Constraining the initial stages of heavy-ion collisions with high-$p_\perp$ theory and data

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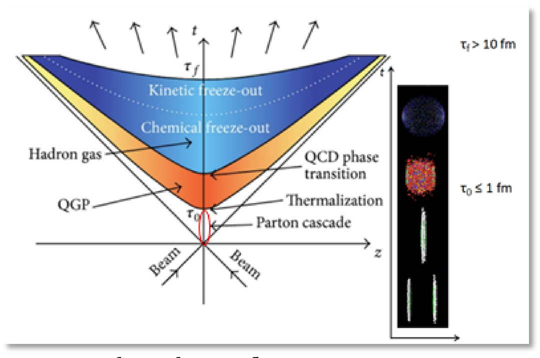
Abstract

Traditionally, low-$p_\perp$ sector is used to infer the features of **initial stages before QGP thermalization**. On the other hand, recently acquired wealth of high-$p_\perp$ experimental data paves the way to utilize the **high-$p_\perp$ particles energy loss** in exploring the initial stages. We here study how **four different commonly considered initial-stage scenarios** – which have the same temperature profile after, but differ in the temperature profile before thermalization – **affect** predictions of **high-$p_\perp$ R_{AA} and v_2 observables**. Contrary to common expectations, we obtain that **high-$p_\perp$ v_2 is insensitive** to the initial stages of medium evolution, being unable to discriminate between different initial conditions. On the other hand, **high-$p_\perp$ R_{AA} is sensitive** to these stages, however, within the current error bars, the sensitivity is not sufficient to distinguish between different initial stages. Moreover, we also reconsider the validity of **widely-used procedure of fitting the energy loss parameters**, individually for each initial-stage case, to reproduce the experimentally observed R_{AA}. We here find that previously reported sensitivity of v_2 to different initial stages is mainly **an artifact** of the **R_{AA} fitting procedure**, which may lead to incorrect conclusions. On the other hand, if a global property, in particular **the same average temperature**, is imposed to test temperature profiles, high sensitivity of high-$p_\perp$ v_2 is again obtained. We however show that this sensitivity would **not** be **a consequence of** differences in **initial, but rather final, stages**. Consequently, the simultaneous study of high-$p_\perp$ R_{AA} and v_2, with consistent energy loss parameters throughout the study and rigorously controlled temperature profiles, is necessary to assess sensitivity of different variables to differences in initial stages.

Introduction

- Traditionally, rare **high-$p_\perp$ probes** ($p_\perp \gtrsim 5$ GeV) are utilized for studying the nature of jet-medium interactions.
- Commonly, **low-$p_\perp$ sector** ($p_\perp \lesssim 5$ GeV) is used to infer the features of initial stages (IS) before the QGP thermalization.
- Initial-stage properties are **poorly-known** up-to-date.



The need for an alternative approach to assessing the IS features emerged and **we here propose to use high-$p_\perp$ probes as a complementary tool** for this purpose, because:

- High-$p_\perp$ partons effectively probe QGP properties, which in turn depend on initial QGP stages.
- Recently a wealth of high-$p_\perp$ experimental data became available.

This issue is moreover intriguing, as **results of current theoretical studies on this subject are questionable**, e.g., the energy loss parameters were fitted to reproduce the experimental R_{AA} data, individually for different analyzed temperature (T) profiles.
Therefore, **more rigorous study** on this issue is required, which implies **higher control over** both **the energy loss** and **the analyzed T profiles**.

Theoretical Framework

For higher control over the energy loss and IS we employ **full-fledged** DREENA-B framework (no fitting parameters), because:

- Bjorken 1+1D:
  - Allows analytical introduction of **different evolutions before**, and **the same evolution after thermalization**.
  - Facilitates the **isolation of IS effects** alone.
  - Presents a **reasonable description of medium evolution** (compared to 3+1D hydrodynamical evolution, [M. Djordjevic *et al.*, In Preparation]).
- Dynamical energy loss formalism:
  - **State-of-the-art** and **complex**, enclosing some unique realistic features.
  - **Dominant** ingredient for **generating high-$p_\perp$ predictions**.

We introduce four commonly considered **IS cases**, which have the same 1+1D Bjorken T profile upon thermalization, but differ for $\tau < \tau_0 = 0.6$ fm:

- *Free streaming* (*fs*), $T = 0$.
- *Linear*, linearly increasing T from T_C=160 MeV to T_0=391 MeV.
- *Constant*, $T = T_0$.
- *Divergent*, Bjorken expansion from $\tau = 0$.

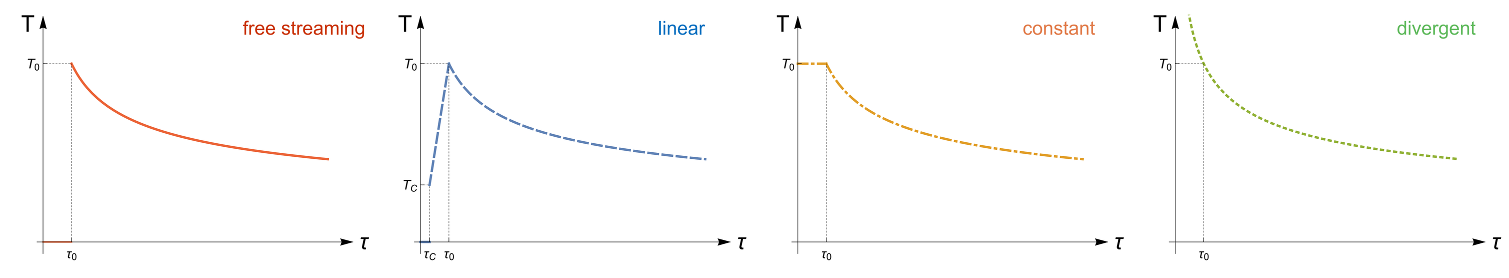


Fig. 2: Four common **IS cases** with the same T_0 value, which differ only before thermalization.

Sensitivity of high-$p_\perp$ R_{AA} and v_2 to the Initial Stages

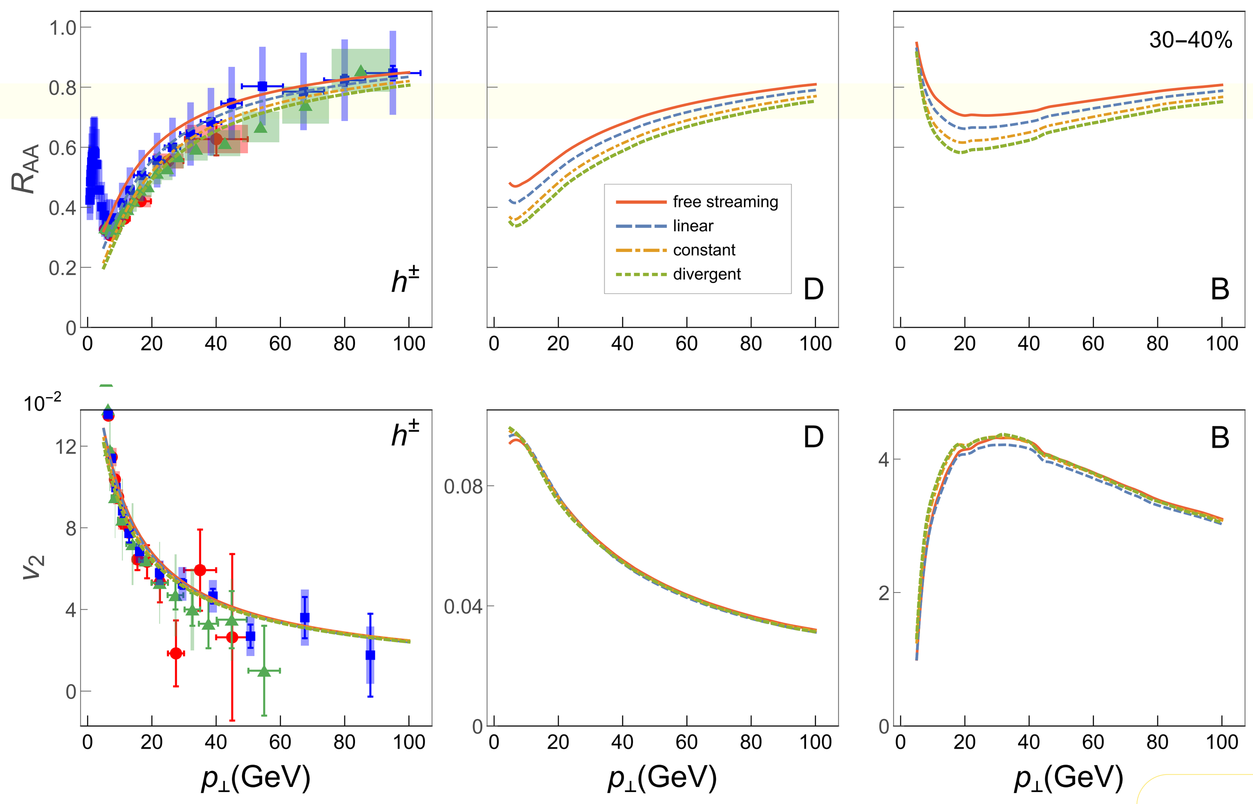


Fig. 3: Sensitivity of high-$p_\perp$ observables to four different IS depicted in Fig. 2.

High-$p_\perp$ R_{AA} is notably affected by the presumed IS, due to difference in energy loss.

However, current error bars at the LHC do not allow distinguishing between these cases.

High-$p_\perp$ v_2 is practically insensitive to the IS!

High-$p_\perp$ v_2 cannot distinguish between different IS scenarios!

Qualitative explanation of R_{AA} results:

5.02 TeV $Pb+Pb$

$1-R_{AA} \sim \frac{\Delta E}{E} \sim \overline{T}$

Different $\overline{T}$s in four IS cases result in different R_{AA}s.

Quantitative explanation of the obtained results:

$R_{AA} \approx \frac{R^{in}_{AA}+R^{out}_{AA}}{2}$

$v_2 \approx \frac{1}{2}\frac{R^{in}_{AA}-R^{out}_{AA}}{R^{in}_{AA}+R^{out}_{AA}}$

$i = lin, const, div$

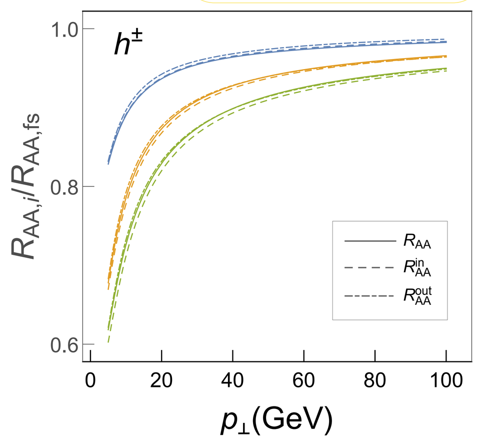


Fig. 4: Quantitative explanation of the obtained results in Fig. 3.

Proportionality functions

$$\gamma_i = \frac{R_{AA,i}}{R_{AA,fs}}, \gamma_i^{in} = \frac{R^{in}_{AA,i}}{R^{in}_{AA,fs}}, \gamma_i^{out} = \frac{R^{out}_{AA,i}}{R^{out}_{AA,fs}}$$

- *Blue* = *Linear* / *Free streaming*
- *Orange* = *Constant* / *Free streaming*
- *Green* = *Divergent* / *Free streaming*

$\gamma_i \approx \gamma_i^{in} \approx \gamma_i^{out}$
$\forall i \in \{Blue, Orange, Green\}, \gamma_i \leq 1$

$$R_{AA,i} \approx \frac{\gamma_i(R^{in}_{AA,fs}+R^{out}_{AA,fs})}{2} = \gamma_i R_{AA,fs}$$
$$v_{2,i} \approx \frac{1}{2}\frac{\gamma_i(R^{in}_{AA,fs}-R^{out}_{AA,fs})}{\gamma_i(R^{in}_{AA,fs}+R^{out}_{AA,fs})} = v_{2,fs}$$

What are the effects of modified T-profile cases, which ensure the same average T? $\Longrightarrow$

Sensitivity of high-$p_\perp$ R_{AA} and v_2 to Modified Temperature Profiles

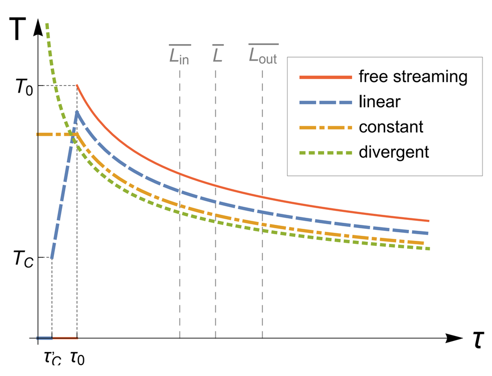


Fig. 5: **Modified T profiles**, with the same average temperature, and therefore different T_0s (with *fs* serving as a baseline).

Modified T-profile cases differ not only at IS, but represent different evolutions altogether!

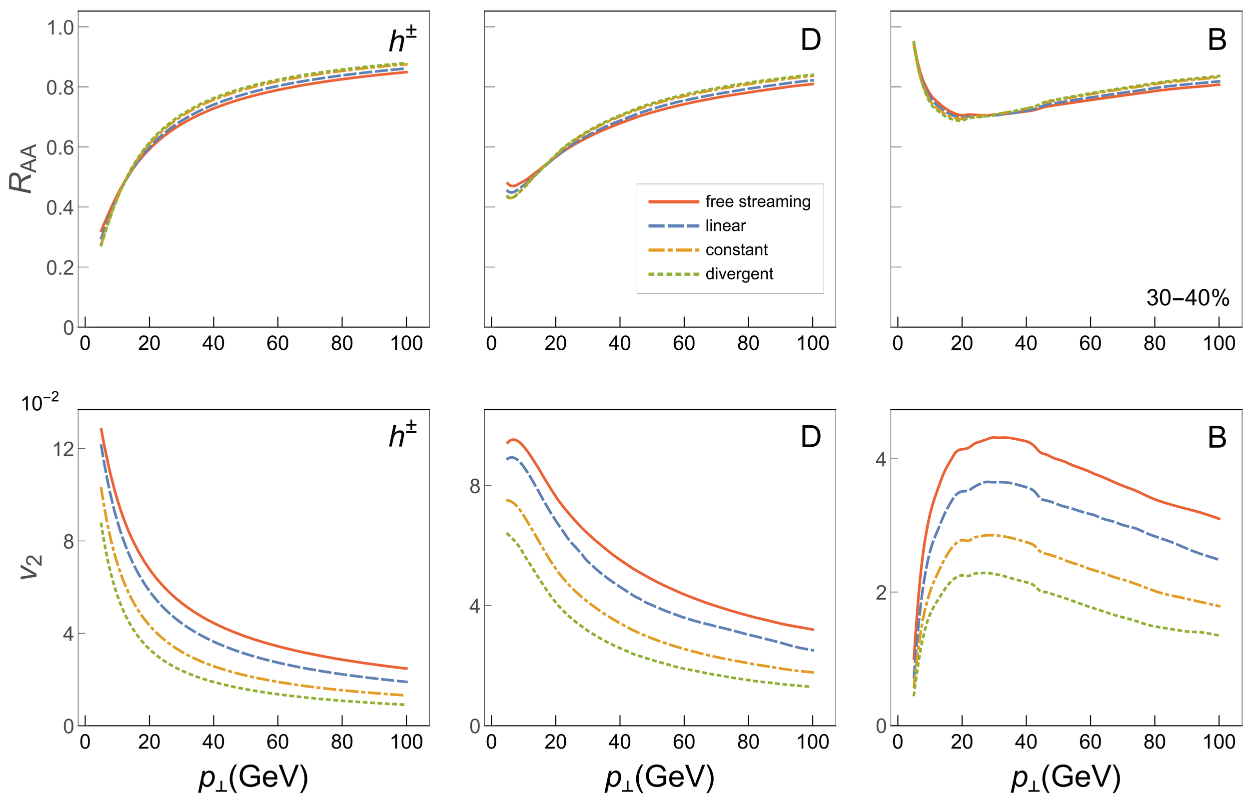


Fig. 6: Sensitivity of high-$p_\perp$ observables to modified T profiles.

The overlap of high-$p_\perp$ R_{AA} curves in all four modified cases is verified.

High-$p_\perp$ v_2 is very sensitive to these different evolutions.

The highest v_2 is observed in *fs* case.

1. Why is high-$p_\perp$ v_2 affected by modified T profiles?

$v_2 \approx \frac{1}{2}\frac{R^{in}_{AA}-R^{out}_{AA}}{R^{in}_{AA}+R^{out}_{AA}}$

R_{AA} is practically unchanged.

$v_2 \sim R^{in}_{AA} - R^{out}_{AA}$

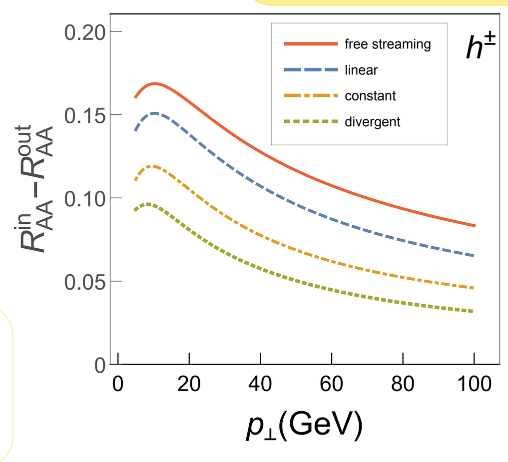
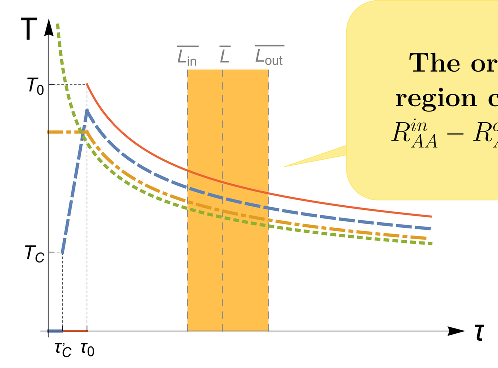


Fig. 7: Explanation of high-$p_\perp$ v_2 discrepancies.

$R^{in}_{AA} - R^{out}_{AA}$ differences are responsible for high-$p_\perp$ v_2 discrepancies.

2. Is IS responsible for high-$p_\perp$ v_2 discrepancies?



The orange-shaded region contributes to $R^{in}_{AA} - R^{out}_{AA}$ differences.

Fig. 8: The origin of high-$p_\perp$ v_2 discrepancies.

Large v_2 sensitivity originates from interactions of high-$p_\perp$ parton with thermalized QGP, and not the initial stages!

Sensitivity of Fitted high-$p_\perp$ R_{AA} and v_2 to Initial Stages

Common approach: Fitting the energy loss through the change of multiplicative fitting factor, to reproduce the high-$p_\perp$ R_{AA} data, individually for each **original IS**.

An additional fitting factor $C_i^{fit}(p_\perp)$ is introduced in our full-fledged calculations, and best fits to $R_{AA,fs}$ yield:

IS case	C_i^{fit}
Free-streaming	1
Linear	0.87
Constant	0.74
Divergent	0.67

Tab. 1: **Fitting factors** values

Decreases to compensate for larger $\frac{\Delta E}{E}$.

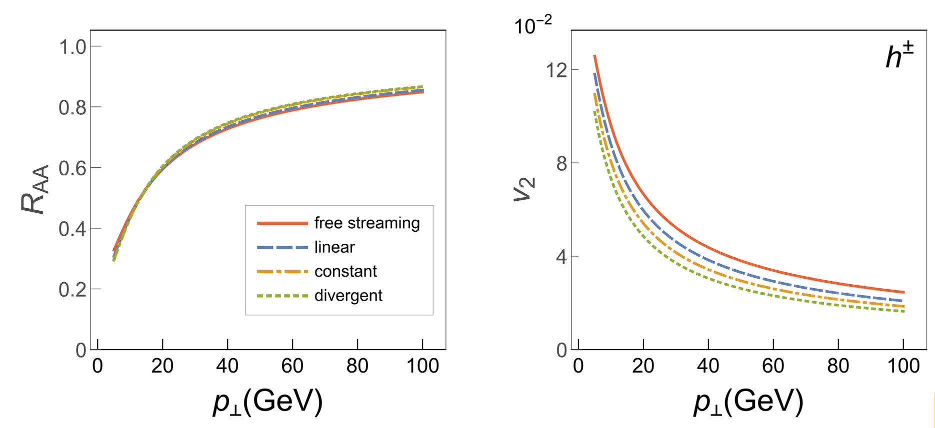


Fig. 9: Sensitivity of fitted high-$p_\perp$ observables to IS from Fig. 2.

High-$p_\perp$ v_2 is notably affected!

Is this a consequence of IS, as previously reported?

Inconsistent with our previous analysis and intuitive expectations.

Quantitative explanation through asymptotic scaling behavior

- For highly energetic jets
- For more peripheral collisions

$R_{AA} \approx 1 - \xi \overline{T}^a \overline{L}^b$

$i = lin, const, div$

$R^{fit}_{AA,i} \approx 1 - C_i(p_\perp)\xi \overline{T}_i^a \overline{L}_i^b$
$R^{fit}_{AA,i} = R_{AA,fs}$

$C_i, \gamma_i < 1$, γ_i approaches 1 at very high $p_\perp$

$v^{fit}_{2,i} = C_i \gamma_i v_{2,fs}$

Diminishing of $v_{2,i}$ compared to the *fs* case is predominantly consequence of a decrease in the artificially imposed fitting factor and not IS.

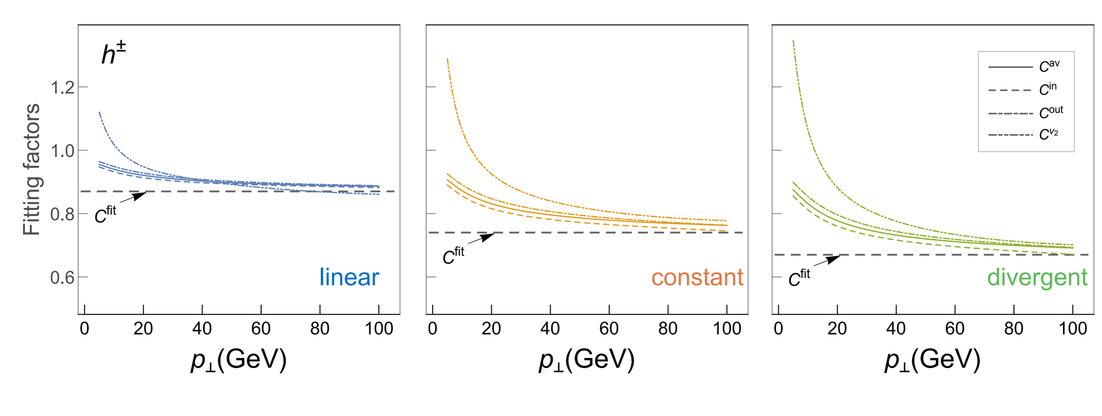


Fig. 10: Comparison of fitting factors obtained from full-fledged calculations.

Conclusions and Outlook

- We studied the effects of commonly considered IS cases on high-$p_\perp$ observables, and obtained that high-$p_\perp$ R_{AA} is sensitive to the presumed IS. However, within the current error bars, the sensitivity is insufficient to distinguish between different initial scenarios.
- Unexpectedly, we found that high-$p_\perp$ v_2 is insensitive to the IS.
- By combining full-fledged numerical predictions and analytical estimates, we inferred that previously reported sensitivity of high-$p_\perp$ v_2 is mostly an artifact of the fitting procedure. All conclusions stand for all types of particles.
- Overall, the simultaneous study of high-$p_\perp$ R_{AA} and v_2, with consistent/fixed energy loss parameters across the entire study, and controlled temperature profiles, is crucial for imposing accurate constraints on the initial stages.

References and Acknowledgments

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