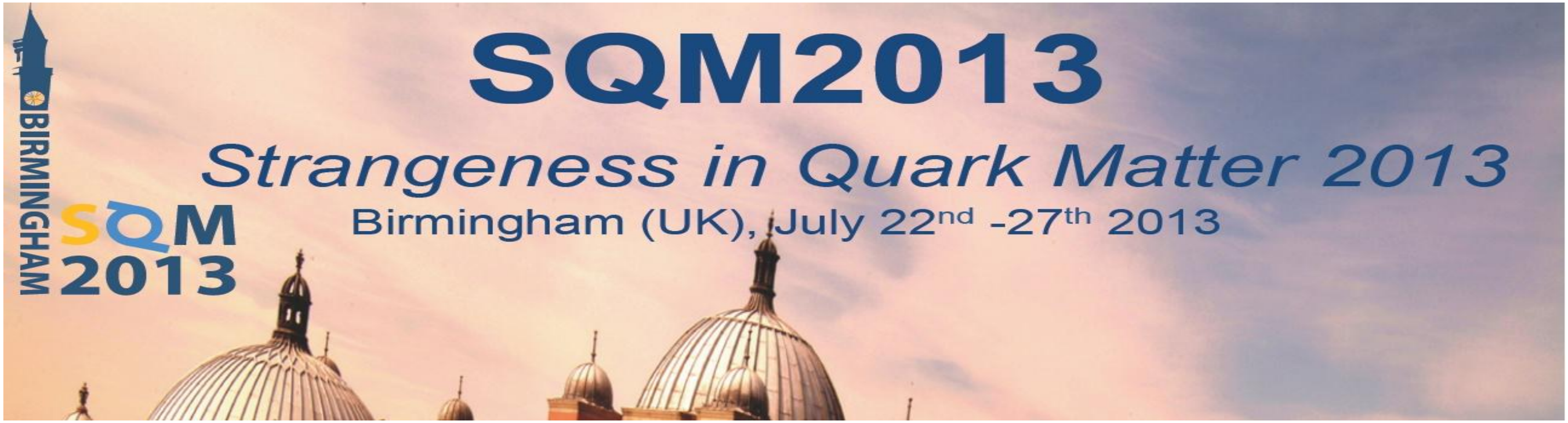

Effect of Quark Gluon Plasma on Charm Quark Produced in Relativistic Heavy Ion Collision

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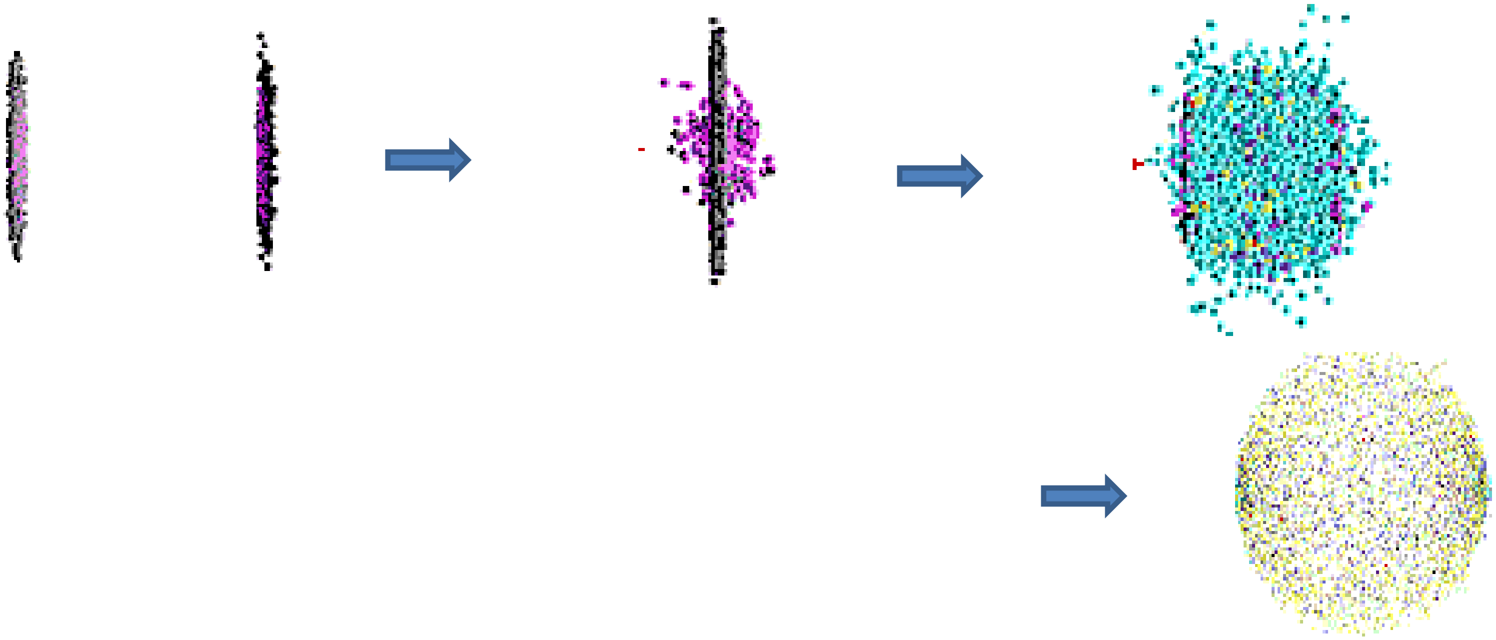
CONTENTS

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

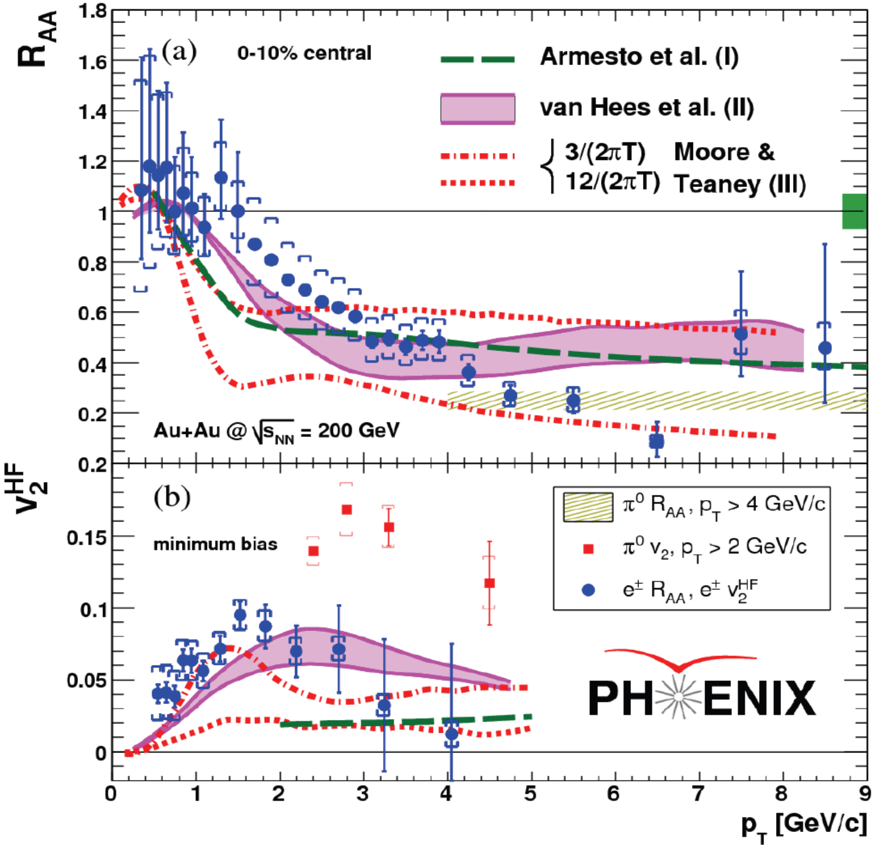


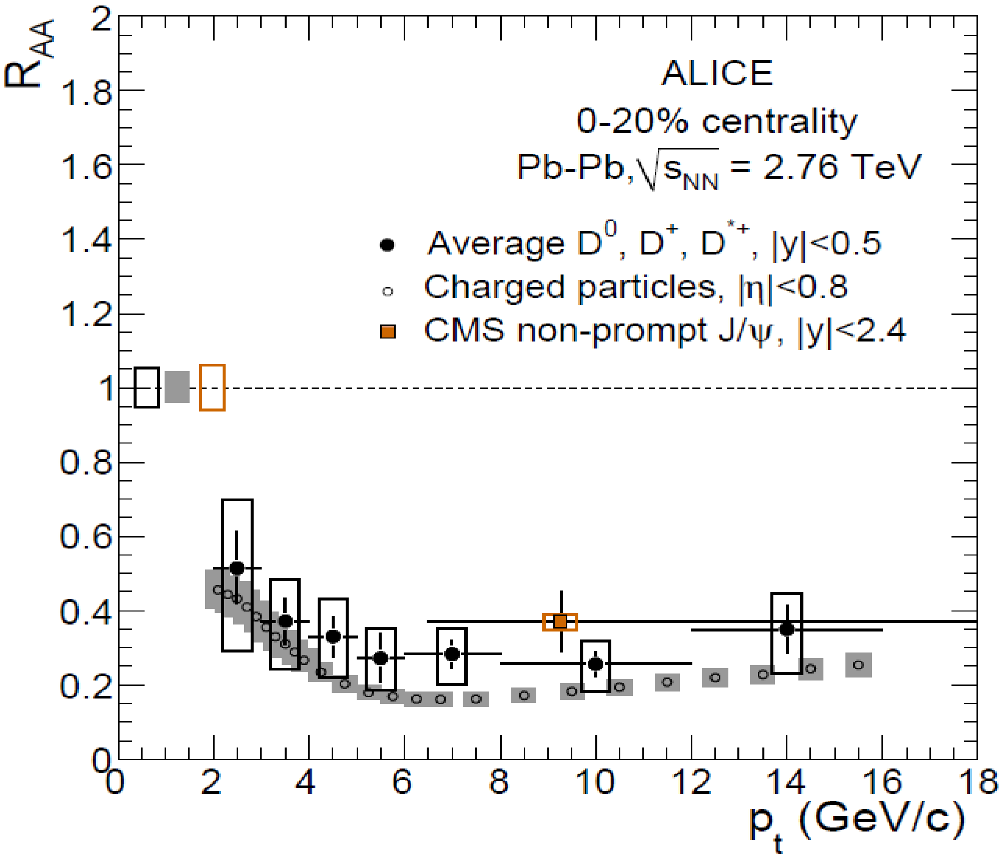
Heavy Quark :

- **Conservation of heavy Flavor** → always produced in pair
- **Large mass** → produced in early phase when temperature is high
- **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
  pQCD based models?

Experiment shows!!!!!

Some spectacular experimental results on heavy quarks at both RHIC and LHC





The results shows similar heavy quark suppression to that of gluons and lighter mesons. How to describe these results? sQGP or pQCD ?

Heavy Quark Production

LO pQCD equation for **prompt charm production** , pp collisions.

$$\frac{d\sigma_{pp\to c\bar{c}}}{dy_1 dy_2 d^2 p_T} = 2x_a x_b \sum_{ij} \left[f_i^{(a)}\left(x_a, Q^2\right) f_j^{(b)}\left(x_b, Q^2\right) \frac{d\hat{\sigma}_{ij}(\hat{s},\hat{t},\hat{u})}{d\hat{t}} + f_j^{(a)}\left(x_a, Q^2\right) f_i^{(b)}\left(x_b, Q^2\right) \frac{d\hat{\sigma}_{ij}(\hat{s},\hat{u},\hat{t})}{d\hat{t}} \right] \cdot \frac{1}{(1+\delta_{ij})}$$

- $f_i(x, Q^2)$ partonic distribution function
- x_a and x_b momentum fraction carried by the interacting gluons or quarks.
- y_1 , y_2 and p_T rapidities and transverse momentum for the charm and anti-charm produced.

$$\frac{d\hat{\sigma}(\hat{s},\hat{t},\hat{u})}{d\hat{t}} = \frac{|M|^2}{16\pi\left(\hat{s}-m_c^2\right)^2}$$ where $|M|^2$ are invariant matrices .

NLO-pQCD $\longrightarrow$ LO X k-factor of 2.5

CTEQ5M structure function and EKS98 shadowing function are used.

$$\frac{dN_{AA\to c\bar{c}}}{d^2p_T dy} = T_{AA}(b)\frac{d\sigma_{pp\to c\bar{c}}}{d^2p_T dy}$$

$T_{AA}(b) \longleftarrow$ Glauber model.

The physical sub processes of order $O\left(\alpha_s^2\right)$ Included are:

$$g+g \to Q+\overline{Q}$$

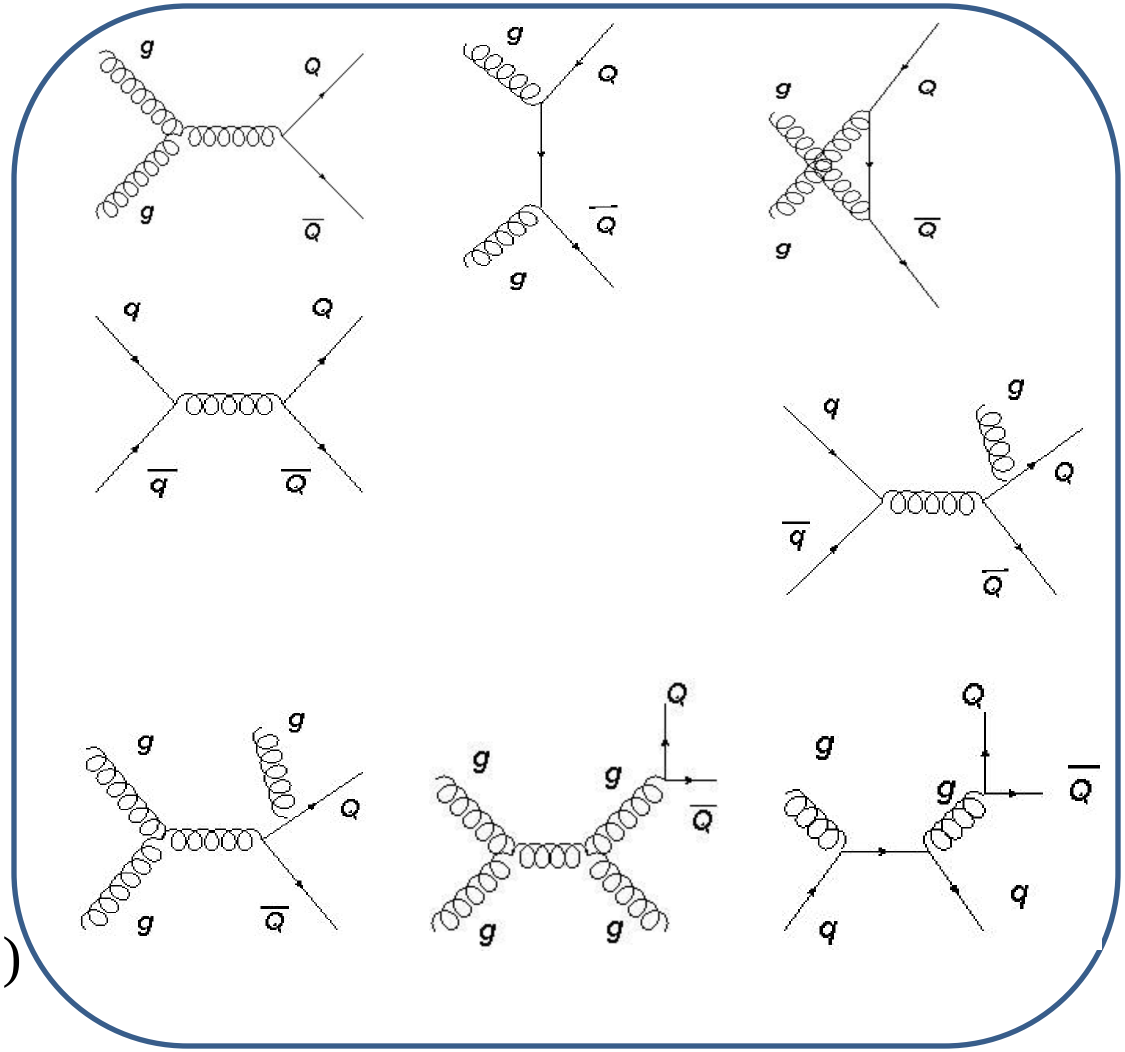
$$q+\overline{q} \to Q+\overline{Q}$$

And of order $O\left(\alpha_s^3\right)$ are

$$g+g \to Q+\overline{Q}+g$$

$$q+\overline{q} \to Q+\overline{Q}+g$$

$$g+q(\overline{q}/g) \to Q+\overline{Q}+q(\overline{q}/g)$$



Heavy Quarks Observables

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

Nuclear Modification Factor

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

Azimuthal Anisotropy

$$C(\Delta\phi)=E_1E_2\frac{dN_{AA}}{d^3p_1d^3p_2}$$

Azimuthal Correlation of charm pair

T_{AA}

= 225 fm^{-2} , 0-10 % centr. RHIC

= 195 fm^{-2} , 0-20 % centr. LHC

Glauber Formalism

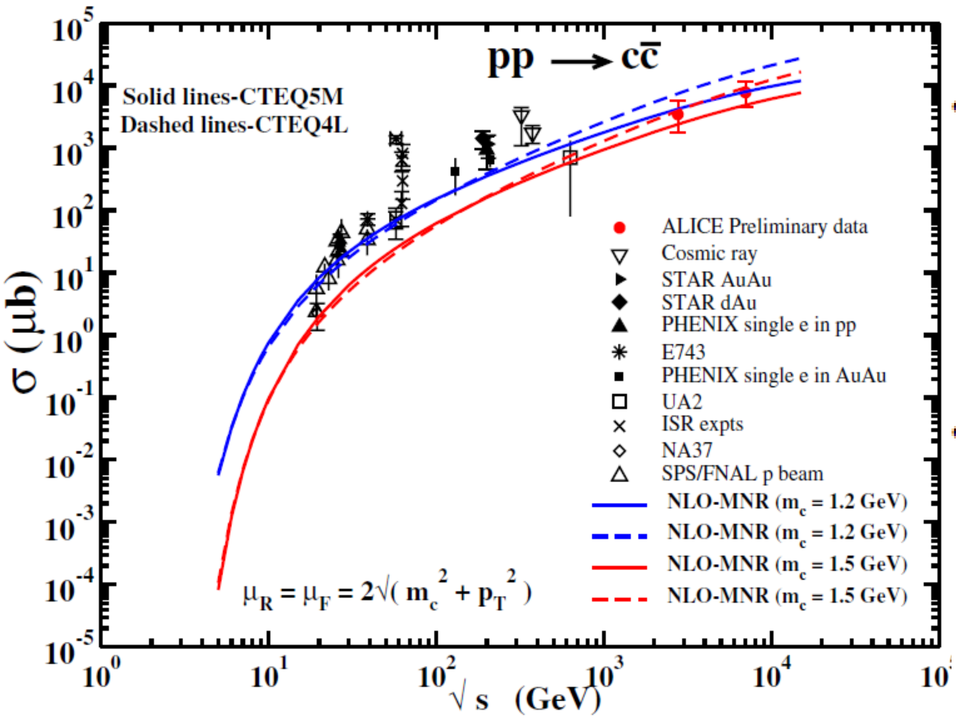
Proton Proton collision

- Heavy quarks pair formed in proton collisions can be described by the perturbative QCD as discussed earlier. And if any medium effect in heavy ion collisions is neglected as a first approximation, then lead on lead results can be identical to proton proton results only scaled by a certain factor (N_{coll}).

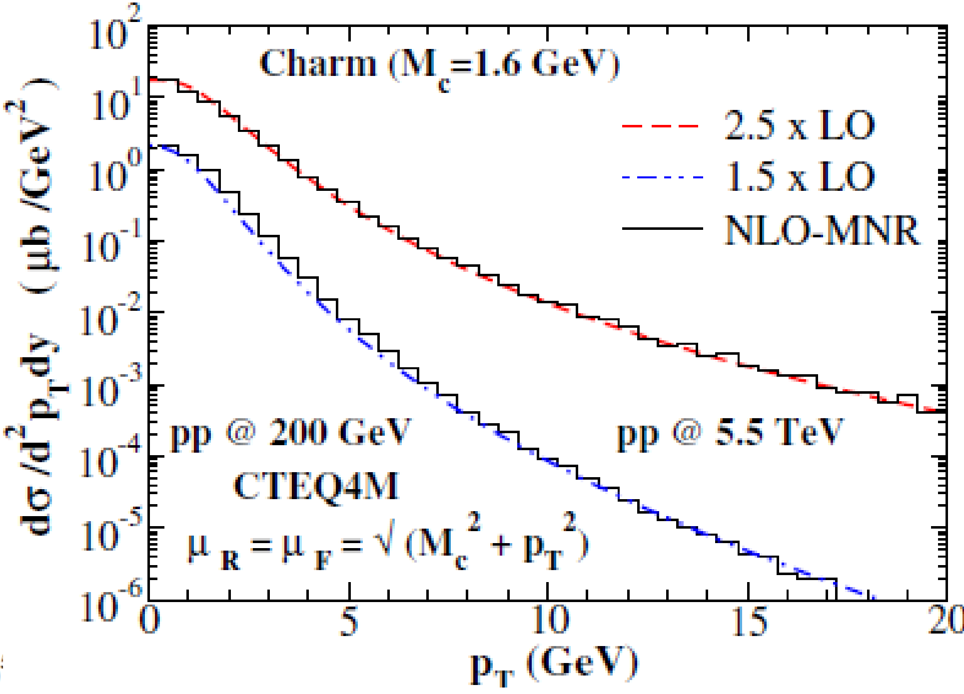
- Considering the medium that will form in lead on lead collision, proton proton results must therefore serve as the baseline for any study in heavy ion collision.

- Different nucleon structure functions ranging from 'MRS-' series to 'CTEQ-'series can be used to check the consistency of our calculations.

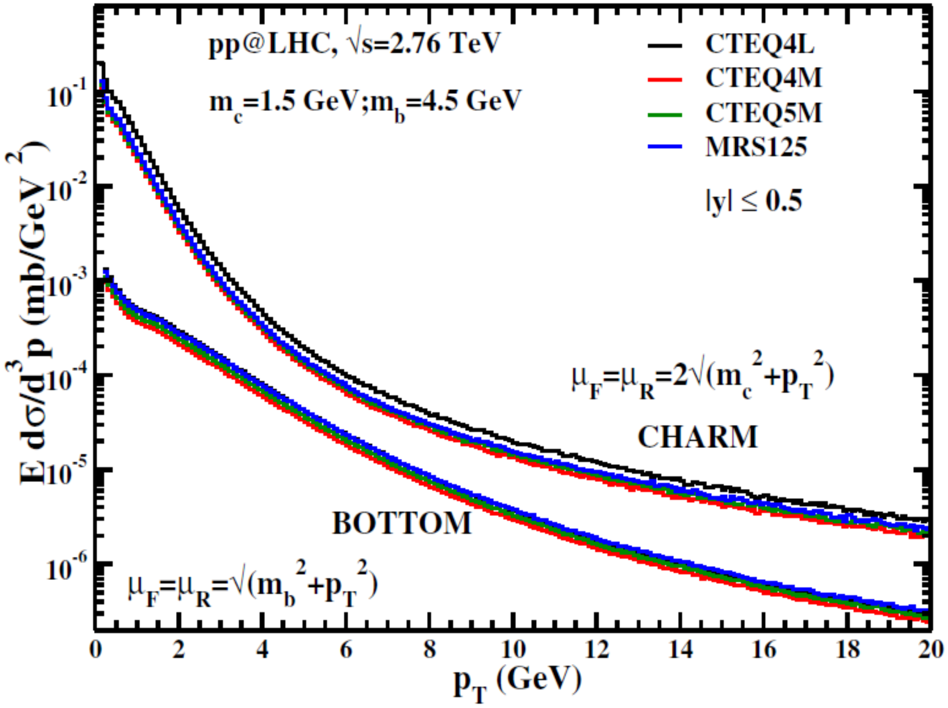
M. Younus, U. Jamil and D. K. Srivastava, J. Phys. **G**: Nucl. Part. Phys. **39**, 025001 (2012)



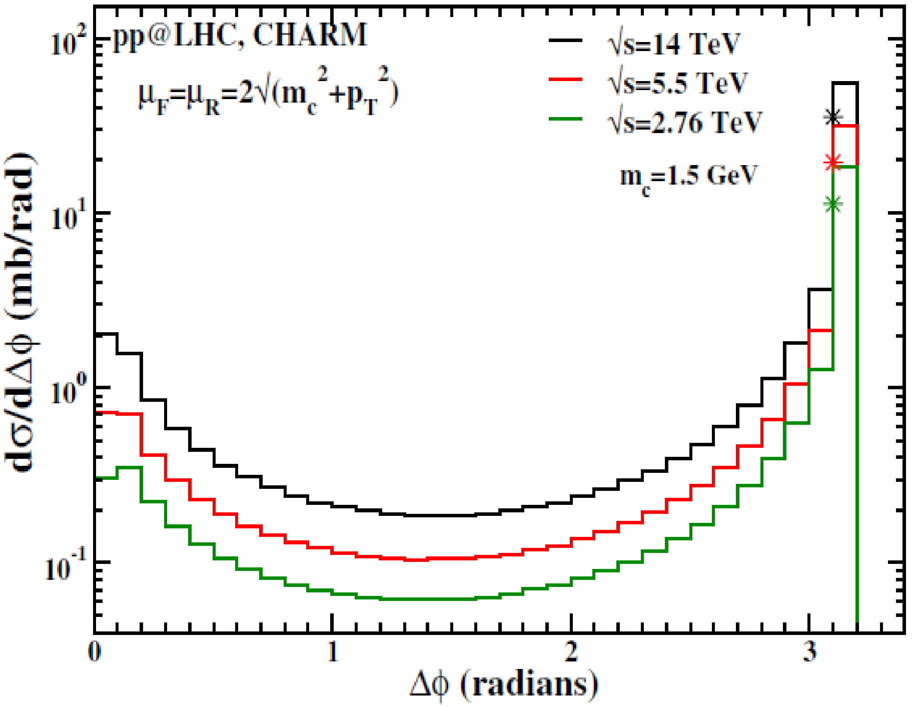
pp → $c\bar{c}$
Solid lines-CTEQ5M
Dashed lines-CTEQ4L
ALICE Preliminary data
Cosmic ray
STAR AuAu
STAR dAu
PHENIX single e in pp
E743
PHENIX single e in AuAu
UA2
ISR expts
NA37
SPS/FNAL p beam
NLO-MNR (m_c = 1.2 GeV)
NLO-MNR (m_c = 1.2 GeV)
NLO-MNR (m_c = 1.5 GeV)
NLO-MNR (m_c = 1.5 GeV)
$\mu_R = \mu_F = 2\sqrt{(m_c^2 + p_T^2)}$
σ (μb)
√s (GeV)
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
10^{0} 10^{1} 10^{2} 10^{3} 10^{4}



Charm (M_c=1.6 GeV)
2.5 x LO
1.5 x LO
NLO-MNR
pp @ 200 GeV
pp @ 5.5 TeV
CTEQ4M
$\mu_R = \mu_F = \sqrt{(M_c^2 + p_T^2)}$
$d\sigma/d^2p_T dy$ (μb/GeV^2)
p_T (GeV)
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
0 5 10 15 20



pp@LHC, √s=2.76 TeV
m_c=1.5 GeV;m_b=4.5 GeV
CTEQ4L
CTEQ4M
CTEQ5M
MRS125
|y| ≤ 0.5
$\mu_F=\mu_R=2\sqrt{(m_c^2+p_T^2)}$
CHARM
BOTTOM
$\mu_F=\mu_R=\sqrt{(m_b^2+p_T^2)}$
$E\,d\sigma/d^3p$ (mb/GeV^2)
p_T (GeV)
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
0 2 4 6 8 10 12 14 16 18 20



pp@LHC, CHARM
$\mu_F=\mu_R=2\sqrt{(m_c^2+p_T^2)}$
√s=14 TeV
√s=5.5 TeV
√s=2.76 TeV
m_c=1.5 GeV
dσ/dΔφ (mb/rad)
Δφ (radians)
10^{-1} 10^{0} 10^{1} 10^{2}
0 1 2 3

Medium Effects on Heavy Quarks Observables : Energy Loss

- An **empirical model** of energy loss by charm quark based on **Huang-Wang-Sarcevic** model of multiple scattering of charm with gluons and light quarks

- Assumption of momentum loss per collision given by : $(\Delta p)_i = \alpha (p_i)^\beta$ where α and β are the parameters .

- We have taken β = 0.5, and 1 for different mechanism of momentum loss per collision .

- Now one can write $\frac{dp}{dx} = -\frac{\Delta p}{\lambda}$, λ is the mean free path taken as 1 fm for initial studies

- We estimate the probability of a charm quark having ***n*** collisions while covering a path length ***L*** is given by a Poisson distribution:

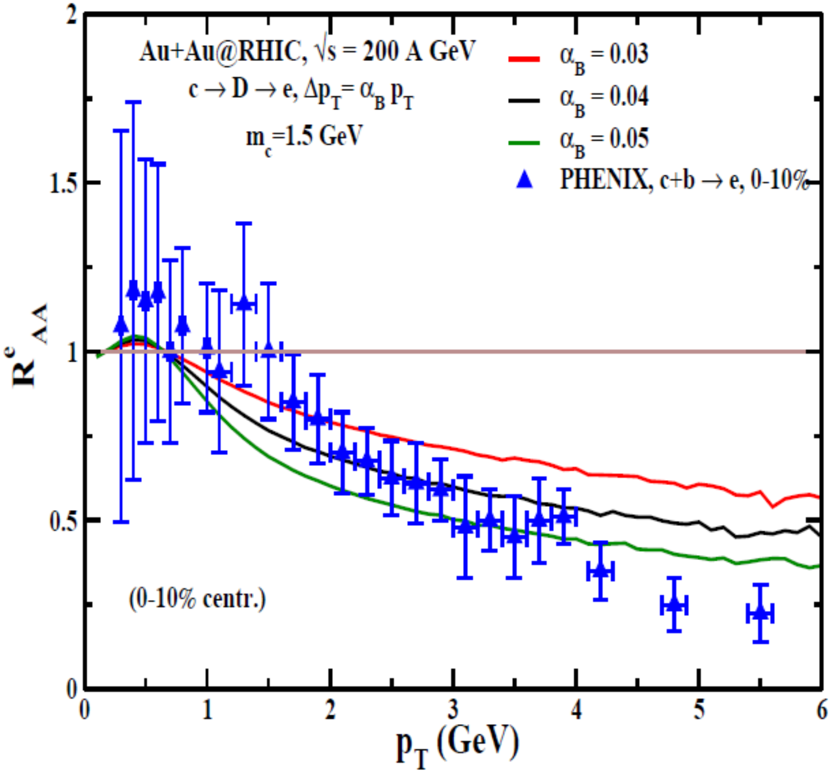
$$P(n,L)=\frac{(L/\lambda)^n}{n!}e^{-L/\lambda}$$

- Assuming central rapidity, the momentum of charm quark after n collisions is given by

$$p_{n+1}=p_n-(\Delta p)_n$$

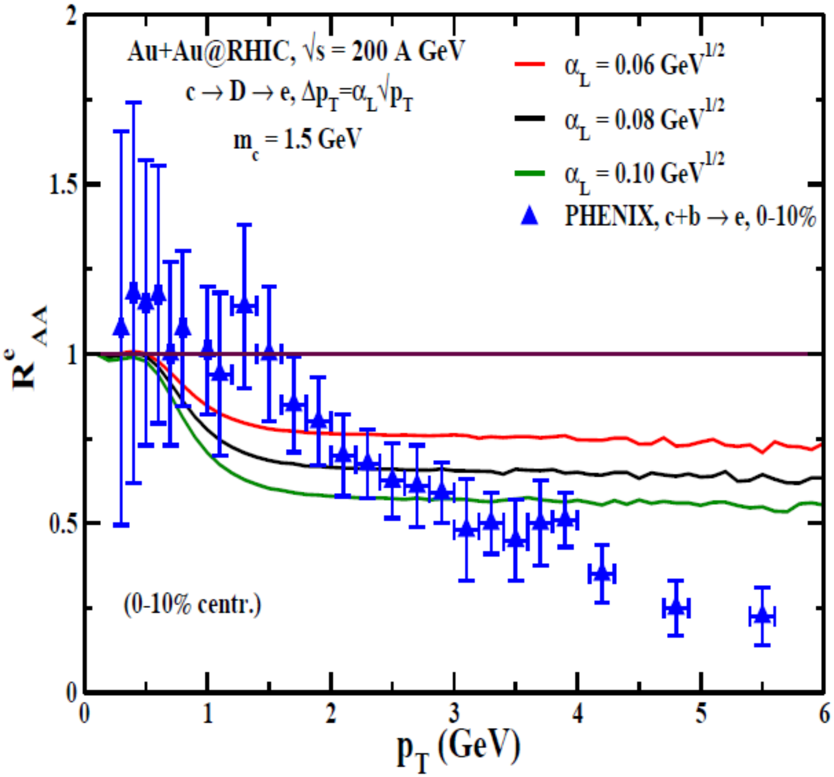
- A Monte Carlo implementation of our model and estimate the momentum loss of charm quarks . Determine nuclear modification and azimuthal anisotropy of charm via D mesons and single non photonic electron

R_{AA} of charm at RHIC energy: We recall that experimental results show a similar suppression of charm to that lighter quarks at RHIC and LHC.



$$\beta = 1.0, \alpha \rightarrow \alpha_B$$

$$\Delta p_T = \alpha_B \, p_T$$

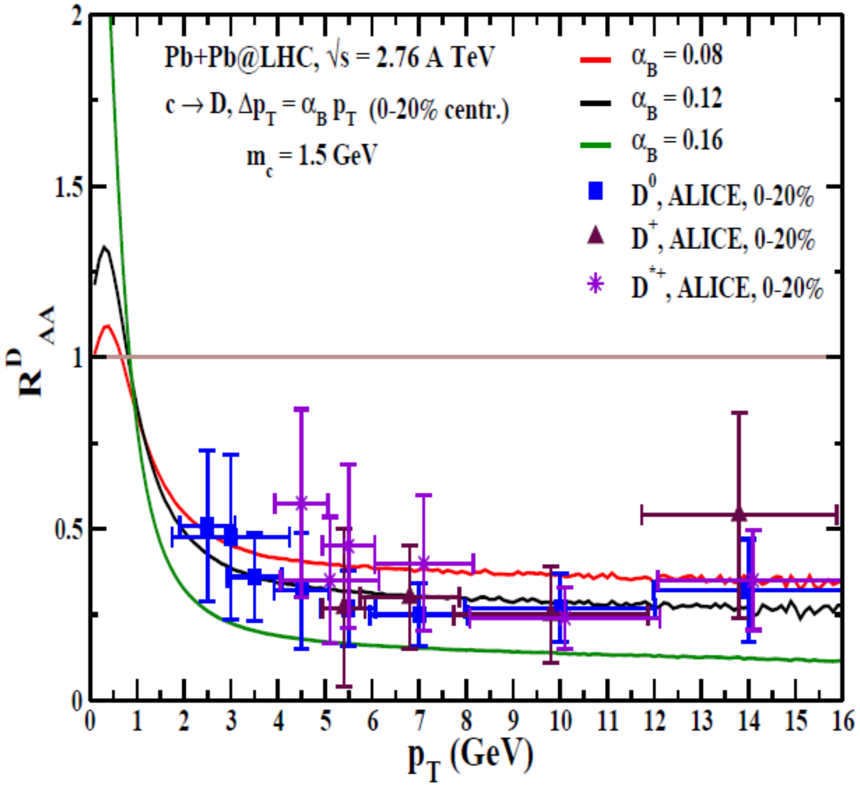


$$\beta = 0.5, \alpha \rightarrow \alpha_L$$

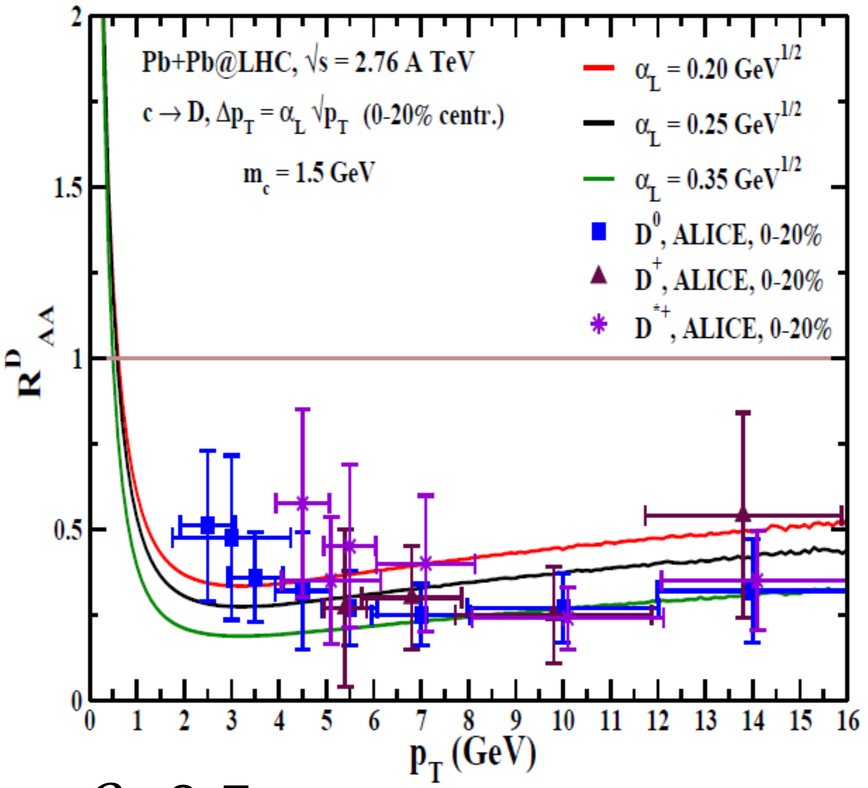
$$\Delta p_T = \alpha_L \sqrt{p_T}$$

RHIC : 0.04 and 0.08 **GeV$^{1/2}$** , model fits well with experimental data especially at mid p_T

R_{AA} of charm at LHC energy:



$$\beta = 1.0,\ \alpha \rightarrow \alpha_B$$
$$\Delta p_T = \alpha_B\, p_T$$

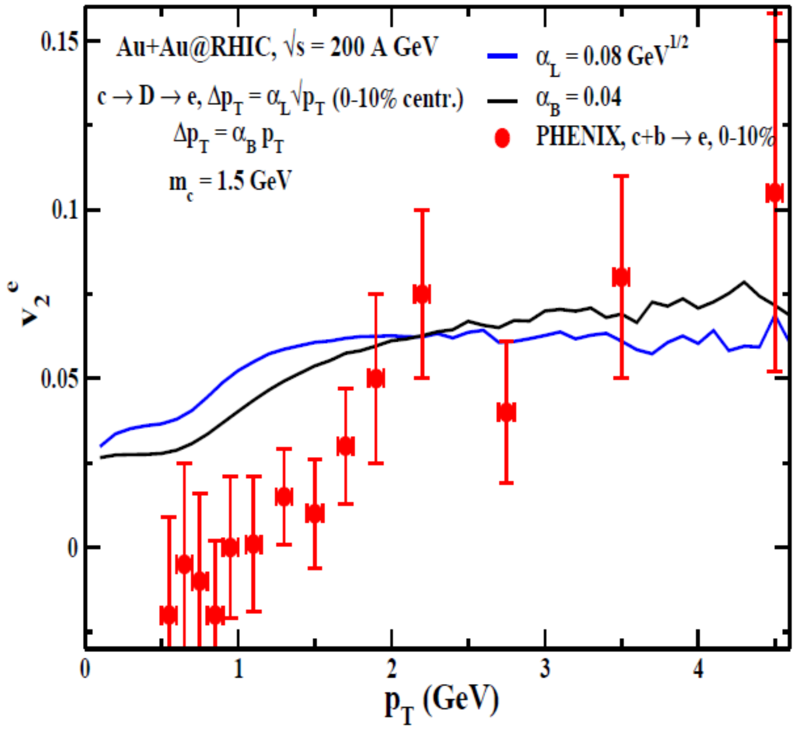


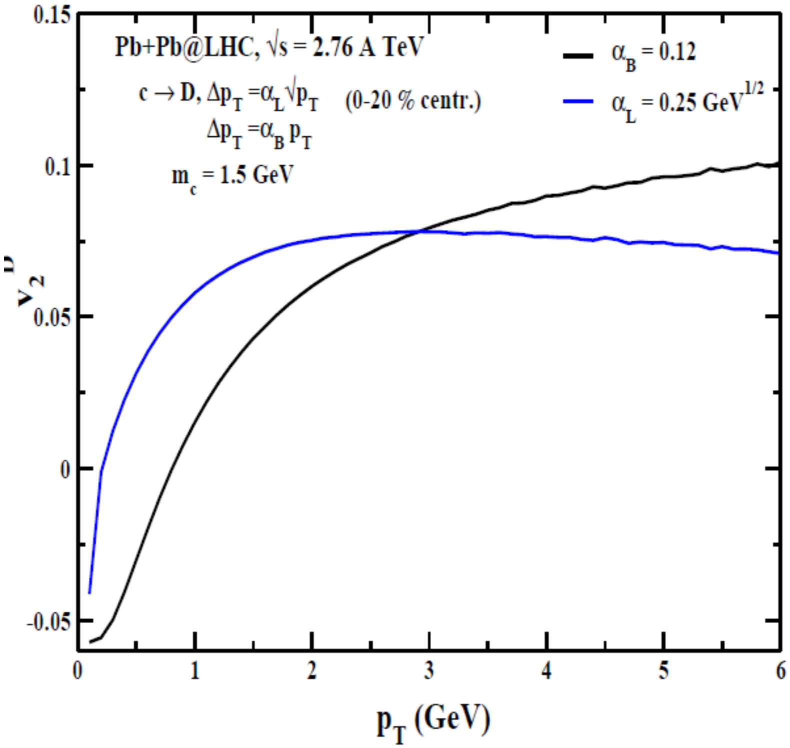
$$\beta = 0.5,\ \alpha \rightarrow \alpha_L$$
$$\Delta p_T = \alpha_L \sqrt{p_T}$$

LHC: **0.12 and 0.25 $\mathrm{GeV}^{1/2}$**, give the best value to fit data upto p_T = 14 GeV.

v_2 of charm at RHIC and LHC energy

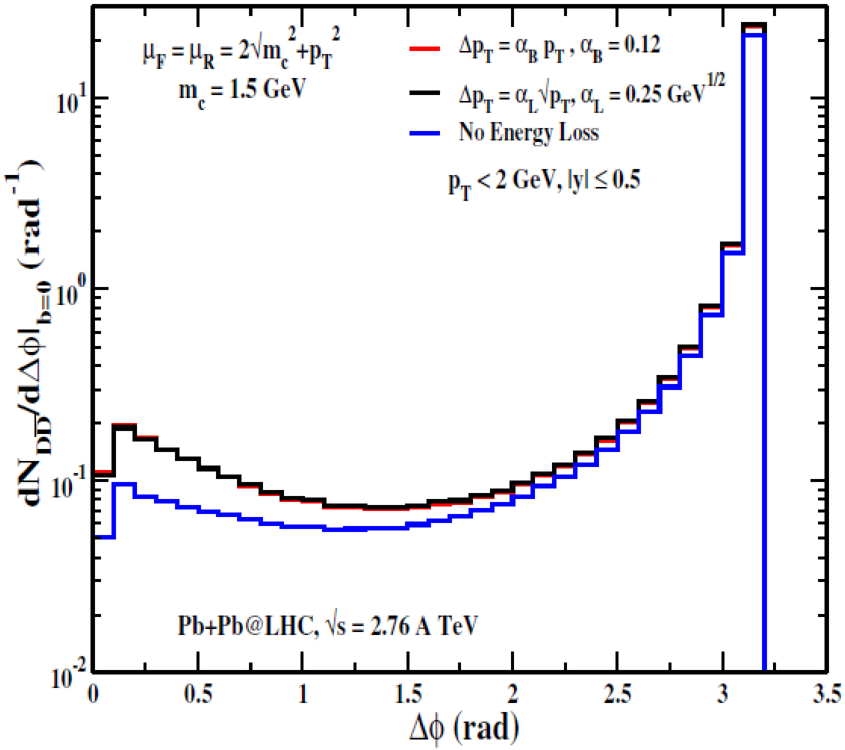
Taking the best value for α_B and α_L we estimate $v_2(p_T)$ for D mesons and single electrons from D decay.

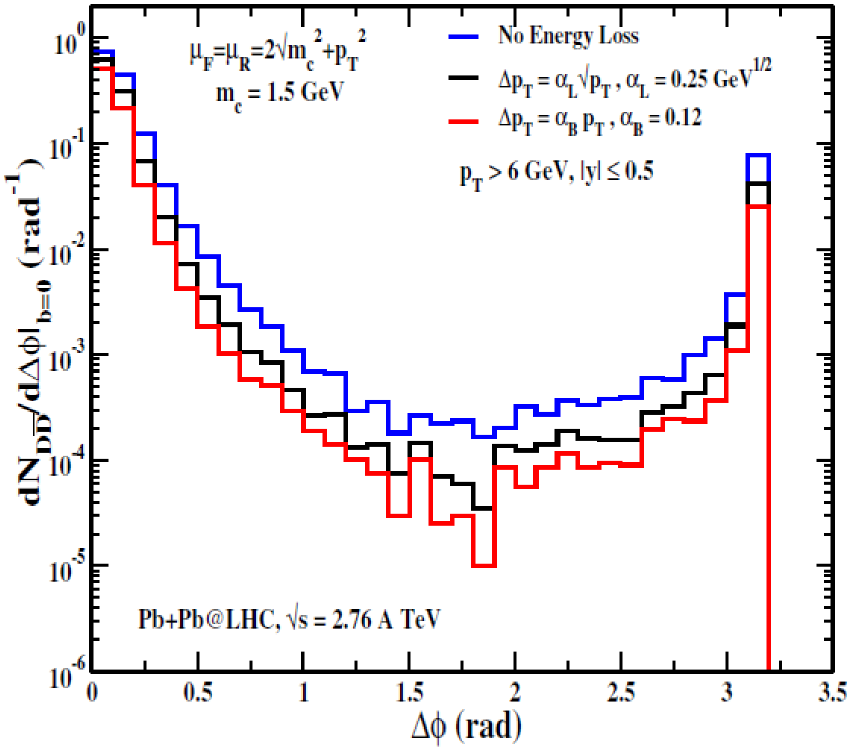




The result doesn't properly explain the data at low p_T but fits the values at mid p_T region. The two different choice of parameters show different trend at higher transverse momentum region.

Results for **Azimuthal Correlations** for charmed meson pairs





With different cuts on final D mesons transverse momenta, we have considerable change in azimuthal correlation of D meson pair when energy loss by charm quarks are included……..a definite observable for heavy quark evolution in QGP.

Consequences of energy loss by charm quarks

- The parameters α depends upon centrality as well as centre of mass energy.

- We know the Fokker -Planck equation as :

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

Where '*f*' is the charm distribution of charm quarks propagating through QGP.

$A_i(p)$ is the drag acting on the charm and $B_{ij}(p)$ is the diffusion of the charm quark.

Assuming $A_i(p) = A(p^2)\, p_i$ only then the energy loss $$\frac{dE}{dx}=-A(p^2)\,p$$

With slight calculations the energy loss per unit length can be written as

$$\frac{dp}{dx} = -A(p^2)\,E,$$ which is momentum loss per unit length.

So from one of our ansatzes i.e. $\Delta p_T = \alpha_B\, p_T$ we can also write

$$\frac{dp}{dx} = -\frac{\alpha_B\, p_T}{\lambda}$$, so that one can equate to write $A_{eff}(p^2) = \frac{\alpha_B}{\lambda}\frac{p_T}{E}$

From our results we note for large p_T $A_{eff} \approx 0.04$ fm^{-1} at RHIC average

temperature of 220 MeV which is almost twice than that of soft collisions

only. $A_{eff} \approx 0.12$ fm^{-1} at LHC average temperature of 270 MeV which is

three times that of soft collisions.

M. Younus and D. K. Srivastava, J. Phys. **G** : Nucl. Part. Phys. **39**, 095003 (2012);
J. Phys. **G** : Nucl. Part. Phys. **40**, 065004 (2013).

M . G. Mustafa, D. Pal and D . K. Srivastava, Phys. ReV. **C57**, 889 (1998)

Medium Effects………

Transport Model –Parton Cascade Model

- In order to investigate the properties of QGP and study QCD within system we need some model which shows evolution of QGP and it's various properties.

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

Lattice QCD: rigorous calculation of QCD properties in equilibrium.

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

What are the transport models available for studying heavy quarks in QGP ?

Microscopic transport models based on the Boltzmann Equation:

- transport of a system of microscopic particles
- all interactions are based on binary scattering

→ Evolution of both probe and QGP

$$\left[\frac{\partial}{\partial t}+\frac{\vec{p}}{E}\times\frac{\partial}{\partial \vec{r}}\right] f_1(\vec{r},\vec{p},t)=\sum_{processes} C(\vec{r},\vec{p},t)$$

Diffusive transport models based on Langevin Equation:

- transport of a system of microscopic particle in a thermal medium
- interactions contain a drag term which is related to the properties of the medium and a noise term related to the random collisions.

$$\vec{p}(t+\Delta t)=\vec{p}(t)-\frac{\kappa}{2T}\vec{v}.\Delta t+\vec{\xi}(t)\Delta t$$

→ Evolution of probe in the QGP

⬆

hydrodynamics

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↔2) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation (2→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

PCM VNI/BMS and Box mode

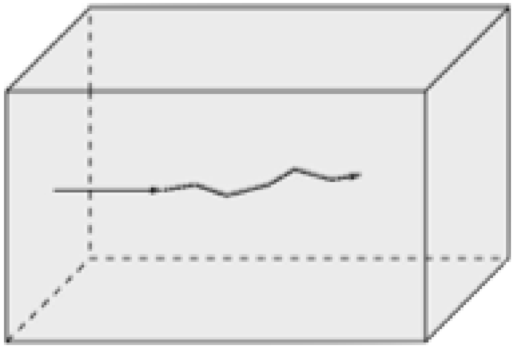
- **PCM** → describes the evolution of the probe jet in the medium but also evaluate the response of the medium.

- There are number of implementations of the **PCM** → **VNI/BMS** → some 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 mode.**

- Box mode provides a controlled set of parameters through which we can follow QGP evolution as well as track the probe. Using this scheme we try to understand the properties of **infinite QGP matter at fixed temperatures.**

Box 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=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

Cross Section:

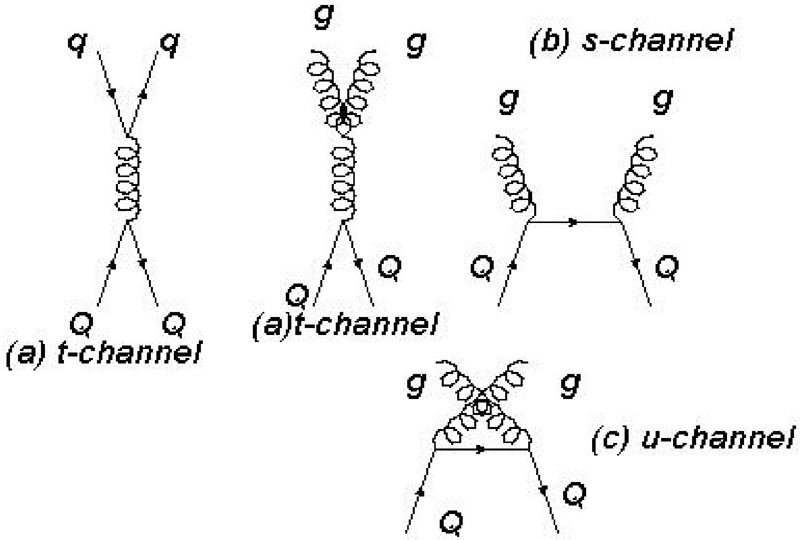
use a Debye-screened elastic cg cross-section:

$$\frac{d\sigma}{d\hat{t}} \propto \frac{1}{\left(\hat{t}-\mu_D^2\right)^2}$$

choose Debye-mass to be:

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

use a fixed coupling: α_s =0.3



Desired Calculations

- distribution of momentum transfers

- energy-loss as function of distance traveled

- energy-loss transport coefficient :

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

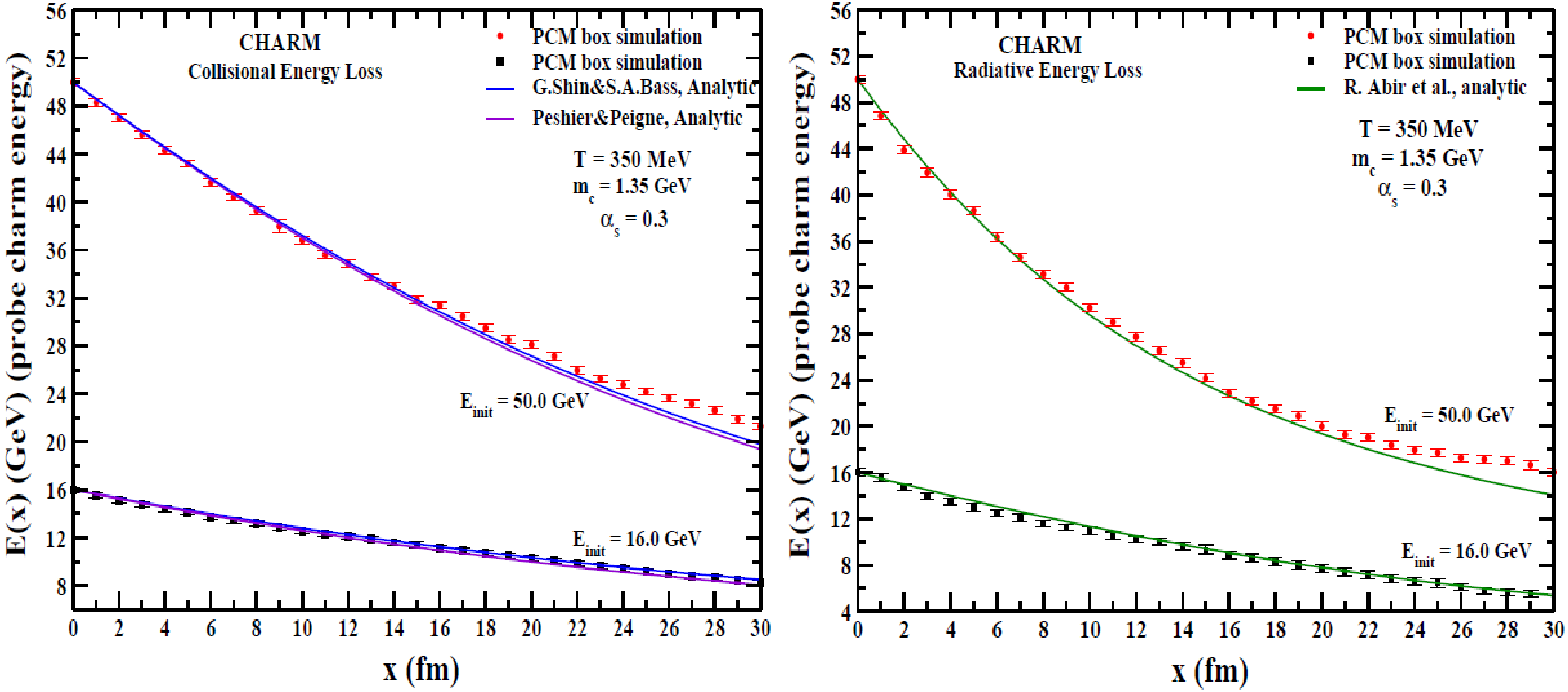
$$\hat{q} = \frac{1}{l_x} \sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2$$

- heavy quark radiative + collisional energy-loss

Extensions :

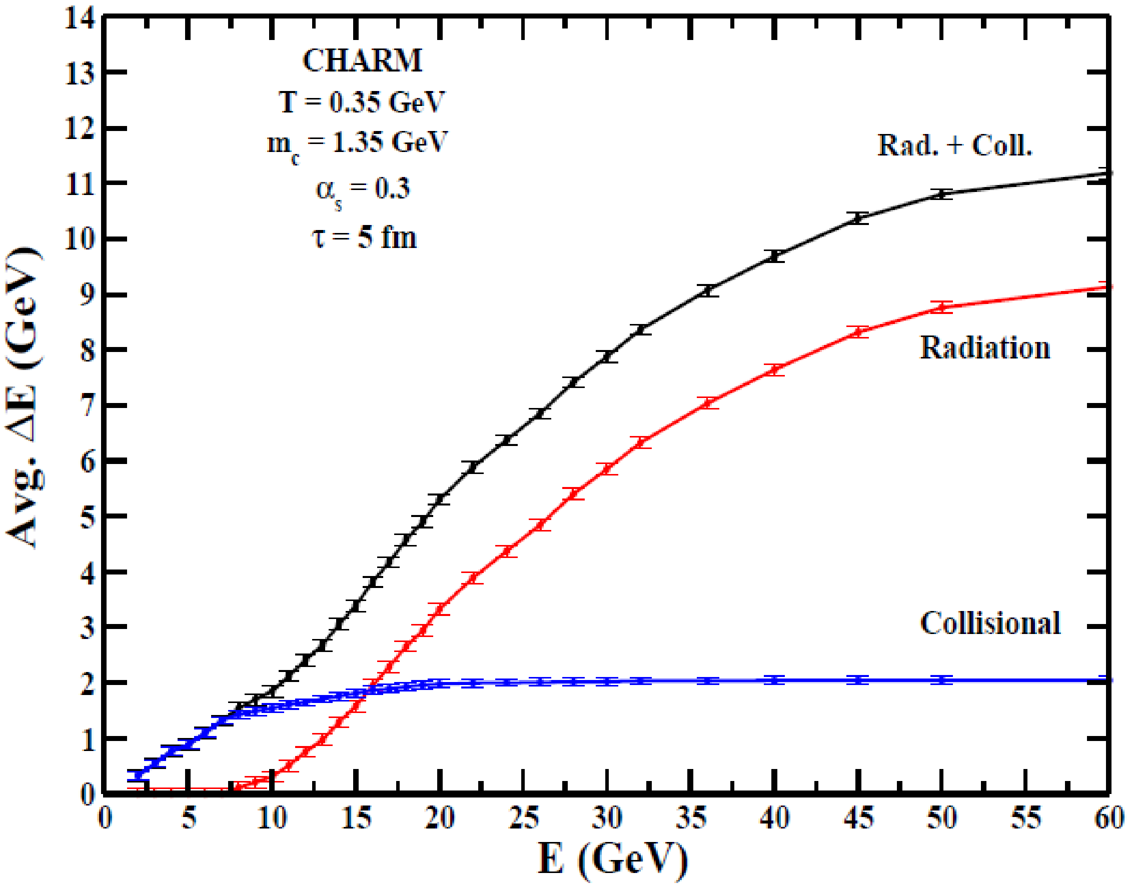
- full QGP: study flavor-dependence

- medium response: correlations etc.



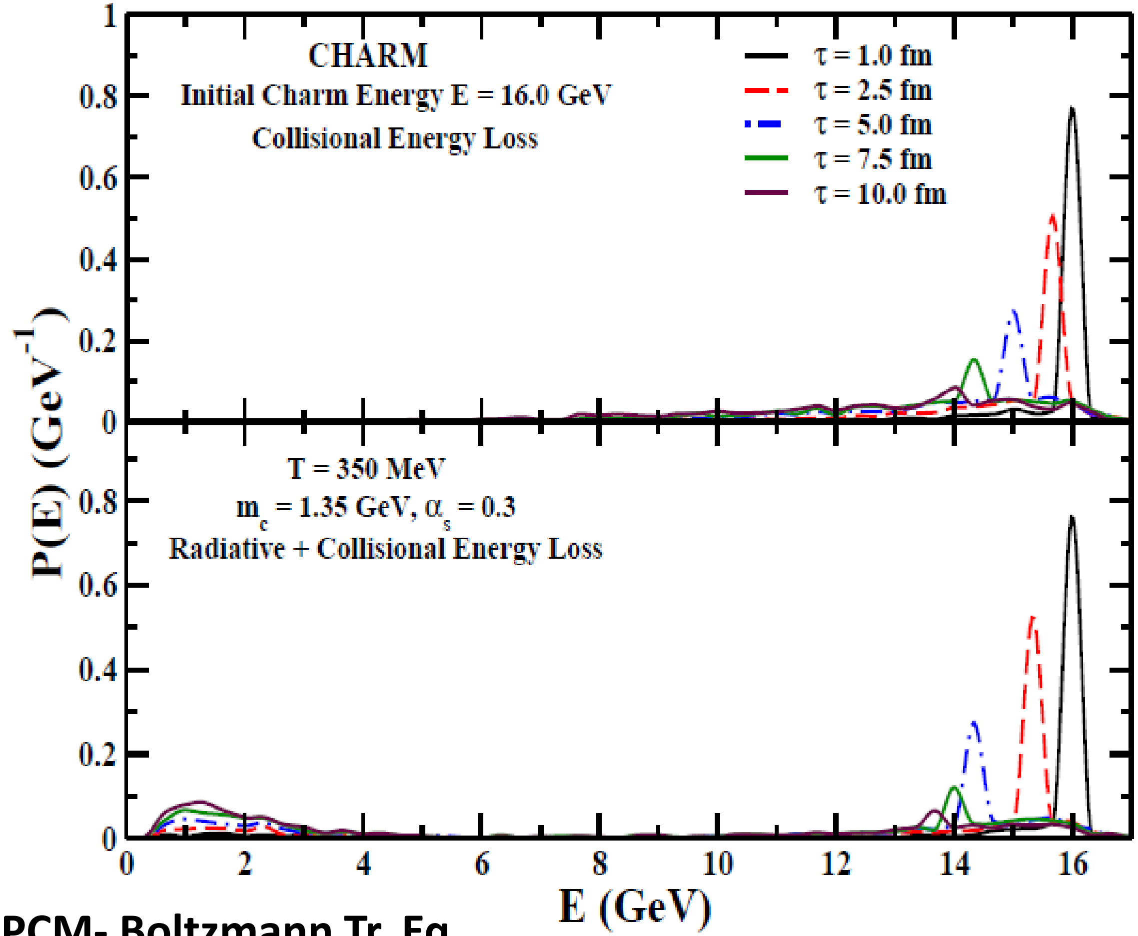
Energy dependence of charm quark energy loss with distance travelled in the box.

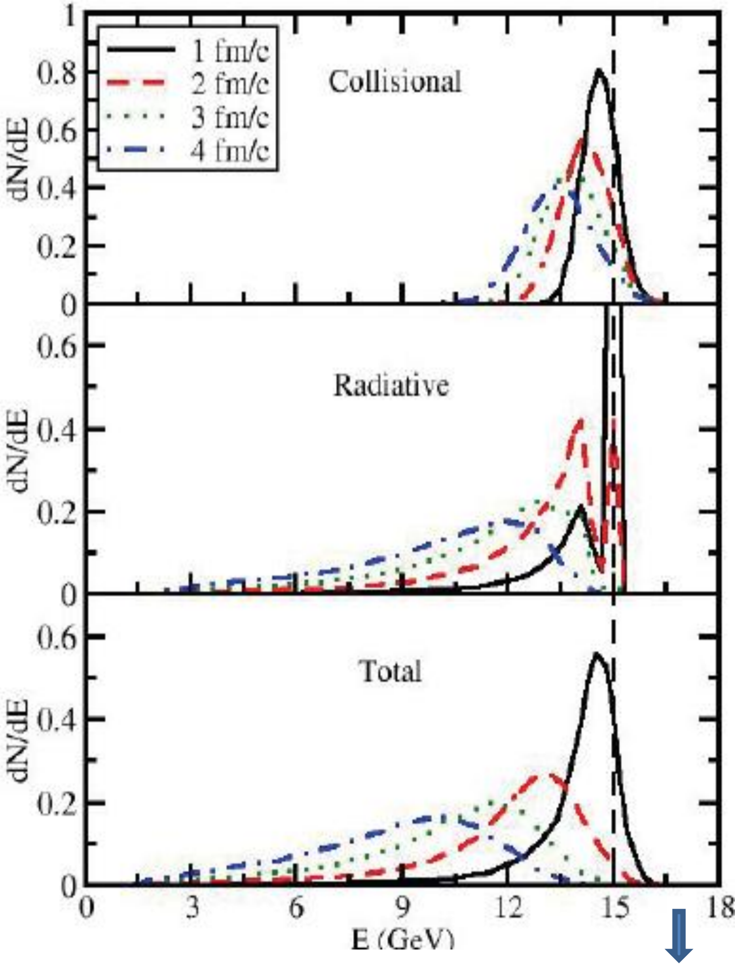
For collisional energy loss only where T = 350 MeV, m_c = 1.35 GeV and $\alpha_s = 0.3$ as the parameters for evolution in PCM box .



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.





PCM- Boltzmann Tr. Eq.

energy-loss transport coefficient for microscopic transport model is defined as: $$\hat{q} = \frac{1}{l_x}\sum_{i=1}^{N_{coll}} (\Delta p_{\perp,i})^2$$

Langevin Eqn. by Shanshan et al.
arXiv: 1209.5410v1 [nucl-th]2012

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

$\hat{q} \sim 1.22$ GeV^2/fm. ⟵ PCM calculations.

Conclusions

- Heavy quarks observables such as nuclear modification factor, azimuthal anisotropy and charm pair azimuthal correlation have been studied.
- Calculations based on phenomenological models by Huang et al. have been done to simulate the effects of quark gluon plasma on heavy quark observables. The model is used to determine R_{AA} , v_2, and $C(\Delta\phi)$.
- The effective drag calculated using the model is high and suggests importance of radiative energy loss compared to soft collisions.
- Transport calculations of Parton Cascade Model have been used to determine the average energy loss of charm quark, energy loss per unit length traversed and momentum broadening per unit length.
- In future the Parton cascade model will be used to study charm evolution for other temperatures as well in order to get a full picture of charm quark dynamics.
- The differences between Boltzmann equation and Langevin equation for probe heavy quark will be further studied.
- The calculations will be extended to include beauty quarks as well. Correlations calculations will be further studied upon to bring out deeper features of heavy quark dynamics and how it can help us better understand QGP properties.

THANK YOU