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Letter

Evidence of medium response to hard probes using correlations of Z bosons with hadrons in heavy ion collisions

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ABSTRACT

The first measurement of pseudorapidity and azimuthal angle distributions relative to the momentum vector of a Z boson for low transverse momentum (p_T) charged hadrons in lead-lead (PbPb) collisions is presented. By studying the hadrons produced in an event with a high-p_T Z boson ($40 < p_T < 350$ GeV), the analysis probes how the quark-gluon plasma (QGP) medium created in these collisions affects the parton recoiling opposite to the Z boson. Utilizing PbPb data at a nucleon-nucleon center-of-mass energy $\sqrt{s_{_{NN}}} = 5.02$ TeV from 2018 with an integrated luminosity of 1.67 nb^{-1} and proton-proton (pp) data at the same energy from 2017 with 301 pb^{-1}, the distributions are examined in bins of charged-hadron p_T. A significant modification of the distributions for charged hadrons in the range $1 < p_T < 2$ GeV in PbPb collisions is observed when compared to reference measurements from pp collisions. The data provide new information about the correlation between hard and soft particles in heavy ion collisions, which can be used to test predictions of various jet quenching models. When compared with theoretical predictions, the results are consistent with expectations of a hydrodynamic wake created when the QGP is depleted of energy by the parton propagating through it. Therefore, this Letter presents the first evidence of probe-induced energy depletion and the resulting response by the QGP medium.

1. Introduction

Quantum chromodynamics (QCD) predicts that a state known as the quark-gluon plasma (QGP), which consists of deconfined quarks and gluons, is formed at high temperatures and high density [1,2]. The QGP is created in relativistic heavy ion collisions [3] and has been the focus of high-energy nuclear physics experiments at BNL RHIC [4–7] and the CERN LHC [8,9]. During heavy ion collisions, parton scattering with high momentum transfer occurs earlier than the formation of the QGP. Therefore, such partons can serve as tomographic probes of the plasma [10]. These partons lose energy by interacting strongly with the QGP medium, an effect which results in "jet quenching" [11]. Experimental measurements of high-transverse-momentum (p_T) hadrons [12–17] and jets [18–24] formed by the fragmentation of high-momentum partons have provided evidence establishing the jet-quenching phenomenon. However, the details of the jet quenching mechanism remain elusive. Processes such as collisional energy loss, where partons lose energy through interactions with medium constituents, and medium-induced radiation in perturbative QCD (pQCD)-based models, reduce the momentum of the parton as it traverses the QGP. In anti-de Sitter/conformal field theory (AdS/CFT)-based models, a drag force, scaled to account for the differences between QCD and infinitely-color-charged field theory, similarly reduces the energy of the parton when passing through the medium [25]. Additionally, medium recoils and the response induced by the hard probes can contribute to producing low-p_T particles linked with the high-energy parton (recent reviews can be found in Refs. [26–28]). Since both contributions are associated with the QGP temperature scale on the order of hundreds of MeV, separating them using their p_T distributions is difficult. This highlights the need for more observables that are sensitive to the different contributions to the jet-quenching mechanism and for determining the relevance of medium recoil and medium response.

Unlike strongly interacting particles, electroweak bosons do not significantly interact with the QGP [29–34]. Therefore, measurements of jets produced in the same hard scattering as these bosons offer a controlled configuration for the initial hard scattering [35–38]. The p_T of the electroweak boson reflects the initial energy of the associated parton before any medium-induced energy loss occurs [39,40]. Among the electroweak bosons, Z bosons offer the most precise means to identify the hard-scattering scale for Z+jet events. Although W bosons have a larger production cross section, the presence of a neutrino in their leptonic decay products complicates the boson p_T measurement. Additionally, compared to the related measurements using isolated photons [29,32,41–43], Z bosons do not require a complex isolation procedure that could introduce measurement biases for particle production in their vicinity. In this analysis, Z bosons are reconstructed via their

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dimuon decay channel, which has negligible background contamination [34] when observed using the CMS detector [38,44]. These advantages enable the experimental verification of the presence of a negative diffusion wake, where the hard-scattered parton pushes the QGP medium forward, leaving a depleted region on the Z boson side. Furthermore, these traits allow for the study of medium response and recoil in a phase space far away from the outgoing parton [43,45–47] by examining the charged-hadron spectra in the vicinity of the Z boson. Looking in the Z boson direction avoids complications faced by previous searches (e.g., Ref. [45,48]) that examined the region opposite the Z boson, where other jet quenching effects contribute in addition to the medium response.

Moreover, examining the angular distributions of hadrons relative to the Z boson as a function of hadron p_{T} allows the determination of where the medium response and recoil effects are the most significant. The study of high-p_{T} charged hadrons (high $p_{\mathrm{T}}^{\mathrm{ch}}$) facilitates searches for the large-angle scattering between high-p_{T} partons and QGP constituents [49,50].

This Letter presents the first measurement of the Z boson-hadron two-particle angular correlation function in bins of hadron p_{T}. Charged-hadron spectra in events containing high-p_{T} Z bosons are studied as functions of the azimuthal angle difference between the Z boson and the charged hadron ($\Delta\phi_{\mathrm{ch,Z}} \equiv \phi^{\mathrm{Z}} - \phi^{\mathrm{ch}}$), as well as their rapidity difference ($\Delta y_{\mathrm{ch,Z}} \equiv y^{\mathrm{Z}} - \eta^{\mathrm{ch}}$), where y^{Z} is the rapidity of the Z boson and η^{ch} is the pseudorapidity of the charged hadron. This study utilizes lead-lead (PbPb) data at a nucleon-nucleon center-of-mass energy $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV recorded in 2018 by CMS with an integrated luminosity of $1.67 \pm 0.03\,\mathrm{nb}^{-1}$, as well as proton-proton (pp) data acquired in 2017 with an integrated luminosity of $301 \pm 6\,\mathrm{pb}^{-1}$ at the same energy [51]. Tabulated results are provided in the HEPData record for this analysis [52].

2. The CMS detector

The central feature of the CMS detector [53] 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 η coverage up to $|\eta| = 5.2$. For PbPb events, the amount of energy measured in HF is used to determine the degree of overlap ("centrality") of the two colliding nuclei [18]. Muons are measured in gas-ionization detectors located outside the solenoid.

3. Monte Carlo simulation

The MadGraph5_aMC@NLO v2.4.2 [54] Monte Carlo (MC) event generator at next-to-leading order (NLO) interfaced with pythia 8.212 [55] with tune CP5 [56] are used to simulate signal Z+jets events. In the case of PbPb collisions, samples are created by embedding the MadGraph5_aMC@NLO+pythia signal events in minimum-bias heavy ion events modeled using the hydjet1.9 MC event generator [57]. These events are then propagated through the CMS apparatus using the Geant4 toolkit [58], and are used to evaluate reconstruction and selection efficiencies, perform calibrations, and study the background.

4. Global-event and physics object selection

The Z boson event samples are selected online using dedicated lepton triggers [59]. The triggers on $Z \to \mu^+\mu^-$ events require one muon with $p_{\mathrm{T}} > 12$ GeV and $|\eta| < 2.4$ [59]. Noncollision events, such as beam-gas interactions, are removed in the data analysis following the procedure in Ref. [17]. The average pileup, defined as the mean number of additional collisions within the same bunch crossing, is 2 in pp collisions and smaller than 0.01 in PbPb collisions. In the pp analysis, events with a single primary vertex, formed by at least two tracks, with a distance from the center of the nominal interaction region of less than 25 cm along the beam axis, are selected to reject events with pileup. Centrality quantifies the overlap of the two colliding nuclei and is related to the initial energy density in the system. It is determined based on percentiles of the total energy deposited in the HF calorimeters, representing the fraction of the total inelastic hadronic cross section, starting at 0% for the most central collisions [18]. The results for PbPb collisions are presented in three centrality intervals: 0–30, 30–50, and 50–90%.

The muon selection requires reconstructed track segments in at least two muon detector planes and a good-quality fit when connecting them to tracker segments [60]. For both pp and PbPb data, muons must have $p_{\mathrm{T}} > 20$ GeV and fall within the acceptance of the muon detectors, $|\eta| < 2.4$. Muon reconstruction efficiencies, found using MC simulations, are corrected according to the their data-to-MC differences, obtained using the "tag-and-probe" method [60,61].

The charged-hadron track reconstruction used in both pp and PbPb collisions is described in Ref. [62]. Corrections for tracking efficiency, detector acceptance, and misreconstruction rate are obtained following the procedure outlined in Ref. [17]. The selection criteria are identical to those described in Ref. [17] for the pp and PbPb data.

5. Analysis technique and corrections

The Z boson candidates are identified using an oppositely-charged muon pair, with a reconstructed invariant mass in the interval 60–120 GeV and $40 < p_{\mathrm{T}}^{\mathrm{Z}} < 350$ GeV. Here, contributions from virtual photons decaying into an oppositely-charged muon pair ($\gamma^* \to \mu^+\mu^-$) are also included in the signal definition. In events with more than one Z boson candidate, which comprises approximately 0.2% of events, the highest p_{T} boson is used for the correlation analysis. About 2000 events pass these selection criteria in the PbPb analysis. Muon pairs are corrected for losses due to detector acceptance, reconstruction efficiency, muon identification, and trigger selection criteria [63]. Each Z boson candidate is correlated with all tracks in the same event that have $p_{\mathrm{T}}^{\mathrm{ch}} > 1$ GeV and $|\eta^{\mathrm{ch}}| < 2.4$. To avoid including the muons from the Z boson candidate decay, each track used in the correlations is required to fall outside a cone around the direction of a muon from the Z boson decay. The cone radius, defined as $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is required to be greater than 0.0025 radians. This is the smallest value that ensures no significant muon contamination, as determined from simulations. The simulation gives a good description of the resulting invariant mass distributions for reconstructed Z bosons [44].

In order to focus on the shape of the charged hadron spectrum associated with the Z boson, the average over the N_{ch} distribution, $\langle N_{\mathrm{ch}}\rangle$ where N_{ch} is the number of associated charged hadrons, needs to be subtracted. Therefore, the averaged normalized associated yield $\Delta\langle N_{\mathrm{ch}}\rangle$, is defined as

$$\Delta\langle N_{\mathrm{ch}}\rangle(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}}) \equiv \frac{1}{N_{\mathrm{Z}}}\sum_{i=1}^{N_{\mathrm{Z}}}(N_{\mathrm{ch},i}(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}}) - \langle N_{\mathrm{ch}}\rangle), \tag{1}$$

where N_{Z} is the number of leading Z boson candidates, defined as the highest p_{T} Z boson in the event. In order to extract the shape $\Delta\langle N_{\mathrm{ch}}\rangle$ of the charged hadrons that are associated with the parton recoiling opposite the Z boson, an event-mixing scheme is employed to subtract the substantial background arising from the many unrelated multiparton interactions in heavy ion collisions. The mixed-event correlation function is calculated by pairing the Z boson from one event with charged hadrons from a different Z boson event within the sample. The impact of not applying any further event criteria (beyond the presence of a Z boson) in selecting events for this mixing was evaluated with MC closure studies and was found to be negligible. To improve the statistical accuracy, this procedure is repeated using 10 other events for each event in the sample. In this context, $S(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}})$ and $B(\Delta\phi_{\mathrm{ch,Z}}, \Delta y_{\mathrm{ch,Z}})$ denote the same-event and mixed-event correlation functions, respectively. The relationship between $\Delta\langle N_{\text{ch}}\rangle$ and these functions can be written as:

$$\Delta\langle N_{\text{ch}}\rangle(\Delta\phi_{\text{ch,Z}}, \Delta y_{\text{ch,Z}}) = S(\Delta\phi_{\text{ch,Z}}, \Delta y_{\text{ch,Z}}) - B(\Delta\phi_{\text{ch,Z}}, \Delta y_{\text{ch,Z}}). \quad (2)$$

This method, applied to both pp and PbPb analyses, subtracts the underlying event and $\langle N_{\text{ch}}\rangle$ contributions, isolating the medium-induced modifications. Note that no unfolding corrections for detector effects in $\Delta\phi_{\text{ch,Z}}$ ($\Delta y_{\text{ch,Z}}$) are applied in this case, as the bin width is much larger than the resolution. Results for positive and negative $\Delta\phi_{\text{ch,Z}}$ ($\Delta y_{\text{ch,Z}}$) are merged to improve statistical precision. These symmetrized results, which are effectively a correlation function in bins of $|\Delta\phi_{\text{ch,Z}}|$ ($|\Delta y_{\text{ch,Z}}|$), are then scaled by a factor of 0.5 to ensure that the total integrated yield accurately reflects the relative excess or depletion observed in the data, thereby allowing direct comparison with theoretical predictions. To make a clearer visual presentation of the data, the results are "reflected," i.e., the same values are plotted at both positive and negative $\Delta y_{\text{ch,Z}}$, while for $\Delta\phi_{\text{ch,Z}}$ data points are reflected around both 0 and π.

6. Systematic uncertainties

Several variations in the analysis are considered to account for uncertainties related to tracking efficiency, muon identification efficiency, muon reconstruction efficiency, pp pileup, and PbPb background subtraction. Systematic uncertainties are either evaluated as the difference between the nominal results and those obtained with varied settings or are based on the differences in various quantities between data and simulation.

The uncertainty related to the tracking efficiency is estimated by comparing the track reconstruction efficiency between data and simulation [17]. An efficiency uncertainty of 5.0 (2.4)% per charged-hadron track is quoted as the systematic uncertainty in the PbPb (pp) analysis. Muon triggering and reconstruction efficiencies are varied within the uncertainties of their data-to-MC differences, as determined with the tag-and-probe method. For systematic uncertainties associated with pileup in pp collisions, nominal distributions are compared to those from events without the single-primary-vertex requirement. The centrality calibration is varied to calculate the effect of the minimum-bias event selection efficiency of the HF calorimeters [9,34]. In order to investigate the uncertainty in the PbPb background subtraction, an MC closure test was performed, which resulted in a negligible non-closure and corresponding uncertainty. The uncertainties are then summed in quadrature to obtain the final systematic uncertainties, and are significantly smaller than the statistical uncertainty. When calculating the systematic uncertainties in the difference between pp and PbPb spectra, the systematic uncertainties in the two systems are assumed to be uncorrelated. The dominant systematic uncertainties are those associated with pileup and the centrality calibration in the pp and PbPb analyses, respectively. The magnitude of the total relative systematic uncertainty varies with centrality and p_{T}^{ch} bin. For $\Delta\phi_{\text{ch,Z}}$, the systematic uncertainty is largest for the lowest-p_{T}^{ch} interval for 30–50% centrality with a total relative systematic uncertainty of ~75%. For $\Delta y_{\text{ch,Z}}$, the systematic uncertainty is largest at lower p_{T}^{ch} and 50–90% centrality, with a total relative systematic uncertainty of $\sim 40\%$. However, in all regions of phase space, the statistical uncertainty is larger than the systematic uncertainty.

7. Results

The distributions of the azimuthal angle difference, $\Delta\phi_{\text{ch,Z}}$, between the Z boson and charged-hadron tracks in three p_{T}^{ch} intervals are shown in Fig. 1. In pp collisions, the distribution features a jet-side peak at $\Delta\phi_{\text{ch,Z}} \sim \pi$, while on the Z boson side, defined as the region close to the Z boson ($\Delta\phi_{\text{ch,Z}} \sim 0$), the normalized associated yield is flat and becomes negative. To investigate the centrality dependence of the medium-induced modification, the results from PbPb data are studied in three centrality classes: 0–30, 30–50, and 50–90%. The fully-corrected PbPb data are then compared to the reference pp data.

In the 0–30% centrality class, significant modifications are observed in the normalized distributions compared to the pp reference in the highest- and lowest-p_{T} intervals. A more pronounced modulation in the $\Delta\phi_{\text{ch,Z}}$ distribution is observed for low-p_{T} tracks within the $1 < p_{\text{T}} < 2$ GeV range, consistent with the expected response from parton-medium interactions. For the intermediate-p_{T} range of $2 < p_{\text{T}} < 4$ GeV, the PbPb data show a closer resemblance to the pp reference than is the case for the lowest-p_{T} charged hadrons. Significant suppression of high-p_{T} particles in PbPb is observed on the jet-side for $4 < p_{\text{T}} < 10$ GeV, especially when $|\Delta\phi_{\text{ch,Z}}| > \pi/2$. The difference between the PbPb and pp data in the jet side diminishes for more peripheral collisions. The pp data and the PbPb data at 50–90% centrality are consistent with each other.

The correlations as a function of the rapidity difference between the charged hadrons and the Z boson, $\Delta y_{\text{ch,Z}}$, are presented in Fig. 2. To focus on the Z direction, the rapidity difference distributions include only particles with $\Delta\phi_{\text{ch,Z}} < \pi/2$. Because of this azimuthal angle selection, these spectra do not average to zero. On the Z boson side, the correlations are sensitive to the medium-recoil effect, which would appear as a dip structure at $\Delta y_{\text{ch,Z}} \sim 0$ relative to the pp reference. As shown in all panels in Fig. 2, the normalized associated yield for pp data on the Z boson side is smaller than zero. The same measurement is also performed with PbPb data. At low p_{T}^{ch} ($1 < p_{\text{T}} < 2$ GeV), the 0–30% centrality PbPb data are below the pp reference, with a significance greater than 3σ using a χ^2 test between the pp and PbPb data points. This difference diminishes for $2 < p_{\text{T}} < 4$ GeV. Bin-to-bin correlations in the systematic uncertainties have only a minor effect on the calculation of χ^2 and are therefore neglected. For the highest p_{T} bin ($4 < p_{\text{T}} < 10$ GeV), the 0–30% centrality PbPb data are higher than the pp reference. This phenomenon is consistent with expectations of jet quenching, likely driven by the suppression of the jet-side yield and potential large-angle parton-medium scattering. In the most peripheral PbPb collisions (centrality 50–90%), the difference between the pp and PbPb data reduces at the low p_{T}^{ch}.

The PbPb data are also compared to jet quenching models. The "PYTHIA-quenched" (PYQUEN 1.5.3) model approximates radiative and collisional energy loss without strictly enforcing local energy-momentum conservation [64]. The model can be used to predict the shower of high-energy partons traversing the QGP, resulting in medium-induced modifications to jet structures and particle correlations. This model predicts that the Z-boson-hadron correlation is influenced by collisional and radiative effects induced by the medium, leading to substantial changes in the jet-fragmentation function.

The "jet evolution with energy loss" (JEWEL 2.2.0) model simulates the interaction between jets and the QGP with pQCD-based calculations, incorporating both radiative and collisional energy losses [65–67]. It predicts jet modifications due to the medium, including the recoil of medium particles. This model can operate in two configurations: with recoil, which conserves energy and momentum, and without recoil, which does not conserve these quantities but allows for focusing on the quenched parton shower [67,68]. According to this model, medium recoils significantly enhance the low-p_{T} normalized associated yield on the jet side. In addition, the normalized yield around the Z boson is predicted to be suppressed by "medium holes," which are regions in the QGP depleted of energy and momentum due to the parton-medium scattering. Neither the recoil partons on the jet side nor the medium holes on the Z boson side rescatter with the medium.

The "HYBRID model [25]," based on the AdS/CFT correspondence, combines pQCD-based calculations with strong-coupling dynamics in order to simulate jet interactions within the QGP. This approach provides a comprehensive framework for understanding the energy loss and modifications of jets traversing the QGP. According to this model, a positive wake associated with the jet shower enhances the jet-side normalized associated yield, while a negative wake suppresses the yield around the Z bosons [69].

Finally, the coupled linear Boltzmann transport (CO-LBT) model combines the linear Boltzmann transport equation, which governs parton energy loss through scattering and radiation in the QGP, with hydro-

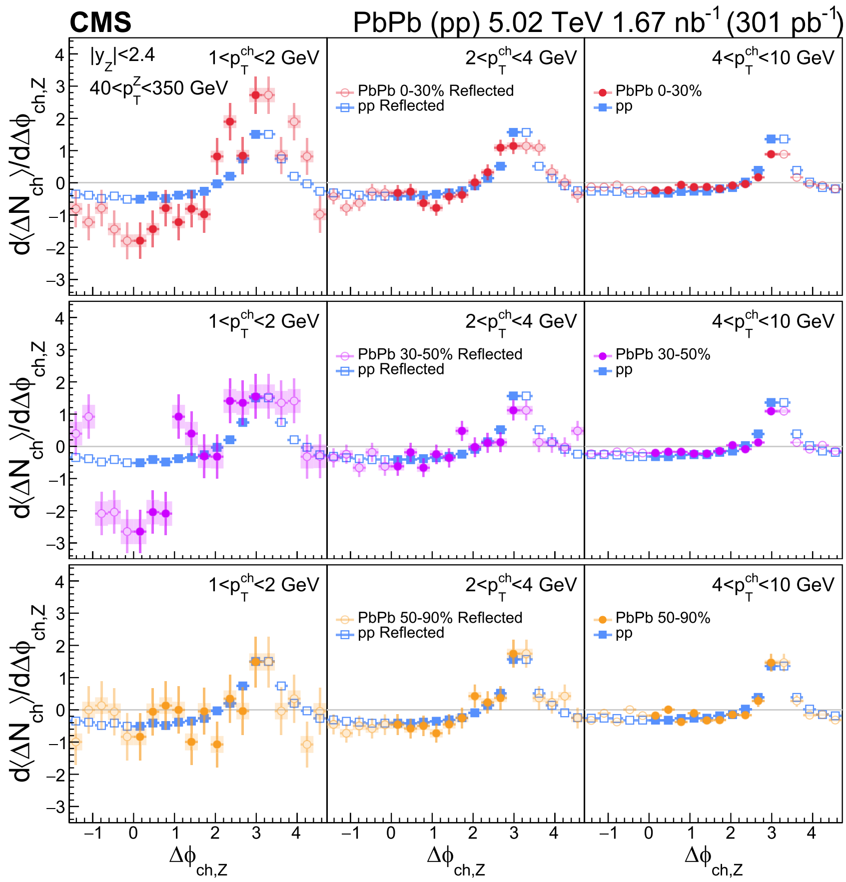

Fig. 1. The $\Delta\phi_{ch,Z}$ spectra for events with Z boson $p_T^Z > 40$ GeV in pp and PbPb collisions. The filled circles (squares) are the PbPb (pp) data and the open circles (squares) are reflected data. The pp data are identical across panels with different centrality intervals. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The results are presented in centrality intervals of 0–30% (top row, red), 30–50% (middle row, purple), and 50–90% (bottom row, yellow) and in the charged-hadron p_T^{ch} intervals of 1–2 (left column), 2–4 (middle column) and 4–10 GeV (right column).

dynamic simulations that describe the bulk evolution of the QGP [70]. In this model, "reheating" refers to the process by which energy lost by high-energy partons is transferred back into the medium and becomes a source term in the hydrodynamic simulation, potentially increasing the local temperature and altering the QGP's properties [50]. At low p_T^{ch}, the reheating is linked to the enhanced associated yield on the jet side of the normalized associated yield. A diffusion wake, the diffusion of the "particle holes" behind the hard-scattered parton, results in the suppression of the normalized associated yield on the Z boson side [46,47].

To summarize, for the implementation of medium response in these models, three approaches are used: no rescattering (JEWEL), iterative recoil treatment with hydrodynamic updates (CO-LBT), and full thermalization of quenched energy and wake (HYBRID). These methods offer complementary insights into the medium's response to parton energy loss and provide an opportunity to examine the extent to which recoil partons are thermalized in the medium.

Figs. 3 and 4 show comparisons between the 0–30% centrality PbPb data and theoretical predictions. The full HYBRID model predicts a dip structure at small $\Delta\phi_{ch,Z}$ and $\Delta y_{ch,Z}$ due to the negative wake, and an excess at $\Delta\phi_{ch,Z} \sim \pi$ due to the positive wake. This model provides a good description of the central PbPb data. However, if the wake contribution is excluded, the HYBRID model does not agree with data, particularly in the low-p_T region for $\Delta\phi_{ch,Z} \sim 0$ and $\Delta y_{ch,Z} \sim 0$. The JEWEL model correctly predicts the peak structure at $\Delta\phi_{ch,Z} = \pi$ as a result of medium recoils, which emphasizes their impact on the azimuthal distribution. Additionally, the dip in $\Delta y_{ch,Z}$ on the Z boson side is also linked to medium recoils. Without medium recoils, JEWEL fails to describe the data. The PYQUEN model predicts smaller modifications of the charged-hadron spectra and fails to describe the dip structures at small $\Delta\phi_{ch,Z}$ and $\Delta y_{ch,Z}$ due to a lack of energy-momentum conservation. The CO-LBT model provides a reasonable description of the $\Delta\phi_{ch,Z}$ spectra in the three ranges of p_T^{ch}. However, this model predicts a larger (i.e., less negative) normalized associated yield at small $\Delta y_{ch,Z}$ compared to the data in the range $1 < p_T^{ch} < 4$ GeV . Finally, the PbPb data are compared to events simulated using PYTHIA 8 with a selection of $p_T^Z > 20$ GeV, where the value is selected to roughly match the high-p_T^{ch} normalized associated yield distribution. This comparison is intended to determine if the higher energy quenched jets in the data, which have $p_T^Z > 40$ GeV, resemble lower energy jets in vacuum generated by the PYTHIA 8 simulation. For charged particles with $1 < p_T^{ch} < 2$ GeV, the lower-p_T^Z PYTHIA predictions do not match the PbPb data, indicating that quenched jets do not resemble lower-p_T vacuum-like jets.

Based on the comparisons of model predictions with the PbPb data, a better description is found using theoretical models that include medium-recoil effects. In addition, a very poor description is found using simulations of lower-energy vacuum jets.

These results provide the first evidence of the presence of medium recoil and hole effects around the Z boson. However, greater statistical precision would be needed to determine which of the theoretical models including medium-recoil effects best matches the data.

8. Summary

This Letter presents the first measurement of correlations between Z bosons and charged hadrons in bins of charged-hadron transverse momentum (p_T) and event centrality for lead-lead (PbPb) collisions at a

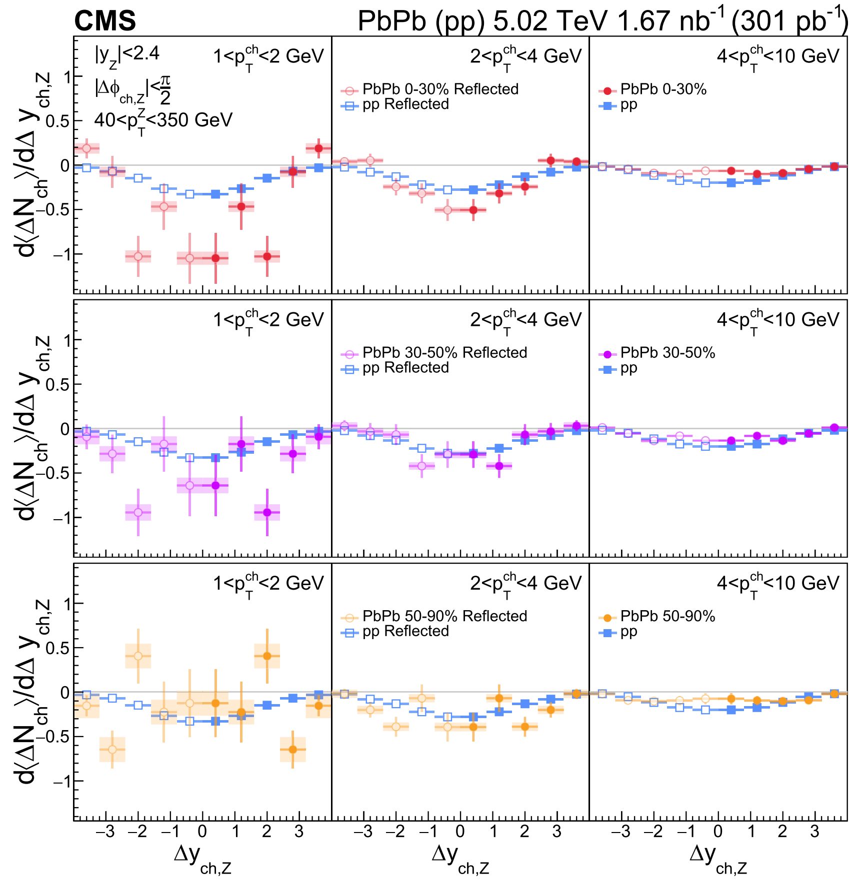

Fig. 2. The $\Delta y_{\mathrm{ch,Z}}$ spectra in the Z boson side ($|\Delta\phi_{\mathrm{ch,Z}}| < \pi/2$) for events with Z boson $p_T^Z > 40$ GeV in pp and PbPb collisions. The filled circles (squares) are the PbPb (pp) data and the open circles (squares) are reflected data. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The results are presented in centrality intervals of 0–30% (top row, red), 30–50% (middle row, purple), and 50–90% (bottom row, yellow) and in the charged-hadron p_T^{ch} intervals of 1–2 (left column), 2–4 (middle column) and 4–10 GeV (right column). The pp data are identical across panels with different centrality intervals.

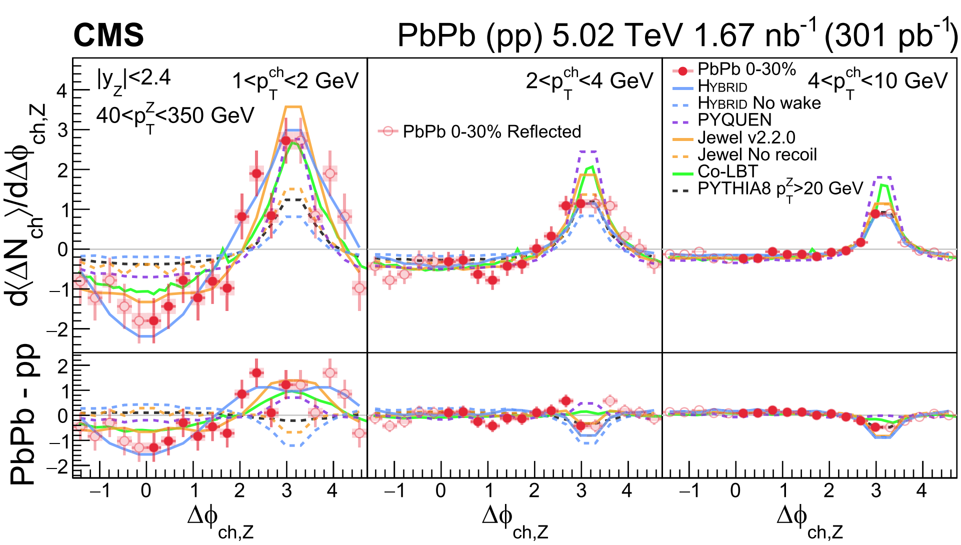

Fig. 3. Upper row: Distributions of $\Delta\phi_{\mathrm{ch,Z}}$ in 0–30% centrality PbPb collisions in the charged hadron p_T^{ch} intervals of 1–2 (left column), 2–4 (middle column) and 4–10 GeV (right column). Lower row: The differences between the PbPb and pp distributions. The filled circles are PbPb data and the open circles are reflected data. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The results are compared to predictions from theoretical models.

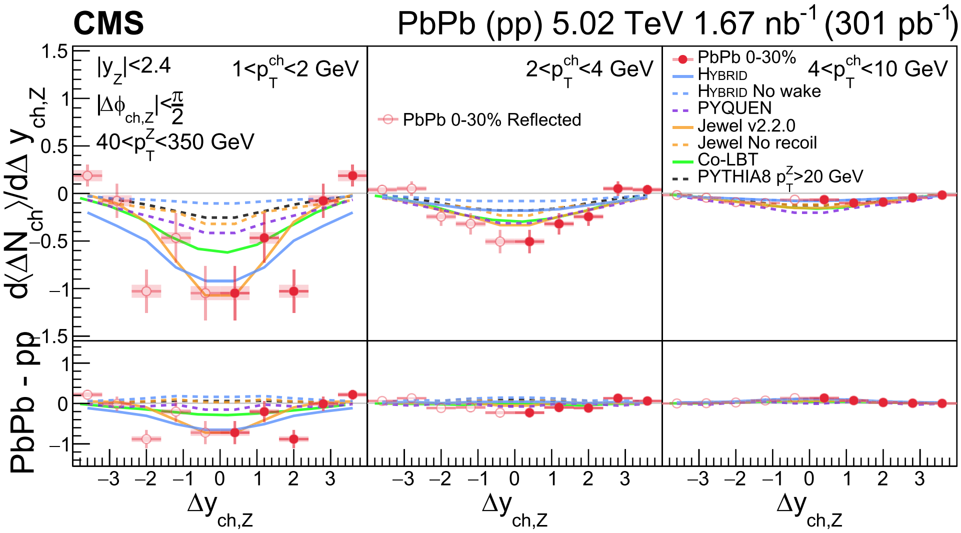

Fig. 4. Upper row: Distributions of $\Delta y_{\mathrm{ch,Z}}$ in 0–30% centrality PbPb collisions in the charged hadron $p_{\mathrm{T}}^{\mathrm{ch}}$ intervals of 1–2 (left column), 2–4 (middle column) and 4–10 GeV (right column). Lower row: The differences between the PbPb and pp distributions. The filled circles are PbPb data and the open circles are reflected data. The vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The results are compared to predictions from theoretical models.

nucleon-nucleon center of mass energy of 5.02 TeV and proton-proton (pp) collisions at the same energy. By studying the hadrons produced along with the Z boson, the analysis probes parton-medium interactions, including modifications to parton showers and medium response. The charged-hadron rapidity and azimuthal angle distributions relative to the direction of Z bosons with $40 < p_{\mathrm{T}}^{\mathrm{Z}} < 350$ GeV are extracted. The analysis utilizes pp (PbPb) data from 2017 (2018) with an integrated luminosity of 301 pb^{-1} (1.67 nb^{-1}).

The normalized associated yield of charged hadrons in Z boson-tagged events is measured in bins of the differences in azimuthal angle ($\Delta\phi_{\mathrm{ch,Z}}$) and in rapidity ($\Delta y_{\mathrm{ch,Z}}$) and is compared between the PbPb and reference pp data. For low-p_{T} ($1 < p_{\mathrm{T}} < 2$ GeV) charged hadrons in PbPb collisions, a dip at $\Delta\phi_{\mathrm{ch,Z}} \sim 0$ indicates the presence of a negative medium wake or medium holes. An excess at $\Delta\phi_{\mathrm{ch,Z}} \sim \pi$ suggests medium-induced radiation, medium recoils, and/or momentum-broadening effects. Central PbPb collisions show larger modulation in the $\Delta\phi_{\mathrm{ch,Z}}$ distribution than pp data for these low-p_{T} charged hadrons, a difference which diminishes in more peripheral events. For particles with higher p_{T} (of $4 - 10$ GeV), a reduction in the jet-side normalized associated yield is consistent with jet quenching. The $\Delta y_{\mathrm{ch,Z}}$ distribution shows significant deviations in central PbPb collisions with respect to the pp reference, especially at low charged-hadron p_{T}, where the PbPb yield is lower than that in pp collisions near the Z boson ($|\Delta y_{\mathrm{ch,Z}}| \sim 0$).

The PbPb data are then compared to a variety of theoretical models including different implementations of jet energy loss and the medium response. Models that do not include medium response effects fail to describe the dip in the data at small $\Delta\phi_{\mathrm{ch,Z}}$ and $\Delta y_{\mathrm{ch,Z}}$ expected from negative response contributions, and an excess at $\Delta\phi_{\mathrm{ch,Z}} \sim \pi$ due to the positive response contributions. In comparison, the models including such response effects provide a better description of the PbPb data. Amongst the different medium response implementations, for example that of a hydrodynamic positive and negative wake or medium recoils with corresponding hole contributions, it is not clear within the current statistical uncertainty which provides the best description of the data.

Overall, the differences between the PbPb and pp data, with a significance greater than 3σ, provide the first evidence of medium-recoil and medium-hole effects caused by a hard probe since the PbPb data are better described by theoretical models that include these effects. Comparisons with theoretical models highlight the unique insights these approaches offer into the properties of the QGP medium, especially its response to the energy loss experienced by partons which pass through it.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.physletb.2025.140120.

Appendix

The CMS Collaboration

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