Heavy mesons in a hot medium: Manifestation of absorption

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In collaboration with

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- Summary & Outlook

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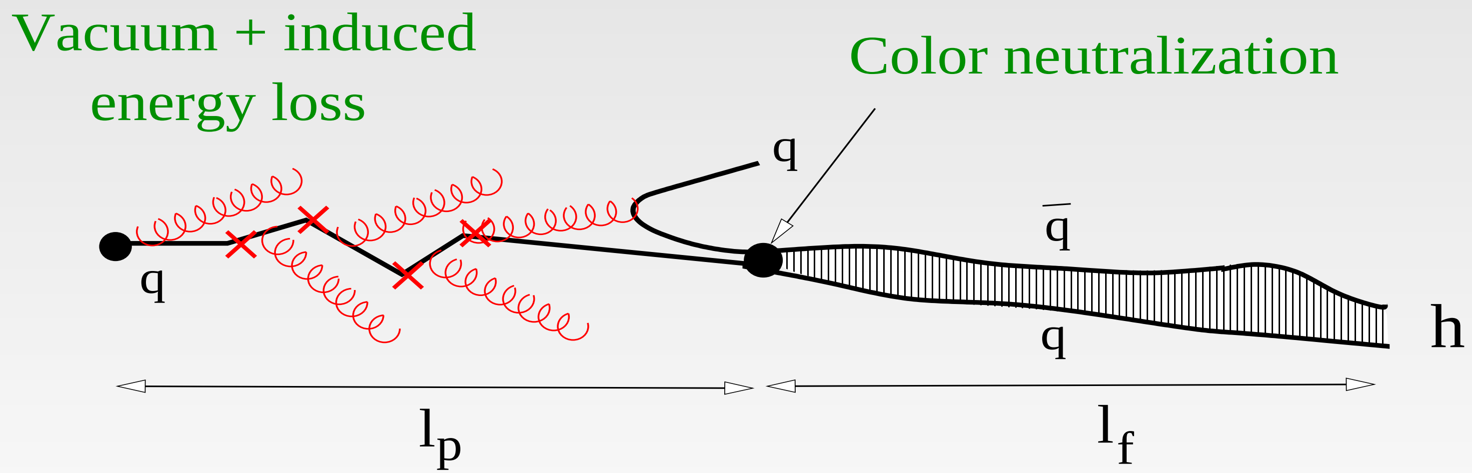
  ⇒ observation of a jet initiated by a parton
  ⇒ detection of a single hadron produced inclusively with large z_h.
- The latter ⟺ to a very rare jet configuration, where the energy deficit imposes certain constraints on its space-time development, which differs from an averaged jet.



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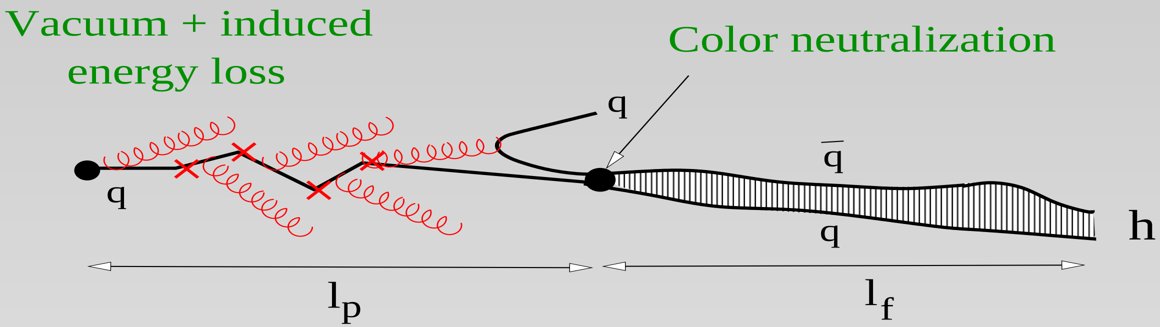


- I. stage ⇒ the quark regererates its color field, which has been stripped off in a hard reaction.

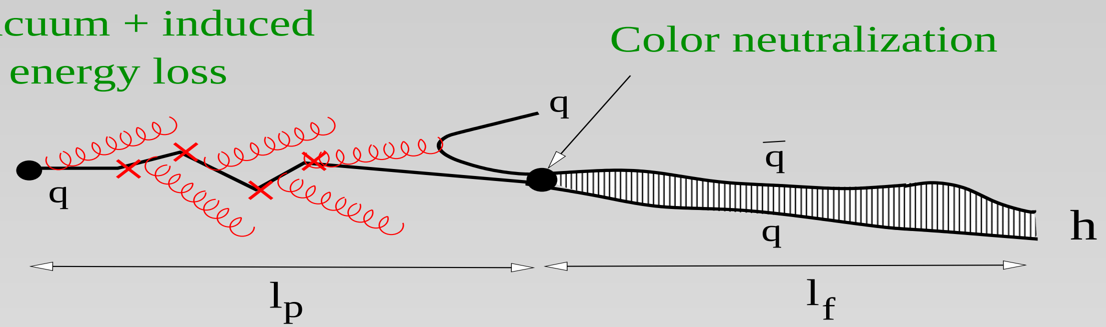
  ⇒ the quark intensively radiates gluons and dissipates energy, either in vacuum or in a medium.

  ⇒ 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.

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

Space-time development of hadronization



- II. stage ⇒ begins with production of colorless dipole (also called prehadron), 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.

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

⇒ 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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- As a result of hard interaction characterized with the scale Q^2 $\Rightarrow$ the parton is produced with part of its color field stripped off, up to T-frequencies $k_T \leq Q$. Subsequent regeneration of the parton color field is associated with radiation of gluons, which take away a part of the parton energy and contribute to formation of the jet.

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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:

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

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

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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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- The step function $\Theta(t-t_c^g)$ creates another dead cone (effective at small distances) $\Rightarrow$ no gluon can be radiated unless its T-momentum is sufficiently high,

$$k^2 > \frac{2Ex(1-x)}{t} - x^2m_q^2$$

Radiative energy loss in vacuum

- This bound relaxes with the rise of t and reaches the magnitude $k^2 \approx x^2 m_q^2$ characterizing the the heavy quark dead cone at

$$t = L = L_q = \frac{E(1-x)}{x m_q^2}$$

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- $\Rightarrow$ L_q for b is an order of magnitude shorter than for c
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- Substantial difference between radiation of energy by c and light quarks onsets already at small distances $L \gtrsim 0.5 \div 1$ fm $\Rightarrow$ revision of the statement from

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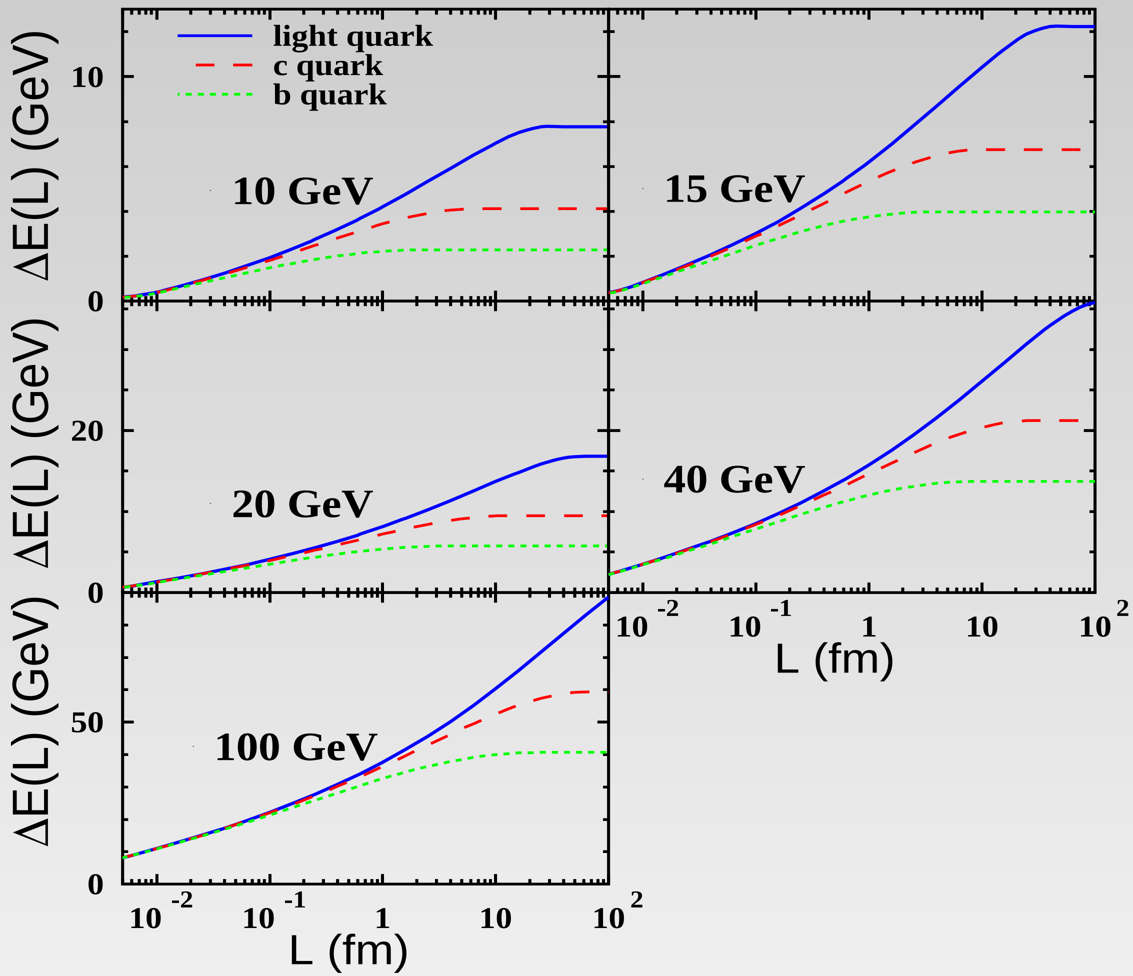
Radiative energy loss in vacuum



- The b-quark radiation is suppressed already at rather short distances.

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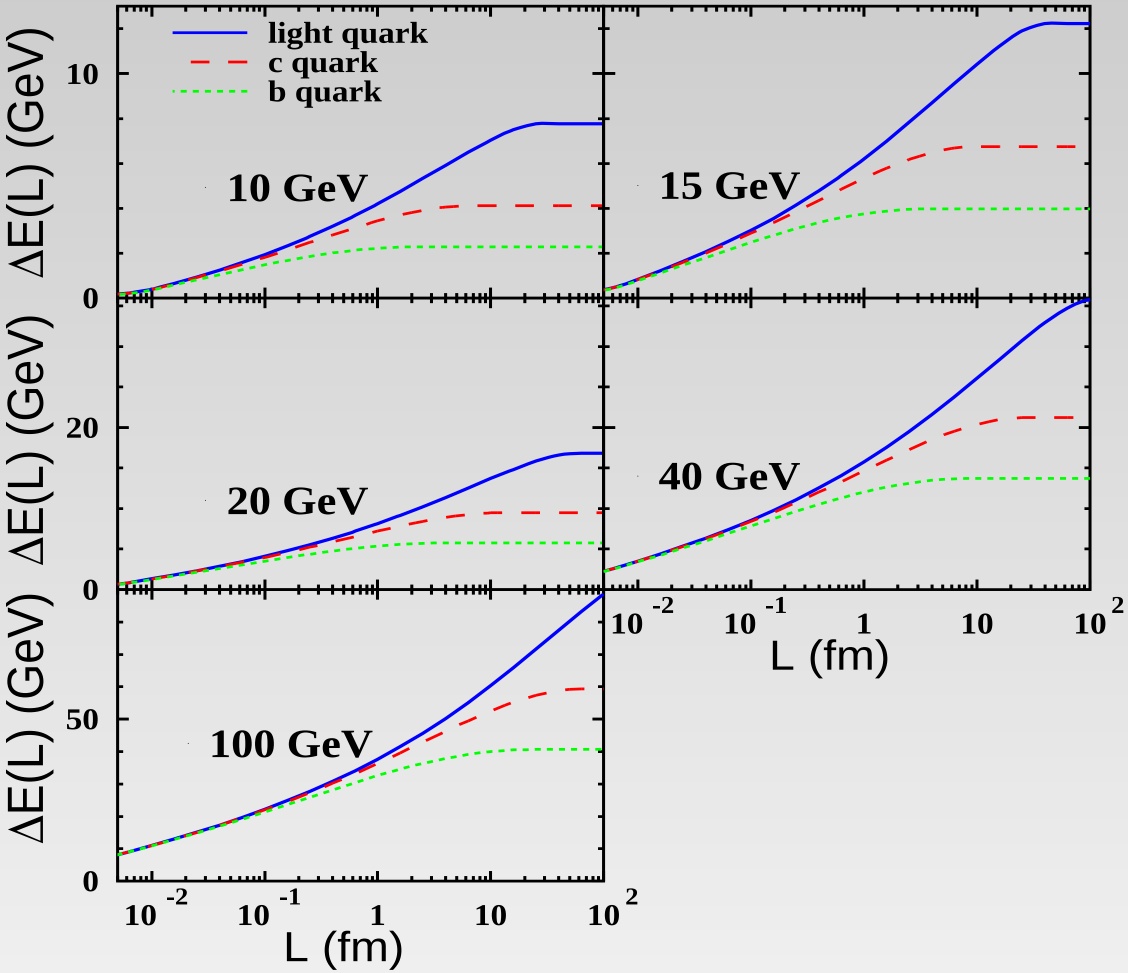
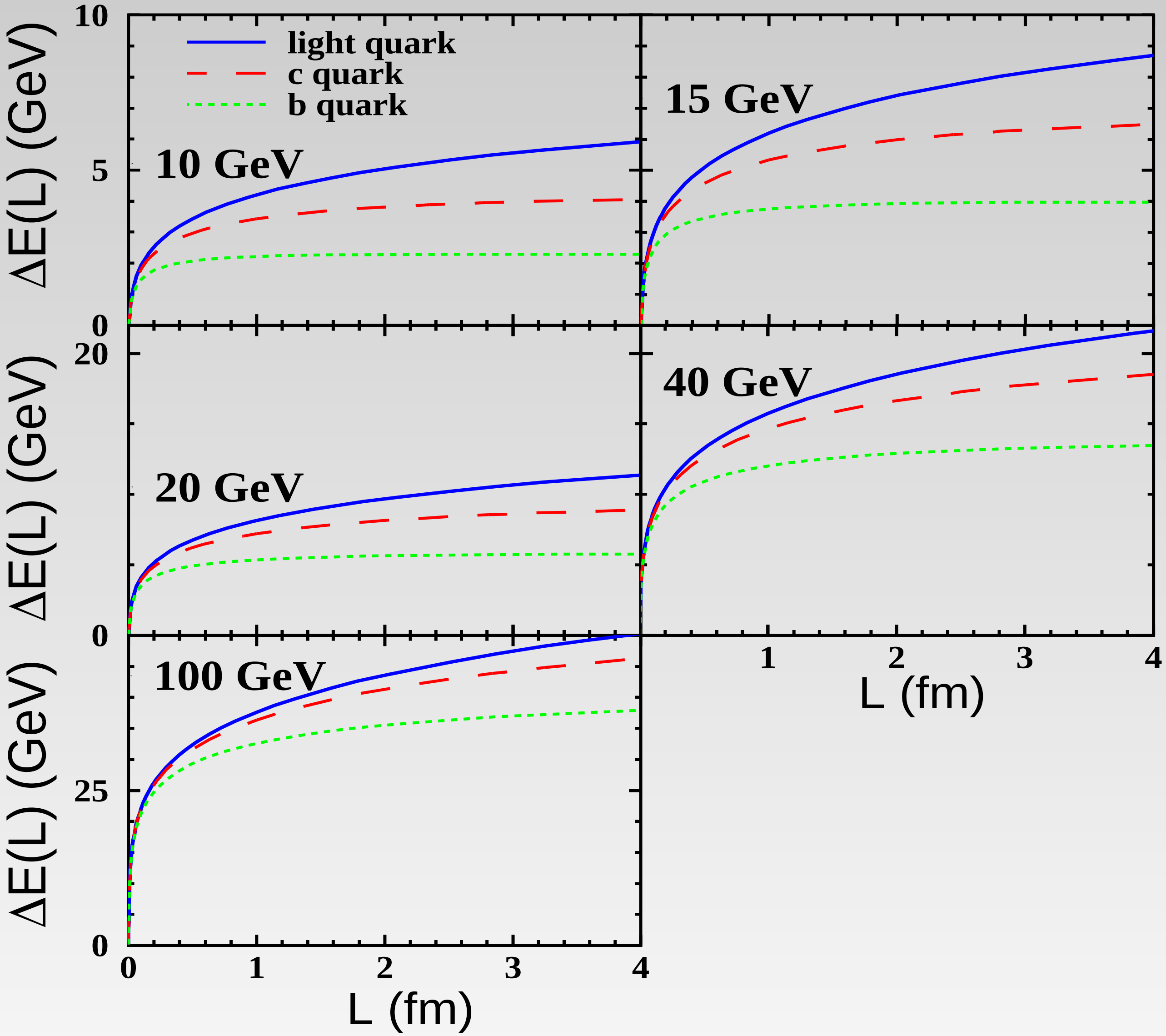


- The b-quark radiation is suppressed already at rather short distances.
- A half of the total radiated energy is lost during the first 1 fm (light quark).

Radiative energy loss in vacuum



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

Radiative energy loss in vacuum

Using the approximate relation

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

SIDIS $\Rightarrow$ the energy and scale are two independent variables and usually $E^2 \gg Q^2$.

- Energy dependence at fixed scale $\Rightarrow$ $\langle|dE/dl|\rangle$ is fixed $\Rightarrow$ $l_p \propto E$.

high-p_T jets $\Rightarrow$ the energy and scale are strongly correlated, $E = p_T, Q^2 \sim p_T^2$.

- l_p rises with E but simultaneously decreases with the scale Q^2 $\Rightarrow$ indefinit answer whether $l_p(p_T)$ rises or falls.

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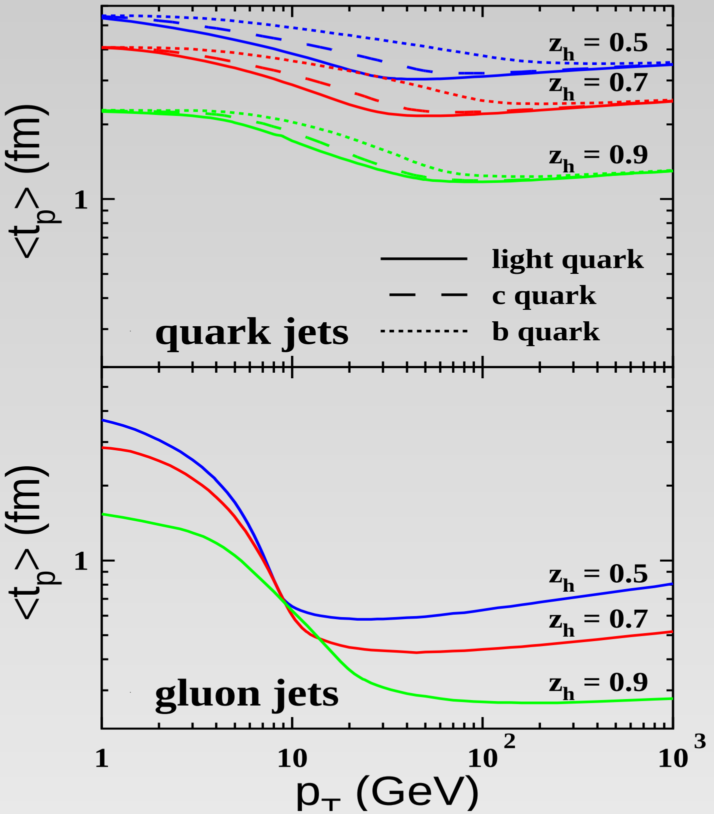

- $\langle l_p(p_T)\rangle$ was derived within a model for perturbative hadronization.

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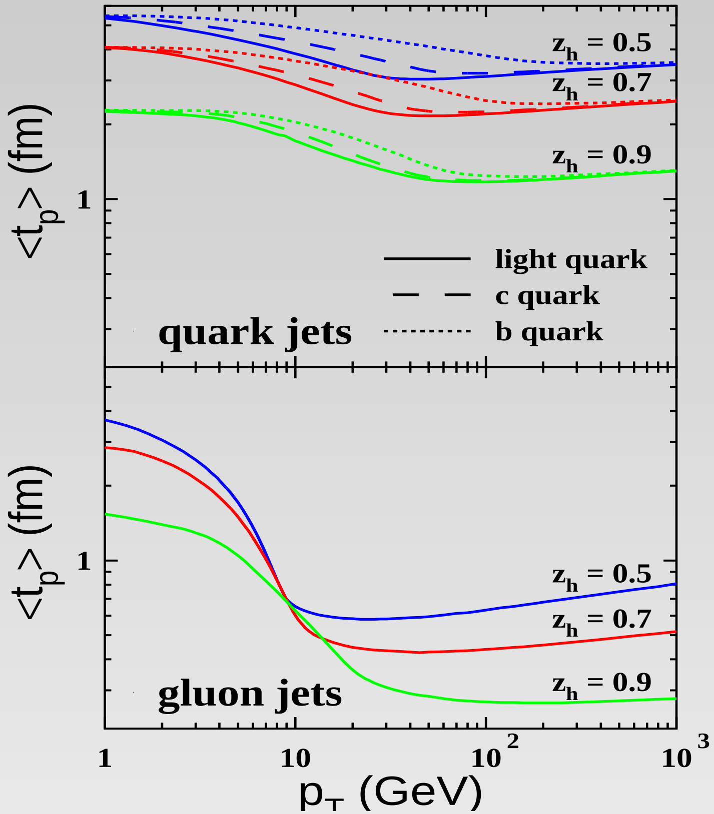

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- Combination of the vacuum energy loss and Sudakov suppression for radiation of gluons with energy $> (1 - z_h)E$ leads to rather short l_p.

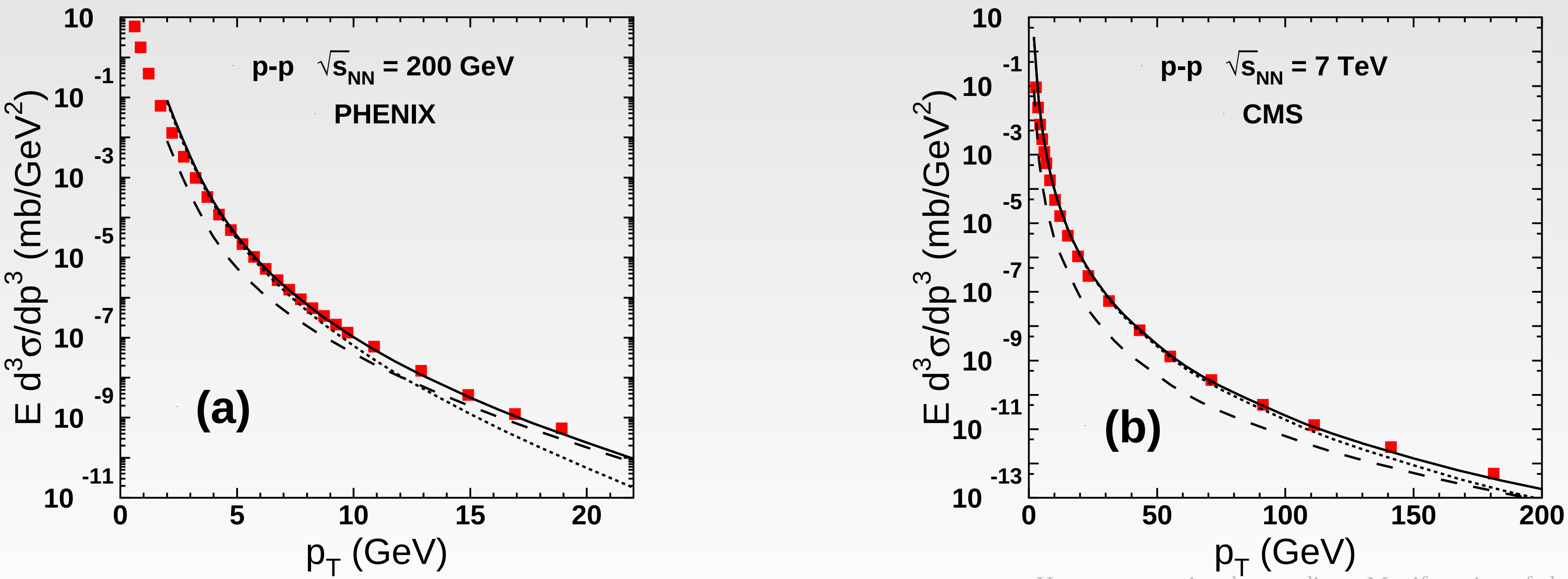
Production length for inclusive hadron production

The mean value $\langle z_h \rangle$ is controlled by the convolution:

$$\frac{d\sigma_{pp}}{dy\, d^2p_T} = K \sum_{i,j,k,l} \int dx_i dx_j d^2k_{iT} d^2k_{jT}$$

$$\times \; F_{i/p}(x_i, k_{iT}, Q^2)\, F_{j/p}(x_j, k_{jT}, Q^2)$$

$$\times \; \frac{d\sigma}{d\hat{t}}(ij \to kl)\, \frac{1}{\pi\, z_h}\, D_{h/k}(z_h, Q^2).$$



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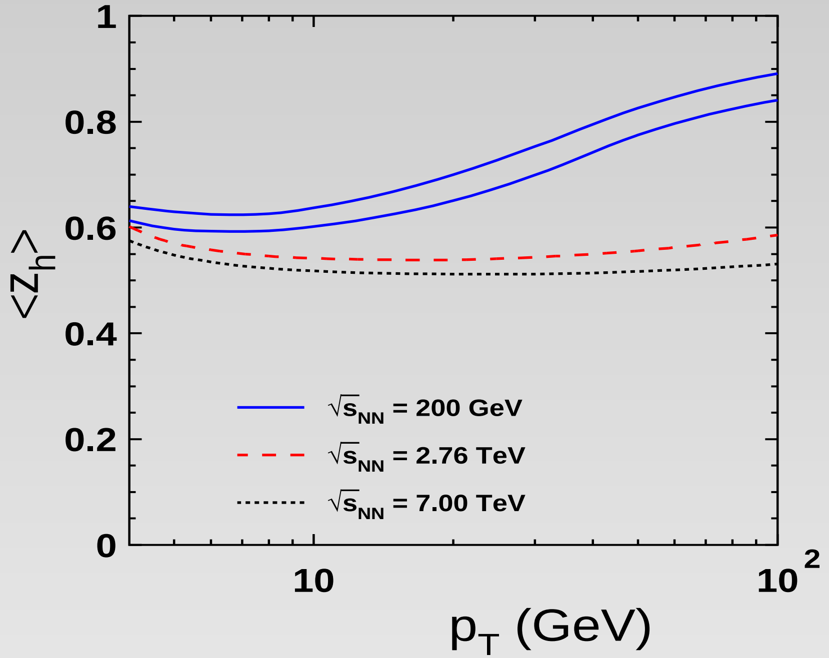

- Inclusive production of hadrons with large p_T enhances the large-z_h part of the FF $D(z_h, Q^2)$.

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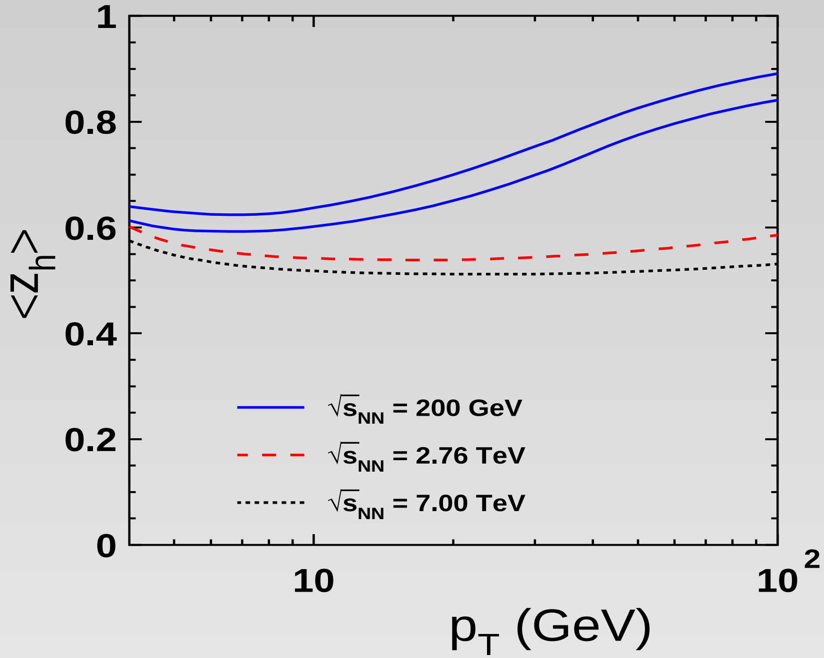

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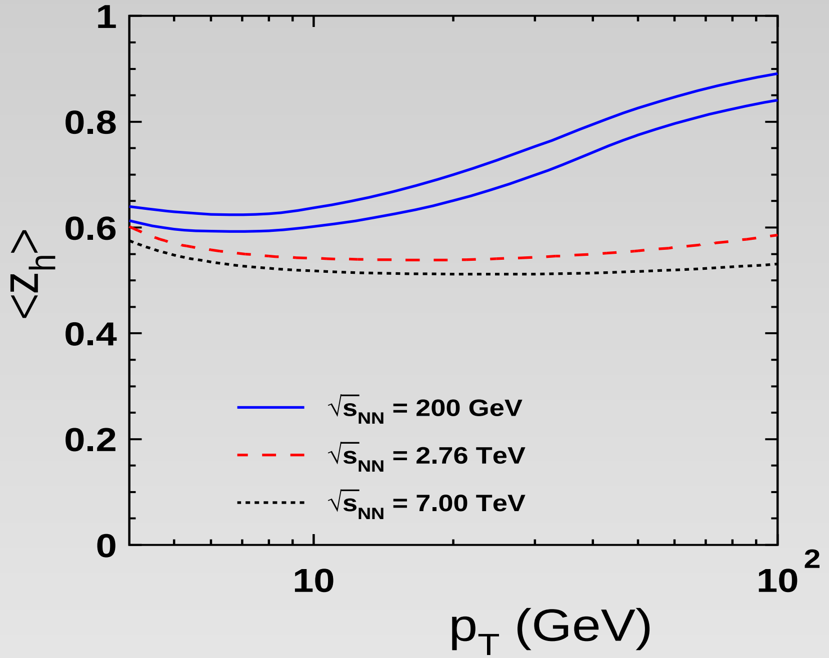

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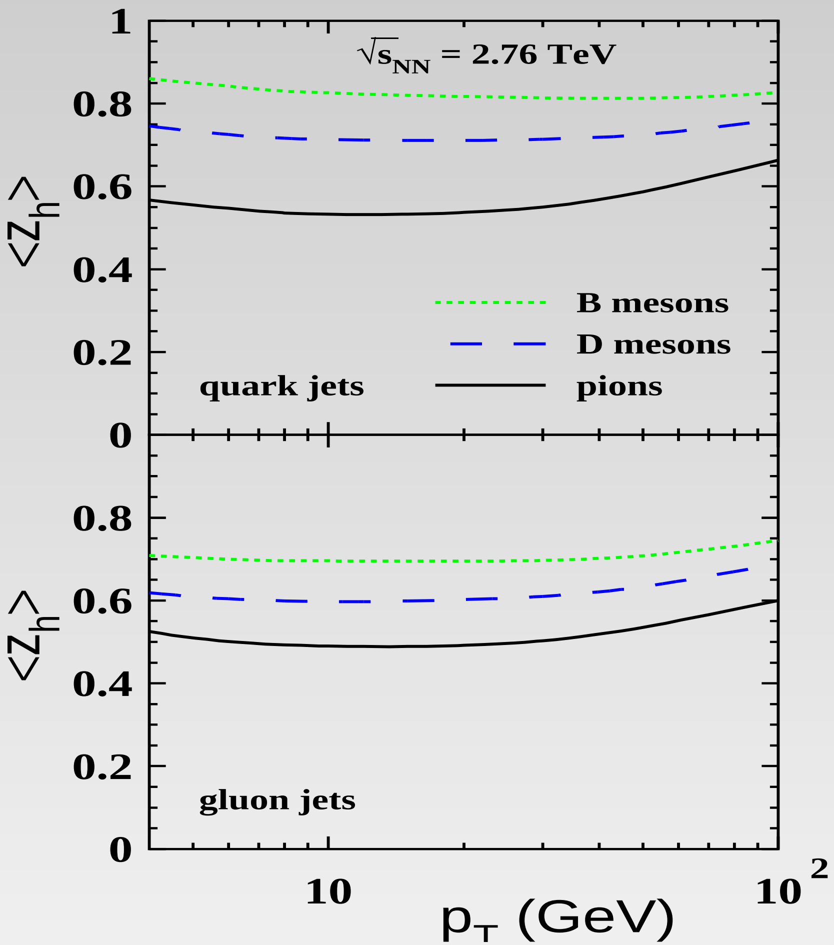
- This happens due to the steepness of the k_T spectrum of the produced partons which has to be convoluted with the FF.

- The mean fractional momentum $\langle z_h \rangle$ decreases with collision energy, but remains large, $\langle z_h \rangle > 0.5$.

Production length for inclusive hadron production



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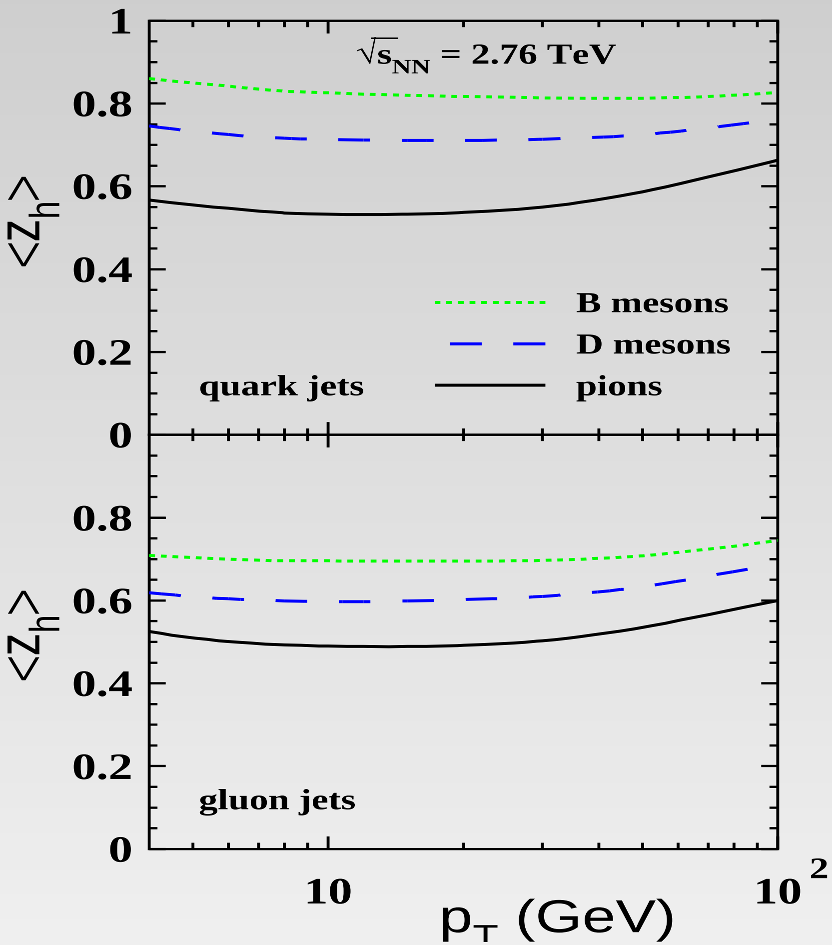

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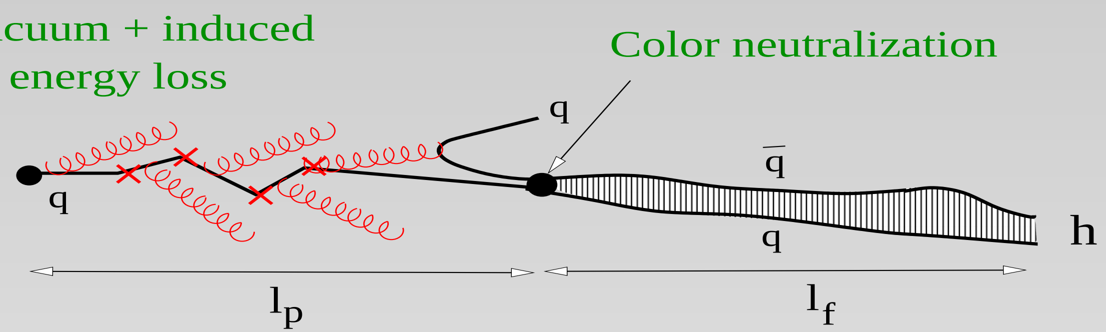
Evolution and attenuation of dipoles



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.

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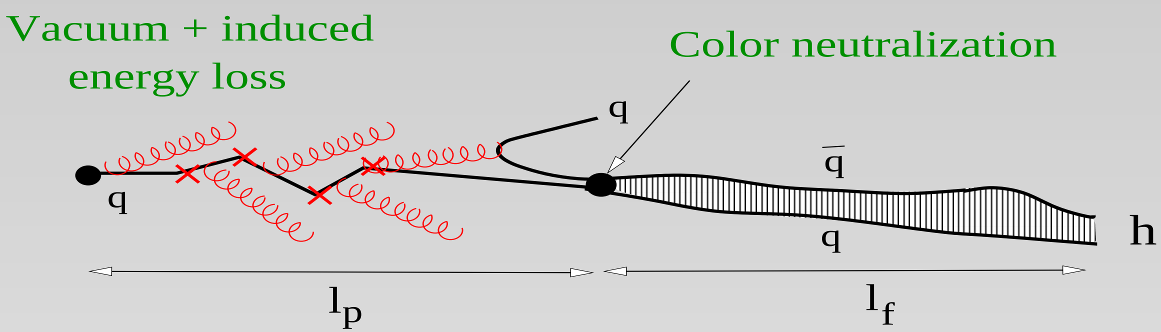

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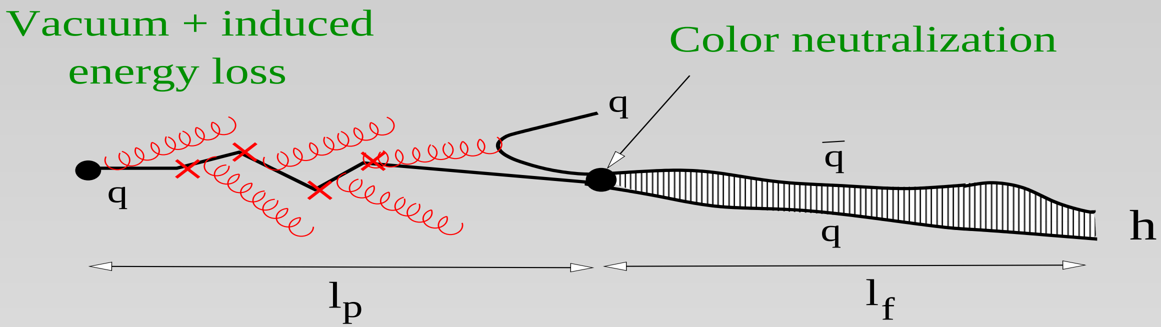

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- Properties of a medium created after heavy ion collisions.

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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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- Variable $\vec{b}$ - impact parameter of collision;
  variable $\vec{\tau}$ - impact parameter of position of the parton.
- The relation between the time and the distance from the hard collision point reads:

$$l = v_D t = \frac{p_D}{E_D} t = \sqrt{1 - \frac{(2m_q^e)^2}{E_D^2}}\, t; \qquad m_q^e = \frac{2m_{q1}m_{q2}}{m_{q1} + m_{q2}}.$$

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- This dipole propagating in a medium attenuates with the cross section $\propto r_T^2$, where r_T^2 is rising with time.
- at low energies - dipole quickly expands to the hadronic size
  at high energies - Lorentz time dilation freezes the initial small size of the dipole for the time of propagation
  $\Rightarrow$ the medium becomes more transparent with rising energy of the dipole, $\tilde{E}$.

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

- During production time t_p a $\bar{q}q$ dipole is created.
- This dipole propagating in a medium attenuates with the cross section $\propto r_T^2$, where r_T^2 is rising with time.
- at low energies - dipole quickly expands to the hadronic size
  at high energies - Lorentz time dilation freezes the initial small size of the dipole for the time of propagation
  $\Rightarrow$ the medium becomes more transparent with rising energy of the dipole, $\tilde{E}$.
- The transverse expansion of a $\bar{q}q$ dipole reads:

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

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 (2011).]

Evolution and attenuation of dipoles

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

- Applying the uncertainty relation $k_T(t) \sim 1/r_T$, 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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Evolution and attenuation of dipoles

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

$$\boldsymbol{C} = \frac{\hat{\boldsymbol{q}}}{2\boldsymbol{\rho}_{\boldsymbol{A}}}\,.$$

[R. Baier, Yu. Dokshitzer, S. Peigne, D. Schiff; Phys.Lett. B**345**, 277 (1995)]

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- It was demonstrated that the same factor C controls both **dipole cross section** and **broadening**.

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

$$S(L) = \exp\left[-\frac{1}{2}\int\limits_0^L dl\,\hat{q}(l)\,r_T^2(l)\right]\,.$$

Evolution and attenuation of dipoles

Survival probability (Heuristic consideration)

- Using above mentioned expression for r_T

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

Evolution and attenuation of dipoles

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

- 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

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

Evolution and attenuation of dipoles

- The attenuation factor $R_{AB}(\vec{b},\vec{\tau},p_T)$ has the form,

$$R_{AB}(\vec{b},\vec{\tau},p_T) = \int\limits_0^{\pi} \frac{d\phi}{\pi} \exp\left[-\frac{1}{\alpha\,(1-\alpha)\,p_T} \int\limits_{l_{max}(p_T,z_h)}^{\infty} dl\, l\, \hat{q}(l,\vec{b},\vec{\tau}+\vec{l})\right]$$

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- $l_{max}(p_T,z_h) = max\{\langle l_p(p_T,z_h)\rangle, l_0\}$ and $l_0 = v_D t_0, t_0 \sim 1\,\mathrm{fm}$.
- The factor $R_{AB}(\vec{b},\vec{\tau},p_T)$ - the medium attenuation factor in a collision of two heavy nuclei at given impact parameter $\vec{b}$ corresponding to production of a high- k_T parton at impact parameter $\vec{\tau}$, propagating then over a path length $\langle l_p\rangle$, radiating gluons and losing energy, and eventually producing a colorless dipole (pre-hadron) with transverse momentum $\vec{p}_T = \vec{k}_T\, z_h$, which propagates through the nucleus evolving its size according to $r_T^2(t)$.

Evolution and attenuation of dipoles

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

- Within the simplified heuristic model, the expression

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

describes the expansion of the dipole in vacuum.

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Evolution and attenuation of dipoles

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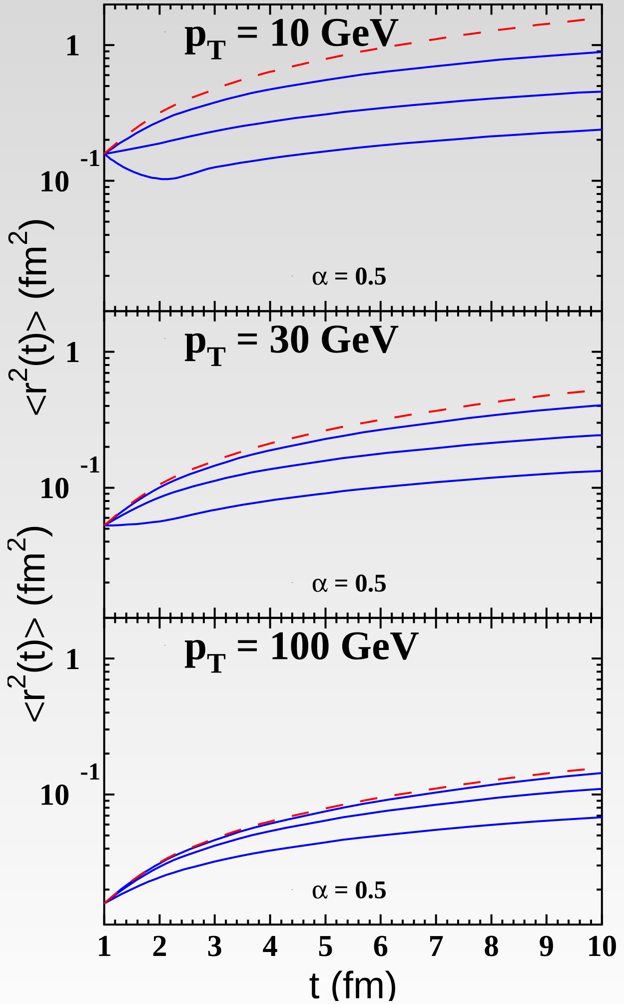
- Including an absorptive term, we arrive at a modified evolution equation:

$$\frac{dr_T^2(t)}{dt} = \frac{2}{\alpha(1-\alpha)\,\tilde{E}} - \frac{1}{2}\,\hat{q}(t) r_T^4(t).$$

Evolution and attenuation of dipoles

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

- The analytical solution of the evolution equation including color filtering (CF) effects can be found in
  [J.N., R. Pasechnik, I.K. Potashnikova; Eur.Phys.J. C**75**, 95 (2015).]



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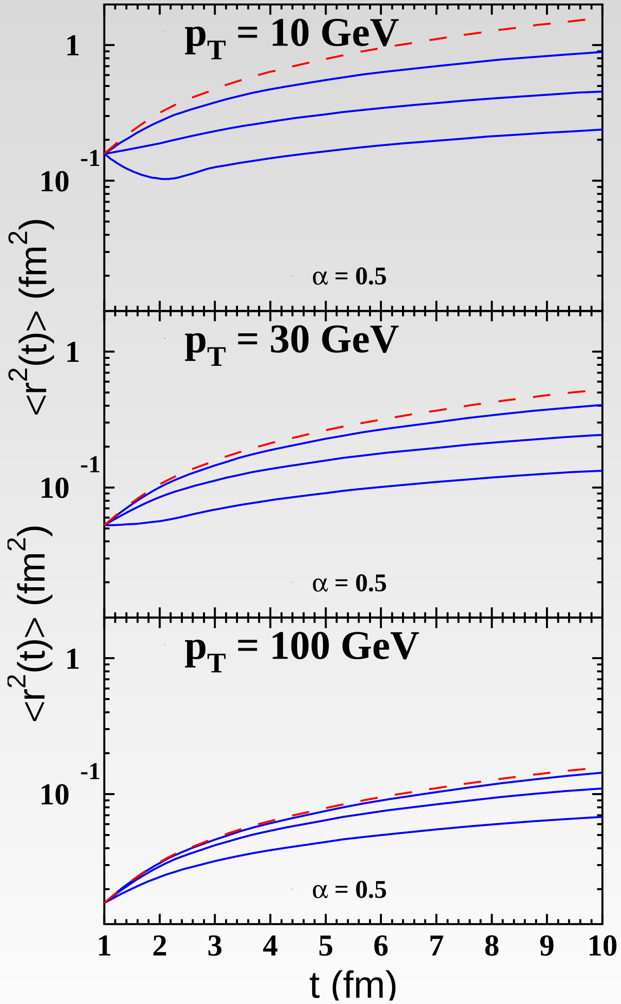

- Reduction of $\langle r_T^2(t)\rangle$ due to CF effects makes the medium more transparent and depends strongly on $\hat{q}_0$. The larger is $\hat{q}_0$, the stronger is the reduction.

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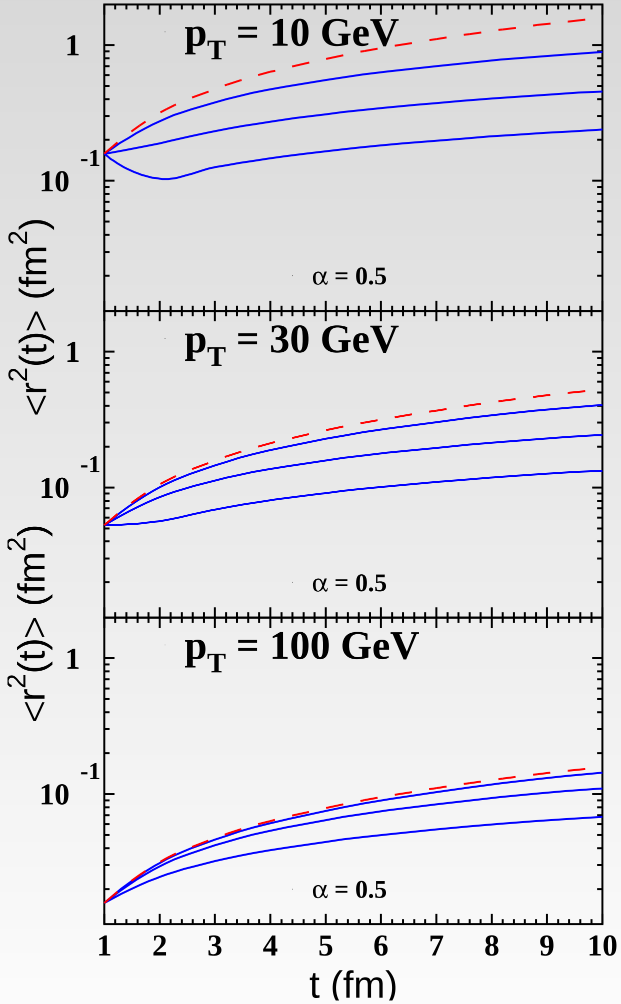

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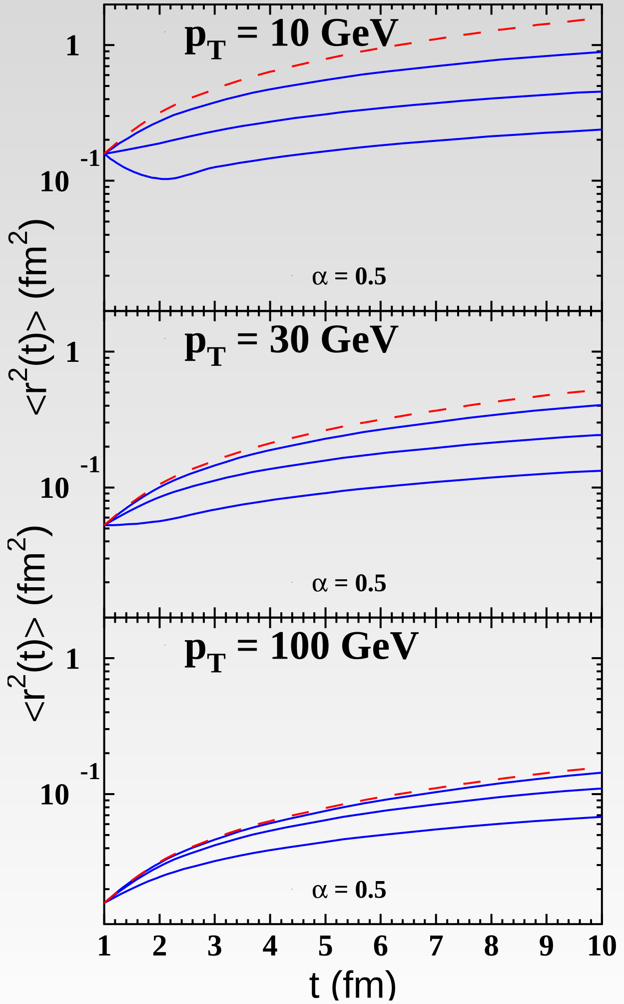

- Reduction of $\langle r_T^2(t)\rangle$ due to CF effects makes the medium more transparent and depends strongly on $\hat{q}_0$. The larger is $\hat{q}_0$, the stronger is the reduction.
- CF reduction of $\langle r_T^2(t)\rangle$ gradually decreases with p_T.
- CF effects are naturally included in the Green function formalism based on the path-integral technique.

Evolution and attenuation of dipoles

(Path-integral technique)

- the corresponding attenuation factor

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

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

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

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

$$= i\delta(l_2 - l_1)\,\delta(\vec{r}_2 - \vec{r}_1),$$

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

Evolution and attenuation of dipoles

(Path-integral technique)

- with the boundary conditions

$$G_{\bar{q}q}(l_1,\vec{r}_1;l_2,\vec{r}_2)\Big|_{l_1=l_2} = \delta(\vec{r}_2-\vec{r}_1);$$

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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.

[B.Z. Kopeliovich, A. Schaefer, A.V. Tarasov; Phys.Rev. D**62**, 054022 (2000)]

[B.Z. Kopeliovich, J.N., A. Schaefer, A.V. Tarasov; Phys.Rev. C**65**, 035201 (2002)]

What are the observables ?

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

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

$$\sum_{i,j,k,l} F_{i/A} \otimes F_{j/B} \otimes \hat{\sigma}_{ij\rightarrow kl} \otimes \tilde{D}_{h/k} R^k_{AB}(\vec{b}, \vec{\tau}, p_T)$$

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

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

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- observable sensitive to the properties of the created medium - azimuthal asymmetry of the produced hadrons relative to the reaction plane ⇒ presented in terms of the second moment of the ϕ distribution, $v_2 \equiv \langle cos(2\phi)\rangle$, at given impact parameter b,

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

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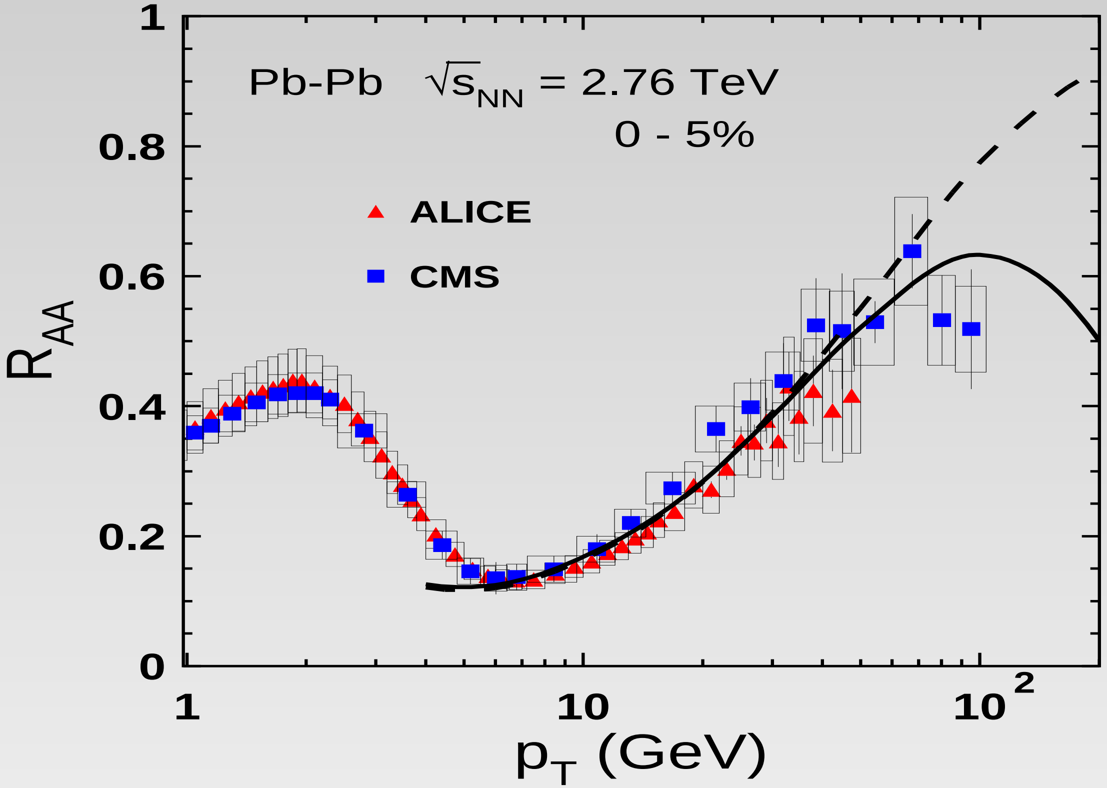
$$J(\vec{b}, \vec{\tau}, \phi) = \int_0^1 d\alpha \int d^2 r_1 d^2 r_2 \, \Psi_h^\dagger(\vec{r}_2, \alpha) G_{\bar{q}q}(\vec{b}, \vec{\tau}; l_1, \vec{r}_1; l_2, \vec{r}_2) \Psi_{in}(\vec{r}_1, \alpha) \,.$$

Numerical results vs. data - R_{AA}

(Inclusive production of light hadrons)



ALICE and CMS data for central, **0-5%**, lead-lead collisions vs. the GF formalism at adjusted $\hat{q}_0 = 2.0\ \mathrm{GeV}^2/\mathrm{fm}$.

[TRIANGLES - ALICE Collaboration, B. Abelev et al.; Phys. Lett. B**720**, 52 (2013).]

[SQUARES - CMS Collaboration, Y.-J. Lee et al.; J. Phys. G **38**, 124015 (2011). A. S. Yoon et al.; J. Phys. G **38**, 124116 (2011).]

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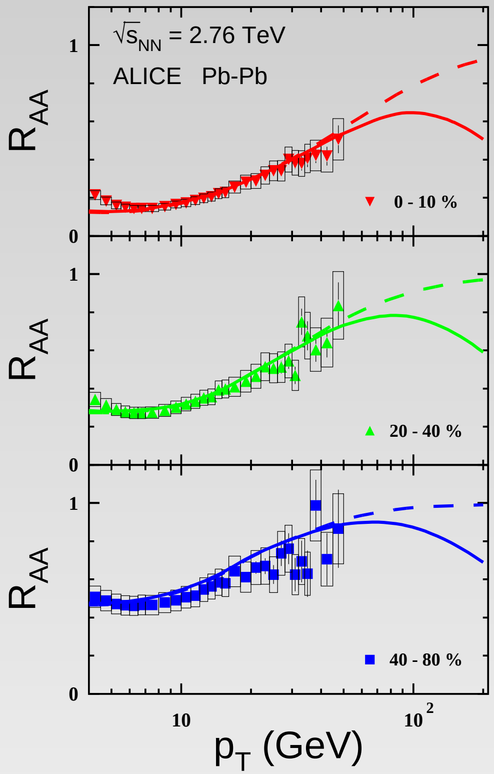

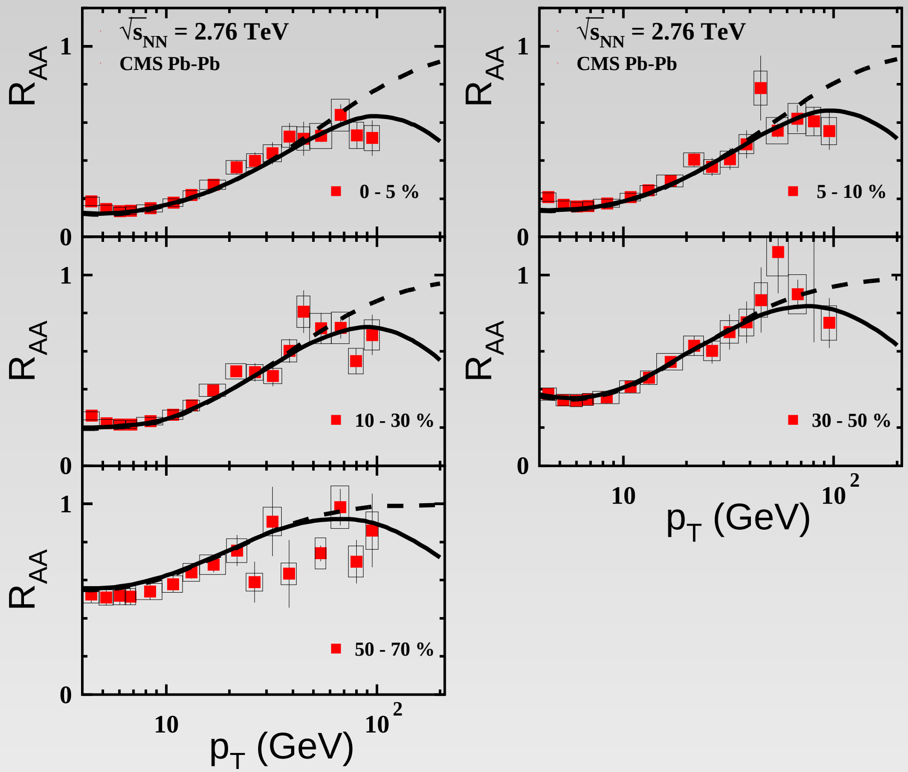

$R_{AA}(p_T)$ for charge hadrons produced in lead-lead collisions at different centralities. Calculations within the GF formalism with $\hat{q}_0 = 2.0\ \ \mathrm{GeV}^2/\ \mathrm{fm}$ are compared with ALICE and CMS data.

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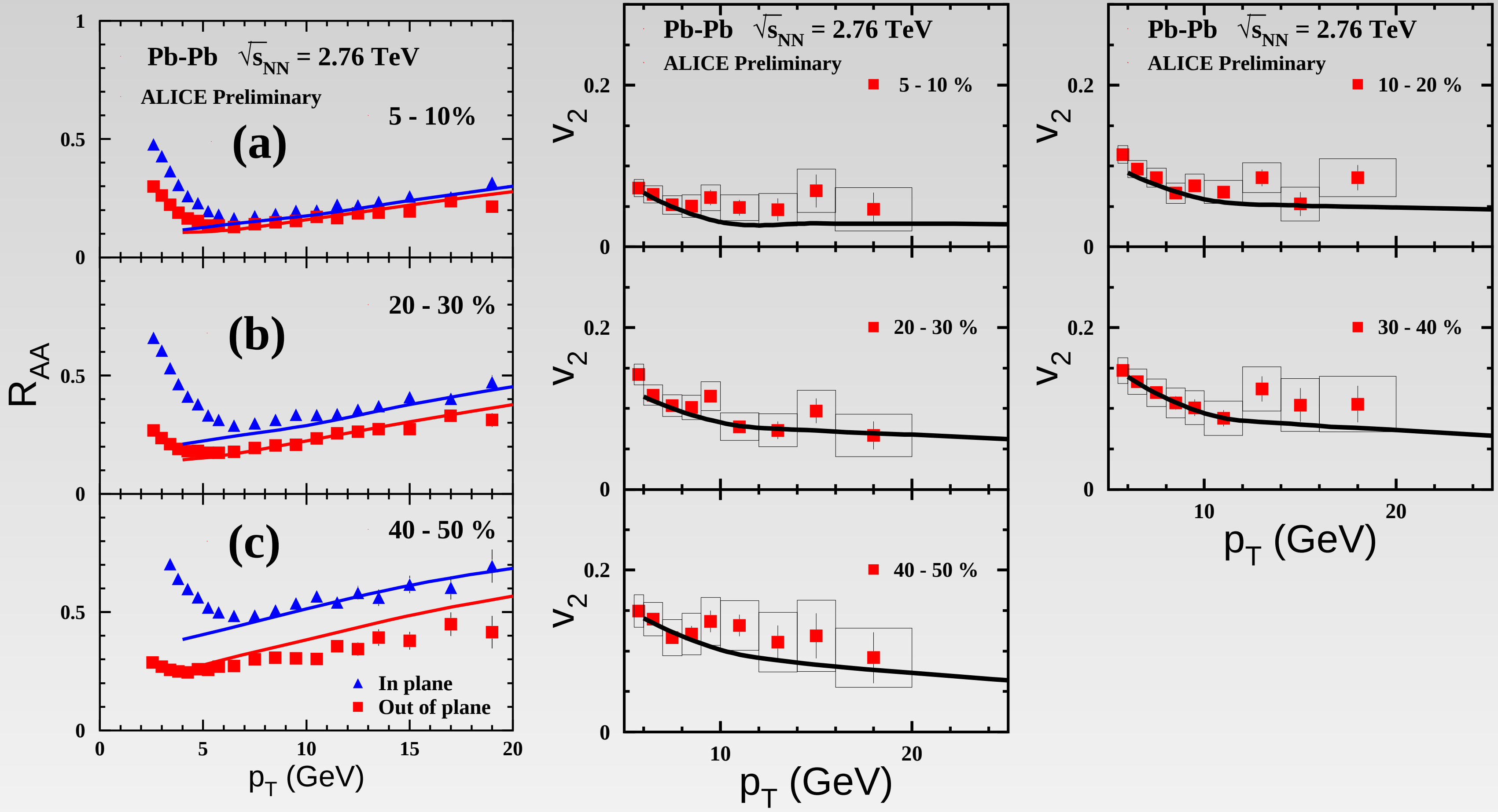

[ALICE Collaboration, A. Dobrin et al.; J. Phys. G **38**, 124170 (2011).]

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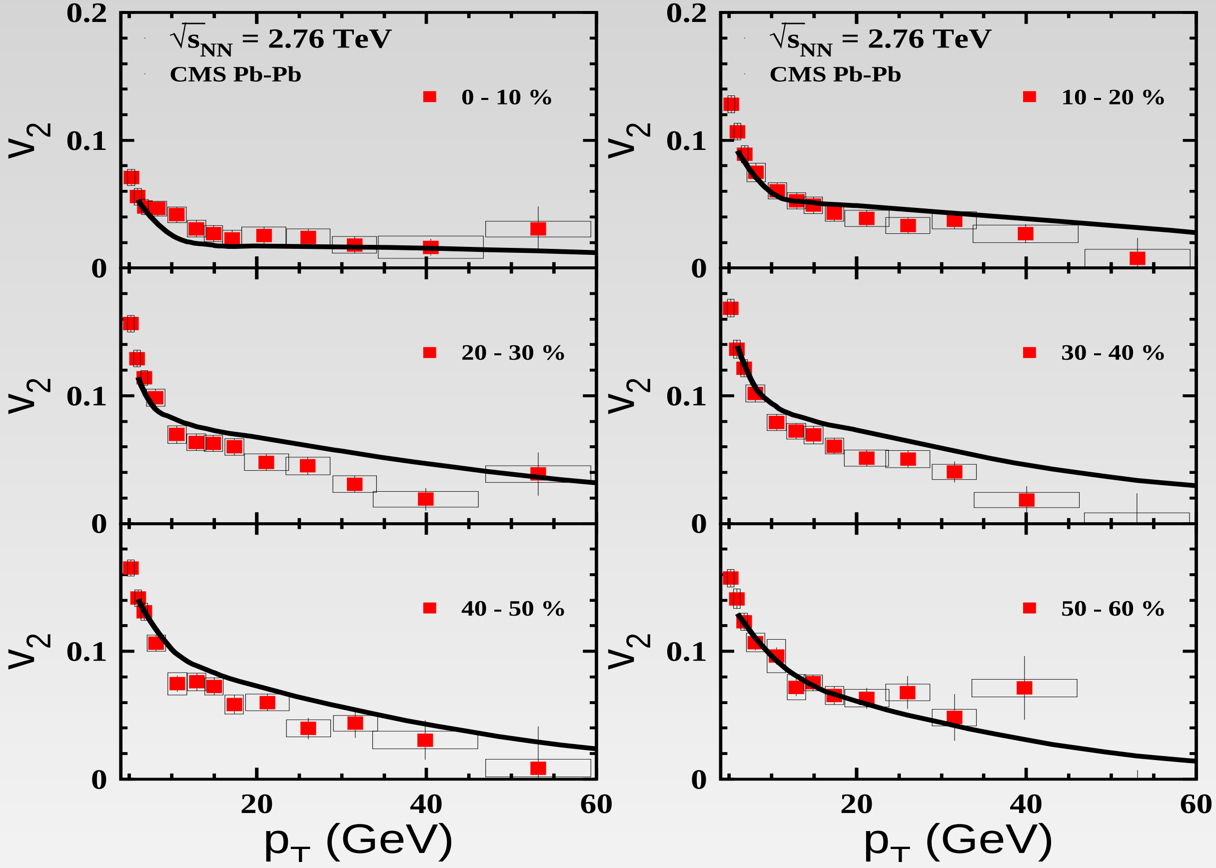

[CMS Collaboration, S. Chatrchyan at al.; Phys. Rev. Lett. **109**, 022301 (2012).]

Production of heavy mesons

(Assumptions)

- We study inclusive production of open charm and open bottom mesons

  $\Rightarrow$ known fragmentation functions into D and B mesons.

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

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- LHC kinematic region
  $\Rightarrow$ more precise data from CMS and ALICE Collaborations in comparison with STAR and PHENIX exp. at RHIC
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- For simplicity we treat the $\bar{q}q$ as free noninteracting partons

  $\Rightarrow$ detailed discussion about binding potential between $\bar{c}c$ in a hot and dense medium can be found in

  [B.Z. Kopeliovich, I.K. Potashnikova, I. Schmidt, M. Siddikov; Phys.Rev. C**91**, 024911 (2015).]

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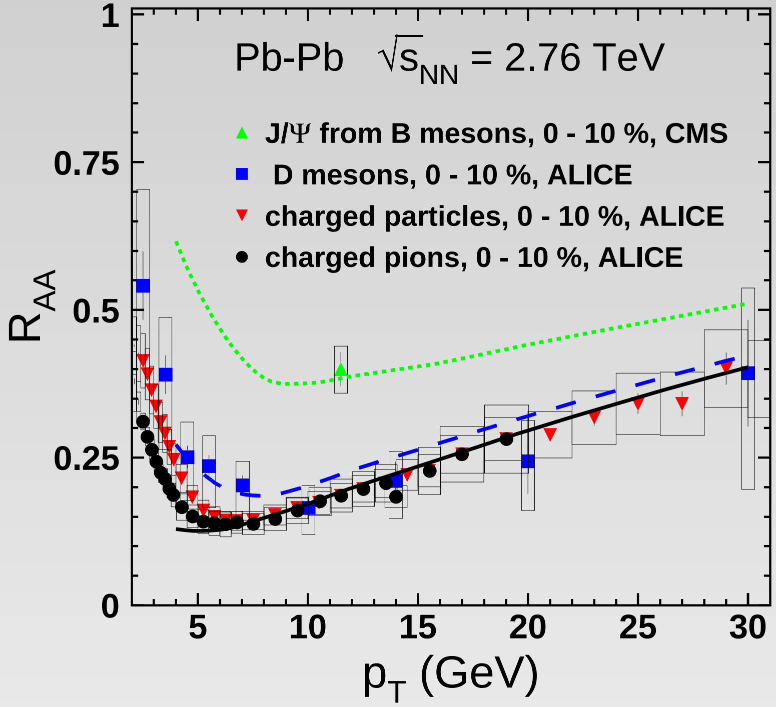
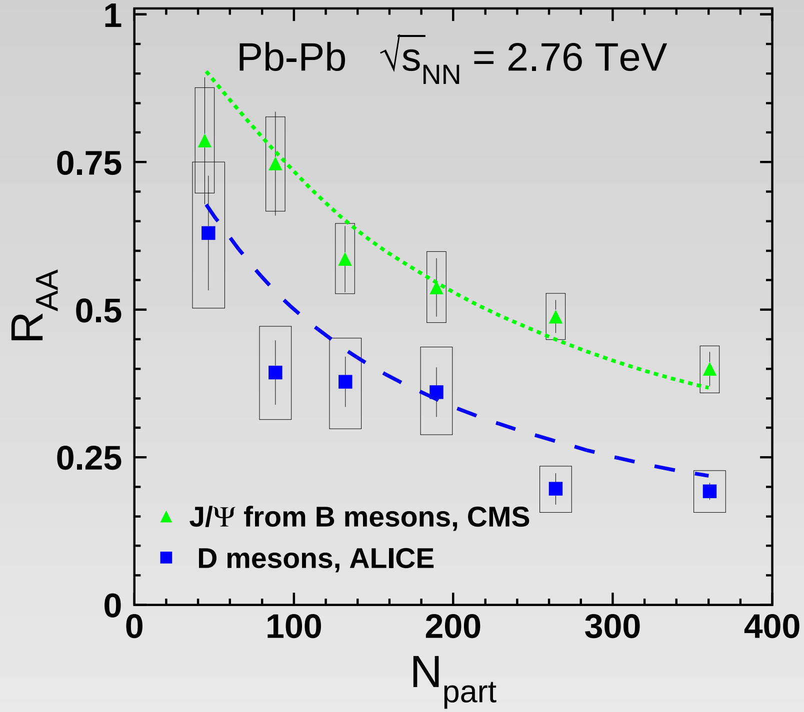
- The HO-values of $\langle r_h^2 \rangle$ correspond to results based on calculations of EM form factors in the light-front framework. [Ch-W Hwang; Eur.Phys.J. C**23**, 585 (2002).]

Numerical results vs. data - R_{AA}

(Inclusive production of heavy mesons)



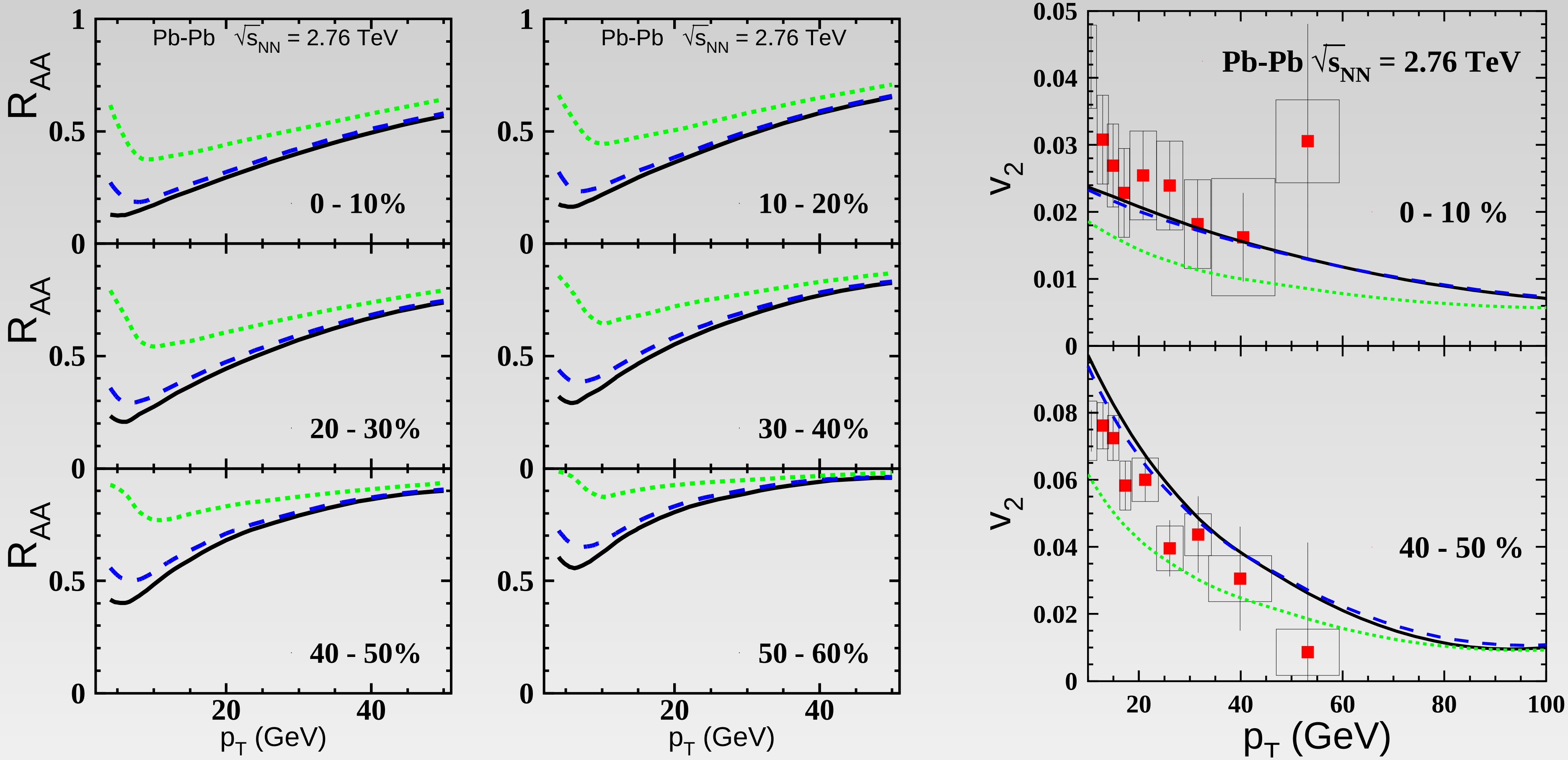


$\boldsymbol{R_{AA}(p_T)}$ for various hadrons produced in central $\boldsymbol{(0 - 10\%)}$ lead-lead collisions and $\boldsymbol{R_{AA}(N_{part})}$ at different centralities. Calculations within the GF formalism with $\boldsymbol{\hat{q}_0 = 2.0 \ \mathrm{GeV}^2/\ \mathrm{fm}}$ are compared with ALICE and CMS data.

[ALICE Collaboration, B. Abelev et al.; Phys.Lett. B**720**, 52 (2013); Phys.Lett. B**736**, 196 (2014).]
[ALICE Collaboration, A. Festanti; Nucl.Phys. A **931**, 514 (2014).]
[CMS Collab., S. Chatrchyan et al.; preprint **CMS-PAS-HIN-12-014**; JHEP **1205**, 063 (2012).]

Numerical results - predictions

(Inclusive production of heavy mesons)



$R_{AA}(p_T)$ and $v_2(p_T)$ for various hadrons produced in lead-lead collisions at different centralities. Calculations within the GF formalism with $\hat{q}_0 = 2.0\ \mathrm{GeV}^2/\mathrm{fm}$.

Summary

- Using the rigorous quantum-mechanical approach based on the path integral technique for description of the $\bar{q}q$ dipole evolution we apply the standard convolution expression for description of high-p_T hadron production in heavy ion collisions at mid rapidities in the RHIC and LHC kinematic range.

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- The dynamics of a strong nuclear suppression of high- p_T hadrons is based on the shortness of the production length, l_p, of a colorless pre-hadrons and on its development and propagation through a dense medium.
- The main part of nuclear suppression is related to the survival probability of colorless dipole propagating through a dense medium $\Rightarrow$ color transparency - steep rise of the nuclear modification factor $R_{AA}(p_T)$ with p_T.

Summary

- Calculations contain only medium density adjustment and we found the transport coefficient to be:
$\hat{q}_0 = 0.60\ GeV^2/fm$ at $\sqrt{s} = 39\ GeV$,
$\hat{q}_0 = 1.20\ GeV^2/fm$ at $\sqrt{s} = 62\ GeV$,
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investigating the inclusive production of light hadrons in central nucleus-nucleus collisions.
- We study production of open charm and open bottom heavy mesons in the LHC kinematic region in order to exclude other effects contributing to nuclear suppression, like initial state energy loss and quark jets with $\langle l_p \rangle$ dependent on m_q and z_h

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- We present also predictions for expected diferent suppression in production of pions, D and B mesons in heavy ion collisions at various centralities.
- Differences in suppresion between light and heavy mesons gradually decrease with $\boldsymbol{p_T}$ since the expansion of the initially small dipole size is slowed down by Lorentz time dilation eliminating so a sensitivity to the meson size.