PROCEEDINGS OF SCIENCE

Heavy Flavor Kinematic Correlations in Cold Nuclear Matter

R. Vogt[*],[*]

Nuclear and Chemical Sciences Divsion, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Physics Department, University of California at Davis, Davis, CA 95616, USA

E-mail: rlvogt@ucdavis.edu

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 was 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 results have been compared to $p+p$ and $p+\overline{p}$ data on $Q\overline{Q}$ azimuthal correlations as well as $b\overline{b}$ correlations in $p+p$ collisions through their decays to $J/\psi J/\psi$, as measured by LHCb. Agreement with the data was found to be excellent. Possible cold and hot matter effects on these correlations are investigated through the effects of nuclear modifications of the parton densities, enhanced k_T broadening and energy loss.

HardProbes2020
1-6 June 2020
Austin, Texas

[*]This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and the US Department of Energy, Office of Science, Office of Nuclear Physics (Nuclear Theory) under contract number DE-SC-0004014.

[*]Speaker

PoS(HardProbes2020)053

1. Introduction

There has been interest in heavy flavor correlations and how they might be modified in heavy-ion collisions. Such correlations have also been measured in more elementary collisions. Correlated production is a stronger test of $Q\overline{Q}$ production than single inclusive distributions. In this proceeding, kinematic correlations of $b\overline{b}$ decays to J/ψ pairs, studied by LHCb in $p+p$ collisions at $\sqrt{s} = 7$ and 8 TeV and employing several cuts on the b quark and J/ψ transverse momenta [3] are compared to next-to-leading order calculations of $b\overline{b}$ production and decay. The implications for cold and hot nuclear matter effects in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and Pb+Pb collisions at $\sqrt{s_{NN}} =$ 5 TeV are also studied. In this proceeding, the discussion is limited to azimuthal correlations. For details of the model, see Ref. [1]. For complete results, see Ref. [2].

These calculations employ the exclusive next-to-leading order (NLO) HVQMNR code [4] for $Q\overline{Q}$ production and decay. It includes fragmentation via the Peterson function [5] as well as k_T broadening, introduced to improve agreement with low p_T fixed-target data [6] and to make the pair p_T distributions finite as $p_T \to 0$. The k_T broadening employed here is the same as that used for Υ production [7] while the Peterson function parameter is adjusted so that the calculated single bottom p_T distribution agrees with FONLL [8].

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. [7] are employed here, $(m, \mu_F/m_T, \mu_R/m_T) = (4.65 \pm 0.09\,\text{GeV}, 1.4^{+0.77}_{-0.40}, 1.1^{+0.22}_{-0.20})$ where μ_F and μ_R, the factorization and renormalization scales respectively, are given relative to the transverse mass of the $b\overline{b}$ 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 [6]. 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 $\sqrt{s}$ [9],

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

Comparison with Υ data found $n = 3$ gave the best description of the p_T distribution [7]. This value is also used to calculate the bottom pair distributions. The parameter Δ can be employed to explore the sensitivity of the pair distributions to the level of k_T broadening for $\Delta \leq 1$ [1]. While $\Delta = 1$ is the default value for $p+p$ collisions, it is increased to 2 in p+Pb collisions and to 4 in Pb+Pb collisions to simulate k_T broadening due to the presence of nuclear matter.

2.2 Fragmentation

The default fragmentation function in HVQMNR is the Peterson function [5], $D(z) = z(1-z)^2/((1-z)^2 + z\epsilon_P)^2$, 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, 0.006 for bottom, had to modified to give a similar average value of z as the default fragmentation scheme for bottom in FONLL. The value $\epsilon_P = 0.0004$ resulted in good agreement with the FONLL single bottom p_T distribution when combined with k_T broadening employing $\Delta = 1$ [1].

3. Comparison to LHCb Data on $b\overline{b} \to J/\psi J/\psi X$

LHCb reconstructed two J/ψs from their decays to dimuons in the forward rapidity region, $2 < y < 4.5$. The two J/ψs were required be associated with the same primary vertex and to be b-decay candidates. They chose different minimum J/ψ transverse momenta, p_T, $p_T > 2, 3, 5$, and 7 GeV, to study the effect of the p_T on the correlations. The data from $p+p$ collisions at $\sqrt{s} = 7$ and 8 TeV were combined for greater statistics. The results were presented as $(1/\sigma)d\sigma/dX$ where X is the observable because the distribution shapes are independent of $\sqrt{s}$.

LHCb presented results for six pair observables, $|\Delta\phi^*|$, the difference in azimuthal angle between the b and $\overline{b}$ mesons; $|\Delta\eta^*|$, the difference in pseudorapidity between the b and $\overline{b}$ mesons; A_T, the asymmetry between the transverse momenta of the J/ψs; and the mass, M, transverse momentum, p_{T_p}, and rapidity, y_p of the J/ψ pair [3]. They also determined the $|\Delta\phi|$ and $|\Delta\eta|$ distributions of the primary b hadrons. All pair observables studied by LHCb were calculated for both the parent $b\overline{b}$ mesons and the subsequent $J/\psi J/\psi$ decays in Ref. [2]. Only the $|\Delta\phi^*|$ distributions are shown here.

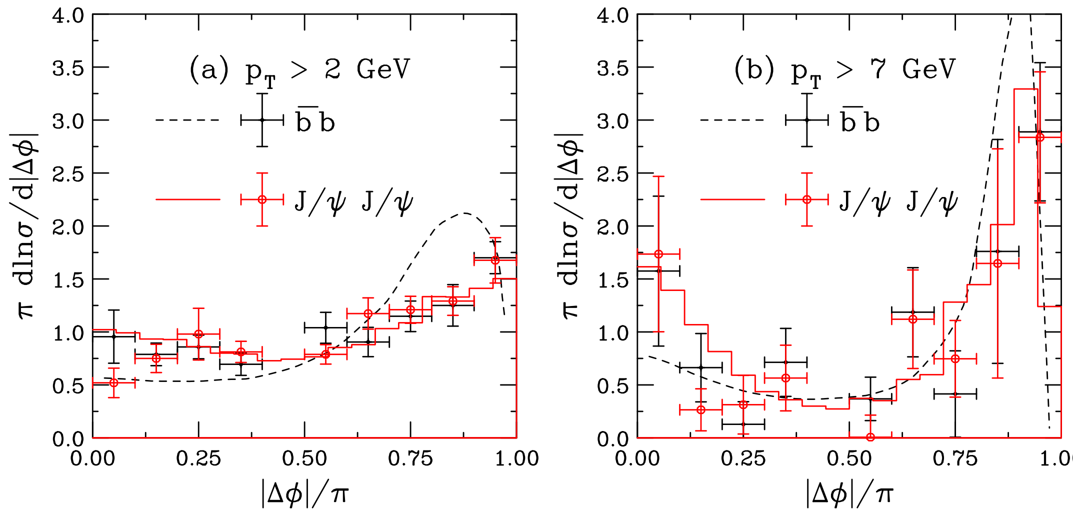

Figure 1: The azimuthal angle difference between the b and $\overline{b}$ (black dashed curves) and the J/ψ's resulting from the bottom quark decays (red histograms) are shown compared to the LHCb data [3] (black for $b\overline{b}$, red circles for J/ψ pairs) for the p_T cuts on the b quarks and the J/ψ of 2 (a) and 7 GeV (b). (From Ref. [2].)

As shown in Fig. 1, the $|\Delta\phi^*|$ and $|\Delta\phi|$ distributions for $b\overline{b}$ and $J/\psi J/\psi$ respectively are compatible with each other within the uncertainties. The $b\overline{b}$ $|\Delta\phi^*|$ distribution has a peak slightly below $|\Delta\phi^*| \approx \pi$ with a flatter distribution as $|\Delta\phi^*| \to 0$ relative to that of the J/ψ pair. As the minimum p_T grows, the peak near back-to-back ($|\Delta\phi^*| \approx \pi$) grows higher and becomes narrower for the $b\overline{b}$ pairs. The distribution at $|\Delta\phi^*| \approx 0$ increases from approximately flat at low $|\Delta\phi^*|$ to an enhancement that becomes more pronounced with increasing minimum p_T because the value of $m_T = \sqrt{p_T^2 + m_b^2}$ relative to $\langle k_T^2 \rangle^{1/2}$ grows, resulting in the development of a double-peaked $\Delta\phi^*$ distribution, suggesting a high p_T $b\bar{b}$ pair balanced against a hard parton in the opposite direction. Note that because the k_T kick is on the bottom quarks as they hadronize rather than on the J/ψ itself, the p_T selected is larger relative to the primary B hadron so that the enhancement grows faster with minimum p_T for J/ψ pairs, as shown in Fig. 1.

4. Simulation of Nuclear Effects

Nuclear effects were also considered on the pair distributions. The EPS09 [10] central set was used to modify the parton distributions in the nucleus. To model p_T broadening in medium, $\Delta = 2$ is used for p+Pb collisions and $\Delta = 4$ is used in the Pb+Pb calculations relative to $p + p$ collisions with $\Delta = 1$. In the case with 'shadowing only', $\Delta = 1$ is still employed. In addition, energy loss in Pb+Pb collisions is modeled by changing the Peterson function parameter, ϵ_P from the value used in these calculations, $\epsilon_P = 0.0004$ [1], to the previous default value, $\epsilon_P = 0.006$ [5].

The calculations shown in Fig. 2 are done at 8.16 TeV for p+Pb collisions and 5 TeV for Pb+Pb collisions. The $p + p$ results used to calculate the nuclear modification factors, $R_{p\mathrm{Pb}}$ and R_{PbPb} respectively, are calculated at the same energies. Increasing Δ in p+Pb and Pb+Pb collisions reduces and broadens the peak at $|\Delta\phi| \approx \pi$ and enhances the distribution at $|\Delta\phi| \approx 0$ [1, 2].

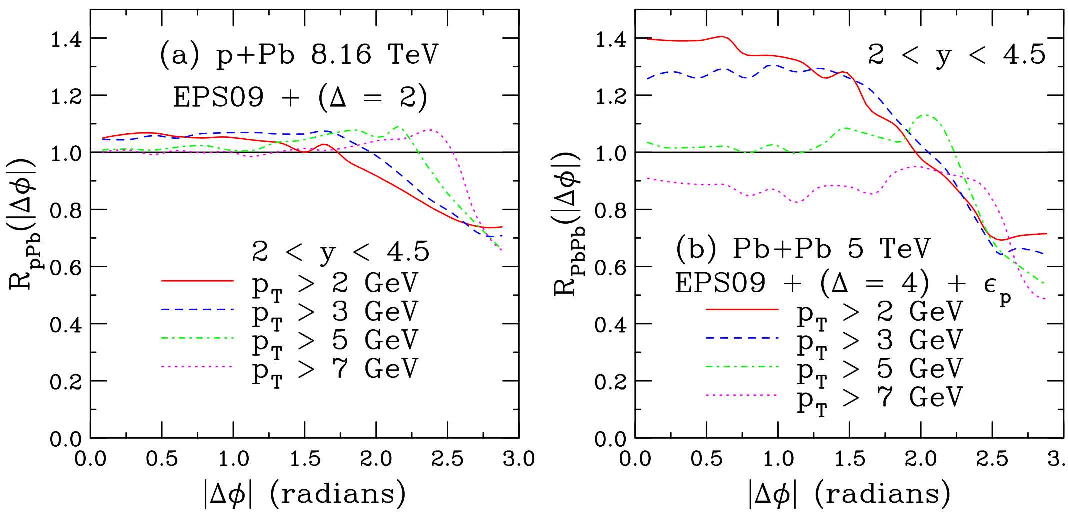

Figure 2: Cold nuclear matter effects at forward rapidity ($2 < y < 4.5$) on the $b\bar{b}$ azimuthal angle difference for $p_T > 2$ (solid red), 3 (dashed blue), 5 (dot-dashed green), and 7 GeV (dotted magenta) for (a) $R_{p\mathrm{Pb}}$ at 8.16 TeV with EPS09 and $\Delta = 2$ in Pb and (b) R_{AA} at 5 TeV with EPS09, $\Delta = 4$ and $\epsilon_P = 0.006$. (From Ref. [2].)

The p+Pb ratios with $\Delta = 2$ in Fig. 2(a) exhibit a kink that occurs at higher $\Delta\phi$ for increasing minimum p_T. This can be understood from the ratios of increasing $\langle k_T^2 \rangle$ relative to the results with no broadening, $\langle k_T^2 \rangle = 0$. Reference [1] studied the turn on of the effect at $\langle k_T^2 \rangle > 0$, becoming increasingly isotropic as $\langle k_T^2 \rangle$ increases. The $|\Delta\phi|$ distributions were seen to peak more sharply at both $|\Delta\phi| \to \pi$ and $|\Delta\phi| \to 0$. The effect at $|\Delta\phi| = 0$ is reduced in $b\bar{b}$ production relative to $c\bar{c}$ since it requires a much harder gluon to balance a more massive $b\bar{b}$ pair than the lighter $c\bar{c}$ pair.

The change in relative height of the peaks for fixed $\langle k_T^2 \rangle$ and increasing minimum p_T causes the location of the kink in $R_{p\mathrm{Pb}}$ to increase as the minimum p_T increases from 2 to 7 GeV.

A clear difference is seen for R_{PbPb} in Figs. 2(b). The fragmentation parameter ϵ_P has almost no effect on the shape of the $\Delta\phi$ distribution, as also shown in Ref. [1] when integrated over all p_T. However, it will change the number of $b\bar{b}$ pairs with both quarks in the rapidity acceptance, producing the inverted hierarchy of ratios seen here. Note that employing $\Delta = 4$ in Pb+Pb collisions also result in the kink in $R_{p\mathrm{Pb}}$ seen in Fig. 2(a) moving to lower $\Delta\phi$.

5. Summary

The $b\bar{b} \to J/\psi J/\psi$ pair observables measured by LHCb in $p + p$ collisions were studied in detail in an exclusive NLO calculation with fragmentation and k_T broadening. Illustrative nuclear modification factors for enhanced k_T broadening and fragmentation function modification in cold nuclear matter were presented. The azimuthal correlation depends strongly on the k_T broadening. While the effects were modeled in the context of cold nuclear matter, enhanced k_T broadening and heavy quark energy loss, as modeled by the modified ϵ_P, could be due to hot matter effects. These calculations suggest that additional correlated observables are required to better quantify such effects, regardless of the medium. For full details and all results, see Refs. [1, 2].

References

[1] R. Vogt, *Heavy Flavor Azimuthal Correlations in Cold Nuclear Matter*, *Phys. Rev. C* **98** (2018) 034907.

[2] R. Vogt, *$b\bar{b}$ Kinematic Correlations in Cold Nuclear Matter*, *Phys. Rev. C* **101** (2020) 024910.

[3] R. Aaij *et al.* (LHCb Collaboration), *Study of $b\bar{b}$ correlations in high energy proton-proton collisions*, *JEHP* **11** (2017) 030.

[4] M. L. Mangano, P. Nason, and G. Ridolfi, *Heavy quark correlations in hadron collisions at next-to-leading order*, *Nucl. Phys. B* **373** (1992) 295.

[5] C. Peterson, D. Schlatter, I. Schmitt, and P. Zerwas, *Scaling Violations in Inclusive e^+e^- Annihilation Spectra*, *Phys. Rev. D* **27** (1983) 105.

[6] S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, *Charm and bottom production: theoretical results versus experimental data*, *Nucl. Phys. B* **431** (1994) 453.

[7] R. E. Nelson, R. Vogt and A. D. Frawley, in preparation.

[8] M. Cacciari, M. Greco and P. Nason, *The p_T spectrum in heavy flavor hadroproduction*, *JHEP* **05** (1998) 007.

[9] R. E. Nelson, R. Vogt and A. D. Frawley, *Narrowing the uncertainty on the total charm cross section and its effect on the J/ψ cross section*, *Phys. Rev. C* **87** (2013) 014908.

[10] K. J. Eskola, H. Paukkunen and C. A. Salgado, *EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions*, *JHEP* **0904** (2009) 065.