PROCEEDINGS OF SCIENCE

# Exclusive measurements at COMPASS

**Po-Ju Lin[a,*] on behalf of the COMPASS Collaboration**

[a] *IRFU, CEA, Université Paris–Saclay, Gif-sur-Yvette, 91191, France*

*E-mail:* po-ju.lin@cern.ch

The Generalized Parton Distributions (GPDs) correlate the transverse spatial distribution of the partons to their longitudinal momentum inside the nucleon and give a three-dimensional description of the nucleon. At COMPASS, GPDs are investigated via exclusive processes including Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP) in the Bjorken variable coverage of the sea-quark domain. The exclusive measurements at COMPASS are discussed and some of the recent progresses are given in this article.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

[*] Speaker

## 1. The COMPASS Experiment

Being a multipurpose fixed-target experiment at the M2 beamline of CERN's Super Proton Synchrotron (SPS), COMPASS can receive a variety of hadron or lepton beams of 100 to 200 GeV. For exclusive measurements, the 160 GeV polarized muon beams were used. The muons of different charge, originating from parity-violating pion decay, carry opposite polarisation. The muon beams impinged on a 2.5m long liquid hydrogen ($LH_2$) target that was surrounded by a barrel-shaped time-of-flight system, the so-called CAMERA detector, to detect the recoiling target proton. The scattered muons and the other produced particles were detected by the COMPASS spectrometer, which was supplemented by an additional electromagnetic calorimeter for large-angle-photon detection. With a one-month test run held in 2012, exclusive measurements were performed at COMPASS in 2016-17 and had accumulated about 10 times more statistics than the one of 2012 in these dedicated runs.

## 2. Deeply Virtual Compton Scattering

With its $x_B$ coverage in the sea-quark domain, the DVCS measurement at COMPASS, using an unpolarized $LH_2$ target, focuses on probing the GPD $H$ and its corresponding Compton Form Factor (CFF) $\mathcal{H}$. By summing up the cross sections measured with $\mu^+$ and $\mu^-$ beams of opposite polarisation (beam charge-spin sum, $\mathcal{S}_{CS,U}$), the $c_0^{DVCS}$ term of the DVCS cross section [1] can be extracted after the removal of Bethe-Heitler (BH) contribution and with the azimuthal dependent terms being integrated out. $c_0^{DVCS}$ is dominated by the contribution of the imaginary part of CFF $\mathcal{H}$, Im$\mathcal{H}$, and the transverse extension of partons inside the proton is subsequently acquired. Using the 2012 data, COMPASS has measured this parton transverse extension as $0.58 \pm 0.04_{stat} {}^{+0.01}_{-0.02}|_{sys} \pm 0.04_{model}$ fm at the average virtuality of the photon mediating the interaction $\langle Q^2 \rangle = 1.8\ (\mathrm{GeV}/c)^2$, and the average of the Bjorken variable $\langle x_B \rangle = 0.056$ [2].

There has been great effort put on the calibration and analysis of the COMPASS 2016-17 data. For the moment, about 25% of the 2016-17 dataset, which has roughly two times the statistics of the 2012 case, has been included for physics analysis. Good agreement on the kinematic distributions between the $\mu^+$ and $\mu^-$ data has been observed, and these distributions can be well described by the Monte-Carlo simulation. To filter out the non-exclusive events, different quantities involving the recoiling proton are investigated, and only the events that have these quantities consistently measured by the CAMERA and by the spectrometer are kept as the exclusive candidates.

The main background of the selected exclusive single photon events comes from the $\pi^0$ decay. This $\pi^0$ background is classified into two categories — the *visible* $\pi^0$ background where both of the photons from the $\pi^0$ decay are detected, and the *invisible* case where one photon is lost. In the removal of visible $\pi^0$ contribution, a high-energy photon candidate is combined with every detected photon of lower energy to form different photon pairs. If there exists a photon pair with mass $M_{\gamma\gamma}$ that lies in the 40 MeV window around the $\pi^0$ mass, this candidate is discarded. On the other hand, the Monte-Carlo is used for estimating the invisible $\pi^0$ background. The LEPTO 6.1 generator is utilized for the production of semi-inclusive $\pi^0$ events, and the HEPGEN generator, with the model from Goloskokov and Kroll (GK) [3, 4] implemented, is employed for generating the exclusive $\pi^0$s. The relative contributions from semi-inclusive and exclusive $\pi^0$ events are determined by

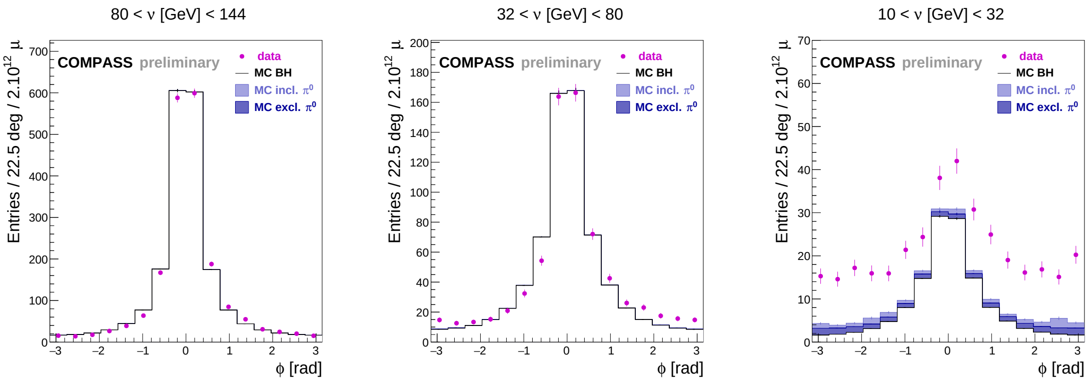


**Figure 1:** The $\phi$ distributions of the exclusive single photons in three different domains of $\nu$. The data, including beams of $\mu^{+}$ and $\mu^{-}$, is shown as the solid circles, the BH Monte-Carlo is given as the white histograms, and the estimated semi-inclusive (exclusive) $\pi^0$ backgrounds are the light (dark) shaded areas. The BH Monte-Carlo is evaluated at the same muon flux as data. In these plots, the visible $\pi^0$ contributions are already removed.

fitting various kinematic distributions of the real data, and the sum of their $M_{\gamma\gamma}$ distributions is normalized to the $\pi^0$ peak in the $M_{\gamma\gamma}$ of the real data. These normalized MC samples thus provides the estimation of the number of single photons that originate from the invisible $\pi^0$s.

The $\phi$ distributions of the data are presented in Fig. 1 in three different domains of the virtual photon energy $\nu$, with $\phi$ being the azimuthal angle between the lepton plane and the photon plane. In the left plot of Fig. 1, the $\langle x_B \rangle$ is about 0.008 and the BH process is expected to dominate in this relative low $x_B$ region. This is confirmed by the well description of the data by the BH Monte-Carlo, which is simply scaled by the luminosity of the data. The satisfactory reproduction of the data in the low-$x_B$ reference region gives the confidence of the estimation of BH contribution at high $x_B$, which is shown in the right of Fig. 1 with $\langle x_B \rangle \approx 0.06$, where the presence of DVCS contribution can be clearly observed as the difference between the data and the BH contribution plus the $\pi^0$ backgrounds. The $c_0^{DVCS}$ term can thus be obtained, which would provide the transverse extension of partons, as discussed previously.

COMPASS is in the process of finalizing the transverse-size measurement using the 25% of data taken in 2016-17, while in the same time incorporating more data available. With the full 2016-17 dataset, COMPASS expects to provide the results at three different $x_B$ values.

## 3. Hard Exclusive Meson Production

COMPASS is capable of the hard exclusive production of a variety of mesons. With the 2012 data, COMPASS has measured the cross-section of exclusive $\pi^0$ production [5] and the Spin Density Matrix Elements (SDMEs) of the exclusive production of $\omega$ [6]. Following this last result, COMPASS has performed the study on the SDMEs of the exclusively produced $\rho^0$ using the 2012 data.

The SDMEs show how the spin components of the virtual photon are transferred to those of the vector meson generated and can be extracted via the angular distributions of particles. There are

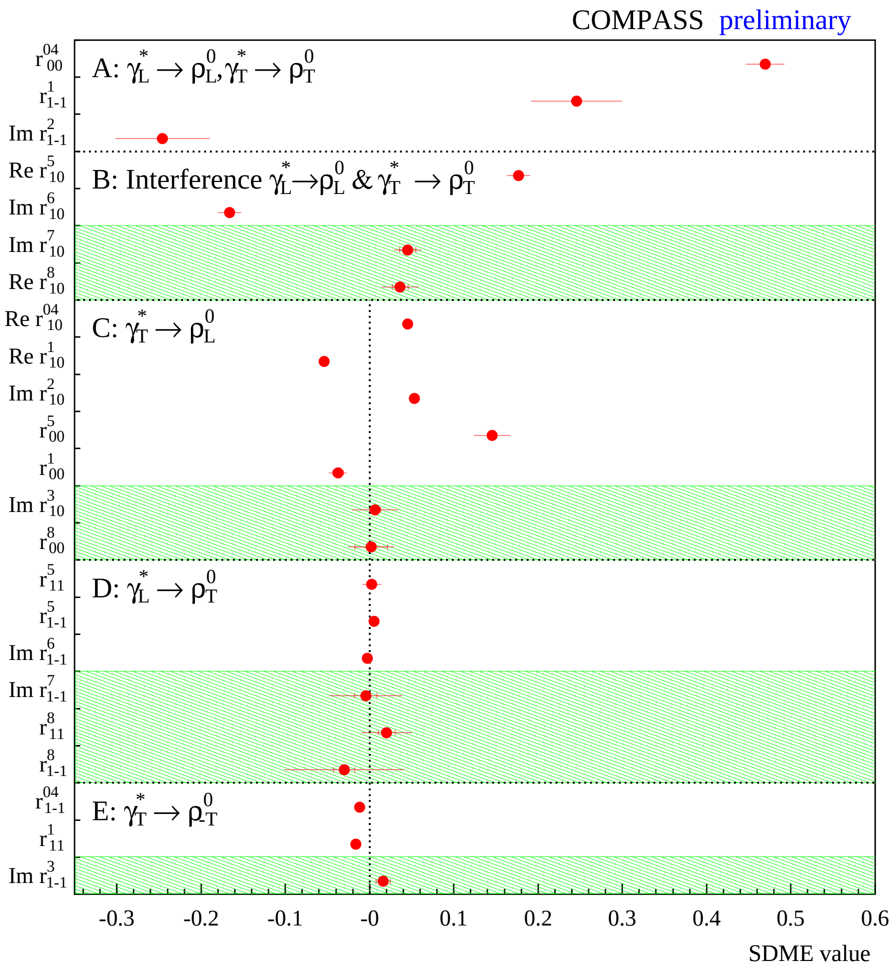


**Figure 2:** The extracted 23 SDMEs of the exclusive $\rho$ production. The polarized SDMEs are given in areas of shaded green. The inner error bars represent statistical uncertainties and the outer ones are the statistical and systematic uncertainties added in quadrature.

15 unpolarized SDMEs and 8 polarized ones. These 23 SDMEs can be grouped into five different classes depending on the corresponding helicity transitions between the virtual photon and the $\rho^0$ produced, as illustrated in Fig 2. With the hypothesis of s-channel helicity conservation (SCHC), it is suggested that:

$$\begin{aligned} r^1_{1-1} &= -\mathrm{Im}\{r^2_{1-1}\}, \\ \mathrm{Re}\{r^5_{10}\} &= -\mathrm{Im}\{r^6_{10}\}, \\ \mathrm{Im}\{r^7_{10}\} &= \ \ \mathrm{Re}\{r^8_{10}\}. \end{aligned}$$

With the SDMEs extracted, these relations are observed to hold within uncertainties. However, SCHC also requires that all the elements in classed C, D, and E in Fig. 2 to be zero, which is clearly violated for the $\gamma^*_T \to \rho^0_L$ transition of class C.

The non-zero SDMEs in class C can be related to the chiral-odd GPDs $H_T$ and $\bar{E}_T$ in the GK model [7]. For example, the $r^5_{00}$ term for the vector meson production is given as

$$r^5_{00} \propto \mathrm{Re}\left[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}\right]. \tag{1}$$

In the case of $\rho^0$, the first term in Eq. 1 dominates and therefore the measurement of $r^5_{00}$ essentially probes $\bar{E}_T$. In addition, the SDMEs allow one to study the contributions of the unnatural-parity exchange (UPE) processes and the natural-parity exchange (NPE) ones. While a significant contribution from UPE transitions was measured in the $\omega$ production, the NPE dominance is observed in the $\rho^0$ case. These results, together with the kinematic dependence of the SDMEs, will be helpful for constraining the GPD models.

With the 2016-17 data, COMPASS has began preliminary HEMP studies such as the exclusive $\pi^0$ production. The planned analyses of SDME and cross sections for the HEMP, including the exclusive $\phi$ and J/$\psi$ will provide not only important inputs for the chiral-odd GPDs, together with the chiral-even ones, but also shed light on the GPD flavor decomposition and the gluon GPDs.

## 4. Acknowledgement

This work has been supported by the French Commissariat à l'Énergie Atomique et aux Énergies Alternatives and by the European Union's Horizon 2020 research program, STRONG-2020 (GPDACT Work Package). The author would also like to thank doctor Nicole d'Hose and doctor Andrzej Sandacz for the helpful discussions.

## References

[1] A.V. Belitsky, D. Müller, A. Kirchner, *Theory of deeply virtual Compton scattering on the nucleon*, *Nucl. Phys. B* **629**, (2002) 323 [hep-ph/0112108].

[2] COMPASS Collaboration, *Transverse extension of partons in the proton probed in the sea-quark range by measuring the DVCS cross section*, *Phys. Lett. B* **793**, (2019) 188 [arXiv:1802.02739].

[3] S. Goloskokov and P. Kroll, *Transversity in hard exclusive electroproduction of pseudoscalar mesons*, *Eur. Phys. J. A* **47**, (2011) 112 [arXiv:1106.4897].

[4] S. Goloskokov and P. Kroll, *private communications* (2016).

[5] COMPASS Collaboration, *Measurement of the cross section for hard exclusive $\pi^0$ muoproduction on the protons*, *Phys. Lett. B* **805**, (2020) 135454 [arXiv:1903.12030].

[6] COMPASS Collaboration, *Spin density matrix elements in exclusive ω meson muoproduction*, *Eur. Phys. J. C* **81**, (2021) 126 [arXiv:2009.03271].

[7] S. Goloskokov and P. Kroll, *Transversity in exclusive vector-meson leptoproduction*, *Eur. Phys. J. C* **74**, (2014) 2725 [arXiv:1310.1472].