



# Recent results with full DREENA framework as a multipurpose tool for QGP tomography

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in collaboration with: Magdalena Djordjevic, Jussi Auvinen, Igor Salom, Marko Djordjevic and Pasi Huovinen



МИНИСТАРСТВО ПРОСВЕТЕ,  
НАУКЕ И ТЕХНОЛОГИЈЕ РАЗВОЈА

# Outline

- Dynamical energy loss formalism
- DREENA framework
- QGP tomography

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# Introduction

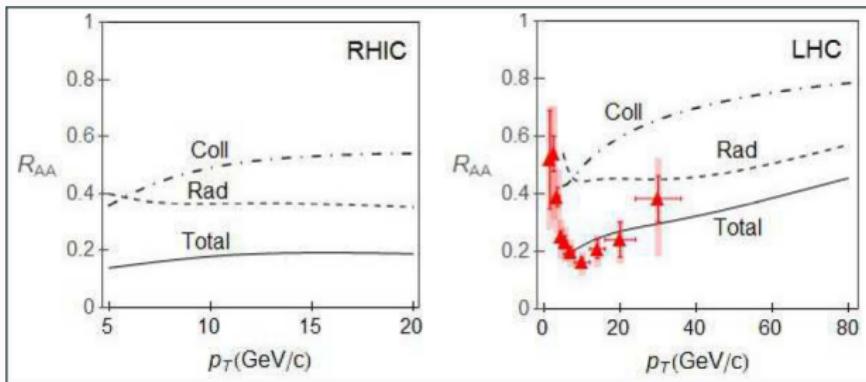
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# Dynamical energy loss formalism

- finite size finite temperature QCD medium
- finite temperature field theory and generalized HTL approach  
M Djordjevic, PRC74 (2006), PRC 80 (2009), M. Djordjevic 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. Djordjevic and M. Djordjevic, PLB 709:229 (2012).
- running coupling  
M. Djordjevic and M. Djordjevic, PLB 734, 286 (2014).
- relaxed soft-gluon approximation  
B. Blagojevic, M. Djordjevic and M. Djordjevic, PRC 99, 024901, (2019).

# Dynamical energy loss formalism

- all effects are important for accurate description of high  $p_T$  data  
B. Blagojevic and M. Djordjevic J.Phys. G42 (2015) 7, 075105



## Numerical implementation

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# DREENA framework

- **Dynamical Radiative and Elastic ENergy loss Approach**
- fully optimized numerical procedure capable of generating high  $p_{\perp}$  predictions
- includes:
  - parton production
  - multi gluon-fluctuations
  - path-length fluctuations
  - fragmentation functions
- keeping all elements of the state-of-the art energy loss formalism, while introducing more complex temperature evolutions

## version C - Constant temperature medium

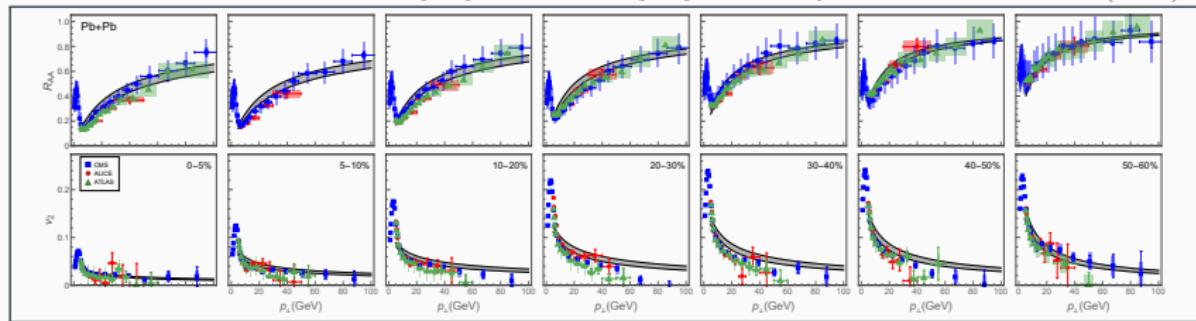
- natural first step
- simplest calculation:  
analytical integration possible in certain cases
- all other version need to have const T limit
- exploring the influence of medium evolution on both light and heavy flavour and different observables

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

# DREENA-C

- Charged hadrons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

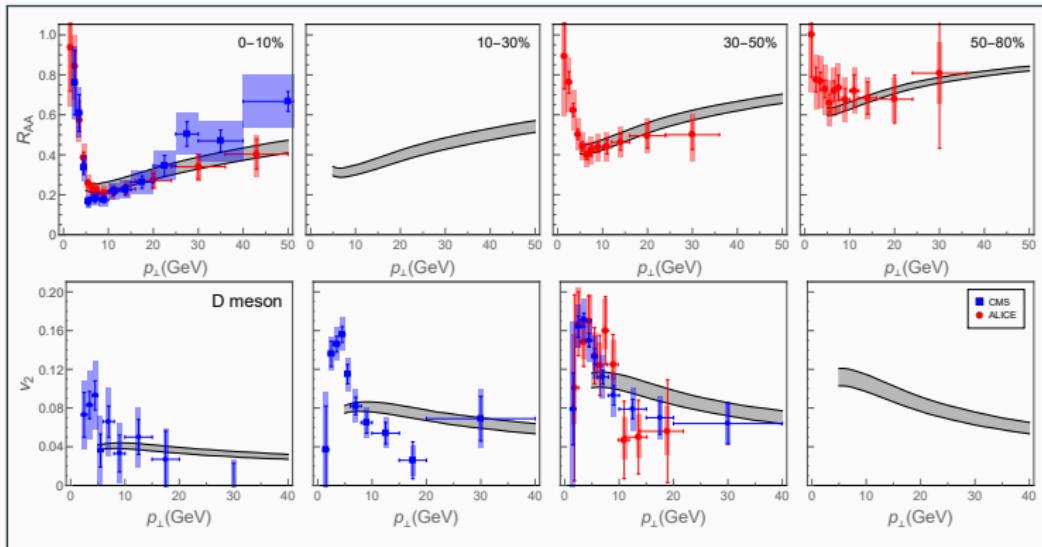


for charged hadrons, qualitatively good agreement,  
but overestimation of  $v_2$  data

# DREENA-C

- D mesons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

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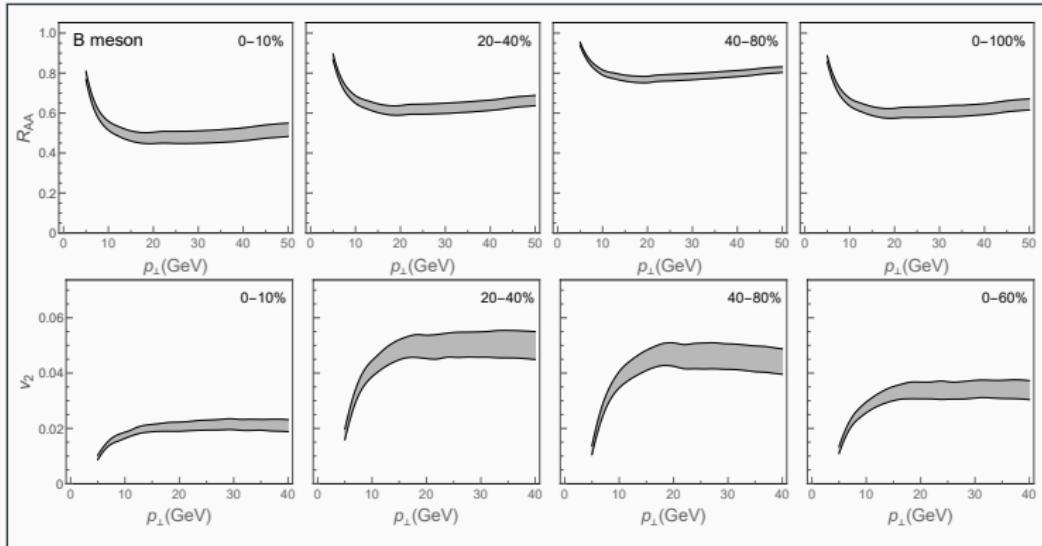


for D mesons, qualitatively good agreement,  
but again overestimation of  $v_2$  data

# DREENA-C

- B mesons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).



for B mesons, our  $v_2$  predictions are non-zero

# DREENA-C

Main conclusions for DREENA-C:

- good agreement with  $R_{AA}$  data
- however,  $v_2$  overestimates the data
- other models underestimate  $v_2 - v_2$  puzzle
- overall good agreement with data given the simplicity of approximation
- why does DREENA-C overestimates  $v_2$  data?

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019).

Using simple scaling arguments:  $\Delta E/E \sim T^a L^b$   
(for simplicity:  $a, b \rightarrow 1$ , but actually  $a \approx 1.2, b \approx 1.4$ )

- in const T medium:

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

- in evolving medium:

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



introduction of medium evolution should lower  $v_2$  predictions?

# DREENA-B

## version **B** - 1+1D **B**jorken evolution

- natural next step
- $T$  introduced through analytical expression, which is only a function of time
- differences in results should suggest the sensitivity of observables to different aspects of medium evolution
- limits prove the validity of models

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

## Technical implementation:

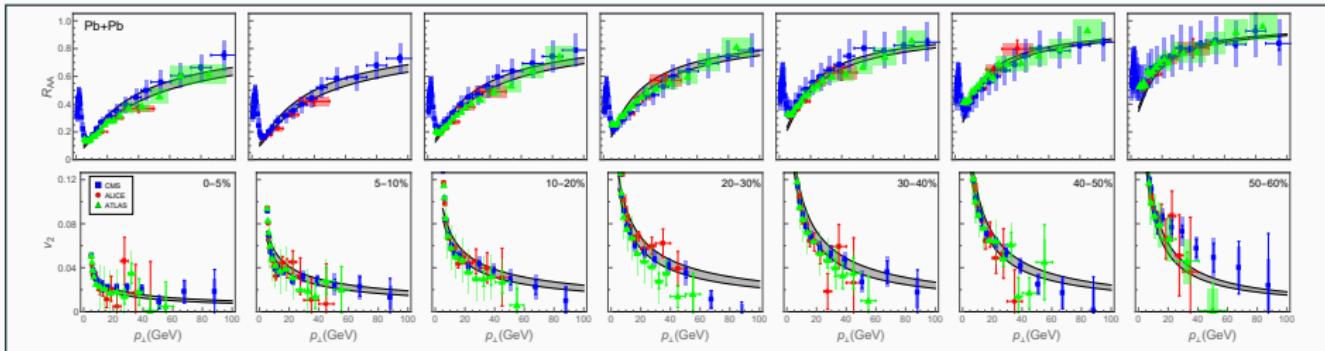
- $T \neq \text{const.}$  leads to additional integration
- better suited methods of numerical integration were used
- optimization allowed for further improvements of the physical model:  
multi-gluon fluctuation procedure (from 3 to 5 radiated gluons)

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).

# DREENA-B

- Charged hadrons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

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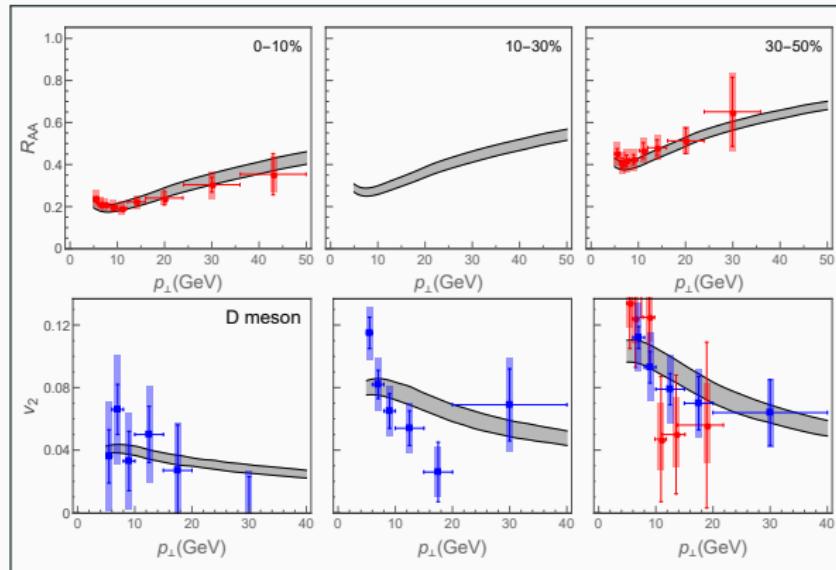


very good joint agreement with both  $R_{AA}$  and  $v_2$  data

# DREENA-B

- D mesons,  $Pb + Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV}$

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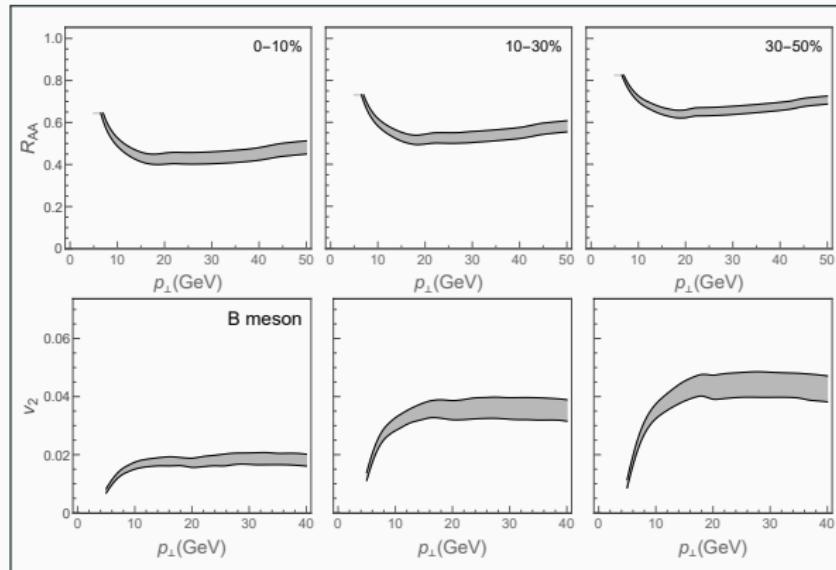


good joint agreement for D mesons as well

# DREENA-B

- B mesons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B 791, 236 (2019).

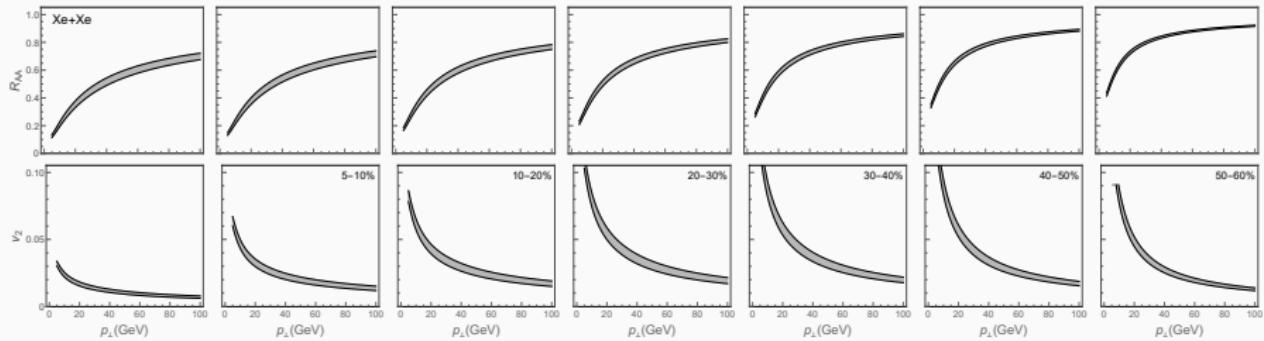


we predict non-zero  $v_2$  for B mesons

# DREENA-B

- $Xe + Xe$ ,  $\sqrt{s_{NN}} = 5.44 \text{ TeV}$  predictions

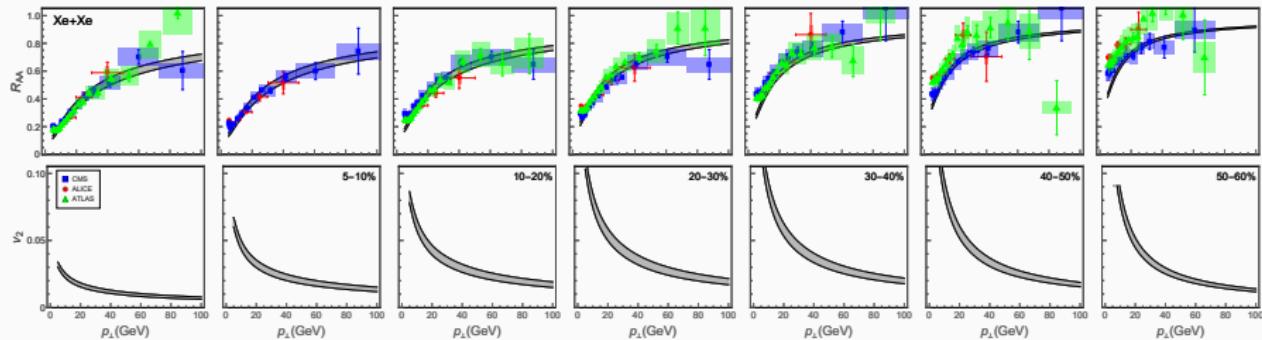
D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019).



# DREENA-B

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good agreement with the data

# DREENA-B

## Main conclusions for DREENA-B:

- takes medium evolution in a simple analytical expression that depends only on time
- explains high  $p_{\perp}$  data for different probes collision energies and centralities
- this form of time evolution is suitable for studying the influence of initial stages of QGP evolution on high  $p_{\perp}$  observables (as discussed in previous talk by Bojana Ilic)
- yet, it can't provide us with further information about the properties of QGP (shear viscosity,...)

D. Z., I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B 791, 236 (2019).

# DREENA-A

## version **A** - Adaptive

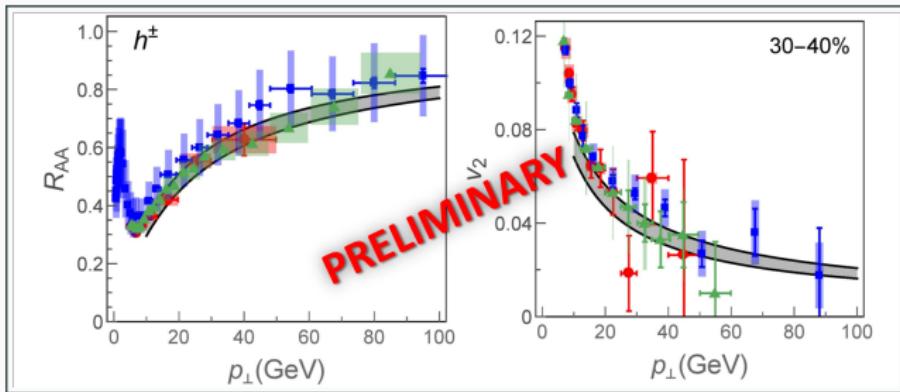
- main goal of our research
- tool for exploiting high  $p_{\perp}$  data for QGP tomography by employing advanced medium model (hydro, transport coefficients,...)
- DREENA-A introduces full medium evolution but not at the expense of simplified energy loss
- also capable to account for event-by-event fluctuations

## Technical implementation:

- full temperature evolution profile (in this talk we present results obtained from 3+1D hydro)  
E. Molnar, H. Holopainen, P. Huovinen and H. Niemi, Phys. Rev. C **90**, no. 4, 044904 (2014).
- different approach than previous versions  
most of the code written from scratch
- previous versions used pre-calculated path-length distributions - now we use dynamical tracking
- we use MonteCarlo to generate trajectories
- in order to recover phase space of jets:  
**1 000 000 trajectories are needed!**
- no fitting parameters

# DREENA-A

- Charged hadrons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$



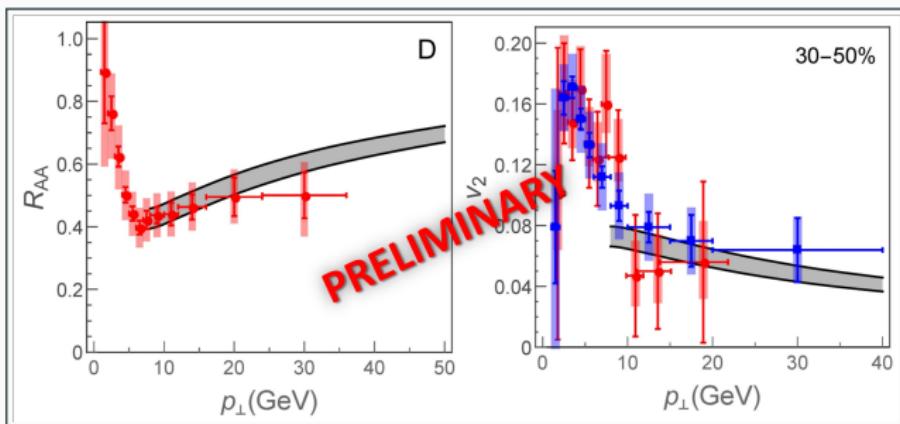
very good joint agreement with  $R_{AA}$  and  $v_2$  data  
**no  $v_2$  puzzle**



for high  $p_\perp$  data, proper description of parton-medium interactions is more important than the medium evolution

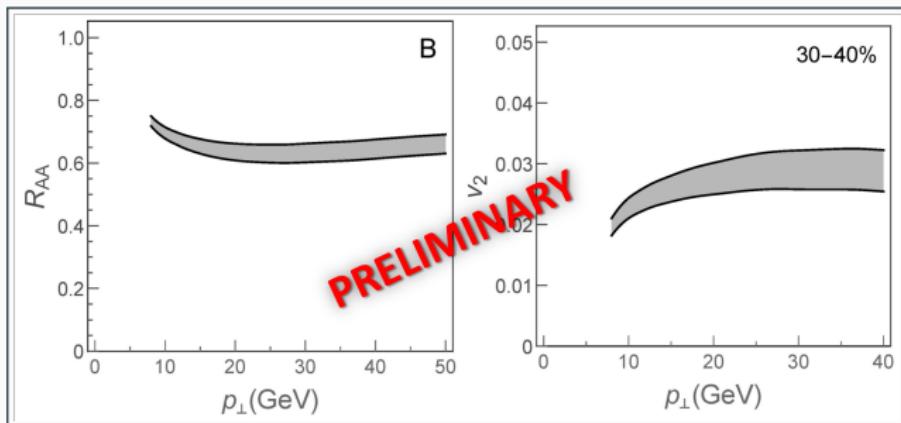
# DREENA-A

- D mesons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$



good joint agreement for D mesons as well

- B mesons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$



we predict non-zero  $v_2$  for B mesons

# DREENA-A

Main conclusions for DREENA-A:

- fully optimized numerical procedure for suppression calculation
- uses full temperature profile without simplification in energy loss
- can use any temperature profile (hydro, transport coefficients,...)
- first framework that contains both state-of-the-art energy loss and state-of-the art medium evolution → uniquely suited for exploring the bulk QGP properties, i.e., for QGP tomography!

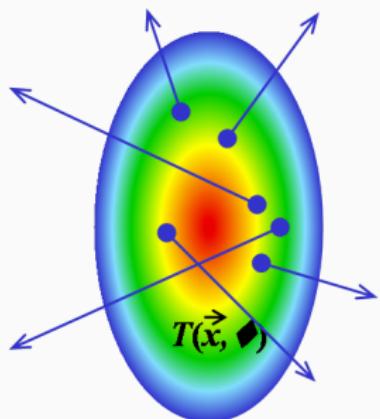
# **Tomography**

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# QGP properties

- Next goal: inferring QGP properties from high  $p_{\perp}$  theory and data

- high energy particles lose energy
- energy loss sensitive to QGP properties
- predict the energy loss of high  $p_{\perp}$  probes
- infer QGP properties:



- initial spatial anisotropy  
M. Djordjevic, S. Stojku, M. Djordjevic and P. Huovinen,  
arXiv:1903.06829 [hep-ph].
- constrain the initial stages by high  $p_{\perp}$  theory and data  
D. Z., B. Ilic, M. Djordjevic and M. Djordjevic, arXiv:1908.11866  
(previous talk by Bojana Ilic)
- path-length dependence of energy loss  
M. Djordjevic, D. Z., M. Djordjevic and J. Auvainen,  
Phys. Rev. C 99, no. 6, 061902(R) (2019).

## Path-length dependence

How to differentiate between different energy loss models?

Path-length dependence directly 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

# Path-length dependence

What is an appropriate system?

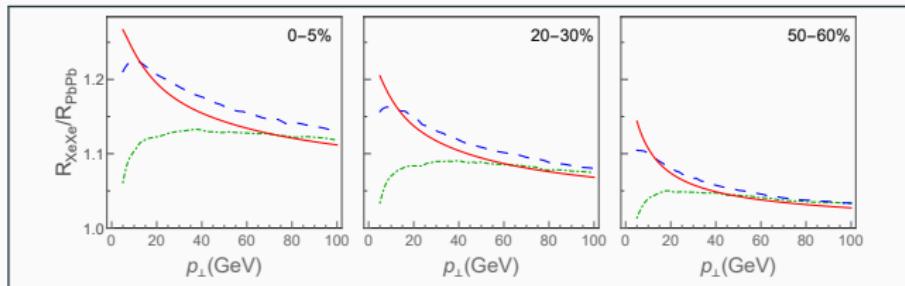
- measurements on 5.02 TeV Pb+Pb already available, 5.44 TeV smaller systems (e.g. Xe+Xe) are also becoming available
- the main property differentiating the two systems is its size ( $A_{PbPb} = 208$ ,  $A_{XeXe} = 129$ )
- all other properties basically remain the same:
  - initial momentum distribution
  - average temperature for each centrality region
  - 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. Djordjevic, D. Z., M. Djordjevic and J. Auvinen, Phys. Rev. C 99, no. 6, 061902(R) (2019).

# Path-length dependence

What is an appropriate observable?

- 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):



- using scaling arguments:

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

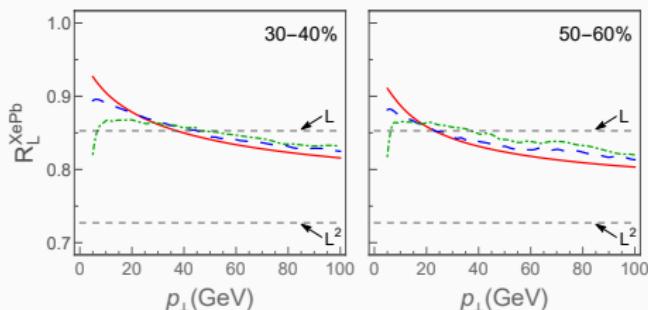
# Path-length dependence

## What we propose?

- use  $1 - R_{AA}$  ratio instead:

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

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



- path-length dependence can be extracted in a simple way
- there is only a weak centrality dependence

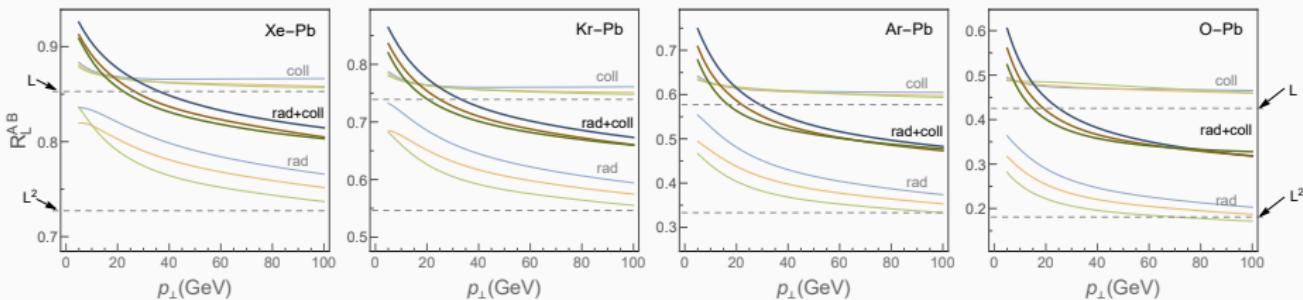
## $1 - R_{AA}$ ratio - path-length sensitive suppression ratio

M. Djordjevic, D. Z., M. Djordjevic and J. Auvinen, Phys. Rev. C 99, no. 6, 061902(R) (2019).

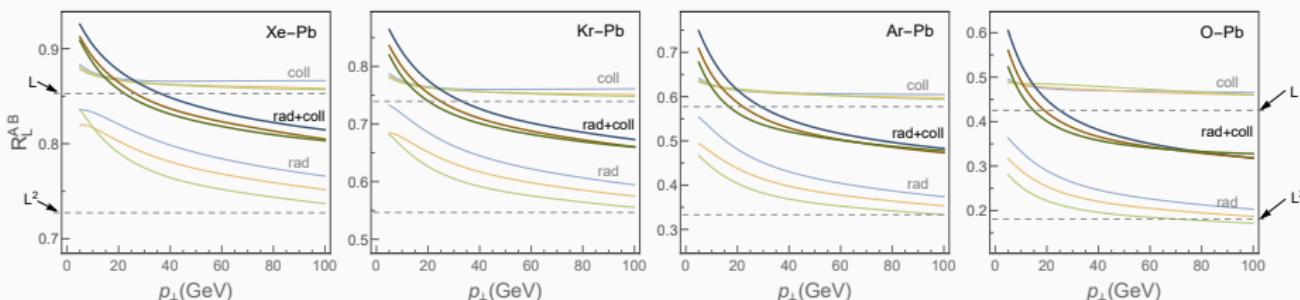
# Path-length dependence

What about other smaller systems?

- 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?



# Path-length dependence



- $R_L^{AB}$  is almost independent of centrality for 30-60% region
- for all four systems,  $R_L^{AB}$  shows the same behavior, i.e. it is very robust with respect extracting path-length dependence
- reliably recovers collisional and radiative energy loss path-length dependence
- 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

we propose that  $R_L^{AB}$  is simple, robust and reliable observable  
for extracting energy loss path-length dependence

## Summary

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## Summary

- we introduce **DREENA** framework - computational implementation of **dynamical energy loss formalism**
- the main purpose of DREENA is to infer QGP properties
- as an example, we here proposed how to, directly from experimental data, extract energy loss path-length dependence in a simple, reliable and robust way
- developed three frameworks, based on Constant T (DREENA-C), 1D Bjorken (DREENA-B) and Adaptive profile (DREENA-A)
- **DREENA-C** predictions overestimate  $v_2$ , while **DREENA-B** and **DREENA-A** predictions are different, they both reasonably explain  $R_{AA}$  and  $v_2$
- for high  $p_\perp$  observables, accurate description of parton-medium interactions is very important for explaining high  $p_\perp$  data
- **DREENA-A** - unique framework that incorporates both state-of-the-art energy loss formalism and state-of-the-art medium evolution, which makes it an optimal framework for exploring the bulk QGP properties by high  $p_\perp$  theory and data

# Acknowledgements



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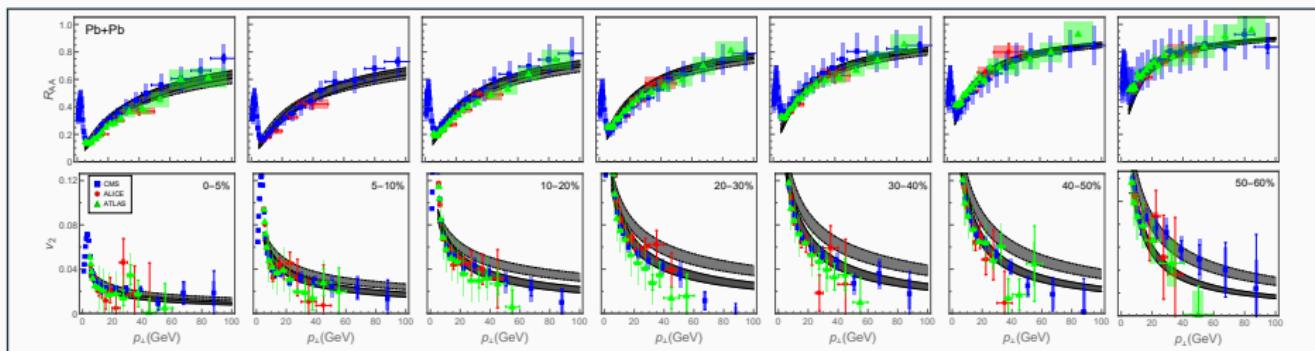


МИНИСТАРСТВО ПРОСВЕТЕ,  
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Thank you for your attention!

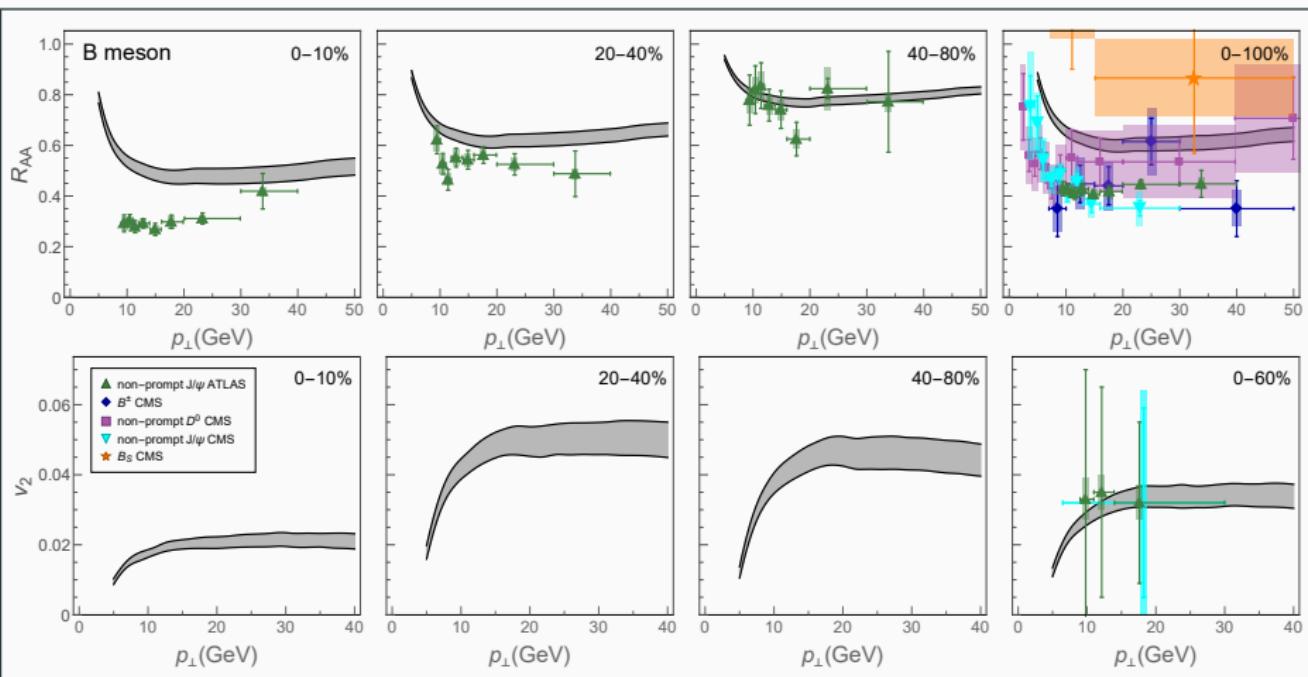
# Backup slides

- Charged hadrons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
DREENA-C & DREENA-B



# Backup slides

- B Meson,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
DREENA-C



# Backup slides

- Charged hadrons,  $Pb + Pb$ ,  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
DREENA-C & DREENA-B & DREENA-A

