R_{AA} of charm quark at RHIC and LHC

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Umme Jamil and Dinesh K Srivastava , *J. Phys. G: Nucl. Part. Phys.* , 37 (2010) 085106

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Outline:

Motivation.

Experimental results and theoretical models.

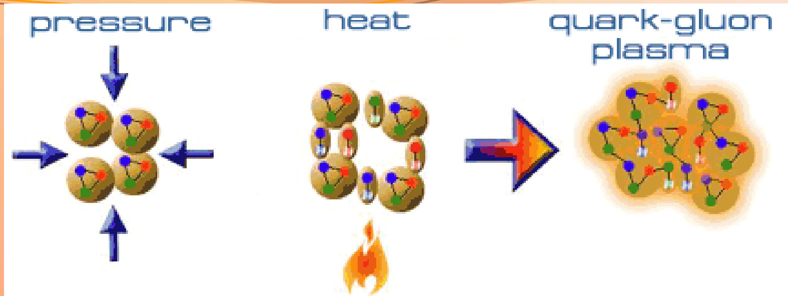
Production of heavy quarks using LO pQCD.

Different energy loss mechanisms.

Calculation of R_{AA} .

Summary.

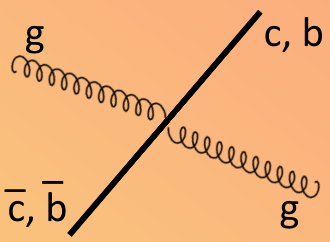
At extremely high energy densities, QCD predicted formation of a new form of matter (QGP), consisting of deconfined (anti)quarks and gluons.



Heavy quarks (charm and bottom, M>1 GeV) are widely recognized as the excellent probes of QGP:

➲ **Heavy quarks can be produced only during the early stage of collision.**

Early stage

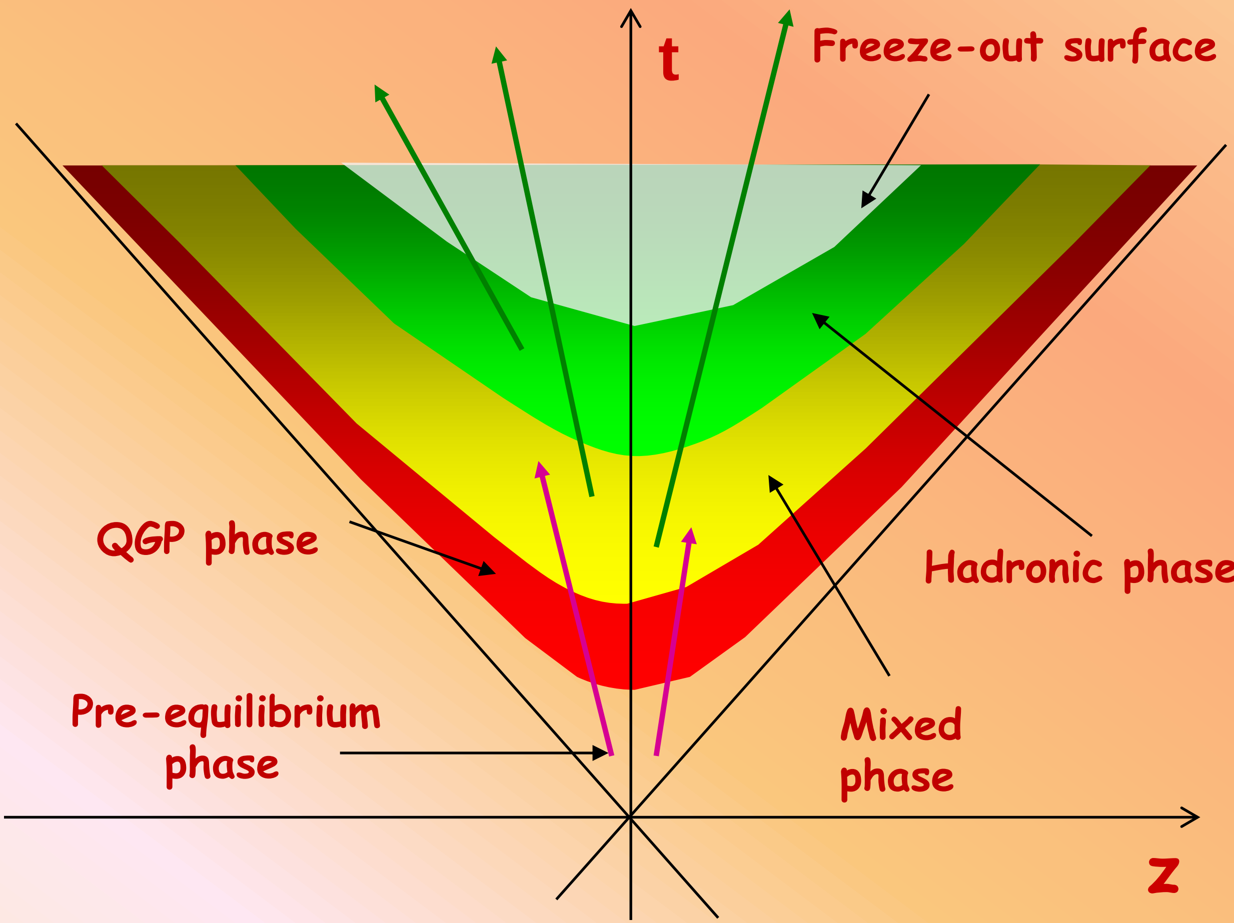


$\tau = 1/2M_Q \ll 0.1$ fm/c

No heavy quark production

➲ **Due to their large mass, the production of heavy quarks is small making them special as a probe for QGP.**

A heavy quark/antiquark produced at the initial time of system evolution will pass through the QGP, colliding with quarks and gluons and radiating gluons. Thus the heavy quark/antiquark will loose energy while passing through the QGP.



Motivation

- The centre of mass energy at LHC is more than 25 times than at RHIC energy. Such a huge difference in the centre of mass energy of collisions throws open an opportunity to compare the energy loss of heavy quarks at both the energies.

- The large rapidity window which opens at LHC provides an environment varying with the rapidity. Thus in one single experiment, dependence on initial temperature of the energy loss formalisms can be put to a rigorous test.

- The different energy loss mechanisms available in the literature can be studied with the same initial conditions to find out the most reliable treatment and also to use the correct one while calculating the nuclear modification factor.

High pt suppression is a consequence of the energy loss.

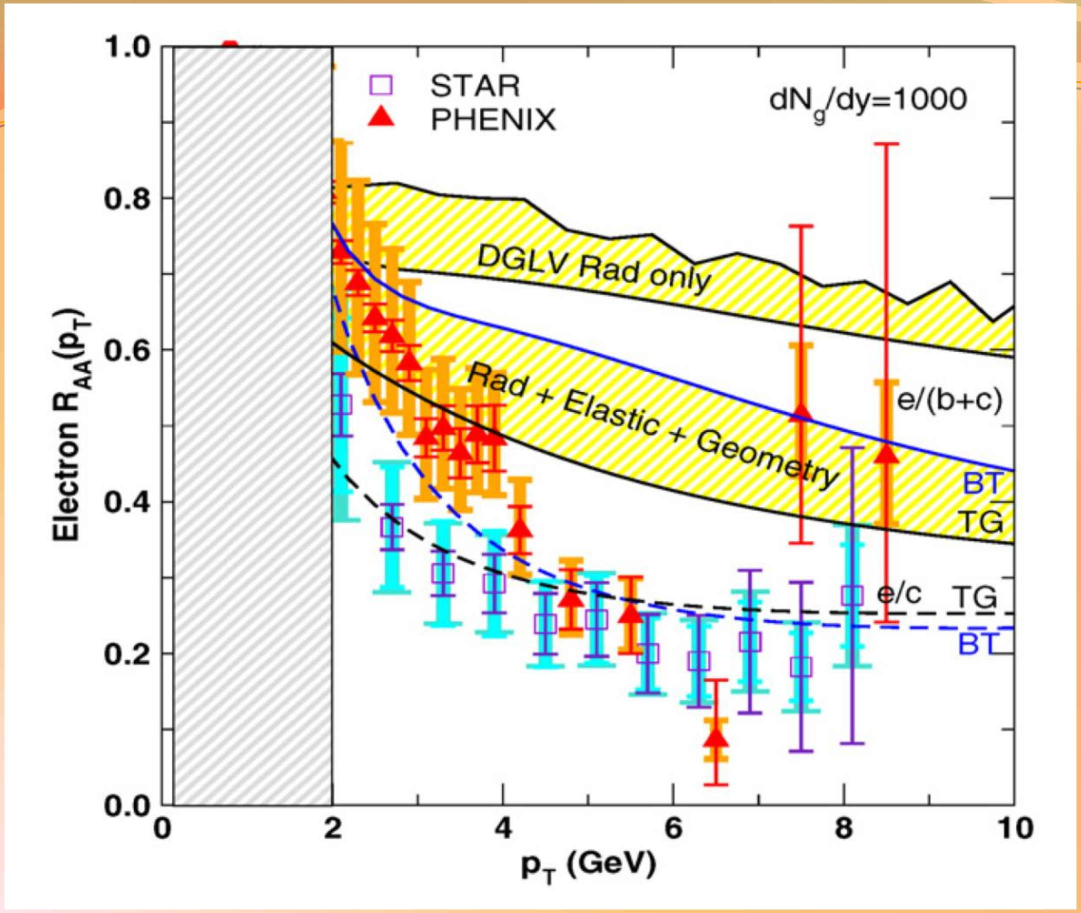
To use heavy flavor suppression data as a tool to study the properties of QGP, reliable theoretical predictions are needed.

Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles.

Collisional energy loss

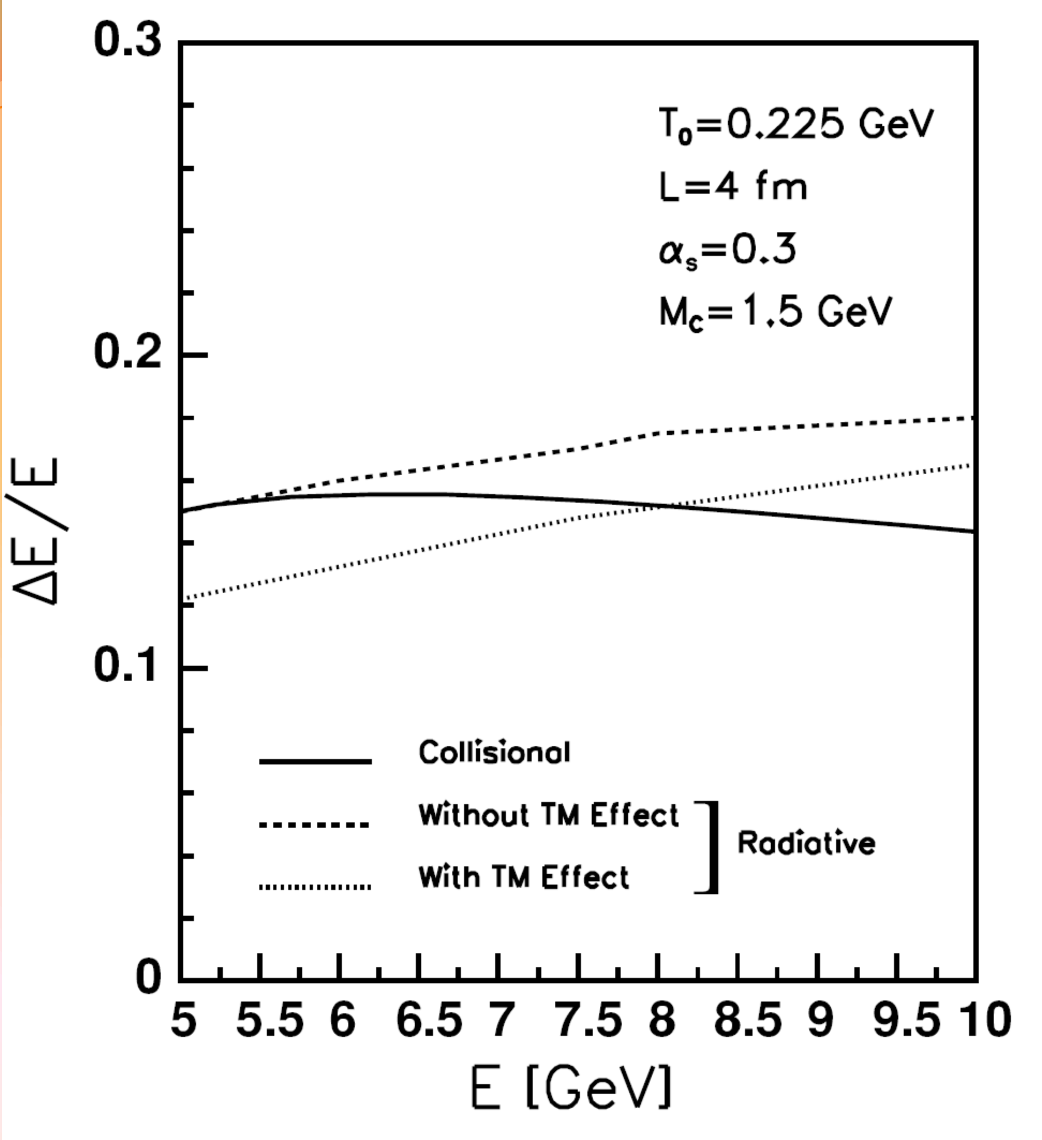
Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles.



Collisional energy loss notably improves the agreement with the data.

The suppression factor, $R_{AA}(p_T)$, electrons from decay of quenched heavy quark (c + b) jets is compared to PHENIX [A. Adare et al. Phys. Rev. Lett. 98, 172301(2007)] and STAR [Nucl. Phys. A 774(2006)697] data in central Au + Au reactions at 200A GeV. All calculations assume initial dNg/dy = 1000.

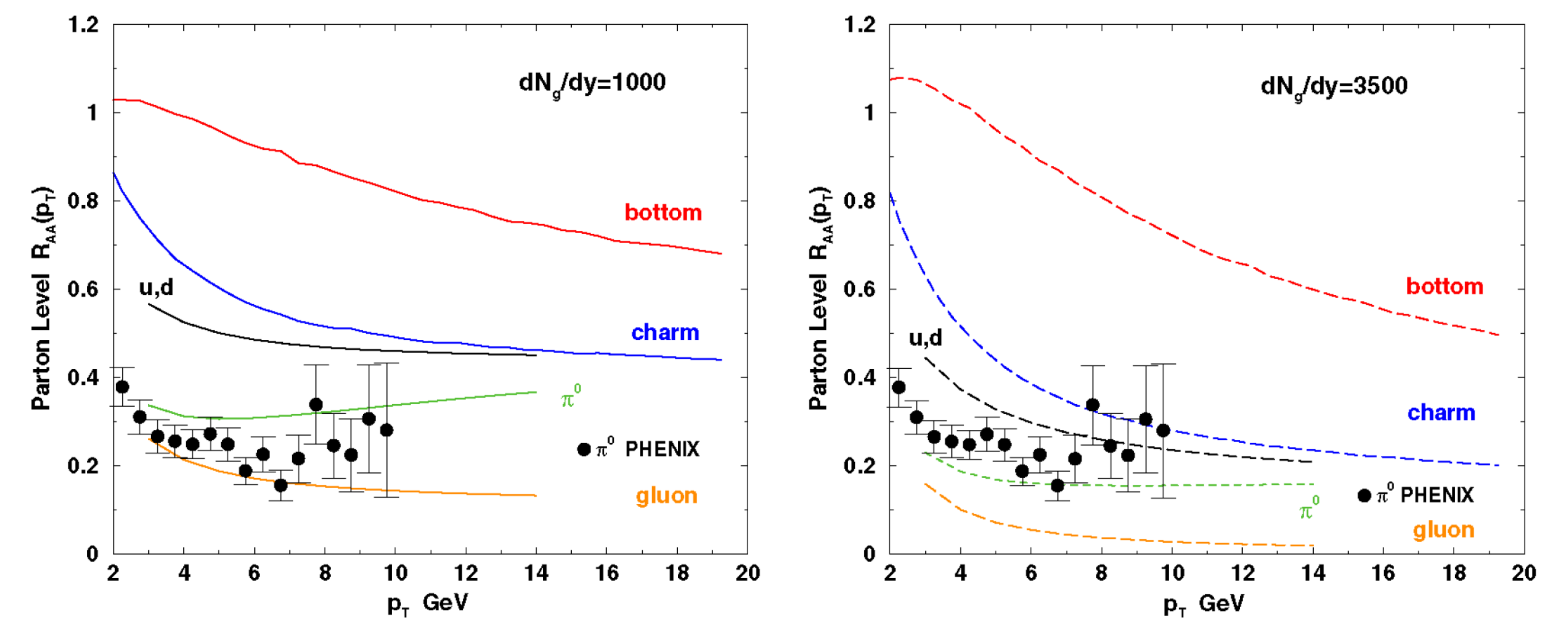
S. Wicks et. al, Nuclear Physics A 784 (2007) 426



Collisional energy loss is according to the calculation presented by Braaten and Thoma where as radiative energy loss is according to the calculation presented by M. Djordjevic and M. Gyulassy. Results are for RHIC energy.

M. G. Mustafa, Phy. Rev. C 72 (2005) 014905

The same behaviour is shown for light quarks also.
P. Roy, J. e. Alam, and A. K. Dutta-Mazumder, J. Phys. G 35 (2008)104047



Heavy quark jet quenching before fragmentation into mesons for $dN_g/dy = 1000$ and 3500 are compared to light (u, d) quark and gluon quenching. The resulting R_{AA} for π^0 is compared to the central 0–10% PHENIX data .

$$R_{AA}(\pi^0) \approx f_g R_{AA}(g) + (1 - f_g) R_{AA}(u), \quad f_g \approx \exp[-p_T/10.5]$$

[S.S. Adler, et al., Phys. Rev. Lett. 91, 072301(2003)
A. Adare et al. Phys. Rev. Lett. 101, 232301(2008)
M. Djordjevic, Physics Letters B 632 (2006) 81]

The Initial distribution of heavy quarks:

$$\frac{d\sigma}{dy_1\,dy_2\,dp_T} = 2\,x_1\,x_2\,p_T \sum_{ij} \Big[f_i^{(1)}\left(x_1, Q^2\right) f_j^{(2)}\left(x_2, Q^2\right) \hat{\sigma}_{ij}\left(\hat{s}, \hat{t}, \hat{u}\right)$$

$$+ f_j^{(1)}\left(x_1, Q^2\right) f_i^{(2)}\left(x_2, Q^2\right) \hat{\sigma}_{ij}\left(\hat{s}, \hat{t}, \hat{u}\right) \Big] \Big/ \left(1 + \delta_{ij}\right)$$

The fractional momenta of the interacting hadrons carried out by the partons can be expressed as:

$$x_1 = \frac{m_T}{\sqrt{s}}\left(e^{y_1} + e^{y_2}\right) \qquad x_2 = \frac{m_T}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)$$

where

$$m_T = \sqrt{M^2 + p_T^2}$$

The short-range subprocess for the heavy-quark production is defined as:

$$\frac{d\sigma}{dt} = \frac{1}{16\pi\hat{s}^2}\left|\mathcal{M}\right|^2$$

with

$$|\mathcal{M}|^2(gg \to Q\bar{Q}) = \pi^2 \alpha_s^2 \left[\frac{12}{\hat{s}^2}(M^2 - \hat{t})(M^2 - \hat{u}) + \frac{8}{3} \frac{(M^2 - \hat{t})(M^2 - \hat{u}) - 2M^2(M^2 + \hat{t})}{(M^2 - \hat{t})^2} \right.$$

$$\frac{8}{3} \frac{(M^2 - \hat{t})(M^2 - \hat{u}) - 2M^2(M^2 + \hat{u})}{(M^2 - \hat{u})^2} - \frac{2M^2(\hat{s} - 4M^2)}{3(M^2 - \hat{t})(M^2 - \hat{u})}$$

$$\left. - 6 \frac{(M^2 - \hat{t})(M^2 - \hat{u}) - M^2(\hat{u} - \hat{t})}{\hat{s}(M^2 - \hat{t})} - 6 \frac{(M^2 - \hat{t})(M^2 - \hat{u}) - M^2(\hat{t} - \hat{u})}{\hat{s}(M^2 - \hat{u})} \right]$$

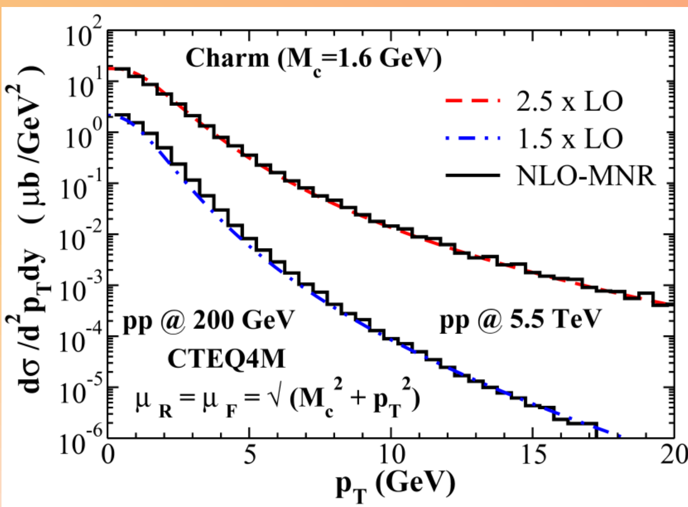
$$|\mathcal{M}|^2(q\bar{q} \to Q\bar{Q}) = \frac{64\pi^2 \alpha_s^2}{9} \left[\frac{(M^2 - \hat{t})^2 + (M^2 - \hat{u})^2 + 2M^2 \hat{s}}{\hat{s}^2} \right]$$

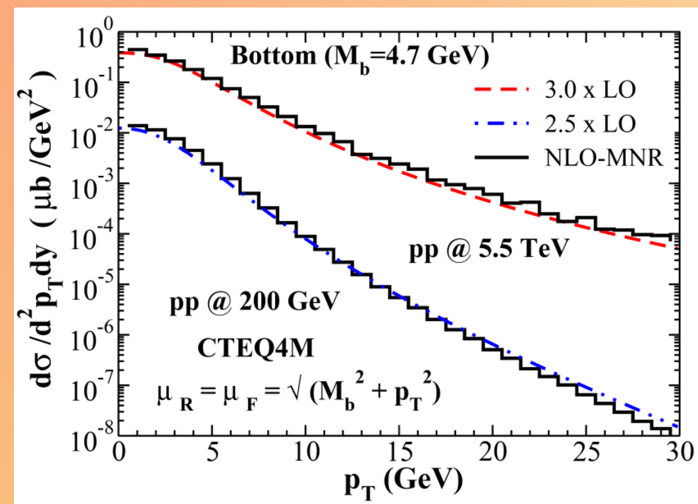
Flavour excitation process is known to be suppressed when the NLO processes are taken into account.

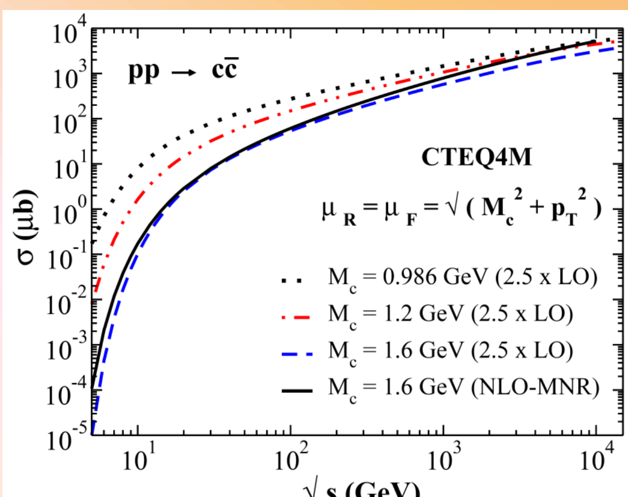
Z. Lin and M. Gyulassy, Phys. Rev. C 51(1995) 2177

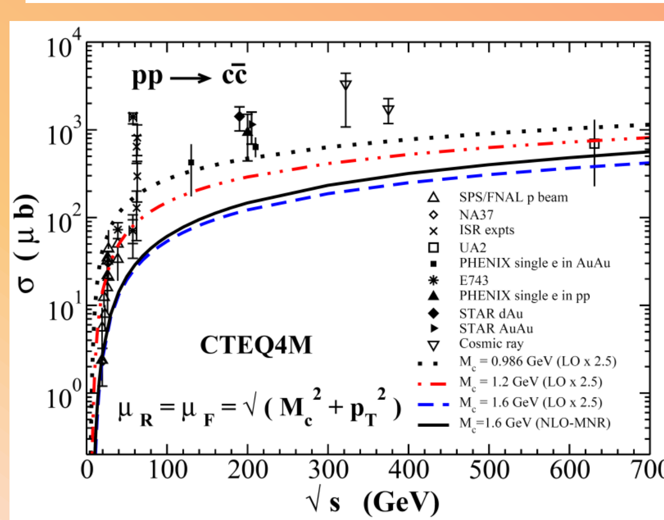
Along with our calculation of differential cross section for heavy quarks in pp collision at LO in pQCD we also carry out the calculation at NLO using the treatment developed by Mangano, Nason, and Ridolfi (MNR-NLO).

M. L. Mangano et al, Nucl. Phys. B 373, 295 (1992).





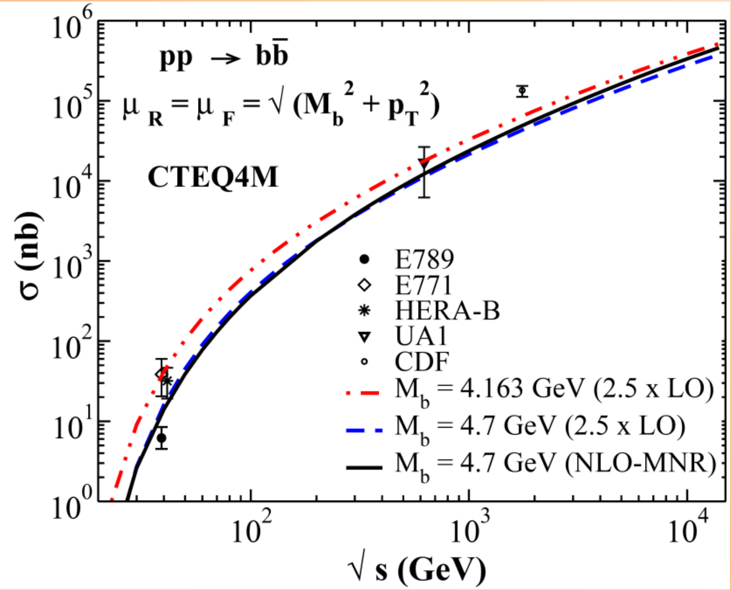


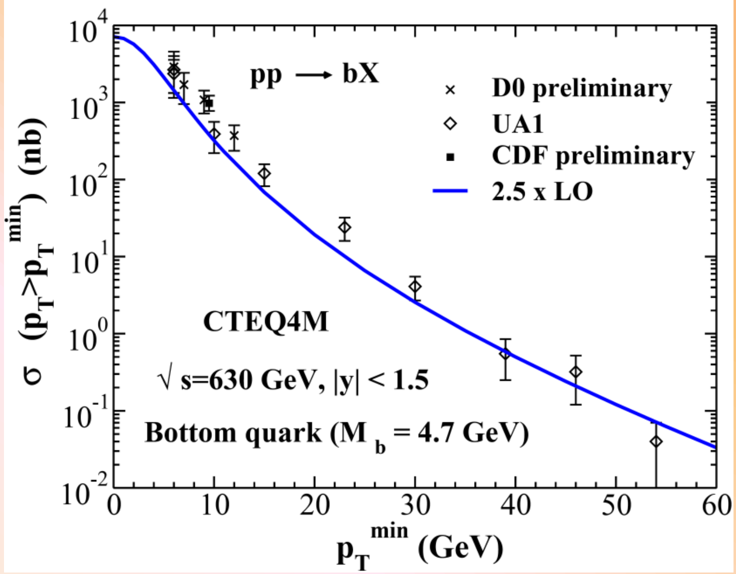


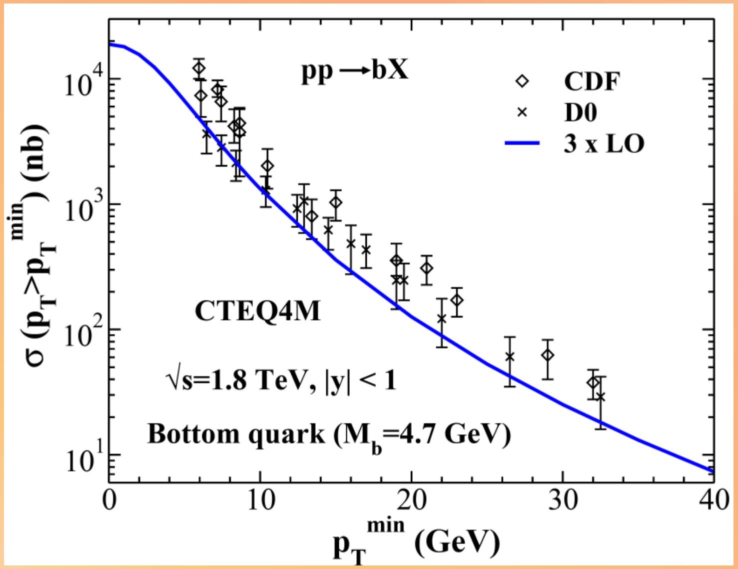
M_c (3 GeV)
=
0.986 GeV

J H Kühn, Acta Phys. Pol. B 3(2010)171

We compare the bottom quark production cross-section using the LO calculation in pp collision with experimental data points.







Collisional energy loss for heavy quarks

➲ Braaten and Thoma (BT) formulation ,

➢ The theoretical formalism used by Braaten and Yuan to find the energy loss of a muon propagating through a plasma to leading order in the QED, is extended by Braaten and Thoma to obtain the energy loss of a heavy quark propagating through QGP to leading order.

➢ Both the mass M_Q and momentum p of the heavy quarks are assumed to be much larger than the temperature of the plasma.

➢The maximum momentum transfer is the energy of the heavy quarks: $q_{max} = E$.

➢The soft contribution from Qg and Qq scattering is obtained from the QED case where (i) QED coupling constant is replaced by QCD coupling constant , (ii) multiplication of a color factor of 4/3 and (iii) thermal photon mass is replaced by thermal qluon mass.

➢ Results can be obtained in two energy regimes, $E<<M^2/T$ and $E>>M^2/T$. The crossover energy is taken as $E_{cross} = 1.8* M^2 /T$.

For $E<<M^2/T$,

$$-\frac{dE}{dx}=\frac{8\pi\alpha_s^2T^2}{3}\left(1+\frac{n_f}{6}\right)\left[\frac{1}{v}-\frac{1-v^2}{2v^2}\log\frac{1+v}{1-v}\right]\log\left(2^{\frac{n_f}{6+n_f}}B(v)\frac{ET}{m_gM}\right)$$

$$m_g=\frac{\mu}{\sqrt{2}}$$

B(v) is a smooth function of velocity v, changing from
B(0)=0.604, B(0.88)=0.731, B(1)=0.629

For $E>>M^2/T$,

$$-\frac{dE}{dx}=\frac{8\pi\alpha_s^2T^2}{3}\left(1+\frac{n_f}{6}\right)\log\left(2^{\frac{n_f}{2(6+n_f)}}0.92\frac{\sqrt{ET}}{m_g}\right)$$

E. Braaten and M. H. Thoma, Phys. Rev. D 44 (1991)2625
M. G. Mustafa, D. Pal, D. K. Srivastava, M. Thoma , PLB, 428(1998)234

➲Peigne and Peshier (PP) formulation

- In BT formalism, it was assumed that the momentum exchange q<<E. PP pointed out that this is not reliable in the energy regime $E \gg M^2/T$, and corrected it in the QED case while calculating the collisional energy loss of a muon in the QED plasma. This work in QED is then used to calculate the collisional energy loss of a heavy quark through QGP.
- A fixed coupling approximation is used.

$$-\frac{dE}{dx} = \frac{4\pi\alpha_s{}^2 T^2}{3}\left[\left(1+\frac{n_f}{6}\right)\log\frac{ET}{\mu^2} + \frac{2}{9}\log\frac{ET}{M^2} + c(n_f)\right]$$

$$\mu^2 = 4\pi\alpha_s T^2\left(1+\frac{n_f}{6}\right),\ c(n_f) = 0.146\,n_f + 0.05$$

Stephane Peigne and Andre Peshier, PRD 77 (2008) 114017

➲ Bjorken formulation

- Bjorken estimated the energy loss of quarks in light of the ionization of charged particles in ordinary matter. The formalism of Bjorken is extended by BT for heavy quark energy loss through QGP matter.

Modified heavy quark energy loss by Bjorken :

$$-\frac{dE}{dx} = \frac{8\pi\alpha_s{}^2 T^2}{3}\left(1+\frac{n_f}{6}\right)\left[\frac{1}{v} - \frac{1-v^2}{2v^2}\log\frac{1+v}{1-v}\right]\log\frac{q_{max}}{q_{min}} \qquad q_{max} = \sqrt{4TE},\ q_{min} = \sqrt{3}\,m_g$$

Radiative energy loss for heavy quarks:

➲Djordjevic, Gyulassy, Levai, and Vitev (DGLV) formulation

➲ For massless case Gyulassy, Levai and Vitev (GLV) computed the induced radiation to an arbitrary order in opacity χ^n ($\chi = L/\lambda$) of the plasma .

➲ DGLV generalize the GLV opacity expansion method to compute the first order induced energy loss including the kinematic effect due to heavy quark mass.

➲ The Ter-Mikayelian effect (plasma modifies the gluon self energy) reduces the induced energy loss.

➲Dead-cone effect (reducing the induced radiation inside the cone ❑ < M/E) is also considered.

Wicks et al. present a simplified form of the DGLV formalism for the average radiative energy loss of heavy quarks. S. Wicks et.al, Nuclear Physics A 784(2007)426

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

$$\beta^2 = m_g^2(1-x) + M^2 x^2,$$

$$\frac{1}{\lambda_g} = \rho_g \sigma_{gg} + \rho_q \sigma_{qg},$$
$$\sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2},$$

$$\sigma_{qg} = \frac{4}{9}\sigma_{gg},$$
$$\rho_g = 16\ T^3 \frac{1.202}{\pi^2},$$
$$\rho_q = 9\ N_f\ T^3 \frac{1.202}{\pi^2},$$
$$A = \frac{2\beta^2}{f_\beta^3}\left(\beta^2 + q^2\right),$$

$$B = \frac{\left(\beta^2 + K\right)\left(\beta^2 Q_\mu^- + Q_\mu^+ Q_\mu^+ + Q_\mu^+ f_\beta\right)}{\beta^2\left(\beta^2\left(Q_\mu^- - K\right) - Q_\mu^- K + Q_\mu^+ Q_\mu^+ + f_\beta f_\mu\right)},$$
$$C = \frac{1}{2q^2 f_\beta^2 f_\mu}\left[\ \beta^2\mu^2\left(2q^2 - \mu^2\right) + \beta^2\left(\beta^2 - \mu^2\right)K + Q_\mu^+\left(\beta^4 - 2q^2 Q_\mu^+\right)\right.$$
$$\left. + f_\mu\left(\beta^2\left(-\beta^2 - 3q^2 + \mu^2\right) + 2q^2 Q_\mu^+\right) + 3\beta^2 q^2 Q_k^-\ \right],$$
$$K = \left(2px(1-x)\right)^2,$$
$$Q_\mu^\pm = q^2 \pm \mu^2,$$
$$Q_k^\pm = q^2 \pm K,$$
$$f_\beta = f\left(\beta, Q_\mu^-, Q_\mu^+\right),$$
$$f_\mu = f\left(\mu, Q_k^+, Q_k^-\right)$$

and

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

➲ Armesto, Salagado, and Wiedemann (ASW) formulation

❖ Path integral formalism for medium-induced gluon radiation is computed.
❖ This formalism provides the analysis of the double differential medium-induced gluon distribution (first order in opacity) as a function of transverse momentum and gluon density.
❖ The medium-induced radiation of massive quarks is suppressed compared to the massless limit if the M/E ratio is sufficiently large.

$$\Delta E = \frac{\alpha_s C_F}{\pi}(2n_0 L)\int_0^E d\omega \int_0^{\bar{R}/2\bar{\gamma}^2} d\bar{k}^2 \int_0^{\infty} d\bar{q}^2 \frac{\left(\bar{q}^2+\bar{M}^2\right)-\left(1/\bar{\gamma}\right)\sin\left[\bar{\gamma}\left(\bar{q}^2+\bar{M}^2\right)\right]}{\left(\bar{q}^2+\bar{M}^2\right)^2}$$

$$\times \frac{\bar{q}^2}{\left(\bar{q}^2+\bar{M}^2\right)} \frac{\left(\bar{k}^2+\bar{M}^2\right)+\left(\bar{k}^2-\bar{M}^2\right)\left(\bar{k}^2-\bar{q}^2\right)}{\left(\bar{k}^2+\bar{M}^2\right)\left[\left(1+\bar{k}^2-\bar{q}^2\right)^2-4\bar{k}^2\bar{q}^2\right]^{3/2}}$$

Gluon energy ⬩$_c$, transverse momentum $K_\perp$ and quark mass M are expressed in rescaled dimensionless quantities as:

$$\bar{\gamma} = \frac{\bar{\omega}_C}{\omega}, \quad \bar{\omega}_C = \frac{1}{2}\mu^2 L, \quad \bar{k}^2 = \frac{\mathbf{k}_\perp^2}{\mu^2}, \quad \bar{M}^2 = \frac{1}{2}\left(\frac{M}{E}\right)^2 \frac{\bar{R}}{\bar{\gamma}^2}, \quad \bar{R} = \bar{\omega}_C L$$

Armesto, Salagado, and Wiedemann , PRD 69, 114003 (2004)

➲ Xiang, Ding, Zhou, and Rohrich (XDZR) formulation

Assumptions:

- ❖ **Static Debye screened scattering centers and all the centers are independent.**
- ❖ **The energy of the partons are high enough.**

Light cone-path integral method is used to deal with the gluon emission and thus obtain an analytical formula for the heavy quark radiative energy loss.

$$\Delta E = \frac{C_F \alpha_s}{4}\frac{L^2\mu^2}{\lambda_g}\left\{\ln\frac{E}{\omega_{cr}} + \frac{m_g^2 L}{3\pi\omega_{cr}}\left(1-\frac{\omega_{cr}}{E}\ln\frac{E^2}{2\mu^2 L\omega_{cr}} + \ln\frac{\omega_{cr}}{2\mu^2 L}\right)\right.$$

$$\left. + \frac{m_q^2 L}{3\pi E}\left(-\frac{\pi^2}{6} - \frac{\omega_{cr}}{E}\ln\frac{\omega_{cr}}{2\mu^2 L} + \ln\frac{E}{2\mu^2 L}\right)\right\}$$

Xiang, Ding, Zhou and Rohrich, EPJA 25, 75 (2005)

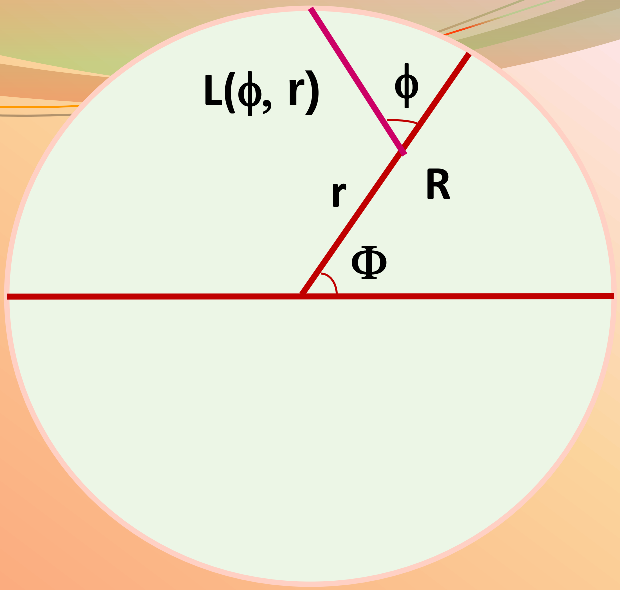
$$1/\lambda_g = \rho_g\,\sigma_{gg} + \rho_q\,\sigma_{qg}, \quad \sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2}, \quad \sigma_{qg} = \frac{4}{9}\sigma_{gg}, \quad m_g = \mu/\sqrt{2}$$

❖ **This expression is derived by using an expression for the Bessel function, which is Valid for not too large mass of the quarks. We use this formalism only for the charm quarks.**

Here, λ_g= 1 fm was assumed but as λ_g is varying with temperature, at central rapidity at LHC, λ_g=1.15 fm and at RHIC λ_g=1.27 fm. The value increases at forward rapidity resulting in a decrease in ΔE.

Average path length:

$$\langle L \rangle = \frac{\int_0^R r\,dr \int_0^{2\pi} L(\phi, r)\, T_{AA}(r, b=0)\, d\phi}{\int_0^R r\,dr \int_0^{2\pi} T_{AA}(r, b=0)\, d\phi}$$

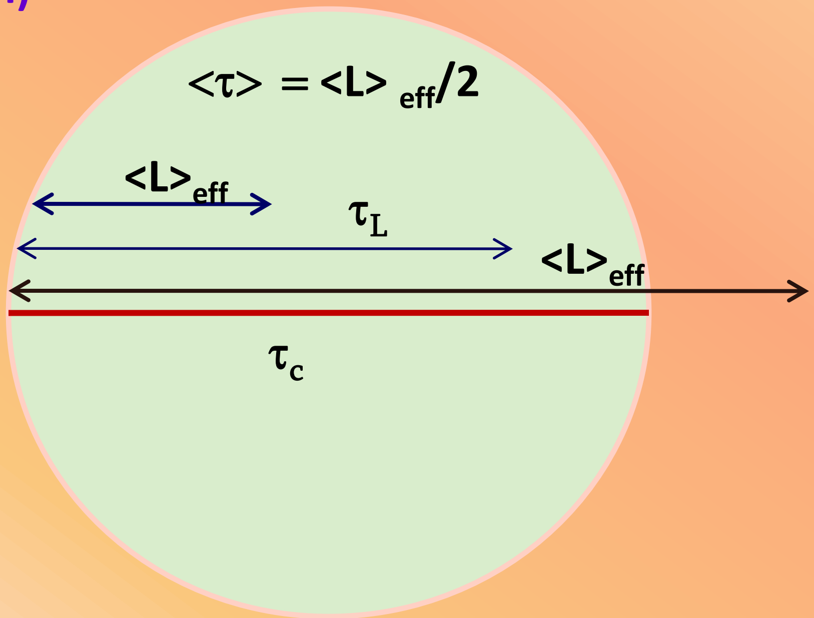


where $L(\phi, r) = \sqrt{R^2 - r^2 \sin^2\phi} - r\cos\phi$

At LHC (Pb+Pb@5.5 TeV), <L>=6.14 fm (R=6.78 fm)

At RHIC (Au+Au@200 GeV), <L>=5.78 fm (R=6.38 fm)

- $v_T = p_T / m_T$, $\Rightarrow \tau_L = \langle L \rangle / v_T$.
- **If $\tau_c \geq \tau_L$, the heavy quark would be inside QGP during the entire period 0 to τ_L.**
- **If $\tau_c < \tau_L$, the heavy quark would be inside QGP only while covering the distance $v_T \times \tau_c$.**
- $\tau = \langle L \rangle_{eff} / 2$, **where** $\langle L \rangle_{eff} = \min[\langle L \rangle, v_T \times \tau_c]$.

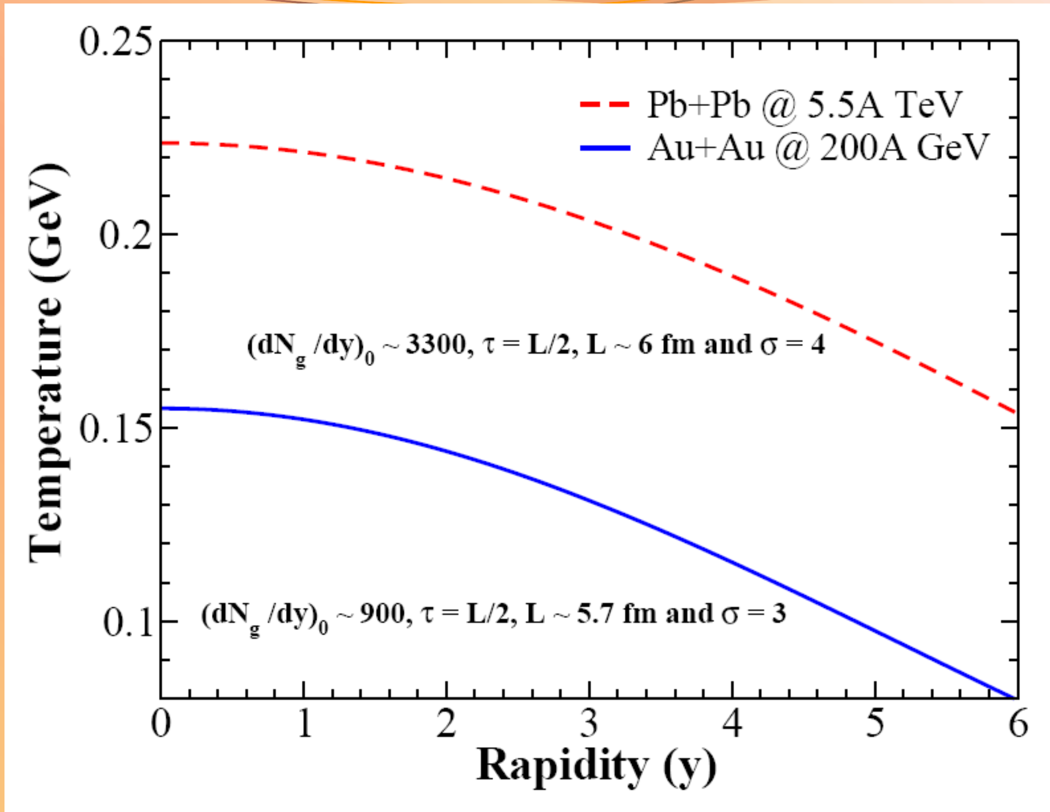


The dependence of temperature of the plasma with rapidity (y):

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

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

S. Wicks et.al, Nuclear Physics A 784(2007)426



Particle rapidity density distribution obeys:

$$\frac{dN}{dy} = \left.\frac{dN}{dy}\right|_{y=0} e^{-\frac{y^2}{2\sigma^2}}$$

S. Gavin et al. Phy. Rev. C 54(1996) 2606

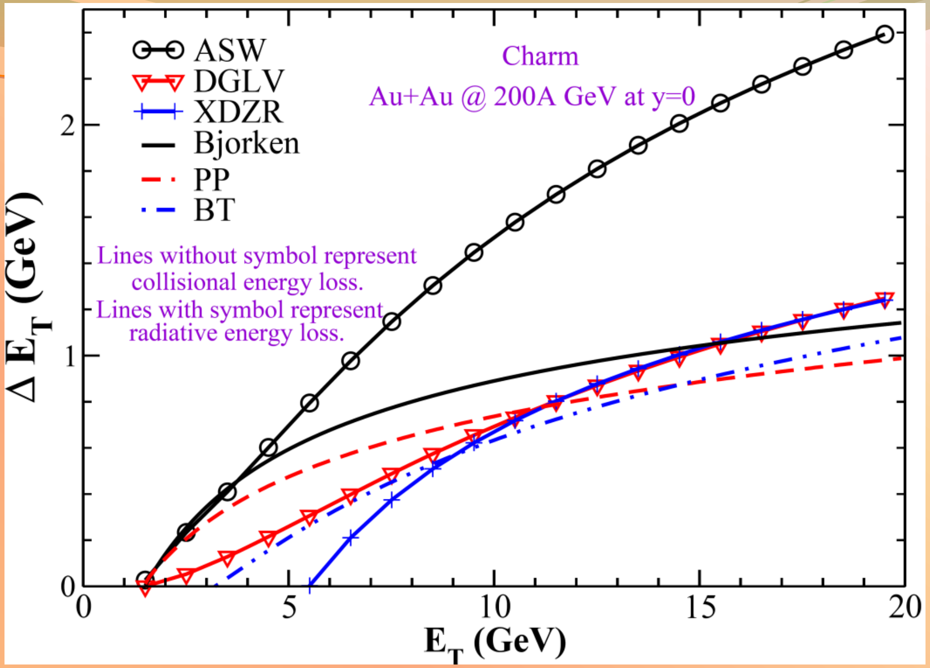
- At LHC $\sigma \approx 4$ and at RHIC $\sigma \approx 3$

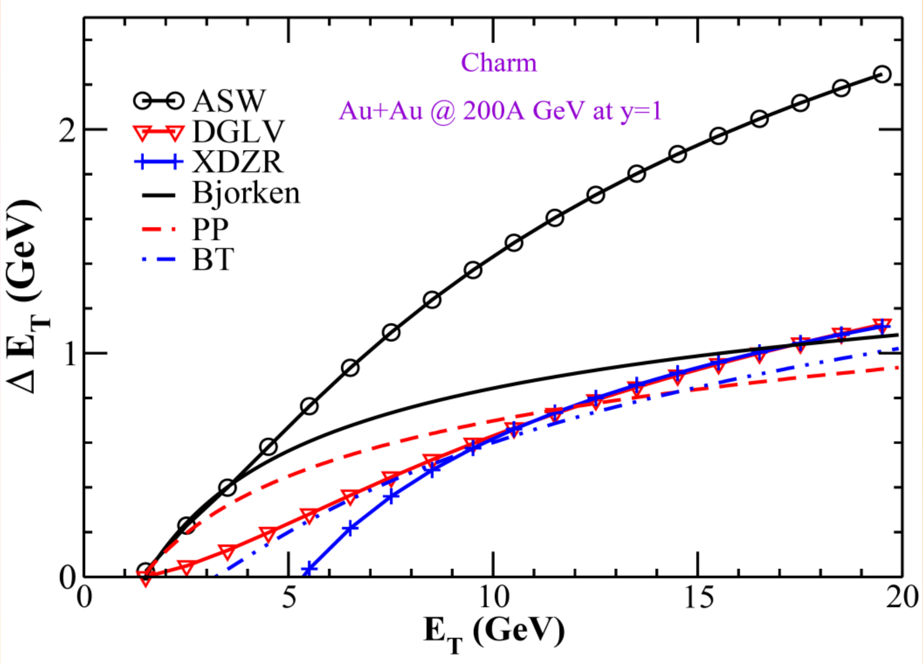
D. Kharzeev, E. Levin, and M. Nardi, Nuclear Physics A 747 (2005)609.
I. G. Bearden et al., Phys. Rev. Lett. 88 (2002) 202301.

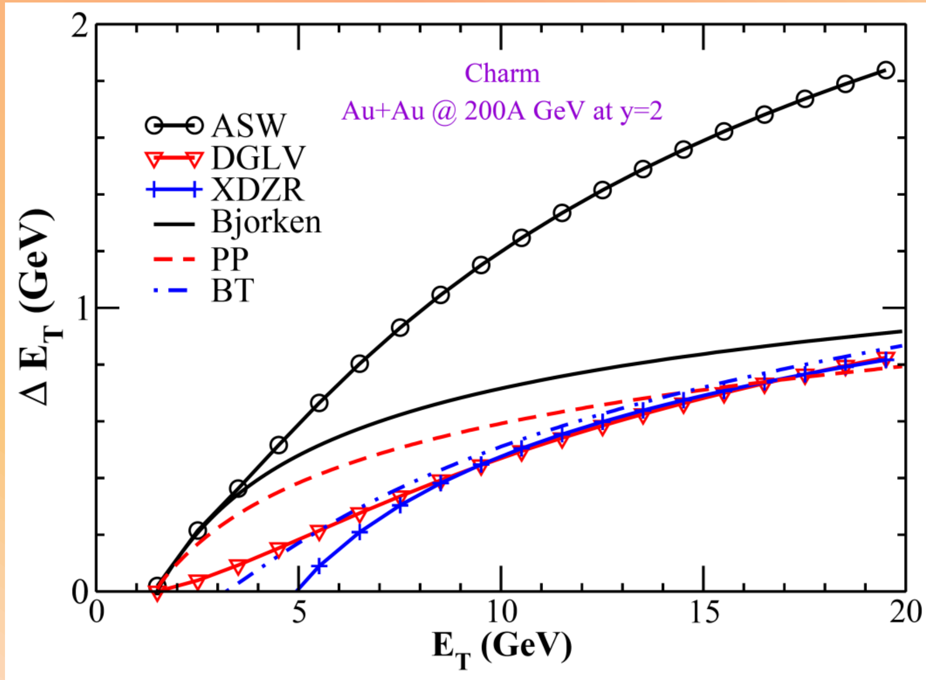
The initial conditions for the energy loss calculations are:

- **Number of flavours $N_f = 3$,**
- **Color factor $C_f = 4/3$,**
- **Mass of charm quark = 1.5 GeV,**
- **Running coupling constant $\alpha_s = 0.3$,**
- **The central particle rapidity density at LHC $(dN_g/dy)_o \approx 3300$,**
- **The central particle rapidity density at RHIC $(dN_g/dy)_o \approx 900$,**
- **The critical temperature T_c for existence of QGP is taken as 160 MeV.**

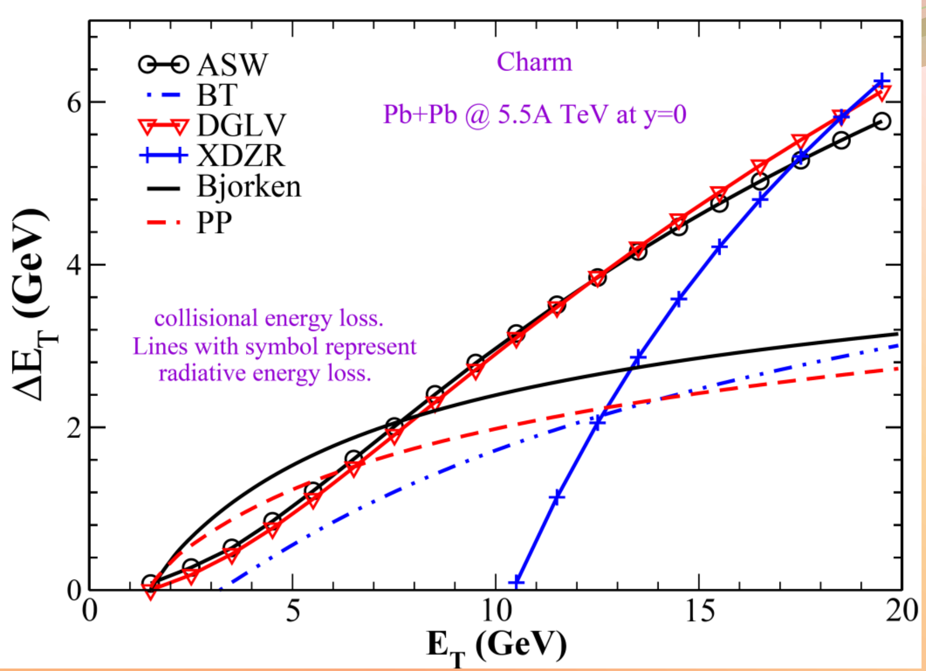
Energy loss of a charm quark at rapidities y=0, 1, 2 at RHIC energy.

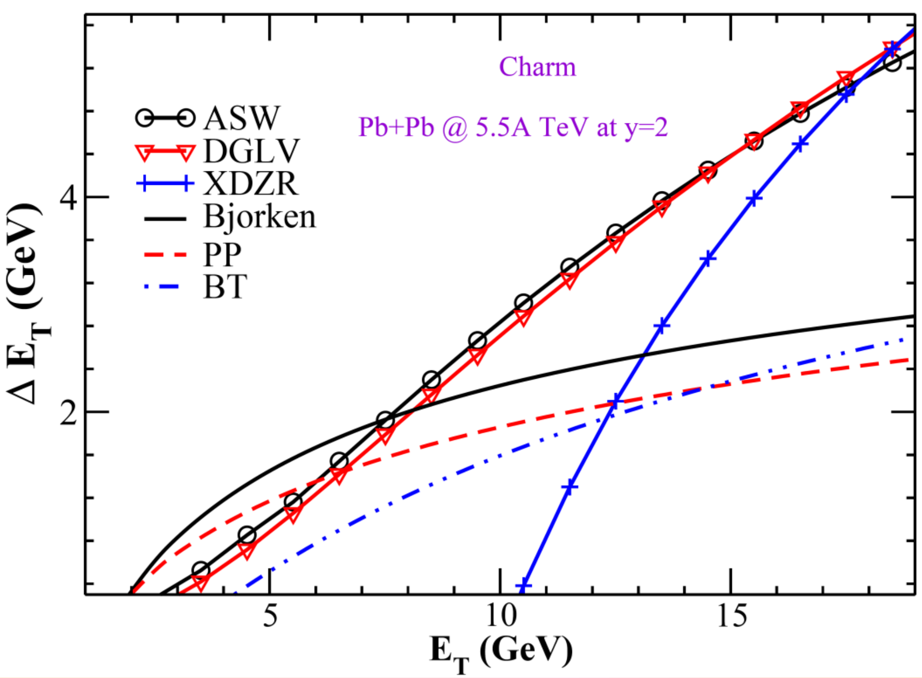


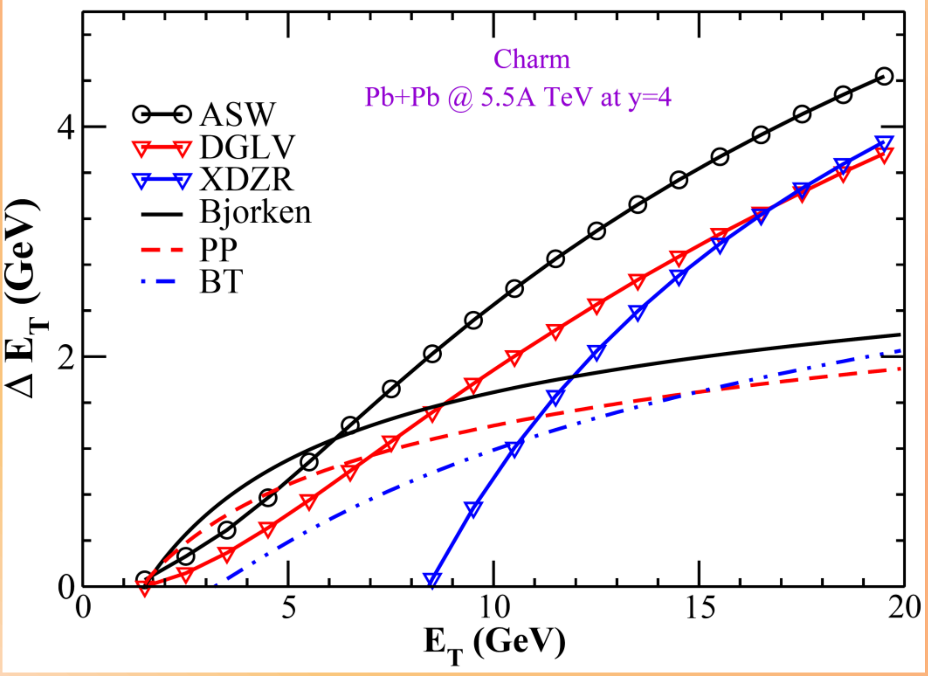


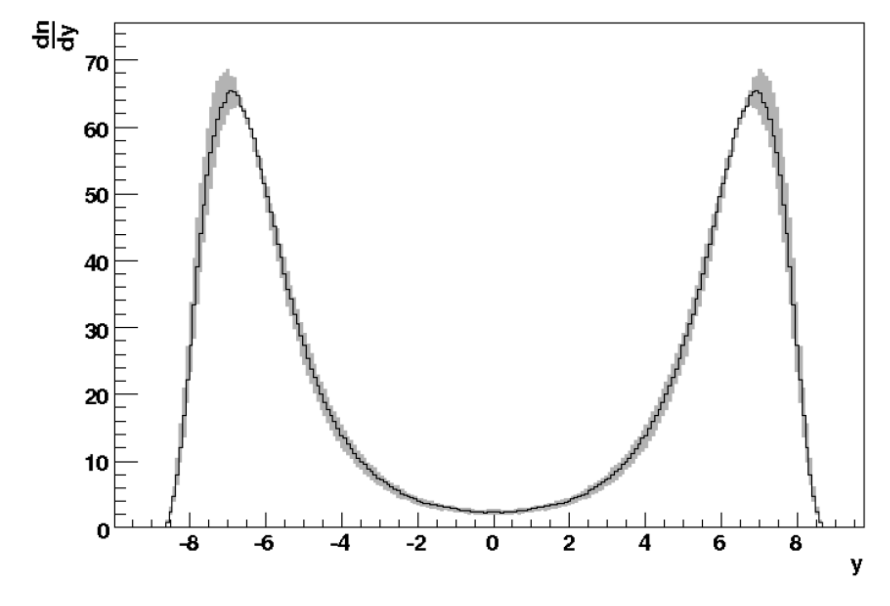


Energy loss of a charm quark at rapidities y=0, 2 , 4 at LHC energy.









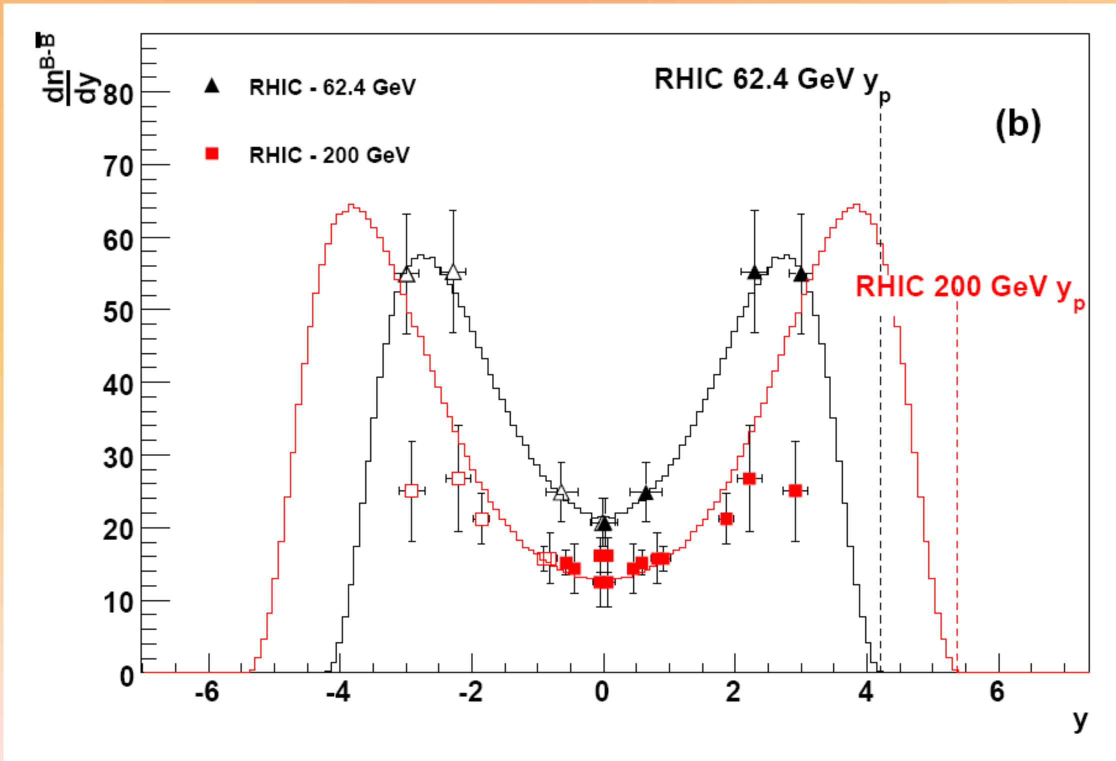
Net-baryon rapidity for central Pb+Pb collision at √s=5.5 TeV

Particle rapidity density at y=4 at LHC is ~2000, so

$$\left.\frac{dN_{B-\bar{B}}}{dy}\right|_{y=4} \Big/ \left.\frac{dN}{dy}\right|_{y=4} \approx 0.007$$

Particle rapidity density at y=2 at RHIC(200 GeV) is ~750, so

$$\left.\frac{dN_{B-\bar{B}}}{dy}\right|_{y=2} \Big/ \left.\frac{dN}{dy}\right|_{y=2} \approx 0.03$$



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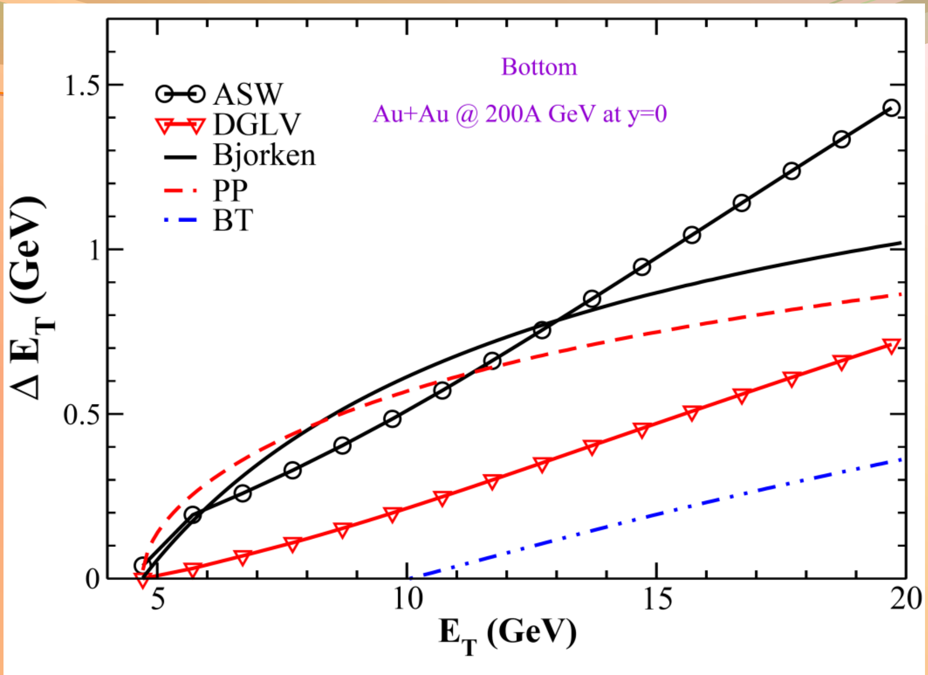
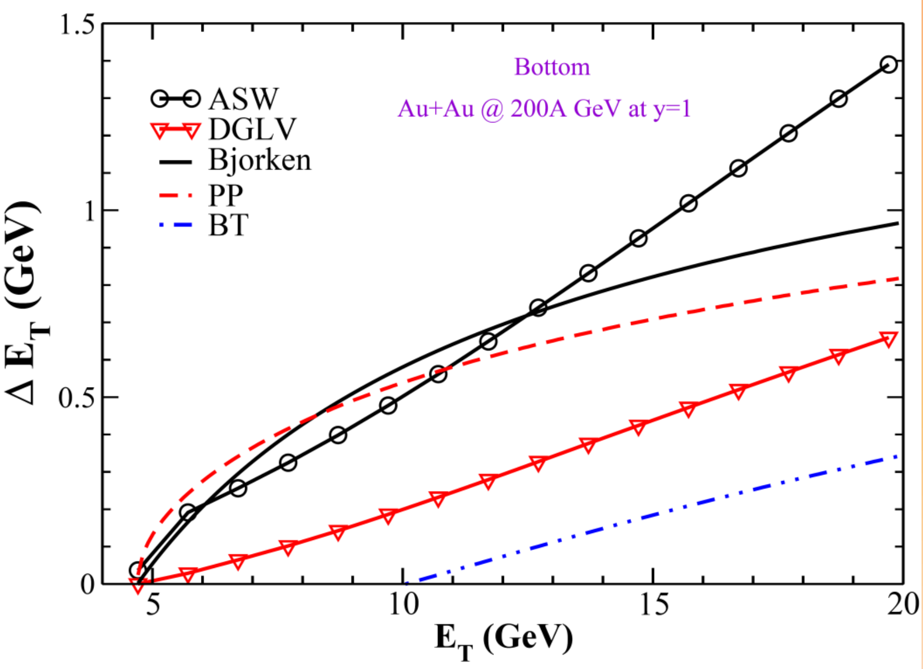
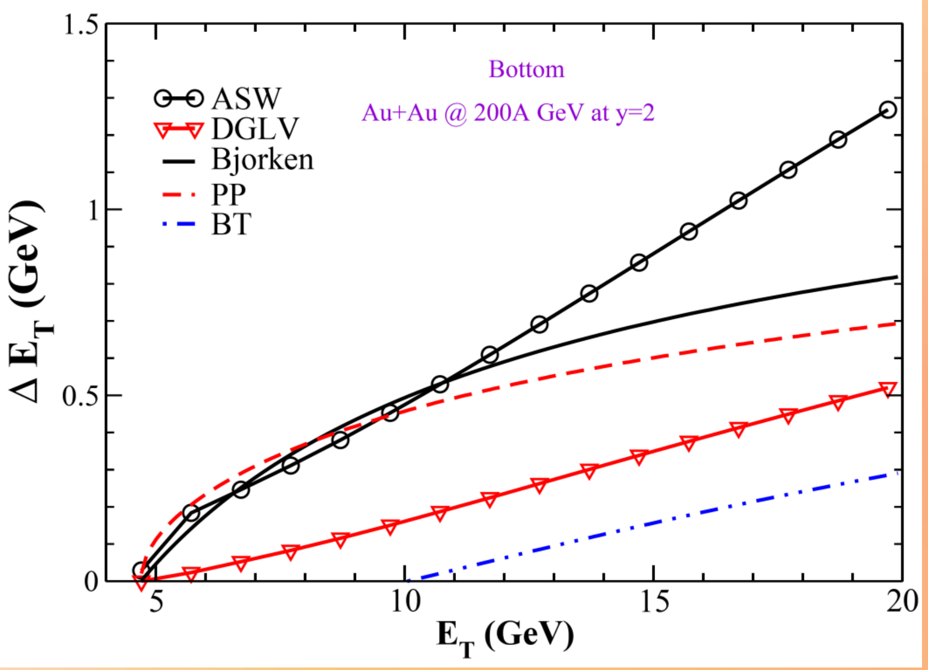
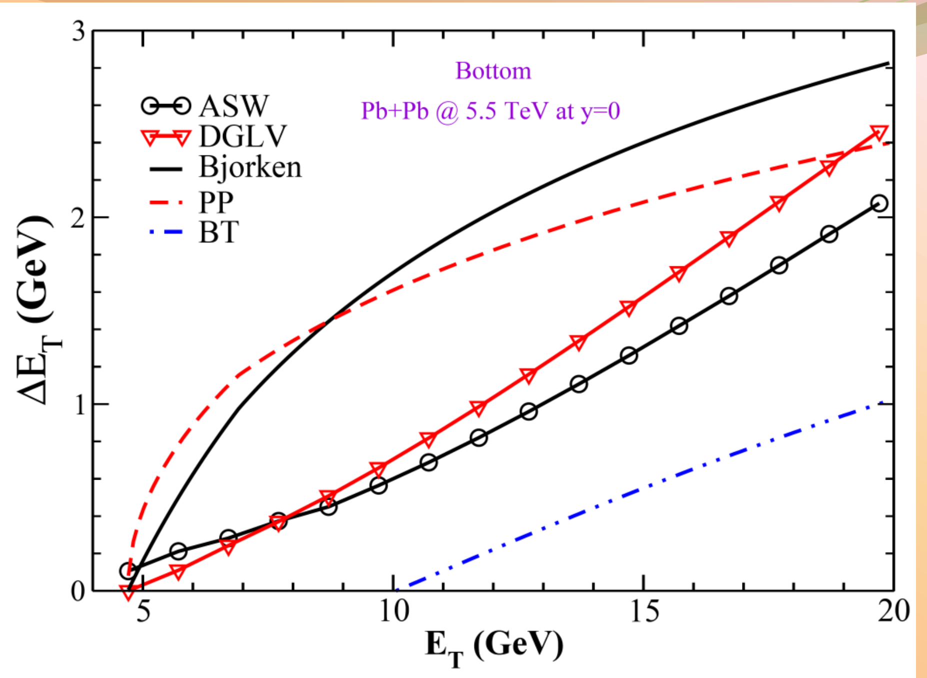
Energy loss suffered by a bottom quark at rapidities y=0, 1 , 2 at RHIC.

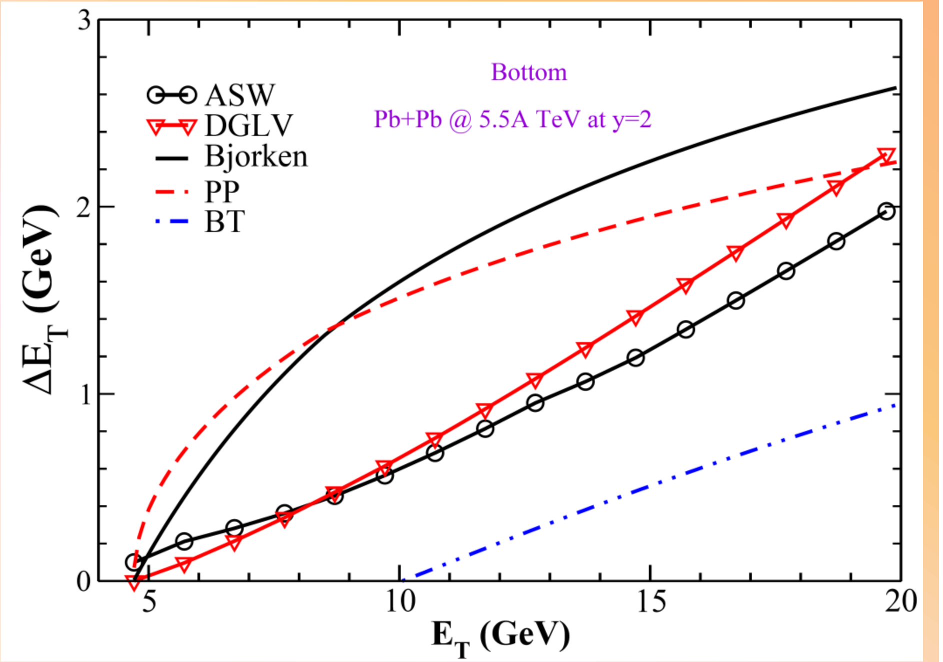


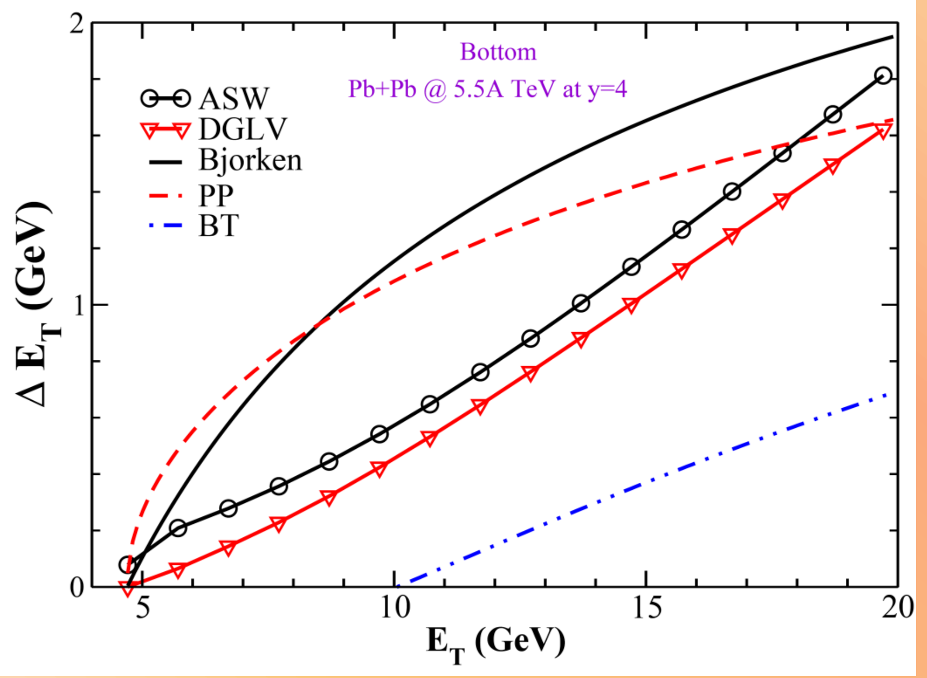




Energy loss suffered by a bottom quark at rapidities y=0, 2, 4 at LHC.







Introducing the energy loss mechanisms along with the nuclear shadowing effect to the heavy quark distributions at LHC and RHIC energy we study the suppression in the nuclear modification factor.

The nuclear modification factor at impact parameter b is:

$$R_{AA}(b) = \frac{dN^{AA}/d\vec{p}_T dy}{T_{AA}(b)\, d\sigma^{NN}/d\vec{p}_T dy}$$

Suppression

=

Final momentum distribution of heavy quarks/Initial momentum distribution of heavy quarks

$T_{AA} \approx 290$ fm^{-2} for 5.5A TeV Pb+Pb collision at LHC for b=0.
$T_{AA} \approx 280$ fm^{-2} for 200A GeV Au+Au collision at RHIC fb=0.

- **We perform the calculations in the frame in which the rapidity of the heavy quark is the same as the fluid rapidity.**

So, energy of the heavy quark $E = m_T = \sqrt{M_Q^2 + p_T^2}$

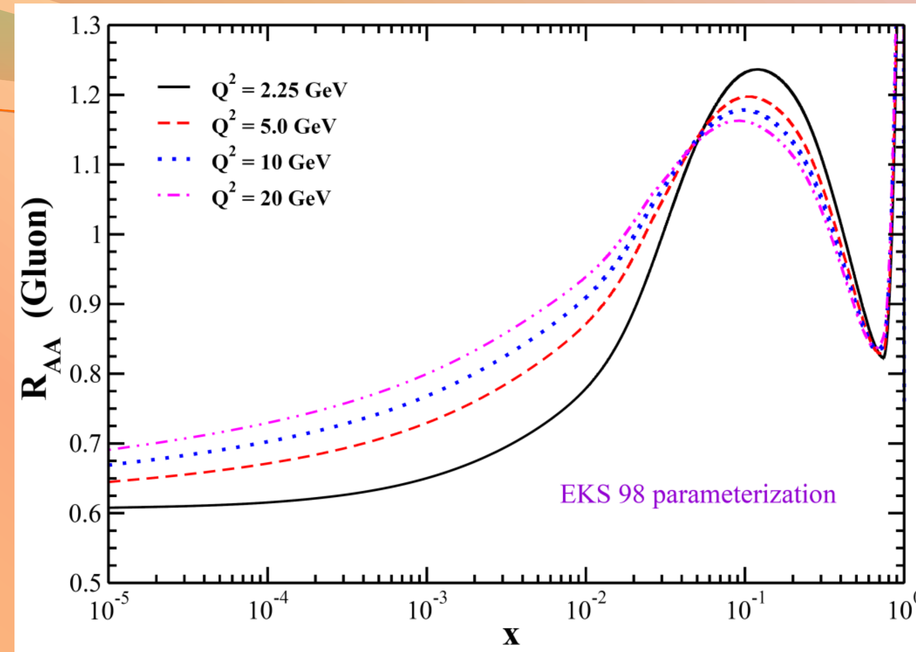
After loosing energy ΔE, the heavy quark new energy: $E' = E - \Delta E = m'_T = \sqrt{M_Q^2 + p'^2_T}$

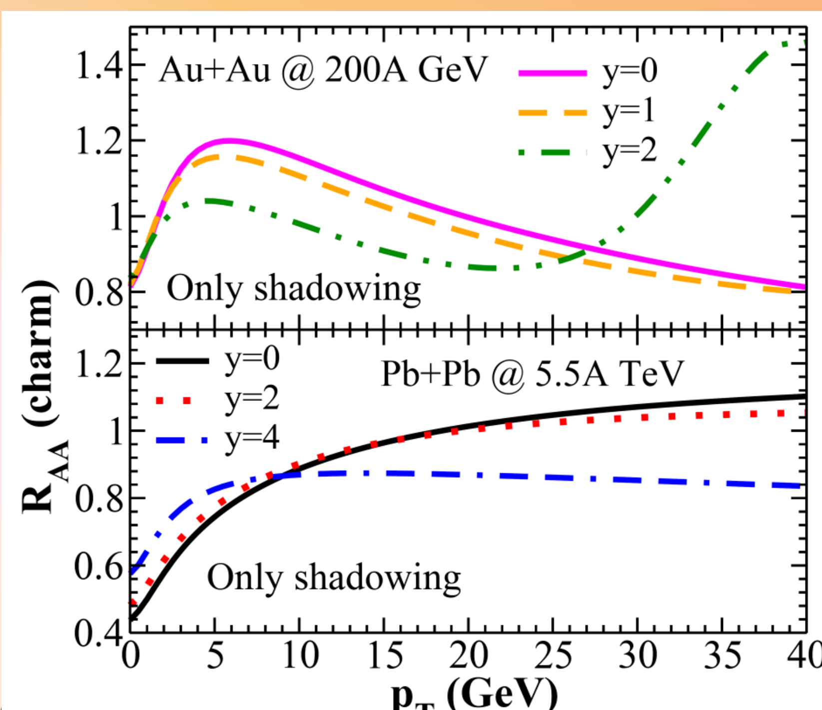
We calculate the average change in the transverse momentum spectra of heavy quarks for nucleus-nucleus collisions using a Monte Carlo calculation and get R_{AA} as a function of p_T for different rapidities.

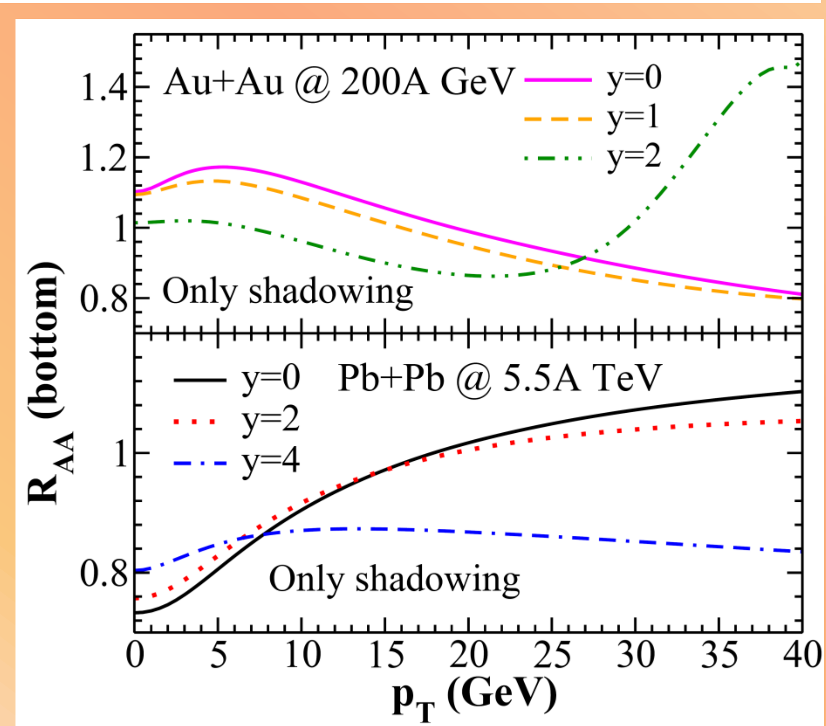
- **We use the CTEQ4M set of structure function for nucleon.**

The nuclear shadowing effect

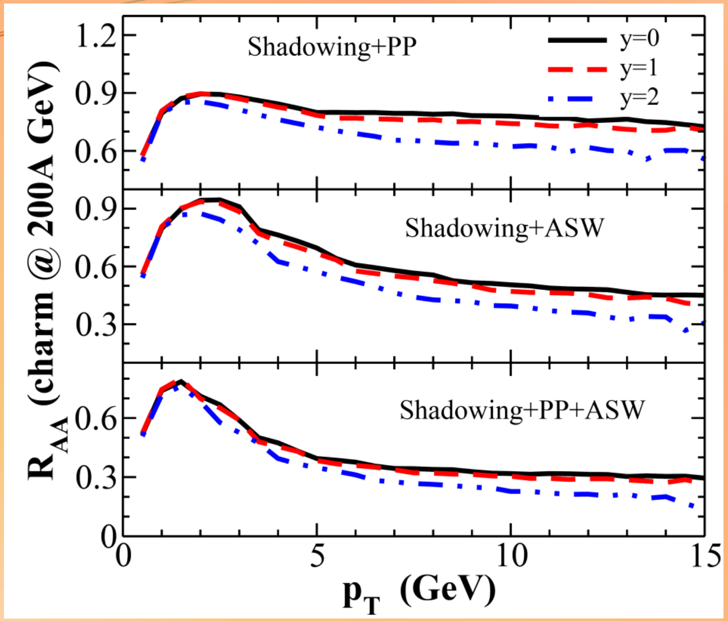
- The x dependence of the shadowing function introduces interesting structures in the nuclear modification factor as a function of p_T, y, and the incident energy.

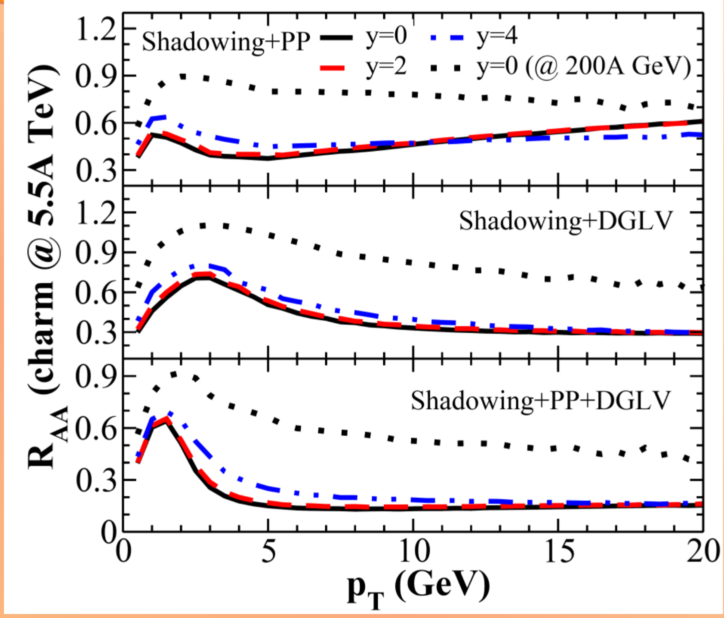


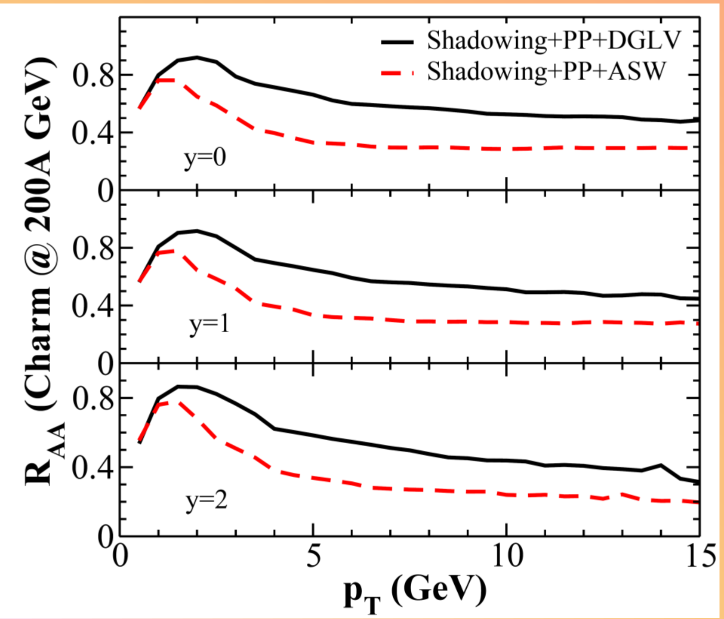




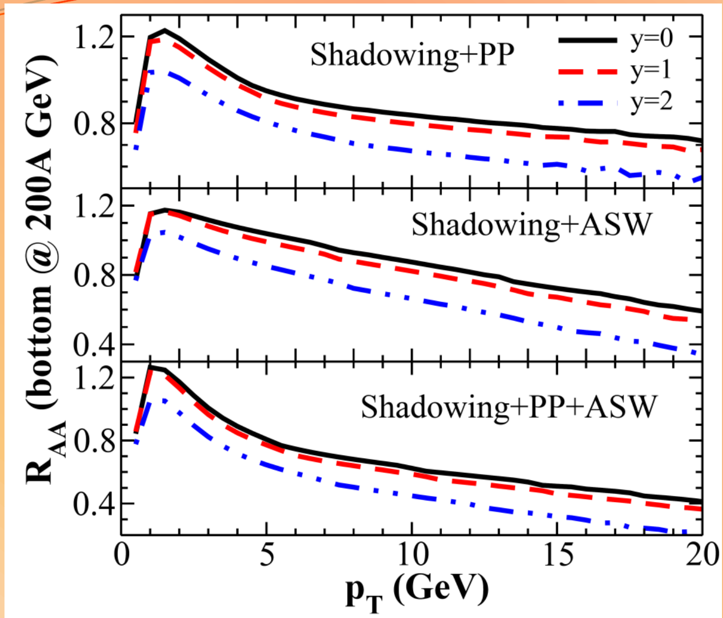
Nuclear suppression factor due to charm quark

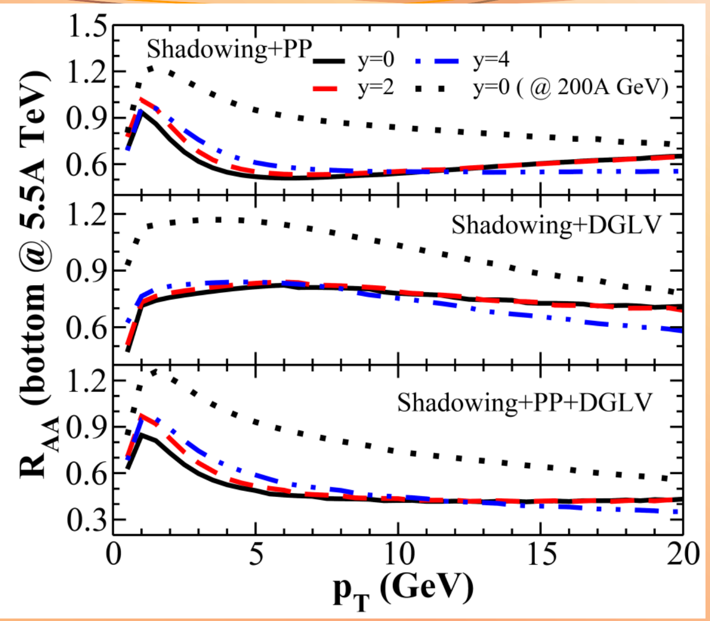


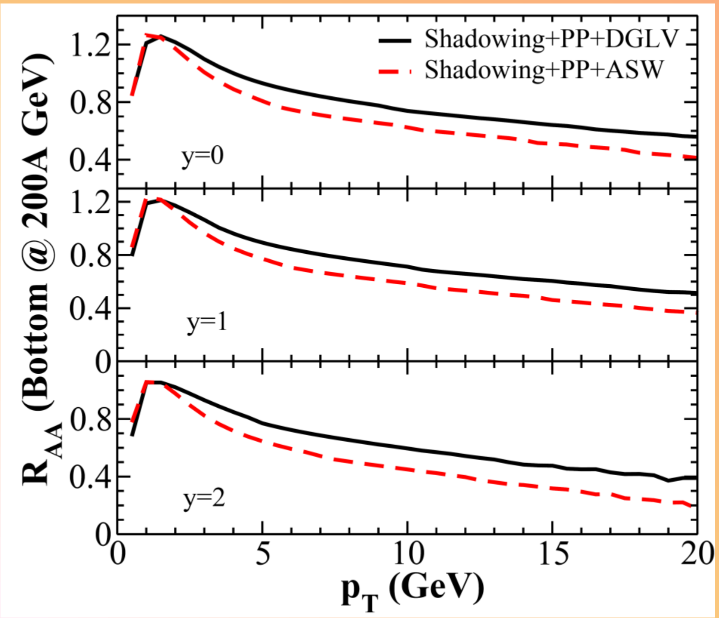




Nuclear suppression factor due to bottom quark







Summary

- The nuclear modification factor R_{AA} changes substantially in going from RHIC to LHC.

- We have noted that our findings would support the suppression of single electrons seen at RHIC.

- We used (1+1) dimensional Bjorken hydrodynamics and assumed it to apply at all y. We are looking at the possibility of using a full fledged (3+1) dimensional hydrodynamics calculations, also at $b \neq 0$.

- The description for energy loss for one quark mass at one single rapidity for a particular incident energy may not be sufficient to identify the most reliable energy loss treatment for either collisional or radiative energy loss.

- As the energy loss at LHC energy is more compared to RHIC energy, it will also effect the correlated charm decay. Extension of this work for correlated charm is underway.

Thank you

Glauber model of Nucleus-Nucleus collision

Glauber model of multiple collision processes provides a quantitative consideration of the geometrical configuration of the nuclei when they collide.

The nuclear thickness function of a nucleus A at impact parameter b (number of nucleons in the nucleus per unit area along a direction z separated from the center of the nucleus by an impact parameter b) :

$$T_A(b) = \int dz\, \rho_A(b, z)$$

The nuclear density ❒$_A$ (b, z) is parametrized by Woods-Saxon distribution:

$$\rho(x, y, z) = \frac{\rho_0}{1 + \exp\frac{r - r_0}{a}}$$

Where ❒ (x, y, z) is normalized as $\int_0^R \rho(r)\, 4\pi r^2 dr = A$

With nuclear radius: $R = 1.19\, A^{1/3} + 1.61\, A^{-1/3}$

Surface thickness a = 0.54 fm. And T_A (b) is normalized so that: $\int d^2b\, T_A(b) = A$

The inclusive inelastic cross section for a collision od nuclei A and B is given in the multiple scattering Glauber approximation by:

$$\sigma_{AB} = \int d^2b \left[1 - e^{-\sigma_{NN} T_{AB}(b)}\right]$$

This is the general expression for the total inelastic cross section. For hard scattering processes, the corresponding cross section is small and one can expand the above expression in orders of : $\sigma_{NN}^{hard}\, T_{AB}$

To first approximation: $\sigma_{AB}^{hard} \approx \int d^2b\, \sigma_{NN}^{hard}\, T_{AB}(b)$

The nuclear overlap function of the nuclei A and B separated by impact parameter b, over the overlapping area d^2s where s(x, y):

$$T_{AB}(b) = \int d^2s\, T_A(s)\, T_B(|b - s|)$$

The function T_{AB} (b) is normalized as: $\int d^2b\, T_{AB}(b) = AB$

Minimum biased cross section for a given hard process in A+B collision relative to the corresponding NN cross section:

$$\left(\sigma_{AB}^{hard}\right)_{MB} = A.B.\,\sigma_{NN}^{hard}$$

Minimum biased multiplicity yield for a given hard process in A+B collision relative to the corresponding NN cross section:

$$N_{AB}^{hard} = \frac{A.B}{\sigma_{AB}^{geo}}\,\sigma_{NN}^{hard}$$

$$\langle T_{AB}\rangle_{MB} = \frac{\int d^2b\, T_{AB}(b)}{\int d^2b} = \frac{A.B}{\pi(R_A + R_B)^2} = \frac{A.B}{\sigma_{AB}^{geo}}$$

For a given b, the average hard scattering yield can be obtained by multiplying each nucleon in nucleus A against the density it sees along the z-direction in nucleus B, then integrated over all the nucleus A resulting:

$$\left\langle N_{AB}^{hard}\right\rangle(b) = \sigma_{NN}^{hard}\,.\,T_{AB}(b)$$