PROCEEDINGS OF SCIENCE

Studying high-p_T momentum azimuthal anisotropies in unpolarized proton-proton collisions using transverse momentum dependent (TMD) parton distribution and fragmentation functions

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Recent experimental results have shown that small systems such as p-p and p-A collisions exhibit a non-zero azimuthal anisotropy even at large p_T. However, no evidence of jet quenching has been observed in these collisions. We investigate the possibility that the azimuthal anisotropy of high-p_T hadrons can be generated by the intrinsic transverse momentum of the partons in the proton. After introducing transverse momentum dependent (TMD) parton distribution and fragmentation functions, additional polarization effects are allowed. Unpolarized protons can generate transversely polarized quarks or linearly polarized gluons through a distribution known as the Boer-Mulders' function. The fragmentation of similarly polarized partons to unpolarized hadrons is called the Collins' function. We find that the high-p_T azimuthal anisotropies can be obtained using these TMD distributions without modification to the angle integrated spectra.

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1. Introduction

The study of heavy ion collisions have significantly advanced our understanding of QCD matter. It is well accepted that during high energy heavy ion collisions a new phase of matter known as the Quark-Gluon Plasma (QGP) is produced [1, 2]. One of the main signatures of the QGP is anisotropic flow, which is characterized by azimuthal correlations in the final momentum distribution of the produced particles. The particle yield can be expressed as a Fourier series in the azimuthal angle ϕ as follows

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)) , \tag{1}$$

where Ψ_n is the n-th order event plane angle. Anisotropies in the initial density distribution leads to large pressure gradients. Coupled with a vanishing viscosity leads to a large non-zero v_2 coefficient, known as elliptic flow.

The creation of the QGP is corroborated by the suppression of high transverse momentum hadrons in heavy ion collisions compared to proton-proton collisions, known as jet quenching [3, 4]. Since high energy jets produced in the initial hard scattering must traverse the medium before reaching the detector, they lose their energy by interacting with the medium.

Recently, experimental results have observed a non-zero v_2 for small systems such as high multiplicity p-p and p-A collisions. While the v_2 decreases at higher transverse momentum, a sizable v_2 is observed even at large $p_T \gtrsim 10$ GeV [5, 6]. Typically, the v_2 at high p_T is attributed to final state effects such as jet-medium interactions. However, studies of jet suppression in p-A collisions have not observed any significant modification of the angle integrated high transverse momentum hadron spectra [7–9].

In these proceedings, we explore the possibility that transverse momentum dependent (TMD) parton distribution (PDF) and fragmentation functions (FF) can generate a non-zero v_2 at high p_T without any modification to the angle integrated spectra.

2. Theoretical Framework

We consider pion production in p-p and p-A collisions at high transverse momentum P_T. Following [10], the cross-section of the unpolarized processes $p + p \longrightarrow \pi + X$ is given by a factorized convolution of the hard partonic processes $a + b \longrightarrow b + c$, as follows,

$$\begin{aligned}\frac{d\sigma}{dy d^2P_T} = \int \frac{dx_a dx_b dz d^2k_{\perp a} d^2k_{\perp b} d^3k_{\perp C}}{2\pi^2 z^3 s} \delta(\boldsymbol{k}_{\perp C} \cdot \hat{p}_c) J(\boldsymbol{k}_{\perp C}) \Gamma^{\sigma\mu}(x_a, k_{\perp a}) \Gamma^{\alpha\nu}(x_b, k_{\perp b}) \\ \times \hat{M}_{\mu\nu\rho} \hat{M}^*_{\sigma\alpha\beta} \Delta^{\rho\beta}(z, k_{\perp C}) \delta(\hat{s} + \hat{t} + \hat{u}),\end{aligned} \tag{2}$$

where $J(\boldsymbol{k}_{\perp C}) = \frac{(E_C^2 + \sqrt{\boldsymbol{p}_C^2 - \boldsymbol{k}_{\perp C}^2})^2}{4(\boldsymbol{p}_C^2 - \boldsymbol{k}_{\perp C}^2)}$. We denote the partonic and hadronic Madelstam variable by $(\hat{s}, \hat{t}, \hat{u})$ and (s, t, u) respectively.

In these proceedings, we consider only the gluon-gluon partonic channel which dominates the cross section for pion production at the p_T's and $\sqrt{s}$ considered. The gluon correlator projected onto the helicity basis can be written as,

$$\Gamma_P^{\lambda_1,\lambda_2}(x,k_\perp) = \frac{-\delta^{\lambda_1,\lambda_2} f(x,k_\perp^2) + \delta^{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M_p^2} h^\perp(x,k_\perp^2)}{2x}, \tag{3}$$

where $f(x,k_\perp^2)$ is the spin-polarization independent TMD-PDFs with longitudinal momentum fraction $x_{(a,b)}$ and transverse momentum $k_{\perp(a,b)}$, relative to the z-axis defined by the incoming proton beams. The distribution of linearly polarized gluons in the proton is given by the Boer-Mulders' function $h_1^\perp(x,k_\perp^2)$ [11].

Similarly, for the fragmentation, the correlator is,

$$\Delta^{\lambda_1,\lambda_2}(z,k_\perp) = \frac{-\delta^{\lambda_1,\lambda_2} D(z,k_\perp^2) + \delta^{\lambda_1,-\lambda_2}\frac{k_\perp^2}{2M_\pi^2} H^\perp(z,k_\perp^2)}{2/z}. \tag{4}$$

Here $D(z_c,k_{\perp C})$ represents the spin-polarization independent TMD-FF for the outgoing parton (c) fragmenting to the pion ($\boldsymbol{\pi}$), carrying momentum $z\boldsymbol{p}_c + \boldsymbol{k}_{\perp C}$. The distribution of fragmenting $\boldsymbol{\pi}$ from a linearly polarized gluon is given by the Collins' function $H^\perp(z,k_\perp)$ [12].

Due to the initial transverse momentum of the hard partons, the hard scattering acquires a net transverse momentum $\boldsymbol{q}_\perp = \boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b}$ with respect to the center of mass of the hadronic scattering. Conversely, the transverse momentum of the remaining soft partons from each hadron must be compensated by the net transverse momentum. While not all the soft partons will participate in the collisions, there will be a strong correlation between the net transverse momentum of the hard scattering and the soft hadrons. To study the azimuthal anisotropies, we will compute the Fourier coefficients of the cross section as follows

$$v_2 = \frac{\int d\phi_\pi \ \cos(2(\phi_{\boldsymbol{q}_T} - \phi_\pi))\frac{d\sigma}{d\phi_\pi}}{\int d\phi_\pi \frac{d\sigma}{d\phi_\pi}} , \tag{5}$$

The Boer-Mulders' and Collins' functions in Eqns. (3-4) flip the helicity between the matrix element and its complex conjugate. Therefore, the only allowed scattering involves two linearly polarized gluons. Due to the phases of the gluon, the contribution most relevant to the azimuthal anisotropy is the scattering involving a linearly polarized gluon in the initial and final state; we will refer to this as the Boer-Mulders' Collins scattering ($BM \otimes C$). The combination of matrix element times complex conjugate with initial and final correlators can be expressed as,

$$\Sigma^{\mathrm{BM}\otimes\mathrm{C}} \equiv \hat{M}_{\mu\nu\rho}\hat{M}^*_{\sigma\alpha\beta}\Delta^{\rho\beta}(z,k_{\perp C})\Gamma^{\sigma\mu}(x_a,k_{\perp a})\Gamma^{\alpha\nu}(x_b,k_{\perp b}) , \tag{6}$$

$$= H^{\perp(1)}(z,k_{\perp C})\Big[h^{\perp(1)}(x_a,k_{\perp a}^2) f(x_b,k_{\perp b}^2)\hat{M}_1\hat{M}_2\cos(4(\phi_{ab}-\phi_{bc})) + f(x_a,k_{\perp a}^2) h^{\perp(1)}(x_b,k_{\perp b}^2)\hat{M}_1\hat{M}_3\cos(4(\phi_{ab}-\phi_{ac}))\Big], \tag{7}$$

where we define $h^{\perp(1)} \equiv (k_\perp^2/2M_p^2)h^\perp$ and $H^{\perp(1)} \equiv (k_\perp^2/2M_\pi^2)H^\perp$. The color and spin averaged matrix elements (times complex conjugate) can be expressed as,

$$\hat{M}_1\hat{M}_2 = g_s^4\frac{N^2}{N^2-1}\frac{t^2+tu+u^2}{t^2} , \quad \hat{M}_1\hat{M}_3 = g_s^4\frac{N^2}{N^2-1}\frac{t^2+tu+u^2}{u^2} , \tag{8}$$

where, using partonic momenta in spherical coordinates $\boldsymbol{p}_i = (p_i,\theta_i,\phi_i)$, the phases are given by

$$\tan\phi_{ij} = \tan\frac{\phi_j-\phi_i}{2}\left(\sin\frac{\theta_j+\theta_i}{2}\right)\Big/\left(\sin\frac{\theta_j-\theta_i}{2}\right) . \tag{9}$$

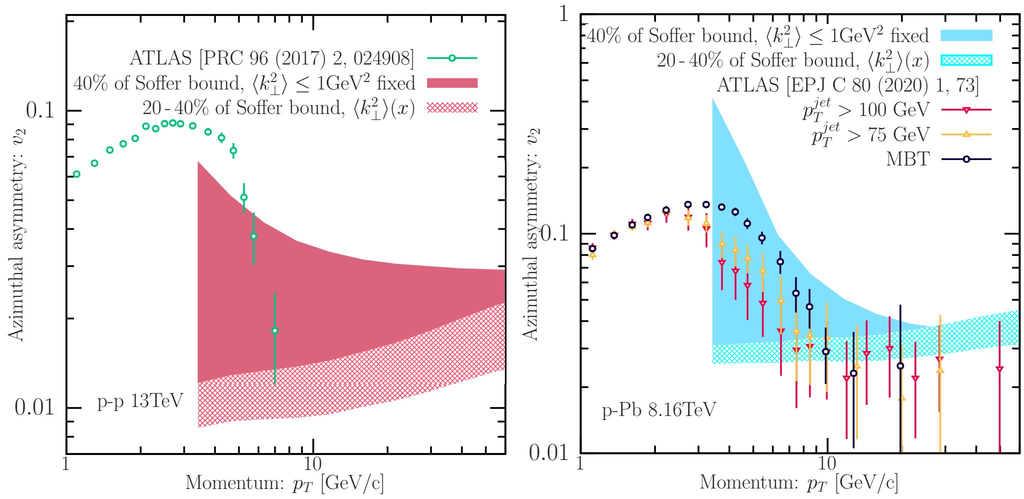

Figure 1: Azimuthal anisotropy coefficient v_2 as a function of the pion transverse momentum p_T for pp collisions at $\sqrt{s} = 13$ TeV (left) and pPb at 8.16 TeV (right). The solid shaded area represent the uncertainty on the momentum $\langle k_\perp^2 \rangle \leq 1\mathrm{GeV}^2$, while the hatched shaded area displays a different choice for the bound $0.2 \leq b \cdot B \leq 0.4$ for x-dependent transverse momentum $\langle k_\perp^2 \rangle^{1/2}(x)$.

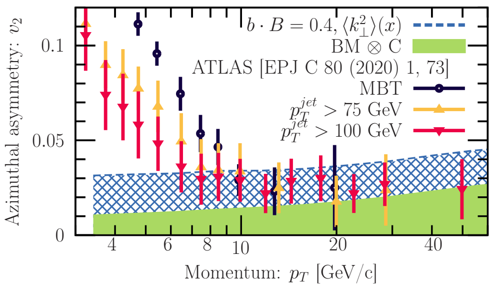

Figure 2: Decomposition of v_2 contributions. The filled green represents the BM $\otimes$ C contribution, the blue hatched represents polarization independent contributions.

3. Results

We employ a Gaussian ansatz for the transverse momentum dependence, and we use the nCTEQ parametrization [13] for the longitudinal dependence of the PDFs and leading order KKP [14] for FFs. The Boer-Mulders' and Collins' functions are taken to be proportional to the unpolarized PDFs and FFs respectively. The polarization independent contributions are only modified by Gaussian transverse momentum distributions that integrate out to unity when computing the angular integrated cross section. Conversely, the BM $\otimes$ C contribution leads to a negligible modification of the angle integrated cross section, because the matrix element in Eq. (7) is proportional to cosine terms that are suppressed after the angular integrations. Accordingly, we find that the TMD contributions lead to minimal modification of the angle integrated cross section.

On the left panel of Fig. 1, we present the azimuthal coefficient for p-p collisions at 13 TeV. This analysis is limited to the leading twist calculation and is only valid at high transverse momentum ($P_T \gg \langle k_\perp^2 \rangle^{1/2}$), which we ensure by limiting the result to $P_T > 3$ GeV. The red filled area represents

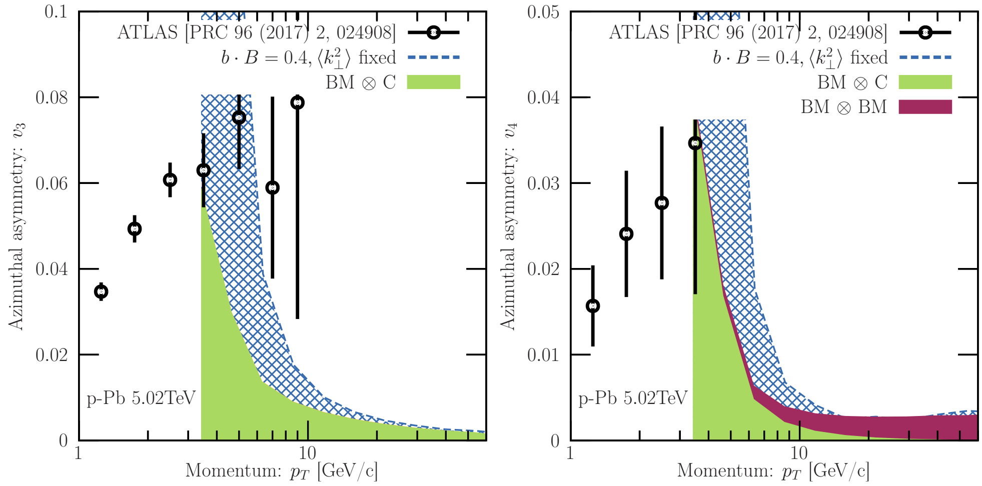

Figure 3: Decomposition of v_3 (left) and v_4 (right) contributions. The filled green represents the BM ⊗ C contribution, filled red area represents the BM⊗BM and the blue hatched represents polarization independent contributions.

our results within uncertainties on the mean transverse momentum of the Gaussian between a fixed value of 1 GeV and an x-dependent ansatz [15]. We find that for $p_T \geq 6$ GeV, the ATLAS data lies within our uncertainty band.

Using the same parametrization, we compute the azimuthal anisotropy for p-Pb collisions at 8.16 TeV by increasing the mean transverse momentum of the Gaussian by a factor of $A^{1/3}$. This $A^{1/3}$ enhancement is obtained from the multiple scatterings of the initial partons before the hard scattering [16–18]. While the effect of multiple scatterings is not well understood for polarized partons, we will assume the same enhancement of the mean transverse momentum. This leads to an enhancement of v_2, as shown in the right panel of Fig. 1, which describes the ATLAS results remarkably well. In Fig. 2, we present the decomposition of the elliptic coefficient in contributions from spin independent and spin dependent partonic scatterings. We find that even though the spin dependent TMD distributions are suppressed, the $BM \otimes C$ contribution dominates the azimuthal anisotropy at high p_T.

In Fig. 3, we present the decomposition of the v_3 and v_4 coefficients. We observe that at high-p_T the $BM \otimes C$ contribution dominates the v_3 coefficient, while the $BM \otimes BM$ contribution dominates the v_4 coefficient. More experimental data is needed to understand these higher order coefficients and constrain the TMD distributions.

We have presented evidence for a v_2 in high-p_T hadron spectra in p-A collisions without any observable modification of the angle integrated spectra, using TMD distributions. The initial transverse momenta of the partons in the proton can lead to anisotropies in the direction of the hard scattering. Moreover, intrinsic transverse momentum allows for spin dependent partonic contributions, which can lead to an enhancement of the v_2.

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