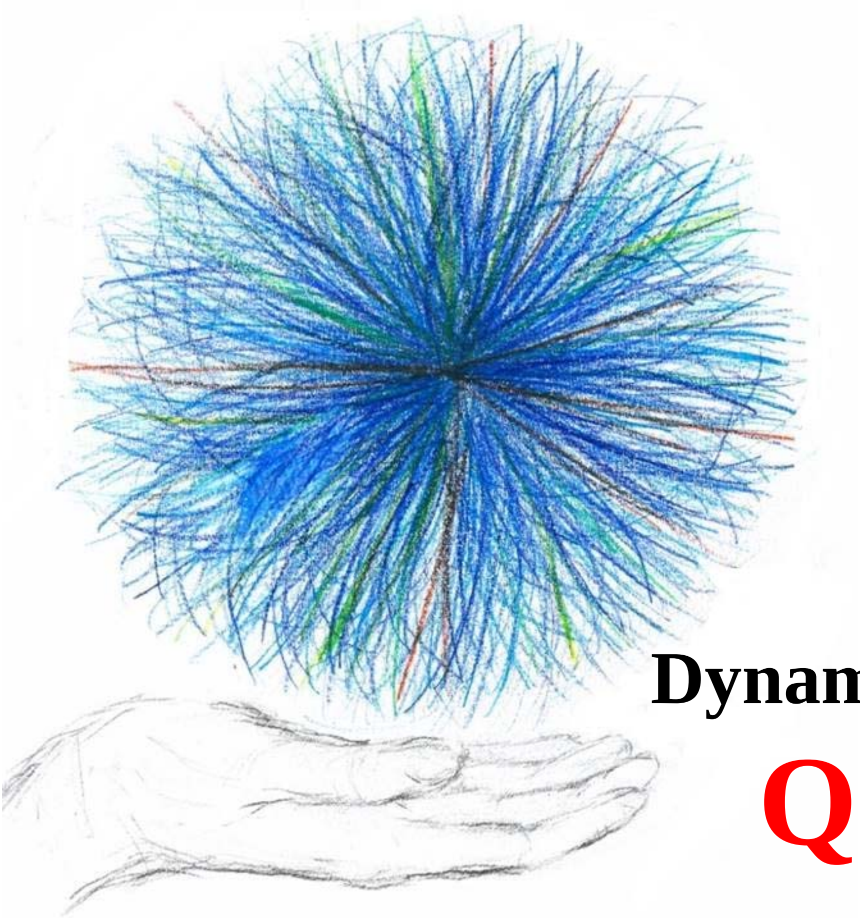
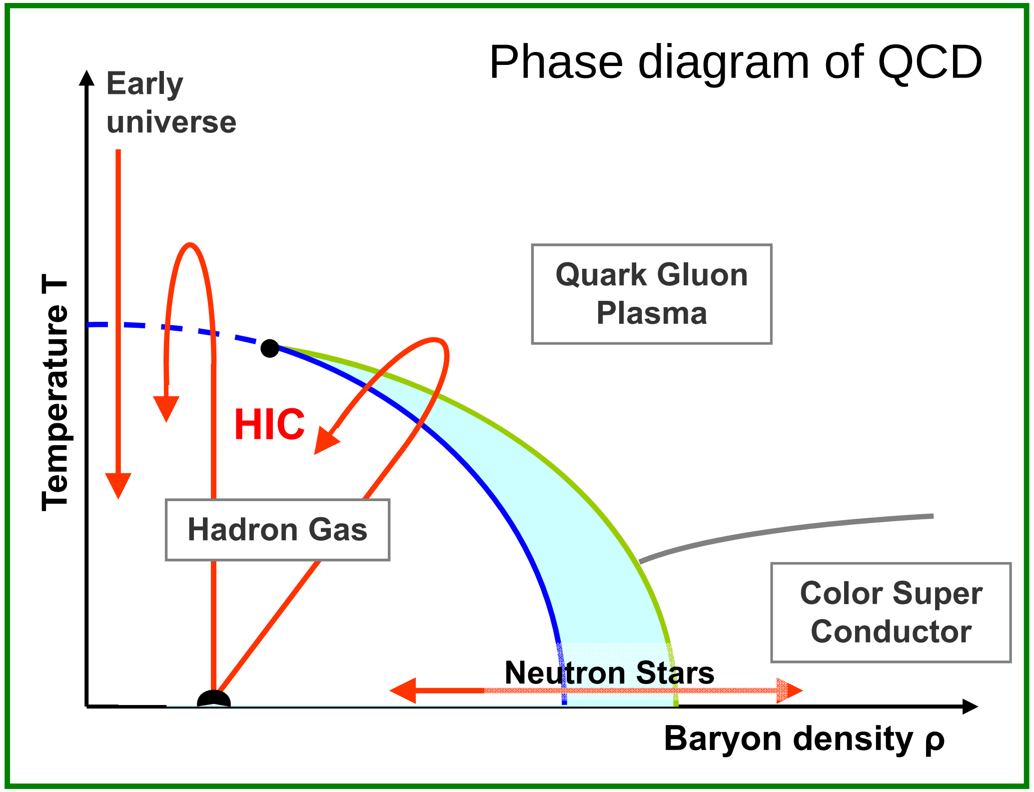


Dynamical energy loss as a tool for
QGP Tomography

Magdalena Djordjevic,

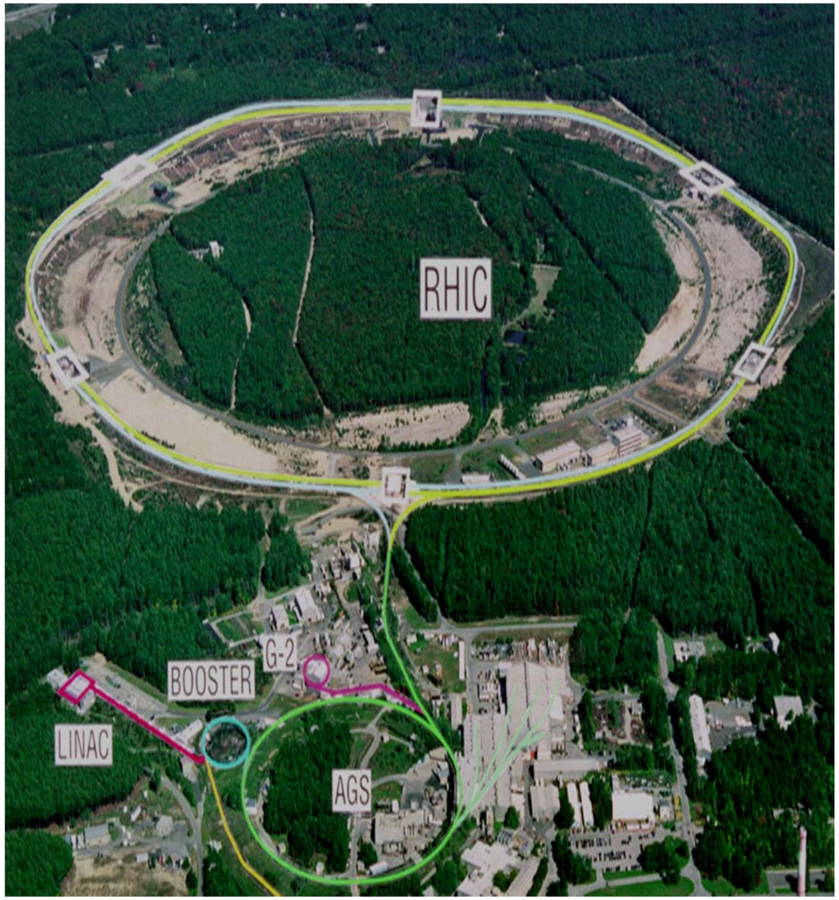
Brief overview of Quark Gluon Plasma

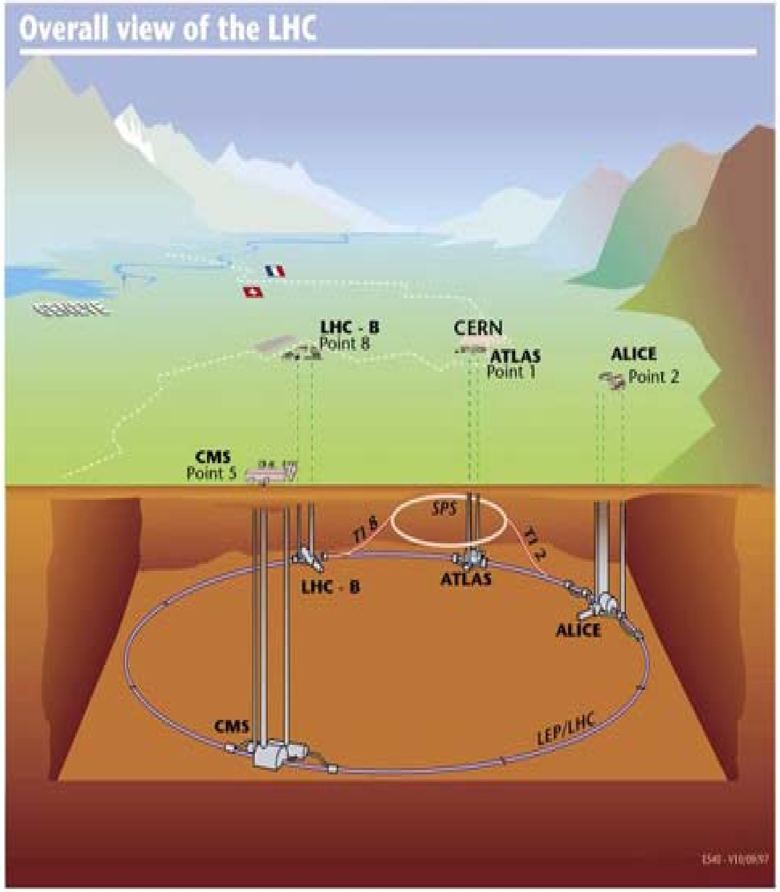
- QGP is a new form of matter, consisting of deconfined and interacting quarks, antiquarks and gluons.
- QGP is predicted by QCD to exist at extremely high energy densities.



One of the most important goals of high energy heavy ion physics is to form, observe and understand QGP.

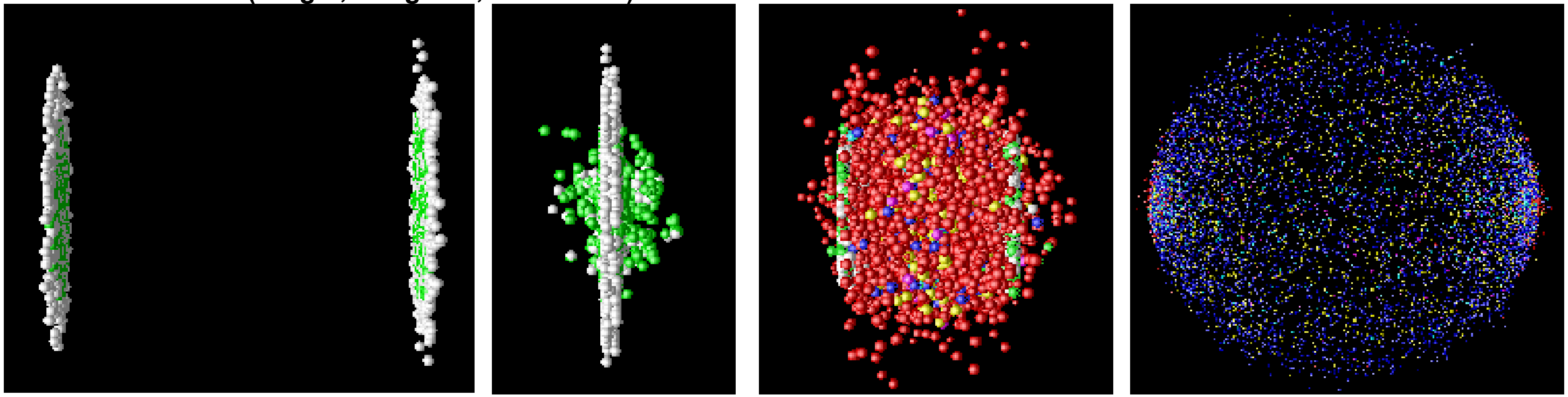
Ultra-Relativistic Heavy Ion Colliders (RHIC and LHC) have been made at BNL and CERN.





Scheme of relativistic heavy ion collisions

Simulation "VNI" (Geiger, Longacre, Srivastava)



To study the properties of QCD matter created at URHIC we need good probes

Heavy flavor (charm and beauty, M>1 GeV) jets are widely recognized as the excellent probes of QGP.

Why are high energy particles good probes?

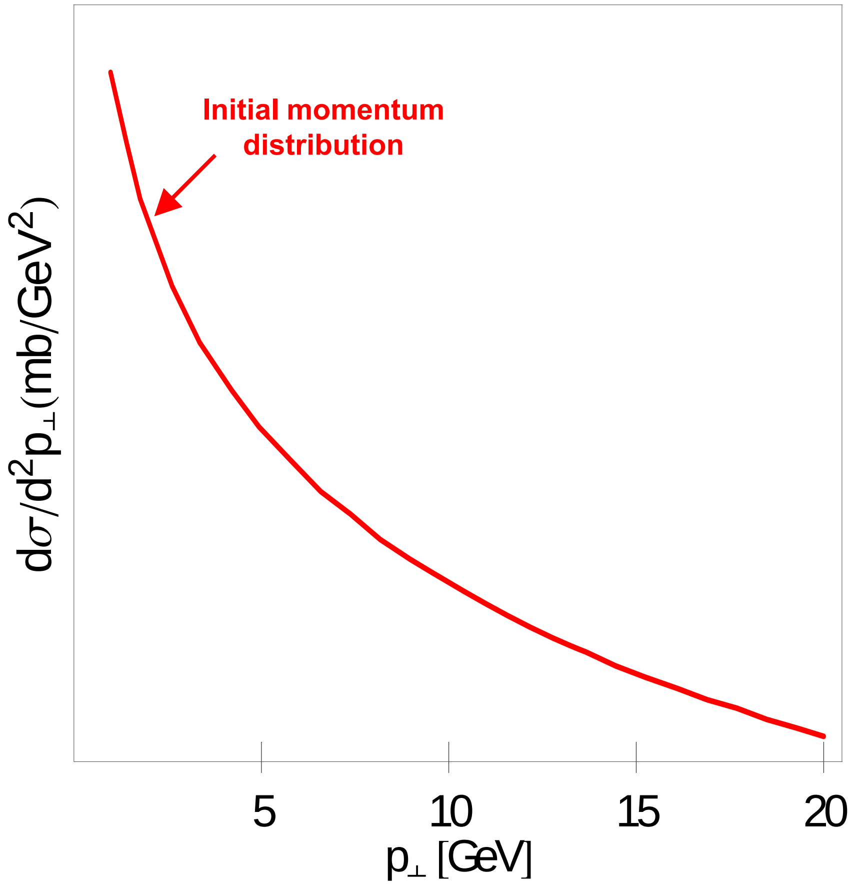
High energy particles:

- Are produced only during the early stage of QCD matter.
- Significantly interact with the QCD medium
- Perturbative calculations are possible

Jet suppression

Heavy meson suppression is considered to be an excellent probe of QCD matter.

What is suppression?



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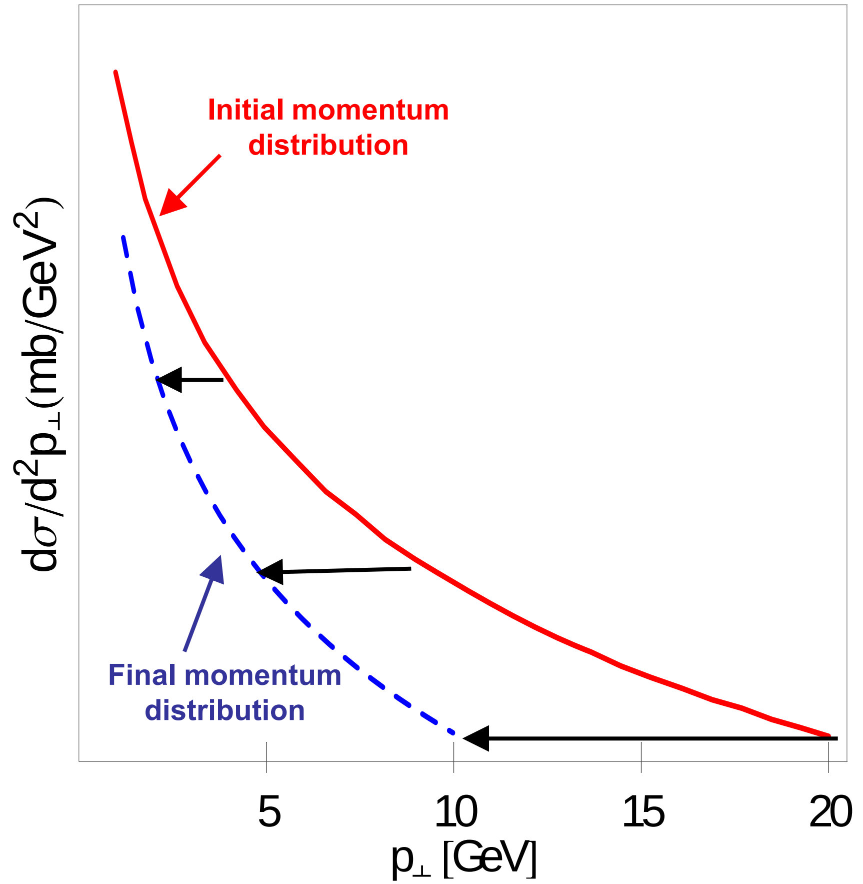

Jet suppression

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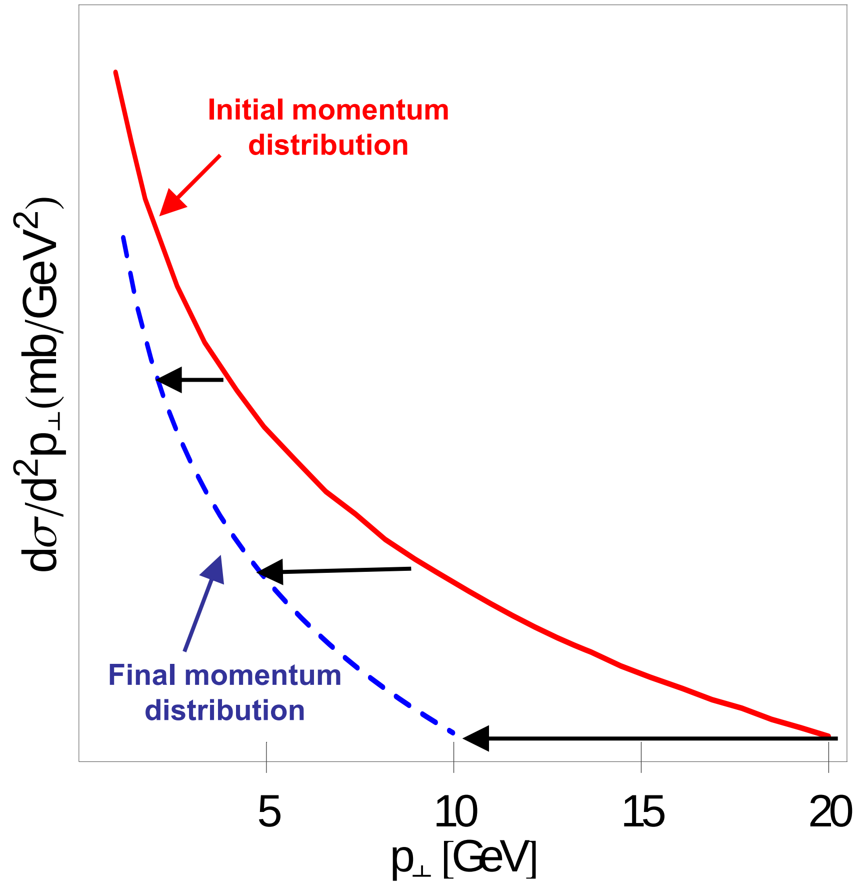
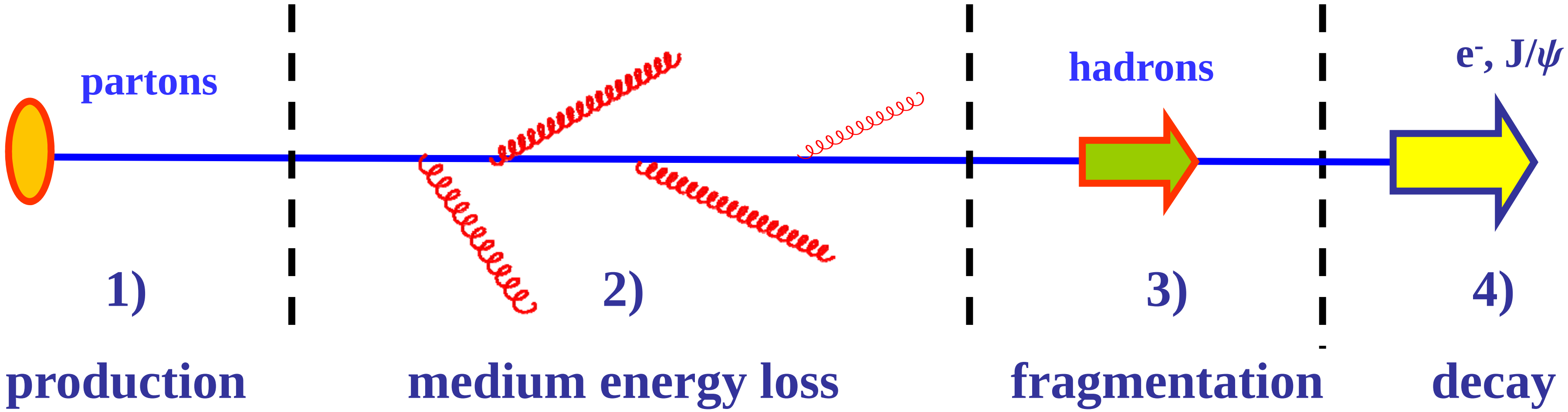
What is suppression?



$$\text{Suppression} = \frac{\text{Final momentum distribution}}{\text{Initial momentum distribution}}$$

Suppression scheme



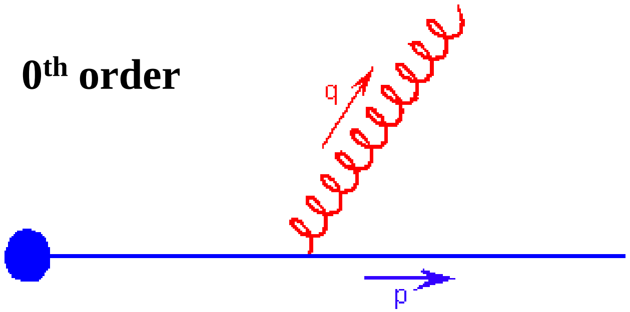
1) Initial momentum distributions for partons
2) Parton energy loss
3) Fragmentation functions of partons into hadrons
4) Decay of heavy mesons to single e$^-$ and J/ψ.

Energy loss in QGP

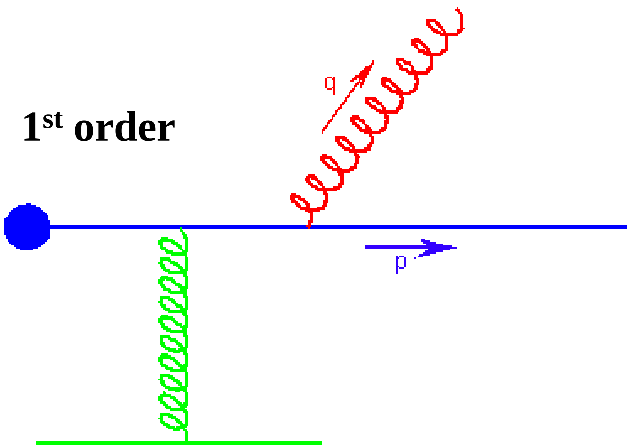
Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

0^{th} order



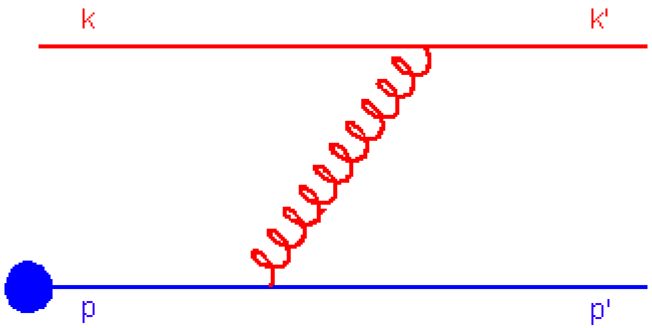
1^{st} order



Collisional energy loss

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

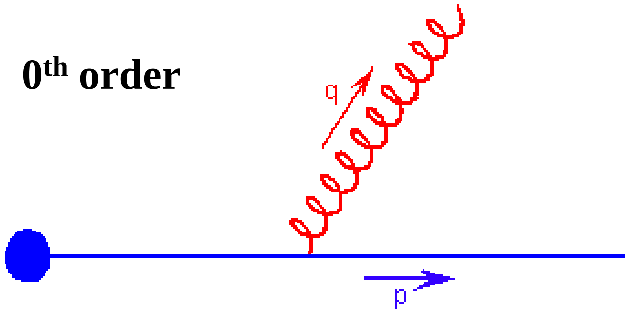
0^{th} order



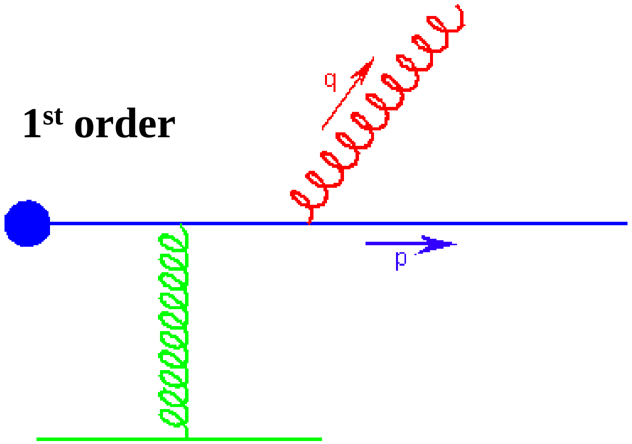
Radiative energy loss

Radiative energy loss comes from the processes in which there are 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:

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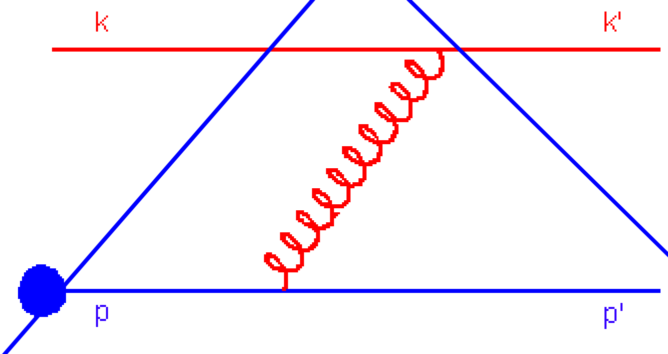
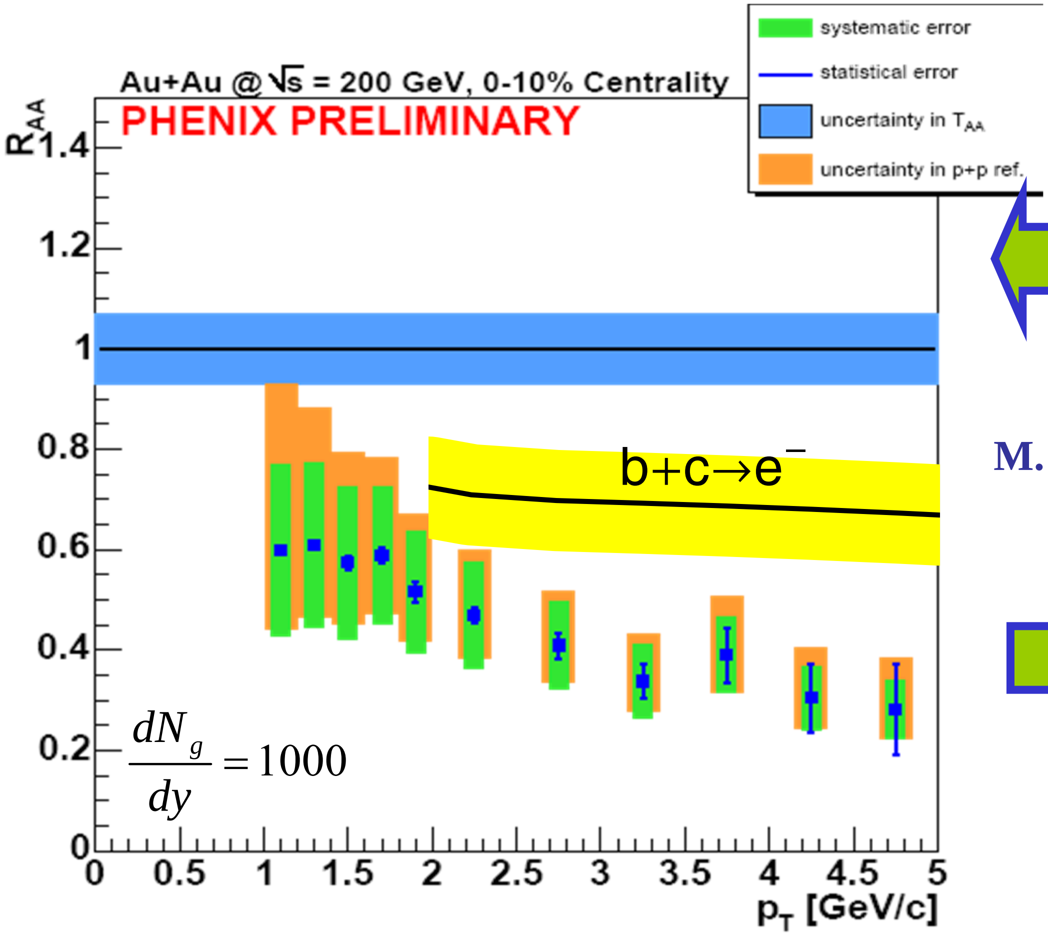


Considered to be negligible compared to radiative!

Heavy flavor puzzle @ RHIC



M. D. et al., Phys. Lett. B 632, 81 (2006)

Radiative energy loss predictions with $dN_g/dy=1000$

M. D. and M. Gyulassy, PRC 2003, PLB 2003, NPA 2004; M. D. PRC 2006;

Disagreement!

Radiative energy loss is not able to explain the single electron data as long as realistic parameter values are taken into account!

Does the radiative energy loss control the energy loss in QGP?

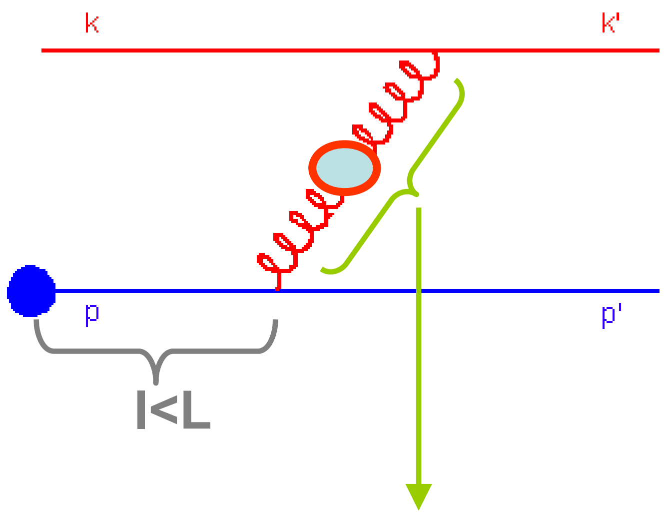
⇓

Is collisional energy loss also important?

Collisional energy loss in a finite size QCD medium

Consider a medium of size L in thermal equilibrium at temperature T.

The main order collisional energy loss is determined from:

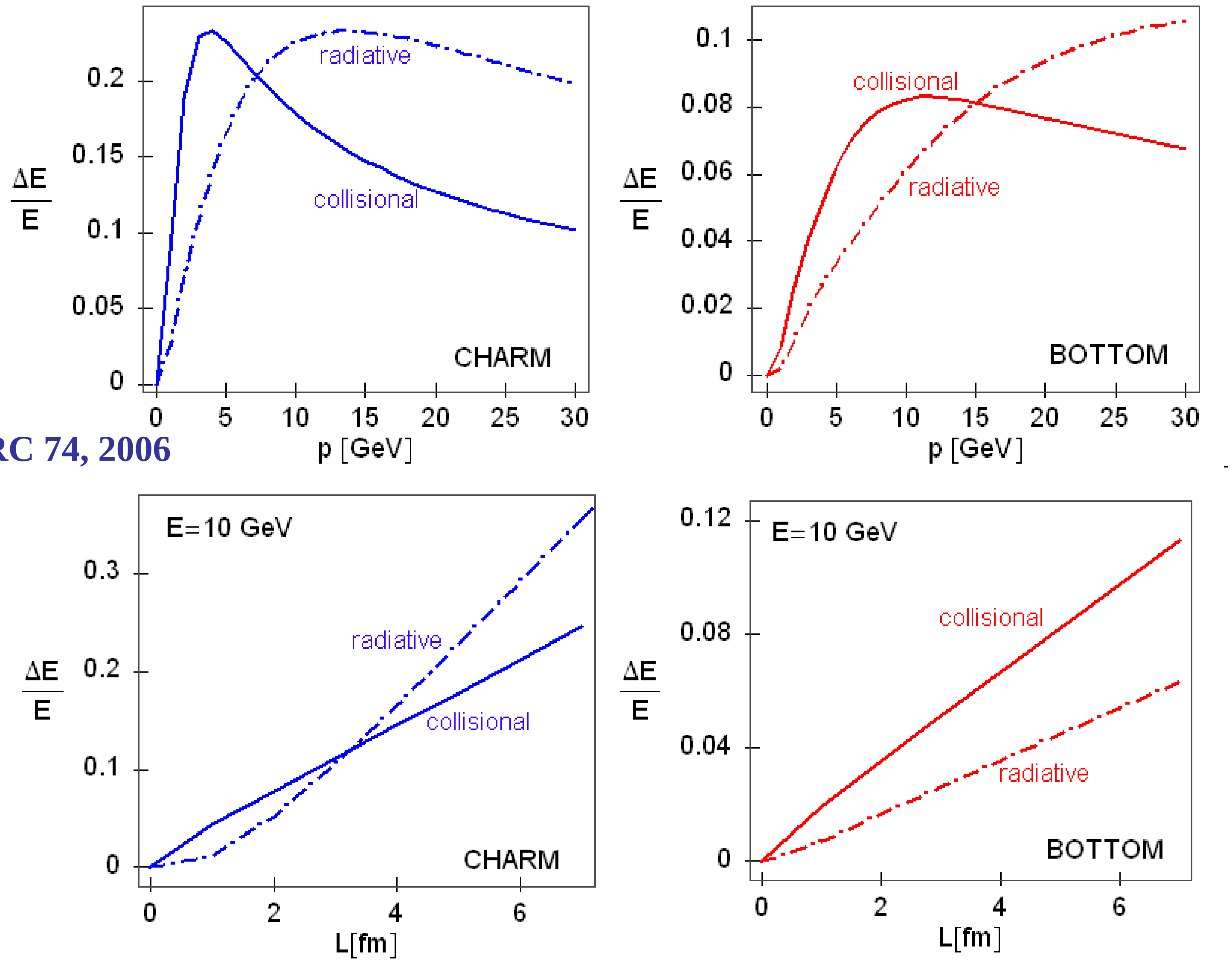


The effective gluon propagator:

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

M. D., Phys.Rev.C74:064907,2006

Collisional v.s. medium induced radiative energy loss



M. D., PRC 74, 2006

Collisional and radiative energy losses are comparable!

Non-zero collisional energy loss - a fundamental problem

Static QCD medium approximation (modeled by Yukawa potential).

With such approximation, collisional energy loss has to be exactly equal to zero!

However, collisional and radiative energy losses are shown to be comparable.

Introducing collisional energy loss is necessary, but inconsistent with static approximation!

Static medium approximation should not be used in radiative energy loss calculations!

Dynamical QCD medium effects have to be included!

Our goal

We want to compute the heavy quark radiative energy loss in dynamical medium of thermally distributed massless quarks and gluons.

Why?

- **To address the applicability of static approximation in radiative energy loss computations.**
- **To compute collisional and radiative energy losses within a consistent theoretical framework.**

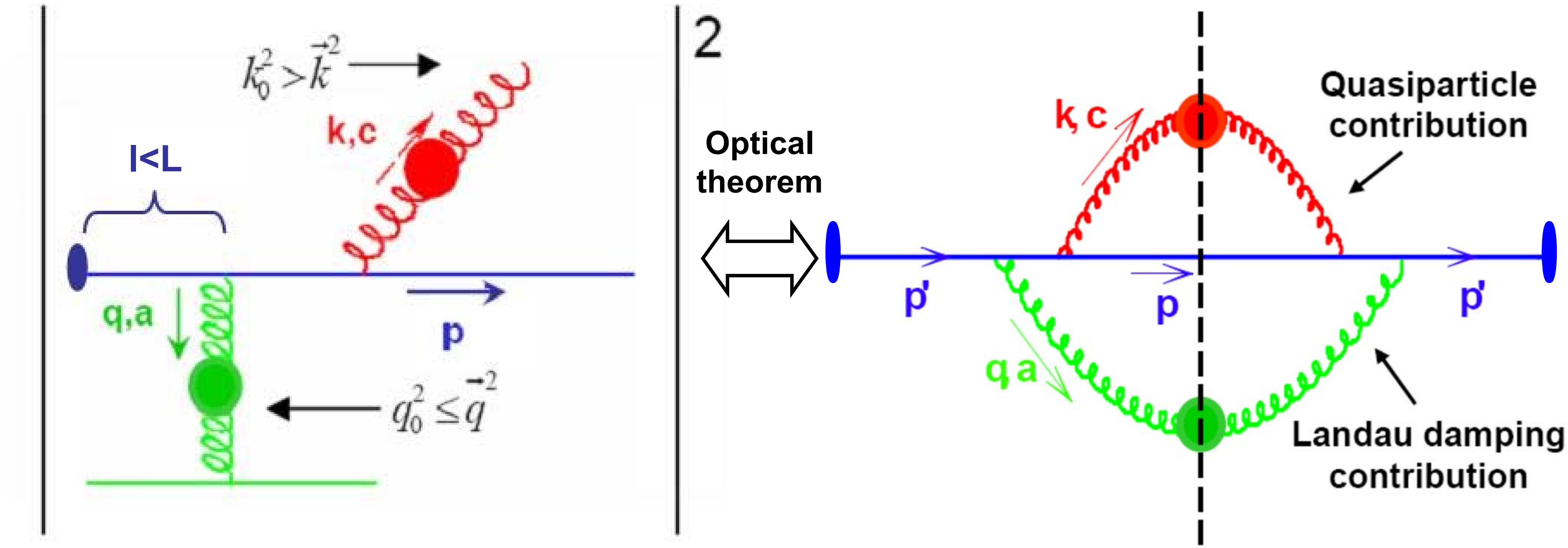
M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

M. D. and U. Heinz, Phys.Rev.Lett.101:022302,2008.

Radiative energy loss in a dynamical medium

We compute the medium induced radiative energy loss for a heavy quark to first (lowest) order in number of scattering centers.

To compute this process, we consider the radiation of one gluon induced by one collisional interaction with the medium.



We consider a medium of finite size L, and assume that the collisional interaction has to occur inside the medium.

The calculations were performed by using two Hard-Thermal Loop approach.

1-HTL gluon propagator:

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

Cut 1-HTL gluon propagator:

$$D^{>}_{\mu\nu}(l) = -(1+f(l_0))\Big(P_{\mu\nu}(l)\rho_T(l) + Q_{\mu\nu}(l)\rho_L(l)\Big) \, ,$$

$$\rho_{L,T}(l) = \underbrace{2\pi\,\delta(l^2-\Pi_{T,L}(l))}_{\text{Radiated gluon}} - \underbrace{2\,\mathrm{Im}\left(\frac{1}{l^2-\Pi_{T,L}(l)}\right)\theta(1-\frac{l_0^2}{\vec{l}^2})}_{\text{Exchanged gluon}}$$

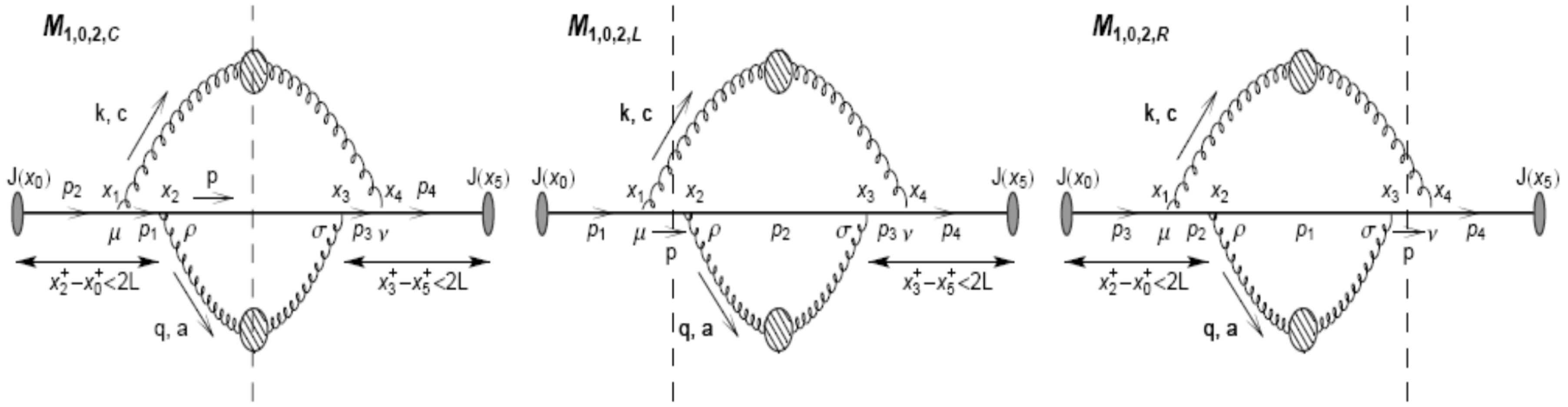
For radiated gluon, cut 1-HTL gluon propagator can be simplified to
(M.D. and M. Gyulassy, PRC 68, 034914 (2003).

$$D^{>}_{\mu\nu}(k) \approx -2\pi\,\frac{P_{\mu\nu}(k)}{2\omega}\,\delta(k_0-\omega) \qquad \omega \approx \sqrt{\vec{k}^2+m_g^2}\,; \; m_g \approx \mu/\sqrt{2}$$

For exchanged gluon, cut 1-HTL gluon propagator cannot be simplified, since both transverse (magnetic) and longitudinal (electric) contributions will prove to be important.

$$D^{>}_{\mu\nu}(q) = \theta(1-\frac{q_0^2}{\vec{q}^2})\,(1+f(q_0))\,2\,\mathrm{Im}\left(\frac{P_{\mu\nu}(q)}{q^2-\Pi_T(q)} + \frac{Q_{\mu\nu}(q)}{q^2-\Pi_L(q)}\right)$$

More than one cut of a Feynman diagram can contribute to the energy loss in finite size dynamical QCD medium:



These terms interfere with each other, leading to the nonlinear dependence of the jet energy loss.

M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

We calculated all the relevant diagrams that contribute to this energy loss

Each individual diagram is infrared divergent, due to the absence of magnetic screening!

The divergence is naturally regulated when all the diagrams are taken into account.
So, all 24 diagrams have to be included to obtain sensible result.

$$\frac{\Delta E_{\rm dyn}}{E} = \frac{C_R \alpha_s}{\pi}\frac{L}{\lambda_{\rm dyn}}\int dx \frac{d^2k}{\pi}\frac{d^2q}{\pi}\frac{\mu^2}{q^2(q^2+\mu^2)}\left(1-\frac{\sin\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}\right)$$
$$\times 2\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}\left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}-\frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right),$$

M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

Finite magnetic mass

The dynamical energy loss formalism is based on HTL perturbative QCD, which requires zero magnetic mass.

↓

However, different non-perturbative approaches show a non-zero magnetic mass at RHIC and LHC.

↓

Can magnetic mass be consistently included in the dynamical energy loss calculations?

Generalization of radiative jet energy loss to finite magnetic mass

$$\frac{\Delta E_{\rm dyn}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\rm dyn}} \int dx \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{\mu^2}{q^2(q^2+\mu^2)}$$
$$\times 2 \frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi} \right) \left(1 - \frac{\sin \frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+} L} \right)$$

zero magnetic mass

From our analysis, only this part gets modified.

Finite magnetic mass: $\dfrac{\mu_E^2 - \mu_M^2}{(q^2+\mu_E^2)(q^2+\mu_M^2)}$**, where** $0.4 \leq \dfrac{\mu_M}{\mu_E} \leq 0.6$.

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

The dynamical energy loss

- **Finite size medium of dynamical (moving) partons**
- **Based on finite T field theory and HTL approach**

M. D., PRC74 (2006), PRC 80 (2009), M. D. and U. Heinz, PRL 101 (2008).

Includes:

- **Same theoretical framework for both radiative and collisional energy loss**
- **Finite magnetic mass effects (M. D. and M. Djordjevic, PLB 709:229 (2012))**
- **Running coupling (M. D. and M. Djordjevic, PLB 734, 286 (2014)).**

Integrated in a numerical procedure including parton production, fragmentation functions, path-length and multi-gluon fluctuations

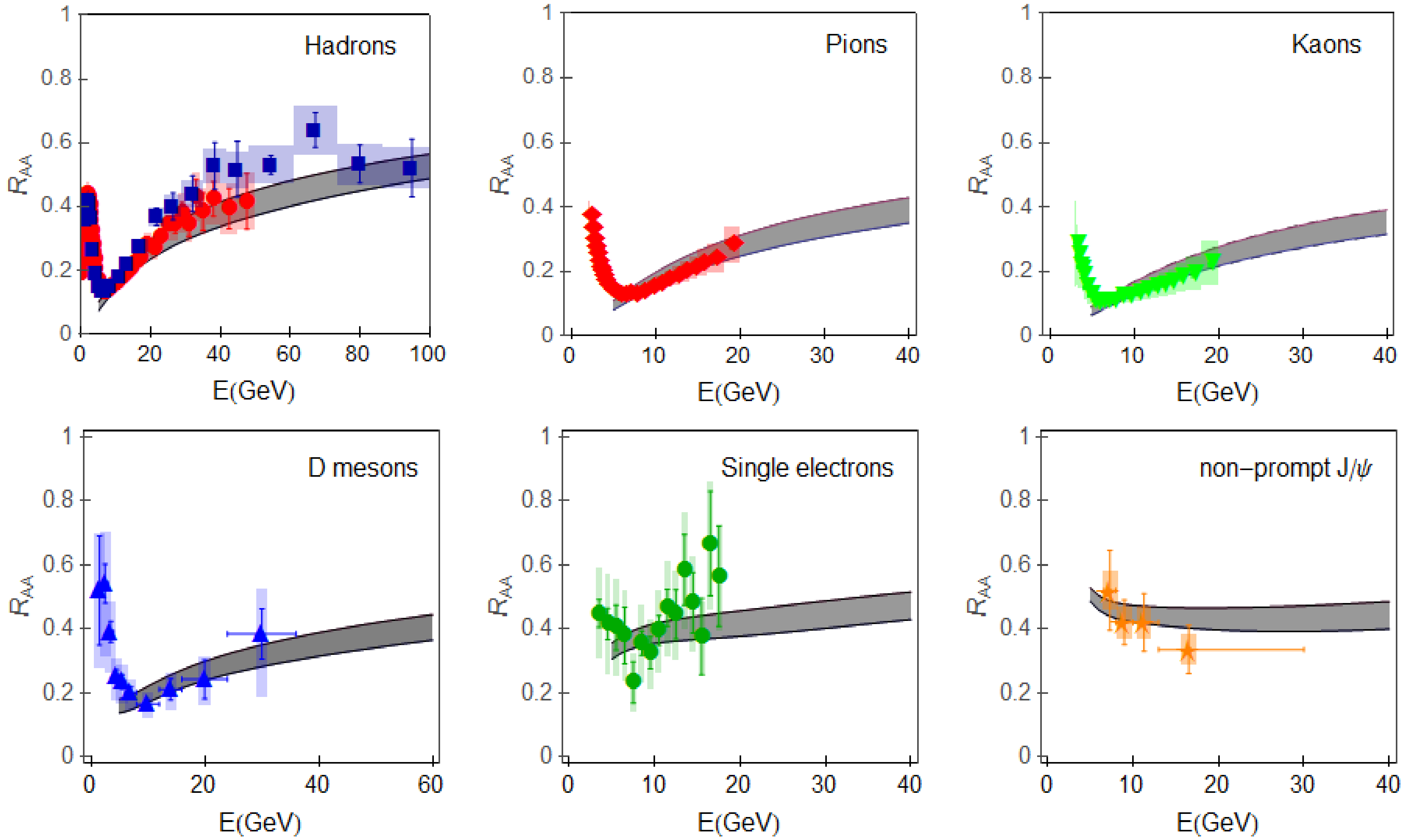
- **No fitting parameters**
- **Treats both light and heavy flavor partons**

Comparison with the experimental data

- **Provide joint predictions across diverse probes**
  - **all predictions generated by the same formalism, with the same numerical procedure, the same parameter set and no fitting parameters in model testing**
- **Concentrate on different experiments, collision energies and centrality regions**
- **Address puzzling data**
- **Provide comparison with most recent experimental data**
- **Propose further experimental tests**

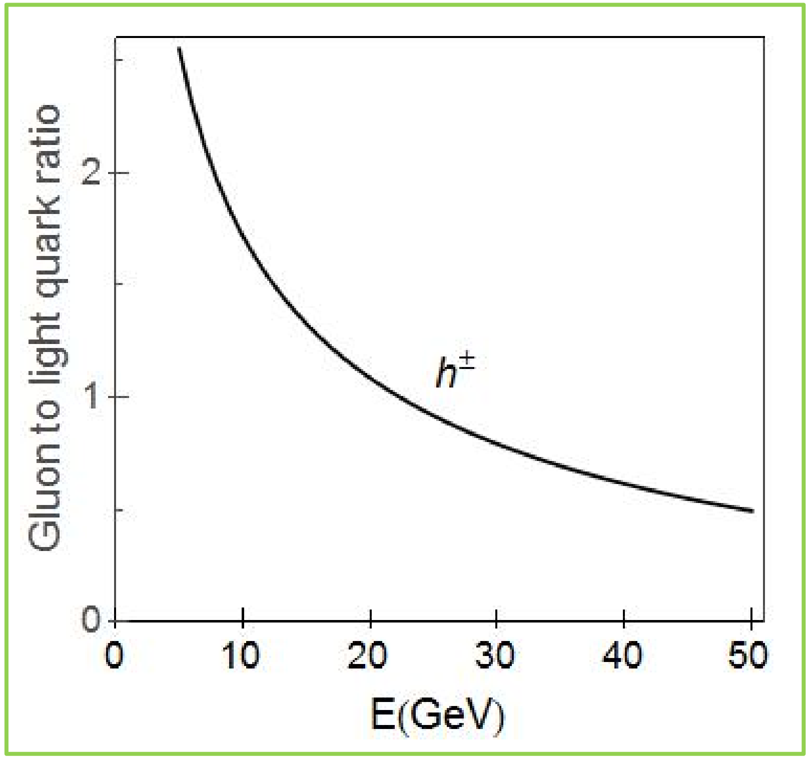
Comparison with Run 1 LHC data (central collisions)

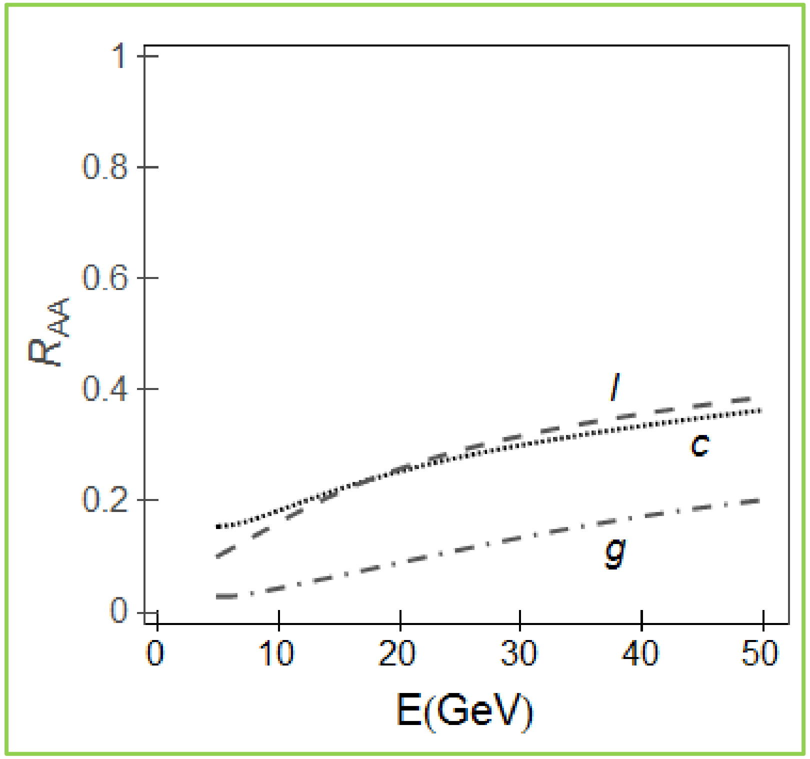
M. D. and M. Djordjevic, PLB 734, 286 (2014)



Very good agreement with diverse probes!

Heavy flavor puzzle @ LHC



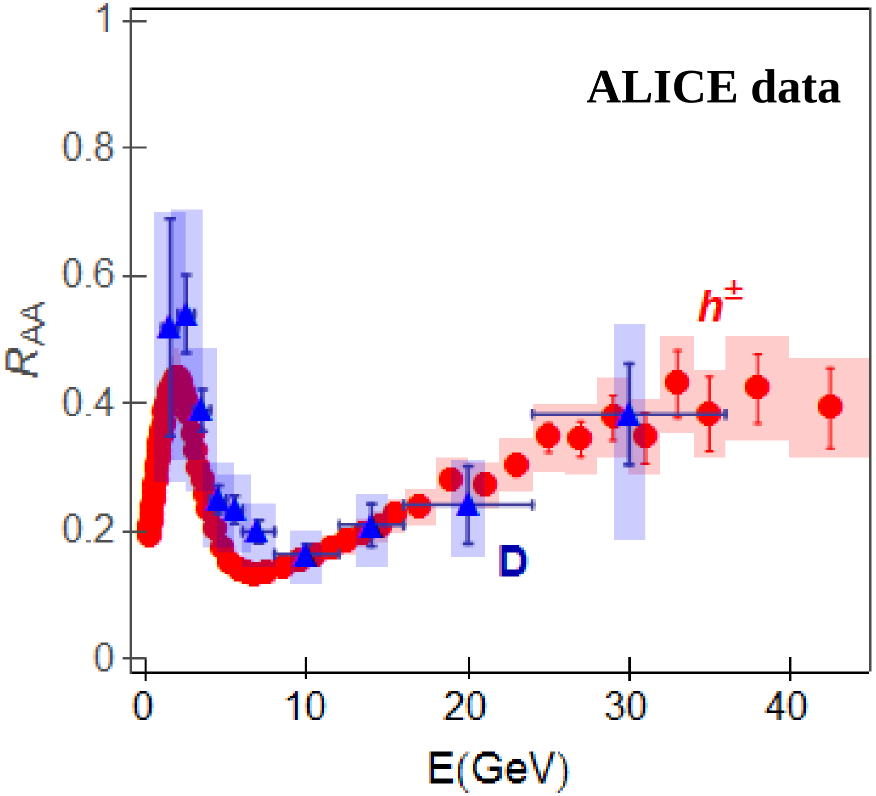


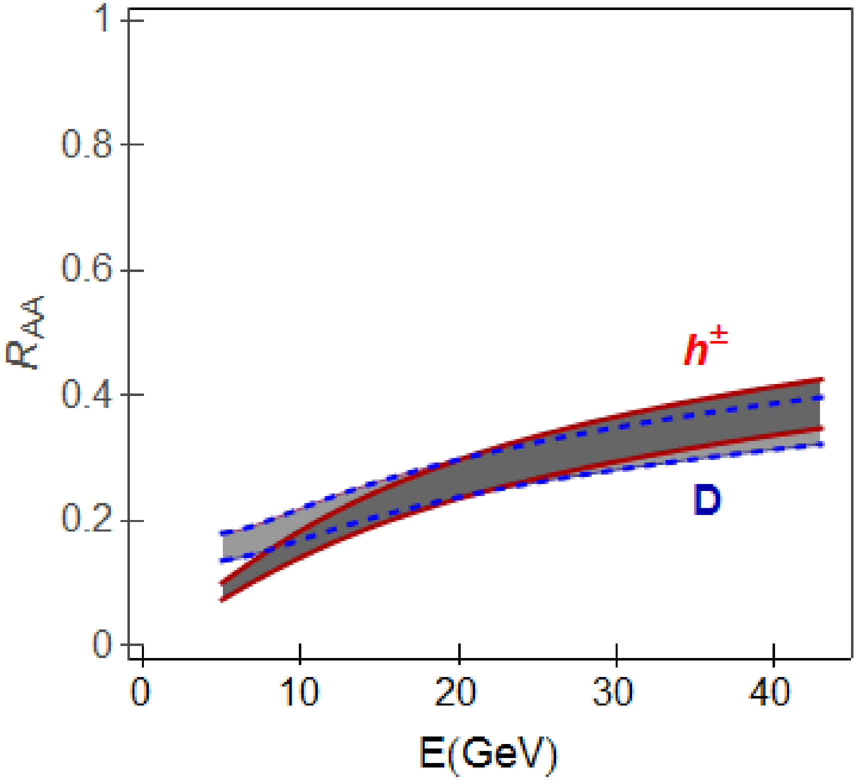
Significant gluon contribution in charged hadrons

Much larger gluon suppression

R_{AA} ($h^{\pm}$) < R_{AA} (D)

Charged hadrons vs. D meson R_{AA}





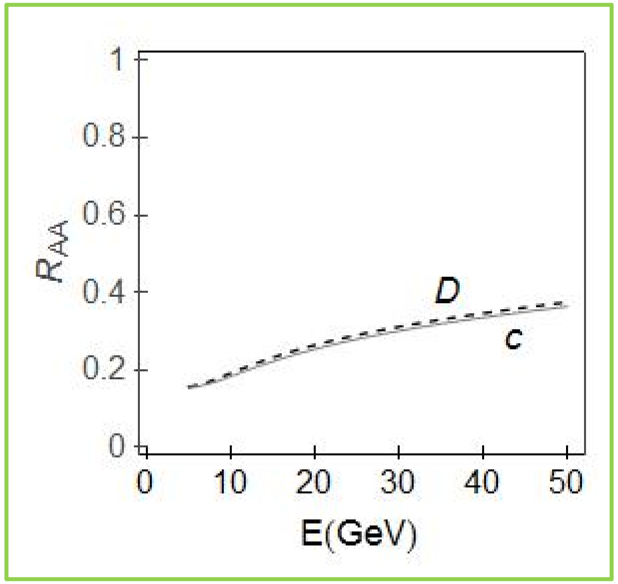
R_{AA} ($h^{\pm}$) = R_{AA} (D)

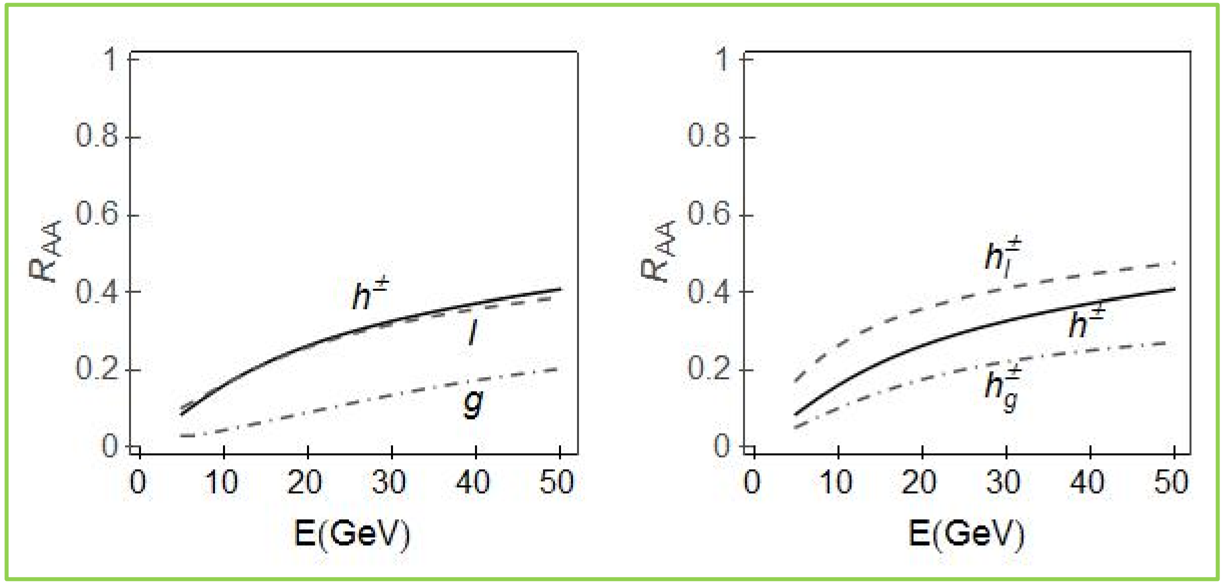
Excellent agreement with the data!

Disagreement with the qualitative expectations!

M.D., PRL 112, 042302 (2014)

Hadron R_{AA} *vs.* parton R_{AA}





D meson is a genuine probe of bare charm quark suppression

Distortion by fragmentation

Charged hadron R_{AA} = (bare) light quark R_{AA}

M.D., PRL 112, 042302 (2014)

Puzzle summary

M.D., PRL 112, 042302 (2014)

R_{AA} ($h^{\pm}$) = R_{AA} (light quarks)

R_{AA} (D) = R_{AA} (charm)

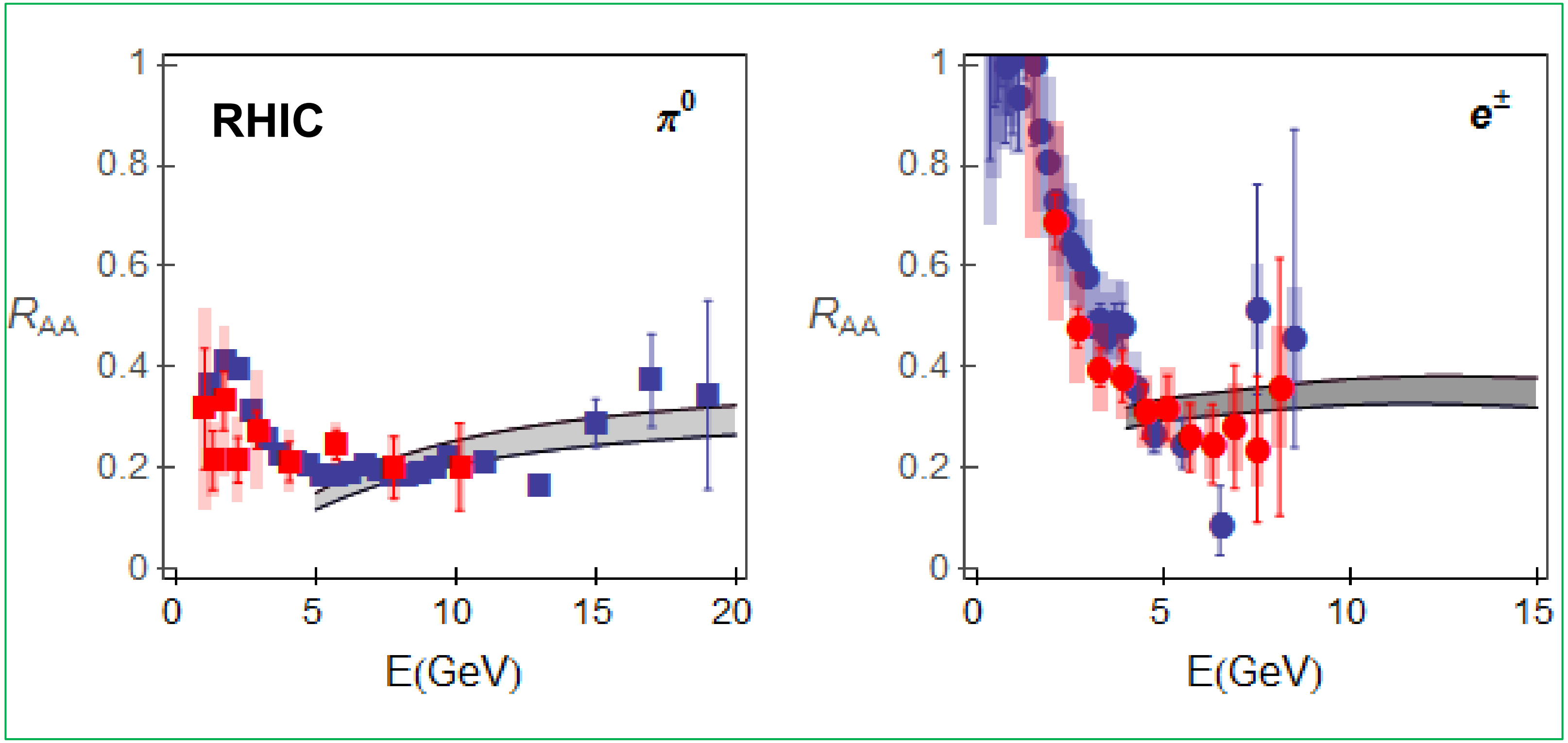
R_{AA} (light quarks) = R_{AA} (charm)

R_{AA} ($h^{\pm}$) = R_{AA} (D)

Puzzle explained!

- **A clear qualitative example that each step in the suppression scheme can be important.**
- **Dynamical energy loss is needed to quantitatively explain the data.**

Heavy flavor puzzle @ RHIC

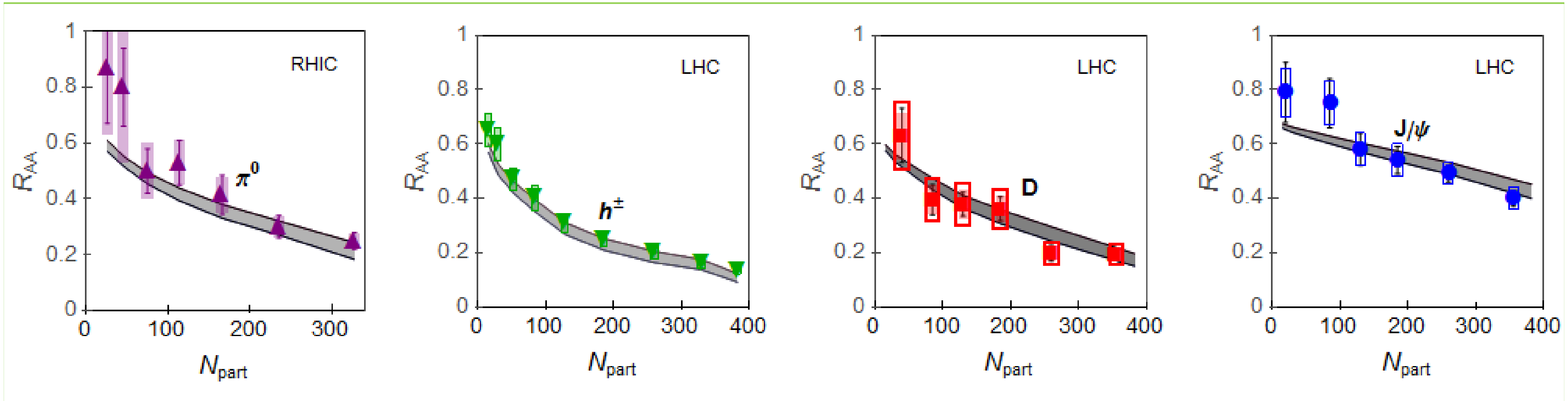


Very good agreement of the dynamical energy loss predictions with the data!

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

Non-central collisions

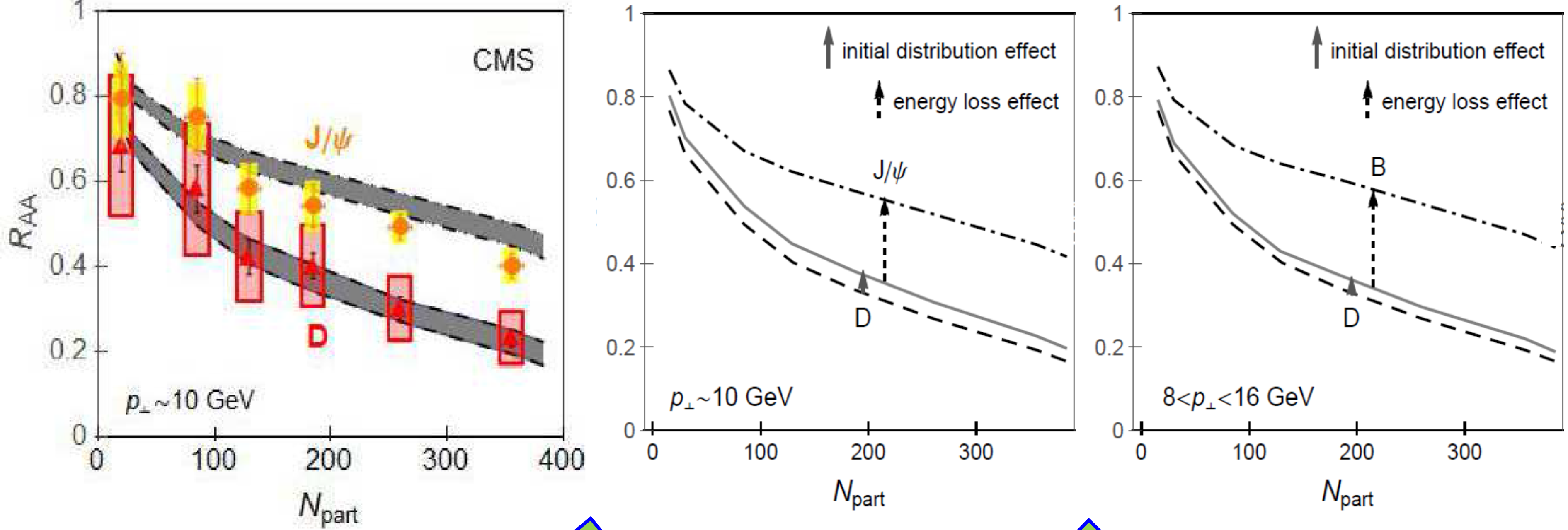
R_{AA} *vs.* N_{part} for RHIC and LHC



Excellent agreement of the dynamical energy loss for both RHIC and LHC and for the whole set of probes!

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

MD, B. Blagojevic and L. Zivic, PRC 94, 044908 (2016)

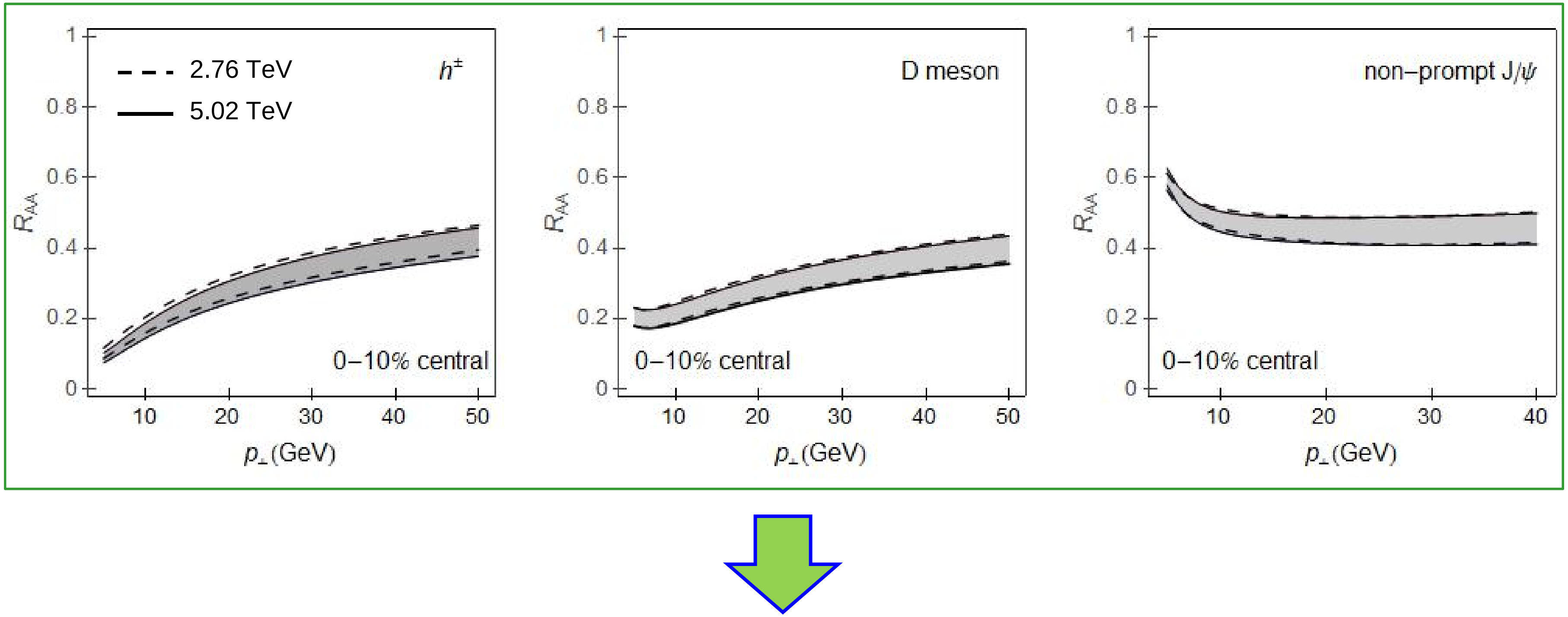


Differences in the heavy flavor RAA are a consequence of the "dead-cone" effect.

Comparison with most recent experimental data

5.02 *vs.* 2.76 TeV Pb+Pb at LHC

M. D. and M. Djordjevic, PRC 92, 024918 (2015)

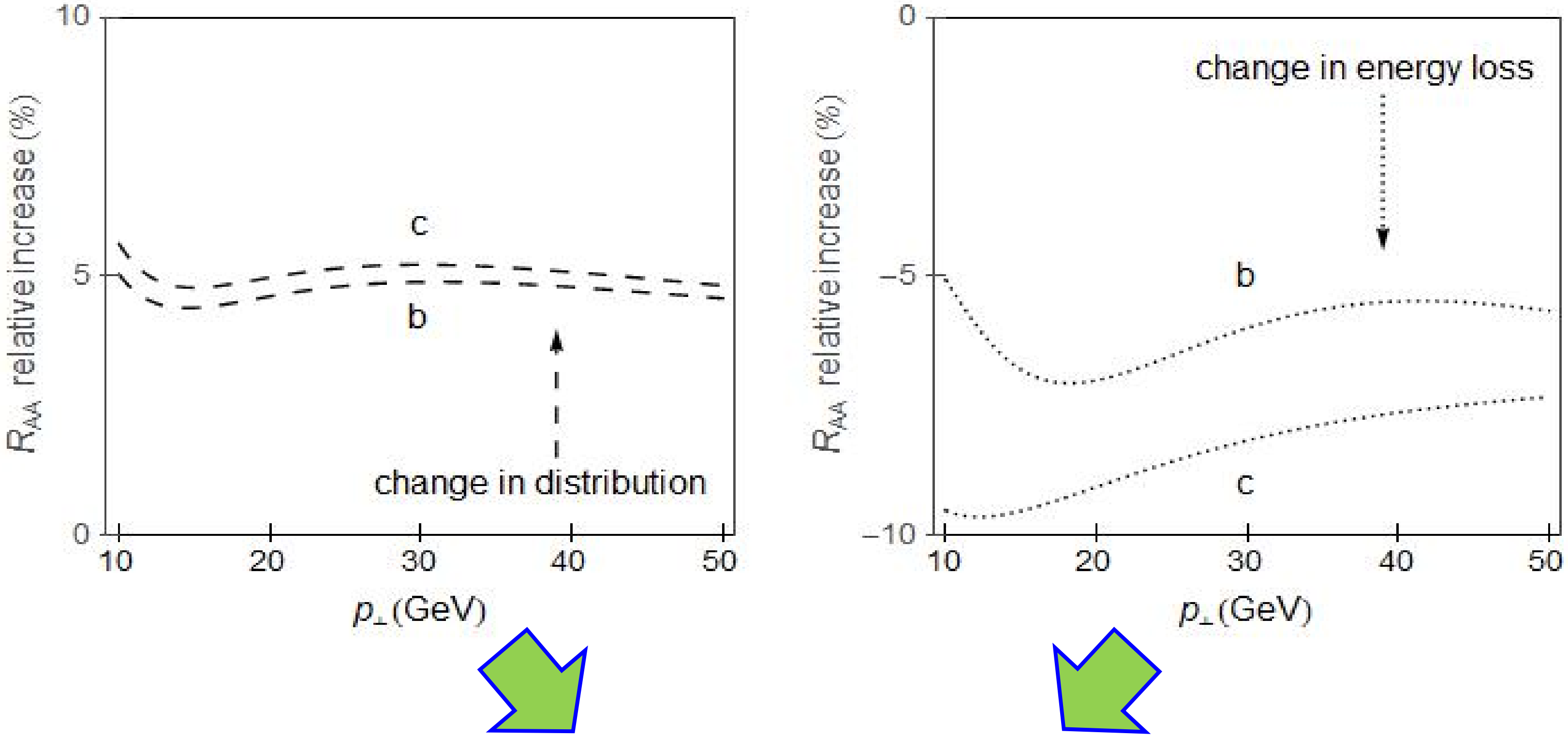


The same suppression predicted at 5.02 TeV and 2.76 TeV for all types of probes!

Why the same suppression?

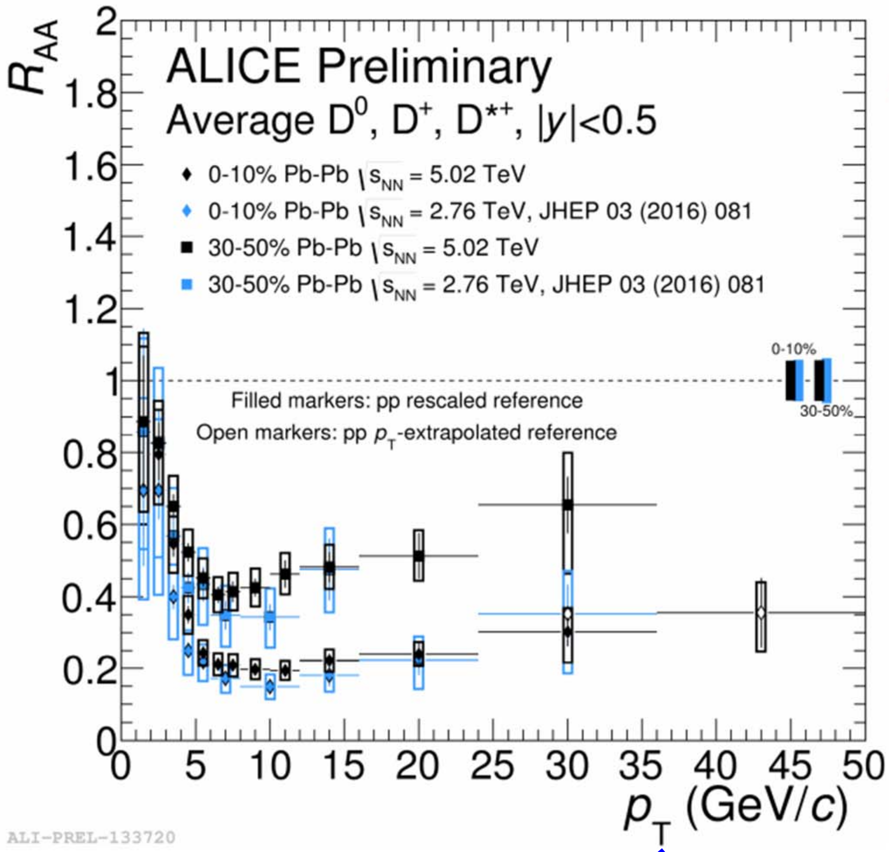
An interplay between initial distribution and energy loss effects.

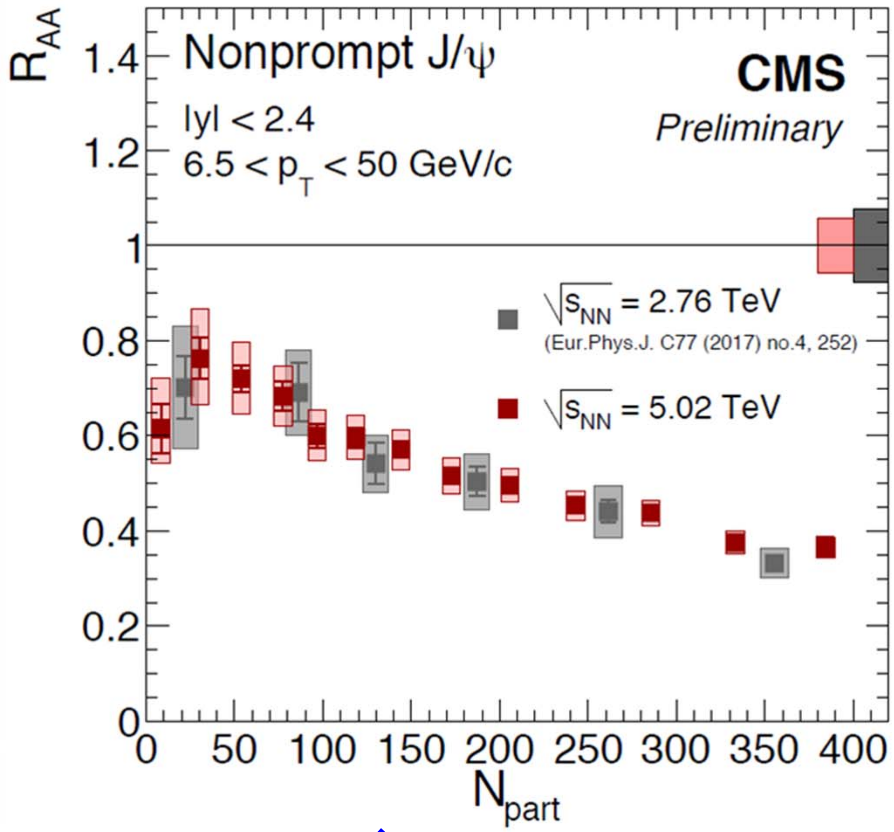
M. D. and M. Djordjevic, PRC 92, 024918 (2015)



The two effects cancel!

Comparison with the experimental data





The predicted overlap between 5.02 TeV and 2.76 TeV subsequently confirmed by the data

Energy loss summary

Dynamical energy loss formalism.

Tested on angular averaged R_{AA} data

Largely not sensitive to the medium evolution.

Good agreement for wide range of probes, centralities and beam energies.

Can explain puzzling data.

Clear predictions for future experiments.

The dynamical energy loss formalism can well explain the jet-medium interactions in QGP.

Outlook

Dynamical energy loss model

+

Bulk medium evolution models (Huovinen/Niemi, BAMPS)

Predictions of angular differential R_{AA} observables (e.g. elliptic flow) for high pt observables.

Presumably highly sensitive to the medium evolution.

A new sophisticated tool for precision QGP tomography.