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Using Z boson events to study parton-medium interactions in PbPb collisions

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Abstract

The spectra measurements of charged hadrons produced in the shower of a parton originating in the same hard scattering with a leptonically decaying Z boson, are reported in lead-lead (PbPb) and proton-proton (pp) collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. Both PbPb and pp data sets are recorded by the CMS experiment at the LHC, and correspond to an integrated luminosity of $1.7\,\mathrm{nb}^{-1}$ and $320\,\mathrm{pb}^{-1}$, respectively. Hadronic collision data with one reconstructed Z boson candidate with the transverse momentum $p_{\mathrm{T}} > 30\,\mathrm{GeV}/c$ are analyzed. The Z boson constrains the initial energy and direction of the associated parton. In heavy ion events, azimuthal angular distributions of charged hadrons with respect to the direction of a Z boson are sensitive to modifications of the in-medium parton shower and medium response. Compared to reference data from pp interactions, the results for central PbPb collisions indicate a modification of the angular correlations. The measurements of the fragmentation functions and p_{T} spectra of charged particles in Z boson events, which are sensitive to medium modifications of the parton shower longitudinal structure, are also reported. Significant modifications in central PbPb events compared to pp reference data are also found for these observables.

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In relativistic heavy ion collisions, quantum chromodynamics (QCD) predicts that a state of deconfined quarks and gluons, known as quark-gluon plasma (QGP), can be formed [1, 2]. Parton scatterings with large momentum transfer, which occur very early in the collision compared to the timescale of QGP formation, can act as tomographic probes of the plasma [3]. The outgoing partons interact strongly with the QGP and lose energy [4, 5]. This phenomenon, known as "jet quenching", has been observed through measurements of hadrons with high transverse momentum with respect to the beam direction (p_{T}) [6–11] and of jets [12–15], both created by the fragmentation of energetic partons.

This Letter presents the measurement of charged hadrons from the shower of a parton (quark or gluon) produced in association with a Z boson in lead-lead (PbPb) and proton-proton (pp) collisions. Measurements of jets produced in the same hard scattering with an electroweak boson (e.g. photon, Z or W bosons), which does not interact strongly with the QGP [16–19], have an advantage [20–22]: the momentum in the transverse plane of the electroweak boson (the 'tag') reflects, on average, the initial direction and energy (i.e., before any medium-induced energy loss) of the associated parton that fragments into the jet. Both PbPb and pp data sets are collected at a nucleon-nucleon center-of-mass energy $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ and correspond to integrated luminosities of $1.7\,\mathrm{nb}^{-1}$ and $320\,\mathrm{pb}^{-1}$, respectively. The goals of the measurement are the following: (i) to study the medium modification of the hadron momentum spectra coming from hard-scattered partons tagged by Z bosons [22–24]; (ii) to reveal possible angular decorrelations between the unmodified Z boson direction and the charged hadrons because of p_{T} broadening originating from interactions of the parent parton with the medium [25, 26] and (iii) to study the possible effects of medium recoil in the angular correlation functions between the charged hadrons from the shower of a parton produced in association with a Z boson [23, 24, 27]. This analysis correlates Z bosons (reconstructed when decaying to pairs of electrons or muons) and charged-particle tracks in relative azimuthal angle (ϕ). The $\mathrm{N}_{\mathrm{trk,Z}}/\mathrm{N}_{\mathrm{Z}}$, number of tracks normalized by the number of Z bosons is measured as a function of the difference between the ϕ angle of the Z boson (ϕ^{Z}) and the angles (ϕ^{trk}) of the other tracks reconstructed in the event, $\Delta\phi_{\mathrm{trk,Z}} = |\phi^{\mathrm{trk}} - \phi^{\mathrm{Z}}|$. This Letter also presents measurements of the Z-tagged jet fragmentation function, defined as $\xi_{\mathrm{T}}^{\mathrm{trk,Z}} = \ln\left[-|\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}}|^2/(\vec{p}_{\mathrm{T}}^{\,\mathrm{trk}}\cdot\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}})\right]$, where $\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{trk}}$ are the p_{T} vectors with respect to the beam direction of the Z boson and charged-particle track, respectively [28]. These results are distinct from previous ξ measurements [29] in which the $\vec{p}_{\mathrm{T}}^{\,\mathrm{Z}}$ in the denominator is replaced by the p_{T} of a jet after it suffered medium-induced energy loss.

The central feature of the CMS detector [30] 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. Hadron forward (HF) calorimeters extend the pseudorapidity coverage up to $|\eta| = 5.2$. For PbPb events, the HF signals are used to determine the degree of overlap ("centrality") of the two colliding nuclei [31]. Muons are measured in gas-ionization detectors located outside the solenoid.

The event samples are selected in real time with dedicated lepton filters ("triggers") [32], and offline by removing noncollision events [11]. The $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ events are triggered if one ECAL cluster has transverse energy greater than 20 GeV and $|\eta| < 2.1$, while the $\mathrm{Z} \to \mu^+\mu^-$ triggers require one muon of $p_{\mathrm{T}} > 12\,\mathrm{GeV}/c$ and $|\eta| < 2.4$ [32]. The average pileup (the mean of the number of additional collisions within the same bunch crossing) is 2 in pp, and negligible in PbPb collisions. For PbPb collisions, the results are presented in four centrality intervals, 70–90, 50–70, 30–50, and 0–30%. The centrality measurement is based on percentiles of the distribu-

tions of the total energy deposited in the HF calorimeters, which corresponds to the fraction of the total inelastic hadronic cross section, starting at 0% for the most central collisions [31].

The PYTHIA 8.212 [33] Monte Carlo (MC) event generator with the underlying event (UE) tune CP5 [34], and MADGRAPH5_aMC@NLO 8.212 [35] next-to-leading order (NLO) program (interfaced with PYTHIA) are used to simulate Z +jet signal events. In the PbPb case, "embedded" samples are created by overlapping PYTHIA and MADGRAPH5_aMC@NLO signal events with minimum bias (MB) heavy ion events generated with the HYDJET 1.9 MC event generator [36]. The generated events are propagated through the CMS apparatus using the GEANT4 toolkit [37]. These MC samples are used to evaluate reconstruction and selection efficiencies, calibrations, and to study the background, separately for pp and PbPb data.

Electrons are identified as ECAL superclusters [38] matched in position and energy to tracks reconstructed in the tracker, using the particle-flow algorithm [39]. They must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$ and their supercluster must be within the acceptance of the trigger, $|\eta| < 2.1$. Muons are selected by requiring reconstructed track segments in at least two muon detector planes and a good-quality fit when connecting them to tracker segments [40]. For both pp and PbPb data, the muons are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$ and they must fall within the acceptance of the muon detectors, $|\eta| < 2.4$.

The track reconstruction used in pp and PbPb collisions is described in Ref. [41]. Corrections for tracking efficiency, detector acceptance, and misreconstruction rate are obtained following the procedure of Ref. [11]. Additional corrections are applied to account for a difference in tracking efficiency (∼1%), from a different particle density, seen between HYDJET and embedded MADGRAPH5_aMC@NLO samples. The selection criteria are the same as in Ref. [11] for both pp and PbPb data.

The Z candidates are identified using an electron or muon pair, with a reconstructed invariant mass in the interval 60–120 GeV/c^2 and $p_{\mathrm{T}}^{\mathrm{Z}} > 30\,\mathrm{GeV}/c$. After all selections, there are ∼5K (23K) Z boson events in PbPb (pp) data. Electron and muon pairs are corrected for losses in acceptance and efficiency during reconstruction, and identification and trigger selections [38, 40]. Each Z candidate is paired with all tracks in the same event that pass the $p_{\mathrm{T}}^{\mathrm{trk}} > 1\,\mathrm{GeV}/c$ and $|\eta^{\mathrm{trk}}| < 2.4$ selections. To avoid including the tracks of the Z candidate decay products, each track used in the correlations is required to fall outside a cone of radius (defined as $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) 0.02 (the smallest value for which no significant contamination is observed) around the direction of a lepton from the Z decay. Intermediate results, corrected for lepton efficiencies only, are obtained separately for Z candidates reconstructed from oppositely-charged electron or muon pairs. In order to minimize the residual contamination from QCD jet physics processes (<3%), the relative contribution from same-charge lepton pairs is subtracted separately for the two decay channels. Finally, the two channels are combined and treated as one.

Combinatorial background originating from tracks from the UE in PbPb collisions is subtracted to obtain the correlation between the Z boson candidate and all tracks coming from the shower of a parton produced in the same hard scattering process. This background is estimated from data with an event mixing procedure [42, 43], where the Z candidate is paired with tracks found in events chosen randomly from an MB PbPb data set with similar event characteristics (i.e., similar energy deposited in the HF, and interaction vertex z position). Events are split into bins of total HF energy, E^{HF}. To ensure that the Z boson and MB events have the same size UE, an event with a Z boson candidate and with $E^{\mathrm{HF,\,Z}}$ is mixed with MB events in the E^{HF} bin containing events with HF energy equal to $E^{\mathrm{HF,\,Z}} - \langle E^{\mathrm{HF,\,Z,\,pp}} \rangle$. The quantity $\langle E^{\mathrm{HF,\,Z,\,pp}} \rangle$ is the average of E^{HF} over events in pp data where a Z boson is produced without additional

pp interactions present in the event. For the events within a given E^{HF} bin, the variation in the number of UE tracks before subtraction can be much larger than the number of tracks after subtraction. In order to reflect this statistical effect of the UE, the statistical uncertainties of the PbPb distributions are calculated using the bootstrap method [44].

Several variations in the analysis are considered in order to account for the uncertainties related to the tracking efficiency and corrections, lepton efficiency and energy scale, as well as pp pileup and PbPb background subtraction. No significant differences are observed in the results obtained with electron and muon pairs separately, therefore uncertainties are quoted after combining the two. With the exception of the lepton energy scale and efficiencies, there are no assumed correlations between the pp and PbPb uncertainties. Unless noted otherwise, the systematic uncertainties are evaluated as the differences between final results and results obtained with varied settings. In the following, we list the variations considered, and provide in Appendix A the numerical values for the average uncertainties corresponding to the most extreme cases, i.e. the pp and most central 0–30% PbPb collisions.

The uncertainty related to the tracking efficiency is estimated as the difference in the track reconstruction efficiency between data and simulation [11]. The uncertainty related to the observed efficiency difference, between HYDJET and embedded MADGRAPH5_aMC@NLO samples, is obtained by comparing corrections obtained from embedded samples. Lepton efficiencies are varied by the uncertainty in their data-to-MC differences obtained using the "tag-and-probe" method [45]. To assess the uncertainty related to the lepton energy scale corrections, the p_{T} of leptons is shifted by their energy correction uncertainties. No corrections are applied to remove the residual pileup effects in pp data. Nominal distributions (no requirement on pileup) are compared to those from events without pileup, i.e. events with only one interaction vertex. The uncertainty in the event mixing procedure is obtained by repeating the procedure after shifting the $\langle E^{\mathrm{HF,\,Z,\,pp}} \rangle$ by 5%, the maximum difference in the HF response between PbPb and pp data-taking periods.

The results are compared to three theoretical calculations, which use the same kinematic selection as data, and incorporate the phenomenon of jet quenching: $\mathrm{SCET_G}$ [24, 46, 47], which does not consider any medium response to jet propagation; Hybrid [26, 27], which considers the effects of a 'wake', induced by the jet as it passes through and interacts with the QCD medium; and CoLBT [23, 48] in which the quenched jet energy feeds into the hydrodynamic evolution.

Figure 1 shows $1/\mathrm{N_Z}\,\mathrm{dN_{trk,Z}}/\mathrm{d}\Delta\phi_{\mathrm{trk,Z}}$, i.e., the distributions of the ϕ angle difference between charged particles and Z bosons, normalized by the number of Z bosons in each data set (and for the PbPb case, in each centrality interval). This type of angular correlation function could reveal medium-induced modification of the away-side ($\Delta\phi_{\mathrm{trk,Z}} \sim \pi$) jet constituents, and effects of the medium response (i.e., modification of the medium induced by the jet traversing through), over all $\Delta\phi_{\mathrm{trk,Z}}$. Different pairs of data sets were compared using χ^2-tests. With a p-value cutoff of 0.05, the tests show that the 0–30% PbPb (pp) distribution is compatible (incompatible) with all data sets except the most peripheral one. The distributions in both pp and PbPb collisions are peaked at $\Delta\phi_{\mathrm{trk,Z}} \sim \pi$, which is the signature of an away-side jet emitted back-to-back with the Z boson. The difference in the number of associated particles, between the PbPb and pp results, is also shown in Fig. 1. The excess observed in all bins except the most peripheral (i.e., the most pp-like) could be caused by the medium response where the traversing jet excites the medium around it, as well as by multiple-parton interactions that are independent of the Z +jet process [48]. The comparison with the CoLBT and the Hybrid (with and without wake) models support these scenarios, although the Hybrid model fails to reproduce the magnitude of the difference between pp and PbPb collisions, in particular in the $\Delta\phi_{\mathrm{trk,Z}} \sim 0$ region.

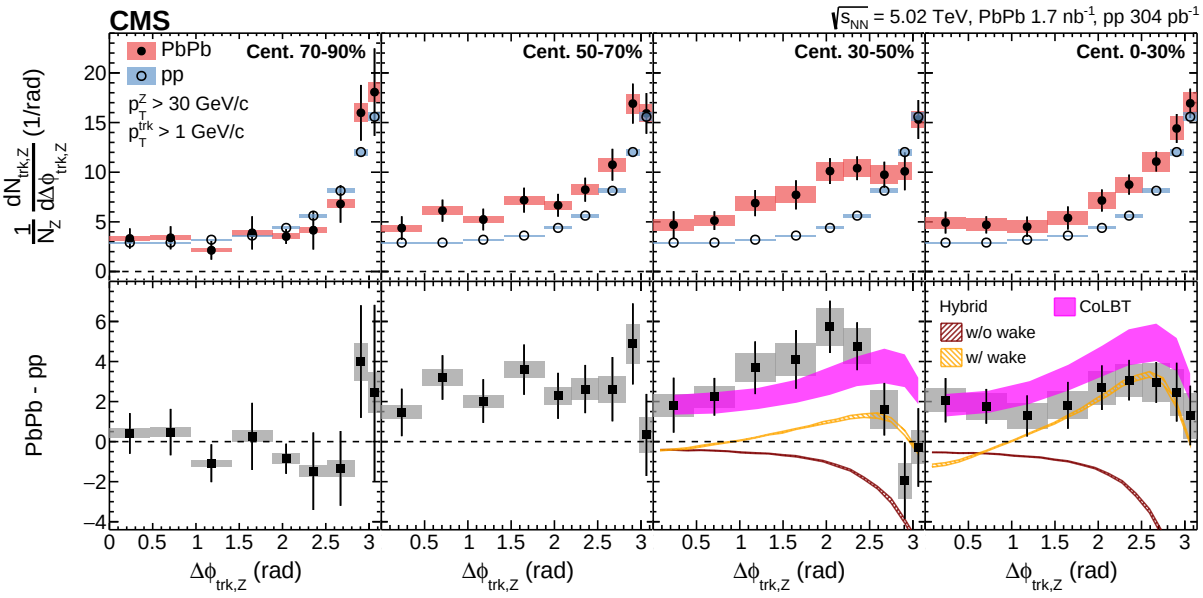

Figure 1: Upper: Distributions of $\Delta\phi_{\mathrm{trk,Z}}$ in pp collisions compared to PbPb collisions (left to right) in the 70–90 (left), 50–70, 30–50, and 0–30% (right) centrality intervals. Lower: Difference between the PbPb and pp distributions. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. Several model calculations are added for comparison: Hybrid [27] and CoLBT [23, 48].

The fragmentation function of the parton emitted back-to-back with the Z boson is studied via the $1/\mathrm{N_Z}\,\mathrm{dN_{trk,Z}}/\mathrm{d}\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ distributions, shown in Fig. 2. For these results (as well as for those shown in Fig. 3), tracks are required to satisfy $\Delta\phi_{\mathrm{trk,Z}} > 7\pi/8$. Because the interest is in the shape dissimilarities, the ratios of the pp and PbPb distributions are presented. All distributions are normalized by the number of Z candidates found in each data set.

In Fig. 2, the low- and high-$\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ regions (i.e., below and above ∼3) correspond to high- and low-p_{T} particles (or lower- and higher-$p_{\mathrm{T}}^{\mathrm{Z}}$), respectively. For instance, for $p_{\mathrm{T}}^{\mathrm{Z}} \sim 30(60)\,\mathrm{GeV}/c$, the high-$\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ region corresponds to $p_{\mathrm{T}}^{\mathrm{trk}} \sim 1.5(3)\,\mathrm{GeV}/c$. No significant modification is observed in the 70–90% PbPb collisions compared to pp data. In central collisions, charged particles are suppressed in the $\xi_{\mathrm{T}}^{\mathrm{trk,Z}} < 3$ (high-energy particles) interval, and enhanced in the $\xi_{\mathrm{T}}^{\mathrm{trk,Z}} > 3$ interval. These features are consistent with a scenario in which the initial parton loses energy (i.e., jet quenching) and/or the medium induces modification of the parton shower. The enhancement is also consistent with a picture in which additional low-energy particles are produced from the recoil of the medium caused by the traversing parton.

The modification of the charged-particle p_{T} spectra is prominent when comparing the per-Z-boson associated yields in PbPb and pp collisions. Figure 3 shows the $1/\mathrm{N_Z}\,\mathrm{dN_{trk,Z}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{trk}}$ distributions in PbPb and pp data, together with their ratio. In the most peripheral event class, there is no significant modification of the charged-particle p_{T} spectrum in PbPb collisions. In central events and at high $p_{\mathrm{T}}^{\mathrm{trk}}$ (>2–5 GeV/c), the particle production is suppressed in PbPb compared to the pp reference data. At the same time, at low $p_{\mathrm{T}}^{\mathrm{trk}}$ (1–2 GeV/c), an enhancement is observed consistent with the one seen in the $\Delta\phi_{\mathrm{trk,Z}}$ results. Modifications of the $\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ and $p_{\mathrm{T}}^{\mathrm{trk}}$ distributions are the largest in the 0–30% centrality interval, indicating the strongest medium effects.

The medium response is not expected to play an important role for the high-$p_{\mathrm{T}}^{\mathrm{trk}}$ and low-$\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$

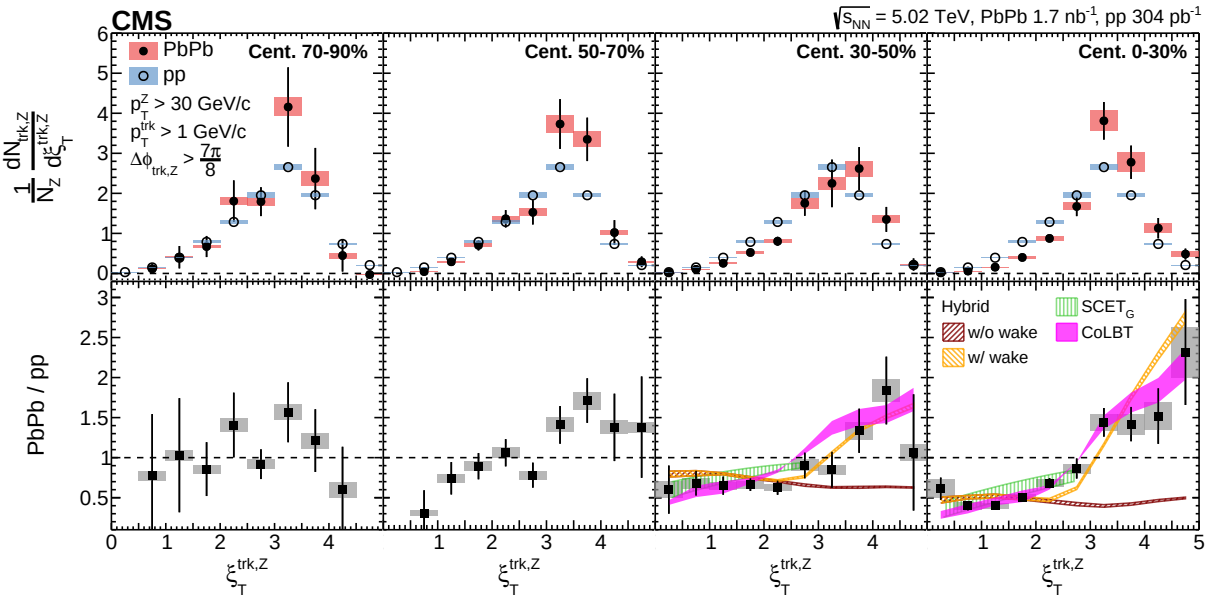

Figure 2: Upper: Distributions of $\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ in pp collisions compared to PbPb collisions (left to right) in the 70–90 (left), 50–70, 30–50, and 0–30% (right) centrality intervals. Lower: ratios of the PbPb to pp distributions. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. Several model calculations are added for comparison: Hybrid [27], CoLBT [23, 48], and $\mathrm{SCET_G}$ [46].

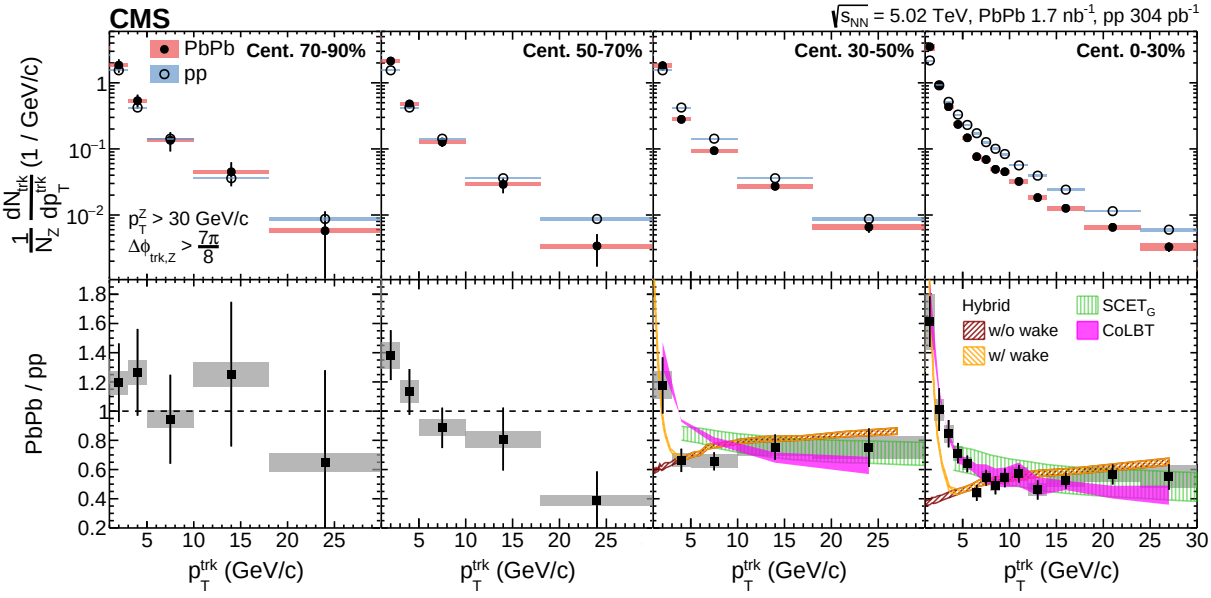

Figure 3: Similar plots as Fig. 2, but for the $1/\mathrm{N_Z}\,\mathrm{dN_{trk,Z}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{trk}}$ distributions.

regions, as is illustrated in the Hybrid model, where calculations with and without wake are indistinguishable. In this region, there is good agreement between data and the $\mathrm{SCET_G}$ and the Hybrid calculations. At low-$p_{\mathrm{T}}^{\mathrm{trk}}$ and high-$\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$, the increase in the charged particle yield can only be reproduced if a feed-back from the medium is considered. In these regions, both the Hybrid with wake and CoLBT models captures the general features seen in data, including the expected weakening of medium effects at higher p_{T} values from 0–30 to 30–50% PbPb event centralities.

In summary, the measurements of charged hadrons produced in the shower of a parton originating in the same hard scattering with a Z boson, are reported in lead-lead (PbPb) and proton-proton (pp) collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. Collision data with a Z boson candidate with transverse momentum $p_{\mathrm{T}} > 30\,\mathrm{GeV}/c$ are analyzed. The Z-tagged fragmentation functions and $p_{\mathrm{T}}^{\mathrm{trk}}$ spectra, which probe the longitudinal structure of the parton shower inside the medium, are measured and significant modifications are observed. Particle yields, which are sensitive to modification of the in-medium parton shower and medium recoils, are measured for all charged particles as a function of the azimuthal angle (ϕ) with respect to the Z boson momentum vector. Comparison of the PbPb and pp results indicates a modification of the angular correlation functions extending to ϕ angles close to the Z boson in central PbPb events. The data favor theoretical models that include the response of the medium to the traversing parton. These results represent the first studies of parton-medium interactions over all ϕ angles, in which the initial state of the scattered parton is known before it enters the medium.

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A Supplemental material

Table 1: Relative systematic uncertainties for $\Delta\phi_{\mathrm{trk,Z}}$, $\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$, and $p_{\mathrm{T}}^{\mathrm{trk}}$, averaged over the whole distribution, for pp and PbPb collisions.

Systematic uncertainty source	$\Delta\phi_{\mathrm{trk,Z}}$ [%]		$\xi_{\mathrm{T}}^{\mathrm{trk,Z}}$ [%]		$p_{\mathrm{T}}^{\mathrm{trk}}$ [%]	
	pp	PbPb	pp	PbPb	pp	PbPb
Tracking efficiency						
Data–MC difference	2.4	5.0	2.4	5.0	2.4	5.0
MC minbias–embedding samples difference	—	2.7	—	2.7	—	2.5
MC generator–reconstruction difference	0.7	8.1	2.3	5.0	1.7	3.8
Leptons						
Data–MC efficiency difference	0.4	0.7	0.4	0.7	0.4	0.7
Energy scale	0.1	1.7	0.4	2.6	0.2	1.7
Pileup pp	1.3	—	1.9	—	2.0	—
Event mixing PbPb	—	3.0	—	1.8	—	0.8

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