Hard Exclusive Measurements at COMPASS

Katharina Schmidt

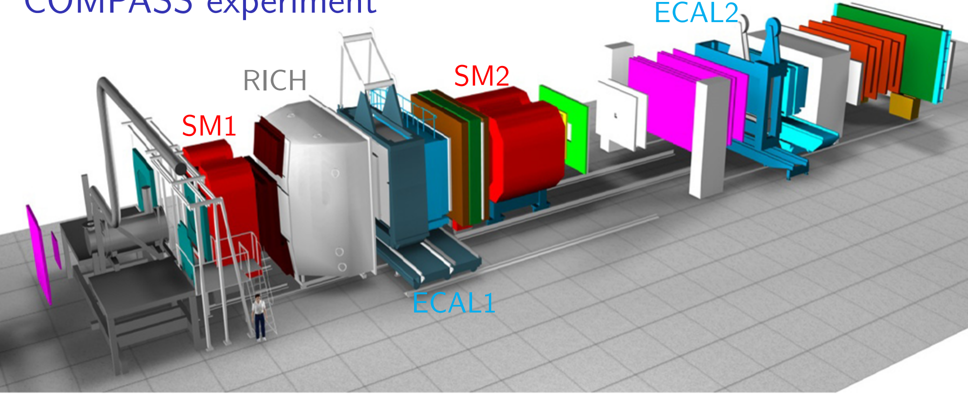
On behalf of the COMPASS Collaboration

KEK theory center workshop
March 13 - 16, 2015, Tsukuba, Japan

COMPASS experiment

240 physicists
24 institutions

COMPASS experiment



Two-stage spectrometer → large angular & momentum acceptance

- μ or π, K, p beam from CERN SPS
- Beam energies about 200 GeV
- Variety of tracking detectors, particle identification
- Transversely/longitudinally polarized target

Hard exclusive measurements at COMPASS

2002	First measurement transversely polarized ^{6}LiD target
2003-2004	Hard Exclusive Meson Production (HEMP) transversely polarized ^{6}LiD target
2007	HEMP transversely polarized NH_3 target
2008, 2009	Deep Virtual Compton Scattering (DVCS) 10 days pilot run
2010	HEMP transversely polarized NH_3 target
2012	1 month DVCS measurement (COMPASS-II)

Hard exclusive measurements at COMPASS

... and COMPASS is even more ...

μ **beam + longitudinally polarized target**
gluon and quark helicities

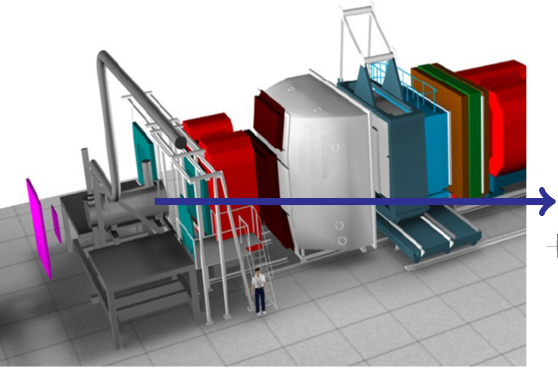
μ **beam + transversely polarized target**
Transversity and Transverse Momentum Dependent distributions

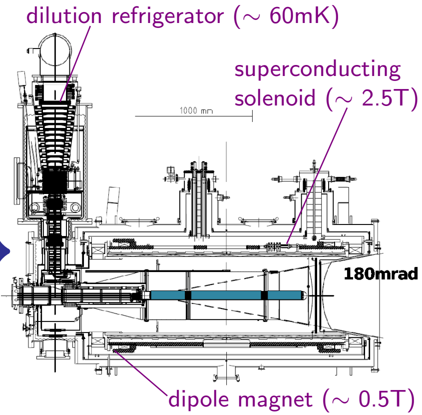
hadron beam
light meson spectroscopy, pion polarisability

hadron beam + transversely polarized target
Drell-Yan

HEMP measurements at COMPASS

COMPASS experiment





Transversely polarized target

- Target material: NH_3, ^{6}LiD
- 2 magnets: solenoid 2.5 T and dipole 0.5 T
- Acceptance: $\pm$180 mrad upstream edge (since 2006)
- ^{3}He - ^{4}He dilution refrigeration (60mK)

Hard exclusive meson production - cross section

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

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

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

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

transversely polarized target

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

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

transversely polarized target + longitudinally polarized beam

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

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

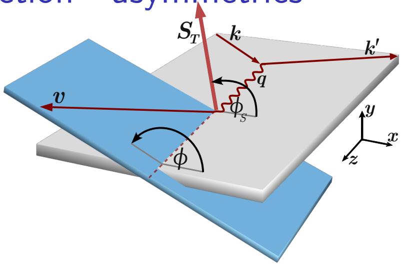
ϵ = virtual photon polarization parameter
σ_{mn}^{ij} = spin dependent photoabsorption cross sections, interference terms
m,n = virtual-photon helicity
i,j = target nucleon helicity

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

Hard exclusive meson production - asymmetries

$$\epsilon = \frac{1 - y - \frac{1}{4}y^2\gamma^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}y^2\gamma^2}$$

$$\gamma = \frac{2x_{\mathrm{Bj}} M_P}{Q}$$



$$A_{\mathrm{UT}}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}(\sigma_{++}^{+-} + \varepsilon\, \sigma_{00}^{+-})}{\sigma_0}$$

$$A_{\mathrm{UT}}^{\sin(\phi+\phi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{+-}}{\sigma_0}$$

$$A_{\mathrm{UT}}^{\sin(3\phi-\phi_s)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{-+}}{\sigma_0}$$

$$A_{\mathrm{UT}}^{\sin(2\phi-\phi_s)} = -\frac{\mathrm{Im}\,\sigma_{+0}^{-+}}{\sigma_0}$$

$$A_{\mathrm{UT}}^{\sin(\phi_s)} = -\frac{\mathrm{Im}\,\sigma_{+0}^{+-}}{\sigma_0}$$

$$A_{\mathrm{LT}}^{\cos(\phi-\phi_S)} = \frac{\mathrm{Re}\,\sigma_{++}^{+-}}{\sigma_0}$$

$$A_{\mathrm{LT}}^{\cos(\phi_s)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0}$$

$$A_{\mathrm{LT}}^{\cos(2\phi-\phi_s)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{-+}}{\sigma_0}$$

$$D_{NN}^{\sin(\phi-\phi_S)} = 1$$

$$D_{NN}^{\sin(\phi+\phi_S),\sin(3\phi-\phi_S)} = \frac{\epsilon}{2}$$

$$D_{NN}^{\sin(\phi_S),\sin(2\phi-\phi_S)} = \sqrt{\varepsilon(1+\varepsilon)}$$

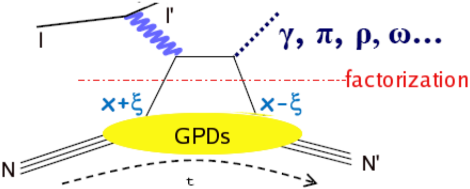
$$D_{NN}^{\cos(\phi-\phi_S)} = \sqrt{1-\varepsilon^2}$$

$$D_{NN}^{\cos\phi_S,\cos(2\phi-\phi_S)} = \sqrt{\varepsilon(1-\varepsilon)}$$

Hard exclusive meson production - GPDs

- Allow extraction of 8 asymmetries
- They are sensitive to different combinations of GPDs e.g.:

$$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\mathcal{E}^{\star}\mathcal{H})$$



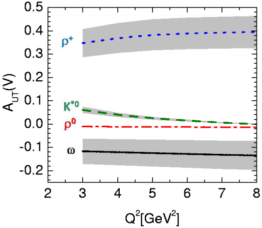
- $\mathcal{E}$ & $\mathcal{H}$ are convolution integrals of hard scattering kernels and the subprocess amplitude $\gamma^* \rightarrow \rho^0$ with GPDs E & H where:

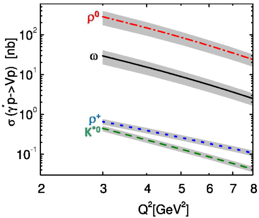
$$E_{\rho^0} = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g)$$

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

- 8 GPDs for quarks and gluons: $H, \widetilde{H}, E, \widetilde{E}, H_T, \widetilde{H}_T, E_T, \widetilde{E}_T$

$\rightarrow$ Constrain GPD E





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

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

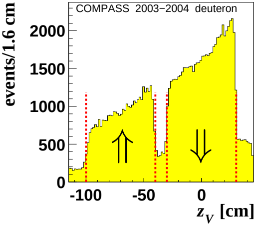
^{6}LiD target (polarized deuterons) 2003&2004

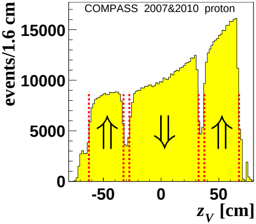
- $\rightarrow$ Dilution factor $\langle f \rangle \sim 0.45$
- $\rightarrow$ Polarization $\langle P_T \rangle \sim 50\%$

NH_3 target (polarized protons) 2007&2010

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

ρ^0 analysis includes all data measured with a transversely polarized target at COMPASS

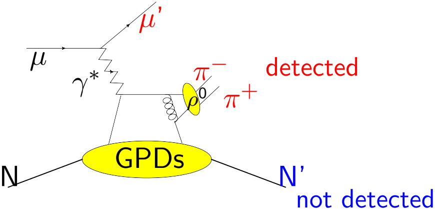


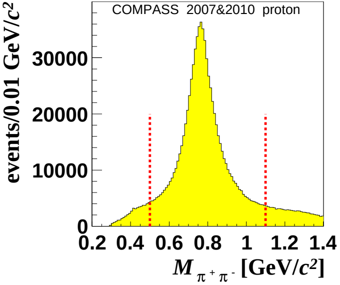


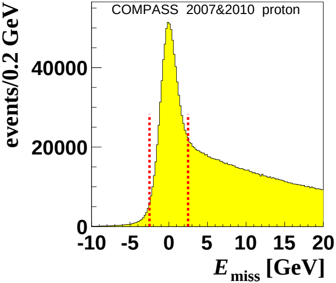
change of polarization $\sim$ weekly

Exclusive ρ^0 production - event selection

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







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

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

Concept of semi-inclusive background correction

1.) Parametrisation of MC:

- MC weighted with the like sign sample

$$w = \frac{N_{\mathrm{data}}^{h^+h^+}(E_{\mathrm{miss}}) + N_{\mathrm{data}}^{h^-h^-}(E_{\mathrm{miss}})}{N_{\mathrm{MC}}^{h^+h^+}(E_{\mathrm{miss}}) + N_{\mathrm{MC}}^{h^-h^-}(E_{\mathrm{miss}})}$$

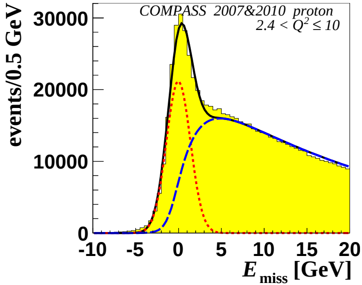
- Parametrise the E_{miss} shape of weighted MC

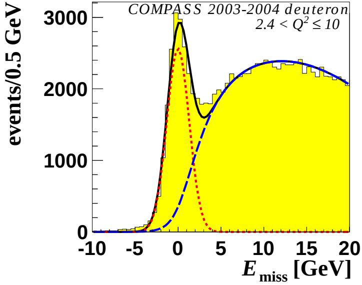
2.) Fit to data:

- Two component fit with: signal (Gauss) + background (parametrised from MC)
- Binning appropriate for asymmetry extraction (x_{Bj}, Q^2 or p_T^2, target cell)

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

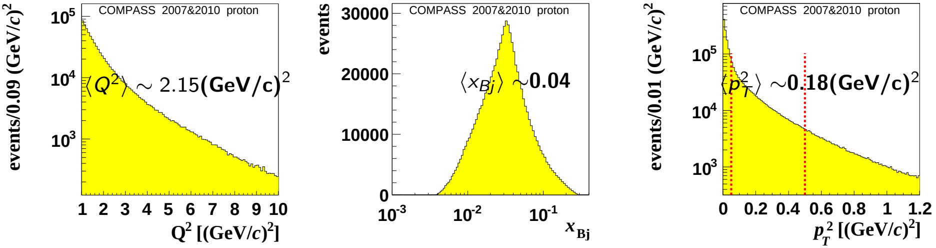
→ Asymmetry extraction with corrected ϕ, ϕ_S distribution



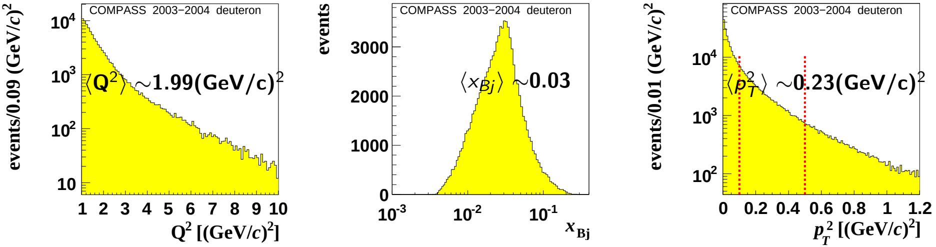


Exclusive ρ^0 production - kinematical distributions

protons

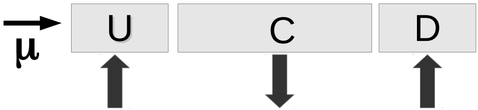


deuterons



Extraction of asymmetries

Example: 3 target cells



$$
\begin{aligned}
N^{\pm}_{ncell}(\phi, \phi_S) &= a^{\pm}_{ncell}\,(1 \pm A(\phi, \phi_S)) \\
a^{\pm}_{ncell} &= F \cdot N \cdot \sigma_0 \cdot \alpha^{\pm}_n
\end{aligned}
$$

σ_0 = spin-averaged cross section

F = the muon flux

N = number of target nucleons

$\alpha^{\pm}_n$ = the acceptance

$$
\begin{aligned}
A(\phi, \phi_S) = \; & A^{\sin(\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(\phi-\phi_S) + A^{\sin(\phi+\phi_S)}_{\mathrm{UT,raw}} \sin(\phi+\phi_S) \\
+ \; & A^{\sin(3\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(3\phi-\phi_S) + A^{\sin(2\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(2\phi-\phi_S) \\
+ \; & A^{\sin(\phi_S)}_{\mathrm{UT,raw}} \sin(\phi_S) + A^{\cos(\phi-\phi_S)}_{\mathrm{LT,raw}} \cos(\phi-\phi_S) \\
+ \; & A^{\cos(\phi_S)}_{\mathrm{LT,raw}} \cos(\phi_S) + A^{\cos(2\phi-\phi_S)}_{\mathrm{LT,raw}} \cos(2\phi-\phi_S)
\end{aligned}
$$

$\pm$ = periods with different target polarizations

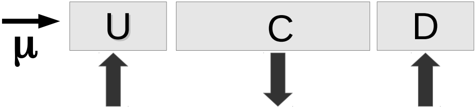
ncell = U+D, C1+C2 (outer cells summed up)

$$
A_{\mathrm{UT}} = A_{\mathrm{UT,raw}}/F_{\mathrm{UT}} \qquad F_{\mathrm{UT}} = < f|P_{\mathrm{T}}|D_{NN} >
$$

$$
A_{\mathrm{LT}} = A_{\mathrm{LT,raw}}/F_{\mathrm{LT}} \qquad F_{\mathrm{LT}} = < f|P_{\mathrm{T}}|P_{\mathrm{B}} D_{NN} >
$$

Extraction of asymmetries

Example: 3 target cells



$$N^{\pm}_{ncell}(\phi,\phi_S) = a^{\pm}_{ncell}\,(1 \pm A(\phi,\phi_S))$$
$$a^{\pm}_{ncell} = F \cdot N \cdot \sigma_0 \cdot \alpha^{\pm}_{n}$$

σ_0 = spin-averaged cross section

F = the muon flux

N = number of target nucleons

$\alpha^{\pm}_{n}$ = the acceptance

$$\begin{aligned} A(\phi,\phi_S) = \; & A^{\sin(\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(\phi-\phi_S) + A^{\sin(\phi+\phi_S)}_{\mathrm{UT,raw}} \sin(\phi+\phi_S) \\ + \; & A^{\sin(3\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(3\phi-\phi_S) + A^{\sin(2\phi-\phi_S)}_{\mathrm{UT,raw}} \sin(2\phi-\phi_S) \\ + \; & A^{\sin(\phi_S)}_{\mathrm{UT,raw}} \sin(\phi_S) + A^{\cos(\phi-\phi_S)}_{\mathrm{LT,raw}} \cos(\phi-\phi_S) \\ + \; & A^{\cos(\phi_S)}_{\mathrm{LT,raw}} \cos(\phi_S) + A^{\cos(2\phi-\phi_S)}_{\mathrm{LT,raw}} \cos(2\phi-\phi_S) \end{aligned}$$

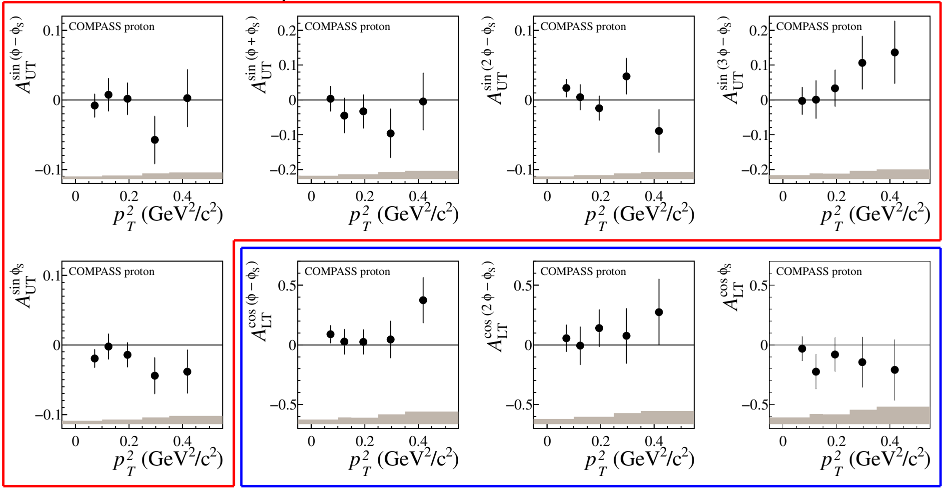
$\pm$ = periods with different target polarizations

ncell = U+D, C1+C2 (outer cells summed up)

Asymmetries are extracted using a 2D binned maximum likelihood fit after subtracting the SIDIS background

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

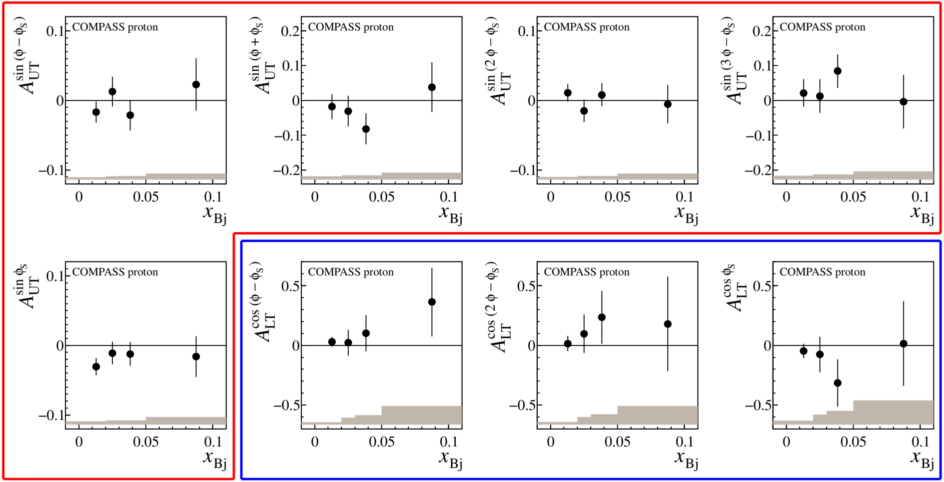
as a function of p_T^2



Phys.Lett. B731 (2014) 19-26

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

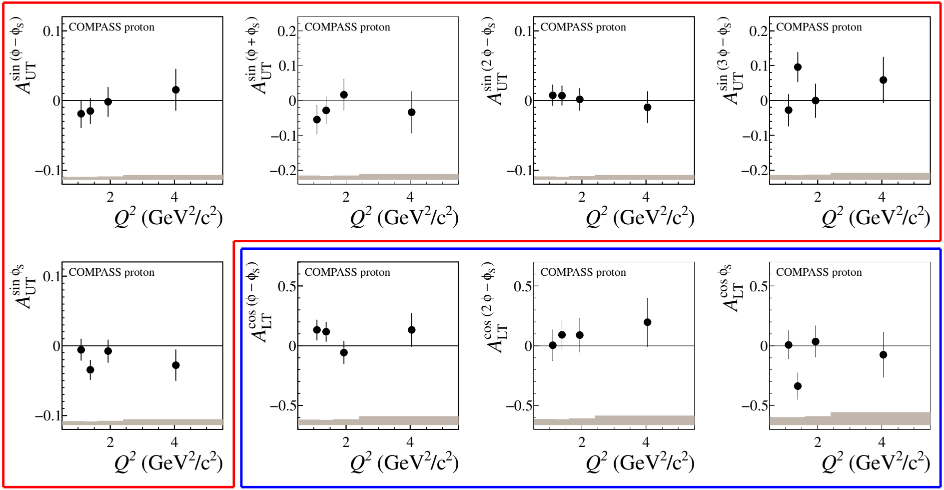
as a function of x_{Bj}



Phys.Lett. B731 (2014) 19-26

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

as a function of Q^2



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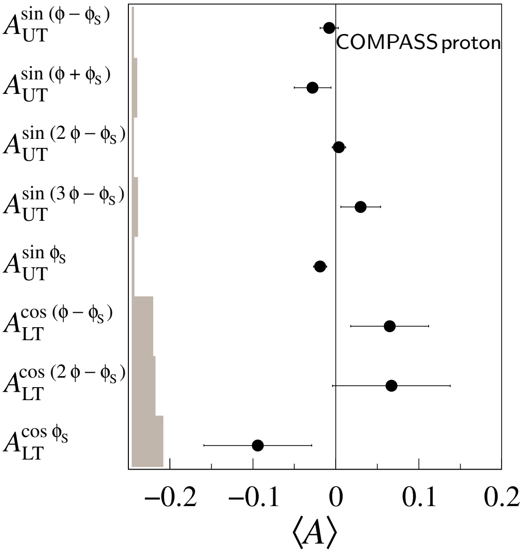
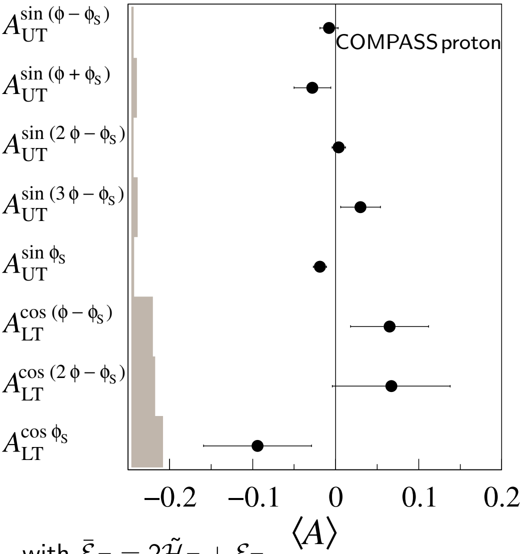
Mean asymmetries - NH_3 target



Phys.Lett. B731 (2014) 19-26

Mean asymmetries - NH_3 target

Goloskokov & Kroll
Eur.Phys.J. C74 (2014)



$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\mathcal{E}^*\mathcal{H})$

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

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

0

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

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

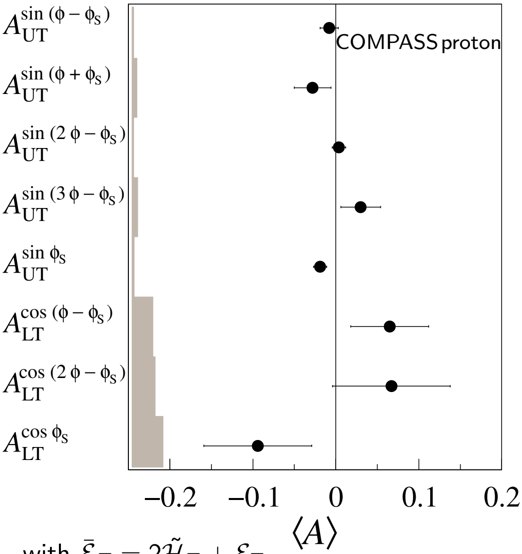
$A_{LT}^{cos(2\phi-\phi_S)} \propto \mathrm{Re}\,(\bar{\mathcal{E}}_T^*\mathcal{E})$

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

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

Mean asymmetries - NH_3 target

Goloskokov & Kroll
Eur.Phys.J. C74 (2014)



$A_{UT}^{sin(\phi-\phi_S)} \propto \mathrm{Im}\,(\mathcal{E}^*\mathcal{H})$

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

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

0

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

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

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

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

- Evidence for existence of H_T

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

GPDs vs. TMDs

$$\mathrm{GTMDs}(x, \xi, k_\perp, t)$$

$\Delta = 0 \;\Swarrow$ $\qquad\qquad$ $\Searrow\; \int dk_\perp^2$

$\mathrm{TMD}(x, k_\perp)$ $\qquad\qquad$ $\mathrm{GPD}(x, \xi, \Delta)$

Nucleon polarization (columns), Parton polarization (rows):

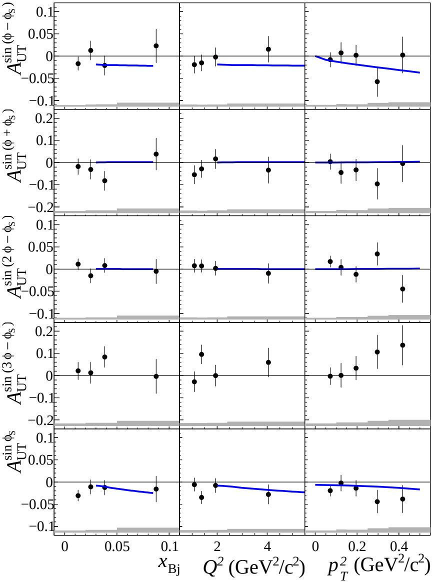
	U	T	L
U	f_1	$h_1^\perp$	
T	$f_{1T}^\perp$	$h_1, h_{1T}^\perp$	g_{1T}
L		$h_{1L}^\perp$	g_{1L}

Nucleon polarization (columns), Parton polarization (rows):

	U	T	L
U	H	E_T	
T	E	$H_T, \widetilde{H}_T$	$\widetilde{E}$
L		$\widetilde{E}_T$	$\widetilde{H}$

Transverse GPDs require an helicity flip between the emitted and reabsorbed quark

Comparison with a phenomenological GPD-based model

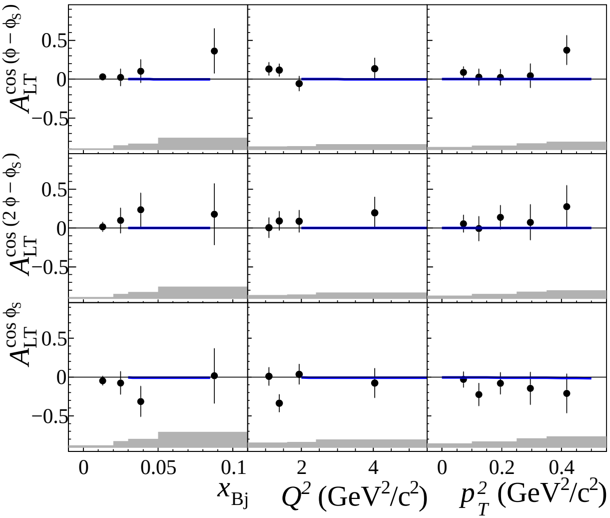


COMPASS proton

- 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^*

Phys.Lett. B731 (2014) 19-26

Comparison with a phenomenological GPD-based model



COMPASS proton

- 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

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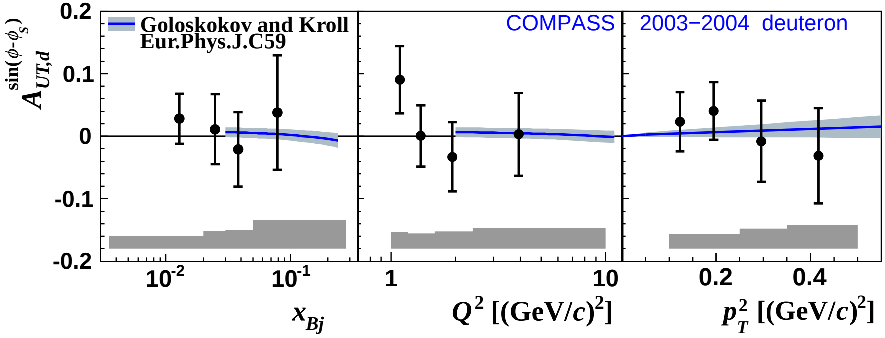
Asymmetry $A_{UT,d}^{sin(\phi-\phi_S)}$ - ^{6}LiD target (2003&2004)



- Contribution from GPDs E^u and E^d approx. cancel in exclusive ρ^0 production
- But this is different for exclusive ω production

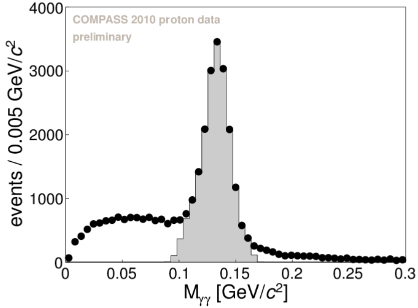
Nucl.Phys. B865 (2012) 1-20

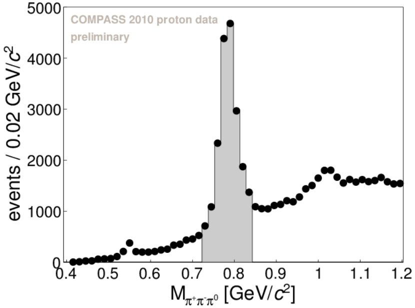
Exclusive ω production - event selection

$$\mu + N^{\uparrow} \rightarrow \mu' + N' + \omega$$
$$\hookrightarrow \pi^{+} + \pi^{-} + \pi^{0}$$
$$\hookrightarrow \gamma + \gamma$$

BR: 89%

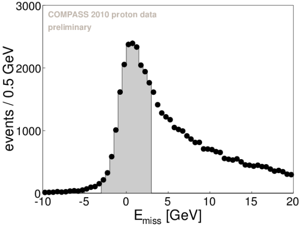
NH_3 target 2010





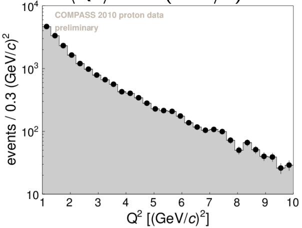
- Reconstruction of γ's with ECAL1&ECAL2
- Energy dependent cut on $M_{\gamma\gamma}$
- $|M_{\omega}^{PDG} - M_{\omega}^{recon}| < 3 \cdot 0.02 \mathrm{GeV}/c^2$

Exclusive ω production - event selection

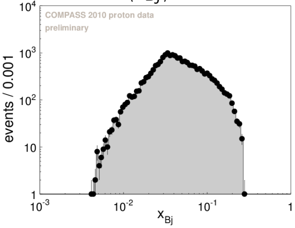


- Cut: $|E_{\text{miss}}| < 3$ GeV
- Comparable concept of semi-inclusive background correction as for ρ^0 analysis
- Total amount of SIDIS background: 34%

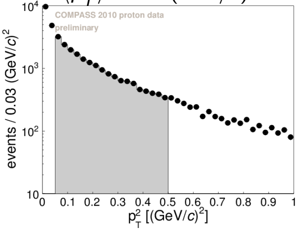
$\langle Q^2 \rangle \sim 2.4 (\text{GeV}/c)^2$



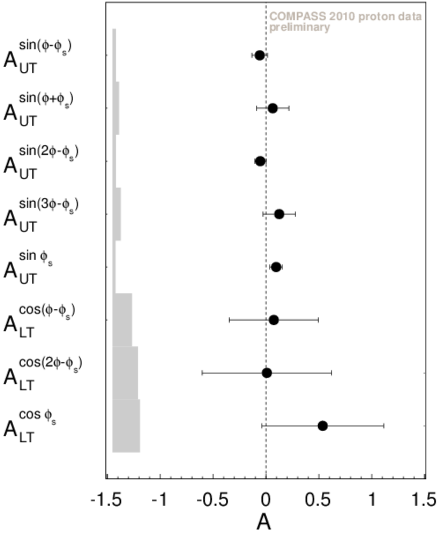
$\langle x_{Bj} \rangle \sim 0.06$



$\langle p_T^2 \rangle \sim 0.19 (\text{GeV}/c)^2$

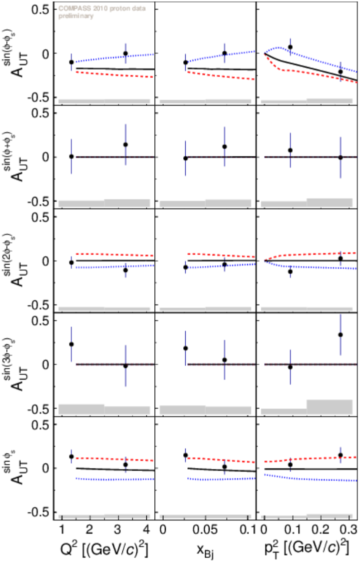


Mean asymmetries

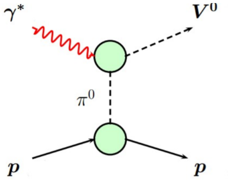


- Asymmetries are extracted using an unbinned maximum likelihood estimator
- Different weight for signal and background

Single-spin asymmetries



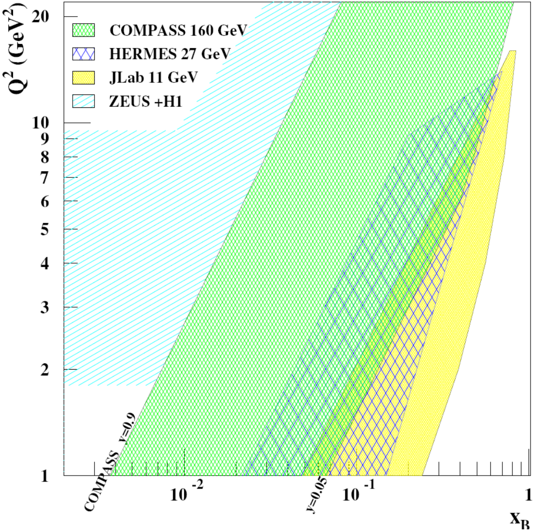
- are extracted with 2 bins in Q^2, x_{Bj} and p_T^2
- GK model predictions
  - positive $\pi\omega$ form factor
  - no pion pole
  - negative $\pi\omega$ form factor
- Contribution from pion pole is
  - small for ρ^0 production
  - sizable for ω production



Goloskokov & Kroll
Eur.Phys.J. A50 (2014) 9, 164
& private communication

DVCS at COMPASS-II

DVCS at COMPASS-II

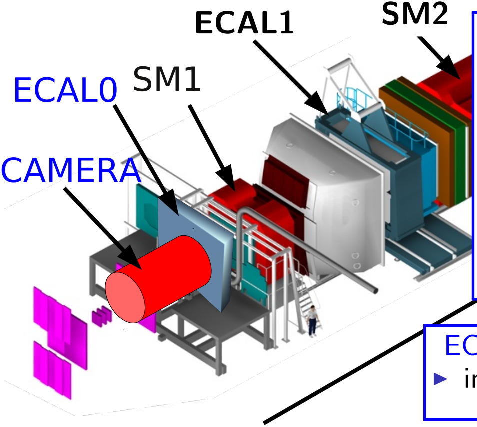


- μ^+ and μ^- beam with opposite polarization
- Momentum: 100-190 GeV/c
- Polarized beam: $\sim$ 80%
- Luminosity: $\mathcal{L} = 10^{32} cm^{-1} s^{-1}$
- Unpolarized target $\rightarrow$ sensitive to GPD H
- Coverage of intermediate x_{Bj}

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

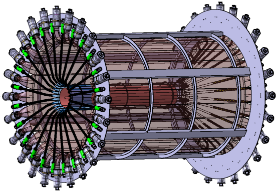
DVCS at COMPASS-II

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



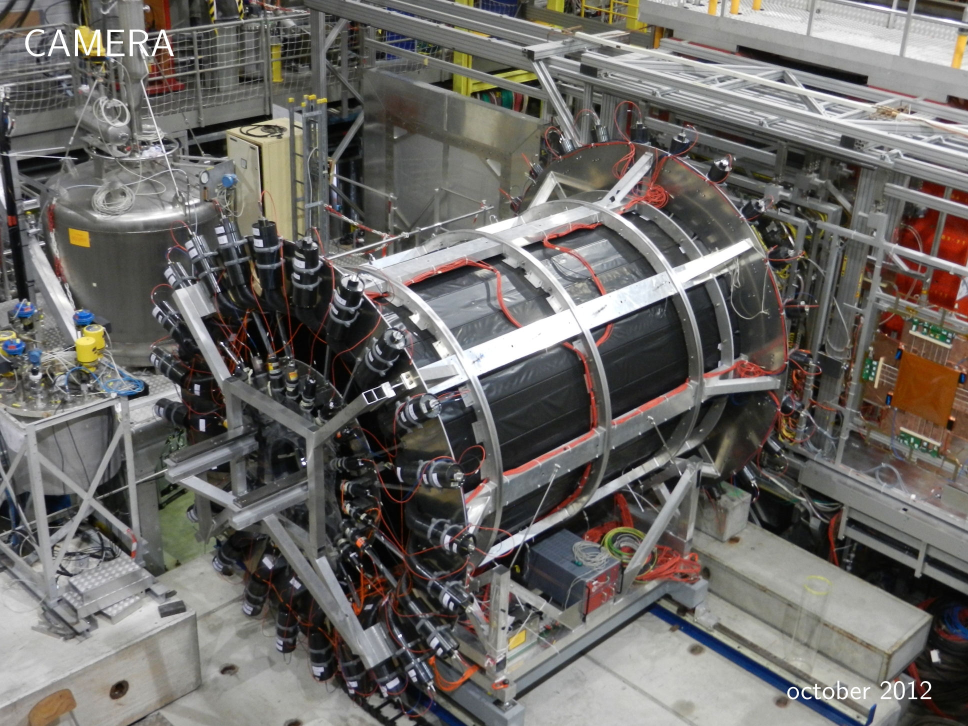
CAMERA

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



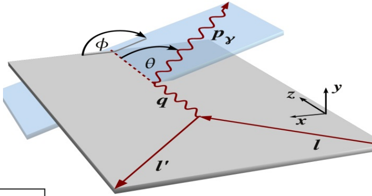
ECAL0

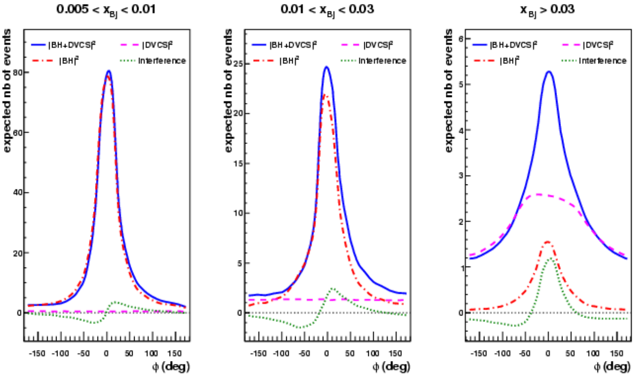
- increase domain in x_{Bj}

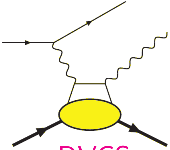

CAMERA
october 2012

DVCS and BH

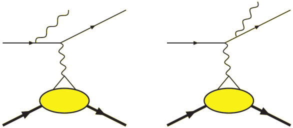
$d\sigma \propto |T^{BT}|^2 + |T^{DVCS}|^2 +$ interference term







DVCS



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

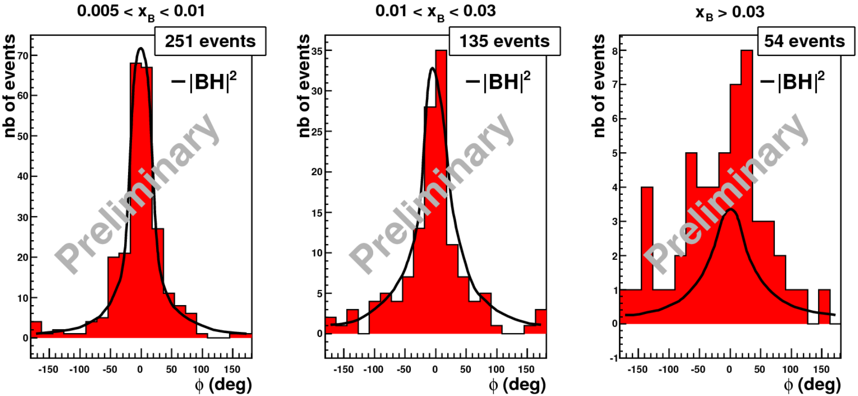
$0.01 < x_{Bj} < 0.03$
study interference

$x_{Bj} > 0.03$
DVCS dominates

Bethe-Heitler (BH)

Monte-Carlo Simulation for COMPASS only with ECAL1+2

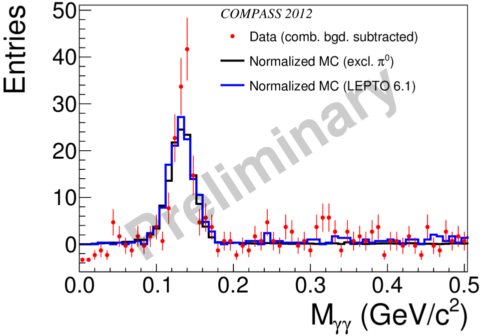
First measurements - pilot run 2009



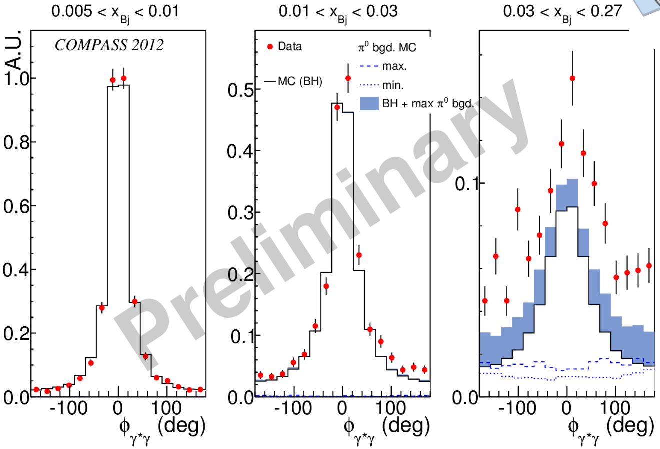
- 10 days data taking
- Shorter recoil proton detector and target length
- Global efficiency: $\epsilon_{\text{global}} \approx 0.13$
- $x_{Bj} > 0.03$: 54 events $\approx$ 20 BH + 34 (DVCS and γ from π^0)

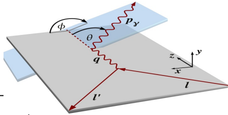
π^0 Background estimation

- Two possible cases:
  - visible: both γ detected
  - invisible: one γ lost $\rightarrow$ estimate with MC
- Consider limits (for the invisible part):
  - Fully semi-inclusive Background $\rightarrow$ estimate with LEPTO
  - Fully exclusive Background $\rightarrow$ HEPGEN/π^0 (GK model)
  - $\rightarrow$ Gives lower and upper limits
- LEPTO&HEPGEN/π^0 MC normalized to $M_{\gamma_{excl}\gamma_{bgd}}$ peak fom real data (visible π^0)



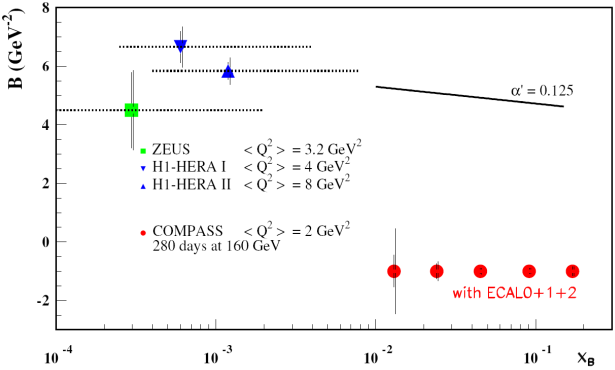
Measurement 2012

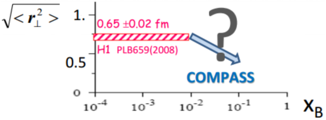




- 4 weeks data taking
- BH contribution is normalized to lowest x_{Bj} bin
- $x_{Bj} > 0.03$: 1268 events

Beam charge & spin sum - MC prediction





Ansatz at small x_{Bj}:

$B(x_{Bj}) = B_0 + 2\alpha' \ln(\frac{x_0}{x_{Bj}})$

$\alpha = 0.125$ GeV^{-2}

$B_0 = 5.83$GeV^{-2}, $x_0 = 0.0012$

→ inspired by HERA

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

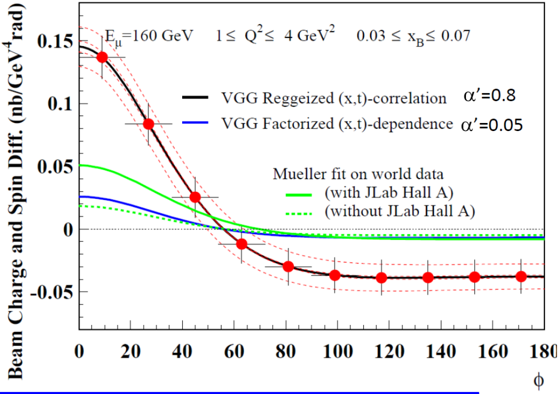
- BH subtraction and integration of $\phi \rightarrow d\sigma^{DVCS}_{unpol}$

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

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

H1 data
Phys. Lett. B659 (2008)
Eur. Phys. J. C44 (2005)
ZEUS data
JHEP 05 (2009)

Beam charge & spin difference - MC prediction

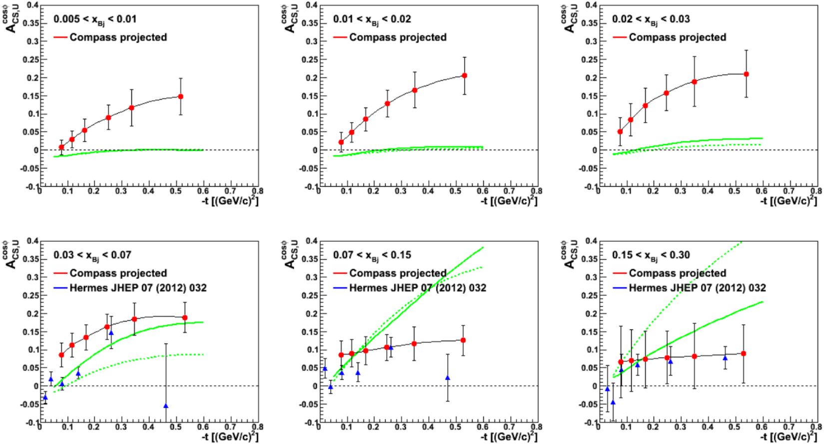


$$D_{CS,U} = d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\leftarrow}) \propto c_0^{Int} + c_1^{Int} cos\phi$$

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

VGG model
Phys. Rev. D60 (1999) 09401
Mueller fit
Nucl.Phys. B841 (2010) 1-58

Beam charge & spin asymmetry - MC prediction

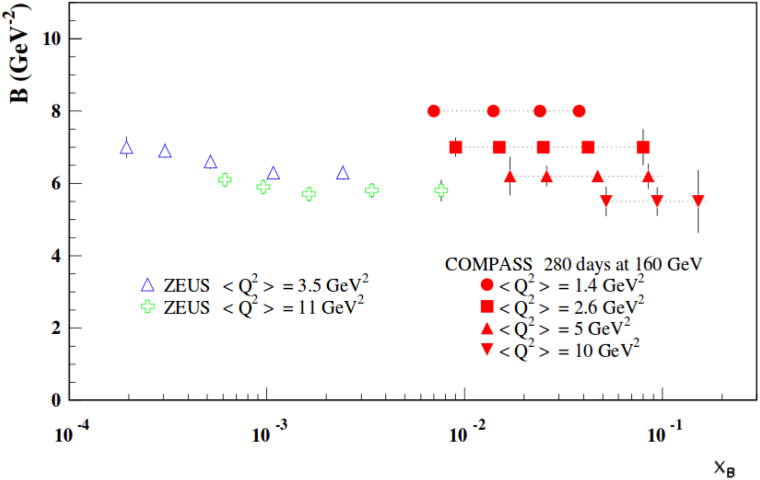


Predictions from VGG and D.Mueller

$$A_{CS,U}^{cos\phi} \text{ related to } c_1^{Int} \sim \mathrm{Re}\,\mathcal{H}$$

VGG model
Phys. Rev. D60 (1999) 09401
Mueller fit
Nucl.Phys. B841 (2010) 1-58

Exclusive ρ^0 production - MC prediction



- Sensitiv to nucleon transverse size + meson transverse size
- Ongoing analysis on 2012 data: DVCS, ρ^0, π^0

ZEUS data
PMC Phys. A1 (2007)

Summary - HEMP

- Exclusive ρ^0 production in high energy muon scattering off transversely polarized protons and deuterons was studied
- Exclusive ω production in high energy muon scattering off transversely polarized protons was studied
- Results for 5 transverse target single-spin asymmetries $A_{\mathrm{UT,p}}$ and 3 transverse target double-spin asymmetries $A_{\mathrm{LT,p}}$ for transversely polarized protons were presented
- Most of the modulations are small, consistent with 0 within experimental uncertainties
- Sensitiv to:
  - GPD $E \rightarrow$ orbital angular momentum
  - GPD $H_T \rightarrow$ transversity
- Future: exclusive ϕ, J/ψ, ...

Summary & outlook - DVCS

- Unique: frequent change of beam charge and polarization
- Dominant BH process visible at small x_{Bj}
- Excess over BH+background observed at large x_{Bj}
- Analysis for 2012 ongoing: DVCS, ρ^0, π^0

- Future: study nucleon transversal dimension as a function of x_{Bj} and $D_{CS,U}$, $S_{CS,U}$
- Next DVCS measurement 2016 and 2017

- Long-term future:
  DVCS & HEMP with transversely polarized target and recoil detector (γ, ρ^0, ω, ϕ, J/ψ, ...)

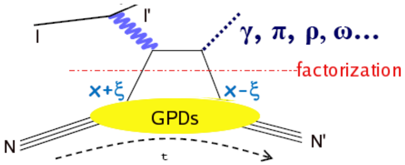
BACKUP

Generalized parton distributions - basic facts

- Factorisation in hard and soft part
- Soft part can be parametrized 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

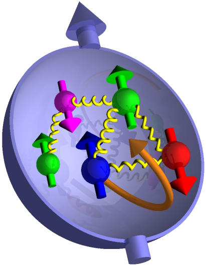
l + N → l' + N' + M (HEMP)
or
l + N → l' + N' + γ (DVCS)



M = ρ^0,ω,ϕ,π, ...

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

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

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