MATTER+LBT (JETSCAPE) based predictions for sPHENIX jet measurements

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(On behalf of JETSCAPE collaboration)
Jet evolution in quark-gluon plasma

JETSCAPE framework overview
- Multi-stage jet energy loss (Ex: MATTER+LBT)
- Coherence effect and reduction of jet-quenching strength
- Jet-medium response through recoils

Jet and leading hadron suppression at RHIC and LHC

Predictions for inclusive jets, groomed jet observables, photon-triggered jet at $\sqrt{s_{NN}} = 200$ GeV
Jet transport coefficients in hot/cold nuclear medium

- **Factorized approach to jet evolution**

\[
\frac{d\mathcal{N}}{dyd\mu^2} = \frac{\alpha_s}{2\pi} \frac{P_{qg}(y)}{\mu^2} \left[ 1 + \int_{\xi_0^+}^{\xi^+ + \tau^+} d\xi^+ K(\xi^+, \xi_0^+, y, q^+, \mu^2) \right];
\]

\[
K(\xi^+, \xi_0^+, y, q^+, \mu^2) = \frac{1}{y(1-y)\mu^2(1+\chi)^2} \left\{ 2 - 2 \cos \left( \frac{\xi^+ - \xi_0^+}{\tau^+} \right) \right\} \times \left\{ C_{qg} \hat{q} + C_{qg} \hat{e} + C_{\bar{q}g} \hat{e}_2 \right\}
\]

- **Transport coefficient \(\hat{q}\):**

Average transverse momentum squared per unit length

\[
\hat{q}(\vec{r}, t) = \frac{\langle \vec{k}_{\perp}^2 \rangle}{L} \propto \langle M | F_+^+(y^-, y_\perp)F_+^+(0) | M \rangle
\]

- **Transport coefficient \(\hat{e}\):**

\[
\hat{e}(\vec{r}, t) = \frac{\langle k_z \rangle}{L} \propto \langle M | \partial^- A^+(y^-, y_\perp)A^+(0) | M \rangle
\]

- **Transport coefficient \(\hat{e}_2\):**

\[
\hat{e}_2(\vec{r}, t) = \frac{\langle k_z^2 \rangle}{L} \propto \langle M | F_+^-(y^-, y_\perp)F_+^-(0) | M \rangle
\]

Higher-twist formalism: (collinear expansion)
Complementary studies between RHIC and LHC plasma

- **Transport coefficient \( \hat{q} \):**
  Average transverse momentum squared per unit length
  \[
  \hat{q}(\vec{r}, t) = \frac{\langle k^2 \rangle}{L} \propto \langle M | F^+(y^-, y_\perp)F^+ (0) | M \rangle
  \]

- Based on fit to single hadron
  \( R_{AA} \) at RHIC and LHC

- \( \hat{q}/T^3 \) is higher at RHIC collision energy compared to LHC energy

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Jet evolution

High E, High Q phase:
(Radiation dominant)

High E, Low Q phase:
(Scattering dominant)

Low E, Low Q phase:
(Thermal partons)

Multi-scale dynamics of jets in evolving plasma

1. How to extract short-distance structure of QGP in terms of PDF?
2. Extract jet energy loss transport coefficient for transverse broadening and longitudinal broadening \( \hat{q}, \hat{e}, \hat{e}_2 \) etc?
3. Typical scale for parton energy loss to switch from radiation dominant to scattering dominant phase
4. Mechanism of Jet-medium response
JETSCAPE instrument: a unified framework for heavy-ion collisions

- Modular, extensible and task-based event generator
- Framework is modular to “multi-stage”, “energy-loss” models
- Statistical package to perform Bayesian analysis

See talk by Raymond (Fri 9AM)

JETSCAPE 3.0 is available: github.com/JETSCAPE

Diagram by: Y. Tachibana

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AA collisions within JETSCAPE framework

A possible choice of models to generate AA collisions

JETSCAPE AA (arXiv:2204.01163)

- TRENTO (2+1)D Nucleus-Nucleus collision
- PYTHIA8 Hard Scattering
- PYTHIA8 based string fragmentation (Color randomized)
- Store Full Event Record into Disk
- MATTER+LBT
- Event-by-event VISHNU (2+1)D (No jet deposition into medium)
- Cooper-Frye Sampling
- Free-Streaming

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Jet evolution in high virtuality and low virtuality phase

MATTER: In-medium DGLAP evolution equation

In limit: $< k_T^2 > \sim \hat{q} \tau^- < < p_T^2 \sim Q^2$

Formation time: $\tau^- \sim q^-/Q^2$

\[
\frac{\partial D(z, Q^2, \xi_i^-)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi} \int_1^y \frac{dy}{z} \left[ P_+(y) D \left( \frac{z}{y}, Q^2, \xi_i^- \right) \right. +
\left. \text{Vacuum term} \right.
\]

\[
\left. + \left( \frac{P(y)}{y(1-y)} \right) D \left( \frac{z}{y}, Q^2, \xi_i^- + \tau^- \right) \times \int_{\xi_i^-}^{\xi_i^+ + \tau^-} d\xi^- \frac{\hat{q}(\xi^-)}{Q^2} \left\{ 2 - 2\cos \left( \frac{\xi^- - \xi_i^-}{\tau^-} \right) \right\} \right]
\]

Medium term

Repeating single emission single scattering kernel

Virtuality ordered emission approximation

LBT: Based on linear Boltzmann transport equation

Evolution of phase-space distribution

\[
p_i \cdot \partial f_i(x_i, p_i) = E_i(\mathcal{R}_{el} + \mathcal{R}_{inel})
\]

Elastic scattering: LO $2 \leftrightarrow 2$ process

Inelastic scattering: Single gluon emission rate using Higher Twist (depends on $\hat{q}$)

Multiple scattering and single emission
Inclusive jet cross section

Jet shape

Jet Mass

Optimized value of parameters:
- Lambda QCD: $\Lambda_{\text{QCD}} = 200\text{MeV}$
- Initial virtuality (off-shellness) of the parton after hard scattering: $Q_{\text{in}} = \frac{p_T}{2}$

Charged hadron yield

- ATLAS [PRD 83, 052003 (2011)]
- CMS [PRD 87, no.11, 112002 (2013)]
- PHENIX [PRD 76, 051106 (2007)]
- JETSCAPE 1.0 (Colored Had.)
- JETSCAPE 1.0 (Colorless Had.)
- PYTHIA 8.230

Charged hadron yield for $p_T > 60\text{GeV}$, $p_T > 30\text{GeV}$, $|y_{\text{had}}| < 0.5$:
- ATLAS (PRD 83, 022003) (2011)
- JETSCAPE 1.0 (Colored Had.)
- JETSCAPE 1.0 (Colorless Had.)
- PYTHIA 8.230

Charged hadron yield for $|\eta| < 1.0$:
- ATLAS (PRD 83, 022003) (2011)
- JETSCAPE 1.0 (Colored Had.)
- JETSCAPE 1.0 (Colorless Had.)
- PYTHIA 8.230

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Soft sector calibration

Central  Semi-peripheral  peripheral

TRENTO+ Free-streaming + VISHNU+UrQMD Bayesian calibration
[Nature Physics vol15, 1113–1117 (2019)]
Scale-resolution dependence of jet-medium interaction

Coherence effects
Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, PLB707, 156-159 (2012)
J. Casalderrey-Solana, E. Iancu, JHEP08, 015 (2011)

- Scale evolution of QGP constituent distribution
  Kumar, Majumder, Shen, PRC101, 034908 (2020)

- Less interaction for large-$Q^2$ partons
  → Implemented in MATTER

Effective jet-quenching strength  $\rightarrow \hat{q}_{HTL} \cdot f(Q^2)$

$$\hat{q}_{HTL} = C_a \frac{42\zeta(3)}{\pi} \alpha_s^{\text{run}} \alpha_s^{\text{fix}} T^3 \ln \left[ \frac{2ET}{6\pi T^2 \alpha_s^{\text{fix}}} \right]$$

$$f(Q^2) = \frac{1 + c_1 \ln^2(Q^2_{sw}) + c_2 \ln^4(Q^2_{sw})}{1 + c_1 \ln^2(Q^2) + c_2 \ln^4(Q^2)}$$
Jets and Leading hadron suppression at $\sqrt{s_{NN}} = 5.02$ TeV

Effective jet-quenching strength $\Rightarrow \hat{q}_{HTL} \cdot f(Q^2)$

Strong coherence effects are observed for high-$p_T$ hadrons

ATLAS [PLB 790, 108 (2019)]
CMS [JHEP 05, 284 (2021)], $|\eta_{jet}|<2.0$
MATTER+LBT (w/ coherence effect)
MATTER+LBT (w/o coherence effect)

PbPb (0-10%), $\sqrt{s_{NN}} = 5.02$ TeV
anti-$k_T$, $R = 0.4$, $|y_{jet}| < 2.8$

Running Coupling $Q_{sw}=2$ GeV

CMS [JHEP 1704, 039 (2017)]
MATTER+LBT (w/ coherence effect)
MATTER+LBT (w/o coherence effect)

$Q_{sw} = 2$ GeV
Running Coupling
Collision energy dependence of Jet and Hadron $R_{AA}$

- **Pb+Pb at 2.76 TeV**

  - Jet $R_{AA}$
  - Particle $R_{AA}$

  ![Diagrams showing jet and particle $R_{AA}$ for Pb+Pb collisions at 2.76 TeV](Image)

  - No further retuning of parameters done

- **Au+Au at 200 GeV**

  ![Diagrams showing jet and particle $R_{AA}$ for Au+Au collisions at 200 GeV](Image)

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Centrality dependence of Jet and hadron $R_{AA}$

Jet $R_{AA}$ (20-30%)

Jet $R_{AA}$ (40-50%)

Hadron $R_{AA}$ (30-50%)

Quenching in hadronic phase is not included. Jet energy loss turns off when $T < 160$ MeV. No further retuning of parameters done.
Jet Fragmentation function

\[ D(p_T) = \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{dN_{\text{trk}}}{dp_T^{ch}} \]

Shows sensitivity to coherence effects

\[ p_T^{\text{jet}} < 158 \text{ GeV} \]  
\[ p_T^{\text{jet}} < 200 \text{ GeV} \]  
\[ p_T^{\text{jet}} < 251 \text{ GeV} \]
Inclusion of heavy-quarks in MATTER and LBT

Allows to explore
(1) parton flavor energy loss dependence
(2) the mass and momentum dependence

Flavor dependence is comparable with Experimental measurements

No further retuning of parameters done.
Predictions at $\sqrt{s_{NN}} = 200\text{GeV}, 0 - 10\%$

(MATTER+LBT@JETSCAPE)
Jet R-dependence of Inclusive jets and charged jets

No strong jet cone size dependence is observed
Jet fragmentation function

\[ D(p_T) = \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{dN_{\text{trk}}}{dp_T^{ch}} \]

\( D(p_T) \) for higher jet \( p_T^{\text{jet}} \) is strongly modified

\[ \sqrt{s_{NN}} = 200 \text{GeV}, \text{AuAu} : \text{0-10\% anti-}k_T, R = 0.4, p_T^{\text{trk}} > 1 \text{GeV} \]

\[ \text{10GeV} < p_T^{\text{jet}} < 30\text{GeV} \]
\[ \text{30GeV} < p_T^{\text{jet}} < 50\text{GeV} \]
Jet grooming and soft drop condition

Take a jet clustered with e.g. anti-kt algorithm

Re-cluster it using Cambridge-Aachen (C/A) algorithm

Traverse the clustering tree backwards

If a branch point satisfies the soft drop condition, stop

Otherwise remove the softer branch and continue down the harder branch

By construction the condition fails for wide-angle soft radiation

\[
\frac{\min(p_{T,j_1}, p_{T,j_2})}{p_{T,j_1} + p_{T,j_2}} > z_{cut} \left( \frac{\Delta R(j_1, j_2)}{R} \right)^\beta; \quad z_{cut} = 0.2, \quad \beta = 0
\]
Prediction for Jet splitting function ($z_g$)

- Momentum fraction in the hardest splitting of jet ($z_g$)

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

$z_{cut} = 0.2, \beta = 0$

The nuclear modification are not significant within the statistical uncertainty

The trend is very similar to ALICE measurement at @5.02TeV
Groomed jet $\theta_g = \frac{r_g}{R}$

$r_g =$ Opening angle between two prongs

$z_{cut} = 0.2, \beta = 0$

The nuclear modification are not significant within the statistical uncertainty

The trend is different compared LHC collision energies
Prediction for groomed jet mass ($m_g$)

**Groomed jet $m_g$**

**Without any smearing**

$z_{\text{cut}} = 0.2, \beta = 0$

Nuclear modifications are not significant in low groomed jet mass region

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**$\sqrt{s_{NN}} = 200$ GeV, AuAu: 0–10% anti-$k_T$, Charged jets**

$p_T^{\text{jet}} < 30$ GeV

$R = 0.2$, $|\eta_{ch,jet}| < 0.7$

$R = 0.4$, $|\eta_{ch,jet}| < 0.5$

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**$\sqrt{s_{NN}} = 200$ GeV, AuAu: 0–10% anti-$k_T$, Charged jets**

$p_T^{\text{jet}} > 30$ GeV

$R = 0.2$, $|\eta_{ch,jet}| < 0.7$

$R = 0.4$, $|\eta_{ch,jet}| < 0.5$
Prediction for $\gamma$-triggered jet results

No isolation cut
Photons produced from hard scattering

AuAu (0-15%) 200 GeV
anti-$k_t$, $R=0.5$
$|\eta_{jet}| < 0.5$

$\gamma - jet$

$11 < E_T^\gamma < 15 GeV$
$15 < E_T^\gamma < 20 GeV$

$\gamma - jet$

$11 < E_T^\gamma < 15 GeV$
$15 < E_T^\gamma < 20 GeV$
Summary

- JETSCAPE—a unified framework for the heavy-ion community—successfully demonstrate that a unified approach effectively captures the physics of multi-scale jet quenching in QCD plasma.

- Simultaneous description of inclusive jets, high-pT hadrons, jet substructure observables
  - pp19 tune give results consistent to the experimental data and PYTHIA
  - Jet $R_{AA}$ and charged hadron $R_{AA}$
    - Constrain Jet $R_{AA}$ and charged-hadron $R_{AA}$ at 0-10% (5.02TeV)
    - Fit parameters provide a consistent description at two collision energies and different centrality

- Predictions at $\sqrt{s_{NN}} = 200$ GeV most central collisions
  - Jet cone size R dependence of Jet $R_{AA}$ and charged jet $R_{AA}$
  - $p_T$ dependence of Jet fragmentation function
  - Groomed jet observables
  - Photon-triggered jets
Sensitivity of inclusive jets from recoils

\[
\frac{dp^\mu}{d\eta d\phi} \bigg|_{\text{jet shower}} - \frac{dp^\mu}{d\eta d\phi} \bigg|_{\text{picked-up}} = \frac{dp^\mu}{d\eta d\phi} \bigg|_{\text{signal}}
\]

[Graphs and diagrams showing event rates and parton interactions]