How to explore initial stages and QGP anisotropy by using high-$p_\perp$ data?

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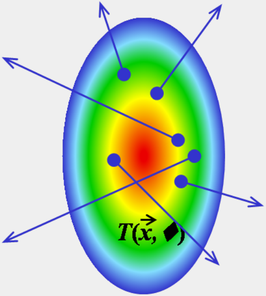
Introduction: QGP tomography

- Quark-gluon plasma is a new form of matter, which consists of interacting quarks, antiquarks and gluons
- Energy loss of high-energy particles traversing QCD medium is an excellent probe of QGP properties.

- DREENA framework: a versatile and fully optimized suppression calculation procedure – generate R_{AA} and v_2 predictions for an arbitrary temperature profile.
  DREENA-A on GitHub: https://GitHub.com/DusanZigic/DREENA-A
  See talk by Dušan Źigić, Tuesday 11:25-11:45

- 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.

How to study early evolution of QGP by using high-$p_\perp$ data?

QGP Initial Time

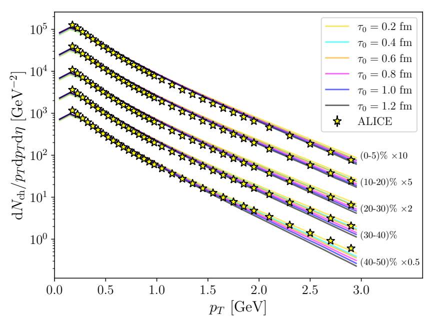
- The dynamics before initial time τ_0 not established (applicability of hydrodynamics, energy loss phenomena); τ_0 is an important parameter
- Conventional hydrodynamics approach: vary τ_0 and compare obtained distributions with data
- An analysis employing Bayesian statistics: low-$p_\perp$ data provides only weak limits to $\tau_0 = 0.59 \pm 0.41 fm/c$
- Further constraints would be useful.
- Our approach: how do high $p_\perp$ R_{AA} and v_2 depend on τ_0?
- First, we neglect pre-equilibrium evolution of the medium. After τ_0: the medium is described using 3+1D viscous hydro model.

  E. Molnar, H. Holopainen, P. Huovinen and H. Niemi,Phys. Rev. C90, 044904 (2014).
- High-$p_\perp$ particles start to lose energy through the interactions with the medium.
- Model parameters are tuned for each τ_0 to match observed charged particle multiplicities and low-$p_\perp$ v_2 in $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 5.01$ TeV.

Model Description

- Bass *et al.* (2017) showed that comparison of relativistic hydrodynamics with low-$p_\perp$ data is insensitive to a wide range of initial times ($0.2fm < \tau_0 < 1.2fm$)
- Independently confirmed by our systematic analysis: 3+1D viscous hydrodynamics model run with six different initial times:

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

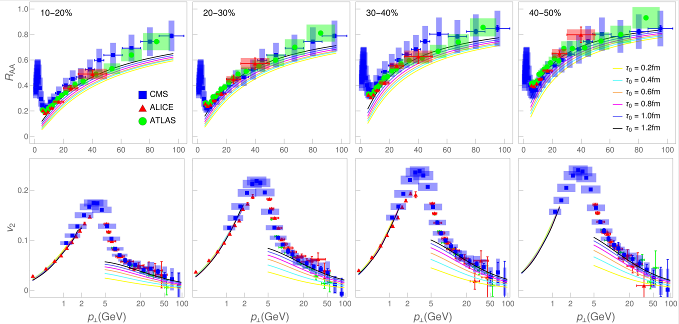


- Good agreement with low-$p_\perp$ data confirms low sensitivity to τ_0.
- Can this indeterminancy be further constrained through high-$p_\perp$ theory and data?

High-$p_\perp$ Results for Various τ_0

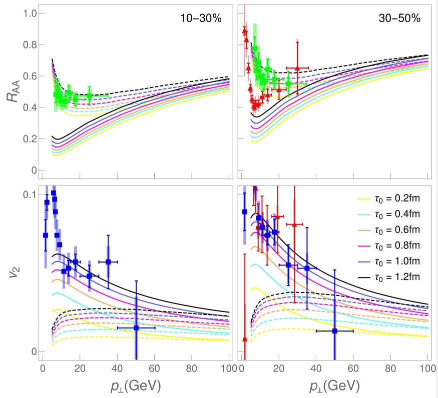
- Next step: use DREENA-A to generate high $p_\perp$ data for all τ_0 (charged hadrons, $Pb + Pb$ @ $\sqrt{s_{NN}} = 5.01$ TeV)

S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Acta Phys. Pol. B Proc. Suppl. 16, 1-A156 (2023)



- Low-$p_\perp$ v_2 is completely insensitive to different τ_0.
- On the other hand, high-$p_\perp$ predictions can clearly be resolved against experimental data.
- Later initial time is clearly preferred by R_{AA} and v_2.
- Resolution increases for higher centrality.

- DREENA-A predictions for D mesons (full curves) and B mesons (dashed curves), $Pb + Pb$ @ $\sqrt{s_{NN}} = 5.01$ TeV
  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen, and M. Djordjevic, Phys. Rev. C 105, L021901 (2022)

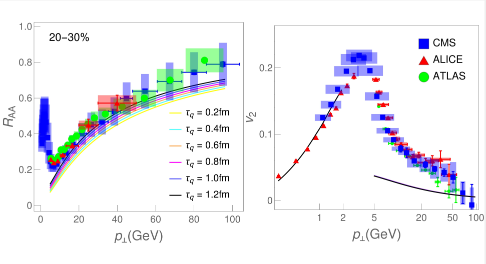


- D meson: ALICE (red triangles), CMS (blue squares)
- B meson: CMS non-prompt J/ψ (green circles)
- Heavy quarks are even more sensitive to τ_0.
- Available data suggests that later initial time is preferred.

Later Quenching Time?

- What if jet quenching starts later than QGP initial time (and subsequent medium evolution) τ_0?
- To test this scenario, we introduce quenching time $\tau_q \geq \tau_0$
- DREENA-A results generated on a temperature profile with $\tau_0 = 0.2$ fm, but τ_q in the range of = 0.2-1.2fm:

S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Acta Phys. Pol. B Proc. Suppl. 16, 1-A156 (2023)

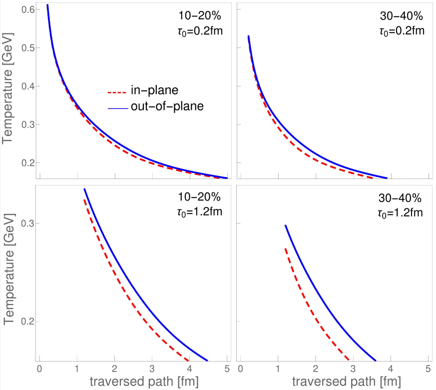


- v_2 surprisingly insensitive to τ_q!

Explaining the Observed Sensitivity

- … of high $p_\perp$ observables R_{AA} and v_2 on τ_0 (and τ_q)
- We evaluated the average temperatures that partons experience while traversing the medium in the in-plane ($\phi = 0$) and out-of-plane ($\phi = \pi/2$) directions for various τ_0

S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Acta Phys. Pol. B Proc. Suppl. 16, 1-A156 (2023)



- As τ_0 increases $\Longrightarrow$ the difference between average in-plane and out-of-plane temperatures increases
- Recall that $v_2 \approx \frac{1}{2}\frac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}}$

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- Explains the observed dependence of v_2 on τ_0.

Explaining the Observed Sensitivity

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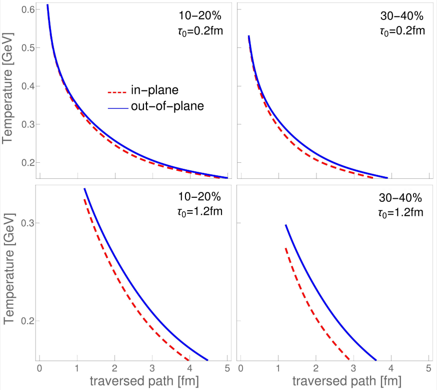
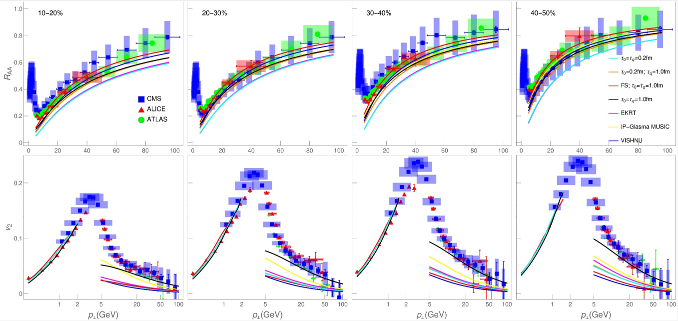


- The difference between Ts is larger in more peripheral collisions $\implies$ explains higher sensitivity of v_2 to τ_0.
- Larger τ_0 have lower overall avg T $\implies$ explains behaviour of R_{AA}.

MORE SOPHISTICATED INITIALIZATIONS

- ...such as EKRT, TRENTO and IP-Glasma (charged hadrons, $Pb + Pb$ @ $\sqrt{s_{NN}} = 5.01$ TeV)

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



- High-$p_\perp$ R_{AA} and v_2 are sensitive to different initializations and early expansion dynamics
- High-$p_\perp$ data prefer later onset of transverse expansion and energy loss!

How to infer the anisotropy of QGP from high-$p_\perp$ data?

Anisotropy

- 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

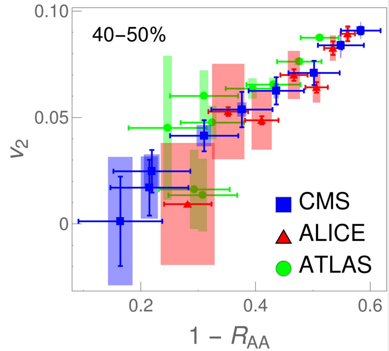
  M. Djordjevic, S. Stojku, M. Djordjevic and P. Huovinen, Phys.Rev. C Rapid Commun. 100, 031901 (2019).

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

ANISOTROPY

- 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, Physics Letters B 835, 137501 (2022)



- 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?

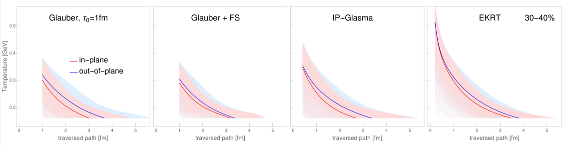
Anisotropy

- 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, Front. Phys. 10:957019 (2022)

- 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, Physics Letters B 835, 137501 (2022)



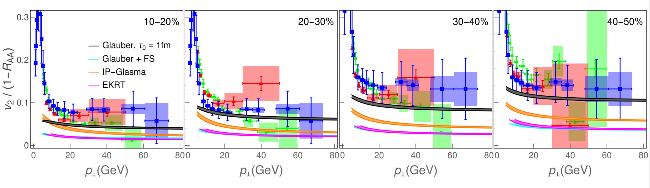
$$\langle T_x(t)\rangle = \frac{1}{N}\sum_{i=1}^{N} T(x_i + t, y_i, t)$$

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

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



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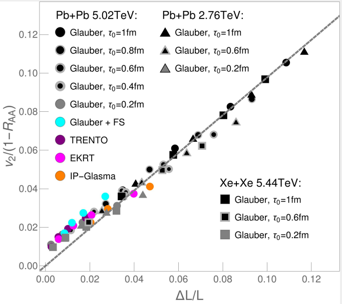
The phenomenon of $v_2/(1-R_{AA})$ saturation is robust!
How to explore if it contains information on the system anisotropy?

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, Physics Letters B 835, 137501 (2022)



- 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 $\approx$ 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-perceived anisotropy:

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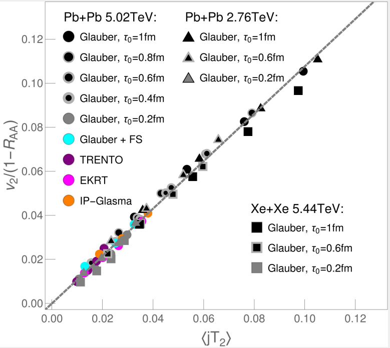
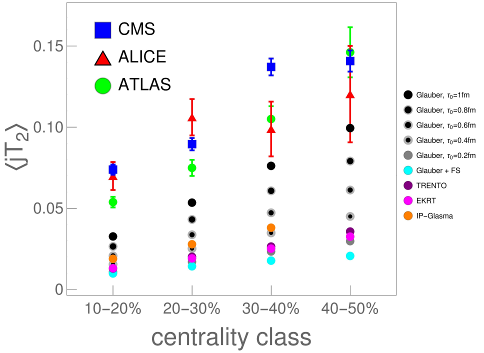
$$\langle jT_2 \rangle = \frac{\int_{\tau_0}^{\tau_{\text{cut}}} d\tau\, jT_2(\tau)}{\tau_{\text{cut}} - \tau_0}$$



- 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-perceived 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-perceived anisotropy provides an important constraint on bulk-medium simulations - they should be tuned to reproduce it.

Conclusion

- High-$p_\perp$ theory and data - traditionally used to explore parton interactions with QGP.
- High-$p_\perp$ probes can become powerful tomography tools, as they are sensitive to global QGP properties.
- Initial stages constrained through high-$p_\perp$ data
- 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-perceived 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.

Acknowledgements

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Backup

2.1. Medium evolution

Our starting point and reference we used for all collision energies and systems is a simple optical Glauber model based initialisation. In Pb+Pb collisions at full LHC energy ($\sqrt{s_{NN}} = 5.02$ TeV) we used initial times $\tau_0 = 0.2, 0.4, 0.6, 0.8$, and 1.0 fm, whereas the lower energy ($\sqrt{s_{NN}} = 2.76$ TeV) Pb+Pb and Xe+Xe ($\sqrt{s_{NN}} = 5.44$ TeV) calculations were carried out for $\tau_0 = 0.2, 0.6$, and 1.0 fm. The initialisation and code used to solve viscous fluid-dynamical equations in 3+1 dimensions are described in detail in Ref. [22], and parameters to describe Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in Ref. [23]. In particular, we use a constant shear viscosity to entropy density ratio $\eta/s = 0.12$ (Pb+Pb) or $\eta/s = 0.10$ (Xe+Xe), and the EoS parametrisation $s95p$-PCE-v1 [25].

Different initial state models lead to slightly different shapes of the initial state. To find if our findings are a feature of the Glauber model, or have broader significance, we did the Pb+Pb calculations at the full LHC energy using several different initial state models. The first option in this extended set, Glauber + Free streaming, is to use the Glauber model to provide the initial distribution of (marker) particles, allow the particles to stream freely from $\tau = 0.2$ to 1.0 fm, evaluate the energy-momentum tensor of these particles, and use it as the initial state of the fluid. We evolve the fluid using the same code as in the case of pure Glauber initialisation. The EoS is $s95p$-PCE175, i.e., a parametrisation with $T_{chem} = 175$ MeV [26], and temperature-independent $\eta/s = 0.16$. For further details, see Ref. [23].

As more sophisticated initialisations, we employ EKRT, IP-Glasma and T$_R$ENTo. The EKRT model [27–29] is based on the NLO perturbative QCD computation of the transverse energy and a gluon saturation conjecture. We employ the same setup as used in Ref. [30] (see also [26]), compute an ensemble of event-by-event fluctuating initial density distributions, average them, and use this average as the initial state of the fluid dynamical evolution. We again use the code of Molnar et al., [22], but restricted to boost-invariant expansion. The shear viscosity over entropy density ratio is temperature dependent with favoured parameter values from the Bayesian analysis of Ref. [30]. Initial time is $\tau_0 = 0.2$ fm, and the EoS is the $s83s_{18}$ parametrisation from Ref. [30].

IP-Glasma model [31,32] is based on Color Glass Condengluon fields by solving classical Yang-Mills equations. The calculated event-by-event fluctuating initial states [37] were further evolved [38] using the MUSIC code [39–41] constrained to boost-invariant expansion. We subsequently averaged the evaluated temperature profiles to obtain one average profile per centrality class. In these calculations, the switch from Yang-Mills to fluid-dynamical evolution took place at $\tau_{\text{switch}} = 0.4$ fm, shear viscosity over entropy density ratio was constant $\eta/s = 0.12$, and the temperature-dependent bulk viscosity coefficient over entropy density ratio had its maximum value $\zeta/s = 0.13$. The equation of state was based on the HotQCD lattice results [42] as presented in Ref. [43].

T$_{\text{R}}$ENTo [44] is a phenomenological model capable of interpolating between wounded nucleon and binary collision scaling, and with a proper parameter value, of mimicking the EKRT and IP-Glasma initial states. As with the EKRT initialisation, we create an ensemble of event-by-event fluctuating initial states, sort them into centrality classes, average, and evolve these average initial states. Unlike in other cases, we employ the version of the VISH2+1 code [45] described in Refs. [46,47]. We run the code using the favoured values of the Bayesian analysis of Ref. [47]; in particular, allow free streaming until $\tau = 1.16$ fm, the minimum value of the temperature-dependent η/s is 0.081, and the maximum value of the bulk viscosity coefficient ζ/s is 0.052. The EoS is the same HotQCD lattice results [42] based parametrisation as used in Refs. [46,47].

It is worth noticing that the initial nuclear configuration in all these cases is similar Woods-Saxon parametrisation of nuclear matter density, which is either assumed to be continuous (optical Glauber), or Monte-Carlo sampled to create ensembles of nucleons (EKRT, IP-Glasma, T$_{\text{R}}$ENTo). The differences in the fluid-dynamical initial state depend on the initial particle production, and subsequent evolution before fluid-dynamical stage (none, Yang-Mills, free streaming).

All these calculations were tuned to reproduce, in minimum, the centrality dependence of charged particle multiplicity, $p_\perp$ distributions and $v_2(p_\perp)$ in Pb+Pb collisions at both collision energies, and the centrality dependence of charged particle multiplicity