Heavy quark energy loss

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- **Motivation**
- **Radiative heavy quark energy loss**

    - **Ter-Mikayelian effect (Djordjevic-Gyulassy)**

    - **Transition energy loss (Zakharov)**

    - **Medium induced radiative energy loss (Dokshitzer-Kharzeev, Djordjevic-Gyulassy, Armesto-Salgado-Wiedemann)**

- **How big is the heavy quark suppression at RHIC?**
- **Conclusion**

Motivation

One of the central questions in high energy heavy ion physics is whether a quark-gluon Plasma (QGP) has been discovered at RHIC.
(M.Gyulassy and L. McLerran, nucl-th/0405013, M.Gyulassy, nucl-th/0403032)

The observation of Collective Flow and Jet Quenching of light partons strongly suggest that it is. However, further detailed tests of jet tomography using heavy quarks could be decisive as a complementary test of the theory.

Open charm suppression, which can now be measured at RHIC by comparing pt distributions of D-mesons in *D-Au* and *Au-Au* collisions, is a novel probe of QGP dynamics.

1997 Shuryak proposed that charm quarks will have **large energy loss** in QGP => large suppression of D mesons.

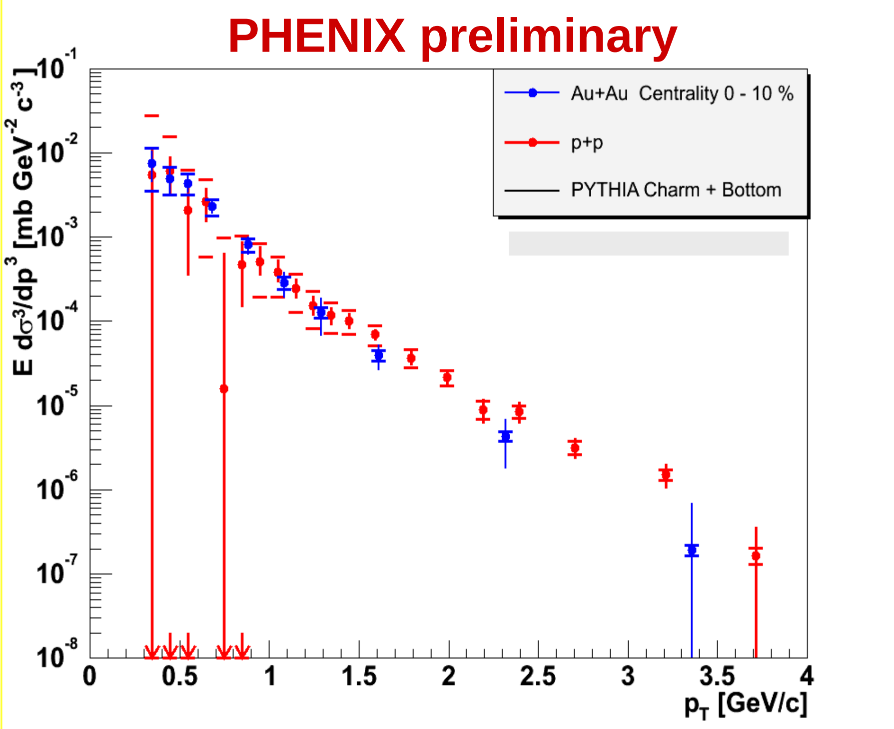
2001 Dokshitzer and Kharzeev proposed **"dead cone"** effect => charm quark **small energy loss**

First Au+Au->e X data show no hint of Charm energy loss ! ??
PHENIX Collaboration (K. Adcox *et al.*) **Phys.Rev.Lett.88:192303,2002**

Moderate p_T charm is not suppressed according to PHENIX.

Takashi Hachiya – QM2004.

But new STAR D data
may indicate large energy loss?



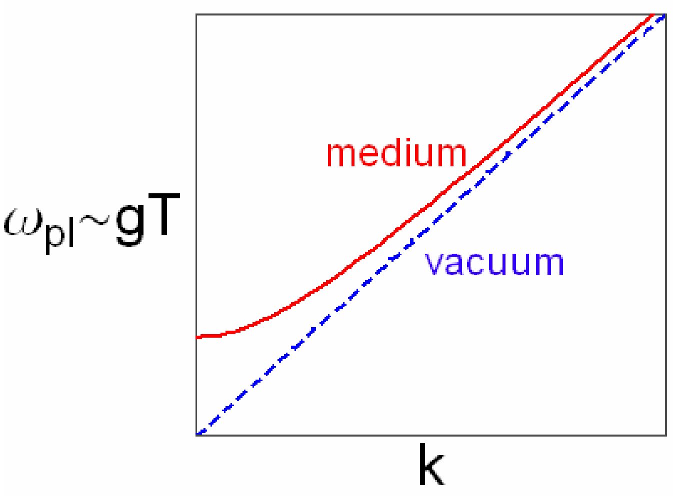
The motivation for our study of heavy quark energy loss in a dense QCD medium:

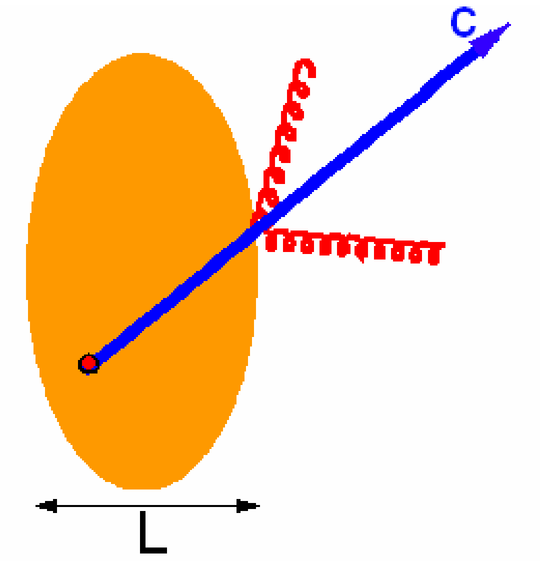
1. To compute quantitatively radiative energy loss for heavy quarks including dielectric and collision sources
2. To present theoretical predictions that can be compared with upcoming experimental results in order to test the QGP theory.

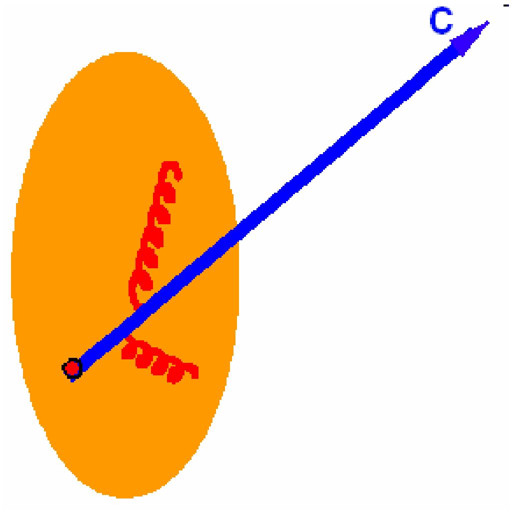
Radiative heavy quark energy loss

There are three important medium effects that control the radiative energy loss at RHIC

1) **Ter-Mikayelian effect** **(Djordjevic-Gyulassy)**
2) **Transition radiation** **(Zakharov)**
3) **Energy loss due to the interaction with the medium** **(DG)**







1) 2) 3)

Ter-Mikayelian effect

This is the non-abelian analog of the well known dielectric plasmon effect $\omega(k) > \omega_{pl} \sim gT$

In pQCD vacuum gluons are massless and transversely polarized.

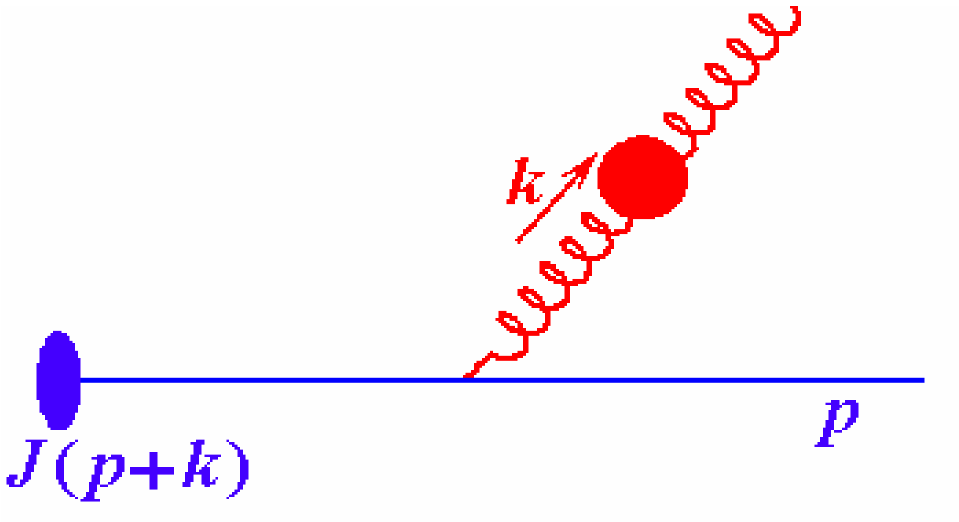
However, in a medium the gluon propagator has both

transverse and longitudinal polarization parts.

We extended the work of Kampfer-Pavlenko (2000) to compute both longitudinal and transverse contributions to the 0^{th} order in opacity.

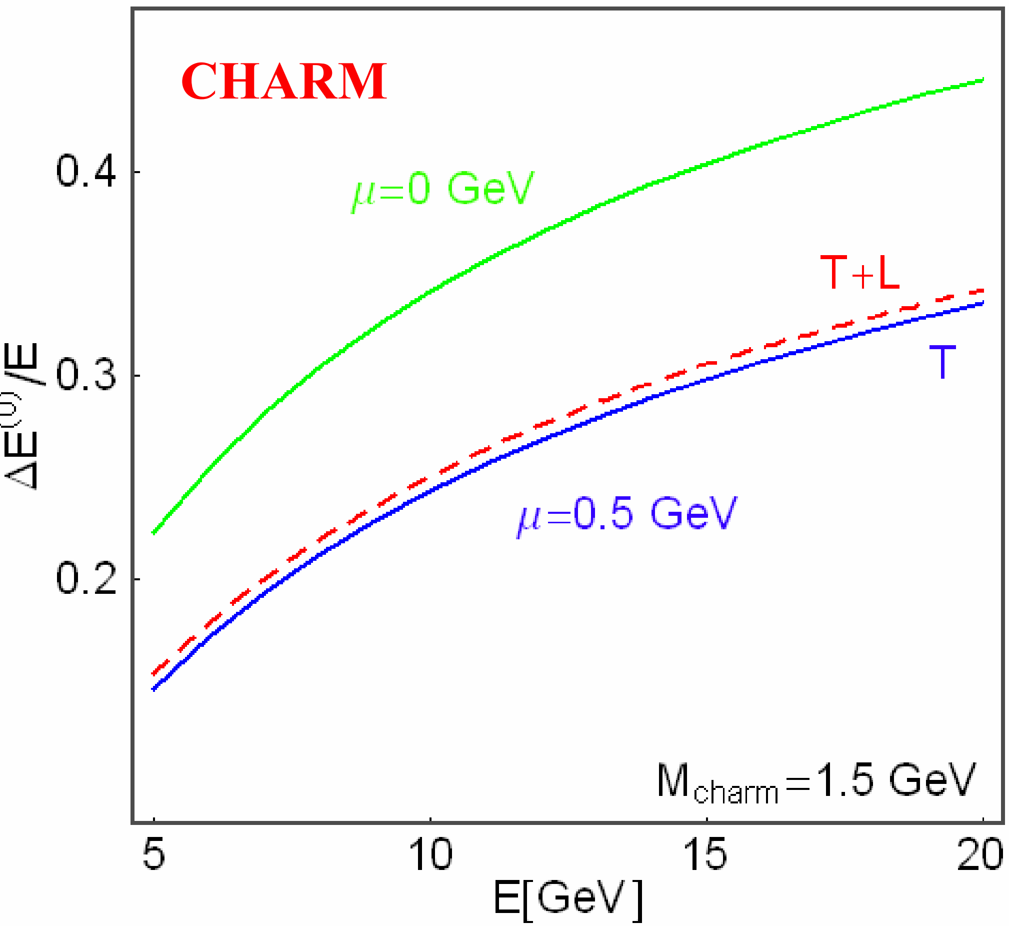
The Ter-Mikayelian effect on QCD Radiative Energy Loss
M. Djordjevic, M. Gyulassy, **Phys.Rev.C68:034914,2003**

In order to calculate the main order radiative energy loss we have to compute $|M_{rad}|^2$, where M_{rad} is given by Feynman diagram:



For this, we have used optical theorem.

Comparison between medium and vacuum 0^{th} order in opacity fractional energy loss is shown on the Fig.1:



- **Longitudinal contribution is negligible.**
- **The Ter-Mikayelian effect on transverse contribution is important, since for charm it leads to ~30% suppression of the vacuum radiation.**

The Ter-Mikayelian effect thus tends to *enhance* the yield of high p_T charm quarks relative to the vacuum case.

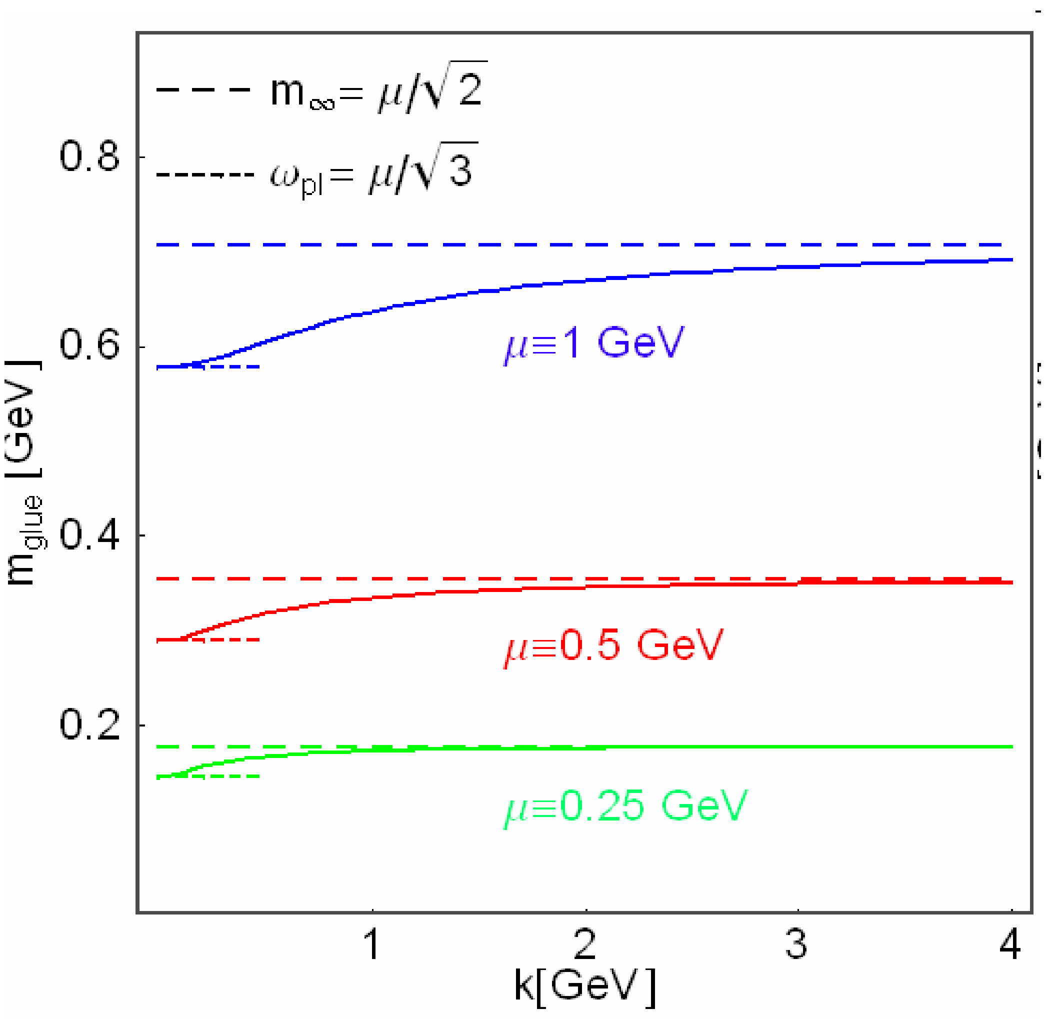


Fig.3 shows the one loop transverse plasmon mass ***$m_g(k) \equiv \sqrt{(\omega^2 - k^2)}$*****.**

We see that ***m_g*** **starts with the value** ***$\omega_{pl} = \mu/\sqrt{3}$*** **at low k, and that as k grows,** ***m_g*** **asymptotically approaches the value of** ***$m_\infty = \mu/\sqrt{2}$*****, in agreement with**

Rebhan A, Lect. Notes Phys. 583, 161 (2002).

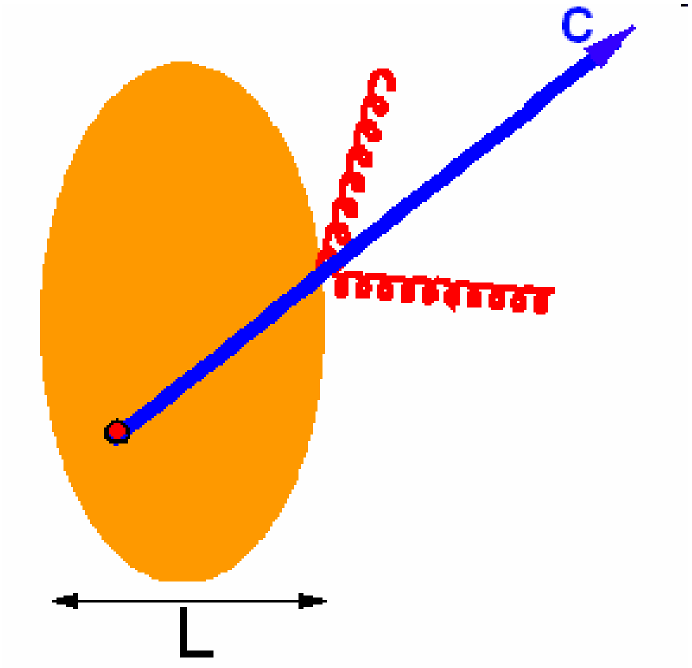
We can conclude that we can approximate the Ter-Mikayelian effect by simply taking ***$m_g \approx m_\infty$*****.**

Transition radiation

An additional dielectric effect at 0th order in opacity.

It must be taken into account if the QGP has finite size.

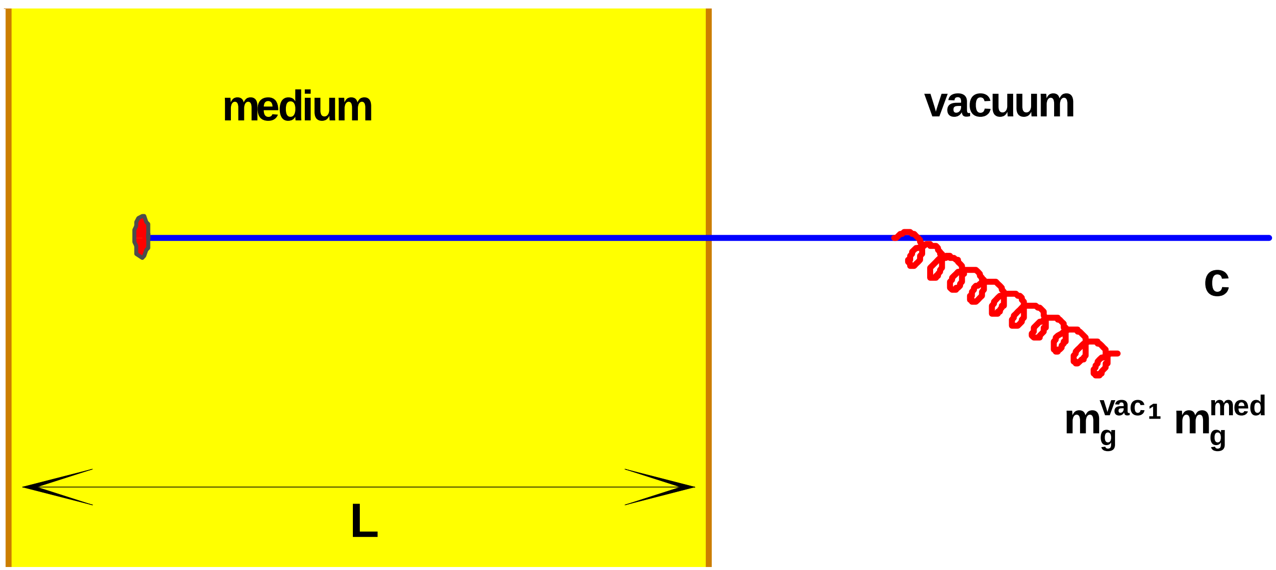
Transition radiation occurs at the boundary between medium and the vacuum.

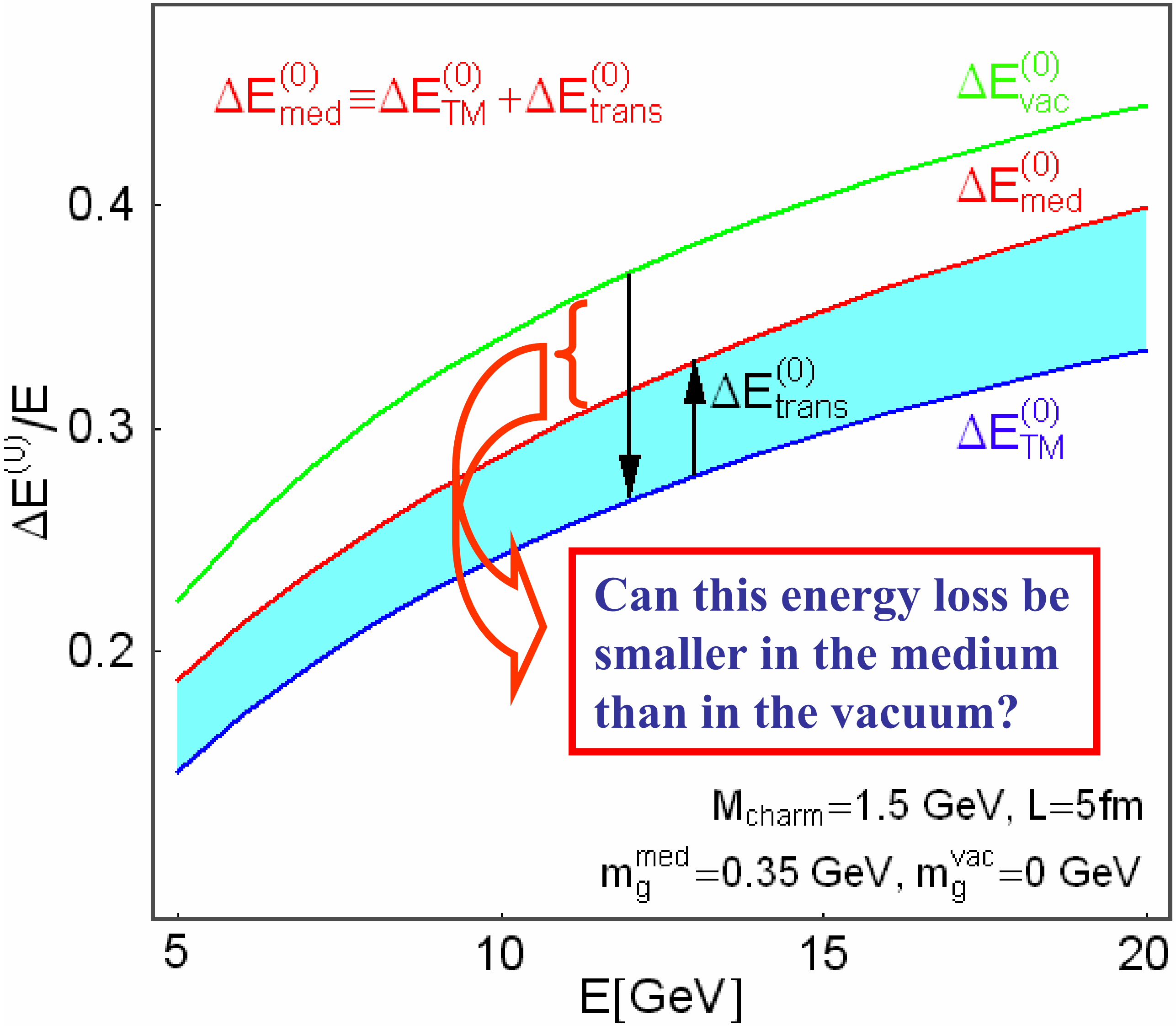


To estimate transition radiation we follow Zakharov

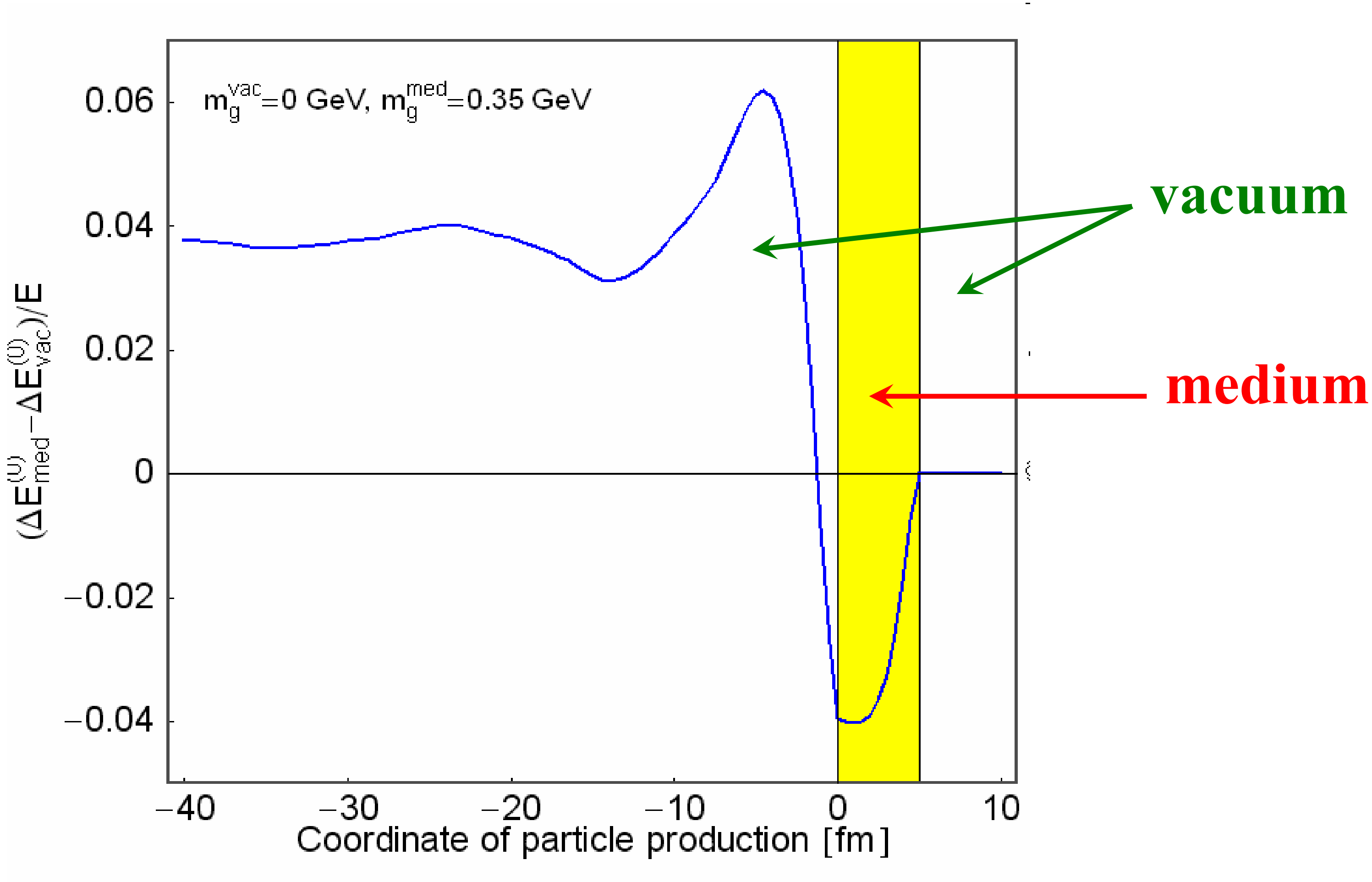
(B.G. Zakharov, JETP Lett.76:201-205,2002).

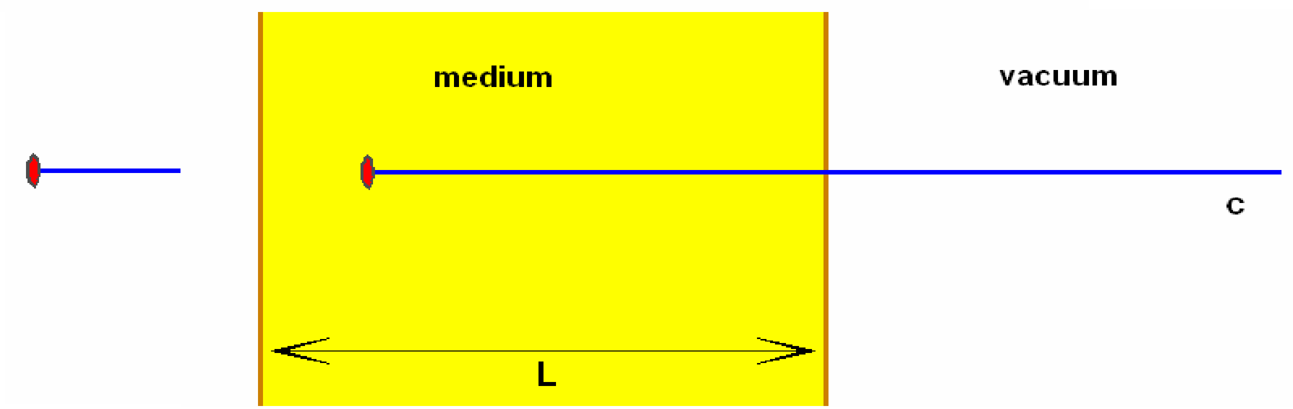
This computation was performed assuming a static medium.





Transition radiation lowers Ter-Mikayelian effect from 30% to 15%.

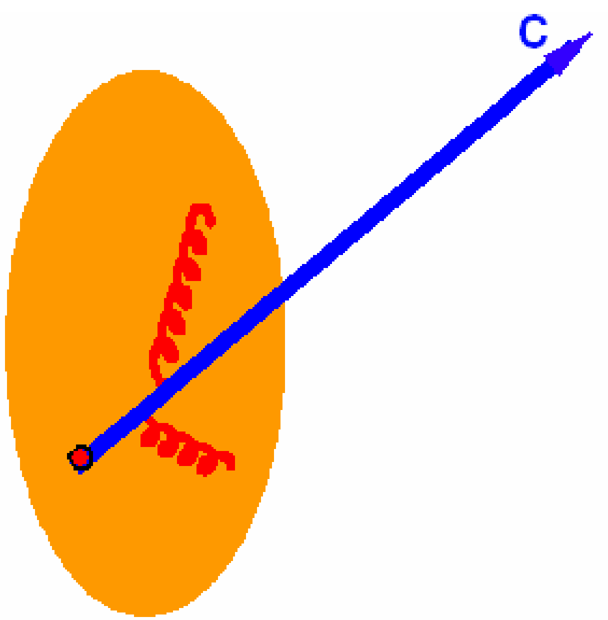

m_g^{vac}=0 GeV, m_g^{med}=0.35 GeV
$(\Delta E_{med}^{(1)} - \Delta E_{vac}^{(1)})/E$
0.06
0.04
0.02
0
−0.02
−0.04
−40
−30
−20
−10
0
10
Coordinate of particle production [fm]
vacuum
medium


medium
vacuum
c
L

Energy loss due to the interaction with the medium

The third important effect is the induced gluon radiation caused by the multiple interactions of partons in the medium.

To compute medium induced radiative energy loss for heavy quarks we extend Gyulassy-Levai-Vitev (GLV) method, by introducing both quark M and gluon mass m_g.



We generalized GLV Opacity Series (NPB594(01)) to M_Q and $m_g > 0$ (DG, Nucl.Phys.A 733, 265 (04))

$$x\frac{dN^{(n)}}{dx\, d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\,\frac{L}{\lambda_g(i)}\left[\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i)\right]\right)\times$$

$$\times\left(-2\,\tilde{\mathbf{C}}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\tilde{\mathbf{B}}_{(m+1,\cdots,n)(m,\cdots,n)}\left[\cos\left(\sum_{k=2}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right)$$

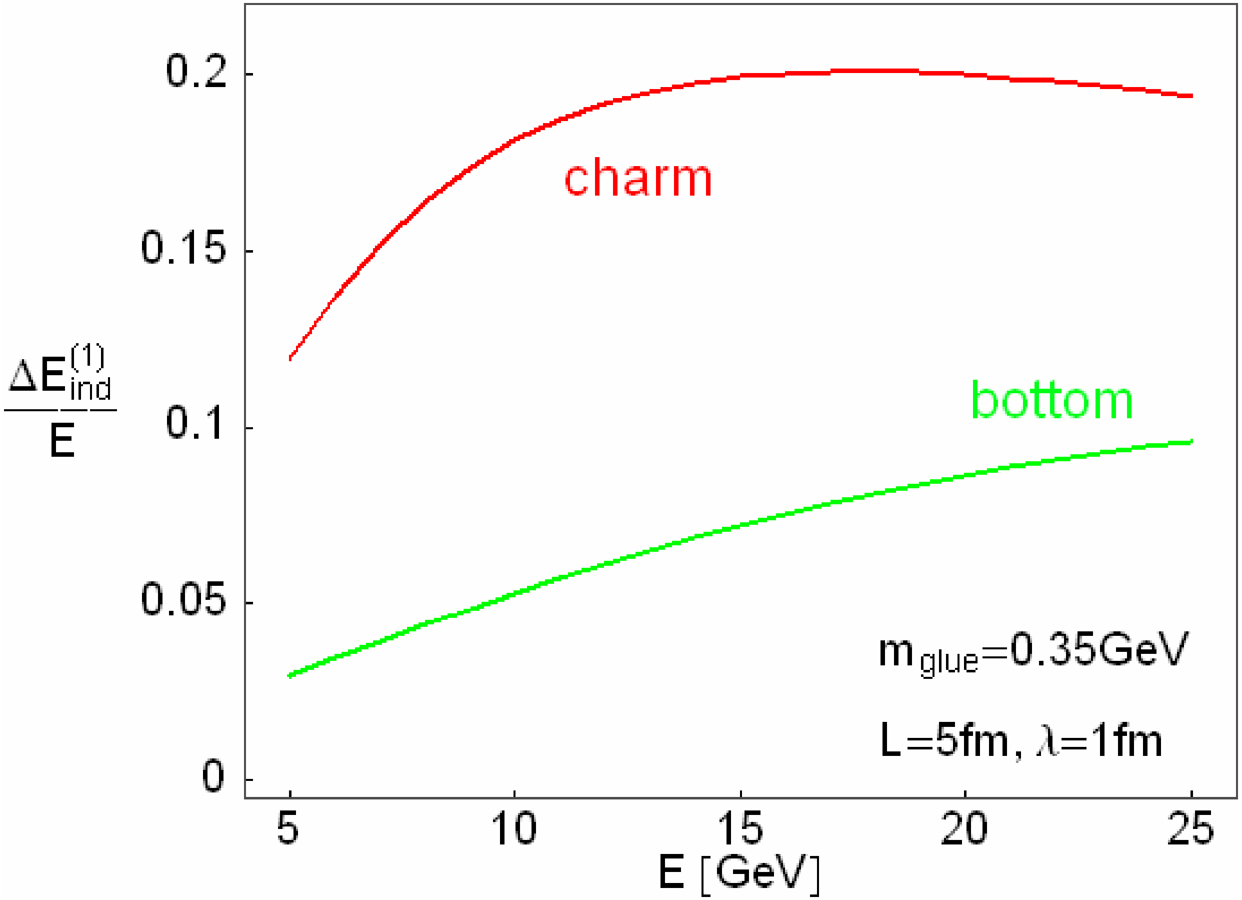
Hard, Gunion-Bertsch, and Cascade ampl. in GLV generalized to finite M

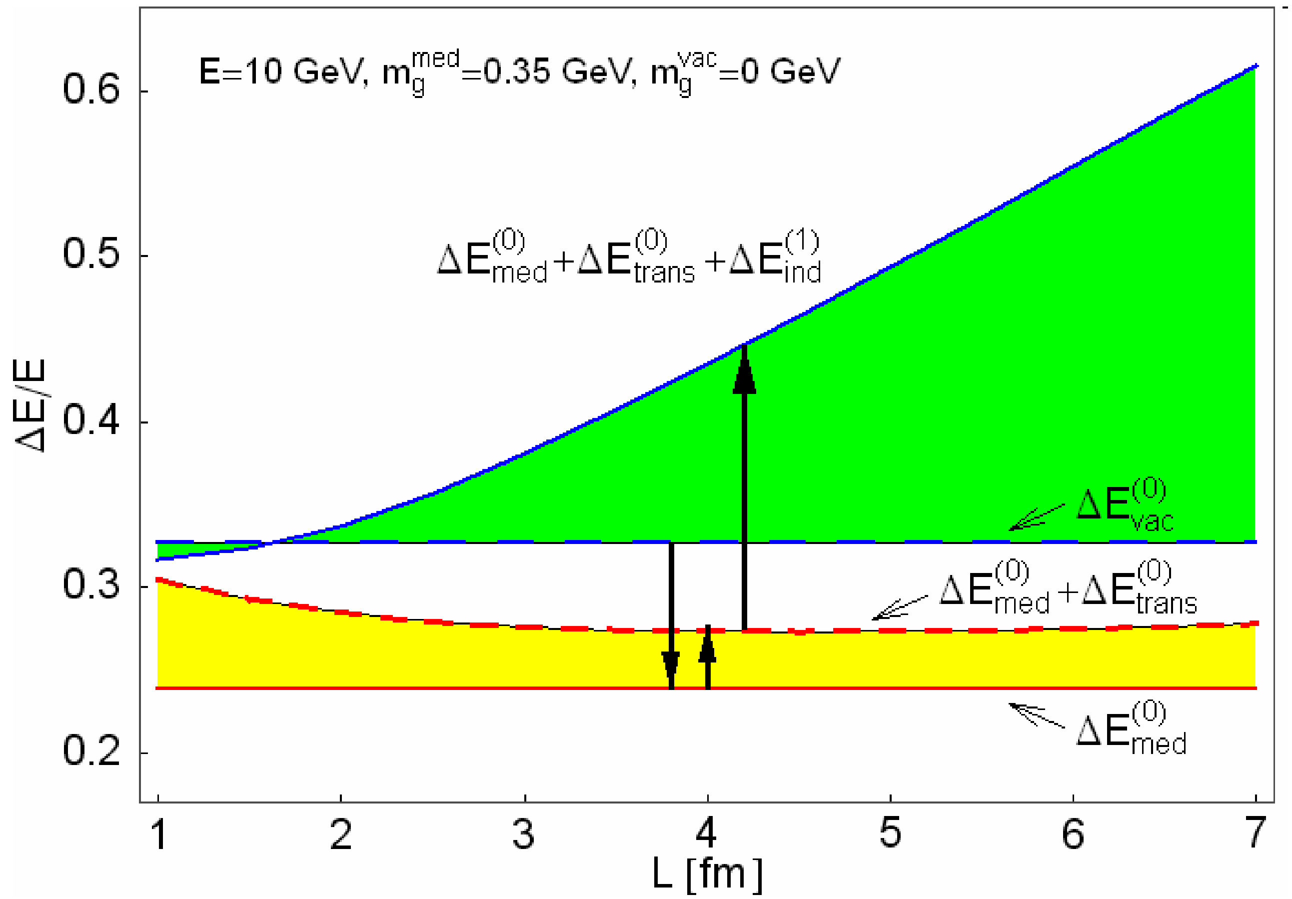
$$\tilde{\mathbf{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}, \qquad \tilde{\mathbf{C}}_{(i_1 i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2}$$

$$\tilde{\mathbf{B}}_i = \tilde{\mathbf{H}}-\tilde{\mathbf{C}}_i\,, \qquad \tilde{\mathbf{B}}_{(i_1 i_2\cdots i_m)(j_1 j_2\cdots i_n)} = \tilde{\mathbf{C}}_{(i_1 i_2\cdots j_m)}-\tilde{\mathbf{C}}_{(j_1 j_2\cdots j_n)}\;.$$

$$\omega_{(m,\cdots,n)} = \frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2}{2xE}\rightarrow\Omega_{(m,\cdots,n)}\equiv\omega_{(m,\cdots,n)}+\frac{m_g^2+M^2x^2}{2xE}$$

The numerical results for induced radiative energy loss are shown for first order in opacity, with assumed opacity of 5 fm.





Result can be used to estimate charm quark suppression at RHIC

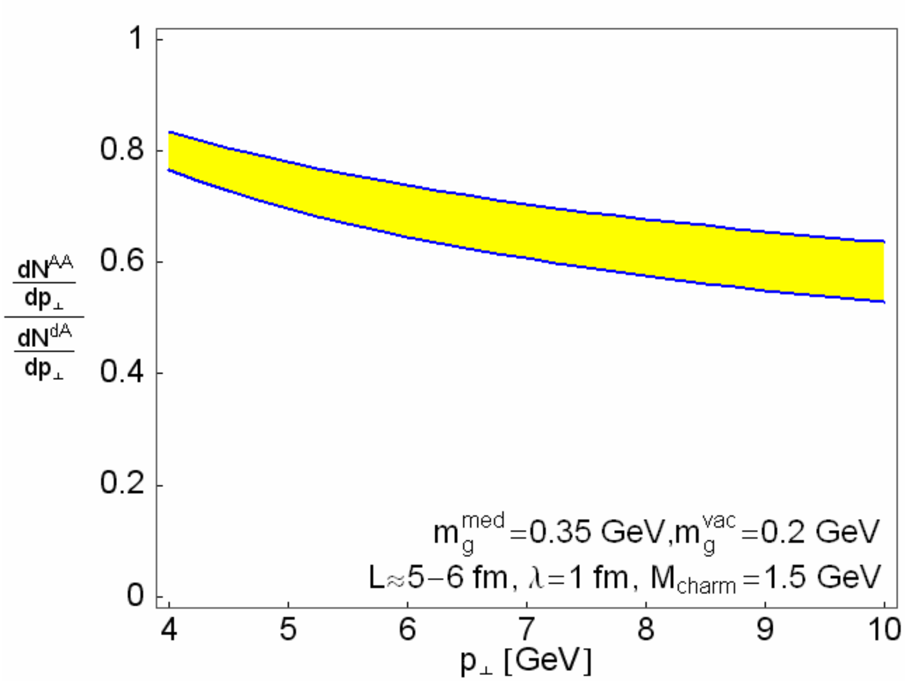
Confinement in physical vacuum modeled by

small finite mass $m_g \sim \Lambda_{QCD}$

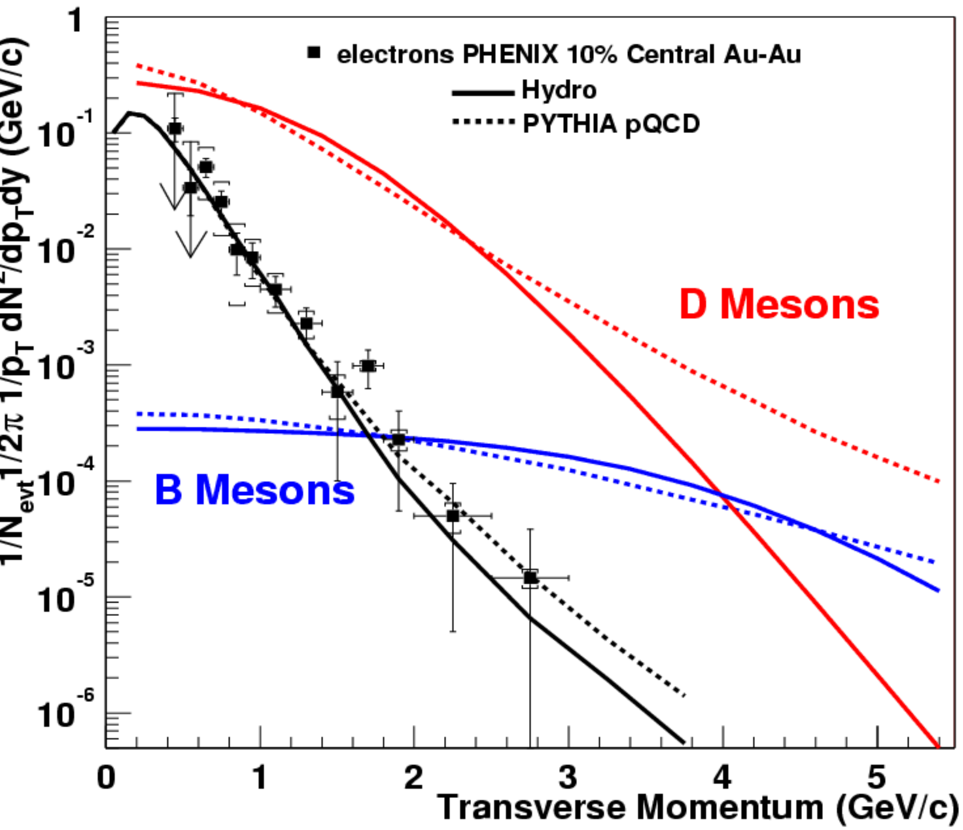
Heavy quark suppression

To estimate quenching we use GLV method PLB538:282-288,2002.

We assume that initial charm pt distribution is in the region $\frac{C_1}{p^4} < \frac{dN}{dp} < \frac{C_2}{p^8}$, where C_1 and C_2 are constants. We take that medium opacity is in the region 5-6 fm.



Small value of suppression (0.5-0.7) is expected because of small energy loss (20%).



This suppression is consistent with PHENIX data.

But possibly inconsistent with STAR?

Caveats:

1) **Error bars are too large in the region 3-4GeV. Therefore, even much larger suppression would nicely fit the data.**
2) **Pt distribution of single electrons is not very sensitive to energy loss. We see that significantly different pt distributions of D mesons from PYTHIA and Hydro produce similar pt distributions of single electrons.**

Conclusions

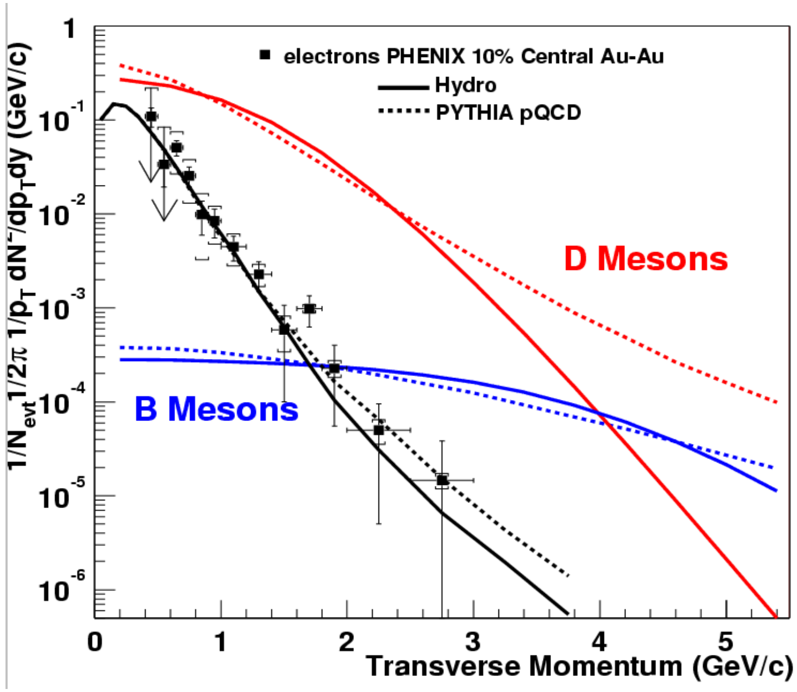
D meson data for 200 GeV *D-Au* and *Au-Au* will soon become available. We predict small charm quark suppression ~ 0.5-0.7. This suppression should be definitely much smaller than the already observed pion suppression (0.2).

This is an important consistency test of Jet Tomography of QGP. Together with already observed jet quenching and collective flow of light partons, this may provide decisive proof in the favor of QGP production at RHIC.

Backup slides

Elliptic flow

Elliptic flow



Single e 10% Central Au-Au data can be explained by two different approaches:

- **Hydro**
- **PYTHIA pQCD**

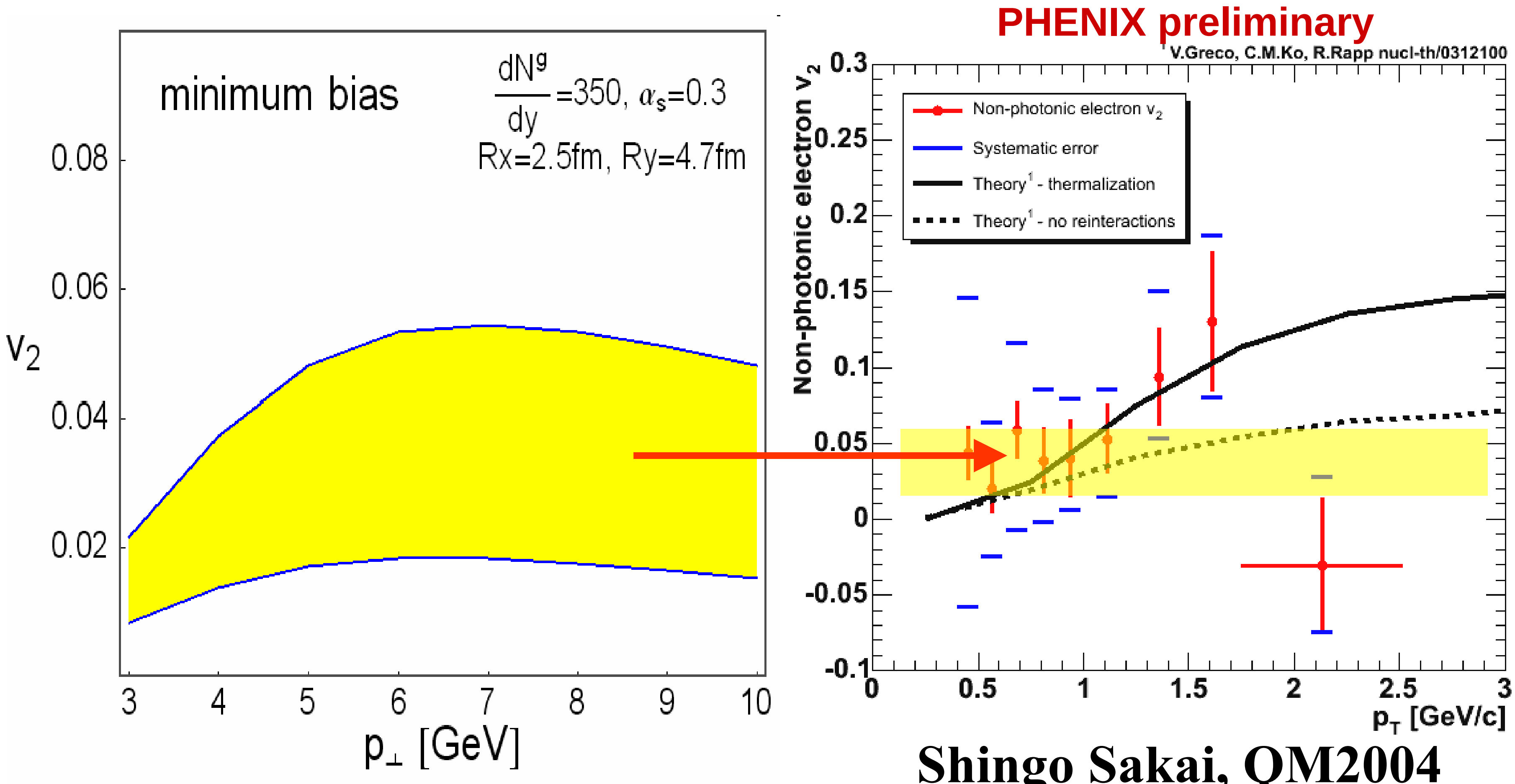
DOES THE CHARM FLOW AT RHIC?
S. Batsouli, S. Kelly, M. Gyulassy , J.L. Nagle
Phys.Lett.B 557 (2003) 26

The answer to this question can give us the measurement of v2 for charm at RHIC.

Observation of the elliptic flow which is much larger than the one predicted by jet quenching, would mean that charm flows at RHIC.

What value of elliptic flow we expect from heavy quark jet quenching?

We have estimated v_2 for minimum bias case. Here, we have assumed 1+1D Bjorken longitudinal expansion.



Shingo Sakai, QM2004

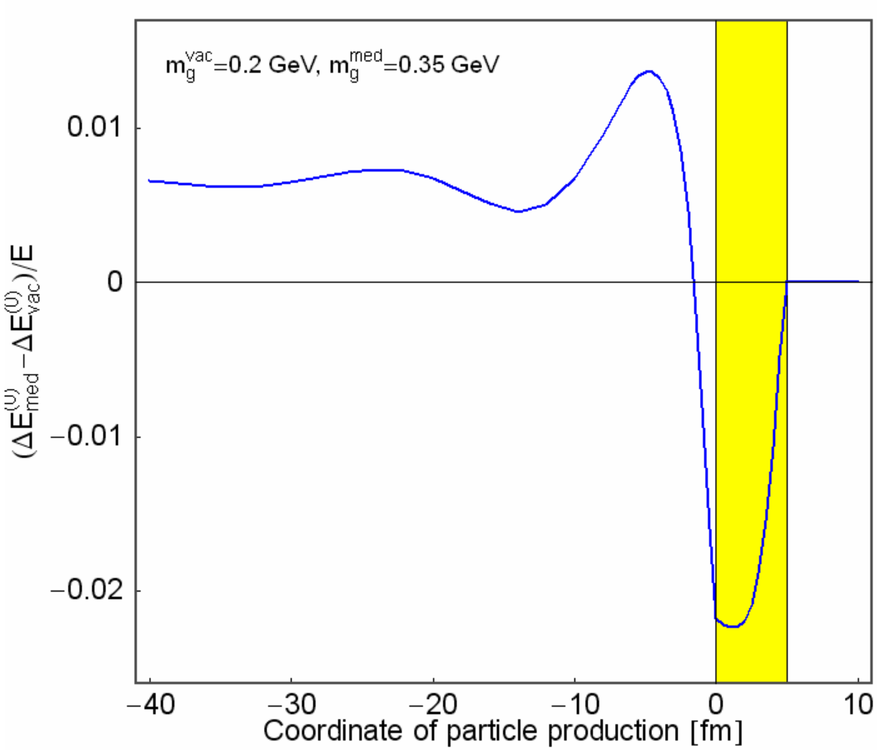
According to our estimates, we expect small charm quark v_2 at RHIC (0.02-0.06).

Two different vacuum gluon masses

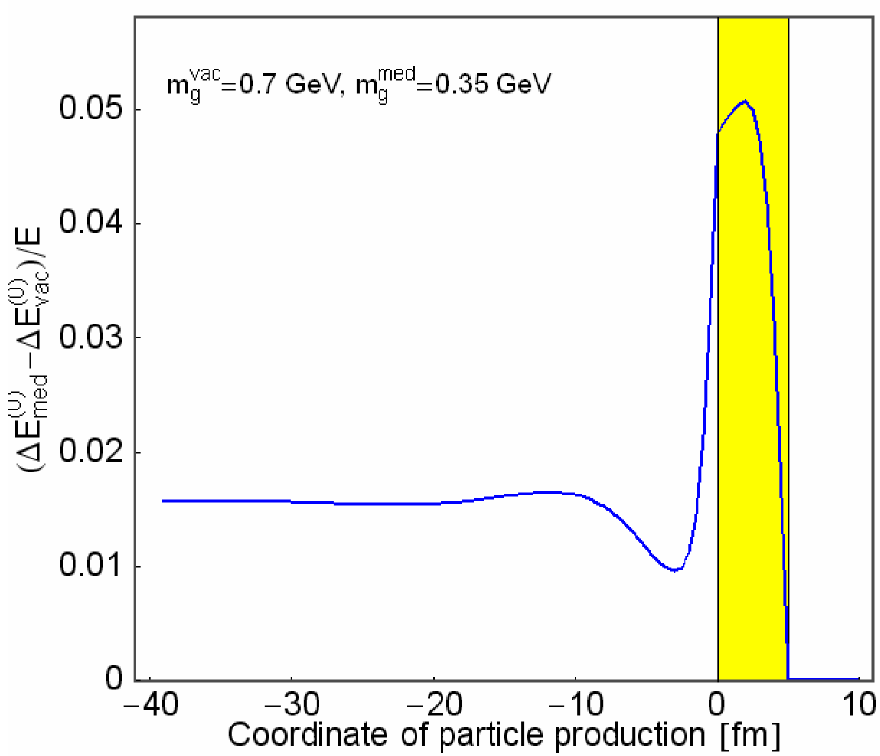
We also have to include the effect of confinement in the vacuum.

There are two approaches to do that:

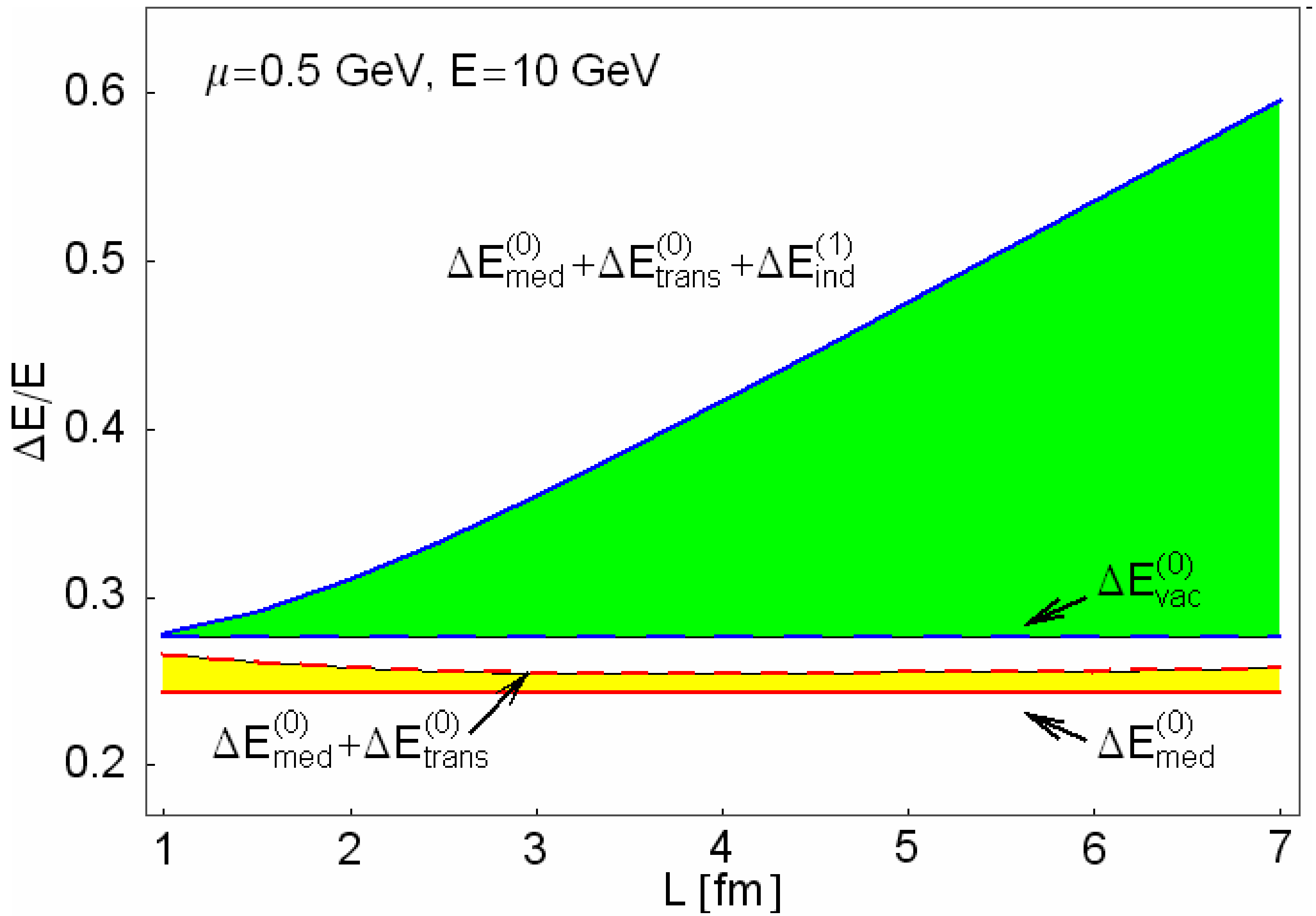
1) **Assume that gluon mass in the vacuum is not exactly zero, but it has some small value on the order of Λ_{QCD}.**



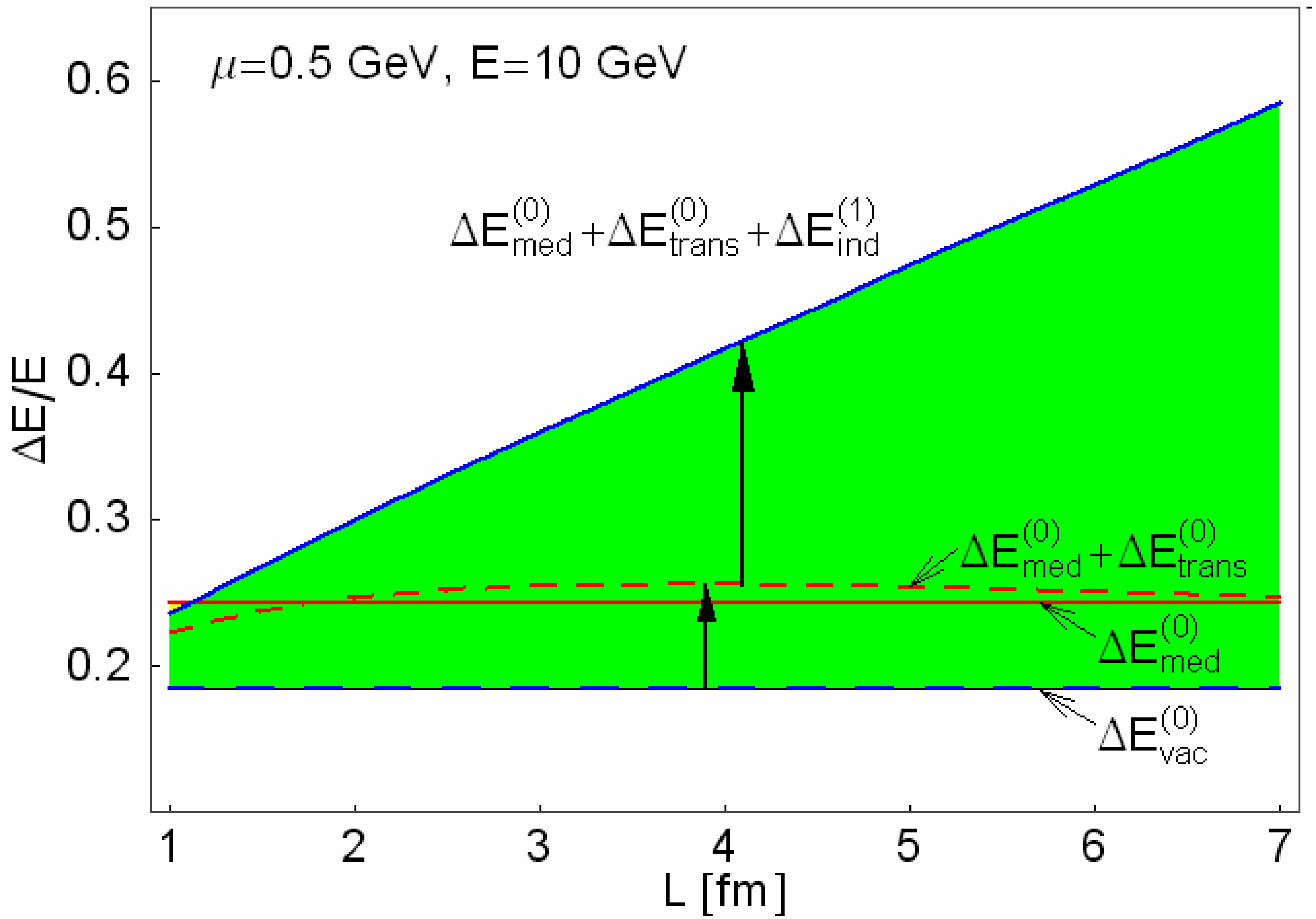
2) **Assume that vacuum gluon mass is large, i.e. approximately 0.7 GeV.**



This figure shows the net energy loss plot for the m_g^{vac}=0.2 GeV.



This figure shows the net energy loss plot for the m_g^{vac}=0.7 GeV.

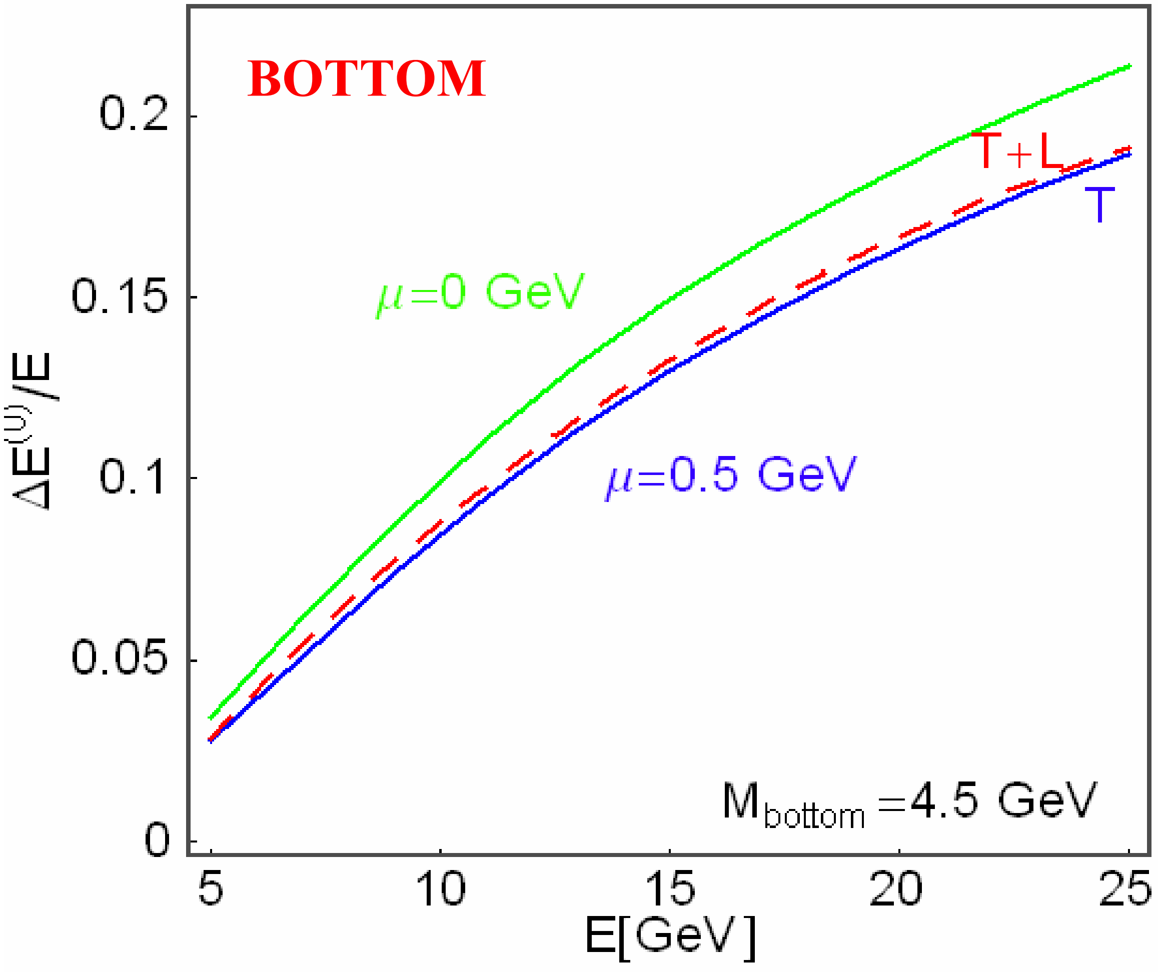


Ter-Mikayelian assumptions and bottom quark

Computation was done in the soft gluon limit, i.e. it was assumed that gluon momentum is much smaller than quark momentum.

Additionally we assumed:

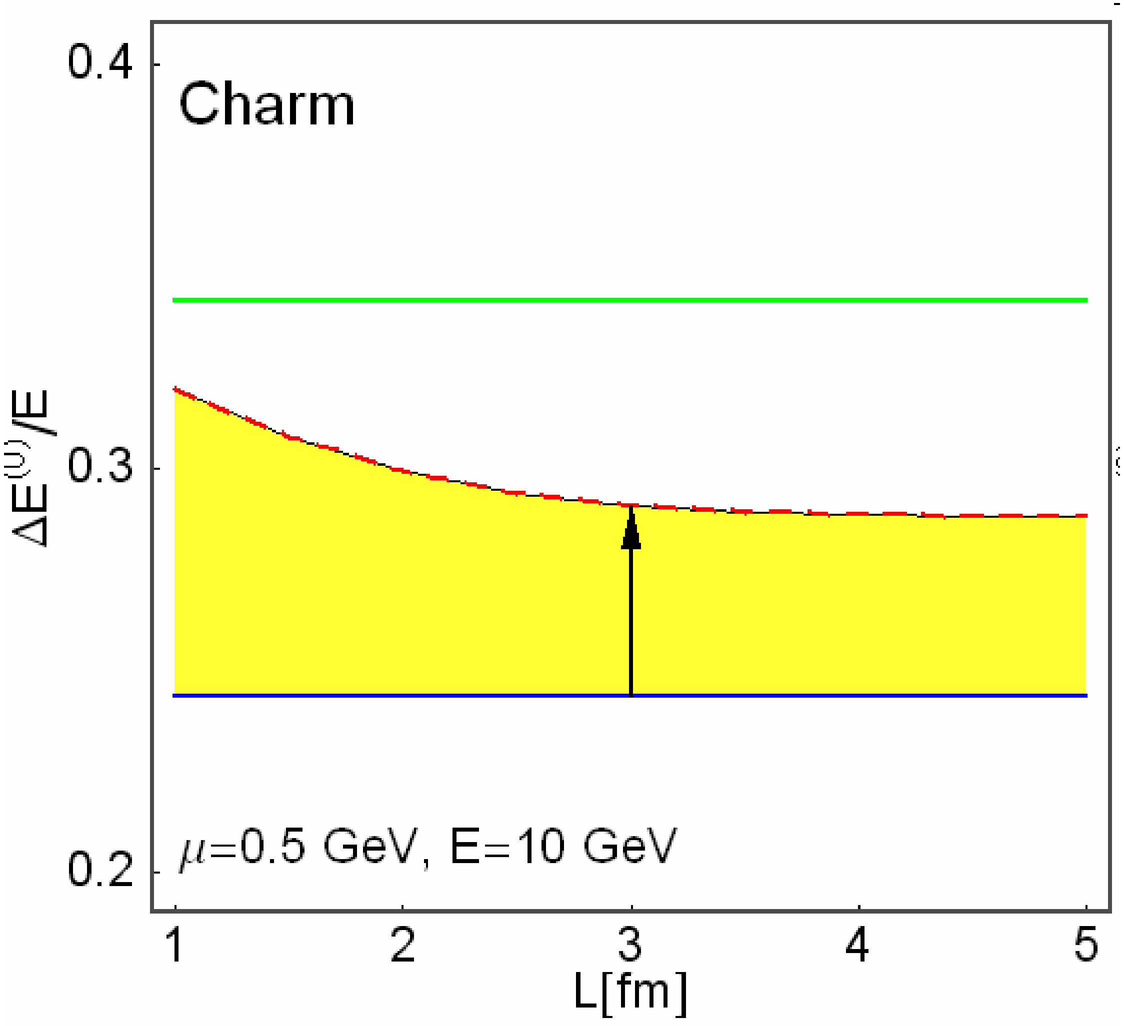
- **Source packet $J(p)$ varies slowly over the range of momentum, i.e. $J(p+k) \simeq J(p)$.**
- **Spin in the problem is neglected.**
- **Quark momentum $\vec{p}$ is large, such that we can assume $m^2/\vec{p}^{\,2} \ll 1$.**



Contrary to the charm, for bottom quark the Ter-Mikayelian effect is negligible.

Transition radiation L dependence

For massive quarks and medium thickness greater than 3 fm transition radiation becomes independent on the thickness of the medium.



First order energy loss:

Assumptions, dead cone effect, quadratic vs linear dependence

In addition to the assumptions used to compute the Ter -Mikayelian effect, we used:

- **Interaction in a deconfined QGP can be modeled by static color screened Yukawa potentials. The Fourier and color structure of the potential is assumed to be**

$$V_n = V(q_n) e^{i q_n x_n} = 2\pi\delta(q^0) v(\vec{q}_n) e^{-i \vec{q}_n \vec{x}_n} T_{a_n}(R) \otimes T_{a_n}(n)$$

where $\vec{x}_n$ is the location of n^{th} (heavy) target parton, and

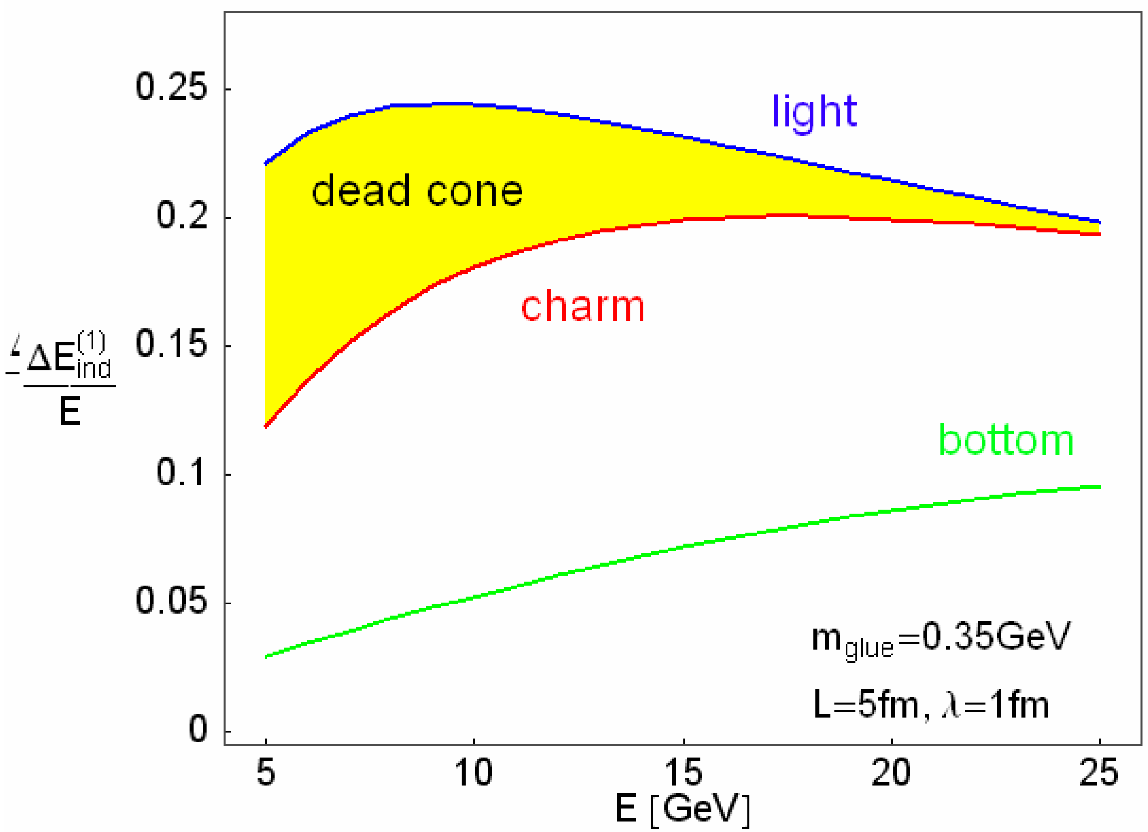
$$v(\vec{q}_n) \equiv \frac{4\pi\alpha_S}{\vec{q}_n^{\,2} + \mu^2}$$

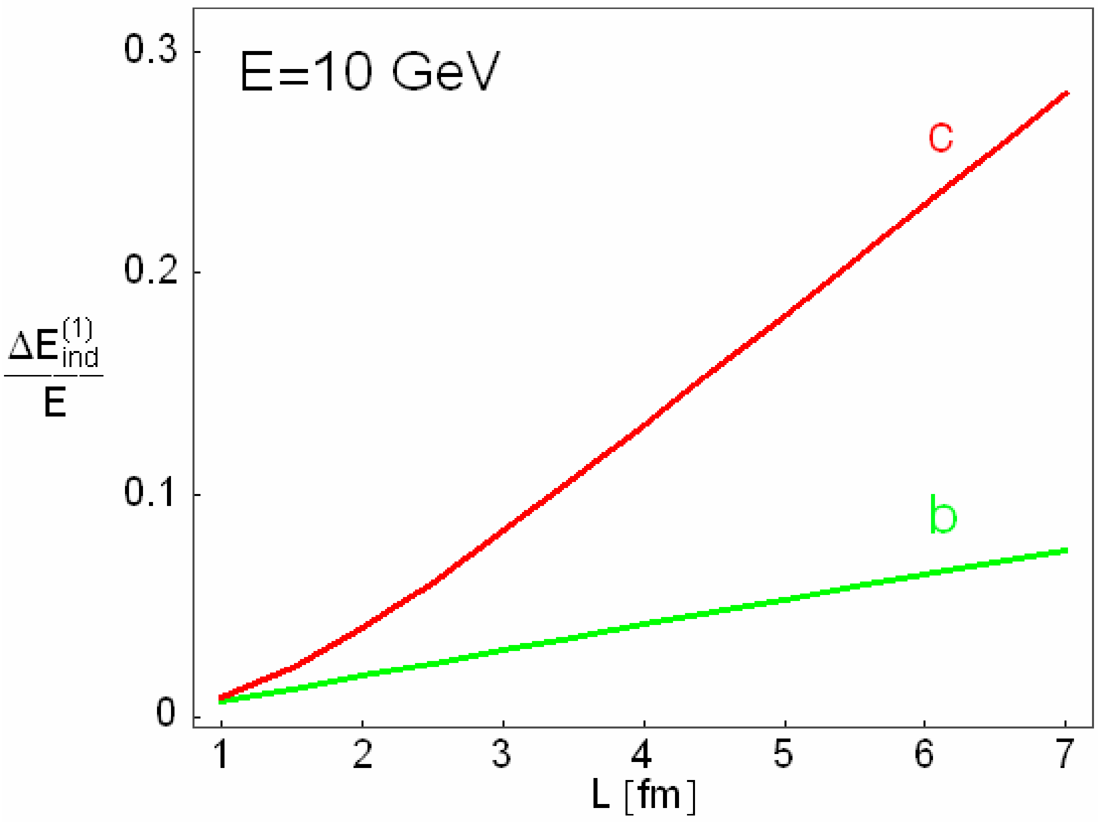
- **All $\vec{x}_n$ are distributed with the same density** $\rho(\vec{x}) = \frac{N}{A_\perp}\tilde{\rho}(z)$ **where** $\int dz\,\tilde{\rho}(z) = 1$

- **The distance between the source and scattering centers is large comparing to the interaction range, i.e.** $z_i - z_0 \gg 1/\mu$.

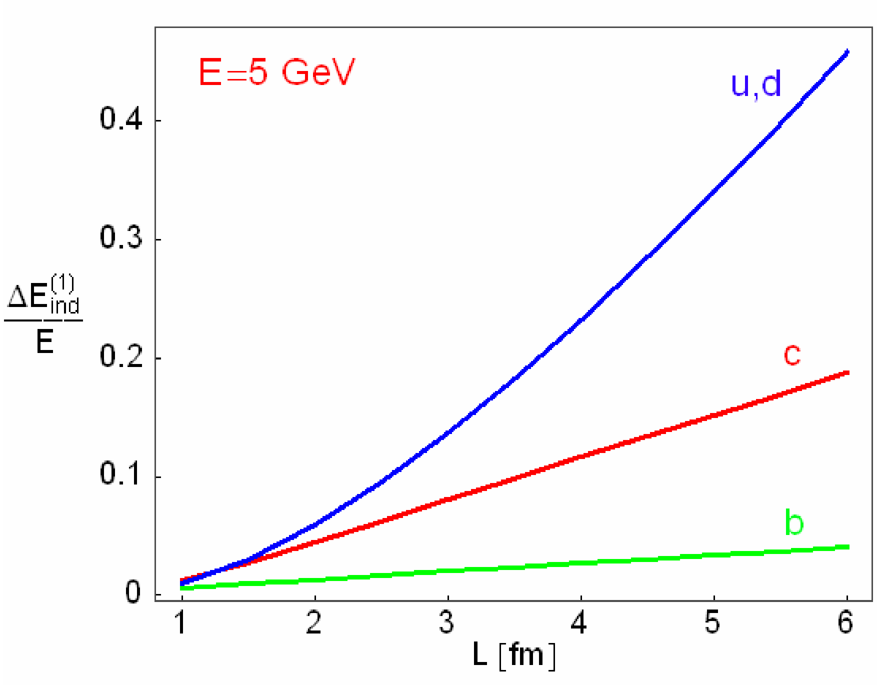
The numerical results for induced radiative energy loss are shown for first order in opacity.

When we include all energy loss effects, we get that effective plasma opacity should be approximately 5 fm.



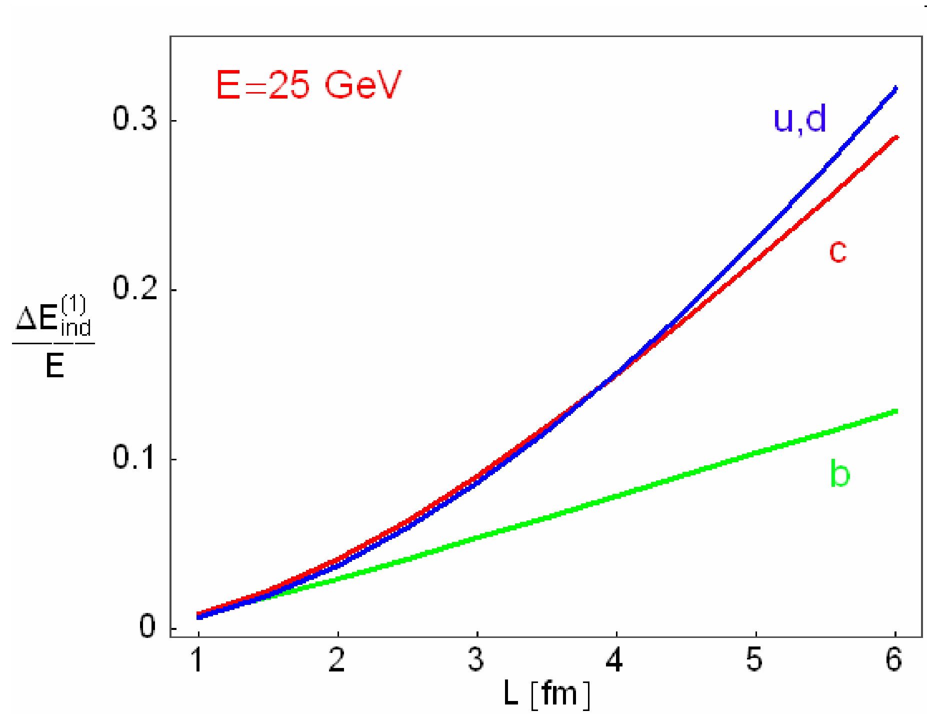


For 10 GeV heavy quark (c, b) jet, thickness dependence is close to linear Bethe-Heitler like form L^1. This is different than the asymptotic energy quadratic form characteristic for light quarks.



As the jet energy increases charm and light quark energy loss become more similar, while bottom quark remains significantly different.

For 5 GeV heavy quark (c, b) jet, thickness dependence is closer to linear Bethe-Heitler like form L^1, than the asymptotic energy quadratic form characteristic for light quarks.



As the jet energy increases, the dead cone effect becomes less important.