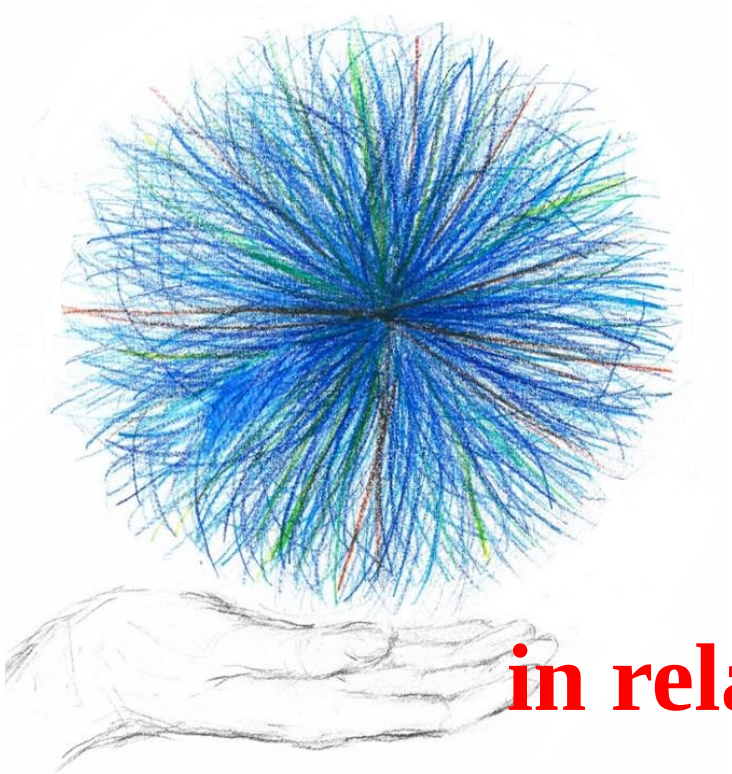


Open high-pt heavy flavor in relativistic heavy ion collisions

Magdalena Djordjevic, IPB

European Research Council

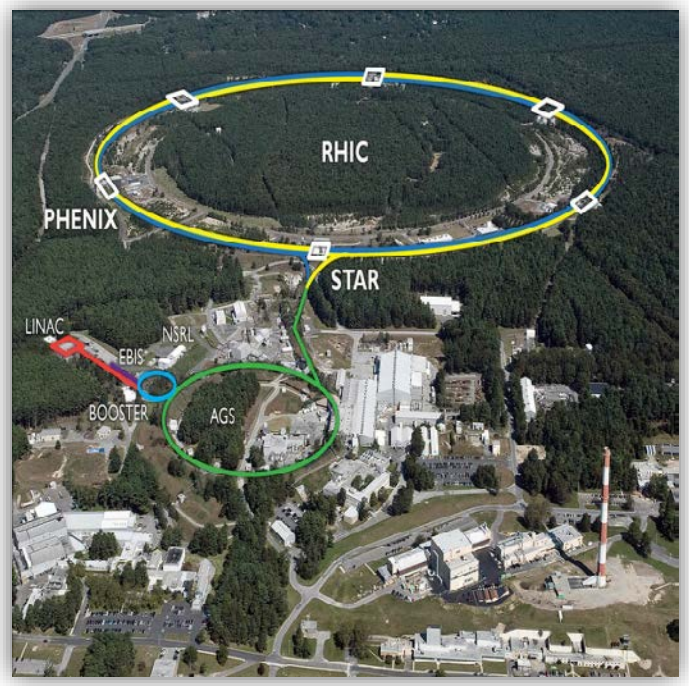
МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Quark Gluon Plasma (QGP)

- **A new state of matter, consisting of deconfined and interacting quarks, antiquarks and gluons.**

Relativistic heavy ion physics:
form, observe and understand QGP

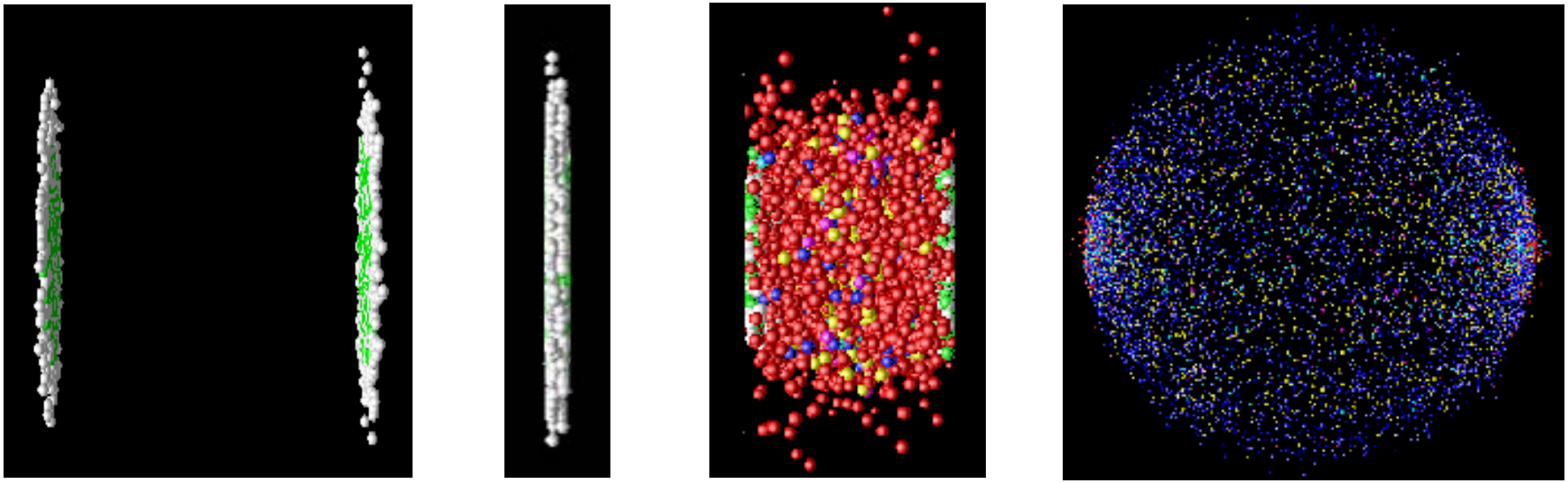
Little Bangs at LHC and RHIC



- **Existed immediately after Big-Bang, today created in Little Bangs**
- **Allows studying the origin of matter at its basic level**

Scheme of relativistic heavy ion collisions

Simulation "VNI" (Geiger, Longacre, Srivastava)



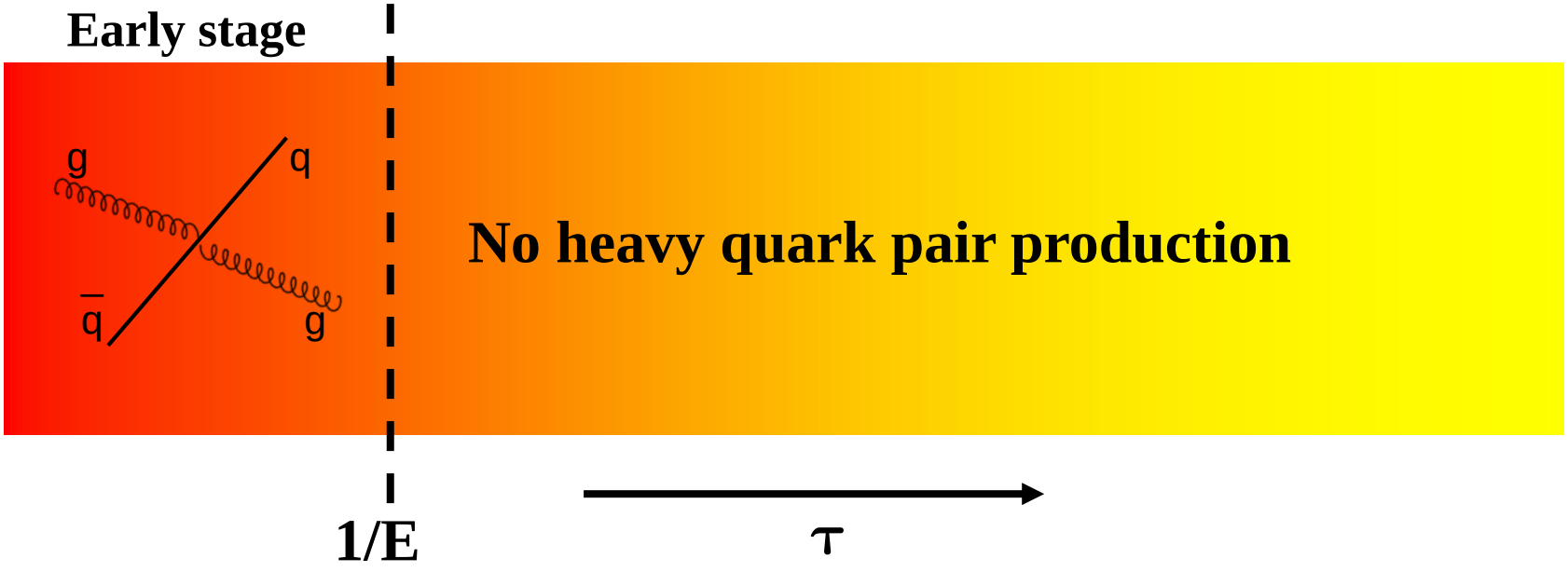
Heavy ion acceleration → Collision → Quark-gluon plasma → Hadron Gas

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

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

Why are heavy quarks good probes?

They can be produced only during the early stage of QCD matter.



Why are heavy quarks good probes?

Heavy flavor mass is large enough.

$$M >> \Lambda_{QCD}$$

Perturbative calculations of heavy quark production and energy loss are possible.

Heavy flavor mass is still small enough.

Significantly interacts with surrounding light quarks and gluons.

Sensitive to the properties of the medium.

High-pt light flavor is also very important

Light quarks have small thermal masses

In comparison, beauty mass is very large.

Light quarks provide a very useful reference for heavy flavor predictions.

I will here show joint predictions for high-pt light and heavy quarks!

Suppression
– a traditional probe of QCD matter

Light and heavy flavour suppressions are considered as excellent probes of QCD matter.

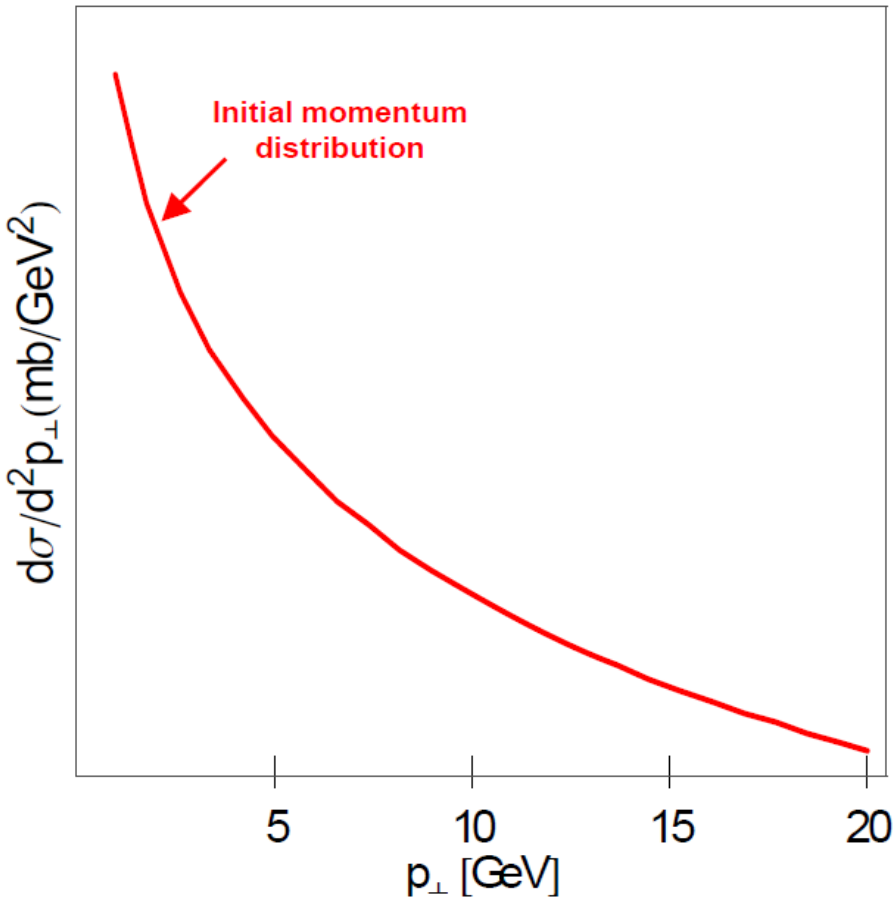
↓

Suppression for a number of observables at RHIC and LHC has been measured.

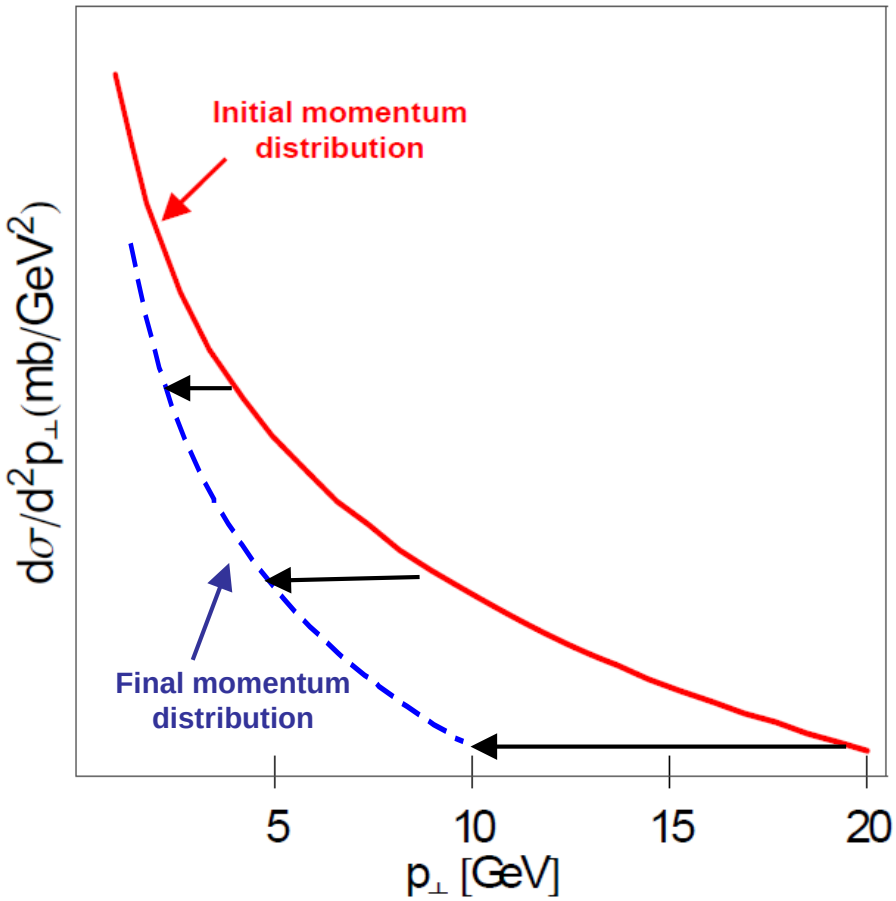
↓

Comparison of theory with the experiments allows testing our understanding of QCD matter.

What is suppression?

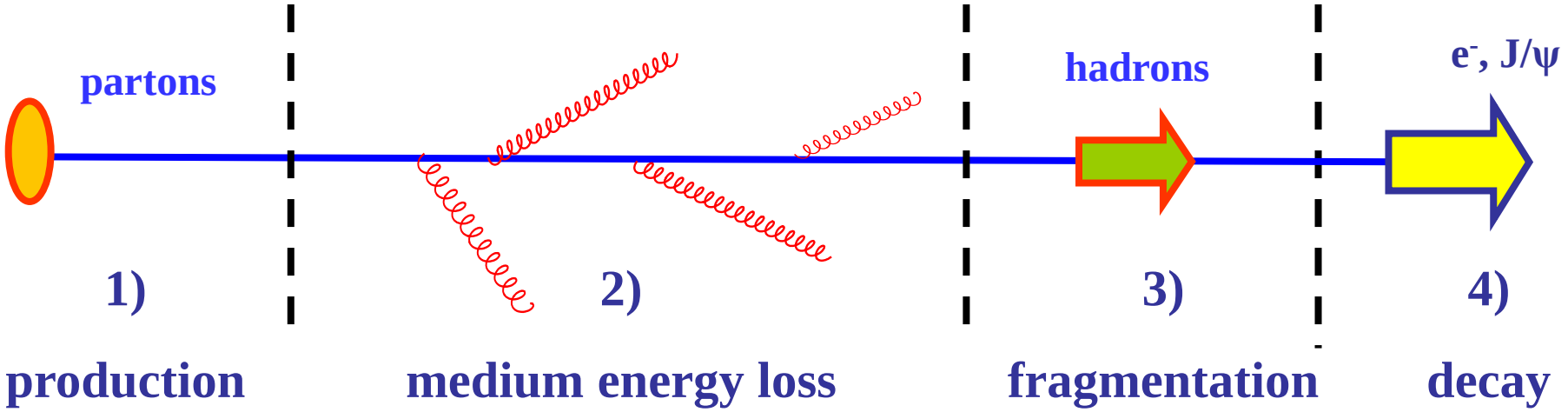


What is suppression?



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

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.

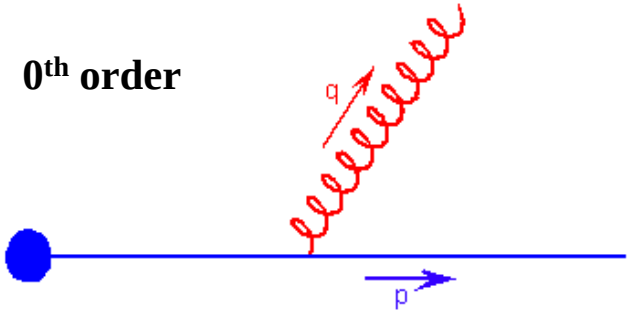
Out of these steps the energy loss is most important!

Energy loss in QGP

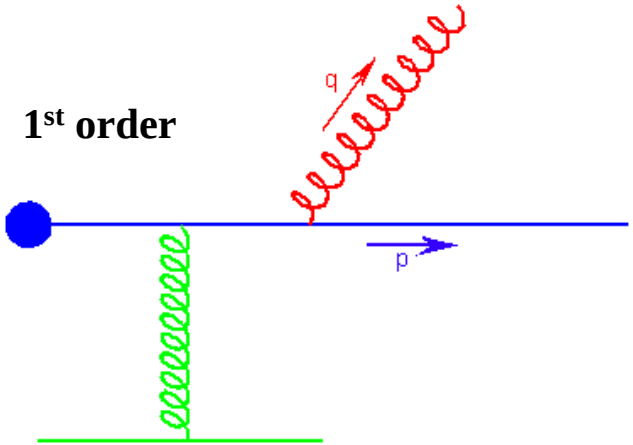
Radiative energy loss

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

0th order



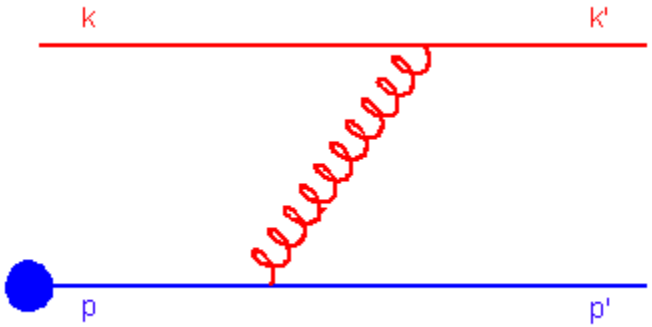
1st order



Collisional energy loss

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

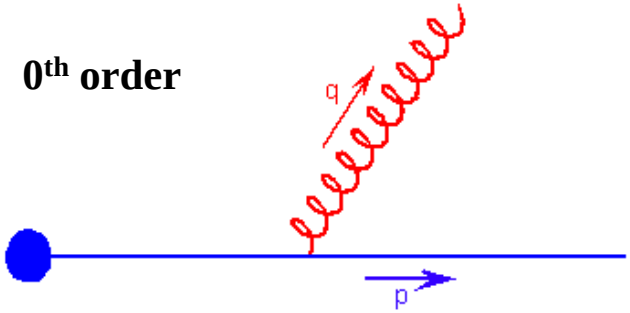
0th order



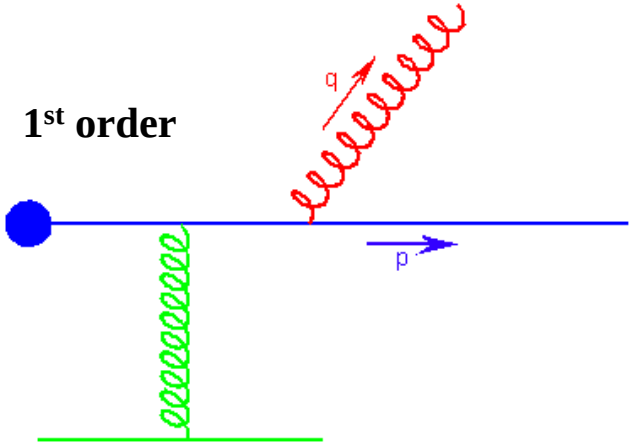
Radiative energy loss

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

0th order



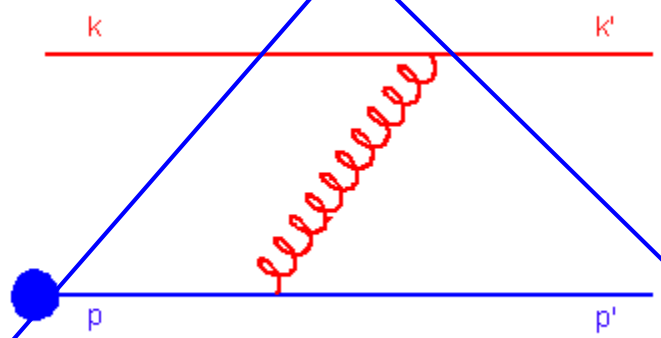
1st order



Collisional energy loss

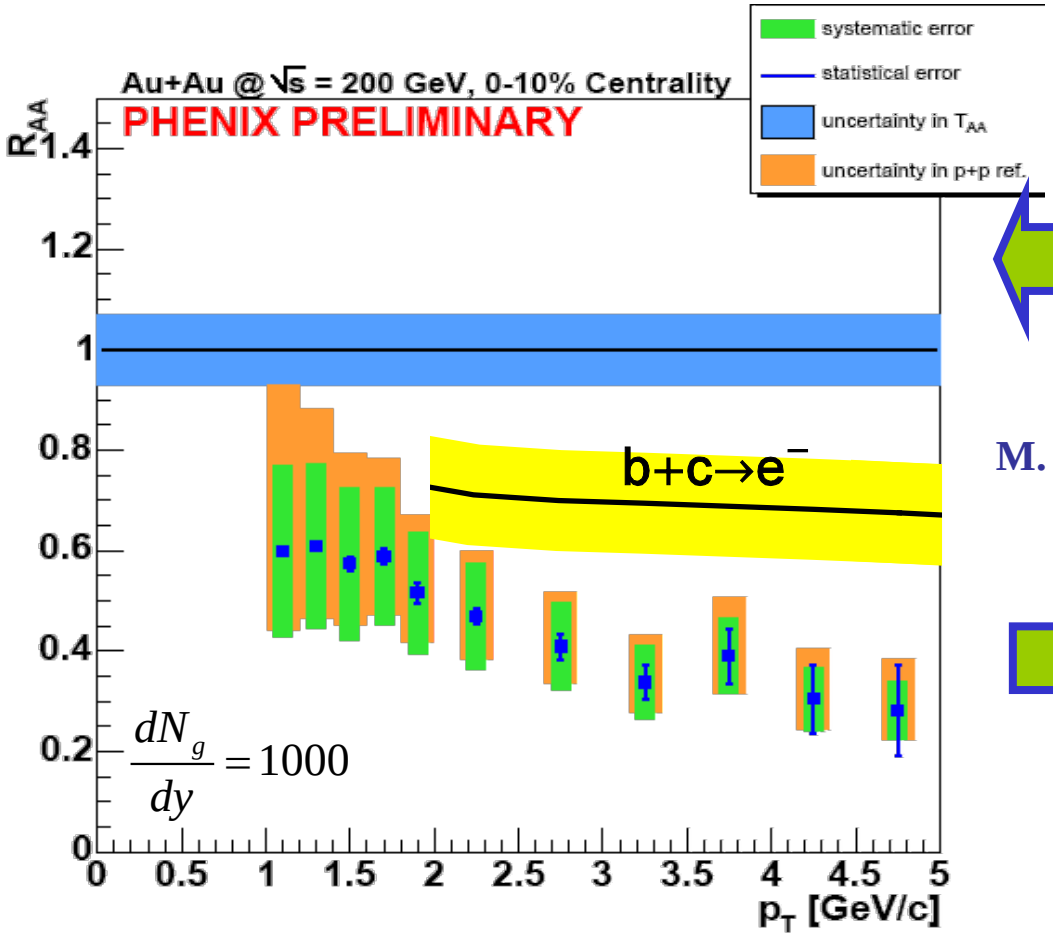
Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

0th order



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!

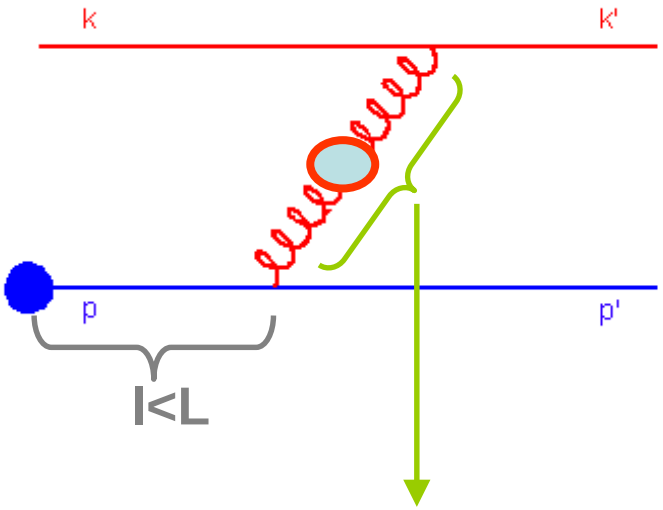
Does the radiative energy loss control the energy loss in QGP?

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:

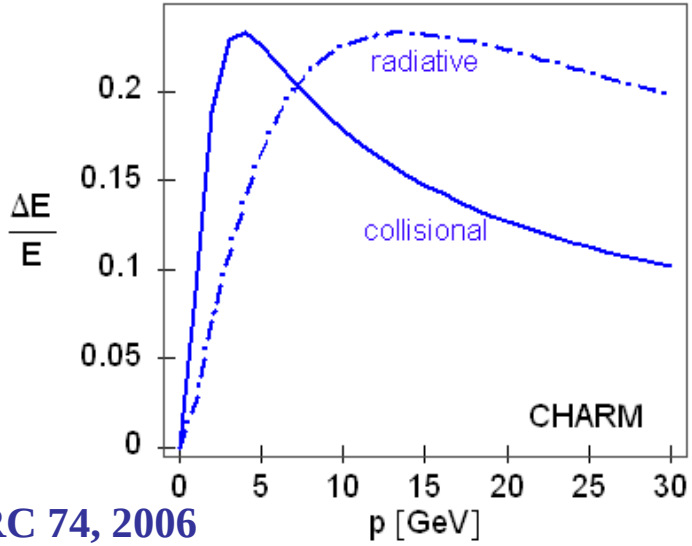


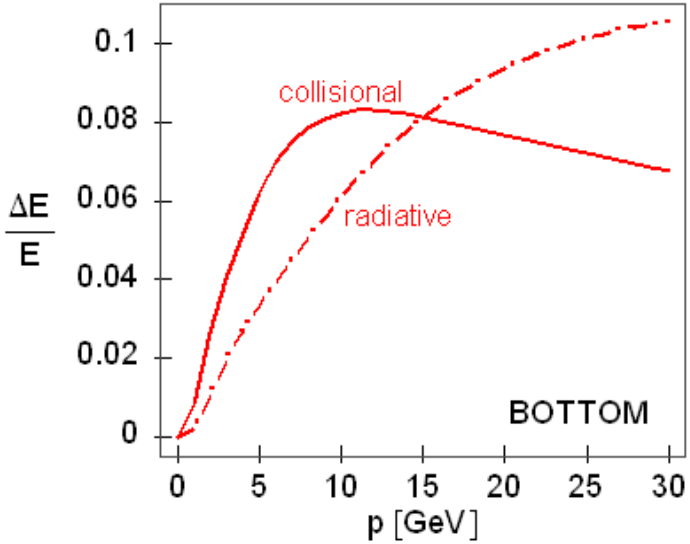
The effective gluon propagator:

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

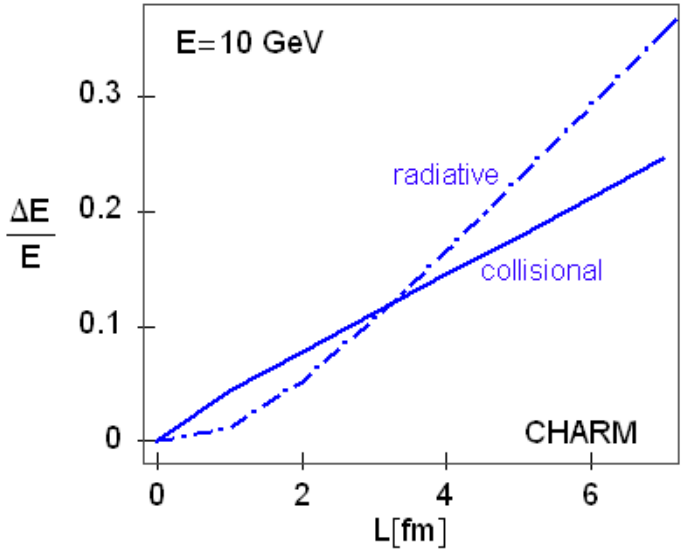
M. D., Phys.Rev.C74:064907,2006

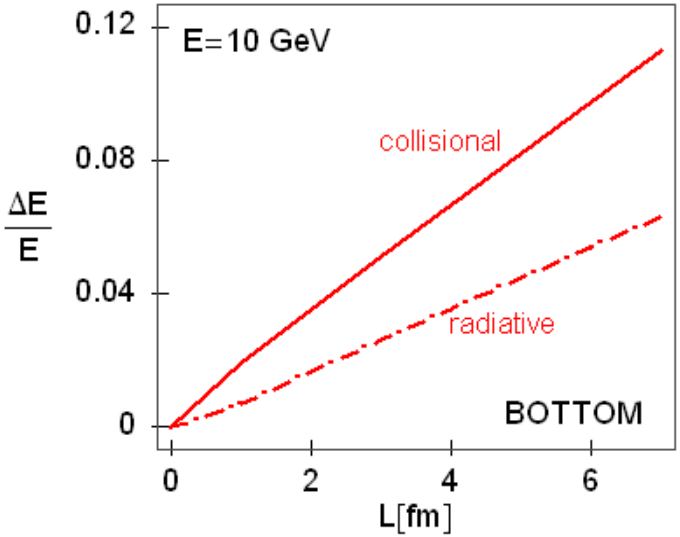
Collisional v.s. medium induced radiative energy loss





M. D., PRC 74, 2006

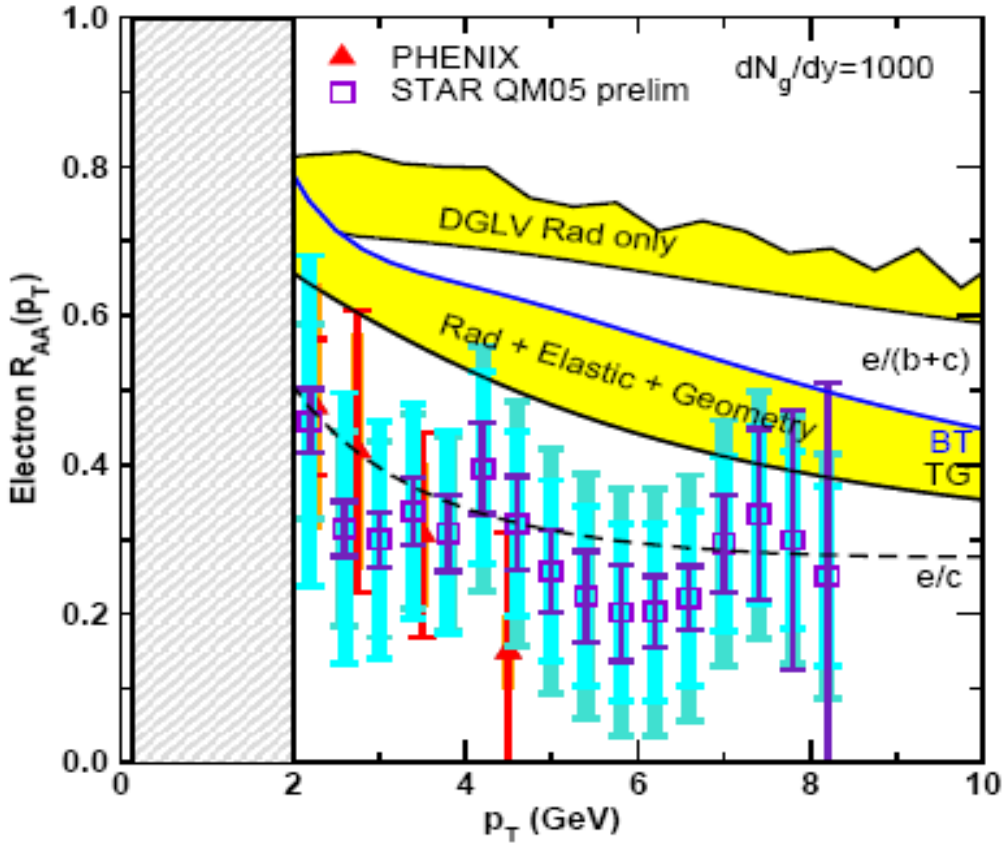




Collisional and radiative energy losses are comparable!

Single electron prediction (collisional + radiative)

(S. Wicks, W. Horowitz, M.D. and M. Gyulassy, Nucl.Phys.A784:426-442,2007)



Inclusion of collisional energy loss leads to better agreement with single electron data.

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 light and 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 which is applicable to both light and heavy flavor.**

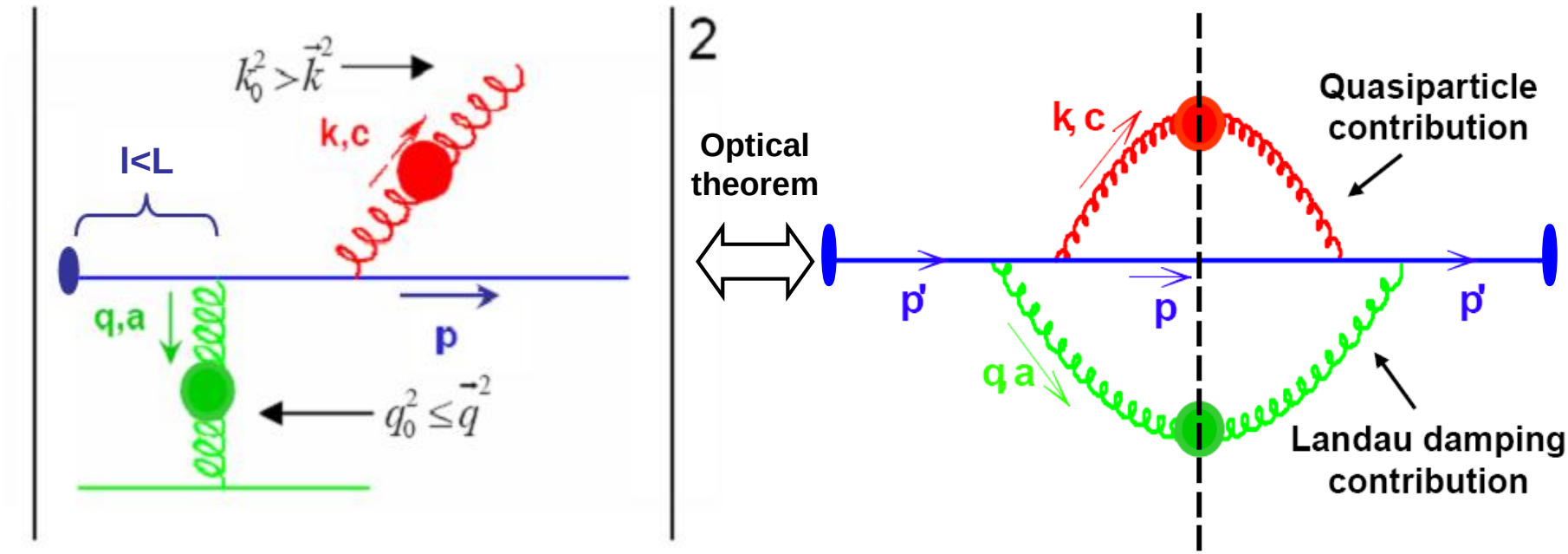
M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

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 light and heavy quark to the 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:

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

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

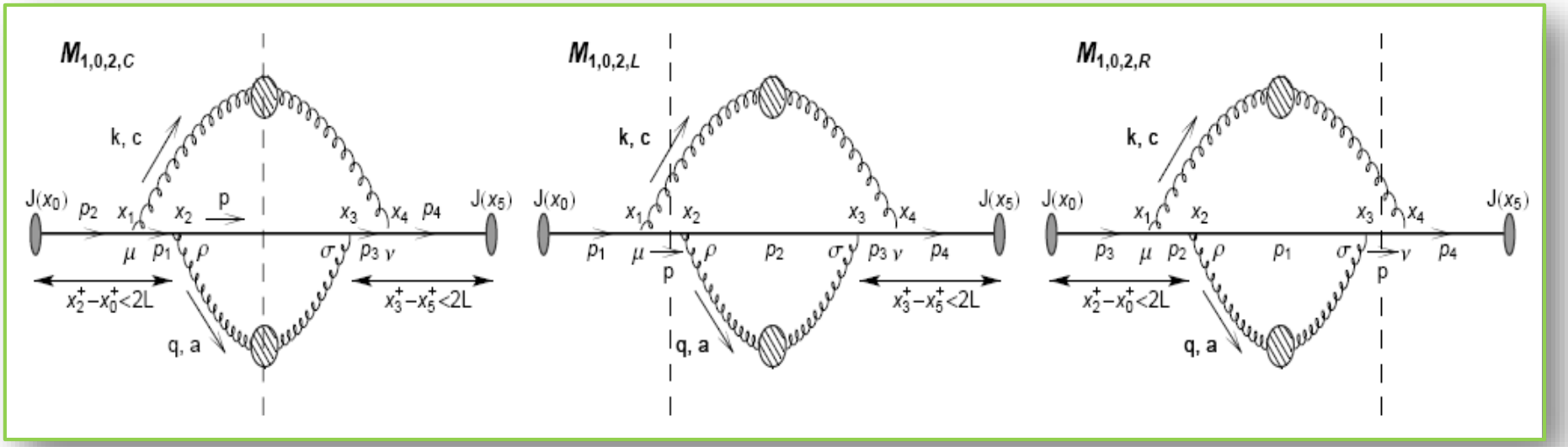
For radiated gluon, cut 1-HTL gluon propagator can be simplified to
(M.D. and M. Gyulassy, PRC 68, 034914 (2003).

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

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.

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

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

The dynamical energy loss formalism

Dynamical energy loss formalism, which has several unique features in the description of high-$p_\perp$ parton medium interactions:

Includes:

- ***Finite size finite temperature*** **QCD medium of** ***dynamical*** **(moving) partons**
- **Based on finite T field theory and generalized HTL approach**
  M. D., PRC74 (2006), PRC 80 (2009), M. D. and U. Heinz, PRL 101 (2008).
- **Same theoretical framework for both radiative and collisional energy loss**
- ***Applicable to both light and heavy flavor.***
- **Finite magnetic mass effects (M. D. and M. Djordjevic, PLB 709:229 (2012))**
- **Running coupling (M. D. and M. Djordjevic, PLB 734, 286 (2014)).**
- **Relaxed soft-gluon approximation (B. Blagojevic, M. D. and M. Djordjevic, PRC 99, 024901, (2019)).**

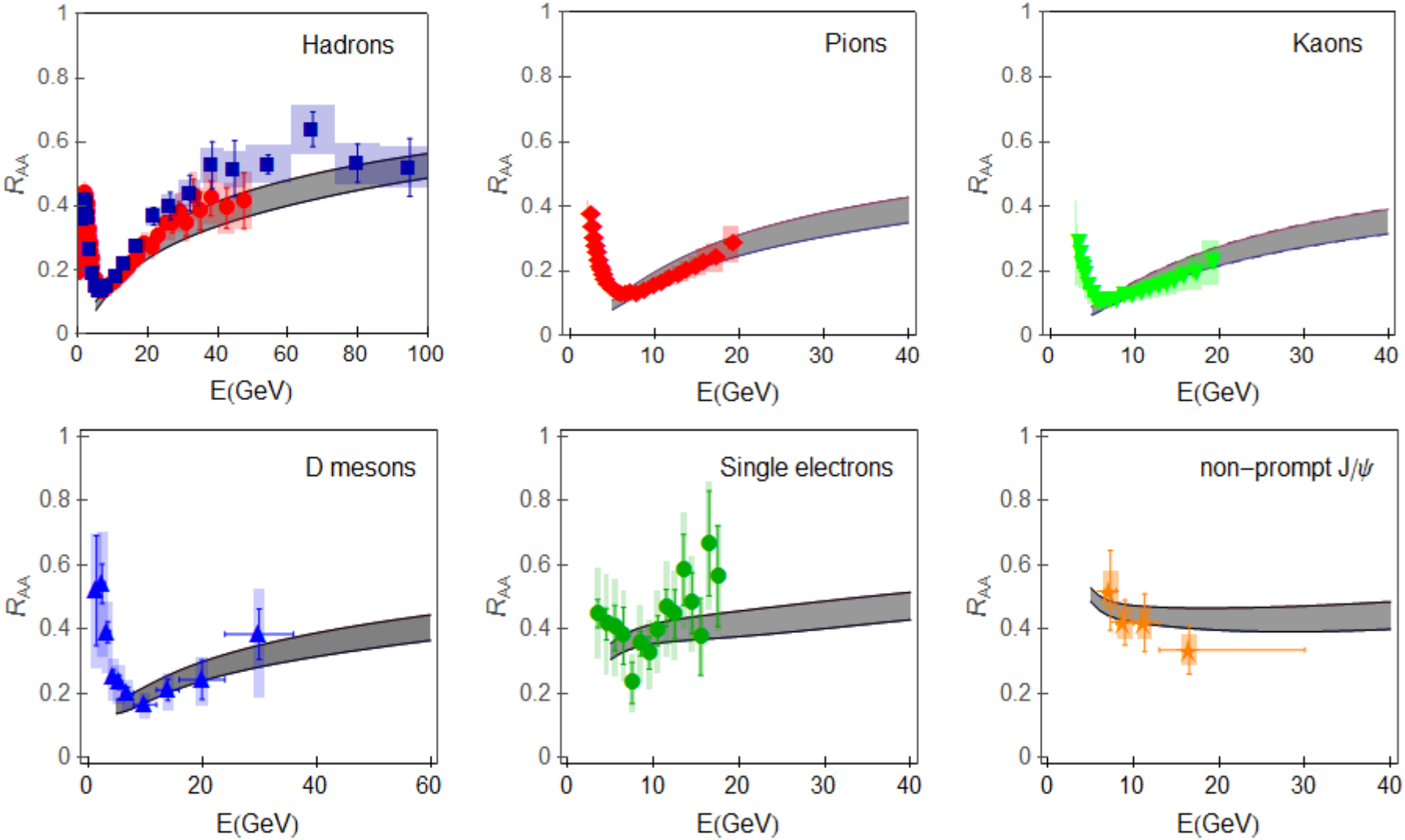
Integrated in a numerical procedure including parton production, fragmentation functions, path-length and multi-gluon fluctuations.

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**
- **Provide comparison with most recent experimental data**
- **Propose further experimental tests, which show the importance of beauty in distingusihing between different energy loss mechanisms.**

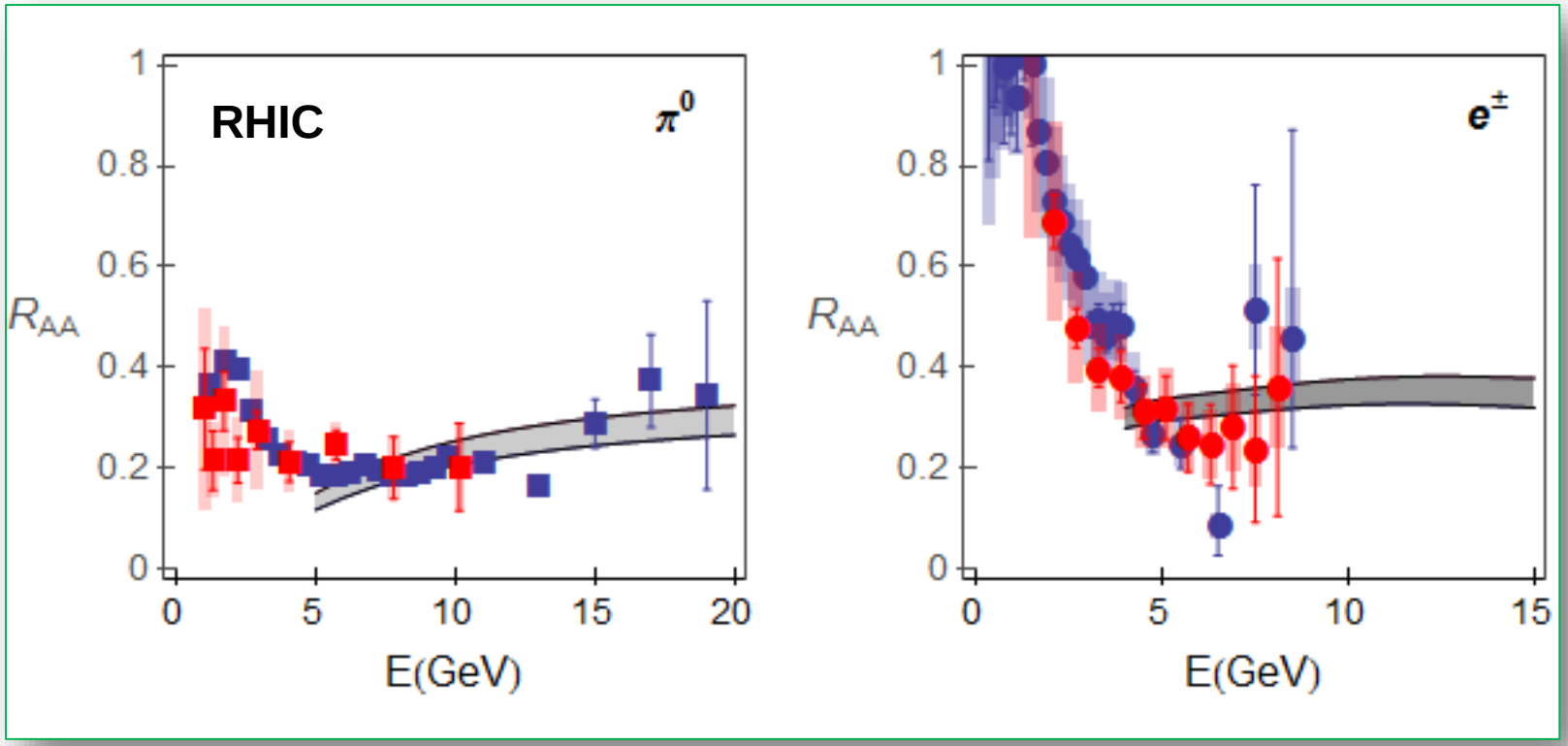
Comparison with Run 1 LHC data (central collisions)

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



Very good agreement with diverse probes!

Also good agreement @ RHIC

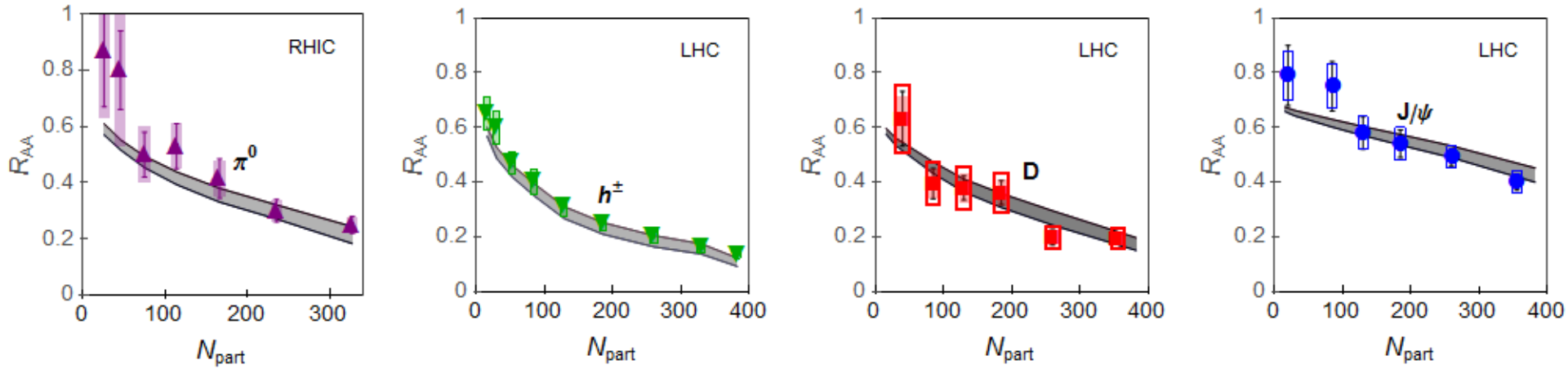


Very good agreement of the dynamical energy loss predictions with the data!

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

Non-central collisions

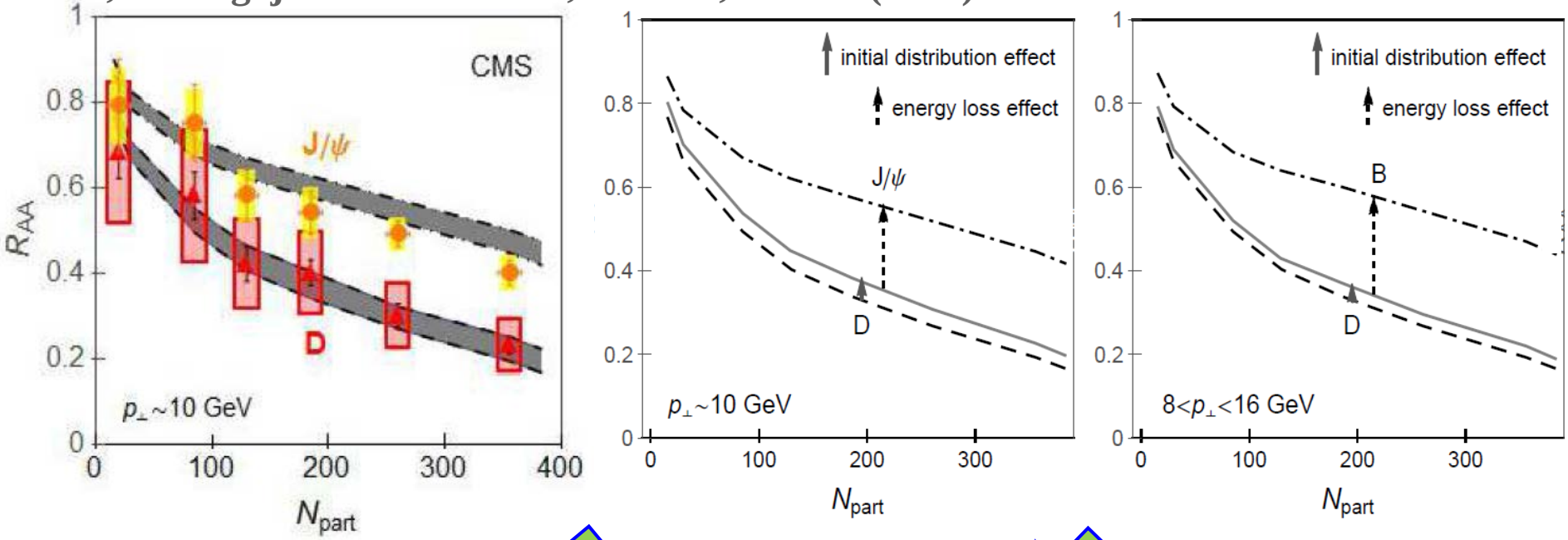
R_{AA} *vs.* N_{part} for RHIC and LHC



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)

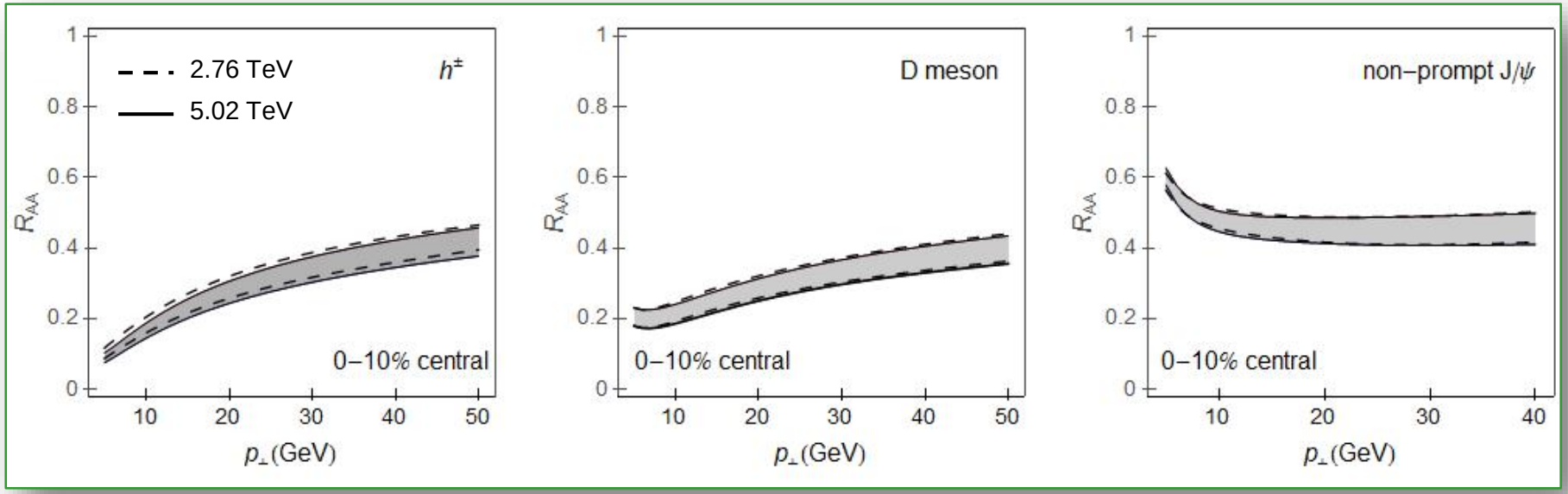


Differences in the heavy flavor R_{AA} are a consequence of the "dead-cone" effect.

Generating predictions and proposing further experimental tests

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

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

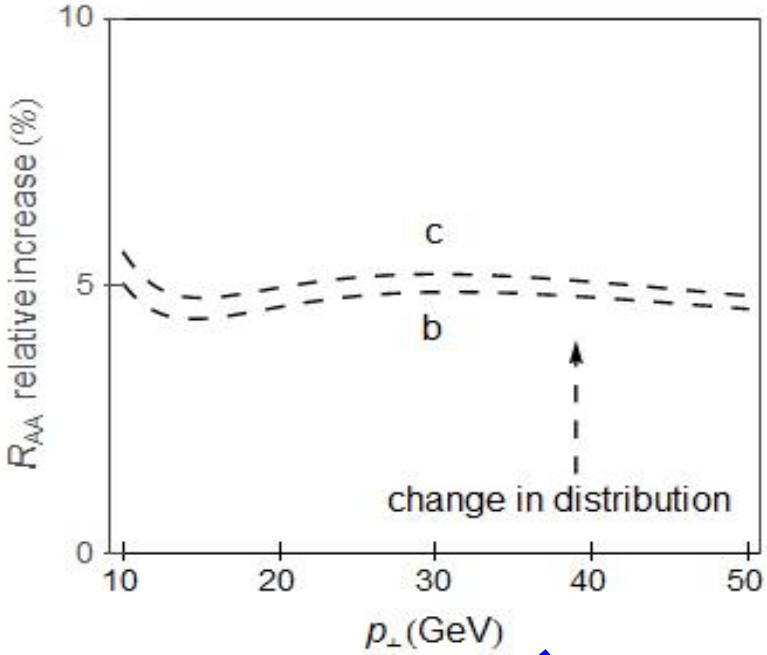


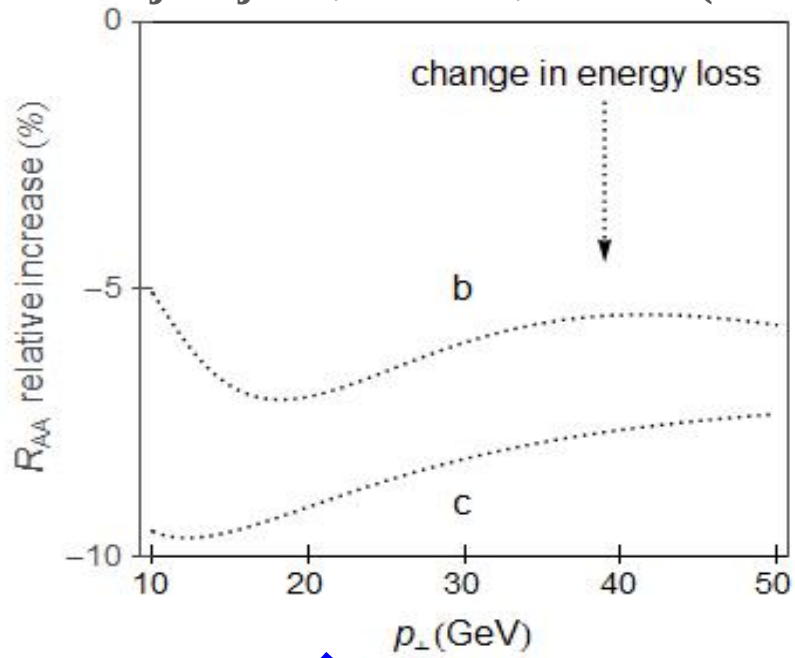
The same suppression predicted at 5.02 TeV and 2.76 TeV for all types of probes!

Why the same suppression?

An interplay between initial distribution and energy loss effects.

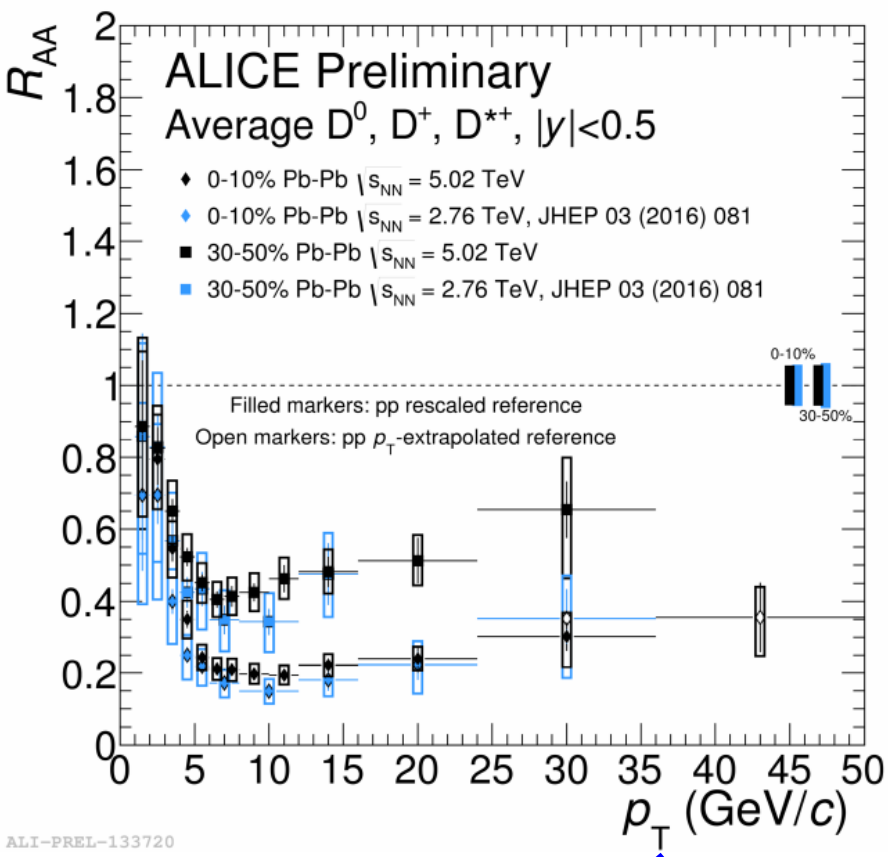
M. D. and M. Djordjevic, PRC 92, 024918 (2015)

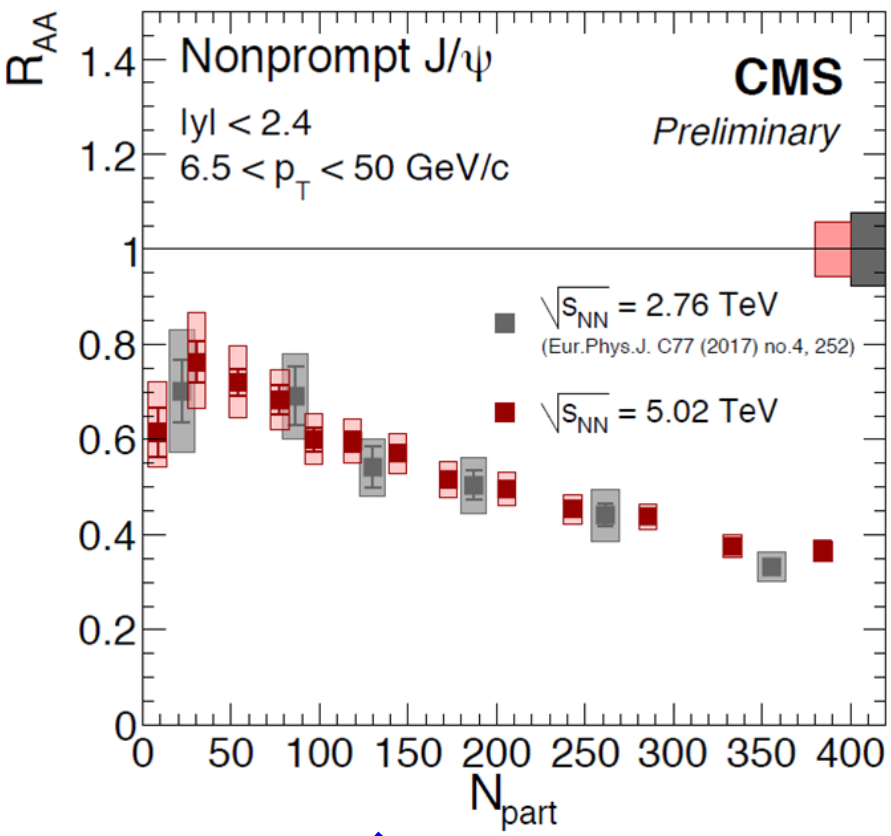




The two effects cancel!

Comparison with the experimental data

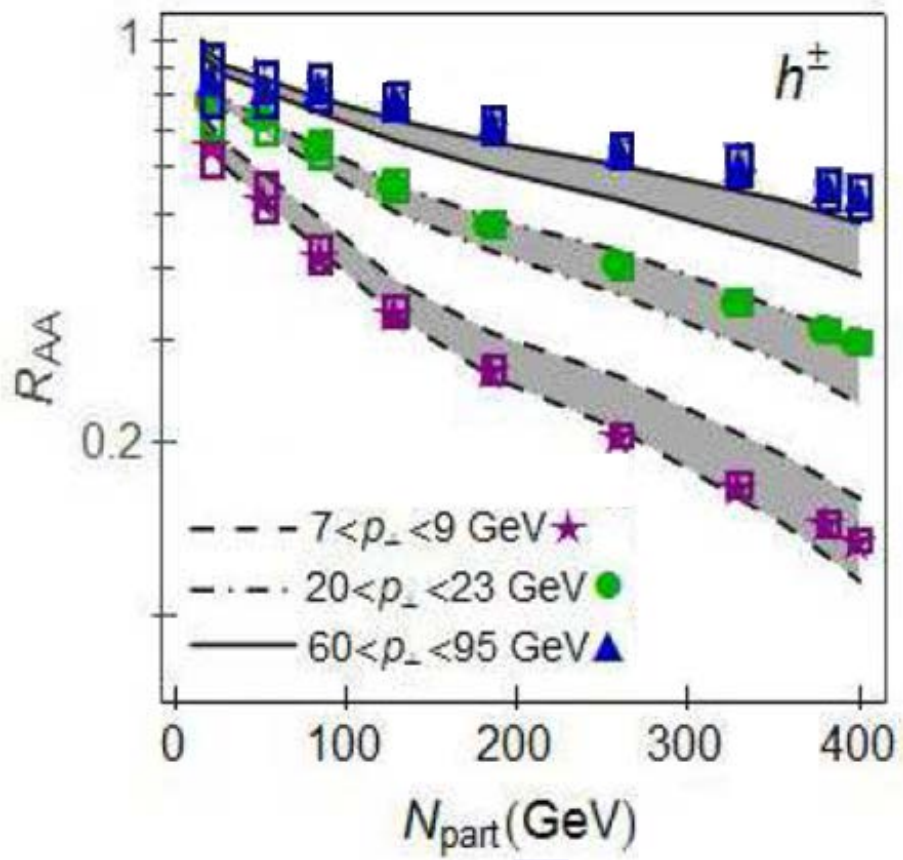


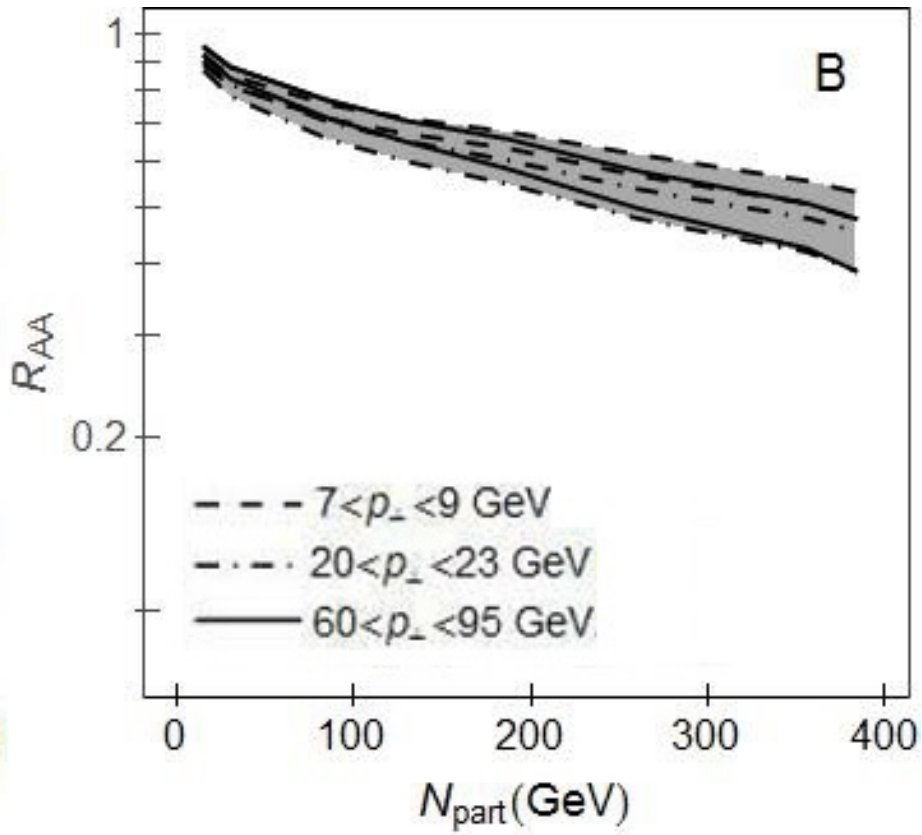


The predicted overlap between 5.02 TeV and 2.76 TeV subsequently confirmed by the data

Suppression patterns for heavy probes

MD, PLB 763, 439 (2016)

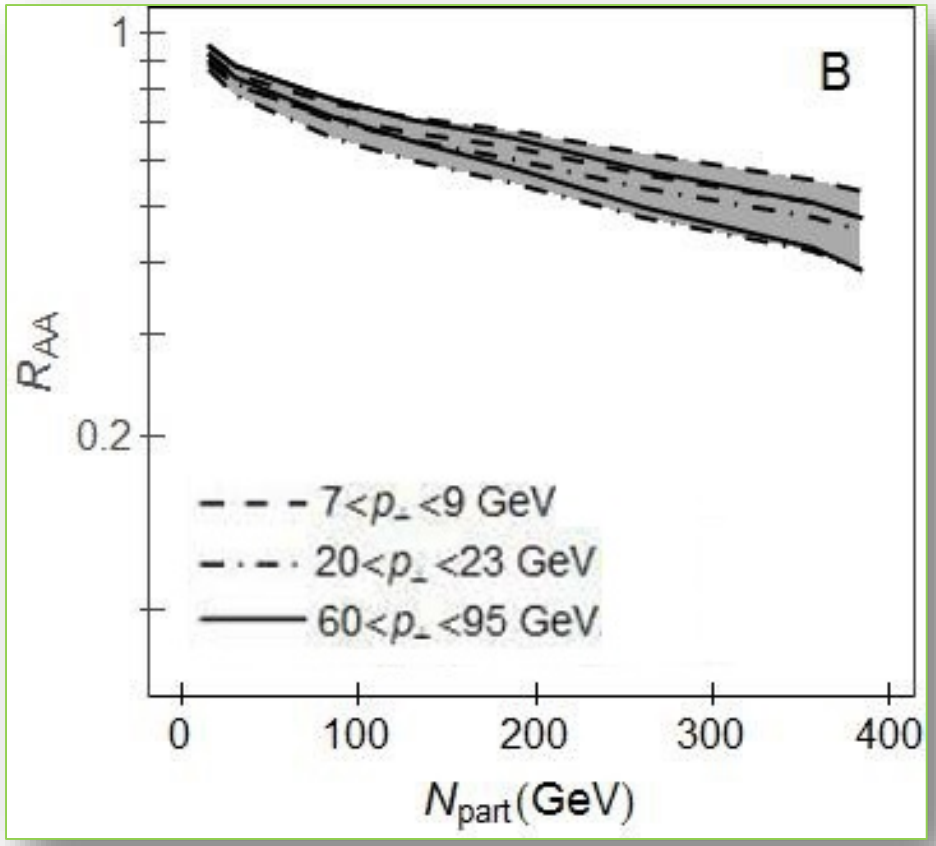




Distinct R_{AA} *vs.* N_{part} for light probes (flattening with increasing *pt* range).

We predict: *The same* R_{AA} *vs.* N_{part} for beauty probes (independently on the *pt* range).

I. Overlap of $R_{AA}(N_{part})$ for different momentum regions



MD, PLB 763, 439 (2016)

Outlook for the future experiments

(also an additional test of radiative and collisional energy loss contributions)

Summary

Dynamical energy loss formalism

Predictions for wide range of probes, centralities and beam energies

By the same model and parameter set, no fitting parameters introduced

Good agreement with existing data

Good agreement with subsequent measurements

Unituitive predictions for future experiments

Beauty provides unique opportunity to qualitatatively distinguish between collisional and radiative energy loss and assess the nature of high-pt interctions with QGP.