The theoretical framework of Generalized Parton Distributions (GPDs) provides a dynamical and geometrical picture of the nucleon. In addition to the longitudinal momentum information of partons they contain information on the transverse localisation of the constituents. The exclusive production of $\rho^0$ mesons off a transversely polarised target allow to constrain the GPD $E$ which is connected, according to Ji’s sum rule, with the total angular momentum of quarks and gluons.

At the COMPASS experiment at CERN measurements were performed by scattering a 160 GeV/c muon beam off transversely polarised $^6$LiD (2003, 2004) and NH$_3$ (2007, 2010) targets. From these data the transverse target spin azimuthal asymmetries $A_{UT}^{\sin(\phi-\phi_S)}$ for proton and deuteron are extracted.
1. Introduction

The concept of Generalized Parton Distributions (GPDs) provides an extensive description of the internal quark-gluon structure of the nucleon [1–3]. It combines the well known form factors and the parton density distributions and allows for a 3-dimensional tomographic picture of the nucleon. GPDs can be experimentally probed via the hard exclusive radiation of a real photon (Deep Virtual Compton Scattering, DVCS) or the hard emission of an exclusive meson (Hard Exclusive Meson Production, HEMP). Both processes are characterized by an intact nucleon in the final state. The measurements of the two channels allow for accessing independent and complementary information towards a full flavour decomposition of GPDs. At leading twist, meson production is described by 4 types of GPDs $H, E, \tilde{H}, \tilde{E}$ for every quark family and the gluon. Each of the GPDs depends on three variables: $x$ the average and $\xi$ half the difference of the longitudinal momenta carried by the struck parton in the initial and final states and $t$ the squared four-momentum transfer to the target nucleon.

For the hard exclusive production of a meson by longitudinal polarised photons the factorisation theorem is valid which allow for a separation of the amplitude into a hard part, described by perturbative QCD and a soft part [4]. The non-perturbative part enfolds the structure of the nucleon described by GPDs and the structure of the emitted meson depicted by the distribution amplitude (DA).

2. The COMPASS experiment

The COMPASS experiment, situated at the SPS M2 beam line at CERN, is a fixed-target experiment with a rich physics program focused on the spin structure of nucleons and hadron spectroscopy [5]. The two stage spectrometer is designed to reconstruct scattered muons and produced hadrons in a wide kinematic range. Each stage is equipped with an open field dipole magnet, different tracking detectors and one hadronic and electromagnetic calorimeter. In addition a RICH allow for charged particle identification. In 2006 a new target magnet was installed increasing the acceptance from ±70 mrad to ±180 mrad.

The presented measurements were performed using a $\mu^+$ beam with an intensity of $\sim 2 \cdot 10^8$ muons per SPS cycle and a momentum of $\sim 160$ GeV/c. It is based on data taken during the years 2003, 2004 with a $^6\text{LiD}$ target (deuterons) and 2007, 2010 with a $\text{NH}_3$ target (protons). Both targets are transversely polarised with respect to the beam direction and are composed of different target cells, arranged along the beam axis. The $^6\text{LiD}$ target is a two cell target, where each target cell is 60 cm long and polarised in opposite direction. The $\text{NH}_3$ target has three target cells, of 30 cm, 60 cm and 30 cm length, were the spin directions in neighbouring cells are opposite. The achieved polarisation is about $P_T \sim 50\%$ for deuterons and $P_T \sim 80\%$ for protons with relative uncertainties of 5% and 3% respectively. The fraction of the polarisable material in the target weighted by the cross section is quantified by the dilution factor $f$, where $f = \sim 45\%$ for $^6\text{LiD}$ and $\sim 25\%$ for the $\text{NH}_3$ target. The setup allows the measurement of both spin polarisation states at the same time. Systematic effects of the acceptance are further reduced by rotating the spin direction periodically about every week.
3. Hard exclusive $\rho^0$ production

The cross section of the analysed process $\mu N \rightarrow \mu N \rho^0$ is described in the COMPASS kinematic region by

$$\frac{d\sigma}{dx_B dQ^2 d\phi d\phi_s} \simeq \sigma_0 \left( 1 - S_T A_{UT}^{\sin(\phi - \phi_s)} \sin(\phi - \phi_s) \right) + \ldots,$$

where only the terms relevant for this analysis are shown explicitly [6]. The unpolarised cross section is given by $\sigma_0$, $\varepsilon$ is the virtual photon polarisation parameter and $S_T$ the transverse component of the target spin vector respective to the direction of the virtual photon. The azimuthal angle between the lepton scattering plane and the plane containing the virtual photon and the produced meson is denoted by $\phi$, and $\phi_s$ is the azimuthal angle of the target spin vector around the virtual photon direction relative to the lepton scattering plane. The transverse target spin azimuthal asymmetry

$$A_{UT}^{\sin(\phi - \phi_s)} \propto \sqrt{|t - t_0|} \frac{\text{Im}(\varepsilon^* H)}{|H|^2}$$

is connected to $\varepsilon$ and $H$ which are weighted sums of convolutions of the GPDs $E$ and $H$ with the DA of the produced meson and a hard scattering kernel [6]. Here $t_0$ describes the minimal kinematically allowed $|t|$ while U and T refer to an unpolarised beam and a transversely polarised target. The asymmetry is sensitive to the poorly known GPD $E$. This GPD is connected, according to Ji’s sum rule, with the total angular momentum of quarks and gluons [3].

4. Event selection and background estimation

The essential steps of the event selection are described in the following. The considered events have an incoming and a scattered muon track and two oppositely charged hadron tracks associated to a vertex in the target region. In order to select a sample in the deep inelastic scattering region cuts on the photon virtuality $Q^2 > 1$ (GeV/c)$^2$, $0.003 < x_{Bj} < 0.3$, the fractional energy of the virtual photon $0.1 < y < 0.9$ and the invariant mass of the $\gamma^* - N$ state $W > 5$ GeV/c$^2$ are applied. The $\rho^0$ meson is selected in the invariant mass range of $0.5$ GeV/c$^2 < M_{\pi^+\pi^-} < 1.1$ GeV/c$^2$, where for each hadron the pion mass hypotheses is assigned. This cut is optimised with regard to a high yield and purity of a resonant $\rho^0$ production compared to the non-resonant $\pi^+\pi^-$ production. The measurements are performed without the detection of the recoiled proton in the final state. The exclusivity selection of the events is based on cuts on the missing energy

$$E_{\text{miss}} = \frac{(p + q - v)^2 - p^2}{2 \cdot M_p} = \frac{M_X^2 - M_p^2}{2 \cdot M_p},$$

where $M_p$ is the rest mass for the proton and $M_X$ the mass of the not detected recoiled system. $M_X$ is calculated with the four-momentum of proton $p$, photon $q$ and meson $v$. For exclusive events $E_{\text{miss}}$ is about 0. To accomodate for the finite experimental resolution we consider events in the range $-2.5$ GeV $< E_{\text{miss}} < 2.5$ GeV. The number of non-exclusive events can be further reduced by a cut on the squared transverse momentum of vector meson with respect to the virtual photon direction $p_T^2 < 0.5$ GeV$^2$/c$^2$, the energy of $\rho^0$ in laboratory system $E_{\rho^0} > 15$ GeV and $Q^2 < 10$...
GeV²/c². A cut on \( p_T^j > 0.1 \) GeV²/c² and \( p_T^f > 0.05 \) GeV²/c² for \( ^6\text{LiD} \) and \( \text{NH}_3 \) respectively is used to suppress coherently produced events. After all applied cuts the final samples for incoherent exclusive \( \rho^0 \) production consist of about 97000 and 797000 events for the \( ^6\text{LiD} \) and \( \text{NH}_3 \) targets, respectively.

The mean values for the kinematic variables \( Q^2, x_{Bj}, y, W \) and \( p_T^f \) are given in Tab. 1.

In order to correct for semi-inclusive events the \( E_{\text{miss}} \) shape of the background is parametrised for each individual target cell in every kinematic bin of \( Q^2, x_{Bj} \) and \( p_T^f \) using a Monte-Carlo (MC) LEPTO sample with the COMPASS tuning of the JETSET parameters [7]. The \( h^+h^- \) MC sample is weighted in every \( E_{\text{miss}} \) bin \( i \) by the ratio of numbers of like-sign events from data and MC

\[
w_i = \frac{N_{h^+h^-}^{i,\text{data}}(E_{\text{miss}}) + N_{h^+h^-}^{i,\text{data}}(E_{\text{miss})}}{N_{h^+h^-}^{i,\text{MC}}(E_{\text{miss}}) + N_{h^+h^-}^{i,\text{MC}}(E_{\text{miss})}},
\]

which improves the agreement between data and MC significantly. The approach is supported by the observation that the weights calculated for the \( \rho^0 \) sample and for the like-sign sample are comparable for large \( E_{\text{miss}} \). In every bin required for the asymmetry extraction, i.e. the kinematic bins \( Q^2, x_{Bj}, \) and \( p_T^f \) and 12 bins in \( \phi - \phi_S \), individually for each target cell and spin orientation, a signal plus background fit is performed, with a Gauss function for the signal and the background shape fixed by MC. As an example, the \( E_{\text{miss}} \) distribution integrated over the angle \( \phi - \phi_S \), target cells and polarisation states for the highest \( Q^2 \) bin is depicted in Fig. 4. The total amount for the semi-inclusive background is estimated as 18\% (\( ^6\text{LiD} \)) and 22\% (\( \text{NH}_3 \)), respectively. Apart of the discussed semi-inclusive fraction of the background the final sample comprise diffractive events where the recoiled nucleon is in an excited \( N^* \) - or \( \Delta \) -state (14\%), visible as an enhancement right from the signal peak in Fig. 4. Furthermore coherently produced \( \rho^0 \) mesons (\( \sim 8\% \) for \( ^6\text{LiD} \), \( \sim 12\% \) for \( \text{NH}_3 \)) and non-resonant \( \pi^+\pi^- \)-pairs (<2\%) contributes. We do not apply a correction for these contributions.

5. Results

The asymmetry is extracted from the final sample, after the subtraction of semi-inclusive background, using a one dimensional maximum likelihood fit. The number of exclusive \( \rho^0 \) mesons for a given bin \( j \) of \( \phi - \phi_S \) and target cell (ncell) can be written as

\[
N^{\pm}_{j,\text{ncell}} = c^{\pm}_{j,\text{ncell}} \left( 1 \pm f|P_T|A^{\sin(\phi - \phi_S)}(\sin(\phi - \phi_S)) \right), \tag{5.1}
\]

where \( f \) is the target dilution factor, \( P_T \) the target polarisation and \( c^{\pm}_{j,\text{ncell}} \) is a product of the spin-averaged cross section, the muon flux, the number of target nucleons and the product of acceptance and efficiency of the spectrometer. For the data taken with the three cell \( \text{NH}_3 \) target the events of the
two outer cells are summed up. The asymmetry is extracted using at the same time the information coming from both cells in two consecutive periods with opposite spin configuration ±.

The results for $A_{UT}^{sin(\phi - \phi_s)}$ as a function of $x_B$, $Q^2$ and $p_T^2$ are shown in Fig. 2. As sources of systematic effects the bias of the applied estimator of the asymmetry, data stability in time, false asymmetries and the uncertainties of target dilution factor and target polarisation value are investigated. For systematic effects related to the background subtraction the sensitivity to the Monte-Carlo description used for the parametrisation of the background shape and the compatibility of results after background subtraction are studied. The overall systematic error is estimated for every kinematic bin i to $\sigma_i^{sys} = 0.5 \sigma_i^{stat}$ for deuteron data and $\sigma_i^{sys} = 0.25 \sigma_i^{stat}$ for proton data, depicted as grey bands in Fig. 2. For both targets the asymmetries are found to be small and compatible with 0 within statistical uncertainties. Averaged over COMPASS kinematical region the values are $A_{UT,d}^{sin(\phi - \phi_s)} = 0.02 \pm 0.03 \pm 0.02$ and $A_{UT,p}^{sin(\phi - \phi_s)} = -0.002 \pm 0.010 \pm 0.003$.

The blue lines in Fig. 2 show the predictions given by the GPD model of Goloskokov and Kroll [8]. The model includes both longitudinal and transverse virtual photons for $W = 8.1 \text{ GeV}/c^2$, $Q^2 = 2.2 \text{ GeV}^2/c^2$ and $p_T^2 = 0.2 \text{ GeV}^2/c^2$ and with $E^s \simeq E^t \simeq 0$. The indicated theoretical error bands reflect uncertainties in the GPD parametrisation. The small value of the asymmetry for $\rho^0$ may be due to an approximate cancellation of two sizable and comparable contributions of opposite sign from GPDs $E$ for valence u and d quarks, $E^u \approx -E^d$.

6. Summary

GPDs provide a dynamical and geometrical picture of the nucleon. Experimentally the asymmetry $A_{UT}^{sin(\phi - \phi_s)}$ can be determined and allow to constrain the GPD $E$. This talk presented $A_{UT}^{sin(\phi - \phi_s)}$ for transversely polarised deuterons ($^6\text{LiD}$ target) and protons ($^7\text{Li}$ target). The measurement was performed at the COMPASS experiment during the year 2003, 2004 and 2007, 2010. Both asymmetries, which are shown as a function of $x_B$, $Q^2$ and $p_T^2$, are small and compatible with 0. The results for the transversely polarised deuterons were measured for the first time. The proton results are compatible with HERMES although the COMPASS measurement is more precise by a factor.
Figure 2: Transverse target spin asymmetry $A_{UT}^{\sin(\phi - \phi_S)}$ measured on proton (upper) and deuteron (lower) as a function of $x_{Bj}$, $Q^2$ and $p_T^2$. Error bars show statistical uncertainties, while the systematic ones are represented by bands at the bottom. The blue curves indicate the predictions of the GPD model [8].

of about 3 and covers a larger kinematic domain. The results agree with predictions of the GPD model [8].

References


