Survival of high-p_T light and heavy flavors in a dense medium

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High p_T physics at LHC
Mexico, Sept. 26-Oct. 1, 2010

Challenging the energy loss scenario

Test #I: Nuclear attenuation of hadrons in SIDIS.
The the medium density and
kinematics are known much better.

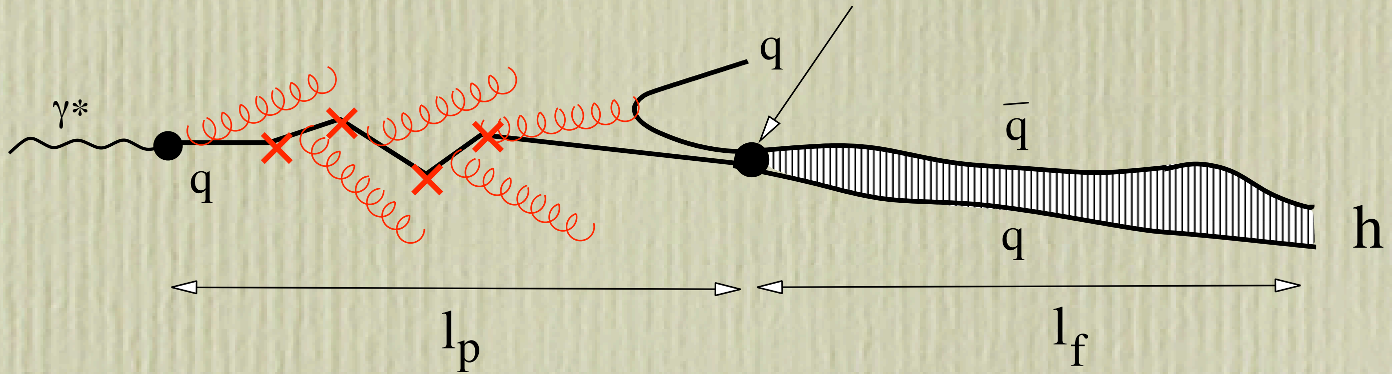
Test #II: Alternative probes for the dense
medium produced in heavy ion collisions:
J/Ψ suppression.

Test #III: Production of heavy flavors.
Why is beauty strongly suppressed?

No amount of experimentation can ever prove me right;
a single experiment can prove me wrong

Albert Einstein

Test #I: Attenuation of leading hadrons in SIDIS.



Hadronization, production of leading pre-hadron

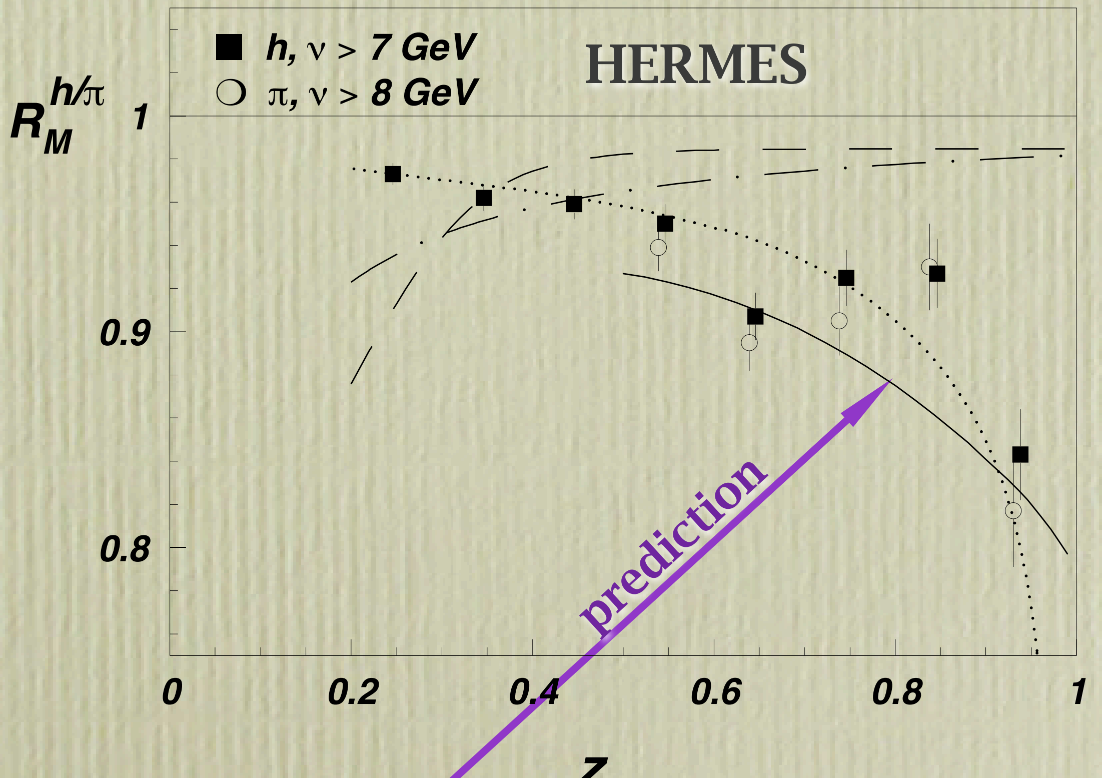
Pre-hadron -> hadron

The energy loss scenario is based on the **unjustified** assumption that the production length is always long, $l_p \gg R_A$.

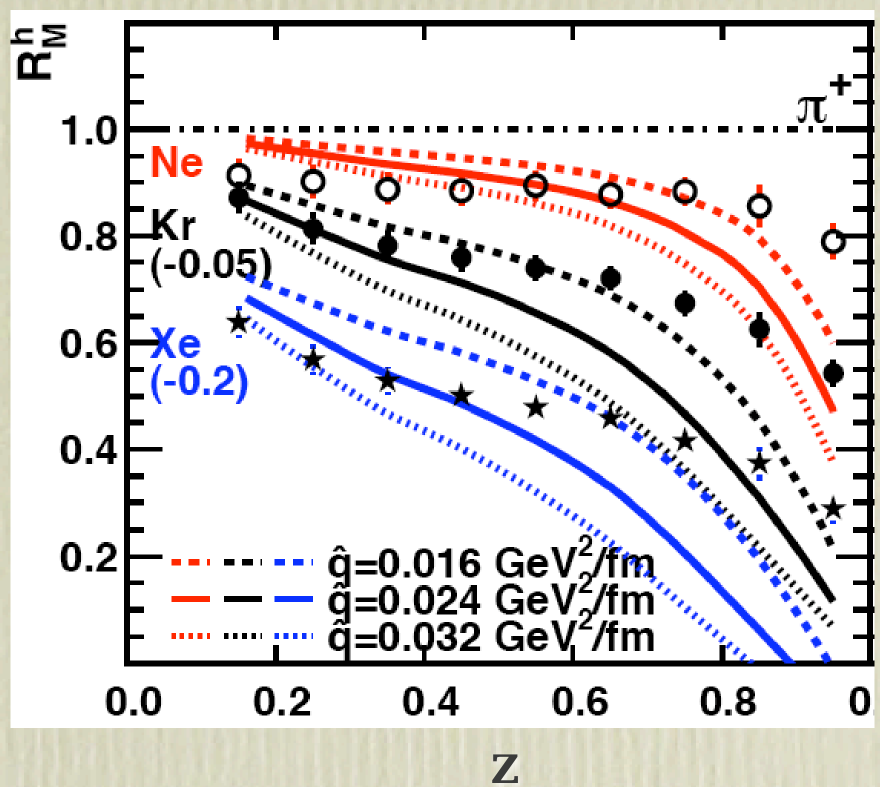
This model **fails** to reproduce SIDIS data for leading hadrons z>0.5.

Energy conservation constraints l_p

Absorption is important for z->1.



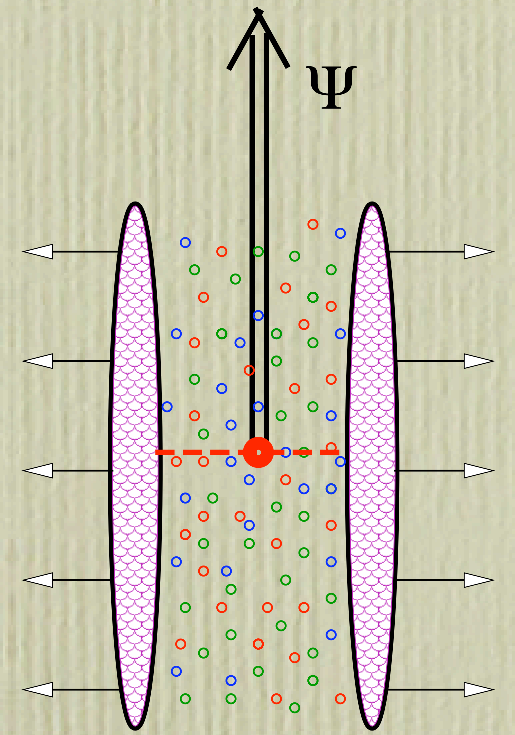
BK, J.Nemchik, E.Predazzi, 1995



W.-T.Deng & X.-N.Wang, 2009

Test #II: Alternative hard probes

J/Ψ suppression in heavy ion collision is a different probe for the medium created in HI collisions. This probe is independent and less ambiguous. Indeed, J/Ψ is produced and formed almost instantaneously at l<1fm. It propagates through the medium without gluon radiation, energy loss.

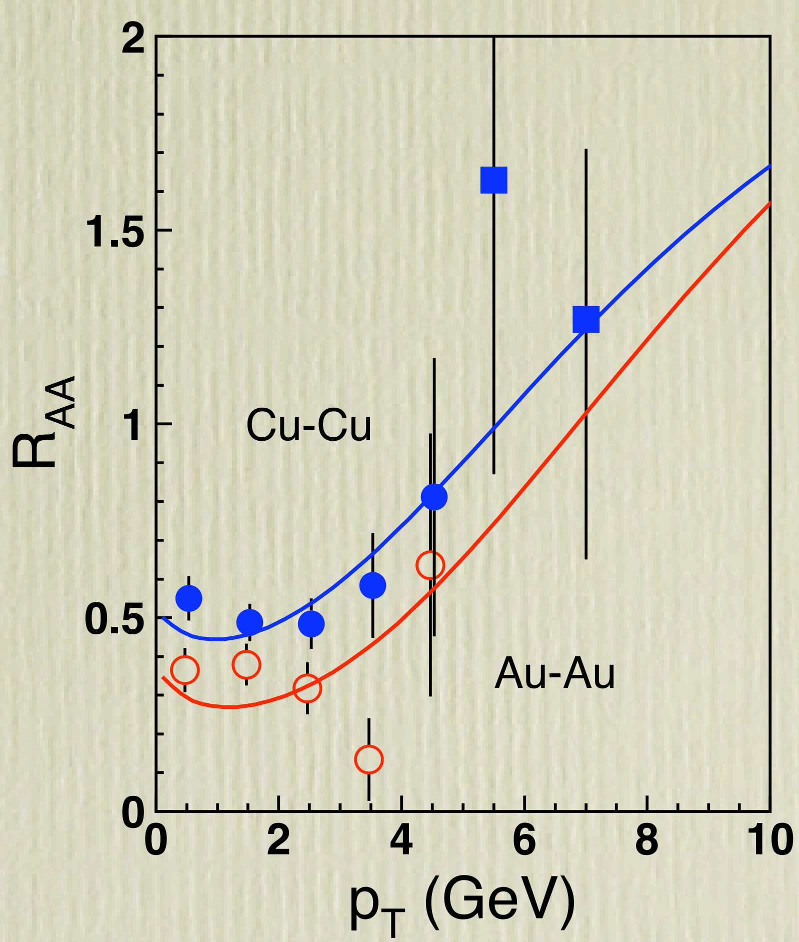


- J/Ψ attenuation is directly related to the transport coefficient

$$S(L) = \exp\left[-\frac{1}{3}\langle r^2_{J/\Psi}\rangle \int\limits_0^L dl\, \hat{q}(l)\right]$$

- J/Ψ is also suppressed by initial state interactions (ISI)

- Saturation ISI effects lead to a modification of the pt distribution (Cronin effect)



BK, I.Potashnikova & I.Schmidt, 2010

Analysis of RHIC data for J/Ψ production in central Au-Au and Cu-Cu collisions led to $\hat{q}_0 \lesssim 0.2\,\mathrm{GeV^2/fm}$ which is about an order of magnitude less compared with the value suggested by the energy loss scenario for jet quenching.

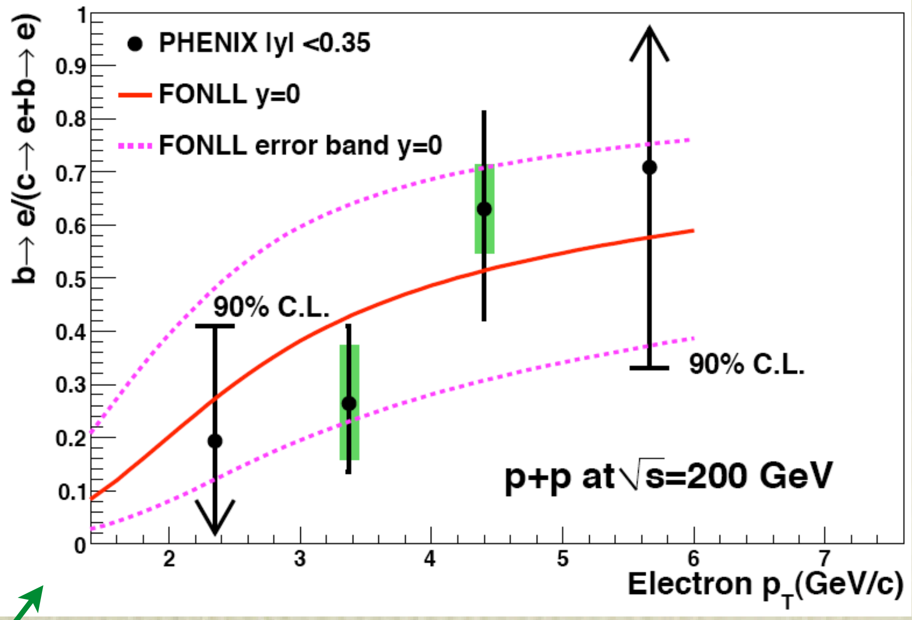
Test #III: Suppression of heavy flavors

Heavy quarks radiate much less than light ones:

$$\frac{dn_g}{dx\,dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi x}\,\frac{k_T^2[1+(1-x)^2]}{[k_T^2+x^2m_q^2]^2}$$

Radiation of gluons with $k_T^2 \lesssim x^2 m_q^2$, i.e.

with $\theta \lesssim m_q/E$ is suppressed: dead cone effect.



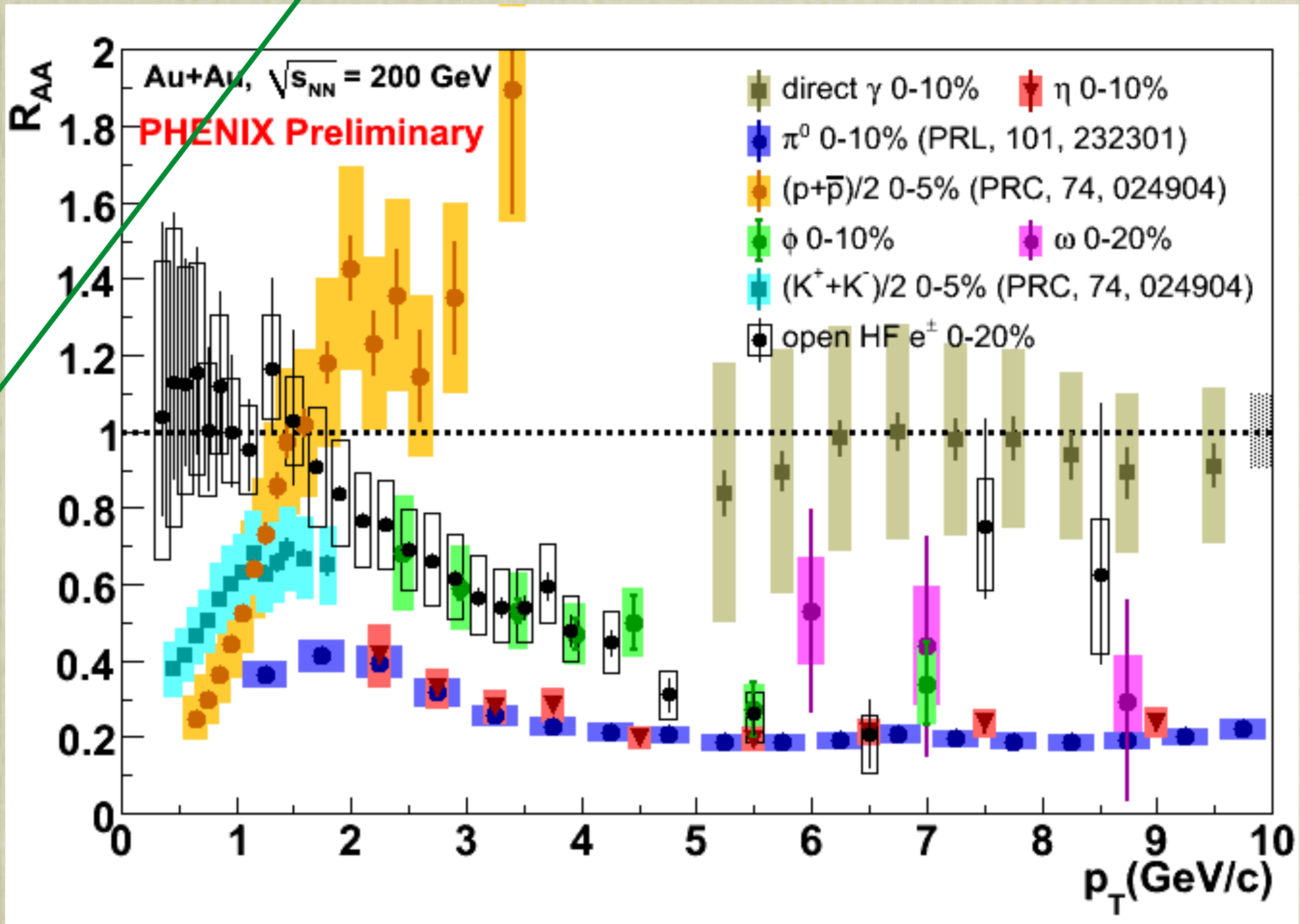
A much weaker suppression of heavy flavors in HI collisions was predicted:

Yu. Dokshitzer & D. Kharzeev, 2001

However, heavy flavors turn out to be suppressed as much as light quarks.

The bottom contribution is significant.

While the strong suppression of charm can be understood (see later), suppression of bottom remains a puzzle.



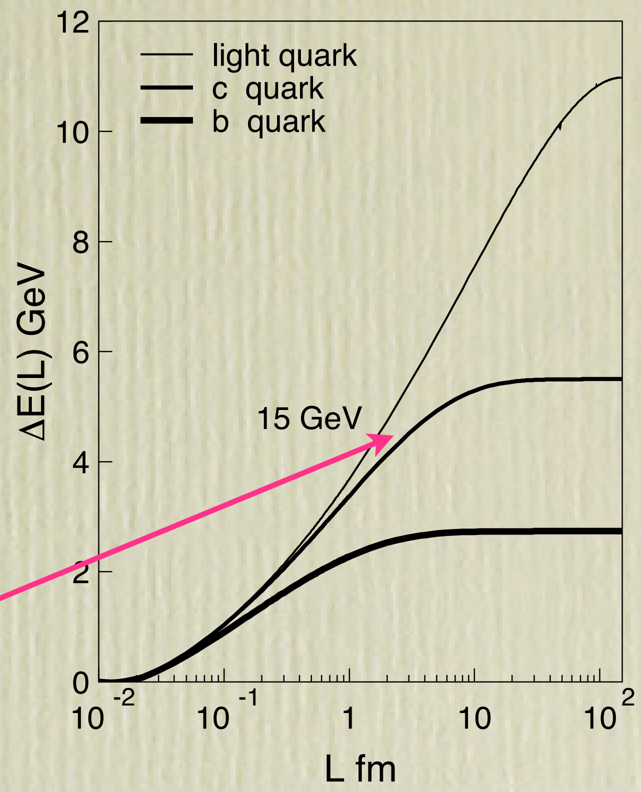
Time dependent vacuum energy loss

The color field of a parton originated from a hard reaction is not shaken off instantaneously. Radiation of a gluon takes coherence time

$$l_c^g = \frac{2Ex(1-x)}{k_T^2 + x^2 m_q^2}$$

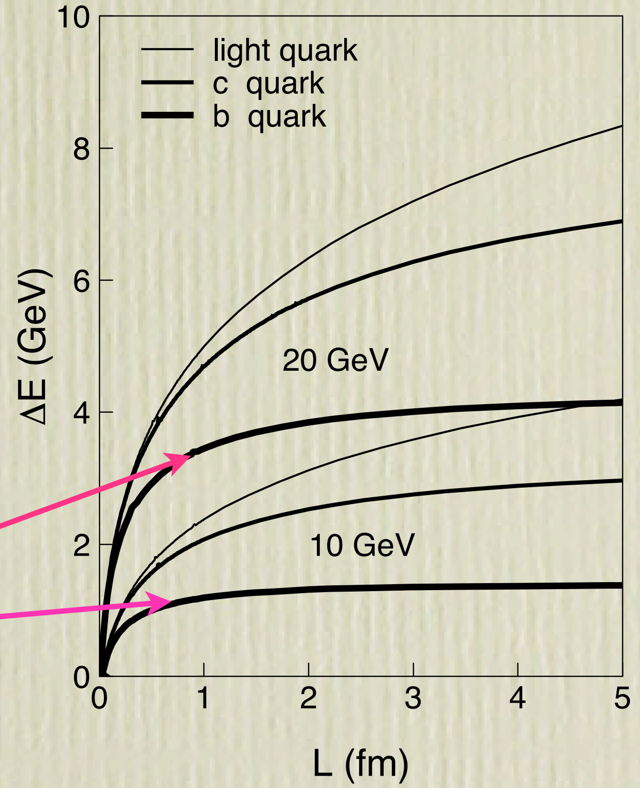
so the energy dissipated for gluons radiated over the pass length L is

$$\Delta E(L) = E \int_{\Lambda^2}^{Q^2} dk_T^2 \int_0^1 dx \, \frac{x\, dn_g}{dx\, dk_T^2}\, \Theta(L - l_c)$$



Important observations:

- Vacuum radiation following a hard process develops a dead cone, which may be stronger than one caused by the heavy quark mass.
- For this reason, charm and light quarks radiate and lose energy similarly during first few fm, which only matter in heavy ion collisions.
- While light and charm quarks take long time (100 or 10 fm) to regenerate their color fields, a bottom quark does it promptly, within a fermi after the hard interaction. Then it stops radiating.



Fast hadronization of a bottom quark

A quark which has regenerated its color field does not radiate gluons, but keeps hadronizing nonperturbatively. The rate of nonpertubtive energy loss is given by string tension $-\mathrm{dE}/\mathrm{dl} = \kappa \approx 1\,\mathrm{GeV}/\mathrm{fm}$

To respect energy conservation a **b-q** hadron with fractional momentum z must be produced not later than on the production length $\mathrm{l_p} \sim \dfrac{\mathrm{E}}{\kappa}(1-\mathrm{z})$

For the $\mathrm{p_T}$ distribution of b-quarks $\mathrm{dn_b}/\mathrm{dp_T^2} \propto \mathrm{p_T^n}$, the mean production length

$$\langle \mathrm{l_p} \rangle = \mathrm{n}\,\frac{\mathrm{E}}{\kappa}\int\limits_0^1 \mathrm{dz}\,(1-\mathrm{z})\,\mathrm{z^{n-1}} = \frac{\mathrm{E}}{(\mathrm{n}+1)\kappa}$$

is quite short $\sim 2\,\mathrm{fm}$

Since the **b-q** dipole is produced by soft interactions, its initial size is rather large $\sim 0.5\,\mathrm{fm}$, so it is promptly absorbed in a dense medium. “Absorption” means that the b-quark starts losing energy and becomes unable to produce a hadron with

This consideration explains why bottom quarks are strongly suppressed in heavy ion collisions.

Probing a deconfined matter by bottom quarks

What happens to a quark after it regenerates its color field?
What does prevent it from propagating freely in vacuum?

The quark forms a string (color flux tube) and start losing energy with a rate equal to the string tension.

In a deconfined matter the quark propagates with no attenuation and easily survives even if it was created in a hard collision deep inside the dense medium.

This offers a solution for the longstanding problem: how can a hard probe discriminate between confined and deconfined media?

If the medium is deconfined, bottom quarks should be produced in AA collisions with no suppression.

Thus, the observed strong suppression of bottom means that no deconfined medium is produced at the RHIC energy.

Nuclear suppression of light hadrons

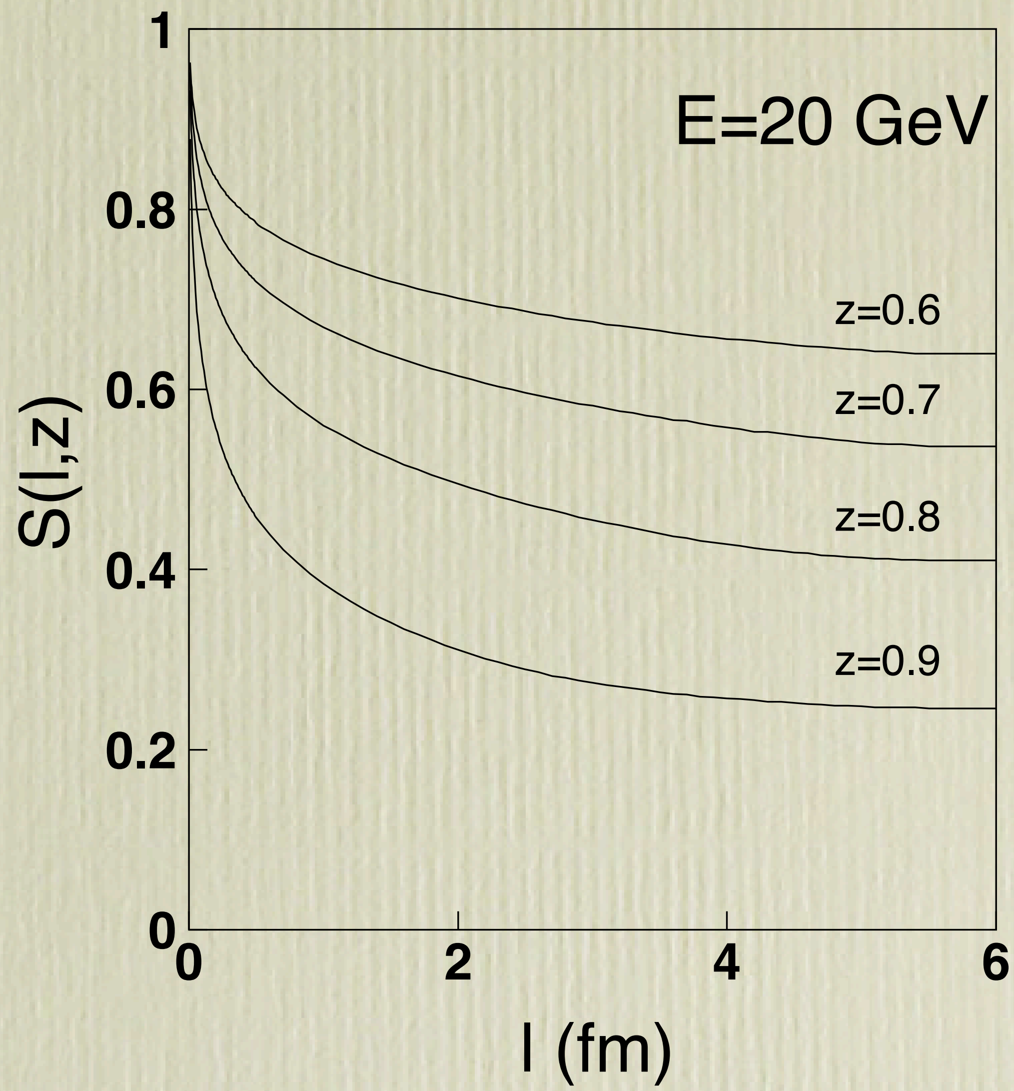
A jet initiated by a light quark is lasting tens and hundreds fermies. However, energy conservation imposes a restriction on the leading hadron production length, like in the string model. It is general and applicable to gluon radiation as well,

$$l_p \sim \frac{E}{|dE/dl|}(1 - z_h)$$

Energy conservation also imposes a ban on a part of gluon radiation, $\omega < E(1 - z_h)$, reducing the rate of energy loss.

Non-radiation of energetic gluons leads to a Sudakov suppression

$$S(L, z_h) = e^{-\langle n_g(L, z_h) \rangle}$$

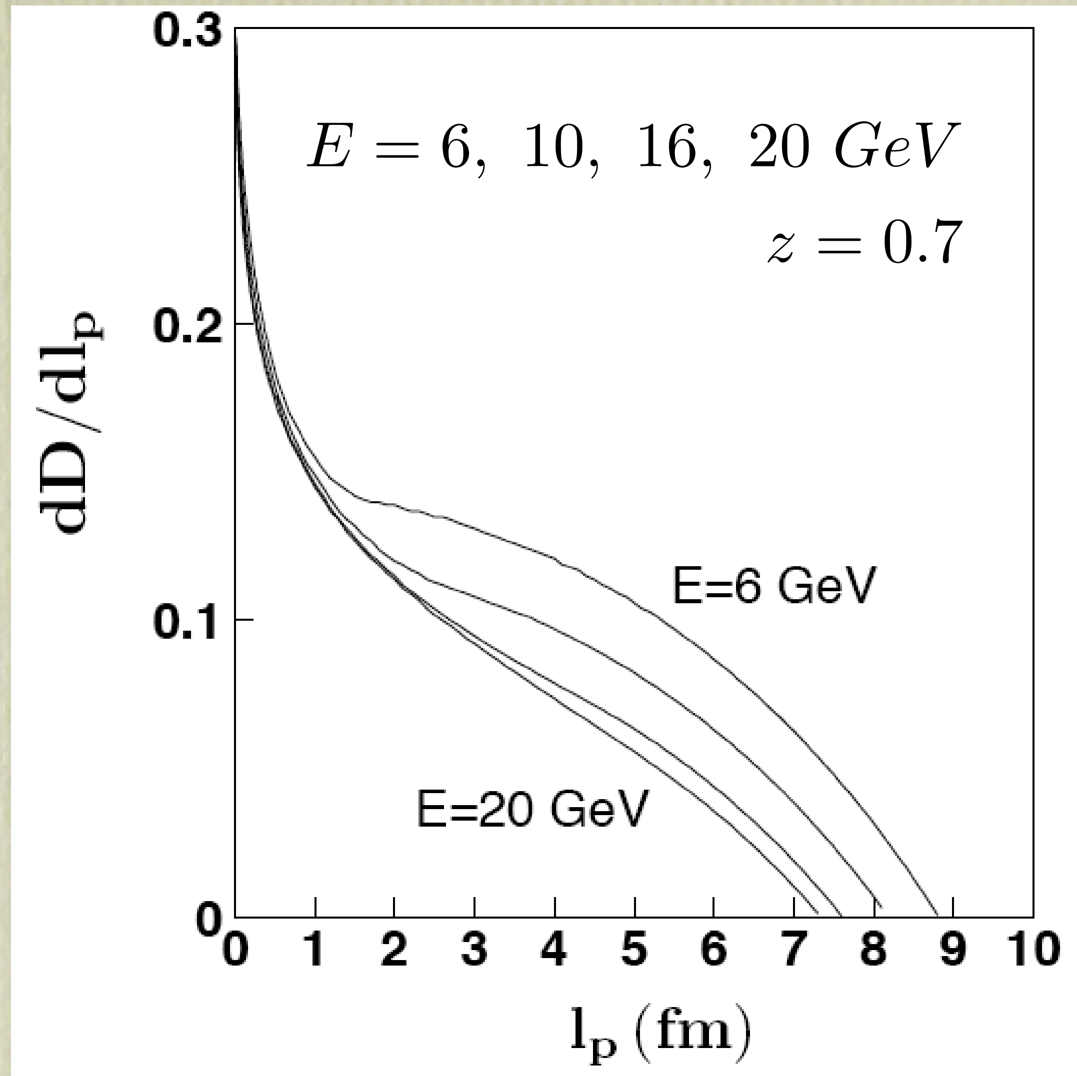


$$\langle n_g(L, z_h) \rangle = \int\limits_{1/Q}^{l_{max}} dl \int\limits_{(2El)^{-1}}^{1} d\alpha \, \frac{dn_g}{dl\, d\alpha} \, \Theta\left(\alpha + \frac{1-\alpha}{2lE} - 1 + z_h\right)$$

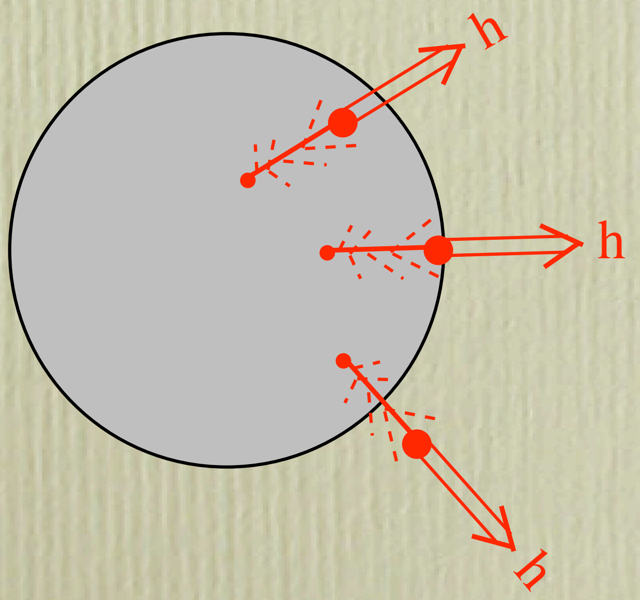
Nuclear suppression of light hadrons

The combination of the constraints imposed by energy conservation and Sudakov suppression leads to a rather short mean production length, which slightly varies with energy.

BK, H.J.Pirner, I.Potashnikova, I. Schmidt, 2008



Thus, like in DIS, leading hadrons are frequently produced inside the medium



Absorption in a dense medium may be strong, if the produced $\bar{q}q$ dipole has a large transverse separation

$$\sigma_{abs} = \mathbf{C}\, \mathbf{r}_T^2\, \rho$$

Nuclear suppression of light hadrons

The stripped color field of a parton is restoring starting from small transverse separations $\mathbf{r_0 \sim 1/p_T}$ and increasing with time as $\mathbf{r_T^2(t) = \frac{8\,t}{E} + r_0^2}$

For central AA collisions

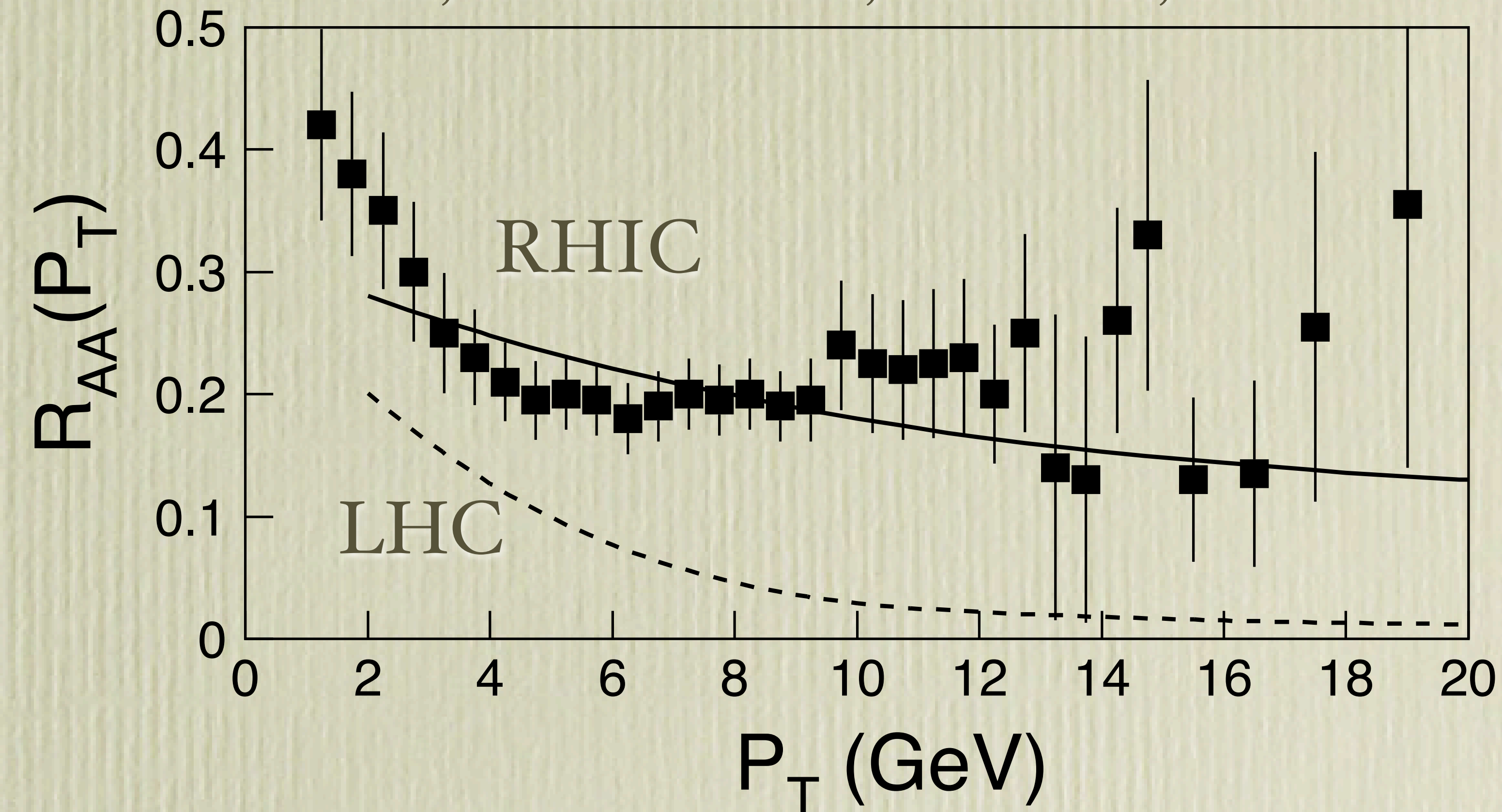
$$\mathbf{R_{AA} = \frac{\langle l_p^2 \rangle}{R_A^2}\left[1 - \alpha\,\frac{L}{\langle l_p \rangle} + \beta\,\frac{L^2}{\langle l_p^2 \rangle}\right]}$$

$$\mathbf{L^3 = \frac{3p_T}{8\,\rho_A^2\,R_A\,X}}$$

In the limit of short mean free path $\mathbf{L \ll \langle l_p \rangle}$

$$\mathbf{R_{AA} = \frac{\langle l_p^2 \rangle}{R_A^2}}$$

BK, I.Potashnikova, I.Schmidt, 2008



Calculations become parameter free in the high density limit.

Summary

☆ The energy loss scenario based on the unjustified assumption of long hadronizations fails to pass several rigorous tests:

- Cannot explain data on leading hadron production in SIDIS
- Overestimates the medium density compared with less ambiguous probes, like J/Ψ production
- Cannot explain the observed strong suppression of beauty

☆ Bottom quarks regenerate their color field on a very short time scale and become an excellent probe for a deconfined medium.
The observed strong suppression of b-quarks demonstrates that a deconfined medium is nit created in HI collisions at RHIC.

☆ A short production time and fast expansion of the produced dipoles makes the medium opaque, so the nuclear ratio R_{AA} can be predicted with no fitting in a good accord with data.