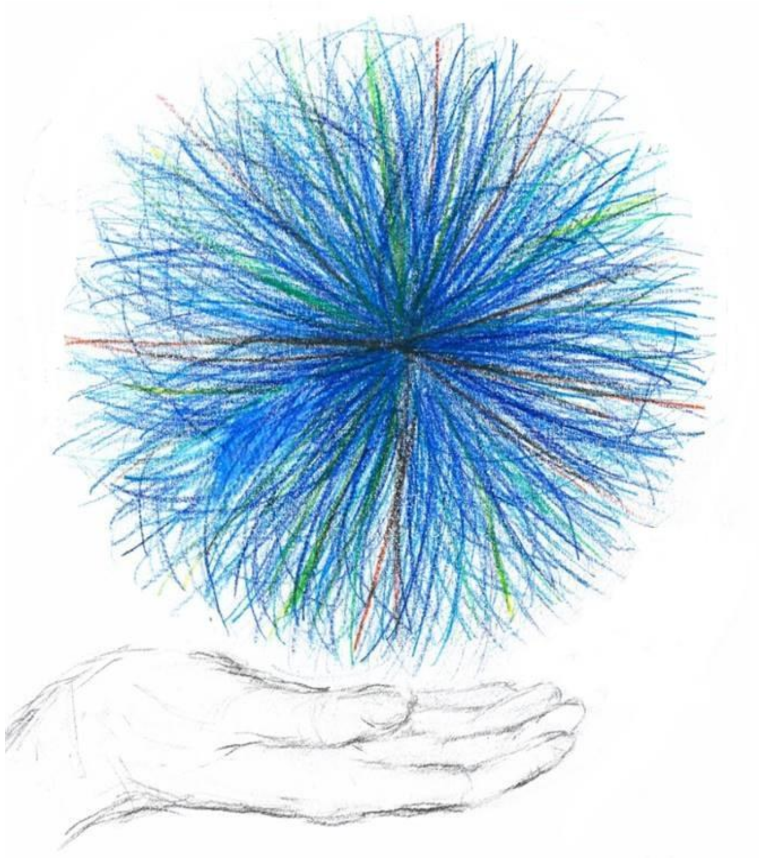


QGP Tomography: Exploring QGP evolution with hard probes

Magdalena Djordjevic, IPB

In collaboration with: Dusan Zigic, Stefan Stojku, Bojana Ilic, Jussi Auvinen, Lidija Zivkovic, Igor Salom, Marko Djordjevic and Pasi Huovinen

erc 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.

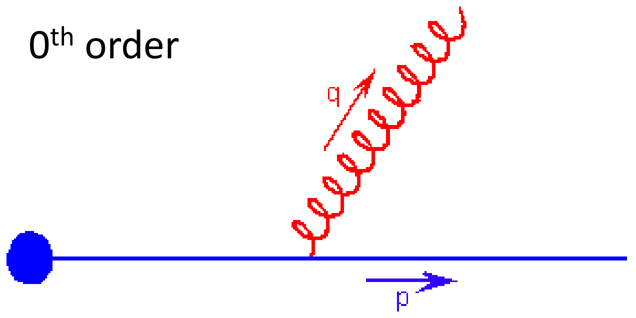
Dynamical energy loss in QGP

Energy loss in QGP

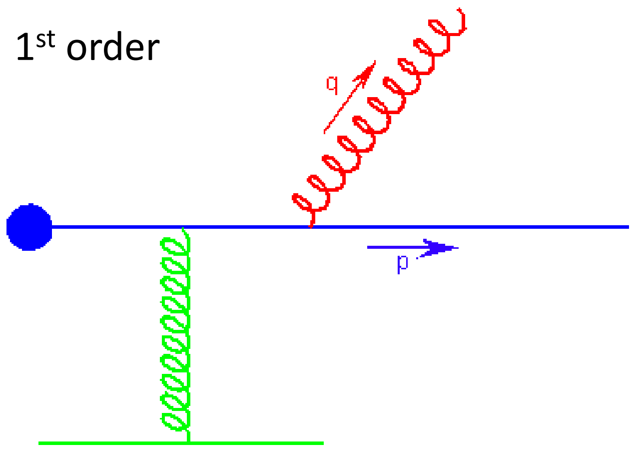
Radiative energy loss

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

0th order



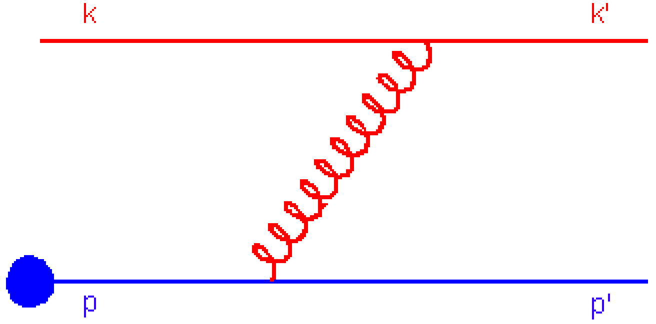
1st order



Collisional energy loss

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

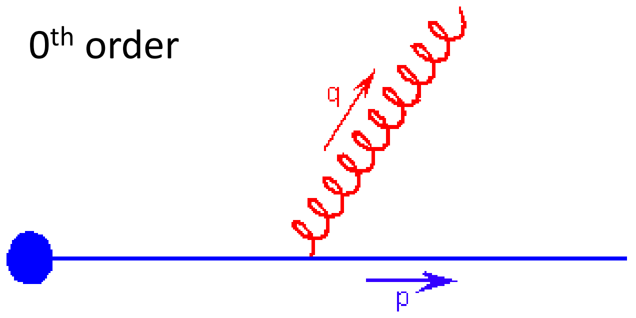
0th order

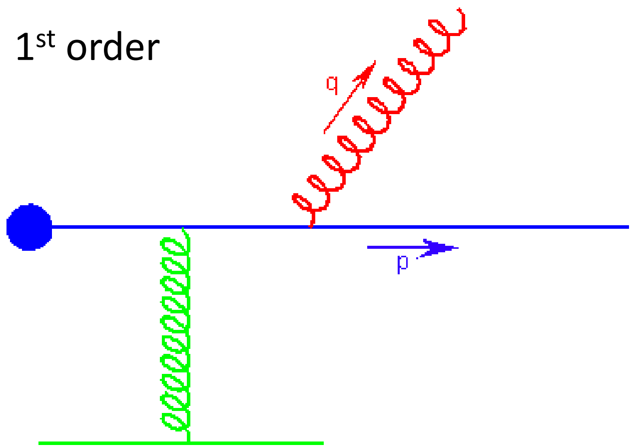


Energy loss in QGP

Radiative energy loss

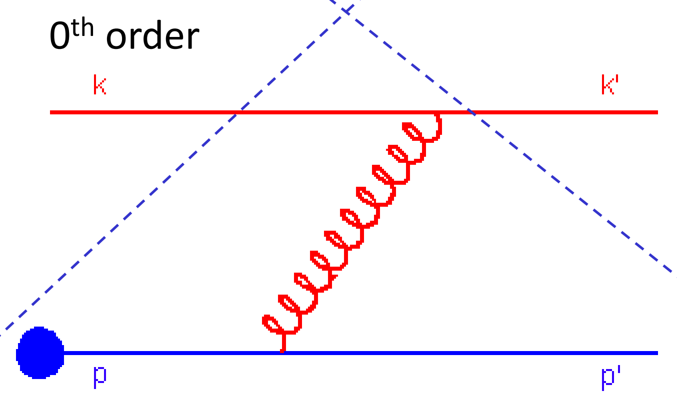
Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:





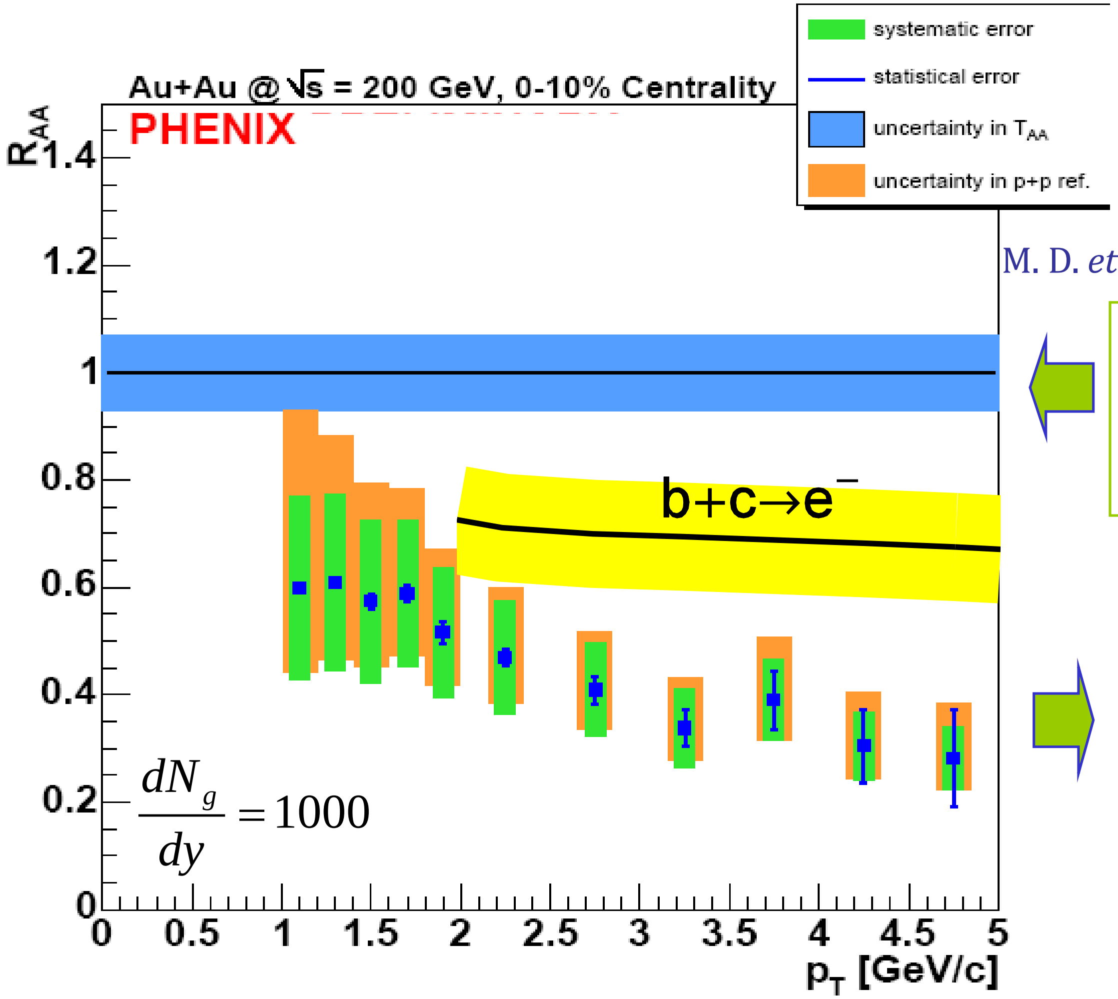
Collisional energy loss

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



Considered to be negligible compared to radiative!

Heavy flavor puzzle @ RHIC



M. D. *et al.*, Phys. Lett. B 632, 81 (2006)

Radiative energy loss predictions with $dN_g/dy=1000$

Disagreement!

Radiative energy loss cannot explain the single electron data as long as realistic parameter values are considered!

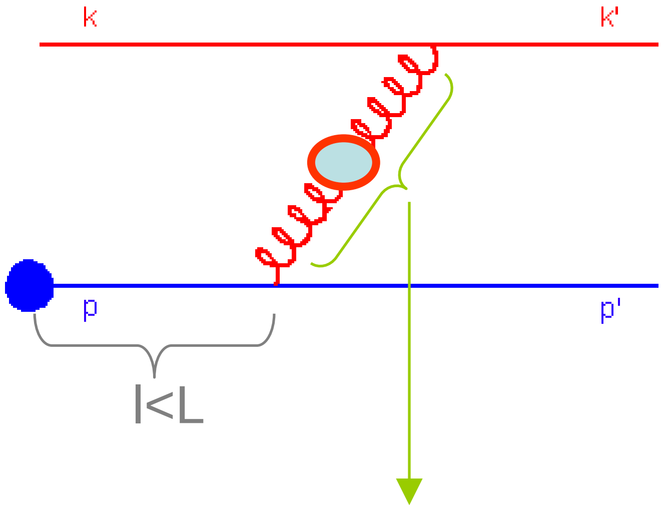
Does the radiative energy loss control the energy loss in QGP?

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.

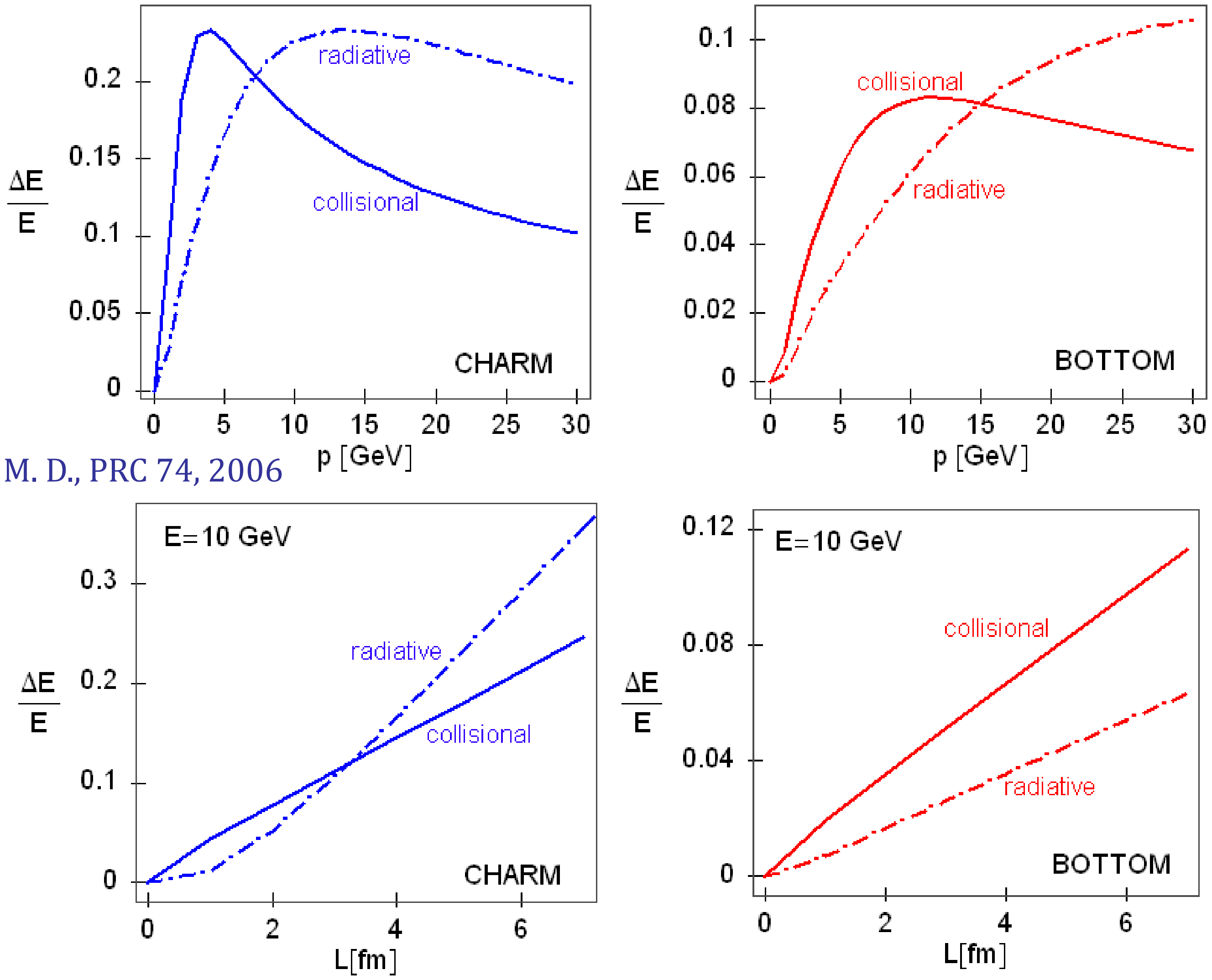
The main order collisional energy loss is determined from:



The effective gluon propagator:

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

M. D., Phys.Rev.C74:064907,2006



M. D., PRC 74, 2006

Collisional and radiative energy losses are comparable!

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

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

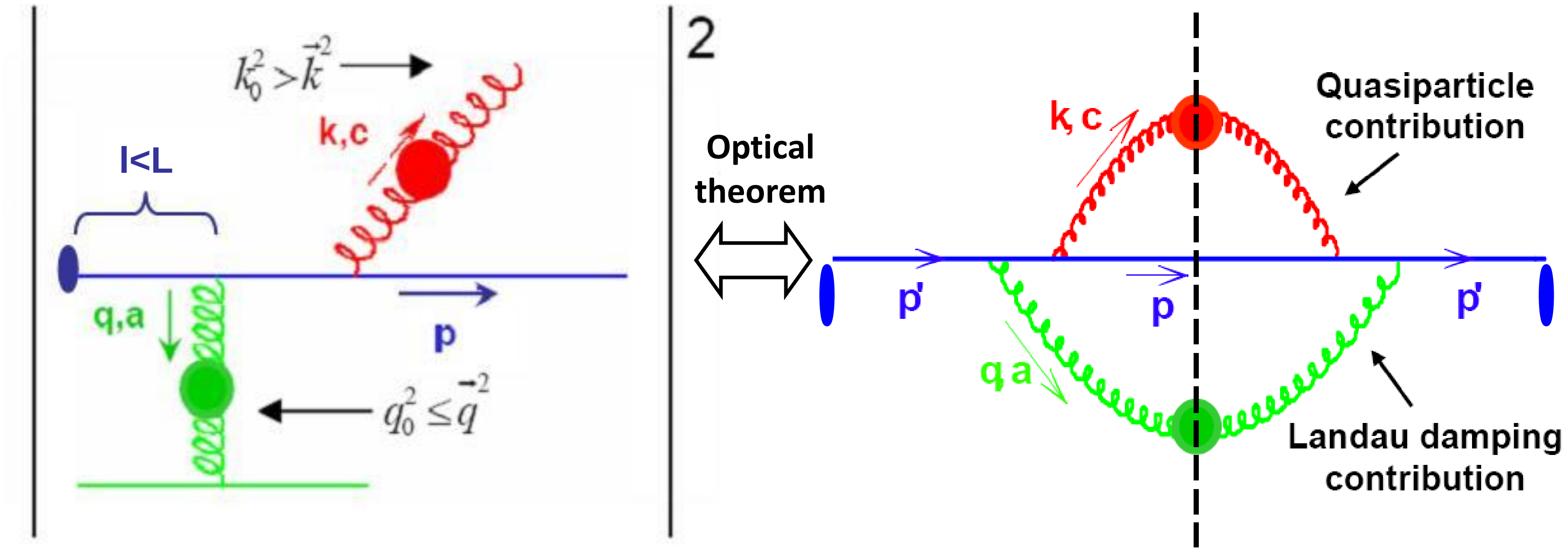
Why?

- Address the applicability of static approximation in radiative energy loss computations.
- Compute collisional and radiative energy losses within a consistent theoretical framework.

Radiative energy loss in a dynamical medium

Compute the medium-induced radiative energy loss for a heavy quark to the first (lowest) order in the number of scattering centers.

Consider the radiation of one gluon induced by one collisional interaction with the medium.



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:

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

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

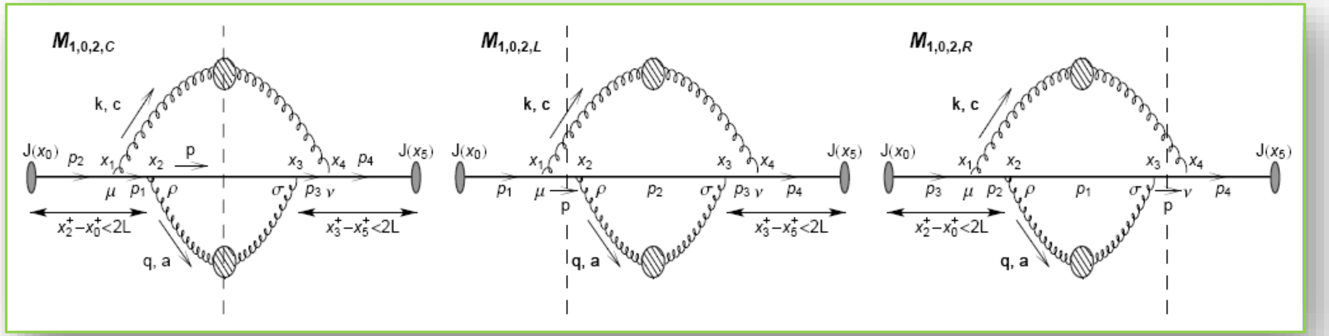
For radiated gluon, the cut 1-HTL gluon propagator can be simplified to (M.D. and M. Gyulassy, PRC 68, 034914 (2003))

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

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

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

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.

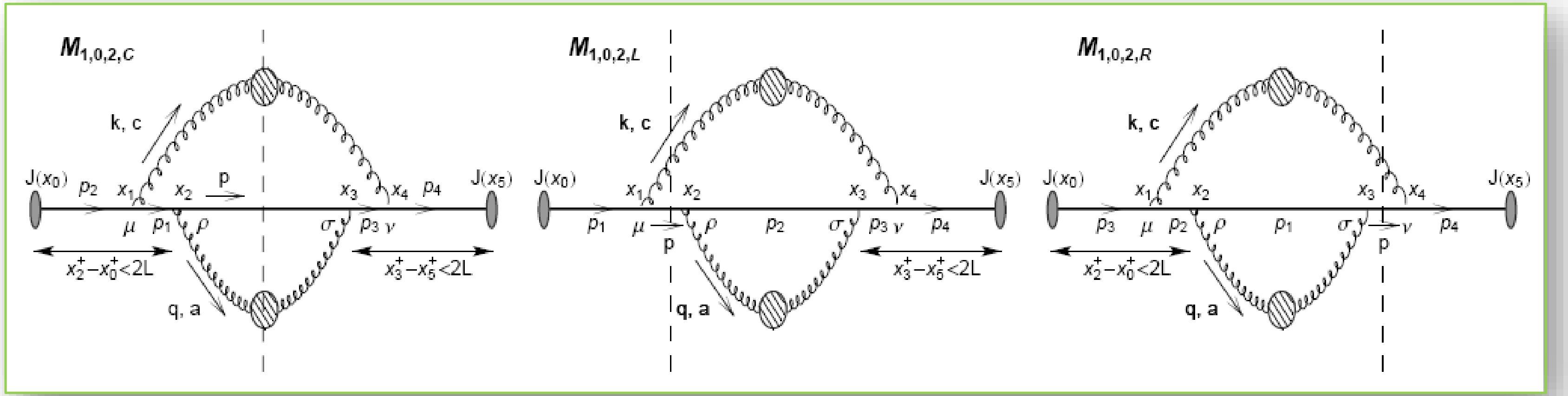
So, all 24 diagrams have to be included to obtain a sensible result.

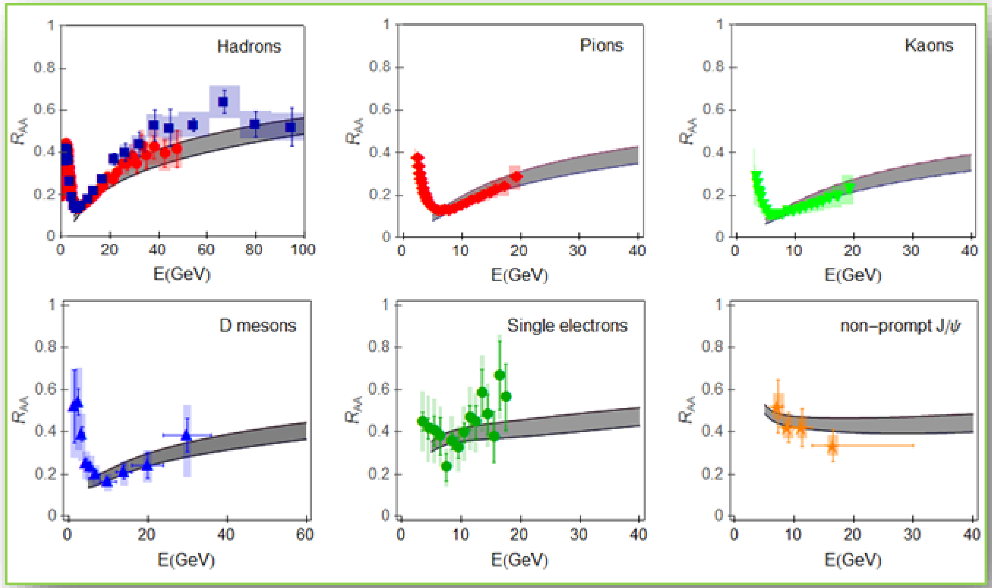
$$\frac{\Delta E_{\rm dyn}}{E} = \frac{C_R \alpha_s}{\pi}\frac{L}{\lambda_{\rm dyn}}\int dx \frac{d^2k}{\pi}\frac{d^2q}{\pi}\frac{\mu^2}{q^2(q^2+\mu^2)}\left(1-\frac{\sin\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}\right) \times 2\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}\left(\frac{(\mathbf{k}+\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

The dynamical energy loss formalism

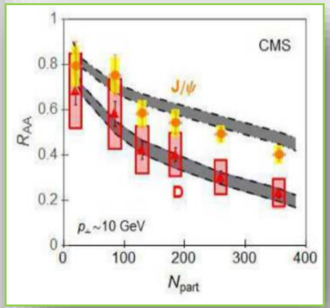
Has the following unique features:

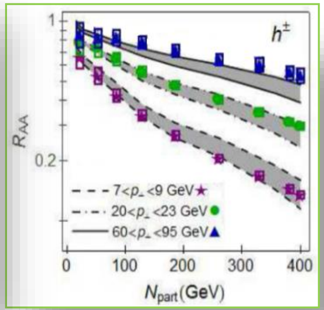
- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite T field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M. D. 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.



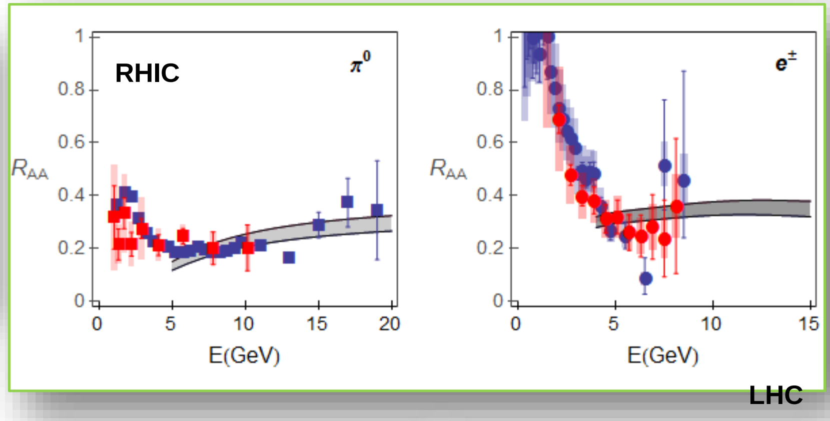


Explains high-pt R_{AA} data for different probes, collision energies, and centralities.



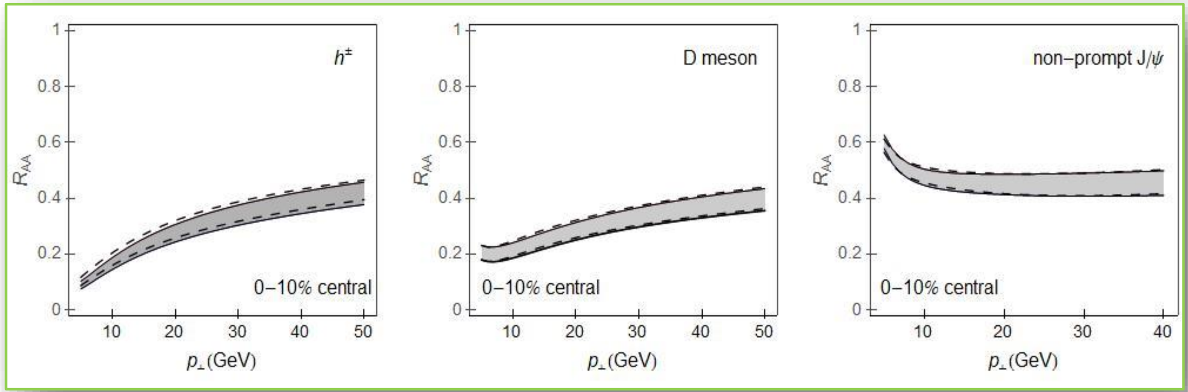


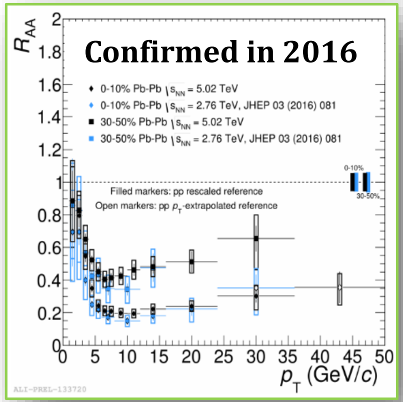
Resolved the longstanding "heavy flavor puzzles at RHIC and LHC".

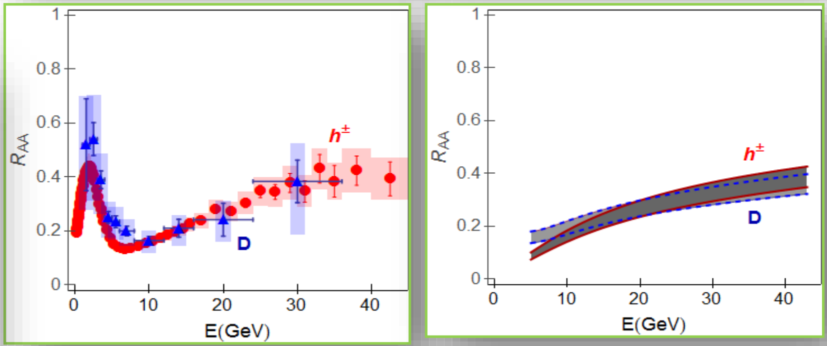


Clear predictive power!

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





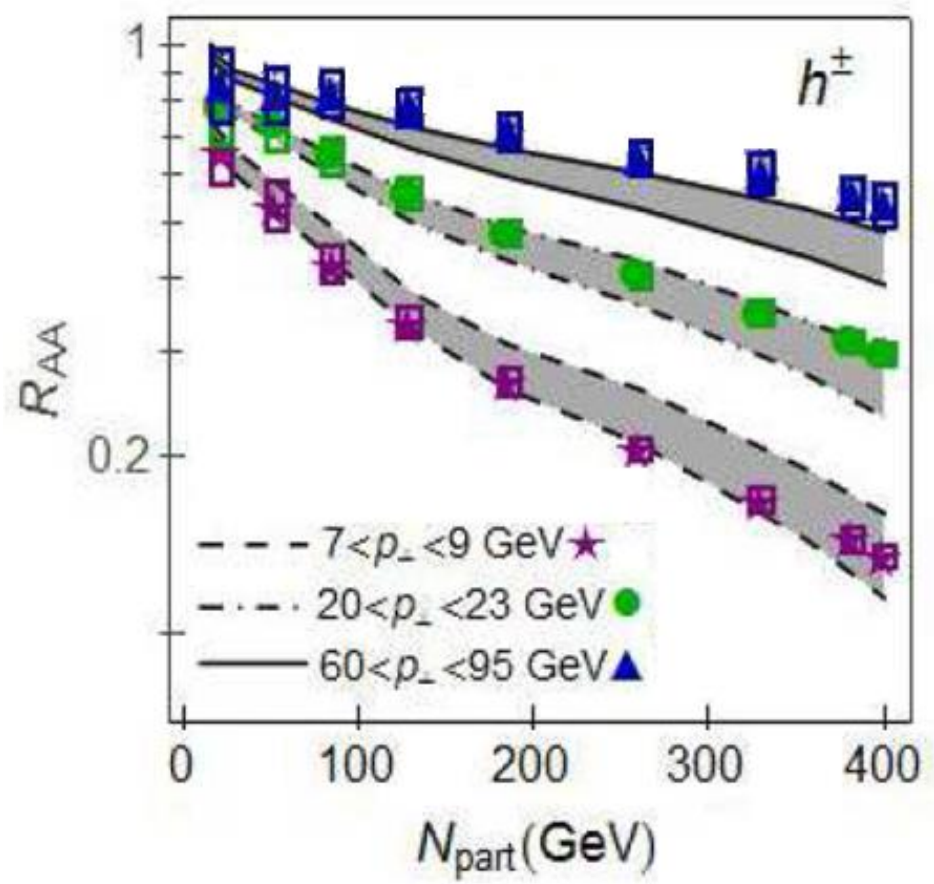


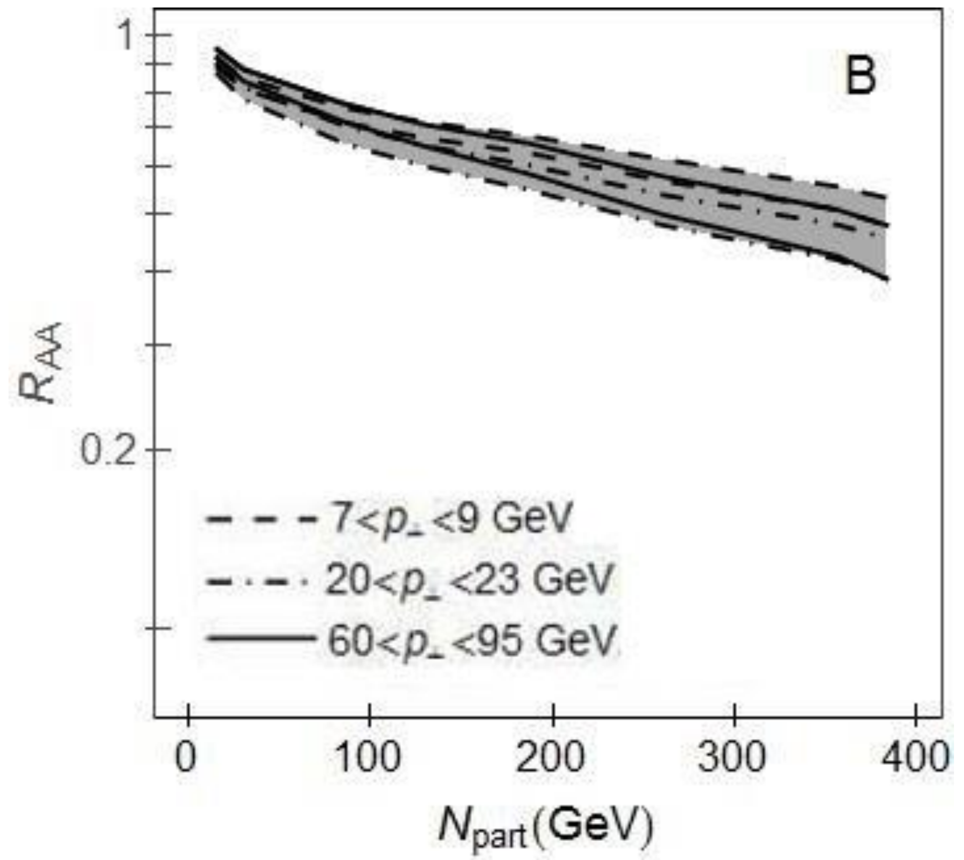
M.D., PRL 112, 042302 (2014)

A realistic description for parton-medium interactions!

Suitable for QGP tomography!

How to use heavy flavor to distinguish collisional vs. radiative energy loss?

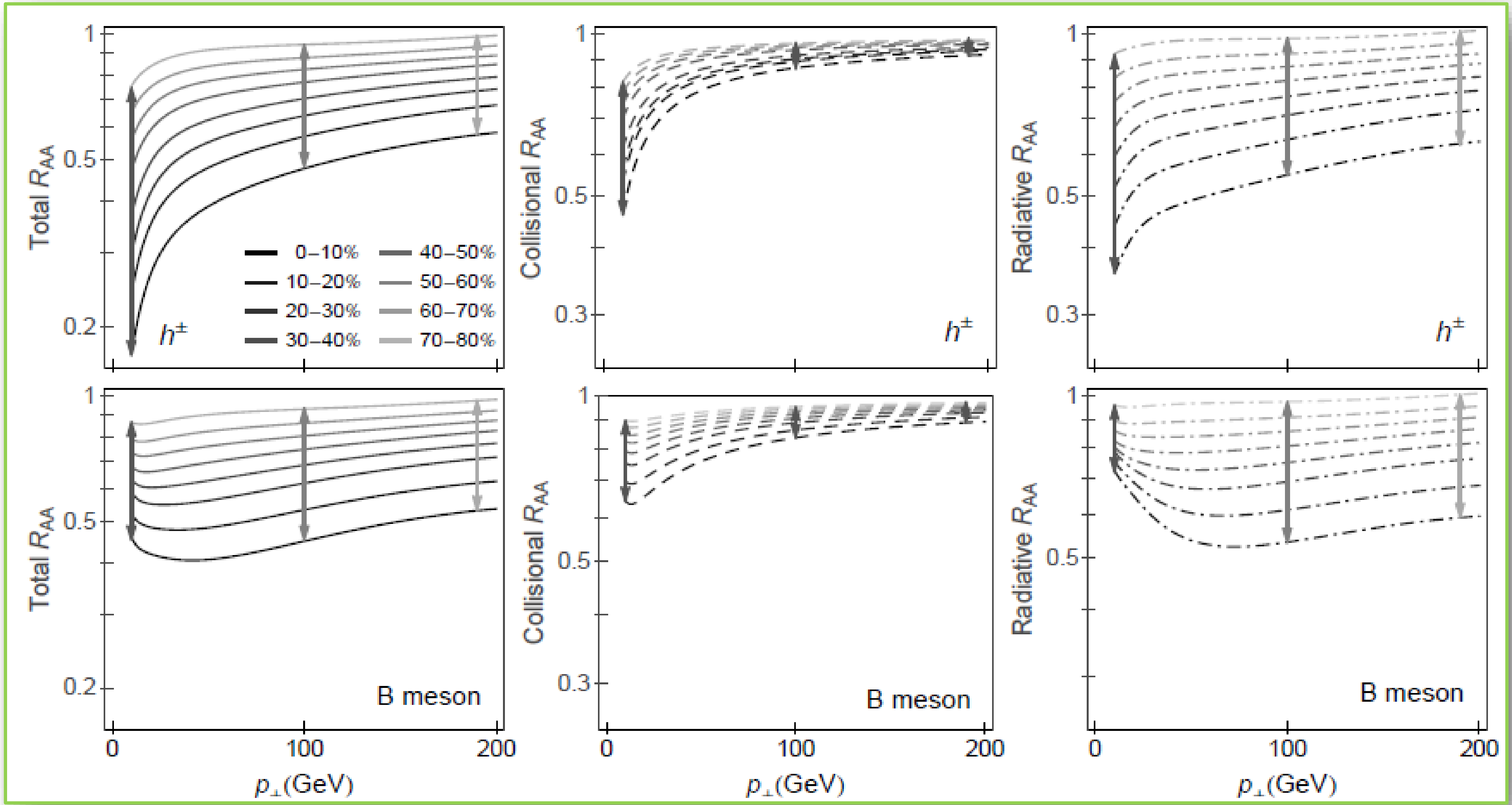




Distinct R_{AA} *vs.* N_{part} for light probes (flattening with increasing *pt* range).

We predict: *The same* R_{AA} *vs.* N_{part} for bottom probes *(*independently on the *pt* range).

MD, PLB 763, 439 (2016)



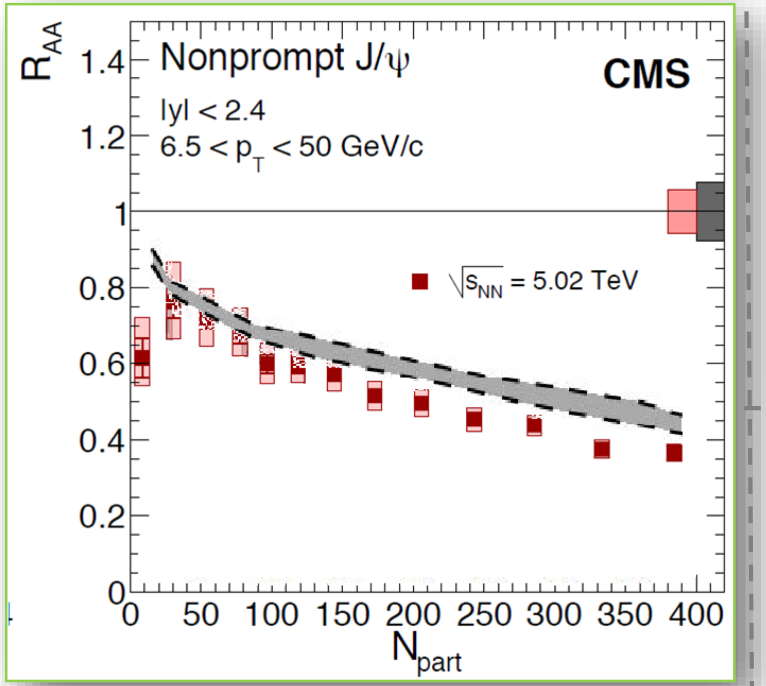
Clear qualitative separation between collisional and radiative energy loss contributions.

Three types of predictions for bottom:

I. Quantitative predictions of the suppression patterns
II. Flattening of the $R_{AA}(pt)$ data
III. Overlap of $R_{AA}(N_{part})$ for different momentum regions

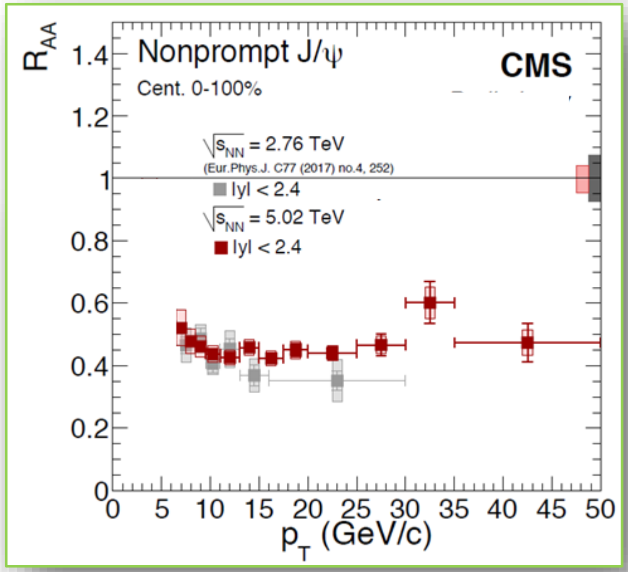
II and III are a consequence of clearly different qualitative contributions from collisional and radiative energy loss effects.

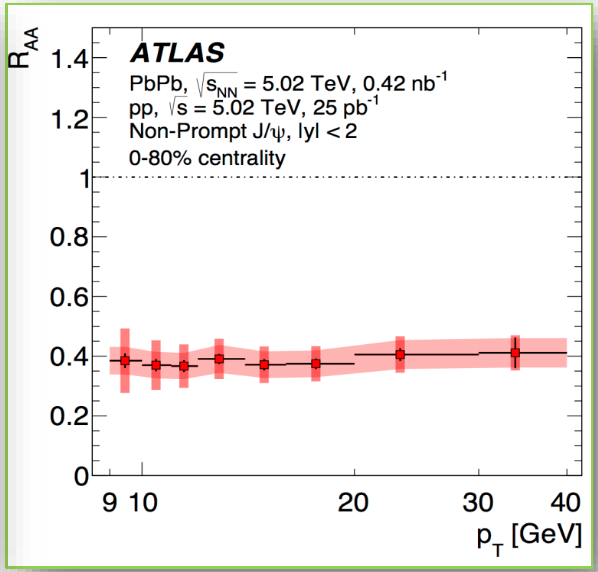
I. Quantitative predictions of the suppression patterns



Good agreement with the data

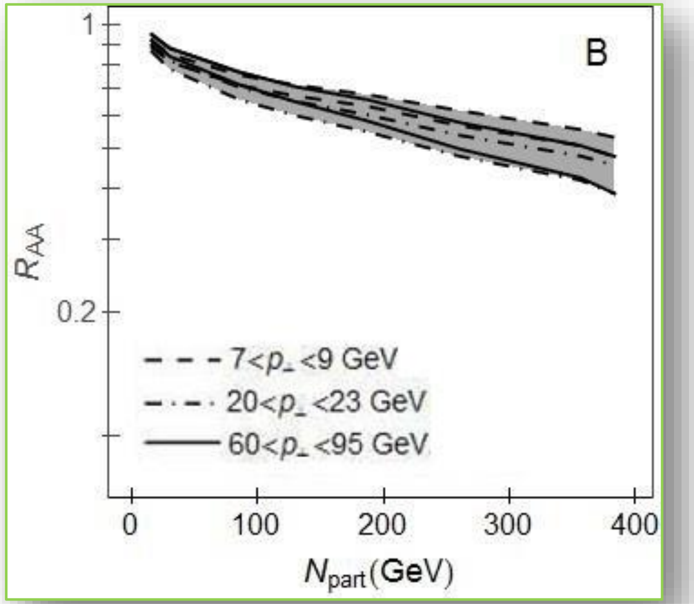
II. Flattening of the R_{AA}(pt) data





Observed by both CMS and ATLAS

III. Overlap of $R_{AA}(N_{part})$ for different momentum regions

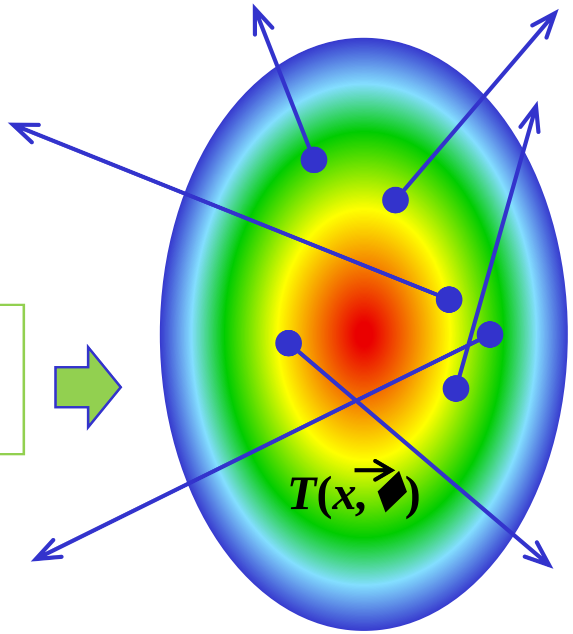


MD, PLB 763, 439, 2016

Outlook for the upcomming experiments
(also an additional test of radiative and collisional energy loss contributions)

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.

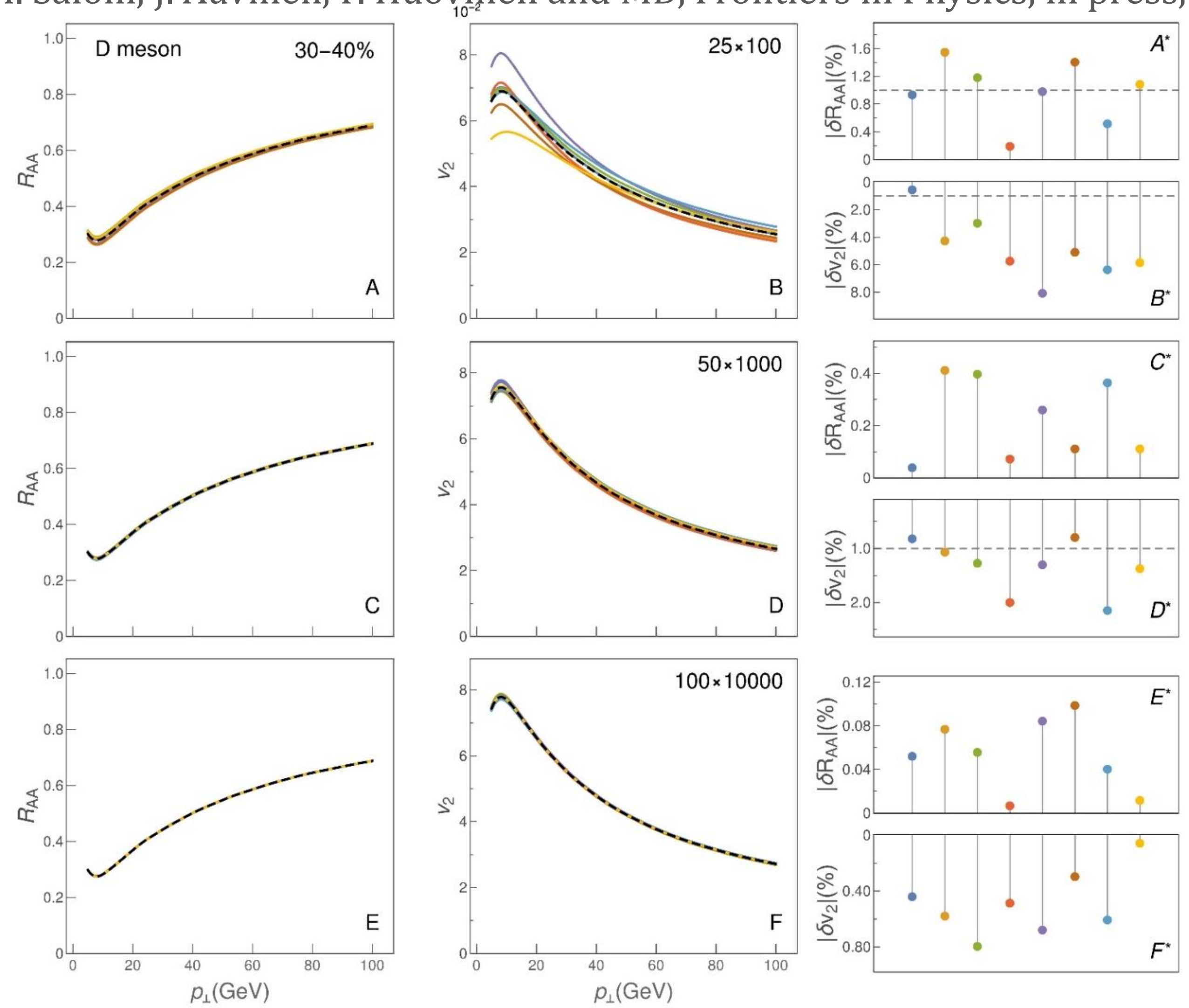
Develop fully optimized DREENA-A framework.

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

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, Frontiers in Physics, in press, 2022

Monte Carlo

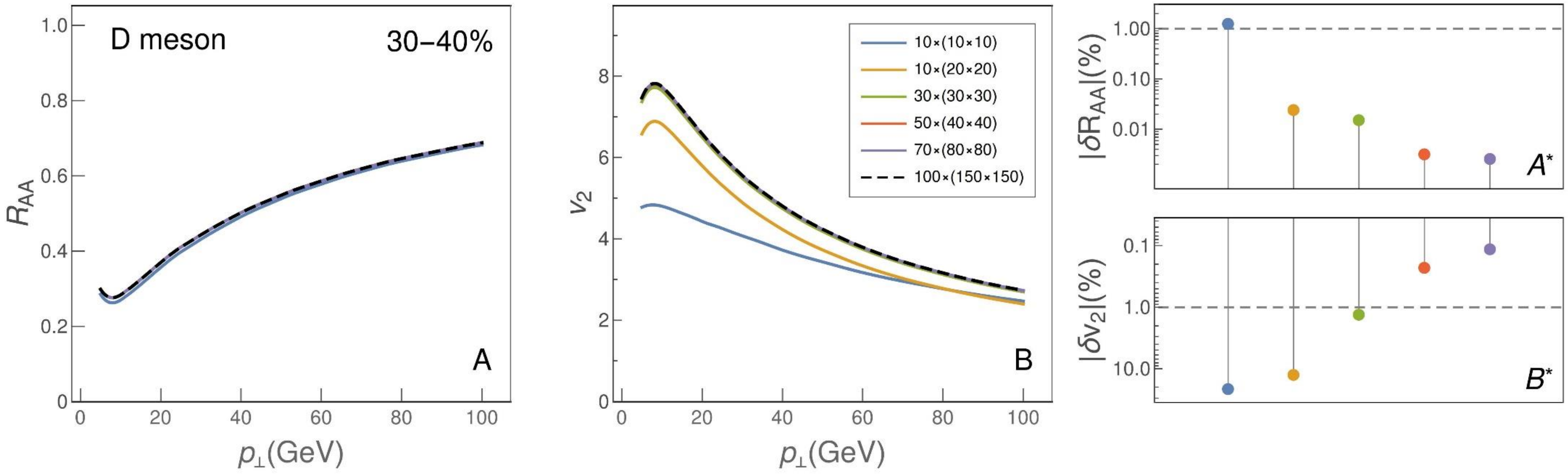
D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, Frontiers in Physics, in press, 2022



Not very efficient!

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

Equidistant sampling



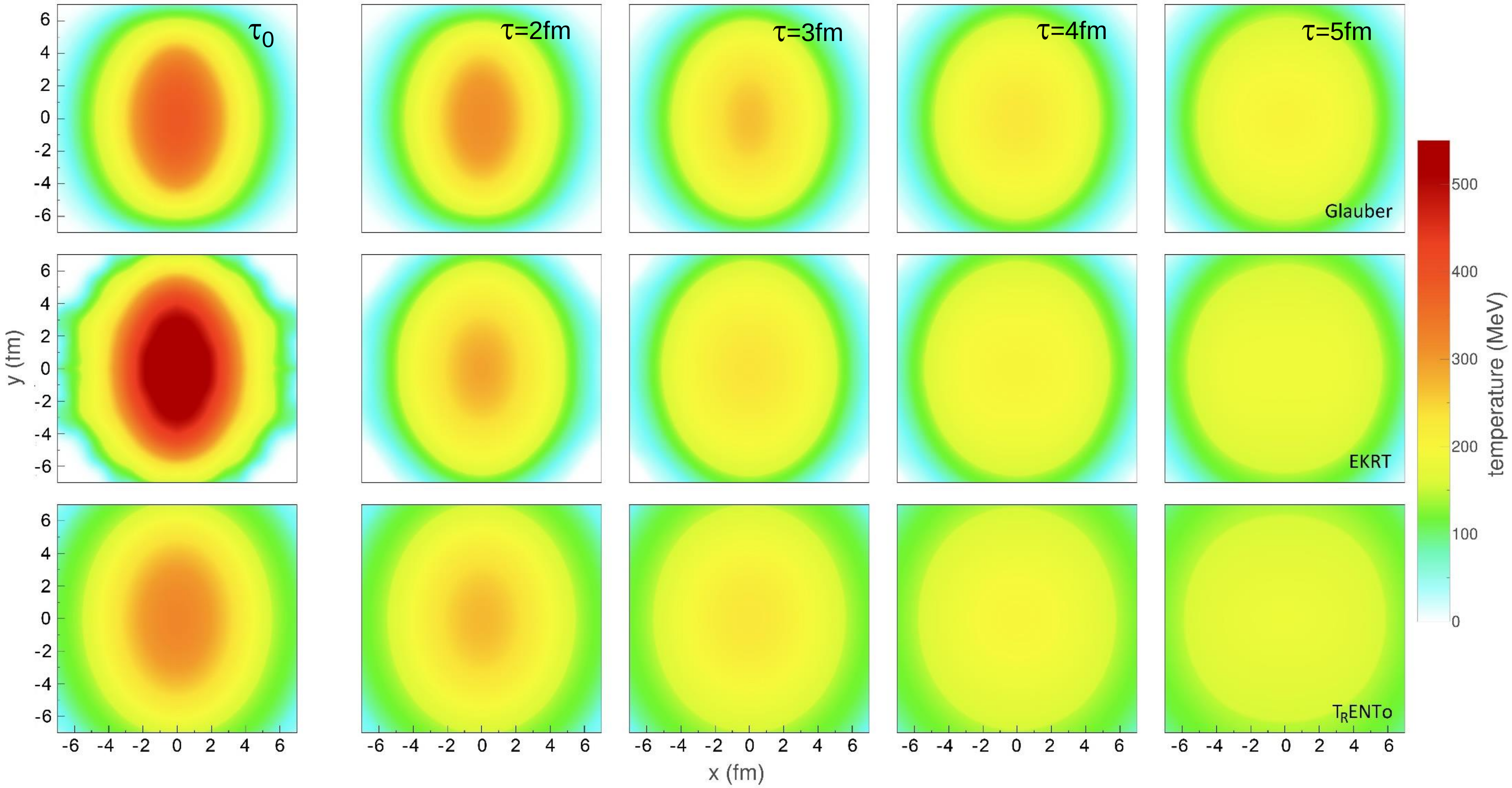
Two orders of magnitude increase in the efficiency!

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, Frontiers in Physics, in press, 2022

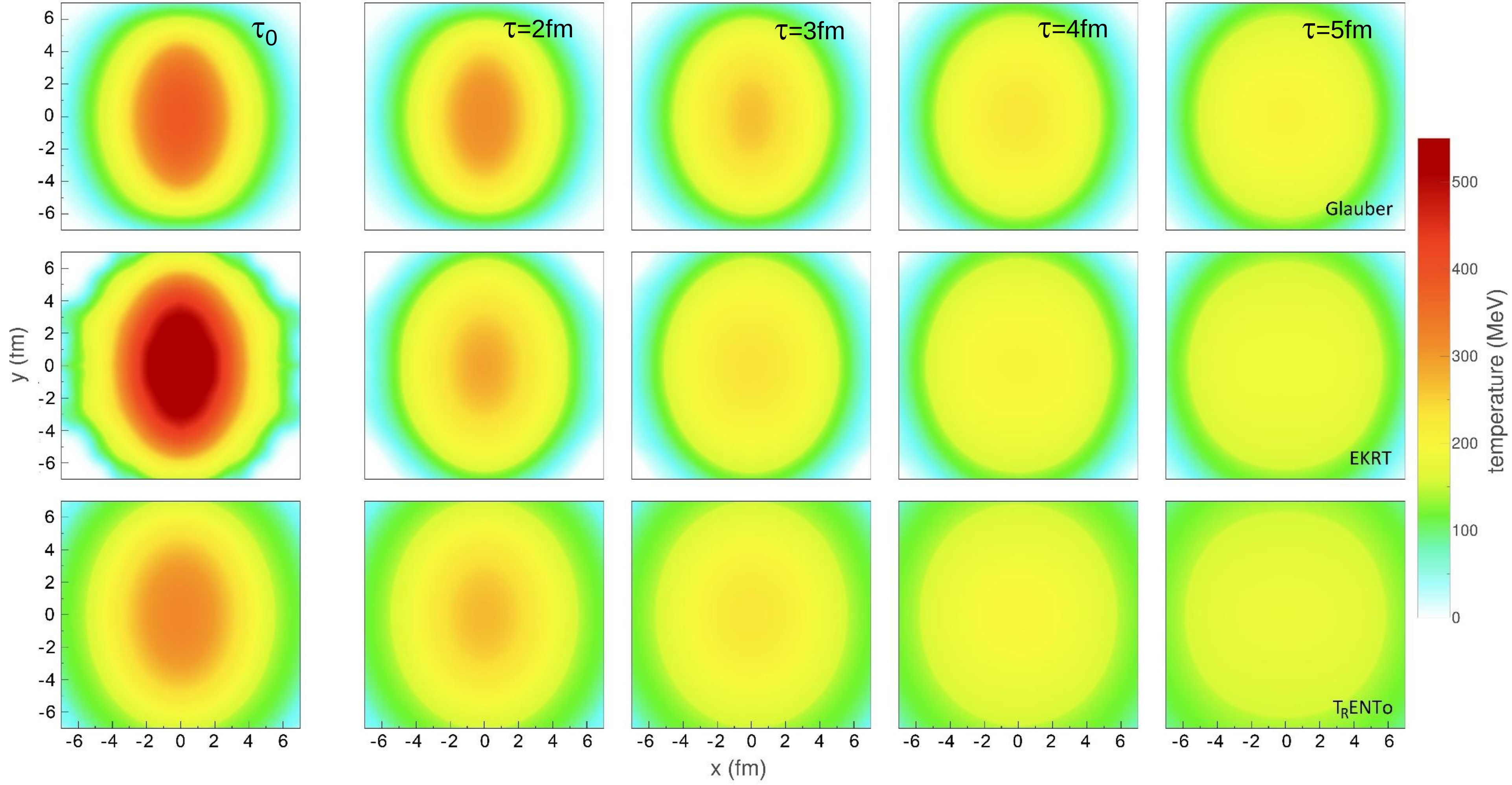
Are high-pt observables indeed sensitive to different T profiles?



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, Frontiers in Physics, in press, 2022

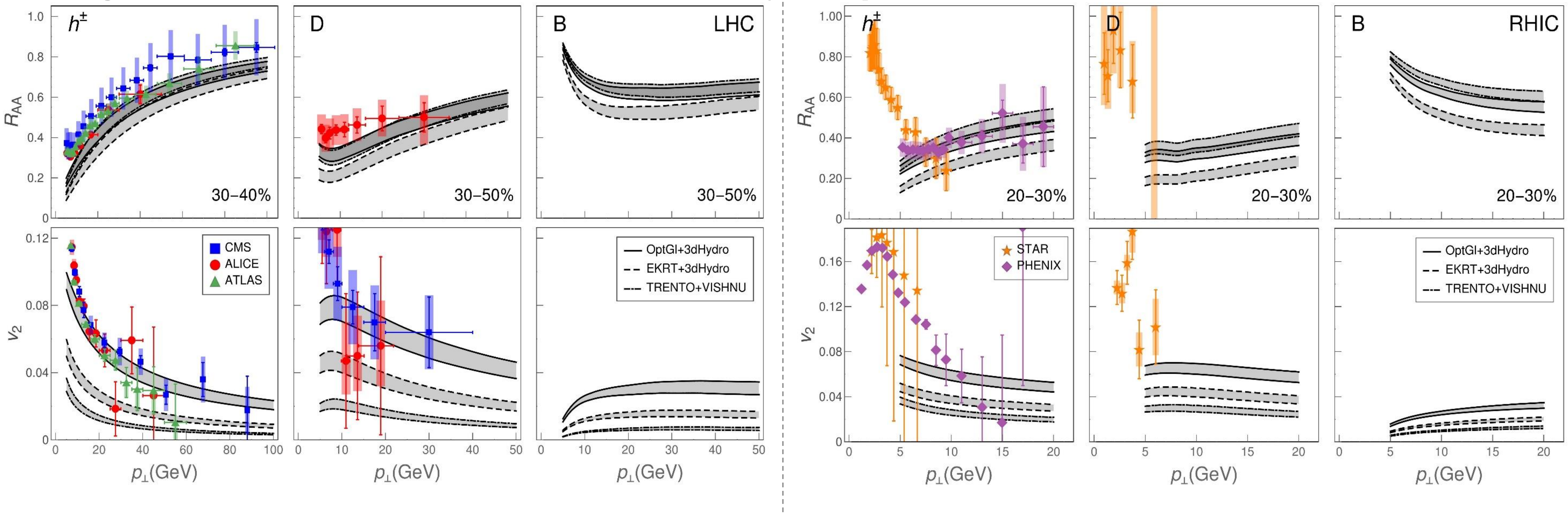
Qualitative differences



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

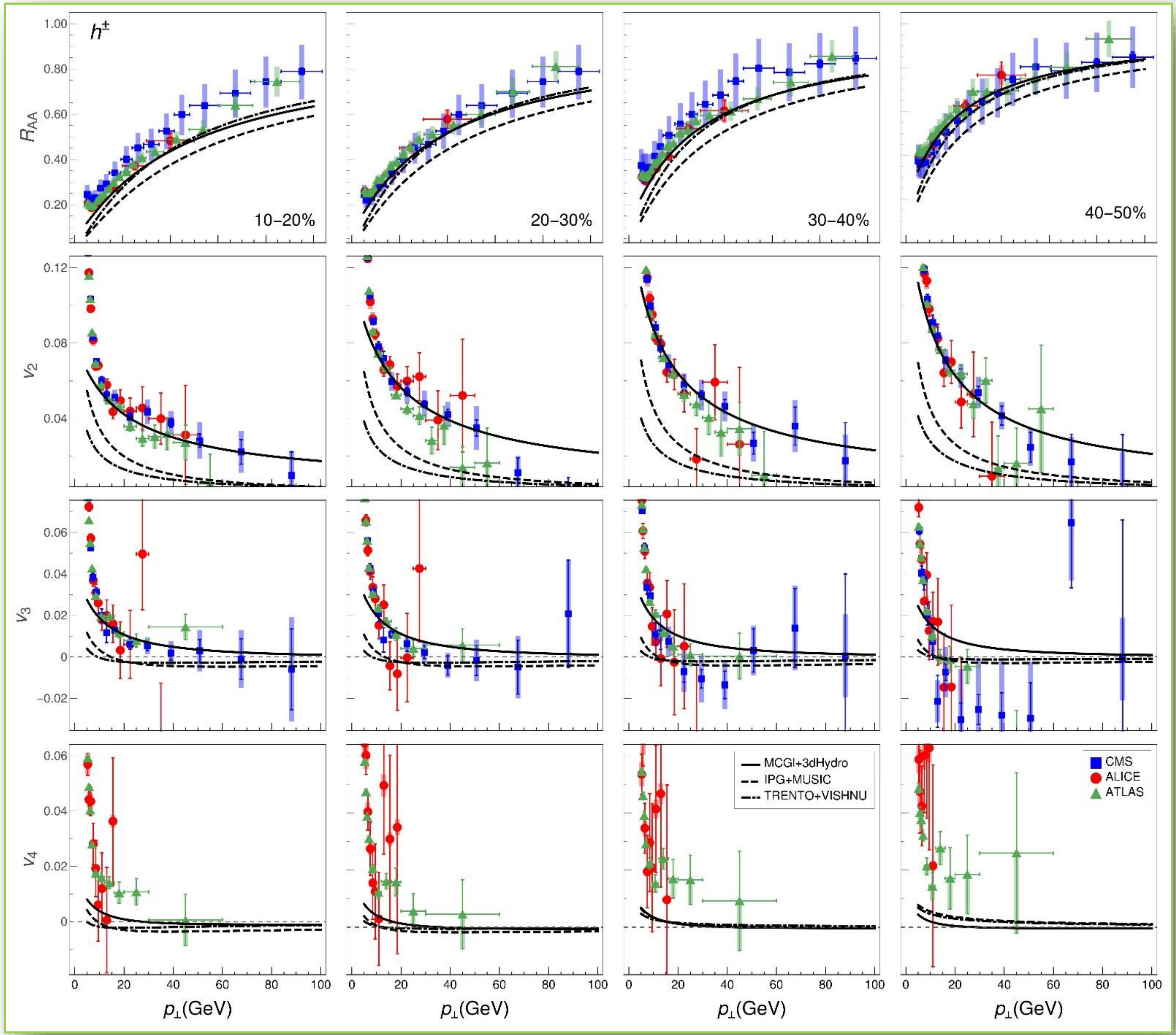
DREENA-A predictions for light and heavy flavor

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and MD, Frontiers in Physics, in press, 2022



- '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

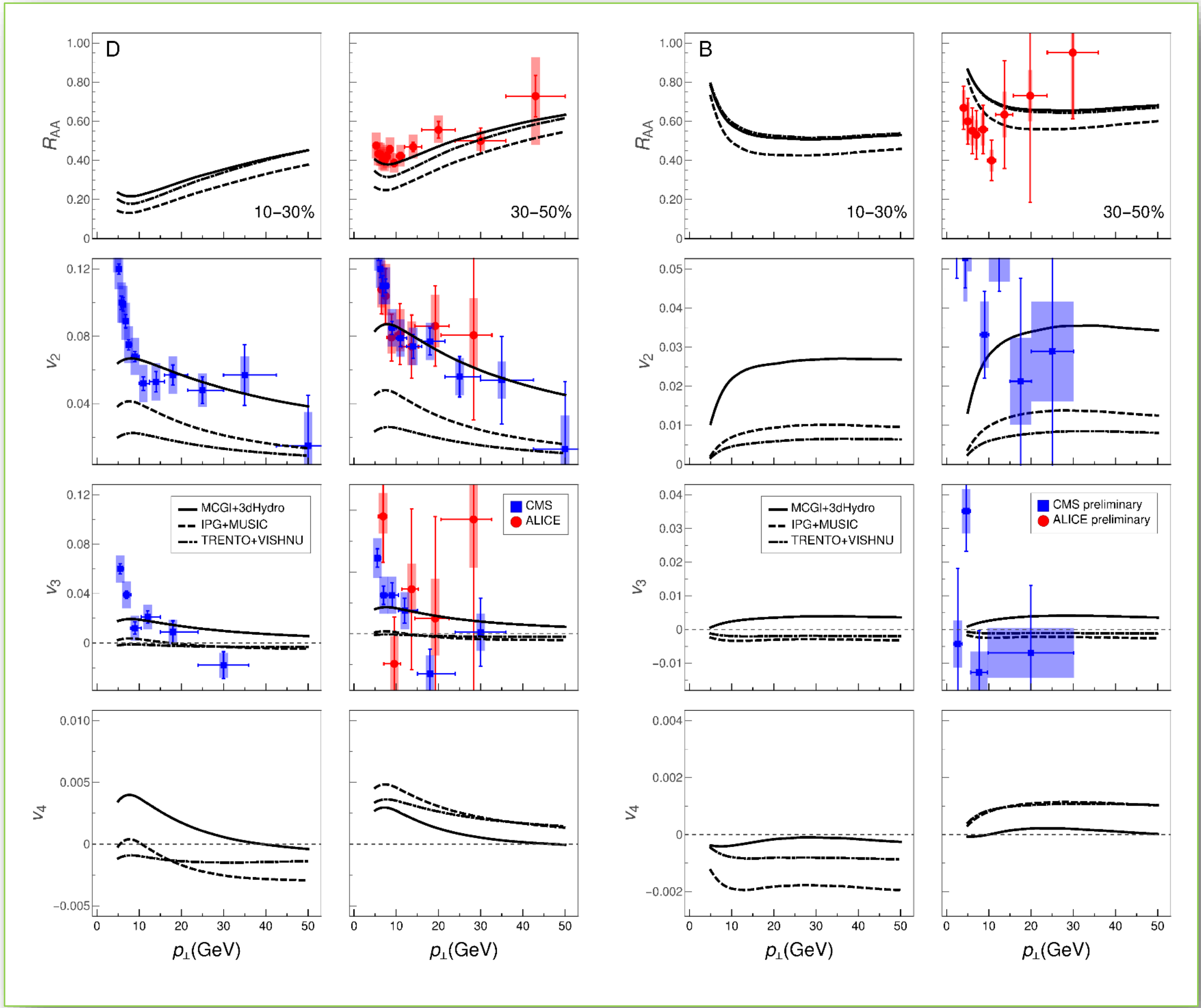


D. Zigic, J. Auvinen, I. Salom, P. Huovinen and MD, PRC, in press (2022).

- 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, in press (2022).

- 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.

The QGP thermalization time

How do 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 that affects both the evolution of the system and interactions of high-pt particles with the medium.

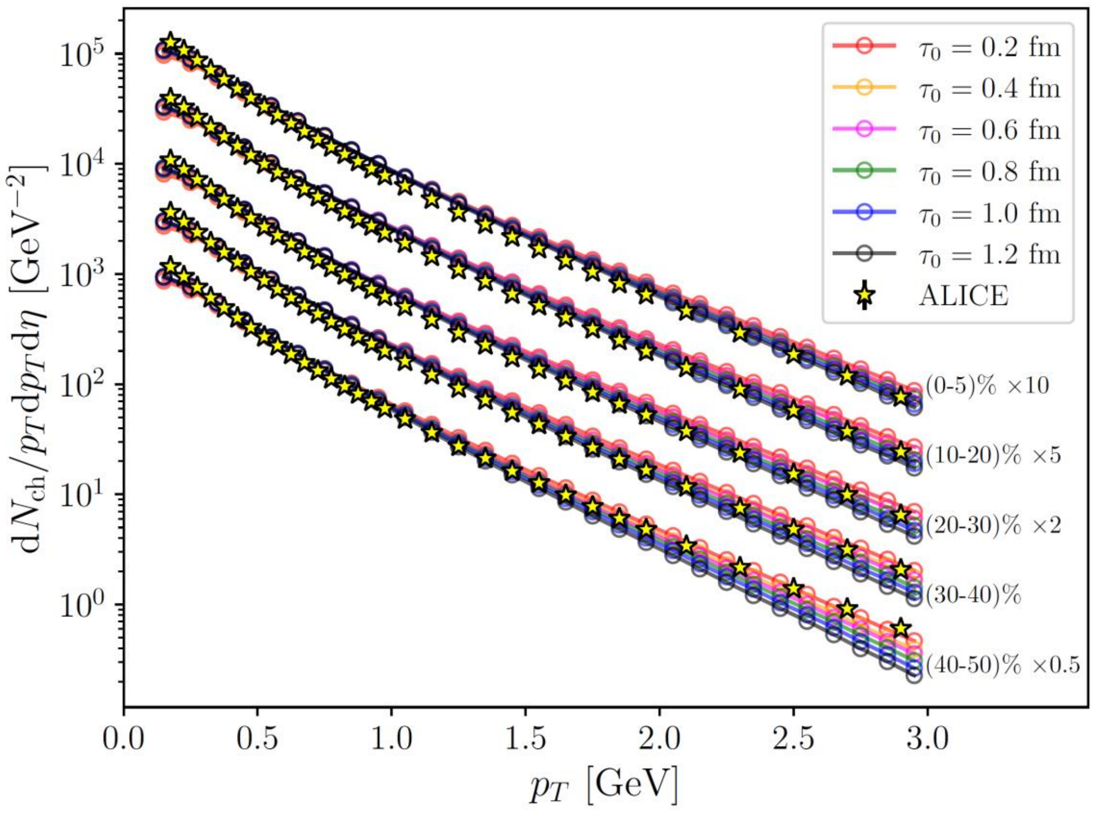
Low-pt physics weakly sensitive to thermalization time

S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, Phys.Rev.C **105** (2022) 2, L021901

Bass *et al.* (2017) showed that the 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.

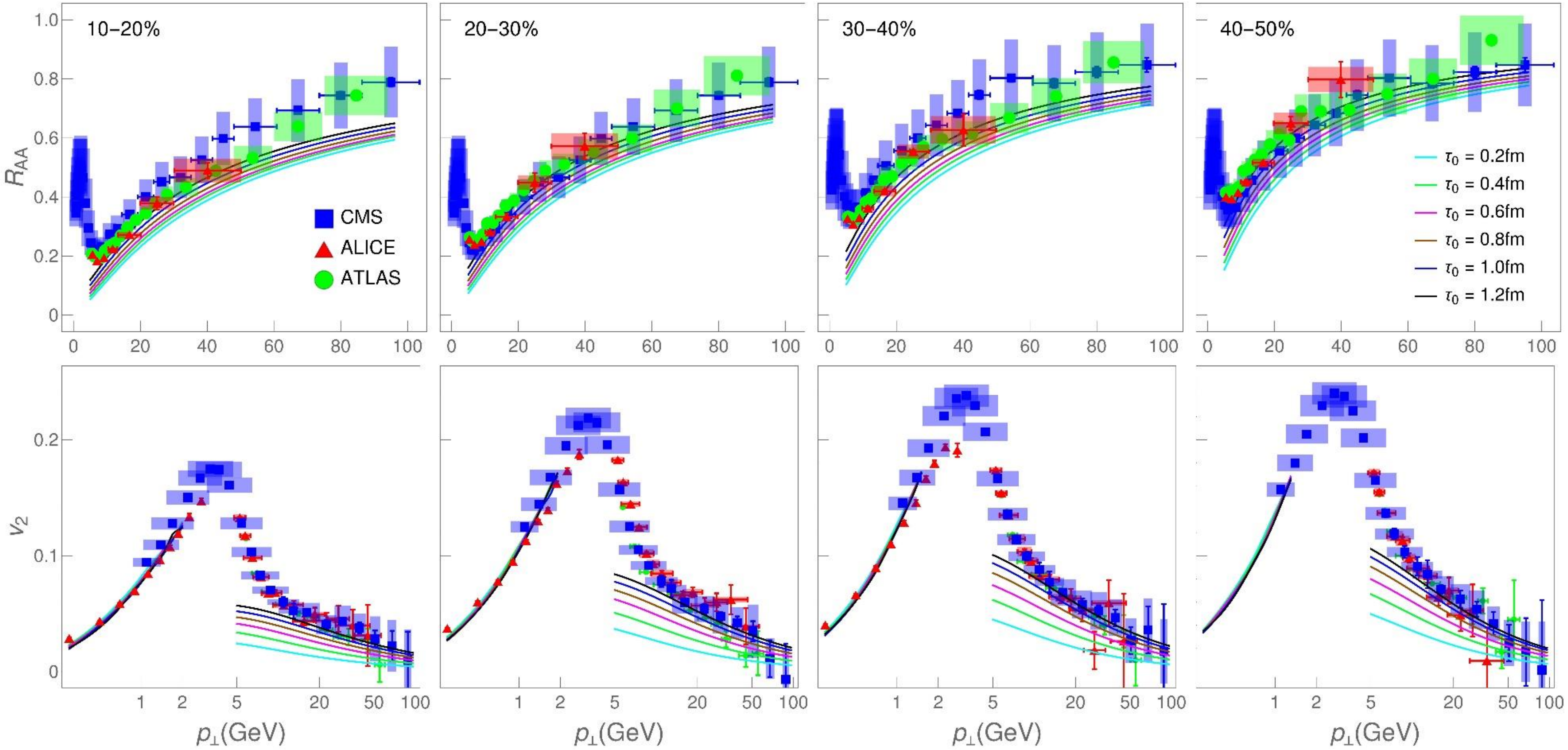


Good agreement with low-pt data, confirming low sensitivity to τ_0!

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

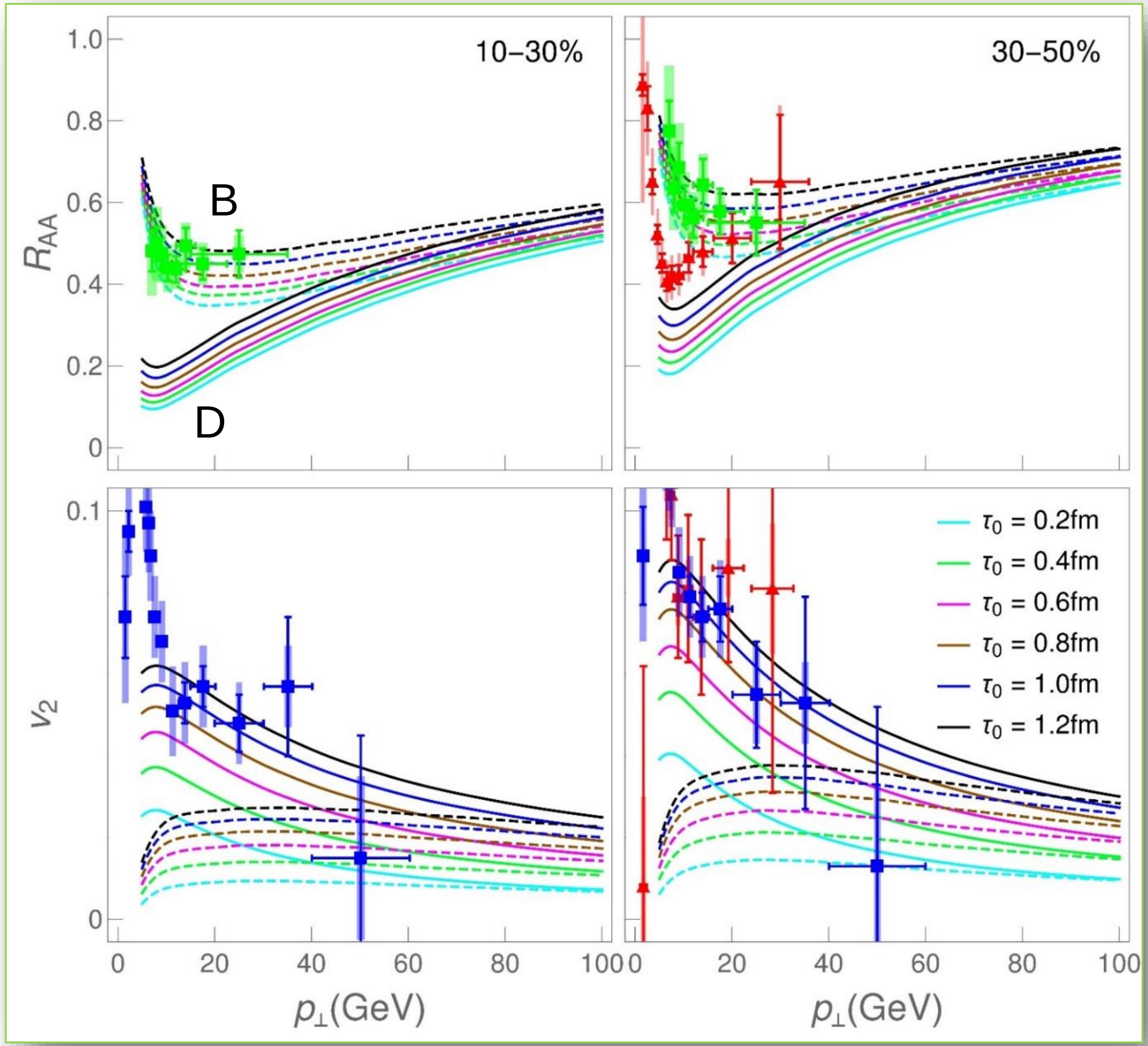
Sensitivity of high-pt theory and data to thermalization time

- 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 the 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

Sensitivity on τ_0 is even larger for heavy than for light flavor!

S. Stojku., J. Auvinen, M. Djordjevic, P. Huovinen and MD, Phys.Rev.C **105** (2022) 2, L021901

What is the reason behind such sensitivity?

Does jet quenching starts later than thermalization?

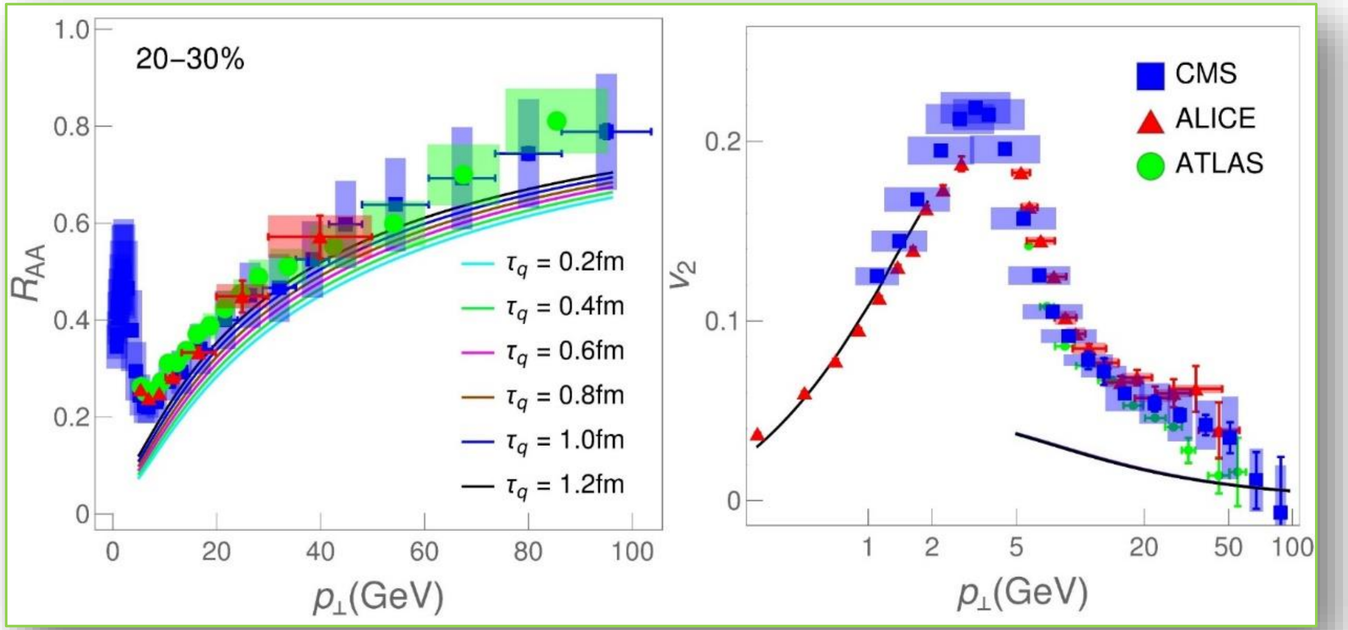
(Andres et al. 2020) proposed that jet quenching may start later than the thermalization of the bulk QCD medium, which may strongly impact high-pt predictions.

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 sensitive 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!



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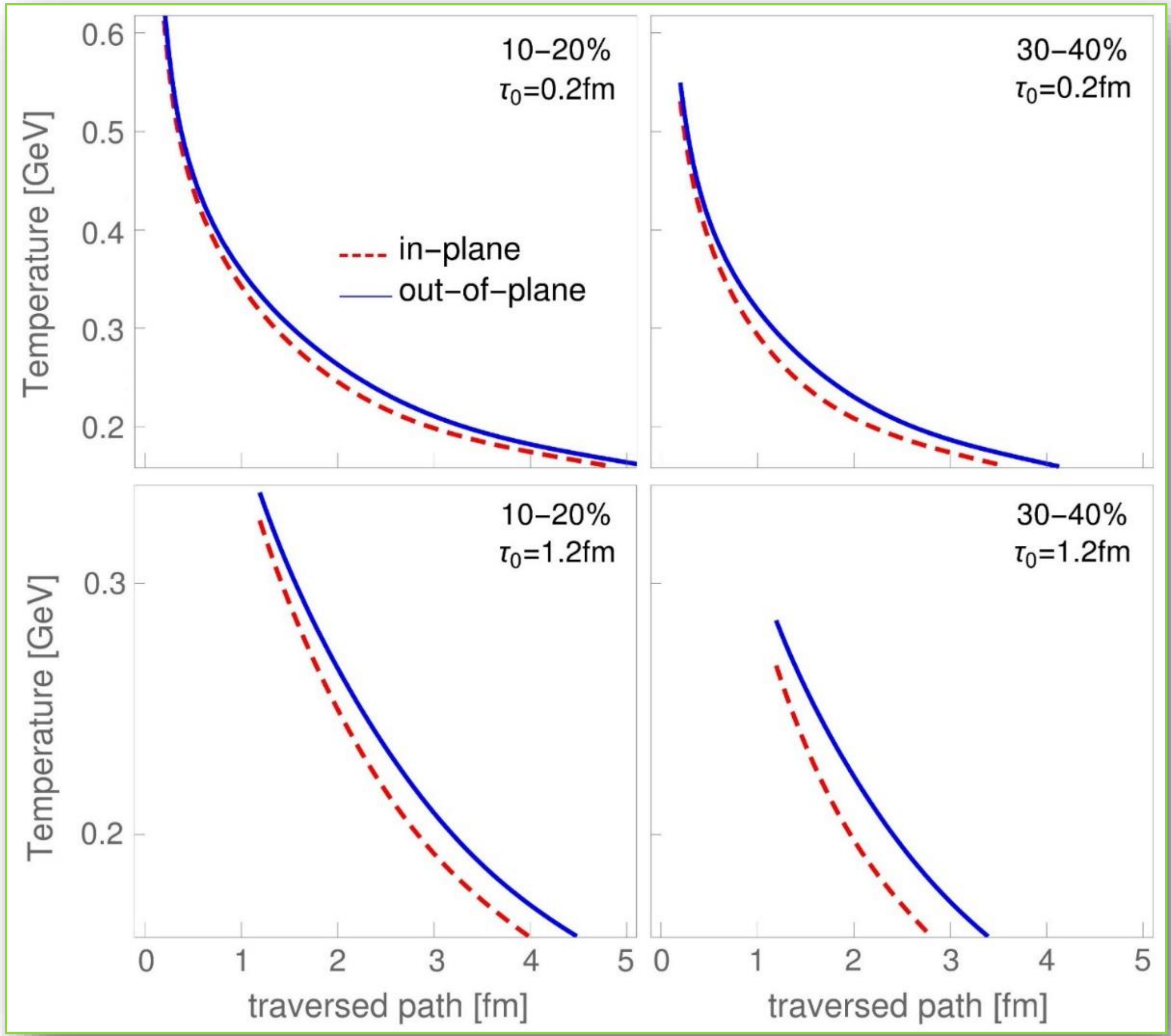
What is the reason behind such sensitivity?

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.
A 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 the observed increase in v_2.

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

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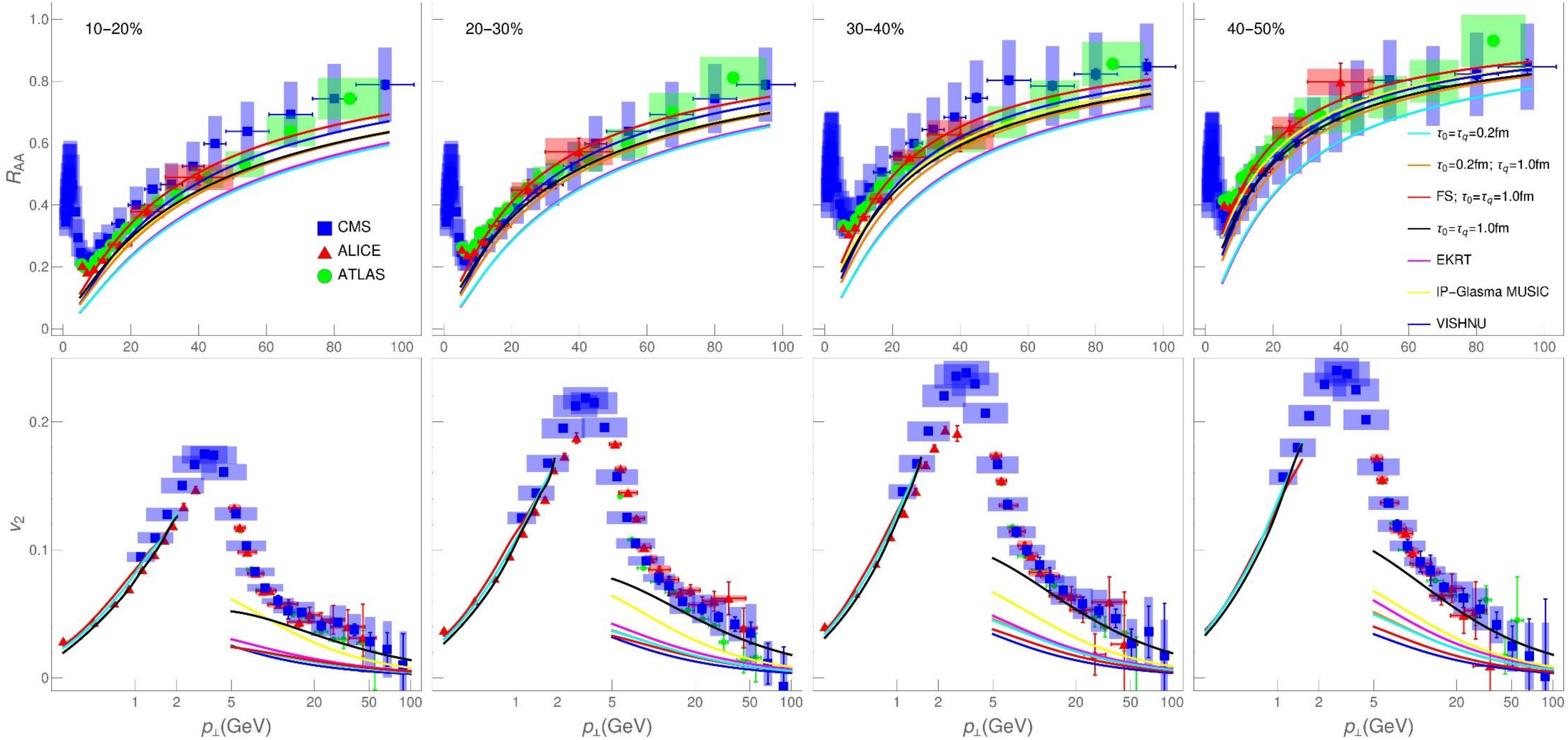
What about more sophisticated hydro initializations?

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!

Significantly weaker interactions in preequilibrium stage are needed than currently expected by different models!

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Summary

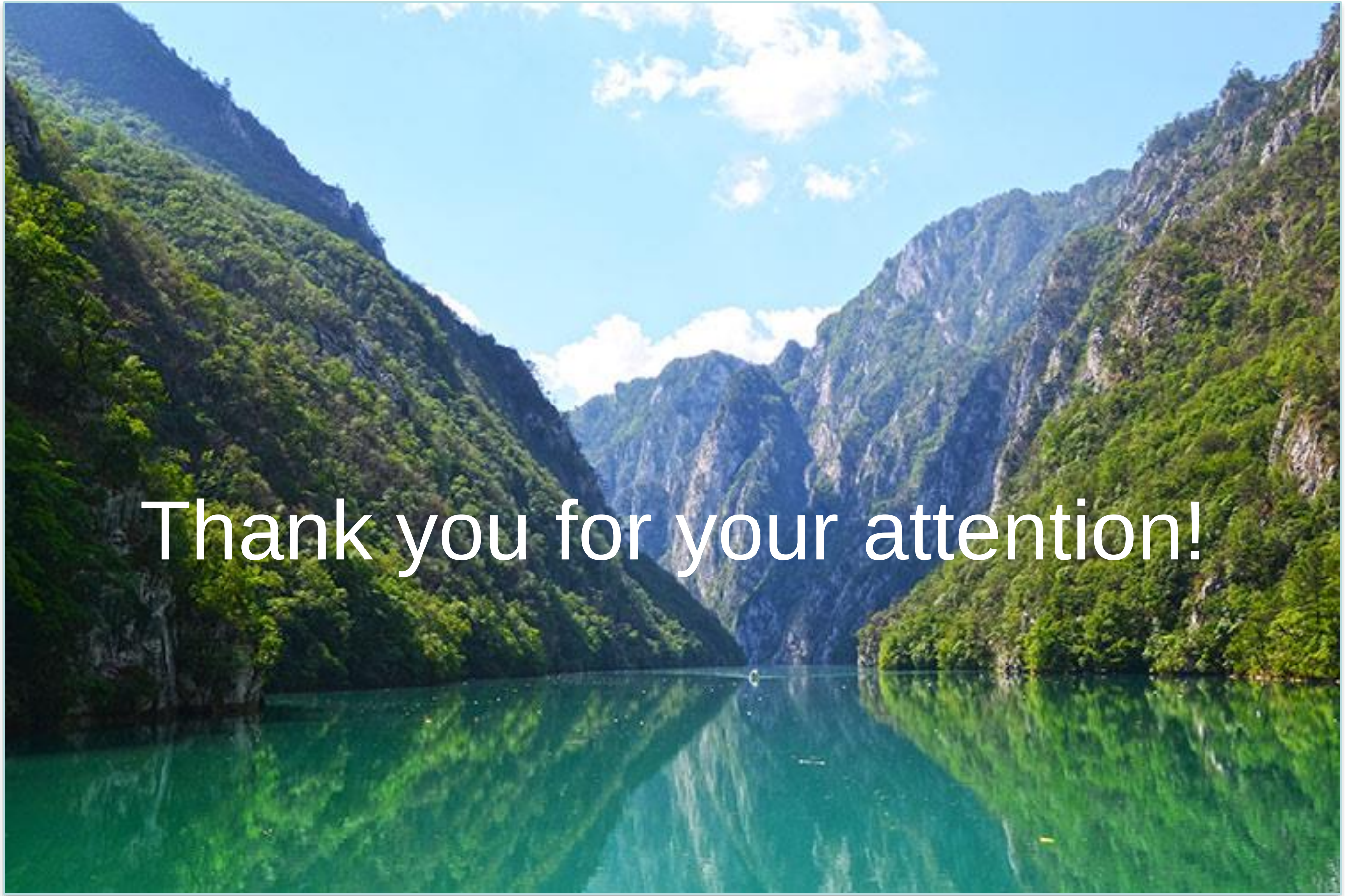
We here presented (to our knowledge) the first example where the parameter critical for simulating bulk QGP evolution, but (to a large extent) insensitive to low-pt physics, is constrained by high-pt theory and data.

Specifically, we here used high-pt R_{AA} and v_2 to infer that 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

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