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

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Outline

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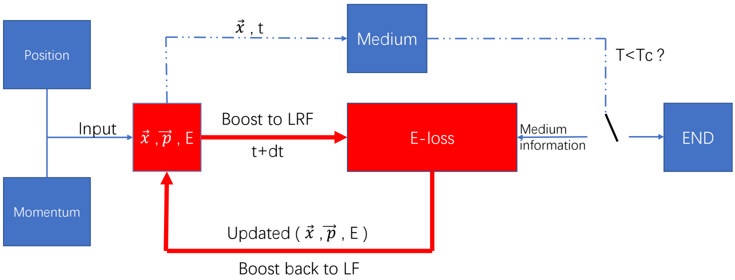
2. Energy Loss Mechanism
   - Treatment for Heavy Quark
   - Treatment for Light Partons
3. Results
   - R_{AA} of Inclusive Jet and Inclusive b-jet
   - x_J of Inclusive Dijet and $b\bar{b}$ Dijet
   - Angular Correlations of $b\bar{b}$ Dijet
4. Summary

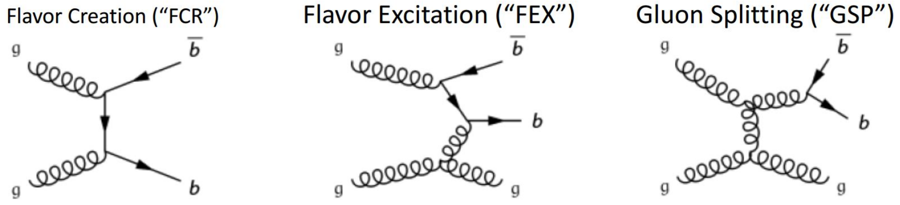
Motivation

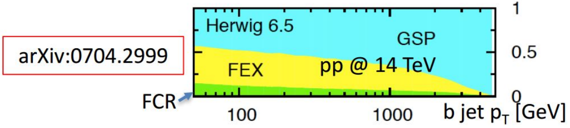
- Heavy flavours are effective and pure probes of the properties of the high energy-density Quark-Gluon Plasma(QGP) formed in the ultrarelativistic nucleus-nucleus collisions.
- The production suppression of heavy mesons in AA collision has been phenomenologycally described by various models.
- The detailed mechanisms of heavy flavoured jets propagation and energy loss in dense QCD matter are not yet fully investigated.
- Recently, the transverse momentum balance and azimuthal angle correlations of $b\bar{b}$ dijet have been measured by the CMS and ATLAS collaborations at the LHC.

The Flow Diagram of Simulation



Bottom Production



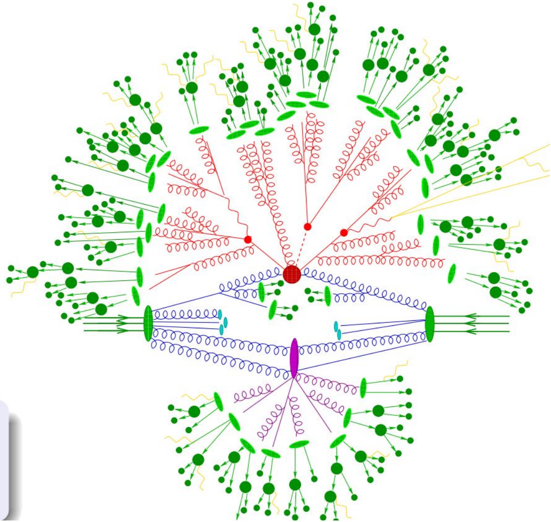


- Herwig(NLO) predicts large contributions from all three production mechanisms in the measured p_T range.

MC@NLO pp Event Generator-SHERPA

- Initial state parton shower (QCD)
- Underlying event
- Signal process
- Final state parton shower (QCD)
- Fragmentation
- Hadron decays
- QED radiation

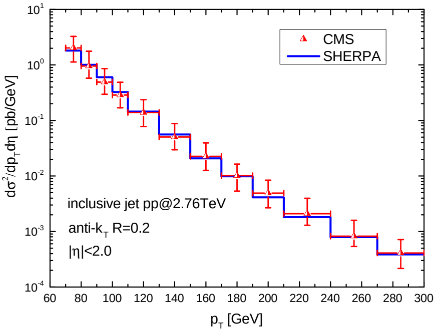
SHERPA is the framework steering these event phases.



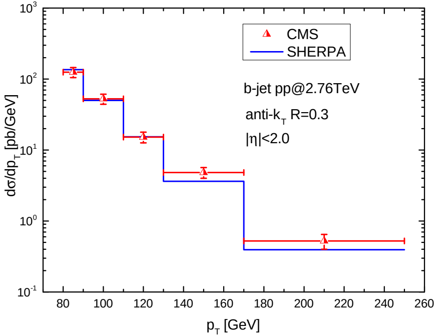
Events Generation and Selection

- The tree-level matrix elements of the cross section are calculated by Amegic[arXiv:0109036 [hep-ph]] and Comix[arXiv:0808.3674 [hep-ph]].
- The one-loop virtual corrections are calculated by BlackHat [Nucl.Phys.Proc.Suppl. 183 (2008) 313-319].
- NNPDF3.0 NNLO PDF[arXiv:1410.8849 [hep-ph]] is used in the calculation.
- Fastjet-3.3.0[Eur.Phys.J.C 72 (2012) 1896] is used for the jet reconstruction at parton level, no hadronization.
- The smooth iEBE-VISHNU hydro[Comput.Phys.Commun.199(2016) 61] has been used for the medium evolution.

The pp Baseline for Jet Production



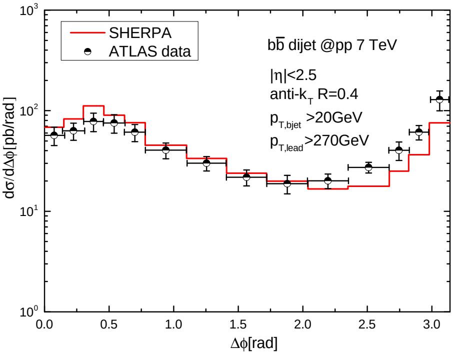
(a) inclusive jet



(b) b-jet

- Sherpa could provide a good description of the production of not only inclusive jet but also b-jet in pp collisions[Phys.Rev.C 96 (2017) no.1, 015202; Phys.Rev.Lett. 113 (2014) no.13, 132301].

The pp Baseline for Angular Correlation



- Sherpa could also well describe the azimuthal angle correlation of $b\bar{b}$ dijet by comparing with ATLAS data[Eur. Phys. J. C 76 (2016) no.12, 670].

Collisional Energy Loss: Langevin Equation

- The discrete Langevin equation is used for description of heavy quark propagation in Quark-Gluon Plasma. [Eur. Phys. J. C 71, 1666 (2011); Physical Review C, 2009, 79(5): 054907.]:

$$\overrightarrow{x}(t+\Delta t)=\overrightarrow{x}(t)+\frac{\overrightarrow{p}(t)}{E}\Delta t \quad (1)$$

$$\overrightarrow{p}(t+\Delta t)=\overrightarrow{p}(t)-\Gamma(p)\overrightarrow{p}\Delta t+\overrightarrow{\xi}(t)\Delta t \quad (2)$$

the time step $\Delta t = 0.1\text{fm}$ in our simulation, the stochastic term $\overrightarrow{\xi}(t)$ obeys a Gaussian white noise distribution:

$$W[\overrightarrow{\xi}(t)] = N\exp[\frac{\overrightarrow{\xi}(t)^2}{2\kappa}] \quad (3)$$

$$\langle \xi_i(t) \rangle = 0 \quad (4)$$

$$\langle \xi_i(t)\xi_j(t`) \rangle = \kappa\delta_{ij}(t-t`) \quad (5)$$

- The relationship between drag coefficient Γ and the stochastic term $\overrightarrow{\xi}(t)$ are determined by Fluctuation-Dissipation Theorem (Einstein Relation):[Kubo R. Reports on progress in physics, 1966, 29(1): 255.]

$$\Gamma = \frac{\kappa}{2ET} \tag{6}$$

where

$$\kappa = \frac{2T^2}{D_s} \tag{7}$$

- The spacial diffusion coefficient D_s is fixed by Lattice calculation as $2\pi TD_s = 3.7 \sim 7.0$ [Phys.Rev.D 92 no.11,(2015) 116003,arXiv:1508.04543 [hep-lat]]

Radiative Energy Loss: Higher-Twist Scheme

- The Higher-Twist calculation for the medium-induced radiative gluon spectra [X.-F. Guo and X.-N. Wang, Phys. Rev. Lett. 85, 3591(2000);B.-W. Zhang, E. Wang, and X.-N. Wang, Phys. Rev.Lett. 93, 072301 (2004);A. Majumder, Phys. Rev. D85, 014023 (2012).]

$$\frac{dN_g}{dxdk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)\hat{q}}{\pi k_\perp^4} \sin^2(\frac{t-t_i}{2\tau_f})(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2})^4 \tag{8}$$

where x is the gluon energy fraction to heavy quark energy, $k_\perp$ is the transverse momentum of gluon related to heavy quark ,M is mass of heavy quark($M_c = 1.5\ GeV, M_b = 4.75\ GeV$), $\alpha_s = 0.3$.

- where $P(x)$ is splitting function[W.-T. Deng and X.-N. Wang, Phys. Rev. C81, 024902 (2010).],

$$P_{Q\to Qg}(x) = \frac{(1+(1-x)^2)(1-x)}{x} \tag{9}$$

- $\hat{q}$ is QGP transport coefficient[X.F.Chen, C.Greiner, E.Wang, X.N.Wang and Z.Xu,Phys.Rev.C 81(2010)064908]:

$$\hat{q}(\tau, r) = q_0 \frac{\rho^{QGP}(\tau, r)}{\rho^{QGP}(\tau_0, 0)} \frac{p^\mu u_\mu}{p^0} \tag{10}$$

- τ_f is gluon formation time :

$$\tau_f = \frac{2Ex(1-x)}{k_\perp^2 + x^2 M^2} \tag{11}$$

- $t - t_i$ is the interval between t to last radiation time t_i.

Higher-Twist for Light Partons

- The Higher-Twist calculation for massless parton:

$$\frac{dN_g}{dxdk_\perp^2 dt} = \frac{2\alpha_s C_i P_i(x)\hat{q}}{\pi k_\perp^4} \sin^2(\frac{t-t_i}{2\tau_f}) \tag{12}$$

- The splitting function for quark and gluon[W.-T. Deng and X.-N. Wang, Phys. Rev. C81, 024902 (2010).]:

$$P_{q\to qg}(x) = \frac{(1+(1-x)^2)(1-x)}{x} \tag{13}$$

$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)} \tag{14}$$

- Low cut-off of gluon energy: $\omega_0 = xE = m_D = gT\sqrt{1+n_f/6}$

Gluon Sampling Method

- The average number of radiative gluon during a time step[Phys.Rev. C94 (2016) no.1, 014909]:

$$\langle N_g(t,\Delta t)\rangle = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt} \quad (15)$$

- Assuming that the number of radiative gluon n obeys the Possion distribution $P(n) = \frac{\langle N_g\rangle^n}{n!} e^{-\langle N_g\rangle}$, the total probability for radiation during a time step Δt:

$$P_{rad}(t,\Delta t) = 1 - e^{-\langle N_g\rangle} \quad (16)$$

- Then it's available to sample the energy xE and transverse momentum $k_\perp$ of the radiative gluons during every time step for arbitrary state (E, T, t) .
- The interval $t - t_i$ would be reset when a radiation occurred .

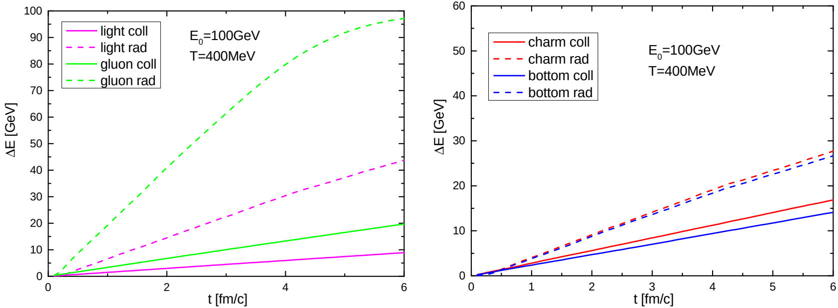
HTL Collisional Energy Loss

Hard Thermal Loop calculation is considered as collisional energy loss of light partons.[J.D. Bjorken, Fermilab preprint PUB-82/59-THY; Markus H.Thoma Physics Letters B 273 (1991)128-132; R.B.Neufeld PRD 83(2011)065012]

$$\frac{dE}{dt} = \frac{\alpha_s C_i m_D^2}{2} ln \frac{\sqrt{ET}}{m_D} \tag{17}$$

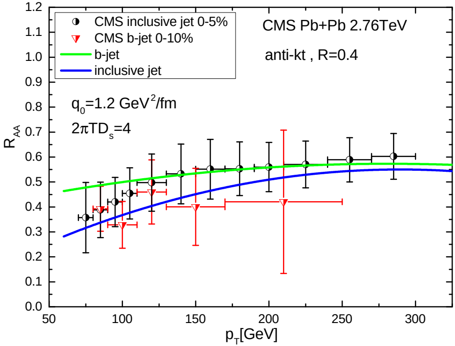
- The Debye screening mass: $m_D^2 = 4\pi\alpha_s T^2(1 + \frac{n_f}{6})$
- The color factor: $C_g = N_c,\ C_q = \frac{N_c^2-1}{2N_c}$

Parton Energy Loss



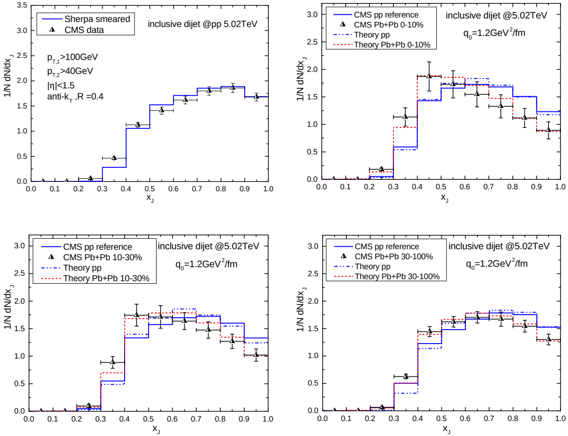
- Radiative energy loss: $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$.
- Collisional energy loss is comparable to radiative energy loss for heavy quarks.

R_{AA} for Inclusive Jet and Inclusive b-jet



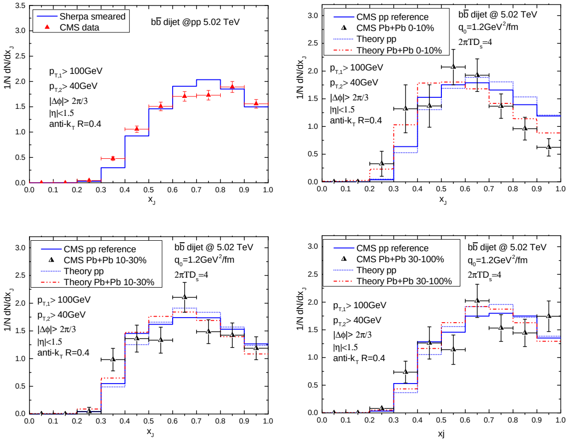
- Establish a framework to describe heavy quark evolution and jet quenching simultaneously[Phys. Rev.C 96 (2017) no.1, 015202; Nucl.Phys.A 932 (2014) 253; arXiv:1806.06332].
- At lower p_T region, the heavy quark suffers less energy loss.
- The mass effect of the jet quenching tends to disappear at higher p_T.

Transverse Momentum Balance of Inclusive Dijet



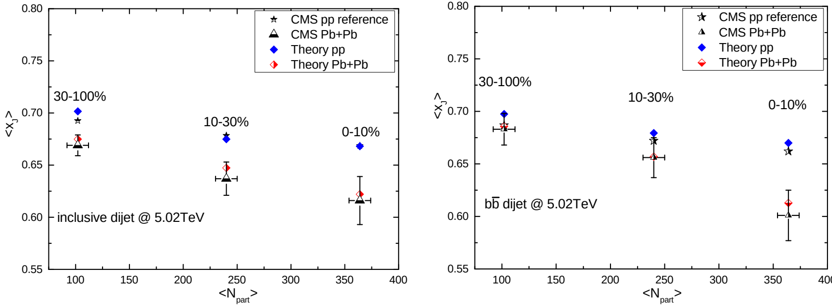
- The x_J shifted to smaller x_J with centrality dependence, the enhancement at the smaller x_J and suppression at larger x_J are observed, where $x_J = \frac{p_{T,2}}{p_{T,1}}$ [JHEP 1803 (2018) 181; arXiv:1806.06332].

Transverse Momentum Balance of $b\bar{b}$ Dijet



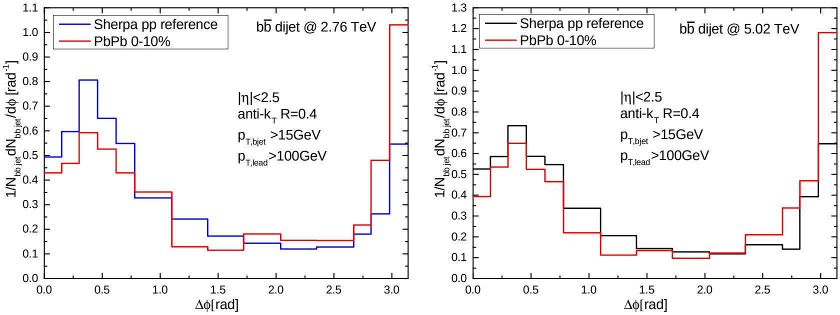
- Similar behaves are observed in transverse momentum balance of $b\bar{b}$ dijet, where $x_J = \frac{p_{T,b2}}{p_{T,b1}}$ [JHEP 1803 (2018) 181; arXiv:1806.06332].
- Large error bar exits in the experimental data.

$\langle x_J \rangle$ for inclusive dijet and $b\bar{b}$ dijet



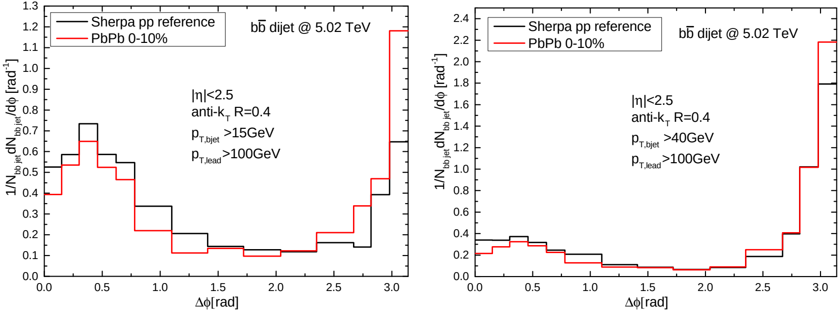
- The imbalance increases with the increasing centrality for inclusive dijet and $b\bar{b}$ dijet.
- The averaged x_J value shift due to the jet quenching effect is much visible in central collision.

The Predictions for Angular Correlations of $b\bar{b}$ Dijet in Pb+Pb Collision



- The two peaks in azimuthal angle distribution are from GSP and FCR.
- The angular correlation of $b\bar{b}$ dijet would be modified by the hot and dense medium.
- The peak on near side suffered more suppression than on away side.

The Predictions for Angular Correlations of $b\bar{b}$ Dijet in Pb+Pb Collision



- The peak on near side disappears when a higher cut $p_{T,bjet} > 40$ GeV used for jet reconstruction.
- Suppression on near side is still observed even with low p_T cut.

Summary

- The MC 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 2.76 TeV with the experimental data.
- We also 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.
- 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.

Backup 1

- The initial space information of partons is produced by Glauber binary distribution.The Woods-Saxon form of the nucleon density: [arXiv:nucl-ex/0701025;ATOMIC DATA AND NUCLEAR DATA TABLES 36,495536 (1987)].

$$\rho(r) = \rho_0 \cdot \frac{1 + \omega(r/R_0)^2}{1 + \exp[\frac{r - R_0}{a}]} \tag{1}$$

And the probability density is available based on:

$$f(\overrightarrow{s}) = N \cdot \hat{T}_A(\overrightarrow{s} + \frac{\overrightarrow{b}}{2})\hat{T}_B(\overrightarrow{s} - \frac{\overrightarrow{b}}{2}) \tag{2}$$

where the thickness function:

$$\hat{T}(\overrightarrow{s}) = \int \rho(\overrightarrow{r})dz \tag{3}$$

Backup 2

The jet p_T resolution is parametrized according the following form[arXiv:1607.03663]:

$$\sigma(p_T)/p_T = \sqrt{C^2 + \frac{S^2}{p_T} + \frac{N^2}{{p_T}^2}} \quad (4)$$

- In pp collisions, the constant C and stochastic S terms are 0.06 and 0.8 GeV^{-1}
- In Pb+Pb collisions the S term is slightly larger value of 1.0 GeV^{-1}, due to the underlying event.
- The noise parameter (N) depends on collision centrality, according to $N = 14.82 - centrality(\%)/5.40(GeV^2)$ subtraction.