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 are the heavy quark suppression and elliptic flow at RHIC?**
- **Conclusion**

Motivation

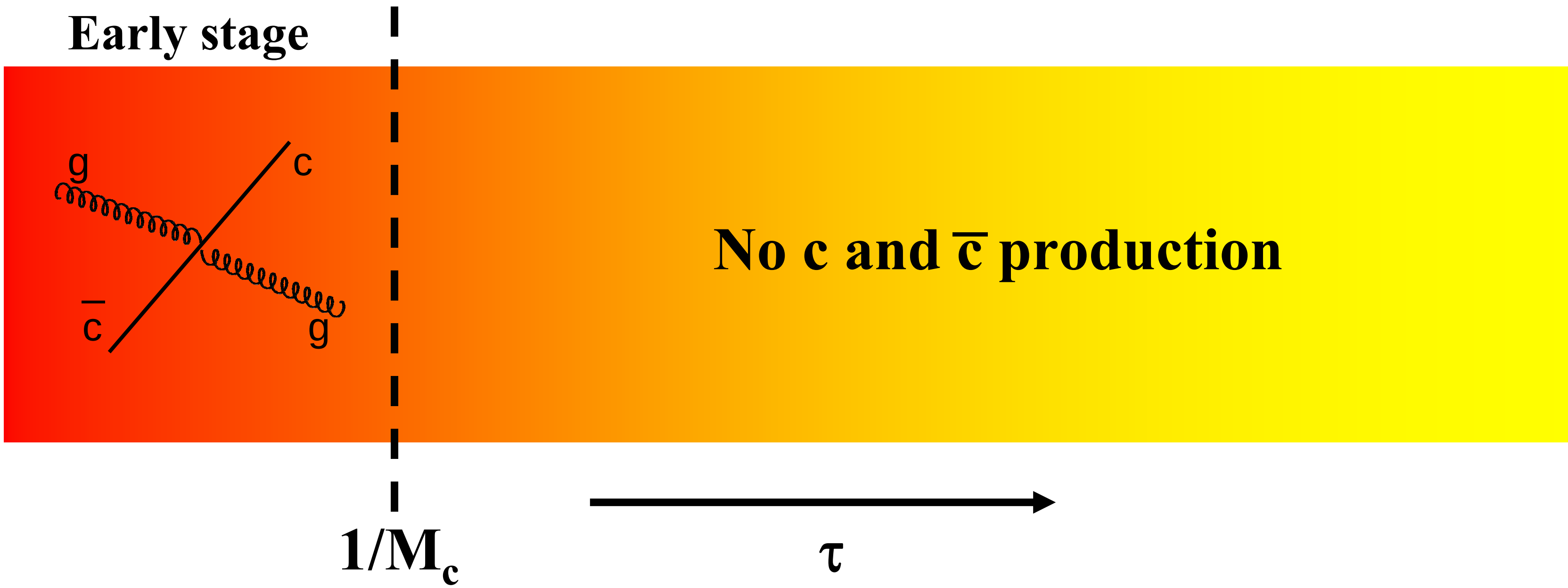
One of the central questions in high energy heavy ion physics is whether a quark-gluon Plasma (QGP) has been discovered at RHIC.
(M.Gyulassy and L. McLerran, nucl-th/0405013, M.Gyulassy, nucl-th/0403032)

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.

Why is charm quark a good probe?

Charm quark can be produced only during the early stage of QCD matter



Charm quark mass is large enough

↓

M_{charm} ? Λ_{QCD}

↓

Perturbative calculations of charm production and energy loss are possible

Charm quark mass is small enough

↓

Significantly interacts with surrounding light quarks and gluons

↓

Sensitive to the properties of the medium

Disadvantages of charm quark

- **Theoretically:** **Computations are, technically, much harder with heavy than with light quarks.**
- **Experimentally:** **Small number of charm quarks is produced, and it is not easy to detect them.**

Conclusion

If technical difficulties are solved, charm quark present very good probe of QCD matter.

What value of heavy quark suppression we can expect at RHIC?

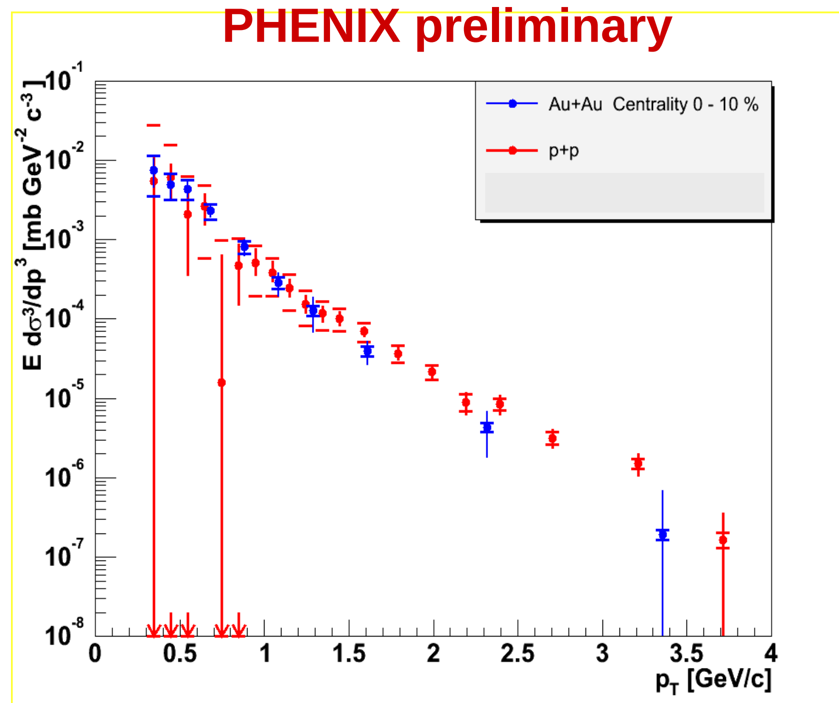
1997 Shuryak proposed that charm quarks will have large energy loss in QGP => large suppression of D mesons.

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.



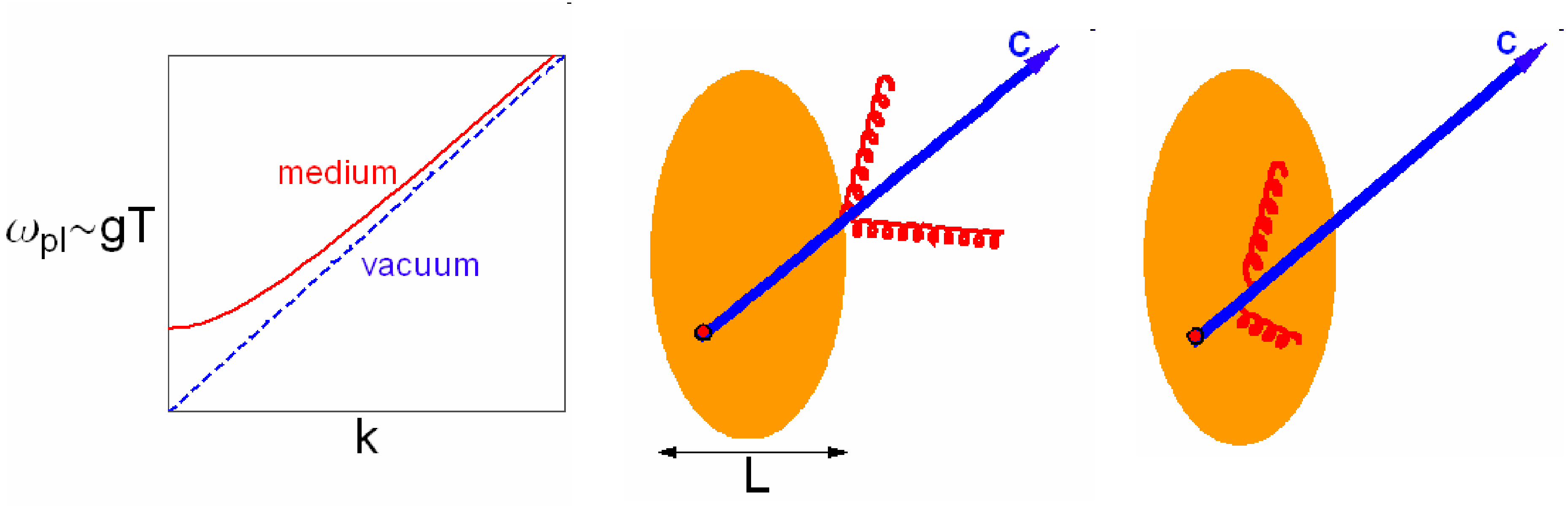
The motivation for our study of heavy quark energy loss in a dense QCD medium:

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.

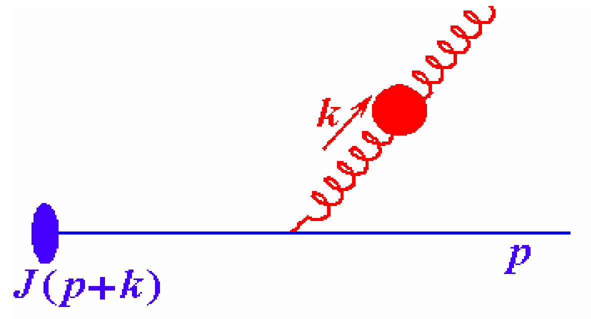
However, in a medium the gluon propagator has both

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**

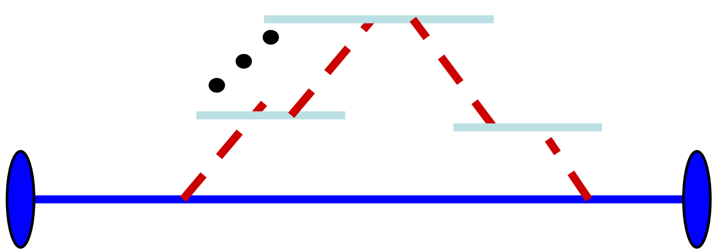
In order to compute the main order radiative energy loss we have to compute $|M_{rad}|^2$, where M_{rad} is given by Feynman diagram:



To compute this, we have used optical theorem, i.e.:

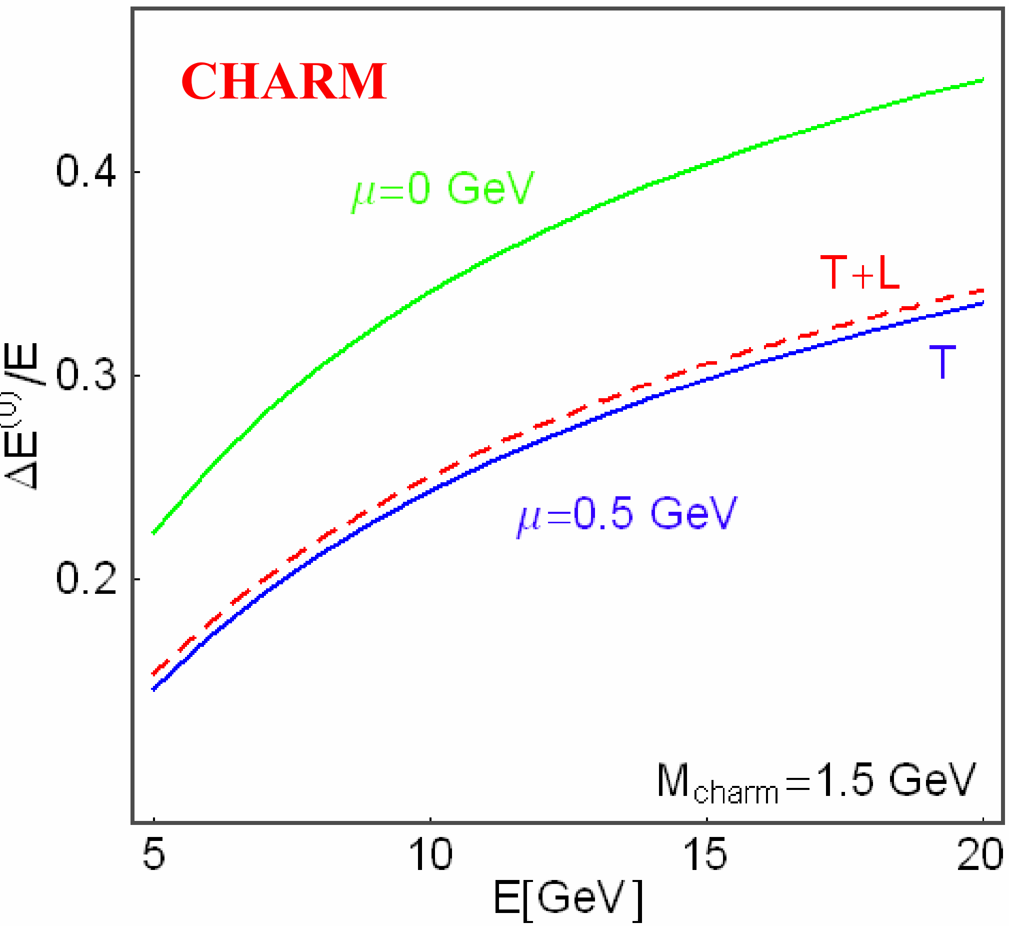
$$2 Im M = \int |M_{rad}|^2 \frac{d^3 p}{(2\pi)^3 2E} \frac{d^3 k}{(2\pi)^3 2\omega}$$

Where M is the amplitude of the fallowing diagram:



Dielectric Effect

Comparison between medium and vacuum 0th 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.

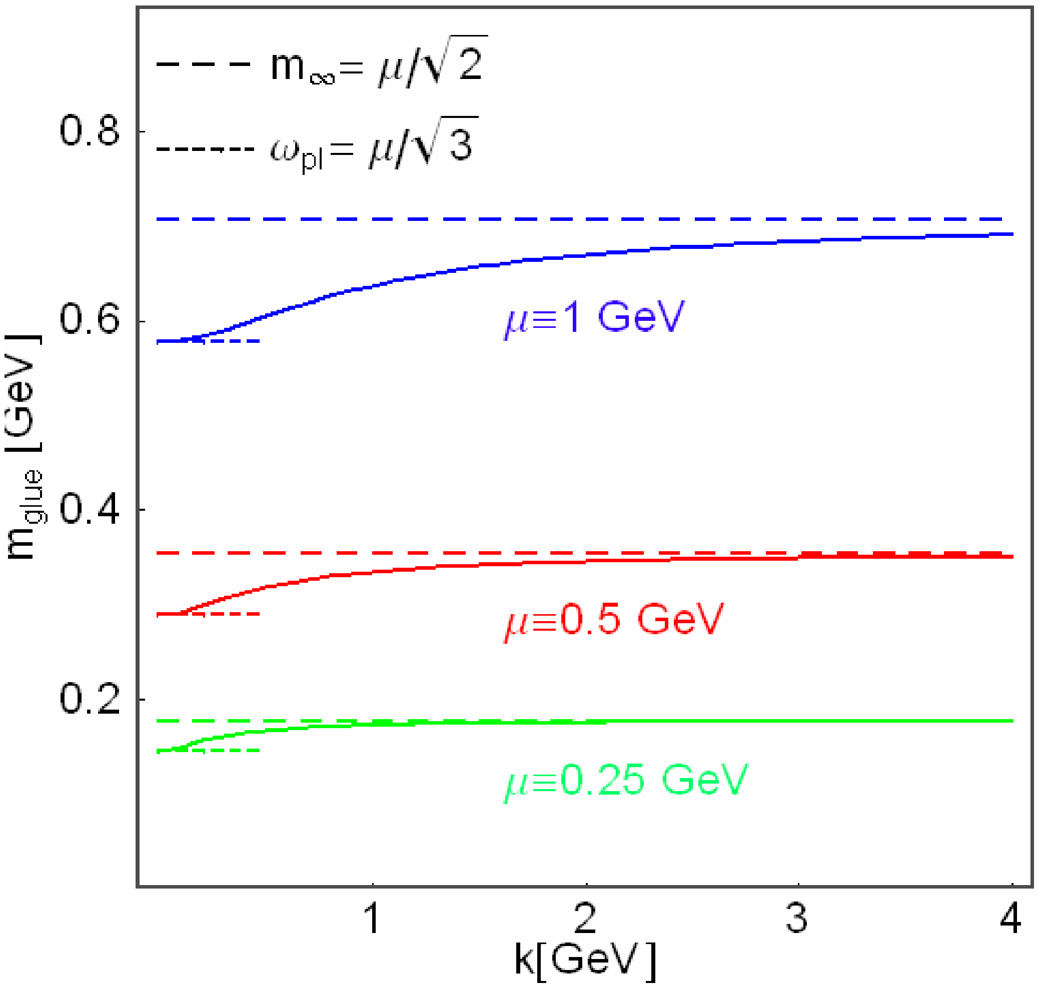


Fig.2 shows the one loop transverse plasmon mass $m_g(k) \equiv \sqrt{(\omega^2 - k^2)}$.

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).

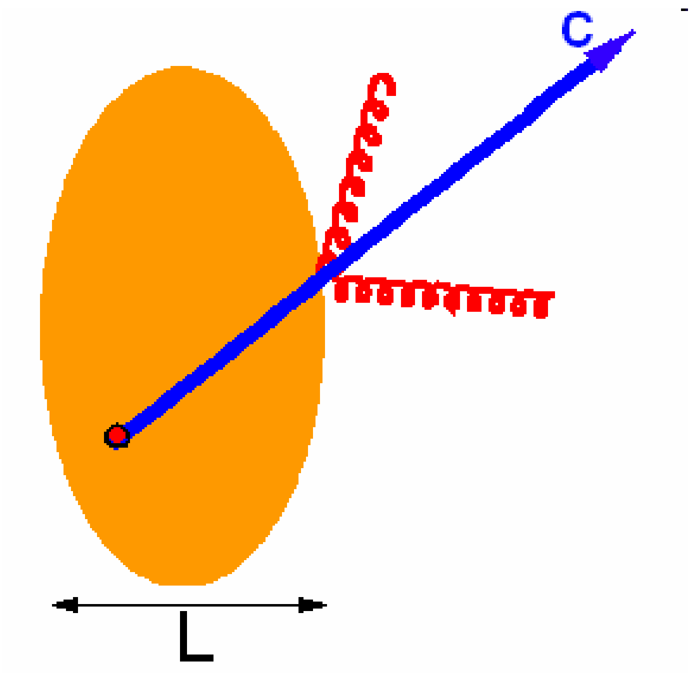
We can conclude that we can approximate the Ter-Mikayelian effect by simply taking $m_g \approx m_\infty$.

Transition radiation

An additional dielectric effect at 0th order in opacity.

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

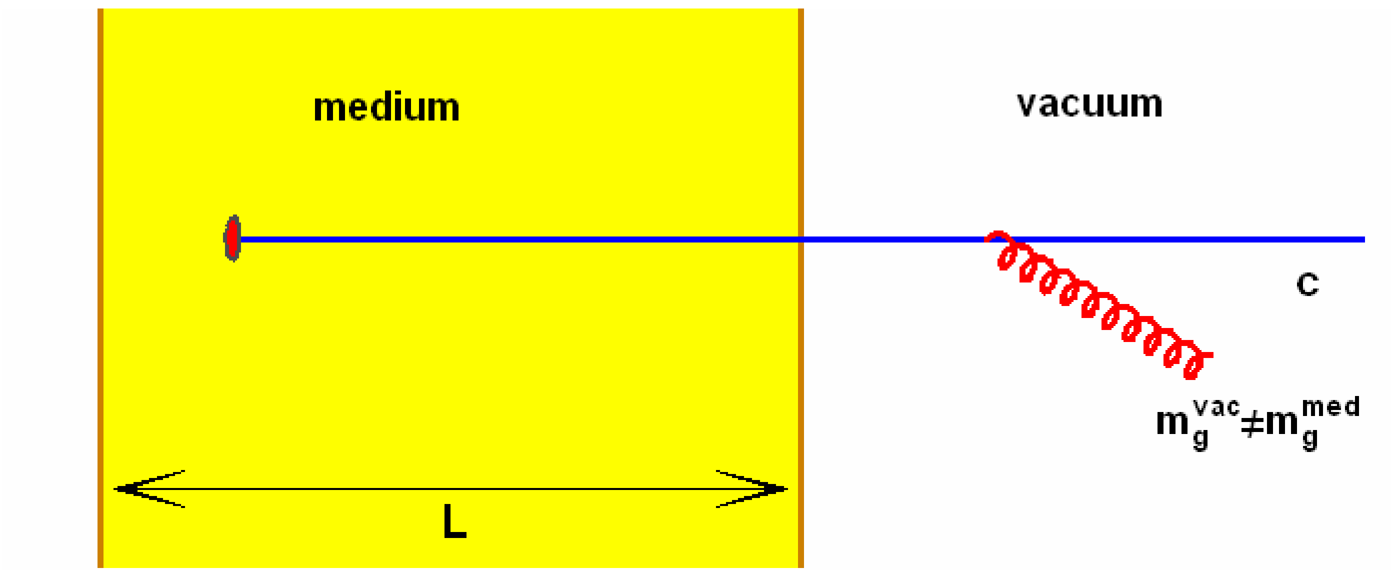
Transition radiation occurs at the boundary between medium and the vacuum.

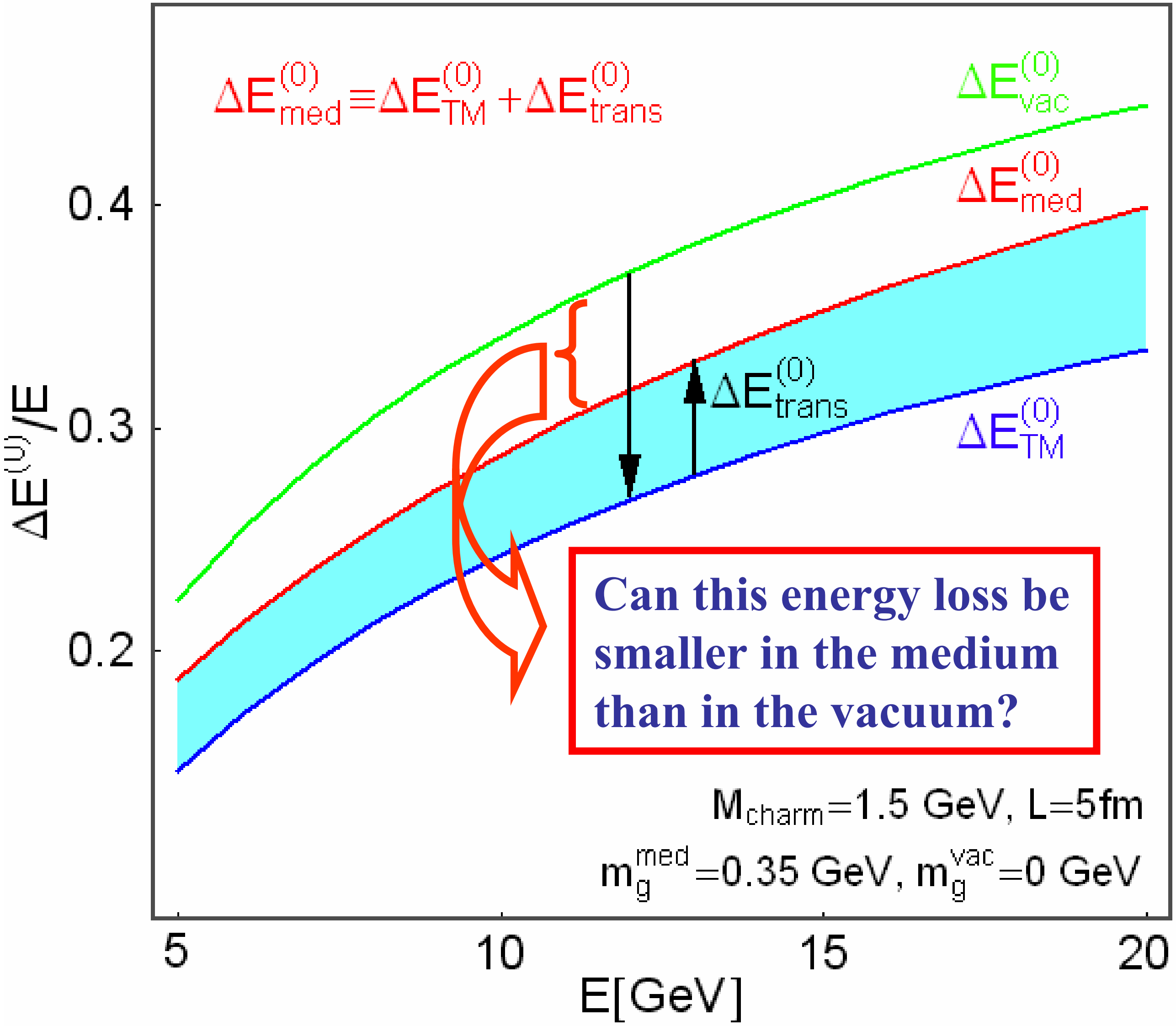


To estimate transition radiation we follow Zakharov

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

This computation was performed assuming a static medium.





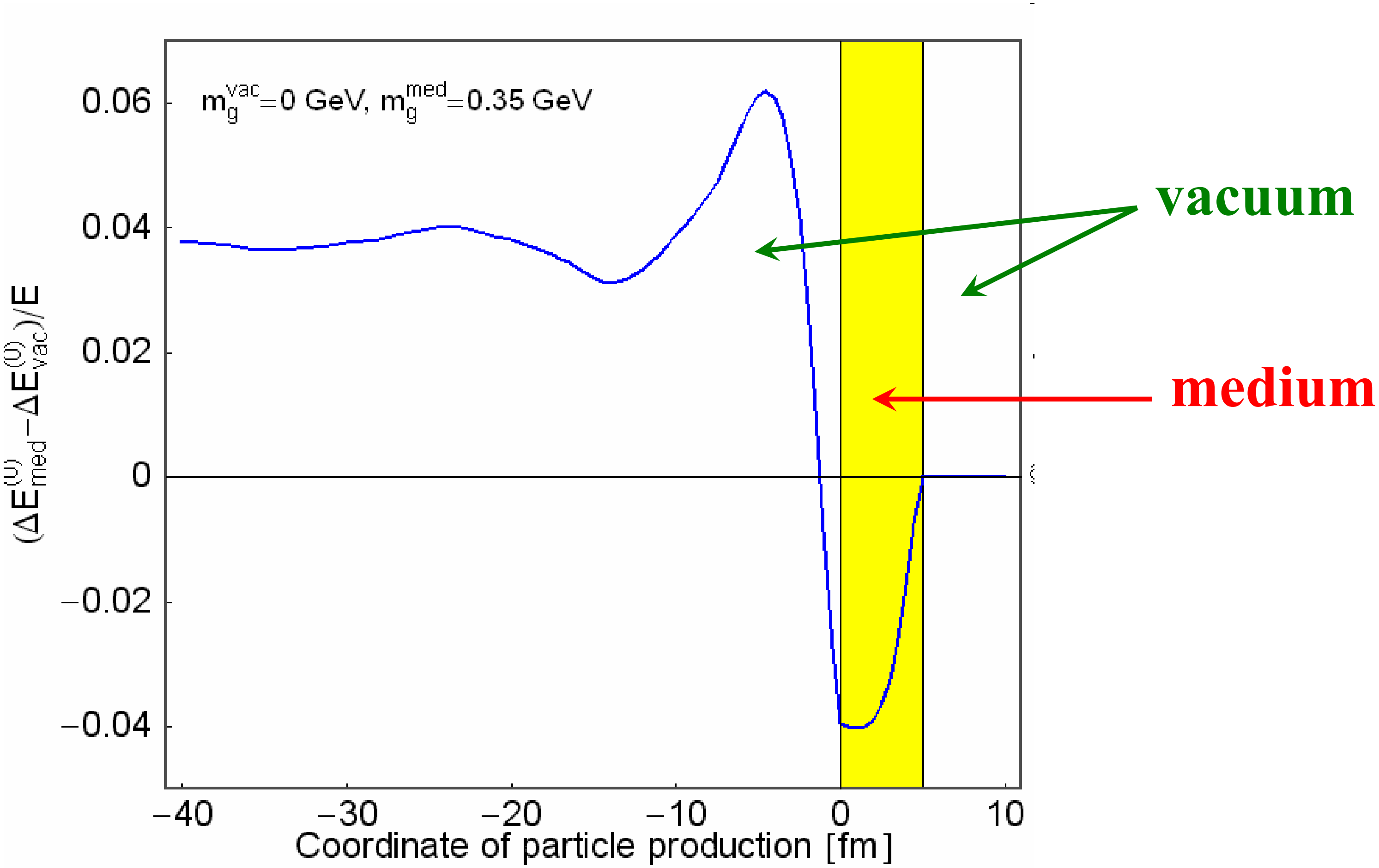
Transition radiation lowers Ter-Mikayelian effect from 30% to 15%.

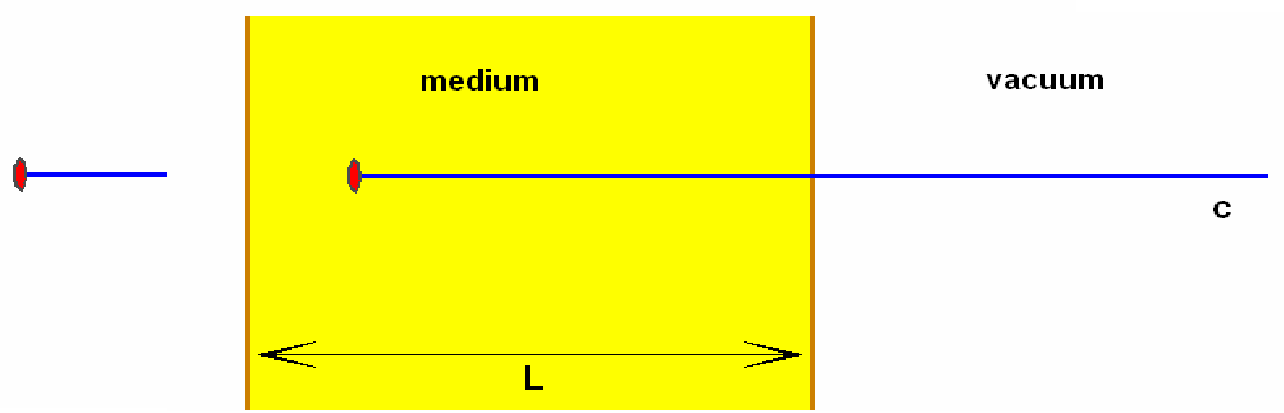
According to Zakharov, for particle produced inside the medium:

$$\Delta E^{(0)}_{med} - \Delta E^{(0)}_{vac} \sim ((m_g^{vac})^2 - (m_g^{med})^2)$$

Therefore,

$$m_g^{vac} < m_g^{med} \Rightarrow \Delta E^{(0)}_{med} < \Delta E^{(0)}_{vac}$$


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


medium
vacuum
c
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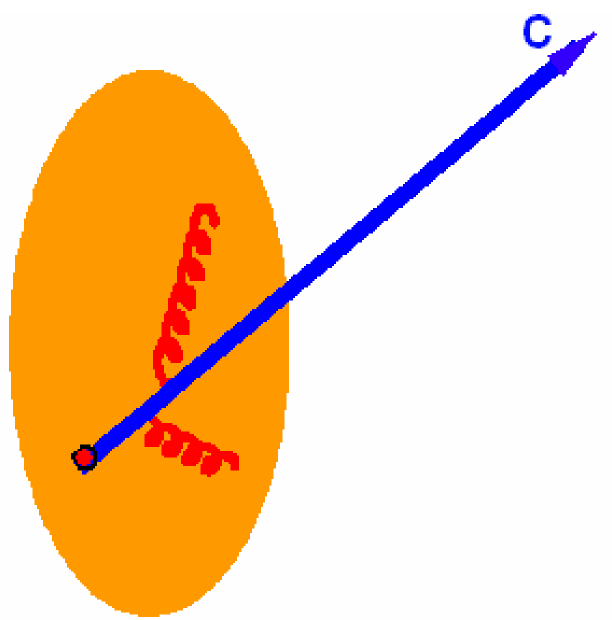
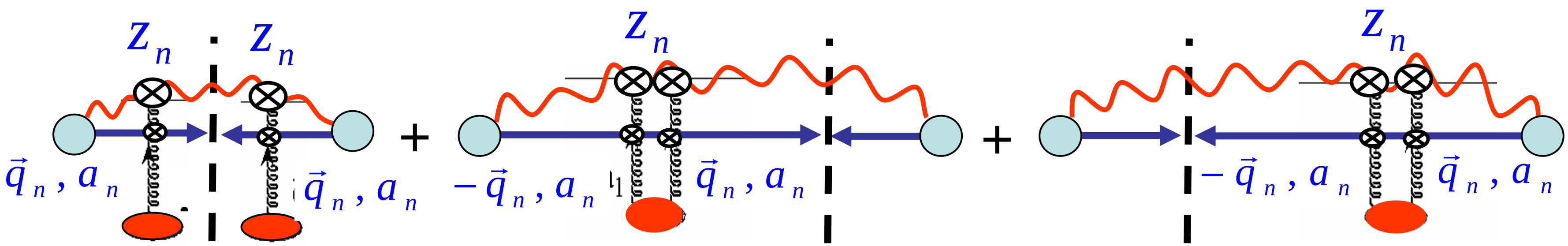
Energy loss due to the interaction with the medium

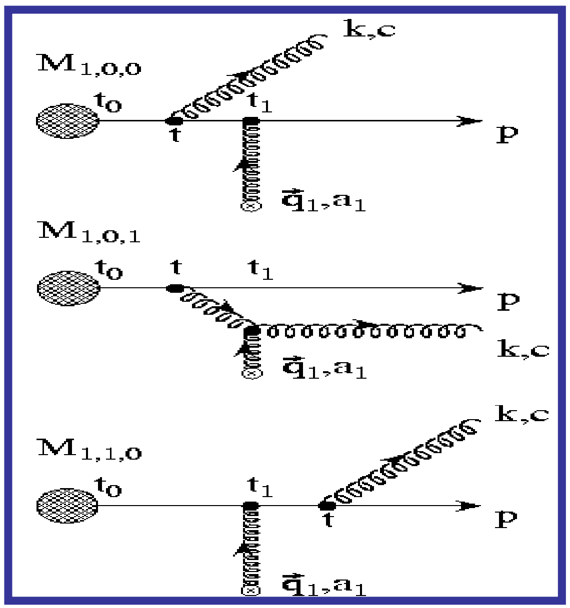
The third important effect is the induced gluon radiation caused by the multiple interactions of partons in the medium.

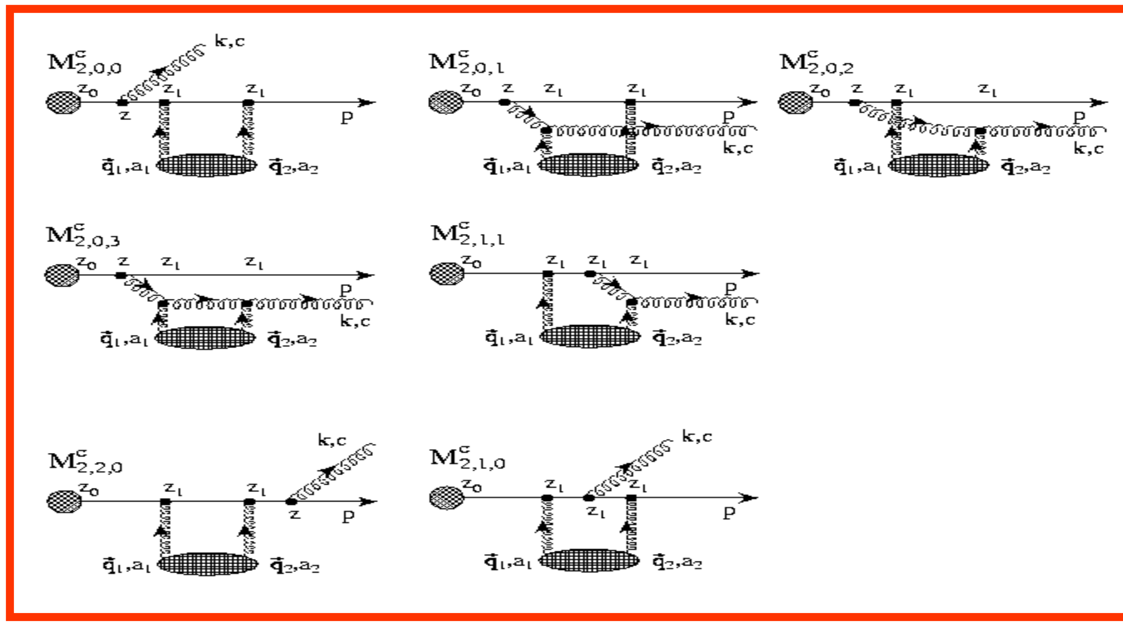
To compute medium induced radiative energy loss for heavy quarks we extend Gyulassy-Levai-Vitev (GLV) method, by introducing both quark M and gluon mass m_g.





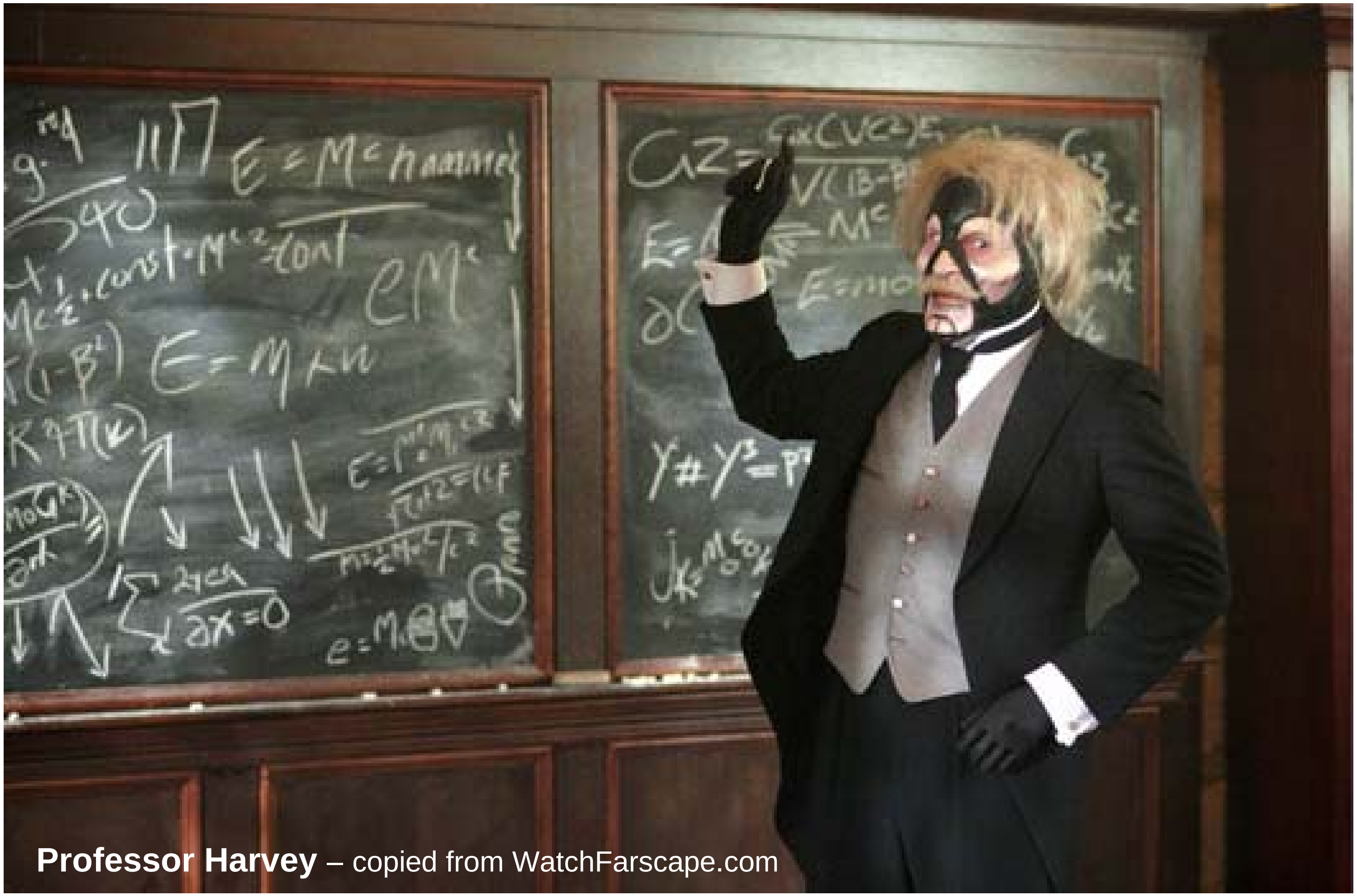
This leads to the computation of the fallowing types of diagrams:





To compute energy loss to all arders in opacity we apply algebraic recursive method described in (GLV,Nucl.Phys.B594(01)).

After computing these diagrams...



Professor Harvey – copied from WatchFarscape.com

we got the fallowing results:

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

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

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

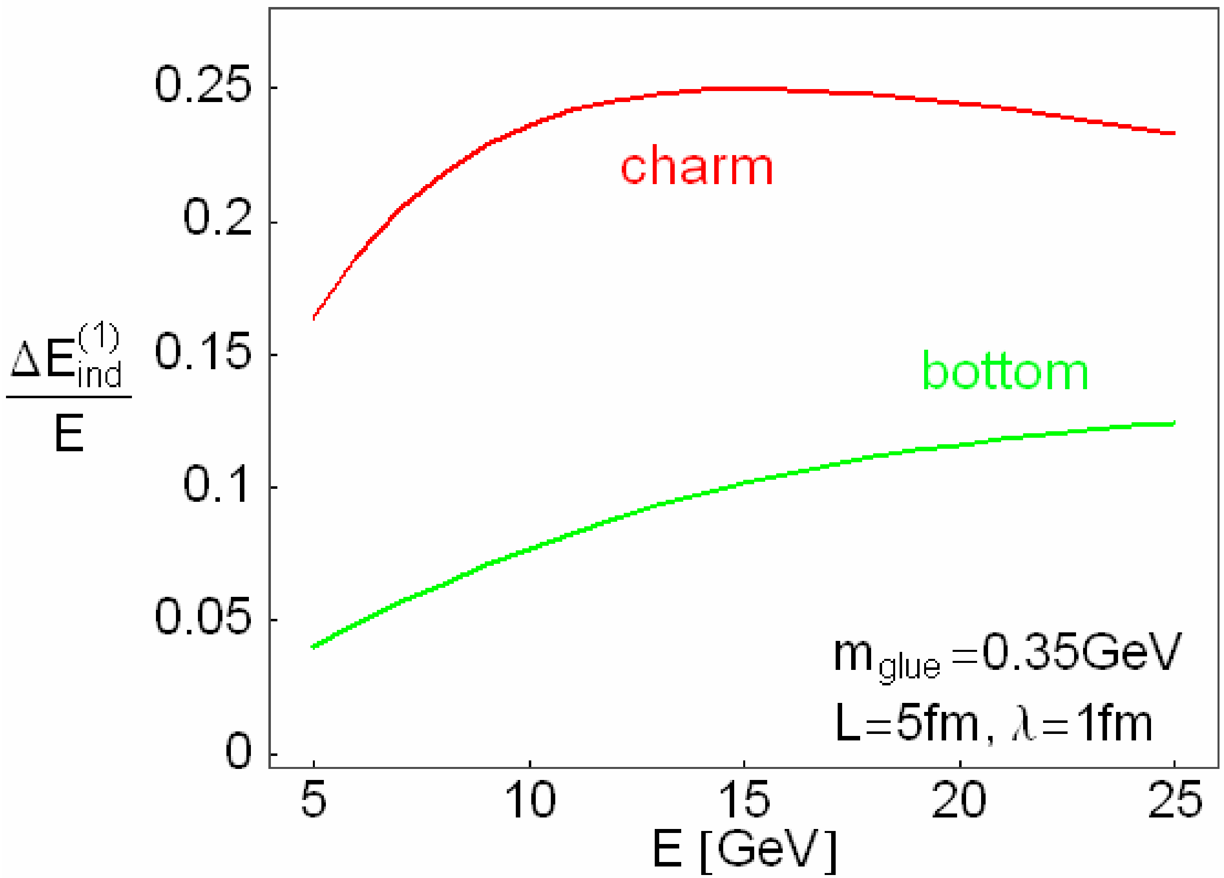
Hard, Gunion-Bertsch, and Cascade ampl. in GLV generalized to finite M

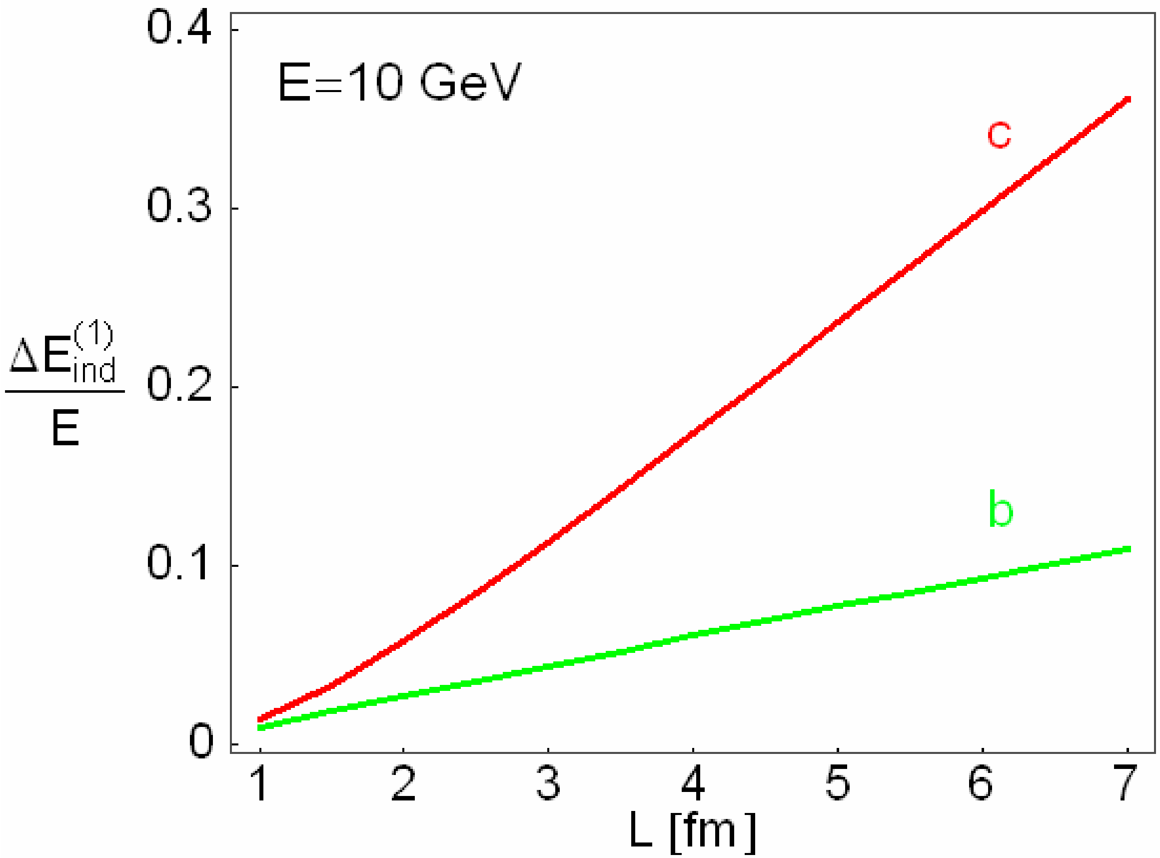
$$\tilde{\mathbf{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}\,, \qquad \tilde{\mathbf{C}}_{(i_1 i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2}$$

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

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

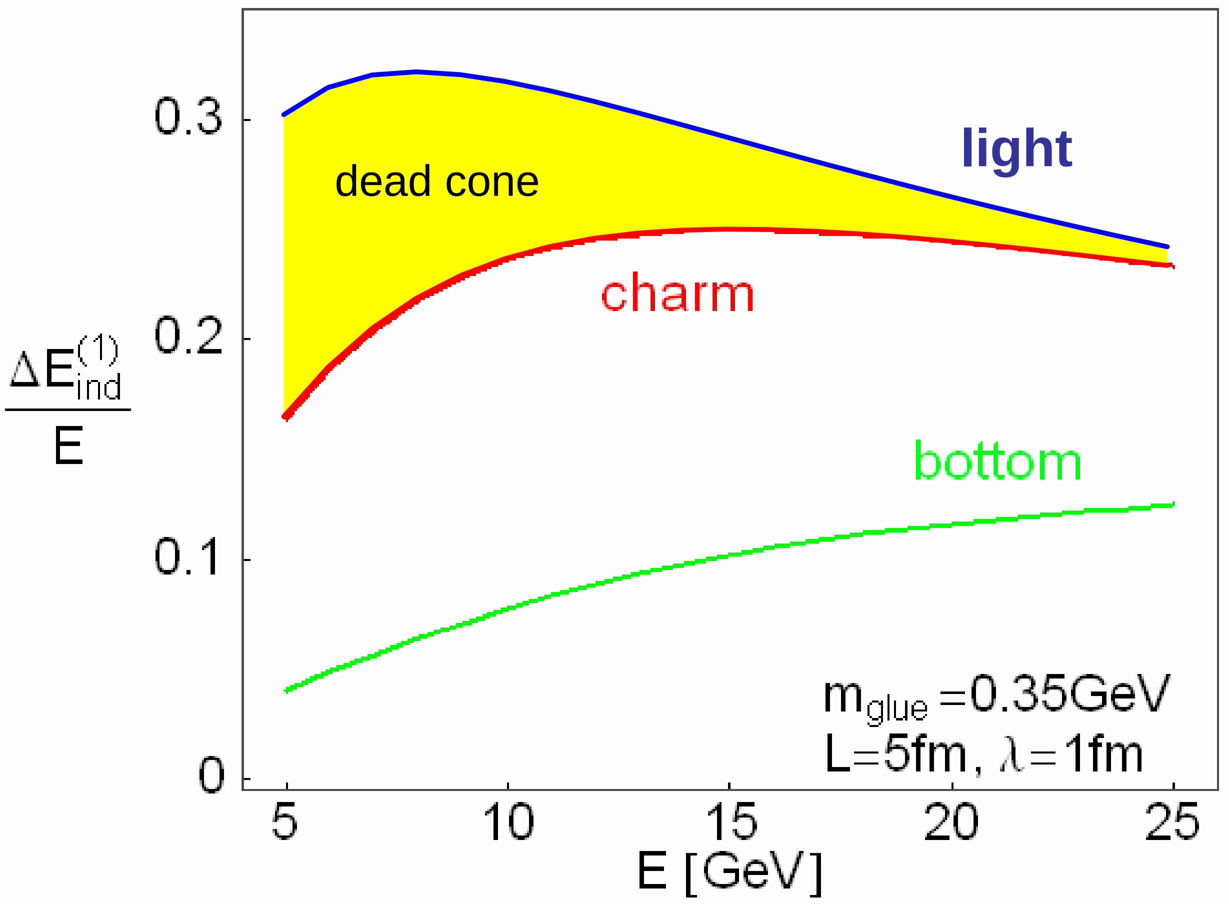
The numerical results for induced radiative energy loss are shown for first order in opacity, with assumed opacity of 5 fm.

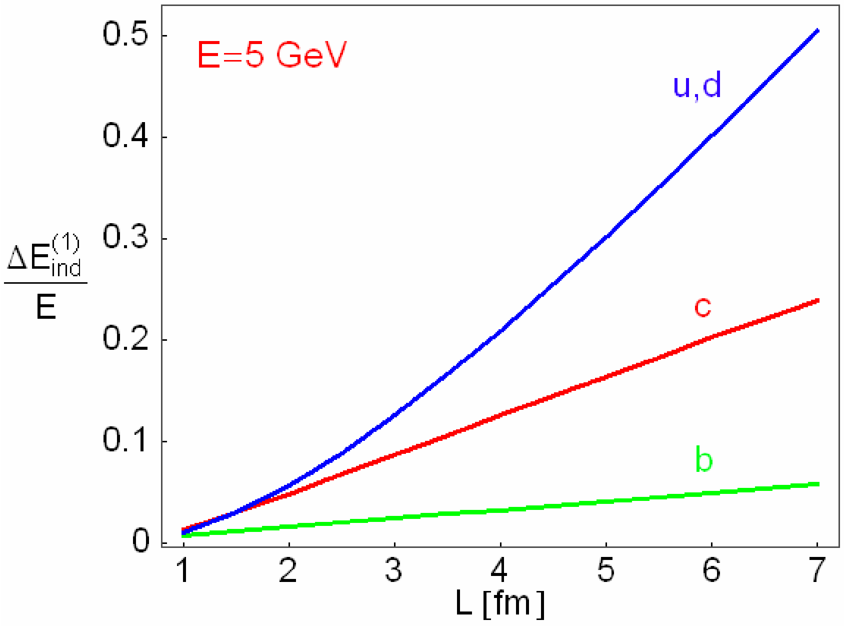




For 10 GeV heavy quark (c, b) jet, thickness dependence is close to linear Bethe-Heitler like form L^1. This is different than the asymptotic energy quadratic form characteristic for light quarks.

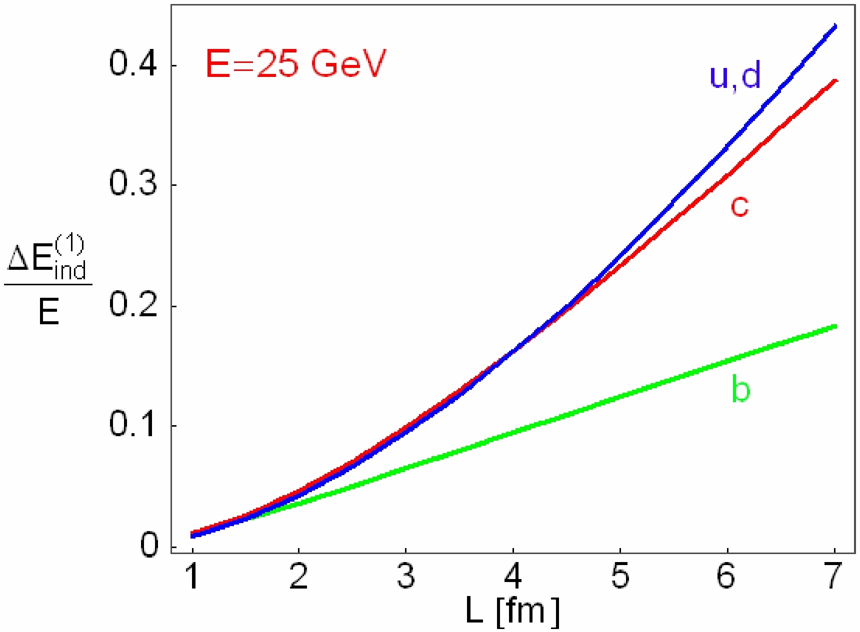
How important is the "dead cone effect" for the heavy quark energy loss?





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, while light quarks are closer to quadratic form.



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

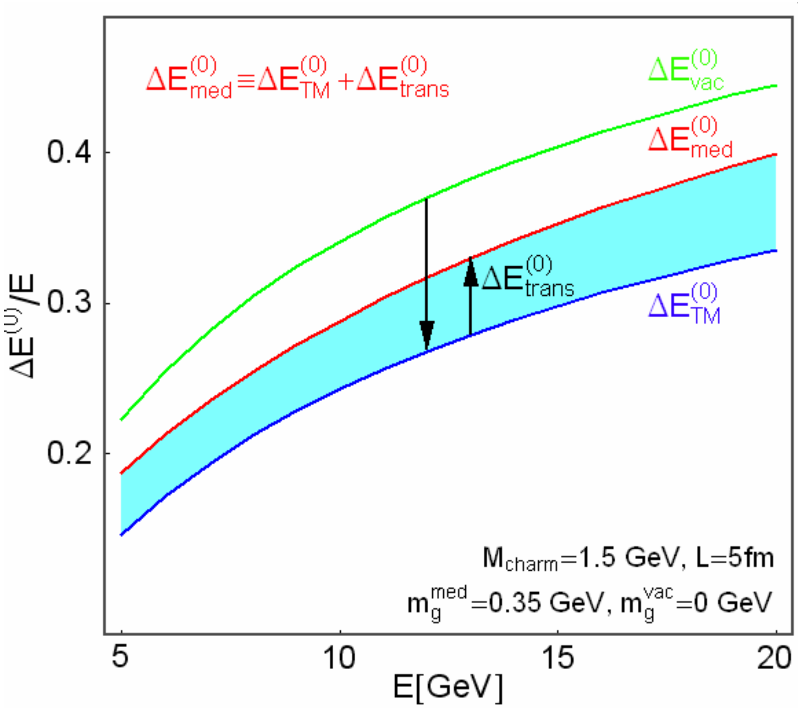
Applications to RHIC

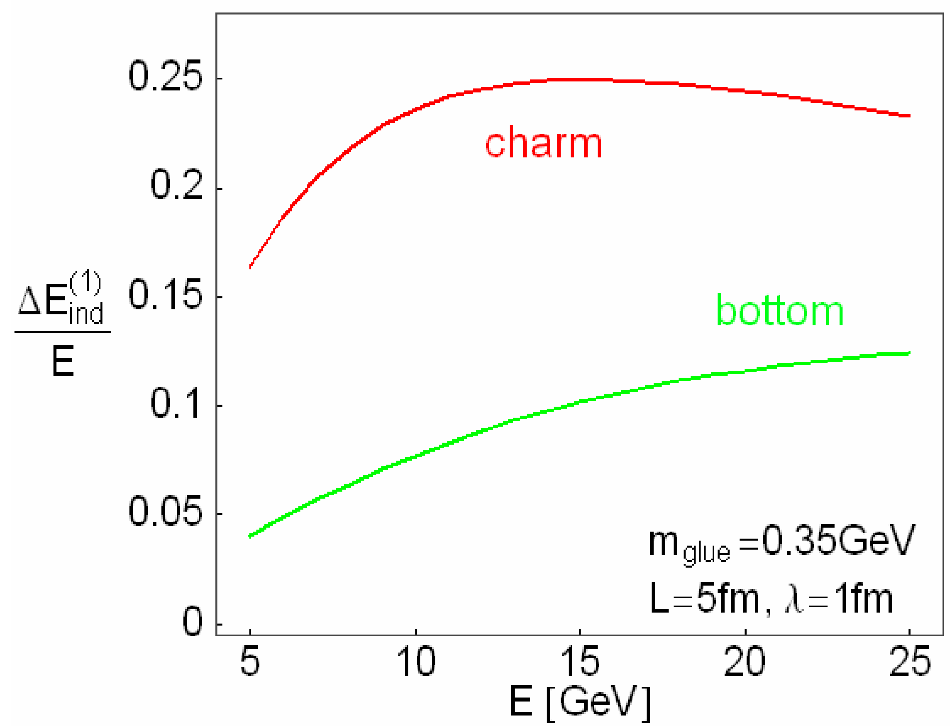
The difference between charm quark energy loss in the medium and in the vacuum can be used to estimate:

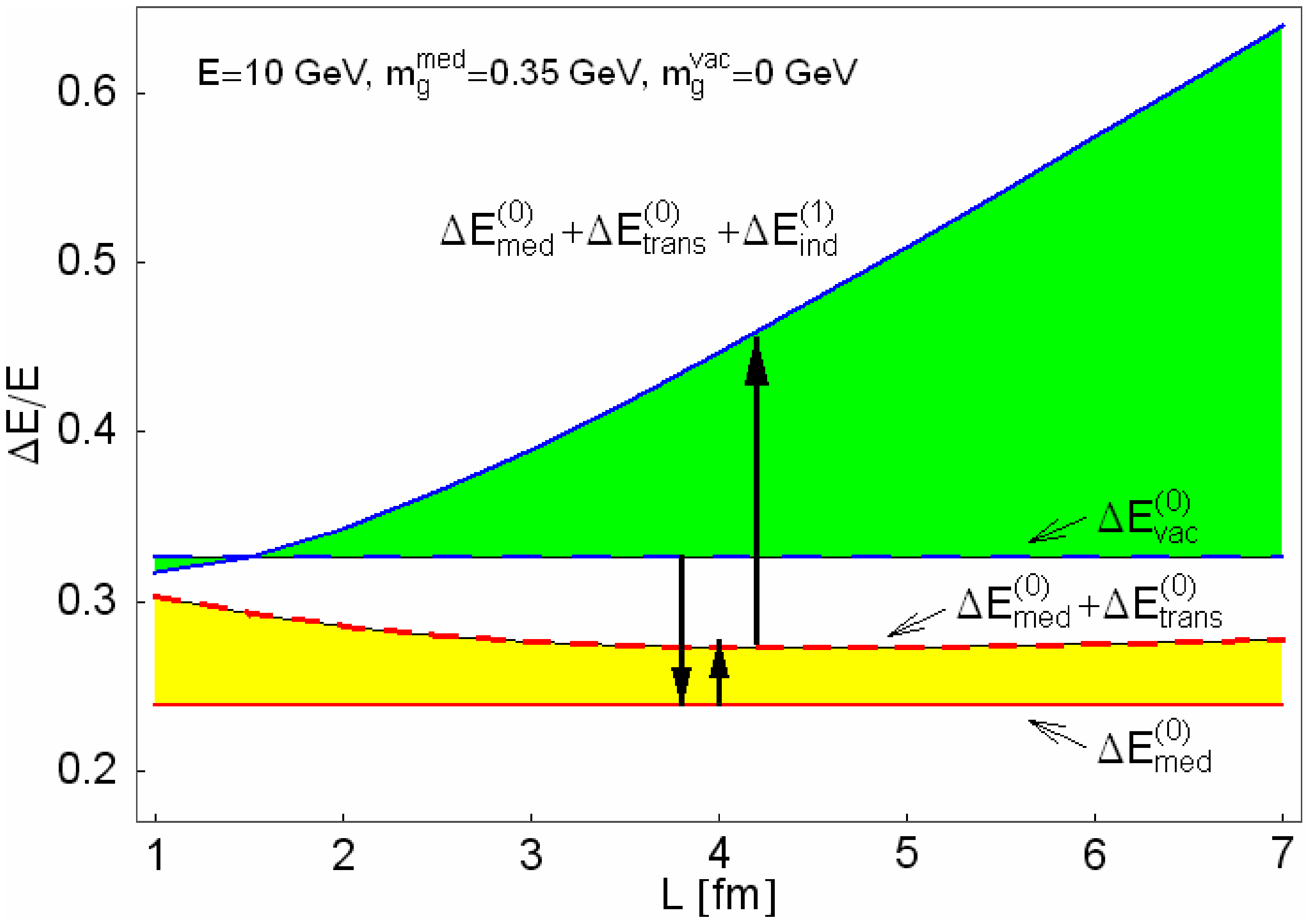
1) Charm quark suppression

2) High pt elliptic flow at RHIC

Reminder of main heavy quark energy loss results:



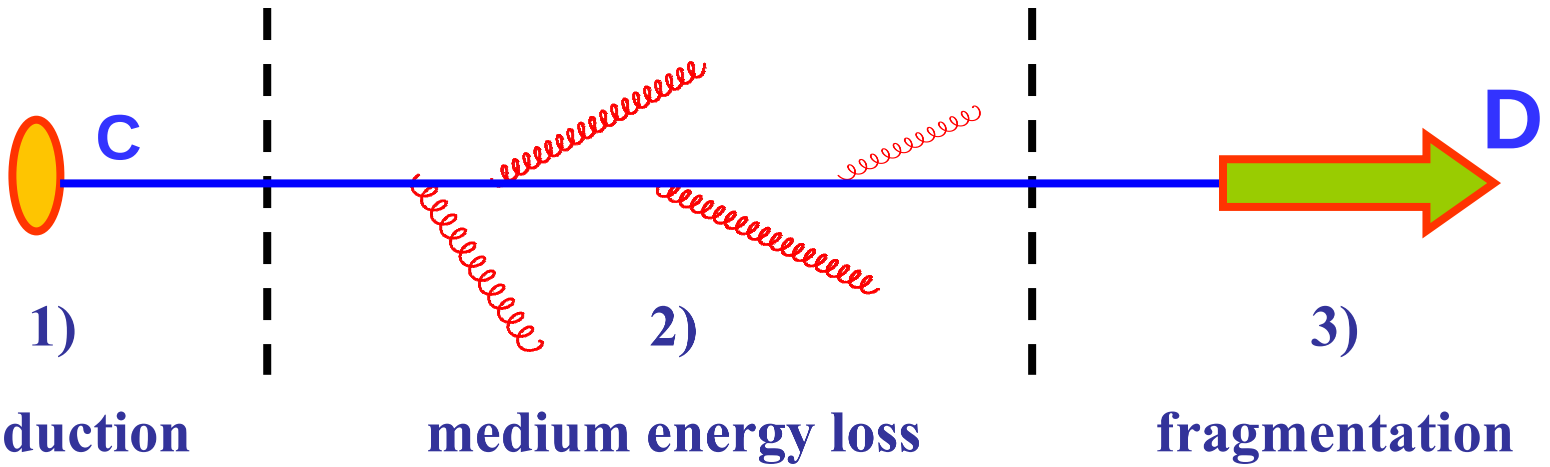




Confinement in physical vacuum modeled by

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

D meson suppression



To make theoretical predictions for D meson pt distributions we have to know:

1) Initial pt distribution of charm quarks

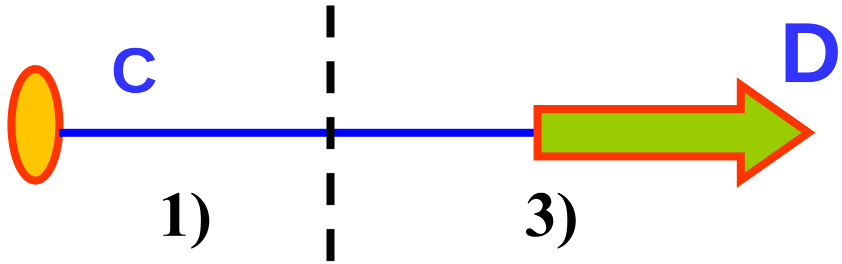
2) Charm quark energy loss

3) D meson fragmentation function.

NOTE: **Vacuum energy loss is already included in DGLAP fragmentation functions. Therefore:**

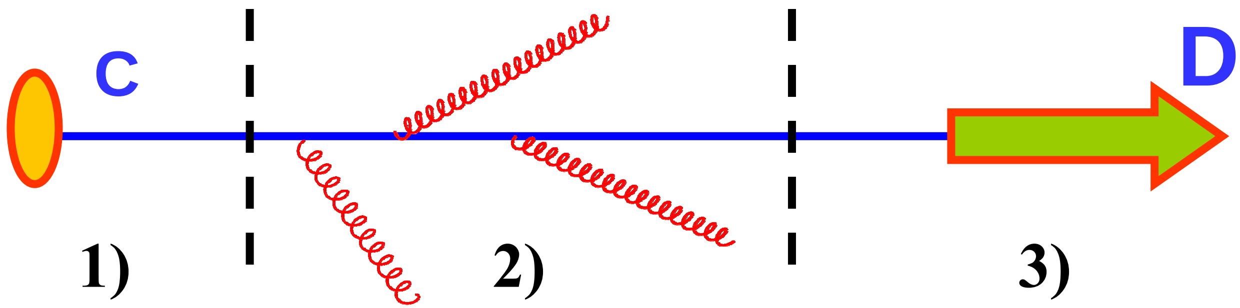
- **In d+Au collissions only steps 1) and 3) contribute:**

d+Au



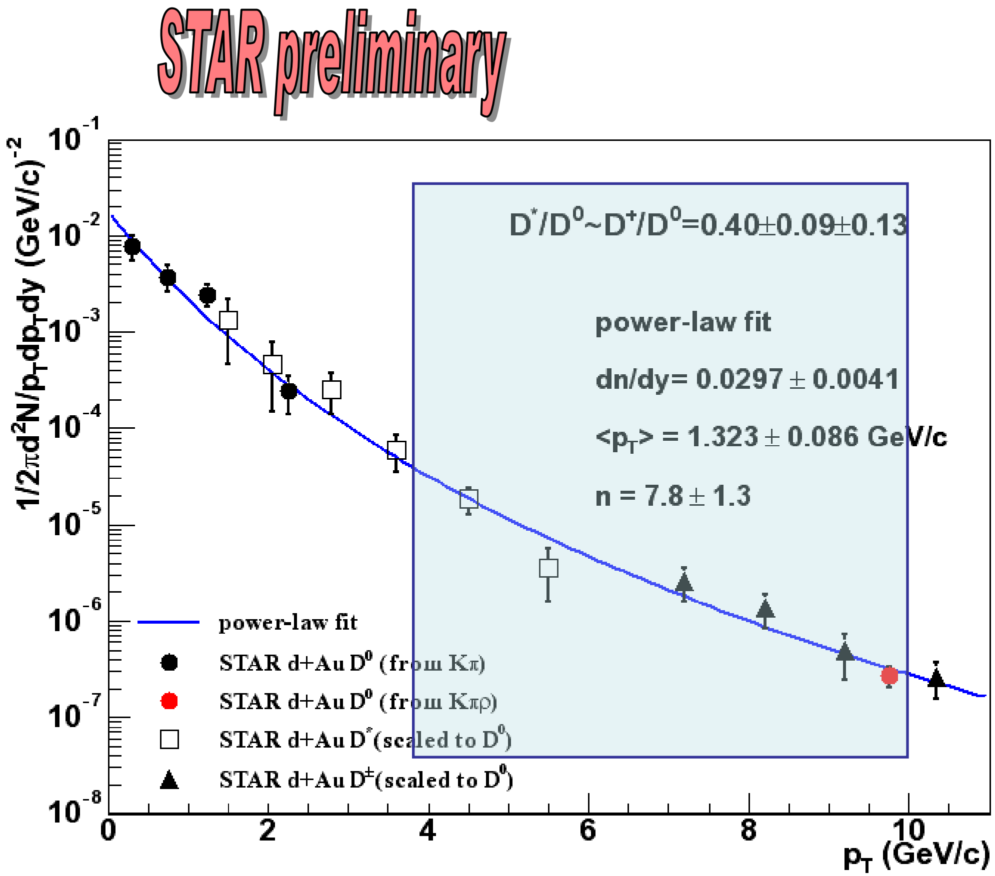
- **In Au+Au collissions all three steps contribute:**

Au+Au



We can obtain D meson suppression by comparing pt distributions of D mesons in d+Au and Au+Au collissions.

We can use D mesons from STAR (d+Au) to obtain 1) and 3)



An Tai - QM2004

According to STAR, (A. Tai *for STAR colaboration*, nucl-ex/0404029) **charm fragmentation function at RHIC should be similar to $\delta(z-1)$.**

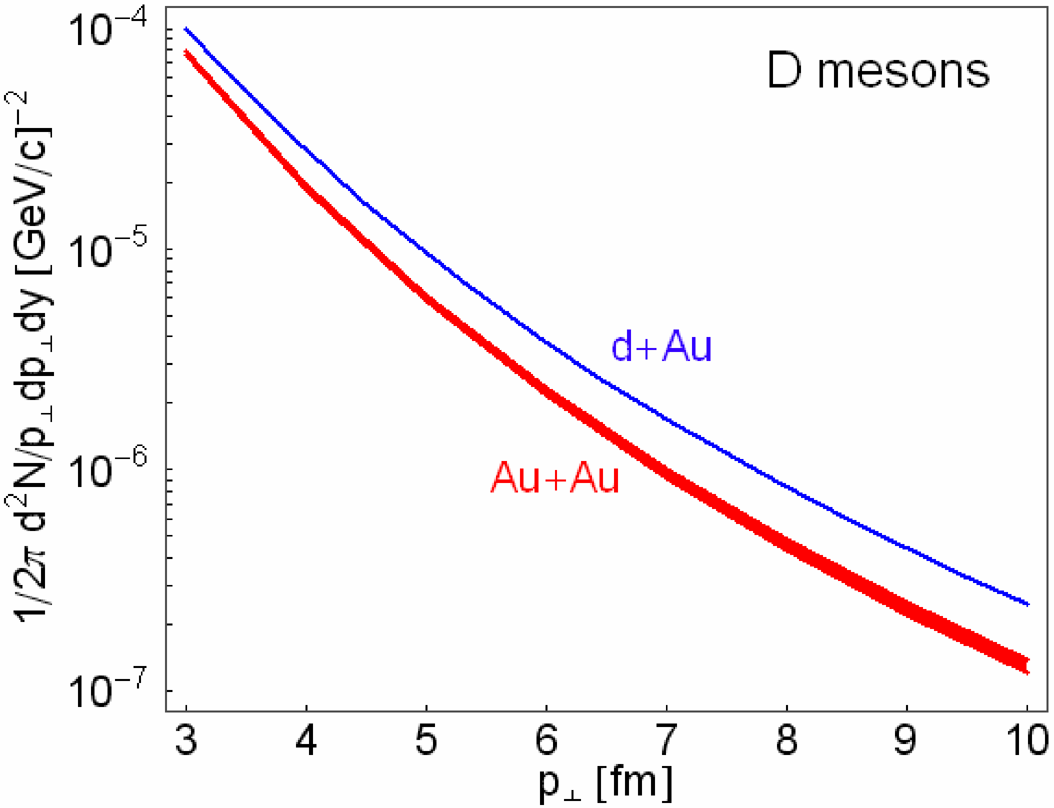
Open Charm and D meson pt distributions should be similar.

To make prediction for STAR D mesons in Au+Au we used GLV method described in PLB538:282-288,2002.

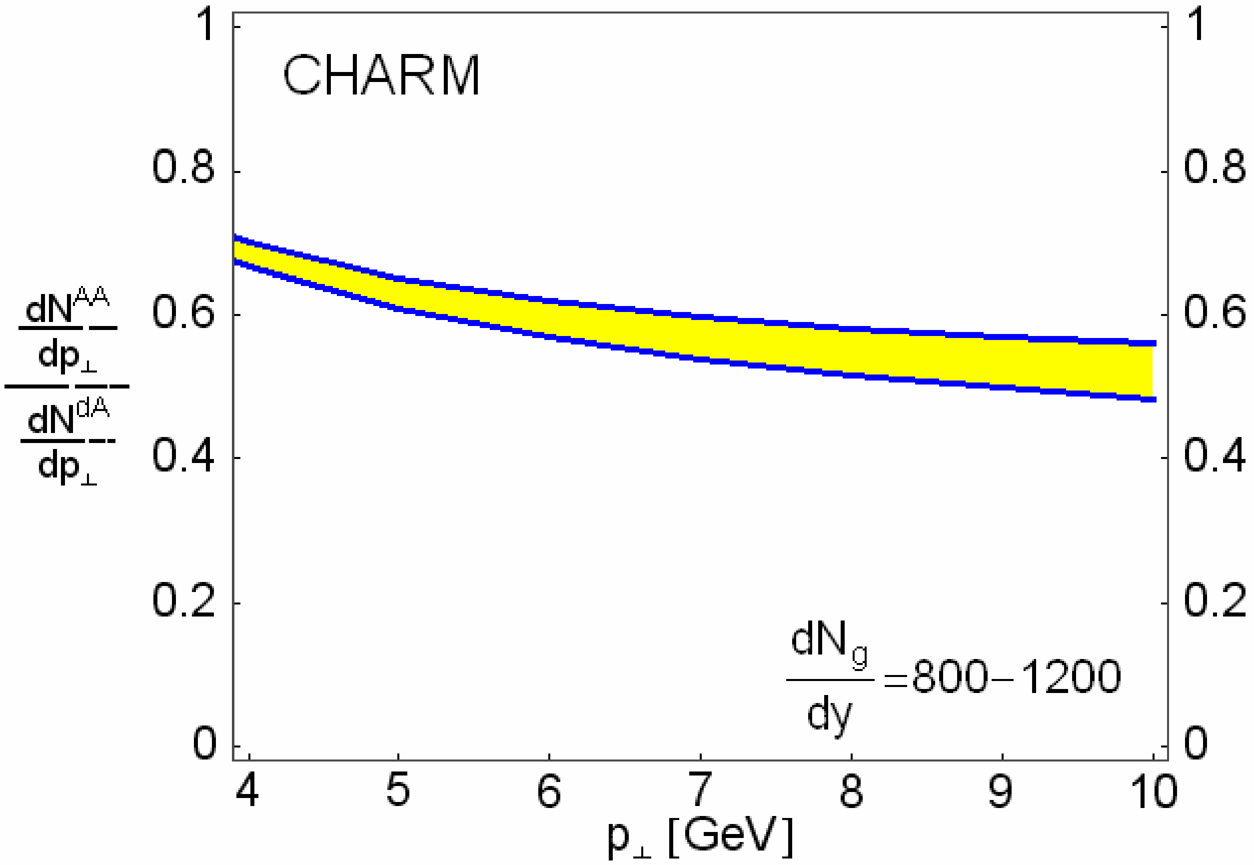
Assumptions:

1) Initial charm pt distribution is the same for D+Au and Au+Au.

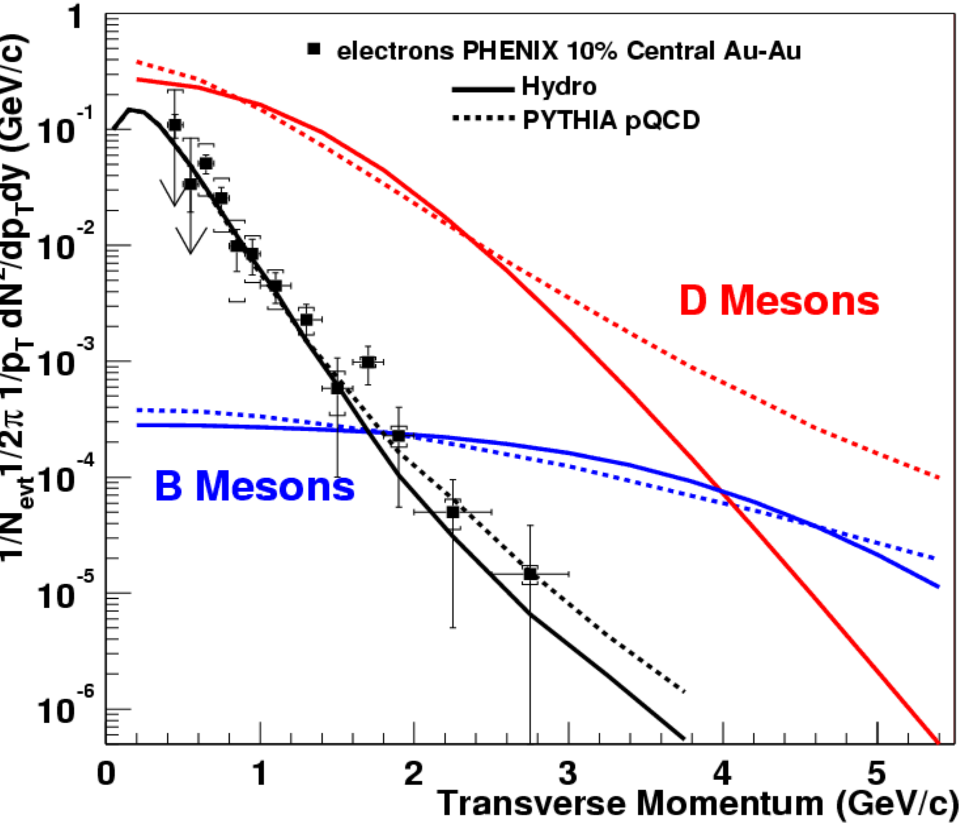
2) Consider 1+1D Bjorken longitudinal expansion, with gluon density dN_g/dy=800-1200.



D meson suppression is obtained by dividing Au+Au and d+Au D meson pt distributions.



We see that estimated D meson suppression is in the range 0.5-0.6



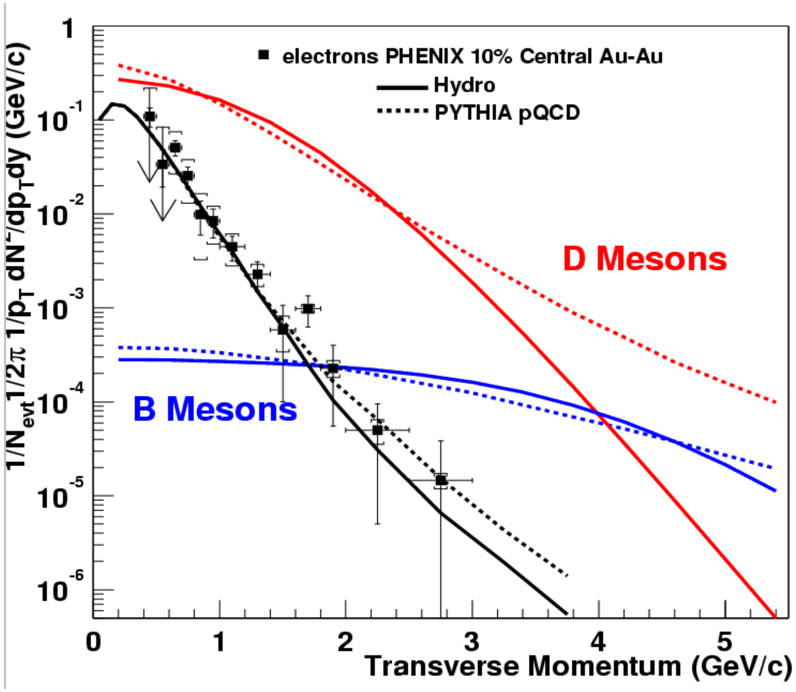
This suppression is consistent with PHENIX data.

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.**

Elliptic flow



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

- Hydro
- PYTHIA pQCD

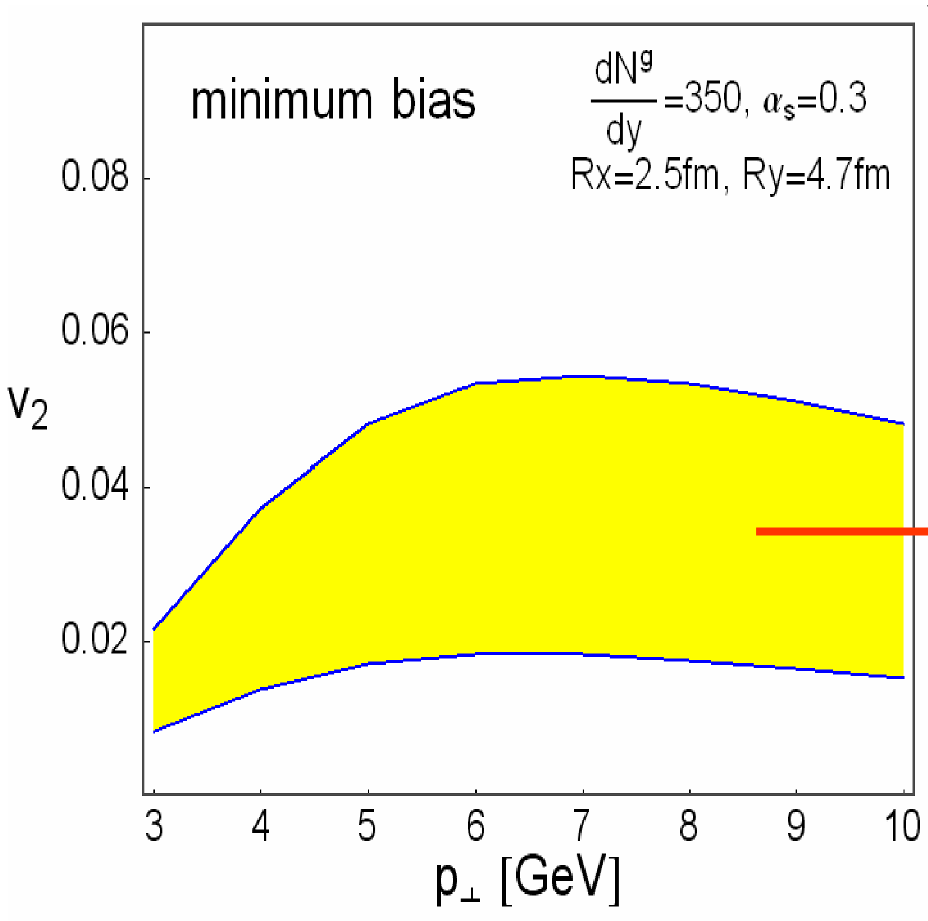
DOES THE CHARM FLOW AT RHIC?
S. Batsouli, S. Kelly, M. Gyulassy , J.L. Nagle
Phys.Lett.B 557 (2003) 26

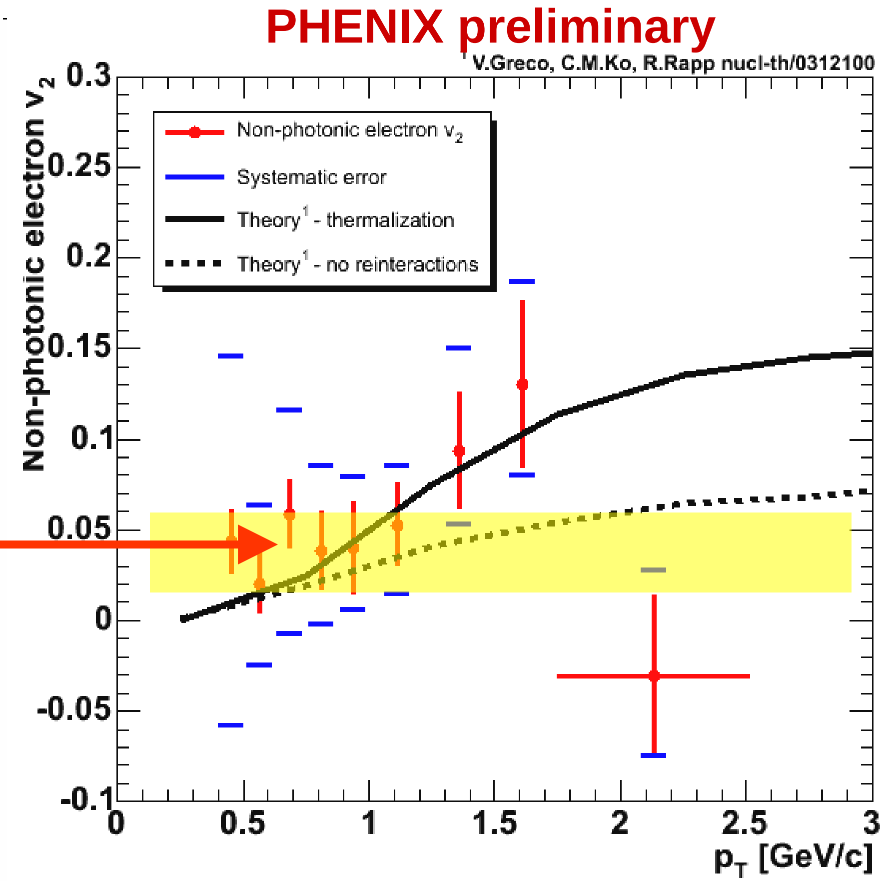
The answer to this question can give us the measurement of v2 for charm at RHIC.

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).

Conclusions

D meson data for 200 GeV *D-Au* and *Au-Au* results, as well as higher statistics charm v2 data will soon become available. We predict small charm quark suppression ~ 0.5-0.6 and elliptic flow (0.02-0.06). Therefore, these values should be definitely much smaller than those already observed for pion case.

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

According to Zakharov, for particle produced inside the medium:

$$\frac{d\left(\Delta E^{(0)}_{med}-\Delta E^{(0)}_{vac}\right)}{dx\, dk_\perp^2}=2\frac{C_R\,\alpha_S}{\pi}\frac{k_\perp^2}{\left(k_\perp^2+M^2x^2+(m_g^{med})^2\right)^2\left(k_\perp^2+M^2x^2+(m_g^{vac})^2\right)}\times$$

$$\times\{1-\cos(\frac{\left(k_\perp^2+M^2x^2+(m_g^{med})^2\right)L}{2Ex})\}\{(m_g^{vac})^2-(m_g^{med})^2\}$$

i.e.

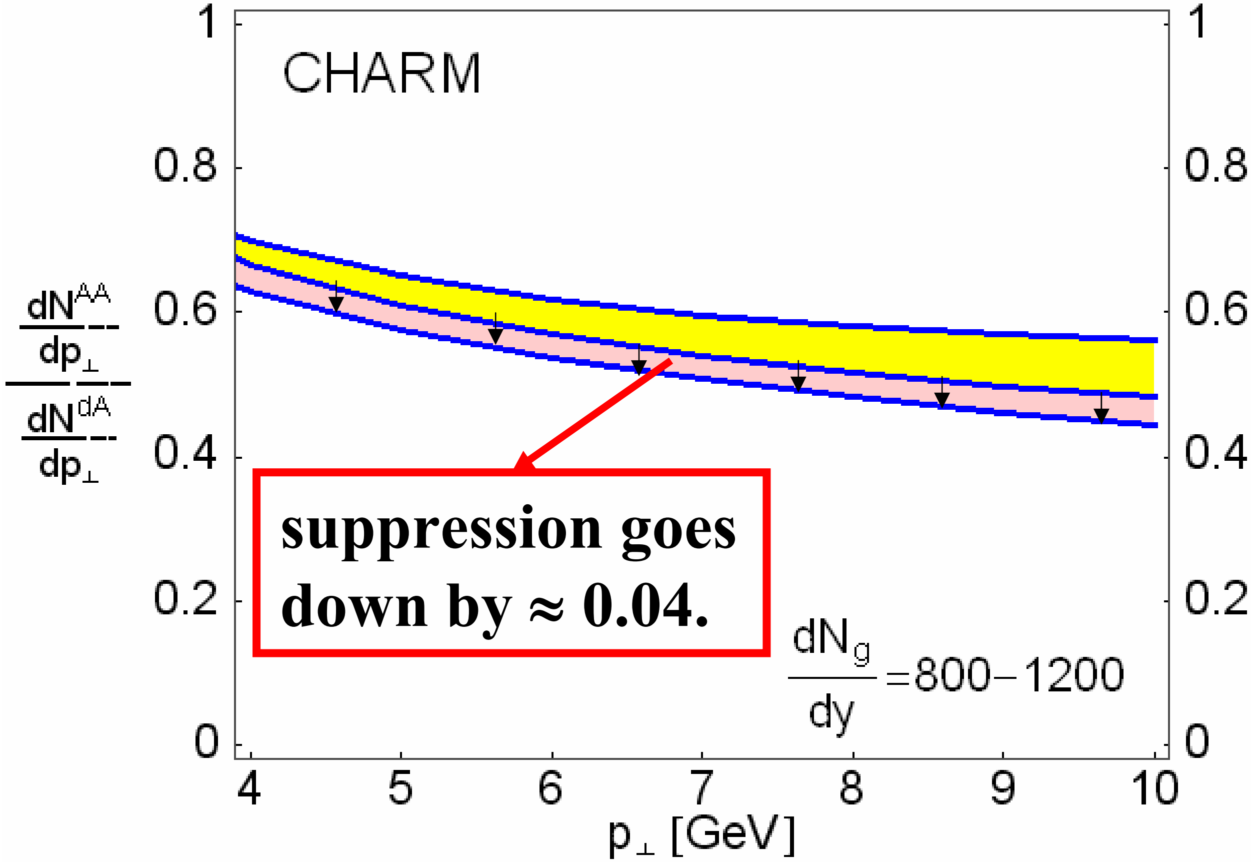
$$\Delta E^{(0)}_{med}-\Delta E^{(0)}_{vac}\sim((m_g^{vac})^2-(m_g^{med})^2)$$

Therefore,

$$m_g^{vac}<m_g^{med} \Rightarrow \Delta E^{(0)}_{med}<\Delta E^{(0)}_{vac}$$

What is the influence of TM effect and transition radiation to this result?

We will get the maximal suppression if we only include the medium induced energy loss.

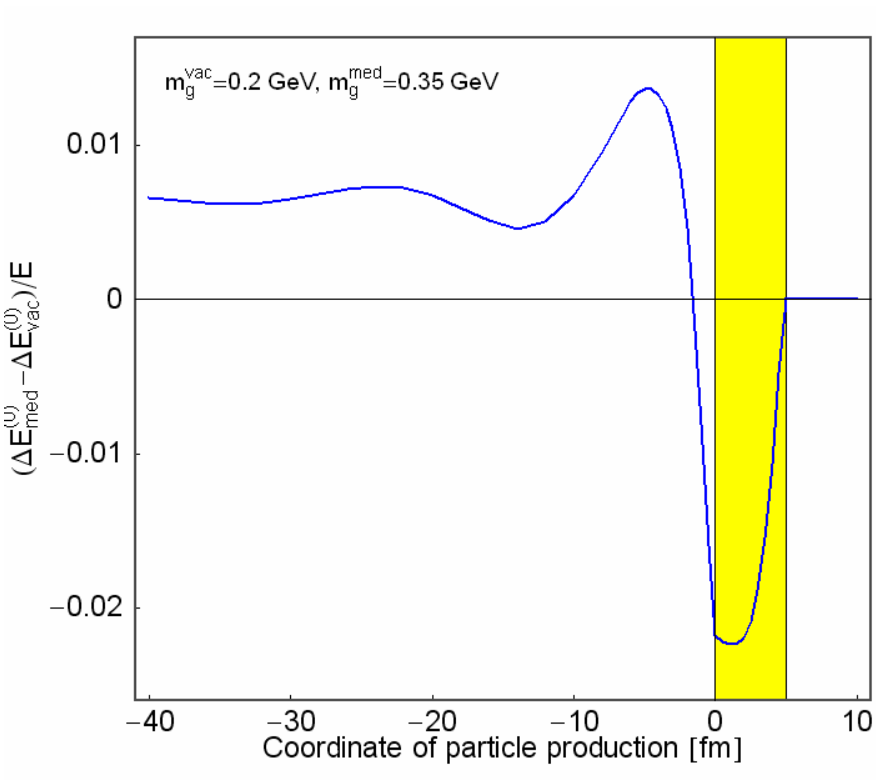


Two different vacuum gluon masses

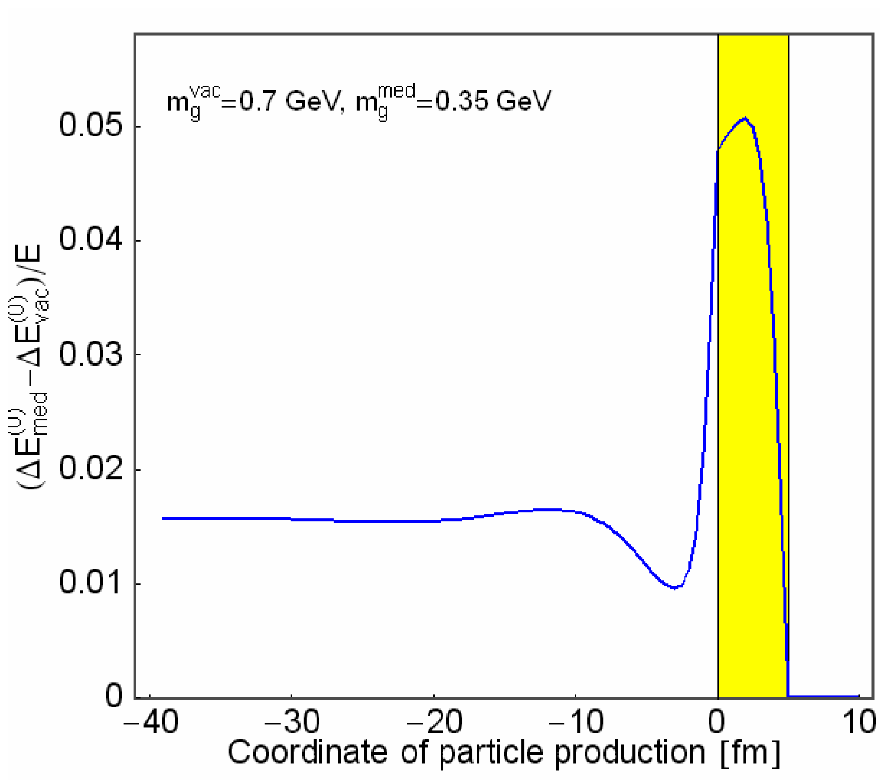
We also have to include the effect of confinement in the vacuum.

There are two approaches to do that:

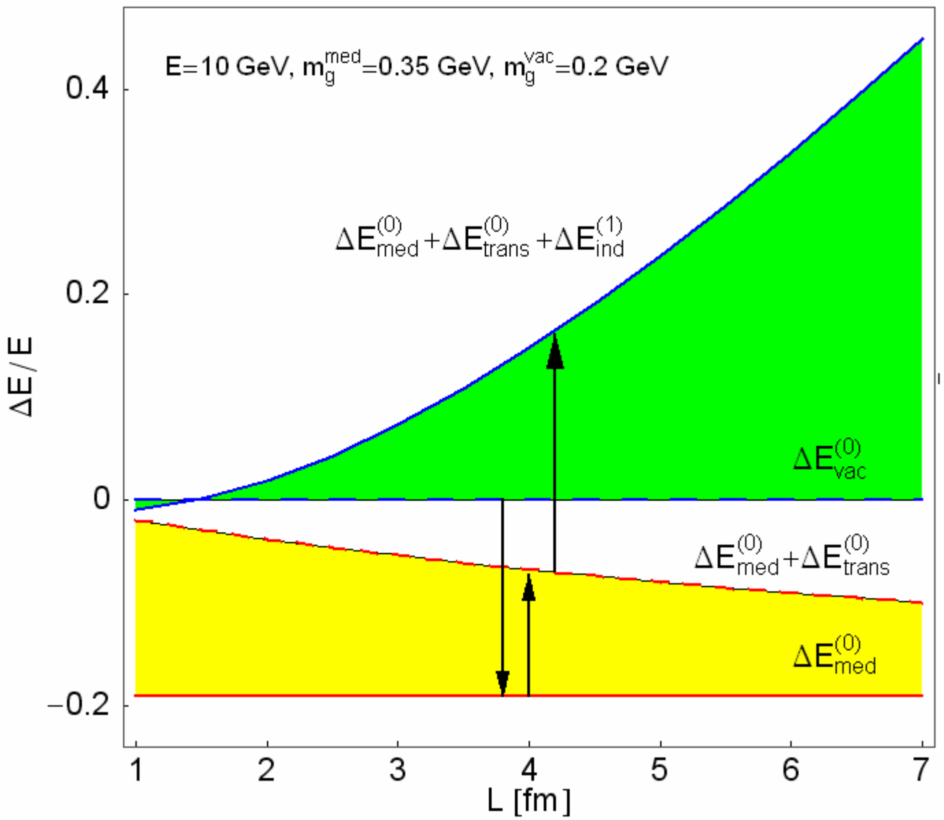
1) **Assume that gluon mass in the vacuum is not exactly zero, but it has some small value on the order of Λ_{QCD}.**



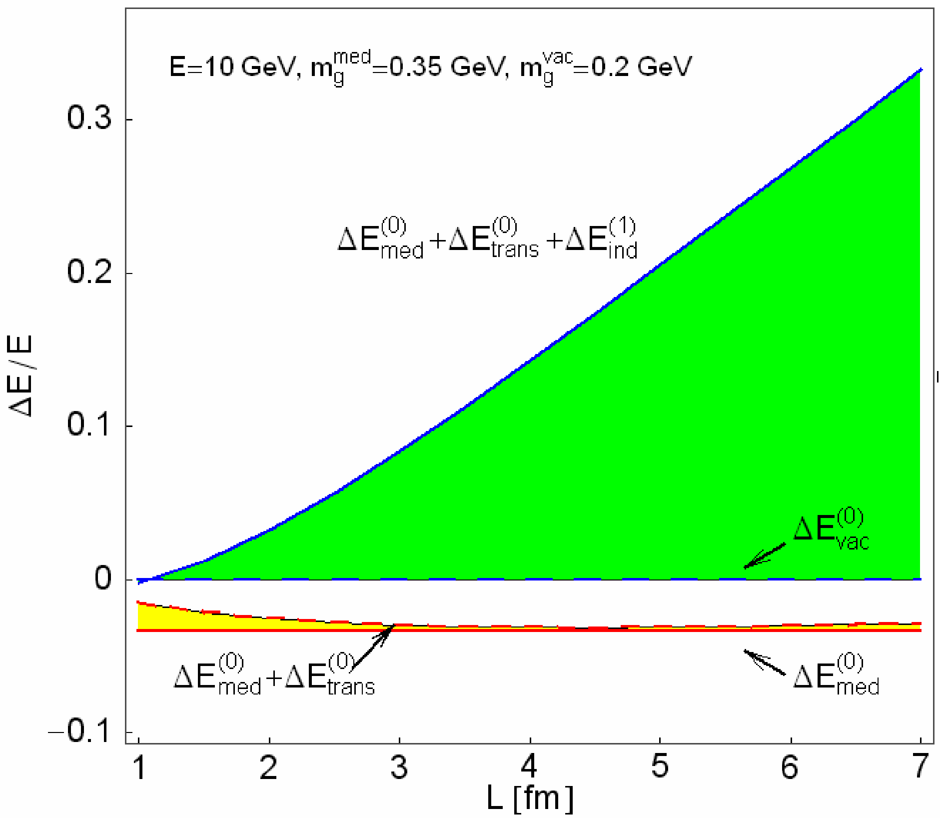
2) **Assume that vacuum gluon mass is large, i.e. approximately 0.7 GeV.**



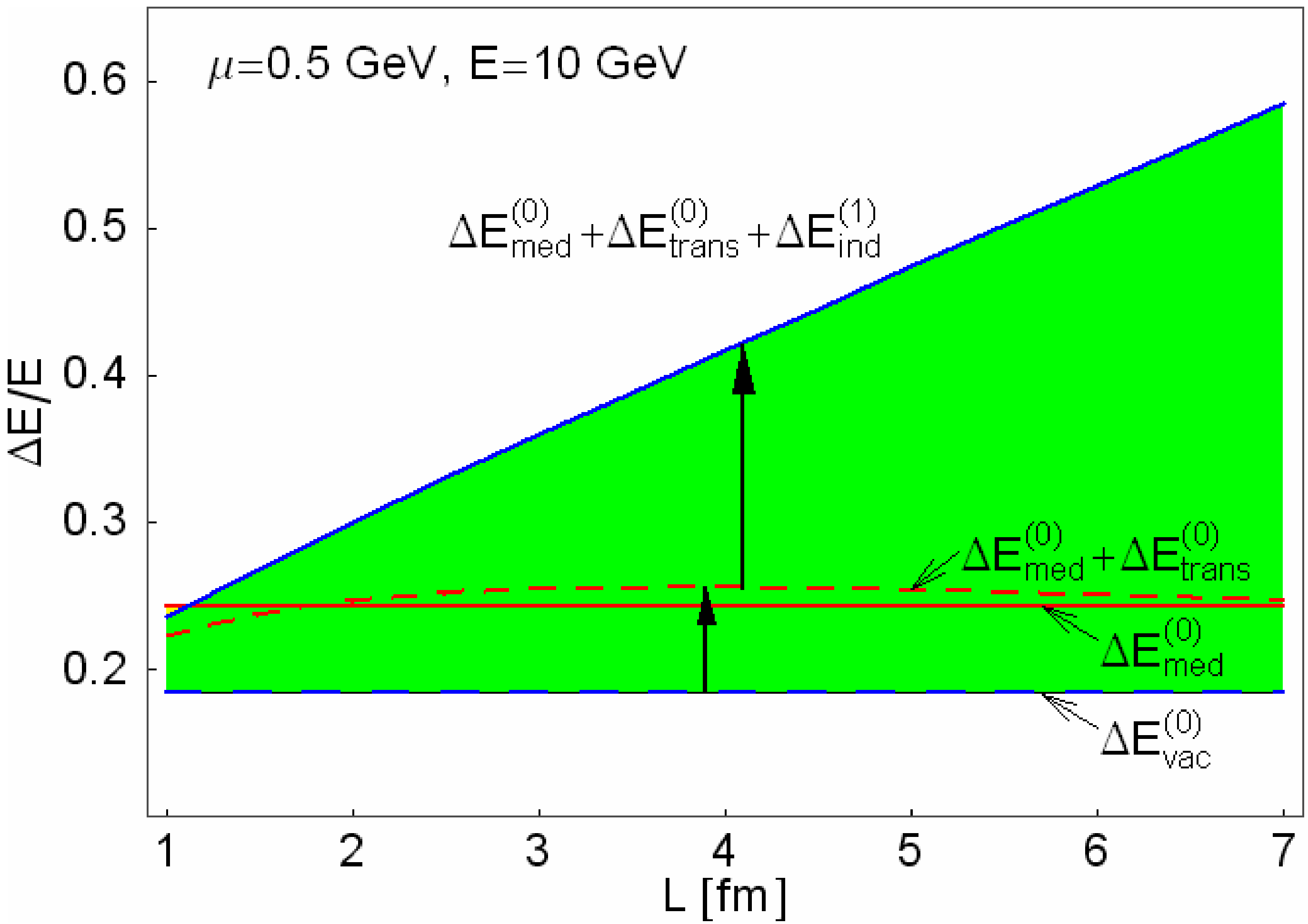
Light quark



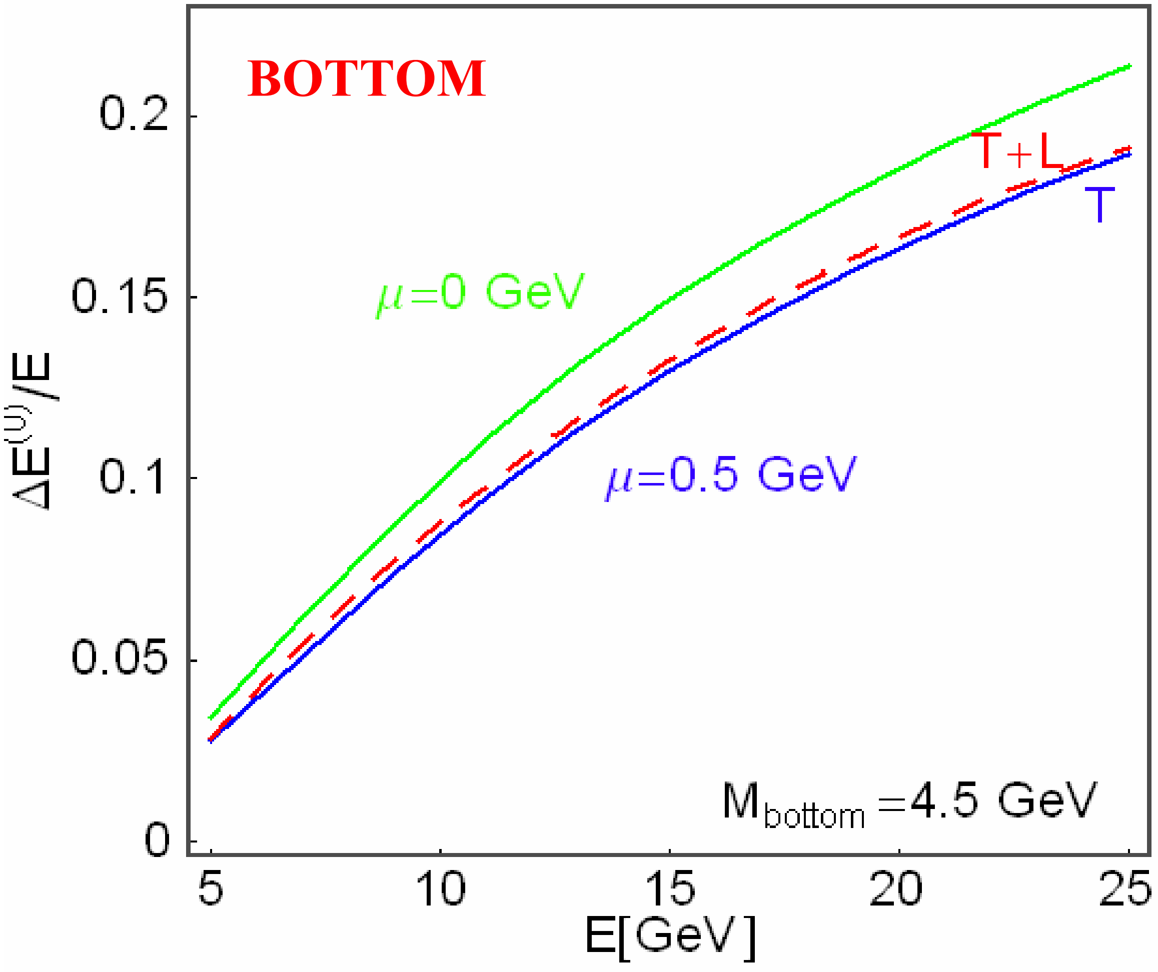
Charm quark



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



Ter-Mikayelian assumptions and bottom quark



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

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