Event-by-event jet suppression, anisotropy and hard-soft tomography

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Motivation

QGP Probes:

**hard probes**: large momentum or short distance. 
**jets**, high-$p_T$ hadrons, heavy quark,…

jet quenching: jet energy loss when a jet propagates in the medium
Jet $R_{AA}$ are almost the same and go flat for 2.76 TeV and 5.02 TeV. Why?

Can we describe both jet $R_{AA}$ and $v_2$ in a unified framework?
The LBT model

\[ p_a \cdot \partial f_a = \int \sum_{bcd} \prod_{i=b,c,d} \frac{d^3 p_i}{2E_i(2\pi)^3} (f_c f_d - f_a f_b) |M_{ab\rightarrow cd}|^2 \]

\[ \times \frac{\gamma_b}{2} S_2(\hat{s}, \hat{t}, \hat{u})(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + \text{inelastic} \]

\[ S_2(\hat{s}, \hat{t}, \hat{u}) = \theta(\hat{s} \geq 2\mu_D^2)\theta(-\hat{s} + \mu_D^2 \leq -\hat{t} \leq -\mu_D^2), \quad \mu_D^2 = \frac{3}{2} g^2 T^2 \]

Re-scattering for shower partons, medium recoils and radiated gluons.
Include back reaction for E–M conservation, subtracted.
Linear approximation, and valid for \( \delta f << f \)

LO perturbative QCD

NLO twist–4
The inclusive jet in pp collisions

$p_T$ distribution of $pp$ collision within PYTHIA 8

The spectrum at 5.02 TeV is higher and much flatter than at 2.76 TeV, which originates from PDFs.
Fix strong coupling constant

\[
\chi^2 = \frac{(Theo. - Exp.)^2}{\delta Exp.}^2
\]

neg.: “negative particles”, back reaction.

UES: underlying event subtraction.

Inclusion of neg. or UES decreases jet energy

Effective \( \alpha_S \): collisional, radiation, Debye screening mass,

\[
\Gamma_g \approx \sum_{b=g,q_i,\overline{q}_i} \Gamma_{gb \rightarrow gb} \approx 42 C_A \zeta(3) \frac{\alpha_s^2 T^3}{\pi \mu_D^2}
\]

\( \alpha_S = 0.15 \)

will be larger in a multistage evolution

see: Chanwook Park, HP 2018
**Inclusive jet suppression**

\[ R_{AA} \] slightly increases with jet \( p_T \) for 2.76 TeV and 5.02 TeV.
Understanding jet $R_{AA}$

Jet energy loss at 5.02 TeV is indeed **larger** than at 2.76 TeV.
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$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d\sigma_{AA}^{jet}}{d\sigma_{pp}^{jet}}$$
Jet energy loss at 5.02 TeV is indeed larger than at 2.76 TeV. But Jet $R_{AA}$ at 5.02 TeV is higher than at 2.76 TeV at large $p_T$ range. Because $p_T$ spectrum at 5.02 TeV is much flatter than at 2.76 TeV.
If $\langle \Delta p_T \rangle / p_T$ is small,

$$R_{AA}(p_T) \approx \frac{d\sigma_{p+p}^{\text{jet}}(p_T + \langle \Delta p_T \rangle)}{d\sigma_{p+p}^{\text{jet}}(p_T)}$$
Effects of medium response and radial expansion

- medium recoil effect up to 15%
- back reaction not negligible
- larger cone size and radial expansion enlarges the effects above.

2.76 TeV
Cone size dependence of $R_{AA}$

$R_{AA}$ vs. $p_T$ (GeV)

- Larger $R$: flatter initial spectrum + smaller energy loss
  -> less suppression

quantitatively relates to medium response
$R_{AA}$ at RHIC energy

Slightly decreases with jet energy because of steeper initial spectrum, although the energy loss is smaller that at LHC energy.
Inclusive jet anisotropy

\[ v_{n}^{jet} = \frac{\langle v_{n}^{soft} \cos(n[\phi^{jet} - \Psi_{n}]) \rangle}{\sqrt{\langle (v_{n}^{soft})^2 \rangle}} \]

\[ \Delta \phi_{2} = \phi^{jet} - \Psi_{2} \]

\[ \begin{align*}
    v_{2}^{jet} &= 0.01499 \pm 0.00009 \\
    &\quad \text{anti-}k_{t}, R = 0.2 \\
    &\quad \text{PbPb } |s_{NN}| = 2.76 \text{ TeV} \\
    v_{2}^{jet} &= 0.0216 \pm 0.00009 \\
    &\quad 5 - 10 \% \\
    v_{2}^{jet} &= 0.0276 \pm 0.00009 \\
    &\quad 10 - 20 \% \\
    v_{2}^{jet} &= 0.0300 \pm 0.00008 \\
    &\quad 20 - 30 \% \\
    v_{2}^{jet} &= 0.0243 \pm 0.00008 \\
    &\quad 30 - 40 \% \\
    v_{2}^{jet} &= 0.0223 \pm 0.00008 \\
    &\quad 40 - 50 \% \\
    v_{2}^{jet} &= 0.0208 \pm 0.00008 \\
    &\quad 50 - 60 \% \\
\end{align*} \]

jet $v_n$ closely follows the centrality dependence of soft $v_n$.

jet $v_3$ is small, but not zero.
Hard-soft correlation

Approximately linear correlation btw jet and bulk anisotropy
The inclusive jet suppression is determined by the initial pp spectrum and jet energy loss, on which medium response has a significant effect.

The LBT model can describe both jet suppression and anisotropy flow. Jet anisotropy correlates with medium anisotropy.

Future work:
Effects of smooth & e-by-e, ideal & viscous hydro on the jet suppression and anisotropy
Thanks!
Underlying Event Subtraction (UES)

UE: collisions of beam remnant, fluctuation of the background, non-perturbative effects. Subtraction is needed to exclude the soft particles.

Seed jet: $E_T > 3$ GeV for at least one parton, and $E_T^{\text{max}} / E_T^{\text{ave}} > 4$


$$E_T^{UES} = E_T^{\text{seedjet}} - A^{\text{seedjet}} \rho(1 + 2v_2 \cos[2(\phi_{\text{jet}} - \Psi_2)])$$

We only subtract the energy of seed jets, and count all the final jets!
The jet-medium transport coefficient is defined as:

\[ \hat{q} = \frac{\langle \Delta p_T^2 \rangle}{\lambda} \]

The figure shows the variation of \( \hat{q}/T^3 \) with temperature (T) for different models and collision energies. The models include MARTINI, HT-BW, HT-M, and McGill-AMY. The collision energies considered are Au+Au at RHIC and Pb+Pb at LHC.
Azimuthal Anisotropy $v_2$

\[
\frac{dN}{d\phi} = C \left( 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_n)] \right)
\]

elliptic flow: $n=2$

\[
v_2 = < \cos[2(\phi - \Psi_2)]>
\]

Coordinate space: initial asymmetry

\[
\epsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}
\]

Momentum space: final asymmetry

\[
v_2 = \frac{< p_y^2 - p_x^2 >}{< p_y^2 + p_x^2 >}
\]
Initial Geometry at 2.76 TeV

averaged over 200 3+1D event-by-event hydro profiles
Results: Inclusive jet suppression

fixed $\alpha_s = 0.15$

Suppression!!

w. neg (whole $p_T$ range); w. UES (low $p_T$ range)
$v_3$ vs $p_T$ for $R = 0.2$ and various centrality classes:

- 5-10% anti-$k_t$
- 10-20% LBT w. fluc.
- LBT w/o fluc.

PbPb at 5.02 TeV and 2.76 TeV.

Centrality classes:
- 20-30%
- 30-40%
- 40-50%
- 50-60%

$v_3$ vs $v_3$ for $100 < p_T < 120$ GeV and $10-20%$ centrality.
\( v_2 \) of soft particles from hydro profiles
anti-$k_t$, $\sqrt{s} = 5.02$ TeV, $|y| < 2.1$

PYTHIA p+p

$\sigma(R = 0.3) / \sigma(R = 0.4)$

$\sigma(R = 0.2) / \sigma(R = 0.4)$
anti-$k_t$ algorithm in FASTJET package is used to reconstruct jets

$$\sqrt{(\eta - \eta_J)^2 + (\phi - \phi_J)^2} < R$$


consider all the jets

modified FASTJET, subtract the “negative” particles

medium recoil re-scattering, back reaction (“negative particles”)
The inclusive jet shower partons from PYTHIA 8

Initial geometry from AMPT

Evolution with hydro profiles: collisional + radiation in QGP phase, free streaming in hadron phase

Final inclusive jet


Energy loss!!!
Inclusive jet anisotropy

\[ v_2 = \langle \cos(2[\phi_{jet} - \Psi_2]) \rangle \]

Multistage evolution, see: Chanwook Park, HP 2018
\[ v_{2}^{\text{jet}} = \frac{\langle \langle v_{2}^{\text{soft}} \cos(2[\phi^{\text{jet}} - \Psi_{2}]) \rangle \rangle}{\sqrt{\langle (v_{2}^{\text{soft}})^2 \rangle}} \]