Z\(^0\)+jet correlation with NLO-matched parton-shower and jet-medium interaction in high-energy nuclear collisions

Shan-Liang Zhang, Tan Luo, Xin-Nian Wang, and Ben-Wei Zhang

1 Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
2 Nuclear Science Division Mailstop 70R0319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

The impact of jet quenching on Z\(^0\)+jet tagged jets in relativistic heavy-ion collisions at the Large Hadron Collider (LHC) is investigated. We employ Sherpa Monte Carlo program that combines next-to-leading order matrix elements with matched resummation of parton shower to compute the initial Z\(^0\)+jet production. 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. With both higher-order corrections and matched soft/collinear radiation as well as a sophisticated treatment of parton energy loss and medium response in LBT, our numerical calculations can provide the best description so far of all available observables of Z\(^0\)+jet simultaneously in both p+p and Pb+Pb collisions, in particular, the shift of the distribution in transverse momentum asymmetry \(x_{2Z} = p_T^{jet}/p_T^Z\), the modification of azimuthal angle correlation in \(\Delta \phi_{2Z} = |\phi_{jet} - \phi_Z|\) and the overall suppression of average number of Z\(^0\)-tagged jets per boson \(R_{2Z}\) at \(\sqrt{s} = 5.02\) TeV as measured by the CMS experiment. We also show that higher-order corrections to Z\(^0\)+jet production play an indispensable role in understanding Z\(^0\)+jet azimuthal angle correlation at small and intermediate \(\Delta \phi_{2Z}\) and momentum imbalance at small \(x_{2Z}\). Jet quenching of the sub-leading jets is shown to lead to suppression of Z\(^0\)+jet correlation at small azimuthal angle difference \(\Delta \phi_{2Z}\) and at small \(x_{2Z}\).

Introduction — Jet quenching or suppression of energetic partons due to energy loss has long been proposed to probe properties of the quark-gluon plasma (QGP) in heavy-ion collisions (HIC) \[1\]–\[22\]. Gauge-boson-tagged jet production is regarded as a “golden channel” to study the jet quenching \[23\]–\[24\]. The boson will not participate in the strong-interactions directly and can be considered as the proxy of the initial energy of the parton before it propagates through the QGP medium and loses energy \[23\]–\[27\]. Though jet production associated with a direct photon in HIC has already been accessible at the Relativistic Heavy-Ion Collider (RHIC), the unprecedented energies available at the Large Hadron Collider (LHC) open a new window for Z\(^0\)-tagged jet production in HIC, where the Z\(^0\) boson not only escapes the QGP medium unattenuated, but is also free from fragmentation processes due to its very large mass.

Recently CMS Collaboration has reported the first measurement of Z\(^0\)-tagged jet production in both p+p and Pb+Pb collisions at \(\sqrt{s} = 5.02\) TeV at the LHC \[28\]. Though the CMS data on Z\(^0\)+jet in Pb+Pb collisions can be qualitatively described by several theoretical models, such as GLV \[29\]–\[31\], Hybrid model \[32\] and JEWEL \[33\], it is still a challenge to quantitatively describe all the available experimental observables of Z\(^0\)+jet simultaneously and their p+p baseline by simulations based on a leading order (LO) matrix element (ME) matched parton shower (PS) event generator. The Z\(^0\)+jet azimuthal angle correlation \(\Delta \phi_{2Z} = |\phi_{jet} - \phi_Z|\) and the distributions in average number of Z\(^0\)-tagged jets \(R_{2Z} = N_{2Z}/N_Z\) are in particular very sensitive to QCD higher-order corrections \[28\]–\[34\]. It is therefore of a great advantage to use the next-to-leading order (NLO) pQCD computations of hard scattering complemented with resummation of soft/collinear parton shower and the state of the art simulations of parton propagation in QGP medium in the study of Z\(^0\)-jet correlation in high-energy HIC.

In this Letter, we report the first numerical study with such a theoretical model: the Monte Carlo program Sherpa \[35\], which combines the NLO pQCD with resummation of a matched PS, is used for the initial Z\(^0\)-tagged jet production and provides an excellent description of Z\(^0\)+jet production in elementary p+p collisions; the parton propagation in QGP medium is simulated by the Linear Boltzmann Transport (LBT) model \[36\]–\[38\] with bulk medium evolution provided by the Berkeley-Wuhan CLVisc 3+1D hydrodynamics \[38\]–\[39\]. We refer this model as NLO+PS LBT model. We will confront our results with available data for all four observables of Z\(^0\)+jet in both p+p and Pb+Pb collisions: azimuthal correlation \(\Delta \phi_{2Z}\), \(p_T\) asymmetry \(x_{2Z}\) distribution and its mean value \(\langle x_{2Z} \rangle\), as well as the average number of associated jets per Z\(^0\) boson \(R_{2Z}\). We will focus in particular on effects of multiple jets associated with Z\(^0\) and their suppression on the azimuthal correlation and \(p_T\) asymmetry in Pb+Pb collisions.

Sherpa — Sherpa is a complete Monte Carlo event generator that simulates all high-energy reactions between particles in the Standard Model. Sherpa employs several emerging approaches \[40\]–\[42\] which provide NLO ME matched to the resummation of the Collins-Soper-Sterman \[43\] dipole PS \[44\]–\[45\] to calculate low jet multiplicities and LO matched parton shower to simulate high jet multiplicities. The matching scheme can be formu-
and significantly underestimates the distribution by a factor of \( \Delta \phi_Z \sim 0.01 \) as compared to the default Pythia 6.4 result and CMS data \([28]\). In our simulations, the Sherpa p+p baseline result shows an excellent agreement with experimental data, while Pythia 6.4 slightly overshoots the azimuthal distribution at large \( \Delta \phi_Z \sim \pi \) and significantly underestimates the distribution by a factor of \( \sim 2 \) at small \( \Delta \phi_Z \). Contributions from \( Z^0 +1 \) jet and \( Z^0 + (\geq 2) \) jets to the azimuthal correlation in p+p collisions from Sherpa are also shown in Fig. 1. Contributions from \( Z^0 + (\geq 2) \) jets from NLO processes are much broader than that of \( Z^0 +1 \) jet and dominate the distribution at small \( \Delta \phi_Z \) region. \( Z^0 +1 \) jet processes contribute mostly in large \( \Delta \phi_Z \) region where soft/collinear radiation from PS dominates.

To obtain the above numerical results and in the rest of this Letter, we adopt the kinematic cuts by CMS experiment \([28]\) to select \( Z^0 \)-tagged jets in both p+p and Pb+Pb collisions. For \( Z^0 \rightarrow e^+e^- \) decay, electrons are required to have \( p_T^e > 20 \text{ GeV}, |\eta|^e < 2.5 \) and are excluded in the kinematic region \( 1.44 < |\eta|^e < 2.47 \). For \( Z^0 \rightarrow \mu^+\mu^- \) decay, kinematic cuts for muons are \( p_T^\mu > 10 \text{ GeV}, |\eta|^\mu < 2.4 \). \( Z^0 \) bosons are reconstructed by opposite-charge electron or muon pairs, with reconstructed mass \( 70 < M_{\mu\mu} < 110 \text{ GeV} \), and transverse momentum \( p_T^{\mu\mu} > 40 \text{ GeV} \). Jets are constructed by FASTJET \([52]\) from final partons with the anti-k\( T \) algorithm \([53]\) and jet cone size \( R = \sqrt{\langle \Delta \phi^2 \rangle + \langle \Delta \eta^2 \rangle} = 0.3 \). We have neglected the effect of hadronization. All the jets tagged by a boson should pass thresholds of \( p_T^{\mu\mu} > 30 \text{ GeV}, |\eta|^\mu < 1.6 \), and are rejected in a cone of \( R < 0.4 \) from a lepton to reduce jet energy contamination.

**LBT Model** — In this study, propagation of fast partons in hot QGP is simulated within the LBT model \([28, 36, 37]\) that includes both elastic and inelastic processes of parton scattering for both jet shower and thermal recoil partons in the QGP. The elastic scattering is described by the linear Boltzmann equation \([26, 36, 37]\),

\[
\frac{dN_g}{dx dk_T^2 dt} = \frac{6 \alpha_s C_A P(x) \hat{q}}{\pi k_T^4} \left( \frac{k_T^2}{k_T^2 + x M^2} \right)^2 \sin^2 \left( \frac{t - t_i}{2 \tau_f} \right),
\]

where \( x \) and \( k_T \) denote the energy fraction and transverse momentum of the radiated gluon, \( P(x) \) the splitting function, \( \hat{q} \) jet transport coefficient, and \( \tau_f = 2E_x(1-x)/(k_T^2 + x M^2) \) the formation time. The information on local temperature and fluid velocity of the dynamically evolving bulk medium is provided by 3+1D CLVisc hydrodynamical model \([38, 39]\) with initial conditions from the AMPT model \([38]\) averaged over 200 events for each centrality. Parameters in the CLVisc are chosen to reproduce experimental data on bulk hadron spectra. The only parameter in LBT model that controls the strength of parton interaction is strong coupling \( \alpha_s \) which is chosen as \( \alpha_s = 0.20 \) in this study for the best fit of the experimental data. LBT model has been used to describe
Results and Discussions — Using Sherpa NLO+PS event generator and LBT model, we can study medium modification of $Z^0$+jet correlation in Pb+Pb at the LHC. Effects of cold nuclear matter are found to be rather small in the kinematics we are interested in [61]. All partons, jet shower, radiated and medium recoil partons, are used for jet reconstruction with FASTJET. In the following calculations of $Z^0$+jet correlation in Pb+Pb, the underlying events background subtraction has been carried out following the procedure adopted by CMS experiment [62]. No subtraction is applied in p+p results. The energy and azimuthal angle resolution of the detector are simulated by a Gaussian smearing with centrality-dependent parametrization as given by CMS experiment [28].

The distribution in average number of tagged jets per $Z^0$ boson $R_{Z^0} = N_{Z^0}/N_Z$ is shown in Fig. 2. We note that the jet selection threshold $p_T^{jet} > 30$ GeV imposes a strong constraint on the phase space of $Z^0$-tagged jets. Significant suppression for $R_{Z^0}$ is observed in Pb+Pb collisions relative to that in p+p collisions. This is a direct consequence of jet energy loss that shifts the final transverse momentum of a larger fraction of $Z^0$-tagged jets below the $p_T^Z = 30$ GeV threshold. The difference between $R_{Z^0}$ in p+p and Pb+Pb changes slowly with $p_T^{jet}$. We note that jets with high recoil $p_T$ associated with a $Z^0$ boson are dominated by quark jets. The contribution of $Z^0$+ multi-jets to $R_{Z^0}$ distribution is small in both p+p and Pb+Pb collisions because of the kinematical constraints of finding multiple high-energy jets whose energy should not exceed half of that of $Z^0$ boson.

Fig. 3 shows our model calculations of the distribution in the transverse momentum asymmetry $x_{Z^0} = p_T^{jet}/p_T^Z$ for $Z^0$-tagged jet at $\sqrt{s} = 5.02$ TeV in p+p and Pb+Pb collisions as compared with CMS data. A cut $\Delta \phi_{Z^0} > 7\pi/8$ has been imposed to select the most back-to-back $Z^0$+jet pairs. Compared to p+p collisions, the asymmetry distribution in $x_{Z^0}$ is broadened and shifted toward a smaller value of $x_{Z^0}$ in $0-30\%$ central Pb+Pb collisions due to jet energy loss in the QGP medium while the transverse momentum of $Z^0$ boson remains the same. The distribution is dominated by $Z^0$+1 jet process at large $x_{Z^0}$, but has almost 50% contributions from higher parton multiplicities.
order corrections at small $x_{jZ} < 0.5$. For completeness we also show our model results on the mean value of momentum imbalance $\langle \Delta x_{jZ} \rangle$ at different $p_T^{jZ}$ bins in Fig. 4.

We show in Fig. 5 our calculations of $Z^0$+jet correlation in the azimuthal angle difference $\Delta \phi_{jZ}$ between $Z^0$ boson and jets in p+p and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV as compared to CMS data. Note that distributions are normalized by the number of $Z^0$ events and a kinematic cut $p_T^{jZ} > 30$ GeV is imposed for the tagged jets. We observe a moderate suppression of the correlation at small $\Delta \phi_{jZ}$ (large angle relative to the opposite direction of the $Z^0$ boson) in Pb+Pb relative to that in p+p collisions. This suppression is mainly caused by suppression of transverse momentum below the $p_T^{jZ} = 30$ GeV threshold due to energy loss.

Summary — We have carried out a systematic study of $Z^0$+jet correlation in Pb+Pb collisions at the LHC by combining NLO matrix elements calculations with matched parton shower in Sharpa for initial $Z^0$+jet production and Linear Boltzmann Transport model for jet propagation in the expanding QGP from 3+1D hydro-dynamics. Results from our model calculations achieve the best agreement so far with the experimental data on all four observables of $Z^0$+jet production in both p+p and Pb-Pb collisions at LHC: azimuthal correlation in $\Delta \phi_{jZ}$, distribution of transverse momentum imbalance $x_{jZ}$, the $p_T^{jZ}$ dependence of the mean value $\langle x_{jZ} \rangle$ and the average number of tagged jets per $Z^0$ boson $R_{jZ}$. We demonstrate the importance of both higher-order corrections and resummed soft/collinear radiation for a satisfactory description of the available experimental data on $Z^0$+jet correlations in p+p and Pb+Pb collisions. Energy loss of both leading and sub-leading jets have to be included consistently to understand the medium modifications of $Z^0$+jet correlations, in particular in azimuthal angle $\Delta \phi_{jZ}$ and momentum imbalance $x_{jZ}$.

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