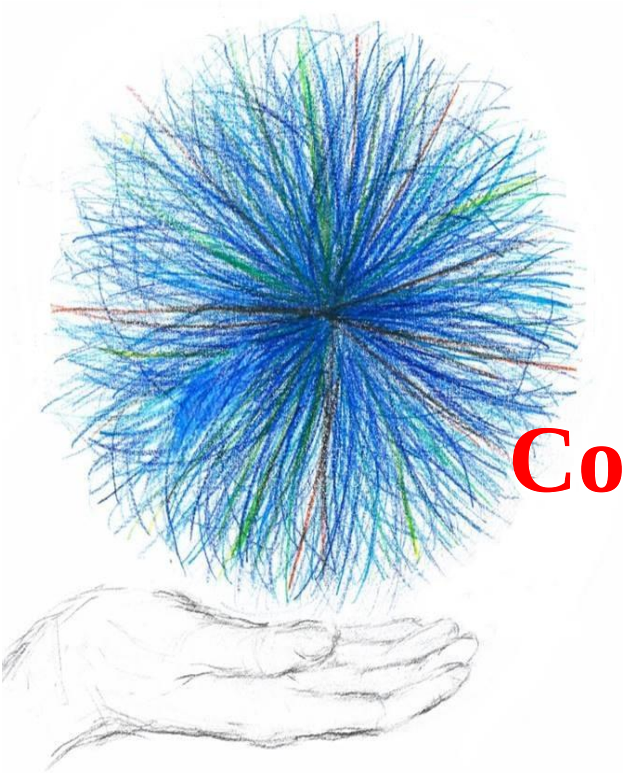


Constraining the QGP properties with high-pt theory and data

Magdalena Djordjevic, IPB

In collaboration with: Dusan Zigic, Stefan Stojku, Bojana Ilic, 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.**

Outline of the talk

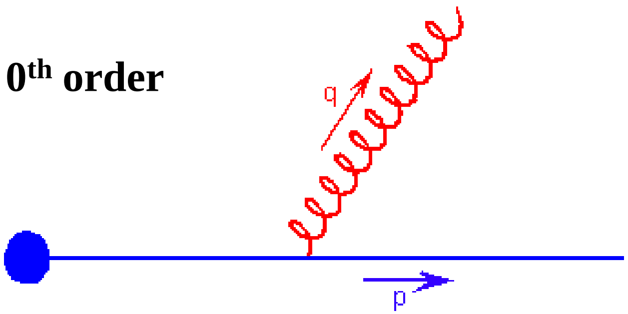
- **Overview of the dynamical energy loss formalism.**
- **Develop a a fully optimized framework DREENA-A that can be used as a multipurpose QGP tomography tool.**
  - **Based on the dynamical energy loss, with no fitting parameters.**
  - **Include any, in principle arbitrary, temperature profile, as an only input in the framework.**
  - **Applies to both light and heavy flavor observables, large and smaller systems, different collision energies and centralities.**
  - **Allows systematic comparison of data and theoretical predictions, obtained by the same formalism and parameter set.**
  - **Can be used jointly with low-pt observables to explore the bulk QGP properties through high-pt theory and data.**
- **Today: Address how high pt theory and data can be used to explore the bulk QGP properties, in particular**
  - **Constrain the QGP thermalization time from the data.**
  - **Infer a anisotropy of bulk QCD medium (talk by Stefan Stojku, this afternoon, arXiv: 2110.02029).**

High pt parton energy loss in QGP

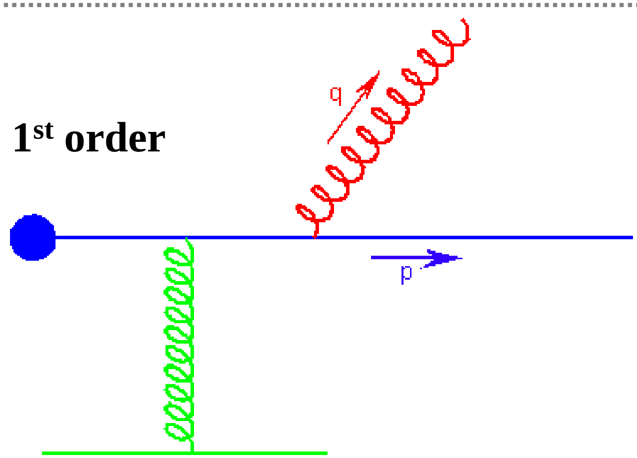
Radiative energy loss

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

0^{th} order



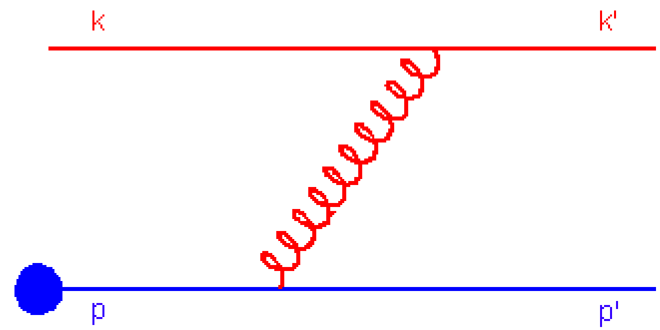
1^{st} order



Collisional energy loss

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

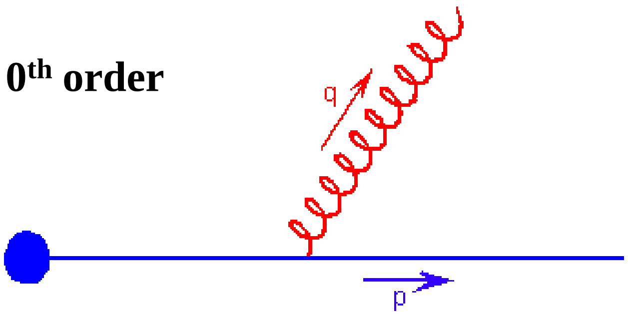
0^{th} order



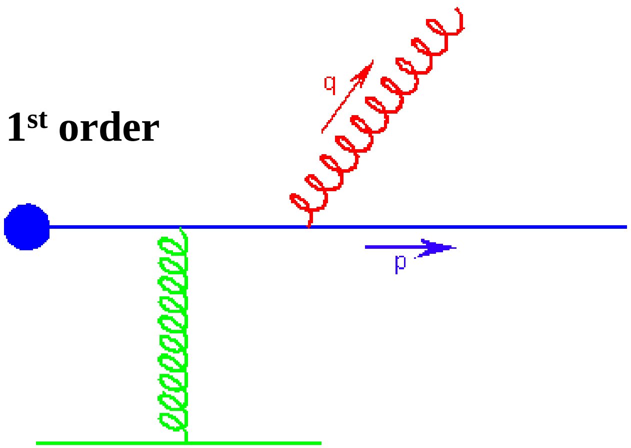
Radiative energy loss

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

0th order



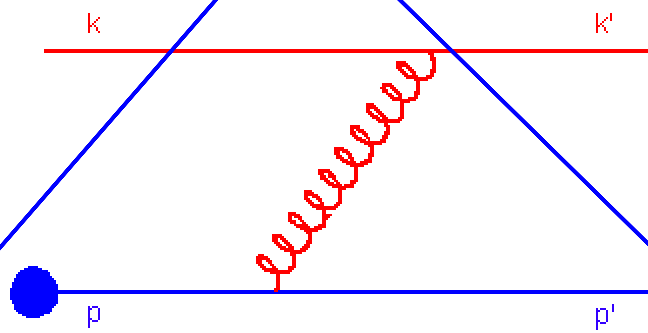
1st order



~~Collisional energy loss~~

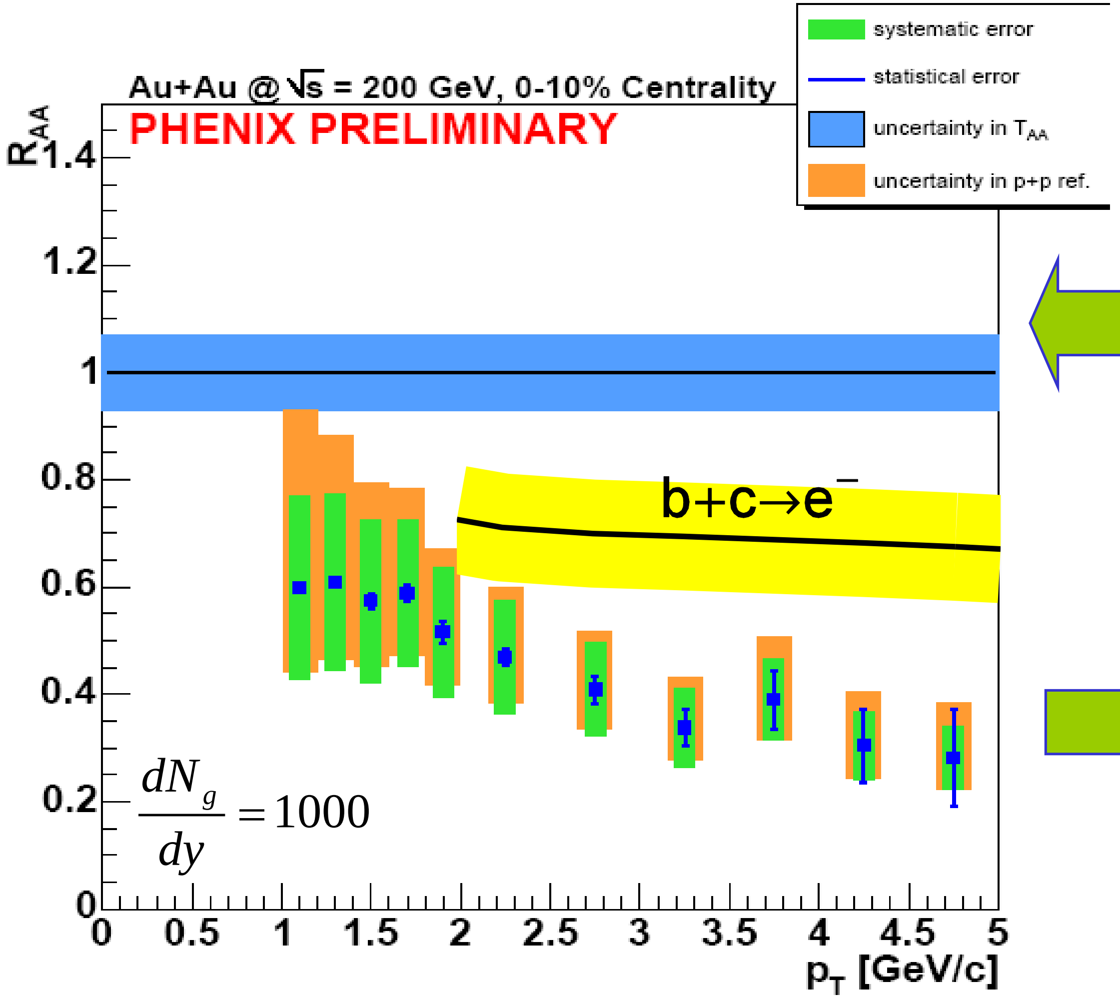
~~**Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:**~~

0th order



Considered to be negligible compared to radiative!

Heavy flavor puzzle @ RHIC



Radiative energy loss predictions with dN_g/dy=1000

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?

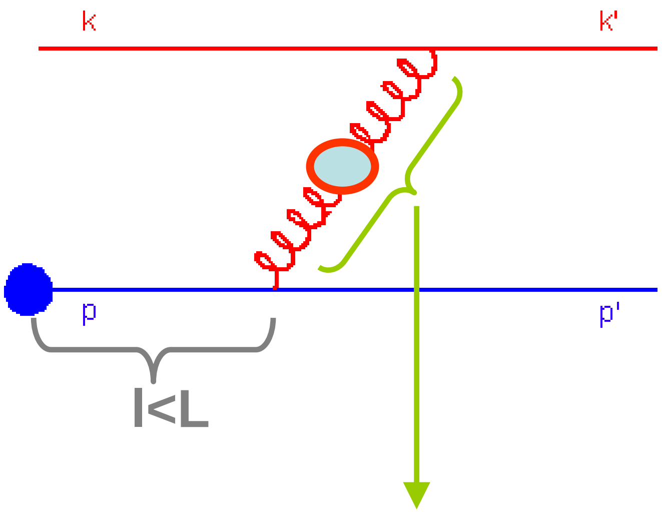
⇓

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.

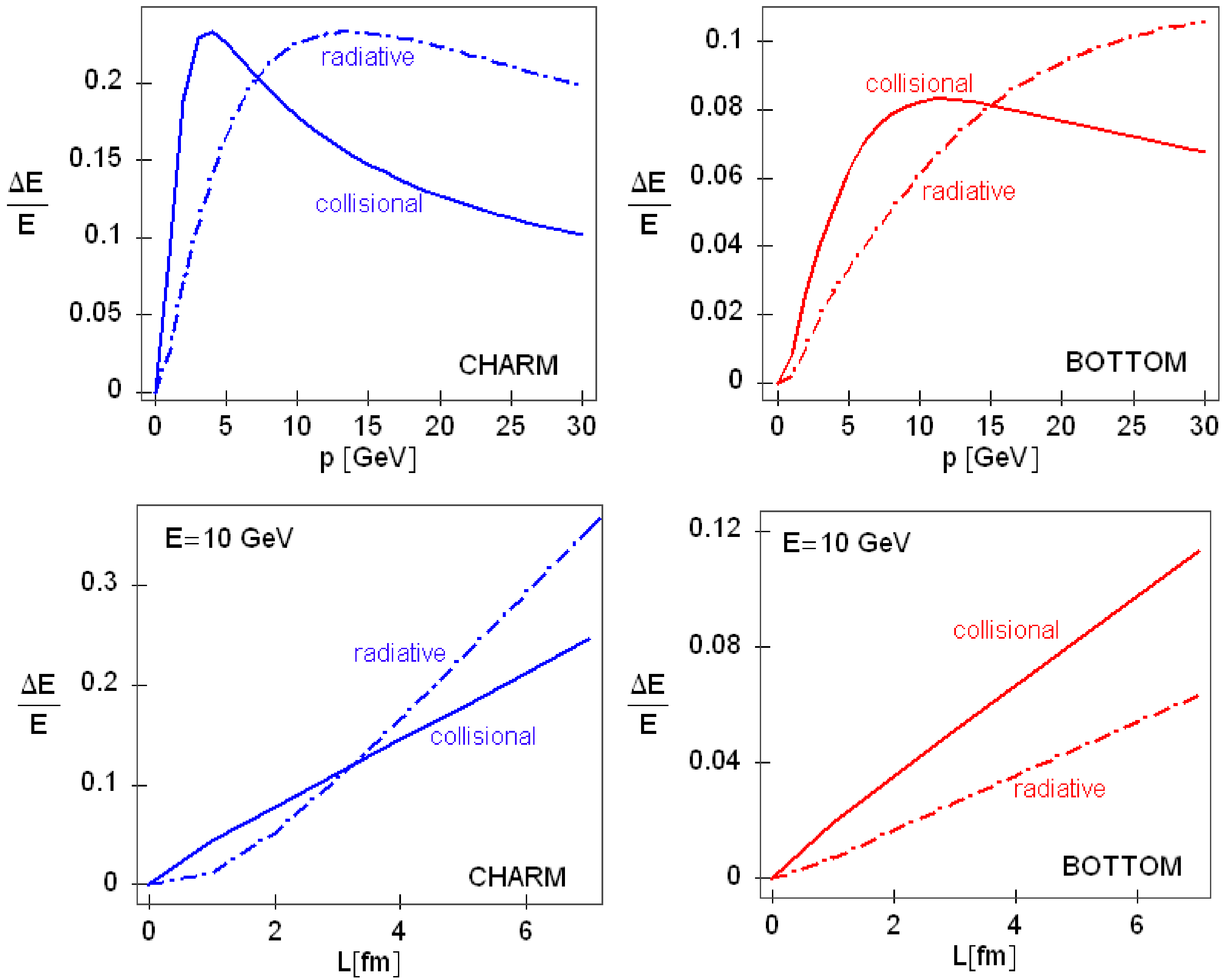
The main order collisional energy loss is determined from:



The effective gluon propagator:

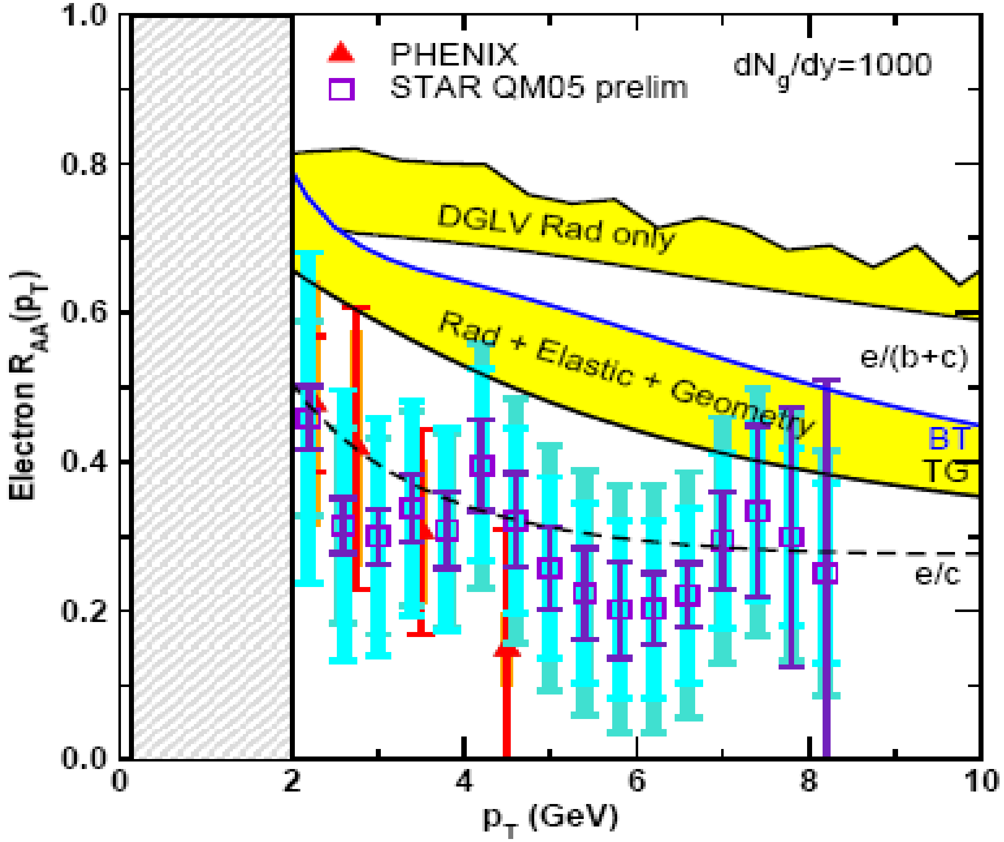
$$D^{\mu\nu}(\omega, \vec{\mathrm{q}}) = -P^{\mu\nu}\Delta_T(\omega, \vec{\mathrm{q}}) - Q^{\mu\nu}\Delta_L(\omega, \vec{\mathrm{q}})$$

Collisional v.s. medium induced radiative energy loss



Collisional and radiative energy losses are comparable!

Single electron prediction (collisional + radiative)



Inclusion of collisional energy loss leads to better agreement with single electron data.

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 light and heavy quark radiative energy loss in dynamical medium of thermally distributed massless quarks and gluons.

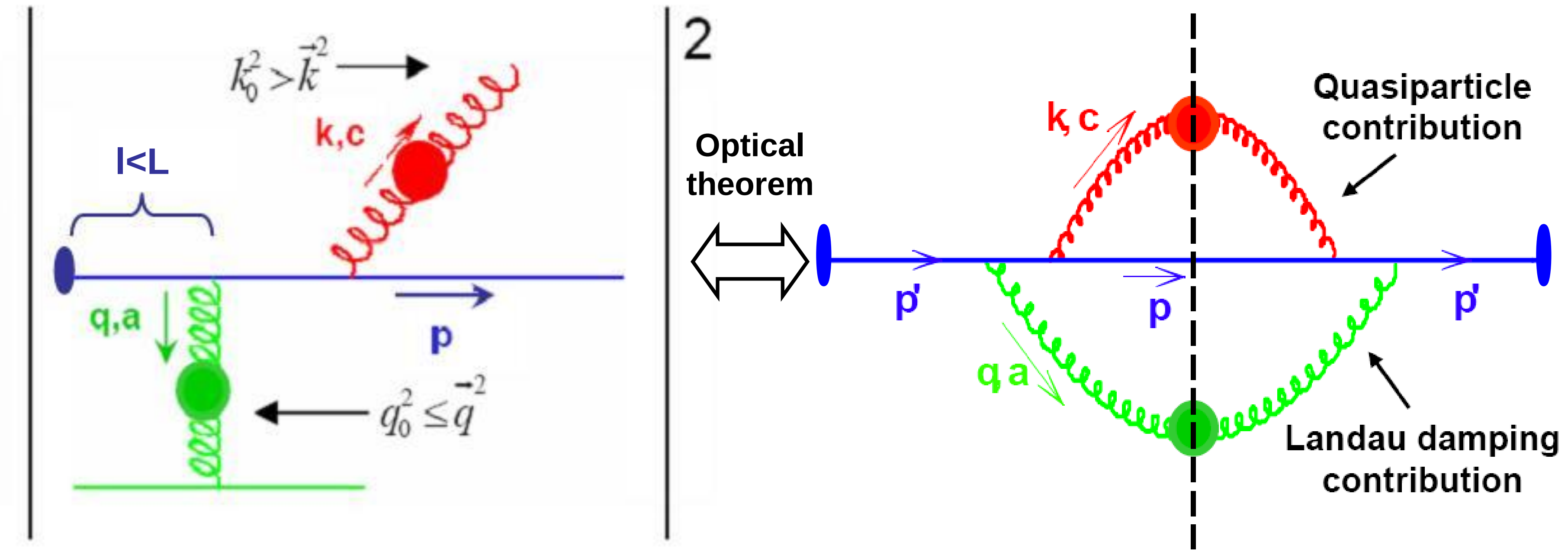
Why?

- **To address the applicability of static approximation in radiative energy loss computations.**
- **To compute collisional and radiative energy losses within a consistent theoretical framework.**

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.

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 in 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:

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

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

Radiated gluon **Exchanged gluon**

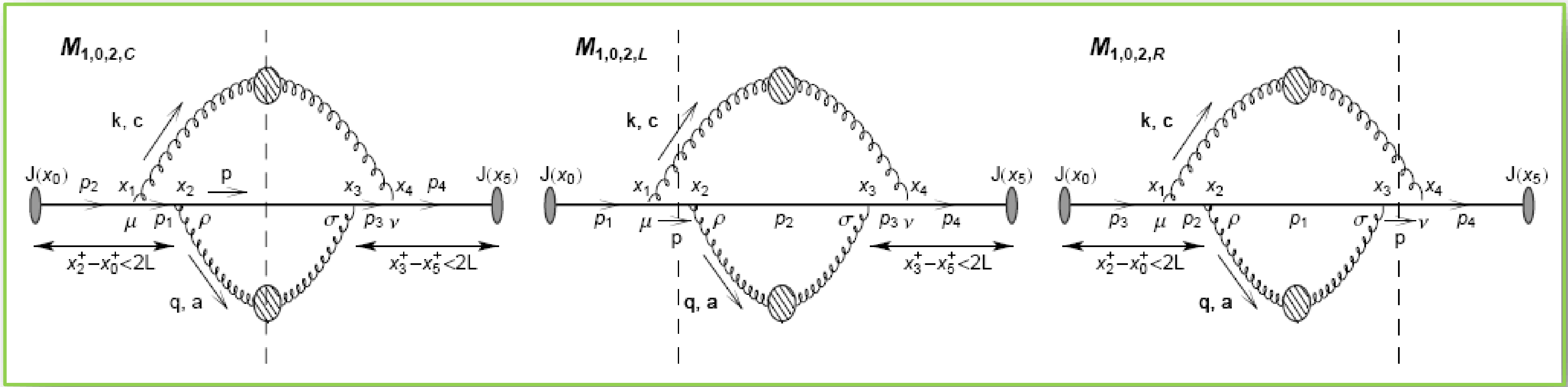
For radiated gluon, cut 1-HTL gluon propagator can be simplified to
(M.D. and M. Gyulassy, PRC 68, 034914 (2003).

$$D^{>}_{\mu\nu}(k) \approx -2\pi\, \frac{P_{\mu\nu}(k)}{2\omega}\, \delta(k_0 - \omega) \qquad \omega \approx \sqrt{\vec{k}^2 + m_g^2}; \quad m_g \approx \mu/\sqrt{2}$$

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

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

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.

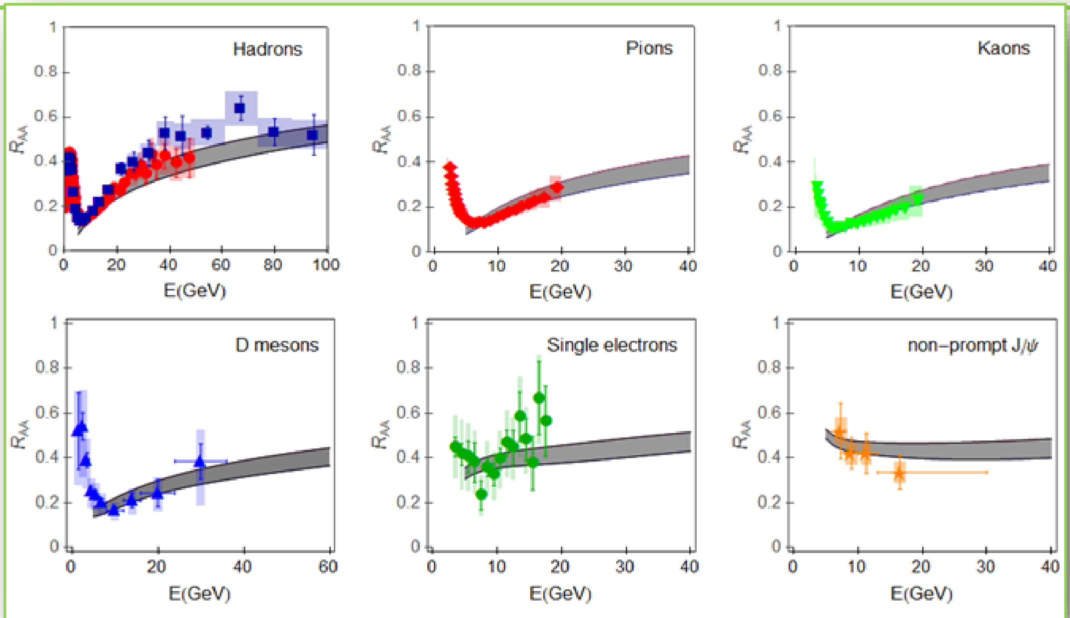
↓

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

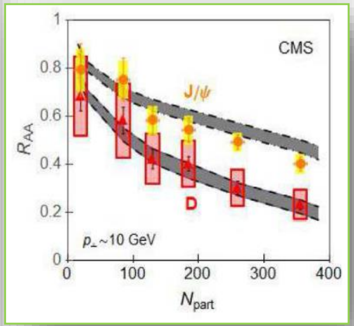
The dynamical energy loss formalism

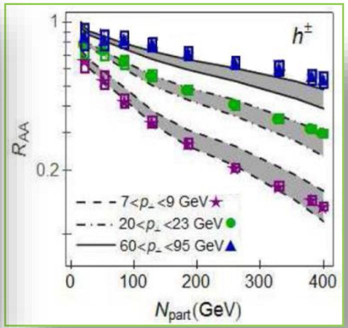
Has the following unique features:

- ***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.**

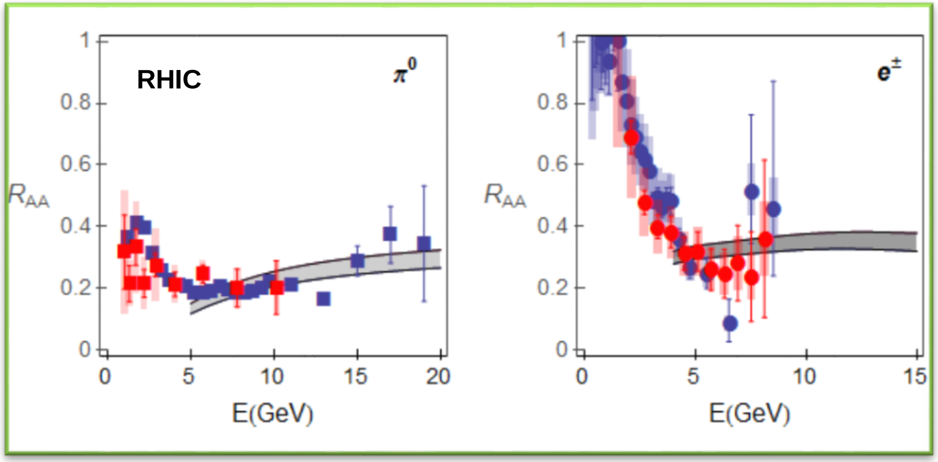


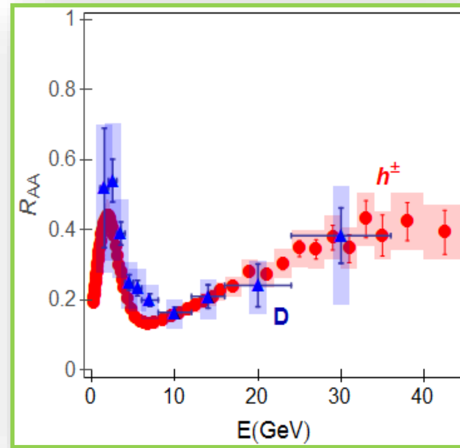
Explains high pt R_{AA} data for different probes, collision energies, and centralities.

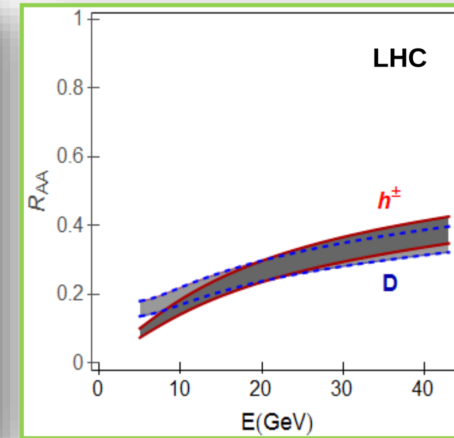




Resolved the longstanding "heavy flavour puzzles at RHIC and LHC".



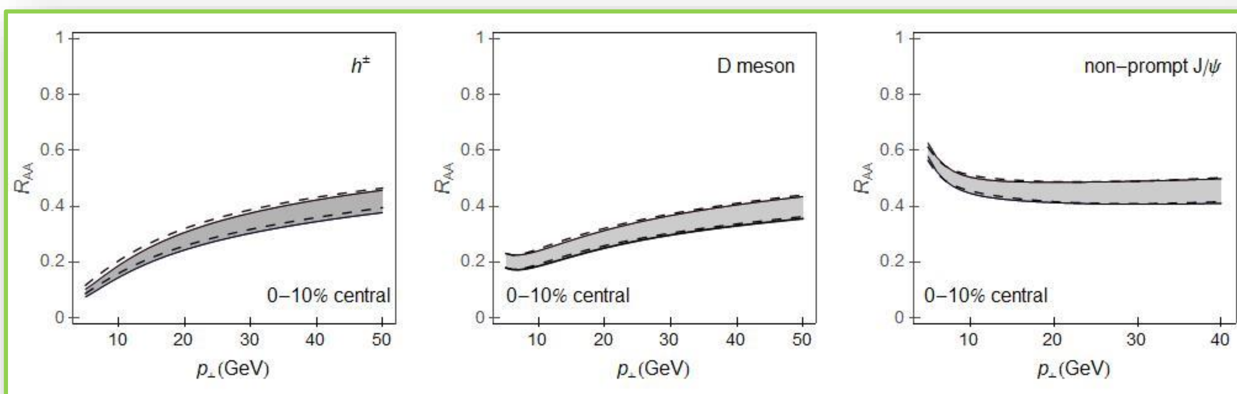


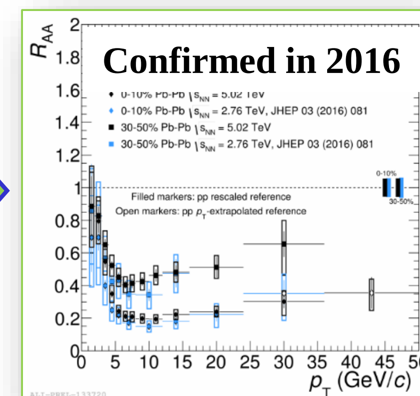


M.D., PRL 112, 042302 (2014)

Clear predictive power!

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





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

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 suppression predictions.**
- **Compare predictions with the available experimental data.**
- **If needed iterate comparison for different combinations of QGP medium parameters.**
- **Extract medium properties consistent with both low and high-pt theory and data.**

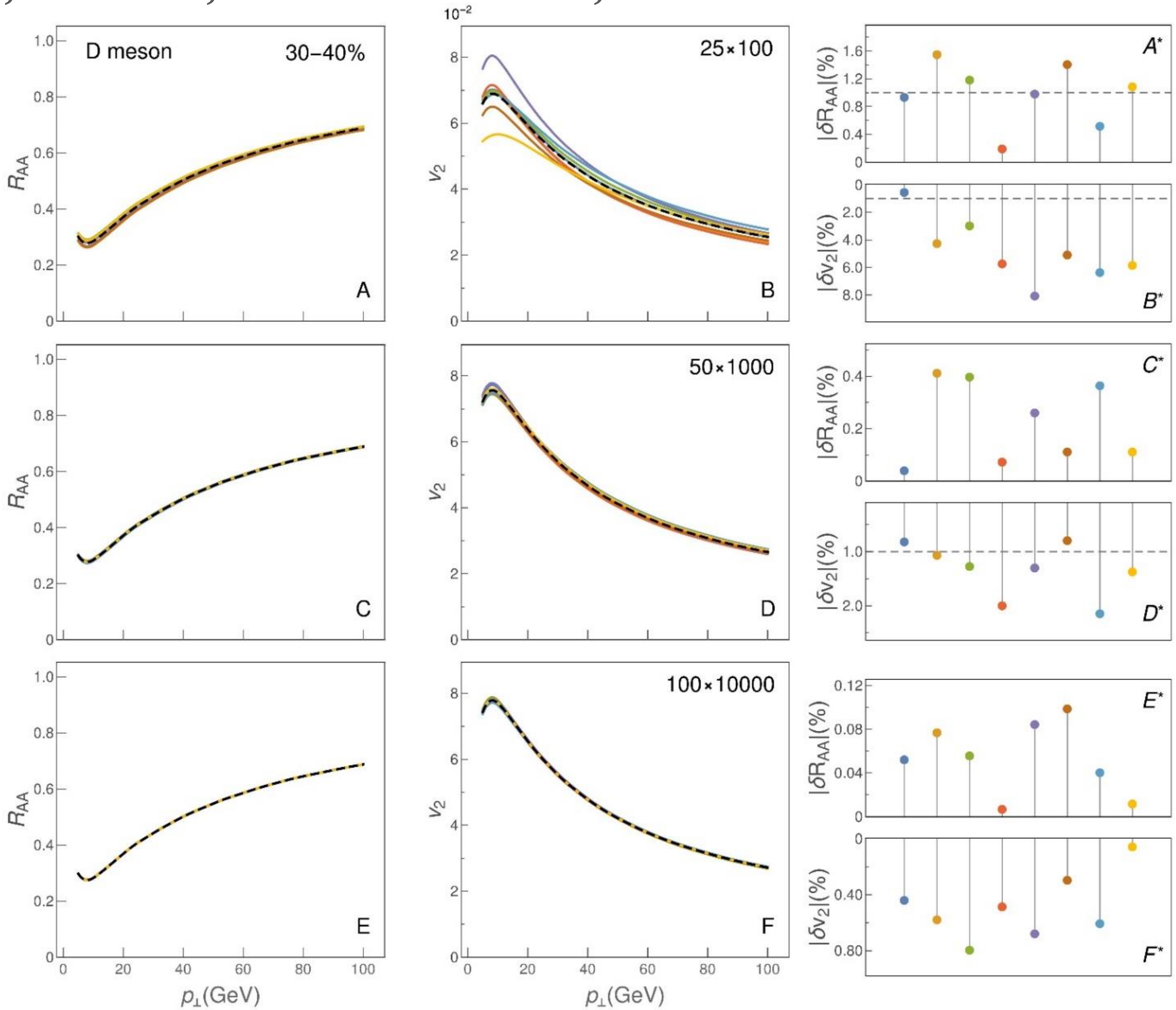
Develop fully optimized DREENA-A framework.

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

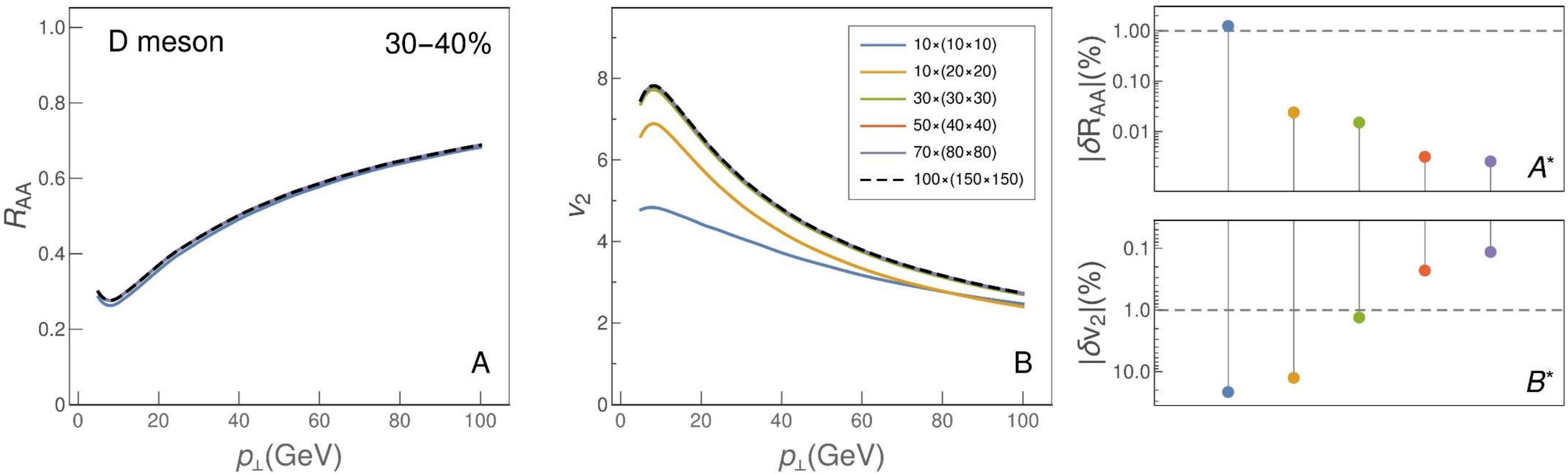
D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, arXiv:2110.01544



Not very efficient!

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

Equidistant sampling



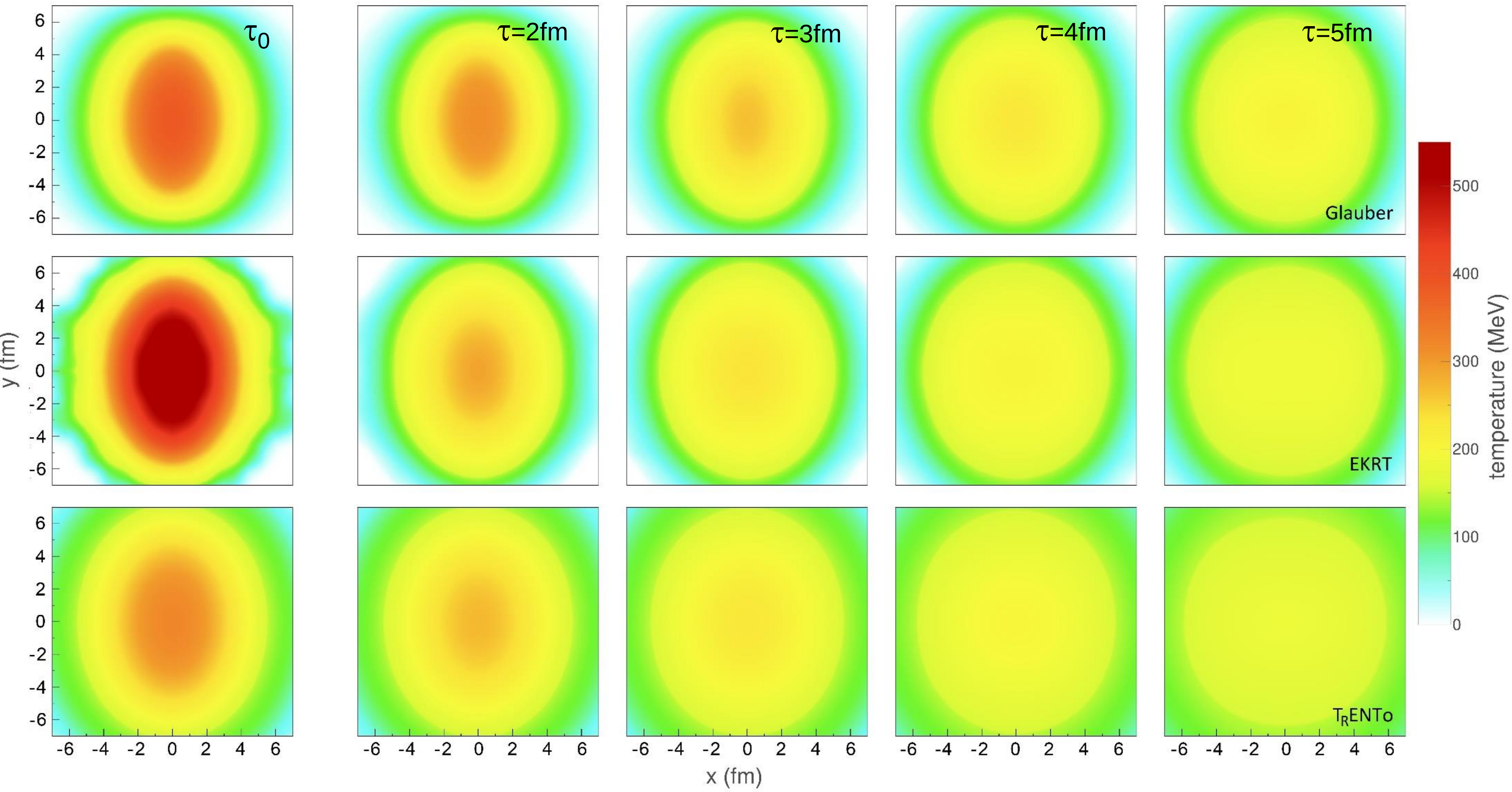
Two orders of magnitude increase in the efficiency!

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

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

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

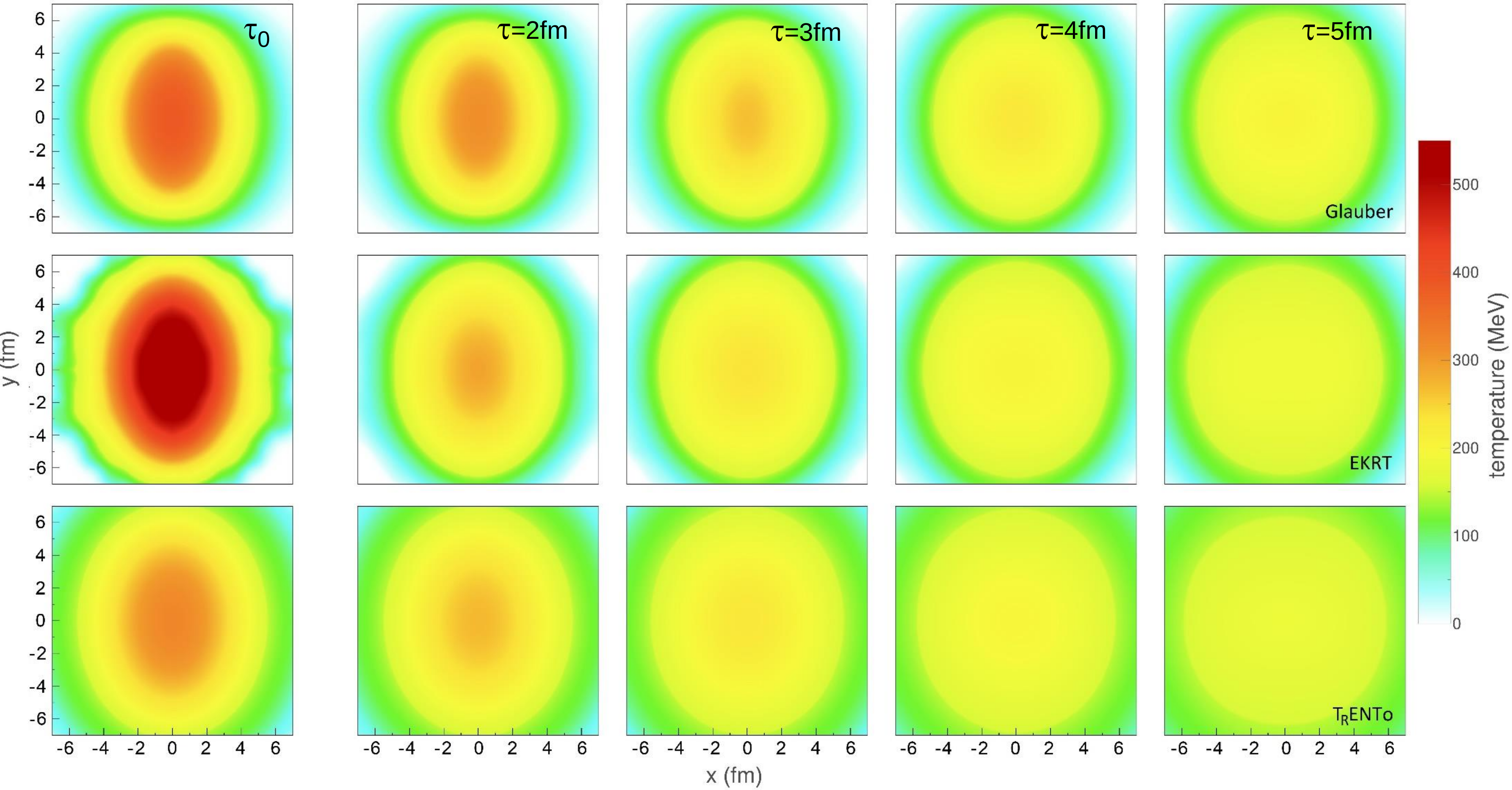
Are high-pt observables indeed sensitive to different T profiles?



All three evolutions agree with low-pt data, can high pt-data provide a further constrain?

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

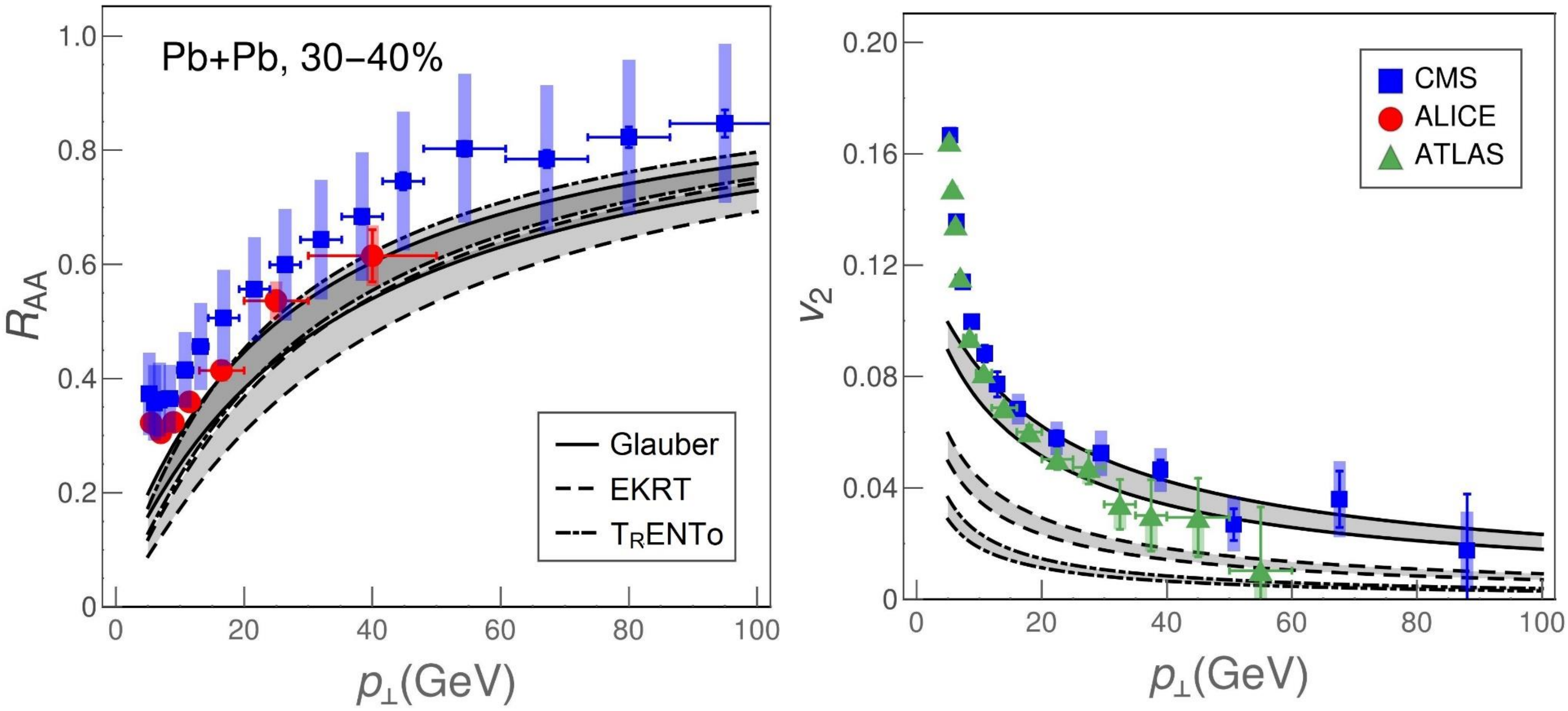
Qualitative differences



- **Largest anisotropy for Glauber (τ_0=1fm) – expected differences in high-pt v2.**
- **EKRT shows larger temperature - smaller RAA expected**

DREENA-A PREDICTIONS

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



- 'EKRT' indeed leads to the smallest R_{AA}
- Anisotropy translates to v2 differences ('Glauber' largest, T_RENTo lowest).
- DREENA-A can differentiate between different *T* profiles.
- Additional (independent) constraint to low-pt data.

Summary up to now

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

Can include arbitrary temperature profiles.

No additional free parameters.

High-pt R_{AA} and v_2 sensitive to details of *T* profile differences.

Intuitive expectations agree with DREENA-A calculations.

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

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

Next Goal: Inferring bulk QGP properties

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.

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

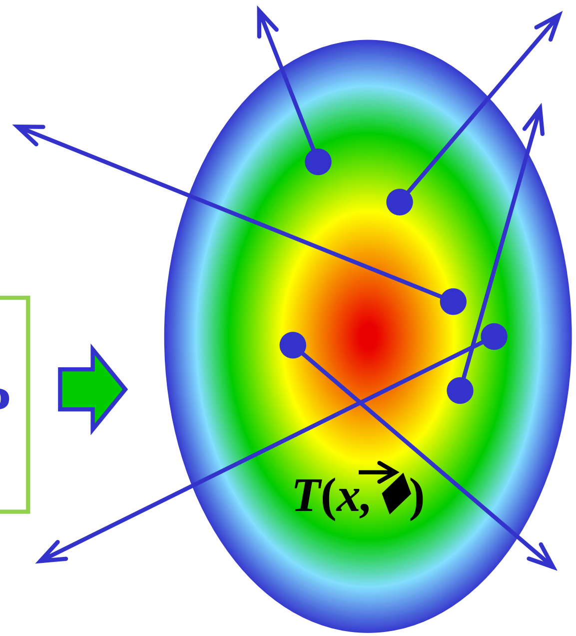
However, some important bulk QGP properties are known to be difficult to constrain by low-pt observables and corresponding theory/simulations.

We therefore advocate 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, implemented into DREENA-A framework.

High pt probes are powerful tomographic tools

Use them to infer some of bulk QGP properties

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.

How to extract anisotropy from high-pt data? – see Stefan Stojku's talk this afternoon!

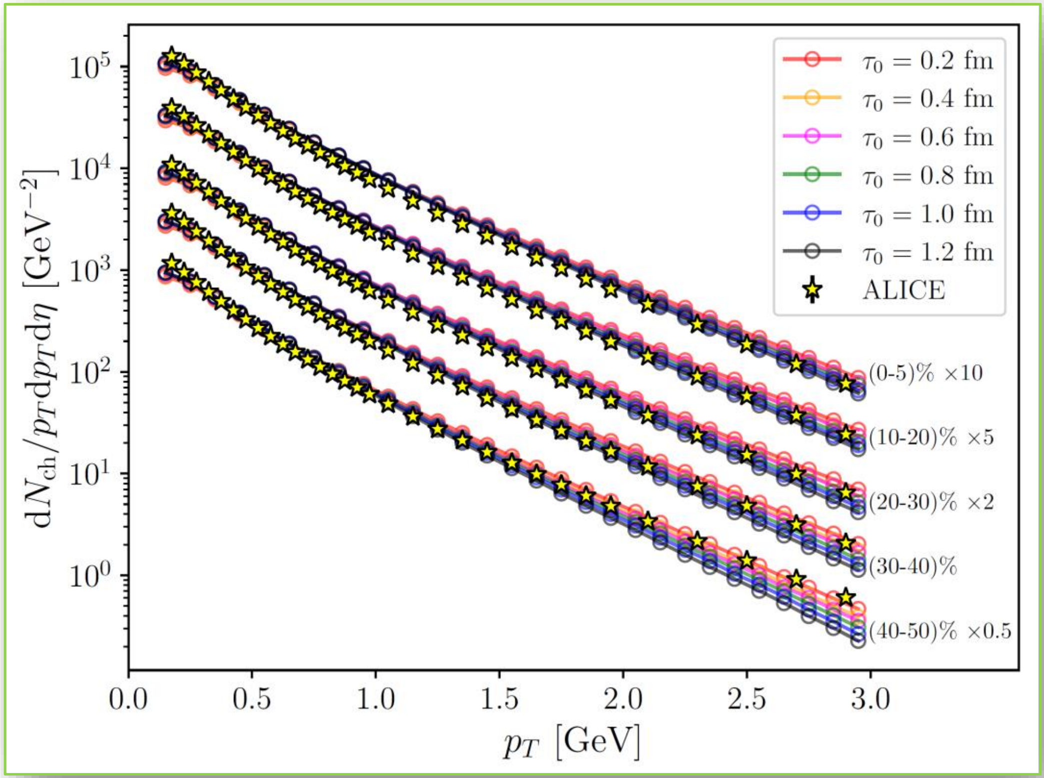
Low-pt physics weakly sensitive to thermalization time

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< τ_0<1.2fm).

Independently confirmed by our systematic analysis

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

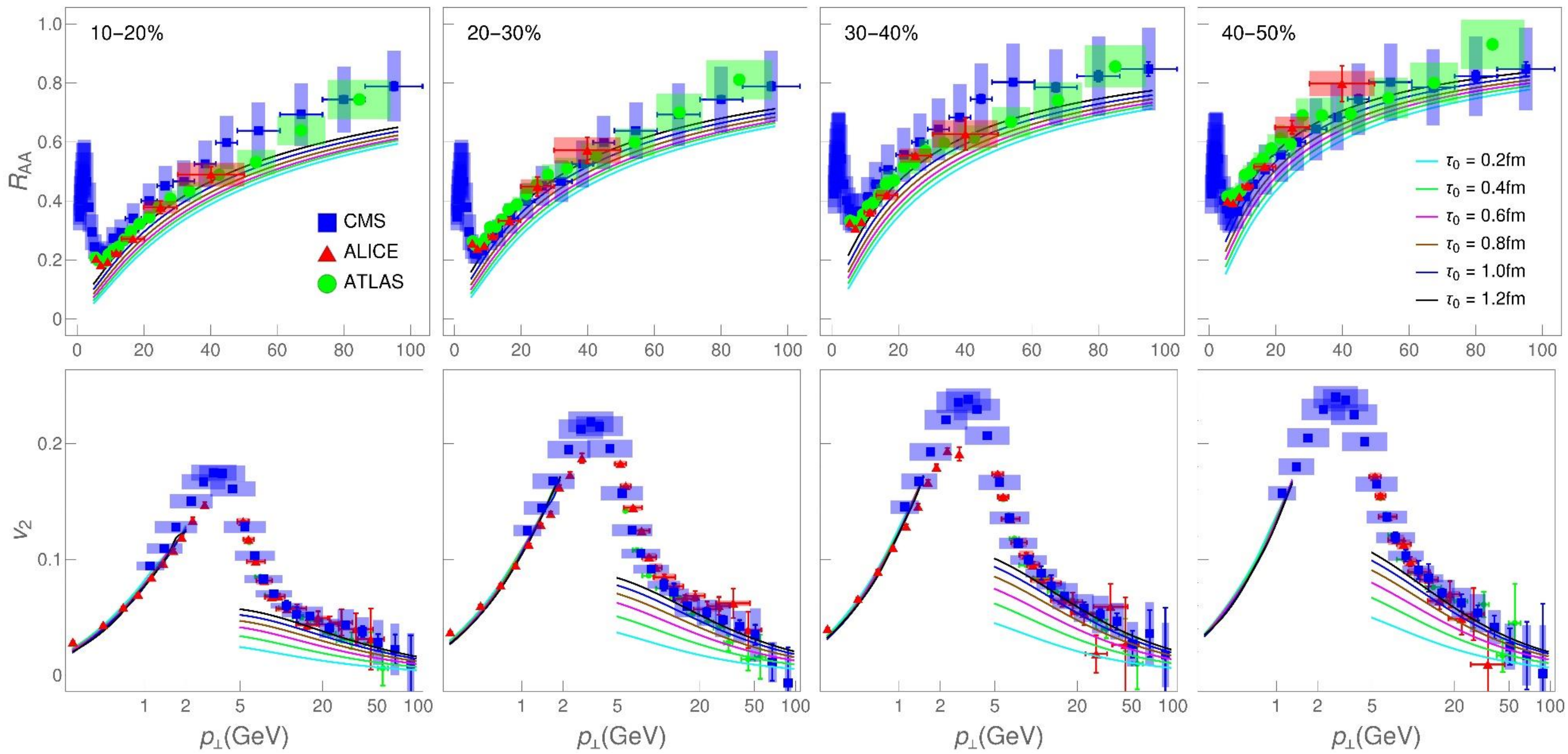


Good agreement with low-pt data, confirming low sensitivity to τ_0!

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

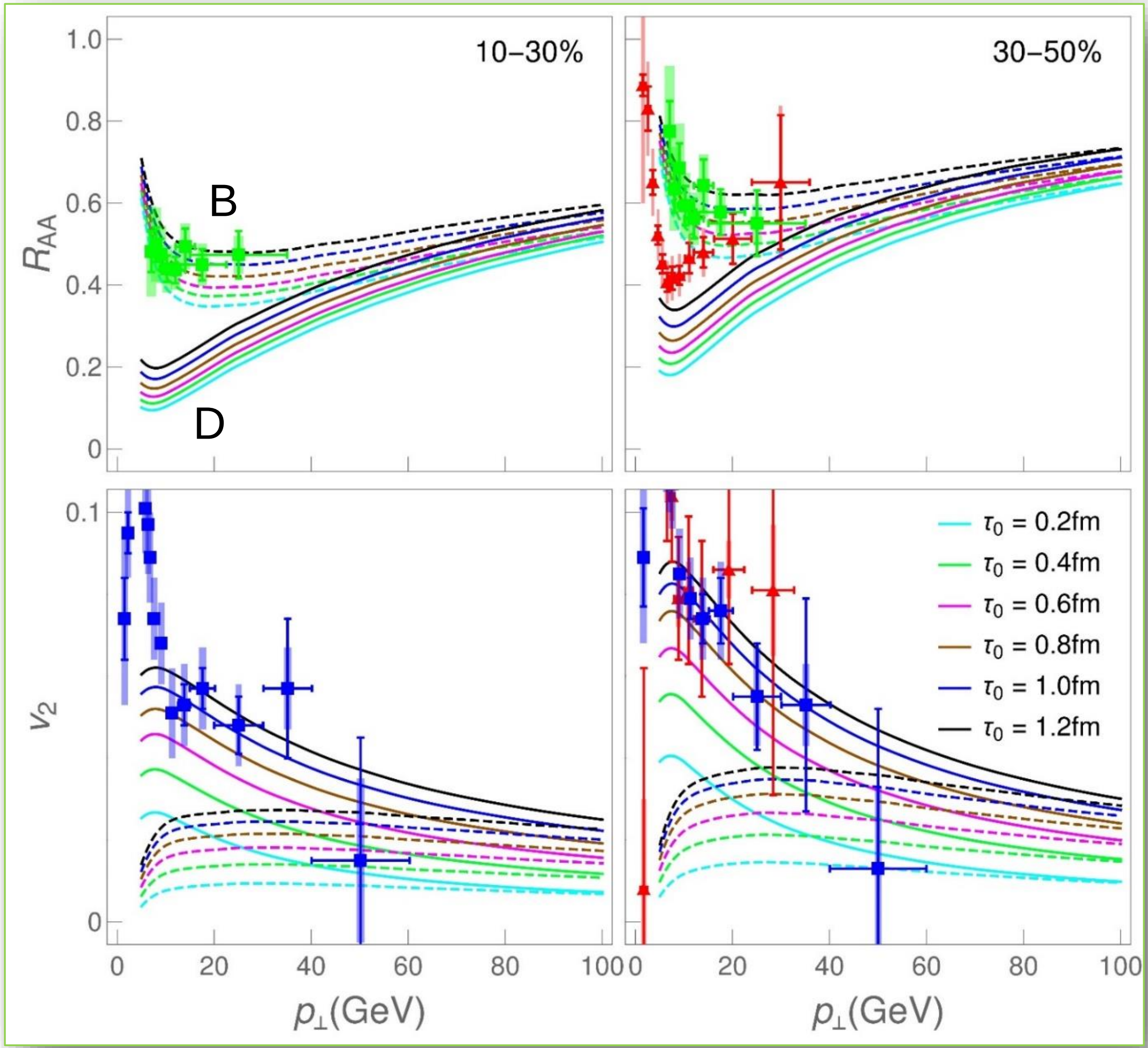
Sensitivity of high-pt theory and data to thermalization time

- Use our DREENA-A framework, which is fully modular, 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



B mesons – dashed curves

D mesons – full curves

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

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

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

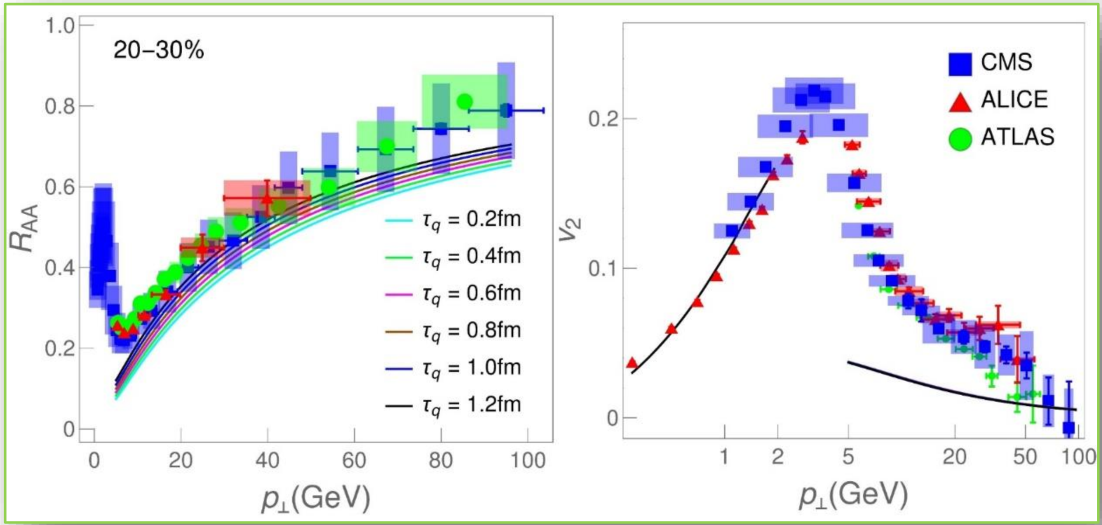
(Andres et al. 2020) recently proposed that jet quenching may start later than the thermalization of the bulk QCD medium, which may strongly impact high-pt predictions.

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.

RAA - weakly sensitivity to τ_q

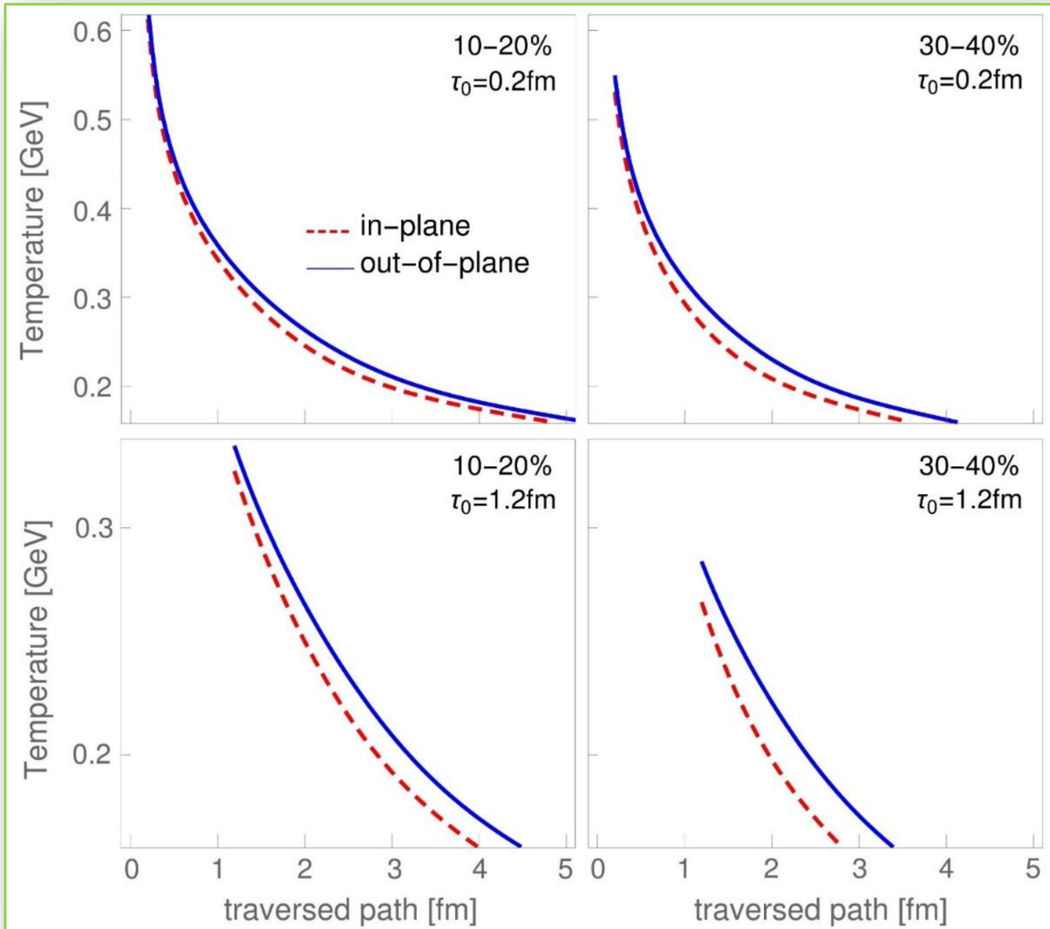
v_2 - surprisingly entirely insensitive to τ_q and does not support the above proposal



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

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!

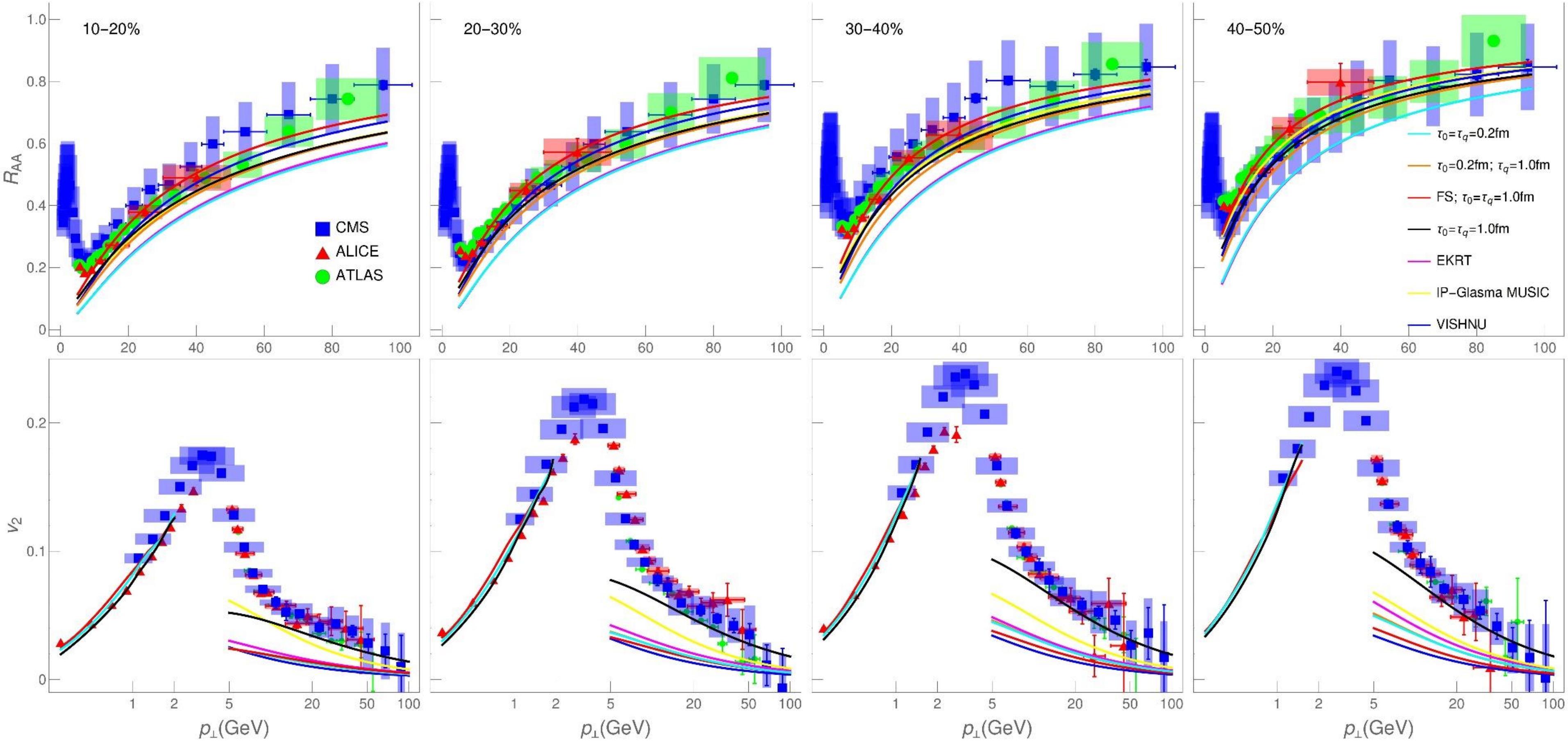
As τ_0 increases, the differences between in- and out-of-plane *T* profiles also increase, explaining observed increase in v_2.

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

What about more sophisticated hydro initializations?

Include more sophisticated initializations, such as EKRT, IP-Glasma, free streaming.



High-pt R_{AA} and v_2 are sensitive to different initializations and early expansion dynamics, and prefer delayed onset of energy loss and transverse expansion!

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

Summary

We here presented 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.

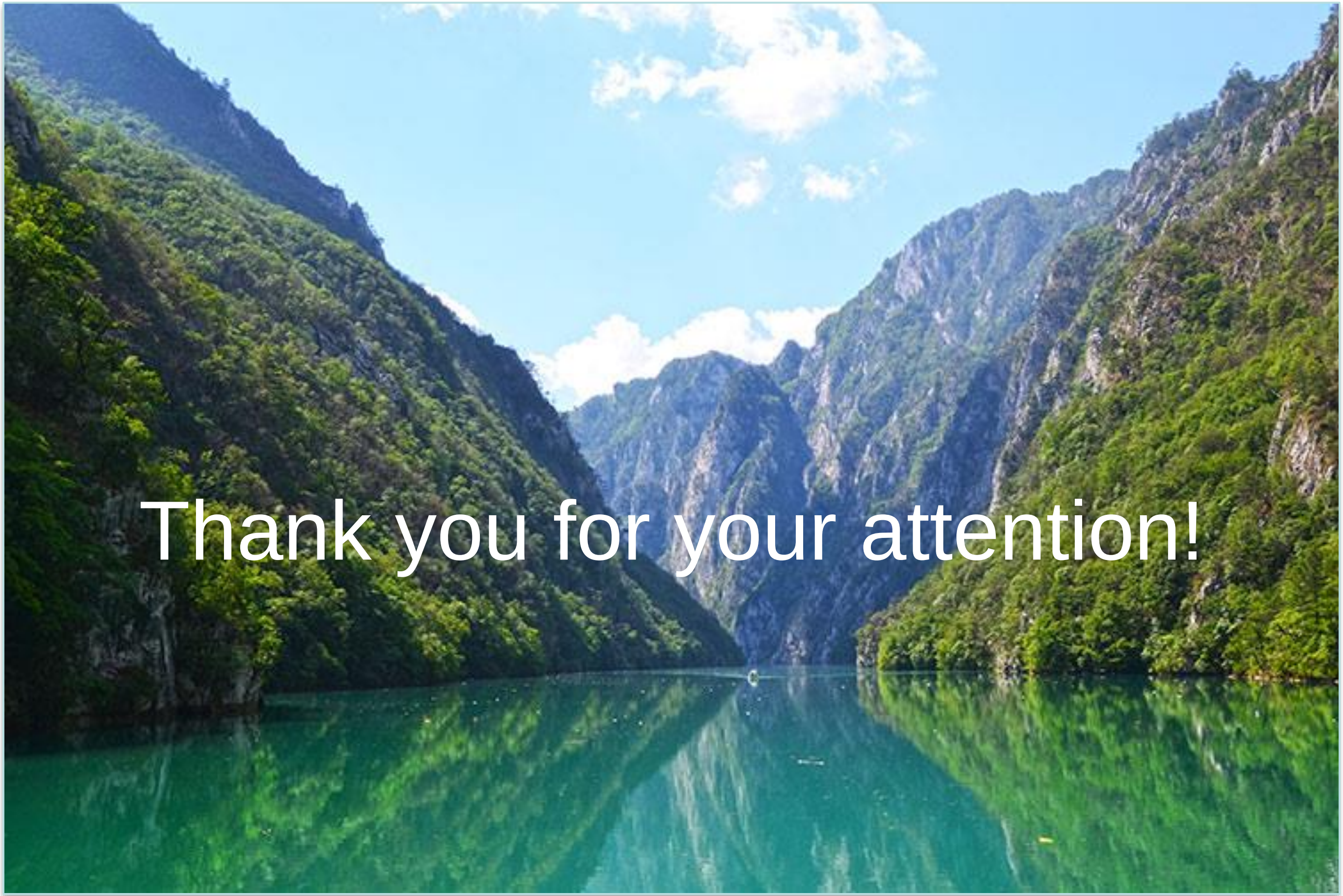
Specifically, we here used high-pt R_{AA} and v_2 to infer that delayed onset of energy loss and transverse expansion is preferred by experimental data!

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.

How to extract anisotropy from high-pt data? – talk by Stefan Stojku's this afternoon



Canyon of river DREENA in Serbia

European Research Council
Established by the European Commission

A postdoc position in bulk medium simulations available within our ERC project.

Contact: magda@ipb.ac.rs

МИНИСТАРСТВО ПРОСВЕТЕ, НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА