Is pQCD energy loss in trouble?

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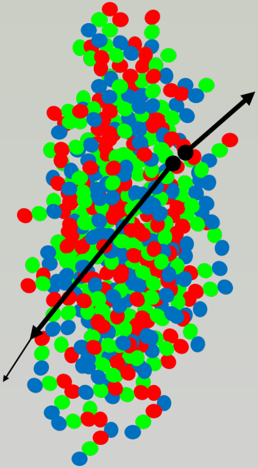
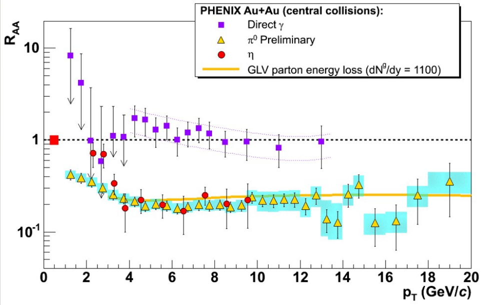
Advisor: Dr. W. A. Horowitz
arXiv:1511.09313

Outline

Characterising the QGP using R_{AA}

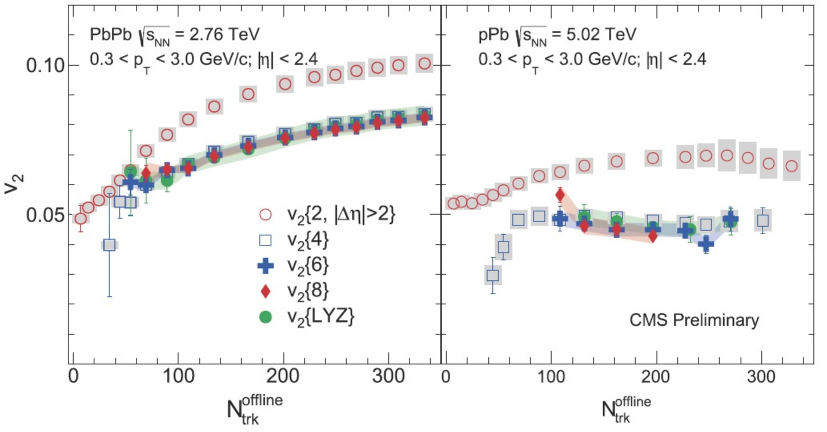


$$R_{AB}(p_T) = \frac{1}{\langle T_{AB} \rangle} \frac{dN_{AB}/dp_T}{d\sigma_{pp}/dp_T}$$



Braz. J. Phys. 2007, vol.37, n.2c, pp.825-829

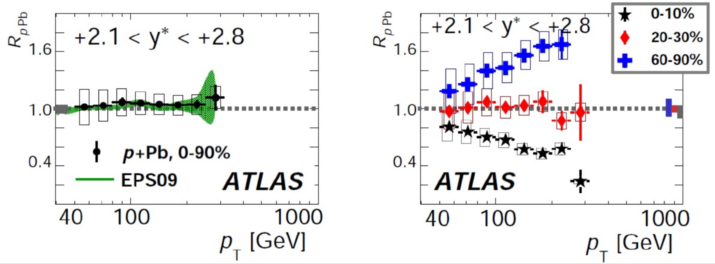
Small system QGP? - v_2



CMS $v_2\{2\}$, $v_2\{4\}$ for PbPb vs. pPb

Phys. Rev. Lett. 115, 012301 (2015)

What about R_{pPb}?



ATLAS, forward rapidity, R_{pPb}

Phys. Let. B 748 (2015) 392–413

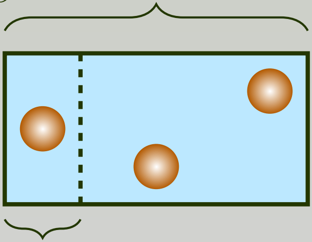
The Gyulassy-Wang framework

We consider the calculation by Gyulassy, Levai and Vitev (GLV), generalized for heavy quarks by Djordjevic (DGLV)

Nucl. Phys. A733 (2004) 265–298. (arXiv:nucl-th/0404006)

M. Gyulassy and X.-N. Wang, Nucl. Phys. B 420 (1994) 583.

$$\frac{1}{\mu_D} \ll \Delta z \sim \lambda_{mfp} \ll L$$



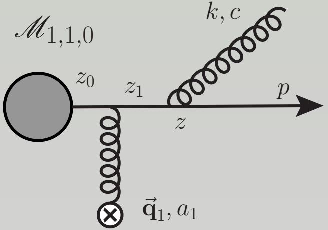
$$\frac{1}{\mu_D} \ll \lambda_{mfp}$$

I. Kolbé and W. A. Horowitz, arXiv:1511.09313

Assumption Scheme

A single adjustment of the DGLV assumption scheme:

- (GW) Small scattering centres: $1/\mu_D \ll \lambda_{mfp}$
- Large System: $z_1 - z_0 = \Delta z_1 \gg 1/\mu_D$
- Large formation time $\omega_i \ll \mu_i$, where $\mu_i^2 \equiv \mu_D^2 + \mathbf{q}_i^2$ and $\omega_i = \frac{(\mathbf{k}-\mathbf{q}_i)^2}{2\omega}$.
- That the impact parameter varies over a large transverse area.
- Collinearity: $k^+ \gg k^-$,
- Factorization
- Eikonal (high energy): $\rightarrow E^+$ is the largest energy scale,
- Soft radiation: $x \ll 1$,



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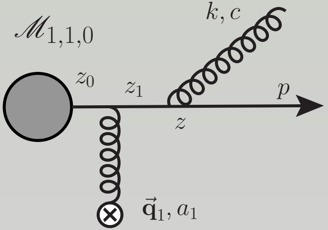
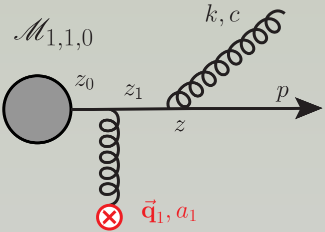


The DGLV calculation generalization

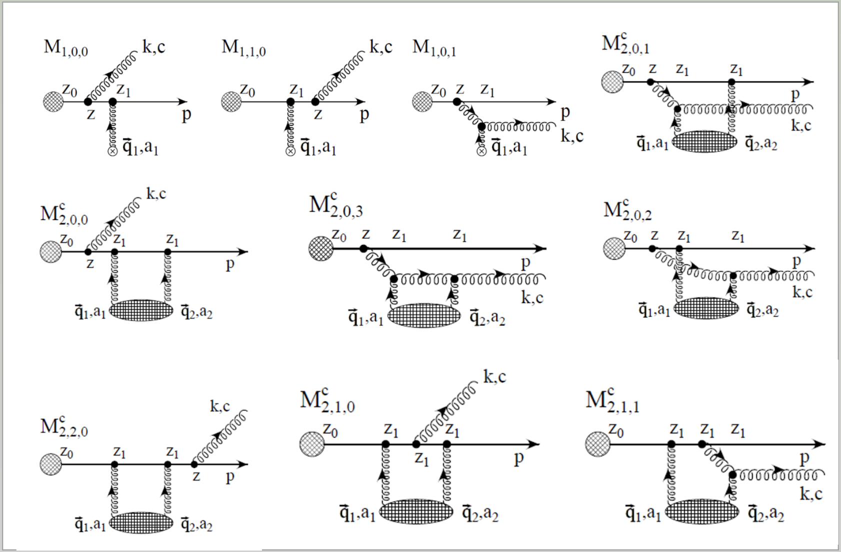


$$v(\vec{\mathbf{q}}_n) = \frac{4\pi\alpha_s}{\vec{\mathbf{q}}_n^2 + \mu_n^2}$$

Residue from third pole $\sim e^{-\mu_1 \Delta z_1}$

$\mu_i^2 \equiv \mu_D^2 + \mathbf{q}_i^2$

$$I_1(p, k, \mathbf{q}_1, z_1 - z_0) = \int \frac{dq_1^z}{2\pi} \frac{\epsilon_\alpha (2p - 2q + k)^\alpha}{(p - q_1 + k)^2 - M^2 + i\epsilon} \times$$
$$\times \frac{1}{(p - q_1)^2 - M^2 + i\epsilon} v(\vec{\mathbf{q}}_1) e^{-iq_1^z (z_1 - z_0)}$$


M1,0,0
k,c
z0
z1
z
p
q1,a1
M1,1,0
k,c
z0
z1
z
p
q1,a1
M1,0,1
z0
z
z1
p
k,c
q1,a1
Mc2,0,1
z0
z
z1
z1
p
k,c
q1,a1
q2,a2
Mc2,0,0
k,c
z0
z1
z1
z
p
q1,a1
q2,a2
Mc2,0,3
z0
z
z1
z1
p
k,c
q1,a1
q2,a2
Mc2,0,2
z0
z
z1
z1
p
k,c
q1,a1
q2,a2
Mc2,2,0
k,c
z0
z1
z1
z
p
q1,a1
q2,a2
Mc2,1,0
k,c
z0
z1
z1
z1
p
q1,a1
q2,a2
Mc2,1,1
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z1
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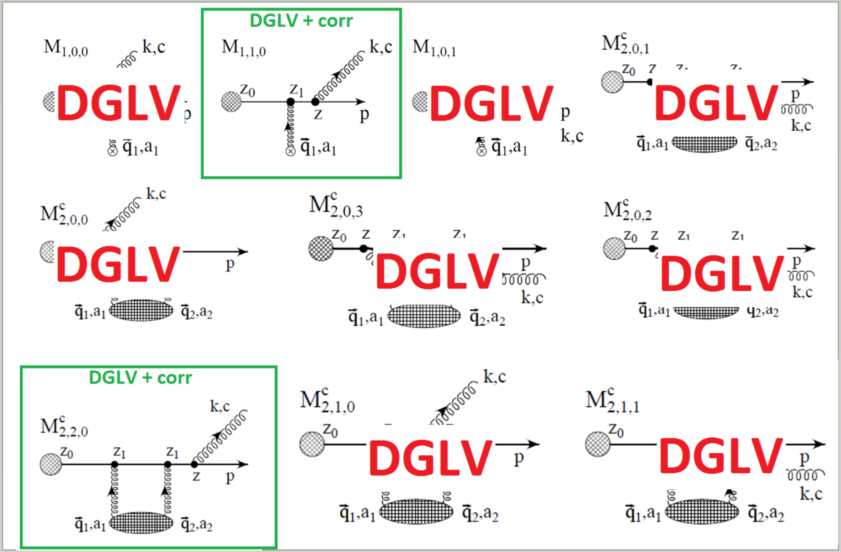
z1
p
k,c
q1,a1
q2,a2


DGLV + corr
$M_{1,0,0}$
k,c
DGLV
p
$\vec{q}_1,a_1$
$M_{1,1,0}$
z_0
z_1
z
p
$M_{1,0,1}$
$M^c_{2,0,1}$
$\vec{q}_2,a_2$
$M^c_{2,0,0}$
$M^c_{2,0,3}$
$M^c_{2,0,2}$
$M^c_{2,2,0}$
$M^c_{2,1,0}$
$M^c_{2,1,1}$

(All system sized) generalized GLV

$$
\begin{aligned}
\Delta E^{(1)}_{ind} = \frac{C_R \alpha_s L E}{\pi \lambda_g} \int dx \int \frac{d^2 \mathbf{q}_1}{\pi} \frac{\mu^2}{(\mu^2 + \mathbf{q}_1^2)^2} \int \frac{d^2 \mathbf{k}}{\pi} \\
\times \int d\Delta z \bar{\rho}(\Delta z) \Bigg[- \frac{2\big(1 - \cos\{(\omega_1 + \tilde{\omega}_m)\Delta z\}\big)}{(\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2} \\
\times \left(\frac{(\mathbf{k} - \mathbf{q}_1) \cdot \mathbf{k}}{\mathbf{k}^2 + m_g^2 + x^2 M^2} - \frac{(\mathbf{k} - \mathbf{q}_1)^2}{(\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2} \right) \\
+ \frac{1}{2} e^{-\mu_1 \Delta z} \Bigg\{ \left(\frac{\mathbf{k}}{\mathbf{k}^2 + m_g^2 + x^2 M^2} \right)^2 \\
\times \left(1 - \frac{2C_R}{C_A}\right) \Big(1 - \cos\{(\omega_0 + \tilde{\omega}_m)\Delta z\}\Big) \\
+ \frac{\mathbf{k} \cdot (\mathbf{k} - \mathbf{q}_1)}{(\mathbf{k}^2 + m_g^2 + x^2 M^2)\big((\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2\big)} \\
\times \Big(\cos\{(\omega_0 + \tilde{\omega}_m)\Delta z\} - \cos\{(\omega_0 - \omega_1)\Delta z\} \Big) \Bigg\} \Bigg].
\end{aligned}
$$

$\sim \log \frac{E}{\mu}$

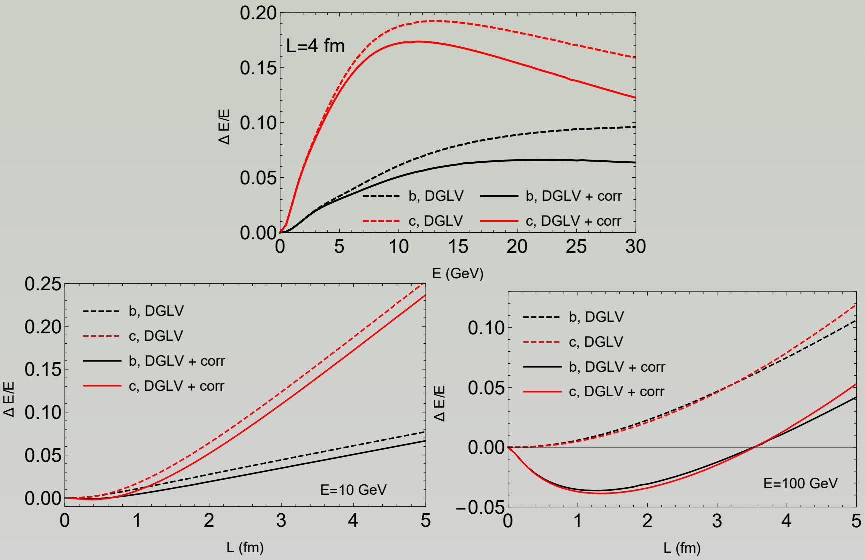
(All system sized) generalized GLV

$$\Delta E^{(1)}_{ind} = \frac{C_R \alpha_s L E}{\pi \lambda_g} \int dx \int \frac{d^2\mathbf{q}_1}{\pi} \frac{\mu^2}{(\mu^2 + \mathbf{q}_1^2)^2} \int \frac{d^2\mathbf{k}}{\pi}$$

$$\left.\begin{aligned} &\times \int d\Delta z \bar{\rho}(\Delta z) \Bigg[- \frac{2\big(1 - \cos\{(\omega_1 + \tilde{\omega}_m)\Delta z\}\big)}{(\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2} \\ &\times \left(\frac{(\mathbf{k} - \mathbf{q}_1)\cdot \mathbf{k}}{\mathbf{k}^2 + m_g^2 + x^2 M^2} - \frac{(\mathbf{k} - \mathbf{q}_1)^2}{(\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2} \right) \end{aligned}\right\} \sim L^2 \mu^2 \log \frac{E}{\mu}$$

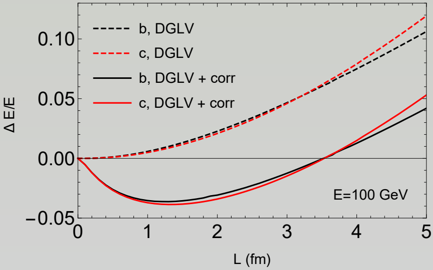
$$\left.\begin{aligned} &+ \frac{1}{2} e^{-\mu_1 \Delta z} \Bigg\{ \left(\frac{\mathbf{k}}{\mathbf{k}^2 + m_g^2 + x^2 M^2} \right)^2 \\ &\times \left(1 - \frac{2C_R}{C_A}\right) \Big(1 - \cos\{(\omega_0 + \tilde{\omega}_m)\Delta z\}\Big) \\ &+ \frac{\mathbf{k}\cdot(\mathbf{k} - \mathbf{q}_1)}{(\mathbf{k}^2 + m_g^2 + x^2 M^2)\big((\mathbf{k} - \mathbf{q}_1)^2 + m_g^2 + x^2 M^2\big)} \\ &\times \big(\cos\{(\omega_0 + \tilde{\omega}_m)\Delta z\} - \cos\{(\omega_0 - \omega_1)\Delta z\}\big) \Bigg\} \Bigg]. \end{aligned}\right\} \sim -LE \log\left(\frac{E}{\mu}\right)$$

Numerical Results



Conclusions - Are we in trouble?

- pA demand better understanding of small system energy loss.
- Performed a small system correction to DGLV.
- Small system, large formation time terms ($\tau_{form} = xE/\mathbf{k}^2 \gg 1/\mu$) *are not small* - cannot be neglected.
- Future work will require the relaxation of both collinearity *and* large formation time assumptions.
- *All* major pQCD energy loss calculations assume a large system.

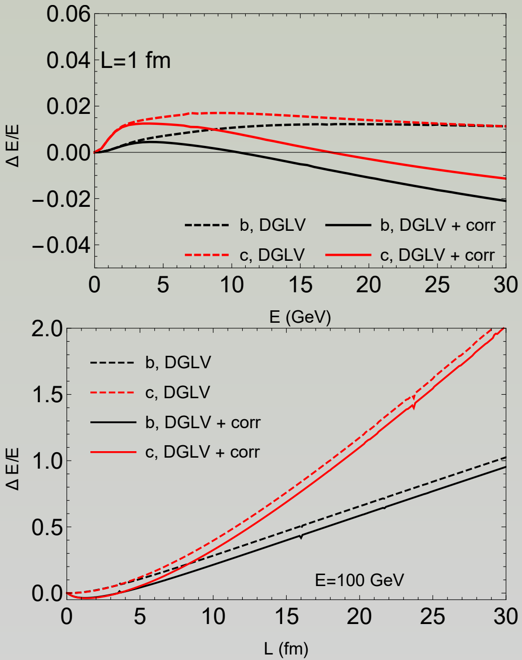


5 Backups

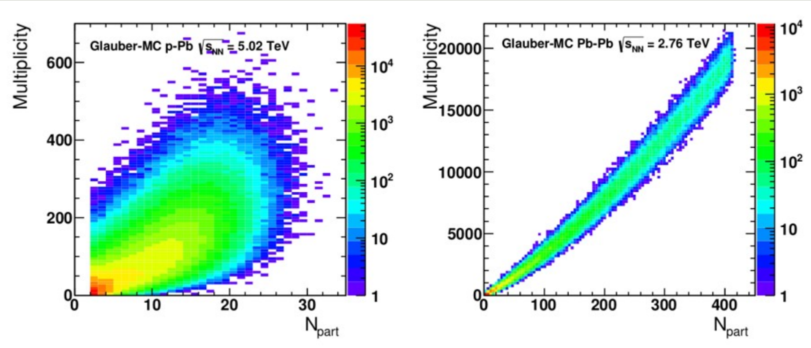
Asymptotic Analysis

$$\Delta E^{(1)}_{\mathrm{DGLV}} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}.$$

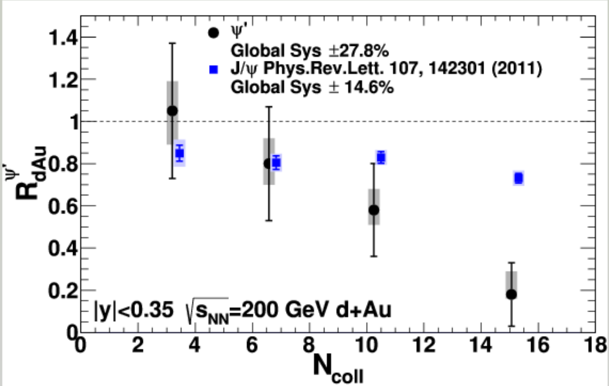
$$\Delta E^{(1)}_{\mathrm{corr}} = \frac{C_R \alpha_s}{2\pi} \frac{L}{\lambda_g} \left(- \frac{2 C_R}{C_A} \right) \frac{1}{2 + \mu L} E \times 2 \int_0^1 dx \log \left(\frac{L\, k_{max}}{2 + \mu L} \right)$$


0.06
0.04
0.02
0.00
−0.02
−0.04
L=1 fm
Δ E/E
b, DGLV
b, DGLV + corr
c, DGLV
c, DGLV + corr
0
5
10
15
20
25
30
E (GeV)
2.0
1.5
1.0
0.5
0.0
Δ E/E
b, DGLV
c, DGLV
b, DGLV + corr
c, DGLV + corr
E=100 GeV
0
5
10
15
20
25
30
L (fm)

Multiplicity vs. Centrality



Suppression in R_{dAu}



PHENIX, PRL 111, 202301 (2013)

Energy Ratios

$$\omega \approx \frac{xE^+}{2} \approx \frac{xP^+}{2}$$

$$\omega_0 = \frac{\mathbf{k}^2}{2\omega}$$

$$\omega_i = \frac{(\mathbf{k} - \mathbf{q}_i)^2}{2\omega}$$

$$\omega_{(ij)} = \frac{(\mathbf{k} - \mathbf{q}_i - \mathbf{q}_j)^2}{2\omega}$$

$$\tilde{\omega}_m = \frac{m_g^2 + M^2 x^2}{2\omega}$$

Kinematic Bounds

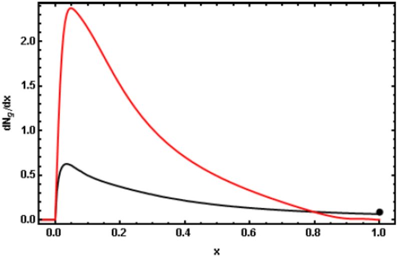


FIG. 5: Single inclusive gluon radiation distribution, dN_g/dx, from the WHDG implementation of the first order in opacity DGLV formula, Eq. (2), in red, and the ASW–SH implementation of Eq. (3), in black, for a 10 GeV up quark traversing a nominal, 2 fm long static brick of QGP held at a constant $T = 485$ MeV. The point at $x = 1$ indicates the integrated weight of dN_g/dx in the ASW–SH implementation for $x > 1$.

- An analysis was done that attempted to discover the reason for the major differences between the two models compared here.
- The analytic expressions, when setting $\omega = xE$, are identical!
- Answer: The assumptions made when performing the integrals *crucially* depend on the choice of kinematic bound.
- The kinematic bound enforces collinearity.
- If it makes such a big difference, we cannot assume collinearity

Energy Loss dependencies

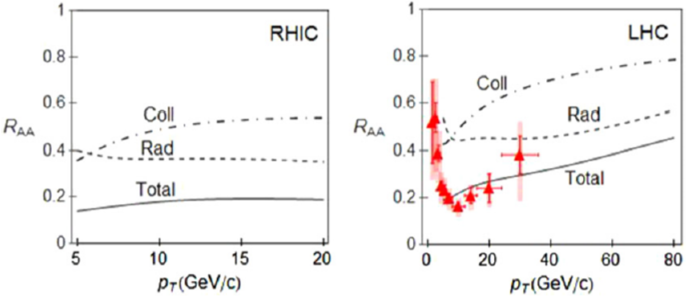


Figure 3. Radiative versus collisional energy loss suppressions in a dynamical QCD medium. D meson suppression predictions are shown, as a function of transverse momentum, for radiative (dashed curve), collisional (dot-dashed curve) and radiative + collisional (solid curve) energy loss. Left (right) panel corresponds to the RHIC (the LHC) case. Right panel also shows the D meson R_{AA} data in 0–7.5% central 2.76 TeV Pb+Pb collisions at the LHC [39] (red triangles). Debye mass is $\mu_E = gT$, coupling constant is $\alpha_S = 0.3$ ($\alpha_S = 0.25$) for the RHIC (the LHC) and no finite magnetic mass effect is included (i.e. $\mu_M = 0$).

J. Phys. G: Nucl. Part. Phys. 42 (2015) 075105 (12pp)

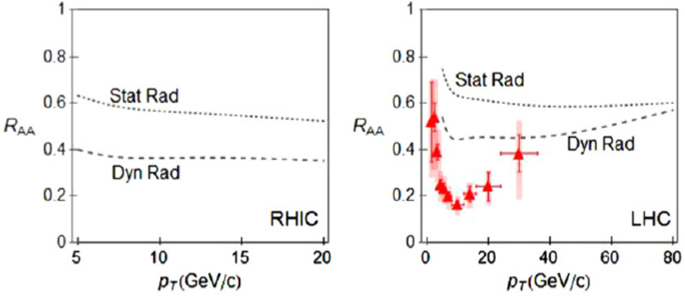


Figure 2. Radiative energy loss suppressions in a static *vs* dynamical QCD medium. D meson suppression predictions are shown, as a function of transverse momentum, assuming only radiative energy loss in static (dotted curve) and in dynamical (dashed curve) QCD medium. Left (right) panel corresponds to the RHIC (the LHC) case. Right panel also shows the D meson R_{AA} data in 0–7.5% central 2.76 TeV Pb+Pb collisions at LHC [39] (red triangles). Debye mass is $\mu_E = gT$, coupling constant is $\alpha_S = 0.3$ ($\alpha_S = 0.25$) for the RHIC (the LHC) and no finite magnetic mass effect is included (i.e. $\mu_M = 0$).

J. Phys. G: Nucl. Part. Phys. 42 (2015) 075105 (12pp)

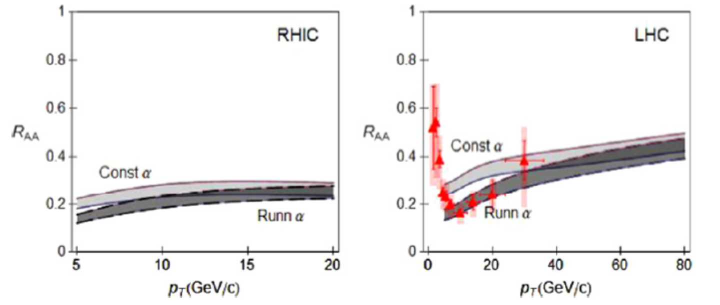
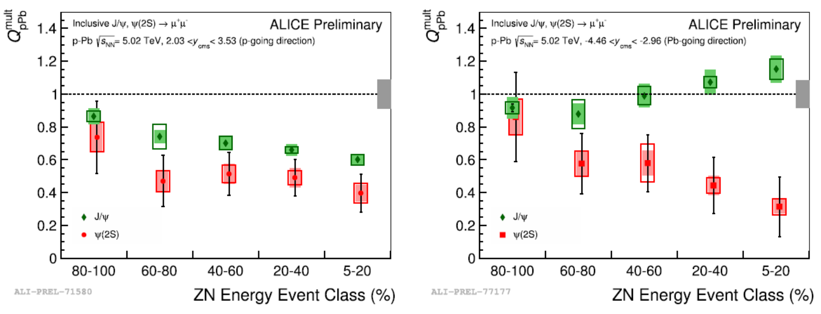


Figure 7. Running coupling and magnetic mass effect on R_{AA}. D meson suppression predictions are shown, as a function of transverse momentum, with the constant coupling $\alpha_S = 0.3$ ($\alpha_S = 0.25$) for the RHIC (the LHC) (light gray band) and with the running coupling (dark gray band). In both cases radiative + collisional contributions in dynamical QCD medium are included. Upper (lower) boundary of each band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$). Left (right) panel corresponds to the RHIC (the LHC) case. Right panel also shows the D meson R_{AA} data in 0–7.5% central 2.76 TeV Pb+Pb collisions at the LHC [39] (red triangles).

J. Phys. G: Nucl. Part. Phys. 42 (2015) 075105 (12pp)

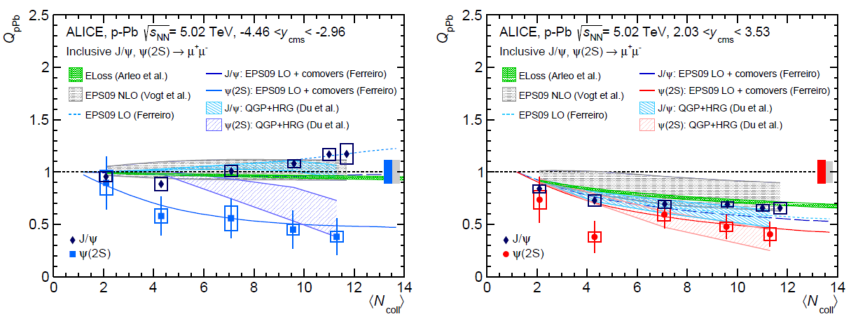
Small system QGP? - J/Ψ and $\Psi(2S)$



ALICE Centrality dependent J/Ψ and $\Psi(2S)$ suppression.

ALICE Overview Quark Matter 2014 (Nucl. Phys. A 931(2014)1179–1183, Nucl. Phys. A 931(2014)628–632)

$$Q_{pPb}^{\textbf{mult},i} = \frac{Y_{pPb}^{i}}{\langle T_{pPb}^{\textbf{mult},i} \rangle \times \sigma_{pp}^{J/\Psi \to \mu^+\mu^-}}$$



The ALICE collaboration, Adam, J., Adamová, D. et al. J. High Energ. Phys. (2016) 2016: 50.
doi:10.1007/JHEP06(2016)050