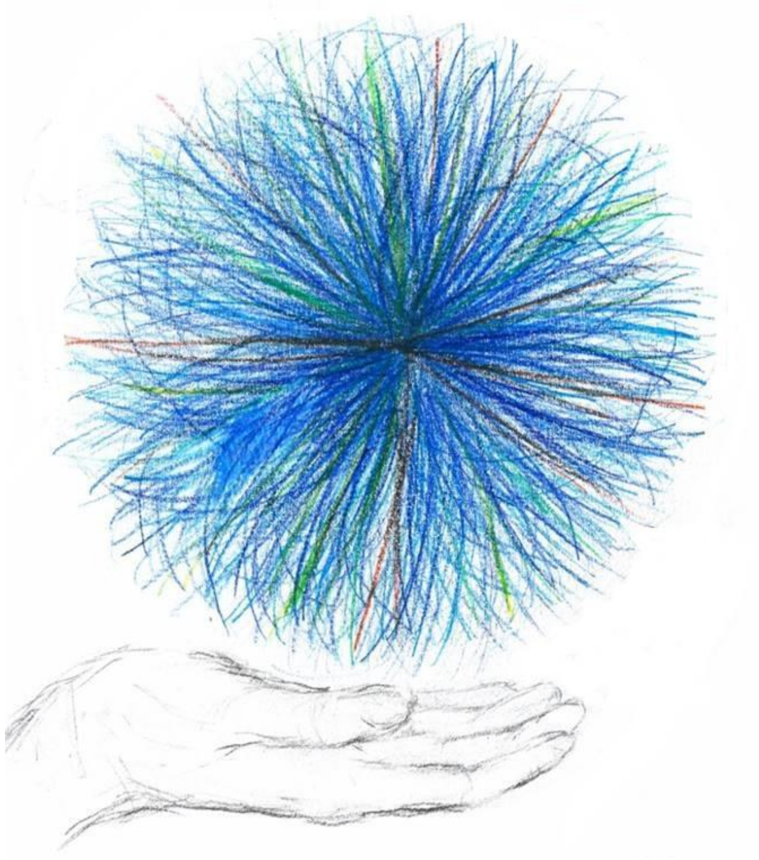

Exploring QGP properties with high-pt heavy flavor

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European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

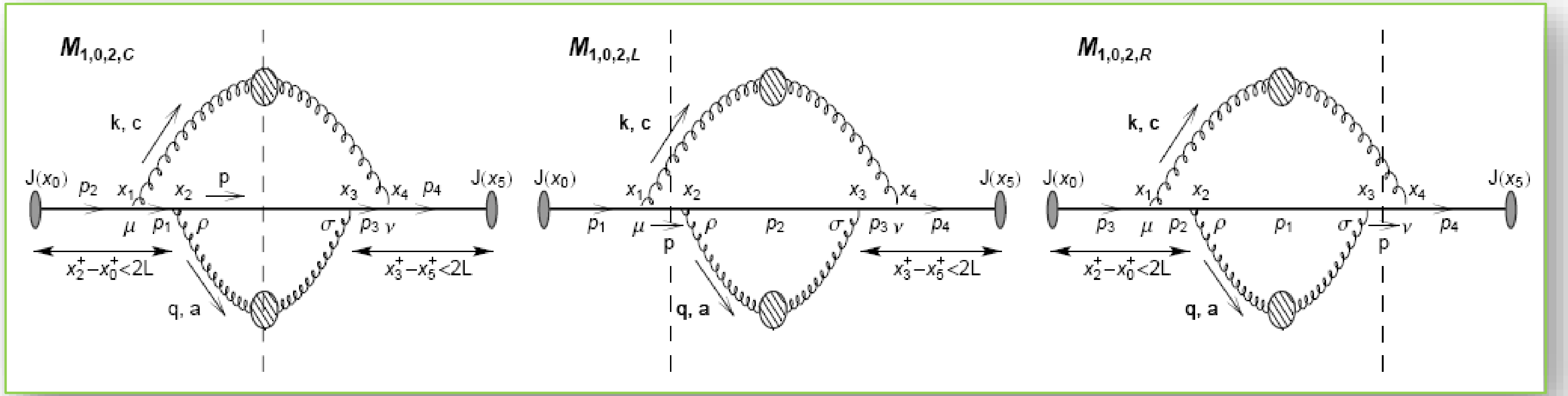
Motivation

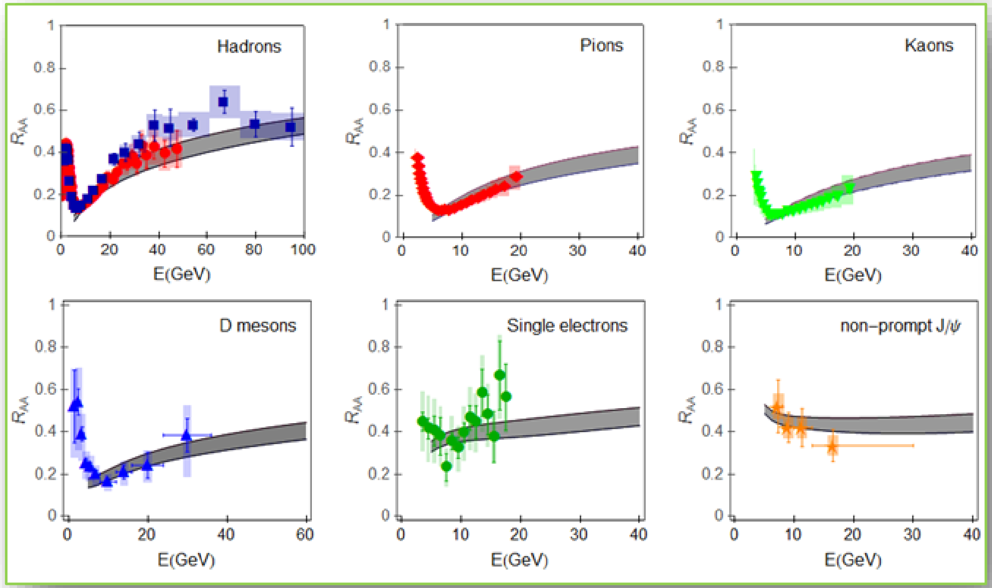
- Energy loss of high-pt light and heavy particles traversing the QCD medium is an excellent probe of QGP properties.
- Theoretical predictions can be compared with a wide range of data from different experiments, collision systems, collision energies, centralities, and observables.
- Can be used with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

The dynamical energy loss formalism

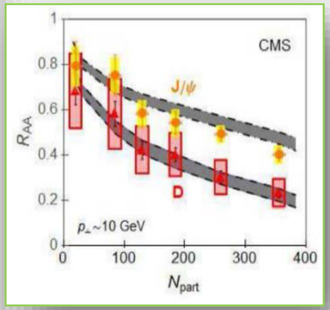
Has the following unique features:

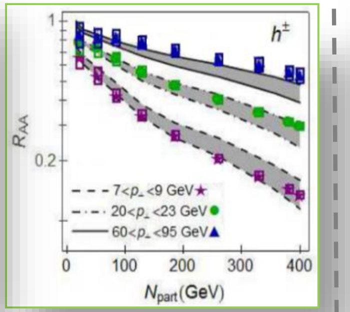
- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite T field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M. D. 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)).
- All these ingredients necessary to accurately explain the data (B. Blagojevic and M.D, J.Phys. G42 (2015) 7, 075105).
- No fitting parameters in the model.
- Temperature as a natural variable in the model.



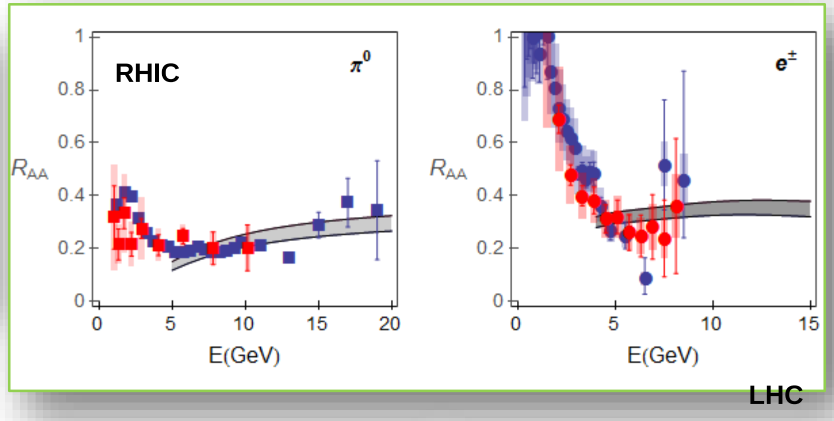


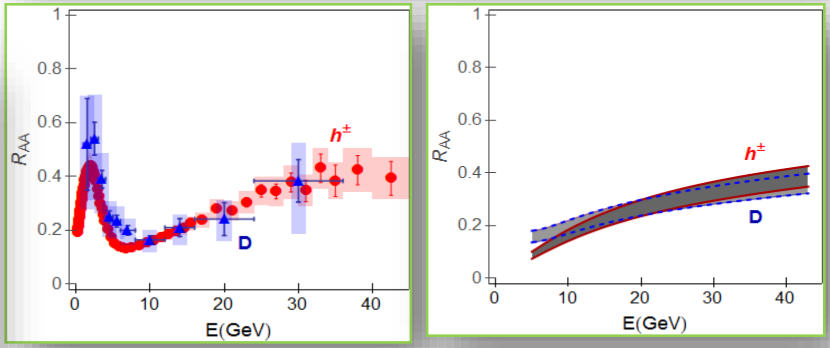
Explains high-pt R_{AA} data for different probes, collision energies, and centralities.





Resolved the longstanding "heavy flavor puzzles at RHIC and LHC".

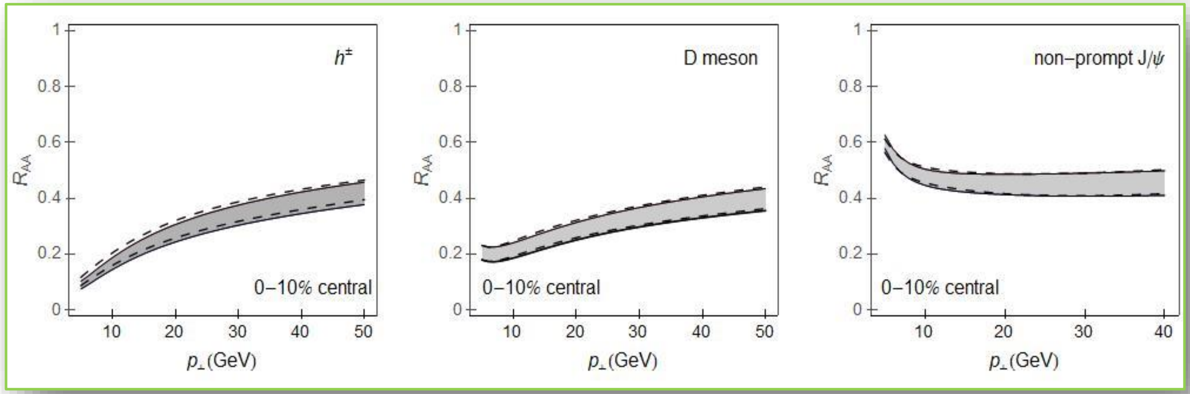


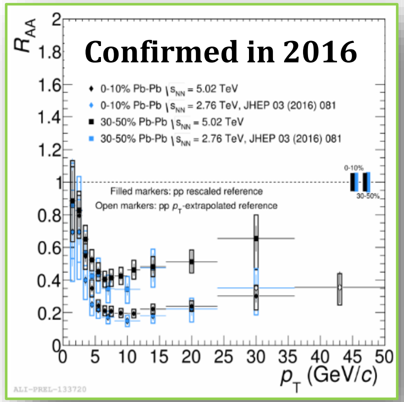


M.D., PRL 112, 042302 (2014)

Clear predictive power!

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

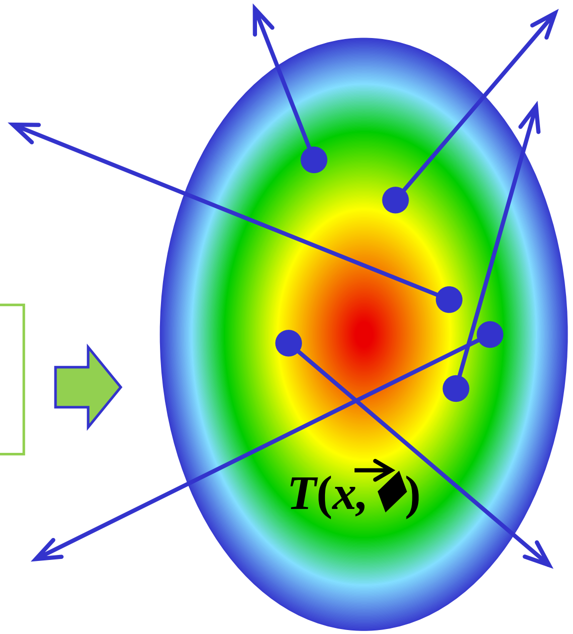




A realistic description for parton-medium interactions! → Suitable for QGP tomography!

The main idea behind high-pt QGP tomography

When high-pt 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 bulk QGP properties.

DREENA-A framework as a QGP tomography tool

To use high pt data/theory to explore the bulk QGP:

- Include any, arbitrary, medium evolution as an input.
- Preserve all dynamical energy loss model properties.
- Develop an efficient (timewise) numerical procedure.
- Generate a comprehensive set of light and heavy flavor predictions.
- Compare predictions with the available experimental data.
- If needed, iterate a comparison for different combinations of QGP medium parameters.
- Extract medium properties consistent with both low and high-pt theory and data.

⇩

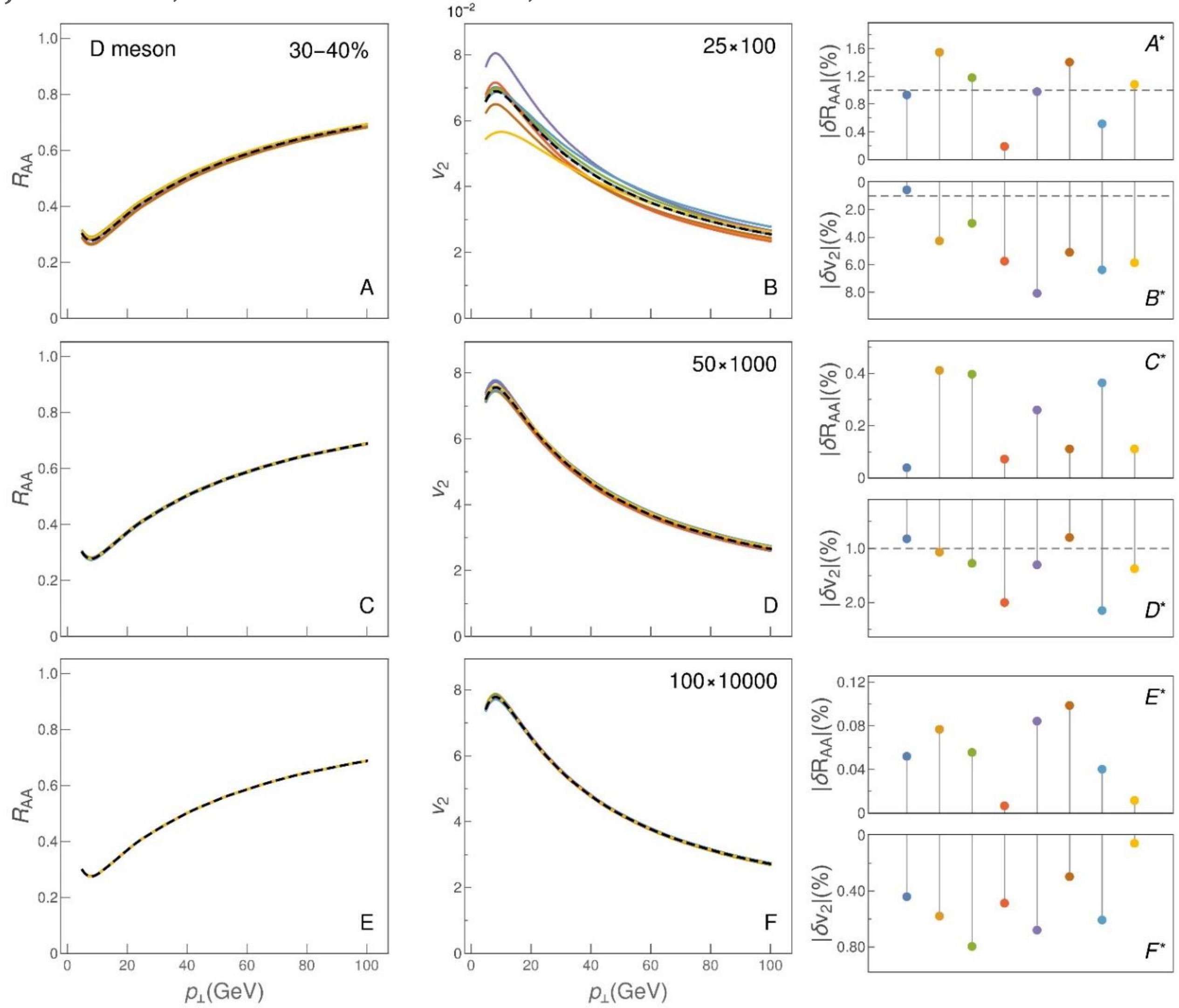
Develop fully optimized DREENA-A framework.

DREENA: Dynamical Radiative and Elastic ENergy loss Approach.
A: Adaptive temperature profile.

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544

Monte Carlo

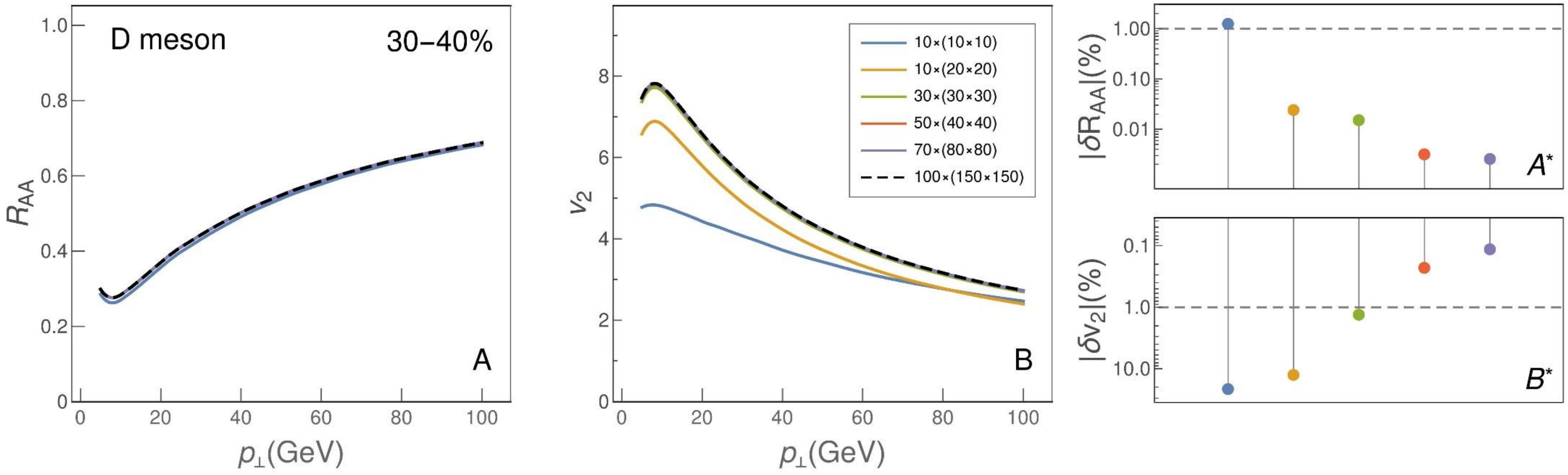
D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544



Not very efficient!

For v_2, one million trajectories needed to achieve a precision below 1%.

Equidistant sampling



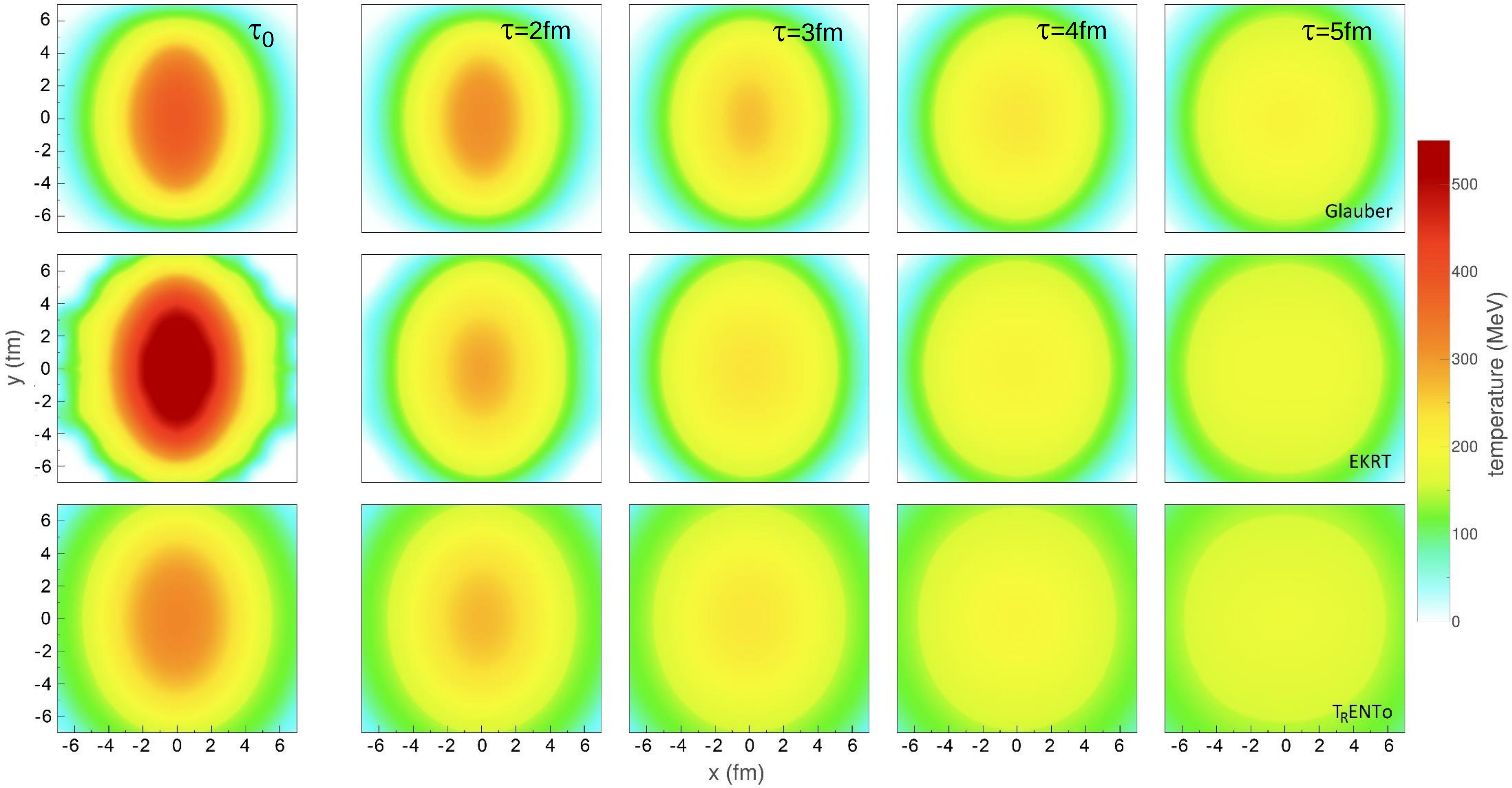
Two orders of magnitude increase in the efficiency!

For v_2, only 10000 trajectories needed to achieve ~ 1% precision.

Can efficiently generate predictions for all types of probes for arbitrary temperature profiles!

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544

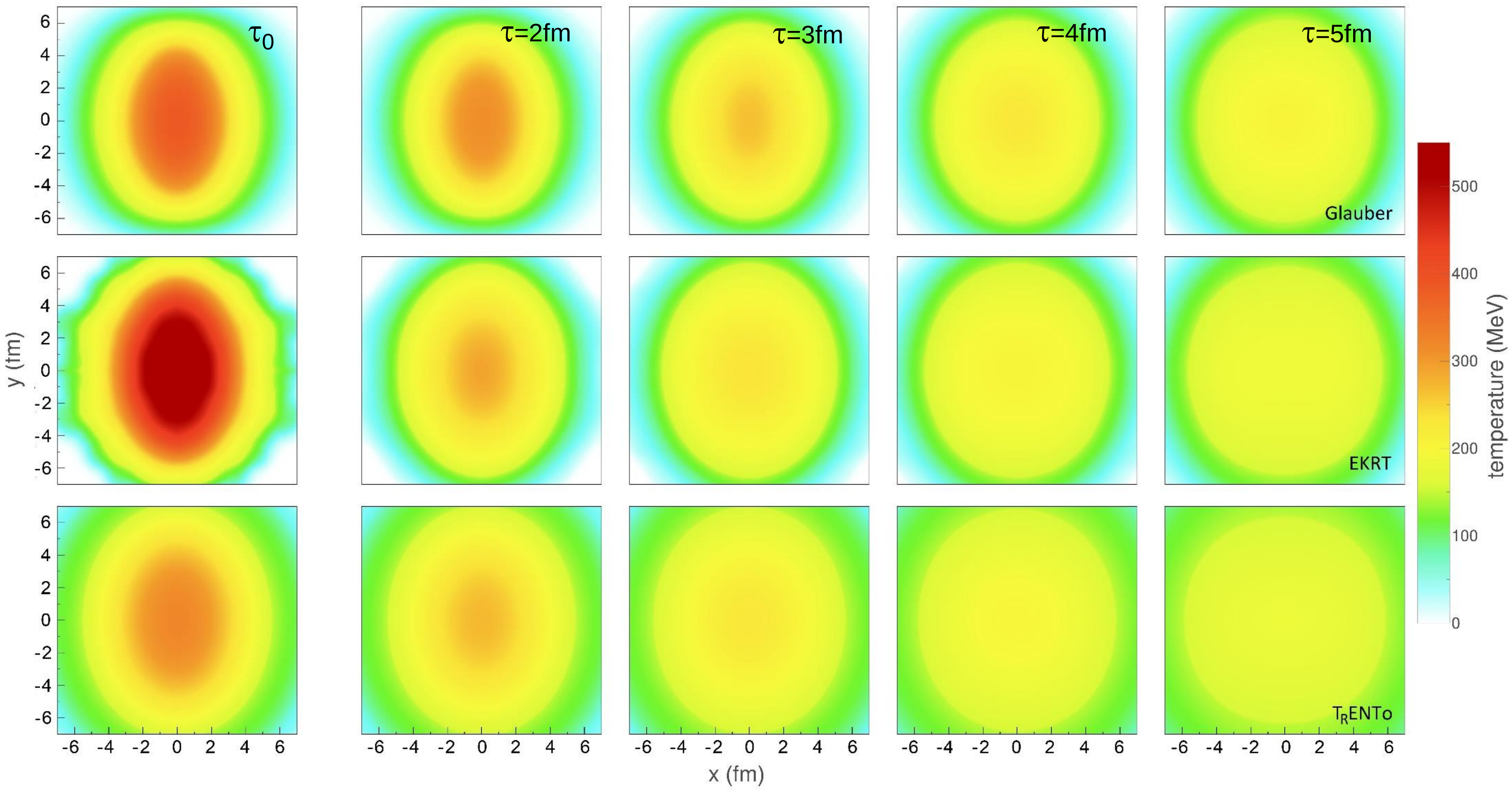
Are high-pt observables indeed sensitive to different T profiles?



All three evolutions agree with low-pt data. Can high pt-data provide further constraint?

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544

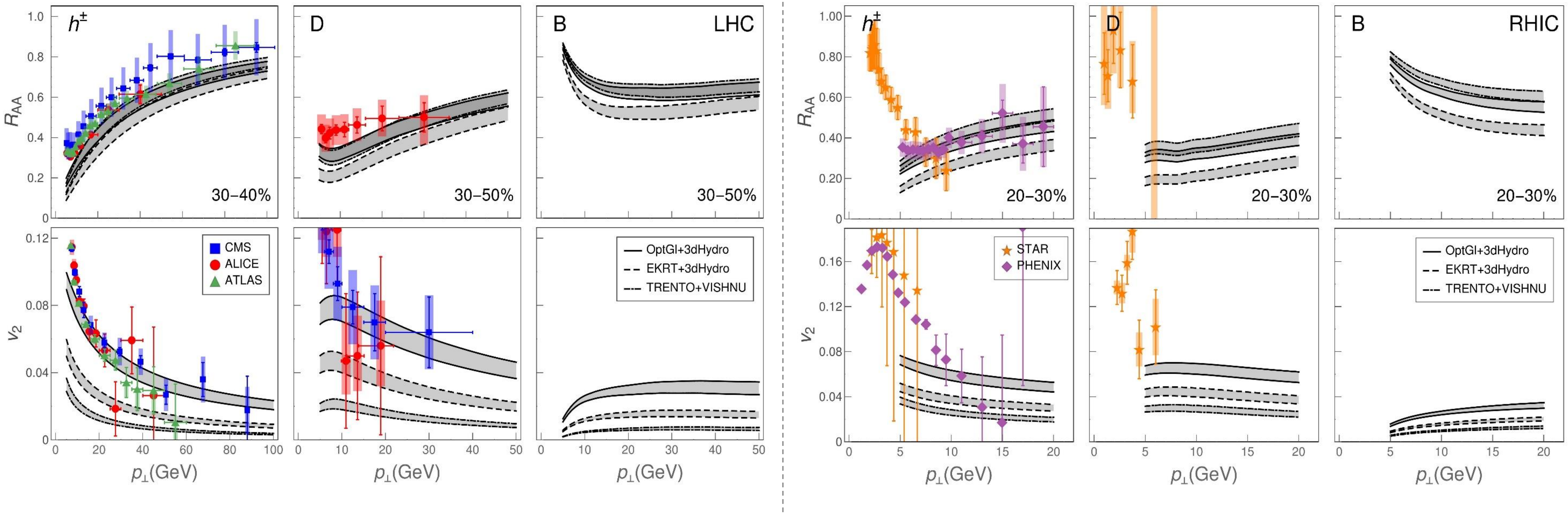
Qualitative differences



- Largest anisotropy for Glauber (τ_0=1fm) – expected differences in high-pt v_2.
- EKRT shows larger temperature - smaller R_{AA} expected.

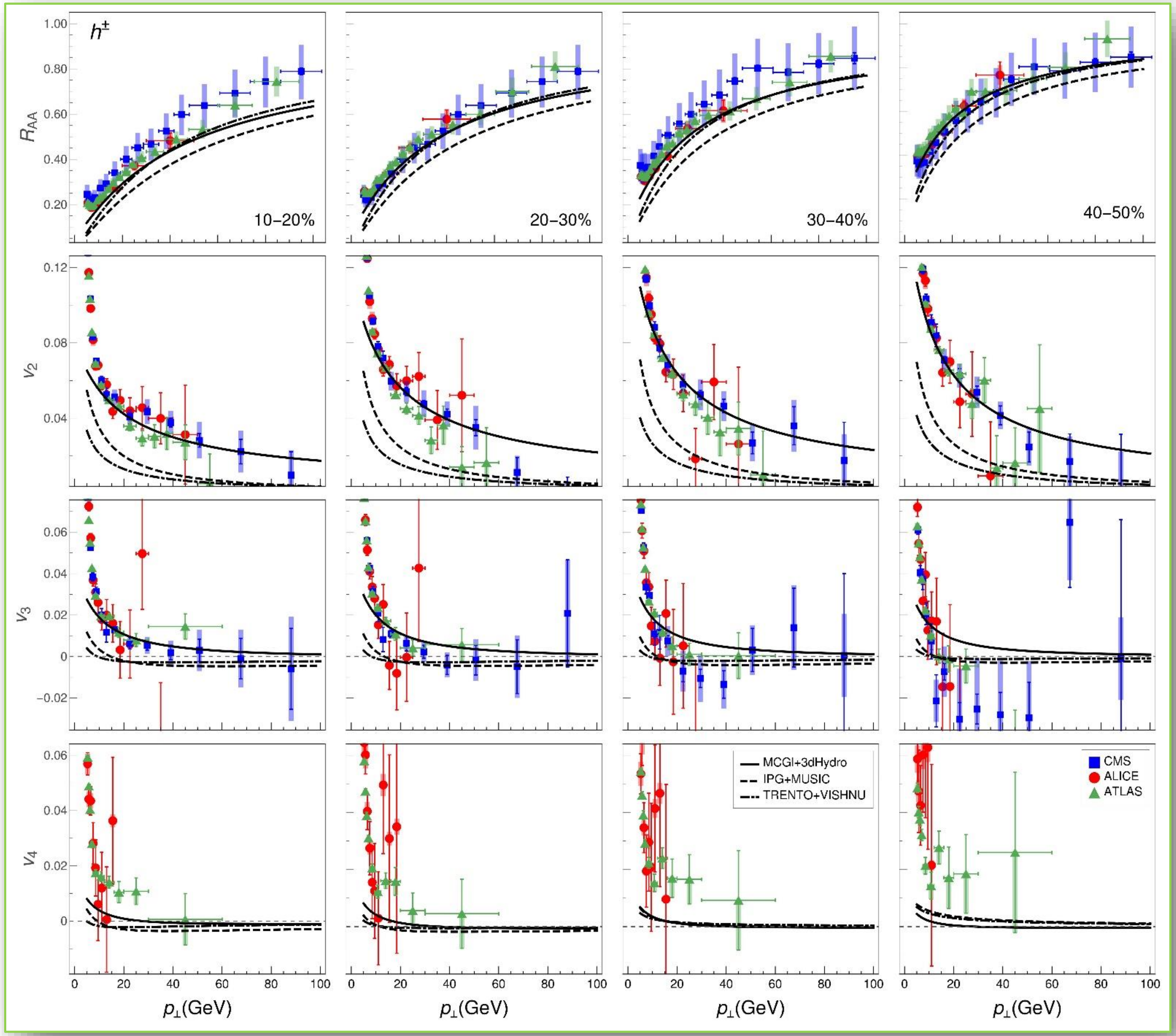
DREENA-A predictions for light and heavy flavor

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544



- 'EKRT' indeed leads to the smallest R_{AA}.
- Anisotropy translates to v_2 differences ('Glauber' largest, T_RENTo lowest).
  - DREENA-A can differentiate between different *T* profiles.
    - Additional (independent) constraint to low-pt data.

Importance of higher harmonics for QGP tomography

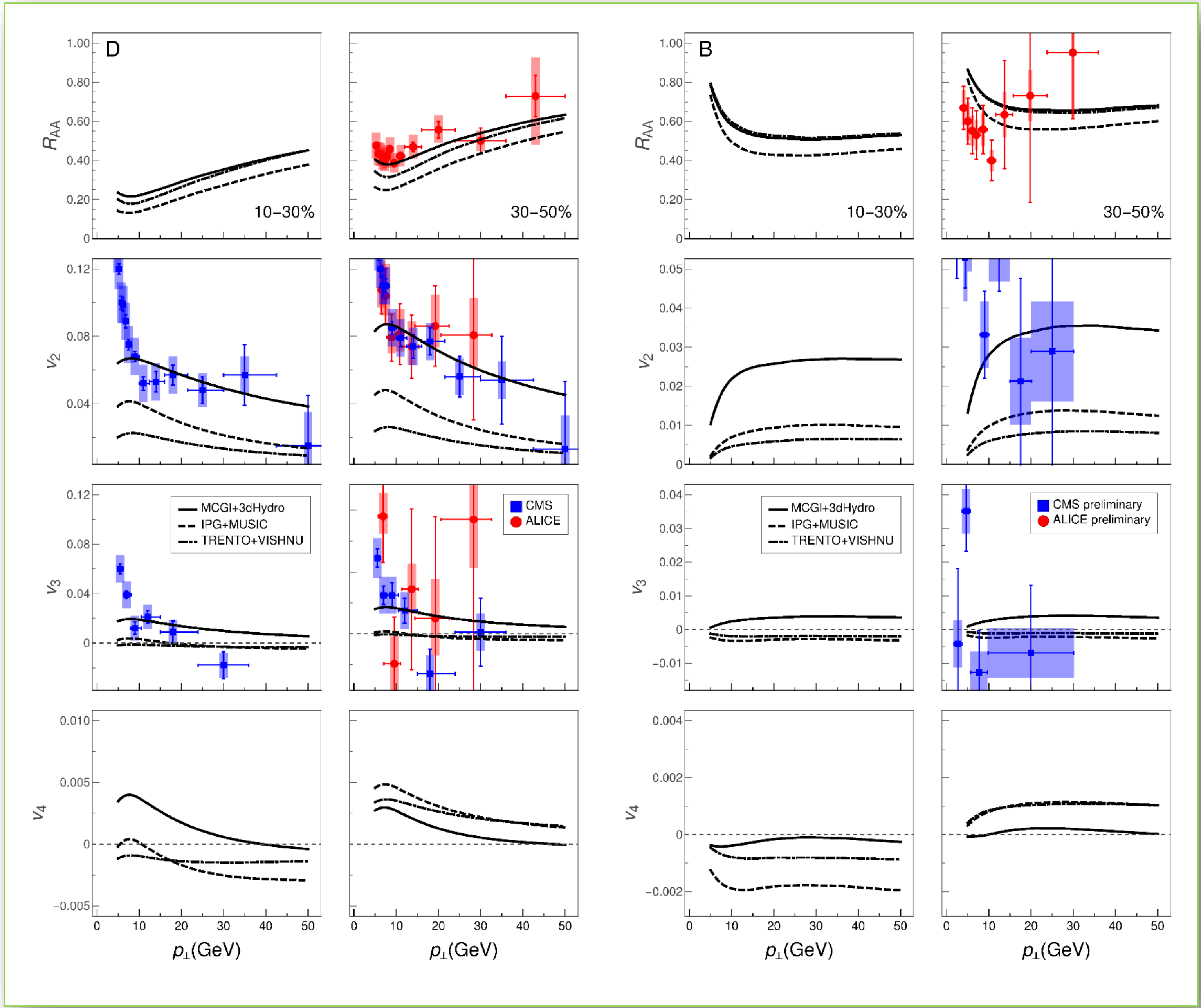


D. Zigic, J. Auvinen, I. Salom, P. Huovinen and MD, PRC under revision

- High-pt data are available up to the 7th harmonic (for ATLAS) and cover the pt region up to 100 GeV (for CMS).
- State of the art in the experimental sector, but theoretically not well explored!
- **Can higher harmonics be used for precision QGP tomography?**

- Higher harmonics can both qualitatively and quantitatively distinguish between different medium evolutions!
- Existent v_4 data are far above all model predictions – a possible v_4 puzzle!

Heavy flavor higher harmonics



D. Zigic, J. Auvinen, I. Salom, P. Huovinen and MD, PRC under revision

- Heavy flavor - even more sensitive to different medium evolutions!
- Upcoming high-luminosity data at RHIC and LHC will provide higher harmonics data with much larger precision.
- Higher harmonics present a unique opportunity for precision QGP tomography.
- Adequate medium evolution should be able to explain all experimental data simultaneously, for both light and heavy flavor, at different centralities, collision energies, and collision systems.

Summary up to now

DREENA-A is a fully optimized numerical implementation of the dynamical energy loss.

Can include arbitrary temperature profiles, both averaged and event-by-event.

No additional free parameters.

High-pt R_{AA}, v_2, and higher harmonics show qualitative and quantitative sensitivity to details of *T* profile differences.

Intuitive expectations agree with DREENA-A calculations.

Applicable to different types of flavor, collision systems, and energies.

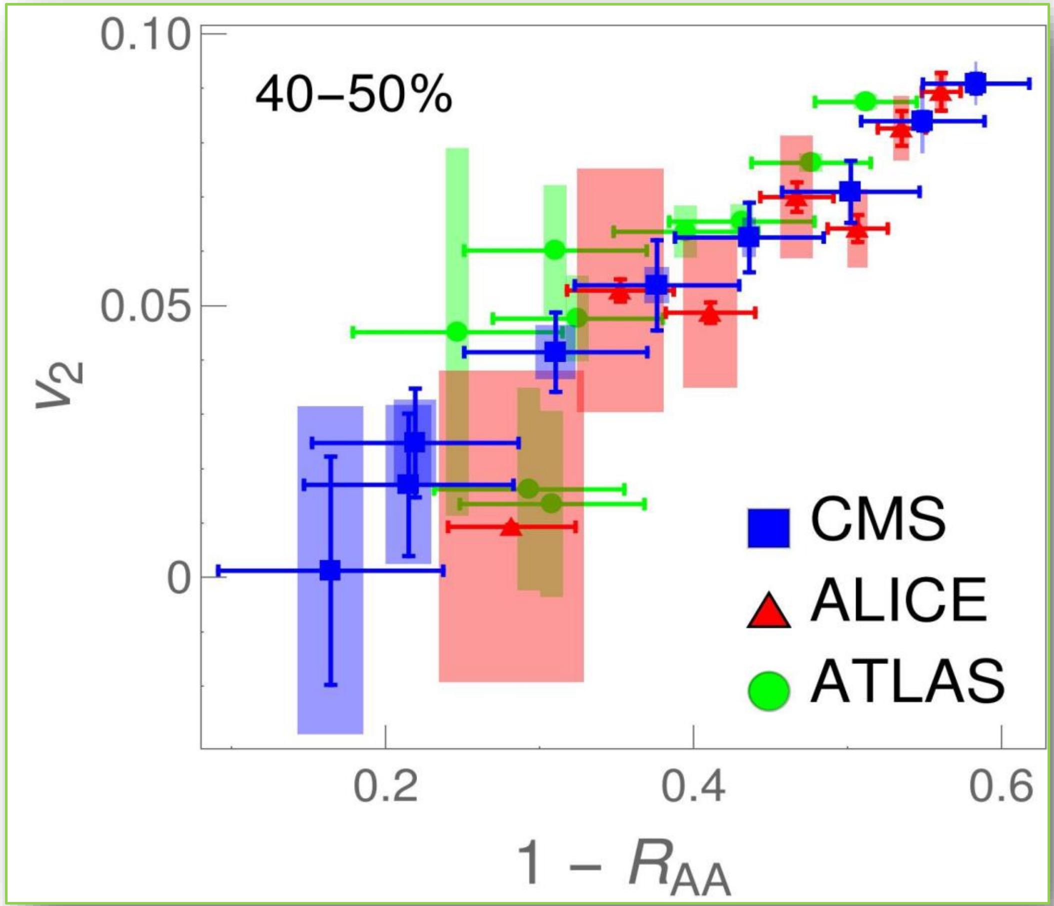
APPLICATION: An efficient QGP tomography tool for constraining the medium properties by both high-pt and low-pt data.

Anisotropy of the QGP droplet

How to use high-pt data to infer spatial anisotropy of QGP?

Spatial anisotropy: one of the main properties of QGP, and a major limiting factor for QGP tomography.

We propose a novel approach, based on inference from already available high-pt R_{AA} and v_2 measurements.

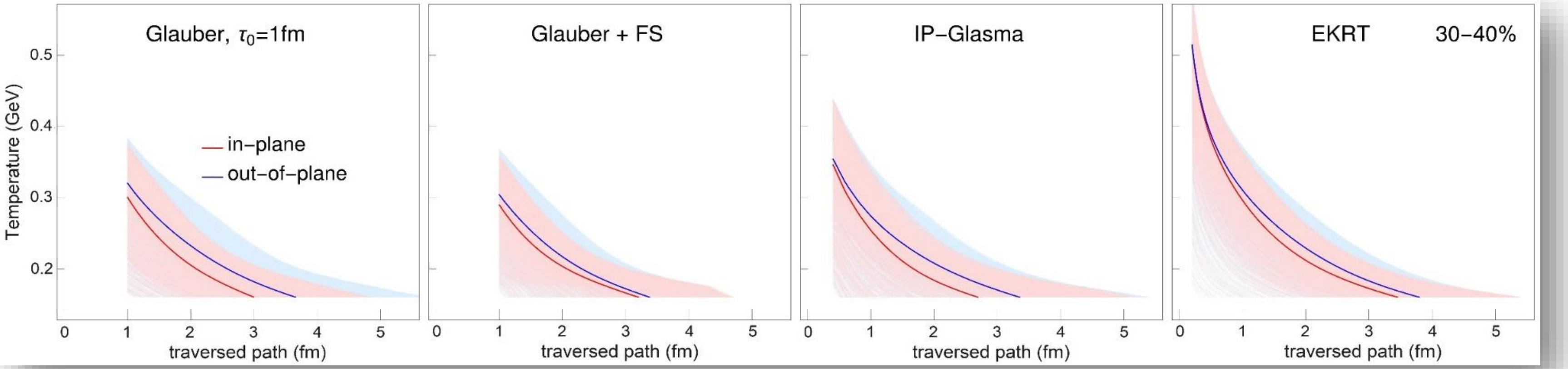


S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, MD, arXiv:2110.02029

Experimental observation: v_2 and $1-R_{AA}$ are directly proportional at high-pt!
Equivalent to a pt-independent ratio of v_2 and $1-R_{AA}$.

Can fluid dynamical calculations reproduce such proportionality?
Can we relate this observation to a physical property of the system, namely to its anisotropy?

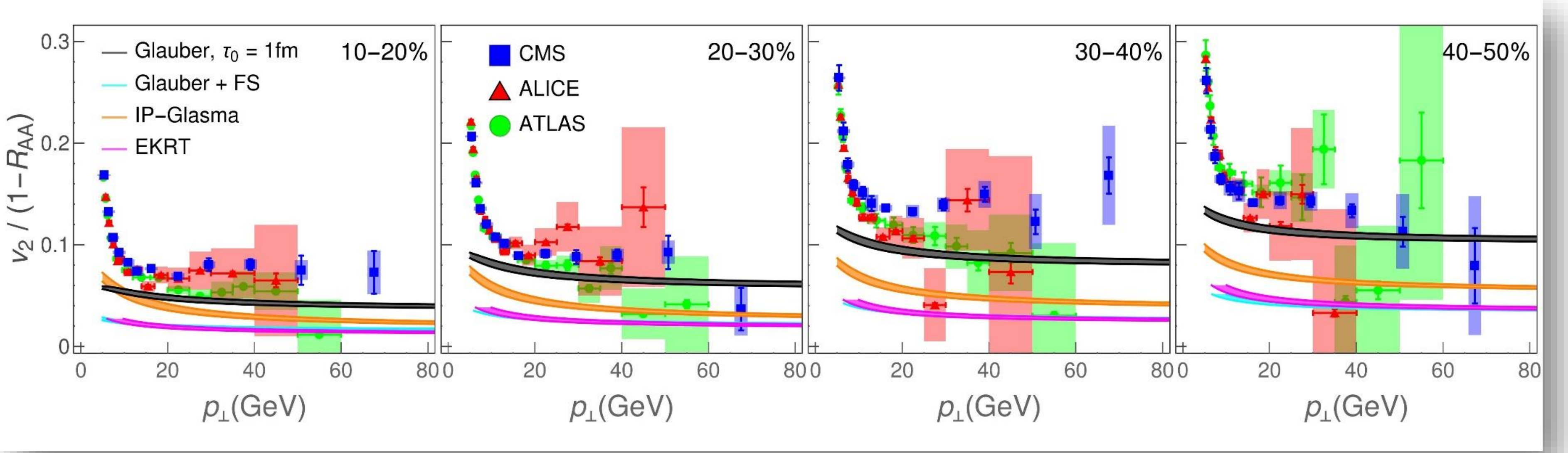
Study 9 different medium evolution scenarios, all tuned to reproduce low-pt data!



S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, MD, arXiv:2110.02029

Partons traveling in the in- and out-of-plane directions experience different temperatures in different scenarios.

- Different v_2 and R_{AA} for high-pt particles are expected.
- Does $v_2/(1 - R_{AA})$ saturate for all scenarios?

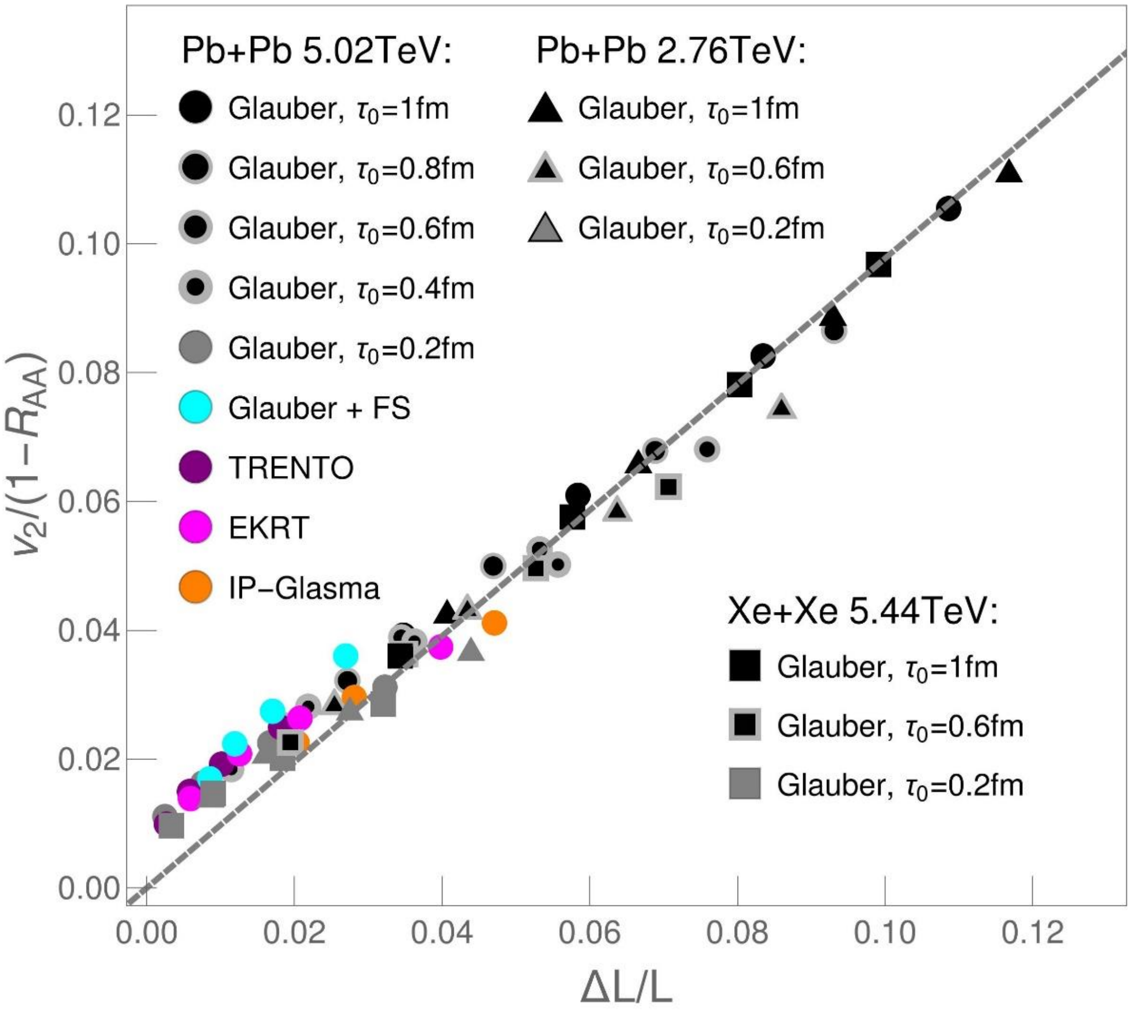


$v_2/(1 - R_{AA})$ saturation is robust!

Does it carry the information on the system's anisotropy?

Connection to anisotropy

- For each evolution scenario, evaluate the average path length of partons $\langle L \rangle$ and its anisotropy $\Delta L/\langle L \rangle$.
- Plot charged hadrons' $v_2/(1 - R_{AA})[100GeV]$ vs. $\Delta L/\langle L \rangle$.



S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, MD, arXiv:2110.02029

- Centrality classes: 10-20%, 20-30%, 30-40%, 40-50%
- Surprisingly simple relation between $v_2/(1 - R_{AA})$ and $\Delta L/\langle L \rangle$.
- Slope ≈ 1.
- $v_2/(1 - R_{AA})$ carries information on the system anisotropy through $\Delta L/\langle L \rangle$.

Is it possible to define a more direct measure of anisotropy with an explicit dependence on time evolution?

We tested various generalizations of the conventional measure of the spatial anisotropy.

We define jT ($n_0(x,y)$ is binary collision density):

$$jT(\tau,\phi) \equiv \frac{\int \mathrm{d}x\mathrm{d}y\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)\, n_0(x,y)}{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y)}$$

jT is not azimuthally symmetric. We define its 2nd Fourier coefficient jT_2:

$$jT_2(\tau) = \frac{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y) \int \mathrm{d}\phi \cos 2\phi\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)}{\int \mathrm{d}x\mathrm{d}y\, n_0(x,y) \int \mathrm{d}\phi\, T^3(x+\tau\cos\phi, y+\tau\sin\phi,\tau)}$$

A simple time-average of jT_2 ⇒ jet-temperature anisotropy:

$$\langle jT_2 \rangle = \frac{\int_{\tau_0}^{\tau_{\mathrm{cut}}} \mathrm{d}\tau\, jT_2(\tau)}{\tau_{\mathrm{cut}} - \tau_0}$$

τ_{cut}: the time when the center of the fireball has cooled to critical temperature Tc.

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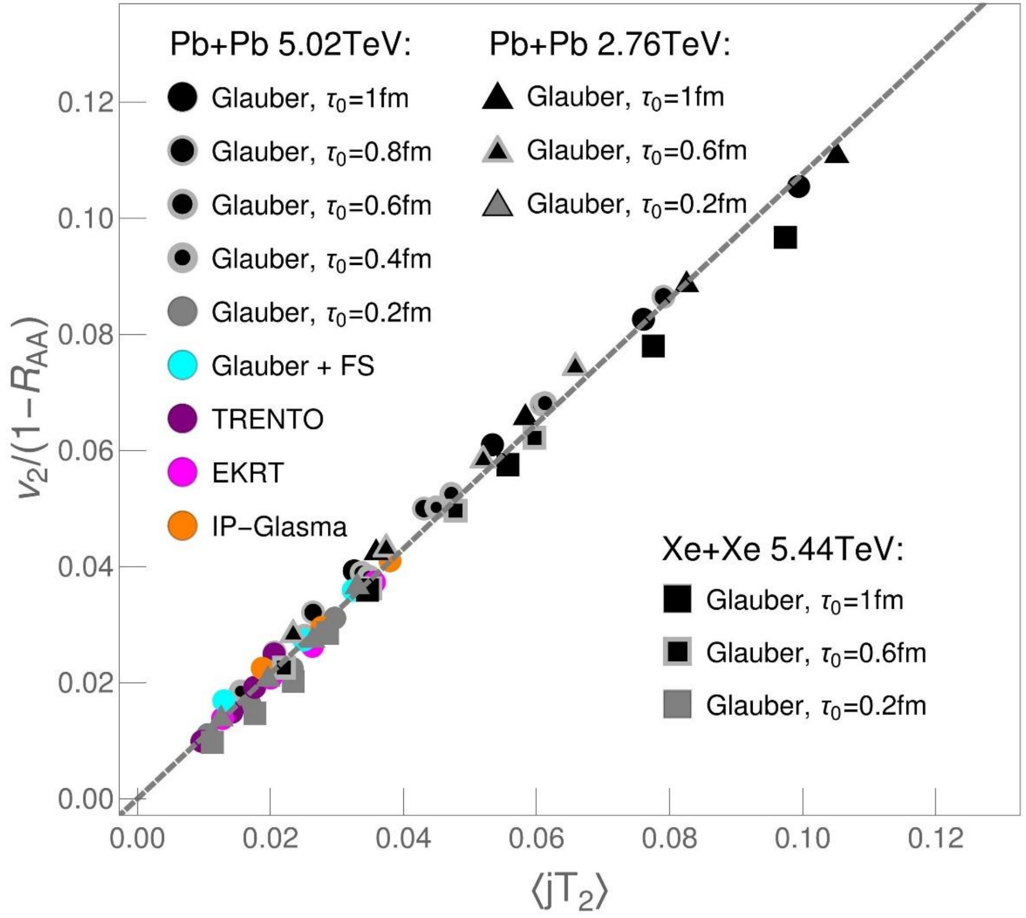
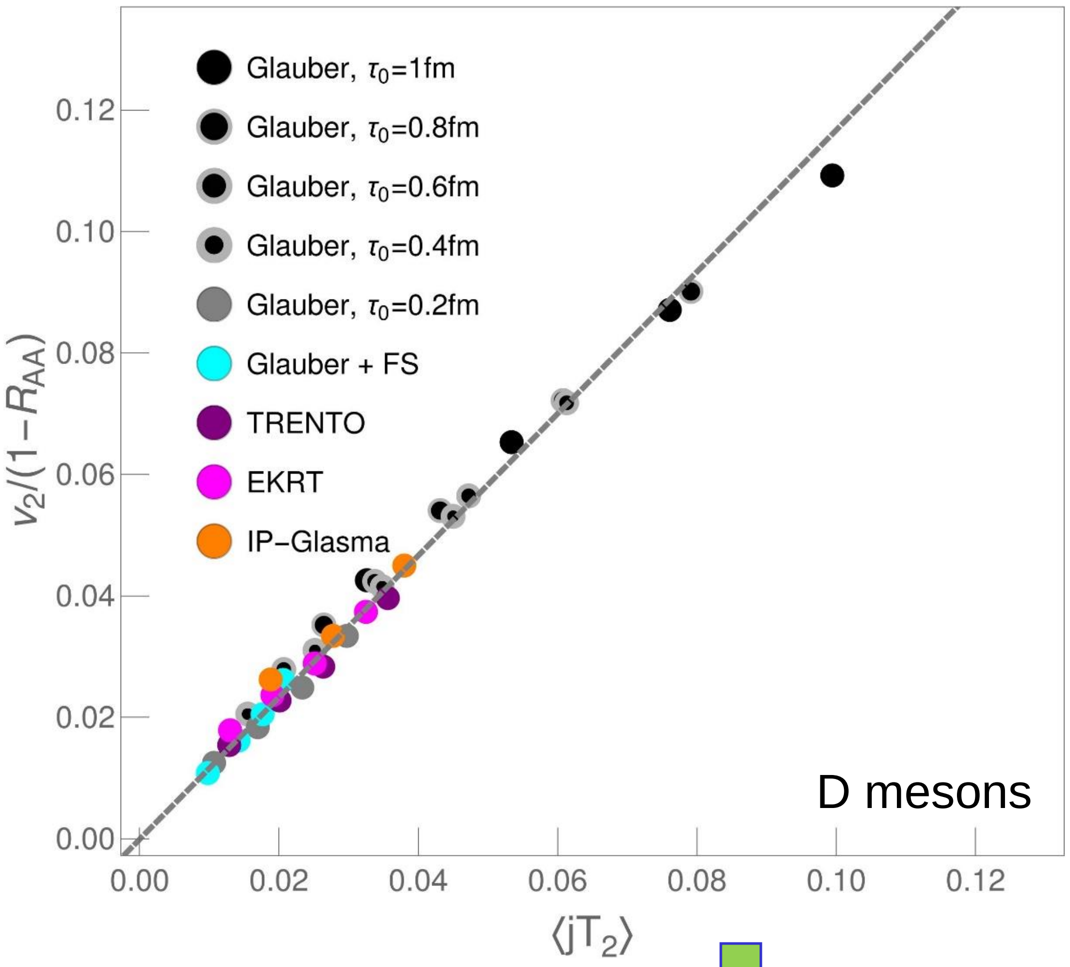
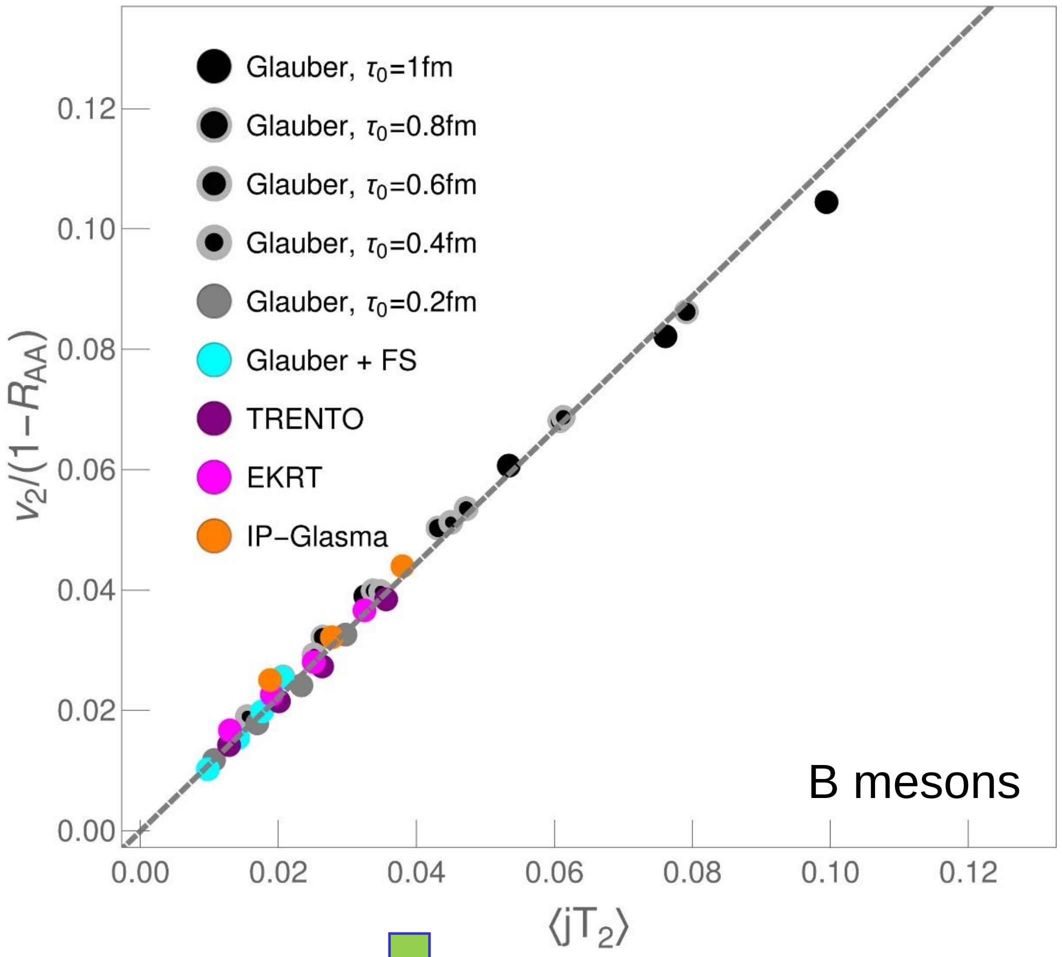


Linear dependence with a slope close to 1.

$v_2/(1 - R_{AA})$ carries direct information on $\langle jT_2 \rangle$!

High-pt heavy flavor





Same dependence as for light flavor!

jT_2 vs experimental data?

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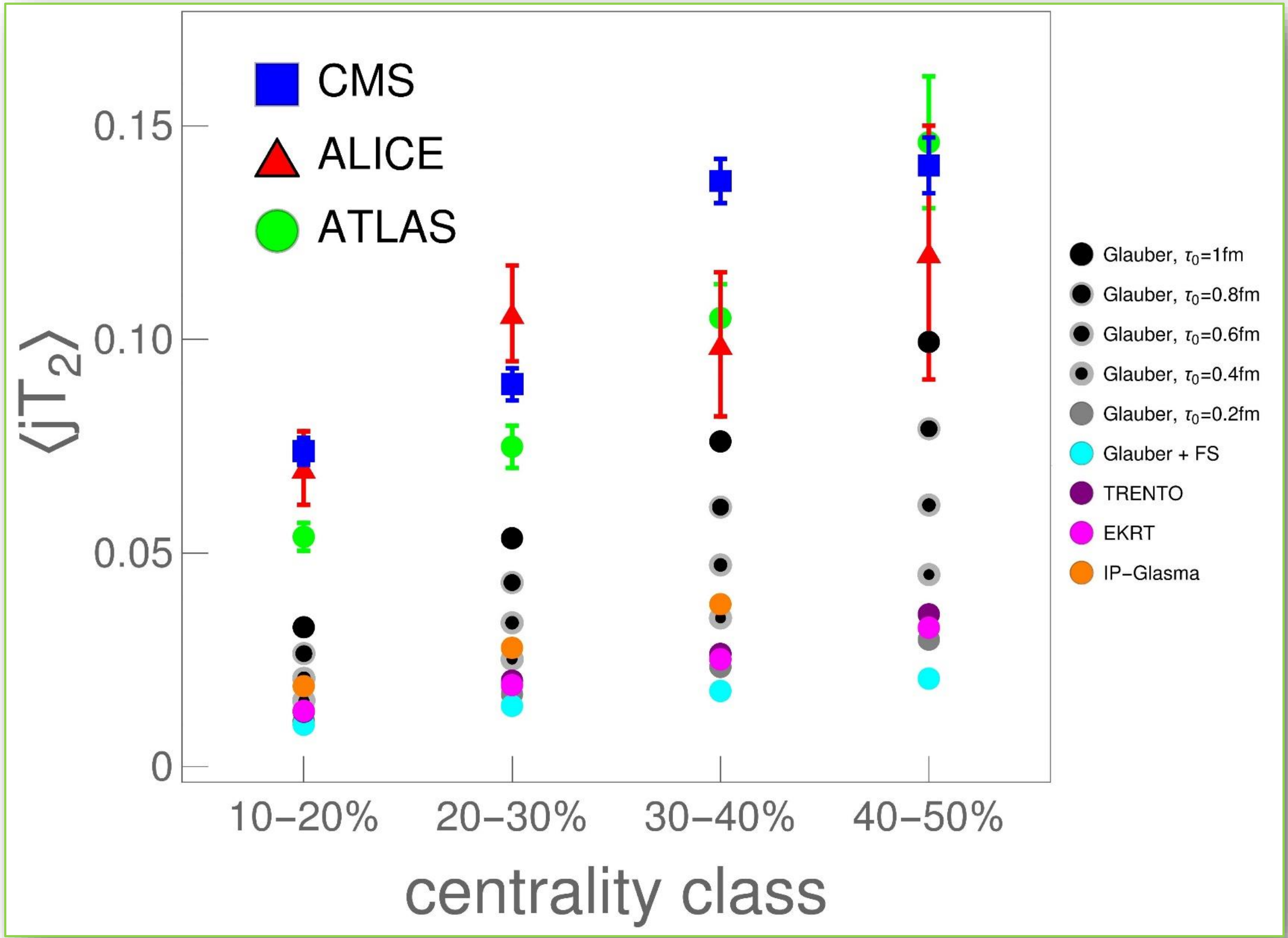
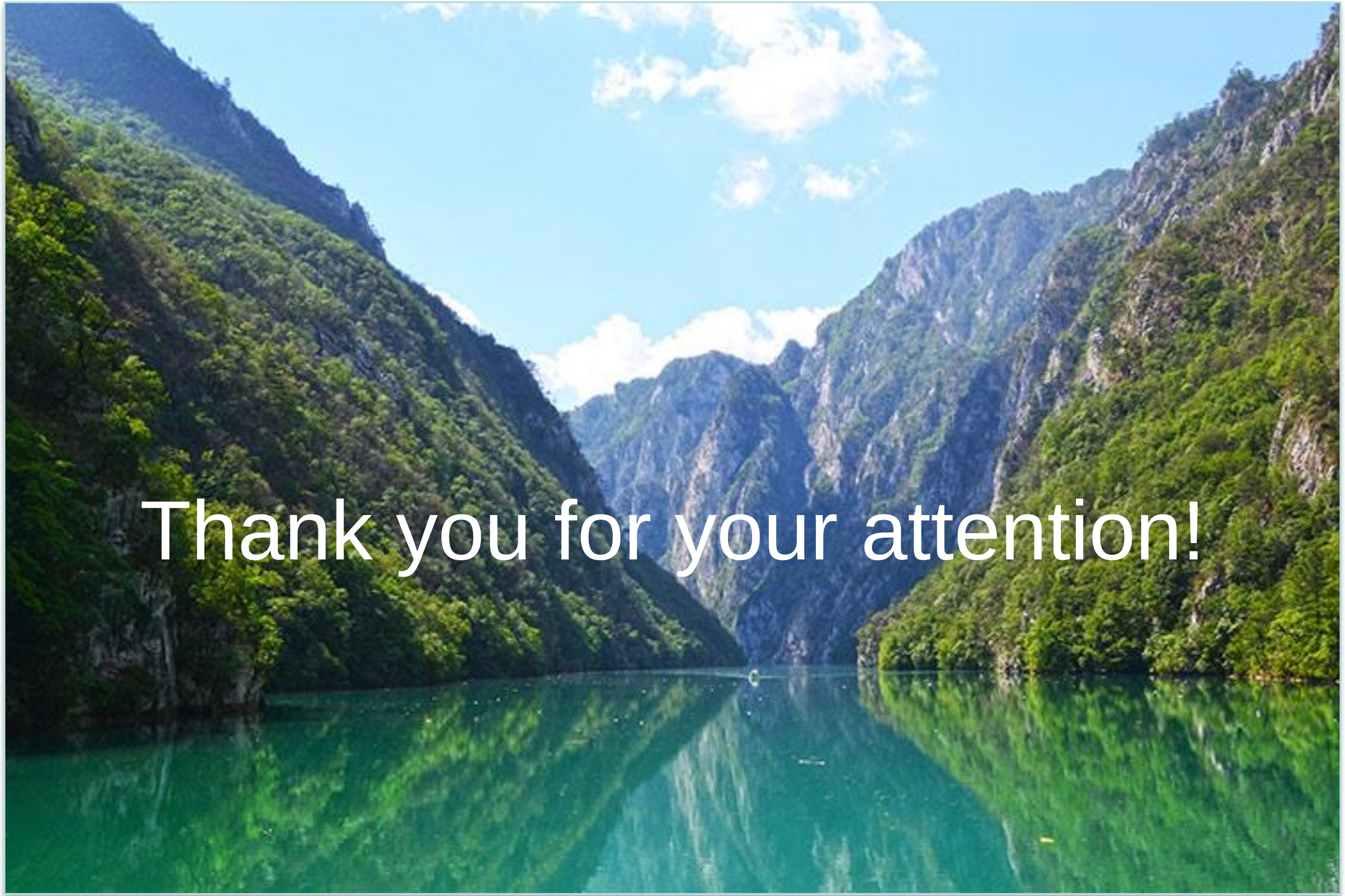


We evaluated $\langle jT_2 \rangle$ from experimentally measured R_{AA}(pt) and v_2(pt): the fitted ratio was converted to $\langle jT_2 \rangle$.

All three experiments lead to similar values of $\langle jT_2 \rangle$.

$\langle jT_2 \rangle$ is a bulk-medium property, which can be directly evaluated from bulk-medium simulations.

Jet-temperature anisotropy provides an important constraint on bulk-medium simulations - they should be tuned to reproduce it.



Canyon of river DREENA in Serbia

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