Generalized Parton Distributions at COMPASS: Present Results and Future Perspectives

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Understanding the nucleon structure remains one of the key challenges of nuclear physics. The Generalized Parton Distributions (GPDs) grant a new insight for the study of the nucleon structure, as they provide a three-dimensional picture of the nucleon. COMPASS at CERN has a great potential for GPD studies, with its forthcoming measurement of deeply virtual Compton scattering and exclusive meson production off the proton with both μ^+ and μ^-. The current COMPASS GPD program will be discussed, as well as an overview of the investigation on future possible developments. Existing results of exclusive meson production will also be presented.

1 Reminder on Generalized Parton Distributions

The Generalized Parton Distributions (GPDs) constitute a new, three dimensional parametrization of the nucleon structure. They correlate the momentum distribution of the partons inside the proton, parametrized by the parton distribution functions, to the transverse spatial distribution of those partons, parametrized by the form factors. As such, those objects grant access to the orbital angular momentum of the quarks [1, 2, 3].

GPDs can be accessed thanks to exclusive processes such as Deeply Virtual Compton Scattering (DVCS $\ell p \to \ell p \gamma$), or exclusive meson production off the nucleon. In such reactions, the virtual photon (with a high virtuality Q^2) emitted by the lepton selects a quark in the nucleon with a longitudinal momentum fraction $x + \xi$, which re-emits a photon (in the case of DVCS) or produces a hadron (in the case of meson production), and is reabsorbed in the proton with a momentum $x - \xi$. During the reaction, a quadrimomentum t is transferred to the nucleon (Figure 1).

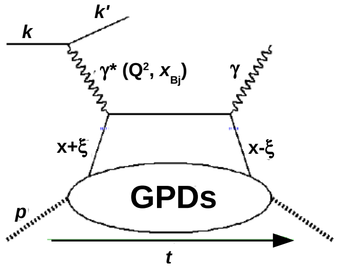

Figure 1: Feynman diagram of DVCS at lowest order.

We count four chiral-even GPDs (which do not involve quark-helicity flip), H, E, $\tilde{H}$, $\tilde{E}$, and as many chiral-odd GPDs (which involve quark-helicity flip). Those GPDs are functions of x, ξ, and t. The second moment in x of the sum of H and E for a given quark flavor gives the quark total angular momentum. This property is called the Ji sum rule [3]. As a consequence, the study of H and E are of first importance to understand the content of the proton in spin, and COMPASS at CERN has the ability to study them both.

2 The COMPASS experiment at CERN

2.1 COMPASS experimental setup

COMPASS (Common Muon Proton Apparatus for Structure and Spectroscopy) at CERN is a large acceptance magnetic spectrometer dedicated to the study of hadronic physics. It is installed on one of the Super-Proton-Synchrotron beam lines, and is able to receive beams of various types: protons, pions, and both positive and negative polarized muons (polarization $\simeq$ 80 %).

The experimental setup is composed of two dipoles and of a large number of tracking detectors for charged particle reconstruction and momentum measurement. A ring imaging Cherenkov detector provides particle identification, and two calorimeters provide energy measurement. A more complete description of the detectors is provided in [4]. Such an apparatus grants COMPASS with a wide kinematic range.

The experimental setup described above can be modified or completed to measure a specific process. Let us review the modifications that have been done for DVCS measurement.

2.2 Compass configuration for DVCS measurement

At COMPASS, the DVCS ($\mu p \to \mu p \gamma$) will be measured using the high intensity ($\sim 4 \times 10^7\,\mu\,\mathrm{s}^-1$) polarized muon beam. DVCS is a relatively low cross section process, so the luminosity will be maximized with a 2.5 meter long liquid hydrogen target. In the DVCS kinematics, the photon is produced at forward angle, and the proton recoils at very large angle. To measure and identify the recoil proton, a 4-meter long Time-Of-Flight detector called CAMERA is surrounding the target. To extend the kinematic coverage of DVCS detection to the higher x_{Bj}, a large angle electromagnetic calorimeter has also been added. With such an apparatus, COMPASS can measure the DVCS process on a wide x_{Bj} range (from 0.005 to $\simeq 0.3$) with a Q^2 up to $\simeq 20\,\mathrm{GeV}^2$ (limited by integrated luminosity).

3 The COMPASS GPD program

Thanks to several advantageous features, which we are going to discuss, COMPASS has the ability to study both GPD H [5] and GPD E. First, both μ^+ and μ^- beams are available at COMPASS (Sec. 2.1), each having one polarization direction. This feature is currently unique, and will provide useful additional information for the extraction of GPDs thanks to DVCS measurement (see Secs. 3.1 and 3.2). In addition to this, the x_{Bj} range covered by COMPASS ($0.005 < x_{Bj} < 0.3$) spans over the existing gap between the DVCS data from HERA in the gluon region ($x_{Bj} \leq 10^{-2}$) on the one hand, and the data from HERMES and Jefferson Lab in the valence region ($x_{Bj} \geq 0.1$). COMPASS is also a versatile detector, in this sense that it is able to measure simultaneously DVCS and several exclusive neutral meson channels, such as π^0, ρ^0, ϕ, ω.

3.1 Study of GPD H

The GPD H is studied with DVCS measurements on unpolarized hydrogen. A 10-day long test run, recorded in 2009 at COMPASS with a reduced DVCS setup (40 cm liquid hydrogen target, short recoil proton calorimeter, no additional calorimetry), proved the capability of such a setup to measure exclusive photon production, but also the capability to isolate, at high x_{Bj} values, a DVCS signal among the total $\mu p \to \mu p \gamma$ signal (composed of the interference of DVCS and Bethe-Heitler, where the photon is radiated by the incident or the scattered lepton).

In 2012, a four-week long pilot run has been recorded, with a mostly complete DVCS setup (full scale recoil proton detector, full luminosity, partially equipped large angle calorimeter). This run, which is still under analysis, has proved that the recoil proton detector is able to detect and identify protons. The results from this run will be available soon.

The full DVCS run will occur in 2016 and 2017 [5]. Interesting information will come from the $\mu p \to \mu p \gamma$ cross sections measurements with both muon charge states ($d\sigma(\mu^{+,\rightarrow})$ and $d\sigma(\mu^{-,\leftarrow})$) both from their sum $\mathcal{S}_{CS,U}$ and their difference $\mathcal{D}_{CS,U}$.50.0 The DVCS cross section can be isolated from $\mathcal{S}_{CS,U}$. Its t-dependence, expected to be in $\exp(-Bt)$, provides the size of the proton $r_\perp$ at the measured x_{Bj}, knowing that $\langle r_\perp^2(x_{Bj})\rangle \simeq 2B(x_{Bj})$. The t-slope parameter B has been measured at HERA at $x_{Bj} < 0.01$ (square and triangles on Fig. 2). In this region, B is measured to be constant. In the x_{Bj} range covered by COMPASS, the proton size is expected to shrink (solid and dashed lines on Fig. 2), and the projected COMPASS uncertainties with two years of data (circles on Fig. 2) should be able to determine the x_{Bj}-slope, α' of this shrink.

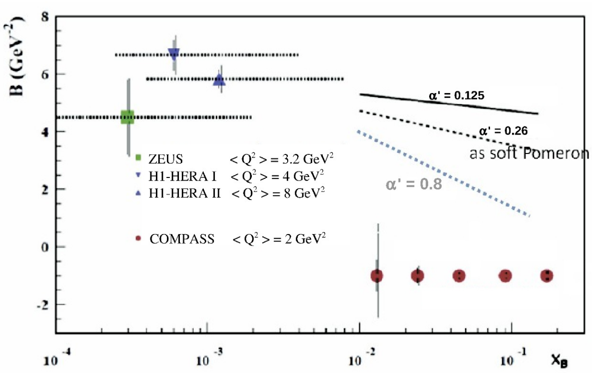

Figure 2: t-slope parameter as a function of x_{Bj} measured by HERA (square and triangles), and projected statistical uncertainty with two years of data at COMPASS (circles).

The study of the ϕ modulation of the Bethe-Heitler-DVCS interference term in $\mathcal{S}_{CS,U}$ and $\mathcal{D}_{CS,U}$ allow to isolate their first ϕ moment (respectively $s_1^{Int}\sin(\phi_{\gamma\gamma})$ and $c_1^{Int}\cos(\phi_{\gamma\gamma})$), which depend respectively on the imaginary part and real part of $F_1 \times \mathcal{H}$. ($\mathcal{H}$ being the observable of the GPD H, called Compton form factor).

3.2 Study of GPD E

The measurements of DVCS and exclusive channels on polarized hydrogen allow to study the GPD E, which allows for nucleon spin flip.

The exclusive production of ρ^0 meson on a transversely polarized hydrogen target (without recoil detection) has been performed with muon data recorded at COMPASS between 2007 and 2010. Eight target spin asymmetries, depending on ϕ and ϕ_S (ϕ_S being the angle between muon scattering plane and proton polarization) have been extracted [6, 7] and successfully interpreted in terms of GPDs [8].

Among these quantities (available on Fig. 3), the $\sin(\phi - \phi_S)$ term sets a good constraint on GPDs E, confirming that the *total* contribution of E for *all* quark flavors and gluons are small [7]. The combined information of the $\sin(2\phi - \phi_S)$ and $\sin\phi_S$ terms also indicate that the chiral-odd GPD H_T should not be small.

In the future, COMPASS might also be able to measure DVCS on a transversely polarized target, with recoil proton detection. The measurement of first moment in $\phi - \phi_s$ of the charge spin cross section difference on a transversely polarized target, $\mathcal{D}_{CS,T}$, provides access to both Compton form factors $\mathcal{H}$ and $\mathcal{E}$ on the same footing. With two years of data, COMPASS could improve by a factor 2 the statistical accuracy on this quantity compared to its previous measurement by HERMES [9], [5]. This challenging prospect is still under investigation, as it is currently technically limited by the combination of a transversely polarized target (which, by order, is surrounded by a magnet) with recoil proton detection.

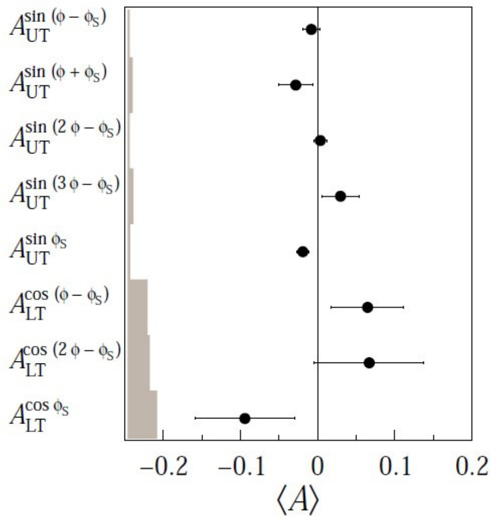

Figure 3: Target spin asymmetries on $\mu p^{\uparrow\downarrow} \to \mu p \rho^0$ measured at COMPASS [6, 7].

4 Summary

The study of the GPDs is one of the hot topics in the structure of the nucleon. The COMPASS experiment, with its unique features (Sec. 3), offers a very promising GPD program. The few existing results (Secs. 3.1 and 3.2) are very encouraging to go forward the forthcoming full DVCS run (2016-2017), which will provide a good accuracy for the measurement of several observables of interest (proton size, Compton form factor $\mathcal{H}$). The possibility to measure DVCS on transversely polarized target at COMPASS, though being a technical challenge, is also being investigated.

Acknowledgments

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