



This is a repository copy of *Search for the jet-induced diffusion wake in the quark-gluon plasma via measurements of jet-track correlations in photon-jet events in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector.*

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/226183/>

Version: Published Version

Article:

Aad, G. orcid.org/0000-0002-6665-4934, Aakvaag, E. orcid.org/0000-0001-7616-1554, Abbott, B. orcid.org/0000-0002-5888-2734 et al. (2939 more authors) (2025) Search for the jet-induced diffusion wake in the quark-gluon plasma via measurements of jet-track correlations in photon-jet events in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. *Physical Review C*, 111 (4). 044909. ISSN 2469-9985

<https://doi.org/10.1103/physrevc.111.044909>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

Search for the jet-induced diffusion wake in the quark-gluon plasma via measurements of jet-track correlations in photon-jet events in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector

G. Aad *et al.**
(ATLAS Collaboration)



(Received 19 August 2024; accepted 25 March 2025; published 22 April 2025)

This paper presents a measurement of jet-track correlations in photon-jet events, using 1.72 nb^{-1} of Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV recorded with the ATLAS detector at the LHC. Events with energetic photon-jet pairs are selected, where the photon and jet are approximately back-to-back in azimuth. The angular correlation between jets and charged-particle tracks with transverse momentum (p_T) in the range 0.5–2.0 GeV in the hemisphere opposite to the jet, $|\Delta\phi(\text{jet}, \text{track})| > \pi/2$, is measured as a function of their relative pseudorapidity difference, $|\Delta\eta(\text{jet}, \text{track})|$. In central Pb+Pb collisions, these correlations are predicted to be sensitive to the diffusion wake in the quark-gluon plasma resulting from the lost energy of high- p_T partons traversing the plasma, with a characteristic modification as a function of $|\Delta\eta(\text{jet}, \text{track})|$. The correlations are examined with different selections on the jet-to-photon p_T ratio to select events with different degrees of energy loss. No diffusion wake signal is observed within the current sensitivity and upper limits at 95% confidence level on the diffusion wake amplitude are reported.

DOI: [10.1103/PhysRevC.111.044909](https://doi.org/10.1103/PhysRevC.111.044909)

I. INTRODUCTION

Collisions of high-energy nuclei at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) produce small droplets of quark-gluon plasma (QGP) [1]. These QGP droplets quickly expand and are well described as a near-perfect (i.e., nearly inviscid) fluid [2]. One of the primary signatures of QGP formation is the substantial energy lost by large transverse momentum (p_T) quarks and gluons passing through the QGP. This energy loss, often termed “jet quenching,” indicates the presence of a medium with large color opacity [3,4]. Numerous measurements at the RHIC and at the LHC, when combined with theoretical predictions, enable the extraction of the total amount of energy lost by these partons while traversing the QGP. This has been most recently achieved via the measurement of jet suppression in events tagged by prompt isolated photons, i.e., γ -jet observables [5].

When a high- p_T parton loses energy, it is important to understand how that energy is distributed in terms of radiated gluons, i.e., what is the overall modification of the parton shower. In addition, energy may also be transferred to the QGP fluid, which is well described by hydrodynamic models with very small dissipation. There are theoretical calculations predicting a “medium response,” including a Mach cone, a wake front (an enhanced amplitude of the medium in the

direction of the parton), and an associated diffusion wake (a depletion in the amplitude of the medium in the opposite direction) [6–8]. Measurements of this medium response would provide important constraints on the speed of sound and viscosity of the QGP. Many papers have detailed calculations of this medium response with different modeling of the lost energy and the QGP fluid itself [9–15].

As detailed in Ref. [15], there are significant challenges to experimentally confirm these different medium response signatures. The medium response in the direction of the parton competes with the modified parton shower and thus has not resulted in an unambiguous signature. Observations of enhanced low- p_T particle production and particles at larger angles relative to the jet have been reported [16–20]. However, their definitive attribution remains ambiguous.

In di-jet events, the diffusion wake (depletion) induced by one jet is contaminated from the wake (enhancement) of the other jet in the opposite direction, which may lead to a cancellation of observable effects. However, in Z/γ -jets events, the diffusion wake can be measured cleanly as Z/γ do not interact strongly in the plasma and thus produce no medium response of their own. Initial experimental results for Z -track correlations have been published [21,22], while Ref. [15] specifically proposes to search for the jet-induced diffusion wake in Z/γ -jets events. In this paper, the higher statistics γ -jet channel is pursued.

In Ref. [23], a new observable is suggested to aid in the separation of the medium response, in this case the diffusion wake, from other correlated particle production referred to as the multiparton interaction (MPI) contribution. Utilizing the coupled linear Boltzmann transport and hydrodynamics (CoLBT-hydro) framework [9], a fully three-dimensional medium response can be mapped out. This framework models γ -jet events and examines the correlation between the jet axis

*Full author list given at the end of the article.

$(\eta_{\text{jet}}, \phi_{\text{jet}})^1$ and low- p_T charged hadrons (η_h, ϕ_h). The absolute medium modification is then obtained by subtracting the correlation from the same hydrodynamic event without the γ -jet. The expected magnitude of the modification to the medium is of order 0.2% [23].

The proposal in Ref. [23] for separating the impacts of the diffusion wake and MPI is to examine this observable as a function of $x_{J\gamma} = p_T^{\text{jet}}/p_T^\gamma$. For events with lower $x_{J\gamma}$, the quark or gluon opposing the photon loses more energy on average in the medium and hence the diffusion wake is larger. On the other hand, the MPI effect, being an initial-state effect, has no dependence on the energy loss effect, i.e., it is independent of $x_{J\gamma}$. Thus testing the MPI independence on $x_{J\gamma}$ using proton-proton (pp) data is an important cross-check.

This paper presents jet-track angular correlations utilizing γ -jet events in Pb+Pb collisions. The jet-track yield as a function of $|\Delta\eta(\text{jet}, \text{track})|$ is compared to the one in events without the presence of a jet to extract the relative amount of diffusion wake compared to the bulk medium. This enables a direct test of these diffusion wake theory predictions.

II. ATLAS DETECTOR

The ATLAS detector [24] at the LHC [25] covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [26,27]. It is followed by the semiconductor tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$,

and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements, respectively.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [28]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1 kHz.

A software suite [29] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

III. EVENT SELECTIONS AND SIMULATIONS

The data sets, photon and jet reconstruction, and simulation samples used in this measurement are identical to those used in a previous measurement of photon-tagged jet production [5] and are briefly summarized here.

Events in data are selected for analysis using triggers requiring a reconstructed photon with transverse energy, E_T , above 35 GeV (20 GeV) in pp (Pb+Pb) collisions [30]. These triggers sample the full luminosity of 255 pb⁻¹ for the 2017 pp data and of 1.72 nb⁻¹ for the 2018 Pb+Pb data, and are fully efficient for the photon selection used in this analysis. In addition, minimum-bias (MB) triggered Pb+Pb events [31] are utilized for event mixing as detailed below. Events are required to satisfy detector and data-quality requirements [32] and to have a reconstructed pp collision vertex from at least two tracks with $p_T > 500$ MeV [33]. The vertex whose associated tracks give the highest sum of squared transverse momentum is designated the event primary vertex.

In Pb+Pb collisions, the forward calorimeters (FCal) covering $3.2 < |\eta| < 4.9$ are used to estimate the event centrality which is defined by the total transverse energy sum, ΣE_T^{FCal} . Events in different intervals of ΣE_T^{FCal} are associated with an underlying geometric configuration according to a Monte Carlo (MC) Glauber simulation [34] using the same event selection criteria as in previous ATLAS analyses [35]. This analysis uses a centrality interval corresponding to the 0–10% of the ΣE_T^{FCal} distribution in MB events. This interval corresponds on average to the Pb+Pb collisions with the largest geometric overlap.

Simulated samples of γ -jet events, including direct and fragmentation photon contributions, were generated at leading order in QCD with PYTHIA8 [36] using the NNPDF2.3LO [37] parton distribution function set and the A14 [38] set of tuned parameters. To include the effects of the underlying event (UE) in Pb+Pb collisions, the PYTHIA8 γ -jet events are overlaid at the detector-hit level with Pb+Pb data recorded with minimum-bias triggers. These samples were simulated [39] using a GEANT4 [40] description of the ATLAS detector and were digitized and reconstructed in a manner identical to that of the data.

Photons are reconstructed following the method used previously in Pb+Pb collisions [41,42], which applies the

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring and the y axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

procedure used in pp collisions [43] after an event-by-event estimation and subtraction of the UE contribution to the energy deposited in each calorimeter cell [44]. Photon candidates must pass shower shape requirements [45] designed to reject those arising from neutral meson decays and hadronic showers starting in the electromagnetic calorimeter. Furthermore, photons are required to be isolated by requiring the sum of the transverse energy (after UE subtraction) in calorimeter cells within a cone of size $\Delta R = 0.3$ cone to be below optimized thresholds, achieving a 90% efficiency for prompt photons in fine bins of centrality classes, as determined using the simulations described above. The photon isolation efficiency is evaluated with respect to generator-level final state photons which are isolated by requiring that the sum of the transverse energy of all the final-state particles, excluding the photon itself, within a cone of size $\Delta R = 0.4$ cone be less than 5 GeV.

Jets are reconstructed following the procedure previously used in Pb+Pb collisions [44,46]. The anti- k_t algorithm [47,48] with distance parameter $R = 0.4$ is applied to logical towers ($\Delta\eta \times \Delta\phi = 0.1 \times \pi/32$), which are a combination of cells in all calorimeter layers. The contribution to the energy deposited in towers by the UE is estimated on an event-by-event basis, and the tower energies are iteratively updated to subtract the UE contribution, which is then reestimated. The resulting jets are corrected using simulation to account for the response of the calorimeter to jets [49], and then using *in situ* studies of jets recoiling against photons, Z bosons, and jets in other regions of the calorimeter in pp collisions [41] for the absolute response in data. After performing this initial calibration, a process known as “cross-calibration” [50] is carried out. This step establishes a connection between the jet energy scale observed in high-luminosity pp collisions at $\sqrt{s} = 13$ TeV [50] and the jets reconstructed using the different method described earlier in the 5.02 TeV Pb+Pb data. The calibration described above is based on inclusive jets and an additional calibration correction is applied to account for the different flavor fraction estimated in the MC simulation between inclusive jets and jets produced in association with a photon.

Charged tracks are reconstructed following the procedure previously used in Pb+Pb collisions [51,52]. A selection criterion optimized for primary charged particles is used [53]. Primary charged particles are defined as charged particles with a mean lifetime $\tau > 0.3 \times 10^{-10}$ s, either directly produced in the collision interactions or from subsequent decays of particles with a shorter lifetime [54]. All reconstructed tracks satisfying the selection criteria with $0.5 < p_T < 2.0$ GeV and $|\eta| < 2.5$ are used in this analysis. This specific p_T range is selected because the medium response is expected to be most significant at lower transverse momenta. The charged-particle yield is corrected for reconstruction inefficiency, as well as tracks which are not associated with primary particles, on a per-track basis using simulation-derived correction factors.

IV. ANALYSIS

Events with photons passing the identification and isolation requirements described previously and with $90 < E_T^\gamma < 180$ GeV and $|\eta^\gamma| < 2.37$ (excluding the region $1.37 <$

$|\eta^\gamma| < 1.52$) are selected. Only the highest- E_T (leading) photon among them is used in the measurement. The kinematic selections of jets in this analysis are $p_T^{\text{jet}} > 40$ GeV and $|\eta^{\text{jet}}| < 2.5$. These photon E_T^γ and jet p_T^{jet} ranges encompass a broad range of $x_{J\gamma}$, from 0.3 to 1.0. The results are reported in three $x_{J\gamma}$ selections: $0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$. These $x_{J\gamma}$ ranges, by construction, impose upper p_T^{jet} limits corresponding to the photon E_T^γ , which is restricted to below 180 GeV. The upper E_T^γ boundary of 180 GeV is imposed to facilitate comparison with the theoretical prediction.

The jet energy resolution (JER) and scale (JES) can lead to migration between $x_{J\gamma}$ ranges. However, this effect is found to be small and accounted for in the systematic uncertainty, so no unfolding is performed. The azimuthal angle between the leading photon and associated jet, $\Delta\phi(\gamma, \text{jet})$, is required to be greater than $3\pi/4$. Only the leading jet in this $\Delta\phi(\gamma, \text{jet})$ window is taken for the measurement. These requirements significantly reduce the rate of jets uncorrelated with the photon-producing hard scattering process as well as the contribution from multijet topologies.

For events with photon-jet pairs passing these selections, the distribution of the absolute pseudorapidity difference between the jet and each track, $|\Delta\eta(\text{jet}, \text{track})|$, is constructed. All jet-track pairs must be in opposite azimuthal hemispheres, i.e., $|\Delta\phi(\text{jet}, \text{track})| > \pi/2$. The $|\Delta\eta(\text{jet}, \text{track})|$ distribution normalized by the number of photon-jet pairs is defined as

$$Y_{\text{corr}} = \frac{1}{N^{\gamma\text{-jet}}} \frac{d^2 N^{\text{jet-track}}}{d\Delta\eta d\Delta\phi}. \quad (1)$$

In Pb+Pb collisions, to gauge the medium modification of the QGP induced by the presence of jets, the tracks produced from the bulk medium constitute a background that is estimated using an event mixing technique and are used as a reference for the track-jet correlation in photon-jet events. This “uncorrelated” track rate is estimated from the per-event track rate in MB Pb+Pb data. A photon-jet pair in a given event is matched with tracks in a different event, i.e., tracks from MB events that should have no *a priori* relationship to a given photon-jet pair are used. When mixing the two events, an MB Pb+Pb event is chosen to have similar properties as the signal event by matching ΣE_T^{FCal} , the event plane angle [55], and the z position of the primary vertex. In Pb+Pb collisions, the value of ΣE_T^{FCal} in events with the photon-jet production (“signal” event) includes a contribution from the photon-jet production and another one from the event without this photon-jet production. The ΣE_T^{FCal} contribution from the photon-jet production is estimated in pp data and has a mean value $\Sigma E_T^{\text{FCal}, pp} = 17$ GeV. When mixing a signal event and an MB event, the ΣE_T^{FCal} required is thus 17 GeV smaller than that of the signal event. Figure 1 shows the $|\Delta\eta(\text{jet}, \text{track})|$ distributions from signal events (Y_{corr}) and from mixed events (labeled as Y_{uncorr}) and the ratio corresponding to $0.3 < x_{J\gamma} < 0.6$. This ratio indicates the relative medium modification.

As a check, the raw $|\Delta\eta(\text{jet}, \text{track})|$ distributions in pp collisions at 5.02 TeV are studied with the identical photon, jet, and track selections as in Pb+Pb collisions. In addition, the number of vertices is required to be exactly one to reject

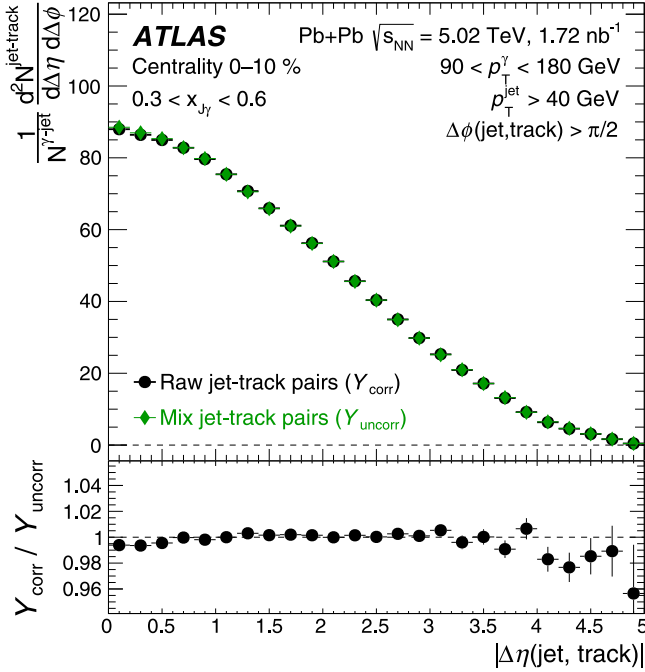


FIG. 1. Top panel: the $|\Delta\eta(\text{jet}, \text{track})|$ distributions for raw (Y_{corr}) and mixed (Y_{uncorr}) events for the Pb+Pb 0–10% centrality interval for $0.3 < x_{J\gamma} < 0.6$. Bottom panel: the ratio $Y_{\text{corr}}/Y_{\text{uncorr}}$ as a function of $|\Delta\eta(\text{jet}, \text{track})|$. The vertical bars associated with symbols indicate the statistical uncertainties.

pileup events in pp collisions. Figure 2 shows the comparison of the yield distributions of tracks per photon-jet pair as a function of $|\Delta\eta(\text{jet}, \text{track})|$ in three selections of $x_{J\gamma}$. According to the theory expectations detailed in Ref. [9], the MPI should be independent of the specifics of the photon-jet kinematics. The presented ratio of the yields in different $x_{J\gamma}$ selections to the one obtained for $0.6 < x_{J\gamma} < 0.8$ is shown to be consistent with unity within statistical uncertainties in Fig. 2, i.e., in agreement with the theoretical expectations.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties are evaluated by repeating the full analysis chain with a given systematic variation, which may result in, e.g., a different reconstructed-level distribution. To avoid double-counting the statistical uncertainties, a χ^2 test is performed for each source of systematic uncertainty. First, the signal samples are split into two halves for statistically independent comparisons between nominal and varied conditions: one half of the events for the nominal condition, the other half for the variation. The χ^2 of the difference between the variation and the nominal is calculated. If the χ^2 value is smaller than a threshold (χ_{cut}^2), the differences are reasonably consistent within statistical fluctuations and thus no systematic uncertainty is assigned for this variation. The χ_{cut}^2 is set to correspond to the 68% probability level, obtained by splitting the data sets 200 times under the same nominal condition, which reflects purely statistical fluctuations. Systematic sources which pass the χ_{cut}^2 are deemed

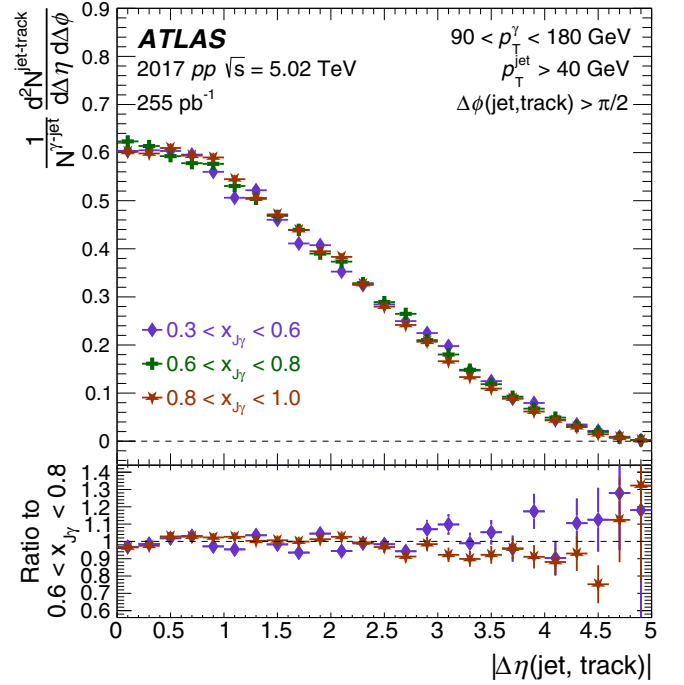


FIG. 2. Top panel: the raw $|\Delta\eta(\text{jet}, \text{track})|$ distributions for different $x_{J\gamma}$ selections in pp collisions at 5.02 TeV. Bottom panel: ratio of yields in different $x_{J\gamma}$ selections to the one obtained for $0.6 < x_{J\gamma} < 0.8$. The vertical bars associated with each bin indicate the statistical uncertainties.

systematically significant, whether due to a real systematic difference or as the result of a residual statistical fluctuation. In this χ^2 procedure, a small but real systematic difference may not be identified due to a statistical fluctuation in the nominal-variation event splitting.

The sources of systematic uncertainty in this measurement are those associated with the track, jet, photon, and event mixing components. For track-related uncertainties, track selection criteria are varied using the same procedure as in Ref. [22]. Additionally, to account for the asymmetric detector performance in the ID, the analysis is repeated for $\eta^{\text{track}} < 0$ and $\eta^{\text{track}} > 0$ separately. Similarly, the η^{jet} asymmetry is considered as another source of systematic uncertainty arising from the imperfections in the calorimeter performance. In addition, the JER can shift jets between different $x_{J\gamma}$ selections. Therefore, the reconstructed jet p_T^{jet} is smeared using the JER for the variation. The JES is also considered as a systematic uncertainty, but its effects are negligible. Regarding photon-related uncertainties, a tighter photon isolation energy requirement is applied, setting the isolation threshold to achieve an 80% isolation efficiency. For the nominal selection, the purity of isolated photons is high and there is thus no explicit correction made for background photons. The tighter isolation criterion is used to account for the impact of potential remaining background photons. Also, to examine the impact of the photon isolation energy cone size ($\Delta R = 0.3$) on the results, the analysis is repeated with $\Delta\eta(\text{jet}, \gamma) > 0.5$. This variation thus excludes tracks that might directly influence the isolation energy calculation. Finally, systematic uncertainties

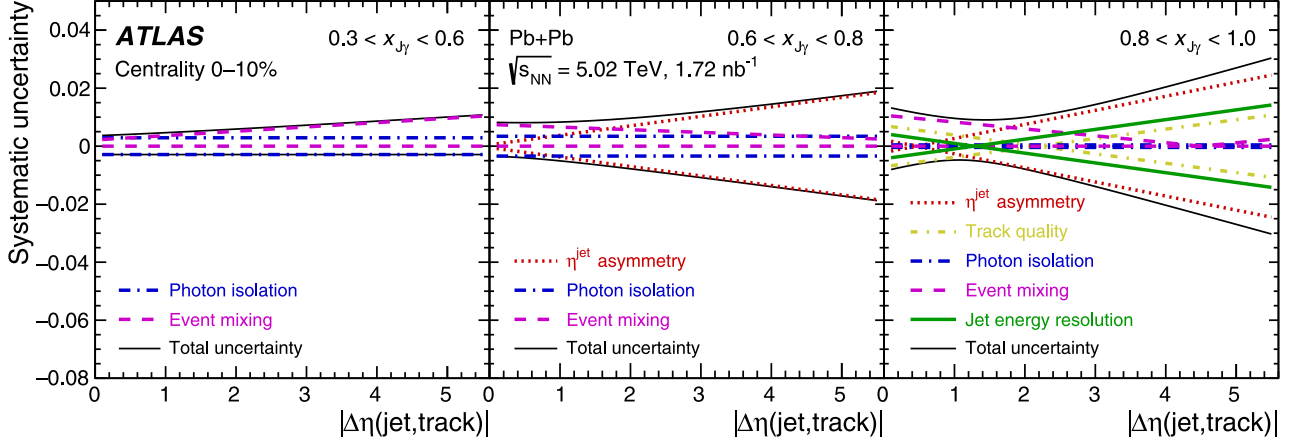


FIG. 3. Breakdown of the systematic uncertainties as a function of $|\Delta\eta(\text{jet}, \text{track})|$ for the Pb+Pb 0–10% centrality interval. Different panels represent different $x_{J\gamma}$ ranges ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$).

related to the event-mixing procedure are considered. The $\Sigma E_T^{\text{FCal}, pp}$ estimation (17 GeV) is varied up and down by a conservative value of $\pm 50\%$. For sources which have distinct “up” and “down” variations, i.e., event mixing, uncertainties are asymmetric. For sources which only have a one-sided variation, uncertainties are symmetrized.

Figure 3 shows the breakdown of absolute systematic uncertainties for $Y_{\text{corr}}/Y_{\text{uncorr}}$. All uncertainties are (partially) correlated between Y_{corr} and Y_{uncorr} , leading to relatively small systematic uncertainties in the ratio $Y_{\text{corr}}/Y_{\text{uncorr}}$. Systematic uncertainty sources which fail the χ^2 test are not depicted in the figure and are not included as a contribution to the total uncertainty. As a result of the χ^2 test procedure, different uncertainty sources may be included in the total uncertainty for the different $x_{J\gamma}$ ranges. For $0.3 < x_{J\gamma} < 0.6$, the dominant systematic uncertainty is the event-mixing uncertainty and the total uncertainty ranges from smaller than 0.5% at small $|\Delta\eta(\text{jet}, \text{track})|$ to approximately 1% at larger $|\Delta\eta(\text{jet}, \text{track})|$. For $0.8 < x_{J\gamma} < 1.0$, the total uncertainty increases from approximately 1% at small $|\Delta\eta(\text{jet}, \text{track})|$ (where the dominant contribution is the event-mixing component) to 2.5% at large

$|\Delta\eta(\text{jet}, \text{track})|$ (where the dominant contribution is the η^{jet} asymmetry).

For the double ratio, $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$, the different uncertainty contributions are evaluated according to the χ^2 test specifically for this quantity by varying the numerator and denominator together. Many uncertainty sources, such as track quality and jet energy resolution, are expected to have a similar impact in the different $x_{J\gamma}$ ranges and thus cancel in this double ratio. After evaluating these contributions, the photon isolation is the dominant remaining uncertainty in this measurement, with an approximately $|\Delta\eta(\text{jet}, \text{track})|$ -independent magnitude of 0.5%.

VI. RESULTS

Figure 4 shows the ratio $Y_{\text{corr}}/Y_{\text{uncorr}}$ in the Pb+Pb 0–10% centrality interval as a function of $|\Delta\eta(\text{jet}, \text{track})|$ for jets and tracks in opposite azimuthal hemispheres ($|\Delta\phi(\text{jet}, \text{track})| > \pi/2$) and in three categories of $x_{J\gamma}$ ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$). For all three $x_{J\gamma}$ selections, the results are consistent with unity within uncertainties.

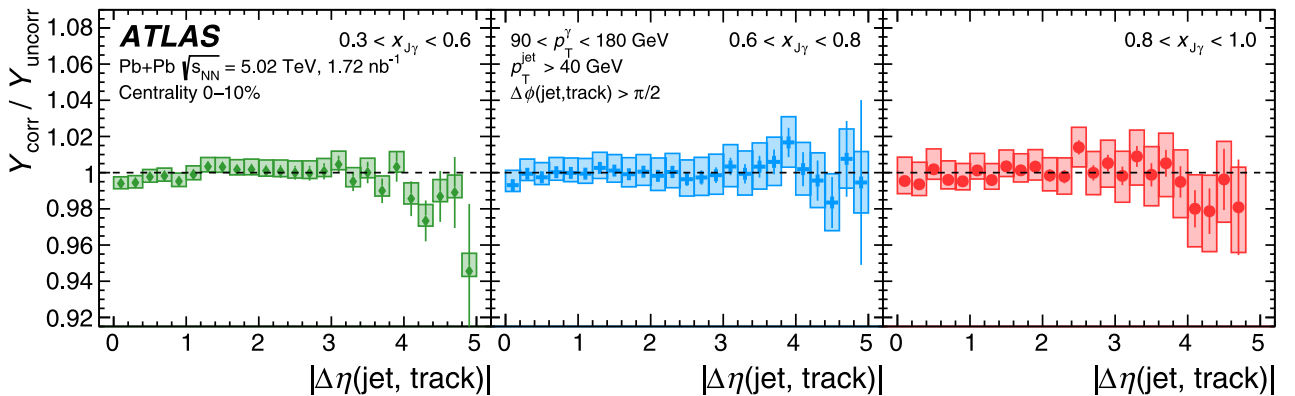


FIG. 4. $Y_{\text{corr}}/Y_{\text{uncorr}}$ distributions are shown as a function of $|\Delta\eta(\text{jet}, \text{track})|$ for the Pb+Pb 0–10% centrality interval. Different panels represent different $x_{J\gamma}$ ranges ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$). The vertical bars indicate the statistical uncertainties. The total systematic uncertainties are shown as boxes in each $|\Delta\eta(\text{jet}, \text{track})|$ bin.

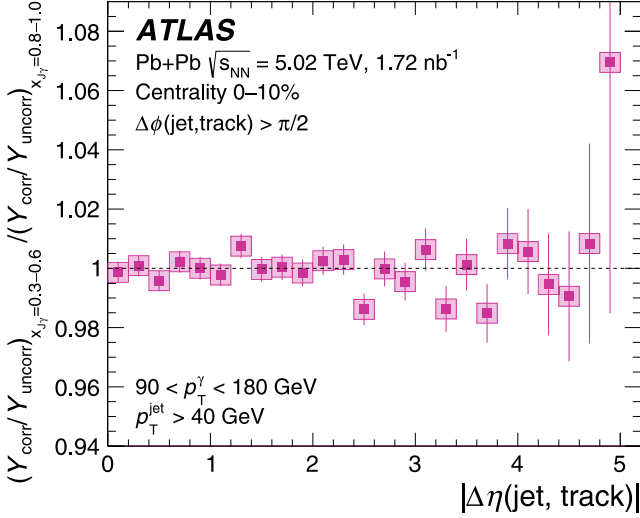


FIG. 5. Double ratio $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$ as a function of $|\Delta\eta(\text{jet}, \text{track})|$ for the Pb+Pb 0–10% centrality interval. The vertical bars indicate the statistical uncertainties. The total systematic uncertainties are shown as boxes.

Figure 5 shows the double ratio, $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$, which is particularly sensitive to whether a larger diffusion wake is present when the parton loses more energy in the QGP. In addition, uncertainty sources that are correlated between $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}$ and $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$, e.g., event mixing uncertainties, partially cancel out in the ratio. Again, the results are consistent with unity within uncertainties, meaning that no significant $x_{J\gamma}$ dependence of the diffusion wake is found.

To quantify these observations further, the $Y_{\text{corr}}/Y_{\text{uncorr}}$ distributions are fitted with a function comprising a constant and a Gaussian term:

$$a_0 + a_{\text{dw}} e^{-|\Delta\eta(\text{jet}, \text{track})|^2/(2\sigma_{\text{dw}}^2)}, \quad (2)$$

where σ_{dw} and a_{dw} correspond to the $|\Delta\eta(\text{jet}, \text{track})|$ width and amplitude of the potential diffusion wake, respectively.

The Gaussian shape of the diffusion wake is theoretically predicted. Such a diffusion wake would have a negative amplitude ($a_{\text{dw}} < 0$). For each value of σ_{dw} , the most probable amplitude a_{dw} is calculated via a MC sampling method including all statistical and systematic uncertainties and their correlations. For input to theoretical models, it is convenient to calculate the best-fit a_{dw} for different possible σ_{dw} values. Thus the fit is repeated with the σ_{dw} parameter fixed, representing a different hypothesis each time, while a_{dw} and a_0 are treated as free parameters.

Figure 6 shows the most probable values as well as the ± 1 and ± 2 standard deviation limits for the three $x_{J\gamma}$ selections. For all diffusion wake widths σ_{dw} and in all $x_{J\gamma}$ selections, the best-fit amplitudes are negative; however, all results are consistent with $a_{\text{dw}} = 0$ (no signal), within approximately one (two) standard deviation for $0.6 < x_{J\gamma} < 0.8$ and $0.8 < x_{J\gamma} < 1.0$ ($0.3 < x_{J\gamma} < 0.6$). The systematic uncertainties between $|\Delta\eta(\text{jet}, \text{track})|$ bins are highly correlated and the statistical uncertainties dominate in the probability distributions of diffusion wake amplitudes.

Similar to the $Y_{\text{corr}}/Y_{\text{uncorr}}$ fits, the $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$ distribution is fitted with the function defined as

$$b_0 + b_{\text{dwr}} e^{-|\Delta\eta(\text{jet}, \text{track})|^2/(2\sigma_{\text{dwr}}^2)}, \quad (3)$$

where σ_{dwr} and b_{dwr} correspond to the $|\Delta\eta(\text{jet}, \text{track})|$ width and amplitude of the double ratio, respectively. Figure 7 shows the best-fit relative diffusion wake amplitude (b_{dwr}) between $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.3-0.6}$ and $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{J\gamma}=0.8-1.0}$ as a function of σ_{dwr} (which is fixed in each fit). The most probable amplitude b_{dwr} is consistent with zero within one or two standard deviations, indicating that the best-fit amplitude a_{dw} in $0.8 < x_{J\gamma} < 1.0$ is very similar to that in $0.3 < x_{J\gamma} < 0.6$. No significant diffusion wake signal that increases with larger parton energy loss is observed.

The theoretical framework CoLBT-hydro predicts a diffusion wake signal that increases for decreasing $x_{J\gamma}$ selections [9]. CoLBT-hydro calculations have been carried out to match the specific kinematic selections of this measurement, including the photon, jet, and track criteria. The

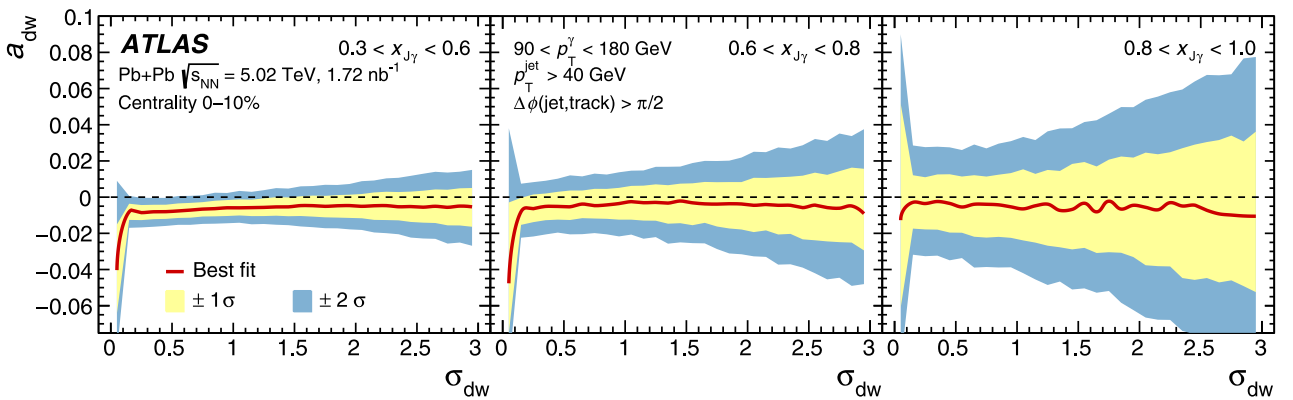


FIG. 6. Diffusion wake amplitude a_{dw} as a function of diffusion wake width σ_{dw} from Gaussian fits for $Y_{\text{corr}}/Y_{\text{uncorr}}$. Different panels represent different $x_{J\gamma}$ ranges ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$). The red solid line is the most probable amplitude. The inner and outer shaded areas represent one ($\pm 1\sigma$) and two ($\pm 2\sigma$) standard deviation ranges, respectively.

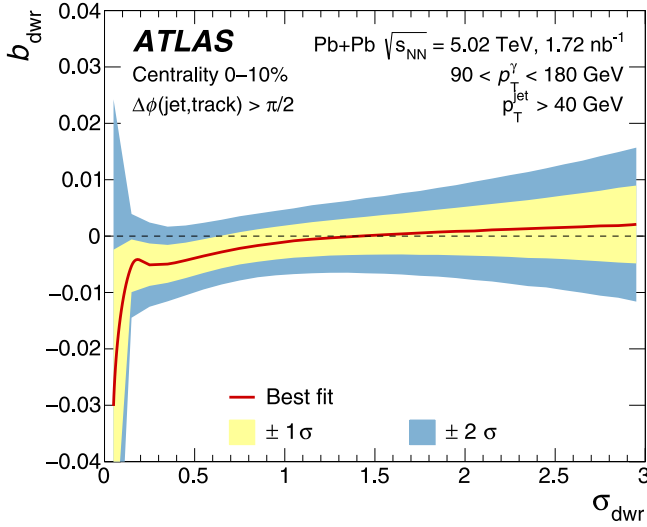


FIG. 7. Amplitude (b_{dwr}) of a Gaussian fit for $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.8-1.0}$ as a function of a given width σ_{dwr} . The red solid line is the most probable amplitude. The inner and outer shaded areas represent one ($\pm 1\sigma$) and two ($\pm 2\sigma$) standard deviation ranges, respectively.

theory predicts diffusion wake parameters in the double ratio $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.8-1.0}$ of $b_{\text{dwr}} = -0.00185$ and $\sigma_{\text{dwr}} = 1.033$. Figure 8 shows the probability distribution for the double ratio when fixing σ_{dwr} to 1.033. The CoLBT-hydro theory expectation is overlaid. The small predicted b_{dwr} value is consistent with the experimental results within uncertainty. A diffusion wake double amplitude b_{dwr} value smaller than -0.0058 can be ruled out at 95% confidence level. The p value for b_{dwr} being positive is 0.38. As above, the constraining power of the measurement is limited by the statistical, rather than the systematic, precision of the data set.

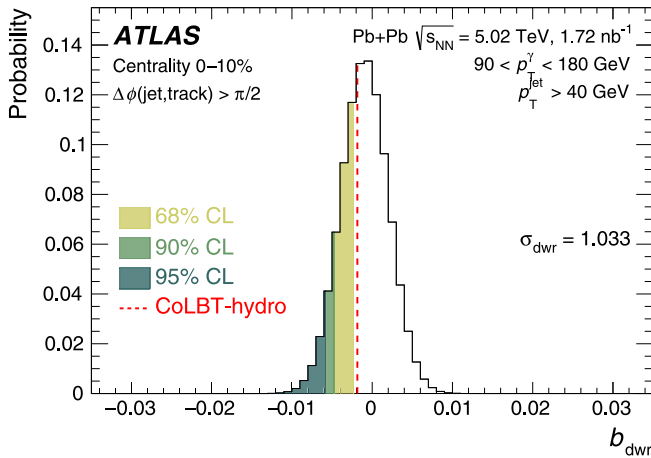


FIG. 8. Probability distribution of the amplitude of the Gaussian fit component b_{dwr} for $(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.3-0.6}/(Y_{\text{corr}}/Y_{\text{uncorr}})_{x_{j\gamma}=0.8-1.0}$ for $\sigma_{\text{dwr}} = 1.033$ (the value predicted by the CoLBT-hydro framework). The yellow, green, and blue lines represent 68%, 90%, and 95% confidence levels, respectively. The red dashed line is the theory expectation from the CoLBT-hydro framework.

VII. CONCLUSION

The bulk quark-gluon plasma medium produced in heavy-ion collisions is expected to be modified by the energy lost from traversing jets. The expected localized depletion of the medium opposite to these jets is called the “diffusion wake.” This paper presents measurements of angular correlations between jets and charged-particle tracks in photon-jet events, using 1.72 nb^{-1} of Pb+Pb data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ recorded with the ATLAS detector at the LHC. The measurement is performed for high- p_T photon-jet pairs, with three different ranges of the jet-to-photon p_T ratio, $x_{j\gamma}$, intended to select events with different amounts of parton energy loss. The yield of charged-particle tracks in the opposite hemisphere to the jet is measured as a function of the relative pseudorapidity separation, $|\Delta\eta(\text{jet}, \text{track})|$, and is divided by the yield of combinatoric jet-track pairs estimated in minimum-bias Pb+Pb events, to search for a localized depletion. The ratio of this ratio between different low and high $x_{j\gamma}$ selections is also studied and the probability of a diffusion signal with different parameters is estimated. The data indicate no significant diffusion wake within the present uncertainties, which are dominated by the statistical uncertainties. The data are further used to set upper limits on the magnitude of the diffusion wake effect at different confidence levels. The CoLBT-hydro theory prediction is consistent with the data within the 68% confidence level upper limit. Assuming a double ratio width, σ_{dwr} , given by the CoLBT-hydro model, values of the amplitude b_{dwr} smaller than -0.0058 are excluded at 95% confidence level.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [56]. We gratefully acknowledge the support of the following: ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRf and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and

Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America. Individual groups and members have received support from the following: BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members wish to acknowledge support from the following. Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (Grants No. FONDECYT 1230812, No. FONDECYT 1230987, and No. FONDECYT 1240864); China: Chinese Ministry of Science and Technology (Grants No. MOST-2023YFA1605700 and No. MOST-2023YFA1609300), National Natural Science Foundation of China (Grants No. NSFC-12175119, No. NSFC-12275265, and No. NSFC-12075060); Czech Republic: Czech Science Foundation (Grant No. GACR-24-11373S), Ministry of Education Youth and Sports (Grant No. FORTE CZ.02.01.01/00/22_-008/0004632), PRIMUS Research Programme (Grant No. PRIMUS/21/SCI/017); EU: H2020 European Research Council (Grant No. ERC-101002463); European Union: European Research Council (Grants No. ERC-948254 and No. ERC-101089007), Horizon 2020 Framework Programme (Grant No. MUCCA-CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (Grant No. FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (Grants No. ANR-20-CE31-0013, No. ANR-21-CE31-0013, No. ANR-21-CE31-0022, and No. ANR-22-EDIR-0002), Investissements d'Avenir Labex (Grant No. ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (Grants No. DFG-469666862 and No. DFG-CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC,

NextGenerationEU), Ministero dell'Università e della Ricerca (Grant No. PRIN-20223N7F8K-PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (Grants No. JSPS KAKENHI JP22H01227, No. JSPS KAKENHI JP22H04944, No. JSPS KAKENHI JP22KK0227, and No. JSPS KAKENHI JP23KK0245); Netherlands: Netherlands Organisation for Scientific Research (Grant No. NWO Veni 2020-VI.Veni.202.179); Norway: Research Council of Norway (Grant No. RCN-314472); Poland: Ministry of Science and Higher Education (Grant IDUB AGH, POB8, D4 No. 9722), Polish National Agency for Academic Exchange (Grant No. PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (Grants No. NCN 2021/42/E/ST2/00350, No. NCN OPUS 2022/47/B/ST2/03059, No. NCN UMO-2019/34/E/ST2/00393, No. NCN & H2020 MSCA 945339, No. UMO-2020/37/B/ST2/01043, No. UMO-2021/40/C/ST2/00187, No. UMO-2022/47/O/ST2/00148, No. UMO-2023/49/B/ST2/04085, and No. UMO-2023/51/B/ST2/00920); Slovenia: Slovenian Research Agency (ARIS Grant No. J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, Grant No. IDIFEDER/2018/048), Ministry of Science and Innovation (Grants No. MCIN & NextGenEU PCI2022-135018-2, No. MICIN & FEDER PID2021-125273NB, No. RYC2019-028510-I, No. RYC2020-030254-I, No. RYC2021-031273-I, and No. RYC2022-038164-I), PROMETEO and GenT Programmes Generalitat Valenciana (Grant No. CIDEAGENT/2019/027); Sweden: Carl Trygger Foundation (Carl Trygger Foundation Grant No. CTS 22:2312), Swedish Research Council (Swedish Research Council Grants No. 2023-04654, No. VR 2018-00482, No. VR 2022-03845, No. VR 2022-04683, No. VR 2023-03403, and VR Grant No. 2021-03651), Knut and Alice Wallenberg Foundation (Grants No. KAW 2018.0157, No. KAW 2018.0458, No. KAW 2019.0447, and No. KAW 2022.0358); Switzerland: Swiss National Science Foundation (Grant No. SNSF-PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust No. RPG-2020-004), Royal Society (Grant No. NIF-R1-231091); United States of America: U.S. Department of Energy (Grant No. ECA DE-AC02-76SF00515), Neubauer Family Foundation.

DATA AVAILABILITY

The public release of data supporting the findings of this article will follow the CERN Open Data Policy [57]. Inquiries about plots and tables associated with this article can be addressed to atlas.publications@cern.ch.

- [1] H. Elfner and B. Müller, The exploration of hot and dense nuclear matter: introduction to relativistic heavy-ion physics, *J. Phys. G* **50**, 103001 (2023).
- [2] P. Romatschke and U. Romatschke, Viscosity information from relativistic nuclear collisions: How perfect is the fluid observed at RHIC? *Phys. Rev. Lett.* **99**, 172301 (2007).
- [3] L. Cunqueiro and A. M. Sickles, Studying the QGP with Jets at the LHC and RHIC, *Prog. Part. Nucl. Phys.* **124**, 103940 (2022).
- [4] M. Connors, C. Nattrass, R. Reed, and S. Salur, Jet measurements in heavy ion physics, *Rev. Mod. Phys.* **90**, 025005 (2018).

- [5] ATLAS Collaboration, Comparison of inclusive and photon-tagged jet suppression in 5.02 TeV Pb+Pb collisions with ATLAS, *Phys. Lett. B* **846**, 138154 (2023).
- [6] J. Casalderrey-Solana, E. V. Shuryak, and D. Teaney, Conical flow induced by quenched QCD jets, *J. Phys.: Conf. Ser.* **27**, 22 (2005).
- [7] J. Ruppert and B. Müller, Waking the colored plasma, *Phys. Lett. B* **618**, 123 (2005).
- [8] B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, I. Mishustin, and D. H. Rischke, Universality of the diffusion wake from stopped

- and punch-through jets in heavy-ion collisions, *Phys. Rev. C* **79**, 034902 (2009).
- [9] W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang, Effects of jet-induced medium excitation in γ -hadron correlation in A+A collisions, *Phys. Lett. B* **777**, 86 (2018).
- [10] D. Pablos, M. Singh, S. Jeon, and C. Gale, Minijet quenching in a concurrent jet+hydro evolution and the nonequilibrium quark-gluon plasma, *Phys. Rev. C* **106**, 034901 (2022).
- [11] W. Chen, Z. Yang, Y. He, W. Ke, L.-G. Pang, and X.-N. Wang, Search for the elusive jet-induced diffusion wake in Z/ γ -jets with 2D jet tomography in high-energy heavy-ion collisions, *Phys. Rev. Lett.* **127**, 082301 (2021).
- [12] J. Casalderrey-Solana, J. G. Milhano, D. Pablos, K. Rajagopal, and X. Yao, Jet Wake from Linearized Hydrodynamics, *J. High Energy Phys.* **05** (2021) 230.
- [13] J. Brewer, Q. Brodsky, and K. Rajagopal, Disentangling jet modification in jet simulations and in Z+jet data, *J. High Energy Phys.* **02** (2022) 175.
- [14] W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang, Medium modification of γ -jet fragmentation functions in Pb+Pb collisions at LHC, *Phys. Lett. B* **810**, 135783 (2020).
- [15] S. Cao and X.-N. Wang, Jet quenching and medium response in high-energy heavy-ion collisions: a review, *Rep. Prog. Phys.* **84**, 024301 (2021).
- [16] S. Cao and G.-Y. Qin, Medium response and Jet-Hadron correlations in relativistic heavy-ion collisions, *Annu. Rev. Nucl. Part. Sci.* **73**, 205 (2023).
- [17] ATLAS Collaboration, Measurement of angular and momentum distributions of charged particles within and around jets in Pb+Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, *Phys. Rev. C* **100**, 064901 (2019).
- [18] CMS Collaboration, Jet properties in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *J. High Energy Phys.* **05** (2018) 006.
- [19] L. Adamczyk *et al.*, Jet-like correlations with direct-photon and neutral-pion triggers at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Lett. B* **760**, 689 (2016).
- [20] U. Acharya *et al.*, Measurement of jet-medium interactions via direct photon-hadron correlations in Au+Au and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* **102**, 054910 (2020).
- [21] CMS Collaboration, Using Z boson events to study parton-medium interactions in Pb-Pb collisions, *Phys. Rev. Lett.* **128**, 122301 (2022).
- [22] ATLAS Collaboration, Medium-induced modification of Z-tagged charged particle yields in Pb+Pb collisions at 5.02 TeV with the ATLAS detector, *Phys. Rev. Lett.* **126**, 072301 (2021).
- [23] Z. Yang, T. Luo, W. Chen, L. Pang, and X.-N. Wang, 3D structure of jet-induced diffusion wake in an expanding quark-gluon plasma, *Phys. Rev. Lett.* **130**, 052301 (2023).
- [24] ATLAS Collaboration, The ATLAS experiment at the CERN large Hadron collider, *J. Inst.* **3**, S08003 (2008).
- [25] L. Evans and P. Bryant, LHC Machine, *J. Inst.* **3**, S08001 (2008).
- [26] ATLAS Collaboration, ATLAS Insertable B-Layer Technical Design Report, ATLAS-TDR-19; CERN-LHCC-2010-013, 2010, <https://cds.cern.ch/record/1291633>, ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, 2012, <https://cds.cern.ch/record/1451888>.
- [27] B. Abbott *et al.*, Production and integration of the ATLAS Insertable B-Layer, *J. Inst.* **13**, T05008 (2018).
- [28] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, *Eur. Phys. J. C* **77**, 317 (2017).
- [29] ATLAS Collaboration, Software and computing for Run 3 of the ATLAS experiment at the LHC, *Eur. Phys. J. C* **85**, 234 (2025).
- [30] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, *Eur. Phys. J. C* **80**, 47 (2020).
- [31] ATLAS Collaboration, Measurement of muon pairs produced via $\gamma\gamma$ scattering in nonultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, *Phys. Rev. C* **107**, 054907 (2023).
- [32] ATLAS Collaboration, ATLAS data quality operations and performance for 2015–2018 data-taking, *J. Inst.* **15**, P04003 (2020).
- [33] ATLAS Collaboration, Vertex Reconstruction Performance of the ATLAS Detector at $\sqrt{s} = 13$ TeV, ATL-PHYS-PUB-2015-026, 2015, <https://cds.cern.ch/record/2037717>.
- [34] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Glauber modeling in high-energy nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).
- [35] ATLAS Collaboration, Prompt and non-prompt J/ψ and $\psi(2S)$ suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment, *Eur. Phys. J. C* **78**, 762 (2018).
- [36] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [37] R. D. Ball *et al.*, NNPDF Collaboration, Parton distributions with LHC data, *Nucl. Phys. B* **867**, 244 (2013).
- [38] ATLAS Collaboration, ATLAS Pythia 8 tunes to 7 TeV data, ATL-PHYS-PUB-2014-021, 2014, <https://cds.cern.ch/record/1966419>.
- [39] ATLAS Collaboration, The ATLAS Simulation Infrastructure, *Eur. Phys. J. C* **70**, 823 (2010).
- [40] S. Agostinelli *et al.*, GEANT4 – a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [41] ATLAS Collaboration, Measurement of photon-jet transverse momentum correlations in 5.02 TeV Pb+Pb and pp collisions with ATLAS, *Phys. Lett. B* **789**, 167 (2019).
- [42] ATLAS Collaboration, Comparison of fragmentation functions for jets dominated by light quarks and gluons from pp and Pb+Pb collisions in ATLAS, *Phys. Rev. Lett.* **123**, 042001 (2019).
- [43] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, *J. Inst.* **14**, P12006 (2019).
- [44] ATLAS Collaboration, Measurement of the jet radius and transverse momentum dependence of inclusive jet suppression in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector, *Phys. Lett. B* **719**, 220 (2013).
- [45] ATLAS Collaboration, Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment, *J. High Energy Phys.* **05** (2024) 162.
- [46] ATLAS Collaboration, Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, *Phys. Lett. B* **790**, 108 (2019).
- [47] M. Cacciari, G. P. Salam, and G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* **04** (2008) 063.

- [48] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [49] ATLAS Collaboration, Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Eur. Phys. J. C* **81**, 689 (2021).
- [50] Jet energy scale and its uncertainty for jets reconstructed using the ATLAS heavy ion jet algorithm, Technical Report, CERN, Geneva, 2015. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-016>.
- [51] ATLAS Collaboration, Measurement of charged-particle spectra in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, *J. High Energy Phys.* **09** (2015) 050.
- [52] ATLAS Collaboration, Early Inner Detector Tracking Performance in the 2015 Data at $\sqrt{s} = 13$ TeV, ATL-PHYS-PUB-2015-051, 2015, <https://cds.cern.ch/record/2110140>.
- [53] ATLAS Collaboration, Measurement of jet fragmentation in Pb+Pb and *pp* collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, *Phys. Rev. C* **98**, 024908 (2018).
- [54] ATLAS Collaboration, Charged-particle multiplicities in *pp* interactions measured with the ATLAS detector at the LHC, *New J. Phys.* **13**, 053033 (2011).
- [55] ATLAS Collaboration, Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, *Phys. Lett. B* **807**, 135595 (2020).
- [56] ATLAS Collaboration, ATLAS Computing Acknowledgements, ATL-SOFT-PUB-2023-001, 2023, <https://cds.cern.ch/record/2869272>.
- [57] CERN, CERN Open Data Policy for the LHC Experiments, CERN-OPEN-2020-013, 2020, <https://cds.cern.ch/record/2745133>, doi:10.17181/CERN.QXNK.8L2G.

G. Aad¹⁰⁴, E. Aakvaag¹⁷, B. Abbott¹²³, S. Abdelhameed^{119a}, K. Abeling⁵⁶, N. J. Abicht⁵⁰, S. H. Abidi³⁰, M. Aboelela⁴⁵, A. Aboulhorma^{36e}, H. Abramowicz¹⁵⁵, H. Abreu¹⁵⁴, Y. Abulaiti¹²⁰, B. S. Acharya^{70a,70b,a}, A. Ackermann^{64a}, C. Adam Bourdarios⁴, L. Adamczyk^{87a}, S. V. Addepalli²⁷, M. J. Addison¹⁰³, J. Adelman¹¹⁸, A. Adiguzel^{22c}, T. Adye¹³⁷, A. A. Affolder¹³⁹, Y. Afik⁴⁰, M. N. Agaras¹³, J. Agarwala^{74a,74b}, A. Aggarwal¹⁰², C. Agheorghiesei^{28c}, F. Ahmadov^{39,b}, W. S. Ahmed¹⁰⁶, S. Ahuja⁹⁷, X. Ai^{63c}, G. Aielli^{77a,77b}, A. Aikot¹⁶⁶, M. Ait Tamlihat^{36e}, B. Aitbenkikh^{36a}, M. Akbiyik¹⁰², T. P. A. Åkesson¹⁰⁰, A. V. Akimov³⁸, D. Akiyama¹⁷¹, N. N. Akolkar²⁵, S. Aktas^{22a}, K. Al Khoury⁴², G. L. Alberghi^{24b}, J. Albert¹⁶⁸, P. Albicocco⁵⁴, G. L. Albouy⁶¹, S. Alderweireldt⁵³, Z. L. Alegria¹²⁴, M. Aleksa³⁷, I. N. Aleksandrov³⁹, C. Alexa^{28b}, T. Alexopoulos¹⁰, F. Alfonsi^{24b}, M. Algren⁵⁷, M. Alhroob¹⁷⁰, B. Ali¹³⁵, H. M. J. Ali^{93,c}, S. Ali³², S. W. Alibocus⁹⁴, M. Aliev^{34c}, G. Alimonti^{72a}, W. Alkakh⁵⁶, C. Allaire⁶⁷, B. M. M. Allbrooke¹⁵⁰, J. S. Allen¹⁰³, J. F. Allen⁵³, C. A. Allendes Flores^{140f}, P. P. Allport²¹, A. Aloisio^{73a,73b}, F. Alonso⁹², C. Alpigiani¹⁴², Z. M. K. Alsolami⁹³, M. Alvarez Estevez¹⁰¹, A. Alvarez Fernandez¹⁰², M. Alves Cardoso⁵⁷, M. G. Alviggi¹¹¹, M. Aly¹⁰³, Y. Amaral Coutinho^{84b}, A. Ambler¹⁰⁶, C. Amelung³⁷, M. Amerl¹⁰³, C. G. Ames¹¹¹, D. Amidei¹⁰⁸, B. Amini⁵⁵, K. J. Amirie¹⁵⁸, S. P. Amor Dos Santos^{133a}, K. R. Amos¹⁶⁶, D. Amperiadou¹⁵⁶, S. An⁸⁵, V. Ananiev¹²⁸, C. Anastopoulos¹⁴³, T. Andeen¹¹, J. K. Anders³⁷, A. C. Anderson⁶⁰, S. Y. Andreev^{48a,48b}, A. Andreazza^{72a,72b}, S. Angelidakis⁹, A. Angerami⁴², A. V. Anisenkov³⁸, A. Annovi^{75a}, C. Antel⁵⁷, E. Antipov¹⁴⁹, M. Antonelli⁵⁴, F. Anulli^{76a}, M. Aoki⁸⁵, T. Aoki¹⁵⁷, M. A. Aparo¹⁵⁰, L. Aperio Bella⁴⁹, C. Appelt¹⁹, A. Apyan²⁷, S. J. Arbiol Val⁸⁸, C. Arcangeletti⁵⁴, A. T. H. Arce⁵², J.-F. Arguin¹¹⁰, S. Argyropoulos⁵⁵, J.-H. Arling⁴⁹, O. Arnaez⁴, H. Arnold¹⁴⁹, G. Artoni^{76a,76b}, H. Asada¹¹³, K. Asai¹²¹, S. Asai¹⁵⁷, N. A. Asbah³⁷, R. A. Ashby Pickering¹⁷⁰, K. Assamagan³⁰, R. Astalos^{29a}, K. S. V. Astrand¹⁰⁰, S. Atashi¹⁶², R. J. Atkin^{34a}, M. Atkinson¹⁶⁵, H. Atmani^{36f}, P. A. Atmasiddha¹³¹, K. Augsten¹³⁵, S. Auricchio^{73a,73b}, A. D. Auriol²¹, V. A. Austrup¹⁰³, G. Avolio³⁷, K. Axiotis⁵⁷, G. Azuelos^{110,d}, D. Babal^{29b}, H. Bachacou¹³⁸, K. Bachas^{156,e}, A. Bachi³⁵, F. Backman^{48a,48b}, A. Badea⁴⁰, T. M. Baer¹⁰⁸, P. Bagnaia^{76a,76b}, M. Bahmani¹⁹, D. Bahner⁵⁵, K. Bai¹²⁶, J. T. Baines¹³⁷, L. Baines⁹⁶, O. K. Baker¹⁷⁵, E. Bakos¹⁶, D. Bakshi Gupta⁸, L. E. Balabram Filho^{84b}, V. Balakrishnan¹²³, R. Balasubramanian⁴, E. M. Baldin³⁸, P. Balek^{87a}, E. Ballabene^{24b,24a}, F. Balli¹³⁸, L. M. Baltes^{64a}, W. K. Balunas³³, J. Balz¹⁰², I. Bamwidhi^{119b}, E. Banas⁸⁸, M. Bandieramonte¹³², A. Bandyopadhyay²⁵, S. Bansal²⁵, L. Barak¹⁵⁵, M. Barakat⁴⁹, E. L. Barberio¹⁰⁷, D. Barberis^{58b,58a}, M. Barbero¹⁰⁴, M. Z. Barel¹¹⁷, T. Barillari¹¹², M.-S. Barisits³⁷, T. Barklow¹⁴⁷, P. Baron¹²⁵, D. A. Baron Moreno¹⁰³, A. Baroncelli^{63a}, A. J. Barr¹²⁹, J. D. Barr⁹⁸, F. Barreiro¹⁰¹, J. Barreiro Guimarães da Costa¹⁴, U. Barron¹⁵⁵, M. G. Barros Teixeira^{133a}, S. Barsov³⁸, F. Bartels^{64a}, R. Bartoldus¹⁴⁷, A. E. Barton⁹³, P. Bartos^{29a}, A. Basan¹⁰², M. Baselga⁵⁰, A. Bassalat^{67,f}, M. J. Basso^{159a}, S. Bataju⁴⁵, R. Bate¹⁶⁷, R. L. Bates⁶⁰, S. Batlamous¹⁰¹, B. Batool¹⁴⁵, M. Battaglia¹³⁹, D. Battulga¹⁹, M. Bause^{76a,76b}, M. Bauer⁸⁰, P. Bauer²⁵, L. T. Bazzano Hurrell³¹, J. B. Beacham⁵², T. Beau¹³⁰, J. Y. Beaucamp⁹², P. H. Beauchemin¹⁶¹, P. Bechtel²⁵, H. P. Beck^{20,g}, K. Becker¹⁷⁰, A. J. Beddall⁸³, V. A. Bednyakov³⁹, C. P. Bee¹⁴⁹, L. J. Beemster¹⁶, T. A. Beermann³⁷, M. Begalli^{84d}, M. Begel³⁰, A. Behera¹⁴⁹, J. K. Behr⁴⁹, J. F. Beirer³⁷, F. Beisiegel²⁵, M. Belfkir^{119b}, G. Bella¹⁵⁵, L. Bellagamba^{24b}, A. Bellerive³⁵, P. Bellos²¹, K. Beloborodov³⁸, D. Benckekroun^{36a}, F. Bendebba^{36a}, Y. Benhammou¹⁵⁵, K. C. Benkendorfer⁶², L. Beresford⁴⁹, M. Beretta⁵⁴, E. Bergeas Kuutmann¹⁶⁴, N. Berger⁴, B. Bergmann¹³⁵, J. Beringer^{18a}, G. Bernardi⁵, C. Bernius¹⁴⁷, F. U. Bernlochner²⁵, F. Bernon³⁷, A. Berrocal Guardia¹³, T. Berry⁹⁷, P. Berta¹³⁶, A. Berthold⁵¹, S. Bethke¹¹²

- A. Betti ^{76a,76b} A. J. Bevan ⁹⁶ N. K. Bhalla ⁵⁵ S. Bhatta ¹⁴⁹ D. S. Bhattacharya ¹⁶⁹ P. Bhattacharai ¹⁴⁷ K. D. Bhide ⁵⁵
V. S. Bhopatkar ¹²⁴ R. M. Bianchi ¹³² G. Bianco ^{24b,24a} O. Biebel ¹¹¹ R. Bielski ¹²⁶ M. Biglietti ^{78a}
C. S. Billingsley ⁴⁵ Y. Bimgdi ^{36f} M. Bindi ⁵⁶ A. Bingul ^{22b} C. Bini ^{76a,76b} G. A. Bird ³³ M. Birman ¹⁷²
M. Biros ¹³⁶ S. Biryukov ¹⁵⁰ T. Bisanz ⁵⁰ E. Bisceglie ^{44b,44a} J. P. Biswal ¹³⁷ D. Biswas ¹⁴⁵ I. Bloch ⁴⁹
A. Blue ⁶⁰ U. Blumenschein ⁹⁶ J. Blumenthal ¹⁰² V. S. Bobrovnikov ³⁸ M. Boehler ⁵⁵ B. Boehm ¹⁶⁹
D. Bogavac ³⁷ A. G. Bogdanchikov ³⁸ L. S. Boggia ¹³⁰ C. Bohm ^{48a} V. Boisvert ⁹⁷ P. Bokan ³⁷ T. Bold ^{87a}
M. Bomben ⁵ M. Bona ⁹⁶ M. Boonekamp ¹³⁸ C. D. Booth ⁹⁷ A. G. Borbély ⁶⁰ I. S. Bordulev ³⁸ G. Borissov ⁹³
D. Bortoletto ¹²⁹ D. Boscherini ^{24b} M. Bosman ¹³ J. D. Bossio Sola ³⁷ K. Bouaouda ^{36a} N. Bouchhar ¹⁶⁶
L. Boudet ⁴ J. Boudreau ¹³² E. V. Bouhova-Thacker ⁹³ D. Boumediene ⁴¹ R. Bouquet ^{58b,58a} A. Boveia ¹²²
J. Boyd ³⁷ D. Boye ³⁰ I. R. Boyko ³⁹ L. Bozianu ⁵⁷ J. Bracnik ²¹ N. Brahimi ⁴ G. Brandt ¹⁷⁴ O. Brandt ³³
F. Braren ⁴⁹ B. Brau ¹⁰⁵ J. E. Brau ¹²⁶ R. Brener ¹⁷² L. Brenner ¹¹⁷ R. Brenner ¹⁶⁴ S. Bressler ¹⁷²
G. Brianti ^{79a,79b} D. Britton ⁶⁰ D. Britzger ¹¹² I. Brock ²⁵ R. Brock ¹⁰⁹ G. Brooijmans ⁴² E. M. Brooks ^{159b}
E. Brost ³⁰ L. M. Brown ¹⁶⁸ L. E. Bruce ⁶² T. L. Bruckler ¹²⁹ P. A. Bruckman de Renstrom ⁸⁸ B. Brüers ⁴⁹
A. Bruni ^{24b} G. Bruni ^{24b} M. Bruschi ^{24b} N. Bruscino ^{76a,76b} T. Buanes ¹⁷ Q. Buat ¹⁴² D. Buchin ¹¹²
A. G. Buckley ⁶⁰ O. Bulekov ³⁸ B. A. Bullard ¹⁴⁷ S. Burdin ⁹⁴ C. D. Burgard ⁵⁰ A. M. Burger ³⁷ B. Burghgrave ⁸
O. Burlayenko ⁵⁵ J. Burleson ¹⁶⁵ J. T. P. Burr ³³ J. C. Burzynski ¹⁴⁶ E. L. Busch ⁴² V. Büscher ¹⁰² P. J. Bussey ⁶⁰
J. M. Butler ²⁶ C. M. Buttar ⁶⁰ J. M. Butterworth ⁹⁸ W. Buttinger ¹³⁷ C. J. Buxo Vazquez ¹⁰⁹ A. R. Buzykaev ³⁸
S. Cabrera Urbán ¹⁶⁶ L. Cadamuro ⁶⁷ D. Caforio ⁵⁹ H. Cai ¹³² Y. Cai ^{14,114c} Y. Cai ^{114a} V. M. M. Cairo ³⁷
O. Cakir ^{3a} N. Calace ³⁷ P. Calafiura ^{18a} G. Calderini ¹³⁰ P. Calfayan ⁶⁹ G. Callea ⁶⁰ L. P. Caloba ^{84b} D. Calvet ⁴¹
S. Calvet ⁴¹ M. Calvetti ^{75a,75b} R. Camacho Toro ¹³⁰ S. Camarda ³⁷ D. Camarero Munoz ²⁷ P. Camarri ^{77a,77b}
M. T. Camerlingo ^{73a,73b} D. Cameron ³⁷ C. Camincher ¹⁶⁸ M. Campanelli ⁹⁸ A. Camplani ⁴³ V. Canale ^{73a,73b}
A. C. Canbay ^{3a} E. Canonero ⁹⁷ J. Cantero ¹⁶⁶ Y. Cao ¹⁶⁵ F. Capocasa ²⁷ M. Capua ^{44b,44a} A. Carbone ^{72a,72b}
R. Cardarelli ^{77a} J. C. J. Cardenas ⁸ G. Carducci ^{44b,44a} T. Carli ³⁷ G. Carlino ^{73a} J. I. Carlotto ¹³
B. T. Carlson ^{132,h} E. M. Carlson ^{168,159a} J. Carmignani ⁹⁴ L. Carminati ^{72a,72b} A. Carnelli ¹³⁸ M. Carnesale ³⁷
S. Caron ¹¹⁶ E. Carquin ^{140f} I. B. Carr ¹⁰⁷ S. Carrá ^{72a} G. Carratta ^{24b,24a} A. M. Carroll ¹²⁶ T. M. Carter ⁵³
M. P. Casado ^{13,i} M. Caspar ⁴⁹ F. L. Castillo ⁴ L. Castillo Garcia ¹³ V. Castillo Gimenez ¹⁶⁶ N. F. Castro ^{133a,133e}
A. Catinaccio ³⁷ J. R. Catmore ¹²⁸ T. Cavaliere ⁴ V. Cavaliere ³⁰ N. Cavalli ^{24b,24a} L. J. Caviedes Betancourt ^{23b}
Y. C. Cekmecelioglu ⁴⁹ E. Celebi ⁸³ S. Cella ³⁷ F. Celli ¹²⁹ M. S. Centonze ^{71a,71b} V. Cepaitis ⁵⁷ K. Cerny ¹²⁵
A. S. Cerqueira ^{84a} A. Cerri ¹⁵⁰ L. Cerrito ^{77a,77b} F. Cerutti ^{18a} B. Cervato ¹⁴⁵ A. Cervelli ^{24b} G. Cesarini ⁵⁴
S. A. Cetin ⁸³ D. Chakraborty ¹¹⁸ J. Chan ^{18a} W. Y. Chan ¹⁵⁷ J. D. Chapman ³³ E. Chapon ¹³⁸ B. Chargeishvili ^{153b}
D. G. Charlton ²¹ M. Chatterjee ²⁰ C. Chauhan ¹³⁶ Y. Che ^{114a} S. Chekanov ⁶ S. V. Chekulaev ^{159a}
G. A. Chelkov ^{39,j} A. Chen ¹⁰⁸ B. Chen ¹⁵⁵ B. Chen ¹⁶⁸ H. Chen ^{114a} H. Chen ³⁰ J. Chen ^{63c} J. Chen ¹⁴⁶
M. Chen ¹²⁹ S. Chen ⁸⁹ S. J. Chen ^{114a} X. Chen ^{63c} X. Chen ^{15,k} Y. Chen ^{63a} C. L. Cheng ¹⁷³ H. C. Cheng ^{65a}
S. Cheong ¹⁴⁷ A. Cheplakov ³⁹ E. Cheremushkina ⁴⁹ E. Cherepanova ¹¹⁷ R. Cherkaoui El Moursli ^{36e} E. Cheu ⁷
K. Cheung ⁶⁶ L. Chevalier ¹³⁸ V. Chiarella ⁵⁴ G. Chiarelli ^{75a} N. Chiedde ¹⁰⁴ G. Chiodini ^{71a} A. S. Chisholm ²¹
A. Chitan ^{28b} M. Chitishvili ¹⁶⁶ M. V. Chizhov ^{39,l} K. Choi ¹¹ Y. Chou ¹⁴² E. Y. S. Chow ¹¹⁶ K. L. Chu ¹⁷²
M. C. Chu ^{65a} X. Chu ^{14,114c} Z. Chubinidze ⁵⁴ J. Chudoba ¹³⁴ J. J. Chwastowski ⁸⁸ D. Cieri ¹¹² K. M. Ciesla ^{87a}
V. Cindro ⁹⁵ A. Ciochio ^{18a} F. Ciotto ^{73a,73b} Z. H. Citron ¹⁷² M. Citterio ^{72a} D. A. Ciubotaru ^{28b} A. Clark ⁵⁷
P. J. Clark ⁵³ N. Clarke Hall ⁹⁸ C. Clarry ¹⁵⁸ J. M. Clavijo Columbie ⁴⁹ S. E. Clawson ⁴⁹ C. Clement ^{48a,48b}
Y. Coadou ¹⁰⁴ M. Cobal ^{70a,70c} A. Coccaro ^{58b} R. F. Coelho Barrue ^{133a} R. Coelho Lopes De Sa ¹⁰⁵ S. Coelli ^{72a}
B. Cole ⁴² J. Collot ⁶¹ P. Conde Muño ^{133a,133g} M. P. Connell ^{34c} S. H. Connell ^{34c} E. I. Conroy ¹²⁹
F. Conventi ^{73a,m} H. G. Cooke ²¹ A. M. Cooper-Sarkar ¹²⁹ F. A. Corchia ^{24b,24a} A. Cordeiro Oudot Choi ¹³⁰
L. D. Corpe ⁴¹ M. Corradi ^{76a,76b} F. Corriveau ^{106,n} A. Cortes-Gonzalez ¹⁹ M. J. Costa ¹⁶⁶ F. Costanza ⁴
D. Costanzo ¹⁴³ B. M. Cote ¹²² J. Couthures ⁴ G. Cowan ⁹⁷ K. Cranmer ¹⁷³ L. Cremer ⁵⁰ D. Cremonini ^{24b,24a}
S. Crépe-Renaudin ⁶¹ F. Crescioli ¹³⁰ M. Cristinziani ¹⁴⁵ M. Cristoforetti ⁷

- K. F. Di Petrillo⁴⁰, M. Diamantopoulou³⁵, F. A. Dias¹¹⁷, T. Dias Do Vale¹⁴⁶, M. A. Diaz^{140a,140b},
 F. G. Diaz Capriles²⁵, A. R. Didenko³⁹, M. Didenko¹⁶⁶, E. B. Diehl¹⁰⁸, S. Díez Cornell⁴⁹, C. Díez Pardo¹⁴⁵,
 C. Dimitriadis¹⁶⁴, A. Dimitrievska²¹, J. Dingfelder²⁵, T. Dingley¹²⁹, I.-M. Dinu^{28b}, S. J. Dittmeier^{64b}, F. Dittus³⁷,
 M. Divisek¹³⁶, B. Dixit⁹⁴, F. Djama¹⁰⁴, T. Djobava^{153b}, C. Doglioni^{103,100}, A. Dohnalova^{29a}, J. Dolejsi¹³⁶,
 Z. Dolezal¹³⁶, K. Domijan^{87a}, K. M. Dona⁴⁰, M. Donadelli^{84d}, B. Dong¹⁰⁹, J. Donini⁴¹, A. D'Onofrio^{73a,73b},
 M. D'Onofrio⁹⁴, J. Dopke¹³⁷, A. Doria^{73a}, N. Dos Santos Fernandes^{133a}, P. Dougan¹⁰³, M. T. Dova⁹²,
 A. T. Doyle⁶⁰, M. A. Draguet¹²⁹, E. Dreyer¹⁷², I. Drivas-koulouris¹⁰, M. Drnević¹²⁰, M. Drozdova⁵⁷, D. Du^{63a},
 T. A. du Pree¹¹⁷, F. Dubinin³⁸, M. Dubovsky^{29a}, E. Duchovni¹⁷², G. Duckeck¹¹¹, O. A. Ducu^{28b}, D. Duda⁵³,
 A. Dudarev³⁷, E. R. Duden²⁷, M. D'uffizi¹⁰³, L. Dufflot⁶⁷, M. Dührssen³⁷, I. Duminica^{28g}, A. E. Dumitriu^{28b},
 M. Dunford^{64a}, S. Dungs⁵⁰, K. Dunne^{48a,48b}, A. Duperrin¹⁰⁴, H. Duran Yildiz^{3a}, M. Düren⁵⁹, A. Durglishvili^{153b},
 D. Duvnjak³⁵, B. L. Dwyer¹¹⁸, G. I. Dyckes^{18a}, M. Dyndal^{87a}, B. S. Dziedzic³⁷, Z. O. Earnshaw¹⁵⁰,
 G. H. Eberwein¹²⁹, B. Eckerova^{29a}, S. Eggebrecht⁵⁶, E. Egidio Purcino De Souza^{84e}, L. F. Ehrke⁵⁷, G. Eigen¹⁷,
 K. Einsweiler^{18a}, T. Ekelof¹⁶⁴, P. A. Ekman¹⁰⁰, S. El Farkh^{36b}, Y. El Ghazali^{63a}, H. El Jarrari³⁷,
 A. El Moussaouy^{36a}, V. Ellajosyula¹⁶⁴, M. Ellert¹⁶⁴, F. Ellinghaus¹⁷⁴, N. Ellis³⁷, J. Elmsheuser³⁰, M. Elsaywy^{119a},
 M. Elsing³⁷, D. Emelianov¹³⁷, Y. Enari⁸⁵, I. Ene^{18a}, S. Epari¹³, P. A. Erland⁸⁸, D. Ernani Martins Neto⁸⁸,
 M. Errenst¹⁷⁴, M. Escalier⁶⁷, C. Escobar¹⁶⁶, E. Etzion¹⁵⁵, G. Evans^{133a,133b}, H. Evans⁶⁹, L. S. Evans⁹⁷,
 A. Ezhilov³⁸, S. Ezzarqtouni^{36a}, F. Fabbri^{24b,24a}, L. Fabbri^{24b,24a}, G. Facini⁹⁸, V. Fadeyev¹³⁹,
 R. M. Fakhrutdinov³⁸, D. Fakoudis¹⁰², S. Falciano^{76a}, L. F. Falda Ulhoa Coelho³⁷, F. Fallavollita¹¹²,
 G. Falsetti^{44b,44a}, J. Faltova¹³⁶, C. Fan¹⁶⁵, K. Y. Fan^{65b}, Y. Fan¹⁴, Y. Fang^{14,114c}, M. Fanti^{72a,72b}, M. Faraj^{70a,70b},
 Z. Farazpay⁹⁹, A. Farbin⁸, A. Farilla^{78a}, T. Farooque¹⁰⁹, S. M. Farrington⁵³, F. Fassi^{36e}, D. Fassouliotis⁹,
 M. Fauci Giannelli^{77a,77b}, W. J. Fawcett³³, L. Fayard⁶⁷, P. Federic¹³⁶, P. Federicova¹³⁴, O. L. Fedin^{38,j},
 M. Feickert¹⁷³, L. Feligioni¹⁰⁴, D. E. Fellers¹²⁶, C. Feng^{63b}, Z. Feng¹¹⁷, M. J. Fenton¹⁶², L. Ferencz⁴⁹,
 R. A. M. Ferguson⁹³, S. I. Fernandez Luengo^{140f}, P. Fernandez Martinez⁶⁸, M. J. V. Fernoux¹⁰⁴, J. Ferrando⁹³,
 A. Ferrari¹⁶⁴, P. Ferrari^{117,116}, R. Ferrari^{74a}, D. Ferrere⁵⁷, C. Ferretti¹⁰⁸, D. Fiacco^{76a,76b}, F. Fiedler¹⁰²,
 P. Fiedler¹³⁵, S. Filimonov³⁸, A. Filipčić⁹⁵, E. K. Filmer¹, F. Filthaut¹¹⁶, M. C. N. Fiolhais^{133a,133c,o}, L. Fiorini¹⁶⁶,
 W. C. Fisher¹⁰⁹, T. Fitschen¹⁰³, P. M. Fitzhugh¹³⁸, I. Fleck¹⁴⁵, P. Fleischmann¹⁰⁸, T. Flick¹⁷⁴, M. Flores^{34d,p},
 L. R. Flores Castillo^{65a}, L. Flores Sanz De Acedo³⁷, F. M. Follega^{79a,79b}, N. Fomin³³, J. H. Foo¹⁵⁸, A. Formica¹³⁸,
 A. C. Forti¹⁰³, E. Fortin³⁷, A. W. Fortman^{18a}, M. G. Foti^{18a}, L. Fountas^{9,q}, D. Fournier⁶⁷, H. Fox⁹³,
 P. Francavilla^{75a,75b}, S. Francescato⁶², S. Franchellucci⁵⁷, M. Franchini^{24b,24a}, S. Franchino^{64a}, D. Francis³⁷,
 L. Franco¹¹⁶, V. Franco Lima³⁷, L. Franconi⁴⁹, M. Franklin⁶², G. Frattari²⁷, Y. Y. Frid¹⁵⁵, J. Friend⁶⁰,
 N. Fritzsche³⁷, A. Froch⁵⁵, D. Froidevaux³⁷, J. A. Frost¹²⁹, Y. Fu^{63a}, S. Fuenzalida Garrido^{140f}, M. Fujimoto¹⁰⁴,
 K. Y. Fung^{65a}, E. Furtado De Simas Filho^{84e}, M. Furukawa¹⁵⁷, J. Fuster¹⁶⁶, A. Gaa⁵⁶, A. Gabrielli^{24b,24a},
 A. Gabrielli¹⁵⁸, P. Gadow³⁷, G. Gagliardi^{58b,58a}, L. G. Gagnon^{18a}, S. Gaid¹⁶³, S. Galantzan¹⁵⁵, J. Gallagher¹,
 E. J. Gallas¹²⁹, B. J. Gallop¹³⁷, K. K. Gan¹²², S. Ganguly¹⁵⁷, Y. Gao⁵³, F. M. Garay Walls^{140a,140b}, B. Garcia³⁰,
 C. García¹⁶⁶, A. Garcia Alonso¹¹⁷, A. G. Garcia Caffaro¹⁷⁵, J. E. García Navarro¹⁶⁶, M. Garcia-Sciveres^{18a},
 G. L. Gardner¹³¹, R. W. Gardner⁴⁰, N. Garelli¹⁶¹, D. Garg⁸¹, R. B. Garg¹⁴⁷, J. M. Gargan⁵³, C. A. Garner¹⁵⁸,
 C. M. Garvey^{34a}, V. K. Gassmann¹⁶¹, G. Gaudio^{74a}, V. Gautam¹³, P. Gauzzi^{76a,76b}, J. Gavranovic⁹⁵,
 I. L. Gavrilenko³⁸, A. Gavriluk³⁸, C. Gay¹⁶⁷, G. Gaycken¹²⁶, E. N. Gazis¹⁰, A. A. Geanta^{28b}, C. M. Gee¹³⁹,
 A. Gekow¹²², C. Gemme^{58b}, M. H. Genest⁶¹, A. D. Gentry¹¹⁵, S. George⁹⁷, W. F. George²¹, T. Gerialis⁴⁷,
 P. Gessinger-Befurt³⁷, M. E. Geyik¹⁷⁴, M. Ghani¹⁷⁰, K. Ghorbanian⁹⁶, A. Ghosal¹⁴⁵, A. Ghosh¹⁶², A. Ghosh⁷,
 B. Giacobbe^{24b}, S. Giagu^{76a,76b}, T. Giani¹¹⁷, A. Giannini^{63a}, S. M. Gibson⁹⁷, M. Gignac¹³⁹, D. T. Gil^{87b},
 A. K. Gilbert^{87a}, B. J. Gilbert⁴², D. Gillberg³⁵, G. Gilles¹¹⁷, L. Ginabat¹³⁰, D. M. Gingrich^{2,d},
 M. P. Giordani^{70a,70c}, P. F. Giraud¹³⁸, G. Giugliarelli^{70a,70c}, D. Giugni^{72a}, F. Giuli^{77a,77b}, I. Gkialas^{9,q},
 L. K. Gladilin³⁸, C. Glasman¹⁰¹, G. R. Gledhill¹²⁶, G. Glemža⁴⁹, M. Glisic¹²⁶, I. Gnesi^{44b}, Y. Go³⁰,
 M. Goblirsch-Kolb³⁷, B. Gocke⁵⁰, D. Godin¹¹⁰, B. Gokturk^{22a}, S. Goldfarb¹⁰⁷, T. Golling⁵⁷, M. G. D. Gololo^{34g},
 D. Golubkov^{133a}, J. P. Gombas¹⁰⁹, A. Gomes^{133a,133b}, G. Gomes Da Silva¹⁴⁵, A. J. Gomez Delegido¹⁶⁶,
 R. Gonçalves^{133a}, L. Gonella²¹, A. Gongadze^{153c}, F. Gonnella²¹, J. L. Gonski¹⁴⁷, R. Y. González Andana⁵³,
 S. González de la Hoz¹⁶⁶, R. Gonzalez Lopez⁹⁴, C. Gonzalez Renteria^{18a}, M. V. Gonzalez Rodrigues⁴⁹,
 R. Gonzalez Suarez¹⁶⁴, S. Gonzalez-Sevilla⁵⁷, L. Goossens³⁷, B. Gorini³⁷, E. Gorini^{71a,71b}, A. Gorišek⁹⁵,
 T. C. Gosart¹³¹, A. T. Goshaw⁵², M. I. Gostkin³⁹, S. Goswami¹²⁴, C. A. Gottardo³⁷, S. A. Gotz¹¹¹,
 M. Goughri^{36b}, V. Goumarre⁴⁹, A. G. Goussiou¹⁴², N. Govender^{34c}, R. P. Grabarczyk¹²⁹, I. Grabowska-Bold^{87a},
 K. Graham³⁵, E. Gramstad¹²⁸, S. Grancagnolo^{71a,71b}, C. M. Grant^{1,138}, P. M. Gravila^{28f}, F. G. Gravili^{71a,71b},
 H. M. Gray^{18a}, M. Greco^{71a,71b}, M. J. Green¹, C. Greife²⁵, A. S. Grefsrud¹⁷, I. M. Gregor⁴⁹, K. T. Greif¹⁶²,
 P. Grenier¹⁴⁷, S. G. Grewe¹¹², A. A. Grillo¹³⁹, K. Grimm³², S. Grinstein^{13,r}, J.-F. Grivaz⁶⁷, E. Gross¹⁷²,
 J. Grosse-Knetter⁵⁶, L. Guan¹⁰⁸, J. G. R. Guerrero Rojas¹⁶⁶, G. Guerrieri³⁷, R. Gugel¹⁰², J. A. M. Guhit¹⁰⁸,
 A. Guida¹⁹, E. Guillon¹⁷⁰, S. Guindon³⁷, F. Guo^{14,114c}, J. Guo^{63c}, L. Guo⁴⁹, Y. Guo¹⁰⁸, A. Gupta⁵⁰,
 R. Gupta¹³², S. Gurbuz²⁵, S. S. Gurdasani⁵⁵, G. Gustavino^{76a,76b}, P. Gutierrez¹²³, L. F. Gutierrez Zagazeta¹³¹,
 M. Gutsche⁵¹, C. Gutschow⁹⁸, C. Gwenlan¹²⁹, C. B. Gwilliam⁹⁴, E. S. Haaland¹²⁸, A. Haas¹²⁰, M. Habedank⁴⁹

- C. Haber^{18a}, H. K. Hadavand⁸, A. Hadeef⁵¹, S. Hadzic¹¹², A. I. Hagan⁹³, J. J. Hahn¹⁴⁵, E. H. Haines⁹⁸, M. Haleem¹⁶⁹, J. Haley¹²⁴, J. J. Hall¹⁴³, G. D. Hallewell¹⁰⁴, L. Halser²⁰, K. Hamano¹⁶⁸, M. Hamer²⁵, G. N. Hamity⁵³, E. J. Hampshire⁹⁷, J. Han^{63b}, K. Han^{63a}, L. Han^{114a}, L. Han^{63a}, S. Han^{18a}, Y. F. Han¹⁵⁸, K. Hanagaki⁸⁵, M. Hance¹³⁹, D. A. Hangal⁴², H. Hanif¹⁴⁶, M. D. Hank¹³¹, J. B. Hansen⁴³, P. H. Hansen⁴³, D. Harada⁵⁷, T. Harenberg¹⁷⁴, S. Harkusha³⁸, M. L. Harris¹⁰⁵, Y. T. Harris²⁵, J. Harrison¹³, N. M. Harrison¹²², P. F. Harrison¹⁷⁰, N. M. Hartman¹¹², N. M. Hartmann¹¹¹, R. Z. Hasan^{97,137}, Y. Hasegawa¹⁴⁴, F. Haslbeck¹²⁹, S. Hassan¹⁷, R. Hauser¹⁰⁹, C. M. Hawkes²¹, R. J. Hawkings³⁷, Y. Hayashi¹⁵⁷, D. Hayden¹⁰⁹, C. Hayes¹⁰⁸, R. L. Hayes¹¹⁷, C. P. Hays¹²⁹, J. M. Hays⁹⁶, H. S. Hayward⁹⁴, F. He^{63a}, M. He^{14,114c}, Y. He⁴⁹, Y. He⁹⁸, N. B. Heatley⁹⁶, V. Hedberg¹⁰⁰, A. L. Heggelund¹²⁸, N. D. Hehir^{96,s}, C. Heidegger⁵⁵, K. K. Heidegger⁵⁵, J. Heilman³⁵, S. Heim⁴⁹, T. Heim^{18a}, J. G. Heinlein¹³¹, J. J. Heinrich¹²⁶, L. Heinrich^{112,t}, J. Hejbal¹³⁴, A. Held¹⁷³, S. Hellesund¹⁷, C. M. Helling¹⁶⁷, S. Hellman^{48a,48b}, R. C. W. Henderson⁹³, L. Henkelmann³³, A. M. Henriques Correia³⁷, H. Herde¹⁰⁰, Y. Hernández Jiménez¹⁴⁹, L. M. Herrmann²⁵, T. Herrmann⁵¹, G. Herten⁵⁵, R. Hertenberger¹¹¹, L. Hervas³⁷, M. E. Hespington¹⁰², N. P. Hessey^{159a}, J. Hessler¹¹², M. Hidaoui^{36b}, N. Hidic¹³⁶, E. Hill¹⁵⁸, S. J. Hillier²¹, J. R. Hinds¹⁰⁹, F. Hinterkeuser²⁵, M. Hirose¹²⁷, S. Hirose¹⁶⁰, D. Hirschbuehl¹⁷⁴, T. G. Hitchings¹⁰³, B. Hiti⁹⁵, J. Hobbs¹⁴⁹, R. Hobincu^{28e}, N. Hod¹⁷², M. C. Hodgkinson¹⁴³, B. H. Hodgkinson¹²⁹, A. Hoecker³⁷, D. D. Hofer¹⁰⁸, J. Hofer¹⁶⁶, T. Holm²⁵, M. Holzbock³⁷, L. B. A. H. Hommels³³, B. P. Honan¹⁰³, J. J. Hong⁶⁹, J. Hong^{63c}, T. M. Hong¹³², B. H. Hooberman¹⁶⁵, W. H. Hopkins⁶, M. C. Hoppesch¹⁶⁵, Y. Horii¹¹³, M. E. Horstmann¹¹², S. Hou¹⁵², A. S. Howard⁹⁵, J. Howarth⁶⁰, J. Hoya⁶, M. Hrabovsky¹²⁵, A. Hrynevich⁴⁹, T. Hryn'ova⁴, P. J. Hsu⁶⁶, S.-C. Hsu¹⁴², T. Hsu⁶⁷, M. Hu^{18a}, Q. Hu^{63a}, S. Huang^{65b}, X. Huang^{14,114c}, Y. Huang¹⁴³, Y. Huang¹⁰², Y. Huang¹⁴, Z. Huang¹⁰³, Z. Hubacek¹³⁵, M. Huebner²⁵, F. Huegging²⁵, T. B. Huffman¹²⁹, C. A. Hugli⁴⁹, M. Huhtinen³⁷, S. K. Huiberts¹⁷, R. Hulsken¹⁰⁶, N. Huseynov^{12,u}, J. Huston¹⁰⁹, J. Huth⁶², R. Hyneman¹⁴⁷, G. Iacobucci⁵⁷, G. Iakovidis³⁰, L. Iconomidou-Fayard⁶⁷, J. P. Iddon³⁷, P. Iengo^{73a,73b}, R. Iguchi¹⁵⁷, Y. Iiyama¹⁵⁷, T. Iizawa¹²⁹, Y. Ikegami⁸⁵, N. Ilic¹⁵⁸, H. Imam^{84c}, G. Inacio Goncalves^{84d}, M. Ince Lezki⁵⁷, T. Ingebretsen Carlson^{48a,48b}, J. M. Inglis⁹⁶, G. Introzzi^{74a,74b}, M. Iodice^{78a}, V. Ippolito^{76a,76b}, R. K. Irwin⁹⁴, M. Ishino¹⁵⁷, W. Islam¹⁷³, C. Issever^{19,49}, S. Istin^{22a,v}, H. Ito¹⁷¹, R. Iuppa^{79a,79b}, A. Ivina¹⁷², J. M. Izen⁴⁶, V. Izzo^{73a}, P. Jacka¹³⁴, P. Jackson¹, C. S. Jagfeld¹¹¹, G. Jain^{159a}, P. Jain⁴⁹, K. Jakobs⁵⁵, T. Jakoubek¹⁷², J. Jamieson⁶⁰, W. Jang¹⁵⁷, M. Javurkova¹⁰⁵, P. Jawahar¹⁰³, L. Jeanty¹²⁶, J. Jejelava^{153a,w}, P. Jenni^{55,x}, C. E. Jessiman³⁵, C. Jia^{63b}, H. Jia¹⁶⁷, J. Jia¹⁴⁹, X. Jia^{14,114c}, Z. Jia^{114a}, C. Jiang⁵³, S. Jiggins⁴⁹, J. Jimenez Pena¹³, S. Jin^{114a}, A. Jinaru^{28b}, O. Jinnouchi¹⁴¹, P. Johansson¹⁴³, K. A. Johns⁷, J. W. Johnson¹³⁹, F. A. Jolly⁴⁹, D. M. Jones¹⁵⁰, E. Jones⁴⁹, K. S. Jones⁸, P. Jones³³, R. W. L. Jones⁹³, T. J. Jones⁹⁴, H. L. Joos^{56,37}, R. Joshi¹²², J. Jovicevic¹⁶, X. Ju^{18a}, J. J. Junggeburth¹⁰⁵, T. Junkermann^{64a}, A. Juste Rozas^{13,r}, M. K. Juzek⁸⁸, S. Kabana^{140e}, A. Kaczmarzka⁸⁸, M. Kado¹¹², H. Kagan¹²², M. Kagan¹⁴⁷, A. Kahn¹³¹, C. Kahra¹⁰², T. Kaji¹⁵⁷, E. Kajomovitz¹⁵⁴, N. Kakati¹⁷², I. Kalaitzidou⁵⁵, C. W. Kalderon³⁰, N. J. Kang¹³⁹, D. Kar^{34g}, K. Karava¹²⁹, M. J. Kareem^{159b}, E. Karentzos⁵⁵, O. Karkout¹¹⁷, S. N. Karpov³⁹, Z. M. Karpova³⁹, V. Kartvelishvili⁹³, A. N. Karyukhin³⁸, E. Kasimi¹⁵⁶, J. Katzy⁴⁹, S. Kaur³⁵, K. Kawade¹⁴⁴, M. P. Kawale¹²³, C. Kawamoto⁸⁹, T. Kawamoto^{63a}, E. F. Kay³⁷, F. I. Kaya¹⁶¹, S. Kazakos¹⁰⁹, V. F. Kazanin³⁸, Y. Ke¹⁴⁹, J. M. Keaveney^{34a}, R. Keeler¹⁶⁸, G. V. Kehris⁶², J. S. Keller³⁵, A. S. Kelly⁹⁸, J. J. Kempster¹⁵⁰, P. D. Kennedy¹⁰², O. Kepka¹³⁴, B. P. Kerridge¹³⁷, S. Kersten¹⁷⁴, B. P. Kerševan⁹⁵, L. Keszeghova^{29a}, S. Ketabchi Haghighat¹⁵⁸, R. A. Khan¹³², A. Khanov¹²⁴, A. G. Kharlamov³⁸, T. Kharlamova³⁸, E. E. Khoda¹⁴², M. Kholodenko^{133a}, T. J. Khoo¹⁹, G. Khoraiuli¹⁶⁹, J. Khubua^{153b,s}, Y. A. R. Khwaira¹³⁰, B. Kibirige^{34g}, D. Kim⁶, D. W. Kim^{48a,48b}, Y. K. Kim⁴⁰, N. Kimura⁹⁸, M. K. Kingston⁵⁶, A. Kirchhoff⁵⁶, C. Kirfel²⁵, F. Kirfel²⁵, J. Kirk¹³⁷, A. E. Kiryunin¹¹², S. Kita¹⁶⁰, C. Kitsaki¹⁰, O. Kivernyk²⁵, M. Klassen¹⁶¹, C. Klein³⁵, L. Klein¹⁶⁹, M. H. Klein⁴⁵, S. B. Klein⁵⁷, U. Klein⁹⁴, P. Klimek³⁷, A. Klimentov³⁰, T. Klioutchnikova³⁷, P. Kluit¹¹⁷, S. Kluth¹¹², E. Kneringer⁸⁰, T. M. Knight¹⁵⁸, A. Knue⁵⁰, D. Kobylanskii¹⁷², S. F. Koch¹²⁹, M. Kocian¹⁴⁷, P. Kodyš¹³⁶, D. M. Koeck¹²⁶, P. T. Koenig²⁵, T. Koffas³⁵, O. Kolay⁵¹, I. Koletsou⁴, T. Komarek⁸⁸, K. Köneke⁵⁵, A. X. Y. Kong¹, T. Kono¹²¹, N. Konstantinidis⁹⁸, P. Kontaxakis⁵⁷, B. Konya¹⁰⁰, R. Kopeliansky⁴², S. Koperny^{87a}, K. Korcyl⁸⁸, K. Kordas^{156,y}, A. Korn⁹⁸, S. Korn⁵⁶, I. Korolkov¹³, N. Korotkova³⁸, B. Kortman¹¹⁷, O. Kortner¹¹², S. Kortner¹¹², W. H. Kostecka¹¹⁸, V. V. Kostyukhin¹⁴⁵, A. Kotskechagia³⁷, A. Kotwal⁵², A. Koulouris³⁷, A. Kourkoulaki-Charalampidi^{74a,74b}, C. Kourkoulis⁹, E. Kourlitis¹¹², O. Kovanda¹²⁶, R. Kowalewski¹⁶⁸, W. Kozanecki¹²⁶, A. S. Kozhin³⁸, V. A. Kramarenko³⁸, G. Kramberger⁹⁵, P. Kramer¹⁰², M. W. Krasny¹³⁰, A. Krasznahorkay³⁷, A. C. Kraus¹¹⁸, J. W. Kraus¹⁷⁴, J. A. Kremer⁴⁹, T. Kresse⁵¹, L. Kretschmann¹⁷⁴, J. Kretschmar⁹⁴, K. Kreul¹⁹, P. Krieger¹⁵⁸, M. Krivos¹³⁶, K. Krizka²¹, K. Kroeninger⁵⁰, H. Kroha¹¹², J. Kroll¹³⁴, J. Kroll¹³¹, K. S. Krowpman¹⁰⁹, U. Kruchonak³⁹, H. Krüger²⁵, N. Krumnack⁸², M. C. Kruse⁵², O. Kuchinskaia³⁸, S. Kuday^{3a}, S. Kuehn³⁷, R. Kuesters⁵⁵, T. Kuhl⁴⁹, V. Kukhtin³⁹, Y. Kulchitsky^{38,j}, S. Kuleshov^{140d,140b}, M. Kumar^{34g}, N. Kumari⁴⁹, P. Kumari^{159b}, A. Kupco¹³⁴, T. Kupfer⁵⁰, A. Kupich³⁸, O. Kuprash⁵⁵, H. Kurashige⁸⁶, L. L. Kurchaninov^{159a}, O. Kurdysh⁶⁷, Y. A. Kurochkin³⁸, A. Kurova³⁸, M. Kuze¹⁴¹, A. K. Kvam¹⁰⁵, J. Kvita¹²⁵, T. Kwan¹⁰⁶, N. G. Kyriacou¹⁰⁸, L. A. O. Laatu¹⁰⁴, C. Lacasta¹⁶⁶, F. Lacava^{76a,76b}, H. Lacker¹⁹, D. Lacour¹³⁰, N. N. Lad⁹⁸, E. Ladygin³⁹, A. Lafarge⁴¹, B. Laforge¹³⁰

- T. Lagouri¹⁷⁵, F. Z. Lahbabi^{36a}, S. Lai⁵⁶, J. E. Lambert¹⁶⁸, S. Lammers⁶⁹, W. Lampl⁷, C. Lampoudis^{156,y},
 G. Lamprinoudis¹⁰², A. N. Lancaster¹¹⁸, E. Lançon³⁰, U. Landgraf⁵⁵, M. P. J. Landon⁹⁶, V. S. Lang⁵⁵,
 O. K. B. Langrekken¹²⁸, A. J. Lankford¹⁶², F. Lanni³⁷, K. Lantzsch²⁵, A. Lanza^{74a}, M. Lanzac Berrocal¹⁶⁶,
 J. F. Laporte¹³⁸, T. Lari^{72a}, F. Lasagni Manghi^{24b}, M. Lassnig³⁷, V. Latonova¹³⁴, A. Laurier¹⁵⁴, S. D. Lawlor¹⁴³,
 Z. Lawrence¹⁰³, R. Lazaridou¹⁷⁰, M. Lazzaroni^{72a,72b}, B. Le¹⁰³, H. D. M. Le¹⁰⁹, E. M. Le Boulicaut¹⁷⁵,
 L. T. Le Pottier^{18a}, B. Leban^{24b,24a}, A. Lebedev⁸², M. LeBlanc¹⁰³, F. Ledroit-Guillon⁶¹, S. C. Lee¹⁵²,
 S. Lee^{48a,48b}, T. F. Lee⁹⁴, L. L. Leeuw^{34c}, H. P. Lefebvre⁹⁷, M. Lefebvre¹⁶⁸, C. Leggett^{18a}, G. Lehmann Miotto³⁷,
 M. Leigh⁵⁷, W. A. Leight¹⁰⁵, W. Leinonen¹¹⁶, A. Leisos^{156,z}, M. A. L. Leite^{84c}, C. E. Leitgeb¹⁹, R. Leitner¹³⁶,
 K. J. C. Leney⁴⁵, T. Lenz²⁵, S. Leone^{75a}, C. Leonidopoulos⁵³, A. Leopold¹⁴⁸, R. Les¹⁰⁹, C. G. Lester³³,
 M. Levchenko³⁸, J. Levêque⁴, L. J. Levinson¹⁷², G. Levrini^{24b,24a}, M. P. Lewicki⁸⁸, C. Lewis¹⁴², D. J. Lewis⁴,
 L. Lewitt¹⁴³, A. Li³⁰, B. Li^{63b}, C. Li^{63a}, C.-Q. Li¹¹², H. Li^{63a}, H. Li^{63b}, H. Li^{114a}, H. Li¹⁵, H. Li^{63b}, J. Li^{63c},
 K. Li¹⁴, L. Li^{63c}, M. Li^{14,114c}, S. Li^{14,114c}, S. Li^{63d,63c,aa}, T. Li⁵, X. Li¹⁰⁶, Z. Li¹²⁹, Z. Li¹⁵⁷, Z. Li^{14,114c},
 Z. Li^{63a}, S. Liang^{14,114c}, Z. Liang¹⁴, M. Liberatore¹³⁸, B. Liberti^{77a},
 K. Lie^{65c}, J. Lieber Marin^{84c}, H. Lien⁶⁹, H. Lin¹⁰⁸, K. Lin¹⁰⁹, R. E. Lindley⁷, J. H. Lindon², J. Ling⁶²,
 E. Lipeles¹³¹, A. Lipniacka¹⁷, A. Lister¹⁶⁷, J. D. Little⁶⁹, B. Liu¹⁴, B. X. Liu^{114b}, D. Liu^{63d,63c}, E. H. L. Liu²¹,
 J. B. Liu^{63a}, J. K. K. Liu³³, K. Liu^{63d}, K. Liu^{63d,63c}, M. Liu^{63a}, M. Y. Liu^{63a}, P. Liu¹⁴, Q. Liu^{63d,142,63c},
 X. Liu^{63a}, X. Liu^{63b}, Y. Liu^{114b,114c}, Y. L. Liu^{63b}, Y. W. Liu^{63a}, S. L. Lloyd⁹⁶, E. M. Lobodzinska⁴⁹, P. Loch⁷,
 E. Lodhi¹⁵⁸, T. Lohse¹⁹, K. Lohwasser¹⁴³, E. Loiacono⁴⁹, M. Lokajicek^{134,s}, J. D. Lomas²¹, J. D. Long⁴²,
 I. Longarini¹⁶², R. Longo¹⁶⁵, I. Lopez Paz⁶⁸, A. Lopez Solis⁴⁹, N. A. Lopez-canelas⁷, N. Lorenzo Martinez⁴,
 A. M. Lory¹¹¹, M. Losada^{119a}, G. Löschcke Centeno¹⁵⁰, O. Loseva³⁸, X. Lou^{48a,48b}, X. Lou^{14,114c}, A. Lounis⁶⁷,
 P. A. Love⁹³, G. Lu^{14,114c}, M. Lu⁶⁷, S. Lu¹³¹, Y. J. Lu⁶⁶, H. J. Lubatti¹⁴², C. Luci^{76a,76b}, F. L. Lucio Alves^{114a},
 F. Luehring⁶⁹, O. Lukianchuk⁶⁷, B. S. Lunday¹³¹, O. Lundberg¹⁴⁸, B. Lund-Jensen^{148,s}, N. A. Luongo⁶,
 M. S. Lutz³⁷, A. B. Lux²⁶, D. Lynn³⁰, R. Lysak¹³⁴, E. Lytken¹⁰⁰, V. Lyubushkin³⁹, T. Lyubushkina³⁹,
 M. M. Lyukova¹⁴⁹, M. Firdaus M. Soberi⁵³, H. Ma^{84c}, K. Ma^{63a}, L. L. Ma^{63b}, W. Ma^{63a}, Y. Ma¹²⁴,
 J. C. MacDonald¹⁰², P. C. Machado De Abreu Farias^{84c}, R. Madar⁴¹, T. Madula⁹⁸, J. Maeda⁸⁶, T. Maeno³⁰,
 H. Maguire¹⁴³, V. Maiboroda¹³⁸, A. Maio^{133a,133b,133d}, K. Maj^{87a}, O. Majersky⁴⁹, S. Majewski¹²⁶, N. Makovec⁶⁷,
 V. Maksimovic¹⁶, B. Malaescu¹³⁰, Pa. Malecki⁸⁸, V. P. Maleev³⁸, F. Malek^{61,ab}, M. Mali⁹⁵, D. Malito⁹⁷,
 U. Mallik^{81,s}, S. Maltezos¹⁰, S. Malyukov³⁹, J. Mamuzic¹³, G. Mancini⁵⁴, M. N. Mancini²⁷, G. Manco^{74a,74b},
 J. P. Mandalia⁹⁶, S. S. Mandarri¹⁵⁰, I. Mandić⁹⁵, L. Manhaes de Andrade Filho^{84a}, I. M. Maniatis¹⁷²,
 J. Manjarres Ramos⁹¹, D. C. Mankad¹⁷², A. Mann¹¹¹, S. Manzoni³⁷, L. Mao^{63c}, X. Mapekula^{34c},
 A. Marantis^{156,z}, G. Marchiori⁵, M. Marcisovsky¹³⁴, C. Marcon^{72a}, M. Marinescu²¹, S. Marium⁴⁹,
 M. Marjanovic¹²³, A. Markhoos⁵⁵, M. Markovitch⁶⁷, E. J. Marshall⁹³, Z. Marshall^{18a}, S. Marti-Garcia¹⁶⁶,
 J. Martin⁹⁸, T. A. Martin¹³⁷, V. J. Martin⁵³, B. Martin dit Latour¹⁷, L. Martinelli^{76a,76b}, M. Martinez^{13,r},
 P. Martinez Agullo¹⁶⁶, V. I. Martinez Outschoorn¹⁰⁵, P. Martinez Suarez¹³, S. Martin-Haugh¹³⁷, G. Martinovicova¹³⁶,
 V. S. Martoiu^{28b}, A. C. Martyniuk⁹⁸, A. Marzin³⁷, D. Mascione^{79a,79b}, L. Masetti¹⁰², J. Masik¹⁰³,
 A. L. Maslennikov³⁸, S. L. Mason⁴², P. Massarotti^{73a,73b}, P. Mastrandrea^{75a,75b}, A. Mastroberardino^{44b,44a},
 T. Masubuchi¹²⁷, T. T. Mathew¹²⁶, T. Mathisen¹⁶⁴, J. Matousek¹³⁶, J. Maurer^{28b}, T. Maurin⁶⁰, A. J. Maury⁶⁷,
 B. Maček⁹⁵, D. A. Maximov³⁸, A. E. May¹⁰³, R. Mazini¹⁵², I. Maznas¹¹⁸, M. Mazza¹⁰⁹, S. M. Mazza¹³⁹,
 E. Mazzeo^{72a,72b}, C. Mc Ginn³⁰, J. P. Mc Gowan¹⁶⁸, S. P. Mc Kee¹⁰⁸, C. C. McCracken¹⁶⁷, E. F. McDonald¹⁰⁷,
 A. E. McDougall¹¹⁷, J. A. Mcfayden¹⁵⁰, R. P. McGovern¹³¹, R. P. Mckenzie^{34g}, T. C. McLachlan⁴⁹,
 D. J. McLaughlin⁹⁸, S. J. McMahon¹³⁷, C. M. Mcpartland⁹⁴, R. A. McPherson^{168,n}, S. Mehlhase¹¹¹, A. Mehta⁹⁴,
 D. Melini¹⁶⁶, B. R. Mellado Garcia^{34g}, A. H. Melo⁵⁶, F. Meloni⁴⁹, A. M. Mendes Jacques Da Costa¹⁰³,
 H. Y. Meng¹⁵⁸, L. Meng⁹³, S. Menke¹¹², M. Mentink³⁷, E. Meoni^{44b,44a}, G. Mercado¹¹⁸, S. Merianos¹⁵⁶,
 C. Merlassino^{70a,70c}, L. Merola^{73a,73b}, C. Meroni^{72a,72b}, J. Metcalfe⁶, A. S. Mete⁶, E. Meuser¹⁰², C. Meyer⁶⁹,
 J.-P. Meyer¹³⁸, R. P. Middleton¹³⁷, L. Mijović⁵³, G. Mikenberg¹⁷², M. Mikestikova¹³⁴, M. Mikuž⁹⁵,
 H. Mildner¹⁰², A. Milic³⁷, D. W. Miller⁴⁰, E. H. Miller¹⁴⁷, L. S. Miller³⁵, A. Milov¹⁷², D. A. Milstead^{48a,48b},
 T. Min^{114a}, A. A. Minaenko³⁸, I. A. Minashvili^{153b}, L. Mince⁶⁰, A. I. Mincer¹²⁰, B. Mindur^{87a}, M. Mineev³⁹,
 Y. Mino⁸⁹, L. M. Mir¹³, M. Miralles Lopez⁶⁰, M. Mironova^{18a}, M. C. Missio¹¹⁶, A. Mitra¹⁷⁰, V. A. Mitsou¹⁶⁶,
 Y. Mitsumori¹¹³, O. Miu¹⁵⁸, P. S. Miyagawa⁹⁶, T. Mkrtchyan^{64a}, M. Mlinarevic⁹⁸, T. Mlinarevic⁹⁸,
 M. Mlynarikova³⁷, S. Mobius²⁰, P. Mogg¹¹¹, M. H. Mohamed Farook¹¹⁵, A. F. Mohammed^{14,114c}, S. Mohapatra⁴²,
 G. Mokgatitswane^{34g}, L. Moleri¹⁷², B. Mondal¹⁴⁵, S. Mondal¹³⁵, K. Mönig⁴⁹, E. Monnier¹⁰⁴,
 L. Monsonis Romero¹⁶⁶, J. Montejo Berlingen¹³, A. Montella^{48a,48b}, M. Montella¹²², F. Montereali^{78a,78b},
 F. Monticelli⁹², S. Monzani^{70a,70c}, A. Morancho Tarda⁴³, N. Morange⁶⁷, A. L. Moreira De Carvalho⁴⁹,
 M. Moreno Llácer¹⁶⁶, C. Moreno Martinez⁵⁷, J. M. Moreno Perez^{23b}, P. Morettini^{58b}, S. Morgenstern³⁷, M. Morii⁶²,
 M. Morinaga¹⁵⁷, M. Moritsu⁹⁰, F. Morodei^{76a,76b}, L. Morvaj³⁷, P. Moschovakos³⁷, B. Moser¹²⁹, M. Mosidze^{153b},
 T. Moskalets⁴⁵, P. Moskvitina¹¹⁶, J. Moss^{32,ac}, P. Moszkowicz^{87a}, A. Moussa^{36d}, E. J. W. Moyse¹⁰⁵,
 O. Mtintsilana^{34g}, S. Muanza¹⁰⁴, J. Mueller¹³², D. Muenstermann⁹³, R. Müller³⁷, G. A. Mullier¹⁶⁴, A. J. Mullin³³,
 J. J. Mullin¹³¹, A. E. Mulski⁶², D. P. Mungo¹⁵⁸, D. Munoz Perez¹⁶⁶, F. J. Munoz Sanchez¹⁰³, M. Murin¹⁰³

- W. J. Murray^{170,137} M. Muškinja⁹⁵ C. Mwewa³⁰ A. G. Myagkov^{38,j} A. J. Myers⁸ G. Myers¹⁰⁸ M. Myska¹³⁵
 B. P. Nachman^{18a} O. Nackenhorst⁵⁰ K. Nagai¹²⁹ K. Nagano⁸⁵ R. Nagasaka¹⁵⁷ J. L. Nagle^{30,ad} E. Nagy¹⁰⁴
 A. M. Nairz³⁷ Y. Nakahama⁸⁵ K. Nakamura⁸⁵ K. Nakkalil⁵ H. Nanjo¹²⁷ E. A. Narayanan¹¹⁵ I. Naryshkin³⁸
 L. Nasella^{72a,72b} M. Naseri³⁵ S. Nasri^{119b} C. Nass²⁵ G. Navarro^{23a} J. Navarro-Gonzalez¹⁶⁶ R. Nayak¹⁵⁵
 A. Nayaz¹⁹ P. Y. Nechaeva³⁸ S. Nechaeva^{24b,24a} F. Nechansky¹³⁴ L. Nedic¹²⁹ T. J. Neep²¹ A. Negri^{74a,74b}
 M. Negrini^{24b} C. Nellist¹¹⁷ C. Nelson¹⁰⁶ K. Nelson¹⁰⁸ S. Nemecek¹³⁴ M. Nessi^{37,ae} M. S. Neubauer¹⁶⁵
 F. Neuhaus¹⁰² J. Neundorff⁴⁹ J. Newell⁹⁴ P. R. Newman²¹ C. W. Ng¹³² Y. W. Y. Ng⁴⁹ B. Ngair^{119a}
 H. D. N. Nguyen¹¹⁰ R. B. Nickerson¹²⁹ R. Nicolaidou¹³⁸ J. Nielsen¹³⁹ M. Niemeyer⁵⁶ J. Niermann⁵⁶
 N. Nikiforou³⁷ V. Nikolaenko^{38,j} I. Nikolic-Audit¹³⁰ K. Nikolopoulos²¹ P. Nilsson³⁰ I. Ninca⁴⁹ G. Ninio¹⁵⁵
 A. Nisati^{76a} N. Nishu² R. Nisius¹¹² J.-E. Nitschke⁵¹ E. K. Nkadimeng^{34g} T. Nobe¹⁵⁷ T. Nommensen¹⁵¹
 M. B. Norfolk¹⁴³ B. J. Norman³⁵ M. Noury^{36a} J. Novak⁹⁵ T. Novak⁹⁵ L. Novotny¹³⁵ R. Novotny¹¹⁵
 L. Nozka¹²⁵ K. Ntekas¹⁶² N. M. J. Nunes De Moura Junior^{84b} J. Ocariz¹³⁰ A. Ochi⁸⁶ I. Ochoa^{133a}
 S. Oerdek^{49,af} J. T. Offermann⁴⁰ A. Ogrodnik¹³⁶ A. Oh¹⁰³ C. C. Ohm¹⁴⁸ H. Oide⁸⁵ R. Oishi¹⁵⁷
 M. L. Ojeda³⁷ Y. Okumura¹⁵⁷ L. F. Oleiro Seabra^{133a} I. Oleksiyuk⁵⁷ S. A. Olivares Pino^{140d}
 G. Oliveira Correa¹³ D. Oliveira Damazio³⁰ J. L. Oliver¹⁶² Ö. O. Öncel⁵⁵ A. P. O'Neill²⁰ A. Onofre^{133a,133e}
 P. U. E. Onyisi¹¹ M. J. Oreglia⁴⁰ G. E. Orellana⁹² D. Orestano^{78a,78b} N. Orlando¹³ R. S. Orr¹⁵⁸
 L. M. Osojnak¹³¹ R. Ospanov^{63a} Y. Osumi¹¹³ G. Otero y Garzon³¹ H. Otono⁹⁰ P. S. Ott^{64a} G. J. Ottino^{18a}
 M. Ouchrif^{36d} F. Ould-Saada¹²⁸ T. Ovsianikova¹⁴² M. Owen⁶⁰ R. E. Owen¹³⁷ V. E. Ozcan^{22a} F. Ozturk⁸⁸
 N. Ozturk⁸ S. Ozturk⁸³ H. A. Pacey¹²⁹ A. Pacheco Pages¹³ C. Padilla Aranda¹³ G. Padovano^{76a,76b}
 S. Pagan Griso^{18a} G. Palacino⁶⁹ A. Palazzo^{71a,71b} J. Pampel²⁵ J. Pan¹⁷⁵ T. Pan^{65a} D. K. Panchal¹¹
 C. E. Pandini¹¹⁷ J. G. Panduro Vazquez¹³⁷ H. D. Pandya¹ H. Pang¹⁵ P. Pani⁴⁹ G. Panizzo^{70a,70c} L. Panwar¹³⁰
 L. Paolozzi⁵⁷ S. Parajuli¹⁶⁵ A. Paramonov⁶ C. Paraskevopoulos⁵⁴ D. Paredes Hernandez^{65b} A. Pareti^{74a,74b}
 K. R. Park⁴² T. H. Park¹⁵⁸ M. A. Parker³³ F. Parodi^{58b,58a} E. W. Parrish¹¹⁸ V. A. Parrish⁵³ J. A. Parsons⁴²
 U. Parzefall⁵⁵ B. Pascual Dias¹¹⁰ L. Pascual Dominguez¹⁰¹ E. Pasqualucci^{76a} S. Passaggio^{58b} F. Pastore⁹⁷
 P. Patel⁸⁸ U. M. Patel⁵² J. R. Pater¹⁰³ T. Pauly³⁷ F. Pauwels¹³⁶ C. I. Pazos¹⁶¹ J. Pearkes¹⁴⁷ M. Pedersen¹²⁸
 R. Pedro^{133a} S. V. Peleganchuk³⁸ O. Penc³⁷ E. A. Pender⁵³ S. Peng¹⁵ G. D. Penn¹⁷⁵ K. E. Penski¹¹¹
 M. Penzin³⁸ B. S. Peralva^{84d} A. P. Pereira Peixoto¹⁴² L. Pereira Sanchez¹⁴⁷ D. V. Perepelitsa^{30,ad} G. Perera¹⁰⁵
 E. Perez Codina^{159a} M. Perganti¹⁰ H. Pernegger³⁷ S. Perrella^{76a,76b} O. Perrin⁴¹ K. Peters⁴⁹ R. F. Y. Peters¹⁰³
 B. A. Petersen³⁷ T. C. Petersen⁴³ E. Petit¹⁰⁴ V. Petousis¹³⁵ C. Petridou^{156,y} T. Petru¹³⁶ A. Petrukhin¹⁴⁵
 M. Pettee^{18a} A. Petukhov³⁸ K. Petukhova³⁷ R. Pezoa^{140f} L. Pezzotti³⁷ G. Pezzullo¹⁷⁵ A. J. Pflieger³⁷
 T. M. Pham¹⁷³ T. Pham¹⁰⁷ P. W. Phillips¹³⁷ G. Piacquadio¹⁴⁹ E. Pianori^{18a} F. Piazza¹²⁶ R. Piegaia³¹
 D. Pietreanu^{28b} A. D. Pilkington¹⁰³ M. Pinamonti^{70a,70c} J. L. Pinfold² B. C. Pinheiro Pereira^{133a} J. Pinol Bel¹³
 A. E. Pinto Pinoargote^{138,138} L. Pintucci^{70a,70c} K. M. Piper¹⁵⁰ A. Pirttikoski⁵⁷ D. A. Pizzi³⁵ L. Pizzimento^{65b}
 A. Pizzini¹¹⁷ M.-A. Pleier³⁰ V. Pleskot¹³⁶ E. Plotnikova³⁹ G. Poddar⁹⁶ R. Poettgen¹⁰⁰ L. Poggioli¹³⁰
 I. Pokharel⁵⁶ S. Polacek¹³⁶ G. Polesello^{74a} A. Poley^{146,159a} A. Polini^{24b} C. S. Pollard¹⁷⁰ Z. B. Pollock¹²²
 E. Pompa Pacchi^{76a,76b} N. I. Pond⁹⁸ D. Ponomarenko⁶⁹ L. Pontecorvo³⁷ S. Popa^{28a} G. A. Popeneciu^{28d}
 A. Poreba³⁷ D. M. Portillo Quintero^{159a} S. Pospisil¹³⁵ M. A. Postill¹⁴³ P. Postolache^{28c} K. Potamianos¹⁷⁰
 P. A. Potepa^{87a} I. N. Potrap³⁹ C. J. Potter³³ H. Potti¹⁵¹ J. Poveda¹⁶⁶ M. E. Pozo Astigarraga³⁷
 A. Prades Ibanez^{77a,77b} J. Pretel¹⁶⁸ D. Price¹⁰³ M. Primavera^{71a} L. Primomo^{70a,70c} M. A. Principe Martin¹⁰¹
 R. Privara¹²⁵ T. Procter⁶⁰ M. L. Proffitt¹⁴² N. Proklova¹³¹ K. Prokofiev^{65c} G. Proto¹¹² J. Proudfoot⁶
 M. Przybycien^{87a} W. W. Przygoda^{87b} A. Psallidas⁴⁷ J. E. Puddefoot¹⁴³ D. Pudzha⁵⁵ D. Pyatiizbyantseva³⁸
 J. Qian¹⁰⁸ D. Qichen¹⁰³ Y. Qin¹³ T. Qiu⁵³ A. Quadt⁵⁶ M. Queitsch-Maitland¹⁰³ G. Quetant⁵⁷
 R. P. Quinn¹⁶⁷ G. Rabanal Bolanos⁶² D. Rafanoharana⁵⁵ F. Raffaelli^{77a,77b} F. Ragusa^{72a,72b} J. L. Rainbolt⁴⁰
 J. A. Raine⁵⁷ S. Rajagopalan³⁰ E. Ramakoti³⁸ L. Rambelli^{58b,58a} I. A. Ramirez-Berend³⁵ K. Ran^{49,114c}
 D. S. Rankin¹³¹ N. P. Rapheeha^{34g} H. Rasheed^{28b} V. Raskina¹³⁰ D. F. Rassloff^{64a} A. Rastogi^{18a} S. Rave¹⁰²
 S. Ravera^{58b,58a} B. Ravina⁵⁶ I. Ravinovich¹⁷² M. Raymond³⁷ A. L. Read¹²⁸ N. P. Readioff¹⁴³
 D. M. Rebuffi^{74a,74b} G. Redlinger³⁰ A. S. Reed¹¹² K. Reeves²⁷ J. A. Reidelsturz¹⁷⁴ D. Reikher¹²⁶ A. Rej⁵⁰
 C. Rembser³⁷ M. Renda^{28b} F. Renner⁴⁹ A. G. Rennie¹⁶² A. L. Rescia⁴⁹ S. Resconi^{72a} M. Ressegotti^{58b,58a}
 S. Rettie³⁷ J. G. Reyes Rivera¹⁰⁹ E. Reynolds^{18a} O. L. Rezanova³⁸ P. Reznicek¹³⁶ H. Riani^{36d} N. Ribaric⁵²
 E. Ricci^{79a,79b} R. Richter¹¹² S. Richter^{48a,48b} E. Richter-Was^{87b} M. Ridel¹³⁰ S. Ridouani^{36d} P. Rieck¹²⁰
 P. Riedler³⁷ E. M. Riefel^{48a,48b} J. O. Rieger¹¹⁷ M. Rijssenbeek¹⁴⁹ M. Rimoldi³⁷ L. Rinaldi^{24b,24a}
 P. Rincke^{56,164} T. T. Rinn³⁰ M. P. Rinnagel¹¹¹ G. Ripellino¹⁶⁴ I. Riu¹³ J. C. Rivera Vergara¹⁶⁸
 F. Rizatdinova¹²⁴ E. Rizvi⁹⁶ B. R. Roberts^{18a} S. S. Roberts¹³⁹ S. H. Robertson^{106,n} D. Robinson³³
 M. Robles Manzano¹⁰² A. Robson⁶⁰ A. Rocchi^{77a,77b} C. Roda^{75a,75b} S. Rodriguez Bosca³⁷
 Y. Rodriguez Garcia^{23a} A. Rodriguez Rodriguez⁵⁵ A. M. Rodríguez Vera¹¹⁸ S. Roe³⁷ J. T. Roemer³⁷
 A. R. Roepe-Gier¹³⁹ O. Røhne¹²⁸ R. A. Rojas¹⁰⁵ C. P. A. Roland¹³⁰ J. Roloff³⁰ A. Romaniouk⁸⁰
 E. Romano^{74a,74b} M. Romano^{24b} A. C. Romero Hernandez¹⁶⁵ N. Rompotis⁹⁴ L. Roos¹³⁰ S. Rosati^{76a}
 B. J. Rosser⁴⁰ E. Rossi¹²⁹ E. Rossi^{73a,73b} L. P. Rossi⁶² L. Rossini⁵⁵ R. Rosten¹²² M. Rotaru^{28b} B. Rottler⁵⁵

- C. Rougier⁹¹, D. Rousseau⁶⁷, D. Rouso⁴⁹, A. Roy¹⁶⁵, S. Roy-Garand¹⁵⁸, A. Rozanov¹⁰⁴, Z. M. A. Rozario⁶⁰, Y. Rozen¹⁵⁴, A. Rubio Jimenez¹⁶⁶, A. J. Ruby⁹⁴, V. H. Ruelas Rivera¹⁹, T. A. Ruggeri¹, A. Ruggiero¹²⁹, A. Ruiz-Martinez¹⁶⁶, A. Rummeler³⁷, Z. Rurikova⁵⁵, N. A. Rusakovich³⁹, H. L. Russell¹⁶⁸, G. Russo^{76a,76b}, J. P. Rutherford⁷, S. Rutherford Colmenares³³, M. Rybar¹³⁶, E. B. Rye¹²⁸, A. Ryzhov⁴⁵, J. A. Sabater Iglesias⁵⁷, H. F.-W. Sadrozinski¹³⁹, F. Safai Tehrani^{76a}, B. Safarzadeh Samani¹³⁷, S. Saha¹, M. Sahinsoy⁸³, A. Saibel¹⁶⁶, M. Saimpert¹³⁸, M. Saito¹⁵⁷, T. Saito¹⁵⁷, A. Sala^{72a,72b}, D. Salamani³⁷, A. Salnikov¹⁴⁷, J. Salt¹⁶⁶, A. Salvador Salas¹⁵⁵, D. Salvatore^{44b,44a}, F. Salvatore¹⁵⁰, A. Salzburger³⁷, D. Sammel⁵⁵, E. Sampson⁹³, D. Sampsonidis^{156,y}, D. Sampsonidou¹²⁶, J. Sánchez¹⁶⁶, V. Sanchez Sebastian¹⁶⁶, H. Sandaker¹²⁸, C. O. Sander⁴⁹, J. A. Sandesara¹⁰⁵, M. Sandhoff¹⁷⁴, C. Sandoval^{23b}, L. Sanfilippo^{64a}, D. P. C. Sankey¹³⁷, T. Sano⁸⁹, A. Sansoni⁵⁴, L. Santi^{37,76b}, C. Santoni⁴¹, H. Santos^{133a,133b}, A. Santra¹⁷², E. Sanzani^{24b,24a}, K. A. Saoucha¹⁶³, J. G. Saraiva^{133a,133d}, J. Sardain⁷, O. Sasaki⁸⁵, K. Sato¹⁶⁰, C. Sauer^{64b}, E. Sauvan⁴, P. Savard^{158,d}, R. Sawada¹⁵⁷, C. Sawyer¹³⁷, L. Sawyer⁹⁹, C. Sbarra^{24b}, A. Sbrizzi^{24b,24a}, T. Scanlon⁹⁸, J. Schaarschmidt¹⁴², U. Schäfer¹⁰², A. C. Schaffer^{67,45}, D. Schaile¹¹¹, R. D. Schamberger¹⁴⁹, C. Scharf¹⁹, M. M. Schefer²⁰, V. A. Schegelsky³⁸, D. Scheirich¹³⁶, M. Schernau¹⁶², C. Scheulen⁵⁶, C. Schiavi^{58b,58a}, M. Schioppa^{44b,44a}, B. Schlag¹⁴⁷, K. E. Schleicher⁵⁵, S. Schlenker³⁷, J. Schmeing¹⁷⁴, M. A. Schmidt¹⁷⁴, K. Schmieden¹⁰², C. Schmitt¹⁰², N. Schmitt¹⁰², S. Schmitt⁴⁹, L. Schoeffel¹³⁸, A. Schoening^{64b}, P. G. Scholer³⁵, E. Schopf¹²⁹, M. Schott²⁵, J. Schovancova³⁷, S. Schramm⁵⁷, T. Schroer⁵⁷, H.-C. Schultz-Coulon^{64a}, M. Schumacher⁵⁵, B. A. Schumm¹³⁹, Ph. Schune¹³⁸, A. J. Schuy¹⁴², H. R. Schwartz¹³⁹, A. Schwartzman¹⁴⁷, T. A. Schwarz¹⁰⁸, Ph. Schwemling¹³⁸, R. Schwienhorst¹⁰⁹, F. G. Sciaccia²⁰, A. Sciandra³⁰, G. Sciolla²⁷, F. Scuri^{75a}, C. D. Sebastiani⁹⁴, K. Sedlaczek¹¹⁸, S. C. Seidel¹¹⁵, A. Seiden¹³⁹, B. D. Seidlitz⁴², C. Seitz⁴⁹, J. M. Seixas^{84b}, G. Sekhniaidze^{73a}, L. Selem⁶¹, N. Semprini-Cesari^{24b,24a}, D. Sengupta⁵⁷, V. Senthilkumar¹⁶⁶, L. Serin⁶⁷, M. Sessa^{77a,77b}, H. Severini¹²³, F. Sforza^{58b,58a}, A. Sfyrta⁵⁷, Q. Sha¹⁴, E. Shabalina⁵⁶, A. H. Shah³³, R. Shaheen¹⁴⁸, J. D. Shahinian¹³¹, D. Shaked Renous¹⁷², L. Y. Shan¹⁴, M. Shapiro^{18a}, A. Sharma³⁷, A. S. Sharma¹⁶⁷, P. Sharma⁸¹, P. B. Shatalov³⁸, K. Shaw¹⁵⁰, S. M. Shaw¹⁰³, Q. Shen^{63c}, D. J. Sheppard¹⁴⁶, P. Sherwood⁹⁸, L. Shi⁹⁸, X. Shi¹⁴, S. Shimizu⁸⁵, C. O. Shimmin¹⁷⁵, J. D. Shinner⁹⁷, I. P. J. Shipsey^{129,s}, S. Shirabe⁹⁰, M. Shiyakova^{39,ag}, M. J. Shochet⁴⁰, D. R. Shope¹²⁸, B. Shrestha¹²³, S. Shrestha^{122,ah}, I. Shreyber³⁸, M. J. Shroff¹⁶⁸, P. Sicho¹³⁴, A. M. Sickles¹⁶⁵, E. Sideras Haddad^{34g}, A. C. Sidley¹¹⁷, A. Sidoti^{24b}, F. Siegert⁵¹, Dj. Sijacki¹⁶, F. Sili⁹², J. M. Silva⁵³, I. Silva Ferreira^{84b}, M. V. Silva Oliveira³⁰, S. B. Silverstein^{48a}, S. Simion⁶⁷, R. Simoniello³⁷, E. L. Simpson¹⁰³, H. Simpson¹⁵⁰, L. R. Simpson¹⁰⁸, N. D. Simpson¹⁰⁰, S. Simsek⁸³, S. Sindhu⁵⁶, P. Sinervo¹⁵⁸, S. Singh¹⁵⁸, S. Sinha⁴⁹, S. Sinha¹⁰³, M. Sioli^{24b,24a}, I. Siral³⁷, E. Sitnikova⁴⁹, J. Sjölin^{48a,48b}, A. Skaf⁵⁶, E. Skorda²¹, P. Skubic¹²³, M. Slawinska⁸⁸, V. Smakhtin¹⁷², B. H. Smart¹³⁷, S. Yu. Smirnov³⁸, Y. Smirnov³⁸, L. N. Smirnova^{38,j}, O. Smirnova¹⁰⁰, A. C. Smith⁴², D. R. Smith¹⁶², E. A. Smith⁴⁰, J. L. Smith¹⁰³, R. Smith¹⁴⁷, M. Smizanska⁹³, K. Smolek¹³⁵, A. A. Snesarev³⁸, H. L. Snoek¹¹⁷, S. Snyder³⁰, R. Sobie^{168,n}, A. Soffer¹⁵⁵, C. A. Solans Sanchez³⁷, E. Yu. Soldatov³⁸, U. Soldevila¹⁶⁶, A. A. Solodkov³⁸, S. Solomon²⁷, A. Soloshenko³⁹, K. Solovieva⁵⁵, O. V. Solovyanov⁴¹, P. Sommer⁵¹, A. Sonay¹³, W. Y. Song^{159b}, A. Sopczak¹³⁵, A. L. Sopio⁵³, F. Sopkova^{29b}, J. D. Sorenson¹¹⁵, I. R. Sotarriva Alvarez¹⁴¹, V. Sothilingam^{64a}, O. J. Soto Sandoval^{140c,140b}, S. Sottocornola⁶⁹, R. Soualah¹⁶³, Z. Soumami^{36e}, D. South⁴⁹, N. Soybelman¹⁷², S. Spagnolo^{71a,71b}, M. Spalla¹¹², D. Sperlich⁵⁵, G. Spigo³⁷, B. Spisso^{73a,73b}, D. P. Spiteri⁶⁰, M. Spousta¹³⁶, E. J. Staats³⁵, R. Stamen^{64a}, A. Stampekis²¹, E. Stanecka⁸⁸, W. Stanek-Maslouska⁴⁹, M. V. Stange⁵¹, B. Stanislaus^{18a}, M. M. Stanitzki⁴⁹, B. Stapf⁴⁹, E. A. Starchenko³⁸, G. H. Stark¹³⁹, J. Stark⁹¹, P. Staroba¹³⁴, P. Starovoitov^{64a}, S. Stärz¹⁰⁶, R. Staszewski⁸⁸, G. Stavropoulos⁴⁷, A. Stefl³⁷, P. Steinberg³⁰, B. Stelzer^{146,159a}, H. J. Stelzer¹³², O. Stelzer-Chilton^{159a}, H. Stenzel⁵⁹, T. J. Stevenson¹⁵⁰, G. A. Stewart³⁷, J. R. Stewart¹²⁴, M. C. Stockton³⁷, G. Stoica^{28b}, M. Stolarski^{133a}, S. Stonjek¹¹², A. Straessner⁵¹, J. Strandberg¹⁴⁸, S. Strandberg^{48a,48b}, M. Stratmann¹⁷⁴, M. Strauss¹²³, T. Streblor¹⁰⁴, P. Strizenec^{29b}, R. Ströhmer¹⁶⁹, D. M. Strom¹²⁶, R. Stroynowski⁴⁵, A. Strubig^{48a,48b}, S. A. Stucci³⁰, B. Stugu¹⁷, J. Stupak¹²³, N. A. Styles⁴⁹, D. Su¹⁴⁷, S. Su^{63a}, W. Su^{63d}, X. Su^{63a}, D. Suchy^{29a}, K. Sugizaki¹⁵⁷, V. V. Sulin³⁸, M. J. Sullivan⁹⁴, D. M. S. Sultan¹²⁹, L. Sultanaliyeva³⁸, S. Sultansoy^{3b}, T. Sumida⁸⁹, S. Sun¹⁷³, O. Sunneborn Gudnadottir¹⁶⁴, N. Sur¹⁰⁴, M. R. Sutton¹⁵⁰, H. Suzuki¹⁶⁰, M. Svatos¹³⁴, M. Swiatlowski^{159a}, T. Swirski¹⁶⁹, I. Sykora^{29a}, M. Sykora¹³⁶, T. Sykora¹³⁶, D. Ta¹⁰², K. Tackmann^{49,af}, A. Taffard¹⁶², R. Tafirout^{159a}, J. S. Tafoya Vargas⁶⁷, Y. Takubo⁸⁵, M. Talby¹⁰⁴, A. A. Talyshev³⁸, K. C. Tam^{65b}, N. M. Tamir¹⁵⁵, A. Tanaka¹⁵⁷, J. Tanaka¹⁵⁷, R. Tanaka⁶⁷, M. Tanasini¹⁴⁹, Z. Tao¹⁶⁷, S. Tapia Araya^{140f}, S. Tapprogge¹⁰², A. Tarek Abouelfadl Mohamed¹⁰⁹, S. Tarem¹⁵⁴, K. Tariq¹⁴, G. Tarna^{28b}, G. F. Tartarelli^{72a}, M. J. Tartarin⁹¹, P. Tas¹³⁶, M. Tasevsky¹³⁴, E. Tassi^{44b,44a}, A. C. Tate¹⁶⁵, G. Tateno¹⁵⁷, Y. Tayalati^{36e,ai}, G. N. Taylor¹⁰⁷, W. Taylor^{159b}, R. Teixeira De Lima¹⁴⁷, P. Teixeira-Dias⁹⁷, J. J. Teoh¹⁵⁸, K. Terashi¹⁵⁷, J. Terron¹⁰¹, S. Terzo¹³, M. Testa⁵⁴, R. J. Teuscher^{158,n}, A. Thaler⁸⁰, O. Theiner⁵⁷, T. Thevenaux-Pelzer¹⁰⁴, O. Thielmann¹⁷⁴, D. W. Thomas⁹⁷, J. P. Thomas²¹, E. A. Thompson^{18a}, P. D. Thompson²¹, E. Thomson¹³¹, R. E. Thornberry⁴⁵, C. Tian^{63a}, Y. Tian⁵⁷, V. Tikhomirov^{38,j}, Yu. A. Tikhonov³⁸, S. Timoshenko³⁸, D. Timoshyn¹³⁶, E. X. L. Ting¹, P. Tipton¹⁷⁵, A. Tishelman-Charny³⁰, S. H. Tlou^{34g}, K. Todome¹⁴¹, S. Todorova-Nova¹³⁶, S. Todt⁵¹, L. Toffolin^{70a,70c}, M. Togawa⁸⁵, J. Tojo⁹⁰, S. Tokár^{29a}, K. Tokushuku⁸⁵, O. Toldaiev⁶⁹, M. Tomoto^{85,113}

- L. Tompkins^{147,aj}, K. W. Topolnicki^{87b}, E. Torrence¹²⁶, H. Torres⁹¹, E. Torró Pastor¹⁶⁶, M. Toscani³¹,
 C. Tosciri⁴⁰, M. Tost¹¹, D. R. Tovey¹⁴³, I. S. Trandafir^{28b}, T. Trefzger¹⁶⁹, A. Tricoli³⁰, I. M. Trigger^{159a},
 S. Trincaz-Duvoid¹³⁰, D. A. Trischuk²⁷, B. Trocme⁶¹, A. Tropina³⁹, L. Truong^{34c}, M. Trzebinski⁸⁸, A. Trzupek⁸⁸,
 F. Tsai¹⁴⁹, M. Tsai¹⁰⁸, A. Tsiamis¹⁵⁶, P. V. Tsiareshka³⁸, S. Tsigaridas^{159a}, A. Tsirigotis^{156,z}, V. Tsiskaridze¹⁵⁸,
 E. G. Tskhadadze^{153a}, M. Tsopoulou¹⁵⁶, Y. Tsujikawa⁸⁹, I. I. Tsukerman³⁸, V. Tsulaia^{18a}, S. Tsuno⁸⁵, K. Tsuri¹²¹,
 D. Tsybychev¹⁴⁹, Y. Tu^{65b}, A. Tudorache^{28b}, V. Tudorache^{28b}, A. N. Tuna⁶², S. Turchikhin^{58b,58a}, I. Turk Cakir^{3a},
 R. Turra^{72a}, T. Turtuvshin^{39,ak}, P. M. Tuts⁴², S. Tzamarias^{156,y}, E. Tzovara¹⁰², F. Ukegawa¹⁶⁰,
 P. A. Ulloa Poblete^{140c,140b}, E. N. Umaka³⁰, G. Unal³⁷, A. Undrus³⁰, G. Unel¹⁶², J. Urban^{29b}, P. Urrejola^{140a},
 G. Usai⁸, R. Ushioda¹⁴¹, M. Usman¹¹⁰, F. Ustuner⁵³, Z. Uysal⁸³, V. Vacek¹³⁵, B. Vachon¹⁰⁶, T. Vafeiadis³⁷,
 A. Vaitkus⁹⁸, C. Valderanis¹¹¹, E. Valdes Santurio^{48a,48b}, M. Valente^{159a}, S. Valentinetti^{24b,24a}, A. Valero¹⁶⁶,
 E. Valiente Moreno¹⁶⁶, A. Vallier⁹¹, J. A. Valls Ferrer¹⁶⁶, D. R. Van Arneman¹¹⁷, T. R. Van Daalen¹⁴²,
 A. Van Der Graaf⁵⁰, P. Van Gemmeren⁶, M. Van Rijnbach³⁷, S. Van Stroud⁹⁸, I. Van Vulpen¹¹⁷, P. Vana¹³⁶,
 M. Vanadia^{77a,77b}, U. M. Vande Voorde¹⁴⁸, W. Vandelli³⁷, E. R. Vandewall¹²⁴, D. Vannicola¹⁵⁵, L. Vannoli⁵⁴,
 R. Vari^{76a}, E. W. Varnes⁷, C. Varni^{18b}, T. Varol¹⁵², D. Varouchas⁶⁷, L. Varriale¹⁶⁶, K. E. Varvell¹⁵¹,
 M. E. Vasile^{28b}, L. Vaslin⁸⁵, G. A. Vasquez¹⁶⁸, A. Vasyukov³⁹, L. M. Vaughan¹²⁴, R. Vavricka¹⁰²,
 T. Vazquez Schroeder³⁷, J. Veatch³², V. Vecchio¹⁰³, M. J. Veen¹⁰⁵, I. Velisek³⁰, L. M. Veloce¹⁵⁸,
 F. Veloso^{133a,133c}, S. Veneziano^{76a}, A. Ventura^{71a,71b}, S. Ventura Gonzalez¹³⁸, A. Verbitskyi¹¹², M. Verducci^{75a,75b},
 C. Vergis⁹⁶, M. Verissimo De Araujo^{84b}, W. Verkerke¹¹⁷, J. C. Vermeulen¹¹⁷, C. Vernieri¹⁴⁷, M. Vessella¹⁰⁵,
 M. C. Vetterli^{146,d}, A. Vgenopoulos¹⁰², N. Viaux Maira^{140f}, T. Vickey¹⁴³, O. E. Vickey Boeriu¹⁴³,
 G. H. A. Viehhauser¹²⁹, L. Vigani^{64b}, M. Vigil¹¹², M. Villa^{24b,24a}, M. Villaplana Perez¹⁶⁶, E. M. Villhauer⁵³,
 E. Vilucchi⁵⁴, M. G. Vinciter³⁵, A. Visibile¹¹⁷, C. Vittori³⁷, I. Vivarelli^{24b,24a}, E. Voevodina¹¹², F. Vogel¹¹¹,
 J. C. Voigt⁵¹, P. Vokac¹³⁵, Yu. Volkotrub^{87b}, E. Von Toerne²⁵, B. Vormwald³⁷, V. Vorobel¹³⁶, K. Vorobev³⁸,
 M. Vos¹⁶⁶, K. Voss¹⁴⁵, M. Vozak¹¹⁷, L. Vozdecky¹²³, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, M. Vreeswijk¹¹⁷,
 N. K. Vu^{63d,63c}, R. Vuillermet³⁷, O. Vujanovic¹⁰², I. Vukotic⁴⁰, I. K. Vyas³⁵, S. Wada¹⁶⁰, C. Wagner¹⁴⁷,
 J. M. Wagner^{18a}, W. Wagner¹⁷⁴, S. Wahdan¹⁷⁴, H. Wahlberg⁹², J. Walder¹³⁷, R. Walker¹¹¹, W. Walkowiak¹⁴⁵,
 A. Wall¹³¹, E. J. Wallin¹⁰⁰, T. Wamorkar⁶, A. Z. Wang¹³⁹, C. Wang¹⁰², C. Wang¹¹, H. Wang^{18a}, J. Wang^{65c},
 P. Wang⁹⁸, R. Wang⁶², R. Wang⁶, S. M. Wang¹⁵², S. Wang^{63b}, S. Wang¹⁴, T. Wang^{63a}, W. T. Wang⁸¹,
 W. Wang¹⁴, X. Wang^{114a}, X. Wang¹⁶⁵, X. Wang^{63c}, Y. Wang^{63d}, Y. Wang^{114a}, Y. Wang^{63a}, Z. Wang¹⁰⁸,
 Z. Wang^{63d,52,63c}, Z. Wang¹⁰⁸, A. Warburton¹⁰⁶, R. J. Ward²¹, N. Warrack⁶⁰, S. Waterhouse⁹⁷, A. T. Watson²¹,
 H. Watson⁵³, M. F. Watson²¹, E. Watton^{60,137}, G. Watts¹⁴², B. M. Waugh⁹⁸, J. M. Webb⁵⁵, C. Weber³⁰,
 H. A. Weber¹⁹, M. S. Weber²⁰, S. M. Weber^{64a}, C. Wei^{63a}, Y. Wei⁵⁵, A. R. Weidberg¹²⁹, E. J. Weik¹²⁰,
 J. Weingarten⁵⁰, C. Weiser⁵⁵, C. J. Wells⁴⁹, T. Wenaus³⁰, B. Wendland⁵⁰, T. Wengler³⁷, N. S. Wenke¹¹²,
 N. Wermes²⁵, M. Wessels^{64a}, A. M. Wharton⁹³, A. S. White⁶², A. White⁸, M. J. White¹, D. Whiteson¹⁶²,
 L. Wickremasinghe¹²⁷, W. Wiedenmann¹⁷³, M. WIELERS¹³⁷, C. Wiglesworth⁴³, D. J. Wilbern¹²³, H. G. Wilkens³⁷,
 J. J. H. Wilkinson³³, D. M. Williams⁴², H. H. Williams¹³¹, S. Williams³³, S. Willocq¹⁰⁵, B. J. Wilson¹⁰³,
 P. J. Windischhofer⁴⁰, F. I. Winkel³¹, F. Winklmeier¹²⁶, B. T. Winter⁵⁵, J. K. Winter¹⁰³, M. Wittgen¹⁴⁷,
 M. Wobisch⁹⁹, T. Wojtkowski⁶¹, Z. Wolffs¹¹⁷, J. Wollrath¹⁶², M. W. Wolter⁸⁸, H. Wolters^{133a,133c}, M. C. Wong¹³⁹,
 E. L. Woodward⁴², S. D. Worm⁴⁹, B. K. Wosiek⁸⁸, K. W. Woźniak⁸⁸, S. Wozniowski⁵⁶, K. Wraight⁶⁰, C. Wu²¹,
 M. Wu^{114b}, M. Wu¹¹⁶, S. L. Wu¹⁷³, X. Wu⁵⁷, Y. Wu^{63a}, Z. Wu⁴, J. Wuerzinger^{112,1}, T. R. Wyatt¹⁰³,
 B. M. Wynne⁵³, S. Xella⁴³, L. Xia^{114a}, M. Xia¹⁵, M. Xie^{63a}, S. Xin^{14,114c}, A. Xiong¹²⁶, J. Xiong^{18a}, D. Xu¹⁴,
 H. Xu^{63a}, L. Xu^{63a}, R. Xu¹³¹, T. Xu¹⁰⁸, Y. Xu¹⁵, Z. Xu⁵³, Z. Xu^{114a}, B. Yabsley¹⁵¹, S. Yacoub^{34a},
 Y. Yamaguchi⁸⁵, E. Yamashita¹⁵⁷, H. Yamauchi¹⁶⁰, T. Yamazaki^{18a}, Y. Yamazaki⁸⁶, S. Yan⁶⁰, Z. Yan¹⁰⁵,
 H. J. Yang^{63c,63d}, H. T. Yang^{63a}, S. Yang^{63a}, T. Yang^{65c}, X. Yang³⁷, X. Yang¹⁴, Y. Yang⁴⁵, Y. Yang^{63a},
 Z. Yang^{63a}, W.-M. Yao^{18a}, H. Ye^{114a}, H. Ye⁵⁶, J. Ye¹⁴, S. Ye³⁰, X. Ye^{63a}, Y. Yeh⁹⁸, I. Yeletsikh³⁹, B. Yeo^{18b},
 M. R. Yexley⁹⁸, T. P. Yildirim¹²⁹, P. Yin⁴², K. Yorita¹⁷¹, S. Younas^{28b}, C. J. S. Young³⁷, C. Young¹⁴⁷,
 C. Yu^{14,114c}, Y. Yu^{63a}, J. Yuan^{14,114c}, M. Yuan¹⁰⁸, R. Yuan^{63d,63c}, L. Yue⁹⁸, M. Zaazoua^{63a}, B. Zabinski⁸⁸,
 E. Zaid⁵³, Z. K. Zak⁸⁸, T. Zakareishvili¹⁶⁶, S. Zambito⁵⁷, J. A. Zamora Saa^{140d,140b}, J. Zang¹⁵⁷, D. Zanzi⁵⁵,
 O. Zaplatilek¹³⁵, C. Zeitnitz¹⁷⁴, H. Zeng¹⁴, J. C. Zeng¹⁶⁵, D. T. Zenger, Jr.²⁷, O. Zenin³⁸, T. Ženiš^{29a}, S. Zenz⁹⁶,
 S. Zerradi^{36a}, D. Zerwas⁶⁷, M. Zhai^{14,114c}, D. F. Zhang¹⁴³, J. Zhang^{63b}, J. Zhang⁶, K. Zhang^{14,114c}, L. Zhang^{63a},
 L. Zhang^{114a}, P. Zhang^{14,114c}, R. Zhang¹⁷³, S. Zhang¹⁰⁸, S. Zhang⁹¹, T. Zhang¹⁵⁷, X. Zhang^{63c}, X. Zhang^{63b},
 Y. Zhang^{63c}, Y. Zhang⁹⁸, Y. Zhang^{114a}, Z. Zhang^{18a}, Z. Zhang^{63b}, Z. Zhang⁶⁷, H. Zhao¹⁴², T. Zhao^{63b},
 Y. Zhao¹³⁹, Z. Zhao^{63a}, Z. Zhao^{63a}, A. Zhemchugov³⁹, J. Zheng^{114a}, K. Zheng¹⁶⁵, X. Zheng^{63a}, Z. Zheng¹⁴⁷,
 D. Zhong¹⁶⁵, B. Zhou¹⁰⁸, H. Zhou⁷, N. Zhou^{63c}, Y. Zhou¹⁵, Y. Zhou^{114a}, Y. Zhou⁷, C. G. Zhu^{63b}, J. Zhu¹⁰⁸,
 X. Zhu^{63d}, Y. Zhu^{63c}, Y. Zhu^{63a}, X. Zhuang¹⁴, K. Zhukov⁶⁹, N. I. Zimine³⁹, J. Zinsser^{64b}, M. Ziolkowski¹⁴⁵,
 L. Živković¹⁶, A. Zoccoli^{24b,24a}, K. Zoch⁶², T. G. Zorbas¹⁴³, O. Zormpa⁴⁷, W. Zou⁴² and L. Zwalinski³⁷

(ATLAS Collaboration)

- ¹Department of Physics, [University of Adelaide](#), Adelaide, Australia
- ²Department of Physics, [University of Alberta](#), Edmonton AB, Canada
- ^{3a}Department of Physics, [Ankara University](#), Ankara, Türkiye
- ^{3b}Division of Physics, [TOBB University of Economics and Technology](#), Ankara, Türkiye
- ⁴[LAPP](#), Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
- ⁵APC, [Université Paris Cité](#), CNRS/IN2P3, Paris, France
- ⁶High Energy Physics Division, [Argonne National Laboratory](#), Argonne, Illinois, USA
- ⁷Department of Physics, [University of Arizona](#), Tucson, Arizona, USA
- ⁸Department of Physics, [University of Texas at Arlington](#), Arlington, Texas, USA
- ⁹Physics Department, National and Kapodistrian [University of Athens](#), Athens, Greece
- ¹⁰Physics Department, [National Technical University of Athens](#), Zografou, Greece
- ¹¹Department of Physics, [University of Texas at Austin](#), Austin, Texas, USA
- ¹²Institute of Physics, [Azerbaijan Academy of Sciences](#), Baku, Azerbaijan
- ¹³[Institut de Física d'Altes Energies \(IFAE\)](#), [Barcelona Institute of Science and Technology](#), Barcelona, Spain
- ¹⁴[Institute of High Energy Physics](#), Chinese Academy of Sciences, Beijing, China
- ¹⁵Physics Department, [Tsinghua University](#), Beijing, China
- ¹⁶Institute of Physics, [University of Belgrade](#), Belgrade, Serbia
- ¹⁷Department for Physics and Technology, [University of Bergen](#), Bergen, Norway
- ^{18a}Physics Division, [Lawrence Berkeley National Laboratory](#), Berkeley, California, USA
- ^{18b}University of California, Berkeley, California, USA
- ¹⁹Institut für Physik, [Humboldt Universität zu Berlin](#), Berlin, Germany
- ²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, [University of Bern](#), Bern, Switzerland
- ²¹School of Physics and Astronomy, [University of Birmingham](#), Birmingham, United Kingdom
- ^{22a}Department of Physics, [Bogazici University](#), Istanbul, Türkiye
- ^{22b}Department of Physics Engineering, [Gaziantep University](#), Gaziantep, Türkiye
- ^{22c}Department of Physics, [Istanbul University](#), Istanbul, Türkiye
- ^{23a}Facultad de Ciencias y Centro de Investigaciones, [Universidad Antonio Nariño](#), Bogotá, Colombia
- ^{23b}Departamento de Física, [Universidad Nacional de Colombia](#), Bogotá, Colombia
- ^{24a}Dipartimento di Fisica e Astronomia A. Righi, [Università di Bologna](#), Bologna, Italy
- ^{24b}INFN Sezione di Bologna, Bologna, Italy
- ²⁵Physikalisches Institut, [Universität Bonn](#), Bonn, Germany
- ²⁶Department of Physics, [Boston University](#), Boston, Massachusetts, USA
- ²⁷Department of Physics, [Brandeis University](#), Waltham, Massachusetts, USA
- ^{28a}[Transilvania University of Brasov](#), Brasov, Romania
- ^{28b}[Horia Hulubei National Institute of Physics and Nuclear Engineering](#), Bucharest, Romania
- ^{28c}Department of Physics, [Alexandru Ioan Cuza University of Iasi](#), Iasi, Romania
- ^{28d}[National Institute for Research and Development of Isotopic and Molecular Technologies](#), Physics Department, Cluj-Napoca, Romania
- ^{28e}[National University of Science and Technology Politehnica](#), Bucharest, Romania
- ^{28f}[West University in Timisoara](#), Timisoara, Romania
- ^{28g}Faculty of Physics, [University of Bucharest](#), Bucharest, Romania
- ^{29a}Faculty of Mathematics, Physics and Informatics, [Comenius University](#), Bratislava, Slovak Republic
- ^{29b}Department of Subnuclear Physics, [Institute of Experimental Physics of the Slovak Academy of Sciences](#), Kosice, Slovak Republic
- ³⁰Physics Department, [Brookhaven National Laboratory](#), Upton, New York, USA
- ³¹[Universidad de Buenos Aires](#), Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
- ³²[California State University](#), Fresno, California, USA
- ³³Cavendish Laboratory, [University of Cambridge](#), Cambridge, United Kingdom
- ^{34a}Department of Physics, [University of Cape Town](#), Cape Town, South Africa
- ^{34b}iThemba Labs, Western Cape, South Africa
- ^{34c}Department of Mechanical Engineering Science, [University of Johannesburg](#), Johannesburg, South Africa
- ^{34d}National Institute of Physics, [University of the Philippines Diliman](#), Philippines
- ^{34e}University of South Africa, Department of Physics, Pretoria, South Africa
- ^{34f}University of Zululand, KwaDlangezwa, South Africa
- ^{34g}School of Physics, [University of the Witwatersrand](#), Johannesburg, South Africa
- ³⁵Department of Physics, [Carleton University](#), Ottawa, Ontario, Canada
- ^{36a}Faculté des Sciences Ain Chock, [Université Hassan II de Casablanca](#), Morocco
- ^{36b}Faculté des Sciences, [Université Ibn-Tofail](#), Kénitra, Morocco
- ^{36c}Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
- ^{36d}LPMP, Faculté des Sciences, [Université Mohamed Premier](#), Oujda, Morocco

- ^{36e}Faculté des sciences, [Université Mohammed V](#), Rabat, Morocco
- ^{36f}Institute of Applied Physics, [Mohammed VI Polytechnic University](#), Ben Guerir, Morocco
- ³⁷[CERN](#), Geneva, Switzerland
- ³⁸Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁹Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ⁴⁰Enrico Fermi Institute, [University of Chicago](#), Chicago, Illinois, USA
- ⁴¹LPC, [Université Clermont Auvergne](#), CNRS/IN2P3, Clermont-Ferrand, France
- ⁴²Nevis Laboratory, [Columbia University](#), Irvington, New York, USA
- ⁴³Niels Bohr Institute, [University of Copenhagen](#), Copenhagen, Denmark
- ^{44a}Dipartimento di Fisica, [Università della Calabria](#), Rende, Italy
- ^{44b}INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ⁴⁵Physics Department, [Southern Methodist University](#), Dallas, Texas, USA
- ⁴⁶Physics Department, [University of Texas at Dallas](#), Richardson, Texas, USA
- ⁴⁷[National Centre for Scientific Research “Demokritos”](#), Agia Paraskevi, Greece
- ^{48a}Department of Physics, [Stockholm University](#), Stockholm, Sweden
- ^{48b}Oskar Klein Centre, Stockholm, Sweden
- ⁴⁹[Deutsches Elektronen-Synchrotron DESY](#), Hamburg and Zeuthen, Germany
- ⁵⁰Fakultät Physik, [Technische Universität Dortmund](#), Dortmund, Germany
- ⁵¹Institut für Kern- und Teilchenphysik, [Technische Universität Dresden](#), Dresden, Germany
- ⁵²Department of Physics, [Duke University](#), Durham, North Carolina, USA
- ⁵³SUPA - School of Physics and Astronomy, [University of Edinburgh](#), Edinburgh, United Kingdom
- ⁵⁴[INFN e Laboratori Nazionali di Frascati](#), Frascati, Italy
- ⁵⁵Physikalisches Institut, [Albert-Ludwigs-Universität Freiburg](#), Freiburg, Germany
- ⁵⁶II. Physikalisches Institut, [Georg-August-Universität Göttingen](#), Göttingen, Germany
- ⁵⁷Département de Physique Nucléaire et Corpusculaire, [Université de Genève](#), Genève, Switzerland
- ^{58a}Dipartimento di Fisica, [Università di Genova](#), Genova, Italy
- ^{58b}INFN Sezione di Genova, Genova, Italy
- ⁵⁹II. Physikalisches Institut, [Justus-Liebig-Universität Giessen](#), Giessen, Germany
- ⁶⁰SUPA - School of Physics and Astronomy, [University of Glasgow](#), Glasgow, United Kingdom
- ⁶¹LPSC, [Université Grenoble Alpes](#), CNRS/IN2P3, Grenoble INP, Grenoble, France
- ⁶²Laboratory for Particle Physics and Cosmology, [Harvard University](#), Cambridge, Massachusetts, USA
- ^{63a}Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, [University of Science and Technology of China](#), Hefei, China
- ^{63b}Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), [Shandong University](#), Qingdao, China
- ^{63c}School of Physics and Astronomy, [Shanghai Jiao Tong University](#), Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
- ^{63d}[Tsung-Dao Lee Institute](#), Shanghai, China
- ^{63e}School of Physics, Zhengzhou University, China
- ^{64a}Kirchhoff-Institut für Physik, [Ruprecht-Karls-Universität Heidelberg](#), Heidelberg, Germany
- ^{64b}Physikalisches Institut, [Ruprecht-Karls-Universität Heidelberg](#), Heidelberg, Germany
- ^{65a}Department of Physics, [Chinese University of Hong Kong](#), Shatin, N.T., Hong Kong, China
- ^{65b}Department of Physics, [University of Hong Kong](#), Hong Kong, China
- ^{65c}Department of Physics and Institute for Advanced Study, [Hong Kong University of Science and Technology](#), Clear Water Bay, Kowloon, Hong Kong, China
- ⁶⁶Department of Physics, [National Tsing Hua University](#), Hsinchu, Taiwan
- ⁶⁷IJCLab, [Université Paris-Saclay](#), CNRS/IN2P3, 91405, Orsay, France
- ⁶⁸[Centro Nacional de Microelectrónica \(IMB-CNM-CSIC\)](#), Barcelona, Spain
- ⁶⁹Department of Physics, [Indiana University](#), Bloomington, Indiana, USA
- ^{70a}INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- ^{70b}[ICTP](#), Trieste, Italy
- ^{70c}Dipartimento Politecnico di Ingegneria e Architettura, [Università di Udine](#), Udine, Italy
- ^{71a}INFN Sezione di Lecce, Lecce, Italy
- ^{71b}Dipartimento di Matematica e Fisica, [Università del Salento](#), Lecce, Italy
- ^{72a}INFN Sezione di Milano, Milano, Italy
- ^{72b}Dipartimento di Fisica, [Università di Milano](#), Milano, Italy
- ^{73a}INFN Sezione di Napoli, Napoli, Italy
- ^{73b}Dipartimento di Fisica, [Università di Napoli](#), Napoli, Italy
- ^{74a}INFN Sezione di Pavia, Pavia, Italy

- ^{74b}Dipartimento di Fisica, [Università di Pavia](#), Pavia, Italy
^{75a}INFN Sezione di Pisa, Pisa, Italy
^{75b}Dipartimento di Fisica E. Fermi, [Università di Pisa](#), Pisa, Italy
^{76a}INFN Sezione di Roma, Roma, Italy
^{76b}Dipartimento di Fisica, [Sapienza Università di Roma](#), Roma, Italy
^{77a}INFN Sezione di Roma Tor Vergata, Roma, Italy
^{77b}Dipartimento di Fisica, [Università di Roma Tor Vergata](#), Roma, Italy
^{78a}INFN Sezione di Roma Tre, Roma, Italy
^{78b}Dipartimento di Matematica e Fisica, [Università Roma Tre](#), Roma, Italy
^{79a}INFN-TIFPA, Trento, Italy
^{79b}[Università degli Studi di Trento](#), Trento, Italy
⁸⁰[Universität Innsbruck](#), Department of Astro and Particle Physics, Innsbruck, Austria
⁸¹[University of Iowa](#), Iowa City, Iowa, USA
⁸²Department of Physics and Astronomy, [Iowa State University](#), Ames, Iowa, USA
⁸³[İstinye University](#), Sarıyer, Istanbul, Türkiye
^{84a}Departamento de Engenharia Elétrica, [Universidade Federal de Juiz de Fora \(UFJF\)](#), Juiz de Fora, Brazil
^{84b}[Universidade Federal do Rio De Janeiro COPPE/EE/IF](#), Rio de Janeiro, Brazil
^{84c}Instituto de Física, [Universidade de São Paulo](#), São Paulo, Brazil
^{84d}[Rio de Janeiro State University](#), Rio de Janeiro, Brazil
^{84e}Federal University of Bahia, Bahia, Brazil
⁸⁵[KEK](#), High Energy Accelerator Research Organization, Tsukuba, Japan
⁸⁶Graduate School of Science, [Kobe University](#), Kobe, Japan
^{87a}[AGH University of Krakow](#), Faculty of Physics and Applied Computer Science, Krakow, Poland
^{87b}Marian Smoluchowski Institute of Physics, [Jagiellonian University](#), Krakow, Poland
⁸⁸[Institute of Nuclear Physics Polish Academy of Sciences](#), Krakow, Poland
⁸⁹Faculty of Science, [Kyoto University](#), Kyoto, Japan
⁹⁰Research Center for Advanced Particle Physics and Department of Physics, [Kyushu University](#), Fukuoka, Japan
⁹¹[L2IT](#), Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France
⁹²Instituto de Física La Plata, [Universidad Nacional de La Plata](#) and CONICET, La Plata, Argentina
⁹³Physics Department, [Lancaster University](#), Lancaster, United Kingdom
⁹⁴Oliver Lodge Laboratory, [University of Liverpool](#), Liverpool, United Kingdom
⁹⁵Department of Experimental Particle Physics, [Jožef Stefan Institute](#) and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
⁹⁶School of Physics and Astronomy, [Queen Mary University of London](#), London, United Kingdom
⁹⁷Department of Physics, [Royal Holloway University of London](#), Egham, United Kingdom
⁹⁸Department of Physics and Astronomy, [University College London](#), London, United Kingdom
⁹⁹[Louisiana Tech University](#), Ruston, Louisiana, USA
¹⁰⁰Fysiska institutionen, [Lunds universitet](#), Lund, Sweden
¹⁰¹Departamento de Física Teórica C-15 and CIAFF, [Universidad Autónoma de Madrid](#), Madrid, Spain
¹⁰²Institut für Physik, [Universität Mainz](#), Mainz, Germany
¹⁰³School of Physics and Astronomy, [University of Manchester](#), Manchester, United Kingdom
¹⁰⁴[CPPM](#), Aix-Marseille Université, CNRS/IN2P3, Marseille, France
¹⁰⁵Department of Physics, [University of Massachusetts](#), Amherst, Massachusetts, USA
¹⁰⁶Department of Physics, [McGill University](#), Montreal QC, Canada
¹⁰⁷School of Physics, [University of Melbourne](#), Victoria, Australia
¹⁰⁸Department of Physics, [University of Michigan, Ann Arbor](#), Michigan, USA
¹⁰⁹Department of Physics and Astronomy, [Michigan State University](#), East Lansing, Michigan, USA
¹¹⁰Group of Particle Physics, [University of Montreal](#), Montreal QC, Canada
¹¹¹Fakultät für Physik, [Ludwig-Maximilians-Universität München](#), München, Germany
¹¹²[Max-Planck-Institut für Physik \(Werner-Heisenberg-Institut\)](#), München, Germany
¹¹³Graduate School of Science and Kobayashi-Maskawa Institute, [Nagoya University](#), Nagoya, Japan
^{114a}Department of Physics, [Nanjing University](#), Nanjing, China
^{114b}School of Science, Shenzhen Campus of Sun Yat-sen University, Shenzhen, China
^{114c}University of Chinese Academy of Science (UCAS), Beijing, China
¹¹⁵Department of Physics and Astronomy, [University of New Mexico](#), Albuquerque, New Mexico, USA
¹¹⁶Institute for Mathematics, Astrophysics and Particle Physics, [Radboud University/Nikhef](#), Nijmegen, Netherlands
¹¹⁷[Nikhef National Institute for Subatomic Physics](#) and University of Amsterdam, Amsterdam, Netherlands
¹¹⁸Department of Physics, [Northern Illinois University](#), DeKalb, Illinois, USA
^{119a}[New York University Abu Dhabi](#), Abu Dhabi, United Arab Emirates
^{119b}[United Arab Emirates University](#), Al Ain, United Arab Emirates

- ¹²⁰Department of Physics, [New York University](#), New York, New York, USA
- ¹²¹[Ochanomizu University](#), Otsuka, Bunkyo-ku, Tokyo, Japan
- ¹²²[Ohio State University](#), Columbus, Ohio, USA
- ¹²³Homer L. Dodge Department of Physics and Astronomy, [University of Oklahoma](#), Norman, Oklahoma, USA
- ¹²⁴Department of Physics, [Oklahoma State University](#), Stillwater, Oklahoma, USA
- ¹²⁵[Palacký University](#), Joint Laboratory of Optics, Olomouc, Czech Republic
- ¹²⁶Institute for Fundamental Science, [University of Oregon](#), Eugene, Oregon, USA
- ¹²⁷Graduate School of Science, [Osaka University](#), Osaka, Japan
- ¹²⁸Department of Physics, [University of Oslo](#), Oslo, Norway
- ¹²⁹Department of Physics, [Oxford University](#), Oxford, United Kingdom
- ¹³⁰[LPNHE](#), Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
- ¹³¹Department of Physics, [University of Pennsylvania](#), Philadelphia, Pennsylvania, USA
- ¹³²Department of Physics and Astronomy, [University of Pittsburgh](#), Pittsburgh, Pennsylvania, USA
- ^{133a}[Laboratório de Instrumentação e Física Experimental de Partículas - LIP](#), Lisboa, Portugal
- ^{133b}Departamento de Física, Faculdade de Ciências, [Universidade de Lisboa](#), Lisboa, Portugal
- ^{133c}Departamento de Física, [Universidade de Coimbra](#), Coimbra, Portugal
- ^{133d}Centro de Física Nuclear da [Universidade de Lisboa](#), Lisboa, Portugal
- ^{133e}Departamento de Física, [Universidade do Minho](#), Braga, Portugal
- ^{133f}Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain
- ^{133g}Departamento de Física, Instituto Superior Técnico, [Universidade de Lisboa](#), Lisboa, Portugal
- ¹³⁴[Institute of Physics of the Czech Academy of Sciences](#), Prague, Czech Republic
- ¹³⁵[Czech Technical University in Prague](#), Prague, Czech Republic
- ¹³⁶[Charles University](#), Faculty of Mathematics and Physics, Prague, Czech Republic
- ¹³⁷Particle Physics Department, [Rutherford Appleton Laboratory](#), Didcot, United Kingdom
- ¹³⁸IRFU, CEA, [Université Paris-Saclay](#), Gif-sur-Yvette, France
- ¹³⁹Santa Cruz Institute for Particle Physics, [University of California Santa Cruz](#), Santa Cruz, California, USA
- ^{140a}Departamento de Física, [Pontificia Universidad Católica de Chile](#), Santiago, Chile
- ^{140b}[Millennium Institute for Subatomic Physics at High Energy Frontier \(SAPHIR\)](#), Santiago, Chile
- ^{140c}Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, [Universidad de La Serena](#), La Serena, Chile
- ^{140d}[Universidad Andres Bello](#), Department of Physics, Santiago, Chile
- ^{140e}Instituto de Alta Investigación, [Universidad de Tarapacá](#), Arica, Chile
- ^{140f}Departamento de Física, [Universidad Técnica Federico Santa María](#), Valparaíso, Chile
- ¹⁴¹Department of Physics, [Institute of Science](#), Tokyo, Japan
- ¹⁴²Department of Physics, [University of Washington](#), Seattle, Washington, USA
- ¹⁴³Department of Physics and Astronomy, [University of Sheffield](#), Sheffield, United Kingdom
- ¹⁴⁴Department of Physics, [Shinshu University](#), Nagano, Japan
- ¹⁴⁵Department Physik, [Universität Siegen](#), Siegen, Germany
- ¹⁴⁶Department of Physics, [Simon Fraser University](#), Burnaby BC, Canada
- ¹⁴⁷[SLAC National Accelerator Laboratory](#), Stanford, California, USA
- ¹⁴⁸Department of Physics, [Royal Institute of Technology](#), Stockholm, Sweden
- ¹⁴⁹Departments of Physics and Astronomy, [Stony Brook University](#), Stony Brook, New York, USA
- ¹⁵⁰Department of Physics and Astronomy, [University of Sussex](#), Brighton, United Kingdom
- ¹⁵¹School of Physics, [University of Sydney](#), Sydney, Australia
- ¹⁵²Institute of Physics, [Academia Sinica](#), Taipei, Taiwan
- ^{153a}E. Andronikashvili Institute of Physics, [Iv. Javakhishvili Tbilisi State University](#), Tbilisi, Georgia
- ^{153b}High Energy Physics Institute, [Tbilisi State University](#), Tbilisi, Georgia
- ^{153c}[University of Georgia](#), Tbilisi, Georgia
- ¹⁵⁴Department of Physics, [Technion](#), Israel Institute of Technology, Haifa, Israel
- ¹⁵⁵Raymond and Beverly Sackler School of Physics and Astronomy, [Tel Aviv University](#), Tel Aviv, Israel
- ¹⁵⁶Department of Physics, [Aristotle University of Thessaloniki](#), Thessaloniki, Greece
- ¹⁵⁷International Center for Elementary Particle Physics and Department of Physics, [University of Tokyo](#), Tokyo, Japan
- ¹⁵⁸Department of Physics, [University of Toronto](#), Toronto ON, Canada
- ^{159a}[TRIUMF](#), Vancouver BC, Canada
- ^{159b}Department of Physics and Astronomy, [York University](#), Toronto ON, Canada
- ¹⁶⁰Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, [University of Tsukuba](#), Tsukuba, Japan
- ¹⁶¹Department of Physics and Astronomy, [Tufts University](#), Medford, Massachusetts, USA
- ¹⁶²Department of Physics and Astronomy, [University of California Irvine](#), Irvine, California, USA

- ¹⁶³*University of Sharjah, Sharjah, United Arab Emirates*
- ¹⁶⁴*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
- ¹⁶⁵*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁶⁶*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- ¹⁶⁷*Department of Physics, University of British Columbia, Vancouver BC, Canada*
- ¹⁶⁸*Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*
- ¹⁶⁹*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
- ¹⁷⁰*Department of Physics, University of Warwick, Coventry, United Kingdom*
- ¹⁷¹*Waseda University, Tokyo, Japan*
- ¹⁷²*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷³*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
- ¹⁷⁴*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷⁵*Department of Physics, Yale University, New Haven, Connecticut, USA*

^aAlso at Department of Physics, King's College London, London, United Kingdom.

^bAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^cAlso at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia.

^dAlso at TRIUMF, Vancouver BC, Canada.

^eAlso at Department of Physics, University of Thessaly, Greece.

^fAlso at An-Najah National University, Nablus, Palestine.

^gAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^hAlso at Department of Physics, Westmont College, Santa Barbara, CA, USA.

ⁱAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^jAlso affiliated with an institute covered by a cooperation agreement with CERN.

^kAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

^lAlso at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria.

^mAlso at Università di Napoli Parthenope, Napoli, Italy.

ⁿAlso at Institute of Particle Physics (IPP), Canada.

^oAlso at Borough of Manhattan Community College, City University of New York, New York, NY, USA.

^pAlso at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines.

^qAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^rAlso at Institutio Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.

^sDeceased.

^tAlso at Technical University of Munich, Munich, Germany.

^uAlso at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC), Azerbaijan.

^vAlso at Yeditepe University, Physics Department, Istanbul, Türkiye.

^wAlso at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^xAlso at CERN, Geneva, Switzerland.

^yAlso at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.

^zAlso at Hellenic Open University, Patras, Greece.

^{aa}Also at Center for High Energy Physics, Peking University, Beijing, China.

^{ab}Also at Department of Physics, Stellenbosch University, Stellenbosch, South Africa.

^{ac}Also at Department of Physics, California State University, Sacramento, CA, USA.

^{ad}Also at University of Colorado Boulder, Department of Physics, Boulder, CO, USA.

^{ae}Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

^{af}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

^{ag}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

^{ah}Also at Washington College, Chestertown, MD, USA.

^{ai}Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.

^{aj}Also at Department of Physics, Stanford University, Stanford, CA, USA.

^{ak}Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.