



# *Transverse target spin asymmetries in exclusive $\omega$ muoproduction at COMPASS*

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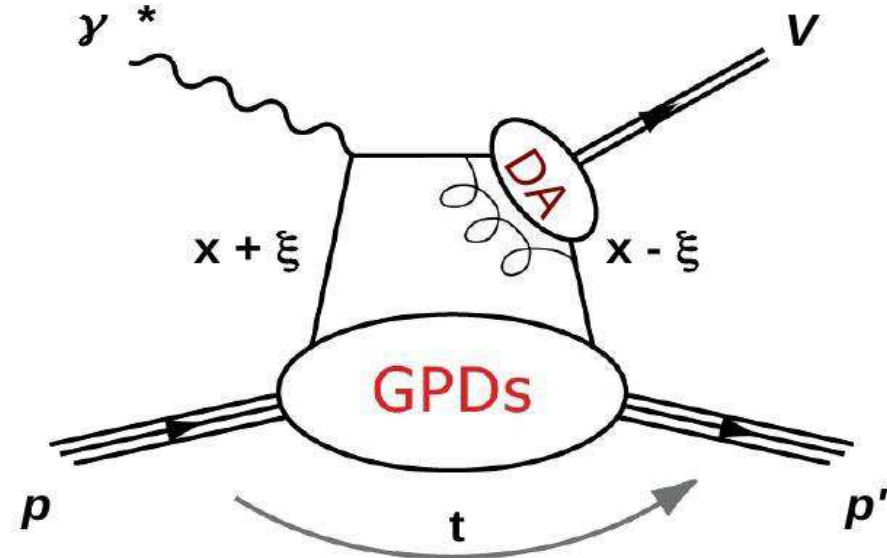
- Hard exclusive vector meson production and GPDs
- Transverse target spin asymmetry ( $A_{UT}$ ,  $A_{LT}$ ) in exclusive vector meson muoproduction
- COMPASS experiment
- Results on transverse target spin asymmetry
- Summary.



# Hard exclusive vector meson production

$$\mu + N \rightarrow \mu + V + N \text{ and GPDs}$$

- Exclusive leptonproduction of vector meson in the process  $\gamma^* + N \rightarrow V + N'$  ( $V = \rho^0, \phi, \omega$ ) provides information both on reaction mechanism and nucleon structure.
- Provide constraints on **Generalized Parton Distribution (GPD)** models.
- The process amplitudes is a convolution of the lepton-quark hard-scattering amplitude with soft part which contains GPDs and vector meson distribution amplitude.



- Chiral-even GPDs (helicity of parton unchanged)

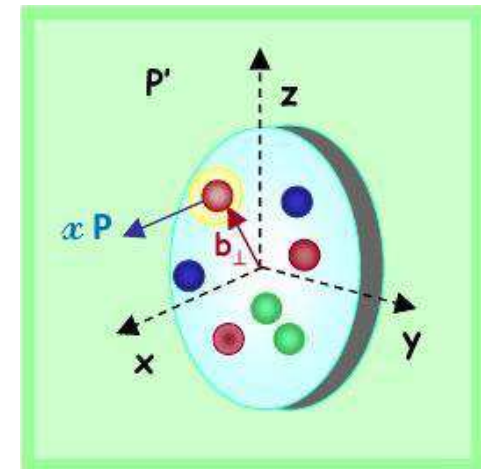
$$H^{q(g)}(x, \xi, t), \quad E^{q(g)}(x, \xi, t)$$

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

- Chiral-odd GPDs (helicity of parton changed)

$$H_T^{q(g)}(x, \xi, t), \quad E_T^{q(g)}(x, \xi, t)$$

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





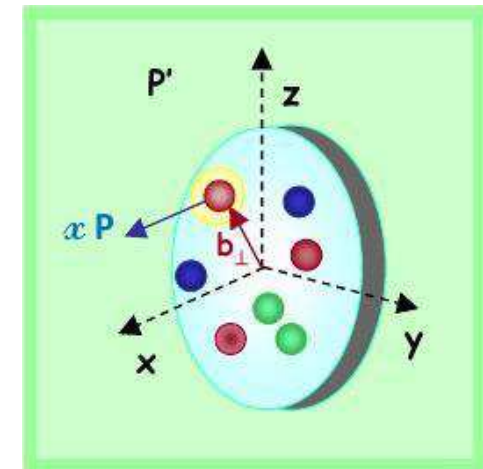
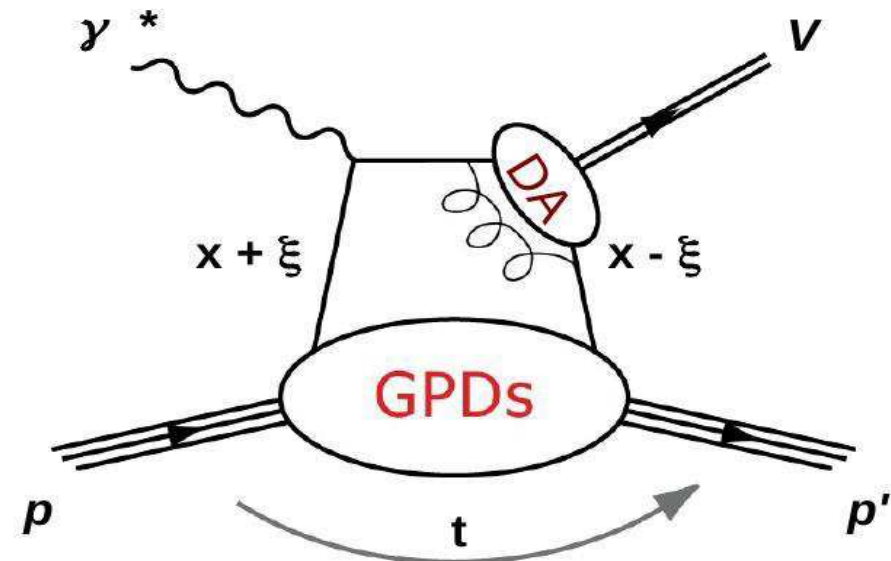
# Hard exclusive vector meson production

$$\mu + N \rightarrow \mu + V + N \text{ and GPDs}$$

- Ji's Sum Rules

$$\frac{1}{2} \int x [H^f(x, \xi, t \rightarrow 0) + E^f(x, \xi, t \rightarrow 0)] dx = \langle J^f \rangle$$

- GPD 3-dimensional image of the partonic structure of the nucleon





# Hard exclusive vector meson production

$$\mu + N \rightarrow \mu + V + N \text{ and GPDs}$$

- Access to various quark-flavor combination of GPDs

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

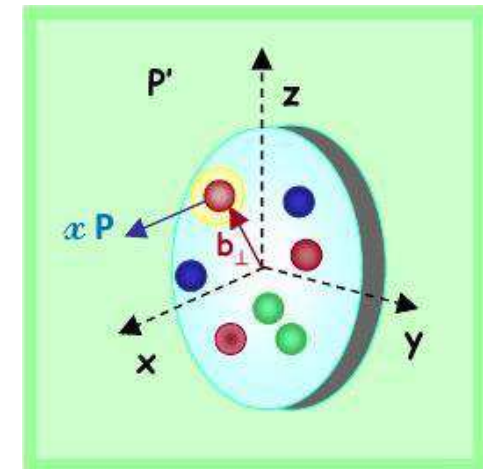
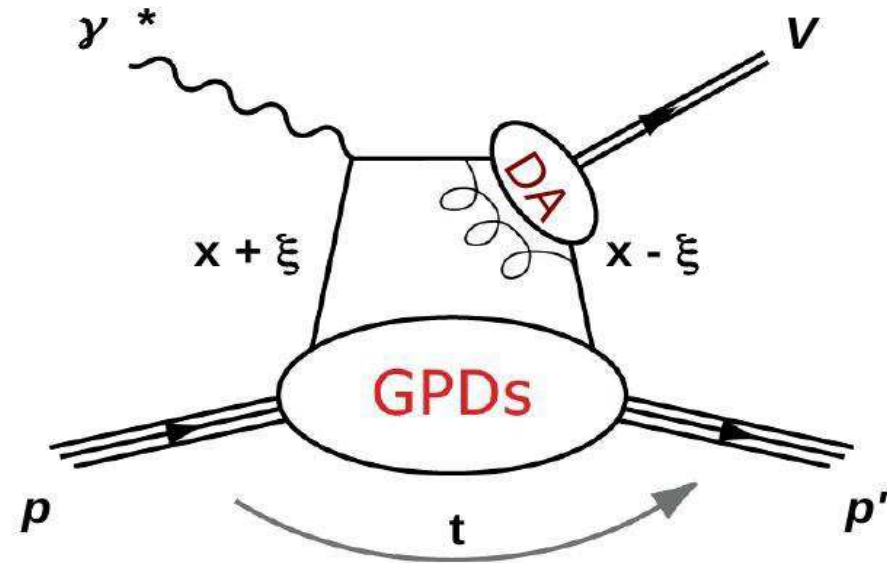
$$E_{\omega} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u - \frac{1}{3} E^d + \frac{1}{8} E^g \right)$$

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

- Natural Parity Exchange (NPE) correspond to GPD H and E.

Unnatural Parity Exchange (UPE) correspond to GPD  $\tilde{H}$  and  $\tilde{E}$ .

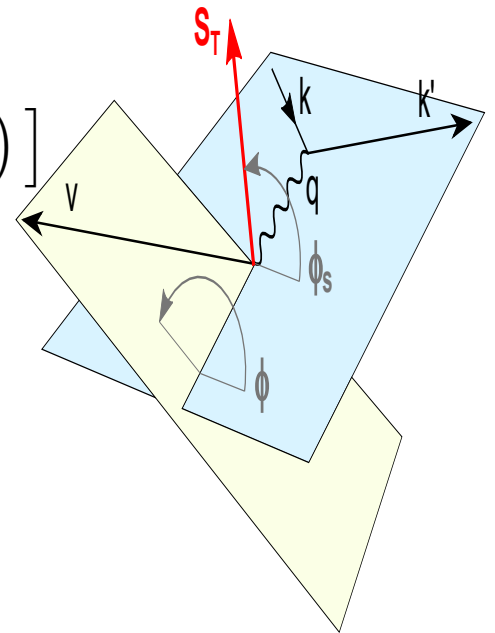
- The factorization is rigorously proven for longitudinal virtual photons only ( $\gamma_L \rightarrow V_L$ ).
- Factorization applied also for transverse photons in phenomenological Goloskokov - Kroll (GK) model.



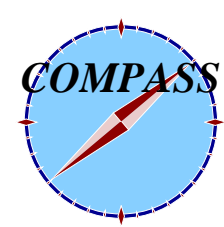


# Cross section for exclusive meson leptonproduction

$$\begin{aligned}
 & \left[ \frac{\alpha_{em}}{8\pi^3} \frac{y^2}{1-\epsilon} \frac{1-x_{Bj}}{x_{Bj}} \frac{1}{Q^2} \right]^{-1} \frac{d\sigma}{dx_{Bj} dQ^2 dt d\phi d\phi_s} = \\
 & \frac{1}{2} \left( \sigma_{++}^{++} + \sigma_{++}^{--} \right) + \epsilon \sigma_{00}^{++} - \epsilon \cos(2\phi) \operatorname{Re} \sigma_{+-}^{++} - \sqrt{\epsilon(1+\epsilon)} \cos\phi \operatorname{Re} \left( \sigma_{+0}^{++} + \sigma_{+0}^{--} \right) \\
 & - P_\ell \sqrt{\epsilon(1-\epsilon)} \sin\phi \operatorname{Im} \left( \sigma_{+0}^{++} + \sigma_{+0}^{--} \right) \\
 & - S_L \left[ \epsilon \sin 2\phi \operatorname{Im} \sigma_{+-}^{++} + \sqrt{\epsilon(1+\epsilon)} \sin\phi \operatorname{Im} \left( \sigma_{+0}^{++} - \sigma_{+0}^{--} \right) \right] \\
 & + S_L P_\ell \left[ \sqrt{1-\epsilon^2} \frac{1}{2} \left( \sigma_{++}^{++} - \sigma_{++}^{--} \right) - \sqrt{\epsilon(1-\epsilon)} \cos\phi \operatorname{Re} \left( \sigma_{+0}^{++} - \sigma_{+0}^{--} \right) \right] \\
 & - S_T \left[ \sin(\phi - \phi_s) \operatorname{Im} \left( \sigma_{++}^{+-} + \epsilon \sigma_{00}^{+-} \right) + \frac{\epsilon}{2} \sin(\phi + \phi_s) \operatorname{Im} \sigma_{+-}^{+-} \right. \\
 & \quad + \frac{\epsilon}{2} \sin(3\phi + \phi_s) \operatorname{Im} \sigma_{+-}^{-+} + \sqrt{\epsilon(1+\epsilon)} \sin\phi_s \operatorname{Im} \sigma_{+0}^{+-} \\
 & \quad \left. + \sqrt{\epsilon(1+\epsilon)} \sin(2\phi - \phi_s) \operatorname{Im} \sigma_{+0}^{-+} \right] \\
 & + S_T P_\ell \left[ \sqrt{1-\epsilon^2} \cos(\phi - \phi_s) \operatorname{Re} \sigma_{++}^{+-} - \sqrt{\epsilon(1-\epsilon)} \cos\phi_s \operatorname{Re} \sigma_{+0}^{+-} \right. \\
 & \quad \left. - \sqrt{\epsilon(1-\epsilon)} \cos(2\phi - \phi_s) \operatorname{Re} \sigma_{+0}^{-+} \right],
 \end{aligned}$$



$\sigma_{mn}^{ij}$  - photoabsorption cross sections or interference terms,  $\sigma_{mn}^{ij}(x_B, Q^2, t) \propto \Sigma(M_m^i)^* M_{\text{mp16/17}}^i$



# Azimuthal asymmetries of cross section for exclusive leptonproduction

For a transversely polarised target five single (UT) and three double (LT) spin asymmetries can be defined:

$$\begin{aligned}
 A_{\text{UT}}^{\sin(\phi-\phi_s)} &= -\frac{\text{Im} \left( \sigma_{++}^{+-} + \epsilon \sigma_{00}^{+-} \right)}{\sigma_0}, & A_{\text{LT}}^{\cos(\phi-\phi_s)} &= \frac{\text{Re} \sigma_{++}^{+-}}{\sigma_0}, \\
 A_{\text{UT}}^{\sin(\phi+\phi_s)} &= -\frac{\text{Im} \sigma_{+-}^{+-}}{\sigma_0}, & A_{\text{LT}}^{\cos \phi_s} &= -\frac{\text{Re} \sigma_{+0}^{+-}}{\sigma_0}, \\
 A_{\text{UT}}^{\sin(3\phi-\phi_s)} &= -\frac{\text{Im} \sigma_{+-}^{-+}}{\sigma_0}, & A_{\text{LT}}^{\cos(2\phi-\phi_s)} &= -\frac{\text{Re} \sigma_{+0}^{-+}}{\sigma_0}, \\
 A_{\text{UT}}^{\sin \phi_s} &= -\frac{\text{Im} \sigma_{+0}^{+-}}{\sigma_0}, \\
 A_{\text{UT}}^{\sin(2\phi-\phi_s)} &= -\frac{\text{Im} \sigma_{+0}^{-+}}{\sigma_0}.
 \end{aligned} \tag{1}$$

Here,  $\sigma_0$  is the total unpolarised cross section, which is the sum of the cross sections for longitudinally and transversely polarised virtual photons,  $\sigma_L$  and  $\sigma_T$ , respectively:

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



# COMPASS Spectrometer

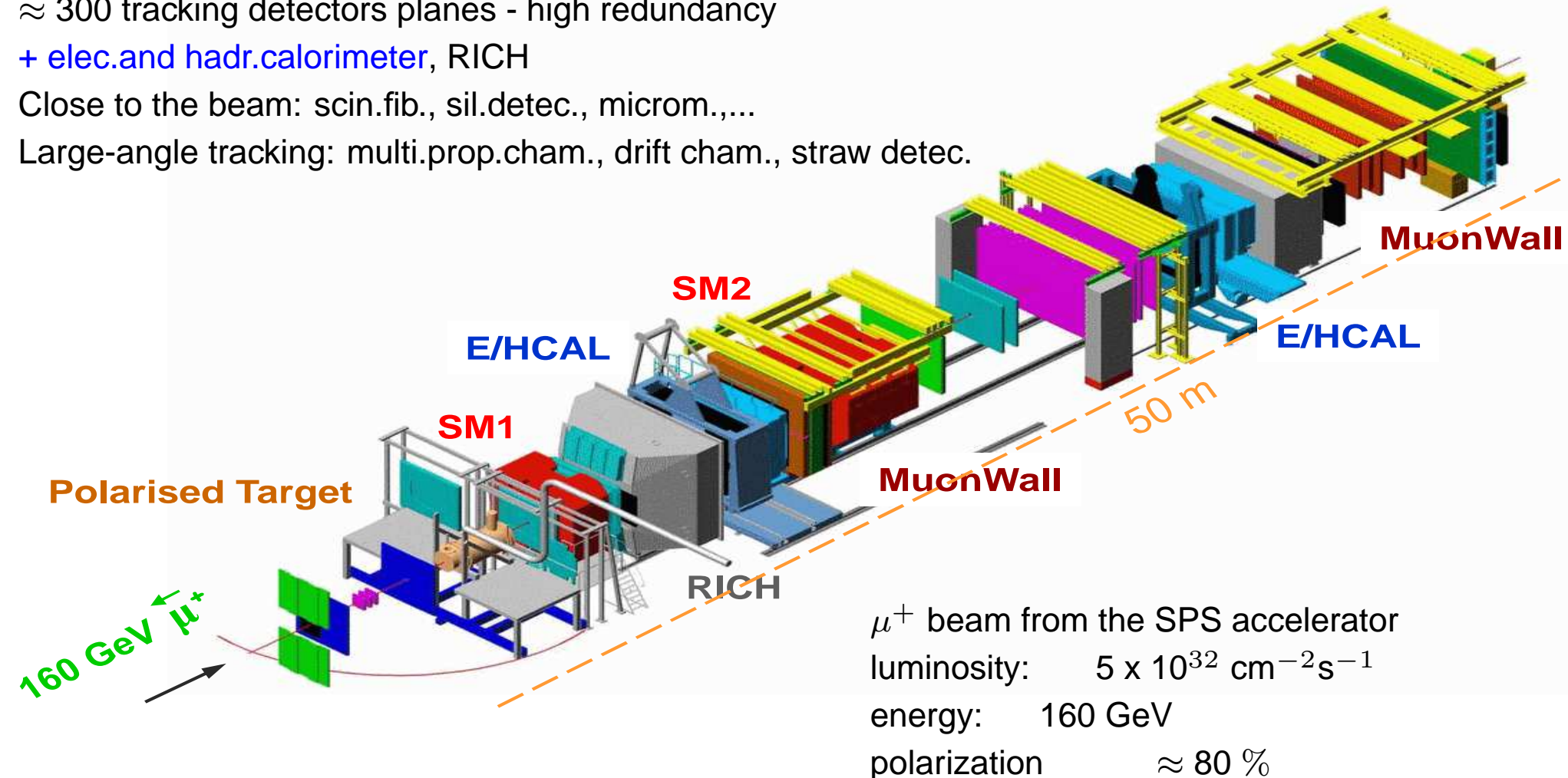
Two-stage forward spectrometer **SM1** + **SM2**

≈ 300 tracking detectors planes - high redundancy

+ elec.and hadr.calorimeter, RICH

Close to the beam: scin.fib., sil.detec., microm.,...

Large-angle tracking: multi.prop.cham., drift cham., straw detec.



$\mu^+$  beam from the SPS accelerator

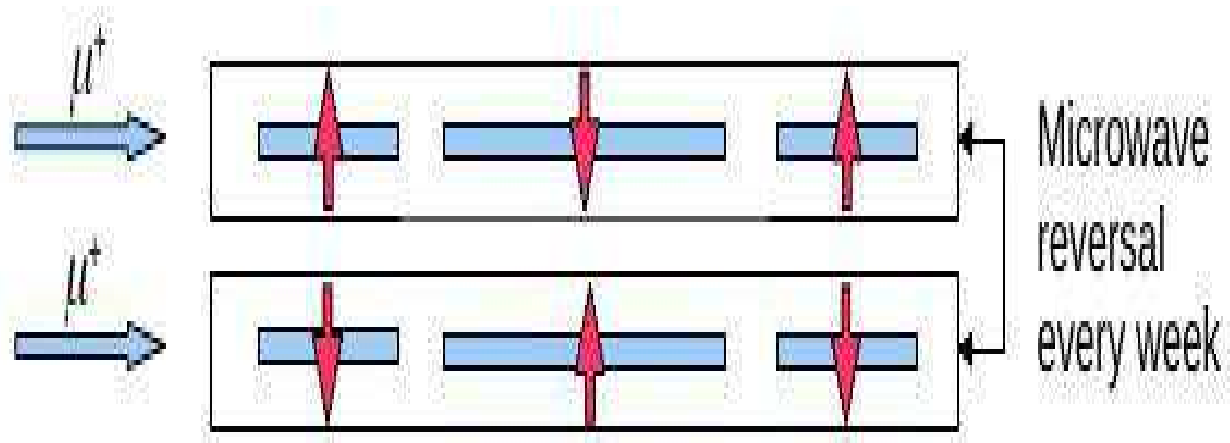
luminosity:  $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

energy: 160 GeV

polarization  $\approx 80 \%$



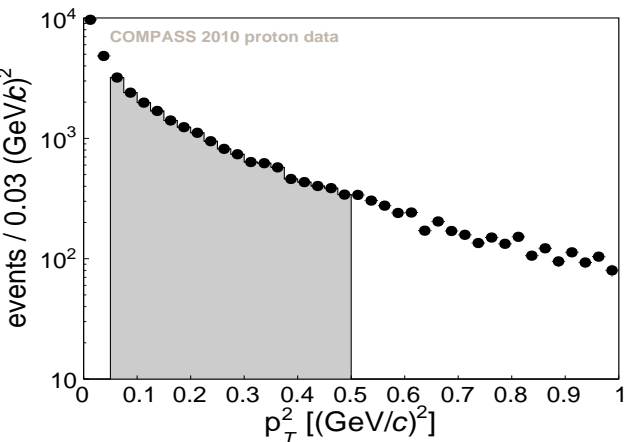
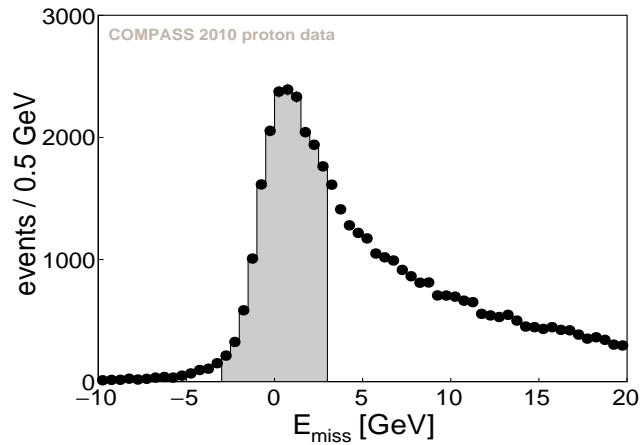
# Polarized target



- Two 30cm and one 60cm long cylindrical target cells
- with opposite polarization
- material:  $\text{NH}_3$  (protons)
- Microwave reversal every week
- Dilution factor for  $\rho^0 \approx 25\%$



# Exclusive $\omega$ -meson production at COMPASS



- Transversely polarized Target ( $\text{NH}_3$ ), 2010 data

$$\mu N \rightarrow \mu' N' \omega$$

$$\begin{array}{l} \searrow \rightarrow \pi^+ \pi^- \pi^0 \quad \text{BR} \approx 89\% \\ \searrow \rightarrow \gamma\gamma \quad \text{BR} \approx 99\% \end{array}$$

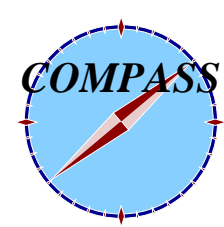
- Event contains three outgoing tracks ( $\mu + h^+, h^-$ ), and only two ECAL clusters time-correlated with beam, checked that they are not caused by charged particles.

- $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$  with  $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-} - p_{\pi^0})^2$  and  $M_X$  being missing mass,  $p, q, p_{\pi^+}, p_{\pi^-}, p_{\pi^0}$  are 4-momenta of proton,  $\gamma^*$  and pions.

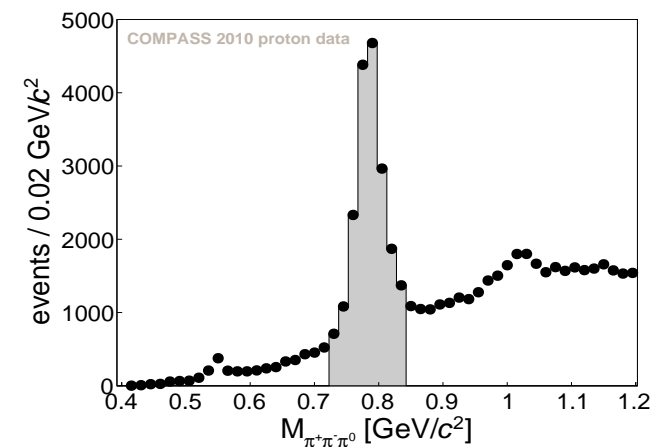
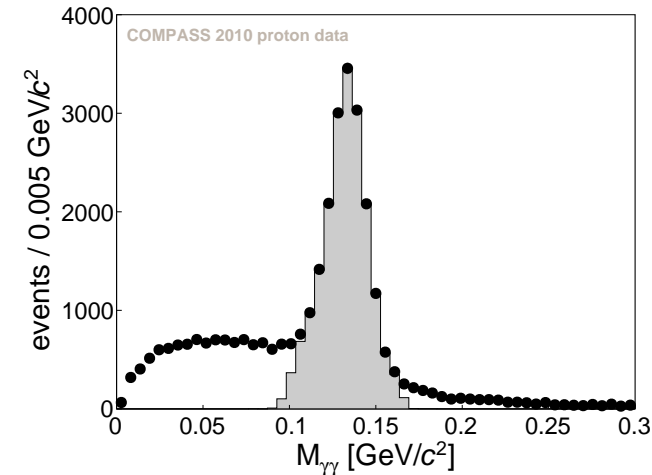
- Exclusive process  $E_{miss} = 0$

- $-3.0 \text{ GeV} < E_{miss} < 3.0 \text{ GeV}$

- $0.05 < P_T^2 < 0.5 \text{ GeV}^2$  to remove coherent production, to suppress non-exclusive background. Squared transverse momentum of  $\omega$  w.r.t  $\gamma^*$



# Exclusive $\omega$ -meson production at COMPASS

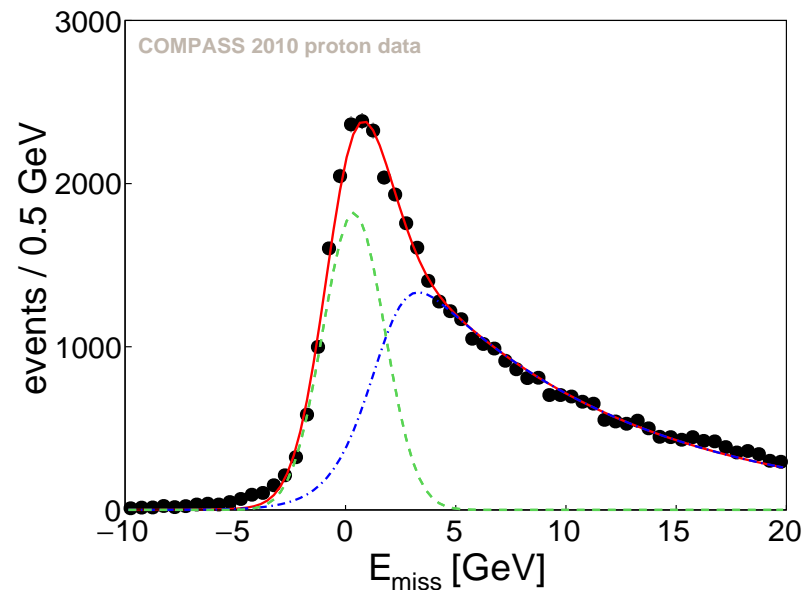


- $Q^2 = -q^2 = -(k - k')^2 = 1.0 \div 10. \text{ GeV}^2, \langle Q^2 \rangle = 2.2 \text{ GeV}^2$
- $W = \sqrt{(q + p)^2} > 5.0 \text{ GeV}, \langle W \rangle = 7.1 \text{ GeV}$
- $x_B = \frac{Q^2}{2pq} = 0.003 \div 0.35, \langle x_B \rangle = 0.049$
- $|M_{\gamma\gamma} - M_{\pi^0, \text{par}}(E_{\gamma\gamma})| < 3 \sigma_{\text{par}}(E_{\gamma\gamma}), \pi^0$  peak are parametrised using semiinclusive data for  $\pi^0$  mesons
- $|M_{\pi^+\pi^-\pi^0} - M_{\omega}^{\text{PDG}}| < 70 \text{ MeV}/c^2$ , where  $M_{\omega}^{\text{PDG}} = 782.65 \text{ MeV}/c^2$  is the nominal  $\omega$  resonance mass.
- Number of  $\omega$  events : **18500**



# Extraction of asymmetries

- Unbinned maximum likelihood method with simultaneous fit of signal and background asymmetries (16 - parameter fit).
- It is assumed that background asymmetries in the exclusive region is the same as in the range  $7 \text{ GeV} < E_{\text{miss}} < 20 \text{ GeV}$ .
- Fraction of background was found for each target cell and polarization state
  - Shape of semi-inclusive background from MC(LEPTO with COMPASS tuning + simulation of spectrometer chain + reconstruction as for real data).
  - MC weighted using ratio between real data and MC for the same charge combination sample ( $h^+ h^+ \gamma\gamma + h^- h^- \gamma\gamma$ )



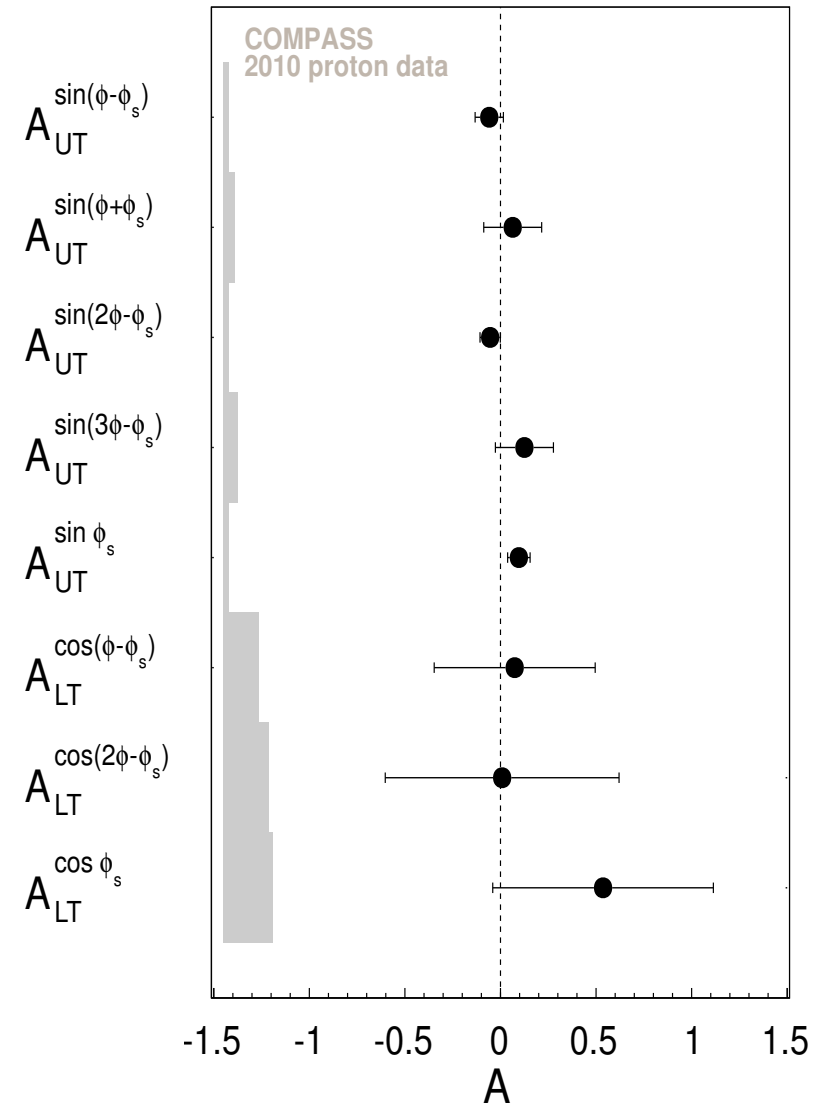
$$w_i = \frac{N_{i, \text{data}}^{\pi^+ \pi^+ \pi^0} + N_{i, \text{data}}^{\pi^- \pi^- \pi^0}}{N_{i, \text{MC}}^{\pi^+ \pi^+ \pi^0} + N_{i, \text{MC}}^{\pi^- \pi^- \pi^0}}$$

Here,  $N_{i, \text{data}}^{\pi^\pm \pi^\pm \pi^0}$  and  $N_{i, \text{MC}}^{\pi^\pm \pi^\pm \pi^0}$  are the numbers of events observed in bin  $i$  for experimental data and MC, respectively

Gaussian function (signal) + shape function from MC(bkg)



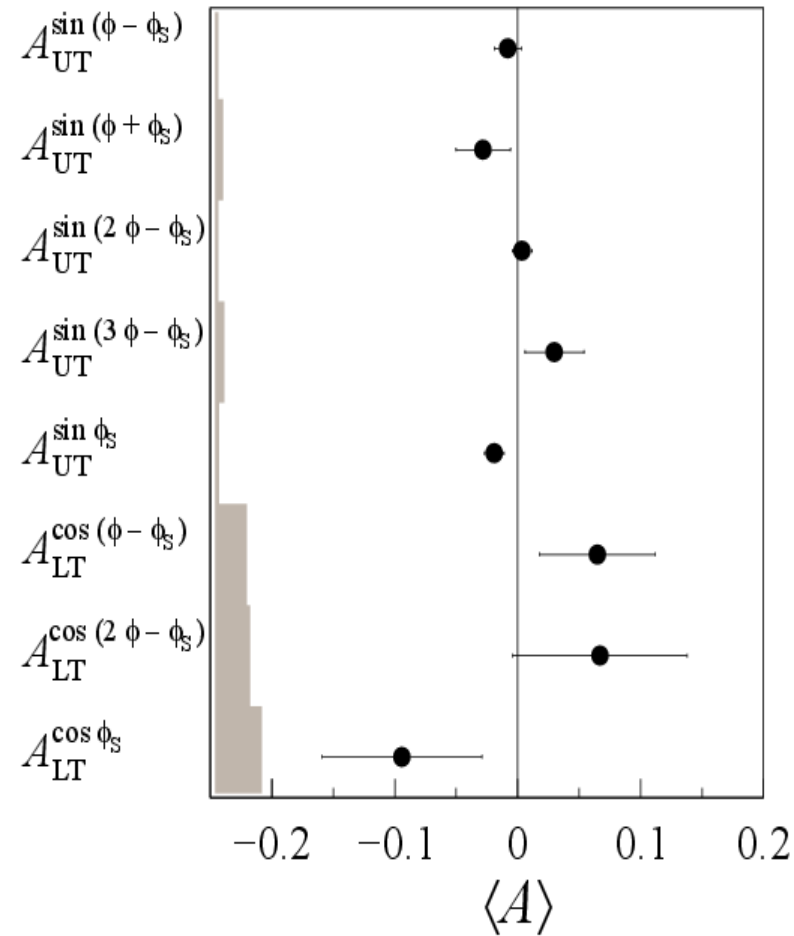
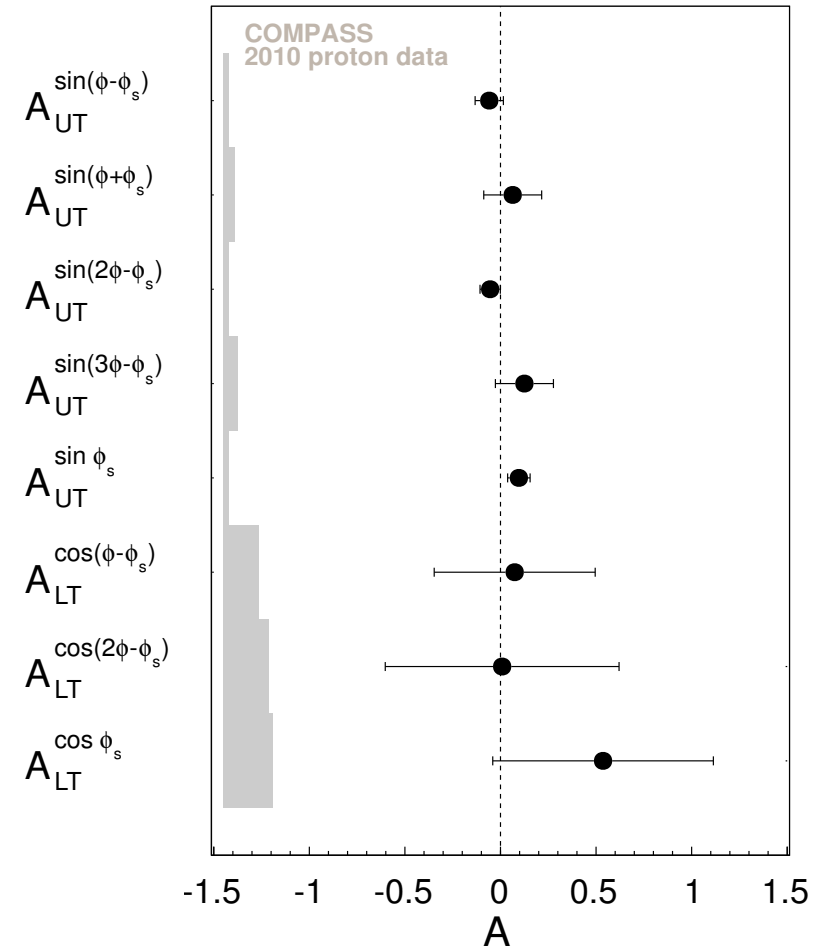
# Transverse target spin asymmetry



- Unbinned maximum likelihood method.
- Five **single spin asymmetries** and three **double spin asymmetries** for exclusive  $\omega$  muoproduction on transversely polarized proton target. The error bars (left bands) represents the statistical (systematic) uncertainties, respectively.
- $Q^2 = 2.2 \text{ GeV}^2$ ,  $x_{Bj} = 0.049$ ,  $p_T^2 = 0.17 \text{ GeV}^2$   $W = 7.1 \text{ GeV}$



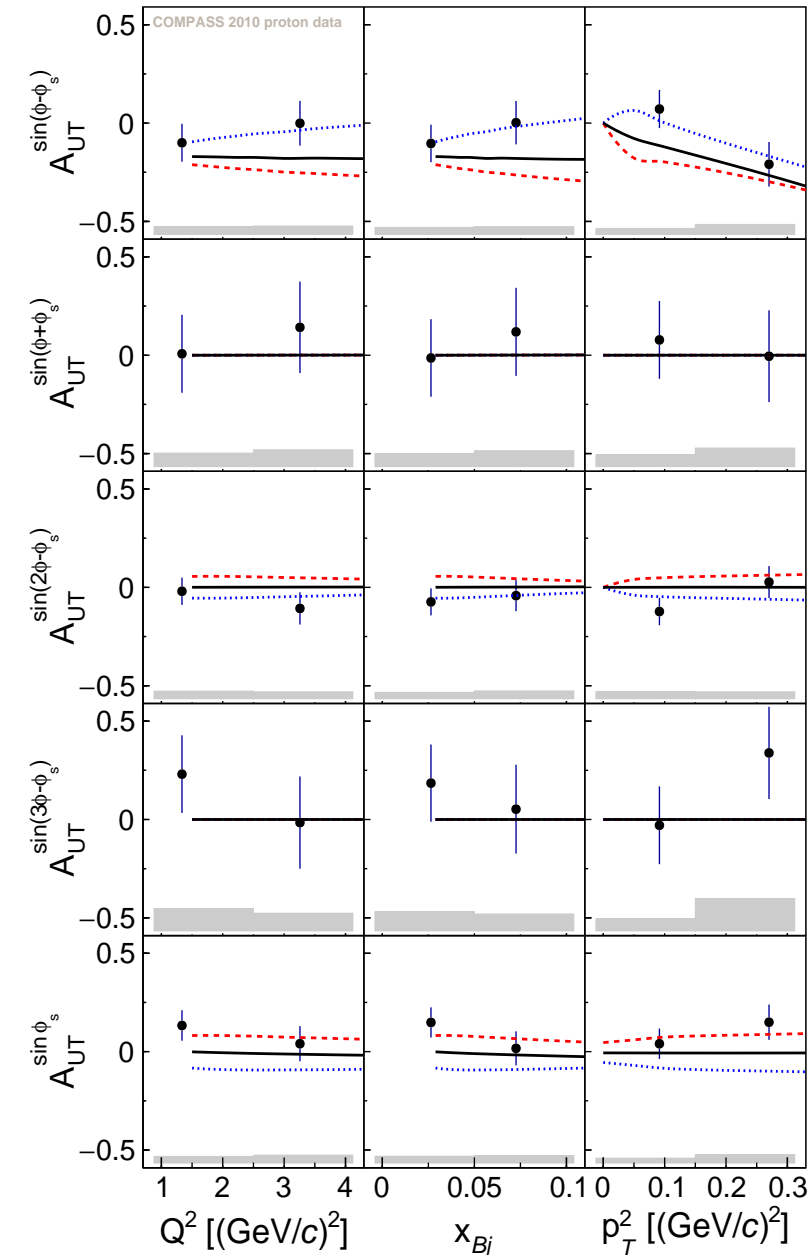
# Comparison of transverse target spin asymmetry for $\omega$ and $\rho$



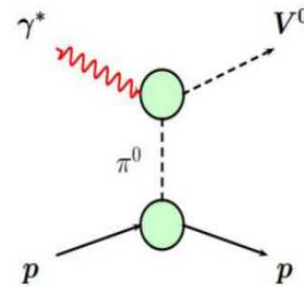
Comparison of  $\omega$  and  $\rho$  results in principle may offer the possibility to disentangle contribution of GPDs for u and d quarks.



# Kinematic dependence of single spin asymmetries



- Unbinned maximum likelihood method.
- Single spin azimuthal asymmetries as a function of  $Q^2$ ,  $x_{Bj}$ , and  $p_T^2$ . The curves show the predictions of the Goloskokov-Kroll model with added  $\pi^0$  pole exchange.



Parameters constrained by HERMES SDMEs for  $\omega$

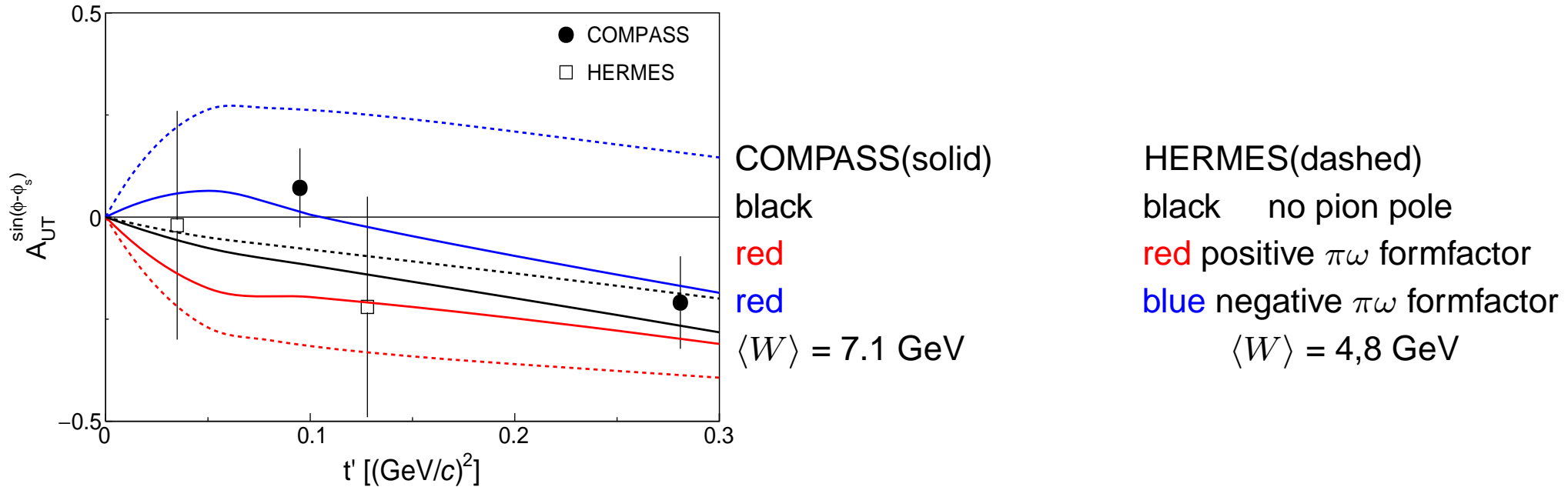
black curve without the pion pole

dashed curves positive  $\pi\omega$  formfactor

dotted curves negative  $\pi\omega$  formfactor

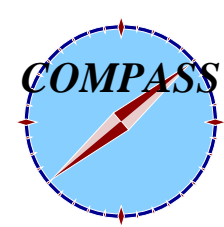


# Comparison between COMPASS and HERMES



- The asymmetry  $A_{UT}^{\sin(\phi-\phi_S)}$  for exclusive  $\omega$  leptonproduction measured by the COMPASS (filled circles) and HERMES (open squares) collaborations as a function of  $t'$ .
- Contribution of pion pole decreases with  $W$ .
- COMPASS uncertainties smaller by a factor  $>2$ .
- These data do not allowed unambiguously determined the sign of  $\pi\omega$  formfactor





# Summary

- Exclusive  $\omega$  muoproduction is studied at COMPASS using a longitudinally polarized muon beam and polarized proton target at the average kinematic values of are  $\langle Q^2 \rangle = 2.2 \text{ GeV}^2$ ,  $\langle W \rangle = 7.1 \text{ GeV}$ ,  $\langle p_T^2 \rangle = 0.17 \text{ GeV}^2$ . and  $\langle x_{Bj} \rangle = 0.049 \text{ GeV}^2$ .
- Using an unbinned maximum likelihood method, **five single spin asymmetries** and **three double spin asymmetries** are extracted.
- Kinematic dependence of single spin asymmetries is compared to Goloskokov - Kroll model with added pion pole exchanges.
- These data do not allowed unambiguously determined the sign of  $\pi\omega$  formfactor