Constraining Heavy Quark Energy Loss Using B and D Mesons in Heavy Ion Collision

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Outline

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4. QGP Evolution Model
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Motivation

- QGP is formed at high temperature or at high density. It consists of deconfined quarks and gluons.
- Heavy quarks (M_c =1.3 GeV and M_b =4.7 GeV) production can be treated using pQCD.
- Heavy quarks interact with the medium and do not become part of the medium and thus probe the opacity of the QGP medium.

Heavy Quark Energy Loss

- When heavy quark traverse the QGP medium, they loose energy either due to the elastic collisions with the plasma partons or by radiating a gluon or both.
- Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles.
- Radiative energy loss comes from the processes in which there are more outgoing than incoming particles.
- Many formalisms have been proposed for the collisional as well as the radiative energy loss of heavy quarks. We used PP (Peigne-Peshier) to calculate the collisional energy loss while DGLV (Djordjevic, Gyulassy, Levai and Vitev) and generalized dead cone approach AJMS (Abir, Jamil, Mustafa and Srivastava) to calculate the radiative energy loss.

Peigne Peshier Formalism

• The rate of energy loss (dE/dx) of heavy quark due to elastic collision given by Braaten and Thoma in the limit $q \ll E$ which is good for $E \ll M^2/T$.
• Peigne and Peshier extended this calculation in the domain $E \gg M^2/T$.

$$\frac{dE}{dx} = \frac{4\pi\alpha_s^2 T^2}{3} \left[\left(1+\frac{N_f}{6}\right)\log\frac{E\ T}{\mu_g^2} + \frac{2}{9}\log\frac{E\ T}{M^2} + c(N_f)\right] \tag{1}$$

Here $\mu_g = \sqrt{4\pi\ \alpha_s\ \ T^2\ \left(1+\frac{N_f}{6}\right)}$ is the Debye screening mass and $c(N_f) = 0.146 N_f + 0.05$.

Phys. Rev. D77, 114017 (2008).

DGLV Formalism

• DGLV used reaction operator formalism to obtain the energy loss of quark jets by gluon radiation.

• Analytical expression is obtained for energy loss in powers of gluon opacity (L/λ). This formalism was extended to obtain the energy loss of heavy quark.

• Wicks simplified this formalism for the first order of opacity expansion.

$$\frac{\Delta E}{L} = E\, \frac{C_F \alpha_s}{\pi} \frac{1}{\lambda} \int_{\frac{m_g}{E+p}}^{1-\frac{M}{E+p}} dx \int_0^\infty \frac{4\ \mu_g^2\ q^3\ dq}{\left(\frac{4Ex}{L}\right)^2 + (q^2+\beta^2)^2} \times (A \log B + C) \quad , \tag{2}$$

where $\beta^2 = m_g^2(1-x) + M^2x^2, \quad \lambda^{-1} = \rho_g \sigma_{Qg} + \rho_q \sigma_{Qq},$

$m_g = \frac{\mu_g}{\sqrt{2}}, \ \ \rho_g = 16^3 \frac{1.202}{\pi^2},$

$\rho_q = 9N_f T^3 \frac{1.202}{\pi^2}, \ \ \sigma_{Qq} = \frac{9\pi\alpha_s^2}{2\mu_g^2}, \quad \sigma_{Qg} = \frac{4}{9}\sigma_{Qq}.$

Nucl. Phys. A784, 426 (2007)

The function A, B and C are given as

$$A = \frac{2\beta^2}{f_\beta^3}\left(\beta^2 + q^2\right), \quad (3)$$

$$B = \frac{(\beta^2 + K)(\beta^2 Q_\mu^- + Q_\mu^+ Q_\mu^+ + Q_\mu^+ f_\beta)}{\beta^2\left(\beta^2(Q_\mu^- - K) - Q_\mu^- K + Q_\mu^+ Q_\mu^+ + f_\beta f_\mu\right)}, \quad (4)$$

$$C = \frac{1}{2q^2 f_\beta^2 f_\mu}\Big[\beta^2\mu_g^2(2q^2 - \mu_g^2) + \beta^2(\beta^2 - \mu_g^2)K + Q_\mu^+(\beta^4 - \quad (5)$$

$$2q^2 Q_\mu^+) + f_\mu\left(\beta^2(-\beta^2 - 3q^2 + \mu_g^2) + 2q^2 Q_\mu^+\right) + 3\beta^2 q^2 Q_k^-\Big]. \quad (6)$$

Here

$$K = 2px(1-x), \;\; Q_\mu^\pm = q^2 \pm \mu_g^2, \;\;\; Q_\mu^\pm = q^2 + K, \quad (7)$$

$$f_\beta = f(\beta, Q_\mu^-, Q_\mu^+), \;\;\; f_\mu = f(\mu_g, Q_k^+, Q_k^-), \quad (8)$$

$$f(x,y,z) = \sqrt{x^4 + 2x^2 y + z^2}\;. \quad (9)$$

Generalized Dead Cone Approach (AJMS)

The rate of radiative energy loss of heavy quark

$$\frac{dE}{dx} = \frac{< \omega >}{\lambda}, \tag{10}$$

here $< \omega >$ is the mean energy of the emitted gluon and λ is the mean free path of the traversing quark.

$$< \omega > = \frac{\int d\omega \ \int \mathcal{D} \ d\eta}{\int \frac{1}{\omega} \ d\omega \int \mathcal{D} \ d\eta}, \tag{11}$$

$$\mathcal{D} = \left(1 + \frac{M^2}{s} e^{2\eta}\right)^{-2}, \ \eta = -\ln\tan\left(\frac{\theta}{2}\right), \tag{12}$$

$$\lambda^{-1} = \left(\rho_q + \frac{9}{4}\rho_g\right)\sigma \quad , \tag{13}$$

$$\sigma = 4C_A\alpha_s^3 \int \frac{1}{(q_\perp^2)^2} \ dq_\perp^2)^2 \int \frac{1}{\omega} d\omega \int \mathcal{D} \ d\eta. \tag{14}$$

arXiv:1109.5539, Phys. Rev. C48, 1275 (1993).

Generalized Dead Cone Approach Continue.....

$$\frac{dE}{dx} = 24\alpha_s^3\left(\rho_q + \frac{9}{4}\rho_g\right) \int_{q_\perp^2|_{min}}^{q_\perp^2|_{max}} \frac{1}{(q_\perp^2)^2} dq_\perp^2 \int_{\omega_{min}}^{\omega_{max}} d\omega \int_{\eta_{min}}^{\eta_{max}} \mathcal{D}\, d\eta. \quad (15)$$

$$\frac{dE}{dx} = 24\alpha_s^3\left(\rho_q + \frac{9}{4}\rho_g\right)\frac{1}{\mu_g}(1-\beta_1)\left(\sqrt{\frac{1}{(1-\beta_1)}\log\left(\frac{1}{\beta_1}\right)} - 1\right)\mathcal{F}(\delta) \quad (16)$$

where

$$\mathcal{F}(\delta) = 2\delta - \frac{1}{2}\log\left(\frac{1+\frac{M^2}{s}e^{2\delta}}{1+\frac{M^2}{s}e^{-2\delta}}\right) - \frac{\frac{M^2}{s}\sinh(2\delta)}{1+2\frac{M^2}{s}\cosh(2\delta)+\frac{M^4}{s^2}} \quad (17)$$

$$\delta = \frac{1}{2}\log\left[\frac{1}{(1-\beta_1)}\log\left(\frac{1}{\beta_1}\right)\left(1+\sqrt{1-\frac{(1-\beta_1)}{\log\left(\frac{1}{\beta_1}\right)}}\right)^2\right]. \quad (18)$$

The previous expression differs with the original AJMS formalism where $\mathcal{F}(\delta)$ is given by

$$\mathcal{F}(\delta) = 2\delta - \frac{1}{2}\log\left(\frac{1+\frac{M^2}{s}e^{2\delta}}{1+\frac{M^2}{s}e^{-2\delta}}\right) - \frac{\frac{M^2}{s}\cosh(\delta)}{1+2\frac{M^2}{s}\cosh(\delta)+\frac{M^4}{s^2}} \qquad (19)$$

$$\delta = \frac{1}{2}\log\left[\frac{1}{(1-\beta_1)}\log\left(\frac{1}{\beta_1}\right)\left(1+\sqrt{1-\frac{(1-\beta_1)^{1/2}}{\left(\log\frac{1}{\beta_1}\right)^{1/2}}}\right)^2\right] \qquad (20)$$

Phys. Lett. B715, 183 (2012).

QGP Evolution Model : Present

Heavy quarks are produced at a point (r, ϕ). The distance travelled by heavy quark in the plasma is given by

$$L(\phi, r) = \sqrt{R^2 - r^2 \sin^2 \phi} - r \cos \phi. \qquad (21)$$

We calculated average path length ($< L >$) considering nucleus as a sharp sphere.

Effective path length is calculated as

$$L_{eff} = \min[< \mathrm{L} >, \mathrm{v_T} \times \tau_{\mathrm{F}}]. \qquad (22)$$

We use entropy conservation condition $s(T)V(\tau) = s(T_0)V(\tau_0)$ to obtain temperature as a function of the time. The EOS obtained by lattice QCD along with hadronic resonance gas (HRG) are used as input.

The transverse size for a given centrality is obtained as $R(N_{part}) = R_A\sqrt{2A/N_{part}}$.

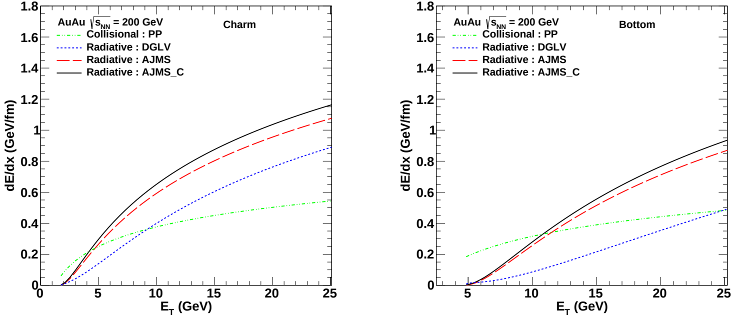
Vineet Kumar and Prashant Shukla, arXiv:1410.3299.

QGP Evolution Model :Parameter

Model	Exp.	Centrality (%)	N_{part}(given)	$dN/d\eta$(measured)
Present	RHIC	0-10	329	623.54
Present	LHC	0-10	355.34	1447.26
Present	LHC	0-20	308.38	1205.77

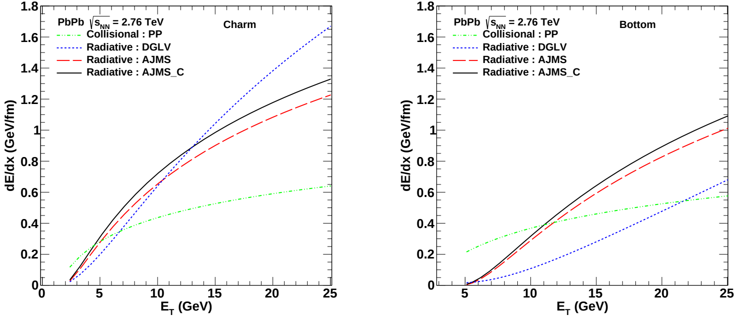
Model	Exp.	Centrality (%)	b (fm)	$< L >$ (fm)	τ_0(given) (fm/c)	τ_F (fm/c)	T_0 (GeV)
Present	RHIC	0-10	3.268	5.63	0.6	3.0	0.340
Present	LHC	0-10	3.32	5.73	0.3	6.0	0.488
Present	LHC	0-20	4.70	5.62	0.3	6.0	0.481
Old	RHIC	0-10	0.0	5.78	0.2	2.63	0.400
Old	LHC	0-10/20	0.0	6.14	0.2	5.90	0.525

dE/dx for charm and bottom quark at $\sqrt{s_{NN}}$ =200 GeV



- Collisional energy loss is similar for charm and bottom quark.
- For radiative energy loss, there is large difference between DGLV and AJMS specially for bottom quark.
- At high p_T, radiative energy loss dominates.

dE/dx for charm and bottom quark at $\sqrt{s_{NN}}$ =2.76 TeV



- Collisional energy loss increases from RHIC to LHC.
- When we move from RHIC to LHC,the radiative energy loss increases.
- dE/dx for charm quark (DGLV) increases dramatically from RHIC to LHC because of explicitly L dependence inside the expression.

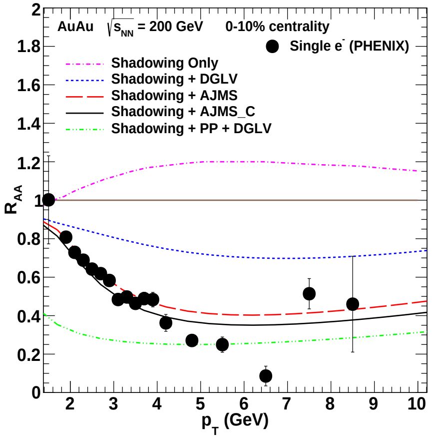
Nuclear modification factor R_{AA}

The nuclear modification factor (R_{AA}) is defined as the ratio of yield in nucleus nucleus (AA) collision to yield in pp collision scaled by a normalizing factor (T_{AA}), known as nuclear overlapping function.

$$R_{AA} = \frac{1}{T_{AA}(b)} \frac{dN^{AA}/dp_T dy}{d\sigma^{pp}/dp_T dy} \tag{23}$$

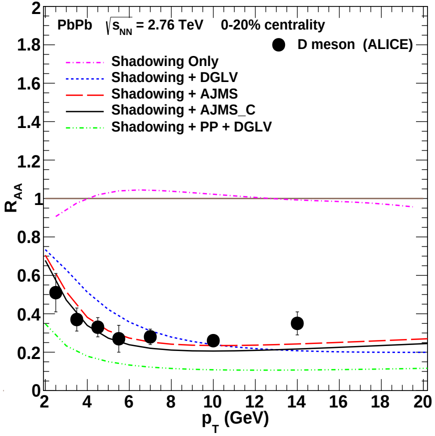
If $R_{AA} = 1$, No medium modification
If $R_{AA} > 1$, Enhancement
If $R_{AA} < 1$, Suppression

R_{AA} for charm quark at $\sqrt{s_{NN}}$ =200 GeV



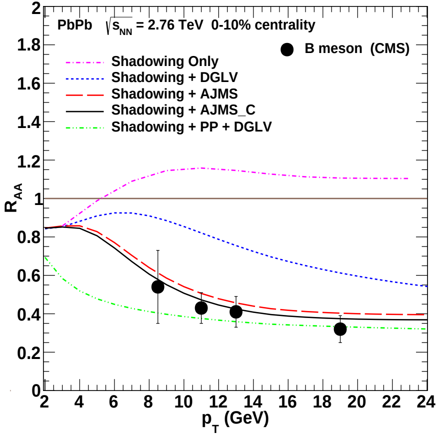
- DGLV+PP describes the data at high p_T range.
- AJMS formalism reproduces the data without collisional energy loss.

R_{AA} for D meson at $\sqrt{s_{NN}}$ =2.76 TeV



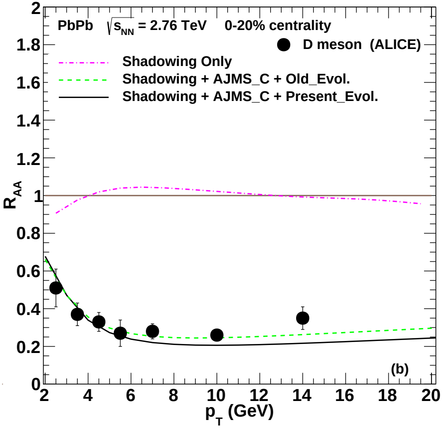
- AJMS and DGLV reproduce similar suppression at high p_T.
- If we include collisional energy loss, there will be large suppression.

R_{AA} for B meson at $\sqrt{s_{NN}}$ =2.76 TeV



- DGLV+PP reproduces the data.
- AJMS (without collisional) reproduces the data.

R_{AA}: Dependence on the QGP evolution model



- We compare AJMS formalism with present and old QGP evolution model.

Summary

- We study the two different radiative energy loss formalisms (DGLV and AJMS). There is large difference between them.
- Collisional energy loss is similar for charm and bottom quark.
- If we add the radiative and collisional energy loss, it does not describe the data specially in low p_T range.
- DGLV+PP are reproducing the data at high p_T range.
- AJMS formalism (radiative only) surprisingly reproduces the data in all measurements.

Thank You

Back up slides

QGP Evolution Model : Old

In old QGP evolution model, the time formation of a quark gluon plasma is calculated as

$$\tau = L_{eff}/2 \tag{24}$$

The gluon density at time τ is calculated as

$$\rho(\tau) = \frac{1}{\pi R^2 \tau} \frac{dN_g}{dy} \tag{25}$$

dN_g/dy is the rapidity distribution of gluon density.
The temperature of the quark gluon plasma is calculated from the gluon density

$$T(\tau) = \left(\frac{\pi^2}{1.202} \frac{\rho(\tau)}{(9N_f + 16)} \right)^{1/3} \tag{26}$$

Nucl. Phys. A784, 426 (2007), Phys. Lett. B715, 183 (2012).

Integration Limits

The minimum limit of the integration

$$q_\perp^2|_{min} \approx \omega_{min}^2 \approx k_\perp^2|_{min} \approx \mu_g^2, \tag{27}$$

The maximum limit of the integration

$$q_\perp^2|_{max} = CET, \; C = \frac{3}{2} - \frac{M^2}{4ET} + \frac{M^4}{48E^2T^2\beta_0} \log\left[\frac{M^2+6ET(1+\beta_0)}{M^2+6ET(1-\beta_0)}\right], \tag{28}$$

$$\beta_0 = \sqrt{1 - \frac{M^2}{E^2}} \; . \tag{29}$$

arXiv:1109.5539, arXiv:9711059 and Chin. Phys. Lett.22, 72 (2005).

$$\omega_{max}^2 = < q_\perp^2 >= \frac{q_\perp^2|_{min} \; q_\perp^2|_{max}}{q_\perp^2|_{max} - q_\perp^2|_{min}} \; \log\left(\frac{q_\perp^2|_{max}}{q_\perp^2|_{min}}\right) \; , \tag{30}$$

$$\omega_{max}^2 = \frac{\mu_g^2}{(1-\beta_1)} \log\left(\frac{1}{\beta_1}\right), \quad \beta_1 = \frac{\mu_g^2}{CET}. \tag{31}$$

arXiv:9711059 and Chin. Phys. Lett.22, 72 (2005).

Integration Limits continue....

Using the relation $\omega = k_\perp \cosh\eta$, the finite cut on ω and $k_\perp$ leads to an inequality

$$\frac{\omega_{max}}{k_\perp|_{min}} < \cosh\eta. \qquad (32)$$

We can write the above expression as $|\eta| < \delta$, where

$$\delta = \frac{1}{2}\log\left[\frac{1}{(1-\beta_1)}\log\left(\frac{1}{\beta_1}\right)\left(1+\sqrt{1-\frac{(1-\beta_1)}{\log\left(\frac{1}{\beta_1}\right)}}\right)^2\right]. \qquad (33)$$