PROCEEDINGS OF SCIENCE

Measurement of azimuthal modulations in SIDIS off proton target at COMPASS

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The azimuthal angle (ϕ_h) distribution of hadrons produced in deep inelastic scattering serves as a powerful tool for probing the nucleon structure in terms of transverse momentum dependent parton distribution functions and fragmentation functions. For an unpolarized nucleon, three azimuthal modulations arise: $\cos\phi_h$ related to the Cahn effect, $\cos 2\phi_h$ linked to the Boer–Mulders function, and $\sin\phi_h$ known as beam-spin asymmetry, each revealing insights into combinations of twist-two or higher-twist distribution and fragmentation functions.

The COMPASS collaboration at CERN collected semi-inclusive deep inelastic scattering events in 2016 and 2017 using a longitudinally polarized 160 GeV/c muon beam scattering off a liquid hydrogen target. Data from 2016 corresponding to about 1/3 of the full sample have been analyzed to measure the azimuthal modulations of charged hadrons. For the first time, the results were corrected for QED radiative effects using the DJANGOH MC generator.

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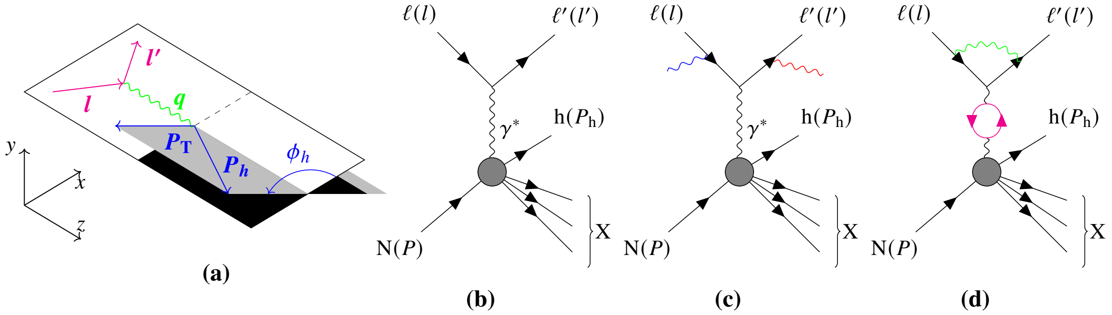

Figure 1: **(a)** Definition of the transverse momentum P_T and azimuthal angle ϕ_h of the final state hadron in the GNS. **(b)** Feynman diagram of the SIDIS process at the tree level. **(c,d)** Examples of $\mathcal{O}(\alpha^2)$ diagrams – an illustration of QED radiative effects: initial-state radiation (blue), final-state radiation (red), vertex correction (green) and virtual photon self-energy (magenta).

1. Theoretical introduction

Semi-inclusive measurement of unpolarized DIS $\ell\mathrm{N} \longrightarrow \ell'\mathrm{hX}$ is a powerful tool for studies of nucleon properties. Namely, the 3D nucleon structure is reflected in distributions of the azimuthal angle ϕ_h of final state hadrons h, which can be described by the following cross-section formula [1]:

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_h\mathrm{d}P_\mathrm{T}} = \sigma_0\left(1+\varepsilon_1 A_\mathrm{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon_2 A_\mathrm{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda\varepsilon_3 A_\mathrm{LU}^{\sin\phi_h}\sin\phi_h\right). \qquad (1)$$

Apart from the standard (SI)DIS variables[1] and azimuthal angle ϕ_h, which is together with other hadronic variables defined in the γ^*–N center-of-mass system (GNS) as shown in figure 1a, the cross-section contains kinematical factors ε_i and beam polarization λ. The amplitudes $A_\mathrm{XU}^{f(\phi_h)}$ – *azimuthal asymmetries* – are ratios of the structure functions $F_\mathrm{XU}^{f(\phi_h)}$:

$$A_\mathrm{XU}^{f(\phi_h)}\left(x,z,P_\mathrm{T}^2,Q^2\right) \equiv \frac{F_\mathrm{XU}^{f(\phi_h)}}{F_\mathrm{UU}}, \qquad F_\mathrm{UU} = F_\mathrm{UU,T}+\varepsilon F_\mathrm{UU,L}\,. \qquad (2)$$

Here, the subscript XU,Z denotes polarization of the beam, the target and optionally the virtual photon (L longitudinal, T transverse and U unpolarized). Assuming TMD factorization, the behaviour of the structure functions can be interpreted with the use of weighted (denoting the weight as $w(\boldsymbol{k}_\mathbf{T},\boldsymbol{P}_\perp)$) convolutions of TMD-PDFs $f^q(x,k_\mathrm{T}^2,Q^2)$ and TMD-FFs[2] $D^{q\to h}(z,P_\perp^2,Q^2)$ [1]:

$$F_\mathrm{XU}^{f(\phi_h)} = \mathscr{C}[wfD] = x\sum_q e_q^2\int \mathrm{d}^2\boldsymbol{k}_\mathbf{T}\mathrm{d}^2\boldsymbol{P}_\perp\delta^{(2)}(z\boldsymbol{k}_\mathbf{T}+\boldsymbol{P}_\perp-\boldsymbol{P}_\mathbf{T})wf^qD^{q\to h}\,. \qquad (3)$$

If we restrict ourselves to the leading twist TMDs, neglect quark-gluon-quark correlations and in the case of $F_\mathrm{UU}^{\cos\phi_h}$ utilize the Wandzura–Wilczek-type approximation [2], only two non-zero structure

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[1] inelasticity y, Bjorken variable x, fractional energy z and transverse momentum P_T of the final state hadron

[2] TMD-PDFs and TMD-FFs are abbreviations for transverse momentum dependent parton distribution functions and fragmentation functions.

functions remain for unpolarized SIDS (denoting $\hat{\boldsymbol{h}} = \boldsymbol{P}_{\mathrm{T}}/|\boldsymbol{P}_{\mathrm{T}}|$):

$$\begin{aligned} F_{\mathrm{UU}}^{\cos 2\phi_h} &= \mathscr{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathrm{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - (\boldsymbol{k}_{\mathrm{T}}\cdot\boldsymbol{P}_{\perp})}{zMM_h} h_1^{\perp} H_1^{\perp}\right] \\ F_{\mathrm{UU}}^{\cos\phi_h} &= \frac{2M}{Q}\mathscr{C}\left[-\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathrm{T}})}{M} f_1 D_1 + \frac{k_{\mathrm{T}}^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp})}{zM^2M_h} h_1^{\perp} H_1^{\perp}\right], \end{aligned} \tag{4}$$

where f_1 is the unpolarised and $h_1^{\perp}$ the Boer–Mulders TMD-PDF, while D_1 is the unpolarised and $H_1^{\perp}$ the Collins TMD-FF.

2. Data analysis

The preliminary results of the 2016 liquid hydrogen data at COMPASS have been presented at previous conferences explaining already many steps of the analysis [3, 4]. Newly, the data sample (both measured and simulated) has been extended and QED radiative effects have been accounted for up to the order of α^2.

2.1 Treatment of background from diffractive vector meson decays

Hadrons produced in hard exclusive processes are a background to the SIDIS measurements. The only significant contributors are the decays $\rho^0(770) \to \pi^+\pi^-$ and $\phi(1020) \to K^+K^-$ [5], which are visible in the invariant mass distributions in figure 2. Two procedures ensure the elimination of the background from diffractive vector mesons (DVM). First, in the case of reconstructing both charged hadrons in the spectrometer, one can apply the following constraint, which is a result of energy conservation, on $z_{\mathrm{t}} \equiv z_{\mathrm{h}^+} + z_{\mathrm{h}^-} < 0.95$ (referred to as *DVM cut*). The cases in which only one of the decay products is reconstructed are simulated by the HEPGEN MC generator [6]. Their azimuthal distributions are scaled according to the size of the peak in the missing energy histograms shown in figure 3 and subtracted from the measured distributions of the data (*DVM subtraction*).

2.2 Radiative correction

The TMD framework outlined in the formulae 1–4 does not account for QED radiative effects depicted in figure 1c and 1d. In particular, the real photon emission affects the measured leptonic DIS variables as well as the hadronic variables. An approach to this problem based on the DJANGOH [7]

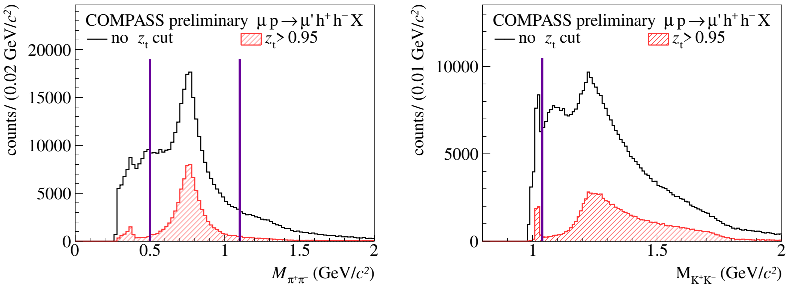

Figure 2: The invariant mass distributions for (left) $\rho^0 \to \pi^+\pi^-$ and (right) $\phi \to K^+K^-$ decay hypotheses.

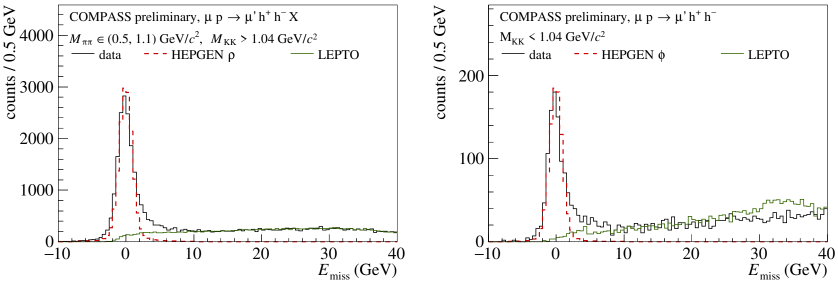

Figure 3: The missing mass distributions for (left) $\rho^0 \to \pi^+\pi^-$ and (right) $\phi \to K^+K^-$ candidates.

MC generator has been recently adopted by COMPASS [8]. We correct the number of events in each ϕ_h bin by the ratio of events simulated in that bin by DJANGOH with radiative effects on and off (normalized to the MC luminosity).

3. Results and conclusion

After applying the DVM and radiative corrections and after correcting for experimental acceptance, the azimuthal distributions are fitted with equation 1, extracting the asymmetries. The one-dimensional dependences on x, z and P_T are presented in the following figures; a multidimensional analysis is currently being finalized for publication.

Figure 4 demonstrates the effect of the background hadrons from DVMs as explained in section 2.1. The high z bins, together with the low x and P_T bins, are the most affected by the background. Figure 5 shows the effect of the radiative corrections on the azimuthal asymmetries. The lower z bins together with the higher x and P_T bins are affected the most by this correction. No effect is observed for $A_{LU}^{\sin\phi_h}$. The final results are shown in figure 6. The systematic uncertainty of the final results includes four contributions (from acceptance, DVM subtraction, radiative correction and period compatibility) evaluated for each bin separately. As expected from the expressions 4, asymmetries $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ show strong kinematical dependences, while $A_{LU}^{\sin\phi_h}$ is close to compatibility with zero. The negative trend of $A_{UU}^{\cos\phi_h}$ is related to the Cahn effect [9].

4. Acknowledgements

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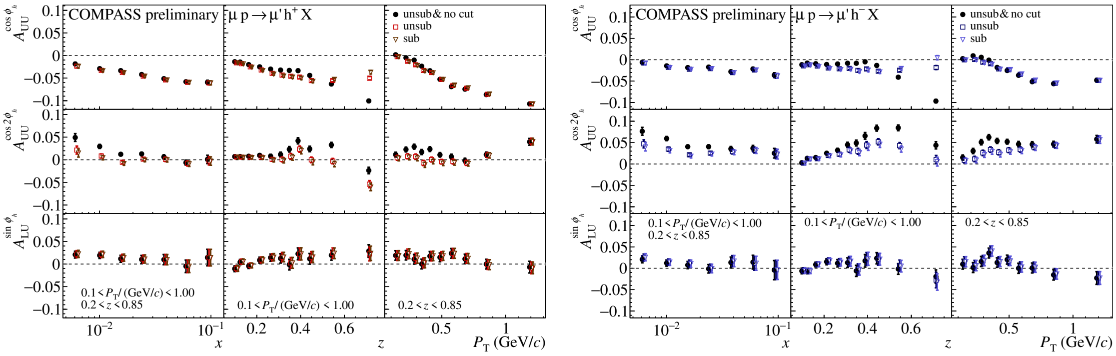

Figure 4: The comparison of the azimuthal asymmetries before applying DVM cut (unsub & no cut), after applying the cut (unsub) and after DVM subtraction (sub) for (left) h^+ and (right) h^-. Note, that the majority of the background is removed by the DVM cut. The radiative correction is not applied.

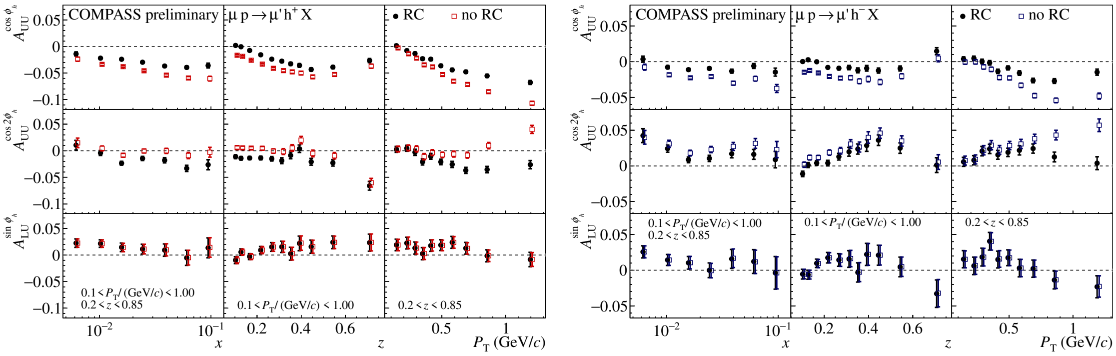

Figure 5: The comparison of the azimuthal asymmetries with and without applied radiative correction for (left) h^+ and (right) h^-. Note the qualitative change for $A_{UU}^{\cos 2\phi_h}$ for h^+, which becomes clearly negative.

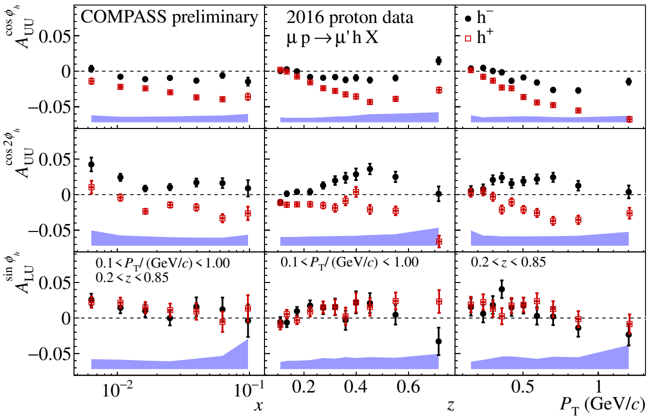

Figure 6: The final results for azimuthal asymmetries in their 1D x, z and P_T dependence. The blue band represents systematic uncertainty and is common for h^+ and h^-.

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