Heavy Quarks in Hot and Dense QCD Medium

MUNSHI G. MUSTAFA

Saha Institute of Nuclear Physics, Kolkata

Content:

- Why Heavy Quark?
- Heavy Quark Production
- Heavy Quark Propagation
  - Collisional Energy Loss
  - Radiative Energy Loss
  - Heavy-flavoured hadron spectra (Jet Quenching)
- Chromoelectric Field Fluctuations
  - Collisional Energy gain
  - Heavy-flavoured Nuclear Suppression factor
- Conclusion

Why Heavy Quarks ?

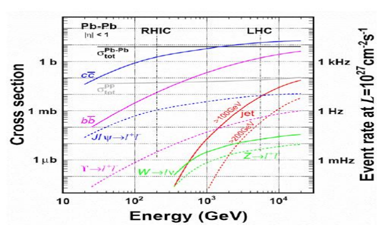
- Heavy Quarks ➤ **Charm (c) & Bottom (b)**
  - **Charm:** $M_c = 1.27^{+0.07}_{-0.09}$ **GeV**
  - **Bottom:** $M_b = 4.19^{+0.18}_{-0.06}$ **GeV**
- Production time: $\tau_Q = 1/2M_Q \leq 0.1$ fm$/c$
- Thermalisation time (τ_{th}):
  - Successive equlibrium: $\tau_{th}^{g} < \tau_{th}^{u,d} < \tau_{th}^{c} < \tau_{th}^{b} < \tau_{th}^{life}$

    [J. Alam, S. Raha & B. Sinha, PRL 73 (1994) 1895]
  - Therma. time for HQs $\tau_{th}^{Q} \sim \frac{M_Q}{T} \times \tau_{th}^{u,d}$ [G. Moore & D. Teaney, PRC 2005]
  - $\tau_{th}^{u,d} < \tau_{th}^{Q}$: no production at QGP and hadronic phase
  - Produced at very early time interactions in Hard Scattering of partons in Nucleons. Initial distribution of HQs ➤ frozen
  - g, u, d thermalize early and provide an expanding thermal background

Why Heavy Quarks ?

- Heavy Quarks propagation:
  - in foreground with gluons & light quarks as an expanding thermal background for the non-equilibrated HQs ➤ expansion dynamics
  - interacts with equilibrated degrees of freedom ➤ energy-loss of HQ
  - requires dynamics ➤ final distr^n of HQs (Transport Eq.)
- Uniqueness of Heavy Quarks:
  - distinguishable down to lowest momenta ➤ medium/quark coupling (Hydro)
  - cleaner energy-loss probe ➤ reflected in leading particle $p_\perp$ spectra, flow
  - tests understanding of mass dependence
  - Quarkonia: QGP thermometer
- True probe: Not glue or light quarks

Heavy Quark Production in Heavy-Ion Collisions:



- Heavy-Ion Coll.: **ALICE: 0809.1062[nucl-ex]**
  - ☛ **Charm:** **LHC** $\sim 10\times$ **RHIC** ☛**Bottom:** **LHC** $\sim 100\times$ **RHIC**
- Produced in pairs $(Q\bar{Q})$ at early times
- QCD describes the structure and dynamics of hadrons interms of their constituents: quarks and gluons
- QCD provides a framework to compute production x-section and distribution

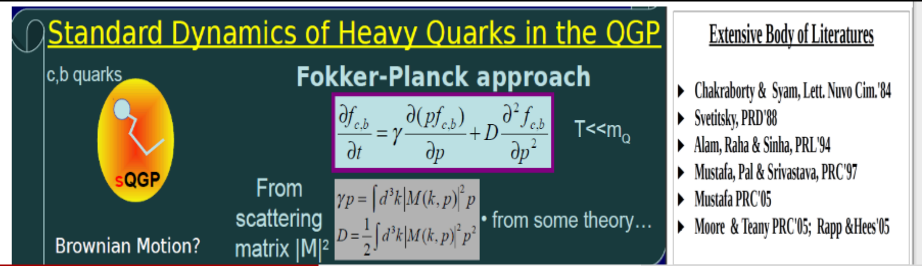
Heavy Quark Propagation and Final distribution

- Produced at early time ($\tau_Q < \tau_{th}$); No production at later time

  - **Total no. of HQ gets frozen very early in the history of collisions**
  - **Immediately upon their production they will propagate through QGP**
  - **One is left with the task of determining the HQ distribution**
  - **Details of the distribution may reflect the characteristics and development of QGP**

Fokker-Planck Equation

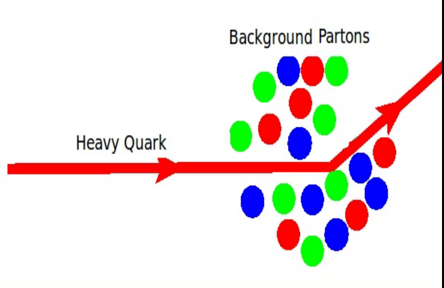
- **Fokker-Planck Eq. ➤ Simplified Boltzmann Eq.**
  - Boltzmann Eq ➤ No external force and isotropic in space
  - Soft Scatt. (Landau approx.) ➤ Taylor expan. ➤ Landau Eq.
  - Landau Eq. ➤ an integro-diff^l Eq. involving transport coeffs. ➤ describes collision processes of two particles
  - Landau Eq. ➤ FP Eq. when distribution of the background particles (QGP) is thermal whereas foreground particle (HQs) is non-thermal

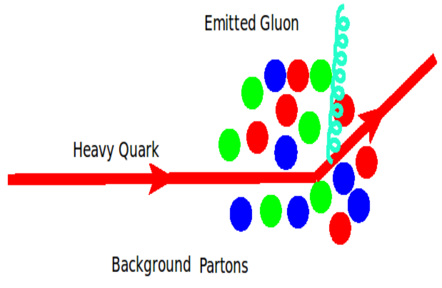


Propagation of Heavy Quark in QGP

- Energy-Loss

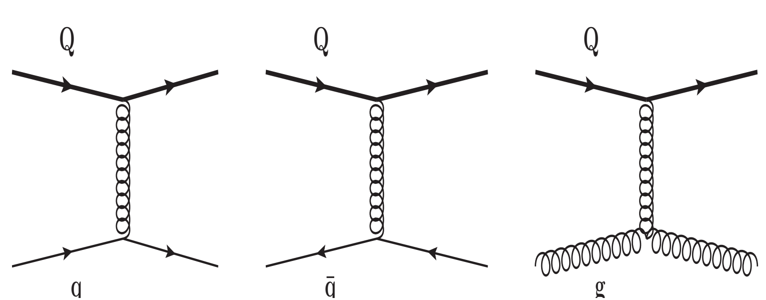
☛ **Collisional Loss** ☛ **Radiative Loss**





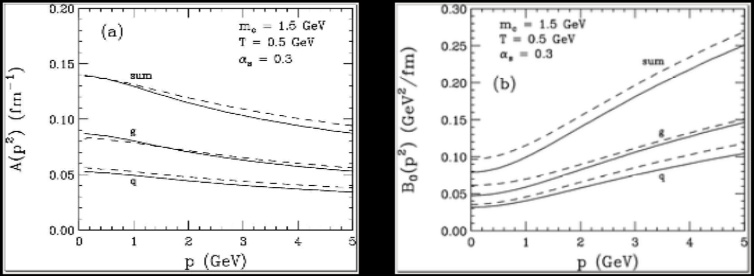
Collisional Processes

- Feynman Diagram



Heavy Quark Transport Coefficients from FP Equation

- Drag $\gamma(p)$ and Diffusions $\mathcal{B}_0(p)$

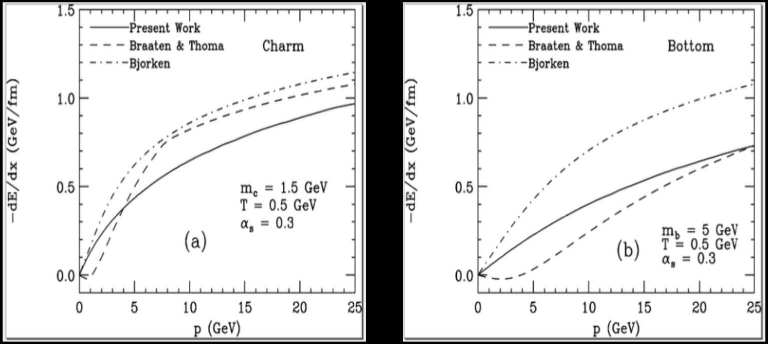


- **Mustafa, Pal & Srivastava, PRC'97**
- **Mustafa PRC'05**

Differential Collisional Energy Loss

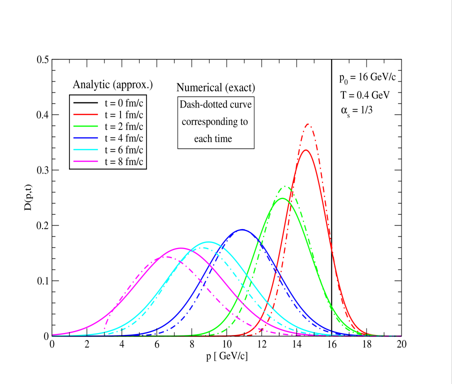
- Drag Coeff.: $\gamma(p) = -\frac{1}{p}\frac{\mathrm{dE}}{\mathrm{dx}}$
  - Differnetial Collisional Energy-Loss: $\frac{\mathrm{dE}}{\mathrm{dx}}$

[Mustafa, Pal, Srivastava, PRC57 (1998) 889]



HQ Energy-Loss Distribution [Mustafa, PRC72 (2005) 014905]

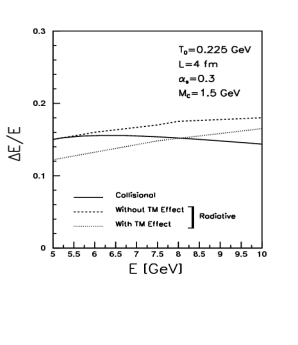
- Collisional Energy-Loss ➤ Transport-coeffs. ➤ Fokker-Planck Eq. ➤ Energy-Loss Distribution

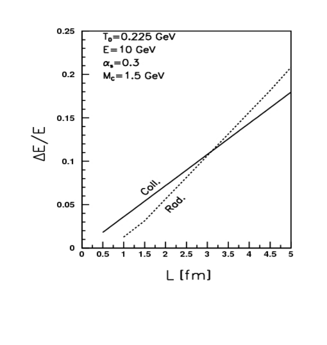


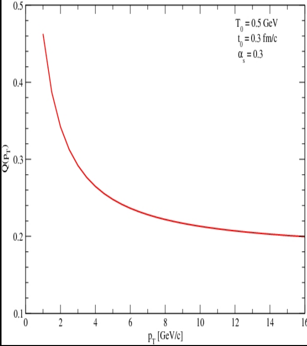
- Mom. diffusion begins
- Peak Shifts to lower p ➤ **Energy Loss**
- Peak broadens ➤ **Momentum Dispersion**

Substantial Collisional E-Loss

- **Mustafa, PRC72 (2005) 014905**





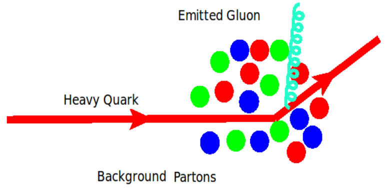


- Coll. E-Loss is important
- Predicted R_{AA} but no data then
- For light quarks R_{AA} :

☛ **Mustafa et al., PRL100 (2008) 072301; Acta Phys.Hung. A22 (2005)**

Radiative Energy Loss

- HQ encounters inelastic scattering as it traveses a medium
  - Emits a gluon



- Differential Loss: dE/dx
- Very simple but first estimation:
  - **Mustafa, Pal, Srivastava, Thoma, PLB 428 (1998) 234**
- Improvements in formalism

Radiative Energy Loss

- Singnificant Points:
  - The nature of the medium through which the energetic parton propagates ➤ thermally equilibrated perturbative medium with a collection of static scatt. centres with specified density
  - Kinematic approximations for interation between medium partons (thermal background) and the projectile parton that is propagating in the medium
  - The virtuality and branching/splitting of hard parton to reduce its off-shellness ➤ multiple splitting may occure in the medium ➤ multigluon final state should include interference of emitted gluons

Suppression due to Mass and Dead Cone

- General notion: **heavy quark radiates less than light quark**

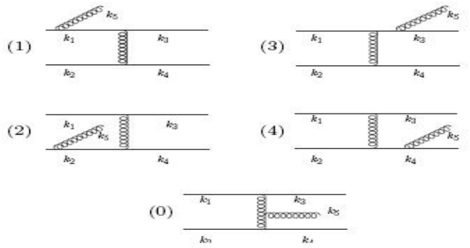
$qq' \to qq'$	$\lvert\mathcal{M}_{qq'\to qq'}\rvert^2 = \frac{8}{9} g^4 \frac{s^2}{t^2}$
$Qq \to Qq$	$\lvert\mathcal{M}_{Qq\to Qq}\rvert^2 = \frac{8}{9} g^4 \frac{s^2}{t^2} \left(1 - \frac{M^2}{s}\right)^2$
$qq' \to qq'g$	$\lvert\mathcal{M}_{qq'\to qq'g}\rvert^2 = 12 g^2 \frac{8}{9} g^4 \frac{s^2}{t^2}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

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

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

Generalised Dead Cone

- RHIC data (PHENIX) ➤ $R_{AA}^{HQ} \sim R_{AA}^{LQ}$ ➤ **(Heavy quark puzzle)**



Hierarchy employed in this study

$$\sqrt{s}, E \gg \sqrt{|t|} \sim q_\perp \gg \omega > k_\perp \gg m_D$$

Mass Range $0 < M/E < 1$

Emission angle Range $-\pi < \theta < +\pi$

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

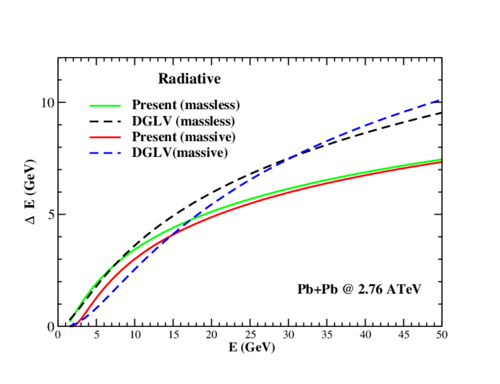
$$= 12g^2\,|\mathcal{M}_{Qq\to Qq}|^2\,\frac{1}{k_\perp^2}\left(1+\frac{M^2}{s}e^{2\eta}\right)^{-2}$$

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

..... *Dead Cone Factor*

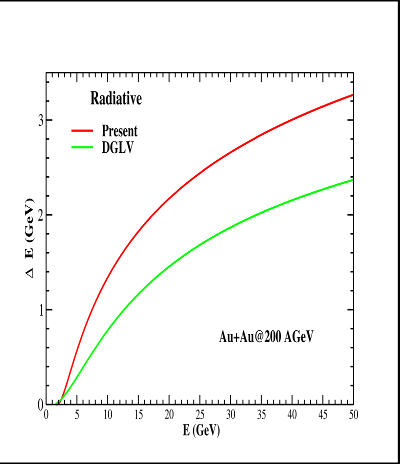
☛ **Abir, Greiner, Martinez, Mustafa, Uphoff, PRD85 (2012) 054012**

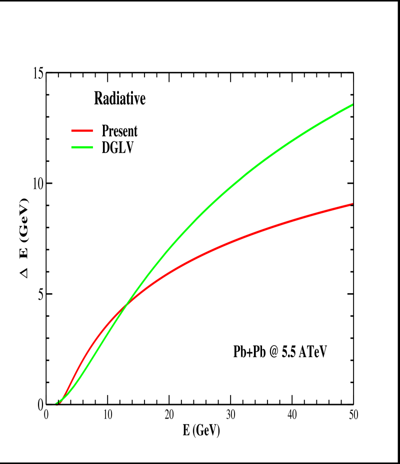
Radiative E-Loss [Abir,Jamil,Mustafa,Sivastava, PLB715 (2012) 183]



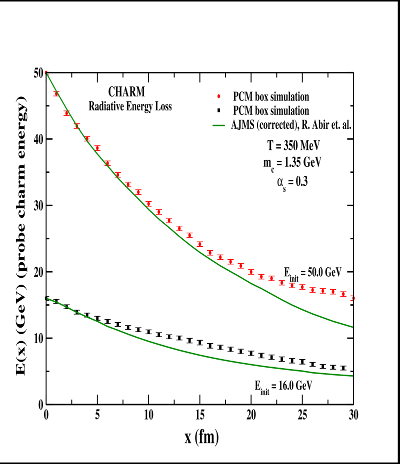
- DGLV: **PRL85 (2000); NPA784 (2007); NPA783 (2000); NPA733 (2004)**

Radiative E-Loss [Abir,Jamil,Mustafa,Sivastava, PLB715 (2012) 183]

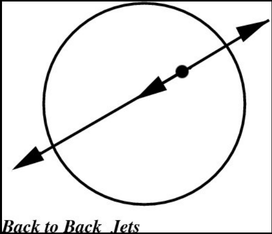




Comparison with Parton Cascade Model [Younus et al, Phys.Rev. C91 (2015) 024912]



Jet Quenching

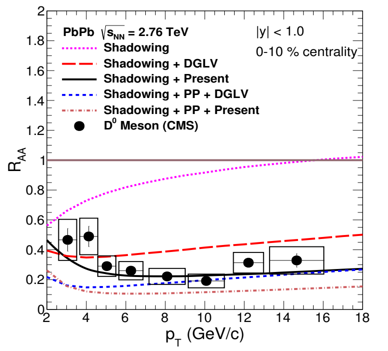


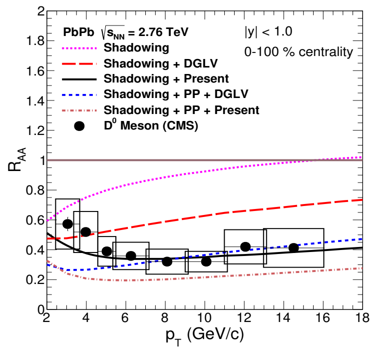
- Jets are produced back to back
  - **Awayside will pass through medium**
  - **Interact with the medium**
  - **Lose energy and quenched**
  - **Results in suppression of hadronic yields in AA than NN**

- Nuclear Suppression Factor: $R_{AA} = \frac{(\text{Yield})^{AA}}{N_{\text{coll}} \ (\text{Yield})^{NN}}$

- Quenching depends on amount of energy-loss suffered in the medium

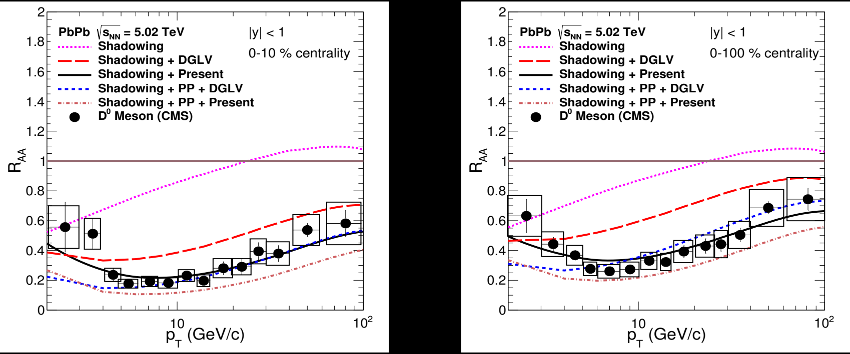
D-Meson @ LHC 2.76ATeV





- DATA: **CMS Collaboration , CMS-PAS-HIN-16-011.**
- Theory: **Abir, Jamil, Mustafa, Srivastava, PLB715 (2012) 183**
- **Saraswat, Shukla, Singh, NPA961(2017)169**

D-Meson @ LHC 5.02ATeV



- Data:**CMS Collaboration, CMS-PAS-HIN-16-001.**
- Theory: **Abir, Jamil, Mustafa, Srivastava, PLB715 (2012) 183**
- **Saraswat, Shukla, Singh, NPA961(2017)169**

Collisional Energy Gain [Chakraborty, Mustafa, Thoma, PRC75 (2007) 064908]

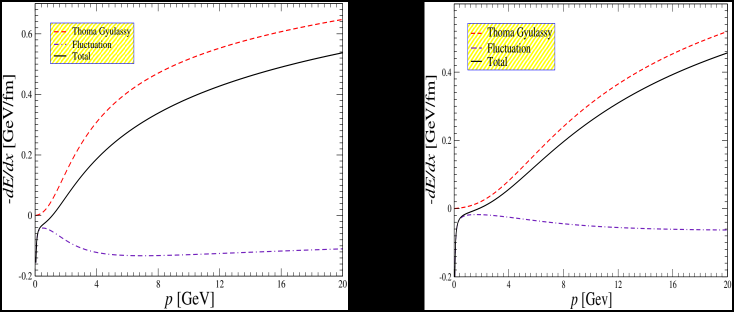
- The collisional energy loss does not take into account :
  - the field fluctuation in the plasma
  - the particle recoil in collisions
- One needs to take in to account both :
  - This leads to energy gain as

$$\left.\frac{dE}{dx}\right|_{fluc} = \frac{C_F\alpha_s}{16\pi^3 E}\int d^3k\left[\frac{\partial}{\partial\omega}\langle w\vec{\mathcal{E}}_L^2\rangle + \langle\vec{\mathcal{E}}_T^2\rangle\right]_{\omega=\vec{k}\cdot\vec{v}}$$

$$= 2\pi C_F\alpha_s^2\left(1+\frac{N_f}{6}\right)\frac{T^3}{Ev^2}\ln\frac{1+v}{1-v}\,\ln\frac{k_{\max}}{k_{\min}}$$

Collisional Energy Gain

- The field fluctuations lead to energy gain:



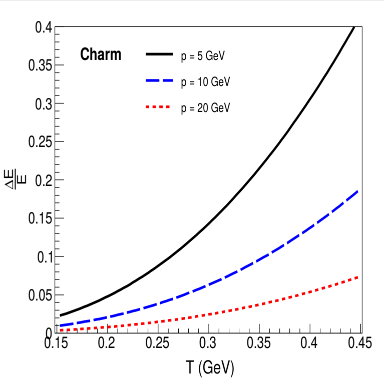
☛ **Chakraborty, Mustafa, Thoma, PRC75 (2007) 064908**

Fractional Energy Gain of Charm Quark

- Coll. Gain/Energy= $\frac{\Delta E}{E}$

A Ikbal, Z Ahamed, M G Mustafa, : arXiv:1902.06989

Ikbal, Ahamed, Shukla, Mustafa, Phys .Rev. C98 (2018) 034915

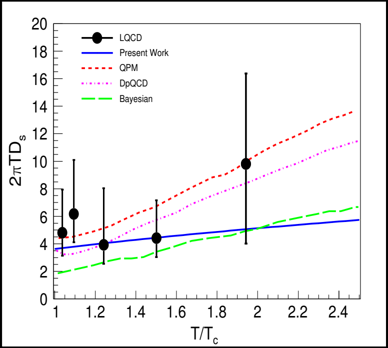


Diffusion Coefficient of Charm Quark

- Langevin Dynamics

A Ikbal, Z Ahamed, M G Mustafa, : arXiv:1902.06989

Ikbal, Ahamed, Shukla, Mustafa, PRC98 (2018) 034915



- Drag : $\gamma = -\frac{1}{p}\frac{dE}{dx}$
- FD Theorem:

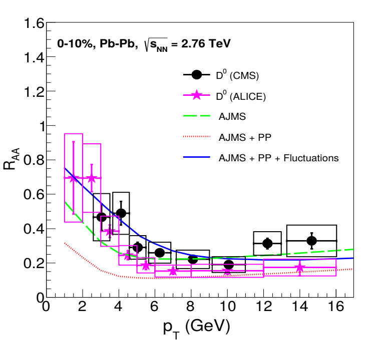
  Mom. Diff.: $D = 2\gamma ET$
- Einstein Relation:

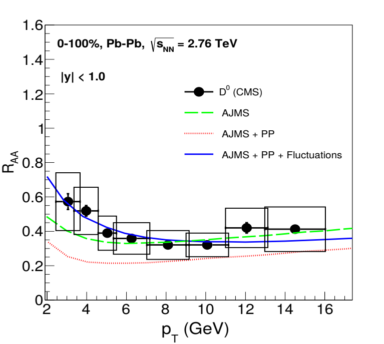
$$D_s \underset{p\to 0}{=} \frac{T}{\gamma M} = \frac{2T^2}{D}$$

- **Banerjee, Datta, Gavai and Majumdar, PRD 85 014510 (2012)**

Open Charm and Field Fluctuation

- Nuclear Modification factor (R_{AA}) for D Meson at 2.76 TeV
  Ikbal, Ahamed, Shukla, Mustafa, Phys .Rev. C98 (2018) 034915

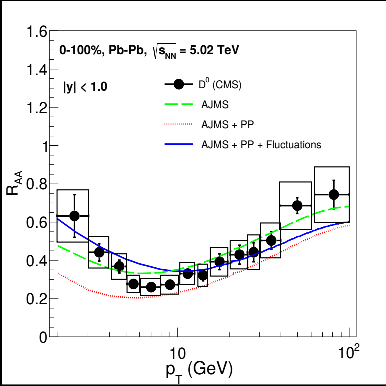


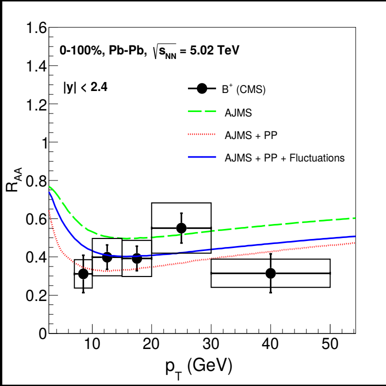


- **DATA:CMS Collaboration , CMS-PAS-HIN-16-011**
- **ALICE Collaboration, JHEP 1603 (2016) 081, 2016**

Open Charm/Beauty and Field Fluctuation

- Nuclear Modification factor (R_{AA}) for D & B-Meson at 5.02 TeV
  Ikbal, Ahamed, Shukla, Mustafa, Phys .Rev. C98 (2018) 034915





☛ **DATA:CMS Collaboration , CMS-PAS-HIN-16-011**

Conclusion:

- **Discussed why are heavy quarks important**
- **Heavy quark production in high energy HIC: X-section in pQCD**
- **Collisional E-Loss & E-Gain**
  - Relation to Transport Coeffs: Drag and Diffusion
  - Coll. E-Loss Distr. & **importance of Coll. E-Loss**
- **Radiative E-Loss**
  - Generalised Dead Cone and radiative E-Loss
  - Light and heavy quark lose energy in a similar fashion
- **Importance Chromoelectric Field Fluctuations & Energy Gain**
- **Nuclear suppression R_{AA} for various heavy quarked meson**
  - Both D and B Meson R_{AA} @ LHC for 2.76ATeV and 5.02ATeV in Pb+Pb

Collaborators:

- **Raktim Abir (AMU, Aligarh)**
- **Purnendu Chakraborty (Basirhat College, W. Bengal)**
- **Umme Jamil (D.R. College, Golaghata, Assam)**
- **Dipali Pal (USA)**
- **Asik Ikbal (VECC, Kolkata)**
- **D. K. Srivastava (VECC, Kolkata)**
- **Zubayer Ahmed (VECC, Kolkata)**
- **Prashant Shukla (BARC, Mumbai)**

- **Markus H. Thoma (Giessen Univ., Germany)**
- **Carsten Greiner (Goethe Univ. Frankfurt, Germany)**
- **Jan Uphoff (Goethe Univ., Frankfurt, Germany)**
- **M. Martinez (FIAS, Frankfurt, Germany)**

THANK YOU