We study di-hadron correlations in proton-proton collisions at $\sqrt{s} = 200$ GeV and interpret experimental data in terms of a fragmentation width and a momentum imbalance. A fragmentation width of $580 \pm 50$ GeV/c is obtained, and the measured momentum imbalance gives an 'intrinsic' transverse momentum width of partons in the proton of $2.6 \pm 0.2$ GeV/c. Consequences to heavy ion collisions are discussed.

1. Introduction

Recent high-statistics runs at RHIC allow the study of two-particle correlations, with pronounced suppression pattern for Au+Au collisions, augmenting information from jet quenching, and are a valuable tool of jet tomography. Questions raised by di-hadron studies motivated programs of three-body correlation measurements to clarify the collective dynamics of nuclear collisions.

To argue about any suppression of the correlation data in heavy-ion collisions a proton-proton ($pp$) reference is needed, preferably at the same energy. Correlation data in $pp$ at $\sqrt{s} = 200$ GeV have become available recently. Our goal here is to provide a physical picture of this rich data set on near and away side correlations. To interpret the data, we want to stay as close as possible to Ref. with the ingredients of our calculation and since fragmentation of pions are best established so far phenomenologically, we focus on pion correlations.
2. Model

The single-pion inclusive production cross section can be written as

\[ \frac{d\sigma}{dp_T^T} = \int \frac{d\sigma_j}{\hat{p}_T d\hat{p}_T} D_j(z) dz = \int \frac{d\sigma_j}{\hat{p}_T d\hat{p}_T} D_j(z) \frac{dz}{z^2} = \int f_j D_j(z) \frac{dz}{z^2}, \]  

(1)

where \( d\sigma_j/\hat{p}_T d\hat{p}_T \) refers to the differential jet cross section in terms of the parton transverse momentum \( \hat{p}_T \), and \( z \) is the momentum fraction carried by the observed hadron. The quantity \( f_j \) is a parton (jet) distribution averaged over quarks, antiquarks, and gluons, and \( D_j(z) \) is an average fragmentation function. Using \( f_j(\hat{p}_T) \propto \hat{p}_T^{-n} \) and \( D_j(z) \propto z^{-\alpha}(1-z)^{\beta}(1+z)^{-\gamma} \) with parameters \( n = 7.4, \alpha = 0.32, \beta = 0.72, \gamma = 10.65 \), we reproduce the measured pion spectra \(2\) for \( p_T > 3 \text{ GeV} \), which is satisfactory for our present analysis.

On this basis, we constructed a simple model to describe two-particle correlations within a jet and between back-to-back jets starting from a hard \( 2 \to 2 \) parton-parton collision. For two pions produced from the same parton (near side correlation) the two-particle cross section can be written as

\[ d\sigma_{\pi_1 \pi_2}^{\text{near}} = \int_0^1 dz_1 \int_0^1 dz_2 d\sigma_j D_{j1}(z_1) D_{j2}(z_2) \Theta(1 - z_1 - z_2), \]  

(2)

while for the away-side (two pions produced from different partons)

\[ d\sigma_{\pi_1 \pi_2}^{\text{away}} = \int_0^1 dz_1 \int_0^1 dz_2 d\sigma_j D_{j1}(z_1) D_{j2}(z_2), \]  

(3)

where the momentum fractions \( z_1 \) and \( z_2 \) describe the relation between the parton and hadron momenta, \( p_{T1}^* = z_1 \hat{p}_T \) and \( p_{T2}^* = z_2 \hat{p}_T \). Moreover, due to fragmentation, the produced hadrons acquire a random transverse momentum component. In addition, the momentum imbalance \( (K_T) \) between the produced partons due to intrinsic transverse momentum, gluon radiation, or any other \( 2 \to 3 \) process will generate a more complicated kinematic situation, where, in the case of back-to-back jets, \( \hat{p}_{T1} \) and \( \hat{p}_{T2} \) are already not collinear.

Considering hadron 1 as the trigger hadron and hadron 2 as the associated hadron, after kinematic transformations,

\[ \frac{d\sigma_{\pi_1 \pi_a}}{dp_T^T d\Delta \phi dp_T^a} = J^* \frac{d\sigma_{\pi_1 \pi_a}}{dp_T^T dz_1 dp_T^a} = J \cdot f_j D_{j1}(z_1) D_{j2}(z_a) \Theta(1 - z_1 - z_a), \]  

(4)

where \( \Delta \phi \) is the azimuthal angle difference between the trigger and associated hadrons, and \( J \) and \( J^* \) represent the proper Jacobi determinants of the variable transformations (without the theta function for away-side).

We have developed a Monte-Carlo based calculation to model Eq. (4). We use Gaussian distributions and uniformly distributed random angles for the fragmentation transverse momenta and the momentum imbalance \( K_T \). The widths of these distributions that best fit the data \(1\) are extracted.
3. Results

We have calculated di-hadron correlation functions in \( pp \) collisions at \( \sqrt{s} = 200 \) GeV at various trigger and associated transverse momenta and compared the results to available experimental data\(^1\) to extract the widths of the fragmentation transverse momentum distribution and the \( K_T \) distribution. A sample comparison is displayed in Fig. 1, where the dashed lines indicate a fit through the data points, and the full lines represent our calculations. The associated transverse momentum is kept in the \( 1.4 \leq p_{T_a} \leq 5.0 \) GeV/c range, while the trigger transverse momentum is increasing from \( 2.5 \leq p_{T_t} \leq 3.0 \) GeV/c to \( 6.5 \leq p_{T_t} \leq 8.0 \) GeV/c moving down through the panels. The “pedestal” of the correlation functions has been cut off. The agreement is very good, although small deviations are visible in a more magnified view.

Figure 2 shows the values of the widths of the fragmentation and ‘intrinsic’ momentum distributions in given \( p_{T_t} \) windows as functions of \( p_{T_a} \). The fragmentation width appears to be constant, \( \sqrt{\langle j_T^2 \rangle} = 580 \pm 50 \) GeV/c, independent of \( p_{T_a} \) and \( p_{T_t} \). The \( k_T \) width shows a dependence on \( p_{T_t} \) (similarly to a simpler treatment\(^3\)), displayed for two limiting data sets in Fig. 3.
Fig. 2. Best fit values of the Gaussian fragmentation width (left) and $k_T$ width (right) to reproduce the near and away side peaks in given $p_T$ windows as a function of $p_T$. Averages for $p_T$ windows (only the grand total average on the left) are indicated by the large filled squares. Data are from Ref. 1.

Fig. 3. Width of the ‘intrinsic’ transverse momentum distribution as a function of the trigger transverse momentum for two sets of data. The spread between the two least-square fitted curves in Fig. 3 is indicative of the uncertainty in our procedure. The behavior of the ‘intrinsic’ transverse momentum width as a function of $p_T$ can be understood in terms of its composition. In addition to the ‘true’ intrinsic transverse momentum of partons in the proton, there is a component from soft gluon radiation that can be handled via resummation.
and a higher-order contribution which is expected to grow with trigger transverse momentum:

\[ \frac{\langle p_T^2 \rangle_{\text{pair}}}{2} = \langle k_T^2 \rangle = \langle k_T^2 \rangle_{\text{intrinsic}} + \langle k_T^2 \rangle_{\text{soft}} + \langle k_T^2 \rangle_{\text{higher-order}}. \]  \hspace{1cm} (5)

A measure of the ‘intrinsic’ transverse momentum of partons in the proton (in which we include the soft gluon radiation component) can be read from Fig. 3 extrapolating to \( p_T = 0 \). This leads to \( \sqrt{\langle k_T^2 \rangle} = 2.6 \pm 0.2 \) GeV/c, in agreement with the value arrived at in Ref. 1, albeit by a different argument.

This value for the ‘intrinsic’ transverse momentum is somewhat larger than the value obtained from our earlier analysis of one-particle pion spectra\(^5\) and other analyses\(^6,7\). However, it fully supports the inclusion of such a quantity in the study of one-particle hadron spectra and hadron-hadron correlation data. Without this momentum imbalance no coherent picture of high-\( p_T \) particle production in proton-proton collisions can be established, neither in leading order, nor in next-to-leading order perturbative QCD calculations.

Furthermore, this momentum imbalance exists in hard particle production in proton-nucleus and heavy ion collisions, also. The measured double-hump structure of away side hadron-hadron correlation data in Au-Au collisions\(^9,10\) has been explained by the formation of a shock wave in the highly excited matter (“Mach-cone”)\(^11,12,13\). The presence of the ‘intrinsic’ transverse momentum immediately after the formation of the jet pairs contributes to the widening of the away-side correlation peak in such a way that the contribution from shock-wave formation becomes smaller and the qualitative description will be different (i.e. the opening angle of the Mach-cone and the obtained speed of sound for the excited matter). The forthcoming quantitative analysis of heavy ion experiments requires more precise understanding of the away-side data in proton-proton collisions.

4. Conclusion

We have developed a constructive method for taking into account the fragmentation width and the momentum imbalance in the treatment of di-hadron correlations. The model has the flexibility to treat any \( K_T \) distribution. Our results have been tested against recent PHENIX data on di-hadron correlations in \( pp \) collisions. A value of \( 2.6 \pm 0.2 \) GeV/c is obtained for the width of the ‘intrinsic’ transverse momentum distribution. Future work includes generalization to \( pA \) and \( AA \) collisions, inclusion of the pseudorapidity dimension of the correlations, and application in jet quenching calculations.

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