Search for a Neutral Gauge Boson with Nonuniversal Fermion Couplings in Vector Boson Fusion Processes in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 26 December 2024; accepted 27 June 2025; published 8 August 2025)

The first search for a heavy neutral spin-1 gauge boson (Z') with nonuniversal fermion couplings produced via vector boson fusion processes and decaying to tau leptons or W bosons is presented. The analysis is performed using LHC data at $\sqrt{s} = 13$ TeV, collected from 2016 to 2018 with the CMS experiment and corresponding to an integrated luminosity of 138 fb^{-1}. The data are consistent with the standard model predictions. Upper limits are set on the product of the cross section for production of the Z' boson and its branching fraction to $\tau\tau$ or WW. The presence of a Z' boson decaying to $\tau^+\tau^-$ (W^+W^-) is excluded for masses up to 2.45(1.60) TeV, depending on the Z' boson coupling to standard model weak bosons, and assuming a $Z' \to \tau^+\tau^-$ (W^+W^-) branching fraction of 50%.

DOI: 10.1103/srvm-f1h3

The standard model (SM) of particle physics has successfully explained many experimental observations. However, it is not an ultimate theory of nature. For example, the SM fails to explain neutrino masses and the matter-antimatter asymmetry of the Universe. Furthermore, recent experimental results from precision measurements, such as the ratios $R(D^0)$ and $R(D^*)$ from B meson decays, show tension with the SM expectations [1,2]. Various models of new physics have been proposed to address the shortcomings of the SM. Examples of such models include $U(1)$ extensions [3,4], top-assisted technicolor models [5], Randall-Sundrum models [6–8], grand unified theories [9], and $E(6)$ models [10]. Such models predict a new heavy neutral gauge boson Z' that could be observed in proton-proton (pp) collisions at the CERN LHC.

Previous searches for Z' bosons have considered production via Drell-Yan processes with various Z' boson couplings g_q to light quarks [11–21]. A widely used benchmark model in those searches is the sequential SM, which assumes a Z' boson with the same couplings to quarks and leptons as the SM Z boson. In this model, 95% confidence level bounds on the Z' boson mass $m_{Z'}$ of up to 5 TeV have been established by the ATLAS [18] and CMS [19] collaborations, assuming a Z' boson with a small decay width and considering decays to electron and muon pairs. However, the bounds are significantly weaker under less stringent assumptions, e.g., ones that allow nonuniversal (i.e., generation-dependent) fermion couplings with small values of g_q, and can have large Z' boson decay widths [22–24]. These models could account for the tensions between SM predictions and precision measurements, and motivate a search for Z' resonances produced through vector boson fusion (VBF) processes, with the Z' boson decaying to a pair of τ leptons [22,25].

This Letter presents the first search for a Z' boson with nonuniversal fermion couplings produced through VBF processes at the LHC, using 138 fb^{-1} of data collected during 2016–2018 from pp collisions at $\sqrt{s} = 13$ TeV. In a VBF reaction, a quark from each of the colliding protons radiates an SM electroweak vector boson, and the merger of these produces a Z' boson. The Z' boson can subsequently decay into a pair of τ leptons, which are accompanied by two jets from the scattered quarks. While the analysis is optimized for the $Z' \to \tau + \tau-$ final state, the possibility of a Z' boson decaying into a pair of W bosons motivates an alternate interpretation of the results. A representative Feynman diagram can be found in Ref. [25]. Four Z' boson decay channels are utilized: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, and $e\mu$, where τ_h refers to a τ lepton that decays hadronically. In the $Z' \to \tau^+\tau^-$ decay mode, the electrons and muons are produced from the leptonic decays of τ leptons, while they may arise from $W \to \ell\nu$ decays in the case of the $Z' \to W^+W^-$ mode, where $\ell = e, \mu, \tau$.

The CMS apparatus [26] is a multipurpose, nearly hermetic detector designed to trigger on [27–29] and identify electrons, muons, photons, and (charged and neutral) hadrons [30–32]. A global particle-flow (PF) algorithm [33] aims to reconstruct all individual particles (PF candidates) in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic (ECAL) and brass-scintillator hadron

[*]Full author list given at the end of the Letter.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP[3].

 © 2025 CERN, for the CMS Collaboration

calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid.

The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Sec. 9.4.1 of Ref. [34]. Electron candidates are reconstructed by matching energy clusters in the ECAL with tracks in the inner tracker. A dedicated electron identification is used to distinguish electrons produced in hard scattering processes from charged hadrons and from electrons produced through photon conversions [30]. Muons are reconstructed using the tracker and muon chambers and by requiring limited associated energy deposited in the calorimeters [31]. The electron and muon selections impose an isolation requirement to suppress lepton candidates from misidentified jets, and genuine leptons from hadron decays. The isolation variable I_ℓ is defined as the scalar p_{T} (transverse momentum) sum, divided by the lepton p_{T}, of charged and neutral PF candidates within a cone in (η, ϕ), with η the pseudorapidity and ϕ the azimuthal angle. The radius of the cone is 0.4 (0.3) around the muon (electron) direction at the interaction vertex. The sum excludes the lepton under consideration as well as particles identified as arising from additional pp interactions within the same or a nearby crossing of proton-beam bunches (pileup) [35,36]. The isolation criterion is $I_\ell < 0.15$ [31].

Jets are clustered using the anti-k_{T} clustering algorithm [37,38] with an angular distance parameter of 0.4. Identification criteria are applied to jet candidates to remove anomalous effects from the calorimeters and jets from secondary pileup interactions [39]. For jets with $p_{\mathrm{T}} >$ 30 GeV and $|\eta| < 2.5$ (>2.5), the identification efficiency is >98 (90)% depending on pseudorapidity. The jet energy scale and resolution are corrected depending on the p_{T} and η of the jet [40]. The missing transverse momentum $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is the negative sum of the individual transverse momentum vectors of all PF candidates [39]. Its magnitude is $p_{\mathrm{T}}^{\mathrm{miss}}$.

Jets originating from the hadronization of b quarks (b jets) are tagged using algorithms that identify secondary vertices. The identification efficiency is 40%–60% for genuine b jets, depending on p_{T}, η, the year of data collection, and the light-flavor quark or gluon jet misidentification rate is 0.1%–0.9% [41].

Each τ_{h} candidate is reconstructed using the hadrons-plus-strips algorithm [42] and is identified with an artificial neural network that combines variables related to isolation and the τ lepton lifetime to identify specific classes of τ_{h} decay modes [43]. The tight-isolation working point is used to define the signal region, which results in a τ_{h} identification efficiency of 60% with a 0.05%–0.3% probability for a jet to be misidentified as a τ_{h}, depending on the p_{T} and η of the τ_{h} candidate [43]. The loose-isolation working point, which is used for background estimation studies, has a τ_{h} identification efficiency of 80% and a 0.1%–1% jet misidentification probability. To suppress muons and electrons misidentified as τ_{h}, a discriminator based on an artificial neural network is used that requires that the lead track of the τ_{h} candidate not be associated with a global muon signature or an electron bremsstrahlung shower [44]. The misidentification rate for muons (electrons) is 0.02% (3.60%) for a genuine τ_{h} identification efficiency of 80%.

Data for this search were collected using single-lepton triggers for final states with muons or electrons, and a double-τ_{h} trigger for the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ analysis [28]. The single muon (electron) trigger requires an isolated muon (electron) with a minimum p_{T} of 24 or 27 GeV (32 or 35 GeV), depending on the data-taking year. The double-τ_{h} trigger uses isolation criteria and $p_{\mathrm{T}}(\tau_{\mathrm{h}})$ thresholds of 32, 35, or 40 GeV, depending on the year.

Events satisfying the trigger selections must pass additional offline lepton requirements targeting the $Z' \to \tau^+\tau^-$ and $Z' \to W^+W^-$ decay chains. An event must contain exactly one pair of leptons having opposite-sign electric charge (OS). The muon in the $\mu\tau_{\mathrm{h}}$ ($e\mu$) channel is required to have $p_{\mathrm{T}} > 35(30)$ GeV within $|\eta| < 2.1$. The electron in the $e\tau_{\mathrm{h}}$ ($e\mu$) channel is required to have $p_{\mathrm{T}} > 55(10)$ GeV within $|\eta| < 2.1$. The τ_{h} candidates in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ ($\mu\tau_{\mathrm{h}}$ and $e\tau_{\mathrm{h}}$) channel are required to have $p_{\mathrm{T}} > 70(20)$ GeV within $|\eta| < 2.1$, where the trigger is fully efficient. These requirements constitute the dilepton selection.

To reduce background from SM processes containing top quarks, events must contain no identified b jet with $p_{\mathrm{T}} >$ 30 GeV and $|\eta| < 2.4$. The associated neutrinos from the τ lepton and W boson decays in the signal events generate sizable $p_{\mathrm{T}}^{\mathrm{miss}}$. We require $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV to suppress the contribution from pure quantum chromodynamic processes (QCD multijet events).

The distinctive signature of events from VBF processes is the presence of two energetic jets with a large η separation ($\Delta\eta$), located in opposite hemispheres of the detector. Therefore, in addition to the lepton pair, we require that each event contain two well-identified jets (j_1 and j_2), each with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 5$, with a reconstructed dijet mass (m_{jj}) greater than 500 GeV, $|\Delta\eta(jj)| > 4.2$, and $\eta_{j_1}\eta_{j_2} < 0$. These jets and the leptons must all be well separated from each other, satisfying the requirement $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$. We refer to these requirements as the VBF criteria. They are effective at suppressing the background by a factor of 10^2–10^4, depending on the background process, while retaining 70%–75% of signal events, depending on $m_{Z'}$. We note that approximately 1% of background events involve a reconstructed VBF dijet pair that includes a pileup jet, while such occurrences are exceedingly rare in signal events. The signal regions (SRs) comprise events that satisfy the dilepton selection criteria, the b jet veto requirement, the $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement, and the VBF selection criteria.

As an approximation to the Z' boson mass, we form the invariant mass of the system comprising the visible lepton pair and the missing momentum,

$$m(\ell_1, \ell_2, p_T^{\text{miss}}) = \sqrt{(E_{\ell_1} + E_{\ell_2} + p_T^{\text{miss}})^2 - (\vec{p}_{\ell_1} + \vec{p}_{\ell_2} + \vec{p}_T^{\text{miss}})^2},$$

which serves as the main observable used to distinguish between signal and background. The strategy is to search for a broad enhancement in the spectrum at large values of $m(\ell_1, \ell_2, p_T^{\text{miss}})$.

The dominant SM background processes contributing to the search are W and Z boson production (W + jets and Z + jets), production of top quark-antiquark pairs (tt), and QCD multijet production. The W + jets and Z + jets events contain genuine lepton candidates, energetic jets, and p_T^{miss} from neutrinos. Background from tt events is characterized by two b jets in addition to genuine leptons. Events from the QCD multijet production process can be mistaken for signal if jets are misidentified as leptons. Smaller backgrounds include the production of events with a single t quark and those with the production of two vector bosons.

Simulated samples of Z + jets, W + jets, and single t quark events are produced with the MADGRAPH5_AMC@NLO2.6.0 program [45] at leading order (LO) in QCD. Events from $t\bar{t}$ are generated with POWHEG2.0 [46–48] at next-to-leading order (NLO) precision. The LO PYTHIA generator [49] is used to model diboson processes. The production of one or two vector bosons in association with two jets exclusively through pure electroweak interactions is simulated with LO MADGRAPH5_AMC@NLO2.6.0, and the leading electroweak QCD interference terms in the cross section are found to be small [50]. Pure electroweak $pp \to Z'jj$ signal samples are generated using MADGRAPH5_AMC@NLO at LO precision. We use the simplified model in Ref. [25], where the Z' boson has Z-like couplings, and the Z' boson masses and couplings to SM particles are free parameters. The Z' boson coupling to first- and second-generation fermions is defined as $g_{1,2}g_{Zff}$, where g_{Zff} is the SM Z boson coupling, and $g_{1,2}$ is a modifier for the coupling. The coupling to tau leptons is similarly defined with g_3 as the modifier for the SM Z boson coupling to tau leptons. Finally, the Z' boson coupling to the SM W boson is defined as $g_{Z'WW} = \kappa_V g_{Z'WW}^{\text{max}}$, where $g_{Z'WW}^{\text{max}}$ is the maximal Z' boson coupling to the SM W boson dictated by the unitarity constraint [25], and κ_V is a modifier for that coupling. The parameter κ_V affects both the signal cross section and event kinematic properties. We do not consider anomalous couplings between the Z' boson and the Z/γ bosons of the SM, and thus Z' decays to Z/γ are not considered. Four sets of signal models are utilized: (i) $Z' \to \tau^+\tau^-$ decays with $g_{1,2} = 0$, henceforth referred to as simplified phenomenological model 1 (SPM1); (ii) $Z' \to \tau^+\tau^-$ decays with $g_{1,2} = 1$ (SPM2); (iii) $Z' \to WW$ decays with $g_{1,2} = 0$ (SPM3); and (iv) $Z' \to WW$ decays with $g_{1,2} = 1$ (SPM4). The $g_{1,2} = 0$ cases are a proxy for nonuniversal fermion coupling scenarios, where the couplings of the Z' boson to light fermions are suppressed. For all sets of signal models described above, five κ_V values are considered, $\kappa_V = \{0.1, 0.25, 0.50, 0.75, 1.0\}$, for Z' masses ranging from 250 to 2500 GeV in steps of 250 GeV. The parameter g_3 is also varied to study the effect of different $Z' \to \tau^+\tau^-$ branching fractions, and results are presented as a function of the branching fractions.

The MADGRAPH5_AMC@NLO and POWHEG generators used to simulate signal and background processes are interfaced with PYTHIA8.212 (8.230) using the CUETP8M1 (CP5) tune [51,52] for parton shower and fragmentation in the 2016 (2017–2018) simulated samples, respectively. The NNPDF3.0 (3.1) NNLO [53,54] parton distribution functions (PDFs) are used in the event generation for 2016 (2017–2018) samples. The simulated background yields are normalized to the integrated luminosity using next-to-NLO (NNLO) or NLO cross sections in QCD, while signal production cross sections are calculated at LO precision. The response of the CMS detector in these Monte Carlo simulated samples is simulated using dedicated software based on the GEANT4 toolkit [55]. Pileup is incorporated by simulating additional interactions that are both in time and out of time with the collision.

For the $\mu\tau_h$ and $e\tau_h$ channels, the main background comes from events with jets misidentified as τ_h candidates, mainly from processes such as W + jets and $t\bar{t}$ with one leptonic W boson decay. This background contribution is estimated from data using control regions (CRs) obtained with no VBF criteria and containing a τ_h candidate that satisfies the loose, but fails the tight isolation requirement [antiISO τ_h]. Events in this CR are weighted with a transfer factor given by the product of a VBF selection efficiency, and a misidentification ratio [misID] ratio defined as the ratio of the number of events with a nominal τ_h candidate to the number of those with an antiISO τ_h. The VBF selection efficiency is determined using a $W(\to \mu\nu)$ + jets CR with transverse mass $m_T(\vec{p}_\mu, \vec{p}_T^{\text{miss}})$ near the m_W Jacobian peak, and is taken to be the fraction of events in this CR that also satisfy the VBF criteria. The misID ratios are derived as a function of $p_T(\tau_h)$ and $\eta(\tau_h)$ in a $Z(\to \mu\mu) + \tau_h$ CR. Nearly all τ_h candidates in this CR arise from misidentified jets. The antiISO τ_h requirement used to determine the misID ratio can slightly bias the angular separation between the τ_h candidate and $\vec{p}_T^{\text{miss}}$, and as a result can slightly bias the $m(\ell_1, \ell_2, p_T^{\text{miss}})$ shape. Therefore, any residual $m(\ell_1, \ell_2, p_T^{\text{miss}})$ shape biases in the misID τ_h background prediction are accounted for using correction factors as a function of $\Delta\phi(\vec{p}_\ell, \vec{p}_T^{\text{miss}})$, derived from the Monte Carlo simulated samples, and validated with simulation and data.

The dominant genuine-τ_h background contribution in the $\mu\tau_h$ and $e\tau_h$ signal regions arises from $t\bar{t}$ fully leptonic events. This background is estimated from simulation scaled by data-to-simulation efficiency factors (SFs) to account for mismodeling of the selection efficiencies in simulation. The SFs are measured in a tt -enriched CR requiring the same lepton pair and VBF criteria as for the SR, but with the b jet veto replaced by the requirement of one b jet.

For the $\tau_h\tau_h$ channel, the main background contribution comes from $Z+$jets processes with genuine τ_h candidates from $Z \to \tau_h\tau_h$, and is estimated from simulation with SFs obtained from a Z-enriched CR. This CR is selected with the same lepton-pair and VBF criteria as those of the SR, but with $p_T^{miss} < 30$ GeV and the reconstructed mass $m(\tau_h\tau_h)$ of the two τ_h candidates between 50 and 100 GeV. An SF is measured from these events, which is used to normalize the $Z+$jets' background yield in the SR. To disentangle the individual contributions of the VBF and non-VBF selections to the overall SF used in the background estimation, the same Z-enriched CR is also studied without the VBF criteria. The normalization SF does not depend on $m(\ell_1, \ell_2, p_T^{miss})$. We correct the yields in these $Z(\to \tau_h\tau_h)+$jets CRs for the contamination from QCD multijet events estimated from data in CRs with same-sign electric charge (SS) τ_h pairs. The transfer factor between SS and OS events is calculated using events with antiISO τ_h and $m(\tau_h\tau_h) > 100$ GeV.

The contribution of QCD multijet events in the $\tau_h\tau_h$ SR is determined using a QCD-enriched CR selected by the requirement of an SS τ_h pair. The transfer factor between this CR and the SR is obtained as the ratio of OS to SS τ_h pairs in CRs that fail the VBF and p_T^{miss} criteria and have an antiISO τ_h pair.

The smaller $W+$jets background contribution in the $\tau_h\tau_h$ SR is determined by correcting the prediction from simulation with SFs derived from high-purity $W(\to \mu\nu)+$jets control samples.

In the $e\mu$ channel, the main background comes from $t\bar{t}$ production with two leptonic t quark decays. An estimation of the $t\bar{t}$ background is performed by defining four regions in data. Region A is the SR, and the events in CR D differ from those in A by failing the VBF criteria. Regions B and C are defined by the same requirements as for A and D respectively, but with one rather than zero b jets. The $t\bar{t}$ yield N_A in the SR for each $m(e, \mu, p_T^{miss})$ bin is obtained as $N_A = (N_B/N_C)N_D$, where N_B and N_C are the data yields in those respective CRs, and N_D is given by the yield in CR D minus an estimate from simulation of the contribution of non-tt processes.

The internal consistency (closure) of all background estimation methods, in all channels, is validated in simulation, with additional tests performed in data CRs. These closure tests demonstrate that the background determination techniques reproduce the expected distributions in both rate and shape.

Various effects impact the shape and normalization of the predicted $m(\ell_1, \ell_2, p_T^{miss})$ background distribution. A leading source of systematic uncertainty is the difference in the misID τ_h ratios between light-quark and gluon jets. We estimate this uncertainty by comparing the misID ratio measured in an SS $W(\to \mu\nu)+\tau_h$ CR, which has a higher fraction of light-quark jets relative to gluon jets, with the nominal one measured in the $Z(\to \mu\mu)+\tau_h$ CR. The difference is found to depend on $p_T(\tau_h)$, varying from 4% to 20%. The statistical uncertainties of the data in the CRs used for measuring SFs give rise to uncertainties in the background predictions of 1%–21%, depending on the process. Another source of systematic uncertainty (<20% for all processes) is the closure of the background estimation methods.

The signal and background yields estimated from simulation are affected by similar sources of systematic uncertainty, with small differences between the 2016, 2017, and 2018 datasets. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2%–2.5% individual uncertainties [56–58], while the overall uncertainty for the 2016–2018 period is 1.6%. Uncertainties associated with the identification of μ and e are 1%–2% for all background and signal processes [30,31]. The uncertainty from the τ_h identification and isolation requirements is 6%–9%, depending on the data-taking year. The uncertainties in the identification and energy scales for μ, e, and τ_h are correlated across processes with genuine μ, e, and τ_h candidates, and correlated across $m(\ell_1, \ell_2, p_T^{miss})$ bins. The uncertainty in the τ_h energy scale amounts to 2% uncertainty in the yields. For the electrons misidentified as τ_h candidates, the identification uncertainties are 1%–6.5% depending on $p_T(\tau_h)$. The jet energy scale uncertainties (2%–5% depending on η and p_T) result in an uncertainty of 1%–3% in the signal yields, depending on $m(\ell_1, \ell_2, p_T^{miss})$. Uncertainties due to the modeling of secondary pileup interactions are less than 1%. The uncertainty in event acceptance from the PDF set used in simulation is determined according to the PDF4LHC recommendations [59] by comparing the outputs from the CTEQ6.6L, MSTW08, and NNPDF10 PDF sets [60–62] to those of the default PDF set. This results in at most a 6% uncertainty in the signal yield, and is correlated across data-taking years. The uncertainty in the b tagging efficiency results in 2%–9% uncertainty in the predicted yields, depending on the process, and is only correlated between backgrounds with top quarks. The trigger uncertainty is 3% for background and signal yields, and is uncorrelated across data-taking years. During the 2016 and 2017 data-taking periods, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region at $|\eta| > 2.0$ caused a specific trigger inefficiency, for which correction factors and uncertainties are computed from data and applied to the acceptance derived from simulation, resulting in a 5%–8% uncertainty in the yields, depending on the process.

Figure 1 shows the $m(\ell_1, \ell_2, p_T^{miss})$ distribution for events in the SRs for all channels. The binning was chosen among several binning options as the one with the best signal significance and discovery reach in $m_{Z'}$.

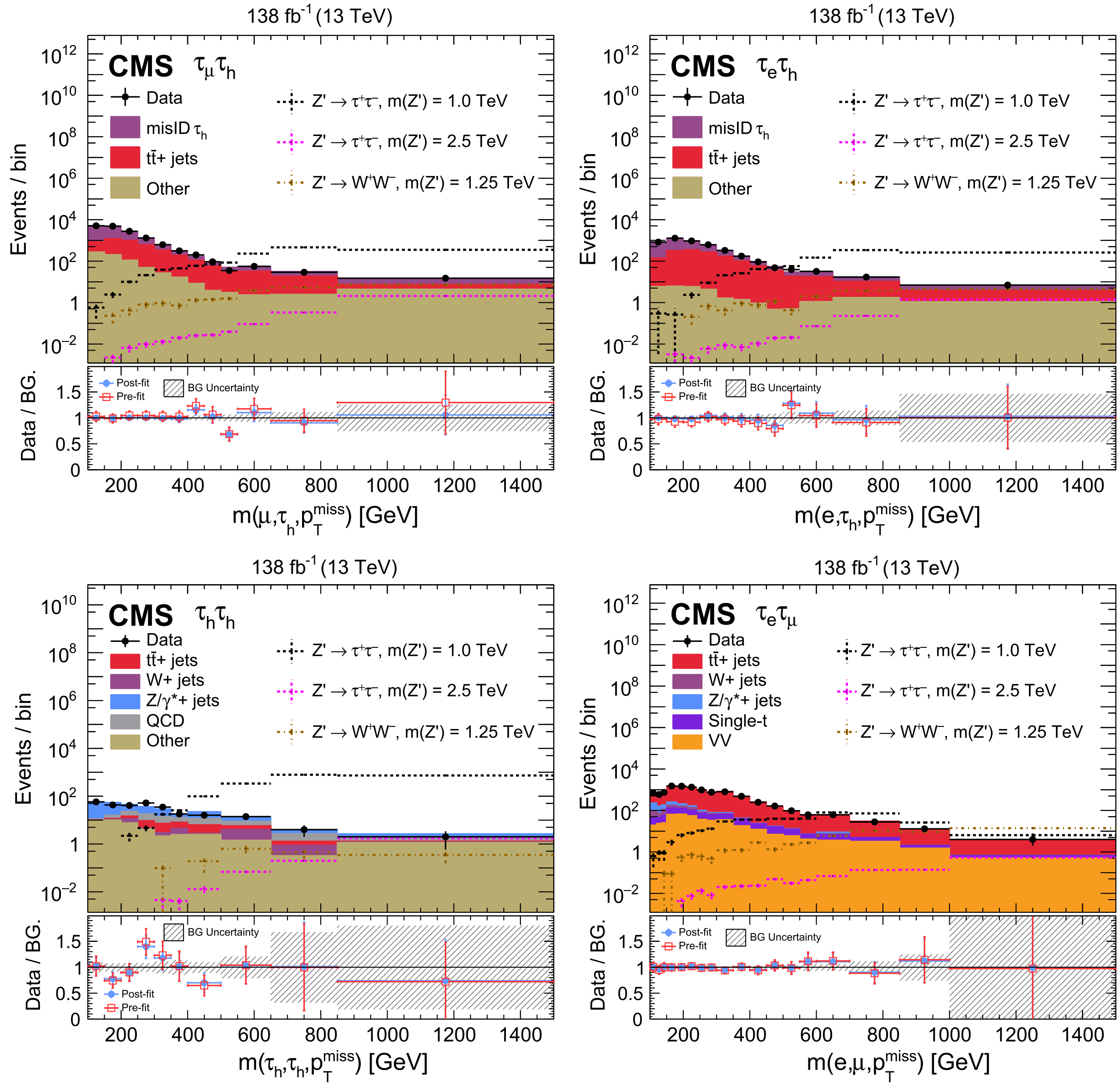

FIG. 1. Observed $m(\ell_1, \ell_2, p_T^{\text{miss}})$ for the data, and the postfit backgrounds (stacked histograms), in the signal region for the $\mu\tau_h$ (upper left), $e\tau_h$ (upper right), $\tau_h\tau_h$ (lower left), and $e\mu$ (lower right) channels. The lower panels show ratios of the data to the prefit background prediction and postfit background yields as red open squares and blue points, respectively. The gray band in the lower panels indicates the systematic component of the postfit uncertainty. The dashed lines correspond to the signal expectation for Z' boson masses of 1 TeV (black) and 2.5 TeV (magenta) decaying to $\tau^+\tau^-$, normalized to cross sections of 199.4 fb and 0.7504 fb respectively. The dashed brown line corresponds to a Z' boson mass of 1.25 TeV decaying to W^+W^-, normalized to a cross section of 61.14 fb. The signal cross sections correspond to $\{\kappa_V, g_3, g_{1,2}\} = \{1, 1, 0\}$.

Backgrounds are estimated using either fully data-driven methods or simulation-based approaches, with CR-derived SFs applied to the SRs, as described above. The observed mass spectra shown in Fig. 1 are consistent with the SM predictions. We set 95% confidence level (CL) upper limits on the product of the VBF Z' cross section and the branching fraction for the decay of the Z' boson to $\tau^+\tau^-$ or W^+W^-. The limits are estimated following the modified frequentist construction CL_s [63–65] using the CMS statistical analysis tool COMBINE [66]. Maximum likelihood fits are performed using the SR distributions to construct a combined profile likelihood ratio test statistic in bins of $m(\ell_1, \ell_2, p_T^{\text{miss}})$. We use the asymptotic approximation to the profile likelihood test statistic. Systematic uncertainties are implemented as nuisance parameters, which are profiled and modeled with gamma or log-normal priors for the normalization parameters and Gaussian priors for the shape uncertainties. The upper limits on signal cross section are then used to derive exclusion bounds.

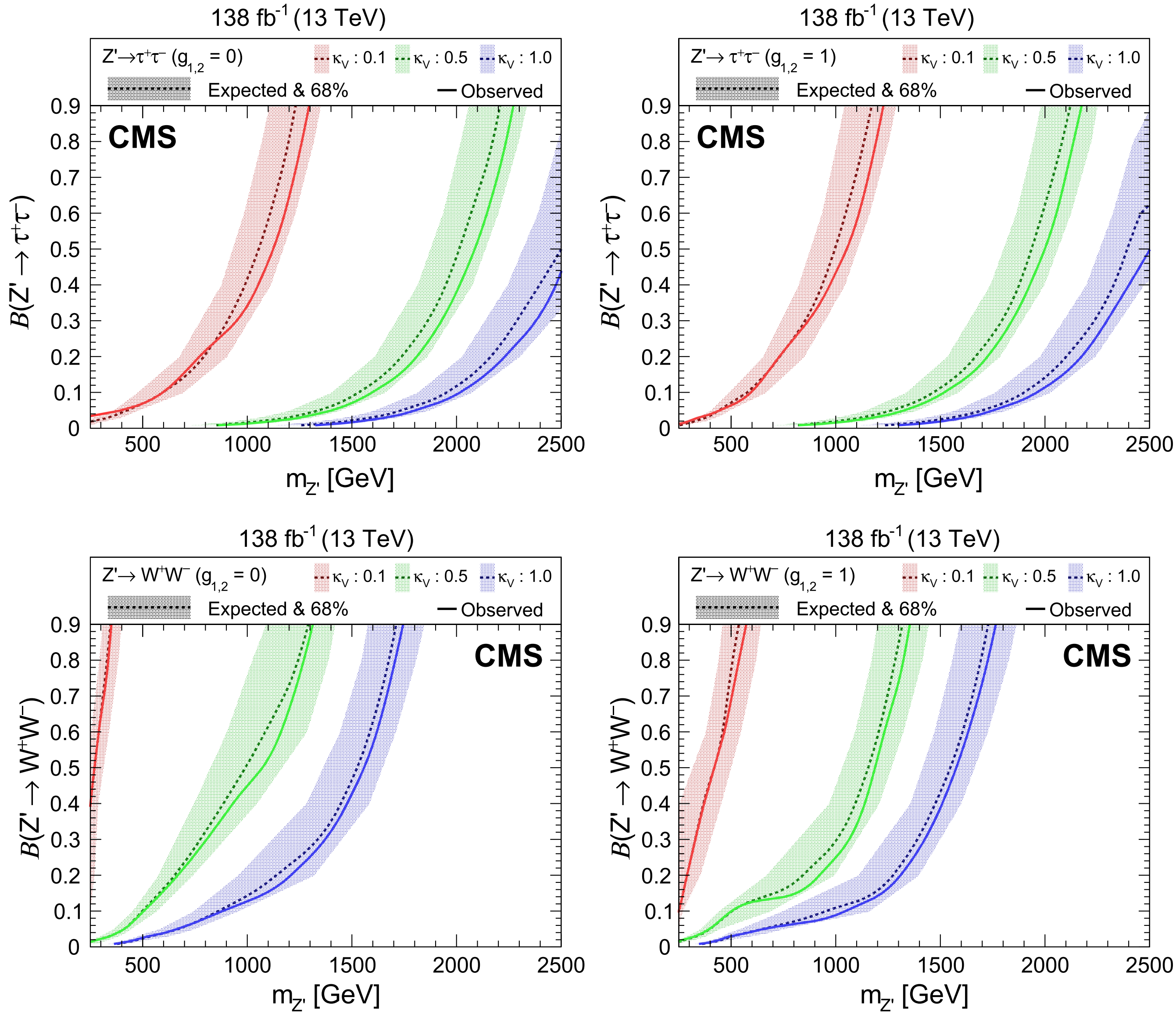

FIG. 2. Combined 95% CL lower limits on $m_{Z'}$ as a function of the Z' branching fraction to $\tau^+\tau^-$ (upper row) and W^+W^- (lower row) for the $g_{1,2} = 0$ (left column) and $g_{1,2} = 1$ (right column) scenario. The red, green, and blue curves show the observed limits corresponding to κ_V equal to 0.1, 0.5, and 1, respectively. The dashed curves and shaded bands show the expected limits with their 68% CL percentile bands.

Figure 2 shows exclusion bounds for the four signal models described above, as a function of $m_{Z'}$ and the $Z' \to \tau^+\tau^-$ and $Z' \to W^+W^-$ branching fractions, assuming different κ_V values.

The $\tau_h\tau_h$ channel contributes most strongly to the $Z' \to \tau^+\tau^-$ exclusion limits, while for $Z' \to W^+W^-$ it is the $e\mu$ channel that contributes most. For SPM1, the data exclude Z' bosons with masses below 1 (2.45) TeV for a $Z' \to \tau^+\tau^-$ branching fraction of 50%, assuming $\kappa_V = 0.1$ (1.0). For SPM2, the bounds on $m_{Z'}$ increase by about 5% due to an increase in the $pp \to Z'jj$ cross section from pure electroweak non-VBF processes when $g_{1,2} = 1$. For SPM3 and SPM4, we exclude Z' with masses below about 1.6 TeV for a 50% $Z' \to W^+W^-$ branching fraction, assuming $\kappa_V = 1.0$. In general, any increment of $g_{1,2}$ for constant values of the other couplings lowers the contribution of VBF diagrams relative to the total cross section, thereby decreasing the acceptance of the VBF selections. Simultaneously, the expected momentum of the Z' boson increases, affecting the signal shapes. For $Z' \to \tau^+\tau^-$, this leads to weakening limits with increasing $g_{1,2}$. For $Z' \to W^+W^-$, because of the mass of the W boson, the additional momentum improves the differentiation of the signal shape from that of the background, in total improving the limits with rising $g_{1,2}$. This analysis is sensitive to models that could resolve tensions between SM predictions and precision measurements. Tabulated results are provided in the associated HEPDATA record [67].

In summary, a first search for a heavy neutral spin-1 gauge boson Z' produced via vector boson fusion processes has been performed using data collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}. The search considers nonuniversal couplings of Z' bosons to fermions, including scenarios with dominant couplings to the third generation. Two decay channels, $Z' \to \tau^+\tau^-$ and $Z' \to W^+W^-$, are investigated. The invariant mass of the dilepton pair plus missing transverse momentum is used to search for the presence of a signal as a broad enhancement above the background expectation. The data are found to be in agreement with standard model predictions. In Z' models with nonuniversal fermion couplings, in particular those with Z' bosons having enhanced couplings to the third generation, the presence of Z' bosons decaying to a τ lepton (W boson) pair is excluded for Z' masses up to 2.45 (1.60) TeV, depending on the Z' boson coupling to SM weak bosons and assuming a $Z' \to \tau^+\tau^-$ (W^+W^-) branching fraction of 50%. These are the first limits to date on models with nonuniversal fermion couplings.

Acknowledgments—We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Data availability—Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse, and open access policy [68].

[1] LHCb Collaboration, Measurement of the ratios of branching fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$, Phys. Rev. Lett. **131**, 111802 (2023).
[2] W. Altmannshofer and P. Stangl, New physics in rare B decays after Moriond 2021, Eur. Phys. J. C **81**, 952 (2021).
[3] A. Das, P. S. Bhupal Dev, Y. Hosotani, and S. Mandal, Probing the minimal $U(1)_X$ model at future electron-positron colliders via fermion pair-production channels, Phys. Rev. D **105**, 115030 (2022).
[4] B. Allanach, LHC di-lepton searches for Z' bosons which explain measurements of $b \to sl^+l^-$ transitions, Phys. Lett. B **858**, 139055 (2024).
[5] C. T. Hill, Topcolor assisted technicolor, Phys. Lett. B **345**, 483 (1995).
[6] L. Randall and R. Sundrum, A large mass hierarchy from a small extra dimension, Phys. Rev. Lett. **83**, 3370 (1999).
[7] L. Randall and R. Sundrum, An alternative to compactification, Phys. Rev. Lett. **83**, 4690 (1999).
[8] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, Experimental probes of localized gravity: on and off the wall, Phys. Rev. D **63**, 075004 (2001).
[9] P. K. Mohapatra, R. N. Mohapatra, and P. B. Pal, Implications of E_6 grand unification, Phys. Rev. D **33**, 2010 (1986).
[10] D. London and J. L. Rosner, Extra gauge bosons in E_6, Phys. Rev. D **34**, 1530 (1986).
[11] S. Abachi *et al.* (D0 Collaboration), Search for additional neutral gauge bosons, Phys. Lett. B **385**, 471 (1996).
[12] V. M. Abazov *et al.* (D0 Collaboration), Search for a heavy neutral gauge boson in the dielectron channel with 5.4 fb^{-1} of $\mathrm{p\bar{p}}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Lett. B **695**, 88 (2011).
[13] T. Aaltonen *et al.* (CDF Collaboration), Search for high mass resonances decaying to muon pairs in $\sqrt{s} = 1.96$ TeV $\mathrm{p\bar{p}}$ collisions, Phys. Rev. Lett. **106**, 121801 (2011).
[14] CMS Collaboration, Search for high-mass resonances decaying into τ-lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B **716**, 82 (2012).
[15] CMS Collaboration, Search for heavy narrow dilepton resonances in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, Phys. Lett. B **720**, 63 (2013).
[16] CMS Collaboration, Search for narrow resonances in dilepton mass spectra in proton-proton collisions at $\sqrt{s} =$ 13 TeV and combination with 8 TeV data, Phys. Lett. B **768**, 57 (2017).
[17] CMS Collaboration, Search for heavy resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 02 (2017) 048.
[18] ATLAS Collaboration, Search for high-mass dilepton resonances using 139 fb^{-1} of pp collision data collected at

$\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B **796**, 68 (2019).

[19] CMS Collaboration, Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2021) 208.

[20] ATLAS Collaboration, Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2018) 055.

[21] ATLAS Collaboration, Search for heavy Higgs bosons decaying into two tau leptons with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. **125**, 051801 (2020).

[22] D. A. Faroughy, A. Greljo, and J. F. Kamenik, Confronting lepton flavor universality violation in B decays with high-p_T tau lepton searches at LHC, Phys. Lett. B **764**, 126 (2017).

[23] P. Langacker, The physics of heavy Z' gauge bosons, Rev. Mod. Phys. **81**, 1199 (2009).

[24] K. R. Lynch, S. Mrenna, M. Narain, and E. H. Simmons, Finding Z' bosons coupled preferentially to the third family at LEP and the Tevatron, Phys. Rev. D **63**, 035006 (2001).

[25] A. Flórez, A. Gurrola, W. Johns, Y. D. Oh, P. Sheldon, D. Teague, and T. Weiler, Searching for new heavy neutral gauge bosons using vector boson fusion processes at the LHC, Phys. Lett. B **767**, 126 (2017).

[26] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. **3**, S08004 (2008), 10.1088/1748-0221/3/08/S08004.

[27] CMS Collaboration, Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **15**, P10017 (2020).

[28] CMS Collaboration, The CMS trigger system, J. Instrum. **12**, P01020 (2017), 10.1088/1748-0221/12/01/P01020.

[29] CMS Collaboration, Performance of the CMS high-level trigger during LHC Run 2, J. Instrum. **19**, P11021 (2024).

[30] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. **16**, P05014 (2021).

[31] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **13**, P06015 (2018).

[32] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. **9**, P10009 (2014).

[33] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. **12**, P10003 (2017).

[34] CMS Collaboration, Technical proposal for the Phase-II upgrade of the compact muon solenoid, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.

[35] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. **15**, P09018 (2020).

[36] D. Bertolini, P. Harris, M. Low, and N. Tran, Pileup per particle identification, J. High Energy Phys. 10 (2014) 059.

[37] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_{T} jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[38] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, Eur. Phys. J. C **72**, 1896 (2012).

[39] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. **14**, P07004 (2019).

[40] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. **12**, P02014 (2017).

[41] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. **13**, P05011 (2018).

[42] CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **13**, P10005 (2018).

[43] CMS Collaboration, Identification of hadronic tau lepton decays using a deep neural network, J. Instrum. **17**, P07023 (2022).

[44] CMS Collaboration, Tau reconstruction and identification with particle-flow techniques using the CMS detector at LHC, Nucl. Phys. B, Proc. Suppl. **189**, 311 (2009).

[45] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079.

[46] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040.

[47] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070.

[48] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043.

[49] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA8.2, Comput. Phys. Commun. **191**, 159 (2015).

[50] CMS Collaboration, Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **78**, 589 (2018).

[51] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C **76**, 155 (2016).

[52] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C **80**, 4 (2020).

[53] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040.

[54] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, Eur. Phys. J. C **77**, 663 (2017).

[55] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[56] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C **81**, 800 (2021).

[57] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018, https://cds.cern.ch/record/2621960.
[58] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019, https://cds.cern.ch/record/2676164.
[59] J. Butterworth *et al.*, PDF4LHC recommendations for LHC Run II, J. Phys. G **43**, 023001 (2016).
[60] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, and C.-P. Yuan, Implications of CTEQ global analysis for collider observables, Phys. Rev. D **78**, 013004 (2008).
[61] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Update of parton distributions at NNLO, Phys. Lett. B **652**, 292 (2007).
[62] M. Ubiali, NNPDF1.0 parton set for the LHC, Nucl. Phys. B, Proc. Suppl. **186**, 62 (2009).
[63] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011); **73**, 2501(E) (2013).
[64] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A **434**, 435 (1999).
[65] A. L. Read, Presentation of search results: the CL_s technique, J. Phys. G **28**, 2693 (2002).
[66] CMS Collaboration, The CMS statistical analysis and combination tool: COMBINE, Comput. Software Big Sci. **8**, 19 (2024).
[67] HEPData record for this analysis (2024), 10.17182/hepdata.155915.
[68] CMS data availability statement, 10.7483/OPENDATA.CMS.1BNU.8V1W.

A. Hayrapetyan,[1] A. Tumasyan,[1,b] W. Adam,[2] J. W. Andrejkovic,[2] L. Benato,[2] T. Bergauer,[2] S. Chatterjee,[2] K. Damanakis,[2] M. Dragicevic,[2] P. S. Hussain,[2] M. Jeitler,[2,c] N. Krammer,[2] A. Li,[2] D. Liko,[2] I. Mikulec,[2] J. Schieck,[2,c] R. Schöfbeck,[2,c] D. Schwarz,[2] M. Sonawane,[2] W. Waltenberger,[2] C.-E. Wulz,[2,c] T. Janssen,[3] T. Van Laer,[3] P. Van Mechelen,[3] N. Breugelmans,[4] J. D'Hondt,[4] S. Dansana,[4] A. De Moor,[4] M. Delcourt,[4] F. Heyen,[4] S. Lowette,[4] I. Makarenko,[4] D. Müller,[4] S. Tavernier,[4] M. Tytgat,[4,d] G. P. Van Onsem,[4] S. Van Putte,[4] D. Vannerom,[4] B. Bilin,[5] B. Clerbaux,[5] A. K. Das,[5] I. De Bruyn,[5] G. De Lentdecker,[5] H. Evard,[5] L. Favart,[5] P. Gianneios,[5] J. Jaramillo,[5] A. Khalilzadeh,[5] F. A. Khan,[5] K. Lee,[5] A. Malara,[5] S. Paredes,[5] M. A. Shahzad,[5] L. Thomas,[5] M. Vanden Bemden,[5] C. Vander Velde,[5] P. Vanlaer,[5] M. De Coen,[6] D. Dobur,[6] G. Gokbulut,[6] Y. Hong,[6] J. Knolle,[6] L. Lambrecht,[6] D. Marckx,[6] K. Mota Amarilo,[6] K. Skovpen,[6] N. Van Den Bossche,[6] J. van der Linden,[6] L. Wezenbeek,[6] A. Benecke,[7] A. Bethani,[7] G. Bruno,[7] C. Caputo,[7] J. De Favereau De Jeneret,[7] C. Delaere,[7] I. S. Donertas,[7] A. Giammanco,[7] A. O. Guzel,[7] Sa. Jain,[7] V. Lemaitre,[7] J. Lidrych,[7] P. Mastrapasqua,[7] T. T. Tran,[7] G. A. Alves,[8] E. Coelho,[8] G. Correia Silva,[8] C. Hensel,[8] T. Menezes De Oliveira,[8] C. Mora Herrera,[8,e] P. Rebello Teles,[8] M. Soeiro,[8] A. Vilela Pereira,[8,e] W. L. Aldá Júnior,[9] M. Barroso Ferreira Filho,[9] H. Brandao Malbouisson,[9] W. Carvalho,[9] J. Chinellato,[9,f] E. M. Da Costa,[9] G. G. Da Silveira,[9,g] D. De Jesus Damiao,[9] S. Fonseca De Souza,[9] R. Gomes De Souza,[9] T. Laux Kuhn,[9,g] M. Macedo,[9] J. Martins,[9] L. Mundim,[9] H. Nogima,[9] J. P. Pinheiro,[9] A. Santoro,[9] A. Sznajder,[9] M. Thiel,[9] C. A. Bernardes,[10,g] L. Calligaris,[10] T. R. Fernandez Perez Tomei,[10] E. M. Gregores,[10] I. Maietto Silverio,[10] P. G. Mercadante,[10] S. F. Novaes,[10] B. Orzari,[10] Sandra S. Padula,[10] A. Aleksandrov,[11] G. Antchev,[11] R. Hadjiiska,[11] P. Iaydjiev,[11] M. Misheva,[11] M. Shopova,[11] G. Sultanov,[11] A. Dimitrov,[12] L. Litov,[12] B. Pavlov,[12] P. Petkov,[12] A. Petrov,[12] E. Shumka,[12] S. Keshri,[13] D. Laroze,[13] S. Thakur,[13] T. Cheng,[14] T. Javaid,[14] L. Yuan,[14] Z. Hu,[15] Z. Liang,[15] J. Liu,[15] G. M. Chen,[16,h] H. S. Chen,[16,h] M. Chen,[16,h] F. Iemmi,[16] C. H. Jiang,[16] A. Kapoor,[16,i] H. Liao,[16] Z.-A. Liu,[16,j] R. Sharma,[16,k] J. N. Song,[16,j] J. Tao,[16] C. Wang,[16,h] J. Wang,[16] Z. Wang,[16,h] H. Zhang,[16] J. Zhao,[16] A. Agapitos,[17] Y. Ban,[17] A. Carvalho Antunes De Oliveira,[17] S. Deng,[17] B. Guo,[17] C. Jiang,[17] A. Levin,[17] C. Li,[17] Q. Li,[17] Y. Mao,[17] S. Qian,[17] S. J. Qian,[17] X. Qin,[17] X. Sun,[17] D. Wang,[17] H. Yang,[17] L. Zhang,[17] Y. Zhao,[17] C. Zhou,[17] S. Yang,[18] Z. You,[19] K. Jaffel,[20] N. Lu,[20] G. Bauer,[21,l] B. Li,[21,m] K. Yi,[21,n] J. Zhang,[21] Y. Li,[22] Z. Lin,[23] C. Lu,[23] M. Xiao,[23] C. Avila,[24] D. A. Barbosa Trujillo,[24] A. Cabrera,[24] C. Florez,[24] J. Fraga,[24] J. A. Reyes Vega,[24] F. Ramirez,[25] C. Rendón,[25] M. Rodriguez,[25] A. A. Ruales Barbosa,[25] J. D. Ruiz Alvarez,[25] D. Giljanovic,[26] N. Godinovic,[26] D. Lelas,[26] A. Sculac,[26] M. Kovac,[27] A. Petkovic,[27] T. Sculac,[27] P. Bargassa,[28] V. Brigljevic,[28] B. K. Chitroda,[28] D. Ferencek,[28] K. Jakovcic,[28] A. Starodumov,[28,o] T. Susa,[28] A. Attikis,[29] K. Christoforou,[29] A. Hadjiagapiou,[29] C. Leonidou,[29] J. Mousa,[29] C. Nicolaou,[29] L. Paizanos,[29] F. Ptochos,[29] P. A. Razis,[29] H. Rykaczewski,[29] H. Saka,[29] A. Stepennov,[29] M. Finger,[30] M. Finger Jr.,[30] A. Kveton,[30] E. Ayala,[31] E. Carrera Jarrin,[32] H. Abdalla,[33,p]

Y. Assran,[33,q,r] B. El-mahdy,[33] A. Lotfy,[34] M. A. Mahmoud,[34] K. Ehataht,[35] M. Kadastik,[35] T. Lange,[35] S. Nandan,[35] C. Nielsen,[35] J. Pata,[35] M. Raidal,[35] L. Tani,[35] C. Veelken,[35] H. Kirschenmann,[36] K. Osterberg,[36] M. Voutilainen,[36] S. Bharthuar,[37] N. Bin Norjoharuddeen,[37] E. Brücken,[37] F. Garcia,[37] P. Inkaew,[37] K. T. S. Kallonen,[37] T. Lampén,[37] K. Lassila-Perini,[37] S. Lehti,[37] T. Lindén,[37] M. Myllymäki,[37] M. m. Rantanen,[37] H. Siikonen,[37] J. Tuominiemi,[37] P. Luukka,[38] H. Petrow,[38] M. Besancon,[39] F. Couderc,[39] M. Dejardin,[39] D. Denegri,[39] J. L. Faure,[39] F. Ferri,[39] S. Ganjour,[39] P. Gras,[39] G. Hamel de Monchenault,[39] M. Kumar,[39] V. Lohezic,[39] J. Malcles,[39] F. Orlandi,[39] L. Portales,[39] A. Rosowsky,[39] M. Ö. Sahin,[39] A. Savoy-Navarro,[39,s] P. Simkina,[39] M. Titov,[39] M. Tornago,[39] F. Beaudette,[40] G. Boldrini,[40] P. Busson,[40] A. Cappati,[40] C. Charlot,[40] M. Chiusi,[40] T. D. Cuisset,[40] F. Damas,[40] O. Davignon,[40] A. De Wit,[40] I. T. Ehle,[40] B. A. Fontana Santos Alves,[40] S. Ghosh,[40] A. Gilbert,[40] R. Granier de Cassagnac,[40] A. Hakimi,[40] B. Harikrishnan,[40] L. Kalipoliti,[40] G. Liu,[40] M. Nguyen,[40] C. Ochando,[40] R. Salerno,[40] J. B. Sauvan,[40] Y. Sirois,[40] L. Urda Gómez,[40] E. Vernazza,[40] A. Zabi,[40] A. Zghiche,[40] J.-L. Agram,[41,t] J. Andrea,[41] D. Apparu,[41] D. Bloch,[41] J.-M. Brom,[41] E. C. Chabert,[41] C. Collard,[41] S. Falke,[41] U. Goerlach,[41] R. Haeberle,[41] A.-C. Le Bihan,[41] M. Meena,[41] O. Poncet,[41] G. Saha,[41] M. A. Sessini,[41] P. Van Hove,[41] P. Vaucelle,[41] A. Di Florio,[42] D. Amram,[43] S. Beauceron,[43] B. Blancon,[43] G. Boudoul,[43] N. Chanon,[43] D. Contardo,[43] P. Depasse,[43] C. Dozen,[43,u] H. El Mamouni,[43] J. Fay,[43] S. Gascon,[43] M. Gouzevitch,[43] C. Greenberg,[43] G. Grenier,[43] B. Ille,[43] E. Jourd'huy,[43] I. B. Laktineh,[43] M. Lethuillier,[43] L. Mirabito,[43] S. Perries,[43] A. Purohit,[43] M. Vander Donckt,[43] P. Verdier,[43] J. Xiao,[43] I. Lomidze,[44] T. Toriashvili,[44,v] Z. Tsamalaidze,[44,w] V. Botta,[45] S. Consuegra Rodríguez,[45] L. Feld,[45] K. Klein,[45] M. Lipinski,[45] D. Meuser,[45] A. Pauls,[45] D. Pérez Adán,[45] N. Röwert,[45] M. Teroerde,[45] S. Diekmann,[46] A. Dodonova,[46] N. Eich,[46] D. Eliseev,[46] F. Engelke,[46] J. Erdmann,[46] M. Erdmann,[46] P. Fackeldey,[46] B. Fischer,[46] T. Hebbeker,[46] K. Hoepfner,[46] F. Ivone,[46] A. Jung,[46] M. y. Lee,[46] F. Mausolf,[46] M. Merschmeyer,[46] A. Meyer,[46] S. Mukherjee,[46] D. Noll,[46] F. Nowotny,[46] A. Pozdnyakov,[46] Y. Rath,[46] W. Redjeb,[46] F. Rehm,[46] H. Reithler,[46] V. Sarkisovi,[46] A. Schmidt,[46] C. Seth,[46] A. Sharma,[46] J. L. Spah,[46] A. Stein,[46] F. Torres Da Silva De Araujo,[46,x] S. Wiedenbeck,[46] S. Zaleski,[46] C. Dziwok,[47] G. Flügge,[47] T. Kress,[47] A. Nowack,[47] O. Pooth,[47] A. Stahl,[47] T. Ziemons,[47] A. Zotz,[47] H. Aarup Petersen,[48] M. Aldaya Martin,[48] J. Alimena,[48] S. Amoroso,[48] Y. An,[48] J. Bach,[48] S. Baxter,[48] M. Bayatmakou,[48] H. Becerril Gonzalez,[48] O. Behnke,[48] A. Belvedere,[48] F. Blekman,[48,y] K. Borras,[48,z] A. Campbell,[48] A. Cardini,[48] C. Cheng,[48] F. Colombina,[48] G. Eckerlin,[48] D. Eckstein,[48] L. I. Estevez Banos,[48] E. Gallo,[48,y] A. Geiser,[48] V. Guglielmi,[48] M. Guthoff,[48] A. Hinzmann,[48] L. Jeppe,[48] B. Kaech,[48] M. Kasemann,[48] C. Kleinwort,[48] R. Kogler,[48] M. Komm,[48] D. Krücker,[48] W. Lange,[48] D. Leyva Pernia,[48] K. Lipka,[48,aa] W. Lohmann,[48,bb] F. Lorkowski,[48] R. Mankel,[48] I.-A. Melzer-Pellmann,[48] M. Mendizabal Morentin,[48] A. B. Meyer,[48] G. Milella,[48] K. Moral Figueroa,[48] A. Mussgiller,[48] L. P. Nair,[48] J. Niedziela,[48] A. Nürnberg,[48] Y. Otarid,[48] J. Park,[48] E. Ranken,[48] A. Raspereza,[48] D. Rastorguev,[48] J. Rübenach,[48] L. Rygaard,[48] A. Saggio,[48] M. Scham,[48,cc,z] S. Schnake,[48,z] P. Schütze,[48] C. Schwanenberger,[48,y] D. Selivanova,[48] K. Sharko,[48] M. Shchedrolosiev,[48] D. Stafford,[48] F. Vazzoler,[48] A. Ventura Barroso,[48] R. Walsh,[48] D. Wang,[48] Q. Wang,[48] K. Wichmann,[48] L. Wiens,[48,z] C. Wissing,[48] Y. Yang,[48] A. Zimermmane Castro Santos,[48] A. Albrecht,[49] S. Albrecht,[49] M. Antonello,[49] S. Bein,[49] S. Bollweg,[49] M. Bonanomi,[49] P. Connor,[49] K. El Morabit,[49] Y. Fischer,[49] E. Garutti,[49] A. Grohsjean,[49] J. Haller,[49] D. Hundhausen,[49] H. R. Jabusch,[49] G. Kasieczka,[49] P. Keicher,[49] R. Klanner,[49] W. Korcari,[49] T. Kramer,[49] C. c. Kuo,[49] V. Kutzner,[49] F. Labe,[49] J. Lange,[49] A. Lobanov,[49] C. Matthies,[49] L. Moureaux,[49] M. Mrowietz,[49] A. Nigamova,[49] Y. Nissan,[49] A. Paasch,[49] K. J. Pena Rodriguez,[49] T. Quadfasel,[49] B. Raciti,[49] M. Rieger,[49] D. Savoiu,[49] J. Schindler,[49] P. Schleper,[49] M. Schröder,[49] J. Schwandt,[49] M. Sommerhalder,[49] H. Stadie,[49] G. Steinbrück,[49] A. Tews,[49] B. Wiederspan,[49] M. Wolf,[49] S. Brommer,[50] E. Butz,[50] T. Chwalek,[50] A. Dierlamm,[50] A. Droll,[50] U. Elicabuk,[50] N. Faltermann,[50] M. Giffels,[50] A. Gottmann,[50] F. Hartmann,[50,dd] R. Hofsaess,[50] M. Horzela,[50] U. Husemann,[50] J. Kieseler,[50] M. Klute,[50] R. Koppenhöfer,[50] O. Lavoryk,[50] J. M. Lawhorn,[50] M. Link,[50] A. Lintuluoto,[50] S. Maier,[50] S. Mitra,[50] M. Mormile,[50] Th. Müller,[50] M. Neukum,[50] M. Oh,[50] E. Pfeffer,[50] M. Presilla,[50] G. Quast,[50] K. Rabbertz,[50] B. Regnery,[50] N. Shadskiy,[50] I. Shvetsov,[50] H. J. Simonis,[50] L. Sowa,[50] L. Stockmeier,[50] K. Tauqeer,[50] M. Toms,[50] N. Trevisani,[50] R. F. Von Cube,[50] M. Wassmer,[50] S. Wieland,[50] F. Wittig,[50] R. Wolf,[50] X. Zuo,[50] G. Anagnostou,[51] G. Daskalakis,[51] A. Kyriakis,[51]

A. Papadopoulos,[51,dd] A. Stakia,[51] P. Kontaxakis,[52] G. Melachroinos,[52] Z. Painesis,[52] I. Papavergou,[52] I. Paraskevas,[52] N. Saoulidou,[52] K. Theofilatos,[52] E. Tziaferi,[52] K. Vellidis,[52] I. Zisopoulos,[52] G. Bakas,[53] T. Chatzistavrou,[53] G. Karapostoli,[53] K. Kousouris,[53] I. Papakrivopoulos,[53] E. Siamarkou,[53] G. Tsipolitis,[53] A. Zacharopoulou,[53] I. Bestintzanos,[54] I. Evangelou,[54] C. Foudas,[54] C. Kamtsikis,[54] P. Katsoulis,[54] P. Kokkas,[54] P. G. Kosmoglou Kioseoglou,[54] N. Manthos,[54] I. Papadopoulos,[54] J. Strologas,[54] C. Hajdu,[55] D. Horvath,[55,ee,ff] K. Márton,[55] A. J. Rádl,[55,gg] F. Sikler,[55] V. Veszpremi,[55] M. Csanád,[56] K. Farkas,[56] A. Fehérkuti,[56,hh] M. M. A. Gadallah,[56,ii] Á. Kadlecsik,[56] P. Major,[56] G. Pásztor,[56] G. I. Veres,[56] B. Ujvari,[57] G. Zilizi,[57] G. Bencze,[58] S. Czellar,[58] J. Molnar,[58] Z. Szillasi,[58] T. Csorgo,[59,hh] F. Nemes,[59,hh] T. Novak,[59] S. Bansal,[60] S. B. Beri,[60] V. Bhatnagar,[60] G. Chaudhary,[60] S. Chauhan,[60] N. Dhingra,[60,jj] A. Kaur,[60] A. Kaur,[60] H. Kaur,[60] M. Kaur,[60] S. Kumar,[60] T. Sheokand,[60] J. B. Singh,[60] A. Singla,[60] A. Ahmed,[61] A. Bhardwaj,[61] A. Chhetri,[61] B. C. Choudhary,[61] A. Kumar,[61] A. Kumar,[61] M. Naimuddin,[61] K. Ranjan,[61] M. K. Saini,[61] S. Saumya,[61] S. Baradia,[62] S. Barman,[62,kk] S. Bhattacharya,[62] S. Das Gupta,[62] S. Dutta,[62] S. Dutta,[62] S. Sarkar,[62] M. M. Ameen,[63] P. K. Behera,[63] S. C. Behera,[63] S. Chatterjee,[63] G. Dash,[63] P. Jana,[63] P. Kalbhor,[63] S. Kamble,[63] J. R. Komaragiri,[63,ll] D. Kumar,[63,ll] T. Mishra,[63] B. Parida,[63,mm] P. R. Pujahari,[63] N. R. Saha,[63] A. Sharma,[63] A. K. Sikdar,[63] R. K. Singh,[63] P. Verma,[63] S. Verma,[63] A. Vijay,[63] S. Dugad,[64] G. B. Mohanty,[64] M. Shelake,[64] P. Suryadevara,[64] A. Bala,[65] S. Banerjee,[65] R. M. Chatterjee,[65] M. Guchait,[65] Sh. Jain,[65] A. Jaiswal,[65] S. Kumar,[65] G. Majumder,[65] K. Mazumdar,[65] S. Parolia,[65] A. Thachayath,[65] S. Bahinipati,[66,nn] C. Kar,[66] D. Maity,[66,oo] P. Mal,[66] V. K. Muraleedharan Nair Bindhu,[66,oo] K. Naskar,[66,oo] A. Nayak,[66,oo] S. Nayak,[66] K. Pal,[66] P. Sadangi,[66] S. K. Swain,[66] S. Varghese,[66,oo] D. Vats,[66,oo] S. Acharya,[67,pp] A. Alpana,[67] S. Dube,[67] B. Gomber,[67,pp] P. Hazarika,[67] B. Kansal,[67] A. Laha,[67] B. Sahu,[67,pp] S. Sharma,[67] K. Y. Vaish,[67] H. Bakhshiansohi,[68,qq] A. Jafari,[68,rr] M. Zeinali,[68,ss] S. Bashiri,[69] S. Chenarani,[69,tt] S. M. Etesami,[69] Y. Hosseini,[69] M. Khakzad,[69] E. Khazaie,[69] M. Mohammadi Najafabadi,[69] S. Tizchang,[69,uu] M. Felcini,[70] M. Grunewald,[70] M. Abbrescia,[71a,71b] A. Colaleo,[71a,71b] D. Creanza,[71a,71c] B. D'Anzi,[71a,71b] N. De Filippis,[71a,71c] M. De Palma,[71a,71b] W. Elmetenawee,[71a,71b,vv] N. Ferrara,[71a,71b] L. Fiore,[71a] G. Iaselli,[71a,71c] L. Longo,[71a] M. Louka,[71a,71b] G. Maggi,[71a,71c] M. Maggi,[71a] I. Margjeka,[71a] V. Mastrapasqua,[71a,71b] S. My,[71a,71b] S. Nuzzo,[71a,71b] A. Pellecchia,[71a,71b] A. Pompili,[71a,71b] G. Pugliese,[71a,71c] R. Radogna,[71a,71b] D. Ramos,[71a] A. Ranieri,[71a] L. Silvestris,[71a] F. M. Simone,[71a,71c] Ü. Sözbilir,[71a] A. Stamerra,[71a,71b] D. Troiano,[71a,71b] R. Venditti,[71a,71b] P. Verwilligen,[71a] A. Zaza,[71a,71b] G. Abbiendi,[72a] C. Battilana,[72a,72b] D. Bonacorsi,[72a,72b] P. Capiluppi,[72a,72b] A. Castro,[72a,72b,a] F. R. Cavallo,[72a] M. Cuffiani,[72a,72b] G. M. Dallavalle,[72a] T. Diotalevi,[72a,72b] F. Fabbri,[72a] A. Fanfani,[72a,72b] D. Fasanella,[72a] P. Giacomelli,[72a] L. Giommi,[72a,72b] C. Grandi,[72a] L. Guiducci,[72a,72b] S. Lo Meo,[72a,ww] M. Lorusso,[72a,72b] L. Lunerti,[72a] S. Marcellini,[72a] G. Masetti,[72a] F. L. Navarria,[72a,72b] G. Paggi,[72a,72b] A. Perrotta,[72a] F. Primavera,[72a,72b] A. M. Rossi,[72a,72b] S. Rossi Tisbeni,[72a,72b] T. Rovelli,[72a,72b] G. P. Siroli,[72a,72b] S. Costa,[73a,73b,xx] A. Di Mattia,[73a] A. Lapertosa,[73a] R. Potenza,[73a,73b] A. Tricomi,[73a,73b,xx] C. Tuve,[73a,73b] P. Assiouras,[74a] G. Barbagli,[74a] G. Bardelli,[74a,74b] B. Camaiani,[74a,74b] A. Cassese,[74a] R. Ceccarelli,[74a] V. Ciulli,[74a,74b] C. Civinini,[74a] R. D'Alessandro,[74a,74b] E. Focardi,[74a,74b] T. Kello,[74a] G. Latino,[74a,74b] P. Lenzi,[74a,74b] M. Lizzo,[74a] M. Meschini,[74a] S. Paoletti,[74a] A. Papanastassiou,[74a,74b] G. Sguazzoni,[74a] L. Viliani,[74a] L. Benussi,[75] S. Bianco,[75] S. Meola,[75,yy] D. Piccolo,[75] M. Alves Gallo Pereira,[76a] F. Ferro,[76a] E. Robutti,[76a] S. Tosi,[76a,76b] A. Benaglia,[77a] F. Brivio,[77a] F. Cetorelli,[77a,77b] F. De Guio,[77a,77b] M. E. Dinardo,[77a,77b] P. Dini,[77a] S. Gennai,[77a] R. Gerosa,[77a,77b] A. Ghezzi,[77a,77b] P. Govoni,[77a,77b] L. Guzzi,[77a] M. T. Lucchini,[77a,77b] M. Malberti,[77a] S. Malvezzi,[77a] A. Massironi,[77a] D. Menasce,[77a] L. Moroni,[77a] M. Paganoni,[77a,77b] S. Palluotto,[77a,77b] D. Pedrini,[77a] A. Perego,[77a,77b] B. S. Pinolini,[77a] G. Pizzati,[77a,77b] S. Ragazzi,[77a,77b] T. Tabarelli de Fatis,[77a,77b] S. Buontempo,[78a] A. Cagnotta,[78a,78b] F. Carnevali,[78a,78b] N. Cavallo,[78a,78c] F. Fabozzi,[78a,78c] A. O. M. Iorio,[78a,78b] L. Lista,[78a,78b,zz] P. Paolucci,[78a,dd] B. Rossi,[78a] R. Ardino,[79a] P. Azzi,[79a] N. Bacchetta,[79a,aaa] D. Bisello,[79a,79b] P. Bortignon,[79a] G. Bortolato,[79a,79b] A. Bragagnolo,[79a,79b] A. C. M. Bulla,[79a] R. Carlin,[79a,79b] P. Checchia,[79a] T. Dorigo,[79a,bbb] F. Gasparini,[79a,79b] S. Giorgetti,[79a] A. Gozzelino,[79a] E. Lusiani,[79a] M. Margoni,[79a,79b] A. T. Meneguzzo,[79a,79b] M. Migliorini,[79a,79b] J. Pazzini,[79a,79b] P. Ronchese,[79a,79b] R. Rossin,[79a,79b] F. Simonetto,[79a,79b] M. Tosi,[79a,79b] A. Triossi,[79a,79b] S. Ventura,[79a] M. Zanetti,[79a,79b] P. Zotto,[79a,79b] A. Zucchetta,[79a,79b] G. Zumerle,[79a,79b] A. Braghieri,[80a] S. Calzaferri,[80a] D. Fiorina,[80a] P. Montagna,[80a,80b] V. Re,[80a] C. Riccardi,[80a,80b] P. Salvini,[80a] I. Vai,[80a,80b]

P. Vitulo,[80a,80b] S. Ajmal,[81a,81b] M. E. Ascioti,[81a,81b] G. M. Bilei,[81a] C. Carrivale,[81a,81b] D. Ciangottini,[81a,81b] L. Fanò,[81a,81b] M. Magherini,[81a,81b] V. Mariani,[81a,81b] M. Menichelli,[81a] F. Moscatelli,[81a,ccc] A. Rossi,[81a,81b] A. Santocchia,[81a,81b] D. Spiga,[81a] T. Tedeschi,[81a,81b] C. Aimè,[82a] C. A. Alexe,[82a,82c] P. Asenov,[82a,82b] P. Azzurri,[82a] G. Bagliesi,[82a] R. Bhattacharya,[82a] L. Bianchini,[82a,82b] T. Boccali,[82a] E. Bossini,[82a] D. Bruschini,[82a,82c] R. Castaldi,[82a] M. A. Ciocci,[82a,82b] M. Cipriani,[82a,82b] V. D'Amante,[82a,82d] R. Dell'Orso,[82a] S. Donato,[82a] A. Giassi,[82a] F. Ligabue,[82a,82c] A. C. Marini,[82a] D. Matos Figueiredo,[82a] A. Messineo,[82a,82b] S. Mishra,[82a] M. Musich,[82a,82b] F. Palla,[82a] A. Rizzi,[82a,82b] G. Rolandi,[82a,82c] S. Roy Chowdhury,[82a] T. Sarkar,[82a] A. Scribano,[82a] P. Spagnolo,[82a] R. Tenchini,[82a] G. Tonelli,[82a,82b] N. Turini,[82a,82d] F. Vaselli,[82a,82c] A. Venturi,[82a] P. G. Verdini,[82a] C. Baldenegro Barrera,[83a,83b] P. Barria,[83a] C. Basile,[83a,83b] F. Cavallari,[83a] L. Cunqueiro Mendez,[83a,83b] D. Del Re,[83a,83b] E. Di Marco,[83a,83b] M. Diemoz,[83a] F. Errico,[83a,83b] R. Gargiulo,[83a,83b] E. Longo,[83a,83b] L. Martikainen,[83a,83b] J. Mijuskovic,[83a,83b] G. Organtini,[83a,83b] F. Pandolfi,[83a] R. Paramatti,[83a,83b] C. Quaranta,[83a,83b] S. Rahatlou,[83a,83b] C. Rovelli,[83a] F. Santanastasio,[83a,83b] L. Soffi,[83a] V. Vladimirov,[83a,83b] N. Amapane,[84a,84b] R. Arcidiacono,[84a,84c] S. Argiro,[84a,84b] M. Arneodo,[84a,84c] N. Bartosik,[84a] R. Bellan,[84a,84b] A. Bellora,[84a,84b] C. Biino,[84a] C. Borca,[84a,84b] N. Cartiglia,[84a] M. Costa,[84a,84b] R. Covarelli,[84a,84b] N. Demaria,[84a] L. Finco,[84a] M. Grippo,[84a,84b] B. Kiani,[84a,84b] F. Legger,[84a] F. Luongo,[84a,84b] C. Mariotti,[84a] L. Markovic,[84a,84b] S. Maselli,[84a] A. Mecca,[84a,84b] L. Menzio,[84a,84b] P. Meridiani,[84a] E. Migliore,[84a,84b] M. Monteno,[84a] R. Mulargia,[84a] M. M. Obertino,[84a,84b] G. Ortona,[84a] L. Pacher,[84a,84b] N. Pastrone,[84a] M. Pelliccioni,[84a] M. Ruspa,[84a,84c] F. Siviero,[84a,84b] V. Sola,[84a,84b] A. Solano,[84a,84b] A. Staiano,[84a] C. Tarricone,[84a,84b] D. Trocino,[84a] G. Umoret,[84a,84b] R. White,[84a,84b] J. Babbar,[85a,85b] S. Belforte,[85a] V. Candelise,[85a,85b] M. Casarsa,[85a] F. Cossutti,[85a] K. De Leo,[85a] G. Della Ricca,[85a,85b] S. Dogra,[86] J. Hong,[86] B. Kim,[86] J. Kim,[86] D. Lee,[86] H. Lee,[86] S. W. Lee,[86] C. S. Moon,[86] Y. D. Oh,[86] M. S. Ryu,[86] S. Sekmen,[86] B. Tae,[86] Y. C. Yang,[86] M. S. Kim,[87] G. Bak,[88] P. Gwak,[88] H. Kim,[88] D. H. Moon,[88] E. Asilar,[89] J. Choi,[89,ddd] D. Kim,[89] T. J. Kim,[89] J. A. Merlin,[89] Y. Ryou,[89] S. Choi,[90] S. Han,[90] B. Hong,[90] K. Lee,[90] K. S. Lee,[90] S. Lee,[90] J. Yoo,[90] J. Goh,[91] S. Yang,[91] H. S. Kim,[92] Y. Kim,[92] S. Lee,[92] J. Almond,[93] J. H. Bhyun,[93] J. Choi,[93] J. Choi,[93] W. Jun,[93] J. Kim,[93] Y. W. Kim,[93] S. Ko,[93] H. Kwon,[93] H. Lee,[93] J. Lee,[93] J. Lee,[93] B. H. Oh,[93] S. B. Oh,[93] H. Seo,[93] U. K. Yang,[93] I. Yoon,[93] W. Jang,[94] D. Y. Kang,[94] Y. Kang,[94] S. Kim,[94] B. Ko,[94] J. S. H. Lee,[94] Y. Lee,[94] I. C. Park,[94] Y. Roh,[94] I. J. Watson,[94] S. Ha,[95] K. Hwang,[95] H. D. Yoo,[95] M. Choi,[96] M. R. Kim,[96] H. Lee,[96] Y. Lee,[96] I. Yu,[96] T. Beyrouthy,[97] Y. Gharbia,[97] F. Alazemi,[98] K. Dreimanis,[99] A. Gaile,[99] C. Munoz Diaz,[99] D. Osite,[99] G. Pikurs,[99] A. Potrebko,[99] M. Seidel,[99] D. Sidiropoulos Kontos,[99] N. R. Strautnieks,[100] M. Ambrozas,[101] A. Juodagalvis,[101] A. Rinkevicius,[101] G. Tamulaitis,[101] I. Yusuff,[102,eee] Z. Zolkapli,[102] J. F. Benitez,[103] A. Castaneda Hernandez,[103] H. A. Encinas Acosta,[103] L. G. Gallegos Maríñez,[103] M. León Coello,[103] J. A. Murillo Quijada,[103] A. Sehrawat,[103] L. Valencia Palomo,[103] G. Ayala,[104] H. Castilla-Valdez,[104] H. Crotte Ledesma,[104] E. De La Cruz-Burelo,[104] I. Heredia-De La Cruz,[104,fff] R. Lopez-Fernandez,[104] J. Mejia Guisao,[104] C. A. Mondragon Herrera,[104] A. Sánchez Hernández,[104] C. Oropeza Barrera,[105] D. L. Ramirez Guadarrama,[105] M. Ramírez García,[105] I. Bautista,[106] I. Pedraza,[106] H. A. Salazar Ibarguen,[106] C. Uribe Estrada,[106] I. Bubanja,[107] N. Raicevic,[107] P. H. Butler,[108] A. Ahmad,[109] M. I. Asghar,[109] A. Awais,[109] M. I. M. Awan,[109] H. R. Hoorani,[109] W. A. Khan,[109] V. Avati,[110] L. Grzanka,[110] M. Malawski,[110] H. Bialkowska,[111] M. Bluj,[111] M. Górski,[111] M. Kazana,[111] M. Szleper,[111] P. Zalewski,[111] K. Bunkowski,[112] K. Doroba,[112] A. Kalinowski,[112] M. Konecki,[112] J. Krolikowski,[112] A. Muhammad,[112] P. Fokow,[113] K. Pozniak,[113] W. Zabolotny,[113] M. Araujo,[114] D. Bastos,[114] C. Beirão Da Cruz E Silva,[114] A. Boletti,[114] M. Bozzo,[114] T. Camporesi,[114] G. Da Molin,[114] P. Faccioli,[114] M. Gallinaro,[114] J. Hollar,[114] N. Leonardo,[114] G. B. Marozzo,[114] A. Petrilli,[114] M. Pisano,[114] J. Seixas,[114] J. Varela,[114] J. W. Wulff,[114] S. Afanasiev,[115] V. Alexakhin,[115] D. Budkouski,[115] I. Golutvin,[115,a] I. Gorbunov,[115] V. Karjavine,[115] V. Korenkov,[115] A. Lanev,[115] A. Malakhov,[115] V. Matveev,[115,ggg] V. Palichik,[115] V. Perelygin,[115] M. Savina,[115] V. Shalaev,[115] S. Shmatov,[115] S. Shulha,[115] V. Smirnov,[115] O. Teryaev,[115] N. Voytishin,[115] B. S. Yuldashev,[115,hhh] A. Zarubin,[115] I. Zhizhin,[115] G. Gavrilov,[116] V. Golovtcov,[116] Y. Ivanov,[116] V. Kim,[116,iii] P. Levchenko,[116,jjj] V. Murzin,[116] V. Oreshkin,[116] D. Sosnov,[116] V. Sulimov,[116] L. Uvarov,[116] A. Vorobyev,[116,a] Yu. Andreev,[117] A. Dermenev,[117] S. Gninenko,[117] N. Golubev,[117] A. Karneyeu,[117] D. Kirpichnikov,[117] M. Kirsanov,[117] N. Krasnikov,[117] I. Tlisova,[117] A. Toropin,[117] T. Aushev,[118] K. Ivanov,[118] V. Gavrilov,[119] N. Lychkovskaya,[119]

A. Nikitenko,[119,kkk,lll] V. Popov,[119] A. Zhokin,[119] R. Chistov,[120,mmm] M. Danilov,[120,mmm] S. Polikarpov,[120,mmm] V. Andreev,[121] M. Azarkin,[121] M. Kirakosyan,[121] A. Terkulov,[121] E. Boos,[122] V. Bunichev,[122] M. Dubinin,[122,nnn] L. Dudko,[122] A. Gribushin,[122] V. Klyukhin,[122] O. Kodolova,[122,lll] S. Obraztsov,[122] M. Perfilov,[122] S. Petrushanko,[122] V. Savrin,[122] G. Vorotnikov,[122] V. Blinov,[123,ooo] T. Dimova,[123,ooo] A. Kozyrev,[123,ooo] O. Radchenko,[123,ooo] Y. Skovpen,[123,ooo] V. Kachanov,[124] D. Konstantinov,[124] S. Slabospitskii,[124] A. Uzunian,[124] A. Babaev,[125] V. Borshch,[126] D. Druzhkin,[126] P. Adzic,[127] P. Milenovic,[127] D. Devetak,[128] M. Dordevic,[128] J. Milosevic,[128] L. Nadderd,[128] V. Rekovic,[128] J. Alcaraz Maestre,[129] Cristina F. Bedoya,[129] J. A. Brochero Cifuentes,[129] Oliver M. Carretero,[129] M. Cepeda,[129] M. Cerrada,[129] N. Colino,[129] B. De La Cruz,[129] A. Delgado Peris,[129] A. Escalante Del Valle,[129] D. Fernández Del Val,[129] J. P. Fernández Ramos,[129] J. Flix,[129] M. C. Fouz,[129] O. Gonzalez Lopez,[129] S. Goy Lopez,[129] J. M. Hernandez,[129] M. I. Josa,[129] J. Llorente Merino,[129] C. Martin Perez,[129] E. Martin Viscasillas,[129] D. Moran,[129] C. M. Morcillo Perez,[129] Á. Navarro Tobar,[129] C. Perez Dengra,[129] A. Pérez-Calero Yzquierdo,[129] J. Puerta Pelayo,[129] I. Redondo,[129] S. Sánchez Navas,[129] J. Sastre,[129] J. Vazquez Escobar,[129] J. F. de Trocóniz,[130] B. Alvarez Gonzalez,[131] J. Cuevas,[131] J. Fernandez Menendez,[131] S. Folgueras,[131] I. Gonzalez Caballero,[131] P. Leguina,[131] E. Palencia Cortezon,[131] J. Prado Pico,[131] C. Ramón Álvarez,[131] V. Rodríguez Bouza,[131] A. Soto Rodríguez,[131] A. Trapote,[131] C. Vico Villalba,[131] P. Vischia,[131] S. Bhowmik,[132] S. Blanco Fernández,[132] I. J. Cabrillo,[132] A. Calderon,[132] J. Duarte Campderros,[132] M. Fernandez,[132] G. Gomez,[132] C. Lasaosa García,[132] R. Lopez Ruiz,[132] C. Martinez Rivero,[132] P. Martinez Ruiz del Arbol,[132] F. Matorras,[132] P. Matorras Cuevas,[132] E. Navarrete Ramos,[132] J. Piedra Gomez,[132] L. Scodellaro,[132] I. Vila,[132] J. M. Vizan Garcia,[132] B. Kailasapathy,[133,ppp] D. D. C. Wickramarathna,[133] W. G. D. Dharmaratna,[134,qqq] K. Liyanage,[134] N. Perera,[134] D. Abbaneo,[135] C. Amendola,[135] E. Auffray,[135] G. Auzinger,[135] J. Baechler,[135] D. Barney,[135] A. Bermúdez Martínez,[135] M. Bianco,[135] A. A. Bin Anuar,[135] A. Bocci,[135] L. Borgonovi,[135] C. Botta,[135] E. Brondolin,[135] C. Caillol,[135] G. Cerminara,[135] N. Chernyavskaya,[135] D. d'Enterria,[135] A. Dabrowski,[135] A. David,[135] A. De Roeck,[135] M. M. Defranchis,[135] M. Deile,[135] M. Dobson,[135] G. Franzoni,[135] W. Funk,[135] S. Giani,[135] D. Gigi,[135] K. Gill,[135] F. Glege,[135] J. Hegeman,[135] J. K. Heikkilä,[135] B. Huber,[135] V. Innocente,[135] T. James,[135] P. Janot,[135] O. Kaluzinska,[135] O. Karacheban,[135,bb] S. Laurila,[135] P. Lecoq,[135] E. Leutgeb,[135] C. Lourenço,[135] L. Malgeri,[135] M. Mannelli,[135] M. Matthewman,[135] A. Mehta,[135] F. Meijers,[135] S. Mersi,[135] E. Meschi,[135] V. Milosevic,[135] F. Monti,[135] F. Moortgat,[135] M. Mulders,[135] I. Neutelings,[135] S. Orfanelli,[135] F. Pantaleo,[135] G. Petrucciani,[135] A. Pfeiffer,[135] M. Pierini,[135] H. Qu,[135] D. Rabady,[135] B. Ribeiro Lopes,[135] F. Riti,[135] M. Rovere,[135] H. Sakulin,[135] R. Salvatico,[135] S. Sanchez Cruz,[135] S. Scarfi,[135] C. Schwick,[135] M. Selvaggi,[135] A. Sharma,[135] K. Shchelina,[135] P. Silva,[135] P. Sphicas,[135,rrr] A. G. Stahl Leiton,[135] A. Steen,[135] S. Summers,[135] D. Treille,[135] P. Tropea,[135] D. Walter,[135] J. Wanczyk,[135,sss] J. Wang,[135] K. A. Wozniak,[135,ttt] S. Wuchterl,[135] P. Zehetner,[135] P. Zejdl,[135] W. D. Zeuner,[135] T. Bevilacqua,[136,uuu] L. Caminada,[136,uuu] A. Ebrahimi,[136] W. Erdmann,[136] R. Horisberger,[136] Q. Ingram,[136] H. C. Kaestli,[136] D. Kotlinski,[136] C. Lange,[136] M. Missiroli,[136,uuu] L. Noehte,[136,uuu] T. Rohe,[136] A. Samalan,[136] T. K. Aarrestad,[137] M. Backhaus,[137] G. Bonomelli,[137] A. Calandri,[137] C. Cazzaniga,[137] K. Datta,[137] P. De Bryas Dexmiers D'archiac,[137,sss] A. De Cosa,[137] G. Dissertori,[137] M. Dittmar,[137] M. Donegà,[137] F. Eble,[137] M. Galli,[137] K. Gedia,[137] F. Glessgen,[137] C. Grab,[137] N. Härringer,[137] T. G. Harte,[137] D. Hits,[137] W. Lustermann,[137] A.-M. Lyon,[137] R. A. Manzoni,[137] M. Marchegiani,[137] L. Marchese,[137] A. Mascellani,[137,sss] F. Nessi-Tedaldi,[137] F. Pauss,[137] V. Perovic,[137] S. Pigazzini,[137] B. Ristic,[137] R. Seidita,[137] J. Steggemann,[137,sss] A. Tarabini,[137] D. Valsecchi,[137] R. Wallny,[137] C. Amsler,[138,vvv] P. Bärtschi,[138] M. F. Canelli,[138] K. Cormier,[138] M. Huwiler,[138] W. Jin,[138] A. Jofrehei,[138] B. Kilminster,[138] S. Leontsinis,[138] S. P. Liechti,[138] A. Macchiolo,[138] P. Meiring,[138] F. Meng,[138] J. Motta,[138] A. Reimers,[138] P. Robmann,[138] M. Senger,[138] E. Shokr,[138] F. Stäger,[138] R. Tramontano,[138] C. Adloff,[139,www] D. Bhowmik,[139] C. M. Kuo,[139] W. Lin,[139] P. K. Rout,[139] P. C. Tiwari,[139,ll] L. Ceard,[140] K. F. Chen,[140] Z. g. Chen,[140] A. De Iorio,[140] W.-S. Hou,[140] T. h. Hsu,[140] Y. w. Kao,[140] S. Karmakar,[140] G. Kole,[140] Y. y. Li,[140] R.-S. Lu,[140] E. Paganis,[140] X. f. Su,[140] J. Thomas-Wilsker,[140] L. s. Tsai,[140] D. Tsionou,[140] H. y. Wu,[140] E. Yazgan,[140] C. Asawatangtrakuldee,[141] N. Srimanobhas,[141] V. Wachirapusitanand,[141] D. Agyel,[142] F. Boran,[142] F. Dolek,[142] I. Dumanoglu,[142,xxx] E. Eskut,[142] Y. Guler,[142,yyy] E. Gurpinar Guler,[142,yyy] C. Isik,[142] O. Kara,[142] A. Kayis Topaksu,[142] U. Kiminsu,[142] Y. Komurcu,[142] G. Onengut,[142] K. Ozdemir,[142,zzz] A. Polatoz,[142]

B. Tali,[142,aaaa] U. G. Tok,[142] S. Turkcapar,[142] E. Uslan,[142] I. S. Zorbakir,[142] G. Sokmen,[143] M. Yalvac,[143,bbbb] B. Akgun,[144] I. O. Atakisi,[144] E. Gülmez,[144] M. Kaya,[144,cccc] O. Kaya,[144,dddd] S. Tekten,[144,eeee] A. Cakir,[145] K. Cankocak,[145,xxx,ffff] G. G. Dincer,[145,xxx] S. Sen,[145,gggg] O. Aydilek,[146,hhhh] B. Hacisahinoglu,[146] I. Hos,[146,iiii] B. Kaynak,[146] S. Ozkorucuklu,[146] O. Potok,[146] H. Sert,[146] C. Simsek,[146] C. Zorbilmez,[146] S. Cerci,[147] B. Isildak,[147,jjjj] D. Sunar Cerci,[147] T. Yetkin,[147] A. Boyaryntsev,[148] B. Grynyov,[148] L. Levchuk,[149] D. Anthony,[150] J. J. Brooke,[150] A. Bundock,[150] F. Bury,[150] E. Clement,[150] D. Cussans,[150] H. Flacher,[150] M. Glowacki,[150] J. Goldstein,[150] H. F. Heath,[150] M.-L. Holmberg,[150] L. Kreczko,[150] S. Paramesvaran,[150] L. Robertshaw,[150] V. J. Smith,[150] K. Walkingshaw Pass,[150] A. H. Ball,[151] K. W. Bell,[151] A. Belyaev,[151,kkkk] C. Brew,[151] R. M. Brown,[151] D. J. A. Cockerill,[151] C. Cooke,[151] A. Elliot,[151] K. V. Ellis,[151] K. Harder,[151] S. Harper,[151] J. Linacre,[151] K. Manolopoulos,[151] D. M. Newbold,[151] E. Olaiya,[151] D. Petyt,[151] T. Reis,[151] A. R. Sahasransu,[151] G. Salvi,[151] T. Schuh,[151] C. H. Shepherd-Themistocleous,[151] I. R. Tomalin,[151] K. C. Whalen,[151] T. Williams,[151] I. Andreou,[152] R. Bainbridge,[152] P. Bloch,[152] C. E. Brown,[152] O. Buchmuller,[152] C. A. Carrillo Montoya,[152] G. S. Chahal,[152,llll] D. Colling,[152] J. S. Dancu,[152] I. Das,[152] P. Dauncey,[152] G. Davies,[152] M. Della Negra,[152] S. Fayer,[152] G. Fedi,[152] G. Hall,[152] A. Howard,[152] G. Iles,[152] C. R. Knight,[152] P. Krueper,[152] J. Langford,[152] K. H. Law,[152] J. León Holgado,[152] L. Lyons,[152] A.-M. Magnan,[152] B. Maier,[152] S. Mallios,[152] M. Mieskolainen,[152] J. Nash,[152,mmmm] M. Pesaresi,[152] P. B. Pradeep,[152] B. C. Radburn-Smith,[152] A. Richards,[152] A. Rose,[152] K. Savva,[152] C. Seez,[152] R. Shukla,[152] A. Tapper,[152] K. Uchida,[152] G. P. Uttley,[152] T. Virdee,[152,dd] M. Vojinovic,[152] N. Wardle,[152] D. Winterbottom,[152] J. E. Cole,[153] A. Khan,[153] P. Kyberd,[153] I. D. Reid,[153] S. Abdullin,[154] A. Brinkerhoff,[154] E. Collins,[154] M. R. Darwish,[154] J. Dittmann,[154] K. Hatakeyama,[154] J. Hiltbrand,[154] B. McMaster,[154] J. Samudio,[154] S. Sawant,[154] C. Sutantawibul,[154] J. Wilson,[154] R. Bartek,[155] A. Dominguez,[155] A. E. Simsek,[155] S. S. Yu,[155] B. Bam,[156] A. Buchot Perraguin,[156] R. Chudasama,[156] S. I. Cooper,[156] C. Crovella,[156] S. V. Gleyzer,[156] E. Pearson,[156] C. U. Perez,[156] P. Rumerio,[156,nnnn] E. Usai,[156] R. Yi,[156] A. Akpinar,[157] C. Cosby,[157] G. De Castro,[157] Z. Demiragli,[157] C. Erice,[157] C. Fangmeier,[157] C. Fernandez Madrazo,[157] E. Fontanesi,[157] D. Gastler,[157] F. Golf,[157] S. Jeon,[157] J. O'cain,[157] I. Reed,[157] J. Rohlf,[157] K. Salyer,[157] D. Sperka,[157] D. Spitzbart,[157] I. Suarez,[157] A. Tsatsos,[157] A. G. Zecchinelli,[157] G. Barone,[158] G. Benelli,[158] D. Cutts,[158] L. Gouskos,[158] M. Hadley,[158] U. Heintz,[158] J. M. Hogan,[158,oooo] T. Kwon,[158] G. Landsberg,[158] K. T. Lau,[158] D. Li,[158] J. Luo,[158] S. Mondal,[158] T. Russell,[158] S. Sagir,[158,pppp] X. Shen,[158] F. Simpson,[158] M. Stamenkovic,[158] N. Venkatasubramanian,[158] X. Yan,[158] S. Abbott,[159] B. Barton,[159] C. Brainerd,[159] R. Breedon,[159] H. Cai,[159] M. Calderon De La Barca Sanchez,[159] M. Chertok,[159] M. Citron,[159] J. Conway,[159] P. T. Cox,[159] R. Erbacher,[159] F. Jensen,[159] O. Kukral,[159] G. Mocellin,[159] M. Mulhearn,[159] S. Ostrom,[159] W. Wei,[159] S. Yoo,[159] F. Zhang,[159] K. Adamidis,[160] M. Bachtis,[160] D. Campos,[160] R. Cousins,[160] A. Datta,[160] G. Flores Avila,[160] J. Hauser,[160] M. Ignatenko,[160] M. A. Iqbal,[160] T. Lam,[160] Y. f. Lo,[160] E. Manca,[160] A. Nunez Del Prado,[160] D. Saltzberg,[160] V. Valuev,[160] R. Clare,[161] J. W. Gary,[161] G. Hanson,[161] A. Aportela,[162] A. Arora,[162] J. G. Branson,[162] S. Cittolin,[162] S. Cooperstein,[162] D. Diaz,[162] J. Duarte,[162] L. Giannini,[162] Y. Gu,[162] J. Guiang,[162] R. Kansal,[162] V. Krutelyov,[162] R. Lee,[162] J. Letts,[162] M. Masciovecchio,[162] F. Mokhtar,[162] S. Mukherjee,[162] M. Pieri,[162] M. Quinnan,[162] B. V. Sathia Narayanan,[162] V. Sharma,[162] M. Tadel,[162] E. Vourliotis,[162] F. Würthwein,[162] Y. Xiang,[162] A. Yagil,[162] A. Barzdukas,[163] L. Brennan,[163] C. Campagnari,[163] K. Downham,[163] C. Grieco,[163] J. Incandela,[163] J. Kim,[163] A. J. Li,[163] P. Masterson,[163] H. Mei,[163] J. Richman,[163] S. N. Santpur,[163] U. Sarica,[163] R. Schmitz,[163] F. Setti,[163] J. Sheplock,[163] D. Stuart,[163] T. Á. Vámi,[163] S. Wang,[163] D. Zhang,[163] S. Bhattacharya,[164] A. Bornheim,[164] O. Cerri,[164] A. Latorre,[164] J. Mao,[164] H. B. Newman,[164] G. Reales Gutiérrez,[164] M. Spiropulu,[164] J. R. Vlimant,[164] C. Wang,[164] S. Xie,[164] R. Y. Zhu,[164] J. Alison,[165] S. An,[165] P. Bryant,[165] M. Cremonesi,[165] V. Dutta,[165] T. Ferguson,[165] T. A. Gómez Espinosa,[165] A. Harilal,[165] A. Kallil Tharayil,[165] C. Liu,[165] T. Mudholkar,[165] S. Murthy,[165] P. Palit,[165] K. Park,[165] M. Paulini,[165] A. Roberts,[165] A. Sanchez,[165] W. Terrill,[165] J. P. Cumalat,[166] W. T. Ford,[166] A. Hart,[166] A. Hassani,[166] G. Karathanasis,[166] N. Manganelli,[166] J. Pearkes,[166] C. Savard,[166] N. Schonbeck,[166] K. Stenson,[166] K. A. Ulmer,[166] S. R. Wagner,[166] N. Zipper,[166] D. Zuolo,[166] J. Alexander,[167] S. Bright-Thonney,[167] X. Chen,[167] D. J. Cranshaw,[167] J. Fan,[167] X. Fan,[167] S. Hogan,[167] P. Kotamnives,[167] J. Monroy,[167] M. Oshiro,[167] J. R. Patterson,[167] M. Reid,[167] A. Ryd,[167] J. Thom,[167] P. Wittich,[167] R. Zou,[167] M. Albrow,[168] M. Alyari,[168] O. Amram,[168] G. Apollinari,[168] A. Apresyan,[168]

L. A. T. Bauerdick,[168] D. Berry,[168] J. Berryhill,[168] P. C. Bhat,[168] K. Burkett,[168] J. N. Butler,[168] A. Canepa,[168] G. B. Cerati,[168] H. W. K. Cheung,[168] F. Chlebana,[168] G. Cummings,[168] J. Dickinson,[168] I. Dutta,[168] V. D. Elvira,[168] Y. Feng,[168] J. Freeman,[168] A. Gandrakota,[168] Z. Gecse,[168] L. Gray,[168] D. Green,[168] A. Grummer,[168] S. Grünendahl,[168] D. Guerrero,[168] O. Gutsche,[168] R. M. Harris,[168] R. Heller,[168] T. C. Herwig,[168] J. Hirschauer,[168] B. Jayatilaka,[168] S. Jindariani,[168] M. Johnson,[168] U. Joshi,[168] T. Klijnsma,[168] B. Klima,[168] K. H. M. Kwok,[168] S. Lammel,[168] C. Lee,[168] D. Lincoln,[168] R. Lipton,[168] T. Liu,[168] C. Madrid,[168] K. Maeshima,[168] C. Mantilla,[168] D. Mason,[168] P. McBride,[168] P. Merkel,[168] S. Mrenna,[168] S. Nahn,[168] J. Ngadiuba,[168] D. Noonan,[168] S. Norberg,[168] V. Papadimitriou,[168] N. Pastika,[168] K. Pedro,[168] C. Pena,[168,nnn] F. Ravera,[168] A. Reinsvold Hall,[168,qqqq] L. Ristori,[168] M. Safdari,[168] E. Sexton-Kennedy,[168] N. Smith,[168] A. Soha,[168] L. Spiegel,[168] S. Stoynev,[168] J. Strait,[168] L. Taylor,[168] S. Tkaczyk,[168] N. V. Tran,[168] L. Uplegger,[168] E. W. Vaandering,[168] I. Zoi,[168] C. Aruta,[169] P. Avery,[169] D. Bourilkov,[169] P. Chang,[169] V. Cherepanov,[169] R. D. Field,[169] C. Huh,[169] E. Koenig,[169] M. Kolosova,[169] J. Konigsberg,[169] A. Korytov,[169] K. Matchev,[169] N. Menendez,[169] G. Mitselmakher,[169] K. Mohrman,[169] A. Muthirakalayil Madhu,[169] N. Rawal,[169] S. Rosenzweig,[169] Y. Takahashi,[169] J. Wang,[169] T. Adams,[170] A. Al Kadhim,[170] A. Askew,[170] S. Bower,[170] R. Hashmi,[170] R. S. Kim,[170] S. Kim,[170] T. Kolberg,[170] G. Martinez,[170] H. Prosper,[170] P. R. Prova,[170] M. Wulansatiti,[170] R. Yohay,[170] J. Zhang,[170] B. Alsufyani,[171] M. M. Baarmand,[171] S. Butalla,[171] S. Das,[171] T. Elkafrawy,[171,rrrr] M. Hohlmann,[171] E. Yanes,[171] M. R. Adams,[172] A. Baty,[172] C. Bennett,[172] R. Cavanaugh,[172] R. Escobar Franco,[172] O. Evdokimov,[172] C. E. Gerber,[172] M. Hawksworth,[172] A. Hingrajiya,[172] D. J. Hofman,[172] J. h. Lee,[172] D. S. Lemos,[172] A. H. Merrit,[172] C. Mills,[172] S. Nanda,[172] G. Oh,[172] B. Ozek,[172] D. Pilipovic,[172] R. Pradhan,[172] E. Prifti,[172] T. Roy,[172] S. Rudrabhatla,[172] N. Singh,[172] M. B. Tonjes,[172] N. Varelas,[172] M. A. Wadud,[172] Z. Ye,[172] J. Yoo,[172] M. Alhusseini,[173] D. Blend,[173] K. Dilsiz,[173,ssss] L. Emediato,[173] G. Karaman,[173] O. K. Köseyan,[173] J.-P. Merlo,[173] A. Mestvirishvili,[173,tttt] O. Neogi,[173] H. Ogul,[173,uuuu] Y. Onel,[173] A. Penzo,[173] C. Snyder,[173] E. Tiras,[173,vvvv] B. Blumenfeld,[174] L. Corcodilos,[174] J. Davis,[174] A. V. Gritsan,[174] L. Kang,[174] S. Kyriacou,[174] P. Maksimovic,[174] M. Roguljic,[174] J. Roskes,[174] S. Sekhar,[174] M. Swartz,[174] A. Abreu,[175] L. F. Alcerro Alcerro,[175] J. Anguiano,[175] S. Arteaga Escatel,[175] P. Baringer,[175] A. Bean,[175] Z. Flowers,[175] D. Grove,[175] J. King,[175] G. Krintiras,[175] M. Lazarovits,[175] C. Le Mahieu,[175] J. Marquez,[175] M. Murray,[175] M. Nickel,[175] M. Pitt,[175] S. Popescu,[175,wwww] C. Rogan,[175] C. Royon,[175] S. Sanders,[175] C. Smith,[175] G. Wilson,[175] B. Allmond,[176] R. Gujju Gurunadha,[176] A. Ivanov,[176] K. Kaadze,[176] Y. Maravin,[176] J. Natoli,[176] D. Roy,[176] G. Sorrentino,[176] A. Baden,[177] A. Belloni,[177] J. Bistany-riebman,[177] Y. M. Chen,[177] S. C. Eno,[177] N. J. Hadley,[177] S. Jabeen,[177] R. G. Kellogg,[177] T. Koeth,[177] B. Kronheim,[177] Y. Lai,[177] S. Lascio,[177] A. C. Mignerey,[177] S. Nabili,[177] C. Palmer,[177] C. Papageorgakis,[177] M. M. Paranjpe,[177] E. Popova,[177,xxxx] A. Shevelev,[177] L. Wang,[177] J. Bendavid,[178] I. A. Cali,[178] P. c. Chou,[178] M. D'Alfonso,[178] J. Eysermans,[178] C. Freer,[178] G. Gomez-Ceballos,[178] M. Goncharov,[178] G. Grosso,[178] P. Harris,[178] D. Hoang,[178] D. Kovalskyi,[178] J. Krupa,[178] L. Lavezzo,[178] Y.-J. Lee,[178] K. Long,[178] C. Mcginn,[178] A. Novak,[178] M. I. Park,[178] C. Paus,[178] C. Reissel,[178] C. Roland,[178] G. Roland,[178] S. Rothman,[178] G. S. F. Stephans,[178] Z. Wang,[178] B. Wyslouch,[178] T. J. Yang,[178] B. Crossman,[179] B. M. Joshi,[179] C. Kapsiak,[179] M. Krohn,[179] D. Mahon,[179] J. Mans,[179] B. Marzocchi,[179] M. Revering,[179] R. Rusack,[179] R. Saradhy,[179] N. Strobbe,[179] K. Bloom,[180] D. R. Claes,[180] G. Haza,[180] J. Hossain,[180] C. Joo,[180] I. Kravchenko,[180] J. E. Siado,[180] W. Tabb,[180] A. Vagnerini,[180] A. Wightman,[180] F. Yan,[180] D. Yu,[180] H. Bandyopadhyay,[181] L. Hay,[181] H. w. Hsia,[181] I. Iashvili,[181] A. Kalogeropoulos,[181] A. Kharchilava,[181] M. Morris,[181] D. Nguyen,[181] S. Rappoccio,[181] H. Rejeb Sfar,[181] A. Williams,[181] P. Young,[181] G. Alverson,[182] E. Barberis,[182] J. Bonilla,[182] B. Bylsma,[182] M. Campana,[182] J. Dervan,[182] Y. Haddad,[182] Y. Han,[182] I. Israr,[182] A. Krishna,[182] J. Li,[182] M. Lu,[182] G. Madigan,[182] R. Mccarthy,[182] D. M. Morse,[182] V. Nguyen,[182] T. Orimoto,[182] A. Parker,[182] L. Skinnari,[182] D. Wood,[182] J. Bueghly,[183] S. Dittmer,[183] K. A. Hahn,[183] Y. Liu,[183] M. Mcginnis,[183] Y. Miao,[183] D. G. Monk,[183] M. H. Schmitt,[183] A. Taliercio,[183] M. Velasco,[183] G. Agarwal,[184] R. Band,[184] R. Bucci,[184] S. Castells,[184] A. Das,[184] R. Goldouzian,[184] M. Hildreth,[184] K. W. Ho,[184] K. Hurtado Anampa,[184] T. Ivanov,[184] C. Jessop,[184] K. Lannon,[184] J. Lawrence,[184] N. Loukas,[184] L. Lutton,[184] J. Mariano,[184] N. Marinelli,[184] I. Mcalister,[184] T. McCauley,[184] C. Mcgrady,[184] C. Moore,[184] Y. Musienko,[184,ggg] H. Nelson,[184] M. Osherson,[184] A. Piccinelli,[184] R. Ruchti,[184] A. Townsend,[184] Y. Wan,[184] M. Wayne,[184] H. Yockey,[184] M. Zarucki,[184]

L. Zygala,[184] A. Basnet,[185] M. Carrigan,[185] L. S. Durkin,[185] C. Hill,[185] M. Joyce,[185] M. Nunez Ornelas,[185] K. Wei,[185] D. A. Wenzl,[185] B. L. Winer,[185] B. R. Yates,[185] H. Bouchamaoui,[186] K. Coldham,[186] P. Das,[186] G. Dezoort,[186] P. Elmer,[186] A. Frankenthal,[186] B. Greenberg,[186] N. Haubrich,[186] K. Kennedy,[186] G. Kopp,[186] S. Kwan,[186] D. Lange,[186] A. Loeliger,[186] D. Marlow,[186] I. Ojalvo,[186] J. Olsen,[186] D. Stickland,[186] C. Tully,[186] L. H. Vage,[186] S. Malik,[187] R. Sharma,[187] A. S. Bakshi,[188] S. Chandra,[188] R. Chawla,[188] A. Gu,[188] L. Gutay,[188] M. Jones,[188] A. W. Jung,[188] A. M. Koshy,[188] M. Liu,[188] G. Negro,[188] N. Neumeister,[188] G. Paspalaki,[188] S. Piperov,[188] V. Scheurer,[188] J. F. Schulte,[188] M. Stojanovic,[188] J. Thieman,[188] A. K. Virdi,[188] F. Wang,[188] A. Wildridge,[188] W. Xie,[188] Y. Yao,[188] J. Dolen,[189] N. Parashar,[189] A. Pathak,[189] D. Acosta,[190] T. Carnahan,[190] K. M. Ecklund,[190] P. J. Fernández Manteca,[190] S. Freed,[190] P. Gardner,[190] F. J. M. Geurts,[190] I. Krommydas,[190] W. Li,[190] J. Lin,[190] O. Miguel Colin,[190] B. P. Padley,[190] R. Redjimi,[190] J. Rotter,[190] E. Yigitbasi,[190] Y. Zhang,[190] A. Bodek,[191] P. de Barbaro,[191] R. Demina,[191] J. L. Dulemba,[191] A. Garcia-Bellido,[191] O. Hindrichs,[191] A. Khukhunaishvili,[191] N. Parmar,[191] P. Parygin,[191,xxxx] R. Taus,[191] B. Chiarito,[192] J. P. Chou,[192] S. V. Clark,[192] D. Gadkari,[192] Y. Gershtein,[192] E. Halkiadakis,[192] M. Heindl,[192] C. Houghton,[192] D. Jaroslawski,[192] S. Konstantinou,[192] I. Laflotte,[192] A. Lath,[192] R. Montalvo,[192] K. Nash,[192] J. Reichert,[192] H. Routray,[192] P. Saha,[192] S. Salur,[192] S. Schnetzer,[192] S. Somalwar,[192] R. Stone,[192] S. A. Thayil,[192] S. Thomas,[192] J. Vora,[192] H. Wang,[192] D. Ally,[193] A. G. Delannoy,[193] S. Fiorendi,[193] S. Higginbotham,[193] T. Holmes,[193] A. R. Kanuganti,[193] N. Karunarathna,[193] L. Lee,[193] E. Nibigira,[193] S. Spanier,[193] D. Aebi,[194] M. Ahmad,[194] T. Akhter,[194] K. Androsov,[194,sss] O. Bouhali,[194,yyyy] R. Eusebi,[194] J. Gilmore,[194] T. Huang,[194] T. Kamon,[194,zzzz] H. Kim,[194] S. Luo,[194] R. Mueller,[194] D. Overton,[194] D. Rathjens,[194] A. Safonov,[194] N. Akchurin,[195] J. Damgov,[195] N. Gogate,[195] V. Hegde,[195] A. Hussain,[195] Y. Kazhykarim,[195] K. Lamichhane,[195] S. W. Lee,[195] A. Mankel,[195] T. Peltola,[195] I. Volobouev,[195] E. Appelt,[196] Y. Chen,[196] S. Greene,[196] A. Gurrola,[196] W. Johns,[196] R. Kunnawalkam Elayavalli,[196] A. Melo,[196] F. Romeo,[196] P. Sheldon,[196] S. Tuo,[196] J. Velkovska,[196] J. Viinikainen,[196] B. Cardwell,[197] H. Chung,[197] B. Cox,[197] J. Hakala,[197] R. Hirosky,[197] A. Ledovskoy,[197] C. Neu,[197] S. Bhattacharya,[198] P. E. Karchin,[198] A. Aravind,[199] S. Banerjee,[199] K. Black,[199] T. Bose,[199] E. Chavez,[199] S. Dasu,[199] P. Everaerts,[199] C. Galloni,[199] H. He,[199] M. Herndon,[199] A. Herve,[199] C. K. Koraka,[199] A. Lanaro,[199] R. Loveless,[199] J. Madhusudanan Sreekala,[199] A. Mallampalli,[199] A. Mohammadi,[199] S. Mondal,[199] G. Parida,[199] L. Pétré,[199] D. Pinna,[199] A. Savin,[199] V. Shang,[199] V. Sharma,[199] W. H. Smith,[199] D. Teague,[199] H. F. Tsoi,[199] W. Vetens,[199] and A. Warden[199]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China*
[19]*Sun Yat-Sen University, Guangzhou, China*
[20]*University of Science and Technology of China, Hefei, China*

[21]Nanjing Normal University, Nanjing, China
[22]Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China
[23]Zhejiang University, Hangzhou, Zhejiang, China
[24]Universidad de Los Andes, Bogota, Colombia
[25]Universidad de Antioquia, Medellin, Colombia
[26]University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
[27]University of Split, Faculty of Science, Split, Croatia
[28]Institute Rudjer Boskovic, Zagreb, Croatia
[29]University of Cyprus, Nicosia, Cyprus
[30]Charles University, Prague, Czech Republic
[31]Escuela Politecnica Nacional, Quito, Ecuador
[32]Universidad San Francisco de Quito, Quito, Ecuador
[33]Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
[34]Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
[35]National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
[36]Department of Physics, University of Helsinki, Helsinki, Finland
[37]Helsinki Institute of Physics, Helsinki, Finland
[38]Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
[39]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[40]Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
[41]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[42]Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
[43]Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[44]Georgian Technical University, Tbilisi, Georgia
[45]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[46]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[47]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[48]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[49]University of Hamburg, Hamburg, Germany
[50]Karlsruher Institut fuer Technologie, Karlsruhe, Germany
[51]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
[52]National and Kapodistrian University of Athens, Athens, Greece
[53]National Technical University of Athens, Athens, Greece
[54]University of Ioánnina, Ioánnina, Greece
[55]HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[56]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[57]Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[58]HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary
[59]Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[60]Panjab University, Chandigarh, India
[61]University of Delhi, Delhi, India
[62]Saha Institute of Nuclear Physics, HBNI, Kolkata, India
[63]Indian Institute of Technology Madras, Madras, India
[64]Tata Institute of Fundamental Research-A, Mumbai, India
[65]Tata Institute of Fundamental Research-B, Mumbai, India
[66]National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
[67]Indian Institute of Science Education and Research (IISER), Pune, India
[68]Isfahan University of Technology, Isfahan, Iran
[69]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[70]University College Dublin, Dublin, Ireland
[71a]INFN Sezione di Bari, Bari, Italy
[71b]Università di Bari, Bari, Italy
[71c]Politecnico di Bari, Bari, Italy
[72a]INFN Sezione di Bologna, Bologna, Italy
[72b]Università di Bologna, Bologna, Italy
[73a]INFN Sezione di Catania, Catania, Italy
[73b]Università di Catania, Catania, Italy
[74a]INFN Sezione di Firenze, Firenze, Italy

[74b]Università di Firenze, Firenze, Italy
[75]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[76a]INFN Sezione di Genova, Genova, Italy
[76b]Università di Genova, Genova, Italy
[77a]INFN Sezione di Milano-Bicocca, Milano, Italy
[77b]Università di Milano-Bicocca, Milano, Italy
[78a]INFN Sezione di Napoli, Napoli, Italy
[78b]Università di Napoli 'Federico II', Napoli, Italy
[78c]Università della Basilicata, Potenza, Italy
[78d]Scuola Superiore Meridionale (SSM), Napoli, Italy
[79a]INFN Sezione di Padova, Padova, Italy
[79b]Università di Padova, Padova, Italy
[79c]Università di Trento, Trento, Italy
[80a]INFN Sezione di Pavia, Pavia, Italy
[80b]Università di Pavia, Pavia, Italy
[81a]INFN Sezione di Perugia, Perugia, Italy
[81b]Università di Perugia, Perugia, Italy
[82a]INFN Sezione di Pisa, Pisa, Italy
[82b]Università di Pisa, Pisa, Italy
[82c]Scuola Normale Superiore di Pisa, Pisa, Italy
[82d]Università di Siena, Siena, Italy
[83a]INFN Sezione di Roma, Roma, Italy
[83b]Sapienza Università di Roma, Roma, Italy
[84a]INFN Sezione di Torino, Torino, Italy
[84b]Università di Torino, Torino, Italy
[84c]Università del Piemonte Orientale, Novara, Italy
[85a]INFN Sezione di Trieste, Trieste, Italy
[85b]Università di Trieste, Trieste, Italy
[86]Kyungpook National University, Daegu, Korea
[87]Department of Mathematics and Physics—GWNU, Gangneung, Korea
[88]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[89]Hanyang University, Seoul, Korea
[90]Korea University, Seoul, Korea
[91]Kyung Hee University, Department of Physics, Seoul, Korea
[92]Sejong University, Seoul, Korea
[93]Seoul National University, Seoul, Korea
[94]University of Seoul, Seoul, Korea
[95]Yonsei University, Department of Physics, Seoul, Korea
[96]Sungkyunkwan University, Suwon, Korea
[97]College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
[98]Kuwait University—College of Science—Department of Physics, Safat, Kuwait
[99]Riga Technical University, Riga, Latvia
[100]University of Latvia (LU), Riga, Latvia
[101]Vilnius University, Vilnius, Lithuania
[102]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[103]Universidad de Sonora (UNISON), Hermosillo, Mexico
[104]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[105]Universidad Iberoamericana, Mexico City, Mexico
[106]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[107]University of Montenegro, Podgorica, Montenegro
[108]University of Canterbury, Christchurch, New Zealand
[109]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[110]AGH University of Krakow, Krakow, Poland
[111]National Centre for Nuclear Research, Swierk, Poland
[112]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[113]Warsaw University of Technology, Warsaw, Poland
[114]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[115]Joint Institute for Nuclear Research, Dubna, Russia
[116]Petersburg Nuclear Physics Institute, Gatchina, Russia
[117]Institute for Nuclear Research, Moscow, Russia

[118]Moscow Institute of Physics and Technology, Moscow, Russia
[119]National Research Center 'Kurchatov Institute', Moscow, Russia
[120]National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
[121]P.N. Lebedev Physical Institute, Moscow, Russia
[122]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[123]Novosibirsk State University (NSU), Novosibirsk, Russia
[124]Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
[125]National Research Tomsk Polytechnic University, Tomsk, Russia
[126]Tomsk State University, Tomsk, Russia
[127]Faculty of Physics, University of Belgrade, Belgrade, Serbia
[128]VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[129]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[130]Universidad Autónoma de Madrid, Madrid, Spain
[131]Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
[132]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[133]University of Colombo, Colombo, Sri Lanka
[134]University of Ruhuna, Department of Physics, Matara, Sri Lanka
[135]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[136]PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
[137]ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
[138]Universität Zürich, Zurich, Switzerland
[139]National Central University, Chung-Li, Taiwan
[140]National Taiwan University (NTU), Taipei, Taiwan
[141]High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[142]Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
[143]Middle East Technical University, Physics Department, Ankara, Turkey
[144]Bogazici University, Istanbul, Turkey
[145]Istanbul Technical University, Istanbul, Turkey
[146]Istanbul University, Istanbul, Turkey
[147]Yildiz Technical University, Istanbul, Turkey
[148]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
[149]National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
[150]University of Bristol, Bristol, United Kingdom
[151]Rutherford Appleton Laboratory, Didcot, United Kingdom
[152]Imperial College, London, United Kingdom
[153]Brunel University, Uxbridge, United Kingdom
[154]Baylor University, Waco, Texas, USA
[155]Catholic University of America, Washington, DC, USA
[156]The University of Alabama, Tuscaloosa, Alabama, USA
[157]Boston University, Boston, Massachusetts, USA
[158]Brown University, Providence, Rhode Island, USA
[159]University of California, Davis, Davis, California, USA
[160]University of California, Los Angeles, California, USA
[161]University of California, Riverside, Riverside, California, USA
[162]University of California, San Diego, La Jolla, California, USA
[163]University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
[164]California Institute of Technology, Pasadena, California, USA
[165]Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
[166]University of Colorado Boulder, Boulder, Colorado, USA
[167]Cornell University, Ithaca, New York, USA
[168]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[169]University of Florida, Gainesville, Florida, USA
[170]Florida State University, Tallahassee, Florida, USA
[171]Florida Institute of Technology, Melbourne, Florida, USA
[172]University of Illinois Chicago, Chicago, Illinois, USA
[173]The University of Iowa, Iowa City, Iowa, USA
[174]Johns Hopkins University, Baltimore, Maryland, USA
[175]The University of Kansas, Lawrence, Kansas, USA
[176]Kansas State University, Manhattan, Kansas, USA
[177]University of Maryland, College Park, Maryland, USA

[178]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[179]*University of Minnesota, Minneapolis, Minnesota, USA*
[180]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[181]*State University of New York at Buffalo, Buffalo, New York, USA*
[182]*Northeastern University, Boston, Massachusetts, USA*
[183]*Northwestern University, Evanston, Illinois, USA*
[184]*University of Notre Dame, Notre Dame, Indiana, USA*
[185]*The Ohio State University, Columbus, Ohio, USA*
[186]*Princeton University, Princeton, New Jersey, USA*
[187]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[188]*Purdue University, West Lafayette, Indiana, USA*
[189]*Purdue University Northwest, Hammond, Indiana, USA*
[190]*Rice University, Houston, Texas, USA*
[191]*University of Rochester, Rochester, New York, USA*
[192]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[193]*University of Tennessee, Knoxville, Tennessee, USA*
[194]*Texas A&M University, College Station, Texas, USA*
[195]*Texas Tech University, Lubbock, Texas, USA*
[196]*Vanderbilt University, Nashville, Tennessee, USA*
[197]*University of Virginia, Charlottesville, Virginia, USA*
[198]*Wayne State University, Detroit, Michigan, USA*
[199]*University of Wisconsin—Madison, Madison, Wisconsin, USA*

[a]Deceased.
[b]Also at Yerevan State University, Yerevan, Armenia.
[c]Also at TU Wien, Vienna, Austria.
[d]Also at Ghent University, Ghent, Belgium.
[e]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[h]Also at University of Chinese Academy of Sciences, Beijing, China.
[i]Also at China Center of Advanced Science and Technology, Beijing, China.
[j]Also at University of Chinese Academy of Sciences, Beijing, China.
[k]Also at China Spallation Neutron Source, Guangdong, China.
[l]Also at Henan Normal University, Xinxiang, China.
[m]Also at University of Shanghai for Science and Technology, Shanghai, China.
[n]Also at The University of Iowa, Iowa City, Iowa, USA.
[o]Also at National Research Center ‘Kurchatov Institute’, Moscow, Russia.
[p]Also at Cairo University, Cairo, Egypt.
[q]Also at Suez University, Suez, Egypt.
[r]Also at British University in Egypt, Cairo, Egypt.
[s]Also at Purdue University, West Lafayette, Indiana, USA.
[t]Also at Université de Haute Alsace, Mulhouse, France.
[u]Also at Istinye University, Istanbul, Turkey.
[v]Also at Tbilisi State University, Tbilisi, Georgia.
[w]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[x]Also at The University of the State of Amazonas, Manaus, Brazil.
[y]Also at University of Hamburg, Hamburg, Germany.
[z]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[aa]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[bb]Also at Brandenburg University of Technology, Cottbus, Germany.
[cc]Also at Forschungszentrum Jülich, Juelich, Germany.
[dd]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[ee]Also at HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary.
[ff]Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[gg]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[hh]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[ii]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[jj]Also at Punjab Agricultural University, Ludhiana, India.
[kk]Also at University of Visva-Bharati, Santiniketan, India.

[ll]Also at Indian Institute of Science (IISc), Bangalore, India.
[mm]Also at Amity University Uttar Pradesh, Noida, India.
[nn]Also at IIT Bhubaneswar, Bhubaneswar, India.
[oo]Also at Institute of Physics, Bhubaneswar, India.
[pp]Also at University of Hyderabad, Hyderabad, India.
[qq]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[rr]Also at Isfahan University of Technology, Isfahan, Iran.
[ss]Also at Sharif University of Technology, Tehran, Iran.
[tt]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[uu]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[vv]Also at Helwan University, Cairo, Egypt.
[ww]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[xx]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[yy]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[zz]Also at Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy.
[aaa]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[bbb]Also at Lulea University of Technology, Lulea, Sweden.
[ccc]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[ddd]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[eee]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[fff]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[ggg]Also at Institute for Nuclear Research, Moscow, Russia.
[hhh]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[iii]Also at St. Petersburg Polytechnic University, St. Petersburg, Russia.
[jjj]Also at Northeastern University, Boston, Massachusetts, USA.
[kkk]Also at Imperial College, London, United Kingdom.
[lll]Also at Yerevan Physics Institute, Yerevan, Armenia.
[mmm]Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[nnn]Also at California Institute of Technology, Pasadena, California, USA.
[ooo]Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[ppp]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[qqq]Also at Saegis Campus, Nugegoda, Sri Lanka.
[rrr]Also at National and Kapodistrian University of Athens, Athens, Greece.
[sss]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[ttt]Also at University of Vienna, Vienna, Austria.
[uuu]Also at Universität Zürich, Zurich, Switzerland.
[vvv]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[www]Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[xxx]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[yyy]Also at Konya Technical University, Konya, Turkey.
[zzz]Also at Izmir Bakircay University, Izmir, Turkey.
[aaaa]Also at Adiyaman University, Adiyaman, Turkey.
[bbbb]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[cccc]Also at Marmara University, Istanbul, Turkey.
[dddd]Also at Milli Savunma University, Istanbul, Turkey.
[eeee]Also at Kafkas University, Kars, Turkey.
[ffff]Also at Istanbul Okan University, Istanbul, Turkey.
[gggg]Also at Hacettepe University, Ankara, Turkey.
[hhhh]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[iiii]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[jjjj]Also at Yildiz Technical University, Istanbul, Turkey.
[kkkk]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[llll]Also at IPPP Durham University, Durham, United Kingdom.
[mmmm]Also at Monash University, Faculty of Science, Clayton, Australia.
[nnnn]Also at Università di Torino, Torino, Italy.
[oooo]Also at Bethel University, St. Paul, Minnesota, USA.
[pppp]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[qqqq]Also at United States Naval Academy, Annapolis, Maryland, USA.
[rrrr]Also at Ain Shams University, Cairo, Egypt.
[ssss]Also at Bingol University, Bingol, Turkey.

[tttt]Also at Georgian Technical University, Tbilisi, Georgia.
[uuuu]Also at Sinop University, Sinop, Turkey.
[vvvv]Also at Erciyes University, Kayseri, Turkey.
[wwww]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[xxxx]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[yyyy]Also at Texas A&M University at Qatar, Doha, Qatar.
[zzzz]Also at Kyungpook National University, Daegu, Korea.