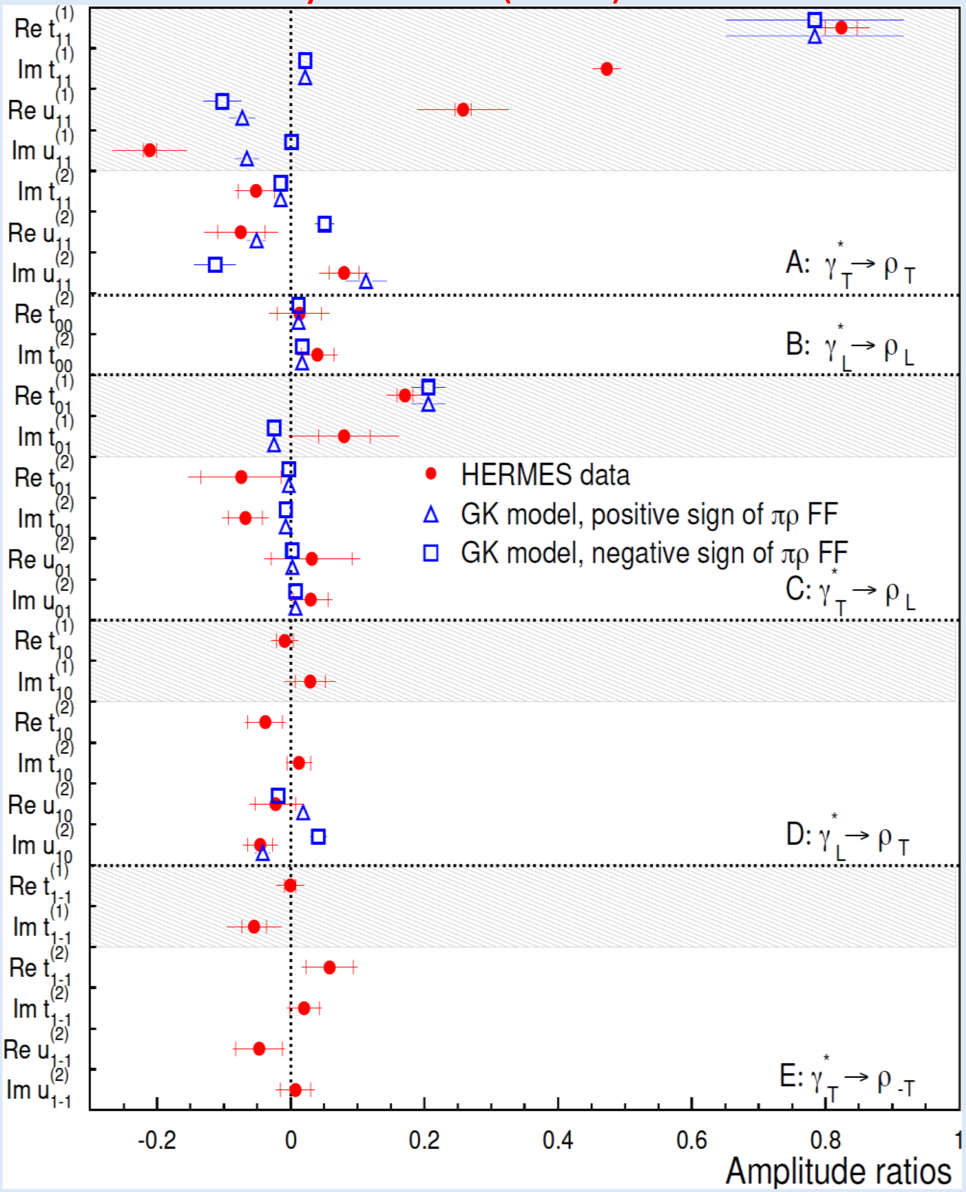
$$n=1 \quad \lambda_N = \lambda_N'$$
$$n=2 \quad \lambda_N \neq \lambda_N'$$

$T^{(n)}_{\lambda_V \lambda_\gamma}$ – NPE Amplitude

$U^{(n)}_{\lambda_V \lambda_\gamma}$ – UPE Amplitude

Exclusive ρ⁰ – meson production: helicity ratios

Eur. Phys. J. C 77 (2017) 378



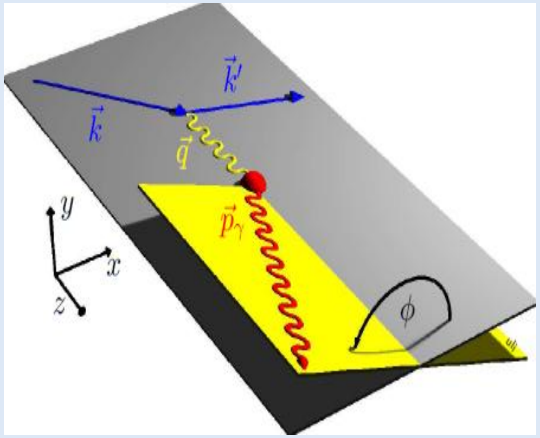
- Comparison with GK model: Eur. Phys. J. A 50 (2014) 146
- Where missing, set to zero in GK model
- Two set of calculations using opposite signs for the πρ transition form factors
- Data clearly favors positive sign
- Good agreement for most ratios, but clearly off for some
- Problem with phases known already

Summary

- 3D picture of the nucleon:
  - HERMES measured "full set" of DVCS-related asymmetries on proton and nuclear targets.
  - Data with recoil-proton detection allows clean separation of DVCS/BH contribution in a signal.
  - Indication of larger amplitude for pure sample.
  - Associated DVCS results consistent with zero and also with model prediction.
- Measurement of ρ^0 /ω –meson SDMEs & A_{UT} asymmetry amplitudes from exclusive DIS: good model description based on GPDs with inclusion of pion pole.
  - The sign of the πω transition form factor
- Measurement of helicity ratios from exclusive ρ^0 –meson production in DIS: model description with inclusion of pion pole.

Backup Slides

Unpolarized proton target



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \propto \left(|\tau_{BH}|^2 + |\tau_{DVCS}|^2 + I \right)$$

$$|\tau_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} C_n^{BH} \cos(n\phi)$$

$$|\tau_{DVCS}|^2 = K_{DVCS} \left\{ \sum_{n=0}^{2} C_n^{DVCS} \cos(n\phi) + \sum_{n=1}^{2} S_n^{DVCS} \sin(n\phi) \right\}$$

$$I = -\frac{e_l K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} C_n^{I} \cos(n\phi) + \sum_{n=1}^{3} S_n^{I} \sin(n\phi) \right\}$$

Fourier coefficients are related to certain linear or bi-linear combinations of Compton Form Factors (CFFs):

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

Azimuthal asymmetries in DVCS off unpolarized targets

$$\sigma_{LU}(\phi, P_l, e_l) = \sigma_{UU}[1 + e_l A_C(\phi) + e_l P_l A_{LU}^I(\phi) + P_l A_{LU}^{DVCS}(\phi)]$$

Charge-difference beam-helicity asymmetry:

$$A_{LU}^I(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=1}^{2} s_n^I \sin(n\phi)$$

A_{LU} (L: beam, U: target)

Charge-averaged beam-helicity asymmetry:

$$A_{LU}^{DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} s_1^{DVCS} \sin(\phi)$$

Beam-Charge asymmetry:

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\rightarrow} + \sigma^{-\leftarrow})} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=0}^{3} c_n^I \cos(n\phi)$$

- Measurement with both beam helicity and both beam charges
  ⟹ separate contributions from DVCS and Interference term
- This separation is impossible in measurements of single-charge beam-helicity asymmetry $A_{LU}(\phi) = (\sigma^{\rightarrow} - \sigma^{\leftarrow})/(\sigma^{\rightarrow} + \sigma^{\leftarrow})$

Asymmetries on longitudinally polarized targets

Single-charge target-spin asymmetry (Hydrogen/Deuterium):

$$A_{UL}(\phi,e_l)=\frac{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Rightarrow}(\phi,e_l)]-[\sigma^{\rightarrow\Leftarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Rightarrow}(\phi,e_l)]+[\sigma^{\rightarrow\Leftarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]}$$

Single-charge double-spin asymmetry (Hydrogen/Deuterium):

$$A_{LL}(\phi,e_l)=\frac{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]-[\sigma^{\leftarrow\Rightarrow}(\phi,e_l)+\sigma^{\rightarrow\Leftarrow}(\phi,e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]+[\sigma^{\leftarrow\Rightarrow}(\phi,e_l)+\sigma^{\rightarrow\Leftarrow}(\phi,e_l)]}$$

Single-charge beam-helicity asymmetry (Deuterium):

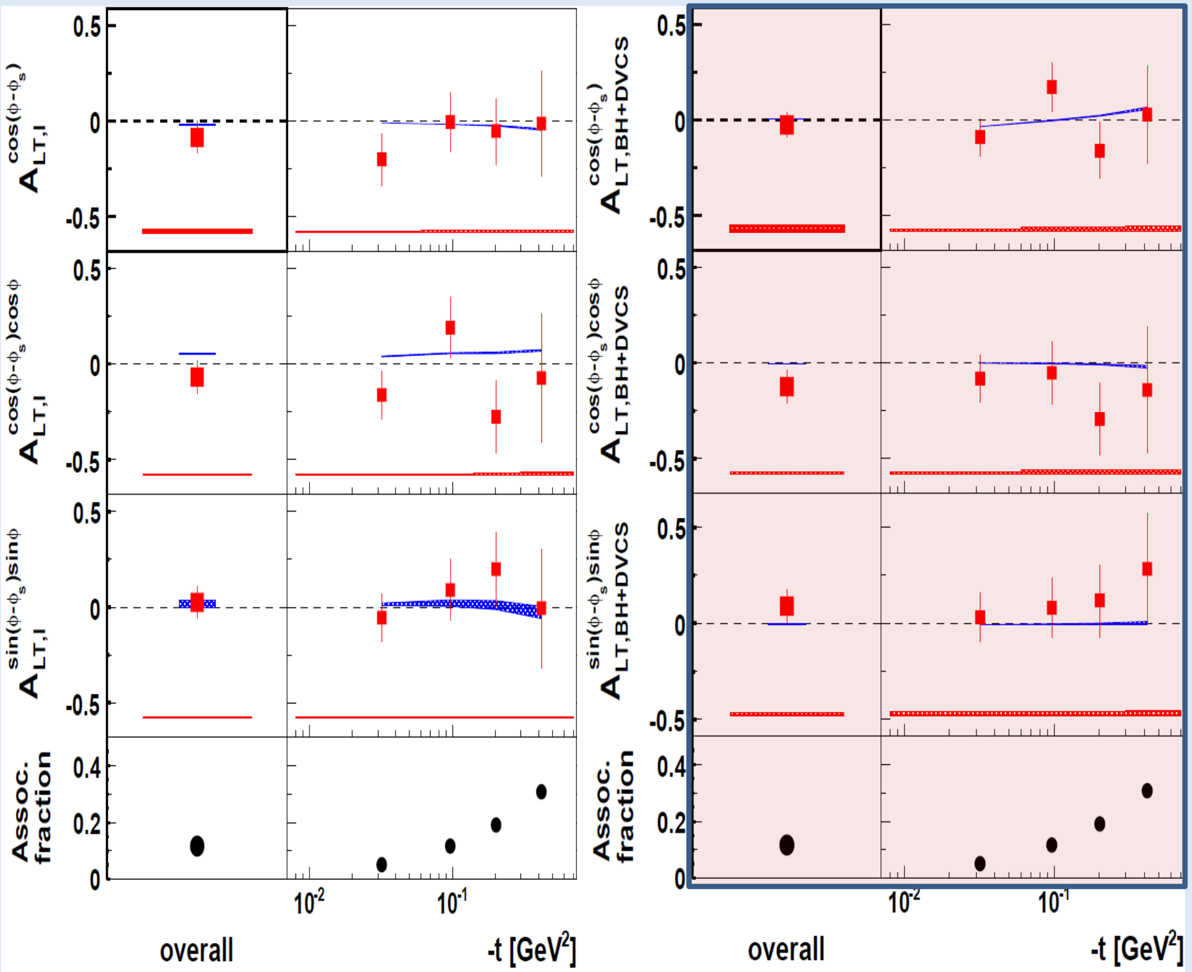
$$A_{L\substack{\Rightarrow\\ \Leftarrow}}(\phi,e_l)=\frac{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\rightarrow\Leftarrow}(\phi,e_l)]-[\sigma^{\leftarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]}{[\sigma^{\rightarrow\Rightarrow}(\phi,e_l)+\sigma^{\rightarrow\Leftarrow}(\phi,e_l)]+[\sigma^{\leftarrow\Rightarrow}(\phi,e_l)+\sigma^{\leftarrow\Leftarrow}(\phi,e_l)]}$$

Single-helicity (⟵) beam-charge asymmetry (Deuterium):

$$A_{C\substack{\Rightarrow\\ \Leftarrow}}(\phi)=\frac{[\sigma^{+\Rightarrow}(\phi)+\sigma^{+\Leftarrow}(\phi)]-[\sigma^{-\Rightarrow}(\phi)+\sigma^{-\Leftarrow}(\phi)]}{[\sigma^{+\Rightarrow}(\phi)+\sigma^{+\Leftarrow}(\phi)]+[\sigma^{-\Rightarrow}(\phi)+\sigma^{-\Leftarrow}(\phi)]}$$

DVCS: Transverse double-spin asymmetry A_{LT}

Phys Lett. B704 (2011) 15, arXiv:1106.2990



Full set of data: e+/e- beams; both helicities; target polarization - positive/negative.

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

$$\Re e\left[F_2\tilde{\mathcal{H}}-(F_1+\xi F_2)\tilde{\mathcal{E}}\right]$$

$$\propto \Re e\left[\mathcal{H}\mathcal{E}^*-\mathcal{E}\mathcal{H}^*-\xi\left(\tilde{\mathcal{H}}\tilde{\mathcal{E}}^*-\tilde{\mathcal{E}}\tilde{\mathcal{H}}^*\right)\right]$$

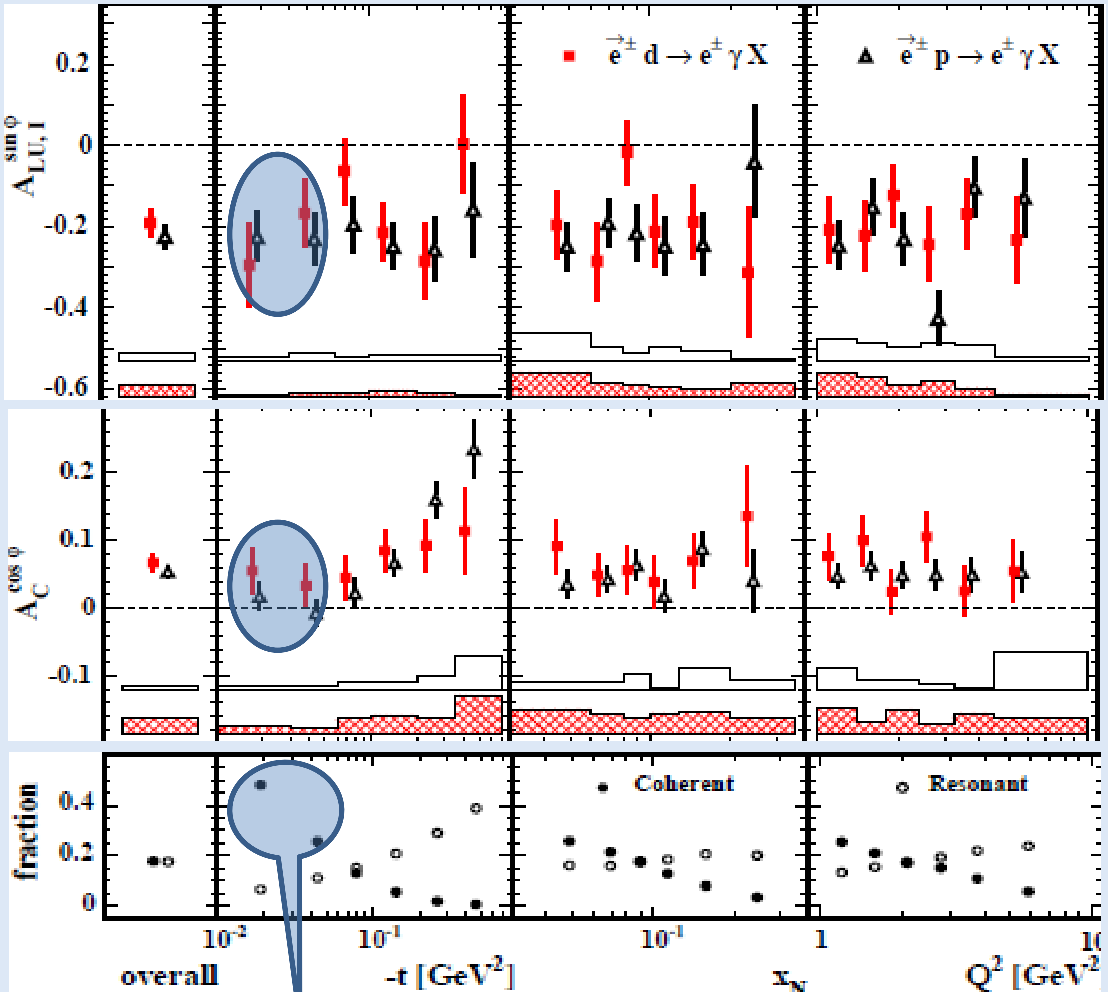
$$\Re e\left[F_2\mathcal{H}-F_1\mathcal{E}\right]$$

$$\propto \Re e\left[-\tilde{\mathcal{H}}\mathcal{E}^*-\tilde{\mathcal{H}}^*\mathcal{E}+\xi\left(\mathcal{H}\tilde{\mathcal{E}}^*+\tilde{\mathcal{E}}\mathcal{H}^*\right)\right]$$

Sensitive to both GPDs entering the Ji sum rule

Consistent with zero, cancellations between E and H
Sensitivity to J_u is suppressed by kinematic factors

Deuterium (Hydrogen): unpolarized target



JHEP 11 (2009) 083

Nucl. Phys. B 829 (2010) 1

$\Im m(\mathcal{H})$

$\Im m(\mathcal{H}_1)$

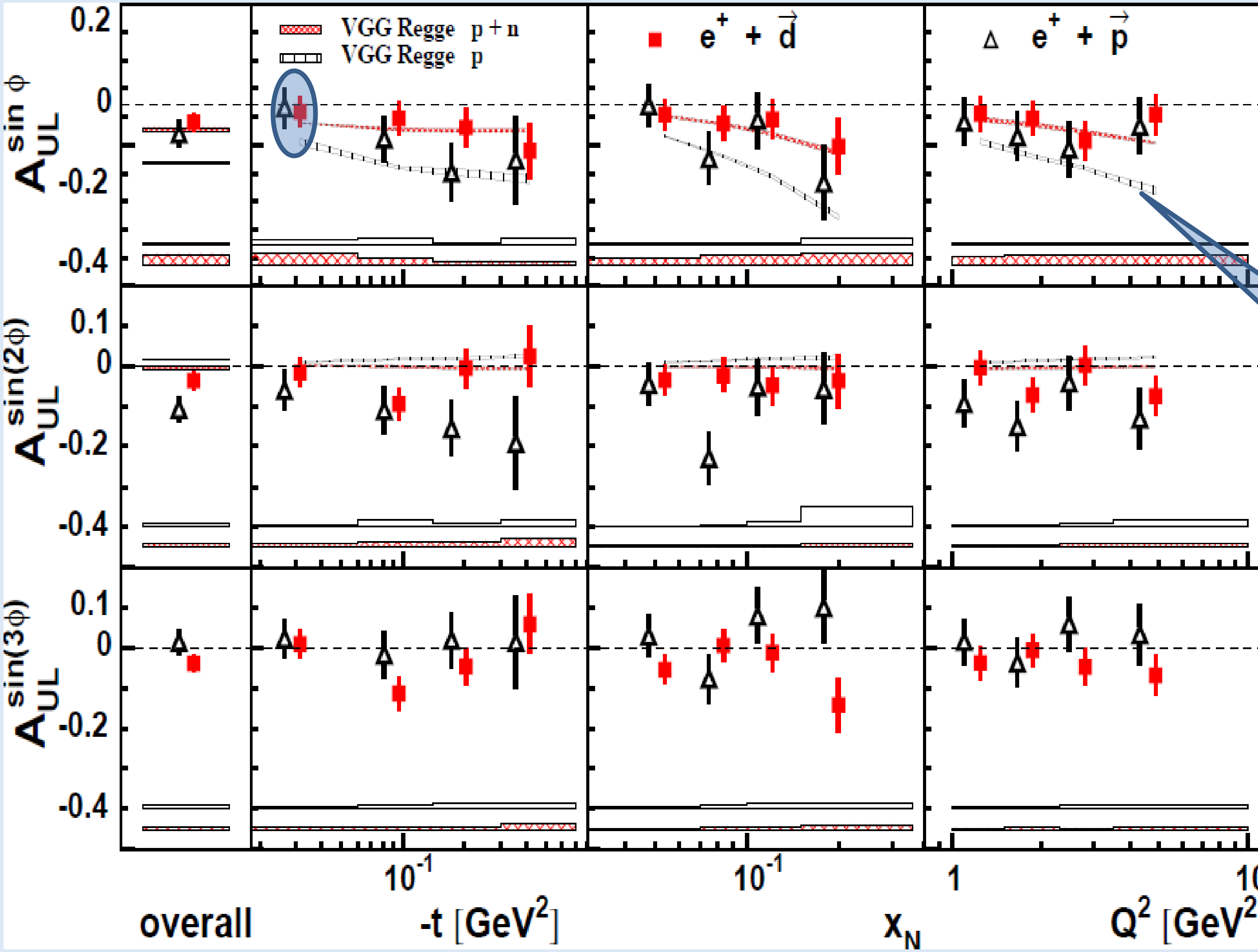
$\Re e(\mathcal{H})$

$\Re e(\mathcal{H}_1)$

- $A_{LU,I,Coh}^{\sin\phi}$ -0.29 ± 0.18 (stat) ± 0.03 (syst)
- $A_{C,Coh}^{\cos\phi}$ 0.11 ± 0.07 (stat) ± 0.03 (syst)

Deuterium (Hydrogen): target-spin asymmetry

JHEP 11 (2009) 083 Nucl. Phys. B 842 (2011) 265



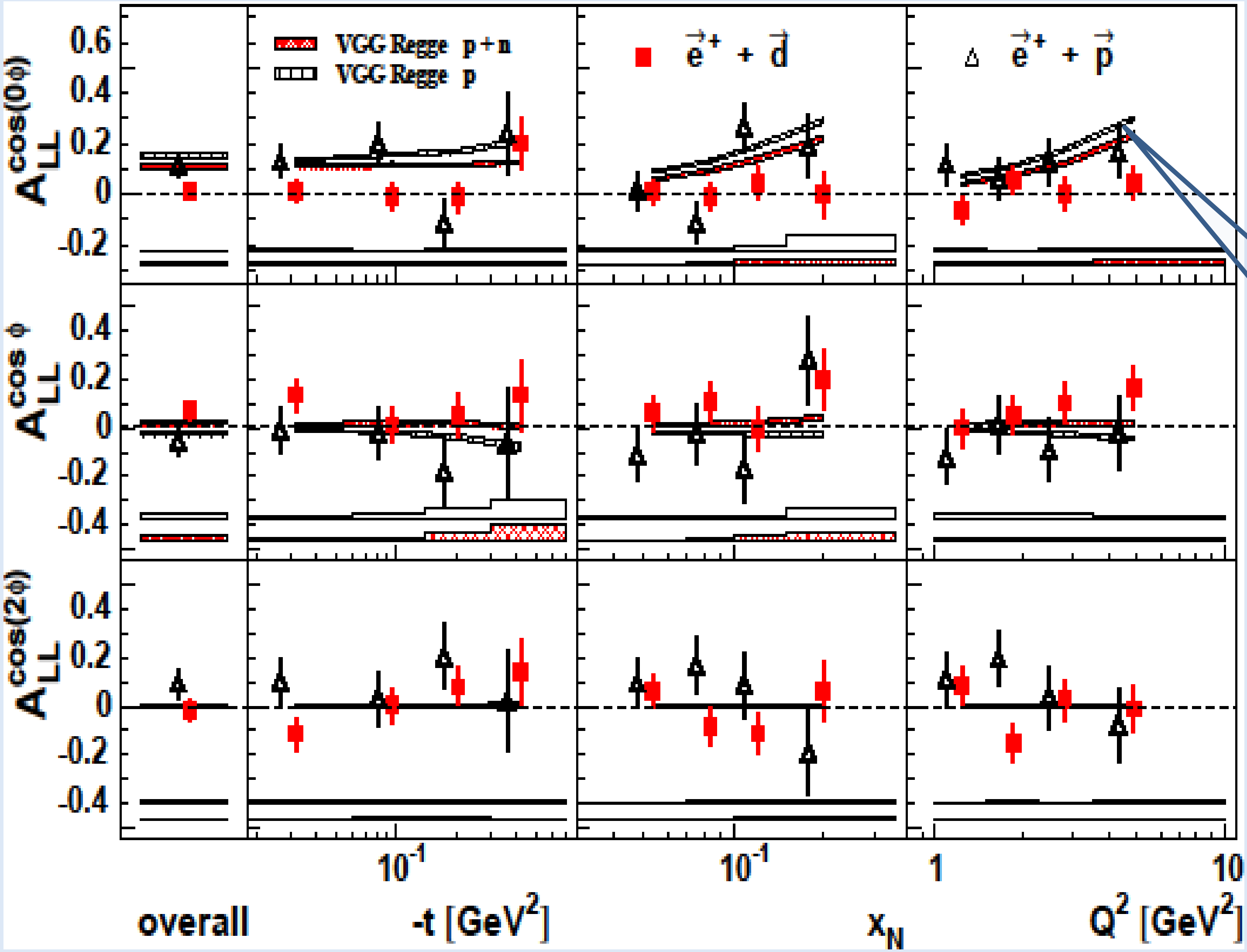
$\Im m(\widetilde{H})$

$\Im m(\widetilde{H}_1)$

VGG:
Phys. Rev. **D60** (1999) 0940177
&
Prog. Nucl. Phys. **47** (2001) 401

Deuterium (Hydrogen): double-spin asymmetry

JHEP 11 (2009) 083 Nucl. Phys. B 842 (2011) 265

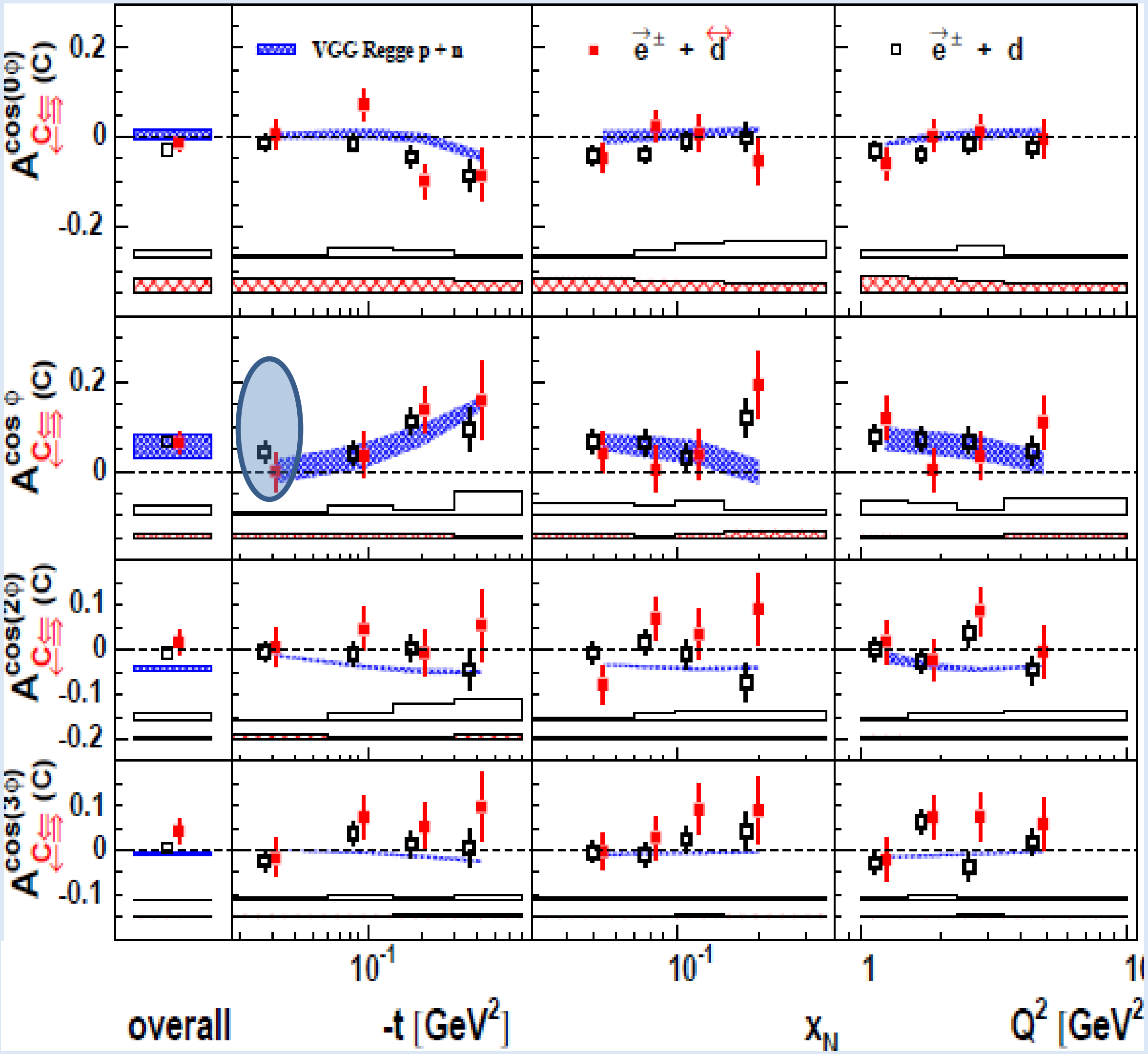


$\propto$ (BH)

VGG:
Phys. Rev. **D60** (1999) 0940177
&
Prog. Nucl. Phys. **47** (2001) 401

A_C ($A_{C\leftrightarrow}$) on (un)polarized Deuterium

Nucl. Phys. B 842 (2011) 265



For coherent scattering

$$\Re e(\mathcal{H}_1)$$

$$\Re e(\mathcal{H}_1 - \tfrac{1}{3}\mathcal{H}_5)$$

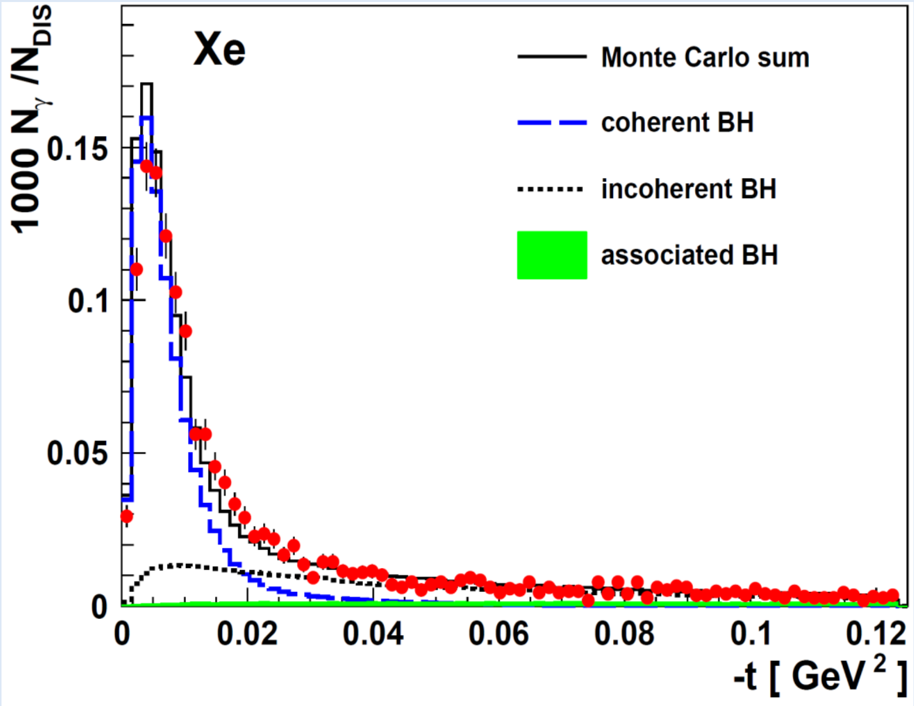
$$\Im m(H_5)$$

A_{LZZ} sin φ amplitude:
0.074 ± 0.196 ± 0.022
(-*t* < 0.06 GeV2, 40% coherent)

Beam-charge /spin asymmetries on heavier nuclei

Phys. Rev. C 81 (2010) 035202

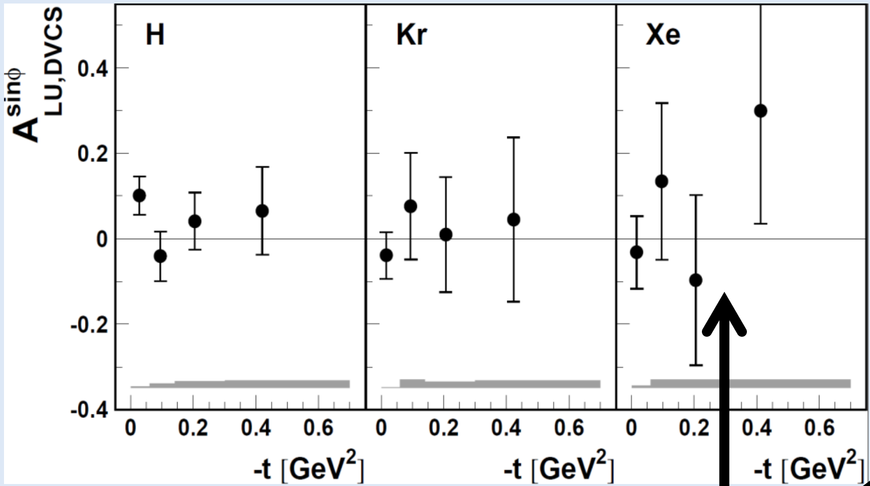
Target	Spin	L (pb^{-1})
^1H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47



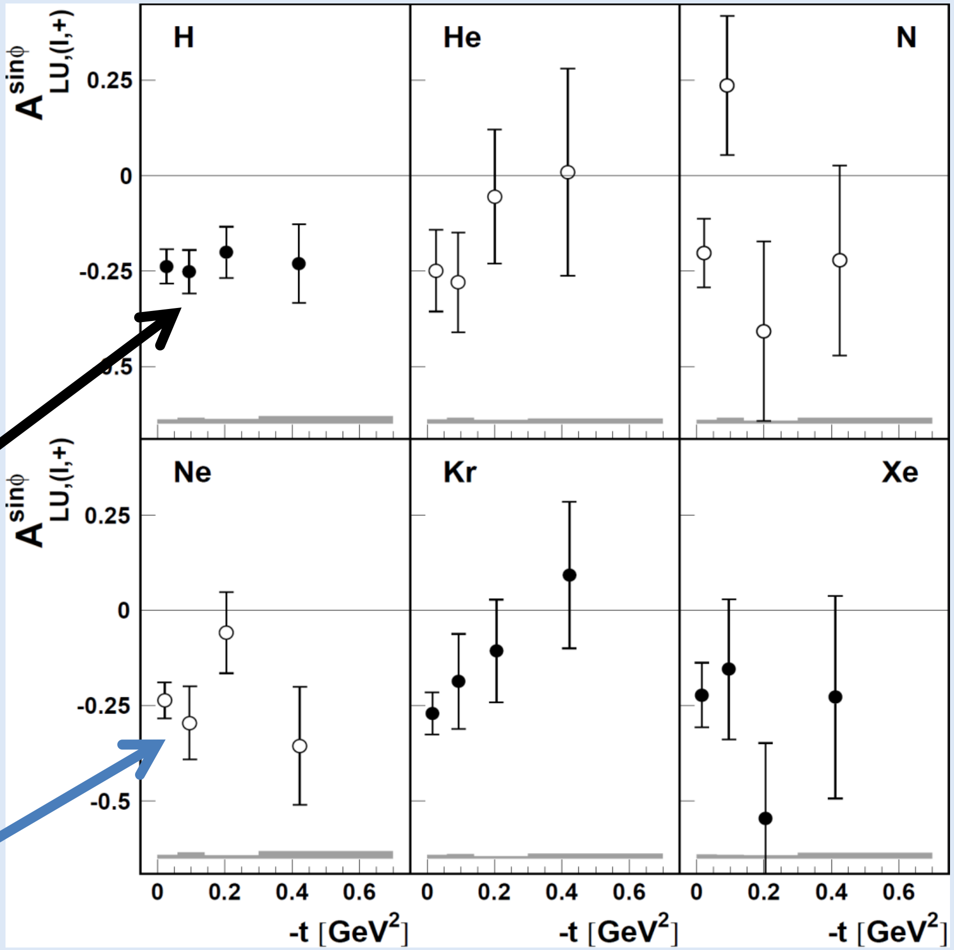
- Separation of coherent-enriched and incoherent-enriched data samples by t- cutoffs : similar average kinematics
- Coherent-enriched samples: ≈ 65 %
- Incoherent enriched samples: ≈ 60 %

Leading amplitudes of asymmetries on nuclei

Leading amplitude of
Beam-charge asymmetry



Leading amplitudes of
Beam-helicity asymmetry

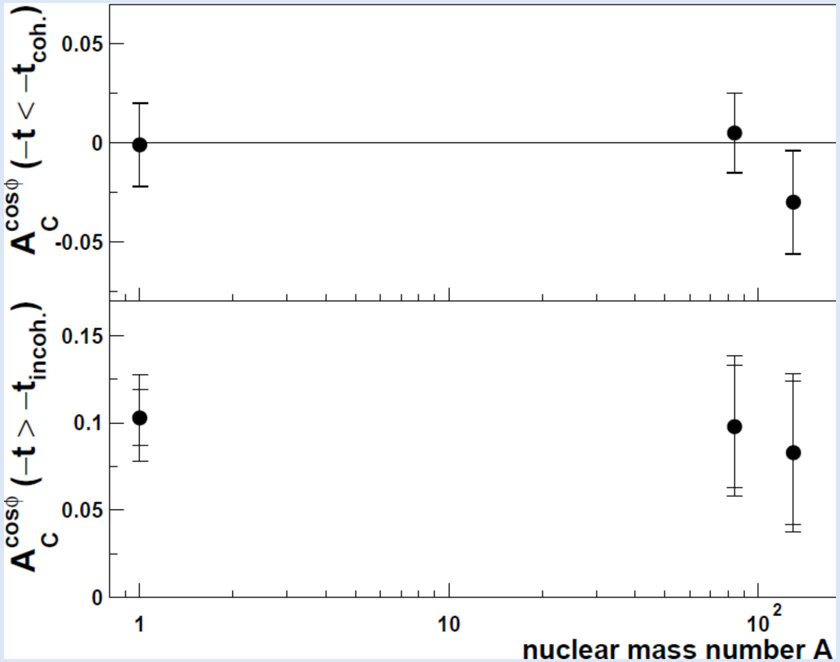


- ● Two beam charges available

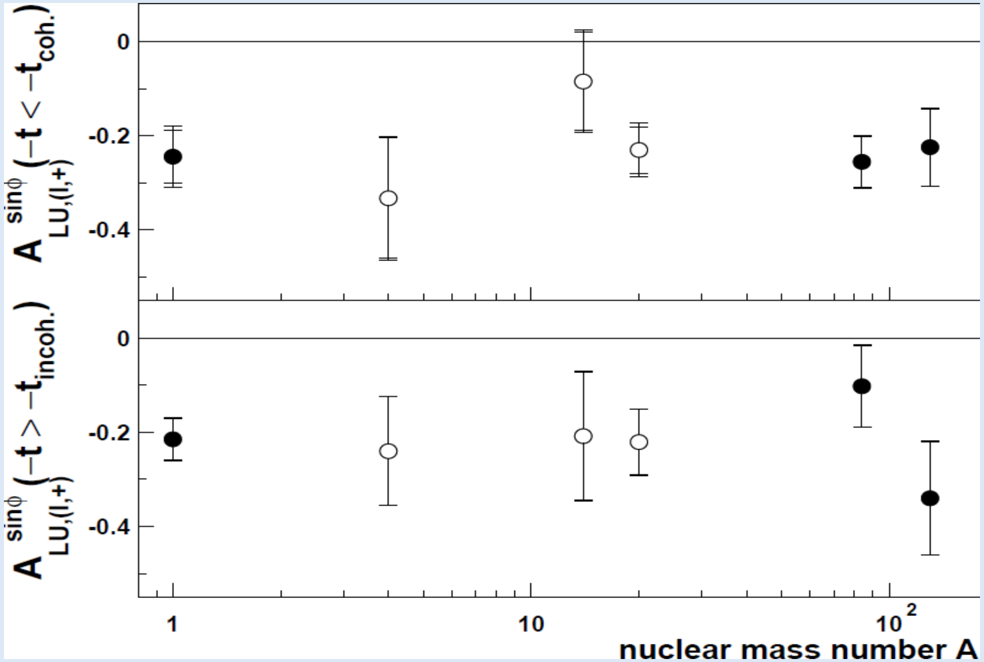
- ○ Only one beam charge available: single-charge asymmetry without entanglement of squared DVCS and Interference terms

Nuclear-mass dependence of asymmetries

$A_C^{\cos\phi}$ vs. A



$A_{LU}^{\sin\phi}$ vs. A

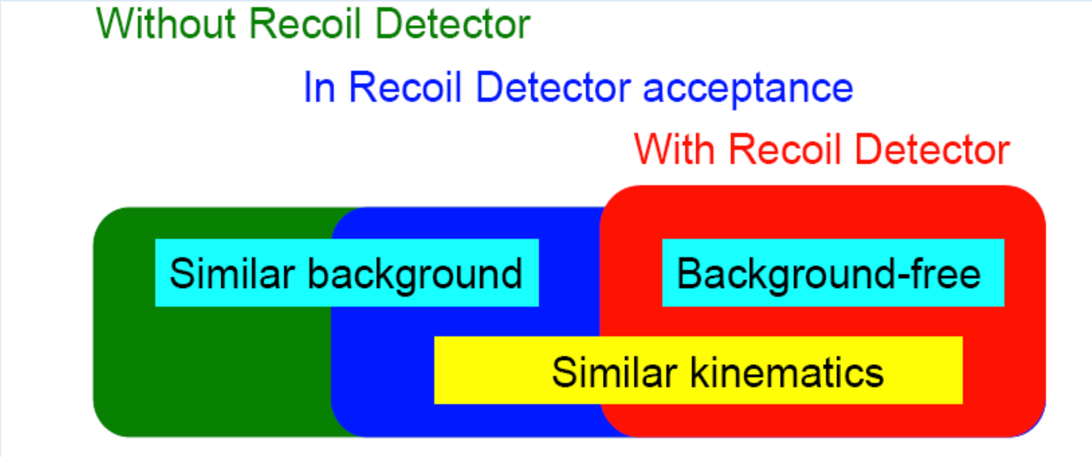


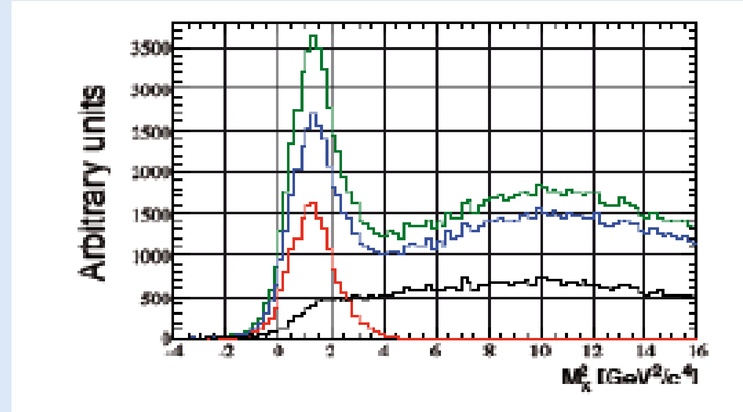
A_{LU}^{A} / A_{LU}^{H} →

Coherent-enriched: 0.91 ± 0.19

Incoherent-enriched: 0.93 ± 0.23

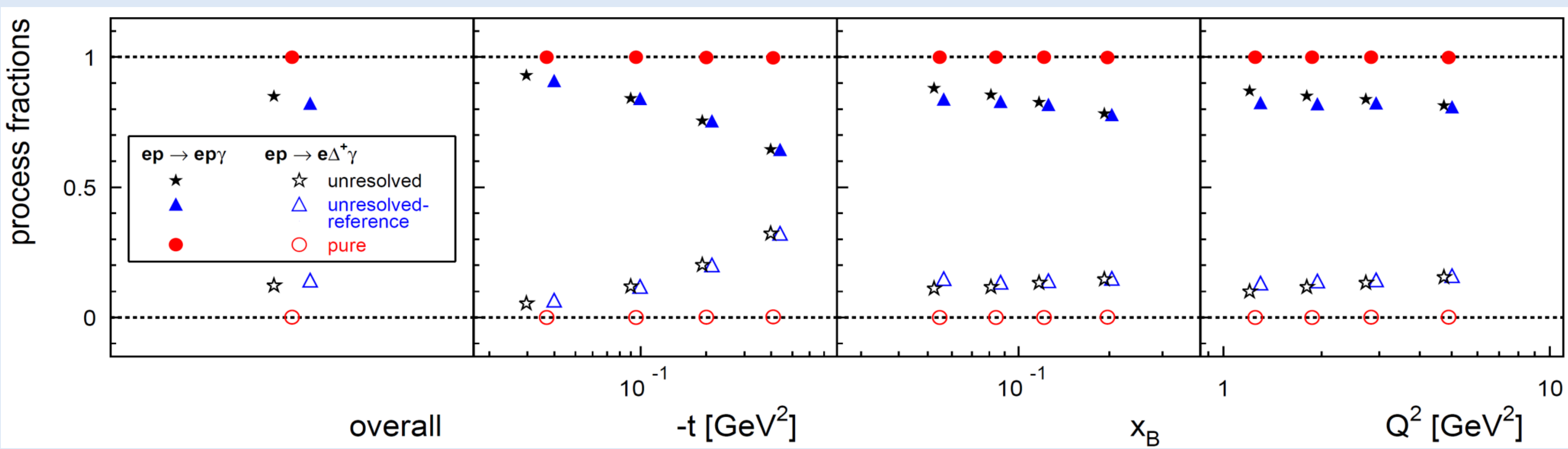
DVCS with recoil detector



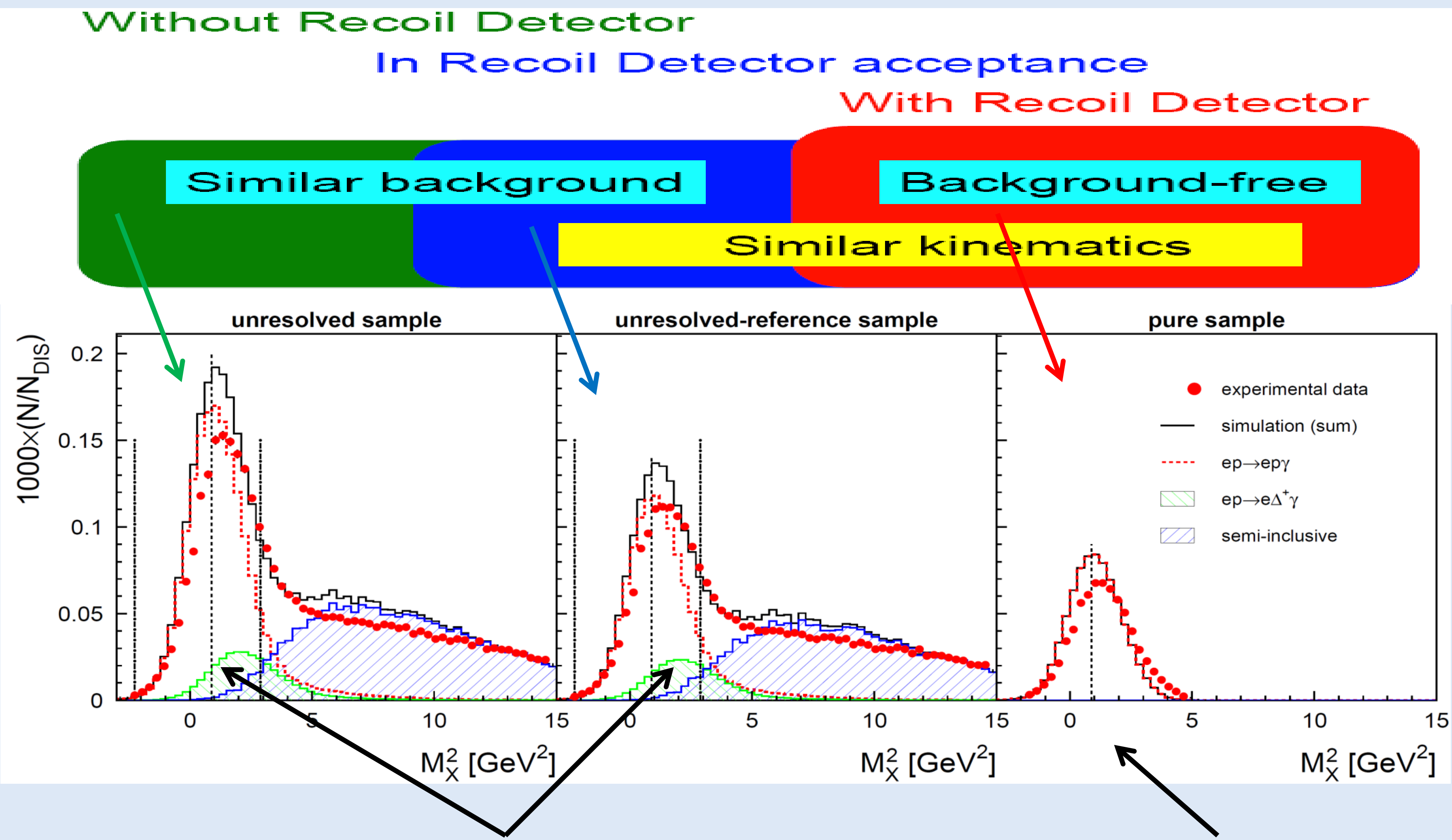


- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %

Kinematic event fitting technique: all 3 particles
In the final state detected should satisfy
4-constraints on energy-momentum conservation



Missing mass distribution: exclusivity with RD

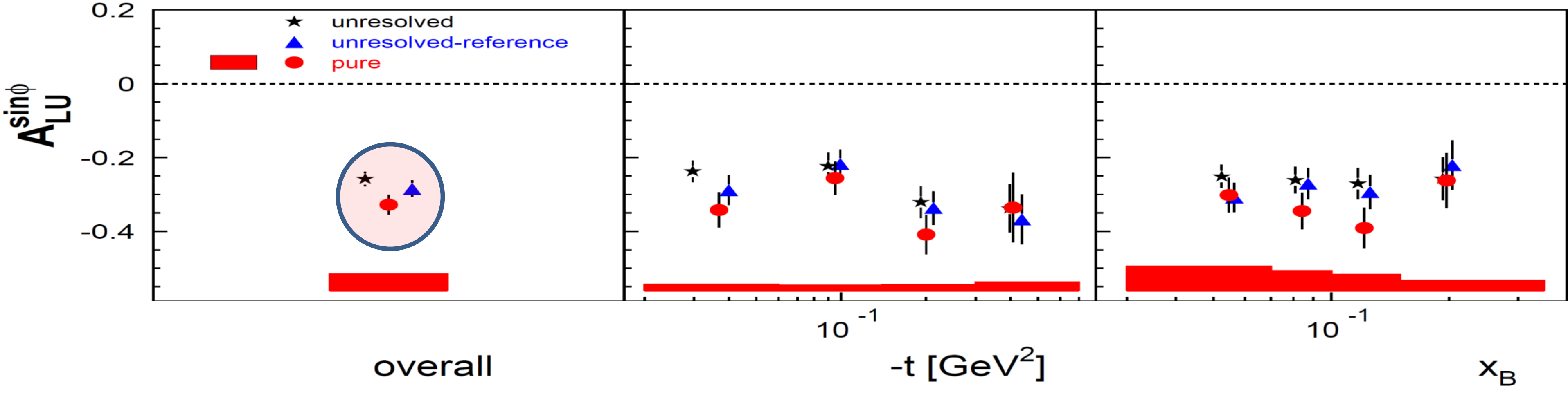


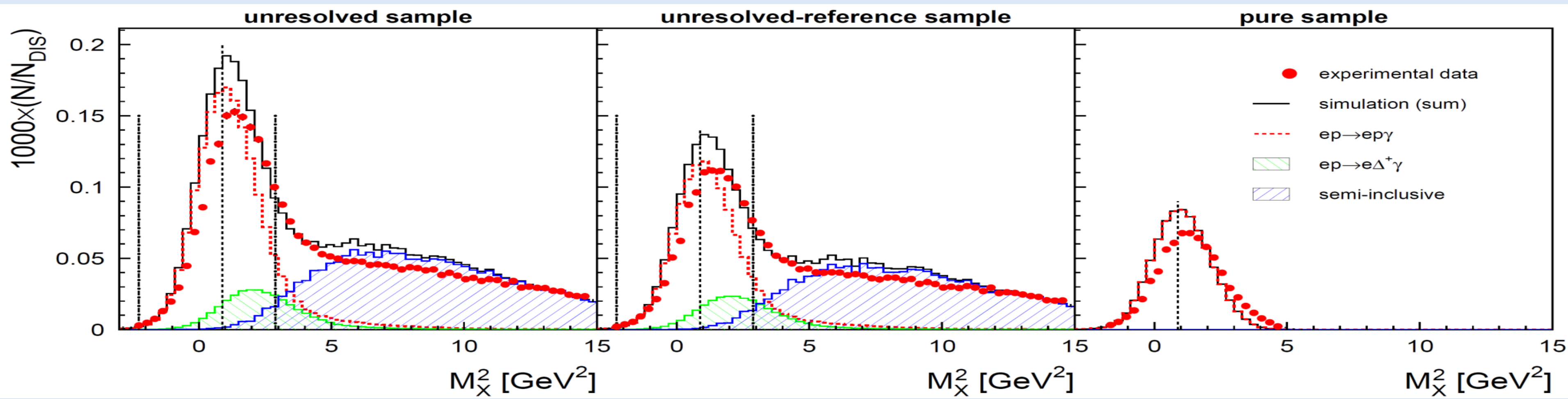
Associated processes (e p ⟶ e' γ Δ^+)

Pure e p ⟶ e' γ p

Missing mass: $M_X{}^2 = (q + P - q')^2 = M^2 + 2M(\nu - E_\gamma + t)$

Pure elastic DVCS

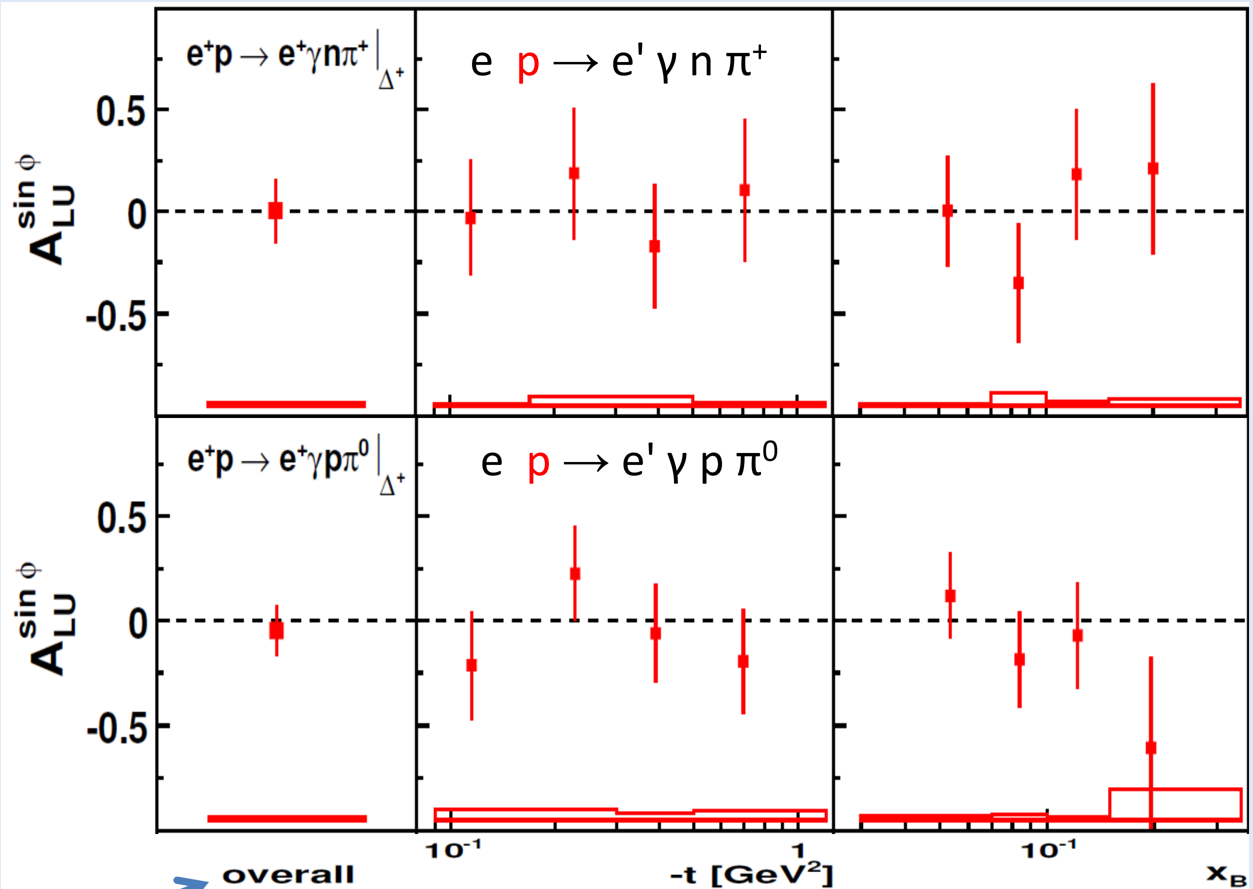


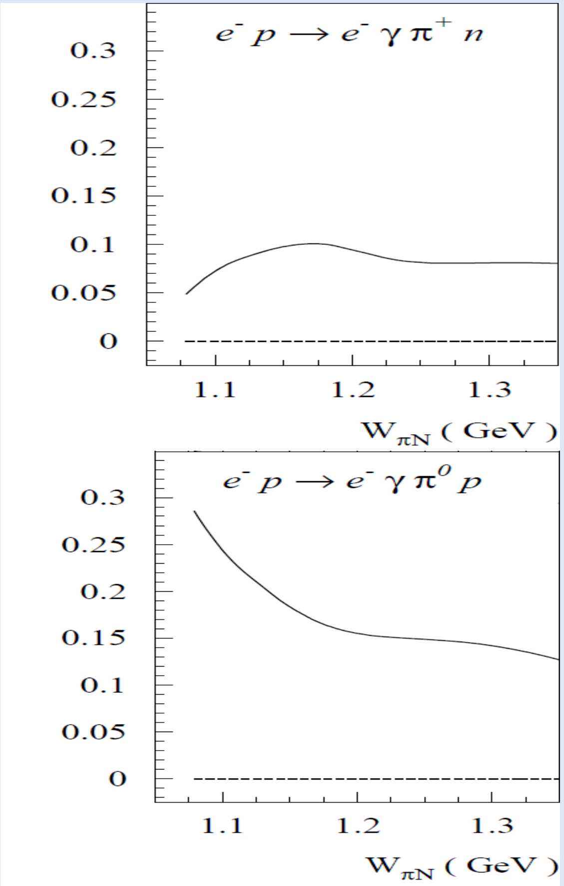


- Practically no contamination of associated process.
- Indication that leading amplitude for pure elastic process is larger (0.054 ± 0.016) than for unresolved signal (elastic+associated).

Beam-spin asymmetry in „associated“ DVCS : $ep \to e\gamma\Delta^+$

JHEP 01 (2014) 077, arXiv:1206.5683





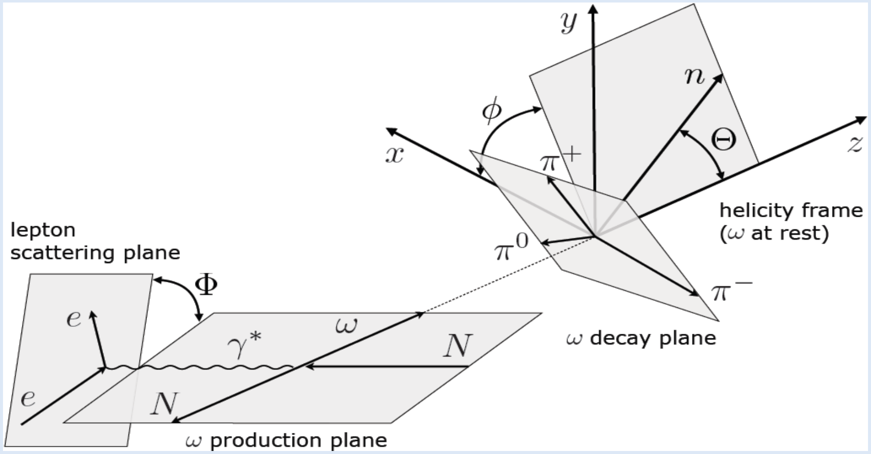
- Associated DVCS/BH: (77 ± 2% for $n\pi^+$ & 85 ± 1% for $p\pi^0$)
- Correction: π^0 SIDIS background: (23 ± 3% for $p\pi^0$ & 11 ± 1% for $n\pi^+$ channel);
- Elastic: (0.2 ± 0.1% for $n\pi^+$ & 4.6 ± 0.1% for $p\pi^0$)

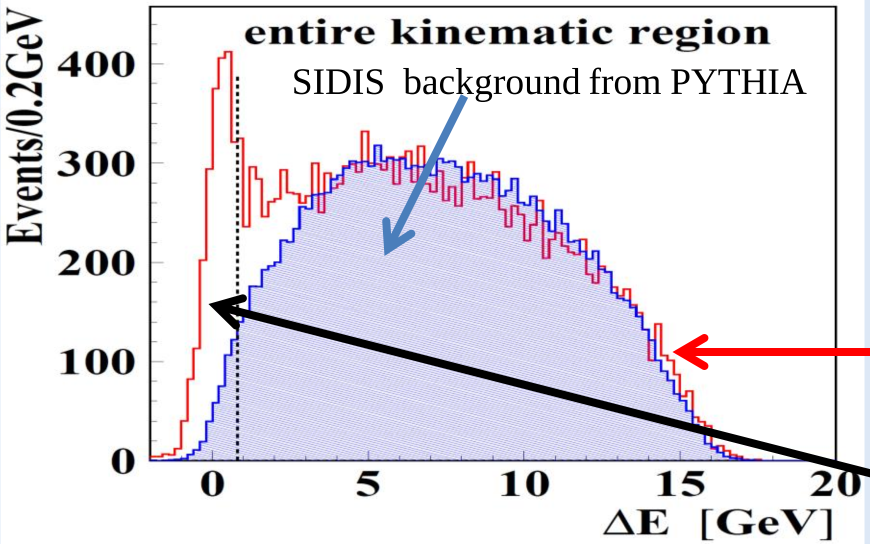
P. Guichon et al., PRD 68 (2003) 034018

Exclusive ω - meson production at HERMES

$$e(k) + N(p) \dashrightarrow e(k') + N(p') + \omega$$

$$\omega \dashrightarrow \pi^+ \pi^- \pi^0, \quad \pi^0 \dashrightarrow 2\gamma$$





Kinematic conditions:

$$1\ \text{GeV}^2 < Q^2 < 10\ \text{GeV}^2,$$
$$0.01 < x_B < 0.35,$$
$$3.0\ \text{GeV} < W < 6.3\ \text{GeV},$$
$$0 \leq -t' = -(t - t_{min}) < 0.2\ \text{GeV}^2$$

Two photon invariant mass:

$$0.11\ \text{GeV} < M(\gamma\gamma) < 0.16\ \text{GeV}$$

Three-pion invariant mass:

$$0.71\ \text{GeV} < M(\pi^+\pi^-\pi^0) < 0.87\ \text{GeV}$$

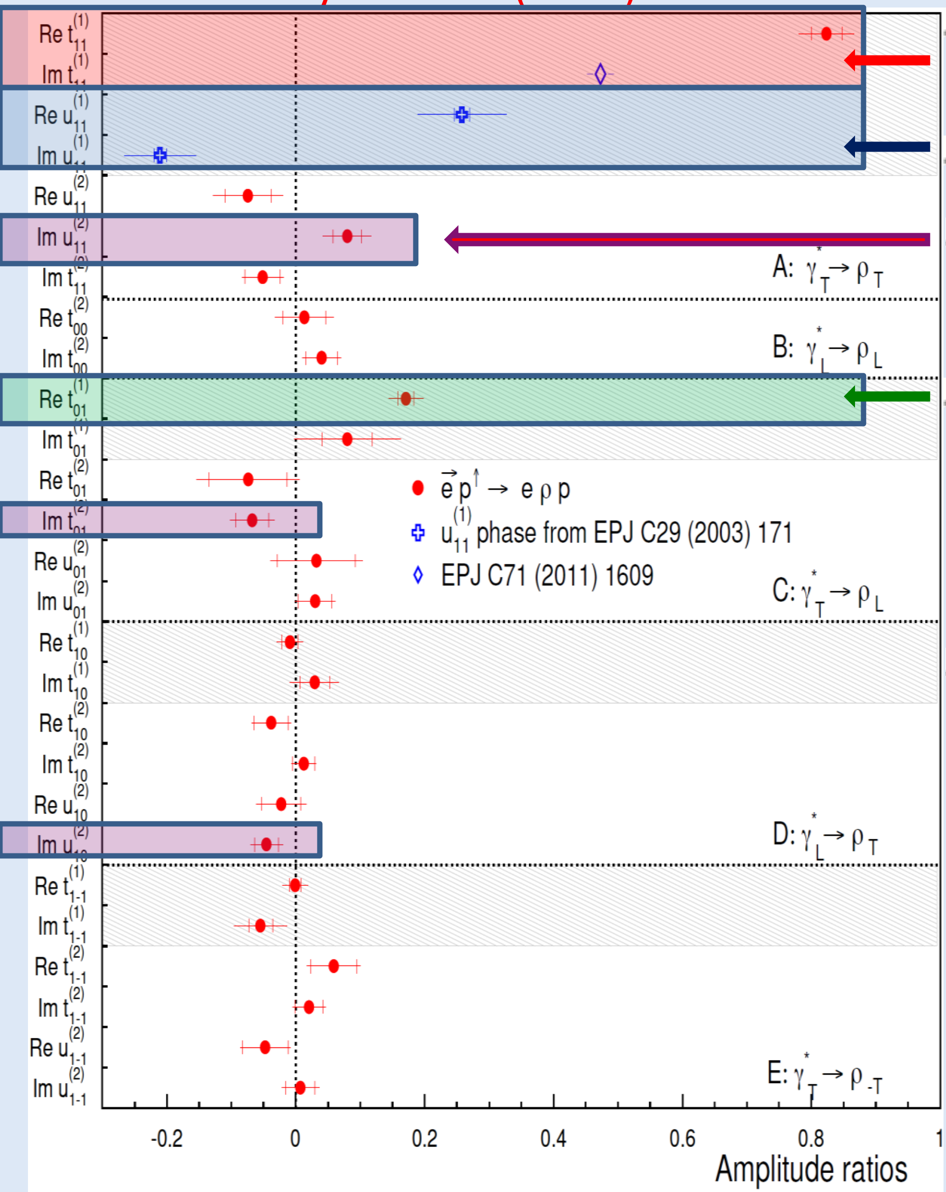
Missing energy:

$$\Delta E = \frac{M_X^2 - M_p^2}{2M_p}, \quad M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-} - p_{\pi^0})^2$$

Exclusive region: $-1.0\ \text{GeV} < \Delta E < 0.8\ \text{GeV}$

Exclusive ρ^0 – meson production: helicity ratios

Eur. Phys. J. C 77 (2017) 378



- Dominant amplitude: NPE nucleon-helicity non-flip $t_{11}^{(1)} \neq 0$ by > 5σ
- UPE nucleon-helicity non-flip $u_{11}^{(1)} \neq 0$ by > 4σ
- Nucleon-helicity flip $\mathrm{Im}\, t_{01}^{(2)}$, $\mathrm{Im}\, u_{11}^{(2)}$, $\mathrm{Im}\, u_{10}^{(2)} \neq 0$ by 2σ
- Significant nucleon-helicity non-flip $\mathrm{Re}\, t_{01}^{(1)} \neq 0$ by > 5σ
- Overall good agreement between direct extraction of SDMEs (Eur. Phys. J. C 71 (2011) 1609) and SDMEs via helicity amplitude ratios (not shown here).