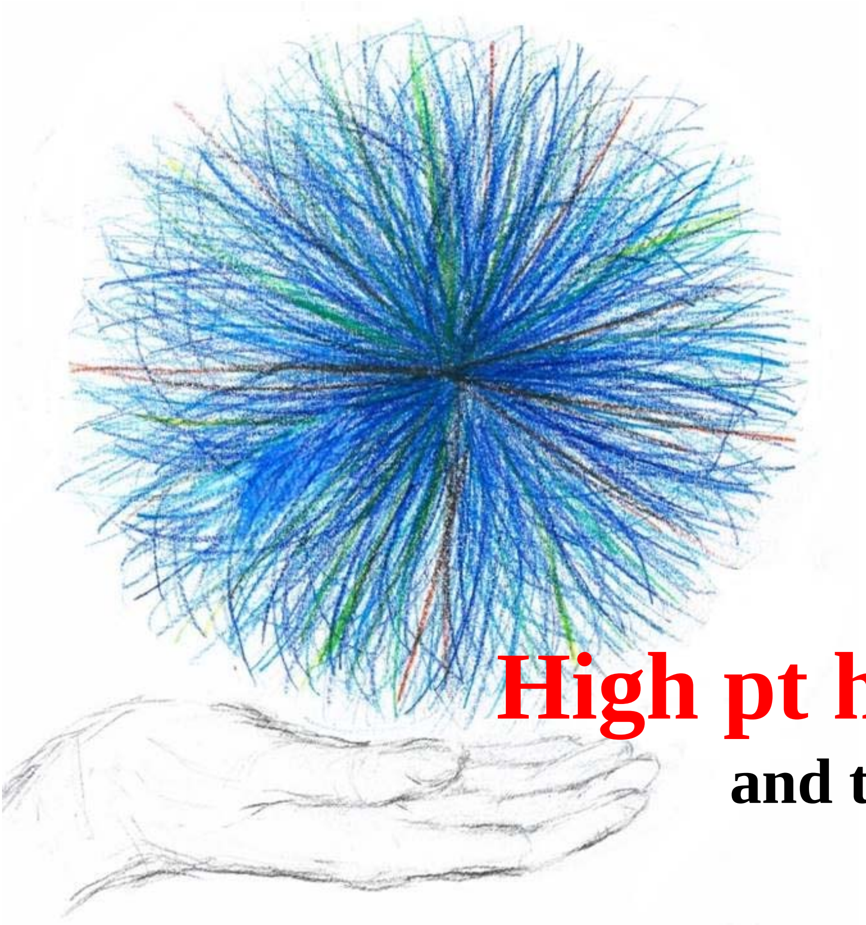


High pt heavy flavor suppression

and the dynamical energy loss formalism

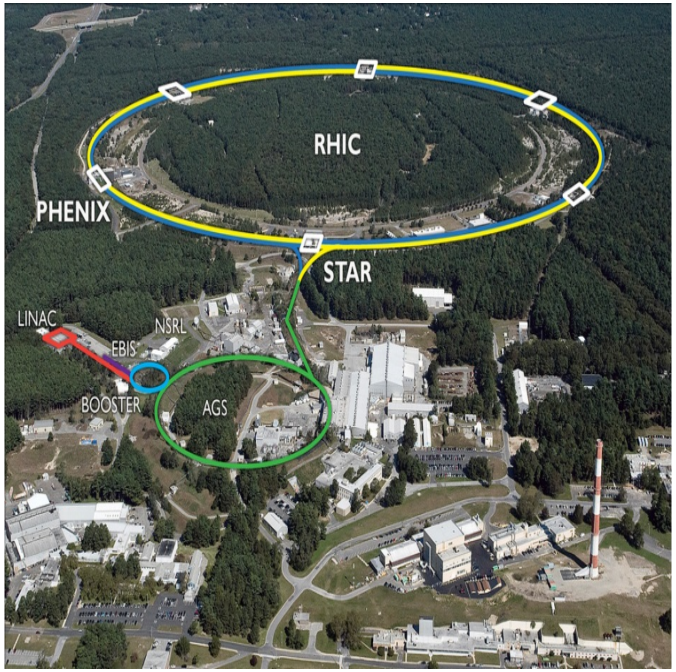
Magdalena Djordjevic,

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

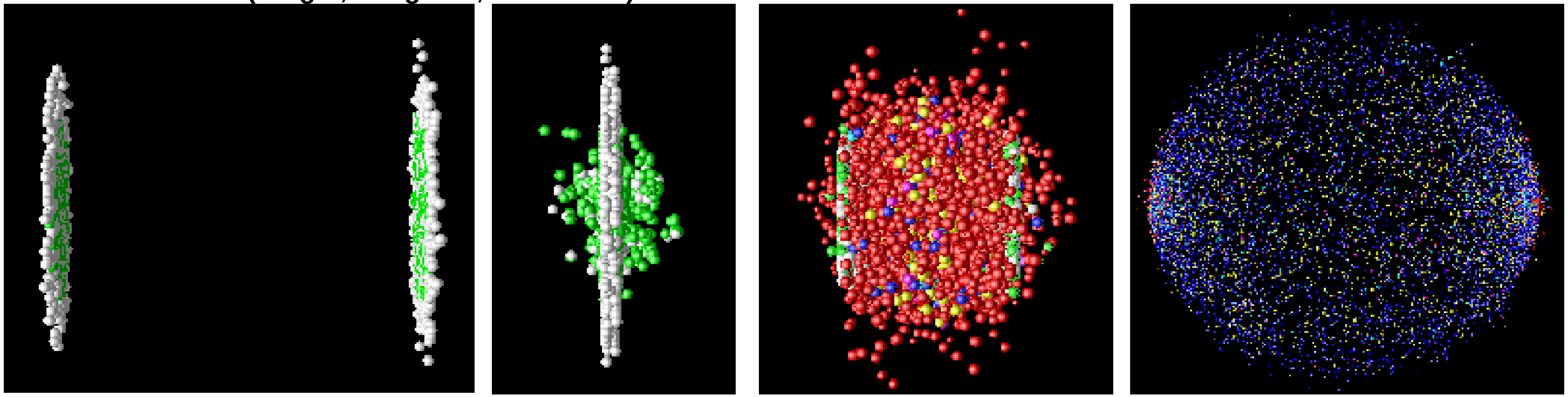
Little Bangs at LHC and RHIC



- 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)



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**

Suppression
– a traditional probe of QCD matter

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

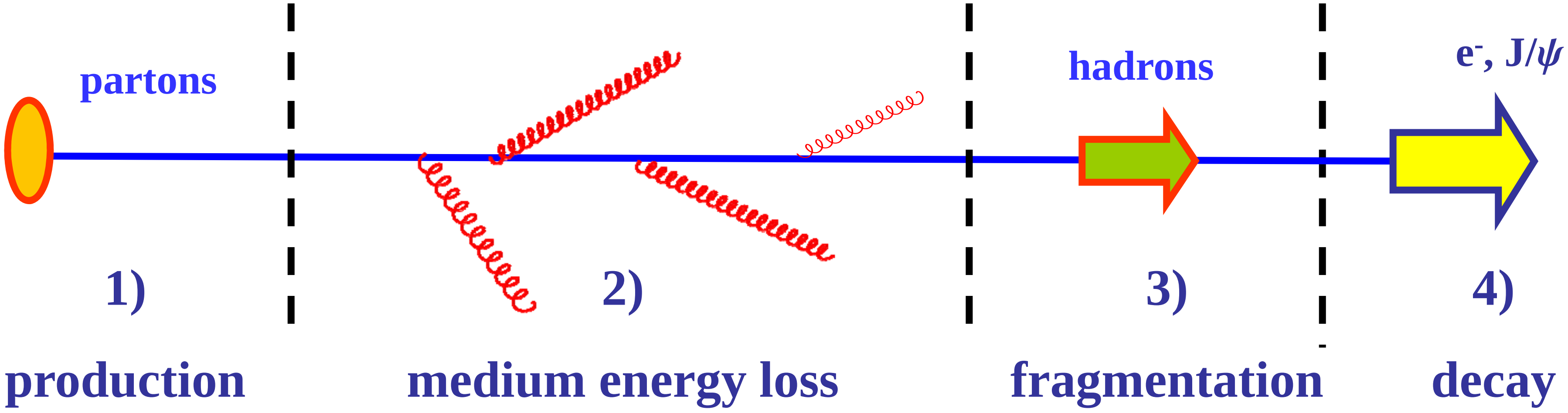
⬇

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.

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.

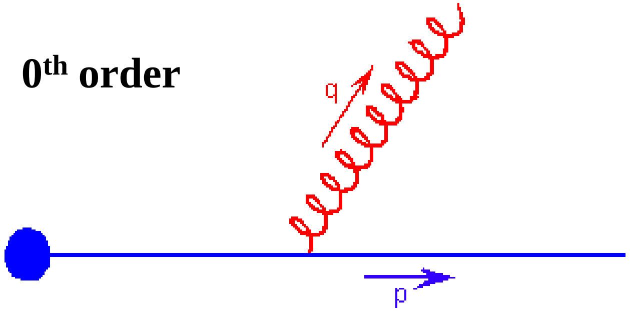
How different steps in the suppression scheme, and different energy loss mechanisms, reflect on measured suppression observables?

Energy loss in QGP

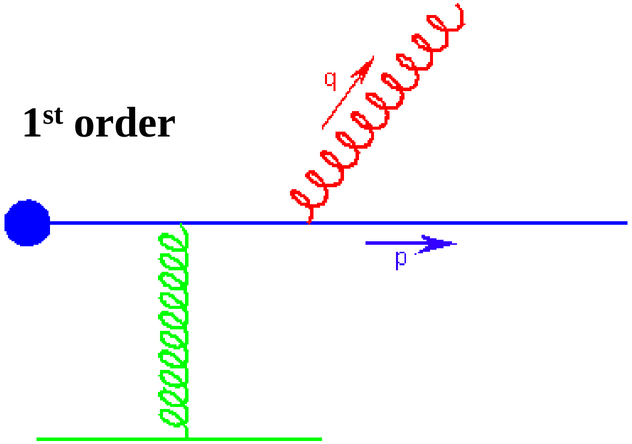
Radiative energy loss

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

0th order



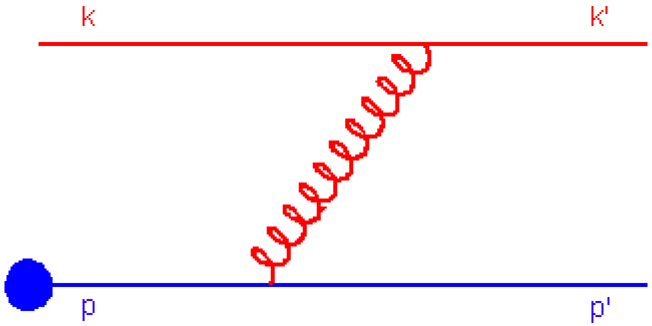
1st order



Collisional energy loss

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

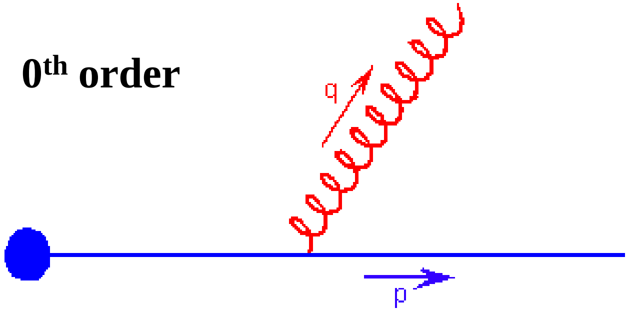
0th order



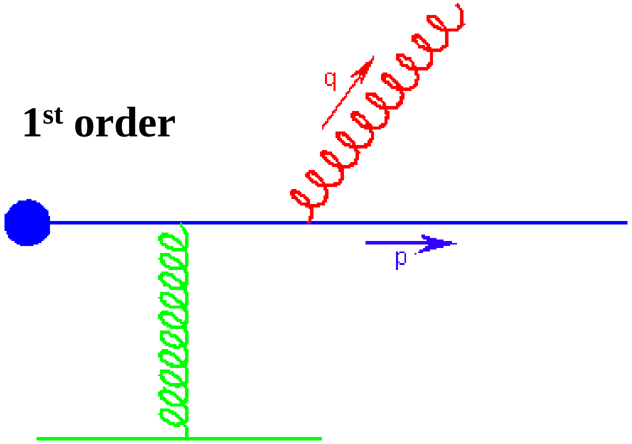
Radiative energy loss

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

0th order



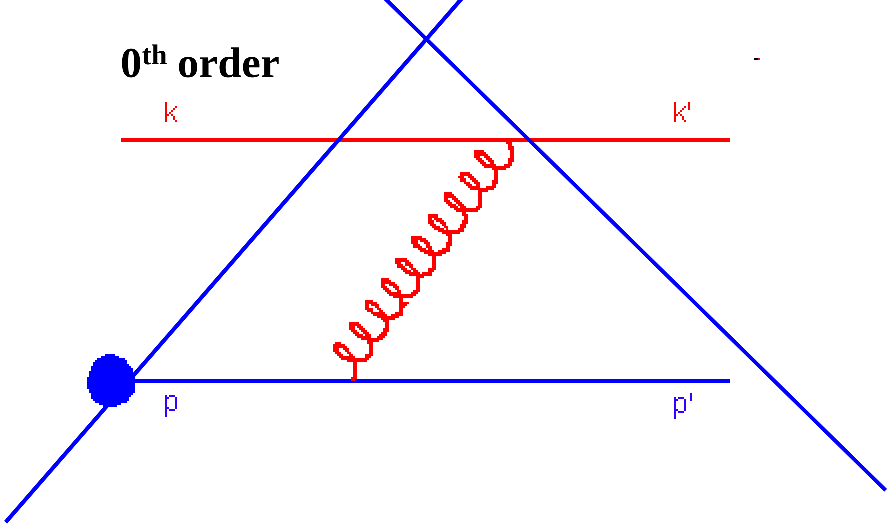
1st order



Collisional energy loss

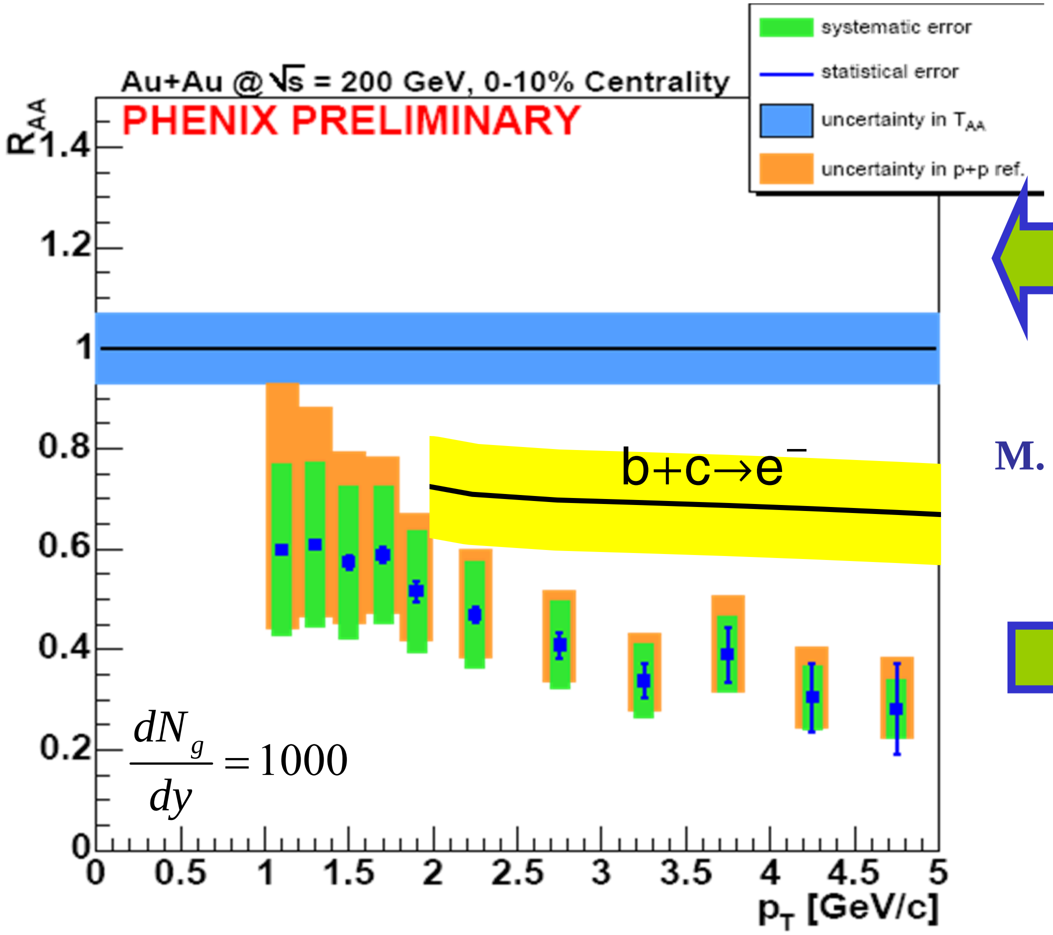
~~Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:~~

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!

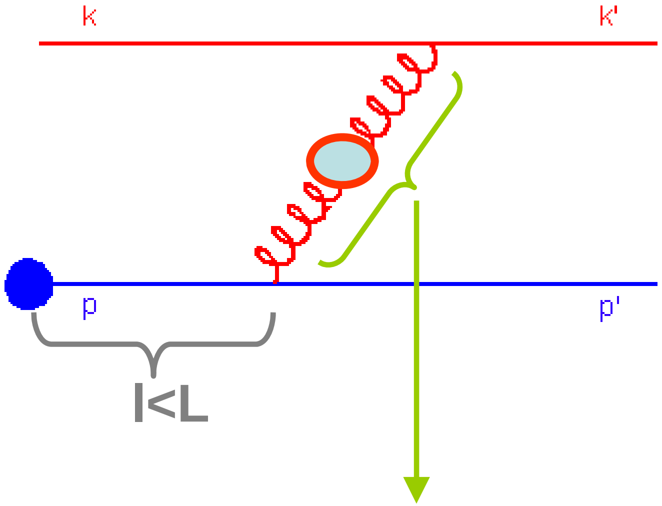
Does the radiative energy loss control the energy loss in QGP?

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:

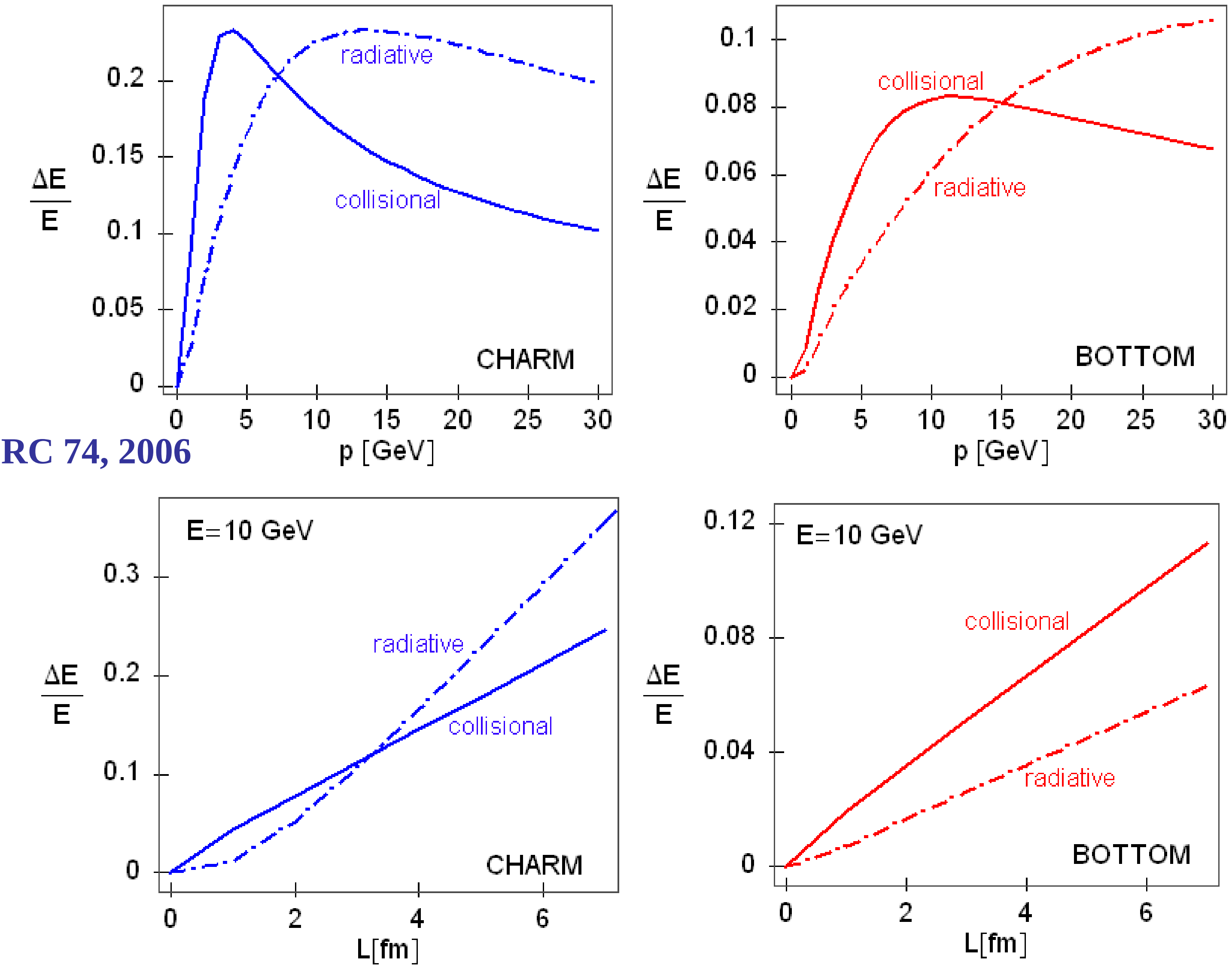


The effective gluon propagator:

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

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!

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.**

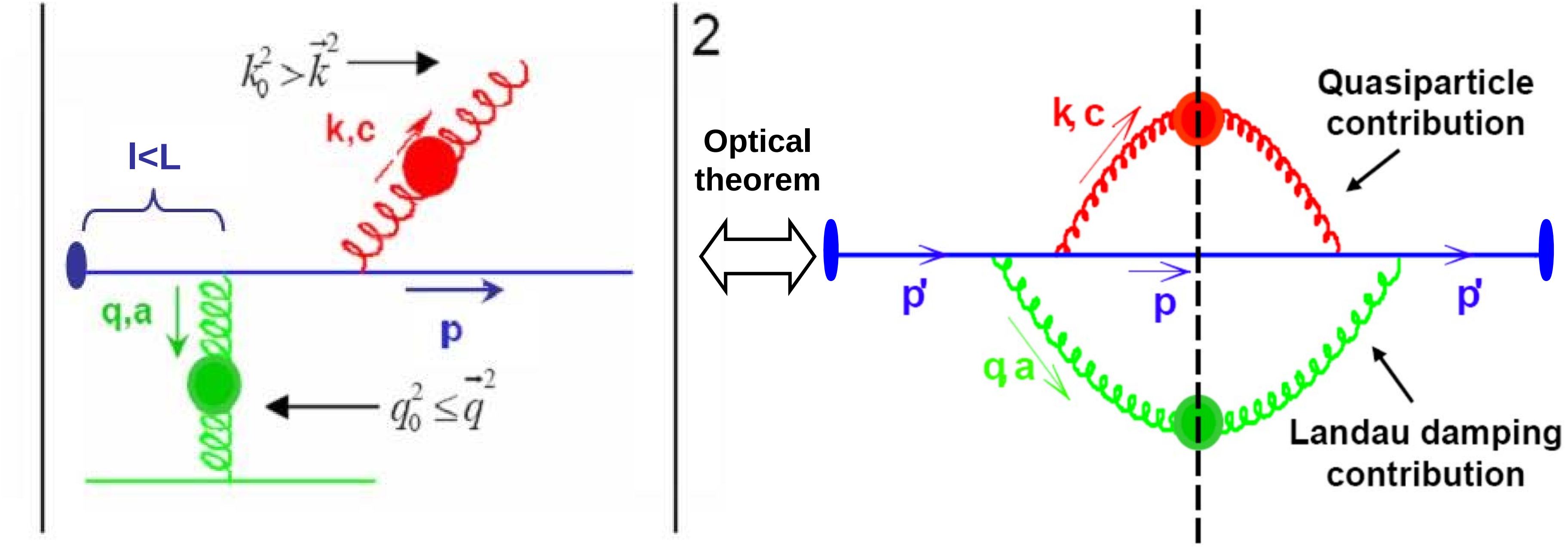
M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

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:

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

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

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

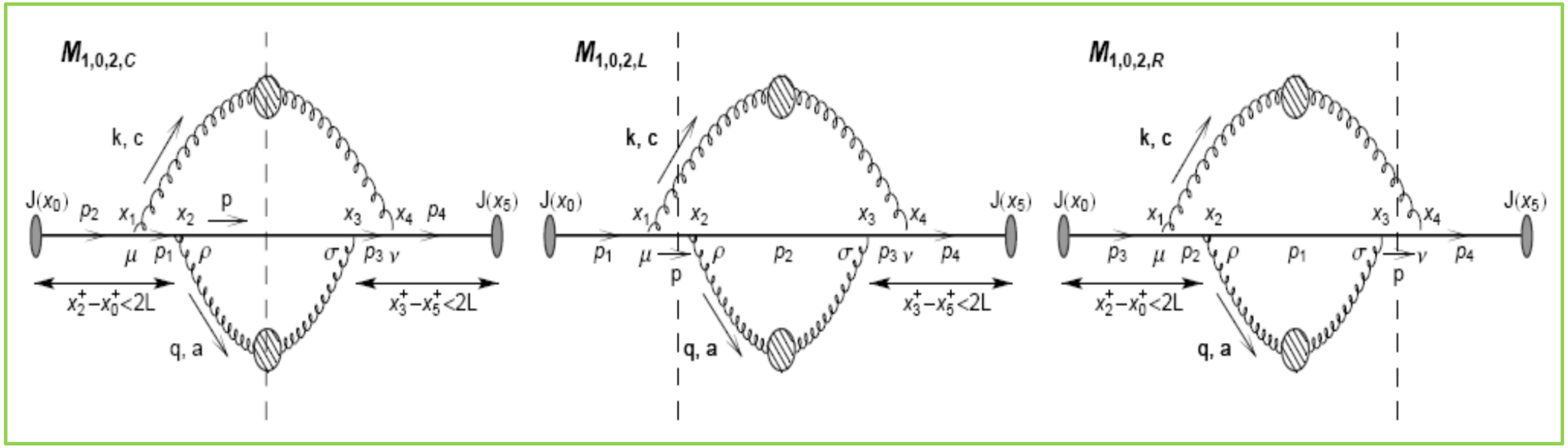
$$D^>_{\mu\nu}(k) \approx -2\pi\frac{P_{\mu\nu}(k)}{2\omega}\delta(k_0-\omega)$$

$\omega \approx \sqrt{\vec{k}^2+m_g^2}$; $m_g \approx \mu/\sqrt{2}$

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

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

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.

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

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

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

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** $0.4 \le \dfrac{\mu_M}{\mu_E} \le 0.6$**.**

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

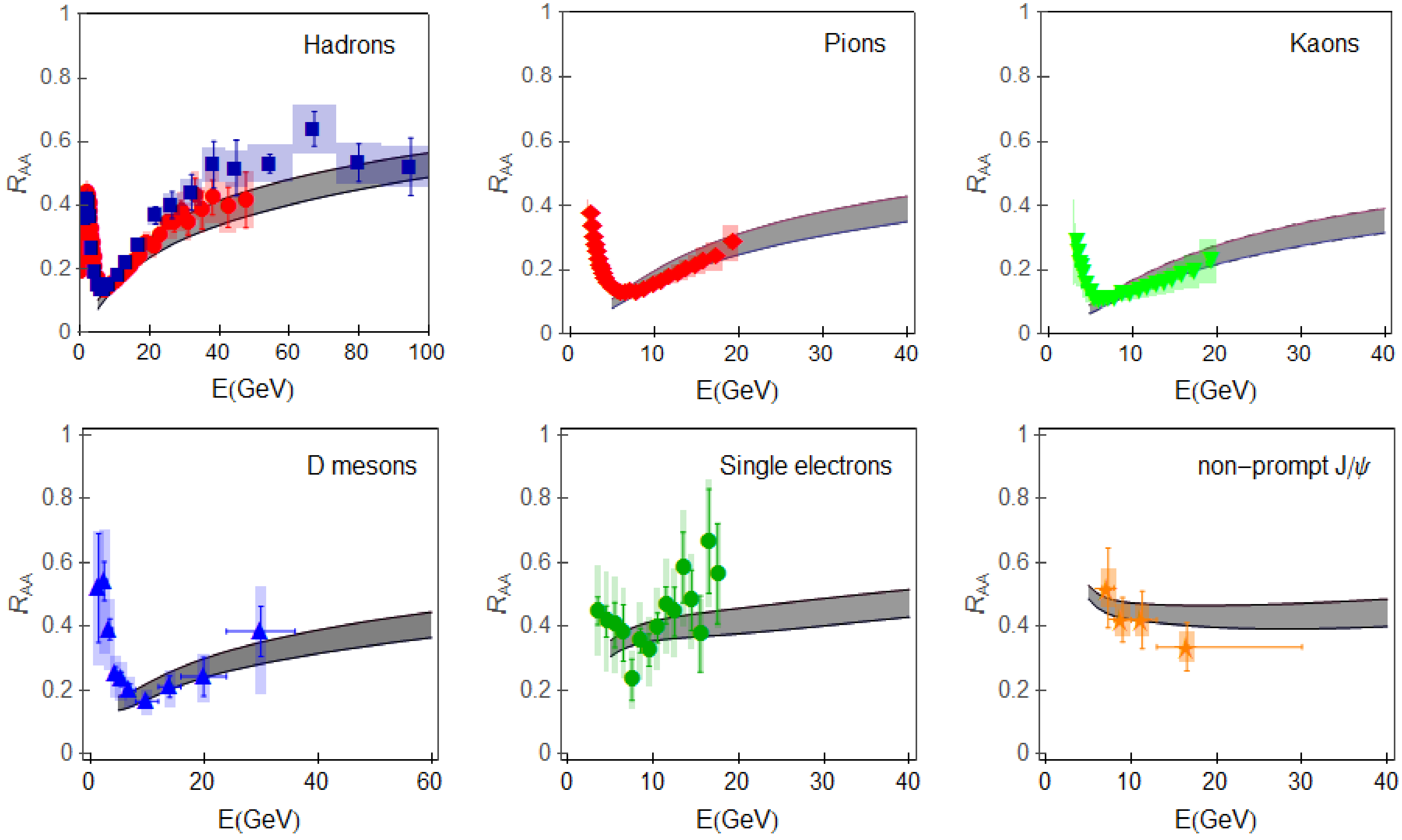
- **No fitting parameters**
- **Treats both light and heavy flavor partons**

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)

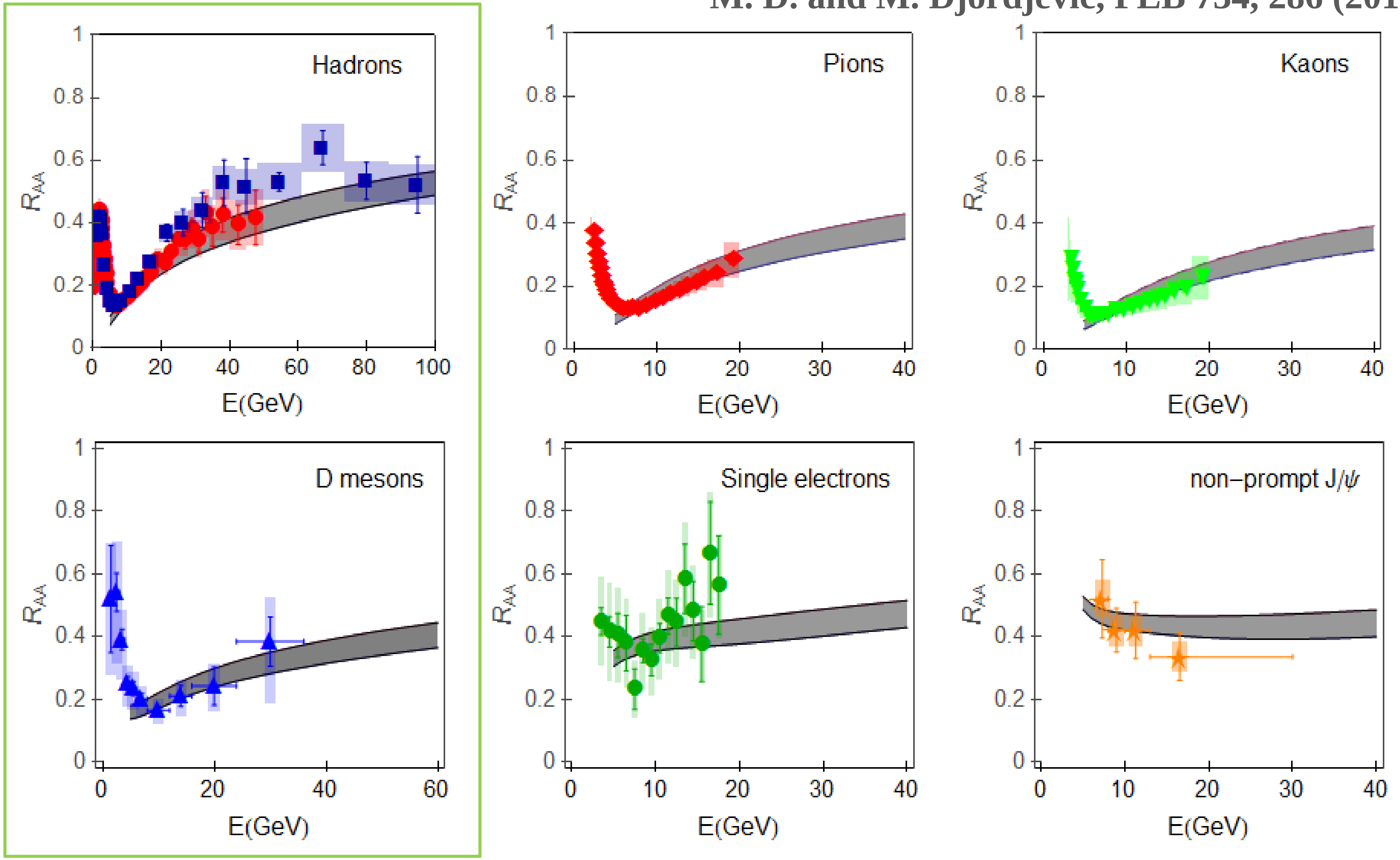
M. D. and M. Djordjevic, PLB 734, 286 (2014)



Very good agreement with diverse probes!

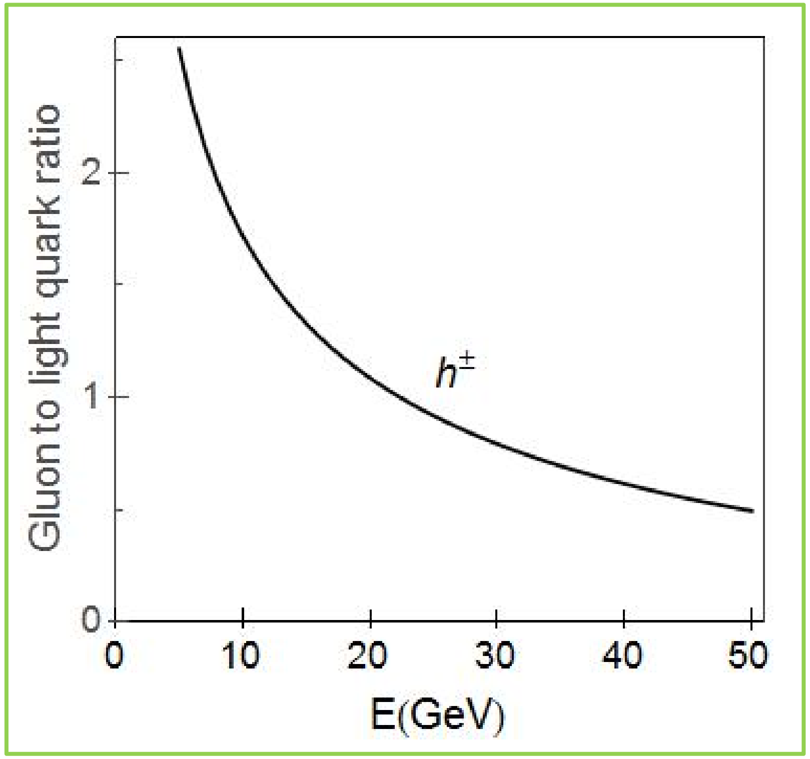
Comparison with Run 1 LHC data (central collisions)

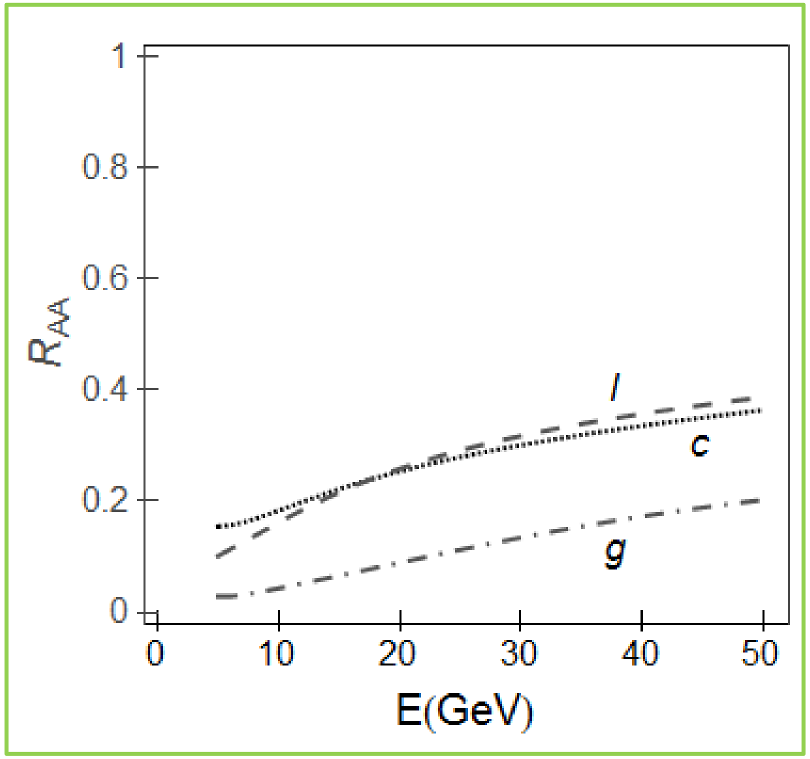
M. D. and M. Djordjevic, PLB 734, 286 (2014)



Very good agreement with diverse probes!

Heavy flavor puzzle at LHC



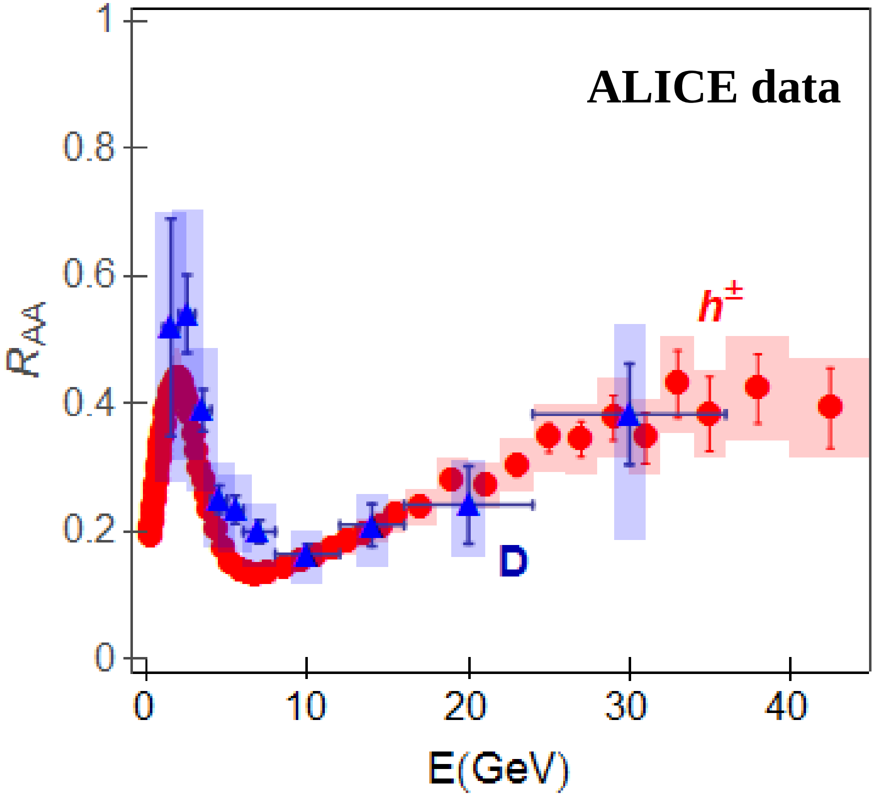


Significant gluon contribution in charged hadrons

Much larger gluon suppression

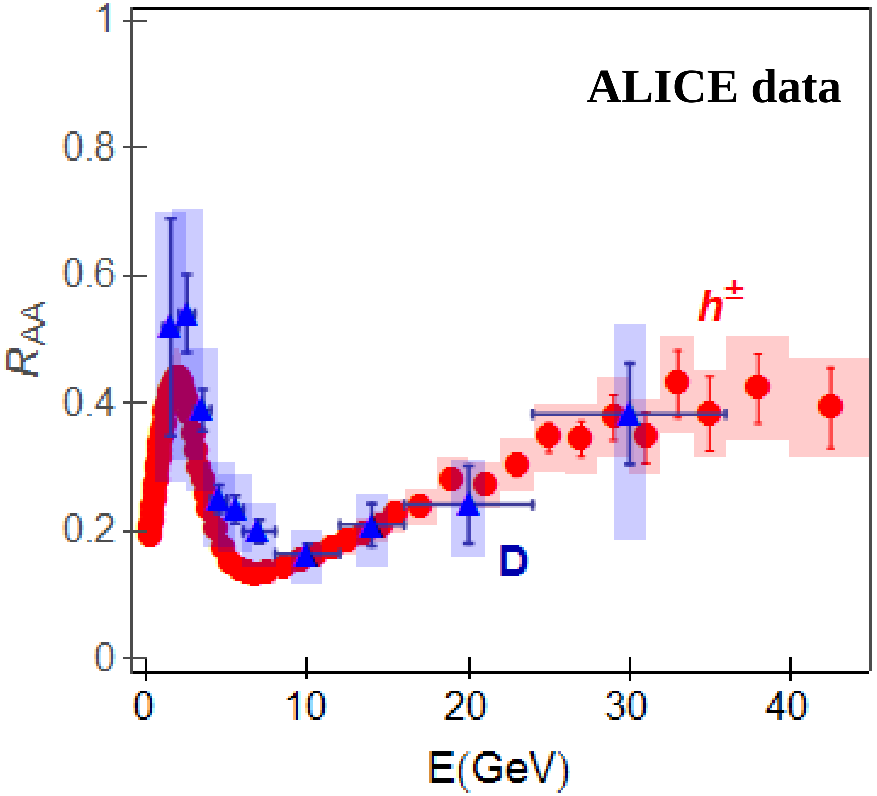
$R_{AA}\,(h^{\pm}) < R_{AA}\,(D)$

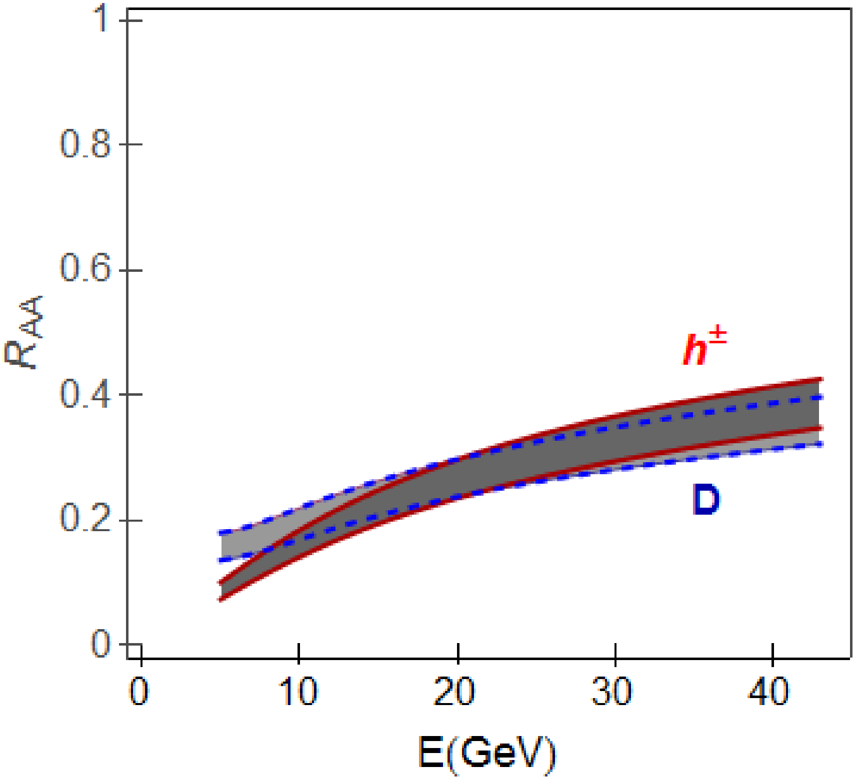
Charged hadrons vs D meson R_{AA}



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

Charged hadrons vs D meson R_{AA}





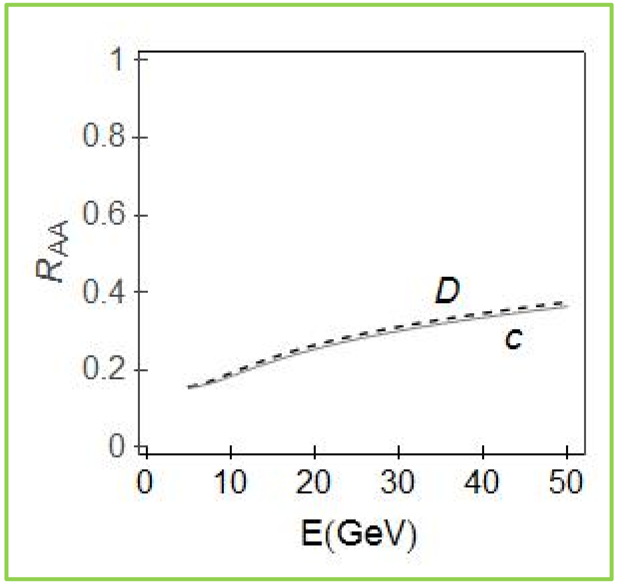
$R_{AA}(h^{\pm}) = R_{AA}(D)$

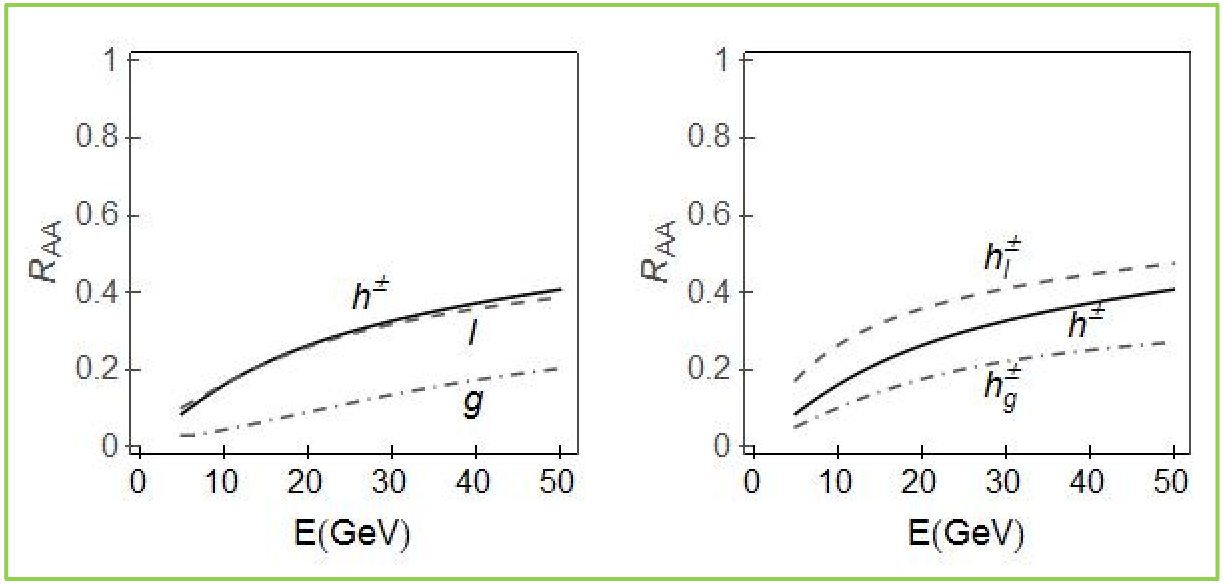
Excellent agreement with the data!

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

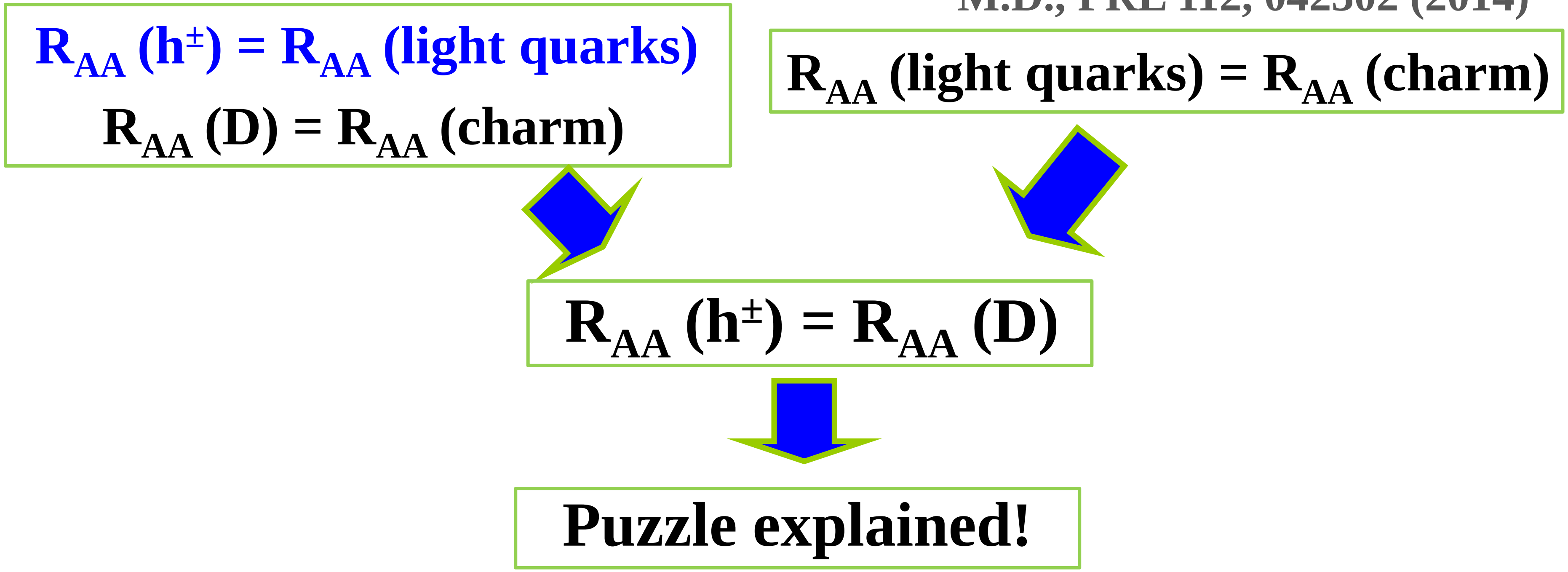
Distortion by fragmentation

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

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

Puzzle summary

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



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

$R_{AA}(D) = R_{AA}(\text{charm})$

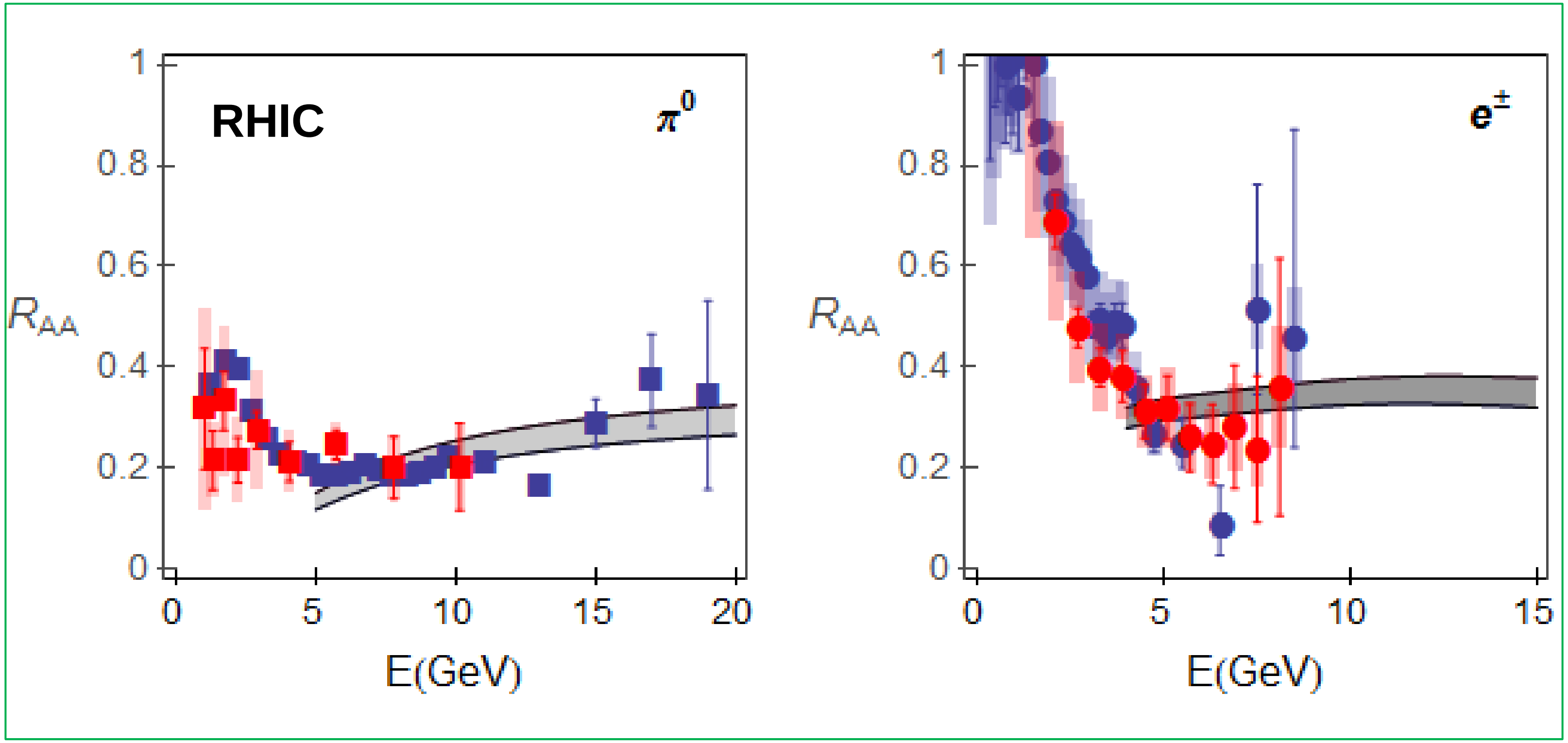
$R_{AA}(\text{light quarks}) = R_{AA}(\text{charm})$

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

Puzzle explained!

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

Interplay of energy loss and fragmentation also @ RHIC

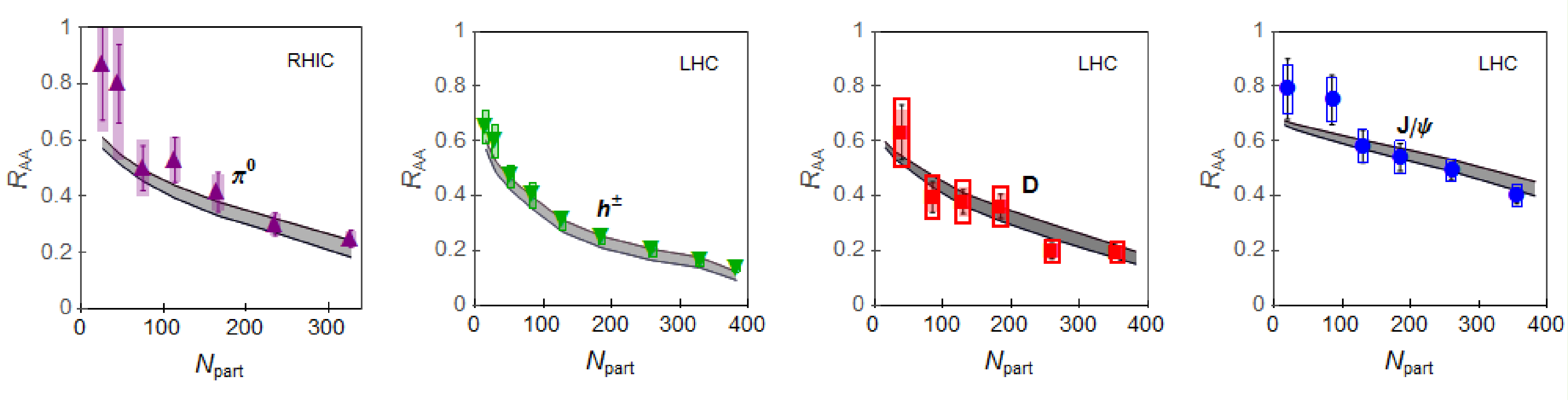


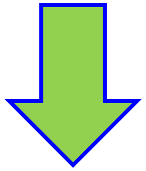
Very good agreement of the dynamical energy loss predictions with the data!

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

Non-central collisions

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

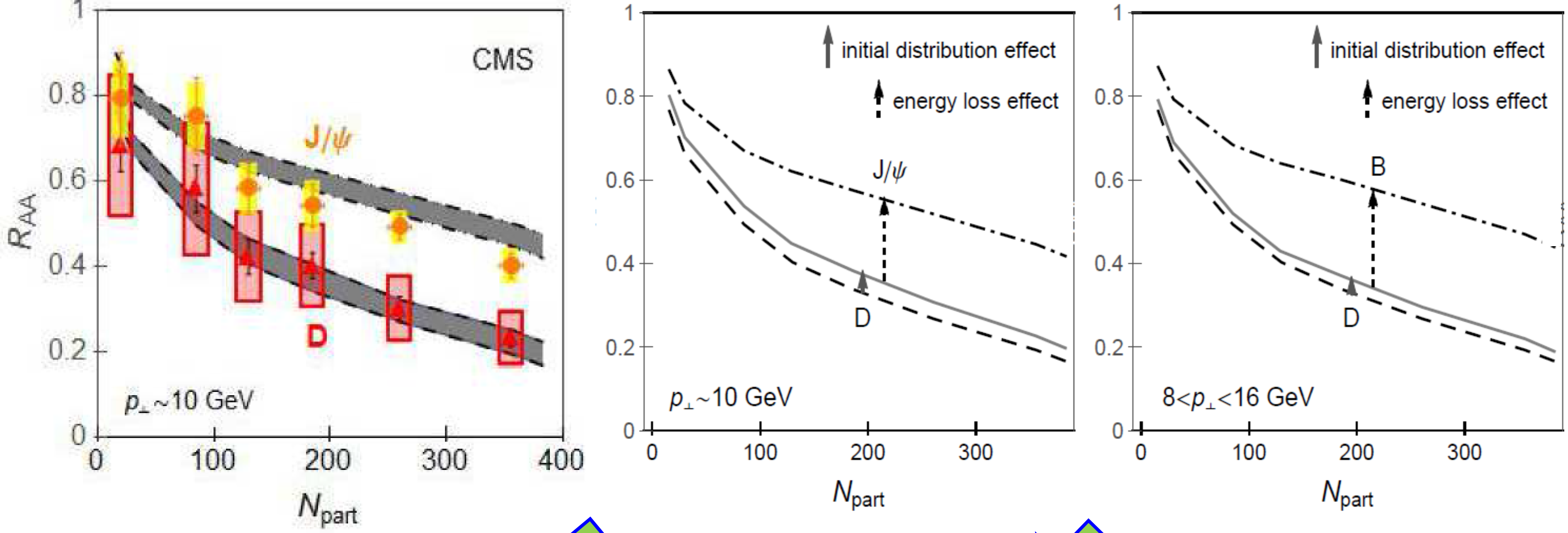




Excellent agreement of the dynamical energy loss for both RHIC and LHC and for the whole set of probes!

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

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



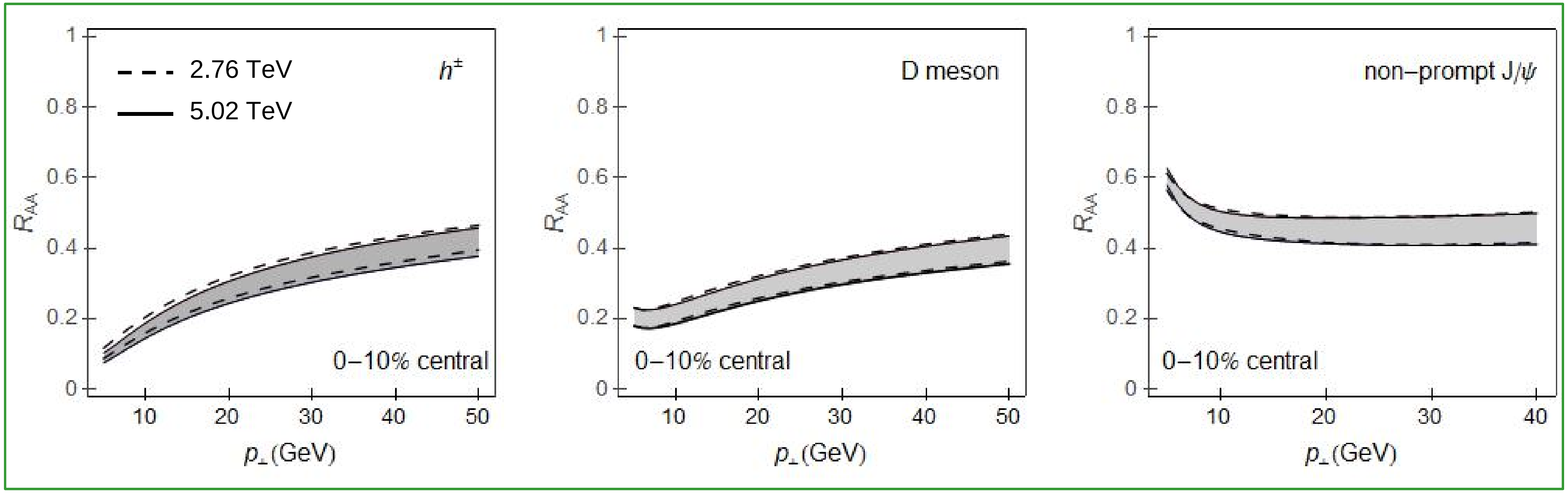
Differences in the heavy flavor RAA are a consequence of the “dead-cone” effect.

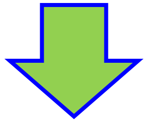
Comparison with most recent experimental data, proposing further experimental tests

- First, show the predictions which were published before the data became available.
- Next, compare these predictions with the most recent experimental data.

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

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



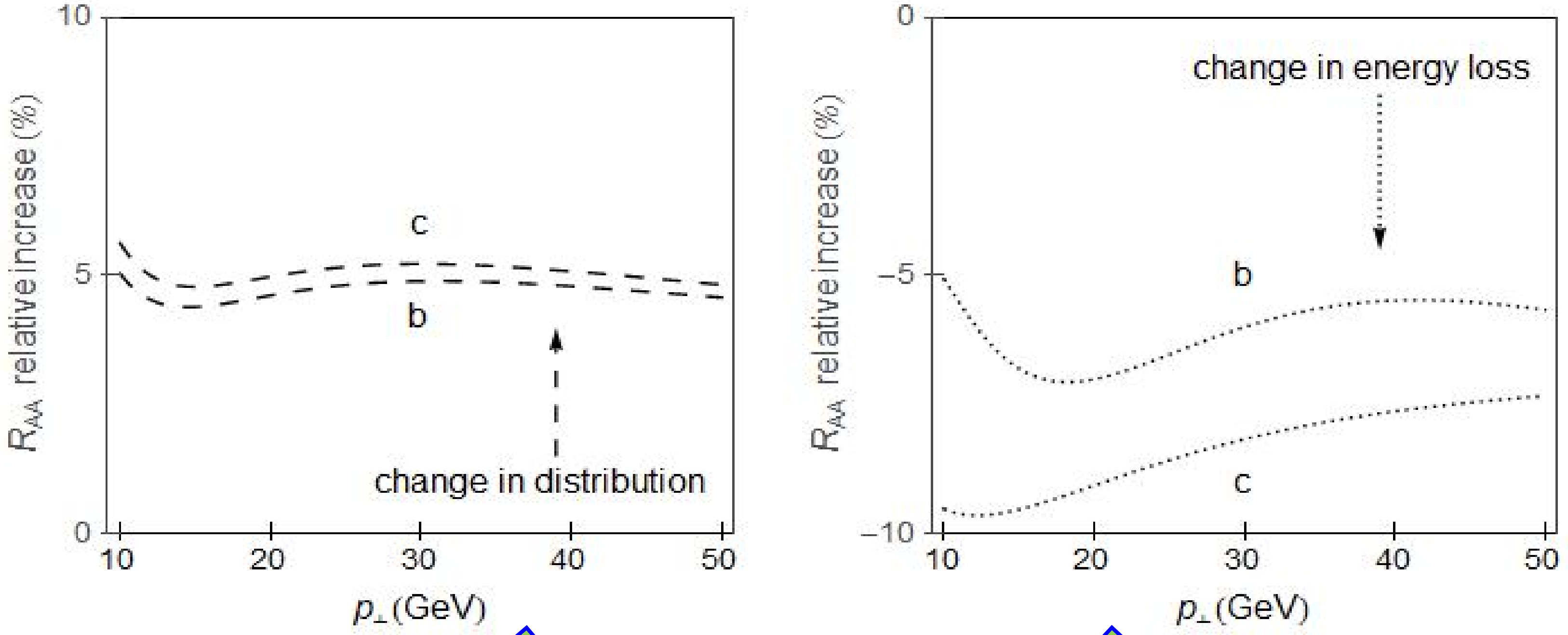


The same suppression predicted at 5.02 TeV and 2.76 TeV for all types of probes!

Why the same suppression?

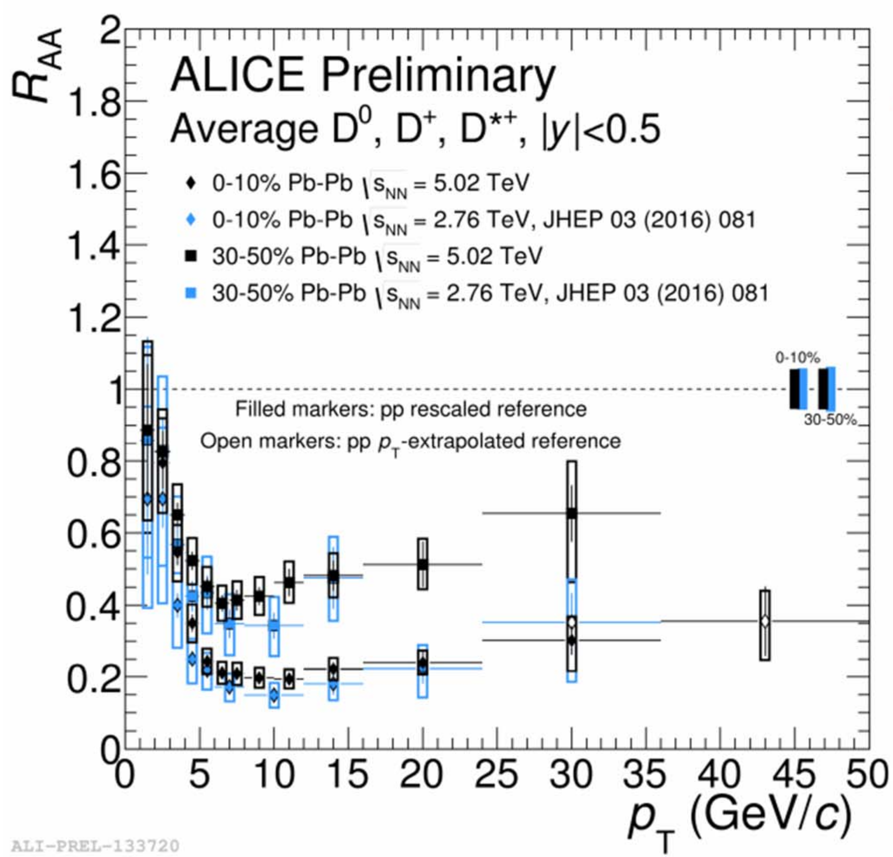
An interplay between initial distribution and energy loss effects.

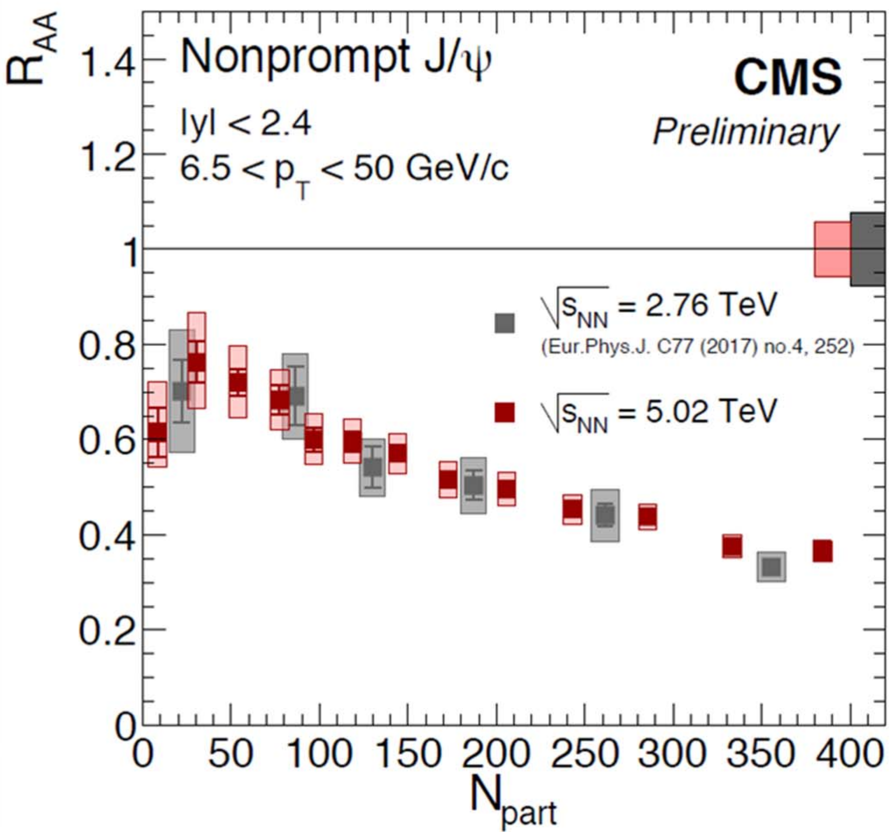
M. D. and M. Djordjevic, PRC 92, 024918 (2015)



The two effects cancel!

Comparison with the experimental data

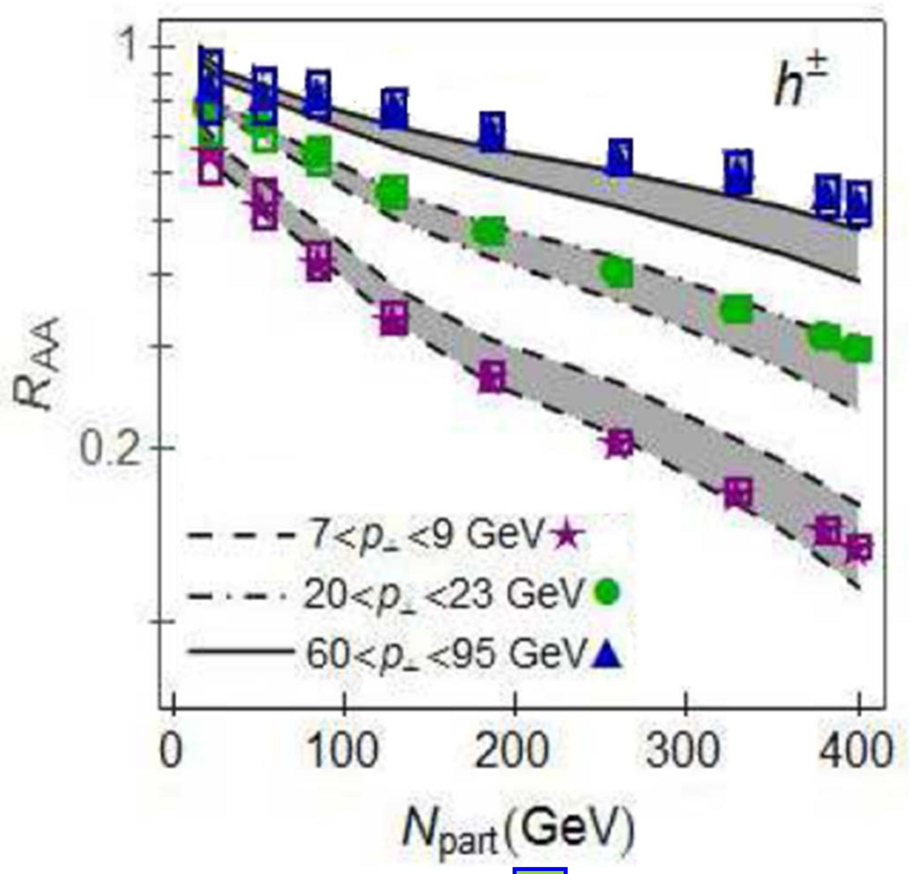


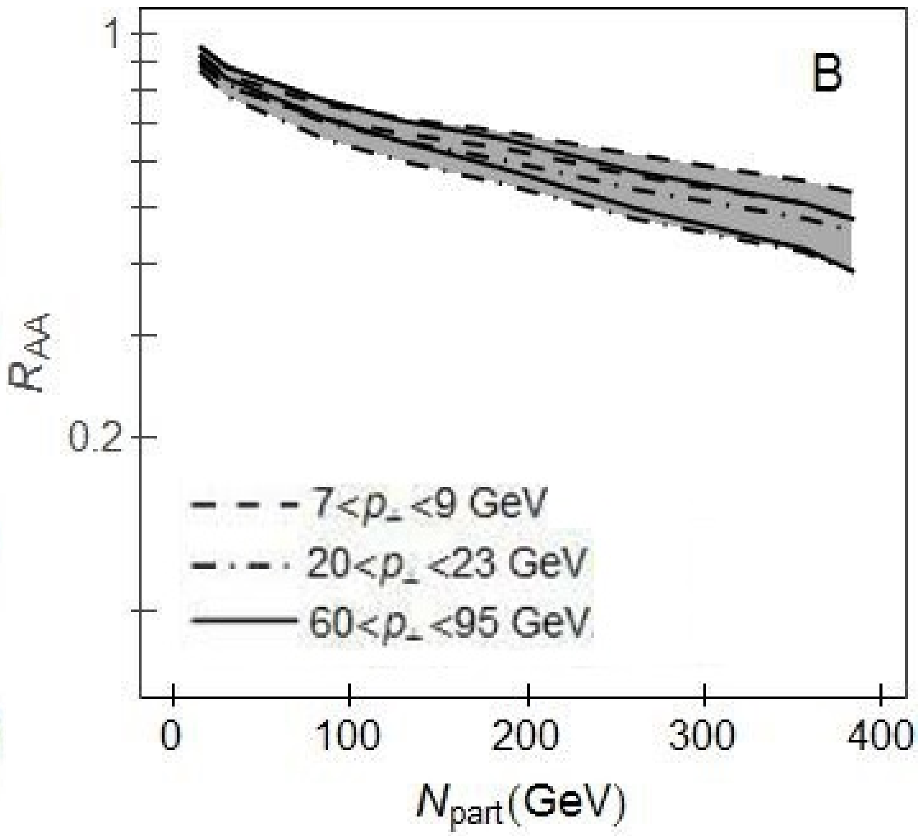


The predicted overlap between 5.02 TeV and 2.76 TeV subsequently confirmed by the data

Suppression patterns for heavy probes

MD, PLB 763, 439 (2016)

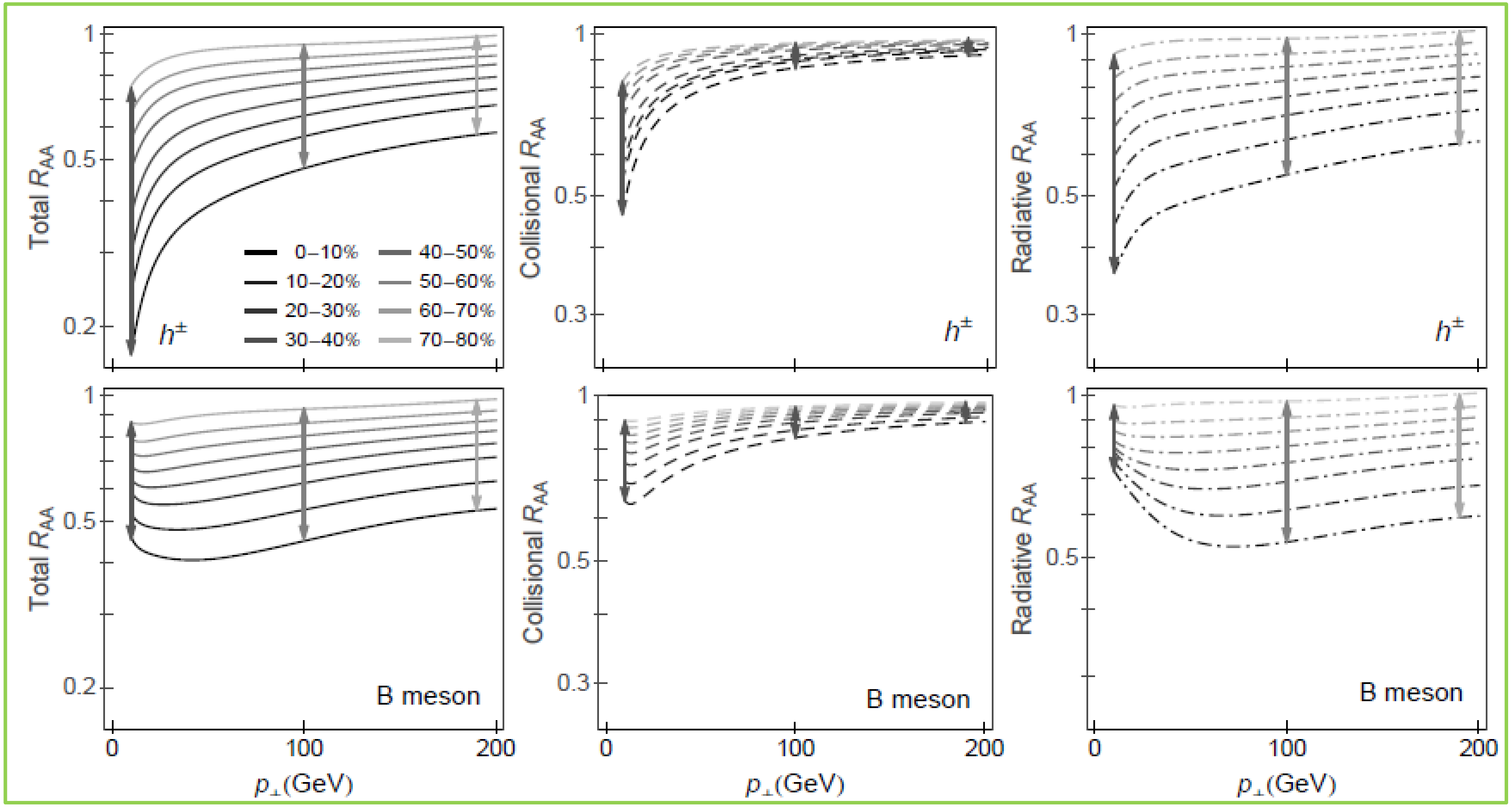




Distinct R_{AA} vs. N_{part} for light probes (flattening with increasing *pt* range).

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

MD, PLB 763, 439, 2016



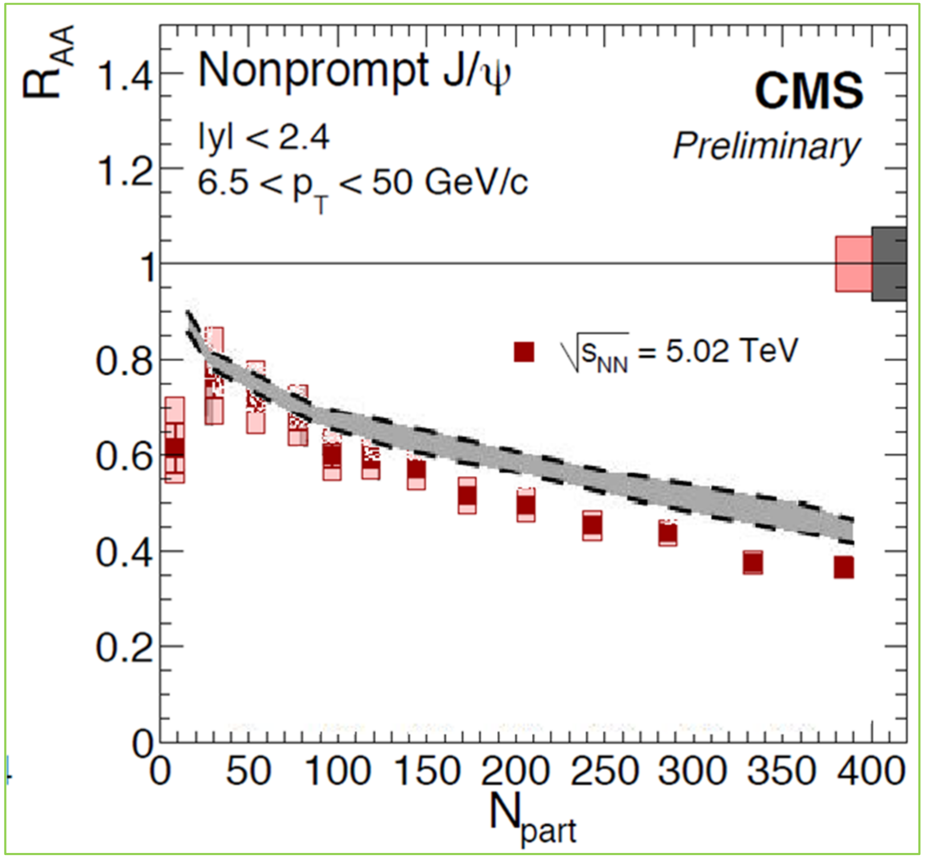
Clear qualitative separation between collisional and radiative energy loss contributions.

Three types of predictions for bottom:

I. Quantitative predictions of the suppression patterns
II. Flattening of the $R_{AA}(pt)$ data
III. Overlap of $R_{AA}(N_{part})$ for different momentum regions

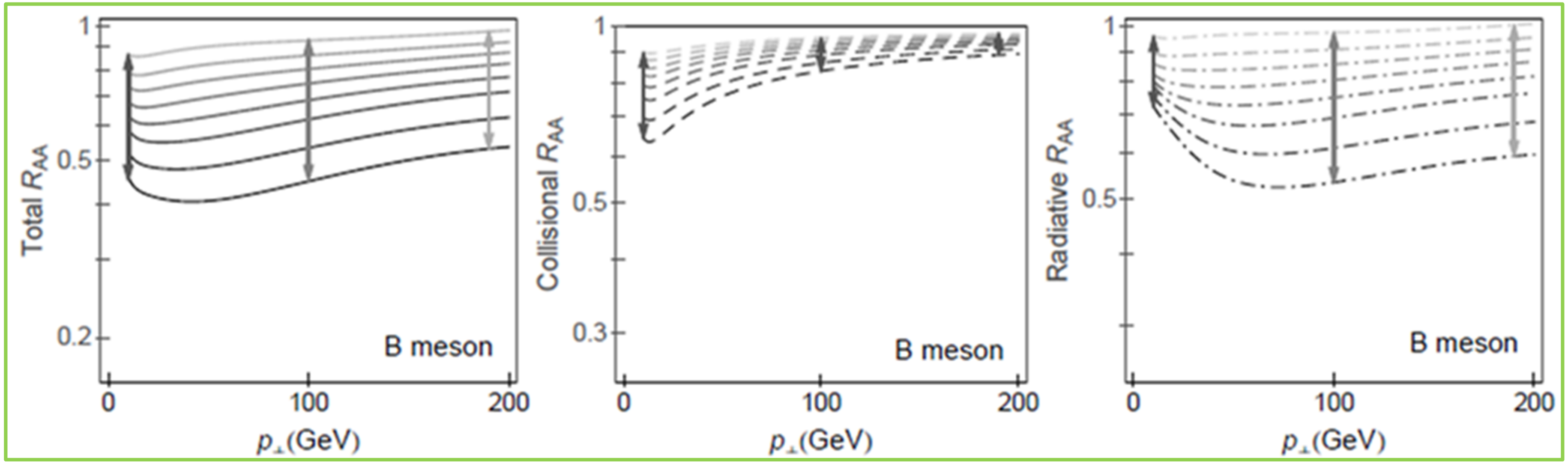
II and III are a consequence of clearly different qualitative contributions from collisional and radiative energy loss effects.

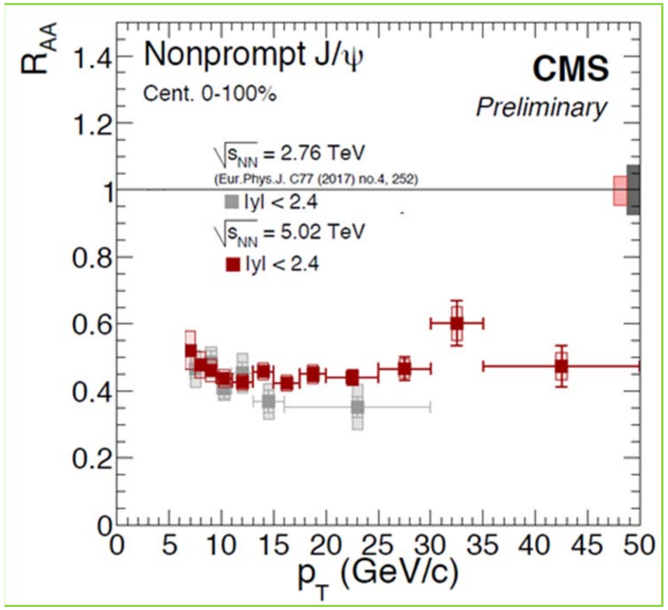
I. Quantitative predictions of the suppression patterns

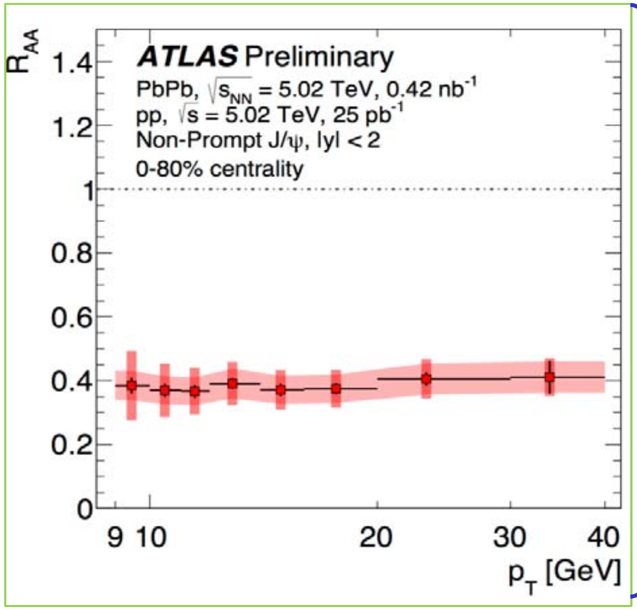


Good agreement with the data

I. Flattening of the R_{AA}(pt) data

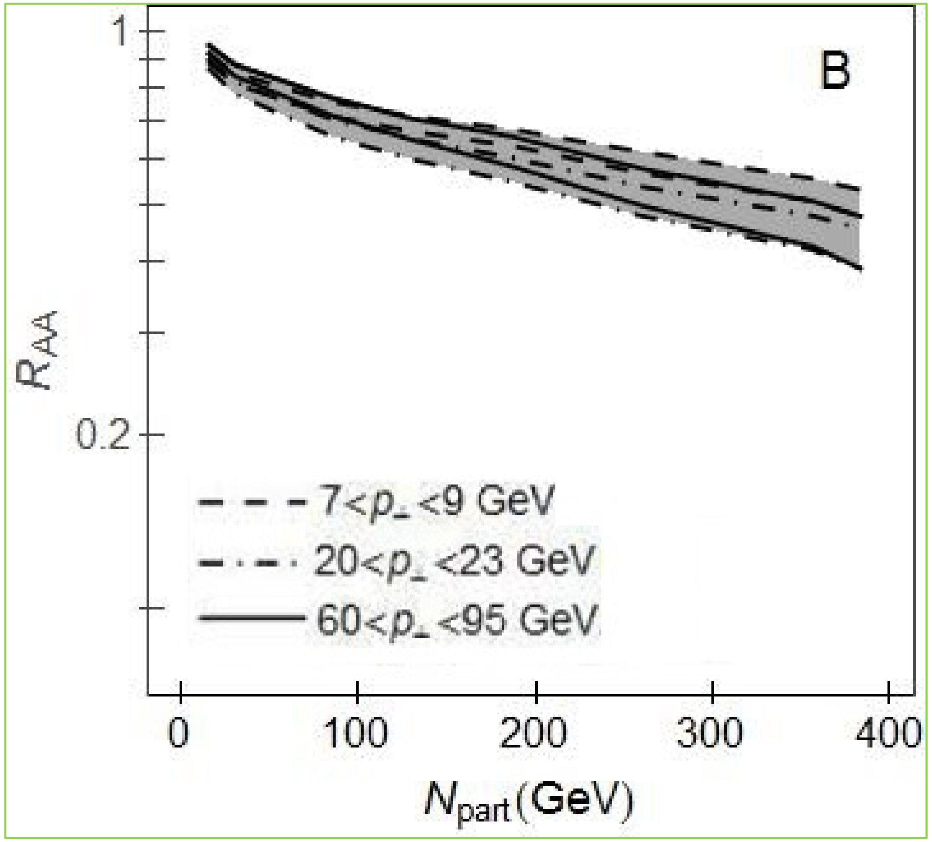






Observed by both CMS and ATLAS data

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

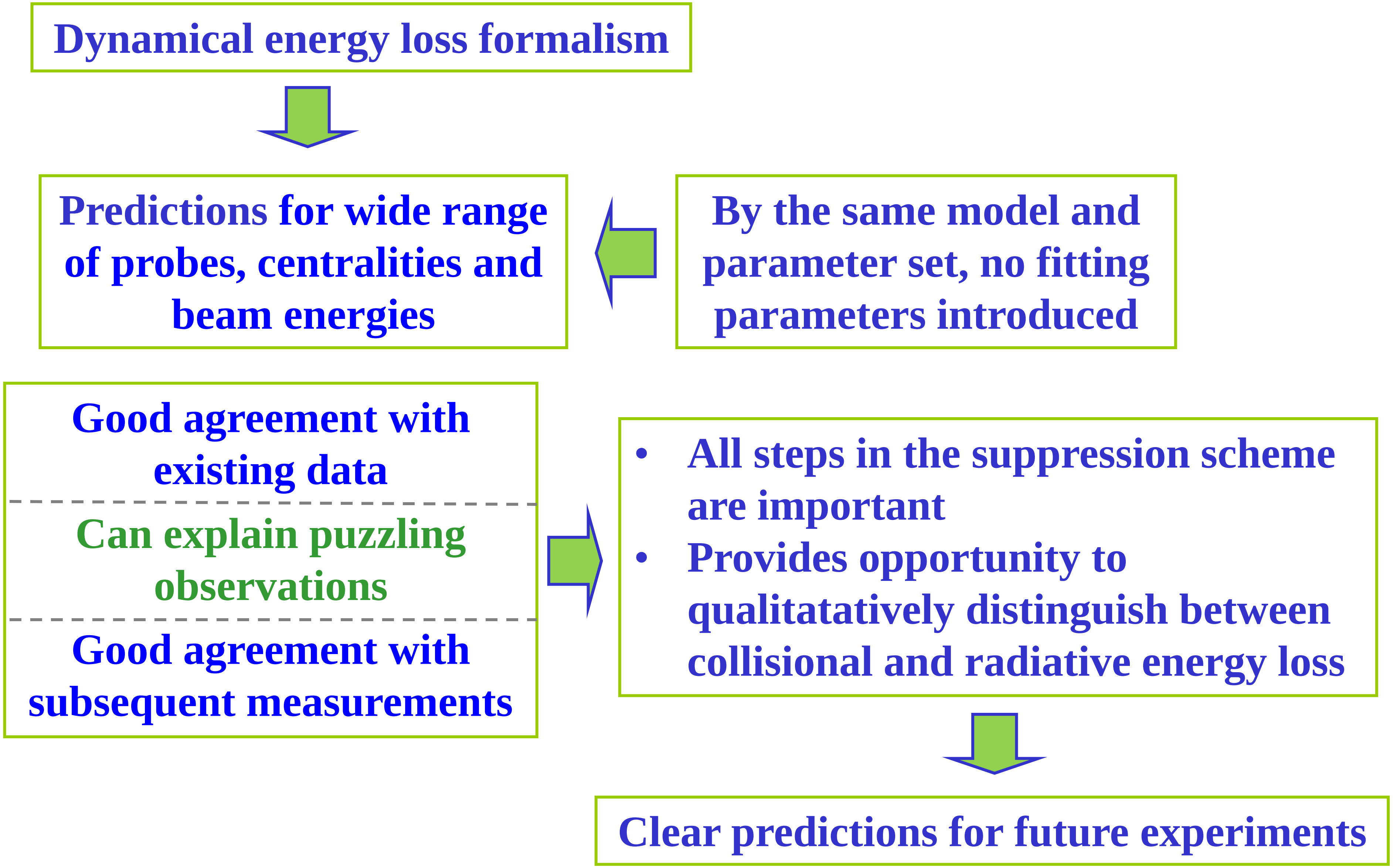


MD, PLB 763, 439 (2016)

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

Can explain puzzling observations

Good agreement with subsequent measurements

- All steps in the suppression scheme are important
- Provides opportunity to qualitatatively distinguish between collisional and radiative energy loss

Clear predictions for future experiments