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VECC

Bose Institute

Charm Quark Evolution In Quark Gluon Plasma

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OUTLINE OF THE TALK

- A Brief Introduction:

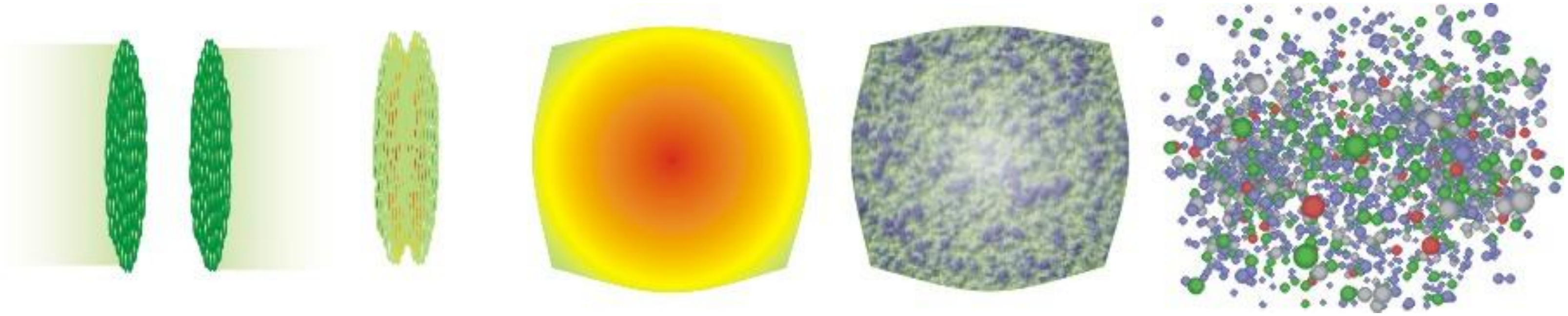
- Charm Quark Evolution : A) Approach I: Phenomenology
  B) Approach II: Transport calc.

- Summary:

Introduction:

Heavy Ion collision :

- **Produces a region** of deconfined gluons and quarks (g, u, d, s, c, b, t)
- **A very small region** → size of a nuclei → high temperature and density



Heavy Quark :

- **Conservation of heavy Flavor** → always produced in pair
- **Large mass** → mostly produced in early phase when parton momenta are high before the formation of QGP.
- **Small number** → isolated from bulk system → serves as probe to QGP
- **Large momentum** transfer required for production → pQCD can safely be applied
- **Medium effect** → different models to explain experimental data that shows large suppression for D mesons and non-photonic electrons

Heavy quark observables to probe the properties of QGP:

- Nuclear medium modification factor and azimuthal anisotropy for heavy quarks, heavy mesons and non-photonic electrons.

- Correlation of charm and D mesons pair in azimuthal angle, space-time and pseudo rapidity, pair transverse momentum, D-h correlation etc.

- Collisional and radiative energy loss of heavy quark within the hot and dense medium and its dependence on system size, temperature, expansion of the medium.

- Transverse momentum broadening , drag and diffusion of heavy quarks.

- Thermalization rate of heavy quarks in QGP.

- Comparison with gluon and lighter quark observables may also bring out flavour dependence of medium effects.

PART A: Charm Production:

- pQCD techniques $\longrightarrow$ p_T distribution of charm pair cross-section in proton on proton collisions is obtained from

$$\frac{d\sigma_{pp\to c\bar{c}}}{dy_1\,dy_2\,d^2p_T} = 2x_a x_b \sum_{ij}\left[f_i^{(a)}\left(x_a, Q^2\right) f_j^{(b)}\left(x_b, Q^2\right)\frac{d\hat{\sigma}_{ij}(\hat{s},\hat{t},\hat{u})}{d\hat{t}} \right.$$

$$\left. + f_j^{(a)}\left(x_a, Q^2\right) f_i^{(b)}\left(x_b, Q^2\right)\frac{d\hat{\sigma}_{ij}(\hat{s},\hat{u},\hat{t})}{d\hat{t}}\right] \cdot \frac{1}{(1+\delta_{ij})}$$

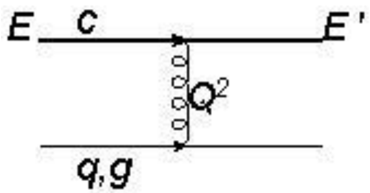
so that $\frac{dN_{AA\to c\bar{c}}}{d^2p_T dy} = T_{AA}(b)\frac{d\sigma_{pp\to c\bar{c}}}{d^2p_T dy}$ where $T_{AA}(b)$ is the nuclear overlap func.

- **CTEQ5M** structure functions as well as **EKS98** shadowing function used for initial parton distribution function, $f_i(x,Q^2)$

U. Jamil et al., J. Phys. G: Nucl. Part. Phys., 37, 085106 (2010)
M. Younus et al., J. Phys. G: Nucl. Part. Phys., 37, 115006 (2010)

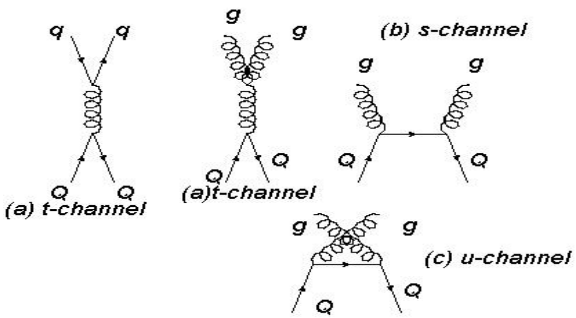
Charm energy loss and phenomenology of medium effects:

Collisional loss:



Energy loss per unit length:

$$\frac{dE_{coll}}{dx} = \sum_i \frac{1}{8EE'} \int d^3k d^3k' \frac{n_i n_i'}{kk'} \delta^4(p^\mu) \frac{1}{d} |M|^2 .(E - E')$$

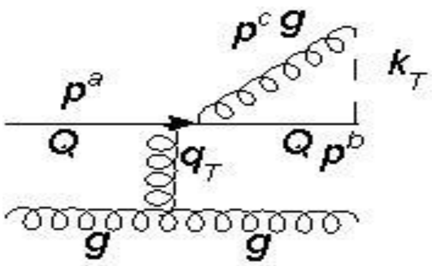


$$\frac{dE_{coll}}{dx} = \pi \alpha_s^2 T^2 \left[\left(1 + \frac{n_f}{6}\right) \ln\left(\frac{ET}{\mu_D^2}\right) + \frac{3}{4} \ln\left(\frac{2ET}{m_c^2}\right) + 0.5 \right]$$

Coll. energy loss per unit length covered by charm in QGP

S. Peigne and A. Peshier, arXiv:0802.4364v1[hep-ph]2008; 1312.6857[nucl-th]2013

Radiative loss:



Average radiated energy:

$$<\omega>_g = \frac{\int d\eta d\omega . \omega . \frac{dn_g}{d\eta d\omega}}{\int d\eta d\omega . \frac{dn_g}{d\eta d\omega}}$$

Average mean free path:

$$<\lambda>^{-1} = \rho_{qgp}\sigma_{2\to 3},$$

$$\sigma_{2\to 3} = \frac{C_A \alpha_s}{\pi} \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t} . \frac{d\hat{\sigma}_{2\to 2}}{d\hat{t}} \int_{\omega_{\min},\eta_{\min}}^{\omega_{\max},\eta_{\max}} d\eta d\omega . \frac{dn_g}{d\eta d\omega}$$

$$\hat{t}_{\min} = \omega_{\min}^2 = \mu_D^2; \qquad \omega_{\max}^2 \approx \mu_D^2 \ln\left(\frac{3E}{4T}\right)$$

$$\hat{t}_{\max} = \frac{3ET}{2} - \frac{M^2}{4} + \frac{M^4}{48pT} \log\left[\frac{M^2 + 6ET + 6pT}{M^2 + 6ET - 6pT}\right]$$

Charm radiative energy loss per unit length:

$$\frac{dE_{rad}}{dx} = \frac{<\omega>_g}{<\lambda>},$$

1) Incoherent Emission of Gluons: Bethe-Heitler Regime:

$$E, E' >> q_\perp >> \omega > k_\perp >> \mu_D;$$

$$\frac{dn_g^B}{d\eta d\omega} = \frac{C_A \alpha_s}{\pi} \frac{1}{\omega} D(\eta)$$

R. Abir et al., Phys. Rev. D, 83, 011501 (2011); Phys. Lett. B, 715, 183 (2012)

2) Coherent Emission of Gluons: Landau-Pomeranchuk-Migdal Regime:

$$E, E' >> q_\perp > \omega >> k_\perp \sim \mu_D;$$

$$\omega \sim < q_\perp^2 > \lambda; \qquad \tau_f = \frac{2\omega}{k_\perp^2} > \lambda$$

$$\frac{dn_g^L}{d\eta d\omega} = \frac{C_A \alpha_s}{\pi} \frac{\sqrt{\omega_L}}{\omega^{3/2}} D$$

$$\omega_L = \hat{q}\, \overline{L}^2; \ \hat{q} = \frac{\langle q_\perp^2 \rangle}{\langle \lambda \rangle} \approx 1.1 - 1.2\, GeV^2\, fm^{-1}$$

D.E. Kharzeev et al., Phys. Lett. B, 519, 199 (2001)

X-N.Wang et al., Phys. Rev. D, 51, 3436 (1995)

M. Younus et al., arXiv: 1309.1276v3[nucl-th] 2015 (accepted. by Phys. Rev. C for publ.)

finally.......

$$\frac{dE_{rad}}{dx} = 12\alpha_s^3 \rho_{qgp} \sqrt{\omega_L} \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t} \frac{d\hat{\sigma}_{2\to 2}}{d\hat{t}} \int_{\omega_{\min}}^{\omega_{\max}} d\omega \frac{1}{\omega^{1/2}} \int_{\eta_{\min}}^{\eta_{\max}} d\eta\, D(\eta)$$

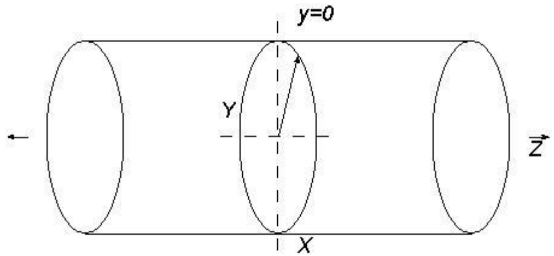
$$\frac{dE_{tot}}{dx} = \frac{dE_{coll}}{dx} + \frac{dE_{rad}}{dx} \longrightarrow \Delta E \longrightarrow \Delta p_T \longrightarrow p_T' = p_T - \Delta p_T$$

$$L(r,\phi) = -r\cos\phi + \sqrt{R(b)^2 - r^2 \sin^2\phi};$$

$$\tau_d \approx \frac{< L >}{\left| p_{Tc} / m_{Tc} \right|} \Rightarrow \min.[\tau_f, \tau_d]$$

$$T(\tau) \propto \left(\frac{\rho(\tau)}{9n_f + 16} \right)^{1/3}; \qquad \rho(\tau) = \frac{1}{\pi R^2 \tau} \frac{dN}{dy}$$

Bjorken longitudinal expansion:



$$T_0^3 \tau_0 = T^3 \tau = T_f^3 \tau_f \rightarrow freezeout$$

M. Djordjevic et al., Nucl. Phys. A, 733, 265 (2004);
S. Wicks et al., Nucl. Phys. A, 783, 493 (2007)
K. Aamodt et al., arXiv: 1012.1657v2[nucl-ex] 2011

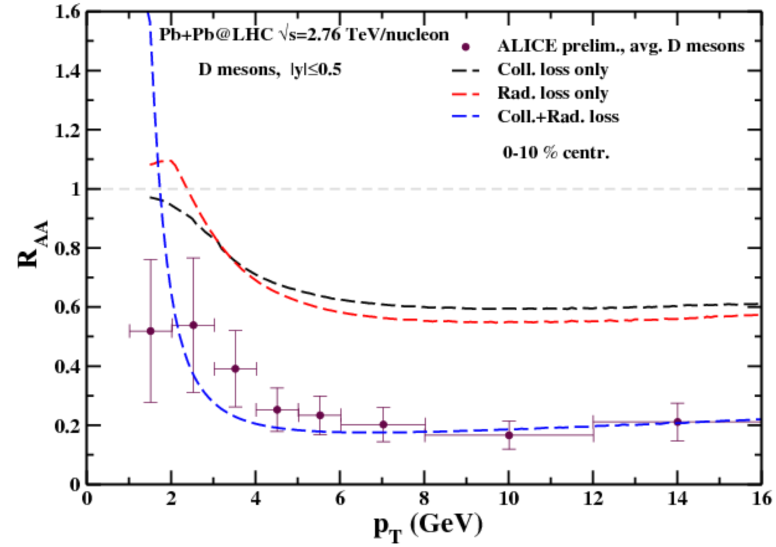
Peterson Fragmentation:

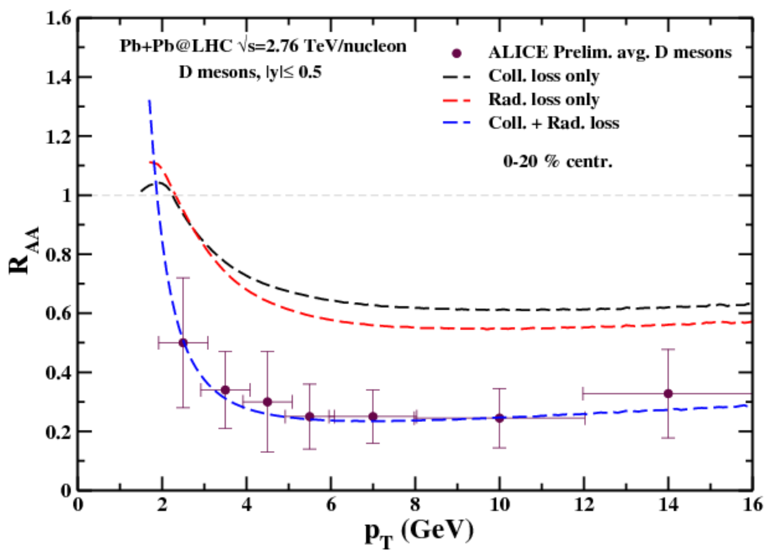
$$D_D^c(z) \sim \frac{1}{z[1 - 1/z + \varepsilon_p/(1-z)]^2}, \; z = p_{TD} / p_{Tc}$$

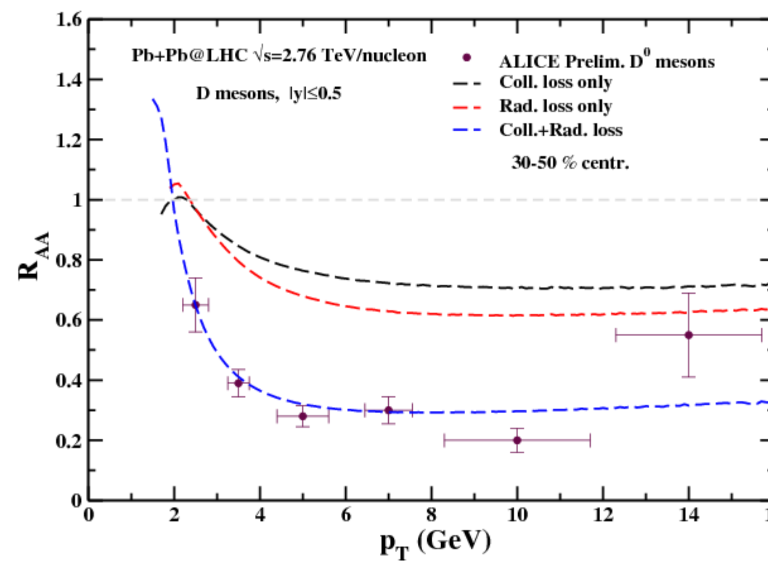
Results: ‘R_{AA}’ of D mesons

$$R_{AA}(p_T, y) = \frac{dN_{AA}/d^2 p_T\, dy}{T_{AA}\, d\sigma_{pp}/d^2 p_T\, dy}$$

Model explains experimental results within error bars:



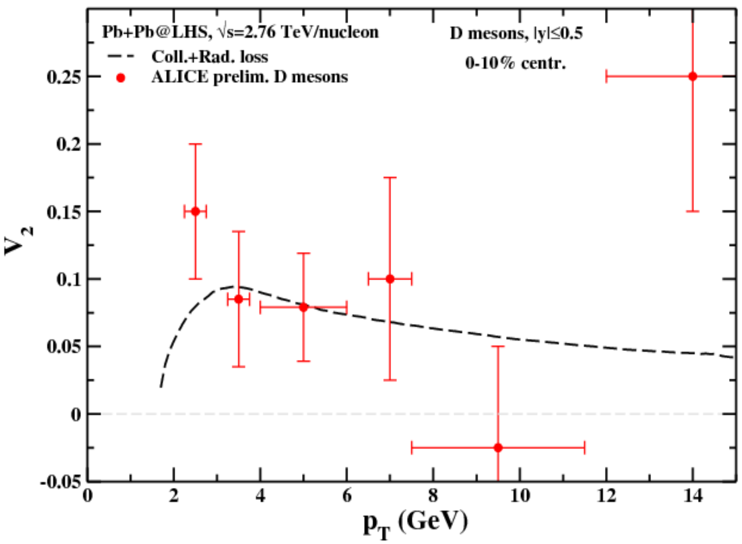


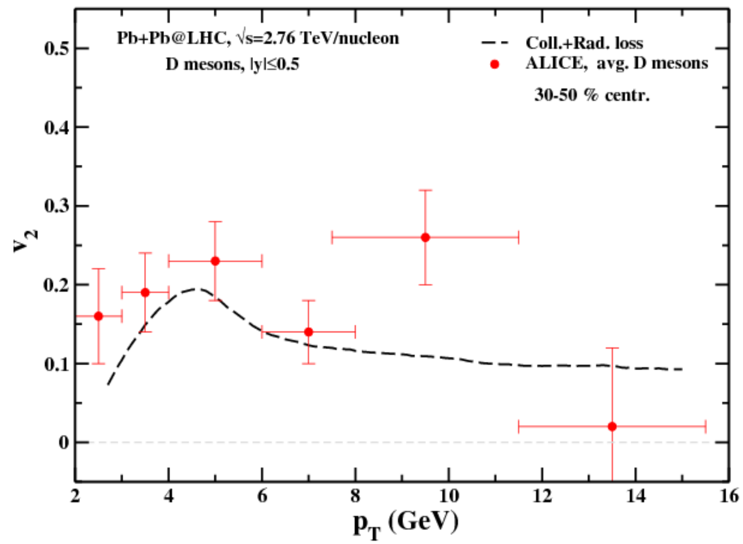


‘v_2’ of D mesons

$$v_2(p_T)=\frac{\int d\phi \frac{dN}{p_T\,dp_T\,d\phi}\cos(2\phi)}{\int d\phi \frac{dN}{p_T\,dp_T\,d\phi}}$$

Model calculation underestimates data:





B. Abelev et al. (for ALICE Collaboration), Phys. Rev. C 90, 034904 (2014)

Some of the recent theoretical works:

- S. Das, F. Scardina et al., **Phys. Rev. C 90, 044901 (2014)**; S. Das, P. Mohanty et al., **Phys. Rev. C 80, 054916 (2009)**; S. Mazumder, T. Bhattacharyya et al., **Phys. Rev. C 84, 044901 (2011)** etc.

- R. Abir, U. Jamil et al., **Phys. Lett. B, 715, 183 (2012)**; U. Jamil et al., **J. Phys. G: Nucl. Part. Phys., 37, 085106 (2010)** etc.

- S. Cao, G-Y. Qin et al., **Nucl. Phys. A, 904, 653 (2013)**; **Phys. Rev. C 88, 044907 (2013)** etc.

- M. He et al., **Nucl. Phys. A 910, 409 (2013)**; H. van Hees et al., **Phys. Rev. C, 73, 034913 (2006)** etc.

- M. Nahrgang, et al., **Nucl. Phys. A, 904, 992c (2013); Phys. Rev. C 91, 014904 (2015); Nucl. Phys. A 910, 301 (2013)** etc.

- J. Uphoff et al., **Nucl. Phys. A 931, 535 (2014), Nucl. Phys. A 931, 937 (2014)** etc.

- M. Younus et al**.,** **J. Phys. G: Nucl. Part. Phys. 39, 095003 (2012).**

- S. Wicks et al., **Nucl. Phys. A, 784, 426 (2007);** ***ibid*****. 872, 265 (2011).**

We can now switch from this phenomenological study to transport calculations……

- Calculation of transport coefficients for various medium temperatures and charm energies can be done and compared to the studies of charm evolution using **transport calculations**.

- Calculation of **‘path length’** and **‘temperature dependence’** of charm energy and momentum evolution will be done using parton cascade model **in Part II.**

PART B: probing QGP using transport calculation:

Experiments: observe the final state and rely on QGP signatures .

Lattice QCD: rigorous calculation of QCD properties in equilibrium.

Transport-calculations : full description of collision dynamics connecting intermediate state to measurements & lattice…..

In order to investigate the properties of QGP and study QCD within system we need Transport model which shows evolution of QGP and its various properties.

The PCM is a microscopic transport model based on the Boltzmann Equation: $$\left[\frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}}\right] f_1(\vec{p},\vec{r},t) = \sum_{processes} C(\vec{p},\vec{r},t)$$

•describes the full time-evolution of a system of quarks and gluons at high density & temperature
•ideally suited for describing the interaction of jet with medium as well as the medium response

classical trajectories in phase space (with relativistic kinematics)
interaction criterion based on geometric interpretation of cross section:

$$d_{\min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}} \qquad \sigma_{tot} = \sum_{p_3 p_4} \int \frac{d\sigma(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4)}{d\hat{t}} d\hat{t}$$

system evolves through a sequence of binary (2$\leftrightarrow$2) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation (2$\rightarrow$N)

guiding scales:

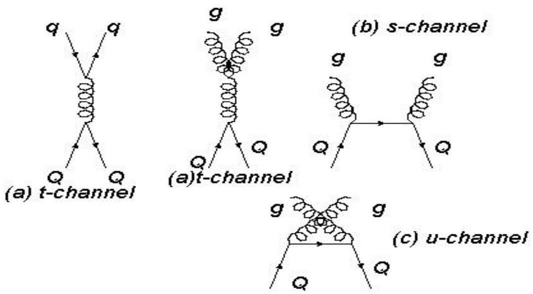
- initialization scale Q_0
- IR divergence regularization: p_T cut-off p_0 or Debye-mass μ_D
- intrinsic k_T
- virtuality > μ_0

Boltzmann transport equation , VNI/BMS:

$$p_\mu \partial^\mu F_i(\vec{p},\vec{r}) = \sum_{processes} C[F]$$

Collision term on r.h.s. :

$$C[F] = \frac{1}{2S_i}\int \prod d\Gamma_j |M|^2 (2\pi)^4 \delta^4(P_{in} - P_{out}) D[F]$$



$$D[F] = \prod_{in} F_j \prod_{out} [1 \pm F_j], \quad \prod d\Gamma_j = \prod_{i \neq j} \frac{d^3 p_j}{(2\pi)^3 (2E_j)}$$

Interaction Amplitudes:

Collisional/Elastic: $|M|^2_{2\to 2} = |M|^2_{ab\to cd}$

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{1}{16\pi(\hat{s} - M_c^2)^2} \sum |M|^2_{2\to 2} \quad , \sigma_{tot} = \sum_{c,d} \int_{p^2_{T\min}}^{\hat{s}} \left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{ab\to cd} d\hat{t}$$

$$p^2_{T\min} \geq \mu_D^2, \; \hat{s} - M_c^2 \geq Q_0^2 \sim 1 GeV^2$$

Radiative/Inelastic:

$$|M|^2_{2\to3} = |M|^2_{2\to2} \times radiative\ terms$$

- After a collision the probe acquires some virtuality: Q^2

- So the particle radiates: $Q^2 \geq m_c^2 \equiv m_1^2 >> m_2^2 >> .... >> m_n^2 \geq \mu_0^2$

Branching probability: $d(br.prob.) \approx \frac{\alpha_s(Q^2)}{2\pi}\frac{dQ^2}{Q^2}P_{c\to c'd'}(z)$

- Sudakov radiative factor: $T(Q^2,\mu_0^2) = \exp\left[-\int_t^{Q_{\max}} dQ^2 \frac{\alpha_s(Q^2)}{2\pi Q^2}\int dz P_{c\to c'd'}(z)\right]$

LPM effect: coherent and destructive interference of emitted gluons:

$$\tau_f^0 = \frac{2\omega}{k_\perp^2}, \qquad \lambda < \tau_f, \qquad \omega\frac{dI_{LPM}}{d\omega} < \omega\frac{dI_{BH}}{d\omega} \qquad \tau_f^n = \frac{2\omega}{\left(k_\perp + \sum_{i=1}^{n=N_{coh}} q_{\perp,i}\right)^2}$$

Baier et al., Nucl. Phys. B, 478, 577 (1996); Nucl. Phys. B, 483, 291 (1997).

K.G. Zapp, J. Stachel & U.A. Wiedemann, Phys. Rev. Lett ., 103, 152302 (2009)

PCM → VNI/BMS and Box/Brick mode

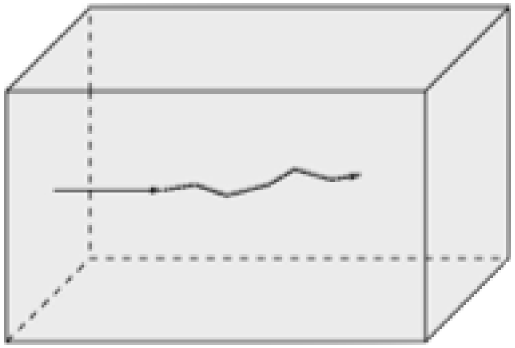
- **PCM** → describes the evolution of the probe jet in the medium but also evaluate the response of the medium.

- A number of implementations of the **PCM** → **VNI/BMS**
  → Limitations in the implementation of the algorithm employed to solve the **Boltzmann equation** → can track charm evolution as well as any other quark or gluon within the framework of **pQCD.**

- One of the mode within **VNI/BMS** that gives the medium effect on charm in controlled fashion is **Box/Brick mode.**

- A controlled set of parameters through which we can follow QGP evolution as well as track the probe → the properties of **QGP matter at fixed temperatures.**

Box/Brick Setup:



- define a box of lengths =5 fm, 10 fm or 30 fm length with periodic boundary conditions
- populate box with an ensemble of thermal partons at T=250, 350, 450, or 550 MeV etc.
- insert a charm with initial momentum p_z=1.0 to 100 GeV or more and track its evolution through the medium

choose Debye-mass to be:

$$\mu_D^2 = \frac{2}{3}\left(2N_c + N_f\right)\pi\alpha_s T^2$$

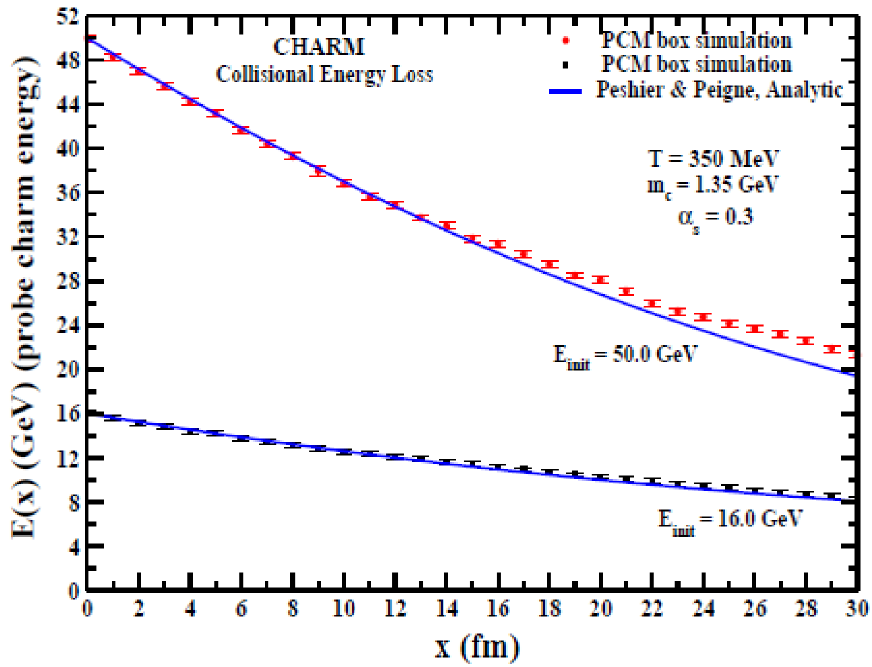
Use coupling constant: $\alpha_s = 0.3$

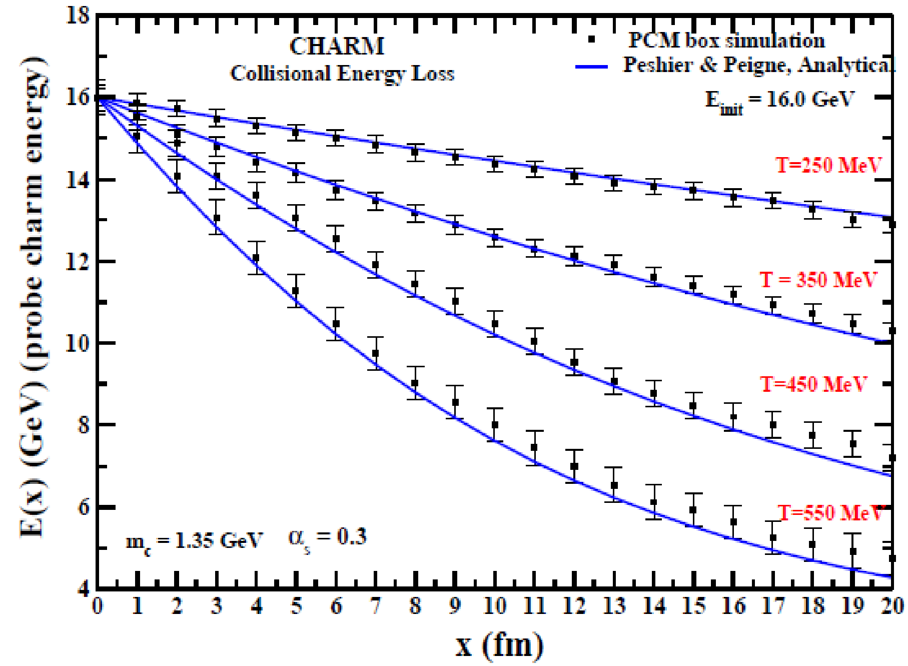
Desired Calculations

- temperature dependence of energy loss per unit distance traveled
- energy-loss as function of distance traveled
- energy-loss transport coefficient : $\hat{q}$
- heavy quark radiative + collisional energy-loss

Future Extensions :

- distribution of momentum transfers with temperatures and probe energies.
- full QGP: study flavor-dependence
- medium response: correlations etc.



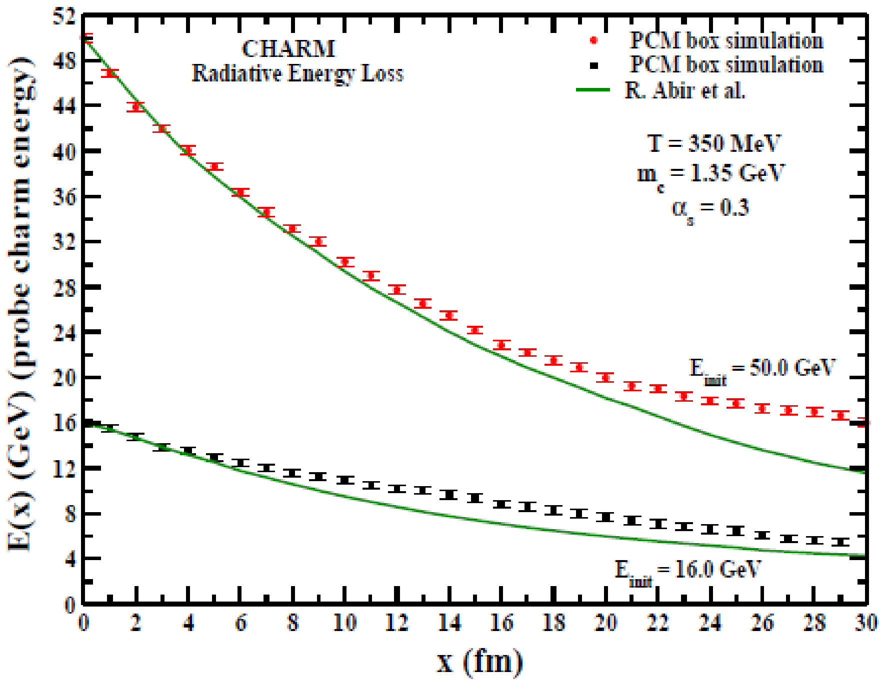


For collisional energy loss where T = 250-350 MeV, m_c = 1.35 GeV and α_s = 0.3 as the parameters for evolution in PCM box .

$$E_p(x) = E_p(0) - x.\left[\frac{4\pi\alpha_s^2 T^2}{3}\left[\left(1+\frac{n_f}{6}\right).\ \ln\frac{E_p(x)T}{\mu_D^2} + \frac{2}{9}\ln\frac{E_p(x)T}{M_c^2} + c(n_f)\right]\right]$$

Peshier and Peigne. (arXiv: 0802.4362v1 [hep-ph] 2008)

stronger path length dependence at higher temperatures…….



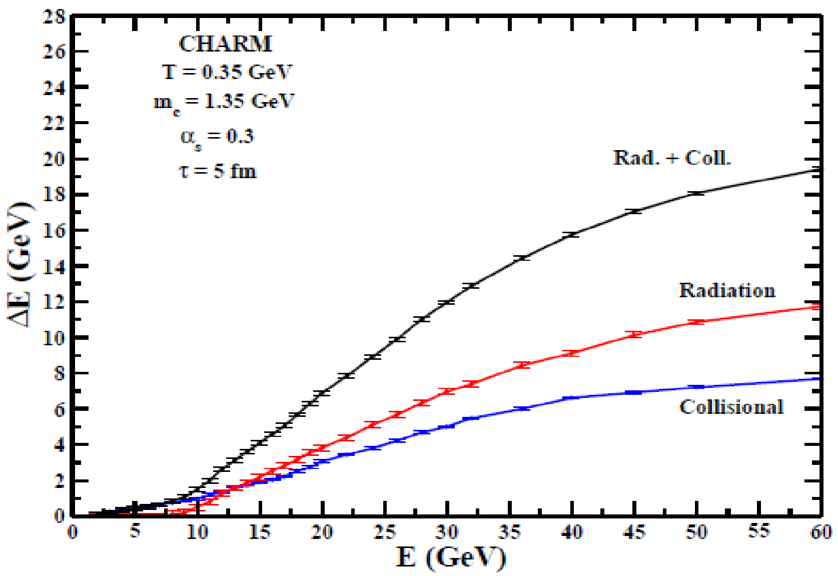
Energy dependence of charm quark radiative energy loss as a function of distance traveled in QGP.

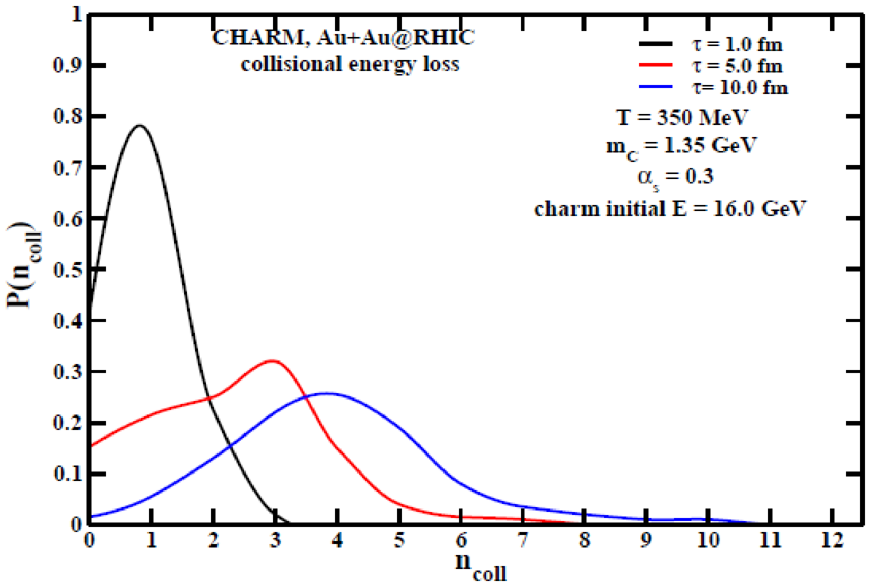
PCM simulation includes LPM effect in the inelastic scattering process.

Analytical calculation by Raktim Abir et al. includes BH type of radiation effect.

Phys. Lett. **B 715**,183 (2012)

T = 350 MeV, m_c = 1.35 GeV and α_s= 0.3 as the parameters for evolution in PCM box .





Charm quark with different initial energies is allowed to evolve through the PCM box for a time of 5 fm and average energy loss is shown .

The charm energy loss increase as the initial energy increases but the rate of energy loss goes on decreasing after 15-20 GeV charm initial energy.

energy-loss transport coefficient for microscopic transport model is defined as:

$$\hat{q} = \frac{d\left(\Delta p_T^2\right)}{dx} = \rho \int d^2 q_\perp \, q_\perp^2 \, \frac{d\sigma}{d^2 q_\perp}$$

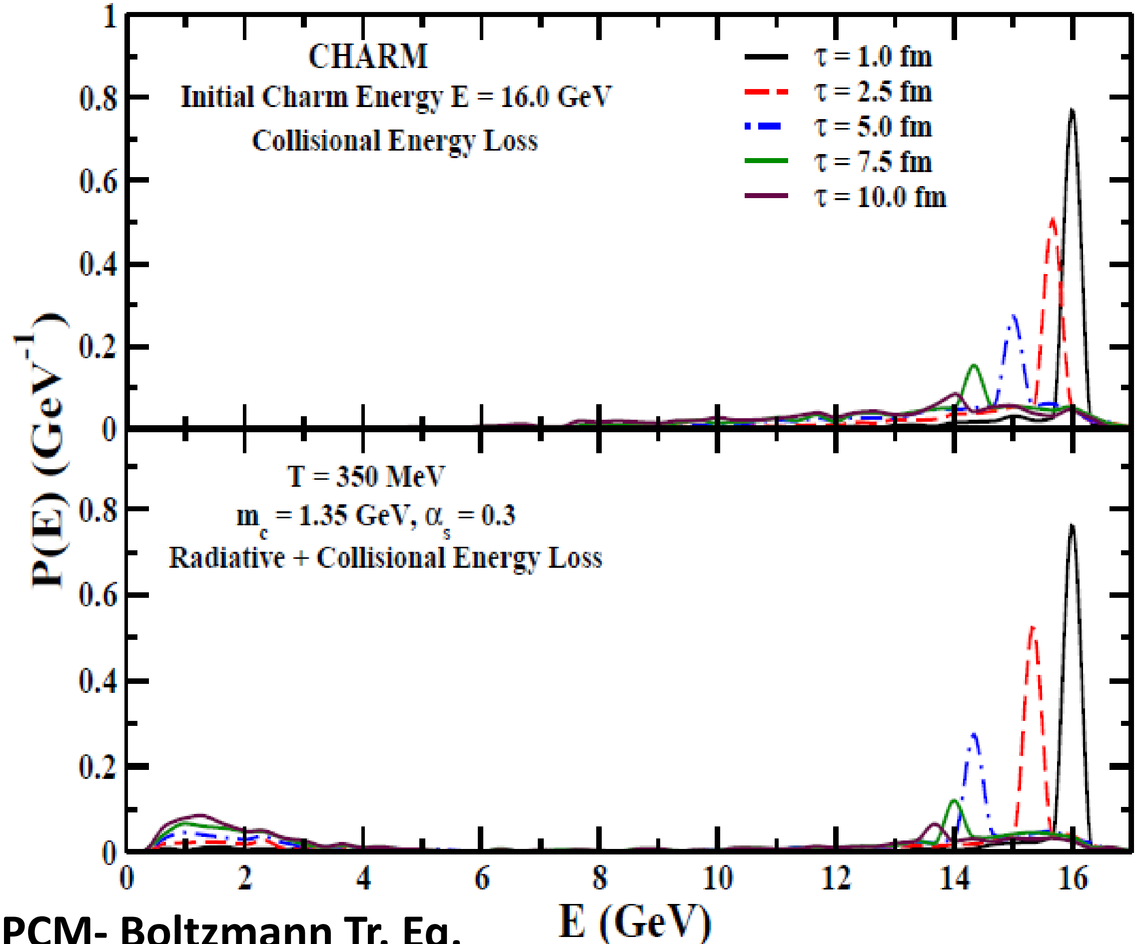
for Monte Carlo simulation:

$$\hat{q} = \frac{1}{l_x} \sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2$$

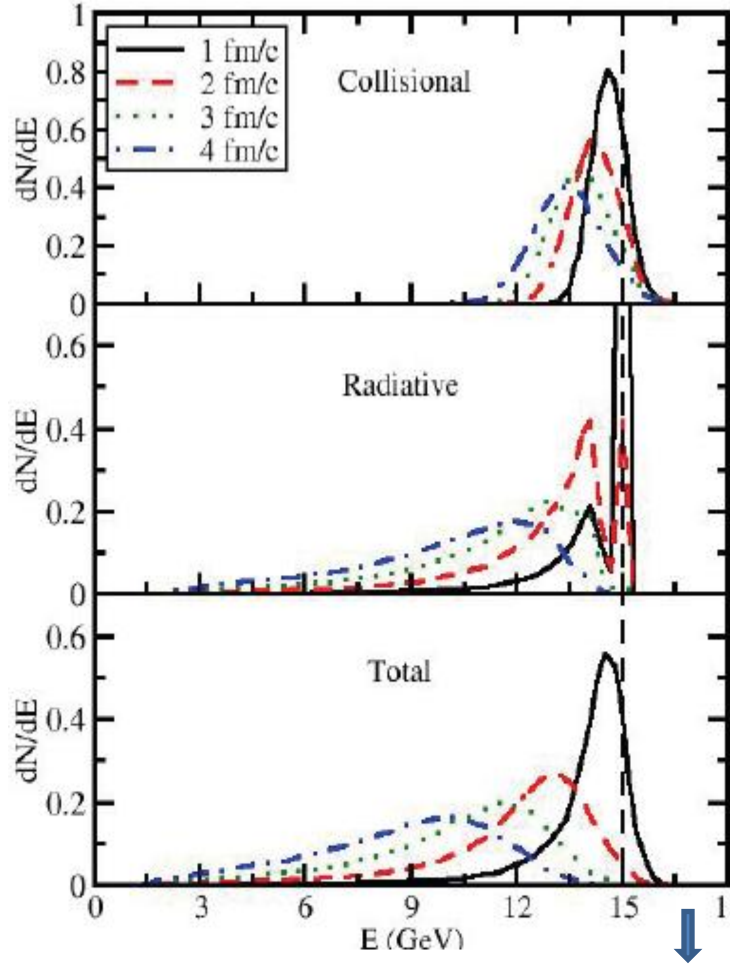
For T = 350 MeV, m_c = 1.35 GeV, α_s = 0.3 and E_{init} = 16.0 GeV

$\hat{q} \sim 1.22$ GeV^2/fm while for E_{init} = 50.0 GeV, $\hat{q} \sim 1.1$ GeV^2/fm.

- For higher energy charms, the medium appears to be more transparent.....



PCM- Boltzmann Tr. Eq.



Langevin Eqn. by Shanshan Cao et al.
Nucl. Phys. A, 904,653 (2013)

- A tail like structure for collisional loss in case of BTE as compared to Langevin Dynamics
- The total loss shows a hump like structure at low 'E' side compared to Langevin picture.

S.K. Das et al. Phys. Rev. C, 90, 044901 (2014).

M. Younus et al., arXiv: 1309.1276v3[nucl-th] 2015 (accepted. by Phys. Rev C for publ.)

Summary

- Transport calculations of parton cascade model have been used to determine the average energy loss of charm quark, path length dependence of energy loss and momentum broadening per unit length.

- The transport coefficients and path length dependence of charm quark energy loss for various temperatures can be compared to calculations from various phenomenological and analytical calculations as discussed in Part I.

- Two-particle correlations calculations can be further studied upon to bring out deeper features of heavy quark or any other probe evolution.

- Comparison of full Boltzmann transport with Langevin equations must be done, to bring out underlying dynamics.

- Finite sized and expanding medium can be incorporated beside static infinite QGP scheme for a more realistic picture.

THANK YOU