DREENA: A State-of-the-Art Tomography Framework for Unveiling the Properties of Quark-Gluon Plasma

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DREENA framework

- **Dynamical Radiative and Elastic Energy loss Approach**

- fully optimized numerical procedure capable of generating high $p_\perp$ predictions

- includes:
  - parton production
  - multi gluon-fluctuations
  - path-length fluctuations
  - fragmentation functions

- keeping all elements of the state-of-the art energy loss formalism, while introducing more complex temperature evolutions:
  - **DREENA-C: constant temperature medium**
  - **DREENA-B: Bjorken expansion**
  - **DREENA-A: smooth (2+1)D temperature evolution**
  - **ebe-DREENA: event-by-event fluctuating hydro background**
C = constant temperature

- Charged hadrons, \( \text{Pb} + \text{Pb} \), \( \sqrt{s_{NN}} = 5.02 \text{TeV} \)


for charged hadrons, qualitatively good agreement, but overestimation of \( v_2 \) data

only average temperature as QGP property
• heavy flavour, \( Pb + Pb, \sqrt{s_{NN}} = 5.02\,\text{TeV} \)

solid agreement w/ data, large error bars

non-zero \( v_2 \) for B mesons

only average temperature as QGP property

• const T approximation is rough, however it can be used to determine path-length dependence of energy loss model

• 5.02TeV Pb+Pb and 5.44TeV Xe+Xe - main property differentiating two systems is their size

• $R_{AA}$ ratio seem a natural choice:

\[ \frac{\Delta E}{E} \sim T^a L^b \Rightarrow \frac{R_{XeXe}}{R_{PbPb}} \approx 1 - \xi T^a L^b Pb \left( 1 - \left( \frac{A_{Xe}}{A_{Pb}} \right)^{b/3} \right) \]

1 – $R_{AA}$ ratio instead - path-length sensitive suppression ratio:

$$R_{L}^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \frac{\xi T^{a} L_{Xe}^{b}}{\xi T^{a} L_{Pb}^{b}} \approx \left( \frac{A_{Xe}}{A_{Pb}} \right)^{b/3}$$

The path length dependence can be extracted in a simple way, and there is only a weak centrality dependence

what about smaller systems?

- $R_{L}^{AB}$ is almost independent on centrality for 30-60% region
- for all systems, $R_{L}^{AB}$ shows same behaviour
- reliably recovers collisional and radiative energy loss path-length dependence

B = 1D Bjorken evolution

- Charged hadrons, \( Pb + Pb, \sqrt{s_{NN}} = 5.02\, TeV \)


very good joint agreement with both \( R_{AA} \) and \( v_2 \) data

only average temperature and thermalization time as QGP properties
• heavy flavour, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02$ TeV

solid agreement w/ data

non-zero $v_2$ for B mesons

only average temperature and $\tau_0$ as QGP properties

• previous results: interaction turned off for $\tau < \tau_0 = 0.6\,fm$
• investigate different T dependencies for $\tau (\leq \tau_0)$:

$R_{AA}$ is notably affected by IS

$v_2$ is practically not affected by IS

DREENA-B

- fitting temperature evolution to $R_{AA}$:

$T_0 \to T_L$ in $L_{in}$

$T_{in} \to T_{out}$

modified $T$-profile cases differ not only at IS, but represent different evolutions altogether

$R_{AA}$ curves overlap is verified

$v_2$ is very sensitive to different evolutions

A = adaptive


- includes any, arbitrary, medium evolution as an input
- preserve all dynamical energy loss model properties
- generate a comprehensive set of light and heavy flavor suppression predictions
- needs to be an efficient (timewise) numerical procedure
Are high-$p_{\perp}$ observables indeed sensitive to different $T$ evolutions?

All three evolutions agree with low-$p_{\perp}$ data. Can high pt-data provide further constraint?
Qualitative differences

- Largest anisotropy for Glauber ($\tau_0 = 1\, fm$) – expected differences in high-$p_{\perp} v_2$
- EKRT shows larger temperature - smaller $R_{AA}$ expected

DREENA-A

• ’EKRT’ initial conditions indeed lead to the smallest $R_{AA}$
• anisotropy translates to $v_2$ differences (’Glauber’ largest, $T_{\text{ResTo}}$ lowest)
• DREENA-A can differentiate between different T profiles
• heavy flavour even more sensitive to different T profiles
• additional (independent) constraint to low-$p_{\perp}$ data

DREENA-A OUTLOOK

- DREENA-A is a fully optimized numerical implementation of the dynamical energy loss
- can include arbitrary smooth temperature profiles
- no additional free parameters
- limitations: higher harmonics

event-by-event DREENA


- generalization of DREENA-A
- high-$p_\perp$ energy loss on fluctuating hydro background
- different initial conditions and hydro models
- can produce high-$p_\perp$ higher harmonics
- 1st question: averaging over events
• **cummulants:** $v_n\{2\}, v_n\{4\}$  

• **event plane:** $v_n\{EP\}$  

• **scalar product:** $v_n\{SP\}$  

• **scalar product - ATLAS:** $v_n\{SP_{ATLAS}\}$  

• **scalar product - CMS:** $v_n\{SP_{CMS}\}$  

![Graphs showing dependencies](#)

all methods, other than $v_n\{4\}$ agree with each other  
no need for rapidity correlations!

• charged hadrons, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02\,\text{TeV}$

we can distinguish between different models with high-$p_T$ energy loss

- heavy flavour, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02 TeV$

we can distinguish between different models with high-$p_T$ energy loss on heavy flavour as well - even more sensitive

DREENA-A is a fully optimized numerical implementation of the dynamical energy loss formalism.

- can include arbitrary temperature profiles, both smooth and event-by-event fluctuating.
- no additional fitting parameters within energy loss.
- high-\( p_\perp \) \( R_{AA} \), \( \nu_2 \), and higher harmonics show qualitative and quantitative sensitivity to details of T profile differences.
- applicable to different types of flavor, collision systems, and energies.
- OUTLOOK: an efficient QGP tomography tool for constraining the medium properties by both high- and low-\( p_\perp \) data.
QGP tomography

Bulk QGP properties are traditionally explored by low-$p_\perp$ observables that describe the collective motion of 99.9% of QCD matter.

However, some important bulk QGP properties are known to be difficult to constrain by low-$p_\perp$ observables and corresponding theory/simulations.

We advocate high-$p_\perp$ QGP tomography, where low- and high-$p_\perp$ physics jointly constrain bulk QGP parameters.

Rare high energy probes are, on the other hand, almost exclusively used to understand high-$p_\perp$ parton - medium interactions.

While high-$p_\perp$ physics had a decisive role in QGP discovery, it has been rarely used to understand bulk QGP properties.
QGP tomography

- high energy particles lose energy
- energy loss sensitive to QGP properties
- predict the energy loss of high $p_\perp$ probes
- use high $p_\perp$ probes to infer QGP properties:
  - early evolution
    talk by Magdalena Djordjevic, Wednesday 10:15
  - QGP anisotropy
    talk by Stefan Stojku, Tuesday 10:00
  - $\eta/s$ parameterization
    talk by Bithika Karmakar, Wednesday 14:50

- DREENA-A on github:
  https://github.com/DusanZigic/DREENA-A
Thank you for your attention!
DREENA-C, Pb + Pb, $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $h^\pm$
DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, $D$
DREENA-C, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02$ TeV, $B$
DREENA-B, \( Pb + Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV}, h^\pm \)
DREENA-B, \( Pb + Pb, \sqrt{s_{NN}} = 5.02\,\text{TeV}, D \)
DREENA-B, \( Pb + Pb, \sqrt{s_{NN}} = 5.02\, TeV, \, B \)
DREENA-B vs DREENA-C, \( Pb + Pb, \sqrt{s_{NN}} = 5.02 \, TeV, \ h^\pm \)
DREENA-B, $Pb + Pb$, $\sqrt{s_{NN}} = 5.02\ TeV$, $\mu$

**ATLAS Preliminary**

- charm muon
- bottom muon

**DREENA-B**

- $D \rightarrow \mu$
- $B \rightarrow \mu$

**Results**

- Preliminary
- ATLAS CONF-2019-053

- $v_2$ vs. $p_T$ [GeV]

- 0-10% and 40-60% centrality

- 5.02 TeV $Pb+Pb$

- 0.3 - 1.9 nb$^{-1}$, $|\eta| < 2$

- ATLAS

- DREENA-B

- Charm and bottom muon

- Considering energy loss inside medium can reproduce the magnitude of $v_2$ both for charm and bottom muon.

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**References**

- ATLAS-CONF-2019-053
DREENA-B, $Xe + Xe$, $\sqrt{s_{NN}} = 5.44\ TeV$, $h^\pm$
Backup slides

DREENA-A limits
ebe averaging methods:

\[ Q_n = \frac{1}{M} \sum_{j=1}^{M} e^{in\phi_j} \equiv |v_n| e^{in\psi_n} \]

\[ R_{AA}(p_\perp) = \frac{1}{2\pi} \int_{0}^{2\pi} R_{AA}(p_\perp, \phi) \, d\phi \]

\[ q_n^{\text{hard}} = \frac{1}{2\pi} \int_{0}^{2\pi} e^{in\phi} \frac{R_{AA}(p_\perp, \phi) \, d\phi}{R_{AA}(p_\perp)} \]

\[ v_n^{\text{hard}} = \frac{1}{2\pi} \int_{0}^{2\pi} \cos[n(\phi - \psi_n^{\text{hard}}(p_\perp))] \frac{R_{AA}(p_\perp, \phi) \, d\phi}{R_{AA}(p_\perp)} \]

\[ \psi_n^{\text{hard}}(p_\perp) = \frac{1}{n} \arctan \left( \frac{\int_{0}^{2\pi} \sin(n\phi) R_{AA}(p_\perp, \phi) \, d\phi}{\int_{0}^{2\pi} \cos(n\phi) R_{AA}(p_\perp, \phi) \, d\phi} \right) \]
ebe averaging methods:

\[ \nu_n^{\text{hard}} \{\text{SP}\} = \frac{\langle \text{Re} (q_n^{\text{hard}} (Q_n)^*) \rangle_{ev}}{\sqrt{\langle Q_n (Q_n)^* \rangle_{ev}}} = \frac{\langle |\nu_n^{\text{hard}}| |\nu_n| \cos[n(\psi_n^{\text{hard}} (p_\perp) - \psi_n)] \rangle_{ev}}{\sqrt{\langle |\nu_n|^2 \rangle_{ev}}} \]

\[ \nu_n \{\text{EP}\} = \langle \langle \cos[n(\phi^{\text{hard}} - \psi_n)] \rangle \rangle_{ev} = \langle \nu_n^{\text{hard}} \cos[n(\psi_n^{\text{hard}} - \psi_n)] \rangle_{ev} \]

\[ \nu_n \{\text{SP ATLAS}\} = \frac{\text{Re} \langle e^{in\phi} (Q_n^{-1})^* \rangle_{ev}}{\sqrt{\langle Q_n^- (Q_n^+)^* \rangle_{ev}}} \]

\[ \nu_n \{\text{SP CMS}\} = \frac{\text{Re} \langle Q_n Q^*_n A \rangle_{ev}}{\sqrt{\langle Q_n A Q^*_n B \rangle_{ev} \langle Q_n A Q^*_n C \rangle_{ev} \langle Q_n B Q^*_n \rangle_{ev}}} \]
ebe averaging methods:

- low-$p_{\perp}$

$$
\tilde{Q}_n = \sum_{j=1}^{M} e^{i n \phi_j}
$$

$$
v_n\{2\} = \sqrt{c_n\{2\}}, \quad c_n\{2\} = \langle\langle 2 \rangle\rangle_{\text{ev}}, \quad \langle 2 \rangle = \frac{|\tilde{Q}_n|^2 - M}{W_2}, \quad W_2 = M(M - 1)
$$

$$
v_n\{4\} = \sqrt[4]{-c_n\{4\}}, \quad c_n\{4\} = \langle\langle 4 \rangle\rangle_{\text{ev}} - 2\langle\langle 2 \rangle\rangle_{\text{ev}}^2
$$

$$
\langle 4 \rangle = \frac{|\tilde{Q}_n|^4 + |\tilde{Q}_{2n}|^2 - 2\text{Re}\,\tilde{Q}_{2n}\tilde{Q}_n^*\tilde{Q}_n^*|}{W_4} - 2\frac{2(M - 2)|\tilde{Q}_n|^2 - M(M - 3)}{W_4}
$$

$$
W_4 = M(M - 1)(M - 2)(M - 3)
$$
ebe averaging methods:

- high-$p_\perp$

\[
q_n = \int_0^{2\pi} e^{in\phi} \frac{dN}{dp_\perp d\phi} d\phi, \quad m_q = \int_0^{2\pi} \frac{dN}{dp_\perp d\phi} d\phi
\]

\[
W'_2 = m_q M, \quad W'_4 = m_q M(M - 1)(M - 2)
\]

\[
\langle 2' \rangle = \frac{q_n \tilde{Q}_n^*}{W'_2}, \quad \langle 4' \rangle = \frac{q_n \tilde{Q}_n \tilde{Q}_n^* \tilde{Q}_n^* - q_n \tilde{Q}_n \tilde{Q}_{2n}^* - 2Mq_n \tilde{Q}_n^* + 2q_n \tilde{Q}_n^*}{W'_4}
\]

\[
d_n\{2\} = \langle \langle 2' \rangle \rangle_{ev}, \quad d_n\{4\} = \langle \langle 4' \rangle \rangle_{ev} - 2\langle \langle 2' \rangle \rangle_{ev} \langle \langle 2 \rangle \rangle_{ev}
\]

\[
\nu'_n\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}, \quad \nu'_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}.
\]
energy loss:

\[
\frac{dE_{\text{col}}}{d\tau} = \frac{2C_R}{\pi v^2} \alpha_S(E T) \alpha_S(\mu_E^2(T)) \times 
\int_0^\infty n_{eq}(|\vec{k}|, T) d|\vec{k}| \left( \int_0^{|\vec{k}|/(1+v)} d|\vec{q}| \int_{-v|\vec{q}|}^v \omega d\omega + \int_{|\vec{k}|/(1+v)}^{|\vec{q}|_{\text{max}}} d|\vec{q}| \int_{|\vec{q}|-2|\vec{k}|}^v \omega d\omega \right) \times 
\left( |\Delta_L(q, T)|^2 \frac{(2|\vec{k}| + \omega)^2 - |\vec{q}|^2}{2} + |\Delta_T(q, T)|^2 \frac{(|\vec{q}|^2 - \omega^2)(2|\vec{k}| + \omega)^2 + |\vec{q}|^2}{4|\vec{q}|^4} \right) 
\]

\[
d^2N_{\text{rad}} \frac{d^2N_{\text{rad}}}{dxd\tau} = \int \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{2C_RC_2(G')T}{x} \frac{\mu_E(T)^2 - \mu_M(T)^2}{(q^2 + \mu_M(T)^2)(q^2 + \mu_E(T)^2)} \alpha_S(E T) \alpha_S\left(\frac{k^2 + \chi(T)}{x}\right) \times 
\left( \frac{k+q}{(k+q)^2 + \chi(T)} \left( 1 - \cos \left( \frac{(k+q)^2 + \chi(T)}{xE^+} \tau \right) \right) \left( \frac{k+q}{(k+q)^2 + \chi(T)} - \frac{k}{k^2 + \chi(T)} \right) \right)
\]