Anisotropy of QGP constrained by high $p_\perp$ data

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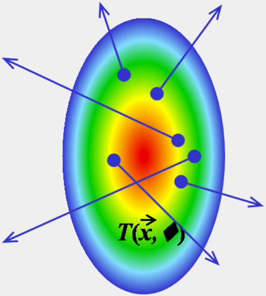
- Energy loss of high energy particles traversing QCD medium is an excellent probe of QGP properties.
- High energy particles:
  - Are produced only during the initial stage of QCD matter
  - Significantly interact with the QCD medium
  - Perturbative calculations are possible
- Theoretical predictions vs. experimental data.
- Dynamical Radiative and Elastic ENergy Loss Approach: a versatile and fully optimized suppression calculation procedure.

- Our main goal: use high-$p_\perp$ data to infer bulk properties of QGP.



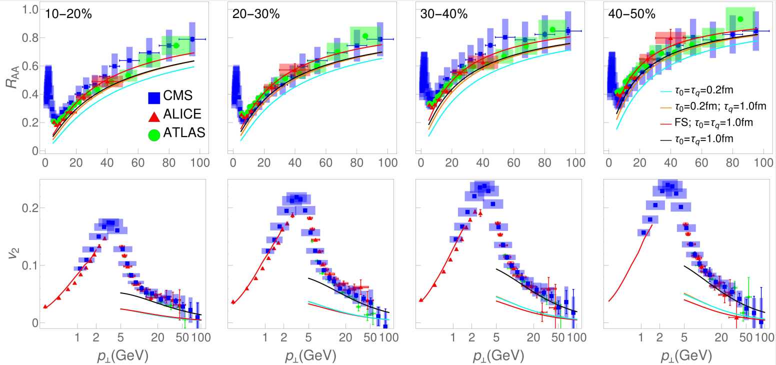
- High energy particles lose energy when they traverse QGP.
- This energy loss is sensitive to QGP properties.
- We can realistically predict this energy loss.

⬇

- High-$p_\perp$ probes are excellent tomoraphy tools.
- We can use them to infer some of the bulk QGP properties.

- We have demonstrated this by constraining the early evolution with high-$p_\perp$ data

Stefan Stojku, Jussi Auvinen, Marko Djordjevic, Pasi Huovinen, Magdalena Djordjevic, Phys. Rev. C 105, L021901 (2022)



- Initial spatial anisotropy: one of the main properties of QGP. One of the major limiting factors for QGP tomography.
- Still not possible to infer anisotropy from experimental data.
- Alternative approaches are necessary.
- We propose a novel approach, based on inference from already available high-$p_\perp$ R_{AA} and v_2 measurements.

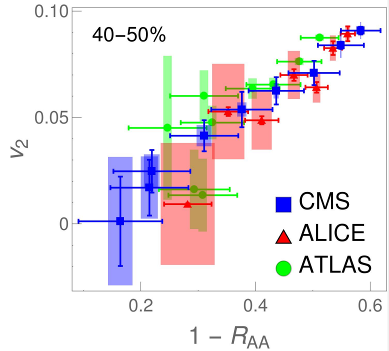
- We previously argued that $v_2/(1 - R_{AA})$ saturates at high-$p_\perp$
- Saturation value reflects the geometry of the system

M. Djordjevic, S. Stojku, M. Djordjevic and P. Huovinen, Phys.Rev. C Rapid Commun. 100, 031901 (2019).

- This argument: analytic considerations and a simple 1+1D medium expansion

- We here study the behavior of $v_2/(1 - R_{AA})$ in a system that expands in both longitudinal and transversal directions.

Stefan Stojku, Jussi Auvinen, Lidija Zivkovic, Pasi Huovinen, Magdalena Djordjevic, arXiv:2110.02029[nucl-th]



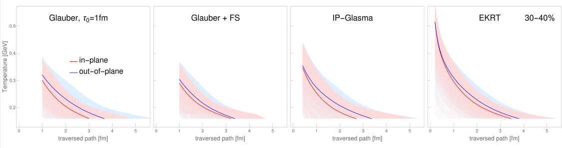
- v_2 and $1 - R_{AA}$ are directly proportional at high $p_\perp$.
- This is equivalent to a $p_\perp$-independent ratio of v_2 and $1 - R_{AA}$.
- Can fluid dynamical calculations reproduce such proportionality? Can we relate this observation to the anisotropy of the system?

- DREENA-A: can accomodate any temperature profile and generate high-$p_\perp$ R_{AA} and v_2 predictions.

  D. Zigic, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, arXiv:2110.01544 [nucl-th].

- We visualize the temperatures partons experience in the in-plane and out-of-plane directions for different initializations and evolutions.

  Stefan Stojku, Jussi Auvinen, Lidija Zivkovic, Pasi Huovinen, Magdalena Djordjevic, arXiv:2110.02029[nucl-th]



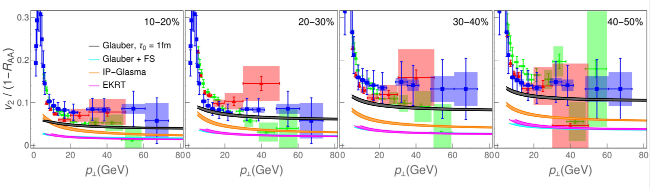
$$\langle T_x(t)\rangle = \frac{1}{N}\sum_{i=1}^{N} T(x_i + t, y_i, t)$$

$$\langle T_y(t)\rangle = \frac{1}{N}\sum_{i=1}^{N} T(x_i, y_i + t, t)$$

$v_2/(1-R_{AA})$ RESULTS

- Does $v_2/(1-R_{AA})$ saturate?
- Does this saturation carry information on the anisotropy of the system?
- What kind of anisotropy measure is revealed through high-$p_\perp$ data?

We calculate $v_2/(1-R_{AA})$ within DREENA-A framework:



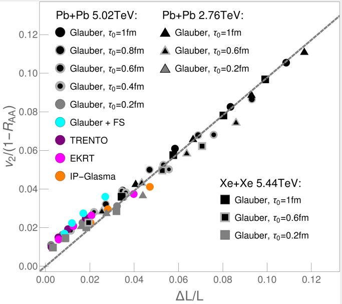
Stefan Stojku, Jussi Auvinen, Lidija Zivkovic, Pasi Huovinen, Magdalena Djordjevic, arXiv:2110.02029[nucl-th]

The phenomenon of $v_2/(1-R_{AA})$ saturation is robust!
How to explore if it contains information on the system anisotropy?

Connection to anisotropy

- **Next:** Plot charged hadrons' $v_2/(1-R_{AA})[100GeV]$ vs. $\Delta L/\langle L\rangle$

  Stefan Stojku, Jussi Auvinen, Lidija Zivkovic, Pasi Huovinen, Magdalena Djordjevic, arXiv:2110.02029[nucl-th]



- 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 $\Delta L/\langle L\rangle$.

- Define a more direct measure of anisotropy? Explicit dependence on time evolution?
- We define jT:

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

- jT is not azimuthally symmetric. We define its 2^{nd} Fourier coefficient jT_2:

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

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

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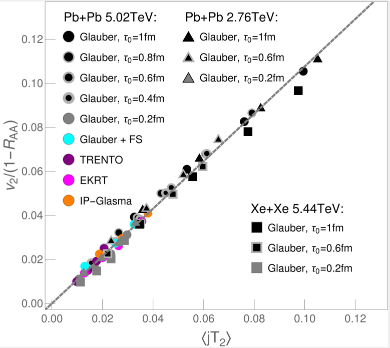
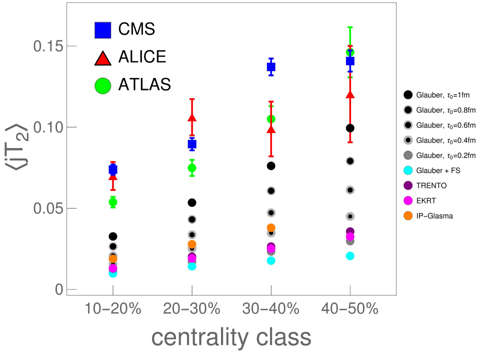
$$\langle jT_2 \rangle = \frac{\int_{\tau_0}^{\tau_{\rm cut}} d\tau \, jT_2(\tau)}{\tau_{\rm cut} - \tau_0}$$



- τ_{cut}: the time when the center of the fireball has cooled to critical temperature T_c.
- $v2/(1 - R_{AA})$ shows a linear dependence on $\langle jT_2 \rangle$, with a slope close to 1.
- $v_2/(1 - R_{AA})$ carries information on this property of the medium.

Jet-temperature anisotropy

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



- All three experiments lead to similar values of $\langle jT_2 \rangle$.
- Jet-temperature anisotropy provides an important constraint on bulk-medium simulations - they should be tuned to reproduce it.

CONCLUSIONS AND ACKNOWLEDGEMENTS

- High-$p_\perp$ theory and data - traditionally used to explore high-$p_\perp$ parton interactions with QGP.
- High-$p_\perp$ probes can become powerful tomography tools, as they are sensitive to global QGP properties (e.g. spatial anisotropy).
- A (modified) ratio of R_{AA} and v_2 - a reliable and robust observable for straightforward extraction of spatial anisotropy.
- The saturation is directly proportional to jet-temperature anisotropy.
- It will be possible to infer anisotropy directly from LHC Run 3 data: an important constraint to models describing the early stages of QGP formation.
- Synergy of more common approaches for inferring QGP properties with high-$p_\perp$ theory and data.

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