Selected recent hermes results for hard exclusive processes

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Workshop on Hard Exclusive Processes
Garching, 9-11 November 2009

Outline

Main topics covered in this talk:

- Deeply Virtual Compton Scattering (DVCS)
- Exclusive Vector Meson (ρ, ω, ϕ) production
- Exclusive π+ production
- Recoil Detector

HERMES Experiment

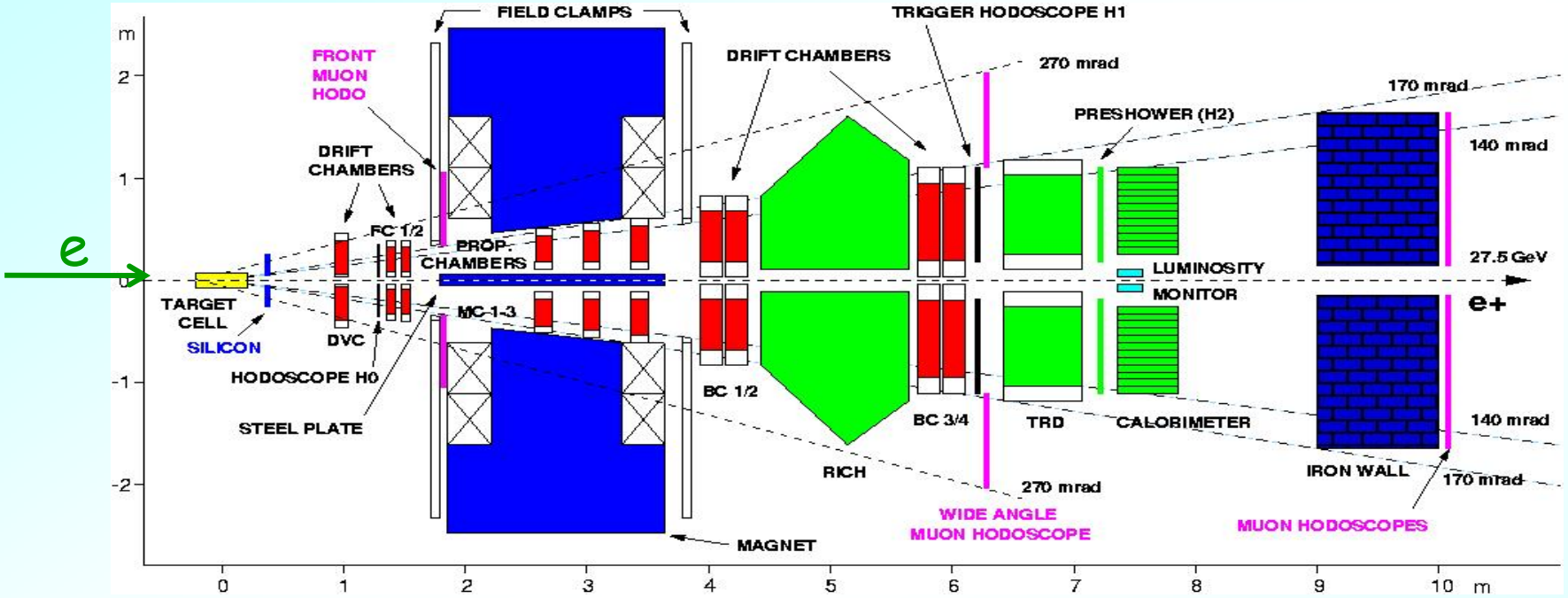
27.5 GeV e^+/e^- beam of HERA

Internal gas targets

polarized : $^{1}\vec{H}, ^{1}\vec{H}, ^{2}\vec{H}, ^{3}\vec{He}$

unpolarized: ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr, ^{131}Xe

HERMES Spectrometer



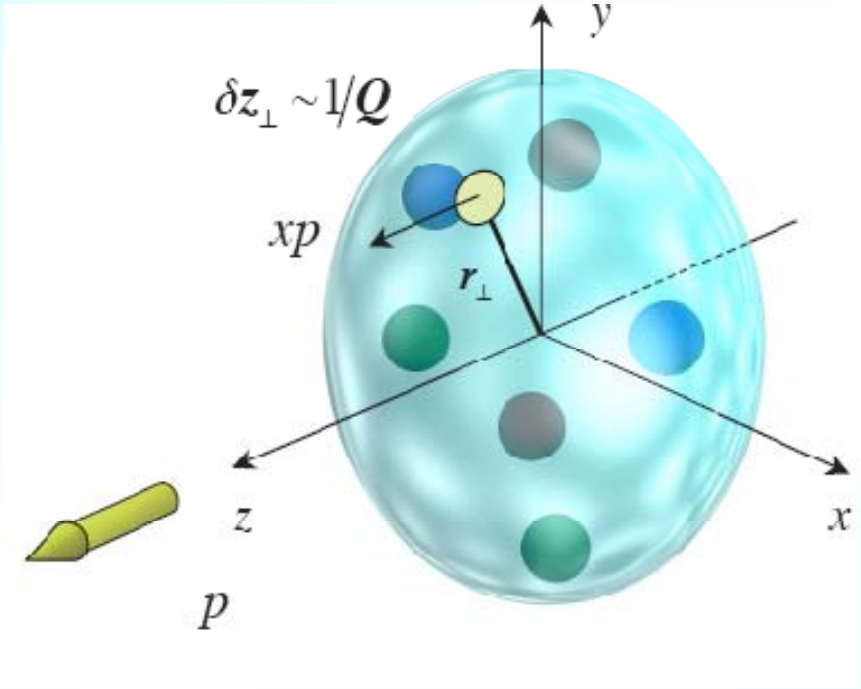
- HERA longitudinally polarized 27.6 GeV e+/e- beam
- Polarized and unpolarized internal gas target (spin flip every 90 s)
- Kinematics: $0.02<x<0.7$, $1.0\ GeV^2<Q^2<15\ GeV^2$
- Data taking: summer 1995 – June 30, 2007
- 1995-2000: longitudinal target polarization, 2002-2005: transverse target pol.

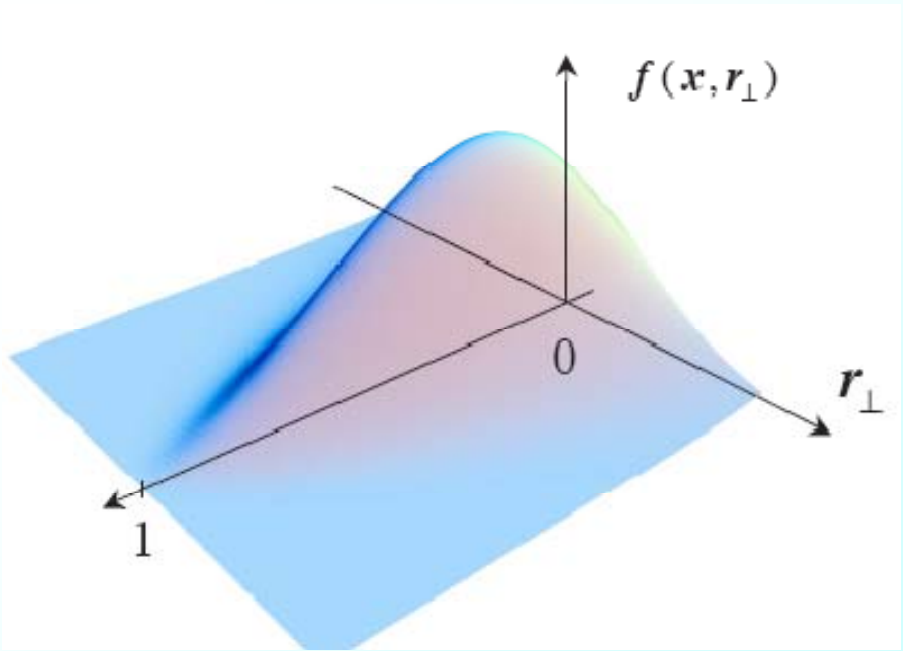
  2006-2007: unpolarized H, D targets + Recoil Detector

Generalised Parton Distributions (GPDs)

Generalisation of Form Factors (moments of GPDs) and PDFs (forward limit)

Generalised description of nucleon structure in 2+1 dim





Number density of quarks with longitudinal momentum fraction x at radial position $r_\perp$

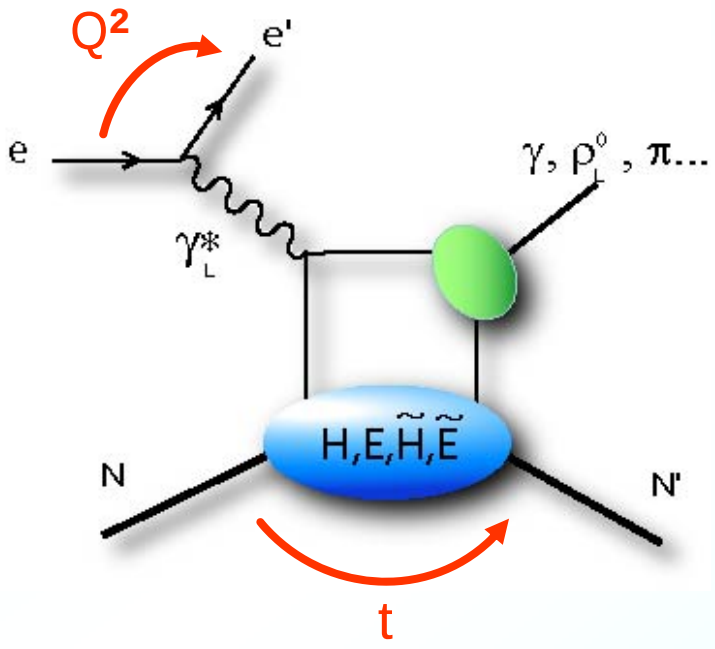
GPDs and quark total angular momentum

Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

$H(x,\zeta,t)$, $E(x,\zeta,t)$: Generalised Parton Distributions

Access: *exclusive processes*



Final state sensitive to different GPDs

Spin-½ target: 4 chiral-even leading-twist quark GPDs

$H, \tilde{H}$ ($E, \tilde{E}$) conserve (flip) nucleon helicity

Vector mesons (ρ, ω, ϕ) H, E

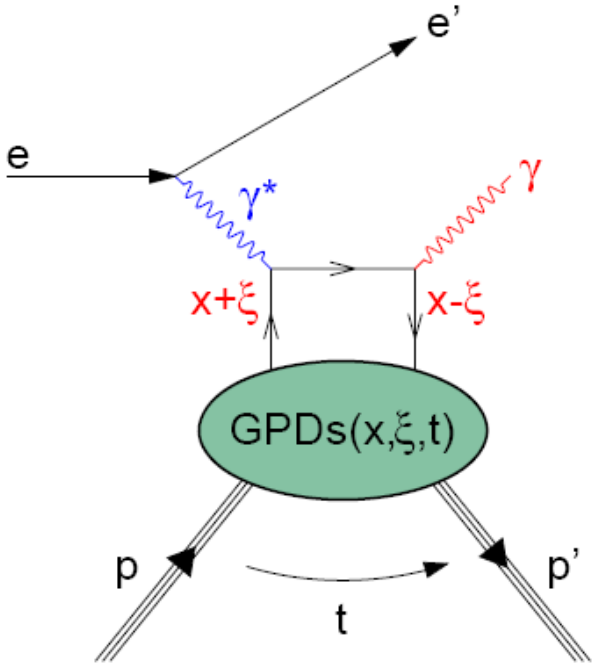
Pseudoscalar mesons(π,η) $\tilde{H}$, $\tilde{E}$

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

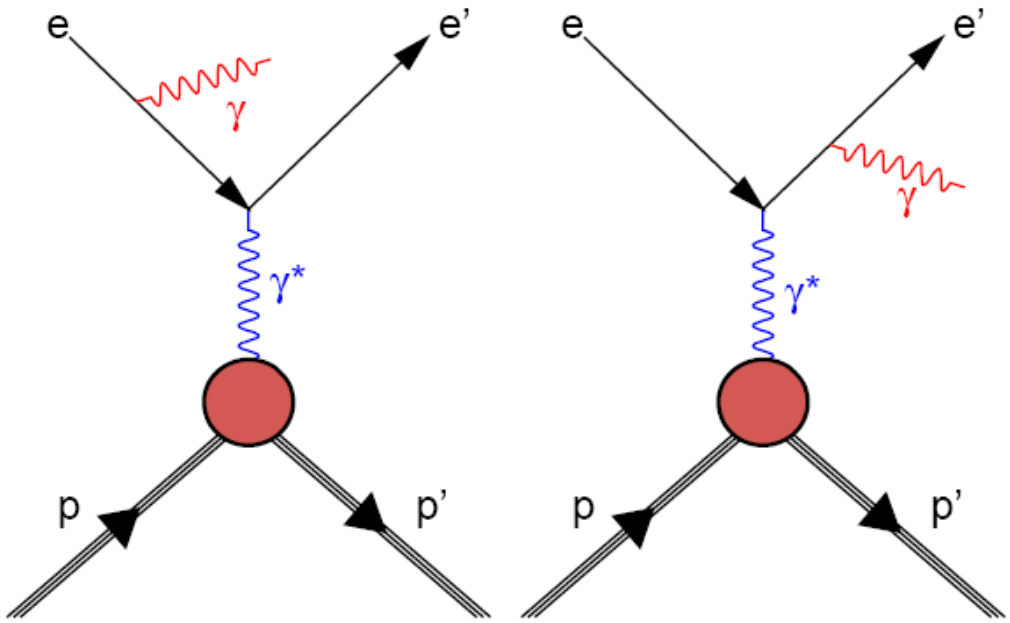
- Deeply Virtual Compton Scattering (DVCS)
- Exclusive Vector Meson (ρ, ω,ϕ) production
- Exclusive π+ production
- Recoil Detector

Deeply Virtual Compton Scattering & GPDs

DVCS



Bethe-Heitler (BH)



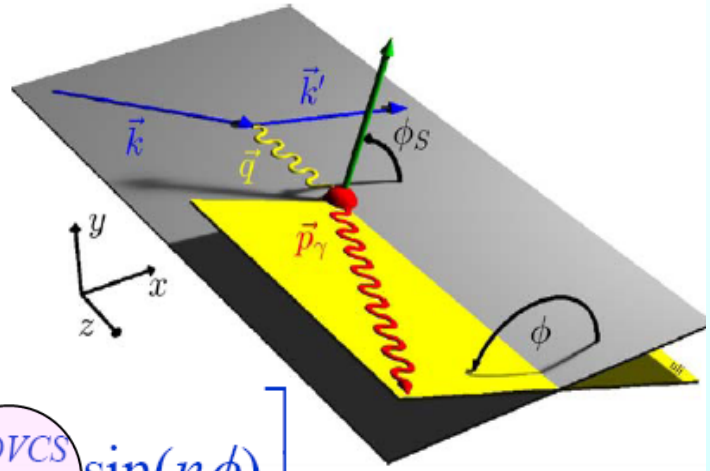
* DVCS and BH: same initial and final state
* BH dominates at HERMES kinematics
* GPDs accessible through cross-section differences and azimuthal asymmetries via interference term

Azimuthal dependences in DVCS

Example: unpolarised proton target

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

$$\left|T_{BH}\right|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$



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

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

from S. Yaschenko

Azimuthal dependences in DVCS

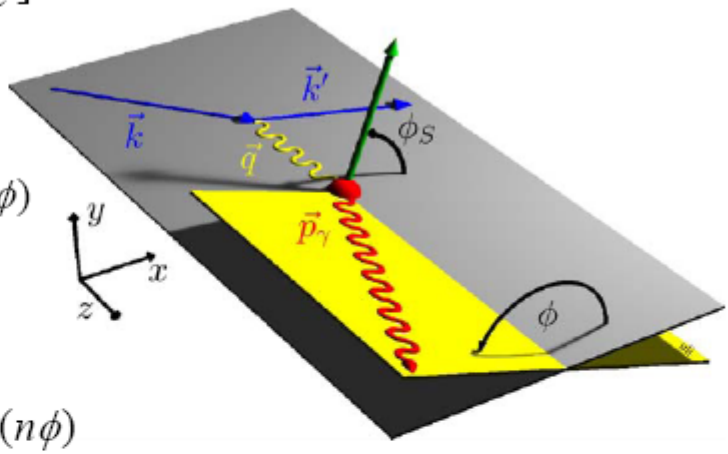
Example: unpolarised proton target

- Cross section

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

- Beam-charge asymmetry

$$A_C(\phi)=\frac{\left(\sigma^{+\rightarrow}+\sigma^{+\leftarrow}\right)-\left(\sigma^{-\leftarrow}+\sigma^{-\rightarrow}\right)}{\left(\sigma^{+\rightarrow}+\sigma^{+\leftarrow}\right)+\left(\sigma^{-\leftarrow}+\sigma^{-\rightarrow}\right)}=-\frac{1}{D(\phi)}\frac{x_B^2}{y}\sum_{n=0}^{3}c_n^I\cos(n\phi)$$



- Charge-difference beam-helicity asymmetry

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

- Charge-averaged beam-helicity asymmetry

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

A_{XY} — beam target

- Measurements of these beam-helicity asymmetries allow to separate contributions from DVCS and interference term

- This separation is impossible in measurements of single-charge beam-helicity asymmetry

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

from S. Yaschenko

Azimuthal dependences in DVCS

See e.g.: A.V. Belitsky, D. Müller, A. Kirchner, Nucl. Phys. B 629 (2002) 323-392

Various azimuthal-asymmetry amplitudes

↓

Fourier expansion in cos(nϕ) and sin(nϕ)terms

↙ ↘

Compare to GPD models

↓

Improve GPD models

↓

GPDs

Extract Compton Form Factors

↓

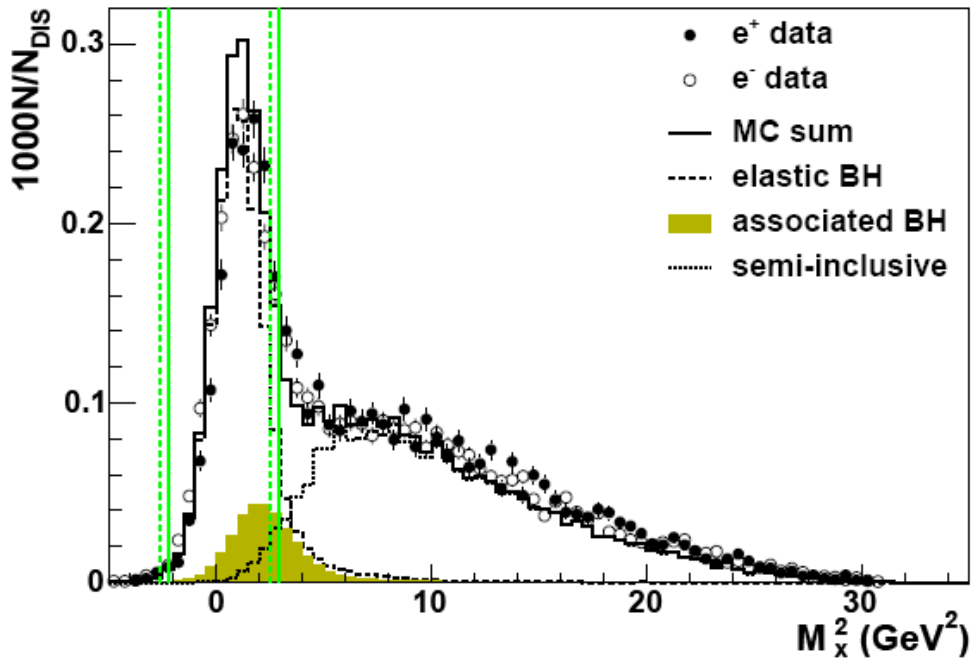
GPDs

DVCS @ HERMES

Rather complete measurement of amplitudes in $eN \rightarrow e'N\gamma$ possible at HERMES:

- Both beam charges
- Longitudinal beam polarisation (both helicities)
- Unpolarised H, D and nuclear targets
- Longitudinally polarised H and D targets
- Transversely polarised H target
- Recoil Detector

DVCS @ HERMES (w/o Recoil)



Kinematic requirements

$0.03 < x_B < 0.35$

$1\ GeV^2 < Q^2 < 10\ GeV^2$

$-t < 0.7\ GeV^2$

$E_\gamma > 5\ GeV$

* Identification by missing mass technique

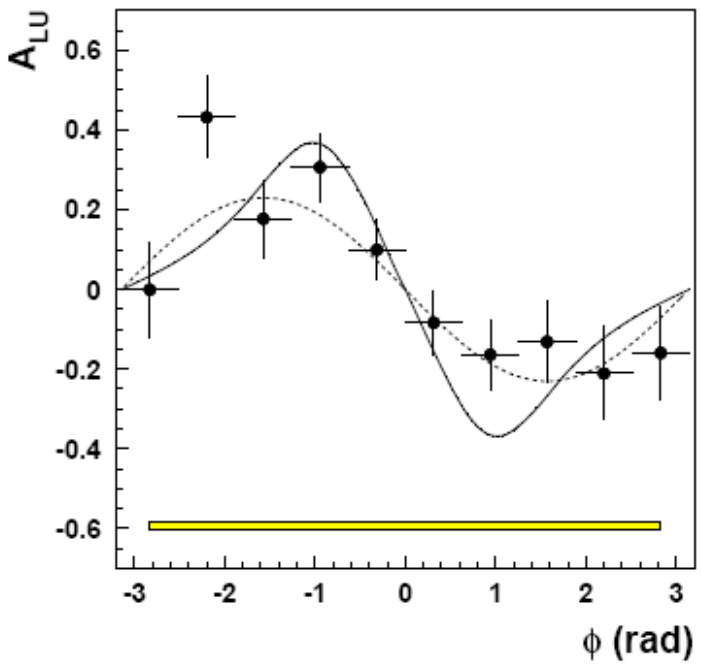
* Semi-inclusive corrected as dilution for charge-dependent asymmetries
  For pure DVCS term asymmetry extracted from π^0 ($z>0.8$) data

* Associated BH $ep \rightarrow e'\Delta\gamma \approx 12$ % (with unknown asymmetry)
  stays part of the signal

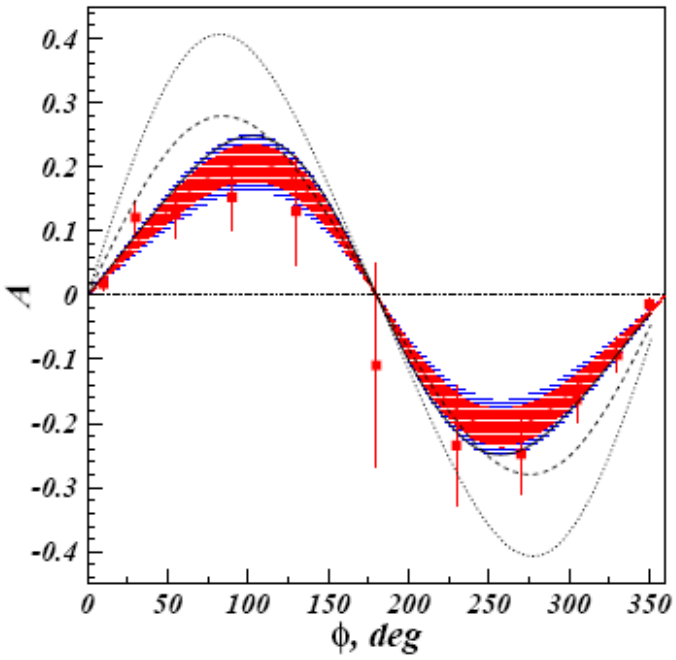
DVCS @ HERMES

First result (2001): Beam-spin asymmetry

HERMES, PRL 87 (2001) 182001

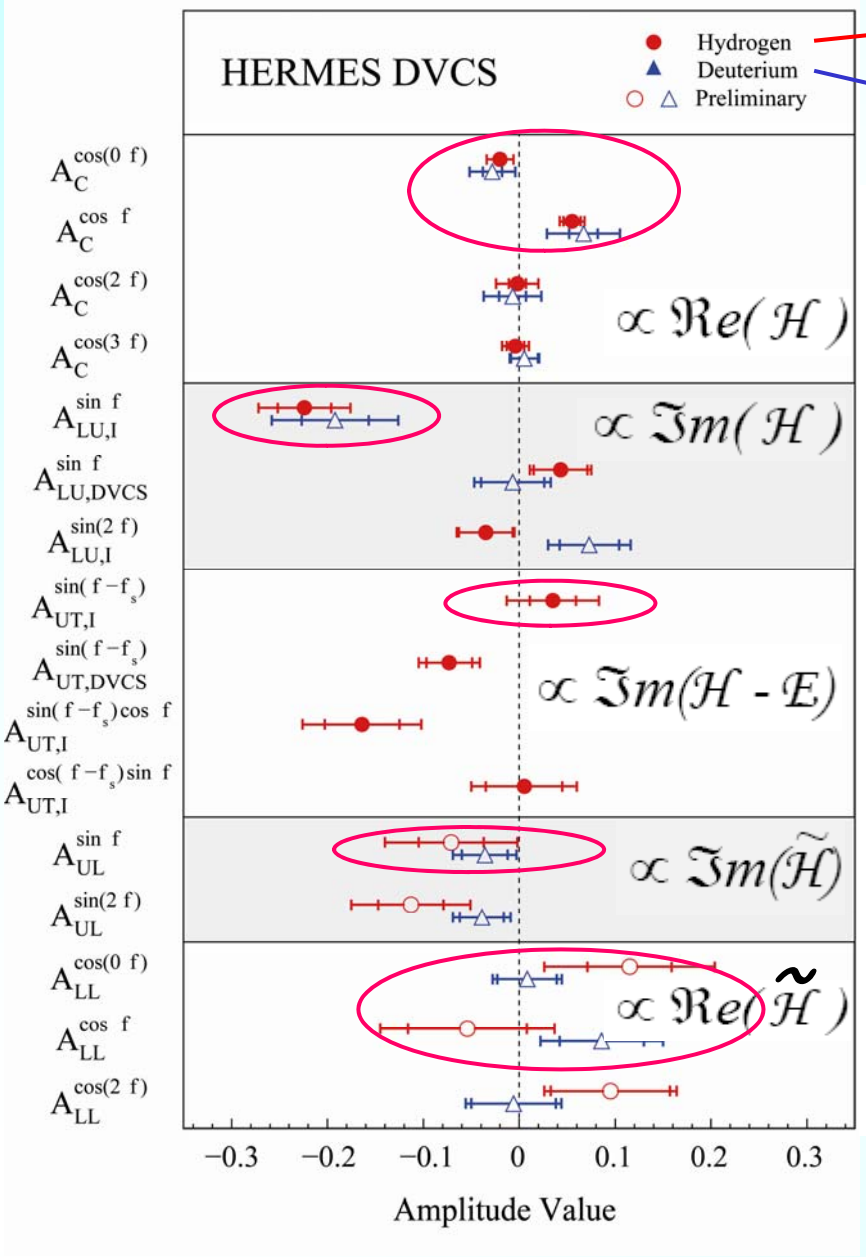


CLAS, PRL 87 (2001) 182002



Now: Simultaneous maximum likelihood fit of all relevant amplitudes

DVCS asymmetries measured @ HERMES



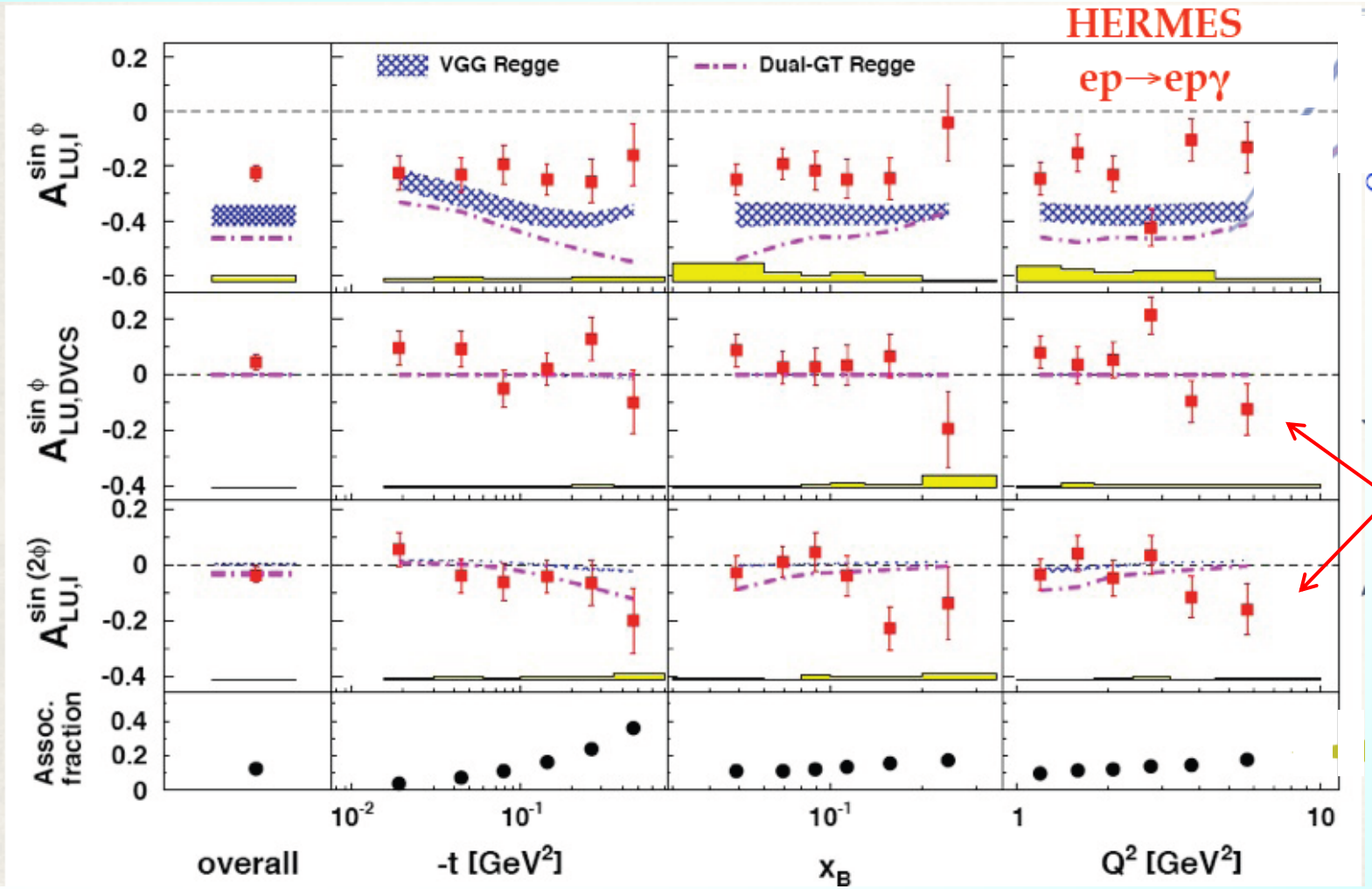
acc. by JHEP, arXiv:0909.3587

subm. to NP B, arXiv:0911.0095

- Beam charge asymmetry
  GPD H
- Beam helicity asymmetry
  GPD H
- Transverse target spin asymmetry
  JHEP 06 (2008) 066, arXiv:0802.2499
  GPD E
- Longitudinal target spin asymmetry
  GPD $\tilde{H}$ (in preparation)
- Double spin asymmetry
  GPD $\tilde{H}$ (in preparation)

Proton: beam helicity asymmetry (Interference)

arXiv:0909.3587



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

twist-3

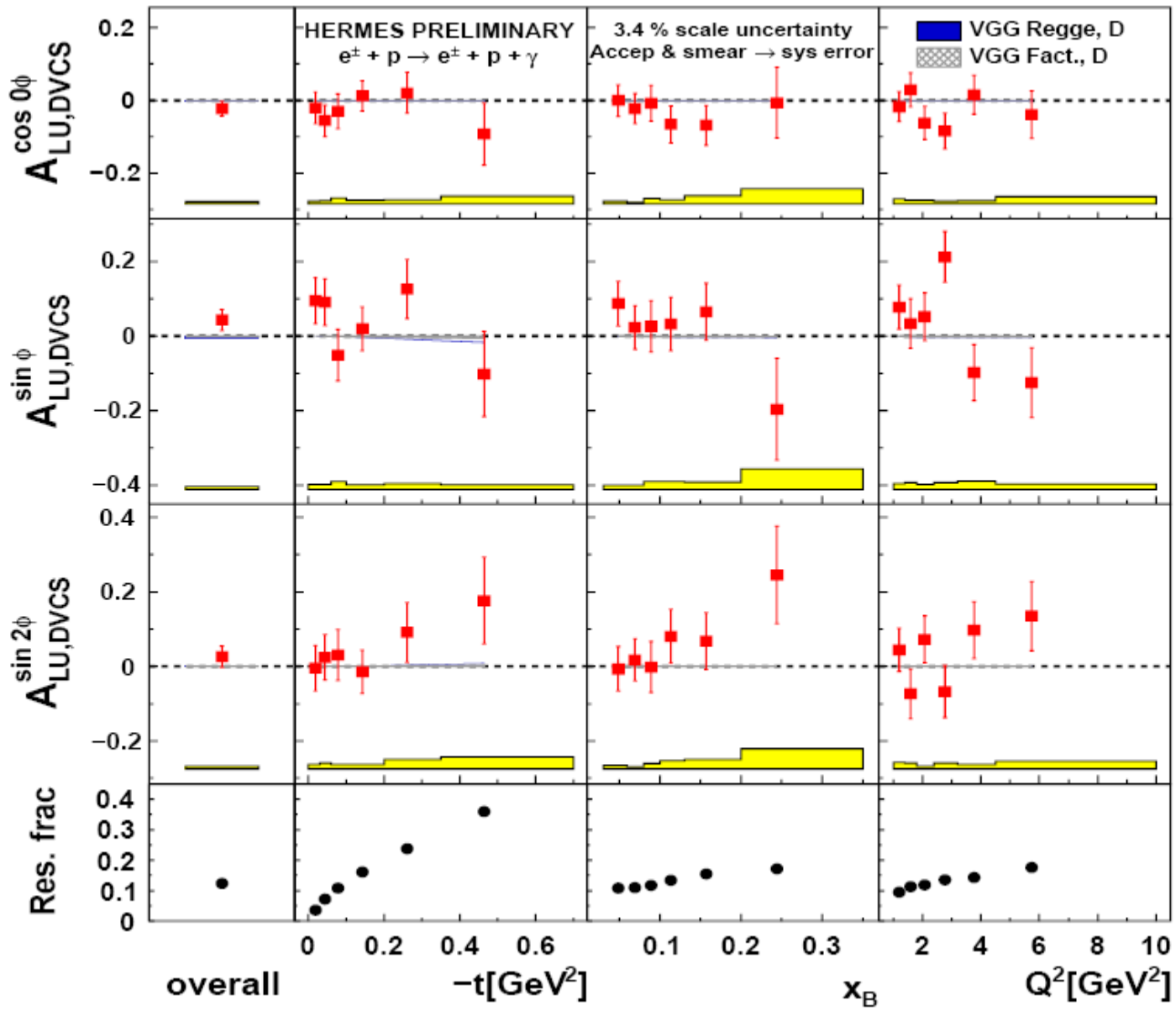
fraction of
ep → e'Δ+ γ

VGG: Phys. Rev D 60 (1999) 4017, Prog. Nucl. Part. Phys. 42 (2001) 401

Dual: Phys. Rev D 79 (2009) 017501

Proton: beam helicity asymmetry (DVCS)

arXiv:0909.3587



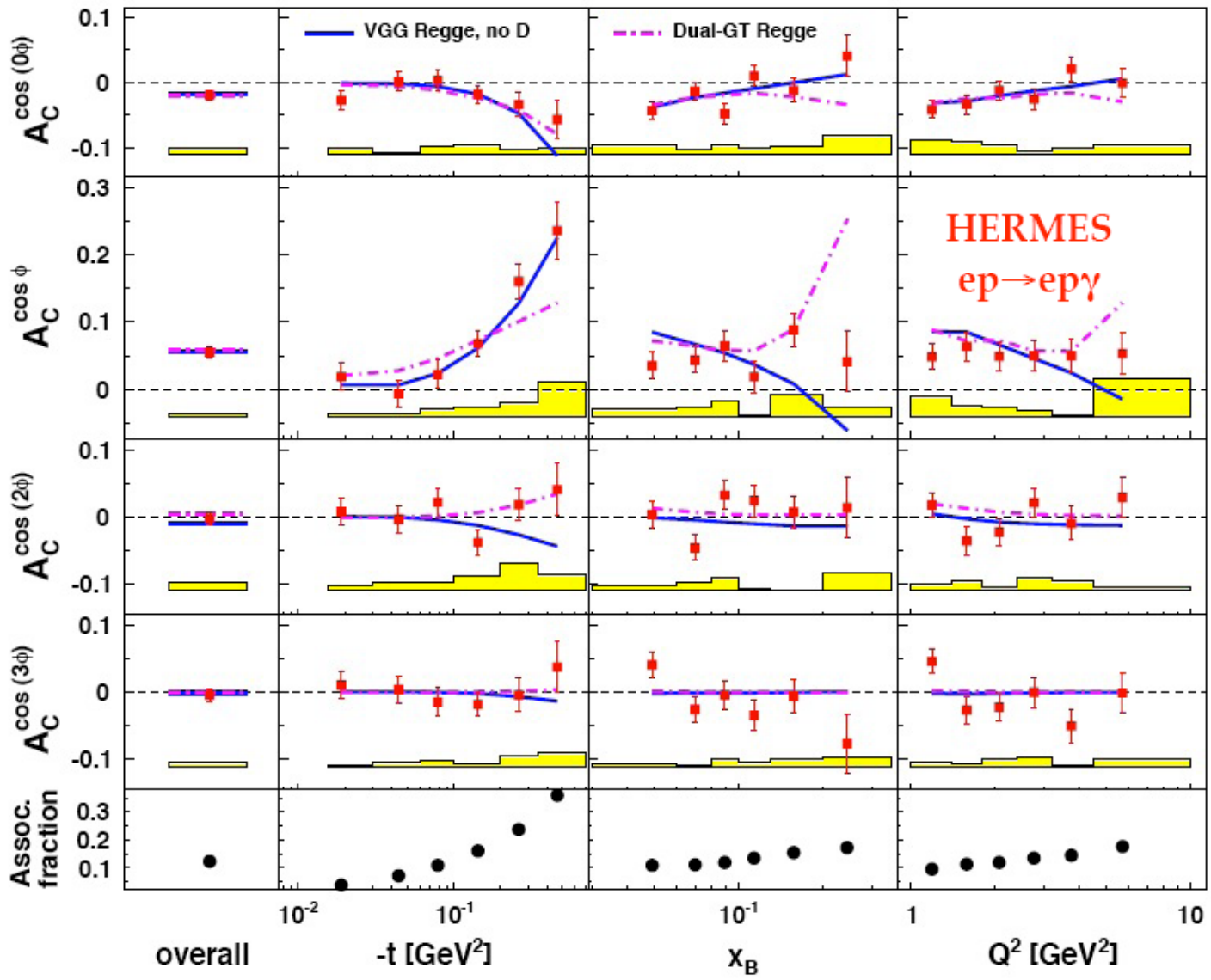
$$\propto [\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*]$$

← Resonance fraction

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

Proton: beam charge asymmetry

arXiv:0909.3587



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

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

← Higher twist

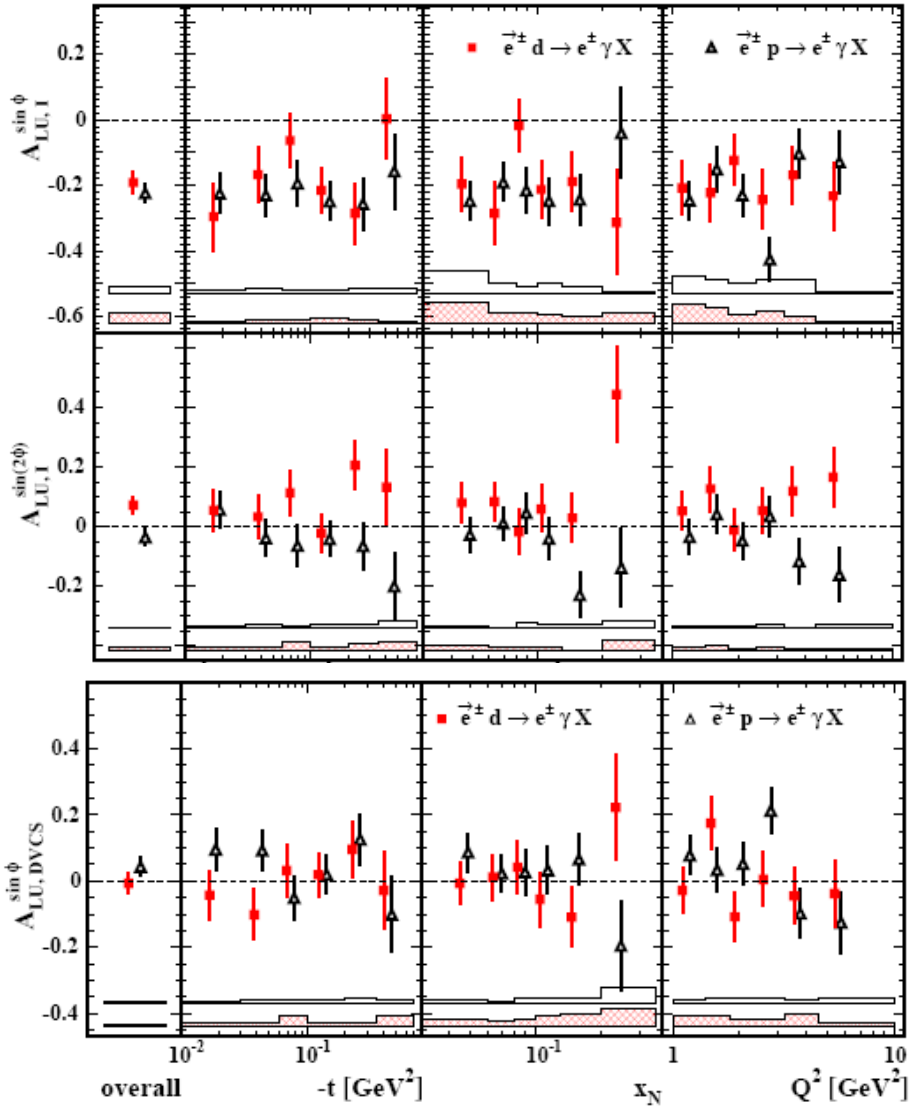
← Gluon leading twist

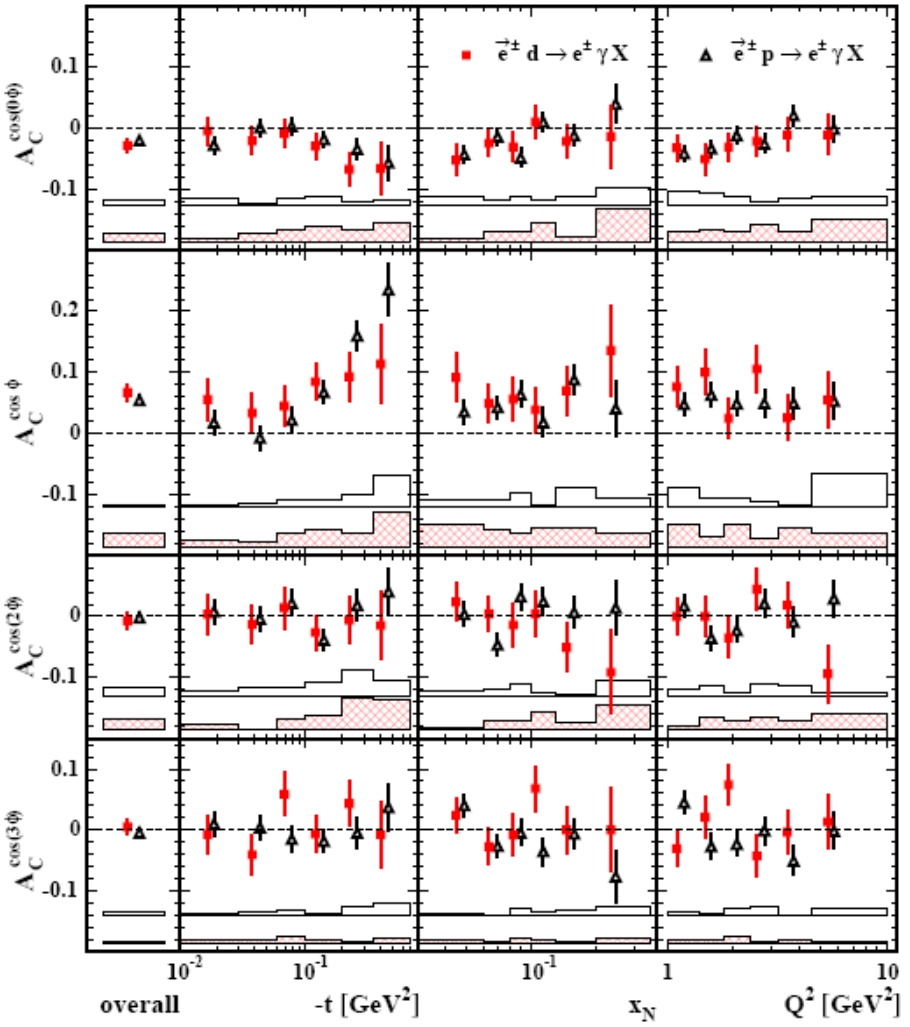
← Resonance fraction

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

$A_{LU,C}$: Proton vs deuteron

arXiv:0911.0095



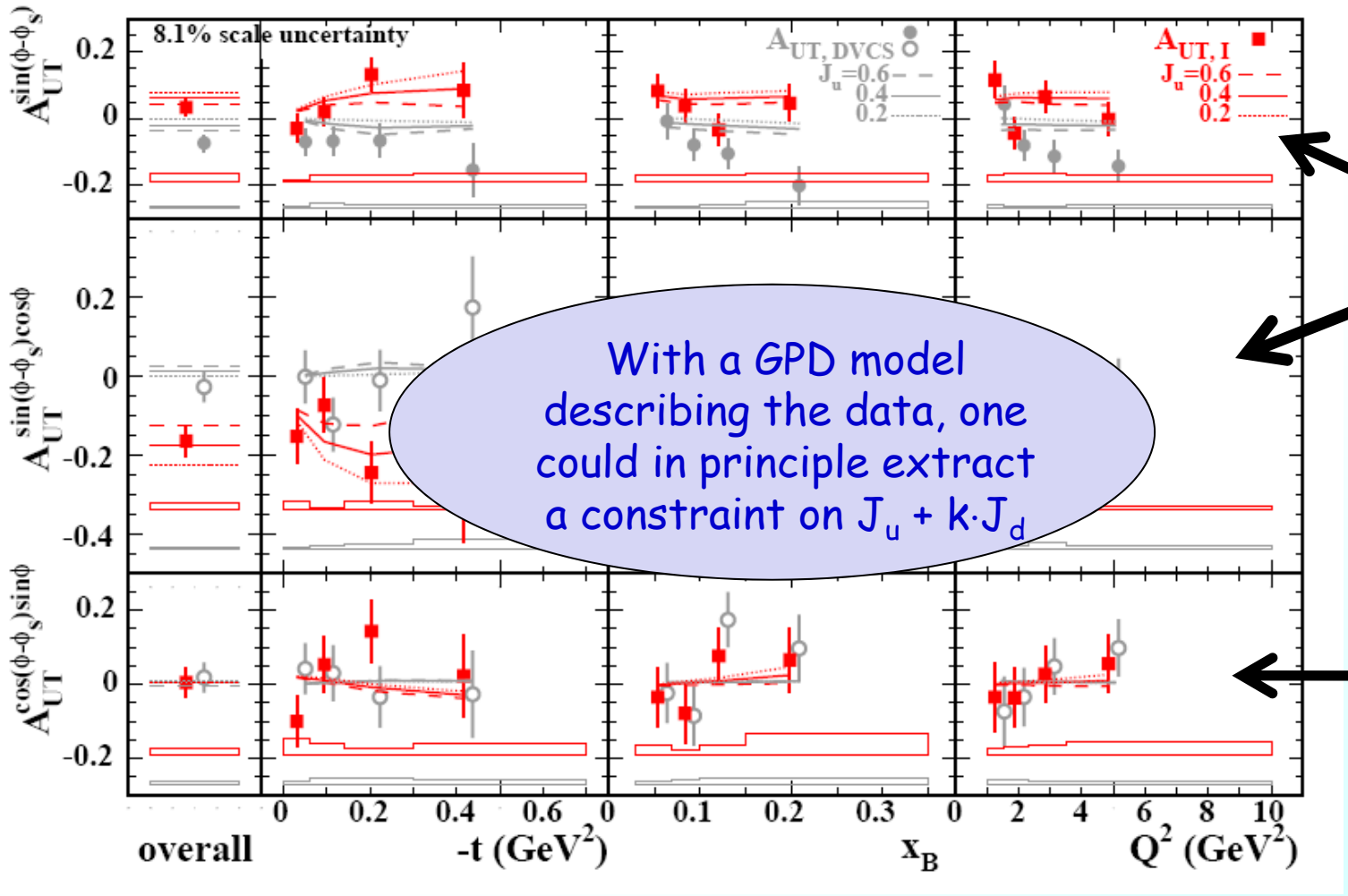


Proton and deuteron data are compatible for all leading amplitudes

Proton: transverse target pol. asymmetry

Sensitive to GPD E

JHEP 06 (2008) 066



With a GPD model describing the data, one could in principle extract a constraint on $J_u + k \cdot J_d$

sensitive to J_u:

$\mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E}) \cdot \sin(\phi - \phi_s)\cos(n\phi)$

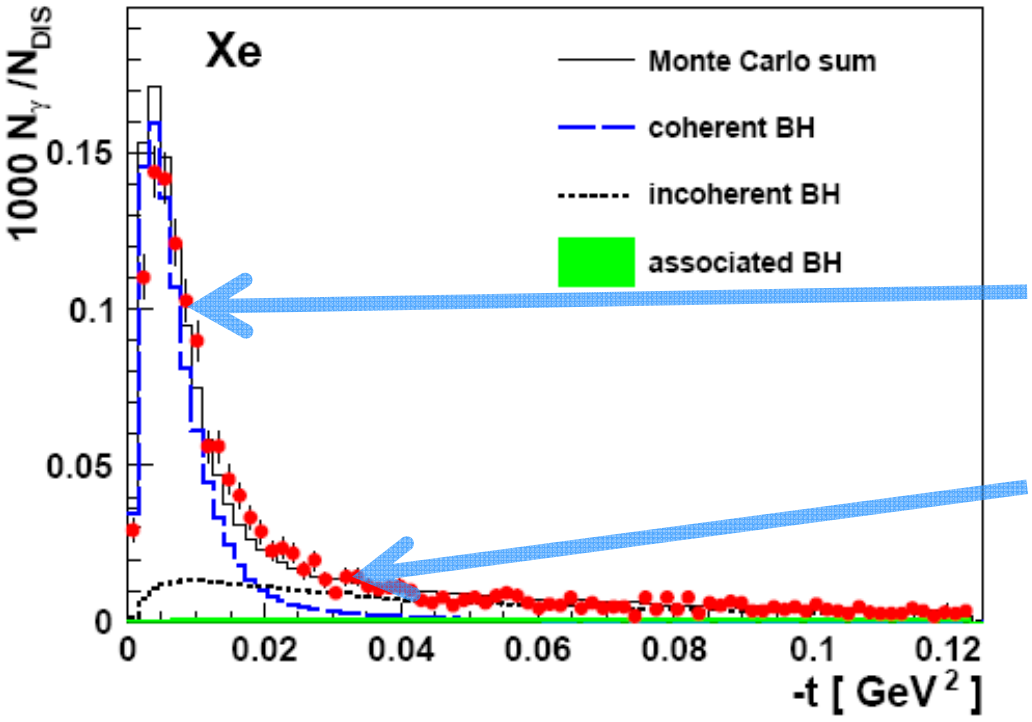
NOT sensitive to J_u:

$\mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1 + \xi F_2)\widetilde{\mathcal{E}}\right) \cdot \cos(\phi - \phi_s)\sin\phi$

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

DVCS - nuclear mass dependence

arXiv:0911.0091



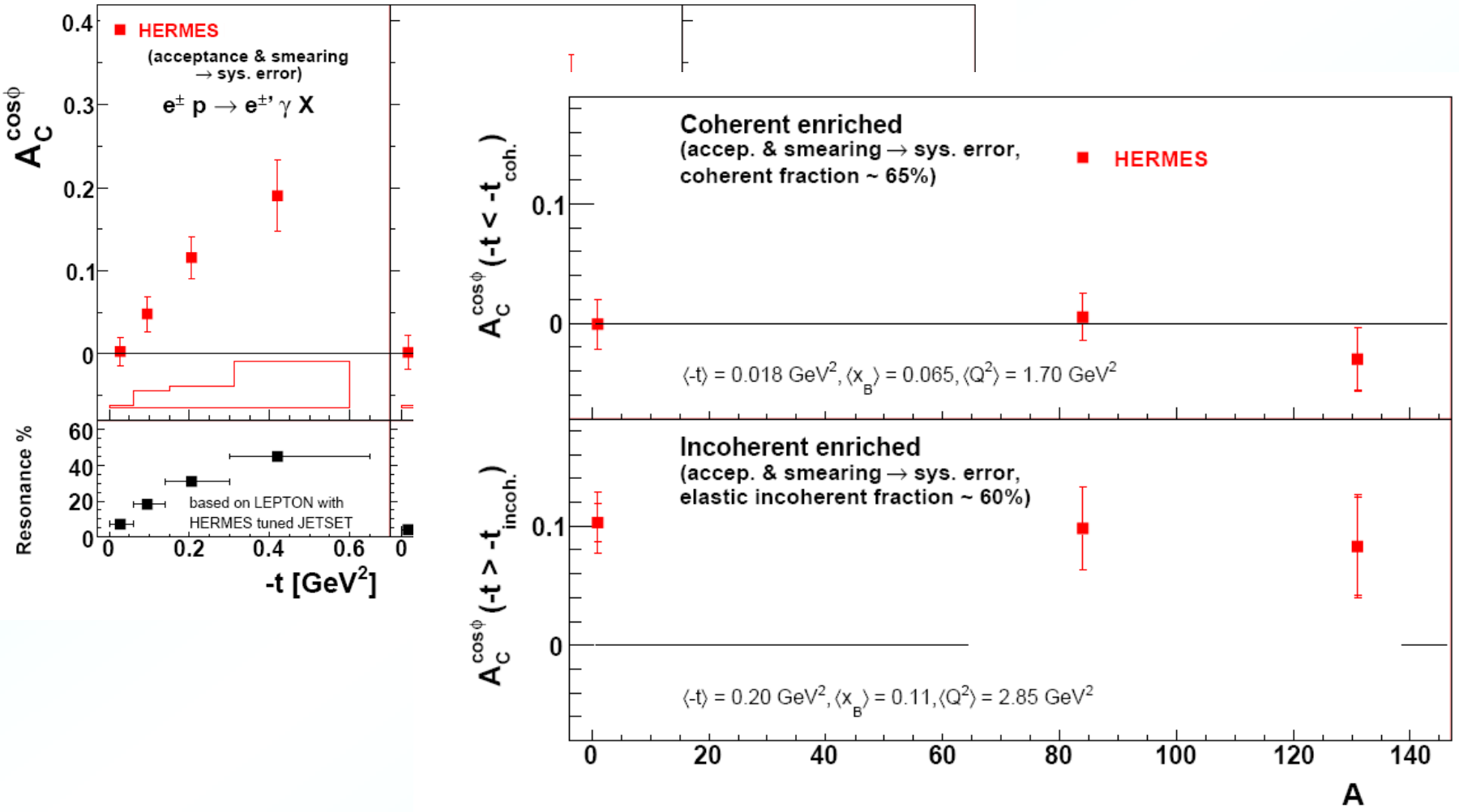
Select for each target
2 samples

- coherent enriched (low t)
  ≈ 65 % coherent fraction
- incoherent enriched (high t)
  ≈ 65 % incoherent fraction

Targets: H, He, N, Ne, Kr, Xe

DVCS - nuclear mass dependence of A_C

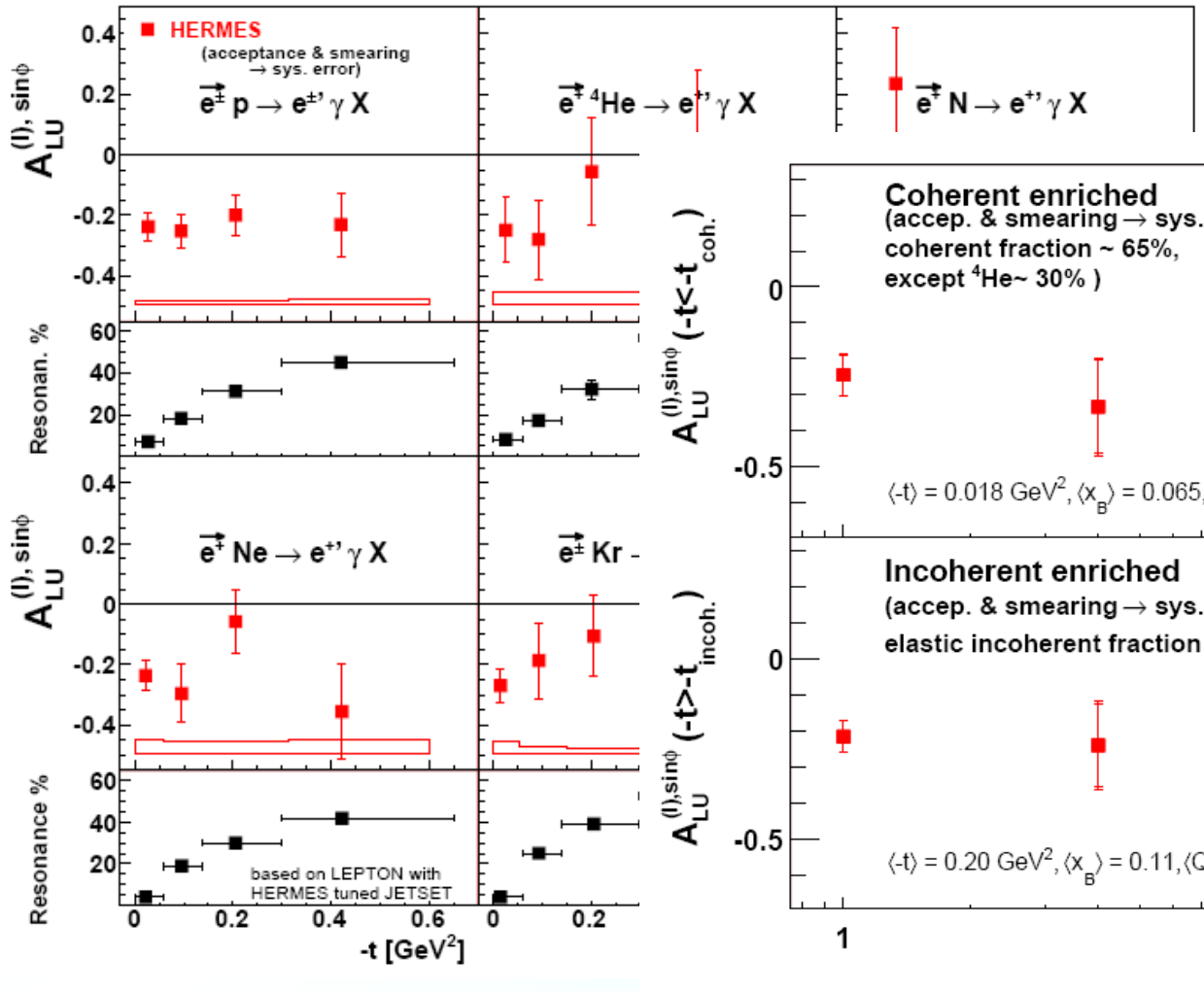
arXiv:0911.0091



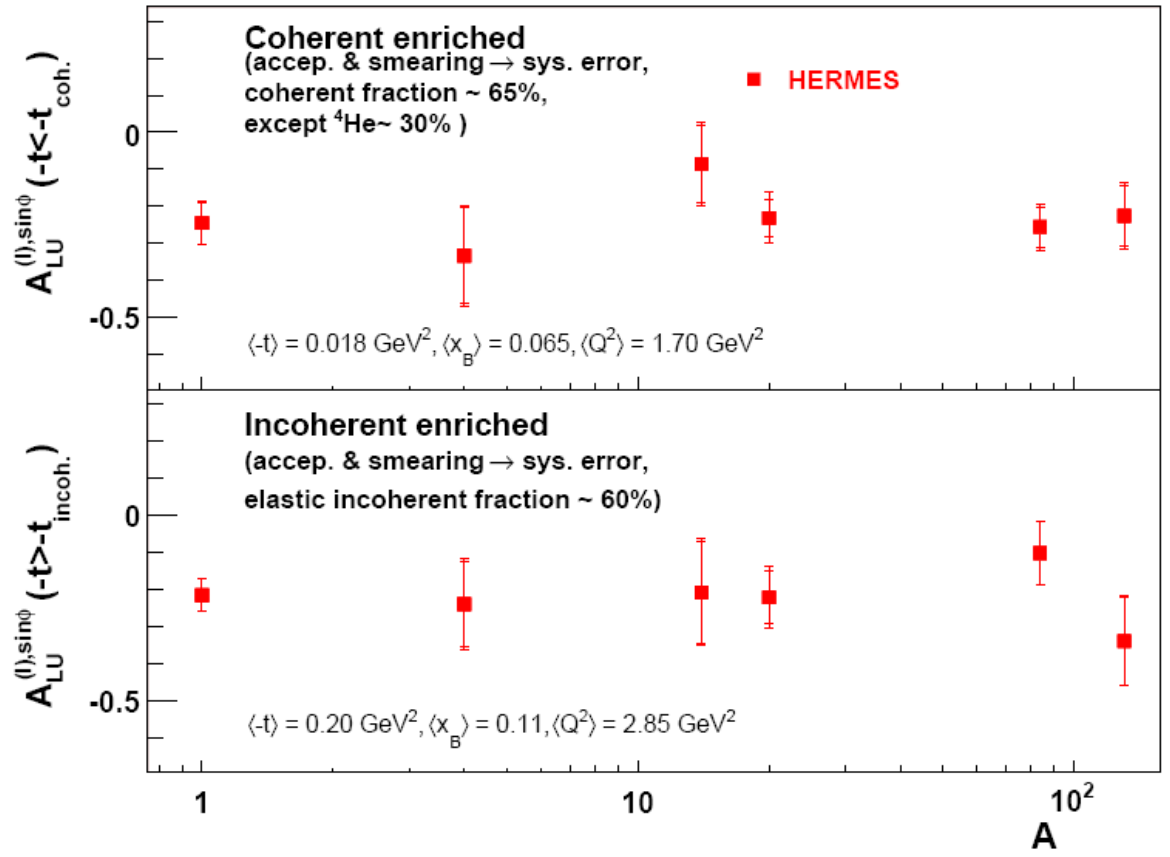
No enhancement of nuclear asymmetries visible!!!

DVCS - nuclear mass dependence

$$H, Kr, Xe: \; A_{LU}^{I}(\phi) = \frac{\left(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}\right) - \left(\sigma^{+\leftarrow} + \sigma^{-\rightarrow}\right)}{\left(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}\right) + \left(\sigma^{+\leftarrow} + \sigma^{-\rightarrow}\right)} \qquad {}^{4}He, N, Ne: \; A_{LU}^{I}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$



arXiv:0911.0091



No enhancement of nuclear asymmetries visible!!!

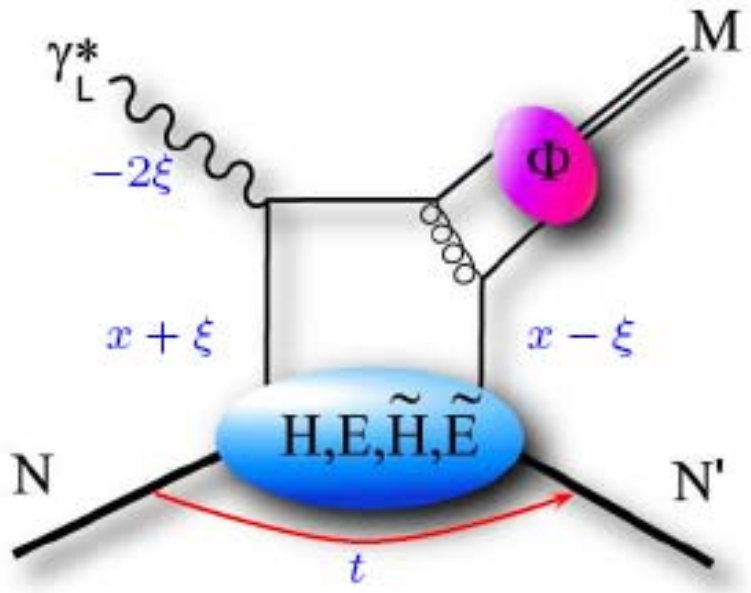
- Deeply Virtual Compton Scattering (DVCS)
- Exclusive Vector Meson (ρ, ω, ϕ) production
- Exclusive π+ production
- Recoil Detector

Hard exclusive vector meson production

modified perturbative approach

-Goloskokov, Kroll (2006)-

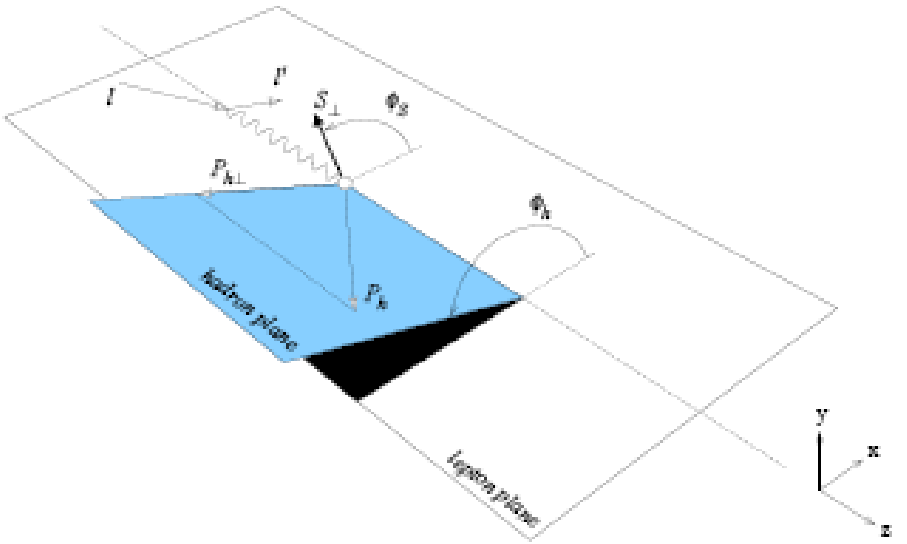
$$\mathcal{A} \propto F(x,\xi,t;\mu^2) \otimes K(x,\xi,z;\log(Q^2/\mu^2) \otimes \Phi(z,k_\perp;\mu^2)$$

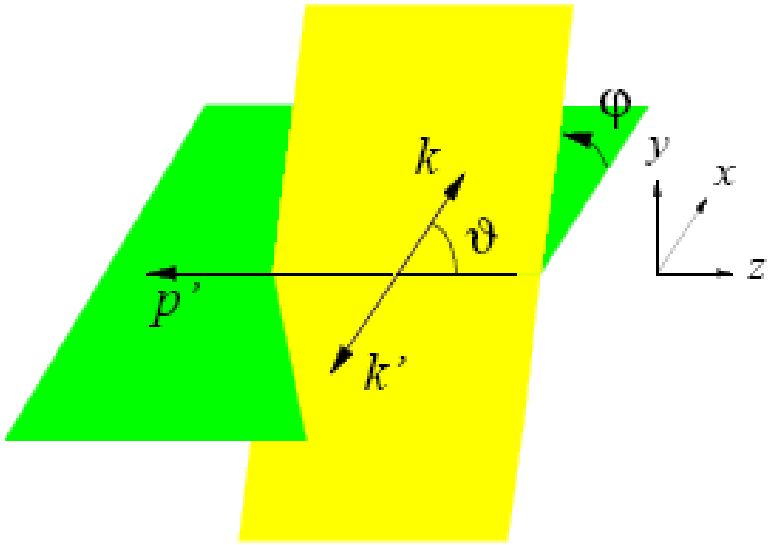


* Factorisation for σ_L only
* $\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L$: GPDs H, E
* σ_L - σ_T suppressed by 1/Q
* σ_T suppressed by 1/Q2
* $\gamma^*_T \rightarrow \rho^0_T$: contr. from $\tilde{H}$, $\tilde{E}$

Hard exclusive vector meson production

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$





Production and decay angular distributions decomposed:

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

W_{XY}

beam: P_L target: S_L, S_T

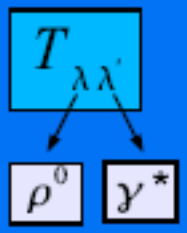
Hard exclusive vector meson production

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \sim \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$

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

- parametrized by helicity amplitudes $T_{\lambda\lambda'}$ or $T^{V\sigma}_{\mu\lambda}$:

-Schilling, Wolf (1973)-



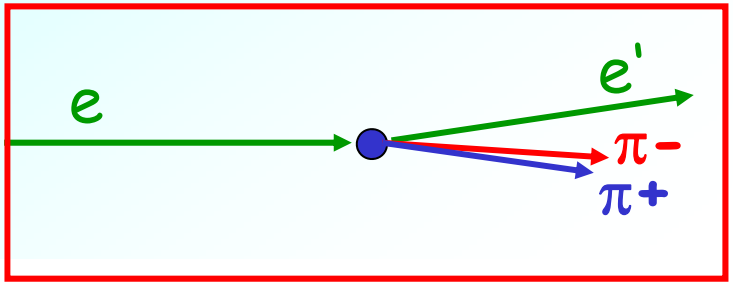
-Diehl notation (2007)-

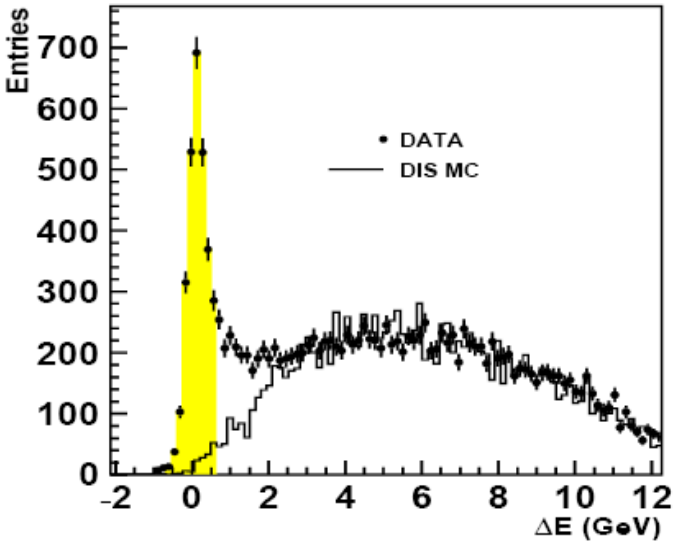
- or alternatively by spin-density matrix elements (SDMEs):

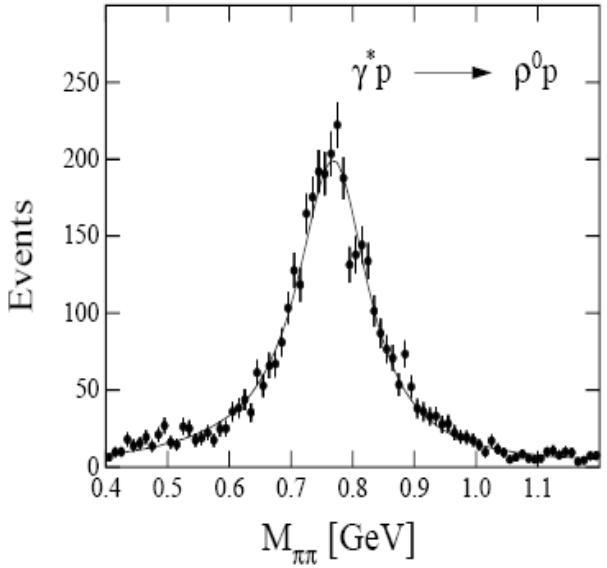
from A. Rostomyan

ρ^0 - event selection

$e\,p \rightarrow e'\,\rho^0\,p$







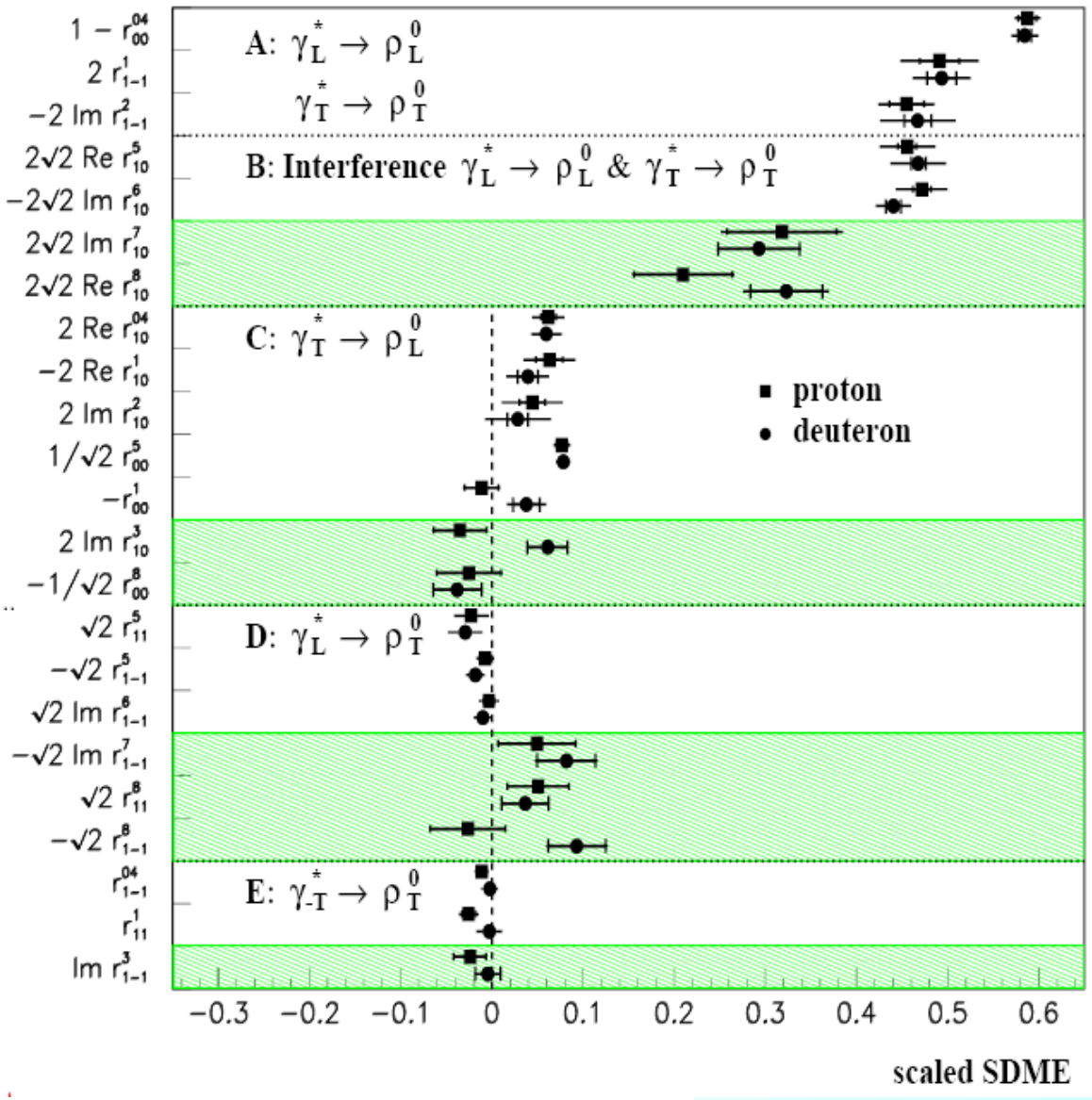
$\Delta E = (M_X^2 - M_p^2)/ 2M_p$

$\langle Q^2 \rangle = 2.3\ GeV^2$, $\langle W \rangle = 4.9\ GeV$

Background subtraction with PYTHIA

$\langle X_B \rangle = 0.07$, $\langle -t \rangle = 0.13\ GeV^2$

Unpolarised ρ^0 SDMEs - $W_{(L,U)U}$



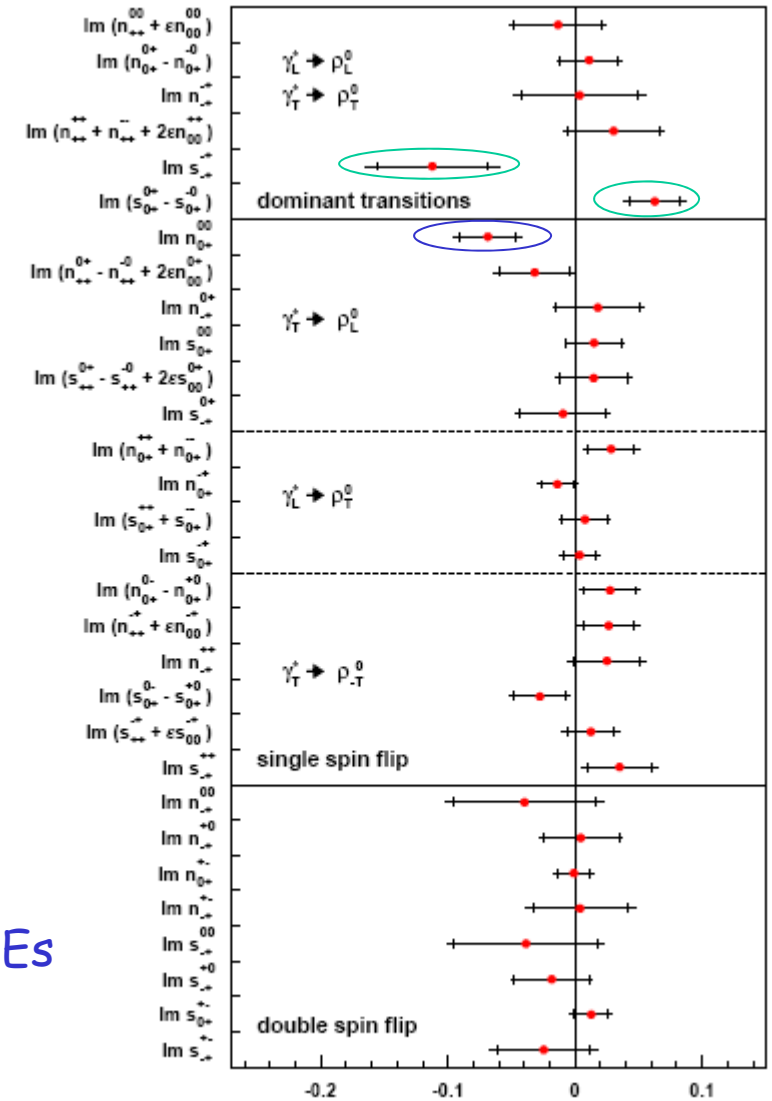
EPJ C62 (2009)659

23 SDMEs

Hierarchy of ρ_0 amplitudes: $|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{1-1}|^2$ $(0 \to L, 1 \to T)$

Transverse ρ^0 SDMEs – $W_{(L,U)T}$

30 SDMEs



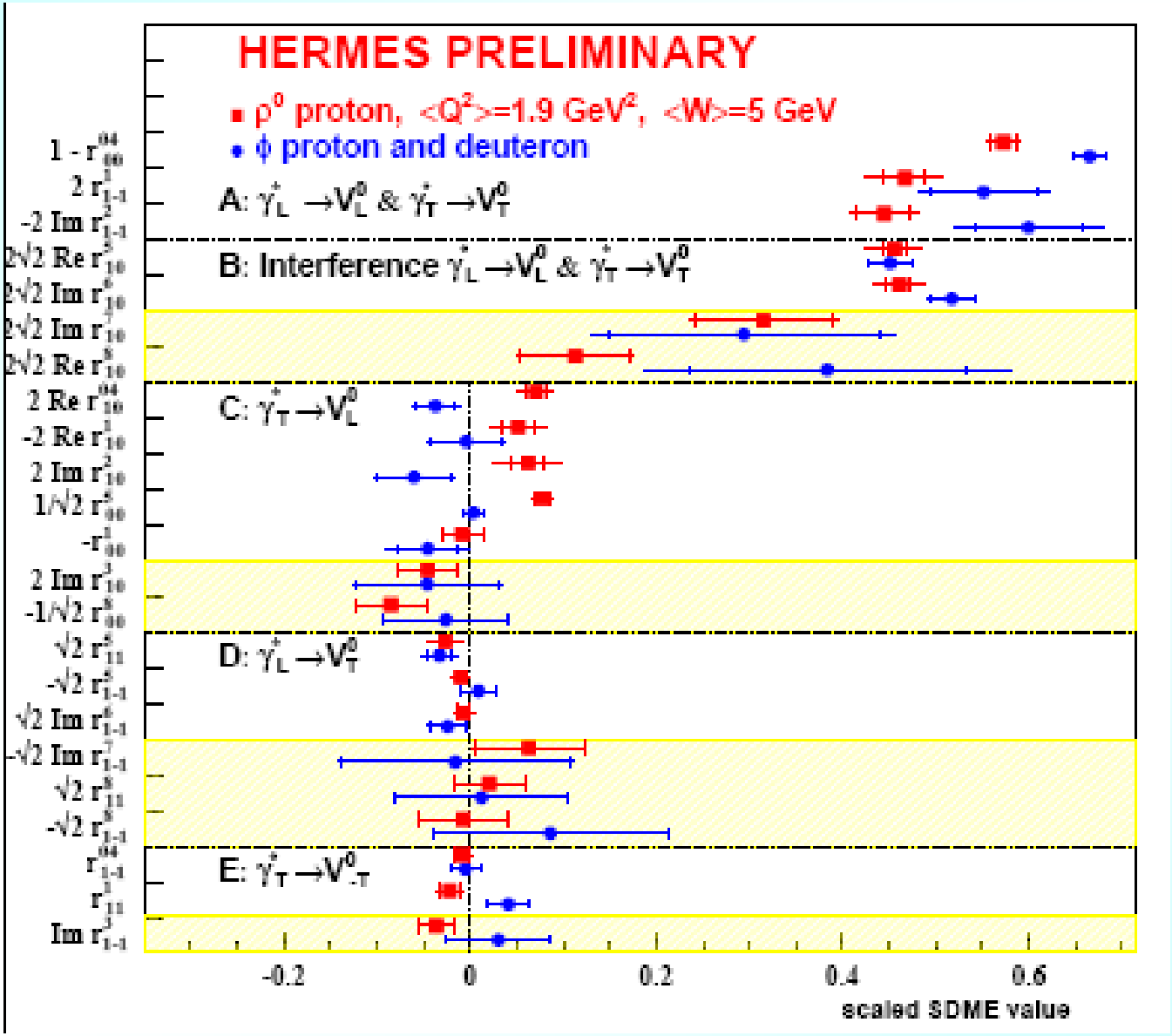
PLB 679 (2009) 100

Measured for the first time

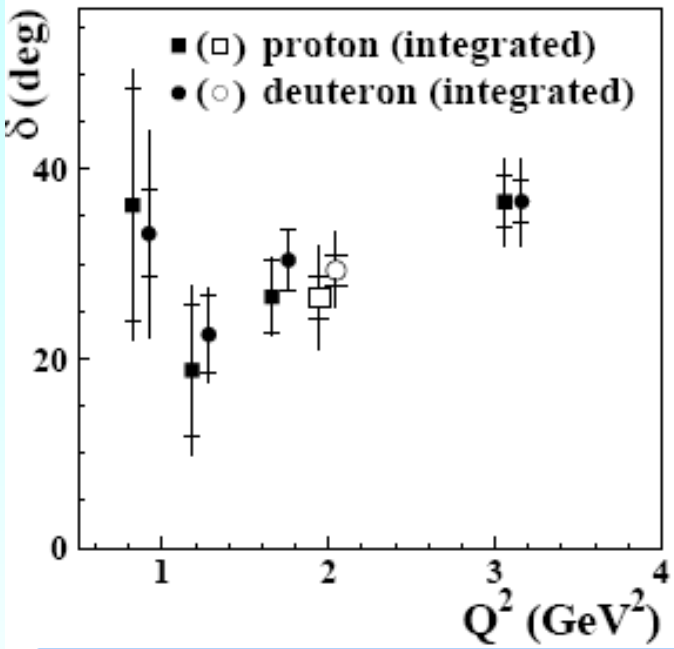
Related to proton helicity-flip amplitude

Suppressed by $\sqrt{-t}/2M_p$

Unpolarised ρ^0 - ϕ SDMEs - $W_{(L,U)U}$



ρ^0: phase difference δ between T_{00} and T_{11}



neglecting spin-flip amplitudes

- $|\delta|$ obtained from unpolarizes SDMEs:

$$\cos\delta = \frac{2\sqrt{\epsilon}(\Re r^5_{10} - \Im r^6_{10})}{\sqrt{r^{04}_{00}(1 - r^{04}_{00} + r^1_{1-1} - \Im r^2_{1-1})}}$$

- sign of δ obtained from polarizes SDMEs:
  (for the first time)

$$\sin\delta = \frac{2\sqrt{\epsilon}(\Re r^8_{10} - \Im r^7_{10})}{\sqrt{r^{04}_{00}(1 - r^{04}_{00} + r^1_{1-1} - \Im r^2_{1-1})}}$$

- results on δ (in degrees):
  - proton: $|\delta| = 26.4 \pm 2.3_{stat} \pm 4.9_{sys}$; $\delta = 30.6 \pm 5.0_{stat} \pm 2.4_{sys}$
  - deuteron: $|\delta| = 29.3 \pm 1.6_{stat} \pm 3.6_{sys}$; $\delta = 36.3 \pm 3.9_{stat} \pm 1.7_{sys}$
- values are consistent
  - with each other
  - with H1 results: $|\delta| = 21.5 \pm 4.3_{stat} \pm 5.3_{sys}$

from A. Rostomyan

More economic: extract the 9 helicity amplitudes directly (in preparation)

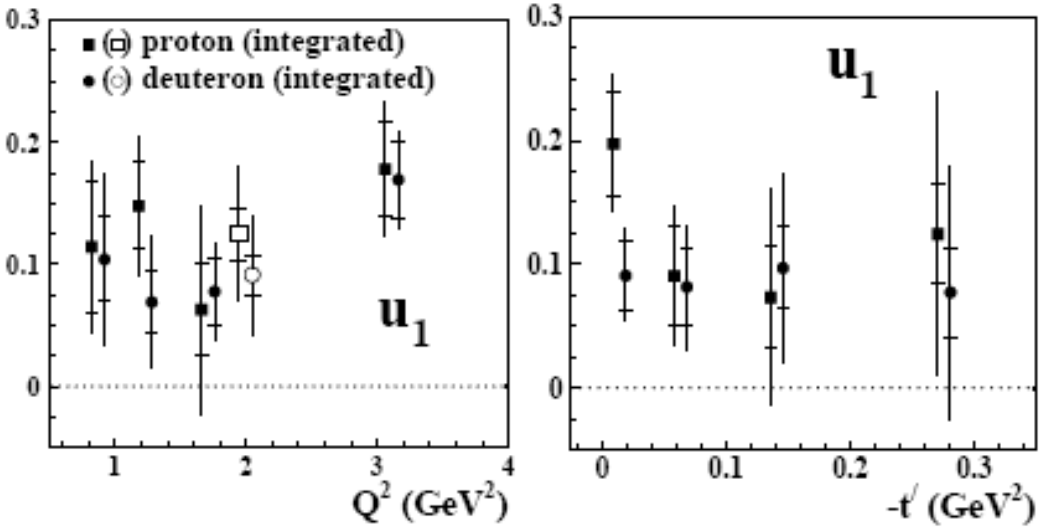
ρ^0: observation of unnatural-parity exchange

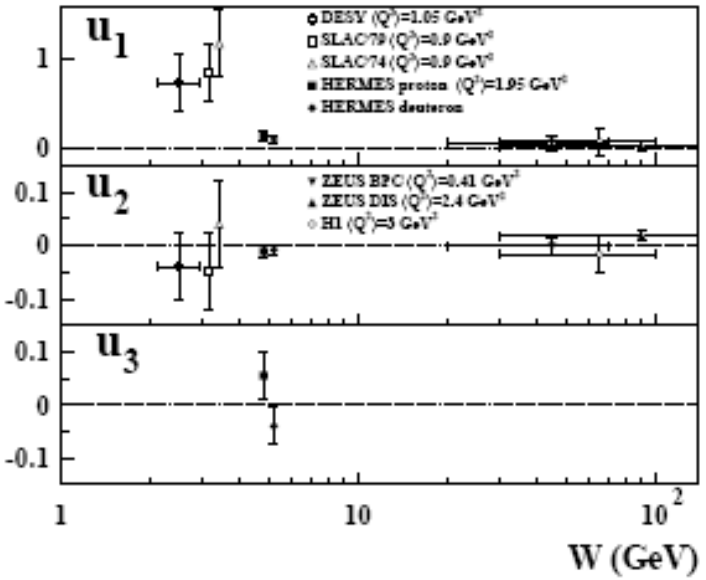
EPJ C62 (2009)659

- UPE contributions measured from SDMEs:

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}, \quad u_2 = r^{5}_{11} + r^{5}_{1-1} \quad , u_3 = r^{8}_{11} + r^{8}_{1-1}$$

- the combinations of SDMEs expected to be the zero in case of NPE dominance



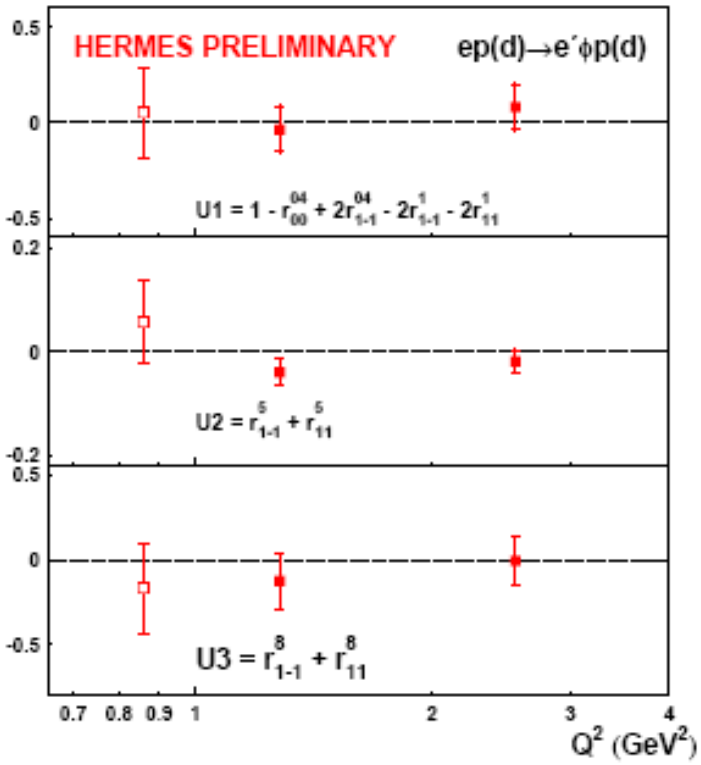


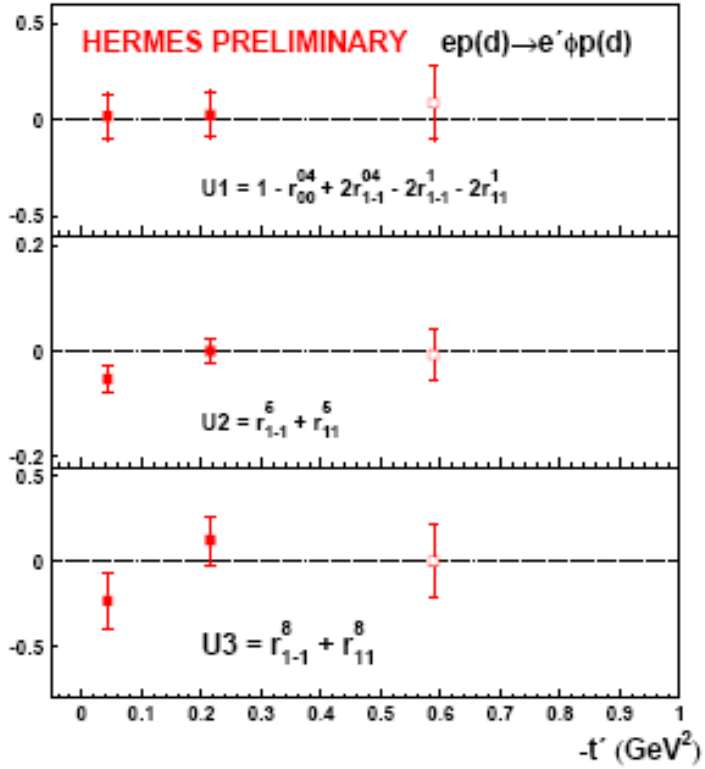
- proton:
  $u_1 = 0.125 \pm 0.021_{stat} \pm 0.050_{sys}$
- deuteron:
  $u_1 = 0.091 \pm 0.016_{stat} \pm 0.046_{sys}$

UPE contribution is W-dependent

from A. Rostomyan

ϕ: search for unnatural-parity exchange





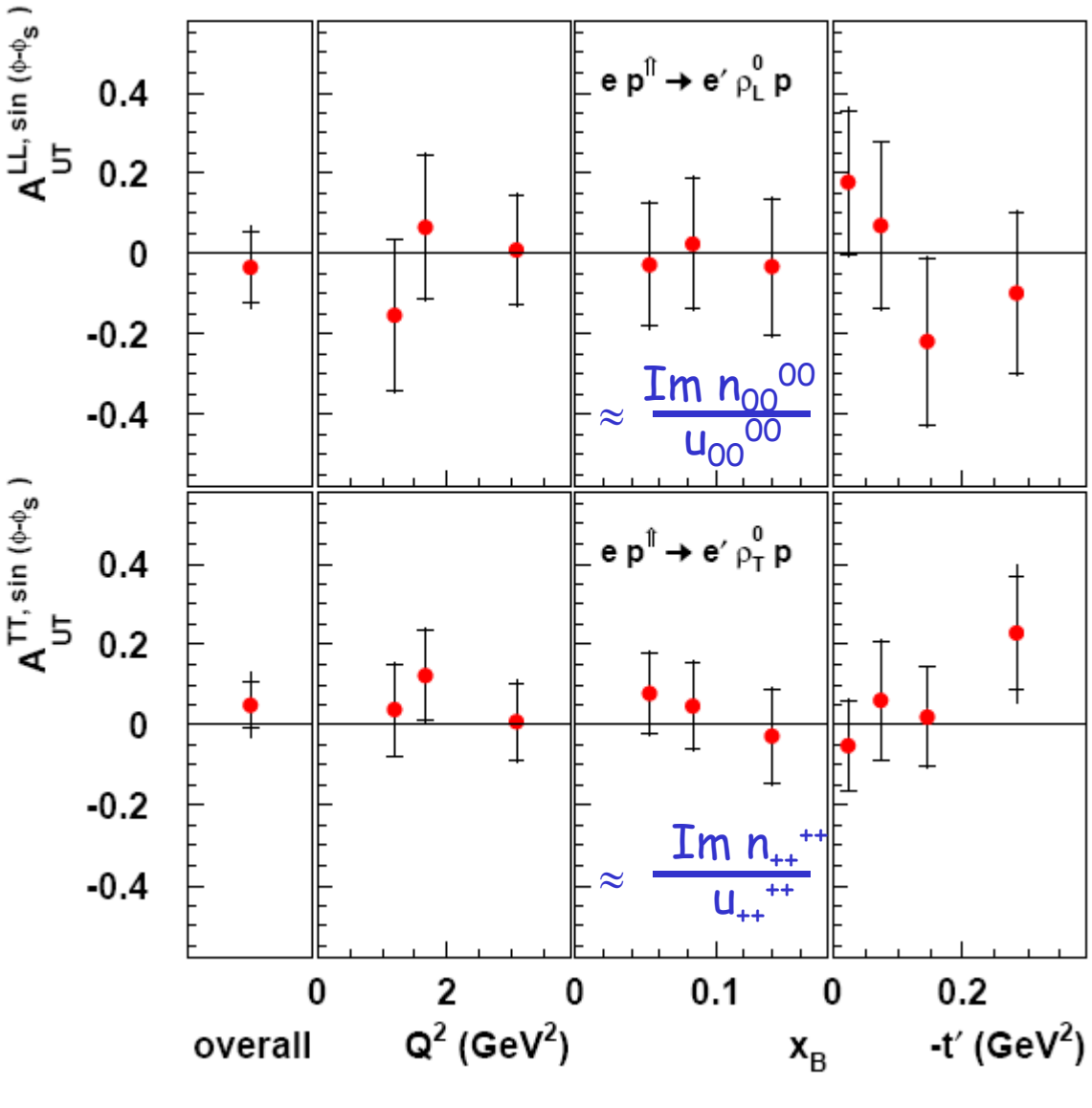
- $u_1 = 0.02 \pm 0.07_{stat} \pm 0.16_{sys}$
- $u_2 = -0.03 \pm 0.01_{stat} \pm 0.03_{sys}$
- $u_3 = -0.05 \pm 0.12_{stat} \pm 0.07_{sys}$
- no signal of unnatural-parity exchange

expected since dominant contribution to the production is from two gluon exchange

from A. Rostomyan

ρ^0 Transverse Target Polarisation Asymmetry

PLB 679 (2009) 100



$$A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

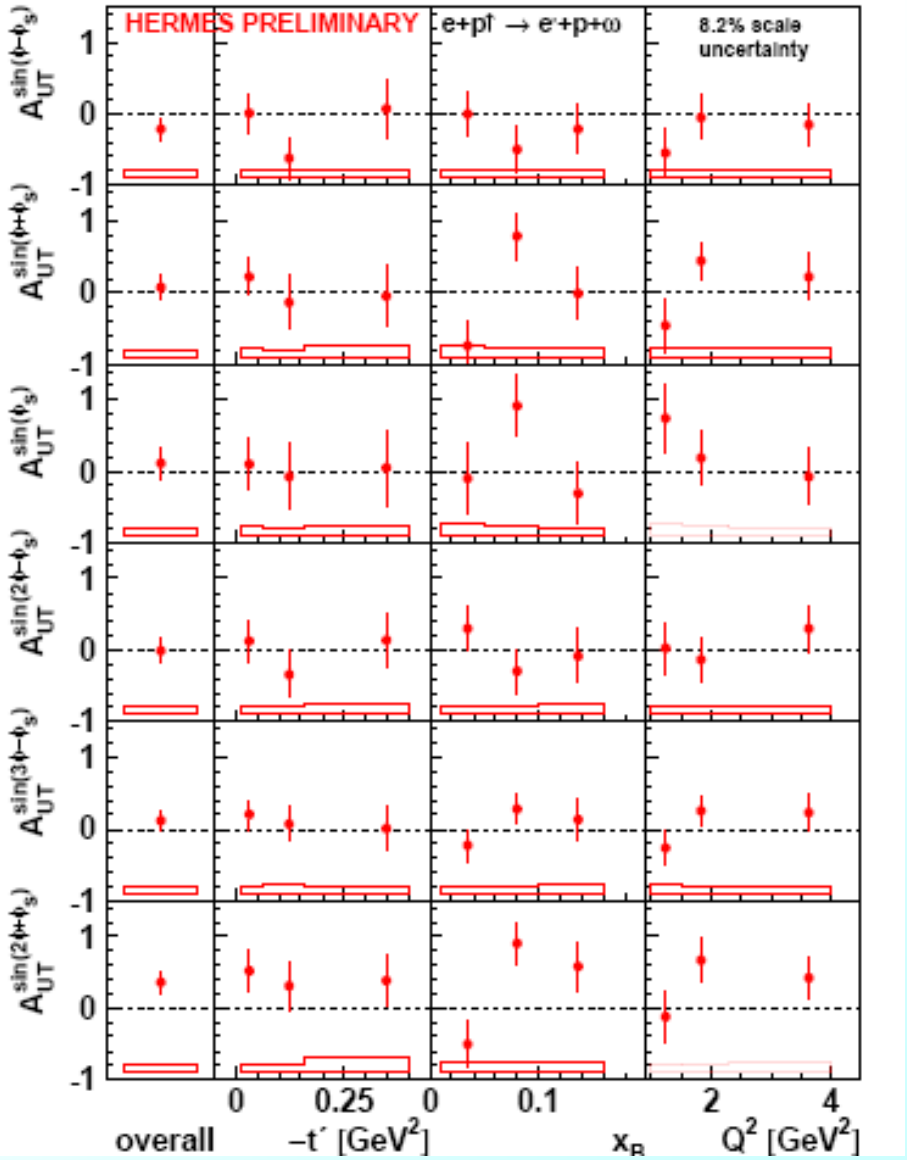
u: unpolarised
n: normal polarisation
s: sideways polarisation

Compatible with zero overall value

$A_{UT}^{\sin(\phi-\phi s)} = -0.033 \pm 0.058$

ω Transverse Target Polarisation Asymmetry

- 6 azimuthal moments extracted using integrated angular distributions
- due to low statistics no ω_L/ω_T separation
- predictions for large asymmetry
  $A_{UT}^{\sin(\phi-\phi_s)} \approx -0.10$
- indication of negative $\sin(\phi-\phi_s)$ amplitude
  $A_{UT}^{\sin(\phi-\phi_s)} = -0.22 \pm 0.16_{stat} \pm 0.11_{sys}$
- no contradiction with ρ^0 predictions
  $A_{UT}^{\rho^0,\sin(\phi-\phi_s)} \propto \Im\left\{\frac{2E^u+E^d}{2H^u+H^d+H^g}\right\}$
  $A_{UT}^{\omega,\sin(\phi-\phi_s)} \propto \Im\left\{\frac{2E^u-E^d}{2H^u-H^d}\right\}$

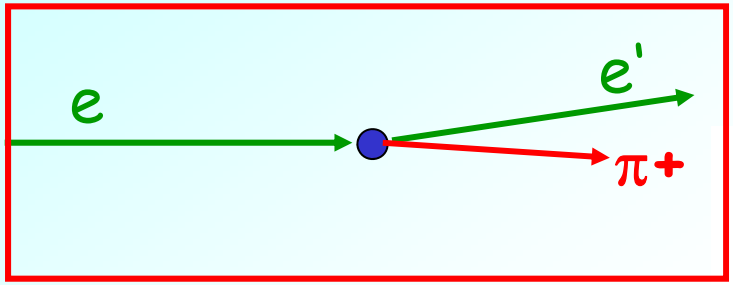


from A. Rostomyan

- Deeply Virtual Compton Scattering (DVCS)
- Exclusive Vector Meson (ρ, ω, ϕ) production
- Exclusive π+ production
- Recoil Detector

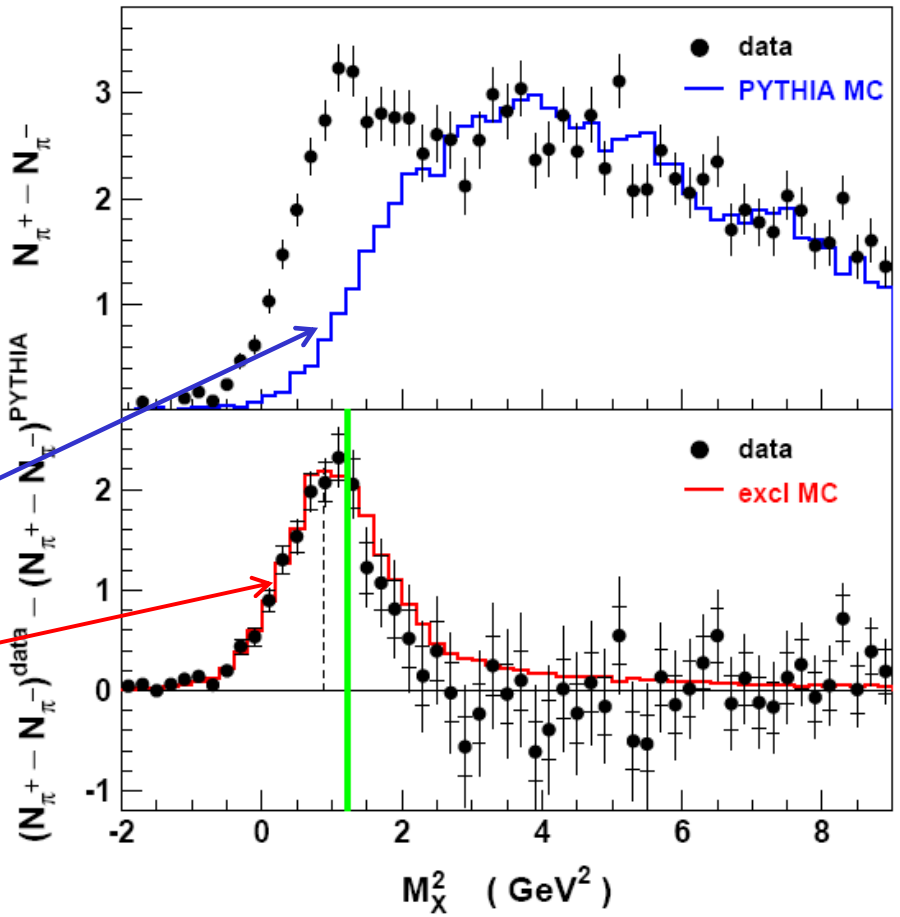
exclusive π+ – event selection

$e\,p \rightarrow e'\,\pi^+ n$



PLB 659 (2008) 486

$\sigma_L \propto (1-\xi^2)\cdot|\tilde{H}|^2 - \xi^2\cdot t\cdot|\tilde{E}|^2 - \xi^2\cdot \mathrm{Re}(\tilde{E}^*\tilde{H})$



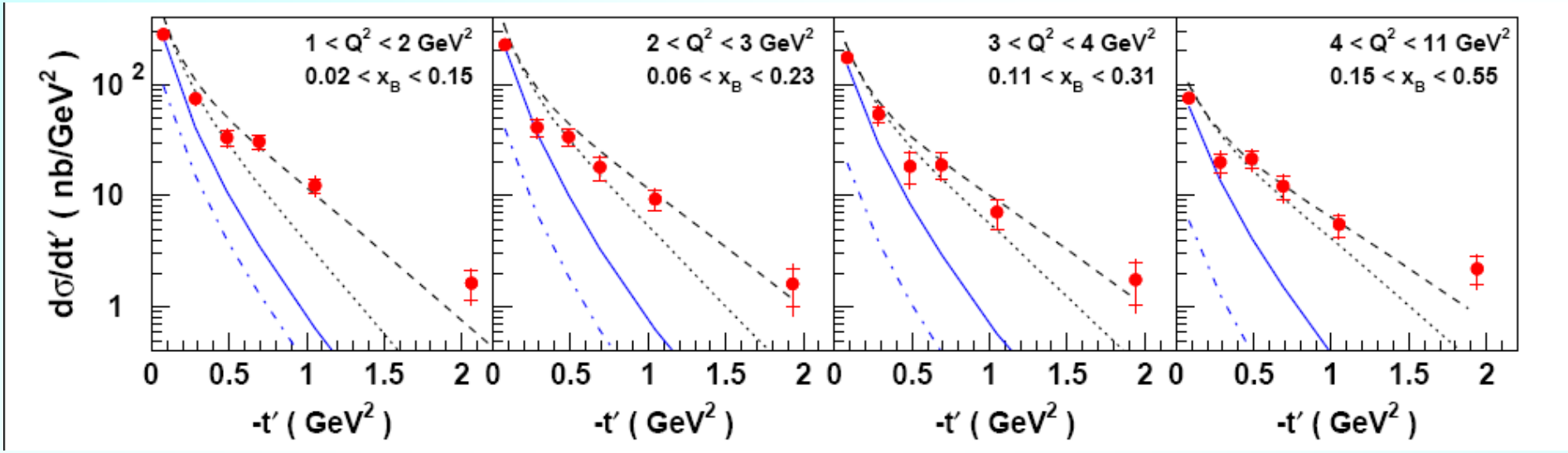
PYTHIA MC without exclusive π+

exclusive MC based on GPD model

$N_{excl} = (\pi+ - \pi-)^{data} - (\pi+ - \pi-)^{PYTHIA}$

$M_X^2 = (P_e + P_p - P_{e'} - P_{\pi+})^2$

exclusive π+ – cross section



– · – · – GPD model , LO – VGG [PRD 60 (1999) 094017]

——— " , with power corrections

------- Regge model , $d\sigma_L/dt$ -J.M. Laget [PRD 70 (2004) 054023]

– – – – " , $d\sigma/dt$ - "

Further examples:

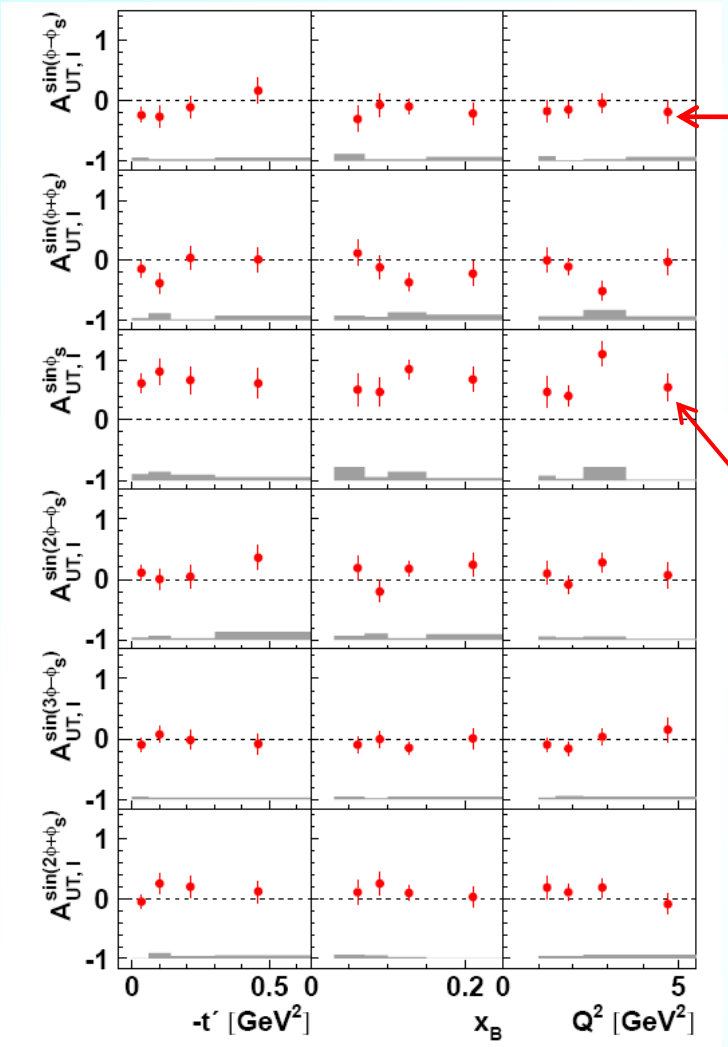
M. Kaskulov, U. Mosel, P.R. C 80 (2009) 028202 (two component model, soft and hard partonic reactions)

Ch. Bechler, D. Müller, arXiv:0906.2571 (Regge inspired + counting rules)

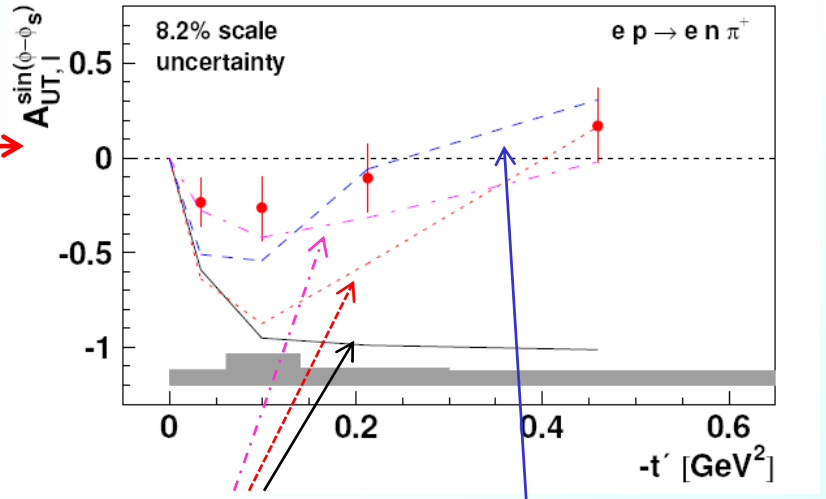
exclusive π+ – transverse target-spin asymmetry

$\sigma_L \propto |S_T| \sin(\phi - \phi_s)\ \mathrm{Im}(\tilde{E}^* \tilde{H})$

arXiv:0907.2596



‚Leading' asymmetry amplitude: small



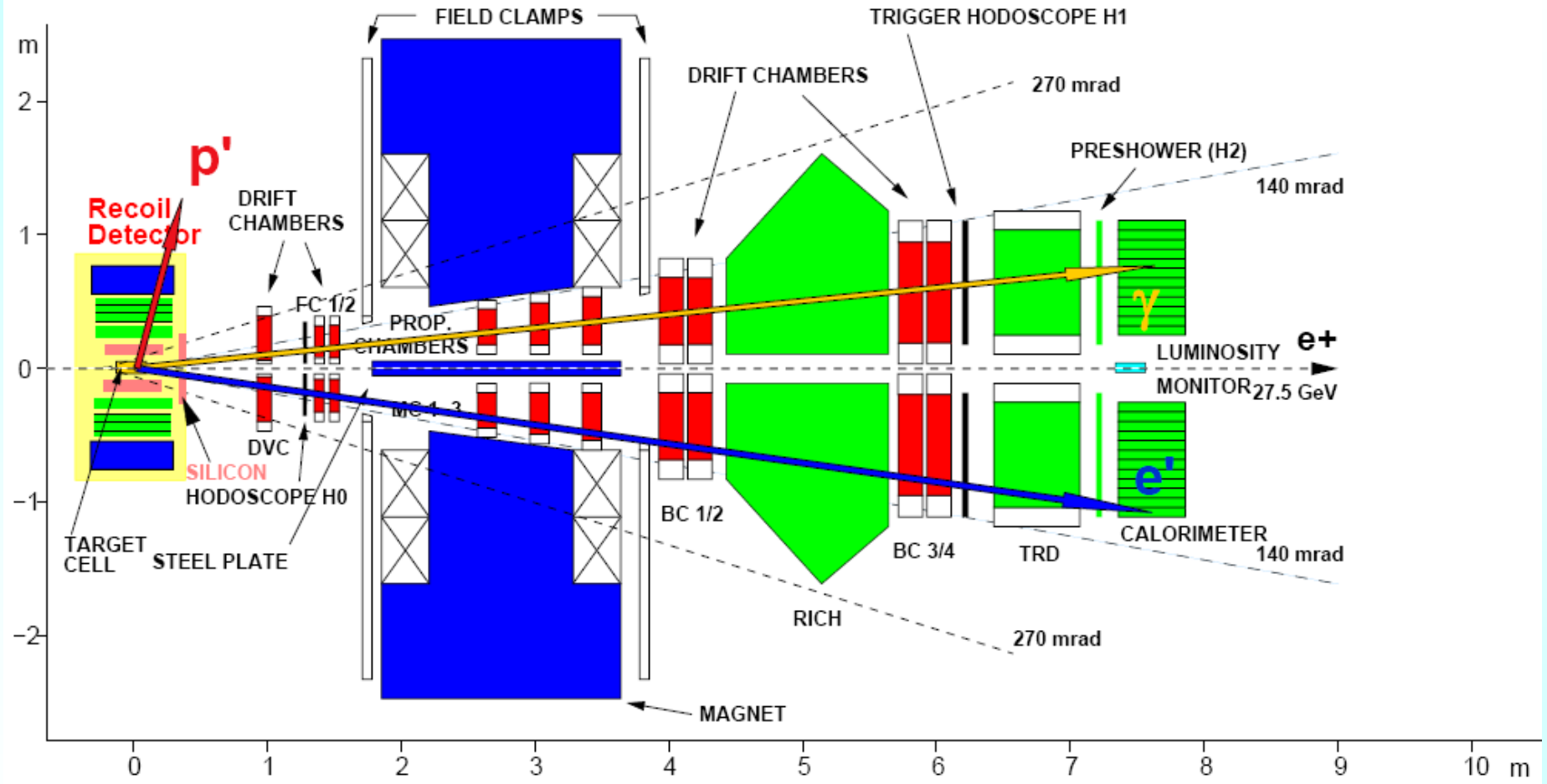
Ch. Bechler, D. Müller, arXiv:0906.2571

S. Goloskokov, P. Kroll, arXiv:0906.0460

Subleading asymmetry amplitude:
Surprisingly large,
expected to be suppressed by 1/Q
(γ^*_L-γ^*_T interference?)

- Deeply Virtual Compton Scattering (DVCS)
- Exclusive Vector Meson (ρ, ω, ϕ) production
- Exclusive π+ production
- Recoil Detector

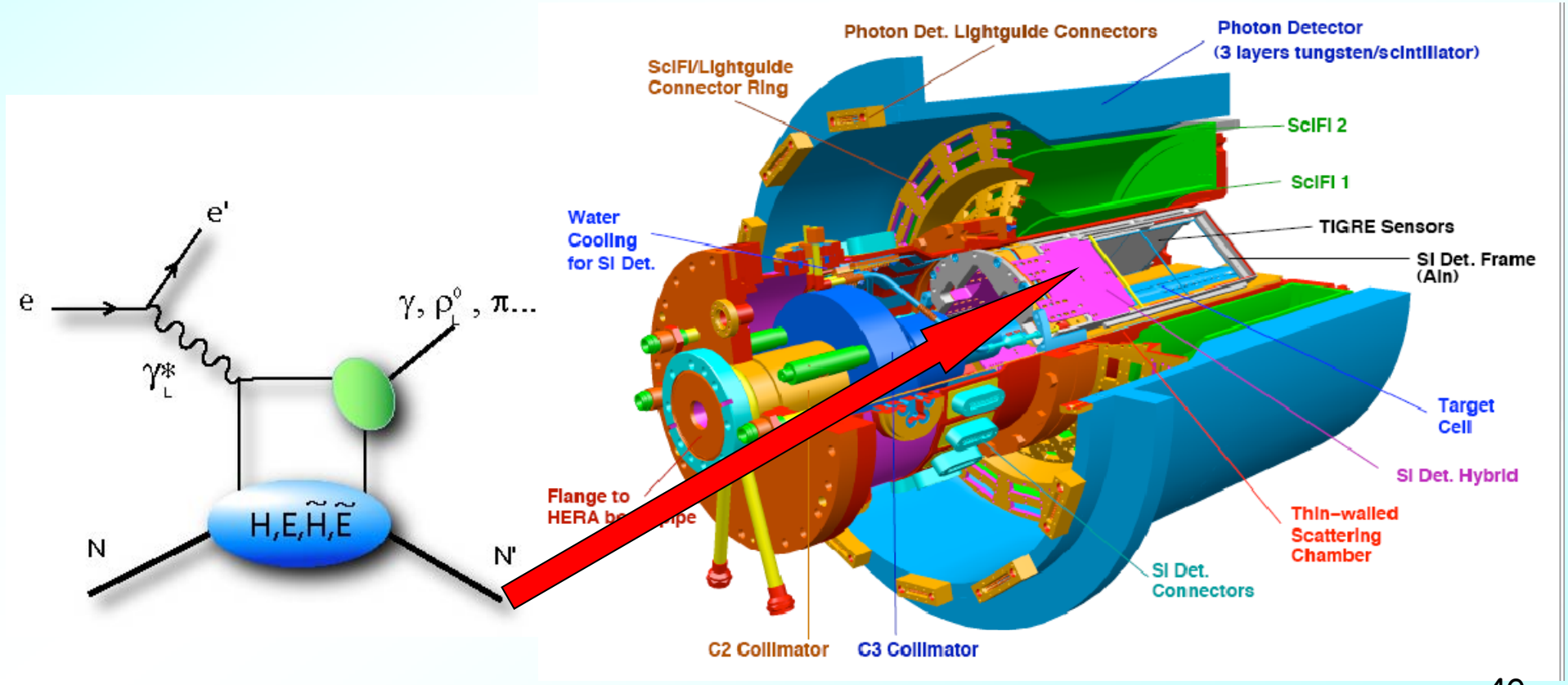
Exclusive Processes with Recoil Detector



- Unpolarized hydrogen target: 38 Mio DIS (41.000 DVCS)
- Unpolarized deuterium target: 10 Mio DIS (7.500 DVCS)
- Two beam helicities, electron and positron beams

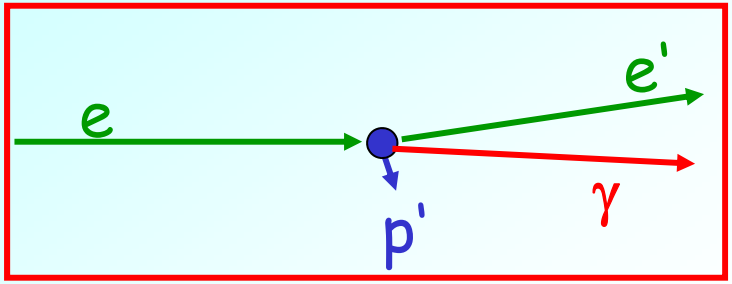
Exclusive Processes with Recoil Detector

Main purpose: reduce background, identify events from resonance production and determine their asymmetries

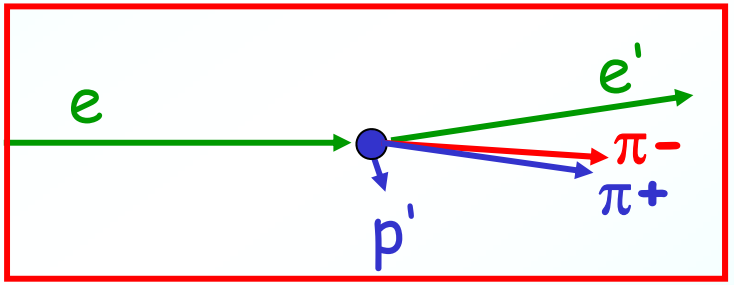


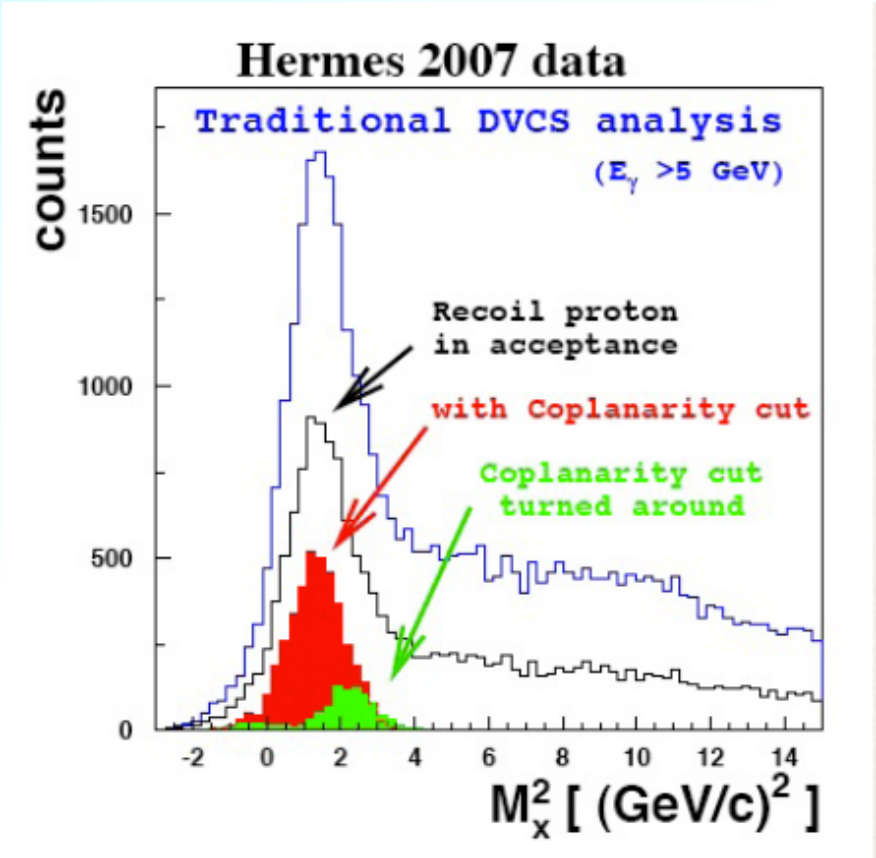
Event Selection with Recoil Detector

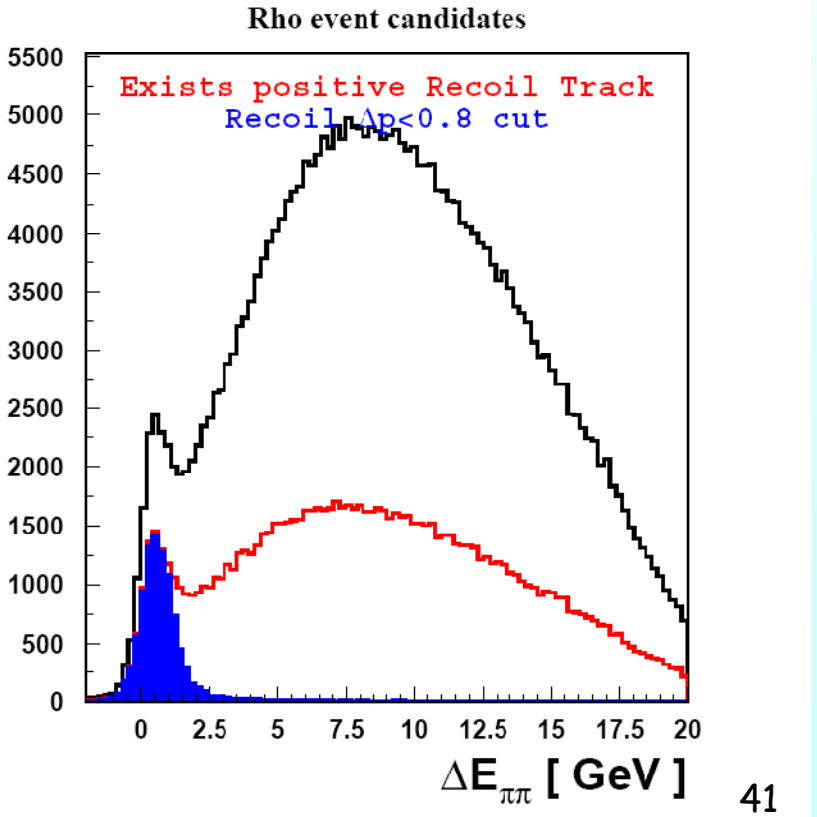
$e\,p \rightarrow e'\,\gamma\,X^+$



$e\,p \rightarrow e'\,\rho\,X^+$

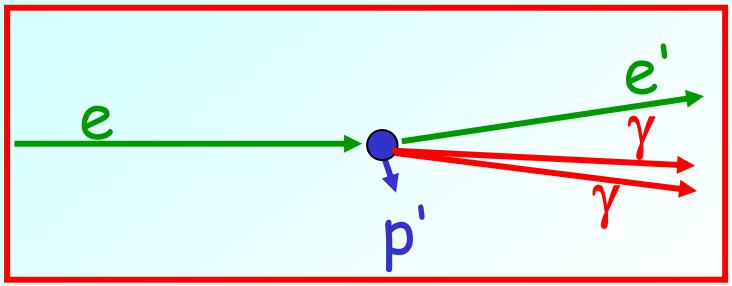






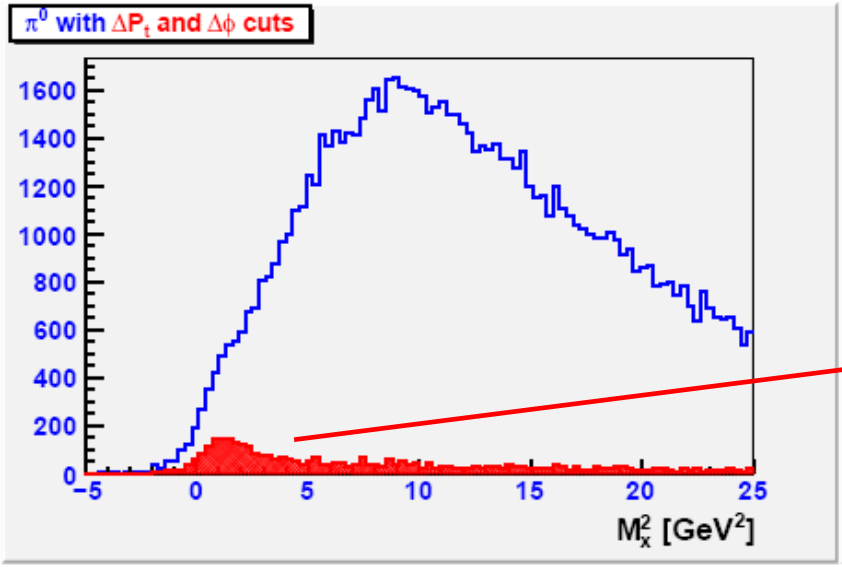
Event Selection with Recoil Detector

$e\,p \rightarrow e'\,\pi^0\,X^+$

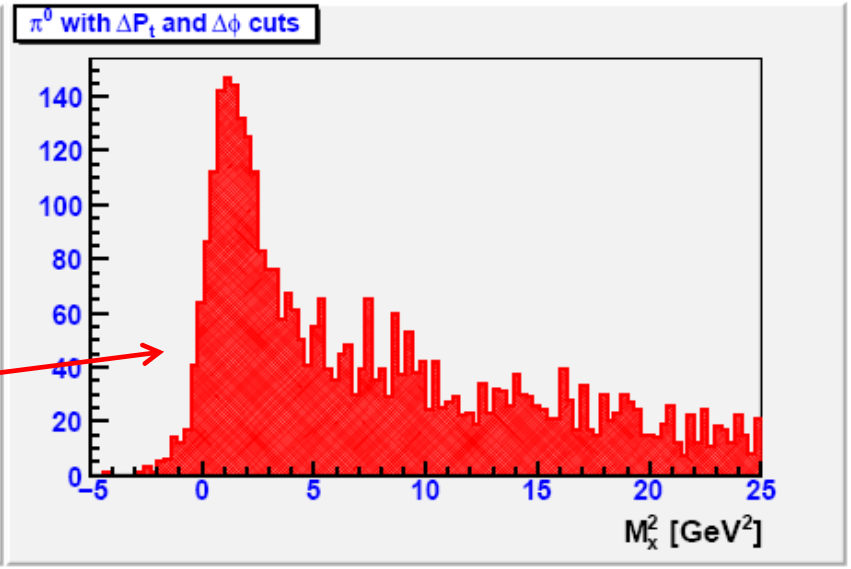


- First signal of exclusive π^0 production at HERMES
- Can provide access to chiral-even and chiral-odd GPDs

Recoil proton required



Cuts on momentum and angle difference applied



Conclusions

- HERMES has produced a plethora of data for hard exclusive processes

- Many more results will be presented and published soon

Stay tuned