Exclusive Meson Production and the future DVCS program at COMPASS

Katharina Schmidt

On behalf of the COMPASS Collaboration

PacSpin 2013
Jinan, Oct 27 - Oct 31

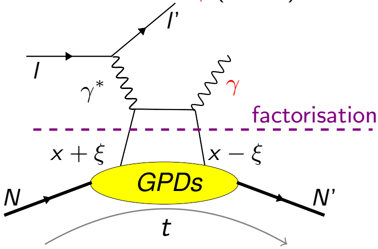
Generalized parton distributions - exclusive processes

- Factorisation in hard and soft part
- Soft part can be parameterized with GPDs
- 8 GPDs for each quarks and gluons:
  4 chiral-even GPDs: H, $\tilde{H}$, E, $\tilde{E}$
  4 chiral-odd GPDs: H_T, $\tilde{H}_T$, E_T, $\tilde{E}_T$
- Two possible processes:
  HEMP and DVCS

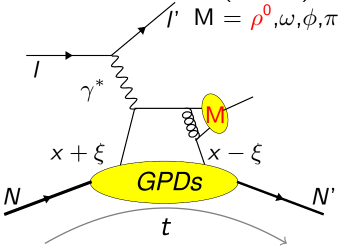
→ Both measurable at COMPASS

x = average long. momentum fraction of the parton
$t = \Delta^2 = (\text{N'-N})^2$
2ξ = long. momentum fraction of Δ

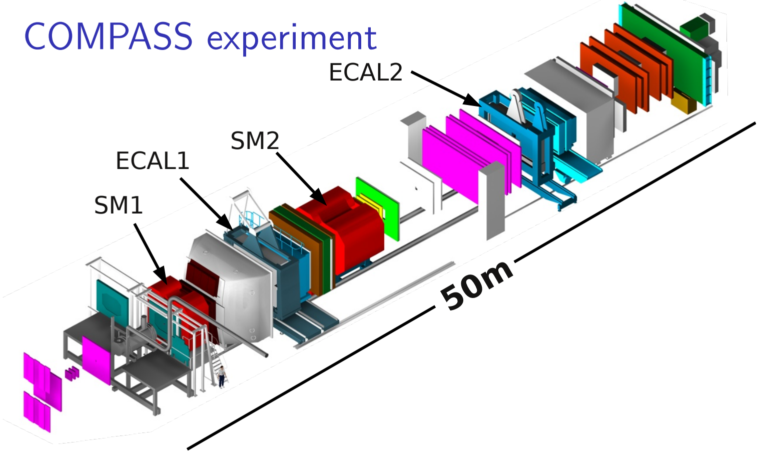
l + N → l' + N' + γ (DVCS)



l + N → l' + N' + M (HEMP)
M = ρ^0,ω,ϕ,π, ...

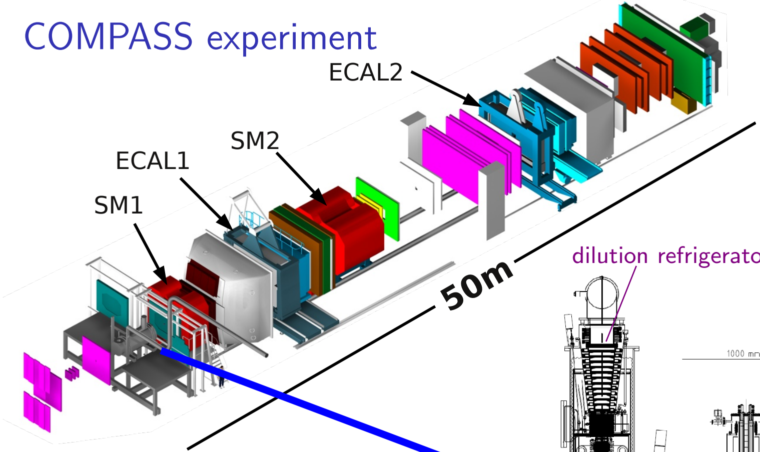


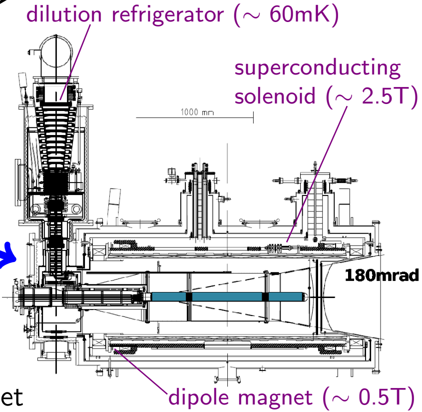
COMPASS experiment



- μ or π, K, p beam from CERN SPS
- Two-stage spectrometer
- Variety of tracking detectors
- Transversely/longitudinally polarized target

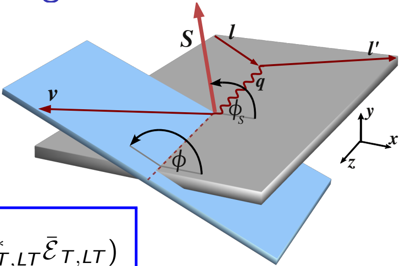
COMPASS experiment





- μ or π, K, p beam from CERN SPS
- Two-stage spectrometer
- Variety of tracking detectors
- Transversely/longitudinally polarized target

HEMP with transversely polarized targets



- Allow extraction of 8 asymmetries
  $A_{UT}^{\sin(\phi-\phi_S)}, A_{UT}^{\sin(\phi+\phi_S)}, A_{UT}^{\sin(2\phi-\phi_S)}, A_{UT}^{\sin(3\phi-\phi_S)}, A_{UT}^{\sin\phi_S}, A_{LT}^{\cos(\phi-\phi_S)}, A_{LT}^{\cos(2\phi-\phi_S)}, A_{LT}^{\cos\phi_S}$
- They are sensitive to different combinations of GPDs e.g.:

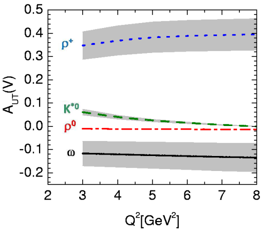
$$A_{UT}^{\sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\epsilon\mathcal{E}_{LL}^{*}\mathcal{H}_{LL} - \mathcal{E}_{TT}^{*}\mathcal{H}_{TT} + \frac{1}{2}\mathcal{H}_{T,LT}^{*}\bar{\mathcal{E}}_{T,LT})$$

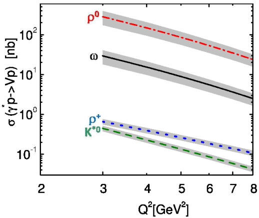
- $\mathcal{E}_{LL}$ & $\mathcal{H}_{LL}$ ($\mathcal{E}_{TT}$ & $\mathcal{H}_{TT}$) are convolution integrals of subprocess amplitude $\gamma_L^* \to \rho_L^0$ ($\gamma_T^* \to \rho_T^0$) with GPDs E & H where:

$$E_{\rho^0} = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g)$$

Goloskokov & Kroll
Eur.Phys.J.C 59 (2009)

$\rightarrow$ Constrain GPD E





Exclusive ρ^0 production at COMPASS

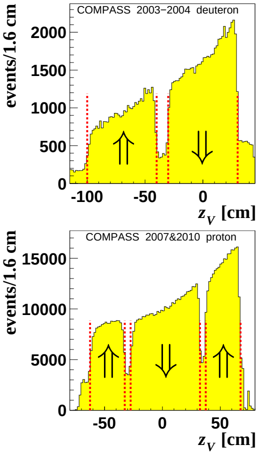
All measurements done with μ^+ 160 GeV beam with polarization $\langle P_B \rangle \sim 80\%$ and a transversely polarized solid state target

^{6}LiD target (polarized deuterons) 2003&2004

- $\rightarrow$ Dilution factor $\langle f \rangle \sim 0.45$
- $\rightarrow$ Polarization $\langle P_T \rangle \sim 50\%$

NH_3 target (polarized protons) 2007&2010

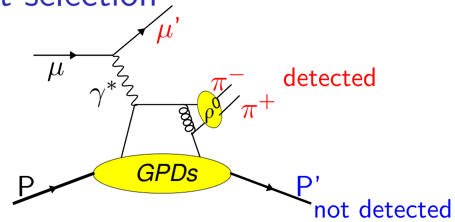
- $\rightarrow$ Dilution factor $\langle f \rangle \sim 0.25$
- $\rightarrow$ Polarization $\langle P_T \rangle \sim 80\%$

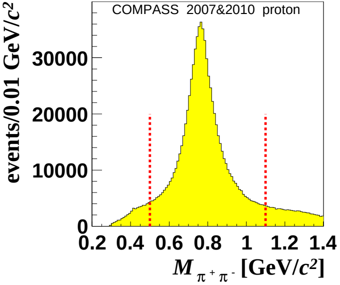


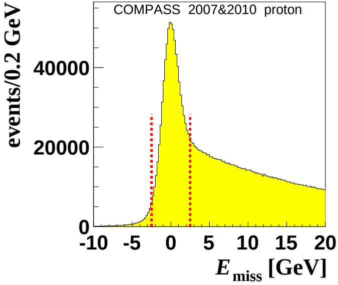
change of polarization $\sim$ weekly

Exclusive ρ^0 production - event selection

$$\mu + N^{\uparrow} \rightarrow \mu' + N' + \rho^0$$
$$\rho^0 \rightarrow \pi^+ + \pi^-$$







- Peak at ρ^0 mass ~ 0.775 GeV$/c^2$
- Signature for exclusivity $E_{\text{miss}} \sim 0$

$$E_{\text{miss}} = \frac{(p+q-\rho)^2 - p^2}{2 \cdot M_p} = \frac{M_X^2 - M_p^2}{2 \cdot M_p}$$

Semi-inclusive background estimation

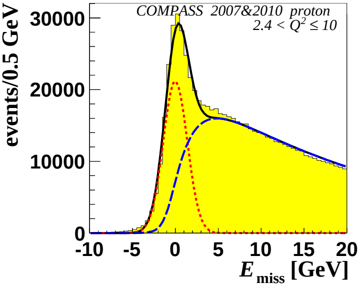
- LEPTO MC (COMPASS tuning)

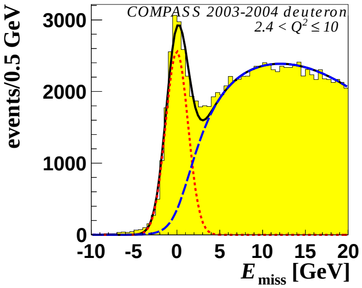
1.) Parameterization of MC:

  - MC weighted with the like sign sample

$$w = \frac{N^{h^+h^+}_{\text{data}}(E_{\text{miss}}) + N^{h^-h^-}_{\text{data}}(E_{\text{miss}})}{N^{h^+h^+}_{\text{MC}}(E_{\text{miss}}) + N^{h^-h^-}_{\text{MC}}(E_{\text{miss}})}$$

  - Parameterize the E_{miss} shape of weighted MC
  - Binning appropriate for asymmetry extraction (x_{Bj}, Q^2 or p_T^2, target cell)





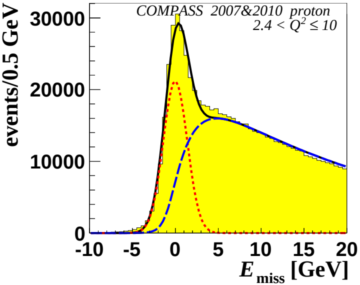
Semi-inclusive background estimation

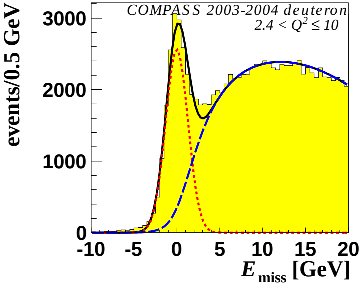
- LEPTO MC (COMPASS tuning)

2.) Fit to data:

  - Two component fit with: signal (Gauss) + background (parameterized from MC)
  - ϕ, ϕ_S distribution for $7 < E_{\text{miss}} < 20$ GeV scaled with the number of background events and subtracted from ϕ, ϕ_S distribution in signal range $-2.5 < E_{\text{miss}} < 2.5$ GeV
  - Asymmetry extraction with corrected ϕ, ϕ_S distribution

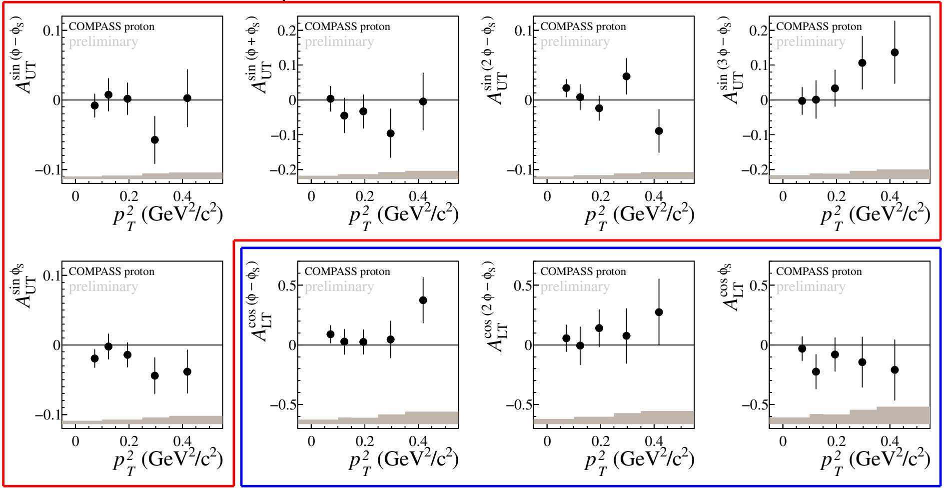
$\rightarrow$ Total amount of SIDIS background: 18% (^{6}LiD), 22% (NH_3)





Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

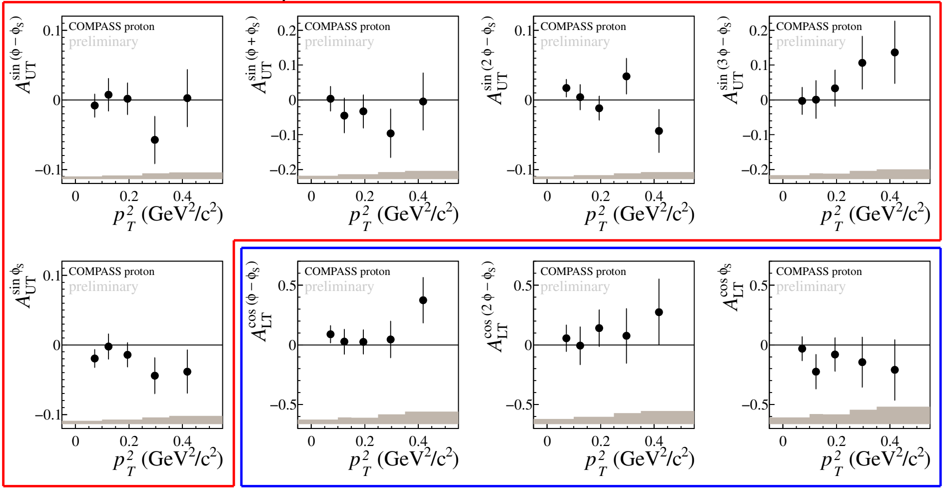
as a function of p_T^2



- Asymmetry extraction using a 2D binned maximum likelihood fit after subtracting the SIDIS background

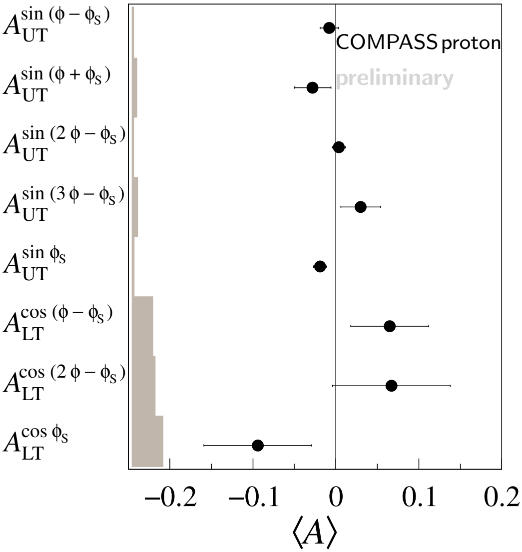
Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

as a function of p_T^2



- Additionally extracted as a function of x_{Bj} and Q^2

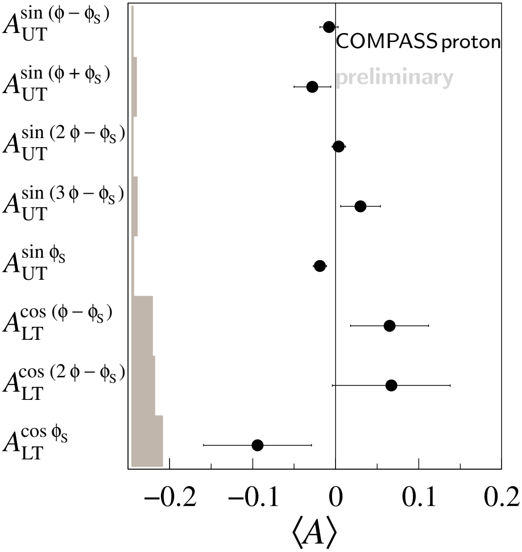
Mean asymmetries - NH_3 target



Mean asymmetries - NH_3 target

Goloskokov & Kroll

arXiv:1310.1472



$$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\epsilon\mathcal{E}_{LL}^{*}\mathcal{H}_{LL} - \mathcal{E}_{TT}^{*}\mathcal{H}_{TT} + \frac{1}{2}\mathcal{H}_{T,LT}^{*}\bar{\mathcal{E}}_{T,LT})$$

$$A_{UT}^{sin(\phi+\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT})$$

$$A_{UT}^{(2\phi-\phi_S)} \propto \mathrm{Im}\,(\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL})$$

0

$$A_{UT}^{sin\phi_S} \propto \mathrm{Im}\,(\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL})$$

$$A_{LT}^{cos(\phi-\phi_S)} \propto \mathrm{Re}\,(\mathcal{H}_{T,LT}^{*}\bar{\mathcal{E}}_{T,LT})$$

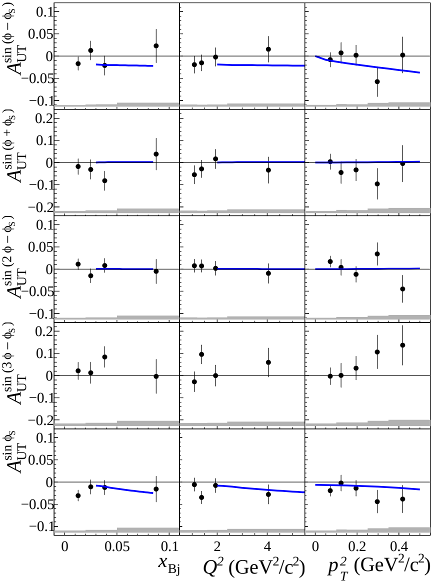
$$A_{LT}^{cos(2\phi-\phi_S)} \propto \mathrm{Re}\,(\bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL})$$

$$A_{LT}^{cos\phi_S} \propto \mathrm{Re}\,(\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \bar{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL})$$

- Evidence for existence of H_T

$$\bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$$

Comparison with a phenomenological GPD-based model

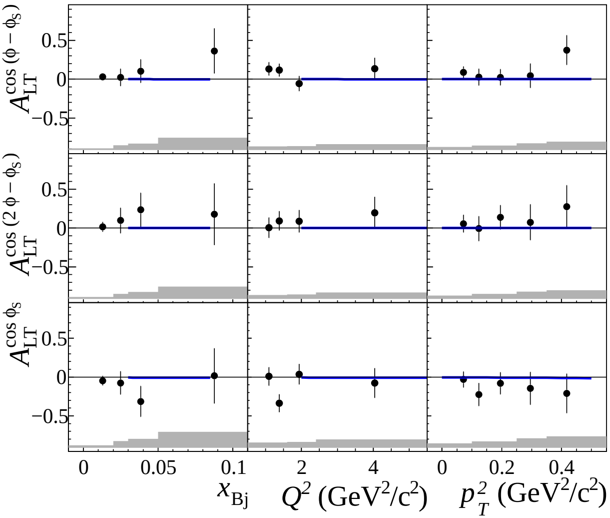


COMPASS proton
preliminary

- Blue line: Model from Goloskokov and Kroll
- phenomenological 'handbag' approach
- includes twist-3 ρ^0 meson wave functions
- includes contributions from γ^*_L and γ^*_T

COMPASS measurement
Submitted to Phys.Lett.B

Comparison with a phenomenological GPD-based model



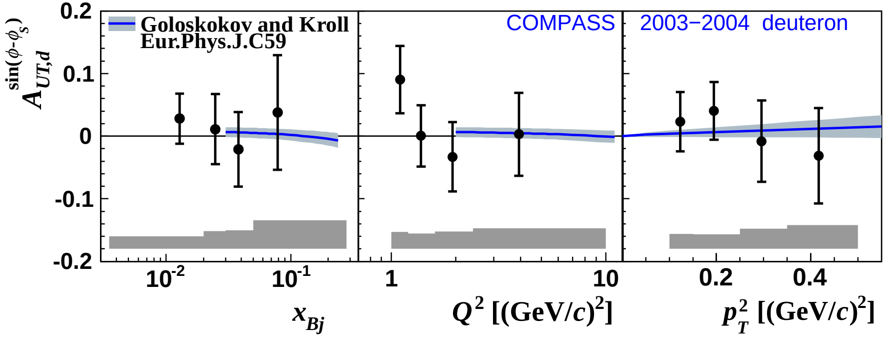
COMPASS proton

preliminary

- Predictions for COMPASS kinematic: $W = 8.1$ GeV$/c^2$, $p_T^2 = 0.2$ (GeV$/c)^2$, $Q^2 = 2.2$ (GeV$/c)^2$

COMPASS measurement
Submitted to Phys.Lett.B

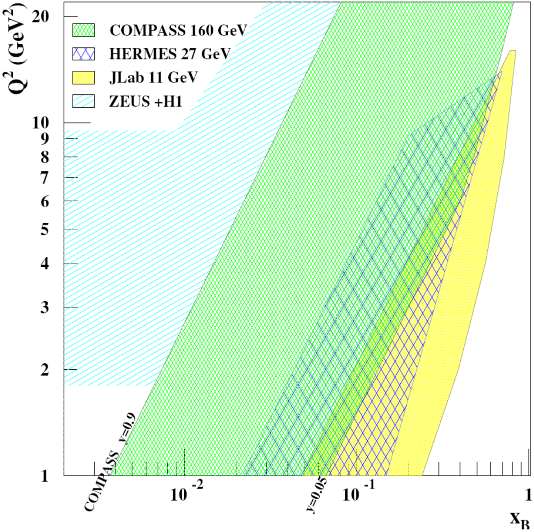
Asymmetry $A_{UT,d}^{sin(\phi-\phi_S)}$ - ^{6}LiD target (2003&2004)



- Contribution from GPDs E^u and E^d approx. cancel in exclusive ρ^0 production (different in exclusive ω production)

Nucl.Phys. B865 (2012) 1-20

DVCS at COMPASS-II

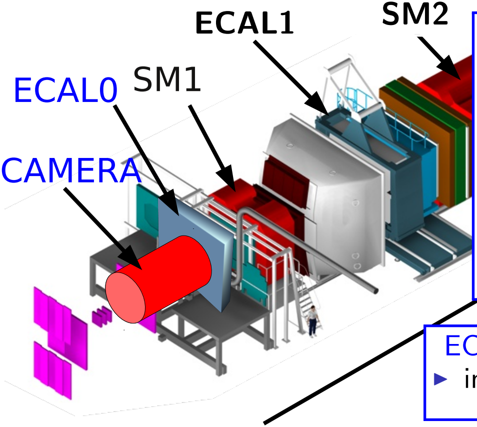


- μ^+ and μ^- beam with opposite polarization
- Momentum: 100-190 GeV$/c$
- Polarized beam: $\sim$ 80%
- Luminosity: $\mathcal{L} = 10^{32} cm^{-1} s^{-1}$
- Unpolarized target $\rightarrow$ sensitive to GPD H
- Coverage of intermediate x_{Bj}

$\rightarrow$ Unexplored region between the collider (H1+ZEUS) and fixed target (HERMES+JLAB) experiments

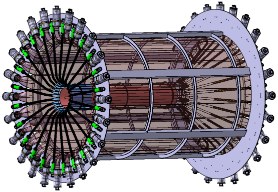
DVCS at COMPASS-II

- 2008/09: first pilot run
- 2012: pilot run, 2,5m LH2 target and CAMERA detector
- 2016/17: measurement foreseen including a third ECAL



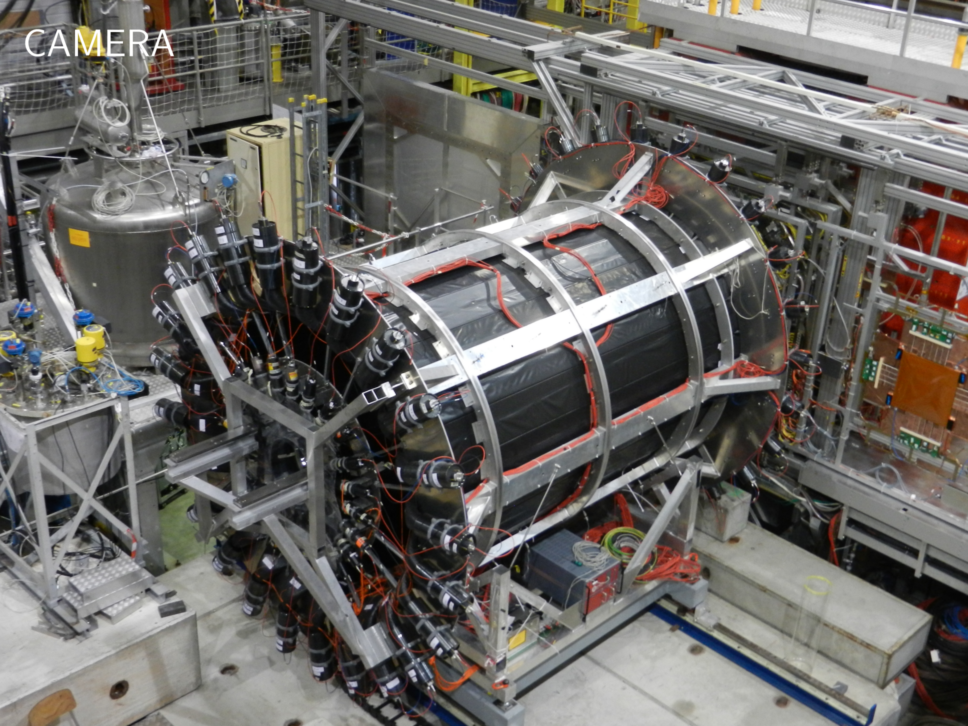
CAMERA

- enables measurement of recoiled proton
- 24 inner & outer scintillators
- $\sim 300\ ps$ TOF resolution



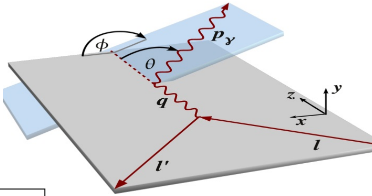
ECAL0

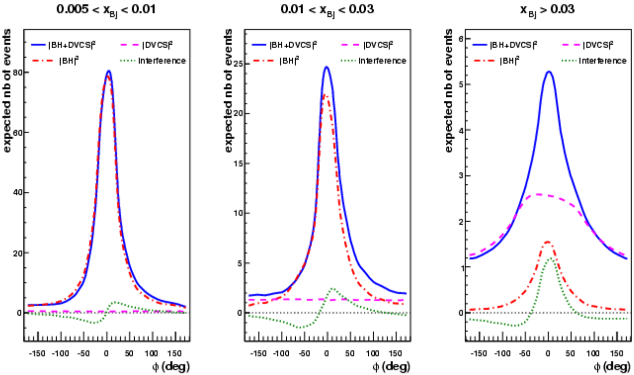
- increase domain in x_{Bj}

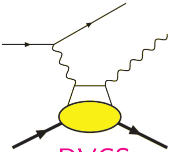

CAMERA

DVCS and BH

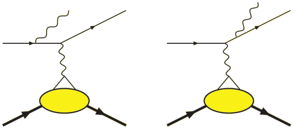
$d\sigma \propto |T^{\mathrm{BT}}|^2 + |T^{\mathrm{DVCS}}|^2 +$ interference term







DVCS



Bethe-Heitler (BH)

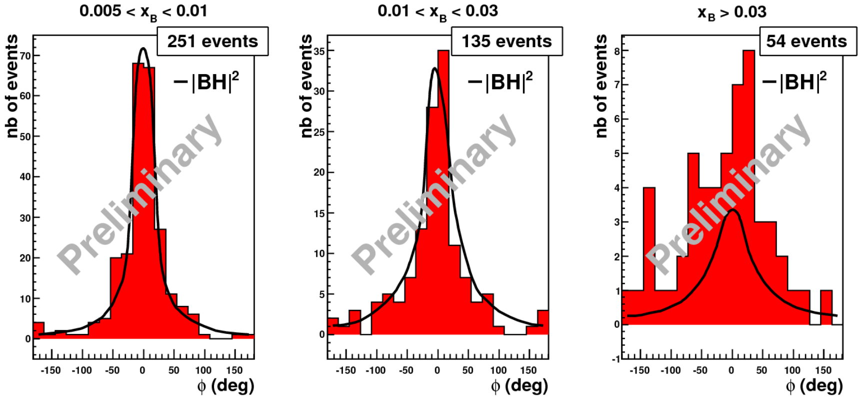
$0.005 < x_{Bj} < 0.01$
BH dominates

$0.01 < x_{Bj} < 0.03$
study interference

$x_{Bj} > 0.03$
DVCS dominates

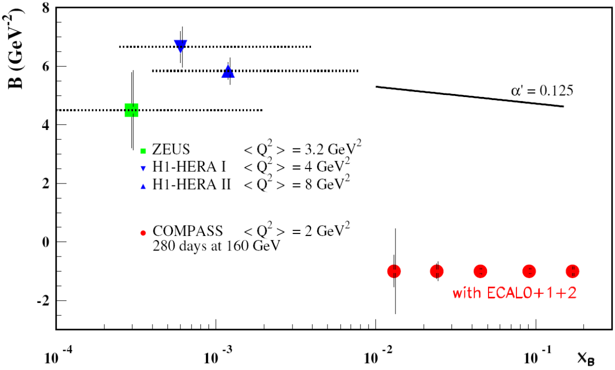
Monte-Carlo Simulation for COMPASS only with ECAL1+2

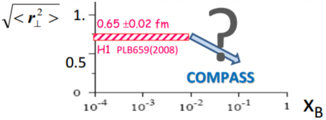
First measurements - pilot run 2009



- 10 days data taking
- Shorter recoil proton detector and target
- Global efficiency: $\epsilon_{\text{global}} \approx 0.13$
- $x_{Bj} > 0.03$: 54 events = 20 BH + 22 DVCS + 12 γ from π^0

Beam charge & spin sum - MC prediction





Ansatz at small x_{Bj}:
$B(x_{Bj}) = B_0 + 2\alpha' \ln(\frac{x_0}{x_{Bj}})$
$\alpha = 0.125 \text{ GeV}^{-2}$
$B_0 = 5.83 \text{GeV}^{-2}$, $x_0 = 0.0012$
$\rightarrow$ inspired by HERA

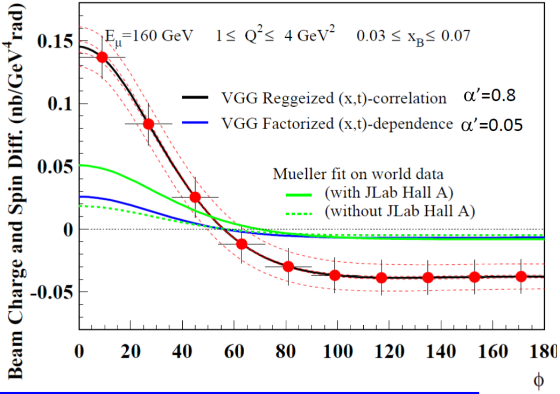
$$S_{CS,U} = d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\leftarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\ I$$

- BH subtraction and integration of $\phi \rightarrow d\sigma^{DVCS}_{unpol}$

$\rightarrow$ $d\sigma^{DVCS}/dt \sim exp(-B|t|)$

$\rightarrow$ Study transverse size of the nucleon: $\langle r_\perp^2(x_{Bj})\rangle \approx 2B(x_{Bj})$

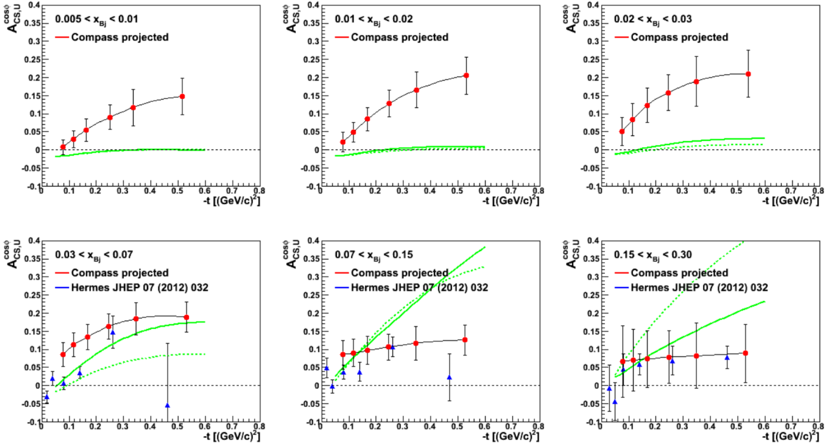
Beam charge & spin difference - MC prediction



$$D_{CS,U} = d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\leftarrow}) \propto c_0^{Int} + c_1^{Int} cos\phi$$

- coefficients c_n are related to combinations of Compton Form Factors (CFFs)
- $c_{0,1}^{int} \sim F_1 \mathrm{Re}\,\mathcal{H}$

Beam charge & spin asymmetry - MC prediction



Predictions from VGG and D.Mueller

$A_{CS,U}^{cos\phi}$ related to c_1^{Int}

Summary - HEMP

- Exclusive ρ^0 production in high energy muon scattering off transversely polarized protons and deuterons was studied
- Results for 5 transverse target single-spin asymmetries $A_{\mathrm{UT,p}}$, 3 transverse target double-spin asymmetries $A_{\mathrm{LT,p}}$ for transversely polarized protons and $A_{UT,d}^{sin(\phi-\phi_S)}$ were presented
- Most of the modulations are small, consistent with 0 within experimental uncertainties
- $A_{\mathrm{UT,p}}^{\sin(\phi_S)} =$ -0.019 $\pm$ 0.008 $\pm$ 0.003 evidence for existence of chiral-odd GPD H_T

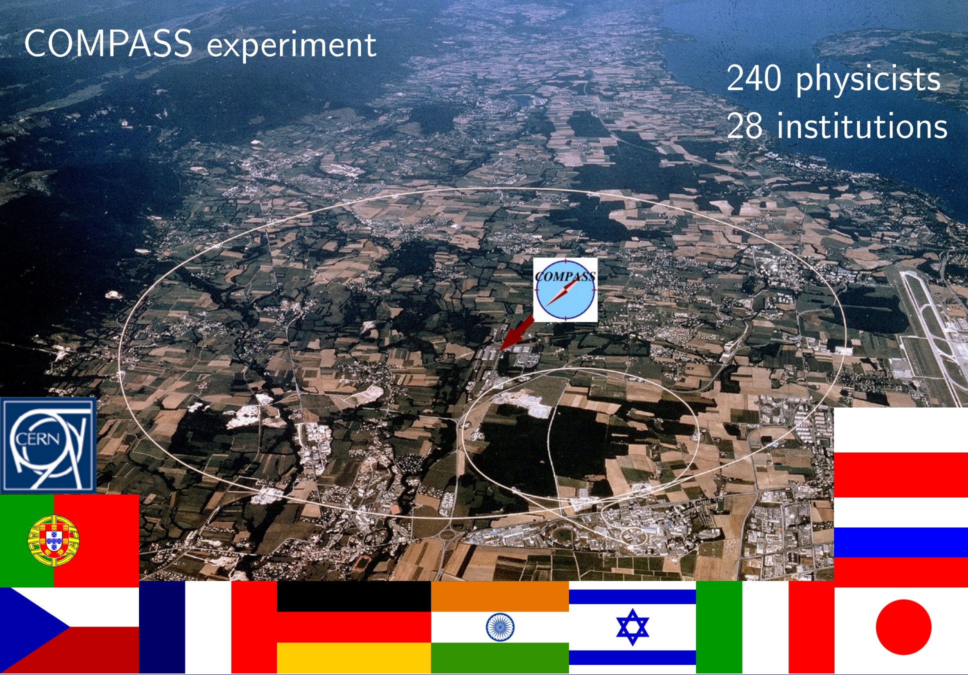
Summary & outlook - DVCS

- DVCS will be studied in the unstudied intermediate x_{Bj} regime
- Unique: frequent change of beam charge and polarization
- Future: study nucleon transversal dimension as a function of x_{Bj} and GPD H ($D_{CS,U}$, $S_{CS,U}$, $A_{CS,U}^{cos\phi}$)

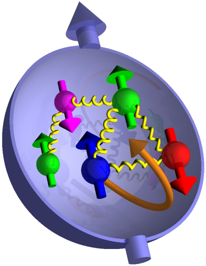
BACKUP

COMPASS experiment

240 physicists
28 institutions



Generalized parton distributions - application



$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}$

(Jaffe&Manohar Nucl.Phys.B337 (1990))

- $\frac{1}{2}\Delta\Sigma \sim 0.15$ known from DIS/SIDIS
- $|\Delta G| \sim 0.2$ first indications from DIS/pp
- $\mathcal{L}$ unknown

Ji's sum rule connects the Generalized Parton Distributions (GPDs) $H(x,\xi,t)$ and $E(x,\xi,t)$ with the total angular momentum $J^{q,g}$

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

(Phys.Rev.Lett.78 (1997))

x = average long. momentum fraction of the parton
$t = \Delta^2 = (N'-N)^2$
2ξ = long. momentum fraction of Δ

Hard exclusive ρ^0 production

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\psi} = \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\mathrm{Re}\,\sigma_{+-}^{++}$$

$$-\sqrt{\varepsilon(1+\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--}) \quad - P_\ell\,\sqrt{\varepsilon(1-\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$-S_L\left[\varepsilon\sin(2\phi)\,\mathrm{Im}\,\sigma_{+-}^{++}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi\,\mathrm{Im}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

$$+S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

transversely polarized target

$$-S_T\left[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}\right.$$

$$\left.+\sqrt{\varepsilon(1+\varepsilon)}\,\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\right]$$

transversely polarized target + longitudinally polarized beam

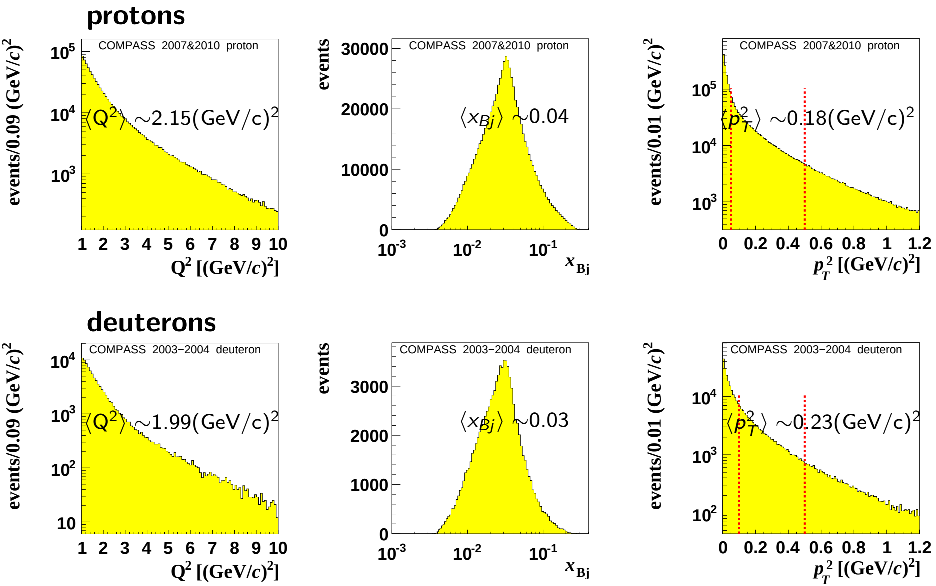
$$+S_T P_\ell\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}\right.$$

$$\left.-\sqrt{\varepsilon(1-\varepsilon)}\,\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\right]$$

ϵ = virtual photon polarization parameter
σ_{mn}^{ij} = spin dependent photoabsorption cross sections, interference terms
m,n = virtual-photon helicity
i,j = target nucleon helicity

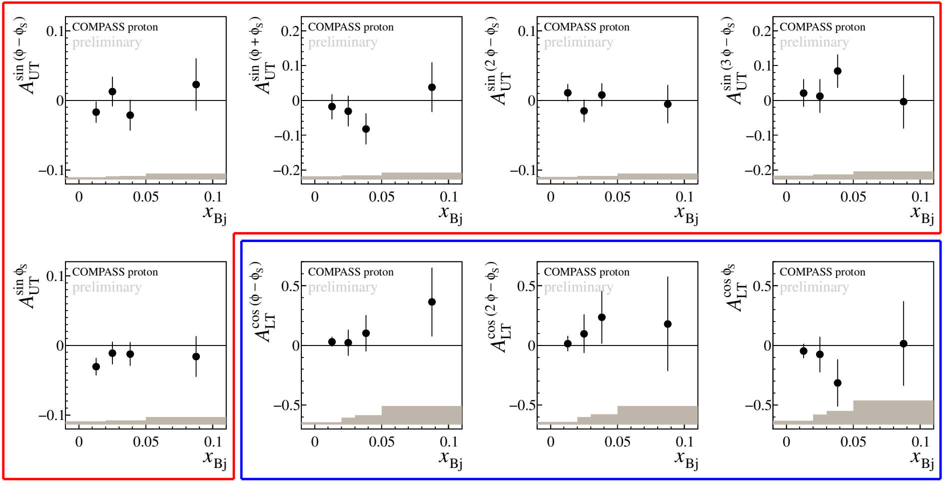
Diehl & Sapeta
Eur.Phys.J.C 41 (2005)

Exclusive ρ^0 production - kinematical distributions



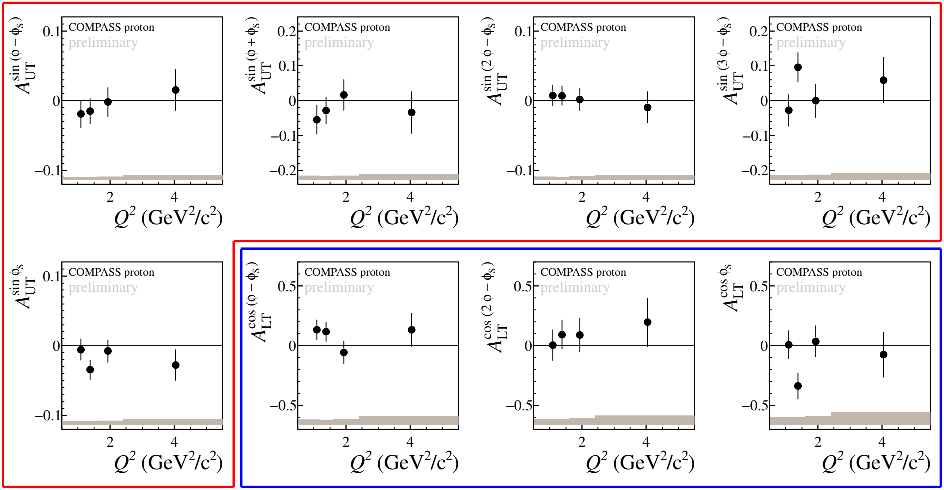
Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

as a function of x_{Bj}



Asymmetry $A_{UT,LT}$ - NH_3 target (2007&2010)

as a function of Q^2



Comparison with a phenomenological GPD-based model

Goloskokov & Kroll

Eur.Phys.J.C 59 (2009)

- phenomenological 'handbag' approach
- based on $k_\perp$ factorisation
- includes twist-3 meson wave functions
- includes contributions from γ^*_L and γ^*_T

$$\sigma^{\nu\lambda}_{\mu\sigma} = \sum \mathcal{M}^*_{\mu'\nu',\mu\nu}\mathcal{M}_{\mu'\nu',\sigma\lambda}$$

$$A_{\mathrm{UT}}^{\sin(\phi-\phi_s)}\sigma_0 = -2\mathrm{Im}\left[\epsilon\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+} + \mathcal{M}^*_{+-,++}\mathcal{M}_{++,++} + \frac{1}{2}\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}\right]$$

$$A_{\mathrm{UT}}^{\sin(\phi_s)}\sigma_0 = -\mathrm{Im}\left[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+} - \mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$$A_{\mathrm{UT}}^{\sin(2\phi-\phi_s)}\sigma_0 = -\mathrm{Im}\left[\mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$$A_{\mathrm{LT}}^{\cos(\phi_s)}\sigma_0 = -\mathrm{Re}\left[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+} - \mathcal{M}^*_{0+,++}\mathcal{M}_{0-,0+}\right]$$

$\mathcal{M}_{\delta\gamma,\beta\alpha}$ = helicity amplitudes
α = initial-state proton helicity
β = virtual-photon helicity
γ = final-state proton helicity
δ = meson helicity

Comparison with a phenomenological GPD-based model

Up to now mainly used to describe DVCS and HEMP:
chiral-even GPDs

$\gamma^*_L \to \rho^0_L$	$\mathcal{M}_{0+,0+} \sim H$; $\mathcal{M}_{0-,0+} \sim E$	dominant
$\gamma^*_T \to \rho^0_T$	$\mathcal{M}_{++,++} \sim H$; $\mathcal{M}_{+-,++} \sim E$	suppressed

Recently introduced: chrial-odd (transverse) GPDs

$$\gamma^*_T \to \rho^0_L \quad \mathcal{M}_{0-,++} \sim H_T;\ \mathcal{M}_{0+,++} \sim \bar{E}_T = 2\tilde{H}_T + E_T$$

$\gamma^*_L \to \rho^0_T$, $\gamma^*_T \to \rho^0{}_{-T}$ known to be suppressed, neglected in the model