Exclusive meson production at COMPASS

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on behalf of the COMPASS experiment

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Theoretical framework (GPD formalism)

COMPASS experiment

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

Exclusive $\pi^0$ production

GPDs at COMPASS-II

Summary and outlook
### GPD formalism

**GPDs (Generalized Parton Distributions):**

<table>
<thead>
<tr>
<th>$H^{q,g}(x,\xi,t)$</th>
<th>$E^{q,g}(x,\xi,t)$</th>
<th>for sum over parton helicities (vector mesons)</th>
</tr>
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<td>$\tilde{H}^{q,g}(x,\xi,t)$</td>
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<td>for difference over parton helicities (pseudoscalar mesons)</td>
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for retained proton helicity for changed proton helicity

where:

- $x$: average longitudinal momentum fraction of the parton
- $2\xi$: longitudinal momentum fraction transferred by the parton

$$\xi \approx \frac{x_{Bj}}{2-x_{Bj}}$$

- $t$: squared momentum transferred to the target nucleon

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**Dependence of meson production on different GPDs:**

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

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

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

- **DVMP can be used as quark flavor filter**
- **contribution from gluons at the same order of $\alpha_s$ as from quarks**

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*Deeply Virtual Meson Production*  
$\gamma^* p \rightarrow V p'$

(for factorization strictly proven only for longitudinal $\gamma^*$)
Nucleon tomography:
3D parton distribution function:

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

where:

- \(b\) : impact parameter

Total angular momentum:

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

(Ji’s sum rule)

where:

\[ J^q = L^q + S^q \]

Angular momentum conservation law

if proton helicity is changed (\( E^q, \tilde{E}^q \neq 0 \)) orbital angular momentum must be involved
Access to GPDs through the exclusive meson production

Cross-section for exclusive meson production (only relevant elements are shown):

\[
\left[ \frac{\alpha}{8\pi^3} \frac{y^2}{1-\epsilon} \frac{1-x_{Bj}}{x_{Bj}} \frac{1}{Q^2} \right]^{-1} \frac{d\sigma}{dx_{Bj}dQ^2dtd\phi d\phi_s} \approx \frac{1}{2} \left( \sigma_{++}^{++} + \sigma_{--}^{--} \right) + \epsilon \sigma_{00}^{+0} - S_T I m \left( \sigma_{++}^{--} + \epsilon \sigma_{00}^{--} \right) \sin(\phi - \phi_s) + ...
\]

\[
\approx \sigma_0 \cdot \left( 1 + S_T A_{UT}^{\sin(\phi-\phi_s)} \sin(\phi - \phi_s) \right) + ...
\]

where:

\( \sigma_{mn}^{ij} \): spin-dependent photoabsorption cross section or interference terms

\( \sigma_{mn}^{ij}(x_B, Q^2, t) \propto \sum_{\text{spins}} (A_m^{i})^* A_n^{j} \)

\( A_m^{i} \): amplitude for subprocess \( \gamma^* p \rightarrow V p' \) with photon helicity \( m \) and target proton helicity \( i \)

\( \phi \): azimuthal angle between lepton plane and hadron plane

\( \phi_s \): azimuthal angle between target spin vector and lepton plane

\[
\sigma_0 = \frac{1}{2} \left( \sigma_{++}^{++} + \sigma_{--}^{--} \right) + \epsilon \sigma_{00}^{+0} \approx \sigma_T + \epsilon \sigma_L
\]

\[
A_{UT}^{\sin(\phi-\phi_s)} = - \frac{I m \left( \sigma_{++}^{--} + \epsilon \sigma_{00}^{--} \right)}{\sigma_0}
\]

\[
\epsilon = \left( 1 - y - \frac{1}{4} y^2 \gamma^2 \right) \left( 1 - y + \frac{1}{2} y^2 + \frac{1}{4} y^2 \right)
\]

\[
y = 2x_{Bj} M_p / Q
\]
Access to GPDs through the exclusive meson production

For vector mesons:

\[
\frac{1}{\Gamma'} \frac{d \sigma_{00}^{++}}{dt} = (1 - \xi^2)|H_M|^2 - \left(\frac{\xi^2 + \frac{t}{4M_p^2}}{1 + \frac{t}{4M_p^2}}\right)|E_M|^2 - 2\xi^2 \text{Re}(E_M^* H_M)
\]

\[
\sigma_0 = \frac{1}{2} \left(\sigma_{++} + \sigma_{++}^* + \epsilon \sigma_{00}^{++}\right) \equiv \sigma_T + \epsilon \sigma_L
\]

\[
\frac{1}{\Gamma'} \text{Im} \frac{d \sigma_{00}^{+-}}{dt} = -\sqrt{1 - \xi^2} \sqrt{t_0 - t} \text{Im}(E_M^* H_M)
\]

transverse target spin asymmetry

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

where:

- \(H_M, E_M\) are convolutions of the GPDs \(H^{q,g}, E^{q,g}\) with hard scattering kernel and meson DA

\[
\Gamma' = \frac{\alpha_{em}}{Q^6} \frac{x_B^2}{1 - x_B}
\]

\[
t_0 = \frac{4\xi^2 M_p^2}{1 - \xi^2}
\]

\[
\xi \approx \frac{x_B}{2 - x_B}
\]
COMPASS experiment at CERN – 2010 setup

μ⁺ beam from the SPS accelerator

- Luminosity: \(5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
- 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: \(\text{NH}_3\) (protons) \([^6\text{LiD} \text{ (deuterons)}]\)
- Polarization: ≈90% \([\approx50\%]\)
- Dilution factor for exclusive \(\rho^0\) production: ≈25% \([\approx44\%]\)

Microwave reversal every week

Paweł Sznajder
DIFF 2012
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

**μ N → μ N $\rho^0$**

$\pi^+ + \pi^-$

**Used data:**
- 2003 – 2004 (deuterons)
- 2007, 2010 (protons)

**Kinematics domain:**
- $Q^2 > 1$ (GeV/c)$^2$
- $W > 5$ GeV

**Target polarization**
- $0.1 < y < 0.9$
- $0.003 < x_{Bj} < 0.35$

**Topology:**
- only incoming and outgoing muon tracks,
- two hadron tracks of opposite charges in PV

**Proton data (~797 000 events)**
**Deuterons data (~97 000 events)**

**Invariant mass**
- Pion mass is assumed for each outgoing hadron track
- $0.5 < M_{\pi\pi} < 1.1$ GeV/c$^2$

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

**Squared transverse momentum of $\rho^0$ candidate w.r.t. $\gamma^*$**
- To remove coherent production off target nuclei
  - $0.05 < p_t^2$ (GeV/c)$^2$ for protons
  - $0.01 < p_t^2$ (GeV/c)$^2$ for deuterons
- To suppress non-exclusive background
  - $p_t^2 < 0.5$ (GeV/c)$^2$

**Asymmetry extracted for each kinematic bin from a fit of the number of signal events (i.e. after correction for SIDIS background) in 12 bins of $\phi$ - $\phi_s$ for each of the two target cells and polarization state (+,-)**
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

COMPASS results  

<table>
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<tr>
<th>$x_B$</th>
<th>$Q^2$</th>
<th>$p_T^2$</th>
</tr>
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<tr>
<td>$\langle x_B \rangle \approx 0.039$</td>
<td>$\langle Q^2 \rangle \approx 2.0 \text{ (GeV}/c)^2$</td>
<td>$\langle p_T^2 \rangle \approx 0.18 \text{ (GeV}/c)^2$</td>
</tr>
<tr>
<td>$\langle x_B \rangle \approx 0.032$</td>
<td>$\langle Q^2 \rangle \approx 2.2 \text{ (GeV}/c)^2$</td>
<td>$\langle p_T^2 \rangle \approx 0.23 \text{ (GeV}/c)^2$</td>
</tr>
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- $A_{UT}^{\sin(\phi-\phi_s)}$ for transversely polarised protons and deuterons compatible with 0
- reasonable agreement with predictions of the GPD model of Goloskokov - Kroll
- for proton data agreement with HERMES results  
  COMPASS results with statistical errors improved by factor 3 and extended kinematic range
- for deuteron data the first measurement

Goloskokov and Kroll  

- “handbag model”
- GPDs constrained by CTEQ6 parametrization and nucleon form factors
- power corrections due to transverse quarks momenta
- predictions both for $\gamma^*_L$ and $\gamma^*_T$
Exclusive $\pi^0$ production

$\mu \, N \rightarrow \mu \, N \, \pi^0 \quad \rightarrow \gamma + \gamma$

**Used data:**
2009 DVCS test run with 40cm LH target and 1m Recoil Proton Detector

**Topology:**
only incoming and outgoing muon tracks in PV +
only two photons in first ECAL with $E > 5\text{GeV}$

- $Q^2 > 1\text{ GeV}$

$\Delta \phi = \phi_{\text{Miss}} - \phi_{\text{RPD}}$

$\Delta \phi < 30\text{ deg}$

$\Delta p_T = p_{T \, \text{Miss}} - p_{T \, \text{RPD}}$

$\Delta p_T < 0.34\text{ GeV/c}$

$E_{\text{Miss}} = E_\mu + M_p - E_\mu' - E_p' - E_{\pi^0}$

Emiss after $\Delta \phi$ and $\Delta p_T$ cuts

Emiss resolution $\sim 2\text{ GeV}$

23 exclusive $\pi^0$ events (more than expected)

Production sensitive to GPDs $\tilde{H}, \tilde{E}$ and $H_T, E_T$

In progress calculation of cross section
The GPD program at COMPASS will explore intermediate $x_{\text{Bj}}$ (0.01-0.10) and large $Q^2$ (up to ~15 GeV$^2$) range.

COMPASS will be the only experiment in this range before availability of new colliders.

For several years COMPASS unique due to availability of lepton beams of both charge.
Future GPD program at COMPASS-II – experimental setup

**Liquid Hydrogen target**
- length 2.5m

**Recoil Proton Detector (CAMERA)**
- 4m long ToF barrel of two scintillator layers
- recoil proton ID by ToF and ∆E

**Large angle Electromagnetic Calorimeter**
- size 204cm x 204cm x 34cm
- hole size 84cm x 60cm
- granularity 4cm x 4cm
Measurement of t-slope for exclusive $\rho^0$ production

sensitive to transverse size of nucleon – meson system
(at large $Q^2$ mostly sensitive to transverse size of nucleon $r_\perp$)

- $Q^2$ and $\nu$ parametrization of cross section from NMC data
  normalized to Goloskokov and Krol predictions
- 160 GeV muon beam
- global efficiency $\epsilon = 10\%$
- $L = 1.2 \text{ nb}^{-1}$ (2 years of data taking) 1/40 statistics expected in 2012 pilot
Summary and outlook

- Exclusive meson production → flavor separation for GPDs

- Transverse target spin asymmetry $A_{UT} \sin(\phi - \phi_s)$ for exclusive $\rho^0$ production was measured both for protons and deuterons
  - Asymmetries are small, compatible with 0
  - Results compatible with HERMES experiment and with GPD predictions by S. V. Goloskokov and P. Kroll
  - In progress measurement for $\phi$ and $\omega$

- Exclusive $\pi^0$ production has been observed
  - Production sensitive to GPDs $\tilde{H}$, $\tilde{E}$ and $H_T$, $E_T$
  - In progress calculation of cross section

- GPD program will be continued at COMPASS-II
  - Data taking in 2012 (pilot) and 2015-2016 with LH target, RPD and new ECAL
  - Example of foreseen results → t-slope for exclusive $\rho^0$ production
  - Measurement with transversely polarized target ($NH_3$) with RPD is considered
The cross section formula for exclusive meson production

General formula for cross-section including beam and target polarization

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

\[
= \frac{1}{2} \left( \sigma_{++} + \sigma_{+-} \right) + \epsilon \sigma_{00} + \epsilon \cos(2\phi) \Re \sigma_{++} - \sqrt{\epsilon(1+\epsilon)} \cos\phi \Re(\sigma_{++} + \sigma_{00})
\]

\[
- P_L \sqrt{\epsilon(1+\epsilon)} \sin\phi \Im(\sigma_{++} + \sigma_{00})
\]

\[
- S_L \left[ \epsilon \sin(2\phi) \Im \sigma_{++} + \sqrt{\epsilon(1+\epsilon)} \sin\phi \Im(\sigma_{++} - \sigma_{00}) \right]
\]

\[
+ S_L P_L \left[ \sqrt{1-\epsilon^2} \frac{1}{2} \left( \sigma_{++} - \sigma_{--} \right) - \sqrt{\epsilon(1-\epsilon)} \cos\phi \Re(\sigma_{++} - \sigma_{00}) \right]
\]

\[
- S_T \left[ \sin(\phi - \phi_S) \Im \sigma_{++} + \epsilon \sigma_{00} + \frac{\epsilon}{2} \sin(\phi + \phi_S) \Im \sigma_{+-} + \frac{\epsilon}{2} \sin(3\phi - \phi_S) \Im \sigma_{++}
\]

\[
+ \sqrt{\epsilon(1+\epsilon)} \sin\phi_S \Im \sigma_{++} + \sqrt{\epsilon(1+\epsilon)} \sin(2\phi - \phi_S) \Im \sigma_{00}
\]

\[
+ S_T P_L \left[ \sqrt{1-\epsilon^2} \cos(\phi - \phi_S) \Re \sigma_{++}
\]

\[
- \sqrt{\epsilon(1-\epsilon)} \cos\phi_S \Re(\sigma_{++} - \sqrt{\epsilon(1-\epsilon)} \cos(2\phi - \phi_S) \Re(\sigma_{++} + \sigma_{00}) \right].
\]

\[
\epsilon = \frac{1-y-\frac{1}{4}y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2} \quad \gamma = 2x_{Bj}M_p/Q
\]
The COMPASS polarized target includes:

- 3 target cells with opposite polarization
- 2 magnets to hold and rotate polarization:
  - solenoid: 2.5T
  - dipol: 0.5T
- Acceptance of ±180 mrad for upstream edge
- $^3$He – $^4$He mixture used to refrigerate (T~50mK)

The diagram shows the position of PV along the beam direction for incoherent exclusive $\rho^0$ production.
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production – bkg rejection

For every kinematic bin, bin of $\phi - \phi_s$, target cell and polarization state:

shape of semi-inclusive background from MC
(lepto with COMPASS tuning + simulation of spectrometer response + data reconstruction)

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

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

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