Jet tomography of AA-collisions at RHIC and LHC energies

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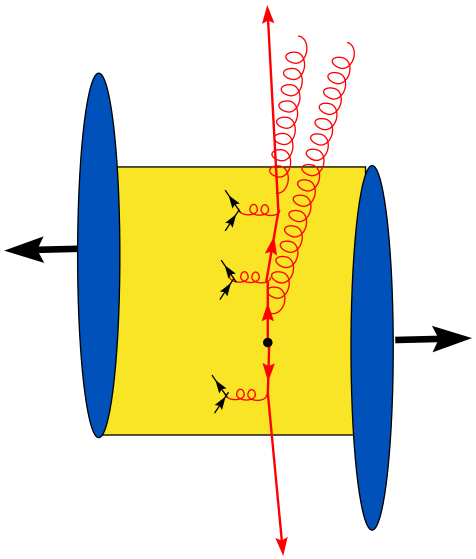
Jet quenching in AA-collisions

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



Both these mechanisms should be treated on even footing. We have not such a formalism. But $\Delta E_{coll} \ll \Delta E_{rad}$. Nevertheless, the theoretical uncertainties in the factor R_{AA} are large (about a factor of 2).

It is interesting to compare R_{AA} for RHIC ($\sqrt{s} \sim 200$ GeV) and LHC ($\sqrt{s} = 2.76$ TeV).

$S(\sqrt{s} = 2760)/S(\sqrt{s} = 200) \sim 2.5 \Rightarrow$the QGP at LHC should be more perturbative.

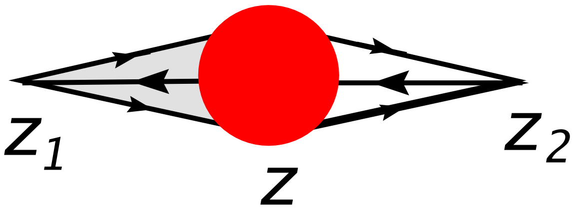
- Can we see reduction of α_s at LHC?
- How strong is suppression of the heavy quarks? Can we describe the suppression of light and heavy flavors with the same parameters in pQCD?

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 (1996,1997)]

$$\frac{d\sigma_{eff}^{BH}(x,z)}{dx} = \text{Re} \int_0^z dz_1 \int_z^\infty dz_2 \int d\vec{\rho}\, \hat{g}(x) \mathcal{K}_v(z_2,\vec{\rho}_2|z,\vec{\rho})\sigma_3(\rho)\mathcal{K}(z,\vec{\rho}|z_1,\vec{\rho}_1)\Big|_{\vec{\rho}_1=\vec{\rho}_2=0}$$

$x = \omega_g/E$, 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)]



$$\frac{d\sigma_{eff}^{BH}(x,z)}{dx} = -\frac{\alpha_s P_{Gq}(x)}{\pi\mu(x)} \text{Im} \int_0^z d\xi \frac{\partial}{\partial\rho}\left(\frac{F(\xi,\rho)}{\sqrt{\rho}}\right)\Big|_{\rho=0},$$

$\mu = Ex(1-x)$, 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

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

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

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

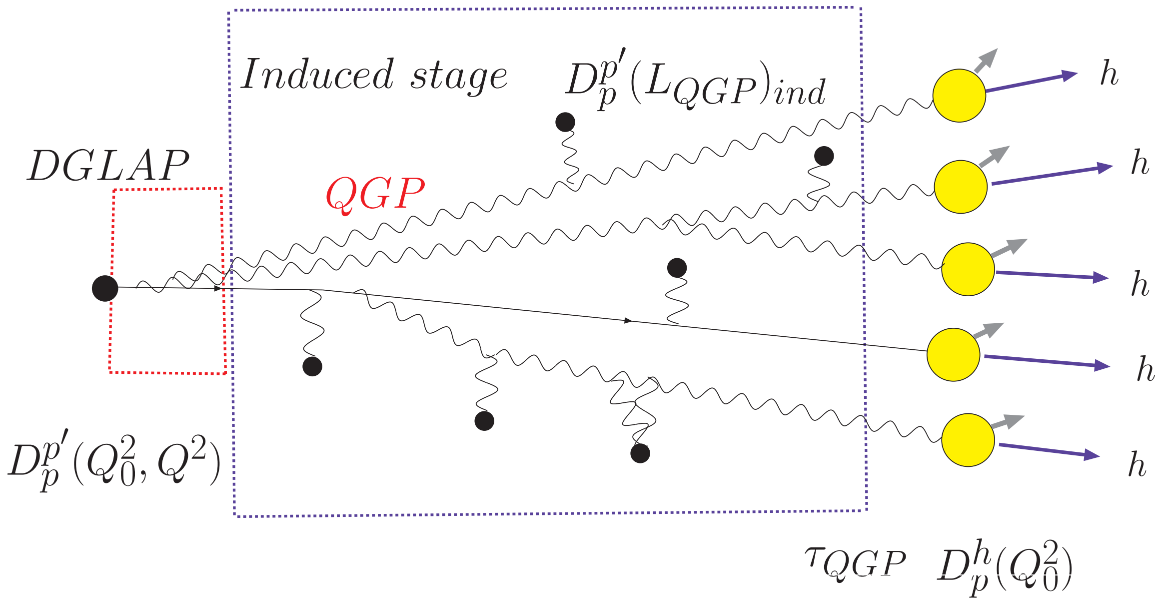
$D_{h/i}^m$ is the medium-modified FF for transition $i \to h$, $Q \sim p_T^i$. Hadronization occurs outside the QGP. The L dependence of the parton virtuality $Q^2(L) \sim \max(Q/L, Q_0^2)$, $Q_0 \sim 1-2$ GeV is some minimal nonperturbative scale. $\Rightarrow$ for partons with $E \lesssim 100$ GeV 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). $\Rightarrow$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 only on the parton energy E), $D^{DGLAP}_{l/i}$ is calculated with the PYTHIA event generator. Our scheme 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.

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

K_{qq} accounts for the leakage of the probability to $\Delta E > E$ (gluons are not soft enough!).
We take $D_{g/q}^{ind}(z) = K_{gq} dP(z)/dz$ with K_{gq} fixed from momentum conservation
$\int dz z [D_{g/q}^{ind}(z) + D_{q/q}^{ind}(z)] = 1$.

For $g \to g$ we first define $\bar{D}_{g/g}^{ind}(z) = P_{Landau}(\Delta E(1-z)) \quad z > 0.5$. At $z < 0.5$

$\bar{D}_{g/g}^{ind}(z) = dP/dz$. $D_{g/g}^{ind}(z) = K_{gg} \bar{D}_{g/g}^{ind}(z)$. K_{gg} is fixed from $\int dz z D_{g/g}^{ind}(z) = 1$.

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

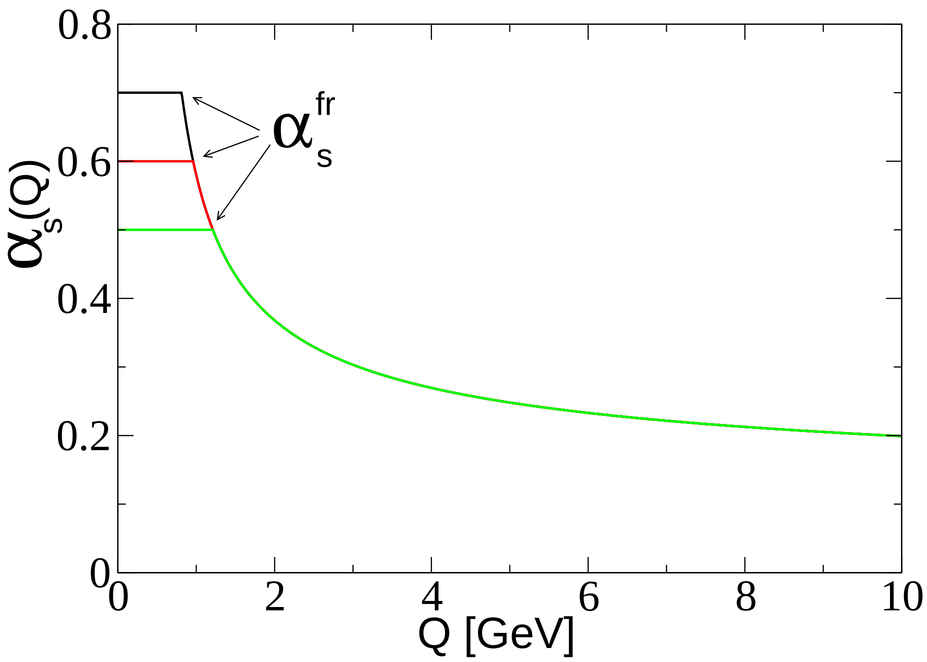
$$\Delta E_{rad}(T') = \Delta E_{rad}(T) + \Delta E_{col}(T)$$

The collisional loss suppresses $R_{AA} \lesssim 15 - 25$ %.

We calculate the $d\sigma(N + N \to i + X)/d\vec{p}_T^{\,i} dy$ using the LO pQCD formula with the CTEQ6 PDFs. To account for the nuclear modification of the PDFs we include the EKS98 correction [K.J. Eskola *et al.* Eur. Phys. J. C9, 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 $D_{h/q(g)}(z, Q_0)$ we use the KKP parametrization [B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B582, 514 (2000)]. For $c \to D$ and $b \to B$ we use Peterson FF with $\epsilon_c = 0.06$, $\epsilon_b = 0.0006$. The FF $B/D \to e$ obtained from the CLEO data [A.H. Mahmood *et al.*, Phys. Rev. D**70**, 032003 (2004); R. Poling, arXiv:hep-ex/0606016].

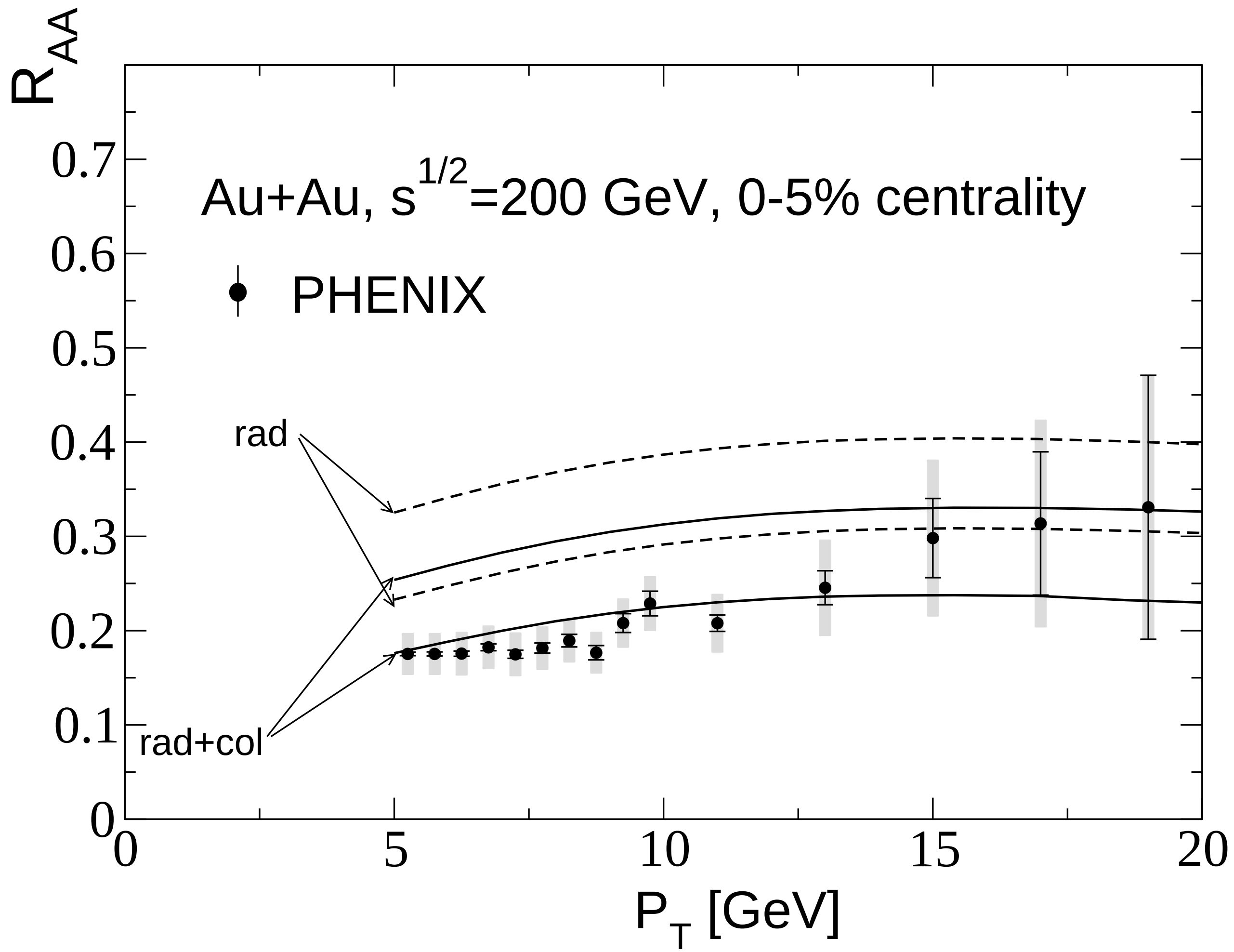
We use the Bjorken $1 + 1$ QGP expansion $T^3\tau = T_0^3\tau_0$. To simplify the numerical calculations for each value of the impact parameter b we neglect the variation of T_0 in the transverse directions. We take $\tau_0 = 0.5$ fm, $\tau_{max} = L_{max} = 8$ fm. We fix T_0 using $S/N \approx 7.25$ [B. Mueller and K. Rajagopal (2005)]
$\Rightarrow \langle T_0 \rangle \approx 320$ MeV (central Au+Au, $\sqrt{s} = 200$ GeV), $\langle T_0 \rangle \approx 420$ MeV (central Pb+Pb, $\sqrt{s} = 2.76$ TeV). We take $m_q = 300$, $m_g = 400$ Mev, $m_c = 1.2$ GeV, $m_b = 4.75$ GeV

Parametrization of $\alpha_s(Q)$

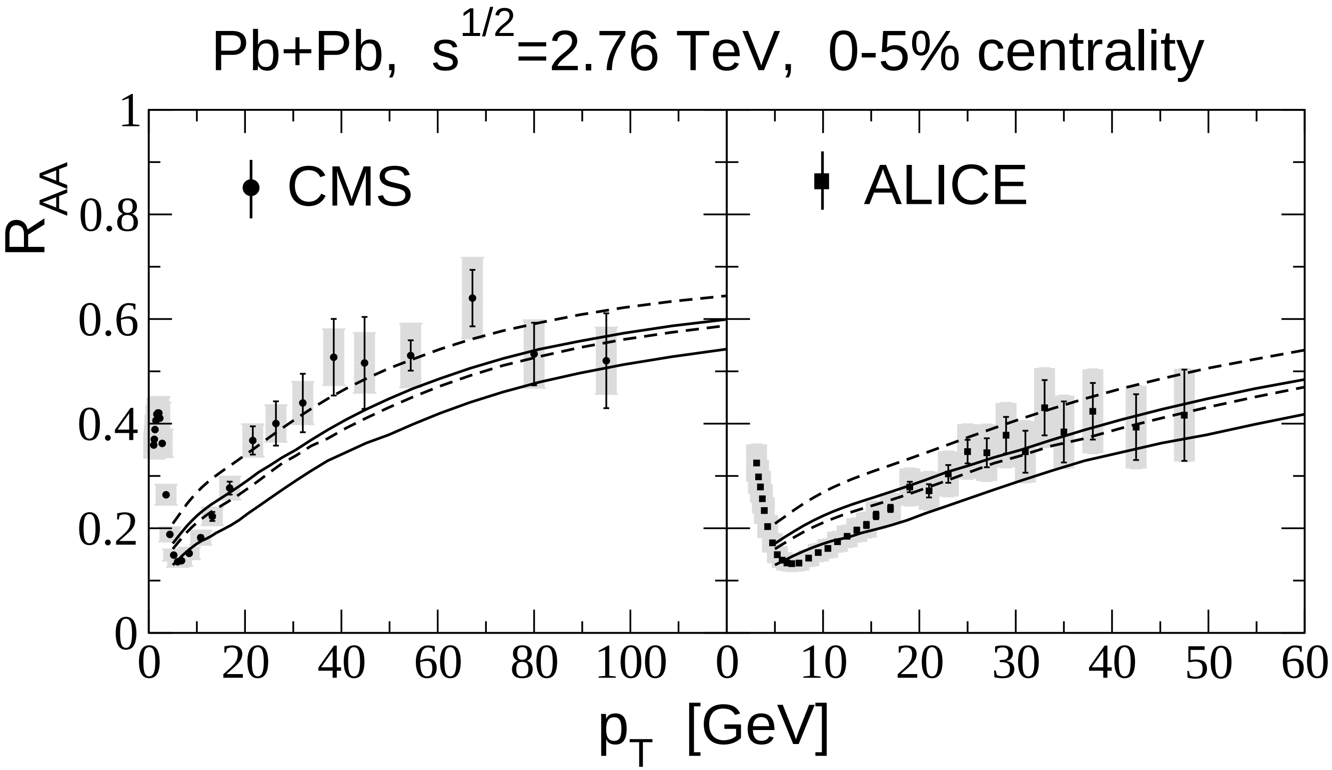


We use running α_s frozen at $\alpha_s^{fr} = 0.4, 0.5$. In vacuum $\alpha_s^{fr} \approx 0.7$ (obtained from the data on F_2^p at low x) [Nikolaev, BGZ (1991,1994)], it agrees with $\int_0^{2\,GeV} dQ \frac{\alpha_s(Q^2)}{\pi} \approx 0.36$ GeV obtained from the analysis of the heavy quark energy loss in vacuum [Dokshitzer, Khoze, Troyan (1996)].

Comparison with RHIC PHENIX data, π^0



$\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves).
The solid line – the radiative and collisional energy loss,
the dashed line – the radiative mechanism alone

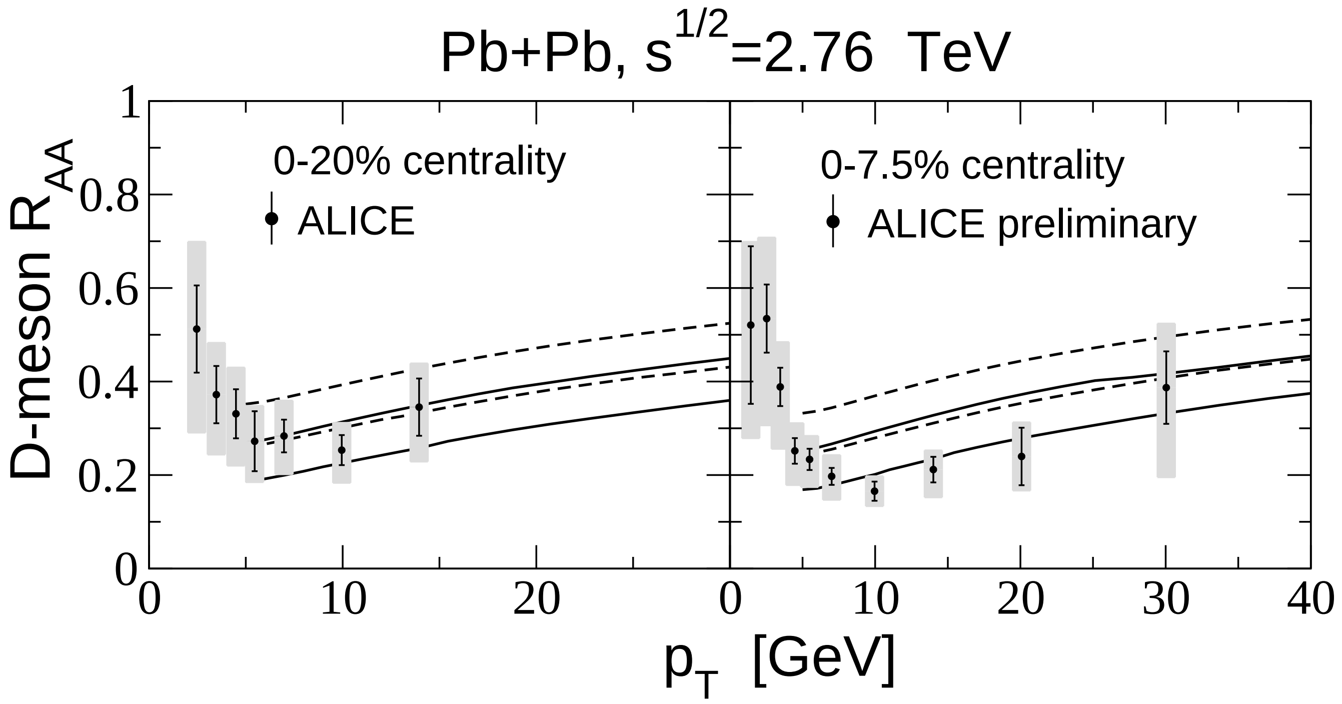


The nuclear modification factor R_{AA} for charged hadrons.

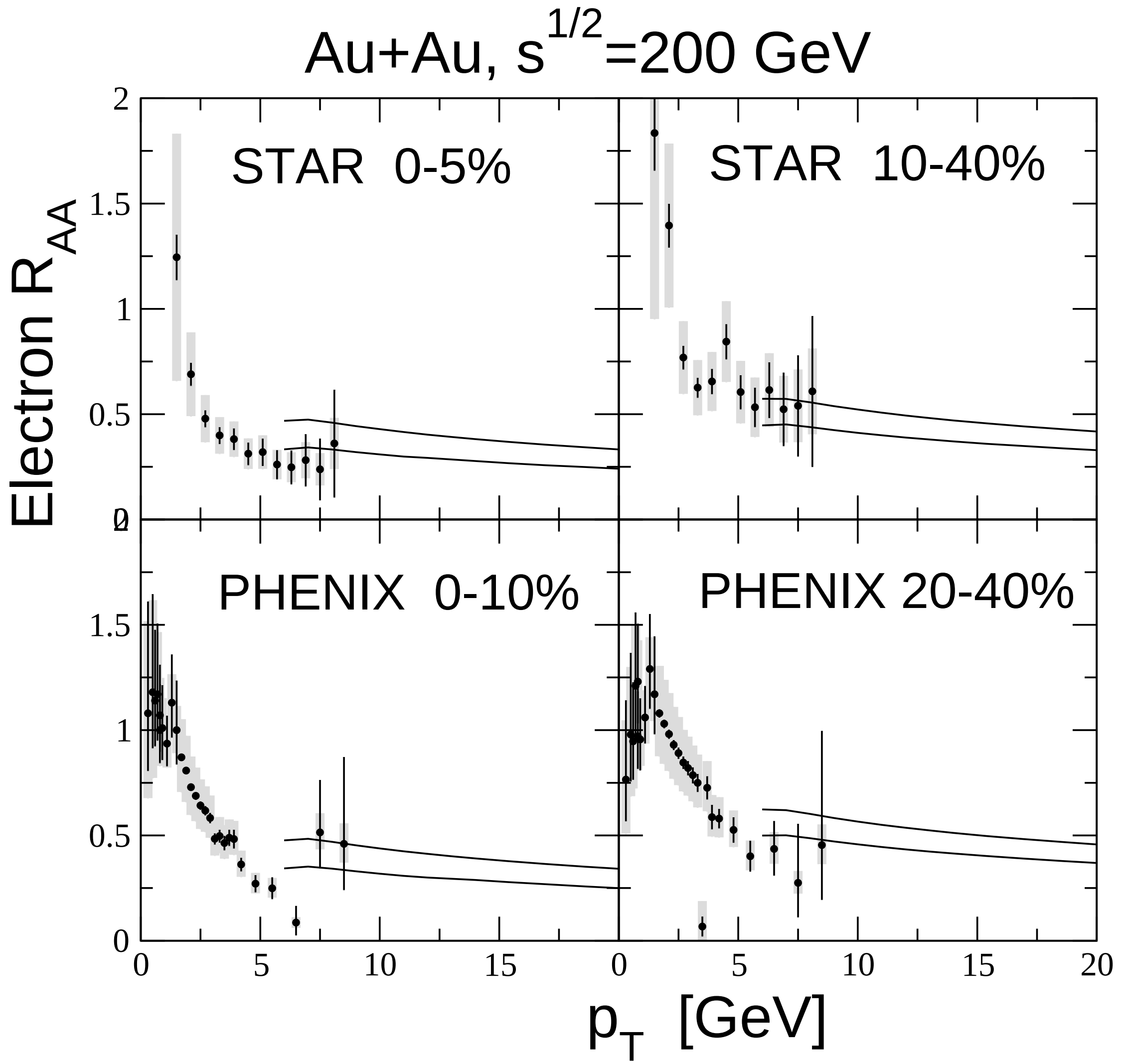
$\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves).

The solid line – the radiative and collisional energy loss,

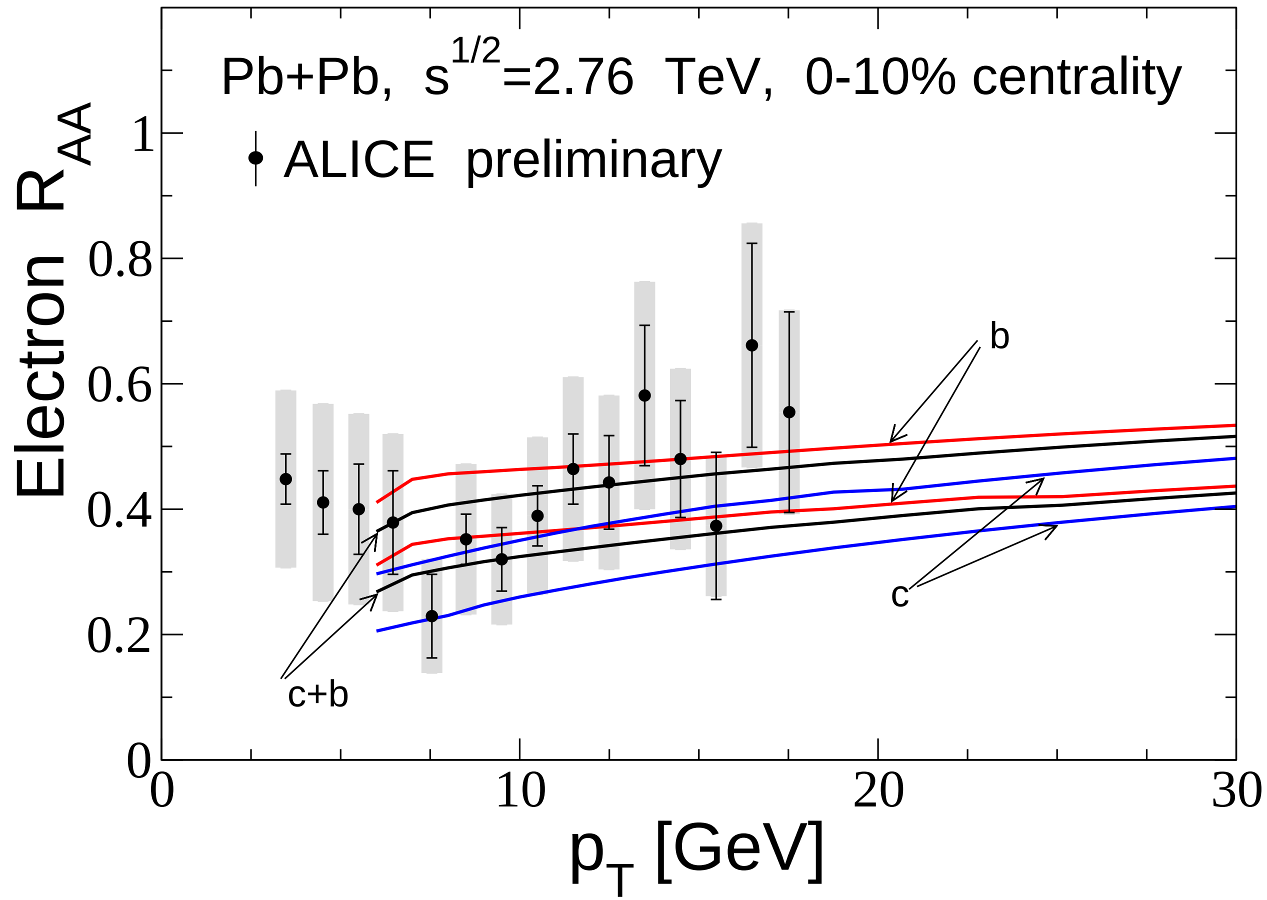
the dashed line – the radiative mechanism alone



The nuclear modification factor R_{AA} for D-mesons.



The electron R_{AA} for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves).

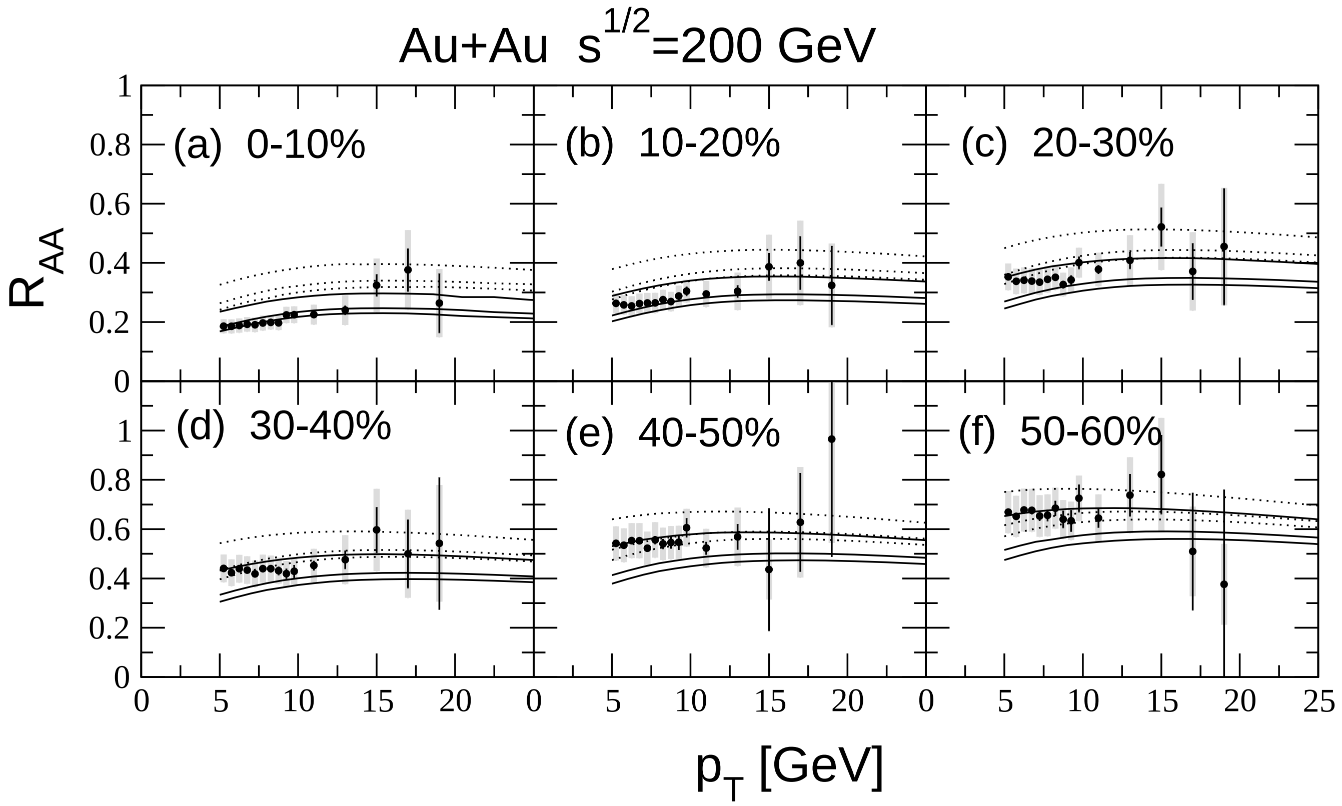


The electron R_{AA} for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves). The total c+b (black) R_{AA}, $c \to D \to e$ (blue), $b \to B \to e$ (red) ($b \to B \to D \to e$ is negligible [M. Cacciari, P. Nason, R. Vogt (2005)])

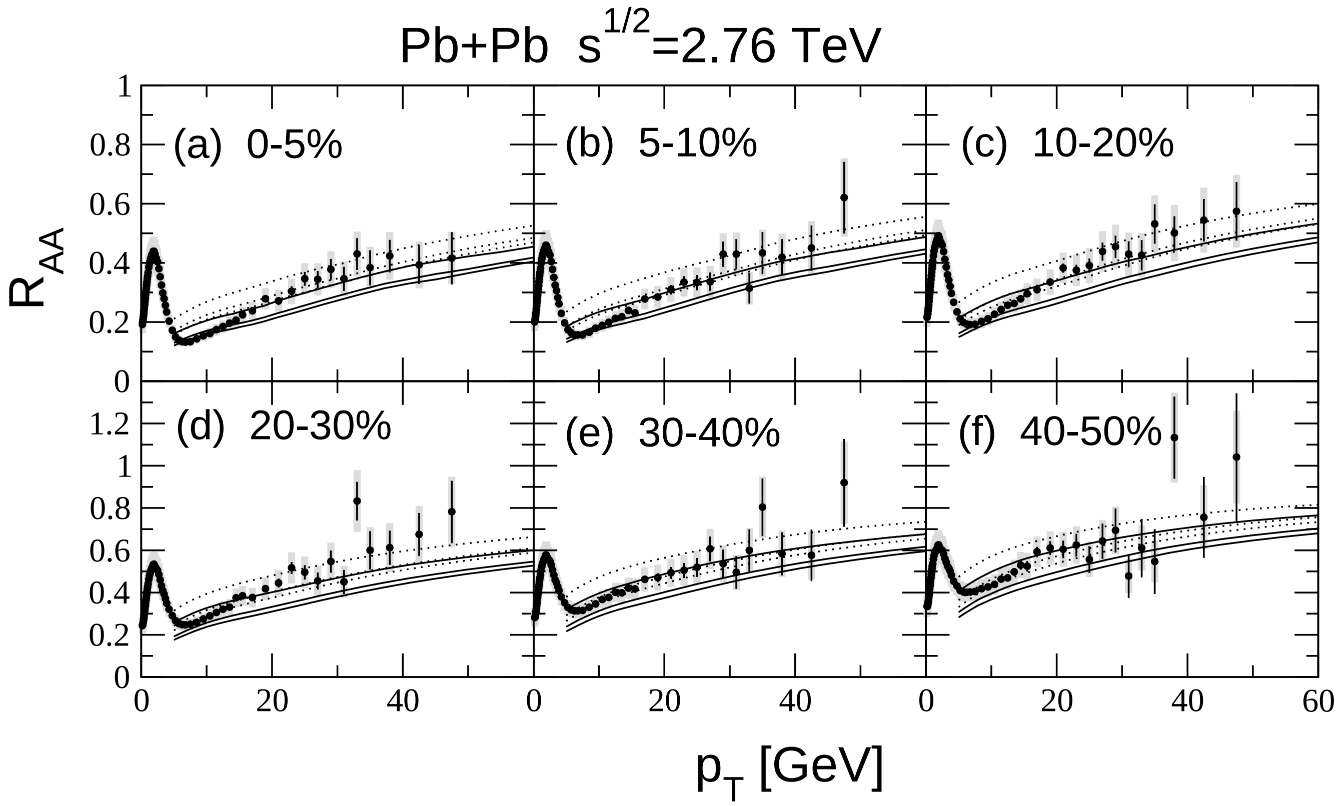
Conclusions:

- We calculated R_{AA} 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 (except for b quark at $E \lesssim 10-15$ GeV). The multiple gluon emission is calculated accounting for the time ordering of the DGLAP and induced gluon emission stages.
- The RHIC data on R_{AA} for π^0 and electrons can be described in the LCPI approach with $\alpha_s^{fr} \approx 0.5$. The LHC data on R_{AA} for charged hadrons, D-mesons and electrons agree better with $\alpha_s^{fr} \approx 0.4$. The difference between $\alpha_s^{fr}(LHC)$ and $\alpha_s^{fr}(RHIC)$ is more pronounced if $\tau_0^{LHC} < \tau_0^{RHIC}$ ($\tau_0 \propto 1/T_0$?).
- The pQCD LCPI formalism gives reasonable description of the flavor dependence of R_{AA} observed at RHIC and LHC at $p_T \gtrsim 6-8$ GeV. But for $p_T \lesssim 5$ GeV we need better understanding of the interplay of the radiative and collisional energy losses (especially for b quark).
- The RHIC and LHC data are consistent with $\hat{q}(T=250\text{MeV}) \sim 0.2-0.4$ GeV^3.

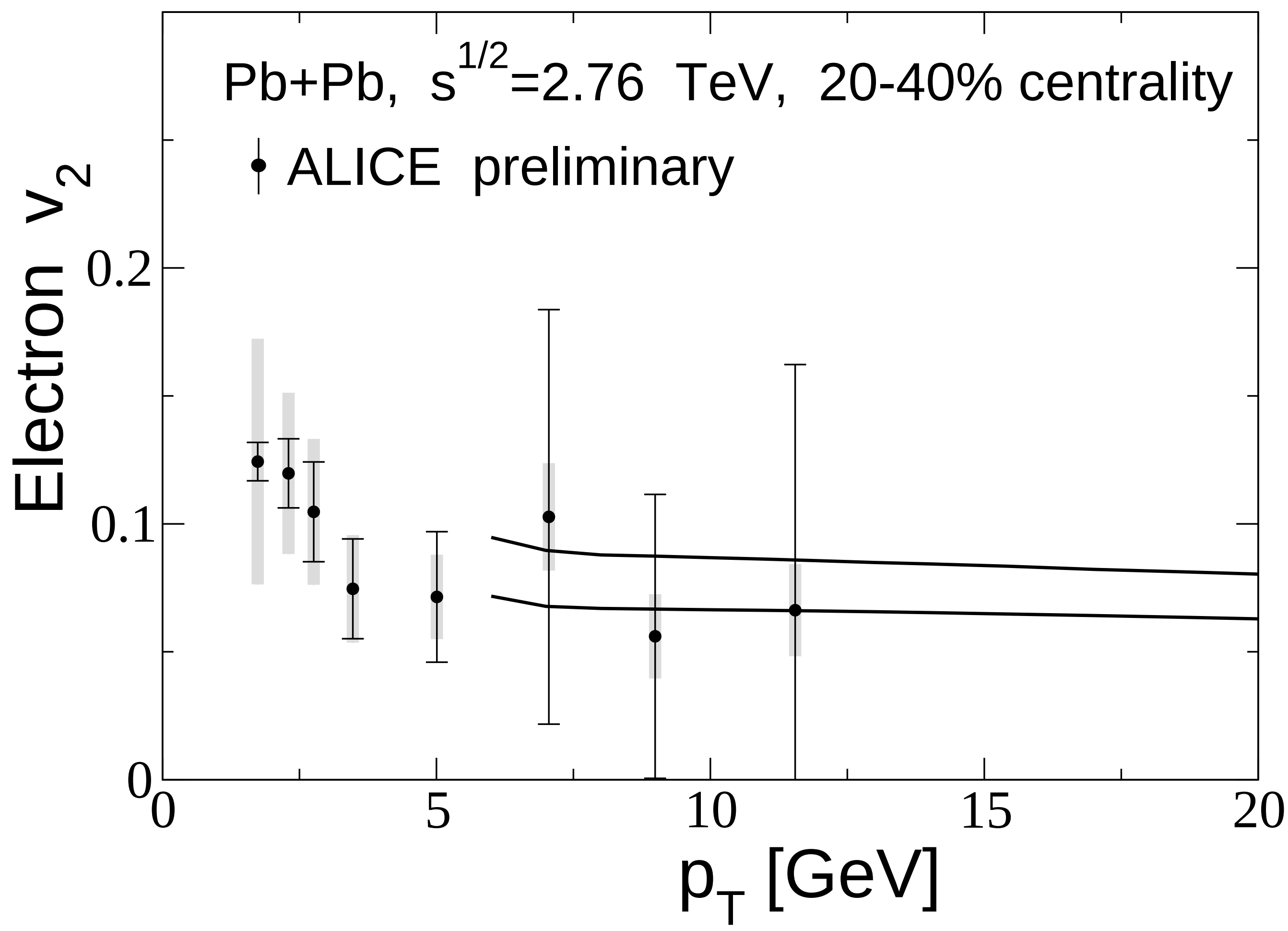
BACK UP SLIDES



The R_{AA} π^0 for $\alpha_s^{fr} = 0.4$ (dotted line) and 0.5 (solid line) for τ_0 =0.3,0.5, 1 fm. The experimental points: PHENIX data [arXiv:1208.2254].



The R_{AA} (charged hadrons) for $\alpha_s^{fr} = 0.4$ (dotted line) and 0.5 (solid line) for τ_0 =0.3, 0.5, and 1 fm. The experimental points: ALICE data [arXiv:1208.2711].



The electron v_2 for $\alpha_s^{fr} = 0.5$ (upper curves) and 0.4 (lower curves).

Dynamical effects in HTL method

The LCPI method applies also to the dynamical pQCD weakly coupled QGP.

$$v(\rho,x)=\frac{in\sigma_{q\bar{q}g}(\rho,x)}{2},\quad \sigma_{q\bar{q}g}(\rho,x)=\frac{9}{8}[\sigma_{q\bar{q}}(\rho)+\sigma_{q\bar{q}}(\rho(1-x))-\sigma_{q\bar{q}}(\rho x)/9],\quad \frac{n\sigma_{q\bar{q}}(\rho)}{2}\Rightarrow P(\vec{\rho})$$

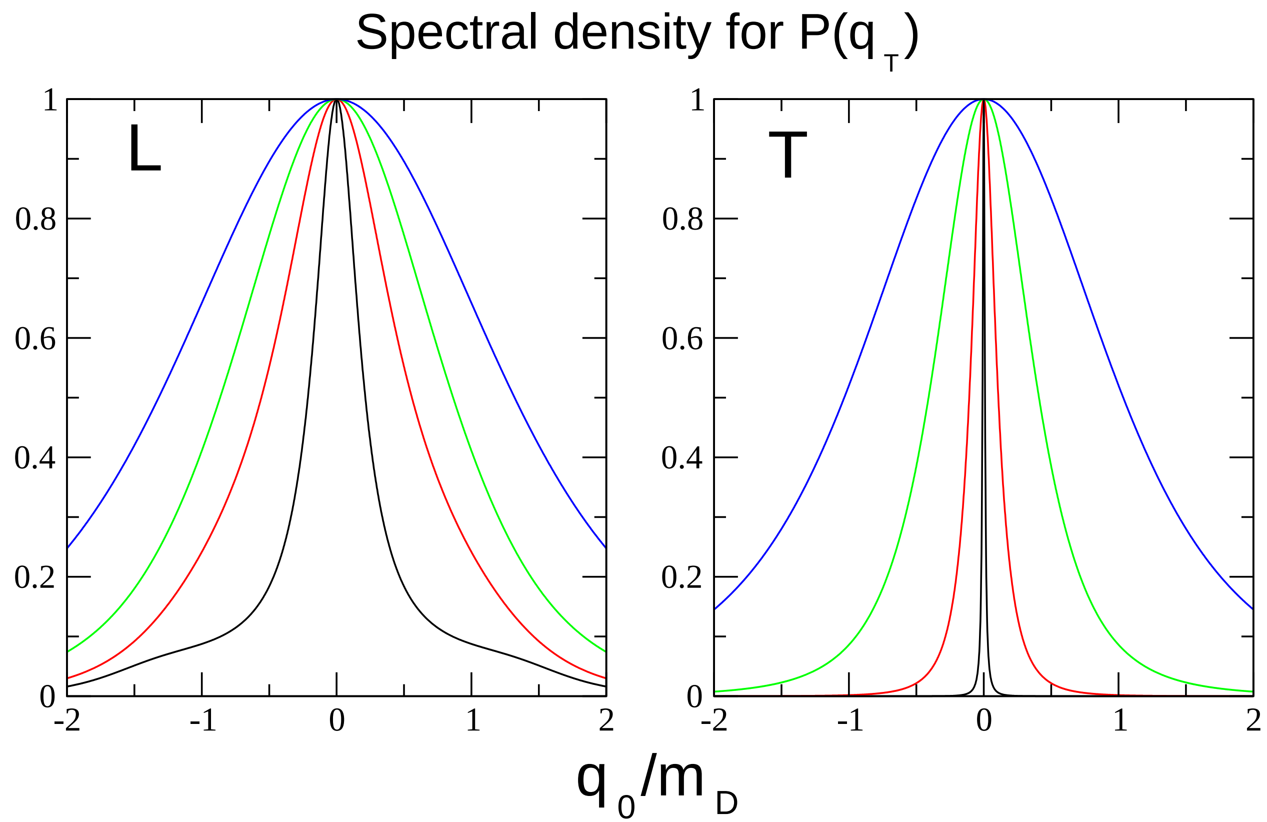
$$P(\vec{\rho})=g^2C_F\int_{-\infty}^{\infty}dz[G(z,0_\perp z)-G(z,\vec{\rho},z)]\,,\quad G(x-y)=u_\mu u_\nu\langle\langle A^\mu(x)A^\nu(y)\rangle\rangle$$ [QED BGZ (1987)]

$$P(\vec{\rho})=\int\frac{d\vec{q}}{(2\pi)^2}[1-\exp(i\vec{\rho}\vec{q})]P(\vec{q})\,.$$

$P(\vec{q})$ can be written in terms of the HTL polarization operator $\Pi\mu\nu$.

$$P(\vec{q})\approx g^2C_FTC(\vec{q})\,,\quad C(\vec{q})=\frac{m_D^2}{\vec{q}^2(\vec{q}^2+m_D^2)}$$ [Aurenche, Gelis, Zaraket (2000)]

In LCPI approach we reproduce all AMY [Arnold, Moore, Yaffe (2001,2002)] results on photon emission [Aurenche, BGZ (2007)]. the pole $1/q^2$ (due to zero magnetic mass) changes the effective dipole cross section at $\rho\gtrsim 1/m_D$, at small ρ it is similar to that in static model.



$T/m_D = 0.5$. The curves:

black- $q_T/m_D = 0.2$

red - $q_T/m_D = 0.5$

green - $q_T/m_D = 1$

blue - $q_T/m_D = 2$.

$P(q_T) = \int dq_0 P(q_T, q_0, q_z = q_0) \Rightarrow$ the "formation time" $\sim 1/q_0$. $\tau_f^T \gtrsim \tau_f^L$. The finite-size effects should lead to magnetic screening at $\rho \gtrsim 1/m_D$.