Transverse Momentum Balance and Angular Distribution of $b\bar{b}$ Dijets in Pb+Pb collisions

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The productions of inclusive $b$-jet and $b\bar{b}$ dijets in Pb+Pb collisions have been investigated by considering the heavy quark and the light quark in-medium evolution simultaneously. The initial hard processes of inclusive $b$-jet and $b\bar{b}$ dijets productions are described by a next-to-leading order (NLO) plus parton shower Monte Carlo (MC) event generator SHERPA which can be well matched with the experimental data in $p+p$ collisions. The framework combines the Langevin transport model to describe the evolution of bottom quark also its collisional energy loss and the higher-twist description to consider the radiative energy loss of both bottom and light quarks. We compare the theoretical simulation of inclusive jet and inclusive $b$-jet $R_{AA}$ in Pb+Pb collisions at $\sqrt{S_{NN}} = 2.76$ TeV with the experimental data, and then present the theoretical simulation of the momentum balance of the $b\bar{b}$ dijet in Pb+Pb collisions at 5.02 TeV with the recent CMS data for the first time. A similar trend as that in dijets has been observed in $b\bar{b}$ dijets, the production-distribution shifted to smaller $x_f$ due to the jet quenching effect. At last, the prediction of the normalized azimuthal angle distribution of the $b\bar{b}$ dijet in Pb+Pb collisions at 5.02 TeV has been reported. The medium induced energy loss effect of the $b\bar{b}$ dijets will overall suppress its production, but the near side ($\Delta\phi \rightarrow 0$ region) suffers more energy loss than away side ($\Delta\phi \rightarrow \pi$ region), therefore lead to the suppression on the near side and the enhancement on the away side in the normalized azimuthal angle distribution.

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To probe the properties of the quark-gluon plasma (QGP) in heavy-ion collisions (HIC), jet quenching phenomenon, which referred as the modification of energetic partons propagated though the hot and dense medium, has long been investigated [1–28]. Among them, the momentum imbalance of back-to-back jets are the fundamental observable. The quenching effect give a net imbalance to the dijets $p_T$ distributions that can exceed the imbalance brought by the QCD correction. This additional imbalance is due to the energy losses that the two jets suffered when they propagated through the QGP medium respectively. To insight into the underlying dynamics, the initial parton flavor dependence of the quenching effect is important, however it is difficult for the experiment to determine in the dijets events. The pairs of $b\bar{b}$ jets that are produced back-to-back in azimuth can provide a golden channel to distinguish the type of parton initiated the jets.

The productions of a $b\bar{b}$ pair could be categorized into three production mechanisms which can be used in understanding the $b\bar{b}$ system [29,32]. The flavour creation (FCR) describes the process that both $b$-jets originate from the hard scattering, therefore these jets are supposed to be the hardest in the event and also tend to be back-to-back in the transverse plane. The gluon splitting (GSP) mechanism produces a pair of $b$-jets which are expected in the same side. Unlike the previous two mechanisms, the flavour excitation (FEX) will reduce the angular separation between the $b$-jets. The NLO calculation (e.g. Herwig) without further kinetic constraint predicts that there are large contributions from all three mechanisms in the investigated $p_T$ region [33]. The measurement of nuclear modification factor of inclusive $b$-jet $R_{AA}$ and $R_{pA}$ can not distinguish these production mechanism and their contributions respectively. But to look at pairs of $b$-jets that are constrained back-to-back in azimuth ($b\bar{b}$ dijet) experimentally, one may largely reduce the contribution from gluon splitting process, and mainly focus on the FCR process by energetic $p_T$ triggers. This configuration are essential to provide a less ambiguous observable.

In the recent experimental publication [31], ATLAS reported the measurements of the $b\bar{b}$ dijet production in $p+p$ collisions at LHC which are compared with several NLO and LO QCD MC simulation. CMS collaboration also released a measurement of the transverse momentum correlations of $b\bar{b}$ dijets in both $p+p$ and Pb+Pb collisions in 2018 [33], it has been demonstrated that the next-to-leading order effects are essential for the modeling of such observable since NLO QCD calculation with POWHEG give a better description than PYTHIA 6 alone. It is noted that the configurations are slightly different in these two experimental publications, though their intention are both to significantly suppress the GSP contribution.

In our simulation, we choose the most up-to-dated SHERPA 2.2.4 [34] to provide the $p+p$ baseline and their event generation of the inclusive $b$ jet and $b\bar{b}$ dijets. The tree-level matrix elements are calculated by Amegic [37] and Comix [38] while one-loop matrix elements are cal-
The in-medium evolution of the reconstructed jet with heavy quarktagging requires a simultaneous description of both heavy quark and light quark evolution and their energy loss processes. At the moment, the exact mechanism of the in-medium interaction between the heavy quarks and the QCD medium is still an open question which has been extensively investigated in both perturbative and non-perturbative approaches [55]. Langevin and Boltzmann transport models cooperated with the evolution profile of the bulk medium are been employed for the heavy quark [41,46,54]. In our simulation, Langevin transport equations are employed to describe the propagating of the heavy quark in the hot and dense medium [55].

\[ \bar{x}(t + \Delta t) = \bar{x}(t) + \frac{\bar{p}(t)}{E} \Delta t \]  (1)

\[ \bar{p}(t + \Delta t) = \bar{p}(t) - \Gamma \bar{p} \Delta t + \xi(t) - \bar{p}_g \]  (2)

where \( \Delta t \) is the time step of the simulation, \( \Gamma \) is the drag coefficient which controls the strength of the elastic energy loss, \( \xi(t) \) is the stochastic term representing the effect of the random kicks by the light quarks or gluon in such thermal medium. The classic fluctuation-dissipation relation [56] has been considered between the drag coefficient \( \Gamma \) and diffusion coefficient \( \kappa \):

\[ \kappa = 2 \Gamma ET \]  (3)

where \( \kappa = 2T^2/D_s \), \( D_s \) is the spatial diffusion coefficient which has been calculated in Lattice QCD with a range of value \( 2\pi T D_s \sim 3.7 - 7.0 \) [45,57]. The four-momentum of the b quark is thus updated accordingly in the local rest frame be boosted to every time step. The inclusion of the last term \( \bar{p}_g \) is to take into account the momentum modification induced by the gluon radiation based on the Higher-Twist scheme [55,64].

\[ \frac{dN}{dx k^2 dt} = \frac{2\alpha_s C_v P(x) \hat{q}}{\pi k^2} \frac{\sin^2(\frac{t-t_i}{2\tau_f})(k^2 + x^2 M^2)^4}{k^2 + x^2 M^2} \]  (4)

is the radiative gluon spectrum, where \( x \) and \( k_\perp \) are the energy fraction and transverse momentum of the radiated gluon, \( M \) is mass of parent parton. In addition, \( C_v \) is the quadratic Casimir in color representation, and \( P(x) \) is the splitting function in vacuum [62].

\[ \tau_f = 2E(1-x)/(k^2 + x^2 M^2) \]  (5)

is the gluon formation time. \( \hat{q} \) is the jet transport parameter proportional to the local parton density in medium when the jet probed. The space and time evolution of the medium will alter the value of \( \hat{q} \) relative to its initial value \( \hat{q}_0 \) in the most center of the overlap region at the initial time when QGP formed. Therefore, \( \hat{q}_0 \) is the parameter controlling the strength of the bremsstrahlung jet-medium interaction. Meanwhile, the product of the four momentum of the jet and the four velocity of the medium along the jet propagation path in the collision frame are also included.

For the determination of the gluon radiation, we first determine whether the radiation happens or not, using the probability expressed as:

\[ P_{rad}(t, \Delta t) = 1 - e^{-N(t, \Delta t)} \]  (6)
If radiation occurs, the number of radiated gluon then would be sampled by a Possion distribution. Finally, the $x$ and $k_T$ could be sampled according to the radiative gluon spectrum in Eq.(4).

Note that each parton propagates in the expanding medium until the temperature of the local medium is under $T_c = 165$ MeV. The smooth IEBE-VISHNU hydro model \cite{1} has been used for the medium evolution. In our simulation, $q_0 = 1.2$ GeV$^2$/fm is directly taken from the $q_0$ extraction of the identified hadron suppression in Pb+Pb collisions at 2.76 TeV using the same evolved QGP medium description \cite{44}.

Employing the p+p events provided by NLO+PS event generator SHERPA as input, we study the medium modification of the $\bar{b}b$ dijets productions in Pb+Pb collisions at the LHC, using the above evolution framework which implements Langevin transport to describe heavy quark evolution and the higher twist approach to give the radiative energy loss of both heavy and light quark. In our treatment, jet reconstruction as well as the jet selection is performed through FASTJET \cite{44} on the final state partons which include produced partons, jet shower, radiated gluon after in-medium evolution. To test the framework and also to get an idea about its performance, we first calculated the nuclear modification factor with respect to the leading jet $p_T$ of both inclusive jets and b-jets at the LHC $\sqrt{s} = 2.76$ TeV to compare with the experimental data \cite{39, 65}. We find, within the spatial diffusion factor $D_s$ extracted from Lattice which satisfied $2\pi T D_s = 4.0$ and jet transport parameter extracted from hadron suppression study which is $q_0 = 1.2$ GeV$^2$/fm, our simultaneous simulation for both inclusive jet and b-jet $R_{AA}$ can describe the CMS data fairly well within the margin of error, only the simulation for b-jet $R_{AA}$ slightly overestimates the CMS data shown in Fig. 2. The establishment of such evolution framework provide a possible tool and baseline to implement different heavy quark evolution and jet quenching models. In the chosen parameters, our prediction indicate that, at lower $p_T$ region, the heavy quark observed to suffer less energy loss, but the mass effect of the jet quenching tend to disappear when it comes to the higher $p_T$ region where $R_{AA}$ of the b-jets coincide with the inclusive jets. It is noted that the nuclear modification factor of b-jets has been calculated in Ref. \cite{27, 28}.

The momentum balance of the $\bar{b}b$ dijets defined as the ratio of the subleading jet to leading jet $p_T$, $x_J = p_{T,2}/p_{T,1}$. We demonstrate the calculated results of the normalised distributions of $x_J$ in p+p and Pb+Pb collisions for $\bar{b}b$ dijets and their comparison with experimental data. The same as the selection of the CMS experiment, we set the minimum $p_T$ of the leading and the subleading jets to be 100 GeV and 40 GeV respectively. Further, the selection of $|\Delta \phi| > 2\pi/3$ has also been applied to require the jets are back-to-back in azimuthal opening angle both in p+p and A+A. A smearing treatment suggested by CMS has been performed to confront the experimental data shown in Fig. 3. Noted that the p+p reference in experiment is obtained from each jet $p_T$ data smeared by resolution parametrization at given centrality, we find our results are consistent with both p+p and Pb+Pb experimental measurement at 5.02 TeV. The energy loss effect will suppress the distribution at larger $x_J$ and enhance it at lower $x_J$, therefore lead to the lower shift of the overall $x_J$ distribution. We note that the shift of the A+A $x_J$ distribution relative to p+p reference is quite visible in central collisions shown in the left plots. Much smaller shift is observed at 10–30% Pb+Pb collision shown in the bottom panel of the Fig. 3 suggesting smaller energy loss suffered in collisions at larger centrality which is consistence with the case in dijets \cite{35}.

To further demonstrate the centrality dependence of the jet quenching effect on momentum balance of the $\bar{b}b$ dijets, we calculate the averaged $x_J$ values as a function of the number of participants estimated from Monte Carlo Glauber Model in Pb+Pb and the smeared p+p reference. The comparison of the calculation in systems with different centralities and the corresponding CMS data are shown in Fig. \cite{43} A good agreement between the theoretical calculation and experimental data is observed. We find the imbalance increases with the increasing centrality, even the averaged $x_J$ of the p+p reference shift to smaller value with the increasing centrality which is due to the resolution effects introduced by the experiment. More importantly, the averaged $x_J$ value shift due to the jet quenching effect is much visible in central collision, but the imbalance in larger centrality such as 30–100% Pb+Pb collision is compatible with their p+p reference which is unlike the case in dijets, indicating a smaller energy loss than inclusive dijets in smaller centrality system.

Since the three production mechanisms can be experi-
mentally separated by three event categories in azimuthal angle plane. It is essential to investigate the azimuthal angle distribution of the $b\bar{b}$ productions in p+p collisions and its modification in A+A collisions. we find its structure is quite sensitive to the jet event selection. When ATLAS define the dijet system as the minimum transverse momentum of the two highest-$p_T$ b-jets in an event should be $p_T > 20$ GeV and also $|\eta| < 2.5$ GeV, requiring their distance will be at least $\Delta R = 0.4$ and the $p_T$ of the trigger jet should be larger than 270 GeV [34], our simulation on the productions for $b\bar{b}$ dijet normalized by the number of events in p+p collision provided by SHERPA can describe the experimental data quite well (as seen in the right panel of Fig. 1). Especially at the near side peak ($\Delta \phi \to 0$) which dominated by the gluon splitting process. Similar as the case in inclusive dijets, the angular correlation of $b\bar{b}$ dijet would also be modified by the hot and dense medium. We present the prediction of the medium modification for angular correlation of $b\bar{b}$ dijets in Pb+Pb collision at $\sqrt{s} = 5.02$ TeV with centrality of $0 - 10\%$ using CMS configuration in the upper panel of Fig. 5 we find the near side peak disappear even in p+p collision comparing to the ATLAS measurement mentioned above, the energy loss effect will suppress the small $\Delta \phi$ distribution and enhance the distribution at large $\Delta \phi$. But if we implement the configuration of ATLAS in Pb+Pb collisions at 5.02 TeV, set the minimum transverse momentum of the two highest-$p_T$ b-jets in an event should be $p_T > 15$ GeV and the leading jet $p_T > 100$ GeV in the bottom panel of Fig. 5. We find the energy loss effect to the $b\bar{b}$ dijets production would suppress and broaden the near side (small $\Delta \phi$) peak, also enhance and sharp the away side (near $\Delta \phi = \pi$) peak. But however, an overall suppression is found, it means, in the small angle region, it suffers a stronger suppression relative to the large angle region.

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[1] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).

[2] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 123-191
FIG. 5: Upper: the productions for $b\bar{b}$ dijets normalized by the number of events as a function of $\Delta \phi$ in p+p and Pb+Pb collisions at 5.02 TeV using the CMS configuration [35] comparing with the p+p data. Bottom: the productions for $b\bar{b}$ dijets normalized by the number of events as a function of $\Delta \phi$ in Pb+Pb collisions at 5.02 TeV using a lower minimum cut on the b jet $p_T = 15$ GeV.

[3] G. Y. Qin and X. N. Wang, Int. J. Mod. Phys. E 24, no. 11, 1530014 (2015).
[4] I. Vitev, S. Wicks and B. W. Zhang, JHEP 0811, 093 (2008).
[5] I. Vitev and B. W. Zhang, Phys. Rev. Lett. 104, 132001 (2010).
[6] J. Casalderrey-Solana, J. G. Milhano and U. A. Wiedemann, JHEP 1303, 080 (2013).
[7] K. C. Zapp, F. Krauss and U. A. Wiedemann, JHEP 1303, 080 (2013).
[8] F. Senzel, O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G 42, no. 11, 115104 (2015).
[9] J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos and K. Rajagopal, JHEP 1410, 019 (2014); Erratum: [JHEP 1509, 175 (2015)].
[10] N. B. Chang and G. Y. Qin, Phys. Rev. C 94, no. 2, 024902 (2016).
[11] A. Majumder and J. Putschke, Phys. Rev. C 93, no. 5, 054909 (2016).
[12] L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, Phys. Lett. B 773, 672 (2017).
[13] Y. T. Chien and I. Vitev, Phys. Rev. Lett. 119, no. 11, 112301 (2017).
[14] L. Apolinario, J. G. Milhano, M. Ploskon and X. Zhang, arXiv:1710.07607 [hep-ph].
[15] M. Connors, C. Nattrass, R. Reed and S. Salur, arXiv:1705.01974 [nucl-ex].
[16] W. Dai, T. Vitev and B. W. Zhang, Phys. Rev. Lett. 110, no. 14, 142001 (2013) doi:10.1103/PhysRevLett.110.142001 [arXiv:1207.5177 [hep-ph]].
[17] X. N. Wang and Y. Zhu, Phys. Rev. Lett. 111, no. 6, 062301 (2013) doi:10.1103/PhysRevLett.111.062301 [arXiv:1302.5874 [hep-ph]].
[18] S. L. Zhang, T. Luo, X. N. Wang and B. W. Zhang, arXiv:1804.11041 [nucl-th].
[19] R. B. Neufeld, I. Vitev and B.-W. Zhang, Phys. Rev. C 83, 034902 (2011) doi:10.1103/PhysRevC.83.034902 [arXiv:1006.2389 [hep-ph]].
[20] G. Y. Qin and B. Muller, Phys. Rev. Lett. 106, 162302 (2011).
[21] C. Young, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C 84, 024907 (2011).
[22] Y. He, I. Vitev and B. W. Zhang, Phys. Lett. B 713, 224 (2012).
[23] C. E. Coleman-Smith and B. Muller, Phys. Rev. C 86, 054901 (2012).
[24] G. L. Ma, Phys. Rev. C 87, no. 6, 064901 (2013).
[25] J. G. Milhano and K. C. Zapp, Eur. Phys. J. C 76, no. 5, 288 (2016).
[26] L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang, arXiv:1612.04302 [hep-ph].
[27] J. Huang, Z. B. Kang, I. Vitev and H. Xing, Phys. Lett. B 750, 287 (2015) doi:10.1016/j.physletb.2015.09.029 [arXiv:1505.03517 [hep-ph]].
[28] J. Huang, Z. B. Kang and I. Vitev, Phys. Lett. B 726, 251 (2013) doi:10.1016/j.physletb.2013.08.009 [arXiv:1306.0909 [hep-ph]].
[29] E. Norrbin and T. Sjostrand, Eur. Phys. J. C 77, 224 (2018) doi:10.1103/PhysRevLett.111.062301 [arXiv:1802.00707 [hep-ph]].
[39] K. Jung [CMS Collaboration], Nucl. Phys. A 932 (2014) 253.
[40] S. Schumann and F. Krauss, JHEP 0803, 038 (2008) doi:10.1088/1126-6708/2008/03/038 [arXiv:0709.1027 [hep-ph]].
[41] M. Nahrgang, J. Aichelin, P. B. Gossiaux and K. Werner, Phys. Rev. C 90, no. 2, 024907 (2014) doi:10.1103/PhysRevC.90.024907 [arXiv:1305.3823 [hep-ph]].
[42] S. Frixione and B. R. Webber, JHEP 0206, 029 (2002) doi:10.1088/1126-6708/2002/06/029 [hep-ph/0204244].
[43] R. D. Ball et al. [NNPDF Collaboration], JHEP 1504, 040 (2015) doi:10.1007/JHEP04(2015)040 [arXiv:1410.8849 [hep-ph]].
[44] R. Rapp et al., arXiv:1803.03824 [nucl-th].
[45] F. Scardina, S. K. Das, V. Minissale, S. Plumari and V. Greco, Phys. Rev. C 96, no. 4, 044905 (2017) doi:10.1103/PhysRevC.96.044905 [arXiv:1707.05452 [nucl-th]].
[46] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, JHEP 1603, 123 (2016) doi:10.1007/JHEP03(2016)123 [arXiv:1512.05186 [hep-ph]].
[47] Z. B. Kang, F. Ringer and I. Vitev, JHEP 1703, 146 (2017) doi:10.1007/JHEP03(2017)146 [arXiv:1610.02043 [hep-ph]].
[48] M. He, R. J. Fries and R. Rapp, Phys. Rev. C 85, 044911 (2012) doi:10.1103/PhysRevC.85.044911 [arXiv:1112.5894 [nucl-th]].
[49] T. Lang, H. van Hees, J. Steinheimer, G. Inghirami and M. Bleicher, Phys. Rev. C 93, no. 1, 014901 (2016) doi:10.1103/PhysRevC.93.014901 [arXiv:1211.6912 [hep-ph]].
[50] R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C 80, 054902 (2009) doi:10.1103/PhysRevC.80.054902 [arXiv:0904.0032 [hep-ph]].
[51] K. Zhou, W. Dai, N. Xu and P. Zhuang, Nucl. Phys. A 956, 120 (2016) doi:10.1016/j.nuclphysa.2016.01.012 [arXiv:1601.00278 [hep-ph]].
[52] Kubo, Rep. Pro. Phys. 29 (1966) 255.
[53] B. W. Zhang, E. Wang and X. N. Wang, Phys. Rev. Lett. 93, 072301 (2004) doi:10.1103/PhysRevLett.93.072301 [nucl-th/0309040].
[54] D. W. Zhang, E. K. Wang and X. N. Wang, Nucl. Phys. A 757 (2005) 493 [hep-ph/0412060].
[55] A. Majumder, Phys. Rev. D 85 (2012) 014023 [arXiv:0912.2987 [nucl-th]].
[56] W. t. Deng and X. N. Wang, Phys. Rev. C 81 (2010) 024902 [arXiv:0910.3403 [hep-ph]].
[57] C. Shen, Z. Qin, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput. Phys. Commun. 199 (2016) 61 [arXiv:1409.8164 [nucl-th]].
[58] W. Dai, G. Y. Ma, B. W. Zhang and E. Wang, In preparation (2018).
[59] V. Khachatryan et al. [CMS Collaboration], Phys. Rev. C 96 (2017) no.1, 015202 [arXiv:1609.05383 [nucl-ex]].