COMPASS results on hard exclusive muoproduction

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Main goals of the GPD program

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

\[ H(x, \xi=0, t) \rightarrow H(x, r_y,z) \]

probability interpretation (Burkardt)

**this talk**

- t-dependence of pure DVCS cross section on unpolarised protons

- Contribution to the nucleon spin puzzle

GPD E related to the orbital angular momentum

\[ 2J_q = \int x (H^q (x,\xi,0) + E^q (x,\xi,0)) \, dx \]

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + < L_z^q > + < L_z^g > \]

**this talk**

- Exclusive vector meson production on transversely polarised protons and deuterons
COMPASS experiment at CERN

Two basic ingredients of versatile COMPASS experimental setup

- **secondary beam line M2 from the SPS**
  - delivers: • high energy polarised $\mu^+$ or $\mu^-$ beams
  • negative or positive hadron beams

- **two-stage forward spectrometer SM1 + SM2**
  - $\approx 300$ tracking detectors planes – high redundancy
  - variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad
  - calorimetry, $\mu$ID, RICH

A flexibility to carry out a diverse physics programs by modifying mainly the target region

- spin structure of nucleons; polarised muon-nucleon scattering
- hadron spectroscopy in diffractive and central hadron production
- Primakoff reactions and test of chiral perturbative theory
- polarised and unpolarised Drell-Yan scattering
- GPD studies; DVCS and hard exclusive meson production
The COMPASS set-up for the GPD program (starting from 2012)

Main new equipments

2.5m-long Liquid H₂ Target

Target TOF System
24 inner & outer scintillators
1 GHz SADC readout
goal: 310 ps TOF resolv

ECAL0 Calorimeter
Shashlyk modules + MAPD readout
~ 2 × 2 m², ~2200 ch.
Mounting of Recoil Proton Detector (‘CAMERA’) in clean area at CERN
Recoil particle reconstruction in CAMERA

Proton signature clearly visible after exclusivity selections

\[ E_{\text{loss}} \sim \sqrt{\text{Ampl}_{\text{up}} \times \text{Ampl}_{\text{down}}} \]

\[ z_{A,B} \sim (t_{\text{up}} - t_{\text{down}})_{A,B} \]

\[ \text{ToF} = (t_{\text{up}} + t_{\text{down}})_{A,B} \]

\[ \beta = \frac{\text{DoF}}{\text{ToF}} \]

counting rate: > 5 MHz in ring A
~ 1 MHz in ring B

Proton signature clearly visible after exclusivity selections
**Extraction of DVCS cross section and amplitude**

**Beam Charge & Spin Sum**

\[
S_{CS,U} \equiv \frac{d\sigma(\mu^+)}{d\sigma(\mu^-)} = 2\left(\frac{d\sigma^{BH}}{d\sigma^{DVCS}} + \frac{d\sigma^{DVCS}_{unpol}}{d\sigma^{DVCS}_{pol}} + e_\mu P_\mu a^{BH} Im T^{DVCS}\right)
\]

\[c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos 2\phi \quad \text{Int} \rightarrow \text{Im}(\mathcal{F}_1 \mathcal{H})\]

\[s_1^{Int} \sin\phi + s_2^{Int} \sin 2\phi\]

**Beam Charge & Spin Difference**

\[
D_{CS,U} \equiv \frac{d\sigma(\mu^+)}{d\sigma(\mu^-)} - \frac{d\sigma(\mu^-)}{d\sigma(\mu^+)} = 2\left(e_\mu a^{BH} Re T^{DVCS} + P_\mu d\sigma^{DVCS}_{pol}\right)
\]

\[c_0^{Int} + c_1^{Int} \cos\phi + c_2^{Int} \cos 2\phi + c_3^{Int} \cos 3\phi \quad \text{Int} \rightarrow \text{Re}(\mathcal{F}_1 \mathcal{H})\]

\[s_1^{DVCS} \sin\phi\]

\[\text{Re} \mathcal{H} (\xi, t) = P \int dx \frac{H(x, \xi, t)}{x-\xi} = P \int dx \frac{H(x, x, t)}{x-\xi} + D(t)\]
Interplay of DVCS and BH at 160 GeV

**DVCS:**

**Bethe-Heitler:**

- BH dominates
- DVCS dominates
- BH and DVCS at the same level

**Low $x_B$: BH dominates**

- $|\text{BH+DVCS}|^2$
- $|\text{DVCS}|^2$
- $|\text{BH}|^2$

**Large $x_B$: DVCS dominates**

- $|\text{BH+DVCS}|^2$
- $|\text{DVCS}|^2$
- $|\text{BH}|^2$

BH dominates

BH and DVCS at the same level

DVCS dominates

excellent reference yield

access to DVCS amplitude through the interference

study of $d\sigma^{\text{DVCS}}/dt$
Selection of exclusive single photon events

Reconstructed vertex in the target volume
1 GeV^2 < Q^2 < 5 GeV^2, 10 GeV < \nu < 32 GeV
0.08 GeV^2 < |t| < 0.64 GeV^2
1 single photon with energy above DVCS threshold

Applied cut

Extended sample
For cross checks: beam flux, \pi^0 background
1 GeV^2 < Q^2 < 20 GeV^2, 8 GeV < \nu < 144 GeV
E_{Ecal(0,1,2)} > (4,5,10) GeV

Vertex pointing

\[ \Delta \phi = \phi_{meas}^{prot} - \phi_{recon}^{prot} \]

\[ \Delta p_T = p_{T,meas}^{prot} - p_{T,rec}^{prot} \]

\[ M_X^2 = (p_{in}^\mu + p_{in}^p - p_{out}^\mu - p_{out}^p - p_\gamma)^2 \]
Estimate of $\pi^0$ background

Major source of background for exclusive photon events

*Two cases:*

- **Visible:** detected second $\gamma$ (below DVCS threshold) $\Rightarrow$ events rejected from final sample
- **Invisible:** one $\gamma$ lost $\Rightarrow$ estimated from MC normalised to $\pi^0$ peak for ‘visible’ sample

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**Visible’ sample**

Semi-inclusive (LEPTO MC) or exclusive (HEPGEN MC based on Goloskokov-Kroll model)

$\pi^0$ contribution normalised to $M_{\gamma\gamma}$ peak

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**‘Invisible’ sample**

Relative contributions from both processes to $\pi^0$ background estimated from combined fits to the distributions of ‘exclusivity variables’ ($M_X^2$, $\Delta\phi$, $\Delta p_T$) and $E_{\text{miss}} = \nu - E_\gamma + t/(2m_p^2)$.
Exclusive $\gamma$ production from 2012 DVCS commissioning run

- dominant BH process at large $\nu$ (small $x_{\text{BJ}}$) clearly visible
- shape of $\phi$ distribution reproduced well by MC
- estimates of $\pi^0$ background contributing at small $\nu$ (large $x_{\text{BJ}}$)
- at small $\nu$ (large $x_{\text{BJ}}$) an excess of DVCS events above BH + background

for normalization of BH MC to the data beam flux measurement used
Transverse imaging of the proton using $d\sigma^{DVCS}/dt$

integrating $S_{CS,U}$ over $\phi$ and subtracting BH

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

'tomography': $B(x) \leftrightarrow \langle r_T^2(x) \rangle$

COMPASS-II projections for B-slope uncertainties

ansatz at small $x_B$
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2 \alpha' \ln(x_0/x_B)$

$\alpha'$ slope of Regge traj ect.

Predictions from COMPASS-II proposal
for 40 weeks in 2016-17

From 4 weeks of 2012 commissioning data
the first measurement of B-slope for DVCS
an $x_B$ above HERA range
COMPASS acceptance for DVCS

Binning of acceptance in $Q^2$, $\nu$ and $|t|$

Recall:

$$
\frac{d^3 \sigma^{\mu p}}{dQ^2 d\nu dt} = \Gamma \frac{d\sigma^{\gamma^* p}}{dt}
$$

with the virtual photon flux $\Gamma = \Gamma (Q^2, \nu)$
DVCS cross section and t-slope

$\sigma(\gamma^* p \rightarrow \gamma p)$ (nb (GeV/c)$^{-2}$)

$\langle x_{Bj} \rangle = 0.056$
$\langle Q^2 \rangle = 1.8$ (GeV/c)$^2$
$\langle W \rangle = 5.8$ GeV/c

COMPASS 2012

$B = 4.31 \pm 0.62 \pm 0.09$ (GeV/c)$^{-2}$

$1 \text{ (GeV/c)}^2 < Q^2 < 5 \text{ (GeV/c)}^2$
$10 \text{ GeV} < \nu < 32 \text{ GeV}$

Preliminary
Comparison of t-slope B to HERA results

Model independent result

- COMPASS 2012: $\langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2$
- ZEUS: JHEP 0905 (2009) 108 $\langle Q^2 \rangle = 3.2 \text{ (GeV/c)}^2$
- H1: Eur. Phys. C44 (2005) 1 $\langle Q^2 \rangle = 4.0 \text{ (GeV/c)}^2$
- H1: Phys. Lett. B681 (2009) 391 $\langle Q^2 \rangle = 8.0 \text{ (GeV/c)}^2$
GPDs and Hard Exclusive Meson Production

- Factorisation proven only for $\sigma_L$
  - $\sigma_T$ suppressed by $1/Q^2$

- Wave function of meson (DA)
  - Additional non-perturbative term

- At $Q^2 \approx$ few GeV$^2$ higher order pQCD terms important

Chiral-even GPDs
helicity of parton unchanged

\[
H^{q,g}(x, \xi, t) \\
\tilde{H}^{q,g}(x, \xi, t) \\
E^{q,g}(x, \xi, t) \\
\tilde{E}^{q,g}(x, \xi, t)
\]

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

\[
H^q_T(x, \xi, t) \\
\tilde{H}^q_T(x, \xi, t) \\
E^q_T(x, \xi, t) \\
\tilde{E}^q_T(x, \xi, t)
\]

Flavour separation for GPDs
example:

\[
E_{\rho^o} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^{u(+)^o} + \frac{1}{3} E^{d(+)^o} + \frac{3}{4} E^g / x \right)
\]

\[
E_{\omega} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^{u(+)^o} - \frac{1}{3} E^{d(+)^o} + \frac{1}{4} E^g / x \right)
\]

\[
E_{\phi} = -\frac{1}{3} E^{s(+)^o} + \frac{1}{4} E^g / x
\]

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

Diehl, Vinnikov
PLB, 2005
Spin-dependent cross section for exclusive meson leptoproduction

\[
\frac{\alpha_{\text{em}}}{8\pi^3} \frac{y^2}{1 - \epsilon} \frac{1}{x_{\text{Bj}} Q^2} \left( 1 - x_{\text{Bj}} \frac{1}{Q^2} \right)^{-1} \frac{d\sigma}{dx_{\text{Bj}} dQ^2 dt d\phi d\phi_s}
\]

\[
= \frac{1}{2} \left( \sigma_{++} + \sigma_{--} \right) + \epsilon \sigma_{00}^{++} - \epsilon \cos(2\phi) \text{Re} \sigma_{++}^{++} - \sqrt{\epsilon(1 + \epsilon)} \cos \phi \text{Re} \sigma_{++}^{0+} + \sigma_{++}^{-+} \\
- P_t \sqrt{\epsilon(1 - \epsilon)} \sin \phi \text{Im} \left( \sigma_{++}^{++} + \sigma_{++}^{-+} \right)
\]

\[
- S_L \left[ \epsilon \sin(2\phi) \text{Im} \sigma_{++}^{++} + \sqrt{\epsilon(1 + \epsilon)} \sin \phi \text{Im} \sigma_{++}^{0+} \right] \\
+ S_L P_t \left[ \sqrt{1 - \epsilon^2} \frac{1}{2} \left( \sigma_{++}^{++} - \sigma_{--}^{-+} \right) - \sqrt{\epsilon(1 - \epsilon)} \cos \phi \text{Re} \sigma_{++}^{0+} - \sigma_{++}^{-+} \right]
\]

\[
- S_T \left[ \sin(\phi - \phi_S) \text{Im} \left( \sigma_{++}^{++} + \epsilon \sigma_{00}^{++} \right) + \frac{\epsilon}{2} \sin(\phi + \phi_S) \text{Im} \sigma_{++}^{0+} + \frac{\epsilon}{2} \sin(3\phi - \phi_S) \text{Im} \sigma_{++}^{++} \\
+ \sqrt{\epsilon(1 + \epsilon)} \sin \phi_S \text{Im} \sigma_{++}^{0+} + \sqrt{\epsilon(1 + \epsilon)} \sin(2\phi - \phi_S) \text{Im} \sigma_{++}^{++} \right] \\
+ S_T P_t \left[ \sqrt{1 - \epsilon^2} \cos(\phi - \phi_S) \text{Re} \sigma_{++}^{++} \\
- \sqrt{\epsilon(1 - \epsilon)} \cos \phi_S \text{Re} \sigma_{++}^{0+} - \sqrt{\epsilon(1 - \epsilon)} \cos(2\phi - \phi_S) \text{Re} \sigma_{++}^{-+} \right]
\]

$\sigma_m^{ij}$: helicity-dependent photoabsorption cross sections and interference terms

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

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

$c = \frac{1 - y - \frac{1}{4} y^2 y'}{1 - y + \frac{1}{2} y^2 + \frac{1}{4} y^2}$

$\gamma = 2x_B M_p / Q$
Azimuthal asymmetries of cross section for exclusive meson leptoproduction

5 single spin asymmetries

\[ A_{UT}^{\sin(\varphi - \varphi_s)} = -\frac{\text{Im} (\sigma_{++}^+ + \epsilon \sigma_{00}^+)}{\sigma_0} \]
\[ A_{UT}^{\sin(\varphi + \varphi_s)} = -\frac{\text{Im} \sigma_{+-}^+}{\sigma_0} \]
\[ A_{UT}^{\sin(2\varphi - \varphi_s)} = -\frac{\text{Im} \sigma_{+-0}^+}{\sigma_0} \]
\[ A_{UT}^{\sin(3\varphi - \varphi_s)} = -\frac{\text{Im} \sigma_{--}^+}{\sigma_0} \]
\[ A_{UT}^{\sin \varphi_s} = -\frac{\text{Im} \sigma_{+0}^+}{\sigma_0} \]

3 double spin asymmetries

\[ A_{LT}^{\cos(\varphi - \varphi_s)} = \frac{\text{Re} \sigma_{++}^+}{\sigma_0} \]
\[ A_{LT}^{\cos(2\varphi - \varphi_s)} = -\frac{\text{Re} \sigma_{+-0}^+}{\sigma_0} \]
\[ A_{LT}^{\cos \varphi_s} = -\frac{\text{Re} \sigma_{+0}^+}{\sigma_0} \]

\[ \sigma_0 \quad \text{‘unpolarised cross section’} \]
\[ \sigma_0 = \frac{1}{2} (\sigma_{++} + \sigma_{--}^+) + \epsilon \sigma_{00}^+ = \sigma_L + \epsilon \sigma_T \]
Luminosity $5 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$

$^3\text{He} - ^4\text{He}$ dilution refrigerator (T~50 mK)

- Solenoid 2.5 T
- Dipole magnet 0.6 T

COMPASS polarised target

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:
  - $\mu^+$ polarization $\approx -80\%$
  - $\text{dilation factor for exclusive } \rho^0$ production:
    - $\approx 25\%$
    - $\approx 44\%$

Microwave reversal every week
Transversely polarised proton target ($\text{NH}_3$), 2010 data

Note: there was no Recoil Detector for these data

Only two hadron tracks of opposite charge associated to the primary vertex

Only two ECAL clusters time-correlated with beam and not associated to a charged particle

$$|M_{\pi\pi\pi} - M_{\omega}^{\text{PDG}}| < 0.07 \text{ GeV}$$

$$-3 < E_{\text{miss}} < 3 \text{ GeV}$$

$$E_{\omega} > 14 \text{ GeV}$$

$$0.05 < p_T^2 < 0.5 \text{ GeV}^2$$

$$E_{\text{miss}} = (M_X^2 - M_p^2)/(2M_p)$$

Dominant coherent contrib.

Dominant non-exclusive bkg.

$$1 < Q^2 < 10 \text{ GeV}^2$$

$$0.1 < y < 0.9$$

$$0.003 < x < 0.35$$

$$W > 5 \text{ GeV}$$
Extraction of asymmetries and subtraction of non-exclusive background

- $\rho^0$ analysis
  - 1D (deuteron) and 2D (proton) binned maximum likelihood estimator with subtraction of background in $(q, q_s)$ bins
- $\omega$ analysis
  - Unbinned maximum likelihood estimator with simultaneous fit of signal and background asymmetries

**Background rejection:**
*For each target cell and polarization state*

![Graph](image)

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

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

Normalization of MC to the real data using two component fit

- Gaussian function (signal) + shape from MC (bkg)
Results on $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive $\rho^0$ production

- For transversely polarised protons and deuterons small, compatible with 0
- For the proton agreement with HERMES results
  COMPASS results with statistical errors improved by factor 3 and extended kinematic range
- For the deuteron the first measurement
- Reasonable agreement with predictions of the GPD model of Goloskokov - Kroll

$A_{UT}^{\sin(\phi-\phi_s)}$ contains twist-2 terms depending on $E^{q,g}$

Small values expected due to approximate cancellation of contributions from $E^u$ and $E^d$, $E^u \approx -E^d$

(cf. upper-right plot)
Complete set of transverse target spin asymmetries for exclusive $\rho^0$ production on $p^\uparrow$

- Improved method of extraction (2D)
- Simultaneous extraction of
  5 single spin asymmetries and
  3 double spin asymmetries
  for transversely polarised protons

→ PLB 731 (2014) 19

- predictions of GPD model of Goloskokov-Kroll

reasonable agreement with GK model
(also for not-shown double spin asym.)
Connection between azimuthal asymmetries and GPDs

Exclusive $p^0$ production on $p^\uparrow$

Asymmetries small, compatible with 0, except

$$ A_{UT}^{\sin \phi} = -0.019 \pm 0.008 \pm 0.003 $$

Indication of $H_T$, ‘transversity’ GPD, contribution

Larger effects for some asymmetries expected for exclusive $\omega$ production

$$ M_{Vp^\gamma p} \quad \text{helicity amplitudes} $$

$$ \sigma_0 \quad \text{unpolarised cross section} $$

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

$$ E_T = 2H_T - E $$

$$ \tilde{E}_T = 2H_T - E $$
Azimuthal asymmetries for exclusive $\omega$ production on $p^{\uparrow}$

New result, to be published
- Unbinned maximum likelihood method
- Extraction of 8 transverse spin asymmetries

Comparison to modified GPD model of GK with added $\pi^0$ pole exchange

EPJ A50 (2014) 146

Parameters constrained by HERMES SDMEs for $\omega$ except sign of $\pi\omega$ transition form factor more sensitivity in azimuthal asymmetries

GK predictions for COMPASS, private com.
- No pion pole
- Positive $\pi\omega$ form factor
- Negative $\pi\omega$ form factor

When 'global' comparison to the data no clear preference for any version
Comparison to HERMES asymmetries for $\omega$ production on $p^\uparrow$

Note: contribution of pion pole decreases with $W$

COMPASS uncertainty smaller by a factor > 2

within large errors combined HERMES data compatible with all 3 scenarios

Future measurements at JLab12 expected to resolve the issue of $\pi\omega$ transition form factor
COMPASS-II time lines

Part of the COMPASS-II proposal approved and scheduled by CERN

- 2012: pion and kaon polarisabilities (Primakoff) + commissioning and pilot run for DVCS
- 2013-2014: long SPS/LHC shutdown
- 2014-2015: Drell-Yan measurements with transversely polarised protons (NH$_3$ target)
- 2016-2017: stage 1 of GPD program and in parallel SIDIS (LH target)
- 2018: Drell-Yan measurements with transversely polarised protons (NH$_3$ target)

Measurements to be pursued at COMPASS-II > 2020 (subject to a new proposal)

- stage 2 of GPD program with transversely polarised NH$_3$ target and RPD
- SIDIS (high statistics) from transversely polarised deuteron and proton targets
- Drell-Yan on transversely polarised deuterons, unpolarised protons and nuclear targets
- hadron spectroscopy program with high-intensity separated kaon and antiproton beams
Thank you!
Generalized Parton Distributions and DVCS

Factorisation: \( Q^2 \text{ large, } -t < 1 \text{ GeV}^2 \)

\[ \xi = \frac{x_B}{2 - x_B} \]

\( P_i, h_i - \) proton momentum and helicity

4 Generalised Parton Distributions: \( H, E, \tilde{H}, \tilde{E} \) (chiral even)
for each quark flavour and for gluons

depend on 3 variables: \( x, \xi, t \)

for DVCS gluons contribute at higher orders in \( \alpha_s \)
Azimuthal dependence of exclusive photon xsec.

from Belitsky, Kirchner, Müller:
polarized beam off unpolarized target

\[
\begin{align*}
\frac{d\sigma}{d\Omega} (\mu p &\rightarrow \mu p \gamma) = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} \\
&+ e_\mu a^{BH} \Re A^{DVCS} + e_\mu P_\mu a^{BH} \Im A^{DVCS}
\end{align*}
\]

Known expression

\[
\begin{align*}
d\sigma^{BH} &= \frac{\Gamma(x_B, Q^2, t)}{P_1(\phi)P_2(\phi)} \left( c^{BH}_0 + c^{BH}_1 \cos \phi + c^{BH}_2 \cos 2\phi \right) \\
d\sigma^{DVCS}_{unpol} &= \frac{e^6}{y^2Q^2} \left( c^{DVCS}_0 + c^{DVCS}_1 \cos \phi + c^{DVCS}_2 \cos 2\phi \right) \\
P_\mu \times d\sigma^{DVCS}_{pol} &= \frac{e^6}{y^2Q^2} \left( s^{DVCS}_1 \sin \phi \right) \\
e_\mu \times a^{BH} \Re A^{DVCS} &= \frac{e^6}{x y^3 P_1(\phi)P_2(\phi)} \left( c^{Int}_0 + c^{Int}_1 \cos \phi + c^{Int}_2 \cos 2\phi + c^{Int}_3 \cos 3\phi \right) \\
e_\mu P_\mu \times a^{BH} \Im A^{DVCS} &= \frac{e^6}{x y^3 P_1(\phi)P_2(\phi)} \left( s^{Int}_1 \sin \phi + s^{Int}_2 \sin 2\phi \right)
\end{align*}
\]

Twist-2 $\gg$ Twist-3  Twist-2 gluon
Symmetric acceptance in $\phi$ leads to cancellation of the interference terms when integrated over $\phi$. 
Beam Charge & Spin Difference of cross sections

\[ D_{CS,U} \equiv d\sigma(\mu^+\downarrow) - d\sigma(\mu^-\uparrow) = \]

\[ c_0^{\text{Int}} \cos \phi + c_1^{\text{Int}} \cos 2\phi + c_2^{\text{Int}} \cos 3\phi + s_1^{\text{DVCS}} \sin \phi \]

COMPASS-II proposal

\[ E_{\mu}=160 \text{ GeV} \quad 1 \leq Q^2 \leq 4 \text{ GeV}^2 \quad 0.03 \leq x_B \leq 0.07 \]

statistical errors only (in 280 days)

VGG Reggeized (x,t)-correlation
VGG Factorized (x,t)-dependence

Mueller fit on world data
- (with JLab Hall A)
- (without JLab Hall A)

Systematic error: 3% mostly due to luminosity measurements for \( \mu^+ \) and \( \mu^- \)
t-slope measurement for exclusive $\rho^0$ production

$$d\sigma_{\gamma N \rightarrow \rho N}/dt \sim \exp(-B|t|)$$

160 GeV muon beam
2.5m LH2 target
$\varepsilon_{\text{global}} = 10\%$, 280 days
$L = 1222\text{pb}^{-1}$

$0.06 < |t| < 0.64 \text{GeV}^2$

At large $Q^2$ slope $B$ sensitive mostly to the nucleon size
Exclusive $\rho^0$ production on $p^\uparrow$ and $d^\uparrow$ at COMPASS

$\mu N \rightarrow \mu \rho^0 N$

i.e. incoherent process

Transversely polarised proton target ($\text{NH}_3$), 2007, 2010

Transversely polarised deuteron target ($^6\text{LiD}$), 2003-2004

note: there was no RPD for these data

only two hadron tracks of opposite charge associated to the primary vertex

DIS cuts

| 1 $< Q^2 < 10 \text{ GeV}^2$ |
| 0.1 $< y < 0.9$ |
| 0.003 $< x < 0.35$ |
| $W > 5 \text{ GeV}$ |

proton data (797 000 evts)
deurton data (97 000 evts)

cuts specific for exclusive $\rho^0$ analysis

| 0.5 $< M_{\pi\pi} < 1.1 \text{ GeV}$ |
| -2.5 $< E_{\text{miss}} < 2.5 \text{ GeV}$ |
| $E_{\rho^0} > 15 \text{ GeV}$ |
| 0.05 $< p_T^2 < 0.5 \text{ GeV}^2$ [NH$_3$] |
| 0.1 $< p_T^2 < 0.5 \text{ GeV}^2$ [LiD] |

$E_{\text{miss}} = (M_X^2 - M_p^2)/(2M_p)$

dominant coherent contrib.
dominant non-exclusive bkg.
Role of pion exchange

- 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 SDMEs data
  → azimuthal asymmetries more sensitive