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Azimuthal asymmetries of hadrons produced in unpolarized SIDIS at COMPASS

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Abstract. The asymmetry in the azimuthal angle distribution of hadrons produced in unpolarized Semi-Inclusive Deep Inelastic Scattering (SIDIS) carries information on the intrinsic transverse momentum of the quark $\vec{k}_T$ and on the still unknown Boer-Mulders parton distribution function $h_1^\perp$. Using the data collected in 2016 and 2017 with 160 GeV/c muon beams scattering off a liquid hydrogen target, the COMPASS Collaboration is measuring the azimuthal asymmetries $A_{UU}^{\cos\phi_h}$, $A_{UU}^{\cos 2\phi_h}$ and $A_{LU}^{\sin\phi_h}$ for charged hadrons. The preliminary results shown here confirm the strong kinematic dependencies observed in previous measurements conducted by COMPASS, HERMES and CLAS. The contribution from hadrons produced in the decay of vector mesons diffractively produced is also discussed.

1. Introduction

One of the building blocks needed for a complete transverse-momentum-dependent (TMD) description of the nucleon structure is the still unknown Boer-Mulders parton distribution function (TMD-PDF) $h_1^\perp$. It encodes the correlation between the quark transverse momentum and its transverse spin in an unpolarized nucleon. In unpolarized SIDIS it couples to the Collins fragmentation function (FF) $H_1^\perp$, originating a well defined azimuthal modulation. The fully differential cross section for the production of a hadron h of transverse momentum P_{hT} in the Gamma-Nucleon System (GNS) reads [1]:

$$\frac{d\sigma}{dP_{hT}^2 dx dy dz d\phi_h} = \sigma_0 \left(1 + \varepsilon_1 A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon_2 A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \varepsilon_3 \lambda A_{LU}^{\sin\phi_h} \sin\phi_h\right), \quad (1)$$

where x is the Bjorken variable, y is the fraction of the beam energy carried by the virtual photon, z is the fraction of the photon energy carried by the hadron, ϕ_h the hadron azimuthal angle in GNS. The ε_i terms are kinematic factors depending on y and λ is the beam polarization. Up to order $1/Q$, the Boer-Mulders TMD $h_1^\perp$ enters the expression of the two azimuthal asymmetries $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$:

$$A_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}\mathcal{C}\left[-\frac{(\hat{h}\cdot\vec{p}_T)\vec{k}_T^2}{M^2 M_h} h_1^\perp H_1^\perp - \frac{(\hat{h}\cdot\vec{k}_T)}{M} f_1 D_1 + \dots\right] \quad (2)$$

$$A_{UU}^{\cos 2\phi_h} \propto \mathcal{C}\left[-2\frac{(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T) - (\vec{k}_T\cdot\vec{p}_T)}{M M_h} h_1^\perp H_1^\perp\right], \quad (3)$$

where $\hat{h} = \vec{P}_{hT}/|\vec{P}_{hT}|$, $\vec{p}_T$ is the transverse momentum acquired by the hadron in the fragmentation, $\vec{k}_T$ the quark intrinsic transverse momentum, M and M_h the proton and hadron masses respectively, f_1 and D_1 are the unpolarized PDF and FF. The symbol $\mathcal{C}$ denotes the convolution over the unobservable transverse momenta $\vec{p}_T$ and $\vec{k}_T$. In the $A_{UU}^{\cos\phi_h}$ asymmetry, the main contribution arises from the Cahn effect [2] and this asymmetry is relevant to get information on $|\vec{k}_T|$.

Measurements of azimuthal asymmetries have been performed in the past by COMPASS [6], HERMES [7] and CLAS [8]. The COMPASS published results, from data collected in 2004 on a ^{6}LiD target with a positive muon beam, showed strong kinematic dependencies of the azimuthal asymmetries for both positive and negative hadrons. Both the evaluation of the intrinsic quark momentum $|\vec{k}_T|$ and the extraction of the Boer-Mulders TMD from published data have not been conclusive so far [3, 4, 5]. Recently, it has been realized by the COMPASS Collaboration that the contribution to the measured asymmetries from hadrons produced in the decay of diffractive vector mesons can be sizable.

2. Experimental results and projections of the statistical uncertainty

Preliminary results have been obtained from $\approx 4\%$ of the data collected at COMPASS during the 2016 and 2017 runs with 160 GeV/c μ^+ and μ^- beams and a 2.5 m long liquid hydrogen target. The DIS events have been selected asking for $Q^2 > 1$ (GeV/c)^2, $0.2 < y < 0.9$, mass of the hadronic final state $W > 5$ GeV/c^2 and $0.003 < x < 0.130$. The hadron tracks have been selected to have $0.2 < z < 0.85$ and 0.1 GeV/$c < P_{hT} <$ 1.0 GeV/c. The selected sample consisted of almost 1 million hadrons.

The unpolarized asymmetries have been alternatively extracted as a function of x, z or P_{hT} by fitting, in each kinematic bin, the acceptance-corrected distribution of the hadron azimuthal angle ϕ_h. The correction for acceptance has been estimated from a Monte Carlo based on the LEPTO generator [10]. The obtained azimuthal asymmetries $A_{UU}^{\cos\phi_h}$, $A_{UU}^{\cos 2\phi_h}$ and $A_{LU}^{\sin\phi_h}$, multiplied by the corresponding kinematic factors ε_i, are shown in Fig. 1. As the agreement between positive and negative beam charges is very good (as expected), the corresponding results have been merged. The dependence on the kinematic variables is strong as previously observed on deuteron. The uncertainties are statistical only. Projections for the statistical uncertainty on the asymmetry from the whole sample, for the full target length and in the same kinematic bins are shown in Fig. 2. The precision that will be achieved, at the permile level, is remarkable. The systematic uncertainty is expected to be of the order of the statistical one.

3. Contribution from diffractively produced vector mesons

The SIDIS process is actually not the only mechanism that can provide azimuthal modulations to the final state hadrons: an important contribution to the observed asymmetries comes also from the hadrons generated in the decay of diffractively produced vector mesons (mostly $\rho^0 \to \pi^+\pi^-$, then $\phi \to K^+K^-$ and $\omega \to \pi^+\pi^-\pi^0$). In this process, which is often exclusive as the scattered nucleon is generally kept intact, the virtual photon spin density matrix is transferred to the vector meson, which itself features an azimuthal modulation that can be inherited by the decay products. These events can not be separated by kinematic cuts and the final SIDIS hadron sample contains also hadrons from diffractive vector mesons, whose contribution to the azimuthal asymmetries has to be evaluated.

The fraction of hadrons from diffractive processes, as well as their azimuthal modulations, has been estimated with the HEPGEN Monte Carlo [11], of which two different samples have been used: one for ρ^0 and one for ϕ. They have been normalized to the experimental data comparing the missing energy (E_{miss}) distribution of exclusive events in which both the decay hadrons were reconstructed. As for the ω meson, since its charged decay products do not satisfy

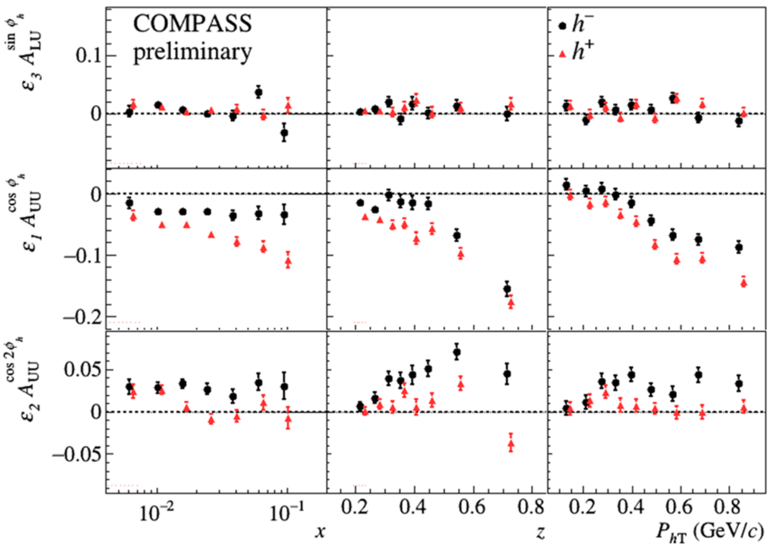

Figure 1. Preliminary results for azimuthal asymmetries as a function of x, z and P_{hT} from part of the 2016 COMPASS run.

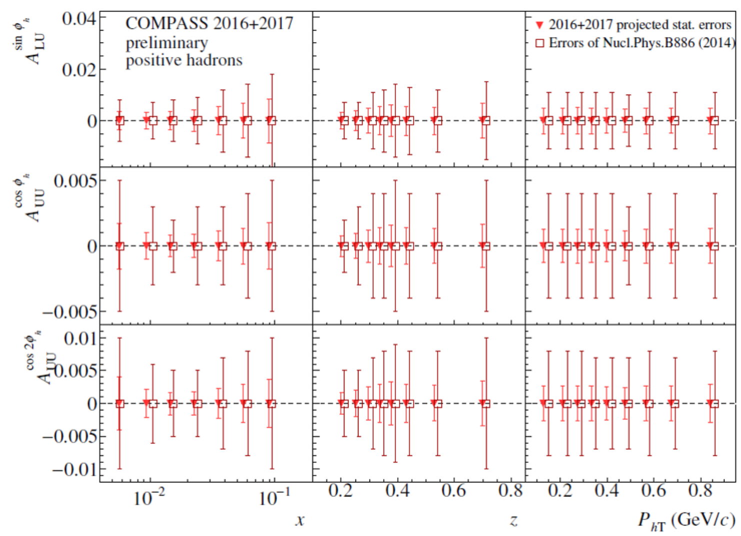

Figure 2. Projections of the statistical uncertainties for the current sample compared to those of the published COMPASS results on deuteron.

exclusivity, a relative normalization equal to a factor 1/9 to the ρ^0 has been adopted. Once the samples have been normalized one can, in each kinematic bin, subtract to the azimuthal distribution for SIDIS hadrons the corresponding Monte Carlo distributions for hadrons from diffractive vector mesons. Currently, the relative uncertainty on the normalization is 10%; the work is in progress and the results encouraging. We expect this correction to be performed with good accuracy. Knowing the three normalization factors one can calculate the whole amount of such 'exclusive' hadrons and their azimuthal modulations, to get an idea of the correction to the standard asymmetries and compare with the previous work [9] on deuteron data. The fraction r_{tot} of exclusive hadrons is shown in Fig. 3. As expected, it is larger than 5% only for z >0.5. When integrating over z, the azimuthal asymmetries for exclusive hadrons are small and the correction to the standard asymmetries is of the order of 1%; however, the correction can be ten times larger at large z. Thus, any detailed analysis of these asymmetries has to take care of the diffractive vector mesons contribution.

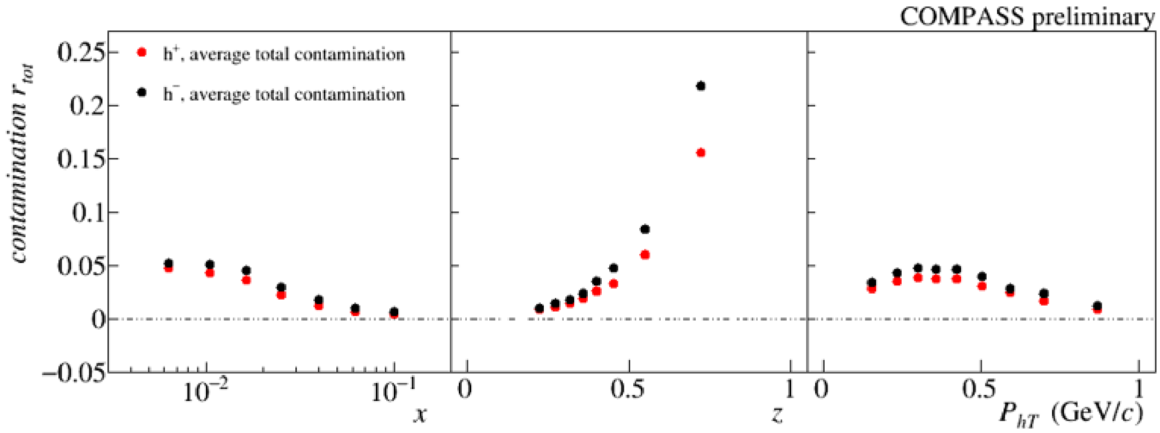

Figure 3. The fraction of hadrons produced in the decay of diffractively produced vector mesons (ρ^0, ϕ and ω), as a function of x, z and P_{hT}.

4. Conclusions

We presented COMPASS preliminary results for unpolarized azimuthal asymmetries for charged hadrons as extracted from part of the data collected in 2016 with a 160 GeV/c muon beam and a liquid hydrogen target. The asymmetries have been extracted as a function of the Bjorken variable x, of the fraction of the virtual photon energy carried by the hadron z and of the hadron transverse momentum in the GNS P_{hT}. The one-dimensional analysis performed so far confirms the strong kinematic dependence of the azimuthal asymmetries already observed in the past. Projections of the statistical uncertainties have also been presented, showing a remarkable reduction to the permile level. The impact on the asymmetries, due to the contribution of hadrons produced in the decay of diffractive vector mesons, has been shown to be sizable, in particular at high z, small x and small P_{hT} and it is presently object of deep investigations.

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