Study of Jet Quenching with $Z +$ jet Correlations in Pb-Pb and $pp$ Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The production of jets in association with $Z$ bosons, reconstructed via the $\mu^+\mu^-$ and $e^+e^-$ decay channels, is studied in $pp$ and, for the first time, in Pb-Pb collisions. Both data samples were collected by the CMS experiment at the LHC, at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The Pb-Pb collisions were analyzed in the 0%-30% centrality range. The back-to-back azimuthal alignment was studied in both $pp$ and Pb-Pb collisions for $Z$ bosons with transverse momentum $p_T^Z > 60$ GeV/$c$ and a recoiling jet with $p_T^{\text{jet}} > 30$ GeV/$c$. The $p_T$ imbalance $x_{jZ} = p_T^{\text{jet}} / p_T^Z$, as well as the average number of jet partners per $Z$, $R_{jZ}$, was studied in intervals of $p_T^Z$. The $R_{jZ}$ is found to be smaller in Pb-Pb than in $pp$ collisions, which suggests that in Pb-Pb collisions a larger fraction of partons associated with the $Z$ bosons fall below the 30 GeV/$c$ $p_T^{\text{jet}}$ threshold because they lose energy.

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The correlated production of vector bosons and jets in hard parton scatterings occurring in ultrarelativistic heavy ion collisions provides an ideal probe of the quark-gluon plasma (QGP), a deconfined state of quarks and gluons [1,2]. Final-state jets are created by the fragmentation of outgoing partons that interact strongly with the produced medium and lose energy [3–11], a phenomenon ("jet quenching") observed at RHIC [12,13] and the LHC [14–18]. The transverse momentum ($p_T$) of the jet is highly correlated (through momentum conservation) with that of the associated $Z$ boson, which is not affected by the medium [19–21] and reflects the initial energy of the parton. The lost energy can be related, via theoretical models, to the thermodynamical and transport properties of the medium [9–11,22–24]. At LHC energies, $Z +$ jet production is dominated by quark jets for $p_T^{\text{jet}} \simeq 30$ GeV/$c$ [21], the primary subprocess being $q(\bar{q}) + g \rightarrow Z + q(\bar{q})$ [19], hence providing information on the parton flavor (quark or gluon) and kinematics, and allowing detailed studies of the energy loss with a well-defined production process. The $Z$-jet correlations are particularly well suited to perform tomographic studies of the QGP, given the minimal contributions from background channels [20,25–27]. Correlations of jets with isolated photons are accessible at higher rates and carry similar information on parton energy loss [25–29] but suffer from an irreducible background of photons from jet fragmentation [17,30] as well as larger uncertainties arising from the experimental selection of photon candidates.

This Letter describes the identification of $Z +$ jet pairs in $pp$ and Pb-Pb collisions, and the first characterization of parton energy loss through angular and $p_T$ correlations between the jet and the $Z$, reconstructed in dimuon or dielectron decays. The back-to-back azimuthal alignment of the $Z$ and jets is studied through the difference $\Delta \phi_{jZ} = |\phi_{\text{jet}} - \phi_{Z}|$. The $Z +$ jet momentum imbalance is studied using the $x_{jZ} = p_T^{\text{jet}} / p_T^Z$ ratio and the $p_T^{\text{jet}}$ dependence of its mean value, $\langle x_{jZ} \rangle$. The average number of jet partners per $Z$ boson, $R_{jZ}$, is also reported. The analysis exploits Pb-Pb and $pp$ data samples collected by CMS at a nucleon-nucleon center-of-mass energy of 5.02 TeV, corresponding to integrated luminosities of 404 $\mu$b$^{-1}$ and 27.4 pb$^{-1}$, respectively.

The central feature of CMS is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Forward hadron calorimeters extend the pseudorapidity ($\eta$) coverage and are used for Pb-Pb event selection. Muons are measured in gas-ionization detectors located outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [31].

The event samples are selected on-line with dedicated lepton triggers and cleaned off-line to remove noncollision events, such as beam-gas interactions or cosmic-ray muons [32]. In addition, events are required to have at least one reconstructed primary interaction vertex. The $Z \rightarrow e^+e^-$

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events are triggered if two ECAL clusters [33] have transverse energy greater than 15 GeV and $|\eta| < 2.5$, while the $Z \to \mu^+\mu^-$ triggers require one muon of $p_T > 15$ GeV/$c$ or two muons of $p_T > 10$ GeV/$c$.

For the analysis of Pb-Pb collisions, the “centrality” (overlap of the two colliding nuclei) is determined by the sum of the total energy deposited in both forward hadron calorimeters [15]. The results refer to the 30% most central collisions, to focus on the region of highest physics interest. After all the other analysis selections, 78% of the $Z$ boson events fall in this centrality range.

The PYTHIA 8.212 [34] Monte Carlo (MC) event generator, with tune CUETSM1 [35], is used to simulate $Z +$ jet signal events, with $p_T^Z > 30$ GeV/$c$ and rapidity $|y^Z| < 2.5$. A sample with a $Z$ boson without any kinematic selection was produced using a next-to-leading order (NLO) generator, MADGRAPH5_AMC@NLO[36]. In the Pb-Pb case, a PYTHIA+HYDJET sample is created by embedding PYTHIA signal events in heavy ion events generated with HYDJET 1.9 [37] and tune HydroQJets. The generated events are propagated through the CMS apparatus using the GEANT4 [38] package. No unfolding is performed for the results presented. The recipe for applying a smearing of the jet $p_T$ resolution is provided in Supplemental Material [39].

Electrons are identified as ECAL superclusters [40] matched in position and energy to tracks reconstructed in the tracker. They must have $p_T > 20$ GeV/$c$, above the trigger threshold, and each supercluster must be within the acceptance of the tracker, $|\eta| < 2.5$. Electron candidates in the transition region between the barrel and end cap subdetectors ($1.44 < |\eta| < 1.57$) are excluded. In pp collisions, the electrons are selected via standard identification criteria [40]. A narrow transverse shape of showers in the ECAL and a low HCAL over ECAL energy ratio are required to reject misidentified electrons. Additional tracking information is used to distinguish electrons from charged hadrons [40]. For Pb-Pb collisions, the identification criteria have been optimized to compensate for the higher background levels in the calorimeters. With these selections, the $pp$ and Pb-Pb electron reconstruction purities (efficiencies) are identical within 1% (10%).

Muons are selected by requiring segments in at least two muon detector planes and a good-quality fit when connecting them to tracker segments. This suppresses hadronic punchthrough and muons from in-flight decays of hadrons. A minimum number of hits in the pixel and strip layers is required, and the reconstructed muon tracks must point to the primary vertex in the transverse and longitudinal directions [41]. The same selections are applied for both $pp$ and Pb-Pb data. In order to suppress the background continuum under the $Z$ peak, mostly originating from uncorrelated simultaneous decays of heavy flavor mesons, the muons are required to have $p_T > 10$ GeV/$c$. In addition, the muon tracks must fall in the acceptance of the muon detectors, $|\eta^\mu| < 2.4$.

Jet reconstruction uses the anti-$k_T$ algorithm implemented in FASTJET [42], following the procedure of Ref. [16]. A small distance parameter, $R = 0.3$, minimizes the effects of fluctuations in the underlying event (UE), dominantly formed by soft processes in heavy ion collisions. The UE energy subtraction [43] is performed for Pb-Pb as described in Refs. [15–17]. Closure tests, done on MC samples without medium-induced jet energy loss, show no over subtraction of the UE in the Pb-Pb sample. No subtraction is applied in the $pp$ sample, where the UE contribution is negligible. The jet energy is calibrated applying $p_T^\text{jet}$- and $p_T^\text{jet}$-dependent correction factors derived with the PYTHIA signal sample [44]. Then, dijet and photon + jet balance techniques [45] are used to correct for the residual detector response differences between measured and simulated samples. In addition, a centrality-dependent correction obtained from simulation studies is applied to remove the residual effects from the UE in Pb-Pb collisions. The UE from Pb-Pb data and MC samples are compared using the $p_T$ density [44,46,47], defined as the median of the ratio of the jet transverse momentum to the jet area, for all jets in the event. Given the coarse centrality range used in the analysis, the difference between the measured and simulated Pb-Pb events has a negligible effect on jet reconstruction.

Except in Fig. 4, the resolutions of the measured jet energy and azimuthal angle in the $pp$ samples are smeared to match those of the Pb-Pb sample. The jet energy resolution can be quantified using the Gaussian standard deviation $\sigma$ of the $p_T^{\text{gen}}/p_T^{\text{reco}}$ ratio, where $p_T^{\text{reco}}$ is the UE-subtracted, detector-level jet $p_T$ and $p_T^{\text{gen}}$ is the generator-level jet $p_T$ without any contributions from the UE in Pb-Pb. It is determined using PYTHIA+HYDJET (for Pb-Pb) and PYTHIA (for $pp$) samples and parametrized as a function of $p_T^{\text{gen}}$ using the expression $\sigma(p_T^{\text{gen}}) = C \oplus (S/\sqrt{p_T^{\text{gen}}}) \oplus (N/p_T^{\text{gen}})$, where $\oplus$ stands for the sum in quadrature and the parameters $C$, $S$, and $N$ are determined from simulation studies. The same parametrization is used to determine the jet azimuthal angle resolution, quantified by the Gaussian standard deviation $\sigma_\phi$ of the $|\phi^{\text{reco}} - \phi^{\text{gen}}|$ difference.

The $Z$ candidates are defined as opposite-charge electron or muon pairs, with a reconstructed invariant mass ($M^{\ell\ell}$) in the interval 70–110 GeV/$c^2$ and $p_T > 40$ GeV/$c$. The invariant mass distributions of all the dileptons used in the Pb-Pb analysis are shown in Fig. 1. Each $Z$ candidate is paired with all jets in the same event that pass the $p_T > 30$ GeV/$c$ and $|\eta^\ell| < 1.6$ selection. Simulation studies show that the jet selection efficiency and the energy resolution are well understood for this kinematic range. Additional energy corrections are applied to the jet $p_T$, to account for residual performance degradations observed in simulation studies. Jets reconstructed within $\Delta R < 0.4$ from a lepton are rejected, to eliminate jet energy contamination by leptons from Z decays.
A systematic uncertainty is evaluated by shifting the interactions not related to the primary multiplicity heavy ion UE or from additional initial hard contribution from jets not produced in the same parton-

The background jet contributions are estimated constructed in subsets of 40 minimum bias events. All events from the raw jet spectrum, eliminating coincidental pairs and ensuring that the final correlations of the deviations between electron $p_T$ and $h_T$ are sizable (negligible) in the dielectron channel. Comparing the measured and simulated reconstruction are sizable (negligible) in the dielectron reconstruction.

For the analysis of Pb-Pb collisions, the background contribution from jets not produced in the same parton-parton interaction as the $Z$ boson needs to be considered. This contribution arises from misidentified jets reconstructed from regional energy fluctuations in the high-multiplicity heavy ion UE or from additional initial hard interactions not related to the primary $Z +$ jet production. The background jet contributions are estimated constructing a mixed-event jet background by correlating the $Z$ boson from each candidate $Z +$ jet event with jets reconstructed in subsets of 40 minimum bias events. All events must pass the off-line event selection and have the same centrality and interaction vertex as the $Z +$ jet candidate event. The resulting background jet spectrum is subtracted from the raw jet spectrum, eliminating coincidental $Z +$ jet pairs and ensuring that the final $Z +$ jet observables reflect the correlations of $Z$ bosons and associated jets.

The systematic uncertainties related to $Z$ boson reconstruction are sizable (negligible) in the dielectron (dimuon) channel. Comparing the measured and simulated dielectron invariant mass peaks shows that the average deviation between electron $p_T^{\text{rec}}$ and $p_T^{\text{gen}}$ is 0.5%. A systematic uncertainty is evaluated by shifting the electron $p_T$ by $\pm 0.5\%$, resulting in changes of $\langle x_{jZ} \rangle$ and $R_{jZ}$ for Pb-Pb $(pp)$ by 0.5% (0.3%) and 3% (0.8%), respectively. The simulated $Z$ dielectrons reconstructed in central Pb-Pb collisions have a $p_T$ resolution of 5% for $p_T^Z > 40$ GeV/c. In Pb-Pb simulated events, $p_T^Z$ is smeared by 5%, resulting in variations of $\langle x_{jZ} \rangle$ and $R_{jZ}$ by 1.5% and 0.8%, respectively. When combining the two lepton results, a weighting is applied to the electron sample, to compensate for the different centrality dependencies of the $Z$ boson reconstruction in the electron and muon channels. The difference between the corrected and uncorrected $\langle x_{jZ} \rangle$ and $R_{jZ}$ values, 0.3% and 5.8%, respectively, is taken as systematic uncertainty.

Simulation studies show that the jet energy scale $\langle p_T^{\text{rec}} / p_T^{\text{gen}} \rangle$ can deviate from unity by up to 2%. Additional deviations can arise from differences between the fragmentation pattern of jets in measured and simulated events. To evaluate the corresponding systematic uncertainty, the jet energy scale is shifted for Pb-Pb $(pp)$ upward by 6% (2%) and downward by 4% (2%). The higher upward variation reflects the relatively high energy scale of quark jets, which contribute more to the $Z +$ jet events than the gluon jets. The relative change in $\langle x_{jZ} \rangle$ and $R_{jZ}$ for Pb-Pb $(pp)$ is 5.4% (2.4%) and 4.6% (2.4%), respectively. Finally, differences between the measured and simulated samples suggest that the jet energy resolution is up to 15% worse in the data. The related systematic uncertainty is evaluated smearing $p_T^{\text{jet}}$ by 15% in the Pb-Pb MC calculations. The $pp$ data are smeared to simulate the poor resolution due to the UE fluctuations in Pb-Pb data. The smearing is performed with the relative resolution $\sigma_{\text{rel}} = \sqrt{\sigma_{\text{rel}}^2 - \sigma_{pp}^2}$, where $\sigma_{\text{rel}}$ and $\sigma_{pp}$ correspond to the parameterizations described above. A systematic uncertainty is assigned by varying the relative resolution by $\pm 15\%$. The Pb-Pb $(pp)$ relative change in $\langle x_{jZ} \rangle$ and $R_{jZ}$ due to jet energy resolution is 2.5% and 3.7% (0.5% and 0.7%), respectively. The jet angular resolution correction implies an additional uncertainty on the $pp$ sample, of 0.1% for $\langle x_{jZ} \rangle$ and 0.2% for $R_{jZ}$.

The total systematic uncertainties for Pb-Pb $(pp)$ amount to 6.2% (2.5%) and 8.9% (2.6%) for the $\langle x_{jZ} \rangle$ and $R_{jZ}$ results, respectively, of which 5.7% and 8.0% are uncorrelated between the $pp$ and Pb-Pb results; the uncorrelated uncertainties do not reflect possible differences between $p_T^{\text{rec}}$ and $p_T^{\text{gen}}$.

Figure 2, top, shows the $\Delta \phi_{jZ}$ distribution of $Z +$ jet pairs that pass all the selections; only $Z +$ jet pairs with $p_T^Z > 60$ GeV/c were included to reduce the fraction of events where energy loss effects cause the jet partner to fall below the $p_T^{\text{jet}} > 30$ GeV/c threshold. There are 678 and 232 events that pass the $p_T^Z > 60$ GeV/c selection in $pp$ and in the 30% most central Pb-Pb collisions, respectively. To study if the angular distribution of jets with respect to
Z Pb-Pb events, respectively. Figure 2, bottom, shows the 0.40, even if systematic uncertainties are excluded. distribution and an overall decrease in the number of distributions for Pb-Pb and  

cant difference is seen between the distributions; the probability to obtain a KS value larger than that observed in the data, the distributions are studied using their means,  

The relative shift between the  and Pb-Pb  distributions is studied using their means, , shown in Fig. 3, top, as a function of  . The minimum  of the partner jet imposes a lower limit on the value of . As  increases relative to the  cutoff, the kinematic phase space for lower  opens up, resulting in a shift towards lower  for higher  . For all ranges,  is found to be lower in Pb-Pb collisions than in  collisions, as expected from energy loss models of partons traversing the medium. Also  is expected to increase as a function of  , as the 30 GeV/c threshold restricts the phase space of jets counted for a given  selection. Figure 3, bottom, shows the dependence of  on  . The  values are significantly different. 

The systematic uncertainties and their correlations were included in these calculations. The combined  value  is 0.0064 when including Z + jet pairs with  > 40 GeV/c, indicating that the two  distributions are significantly different. 

For the  and  results, shown in Figs. 2 and 3, only events with  > 7π/8 are used, to select mostly back-to-back  + jet pairs; it keeps 63% and 73% of the  and Pb-Pb events, respectively. Figure 2, bottom, shows the  distributions for Pb-Pb and  collisions. Jet energy loss is expected to manifest itself both as a shift in the  distribution and an overall decrease in the number of  + jet pairs as jets fall below the  threshold. Therefore, the KS test was applied to the  distribution, and a separate overall normalization  test was applied to the total number of  + jet pairs per  leading to  values of  = 0.07 and  = 0.01, respectively. The systematic uncertainties are included in these calculations. The combined  value  is 1−[ln(1/p)] = 0.0064 when including Z + jet pairs with  > 40 GeV/c, indicating that the two  distributions are significantly different.

FIG. 2. Distributions of the azimuthal angle difference  between the Z boson and the jet (top) and of the transverse momentum ratio  between the jet and the Z boson with  > 7π/8 (bottom). The distributions are normalized by the number of Z events, . Vertical lines (bands) indicate statistical uncertainties.

FIG. 3. The mean value of the  distribution (top) and the average number of jet partners per Z boson  (bottom), as a function of . Vertical lines (bands) indicate statistical (systematic) uncertainties.
found to be smaller in Pb-Pb than in $pp$. As their difference is approximately constant as a function of $p_T^Z$, a relatively smaller fraction of jets is lost in Pb-Pb collisions for larger initial (before traversing the medium) parton energies.

Figure 4 compares the $x_{jZ}$ results to several theoretical calculations, using the same kinematic selections as the data. The Pb-Pb results are compared to three models that incorporate the phenomenon of jet quenching: Jet Evolution With Energy Loss (JEWEL) [26], Hybrid [25], and GLV [27]. The JEWEL error bars represent statistical uncertainties, while the widths of the hybrid bands represent systematic variations. A MadGraph5_AMC@NLO calculation [36] is also shown.

In summary, correlations of $p_T^Z > 40$ GeV/c $Z$ bosons with $p_T^{pZ} > 30$ GeV/c jets have been studied in $pp$ and, for the first time, in Pb-Pb collisions. The data were collected with the CMS experiment during the 2015 data-taking period, at $\sqrt{s_{NN}} = 5.02$ TeV. No significant difference was found between the distributions of the azimuthal angle difference of the $Z$ and the jet in $pp$ and Pb-Pb collisions. The $x_{jZ}$ distributions indicate that the Pb-Pb values tend to be lower than those measured in $pp$ collisions. Correspondingly, the average value of the transverse momentum ratio ($x_{jZ}$) is smaller in Pb-Pb than in $pp$ collisions, for all $p_T^Z$ intervals. The average number of jet partners per $Z$, $R_{jZ}$, is lower in Pb-Pb than in $pp$ collisions, for all $p_T^Z$ intervals, which suggests that in Pb-Pb collisions a larger fraction of partons associated with $Z$ bosons lose energy and fall below the $30$ GeV/c $p_T^{jet}$ threshold. These measurements provide new input for the determination of jet quenching parameters using a selection of partons with well-defined flavor and initial kinematics.

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