Can we see from jet quenching that quark-gluon plasma becomes more perturbative at LHC than at RHIC?

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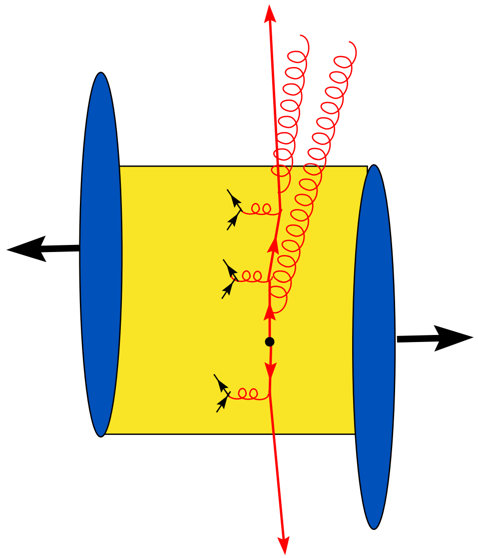
Quark Matter 2011,

Annecy, France, May 27, 2011.

Jet quenching in AA-collisions

Radiative (Bethe-Heitler) and collisional (Bjorken) energy losses modify jet evolution.



The radiative mechanism dominates, $\Delta E_{rad}^{N=1} \propto \alpha_s^3$. The theoretical uncertainties in R_{AA} are large (about a factor of 2) but the variation of R_{AA} from RHIC to LHC is more robust.

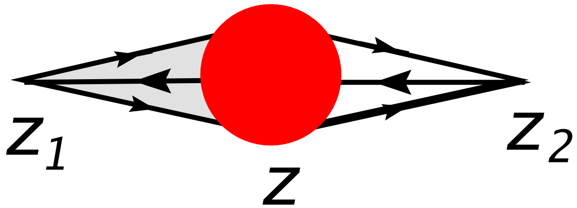
It is interesting to compare R_{AA} for RHIC ($\sqrt{s} \sim 200$ GeV) and LHC ALICE ($\sqrt{s} = 2.76$ TeV). $S(\sqrt{s} = 2760)/S(\sqrt{s} = 200) \sim 2.2 \Rightarrow T_0(2.76\text{TeV}) \sim 1.3 T_0(0.2\text{TeV}) \Rightarrow \alpha_s$ should be suppressed at LHC. Can we see it from jet quenching?

Induced one gluon emission in LCPI approach

$dP/dx = \int_0^L dz n(z) d\sigma_{eff}^{BH}(x,z)/dx$. The effective Bethe-Heitler cross section for $q \to g + q$ reads [BGZ (1997)]

$$\frac{d\sigma_{eff}^{BH}(x,z)}{dx} = \text{Re} \int\limits_0^z dz_1 \int\limits_z^\infty dz_2 \int d\vec{\rho}\, \hat{g}(x) \mathcal{K}_v(z_2,\vec{\rho}_2|z,\vec{\rho})\sigma_3(\rho)\mathcal{K}(z,\vec{\rho}|z_1,\vec{\rho}_1)\Big|_{\vec{\rho}_1=\vec{\rho}_2=0}$$

$x = \omega_g/E$, z is the position of the scattering center in QGP, $\sigma_3 = \sigma_{q\bar{q}g}$. For the vacuum Green's function $\mathcal{K}_v$ z_2-integration up to infinity gives the LCWF with the azimuthal quantum number $m = \pm 1$ $\psi(\vec{\rho},x) \propto K_1(\epsilon\rho)\exp(im\phi)$ with $\epsilon^2 = m_q^2 x^2 + m_g^2(1-x)$. The result reads [BGZ (2004)]



$$\frac{d\sigma_{eff}^{BH}(x,z)}{dx} = -\frac{P_{Gq}(x)}{\pi\mu(x)} \text{Im} \int\limits_0^z d\xi \alpha_s(Q_{eff}) \frac{\partial}{\partial\rho}\left(\frac{F(\xi,\rho)}{\sqrt{\rho}}\right)\Big|_{\rho=0},$$

$\mu = Ex(1-x)$, $Q_{eff}^2 = 1.85\mu/\xi$, F is the solution to the radial Schrödinger equation for $m=1$

$$i\frac{\partial F(\xi,\rho)}{\partial\xi} = \left[-\frac{1}{2\mu(x)}\left(\frac{\partial}{\partial\rho}\right)^2 - i\frac{n(z-\xi)\sigma_3(\rho)}{2} + \frac{4m^2-1}{8\mu(x)\rho^2} + \frac{1}{L_f}\right]F(\xi,\rho)$$

with $L_f = 2\mu(x)/\epsilon^2$, $F(\xi=0,\rho) = \sqrt{\rho}\sigma_3(\rho)\epsilon K_1(\epsilon\rho)$. We solve the Schrödinger equation backward in time to have a smooth boundary condition.

Collisional energy loss, $2 \to 2$ processes

$$\frac{dE_{col}}{dz} = \frac{1}{2Ev} \sum_{p=q,g} g_p \int \frac{d\vec{p}'}{2E'(2\pi)^3} \int \frac{d\vec{k}\, n_p(k)}{2k(2\pi)^3}$$

$$\times \int \frac{d\vec{k}'[1+\epsilon_p n_p(k')]}{2k'(2\pi)^3} (2\pi)^4 \delta^4(P+K-P'-K')\omega \langle |M(s,t)|^2 \rangle \theta(\omega_{max}-\omega)$$

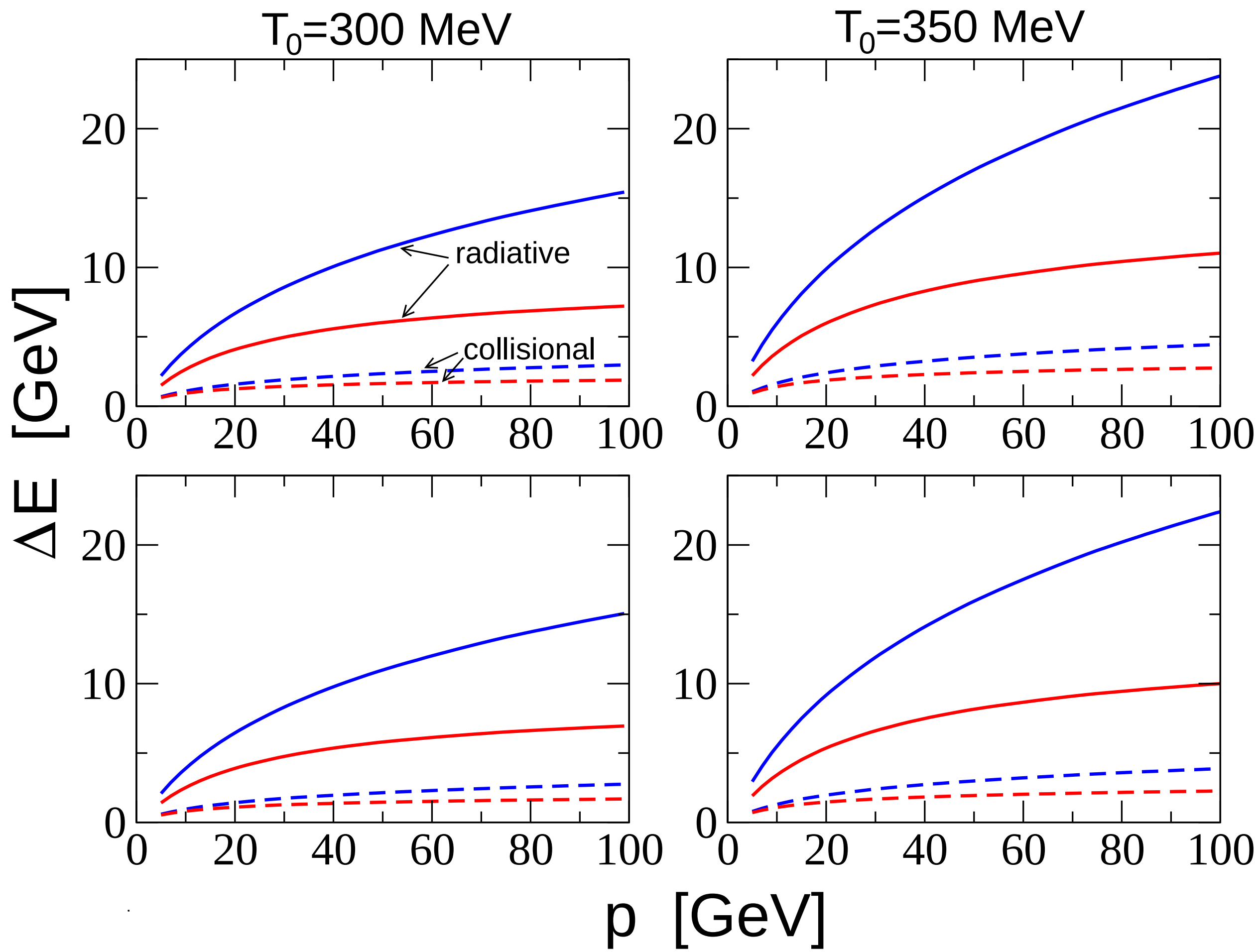
$\omega = E - E'$ is the energy transfer, $v \approx 1$ is the quark velocity, $P = (E, \vec{p})$ and $K = (k, \vec{k})$ 4-momenta for incoming partons, $P' = (E', \vec{p}')$ and $K' = (k', \vec{k}')$ 4-momenta for outgoing partons, $M(s,t)$ is matrix element for $Qp \to Qp$ scattering, $n_q(k) = (e^{k/T}+1)^{-1}$ and $n_g(k) = (e^{k/T}-1)^{-1}$, $\epsilon_q = -1$, $\epsilon_g = 1$, $g_q = 4N_c N_f$, $g_g = 2(N_c^2 - 1)$. Similarly to the radiative energy loss we take $\omega_{max} = E/2$.

$$\omega = \frac{-t - tk_z/E + 2\vec{k}_\perp \vec{q}_\perp}{2(k-k_z)} \,.$$

Bjorken neglected the red terms. In this case neglecting the statistical Pauli-blocking and Bose enhancement factors one can obtain

$$\frac{dE_{col}}{dz} \approx \frac{1}{2(2\pi)^3} \sum_{p=q,g} g_p \int d\vec{k} \frac{n_p(k)}{k} \int_0^{|t|_{max}} dt |t| \frac{d\sigma}{dt} \,, \quad |t|_{max} \approx 2(k-k_z)\omega_{max} \,.$$

Why running α_s is important



The radiative and collisional quark energy losses in expanding QGP for $L = 5$ fm, $\tau_0 = .5$ fm, $m_q = 300$ MeV, $m_g = 400$ MeV [Lévai, Heinz (1998)].

red: running α_s, blue: $\alpha_s = 0.5$.

The higher panels: $\mu_D = \sqrt{2} m_g \approx 0.57$ GeV, and the lower panels for the T-dependent Debye mass from the lattice calculations [O. Kaczmarek and F. Zantow, Phys. Rev., D71, 114510 (2005)]

The nuclear modification factor for AA-collisions

$$R_{AA}^{th}(b) = \frac{dN(A+A\to h+X,\vec{b})/d\vec{p}_T dy}{T_{AA}(b)d\sigma(N+N\to h+X)/d\vec{p}_T dy}\,,$$

$T_{AA}(b) = \int d\vec{\rho} T_A(\vec{\rho})T_A(\vec{\rho}-\vec{b})$, T_A is the nucleus profile function.

$$\frac{dN(A+A\to h+X,\vec{b})}{d\vec{p}_T dy} = \int d\vec{\rho} T_A(\vec{\rho})T_A(\vec{\rho}-\vec{b})\frac{d\sigma_m(N+N\to h+X,\vec{\rho})}{d\vec{p}_T dy}\,,$$

$d\sigma_m(N+N\to h+X,\vec{\rho})/d\vec{p}_T dy$ is the medium-modified cross section for a hard reaction at $\vec{\rho}$. In analogy to the ordinary pQCD we write

$$\frac{d\sigma_m(N+N\to h+X)}{d\vec{p}_T dy} = \sum_i \int_0^1 \frac{dz}{z^2} D_{h/i}^m(z,Q)\frac{d\sigma(N+N\to i+X)}{d\vec{p}_T^{\,i} dy}\,, \quad \vec{p}_T^{\,i} = \vec{p}_T/z$$

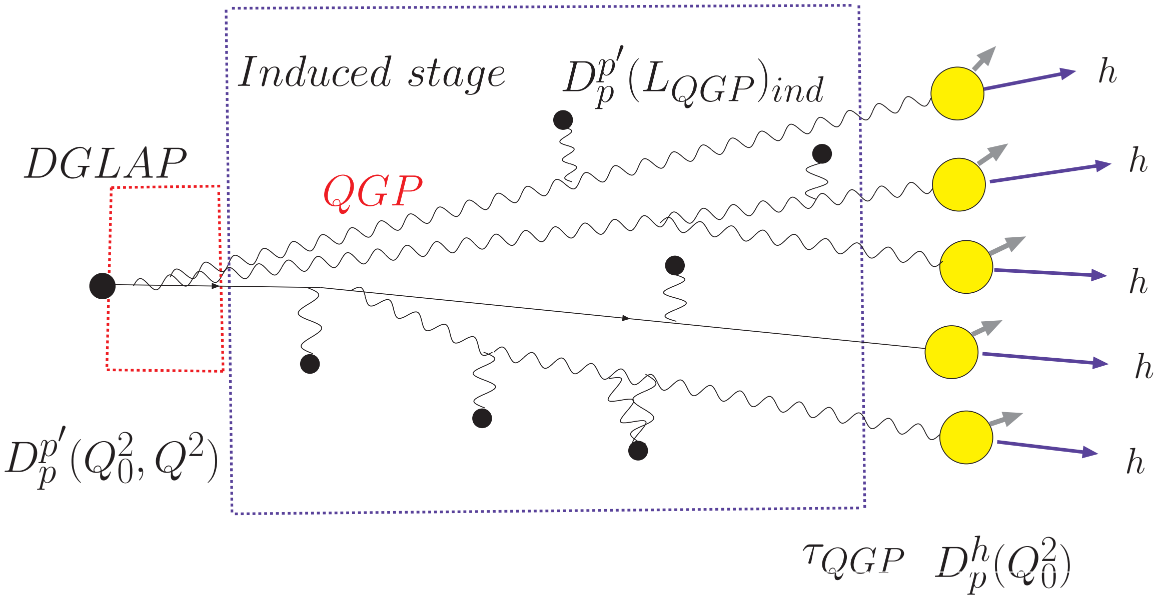
$D_{h/i}^m$ is the medium-modified FF for transition $i\to h$, $Q\sim p_T^i$. Hadronization happens outside the QGP. The L dependence of the parton virtuality $Q^2(L)\sim\max(Q/L, Q_0^2)$, $Q_0\sim 1-2$ GeV is some minimal nonperturbative scale. $\Rightarrow$ for partons with $E\lesssim 100$ GeV the hadronization of the final partons at $L\gtrsim L_{QGP}$ is described by the FFs at a small scale $\mu_h\sim Q_0$.

The space-time pattern of jet distortion

The formation length for the DGLAP $\bar{l}_F \sim 0.3 - 1$ fm for $E \lesssim 100$ GeV (if $m_q \sim 0.3$ GeV and $m_g \sim 0.75$ GeV). ⇒The DGLAP stage gives initial condition for the induced emission stage at $\tau_{DGLAP} \sim \tau_0$.

$$\Rightarrow \quad D^m_{h/i}(Q) \approx D_{h/j}(Q_0) \otimes D^{ind}_{j/l}(E_l) \otimes D^{DGLAP}_{l/i}(Q_0, Q)\,,$$

$D^{ind}_{j/l}$ is the induced radiation FF (it depends on the parton energy E, but not the virtuality), $D^{DGLAP}_{l/i}$ is calculated with the PYTHIA event generator. Our scheme of the stages of jet evolution



The FF for the induced stage

To calculate the $D_{j/l}^{ind}$ one needs to take into account the multiple gluon emission. There is no an accurate method of incorporating the multiple gluon emission.
We use Landau method developed for photon emission [BDMS (2001)]

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dP(\omega_i)}{d\omega} \right] \delta \left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int d\omega \frac{dP}{d\omega} \right] ,$$

$dP/d\omega$ is the distribution for one gluon emission. The situation is similar to multi-photon emission QED

$$P(\Delta E) = \frac{dP_\gamma}{d\omega} K(x) \, , \; \Delta E = \omega = xE$$

For thin targets the multi-photon K-factor can be evaluated analytically [BGZ (1998)]

$$K(x) = \exp\left[- \int_x^1 dx_1 \frac{dP_\gamma}{dx_1} \right] \left\{ 1 - \frac{1}{2} \int_0^x dx_1 \left[\frac{dP_\gamma}{dx_1} + \frac{dP_\gamma}{dx_2} - \frac{dP_\gamma}{dx_1} \frac{dP_\gamma}{dx_2} \left(\frac{dP_\gamma(x)}{dx} \right)^{-1} \right] \right\} ,$$

where $x_2 = x - x_1$. The major x-dependence of the K-factor comes from the Sudakov exponential factor.

Induced FF for $q \to q$, $q \to g$, and $g \to g$

For $q \to q$ we take (like Eskola, Honkanen, Salgado and Wiedemann (2004))

$$D^{ind}_{q/q}(z) = K_{qq} P_{Landau}(\Delta E = E(1-z)), \quad K_{qq} = \int_0^\infty d\Delta E P(\Delta E) / \int_0^E d\Delta E P(\Delta E)$$

K_{qq} accounts for the leakage of the probability to $\Delta E > E$ (gluons are not soft enough!). For momentum conservation we include $q \to g$ transition. At the one gluon level

$$D^{ind}_{g/q}(z) = dP(z)/dz, \quad \text{and} \quad \int dz z[D^{ind}_{g/q}(z) + D^{ind}_{q/q}(z)] = 1$$

.
FF for multiple gluon emission we take $D^{ind}_{g/q}(z) = K_{gq} dP(z)/dz$ with K_{gq} fixed from momentum conservation $\int dz z[D^{ind}_{g/q}(z) + D^{ind}_{q/q}(z)] = 1$.
It is reasonable since R_{AA} is sensitive to FFs at $z \sim 1$ [BDMS (2001)] where $q \to g$ distribution should not be very sensitive to the multiple gluon emission.

For $g \to g$ we can use only the momentum conservation. In the first step we define $\bar{D}^{ind}_{g/g}(z) = P_{Landau}(\Delta E(1-z)) \quad z > 0.5$. At $z < 0.5$ (where the multiple gluon emission and the Sudakov suppression strongly compensate each other) we use the one gluon formula $\bar{D}^{ind}_{g/g}(z) = dP/dz$. Finally we define $D^{ind}_{g/g}(z) = K_{gg}\bar{D}^{ind}_{g/g}(z)$. K_{gg} is fixed from the momentum sum rule $\int dz z D^{ind}_{g/g}(z) = 1$.

We treat the collisional loss as a perturbation and incorporate it by a small renormalization of T_{QGP} according to the change in the ΔE due to the collisional energy loss

$$\Delta E_{rad}(T') = \Delta E_{rad}(T) + \Delta E_{col}(T)$$

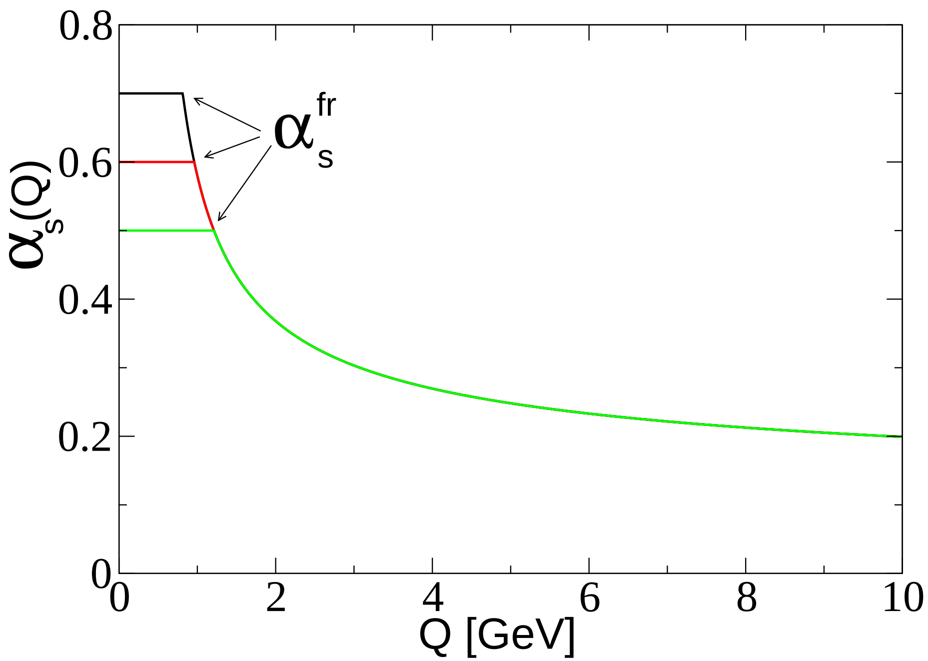
The collisional loss decreases R_{AA} by 15-25 %.

We calculate the cross sections $d\sigma(N+N \to i+X)/d\vec{p}_T^{\,i}dy$ using the LO pQCD formula with the CTEQ6 PDFs. To account for the nuclear modification of the PDFs (which leads to some small deviation of R_{AA} from unity even without energy loss) we include the EKS98 correction [K.J. Eskola, V.J. Kolhinen, and C.A. Salgado, Eur. Phys. J. C**9**, 61 (1999)]. . To simulate the higher order K-factor in the hard cross sections we use $\alpha_s(cQ)$ with $c = 0.265$ (like that in PYTHIA). For the FFs $D_{h/q(g)}(z, Q_0)$ we use the KKP parametrization [B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B**582**, 514 (2000)]

We use the Bjorken $1+1$ QGP expansion $T^3\tau = T_0^3\tau_0$. To simplify the numerical calculations for each value of the impact parameter b we neglect the variation of T_0 in the transverse directions. We take $\tau_0 = 0.5$ fm, $\tau_{max} = L_{max} = 8$ fm. We fix T_0 using $dS/dy\Big/dN_{ch}/d\eta \approx 7.67$ [B. Mueller and K. Rajagopal (2005)]

$\Rightarrow \langle T_0\rangle \approx 300$ MeV (central Au+Au, $\sqrt{s} = 200$ GeV), $\langle T_0\rangle \approx 400$ MeV (central Pb+Pb, $\sqrt{s} = 2.76$ TeV).

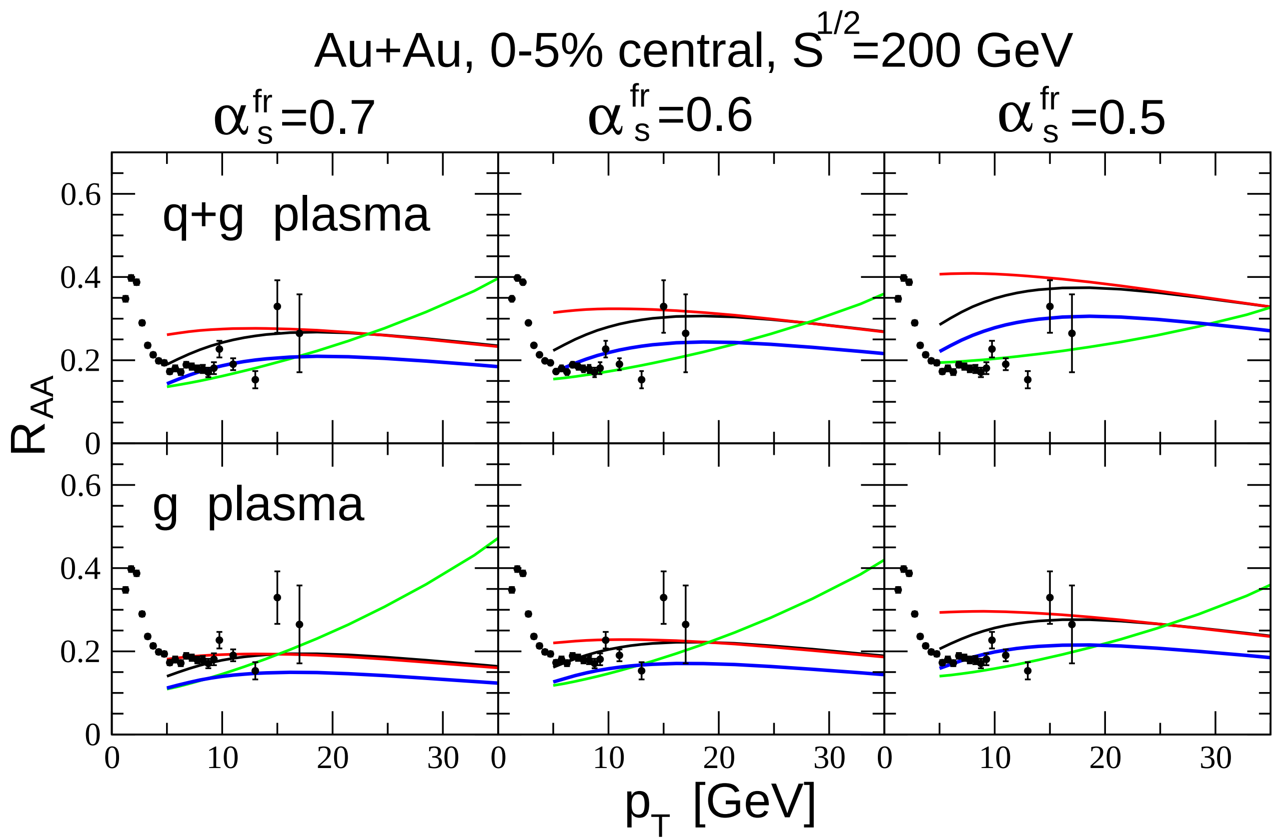
Parametrization of $\alpha_s(Q)$



We use running α_s frozen at $\alpha_s^{fr} = 0.7,\ \ 0.6,\ \ 0.5,\ \ 0.4$. $\alpha_s^{fr} = 0.7$ was obtained from the data on F_2^p at low x [Nikolaev, BGZ (1991,1994)], it agrees with

$\int_0^{2\,GeV} dQ \frac{\alpha_s(Q^2)}{\pi} \approx 0.36$ GeV obtained from the analysis of the heavy quark energy loss in vacuum [Dokshitzer, Khoze, Troyan (1996)].

Comparison with RHIC PHENIX data, π^0



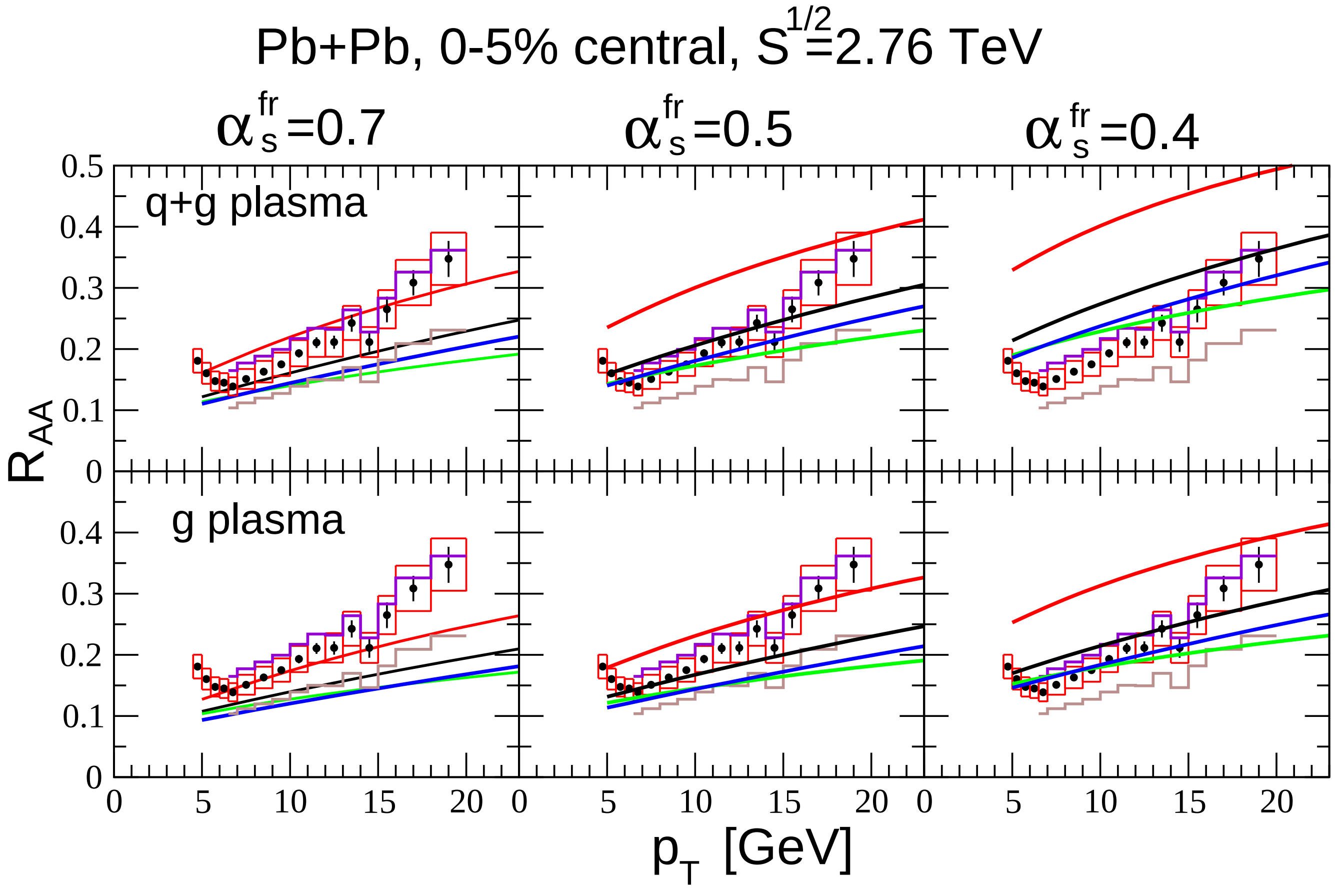
red: the radiative for quarks.

green: the radiative for gluons.

black: the radiative for quarks plus gluons.

blue: the total (quarks plus gluons) radiative plus collisional energy loss and the energy gain.

Comparison with LHC ALICE data. $(h^+ + h^-)/2$



red: the radiative for quarks.

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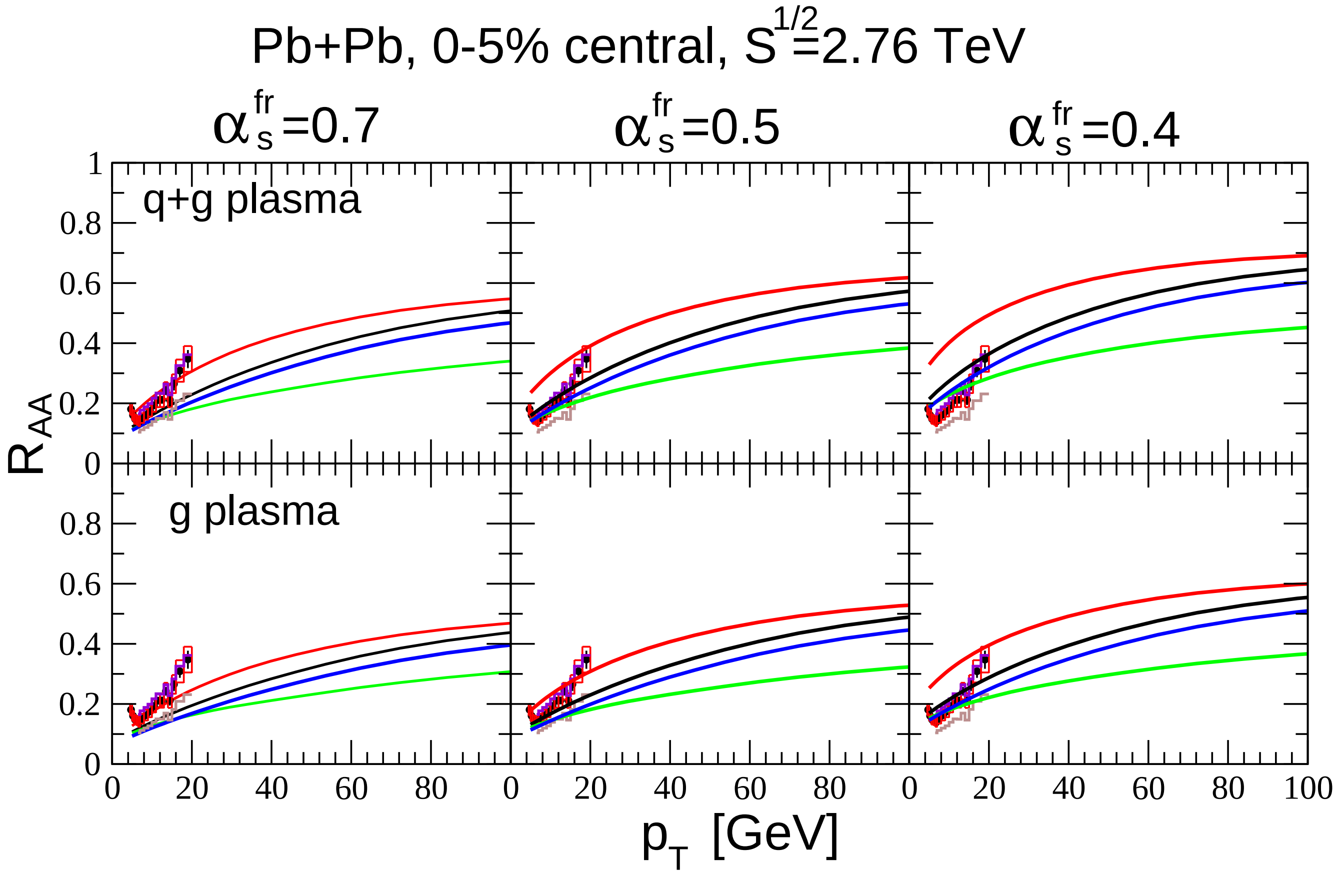
blue: the total (quarks plus gluons) radiative plus collisional energy loss and the energy gain.

Conclusions:

- R_{AA} for the RHIC and LHC is calculated accounting for both the radiative and collisional energy losses with the running α_s and fluctuations of parton path length in QGP. The effect of the collisional energy loss is relatively small. The effect of the energy gain due to the induced gluon absorption is negligible.
- The multiple gluon emission is calculated accounting for the time ordering of the DGLAP and induced gluon emission stages. The effect of the DGLAP and induced stages ordering is relatively small (for LHC it is bigger than for RHIC).
- The RHIC data on R_{AA} can be described in the scenario with the chemically equilibrium QGP with the entropy extracted from the hadron multiplicities with a small thermal suppression of α_s. The scenario of the purely gluonic plasma is also possible, but requires somewhat stronger thermal suppression of α_s. The RHIC data are consistent with $\hat{q}(T = 250\text{MeV}) \sim 0.3 - 0.5$ GeV^3.
- Comparison with the LHC ALICE data on R_{AA} gives evidence in favor of somewhat stronger thermal suppression of α_s at LHC. We have $\alpha_s^{fr} \approx 0.6 \div 0.7$ at $\sqrt{s} = 200$ GeV and $\alpha_s^{fr} \approx 0.4 \div 0.5$ at $\sqrt{s} = 2.76$ TeV. It seems that the QGP really becomes more perturbative at LHC.

BACK UP SLIDES

Comparison with LHC ALICE data, $(h^+ + h^-)/2$



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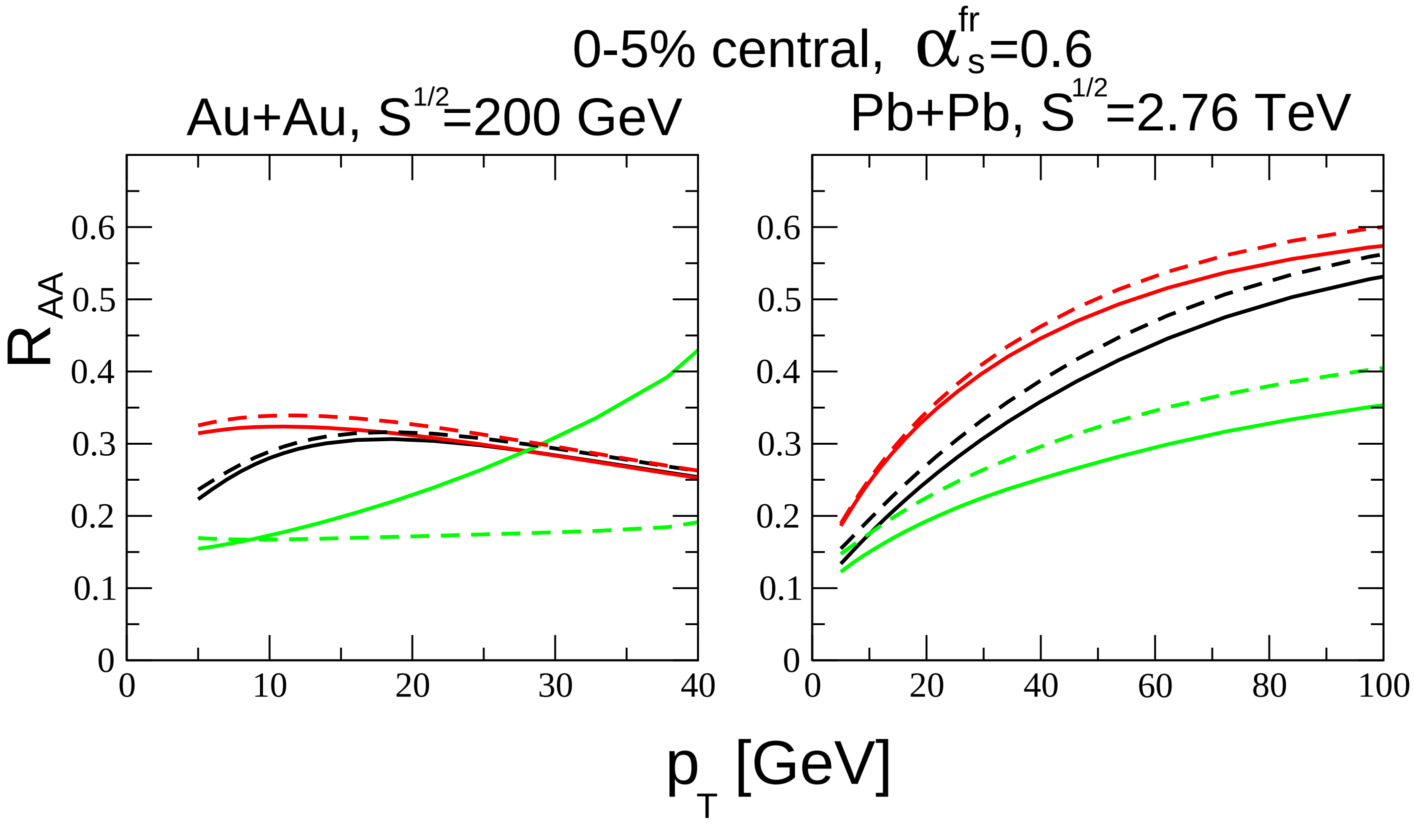
The role of time ordering



red: the radiative for quarks; green: the radiative for gluons; black: the radiative for quarks plus gluons.

solid – INDUCED⊗DGLAP, dashed – DGLAP⊗INDUCED