Exclusive $\omega$ meson production at COMPASS

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• Formalism: GPDs, cross section, asymmetries
• COMPASS experiment
• Transverse target spin asymmetries for exclusive $\omega$ production in muon-nucleon scattering
• Summary and outlook
**Formalism: Generalised Parton Distributions (GPDs)**

**Hard Exclusive Meson Production**

\[ \gamma^* p \rightarrow V p' \]

**Chiral-even GPDs**

- Helicity of parton unchanged
  - \( H^{q,g} (x, \xi, t) \)
  - \( \widetilde{H}^{q,g} (x, \xi, t) \)
  - \( E^{q,g} (x, \xi, t) \)
  - \( \widetilde{E}^{q,g} (x, \xi, t) \)

**Chiral-odd GPDs**

- Helicity of parton changed (not probed by DVCS)
  - \( H_T^{q} (x, \xi, t) \)
  - \( \widetilde{H}_T^{q} (x, \xi, t) \)
  - \( E_T^{q} (x, \xi, t) \)
  - \( \widetilde{E}_T^{q} (x, \xi, t) \)

**Flavour separation for GPDs**

Example of ‘effective’ GPDs:

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

- Contribution from gluons at the same order of \( \alpha_s \) as from quarks

**Note:**

- Large \( Q^2 \) and \( W, -t/Q^2 \ll 1 \)
- Factorization strictly proven only for longitudinal \( \gamma^* \)
GPD formalism – highlights

Nucleon tomography:

(quasi-) 3D parton distribution function:

\[ q(x,b) = \left( \frac{2 \pi}{\Delta} \right)^{-2} \int d^2 \Delta e^{-ib \cdot \Delta} H^q(x,0,t=-\Delta^2) \]

where:

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

\[ H^q(x,0,t=-\Delta^2) \]

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

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

Transversity:

\[ H^q_T(x,0,0) = h^q_T(x) \]
Cross section formula for exclusive meson production

\[
\frac{\alpha_{em}}{8\pi^3} \frac{y^2}{1-x_B} \left[ \frac{1}{Q^2} \right]^{-1} \frac{d\sigma}{d x_B dQ^2 d\phi d\phi_S} = \frac{1}{2} \left( \sigma^{++} + \sigma^{+-} \right) + \varepsilon \sigma^{++}_{00} - \varepsilon \cos(2\phi) \text{Re} \sigma^{++} - \sqrt{\varepsilon(1+\varepsilon)} \cos \phi \text{Re} \left( \sigma^{++}_{00} + \sigma^{+-} \right) \\
- P_\ell \sqrt{\varepsilon(1-\varepsilon)} \sin \phi \text{Im} \left( \sigma^{++}_{00} + \sigma^{+-} \right) \\
- S_L \left[ \varepsilon \sin(2\phi) \text{Im} \sigma^{++} + \sqrt{\varepsilon(1+\varepsilon)} \sin \phi \text{Im} \left( \sigma^{++}_{00} - \sigma^{+-} \right) \right] \\
+ S_L P_\ell \left[ \sqrt{1-\varepsilon^2} \frac{1}{2} \left( \sigma^{++} - \sigma^{+-} \right) - \sqrt{\varepsilon(1-\varepsilon)} \cos \phi \text{Re} \left( \sigma^{++}_{00} - \sigma^{+-} \right) \right] \\
- S_T \left[ \sin(\phi - \phi_S) \text{Im} \left( \sigma^{++} + \varepsilon \sigma^{++}_{00} \right) + \frac{\varepsilon}{2} \sin(\phi + \phi_S) \text{Im} \sigma^{++} + \frac{\varepsilon}{2} \sin(3\phi - \phi_S) \text{Im} \sigma^{++} \right] \\
+ \sqrt{\varepsilon(1+\varepsilon)} \sin \phi_S \text{Im} \sigma^{+-} + \sqrt{\varepsilon(1+\varepsilon)} \sin(2\phi - \phi_S) \text{Im} \sigma^{++}_{00} \right] \\
+ S_T P_\ell \left[ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) \text{Re} \sigma^{++} \right] \\
- \sqrt{\varepsilon(1-\varepsilon)} \cos \phi_S \text{Re} \sigma^{+-}_{00} - \sqrt{\varepsilon(1-\varepsilon)} \cos(2\phi - \phi_S) \text{Re} \sigma^{++}_{00} \right] .
\]

\( \sigma_{mn}^{ij} \): helicity-dependent photoabsorption cross sections and interference terms

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

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

\[
\epsilon = \frac{1-y-\frac{1}{4}y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2} \\
y = 2 x_{Bj} M_p / Q
\]
5 transverse-target single-spin asymmetries and 3 transverse-target double-spin asymmetries

\[
A_{UT}^{\sin (\phi - \phi_s)} = -\frac{\text{Im} \left( \sigma_{++}^+ + e \sigma_{00}^+ \right)}{\sigma_0}
\]

\[
A_{UT}^{\sin (2 \phi - \phi_s)} = -\frac{\text{Im} \sigma_{0+}^-}{\sigma_0}
\]

\[
A_{UT}^{\sin \phi_s} = -\frac{\text{Im} \sigma_{++}^+}{\sigma_0}
\]

\[
A_{UT}^{\sin (3 \phi - \phi_s)} = -\frac{\text{Im} \sigma_{+-}^-}{\sigma_0}
\]

\[
A_{UT}^{\sin (\phi + \phi_s)} = -\frac{\text{Im} \sigma_{+-}^-}{\sigma_0}
\]

unpolarised cross section

\[
\sigma_0 = \frac{1}{2} \left( \sigma_{++}^+ + \sigma_{+-}^- \right) + e \sigma_{00}^+ = \sigma_L + e \sigma_T
\]
Effect known since early photoproduction experiments

- At COMPASS kinematics:
  - small for $\rho^0$ production
  - sizable for $\omega$ production

- Unnatural parity exchange process
  → impact on helicity-dependent observables

- Crucial for description of SDMEs for excl. $\omega$ production

- Sign of $\pi\omega$ form factor not resolved from SDME data
  → azimuthal asymmetries more sensitive

\[ @ W=4.8 \text{ GeV}, Q^2=2.42 \text{ GeV}^2 \]
\[ @ W=8 \text{ GeV}, Q^2=2.42 \text{ GeV}^2 \]
Wolf-Dieter Nowak

COMPASS experiment at CERN – setup with transversely polarized target

μ⁺ beam from the SPS accelerator

- Luminosity: $5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Energy: 160 GeV
- Polarization: ≈ 80%

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

- Material: NH₃ (protons) [$^6\text{LiD (deuterons)}$]
- Polarization: ≈90% [≈50%]
- Dilution factor for exclusive $\rho^0$ production: ≈25% [≈44%]

Microwave reversal every week
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

**Used data:**

\[ \mu N \rightarrow \mu N \omega \]
\[ \rightarrow \pi^+ + \pi^- + \pi^0 \]
\[ \rightarrow \gamma + \gamma \]

2010 (transversely polarised protons)

**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:**

- \( 1 \text{ (GeV/c)}^2 < Q^2 < 10 \text{ (GeV/c)}^2 \)
- \( W > 5 \text{ GeV} \)
- \( 0.1 < y < 0.9 \)
- \( 0.003 < x_{Bj} < 0.35 \)
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

**Missing energy and energy of $\omega$ candidate**

- Check if the proton stayed intact
  \[ E_{\text{miss}} = \frac{M_x^2 - M_p^2}{2 M_p} \in (-3, 3) \text{ GeV} \]
  \[ E_{\text{miss}} = 0 \] is the signature of exclusivity
- Check if $E_\omega > \nu_{\text{min}}$ (minimal energy of $\gamma^*$ allowed by the kinematic cuts)
  \[ E_\omega > 15 \text{ GeV} \]

**Squared transverse momentum of $\omega$ candidate w.r.t. $\gamma^*$**

To remove coherent production off target nuclei
\[ 0.05 < p_T^2 \left[ \text{GeV} / c \right]^2 \]
To suppress non-exclusive
\[ p_T^2 < 0.5 \left[ \text{GeV} / c \right]^2 \]
Extraction of asymmetries

- 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 \( (h^+h^+\gamma\gamma + h^-h^-\gamma\gamma) \)

\[
\omega(E_{miss}) = \frac{N_{RD}^{h^+h^+\gamma\gamma} E_{miss} + N_{RD}^{h^-h^-\gamma\gamma} E_{miss}}{N_{MC}^{h^+h^+\gamma\gamma} E_{miss} + N_{MC}^{h^-h^-\gamma\gamma} E_{miss}}
\]

Normalization of MC to the real data using two component fit Gaussian function (signal) + shape from MC (bkg)
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

New result → to be published

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

$Q^2 = 2.2 \text{ GeV}^2$
$x_{Bj} = 0.049$
$p_T^2 = 0.17 \text{ GeV}^2$
$W = 7.1 \text{ GeV}$
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

New result → to be published

GK model predictions

private communication

- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor
Comparison between COMPASS and HERMES

COMPASS

HERMES

GK predictions @ COMPASS kinematics

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 $\rho$ production
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

**Used data:**

- 2007, 2010 (transversely polarised protons)
- 2003, 2004 (transversely polarised deuterons)

**Kinematics domain:**

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

**Topology of vertex:**

- One incoming and one outgoing muon track
- Two hadron tracks of opposite charges

**Diagram:**

- Black line: proton data
- Red line: deuteron data
Missing energy and energy of $\rho^0$ candidate

- Check if the proton is intact
  \[ E_{\text{miss}} = \frac{M_x^2 - M_p^2}{2 M_p} \in (-2.5, 2.5) \text{ GeV} \]
  \[ E_{\text{miss}} = 0 \] is the signature of exclusivity

- Check if $E \rho^0 > \gamma_{\text{min}}$ (minimal energy of $\gamma^*$ allowed by the kinematic cuts)
  \[ E_{\rho^0} > 15 \text{ GeV} \]

Squared transverse momentum of $\rho^0$ candidate w.r.t. $\gamma^*$

To remove coherent production off target nuclei
  \[ 0.05 < p_T^2 \left(\text{GeV/c}\right)^2 \] for protons
  \[ 0.1 < p_T^2 \left(\text{GeV/c}\right)^2 \] for deuterons

To suppress non-exclusive background
  \[ p_T^2 < 0.5 \left(\text{GeV/c}\right)^2 \]
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

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

\[ A_{UT}^{\sin (\phi - \phi_s)} = -2 \text{Im} \left[ e^{M_{0,-,0}^* M_{0,+,-}} + e^{M_{+,++,}^* M_{--,+}} + \frac{1}{2} e^{M_{0,-,0}^* M_{0,+,-}} \right] \]

\[ A_{UT}^{\sin (2 \phi - \phi_s)} = -\text{Im} \left[ e^{M_{0,+,-}^* M_{0,-,0}} \right] \]

\[ A_{UT}^{\sin \phi_s} = -\text{Im} \left[ e^{M_{0,-,0}^* M_{0,+,-}} - e^{M_{+,++,}^* M_{--,+}} \right] \]

\[ A_{LT}^{\cos (\phi - \phi_s)} = -\text{Re} \left[ e^{M_{0,-,0}^* M_{0,+,-}} - e^{M_{+,++,}^* M_{--,+}} \right] \]

\[ A_{LT}^{\cos \phi_s} = -\text{Re} \left[ e^{M_{0,-,0}^* M_{0,+,-}} + e^{M_{+,++,}^* M_{--,+}} \right] \]

\[ x_B \approx 0.039 \]

\[ Q^2 \approx 2.0 \text{[GeV}/c]^2 \]

\[ p_T^2 \approx 0.18 \text{[GeV}/c]^2 \]
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

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

- $A_{UT}^{\sin(\phi - \phi_S)}$ 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

**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 $\gamma^*_L$ and $\gamma^*_T$
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ 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 \\
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Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

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\[
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\]