Novel mechanism for suppression of heavy flavored mesons in heavy ion collisions

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In collaboration with
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Outline

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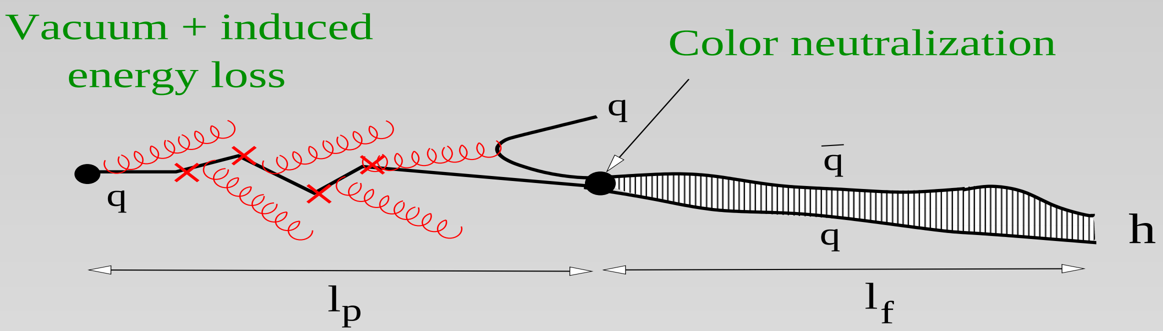
- Summary & Outlook

Space-time development of hadronization



- I. stage ⇒ the quark regenerates its color field, which has been stripped off in a hard reaction.

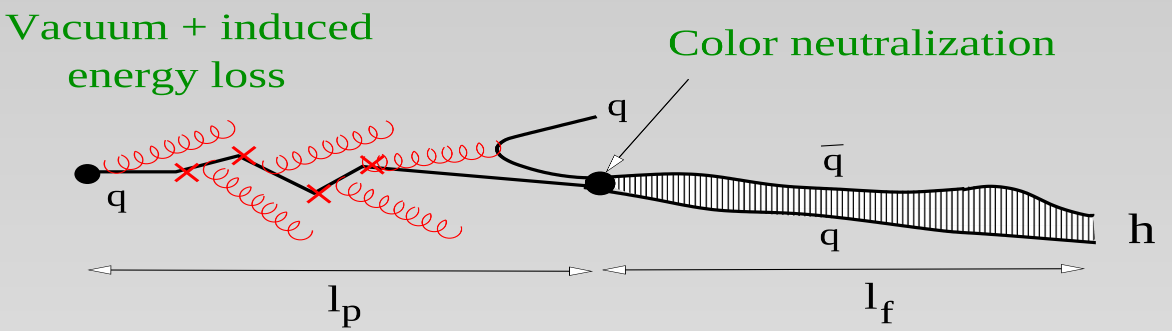
  ⇒ the quark intensively radiates gluons and dissipates energy, either in vacuum or in a medium.

  ⇒ multiple interactions in the medium induce additional, usually less intensive, radiation.

  ⇒ the loss of energy ceases at the moment, which is called the production time t_p, when the q picks up an $\bar{q}$ neutralizing its color.

$$t_p \lesssim \frac{E}{\langle |dE/dt| \rangle} (1 - z)$$

Space-time development of hadronization



- II. stage ⇒ begins with production of colorless dipole (also called pre-hadron), which does not have either the wave function or hadronic mass.

  ⇒ it takes the formation time t_f to develop both.

  ⇒ can be described within a simplified model or the path integral method.

$$t_f \lesssim \frac{2zE}{m_{h*}^2 - m_h^2}$$

⇒ Lorents boosting factor & the uncertainty principle - it takes a proper time $t_f^* = 1/(m_{h*} - m_h)$ to resolve between these two levels.

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- Medium-induced energy loss $\Rightarrow$ corresponds to the additional energy loss caused by the multiple interactions of the jet in the medium.
- Vacuum rate of energy loss usually significanly exceeds the medium-induced one, especially at large virtualities Q^2.

Radiative energy loss in vacuum

- The time-dependent radiational energy loss reads:

$$\Delta E_{rad}(t) = E \int\limits_{\lambda^2}^{Q^2} dk^2 \int\limits_0^1 dx\, x\, \frac{dn_g}{dx\, dk^2}\, \Theta(t - t_c^g),$$

[B.Z. Kopeliovich, J.N., E. Predazzi; arXiv:nucl-th/9607036]

[B.Z. Kopeliovich, J.N., E. Predazzi and A. Hayashigaki; Nucl.Phys. A**740**, 211 (2004)]

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- where the step function $\Theta(t - t_c^g)$ excludes those gluons which are still in coherence with the radiation source.
- The coherence time for radiation of a gluon with fractional LC momentum x and T-momentum k reads

$$t_c^g = \frac{2Ex(1-x)}{k^2 + x^2\, m_q^2}.$$

Radiative energy loss in vacuum

CFRJS

- The spectrum of radiated gluons has the form

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

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- This expression shows that gluon radiation is subject to a dead cone effect $\Rightarrow$ gluons with $k^2 < x^2 m_q^2$ are suppressed $\Rightarrow$ heavy quarks radiate less energy than the light ones.
- Substantial difference between radiation of energy by c and light quarks onsets at rather long distances $L \gtrsim 5 \div 10$ fm $\Leftarrow$ [B.Z. Kopeliovich, I. K. Potashnikova, I. Schmidt; Phys.Rev. C**82**, 037901 (2010)]

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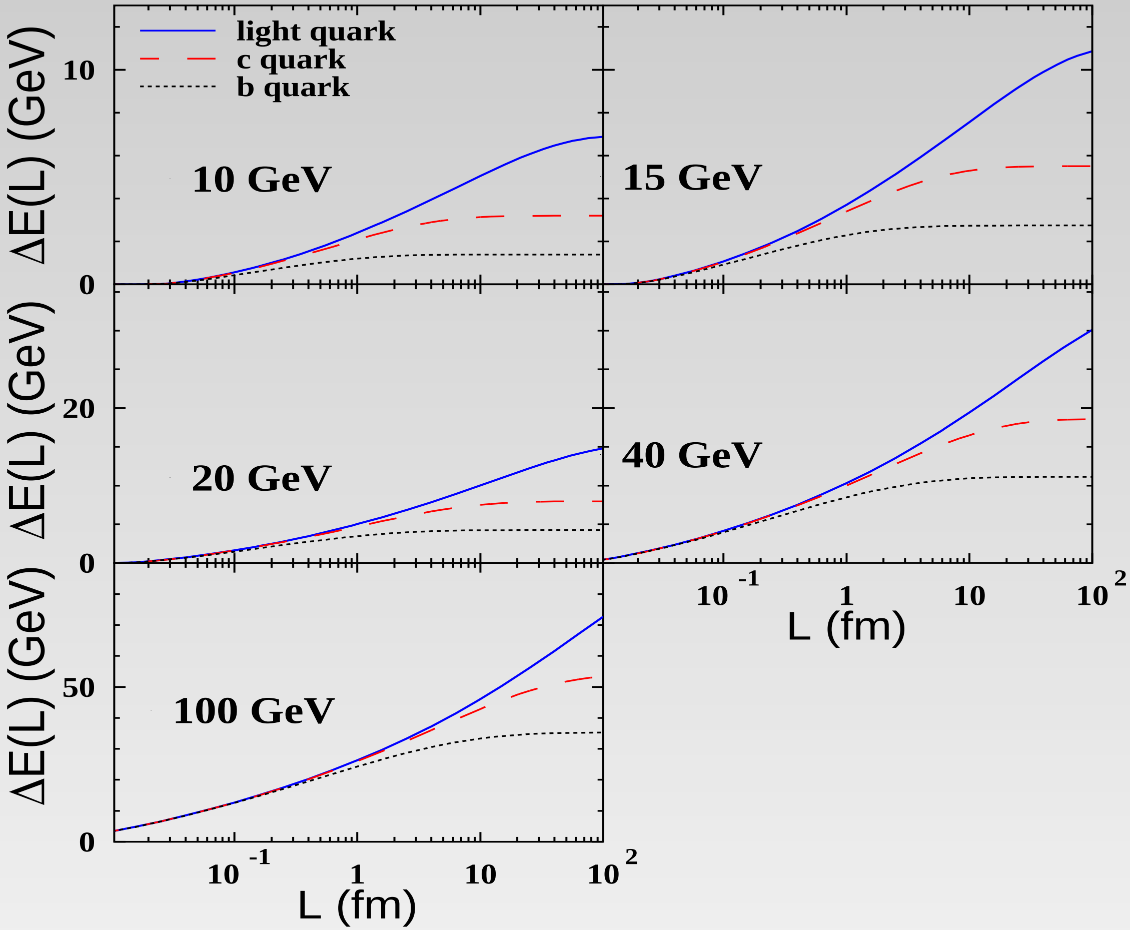

- The b-quark radiation is suppressed already at rather short distances $L \sim 0.5 \div 1.0$ fm.

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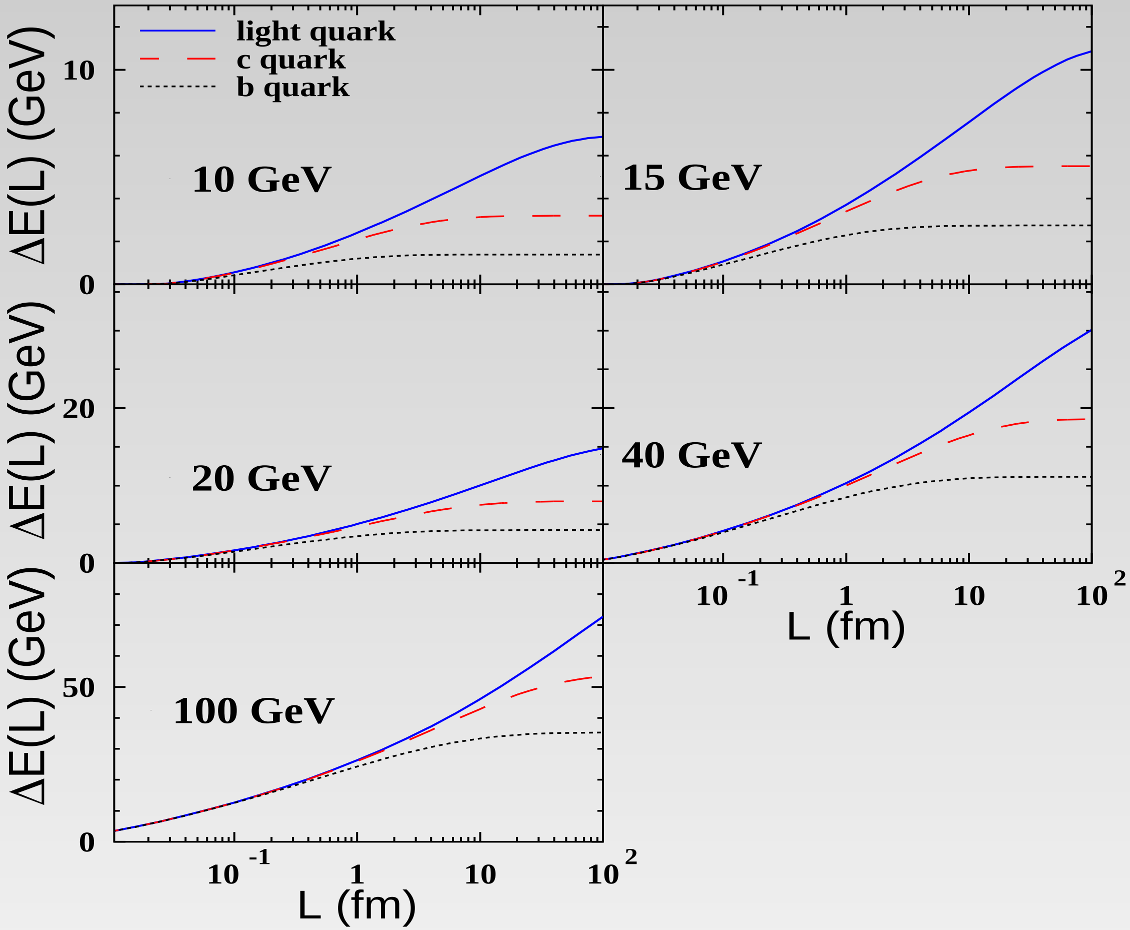

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- A half of the total radiated energy is lost during the first 1 fm

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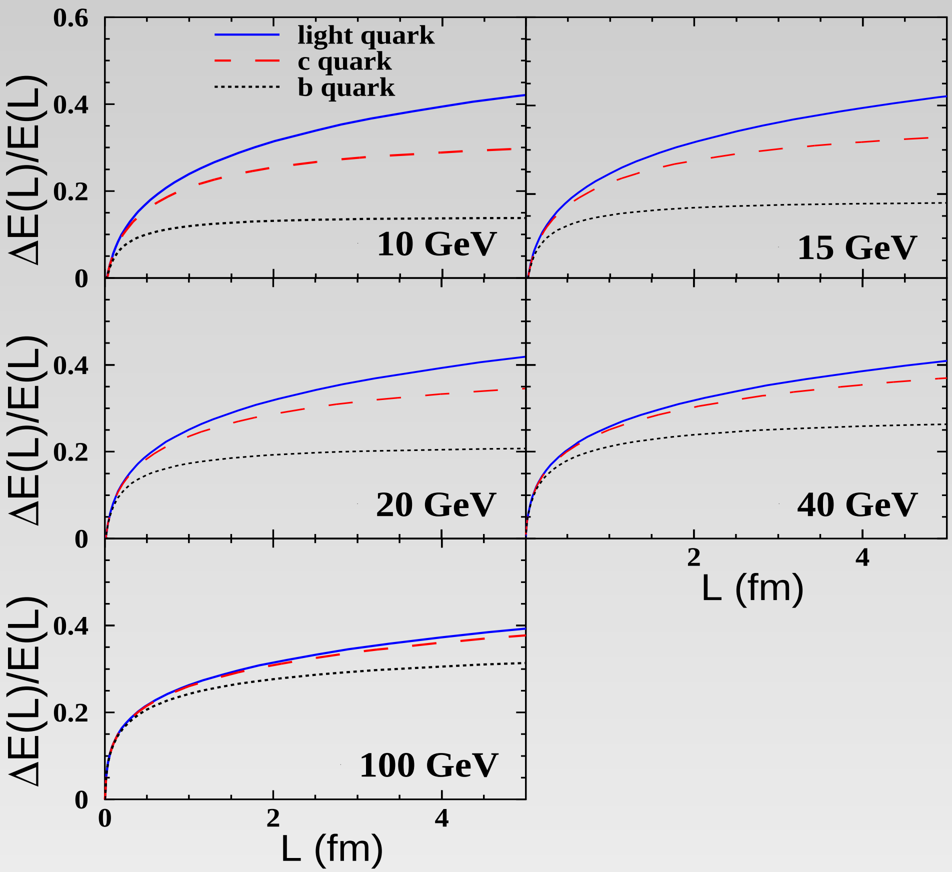

- The difference between radiation by heavy and light quarks is insignificant only at small $L \lesssim 0.5 \div 1\, fm$.

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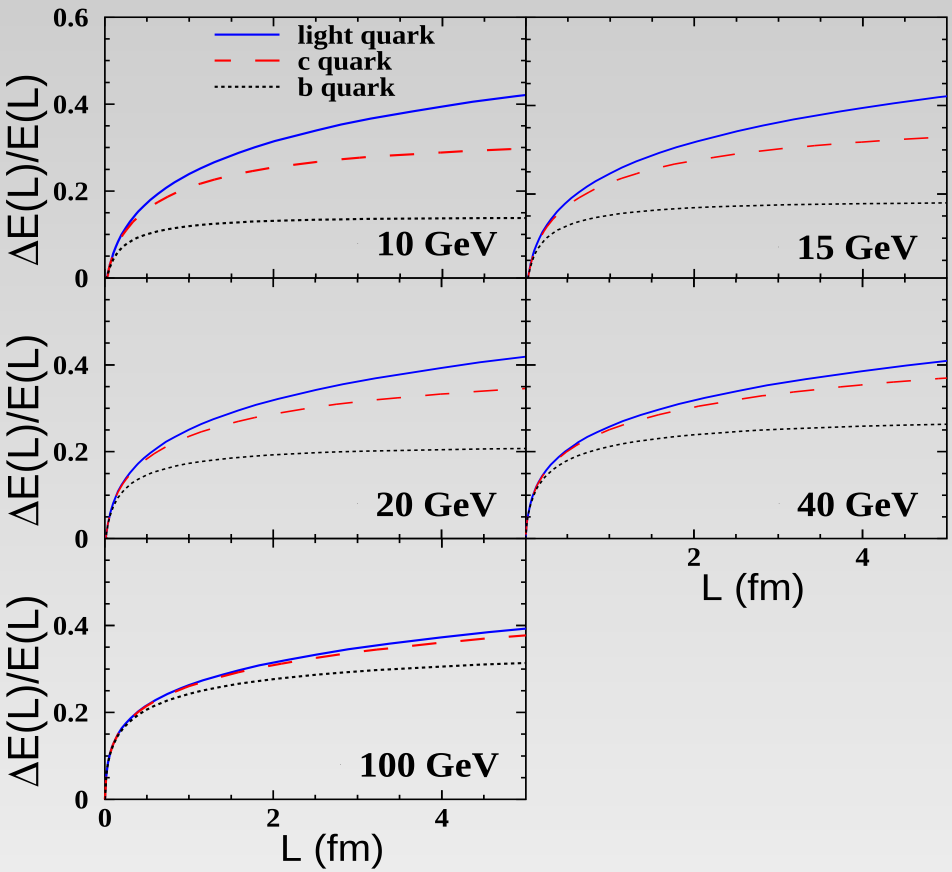
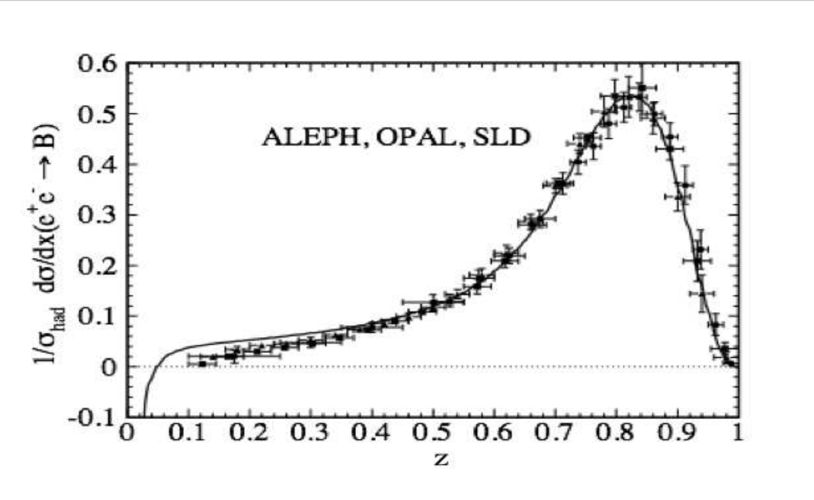


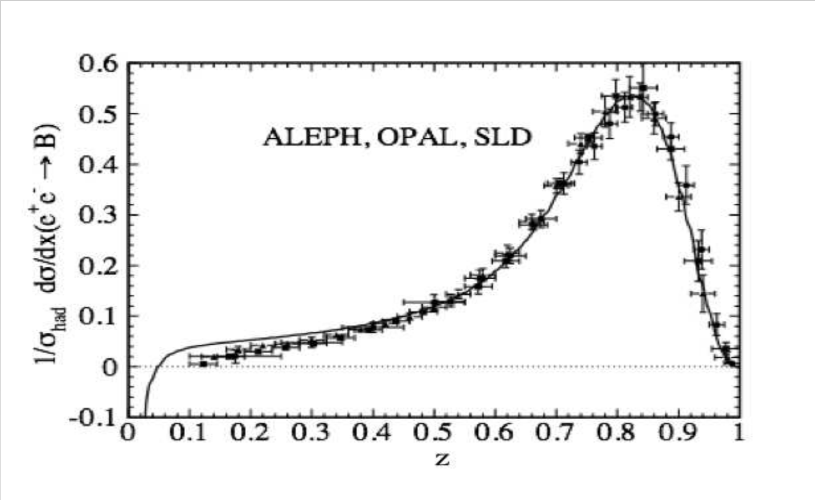
- The difference between radiation by heavy and light quarks is insignificant only at small $L \lesssim 0.5 \div 1\, fm$.
- Light quarks ⇒ keep radiating a long time and lose the most of the initial energy E
  Heavy quarks ⇒ radiate only a small fraction of E

Radiative energy loss in vacuum



- Radiation of heavy quarks ceases shortly

Radiative energy loss in vacuum



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- A small fraction of the initial quark energy $\Delta z = \Delta E/E$ is radiated (differently from light quarks) $\Rightarrow$ the final heavy flavored D and B mesons carry almost the whole momentum of the jet

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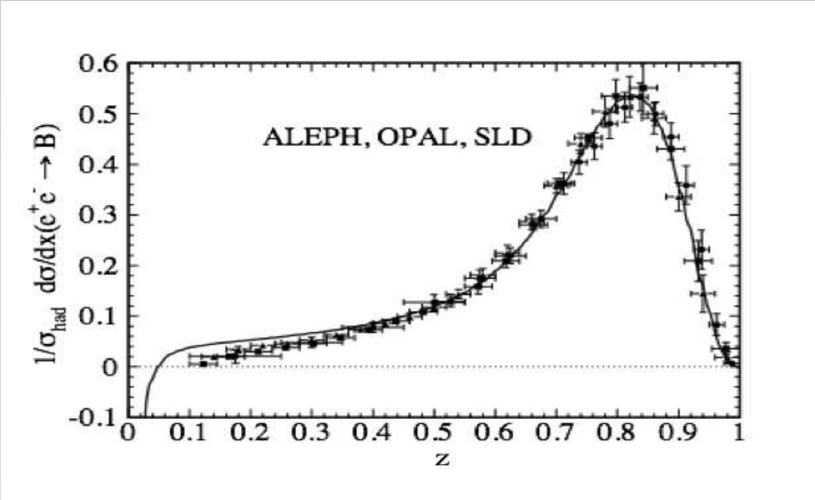

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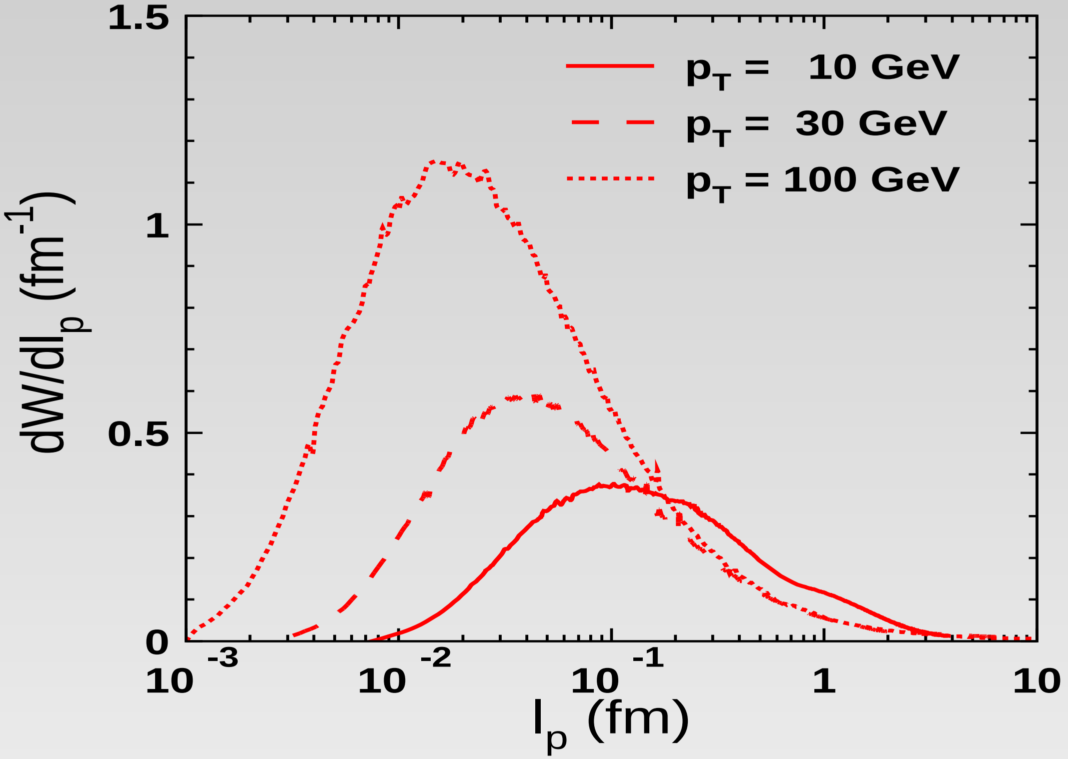
- A small fraction of the initial quark energy $\Delta z = \Delta E/E$ is radiated (differently from light quarks) $\Rightarrow$ the final heavy flavored D and B mesons carry almost the whole momentum of the jet
- Such an expectation is in accordance with the direct measurements of the fragmentation function $b \to B$ in e^+e^- annihilation $\Rightarrow$ large z are enhanced.

[T. Kneesch, B.A. Kniehl, G. Kramer and I. Schienbein; Nucl.Phys. B**799**, 34 (2008)]

Radiative energy loss in vacuum production length



- From the known magnitude of the radiational vacuum energy loss dE/dl and correspondingly $\Delta z(L)$ one can directly relate the production length distribution $W(l_p)$ to the $b \to B$ fragmentation function $D_{b/B}(z)$.

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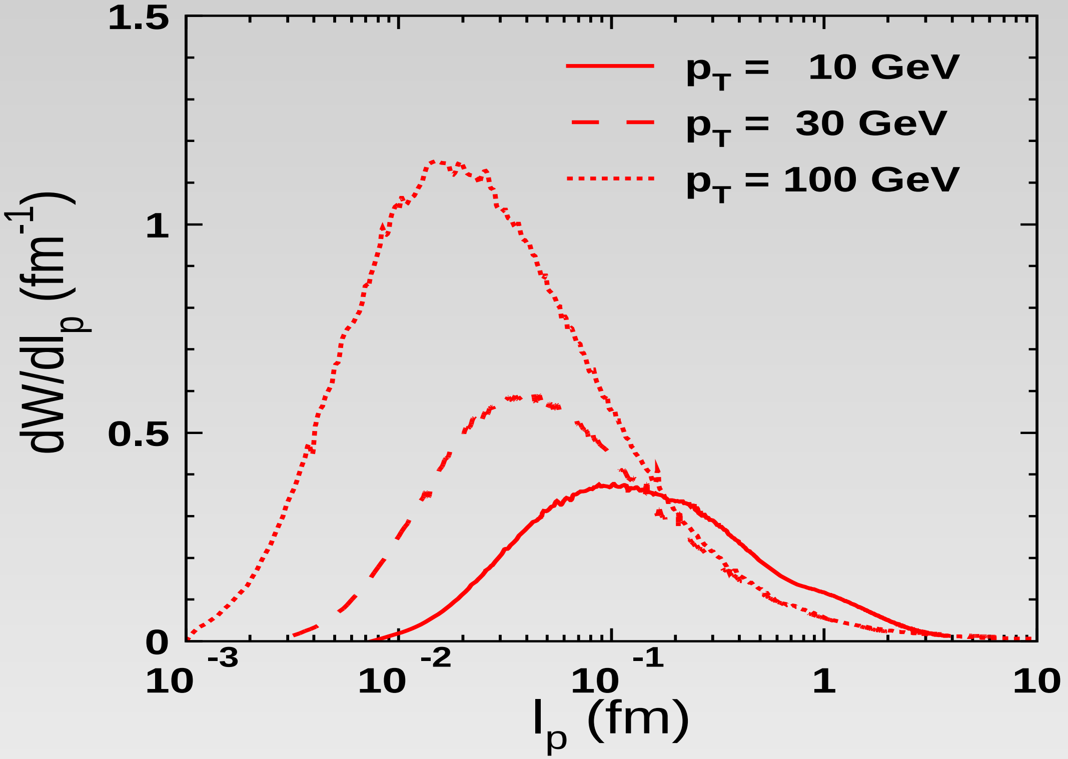

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- The mean value of l_p shrinks with rising p_T

Fragmentation in a hot medium

- Light mesons $\Rightarrow$ the q and/or $\bar{q}$ carries almost the same fraction of the meson momentum, $\alpha \sim 0.5$
  Heavy flavored B meson $\Rightarrow$ the light q or $\bar{q}$ carries a tiny momentum fraction, $\alpha \sim m_q/m_b \approx 0.05$

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- In the medium rest frame $\Rightarrow$ very short formation time of the B meson wave function

$$t_f^B = \frac{\sqrt{p_T^2 + m_B^2}}{2\, m_B\, \omega}$$

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- For instance at $p_T = 10$ GeV the B meson is formed on a short distance ~ 0.8 fm

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- Due to a quick expansion of the transverse size of the $b - \bar{q}$ dipole the corresponding mean free path of such a meson in a hot medium is very short

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  [C.W. Hwang; Eur.Phys.J C**23**, 585 (2002)]

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- For instance, at $\hat{q} = 1\ \mathrm{GeV}^2/fm$ the mean free path $\lambda_B = 0.04\ \mathrm{fm} \Rightarrow$ the b-quark propagates through the hot medium, frequently picking up and losing light antiquark comovers. Meanwhile the b-quark keeps losing energy with a rate, enhanced by medium-induced effects. Eventually the detected B-meson is formed and can survive in the dilute periphery of the medium.

Suppression of heavy mesons

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- b-quark loses $20 - 30\%$ of its initial energy on a very short distance l_p and picks-up a light $\bar{q}$.
- The produced colorless B-meson does not radiate keeping its fractional momentum z
- The corresponding differential cross section has the form:

$$\frac{d\sigma(pp \to BX)}{d^2p_T} = \int d^2p_+^b \, \frac{d\sigma(pp \to bX)}{d^2p_+^b} \, \frac{1}{z} D_{b/B}(z) \, .$$

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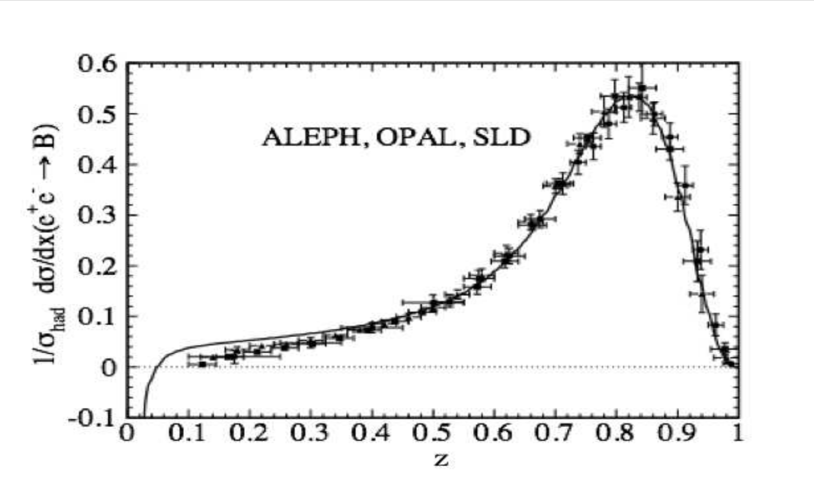
$$S(l_p^{AA}) = exp\left[-\int\limits_{l_p^{AA}}^{\infty} \frac{dl}{\lambda_B(l)}\right].$$

Suppression of heavy mesons



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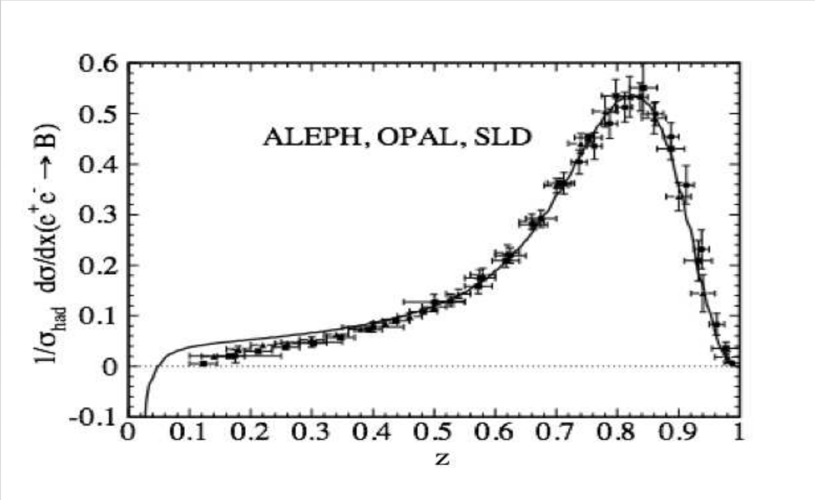

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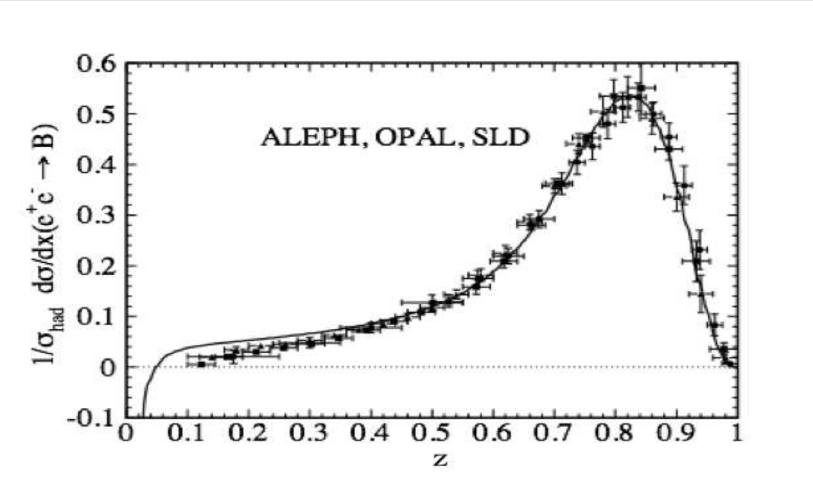

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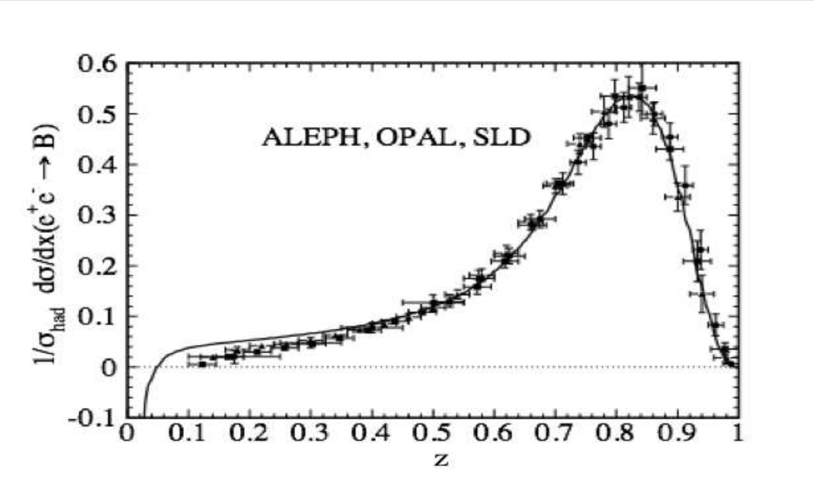

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- Energy loss on a longer path l_p^{AA} causes a smaller $z_{AA} \ll z$, suppressed by FF
- Two sources of suppression work in opposite directions $\Rightarrow$ there is no definite answer which of them dominates.

Interplay between energy loss and absorption

- In vacuum ⇒ radiational energy loss caused by gluon radiation plus string with the rate of E-loss:

$$\frac{dE}{dl} = \frac{dE_{rad}}{dl} + \frac{dE_{string}}{dl} = \frac{dE_{rad}}{dl} - \kappa$$

where $\kappa = 1\ \text{GeV}/\ \text{fm}$

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where $\kappa = 1$ GeV/ fm

- In a hot medium ⇒ radiational vacuum and induced E-loss, collisional, string. However, the string tension is falling as a function of temperature

$$\kappa(T) = \kappa\left(1 - T/T_c\right)^{1/3}$$

where $T_c = 0.280$ GeV

[H. Ichie, H. Suganuma and H. Toki; Phys.Rev. D**52**, 2944 (1995); Phys.Rev. D**54**, 3382 (1996)]

Attenuation of a $\bar{q}Q$ in a hot medium

- Green function formalism based on the path-integral technique $\Rightarrow$ suppression factor (survival probability) for a $\bar{q}Q$ dipole in a medium

$$S(l_1,l_2) \propto \left| \int_0^1 d\alpha \int d^2r_1 d^2r_2 \Psi^{\dagger}_M(r_2,\alpha) G_{\bar{q}Q}(l_1,\vec{r}_1;l_2,\vec{r}_2) \Psi_{in}(r_1,\alpha) \right|^2$$

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- The Green function $G_{\bar{q}Q}(l_1,\vec{r}_1;l_2,\vec{r}_2)$ describes propagation of the $\bar{q}Q$ dipole between longitudinal coordinates l_1, l_2 with initial and final separations $\vec{r}_1$ and $\vec{r}_2$. It satisfies the 2-dimensional LC equation,

$$\left[i\frac{d}{dl_2} - \frac{m^2_{\bar{q}Q} - \Delta_{r_2}}{2\,p^b_+\,\alpha\,(1-\alpha)} - V_{\bar{q}Q}(l_2,\vec{r}_2)\right] G_{\bar{q}Q}(l_1,\vec{r}_1;l_2,\vec{r}_2) = i\delta(l_2-l_1)\,\delta(\vec{r}_2-\vec{r}_1)$$

Attenuation of a $\bar{q}Q$ in a hot medium

CFRJS

- Green function formalism based on the path-integral technique $\Rightarrow$ suppression factor (survival probability) for a $\bar{q}Q$ dipole in a medium

$$S(l_1, l_2) \propto \left| \int_0^1 d\alpha \int d^2r_1 d^2r_2 \Psi^\dagger_M(r_2, \alpha) G_{\bar{q}Q}(l_1, \vec{r}_1; l_2, \vec{r}_2) \Psi_{in}(r_1, \alpha) \right|^2$$

- The Green function $G_{\bar{q}Q}(l_1, \vec{r}_1; l_2, \vec{r}_2)$ describes propagation of the $\bar{q}Q$ dipole between longitudinal coordinates l_1, l_2 with initial and final separations $\vec{r}_1$ and $\vec{r}_2$. It satisfies the 2-dimensional LC equation,

$$\left[i\frac{d}{dl_2} - \frac{m^2_{\bar{q}Q} - \Delta_{r_2}}{2\,p^b_+\,\alpha\,(1-\alpha)} - V_{\bar{q}Q}(l_2, \vec{r}_2) \right] G_{\bar{q}Q}(l_1, \vec{r}_1; l_2, \vec{r}_2) = i\delta(l_2 - l_1)\,\delta(\vec{r}_2 - \vec{r}_1)$$

- The variable $m^2_{\bar{q}Q}(\alpha) = m^2_Q(1-\alpha) + m^2_q\alpha$.

Attenuation of a $\bar{q}Q$ in a hot medium

- The imaginary part of the LC potential $V_{Q\bar{q}}(l_2, \vec{r}_2)$ is responsible for attenuation in a medium

$$Im V_{\bar{q}Q}(l, \vec{r}) = -\frac{1}{4}\,\hat{q}(l)\,r^2$$

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- $Re V_{Q\bar{q}}(l_2, \vec{r}_2)$ is the phenomenological Cornell-type potential, adjusted to reproduce the masses and decay constants for B and D mesons

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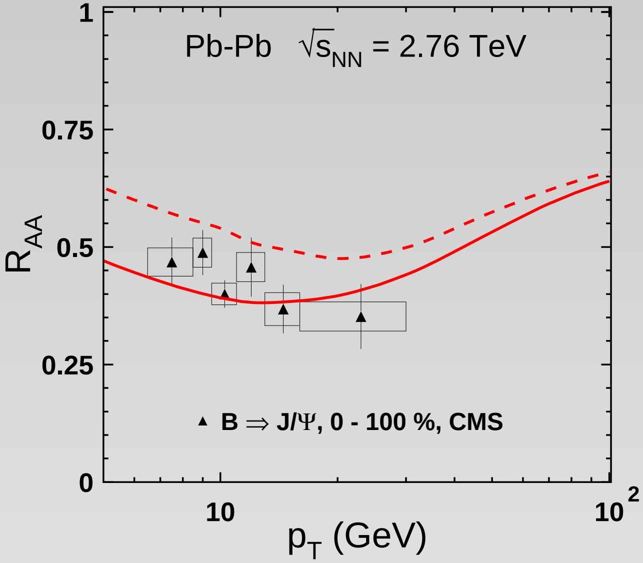
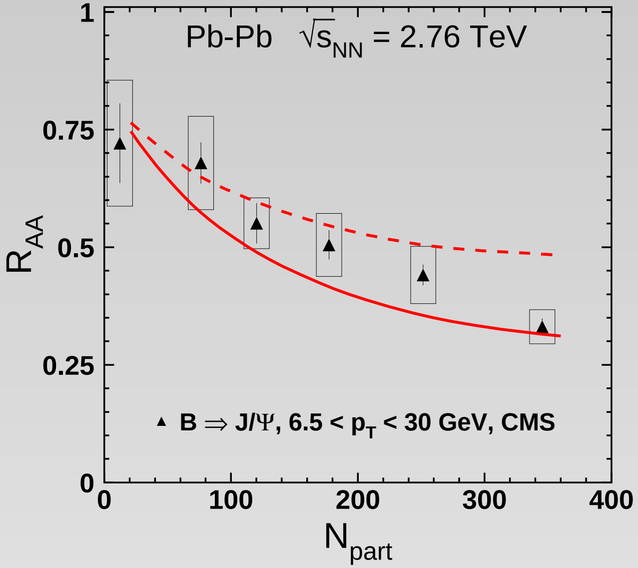
- The transport coefficient $\hat{q}(l)$ is the rate of broadening of the quark transverse momentum in the medium. We employ the popular model

$$\hat{q}(l) = \frac{\hat{q}_0\, l_0}{l}\, \frac{n_{part}(\vec{b}, \vec{\tau})}{n_{part}(0,0)}\, \Theta(l - l_0)$$

[X.F. Chen, C. Greiner, E. Wang, X.N. Wang and Z. Xu: Phys.Rev. C**81**, 064908

Predictions vs data





- The maximal transport coeff. $\hat{q}_0 \sim 2\ \mathrm{GeV}^2/\ \mathrm{fm}$ has been fixed in our previous studies of quenching of pions at LHC

  [B.Z. Kopeliovich, JN, I.K. Potashnikova, I. Schmidt, Phys.Rev. C**86**, 054904 (2012)]

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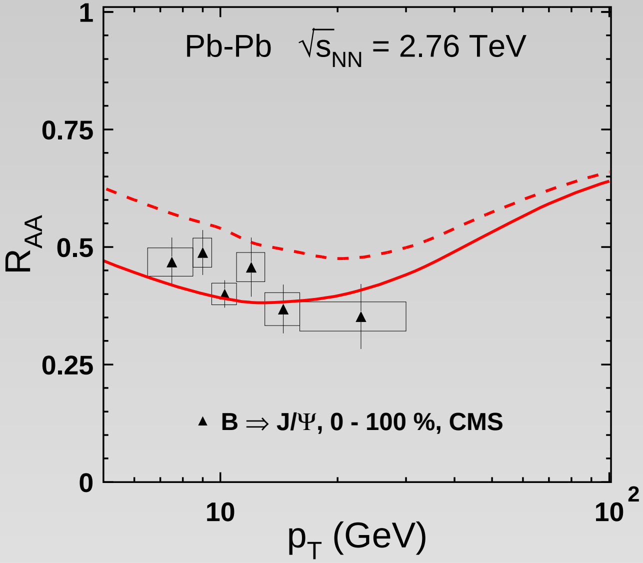

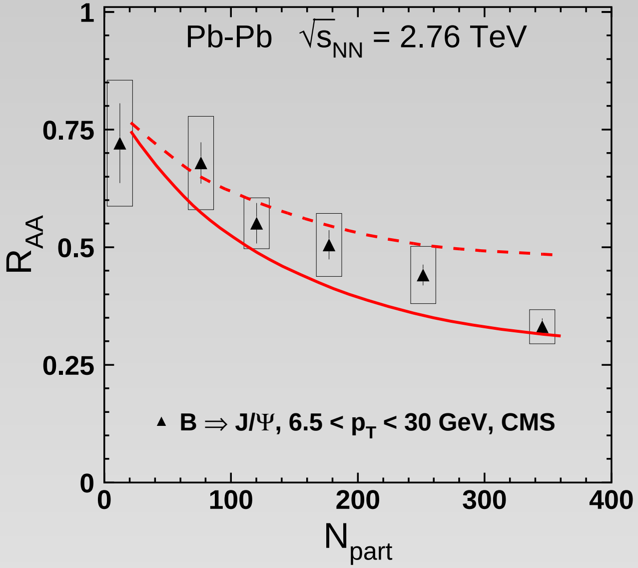

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- Different sources of time-dependent medium-induced energy loss were added, including radiative and collisional mechanisms [R. Baier: Nucl.Phys. A**715**, 209 (2003)]

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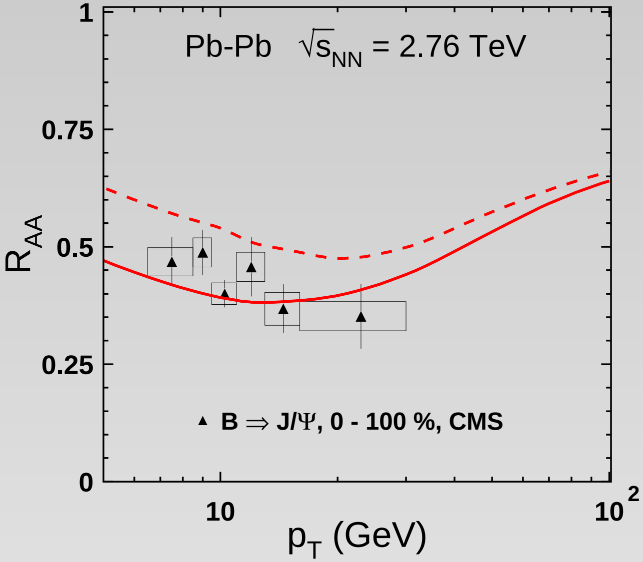
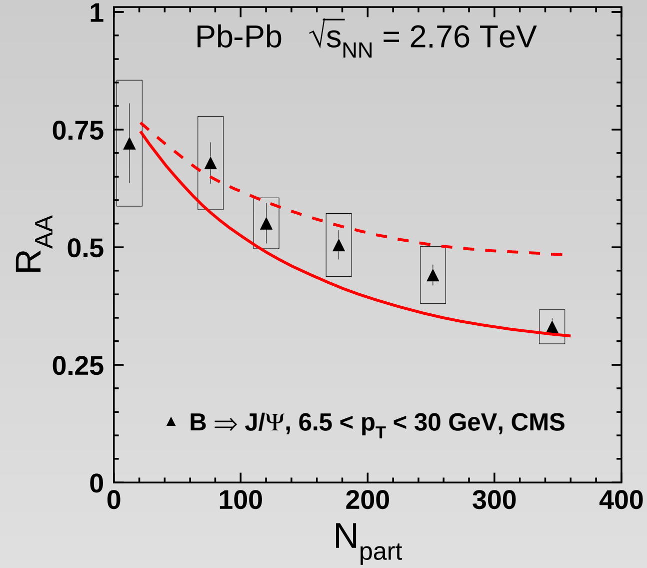
CFRJS





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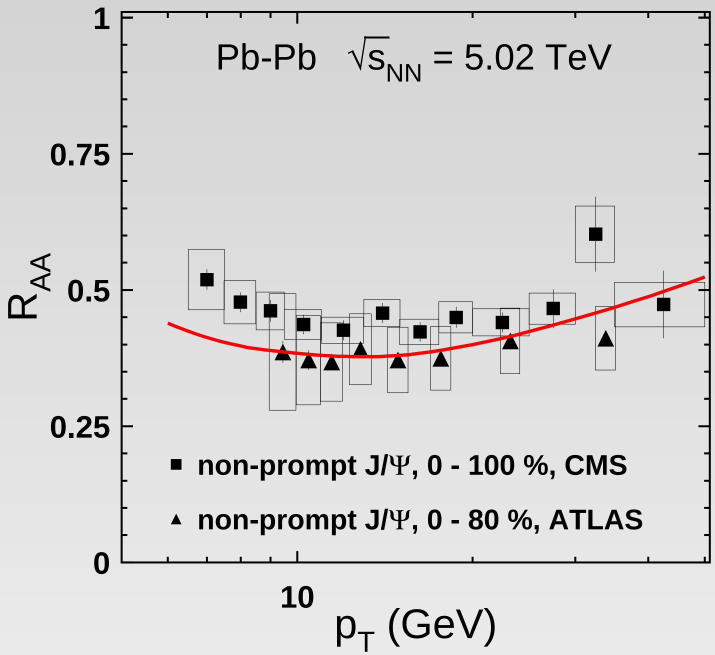
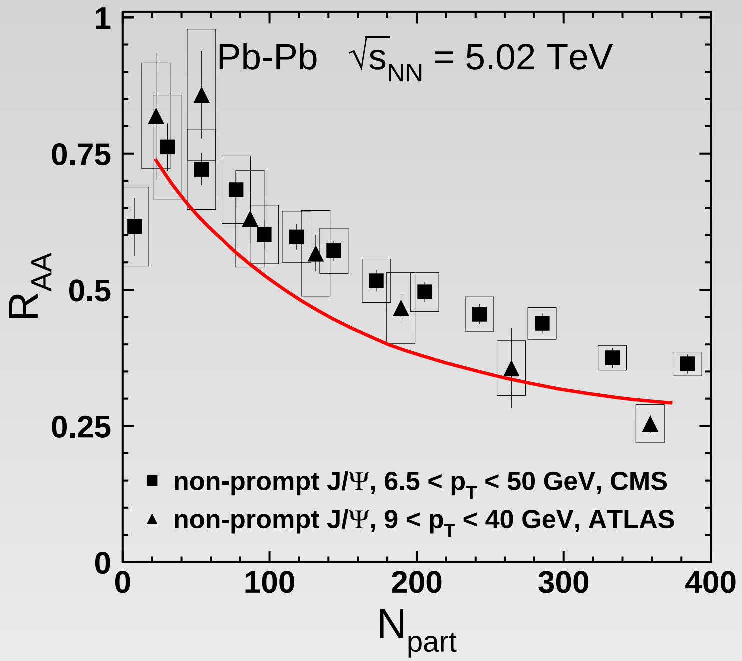
- Different sources of time-dependent medium-induced energy loss were added, including radiative and collisional mechanisms [R. Baier: Nucl.Phys. A**715**, 209 (2003)]
- Medium-induced energy loss is much smaller than the vacuum one, and does not produce a dramatic effect. They are particularly small for heavy flavors.

Predictions vs data





- We predict a similar suppression of B mesons at larger c.m. collision energy $\sqrt{s_{NN}} = 5.02$ TeV.

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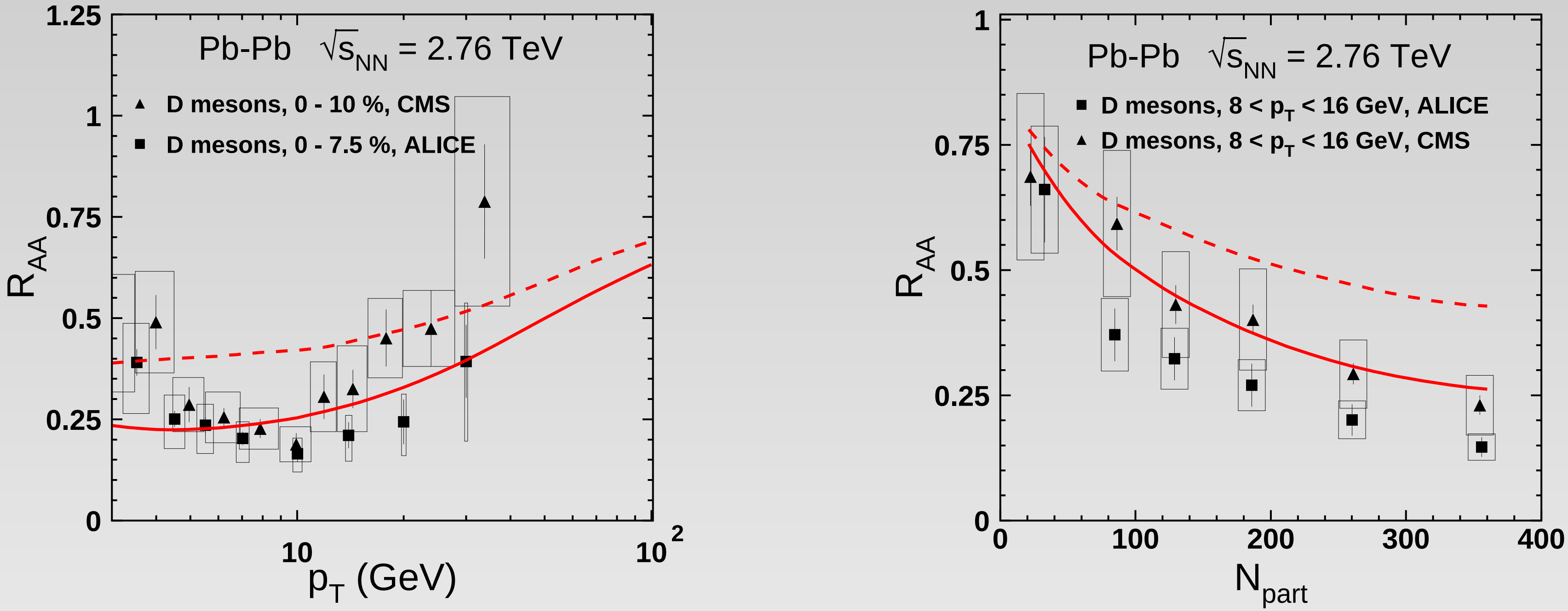

- The gluon radiation by ***c***-quarks in vacuum is much more intensive than by ***b***-quarks.

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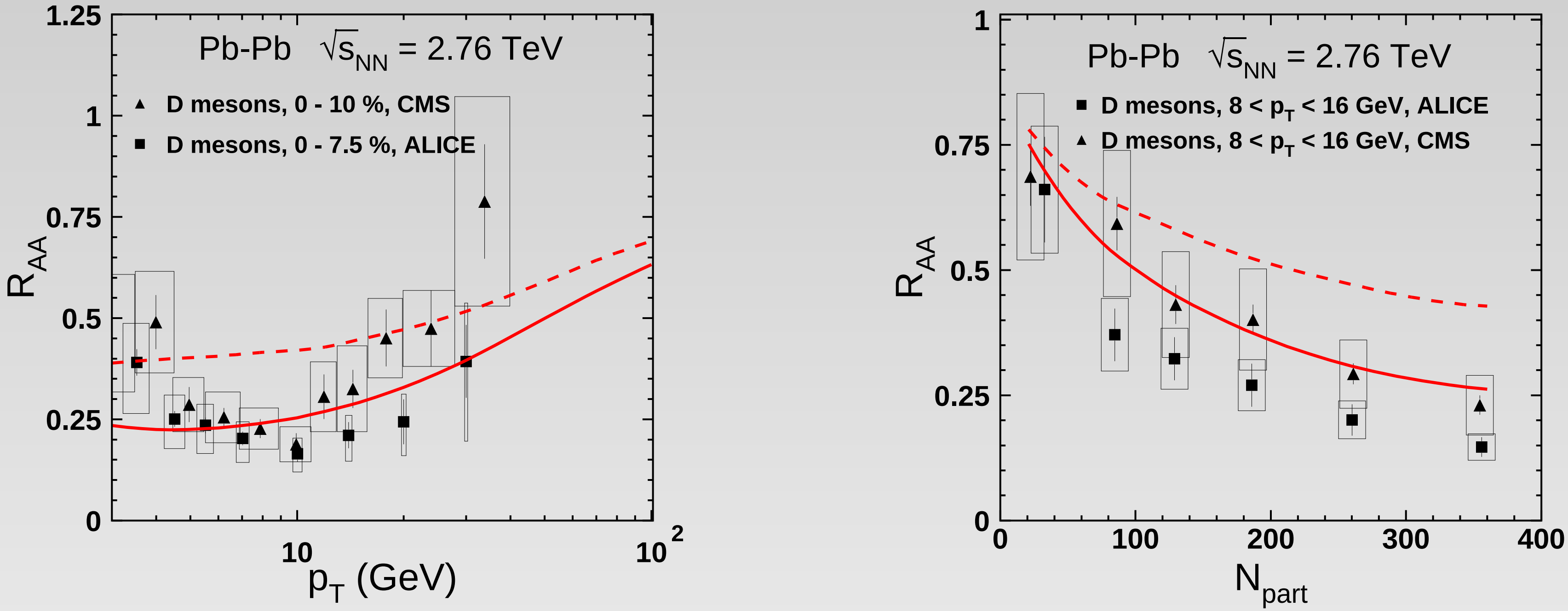

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- Absorption of $\bar{q}c$ and $\bar{q}b$ dipole in a hot medium is similar

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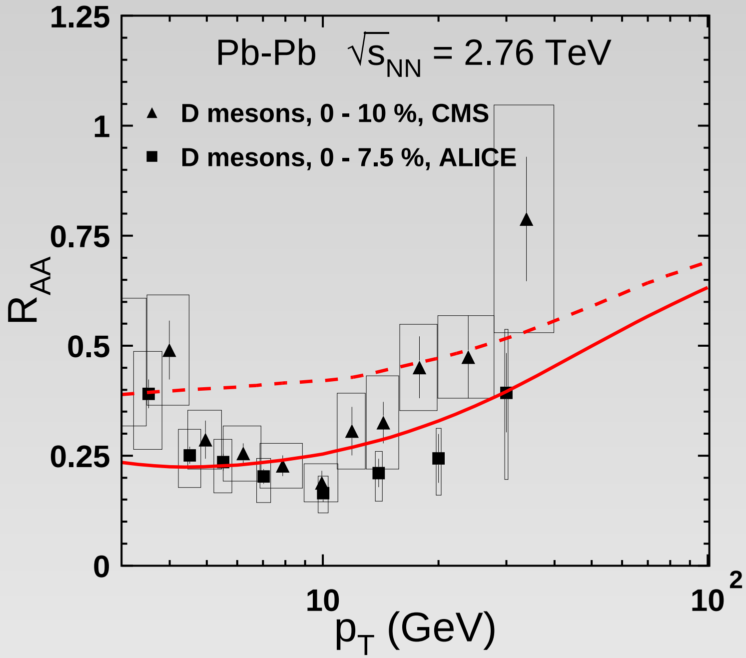
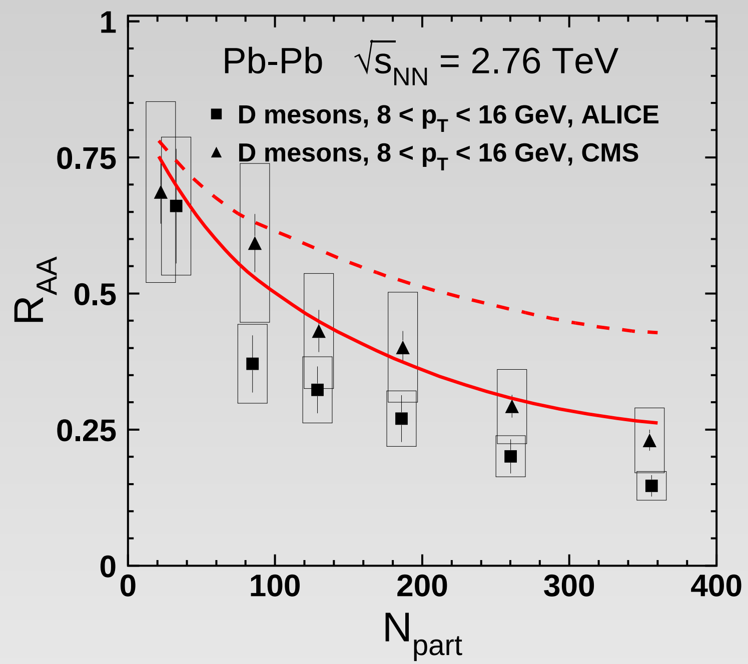
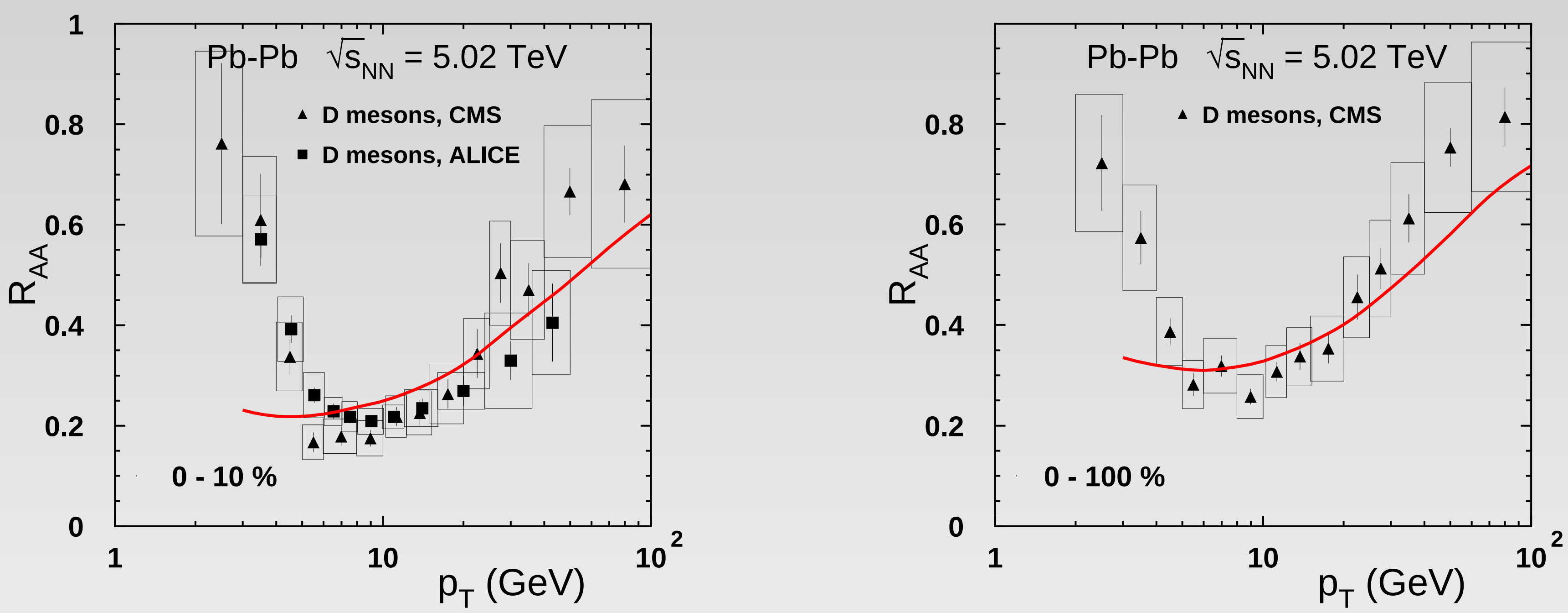




- The gluon radiation by c-quarks in vacuum is much more intensive than by b-quarks.
- Absorption of $\bar{q}c$ and $\bar{q}b$ dipole in a hot medium is similar
- Consequently, D mesons are suppressed in heavy ion collisions more than B mesons

Predictions vs data



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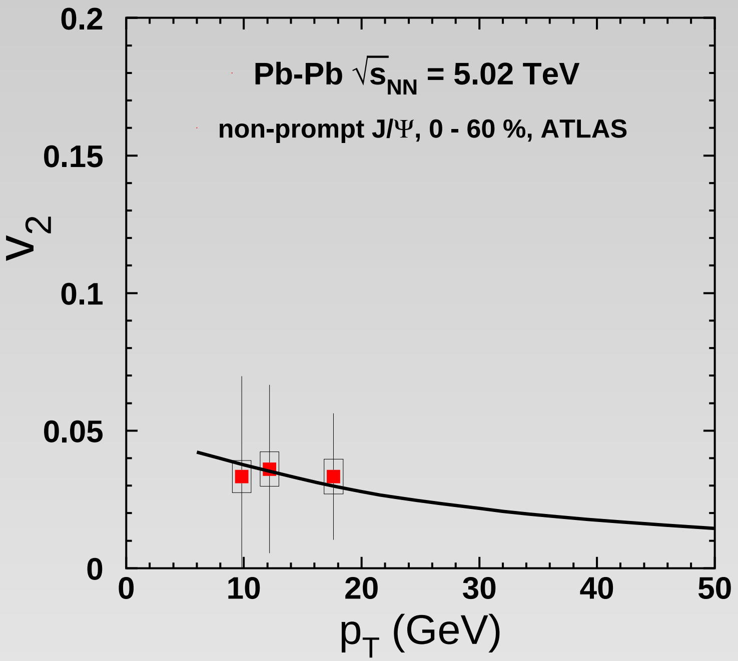

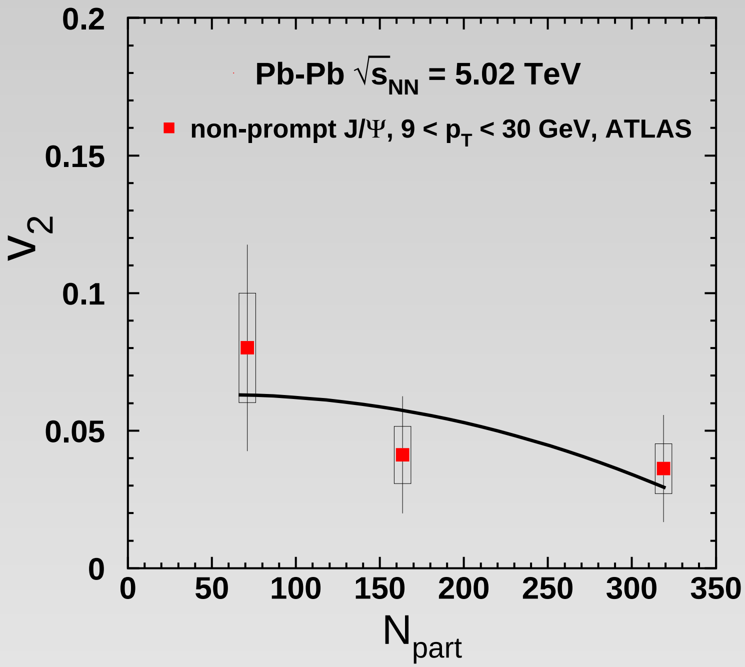

- We predict a weak p_T- and centrality- dependence of the azimuthal asymmetry presented in terms of the second moment of the ϕ distribution, $v_2 \equiv \langle cos(2\phi)\rangle$,

$$v_2(p_T, b) = \frac{\int d^2\tau T_A(\tau) T_B(\vec{b}-\vec{\tau}) \int_0^{2\pi} d\phi \cos(2\phi) \left| S(l_1, l_2; \vec{b}, \vec{\tau}, \phi) \right|^2}{\int d^2\tau T_A(\tau) T_B(\vec{b}-\vec{\tau}) \int_0^{2\pi} d\phi \left| S(l_1, l_2; \vec{b}, \vec{\tau}, \phi) \right|^2}$$

Summary

In comparison to light hadrons, we demonstrate that the production of heavy flavored mesons in heavy ion collisions (HICs) shows new nontrivial features:

- During the first stage of hadronization succeeding **high-p_T** partonic collisions the heavy and light quarks radiate differently. Heavy quarks radiate a significantly smaller fraction of the initial energy regenerating their stripped-off color field much faster than light ones.

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- During the first stage of hadronization succeeding **high-p_T** partonic collisions the heavy and light quarks radiate differently. Heavy quarks radiate a significantly smaller fraction of the initial energy regenerating their stripped-off color field much faster than light ones.
- This leads to a specific shape of the fragmentation functions for heavy-quark jets. Differently from light flavors, the heavy quark fragmentation functions strongly peak at large fractional momentum, $z \sim 0.60 \div 0.65$ and $z \sim 0.85$ for $c \to D$ and $b \to B$ respectively, i.e. the produced heavy-light meson, B or D, carry the main fraction of the jet momentum. This is a clear evidence of a short production time of heavy-light mesons.

Summary

- The second stage of hadronization is controlled by the propagation of colorless dipoles in the medium. Whereas in **large-p_T** production of **light hadrons** a small $\bar{q}q$ dipole can survive in the medium due to **color transparency**, in heavy flavor production a $\bar{q}Q$ dipole promptly expands to a large size. This fact leads to much lower survival probability of such a big dipole in a hot medium. Multiple breakups and recreations of $\bar{q}Q$ dipoles increase E-loss preceding the final production of heavy flavored mesons pushing the production point to the dilute medium surface, This is different from the scenario of high- p_T production of light $\bar{q}q$ mesons.

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- Model predictions in a parameter-free way are in a good agreement with data for production of high- p_T B and D mesons. The extracted max. value of the transport coefficient $\hat{q}_0$ $\sim 2\ \mathrm{GeV}^2/\,\mathrm{fm}$ agree well with the results of our previous analyses of inclusive light hadron production in HICs.