The t-dependence of the pure DVCS cross section at COMPASS

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The key reactions to study the Generalised Parton Distributions are Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). At COMPASS, these processes are investigated using a high intensity muon beam with a momentum of 160 GeV/c and a 2.5 m-long liquid hydrogen target. In order to optimize the selection of exclusive reactions at these energies, the target is surrounded by a new barrel-shaped time-of-flight system to detect the recoiling particles. COMPASS-II covers the up to now unexplored x_B domain ranging from 0.01 to 0.15. From the sum of cross sections measured with positive and negative beam polarities, the pure DVCS cross-section and its t-dependence have been extracted resulting in a first model-independent determination of the transverse size of the partonic distribution of the nucleon $\sqrt{< r_\perp^2 >} = (0.578 \pm 0.042 \, {}^{+\,0.006}_{-\,0.018})$ fm at a mean x_B value of 0.056.

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1. Introduction

Diffractive reactions are sensitive to the transverse size of the nucleon as a function of the Bjorken scaling variable x_B. It is a natural consequence of Lorentz invariance (Ref. [1]) that the transverse nucleon size, $r_\perp$, decreases as soon as x_B starts to increase and a large amount of the nucleon momentum is carried by less of its constituents. However, the precise evolution of $r_\perp$ as a function of x_B, often referred as "nucleon tomography", is poorly known and needs to be determined experimentally. The dependence of the cross section of Deeply Virtual Compton Scattering, $\mu p \rightarrow \mu' p' \gamma$, as a function of the square of the 4-momentum transfer between initial and final state proton gives experimental access to the transverse size of the nucleon (Ref. [2]). Deeply Virtual Compton Scattering (DVCS), though experimentally challenging, is the most pure channel to study nucleon tomography, since in contrast to Deeply Virtual Meson Production no final state interaction and no meson wave function has to be taken into account. Extracting the slope B of the exponential t-dependence of the t-differential DVCS cross section $r_\perp(x_B)$ can be defined as

$$< r_\perp(x_B)^2 > = 2 < B(x_B) > \hbar^2. \tag{1.1}$$

The measurements of B by HERA (Ref. [6]-[7]) up to x_B of approximately 10^{-3} do not show an evolution of $r_\perp(x_B)$ in the kinematic range of the sea quarks and gluons. COMPASS is able to reach values of x_B from 0.01 to 0.15 and thus gives new and vital input.

In this paper we present a measurement of the differential cross section

$$\frac{\mathrm{d}^4 \sigma^{\mu p \rightarrow \mu' p' \gamma}}{\mathrm{d}Q^2 \mathrm{d}\nu \mathrm{d}|t| \mathrm{d}\phi_{\gamma^* \gamma}} \tag{1.2}$$

for hard exclusive muoproduction of real photons off an unpolarised proton target at fixed incident muon energy. Here Q^2 and ν denote the virtual photon virtuality and its energy respectively, t the square of the total 4-momentum transfer between initial and final proton, and $\phi_{\gamma^* \gamma}$ the azimuthal angle between the lepton scattering plane and the photon production plane, according to the Trento convention. For better readability the differential cross section of equation 1.2 is abbreviated in the following by $\mathrm{d}\sigma$, while the orientation of the muon charge and helicity are depicted by $\pm$ respectively $\overset{\rightarrow}{\leftarrow}$. The sum of the cross sections for μ^+ or μ^- incident beams

$$\mathscr{S}_{CS,U} \equiv \mathrm{d}\sigma^{\overset{+}{\leftarrow}} + \mathrm{d}\sigma^{\overset{-}{\rightarrow}} = 2(\mathrm{d}\sigma^{BH} + \mathrm{d}\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I) \tag{1.3}$$

allows us to access the "pure" DVCS contribution after subtraction of the Bethe Heitler term. Furthermore recalling (Ref. [3])

$$\mathrm{d}\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2 Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi_{\gamma^* \gamma} + c_2^{DVCS}\cos 2\phi_{\gamma^* \gamma}) \tag{1.4}$$

and

$$\mathrm{Im}\, I = \frac{e^6}{x_B y^3 t P_1(\phi) P_2(\phi)}(s_1^I \sin\phi_{\gamma^* \gamma} + s_2^I \sin 2\phi_{\gamma^* \gamma}), \tag{1.5}$$

an integration of $\mathscr{S}_{CS,U}$ in $\phi_{\gamma^* \gamma}$ is performed for the cancellation of the interference term. The lepton propagators are denoted by $P_1(\phi)$ and $P_2(\phi)$, while c_i^{DVCS} and s_i^I are combinations of Compton

form factors and only c_0^{DVCS} and s_1^I are the leading twist-2 contributions. It should be underlined that the interference term has $\sin n\phi_{\gamma^*\gamma}$ modulations and thus an experimental acceptance symmetric around $\phi_{\gamma^*\gamma} = 0$ supresses its contribution. Hence, only a contribution of the term c_0^{DVCS} remains, which corresponds to the dominant transversely polarised virtual photon contribution of the pure DVCS cross section. The goal of this measurement is to measure the $|t|$-dependence of the pure DVCS cross section and to extract the slope parameter B. The virtual photon-proton scattering cross section is derived from the measured muon-proton cross section by correcting for the virtual photon flux term:

$$\frac{\mathrm{d}^4\sigma^{\mu p}}{\mathrm{d}Q^2 \mathrm{d}\nu \mathrm{d}|t|} = \Gamma\left(1 + \varepsilon \frac{\sigma_L}{\sigma_T}\right)\frac{\mathrm{d}\sigma^{\gamma^* p}}{\mathrm{d}|t|}, \tag{1.6}$$

where

$$\Gamma = \frac{\alpha_{em}(1 - x_{Bj})}{2\pi Q^2 y E_\mu}\left[y^2\left(1 - \frac{2m_\mu^2}{Q^2}\right) + \frac{2}{1 + \frac{Q^2}{\nu^2}}\left(1 - y - \frac{Q^2}{4E_\mu^2}\right)\right] \tag{1.7}$$

for which the Hand convention is used. Since only the transversely polarised virtual photon contribution of the pure DVCS cross section is selected, the kinematic factor ε and the ratio of $\frac{\sigma_L}{\sigma_T}$ is not taken into account.
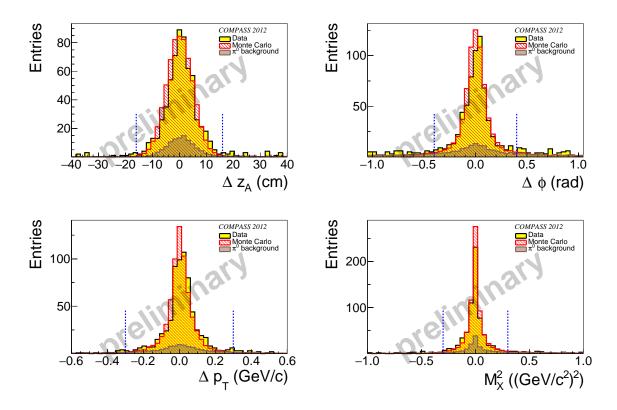
2. Experimental setup

COMPASS is a fixed target experiment at CERN. It can be operated with a tertiary μ^+ or μ^- beam with an incident momentum of 100-200 GeV/c. The beam polarisation of $\pm$ 80 % for $\mu^\mp$ changes together with the beam charge. The COMPASS II detector is an open field two stage spectrometer. The beam is centered on a 2.5 m long unpolarised liquid hydrogen target surrounded by two concentric rings of scintillating counters, which detect the recoil protons by means of the Time of Flight (ToF) technique. Directly downstream of the target a new electromagnetic calorimeter is placed. The particles emitted in the forward direction are reconstructed by a two-stage magnetic spectrometer, equipped with a variety of tracking detectors, a muon filter for muon identification and a hadronic as well as an electromagnetic calorimeter. A detailed description of the spectrometer can be found in Ref. [5].

The data shown in the following is extracted from a pilot run for the DVCS program, performed during four weeks in 2012. The major upgrades for this pilot run are the proton recoil detector and the electromagnetic calorimeter located directly downstream of the target.

3. Event selection

The aim is to select exclusive single photon production, $\mu p \rightarrow \mu' p' \gamma$, while minimising the impact of events associated with background due to pile-up. First, events containing a single outgoing muon and a single neutral cluster above the DVCS calorimeter thresholds are selected. The muon and photon are then combined with all possible recoil proton candidates reconstructed inside the ToF detector surrounding the liquid hydrogen target. The selection of exclusive events is further refined by applying cuts that take advantage of the over-constrained kinematics of the reaction: coplanarity

$$\Delta\varphi = \varphi_{meas}^{proton} - \varphi_{reco}^{proton}, \tag{3.1}$$

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Figure 1: Exclusivity variables: The whole Monte Carlo estimate is shown in red while in grey only the π^0 contamination is shown. The variables $\Delta\varphi$, $\Delta p_\perp$ and M_X^2 are defined in equation 3.1-3.3 while Δz_A encodes a reverse vertex pointing. The blue dotted lines indicate the applied cuts.

the transverse momentum balance

$$\Delta p_\mathsf{T} = p_{\mathsf{T},meas}^{proton} - p_{\mathsf{T},reco}^{proton}, \tag{3.2}$$
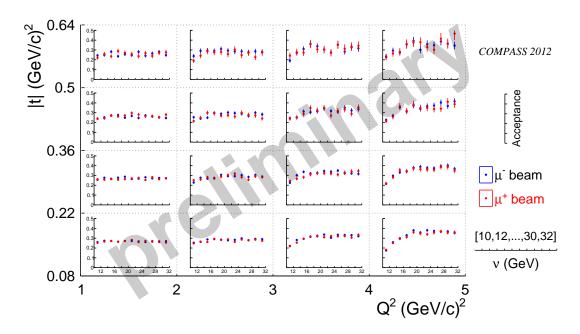
as well as the total 4-momentum balance

$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2 . \tag{3.3}$$

The subscript "meas" denotes measured quantities by the recoil detector while the subscript "reco" denotes that the same quantity has been calculated from the reconstructed incident and final state muon together with the measured photon energy and the assumption of exclusivity.

In addition the longitudinal hit position z_A inside the recoil detector, predicted from the interaction vertex and the hit in the outer ring of the recoil detector, is compared to the measured hit position. This reverse vertex pointing is encoded in the variable Δz_A, which gives the difference of the two hit positions.

4. Results

For the extraction of the cross section and the t-slope the data has been corrected for acceptance effects using binwise acceptance correction factors according to figure 2. The Bethe Heitler
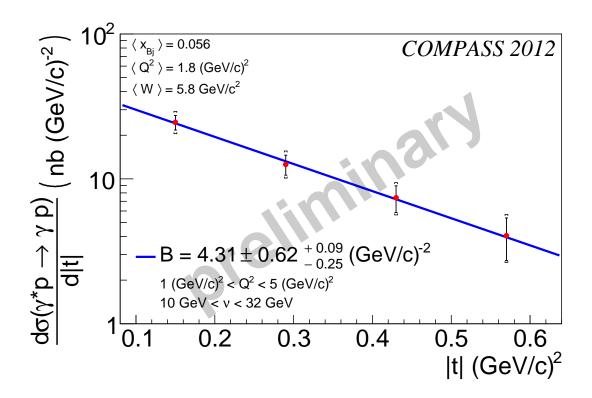
Figure 2: Acceptance correction factors as a function of t, Q^2 and ν.

contribution has been subtracted from the data for each of these bins individually. A major background source for single photon events is the production of pi0 mesons, where one of the two photons originating from the π^0 decay stays undetected. The contamination arising from π^0 production was estimated and subtracted from the data inside each bin using LEPTO 6.5.1 together with an exclusive π^0 Monte-Carlo linked to a parametrisation from Goloskokov and Kroll (Ref. [4]). A kinematically constrained fit, making full use of the exclusive measurement, has been applied to obtain the most precise determination of the particle parameters at the interaction vertex. The values of the differential cross section inside the four bins in $|t|$ have been fitted following an exponential law by using the binned maximum likelihood method to determine the t-slope parameter.
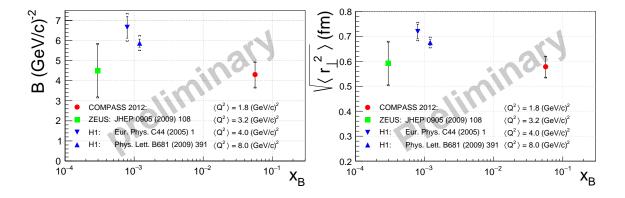
The resulting parameter B of the slope of the sum of the differential cross sections was determined to be $B = (4.31 \pm 0.62 {}^{+0.09}_{-0.25})(\text{GeV/c})^{-2}$ inside the kinematic range shown in figure 3, which corresponds to mean kinematic values of $<x_B>= 0.056$, $<Q^2>= 1.8\,(\text{GeV/c})^2$ and $<W>= 5.8\,\text{GeV/c}^2$.

The main systematic uncertainty on the cross section is linked to the absolute normalisation of the measurement, which results in an upward uncertainty of up to 20 percent and a downward uncertainty of approximately 10 percent. Furthermore, the subtracted amount of π^0 background can be translated into an additional upward uncertainty of up to 10 percent. In case of the extracted parameter B the systematic error originating from the absolute normalisation plays a minor role, while the main systematic uncertainty of six percent originates from the absolute normalisation of the π^0 background and prefers a downward fluctuation.

Figure 4 shows the parameter B and the resulting transverse size of the partonic distribution of a proton at $x_B = 0.056$ extracted at COMPASS in comparison with results obtained by HERA. This

Figure 3: The *t*-differential DVCS cross section as a function of *t*

Figure 4: COMPASS results for the t-slope parameter (**left**) and the extracted transverse size of the partonic distribution of the nucleon (**right**), compared with previous HERA measurements.

first model-independent determination of $\sqrt{<r_\perp^2>}$ may indicate a decrease of the transverse size of the proton as a function of the longitudinal momentum fraction x_B. The statistics used in this analysis is approximately 7 percent of the data expected from the dedicated data takings in 2016 and 2017. With the full statistics the granularity in x_B will increase dramatically and the question whether a sizeable decrease of the transverse size of the proton can be observed in this x_B region will be answered.

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