Universal suppression in production of different high-p_T hadrons in heavy ion collisions

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In collaboration with
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Outline

- **Space-time development of hadronization**
  $\Rightarrow$ **production of leading hadrons**

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  $\Rightarrow$ path-integral technique

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- Production of different particles in a medium
  ⇒ universality of suppression vs available LHC data
  ⇒ predictions for $R_{AA}(p_T)$

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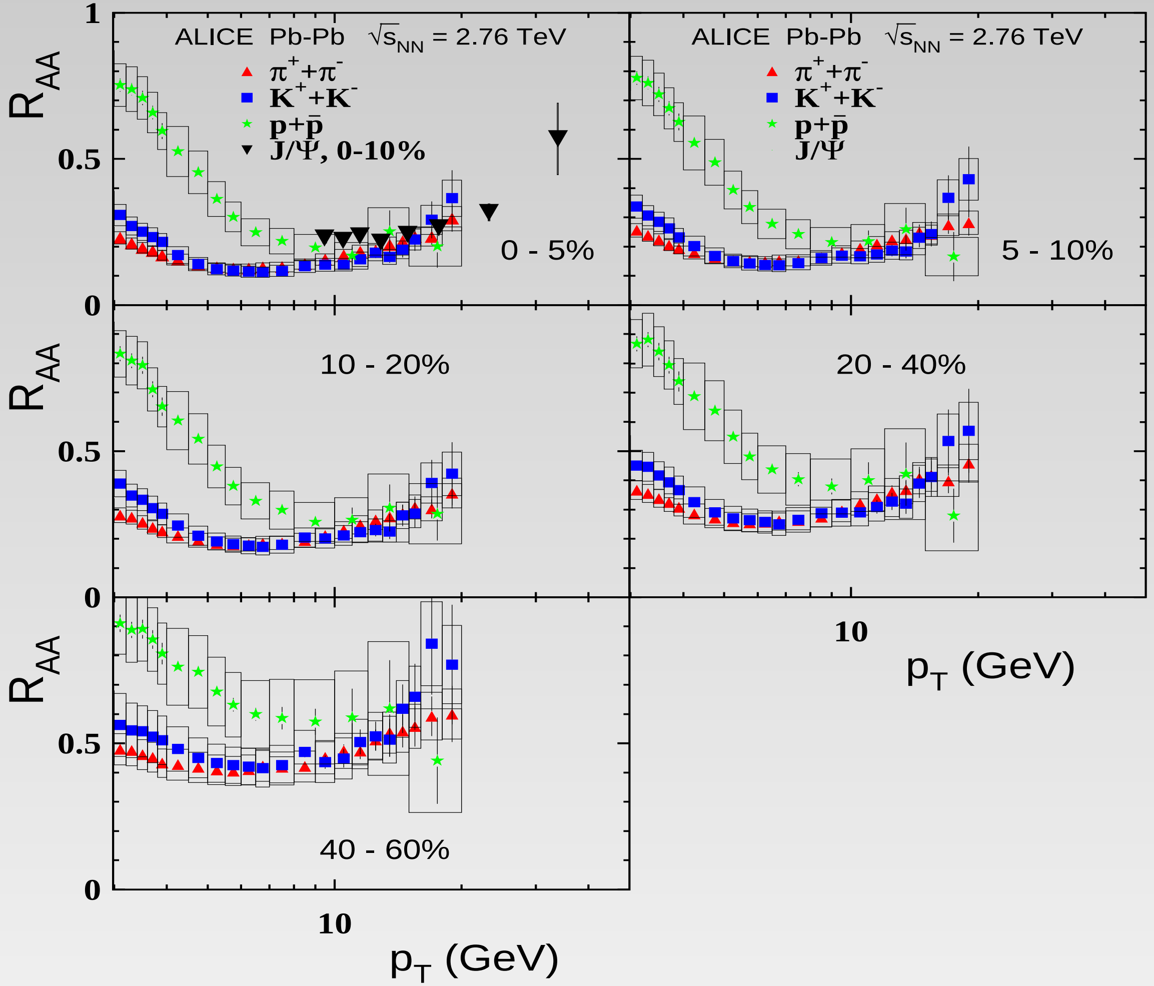
  $\Rightarrow$ universality of suppression vs available LHC data
  $\Rightarrow$ predictions for $R_{AA}(p_T)$
- Summary & Outlook

Introduction - data

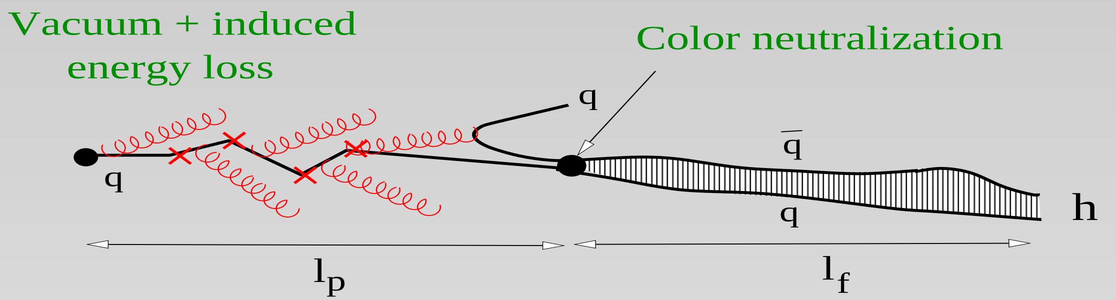


Similar suppression in production of pions, kaons, protons and J/Ψ at large p_T

[J. Adam *et al.* [The ALICE Collaboration], Phys.Rev. C**93**, 034913 (2016)]

[M. Aaboud *et al.* [The ATLAS Collaboration], e-Print: arXiv:*1805.04077* [nucl-ex]]

Space-time development of hadronization



- I. stage ⇒ the quark regenerates its color field, which has been stripped off in a hard reaction characterized by the scale $Q^2 = p_T^2$

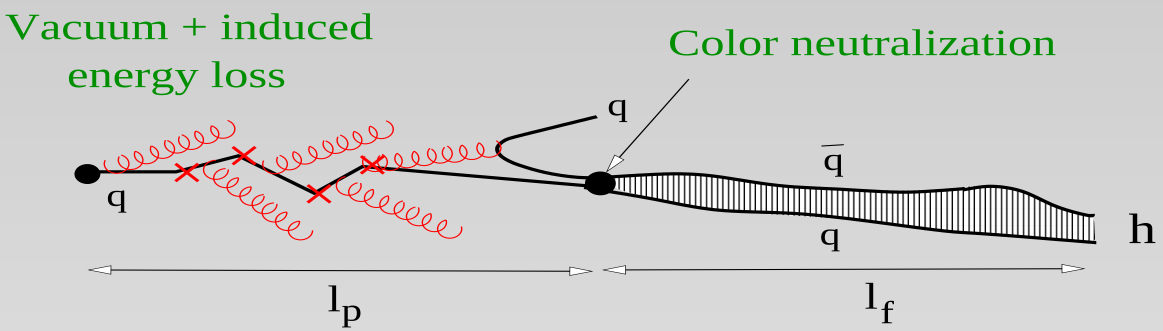
  ⇒ the quark intensively radiates gluons and dissipates energy, either in vacuum or in a medium.

  ⇒ 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.

Radiative energy loss in vacuum

- The time-dependent radiational energy loss reads:

$$\Delta E_{rad}(t) = E \int_{\lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x\, \frac{dn_g}{dx\, dk^2}\, \Theta(t - t_c^g),$$

[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)]

[B.Z. Kopeliovich, I. K. Potashnikova, I. Schmidt; Phys.Rev. C**82**, 037901 (2010)]

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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

- 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.

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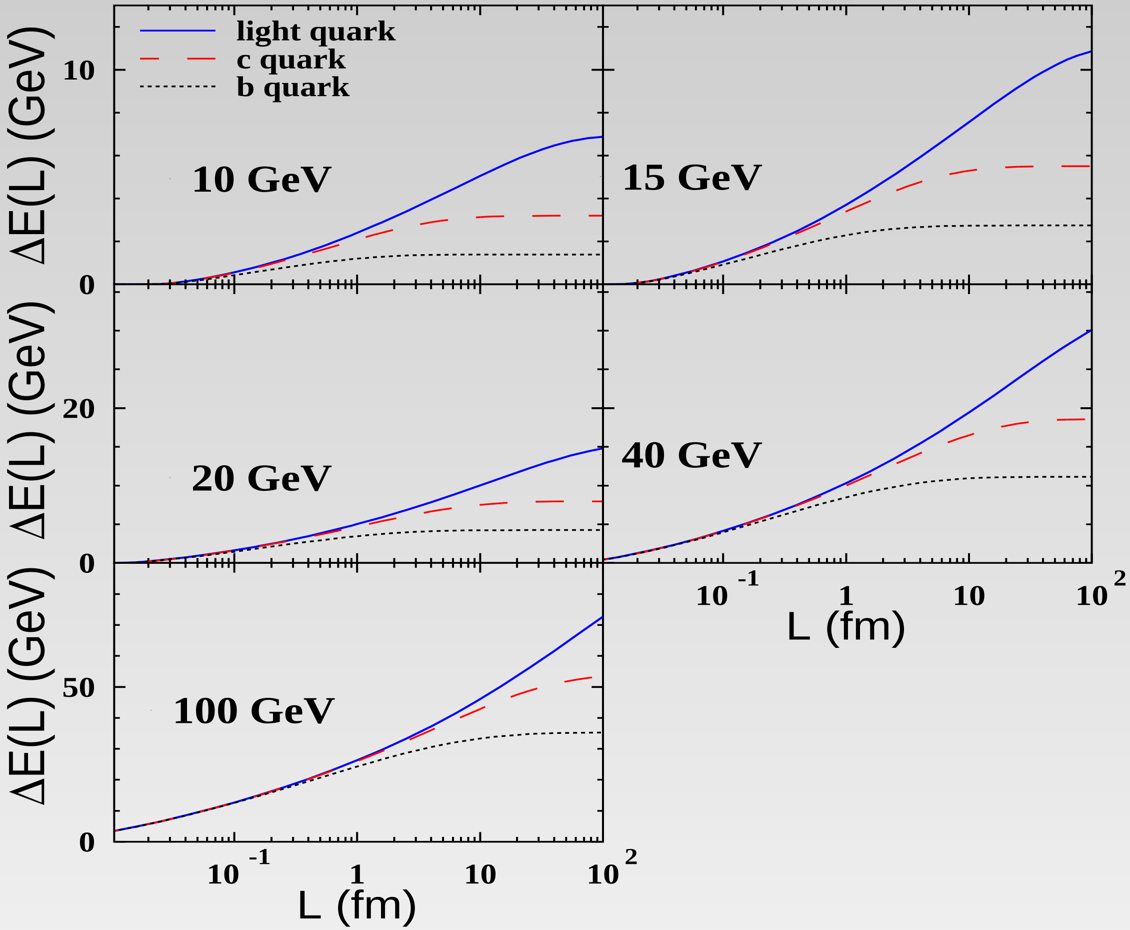
- Substantial difference between radiation of energy by c and light quarks onsets at rather long distances $L \gtrsim 5 \div 10$ fm

  $\Leftarrow$ [B.Z. Kopeliovich, I. K. Potashnikova, I. Schmidt; Phys.Rev. C**82**, 037901 (2010)]

Radiative energy loss in vacuum



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

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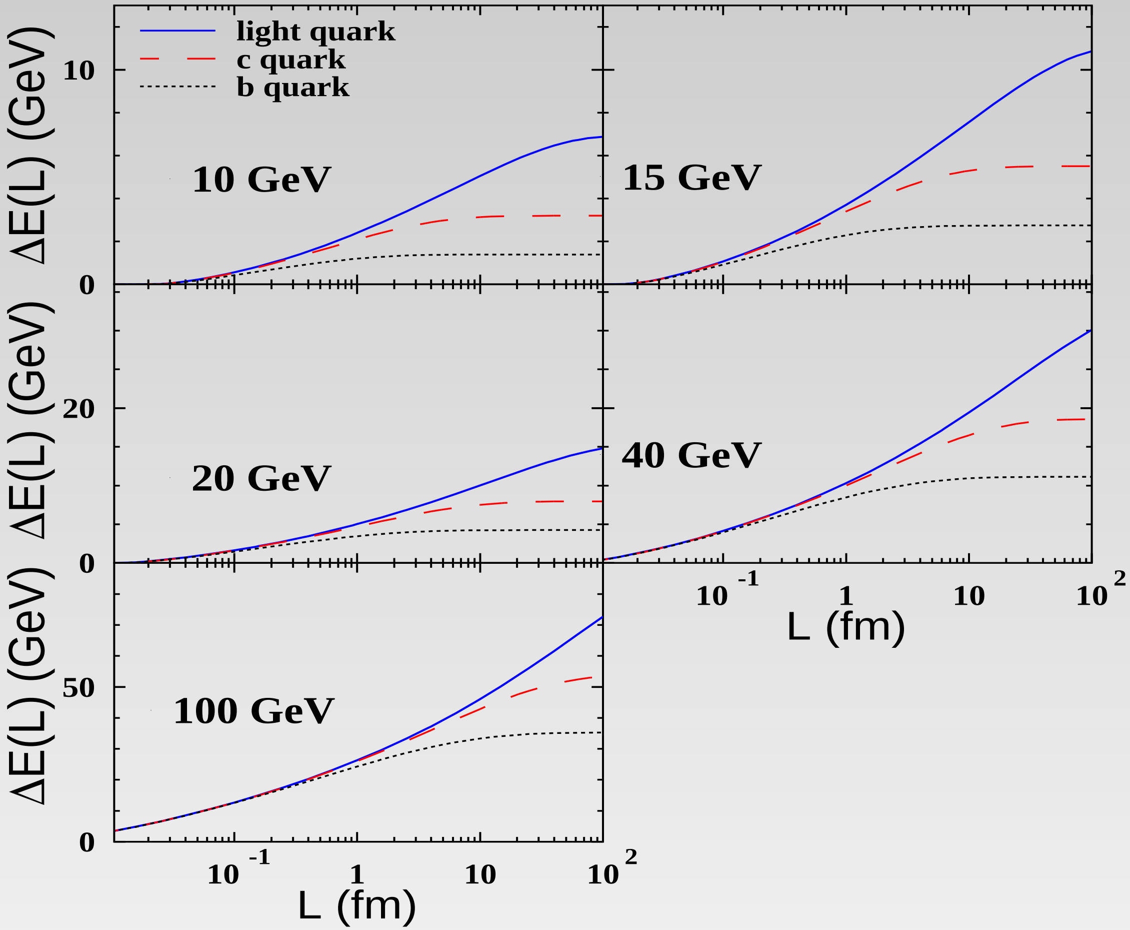

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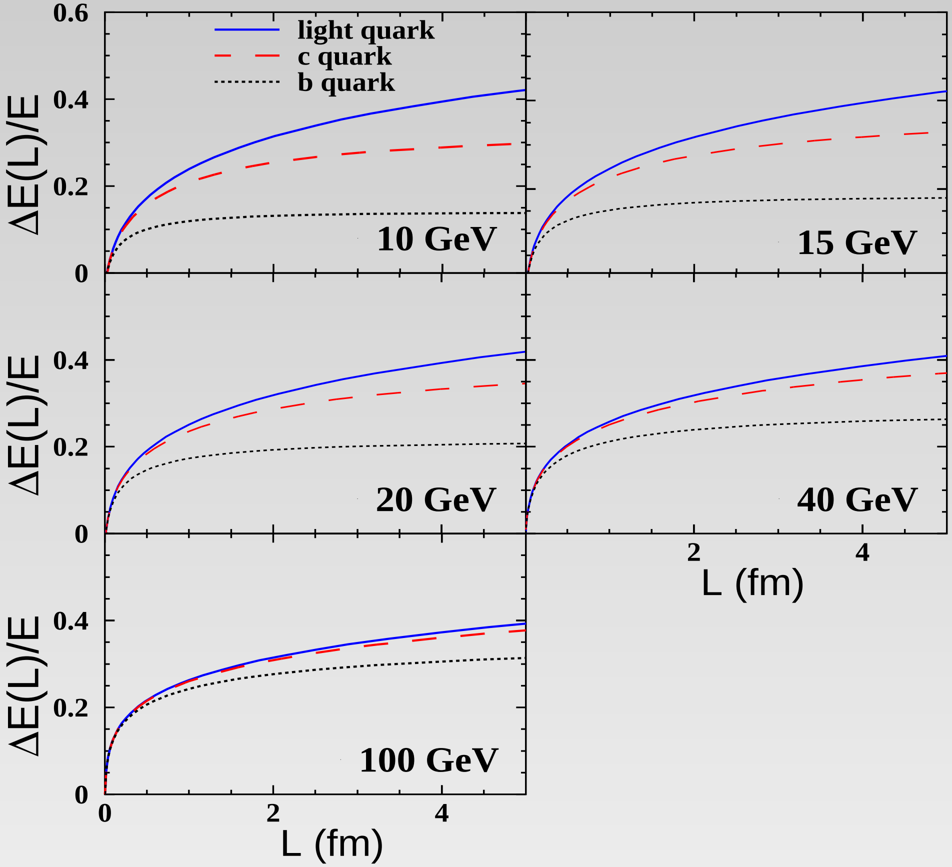
- A half of the total radiated energy is lost during the first 1 fm

Radiative energy loss in vacuum



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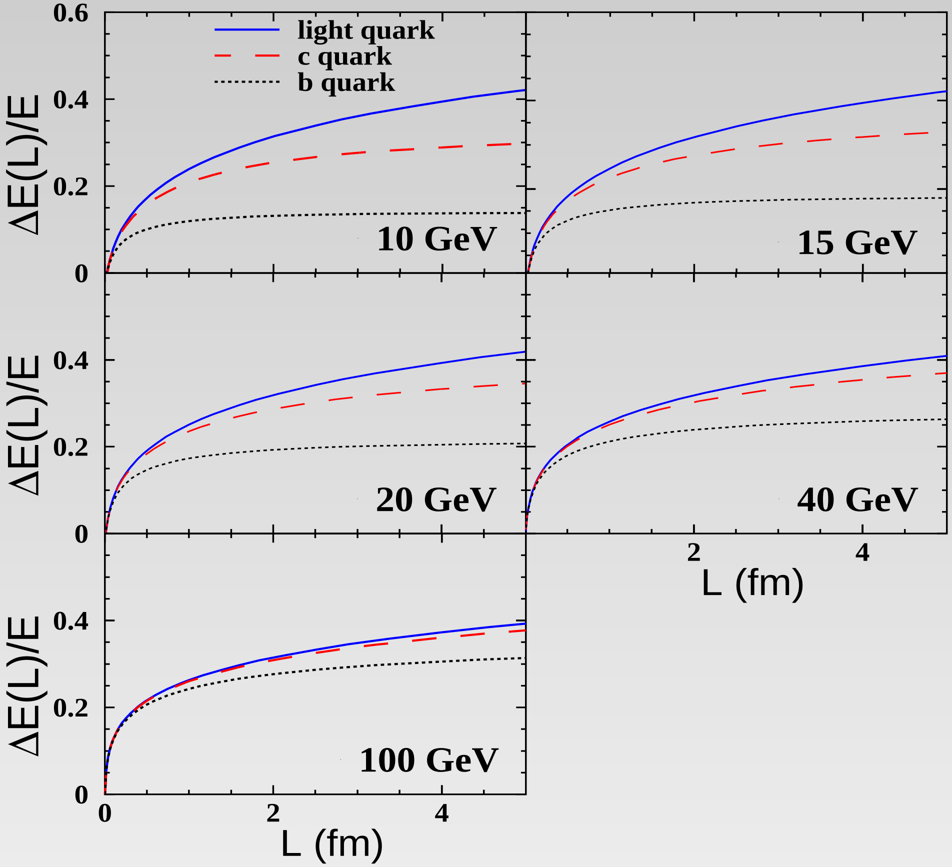
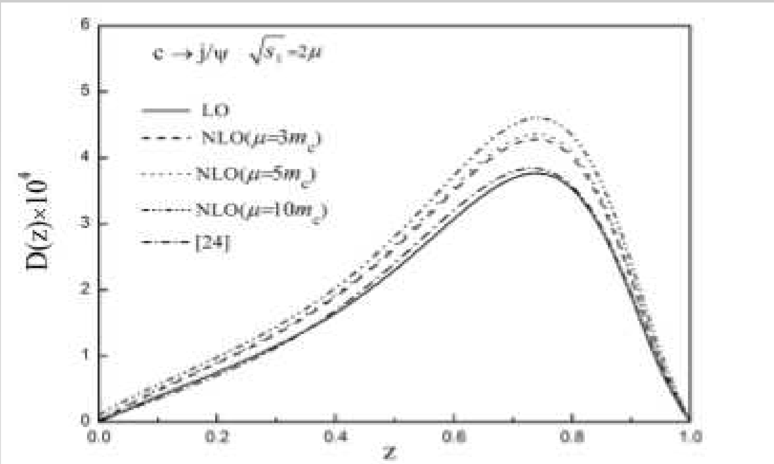
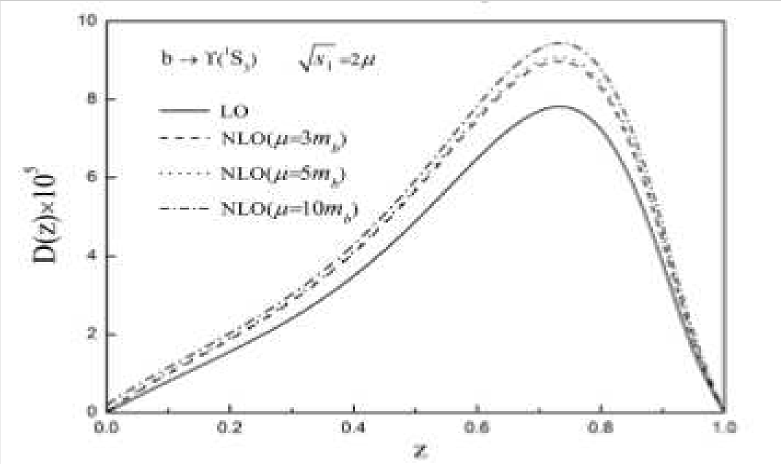


- The difference between radiation by heavy and light quarks is insignificant only at small $L \lesssim 0.5 \div 1\, fm$.
- Light quarks $\Rightarrow$ keep radiating a long time and lose the most of the initial energy E
  Heavy quarks $\Rightarrow$ radiate only a small fraction of E

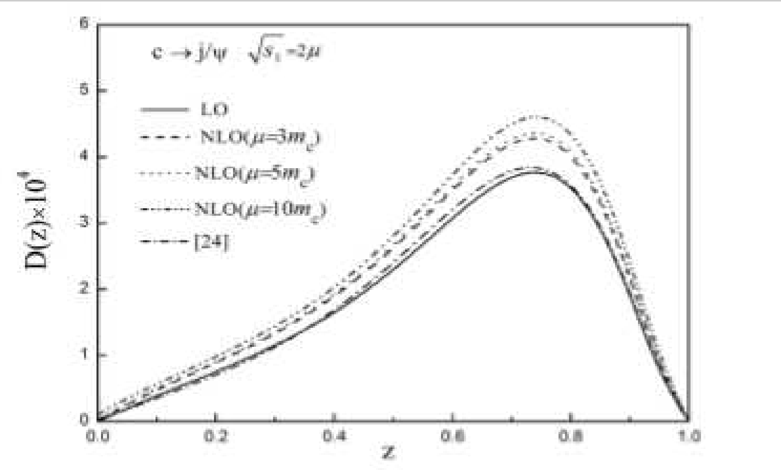
Radiative energy loss in vacuum

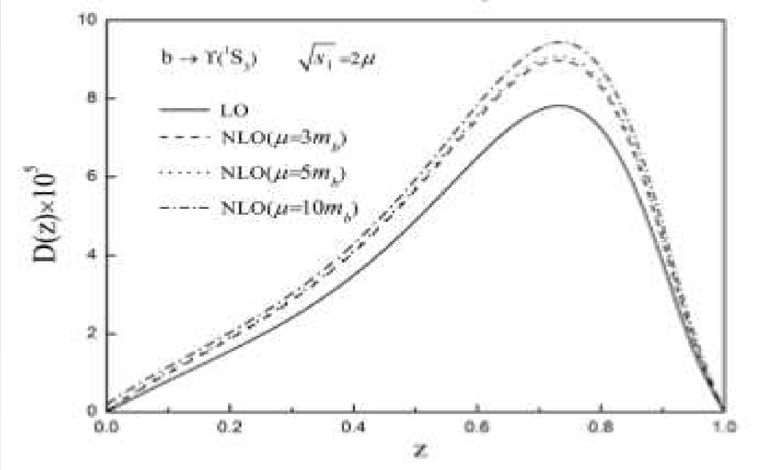




- Radiation of heavy quarks ceases shortly

Radiative energy loss in vacuum





- Radiation of heavy quarks ceases shortly
- A small fraction of the initial quark energy $\Delta z = \Delta E/E$ is radiated (differently from light quarks) $\Rightarrow$ the final heavy-heavy mesons (quarkonia) J/Ψ and Υ carry almost the whole momentum of the jet

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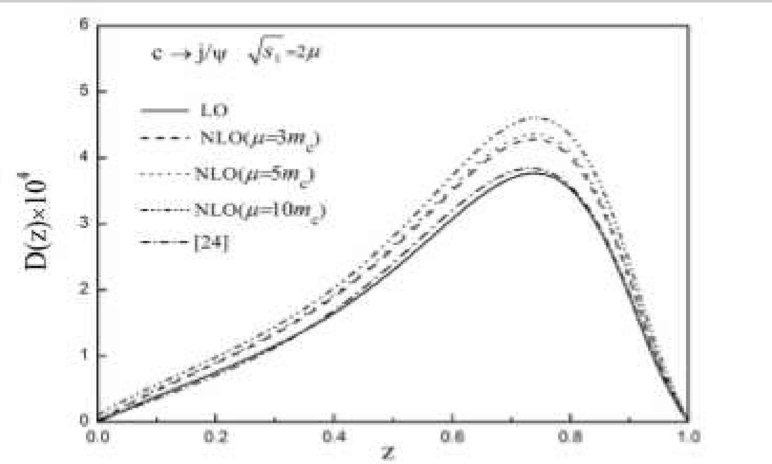

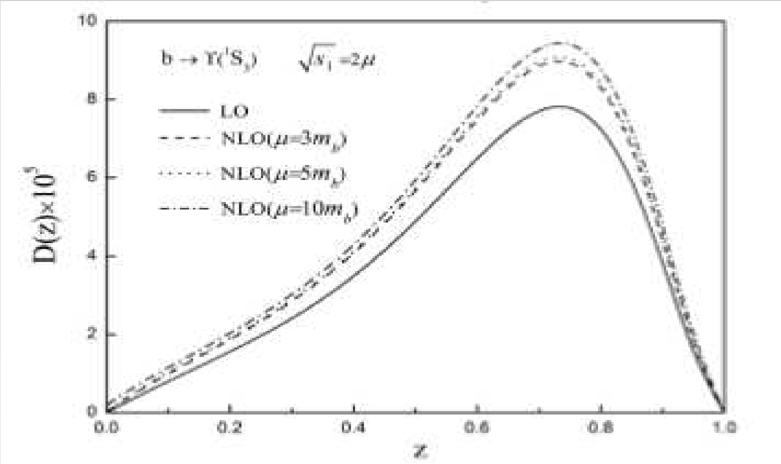

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- Such an expectation is in accordance with calculations of the FFs $c \to J/\Psi$ and $b \to \Upsilon$ $\Rightarrow$ large z are enhanced.

  [R. Sepahvand, and S. Dadfar; Phys.Rev. D**95**, 034012 (2017)]

  [Y.-Q. Ma, J.-W. Qiu, and H. Zang; Phys.Rev. D**89**, 094029 (2014)]

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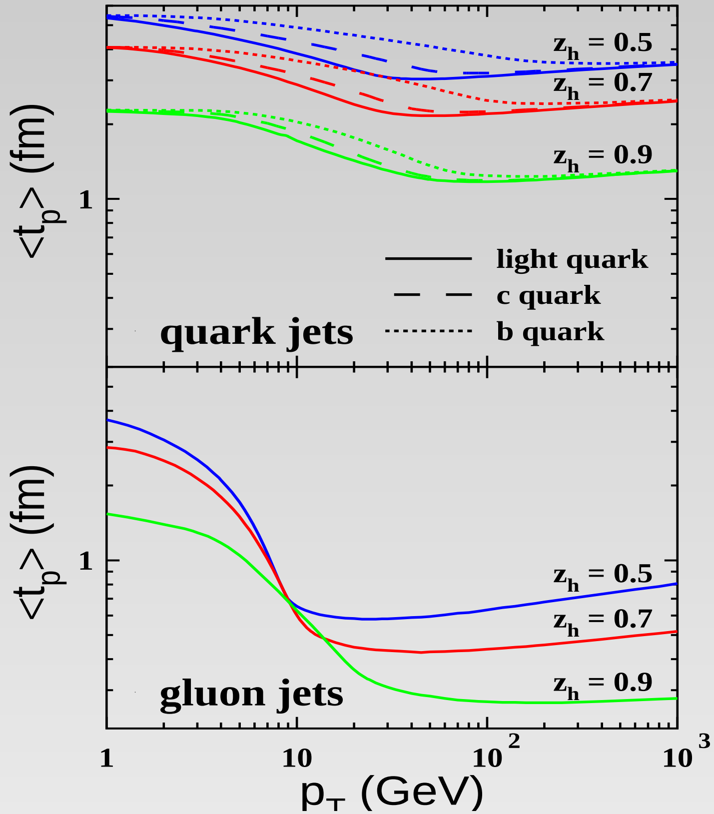

- $\langle l_p(p_T) \rangle$ was derived within a model for perturbative hadronization.

[B.Z. Kopeliovich, et al.; Phys.Lett. B**662**, 117 (2008); Phys.Rev. C**83**, 021901 (2011)]

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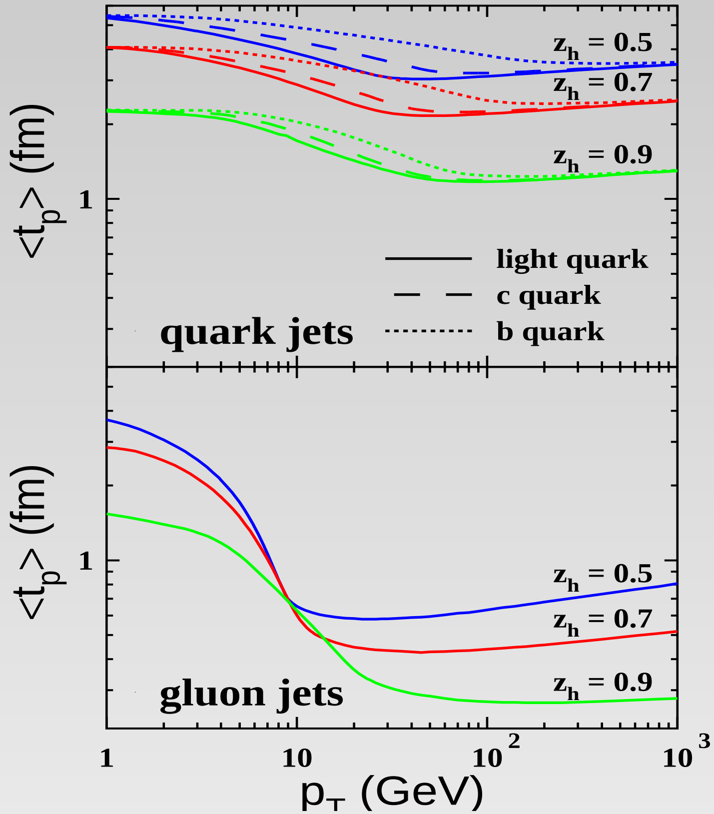

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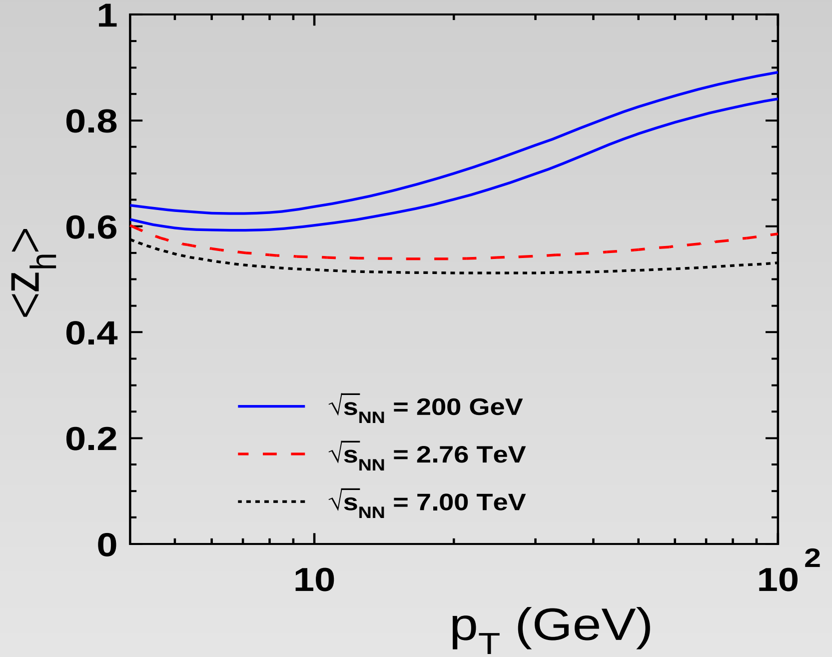
- Combination of the vacuum energy loss and Sudakov suppression for radiation of gluons with energy $> (1 - z_h)E$ leads to rather short l_p.

Radiative energy loss in vacuum production length



- Inclusive production of hadrons with large p_T enhances the large-z_h part of the FF $D(z_h, Q^2)$.

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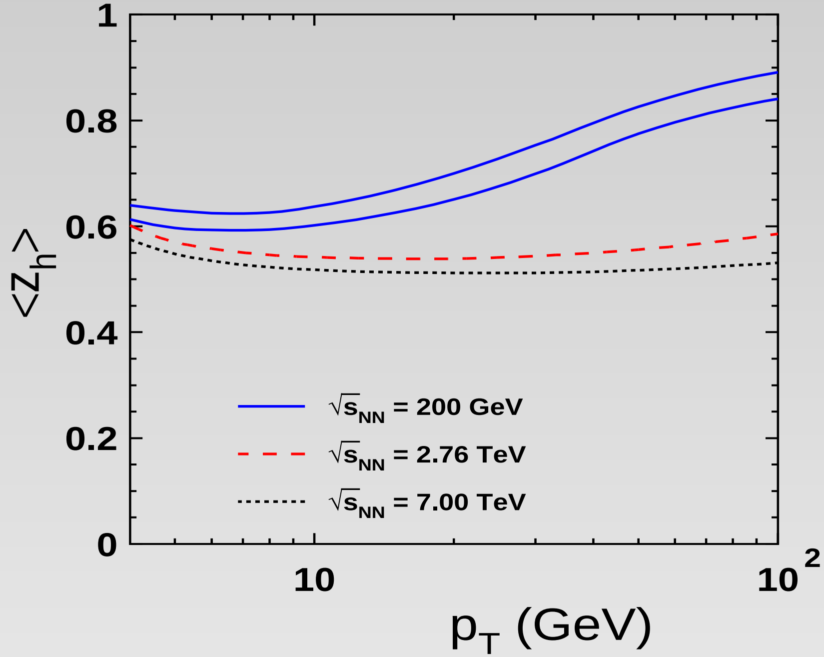

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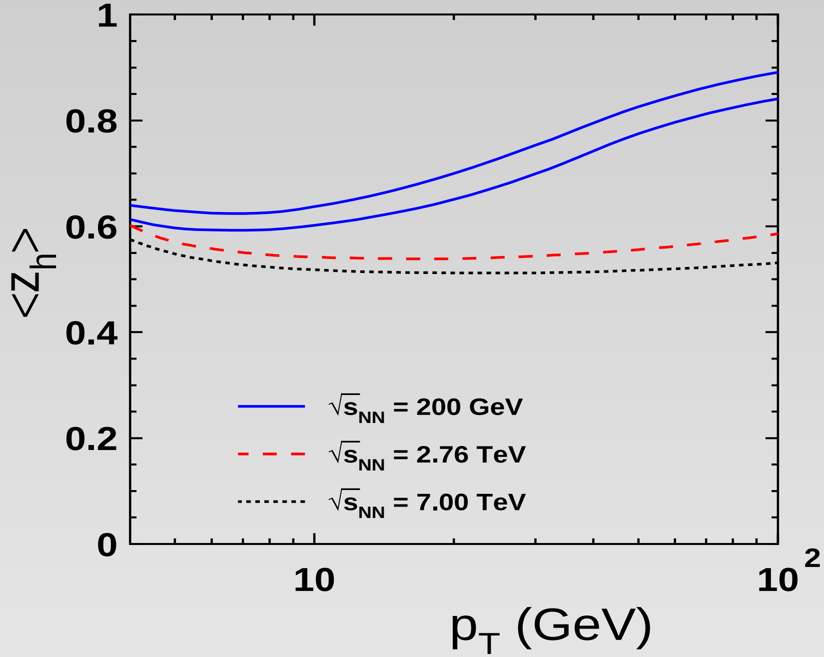

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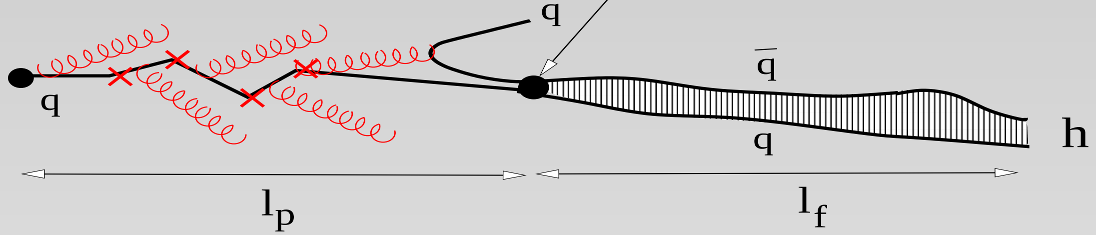
- For heavy quarks the mean $\langle z_h \rangle$ is even larger due to a shape of FFs peaking at $z_h \sim 0.7 \div 0.8$.

Evolution and attenuation of dipoles



II. stage - ⇒ ingredients for calculation of attenuation of dipoles:

- Production length $\boldsymbol{l_p}$ - we demonstrated that $\boldsymbol{l_p}$ is short ⇒ evolution and attenuation of the produced dipole in a medium represents the main source of the observed suppression in production of high-$\boldsymbol{p_T}$ hadrons.

⇒ Survival probability for $\bar{q}q$ dipole propagating through a medium

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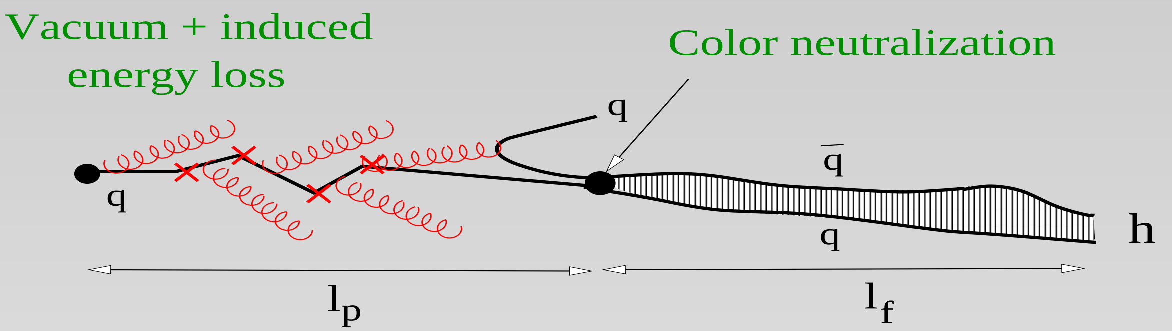

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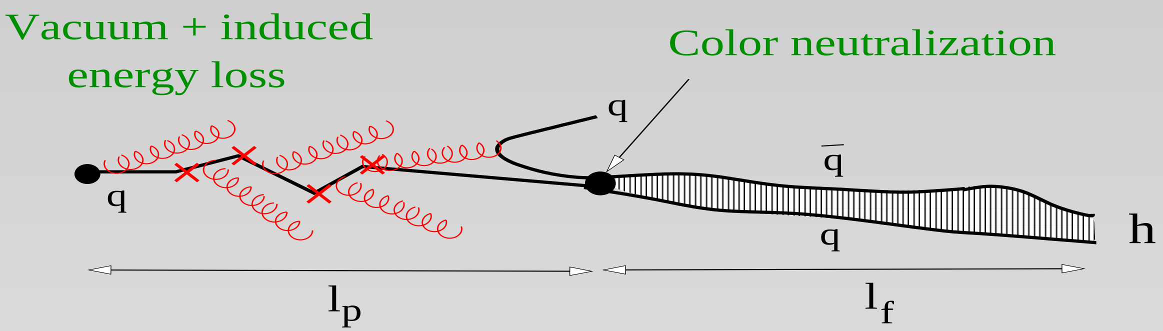

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- Evolution of the transverse dipole size, $r_T(t)$ or $r_T(l)$.
- Properties of a medium created after heavy ion collisions.

⇒ Survival probability for $\bar{q}q$ dipole propagating through a medium

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- Then the time dependent transport coefficient reads:

$$\hat{q}(t, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0\, t_0}{t} \frac{n_{part}(\vec{b}, \vec{\tau})}{n_{part}(0, 0)}.$$

[X.F. Chen, C. Greiner, E. Wang, X.N. Wang, Z. Xu; Phys.Rev. C81, 064908 (2010)]

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- The parameter $\hat{q}_0$ represents the maximal value of $\hat{q}$, for the medium produced at $t = t_0$ in central collision at $b = \tau = 0$.

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- $\hat{q}_0 \sim 2.0\ \mathrm{GeV}^2/\ \mathrm{fm}$ is the fitted parameter from the analysis of LHC data on production of light hadrons in central heavy-ion collisions.

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- Variable $\vec{b}$ - impact parameter of collision; variable $\vec{\tau}$ - impact parameter of position of the parton.

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$r_T(t)$- evolution of a dipole (Heuristic consideration)

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  $\Rightarrow$ the medium becomes more transparent with rising energy of the dipole, E.

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- The transverse expansion of a $\bar{q}q$ dipole reads:

$$\frac{dr_T}{dt} = \frac{k_T(t)}{\alpha(1-\alpha)\,E}$$

α - fractional light-cone momentum of the parton.

[B. Kopeliovich, J.N.; J.Phys. G**38**, 043101 (2011); B. Kopeliovich, et al.; Phys.Rev. C83, 021901

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- Applying the uncertainty relation $k_T(t) \sim 1/r_T(t)$, we get,

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- Such a behavior of the mean separation can be also obtained within the more rigorous path integral technique for the early stage of expansion, while $r_T < r_h$.

  [B.Z. Kopeliovich, B.G. Zakharov; Phys.Rev. D**44**, 3466 (1991), B.Z. Kopeliovich, A. Schäfer, A.V. Tarasov; Phys.Rev. D**62**, 054022 (2000), J.N.; Phys.Rev. C**68**, 035206 (2003)].

Evolution and attenuation of dipoles

Survival probability (Heuristic consideration)

- Survival probability characterizing a propagation of a dipole over path length L in a medium reads:

$$S(L) = \exp\left[-\int_0^L dl\,\sigma[r_T(l)]\,\rho_A(l)\right]$$

(dipole cross section $\sigma(r_T)$ times the medium density ρ_A) $\equiv$ the attenuation rate of the dipole.

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- The dipole cross section for small dipoles: $\sigma(r_T) = C\,r_T^2$, where the factor C for dipole-proton interaction is fixed from DIS data.
- The factor C is unknown for a hot medium $\Rightarrow$ it is convenient to express it in terms of the transport coefficient.

Evolution and attenuation of dipoles

Survival probability (Heuristic consideration)

- The factor C is related to the transport coefficient $\hat{q}$, which is broadening per unit of length:

$$C = \frac{\hat{q}}{2\rho_A}\,.$$

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Evolution and attenuation of dipoles

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CFRJS

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- Then the survival probability of the dipole in a medium reads:

$$S(L) = \exp\left[-\frac{1}{2}\int_0^L dl\,\hat{q}(l)\,r_T^2(l)\right].$$

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- Using above mentioned expression for r_T

$$r_T^2(l) = \frac{2\,l}{\alpha(1-\alpha)\,\tilde{E}} + r_0^2\,.$$

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- and neglecting $r_0^2 \sim 1/p_T^2$ at large p_T, we get the final expression for the survival probability of the dipole in a medium

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Evolution and attenuation of dipoles

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Evolution and attenuation of dipoles CFRJS

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- For instance at $p_T = 10$ GeV the light mesons are formed on a long distance $\sim 10 \div 20$ fm, but $t_f^{J/\Psi} \sim 1.2$ fm and $t_f^{\Upsilon} \sim 0.5$ fm.

Evolution and attenuation of dipoles

(Path-integral technique)

- the corresponding attenuation factor

$$S_{AB}(\vec{b},\vec{\tau},p_T) = \frac{\int\limits_0^{2\pi} \frac{d\phi}{2\pi} \left| \int\limits_0^1 d\alpha \int d^2r_1 d^2r_2\, \Psi_h^\dagger(\vec{r}_2,\alpha) G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2) \Psi_{in}(\vec{r}_1,\alpha) \right|^2}{\left| \int\limits_0^1 d\alpha \int d^2r_1 d^2r_2\, \Psi_h^\dagger(\vec{r}_2,\alpha) \Psi_{in}(\vec{r}_1,\alpha) \right|^2}$$

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- where the Green function satisfies the two-dimensional Schrodinger equation:

$$\left[i\frac{d}{dl_2} - \frac{m_q^2 - \Delta_{r_2}}{2\, m_T\, \alpha\, (1-\alpha)} - V_{\bar{q}q}(\vec{b},\vec{\tau};l_2,\vec{r}_2) \right] G_{\bar{q}q}(\vec{b},\vec{\tau};l_1,\vec{r}_1;l_2,\vec{r}_2) = i\delta(l_2-l_1)\,\delta(\vec{r}_2-\vec{r}_1),$$

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- The imaginary part of the light-cone potential $V_{\bar{q}q}(\vec{b},\vec{\tau};l_2,\vec{r}_2)$ is responsible for absorption in the medium:

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

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- The real part of the light-cone potential describes the nonperturbative interaction between q and $\bar{q}$ in the dipole $\Rightarrow$ for simplicity, $ReV_{\bar{q}q} = 0$ - maximal melting.

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

Evolution and attenuation of dipoles

(Baryons)

- We introduce the Jacobi coordinates, $\vec{s}_1 = (\vec{x}_1 - \vec{x}_2)/\sqrt{2}$ and $\vec{s}_2 = \sqrt{2/3}[\vec{x}_3 - (\vec{x}_1 + \vec{x}_2)/2]$.

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$$\sigma_{3q}(\vec{\rho}_1, \vec{\rho}_2) = \frac{\sigma_{\bar{q}q}(\rho_1)\,\langle\rho_1^2\rangle + \sigma_{\bar{q}q}(\rho_2)\,\langle\rho_2^2\rangle}{\langle\rho_1^2 + \rho_2^2\rangle}\,,$$

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- 3q-Green function:

$$G_{3q}(l_1, \vec{\rho}_{1i}, \vec{\rho}_{2i}; l_2, \vec{\rho}_{1f}, \vec{\rho}_{2f}) =$$
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What are the observables ?

- the cross section of the reaction, $\boldsymbol{A + B \to h + X}$, at given impact parameter $\boldsymbol{b}$ reads

$$\boldsymbol{\sigma_{AB}(b, p_T) = \int_0^\infty d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \times}$$

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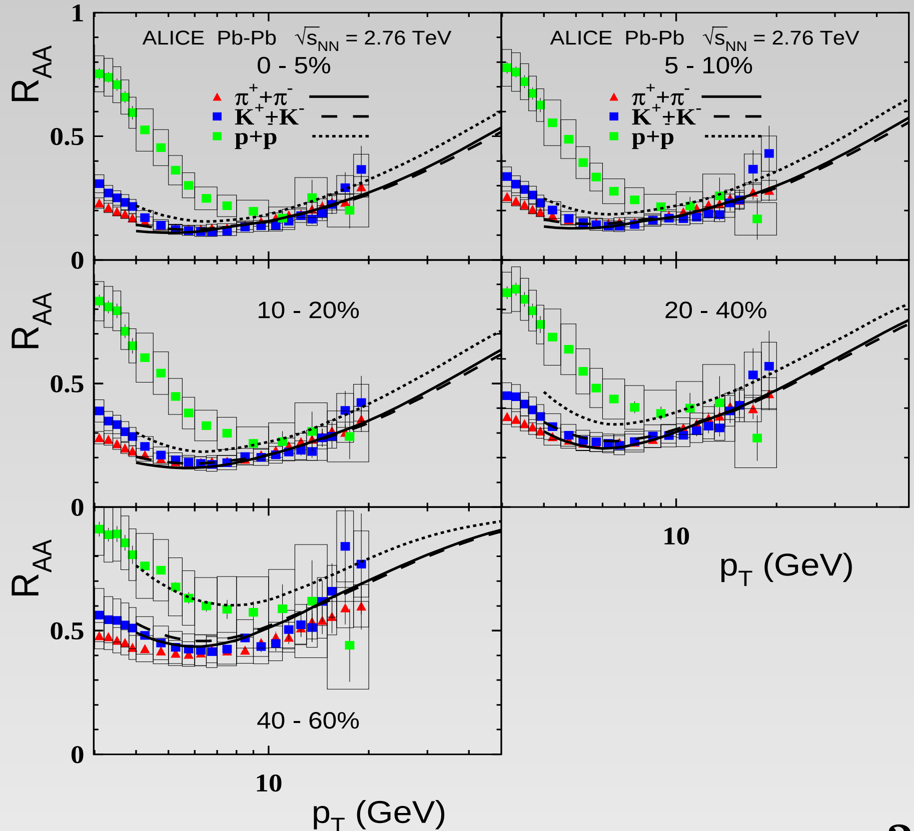
- nuclear attenuation (modification) factor at given impact parameter b

$$R_{AB}(b, p_T) = \frac{\sigma_{AB}(b, p_T)}{\int\limits_0^\infty d^2\tau T_A(\tau) T_B(\vec{b} - \vec{\tau}) \sigma_{pp}(p_T)}$$

Predictions vs data

CFRJS



- The maximal transport coeff. $\hat{q}_0 \sim \mathbf{2}\ \mathrm{GeV}^2/\ \mathrm{fm}$ 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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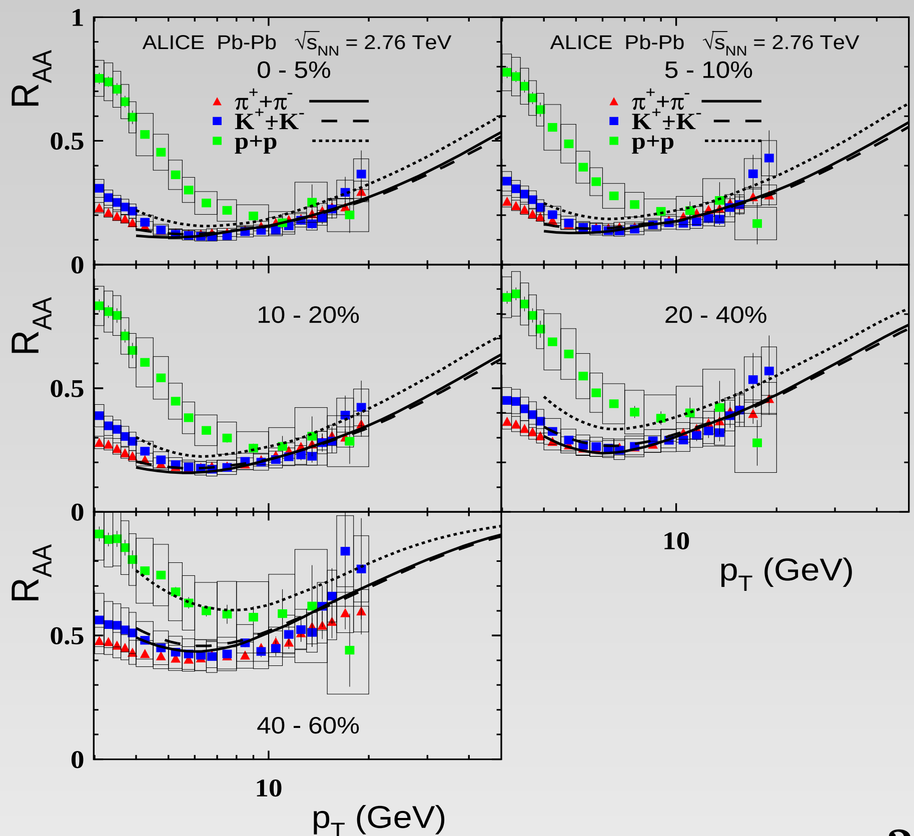

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  [B.Z. Kopeliovich, JN, I.K. Potashnikova, I. Schmidt, Phys.Rev. C**86**, 054904 (2012)]

- Similar suppression in production of pions, kaons and protons in a good agreement with ALICE data

  [J. Adam *et al.* [The ALICE Collaboration], Phys.Rev. C**93**, 034913 (2016)]

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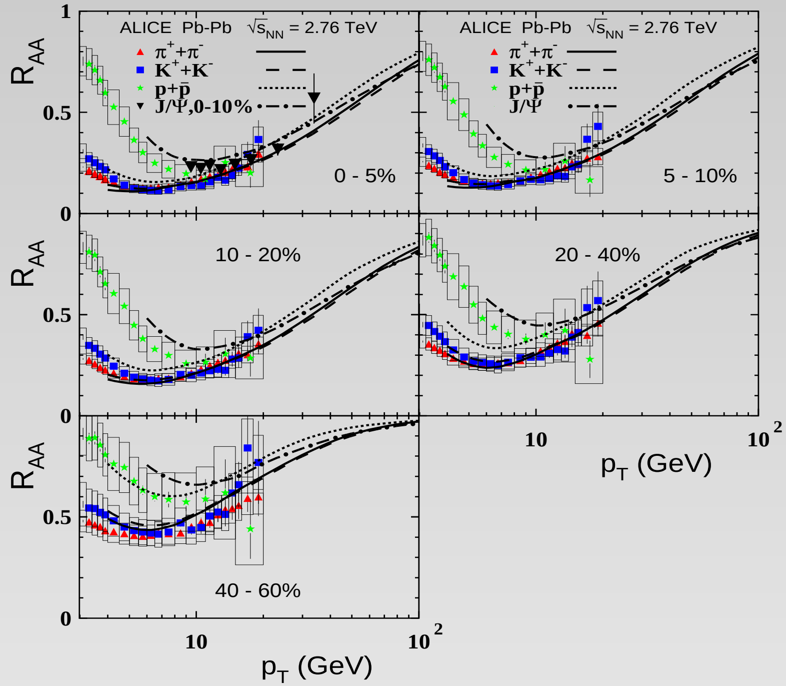

- Universal suppression is controlled by the formation time

$$t_f = \frac{1}{3} \langle r_{ch}^2 \rangle_h \sqrt{p_T^2 + m_h^2}$$

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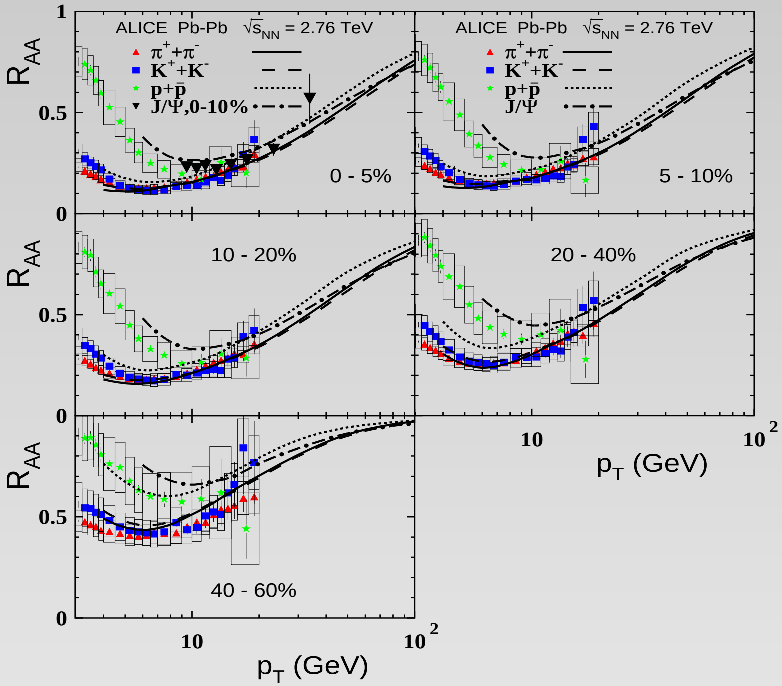

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- As a manifestation of color transparency effects, taking $\langle r_{ch}^2 \rangle_\pi = 0.657^2 \ \mathrm{fm}^2$ and $\langle r_{ch}^2 \rangle_{J/\Psi} = 0.209^2 \ \mathrm{fm}^2 \Rightarrow$ exact universality - $p_T \gtrsim 70 \div 100$ GeV.

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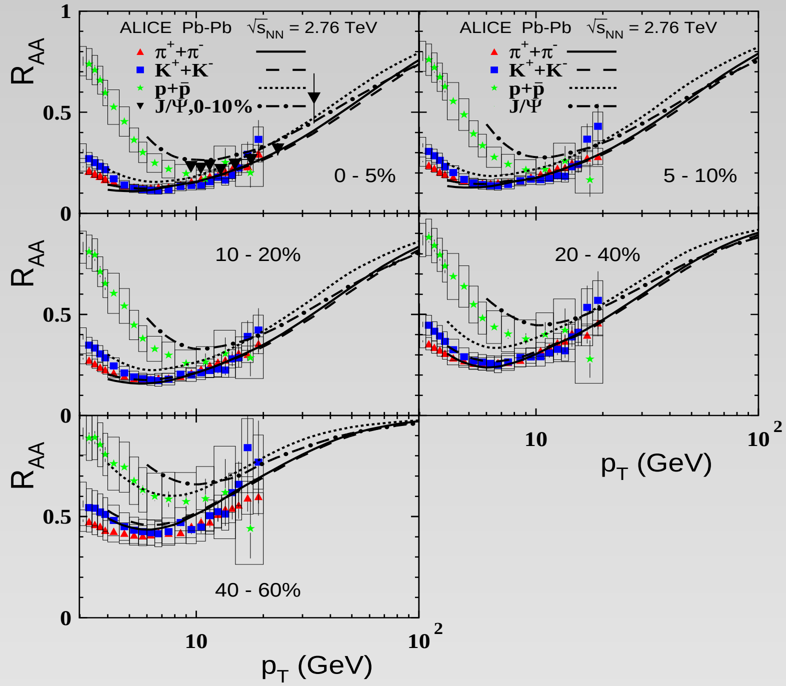

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- The approximate universality is predicted at $p_T \gtrsim 15 \div 20$ GeV in accordance with ATLAS data.

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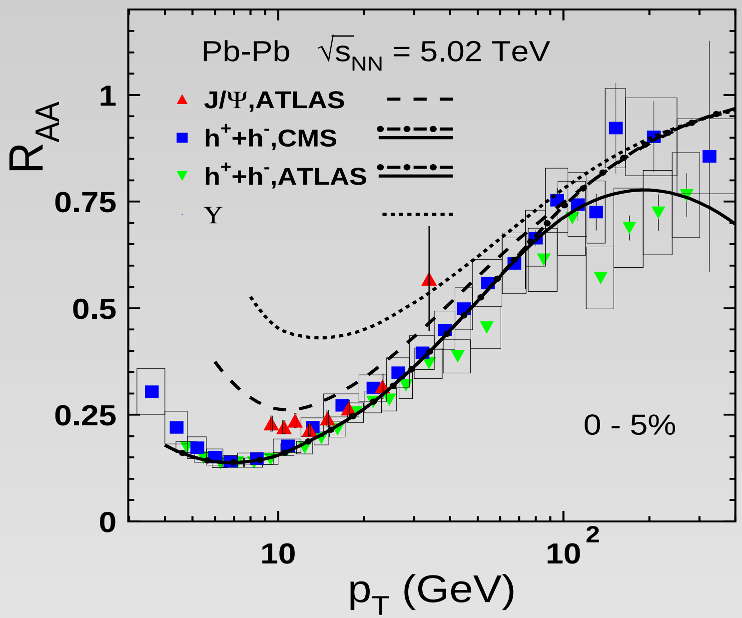

- Taking $\langle r^2_{ch} \rangle_\Upsilon = 0.147^2$ fm^2 ⇒ exact universality - $p_T \gtrsim 300 \div 400$ GeV.

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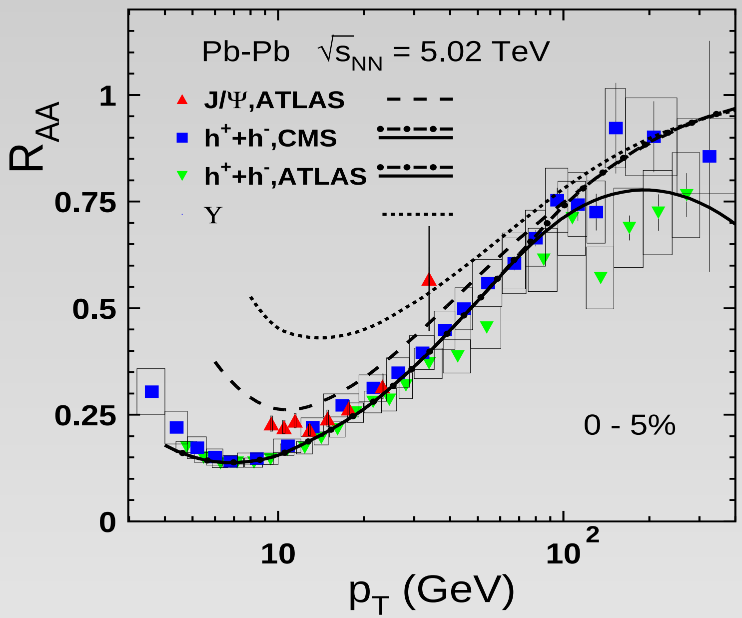

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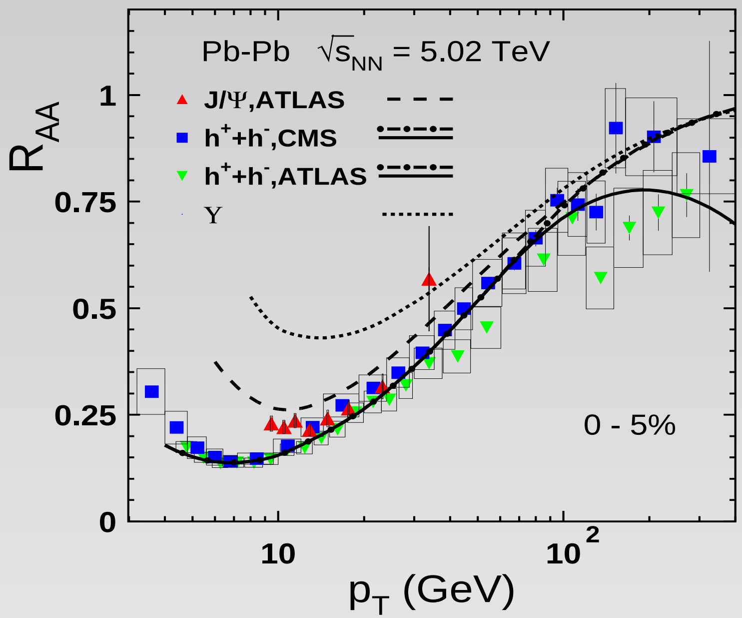

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- Similar suppression in production of light hadrons and Υ is predicted at $p_T \gtrsim 70 \div 100$ GeV which can be tested by future measurements at the LHC.

Summary

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- We predicted the onset of universal suppression controlled by the formation length in production of J/Ψ and Υ.