Studying the (pre)equilibrium stage using high-$p_{\perp}$ partons

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• Summary
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

- **Dynamical Radiative and Elastic Energy loss Approach**
  - Based on finite temperature field theory and generalized HTL approach
  - 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

\[
\frac{E_f d^3 \sigma_q(H_Q)}{d^3 p_f^3} = \frac{E_i d^3 \sigma(Q)}{d^3 p_i^3} \otimes P(E_i \rightarrow E_f) \otimes D(Q \rightarrow H_Q),
\]

\[
\frac{E_f d^3 \sigma_u(H_Q)}{d^3 p_f^3} = \frac{E_i d^3 \sigma(Q)}{d^3 p_i^3} \otimes D(Q \rightarrow H_Q).
\]

- No fitting parameter used
• **DREENA-C**


- 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**


- 1D Bjorken evolution has been considered: Analytically tractable
- Now the temperature changes with proper time $\tau$
- Reasonable agreement with data
DREENA-C and DREENA-B predictions


• 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)
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


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

- Smallest $R_{AA}$ expected in case d)
High-$p_{\perp}$ $R_{AA}$ is notably affected by pre-equilibrium stage

$\nu_2$ is insensitive to the pre-equilibrium stage

High-$p_{\perp}$ $\nu_2$ 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 $\phi$
  3. Then it is integrated over the angle.
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
\[ \tau_0 = 1\, fm ; \text{No FS} \]

EKRT
\[ \tau_0 = 0.2\, fm \]

TRENT\(\text{To} \)
\[ \tau_0 = 1.16\, fm; \text{FS} \]

Pb + Pb, (30-40)% centrality

Agrees well with low-$p_\perp$ data
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

1. Cyan → $\tau_q = \tau_0 = 0.2\text{fm}$
2. Orange → $\tau_0 = 0.2\text{fm}; \tau_q = 1\text{fm}$
3. Red → FS; $\tau_0 = \tau_q = 1\text{fm}$
4. Black → $\tau_0 = \tau_q = 1\text{fm}$
   - Fits low-$p_{\perp}$ data well
   - Divergent is disfavored by $R_{AA}$ data
   - Delaying $\tau_q$ hardly changes $v_2$
   - Early FS does not fit data as well
   - $v_2$ predictions approach data when $\tau_0 = \tau_q = 1\text{fm}$ (No early free steaming)

$\text{Pb + Pb } \sqrt{s} = 5.02\text{ TeV}$
Generalized DREENA-A


• Further optimization of DREENA-A to incorporate event-by-event fluctuating temperature profiles
• Three different event-by-event initializations
  ○ Full = MC Glauber, $\tau_0 = 1 fm$, No FS
  ○ Dashed = IP Glasma, $\tau_0 = 0.4 fm$
  ○ Dotdashed = TRENTo, $\tau_0 = 1.16 fm$, 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
\( \eta/s \) of QCD matter


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

Can high-$p_{\perp}$ observables constrain $\eta/s$?


$R_{AA}$, 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-equilibrium 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 initial stage, Can not differentiate among the three $\eta/s$ parametrizations considered
Thank you
Quantitative explanation of DREENA-B results


• \( R_{AA} \approx \frac{R_{AA}^{in} + R_{AA}^{out}}{2} \), \( v_2 \approx \frac{1}{2} \frac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}} \)

1. **Blue** = Linear/FS
2. **Orange** = Constant/FS
3. **Green** = Divergent/FS

• Proportionality factors

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

\( \gamma_i \approx \gamma_i^{in} \approx \gamma_i^{out} \) for all \( i \) \( \implies \) \( v_2 \) same for all cases

\( \gamma \) different for different \( i \) \( \implies \) \( R_{AA} \) sensitive to pre-equilibrium stage
D. Zigic, I. Salom, J. Auvinen, P. Huovinen and M. Djordjevic, Front. in Phys. 10 (2022) 957019

\[ \text{Au + Au } \sqrt{s} = 200 \text{ GeV} \]
Early evolution from DREENA-A


Full- D meson, Dashed - B meson

\[ \text{Pb+Pb} \sqrt{s} = 5.02 \text{ TeV} \]
Study of $\eta/s$ using Generalized DREENA-A

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

Study of $\eta/s$ using Generalized DREENA-A


- $\text{Pb} + \text{Pb} \sqrt{s} = 5.02$ TeV
- Full = LHHQ; DotDashed = Nature, Dashed = Constant
- Inset: Dotdashed = Nature, Dashed = LHHQ