Jet quenching in Z+jet in heavy-ion collisions

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Motivation

- **Z+jet**: Golden channel to study jet quenching.
  
  
  - High energy parton from hard scattering lose energy due to strong interactions.
  - Z boson will not participate in strong interactions directly.
  - Mean-free-path of Z boson is longer than the size of QGP.
  - No fragmentation contributions due to large mass ($M_Z = 91.18$ GeV).
  - Large fraction of quark jets ($> 70\%$).

- Important background to new physics, e.g. tops and Higgs.
Current status


Z+jet correlations in pp

- Z+jet azimuthal angle correlations
  

- NLO calculations suffer divergency at $\Delta \phi_{jZ} \sim \pi$. NLO

- LO+PS calculations underestimate at $\Delta \phi_{jZ} < 2$. LO+PS

- We adopt NLO+PS and Eloss to study Z+jet correlations.
Sherpa: Simulate of High-Energy Reactions of PArticals in the SM. Merging schemes are provided to calculate multijets.


- Low multiplicities: NLO matched to the parton shower.
- High multiplicities: LO merged on the parton shower.

Matching scheme can be simply formulated as:

\[
\langle O \rangle^{(NloPs)} = \int d\Phi_B \left[ B + \tilde{V} + I^S \right] (\Phi_B) \tilde{PS}_B(\mu^2_Q, O) \\
+ \int d\Phi_R \left[ R - D^S \right] (\Phi_R) \tilde{PS}_R(t_R, O)
\]

- B, \(\tilde{V}\) and R is born, virtual and real terms respectively.
- D (\(I^S = \int d\Phi_1 D^{(S)}\)) is the (Integrated) subtraction term.
- \(\tilde{PS}\): the parton shower branch.

Sherpa: Gauge boson(\(\gamma, Z, W\)) + jets, b(c) jets, tops, Higgs...
• Z+jet correlations in p+p collisions.
  – PDF: CETQ14nlo.

• NLO matched PS calculations show excellent agreement with experimental data in p+p collisions.
• Z+1jet dominate at $\Delta \phi_{jZ} \simeq \pi$, while Z+multijets dominate at $\Delta \phi_{jZ} < 2.2$ region.

CMS p+p smeared
CMS Pb+Pb 0-30%
Sherpa p+p $Z^0$+jets
Sherpa p+p $Z^0$+1jet
Sherpa p+p $Z^0$+(≥2)jets

$\sqrt{s}=5.02$ TeV $Z^0$+jet $p_T^Z>60$ GeV/c
anti-$k_T$ jet $R=0.3$
$p_T^{j}>30$ GeV/c
$|\eta_j|<1.6$

$\Delta \phi_{jZ}>\frac{7}{8}\pi$

CMS p+p
Sherpa NLO
NLO $Z^0$+(≥2)jets
Linear Boltzmann Transport (LBT) model

**Linear Boltzmann jet Transport**

- Elastic collision + Induced gluon radiation.
- **Follow the propagation of recoiled parton.**
- Back reaction of the Boltzmann transport.

\[
p_1 \cdot \partial f_a(p_1) = - \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times \frac{1}{2} \sum b_{(c,d)} \left[ f_a(p_1)f_b(p_2) - f_c(p_3)f_d(p_4) \right] |M_{ab\rightarrow cd}|^2 \\
\times S_2(s, t, u)(2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)
\]

Elastic Scattering—Complete set of 2-2 scattering precesses.


\[
\frac{dN_g}{dxdk_{\perp}^2 dt} = \frac{2\alpha_s C_A P(x) k^4}{\pi (k_{\perp}^2 + x^2 M^2)^4} \hat{q} \sin^2 \left( \frac{t - t_i}{2\tau_f} \right)
\]

LBT: \(\gamma\)-jet, single inclusive jets, \(\gamma\)-hadron, light/heavy flavor hadron.

T. Luo, S. Cao, Y. He and X. N. Wang, arXiv:1803.06785;
W. Chen, S. Cao, T. Luo, L. G. Pang and X. N. Wang, Phys. Lett. B 777, 86 (2018);
Framework

1. Jet production (Sherpa)
   - Jets location are decided by probability of binary collisions

2. Jet propagation (LBT+(3+1)D hydro)
   - UE subtraction

3. Jet reconstruction (Fastjet)
   - $R_{jZ}$, $\phi_{jZ}$, $x_{jZ}$, $\langle x_{jZ} \rangle$, $I_{AA}$...
• Fix the parameter $\alpha_s$ via the comparison with the $R_{jZ} = N_{jZ}/N_Z$.


$R_{jZ}$ is overall suppressed.
- Large fraction of jets lose energy and fall below 30 GeV threshold.
- $\alpha_s = 0.20$ is fixed to best describe experimental data in Pb+Pb collisions.

Multijets have small contributions to $R_{jZ}$, $p_T^{Z} > 80 \text{ GeV} : 15\%$.
Z+jet azimuthal angle correlations

- Suppression of azimuthal angle correlations $\Delta \phi_{jZ} = |\phi_{jet} - \phi_Z|$.


$\Delta \phi_{jZ}$ is moderately suppressed in Pb+Pb collisions, almost a constant.
- Z-jet angle correlations is modified by jet-medium interactions?
- Reduction of jet yields above 30 GeV threshold?
The modification of angle correlations due to multi-jets suppression

- **Z+1jet and Z+multijets contributions to** $\Delta \phi_{jZ} = |\phi_{jet} - \phi_{Z}|$.


$\Delta \phi_{jZ}$ is moderately suppressed in Pb+Pb collisions, almost a constant.
- The suppression of Z+1 jet angle correlations is mild.
- Z+Multi-jets angle correlations is considerably suppressed.

Suppression of multi-jets lead to the modification of Z+jet azimuthal angle correlations.
• Shift of momentum imbalance \( x_{jZ} = \frac{p_{T}^{jet}}{p_{T}^{Z}} \).


\( x_{jZ} \) is shifted to smaller value.
- Transverse momentum of Z boson is unattenuated.
- Jet transverse momentum is modified by medium.

Multi-jets have almost 50% contributions to \( x_{jZ} < 0.5 \) region.
Shift of momentum asymmetry $x_{jZ} = \frac{p_{T}^{jet}}{p_{T}^{Z}}$ in different $p_{T}^{Z}$ bins.
Mean value of momentum imbalance

- Reduction of mean value of momentum imbalance.


\[ \langle x_{jZ} \rangle \text{ is smaller in Pb+Pb.} \]

\[ p_T^Z > 60 \text{ GeV: } \langle x_{jZ} \rangle \text{ is lowered by } 15\%. \]

\[ \Delta \langle x_{jZ} \rangle = \langle x_{jZ} \rangle_{pp} - \langle x_{jZ} \rangle_{PbPb} \]

<table>
<thead>
<tr>
<th>( p_T^Z )</th>
<th>40-50</th>
<th>50-60</th>
<th>60-80</th>
<th>80-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>0.07 ± 0.106</td>
<td>0.12 ± 0.148</td>
<td>0.13 ± 0.158</td>
<td>0.06 ± 0.088</td>
</tr>
<tr>
<td>( \Delta \langle x_{jZ} \rangle )</td>
<td>0.074873</td>
<td>0.105597</td>
<td>0.127888</td>
<td>0.142805</td>
</tr>
</tbody>
</table>
Tagged jet $p_T^{jet}$ spectrums

- Shift of $p_T^{jet}$ spectrum in different $p_T^Z$ bins.

\[ I_{AA} = \frac{dN_{Pb+Pb}}{dp_T^{jet}} / \frac{dN_{p+p}}{dp_T^{jet}} \]

$p_T^{jet}$ spectrums are shifted to lower value.

The largest suppression is near $p_T^{jet} \sim p_T^Z$. 
W+jet have similarly behaviors as Z+jet.
Z+jet correlation in Pb+Pb at the LHC is studied by combining NLO+PS in Sherpa for initial Z+jet production and LBT for jet propagation in the expanding QGP from 3+1D hydrodynamics.

\[ R_{jZ} \] is smaller in Pb+Pb.

Large fraction of jets shift their final transverse momentum below \( p_T^{\text{jet}} \) threshold.

\[ \Delta \phi_{jZ} \] is moderately suppressed in Pb+Pb collisions.

Suppression of multijets lead to the modification of Z+jet azimuthal angle correlations.

\[ x_{jZ} \] is shifted to smaller value.

\[ \langle x_{jZ} \rangle \] is smaller in Pb+Pb.

NLO+PS LBT describe precisely Z+jet asymmetry.

W+jet correlations are calculated in our model.

- NLO calculations is divergency at $\Delta \phi_{jZ} \sim \pi \times$.
- LO+PS calculations underestimate at $\Delta \phi_{jZ} < 2.5 \times$. 

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Jet quenching in Z+jet in heavy-ion collisions
\[ \langle O \rangle^{(NLO)} = \int d\Phi_B \left[ B + \tilde{V} + I^S \right] (\Phi_B)O(\Phi_B) \]
\[ + \int d\Phi_R \left[ R(\Phi_R) - D^S(\Phi_B * \Phi_1) \right] O(\Phi_R) \]  

1. PDFS and FFS are emitted.
2. \( \Phi_B \) is Born(Virtual) phase-space, \( \Phi_R \) is real phase-space
3. \( B, \tilde{V} \) and \( R \) is born, virtual and real matrix element respectively
4. \( D \left( I^S = \int d\Phi_1 D^{(S)} \right) \) is the (Integrated)subtraction terms which has the same divergency as the real terms.
5. Both term are finite.

PS(Soft emissions)-Sudakov form factor
arXiv:1111.1220,0709.1027,0709.2881

\[ \mathcal{P}S_n(\mu_Q^2, O) = \Delta(t_c, \mu_Q^2)O(\phi_n) + \int_{t_c}^{\mu_Q^2} \Delta(t, \mu_Q^2) \kappa(\phi_1) \mathcal{P}S_{n+1}(t, O) dt d\phi_1 \]  

(2)

\[ \Delta(t_c, \mu_Q^2) = \exp \left\{ - \int_{t_c}^{\mu_Q^2} dt \int d\phi \kappa(\phi_1(t, \phi)) \right\} \]  

(3)

\[ \kappa_{ab}(z, t) \rightarrow \frac{\alpha_s(z, t)}{2\pi} P_{ab}(z) \]  

are evolution kernels, \( P_{ab}(z) \) are splitting functions.
Underlying Event Subtraction

Following the procedure in CMS experiment.

- UE subtraction has negligible effect on $R_{jZ}$
- UE subtraction has a little effect on $x_{jZ}$.