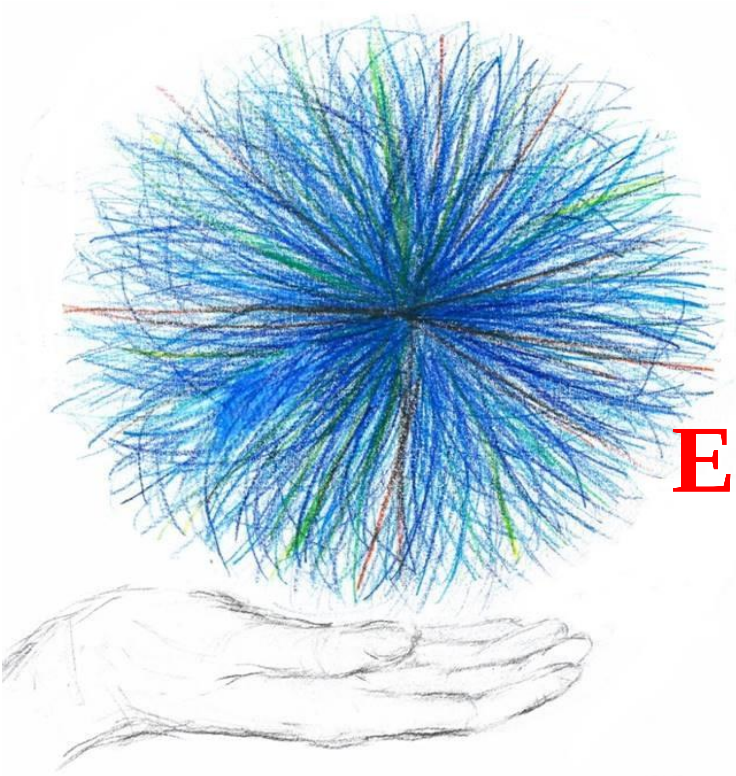

Exploring bulk QGP properties through high-pt theory and data

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МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

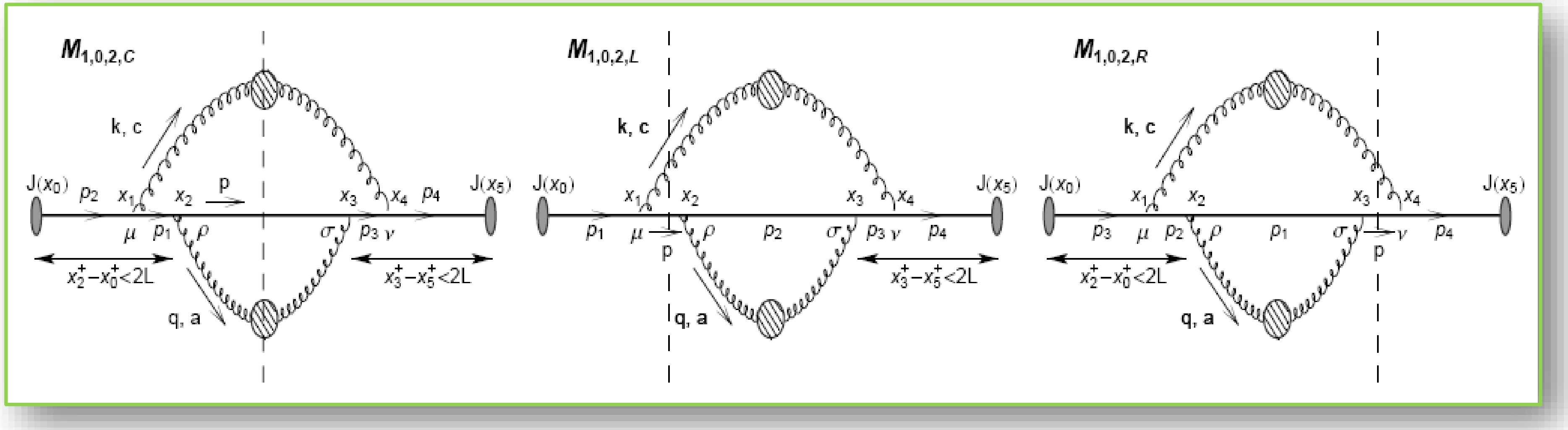
Motivation

- 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.
- Today: Address how high pt theory and data can be used to explore the bulk QGP properties, in particular
  - infer a geometrical property of bulk QCD medium
  - constrain the QGP thermalization time from the data

The dynamical energy loss formalism

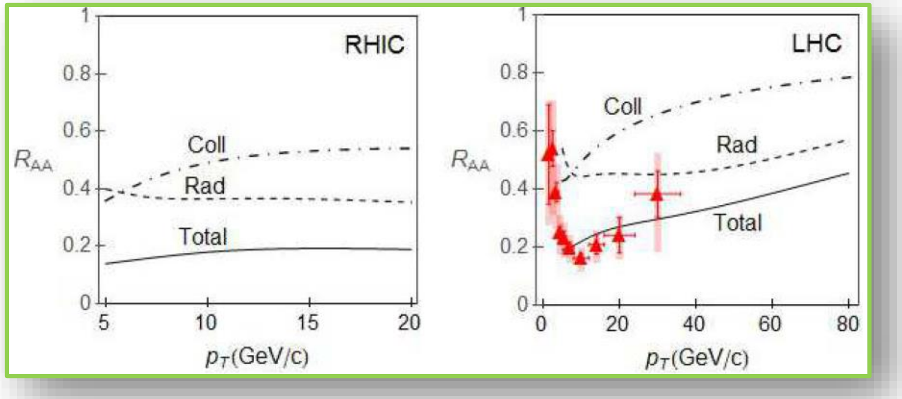
Includes:

- ***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)).**



The dynamical energy loss formalism

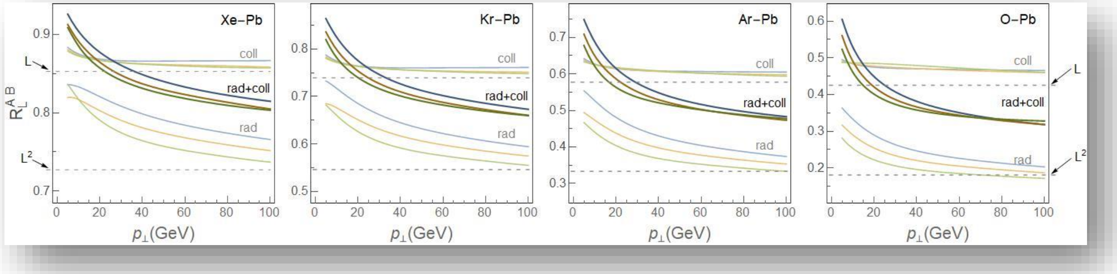
All effects are important for accurate description of high pt suppression (B. Blagojevic and M.D, J.Phys. G42 (2015) 7, 075105 (highlighted in LabTalk).



Proposed observable for distinguishing different energy loss mechanisms

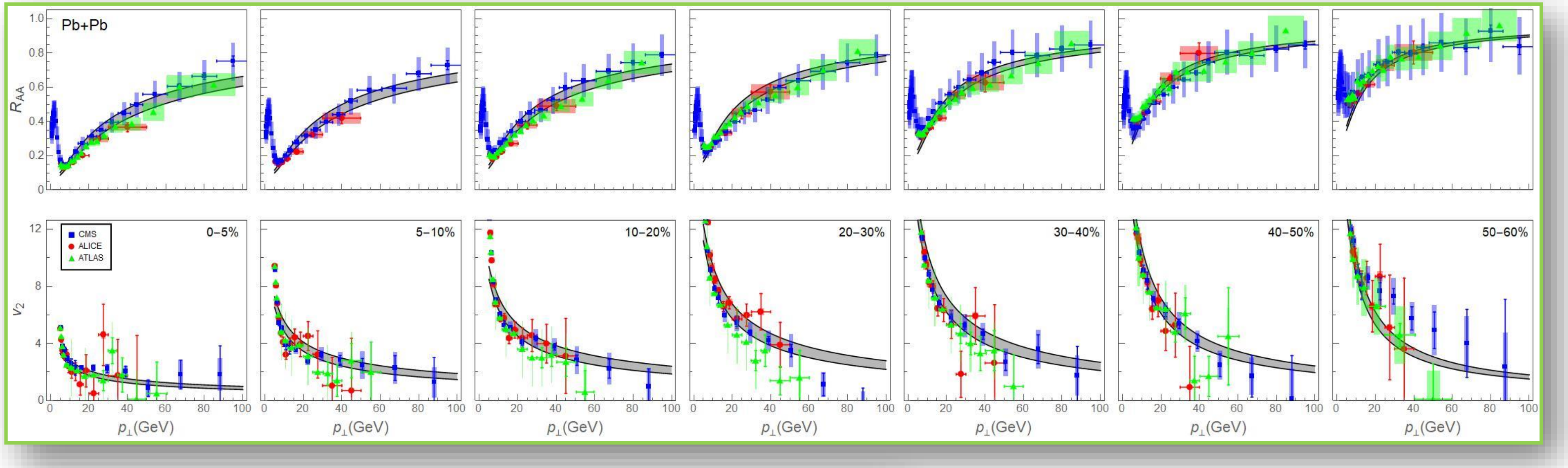
(M.D., D. Zigic, M. Djordjevic and J. Auvinen, Phys. Rev. C Rapid Commun. 99, 061902 (2019).)

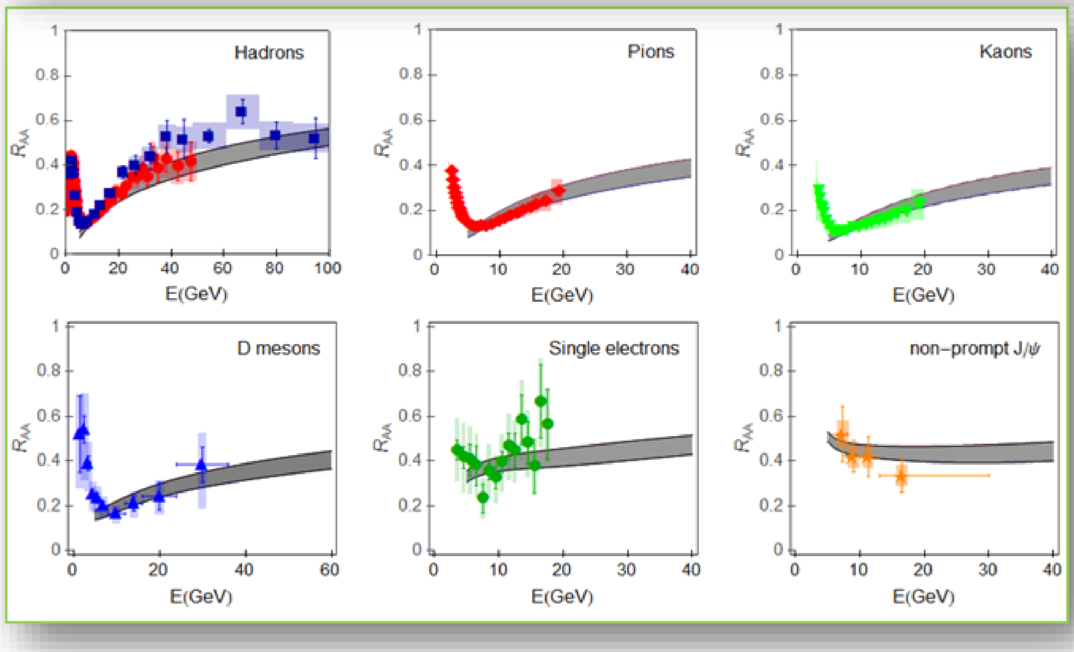
$$R_L^{XePb} \equiv \frac{1-R_{XeXe}}{1-R_{PbPb}} \approx \frac{\xi T^a L^b_{Xe}}{\xi T^a L^b_{Pb}} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$



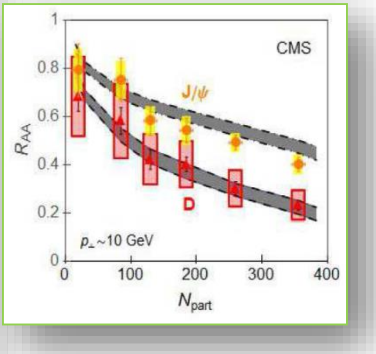
Integrated in DREENA (Dynamical Radiative and Elastic ENergy loss Approach) framework to provide predictions for high pt observables

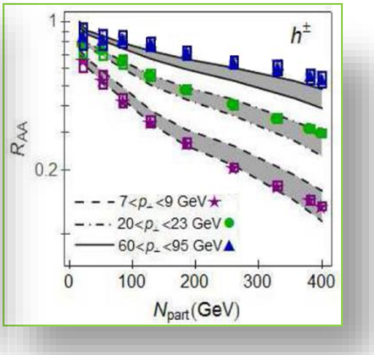
DREENA-B predictions (1+1D Bjorken evolution medium)





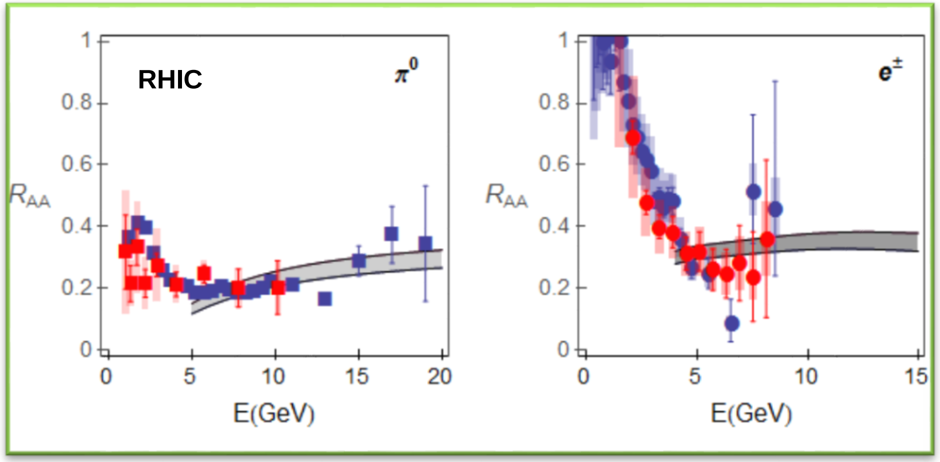
D. Zigic, I. Salom, J. Auvinen, M. Djordjevic
and M.D., PLB 791 (2019) 236

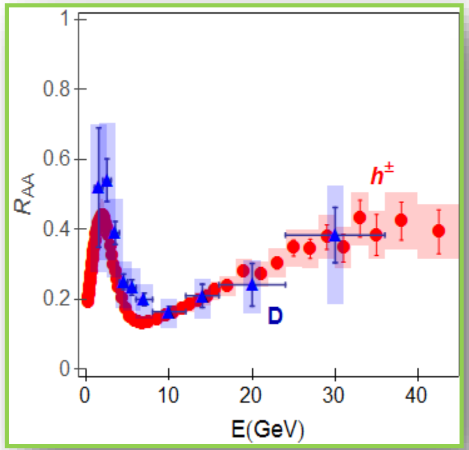


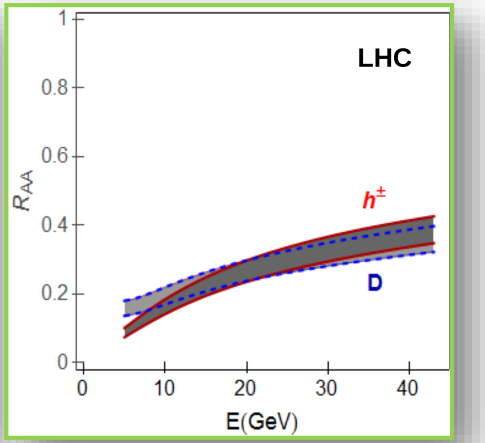


Explains high pt data for different probes, collision energies, and centralities.

Resolved the longstanding “heavy flavour puzzles at RHIC and LHC”.



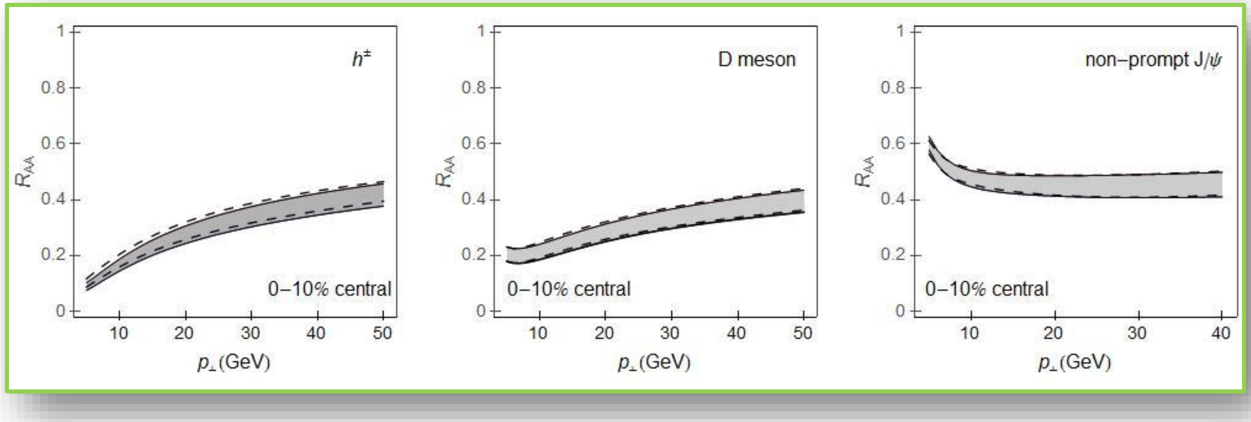


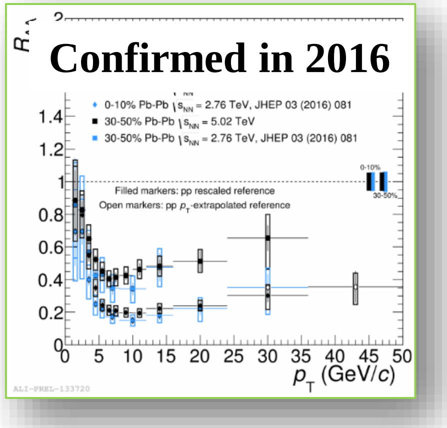


M.D., PRL 112, 042302 (2014)

Clear predictive power!

M.D. et al., PRC 92 (2015)



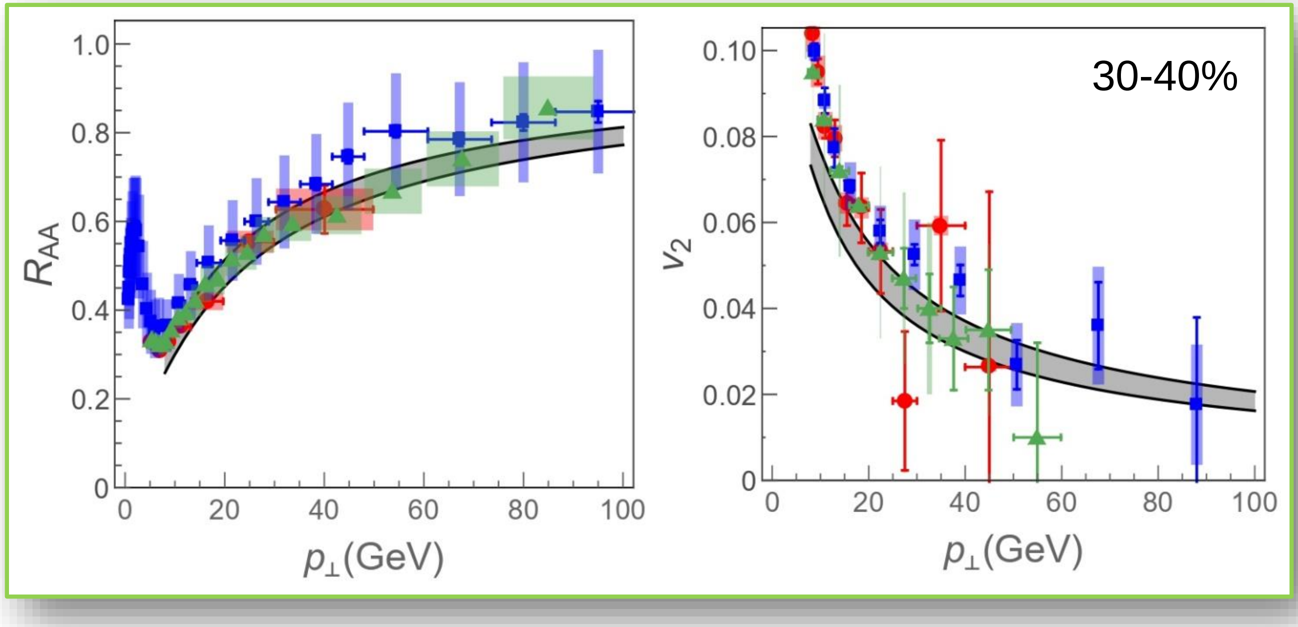


Confirmed in 2016

Agreement obtained by the same model and parameter set, no fitting parameters introduced.

High pt predictions with 3+1D hydro DREENA (DREENA-A)

D. Zigic, *et al.*, in preparation



No free parameters!

3+1D hydro: E. Molnar, H. Holopainen, P. Huovinen and H. Niemi, Phys. Rev. C 90, 044904 (2014).

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

No v_2 puzzle!

For high pt data, proper description of parton-medium interactions is much more important than the medium evolution!

Next Goal: Inferring bulk QGP properties from high pt theory and data

Bulk QGP properties are traditionally explored by low-pt observables that describe collective motion of 99.9% of QCD matter.

Rare high energy probes are, on the other hand, almost exclusively used to understand high-pt parton - medium interactions.

However, some important bulk QGP properties are known to be difficult to constrain by low-pt observables and corresponding theory/simulations

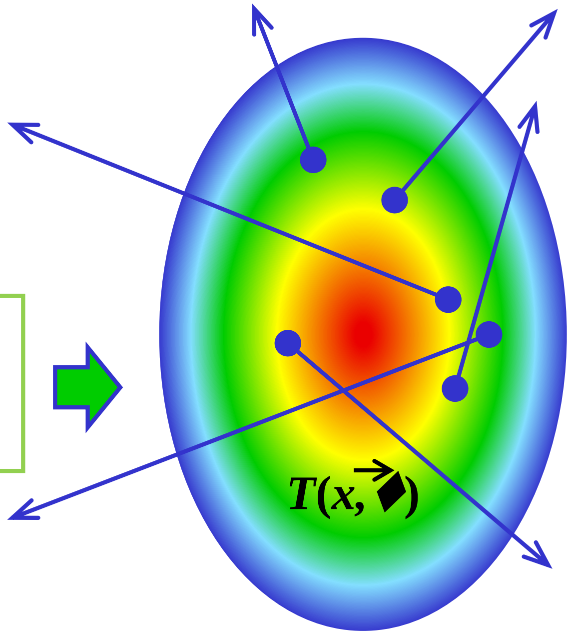
While high-pt physics had a decisive role in QGP discovery, it has been rarely used to understand bulk QGP properties.

We therefore advocate so-called high-pt QGP tomography, where bulk QGP parameters are jointly constrained by low- and high-pt physics.

We demonstrate how the analysis of one of these separate regimes can be useful for the description of another, and for the first time constrain the description of the bulk by the analysis of the hard probes.

The main idea behind high-pt QGP tomography

When high energy particles go through QGP they lose energy



This energy loss is sensitive to QGP properties

We can realistically predict this energy loss

High pt probes are powerful tomographic tools

Use them to infer some of bulk QGP properties

I. 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, Phys. Rev. C Rapid Commun. 100, 031901 (2019).

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 (D. Zigic *et al*, JPG 46, 085101 (2019))

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

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

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

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

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

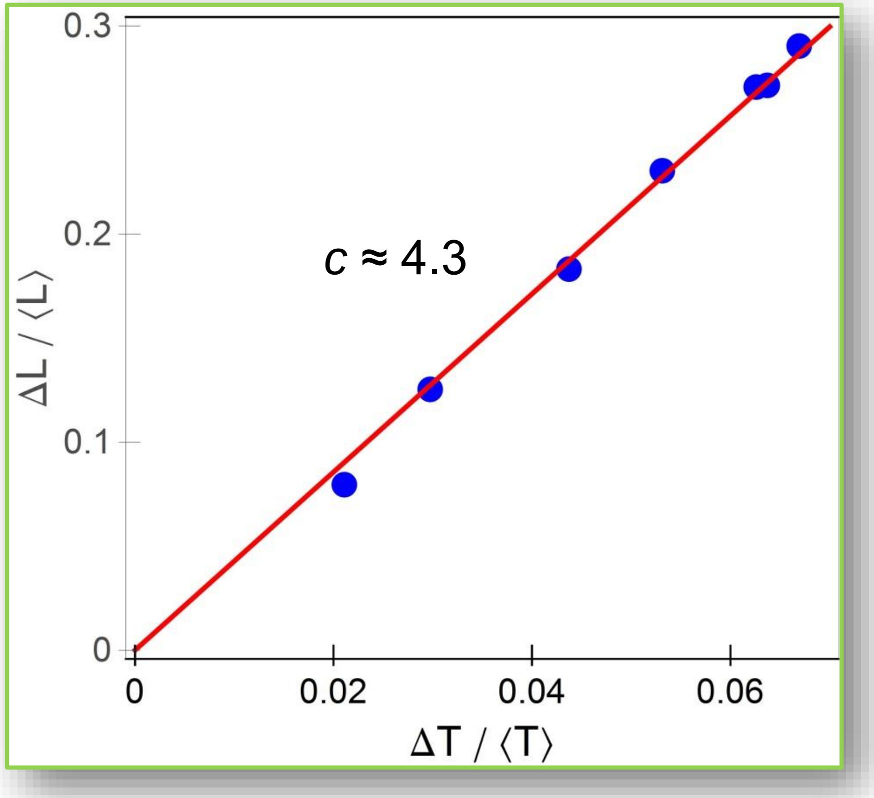
This ratio carries information on the asymmetry of the system, but through both spatial and temperature variables.

M.D., S. Stojku, M. Djordjevic and P. Huovinen, Phys.Rev. C Rapid Commun. 100, 031901 (2019).

Anisotropy parameter ς

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

Temperature and spatial assymetry:



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

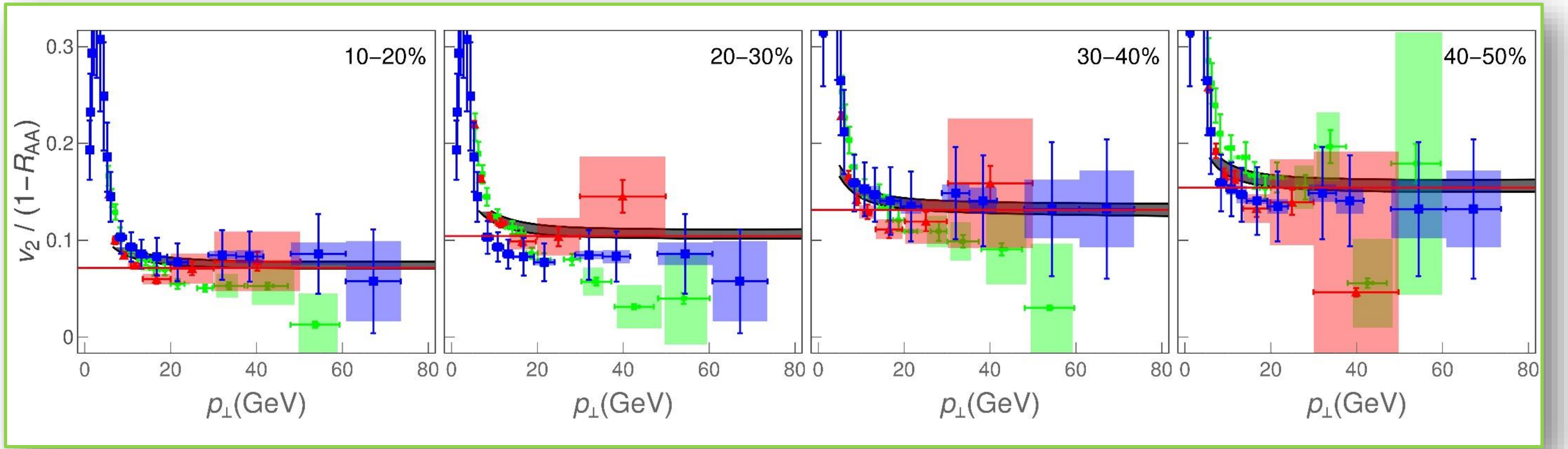
$$\varsigma = \frac{\Delta L}{\langle L\rangle} = \frac{\langle L_{out} - L_{in}\rangle}{\langle L_{out} + L_{in}\rangle}$$

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, Phys.Rev. C Rapid Commun. 100, 031901 (2019).

Predictions *vs.* data



- **Solid red line – analytically derived asymptote.**
- **For each centrality and from pt~20 GeV, $v_2/(1\text{-}R_{AA})$ 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.**

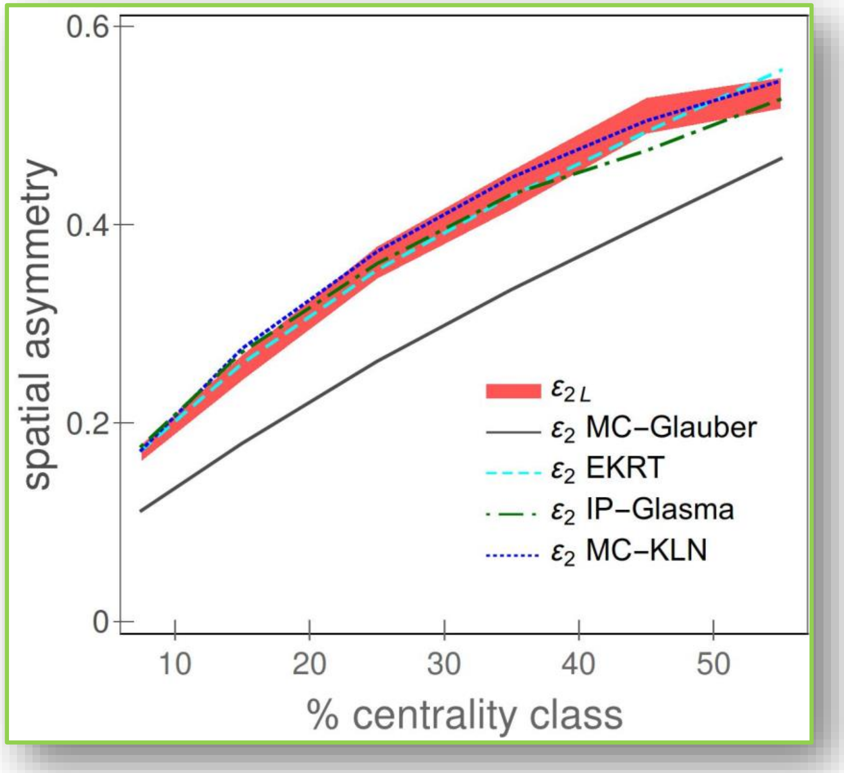
$v_2/(1\text{-}R_{AA})$ indeed carries the information about the system's anisotropy, which can be simply (from the straight line high-pt limit) and robustly (in the same way for each centrality) inferred from the experimental data.

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 for anisotropy inference.

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, Phys. Rev. C Rapid Commun. 100, 031901 (2019).

Summary of part I

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.

With a proper description of high-pt medium interactions, high-pt probes can also become powerful tomography tools, as they are sensitive to global QGP properties. We here showed that in the case of spatial anisotropy of the QCD matter.

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.

II. The QGP thermalization time

How high-pt R_{AA} and v_2 depend on the QGP thermalization time τ_0?

The dynamics before thermalization is not established yet.

As a baseline, we assume free streaming of high-pt particles before thermalization, and neglect the pre-equilibrium evolution.

After thermalization, the QCD medium is described as relativistic viscous fluid, and high-pt probes start to lose energy through medium interactions.

Consequently, the thermalization time is an important parameter, which affects both the evolution of the system and interactions of the high-pt particles with the medium.

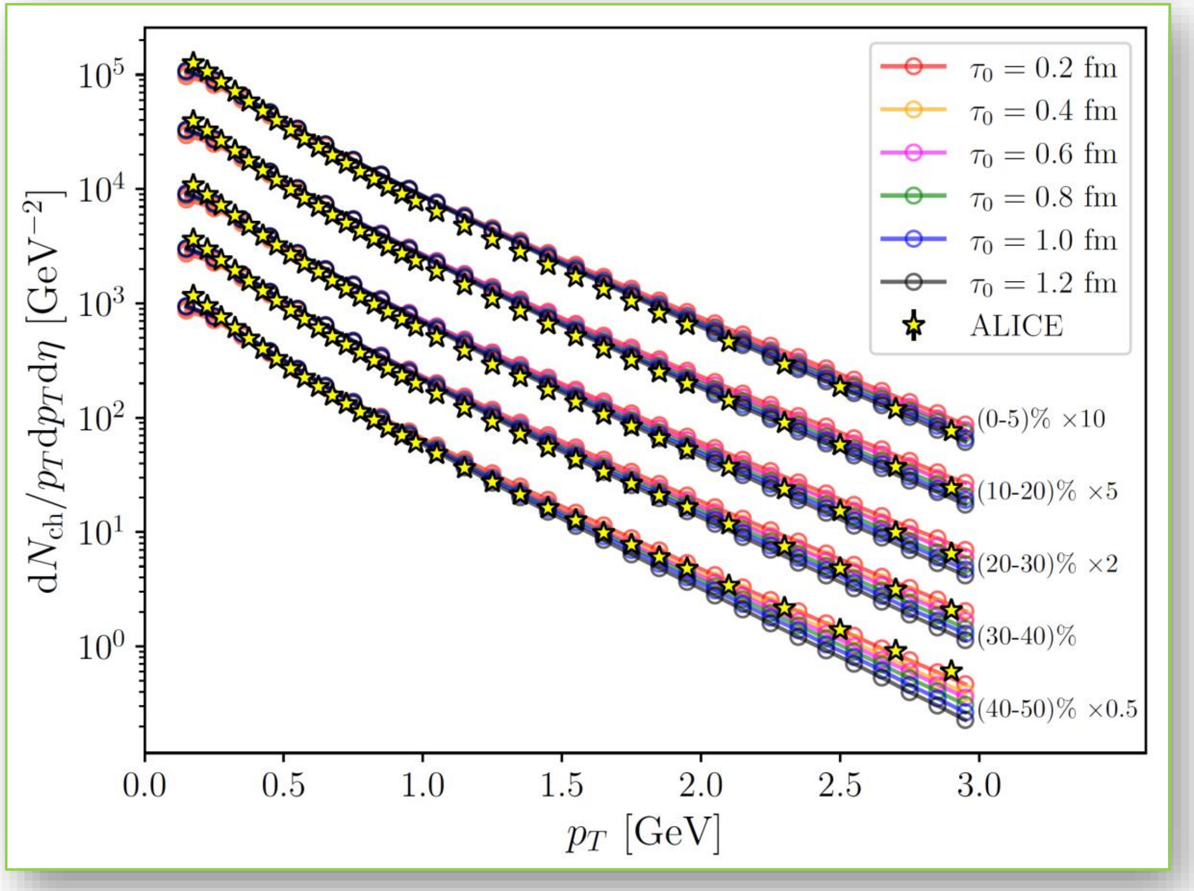
Low-pt physics weakly sensitive to thermalization time

S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, arXiv: 2008.08987

Bass *et al.* (2017) showed that comparison of relativistic hydrodynamics with low-pt data is insensitive to a wide range of thermalization time ($0.2 < \tau_0 < 1.2$fm).

Independently confirmed by our systematic analysis

3+1d viscous hydrodynamics model run with six different thermalization times.

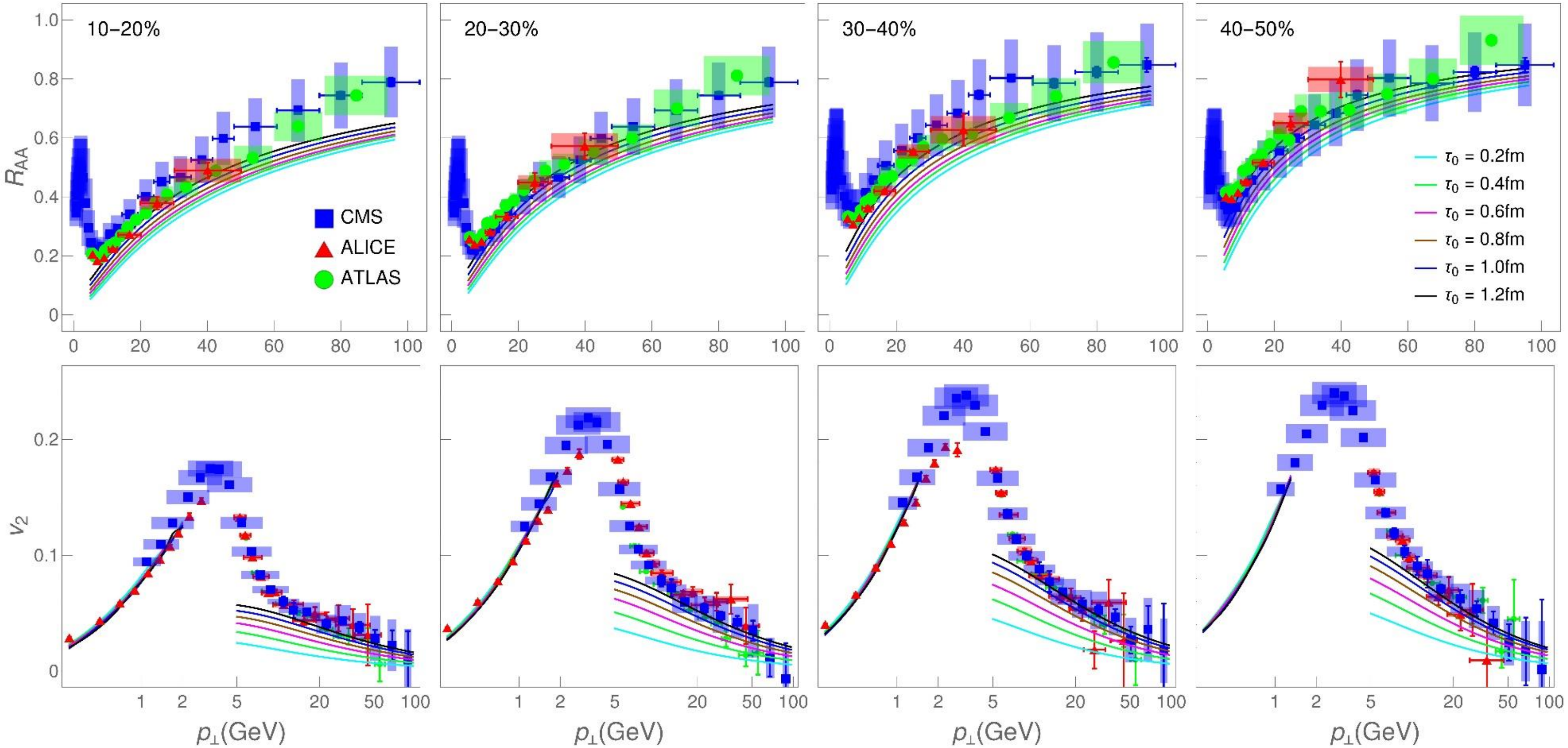


Good agreement with low-pt data, confirming low sensitivity to τ_0!

Can this indeterminacy be further constrained through high pt theory and data?

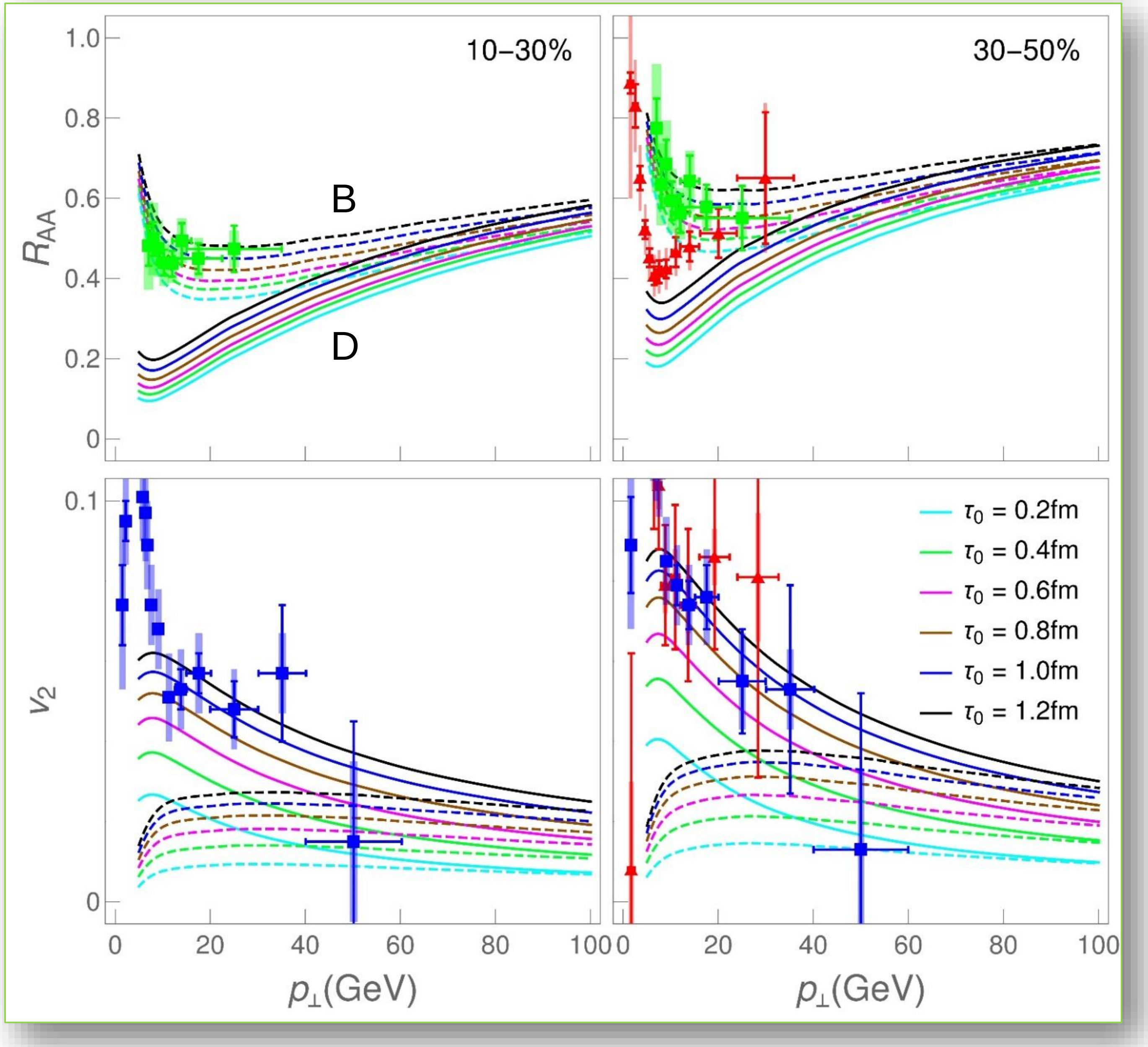
Sensitivity of high-pt theory and data to thermalization time

- Use our most recently developed DREENA-A framework, which is fully modular (‘Adaptive’), i.e. can include any *T* profile.
- **3+1d hydro profiles with different τ_0 included in DREENA-A to test the sensitivity.**



- **High-pt predictions can be clearly resolved against experimental data**
- **Robustly prefer latter τ_0 for both R_{AA} and v_2.**
- **Larger sensitivity of v_2 predictions. Asymptotically approach the high-pt tail of the experimental data, as τ_0 is increased.**

High-pt heavy flavor



S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, arXiv: 2008.08987

B mesons – dashed lines

D mesons – full lines

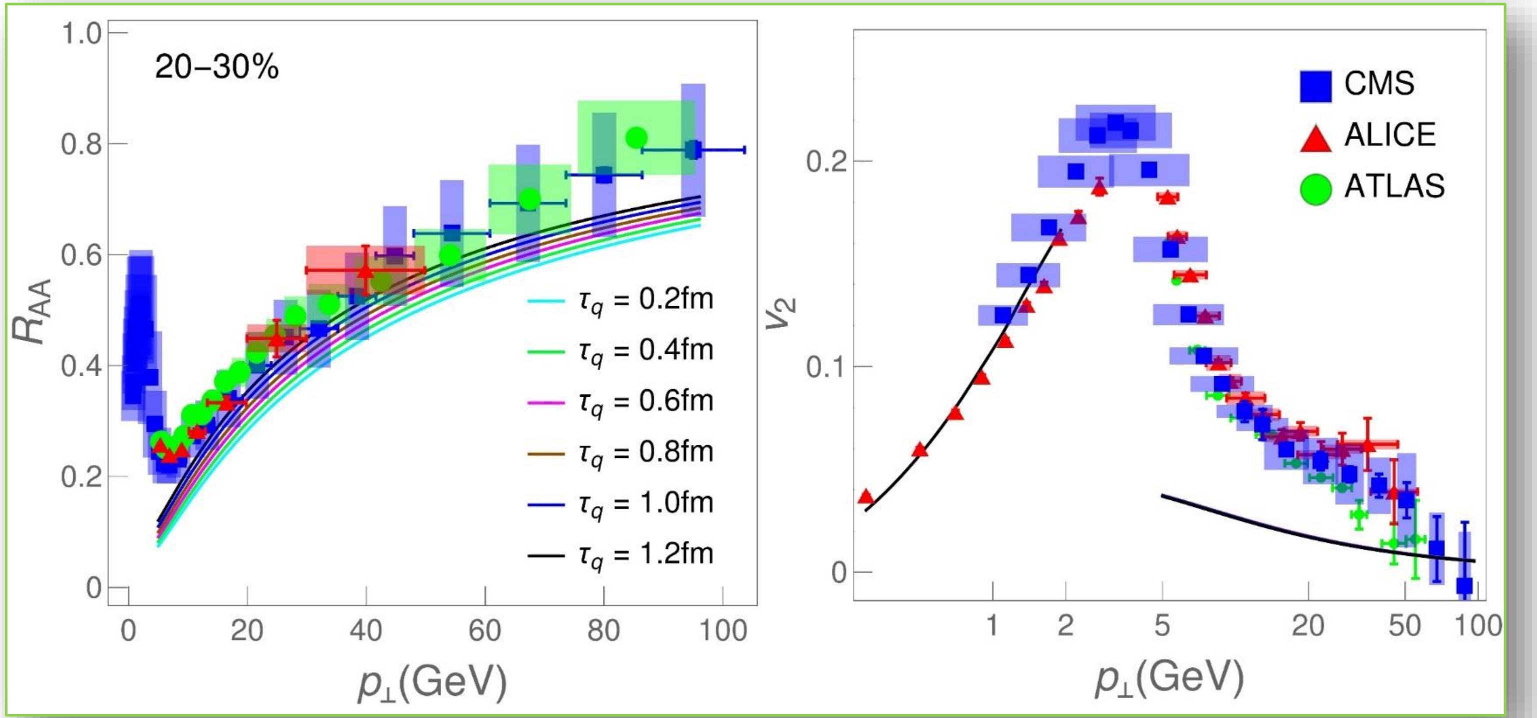
Moreover, sensitivity on τ_0 is even larger for heavy than for light flavor!

What is the reason behind such sensitivity? –
Does jet quenching starts later then thermalization?

(Andres et al. 2020) recently proposed that jet quenching may start later than the thermalization of the bulk QCD medium, which may strongly impact high-pt predictions.

To test this, we assume τ_0 = 0.2 fm, and generate T profile from full 3+1d hydro.

We then introduce the staring quenching time τ_q and generate joint R_{AA} and v_2 predictions for different τ_q.



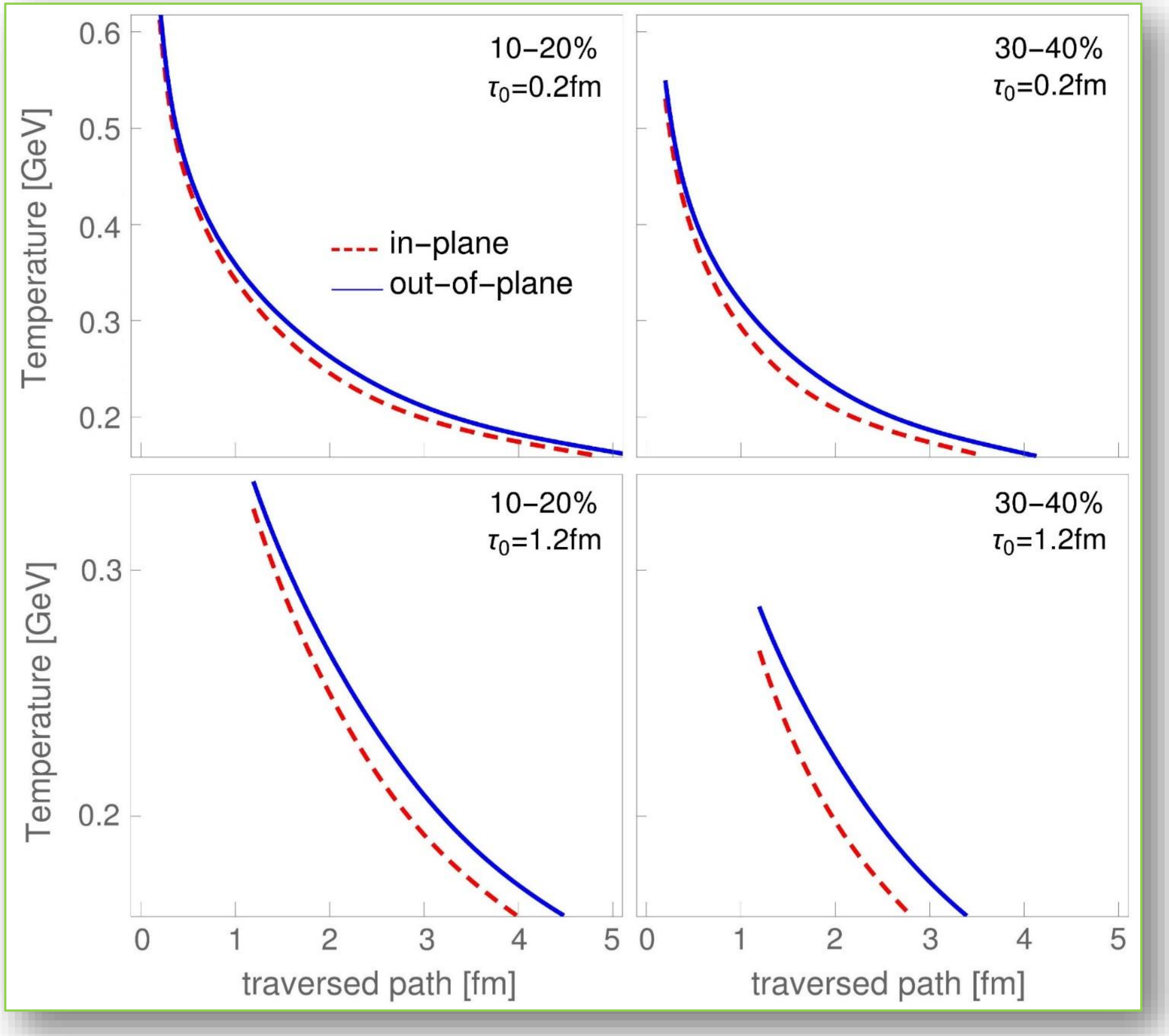
S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, arXiv: 2008.08987

RAA - weakly sensitivity to τ_q
v_2 - surprisingly entirely insensitive to τ_q and does not support the above proposal

Disputes the idea that jet quenching starts later than hydro evolution!

What is the reason behind such sensitivity? –

Is it due to the difference in the temperature profiles?



For two different centrality regions and two different τ_0, we compare in-plane and out-of-plane *T* profiles, averaged for all sampled jet paths.

v_2 is proportional to the difference in R_{AA}s along in-plane and out-of-plane directions.
Larger difference in R_{AA}s → larger v_2!

As τ_0 increases, the differences between in- and out-of-plane *T* profiles also increase, explaining observed increase in v_2.

Consequently, the temperature profile differences are a major contributor to such sensitivity.

S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, arXiv: 2008.08987

Summary of part II

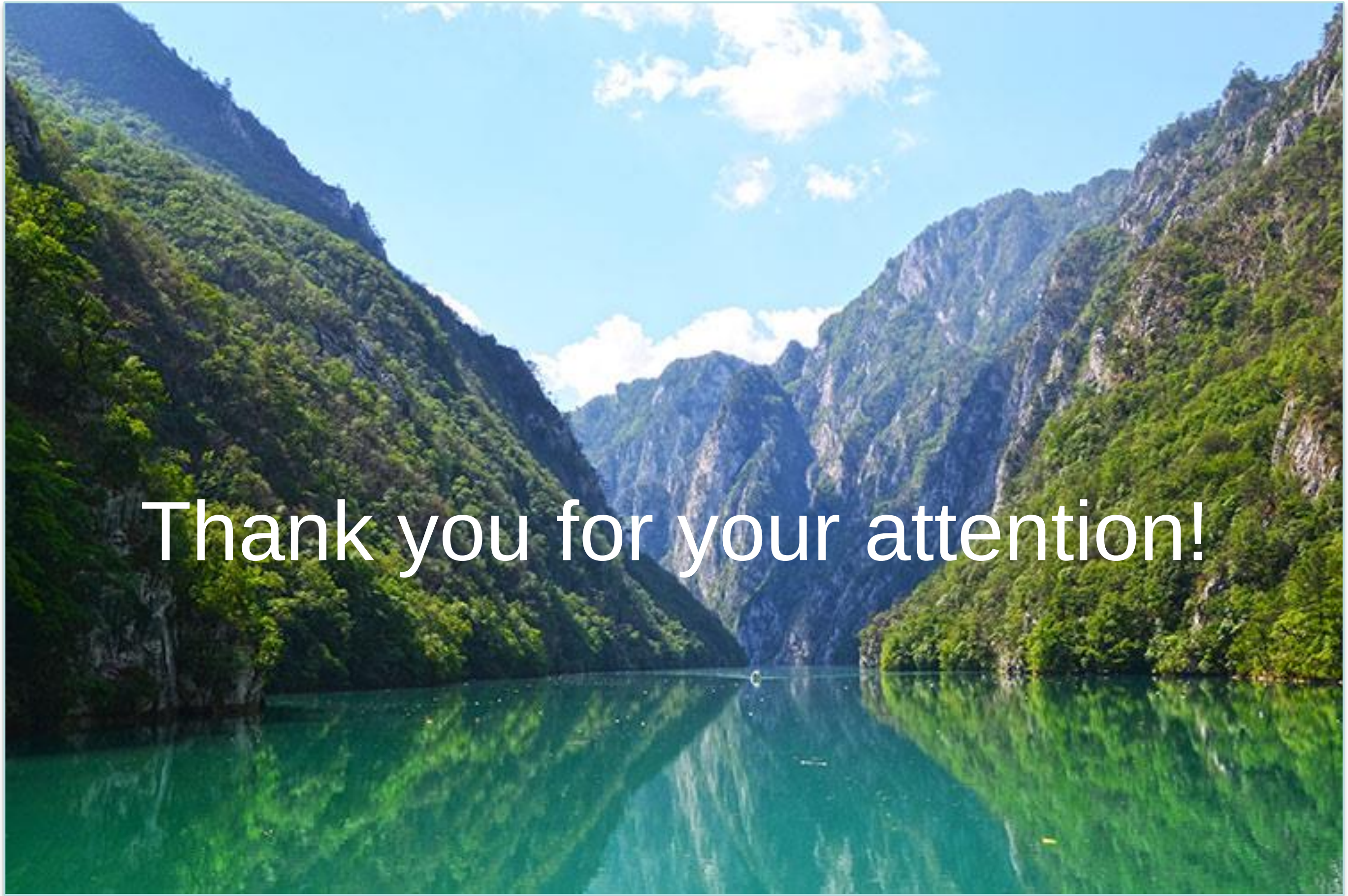
We here presented (to our knowledge) the first example where the parameter critical for simulating bulk QGP evolution, but (to a large extent) insensitive to low-pt physics, is constrained by high-pt theory and data.

Specifically, we here used high-pt R_{AA} and v_2 to infer that the late thermalization times are clearly preferred by experimental data!

Heavy flavor show larger sensitivity to τ_0, to be tested by the upcoming high luminosity measurements.

v_2 is more sensitive to τ_0 than R_{AA}, where this sensitivity is due to differences in the in- and out-of-plane T profiles.

This study demonstrates inherent interconnections between low and high-pt physics, strongly supporting the utility of our proposed QGP tomography approach, where bulk QGP properties are *jointly* constrained by low and high-pt data.



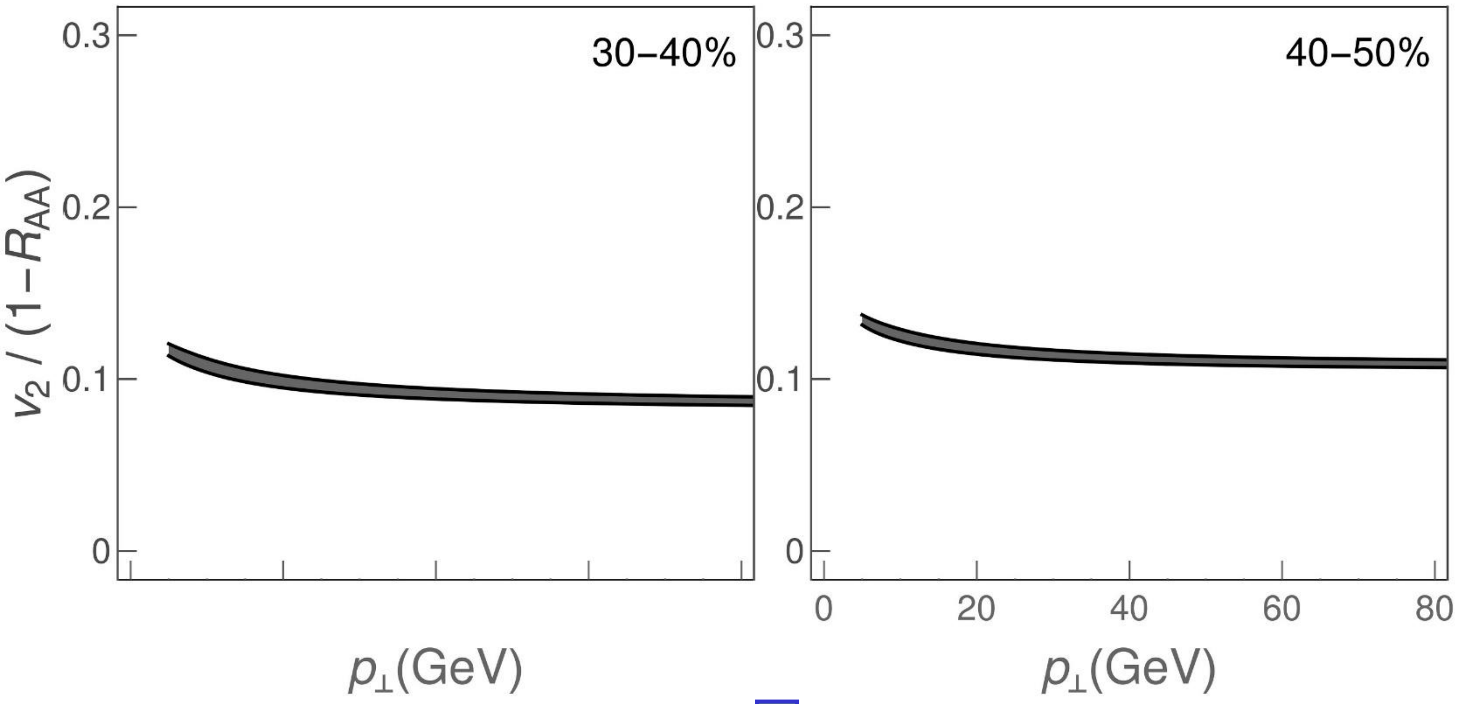
Canyon of river DREENA in Serbia

European Research Council
Established by the European Commission

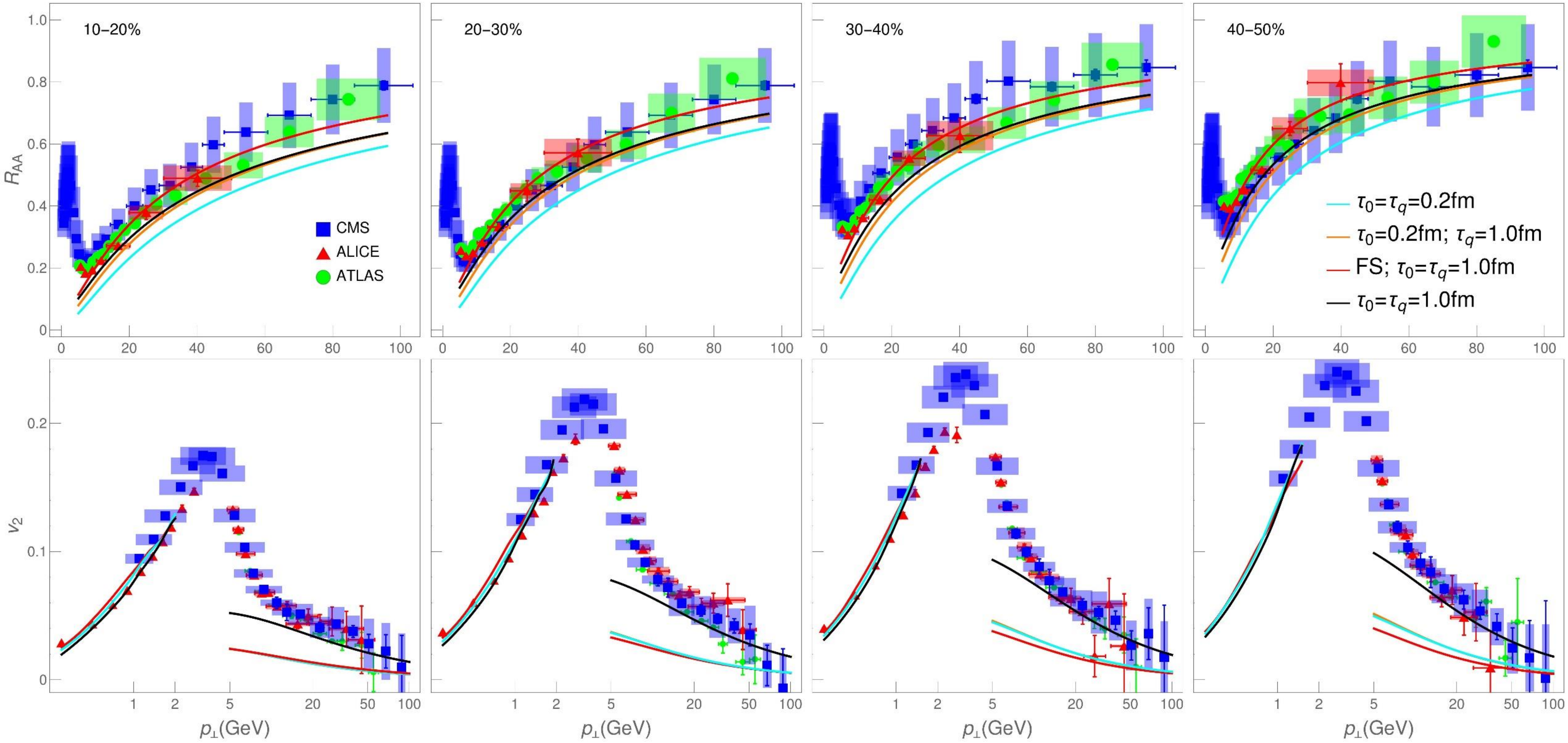
МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

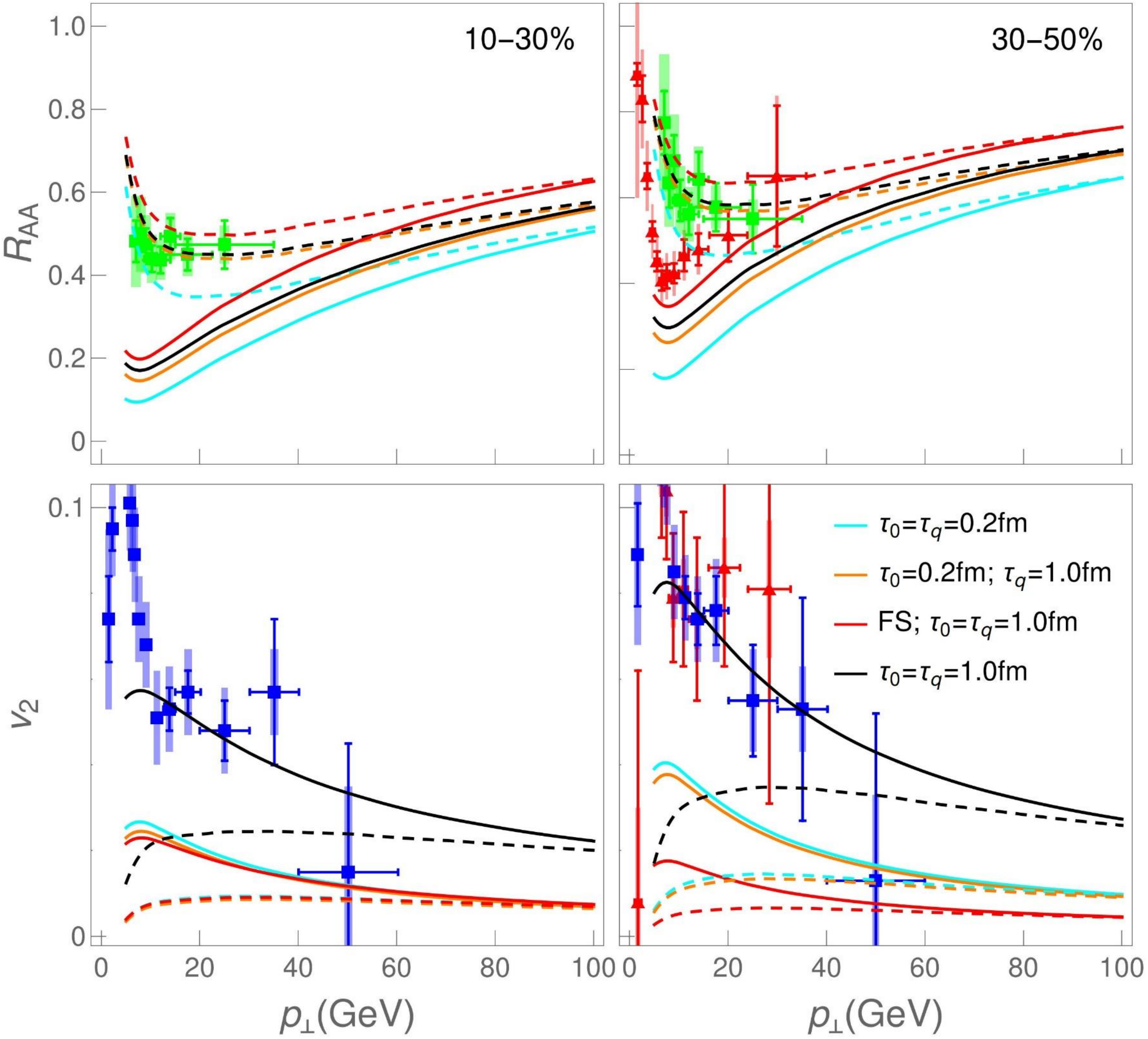
Backup

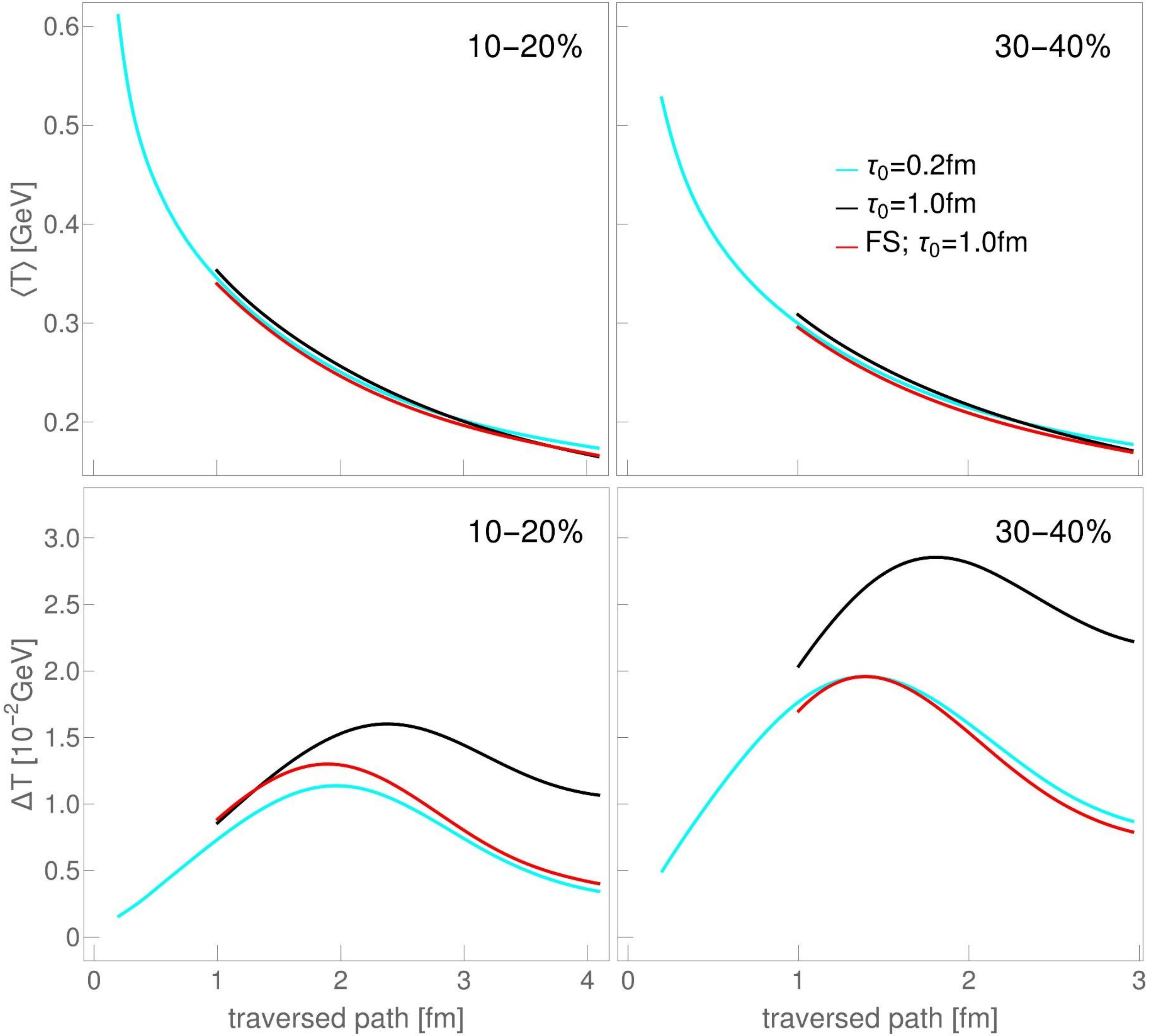
$v_2/(1-R_{AA})$predictions with 3+1D hydro DREENA



Flattnes still observed when full hydro is implemented.


10–20%
20–30%
30–40%
40–50%
R_{AA}
v_2
CMS
ALICE
ATLAS
τ_0=τ_q=0.2fm
τ_0=0.2fm; τ_q=1.0fm
FS; τ_0=τ_q=1.0fm
τ_0=τ_q=1.0fm
0
0.2
0.4
0.6
0.8
1.0
20
40
60
80
100
0.1
1
2
5
50
$p_\perp$(GeV)

10−30%
30−50%
R_{AA}
v_2
1.0
0.8
0.6
0.4
0.2
0
0.1
0
0
20
40
60
80
100
$p_\perp$(GeV)
$p_\perp$(GeV)
$\tau_0=\tau_q=0.2$fm
$\tau_0=0.2$fm; $\tau_q=1.0$fm
FS; $\tau_0=\tau_q=1.0$fm
$\tau_0=\tau_q=1.0$fm

10−20%
30−40%
τ₀=0.2fm
τ₀=1.0fm
FS; τ₀=1.0fm
⟨T⟩ [GeV]
0.6
0.5
0.4
0.3
0.2
ΔT [10⁻²GeV]
3.0
2.5
2.0
1.5
1.0
0.5
0
0
1
2
3
4
traversed path [fm]
0
1
2
3
traversed path [fm]