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Azimuthal Correlations in $c\overline{c}$ Production

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It has been proposed that the azimuthal distributions of heavy flavor quark-antiquark pairs may be modified in the medium of a heavy-ion collision. This assumption is tested through next-to-leading order (NLO) calculations of the azimuthal distribution, $d\sigma/d\phi$, including transverse momentum broadening, employing $\langle k_T^2 \rangle$ and fragmentation in exclusive $Q\overline{Q}$ pair production. The differences between NLO calculations and heavy $Q\overline{Q}$ pair production in event generators are also discusssed.

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1. Introduction

Recently there has been interest in heavy flavor correlations and how they might be modified in heavy-ion collisions, see *e.g.* Refs. [1]. However, before drawing any conclusions about hot matter effects, it is worth studying these correlations in more elementary collisions. Correlated production, specifically of the azimuthal angle between heavy flavors, ϕ, is a stronger test of $Q\overline{Q}$ production than single inclusive distributions. In this proceeding, the sensitivity of the azimuthal correlation to the p_T of the individual charm quarks is explored. For more details about the calculation and the application to bottom quarks, see Ref. [2].

There are currently two approaches to heavy flavor production at colliders: collinear factorization and the k_T-factorization approach which is usually employed at low x.

Collinear factorization approaches such as FONLL [3] and GM-VFN [4] offer improved calculations of single heavy flavor observables at high p_T but cannot provide calculations of correlated observables, such as the ϕ distribution. These calculations employ fragmentation functions determined within their calculational scheme but do not include k_T broadening. Exclusive next-to-leading order (NLO) $Q\overline{Q}$ calculations can provide correlations between heavy flavor pairs. The HVQMNR code [5] is a standalone calculation, including fragmentation via the Peterson function [6]. In HVQMNR, k_T broadening was introduced to improve agreement with low p_T fixed-target data [7] but is also employed to make the pair p_T distributions finite as $p_T \to 0$. POWHEG-hvq [8] is a more recent code but requires an event generator to make a complete event.

The k_T factorization approach has been applied to both single inclusive and exclusive heavy flavor pair calculations [9]. Because the unintegrated gluon distributions depend on k_T, no additional broadening is required.

Experimentalists often rely on leading order (LO) event generators for their analyses of heavy flavor production. In these simulations, NLO distributions are approximated by LO diagrams of different topologies, often referred to as flavor creation, flavor excitation and gluon splitting. However, these are not unique production mechanisms and the results must be interpreted carefully.

The HVQMNR code is employed to calculate the azimuthal correlation between the c and $\overline{c}$ quarks. The focus is on the effects due to the NLO contribution alone, including k_T-broadening and fragmentation but excluding the parton showers which can further randomize the pair momenta and thus affect the angular correlations. The k_T broadening employed here is the same as that used for J/ψ production [10] while the Peterson function parameter is adjusted so that the calculated single charm p_T distribution from HVQMNR agrees with the FONLL result. The implementation of these effects is discussed in the next section. The sensitivity of the azimuthal distribution to k_T broadening and the p_T of the heavy quarks is then discussed, followed by comparison to azimuthal distributions measured by LHCb [11] and CDF [12].

2. k_T broadening and fragmentation

The transition from bare quark distributions to final-state hadrons is accomplished by including a fragmentation function and intrinsic transverse momentum, k_T, broadening, as described here. The same values of the charm quark mass and scale parameters as in Ref. [10] are employed here,

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$(m, \mu_F/m_T, \mu_R/m_T) = (1.27 \pm 0.09\,\text{GeV}, 2.1^{+2.55}_{-0.85}, 1.6^{+0.11}_{-0.12})$ where μ_F and μ_R, the factorization and renormalization scales respectively, are given relative to the transverse mass of the $c\overline{c}$ pair.

2.1 Intrinsic k_T broadening

Calculations of charm production at fixed-target energies required transverse momentum broadening to obtain agreement with the data after fragmentation [7]. Such broadening is typically included by smearing the initial-state parton densities with a Gaussian k_T distribution. It can be related to QCD resummation at low p_T and was applied first to Drell-Yan production. The value of $\langle k_T^2 \rangle$ is assumed to increase with $\sqrt{s}$ [10],

$$\langle k_T^2 \rangle = 1 + \frac{\Delta}{n} \ln \left(\frac{\sqrt{s}}{20\,\text{GeV}} \right) \text{GeV}^2 \, . \tag{2.1}$$

Comparison with J/ψ data found $n = 12$ gave the best description of the p_T distribution [10]. This value is also used to calculate the charm pair distributions. The parameter Δ is used to explore the sensitivity of the azimuthal distribution to the level of k_T broadening. The values $\Delta = -3/2$, -1, $-1/2$, 0, 1/2, and 1 are used, effectively changing $\langle k_T^2 \rangle$ by ~ 0.25 GeV^2 at $\sqrt{s} = 7$ TeV as Δ is increased by 1/2. Note that $\Delta = 1$ is the default value.

2.2 Fragmentation

The default fragmentation function in HVQMNR is the Peterson function [6], $D(z) = z(1-z)^2/((1-z)^2 + z\varepsilon_P)^2$, where z represents the fraction of the parent heavy flavor quark momentum carried by the resulting heavy flavor hadron. The nominal values of the fragmentation parameter ε_P, 0.06 for charm, had to modified to give a similar average value of z as the default fragmentation scheme for charm in FONLL. The value $\varepsilon_P = 0.008$ resulted in good agreement with the FONLL single charm p_T distribution when combined with k_T broadening employing $\Delta = 1$.

3. Sensitivity of $d\sigma/d\phi$ to k_T broadening and p_T cuts

The shape of $d\sigma/d\phi$ depends on the charm quark p_T. At LO, the p_T of the $c\overline{c}$ is zero and $d\sigma/d\phi$ is represented by a delta function, $\delta(\phi - \pi)$. At NLO, both virtual and real conntributions arise. The virtual corrections are typically the exchange of soft gluons at the vertices while real corrections give rise to $2 \rightarrow 3$ processes. The virtual corrections smear out the azimuthal separation so that the pairs are no longer strictly back-to-back. The real NLO contributions, similar to the 'flavor excitation' and 'gluon splitting' contributions in PYTHIA make the azimuthal correlation more isotropic. In a $2 \rightarrow 3$ configuration, both the c and $\overline{c}$ can be aligned opposite a high p_T light parton ($\phi = 0$), the light parton can be soft and collinear with the c quark that emitted it ($\phi \sim \pi$), or somewhere in between. Thus, at low p_T, $d\sigma/d\phi$ is likely to be more isotropic, while high p_T heavy quarks will more likely result in a doubly-peaked ϕ distribution, with peaks at $\phi \sim 0$ and π and a dip between. Fragmentation does not change the direction of the parent c quark and thus does not affect the $d\sigma/d\phi$. On the other hand, k_T broadening has a substantial effect on $d\sigma/d\phi$ [2].

Broad illustrative p_T cuts, $p_T < 10$ GeV and $p_T > 10$ GeV, were chosen to study the dependence of $d\sigma/d\phi$ on the broadening by varying Δ in Eq. (2.1) between -3/2 and 1. The midrapidity results are shown in Fig. 1. Note that, at low p_T, increasing $\langle k_T^2 \rangle$ from 0 to 0.25 GeV^2 already

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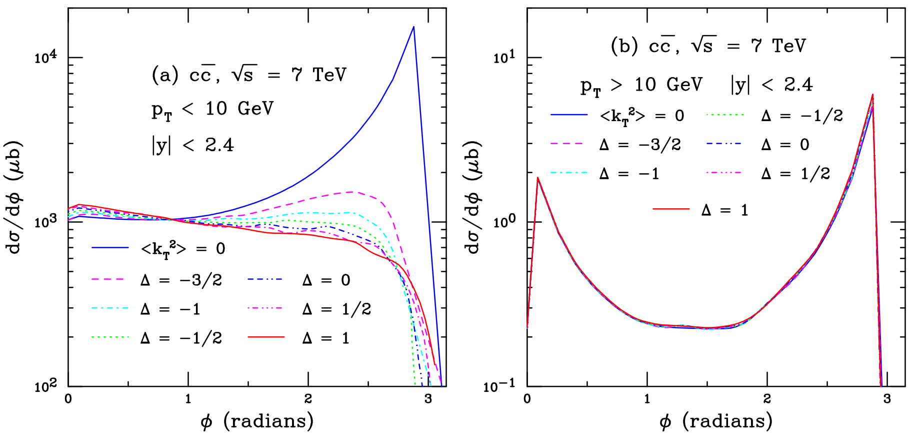

Figure 1: The midrapidity $d\sigma/d\phi$ for $c\overline{c}$ pairs with $p_T < 10$ GeV (a) and $p_T > 10$ Gev (b). Calculations are shown for $\langle k_T^2 \rangle = 0$ and values of Δ from $-3/2$ to 1 in Eq. (2.1).

shows a significant change in $d\sigma/d\phi$. The peak at $\phi \sim \pi$ is largely erased and only a weak variation with ϕ can be seen on the log scale for $\phi < \pi/2$. As $\langle k_T^2 \rangle$ increases, the enhancement at $\phi \sim 0$ increases while the peak near $\phi \sim \pi$ decreases and disappears. When $p_T > 10$ GeV, the results are independent of Δ, showing that broadening is no longer effective at high p_T. Two peaks, at $\phi \sim 0$ and π can be seen, as described previously.

4. Comparison to Data

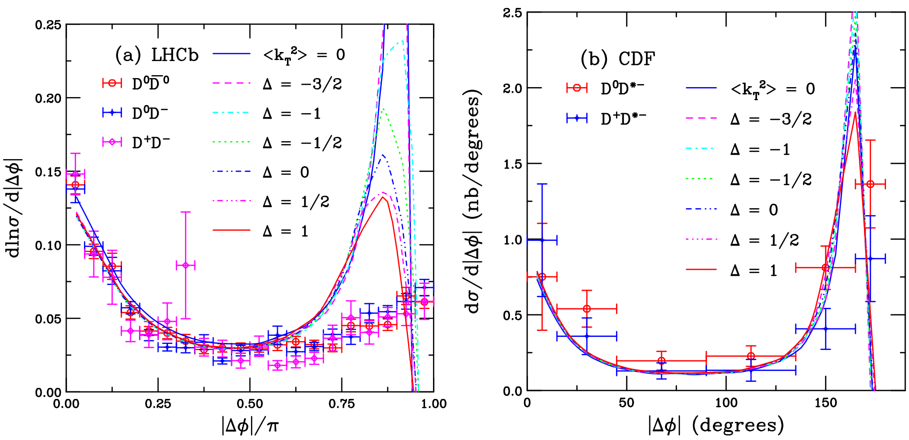

Figure 2: The azimuthal angle distributions for $D\overline{D}$ pairs measured by LHCb in $p+p$ collisions at $\sqrt{s} = 7$ TeV [11] (a) and $D\overline{D}^*$ pairs measured by CDF in $p+\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV [12]. In both cases, the data are compared to calculations in the same acceptance with $\langle k_T^2 \rangle = 0$ and $-3/2 \leq \Delta \leq 1$ in Eq. (2.1).

LHCb measured $c\overline{c}$, cc, and $(c+\overline{c})J/\psi$ correlations in $p+p$ collisions at 7 TeV for $2 < y < 4$ and $3 < p_T < 12$ GeV [11]. Figure 2(a) shows the azimuthal angle distributions of $c\overline{c}$ pairs as a function of Δ. The results for $\phi < 2$ are in good agreement with the data. However, as $\phi \to \pi$, there

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is a strong effect on the peak value as a function of Δ which gets broader and lower as Δ increases. The larger values of Δ are closer to the data.

The CDF Collaboration studied charm hadron correlations in $p+\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV [12] in the rapidity interval $|y| < 1$ and p_T ranges $5.5 < p_T^{D^0,D^{*-}} < 20$ GeV, $7 < p_T^{D^+} < 20$ GeV. The calculations agree rather well with the data, as shown in Fig. 2(b). The results are independent of Δ, as might be expected for the given p_T range.

5. Summary

The high p_T behavior of $d\sigma/d\phi$ is indicative of the contribution of next-to-leading order production while the low p_T behavior of $d\sigma/d\phi$ is extremely sensitive to the chosen $\langle k_T^2 \rangle$ and essentially independent of fragmentation. Therefore, for p_T cuts on the order of a few GeV, the calculations of the azimuthal angle distributions are rather insensitive to fragmentation and k_T broadening which affect the correlations at low p_T.

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