Hard exclusive meson production at COMPASS

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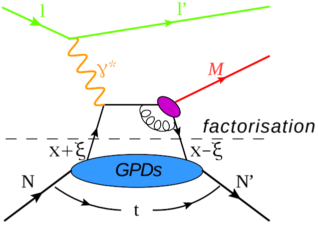
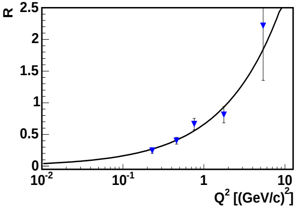
COMPASS
Großgeräte der physikalischen Grundlagenforschung

Outline

GPDs and hard exclusive meson production

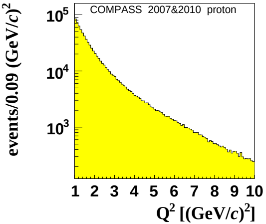


- factorization into a hard and a soft part - only valid for a long. polarized γ^*

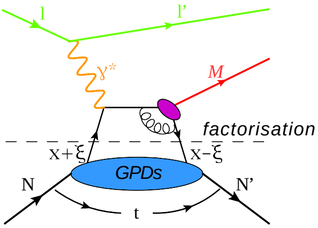


EPJ C52 (2007)

Ratio $R = \sigma_L/\sigma_T > 1$, for $Q^2 > 2\,(\mathrm{GeV}/c)^2$



GPDs and hard exclusive meson production



- factorization into a hard and a soft part
  - only valid for a long. polarized γ^*
- 4 chiral-even GPD: $H^{q,g}$, $\tilde{H}^{q,g}$, $E^{q,g}$, $\tilde{E}^{q,g}$
  (parton helicity is unchanged)
- 4 chiral-odd GPD: H_T^q, $\tilde{H}_T^q$, E_T^q, $\tilde{E}_T^q$
  (quark helicity is flipped)
- HEMP as 'flavor filter':

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

$$E_\omega = \frac{1}{\sqrt{2}}(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{8}E^g)$$

$$E_\phi = -\frac{1}{3}E^s - \frac{1}{8}E^g$$

gluons contribute at the same order of α_s as quarks

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

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

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

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

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

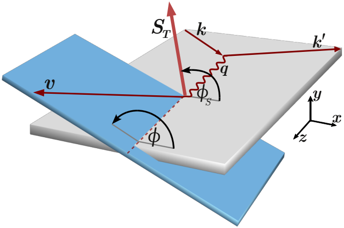
$$-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\Big]$$

σ_{mn}^{ij} = spin − dependent photoabsorption cross sections

m, n = virtual − photon helicity $(-, 0, +)$

i, j = target nucleon helicity $(-, +)$

ε = virtual photon polarization parameter (ratio of long. transv. photon − flux) enters in prefactors (Depolarization factor)



HEMP cross section (trans. pol. target) Diehl, Sapeta EPJ C41 (2005)

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

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

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

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

$$+S_TP_\ell\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}$$

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

unpolarized cross section : $\sigma_0=\sigma_T+\varepsilon\sigma_L$

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

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

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

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

unpolarized cross section : $\sigma_0=\sigma_T+\varepsilon\sigma_L$

Unpolarized beam + **T**ransv. polarized target : 5 sine modulations

HEMP cross section (trans. pol. target) Diehl, Sapeta EPJ C41 (2005)

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

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

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

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

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

unpolarized cross section : $\sigma_0 = \sigma_T + \varepsilon\sigma_L$

8 orthogonal modulations of ϕ and ϕ_S :

Unpolarized beam + **T**ransv. polarized target : 5 sine modulations

Long. polarized beam + **T**ransv. pol. target : 3 cosine modulations

HEMP cross section (trans. pol. target)

Unpolarized beam + Transv. polarized target:

$$A_{UT}^{\sin(\phi-\phi_S)} = -\frac{\mathrm{Im}\,(\sigma_{++}^{+-} + \varepsilon\sigma_{00}^{+-})}{\sigma_0} \propto \mathrm{Im}\,(\mathcal{E}_{LL}^{*}\mathcal{H}_{LL} - \mathcal{E}_{TT}^{*}\mathcal{H}_{TT} + \frac{1}{2}\mathcal{H}_{T,LT}^{*}\overline{\mathcal{E}}_{T,LT}),$$

$$A_{UT}^{\sin(\phi+\phi_S)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{+-}}{\sigma_0} \propto \mathrm{Im}\,(\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{H}_{T,LT}),$$

$$A_{UT}^{\sin(3\phi-\phi_S)} = -\frac{\mathrm{Im}\,\sigma_{+-}^{-+}}{\sigma_0} = 0,$$

$$A_{UT}^{\sin\phi_S} = -\frac{\mathrm{Im}\,\sigma_{+0}^{+-}}{\sigma_0} \propto \mathrm{Im}\,(\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}),$$

$$A_{UT}^{\sin(2\phi-\phi_S)} = -\frac{\mathrm{Im}\,\sigma_{+0}^{-+}}{\sigma_0} \propto \mathrm{Im}\,(\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}),$$

Long. polarized beam+Transv. pol. target:

$$A_{LT}^{\cos(\phi-\phi_S)} = -\frac{\mathrm{Re}\,\sigma_{++}^{+-}}{\sigma_0} \propto \mathrm{Re}\,(\mathcal{H}_{T,LT}^{*}\overline{\mathcal{E}}_{T,LT}),$$

$$A_{LT}^{\cos\phi_S} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0} \propto \mathrm{Re}\,(\mathcal{H}_{T,LT}^{*}\mathcal{H}_{LL} - \overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}),$$

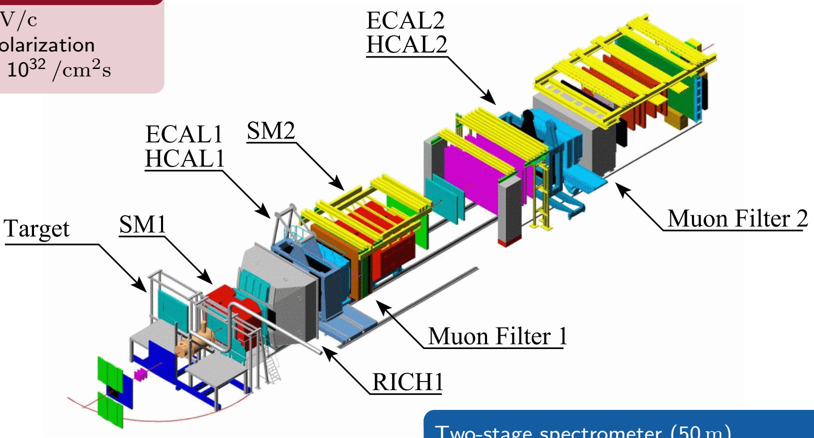
$$A_{LT}^{\cos(2\phi-\phi_S)} = -\frac{\mathrm{Re}\,\sigma_{+0}^{-+}}{\sigma_0} \propto \mathrm{Re}\,(\overline{\mathcal{E}}_{T,LT}^{*}\mathcal{E}_{LL}),$$

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

COMPASS-Experiment at CERN

μ^+-Beam from SPS:

160 GeV/c
80 % polarization
$\mathcal{L} \sim 5 \cdot 10^{32}$ /cm^{2}s



Two-stage spectrometer (50 m)

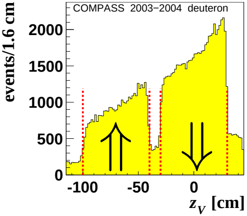
large angular & momentum acceptance
variety of tracking detectors
transversely polarized solid-state target

Asymmetries from exclusive ρ^0 production

Two periods of data taking using different kinds of transversely polarized targets:

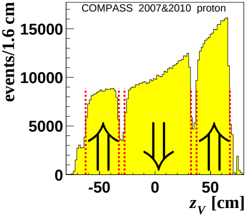
2003+2004: ^{6}LiD target (polarized deuterons)

dilution factor $\langle f \rangle \sim 0.45$
polarization $\langle P_T \rangle \sim 0.5$



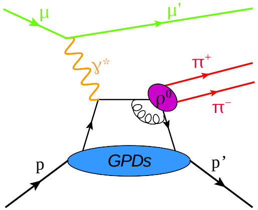
2007+2010: NH_3 target (polarized protons)

dilution factor $\langle f \rangle \sim 0.25$
polarization $\langle P_T \rangle \sim 0.8$



In both cases the target polarization was inverted once a week

Asymmetries from exclusive ρ^0 production



$$\mu + p \rightarrow \mu' + p' + \rho^0$$
$$\hookrightarrow \pi^+ + \pi^-$$

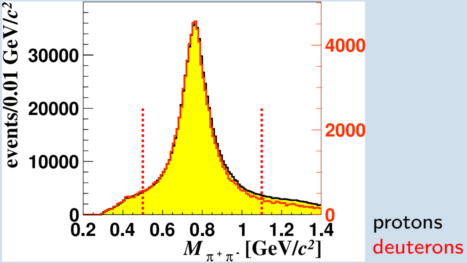
Kinematic cuts

$1\,(\mathrm{GeV}/c)^2 < Q^2 < 10\,(\mathrm{GeV}/c)^2$
$W > 5\,\mathrm{GeV}$
$0.1 < y < 0.9$
$0.003 < x_{Bj} < 0.35$

Specific cuts

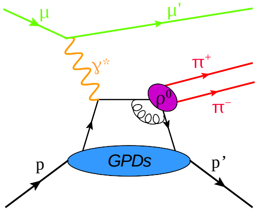
$E_{\rho^0} > 15\,\mathrm{GeV}$

ρ^0 meson is reconstructed from two hadron tracks with opposite charge and assuming the pion mass



$0.5\,\mathrm{GeV}/c^2 < M_{\pi^+\pi^-} < 1.1\,\mathrm{GeV}/c^2$

Asymmetries from exclusive ρ^0 production



$$\mu + p \rightarrow \mu' + p' + \rho^0$$
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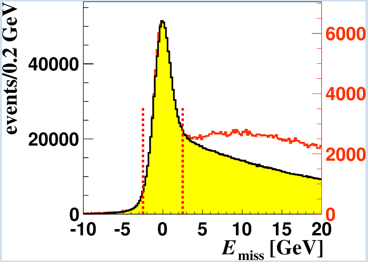
$W > 5\,\mathrm{GeV}$
$0.1 < y < 0.9$
$0.003 < x_{Bj} < 0.35$

Specific cuts

$E_{\rho^0} > 15\,\mathrm{GeV}$
$0.5\,\mathrm{GeV}/c^2 < M_{\rho^0} < 1.1\,\mathrm{GeV}/c^2$

Proton is not detected:
$E_{miss} = 0$ is a signature for exclusivity

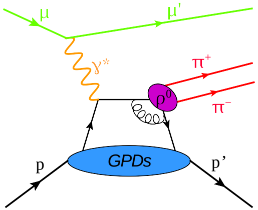
$$E_{miss} = \frac{M_X - M_P}{2 \cdot M_P}$$



protons
deuterons

$|E_{miss}| < 2.5\,\mathrm{GeV}$

Asymmetries from exclusive ρ^0 production



$$\mu + p \rightarrow \mu' + p' + \rho^0$$
$$\hookrightarrow \pi^+ + \pi^-$$

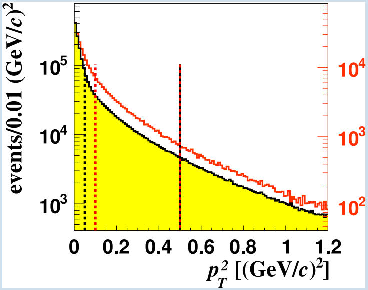
Kinematic cuts

$1\,(\mathrm{GeV}/c)^2 < Q^2 < 10\,(\mathrm{GeV}/c)^2$
$W > 5\,\mathrm{GeV}$
$0.1 < y < 0.9$
$0.003 < x_{Bj} < 0.35$

Specific cuts

$E_{\rho^0} > 15\,\mathrm{GeV}$
$0.5\,\mathrm{GeV}/c^2 < M_{\rho^0} < 1.1\,\mathrm{GeV}/c^2$
$|E_{miss}| < 2.5\,\mathrm{GeV}$

Further background suppression: p_T^2 of the ρ^0 with respect to the γ^*



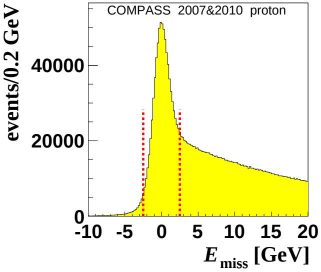
protons
deuterons

$p_T^2 > 0.05\,(\mathrm{GeV}/c)^2$ $\quad 0.1\,(\mathrm{GeV}/c)^2$
suppresses contribution of coherent events
$p_T^2 < 0.5\,(\mathrm{GeV}/c)^2$
removes non-exclusive background

Asymmetries from exclusive ρ^0 production

Asymmetry extraction method - proton data

- 8 asymmetries are calculated in parallel using a 2D max LH fit
- calculations are based on four 2-dim (ϕ, ϕ_S) matrices (different target cells (U+D, C) and target polarizations (↑↓↑, ↑↓↑))
- done for various number of kinematic bins: 4 x_{Bj}-bins, 4 Q^2-bins, 5 p_T^2-bins



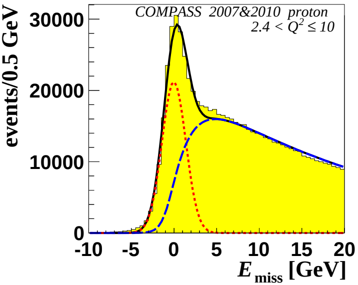
- mean background amount in signal region ~ 22 %
- Background subtraction necessary

Asymmetries from exclusive ρ^0 production

Background rejection with Monte Carlo

- LEPTO MC (COMPASS tuning) for SIDIS background
- MC weighting based on comparison RD/MC for wrong charge combination sample (h^+h^+, h^-h^-):

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



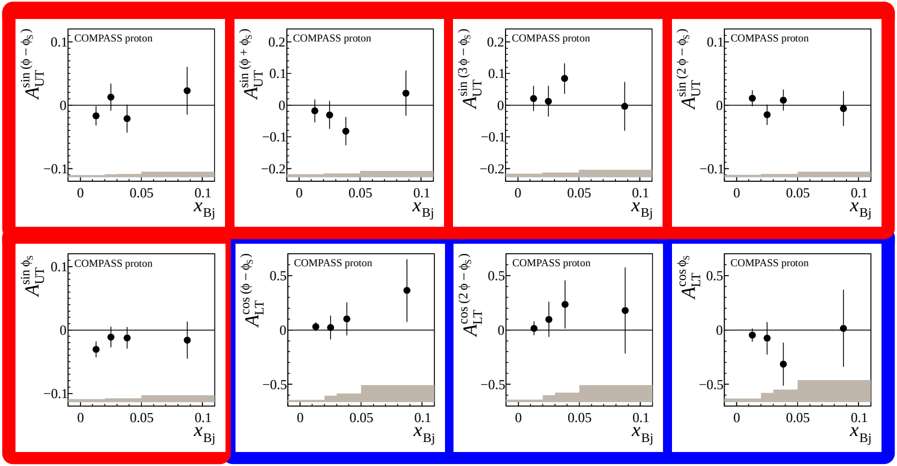
Two component fit of E_{miss} shape

- signal (Gaussian shape)+background (parametrized from weighted MC)
- $(\phi, \phi_S)_{bg}$ from SIDIS region ($7\,\mathrm{GeV} < E_{miss} < 20\,\mathrm{GeV}$)
- $(\phi, \phi_S)_{sig}$ corrected by $(\phi, \phi_S)_{bg}$, scaled with amount of background in signal region
- done for each kinematic bin, target cell and polarization separately

Asymmetries from exclusive ρ^0 production

NEW COMPASS RESULTS

x_{Bj}-dependent A_{UT} and A_{LT} for 2007&2010 data with NH_3 target

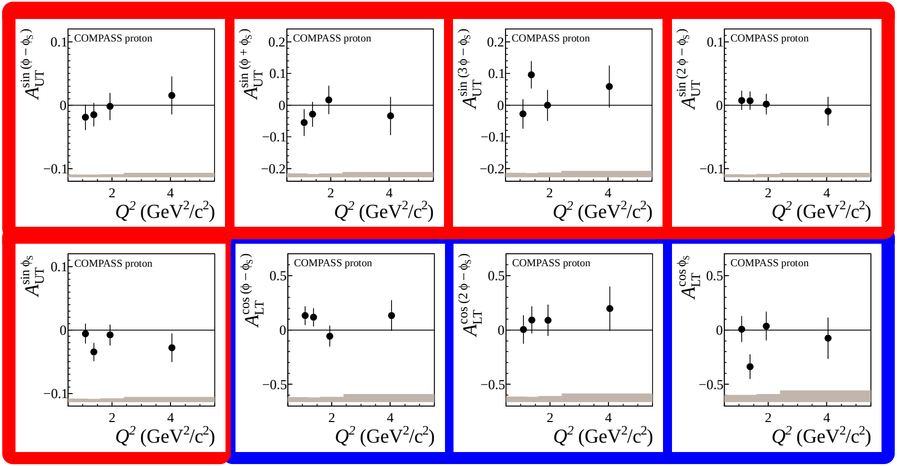


Phys. Letter B731 (2014)

Asymmetries from exclusive ρ^0 production

NEW COMPASS RESULTS

Q^2-dependent A_{UT} and A_{LT} for 2007&2010 data with NH_3 target

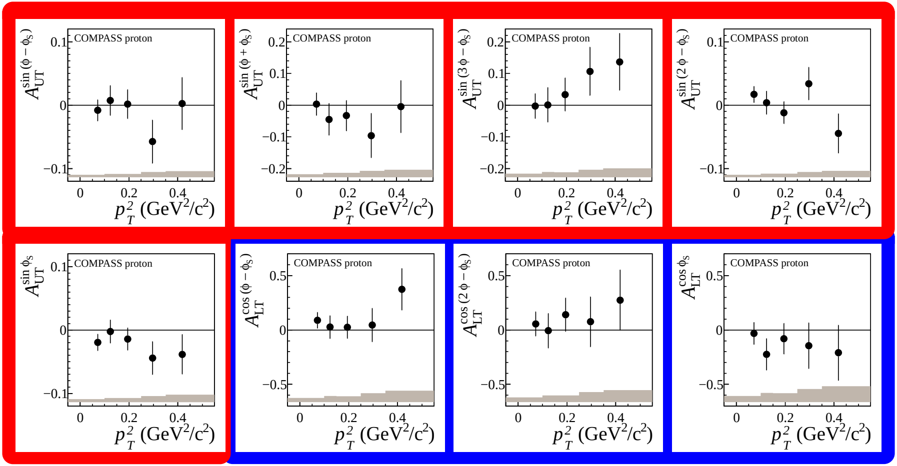


Phys. Letter B731 (2014)

Asymmetries from exclusive ρ^0 production

NEW COMPASS RESULTS

p_T^2-dependent A_{UT} and A_{LT} for 2007&2010 data with NH_3 target



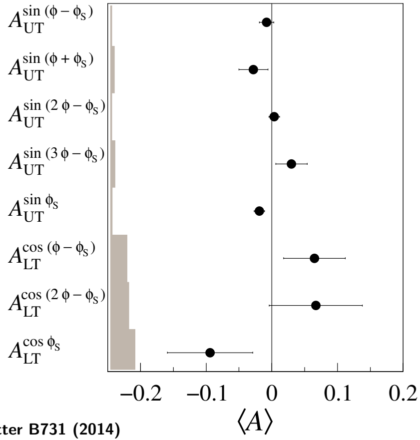
Phys. Letter B731 (2014)

Asymmetries from exclusive ρ^0 production

Physikalisches Institut
Albert-Ludwigs-Universität Freiburg

Mean asymmetries extracted for entire kinematic range (protons)

- most asymmetries compatible with 0
- $A_{UT}^{\sin(\phi_S)} = -0.019 \pm 0.008 \pm 0.003 \rightarrow$ indicates $H_T \neq 0$



$\propto \mathrm{Im}\,(\mathcal{E}^*_{LL}\mathcal{H}_{LL} - \mathcal{E}^*_{TT}\mathcal{H}_{TT} + \frac{1}{2}\mathcal{H}^*_{T,LT}\overline{\mathcal{E}}_{T,LT})$

$\propto \mathrm{Im}\,(\overline{\mathcal{E}}^*_{T,LT}\mathcal{H}_{T,LT})$

$\propto \mathrm{Im}\,(\overline{\mathcal{E}}^*_{T,LT}\mathcal{E}_{LL})$

$= 0$

$\propto \mathrm{Im}\,(\mathcal{H}^*_{T,LT}\mathcal{H}_{LL} - \overline{\mathcal{E}}^*_{T,LT}\mathcal{E}_{LL})$

$\propto \mathrm{Re}\,(\mathcal{H}^*_{T,LT}\overline{\mathcal{E}}_{T,LT})$

$\propto \mathrm{Re}\,(\overline{\mathcal{E}}^*_{T,LT}\mathcal{E}_{LL})$

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

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

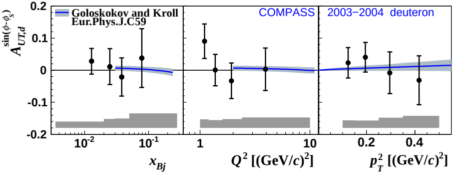
Phys. Letter B731 (2014)

Asymmetries from exclusive ρ^0 production

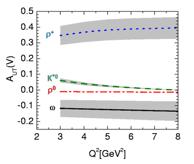
COMPASS results on $A_{UT}^{\sin(\phi-\phi_S)}$ for 2003&2004 data with ^{6}LiD target (deuterons) compared to predictions of the GPD model from Goloskokov/Kroll

- limited statistic
- only $A_{UT}^{\sin(\Phi-\Phi_S)}$ extracted using 1D max LH fit
- background subtraction similar to 2D method

Nuclear Phys. B865 (2012)



GPD model from Goloskokov/Kroll



COMPASS kinematic:
$W = 8.1$ GeV
$Q^2 = 2.2\,(\mathrm{GeV}/c)^2$
$p_T^2 = 0.2\,(\mathrm{GeV}/c)^2$

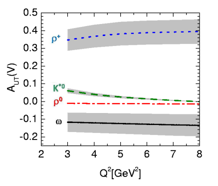
Goloskokov, Kroll EPJ C53 (2008)

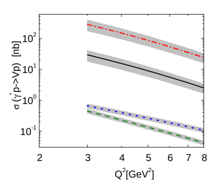
- phenomenological 'handbag model'
- contains γ_L^* and γ_T^*

- Results for $A_{UT}^{\sin(\phi-\phi_S)}$ are compatible with 0(as predicted)
- deuterons: first and unique measurements by COMPASS

Outlook - exclusive ω analysis

- sizable asymmetries predicted for exclusive ω production:





Goloskokov, Kroll EPJ C53 (2008)

- $\sigma_\omega \sim \frac{1}{40}\sigma_{\rho^0}$
- decay channel: $\omega \to \pi^+\pi^-\pi^0 \to \pi^+\pi^-\gamma\gamma$
  - good ECAL performance with time measurement essential
  - only proton data from 2010 available!

$\to \sim 1\,\%$ of statistic expected

- no kinematic binning
- 2D max LH fit susceptible for low statistic!

Outlook - exclusive ω analysis

New extraction method: weighted unbinned max LH

- the 8 asymmetries are extracted simultaneously to the background asymmetries
- events are weighted individually with the appropriate signal-to-background ratio, depending on E_{miss}
- correction factors are calculated for each event and enter the fit directly

Advantages of the weighted unbinned max LH

- more stable at low statistic, statistical error reduced by 20 %
- kinematic dependence of the dilution factor considered more precisely

Summary & Outlook

Summary

- protons: transverse target spin asymmetries were measured at COMPASS
  8 (5 single spin + 3 double spin)
- deuterons: leading order single spin asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ was measured
- the asymmetries are mostly compatible with 0
- $A_{UT}^{\sin(\phi_S)} = -0.019 \pm 0.008 \pm 0.003 \rightarrow$ evidence for $H_T \neq 0$

Outlook

- theory predicts sizable asymmetries for ω production
- analysis on exclusive ω in progress
  - only proton data from 2010 available
    $\rightarrow \sim 1\,\%$ of statistic expected $\rightarrow$ no kinematic binning
- new fit method
  - reduced statistical and systematical errors