# Energy loss in jet suppression – what effects matter?

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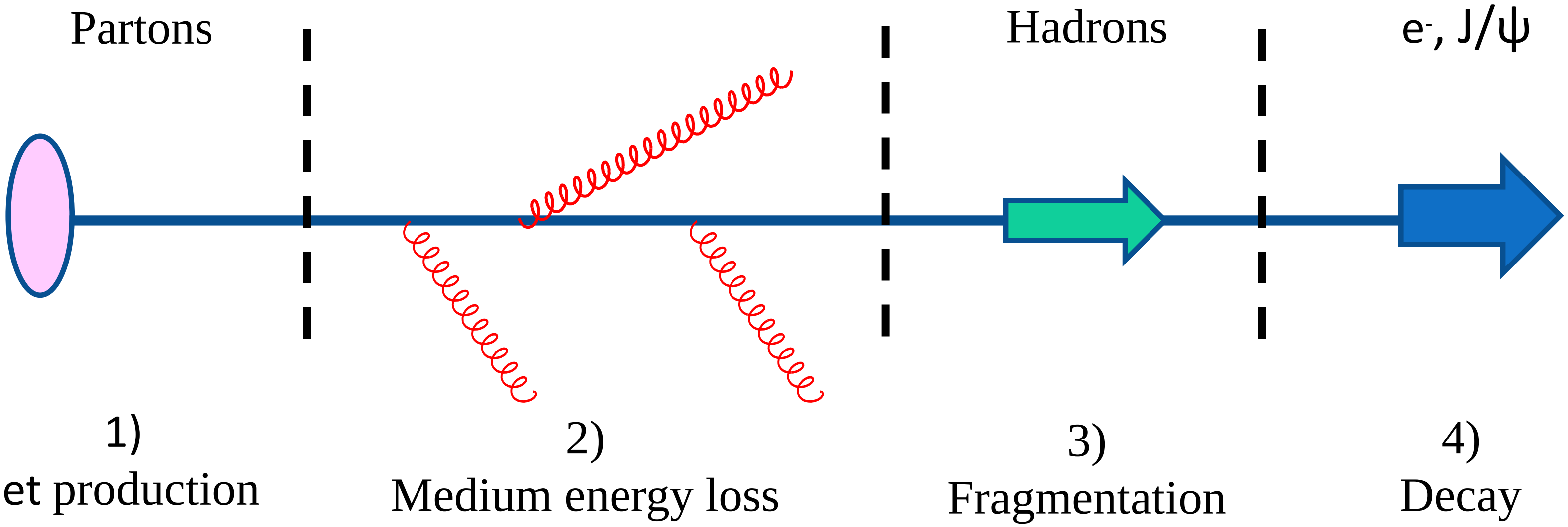
# Jet suppression

- **Light and heavy flavor suppressions are considered to be excellent probes of QCD matter**
- **RHIC and LHC suppression data for different probes are available**
- **Comparison of theoretical predictions with experiments tests our understanding of QCD matter.**

# Computational scheme



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

# Computational formalism

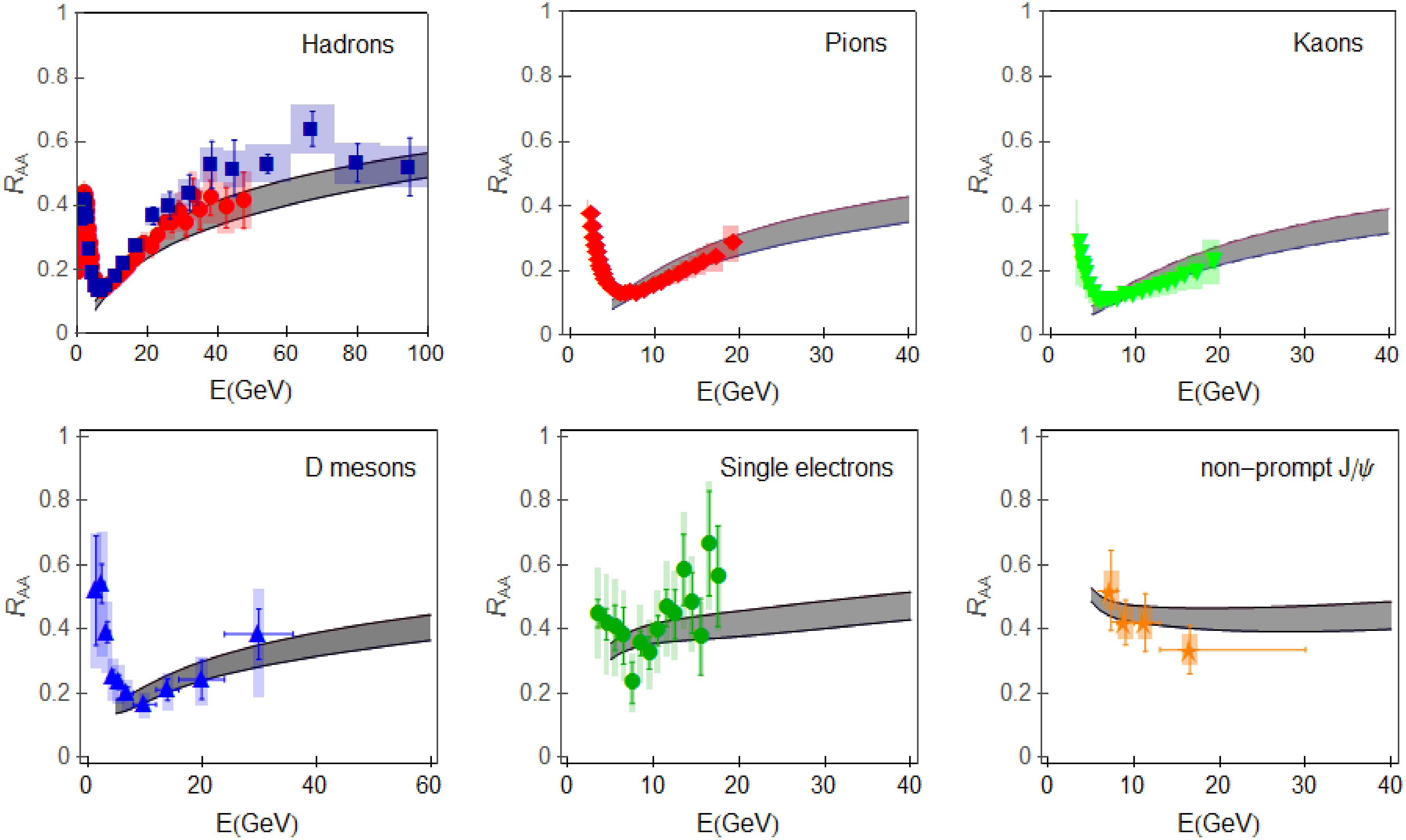
- **Light flavor production**
  (Z.B. Kang, I. Vitev, H. Xing, PLB 718:482 (2012))
- **Heavy flavor production**
  (M. Cacciari et al., JHEP 1210, 137 (2012))
- **Dynamical energy loss in a finite size QCD medium**
  (M. Djordjevic. PRC 80:064909 (2009))
- **Multi-gluon fluctuations**
  (M. Gyulassy, 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 $J/\psi$**
  (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 approximation of static scatterers.**
- **Collisional + radiative energy losses**
- **Finite magnetic mass effects** (M. Djordjevic and M. Djordjevic, PLB 709:229 (2012))
- **Running coupling** (M. Djordjevic and M. Djordjevic, PLB 734:286, 2014)

# Comparison with LHC data (central collisions)

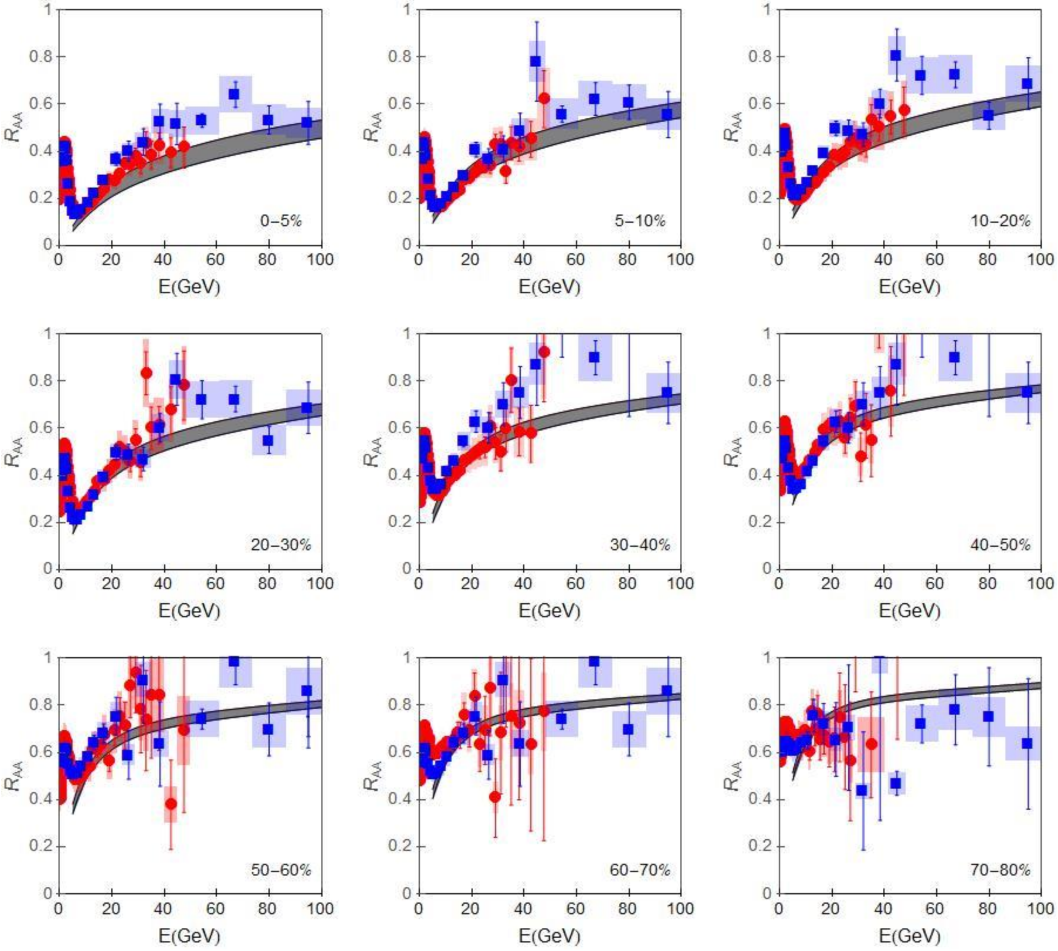
M. Djordjevic and M. Djordjevic, PLB 734:286 (2014)



**Very good agreement for diverse probes!**

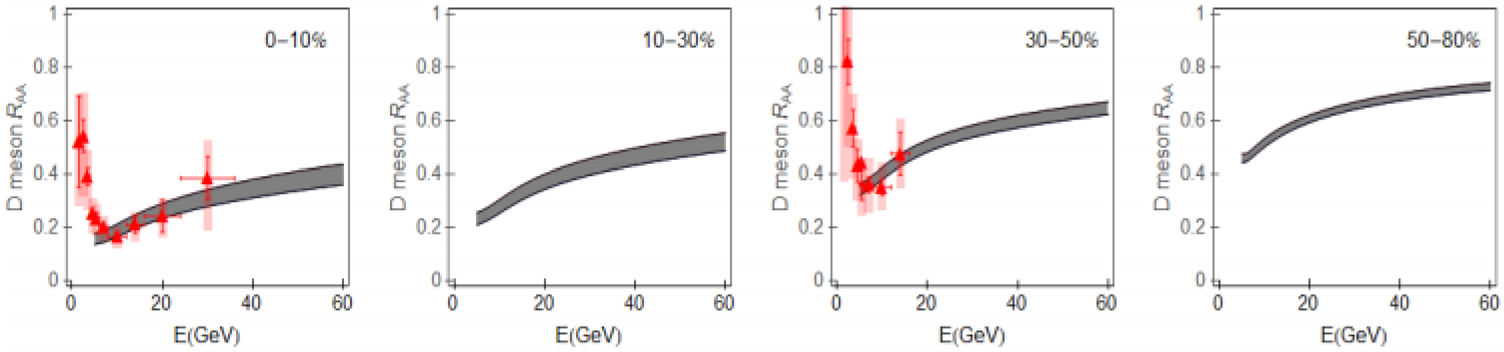
# Non-central collisions at LHC
## (charged hadrons)

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



**Very good agreement for all centrality ranges!**

# Non-central collisions at LHC (D mesons)



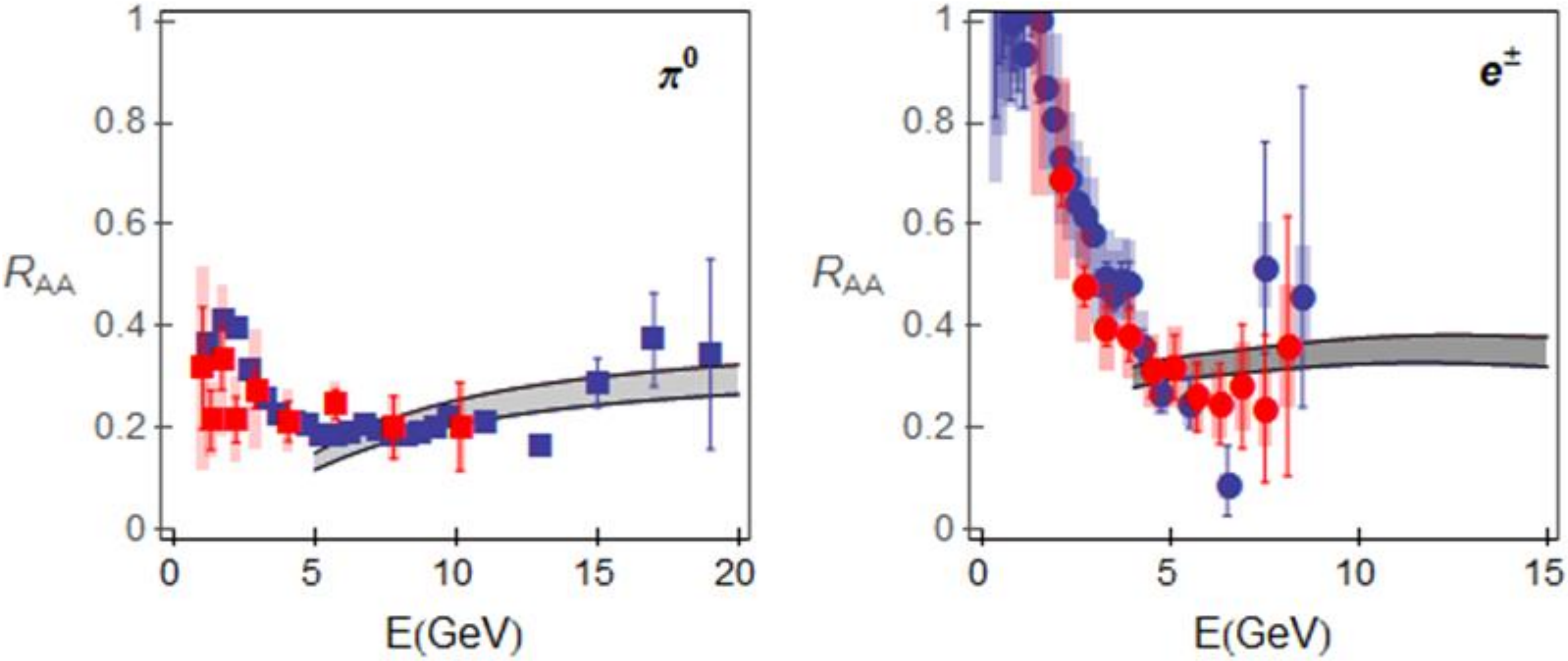
**Very good agreement for 0-10% and 30-50% centrality ranges!**

**10-30% and 50-80% centrality ranges are awaiting for upcoming measurements.**

**M.D.Djordjevic, M. Djordjevic and B.Blagojevic, PLB737,298 (2014)**

# Comparison with RHIC data

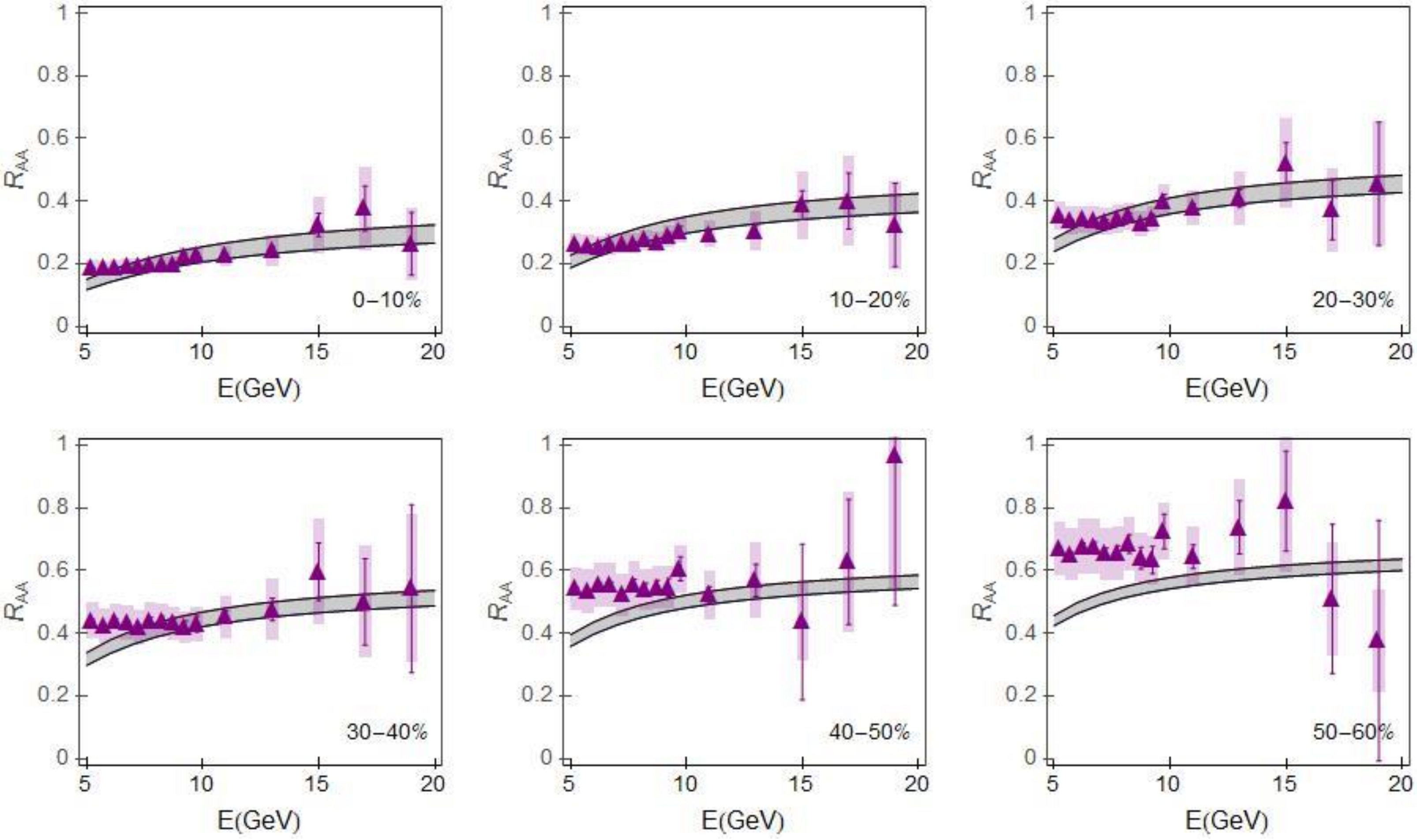
## (central collisions)



**Very good agreement!**

**M.Djordjevic and M. Djordjevic, arXiv:1407.3670**

# Non-central collisions at RHIC
## (neutral pions)



**Very good agreement!**

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

# Comparison summary

- Observed good agreement for
  - Both RHIC and LHC
  - Various observables
  - Different centralities

- All predictions generated
  - By the same formalism
  - With the same numerical procedure
  - No free parameters in model testing

# Energy loss ingredients

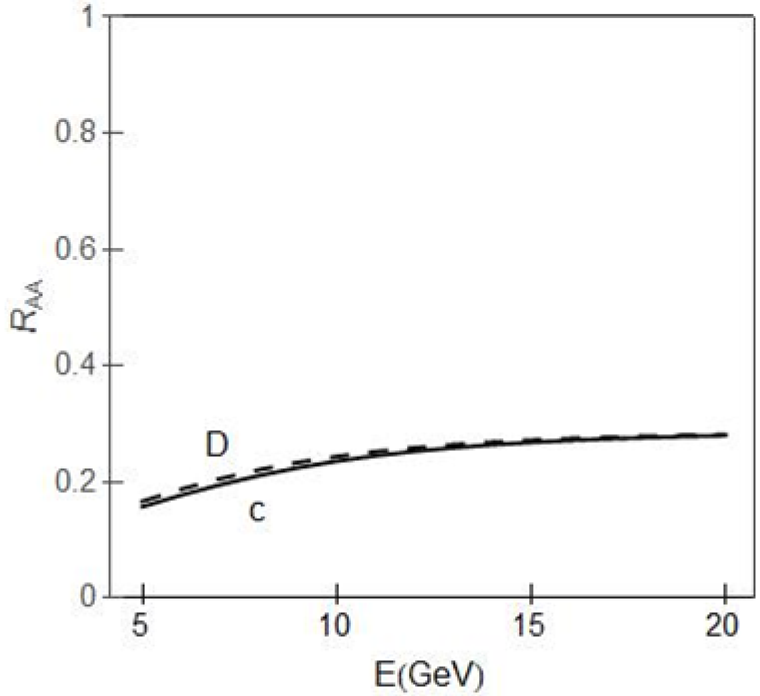
- **Radiative contribution**
- **Collisional contribution**
- **Dynamical scatterers**
- **Finite magnetic mass**
- **Running coupling**

**Different models use some, or all of them**

**How important are they for the reliable predictions?**

**B. Blagojevic and M. Djordjevic, to be submitted (2014)**

# Charm quark as a probe for energy loss testing (RHIC)



**Fragmentation does not modify the suppression!**

**The clearest energy loss probe**

# Our approach: systematically include different ingredients

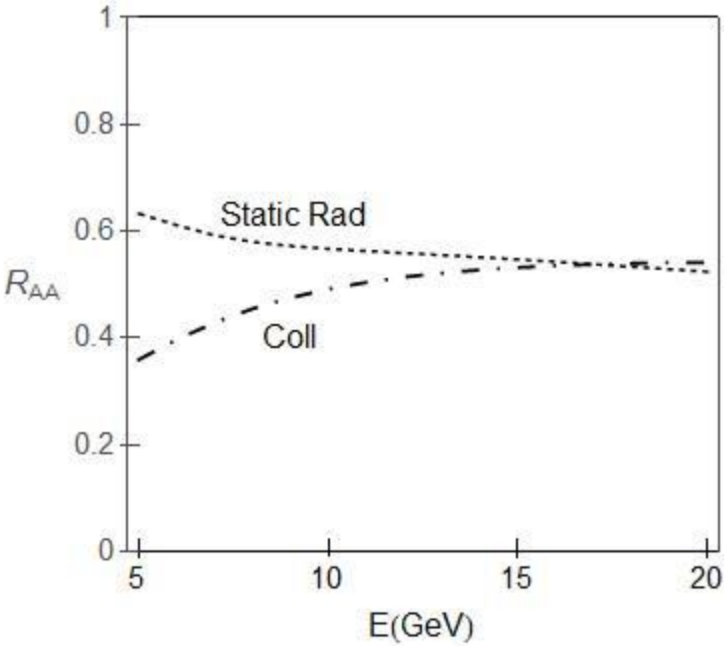
- Static radiative vs. collisional
- Include dynamical scattering centers
- Include finite magnetic mass
- Include running coupling

How suppression predictions are affected?

# Static radiative vs. collisional energy loss

**Historically:**
**Static approximation was used**

- **Radiation is the dominant energy loss mechanism**
- **Collisional energy loss = 0**



**Collisional suppression is even larger than radiative suppression!**

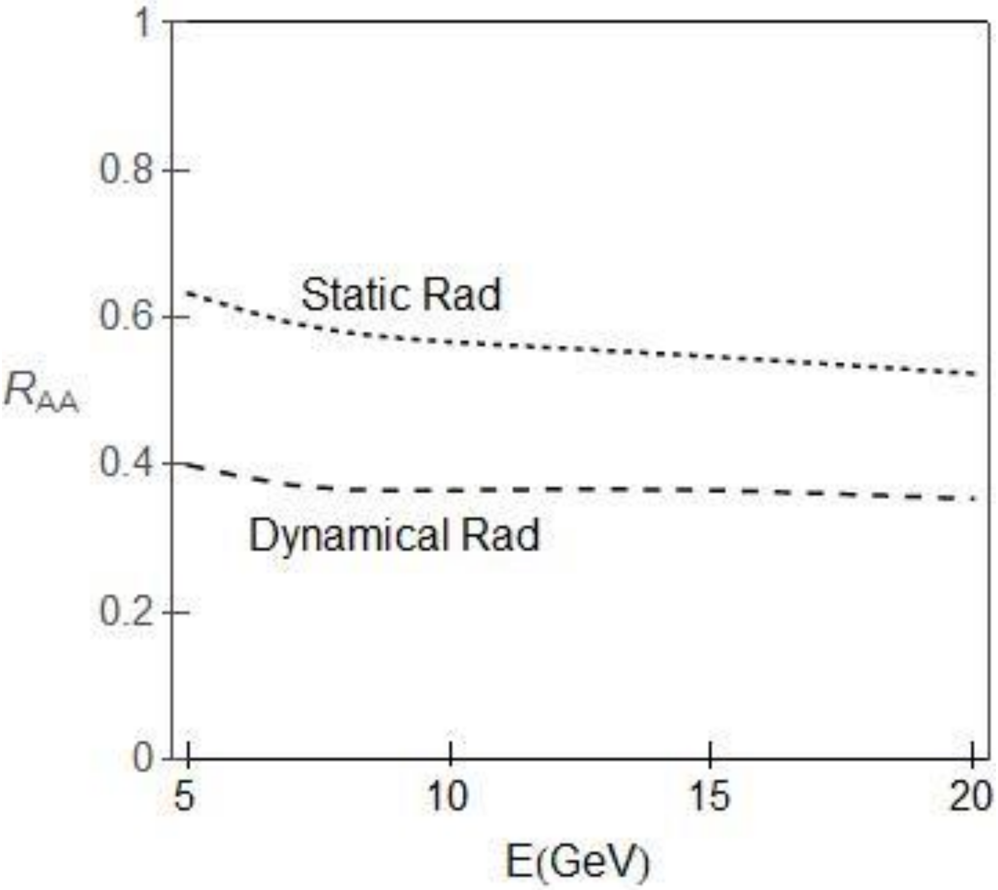
**Static approximation is not valid!**

**Dynamical effects have to be included!**

B. Blagojevic and M. Djordjevic, to be submitted (2014)

# Radiative energy loss - static vs. dynamical

**Dynamical energy loss according to:** M. Djordjevic. PRC 80:064909 (2009))

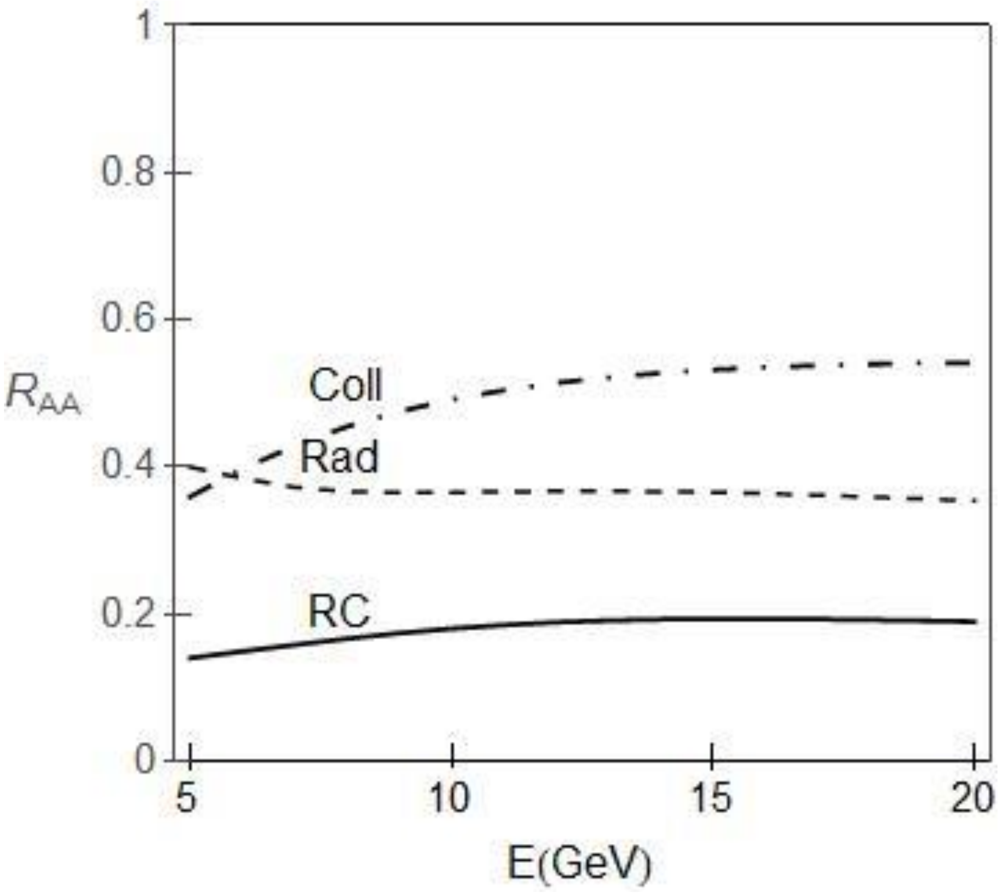


**Dynamical radiative energy loss leads to significantly larger suppression compared to static radiative energy loss!**

**Dynamical effects are important!**

B. Blagojevic and M. Djordjevic, to be submitted (2014)

# Collisional vs. radiative energy losses in dynamical approximation



**Even when dynamical effects are included, both radiative and collisional energy losses are important!**

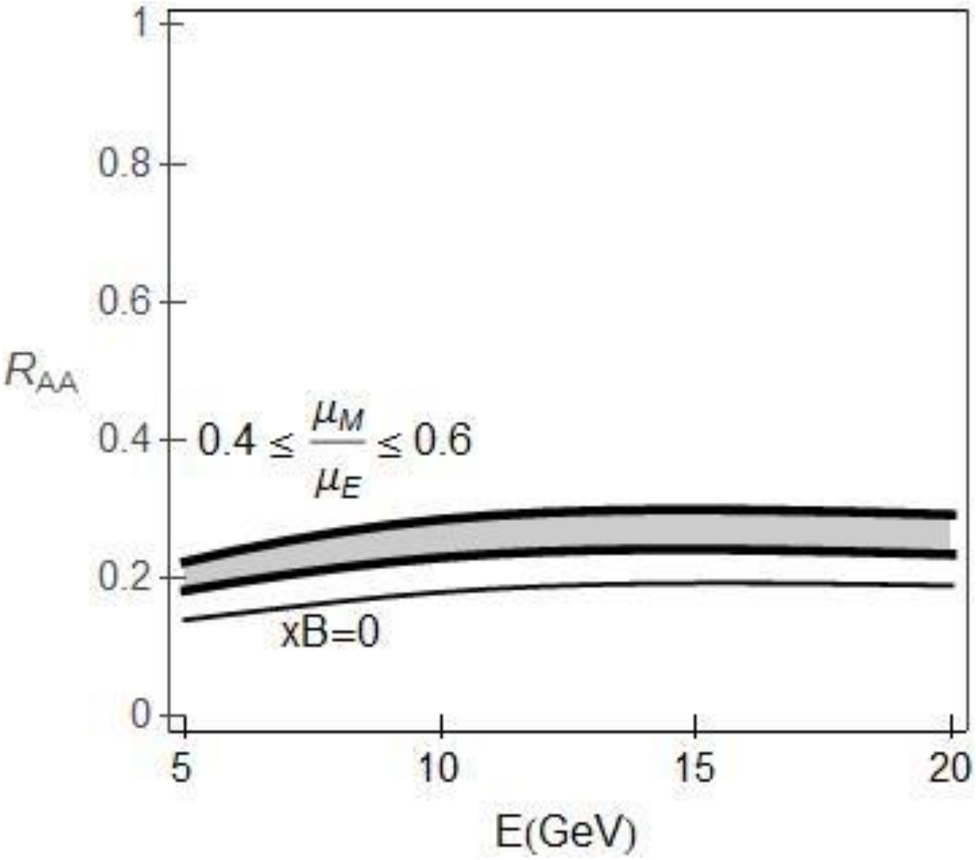
**Resultant suppression is significantly larger than both collisional and radiative contributions!**

**B. Blagojevic and M. Djordjevic, to be submitted (2014)**

# Finite magnetic mass effects on $R_{AA}$ (radiative+collisional energy losses in dynamical medium)

## Magnetic mass included according to:

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



**Inclusion of finite magnetic mass effects leads to a notable decrease in the suppression.**

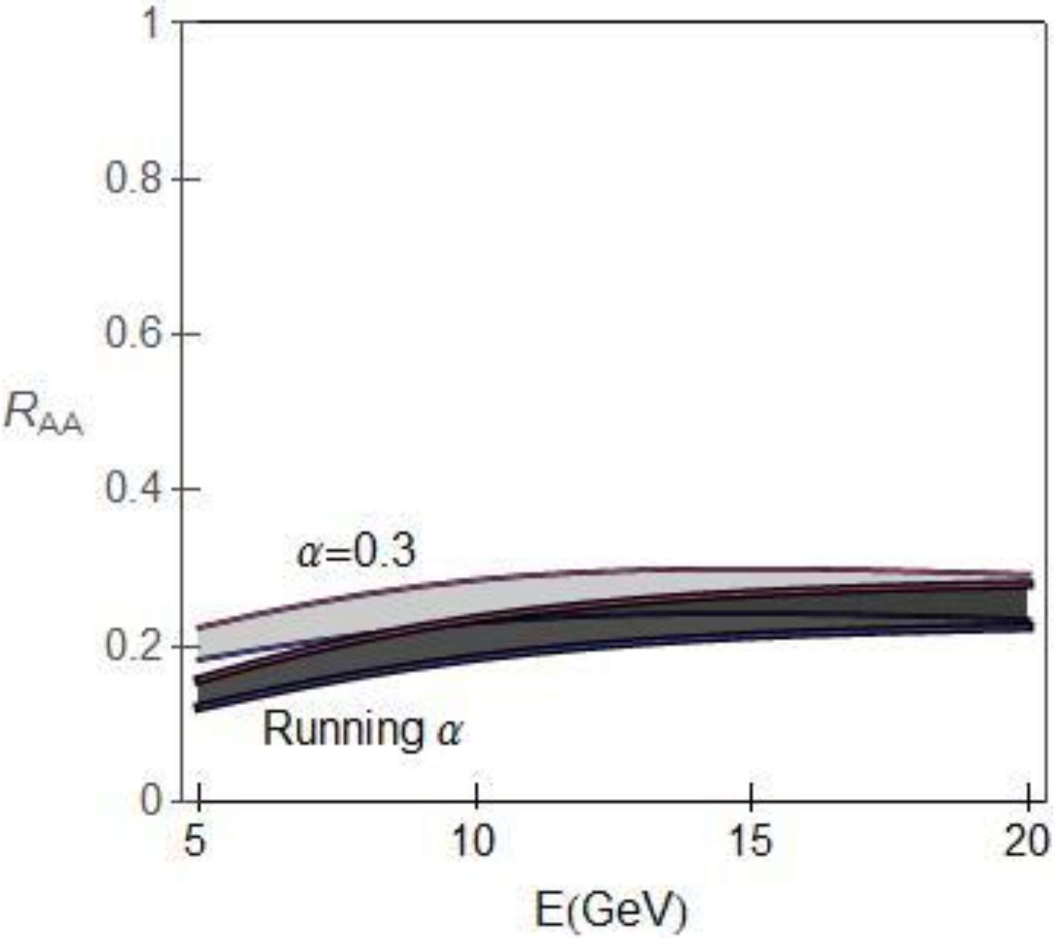
**Finite magnetic mass effects are also important.**

**B. Blagojevic and M. Djordjevic, to be submitted (2014)**

# Running coupling

**Running coupling included according to:**

**M. Djordjevic and M. Djordjevic, PLB 734:286, 2014.**



**Running coupling: suppression increase at lower energies, and no difference at higher energies**

B. Blagojevic and M. Djordjevic, to be submitted (2014)

# Conclusion

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

**Different ingredients in the energy loss: what is the relative importance of these components?**

↓

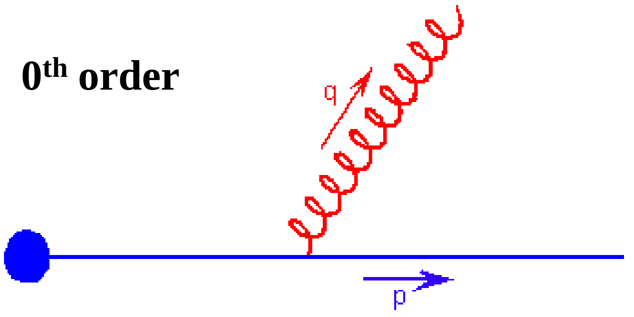
**Good agreement is a cumulative effect of smaller improvements!**

# Back up

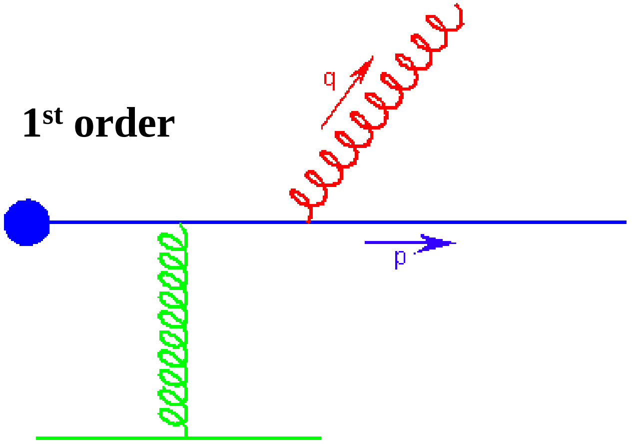
# Radiative energy loss

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

0th order



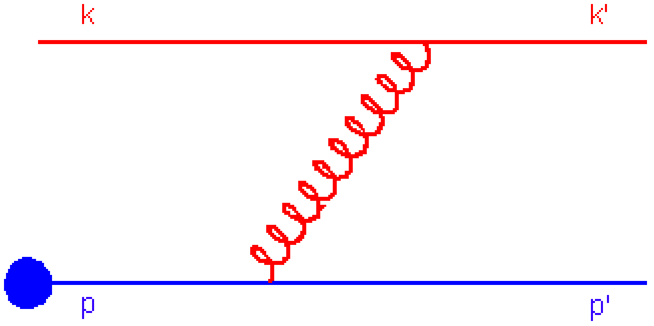
1st order



# Collisional energy loss

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

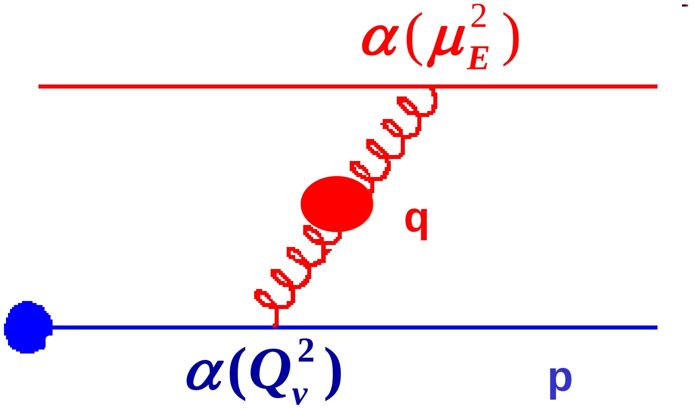
0th order



# Running coupling

## Collisional energy loss

S. Peigne, A. Peshier, Phys. Rev. D **77**, 114017 (2008).



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

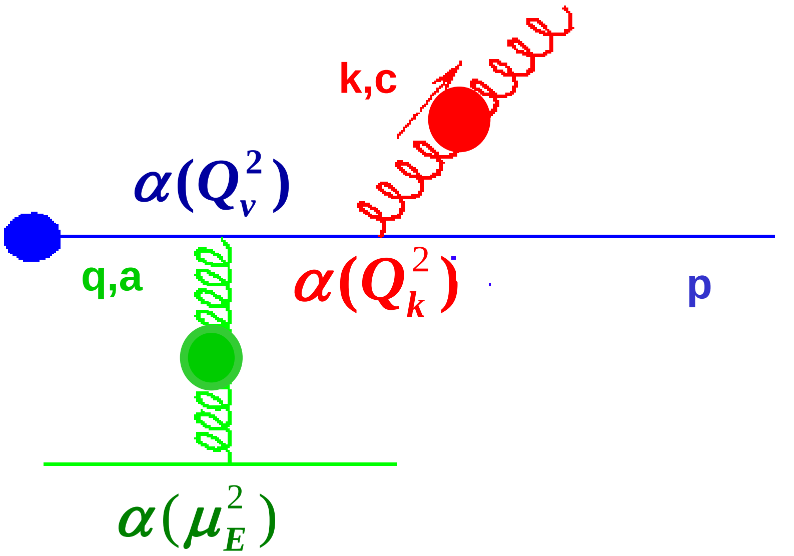
$$\alpha_S(Q^2) = \frac{4\pi}{(11 - 2/3n_f)\ln(Q^2/\Lambda^2_{QCD})}$$

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

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

## Radiative energy loss

M. D. and M. Djordjevic, arXiv:1307.4098

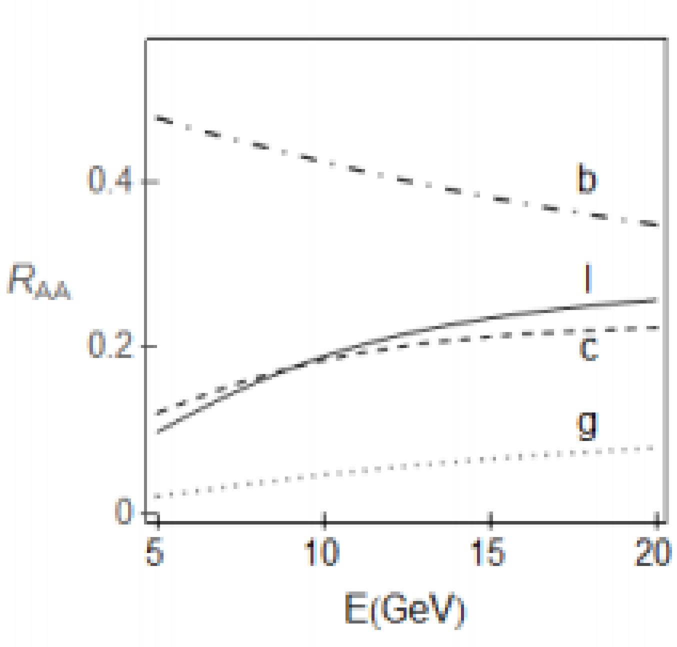


$$\Delta E_{rad} \sim \alpha(Q_k^2)\,\alpha(Q_v^2)\,\alpha(\mu_E^2)$$

$$Q_v^2 = ET$$

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

# Parton suppression predictions



# Finite magnetic mass effects

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

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

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

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

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

# 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:

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

- HTL gluon propagator

$$D^{\mu\nu}(\omega, \mathbf{q}) = -P^{\mu\nu}\Delta_T(\omega, \mathbf{q}) - Q^{\mu\nu}\Delta_L(\omega, \mathbf{q})$$

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

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

# 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** (M. Cacciari et al., JHEP 1210, 137 (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 and KLP fragmentation for heavy flavor** (M. Cacciari, P. Nason, JHEP 0309: 006 (2003))
- **Decay of heavy meson into $e^-$ and $J/\psi$** (M. Cacciari et al., JHEP 1210, 137 (2012))

# Static vs. dynamical radiative energy loss (theory)

**Can static approximation still be used for radiative energy loss calculations?**

$$\frac{\Delta E_{rad}}{E} = \frac{C_R \alpha_S}{\pi} \frac{L}{\lambda} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} v(\mathbf{q}) f(\mathbf{k}, \mathbf{q}, x)$$

**Two differences:**

*v*(**q**) effective crosssection:

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

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 $R_{AA}$ (radiative+collisional energy losses in dynamical medium)

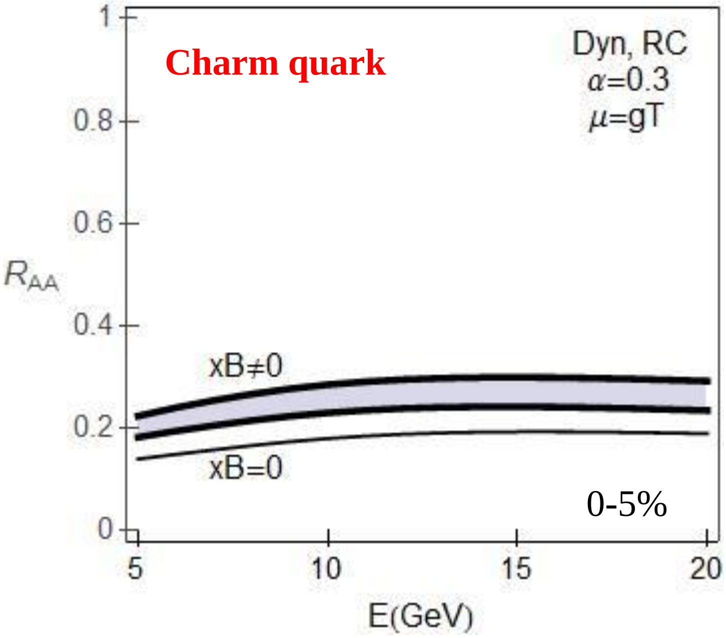
$$\frac{\Delta E_{rad}}{E} = \frac{C_R \alpha_S}{\pi}\frac{L}{\lambda}\int dx\, \frac{d^2k}{\pi}\frac{d^2q}{\pi}\, v(\mathbf{q}) f(\mathbf{k},\mathbf{q},x)$$

Only this part gets modified

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

We obtained:

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



The inclusion of magnetic mass effects causes decrease of suppression

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

# Nuclear modification factor $R_{AA}$

1. p – p collisions → QCD vacuum
2. A – A collisions → hot/dense QCD matter (QGP)

$$R_{AA} \sim \frac{\text{Yield(A A)}}{\text{Yield(p p)}} \sim \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}}$$

- **Nuclear modification factor**:

$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dy\,dp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma_{pp}/dy\,dp_T}$$

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