Exclusively produced ρ^0 asymmetries on the deuteron and future GPD measurements at COMPASS

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Generalized parton distributions (GPDs) provide a new and powerful framework for a complete description of the nucleon structure. They can provide a three-dimensional picture of how the quarks and gluons form a nucleon. GPDs can be probed experimentally in hard exclusive meson production or deeply virtual Compton scattering (DVCS). The COMPASS experiment at CERN is a unique place to study these reactions. At COMPASS, a high energy polarized positive or negative muon beam is scattered off a polarized or unpolarized fixed target. First results for exclusive ρ^0 meson production are shown. The transverse target spin asymmetry for exclusively produced ρ^0 on a transversely polarized deuteron target has been measured. Prospects for future measurements of DVCS and exclusive meson production at COMPASS will be shown. The experiment will use the existing COMPASS spectrometer with a new target, a new recoil detector and extended calorimetry. Simulations for different models and a test of the recoil detector have been performed.

Keywords: nucleon structure, Generalized Parton Distributions, COMPASS, recoil detector

1. Introduction

Generalized parton distributions (GPDs) have been introduced about 10 years ago[1–3] and provide a comprehensive description of the nucleon. They can describe elastic form factors and polarized and unpolarized parton distributions at the same time. In addition, they may provide a handle on the orbital angular momentum of the quarks in the nucleon via the Ji sum rule.[3] GPDs may be accessed experimentally by measuring cross-sections and asymmetries in deeply virtual Compton scattering and exclusive meson production processes at COMPASS.

GPDs describe the quantum-mechanical amplitude for "taking out" a parton (quark or gluon) from a fast moving nucleon and "putting it back" with a different momentum, leading to a small momentum transfer to the nucleon. The GPDs are functions of three parameters, the longitudinal quark momentum fraction x, the longitudinal momentum transfer to the nucleon $\xi = x_{bj}/(2 - x_{bj})$ and the squared momentum transfer to the target nucleon t. The latter is the Fourier conjugate of the transverse impact parameter r of the scattering.

At leading twist four GPDs are necessary to describe the quark structure of the proton. The GPDs H and $\tilde{H}$ conserve the helicity of the proton and are generalizations of the ordinary parton distributions measured in DIS. In the forward limit $\xi = 0$ and $t = 0$ the unpolarized GPD H reproduces the unpolarized quark distribution $q(x)$. The polarized GPD $\tilde{H}$ gives the polarized quark distribution $\Delta q(x)$.

The GPDs E and $\tilde{E}$ allow a proton helicity flip and imply a transfer of orbital angular momentum to the nucleon. This is only possible for a non-zero transverse momentum transfer t, which is new with respect to ordinary parton distribution functions.

2. The COMPASS experiment

The COMPASS experiment is a fixed target experiment at the SPS accelerator at CERN. It scatters a longitudinally polarized muon beam on a polarized solid state target. From 2002 to 2004, COMPASS took data with a muon beam of 160 GeV and a longitudinally or transversely polarized ^{6}LiD target. For about 20% of the beam time, the target nucleons have been polarized transversely with respect to the beam polarization. The data presented here for the exclusive ρ^0 production have been taken with a transverse polarization of the target of about 50%.

The scattered muon and produced hadrons are detected in a two-stage spectrometer,[4] which provides high momentum resolution and excellent particle identification.

3. Exclusive ρ^0 production

One observable sensitive to the GPDs E and H is the transverse target spin asymmetry in the exclusive ρ^0 vector meson production. The reaction studied is

$$\mu N \rightarrow \mu \rho^0 N,$$

where N is a quasi-free nucleon in the polarized deuteron target. The reaction can be described as virtual photoproduction of a ρ^0: $\gamma^* N \rightarrow \rho^0 N$.

To interpret the results in terms of GPDs, the following conditions have to be fulfilled: The virtual photon has to be longitudinally polarized, since only for longitudinal photons factorization between the hard reaction and the soft GPD part has been shown. The negative four-momentum transfer squared of the virtual photon Q^2 has to be large[5] and the momentum transfer squared t between initial and final nucleon has to be small.

At COMPASS, the outgoing ρ^0 and the scattered muon is detected, but the recoil proton is not. The ρ^0 is reconstructed from the invariant mass of the two pions by applying an invariant mass cut of $|M_{\pi^+\pi^-} - M_\rho| < 0.3$ GeV. The exclusivity is insured by a cut on the missing energy of $|E_{miss}| <$ 2.5 GeV. To further minimize the non-exclusive background, a cut on the transverse momentum of the ρ^0 of $p_T^2 < 0.5$ (GeV/c)^2 has been applied. For a reliable definition of the azimuthal angle of the produced ρ^0 with respect to the lepton scattering plane, a lower limit has been imposed on the transverse momentum $p_T^2 > 0.01$ (GeV/c)^2.

Deep-inelastic scattering events were selected by a cut on the negative four-momentum transfer $Q^2 > 1$ (GeV/c)^2 and on the invariant mass of the hadronic system $W > 5.0$ GeV/c. The energy fraction of the virtual photon with respect to the beam momentum is limited in the range $0.1 < y < 0.9$. After all cuts $270k$ exclusively produced ρ^0 mesons have been obtained in total.

The azimuthal target spin asymmetry has been evaluated with respect to the angle $(\phi_h - \phi_S)$ (Fig. 1), where ϕ_h is the azimuthal angle of the produced ρ^0 meson with respect to the lepton scattering plane and ϕ_S the azimuthal angle of the target spin vector.

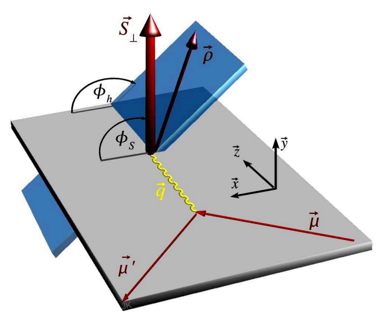

Fig. 1. Definition of ϕ_h and ϕ_S for exclusive ρ^0 production.

The transversely polarized target consists of two target cells with opposite polarization direction. Their polarization is reversed about once per week. To minimize systematic effects, the asymmetry is extracted from the counting rates in both cells and both target configurations with the double ratio method described in.[6] The extracted raw asymmetry ϵ is normalized to the target polarization $\langle P \rangle$ and the dilution factor $f = 0.38$ of the target:

$$A_{UT} = \frac{\epsilon}{f \cdot \langle P \rangle} \tag{1}$$

4. Results for exclusive ρ^0 production

The transverse target spin asymmetry A_{UT} in exclusive ρ^0 production is plotted in Fig. 2 as a function of x_{bj} and p_T. The measured asymmetries are small and within their statistical precision compatible with zero. Further analysis will allow to disentangle the contribution of the incoherent production on a quasi-free nucleon from the coherent production on the deuteron. Both mechanisms can be distinguished by the produced transverse momentum, since coherent production happens preferable at lower transverse momenta.

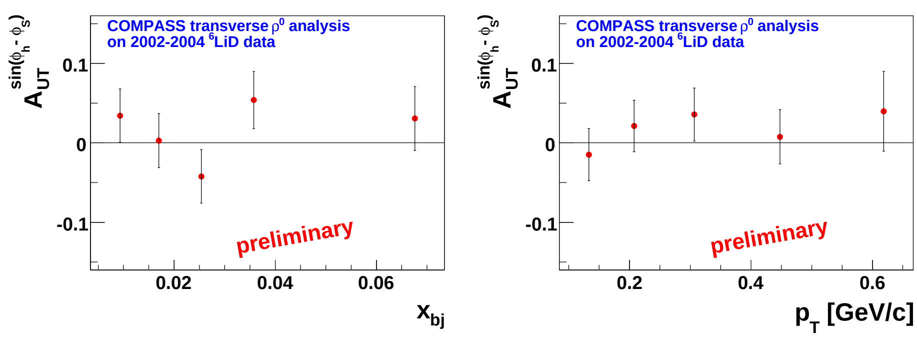

Fig. 2. Transverse ρ^0 target spin asymmetries as a function of x_{bj} (left) and p_T (right).

For a comparison to GPD model calculations, the asymmetry for longitudinal photons has to be extracted.[5] A method to extract the asymmetry for longitudinal photons was proposed in:[7] the contributions of longitudinal and transverse ρ^0 can be estimated from the angular distribution of the decay products. By assuming s-channel helicity conservation, we can determine the contribution from longitudinal photons.

In addition, in 2007 we took data with a transversely polarized proton target. Repeating the analysis on our proton data will provide new results on A_{UT} on the proton.

5. Future GPD measurements at COMPASS

The COMPASS experiment at CERN is a perfect place to study generalized parton distributions.[8] The GPDs will be accessed through deeply virtual Compton scattering and hard exclusive meson production. Due to the high energy of the muon beam available at COMPASS (between 100 and 190 GeV) the kinematic range covered by the proposed GPD program will be large enough to provide a bridge between the HERA collider experiments[9,10] at very small x_{bj} and the JLAB[11,12] and HERMES[13] experiments at large x_{bj} (Fig. 3).

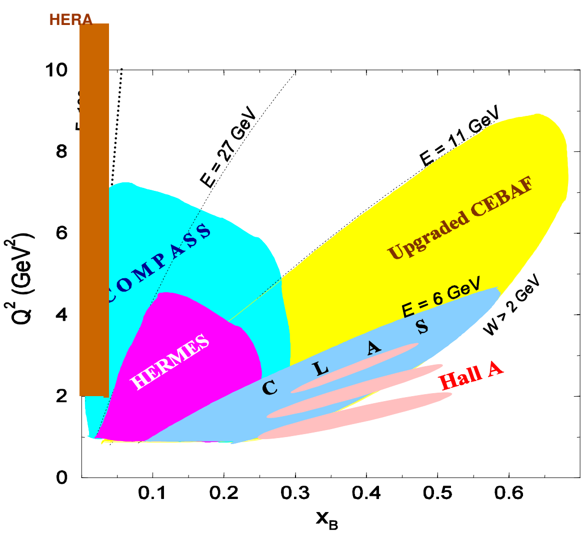

Fig. 3. Kinematic coverage for various DVCS experiments.

The measurements of generalized parton distributions at COMPASS will be performed with an unpolarized liquid hydrogen or deuterium target surrounded by a recoil detector.[8] The CERN beam-line can provide both positive and negative muons with opposite polarization of 80%. For beam charge asymmetry measurements the beam charge can be changed once a day. The goal of the experiment is to measure the cross section as well as spin and charge asymmetries as a function of x_{bj}, Q^2 and t. At 190 GeV, the DVCS process is dominant over the competing Bethe-Heitler process and the cross section can be measured. At 100 GeV, the possibility to use muon beams of opposite charge and polarization will allow to measure the charge and spin asymmetries arising from the interference between DVCS and the Bethe-Heitler process. Measurements of the cross section difference of oppositely charged and polarized muons give access to the real part of the DVCS amplitude, while the cross section sum provides information about the imaginary part of the DVCS amplitude.[14,15] These observables have great sensitivity to GPD models.[16] Hard exclusive meson production cross sections will also be measured at the same time providing different constraints on GPDs.

6. Simulations

Simulations of the beam charge asymmetry for COMPASS have been performed using three different model assumptions for the DVCS cross section. Two models are based on double distribution parameterizations of GPDs. Model 1 assumes $H(x, \xi, t) \propto q(x)F(t)$,[17] while model 2 includes a correlation between x and t: $H(x, \xi, t) \propto q(x)e^{tb_\perp^2}$ with a parameter $b_\perp$ describing the transverse extension of the partons. This ansatz reproduces the chiral quark soliton model.[18] The model 3 uses a dual parametrization, where the x, ξ dependence is separated from the ξ, t dependence. These calculations have been performed by.[16]

With a luminosity of $1.3 \cdot 10^{32}$ cm^{-2}s^{-1} and an global efficiency of 25% and a running of 150 days the statistical precision shown in Fig. 4 can be achieved. It is possible to split the data into 6 bins in Q^2 from 1.5 (GeV/c)^2 to 7.5 (GeV/c)^2 and in 3 bins in x_{bj} from 0.03 to 0.27. A separation between the different models can be achieved as shown in Fig. 4.

7. Experimental realization

The GPD experiment will use the existing COMPASS spectrometer with several new detectors added. The interaction will take place in a newly designed 2.5 m long liquid hydrogen or deuterium target. It will be surrounded by a recoil detector for the detection of the recoiling particles and to insure exclusivity of the reaction. It will use the time-of-flight technique to determine the recoiling proton momentum with a few percent precision. The recoil detector will consist of two concentric barrels of scintillators read at both sides. To allow for 10 bins in t, a minimum time resolution of

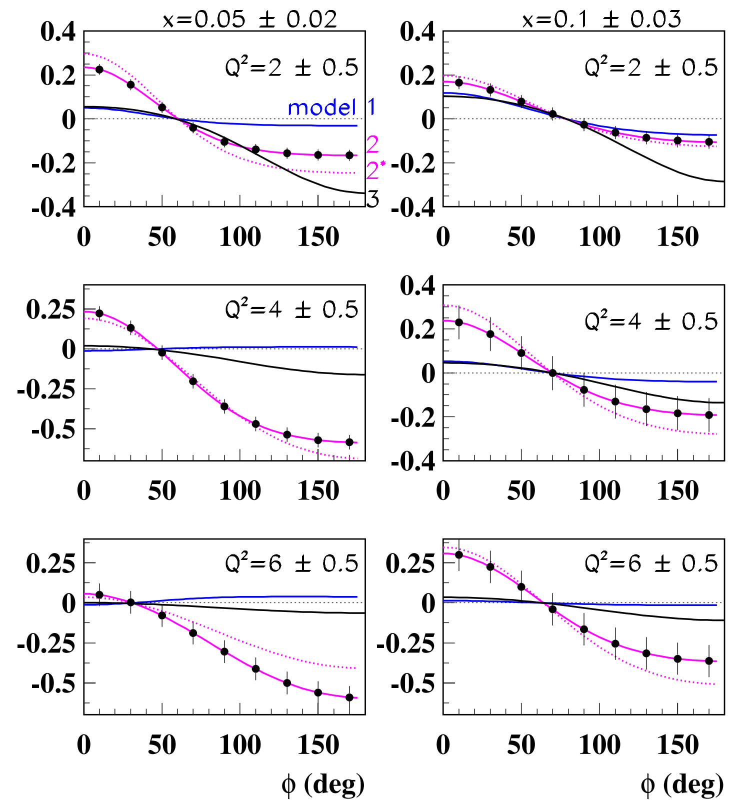

Fig. 4. Projected error bars for a measurement of the beam charge DVCS asymmetry as an example for these simulations in two domains of x_{bj} (0.05 on left and 0.10 on right) and 3 bins of Q^2 (2, 4, 6 $(\mathrm{GeV/c})^2$) from top to bottom. Projected error bars are compared to 3 different GPD models described in the text: model 1 (blue line), model 2 (line with points and error bars), model 3 (black line).

300 ps is needed. A full size prototype has been tested in the COMPASS experimental area in fall 2006 and achieved a time resolution of 310 ps.

In case of DVCS, the photon will be detected in the existing forward calorimeters, an additional wide angle calorimeter covering lab angles up to 20 degrees will be added to improve the acceptance at high x_{bj} and to reject the π^0 background.

8. Outlook

A big advantage of studying GPDs at the COMPASS experiment is that its kinematic domain covers both the valence and the sea quark region in terms of x_{bj}. Currently a proposal for GPD measurements at COMPASS is being prepared. In 2008-2010 the recoil detector, the liquid hydrogen target and the large angle calorimeter are being constructed. Data taking could start with the full set-up as early as 2010. Therefore first results are expected well before possible future projects at the JLAB 12 GeV upgrade and the FAIR project at the GSI.

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