COMPASS results on DVCS and exclusive $\pi^0$ production

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Abstract. The high energy polarised muon beam available at CERN, with positive or negative charge, makes COMPASS a unique place for studies of General Parton Distributions (GPDs). The dedicated COMPASS GPD program started in 2012 with commissioning of a new long liquid hydrogen target and new detectors, such as the large recoil particle detector CAMERA and the large-angle electromagnetic calorimeter. It was followed by a short pilot ‘DVCS run’. The first results on DVCS and exclusive $\pi^0$ channels have been obtained. From the sum of cross sections measured with positive and negative beam polarities the pure DVCS cross-section and its dependence on the squared four-momentum transfer $t$ have been extracted. It allowed a first estimate of the transverse size of the partonic distribution of the nucleon $\langle r_\perp^2 \rangle$ in a range of intermediate $x_B$, with a mean $x_B$ value of 0.056. We report also on the absolute value of the cross section for exclusive $\pi^0$ production and its dependence on $t$ and azimuthal angle $\phi$ between the scattering plane and $\pi^0$ production plane. These measurements are aiming to constrain the GPDs, in particular chiral-odd (transversity) GPDs. The full data taking for the GPD program approved within the COMPASS-II proposal continues in 2016 and 2017.

1. Introduction

The theoretical framework of General Parton Distributions (GPDs) [1, 2, 3] provides a novel description of the nucleon’s partonic structure and contains a wealth of new information. In particular, GPDs embody both the nucleon form factors and Parton Distribution Functions (PDF), such as parton number, helicity and transversity densities. Very importantly, GPDs provide a description of the nucleon as an extended object, sometimes referred to as a 3-dimensional ‘nucleon tomography’ [4], which correlates (transverse) spatial and (longitudinal) momentum degrees of freedom. The GPDs also allow access to such a fundamental property of the nucleon as the orbital angular momentum of quarks [2]. Like ordinary PDFs, GPDs describe the structure of the nucleon independently of the specific reaction by which the nucleon is probed, i.e. they are expected to be universal. The mapping of the nucleon GPDs requires a comprehensive program of measuring various hard processes in a broad kinematic range, in particular Deeply Virtual Compton Scattering (DVCS). In addition, Hard Exclusive Meson Production (HEMP) is expected to add an independent and complementary information. A

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comprehensive experimental overview of DVCS is presented in Ref. [5] and results of a recent phenomenological studies and predictions for DVCS can be found in Ref. [6].

The GPD part of COMPASS-II proposal [7] is devoted to measurements of both DVCS and HEMP with polarised $\mu^+$ and $\mu^-$ beams and a liquid hydrogen target. The new detectors, the 4-m long recoil proton detector CAMERA and (a central part of) the new large-angle electromagnetic calorimeter ECAL0, which are essential for measurements of exclusive processes, were constructed and incorporated into the COMPASS set-up in 2012. The commissioning of these new detectors was done in 2012 and was followed by a 4-week pilot run. The results on DVCS and exclusive $\pi^0$ production, which are presented in this contribution, have been obtained from this pilot run. The dedicated data taking for the GPD program, with the complete ECAL0, is continuing in 2016-2017.

2. Experimental set-up

COMPASS is a fixed-target experiment situated at the high-intensity M2 beam-line of the CERN SPS. It can deliver either hadron or naturally polarised muon beams of a given charge in the energy range between 50 and 280 GeV. For the GPD program the data are collected with the muon beam nominal energy of 160 GeV and with muons of both polarities: $\mu^+$ ($\mu^-$) with polarisation of about -0.8 (+0.8).

The COMPASS apparatus [8] consists of a two-stage forward spectrometer comprising various tracking detectors, electromagnetic and hadronic calorimeters, muon identification detectors, and a ring imagining Cherenkov counter grouped around two dipole magnets SM1 and SM2. For the GPD program the set-up was complemented by installing a large proton recoil detector CAMERA around the new 2.5 m long liquid hydrogen target and a new large-angle electromagnetic calorimeter ECAL0. The 4-meter long CAMERA consists of two concentric barrels, each of 24 scintillator slats with a read out at both ends. The recoil proton detection is based on the ToF measurement between the two barrels. The calorimeter ECAL0 that is situated just downstream of CAMERA allows to extend the accessible kinematic domain for DVCS and exclusive $\pi^0$ production towards higher $x_{Bj}$, improve hermeticity for detection of exclusive events and reduce the background to single-photon events production, which originates from $\pi^0$ and other decays.

By adding these detectors COMPASS has been converted into a facility measuring exclusive reactions within kinematic domain from $x \sim 0.01$ to $\sim 0.15$, which cannot be explored at any other existing or planned facility in the near future.

3. Event selection

For brevity, in this section we discuss in more detail only the selections for the single photon channel. As for the exclusive $\pi^0$ sample the analysis is analogous, we will just only mention those issues that are specific for the $\pi^0$ channel.

The event selection exploits the overconstrained kinematics for the measured exclusive process $\mu p \rightarrow \mu' p' \gamma$. Events with a single outgoing muon and a single neutral cluster above the DVCS thresholds for the electromagnetic calorimeters are selected first. The muon and photon are then combined with all possible proton candidates reconstructed in CAMERA. The combinatorial ambiguity is resolved by applying cuts on variables that are sensitive to the exclusivity of events such as: coplanarity

$$\Delta \phi = \phi_{meas} - \phi_{spec},$$

the transverse momentum balance

$$\Delta p_T = p_{T,meas} - p_{T,spec},$$
as well as the four-momentum balance

$$M^2_X = (k + p - k' - q' - p'^{\text{meas}})^2.$$  

(3)

Here, the symbols $k$, $p$, $k'$, $q'$ and $p'^{\text{meas}}$ denote the four-momenta of the incident muon, target proton, scattered muon, produced photon and recoil proton, respectively. The subscript 'meas' denotes a quantity measured by the recoil proton detector, while 'spec' denotes a quantity derived from the spectrometer measurements only, when assuming exclusivity, i.e. $p'^{\text{spec}} = k + p - k' - q'$.

In addition, the measured longitudinal hit position $z_A$ in the inner barrel of the recoil detector is compared to the one obtained from an interpolation between the interaction vertex and the hit in the outer barrel, $z_{\text{interp}}$. This reverse vertex pointing is encoded in the variable $\Delta z_A = z_{\text{interp}} - z_A$. The distributions of exclusivity variables are shown in Fig. 1.

![Distributions of exclusivity variables](data:image/png;base64,...)

Figure 1: Distributions of exclusivity variables the single photon sample. The variables $\Delta \phi$, $\Delta p_T$ and $M_X^2$ are defined by Eqs. (1-3), while $\Delta z_A$ encodes the reverse vertex pointing. The whole Monte Carlo estimate is displayed in red, while in grey only contamination from exclusive $\pi^0$ production is shown. The blue dotted lines indicate the applied cuts.

The background is further reduced by applying a kinematic constrained fit. The input to the fit is supplied with all measured quantities, their uncertainties and correlations. The fit performs a chi-squared minimisation using constraints on the energy and momentum conservation. In the following the kinematic variables determined by the kinematic fit are used since the fit offers their most precise determination.

For selection of the sample of exclusive $\pi^0$ production, $\mu p \rightarrow \mu' p' \pi^0$, an analogous procedure is used as described for the DVCS sample. Now, the variable $q'$ corresponds to the four-momentum of $\pi^0$ instead of single photon. In addition to the cuts on the four exclusivity variables introduced above, a cut on the invariant mass of two-photon system is applied as shown in Fig. 2. For exclusive $\pi^0$ sample an additional constraint is included in the kinematic constrained fit. In addition to the conservation of energy and momentum, the invariant mass of two photons is required to be constrained by the PDG $\pi^0$ mass.
4. Results on DVCS

In this analysis we determine the differential cross section

$$\frac{d^4 \sigma_{\mu p \rightarrow \mu' p' \gamma}}{dQ^2 \, d\nu \, |t| \, d\phi}$$

(4)

for exclusive production of single photon. Here, $Q^2$ and $\nu$ denote the virtual photon virtuality and its energy in the lab. system, $t$ is the square of the four-momentum transfer between the target and recoil protons and $\phi$ is the azimuthal angle between the lepton scattering plane and the photon production plane. In order to extract the differential cross section as a function of $Q^2$, $\nu$, $t$ and $\phi$ the data has been corrected for acceptance effects using bin-wise acceptance correction factors. As an example, acceptance factors as a function of $t$, $Q^2$ and $\nu$ are shown in Fig. 3.

The Bethe Heitler contribution has been subtracted from the data for each of the bins individually. A major background source for single photon production is the production of $\pi^0$ mesons, where one of the decay photons is undetected. The contamination arising from $\pi^0$ production was estimated and subtracted from the data inside each bin using LEPTO 6.5.1.
together with an exclusive $\pi^0$ Monte Carlo based on a parameterisation from Goloskokov-Kroll model [9].

For brevity the differential cross section of Eq. (4) will be denoted in the following by $d\sigma$, while the signs of muon charge and its helicity will be indicated by $+(-)$ and $-(-)$, respectively. The sum of cross sections for $\mu^+$ and $\mu^-$ incident beams

$$S_{CS,U} = d\sigma^{+} + d\sigma^{-} = 2(d\sigma^{BH} + d\sigma^{DVCS\ unpol} + c_\mu P_\mu \text{Im} I)$$

(5)

allows us to access the unpolarised DVCS cross section after subtracting the Bethe Heitler term. Furthermore, using the notation of Ref. [10] for

$$d\sigma^{DVCS\ unpol} = \frac{e^6}{y^2 Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos2\phi)$$

(6)

and

$$\text{Im} I = \frac{e^6}{x_B y^4 P_1(\phi) P_2(\phi)}(s_1 \sin \phi + s_2 \sin 2\phi)$$

(7)

one observes that upon integration of $S_{CS,U}$ over $\phi$ the contributions of all terms cancel, except $c_0^{DVCS}$. The latter corresponds to the dominant leading-twist and helicity-conserving contribution to the DVCS cross section.

The goal of this measurement is to determine the $t$-dependence of the unpolarised (phi-integrated) DVCS cross section in virtual photon-proton scattering. The $\gamma^* p$ cross section is derived from the measured muon-proton cross section by taking into account the transverse virtual photon flux $\Gamma$

$$\frac{d^3\sigma_{\mu p}}{dQ^2 dv dt} = \Gamma \left( \frac{d\sigma^\gamma_{\gamma p}}{dt} + \epsilon \frac{d\sigma_{\gamma p}}{dt} \right),$$

(8)

where according to the Hand’s convention

$$\Gamma = \frac{\alpha_{em}(1 - x_B)}{2\pi Q^2 y E_\mu} \left[ y^2 \left( 1 - \frac{2m^2}{Q^2} \right) + \frac{2}{1 + Q^2/v^2} \left( 1 - y - \frac{Q^2}{4E_\mu^2} \right) \right]$$

(9)

and the subscript $T$ ($L$) refers to transverse (longitudinal) virtual photons. Since the extracted DVCS cross section is proportional to the helicity-conserving term $c_0^{DVCS}$, the term containing $\sigma_L$ in Eq. (8) is discarded for the present analysis.

The values of the differential cross section

$$\frac{d\sigma^\gamma_{\gamma p\rightarrow \gamma p}}{d|t|}$$

(10)

for four bins of $|t|$ are shown in Fig. 4 (left). They have been fitted with an exponential function in order to determine the $t$-slope parameter $B$. The value of $B$ is equal to $(4.31 \pm 0.62^{+0.09}_{-0.20})(\text{GeV}/c)^{-2}$ inside the kinematic range that is indicated in the legend of Fig. 4 (left), and which corresponds to $\langle x_{Bj} \rangle = 0.056$, $\langle Q^2 \rangle = 1.8 \text{ (GeV}/c)^2$ and $\langle W \rangle = 5.8 \text{ GeV}$. The extracted value of $B$ allows us to estimate the transverse size of partonic distribution in the nucleon $r_\perp$ using the relation

$$\langle r_\perp^2(x_{Bj}) \rangle = 2B(x_{Bj}),$$

(11)

which for our measurement results in $\sqrt{\langle r_\perp^2 \rangle} = (0.578 \pm 0.042^{+0.006}_{-0.018}) \text{ fm at a mean } x_{Bj} \text{ value of } 0.056$. 

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The main systematic error of the cross section is due to uncertainties of absolute normalisation and determination of the amount of $\pi^0$ background. In case of parameter $B$ the error from the absolute normalisation plays a minor role, while the main systematic uncertainty originates from the normalisation of the $\pi^0$ background.

In Fig. 4 (right) the values of parameter $B$ from COMPASS and HERA [11, 12] are plotted as a function of $x_{BJ}$. As the slope $B$ is related to the transverse size of the partonic distribution (see Eq. (10)), one may conclude that these model-independent results indicate a decrease of the transverse size of the proton with increasing $x_{BJ}$.

5. Results on exclusive $\pi^0$ production

The analysis of the exclusive $\pi^0$ sample mostly follows the lines of the DVCS analysis. A complete simulation of the experimental set-up is used to determine acceptance of the experiment. In order to determine background originating from non-exclusive events, the data are modeled with Monte Carlo in both kinematic regions where either the signal or the background dominates. Here, LEPTO 6.5.1 is used for a non-exclusive part. For the signal contribution a dedicated Monte Carlo generator [13] was used with the cross section parameterisation from the Goloskokov-Kroll model. The background is subtracted bin-wise from the data. Other sources of background, like misidentified exclusive $\omega \rightarrow \gamma\gamma\gamma$ events, where one photon is lost, are found to be negligible.

First, we extract the four-fold differential $\mu\mu$ cross sections separately for $\mu^+$ and $\mu^-$ data. Then the unpolarised cross section is obtained as the weighted mean of the two. In this way the dependence on the beam polarisation cancels. In order to convert $\mu\mu$ cross section into $\gamma^*\mu$ cross section we divide the former one by the transverse virtual photon flux (cf. Eq. (9)).

The systematic uncertainty in this measurement is mostly due to scaling, which can be decomposed into effects depending on the absolute normalisation and background estimate, as well as to the threshold effects and kinematic uncertainties.

The unpolarised $\gamma^*\mu$ cross section for exclusive $\pi^0$ production reads

\[
\frac{d^2\sigma_{\gamma^*\mu}}{dt d\phi} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi) \frac{d\sigma_{LT}}{dt} \right],
\]

where $\sigma_T$, $\sigma_L$, $\sigma_{TT}$, $\sigma_{LT}$ are the structure functions, $\epsilon$ is the virtual photon polarisation parameter and $\phi$ represents the azimuthal angle between lepton scattering plane and $\pi^0$ production plane. Here, the subscript $T(L)$ denotes the contribution from transversely (longitudinally) polarised...
virtual photons, while the subscripts $TT$ and $LT$ denote the contributions from the interference between transversely-transversely and longitudinally-transversely polarised photons.

After integration over $\phi$, we extract the cross section in bins of $|t|$, which is displayed in Fig. 5 (left). Note, that it decreases exponentially with increasing $|t|$ at values of $|t|$ larger than about 0.25 (GeV/c)$^2$, while at smaller $|t|$ the $t$-dependence becomes weaker. Being the first measurement at energies significantly higher than previous results, it is worth to compare it to the model prediction. In Fig. 5 (right) the COMPASS result is compared to the prediction of the Goloskokov-Kroll model \[14\]. The blue curve represents the cross section from the model as a function of $t$, while the blue points correspond to the cross section averaged over $|t|$ bins of the data. The mean cross sections for the full $t$-range are compared at the rightmost part of the plot. We observe that the magnitude of the predicted cross section overshoots our measurement by approximately a factor of two.

![Figure 5](image)

Figure 5: **Left:** The exclusive $\pi^0$ cross section as a function of $|t|$ (note vertical log scale). **Right:** COMPASS results compared to predictions of the GPD model of Ref. \[14\].

Furthermore, we extract the cross section as a function of $\phi$ in one bin of $t$ and eight bins of $\phi$ of equal width. The red dots in Fig. 6 (left) show the measured cross section for each bin and a fit of the function given by Eq. (11), which is represented by the red curve. The values of the fitted parameters are indicated in the legend of the plot. We observe a large contribution from $\sigma_{TT}$ and a smaller positive one from $\sigma_{LT}$. This indicates a significant role of transversely polarised photons in exclusive $\pi^0$ production.

The comparison to the prediction of the Goloskokov-Kroll model is shown in Fig.6 (right). Apart from the discrepancy in the magnitude of cross sections mentioned before, here we observe also different shapes of $\phi$-dependence for the measurement and the model prediction. It indicates that relative contributions of the interference terms $\sigma_{TT}$ and $\sigma_{LT}$ are different for the measurement and the model.

According to Refs. \[14, 15\] the structure functions for exclusive pseudo-scalar meson production, which appear in Eq. (11), depend on GPDs $\bar{H}_T^q$, $\bar{E}_T^q$, $H_T^q$ and $E_T^q = 2H_T^q + E_T^q$. For $\pi^0$ production a large contribution from transversely polarised virtual photons is expected, which is mainly generated by the chiral-odd (‘transversity’) GPDs $\bar{E}_T^q$. It manifests itself in a large contribution from $\sigma_{TT}$ and a dip in the differential cross section $d\sigma/dt$ as $|t|$ decreases to zero. These features are in a qualitative agreement with our results, although the predicted values of cross section overshoot the measured ones by a factor of about 2.

6. Outlook

In 2016 and 2017 the COMPASS collaboration is continuing to take data on the GPD program.
\[ \frac{\sigma_{d}(T, L)}{\text{nb}} = (8.1 \pm 0.9) \]

\[ \left| t \right| < 0.64 \text{ (GeV/c)} \]

The exclusive \( \pi^0 \) cross section as a function of \( \phi \).

Figure 6: \textbf{Left:} The exclusive \( \pi^0 \) cross section as a function of \( \phi \). \textbf{Right:} COMPASS results compared to predictions of the GPD model of Ref. [14].

An expected increase of the statistic is by a factor of about 15 compared to the 2012 data. An investigation of GPDs with DVCS and HEMP on unpolarised protons using the data from 2016-2017 will allow us to determine the \( x_B \)-dependence of \( t \)-slope of the differential cross sections. That is related to the spatial transverse distribution of partons and the ‘nucleon tomography’. Measurements of the beam charge and spin sum and difference of single-\( \gamma \) cross sections will give access to the real and imaginary parts of the DVCS amplitude, and will allow to further constrain GPDs \( H \). Studies of exclusive production of vector mesons (\( \rho^0, \omega, \phi \)) will lead to the quark flavour and gluon separation for GPDs \( H \), while that of exclusive \( \pi^0 \) production will provide constraints on chiral-odd GPDs. The projected accuracies for measurements of various observables within the GPD program are presented in the COMPASS-II proposal [7].

References

[1] D. Mueller et al, Fortsch. Phys. 42 (1994) 101.
[2] X. Ji, Phys. Rev. Lett. 78 (1997) 610; Phys. Rev. D 55 (1997) 7114.
[3] A.V. Radyushkin, Phys. Lett. B 385 (1996) 333; Phys. Rev. D 56 (1997) 5524.
[4] M. Burkardt, Phys. Rev. D 62 (2000) 071503; erratum-ibid. D 66 (2002) 119903;
   Int. J. Mod. Phys. A 18 (2003) 173; Phys. Lett. B 595 (2004) 245.
[5] N. d'Hose, S. Niccolai and A. Rostomyan, Eur. Phys. J. A 52 (2016) 157.
[6] K. Kumerički, S. Liuti and H. Moutarde, Eur. Phys. J. A 52 (2016) 151.
[7] F. Gautheron et al, [COMPASS Collaboration], CERN-SPSC-2010-014, SPSC-P-340, May 2010.
[8] COMPASS Collaboration, P. Abbon et al., Nucl. Instr. Meth. A 577 (2007) 455.
[9] S.V. Goloskokov and P. Kroll, Eur. Phys. J. C 65 (2010) 137.
[10] A.V. Belitsky, D. Mueller and A. Kirchner, Nucl. Phys. B 629 (2002 173.
[11] ZEUS Collaboration, S. Chekanov et al., JHEP 0905 (2009) 108.
[12] H1 Collaboration, F.D. Aaron et al. Phys. Lett. B 681 (2009) 391;
    A. Aktas et al. Eur. Phys. J. C 44 (2005) 1.
[13] A. Sandacz and P. Szajner, arXiv:1207.0333 [hep-ph].
[14] S.V. Goloskokov and P. Kroll, Eur. Phys. J. A 47 (2011) 112.
[15] CLAS Collaboration, I. Bedlinsky et al., Phys. Rev. C 90 (2014) 025205.