Azimuthal anisotropies at high-p_T from transverse momentum dependent (TMD) parton distribution and fragmentation functions

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Abstract. 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. Both of these functions include correlations between the spin or polarization and the relative transverse momentum of the incoming parton or outgoing hadron, with respect to the parent particle. We explore the effect of including these and other TMDs on the production of high-p_T (unpolarized) hadron production from (unpolarized) proton-proton scattering. The resulting initial state anisotropies, modulated with similar final state effects, may account for the observed azimuthal anisotropy of the produced high transverse momentum hadrons, without modification to the angle integrated spectra (R_{AA}). This may be an explanation for the existence of a v_2 in high-p_T hadron spectra in p-A collisions without any observable nuclear modification of the spectra.

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. 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

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

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. 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.

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Recently, experimental results have observed a non-zero v_2 for small systems such as 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 [1, 2]. 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 [3–5].

In these proceedings, we explore the possibility that transverse momentum dependent (TMD) parton distribution and fragmentation functions 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 [6], the cross-section can be written as,

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

where $J(\boldsymbol{k}_{\perp C}) = \frac{(E_C^2+\sqrt{\boldsymbol{p}_C^2-\boldsymbol{k}_{\perp C}^2})^2}{4(\boldsymbol{p}_C^2-\boldsymbol{k}_{\perp C}^2)}$.

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 $h_1^\perp(x, k_\perp^2)$ [7].

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 $H^\perp(z, k_\perp)$ [8].

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 compensate to the net transverse momentum. This transverse momentum is transferred to the final state hadrons, leading to a preferred direction generally in the opposite direction $-\boldsymbol{q}$. To study the azimuthal anisotropies, we will compute the Fourier coefficients of the cross section as follows

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

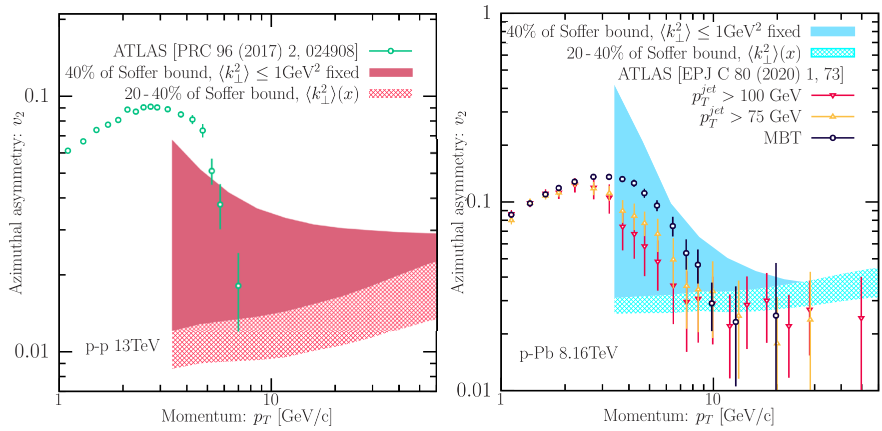

Figure 1. Azimuthal anisotropy coefficient v_2 as a function of the pion transverse momentum p_T for pp collisions at $\sqrt{s}$ = 13 TeV (left) and pPb at 8.16 TeV (right). The solid shaded area represent the uncertainty on the momentum $\langle k_\perp^2\rangle \le 1\text{GeV}^2$, while the hatched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

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 can be written as

$$\begin{aligned}\Sigma^{\text{BM}\otimes\text{C}} =& H^{\perp(1)}(z, k_{\perp C}) \Big[h^{\perp(1)}(x_a, k_{\perp a}^2) f(x_b, k_{\perp b}^2) \hat{M}_1 \hat{M}_2 \cos(4(\phi_{ab} - \phi_{bc})) \\ &+ f(x_a, k_{\perp a}^2) h^{\perp(1)}(x_b, k_{\perp b}^2) \hat{M}_1 \hat{M}_3 \cos(4(\phi_{ab} - \phi_{ac})) \Big], \end{aligned} \tag{6}$$

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,

$$\hat{M}_1 \hat{M}_2 = g_s^4 \frac{N^2}{N^2-1} \frac{t^2+tu+u^2}{t^2}, \quad \hat{M}_1 \hat{M}_3 = g_s^4 \frac{N^2}{N^2-1} \frac{t^2+tu+u^2}{u^2}, \tag{7}$$

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

$$\tan \phi_{ij} = \tan \frac{\phi_j - \phi_i}{2} \left(\sin \frac{\theta_j + \theta_i}{2} \right) \Big/ \left(\sin \frac{\theta_j - \theta_i}{2} \right). \tag{8}$$

3 Results

We employ a Gaussian ansatz for the transverse momentum dependence, and we use the nCTEQ parametrization [9] for the longitudinal dependence of the PDFs and leading order KKP [10] for FFs. The Boer-Mulders' and Collins' functions are taken to be proportional to the unpolarized PDFs and FFs respectively. On the left panel of Fig. 1, we present the azimuthal coefficient for p-p collisions at 13 TeV. The red filled area represents our results within uncertainties on the mean transverse momentum of the Gaussian between a fixed value

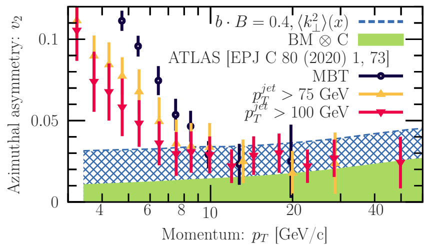

Figure 2. Decomposition of v_2 contributions. The filled green represents the BM ⊗ C contribution, the blue hatched represents polarization independent contributions.

of 1 GeV and an x-dependent ansatz [11]. We find that 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 $A^{1/3}$ [12–14]. 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.

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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