Latest results on hard exclusive processes at HERMES

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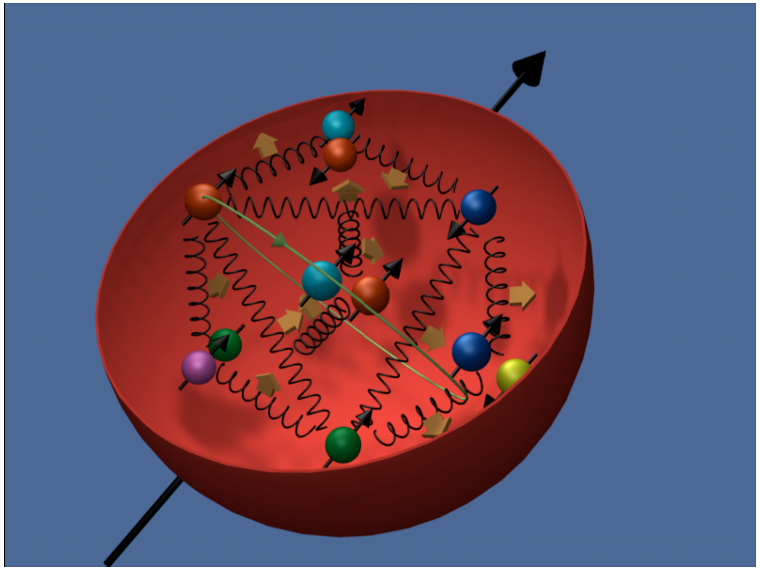
for the HERMES collaboration

DPG Spring Meeting, March 19, 2010

Outline

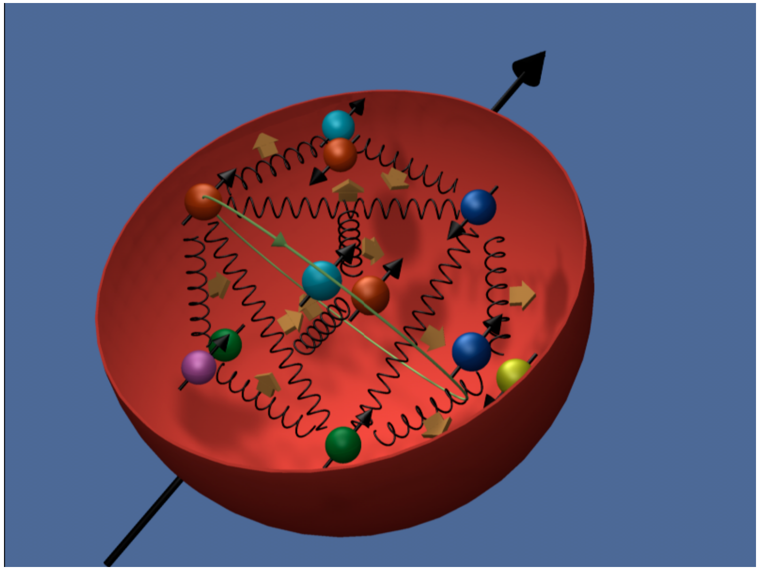
- Introduction
- HERMES experiment
- Generalized parton distributions
- Selected results
  - Deeply virtual Compton scattering
  - Exclusive meson production
- Recoil detector
- Conclusion

Study of spin structure of the nucleon at HERMES



- Longitudinal spin/momentum structure, hadronization
- Transverse spin/momentum structure → transversity, TMDs
- DVCS, exclusive meson production → GPDs, "nucleon tomography"
- Strange-baryon production

Study of spin structure of the nucleon at HERMES



- Longitudinal spin/momentum structure, hadronization
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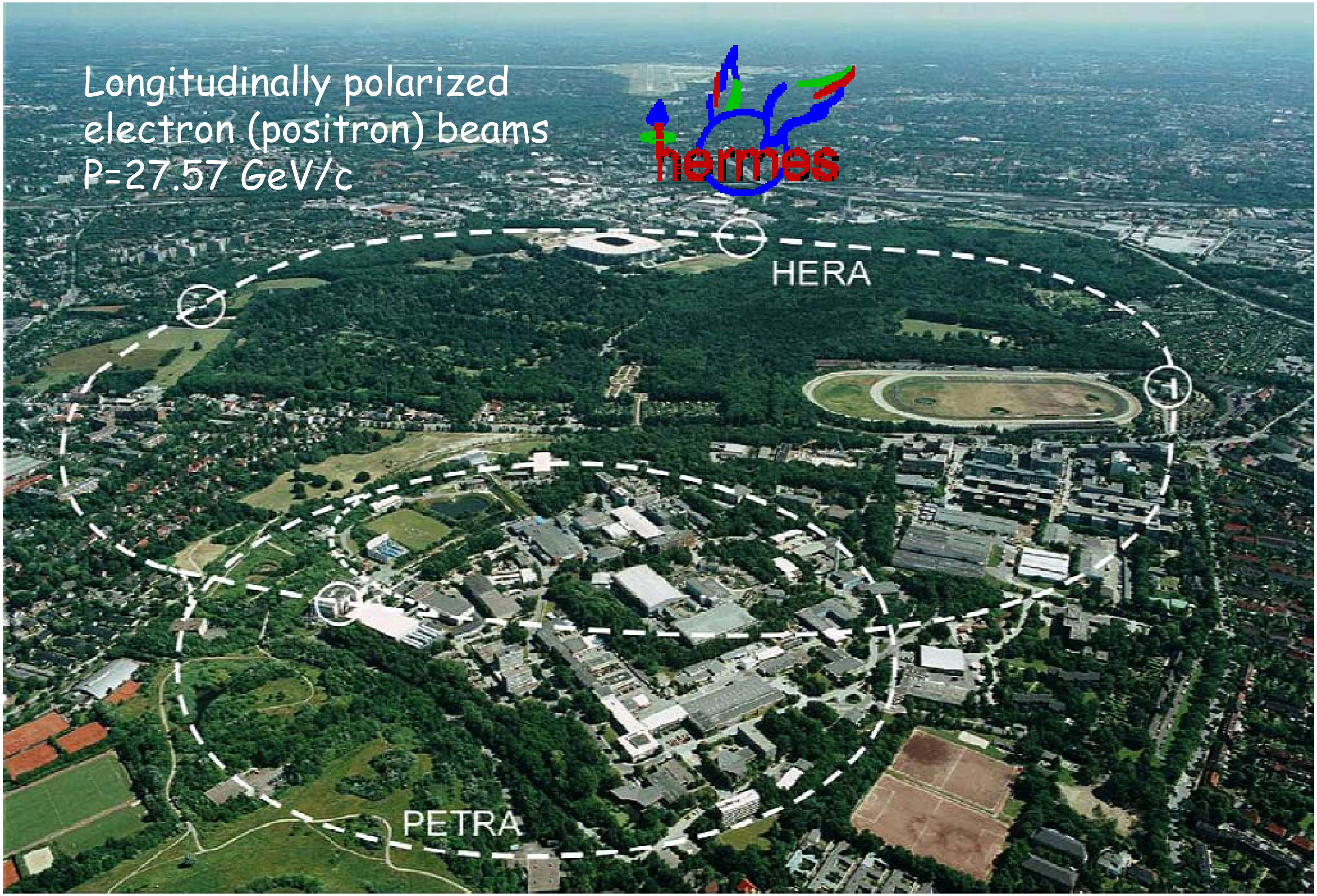
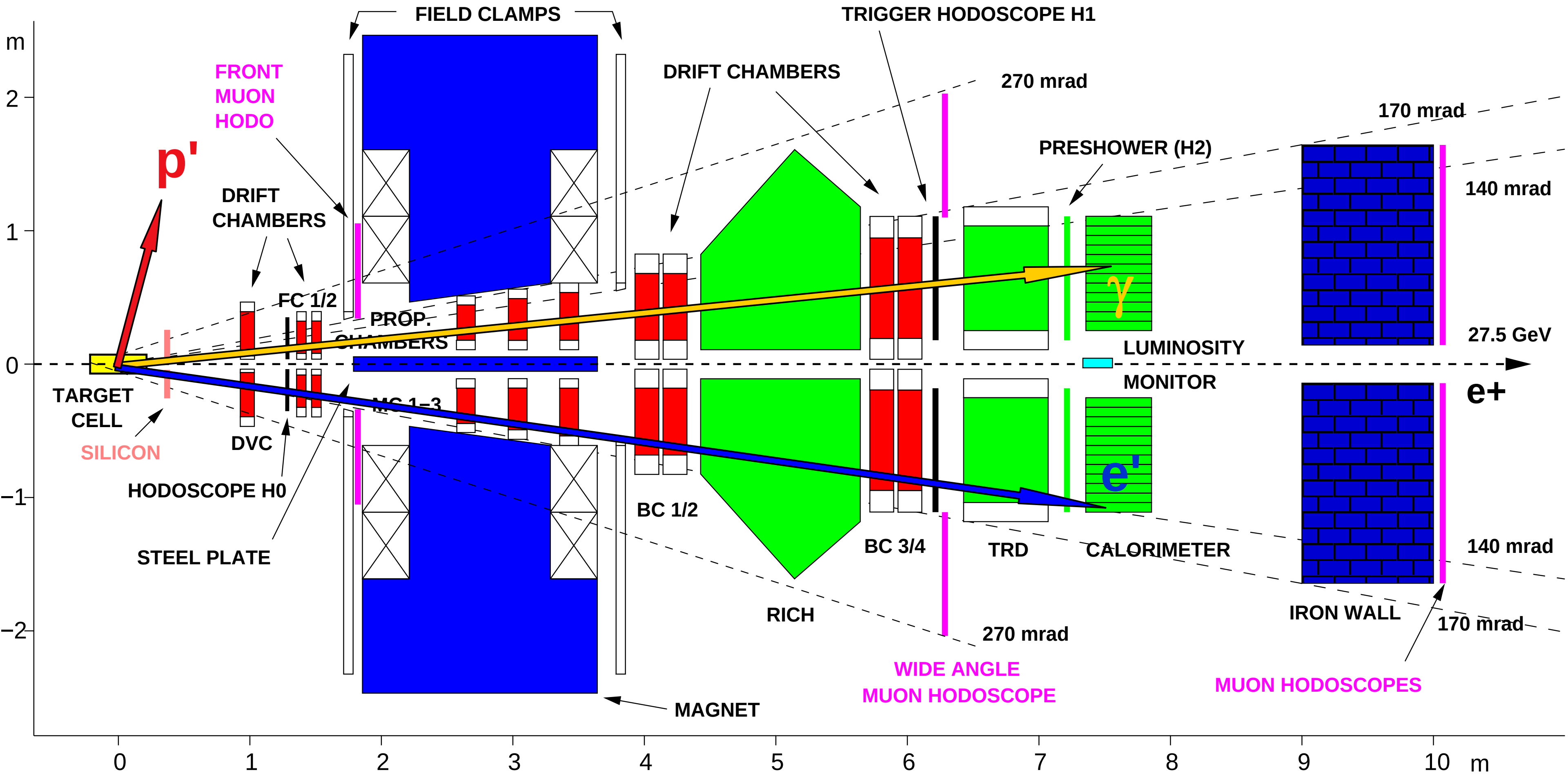
HERA at DESY


Longitudinally polarized
electron (positron) beams
P=27.57 GeV/c
hermes
HERA
PETRA

The HERMES experiment



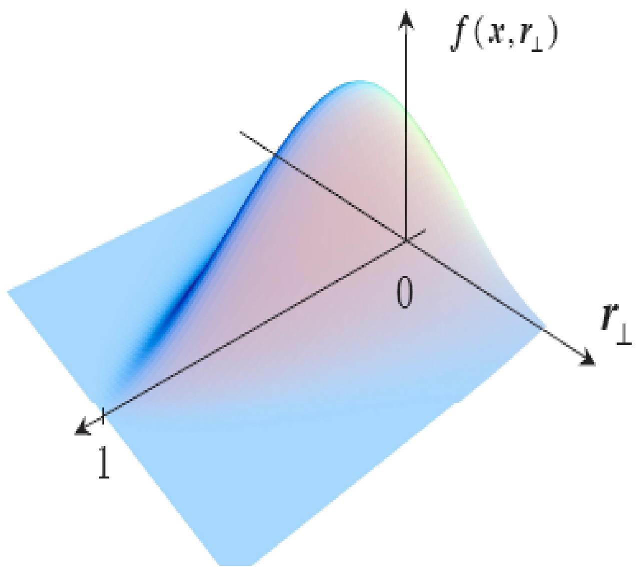
Gas targets:

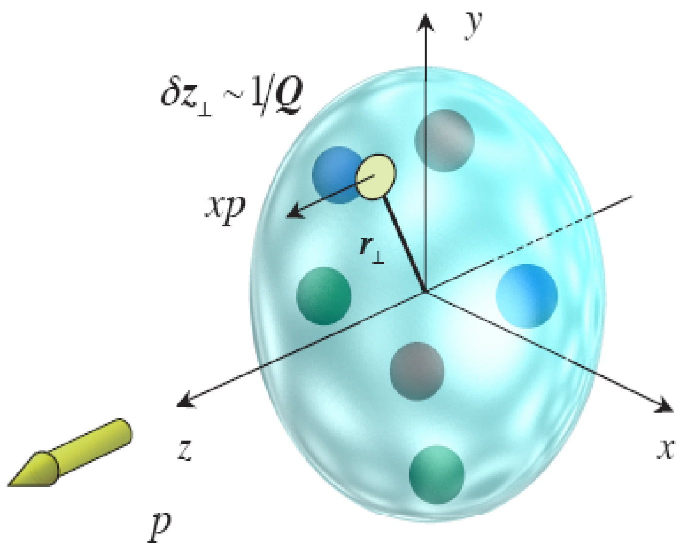
- Longitudinally polarized H, D
- Unpolarized H, D, ^{4}He, N, Ne, Kr, Xe
- Transversely polarized H

Beam:

- Longitudinally polarized e^+ and e^- with both helicities
- Energy 27.6 GeV

Generalized Parton Distributions (GPDs)





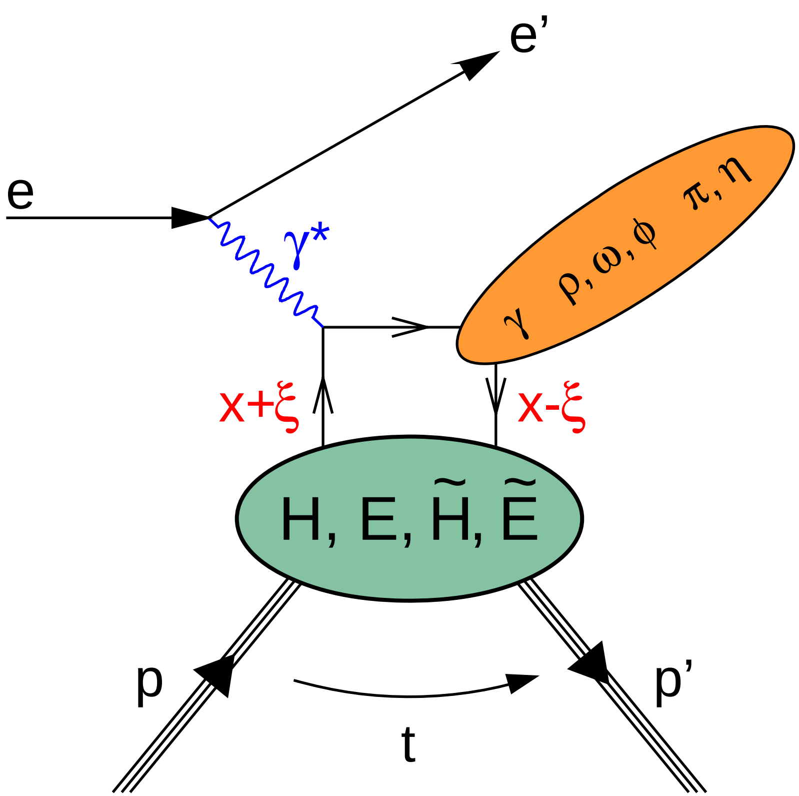
- Include Form Factors (FFs) and Parton Distribution Functions (PDFs) as moments and forward limits

- Multidimensional description of nucleon structure

- Access to the quark total angular momentum via Ji relation

$$J_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x \left[H_q(x, \xi, t) + E_q(x, \xi, t) \right]$$

Access to GPDs via exclusive processes

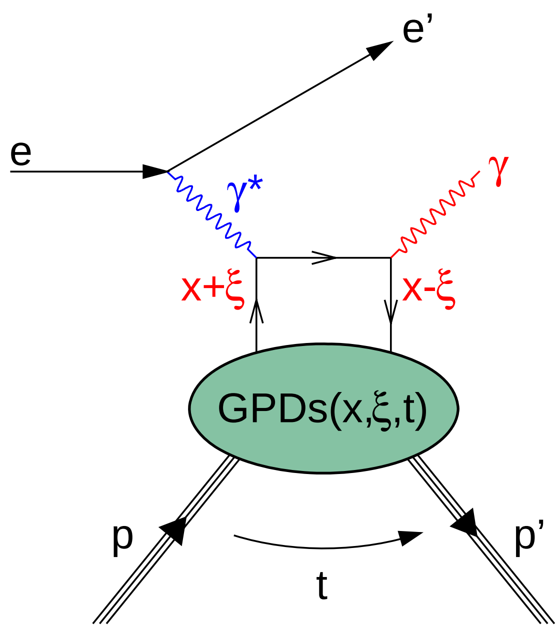


- Sensitivity of different final states to different GPDs
- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ flip nucleon helicity
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π,η) → $\tilde{H}, \tilde{E}$

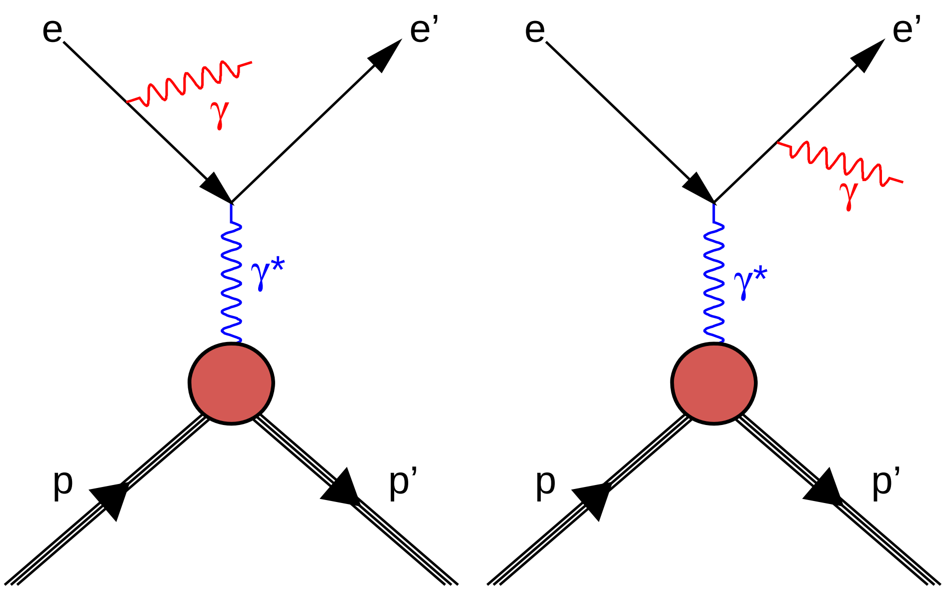
Deeply Virtual Compton Scattering (DVCS)

(more details in talk of Dietmar Zeiler: HK 16.4)

DVCS



Bethe-Heitler



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

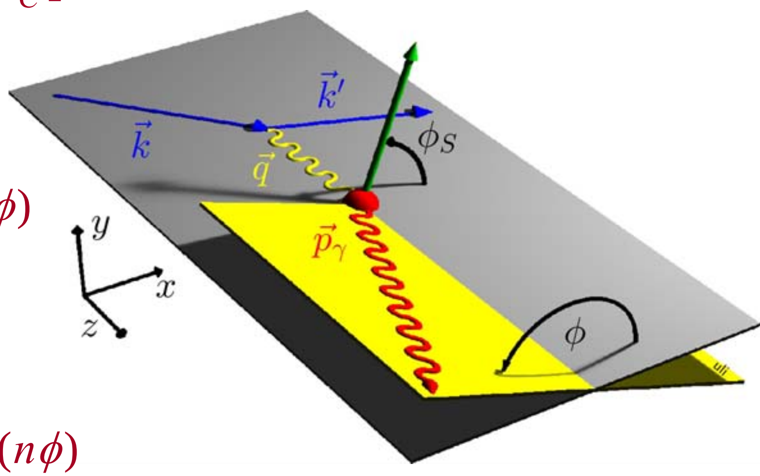
Azimuthal asymmetries in DVCS

- Cross section

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

- Beam-charge asymmetry

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



- Charge-difference beam-helicity asymmetry

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

- Charge-averaged beam-helicity asymmetry

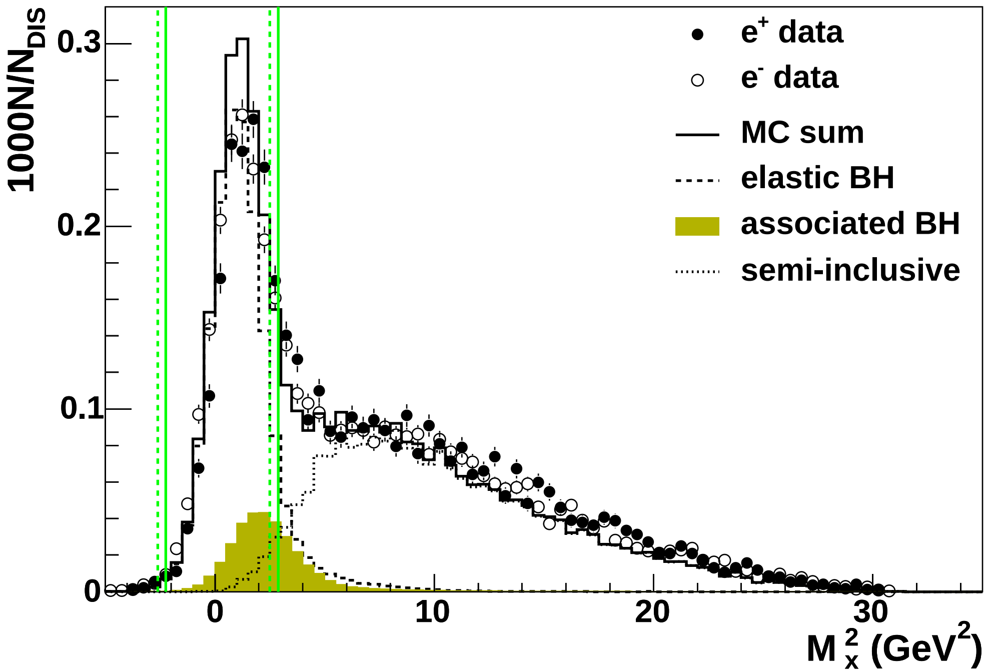
$$A_{LU}^{DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) - (\sigma^{-\leftarrow} - \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})} = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2}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

- 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

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

DVCS event selection, uncertainties and corrections



Kinematic requirements

$0.03 < x_B < 0.35$

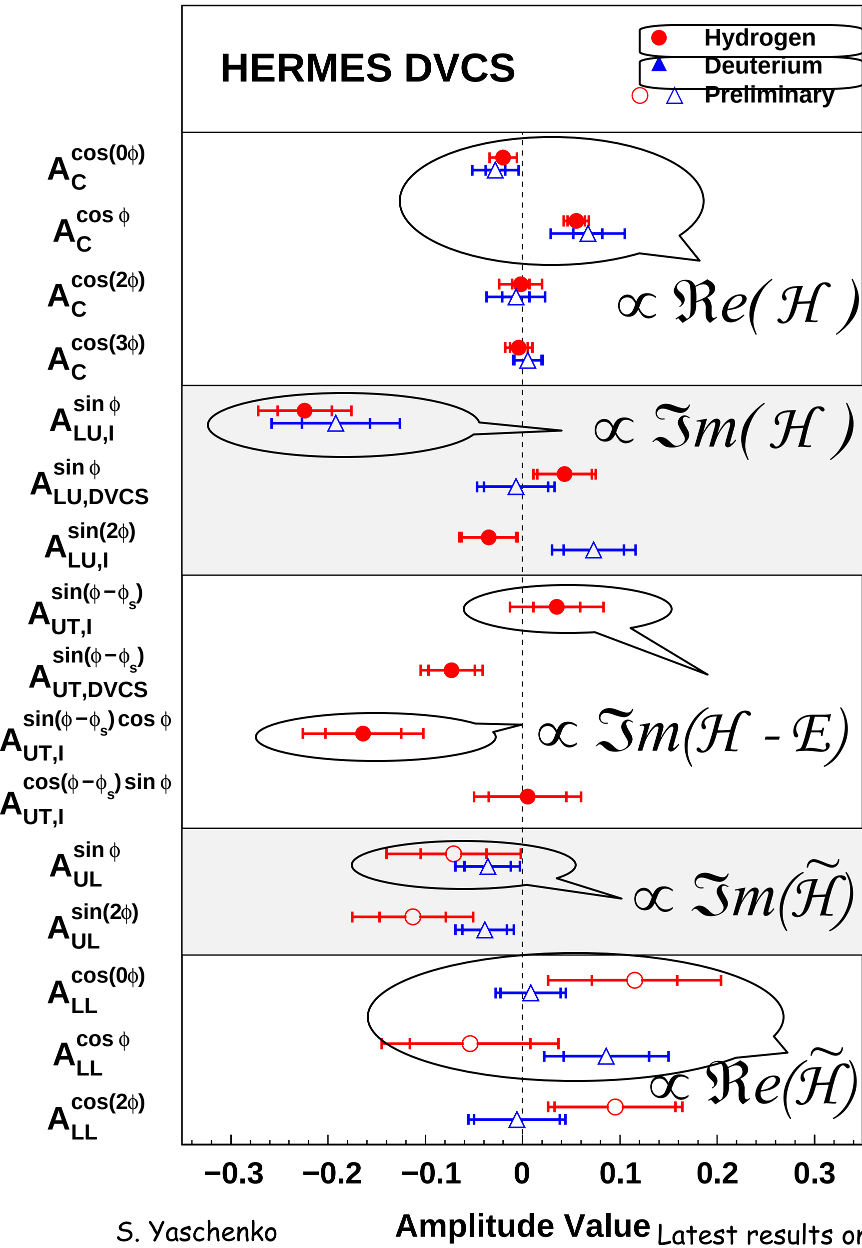
$1\ GeV^2 < Q^2 < 10\ GeV^2$

$-t < 0.7\ GeV^2$

$E_\gamma > 5\ GeV$

- Identification by missing mass technique *(ep → e′γX)*
- Semi-inclusive corrected as dilutions for charge dependent asymmetries. For pure DVCS term asymmetry extracted from π^0 $(z_\pi > 0.8)$ data
- Associated Bethe-Heitler *ep → e′Δ⁺γ ~12%* stays part of the signal

DVCS asymmetries and connections with GPDs



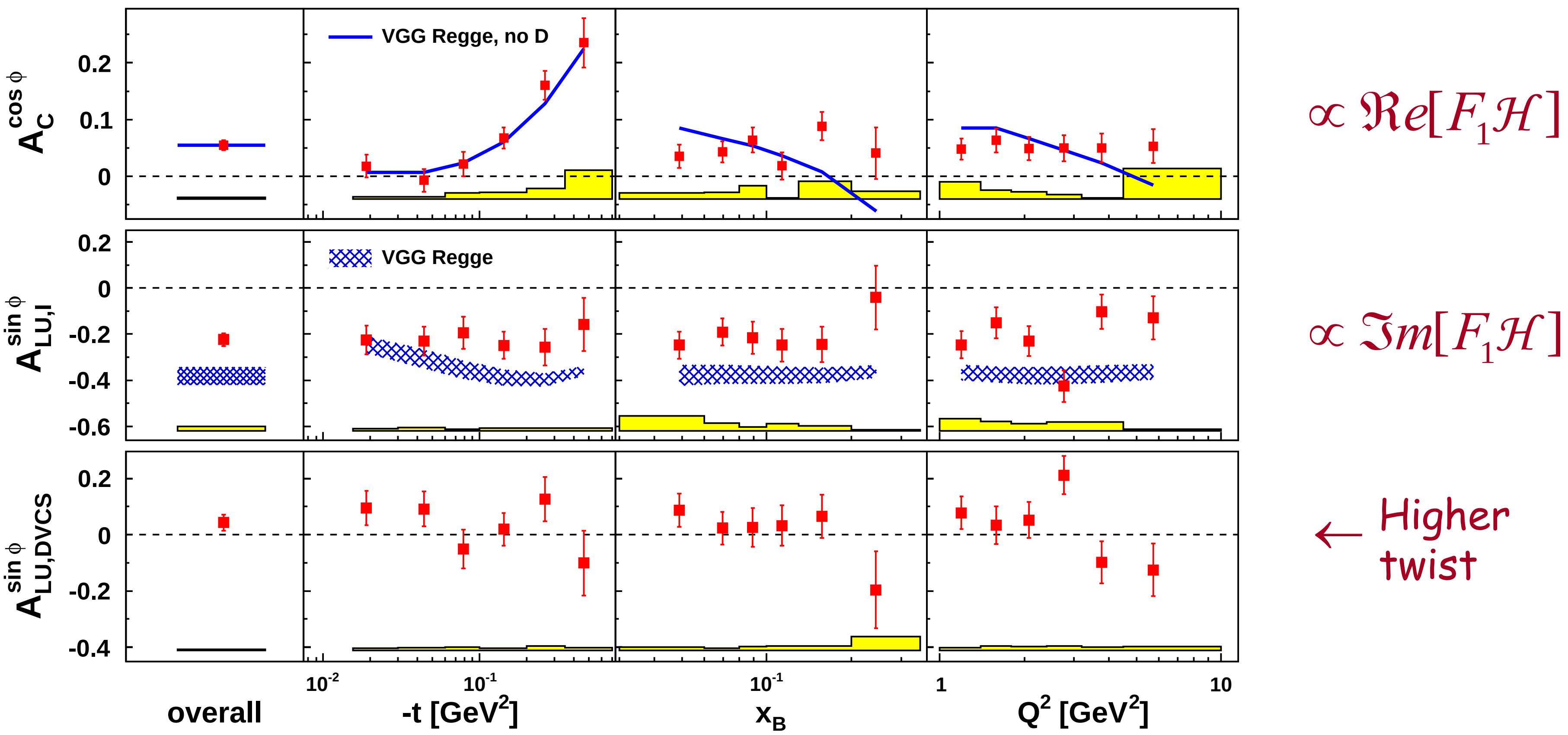
Red - JHEP 11 (2009) 083

Blue - Nucl. Phys. B 829 (2010) 1-27

- 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 $\tilde{H}$
- Double spin asymmetry
  GPD $\tilde{H}$

Results on beam-charge and beam-helicity asymmetry amplitudes in DVCS

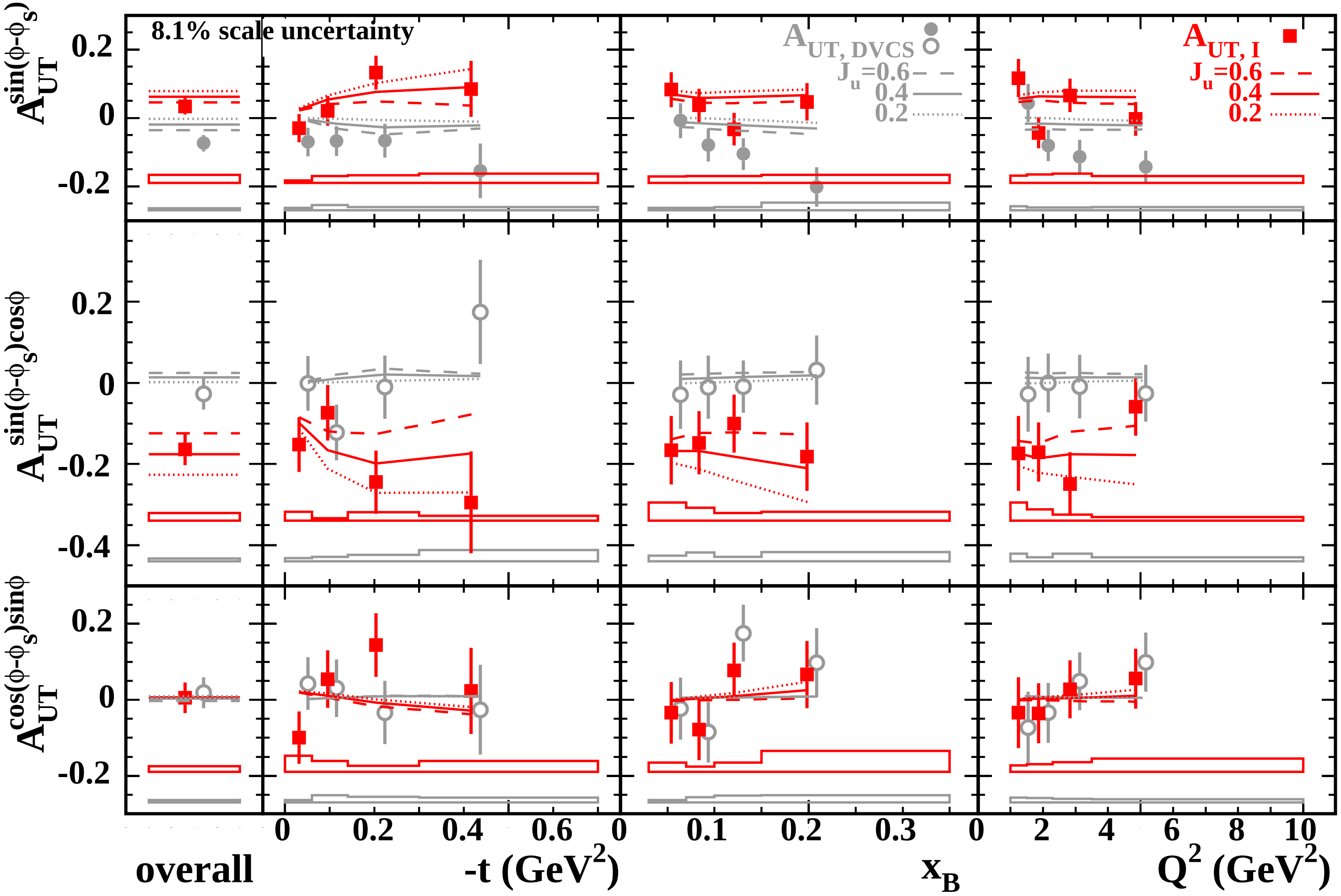
JHEP 11 (2009) 083



- Comparisons with GPD model, Vanderhaeghen, Guichon, Guidal
  Phys. Rev. D60 (1999) 094017, Prog. Part. Nucl. Phys. 47 (2001) 401
- Resonance fraction from $ep \to e\Delta^+\gamma$ is about *12%*

Transverse target polarization asymmetry in DVCS

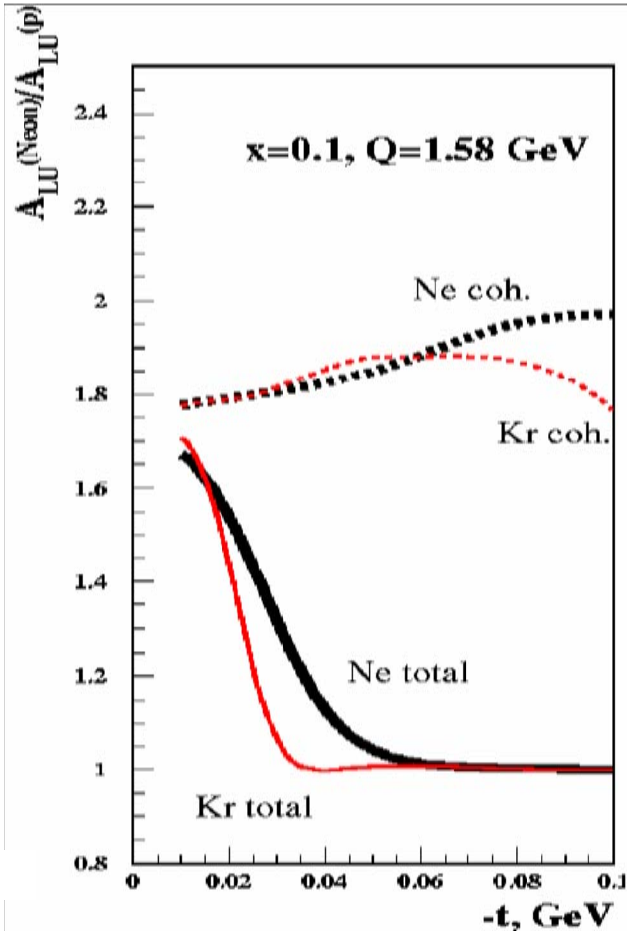
JHEP 06 (2008) 066



Sensitivity of GPD model predictions to J_u at fixed J_d=0

DVCS on nuclear targets

- Additional information on GPDs and their modification in nuclear matter
- New opportunity to study the origin of nuclear forces
- Access to 3-D distribution of quarks and gluons in nuclei



Ratio of asymmetries measured on nuclear targets to asymmetries measured with proton target

⇒ R_{coh}=1.8-2.0 for A=12-90
Guzey, Strikman [*PRC 68 (2003) 015204*]

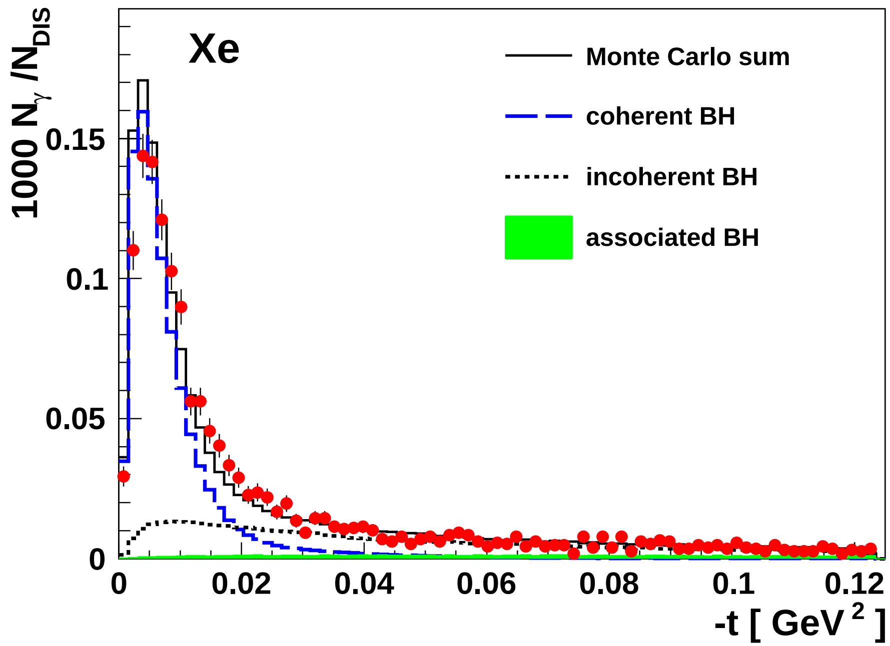
R_{coh}=1.0-1.1 for A=^{4}He
Liuti, Taneja [*PRC 72 (2005) 032201*]

R_{coh}=5/3 for spin-0, 1/2
Kirchner, Müller [*EPJ C32 (2003) 347*]

$A^{\sin\phi}_{LU,nucleus} / A^{\sin\phi}_{LU,proton} \propto A/Z$
Guzey, Siddikov [*JPG 32 (2006) 251*]

Analysis of DVCS on nuclear targets

- Nuclear DVCS involves two contributions:
  - Coherent process: nuclear target stays intact
  - Incoherent process: nuclear target breaks up, photon is emitted by a nucleon
- Separate coherent/incoherent part by cutoff values for *t*
- Find upper (lower) –t cut for each target. Asymmetries for coherent (incoherent) production at similar average kinematics
  - coherent: $\langle -t \rangle = 0.018\ GeV^2$
  - incoherent: $\langle -t \rangle = 0.20\ GeV^2$



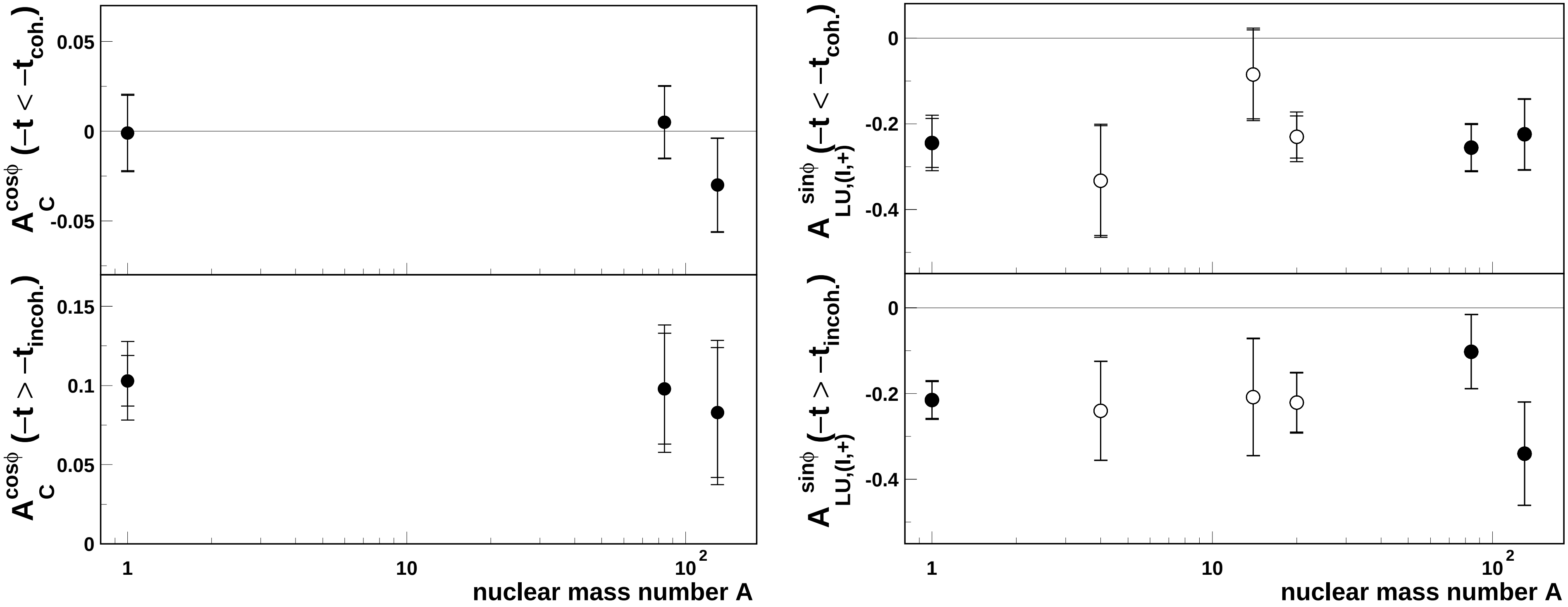
- Results on beam-charge asymmetries for $^4He, N, Ne$ and beam-helicity asymmetries for

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

$$^4He, N, Ne:\ A_{LU}^{I}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

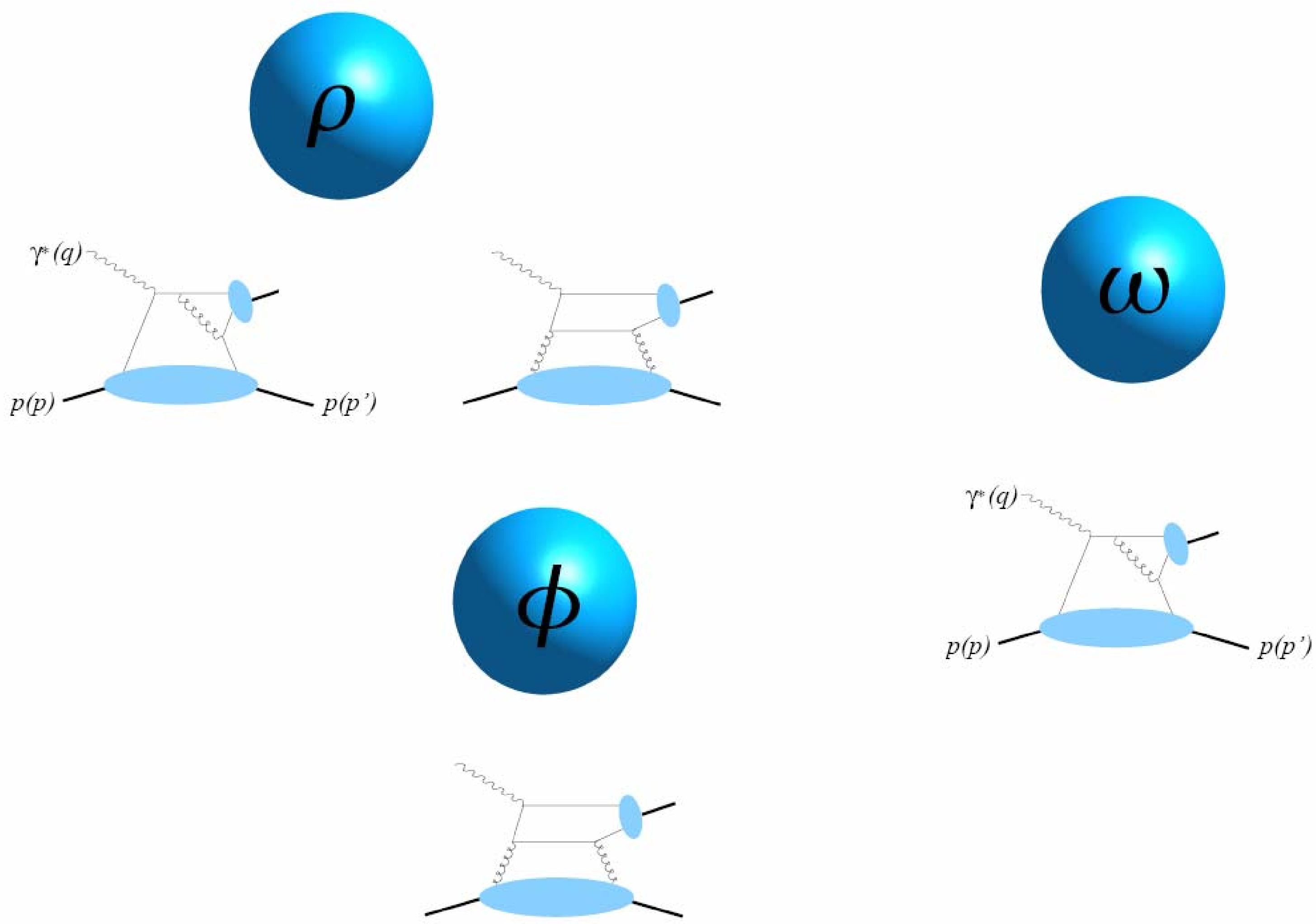
A-dependence of beam-charge and beam-helicity asymmetry amplitudes

Phys. Rev. C 81 (2010) 035202



- The results do not support models which predict an enhancement of nuclear asymmetries
- Data contradict the predicted strong A-dependence of the asymmetries resulting from mesonic degrees of freedom in the nuclei

Exclusive vector meson production

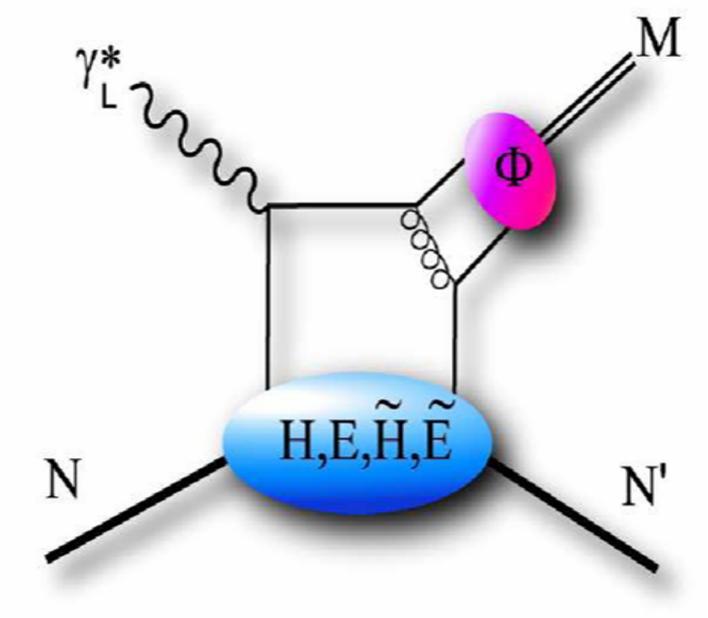


Exclusive vector meson production

Modified perturbative approach

S. V. Goloskokov and P. Kroll, EPJ C 50, 829 (2007)

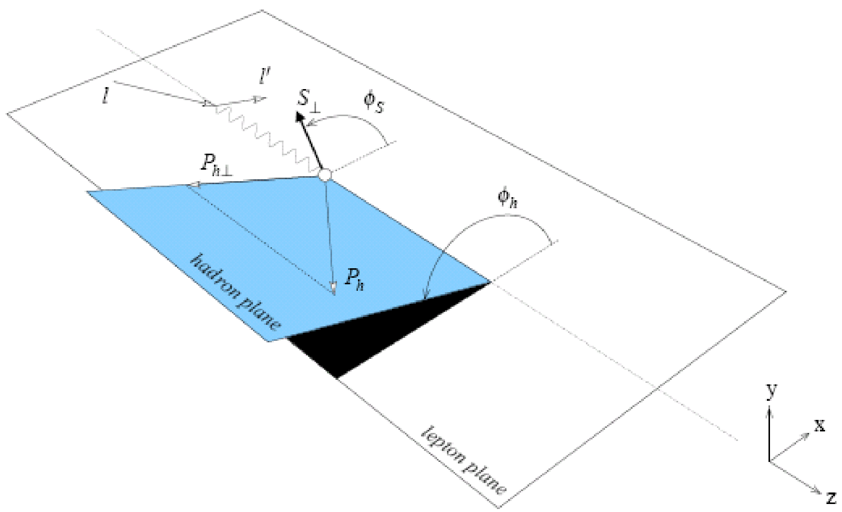
$$A \propto F(x,\xi,t;\mu^2) \otimes K(x,\xi,z;log(Q^2/\mu^2)) \otimes \Phi(z,k_\perp;\mu^2)$$

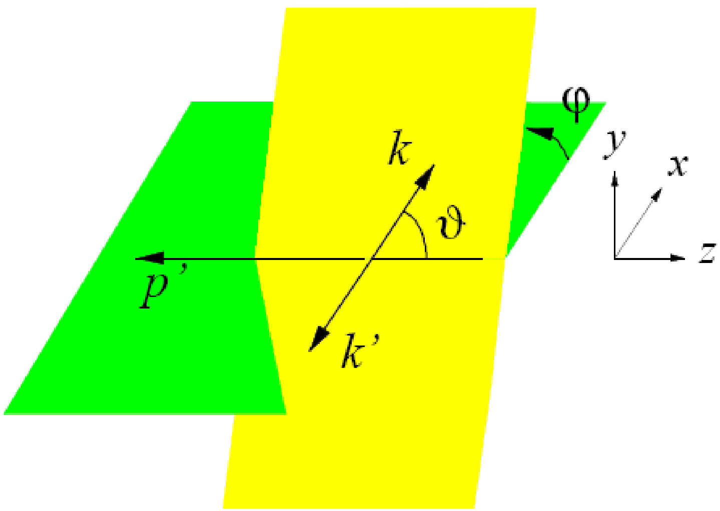


- Factorization for σ_L (and ρ_L, ω_L, φ_L) only
- σ_L - σ_T suppressed by $1/Q$
- σ_T suppressed by $1/Q^2$
- Power corrections: $k_\perp$ is not neglected
- Regulate the singularity in the transverse amplitude
- $\gamma^*_T \rightarrow \rho^0_T$ transitions can be calculated (model dependent)
  - ρ^0: contributions from $\tilde{H}$ and $\tilde{E}$
  - π^+: contributions from H_T and $\tilde{H}_T$

Exclusive vector meson production

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





- 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}

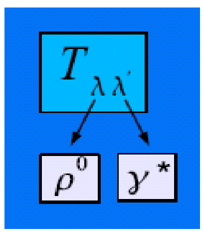
beam $\leftarrow$ P_l target $\rightarrow$ S_L, S_T

Exclusive vector meson production

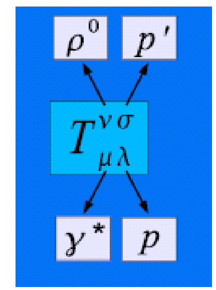
$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi_s\, d\phi\, d\cos\vartheta\, d\varphi} \approx \frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi_s, \phi, \cos\vartheta, \varphi)$$

- Parameterized by helicity amplitudes

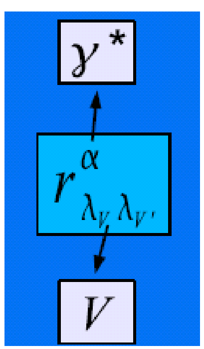
K. Schilling, G. Wolf, Nucl. Phys. B 61 (1973) 381

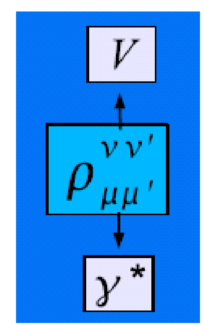


M. Diehl, JHEP09 (2007) 064

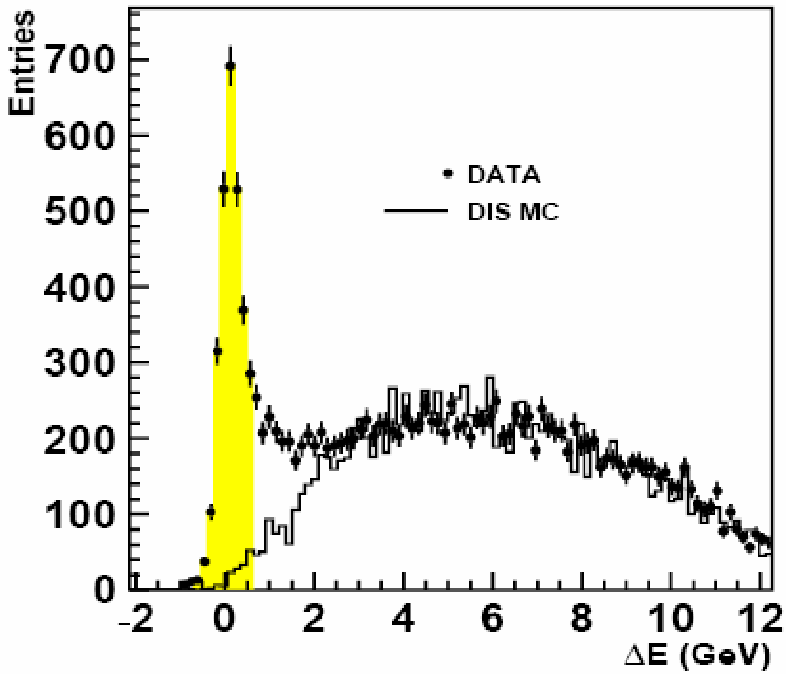


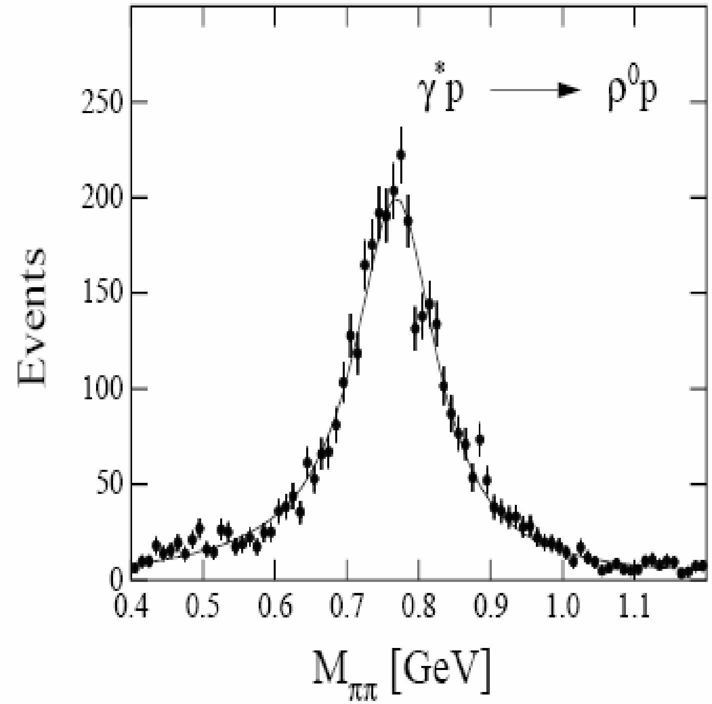
- Or by Spin Density Matrix Elements (SDMEs)





Exclusive ρ^0 event selection





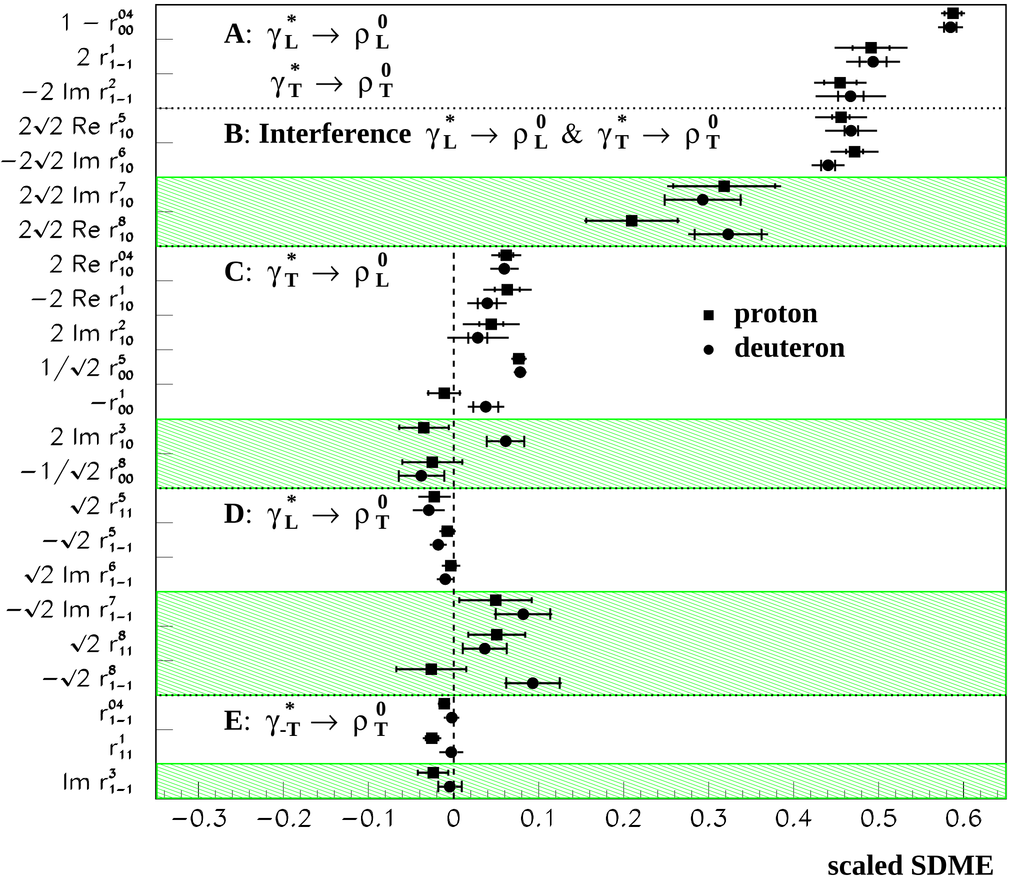
- $\Delta E = (M_X^2 - M_p^2)/\ 2M_p$
- Background subtraction with PYTHIA

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

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

ρ^0 unpolarized SDMEs

EPJ C62 (2009) 659

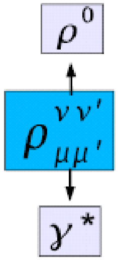


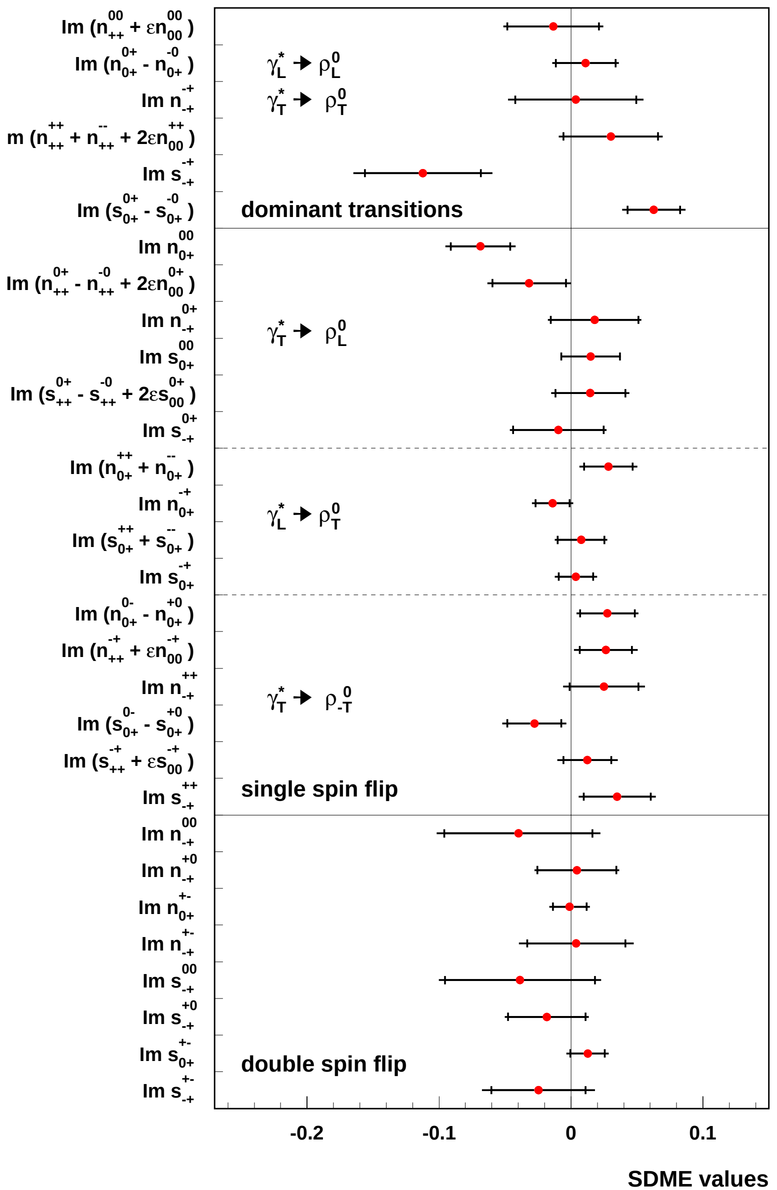
- Unpolarized SDMEs: W_{UU}
- Beam-polarized SDMEs: W_{UL}
- Hierarchy confirmed experimentally
- Proton and deuteron data consistent
- s-channel helicity conservation: (ρ^0 conserves the helicity of γ^*)
  - significant $\gamma^*_L \to \rho^0_L$ and $\gamma^*_T \to \rho^0_T$
  - a substantial interference
- s-channel helicity violation
  - significant $\gamma^*_T \to \rho^0_L$
  - smaller $\gamma^*_L \to \rho^0_T$ and $\gamma^*_{-T} \to \rho^0_T$
  - $2 - 10\,\sigma$ level violation

- Hierarchy of ρ^0 amplitudes: $|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{1-1}|^2$

ρ^0 transverse SDMEs

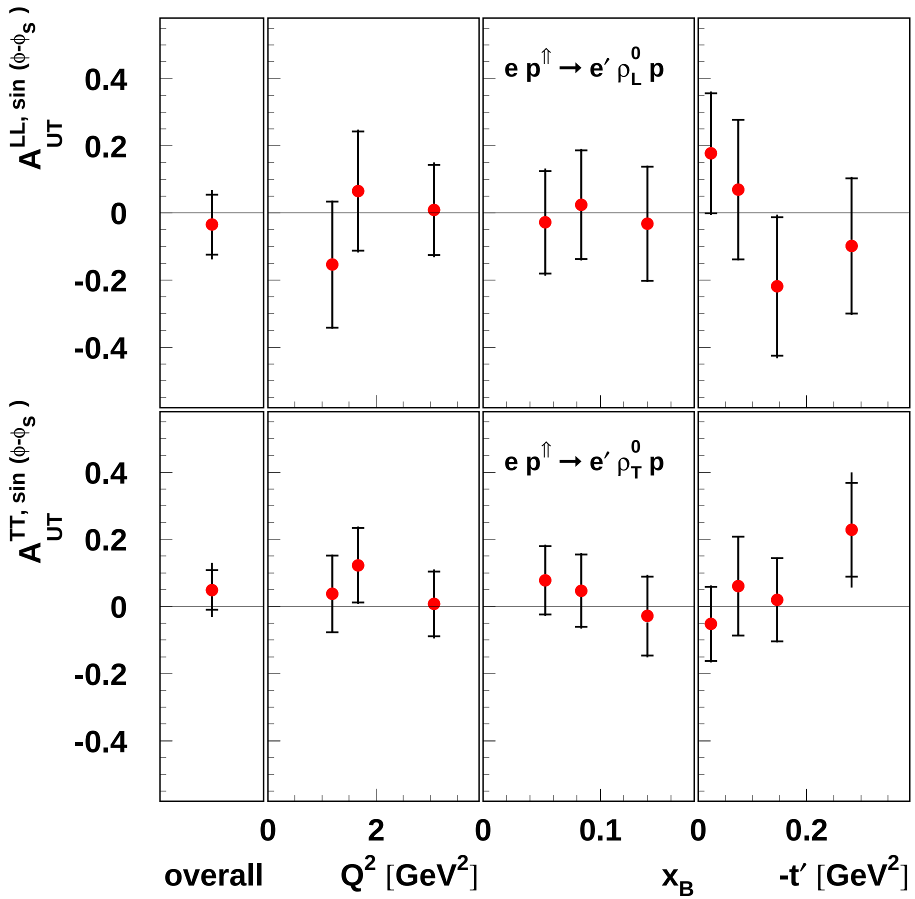
PLB 679 (2009) 100





- Transverse SDMEs: W_{UT}
- Measured for the first time
- Average kinematics:
  - $\langle -t' \rangle = 0.13$ GeV^2
  - $\langle x_B \rangle = 0.09$
  - $\langle Q^2 \rangle = 2.0$ GeV^2
- Related to proton helicity-flip amplitude
- Suppressed by $\sqrt{t}\,/\,2M_p$

ρ^0 transverse target spin asymmetry

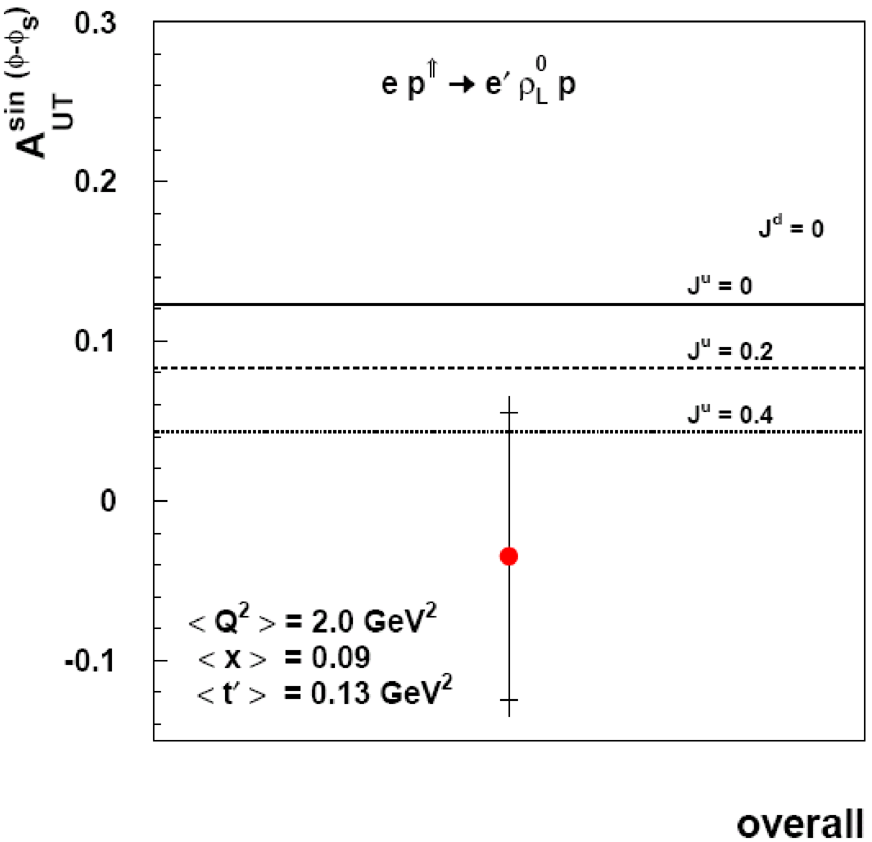


$$\approx \frac{\Im m(n_{00}^{00})}{u_{00}^{00}}$$

$$\approx \frac{\Im m(n_{++}^{++})}{u_{++}^{++}}$$

- Connection with GPDs $\quad A_{UT}^{\sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$
- Compatible with zero overall value $\quad A_{UT}^{\sin(\phi-\phi_s)} = -0.033 \pm 0.058$

Connection of ρ^0 transverse target spin asymmetry to GPDs



- Asymmetry in terms of GPDs

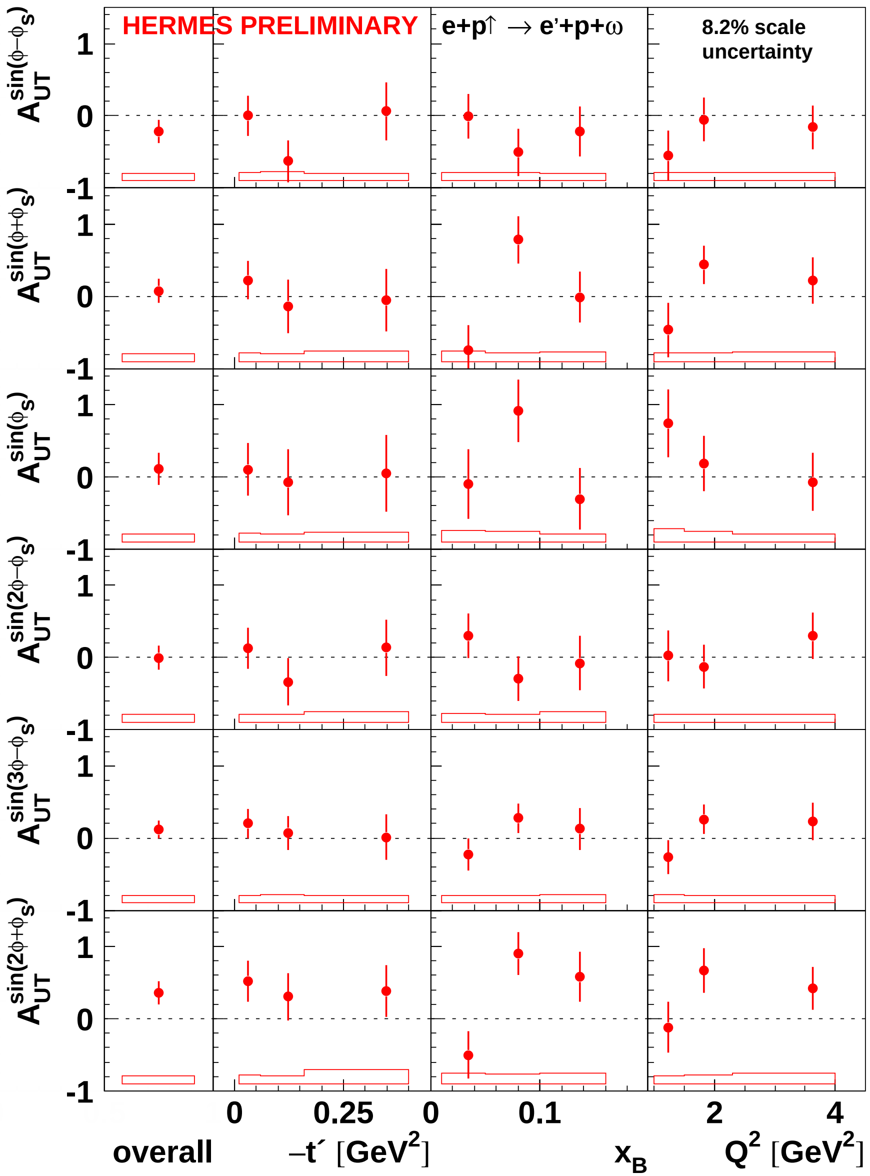
$$A_{UT}^{sin(\phi-\phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}$$

  - *F. Ellinghaus, W.-D. Nowak, A.V. Vinnikov, Z. Ye, Eur. Phys. J. C (2006) 729*
- Parameterization for $H_q, H_{\bar{q}}, H_g$
- E_q is related to the total angular momenta J_u and J_d
  - predictions for $J_d = 0$
- $E_{\bar{q}}, E_g$ are neglected

- Data favours positive J_u
  - statistics too low to reliably determine the value of J_u and its uncertainty
- Within the statistical uncertainty in agreement with theoretical calculations
  - indication of small $E_{\bar{q}}, E_g$?

- Other GPD model calculations
  - *K. Goeke, M.V. Polyakov, M. Vandehaegen, Prog. Part. Nucl. Phys. 47 (2001)*
  - *S.V. Goloskokov, P. Kroll, Eur. Phys. J. C 59 (2009) 809*
  - *M. Diehl, W. Kugler, Eur. Phys. J. C 52 (2007) 933*

ω transverse target spin asymmetry



- Low statistics – no ω_L / ω_T separation
- Predictions for large $\sin(\phi-\phi_s)$ asymmetry amplitude

$$A_{UT}^{\sin(\phi-\phi_s)} \approx -0.1$$

- Indication of negative $\sin(\phi-\phi_s)$ asymmetry amplitude

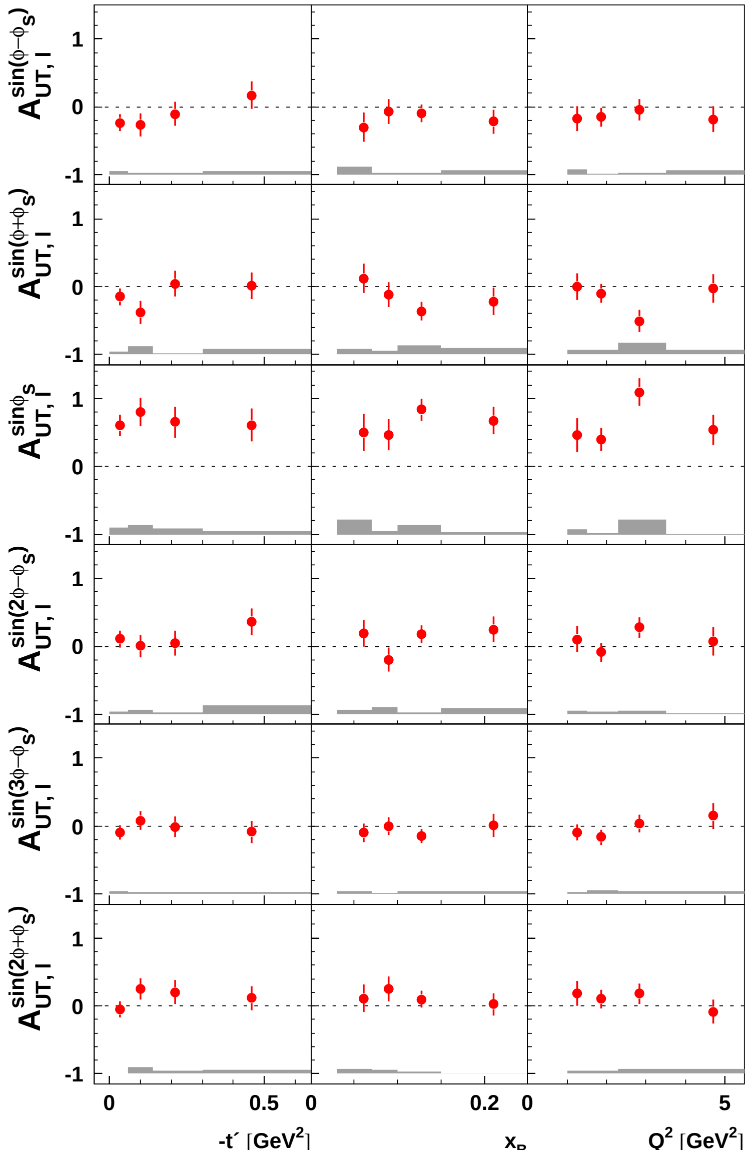
$$A_{UT}^{\sin(\phi-\phi_s)} = -0.22 \pm 0.16_{stat} \pm 0.11_{syst}$$

- No contradiction with ρ^0 predictions

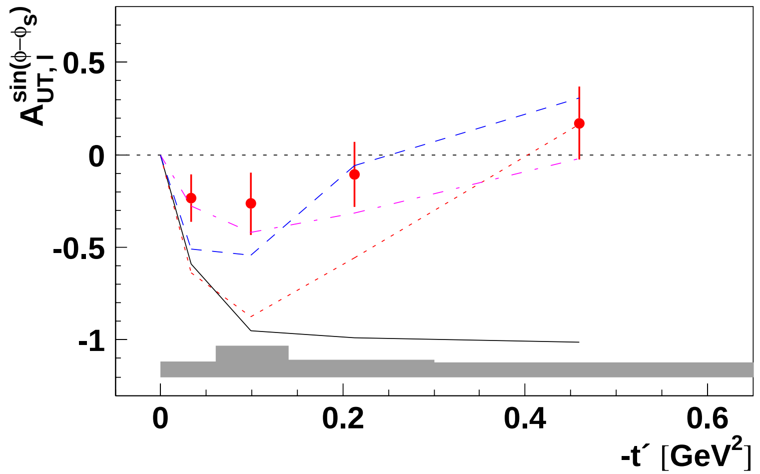
$$A_{UT}^{\rho^0,\sin(\phi-\phi_s)} \propto \Im m\left(\frac{2E^u + E^d}{2H^u + H^d + H^g}\right)$$

$$A_{UT}^{\omega,\sin(\phi-\phi_s)} \propto \Im m\left(\frac{2E^u - E^d}{2H^u - H^d}\right)$$

π^+ transverse target spin asymmetry



- Leading asymmetry amplitudes: small



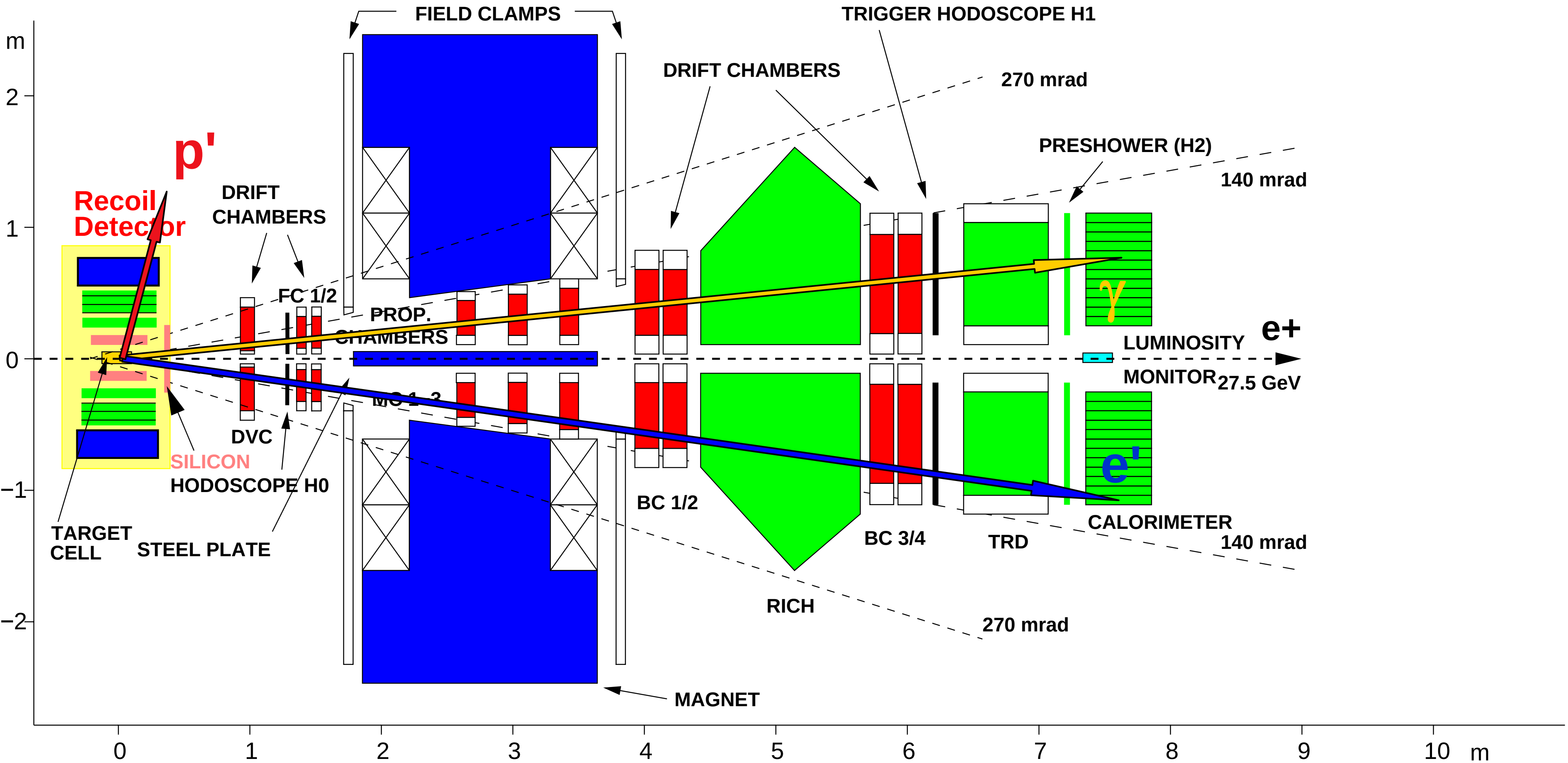
Ch. Bechler, D. Müller, *arXiv:0906.2571*

K. Kumericki, D. Müller, and K. Passek-Kumericki, Eur. Phys. J. C 58 (2008) 193

S. Goloskokov, P. Kroll, *Eur.Phys.J.C65:137-151,2010*

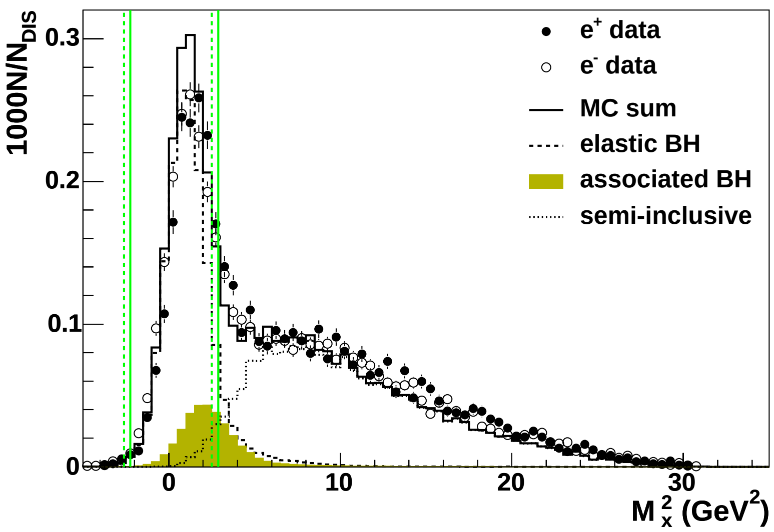
- Subleading asymmetry amplitude: surprisingly large, expected to be suppressed by *1/Q* (γ^*_L-γ^*_T interference?)

Exclusivity at HERMES: Recoil detector



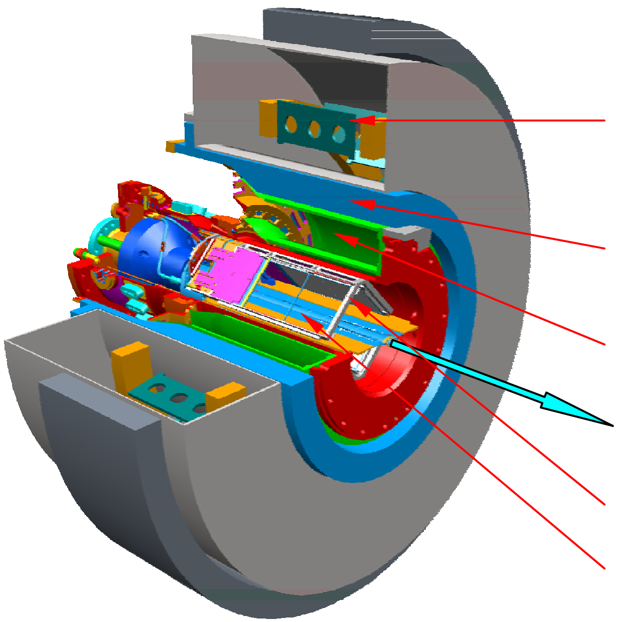
- Unpolarized hydrogen target: 38 Mio DIS (41.000 DVCS)
- Unpolarized deuterium target: 10 Mio DIS (7.500 DVCS)
- Two beam helicities, electron and positron beams

DVCS measurement without and with Recoil Detector

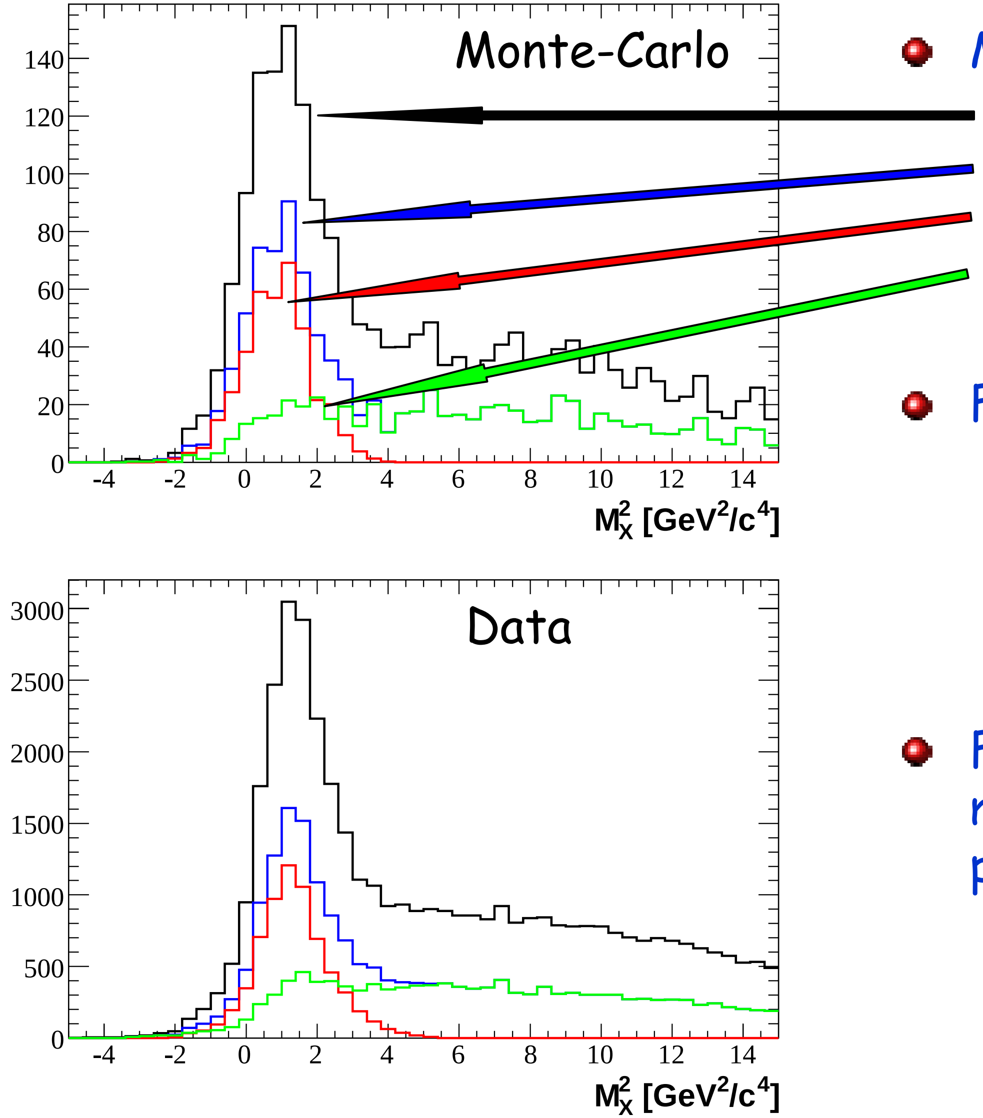


- Pre-Recoil data
  - Scattered lepton and photon were detected in the forward spectrometer
  - Recoil proton was not detected
  - Exclusivity achieved via missing mass technique
  - Associated processes were not resolved (12% contribution in the signal)

- Recoil data
  - Detection of recoil proton
  - Suppression of background to <1% level



DVCS event selection with the Recoil detector



- Missing mass for Monte Carlo
  - No requirement for Recoil
  - Positively charged Recoil track
  - Kinematic fit probability > 1%
  - Kinematic fit probability < 1%

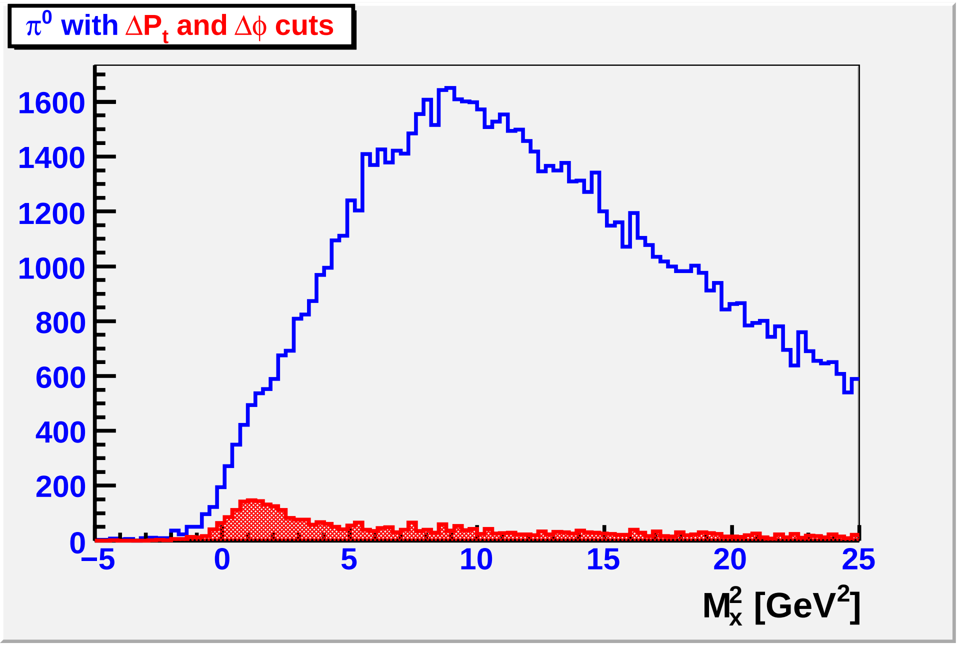
- Fit works well for Monte-Carlo
  - After chi-square cut associated Bethe-Heitler and semi-inclusive background is suppressed to negligible level

- For data optimization of measurement errors of kinematic parameters is necessary
  - Preliminary optimization done
  - Systematic studies are in progress

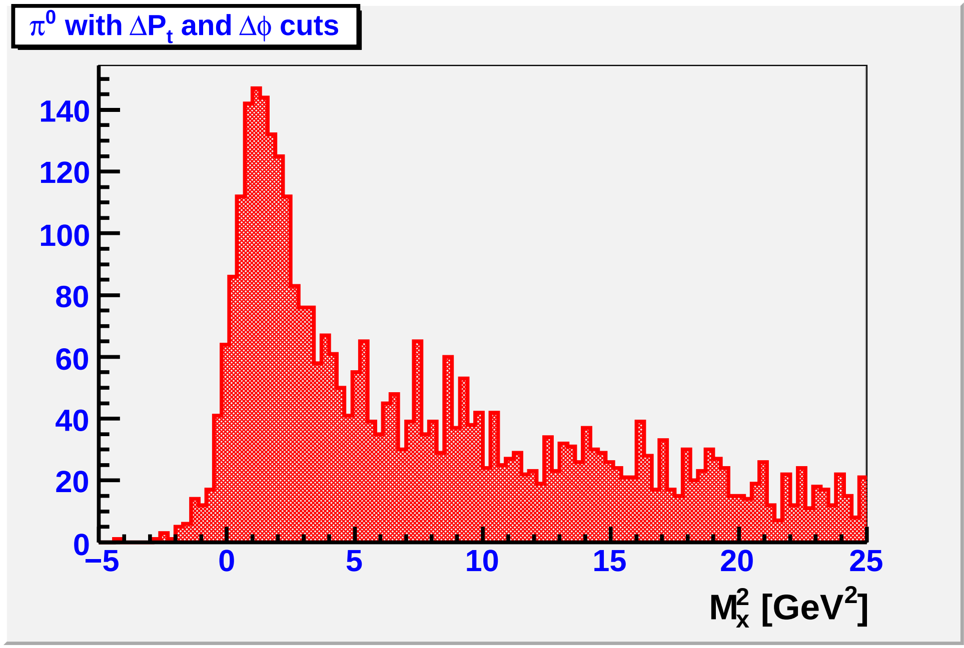
First signal of exclusive π^0 production at HERMES

- Can provide access to chiral-even and chiral-odd GPDs
- Impossible without recoil proton detection
- With recoil information clear signal is observed

Recoil proton required



Cuts on momentum and angle difference applied



Conclusion

- HERMES produced and published many results on exclusive processes
  - DVCS
  - Exclusive vector meson production
  - Exclusive pseudoscalar meson production

- New results will be presented and published soon