Heavy Flavor Kinematic Correlations in Cold Nuclear Matter

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based on:
Outline

- Heavy flavor production
  - fragmentation
  - $k_T$ broadening
  - Comparison to single inclusive $p_T$ data
- Heavy flavor pairs
  - Effects of fragmentation and broadening on pair production
  - $b\bar{b} \rightarrow J/\psi J/\psi$ comparison with data
- Cold nuclear matter effects
Motivation

- Correlations are more complex observables of heavy flavor production
- Naive expectation is that pairs are produced back-to-back (as at leading order) but next-to-leading order contributions change correlation
- Result depends more on $k_T$ broadening than fragmentation/hadronization
- Correlation measurements probe event topologies by applying different kinematic cuts
  - *a different topology does not mean a different production mechanism*
- The presence of cold or hot nuclear matter can modify these correlations
Production of $Q\bar{Q}$ Pairs

NLO and higher order heavy flavor production can be calculated as total cross sections (all momenta integrated away); single inclusive (keep only momentum of one quark or antiquark, momenta of other final-state partons integrated away); exclusive pair production (keep all momenta of final-state partons)

Total cross sections are generally somewhat larger: fixed flavors, $\alpha_s$ does not run

Single inclusive distributions: $\alpha_s(\mu_R \propto m_T)$; NLO calculations improved by resummed terms at high $p_T$, $p_T \gg m$ (finite heavy quark mass keeps single inclusive distribution finite at $p_T \to 0$ by subtracting massless limit) and scheme-appropriate fragmentation functions (examples: FONLL (Cacciari and Nason) and GM-VFN (Kniehl et al., Helenius et al. calculations), employ $n_f + 1$ flavors in $\alpha_s$

Exclusive pair production needed for correlations, retains all kinematic quantities, two general approaches:

- HVQMNMR (Mangano, Nason and Ridolfi): no resummation, negative weight MC, incomplete numerical cancellation of divergences at $p_T \to 0$, Peterson function is default fragmentation scheme

- POWHEG-hvq (Frixione, Nason and Ridolfi): leading log resummation, positive weight MC, generally interfaces with parton shower LO MC like HERWIG or PYTHIA for fragmentation and decay

Here, HVQMNMR calculates correlations with fragmentation function and $k_T$ broadening adjusted to reproduce FONLL $p_T$ distribution with same $m_Q$, $\mu_F$ and $\mu_R$
Implementing Fragmentation

FONLL uses different fragmentation schemes for charm and bottom

bottom quarks: Polynomial

\[ D(z) = z(1-z)^\epsilon \]

\[ \epsilon = 27.5 \text{ for } m_b = 4.65 \text{ GeV}, \langle z \rangle = 0.934 \]

HVQMNMR employs Peterson function for fragmentation with parameter \( \epsilon_P \) for both charm and bottom,

\[ D(z) = \frac{z(1-z)^2}{((1-z)^2 + z\epsilon_P)^2} \]

- Standard value of \( \epsilon_P \), 0.006 for bottom, too large for hadroproduction, \( \langle z \rangle = 0.82 \)
- To match the FONLL result at high \( p_T \), with \( k_T \) broadening, \( \epsilon_P \) needs to be reduced to 0.0004 for \( b \) quarks, resulting in \( \langle z \rangle = 0.930 \)
Figure 2: The fragmentation functions used in the HVQMR code and FONLL for bottom are compared. The red curves show the standard Peterson function parameter while the black curves are calculated with the values of $\epsilon_p$ used in this paper. The FONLL results are shown in the dashed blue curves.
Implementation of $k_T$ Broadening

FONLL only includes fragmentation, not broadening

Default HVQMNR combines broadening with fragmentation based on $p_T$ distributions at fixed-target energies: including standard Peterson $\epsilon_P$ reduced average $p_T$ at fixed-target energies considerably; rather large $k_T$ broadening had to be included to make up difference and match data

Precedent from Drell-Yan, $k_T$ broadening included to make low $p_T$ distribution finite and take the place of full resummation

$$g(k_T) = \frac{1}{\pi \langle k_T^2 \rangle} \exp\left(-k_T^2/\langle k_T^2 \rangle\right)$$

In HVQMNR Gaussian factors are applied to each heavy quark in the final state, should be equivalent to application to initial-state partons as long as $\langle k_T^2 \rangle \sim 2 - 3$ GeV$^2$

Energy dependence of broadening assumed,

$$k_T^2 = 1 + \frac{1}{n} \ln \left( \frac{\sqrt{s}}{20 \text{ GeV}} \right) \text{ GeV}^2$$

$n$ fixed from $\Upsilon p_T$ distributions, $n = 3$
**Fragmentation and Broadening Effects on Single Inclusive $p_T$ Distributions**

Figure 3: (Left) The single inclusive bottom quark distributions in $\sqrt{s} = 7$ TeV $p + p$ collisions at next-to-leading order using the HVQMNR code. The distributions are shown at midrapidity, $|y| < 2.4$. Results are given for various combinations of $\left\langle k_T^2 \right\rangle$ and $\epsilon_p$. (Right) The single inclusive $b$-quark hadron, $H_b$, distributions in $\sqrt{s} = 7$ TeV $p + p$ collisions are compared to data from ATLAS (G. Aad et al. [ATLAS Collaboration], Nucl. Phys. B 864, 341 (2012)) at $|\eta| < 2.5$ respectively. The curves show the extent of the theoretical uncertainty bands. The HVQMNR code (blue dashed curves) utilizes $\left(\left\langle k_T^2 \right\rangle (\text{GeV}^2), \epsilon_p\right) = (1.5, 0.008)$ for charm and $(3.0, 0.0004)$ for bottom. The corresponding FONLL uncertainty band (red curves) is also shown. The same quark mass and scale parameters are used in both calculations.
Fragmentation and Broadening Effects on Azimuthal Angle Difference Between Heavy Quarks

Figure 4: The NLO azimuthal distribution between two heavy quarks, $d\sigma/d\phi$ in $p + p$ collisions at $\sqrt{s} = 7$ TeV using the HVQMN RJ code for $b\bar{b}$ pairs at midrapidity, $|y| < 2.4$. The results are shown for various choices of $\langle k_T^2 \rangle$ and $\epsilon_P$. 

$\langle k_T^2 \rangle$ (GeV$^2$), $\epsilon_P$
- (0,0)
- (0,0.006)
- (0,0.0008)
- (0,0.0004)
- (3.0,0.0004)

$|y| < 2.4$

(b) $b\bar{b}$, $\sqrt{s} = 7$ TeV
Dependence of Azimuthal Correlations on $\langle k_T^2 \rangle$

Studied sensitivity of azimuthal correlations on $\langle k_T^2 \rangle$ and $p_T$ cut

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

Studied $\Delta = -1/2, 0, 1/2, 1$

Low $p_T$ is most sensitive to $k_T$ in azimuthal correlation, as is now shown

Effect is independent of rapidity
Bottom Pairs, $p_T < 10$ GeV

Figure 5: The azimuthal angle distributions (left) and ratios relative to $\langle k_T^2 \rangle = 0$ (right) for $b\bar{b}$ in the central rapidity range $|y| < 2.4$ with $p_T < 10$ GeV. Calculations are shown with $\langle k_T^2 \rangle = 0$ and for values of $\Delta$ from $-1/2$ to 1.
Figure 6: The azimuthal angle distributions (left) and ratios relative to $\langle k_T^2 \rangle = 0$ (right) for $b\bar{b}$ in the central rapidity range $|y| < 2.4$ with $p_T > 10$ GeV. Calculations are shown with $\langle k_T^2 \rangle = 0$ and for values of $\Delta$ from $-1/2$ to 1.
LHC $b\bar{b} \rightarrow J/\psi J/\psi$ Correlations

LHCb measured $b\bar{b} \rightarrow J/\psi J/\psi$ at $\sqrt{s} = 7$ and 8 TeV (R. Aaij et al. (LHCb Collaboration), JEHP 11 (2017) 030)

Presented results for six pair observables:

- $|\Delta\phi^*|$, the difference in azimuthal angle between the $b$ and $\bar{b}$ mesons, also $|\Delta\phi|$, the azimuthal opening angle between the two $J/\psi$s
- $|\Delta\eta^*|$, the difference in pseudorapidity between the $b$ and $\bar{b}$ mesons and $|\Delta\eta|$ between the two $J/\psi$s
- $A_T$, the asymmetry between the transverse momenta of the $J/\psi$s
- Mass, $M$, of the $J/\psi$ pair
- $J/\psi$ pair transverse momentum, $p_Tp$
- $J/\psi$ pair rapidity, $y_p$

Each observable was studied with four different $p_T$ cuts: $p_T > 2$, 3, 5 and 7 GeV

All the pair observables studied by LHCb will be calculated for both the parent $b\bar{b}$ mesons and the subsequent $J/\psi J/\psi$ decays.
Azimuthal Distributions, $|\Delta\phi^*|$ and $|\Delta\phi|$  

Figure 7: The azimuthal angle difference between the $b$ and $\bar{b}$ (black dashed curves) and the $J/\psi$'s resulting from $B$ decays (red histograms) are compared to the LHCb data (black: $b\bar{b}$, red circles: $J/\psi$ pairs) for $p_T$ cuts on the $B$ and the $J/\psi$ of 2 (a), 3 (b), 5 (c) and 7 GeV (d).
Rapidity Difference, $|\Delta y^*|$ and $|\Delta y|$  

Figure 8: The rapidity difference $|\Delta y|$ between the $b$ and $\bar{b}$ (black dashed curve) and the $J/\psi$'s resulting from $B$ decays (red solid curve) are compared to the LHCb data (black: $b\bar{b}$, red circles: $J/\psi$ pairs) for $p_T$ cuts on the $B$ and the $J/\psi$ of 2 (a), 3 (b), 5 (c) and 7 GeV (d).
$p_T$ Asymmetry $A_T = \left| \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \right|$
Figure 10: The transverse momentum of the $b$ and $\bar{b}$ (black dashed lines) and the $J/\psi$'s resulting from $B$ decays (red histograms) are shown compared to the LHCb data (red circles) for the $p_T$ cuts on the $B$ and the $J/\psi$ of 2 (a), 3 (b), 5 (c) and 7 GeV (d).
Figure 11: The pair mass of the $b$ and $\bar{b}$ (black dashed lines) and the $J/\psi$’s resulting from $B$ (red histograms) are compared to the LHCb data (red circles) for $p_T$ cuts on the $B$ and the $J/\psi$ of 2 (a), 3 (b), 5 (c) and 7 GeV (d).
Figure 12: The pair rapidity of the $b$ and $\bar{b}$ (black dashed curves) and the $J/\psi$'s resulting from $B$ decays (red solid curves) are compared to the LHCb data (red circles) for $p_T$ cuts on the $B$ and the $J/\psi$ of 2 (a), 3 (b), 5 (c) and 7 GeV (d).
Sensitivity to $\langle k_T^2 \rangle$

Figure 13: The difference in the $b\bar{b}$ and $J/\psi J/\psi$ pair results for $\langle k_T^2 \rangle = 0$ and the default $k_T$ kick. The $\langle k_T^2 \rangle = 0$ results are shown by the blue dot-dashed curves ($b\bar{b}$) and blue dot-dashed histograms ($J/\psi J/\psi$) and with the default $k_T$ kick by the black dashed curves ($b\bar{b}$) and red histograms ($J/\psi J/\psi$). Results are shown for the azimuthal angle difference (a) and (b) and $p_T$ asymmetry (g) and (h).
Nuclear Matter Effects

Cold nuclear matter effects include modification of the parton densities, energy loss and $p_T$ broadening (Cronin effect), last two are also hot matter effects

Usually defined in terms of nuclear modification factors, per nucleon cross sections in $pA$ or $AA$ collisions relative to $pp$

$$R_{pA} = \frac{1}{T_A} \frac{d\sigma_{pA}/dp_T dy}{d\sigma_{pp}/dp_T dy} \quad R_{AA} = \frac{1}{T_{AA}} \frac{d\sigma_{AA}/dp_T dy}{d\sigma_{pp}/dp_T dy}$$

Nuclear modification of parton densities (shadowing) changes parton distributions in the nucleus: $f^A_i(x, Q^2) = S^A_i(x, Q^2)f^p_i(x, Q^2)$ where $f_i$ is the parton density ($i = q, \bar{q}$ or $g$) and $S^A_i$ is the shadowing factor, determined from global analyses

Cronin effect modeled by enhanced $k_T$ broadening in the nucleus:

$$k^2_T = 1 + \frac{\Delta}{n} \ln \left( \frac{\sqrt{s}}{20 \text{ GeV}} \right) \text{ GeV}^2 \quad [pA : \Delta = 2, \quad AA : \Delta = 4]$$

Energy loss modeled by assuming that the fragmentation parameter is increased, to do so $\epsilon_P$ is taken to be the $e^+e^-$ value in $AA$ collisions
Single Hadron $p_T$ Distributions and Pair Observables

Several scenarios are studied for bottom production:

- Nuclear modification of parton densities (shadowing) only in $pA$ and $AA$
- Shadowing plus additional broadening ($\Delta = 2$) in $pA$
- Shadowing, additional broadening ($\Delta = 4$), and increased $\epsilon_P$ in $AA$
- $pA$ calculated at $\sqrt{s_{NN}} = 8.16$ TeV; $AA$ at $\sqrt{s_{NN}} = 5.02$ TeV; $pp$ calculated at the same energies
- Results shown only for forward rapidities, similar dependence at central rapidity, see paper for more details
- Studied pair quantities $|\Delta \phi|$ and $y_p$

The results for pair rapidities are more sensitive to changes in fragmentation while azimuthal effects are more sensitive to enhanced $k_T$ broadening

Sensitivity to transverse momentum studied by employing the same $p_T$ cuts as LHCb $b\bar{b} \rightarrow J/\psi J/\psi$ studies, $B \ p_T > 2, 3, 5$ and $7$ GeV
Figure 14: Cold nuclear matter effects on $b$ quark $p_T$ distributions for (a) $p+Pb$ collisions at 8.16 TeV with central EPS09 and the same $k_T$ kick as in $p+p$ (solid) and additional $k_T$ broadening in Pb (dashed); (c) Pb+Pb collisions at 5 TeV with central EPS09 with the same $k_T$ kick in $p+p$ and Pb+Pb (solid) and additional $k_T$ broadening in the Pb nuclei with a modified fragmentation function in Pb (dashed). In (a) the calculations are compared to the LHCb data on non-prompt $J/\psi$ (R. Aaij et al. [LHCb Collaboration], Phys. Lett. B 774, 159 (2017).) and direct $B^+$ (R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 99, 052011 (2019).).
Figure 15: The $b\bar{b}$ pair rapidity in the range $2 < y_p < 4.5$ for $p_T > 2$ (a) and 7 GeV (b) for $p+p$ collisions at 7 TeV (solid blue), $p+Pb$ collisions at 8.16 TeV (dashed red) and $Pb+Pb$ collisions at 5 TeV (dot-dashed black). The $p+Pb$ calculations include shadowing and enhanced broadening ($2\Delta$) while the $Pb+Pb$ calculations include shadowing, broadening ($4\Delta$), and fragmentation function modification.
Figure 16: Cold nuclear matter effects in $2 < y < 4.5$ on the $\bar{b}b$ pair rapidity for $p_T > 2$ (solid red), 3 (dashed blue), 5 (dot-dashed green), and 7 GeV (dotted magenta) for (a) $p+\text{Pb}$ collisions at 8.16 TeV with central EPS09 and the same $k_T$ kick as in $p+p$; (b) $R_{ppb}$ at 8.16 TeV with EPS09 and additional $k_T$ broadening in Pb; (c) $\text{Pb}+\text{Pb}$ collisions at 5 TeV with central EPS09 with the same $k_T$ kick in $p+p$ and $p+\text{Pb}$; and (d) $R_{AA}$ at 5 TeV with EPS09, additional $k_T$ broadening in the Pb nuclei, and a modified fragmentation function in Pb.
Energy Dependence of Effects on $|\Delta \phi|$ on the $\bar{b}b$ azimuthal difference in the range $2 < y_p < 4.5$ for $p_T > 2$ GeV (a) and 7 GeV (b) for $p+p$ collisions at 7 TeV (solid blue), $p+Pb$ collisions at 8.16 TeV (dashed red) and Pb+Pb collisions at 5 TeV (dot-dashed black). The $p+Pb$ calculations include shadowing and enhanced broadening ($2\Delta$) while the Pb+Pb calculations include shadowing, broadening ($4\Delta$), and fragmentation function modification.
Effects on Azimuthal Distributions

Figure 18: 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) $p$+Pb collisions at 8.16 TeV with central EPS09 and the same $k_T$ kick as in $p+p$; (b) $R_{pPb}$ at 8.16 TeV with EPS09 and additional $k_T$ broadening in Pb; (c) Pb+Pb collisions at 5 TeV with central EPS09 with the same $k_T$ kick in $p+p$ and $p$+Pb; and (d) $R_{AA}$ at 5 TeV with EPS09, additional $k_T$ broadening in the Pb nuclei and a modified fragmentation function in Pb.
Summary

• Heavy quark pair correlations in $p+p$ and $p\bar{p}$ collisions can be explained by NLO heavy flavor production processes

• Results are most sensitive to $k_T$ broadening at low $p_T$, practically insensitive to fragmentation/hadronization

• All $b\bar{b} \rightarrow J/\psi J/\psi$ observables are in good agreement with NLO $b\bar{b}$ pair production and decay to $J/\psi$

• $b\bar{b}$ pair quantities sensitive to $k_T$ effects but daughter $J/\psi$s are not because the decay results in de-correlation of $k_T$

• Effects on pair observables sensitive to hot and cold nuclear matter effects; results here are illustrative only but show that pair rapidity can be sensitive to energy loss while azimuthal angle difference is sensitive to Cronin-like $p_T$ broadening effects
Contributions to $Q\bar{Q}$ Pair Production

Only $gg$ and $q\bar{q}$ at LO, at NLO there is new channel, $q(\bar{q})g$

Contributions sorted by initial state, not diagram topology as in LO event generators with labels like flavor creation, flavor excitation and gluon splitting

These labels are for topologies, not production mechanisms, and are properly weighted in a NLO calculation by color factors, then initial state contributions are summed and amplitudes squared, not possible in event generators

Squaring amplitudes of individual diagrams, as in LO generators, eliminates interferences and will not produce correct cross sections

Some experiments use LO event generators and try to model data by fitting individual diagram weights, this is wrong

Figure 19: Examples of real contributions to next-to-leading order $Q\bar{Q}$ production. Diagrams (a)-(c) illustrate contributions to $gg \rightarrow Q\bar{Q}g$ while (d) shows an example of $qg \rightarrow qQ\bar{Q}$ production.
Calculating Theoretical Uncertainties

Scales fit to total heavy flavor cross section data

- Take $1S$ value for $m_b$, $4.65 \pm 0.09$ GeV

- Vary scales independently within $1\sigma$ of fitted region:
  $$(\mu_F/m, \mu_R/m) = (C,C), (H,H), (L,L), (H,C), (C,H), (L,C), (C,L)$$

- For bottom production, $$(\mu_F/m_T, \mu_R/m_T) = (1.4_{-0.49}^{+0.77}, 1.1_{-0.20}^{+0.22})$$

The uncertainty band in all cases comes from the upper and lower limits of mass and scale uncertainties added in quadrature

$$\frac{d\sigma_{\text{max}}}{dX} = \frac{d\sigma_{\text{cent}}}{dX} + \sqrt{\left(\frac{d\sigma_{\mu,\text{max}}}{dX} - \frac{d\sigma_{\text{cent}}}{dX}\right)^2 + \left(\frac{d\sigma_{m,\text{max}}}{dX} - \frac{d\sigma_{\text{cent}}}{dX}\right)^2},$$

$$\frac{d\sigma_{\text{min}}}{dX} = \frac{d\sigma_{\text{cent}}}{dX} - \sqrt{\left(\frac{d\sigma_{\mu,\text{min}}}{dX} - \frac{d\sigma_{\text{cent}}}{dX}\right)^2 + \left(\frac{d\sigma_{m,\text{min}}}{dX} - \frac{d\sigma_{\text{cent}}}{dX}\right)^2},$$

The resulting theoretical uncertainties can be large for charm, relatively small for bottom