Constraining the (pre)equilibrium stage using high-$p_\perp$ tomography

Bithika Karmakar
Incubator of Scientific Excellence - Centre for simulations of superdense fluids
University of Wrocław, Poland

Collaborators: Dusan Zigic, Igor Salom, Jussi Auvinen, Pasi Huovinen, Marko Djordjevic and Magdalena Djordjevic

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Heavy Ion Physics in the EIC Era - INT Workshop

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Motivation

- Quark Gluon Plasma (QGP) is created in ultrarelativistic heavy-ion collisions.
- Consists of interacting quarks, antiquarks and gluons.
- Low-$p_\perp (p_\perp \leq 5 GeV)$ observables are generally used to study the medium properties.
- High-$p_\perp$ partons propagate through the medium. Jet looses energy by interacting with the medium.
- The rare high-$p_\perp$ particles can also become excellent probe of the QCD matter.

DREENA

- **D**ynamical **R**adiative and **E**lastic **EN**ergy loss **A**pproach
  - Based on finite temperature field theory and generalized HTL approach

M. Djordjevic, PRC **74**, 064907, (2006) ; PRC **80**, 064909 (2009), M. Djordjevic and U. Heinz, PRL **101**, 022302

  - Finite size dynamical medium is considered
  - Takes into account both radiative and collisional energy losses
  - Generalized to the case of magnetic mass and running coupling
- $$\frac{E_f d^3\sigma_q(H_Q)}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes P(E_i \rightarrow E_f) \otimes D(Q \rightarrow H_Q),$$
- $$\frac{E_f d^3\sigma_u(H_Q)}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes D(Q \rightarrow H_Q).$$
- No fitting parameter used

DREENA-A (Adaptive)

D. Zigic, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, Front. in Phys. **10** (2022) 957019

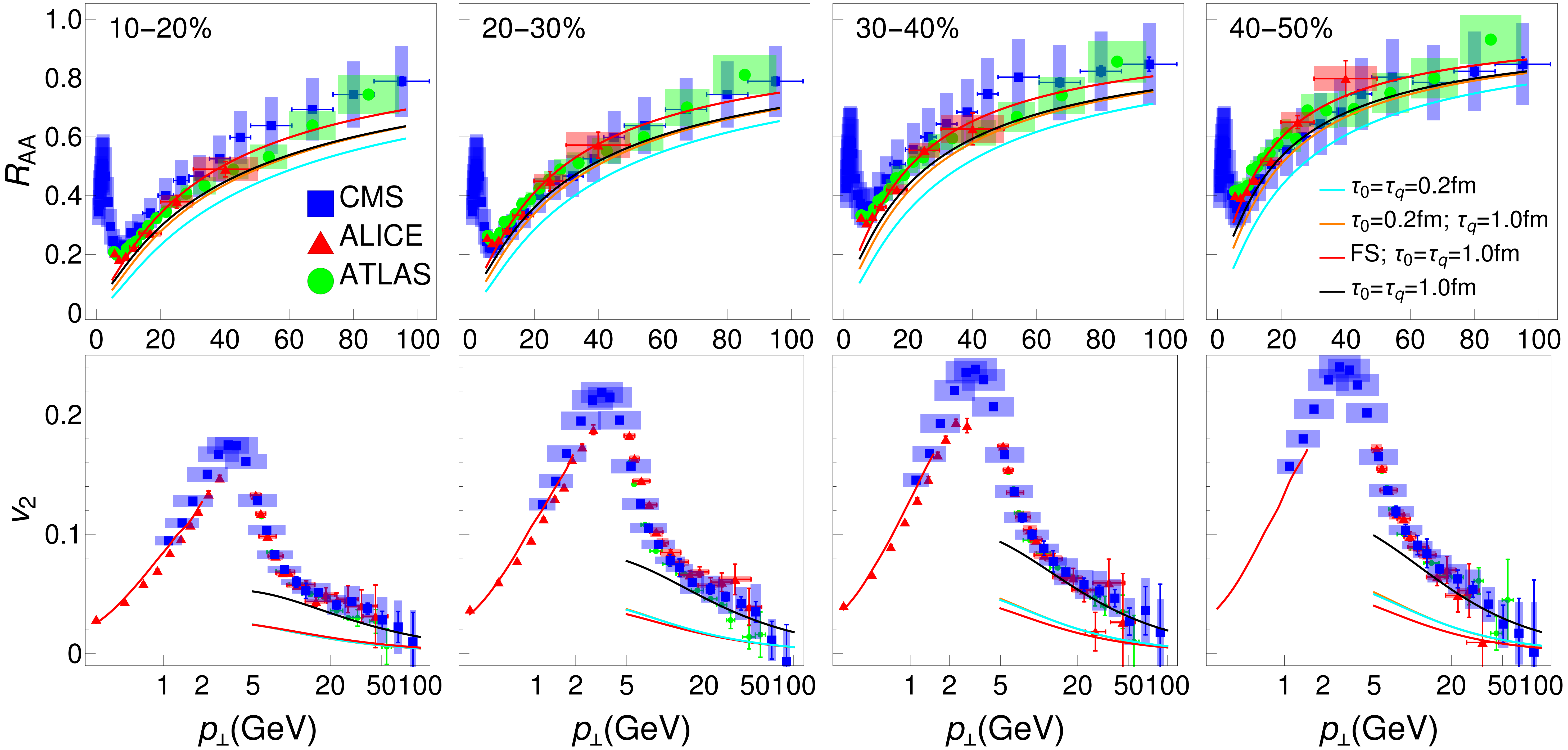
- Includes arbitrary temperature profile as input
- Allows to extract bulk medium properties
- Preserves all the dynamical energy loss model properties
- Now, the medium temperature depends on the position of the parton
    1. R_{AA} along a single trajectory is calculated
    2. It is averaged over the trajectories with same direction angle ϕ
    3. Then it is integrated over the angle.
- Can differentiate different temperature evolutions.

Early evolution using DREENA-A

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

1. Cyan→ $\tau_q = \tau_0 = 0.2fm$
2. Orange → $\tau_0 = 0.2fm; \tau_q = 1fm$
3. Red → FS; $\tau_0 = \tau_q = 1fm$
4. Black → $\tau_0 = \tau_q = 1fm$

- Fits low-$p_\perp$ data well (Optical Glauber, 3+1D Hydro, const η/s)
- Divergent is disfavored by R_{AA} data
- Delaying τ_q hardly changes v_2
- Early FS does not fit data as well
- v_2 predictions approach data when $\tau_0 = \tau_q = 1fm$ (No early free steaming)



Pb + Pb 5.02 TeV

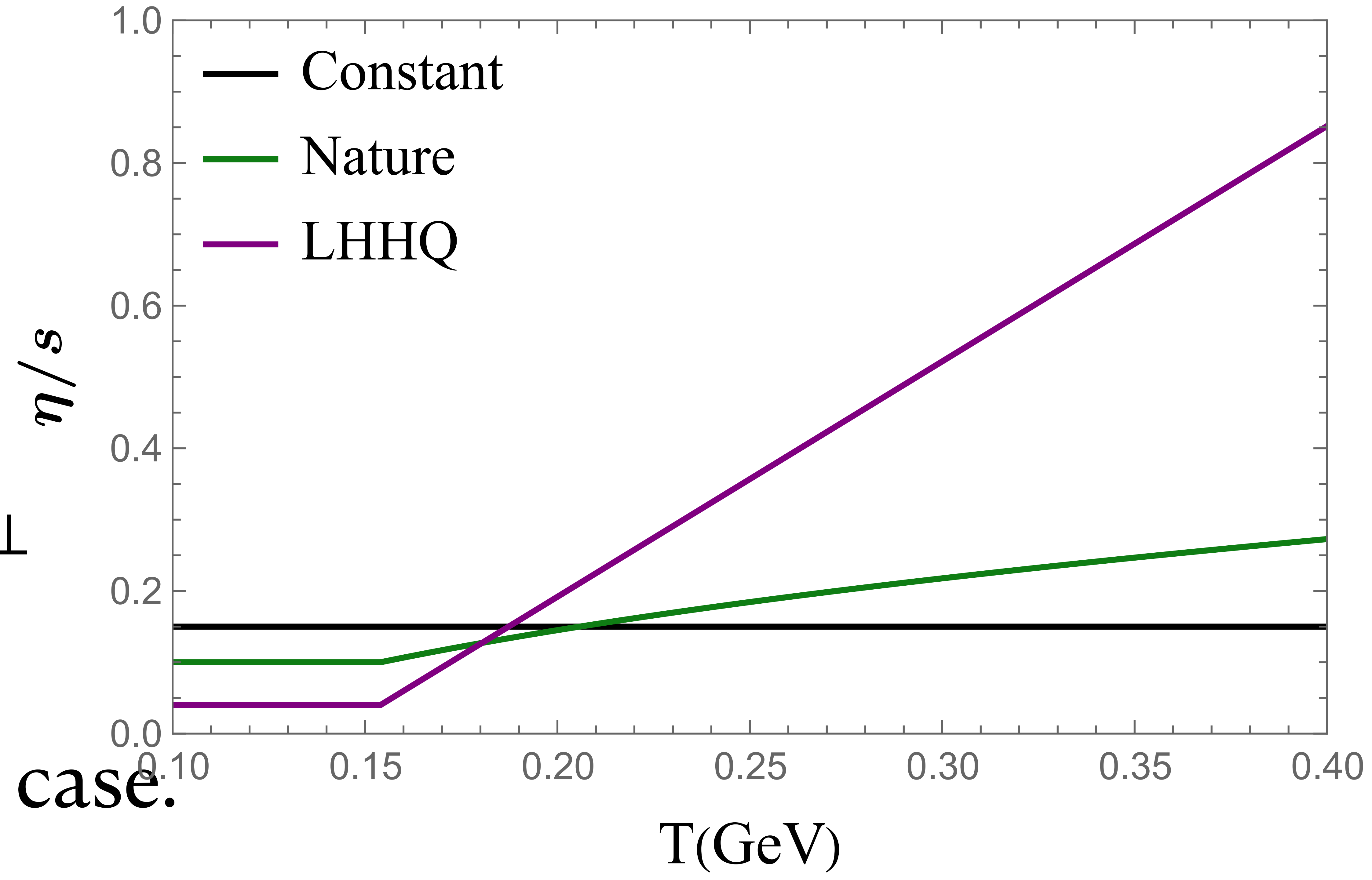
Constraining η/s of the medium

η/s of the medium : Soft-to-hard boundary

- QGP is expected to behave as weakly interacting gas: Weakly coupled
- Fluid dynamics predicts the η/s to be very low: Strongly coupled
- QGP may behave as perfect fluid near T_c (soft regime) and η/s may increase at high temperature (hard regime).
- Testing the soft-to-hard hypothesis is difficult: Anisotropy is weakly affected by the η/s at high temperature.
- High-$p_\perp$ data/theory can serve as complementary tool.

Phenomenological approach

- Three $(\eta/s)(T)$ parametrizations have been considered.
- Parameters are adjusted to reproduce low-$p_\perp$ data.
- Temperature profiles are generated for each case.
- Three scenarios agree well with the low-$p_\perp$ data.



Nature→ Nature Phys. 15, no. 11, 1113-1117 (2019)

LHHQ→ Phys. Rev. Lett. **106**, 212302 (2011)

Modeling the bulk evolution

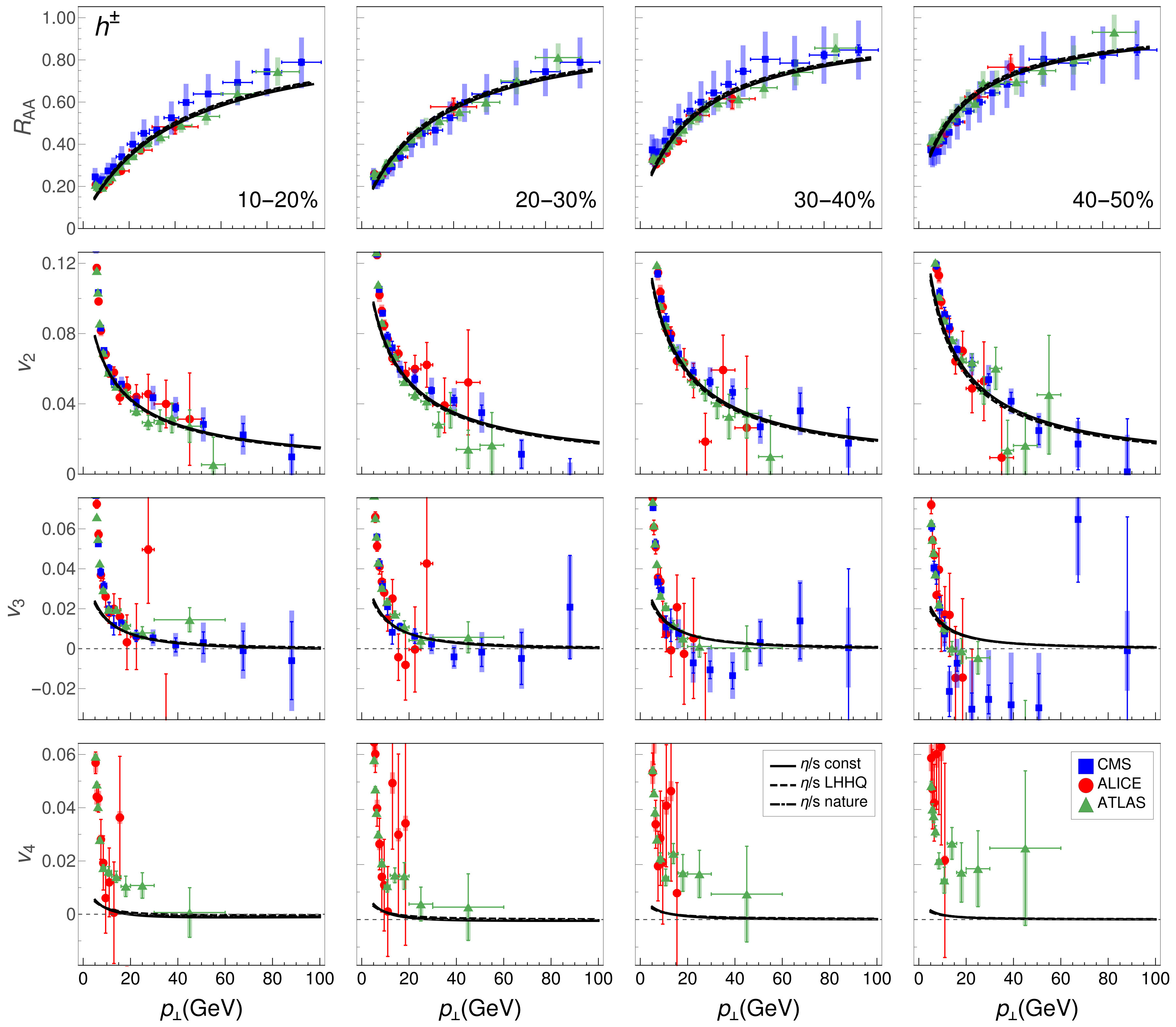
- Initial entropy profiles are generated using TRENTo model.
- 10^4 events for Pb+Pb (5.02 TeV) and Au+Au (200 GeV) collisions.
- Events are sorted in centrality classes.
- Initial free streaming is not preferred by high-$p_\perp$ data.

  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C 105 (2022) 2, L021901
- Onset time for hydrodynamics: $\tau_0 = 1fm$.

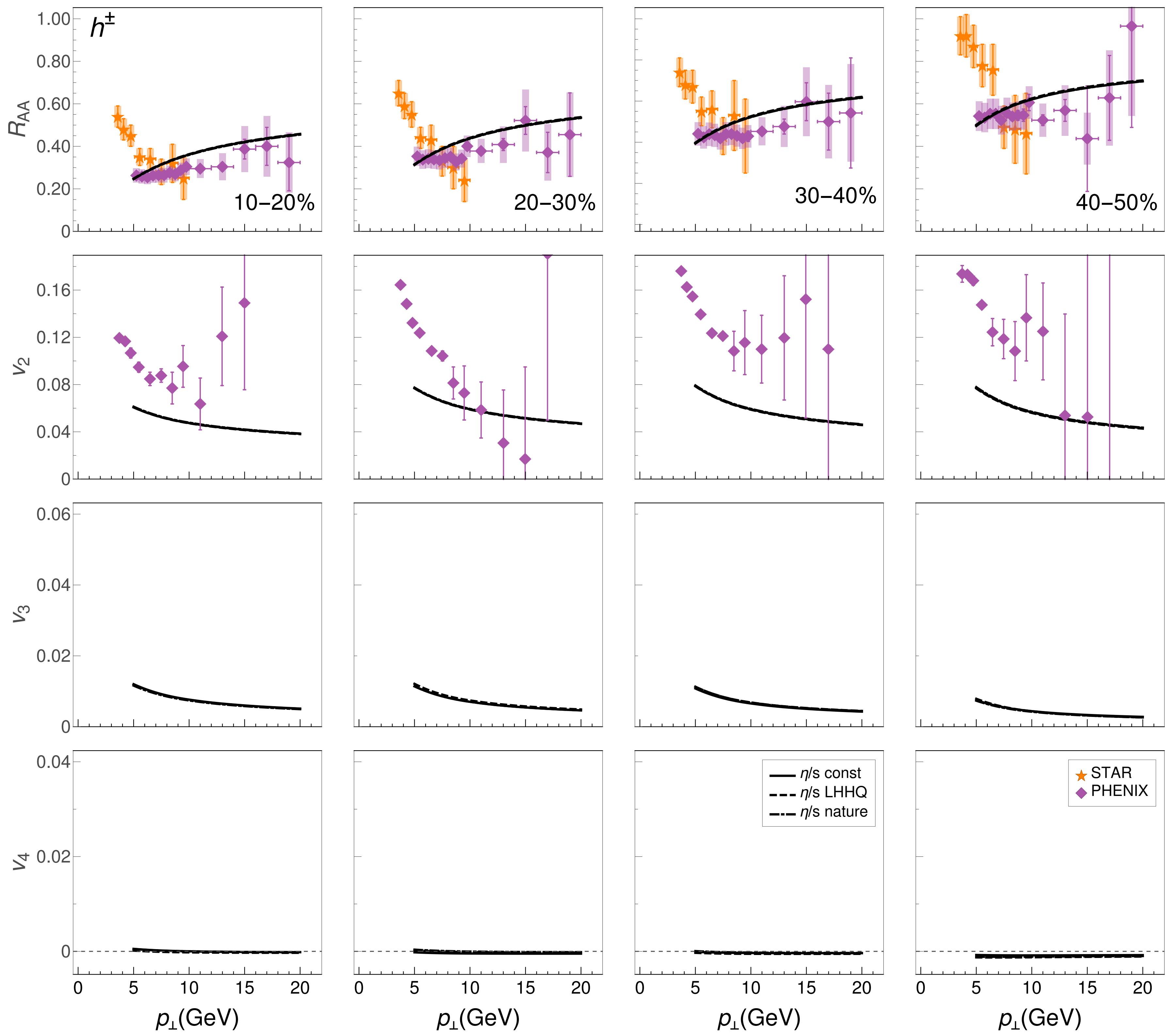
  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C 105 (2022) 2, L021901
- (2+1)-dimensional fluid dynamical model (VISHNew) used to simulate the medium evolution.

Results

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic Phys. Rev. C **108** (2023) 4, 044907



Pb+Pb (5.02 TeV)

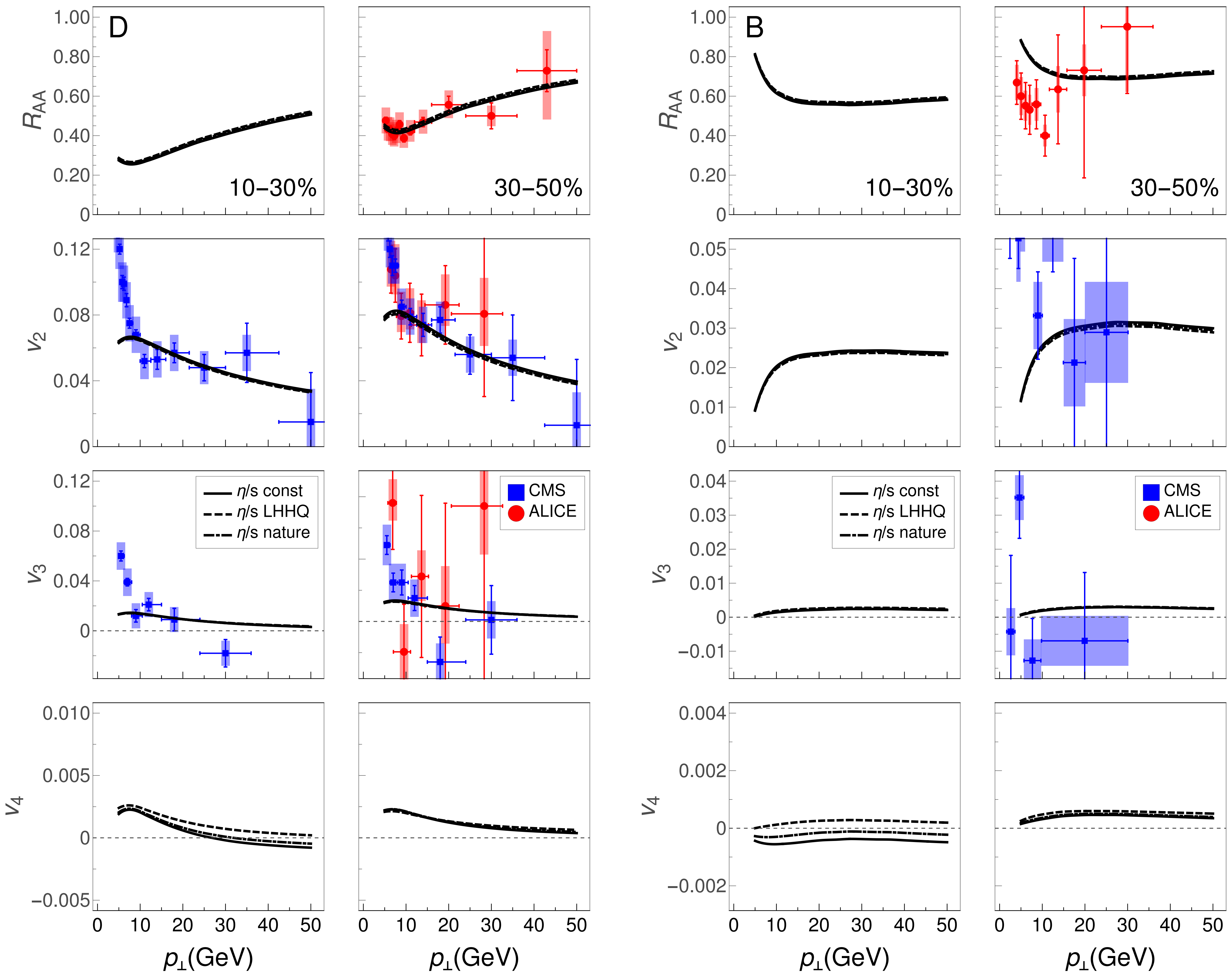


Au+Au (200 GeV)

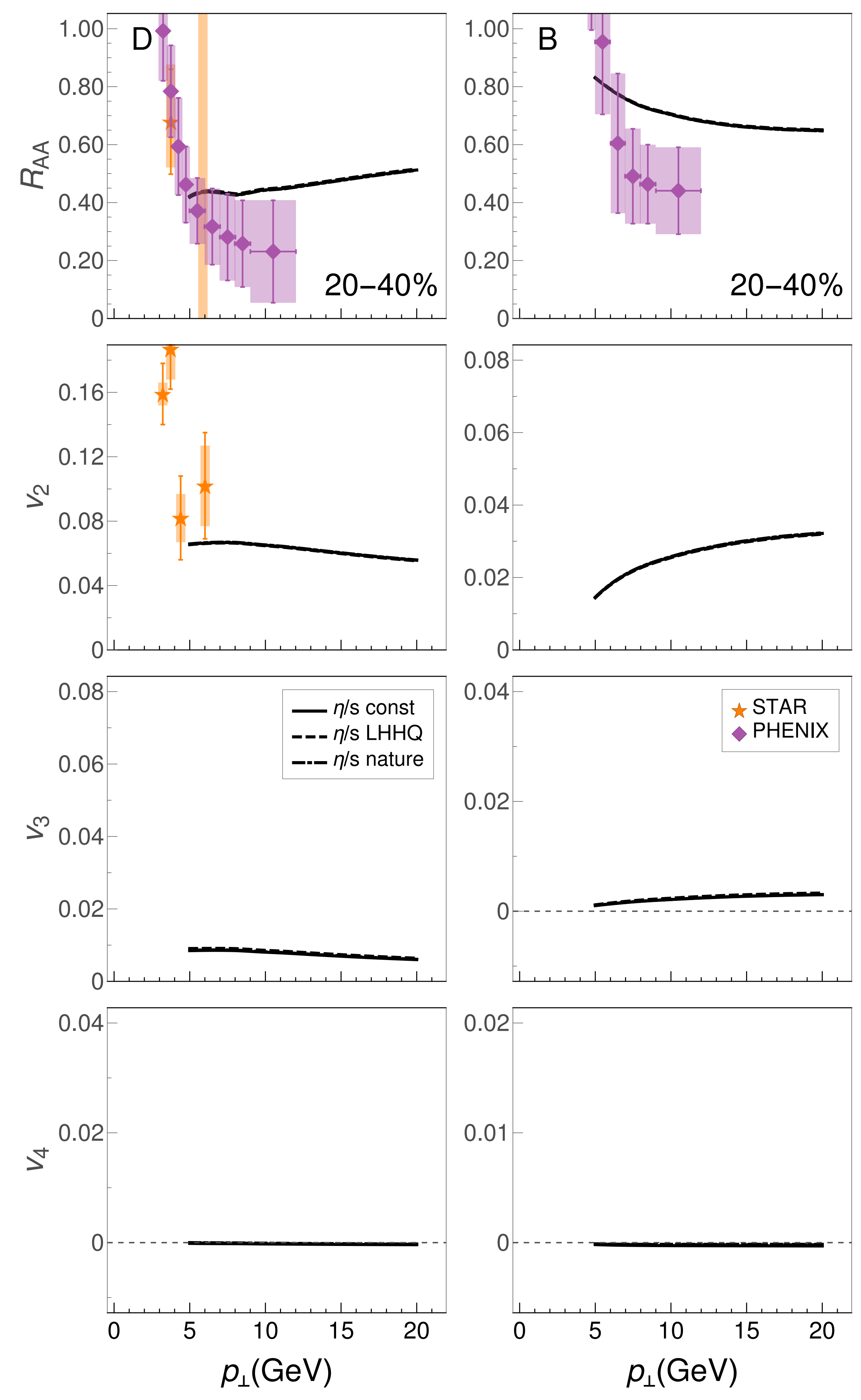
- R_{AA}, high-$p_\perp$ v_2, v_3, v_4 can not differentiate between the three cases due to small temperature differences.

Results

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic Phys. Rev. C **108** (2023) 4, 044907



Pb + Pb (5.02TeV)

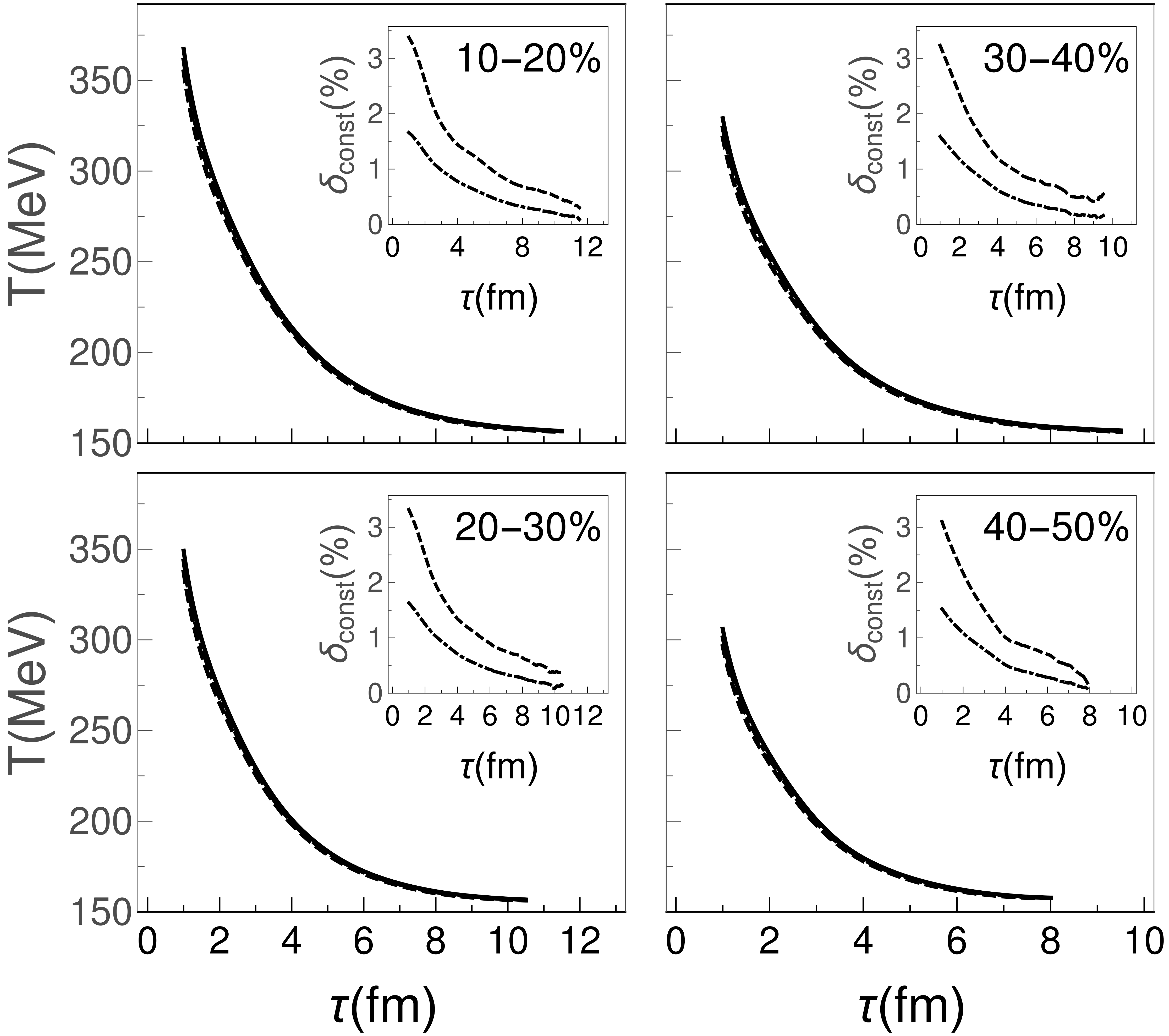


Au + Au (200GeV)

Study of η/s using Generalized DREENA-A

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic Phys. Rev. C **108** (2023) 4, 044907

- Pb + Pb 5.02 TeV
- Full = LHHQ; DotDashed = Nature,
  Dashed = Constant
- Inset: Dotdashed = Nature,
  Dashed = LHHQ



Theoretical approach :

Transport coefficient from dynamical energy loss formalism

- Transport coefficient ($\hat{q}$) ≡ Squared average transverse momentum exchange between the medium and the fast parton per unit length
- Interaction between the parton and medium is characterized by the HTL resummed elastic collision rate after including running coupling and finite magnetic mass:

$$\frac{d\Gamma_{el}}{d^2q} = \frac{C_A}{\pi} T\alpha(ET) \frac{\mu_E^2 - \mu_M^2}{(q^2 + \mu_E^2)(q^2 + \mu_M^2)}$$

- In fluid rest frame:

$$\hat{q} = \int_0^{6ET} d^2q\, q^2 \cdot \frac{d\Gamma_{el}}{d^2q} = C_A T \frac{4\pi}{(11 - \frac{2}{3}n_f)} \frac{\mu_E^2 \ln \frac{6ET + \mu_E^2}{\mu E^2} - \mu_M^2 \ln \frac{6ET + \mu_M^2}{\mu_M^2}}{\ln(\frac{ET}{\Lambda^2})}$$

- In weakly coupled limit:

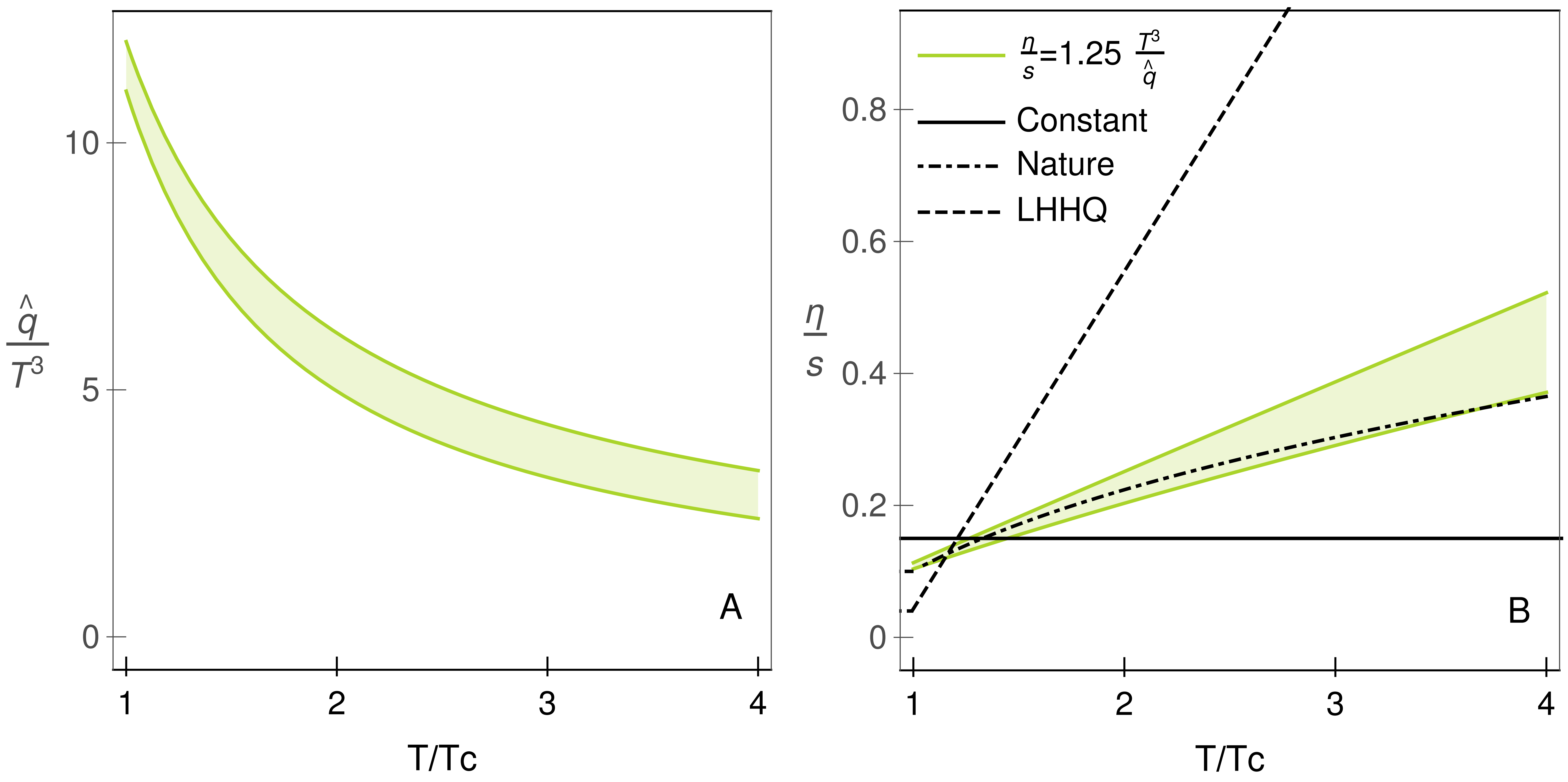
$$\eta / s \approx 1.25 T^3 / \hat{q}$$

Phys. Rev. Lett. 99 192301 (2007), Phys. Rev. D 104, L071501 (2021)

η/s from the transport coefficient

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic Phys. Rev. C **108** (2023) 4, 044907

- $\hat{q}/T^3$ shows expected behavior.
- Enhanced quenching near T_c.
- η/s is surprisingly close to the constraints from Bayesian analysis.



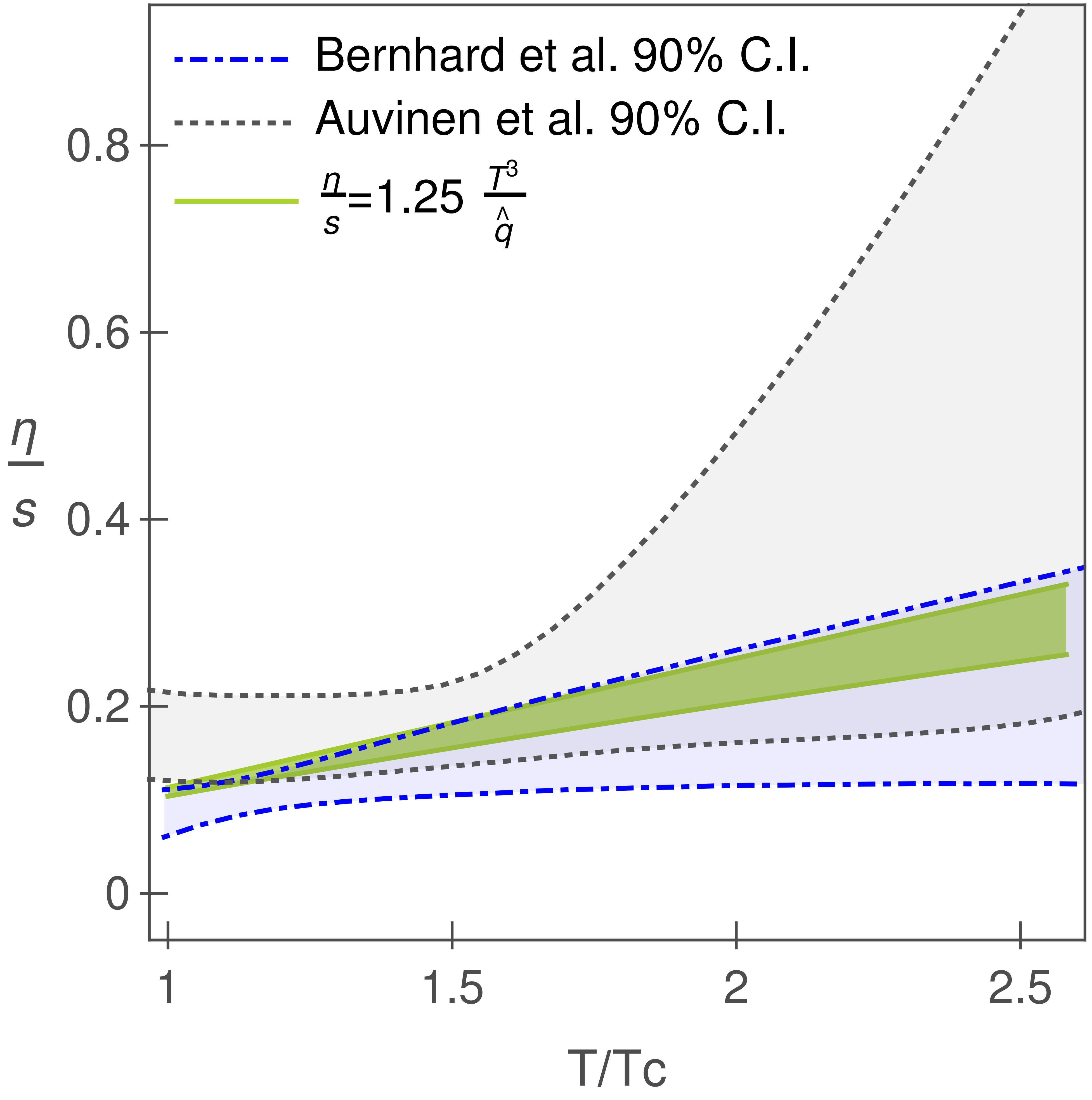
η/s from the transport coefficient

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic Phys. Rev. C **108** (2023) 4, 044907

- Uncertainty due to initial jet energy is very small
- Surprisingly close to the parametrization inspired by the Bayesian analysis.
- Does not drop significantly below the inferred η/s values near T_c .

Blue → Nature Phys. 15, no. 11, 1113-1117 (2019)

Black → Phys. Rev. C 102, 044911 (2020)



Summary

- We use generalized DREENA-A to compute high-$p_\perp$ energy loss.
- In the phenomenological approach:
  - Three different $(\eta/s)(T)$ parametrizations have been considered.
  - The predictions from the generalized DREENA-A for three η/s scenarios lead to results that are almost indistinguishable.
- In the theoretical approach:
  - Transport coefficient and jet quenching strength are calculated from the dynamical energy loss formalism.
  - η/s shows surprisingly good agreement all the way to T_c with constraints extracted from existing Bayesian analyses. Provides much smaller uncertainties at high temperature.

Study of the early evolution

Initial condition model

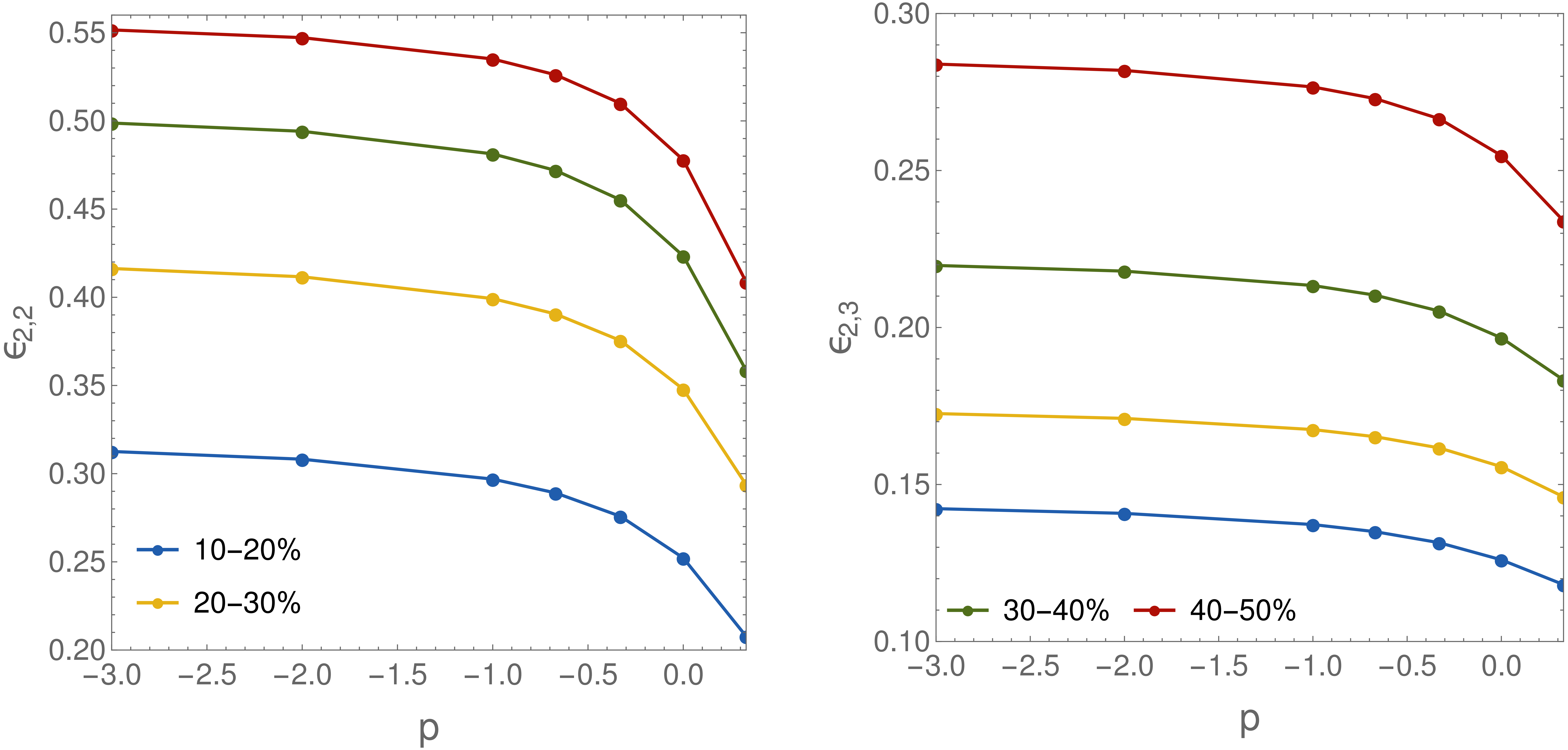
- Initial condition models (e.g., Glauber, MC-KLN, IP Glasma etc) aim to determine the initial energy or entropy deposition.
- Bayesian analysis has been used to constrain the initial conditions using $\mathrm{T_R ENTo}$ model. Nature Phys. 15, no. 11, 1113-1117 (2019)
- For a pair of projectiles A and B colliding along z axis, the participant thickness is $T_{A,B}(x, y) = \int dz\, \rho_{A,B}^{part}(x, y, z)$.
- The initial entropy density is $s(x, y) \propto T_R(p; T_A, T_B) = \frac{T_A^p + T_B^p}{2}^{1/p}$.
- $p = 0$ is found to be preferred in Bayesian analysis when initial free streaming is considered.

Probing the shape of QGP droplet

- Initial free streaming not favored by high-$p_\perp$ data.
- Can lead to different results without free streaming.
- DREENA can be used to constrain the initial profiles with no free streaming.
- We use $p \in \{1/3, 0, -1/3, -2/3, -1\}$ to see which value the high-$p_\perp$ data prefers.
- Other parameters of the bulk evolution are tuned to agree with the low-$p_\perp$ data.
- We use constant η/s in each case.

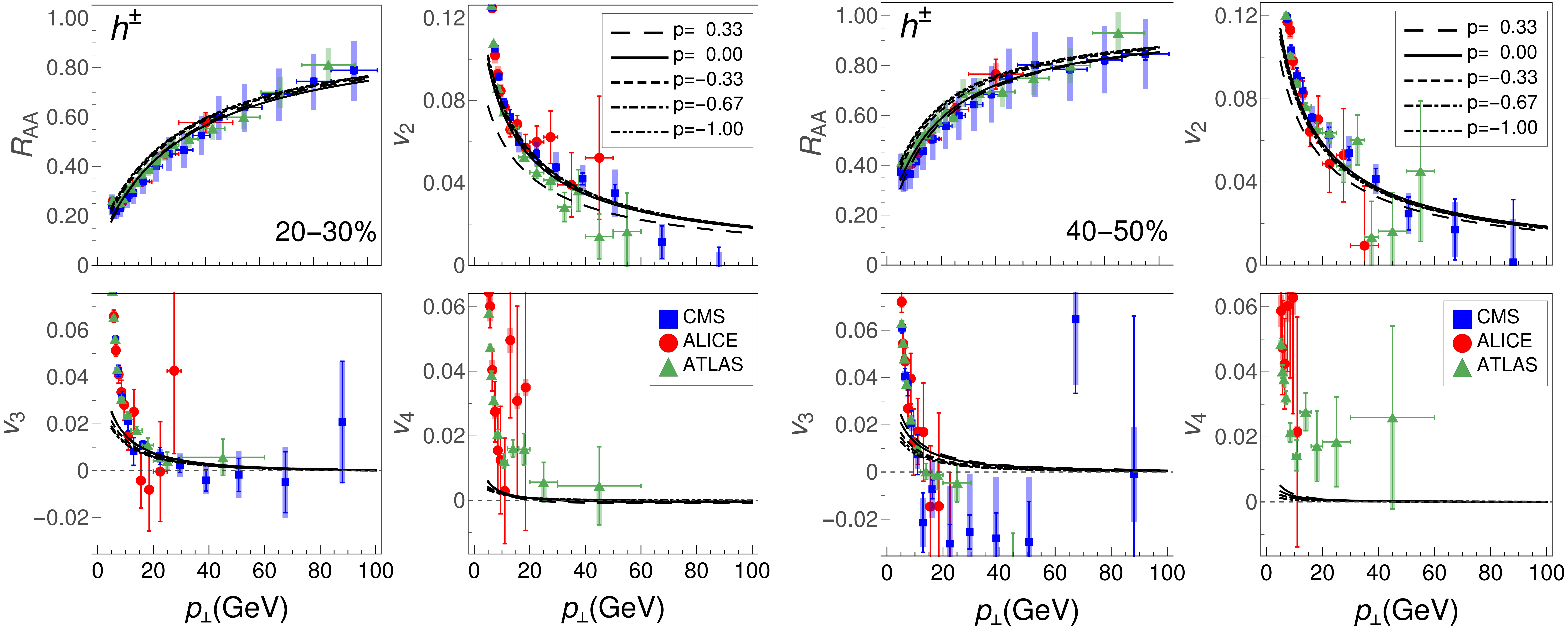
Initial state anisotropy

BK, D. Zigic, P. Huovinen, M. Djordjevic, M. Djordjevic and J. Auvinen arXiv:2403.17817



Charged hadron R_{AA} and high-$p_\perp$ v_n in Pb+Pb 5.02 TeV

BK, D. Zigic, P. Huovinen, M. Djordjevic, M. Djordjevic and J. Auvinen arXiv:2403.17817

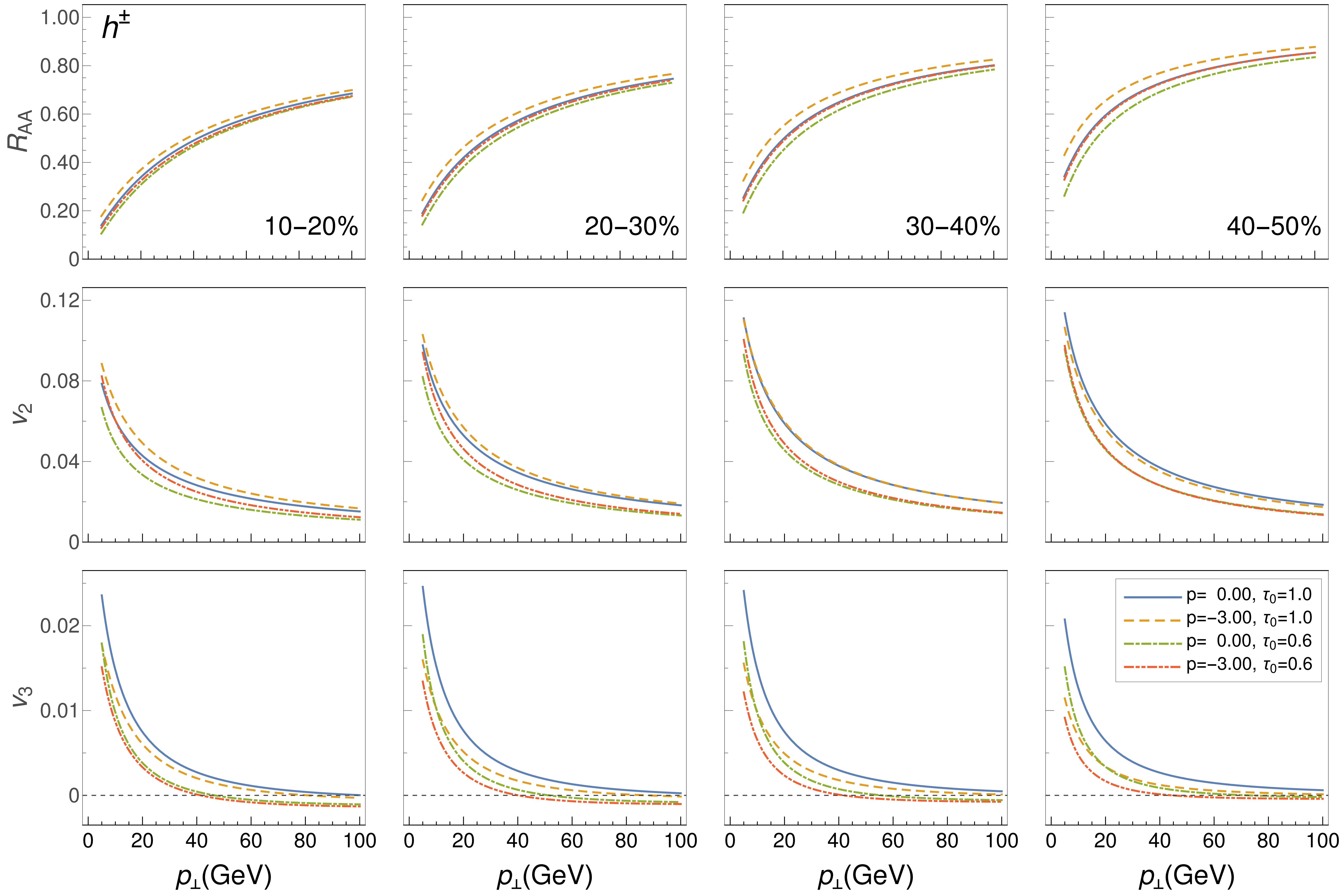


Study of early evolution of heavy-ion collision

- Although high-$p_\perp$ data prefer no initial free streaming and delayed onset of hydrodynamics, it may appear unrealistic.
- We try to accommodate earlier onset of hydrodynamic evolution by considering the highly anisotropic initial profiles (TRENTo $p < 0$).
- We consider $\tau_0 = 1\,fm, 0.6\,fm$ and $0.2\,fm$.
- Readjusted η/s and TRENTo normalization to reproduce the low-$p_\perp$ data.

Charged hadron R_{AA} and high-$p_\perp$ v_n in Pb+Pb 5.02 TeV

BK, D. Zigic, P. Huovinen, M. Djordjevic, M. Djordjevic and J. Auvinen arXiv:2403.17817



Summary

- The shape of the initial state has been modulated by varying the parameter p of T$_{\text{R}}$ENTo model.
- It is found that $p \approx 0$ gives the best overall fit which is consistent with the Bayesian analysis of low-$p_\perp$ data.
- We tested if larger anisotropy of the initial profiles ($p \ll 0$) would allow an earlier onset of fluid dynamical evolution.
- Lower values of p enhance R_{AA} and high-$p_\perp$ v_2, the enhancement is insufficient for facilitating an earlier onset of transverse expansion.

Thank you for your attention

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DREENA-C and DREENA-B predictions

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

- No fitting parameter used
- Good agreement with data for both R_{AA} and v_2
- No v_2 puzzle
- R_{AA} is weakly sensitive to medium evolution:

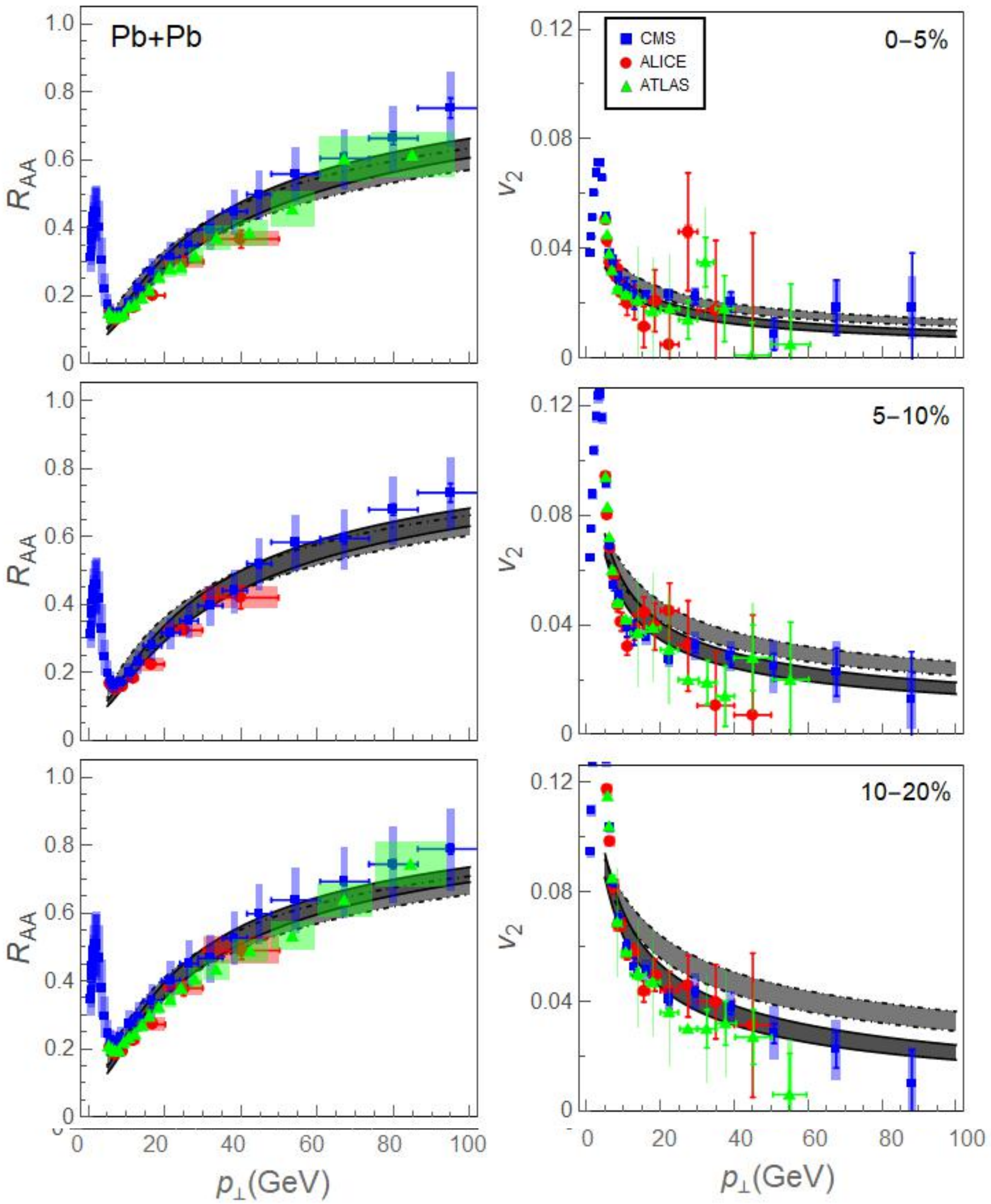
  Excellent probe for jet-medium interactions
- Significant influence of medium evolution on v_2:

  Ideal probe to study medium properties

ALICE:JHEP 1811, 013; JHEP 1807, 103 (2018)

ATLAS-CONF-2017-012; EPJC 78, 997 (2018)

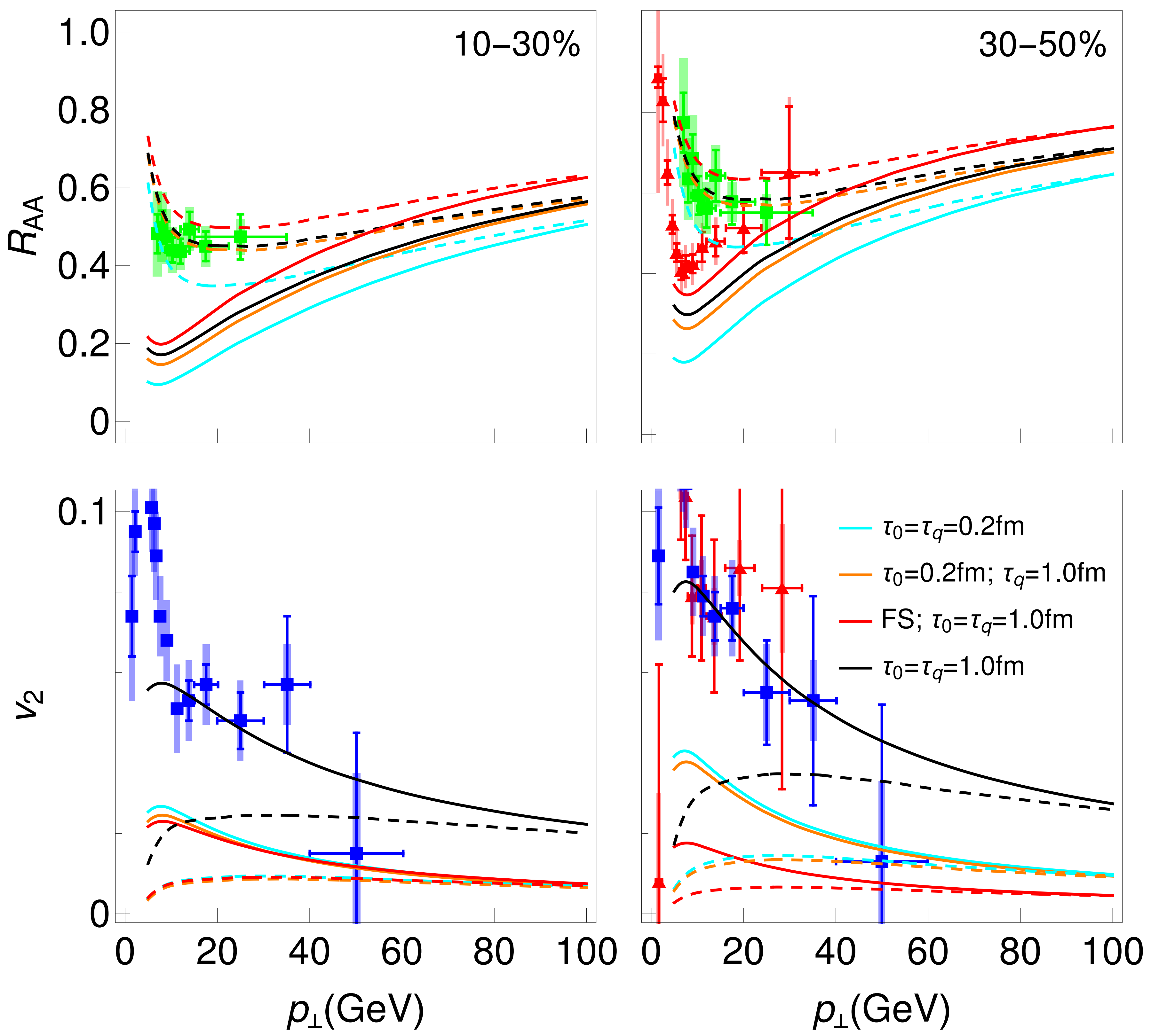
CMS:JHEP 1704, 039 (2017); PLB 776, 195 (2018)



Full = B, Dashed = C, Pb+Pb $s_{NN} = 5.02$ TeV ($h^{\pm}$)

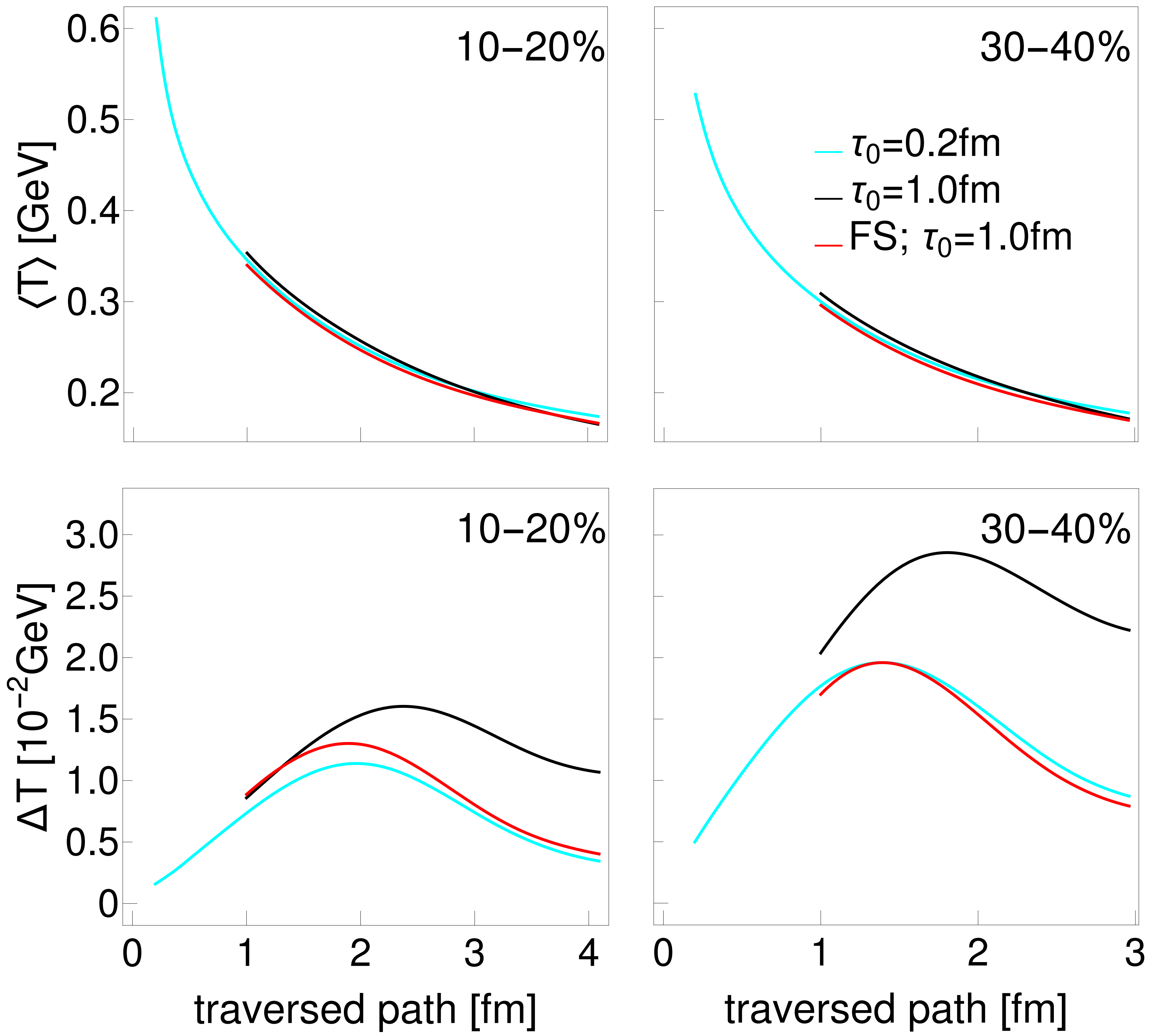
Early evolution from DREENA-A

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



Full- D meson, Dashed - B meson

Pb+Pb $s = 5.02$ TeV



Generalized DREENA-A

D. Zigic, J. Auvinen, I. Salom, M. Djordjevic and P. Huovinen Phys. Rev. C **106** (2022) 4, 044909

- Further optimization of DREENA-A to incorporate event-by-event fluctuating temperature profiles
- Three different event-by-event initializations
  - ○ Full = MC Glauber , $\tau_0 = 1fm$, No FS
  - ○ Dashed = IP Glasma, $\tau_0 = 0.4fm$
  - ○ Dotdashed = TRENTo, $\tau_0 = 1.16fm$, FS
- Different initializations lead to different high-$p_\perp$ predictions.
- Best agreement with Glauber + no FS.
- Predictions vastly underestimates v_4: High-$p_\perp$ v_4 puzzle