Correlations of $\mu\mu$, $e\mu$, and $ee$ pairs in $p+p$ collisions at $\sqrt{s} = 200$ GeV and implications for $c\bar{c}$ and $b\bar{b}$ production mechanisms

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PHENIX has measured the azimuthal correlations of muon pairs from charm and bottom semi-leptonic decays in $p+p$ collisions at $\sqrt{s} = 200$ GeV, using a novel analysis technique utilizing both unlike- and like-sign muon pairs to separate charm, bottom and Drell-Yan contributions. The dimuon measurements combined with the previous electron-muon and dielectron measurements span a wide range in rapidity, and are well described by PYTHIA Tune A. Through a Bayesian analysis...
Based on PYTHIA Tune A, we show that leading order pair creation is the dominant (76% $\pm$13%) contribution for $b\bar{b}$ production, whereas the data favor the scenario in which next-to-leading-order processes dominate $c\bar{c}$ production. The small contribution of next-to-leading-order processes in $b\bar{b}$ production at the collision energies of the Relativistic Heavy Ion Collider contrasts with the case at Large-Hadron-Collider energies, where next-to-leading-order processes are expected to dominate.

Despite substantial experimental and theoretical efforts in recent years, our understanding of heavy flavor production in $p+p$ collisions remains incomplete. Differential cross section measurements, particularly for charm, are systematically higher than the central values of theoretical predictions [11,16] for collision energies from the Relativistic Heavy Ion Collider (RHIC) [7,9] to the Large Hadron Collider (LHC) [10,13], and are only consistent when large theoretical uncertainties are considered.

Angular correlations of quarks and anti-quarks are a unique probe for studying heavy flavor production in $p+p$ collisions. Leading-order (LO) pair-creation processes feature a strong back-to-back azimuthal angular correlation, while the distributions from next-to-leading order (NLO) processes are broader [3,15]. Thus, relative contributions from different production mechanisms can be disentangled by studying the azimuthal angular correlations of heavy mesons or their decay products. As the fraction of NLO processes is expected to increase with beam energy [8], angular correlations provide an important handle for investigating the energy dependence of heavy flavor production.

Only a few heavy-flavor correlation measurements have been performed at high energies. At the Tevatron [16] and the LHC [17,18] data are reasonably well described by NLO perturbative quantum chromodynamics (pQCD) calculations, but only a few quantitative constraints have been extracted on the relative contributions of different heavy-flavor production mechanisms. At RHIC, inclusive heavy flavor (dominated by $c\bar{c}$) $ee$ [19] and $e\mu$ [20] measurements at mid-midrapidity and mid-forward rapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV are consistent with pQCD models within experimental uncertainties. However, the limited statistical accuracy of these measurements prohibit us from providing strong constraints on heavy flavor production mechanisms.

PHENIX [21] has recently measured azimuthal correlations of $\mu\mu$ pairs from $c\bar{c}$ and $b\bar{b}$ [22] in $p+p$ collisions at $\sqrt{s} = 200$ GeV, using the high statistics data set taken in 2015 that corresponds to an integrated luminosity of $\int L dt = 51$ pb$^{-1}$. The $\mu\mu$ data, together with the previous $ee$ and $e\mu$ measurements cover a wide kinematic range. Here, we present an analysis of $c\bar{c}$ and $b\bar{b}$ correlations in $p+p$ collisions at $\sqrt{s} = 200$ GeV, where we combine the $\mu\mu$, $e\mu$ and $ee$ measurements to constrain the $c\bar{c}$ and $b\bar{b}$ production mechanisms.

A complete description of the $\mu\mu$ analysis can be found in [22]. The $\mu\mu$ pairs from $c\bar{c}$, $b\bar{b}$, Drell-Yan and hadronic pairs (arising from kaons and pions) are separated via a simultaneous fit to unlike- and like-sign pairs in mass and transverse momentum $p_T$. The highlight of the analysis is the extraction of azimuthal correlations of $\mu\mu$ from $b\bar{b}$ utilizing like-sign pairs. Decays from $c\bar{c}$ or the Drell-Yan mechanism result in unlike-sign pairs only; in contrast $b\bar{b}$ can result in like-sign pairs either via a combination of $B \rightarrow \mu$ and $B \rightarrow D \rightarrow \mu$ decay chains or decays following $B^0\bar{B}^0$ oscillations. These pairs dominate the high mass like-sign spectrum ($3.5 < m_{\mu\mu} [\text{GeV}/c^2] < 10.0$), which

**FIG. 1.** Dimuon azimuthal correlations from $c\bar{c}$ (a) and $b\bar{b}$ (b) compared to PYTHIA and POWHEG.
allows isolating a sample of dimuons from $b\bar{b}$ and hadronic pairs with $S/B \sim 1$. The hadronic pairs are subtracted, and the remaining $\mu\mu$ pairs are corrected for efficiency to obtain the $b\bar{b}$ yields.

Figure [1] shows the $\mu\mu$ pair yield from $c\bar{c}$ and $b\bar{b}$ separately as a function of the azimuthal angle between the two muons. Distributions from the event generators, PYTHIA v6.428 and POWHEG v1.0 [1] (interfaced with PYTHIA v8.100 [23]) are compared to the data. For PYTHIA, contributions from parton creation (PC), flavor excitation (FE), and gluon splitting (GS) [3] are shown separately. PYTHIA and POWHEG treat the NLO corrections differently: PYTHIA implements NLO corrections with a parton-shower approach, while NLO corrections are directly implemented in the hard process using NLO matrix elements in POWHEG. Tune A parameters [24] are used for PYTHIA; default settings are used for POWHEG. Details on the simulation setup can be found in [22]. Generated distributions are normalized using cross sections obtained in the fitting procedure documented in [22] ($\sigma_{c\bar{c}} = 343.6\, \mu b$, $\sigma_{b\bar{b}} = 3.59\, \mu b$ for PYTHIA, $\sigma_{c\bar{c}} = 316\, \mu b$, $\sigma_{b\bar{b}} = 3.94\, \mu b$ for POWHEG).

Figure [2] shows the measured heavy flavor $ee$ [19] and $e\mu$ [20] yields, as a function of the azimuthal opening angle $\Delta\phi_{e\mu}$ and the opening angle $\theta_{e\mu}$, respectively. These yields are extracted in distinctly different (pseudo)rapidity regions ($e\mu : |\eta_e| < 0.5, 1.4 < |\eta_\mu| < 2.1$; $ee : |y_e| < 0.35$) compared to the $\mu\mu$ pairs ($\mu\mu : 1.2 < |\eta_{\mu}| < 2.2$). The $e\mu$ pairs contain contributions from $c\bar{c}$ and $b\bar{b}$, while the $ee$ pairs contain also additional but negligible ($<0.5\%$) contributions from Drell-Yan. Distributions from $c\bar{c}$ and $b\bar{b}$ generated from PYTHIA and POWHEG are normalized using the cross sections obtained in the $\mu\mu$ analysis [22], and compared to data. In both cases, the yield is dominated by pairs from $c\bar{c}$.

Although the correlations of the lepton pairs are measured within limited detector acceptance and have additional kinematic constraints, a strong back-to-back peak is observed for leading order PC for both $c\bar{c}$ and $b\bar{b}$. Distributions from FE and GS are significantly broader than those from PC. To quantify the consistency with data, we calculate a modified $\chi^2$ [25] that takes systematic uncertainties into account. For $b\bar{b}$, the $\chi^2/NDF$ values for PYTHIA and POWHEG are 9.8/7 and 7.2/7, respectively, which indicates that the the azimuthal correlations for $b\bar{b}$ are well described by both models. For $c\bar{c}$, the $\chi^2/NDF$ values of PYTHIA and POWHEG are 20.1/14 and 35.8/14, respectively. While the $\mu\mu$ data are well described by PYTHIA, the distribution from POWHEG are wider than in the data. The $\chi^2/NDF$ value obtained by comparing PYTHIA to the $c\bar{c}$ dominated $ee$ and $e\mu$ measurements and the $c\bar{c}$ only $\mu\mu$ measurement is 59.6/47. This indicates PYTHIA can describe both the rapidity dependence and angular correlations of $c\bar{c}$ production well. The corresponding $\chi^2/NDF$ value for POWHEG is 94.2/47.

Because distributions of decay lepton pairs are highly correlated to the $c$ and $\bar{c}$ quarks [19], this indicates that the description of $c\bar{c}$ quark correlations between PYTHIA and POWHEG is intrinsically different at the quark level. In addition, we observe that at $\Delta\phi < \pi/2$ which is dominated by NLO processes, POWHEG always predicts more yield than PYTHIA; while the ratio of the yields at $\Delta\phi > \pi/2$ of POWHEG to PYTHIA decreases with rapidity in the measured phase spaces. Because leading order processes are peaked near $\Delta\phi = \pi$, this may imply that...
the rapidity dependence of the ratio of LO to NLO contributions is different between the two models.

To further constrain the production mechanisms of $c\bar{c}$ and $b\bar{b}$, we perform a simultaneous shape analysis of the $\mu\mu$, $e\mu$, and $ee$ data shown in Figs. 1 and 2 using Bayesian inference. Because the measurements cover different parts of phase space, extrapolations are unavoidable. PYTHIA Tune A gives good agreement with multiple measurements made at the Tevatron [20], as well as jet and underlying event measurements from PHENIX [27] and STAR [25]; we thus focus on Tune A for this study.

The analysis is performed separately for $c\bar{c}$ and $b\bar{b}$. For $b\bar{b}$, we only use the $\mu\mu$ data set, whereas for $c\bar{c}$, the $ee$, $e\mu$ and $\mu\mu$ data sets are used. For $ee$ and $e\mu$ data, we first subtract the expected $b\bar{b}$ yield from the two data sets and assign additional systematic uncertainties on extrapolation ($\sim 2\%$) and normalization ($\sim 6\%$). The extrapolation uncertainties are estimated by taking the difference between PYTHIA and POWHEG; the uncertainties on the normalization are taken from [22].

For $c\bar{c}$ or $b\bar{b}$, the model prediction of the yield, $T = \{T_{i,j}\}$ for the $i^{th}$ data set, either $\mu^+\mu^-$, $e\mu$, or $ee$ for $c\bar{c}$ and $\mu^+\mu^-$ for $b\bar{b}$, in the $j^{th}$ (azimuthal) opening angle bin can be written as:

$$T_{i,j}(F, \sigma_{HF}) = \sigma_{HF} \sum_{a} f_{a} Y_{a,i,j}, \quad (1)$$

where $F = \{F_{PC}, F_{FE}, F_{GS}\}$ is the relative contribution to heavy flavor production in 4$\pi$ phase space from the three considered processes PC, FE, and GS, $\sigma_{HF}$ is the total heavy flavor cross section in 4$\pi$, and $Y_{a,i,j}$ is the yield in the measured phase space of the $i^{th}$ data set (indicated in Figs. 1 and 2) for the $j^{th}$ bin generated involving the $\alpha$ process, where $\alpha = PC, FE$ or GS. The quantity that we constrain from the data is the relative contribution $F$, which is directly related to the shape of the angular distributions. The total heavy flavor cross section $\sigma_{HF}$ sets the overall normalization and is unimportant for this shape analysis.

The shape analysis of the angular distributions is sensitive to systematic uncertainties. The background subtraction is the dominant source of systematic uncertainty for all lepton-pair combinations. It introduces systematic uncertainties of $\sim 20\%$ for $\mu\mu$ from $c\bar{c}$ [22], $\sim 15\%$ for $\mu\mu$ from $b\bar{b}$ [22], $\sim 30\%$ for $e\mu$ [20], and $\sim 20\%$ for $ee$ [19], which affects the data points in a correlated manner. We adopt a Bayesian approach to account for these systematic variations.

Based on Eq. 1, we can construct a vector of model parameters $\theta$, which comprise the relative fractions of heavy flavor production processes $F$ and the heavy flavor cross section $\sigma_{HF}$. In the Bayesian approach, systematic uncertainties are naturally accounted for by incorporating nuisance parameters $n$ into $\theta$, where each nuisance parameter corresponds to one source of systematic uncertainty (see [29] for a pedagogical review). From Bayes’ rule, one can write:

$$P(F, \sigma_{HF}, n|D) = \frac{P(D|F, \sigma_{HF}, n) \cdot P(F, \sigma_{HF}, n)}{P(D)}. \quad (2)$$

The quantity that we want to obtain is $P(F|D)$. We assume a noninformative prior for $F$, i.e. a uniform distribution in the physical region, in which the values $F_i$, where $i = PC, FE, GS$, lie between zero and one and sum to one.

To compute $P(F|D)$ from Eq. 2, we adopt a Monte Carlo approach, in which multiple sets of nuisance parameters $n^*$ are randomly generated. For each set of $n^*$, the data $D$ are perturbed according to $n^*$, and $\sigma_{HF}$ is constrained via a 1-parameter $\chi^2$ fit to the data. The posterior probability density $P(F, \sigma_{HF}, n^*|D)$ is then summed over different sets of $n^*$ and normalized to unity in order to obtain $P(F|D)$. Finally, we construct 68% and 95% credible intervals from $P(F|D)$; boundaries of the intervals are contours of the posterior probability density $P(F|D)$.

The final results are presented in Fig. 3 in different projections of $F$. For $c\bar{c}$ ($b\bar{b}$), the PYTHIA Tune A implementation lies within the 68% (95%) credible intervals obtained from our analysis. For the case of $c\bar{c}$, a positive correlation is observed between $F_{PC}$ and $F_{GS}$, both of which are individually anti-correlated with $F_{FE}$. This is explained by the observation that the data sets can be reasonably well described by the following two cases: $F = (0\%, 100\%, 0\%)$ and $F = (62\%, 0\%, 38\%)$. From the posterior probability distributions, it is observed that the hierarchy $F_{FE} > F_{PC} > F_{GS}$ is favored, consistent with the expectation from PYTHIA.

In contrast to $c\bar{c}$, PC is clearly the dominant ($76\% \pm 14\%$) production process for $b\bar{b}$. Compared to $c\bar{c}$, the ordering of contributions from of PC and FE is reversed $F_{PC} > F_{FE} > F_{GS}$, again consistent with the expectation from PYTHIA. The reversal in the hierarchy for $b\bar{b}$ arises from the larger $b$ quark mass, which sets more demanding kinematic requirements for NLO processes.

The upper limits corresponding to the 95% credible intervals for $F_{GS}$ for $c\bar{c}$ and $b\bar{b}$ are 52% and 31% respectively. These limits take into consideration extreme cases in which only PC and GS contribute to the yield but FE does not. Priors with extra physical considerations may be incorporated to impose more stringent constraints in $F$, however this is beyond the scope of our study.

In summary, we have presented an analysis of angular correlations of $\mu\mu$, $e\mu$, and $ee$ pairs from $c\bar{c}$ and $b\bar{b}$ measured in $p+p$ collisions at $\sqrt{s} = 200$ GeV at forward-forward, mid-forward, and mid-midrapidity, respectively. All measured angular correlations can be consistently described by distributions obtained from PYTHIA Tune.
splitting process, particularly at LHC energies [30, 31].

Suffer complications due to the contribution from gluon splitting processes, separately for heavy quarks. Besides heavy quark production mechanisms, similar measurements in $p+p$ collisions at different energies will provide insight on the energy dependence of heavy quark production mechanisms.

At RHIC energies, heavy quarks can be utilized to study initial gluon dynamics due to the small fraction of gluon splitting contribution. Besides $p+p$ collisions, heavy quarks are commonly used to study nuclear matter effects in $p+A$ and $A+A$ collisions with the assumption that heavy quarks are mostly produced in the early stages of collisions. Similar measurements in $p+A$ may shed light on process dependent cold nuclear matter effects. A solid understanding of the contributions of heavy flavor processes in $p+p$ and $p+A$ collisions will be critical to precisely interpret results in $A+A$ collisions, which suffer complications due to the contribution from gluon splitting process, particularly at LHC energies [30, 31].

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Based on PYTHIA Tune A, we have performed a shape analysis using the combined data on heavy flavor angular correlations at $\sqrt{s} = 200\text{ GeV}$. This analysis constrains the relative contributions of the leading order pair creation, and next-to-leading order flavor excitation and gluon splitting processes, separately for $c\bar{c}$ and $b\bar{b}$. The data indicate that the dominant production mechanism of $b\bar{b}$ production is pair creation, and supports the scenario in which flavor excitation dominates $c\bar{c}$ production. Similar measurements in $p+p$ collisions at different energies will provide insight on the energy dependence of heavy quark production mechanisms.

At RHIC energies, heavy quarks can be utilized to study initial gluon dynamics due to the small fraction of gluon splitting contribution. Besides $p+p$ collisions, heavy quarks are commonly used to study nuclear matter effects in $p+A$ and $A+A$ collisions with the assumption that heavy quarks are mostly produced in the early stages of collisions. Similar measurements in $p+A$ may shed light on process dependent cold nuclear matter effects. A solid understanding of the contributions of heavy flavor processes in $p+p$ and $p+A$ collisions will be critical to precisely interpret results in $A+A$ collisions, which suffer complications due to the contribution from gluon splitting process, particularly at LHC energies [30, 31].

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