

HARD PROBES 2018

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

Sa Wang

In Collaboration with W. Dai, S.L Zhang, B.-W Zhang, Enke Wang

[arXiv:1806.06332]

10/2/2018

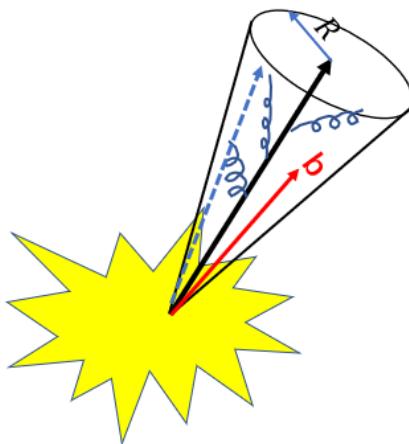
Key Laboratory of Quark & Lepton Physics (MOE) and Institute of Particle Physics
Central China Normal University



Outline

- Introduction
- pp baseline and setup of simulation
- Implementation of parton energy loss
- Results
 - ✓ Transverse momentum balance of $b\bar{b}$ dijet
 - ✓ Angular correlation of $b\bar{b}$ dijet
- Summary

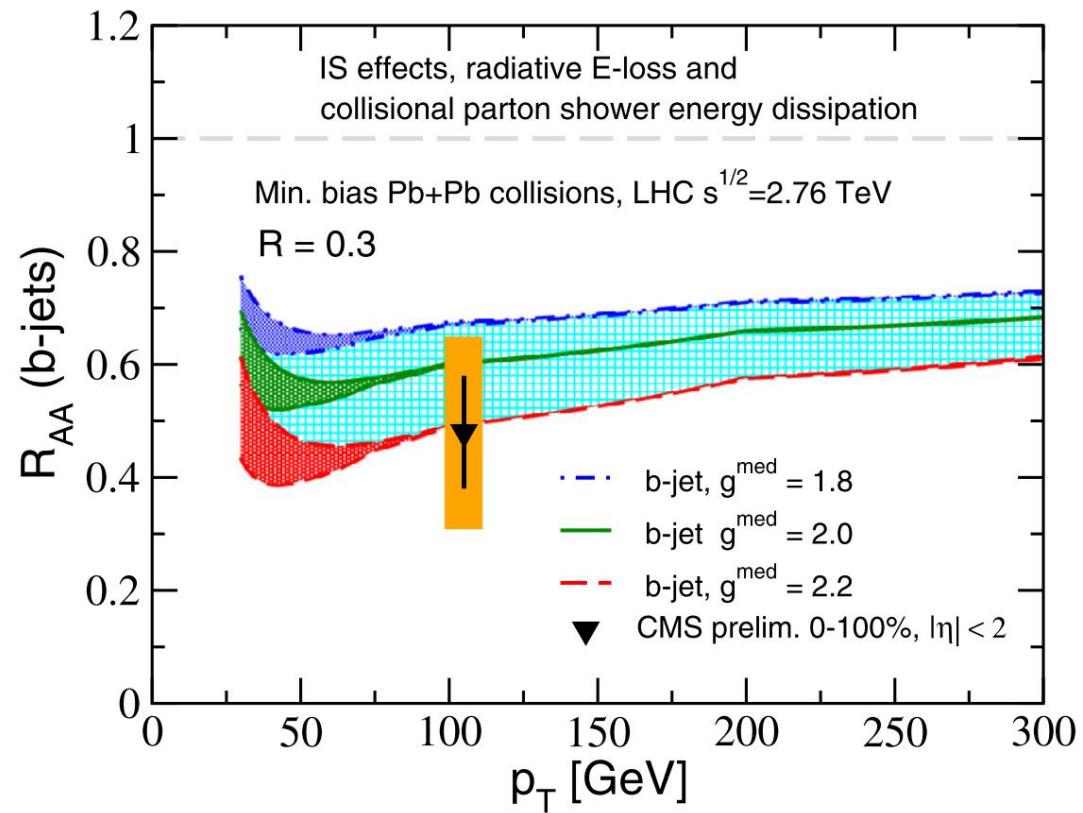
Inclusive b-jet



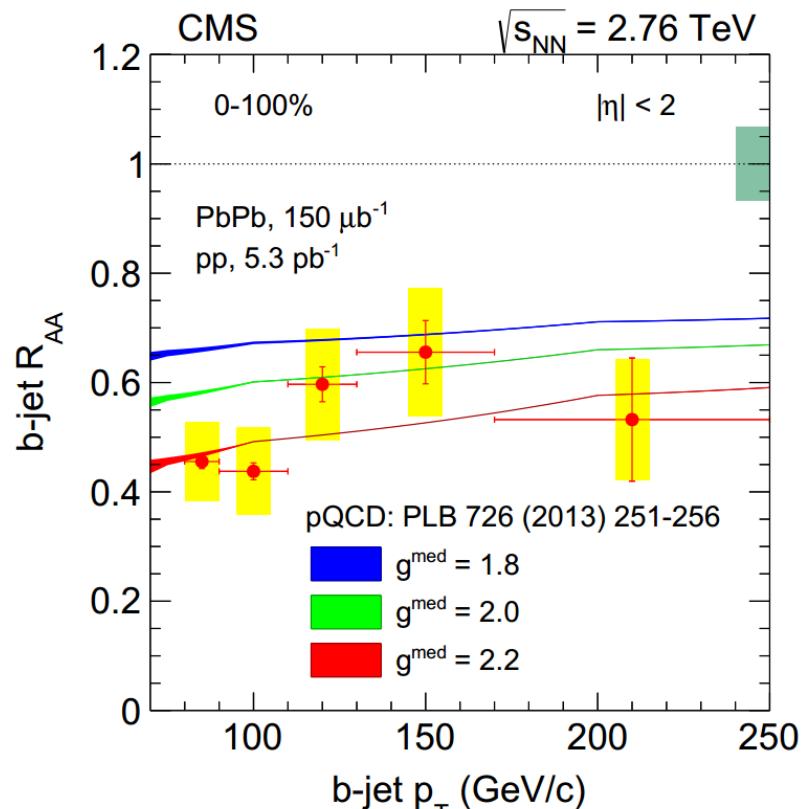
b jet---at least one b or \bar{b} quark inside the jet cone with the jet radius parameter R .

$$R_{AA}^{\text{b-jet}}(p_T; R) = \frac{\frac{d^2\sigma^{AA}(p_T; R)}{dy dp_T}}{\langle N_{\text{bin}} \rangle \frac{d^2\sigma^{pp}(p_T; R)}{dy dp_T}}$$

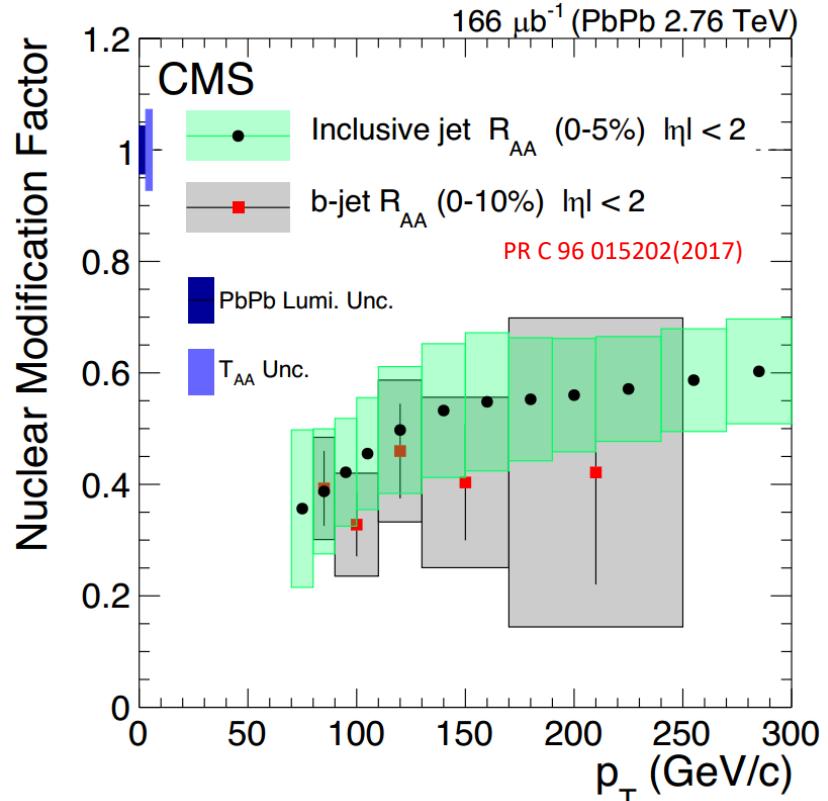
Jinrui Huang, Zhong-Bo Kang
, Ivan Vitev [PLB 726\(2013\)251-256](#)



Inclusive b-jet R_{AA}

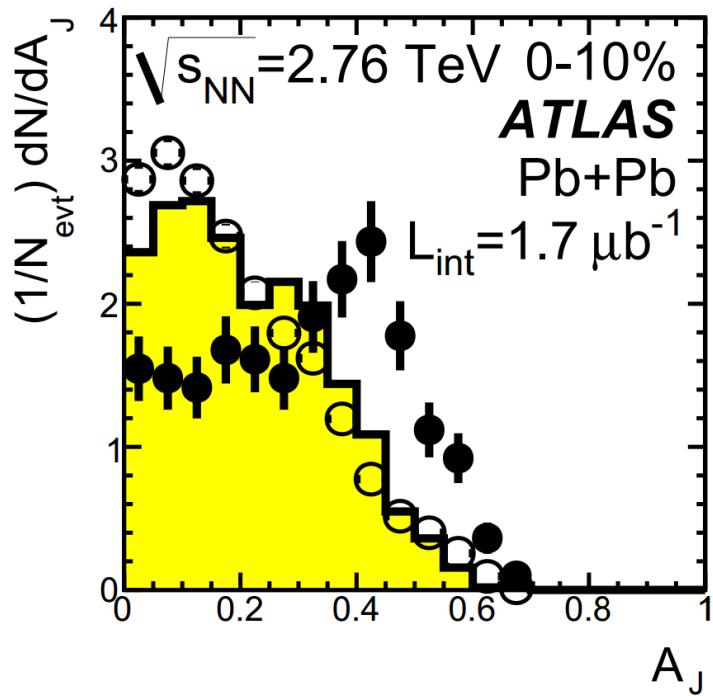


CMS collaboration, PRL 113(2014)132301



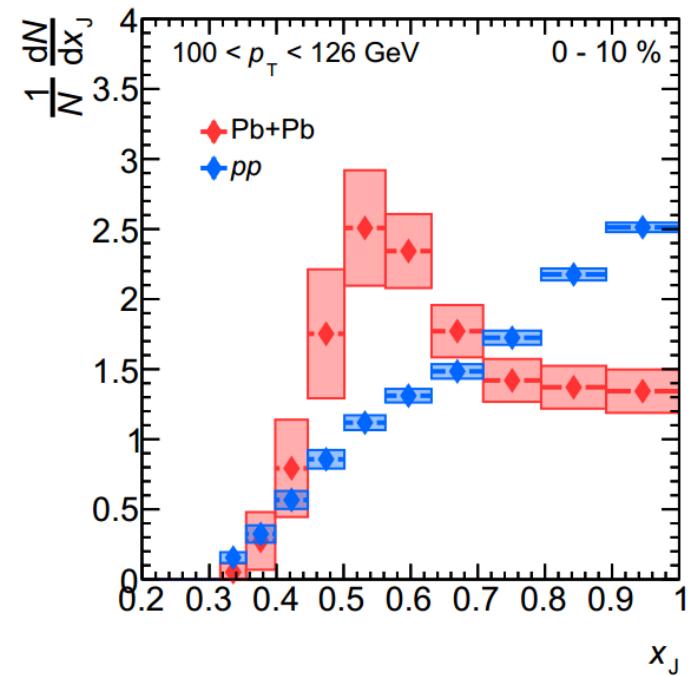
Kurt Jung, talk on QM2017

Dijet asymmetry



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

ATLAS Collaboration
Phys. Rev. Lett. 105 (2010) 252303

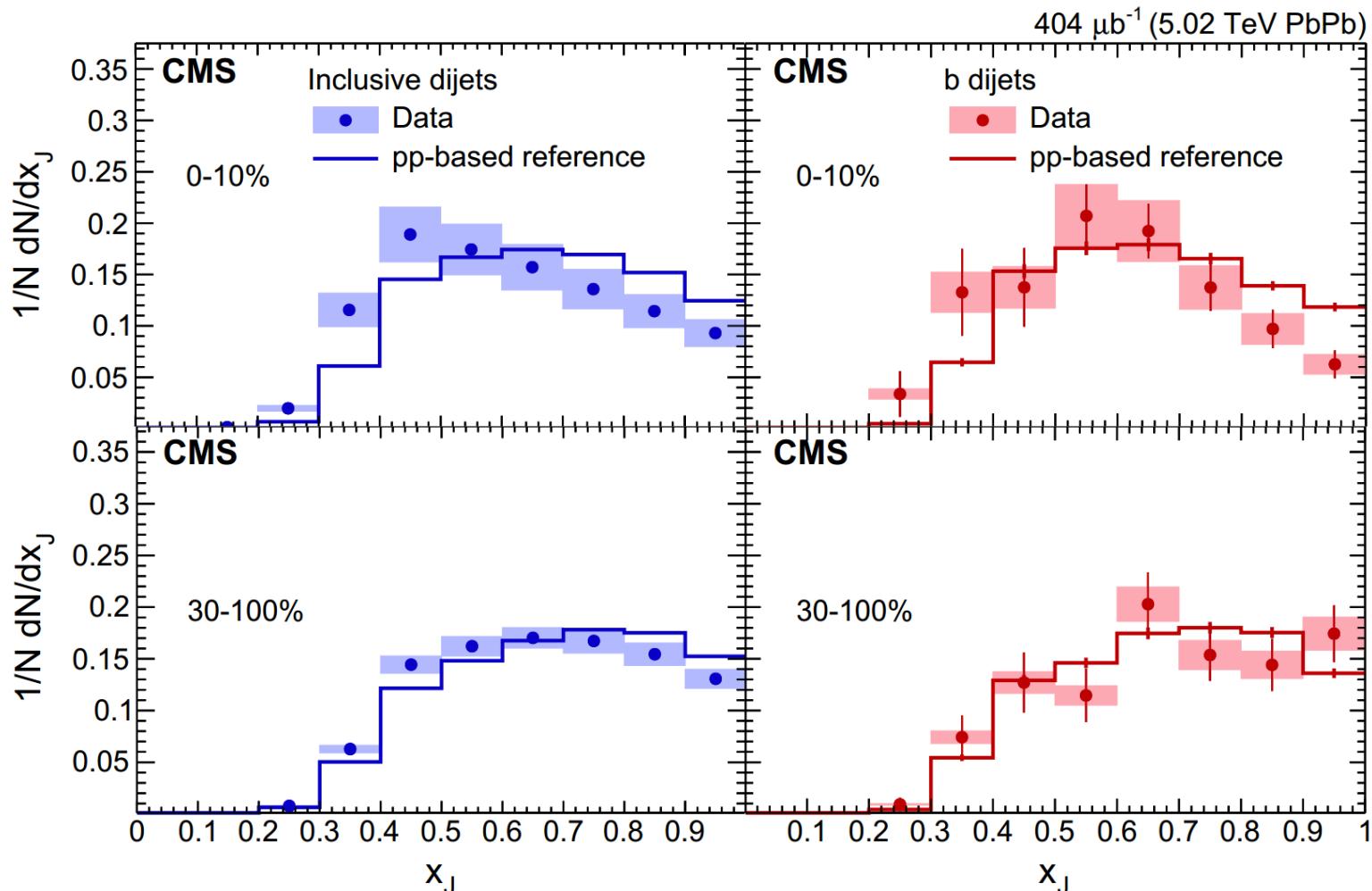


$$x_J = \frac{p_{T2}}{p_{T1}}, \Delta\phi > \frac{7\pi}{8}$$

ATLAS Collaboration
Phys. Lett. B774 (2017) 379

Are there flavor dependences of dijet observable ?

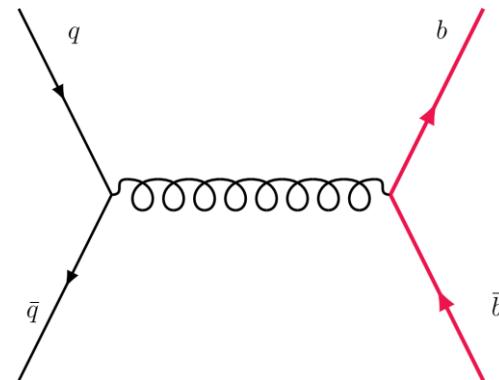
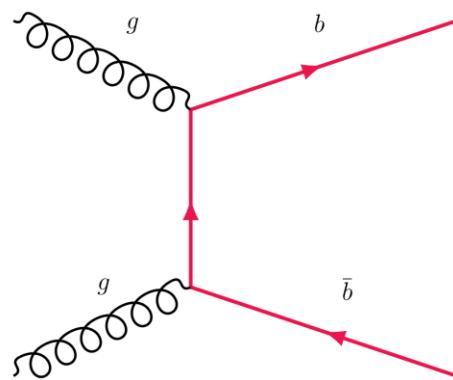
$b\bar{b}$ dijet asymmetry



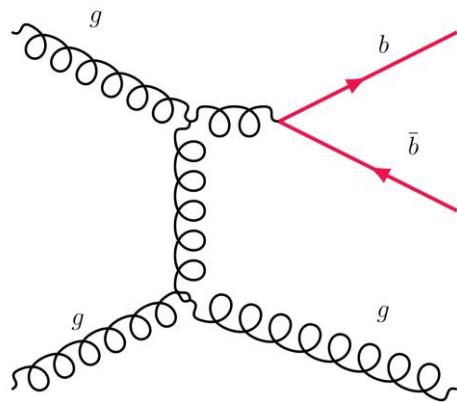
$$x_J = \frac{p_{T2}}{p_{T1}}, \Delta\phi > \frac{2\pi}{3}$$

CMS Collaboration JHEP 03(2018)181

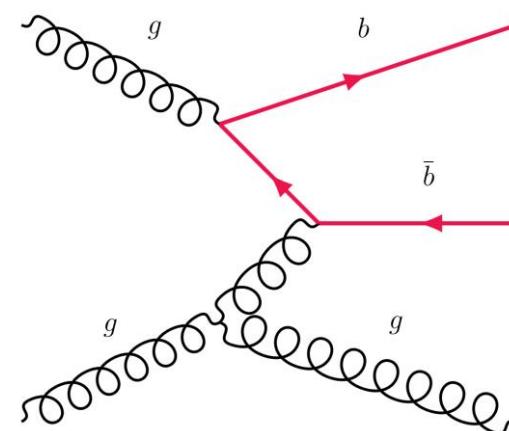
Bottom Production



Flavor Creation (FCR)

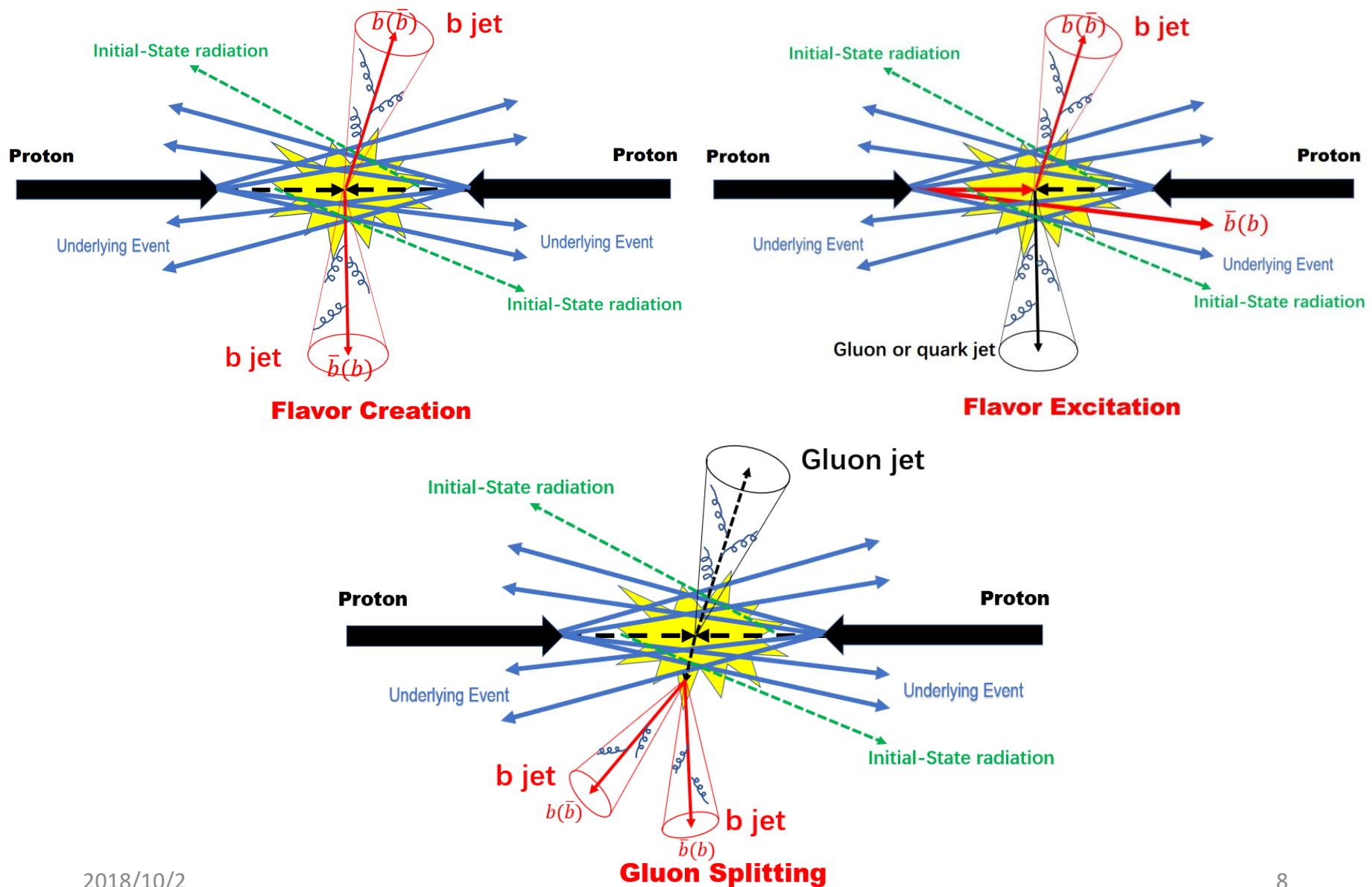


Gluon Splitting(GSP)



Flavor Excitation(FEX)

b-jet Production

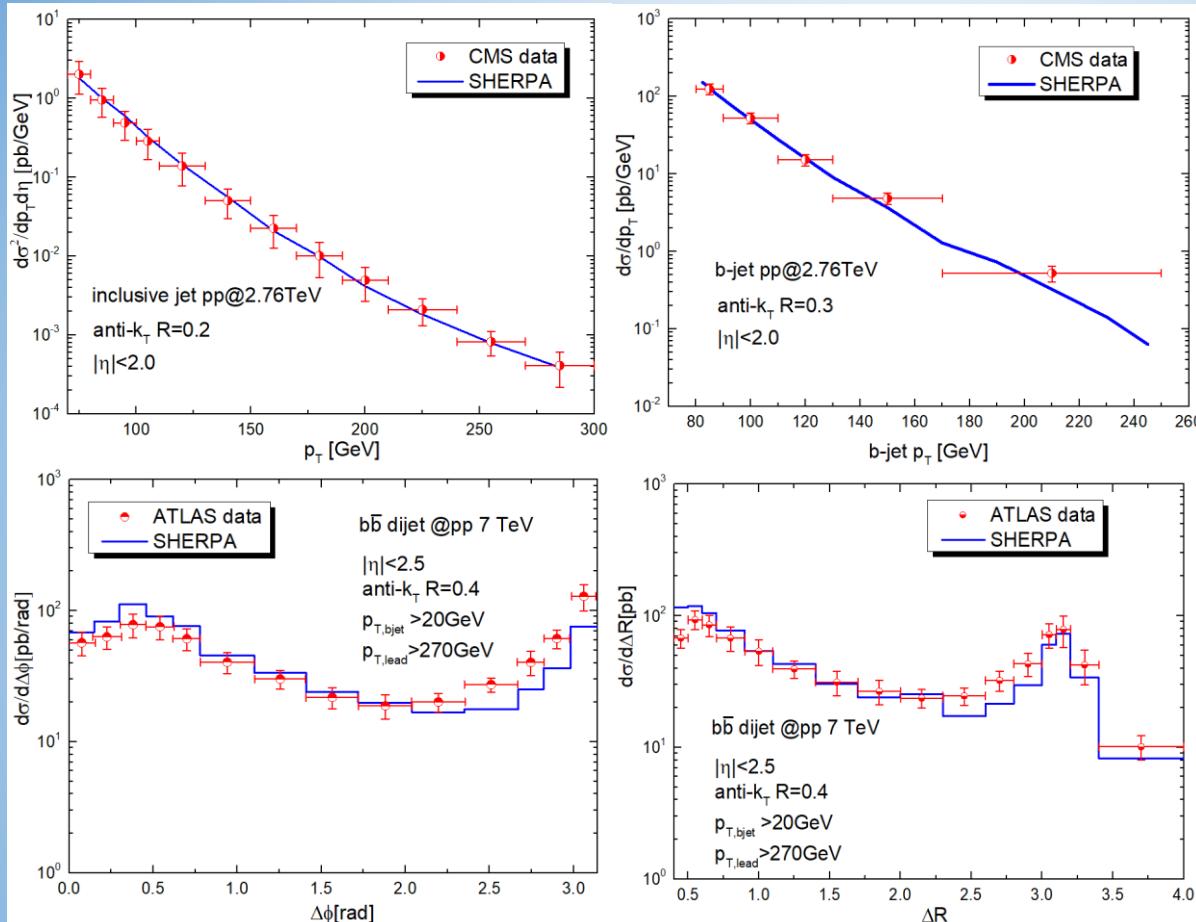


Event generation

Monte Carlo event generator: **Sherpa**

- The tree-level matrix elements---**Amegic** and **Comix**.
- The one-loop virtual corrections ---**BlackHat**.
- Parton Shower---**Catani-Seymour subtraction method** .
- Matching of NLO+PS: **MC@NLO**.
- **NNPDF3.0** NLO-5FS PDF .
- **Fastjet** ---jet reconstruction at parton level.

p+p baseline produced by SHERPA



Azimuthal angle difference between two b jets:

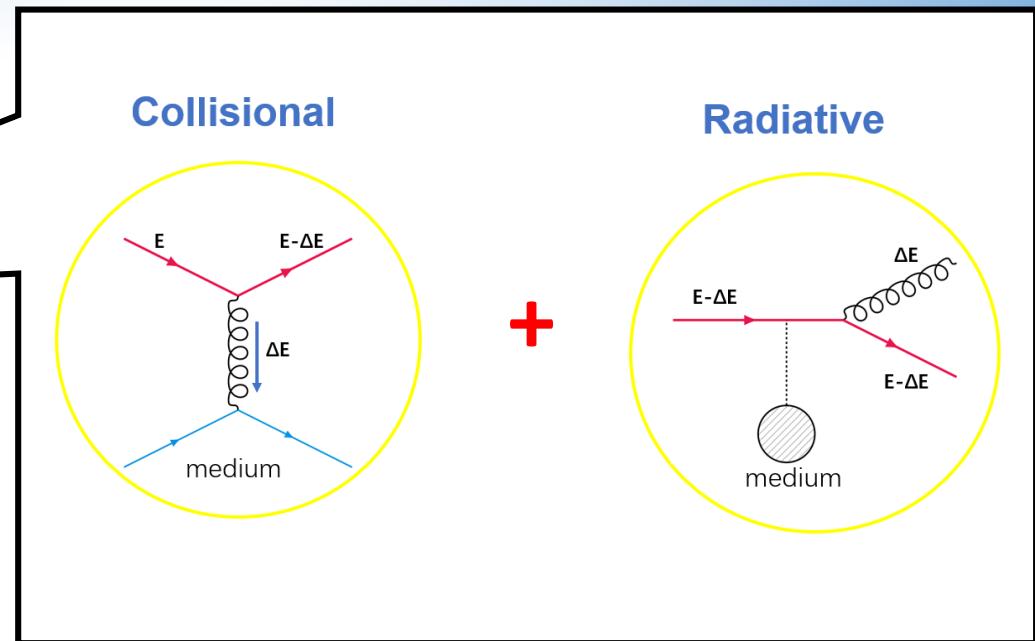
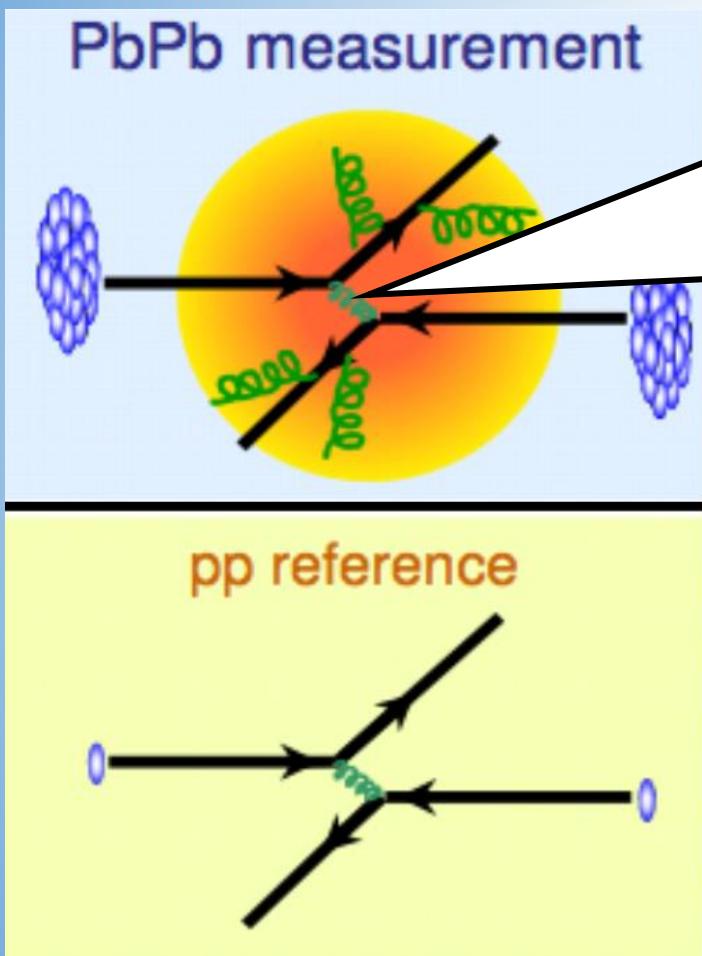
$$\Delta\phi = |\phi_{b1} - \phi_{b2}|$$

Angular distance:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

SHERPA could provide a good pp baseline for not only jet production but also angular distribution by comparing with CMS and ATLAS data [CMS ,PRC 96 015202(2017); CMS,PRL 113(2014)132301; ATLAS, Eur. Phys. J. C 76, no. 12, 670 (2016)]

In-Medium Energy Loss



In-Medium E-loss: Radiative

- The medium-induced radiative energy loss of final-state partons is described by the Higher-Twist scheme [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).]

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

- \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]:

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

In-Medium E-loss: Collisional

- For heavy quark, the discrete Langevin transport equations are used to describe the propagating of heavy quarks in the QGP. [[Eur. Phys. J. C 71, 1666 \(2011\); Physical Review C, 2009, 79\(5\): 054907.](#)]:

$$\begin{aligned}\vec{x}(t + \Delta t) &= \vec{x}(t) + \frac{\vec{p}(t)}{E} \Delta t \\ \vec{p}(t + \Delta t) &= \vec{p}(t) - \Gamma(p) \vec{p} \Delta t + \vec{\xi}(t) \Delta t\end{aligned}$$

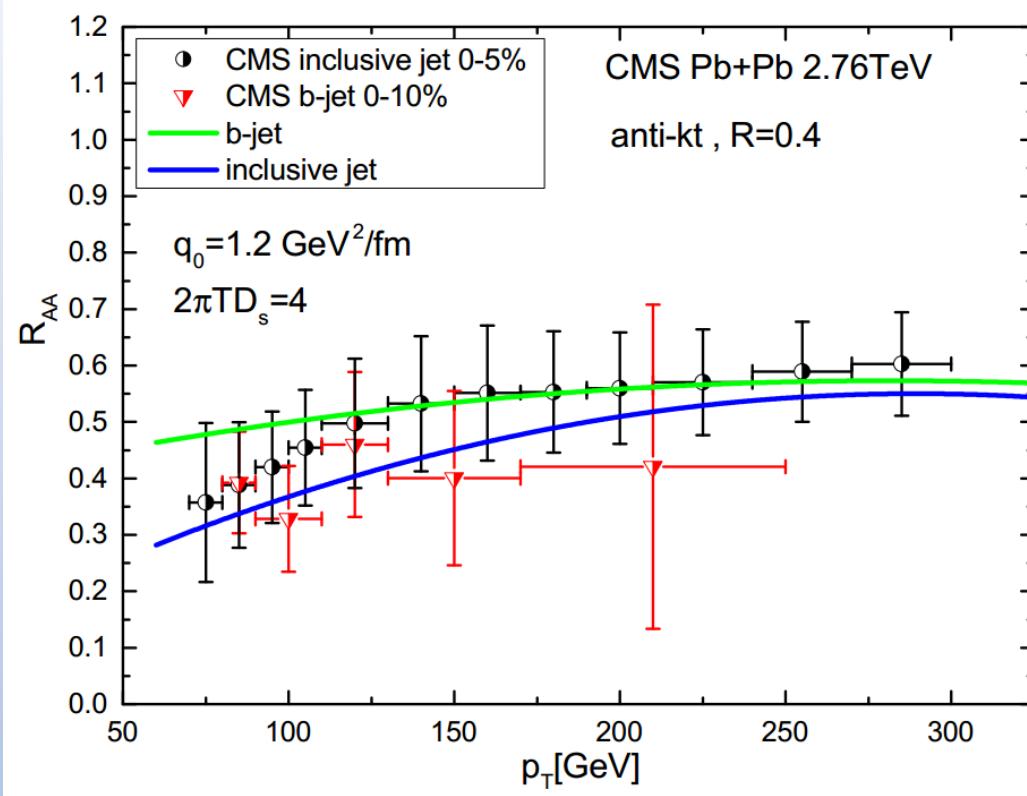
The Fluctuation-Dissipation Theorem: $\kappa = 2ET\Gamma = \frac{2T^2}{D_s}$. Based on the Lattice calculation [[arXiv:1508.04543 \[hep-lat\]](#)], D_s is fixed as $2\pi TD_s = 4$.

- For light partons, the collisional energy loss is described by Hard Thermal Loop calculation. [[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](#)]

$$\frac{dE}{dz} = \frac{\alpha_s C_i m_D^2}{2} \ln \frac{\sqrt{ET}}{m_D}$$

- The smooth iEBE-VISHNU hydro [[Comput.Phys.Commun.199\(2016\) 61](#)] has been used for the medium evolution.

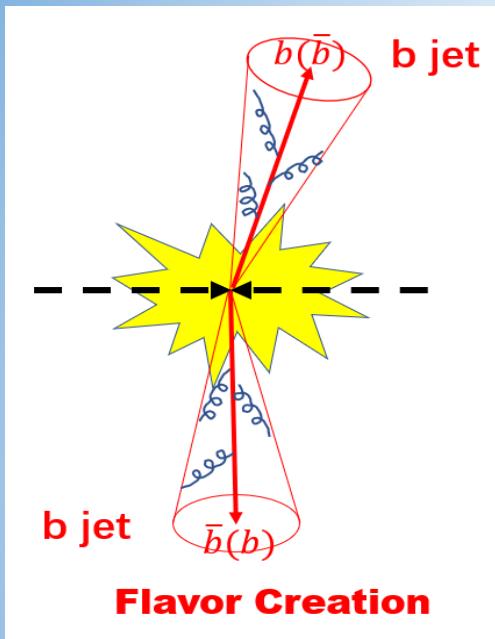
R_{AA} for inclusive jet and b jet



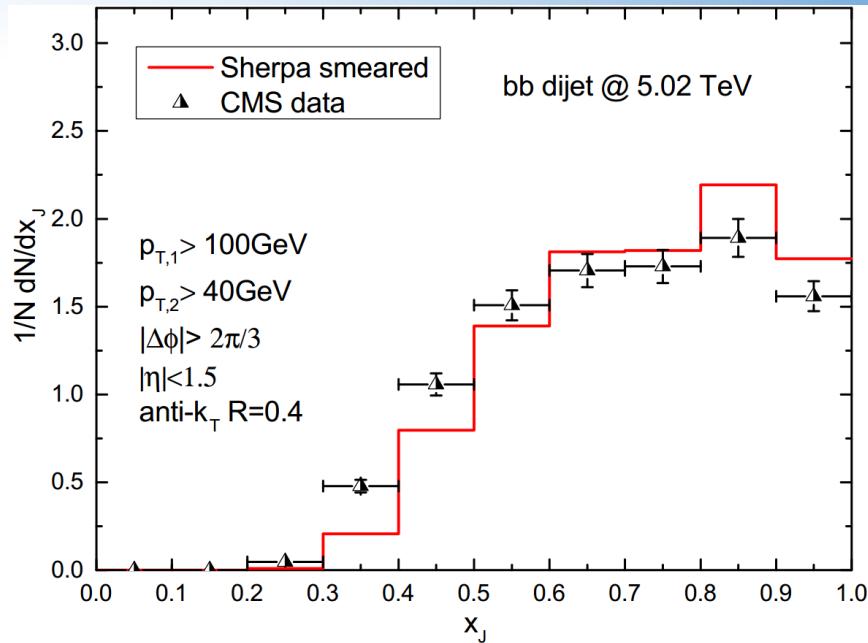
arXiv:1806.06332

- Our simulation can fairly describe the CMS data though b-jet R_{AA} slightly overestimates at low p_T region .
- The mass effect of the jet quenching trends to disappear.

Transverse momentum balance- x_J



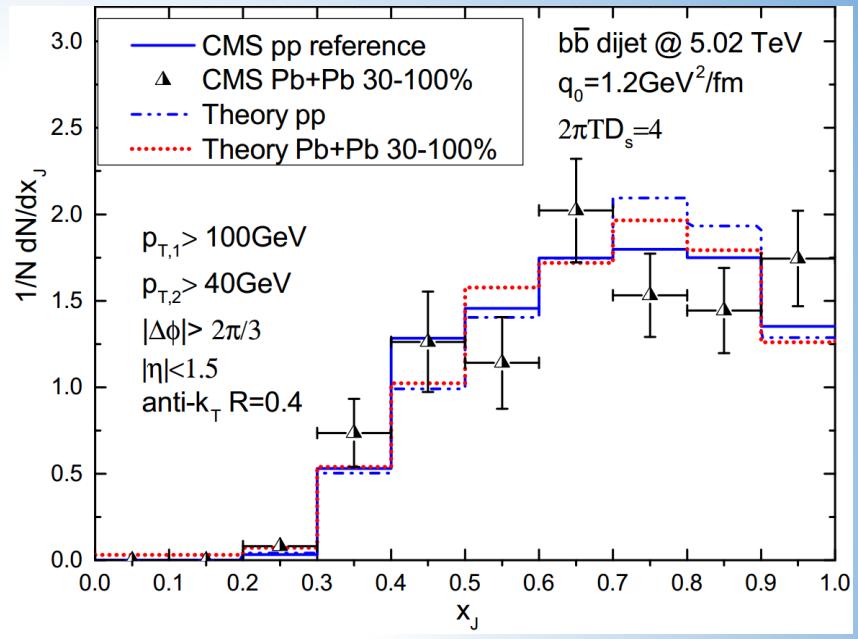
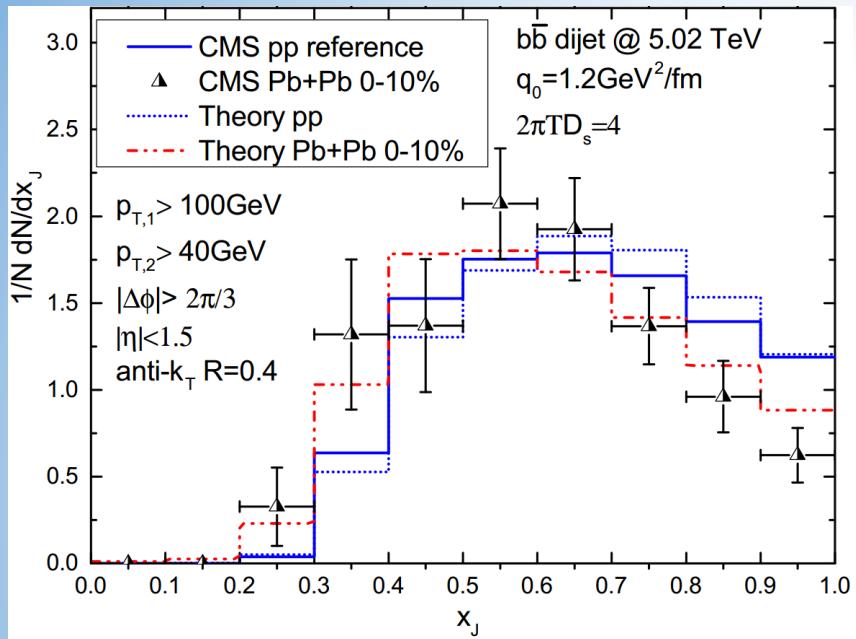
$$x_J = \frac{p_{T,2}}{p_{T,1}}$$



arXiv:1806.06332

- $|\eta| < 1.5, R = 0.4$
- Leading jet $p_T > 100\text{GeV}$
- Subleading jet $p_T > 40\text{GeV}$
- Leading and subleading jets must be b-tagged.
- $|\Phi_1 - \Phi_2| > \frac{2\pi}{3}$ suppresses the gluon splitting process, the two b jets are back-to-back.

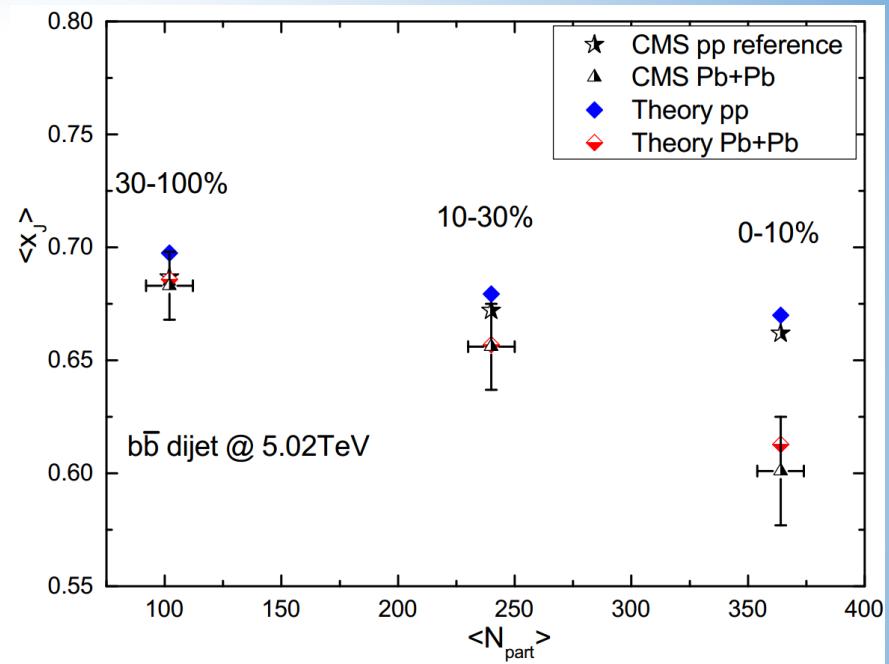
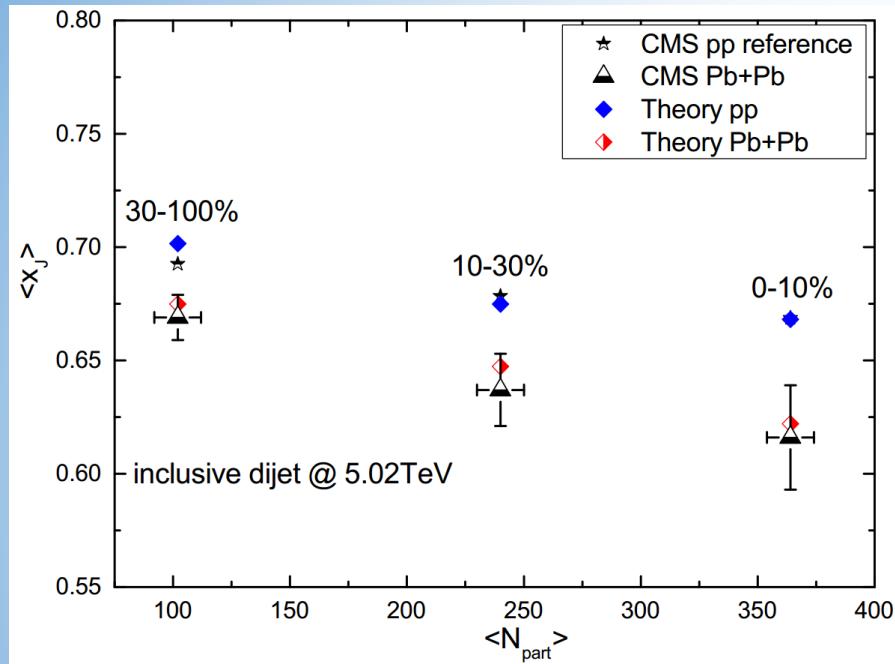
x_J for $b\bar{b}$ dijet



arXiv:1806.06332

- A quiet visible shift of x_J towards smaller value is observed in central Pb+Pb collision, relative to pp reference .
- Much smaller shift is observed peripheral Pb+Pb collision since smaller energy loss.

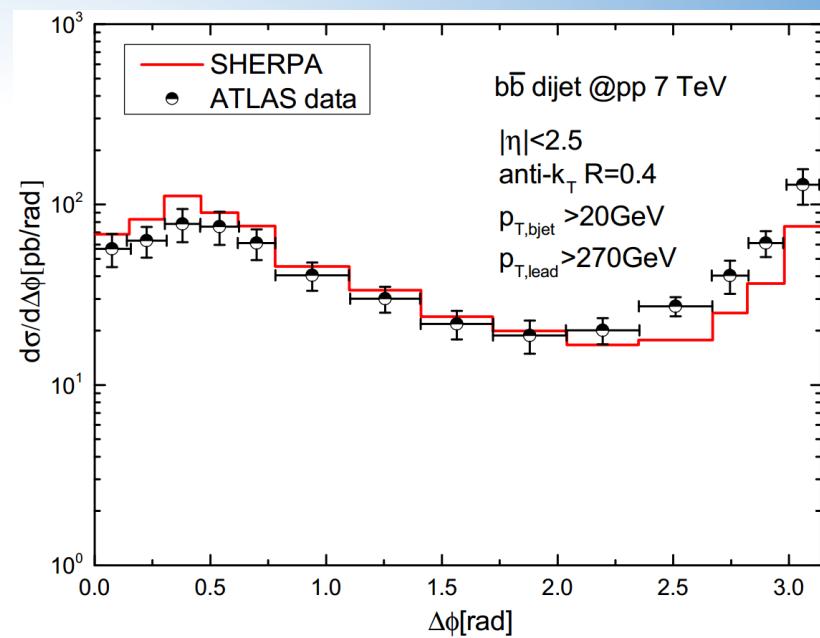
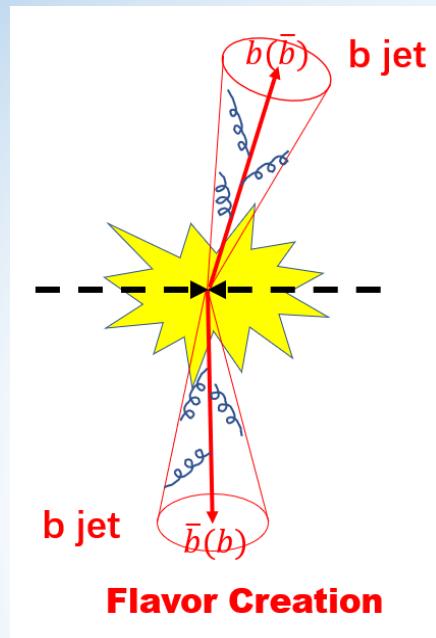
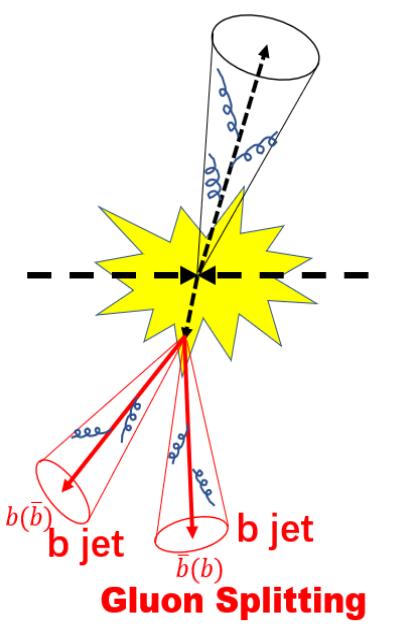
χ_J for $b\bar{b}$ dijet



arXiv:1806.06332

- Imbalance of $b\bar{b}$ dijet increasing due to jet quenching is visible in central Pb+Pb collision.
- A smaller energy loss of $b\bar{b}$ dijets than inclusive dijet in peripheral Pb+Pb collision.

Azimuthal angle correlation

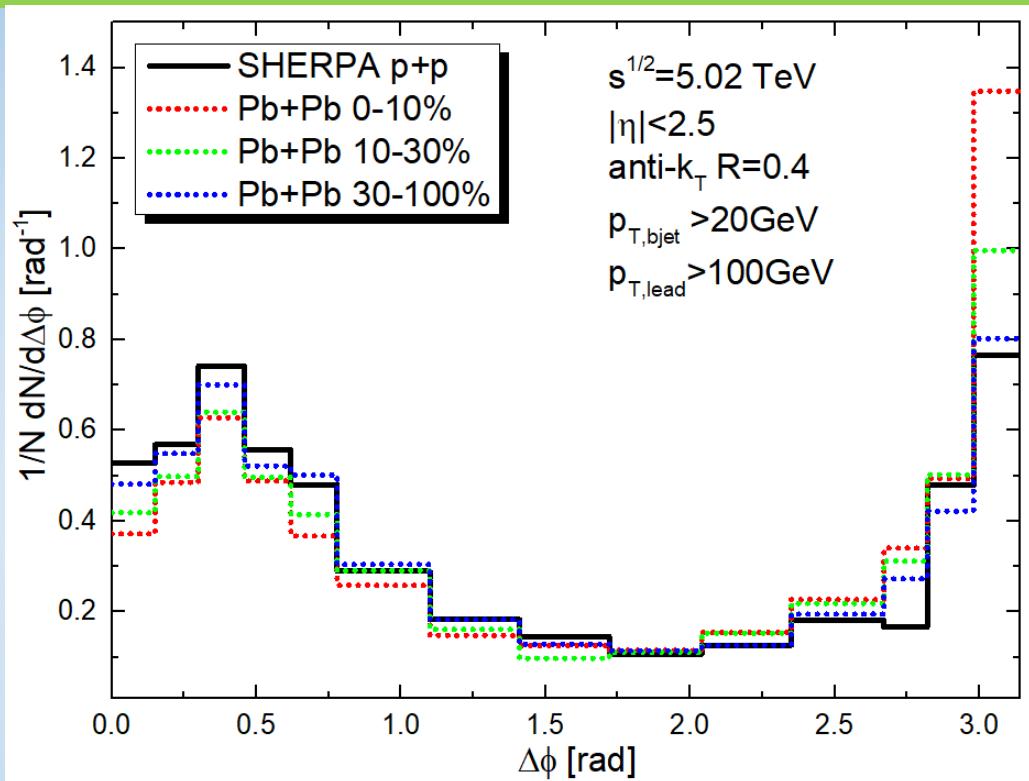


$$\Delta\phi = |\phi_{b1} - \phi_{b2}|$$

arXiv:1806.06332

- $0 < \Delta\phi < \pi, |\eta| < 2.5, R = 0.4$
- Leading jet $p_T > 270 \text{ GeV}$
- $p_{T,bjet} > 20 \text{ GeV}$
- Leading and subleading jets are not required to be b-tagged.
- 2 b jets separated by $\Delta R > 0.4$

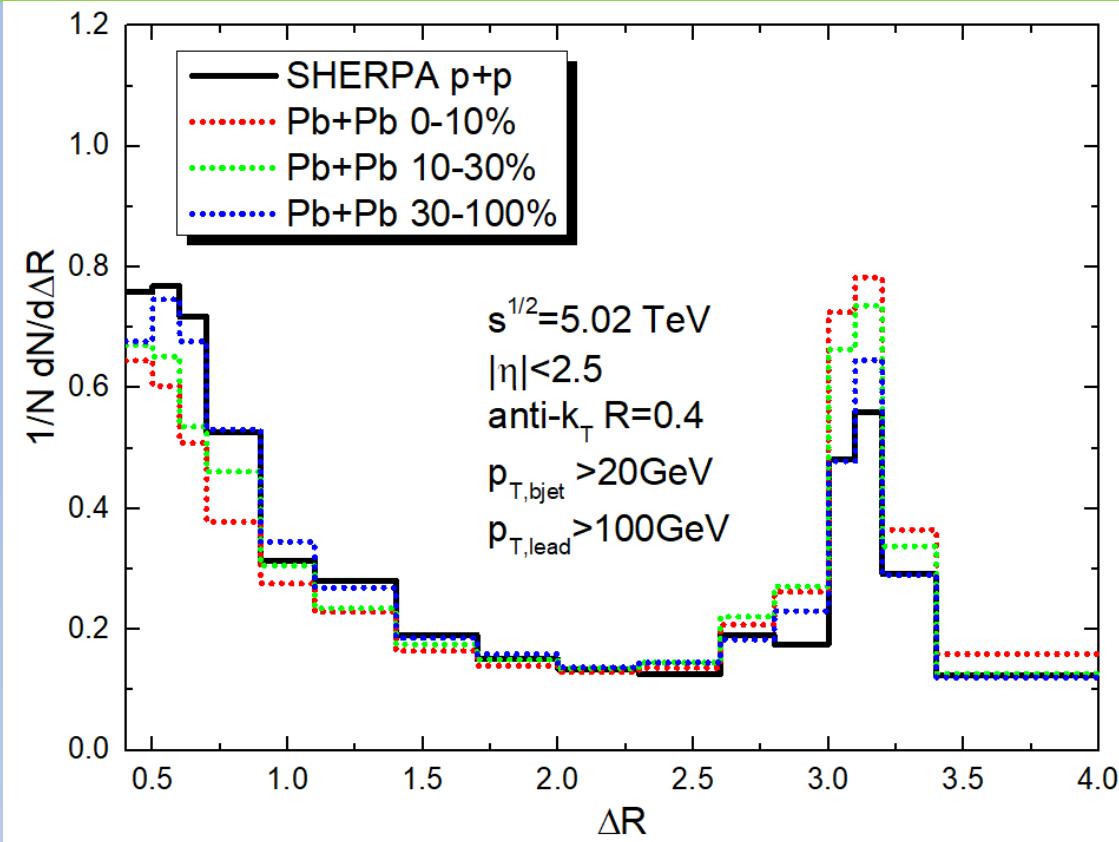
Azimuthal Angle Distribution--- $\frac{1}{N} \frac{dN}{d\Delta\phi}$



arXiv:1806.06332

- The energy loss effect would suppress and broaden the near side (small $\Delta\phi$) peak, and also enhance and sharp the away side (near $\Delta\phi = \pi$) peak in the normalized $\Delta\phi$ distribution.
- In the small angle region, it suffers stronger suppression relative to the large angle region.

Angular Distance Distribution--- $\frac{1}{N} \frac{dN}{d\Delta R}$



$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

- Suppression on small ΔR and enhancement on large ΔR with centrality dependence.

Summary

- A MC simulation which combines **SHERPA** for pp baseline, **HT+ Langevin +HTL** framework for parton energy loss has been implemented to study the in-medium modification for the $b\bar{b}$ dijet production in Pb+Pb collision .
- x_J

x_J shift to smaller value consistent with CMS data, and a similar trend as that in dijet has been observed.
- $\Delta\phi$ and ΔR

Suppression on the near side and the enhancement on the away side in the normalized distribution are predicted.

Thanks for your attention !

Backup-1 Gluon Sampling Method

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

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

- 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 :

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

- 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 .

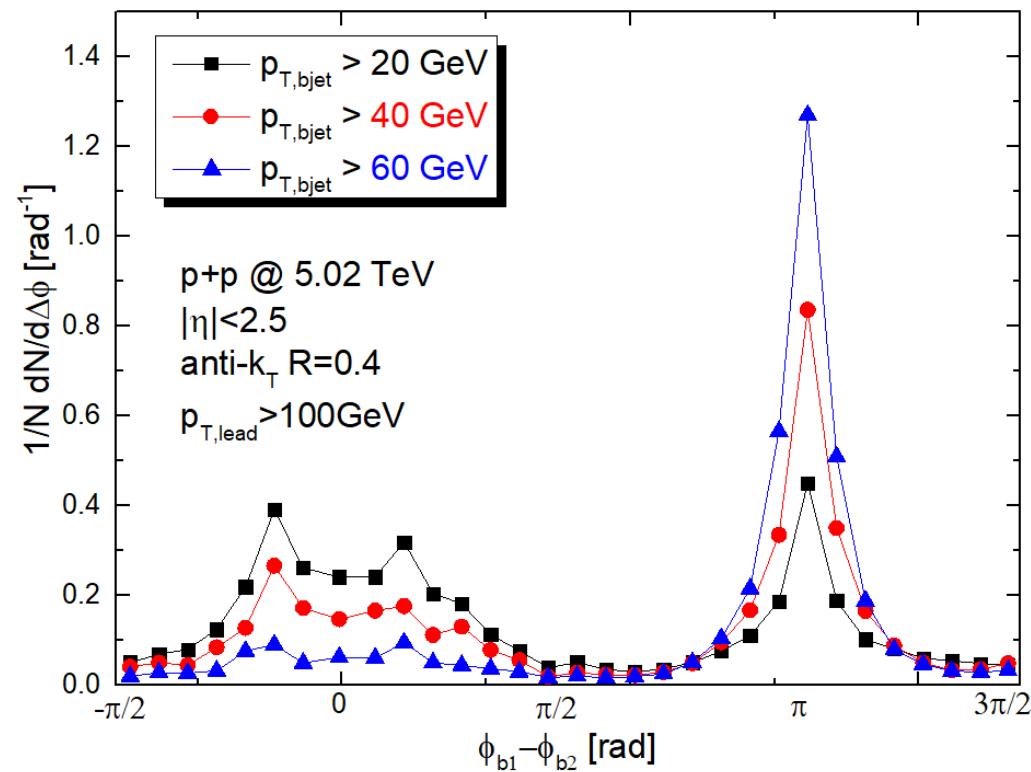
Backup-2 Smearing parameter

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

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

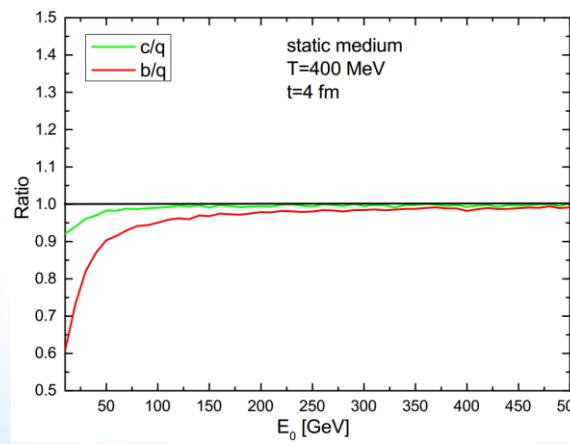
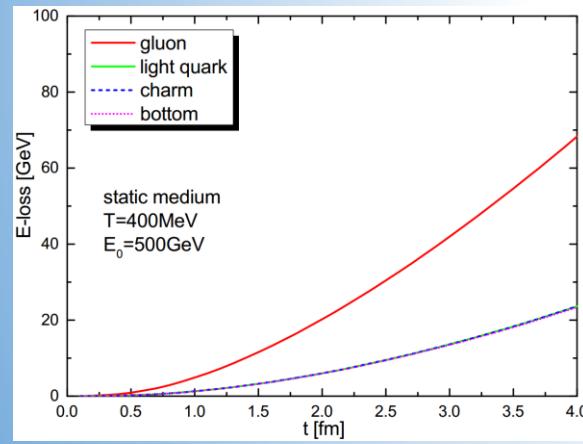
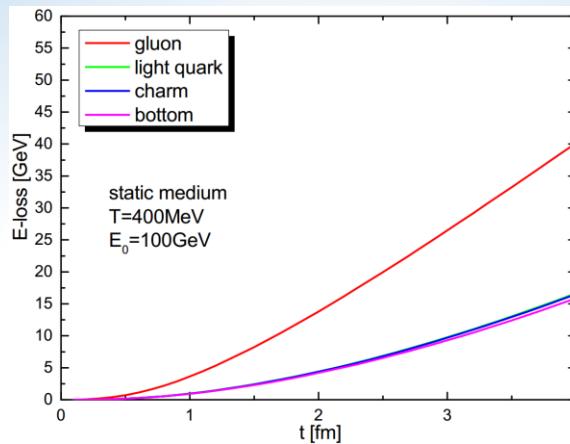
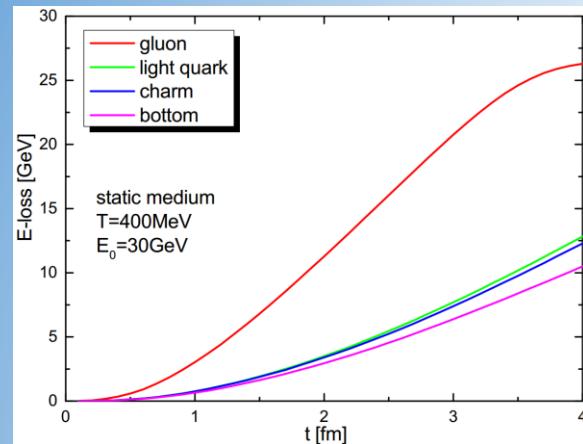
- In pp collisions, the constant C and stochastic S terms are 0.06 and 0.8 GeV^{-1}
- In Pb+Pb collisions the S term is slightly larger value of 1.0 GeV^{-1} , due to the underlying event.
- The noise parameter (N) depends on collision centrality, according to $N = 14.82 - \text{centrality}(\%)/5.40(\text{GeV}^2)$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

Azimuthal angle correlation



- The structure of azimuthal angle distribution between the two b jets was sensitive to the minimum p_T cut of b jet.
- GSP more likely produces two b jets with relatively lower p_T compared with FCR.

Radiative E-loss: gluon & light quark & heavy quark

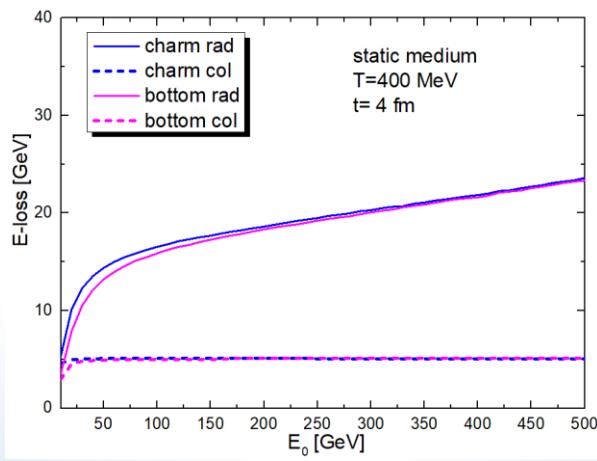
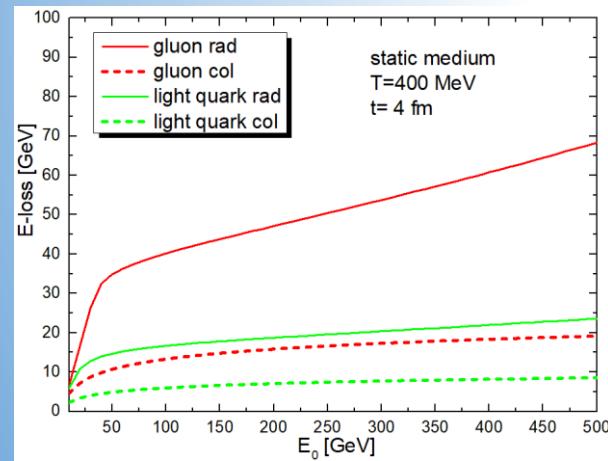
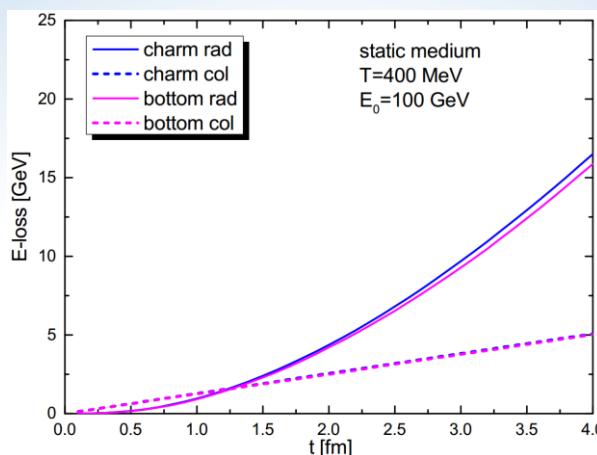
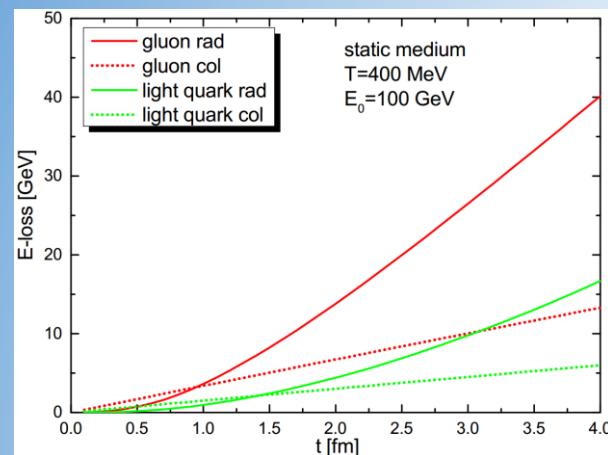


- The radiative energy loss of gluon is much larger than quarks.

- $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$.

- Mass effect of heavy quarks trends to disappear as energy increasing.

Radiative Vs. Collisional E-loss



- In-medium energy loss is dominated by gluon radiation both for light and heavy flavor.
- Collisional E-loss shown no initial energy dependence.