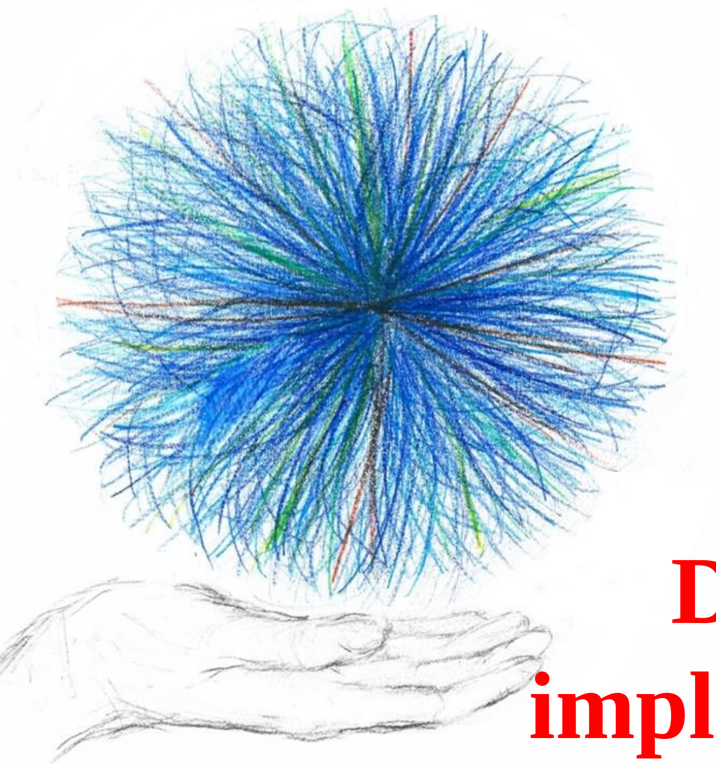


Dynamical energy loss and its implications to QGP tomography

Magdalena Djordjevic,

In collaboration with: **Dusan Zigic, Stefan Stojku, Bojana Blagojevic, Jussi Auvinen, Igor Salom, Marko Djordjevic and Pasi Huovinen**

European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Motivation

- **Energy loss of high-pt particles traversing QCD medium is an excellent probe of QGP properties.**
- **Theoretical predictions can be compared with a wide range of data, coming from different experiments, collision systems, collision energies, centralities, observables…**
- **Can be used together with low-pt theory and experiments to study the properties of created QCD medium, i.e. for precision QGP tomography.**

The dynamical energy loss formalism

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

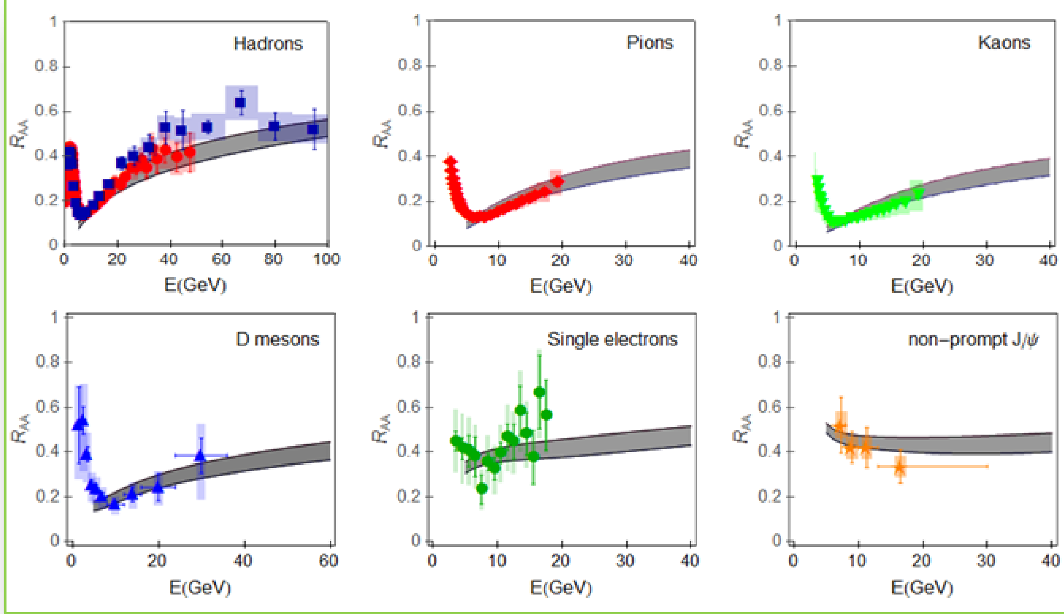
M. D., PRC74 (2006), PRC 80 (2009), M. D. and U. Heinz, PRL 101 (2008).

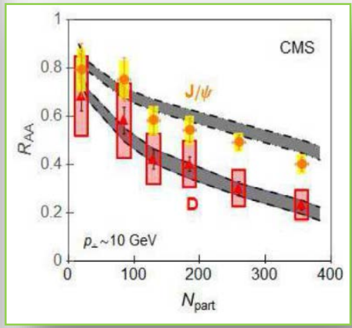
Includes:

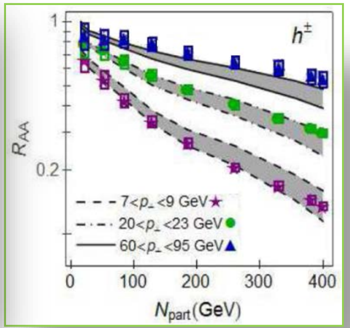
- **Same theoretical framework for both radiative and collisional energy loss**
- **Finite magnetic mass effects** **(M. D. and M. Djordjevic, PLB 709:229 (2012))**
- **Running coupling** **(M. D. and M. Djordjevic, PLB 734, 286 (2014)).**
- **Most recently: Relaxed soft-gluon approximation** **(B. Blagojevic, M.D. and M. Djordjevic, arXiv:1804.07593, talk by B. Blagojevic on Tuesday)**

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**





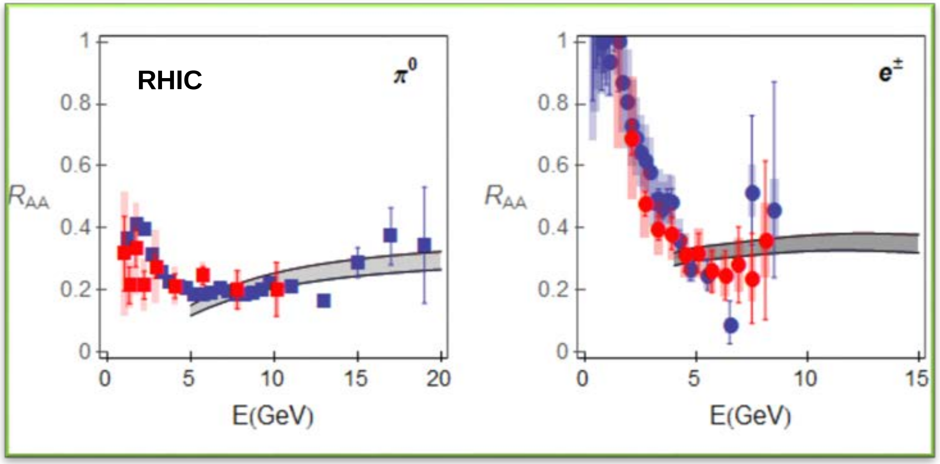


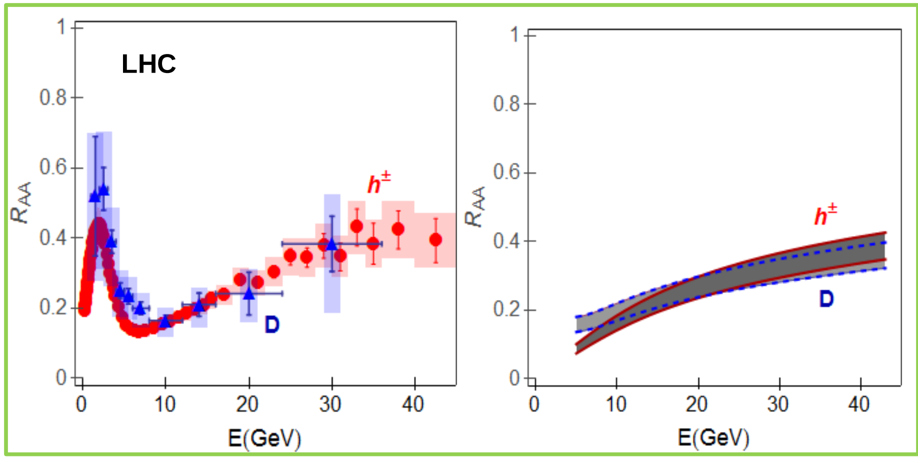
- Explains R_{AA} for different probes, collision energies, and centralities.
- Resolved the longstanding "heavy flavour puzzles at RHIC and LHC".
- Good agreement with subsequent measurements.
- Clear predictions for future experiments.
- Agreement obtained by the same model and parameter set, no fitting parameters introduced.
- All steps in the suppression scheme are important, and have to be kept in all future framework developments.

A realistic description parton-medium interactions.

However, until recently, the model did *not* include QGP evolution.

Predictions only for the observables weakly sensitive to QGP evolution (i.e. R_{AA}).





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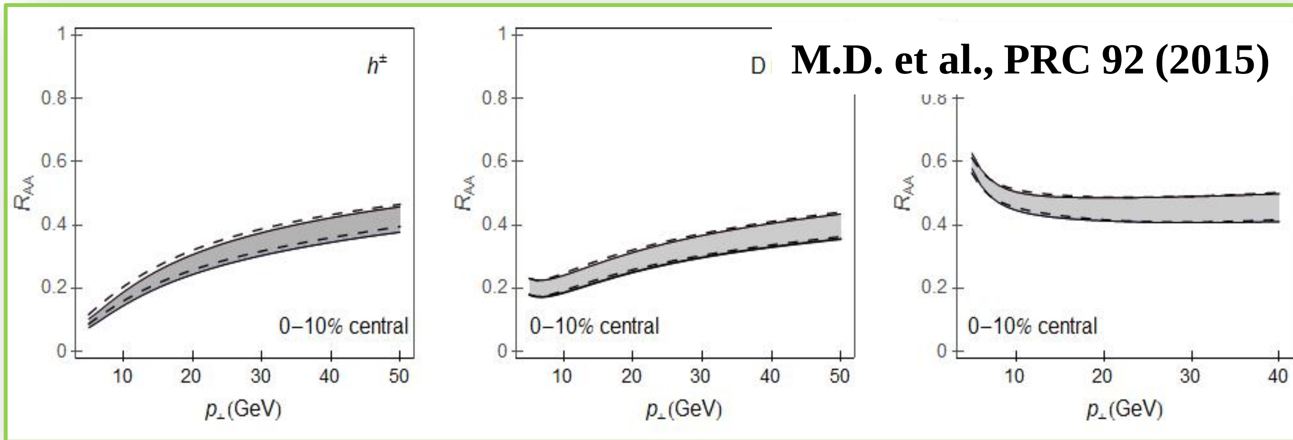

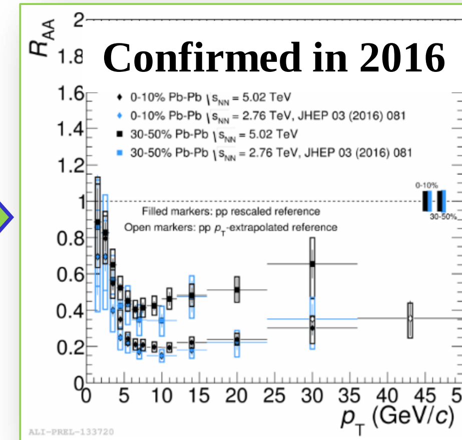

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Goals

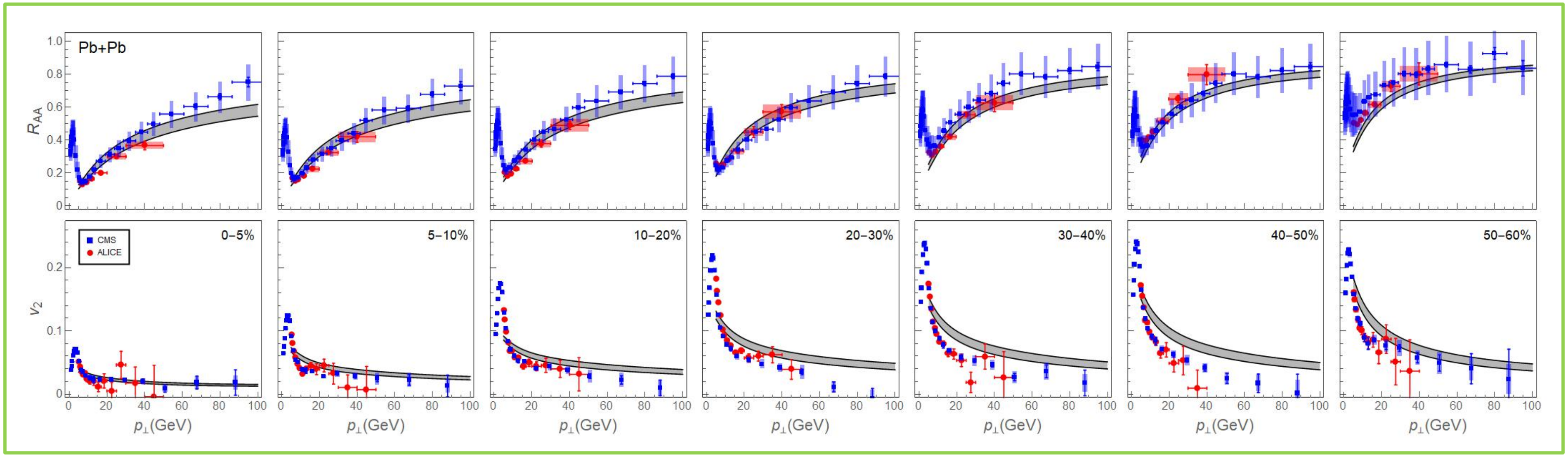
- **Allow systematic comparison of experimental data and theoretical predictions, obtained by the same formalism and the same parameter set. In particular:**
  - **For different observables (both R_{AA} and v_2)**
  - **Different collision systems (Pb+Pb and Xe+Xe)**
  - **Different probes (light and heavy)**
  - **Different collision energies**
  - **Different centralities**
- **Introduce medium evolution in the model, for now through Bjorken expansion.**
- **Differentiate between different energy loss models**
  - **What is an appropriate observable, and what are appropriate systems, to assess energy loss path-length dependence?**
- **Infer the shape of the QGP droplet from the data**

DREENA-C

DREENA (Dynamical Radiative and Elastic ENergy loss Approach) is a computational framework in which dynamical energy loss is implemented.

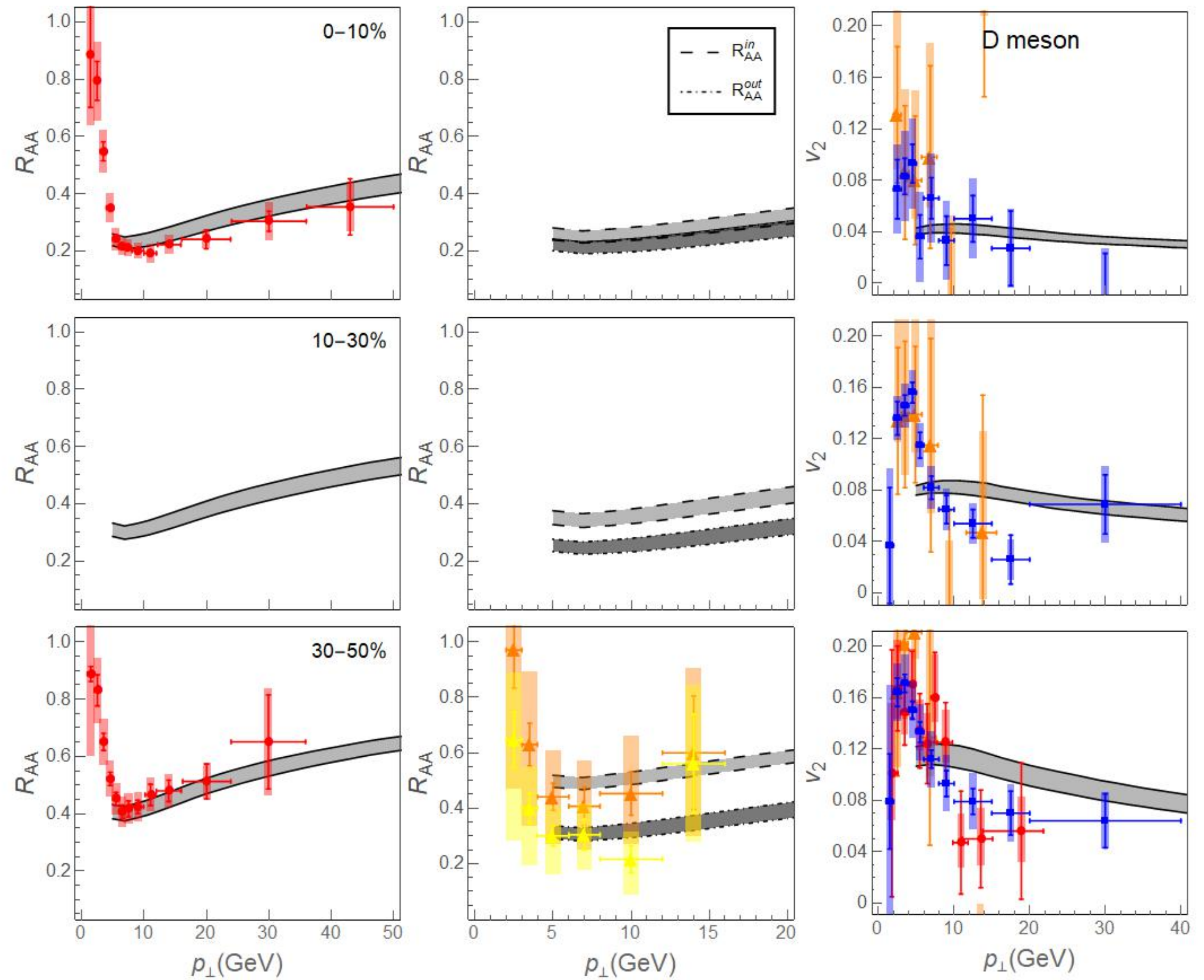
Version C – Constant temperature medium

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., arXiv:1805.03494



For charged hadrons, qualitatively good agreement, but overestimation of v_2 data.

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., arXiv:1805.03494



ALICE and CMS data

For D mesons, qualitatively good agreement, but again overestimation of v_2 data.

The theoretical models up-to-now, faced difficulties in jointly explaining R_{AA} and v_2 data, i.e. lead to under-prediction of v_2, so called v_2 puzzle.

Overestimation of v_2, obtained by DREENA-C, might seem surprising.

However, by using a scaling arguments: $\Delta E/E \sim T^a L^b$, where for simplicity we take $a, b \rightarrow 1$ (as $a \approx 1.2, b \approx 1.4$) in our model, we obtain:

In const *T* medium:

$$R_{AA} \approx (1 - \xi\, T\, L), \quad v_2 \approx \frac{\xi\, T\, \Delta L}{2}$$

In evolving medium:

$$R_{AA} \approx (1 - \xi\, T\, L), \quad v_2 \approx \frac{\xi\, T\, \Delta L - \xi\, \Delta T\, L}{2}$$

Introduction of medium evolution in our model, should lower the v_2 predictions.

Is this really so?

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., arXiv:1805.03494

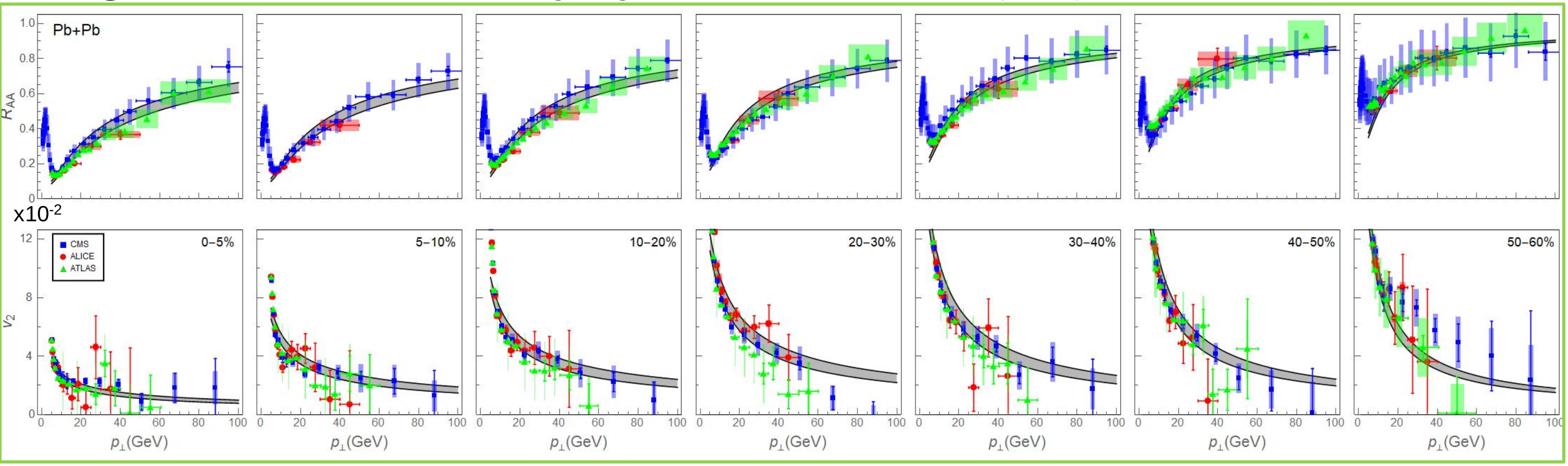
DREENA-B

To check this, we introduce DREENA-B framework.

Version B – 1+1D Bjorken expansion.

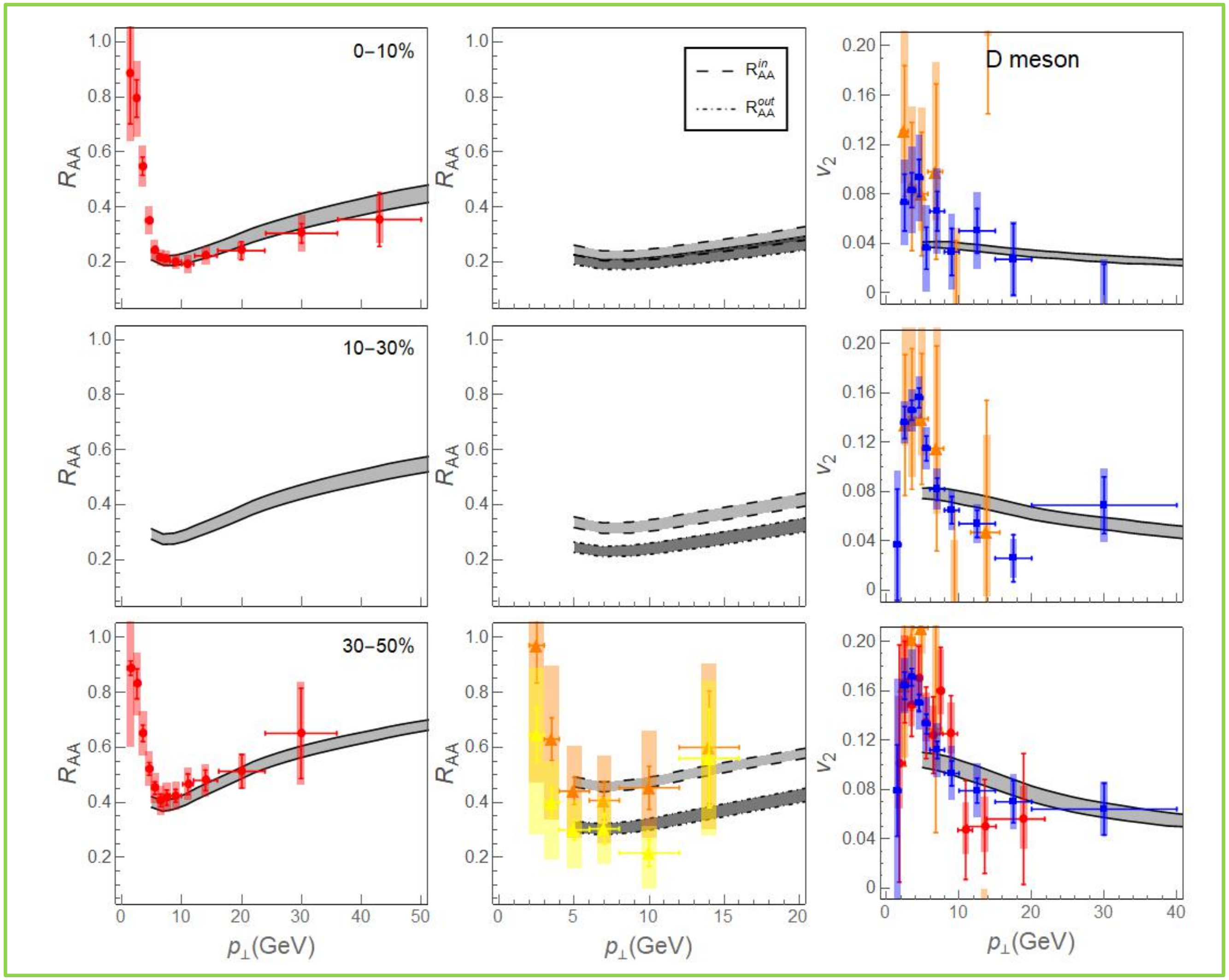
First joint R_{AA} and v_2 predictions with dynamical energy loss formalism in expanding QCD medium:

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., PLB 791 (2019) 236



Very good joint agreement with R_{AA} and v_2 data!

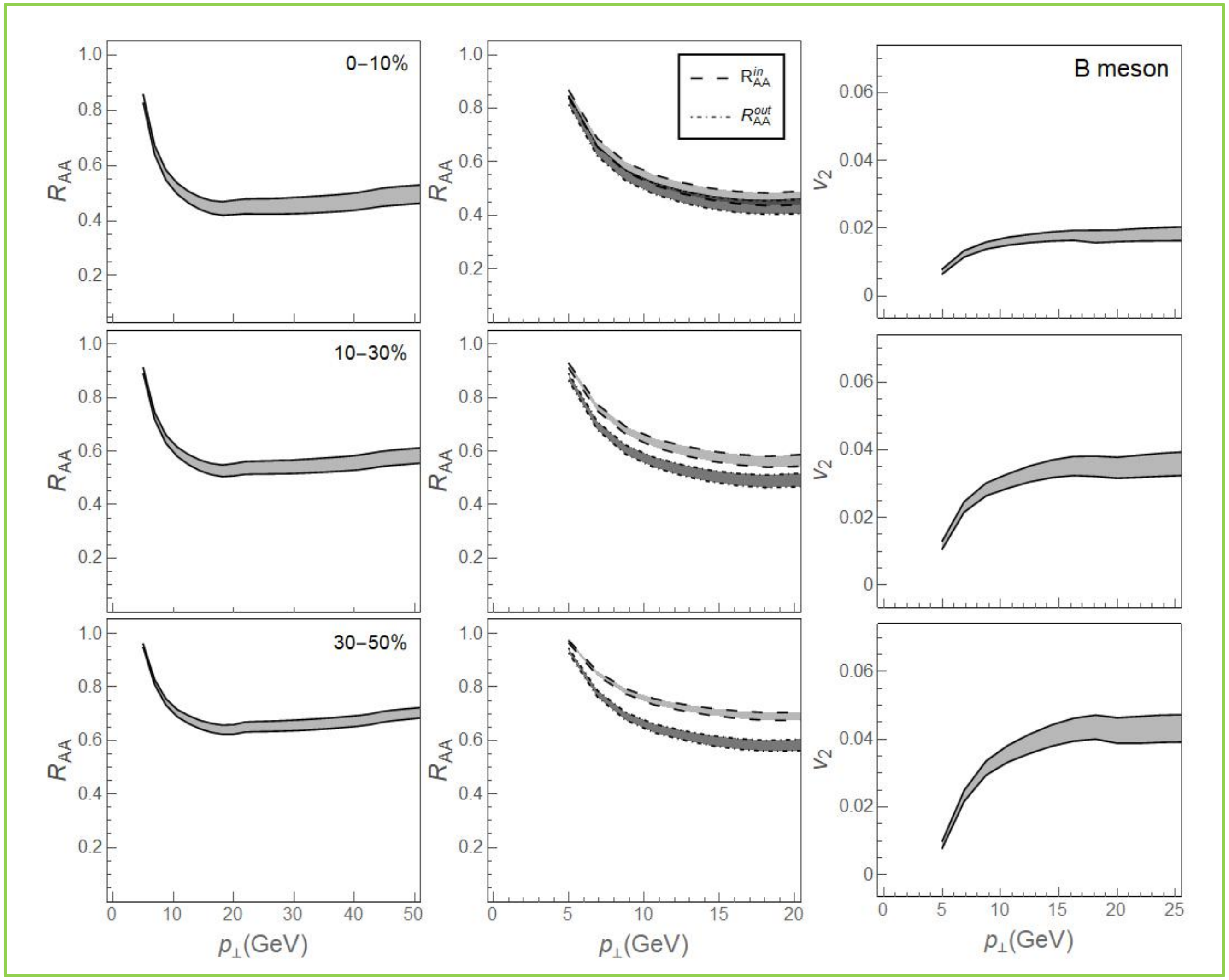
D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., PLB 791 (2019) 236



ALICE and CMS data

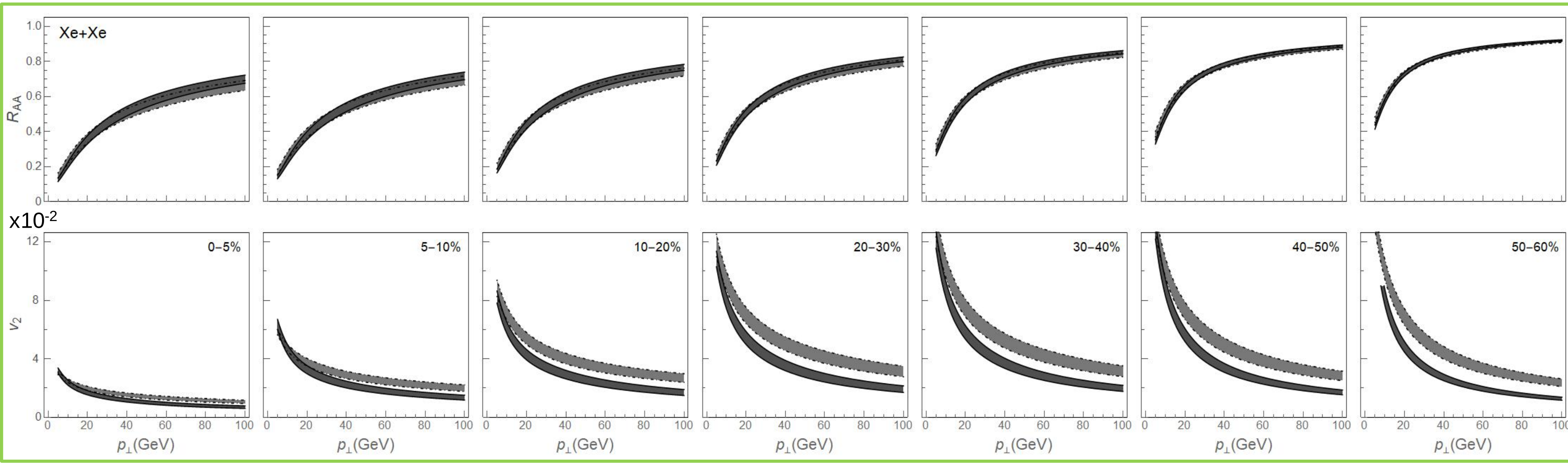
Good joint agreement for D mesons as well!

D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., PLB 791 (2019) 236



We predict non-zero v_2 for high pt B mesons.

5.44 TeV Xe+Xe predictions with DREENA-C and DREENA-B frameworks



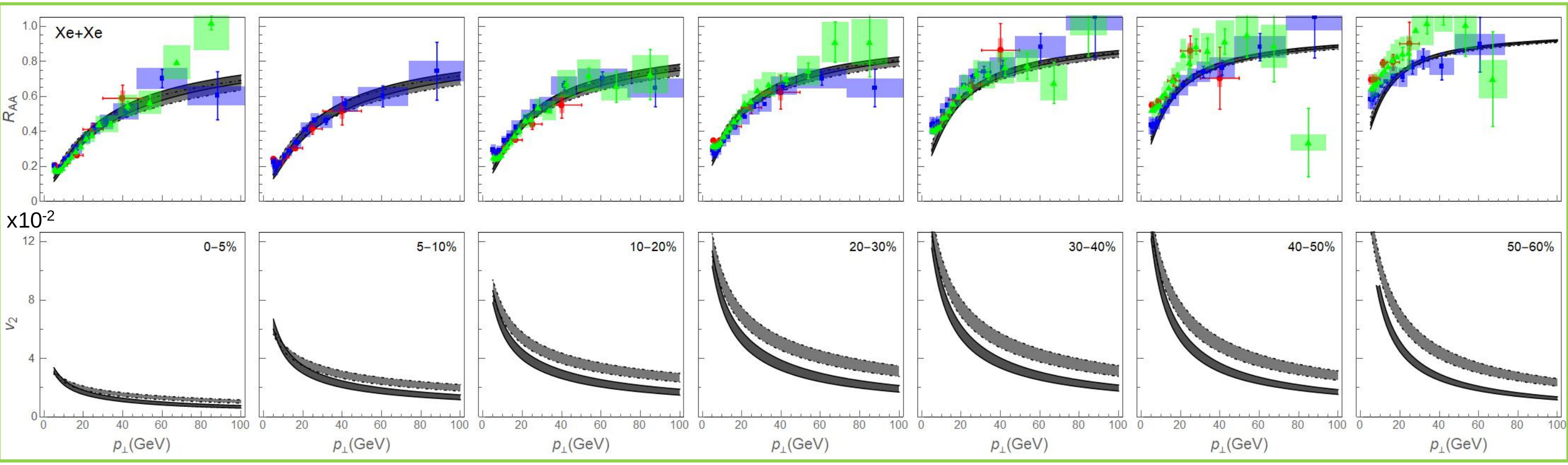
D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., PLB 791 (2019) 236

Inclusion of QGP evolution has small effect on R_{AA}, while notably decreasing v_2.

Large influence on v_2, confirming previous observations that v_2 observable is sensitive QGP evolution.

Small effect on R_{AA}, consistent with the notion that R_{AA} is not very sensitive to medium evolution.

5.44 TeV Xe+Xe predictions with DREENA-C and DREENA-B frameworks



D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M.D., PLB 791 (2019) 236

Inclusion of medium evolution has no effect on R_{AA}, while notably decreasing v_2.

Large influence on v_2, confirming previous observations that v_2 observable is sensitive QGP evolution.

Negligible effect on R_{AA}, consistent with the notion that R_{AA} is not very sensitive to medium evolution.

How to differentiate between different energy loss models?

Path length dependence (energy loss ~L^b) straightforwardly differentiates different energy loss models.

- **Many energy loss models have linear (b=1) or quadratic (b=2) path-length dependence.**
- **The dynamical energy loss path-length dependence is between linear and quadratic, due to both collisional and radiative energy loss mechanisms included in the model.**
- **Therefore, the path length dependence provides an excellent signature differentiating between different energy loss models, and consequently also between the underlying energy loss mechanisms.**

What is an appropriate system?

Measurements on 5.02 TeV Pb+Pb already available, 5.44 TeV smaller systems (e.g. Xe+Xe) are also becoming available.

The main property differentiating the two systems is its size (A_{PbPb}=208, A_{XeXe}=129) .

All other properties basically remain the same:

i. **Initial momentum distribution**

ii. **Average temperature for each centrality region**

iii. **Path length distributions (up to rescaling factor $A^{1/3}$)**

Consequently, comparison of suppressions in Pb+Pb and Xe+Xe is an excellent way to study the path length dependence.

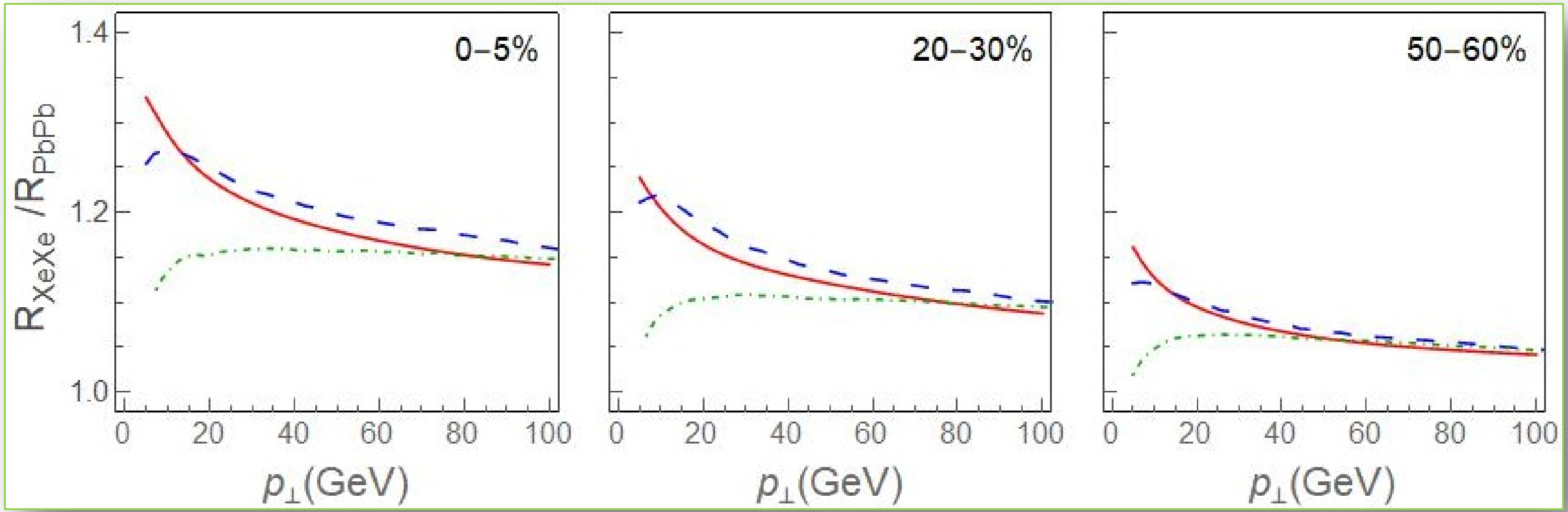
M.D., D. Zigic, M. Djordjevic and J. Auvinen, arXiv:1805.04030

What is appropriate observable?

M.D., D. Zigic, M. Djordjevic and J. Auvinen, arXiv:1805.04030

The ratio of the two R_{AA}s seems a natural choice, and has been proposed before.

However, in this way the path length dependence cannot be naturally extracted (also a strong centrality dependence):



What is the reason for this? – use scaling arguments:

$$\Delta E/E \sim T^a L^b \Longrightarrow \frac{R_{XeXe}}{R_{PbPb}} \approx 1 - \xi T^a L^b_{Pb} \left(1 - \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}\right)$$

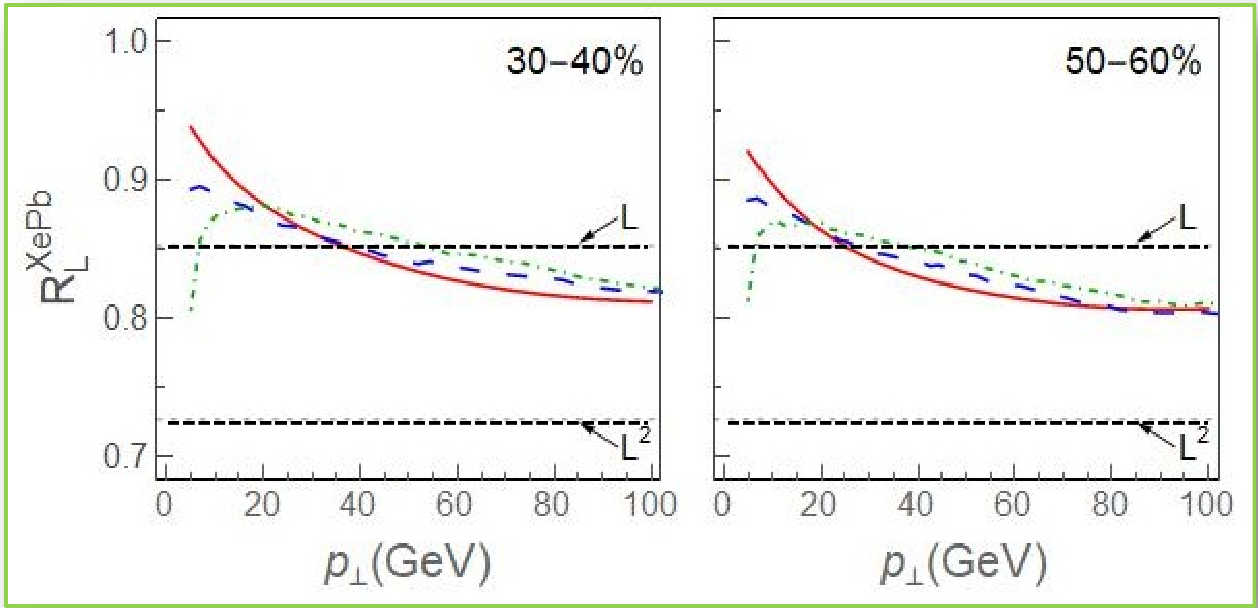
We see that the ratio includes a complicated relationship.

What we propose?

Use 1-R_{AA} ratio instead:

$$R_L^{XePb} \equiv \frac{1-R_{XeXe}}{1-R_{PbPb}} \approx \frac{\xi T^a L^b_{Xe}}{\xi T^a L^b_{Pb}} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$

We see a simple dependence on only size of the medium ($A^{1/3}$ ratio) and the path length dependence (exponent b).



M.D., D. Zigic, M. Djordjevic and J. Auvinen, arXiv:1805.04030

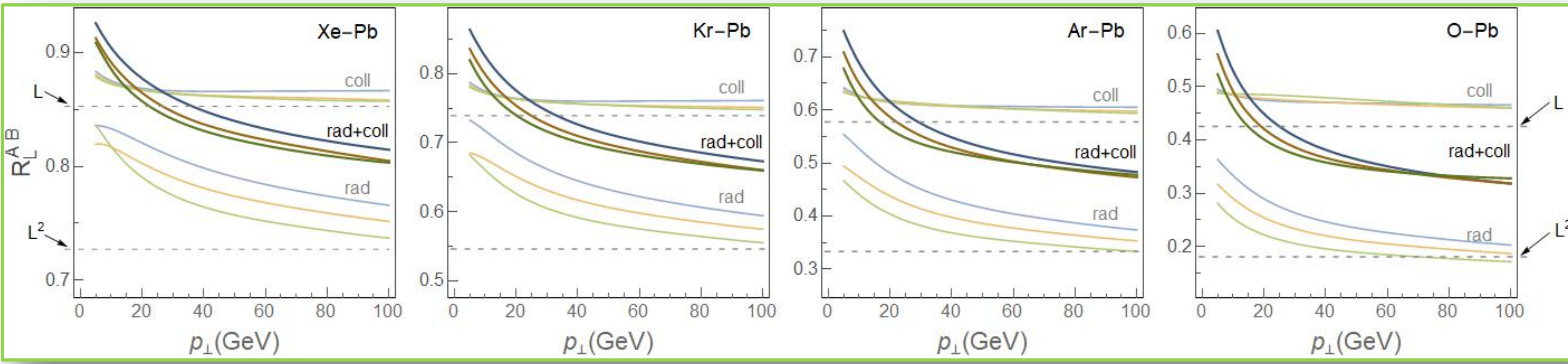
The path length dependence can be extracted in a simple way, and there is only a weak centrality dependence.

1-R_{AA} ratio therefore seems as a natural observable, which we call path-length sensitive suppression ratio.

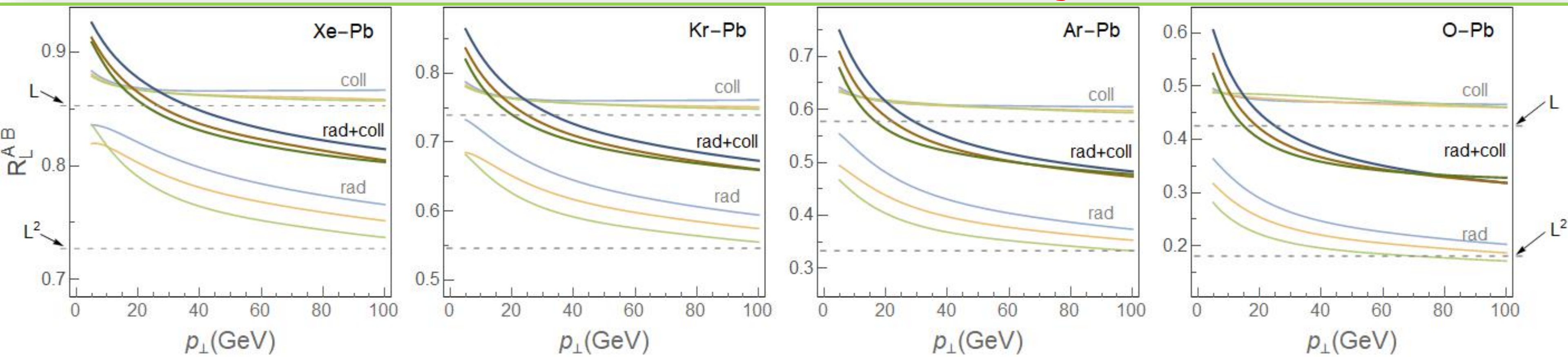
What about other smaller systems ?
- BSS at the LHC

Precision measurements of smaller systems, i.e. Kr+Kr, Ar+Ar and O+O, are expected to become available in the future Beam Size Scan (BSS) at the LHC.

Can these systems be also used to extract path length dependence of the energy loss?



What about other smaller systems?



i. R_L^{AB} is almost independent on centrality for the 30-60% centrality region.

ii. For all four systems, R_L^{AB} shows the same behavior, i.e. it is very robust with respect to extracting path-length dependence.

iii. Reliably recovers collisional and radiative energy loss path-length dependences.

iv. From experimental perspective, smaller systems might be more convenient for applying this observable, as the region of applicability (between L and L^2) increases with decreasing system size.

Consequently, we propose that R_L^{AB} is simple, robust and reliable observable for extracting the path-length of the energy loss.

Summary up to now

We introduce DREENA-C and DREENA-B frameworks, where DREENA is a computational implementation of the dynamical energy loss formalism.

At constant *T* our predictions overestimate v_2. With Bjorken expansion, we have a good agreement with both R_{AA} and v_2 data.

We propose a new observable which we call path length sensitive suppression ratio, from which energy loss path length dependence can be extracted in a simple, robust and reliable manner.

Beam Size Scan (BSS) at the LHC (with Kr+Kr, Ar+Ar, O+O) provides an excellent opportunity to assess the path length dependence.

OUTLOOK: Dynamical energy loss formalism can provide a basis for a state of the art QGP tomography tool – e.g. to jointly constrain the medium properties from the point of both high-pt and low-pt data.

How to infer the shape of the QGP droplet from the data?

Initial spatial anisotropy is one of the main properties of QGP.

A major limiting factor for precision QGP tomography.

Still not possible to directly infer the initial anisotropy from experimental measurements.

Several theoretical studies (MC-Glauber, EKRT, IP-Glasma, MC- KLN) infer the initial anisotropy; lead to notably different predictions, effecting predictions of both low and high pt observables.

Alternative approaches for inferring anisotropy are necessary!

Optimally, these approaches should be complementary to existing predictions.

Based on a method that is fundamentally different to models of early stages of QCD matter.

A novel approach to extract the initial state anisotropy

- **Inference from already available high pt R_{AA} and v_2 measurements (also to be measured with much higher precision in the future).**
- **Use experimental data (rather than on calculations of early stages of QCD matter).**
- **Exploit information from interactions of rare high-pt partons with QCD medium .**
- **Advances the applicability of high pt data.**
- **Up to now, these data mainly used to study the jet-medium interactions, rather then inferring bulk QGP parameters, such as spatial asymmetry.**

What is appropriate observable?

M.D., S. Stojku, M. Djordjevic and P. Huovinen, arXiv:1903.06829

The initial state anisotropy is quantified in terms of eccentricity parameter ε_2:

$$\epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} = \frac{\int \mathrm{d}x\, \mathrm{d}y\, (y^2 - x^2)\, \rho(x,y)}{\int \mathrm{d}x\, \mathrm{d}y\, (y^2 + x^2)\, \rho(x,y)}$$

where $\rho(x,y)$ is the initial density distribution of the QGP droplet.

High pt v_2 is sensitive to both the anisotropy of the system and its size.

R_{AA} is sensitive only to the size of the system.

Can we extract eccentricity from high pt v_2 and R_{AA} data?

Anisotropy observable

Use a scaling arguments for high pt (M.D., *et al.*, arXiv:1805.04030; M. D. and M. Djordjevic, PRC 92, 024918 (2015))

$$\Delta E/E \sim \langle T\rangle^a \langle L\rangle^b$$

where within our model $a \approx 1.2$, $b \approx 1.4$, consistent with the data.

$$R_{AA} \approx 1 - \xi \langle T\rangle^a \langle L\rangle^b$$
$$1 - R_{AA} \approx \xi \langle T\rangle^a \langle L\rangle^b$$

$$v_2 \approx \frac{1}{2}\frac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}} \approx \xi \langle T\rangle^a \langle L\rangle^b \left(\frac{b}{2}\frac{\Delta L}{\langle L\rangle} - \frac{a}{2}\frac{\Delta T}{\langle T\rangle}\right)$$

$$\frac{v_2}{1 - R_{AA}} \approx \left(\frac{b}{2}\frac{\Delta L}{\langle L\rangle} - \frac{a}{2}\frac{\Delta T}{\langle T\rangle}\right)$$

This ratio carries information on the asymmetry of the system, but through both spatial and temperature variables.

M.D., S. Stojku, M. Djordjevic and P. Huovinen, arXiv:1903.06829

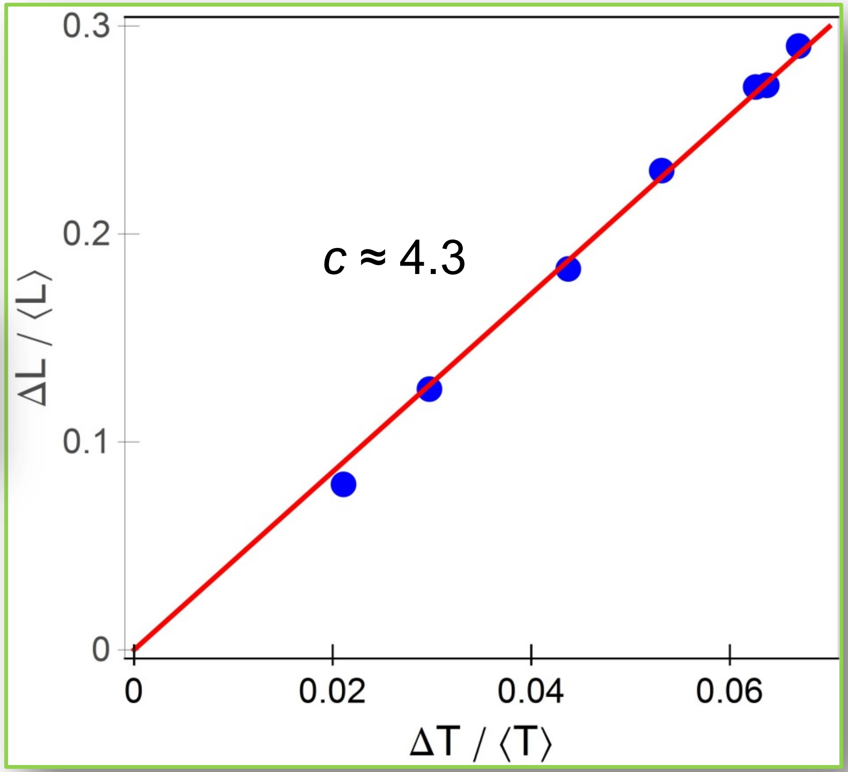
Anisotropy parameter ς

$$\frac{v_2}{1-R_{AA}} \approx \left(\frac{b}{2}\frac{\Delta L}{\langle L\rangle} - \frac{a}{2}\frac{\Delta T}{\langle T\rangle}\right)$$

$$\frac{v_2}{1-R_{AA}} \approx \frac{1}{2}(b - \frac{a}{c})\frac{\Delta L}{\langle L\rangle} \approx 0.57\varsigma$$

$$\varsigma = \frac{\Delta L}{\langle L\rangle} = \frac{\langle L_{out} - L_{in}\rangle}{\langle L_{out} + L_{in}\rangle}$$

Temperature and spatial assymetry:

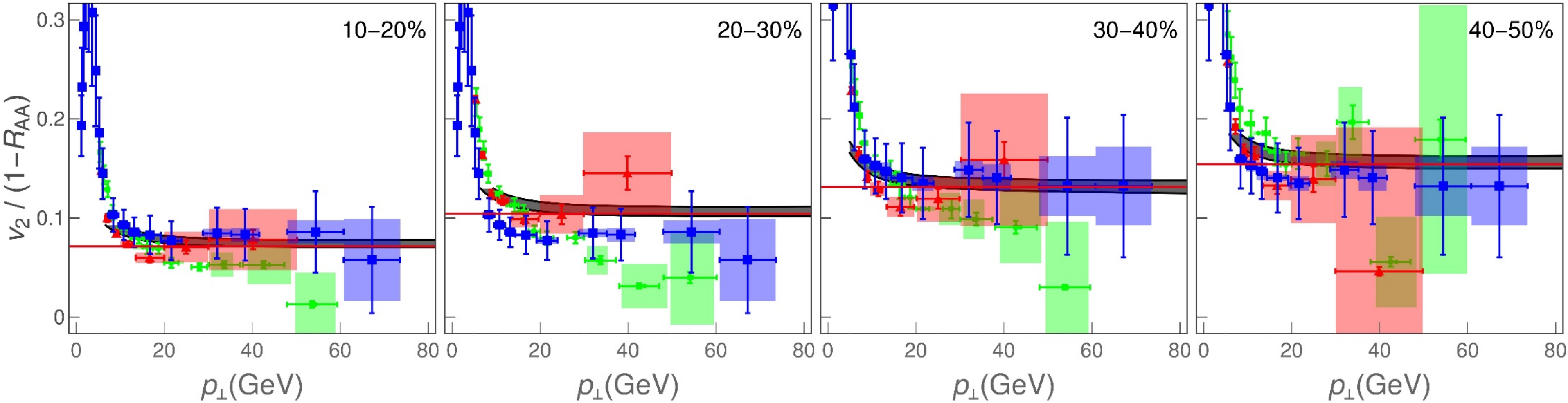


At high pt v_2 over 1-R_{AA} ratio is dictated *solely* by the geometry of the initial fireball.

Anisotropy parameter ς can be *directly* extracted from the high-pt experimental data.

M.D., S. Stojku, M. Djordjevic and P. Huovinen, arXiv:1903.06829

Predictions *vs.* data



- **Solid red line – analytically derived asymptote.**
- **For each centrality and from pt~20 GeV, $v_2/(1-R_{AA})$ does not depend on pt, but is determined by the geometry of the system.**
- **The experimental data for ALICE, CMS and ATLAS, show the same tendency, though the error bars for the data are still large.**
- **In the LHC Run 3, the error bars should reduce by two orders of magnitude.**

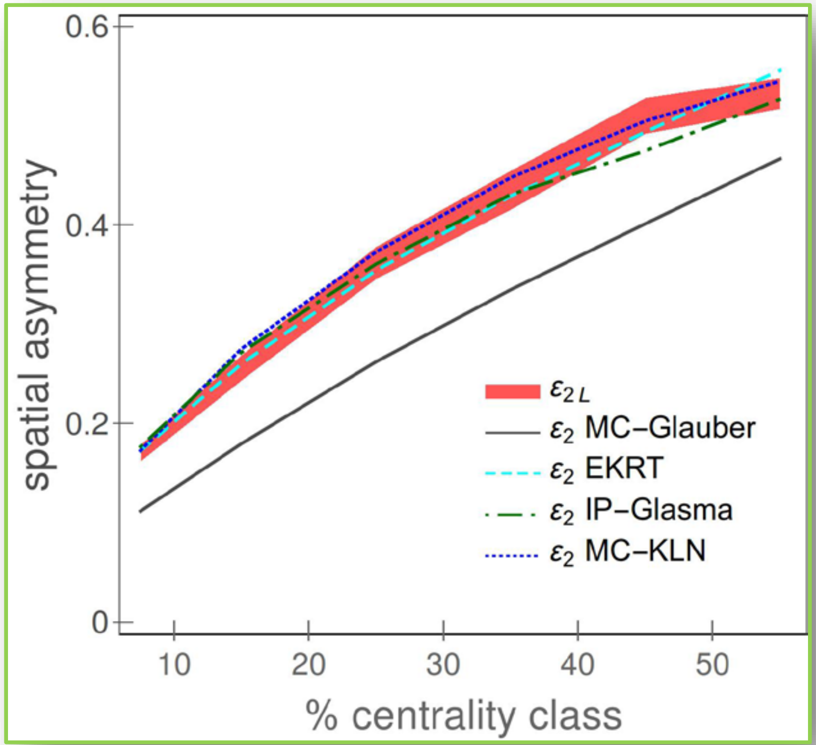
$v_2/(1-R_{AA})$ indeed carries the information about the system's anisotropy, which can be simply (from the straight line high-pt limit) and robustly (in the same way for each centrality) inferred from experimental data.

Eccentricity

Note that the anisotropy parameter ς is not the commonly used anisotropy parameter ε_2. To facilitate comparison with ε_2 values in the literature, we define:

$$\epsilon_{2L} = \frac{\langle L_{out}\rangle^2 - \langle L_{in}\rangle^2}{\langle L_{out}\rangle^2 + \langle L_{in}\rangle^2} = \frac{2\varsigma}{1+\varsigma^2}$$

and compare with results in the literature.



ε_{2L} is in an excellent agreement with ε_2 from which we stared from.

$v_2/(1-R_{AA})$ – reliable/robust procedure to recover initial state anisotropy.

The width of our ε_{2L} band is smaller than the difference in the ε_2 values obtained by using different models (e.g. MC-Glauber vs. MC-KLN).

Resolving power to distinguish between different initial state models, although it may not be possible to separate the finer details of more sophisticated models.

M.D., S. Stojku, M. Djordjevic and P. Huovinen, arXiv:1903.06829

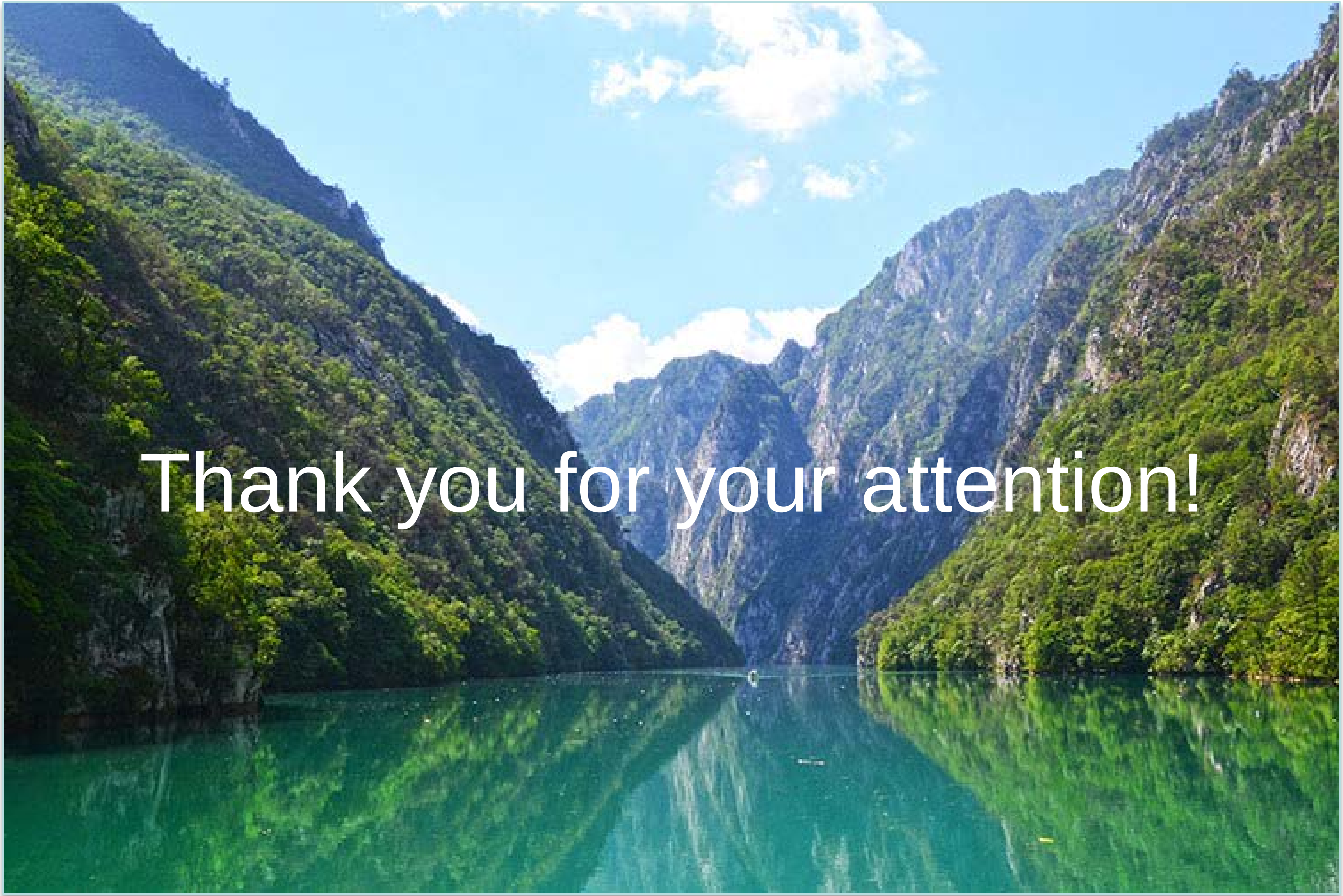
Summary

High-pt theory and data are traditionally used to explore high-pt parton interactions with QGP, while QGP bulk properties are explored through low-pt data and corresponding models.

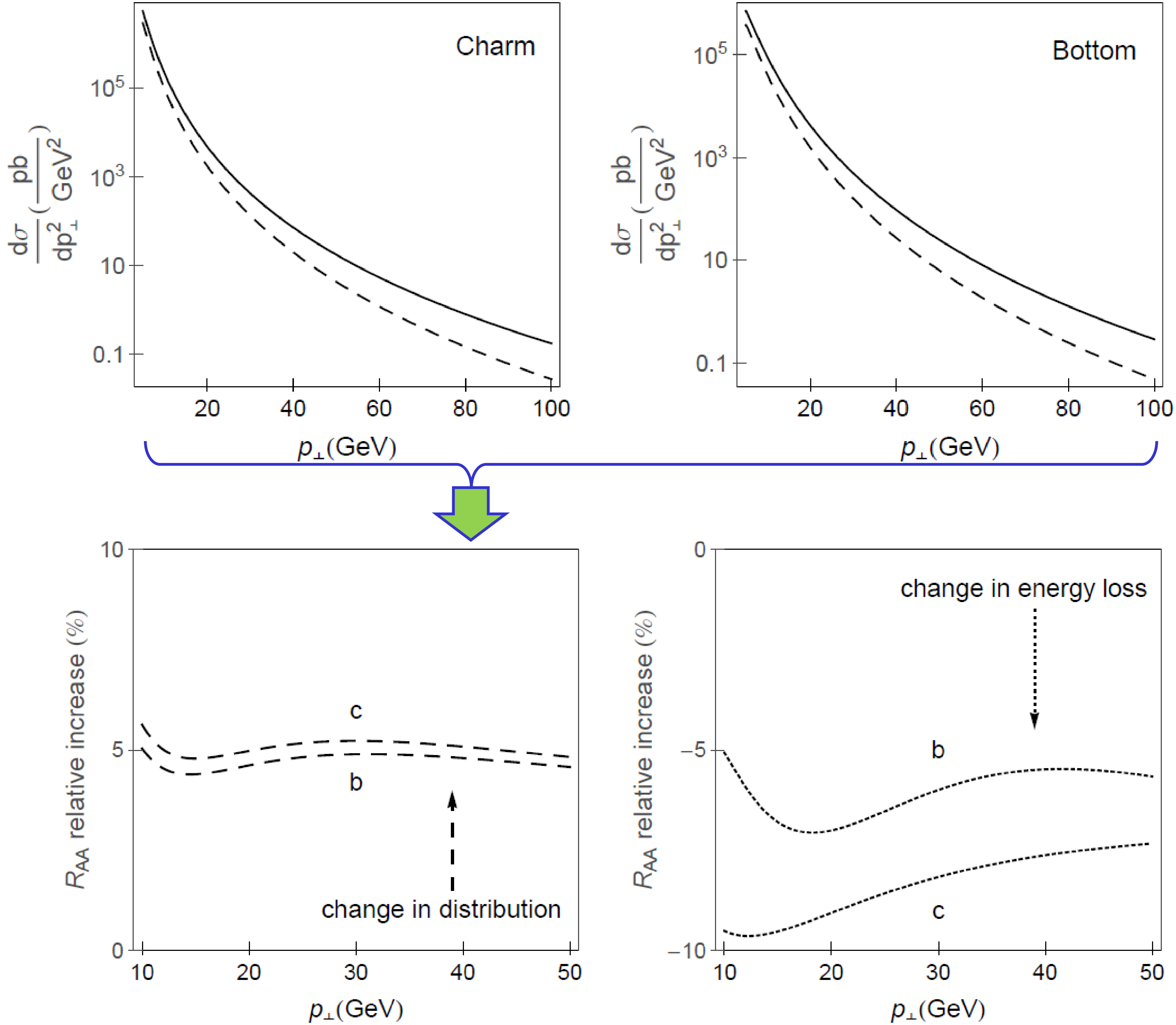
We here showed that, in the case of spatial anisotropy of the QCD matter, high-pt probes are also powerful tomography tools, as they are sensitive to global QGP properties.

With our dynamical energy loss formalism, we showed that a (modified) ratio of R_{AA} and v_2, presents a reliable and robust observable for straightforward extraction of a initial state anisotropy.

It will be possible to infer the anisotropy directly from LHC Run 3 data; an important constraint to models describing the early stages of QGP formation. This demonstrates the synergy of combining more common approaches for inferring QGP properties with high-pt theory and data.



Canyon of Serbian river DREENA


Charm
Bottom
$\frac{d\sigma}{dp_\perp^2}\left(\frac{pb}{GeV^2}\right)$
10^5
10^3
10
0.1
20 40 60 80 100
$p_\perp$(GeV)
R_{AA} relative increase (%)
c
b
change in distribution
change in energy loss
10
5
0
−5
−10
10 20 30 40 50

Temperature dependence of the energy loss