Quenching of heavy flavors in heavy-ion collisions

Hongxi Xing

J. Huang, Z. Kang, I. Vitev, PLB 726, 251 (2013)
J. Huang, Z. Kang, I. Vitev, H. Xing, PLB 750, 287 (2015)
Y. Chien, Z. kang, F. Ringer, I. Vitev, H. Xing, arXiv:1512.06851 (2015)

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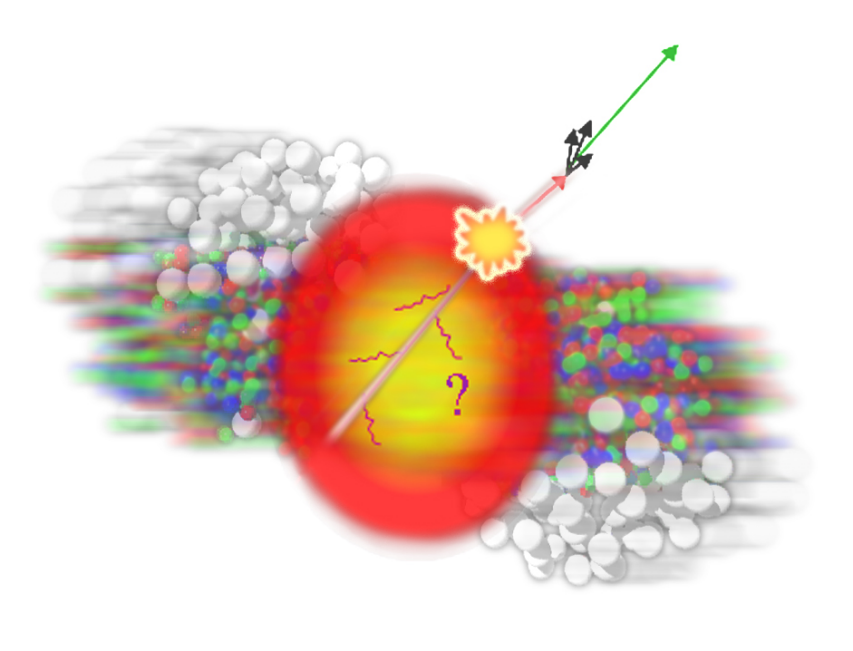
Outline

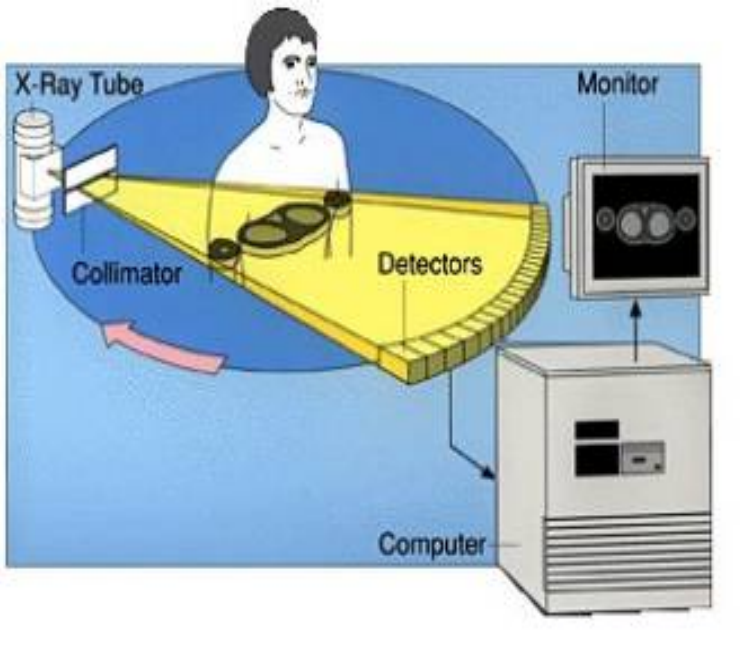
- Motivation
- Quenching of inclusive and tagged b-jet at the LHC
- Jet fragmentation function
- Summary

Probe of parton energy loss mechanism

Jet tomography



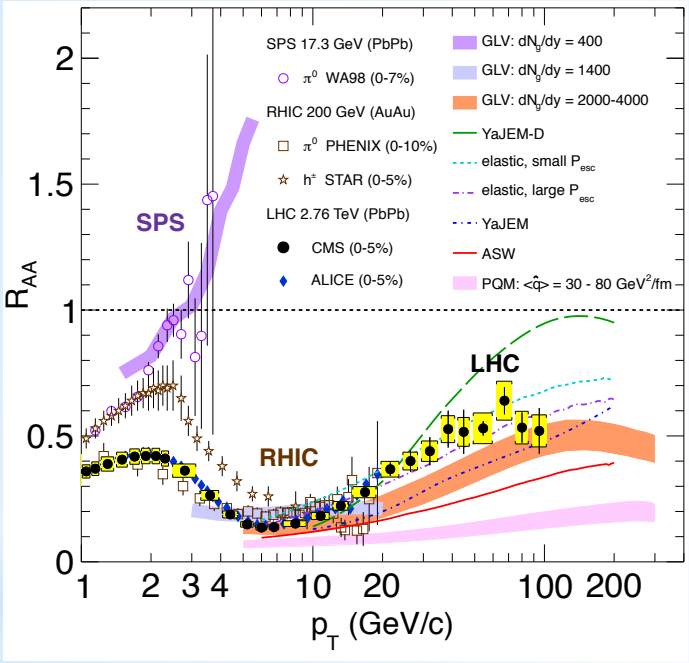
Computed tomography



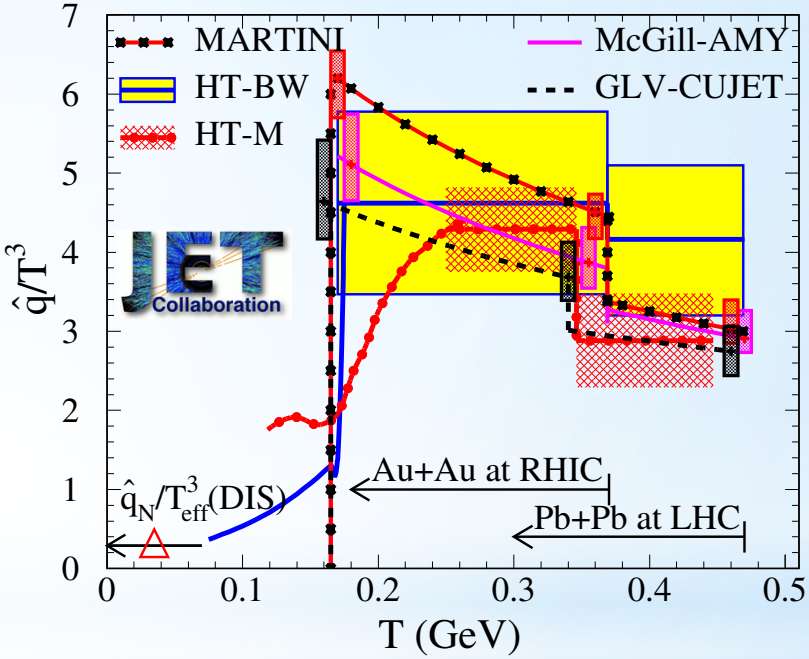
- One cannot directly measure the softening of the jet energy after it emerges from the medium, different with X-ray CT.
- Understanding the flavor origin of the observed jet is of particular importance in probing the energy loss mechanism.

Light hadron suppression

Jet quenching for light hadron



Extraction of the medium property



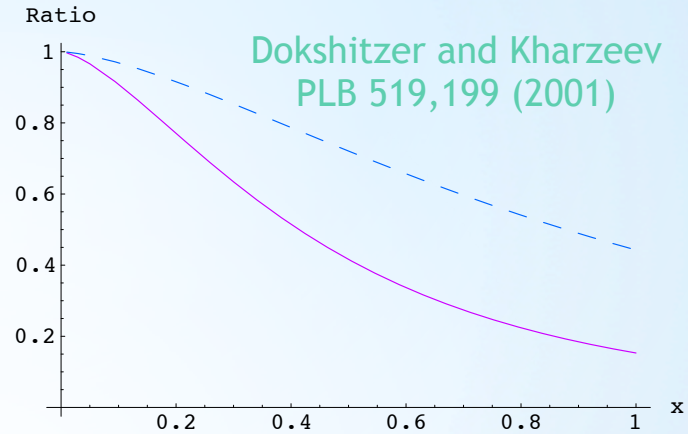
JET collaboration, PRC 90,014909 (2014)

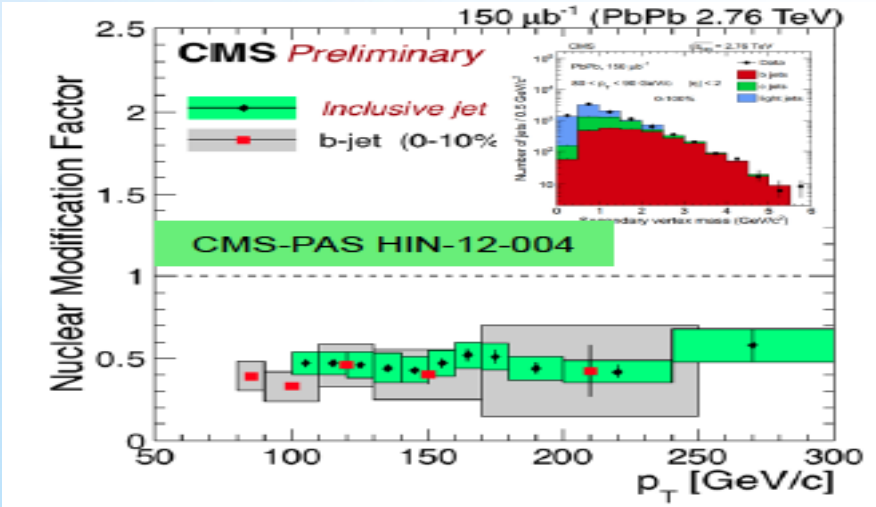
Heavy quark energy loss puzzle

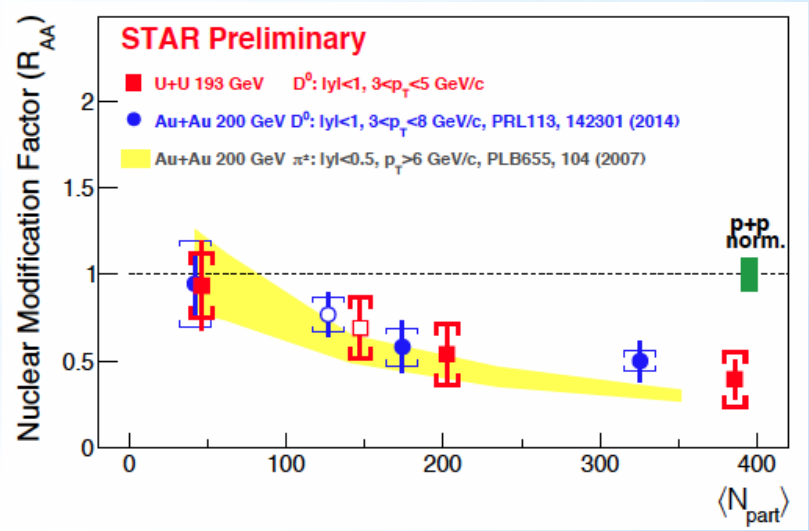
- Quark mass leads to dead-cone effect: less radiative energy loss

$$dP_{HQ} = dP_0 \cdot \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2}$$

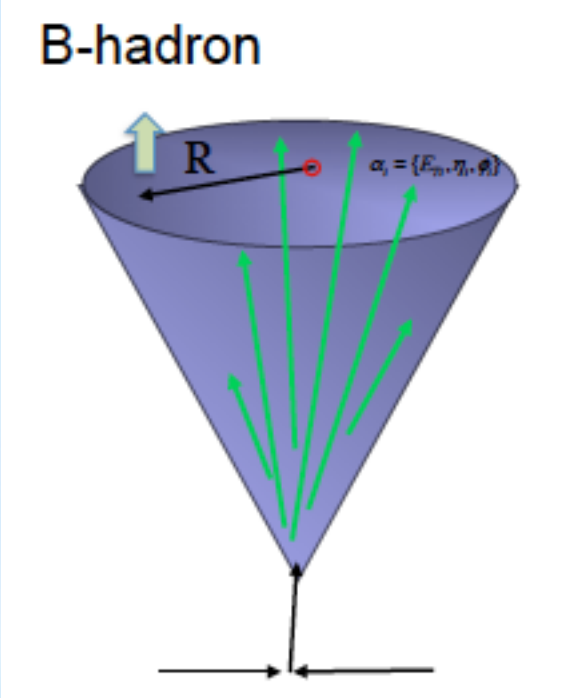
$$\theta_0 = \frac{M}{E}$$





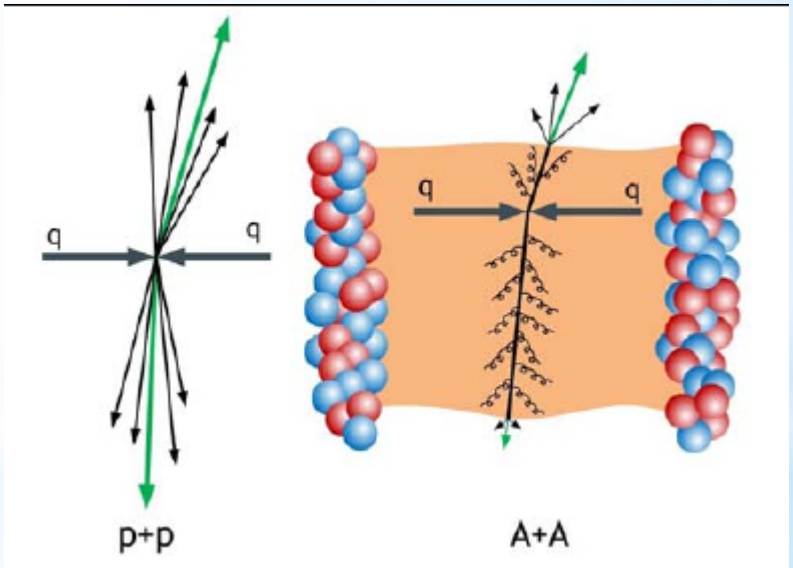


B-jet definition



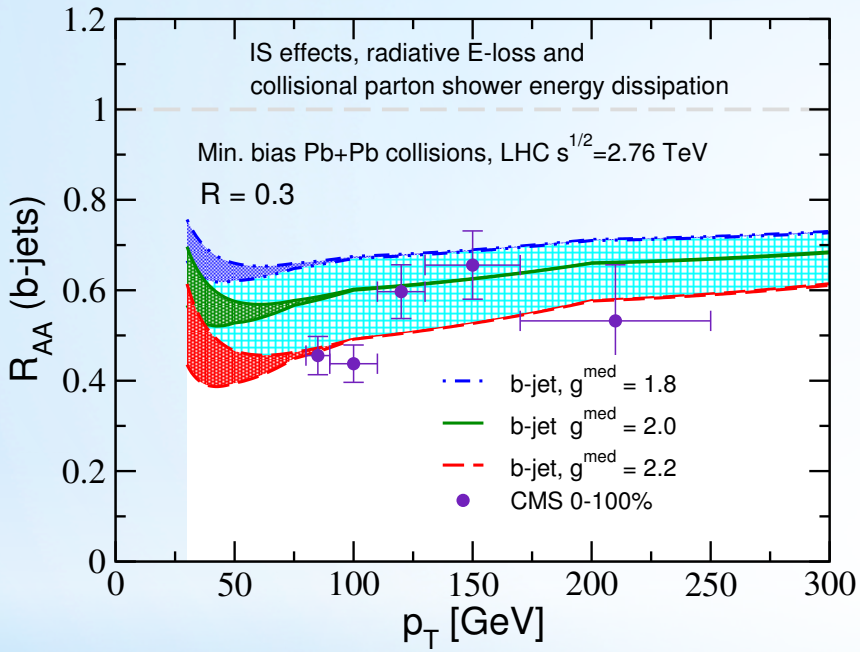
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta y)^2} < R$$

- Find a jet (kt, anti-kt and cone algorithm)
- Within the jet cone, find a b quark or more
- B-jet is not necessarily from b-quark



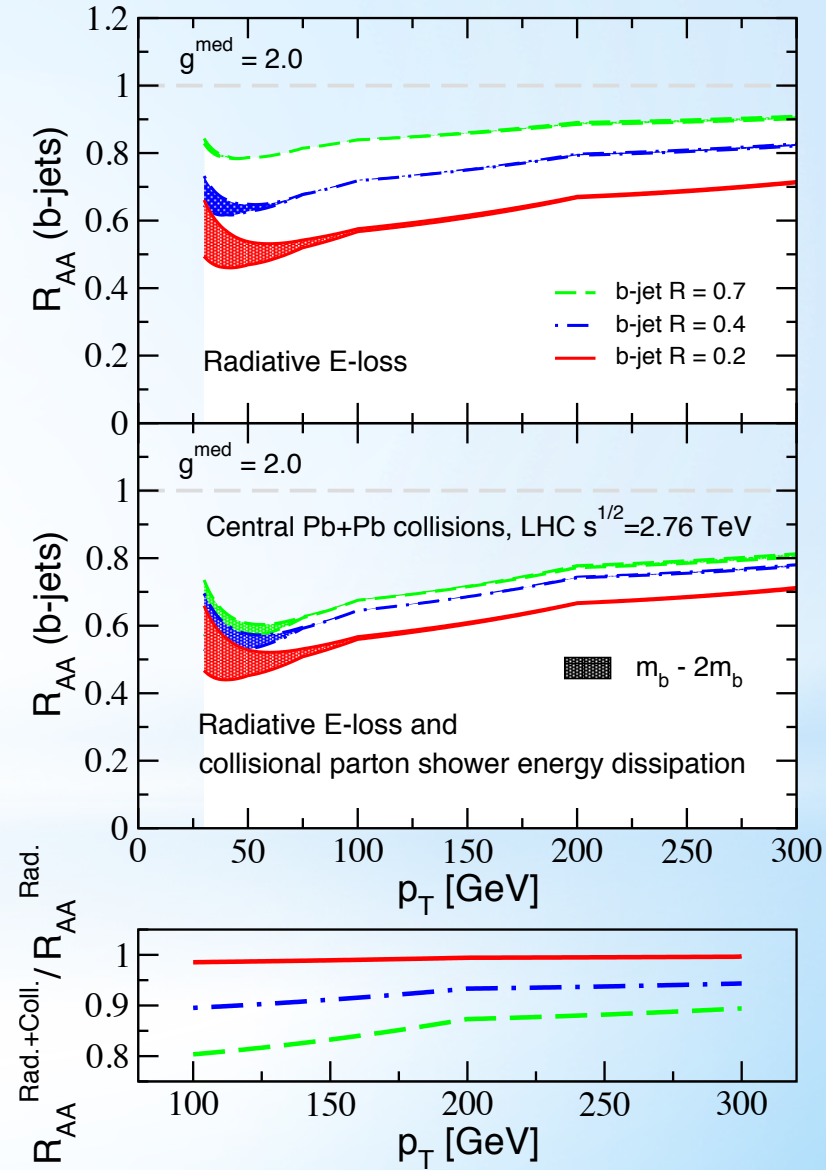
Quenching of inclusive b-jet

Huang, Kang and Vitev, Phys. Lett. B 726 251 (2013)

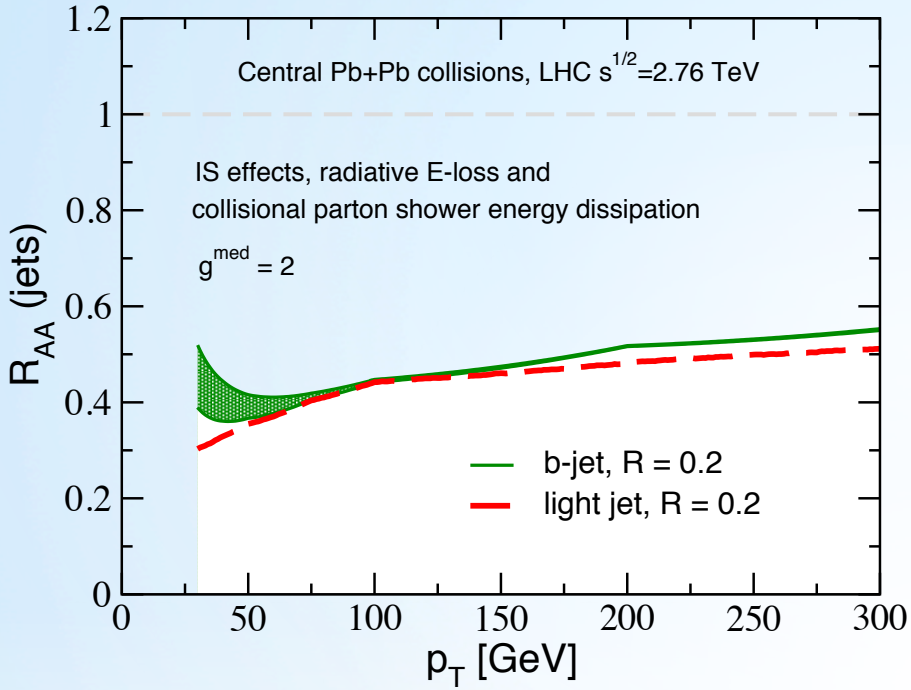


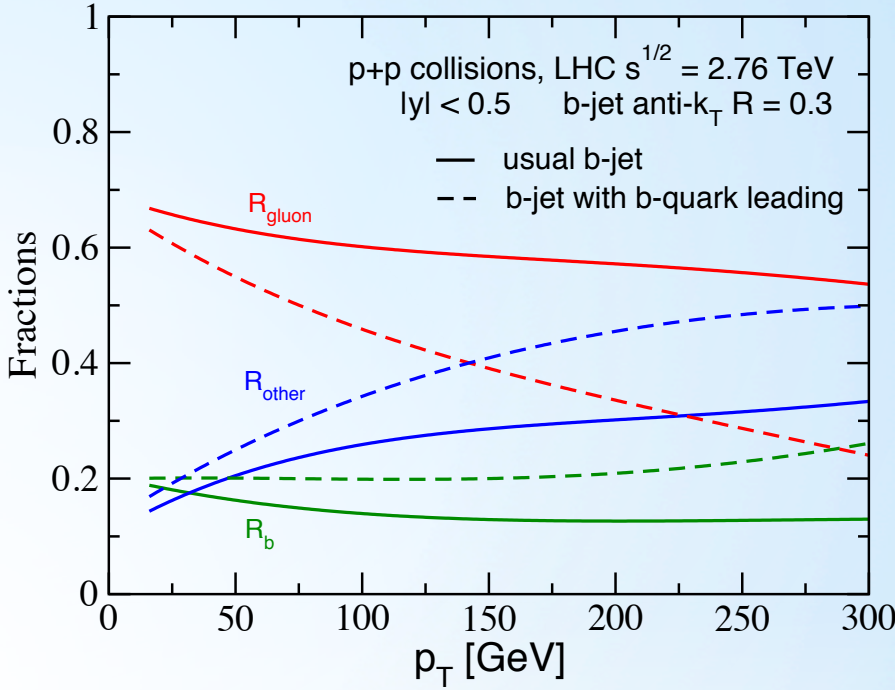
Agreement between the simulations and CMS data

Cone size dependence



- B-jet vs. light quark-jet





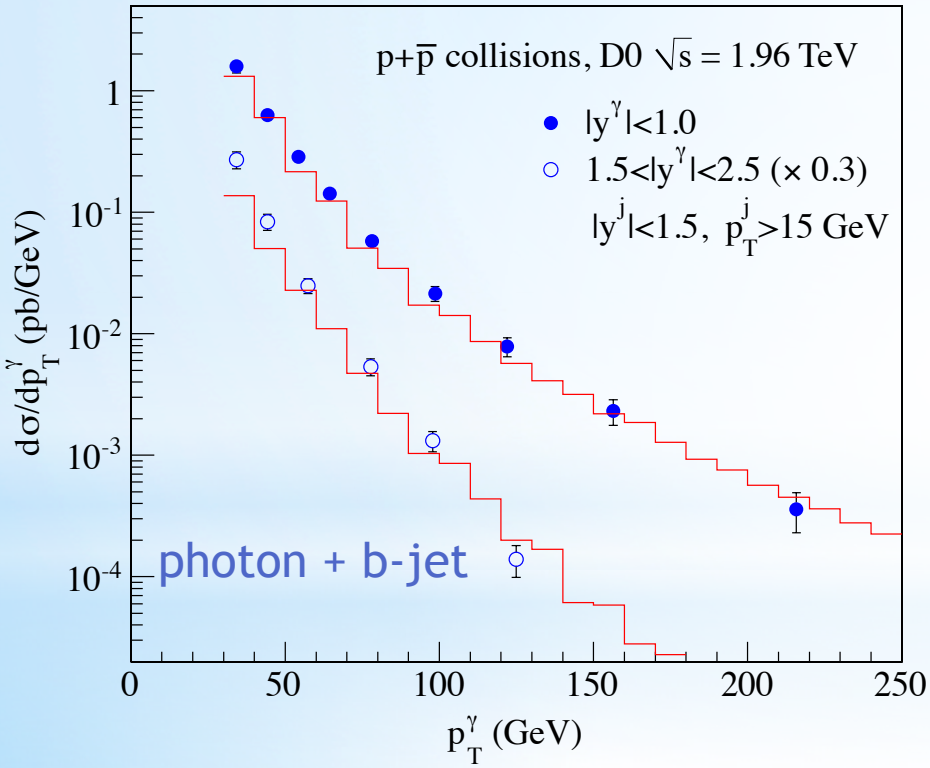
- At high pt region, mass effect can be neglected
- Small fraction of b-jet originate from b-quark

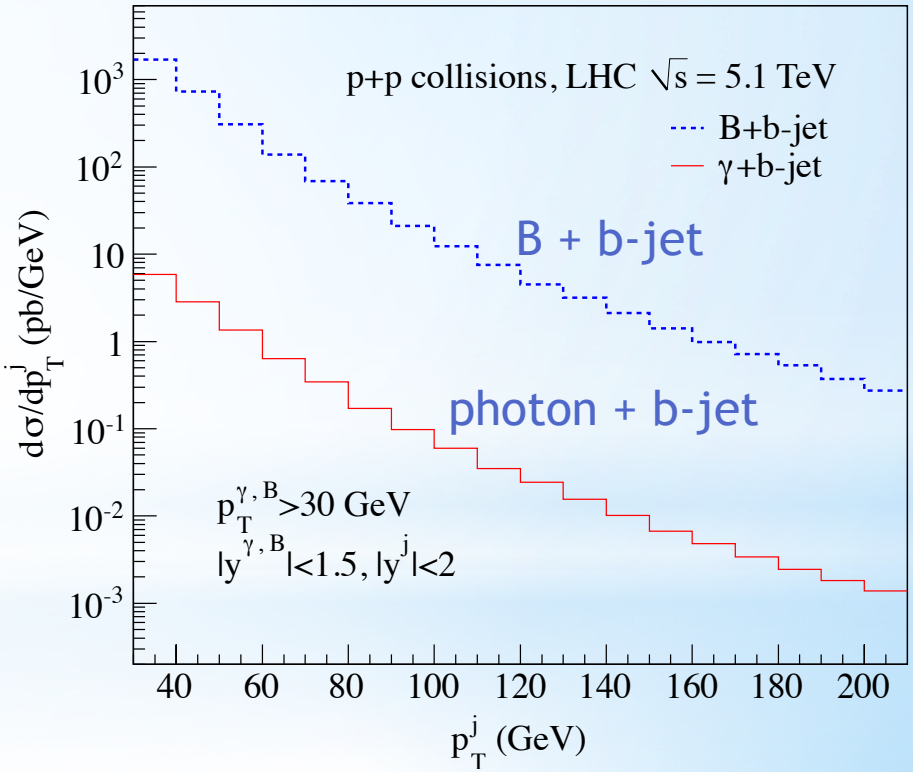
- R_{gluon}: fraction of g -> b
- R_b : fraction of b -> b
- R_{other}: fraction of q -> b

Which process has more direct connection to b-quark energy loss?

PP baseline for tagged b-jets

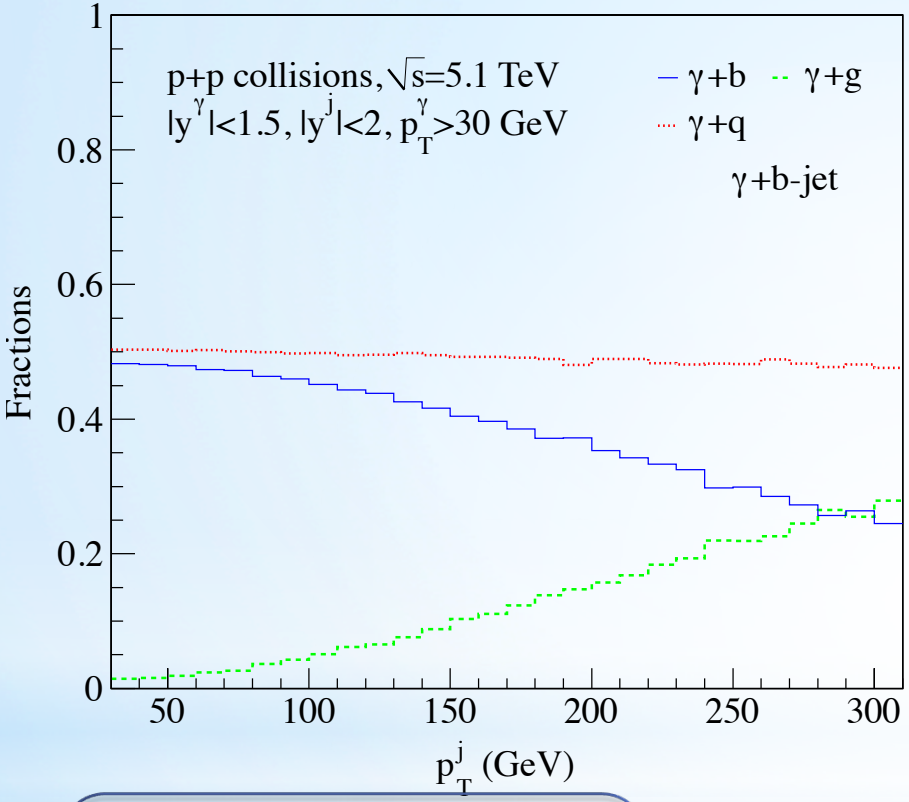
- PYTHIA8 + SlowJet (anti-kt)
- Good description to the photon-b-jet cross section measured by Tevatron
- B-meson tagged b-jet cross section is large, accessible at the LHC

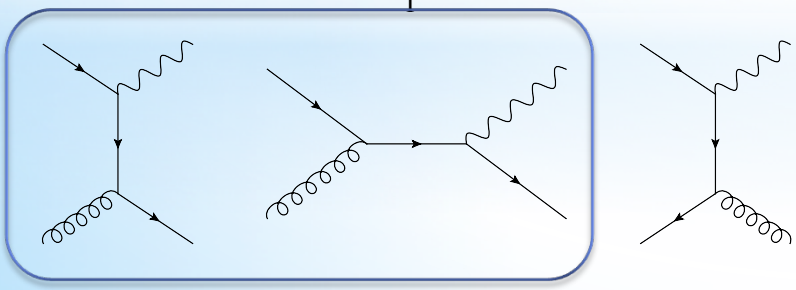




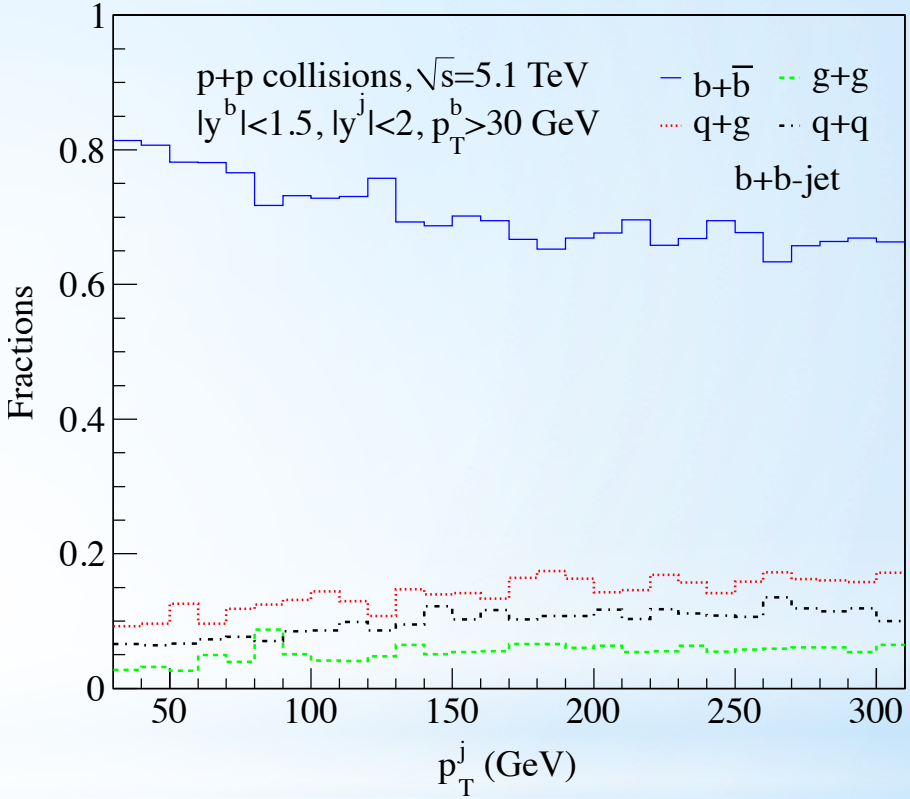
Hard partonic structure for tagged b-jets

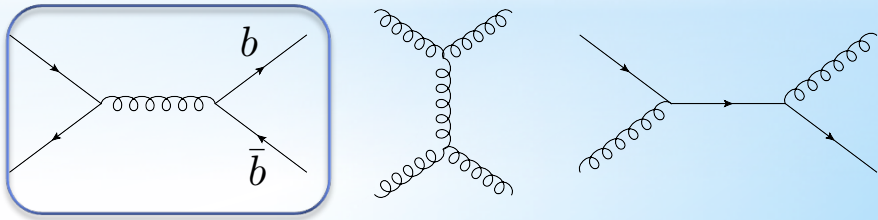
photon + b-jet



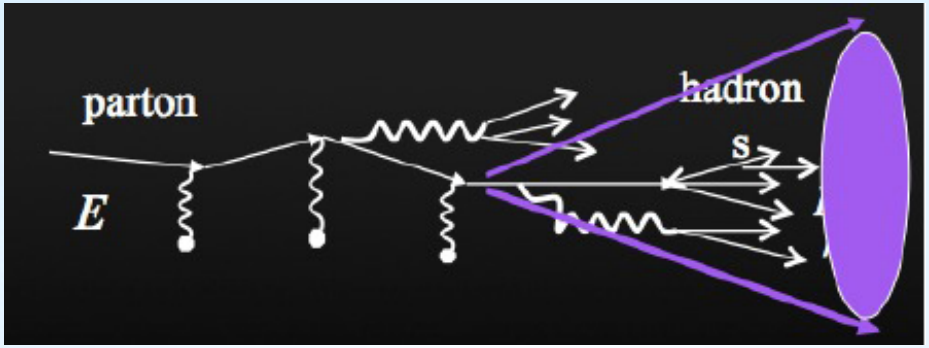


B + b-jet





Jet energy loss in nuclear medium



- The fraction of the lost energy falls inside the cone

$$f_{(s)}(R,\omega^{\rm coll}) = \frac{\int_0^R dr \int_{\omega^{\rm coll}}^E d\omega \frac{\omega d^2 N^g_{(s)}}{d\omega dr}}{\int_0^{R\infty} dr \int_0^E d\omega \frac{\omega d^2 N^g_{(s)}}{d\omega dr}}$$

- Prepare a initial higher energy jet to get the final jet that we observed

$E'_T = \frac{E_T}{1-(1-f_{q,g})\cdot\epsilon}$ (jet eloss) vs. $E'_T = \frac{E_T}{1-\epsilon}$ (parton eloss)

Tagged b-jets production in heavy ion collisions

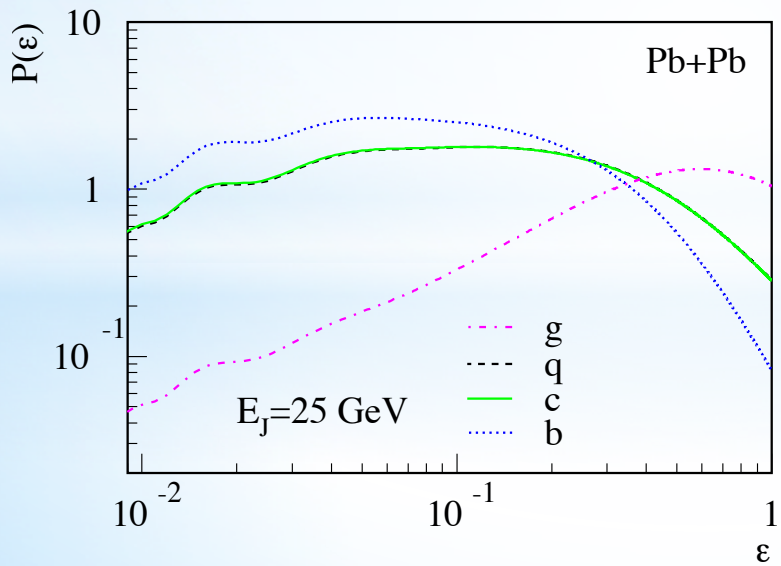
- Medium modified photon+b-jet cross section

$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}}{dp_T^\gamma dp_T^j} = \sum_{(s)}\int_0^1 d\epsilon P_{(s)}(\epsilon) J_{(s)}(\epsilon)\frac{d\sigma_{(s)}^{\rm LO+PS}\left(p_T^\gamma, J_{(s)}(\epsilon)p_T^j\right)}{dp_T^\gamma dp_T^j}$$

- Medium modified b-quark+b-jet cross section

$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}}{dp_T^b dp_T^j} = \sum_{(s,s')}\int_0^1 d\epsilon P_{(s)}(\epsilon)\frac{1}{1-\epsilon}\int_0^1 d\epsilon' P_{(s')}(\epsilon') J_{(s')}(\epsilon')\frac{d\sigma_{(s,s')}^{\rm LO+PS}\left(p_T^b/(1-\epsilon), J_{(s')}(\epsilon')p_T^j\right)}{dp_T^b dp_T^j}$$

$P(\epsilon)$ is the probability to lose energy due to multiple gluon emission



$$\int d\epsilon P(\epsilon) = 1$$

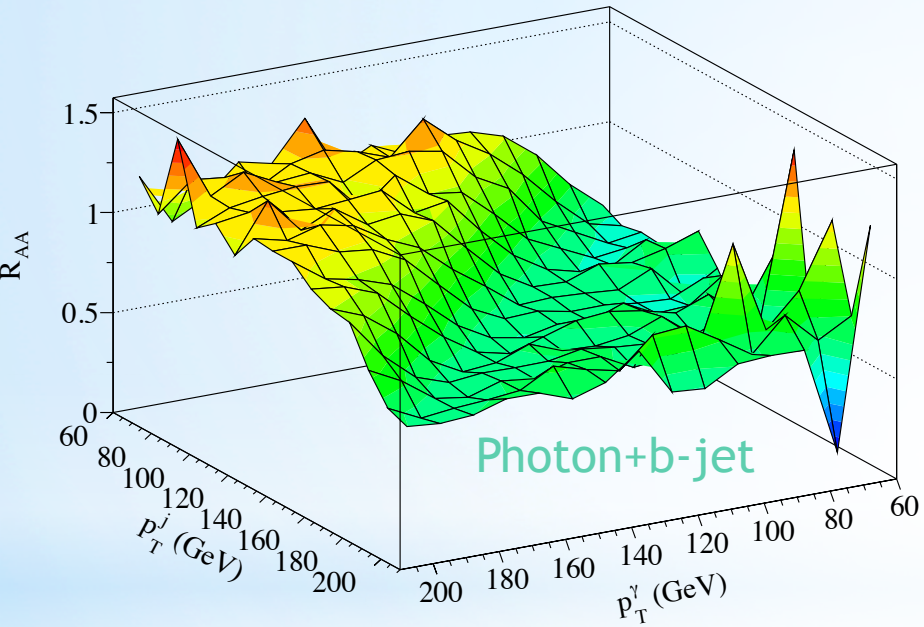
Kang and Vitev, PRD 84,014034 (2011)

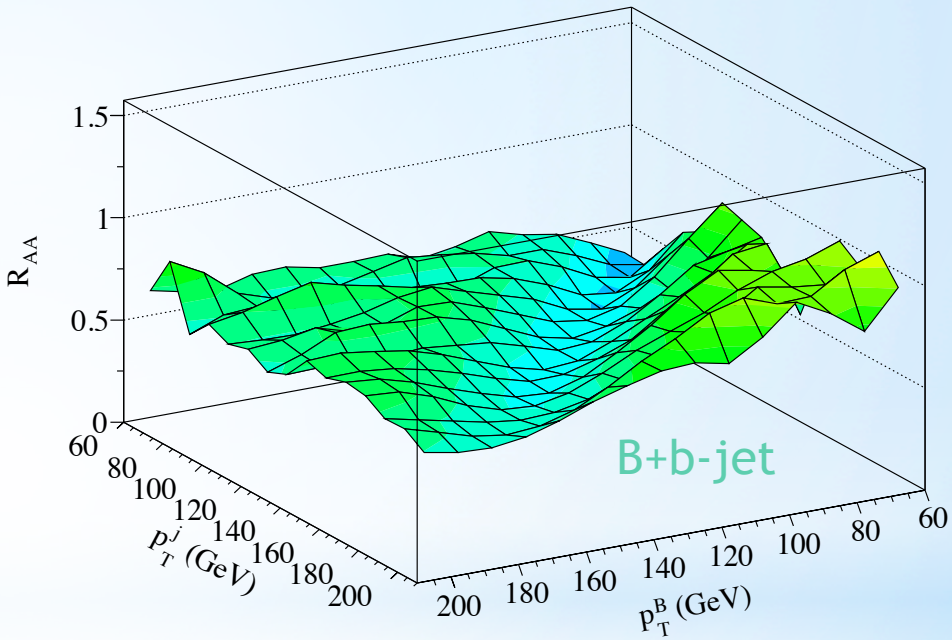
Nuclear modification factor

J. Huang, Z. Kang, I. Vitev, H. Xing, PLB 750, 287 (2015)

$$R_{AA}^{\gamma+b\text{-}jet} = \left(\frac{d\sigma^{AA}}{dp_T^{\gamma}dp_T^{j}}\right) \Big/ \left(\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}}{dp_T^{\gamma}dp_T^{j}}\right)$$

$$R_{AA}^{B+b\text{-}jet} = \left(\frac{d\sigma^{AA}}{dp_T^{B}dp_T^{j}}\right) \Big/ \left(\langle N_{\rm bin}\rangle \frac{d\sigma^{pp}}{dp_T^{B}dp_T^{j}}\right)$$



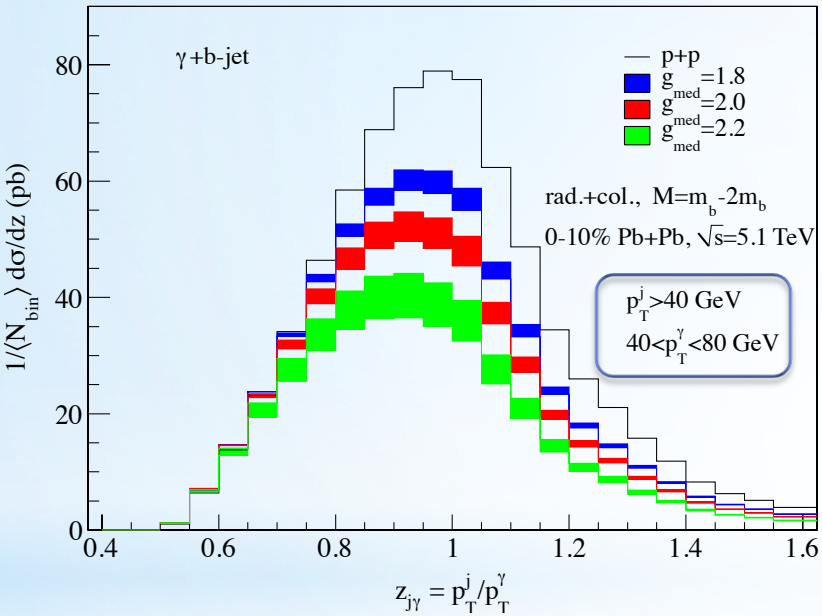


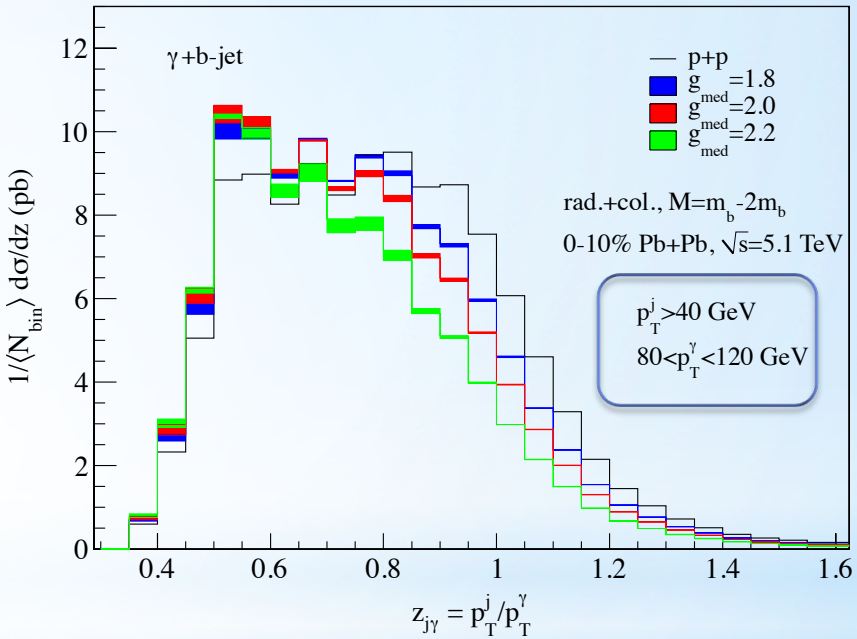
- Large suppression in symmetric region
- Overall smaller suppression than inclusive b-jet

Momentum imbalance: photon+jet

$$\frac{d\sigma}{dz_{j\gamma}} = \int_{p_T^{j,\min}}^{p_T^{j,\max}} dp_T^j \, \frac{p_T^j}{z_{j\gamma}^2} \frac{d\sigma(p_T^\gamma = p_T^j / z_{j\gamma})}{dp_T^\gamma dp_T^j} \qquad z_{j\gamma} = \frac{p_T^j}{p_T^\gamma}$$

arXiv: 1505.03517

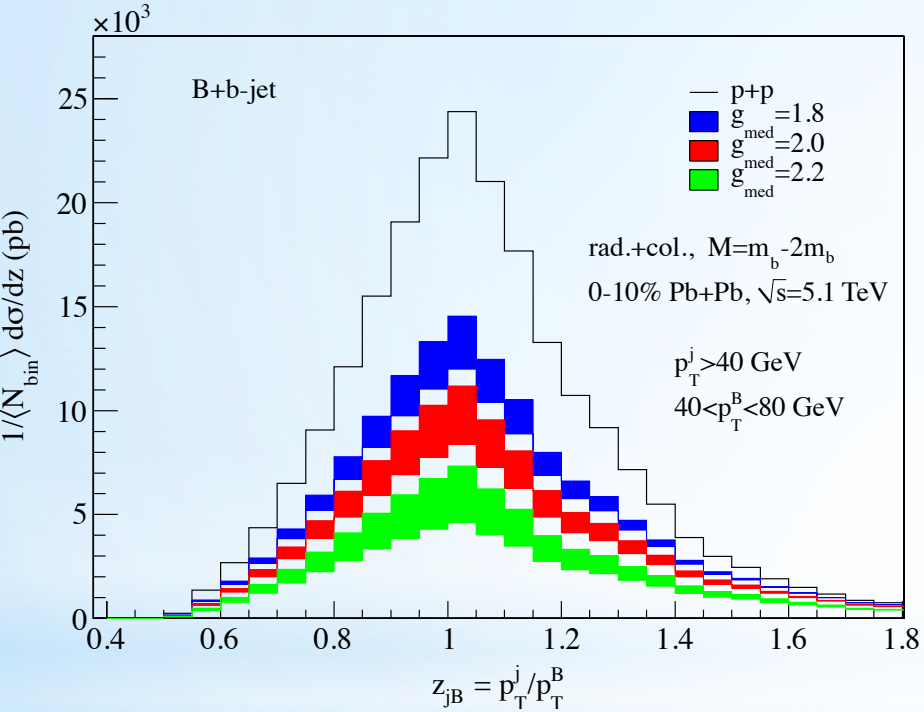


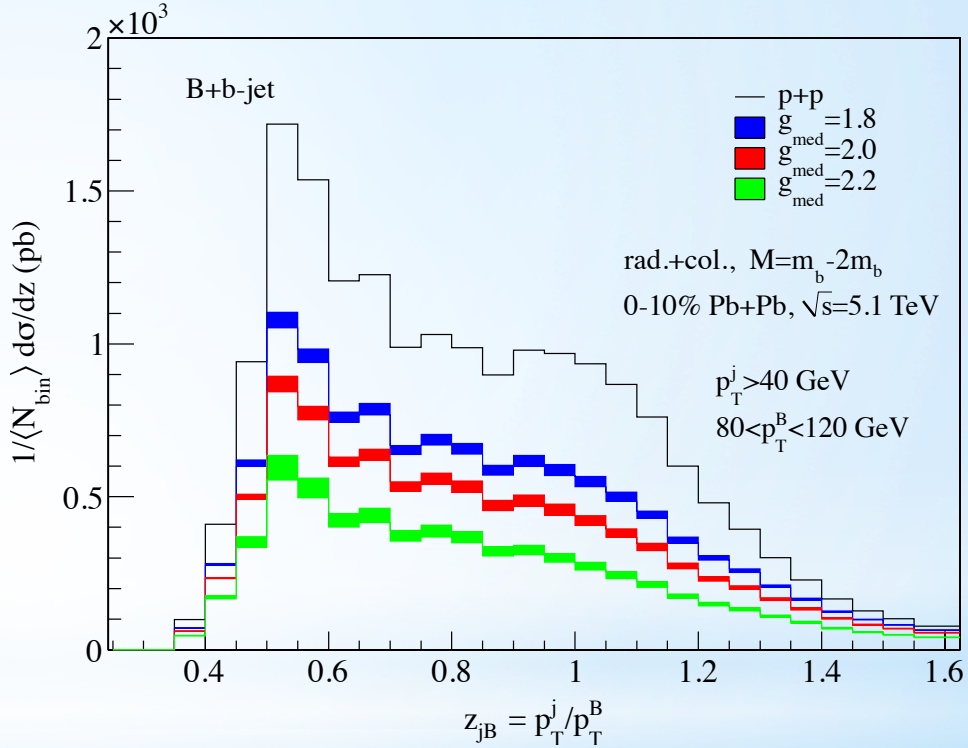


- B-jet quenching shifts the asymmetry variable z down to smaller values.
- Shape change in asymmetric cut, even enhancement occurs.

Momentum imbalance: B+b-jet

$$\frac{d\sigma}{dz_{jB}} = \int_{p_T^{j,\min}}^{p_T^{j,\max}} dp_T^j \, \frac{p_T^j}{z_{jB}^2} \, \frac{d\sigma(p_T^B = p_T^j/z_{jB})}{dp_T^B \, dp_T^j} \qquad z_{jB} = \frac{p_T^j}{p_T^B}$$





- Strong suppression for both cuts
- No noticeable down-shift of the asymmetry distribution

- Mean value of z

$$\langle z_{j\gamma}\rangle = \left(\int dz_{j\gamma} z_{j\gamma} \frac{d\sigma}{dz_{j\gamma}}\right) \Big/ \left(\int dz_{j\gamma} \frac{d\sigma}{dz_{j\gamma}}\right) \qquad \langle z_{jB}\rangle = \left(\int dz_{jB} z_{jB} \frac{d\sigma}{dz_{jB}}\right) \Big/ \left(\int dz_{jB} \frac{d\sigma}{dz_{jB}}\right)$$

TABLE I. Theoretical results for $\langle z_{j\gamma}\rangle$ ($\langle z_{jB}\rangle$) in photon-tagged (B-tagged) b-jet production in p+p and central Pb+Pb reactions at center-of-mass energy $\sqrt{s_{NN}} = 5.1$ TeV at LHC. For the photon (B-meson), we have two kinematic cuts, while $p_T^j > 40$ GeV for the b-jet.

System	$\langle z_{j\gamma}\rangle$		$\langle z_{jB}\rangle$	
	$40 < p_T^\gamma < 80$ GeV	$80 < p_T^\gamma < 120$ GeV	$40 < p_T^B < 80$ GeV	$80 < p_T^B < 120$ GeV
p+p	0.98	0.78	1.04	0.82
A+A, $g = 1.8$, $M = 2m_b$	0.95	0.74	1.06	0.83
A+A, $g = 1.8$, $M = m_b$	0.95	0.74	1.07	0.83
A+A, $g = 2.0$, $M = 2m_b$	0.94	0.73	1.07	0.83
A+A, $g = 2.0$, $M = m_b$	0.94	0.73	1.09	0.83
A+A, $g = 2.2$, $M = 2m_b$	0.93	0.71	1.08	0.83
A+A, $g = 2.2$, $M = m_b$	0.93	0.71	1.10	0.83

Photon+b-jet B+b-jet

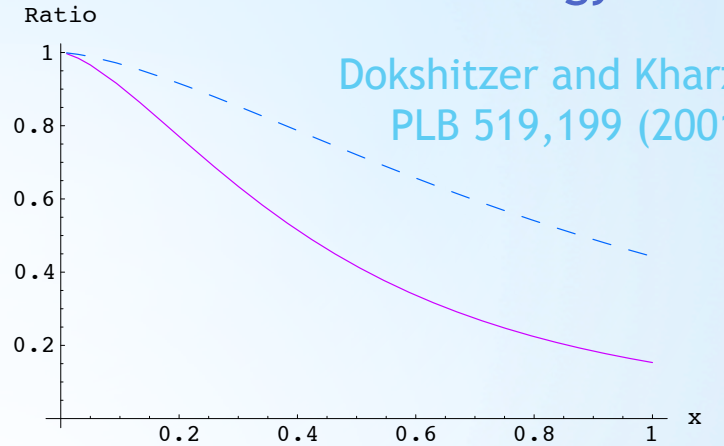
- Down-shift of z in photon + b-jet
- Increase of z in B + b-jet

Heavy quark energy loss puzzle

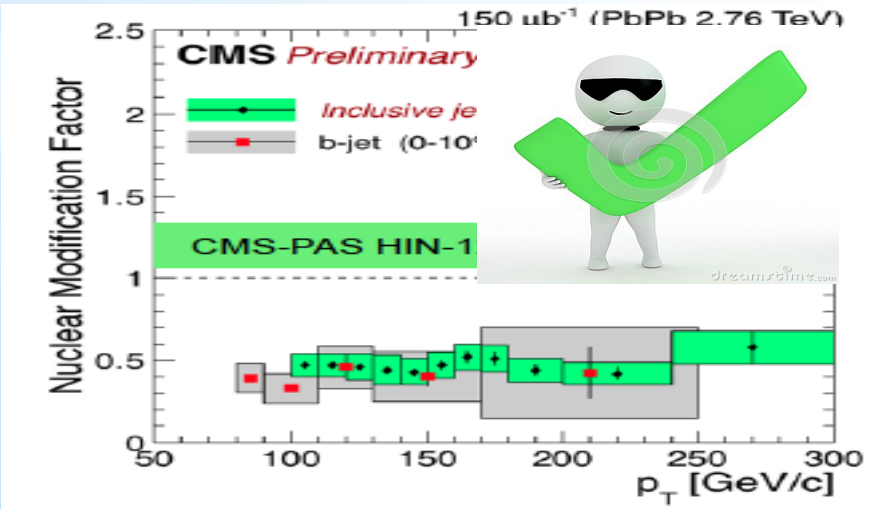
- Quark mass leads to dead-cone effect: less radiative energy loss

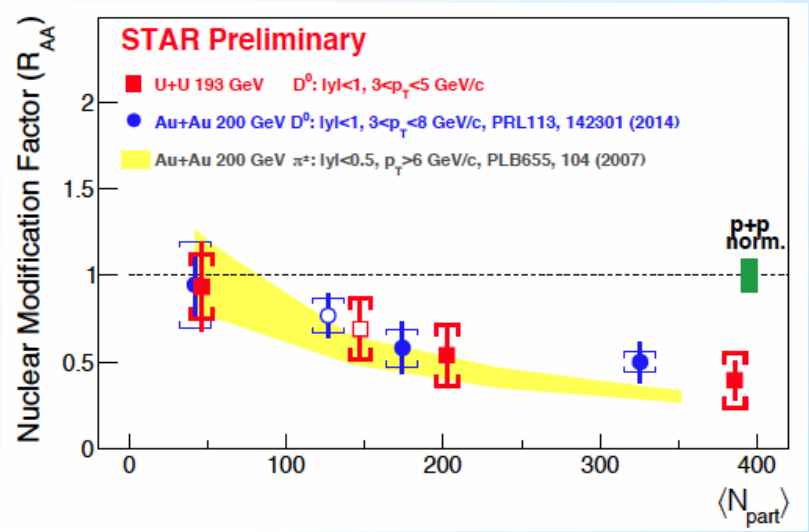
$$dP_{HQ} = dP_0 \cdot \left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2}$$

$$\theta_0 = \frac{M}{E}$$



Dokshitzer and Kharzeev
PLB 519,199 (2001)

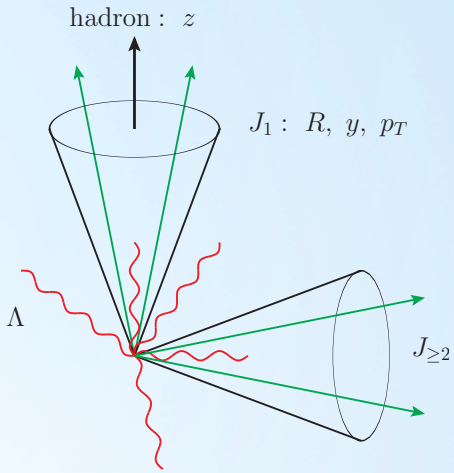




Jet Fragmentation Function

- Longitudinal momentum distribution of hadrons inside a jet

$$F(z, p_T) = \frac{d\sigma^h}{dy dp_T dz} \Big/ \frac{d\sigma}{dy dp_T}$$



- Differential cross section

$$\frac{d\sigma^h}{dy_i dp_{T_i} dz} = H(y_i, p_{T_i}, \mu)\, \mathcal{G}^h_{\omega_1}(z, \mu) J_{\omega_2}(\mu) \cdots J_{\omega_N}(\mu) S_{n_1 n_2 \cdots n_N}(\Lambda, \mu) + \mathcal{O}\left(\frac{\Lambda}{Q}\right) + \mathcal{O}(R)$$

$$\frac{d\sigma}{dy_i dp_{T_i}} = H(y_i, p_{T_i}, \mu) J_{\omega_1}(\mu) \cdots J_{\omega_N}(\mu) S_{n_1 n_2 \cdots n_N}(\Lambda, \mu) + \mathcal{O}\left(\frac{\Lambda}{Q}\right) + \mathcal{O}(R)$$

Unmeasured jet: $J^q(\omega, R, \mu) = 1 + \frac{\alpha_s}{\pi} C_F \left[L^2 - \frac{3}{2} L + d_J^{q,\mathrm{alg}}\right], \quad J^g(\omega, R, \mu) = 1 + \frac{\alpha_s}{\pi} C_A \left[L^2 - \frac{\beta_0}{2C_A} L + d_J^{g,\mathrm{alg}}\right]$

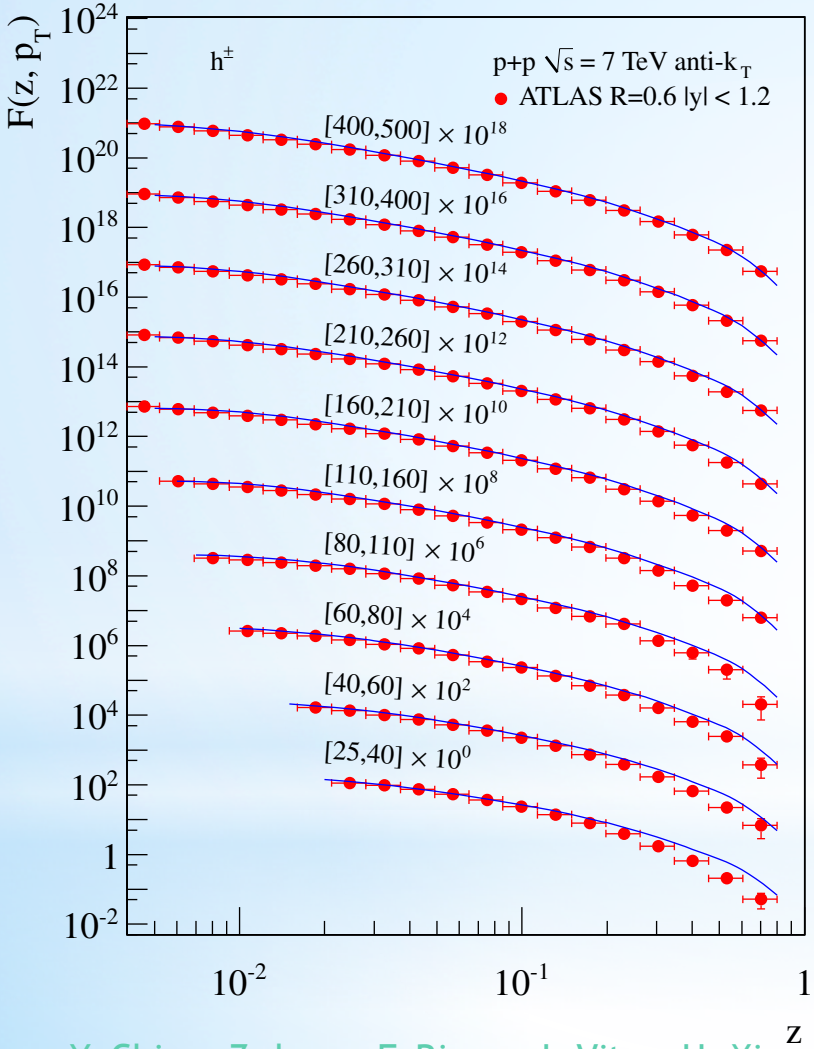
Fragmenting jet function: $\mathcal{G}^h_i(\omega, R, z, \mu) = \sum_j \int_z^1 \frac{dx}{x} \mathcal{J}_{ij}(\omega, R, x, \mu)\, D^h_j(\frac{z}{x}, \mu) + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{\omega^2 \tan^2(R/2)}\right)$

- Jet Fragmentation Function

$$F(z, p_T) = \frac{1}{\sigma_{\mathrm{total}}} \sum_{i=q,g} \int_{\mathrm{PS}} dy\, dp_T \frac{d\sigma^i}{dy\, dp_T} \frac{\mathcal{G}^h_i(\omega, R, z, \mu)}{J^i(\omega, R, \mu)}$$

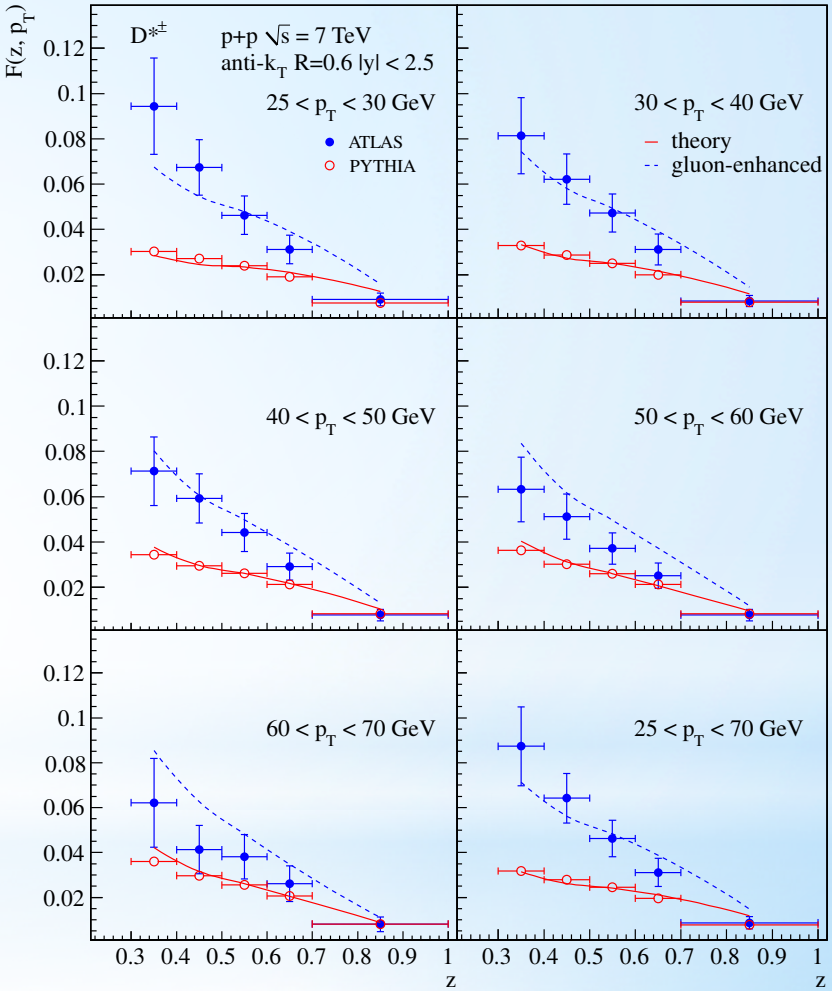
Comparison to experimental data

Light charged hadrons



Y. Chien, Z. kang, F. Ringer, I. Vitev, H. Xing, arXiv:1512.06851 (2015)

Heavy meson (D)



Good observable to constrain gluon fragmentation function

Summary

- Detailed study of flavor origin of observed final state is significant to probe energy loss mechanism in heavy ion collisions

- Flexibility of b-jet tagging can provide us with unique new insights into the heavy flavor dynamics in hot dense medium

- Heavy meson (D) distribution inside a reconstructed jet is sensitive to gluon fragmentation function, this is a good observable to constrain the flavor origin of heavy flavor meson

Summary

- Detailed study of flavor origin of observed final state is significant to probe energy loss mechanism in heavy ion collisions

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- Heavy meson (D) distribution inside a reconstructed jet is sensitive to gluon fragmentation function, this is a good observable to constrain the flavor origin of heavy flavor meson

Thanks for your attention!