Studying the (pre)equlibrium stage using high-$p_\perp$ partons

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LHCP 2023

LHCPhysics

Belgrade, 22 - 26 May 2023

23 May 2023

European Research Council

Established by the European Commission

Contents

Introduction

- Quark Gluon Plasma (QGP) is created in ultrarelativistic heavy-ion collisions.
- Consists of interacting quarks, antiquarks and gluons.
- Low-$p_{\perp}$($p_{\perp} \leq 5GeV$) 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
- $$\frac{E_f d^3\sigma_q(H_Q)}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes P(E_i \to E_f) \otimes D(Q \to H_Q),$$
- $$\frac{E_f d^3\sigma_u(H_Q)}{dp_f^3} = \frac{E_i d^3\sigma(Q)}{dp_i^3} \otimes D(Q \to H_Q).$$
- No fitting parameter used

DREENA

- **DREENA-C**

  D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, J. Phys. G **46**, no. 8, 085101 (2019)

  - Constant temperature medium
  - Qualitatively good agreement with data
  - Joint prediction for R_{AA} and v_2
  - Prediction for soft and hard probes
  - Overestimates v_2 data

- **DREENA-B**

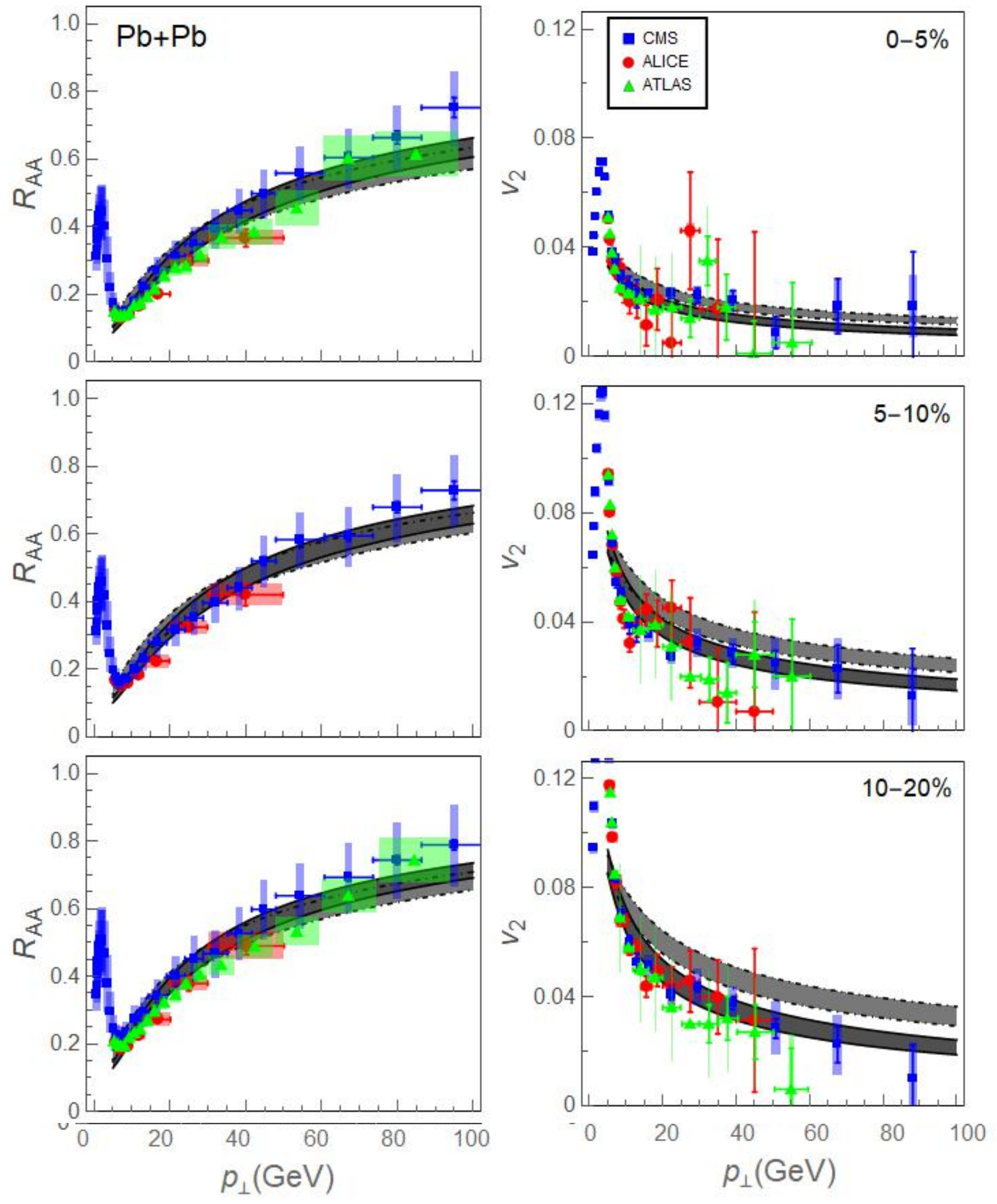
  D. Zigic, I. Salom, J. Auvinen, M. Djordjevic and M. Djordjevic, Phys. Lett. B **791**, 236 (2019)

  - 1D Bjorken evolution has been considered: Analytically tractable
  - Now the temperature changes with proper time τ
  - Reasonable agreement with data

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)

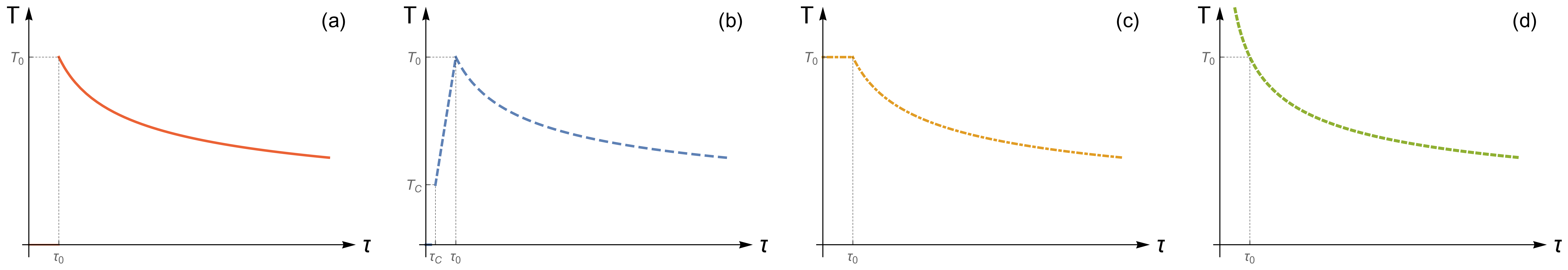
CMS:JHEP 1704, 039 (2017); PLB 776, 195 (2018)

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

Study of initial stages using DREENA-B

D. Zigic, B. Illic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no. 6, 064909 *(2020)*

- Four different initial-stage scenarios have been considered
- Same temperature profile after thermalization ($\tau_0 = 0.6 fm$)
- Allows to study only the effects of different inital stages on the observables



Free streaming — Linear (from $T_c = 160$ MeV to T_0) — Constant — Divergent

- Smallest R_{AA} expected in case d)

DREENA-B

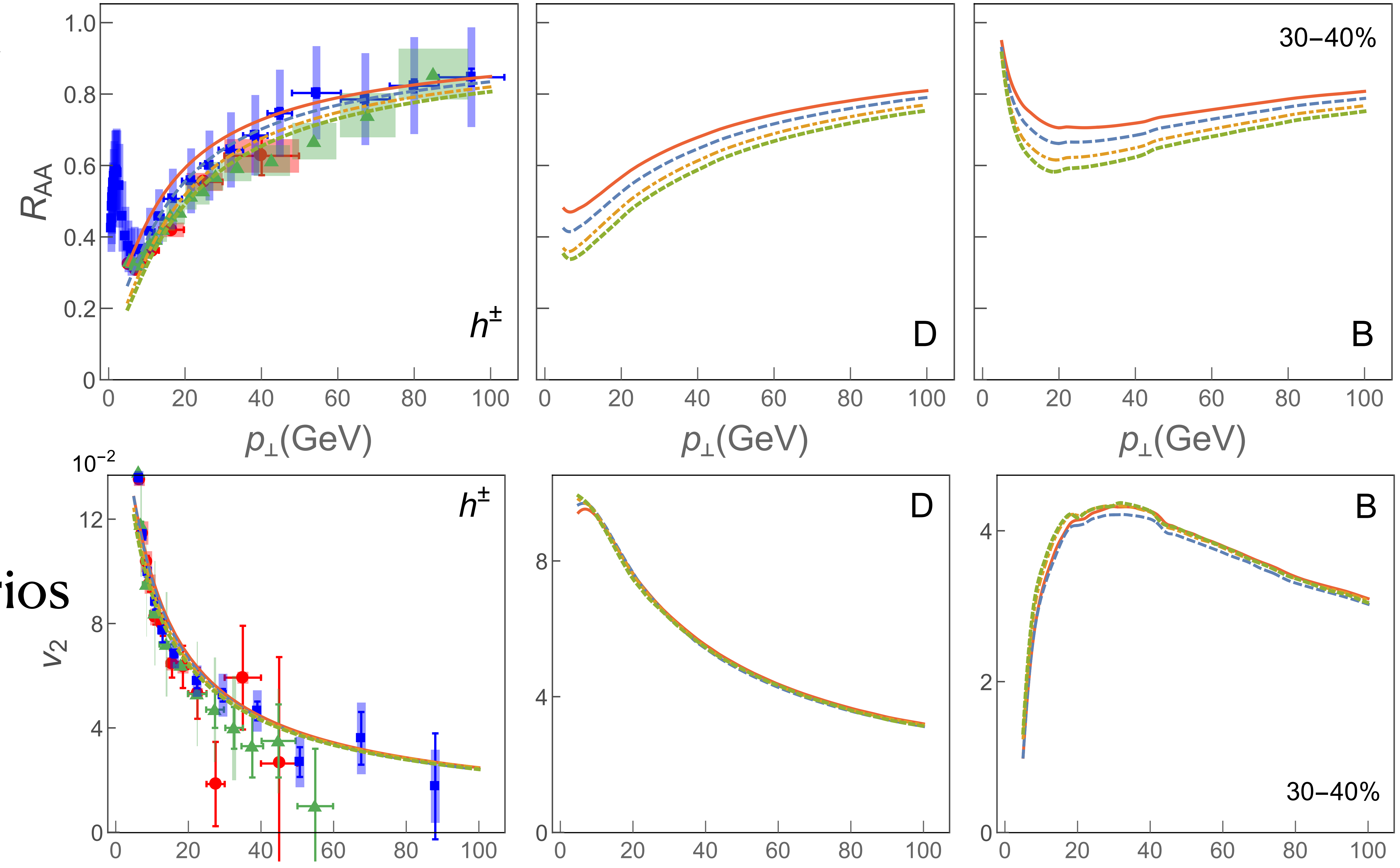
D. Zigic, B. Illic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no. 6, 064909 *(2020)*

- High-$p_\perp$ R_{AA} is notably affected by pre-equlibrium stage
- v_2 is insensitive to the pre-equlibrium stage
- High-$p_\perp$ v_2 unable to differentiate different early time evolution scenarios

ALICE: JHEP 1807, 103 (2018)

ATLAS:EPJC 78, 997 (2018)

CMS: PLB 776, 195 (2018)



Red = FS , Blue = Linear, Orange = Constant , Green = Divergent

DREENA-A (Adaptive)

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

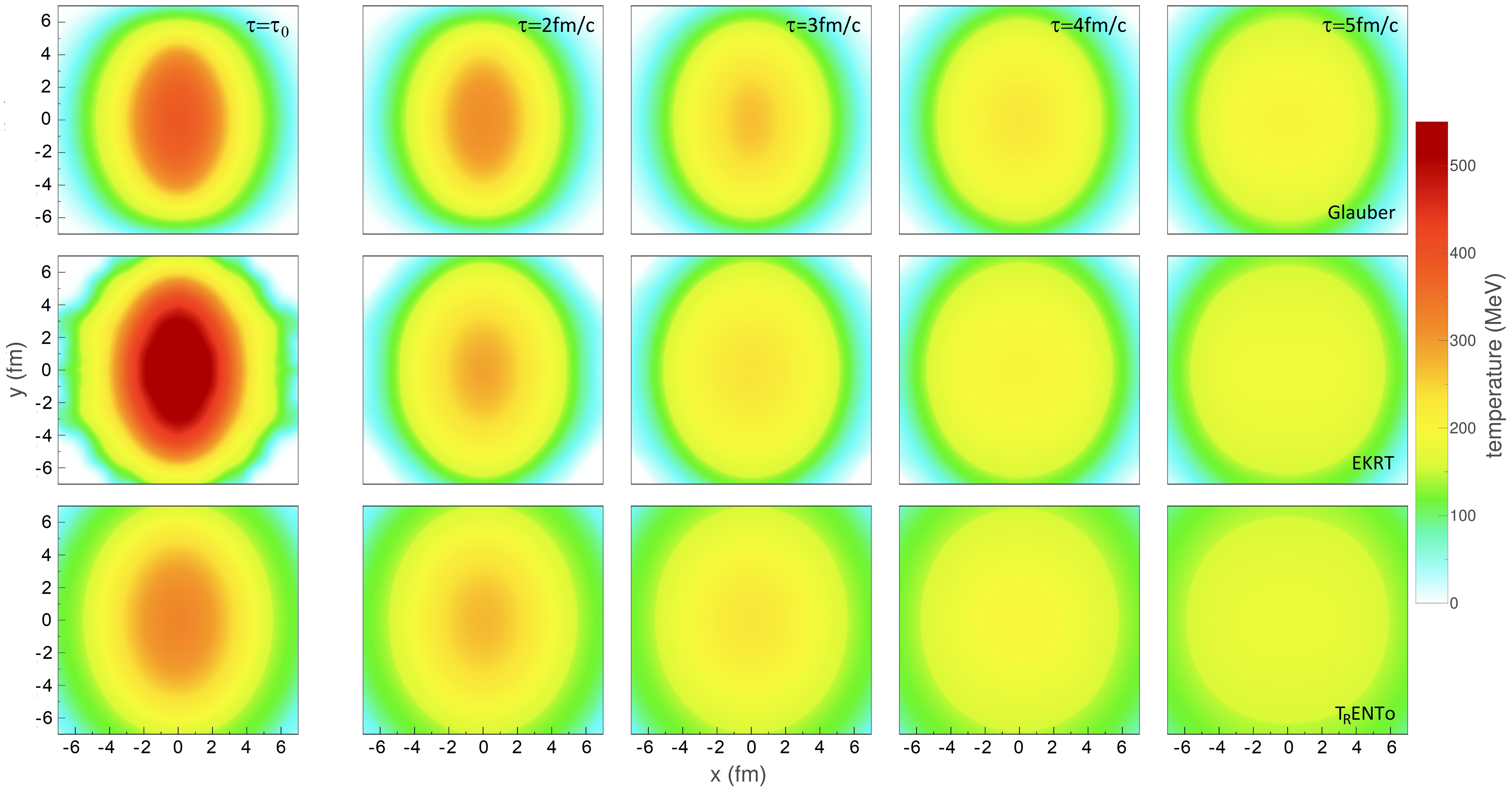
- Includes arbitrary temperature profile as input
- Allows to extract bulk medium properties
- Preserves all the dynamical energy loss model properties
- Now, the medium temperature depends on the position of the parton

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.

DREENA-A

Are high-$p_\perp$ observables sensitive to different T profiles?

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



Glauber

$\tau_0 = 1fm$; No FS

EKRT

$\tau_0 = 0.2fm$

TRENTo

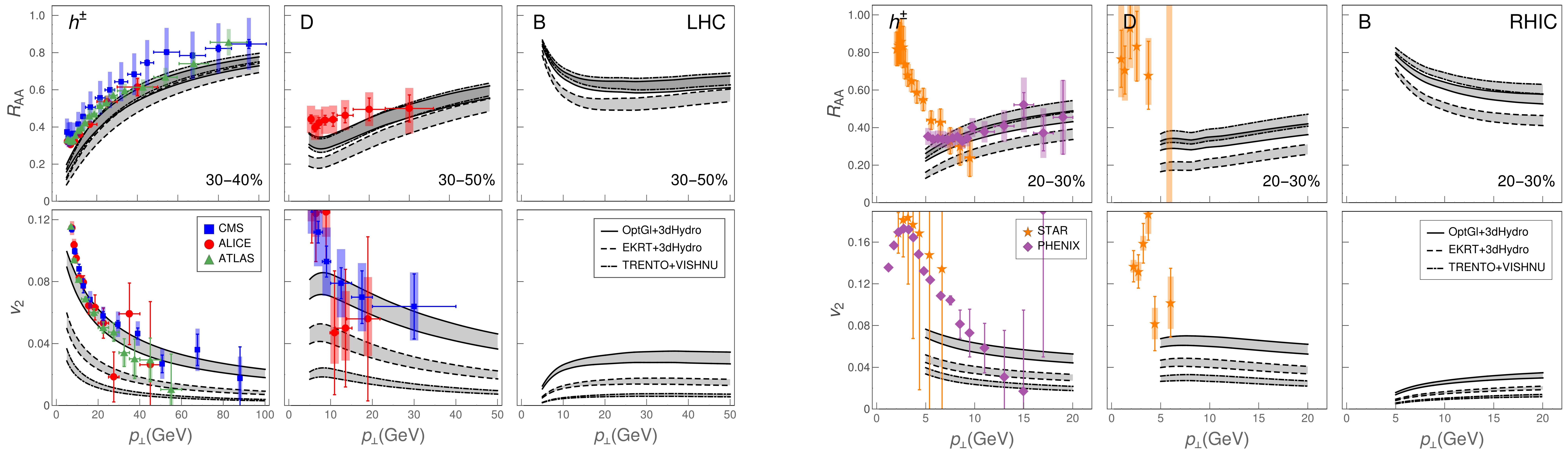
$\tau_0 = 1.16fm$; FS

Pb + Pb, (30-40)% centrality

Agrees well with low-$p_\perp$ data

DREENA-A

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



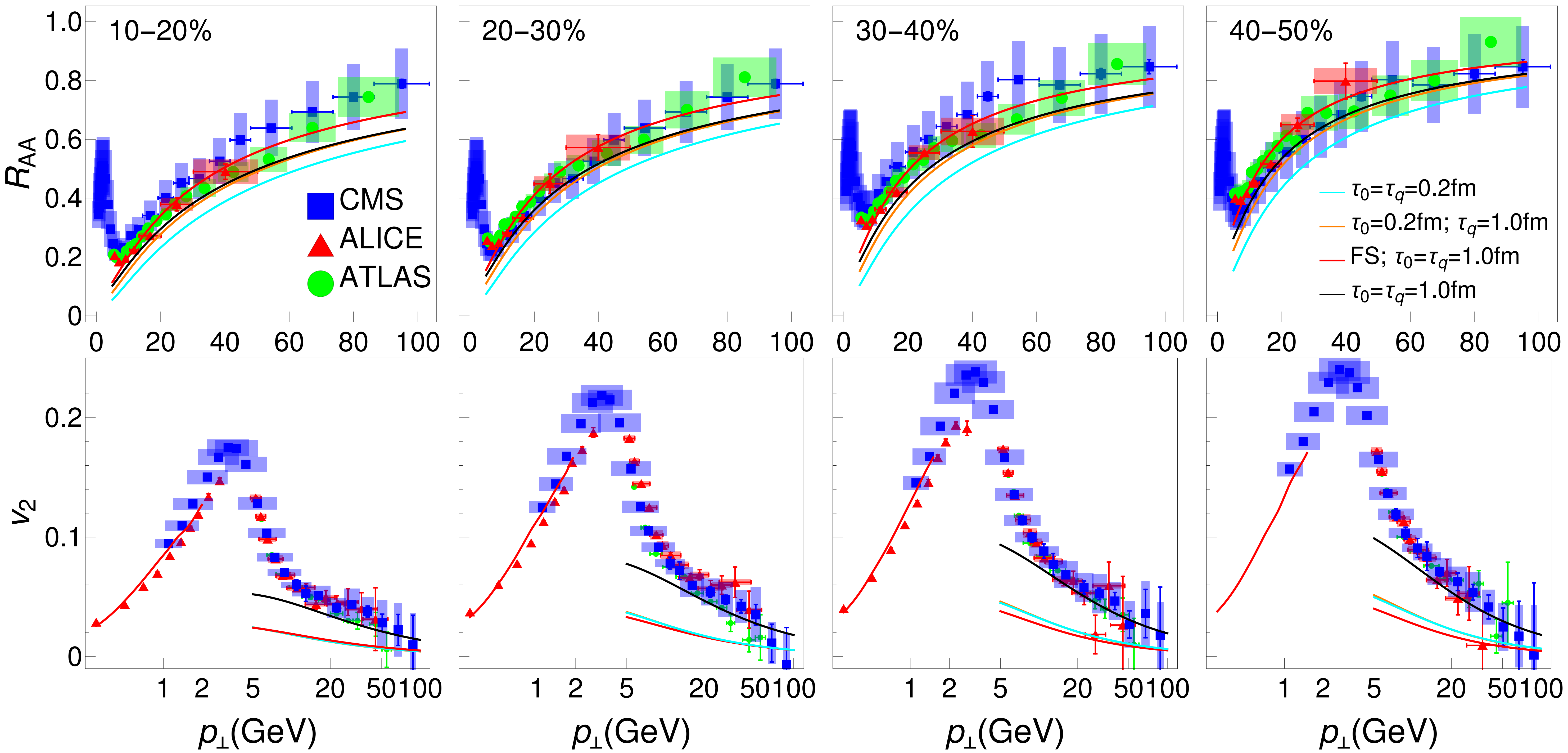
- EKRT initializations lead to the smallest R_{AA}
- Largest anisotropy in Glauber initializations leads to largest v_2
- DREENA-A can differentiate different temperature profiles. Excellent tool to infer bulk properties of the medium.

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
- Divergent is disfavored by R_{AA} data
- Delaying τ_q hardly changes v_2
- Early FS does not fit data as well



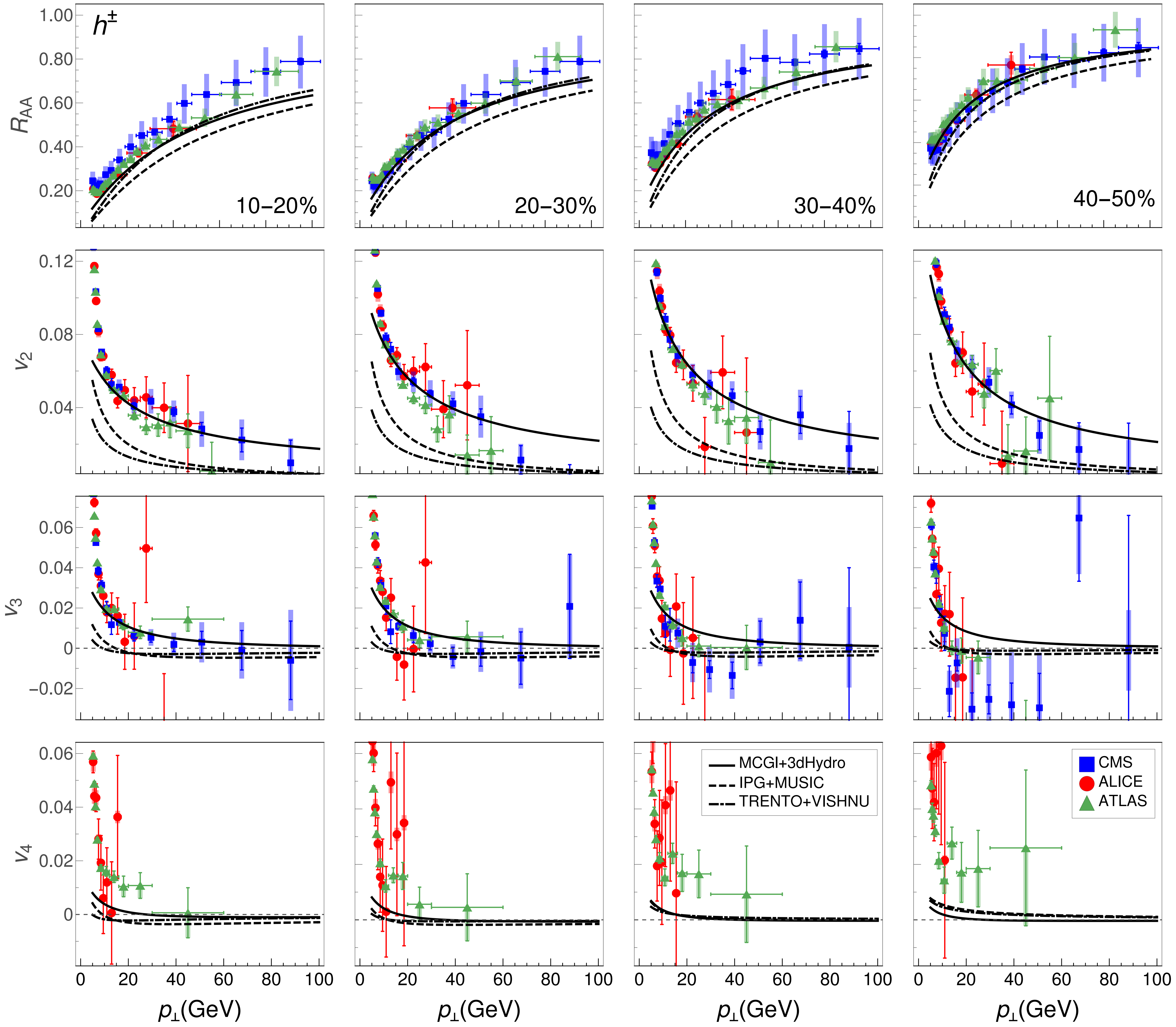
Pb + Pb $\sqrt{s} = 5.02$ TeV

- v_2 predictions approach data when $\tau_0 = \tau_q = 1fm$ (No early free steaming)

Generalized DREENA-A

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

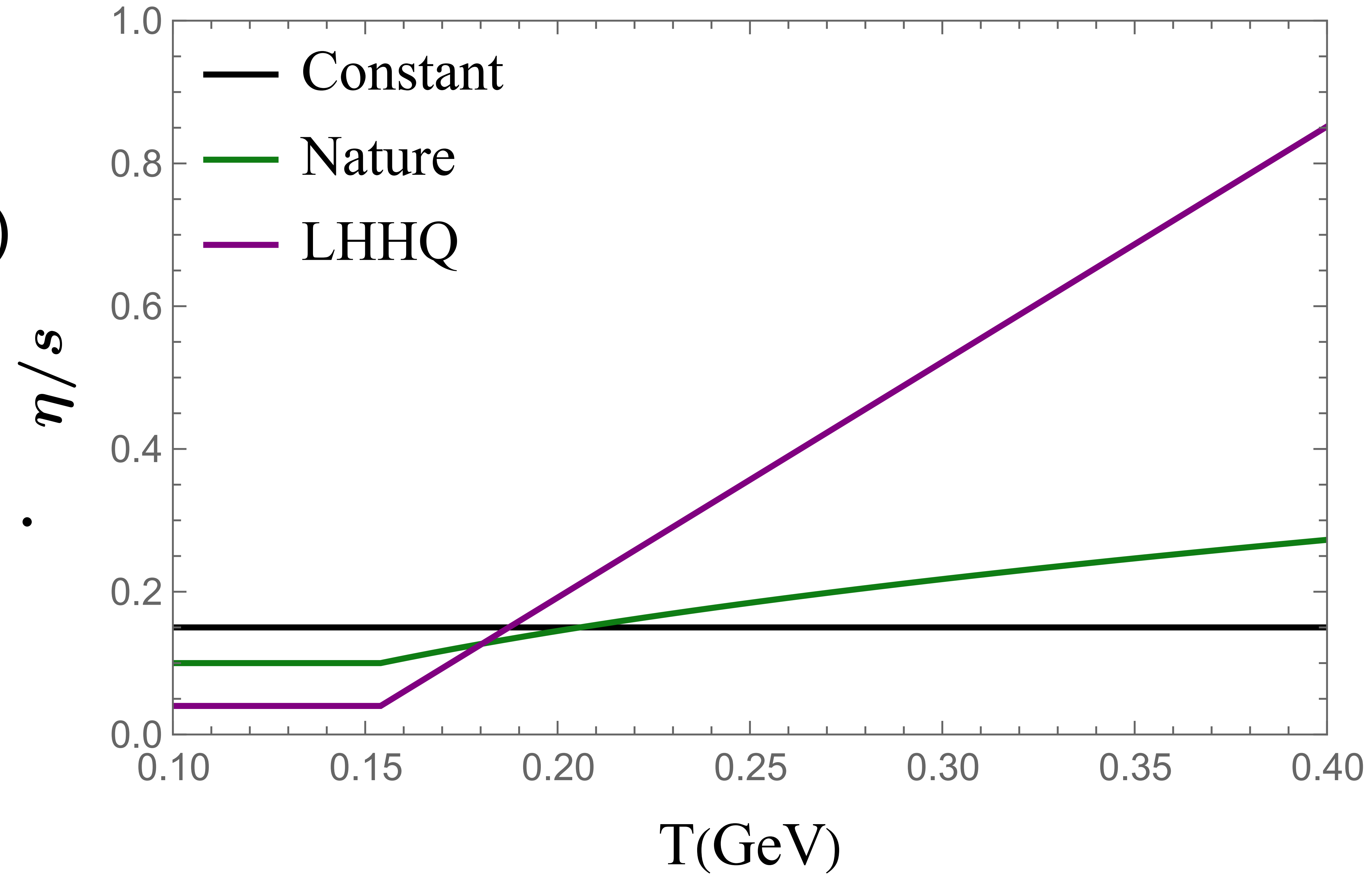
- Further optimization of DREENA-A to incorporate event-by-event fluctuating temperature profiles
- Three different event-by-event initializations
  - Full = MC Glauber , $\tau_0 = 1fm$, No FS
  - Dashed = IP Glasma, $\tau_0 = 0.4fm$
  - Dotdashed = TRENTo, $\tau_0 = 1.16fm$, FS
- Different initializations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



η/s of QCD matter

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic arXiv:2305.11318

- 10^4 $T_R ENTo$ events generated for Pb+Pb ($\sqrt{s} = 5.02$ TeV) and Au+Au ($\sqrt{s} = 200$ GeV) collisions.
- No pre-equlibrium free streaming of particles .
- $\tau_0 = 1fm$ + (2+1)D evolution
- Three $(\eta/s)(T)$ parametrizations have been considered
- Three scenarios agree well with the low-$p_\perp$ data.

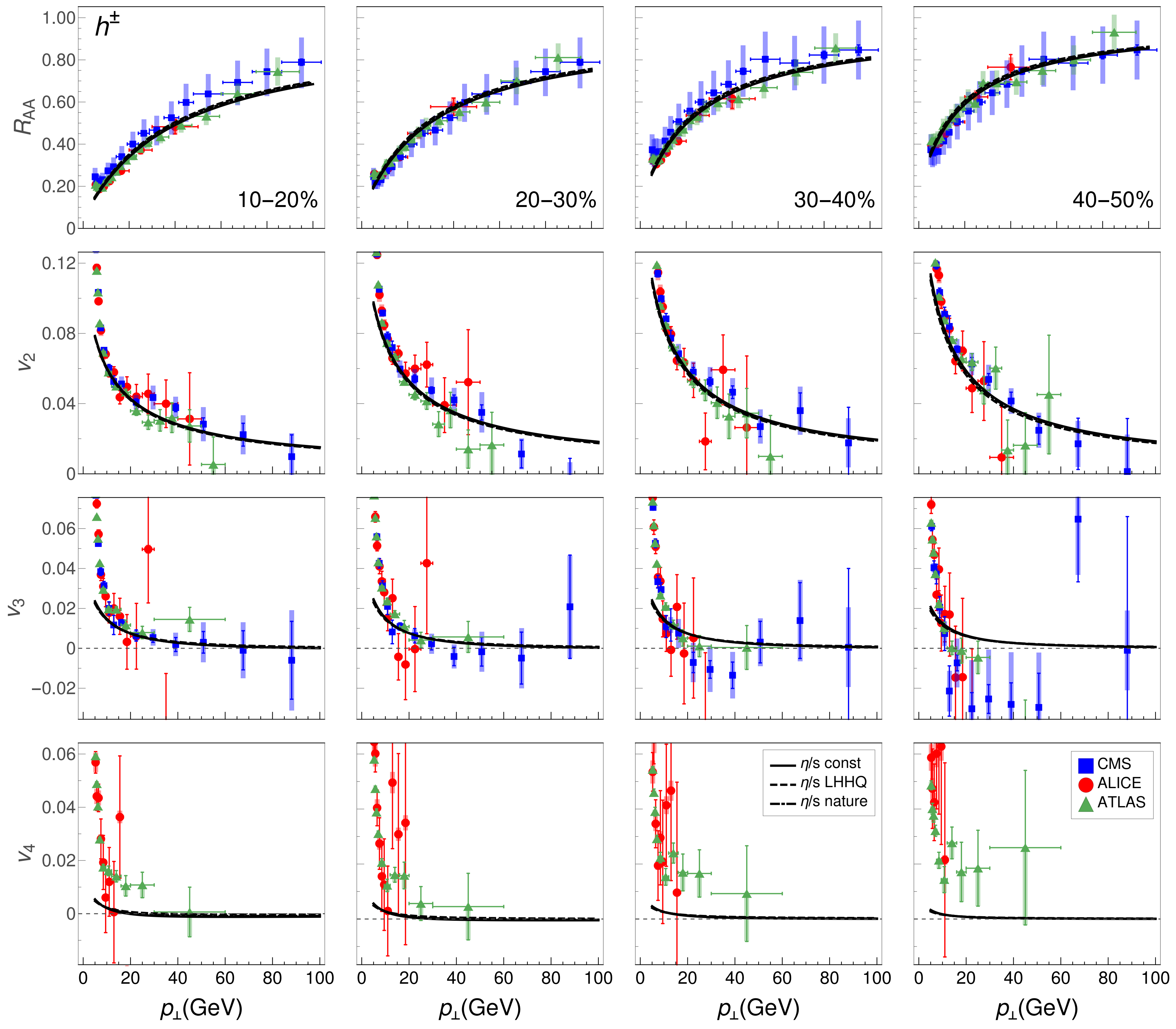


Nature→ Nature Phys. 15, no. 11, 1113-1117 (2019)

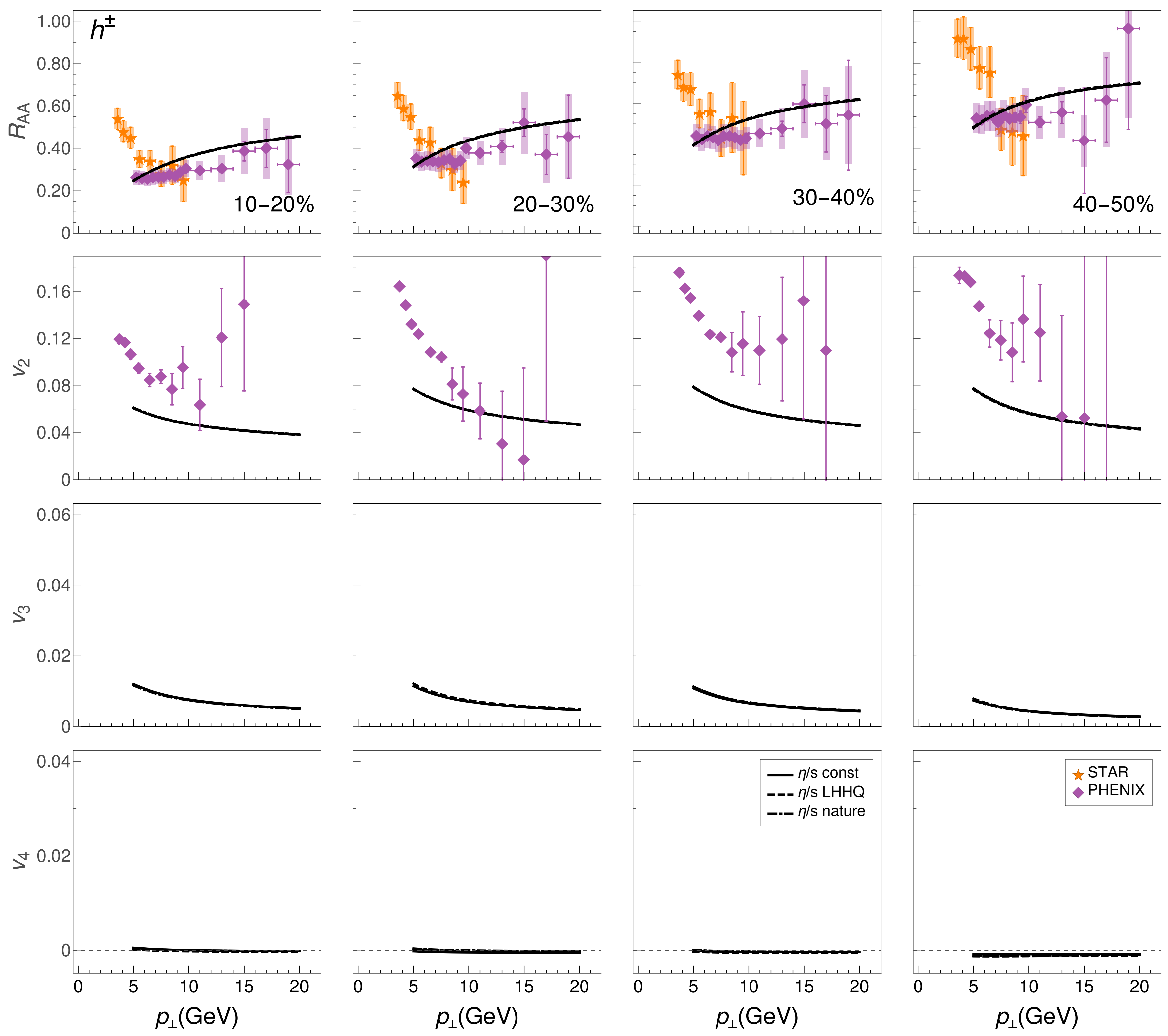
LHHQ→ Phys. Rev. Lett. **106**, 212302 (2011)

Can high-$p_\perp$ observables constrain η/s?

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic arXiv:2305.11318



Pb+Pb($\sqrt{s}$ = 5.02 TeV)



Au+Au($\sqrt{s}$ = 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.

Summary

1. High-$p_\perp$ particles traverses through and interact with the medium created in HICs.
2. Can be used to study medium properties along with the low-$p_\perp$ sector.
3. Numerical implementation of the radiative and collisional energy loss formalism within the DREENA framework
4. DREENA-C (Constant temperature): **Joint predictions for R_{AA} and v_2, Agrees well with the high-$p_\perp$ data.**
5. DREENA-B (Bjorken expansion): R_{AA} **affected by pre-equlibrium stage,** v_2 **insensitive to pre-equilibrium stage**
6. DREENA-A(Adaptive temperature): **Can differentiate different temperature profiles, Still R_{AA} and not v_2 sensitive to pre-equilibrium energy loss**
7. Generalized DREENA-A (event-by-event): **High-$p_\perp$ observables, especially higher harmonics sensitive to intial stage, Can not differentiate among the three η/s parametrizations considered**

Thank you

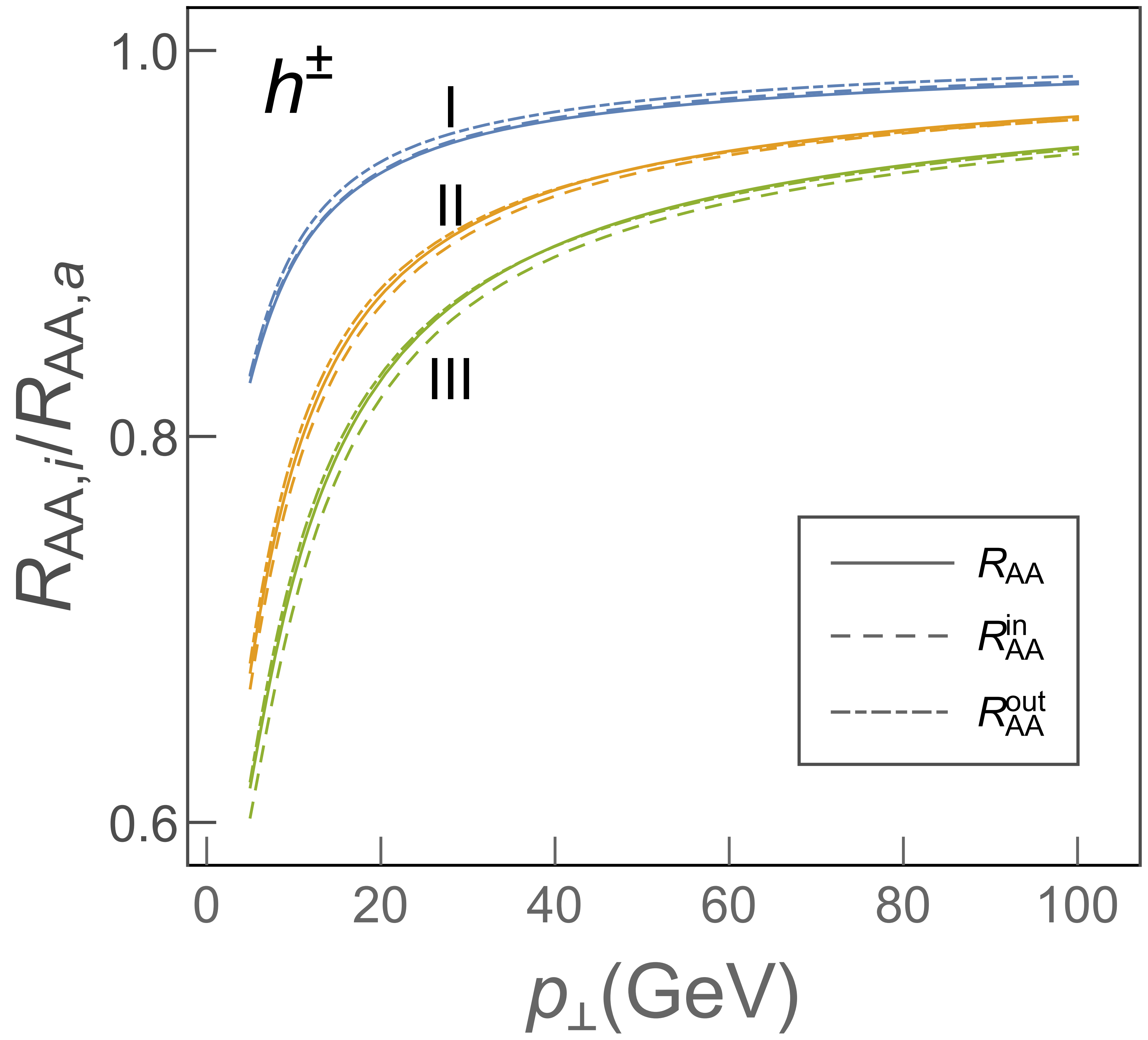
Quantitative explanation of DREENA-B results

D. Zigic, B. Illic, M. Djordjevic and M. Djordjevic, Phys. Rev. C **101**, no. 6, 064909 *(2020)*

- $R_{AA} \approx \dfrac{R_{AA}^{in} + R_{AA}^{out}}{2}, \quad v_2 \approx \dfrac{1}{2}\dfrac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}}$
  1. Blue = Linear/FS
  2. Orange = Constant/FS
  3. Green = Divergent/FS
- Proportionality factors

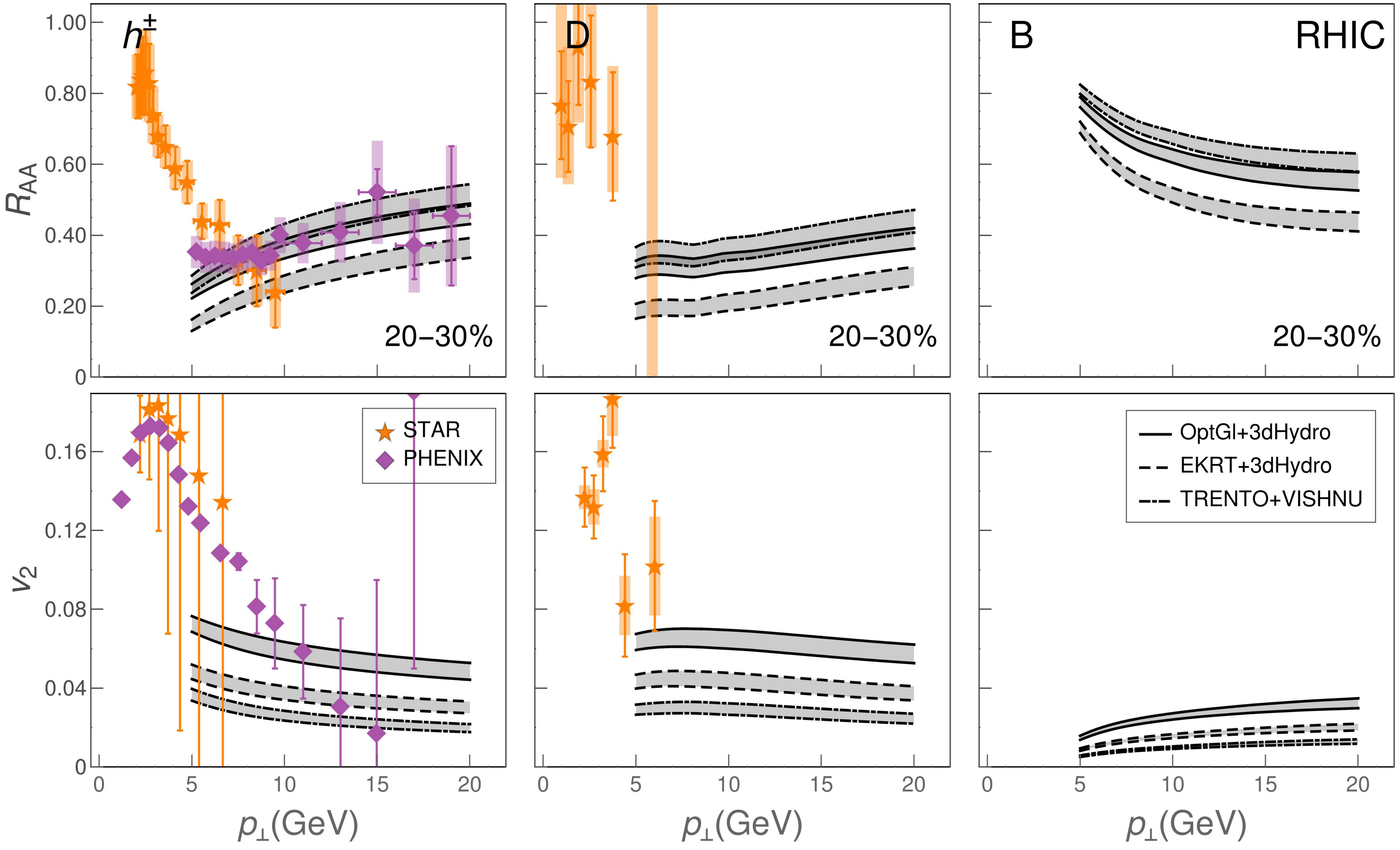
$$\gamma_i = \frac{R_{AA,i}}{R_{AA,FS}}, \quad \gamma_i^{in} = \frac{R_{AA,i}^{in}}{R_{AA,FS}^{in}}, \quad \gamma_i^{out} = \frac{R_{AA,i}^{out}}{R_{AA,FS}^{out}}$$

- $\gamma_i \approx \gamma_i^{in} \approx \gamma_i^{out}$ for all i $\implies v_2$ same for all cases
- γ different for different i $\implies R_{AA}$ sensitive to pre-equlibrium stage



DREENA-A

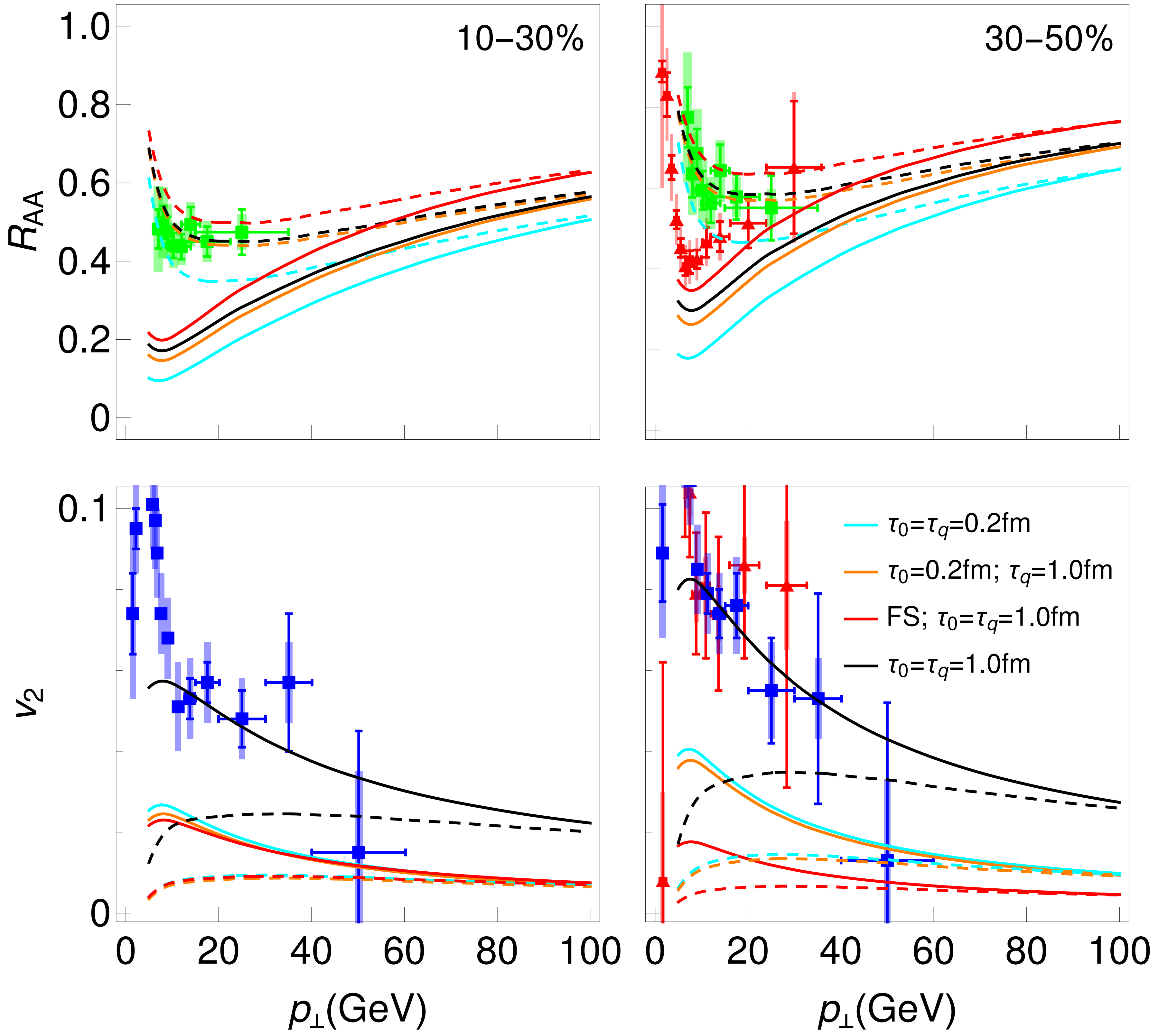
D. Zigic, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, Front. in Phys. 10 (2022) 957019



$$\text{Au} + \text{Au}\ \sqrt{s} = 200\ \text{GeV}$$

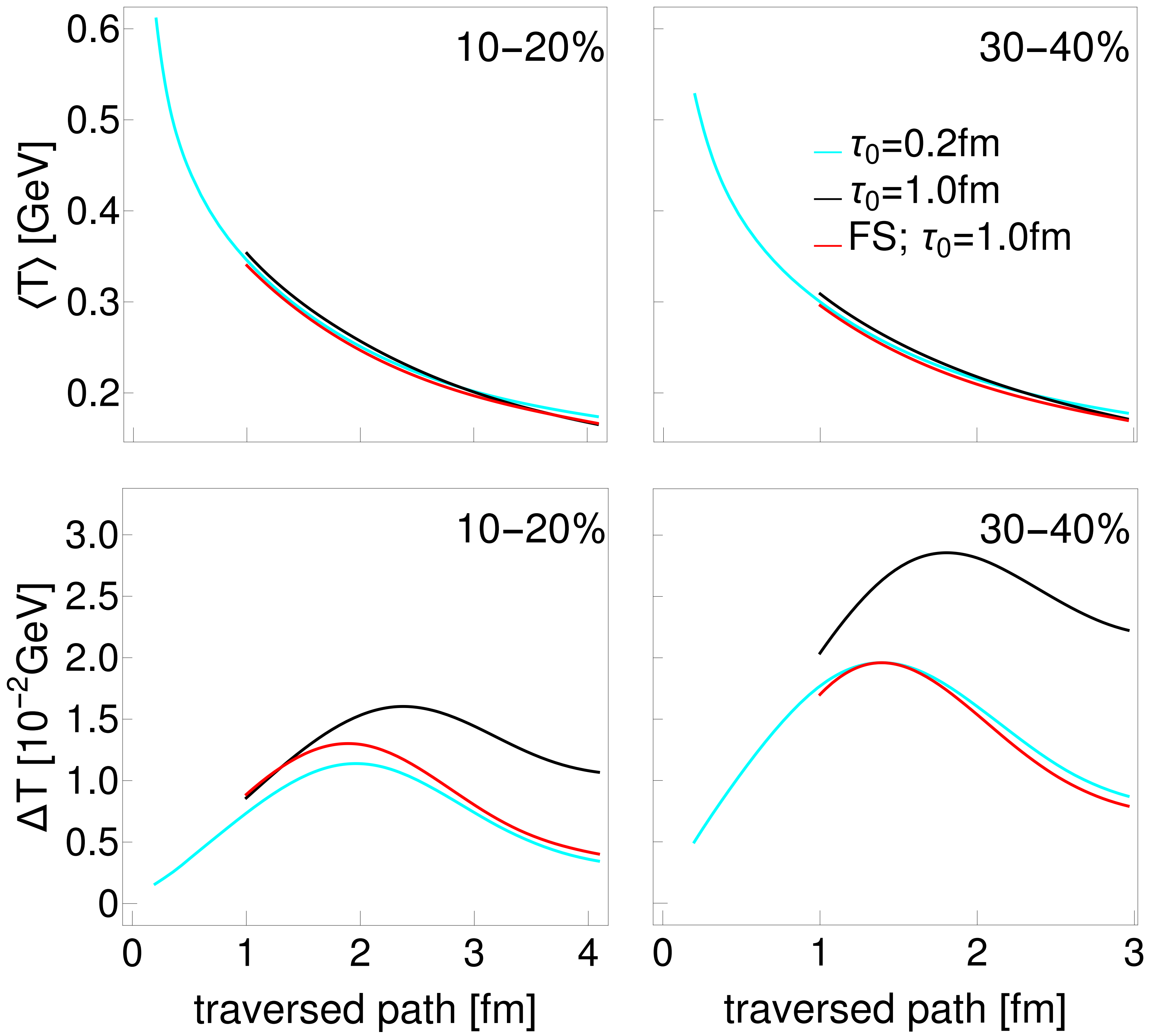
Early evolution from DREENA-A

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

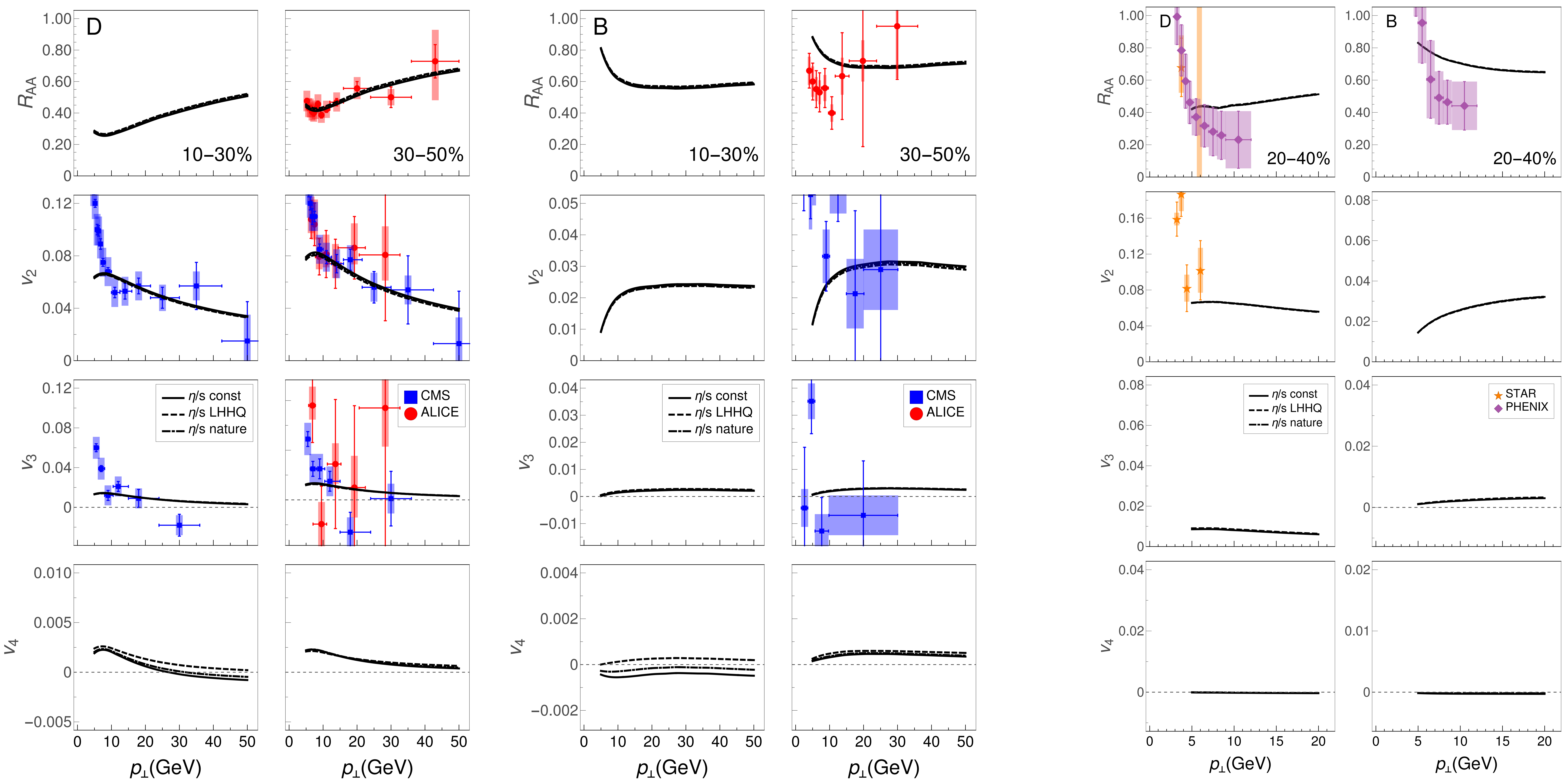


Full- D meson, Dashed - B meson

Pb+Pb $\sqrt{s} = 5.02$ TeV



Study of η/s using Generalized DREENA-A



Pb+Pb($\sqrt{s}$ = 5.02 TeV) Au+Au($\sqrt{s}$ = 200 GeV)

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic arXiv:2305.11318

Study of η/s using Generalized DREENA-A

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic arXiv:2305.11318

- Pb + Pb $\sqrt{s} = 5.02$ TeV
- Full = LHHQ; DotDashed = Nature,

  Dashed = Constant
- Inset: Dotdashed = Nature,

  Dashed = LHHQ