Importance of different energy loss effects in jet suppression at RHIC and LHC

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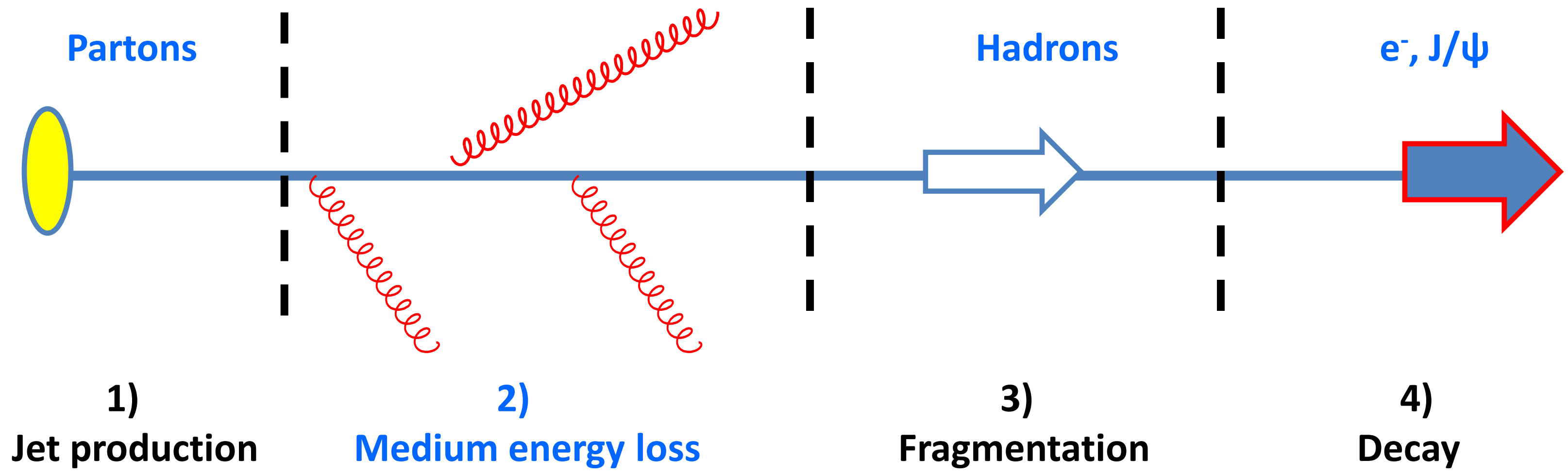
Jet suppression

- **High momentum light and heavy flavor suppressions are considered to be excellent tool for studying QCD matter**
- **RHIC and LHC R_{AA} experimental data for different probes and centrality regions are available**
- **Comparison of theoretical predictions with experiments tests our understanding of QCD matter**

Computational scheme for jet suppression



1) Initial momentum distributions
2) Energy loss calculation
3) Fragmentation functions
4) Decay functions

Computational formalism

- **Light and heavy flavor production**
  (Z.B. Kang, I. Vitev, H. Xing, PLB 718 : 482 (2012))
- **Dynamical energy loss in a finite size QCD medium**
  (M. Djordjevic, PRC 80 : 064909 (2009))
- **Multi-gluon fluctuations**
  (M. Gyulassy, P. Levai, I. Vitev, PLB 538 : 282 (2002))
- **Path-length fluctuations**
  (A. Dainese, EPJ C33 : 495 (2004))
- **Fragmentation for light and heavy flavor**
  (D. de Florian, R. Sassot, M. Stratmann, PRD 75:114010 (2007); M. Cacciari, P. Nason, JHEP 0309 : 006 (2003))
- **Decay of heavy meson into e^- and J/ψ**
  (M. Cacciari et al., JHEP 1210 : 137 (2012))

Dynamical energy loss formalism

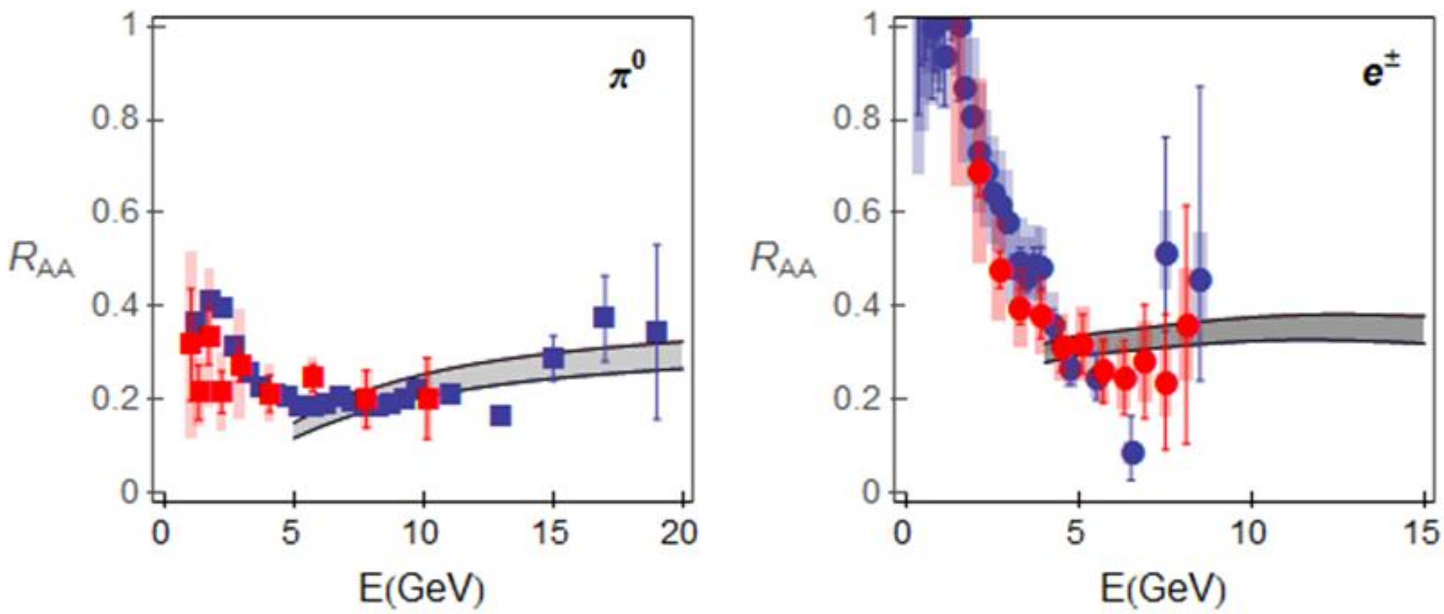
- **Jet energy loss calculated in a finite size dynamical QCD medium** (M.Djordjevic, PRC 80 : 064909 (2009), M. Djordjevic and U. Heinz, PRL 101 : 022302 (2008))
- **Abolishes static in favor of dynamical approximation**
- **Collisional + radiative energy losses** computed within the same theoretical framework
- **Finite magnetic mass effect** (M. Djordjevic and M. Djordjevic, PLB 709 : 229 (2012))
- **Running coupling** (M. Djordjevic and M. Djordjevic, PLB 734 : 286 (2014))

In generating all R_{AA} predictions we used:

- The same numerical procedure
- The same energy loss formalism
- No free parameters

We observed a very good agreement for:

- Both RHIC and LHC
- Diverse set of probes
- Different centrality ranges



M.Djordjevic and M. Djordjevic, PRC 90 : 034910 (2014)

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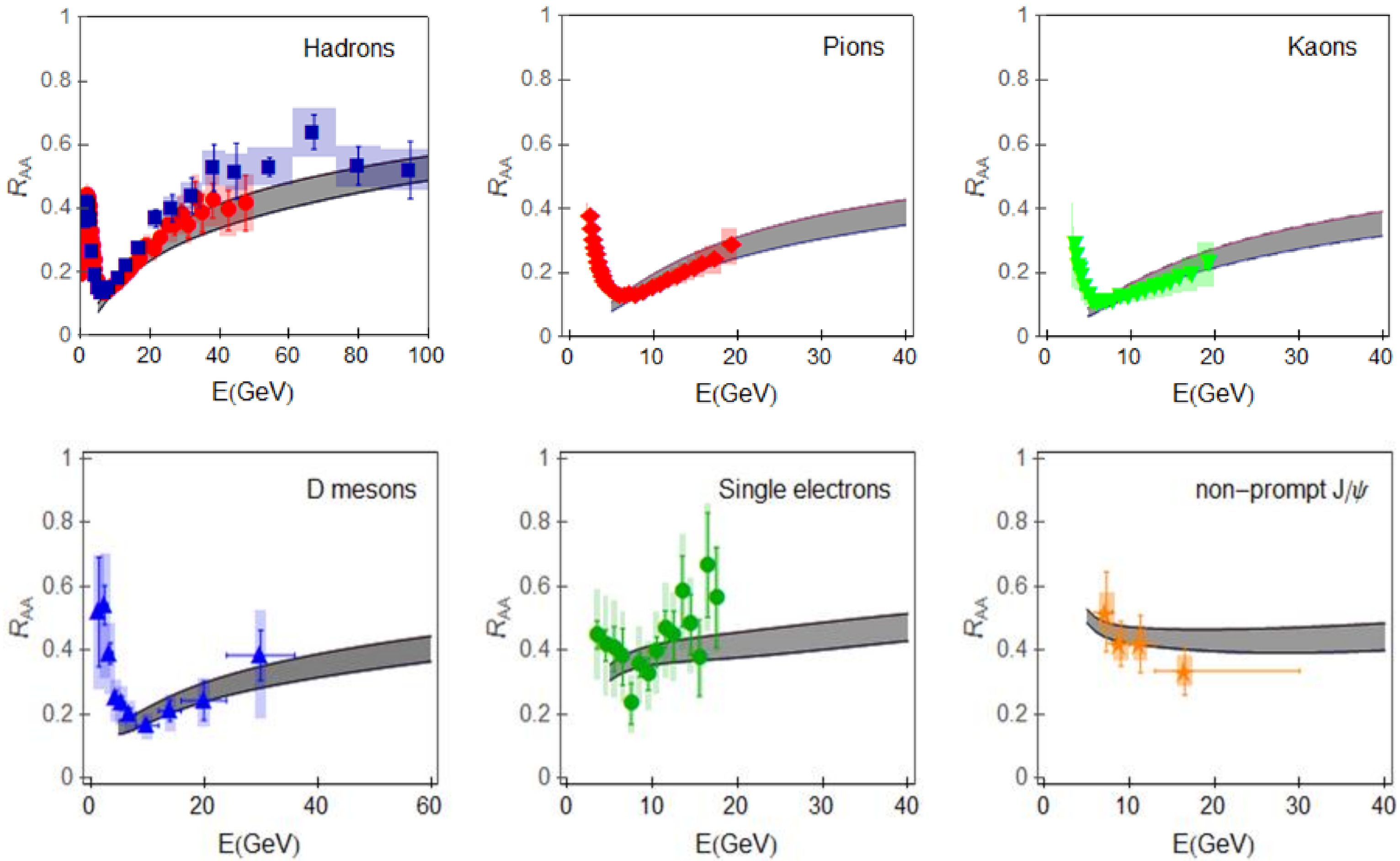

M. Djordjevic and M. Djordjevic, PLB 734 : 286 (2014)

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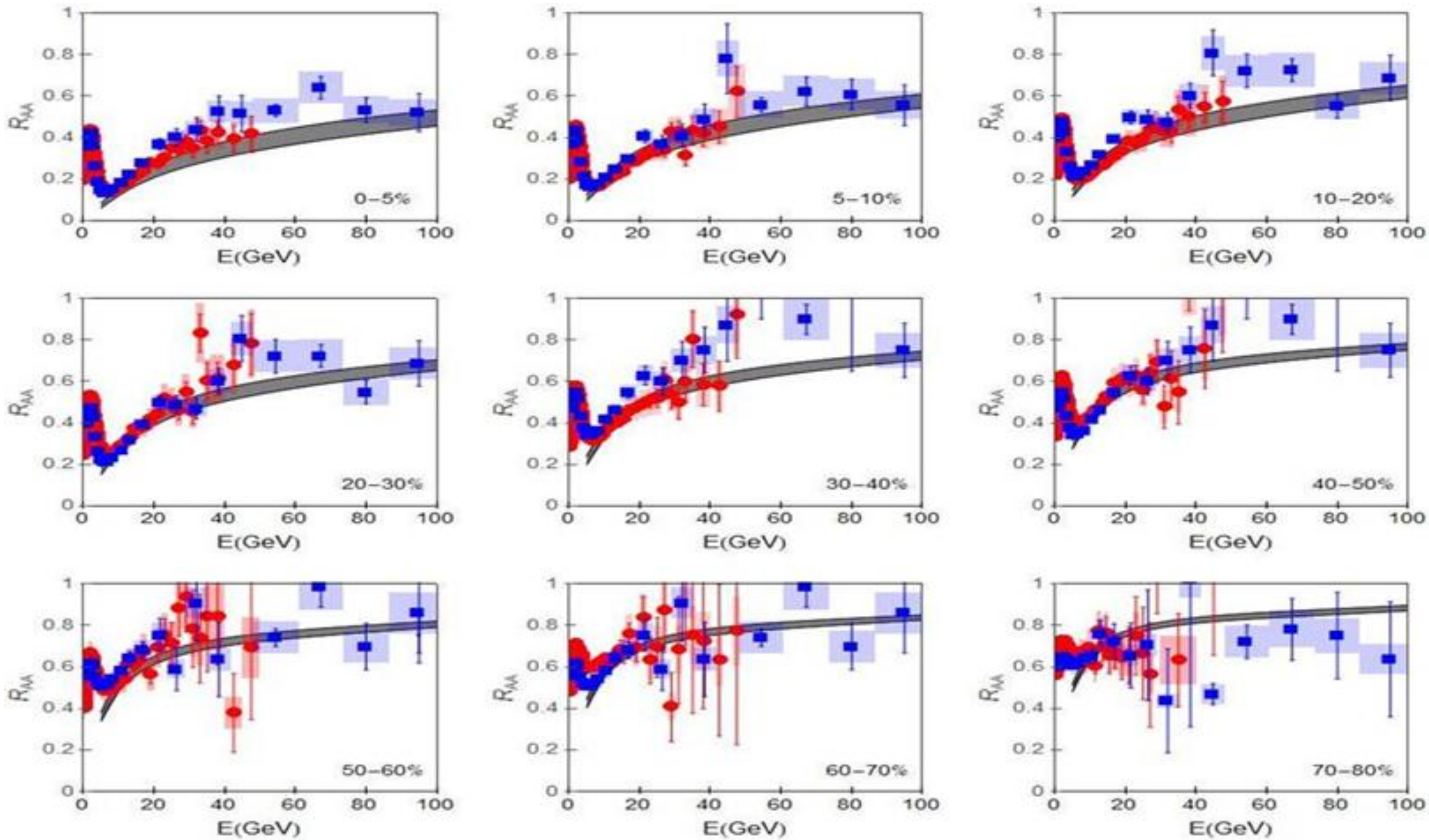

M.D.Djordjevic, M. Djordjevic and B.Blagojevic, PLB 737 : 298 (2014)

Energy loss ingredients

- Radiative energy loss
- Collisional energy loss
- Dynamical scatterers
- Finite size QCD medium
- Running coupling
- Finite magnetic mass

Different models neglect some or most of these effects.

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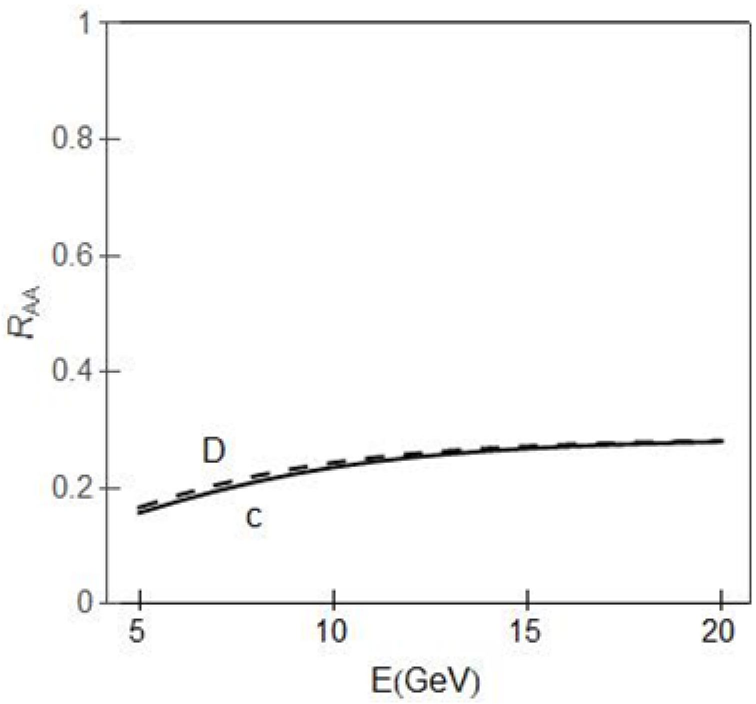
What is their relative importance?

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Charm quark as a clear energy loss probe



Fragmentation does not modify suppression!

The clearest energy loss probe.

M.Djordjevic and M. Djordjevic, PRL 112 : 042302 (2014)

Different energy loss effects and our approach

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Effects:

- Radiative energy loss
- Collisional energy loss
- Dynamical scatterers
- Running coupling
- Finite magnetic mass

Our approach:

vs. 1.

2.

3.

4.

Different models neglect some or most of these effects.

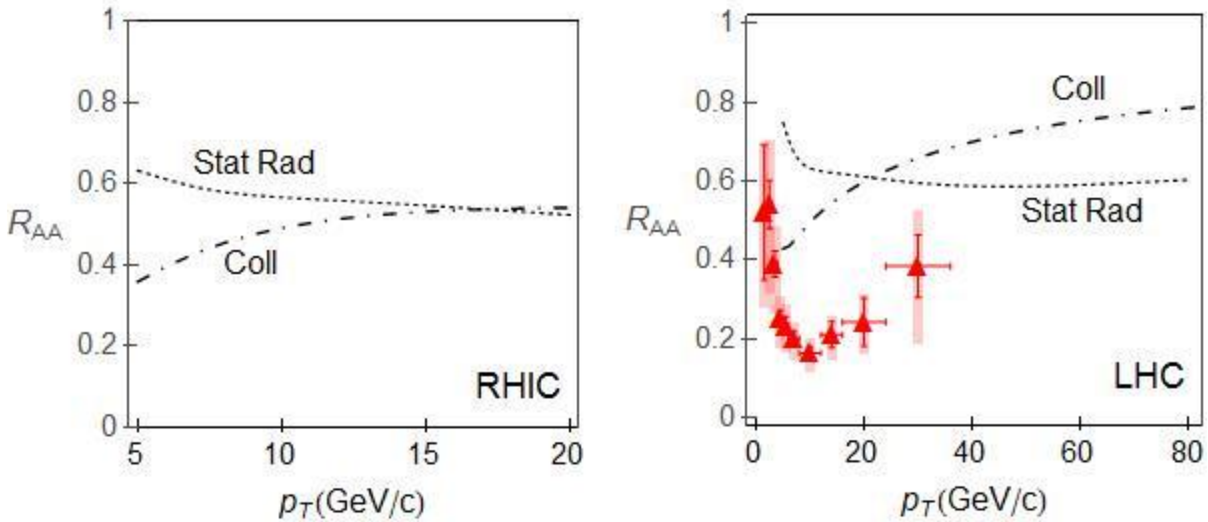
What is their relative importance?

How does each one of them affect $R_{AA?}$

Static radiative vs. collisional energy loss

Previously: Static approximation

Only radiative energy loss important! Collisional energy loss = 0!



▲ : A. Grelli [for the ALICE Collaboration], NPA 904-905 : 635c (2013) ;
B. Abelev etal., JHEP 1209 : 112 (2012)

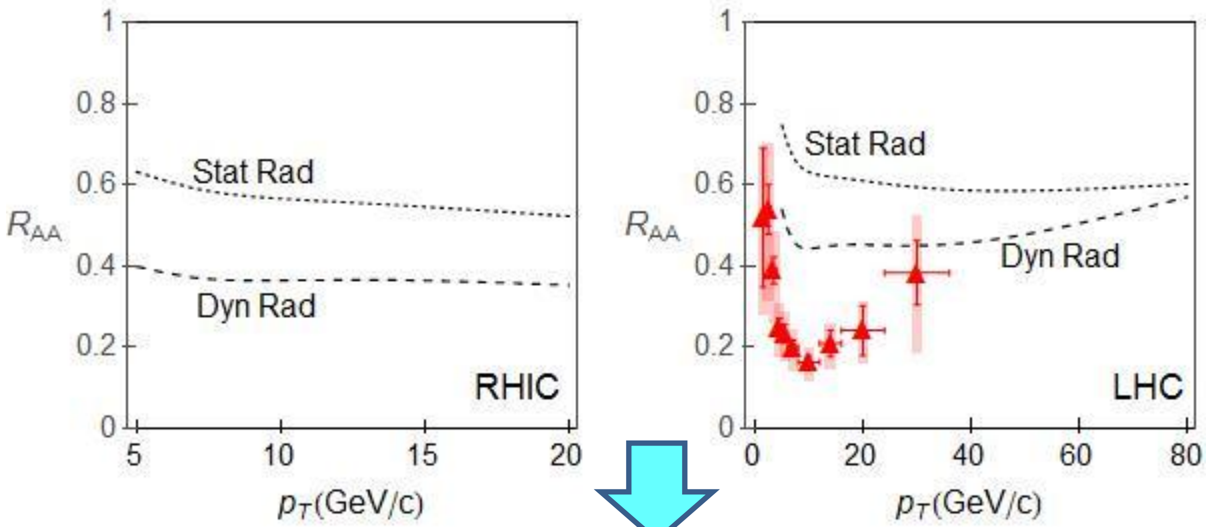
Collisional suppression comparable with static radiative suppression!

Static approximation is not adequate!

Dynamical effects have to be included!

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Radiative energy loss – static vs. dynamical



Dynamical approximation introduced according to:
M. Djordjevic, PRC 80 : 064909 (2009)

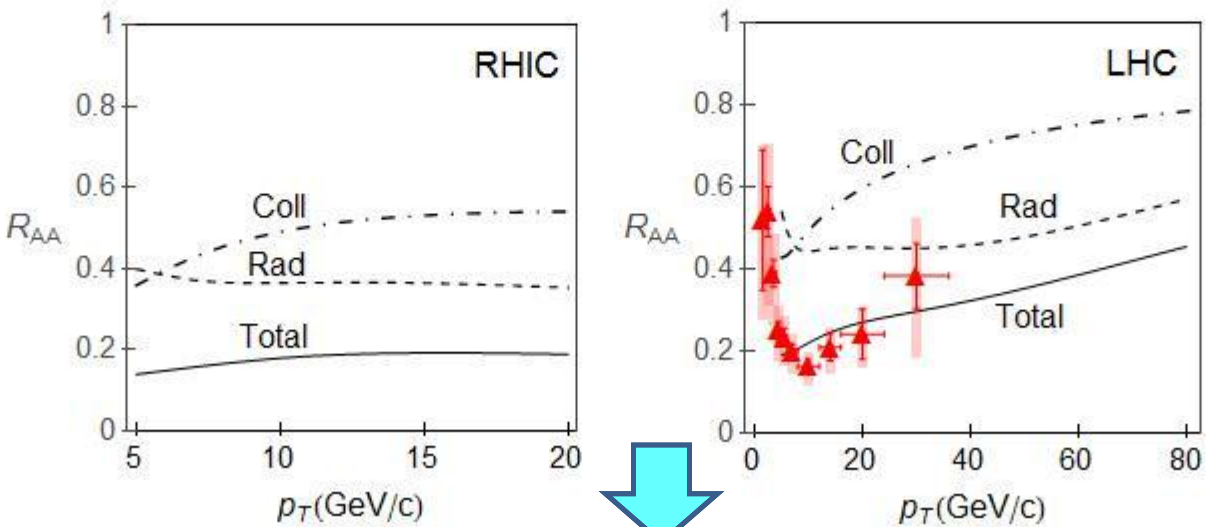
Dynamical radiative suppression leads to a significant suppression increase.

Dynamical effects are important.

Dynamical radiative suppression alone is not sufficient to explain the data (LHC).

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Radiative vs. collisional energy loss in <u>dynamical approximation</u>



A **rough agreement** between total suppression and LHC data!

Even when dynamical effects are accounted, again **both** radiative and collisional contributions are important.

<u>Total suppression</u> is a **significantly larger** than either of the two contributions.

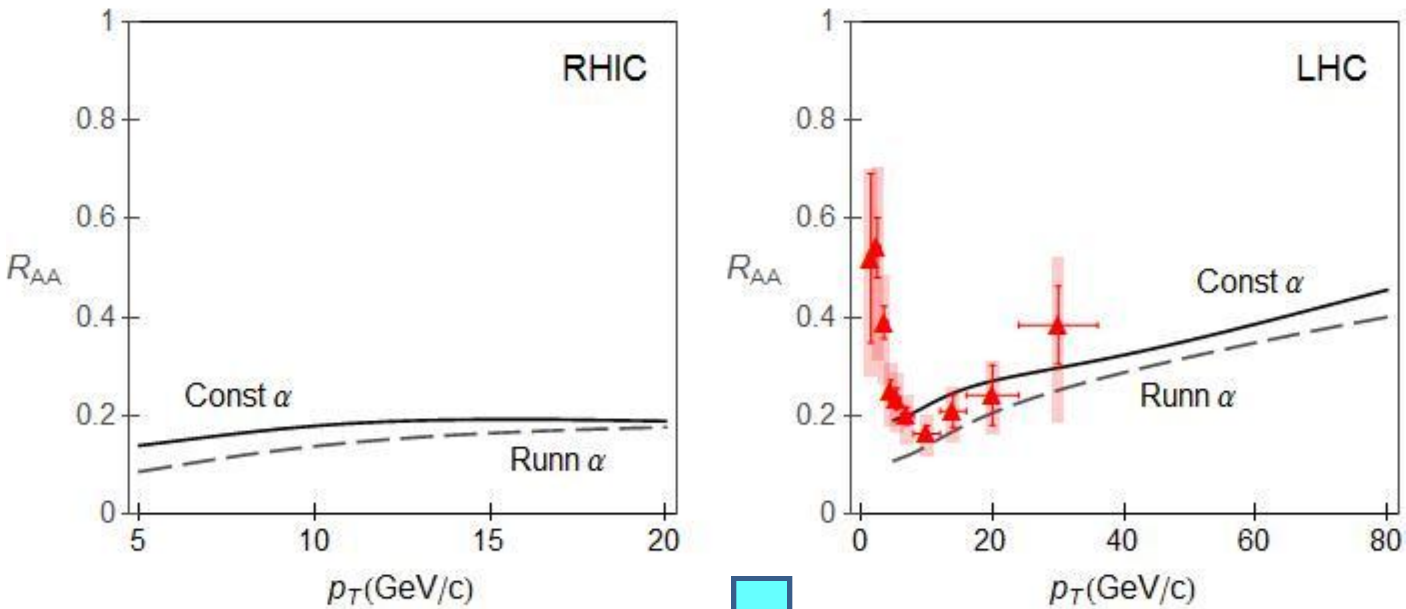
Dynamical approximation – the main effect!

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Running coupling effect on R_{AA}

Running coupling introduced according to:

M. Djordjevic and M. Djordjevic, PLB 734 : 286 (2014)



Slightly worse agreement with LHC R_{AA} data!

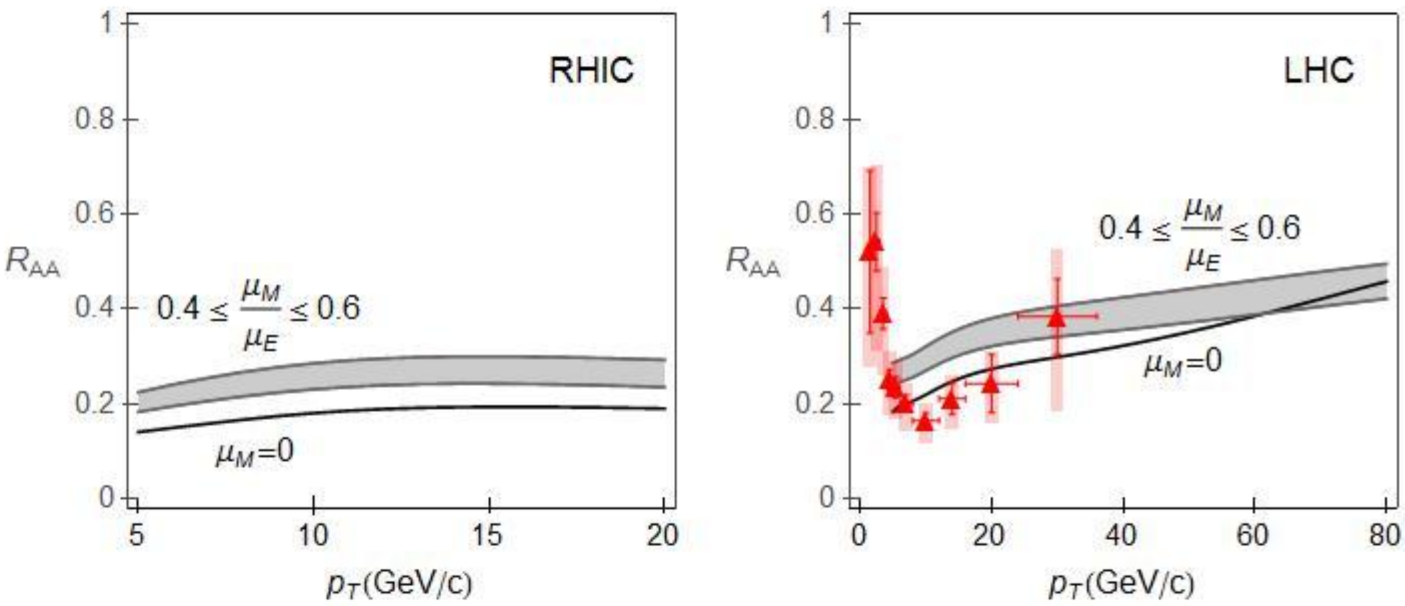
Suppression increase at lower jet energies by a factor of ~ 2.

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Finite magnetic mass effect on R_{AA}

Finite magnetic mass introduced according to:

M.Djordjevic and M. Djordjevic, Phys. Lett.B709 : 229 (2012)

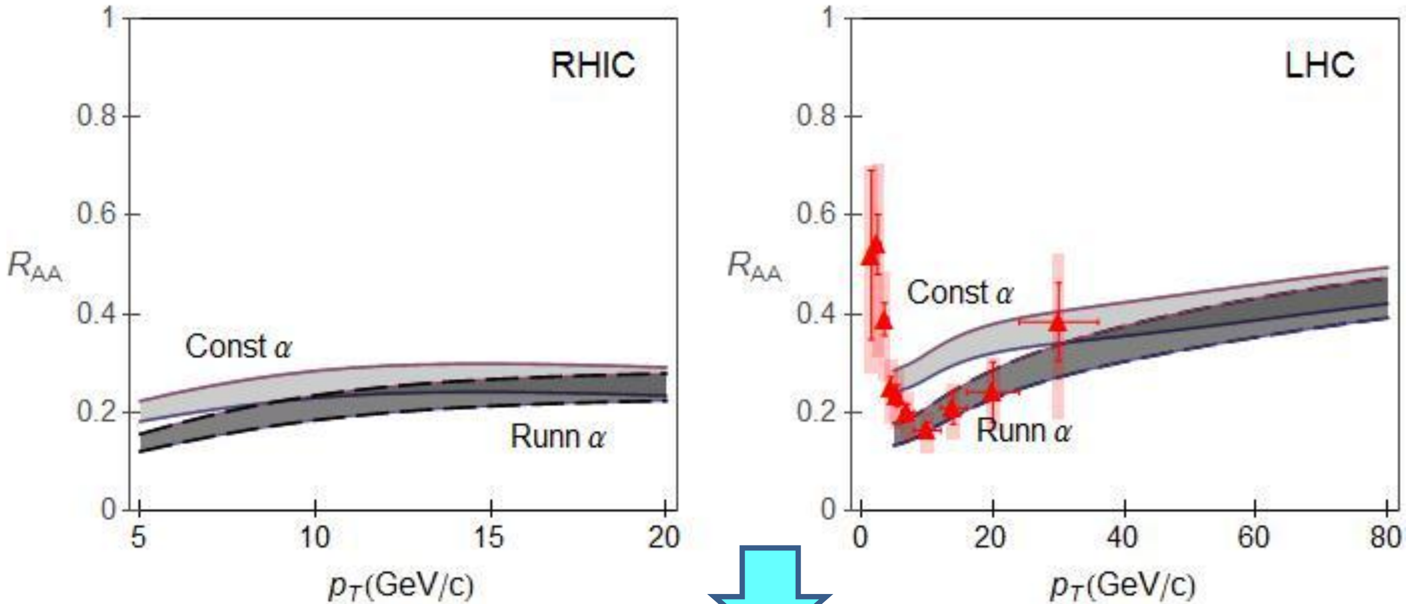


Slightly worse agreement with LHC R_{AA} data and runs in opposite direction from running coupling!

Suppression decrease by ~ 30 %

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Running coupling and finite magnetic mass effect on R_{AA}



Improves the agreement with LHC R_{AA} data!

Both effects are important and contribute to the finer agreement with the experimental data!

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Conclusion

Finite size dynamical energy loss leads to a robust agreement with suppression data, for different energies, probes and centrality ranges.

⬇

Which effect in modeling jet-medium interactions contributes the most?

⬇

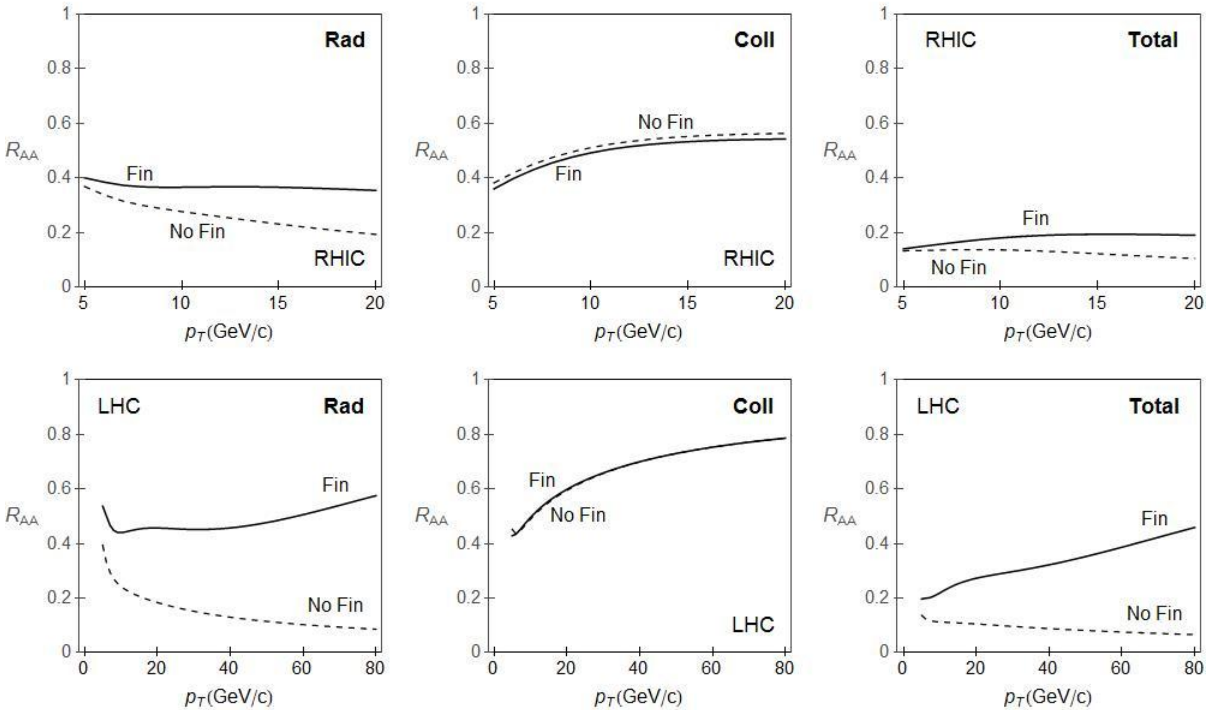
The most important effect is the inclusion of the dynamical approximation, but all the other effects contribute to the finer agreement with the data. Therefore, the agreement is a result of a superposition of all improvements.

Thank you for the attention!

Back up

Finite size effect on R_{AA}

LPM introduced according to: M.Djordjevic, PRC 80 : 064909 (2009);
M.Djordjevic, PRC 74, : 064907 (2006)



Finite size effect is negligible for collisional, but significant for radiative and total suppression!

Finite size effect is also important!

B.Blagojevic and M. Djordjevic, JPG 42 : 075105 (2015)

Angular averaged R_{AA} vs. medium evolution

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{\rm bin} dN_{pp}/dp_T}$$

Angular averaged R_{AA} sensitive only to the average temperature of evolving QCD medium.

↓

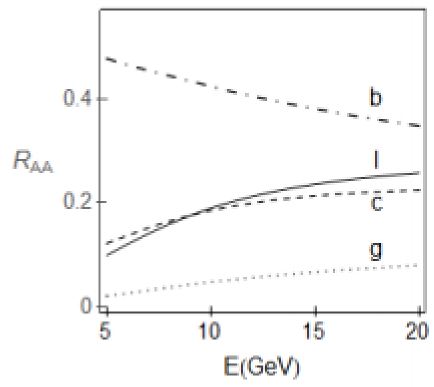
Angular averaged R_{AA} a pure probe for jet-medium interactions.

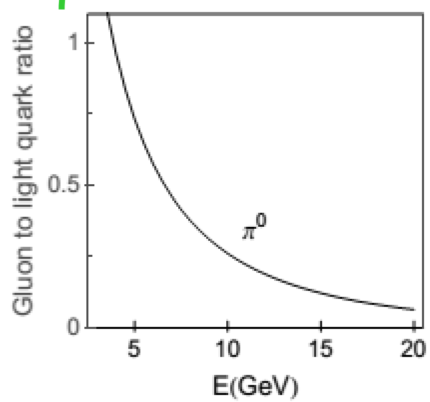
D. Molnar and D. Sun, NPA 932 : 140 (2014) ;
D. Molnar and D. Sun, NPA 910-911 : 486 (2013);
T. Renk, PRC 85 : 044903 (2012)

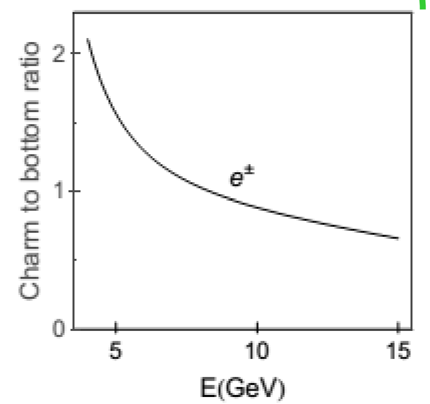
Heavy flavor puzzle at RHIC

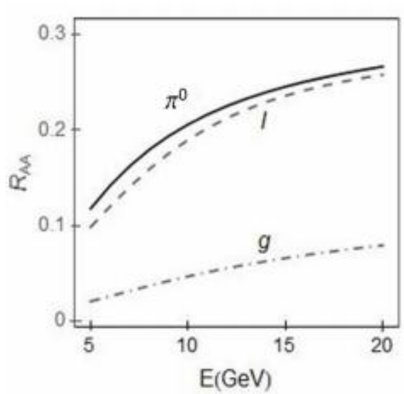
M.Djordjevic and M. Djordjevic, PRC 90 : 0334910 (2014)

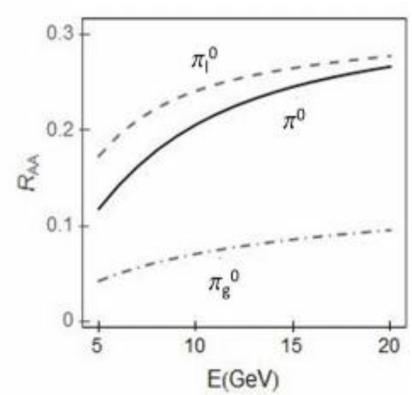
Initial distribution

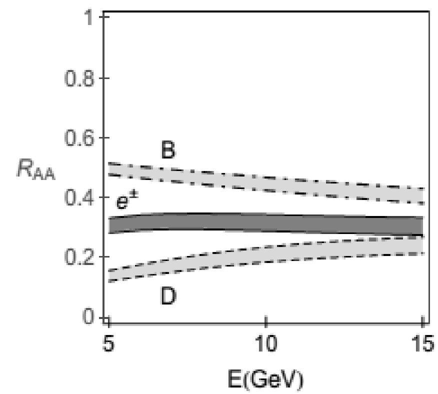


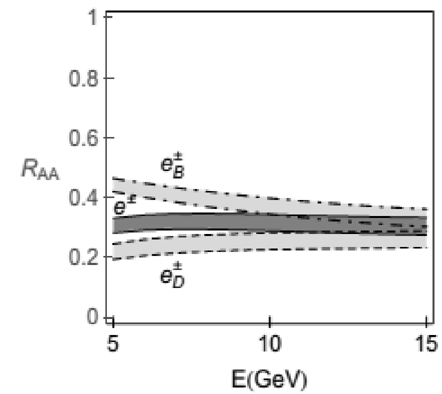




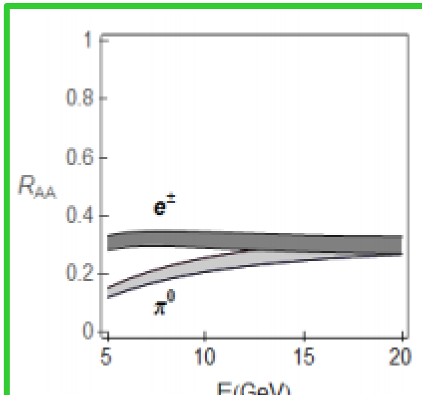






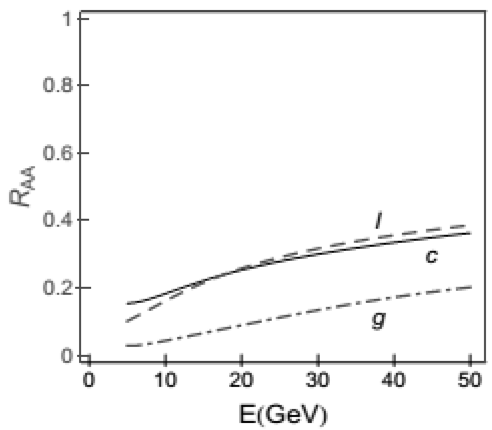


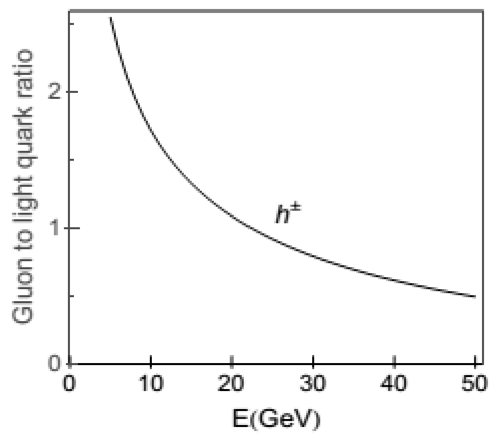
Fragmentation



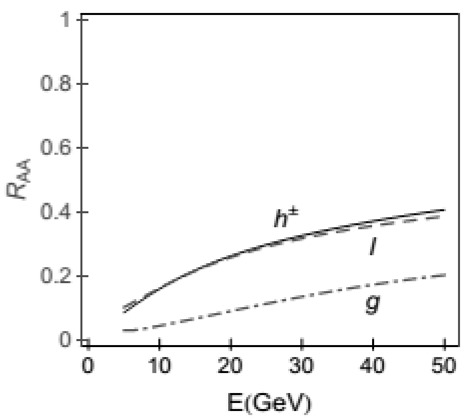
Decay

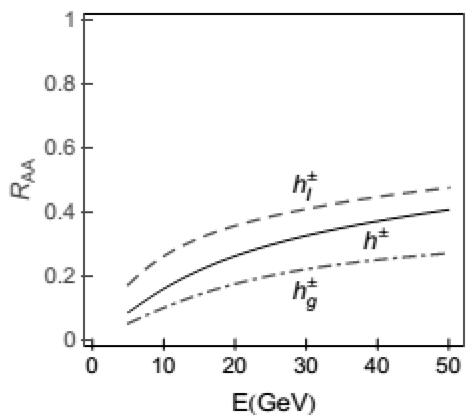
Heavy flavor puzzle at LHC

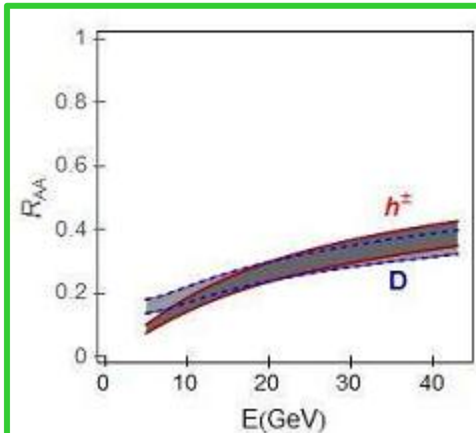




Initial distribution







Fragmentation

M.Djordjevic, PRL 112 : 042302 (2014)

Static vs. dynamical radiative energy loss (theory)

$$\frac{\Delta E_{rad}}{E} = \frac{C_R \alpha_S}{\pi} \frac{L}{\lambda} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} v(\mathbf{q}) \left(1 - \frac{\sin \frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}\right) \frac{2(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right)$$

Two differences:

***v*(q) effective cross section:**

$$\left[\frac{\mu^2}{(\mathbf{q}^2+\mu^2)^2}\right]_{stat} \longrightarrow \left[\frac{\mu^2}{\mathbf{q}^2(\mathbf{q}^2+\mu^2)}\right]_{dyn}$$

λ mean free path:

$$\frac{1}{\lambda_{stat}} \longrightarrow \frac{1}{\lambda_{dyn}} = \frac{1}{c(n_f)} \frac{1}{\lambda_{stat}}$$

Increases energy loss rate in dynamical medium

where: $$\frac{1}{\lambda_{dyn}} = 3\alpha_S T$$

$$c(n_f) = 6\frac{1.202}{\pi^2} \frac{1+n_f/4}{1+n_f/6}$$

Finite magnetic mass effect on R_{AA} (theory)

$$\frac{\Delta E_{rad}}{E} = \frac{C_R \alpha_S}{\pi}\frac{L}{\lambda}\int dx \frac{d^2k}{\pi}\frac{d^2q}{\pi} v(\mathbf{q}) \left(1 - \frac{\sin\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}\right) \frac{2(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}\left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right)$$

Only this part gets modified

$$v(\mathbf{q}) = \frac{\mu_E^2}{\mathbf{q}^2(\mathbf{q}^2+\mu_E^2)} \longrightarrow \frac{\mu_E^2 - \mu_M^2}{(\mathbf{q}^2+\mu_E^2)(\mathbf{q}^2+\mu_M^2)}$$

$$0.4 \leq \frac{\mu_M}{\mu_E} \leq 0.6$$

Causes suppression decrease

M.Djordjevic and M. Djordjevic, PLB 709 : 229 (2012)

Finite magnetic mass effect

$$v(\mathbf{q}) = v_L(\mathbf{q}) - v_T(\mathbf{q})$$

$$v_{L,T}(\mathbf{q}) = \frac{1}{\mathbf{q}^2 + Re\Pi_{L,T}(\infty)} - \frac{1}{\mathbf{q}^2 + Re\Pi_{L,T}(0)}$$

$$Re\Pi_T(\infty) = Re\Pi_L(\infty) \equiv \mu_{pl}^2$$

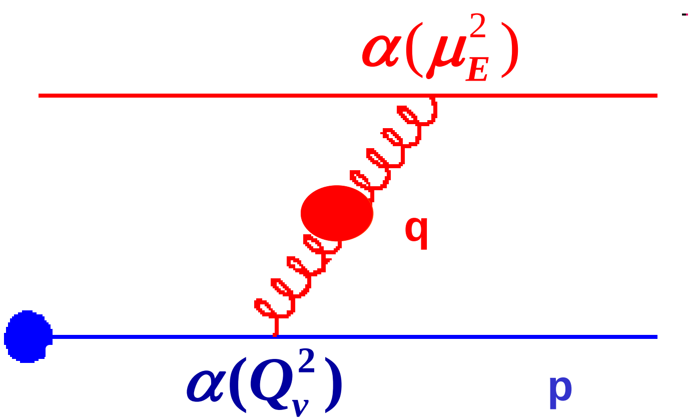
$$\mu_E^2 \equiv Re\Pi_L(x=0)$$

$$\mu_M^2 \equiv Re\Pi_T(x=0)$$

Running coupling

Collisional energy loss

S. Peigne, A. Peshier, PRD 77 : 14017 (2008)



$$\Delta E_{coll} \sim \alpha(Q_v^2)\,\alpha(\mu_E^2)$$

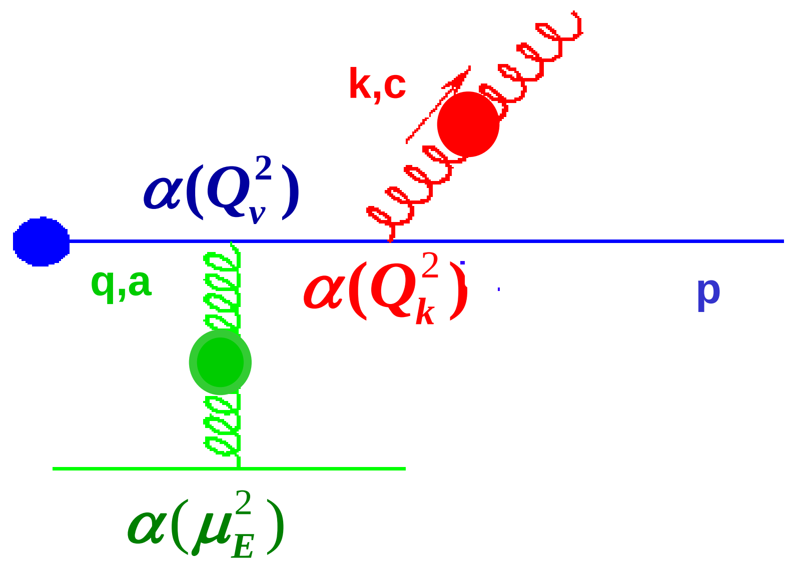
$$\alpha_S(Q^2) = \frac{4\pi}{(11 - 2/3 n_f)\ln(Q^2/\Lambda_{QCD}^2)}$$

$$\frac{\mu_E^2}{\Lambda_{QCD}^2}\ln\left(\frac{\mu_E^2}{\Lambda_{QCD}^2}\right) = \frac{1+n_f/6}{11-2/3\,n_f}\left(\frac{4\pi T}{\Lambda_{QCD}}\right)^2$$

A. Peshier, hep-ph/0601119 (2006)

Radiative energy loss

M. D. and M. Djordjevic, PLB 734 : 286 (2014)



$$\Delta E_{rad} \sim \alpha(Q_k^2)\,\alpha(Q_v^2)\,\alpha(\mu_E^2)$$

$$Q_v^2 = ET$$

$$Q_k^2 = \frac{\mathbf{k}^2 + M^2 x^2 + m_g^2}{x}$$

1-HTL gluon propagator

$$iD^{\mu\nu}(l) = \frac{P^{\mu\nu}(l)}{l^2 - \Pi_T(l)} + \frac{Q^{\mu\nu}(l)}{l^2 - \Pi_L(l)}$$

$$\Pi_T(l) \;=\; \mu^2 \left[\frac{y^2}{2} + \frac{y(1-y^2)}{4}\ln\left(\frac{y+1}{y-1}\right)\right], \qquad \Pi_L(l) = \mu^2\left[1 - y^2 - \frac{y(1-y^2)}{2}\ln\left(\frac{y+1}{y-1}\right)\right]$$

$$y \equiv \frac{l_0}{|\mathbf{l}|}$$

Numerical procedure

- **Light flavor production** (Z.B. Kang, I. Vitev, H. Xing, PLB 718 : 482 (2012))
- **Heavy flavor production** (Z.B. Kang, I. Vitev, H. Xing, PLB 718 : 482 (2012))
- **Multi-gluon fluctuations** (M. Gyulassy, P. Levai, I. Vitev, PLB 538 : 282 (2002))
- **Path-length fluctuations** (A. Dainese, EPJ C33 : 495 (2004))
- **DSS and KKP fragmentation for light flavor** (D. de Florian, R. Sassot, M. Stratmann, PRD 75 : 114010 (2007), B. A. Kniehl, G. Kramer, B. Potter, NPB 582 :
- 514 (2000))
- **BCFY** (Braaten,Cheung,Fleming,Yuan) **and KLP** (Kartvelishvill, Likhoded, Petrov) **fragmentation for heavy flavor** (M. Cacciari, P. Nason, JHEP 0309 : 006 (2003))
- **Decay of heavy meson into e^- and J/ψ** (M. Cacciari et al., JHEP 1210 : 137 (2012))

Collisional energy loss

$$\Delta E_{el} = \frac{C_R g^4}{2\pi^4} \int_0^\infty n_{eq}(|\vec{\mathbf{k}}|) d|\vec{\mathbf{k}}| \left(\int_0^{|\vec{\mathbf{k}}|} |\vec{\mathbf{q}}| d|\vec{\mathbf{q}}| \int_{-|\vec{\mathbf{q}}|}^{|\vec{\mathbf{q}}|} \omega d\omega + \int_{|\vec{\mathbf{k}}|}^{|\vec{\mathbf{q}}|_{max}} |\vec{\mathbf{q}}| d|\vec{\mathbf{q}}| \int_{|\vec{\mathbf{q}}|-2|\vec{\mathbf{k}}|}^{|\vec{\mathbf{q}}|} \omega d\omega \right)$$
$$\left(|\Delta_L(q)|^2 \frac{(2|\vec{\mathbf{k}}|+\omega)^2 - |\vec{\mathbf{q}}|^2}{2} \mathcal{J}_1 + |\Delta_T(q)|^2 \frac{(|\vec{\mathbf{q}}|^2-\omega^2)((2|\vec{\mathbf{k}}|+\omega)^2+|\vec{\mathbf{q}}|^2)}{4|\vec{\mathbf{q}}|^4} \left[(v^2|\vec{\mathbf{q}}|^2-\omega^2)\mathcal{J}_1 + 2\omega\mathcal{J}_2 - \mathcal{J}_3 \right] \right)$$

$$\frac{dE_{el}}{dL} = \frac{g^4}{6\, v^2\, \pi^3} \int_0^\infty n_{eq}(|\vec{\mathbf{k}}|) d|\vec{\mathbf{k}}| \left(\int_0^{|\vec{\mathbf{k}}|/(1+v)} d|\vec{\mathbf{q}}| \int_{-v|\vec{\mathbf{q}}|}^{v|\vec{\mathbf{q}}|} \omega d\omega + \int_{|\vec{\mathbf{k}}|/(1+v)}^{|\vec{\mathbf{q}}|_{max}} d|\vec{\mathbf{q}}| \int_{|\vec{\mathbf{q}}|-2|\vec{\mathbf{k}}|}^{v|\vec{\mathbf{q}}|} \omega d\omega \right)$$
$$\left(|\Delta_L(q)|^2 \frac{(2|\vec{\mathbf{k}}|+\omega)^2 - |\vec{\mathbf{q}}|^2}{2} + |\Delta_T(q)|^2 \frac{(|\vec{\mathbf{q}}|^2-\omega^2)((2|\vec{\mathbf{k}}|+\omega)^2+|\vec{\mathbf{q}}|^2)}{4|\vec{\mathbf{q}}|^4} (v^2|\vec{\mathbf{q}}|^2-\omega^2) \right). \quad (16)$$

$$\Delta_T^{-1} = \omega^2 - \vec{\mathbf{q}}^2 - \frac{\mu^2}{2} - \frac{(\omega^2-\vec{\mathbf{q}}^2)\mu^2}{2\vec{\mathbf{q}}^2}\left(1 + \frac{\omega}{2|\vec{\mathbf{q}}|} \ln\left|\frac{\omega-|\vec{\mathbf{q}}|}{\omega+|\vec{\mathbf{q}}|}\right|\right),$$

$$\Delta_L^{-1} = \vec{\mathbf{q}}^2 + \mu^2\left(1 + \frac{\omega}{2|\vec{\mathbf{q}}|} \ln\left|\frac{\omega-|\vec{\mathbf{q}}|}{\omega+|\vec{\mathbf{q}}|}\right|\right),$$

$$\begin{aligned}\mathcal{J}_1 &= \int \frac{d\Omega}{4\pi}\,\frac{\sin[(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})\frac{L}{2v}]^2}{(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})^2}\\ &= \frac{L}{4|\vec{\mathbf{q}}|v^2}\left[Si((v|\vec{\mathbf{q}}|+\omega)\frac{L}{v})+Si((v|\vec{\mathbf{q}}|-\omega)\frac{L}{v})\right]\\ &- \frac{1}{4v|\vec{\mathbf{q}}|}\left[\frac{1-\cos((v|\vec{\mathbf{q}}|-\omega)\frac{L}{v})}{v|\vec{\mathbf{q}}|-\omega}+\frac{1-\cos((v|\vec{\mathbf{q}}|+\omega)\frac{L}{v})}{v|\vec{\mathbf{q}}|+\omega}\right]\ ,\end{aligned}$$

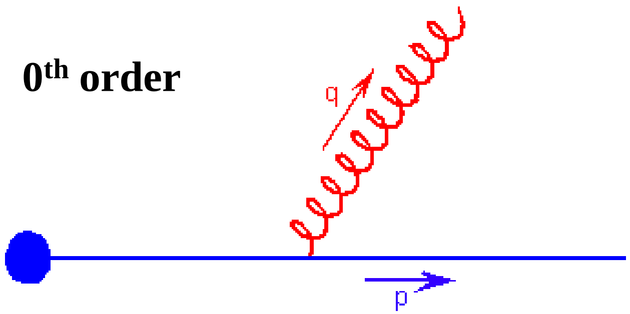
$$\begin{aligned}\mathcal{J}_2 &= \int \frac{d\Omega}{4\pi}\,\frac{\sin[(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})\frac{L}{2v}]^2}{(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})^2}\,(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})\\ &= \frac{1}{4v|\vec{\mathbf{q}}|}\left[Ci((v|\vec{\mathbf{q}}|-\omega)\frac{L}{v})-Ci((v|\vec{\mathbf{q}}|+\omega)\frac{L}{v})+\ln(\frac{v|\vec{\mathbf{q}}|+\omega}{v|\vec{\mathbf{q}}|-\omega})\right]\end{aligned}$$

$$\mathcal{J}_3 = \int \frac{d\Omega}{4\pi}\,\frac{\sin[(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})\frac{L}{2v}]^2}{(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})^2}\,(\omega-\vec{\mathbf{v}}\cdot\vec{\mathbf{q}})^2 = \frac{1}{2}\left(1-\frac{\cos(\frac{L\omega}{v})\sin(L|\vec{\mathbf{q}}|)}{L|\vec{\mathbf{q}}|}\right)$$

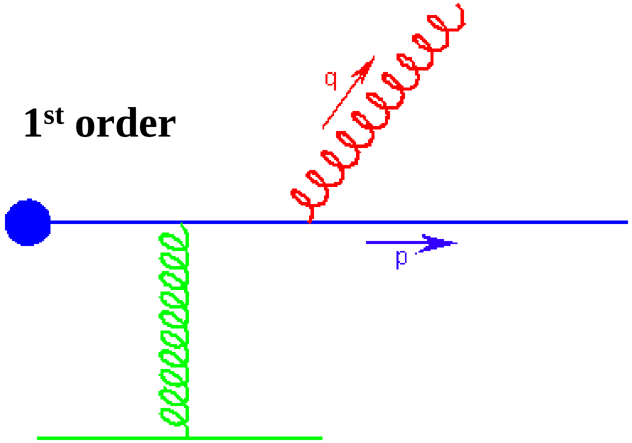
Radiative energy loss

Radiative energy loss comes from the processes which have more outgoing than incoming particles:

0^{th} order



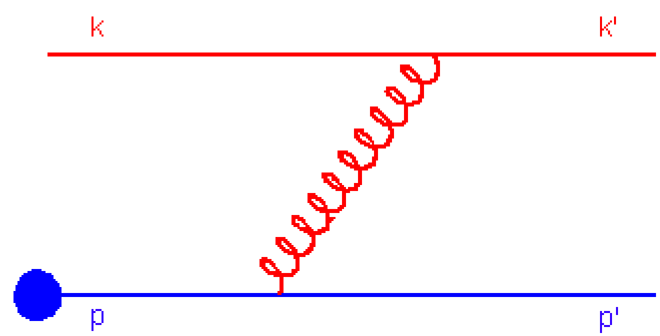
1^{st} order



Collisional energy loss

Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

0^{th} order



$$\frac{E_f d^3\sigma}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes P(E_i \to E_f)$$
$$\otimes \; D(Q \to H_Q) \otimes f(H_Q \to e, J/\psi).$$

Constant coupling case $\alpha=0.3$ (RHIC), $\alpha=0.25$ (LHC)

B. Betz and M. Gyulassy, PRC 86 : 024903 (2012)

Temperature determination for non-central collisions

Gluon rapidity density

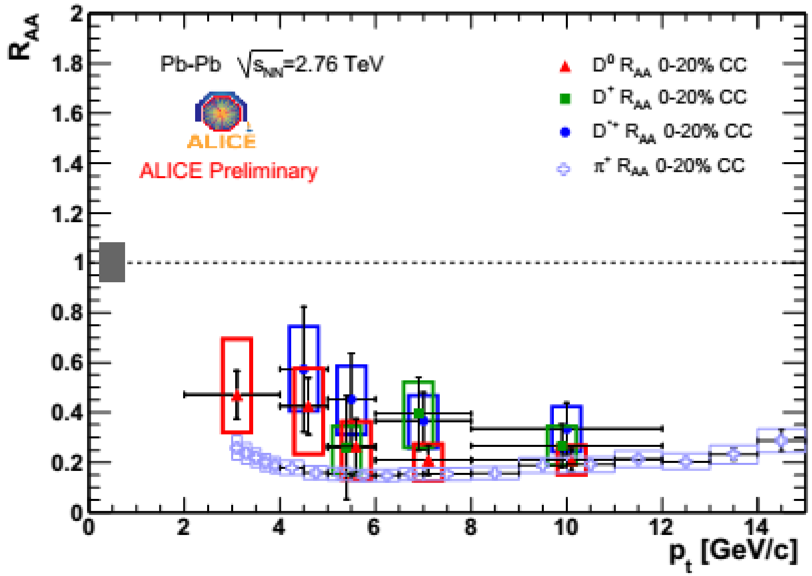
$$T^3 \sim \frac{\frac{dN_g}{dy}}{V} \rightarrow T = c\left(\frac{\frac{dN_g}{dy}}{N_{part}}\right)^{1/3}$$

$$V \sim N_{part}$$

$$\frac{\frac{dN_g}{dy}}{N_{part}} \sim \left(\frac{\frac{dN_{ch}}{dy}}{N_{part}/2}\right)$$

Experimentally measurable: Charged particle multiplicity per participant pair.

M. Gyulassy, P. Levai and I. Vitev, NPB 594 : 371 (2001);
M.D.Djordjevic, M. Djordjevic and B.Blagojevic, PLB 737 : 298 (2014)



All D meson species have very similar high momentum R_{AA}.

Therefore, we do not specify the exact species.

A. Grelli (for the ALICE collaboration), APPS 5 : 585 (2012)

Collisional energy loss

- We approximate the full fluctuation spectrum in collisional energy loss probability by a Gaussian with a mean determined by the average energy loss and the variance determined by:

$$\sigma^2_{coll} = 2T < \Delta E^{coll}(p_\perp, L) >$$