Heavy quark jet propagation and heavy flavour suppression in a fluctuating quark-gluon plasma at the LHC energies

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Outline

- Heavy Quarks(HQs) and QGP
- Chromoelectro-magnetic field fluctuations in the QGP
- HQ Energy loss and gain
- HQ Dynamics
- Nuclear Modification Factor(R_{AA}) of D and B mesons
- Summary and Outlook

Heavy Quarks(HQs) & QGP

- HQs are produced in the early stage by pQCD process

  ($\mathbf{M_Q >> \Lambda_{QCD}}$). i.e., early production (before equilibrium).

  Production time : $\boldsymbol{\tau_Q = 1/2M_Q \leq 0.1}$ **fm**

- No later production (no thermal production) of HQs.

  Since, $\mathbf{M_Q >> T}$. Initial distribution of heavy quarks becomes frozen.

- Thermalization time for HQs : $\boldsymbol{\tau_{th}^{Q} \sim (M_Q/T) \times \tau_{th}^{u,d}}$

  i.e., $\boldsymbol{\tau_{th}^{g} < \tau_{th}^{u,d} < \tau_{th}^{Q}}$. **[G. Moore & D. Teaney, Phys.Rev. C71 (2005) 064904]**

- They go through all the QGP life time, can be considered as a probe of QGP.

- g, u, d thermalize early and provide an expanding thermal background and HQs execute Brownian motion in this background.

Chromoelectro-magnetic field fluctuations in QGP

- Partons inside the QGP produce chromoeletro-magnetic field due to their motions.
- The chromoeletro-magnetic field produced is fluctuating in nature.
- The HQs experience a statistical change in energy due to the fluctuations of this field and the velocity of HQs under the influence of this field.
- This effect leads to the energy gain of heavy qaurks, significantly at the lower momentum.

[Chakraborty, Mustafa and Thoma, Phys. Rev. C 75, 064908 (2007)]

HQ Energy gain

- The leading-log contribution of this energy gain is obtained as,

$$\left(\frac{dE}{dx}\right)_{\rm fl}^{\rm LL} = 2\pi C_F \alpha_s^2 \left(1+\frac{n_f}{6}\right)\frac{T^3}{Ev^2}\ln\frac{1+v}{1-v}\ln\frac{k_{\rm max}}{k_{\rm min}}$$

$k_{\rm min} = \mu_g =$ Debye mass, $k_{\rm max} = \min\left[E, \frac{2q(E+p)}{\sqrt{M^2+2q(E+p)}}\right]$

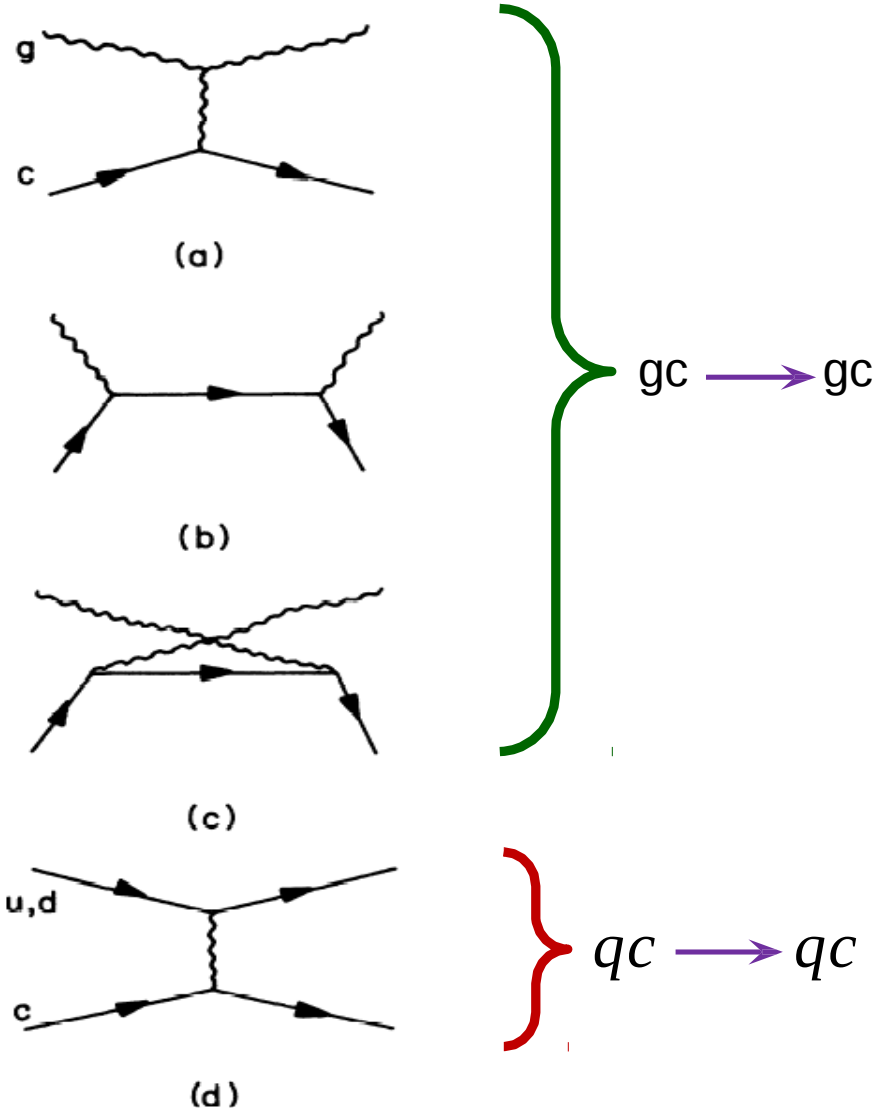
q ~ T is the typical momentum of the thermal partons.

- Physically this energy gain of a heavy quark is interpreted as the heavy quark absorbs gluons during its propagation.

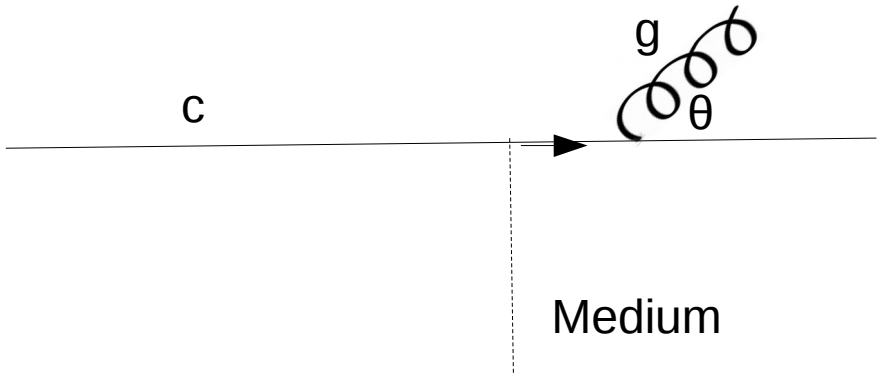
[P. Chakraborty, M.G. Mustafa and M.H. Thoma, Phys. Rev. C 75, 064908 (2007)]

HQ Energy loss: Collisonal vs Radiative

Elastic processes



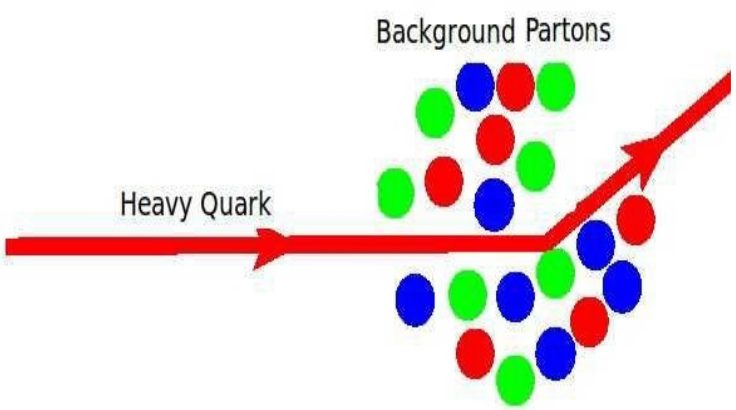
Radiative processes

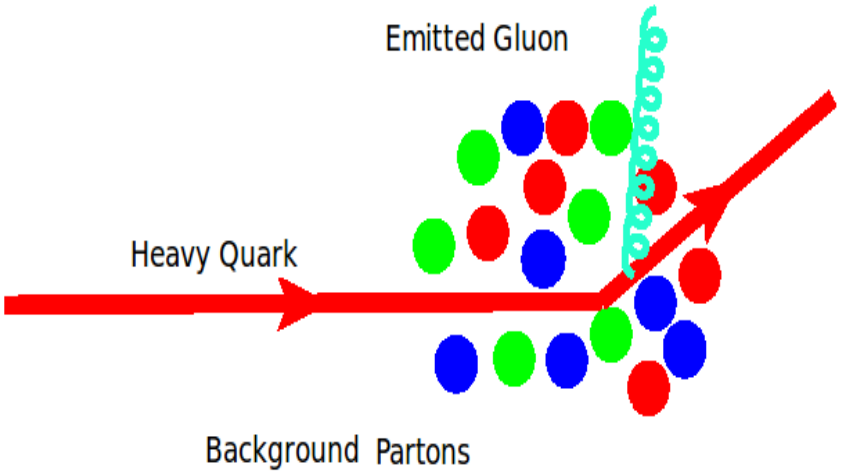


- HQ looses energy in two different ways:
  - i. Elastic collisions
  - ii. Gluon radiations

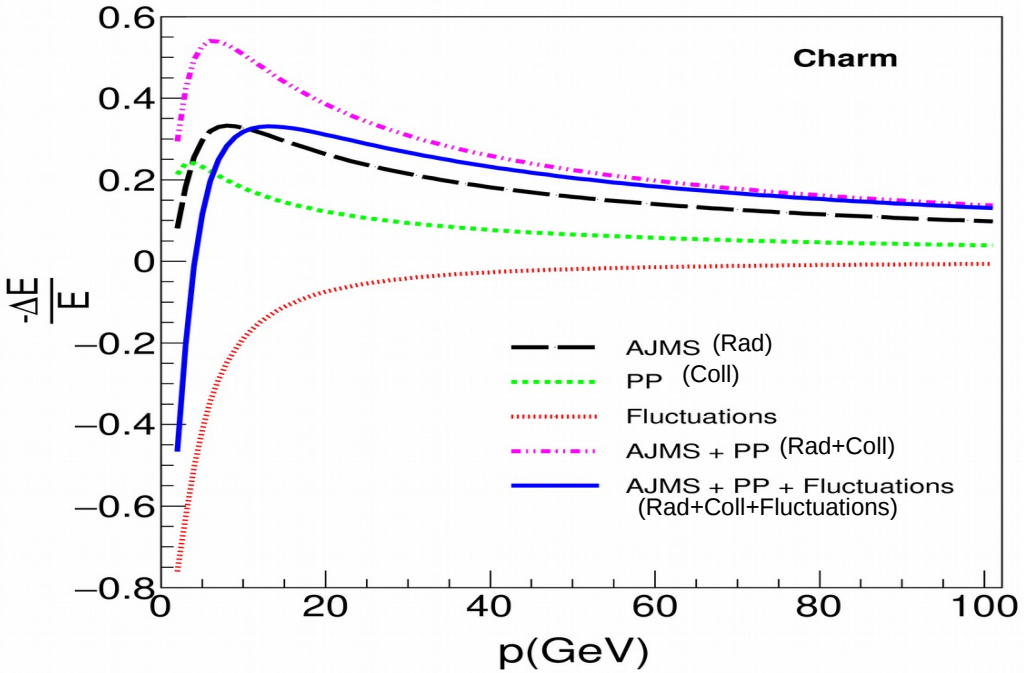
HQ Energy loss: Collisonal and Radiative Loss

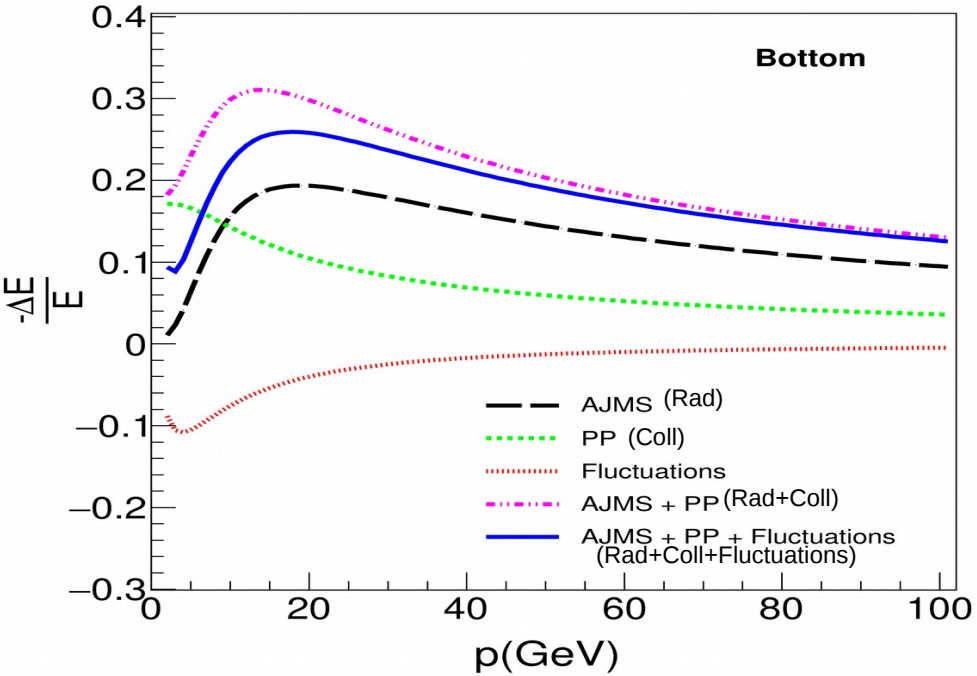
- Detailed calculation of collisional energy loss was made by Brateen and Thoma, assumed momentum transfer q << E.
  [E. Brateen and M.H. Thoma, Phys. Rev. D 44, R2625 (1991)]
- Not valid for E >> M^2/T.
- The improved differential collisional energy loss calculation by Peigne and Pashier (PP). **[S. Peigne and A. Peshier, Phys. Rev. D 77, 114017 (2008)]**
- Differential Radiative Loss dE/dx first estimation:
  [Pal, Mustafa and Srivastava, Phys. Lett. B 428 (1998) 234]
- The dead cone corrected calculation for radiative energy loss by Abir, Jamil, Mustafa and Srivastava (AJMS).
  [Abir, Jamil, Mustafa and Srivastava, Phys. Lett. B 715 (2012) 183]





HQ Energy loss and gain

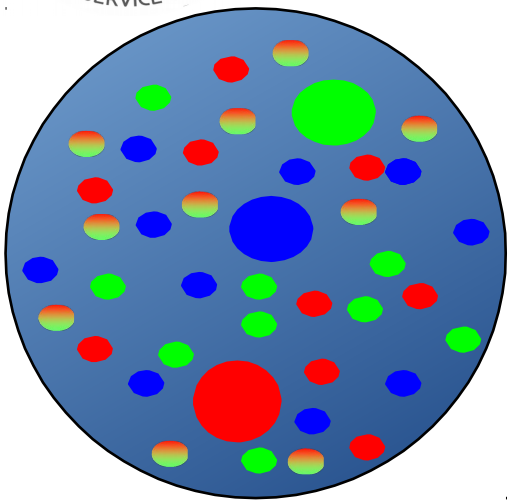




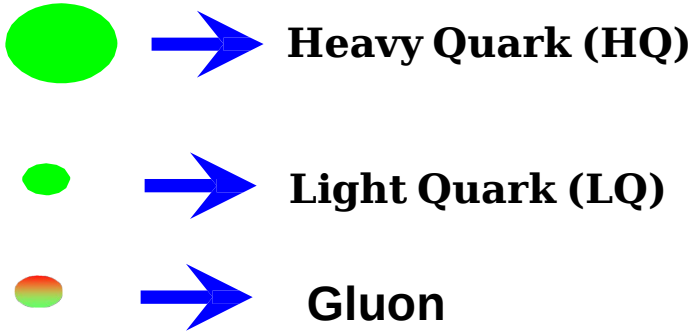
[A.I. Sheikh, Z. Ahammed, P. Shukla and M.G. Mustafa, Phys. Rev. C 98, 034915 (2018)]

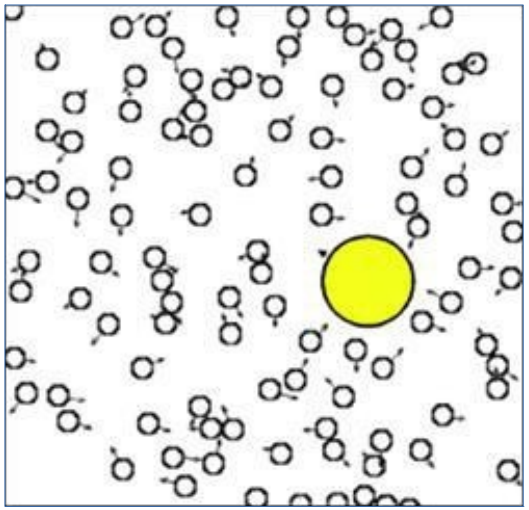
- At lower momentum(below 7-8 GeV), the collisional loss dominates over radiative energy loss both for charm and bottom quarks. At higher momentum radiative loss dominates.
- The effect of fluctuations on HQ energy loss is significant at lower momentum. The energy gain is more at lower momentum. i.e. gained energy becomes substantial in the low velocity limit.
- The energy gain due to fluctuations reduces the total energy loss and it has certainly an effect on heavy flavour Nuclear Modification Factor(R_{AA}).

HQ Dynamics



Heavy Quark Brownian Motion





The propagation of heavy quarks through the QGP can be treated as interactions between **equilibrium** and **non equilibrium** degrees of freedom.

Fokker-Planck equation can be used to study the evolution of charm and bottom quarks. Just like evolution of pollen grains on the background of water molecules, where water molecules are in equilibrium and the pollen grains execute Brownian motion in the water.

Water → **Light quarks and gluons**

Pollen grains → **Heavy quarks**

Boltzmann transport equation

$$\left(\frac{\partial}{\partial t} + \frac{p}{E}\frac{\partial}{\partial x} + F\frac{\partial}{\partial p}\right) f(x,p,t) = \left(\frac{\partial f}{\partial t}\right)_{\text{coll}}$$

[B. Svetitsky PRD 37(1987)2484]

- Uniform plasma, i.e the distributon function is independent of x.
- No external force.
- Soft scatterings

Fokker-Planck equation

$$\frac{\partial f}{\partial t} = \left(\frac{\partial f}{\partial t}\right)_{\text{coll}} = \frac{\partial}{\partial p_i}\left(A_i(p)f + \frac{\partial}{\partial p_i}[B_{ij}(p)f]\right)$$

$$A_i = \int d^3p\,\omega(p,k)k_i$$

and

$$B_{ij} = \int d^3p\,\omega(p,k)k_ik_j$$

Drag coefficient

Diffusion coefficient

Rate of collisions which changes the momentum of the heavy quark from p to p-k

$$\omega(p,k) = g_j \int \frac{d^3q}{(2\pi)^3} f'(q) v \sigma_{p,q\to p-k,p+k}$$

Langevin equation

- Fokker-Planck eqn. can be recast to Langevin eqn.

Drag coefficient

$$\frac{dp}{dt} = -\gamma(p)p + \xi$$

Determinstic force or drag force

Stochastics force, satisfies $< \xi_i(t)\xi_j(t') >= D\delta(t-t')\delta_{ij}$

- Transport coefficients are connected by Fluctuation dissipation theorem : $D = \gamma ET$

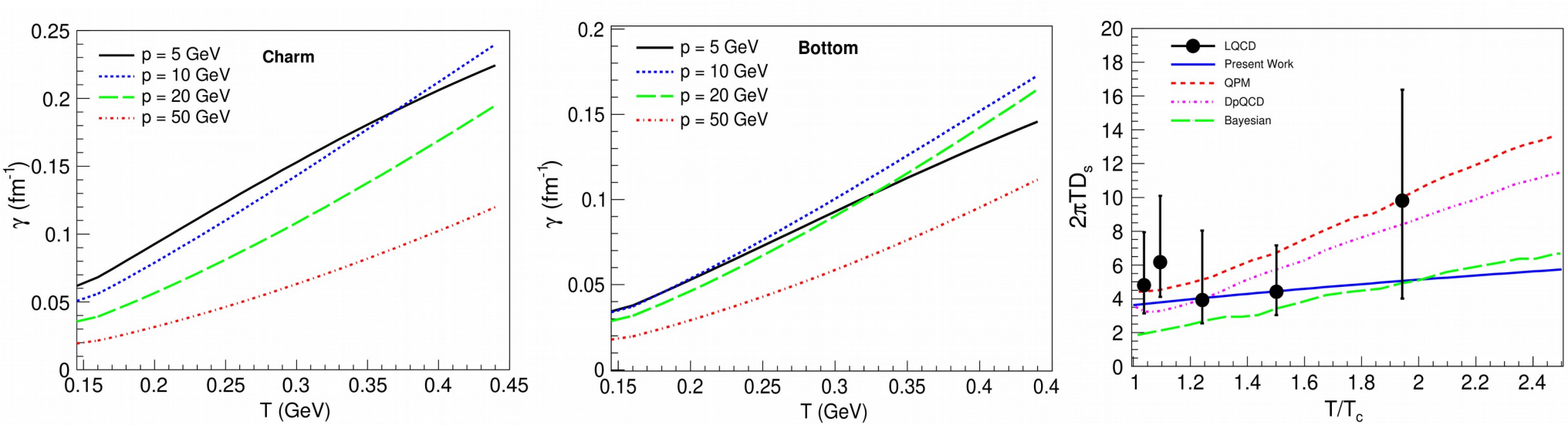
- For numerical simulation, Heavy quark initial production :

  for position space, Glauber Model

  for momentum space, NLO pQCD

Transport coefficients

- Backgrond matter is hydrodynamically evolving, described by (3+1)-D viscous hydro model, vHLLE **[Karpenko et. al., Comput. Phys. Commun. 185, 3016 (2014)]**
- Drag coefficient is estimated by, $\gamma = \frac{1}{p}\left(-\frac{dE}{dx}\right)$
- Estimated spatial diffusion coefficient is consistent with other model calculations



[A.I. Sheikh and Z. Ahammed; arXiv:1902.02477]

Nuclear Modification factor (R_{AA})

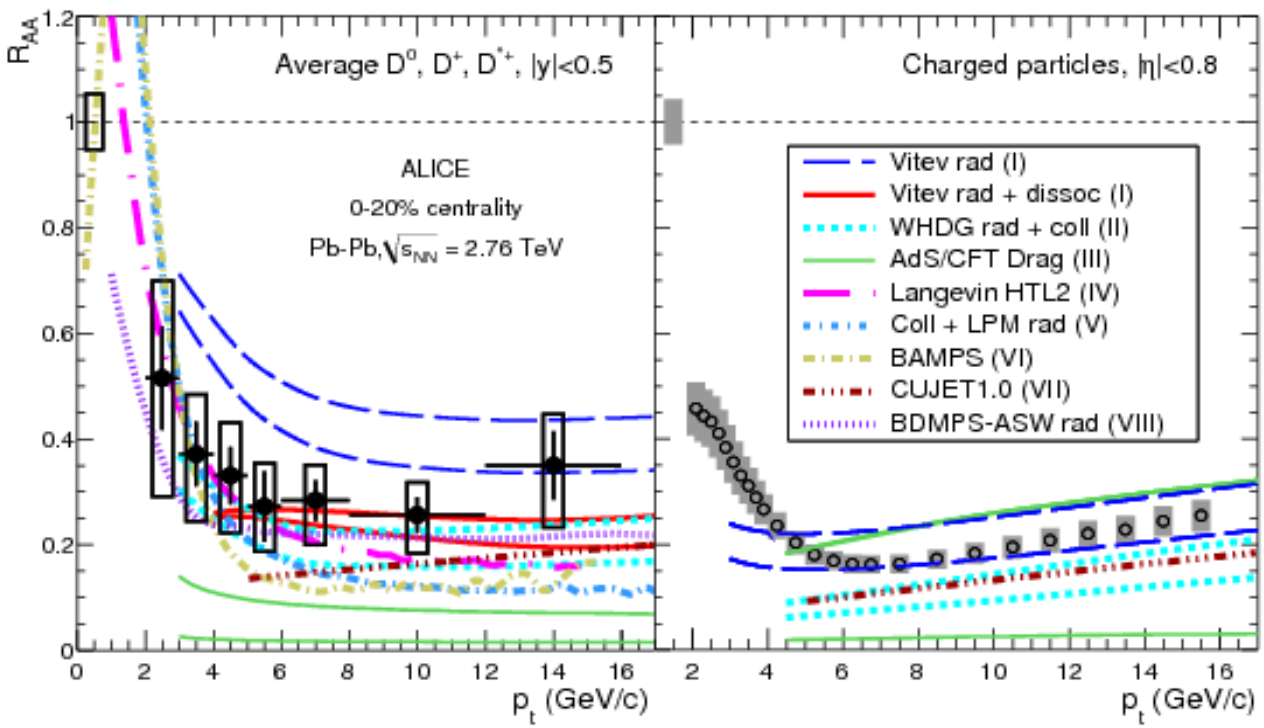
Nuclear Modification factor :

$$R_{AA} = \frac{\left(\frac{dN}{d^2p_T\,dy}\right)^{AA}}{N_{coll}\left(\frac{dN}{d^2p_T\,dy}\right)^{pp}}$$

- i.e. R_{AA} is the ratio b/w the yields in nuclear collisions and binary scalled p-p collisions.

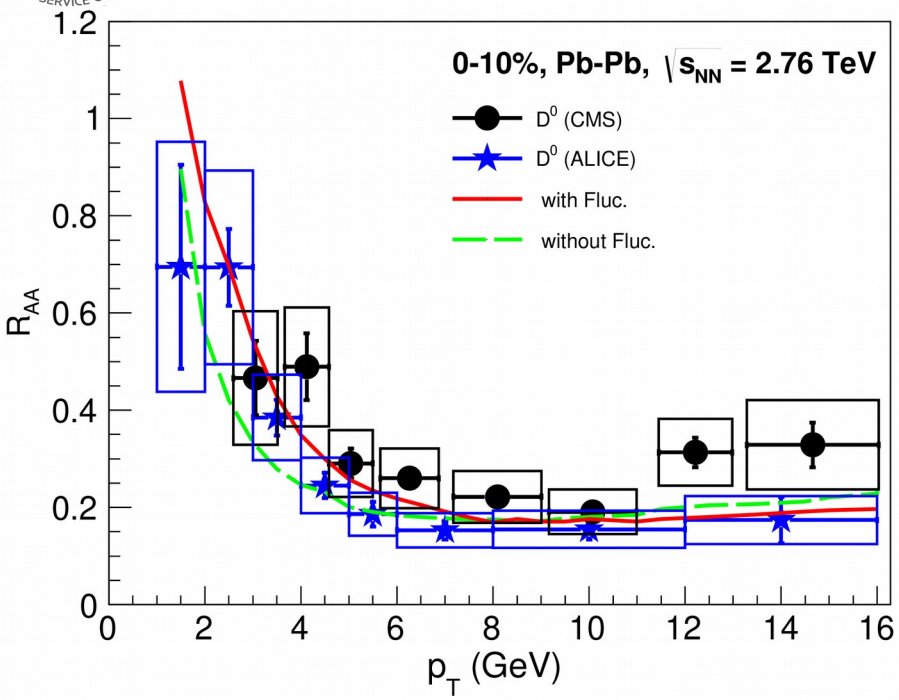
  If R_{AA} = 1 ; No medium / No Interactions

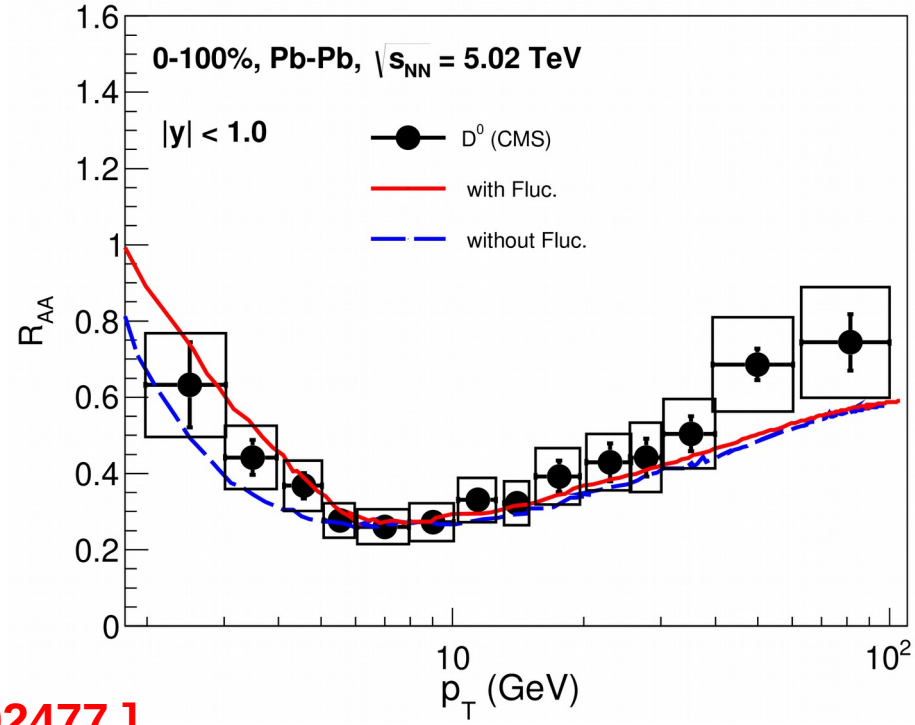
  If R_{AA} < 1 ; Medium / Interactions



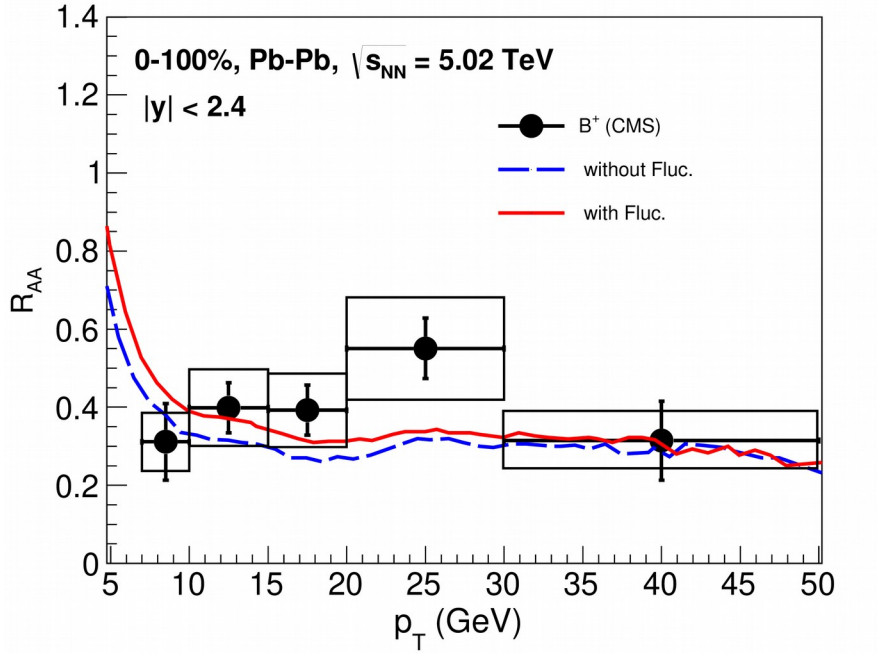
- Previous models, trying to explain the experimental results for R_{AA}.
- Explanation of R_{AA} of heavy mesons is top chalange for all models.

R_{AA} of D and B mesons





[A.I. Sheikh and Z. Ahammed, arXiv:1902.02477]



- Calculated R_{AA} for both with and without fluctuations describes the experimental measurements within uncertainities.
- However, at lower momentum, results with fluctuations are better.
- Energy gain due to fluctuations has great impact on R_{AA}, significantly at lower momenta.

Summary and Outlook

- We have developed a heavy flavour Langevin diffusion framework under the hydrodynamically evolving background medium.
- The chromoelectro-magnetic field fluctuations are important to study the heavy flavour suppressions at the LHC.
- The effect of the fluctuations is more at the lower momentum region.
- The hadronization for heavy quarks is done only by fragmentation. Coalescence is also important, will be developed in future.

Thank You!

Backup

HQ Energy loss: Radiative
Suppression due to Mass and Dead Cone

- General notion: heavy quark radiates less than light quark

$qq' \to qq'$	$\lvert\mathcal{M}_{qq'\to qq'}\rvert^2 = \frac{8}{9} g^4 \frac{s^2}{t^2}$
$Qq \to Qq$	$\lvert\mathcal{M}_{Qq\to Qq}\rvert^2 = \frac{8}{9} g^4 \frac{s^2}{t^2} \left(1 - \frac{M^2}{s}\right)^2$
$qq' \to qq'g$	$\lvert\mathcal{M}_{qq'\to qq'g}\rvert^2 = 12 g^2 \frac{8}{9} g^4 \frac{s^2}{t^2} \frac{1}{k_\perp^2}$
$Qq \to Qqg$	$\lvert\mathcal{M}_{Qq\to Qqg}\rvert^2 = 12 g^2 \frac{8}{9} g^4 \frac{s^2}{t^2} \frac{1}{k_\perp^2}$?

2001 Dokshitzer and Kharzeev proposed (Phys. Lett. B 519, 199 (2001)) "dead cone" effect => heavy quark small energy loss.

$$\left(1 + \frac{\theta_0^2}{\theta^2}\right)^{-2} \qquad \theta_0 = M/E$$

Generalized dead cone

$$|\mathcal{M}_{Qq\to Qqg}|^2 = 12g^2 |\mathcal{M}_{Qq\to Qq}|^2 \frac{1}{k_\perp^2}\left(1+\frac{M^2}{s\tan^2(\frac{\theta}{2})}\right)^{-2}$$

$$= 12g^2 |\mathcal{M}_{Qq\to Qq}|^2 \frac{1}{k_\perp^2}\left(1+\frac{M^2}{s}e^{2\eta}\right)^{-2}$$

$$\boxed{\mathcal{D} = \left(1+\frac{M^2}{s\tan^2(\frac{\theta}{2})}\right)^{-2}}$$

..... *Dead Cone Factor*

Abir, Greiner, Martinez, Mustafa, Uphoff, PRD 85 (2012) 054012

HQ energy gain

[P. Chakraborty, M.G. Mustafa and M.H. Thoma, Phys. Rev. C 75, 064908 (2007)]

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$$\epsilon_T(\omega,k) = 1 - \frac{m_D^2}{2\omega^2}\left\{\frac{\omega}{k^2} + \left(1 - \frac{\omega^2}{k^2}\right)\frac{\omega}{2k}\left[\ln\left|\frac{\omega+k}{\omega-k}\right| - i\pi\Theta(k^2-\omega^2)\right]\right\},$$

where $m_D^2 = g^2T^2(1+N_f/6)$ is the Debye mass squared. Substitution of Eq. (3) together with Eqs. (4) and (5) in Eq. (2) gives the polarization loss of the moving parton [9,10].

The previous formula for the energy loss in Eq. (2) does not take into account the field fluctuation in the plasma and the particle recoil in collisions. To accommodate these effects it is necessary to replace Eq. (2) with [16,17],

$$\frac{dE}{dt} = \left\langle Q^a \vec{v}(t)\cdot\vec{\mathcal{E}}_t^a(\vec{r}(t),t)\right\rangle, \tag{6}$$

where $\langle\cdots\rangle$ denotes the statistical averaging operation. It is to be noted that here two averaging procedures are performed: (i) an ensemble average with respect to the equilibrium density matrix and (ii) a time average over random fluctuations in plasma. These two operations are commuting and only after both of them are performed the average quantity takes up a smooth value [18]. In the following, we will explicitly denote the ensemble average by $\langle\cdots\rangle_\beta$ wherever required to avoid possible confusion.

$$\vec{v}(t) = \vec{v}_0 + \frac{1}{E_0}\int_0^t dt_1\, Q^a \vec{\mathcal{F}}_t^a(\vec{r}_0(t_1),t_1),$$

$$\vec{\mathcal{E}}_t^a(\vec{r}(t),t) = \vec{\mathcal{E}}_t^a(\vec{r}_0(t),t) + \frac{Q^b}{E_0}\int_0^t dt_1\int_0^{t_1} dt_2 \times \sum_j \mathcal{E}_{j,t}^b(\vec{r}_0(t_2),t_2)\frac{\partial}{\partial r_{0j}}\vec{\mathcal{E}}_t^a(\vec{r}_0(t),t), \tag{10}$$

where, $\vec{r}_0(t) = \vec{v}_0 t$. Substituting Eq. (10) into Eq. (6) and using $\langle \mathcal{E}_i^a \mathcal{B}_j^a\rangle_\beta = 0$ [24], we get

$$\begin{aligned}\frac{dE}{dt} &= \left\langle Q^a \vec{v}_0\cdot\vec{\mathcal{E}}_t^a(\vec{r}_0(t),t)\right\rangle_\beta \\ &+ \frac{Q^aQ^b}{E_0}\int_0^t dt_1\left\langle\vec{\mathcal{E}}_t^b(\vec{r}_0(t_1),t_1)\cdot\vec{\mathcal{E}}_t^a(\vec{r}_0(t),t)\right\rangle_\beta \\ &+ \frac{Q^aQ^b}{E_0}\int_0^t dt_1\int_0^{t_1} dt_2\left\langle\sum_j \mathcal{E}_{t,j}^b(\vec{r}_0(t_2),t_2) \times \frac{\partial}{\partial r_{0j}}\vec{v}_0\cdot\vec{\mathcal{E}}_t^a(\vec{r}_0(t),t)\right\rangle_\beta .\end{aligned} \tag{11}$$

Because the mean value of the fluctuating part of the field equals zero, $\langle\vec{\mathcal{E}}\rangle_\beta = 0$, $\langle\vec{\mathcal{E}}_t(\vec{r}(t),t)\rangle_\beta$ equals the chromoelectric

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HQ energy gain

[P. Chakraborty, M.G. Mustafa and M.H. Thoma, Phys. Rev. C 75, 064908 (2007)]

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Using the Fourier transform of $\tilde{\mathcal{E}}_i$ together with Eqs. (12) and (13), we obtain from Eq. (11) the energy loss of the parton due to fluctuations as (see the Appendix),

$$\left.\frac{dE}{dt}\right|_{\rm fl} = \frac{C_F\alpha_s}{16\pi^3 E}\int d^3k\left[\frac{\partial}{\partial\omega}\langle\omega\vec{\tilde{\mathcal{E}}}_L^2\rangle_\beta + \langle\vec{\tilde{\mathcal{E}}}_T^2\rangle_\beta\right]_{\omega=\vec{k}\cdot\vec{v}}, \quad (14)$$

where $\langle\vec{\tilde{\mathcal{E}}}_L^2\rangle$ and $\langle\vec{\tilde{\mathcal{E}}}_T^2\rangle$ denote the longitudinal and transverse field fluctuations, respectively, and $E = E_0$ is the initial energy of the parton.

Equation (14) can be recast as (see the Appendix),

$$\left.\frac{dE}{dt}\right|_{\rm fl} = \frac{C_F\alpha_s}{8\pi^2 E v^3}\int_0^{k_{\max}v} d\omega \coth\frac{\beta\omega}{2}F(\omega, k=\omega/v) + \frac{C_F\alpha_s}{8\pi^2 E v}\int_0^{k_{\max}} dk\,k\int_0^{kv} d\omega\coth\frac{\beta\omega}{2}G(\omega,k), \quad (15)$$

where $F(\omega,k) = 8\pi\omega^2 \mathrm{Im}\,\epsilon_L/|\epsilon_L|^2$ and $G(\omega,k) = 16\pi\,\mathrm{Im}\,\epsilon_T/|\epsilon_T - k^2/\omega^2|^2$ and $v_0 = v$. This result is obviously gauge invariant if we use there the semiclassical, gauge-invariant expression for the dielectric functions (5).

The above expression gives the mean energy (per unit time) absorbed by a propagating particle from the heat bath. Physically, this arises from gluon absorption. Thermal absorption of gluons was also shown to reduce the radiative energy loss [25]. We arrive at a somewhat similar conclusion as there, albeit in a different context. It is to be noted here that because the spectral density of field fluctuations $\langle\vec{\tilde{\mathcal{E}}}_{L/T}^2\rangle$ are positive for positive frequencies by definition, according to Eq. (15) the particle energy will grow due to interactions with the fluctuating fields.

$$k_{\max} = \min\left[E, \frac{2q(E+p)}{\sqrt{m^2+2q(E+p)}}\right], \quad (16)$$

where $q \sim T$ is the typical momentum of the thermal partons of the QGP.

In Fig. 3 and Fig. 4 we show the relative collisional energy loss of a charm and bottom quark where the effect of field fluctuations is taken into account. It is evident that the effect of the fluctuations on the heavy quark energy loss is significant at low momenta. For momenta 4–20 GeV the fluctuation effect reduces the collisional loss by 17–39% for charm and 12–31% for bottom. At higher momenta, as it will be relevant for LHC, the relative importance of the fluctuation gain to the collisional

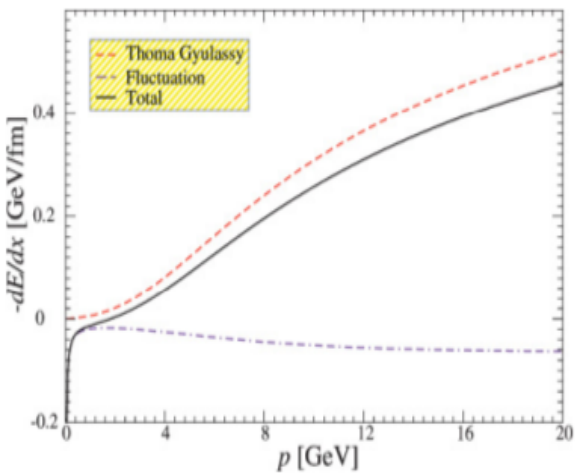

FIG. 2. (Color online) Same as shown in Fig. 1 but for a bottom quark.

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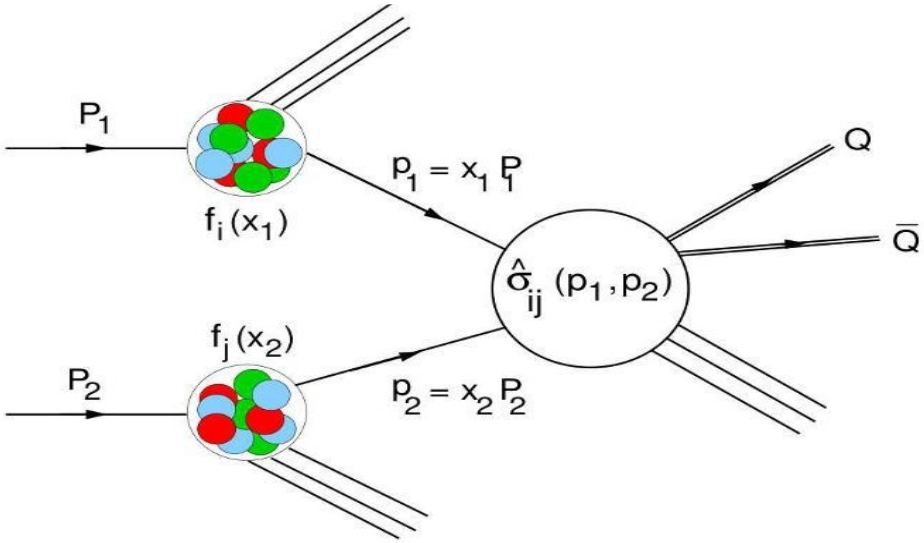
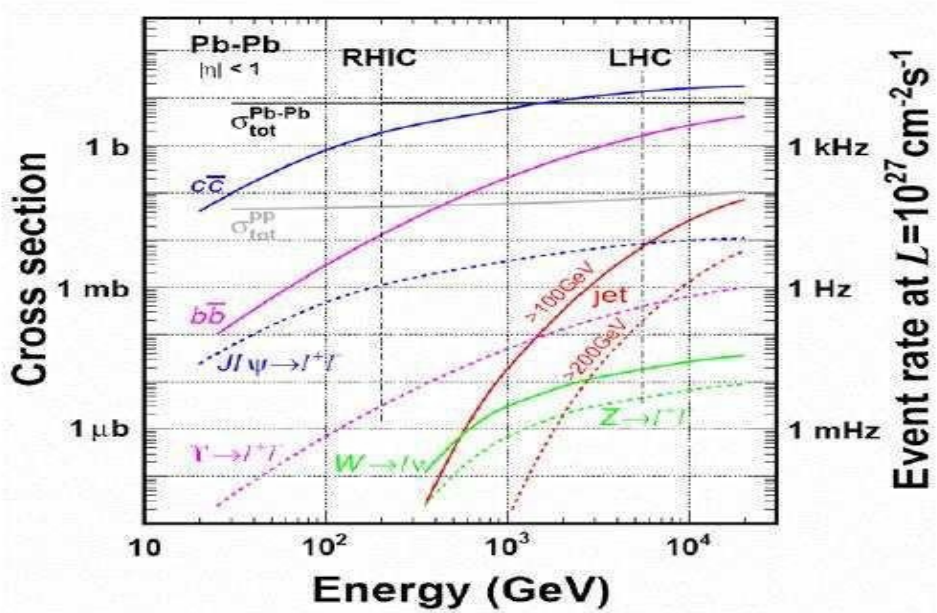
HQ Production in Heavy-Ion Collisions





- In Heavy-Ion collisions, **ALICE: 0809.1062[nucl-ex]**

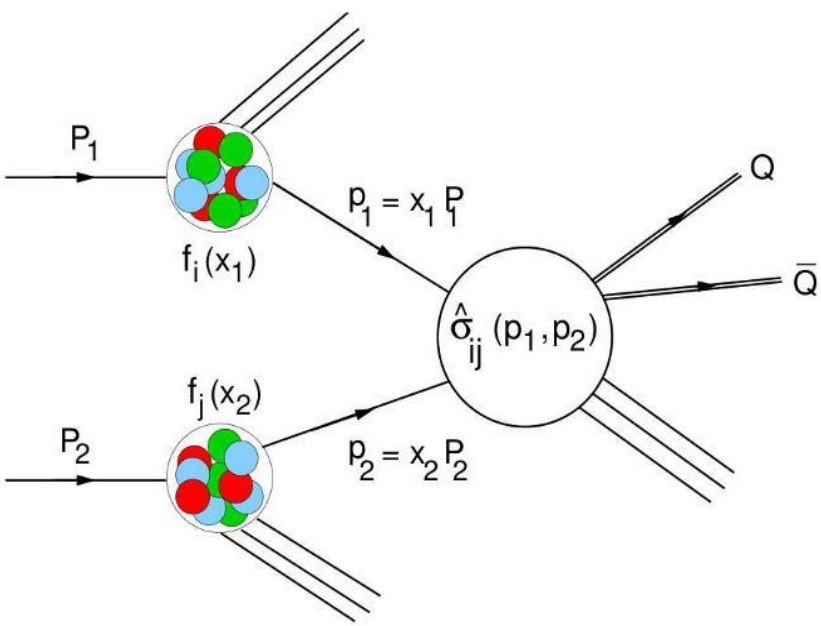
  Charm : LHC ~ **10× RHIC**, Bottom : LHC ~ **100× RHIC**

- QCD provides a framework to compute HQ production x-section and distribution.

Heavy Quark Production in Heavy-Ion Collisions

- Factorisation allows that an observable can be expressed as a convolution of short distance (hard scattering of partons) and the long distance contribution describing the initial hadrons

$$\frac{d\sigma}{dy_1 dy_2 dp_T} = x_1 x_2 p_T \sum_{i,j} f_i^{(1)}(x_1, \mu_F^2) f_j^{(2)}(x_2, \mu_F^2) \hat{\sigma_{ij}}(x_i, x_j, \alpha_s(\mu_F^2), \mu_F^2)$$



- i, j are partons in hadron1(P1) and hadron2(P2) respectively
- σ_{ij} is the partonic x-sections, comes from pQCD
- $f_{i,j}$ is the parton distribution functions(PDFs) in hadrons
- μ_F is the factorization scale between hard processes and the non-perturbative PDFs

HQ Hadronization

- Fragmentation function gives the probability to get a hadron from a parton:

$$f_H(p_T) = \sum_p f_p(p_T/z) \otimes D_{p\to H}(z)$$

Heavy meson production cross-section

Heavy quark production cross-section

Fragmentation function

$z = p_T/p_T^Q$

- Two/three partons may coalesce and form a hadron by Coalescence mechanism.

[V. Greco, C.M. Ko, and P. L´evai, PRL 90 , 202302 (2003)]