Exclusive ω meson production at COMPASS

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on behalf of the COMPASS Collaboration

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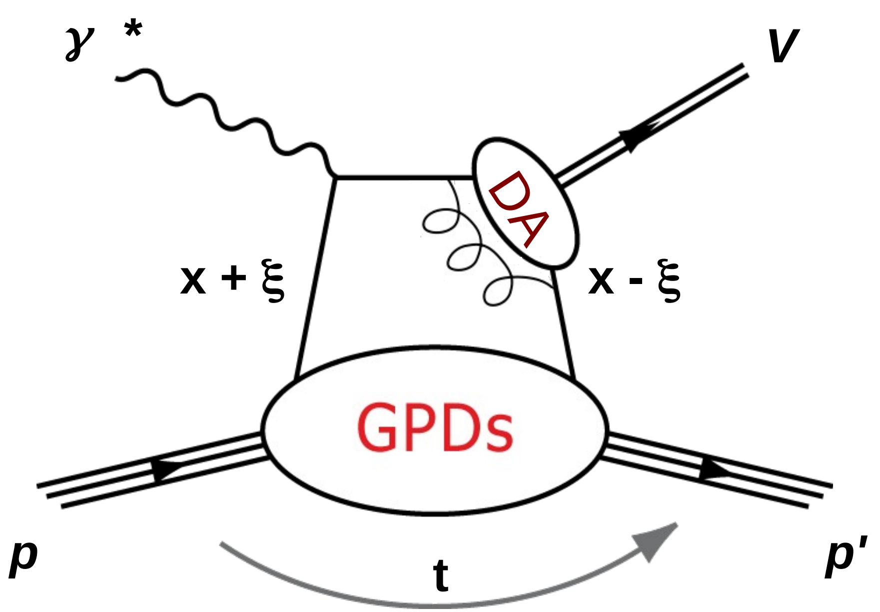
Outline

- Formalism: GPDs, cross section, asymmetries
- COMPASS experiment
- Transverse target spin asymmetries for exclusive ω production in muon-nucleon scattering
- Summary and outlook

Formalism: Generalised Parton Distributions (GPDs)

***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 of ‚effective' GPDs:

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

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

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

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

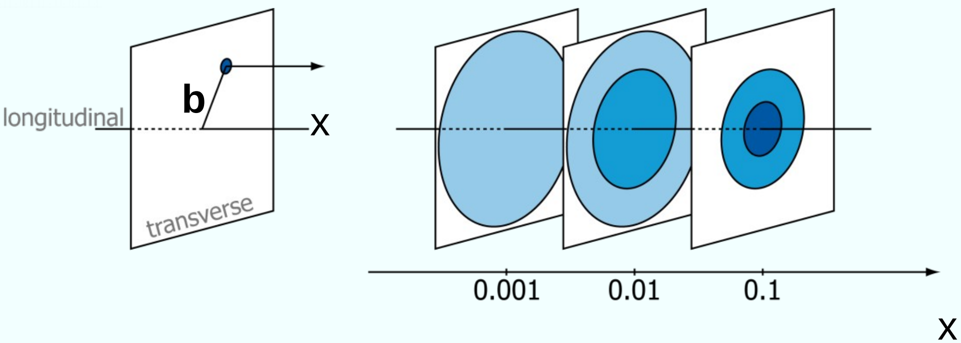
Nucleon tomography:

(quasi-) 3D parton distribution function:

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

where:

x - longitudinal momentum fraction of hit parton
b - 2-dim. position of hit parton



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

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

Transversity:

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

Cross section formula for exclusive meson production

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

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

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

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

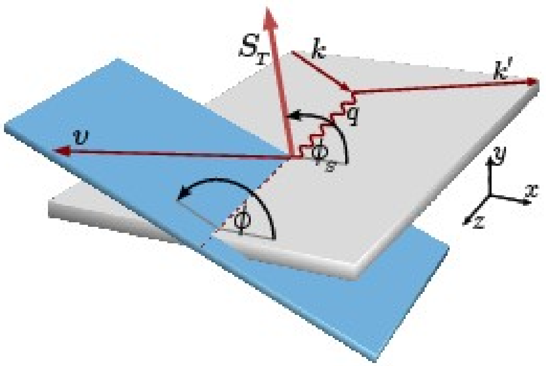
$$+\,S_L P_\ell\left[\sqrt{1-\varepsilon^2}\,\frac{1}{2}\left(\sigma_{++}^{++}-\sigma_{++}^{--}\right)-\sqrt{\varepsilon(1-\varepsilon)}\,\cos\phi\,\mathrm{Re}\,(\sigma_{+0}^{++}-\sigma_{+0}^{--})\right]$$

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

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

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

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



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 process $\gamma^*\,p \rightarrow V\;p'$ with photon helicity *m* and target proton helicity *i*

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

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

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

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

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

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

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

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

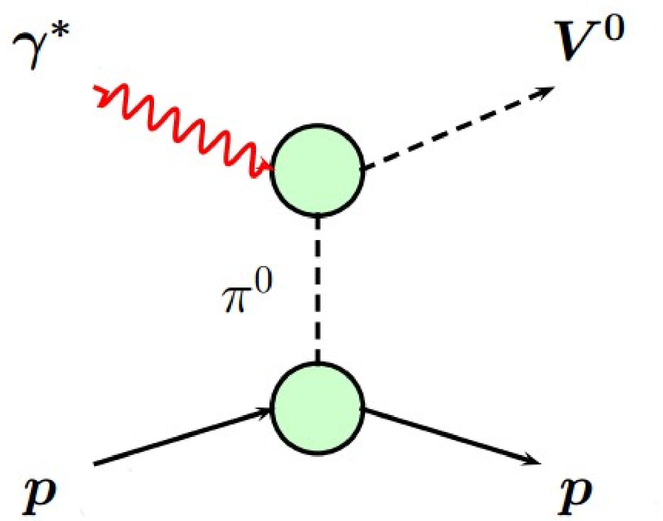
$$A_{LT}^{\cos(\phi-\phi_s)} = \frac{\mathrm{Re}\,\sigma_{++}^{+-}}{\sigma_0}$$

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

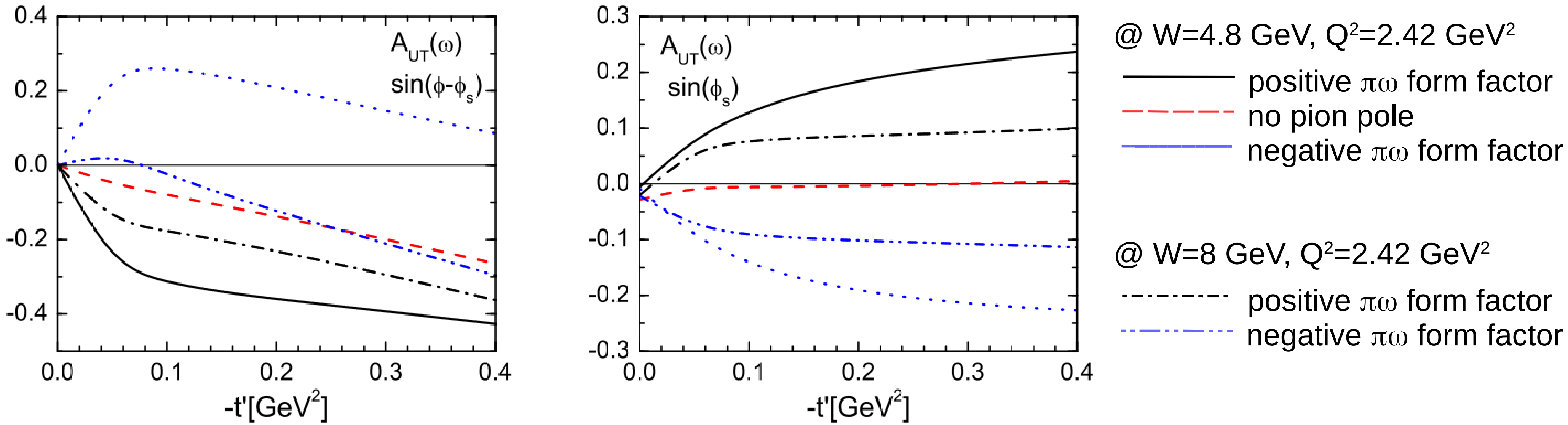
$$A_{LT}^{\cos\phi_s} = -\frac{\mathrm{Re}\,\sigma_{+0}^{+-}}{\sigma_0}$$

unpolarised cross section

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



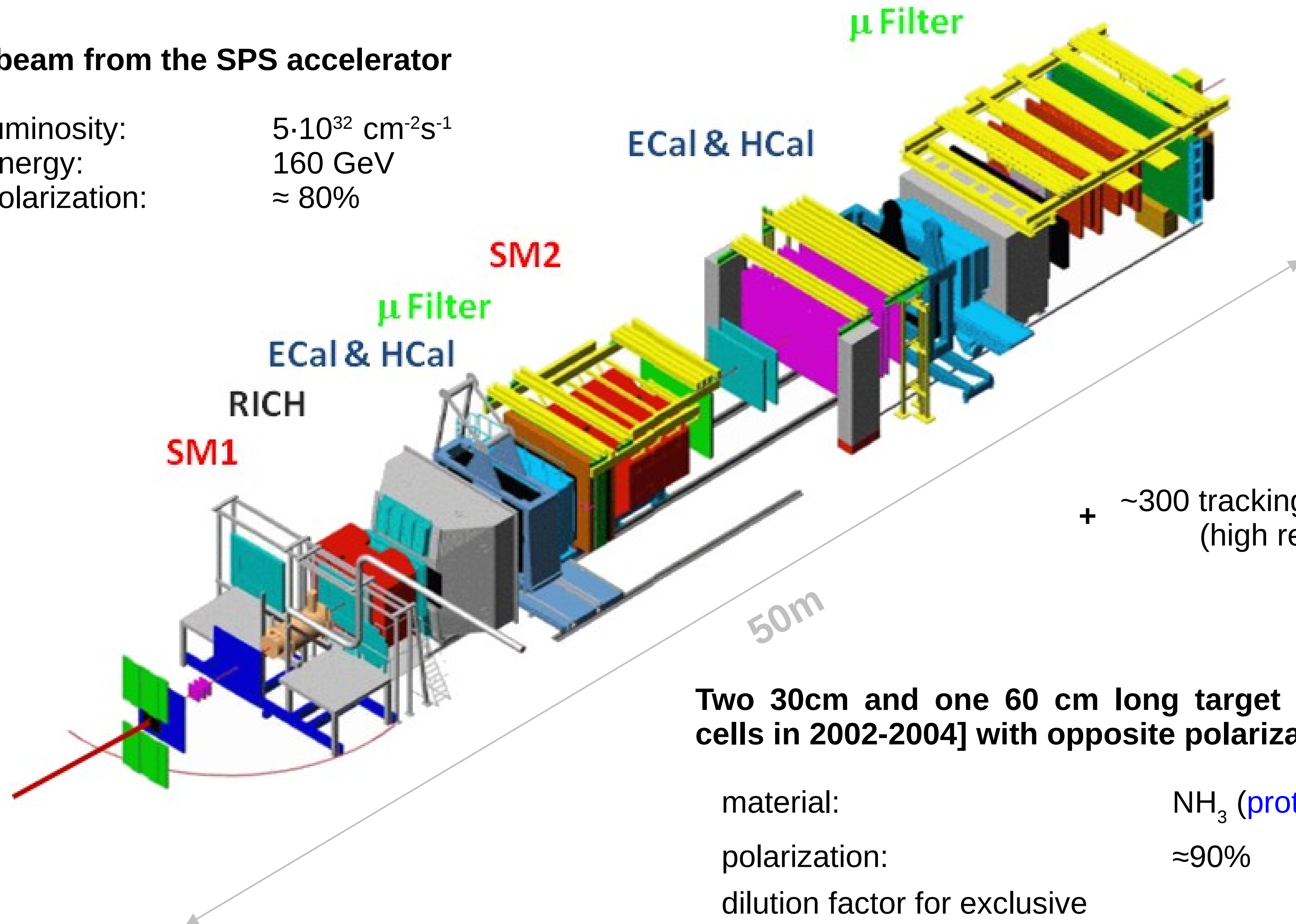
- Effect known since early photoproduction experiments
- At COMPASS kinematics:
  - small for ρ^0 production
  - sizable for ω production
- Unnatural parity exchange process
→ impact on helicity-dependent observables
- Crucial for description of SDMEs for excl. ω production
→ Goloskokov and Kroll, Eur.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



COMPASS experiment at CERN – setup with transversely polarized target

μ^+ beam from the SPS accelerator

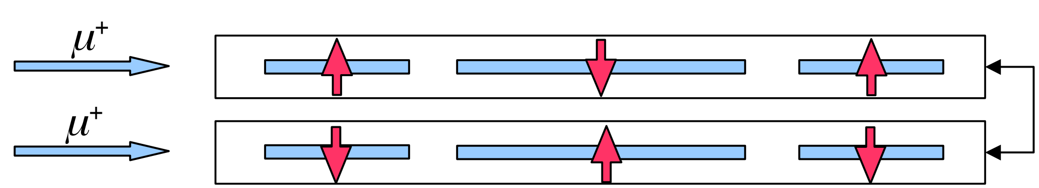
luminosity:	$5\cdot10^{32}$ cm^{-2}s^{-1}
energy:	160 GeV
polarization:	≈ 80%



+ ~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%]



Transverse target spin asymmetry for incoherent exclusive ω production

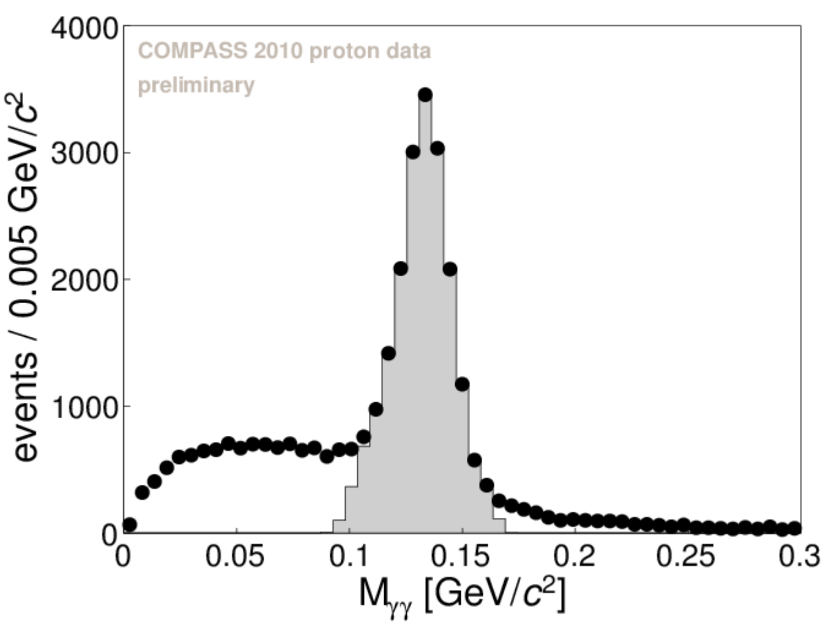
Used data:

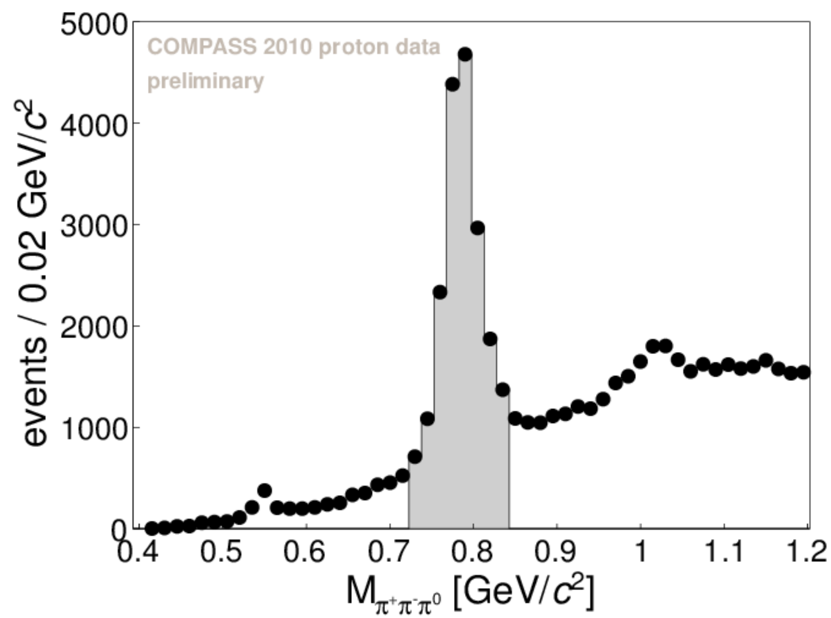
2010 (transversely polarised protons)

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

Topology of vertex:

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

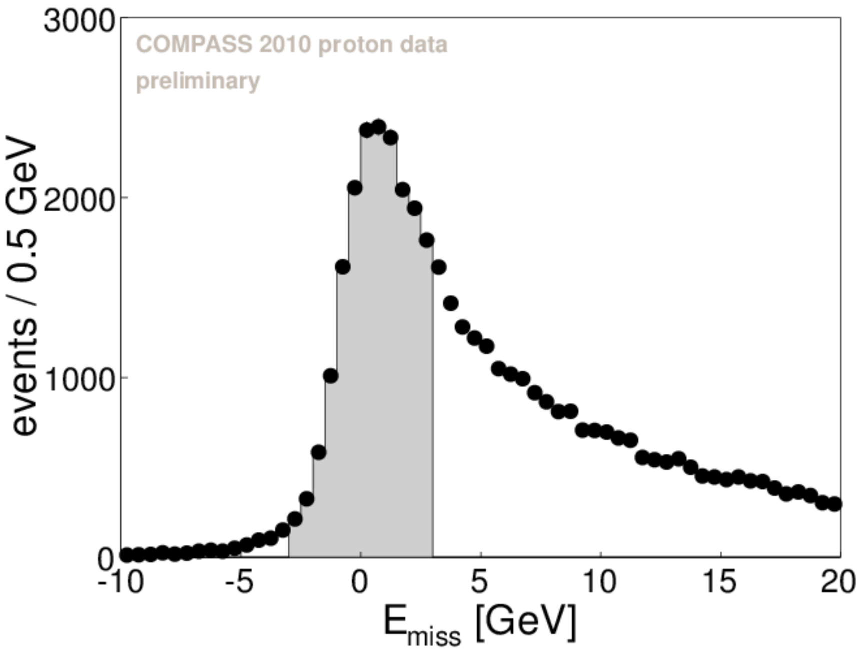




Kinematics domain:

- 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

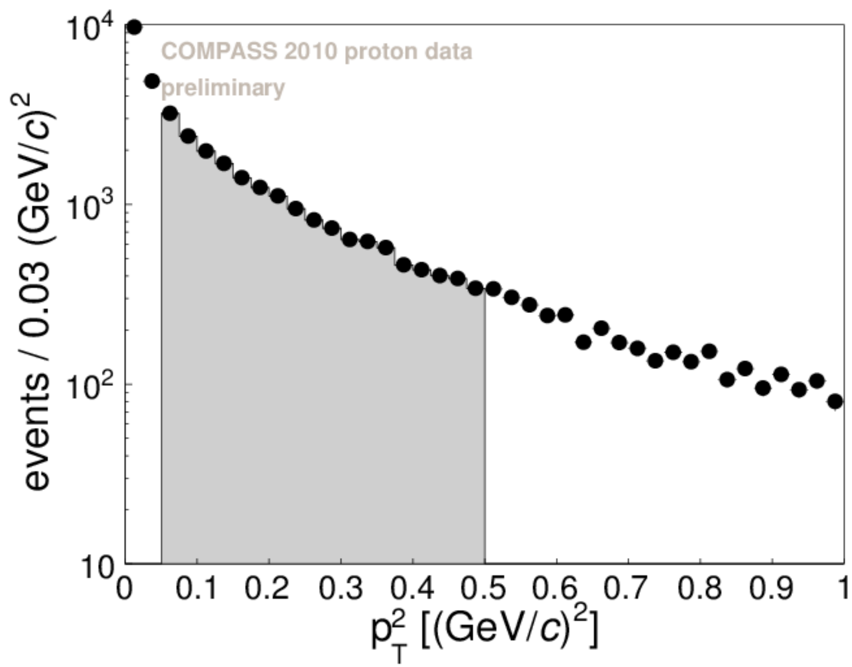
- Check if the proton stayed intact

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

$E_{miss} = 0$ 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

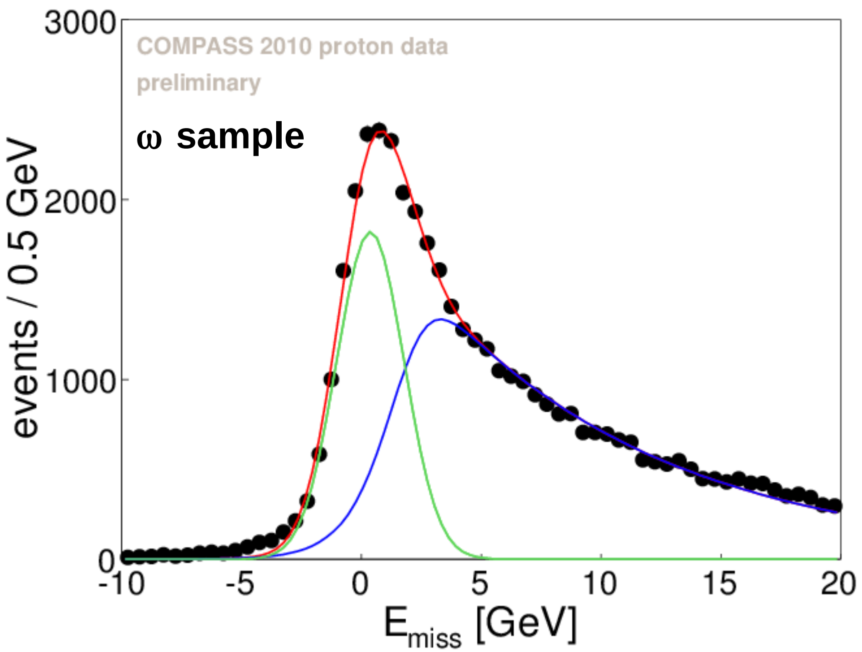
$$0.05 < p_T^2\ (GeV/c)^2$$

To suppress non-exclusive background

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

- Unbinned maximum likelihood estimator with simultaneous fit of signal and background asymmetries

Background rejection:
For each target cell and polarization state

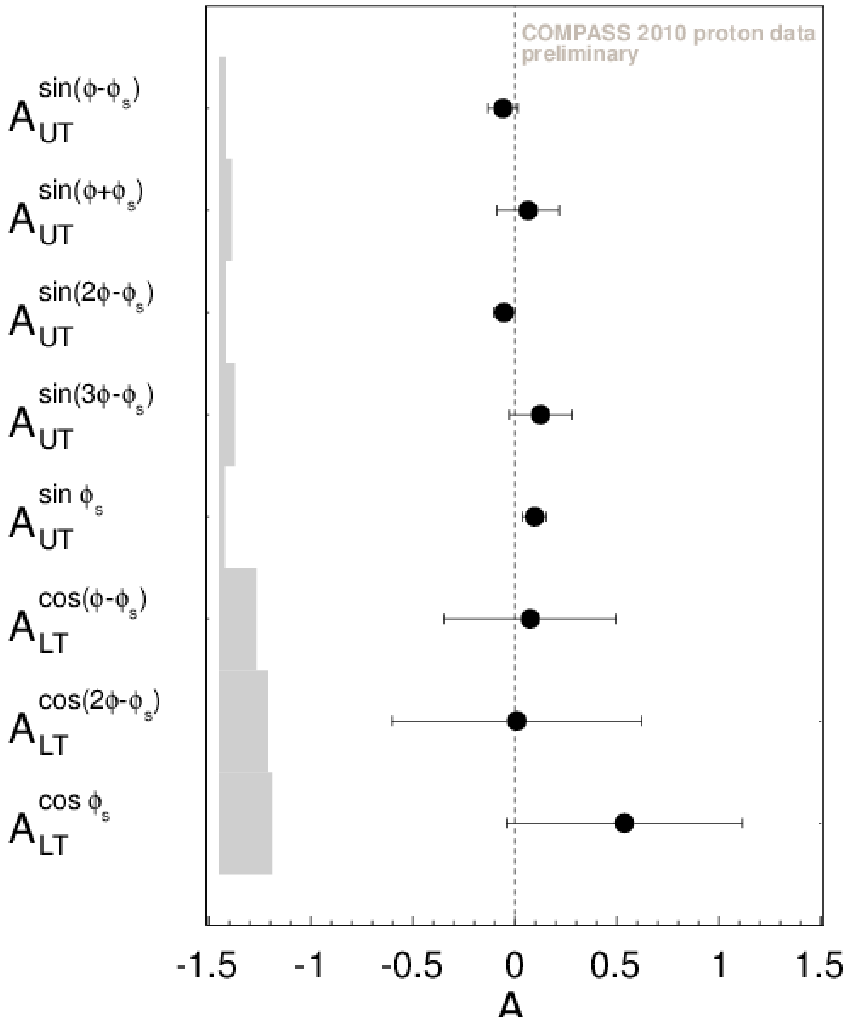


shape of semi-inclusive background from MC
(LEPTO with COMPASS tuning + simulation of spectrometer response + reconstruction as for real data)

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)

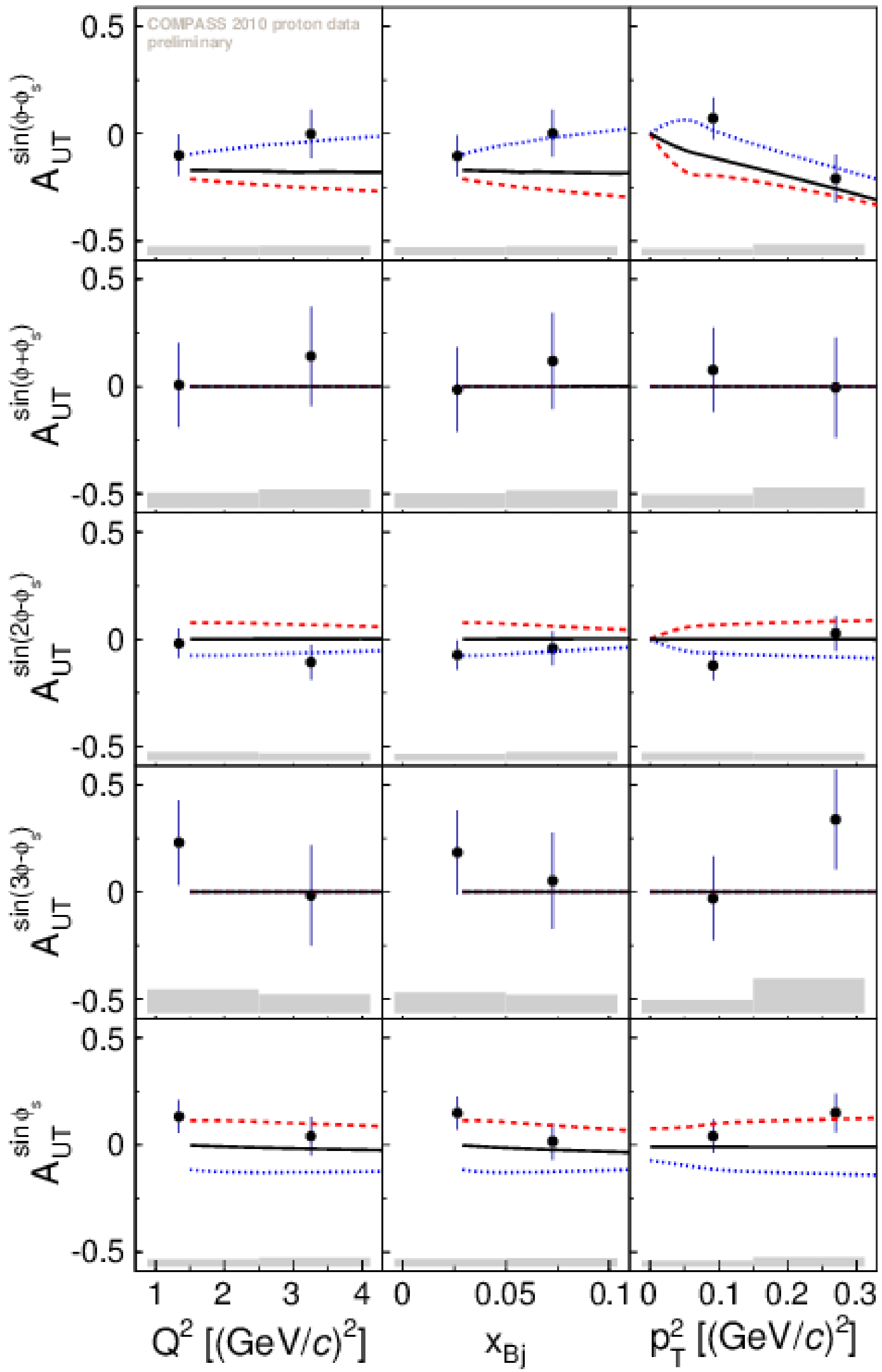


Q^2=2.2 GeV^2
x_{Bj} =0.049
p_T^2 = 0.17 GeV^2
W=7.1 GeV

New result → to be published

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

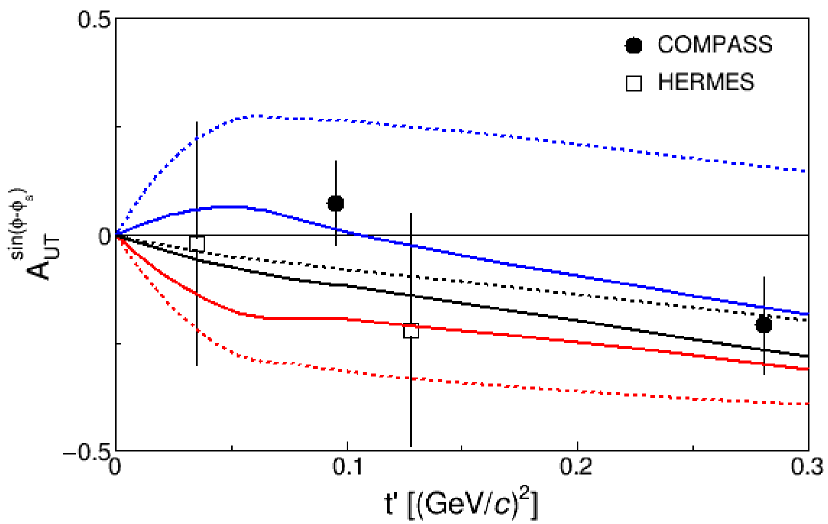
Transverse target spin asymmetry for incoherent exclusive ω production



New result → to be published

GK model predictions
private communication

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



● COMPASS

negative
null
positive

GK predictions @ COMPASS kinematics

□ HERMES

negative
null
positive

GK predictions @ HERMES kinematics

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 are (in principle) sensitive to
  - GPDs E (→ orbital angular momentum)
  - GPDs H_T (→ transversity)
  - pion pole (→ production mechanism)
  - can be used to constrain GPD models (presently exists only Goloskokov/Kroll model)
- COMPASS results, although 2-3 times more accurate than HERMES ones, can (still) not conclusively decide on the sign of the pion-pole contribution.
- Need to wait for next generation of experiments (JLab12)

Spare Slides

Results on exclusive ρ production

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

Used data:

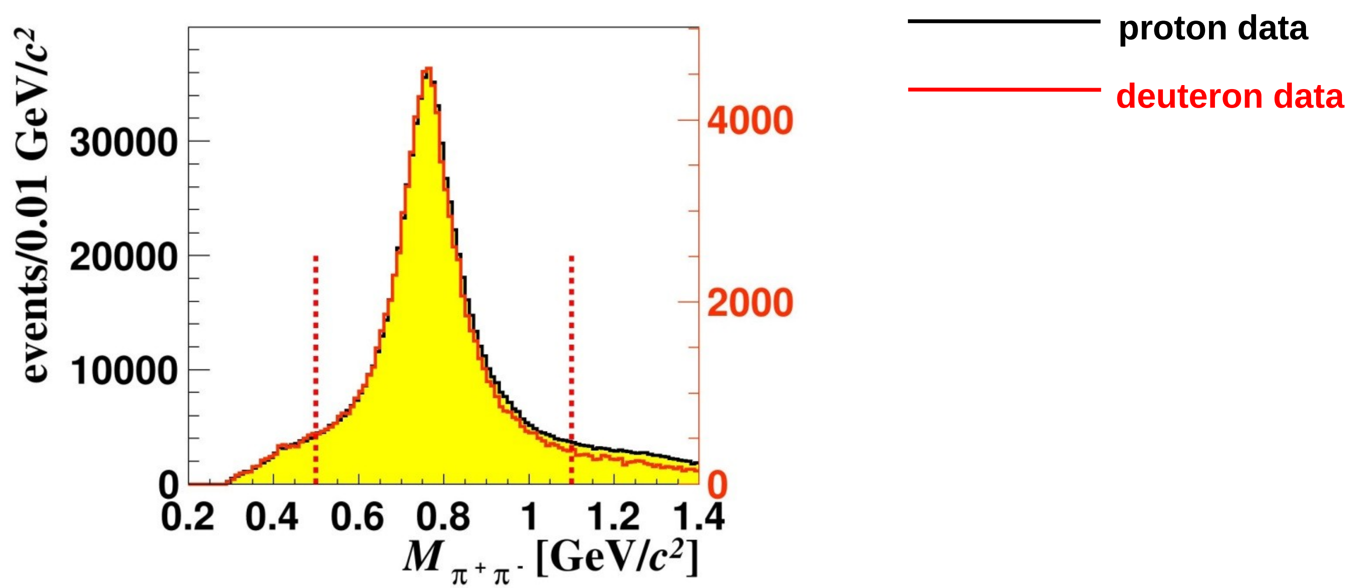
2007, 2010 (transversely polarised protons)

2003, 2004 (transversely polarised deuterons)

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

Topology of vertex:

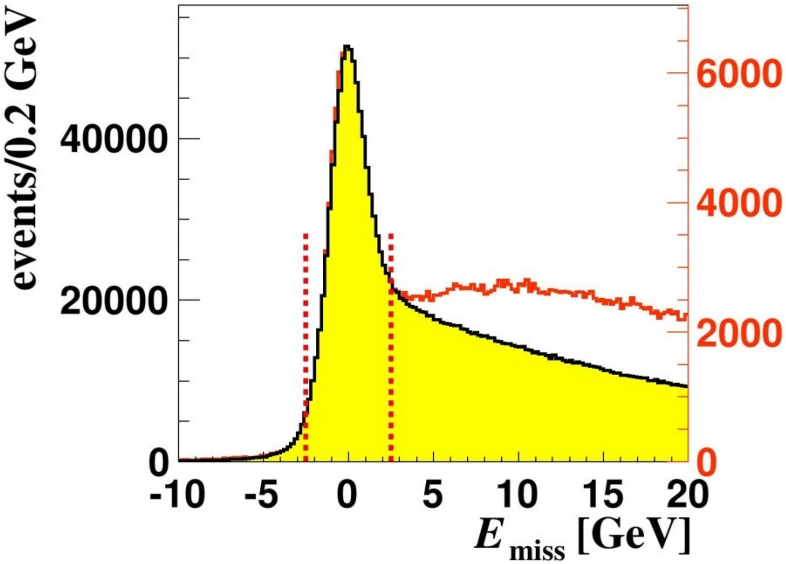
one incoming and one outgoing muon track
two hadron tracks of opposite charges



Kinematics domain:

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

Transverse target spin asymmetry for incoherent exclusive ρ^0 production



Missing energy and energy of ρ^0 candidate

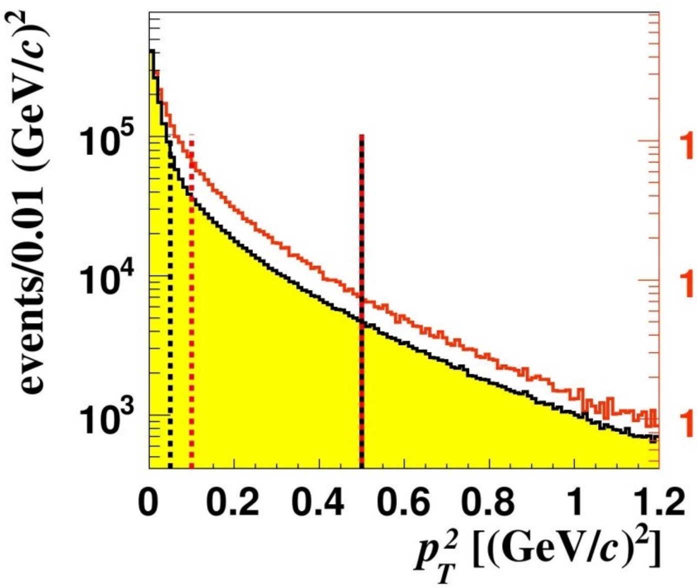
- Check if the proton is intact

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

$E_{miss} = 0$ 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

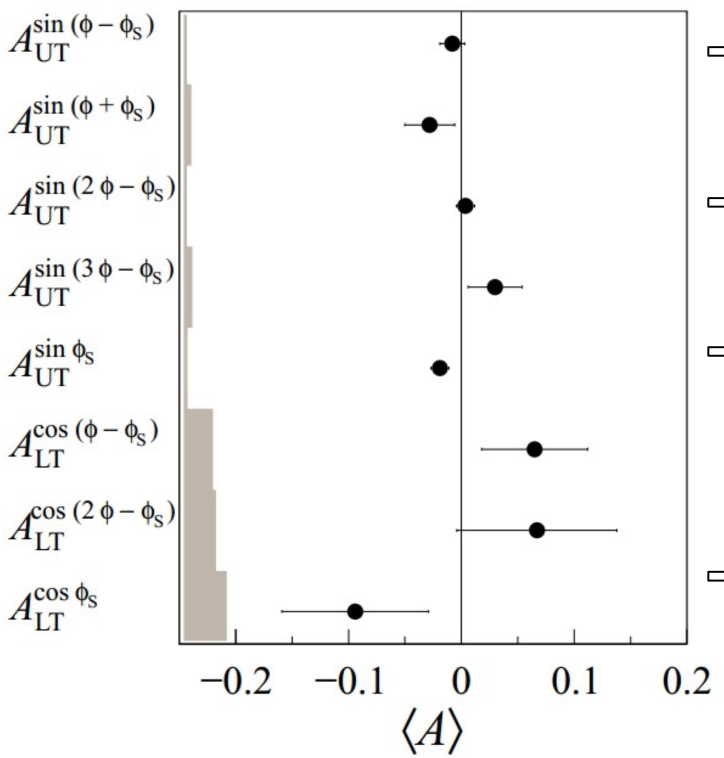
$0.05 < p_T^2\ (GeV/c)^2$ *for protons*

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

To suppress non-exclusive background

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

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



$\langle x_B \rangle \approx 0.039$

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

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

⇨ $$A_{UT}^{\sin(\phi-\phi_s)}\sigma_0 = -2\,Im\left[\epsilon M^*_{0-,0+} M_{0+,0+} + M^*_{+-,++} M_{++,++} + \frac{1}{2} M^*_{0-,++} M_{0+,++}\right]$$
(~E, ~H, ~E, ~H, ~H_T, ~E_T)

⇨ $$A_{UT}^{\sin(2\phi-\phi_s)}\sigma_0 = -Im\left[M^*_{0+,++} M_{0-,0+}\right]$$
(~E_T, ~E)

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

⇨ $$A_{UT}^{\sin\phi_s}\sigma_0 = -Im\left[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}\right]$$
(~H_T, ~H, ~E_T, ~E)

⇨ $$A_{LT}^{\cos\phi_s}\sigma_0 = -Re\left[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}\right]$$
(~H_T, ~H, ~E_T, ~E)

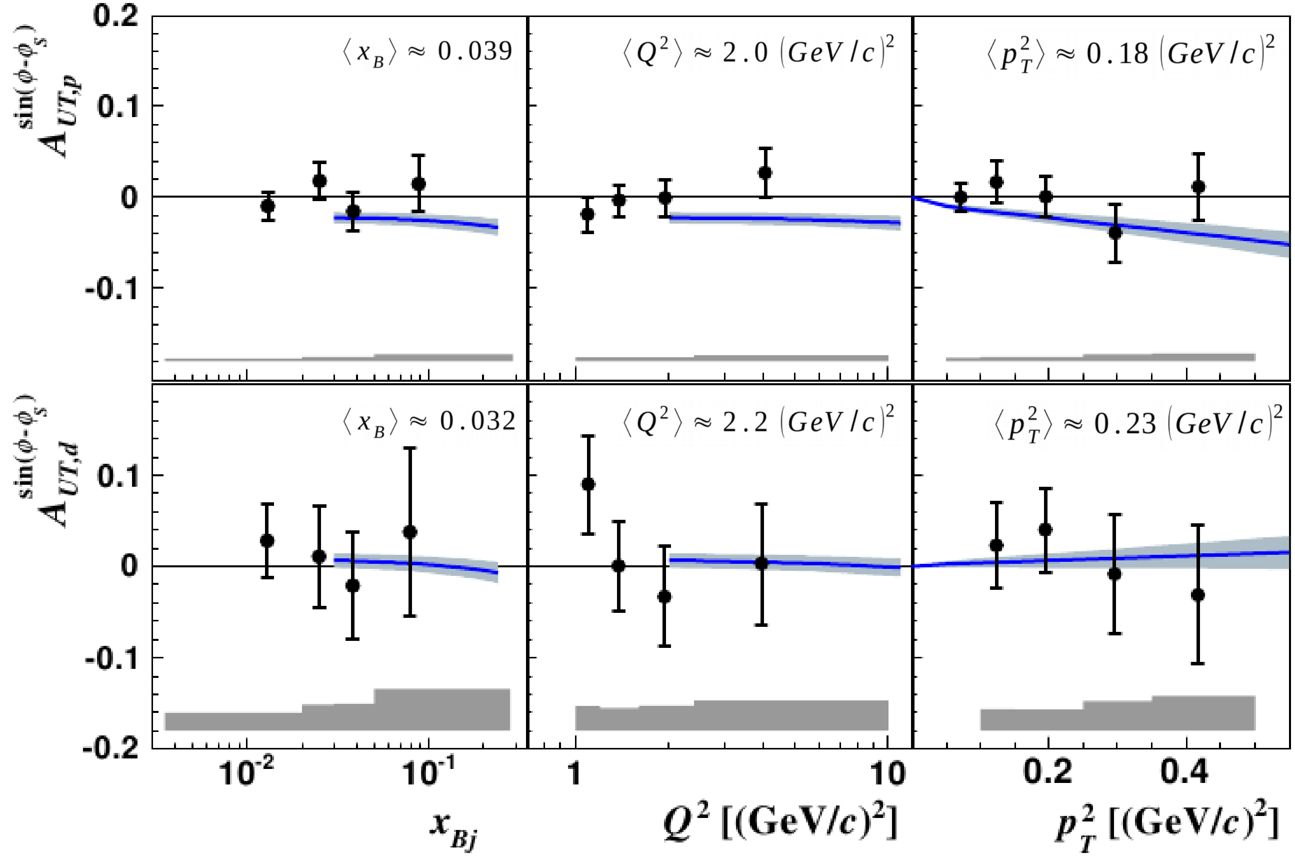
Helicity amplitudes:

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

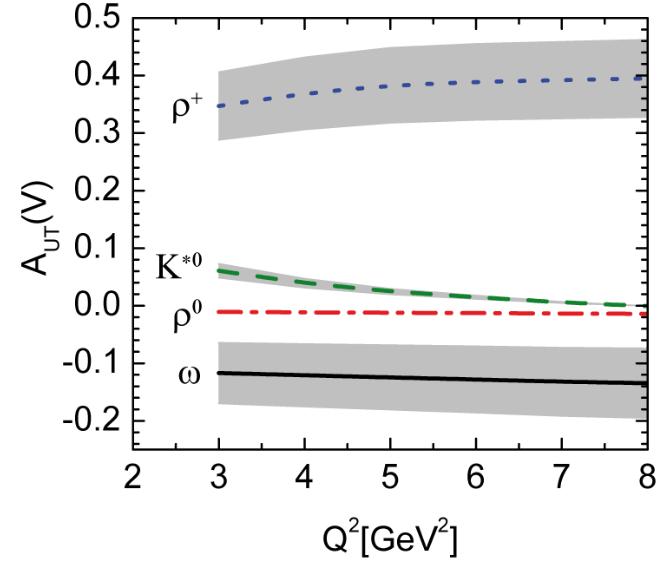
- V: meson helicity
- p': recoiled proton helicity
- γ^*: virtual photon helicity
- p: initial proton helicity

Transverse target spin asymmetry for incoherent exclusive ρ^0 production

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

→ **PLB 731 (2014) 19**

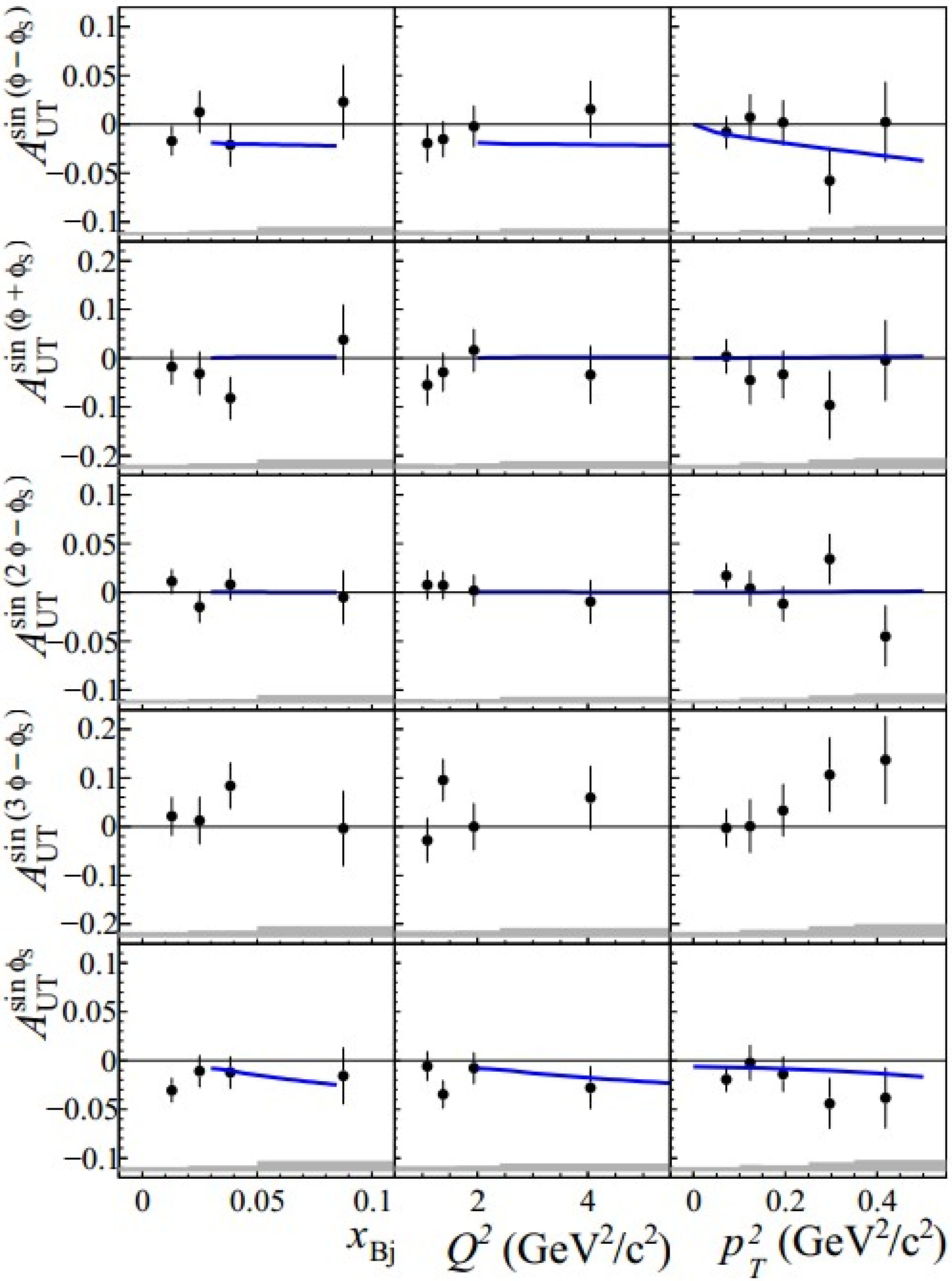
- Improved method of extraction (2D)
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

$\langle x_B \rangle \approx 0.039$

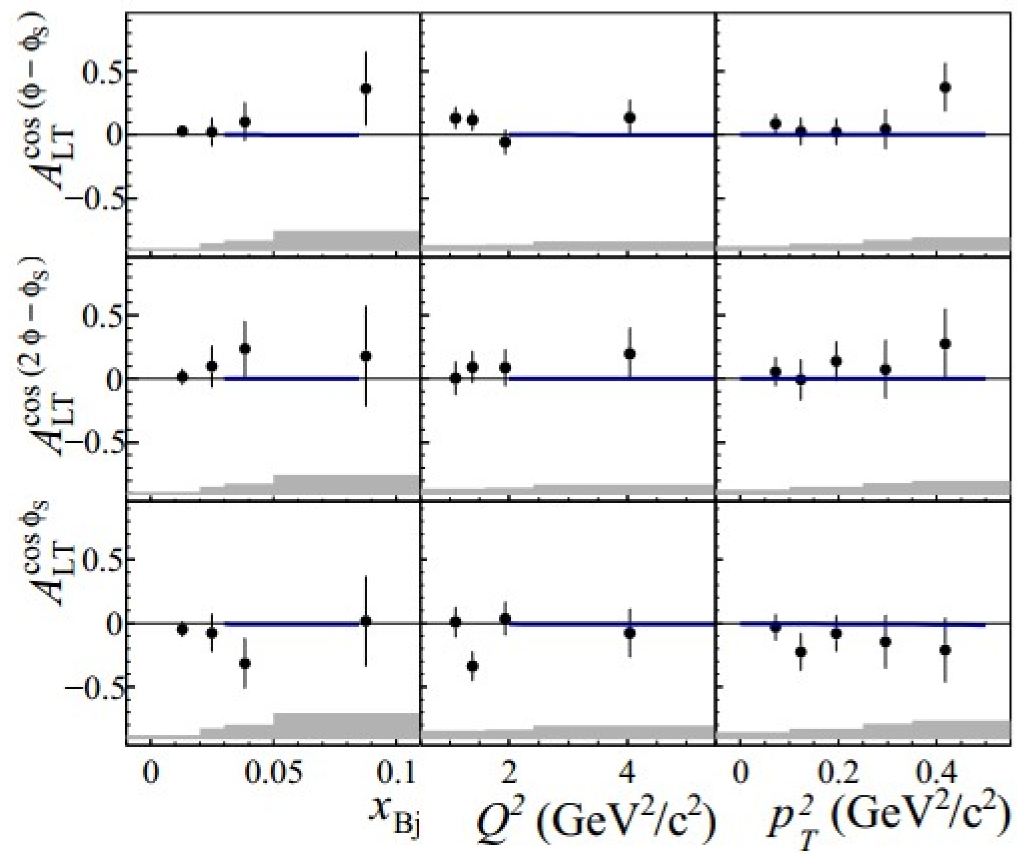
$\langle Q^2 \rangle \approx 2.0 \, (GeV/c)^2$

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

Single spin asymmetries



Double spin asymmetries



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