Cross Section for High-p_T Hadron Production in Muon-Nucleon Scattering at $\sqrt{s} = 17.4\,\text{GeV}$

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The measurement of the cross section for quasi-real photoproduction of charged hadrons with high transverse momenta (high p_T) in muon-nucleon scattering at COMPASS ($\sqrt{s} = 17.4\,\text{GeV}$) is presented. The results are compared to a next-to-leading order perturbative QCD (NLO pQCD) calculation of the cross section to evaluate the applicability of pQCD to this process at the COMPASS energy. The calculation is found to reproduce the shape of the differential cross section well, but to underestimate the normalization of the cross section by a factor of three to four. It is shown that this underestimation increases with decreasing energy of the photon, which is emitted by the muon.

The measurement of the polarization of gluons in the nucleon has been a long-standing goal of hadron physics. Gluon polarization can be directly accessed in lepton-nucleon scattering experiments by measuring double-spin asymmetries of cross sections that have contributions from the photon-gluon fusion (PGF) process. The PGF is the interaction of a photon, emitted by the lepton, with a gluon inside the nucleon via the formation of a quark-antiquark pair. It dominates the cross section for the production of charmed mesons in lepton-nucleon scattering in the kinematic domain of the COMPASS experiment [1] and also has a considerable contribution to the cross section for the production of hadrons with high transverse momenta (high p_T) [2, 3]. The polarized and unpolarized cross sections for single-inclusive high-p_T hadron production in the quasi-real photoproduction limit, i.e. at low photon virtualities, Q^2, have been calculated in next-to-leading order perturbative QCD (NLO pQCD) [4] for the COMPASS kinematics. The calculations show that the gluon polarization can be constrained in the gluon-momentum-fraction range $0.1 \leq x_g \leq 0.3$ using the pQCD framework by comparing the calculated double-spin asymmetries of the cross section, using different input distributions for the gluon polarization, with the asymmetries extracted from the COMPASS data. This approach would be complementary to the gluon polarization measurements of Refs. [2, 3], which are based on the Monte Carlo (MC) generators PYTHIA [5] and LEPTO [6], respectively, for the quantification of the PGF contribution to the cross section. However, before the pQCD-based gluon-polarization analysis can be performed with confidence, the applicability of pQCD to this process at the COMPASS energy has to be proven by comparing the calculated and measured values of the unpolarized cross sections. In this contribution, the measurement of the

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cross section for quasi-real photoproduction of high-p_T hadrons in muon-nucleon (μ-N) scattering at the center-of-mass system (c.m.s.) energy, $\sqrt{s} = 17.4\,\mathrm{GeV}$, at the COMPASS experiment is presented and compared to the NLO pQCD results.

The experimental data were recorded in 2004 with the COMPASS spectrometer at CERN [7]. In the experiment, a $160\,\mathrm{GeV}/c$ μ^+-beam scatters off a polarized, isoscalar target which consists of granulated ^{6}LiD in a liquid helium bath. The target is arranged in two oppositely polarized 60 cm long cells. The unpolarized cross section is obtained by averaging over the target polarizations. The integrated luminosity was determined via the direct measurement of the rate of beam muons crossing the target and is found to be equal to $142.4\,\mathrm{pb}^{-1} \pm 10\%(\mathrm{syst.})$. As an independent check of the luminosity result, the structure function of the nucleon F_2 was determined from this data set and successfully compared [8] to the NMC parametrization of F_2 [9]. The high-p_T analysis is based on events that were recorded by the quasi-real photoproduction trigger systems [10], which are based on the coincidence between the detection of the scattered muon at low scattering angles and an energy deposit of at least 5 GeV in one of the hadronic calorimeters. Events are accepted if $Q^2 < 0.1\,(\mathrm{GeV}/c)^2$ and if the fractional energy of the virtual photon, emitted by the incident muon, is $0.2 \leq y \leq 0.8$, where the acceptance of the triggers is maximal. Hadrons with an energy in units of the photon energy $z < 0.2$ are rejected to ensure the applicability of current fragmentation, and exclusively produced hadrons are excluded by rejecting particles with $z > 0.8$. Moreover, hadron candidates are required to have momenta $p > 15\,\mathrm{GeV}/c$ and to hit one of the hadronic calorimeters to ensure full trigger efficiency. The angle of the hadron with respect to the direction of the virtual photon has to be in the range $10 \leq \theta \leq 120\,\mathrm{mrad}$, which corresponds to a range of c.m.s. pseudo-rapidities $2.4 \geq \eta_{\mathrm{c.m.s.}} \geq -0.1$.
The hadron-production cross section is measured in bins of p_T (with the width Δp_T) and is defined as

$$\frac{1}{2\pi p_T}\frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \frac{1}{2\pi p_T}\frac{N_h}{\Delta p_T \cdot L \cdot \epsilon} \quad , \tag{1}$$

where $p_T = p \cdot \sin\theta$ is the transverse momentum of the hadron with respect to the direction of the photon, L is the integrated luminosity, and N_h is the number of observed hadrons in the p_T bin. The cross section is integrated over the above-stated range of $\eta_{\mathrm{c.m.s.}}$. The acceptance-correction factor, ϵ, is determined with an MC simulation of μ-N scattering in the COMPASS experiment. Events are generated with PYTHIA [5], the response of the spectrometer is simulated with a GEANT3-based program [11], and the data are reconstructed with the same software as the experimental data [7]. ϵ is defined as the ratio of the number of reconstructed hadrons over the number of generated hadrons in each p_T bin. It corrects the number of observed hadrons for geometrical acceptance and detection efficiency of the spectrometer as well as for kinematic smearing.
A possible source of background for this measurement are hadrons which are created by secondary interactions of other hadrons in the rather thick target. The background contribution is estimated by fitting the shapes of particular vertex distributions [12] and is found to be consistent with zero. A cross check of this procedure with MC data shows that the background contribution can be underestimated by 6%. The systematic error band associated with the possibility of residual background is chosen to span between a background level of zero and $2 \times 6\%$. The central value for the acceptance factor is placed in the middle of the band. The second contribution to the systematic error of the acceptance factor is due to the fact that it is determined in a one-dimensional way, i.e. by integrating over all kinematic variables other

than p_T. This uncertainty is quantified by determining the acceptance correction and the cross section binned in two variables, p_T and each of the variables Q^2, y, x_{Bj} (Bjorken scaling variable), W (invariant mass of the hadronic system), z, and θ. The results are compared to the one-dimensional case and the deviations are below 3%. This uncertainty is added in quadrature to the uncertainty from background contamination, yielding a point-to-point systematic error of 7%. Another systematic uncertainty of the cross section is the 10% normalization uncertainty from the luminosity determination.

The cross section for quasi-real photoproduction ($Q^2 < 0.1\,(\mathrm{GeV}/c)^2$) of charged high-$p_T$ hadrons in μ-N scattering at $\sqrt{s} = 17.4\,\mathrm{GeV}$ is presented in Fig. 1. The cross section drops about four orders of magnitude over the measured p_T range and the only apparent feature is a slight hardening of the spectrum around $p_T = 2.5\,\mathrm{GeV}/c$. The presented cross section is not corrected for QED radiative effects. The data are compared to the updated [13] NLO pQCD calculation of Ref. [4]. The three curves correspond to different choices of the renormalization (μ_r) and factorization (μ_f) scales in the pQCD calculation. The scale uncertainty of the calculation is estimated by varying the scale $\mu = \mu_r = \mu_f$ in the range $2p_T \geq \mu \geq p_T/2$ with the central value $\mu = p_T$. The NLO pQCD results follow the shape of the differential cross section remarkably well, but the central result ($\mu = p_T$) underestimates the experimental cross section by a factor of three to four. This underestimation is of the same order of magnitude as the underestimation of cross sections for high-p_T hadron production in proton-proton (p-p) scattering at the energies of fixed-target experiments, $\sqrt{s} \sim 20\,\mathrm{GeV}$ [14]. It has been shown that this low-energy discrepancies in p-p scattering can be reconciled by the inclusion of all-order resummations of threshold logarithms beyond NLO, which are related to soft-gluon emissions [15]. Such calculations have not yet been published for the quasi-real photoproduction process, but preliminary results were presented at this conference [16]. They indicate that the normalizations of the pQCD cross section and the measured cross section agree with each other after the inclusion of the resummations.

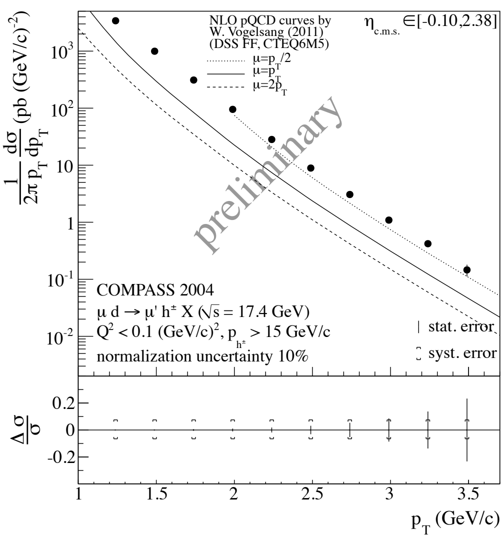

Figure 1: Cross section for high-p_T hadron production. The data are compared to the NLO pQCD calculation [4, 13]. The plot in the upper panel contains the total error bars and the lower panel shows the relative statistical and systematic errors of the measurement.

Figure 2 presents the ratio of the y-differential cross section measured in COMPASS over the cross section calculated in NLO pQCD ($\mu = p_T$) [13] in bins of p_T. It is clearly visible that the underestimation of the cross section by NLO pQCD increases with decreasing photon energy. This shows that the contributions to the cross section which are neglected in the NLO calculation become more significant with decreasing photon-nucleon c.m.s. energy. It will be an interesting test of the resummed calculations, once available, to check whether they can account for the energy dependence of the missing part of the cross section, visible in Fig. 2.

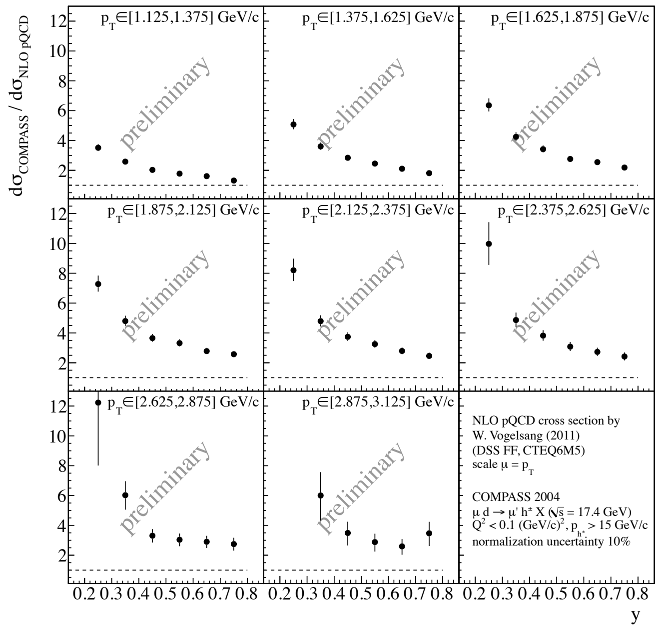

Figure 2: Ratio of the measured y-differential cross section over the NLO pQCD cross section (scale $\mu = p_T$) [13] in bins of p_T.

In conclusion, the measurement of the cross section for the production of charged high-p_T hadrons in μ-N scattering at $\sqrt{s} = 17.4\,\text{GeV}$ has been presented and compared to an NLO pQCD calculation. The calculated p_T-differential cross section follows the shape of the measured cross section well, but underestimates the normalization of the experimental result by a factor of three to four. The y-dependent comparison of the cross sections shows that the underestimation by NLO pQCD clearly increases with decreasing photon energy. Hence, the NLO pQCD calculation seems to be insufficient to fully describe the quasi-real photoproduction of high-p_T hadrons at the COMPASS energy. This discrepancy might be resolved by the inclusion of all-order resummations of threshold logarithms beyond NLO. Establishing an agreement between the cross sections is a prerequisite for the extraction of the gluon polarization in the nucleon from the COMPASS data with the pQCD framework.

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