Exclusive meson production at COMPASS

Paweł Sznajder

National Centre for Nuclear Research, Warsaw

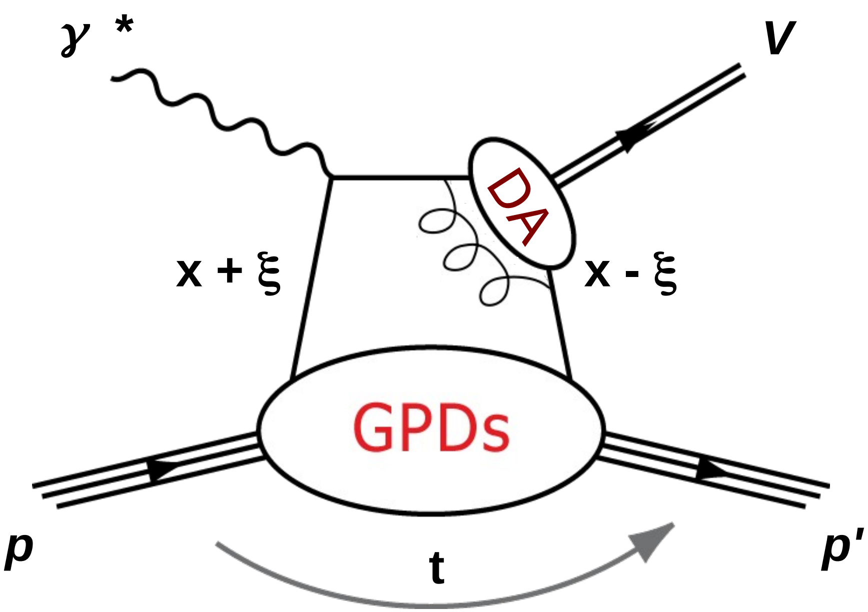
on behalf of the COMPASS Collaboration

XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects
Dallas, 27 April – 1 May 2015

Outline

- Introduction
- COMPASS experiment
- Transverse target spin asymmetries for incoherent exclusive ρ^0 and ω production
- Projections for COMPASS-II
- Summary and outlook

***H**ard **E**xclusive **M**eson **P**roduction*
$\gamma^* p \rightarrow V\ p'$



large Q^2 and W, $-t/Q^2 << 1$

factorization strictly proven only for longitudinal γ^*

Chiral-even GPDs
helicity of parton unchanged

$$H^{q,g}(x,\xi,t) \quad E^{q,g}(x,\xi,t)$$
$$\widetilde{H}^{q,g}(x,\xi,t) \quad \widetilde{E}^{q,g}(x,\xi,t)$$

Chiral-odd GPDs
helicity of parton changed (not probed by DVCS)

$$H_T^q(x,\xi,t) \quad E_T^q(x,\xi,t)$$
$$\widetilde{H}_T^q(x,\xi,t) \quad \widetilde{E}_T^q(x,\xi,t)$$

Flavour separation for GPDs
example:

$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{8}E^g\right)$$

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

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

- *contribution from gluons at the same order of α_s as from quarks*

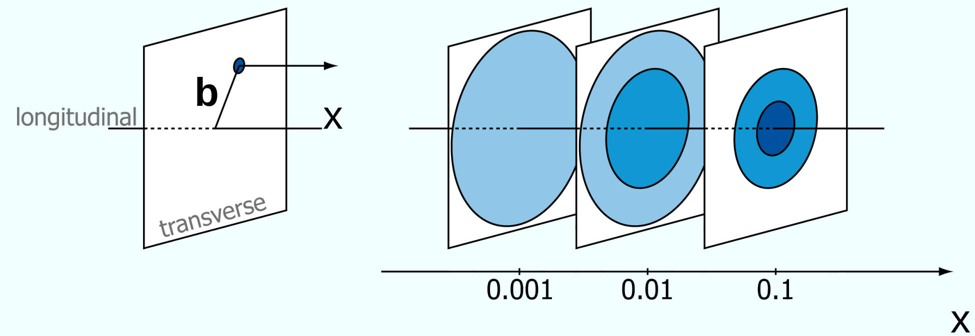
Nucleon tomography:

3D parton distribution function:

$$q(x, \boldsymbol{b}) = (2\pi)^{-2} \int d^2\boldsymbol{\Delta}\, e^{-i\boldsymbol{b}\cdot\boldsymbol{\Delta}} H^q(x, 0, t = -\boldsymbol{\Delta}^2)$$

where:

$\boldsymbol{b}$: impact parameter



Ji's sum rule (access to total angular momentum):

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

Transversity:

$$H_T^q(x, 0, 0) = h_1^q(x)$$

Cross section formula for exclusive meson production

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_S}$$

$$= \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

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

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

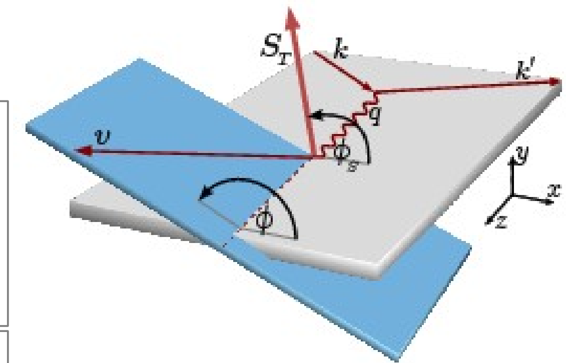
$$+S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

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

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

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

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



σ_{mn}^{ij}: helicity-dependent photoabsorption cross sections and interference terms

$$\sigma_{mn}^{ij}\left(x_B, Q^2, t\right) \propto \sum \left(M_m^i\right)^* M_n^j$$

M_m^i: amplitude for subprocess $\gamma^* p \rightarrow V\ p'$ with photon helicity *m* and target proton helicity *i*

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

$$\gamma = 2x_{Bj}M_P/Q$$

Access to GPDs through exclusive meson production

5 transverse target spin asymmetries and 3 transverse target double spin asymmetries

$$A_{UT}^{\sin(\varphi-\varphi_s)} = -\frac{\mathrm{Im}\left(\sigma_{++}^{+-}+\epsilon\,\sigma_{00}^{+-}\right)}{\sigma_0}$$

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

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

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

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

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

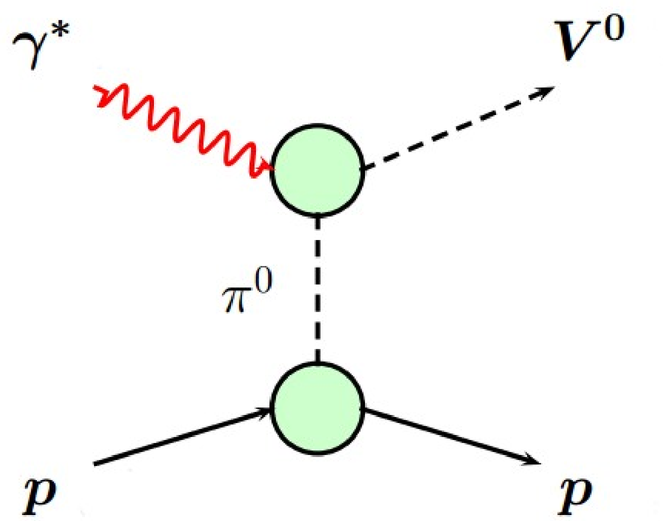
$$A_{LT}^{\cos\varphi_s} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0}$$

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

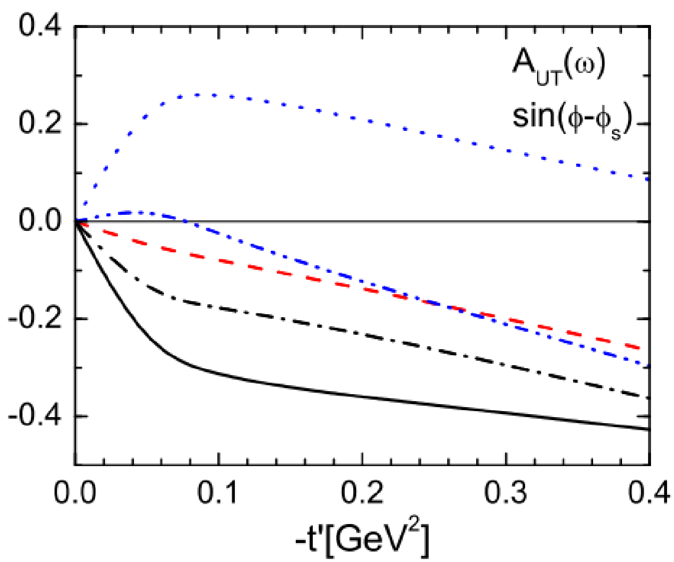
unpolarised cross section

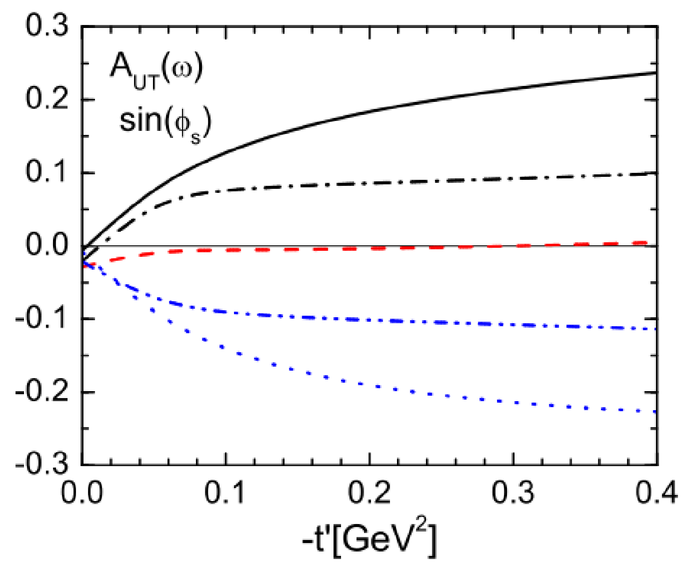
$$\sigma_0 = \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\epsilon\,\sigma_{00}^{++}=\sigma_L+\epsilon\,\sigma_T$$

Pion pole



- Effect known since early photoproduction experiments
- At COMPASS kinematics:
  - small for ρ^0 production
  - sizable for ω production
- Unnatural parity exchange process
  → impact on helicity-dependent observables
- Crucial for description of SDMEs for excl. ω production
  → Goloskokov and Kroll, Eur. Phys. J. A50 (2014) 9, 146
- Sign of $\pi\omega$ form factor not resolved from SDMEs data
  → azimuthal asymmetries more sensitive





@ W=4.8 GeV, Q^2=2.42 GeV^2

- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

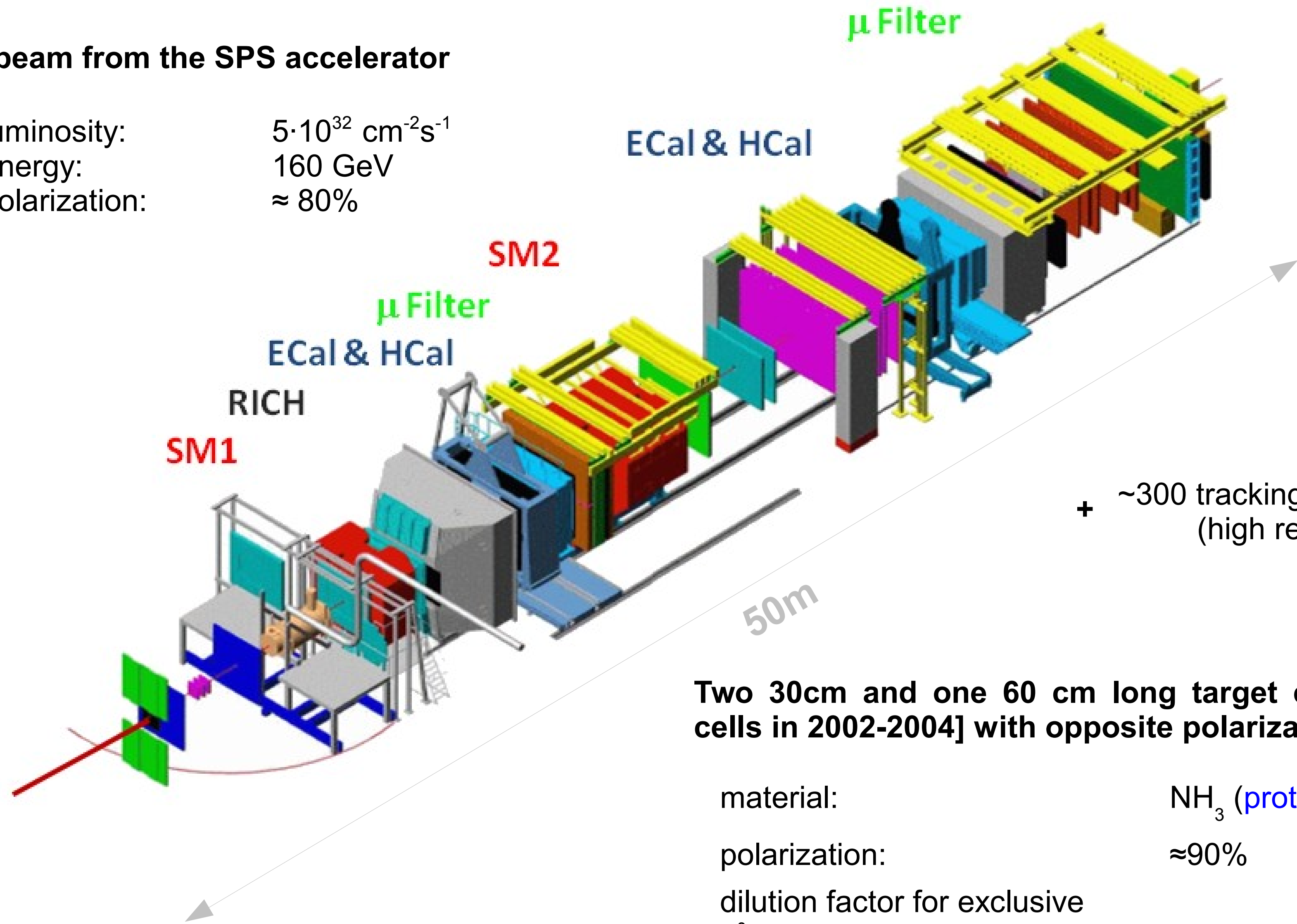
@ W=8 GeV, Q^2=2.42 GeV^2

- positive $\pi\omega$ form factor
- negative $\pi\omega$ form factor

COMPASS experiment at CERN – setup with transversely polarized target

μ^+ beam from the SPS accelerator

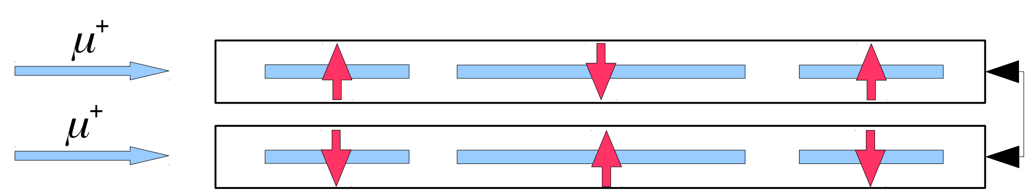
luminosity:	$5 \cdot 10^{32}$ cm^{-2}s^{-1}
energy:	160 GeV
polarization:	≈ 80%



+ ~300 tracking detector planes (high redundancy)

Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

material:	NH_3 (protons)	[^{6}LiD (deuterons)]
polarization:	≈90%	[≈50%]
dilution factor for exclusive ρ^0 production:	≈25%	[≈44%]



Microwave reversal every week

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Used data:

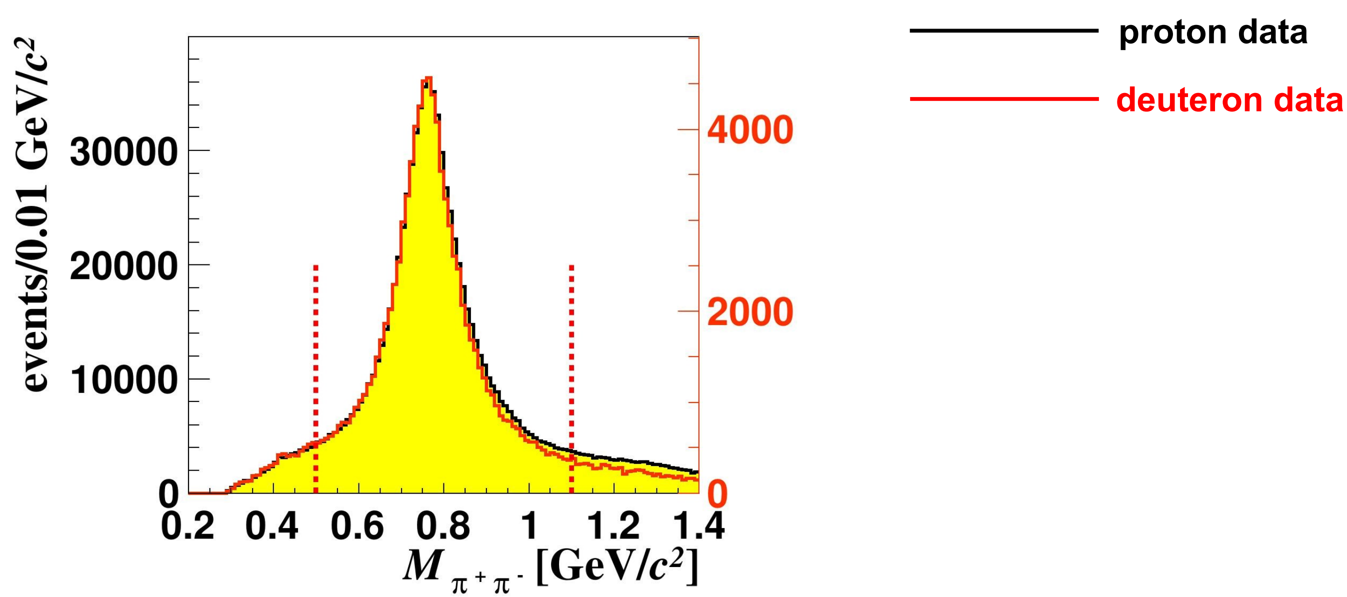
2007, 2010 (transversely polarised protons)

2003, 2004 (transversely polarised deuterons)

$$\mu N \rightarrow \mu N \rho^0, \quad \rho^0 \rightarrow \pi^+ + \pi^-$$

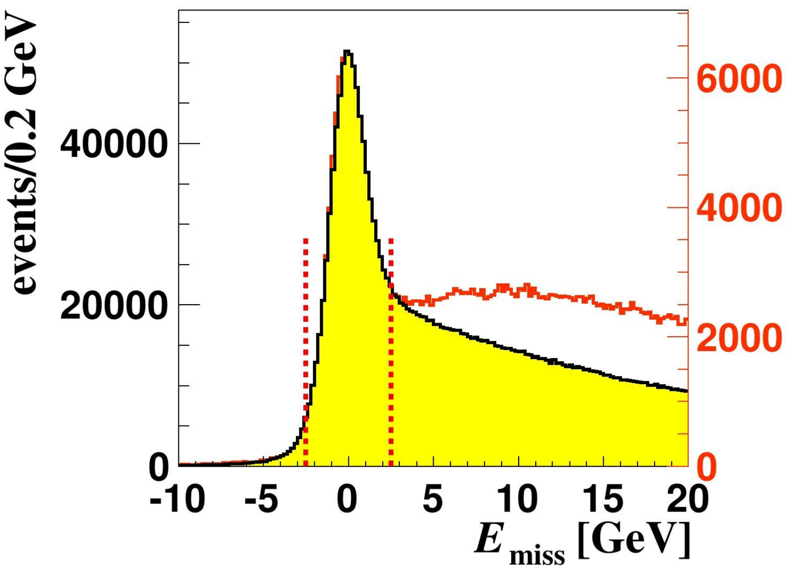
Topology of vertex:

only incoming and outgoing muon tracks
only two hadron tracks of opposite charges



Kinematics domain:

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



Missing energy and energy of ρ^0 candidate

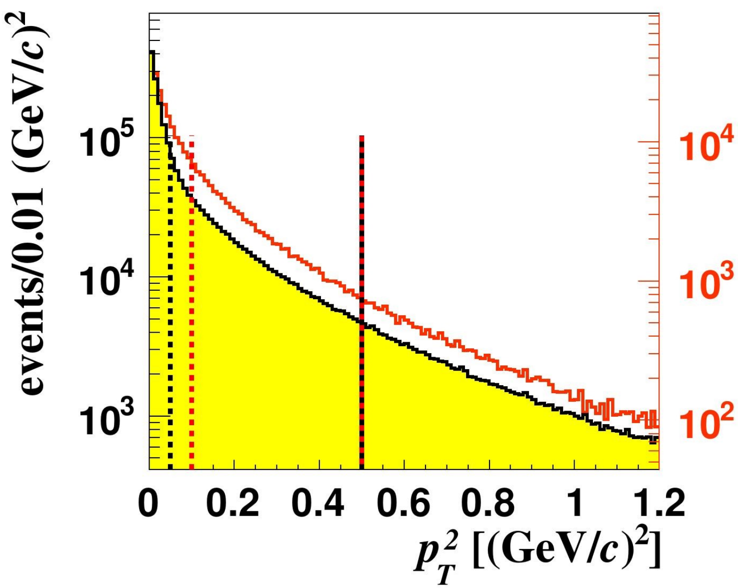
- Check if the proton is intact

$$E_{miss} = \frac{M_x^2 - M_p^2}{2M_p} \in (-2.5,\ 2.5)\ GeV$$

$E_{miss} = 0$ is the signature of exclusivity

- Check if $E_{\rho^0} > \nu_{min}$ (minimal energy of γ^* allowed by the kinematic cuts)

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



Squared transverse momentum of ρ^0 candidate w.r.t. γ^*

To remove coherent production off target nuclei

$0.05 < p_T^2\ (GeV/c)^2$ *for protons*

$0.1 < p_T^2\ (GeV/c)^2$ *for deuterons*

To suppress non-exclusive background

$$p_T^2 < 0.5\ (GeV/c)^2$$

Transverse target spin asymmetry for incoherent exclusive ω production

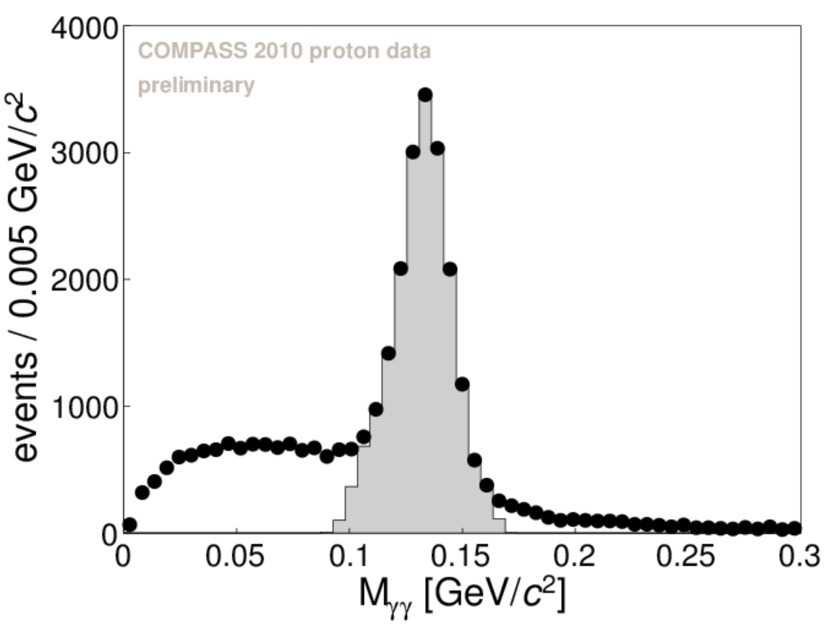
Used data:

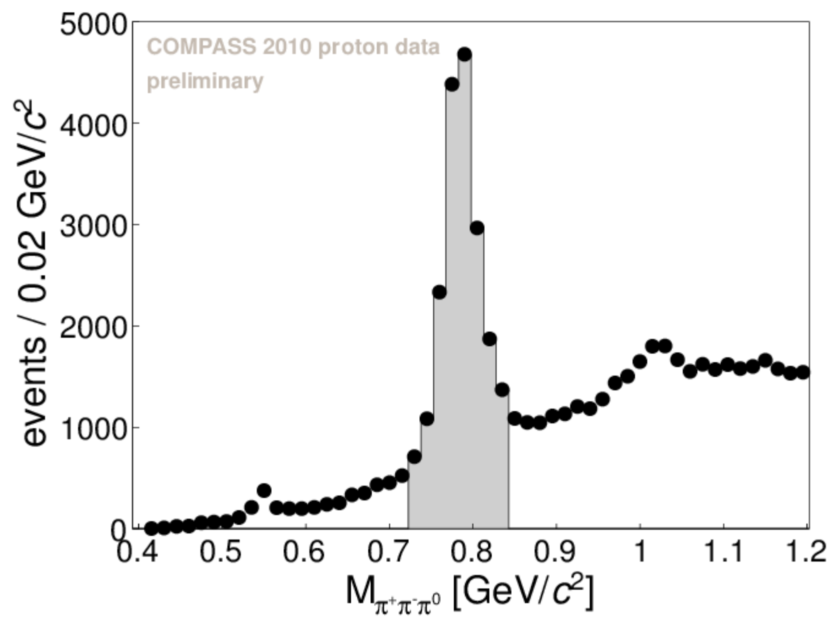
2010 (transversely polarised protons)

$$\mu N \rightarrow \mu N \omega$$
$$\omega \rightarrow \pi^{+} + \pi^{-} + \pi^{0}, \quad \pi^{0} \rightarrow \gamma + \gamma$$

Topology of vertex:

only incoming and outgoing muon tracks
only two hadron tracks of opposite charges
only two clusters in ECALs timely correlated with vertex and not associated to any charged particle

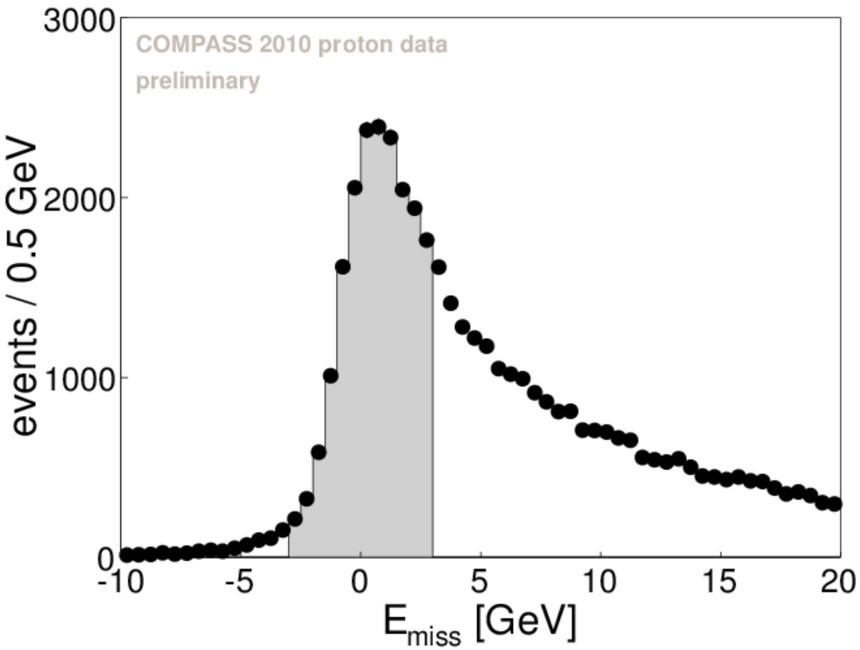




Kinematics domain:

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

Transverse target spin asymmetry for incoherent exclusive ω production



Missing energy and energy of ω candidate

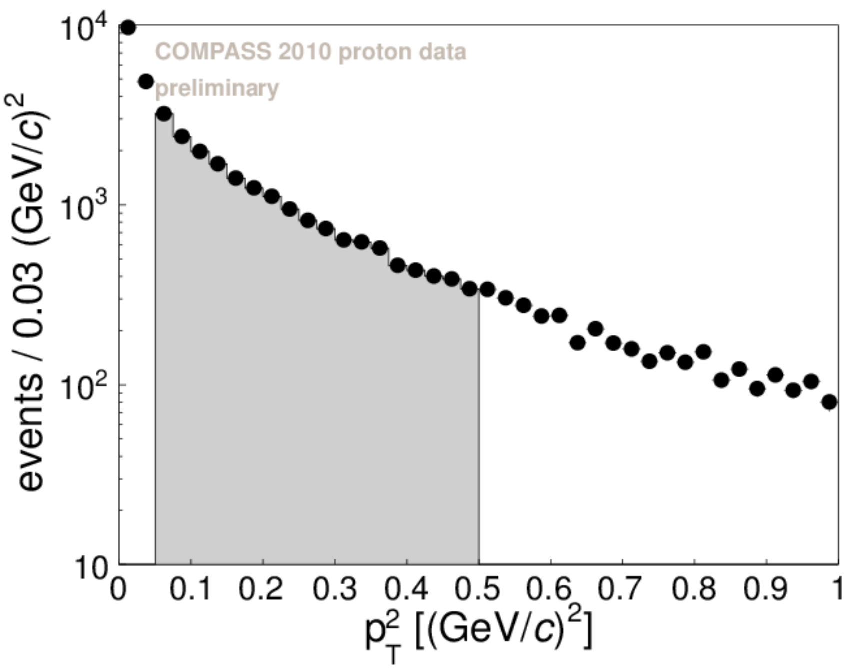
- Check if the proton is intact

$$E_{miss} = \frac{M_x^2 - M_p^2}{2M_p} \in (-3, 3)\ GeV$$

$E_{miss} = 0$ is the signature of exclusivity

- Check if Eω > ν_{min} (minimal energy of γ* allowed by the kinematic cuts)

$$E_{\omega} > 15\,GeV$$



Squared transverse momentum of ω candidate w.r.t. γ*

To remove coherent production off target nuclei

$$0.05 < p_T^2\ (GeV/c)^2$$

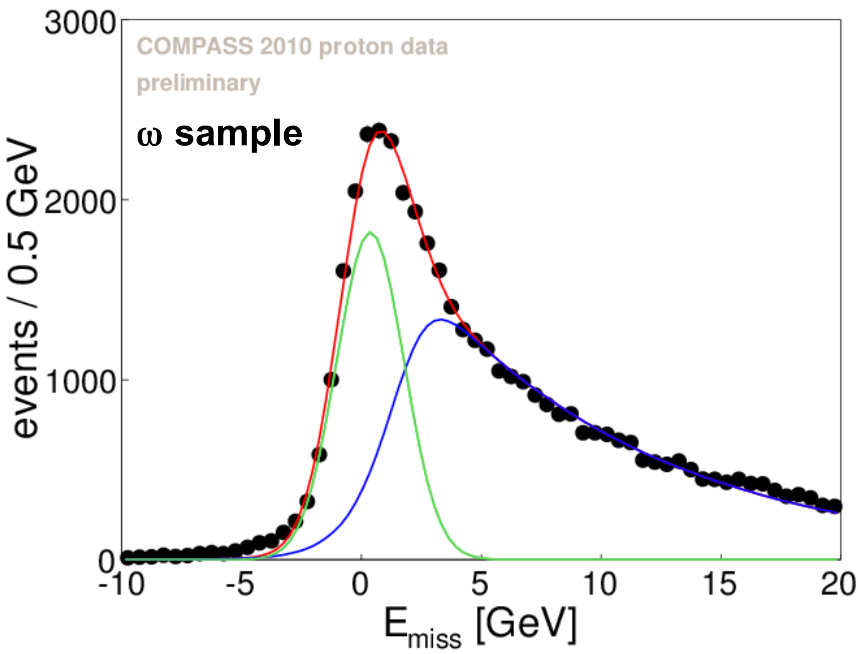
To suppress non-exclusive background

$$p_T^2 < 0.5\ (GeV/c)^2$$

Extraction of asymmetries

- ρ^0 analysis
  - 1D (deuteron) and 2D (proton) binned maximum likelihood estimator with subtraction of background in (φ, φ_S) bins
- ω analysis
  - Unbinned maximum likelihood estimator with simultaneous fit of signal and background asymmetries

Background rejection:
For each target cell and polarization state



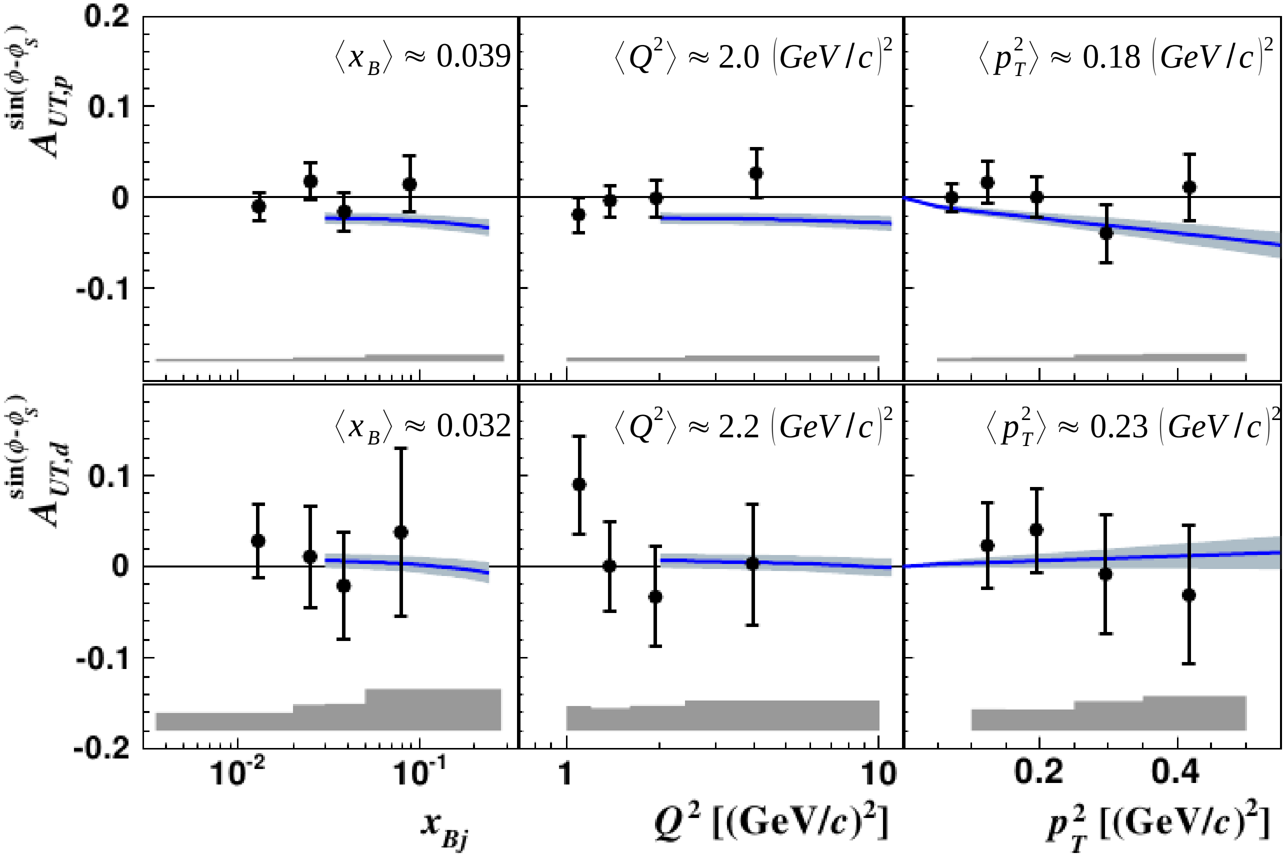
shape of semi-inclusive background from MC
(LEPTO with COMPASS tuning + simulation of spectrometer response + reconstruction as for real data)

MC weighted using ratio between real data and MC for wrong charge combination sample ($h^+h^+\gamma\gamma$ + $h^-h^-\gamma\gamma$)

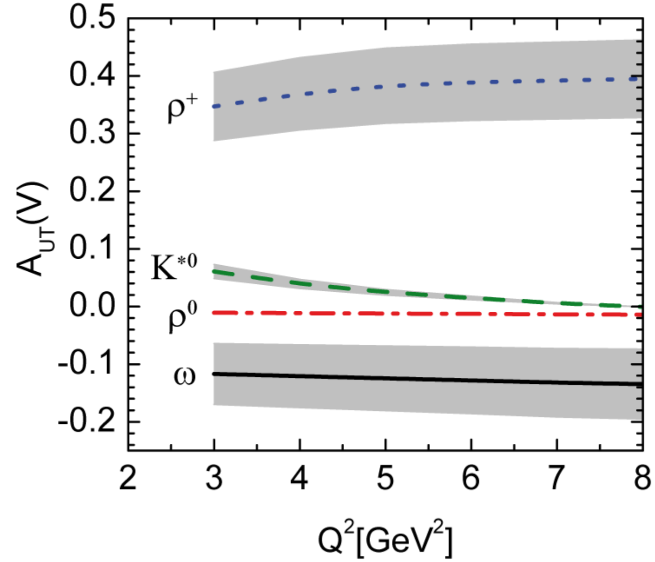
$$w(E_{miss}) = \frac{N_{RD}^{h+h+\gamma\gamma}(E_{miss}) + N_{RD}^{h-h-\gamma\gamma}(E_{miss})}{N_{MC}^{h+h+\gamma\gamma}(E_{miss}) + N_{MC}^{h-h-\gamma\gamma}(E_{miss})}$$

Normalization of MC to the real data using two component fit
Gaussian function (signal) + shape from MC (bkg)

COMPASS results
(*NPB 865 (2012) 1*)



Goloskokov and Kroll
(*EPJC 59 (2009) 809*)

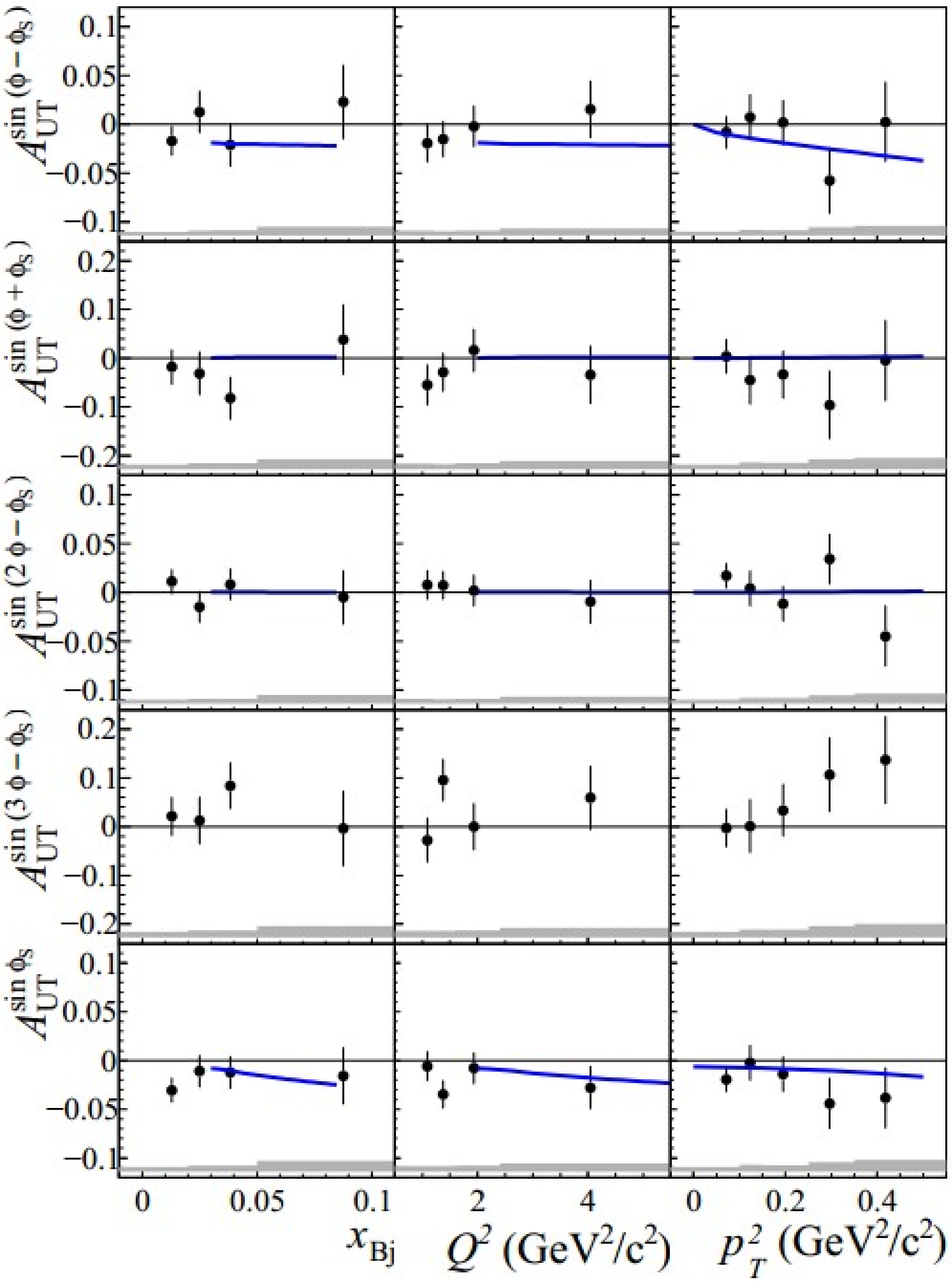


- "handbag model"
- GPDs constrained by CTEQ6 parametrization and nucleon form factors
- power corrections due to transverse quarks momenta
- predictions both for γ^*_L and γ^*_T

- $A_{UT}^{\sin(\varphi-\varphi s)}$ for transversely polarised protons and deuterons small
- for proton data in agreement with HERMES results
  COMPASS results with statistical errors improved by factor 3 and extended kinematic range
- for deuteron data the first measurement
- reasonable agreement with predictions of the GPD model of Goloskokov - Kroll

Transverse target spin asymmetry for incoherent exclusive ρ⁰ production

Single spin asymmetries



→ **PLB 731 (2014) 19**

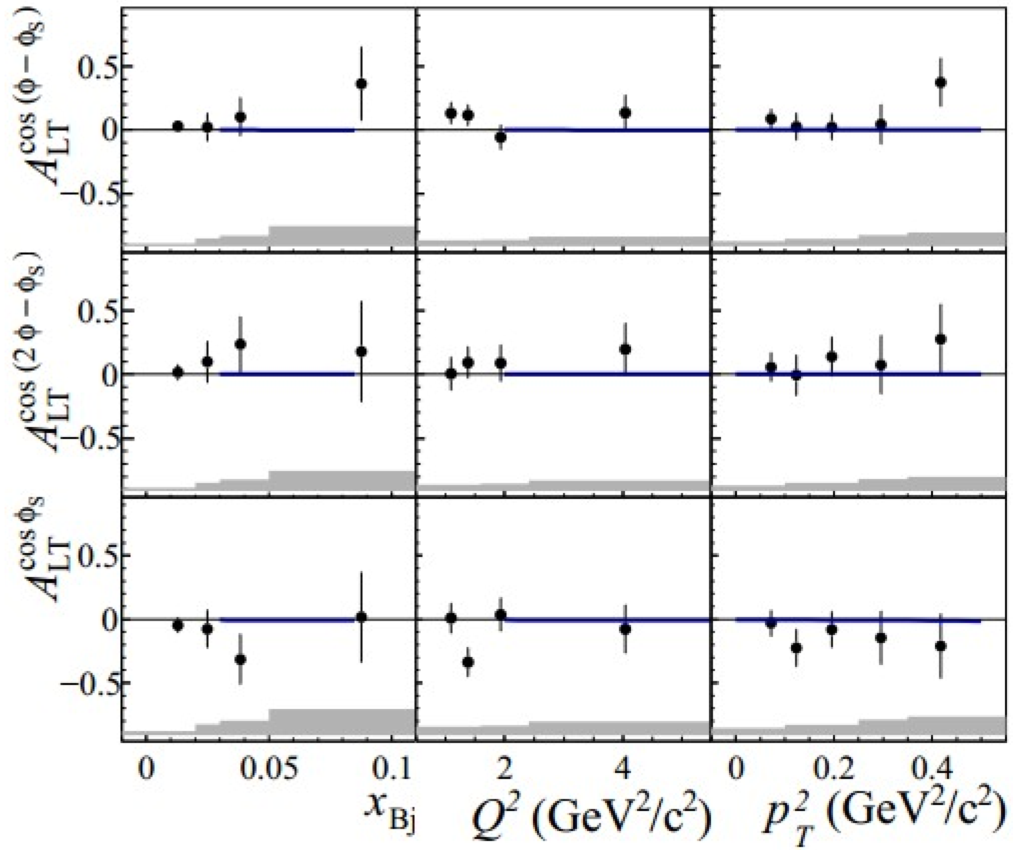
- Improved method of extraction (2D)
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0\ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18\ (GeV/c)^2$

Double spin asymmetries



→ **PLB 731 (2014) 19**

- Improved method of extraction (2D)
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

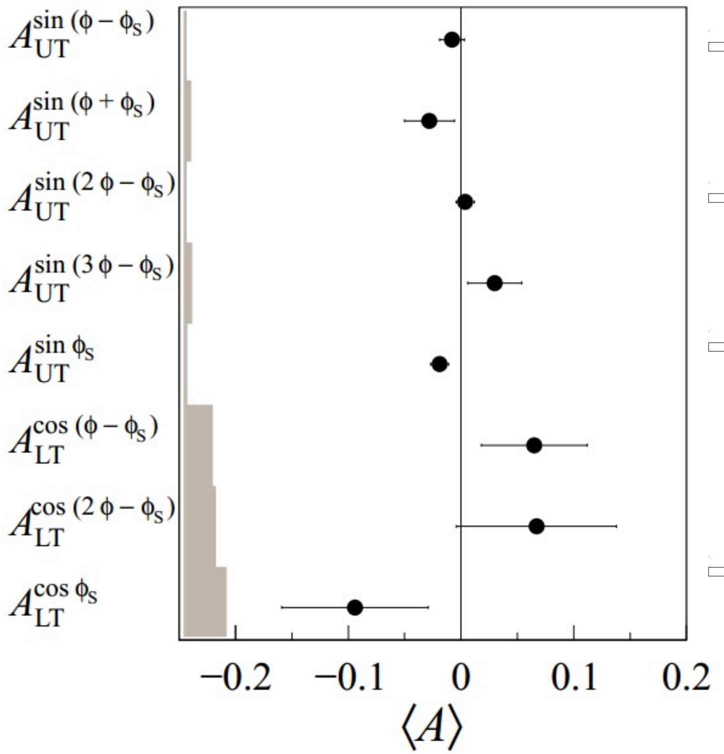
$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0\ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18\ (GeV/c)^2$

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

- All asymmetries small and compatible with predictions of GK model
- $A_{UT}^{\sin\varphi_S} = -0.019 \pm 0.008 \pm 0.003$
- Indication of H_T contribution → relation with transitivity at forward limit: $H_T(x, 0, 0) = h_1(x)$



$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0\ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18\ (GeV/c)^2$

$$A_{UT}^{\sin(\varphi-\varphi_S)}\sigma_0 = -2\,Im[\epsilon M^*_{0-,0+} M_{0+,0+} + M^*_{+-,++} M_{++,++} + \frac{1}{2} M^*_{0-,++} M_{0+,++}]$$

(~E, ~H, ~E, ~H, ~H_T, ~$\bar{E}_T$)

$$A_{UT}^{\sin(2\varphi-\varphi_S)}\sigma_0 = -Im[M^*_{0+,++} M_{0-,0+}]$$

(~$\bar{E}_T$, ~E)

$\bar{E}_T = 2\tilde{H}_T - E_T$

$$A_{UT}^{\sin\varphi_S}\sigma_0 = -Im[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

(~H_T, ~H, ~$\bar{E}_T$, ~E)

$$A_{LT}^{\cos\varphi_S}\sigma_0 = -Re[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

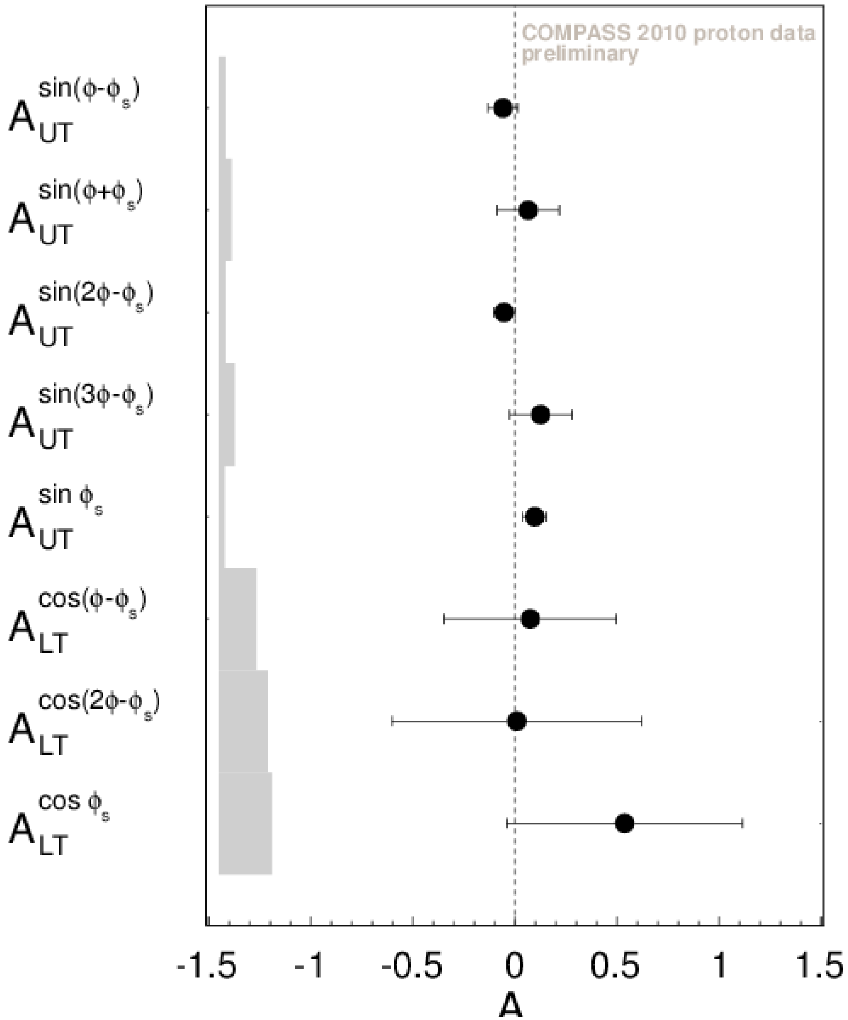
(~H_T, ~H, ~$\bar{E}_T$, ~E)

Helicity amplitudes:

$M_{V p', \gamma^* p}$

- V: meson helicity
- p': recoiled proton helicity
- γ^*: virtual photon helicity
- p: initial proton helicity

Transverse target spin asymmetry for incoherent exclusive ω production

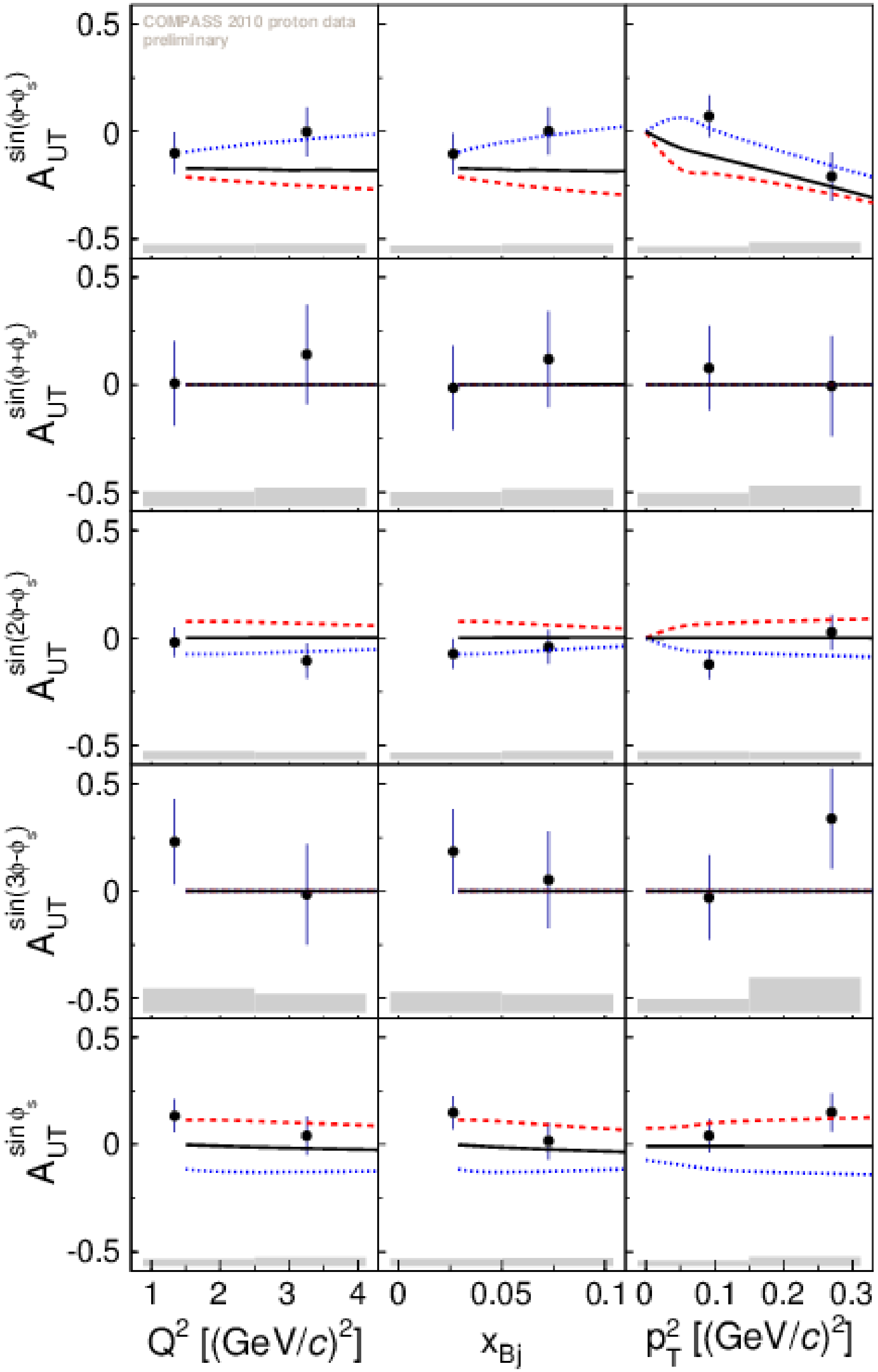


Q^2=2.2 GeV^2
x_{Bj} =0.049
p_T^2 = 0.17 GeV^2
W=7.1 GeV

New result → to be published

- Unbinned maximum likelihood method
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

Transverse target spin asymmetry for incoherent exclusive ω production



New result → to be published

GK model predictions
private communication

- positive πω form factor
- no pion pole
- negative πω form factor

Study of exclusive meson production will be continued at COMPASS-II

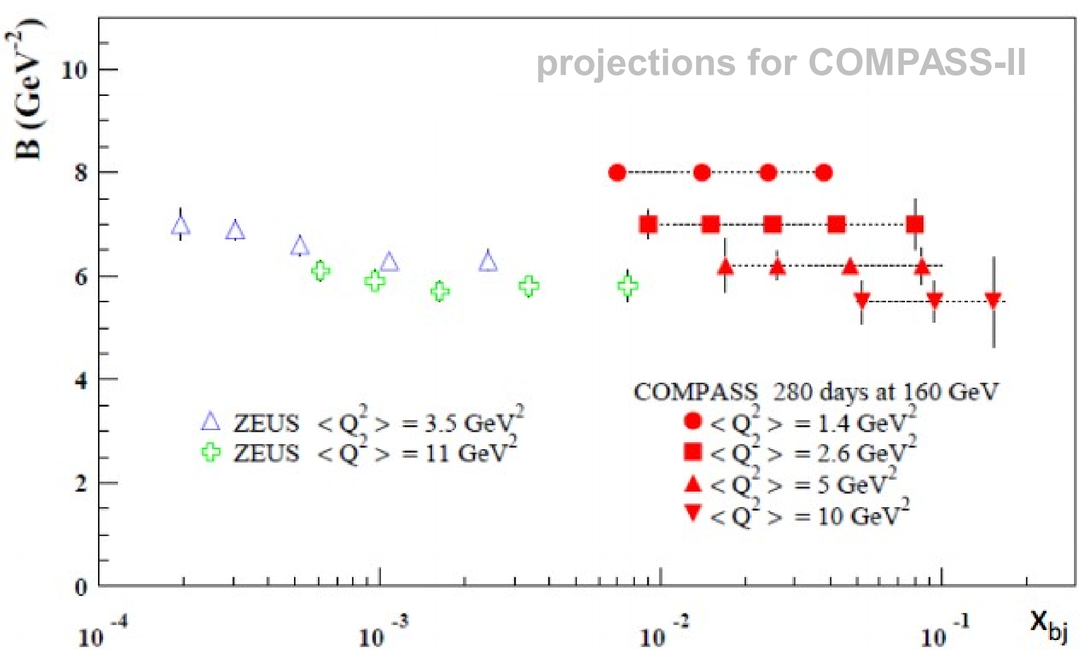
- 2012 pilot + 2016, 2017 with unpolarized LH target and RPD
- > 2017 with polarized target and RPD (*subject of addendum to the proposal*)

Measurement of t-slope for exclusive ρ^0 production
sensitive to transverse size of nucleon – meson system

$$\frac{d\sigma}{dt} \sim \exp(-b|t|)$$

$$b(x_{Bj}) \approx \frac{1}{2}\langle r_\perp^2(x_{Bj})\rangle$$

- Q^2 and ν parametrization of cross section from NMC data normalized to Goloskokov and Kroll predictions
- 160 GeV muon beam
- global efficiency ε = 10%
- L = 1.2 nb^{-1} (2 years of data taking)



→ *more in:*
The GPD program at COMPASS II
Philipp Karl Joerg
Wednesday, WG6 session

Summary and outlook

- COMPASS is unique to probe GPDs due to covered kinematic region of intermediate x_{Bj} and availability of beams of two charges and polarizations
- Exclusive meson production → complementary measurement to DVCS, flavour separation for GPDs, sensitivity to chiral-odd GPDs
- Transverse target spin asymmetries sensitive to
  - GPDs E (→ orbital angular momentum)
  - GPDs H_T (→ transversity)
  - pion pole (→ production mechanism)

  - can be used to constrain GPD models
  - results for ρ^0 and ω can be used to distinguish between GPDs for u and d quarks
- GPD program is continued at COMPASS-II