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Observation of the jet diffusion wake using dijets in heavy ion collisions

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Abstract

Energetic quarks and gluons traversing a hot and dense quark-gluon plasma deposit energy and momentum into the medium before hadronizing to collimated sprays of particles, known as jets. This energy-momentum deposition is expected to produce medium responses, collectively known as jet wakes, with “diffusion wake” denoting a depletion of particles in the direction opposite to the propagating jet. These phenomena are studied by comparing dijet-hadron correlations measured in lead-lead (PbPb) and proton-proton (pp) collisions to assess jet-induced modifications of bulk particle production. The analysis uses PbPb and pp data recorded at a nucleon-nucleon center-of-mass energy $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ with the CMS detector at the CERN LHC. By exploring how the dijet-hadron correlation distributions differ for various pseudorapidity separations of the two jets in the dijet, the presence of a jet diffusion wake is firmly established. The wake has a significance greater than 5 standard deviations for charged particles in the transverse momentum range $1 < p_{\mathrm{T}} < 2\,\mathrm{GeV}$. The measurements are compared with various model predictions with and without jet wake effects, providing new insights into quark-gluon plasma properties and the formation of jet-induced wakes.

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Jets are collimated streams of particles resulting from hard-scattered quarks and gluons, collectively known as partons, and are effective probes of the quark-gluon plasma (QGP) [1]. The QGP, a hot and dense form of matter consisting of deconfined quarks and gluons, is created in ultrarelativistic heavy ion collisions, and its study enables experimental tests of quantum chromodynamics. The opacity of the QGP to the propagation of partonic probes causes substantial energy loss for the partons that traverse the hot medium. This energy loss manifests itself in various experimental observables, such as suppression of high transverse momentum (p_{T}) hadrons and jets, as well as modifications in the features of parton showers. Collectively referred to as jet quenching, these phenomena were first observed at the BNL RHIC [2, 3] and later at the CERN LHC [4–6].

Jet quenching processes and their impact on jet substructure observables have been studied extensively [7–9]. However, separating the modifications of jets from jet-induced changes in the medium is often nontrivial. It is theoretically clear that both types of modification coexist in the presence of a QGP medium. Disentangling them will help improve the precision of QGP transport coefficients and enhance our understanding of medium evolution and dynamics.

Jet-medium interactions have long been predicted to create a Mach cone like effect in the QGP [10–20]. Until recently, experimental attempts to observe this effect remained inconclusive, in large part because both the Mach cone and medium-induced modifications to the jet shower appear in the direction of jet propagation and mix, masking the signal. However, a related effect producing a depletion of particles in the opposite direction of the propagating jet, known as a "diffusion" wake, is also expected [21–26]. The first evidence of a diffusion wake using Z-boson-hadron correlations was reported by the CMS experiment [26]. The use of the colorless boson, which does not interact with the QGP, allowed isolation of the diffusion wake from other medium effects. Similarly, the ATLAS experiment searched for the diffusion wake effect in photon-jet events but found no significant evidence within current uncertainties [25].

Recent theoretical developments [27, 28] have proposed the use of dijet events, where the two jets are back-to-back in azimuthal angle (φ), but chosen to be separated in pseudorapidity (η), to resolve the ambiguity by spatially separating the jet modification and diffusion wake. Specifically, the rapidity asymmetry of dijet-hadron correlations for a selection of dijets having a sizeable η separation relative to dijets without any separation is predicted to give a robust signal of the diffusion wake.

This Letter presents the first measurement of the QGP diffusion wake using dijet events. A sample of lead-lead (PbPb) collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ is used for signal extraction. A reference measurement is derived from proton-proton (pp) collisions at the same energy. Data samples, corresponding to integrated luminosities of $0.66\,\mathrm{nb}^{-1}$ for PbPb collisions and $299\,\mathrm{pb}^{-1}$ for pp collisions [29, 30], were collected with the CMS detector at the LHC during 2018 and 2017, respectively. Dijets are defined as the two highest p_{T} back-to-back jets, labeled "jet$_1$" (leading) and "jet$_2$" (subleading). The back-to-back requirement is that the azimuthal angle separation of the two jets satisfies $\Delta\varphi^{\mathrm{jet}_1,\mathrm{jet}_2} > 5\pi/6$. For samples requiring different η separations between the two jets in the dijet, the distributions of charged particles relative to the leading jet axis direction are studied as functions of $\Delta\eta^{\mathrm{ch,\,jet}_1}$ and $\Delta\varphi^{\mathrm{ch,\,jet}_1}$, where the "ch" superscript denotes charged particles. To isolate the diffusion wake effect, the correlation distributions obtained for dijets with a small η gap are subtracted from those with large gaps. The resulting distributions from PbPb events are compared to those measured using pp collisions. The results are presented differentially in charged-particle $p_{\mathrm{T}}^{\mathrm{ch}}$ and PbPb collision centrality, defined as the percentile of the total inelastic hadronic cross section (with 0% corresponding to the most central collisions). The diffusion wake signal, seen as a depletion of the particle yield in the underlying-event (UE) distribution, is extracted and compared to theoretical models with and without medium effects. The tabulated results are provided in the HEPData record for this analysis [31].

The CMS apparatus [32, 33] is a multipurpose, nearly hermetic detector designed to trigger on [34–36] and identify electrons, muons, photons, and (charged and neutral) hadrons [37–39]. A global "particle-flow" algorithm [40] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic, and a brass and scintillator calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Reconstructed particles are used to build τ leptons, jets, and missing p_{T} [41–43]. The silicon tracker measures charged particles within the η range $|\eta| < 3.0$. For the data samples in this study, the silicon tracker consisted of 1856 silicon pixels and 15,148 silicon strip detector modules. Details on the pixel detector can be found in Ref. [44]. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 3.0$, the track resolutions are typically 1.5% in p_{T} and 20–75 μm in the transverse impact parameter [45]. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$.

The pp and PbPb samples were selected with a calorimeter-based trigger that uses the anti-k_{T} jet clustering algorithm with a distance parameter of $R = 0.4$ [46]. This trigger selected events containing at least one jet with $p_{\mathrm{T}} > 80\,\mathrm{GeV}$ and is fully efficient for events with reconstructed jets of $p_{\mathrm{T}} > 130\,\mathrm{GeV}$. The same data samples are used to correct for the limited jet and track acceptance via the mixed-event technique [47–52].

The PbPb and pp events selected for further analysis must have at least one primary interaction vertex containing at least two tracks [39] located within 15 cm of the nominal interaction point along the beam axis. Each PbPb event must have at least two detector elements (towers) in each HF detector that contain energy deposits exceeding 4 GeV per tower to remove contamination from ultraperipheral collisions [53]. The shapes of the clusters in the pixel detector are required to be compatible with those expected in PbPb collisions [54]. Background events from beam-gas interactions and other nonhadronic collisions are removed offline using the criteria described in Ref. [55] for both PbPb and pp collisions. Collision centrality is determined based on the total sum of transverse energy (defined as $E_{\mathrm{T}} = E/\cosh\eta$, where E is the measured energy) detected in the HF region covering $2.9 < |\eta| < 5.2$. Reference [4] provides a detailed description of the centrality determination. Events in PbPb collisions are divided into three centrality intervals: 0–30% (most central), 30–50%, and 50–80% (most peripheral).

Simulated Monte Carlo (MC) events are used to correct for reconstruction and detector resolution-related effects. The PYTHIA 8.226 [56] event generator, configured with the CP5 tune [57] and NNPDF3.1 parton distribution functions at next-to-next-to-leading order [58], models the hard scattering processes, parton showering, and hadronization that produce jets of interest. These events are also embedded into simulated minimum bias PbPb collisions, generated using HYDJET 1.9 [59] to represent the soft underlying activity in PbPb collisions. The HYDJET generator is fine-tuned to reproduce key characteristics of PbPb events: namely the hadron p_{T} distribution and particle multiplicity. The data set combining PYTHIA hard interactions and HYDJET underlying events, is referred to as PYTHIA+HYDJET. The CMS detector response is simulated using the GEANT4 [60] toolkit.

In PbPb collisions, dijets are produced more frequently in central events than in noncentral ones due to the larger number of binary nucleon-nucleon collisions per nuclear interaction. Since the HYDJET event generator simulates only minimum bias PbPb collisions, a centrality-based reweighting is applied to the PYTHIA+HYDJET sample to match the centrality distribution of the jet-triggered PbPb data. Additionally, a reweighting procedure is performed to match the distribution of the primary vertex position along the beam direction between the MC simulations and the data.

Jet reconstruction is performed by the anti-k_T jet algorithm with a distance parameter of $R = 0.4$, as implemented in the FASTJET framework [61], using particles reconstructed by the particle-flow algorithm. The constituent subtraction method [62] is used to remove UE contributions. The jet axis direction in η–φ is determined for each jet by the vector sum of the four-momenta of its constituent particles.

Jet energy corrections are derived from MC to make the average reconstructed jet energy identical to that of particle-level jets. In situ measurements of the dijet momentum balance from pp collisions are used for evaluating and correcting any residual differences between the jet energy scale (JES) in data and MC simulation [42]. Additional selection criteria are applied to remove jets potentially dominated by instrumental effects or reconstruction failures [63].

After jet reconstruction and energy corrections, leading jets are required to satisfy $p_T^{jet_1} > 130\,GeV$ and $|\eta^{jet_1}| < 1.0$. Subleading jets must fulfill $p_T^{jet_2} > 50\,GeV$ and $|\eta^{jet_2}| < 2.0$, in addition to the back-to-back requirement $\Delta\varphi^{jet_1,jet_2} > 5\pi/6$. This kinematic selection ensures full trigger efficiency and optimal jet energy resolution (JER). The dijet sample is divided based on the η separation of leading and subleading jets, with $|\Delta\eta^{jet_1,jet_2}| < 0.5$ representing small gaps and $|\Delta\eta^{jet_1,jet_2}| \in (0.5, 1.0)$, $|\Delta\eta^{jet_1,jet_2}| \in (1.0, 1.5)$, and $|\Delta\eta^{jet_1,jet_2}| \in (1.5, 2.0)$ representing large gaps.

The reconstruction of charged-particle tracks is described in Ref. [39]. Tracks with $1 < p_T^{ch} < 2$ and $2 < p_T^{ch} < 4\,GeV$ within $|\eta^{ch}| < 2.4$ are used, and only high-purity tracks [39] with relative p_T^{ch} uncertainty below 10% are considered. In PbPb collisions, tracks must have at least 11 hits in the tracker layers and a χ^2 per degree of freedom per silicon-detector layer below 0.18. The distance of closest approach to the primary vertex in both the x–y plane and the z direction must have a significance below three standard deviations to reduce secondary-track contributions.

Correlations between the charged-particle tracks and the leading jet direction are constructed following Refs. [48–52]. Distributions are formed in the ($\Delta\eta^{ch,\,jet_1}$, $\Delta\varphi^{ch,\,jet_1}$) space for each of the two p_T^{ch} bins. Following Ref. [28], an η ordering of $\eta^{jet_1} > \eta^{jet_2}$ is enforced; a reflection of the correlation distribution is made via the reversal of the sign of $\Delta\eta^{ch,\,jet_1}$ when this condition is not satisfied. The correlated yields are normalized by the number of dijet pairs and corrected for tracking efficiency and misreconstruction on a per-track basis, following the procedure outlined in Ref. [55]. This results in a per-jet averaged correlation distribution as a function of $\Delta\eta^{ch,\,jet_1}$ and $\Delta\varphi^{ch,\,jet_1}$. Pair-acceptance effects due to limited detector acceptance are corrected using a mixed-event method, in which the leading jet from one event is paired with charged particles from 30 other dijet events selected randomly. This number of random samples ensures that all kinematic bins are adequately populated. To ensure proper acceptance matching, mixing is performed only between events with similar primary vertex positions along the beam axis (within 0.5 cm) and collision centrality (within 0.5%).

Additional corrections typically applied to account for jet position resolution and selection biases (favoring jets with harder constituents or those affected by upward p_T fluctuations) are omitted, as they cancel when subtracting correlation distributions with large and small η gaps and do not affect the charged-particle densities in the UE, which is the focus of this study. The jet selections are made without corrections for detector resolution, as the observable is found to be insensitive to jet energy resolution effects. Examples of the final correlation distributions for pp and 0–30% PbPb collisions are shown in Appendix A.

Two peaks are observed in the resulting correlations, as shown in Fig. A.1. The near-side ($\Delta\varphi^{\mathrm{ch,\,jet_1}} \approx 0$) peak is associated with leading-jet particles, while the away-side ($\Delta\varphi^{\mathrm{ch,\,jet_1}} \approx \pi$) peak corresponds to the subleading jet. Because $\eta^{\mathrm{jet_1}} > \eta^{\mathrm{jet_2}}$, the away-side jet peak and the associated diffusion wake would always appear in the negative $\Delta\eta^{\mathrm{ch,\,jet_1}}$ region. For small dijet η gaps, the correlation distribution (denoted as $\mathrm{R^{sym}}$) is roughly symmetric in $\Delta\eta^{\mathrm{ch,\,jet_1}}$, with both peaks located around $\Delta\eta^{\mathrm{ch,\,jet_1}} \approx 0$. Consequently, the diffusion wakes are hidden by the jet peaks, and no wake signal is visible. In contrast, for large η gaps, the away-side peak and its diffusion wake are displaced toward a larger negative $\Delta\eta^{\mathrm{ch,\,jet_1}}$. The subleading-jet wake then manifests as a dip in the near-side correlation, while the leading-jet wake appears as a dip on the away side in the asymmetric distribution, $\mathrm{R^{asym}}$.

Near-side ($|\Delta\varphi^{\mathrm{ch,\,jet_1}}| < \pi/2$) projections of the two-dimensional correlations onto $\Delta\eta^{\mathrm{ch,\,jet_1}}$ are used to isolate the wake signal. The long-range uncorrelated background is estimated from the positive $\Delta\eta^{\mathrm{ch,\,jet_1}}$ region ($1.5 < \Delta\eta^{\mathrm{ch,\,jet_1}} < 2.5$) similar to previous jet–track correlation studies [48–52] and subtracted separately for $\mathrm{R^{sym}}$ and $\mathrm{R^{asym}}$. In this region, no wake signal is expected due to the η ordering requirement $\eta^{\mathrm{jet_1}} > \eta^{\mathrm{jet_2}}$. The resulting $\mathrm{R^{sym}}$ distribution is then subtracted from $\mathrm{R^{asym}}$, isolating the diffusion wake signal [28]. The away-side correlation for the case of asymmetric dijets also shows wake-like yield depletion, but the different position of the away-side jet peak in large and small η gap samples prevents signal extraction in a data-driven manner.

Various sources of systematic uncertainties are considered. The signal is largely insensitive to jet reconstruction systematic uncertainties, namely, the JES and JER. In the data, variations of the JES within its uncertainty and smearing of the jet momentum according to the JER uncertainty produce results consistent with the nominal values, indicating that these effects are negligible. In MC simulations without medium effects, the UE shows no variation with respect to the subleading jet location, as expected, and closure tests (ratios of reconstructed to particle-level signals) are consistent with unity.

Systematic uncertainties arise from the tracking efficiency determination, pair acceptance corrections, and residual UE mismatches between small- and large-gap dijet selections. The tracking efficiency uncertainty is estimated by comparing response to variations in track selections between data and MC simulation [55], resulting in uncertainties of 5% (2.5%) for PbPb (pp) events [26]. The largest observed per-$\Delta\eta^{\mathrm{ch,\,jet_1}}$ difference is conservatively applied to all $\Delta\eta^{\mathrm{ch,\,jet_1}}$ bins, corresponding to an absolute uncertainty ranging from 0 to 0.025 across different $p_{\mathrm{T}}^{\mathrm{ch}}$, centrality, and dijet η gap intervals. Pair-acceptance uncertainties are quantified by examining long-range $\Delta\eta^{\mathrm{ch,\,jet_1}}$-dependent asymmetries in the mixed-event-corrected $\mathrm{R^{sym}}$ distribution, using differences between the negative and positive sidebands ($-2.5 < \Delta\eta^{\mathrm{ch,\,jet_1}} < -1.5$ and $1.5 < \Delta\eta^{\mathrm{ch,\,jet_1}} < 2.5$), with an absolute uncertainty ranging from 0 to 0.01. Residual UE levels are estimated by comparing the subtracted distributions in the positive $\Delta\eta^{\mathrm{ch,\,jet_1}}$ region using different $\Delta\varphi^{\mathrm{ch,\,jet_1}}$ ranges to perform the projection from the two-dimensional to one-dimensional correlations. The varied ranges ($0 < \Delta\varphi^{\mathrm{ch,\,jet_1}} < \pi$ and $13\pi/20 < \Delta\varphi^{\mathrm{ch,\,jet_1}} < 3\pi/2$) were chosen for their sensitivity to long-range correlations. The resulting absolute uncertainty ranges from 0.01 to 0.04. The subtracted UE level addresses uncorrelated background contributions and therefore is flat; the assigned uncertainty reflects the degree to which it can be constrained by the data. The effects of the centrality calibration, evaluated by varying the minimum bias event selection efficiency of the HF calorimeters [7], are negligible. The residual UE level mismatch provides the dominant contribution to the systematic uncertainty, followed by the tracking efficiency and pair-acceptance corrections. Uncertainties from all above sources are added in quadrature for the total systematic uncertainty.

Figure 1 shows the near-side correlation differences $\mathrm{R}^{\mathrm{asym}} - \mathrm{R}^{\mathrm{sym}}$ for pp and PbPb collisions, with $\mathrm{R}^{\mathrm{asym}}$ having $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| \in (1.0, 1.5)$. In the region of interest, $-2.4 < \Delta\eta^{\mathrm{ch,\,jet}_1} < -0.6$, the pp distributions are approximately flat, with minimal deviation from zero. In contrast, PbPb collisions show a pronounced dip, most prominent at low $p_{\mathrm{T}}^{\mathrm{ch}}$. The strength of the depletion increases from peripheral (50–80%) to central (0–30%) collisions. The pp and 50–80% PbPb results are statistically consistent, whereas the 0–30% PbPb data for $1 < p_{\mathrm{T}}^{\mathrm{ch}} < 2\,\mathrm{GeV}$ lie significantly below the pp reference. A similar depletion is expected and is visible on the away-side of $\mathrm{R}^{\mathrm{asym}}$ (as shown in the lower right panel of Fig. A.1); however, the displacement of the away-side peaks observed in $\mathrm{R}^{\mathrm{sym}}$ and $\mathrm{R}^{\mathrm{asym}}$ precludes a direct subtraction.

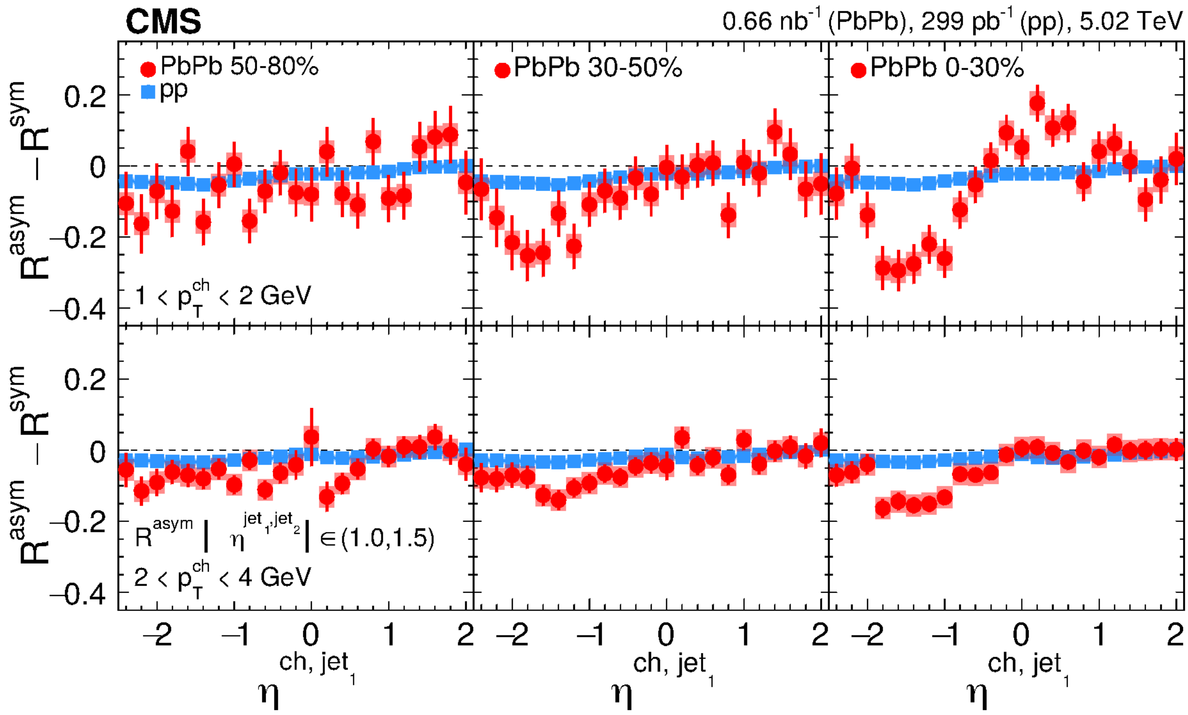

Figure 1: The difference of the near-side charged-particle yields $\mathrm{R}^{\mathrm{asym}} - \mathrm{R}^{\mathrm{sym}}$ as a function of $\Delta\eta^{\mathrm{ch,\,jet}_1}$ in pp (blue squares) and different centrality PbPb collisions (red circles), with the most central (0–30%) shown in the right panels. Results are shown for two $p_{\mathrm{T}}^{\mathrm{ch}}$ ranges: $1 < p_{\mathrm{T}}^{\mathrm{ch}} < 2\,\mathrm{GeV}$ (upper) and $2 < p_{\mathrm{T}}^{\mathrm{ch}} < 4\,\mathrm{GeV}$ (lower). Solid vertical lines (shaded areas) show statistical (systematic) uncertainties.

Figure 2 quantifies the medium modification of the yield difference $\mathrm{R}^{\mathrm{asym}} - \mathrm{R}^{\mathrm{sym}}$ by subtracting the pp data from 0–30% PbPb results. For the $1 < p_{\mathrm{T}}^{\mathrm{ch}} < 2\,\mathrm{GeV}$ data, the mean position of the observed depletion shifts toward negative $\Delta\eta^{\mathrm{ch,\,jet}_1}$ as the $\mathrm{R}^{\mathrm{asym}}$ $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}|$ selection increases from $(0.5, 1.0)$ to $(1.5, 2.0)$. Medium-induced jet peak modifications and out-of-cone radiation can interfere with the diffusion wake signal, reducing the strength of the depletion for smaller gaps. As a result, larger $\Delta\eta^{\mathrm{ch,\,jet}_1}$ gaps are expected to exhibit stronger diffusion wake signals, an effect which can be seen in Fig. 2. The results for $2 < p_{\mathrm{T}}^{\mathrm{ch}} < 4\,\mathrm{GeV}$ with $\mathrm{R}^{\mathrm{asym}}|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| \in (1.0, 1.5)$ are shown in the lower panel of the same figure, showing reduced diffusion wake strength consistent with theoretical expectations.

Figure 2 also presents comparisons with theoretical models. The PYTHIA model with the CP5 tune (green bands) shows no $\Delta\eta^{\mathrm{ch,\,jet}_1}$ dependence, as expected in the absence of jet-medium

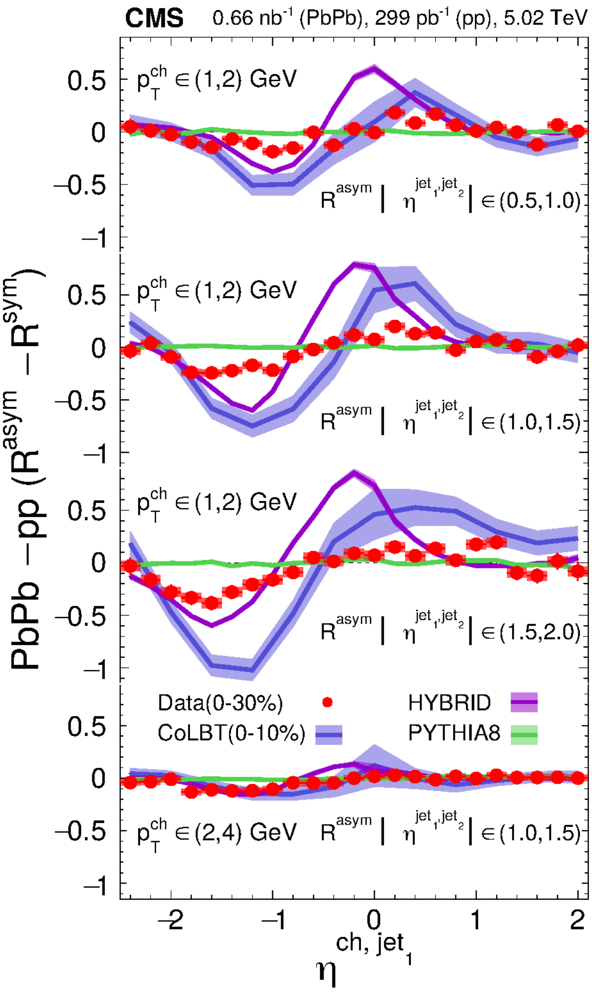

Figure 2: The difference between PbPb and pp collisions for the particle yield difference observable ($R^{asym} - R^{sym}$) as a function of $\Delta\eta^{ch,\,jet_1}$ for central (0–30%) collisions. Results for $1 < p_T^{ch} < 2\,GeV$ are shown for $R^{asym}|\Delta\eta^{jet_1,jet_2}| \in (0.5, 1.0)$ (upper panel), $|\Delta\eta^{jet_1,jet_2}| \in (1.0, 1.5)$ (upper middle panel), and $|\Delta\eta^{jet_1,jet_2}| \in (1.5, 2.0)$ (lower middle panel). The result for $2 < p_T^{ch} < 4\,GeV$ with $R^{asym}|\Delta\eta^{jet_1,jet_2}| \in (1.0, 1.5)$ is shown in the lower panel. Predictions from the PYTHIA [56–59], HYBRID [64, 65], and CoLBT-hydro [66] models are shown as colored bands. Solid vertical lines (shaded areas) show statistical (systematic) uncertainties. For the models, only statistical uncertainties are shown.

interactions or quenching effects. The HYBRID model, combining DGLAP-based weakly coupled jet evolution with strongly coupled interactions between jet constituents and the QGP [64], is shown as purple bands for the fully incoherent energy loss scenario [65]. The model overpredicts the observed depletion for $1 < p_T^{ch} < 2\,GeV$, while better capturing the data trends for $2 < p_T^{ch} < 4\,GeV$. The enhancement near $\Delta\eta^{ch,\,jet_1} \approx 0$ arises in the model from the diffusion wake caused by the subleading jet that should reduce the near-side peak magnitude in R^{sym}, where the leading and subleading jets occupy similar η regions, unlike in R^{asym}. A much smaller enhancement than predicted by the HYBRID model is observed in 0–30% central data for $1 < p_T^{ch} < 2\,GeV$. The CoLBT-hydro model (blue bands) describes jet propagation and jet-induced medium excitation by coupling linear Boltzmann transport for parton energy loss with a (3+1)D hydrodynamic evolution of the QGP [66]. For this model, predictions are available for 0–10% central collisions. Similarly to HYBRID, it overpredicts both the negative and positive yields. The predicted $\Delta\eta^{ch,\,jet_1}$ location of the mean position of the negative dip appears to be captured by both the HYBRID and CoLBT models.

Figure 3 quantifies the centrality and p_T^{ch} dependences of the diffusion wake signal using medium-modified correlated yields integrated over $-2.4 < \Delta\eta^{ch,\,jet_1} < -0.6$ for $R^{asym}|\Delta\eta^{jet_1,jet_2}| \in (1.0, 1.5)$ and $R^{asym}|\Delta\eta^{jet_1,jet_2}| \in (1.5, 2.0)$. The depletion of the yields is greatest in 0–30% collisions, with the $1 < p_T^{ch} < 2\,GeV$ data deviating from zero by more than five standard deviations for both $|\Delta\eta^{jet_1,jet_2}|$ selections based on a χ^2 test. The yield depletion is smaller for more peripheral collisions, higher p_T^{ch} selections, and smaller dijet η separations. The diffusion wake effect in the QGP is the only known mechanism capable of producing such structures in the UE distribution in the direction opposite to the propagating jet, and therefore, this work provides an observation of the diffusion wake effect in the QGP.

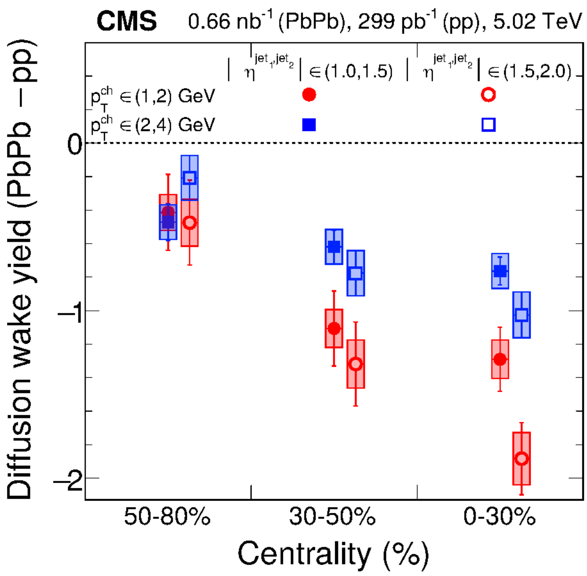

Figure 3: Charged-particle yield difference integrated over $-2.4 < \Delta\eta^{ch,\,jet_1} < -0.6$ as a function of PbPb collision centrality for $|\Delta\eta^{jet_1,jet_2}| \in (1.0, 1.5)$ (closed markers) and $|\Delta\eta^{jet_1,jet_2}| \in (1.5, 2.0)$ (open markers). Red markers indicate $1 < p_T^{ch} < 2\,GeV$, and blue markers indicate $2 < p_T^{ch} < 4\,GeV$. Solid vertical lines (shaded areas) show statistical (systematic) uncertainties.

In summary, we report the first observation of the diffusion wake using dijets in heavy ion collisions. The measurements use pseudorapidity-separated dijets in lead-lead (PbPb) and proton-proton (pp) collisions at a center-of-mass energy per nucleon pair of 5.02 TeV. Charged-particle correlations were studied relative to the highest transverse momentum (p_T) jet of each dijet.

Correlations are measured for dijets with different pseudorapidity separations, and the difference between correlations from large and small separation samples is used for the jet diffusion wake extraction. When isolating medium modifications by examining the difference between PbPb and pp collisions, a pronounced depletion of charged-particle yields is observed in the region where a wake signal is expected. The integrated signal for low-p_T charged particles ($1 < p_T^{ch} < 2$ GeV) in central collisions deviates from zero with a significance exceeding 5 standard deviations. The depletion is less pronounced in more peripheral collisions and when examining a higher p_T^{ch} selection. Theoretical models incorporating jet energy loss and medium response show qualitatively similar trends with magnitudes that are larger than what is seen in the data, whereas models without jet-medium interactions do not show any depletion. This observation of the diffusion wake offers new insights into quark-gluon plasma properties and jet-induced medium response.

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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.

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A Two-dimensional angular correlations

Figure A.1 shows the two-dimensional distributions of charged-particle yields in pp and 0–30% PbPb collisions for $1 < p_{\mathrm{T}}^{\mathrm{ch}} < 2\,\mathrm{GeV}$, as functions of $\Delta\eta^{\text{ch, jet}_1}$ and $\Delta\varphi^{\text{ch, jet}_1}$ relative to the leading jet. Distributions for small ($\mathrm{R}^{\mathrm{sym}}$ $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| < 0.5$) and large ($\mathrm{R}^{\mathrm{asym}}$ $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| \in (1.0, 1.5)$) dijet η gaps are shown. Charged-particle tracks associated with the fragmentation of the leading jet produce a peak near $(\Delta\eta^{\text{ch, jet}_1}, \Delta\varphi^{\text{ch, jet}_1}) \approx (0, 0)$, while those from the subleading jet cluster around $(\Delta\eta^{\text{ch, jet}_1}, \Delta\varphi^{\text{ch, jet}_1}) \approx (0, \pi)$ or $(-1, \pi)$ for small and large η gaps, respectively. These distributions are then projected onto $\Delta\eta^{\text{ch, jet}_1}$ to isolate the wake signal.

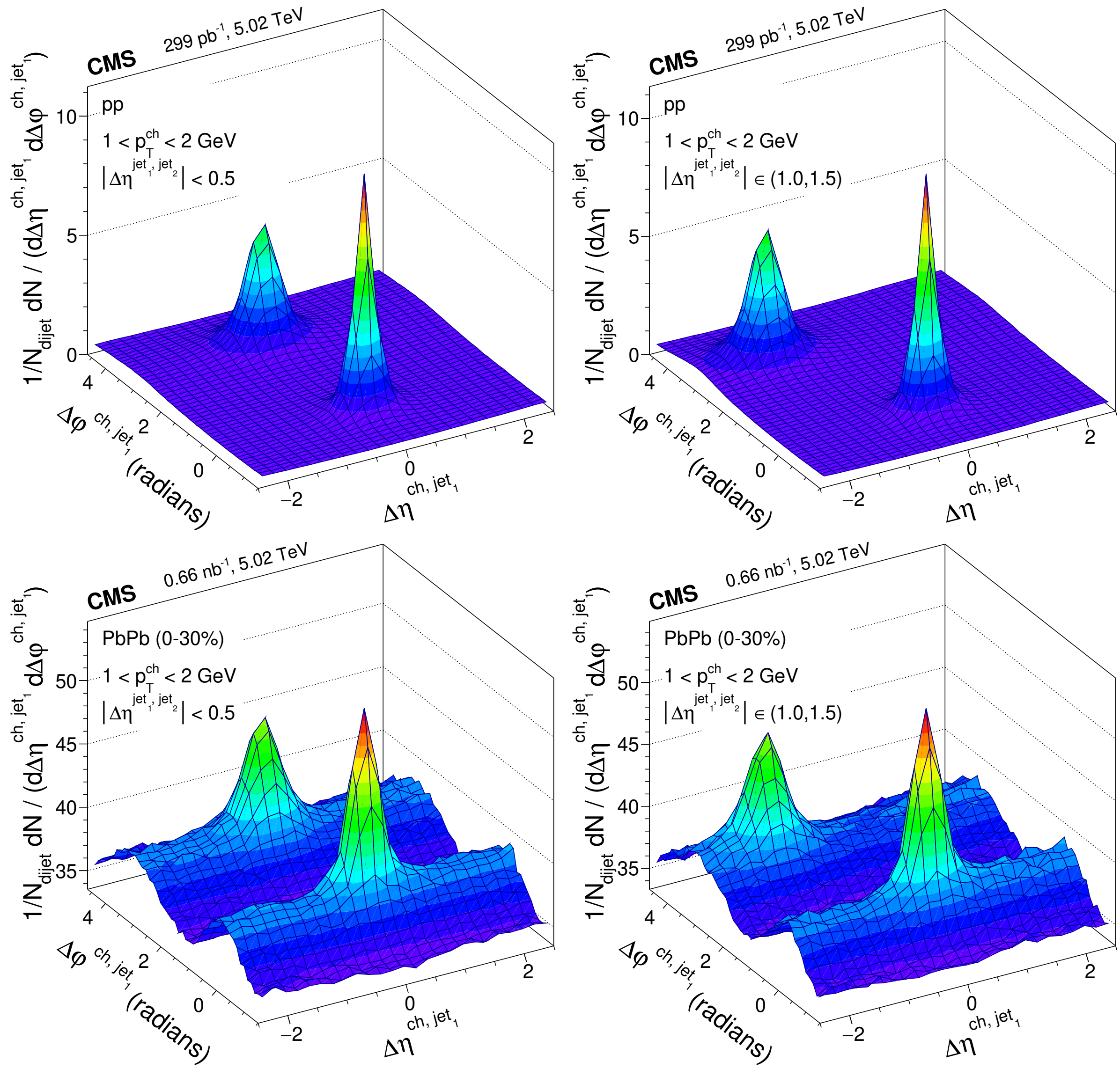

Figure A.1: Distributions of charged-particle yields with $1 < p_{\mathrm{T}}^{\mathrm{ch}} < 2\,\mathrm{GeV}$ as functions of $\Delta\eta^{\text{ch, jet}_1}$ and $\Delta\varphi^{\text{ch, jet}_1}$, measured relative to the leading jet direction in pp (upper panels) and 0–30% PbPb (lower panels) collisions. The left (right) column shows the results for small ($\mathrm{R}^{\mathrm{sym}}$ $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| < 0.5$) and large ($\mathrm{R}^{\mathrm{asym}}$ $|\Delta\eta^{\mathrm{jet}_1,\mathrm{jet}_2}| \in (1.0, 1.5)$) dijet configurations.

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