Parton energy loss effect on Z+jet production in high-energy nuclear collisions

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We give a report of medium modification of Z+jet correlations in Pb+Pb collisions at the Large Hadron Collider using Sherpa to generate initial Z+jet at next-leading-order matrix element matched parton shower, and the Linear Boltzmann Transport Model for jet propagation in the expanding quark-gluon-plasma. Our numerical calculations show excellent agreement with all available observables of Z+jet simultaneously in both proton + proton and Pb+Pb collisions. Our results can well explain the shift of momentum asymmetry $x_{jZ} = p_{Tj} / p_{TZ}$ as well as its mean values, the suppression of the jet yields per Z trigger $R_{jZ}$ and the modification of azimuthal angle correlation $\Delta \phi_{jZ}$. We also demonstrate that it is the energy loss effect on multi-jets from high-order corrections that leads to the suppression of the Z+jet correlation at small azimuthal angle difference $\Delta \phi_{jZ}$ and at small $x_{jZ}$. The jet shape reflecting transverse momentum distribution inside the jet is also calculated, which indicates that large fraction of jet energy is carried away from the jet axis in Pb+Pb collisions.

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1. introduction

Jet production in association with Z boson provides an ideal probe of the properties of the quark-gluon plasma (QGP) [1]. The outgoing partons interact strongly with the hot/dense medium and lose energy in the QGP [2], while Z boson will not participate in the strong-interactions directly, escaping the QGP unscathed. Besides, Z boson is free from fragmentation and decay due to its large mass ($M_Z = 91.18$ GeV). Therefore, the Z boson transverse momentum closely reflects the initial energy of the associated parton that fragments into the final-state jet.

$Z+\text{jet}$ correlations on transverse momentum asymmetry $x_{jZ} = p_{T,jet} / p_{T,Z}$ as well as its mean value $\langle x_{jZ} \rangle$, jet yields per Z trigger $R_{jZ} = N_{jZ} / N_Z$, and azimuthal correlation $\Delta \phi_{jZ} = |\phi_{jet} - \phi_{Z}|$ both in proton+proton (p+p) and lead+lead (Pb+Pb) collisions at 5.02 TeV have been measured by CMS experiment [3]. It is noted when computing $\Delta \phi_{jZ}$, the next-leading-order (NLO) calculations suffer divergence in the region $\Delta \phi_{jZ} \sim \pi$, because of soft/collinear radiation. Furthermore, even though leading-order (LO) matched parton shower (PS) calculations have already contained some high-order corrections from real and virtual contributions, it is short of additional hard radiation from high-order matrix element calculations, as a consequence of which, it underestimates the azimuthal angle correlation at small angle difference region [4, 5]. Motivated by this, we present in this talk a state-of-art calculations of $Z+\text{jet}$ [4], with p+p baseline computed at NLO+PS with Sherpa [6], and the Linear Boltzmann Transport (LBT) model [7] for jet propagation in heavy-ion collisions.

2. Model setup for $Z+\text{jet}$ in heavy-ion collisions

Initial reference $Z+\text{jet}$ events in p+p collisions is simulated at NLO matrix element perturbative calculations matched to the resummation of parton shower [8, 9] within a Monte Carlo event generator Sherpa [6] at $\sqrt{s_{NN}} = 5.02$ TeV. NLO +PS calculations of azimuthal angle correlation and momentum asymmetry for $Z+\text{jet}$ agree well with experiment data [3] in all kinetic ranges in p+p collisions [4]. EPPS16 modified npdfs is used to study cold nuclear matter effects, but no modifications is observed as in [10].

The Linear Boltzmann Transport (LBT) model is then used to simulate the propagation, energy attenuation of, and medium response induced by jet partons in the quark-gluon plasma [7]. LBT is based on a Boltzmann equation [7]:

$$p_a \cdot \partial_f f_a(p_a) = -\frac{1}{2} \int \sum_{i=b,c,d} \frac{d^3 p_i}{(2\pi)^3 2E_i} \times [f_a f_b - f_c f_d] |M_{ab\rightarrow cd}|^2 \times S_2(s,t,u)(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d)$$

where $f_i$ are phase-space distributions of partons, $S_2(s,t,u)$ is Lorentz-invariant regulation condition. Elastic scattering is introduced by the complete set of $2 \rightarrow 2$ matrix element $|M_{ab\rightarrow cd}|$, and the inelastic scattering is described by high-twist formalism for induced gluon radiation [11, 12, 13].

3. Numerical results

To compare with the experimental data, we select the Z boson and jets according to the kinematic cut adopted by CMS [3]. The information of the evolving bulk matter is provided by (3+1)D hydrodynamics [14]. The underlying event background energy is subtracted event-by-event for
Pb+Pb collisions following the procedure applied in CMS [15], while no subtraction is applied in p+p collisions.

We first fix the only parameter $\alpha_s$ that controls the strength of jet-medium interactions via the comparison with the CMS data of Z+jets [3]. When $\alpha_s$ is set to 0.2, our numerical results of average number of jet partners per Z boson $R_{jZ}$ in central Pb+Pb collisions show well agreement with CMS data as in Fig. 1 (left). $R_{jZ}$ is overall suppressed in Pb+Pb, because a large fraction of jets lose energy and then shift their final transverse momenta below the threshold $p_{T,jet} = 30$ GeV.

The imbalance in the transverse momentum of the associated jet relative to that of recoiled Z boson $x_{jZ} = p_{T,jet} / p_{T,Z}$ is presented in Fig. 1 (right). Compared to p+p collisions, there is a significant displacements of the peak value of $x_{jZ}$ towards a smaller value in Pb+Pb, due to jet energy loss in the medium while the transverse momentum of Z boson is unattenuated. Multi-jets processes are rather important when $x_{jZ} < 0.5$, where the multi-jets energy can hardly exceed half of the energy of Z boson in the phase space $\Delta \phi_{jZ} \geq \pi / 8$.

To quantify the relative shift between p+p and 0-30% central Pb+Pb collisions, the mean value of the momentum asymmetry $\langle x_{jZ} \rangle$ is calculated and shown in Fig. 2 (left). It is much smaller in Pb+Pb relative to p+p collisions. Fig. 2 (right) plots the nuclear modification factor $I_{AA} = (dN_{Pb+Pb} / dp_{T,jet}^Z) / (dN_{p+p}^Z / dp_{T,jet}^Z)$ of the leading jet tagged by Z boson. An enhancement is
Z+jet azimuthal angle correlation $\Delta \phi_{jZ} = |\phi_{jet} - \phi_Z|$ (left), and the contributions from Z plus only one jet (middle), and Z plus more than one jets (right) both in central Pb+Pb collisions and p+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

observed at $p_T^{jet} < p_T^Z$ region, and a suppression in $p_T^{jet} > p_T^Z$ region. We find $I_{AA}$ is quite sensitive to the kinematic cut due to the steep falling cross section in the kinematic cut window.

Z+jet azimuthal angle correlation $\Delta \phi_{jZ} = |\phi_{jet} - \phi_Z|$ in p+p and Pb+Pb are shown in Fig. 3 (left). It is moderately suppressed in Pb+Pb collisions. To illustrate the suppression mechanism, separated contributions from Z+1jet and Z associated with more than one jets in both p+p and Pb+Pb collisions are revealed in Fig. 3. We see Z + 1jet dominates in large angle region and there is no significant difference between p+p and Pb+Pb collisions. These processes mainly come from the LO ME and the azimuthal angle decorrelation from which is dominated by soft/collinear radiation. The transverse momentum broadening of jets due to jet-medium interaction is negligible at such high energy scale. The right panel of Fig. 3 illustrates that Z+ multi-jets processes are considerably suppressed in Pb+Pb collisions.

In addition to Z+jet correlations, we calculated the differential jet profile which describes the radial distribution of transverse momentum inside the jet cone [16]. The differential jet shape in Pb+Pb and p+p collisions are displayed in Fig. 4. The result is normalized to unity over $r < 0.3$. We see that, a large fraction of jet energy is carried in the core of the jet within $r < 0.1$. To quantify the modification, we present the ratio of the jet shape in Pb+Pb to that in pp collisions in Fig. 4 (right). We observe a deletion in the region $0.05 < r < 0.1$ and a enhancement at large radius $r > 0.1$. It indicates that the energy is redistributed in Pb+Pb collisions due to jet-medium interactions and large amount of jet energy is carried by particles far away from the jet axis.

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Figure 4: (Color online) Differential jet shape $\rho(r)$ of jets triggered by Z boson in 0-30% central Pb+Pb and p+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV as well as the ratio of jet shape in central Pb+Pb to that in p+p collisions.

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