Observation of Same-Sign WW Production from Double Parton Scattering in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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The first observation of the production of $W^{\pm}W^{\pm}$ bosons from double parton scattering processes using same-sign electron-muon and dimuon events in proton-proton collisions is reported. The data sample corresponds to an integrated luminosity of 138 fb^{-1} recorded at a center-of-mass energy of 13 TeV using the CMS detector at the CERN LHC. Multivariate discriminants are used to distinguish the signal process from the main backgrounds. A binned maximum likelihood fit is performed to extract the signal cross section. The measured cross section for production of same-sign W bosons decaying leptonically is $80.7 \pm 11.2(\mathrm{stat})\,^{+9.5}_{-8.6}(\mathrm{syst}) \pm 12.1(\mathrm{model})$ fb, whereas the measured fiducial cross section is $6.28 \pm 0.81(\mathrm{stat}) \pm 0.69(\mathrm{syst}) \pm 0.37(\mathrm{model})$ fb. The observed significance of the signal is 6.2 standard deviations above the background-only hypothesis.

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Double parton scattering (DPS) events, in which two hard parton-parton interactions occur in a single proton-proton (pp) collision, have been proposed and studied since the advent of the parton model and hadron colliders [1–9]. The study of such events sheds light on the internal structure of the colliding protons. Primarily, the study of DPS processes provides information on the transverse profile of the proton and its energy evolution, information that is otherwise not accessible in single parton scattering (SPS) events. In addition, processes with two or more hard parton-parton scatterings allow the study of correlations among the partons from the same proton in terms of momentum, flavor, color, and spin.

In the simplest theoretical model [10], the two parton-parton interactions in DPS can be considered entirely uncorrelated, and the expected DPS cross section can be written as the (normalized) product of the SPS cross sections to produce processes A and B independently, as

$$\sigma_{AB}^{\mathrm{DPS}} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}}, \tag{1}$$

where n is a combinatorial factor that takes a value of unity if $A = B$ and two otherwise. The denominator σ_{eff} can be interpreted as being proportional to the average squared transverse distance between the interacting partons, and it serves as a useful quantity to compare DPS processes in different production modes. Its experimental value ranges between 2 and 10 mb for gluon-initiated and 10 and 25 mb for quark-initiated DPS production processes [11–29].

As the center-of-mass energy of pp collisions increases, so does the density of sea quarks and gluons, which, in turn, leads to increased DPS contributions to many final states where pairs of heavy particles are produced. These additional DPS contributions can limit the precision of searches for new physics [30] and the accuracy of high-precision standard model analyses [31]. Therefore, it is important to study DPS processes in different production modes and final states. Theoretical advancements [8] have improved upon the simple "geometric" approach on which Eq. (1) is based. The introduction of interparton correlations via double parton distribution functions (dPDF) [32–35], which include parton splitting effects and impact parameter dependence, has led to the first dPDF-based Monte Carlo (MC) event generator for DPS events, dShower [36].

The production of leptonically decaying same-sign (SS) W boson pairs is a promising process to study DPS [37]. Its experimental signature is rather clean and easy to trigger on, and the SPS $W^{\pm}W^{\pm}$ production is highly suppressed because of two additional partons produced in the final state compared with the opposite-sign configuration. Figure 1 illustrates the production of $W^{\pm}W^{\pm}$ via the DPS and SPS processes at leading order (LO) accuracy in electroweak and perturbative quantum chromodynamics (QCD). The DPS $W^{\pm}W^{\pm}$ production has not been observed experimentally, and the existing searches for the process are not statistically significant due to the size of the available data samples [25,38].

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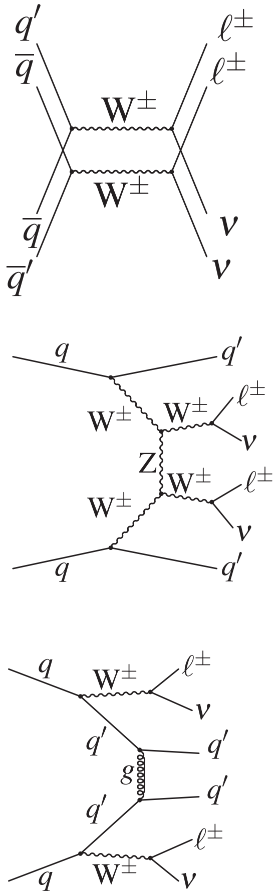

FIG. 1. Example Feynman diagrams for leptonically decaying $W^{\pm}W^{\pm}$ bosons produced via DPS (upper) and SPS (middle and lower) processes.

This Letter presents the first observation of DPS $W^{\pm}W^{\pm}$ production using pp collision data at $\sqrt{s} = 13$ TeV. The data sample corresponds to an integrated luminosity of 138 fb^{-1} collected using the CMS detector during the 2016–2018 operation of the LHC. The W bosons are required to decay into final states consisting of two SS leptons ($e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$), including the contributions from leptonic τ decays. As in Refs. [25,38], the dielectron final state is not considered because of the larger background, but the overall analysis strategy has been reoptimized to enhance the signal sensitivity.

The CMS apparatus [39] is a multipurpose, nearly hermetic detector, designed to trigger on [40,41] and identify electrons, muons, photons, and hadrons [42–45]. A global "particle-flow" (PF) algorithm [46] reconstructs all individual particles in an event, combining information from the silicon tracker and the crystal electromagnetic (ECAL) and the brass-scintillator hadron calorimeters, which all operate within a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Details of the event reconstruction used to define the primary vertex (PV) and build leptons, jets, hadronically decaying τ leptons (τ_h), and missing transverse momentum (p_T^{miss}) are provided in Refs. [47–52]. Events of interest are selected using a two-tiered trigger system. The first level ($L1$), composed of custom hardware processors, selects events at a rate of around 100 kHz [40]. The second level, known as the high-level trigger, further reduces the event rate to around 1 kHz before data storage [41].

Charged leptons are required to originate from the primary vertex (PV) to avoid contributions from additional pp interactions in the same and nearby bunch crossings (pileup). Electrons are identified using a multivariate analysis (MVA) discriminant that combines observables sensitive to the matching of charged-particle tracks in the tracker to the energy deposits in the ECAL and the number of bremsstrahlung photons emitted along their trajectory [42,53]. The identification of muons is based on linking track segments reconstructed in the silicon tracker to hits in the muon detectors [43]. Further selection criteria are applied to ensure the correct assignment of the electric charge of the leptons in the reconstruction [42]. Lepton isolation requirements are imposed following the same approach as in Ref. [54]. The electron (muon) candidates are required to pass minimal kinematic selection criteria of $p_T > 10$ GeV and $|\eta| < 2.5(2.4)$ and are referred to as "loose" leptons. The "tight" lepton selection used in the analysis employs an MVA discriminant to separate prompt leptons coming from the decays of W or Z (V) bosons, or τ leptons and nonprompt leptons [54]. The nonprompt leptons originate from the decays of light- and heavy-flavor hadrons inside jets produced via strong interactions (QCD multijet), hadrons misidentified as leptons, and electrons from photon conversions. The MVA discriminant is trained using a set of observables related to the lepton kinematics, isolation, and identification, as well as variables relating the lepton to the PV and to the nearest reconstructed PF jet [54]. Reconstructed jets must not overlap with identified electrons, muons, or τ_h within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$, where ϕ is the azimuthal angle in radians. The DeepJet b-tagging algorithm [55,56] is used to identify jets originating from the hadronization of b quarks. The chosen working point corresponds to a b-tagging efficiency of 84% and a mistag rate of 11% for light-flavor quark and gluon jets.

Collision events are collected using a combination of single-lepton and dilepton triggers that require the presence of one or two isolated leptons above certain p_T thresholds [41]. The resulting trigger efficiency is above 98% for events passing the subsequent offline selection criteria.

The dominant background contribution arises from the WZ process, in which both bosons decay leptonically and one of the leptons from the Z boson decay either is out of the detector acceptance or does not pass the lepton identification criteria. The nonprompt-lepton backgrounds include predominantly W + jets and QCD multijet events, with smaller contributions from $t\bar{t}$ production. Other sources of background include $W\gamma^*$ events, $V\gamma$ events with a photon conversion, and ZZ, as well as rare backgrounds, which include SPS $W^\pm W^\pm$, VVV, and $t\bar{t}V$ production. A minor background contribution stems from Drell-Yan (DY) events when the charge of one lepton is mismeasured. The charge mismeasurement in dimuon events is negligible [43], although it is nonzero for electrons [42]. Hence, the lepton charge misidentification ("charge misid") background contributes to the $e^\pm\mu^\pm$ channel only. The contribution to the signal yield from the production of two overlapping W bosons from pileup is negligible.

The signal process is characterized by the presence of a SS lepton pair with a moderate amount of p_T^{miss} and little jet activity. The signal region (SR) selection requires events with exactly one pair of $e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$ with $p_T > 25(20)$ GeV for the leading (subleading) lepton. To reduce the contribution from WZ background, events having either a third loosely identified lepton with $p_T > 10$ GeV or a τ_h candidate with $p_T > 20$ GeV and $|\eta| < 2.3$ are rejected. The contributions from nonprompt-lepton backgrounds are reduced by selecting events with $p_T^{\text{miss}} > 15$ GeV and dilepton invariant mass, $m_{\ell\ell} > 12$ GeV.

Events are required to have at most one jet with $p_T^{\text{jet}} > 30$ GeV within $|\eta_{\text{jet}}| < 2.4$. Events with a b-tagged jet having $p_T^{b\,\text{jet}} > 25$ GeV and $|\eta_{b\,\text{jet}}| < 2.4$ are vetoed to reject top quark events. For the $e^\pm\mu^\pm$ channel, the dilepton transverse momentum should satisfy $p_T^{\ell\ell} > 20$ GeV to suppress contributions from $V\gamma$ and DY processes. To increase the signal sensitivity, events in the SR are split into four lepton flavor and charge categories: $e^+\mu^+$, $e^-\mu^-$, $\mu^+\mu^+$, and $\mu^-\mu^-$.

The normalization of the WZ (ZZ) background is estimated using $WZ \to 3\ell\nu$ ($ZZ \to 4\ell$) lepton control regions (CR) by means of a maximum likelihood (ML) fit to the invariant mass of the three- (four-) lepton system. The $WZ \to 3\ell\nu$ CR is defined by requiring three tight leptons including at least one opposite-sign same-flavor (OSSF) lepton pair with $|m_{\ell\ell} - m_Z| < 10$ GeV. The invariant mass of the three-lepton system must be > 100 GeV. The leading lepton is required to have $p_T > 25$ GeV, and trailing leptons with $p_T > 15$ GeV are selected. The p_T^{miss} threshold is raised to 50 GeV for this CR, and the rest of the selection requirements are taken from the SR. The $ZZ \to 4\ell$ CR requires an additional fourth tight lepton with $p_T > 10$ GeV without any requirement on jets and p_T^{miss}. Both the OSSF lepton pairs should have $m_{\ell\ell}$ compatible with the Z boson mass.

Various MC event generators are used to simulate the signal and background processes. The signal process is simulated at LO using the PYTHIA [57], HERWIG [58], and dShower [36] generators. The PYTHIA sample, with leptonically decaying W bosons, is taken as the nominal signal sample, and it predicts a signal cross section value of $\sigma_{\text{DPS}}^{W^\pm W^\pm} = 86.4$ fb with the tune cuetp8m1 [14]. The tune dependence of the PYTHIA8 cross section is around 40%, emphasizing the need for an experimental measurement. The sample from HERWIG is used for estimating systematic uncertainties. The PYTHIA v8.226 (8.230) using the NNPDF 2.3 [59] parton distribution functions (PDFs) with the underlying tune cuetp8m1 (cp5 [60]) is used for the simulation of the 2016 (2017 and 2018) data-taking periods. The event generator HERWIG++ (v2.7) [58,61] using the CTEQ6L1 [62] PDF set with the tune CUETHppS1 [14] is used for the 2016 data-taking period, whereas HERWIG7 (v7.1.4) using the NNPDF 3.1 [63] with PDF set ch3 tune [64] is employed for 2017 and 2018. The dShower generator uses dPDF [33,65] developed using the LO MSTW2008 [65] PDF set. For a given event generator, neither the underlying event tune nor the PDF sets used to simulate the signal samples impact the kinematic observables relevant to the analysis.

The WZ background is simulated at next-to-LO (NLO) in QCD with the MadGraph5_aMC@NLO v2.4.2 (2.6.5) generator [66] using the FxFx jet merging scheme [67] for the 2016 (2017 and 2018) data-taking period. The MadGraph5_aMC@NLO generator is also used to simulate $V\gamma$, $t\bar{t}V$, and triboson (VVV) production. The POWHEG BOX (v2.0) code [68–70] is used to simulate SPS $W^\pm W^\pm$, ZZ, and $W\gamma^*$ production processes. The simulated samples of backgrounds for the 2016 data-taking period use the NNPDF 3.0 [71,72] PDF set, whereas the NNPDF 3.1 set is used for 2017 and 2018. Background simulations and the dShower event generator are interfaced with PYTHIA8 for modeling of the parton showering, hadronization, and underlying event processes, which have similar versions and tunes as the signal process. The CMS detector response is modeled using GEANT4 [73], and the simulated events are reconstructed with the same algorithms used for the data. Simulated events are weighted to reproduce the pileup distribution measured in the data. The average number of pileup interactions was 23 (32) in 2016 (2017 and 2018). Scale factors are applied to simulated samples to correct for differences in the reconstruction and selection of physics objects and in the trigger efficiencies between simulation and data. These scale factors are measured with the "tag-and-probe" method using DY events [74].

The nonprompt-lepton background is estimated directly from data using the lepton misidentification rate method [54]. The probability for a loose nonprompt lepton to pass the tight lepton selection criteria (f_p) is estimated using a data control sample dominated by nonprompt leptons and is parametrized as a function of p_T and $|\eta|$. Events in a sideband of the SR, with at least one lepton failing the tight lepton selection criteria, are reweighted with f_p to estimate the nonprompt-lepton background contribution. A similar approach is used to estimate the background contribution from "charge misidentification" events by applying the lepton charge misidentification rate to opposite-sign events in data. The charge misidentification rate is about 0.01% (0.10%) for electrons in the barrel (end cap) regions.

Because of the topological differences between the dominant WZ and nonprompt-lepton backgrounds, two separate boosted decision tree (BDT) discriminants [75] are trained to distinguish the signal from these background components. Addition of the BDT discriminant trained against the nonprompt-lepton backgrounds improves the signal sensitivity by 13%. The BDT training against the WZ sample is done using its simulated sample, whereas the training against nonprompt leptons is carried out using a "tight-loose" control sample in data. Kinematic differences between the signal and these backgrounds are explored to define a set of input variables for the training of two discriminants, which are optimized based on their discriminating power. These input variables include transverse momenta of the two leptons; p_T^{miss}; product and absolute sum of the η of the two leptons; separation in ϕ between the leptons; separation in ϕ between the subleading lepton and p_T^{miss}; separation in ϕ between the dilepton system and the subleading lepton; transverse mass of the two leptons; transverse mass of the leading lepton and p_T^{miss}; and the "stransverse mass" of the dilepton and p_T^{miss} system [76,77]. The two BDT scores are mapped into a two-dimensional (2D) plane in both discriminants. Further, the 2D plane is divided into 13 contiguous regions on which the final fit is performed. This division into regions is performed through optimization of the expected signal significance.

The integrated luminosities for the 2016–2018 data-taking years have individual uncertainties of 1.2%–2.5% [78–80], while the overall uncertainty for the 2016–2018 period is 1.6%. The simulation of pileup events assumes an inelastic pp cross section of 69.2 mb, with an associated uncertainty of 5% [81], which impacts the expected signal and background yields by 1%. The uncertainties in data to simulation scale factors corresponding to the lepton trigger, reconstruction, and identification result in an uncertainty of 3.3% (2.8%) for the $e^\pm\mu^\pm$ ($\mu^\pm\mu^\pm$) final states. This also includes an uncertainty in the scale factors applied to account for the $L1$ trigger inefficiency observed in the $|\eta| > 2.0$ region for the 2016 and 2017 data-taking periods [40]. The jet energy scale uncertainties affect the expected event yields by 3%. Uncertainties in the p_T^{miss} are calculated by varying the momenta of unclustered particles that are identified neither as a jet nor as a lepton and affect the expected event yields by ≈2%. The uncertainty in the b-tagging efficiency has an effect of ≈1.8% on the expected event yields.

For the $e^\pm\mu^\pm$ ($\mu^\pm\mu^\pm$) channels, a normalization uncertainty of 30% (25%) in the nonprompt-lepton background accounts for the observed variations in the background estimation method when applied to simulated samples. The dependence of f_p on the kinematics of the event sample in which it is measured is included as a shape uncertainty [54]. A normalization uncertainty of 20% is applied to the "charge misid" background, covering the differences in the measurement of the charge misidentification rate in data and simulation. The data-to-MC normalization factors of the $V\gamma$ background, measured using a dedicated CR [82], are close to unity.

A 50% normalization uncertainty is applied to all other small simulated backgrounds, accounting for the theoretical uncertainties in the predicted cross sections. The theoretical uncertainties associated with the choice of the renormalization and factorization scales and the variations in the PDFs and the strong coupling constant [83,84] affect the simulated background yields by ≈1%. The effect of variation in PDF sets is negligible for the signal simulations. Any residual model dependence of the signal process is estimated by allowing the shape of the final BDT discriminant to vary between the PYTHIA and HERWIG simulations, and the resulting effect is small. The statistical uncertainties due to the limited size of the MC samples are treated according to the Barlow-Beeston-lite method [85,86].

The yield of the DPS $W^\pm W^\pm$ process in the SR is obtained by performing a binned ML fit simultaneously in the SR and in the two CRs [87–89]; i.e., the normalization factors for the WZ and ZZ backgrounds are included as free parameters in the fit together with the signal process. The fit is performed after combining all the background and signal processes in the aforementioned lepton flavor and charge categories, resulting in four independent distributions of the final BDT discriminant per data-taking year. An excess of events with respect to the background-only hypothesis is observed, which is quantified by calculating the p value using a profile likelihood ratio test statistic [87]. Figure 2 shows the BDT discriminant distribution after the ML fit (postfit) for the four lepton flavor and sign categories. The contributions from different backgrounds and the signal processes are stacked on top of each other, and the associated postfit uncertainties are also shown. The distributions of the kinematic variables used to train the BDT discriminants along with the two BDT discriminants are shown in Supplemental Material [90].

The measured value of $\sigma_{\text{DPS}}^{W^\pm W^\pm}$ is $80.7 \pm 11.2(\text{stat}) {}^{+9.5}_{-8.6}(\text{syst}) \pm 12.1(\text{model})$ fb, where the model uncertainty accounts for the difference in cross sections obtained in the experimental acceptance region with the PYTHIA and HERWIG simulations. The observed statistical significance of the signal is 6.2 standard deviations above the background-only hypothesis. Separate fits to the $e^\pm\mu^\pm$ and $\mu^\pm\mu^\pm$ channels indicate that the two measurements agree within 1.7 standard deviations. The DPS $W^\pm W^\pm$ production cross section is also measured in a fiducial volume, defined using two generator-level SS "dressed" leptons ($e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$) from W boson decays excluding the events with leptonically decaying τ leptons. The leptons are dressed by adding the momenta of generator-level

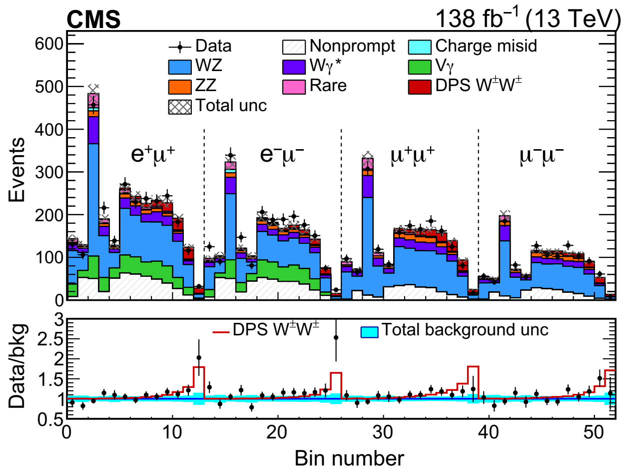

FIG. 2. Postfit distribution of the final BDT discriminant output for the four lepton flavor and sign categories. The SPS $W^{\pm}W^{\pm}$, $t\bar{t}V$, and VVV contributions are grouped as the "rare" background. The total postfit uncertainty in the signal and background predictions is shown as the hatched band. The bottom panels show the ratio of data to the sum of all background contributions as the black data points along with the extracted signal shown by the red line. The vertical error bars on the data points represent the statistical uncertainty of the data.

photons within a cone of $\Delta R(\ell,\gamma) < 0.1$ to their momenta and are required to pass kinematic requirements on the p_T, η, $m_{\ell\ell}$, and $p_T^{\ell\ell}$ variables from the SR selection. The measured fiducial cross section is $6.28 \pm 0.81(\text{stat}) \pm 0.69(\text{syst}) \pm 0.37(\text{model})$ fb, where the model uncertainty represents the observed difference in reconstruction efficiencies within the fiducial region obtained using the PYTHIA and HERWIG simulations. The measured value of the inclusive (fiducial) cross section is in agreement with the predicted value of 86.4 (6.74) fb by PYTHIA8 with the tune cuetp8m1 and dShower. A value of σ_{eff} is extracted from Eq. (1), using the measured $\sigma_{\text{DPS}}^{W^{\pm}W^{\pm}}$ value and the next-to-NLO prediction for the single W^{+} (W^{-}) production cross section including leptonic decays of $35.4 \pm 1.4(26.0 \pm 1.0)$ nb [91,92]. This procedure results in a value of $12.2^{+2.9}_{-2.2}$ mb, consistent with previous measurements of this quantity from final states with vector bosons [19,26]. Tabulated results are provided in HEPData [93].

In summary, the first observation of $W^{\pm}W^{\pm}$ production from double parton scattering processes in proton-proton collisions at $\sqrt{s} = 13$ TeV has been reported. The analyzed dataset corresponds to an integrated luminosity of 138 fb^{-1} collected in 2016–2018 using the CMS detector at the LHC. Events are selected by requiring same-sign electron-muon or dimuon pairs with moderate missing transverse momentum and low jet multiplicity. Boosted decision trees are used to discriminate between the signal and the dominant background processes. A fiducial cross section of $6.28 \pm 0.81(\text{stat}) \pm 0.69(\text{syst}) \pm 0.37(\text{model})$ fb is extracted, and an inclusive cross section of $80.7 \pm 11.2(\text{stat}) {}^{+9.5}_{-8.6}(\text{syst}) \pm 12.1(\text{model})$ fb is measured. This corresponds to an observed significance of the signal above the background-only hypothesis of 6.2 standard deviations. A value of the DPS effective cross section, characterizing the transverse distribution of partons in the proton, $\sigma_{\text{eff}} = 12.2^{+2.9}_{-2.2}$ mb is extracted.

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Estevez Banos,[43] O. Filatov,[43] E. Gallo,[43,v] A. Geiser,[43] A. Giraldi,[43] G. Greau,[43] A. Grohsjean,[43] V. Guglielmi,[43] M. Guthoff,[43] A. Jafari,[43,x] N. Z. Jomhari,[43] B. Kaech,[43] A. Kasem,[43,w] M. Kasemann,[43] H. Kaveh,[43] C. Kleinwort,[43] R. Kogler,[43] M. Komm,[43] D. Krücker,[43] W. Lange,[43] D. Leyva Pernia,[43] K. Lipka,[43] W. Lohmann,[43,y] R. Mankel,[43] I.-A. Melzer-Pellmann,[43] M. Mendizabal Morentin,[43] J. Metwally,[43] A. B. Meyer,[43] G. Milella,[43] M. Mormile,[43] A. Mussgiller,[43] A. Nürnberg,[43] Y. Otarid,[43] D. Pérez Adán,[43] A. Raspereza,[43] B. Ribeiro Lopes,[43] J. Rübenach,[43] A. Saggio,[43] A. Saibel,[43] M. Savitskyi,[43] M. Scham,[43,w,z] V. Scheurer,[43] S. Schnake,[43,w] P. Schütze,[43] C. Schwanenberger,[43,v] M. Shchedrolosiev,[43] R. E. Sosa Ricardo,[43] D. Stafford,[43] N. Tonon,[43,a] M. Van De Klundert,[43] F. Vazzoler,[43] A. Ventura Barroso,[43] R. Walsh,[43] D. Walter,[43] Q. Wang,[43] Y. Wen,[43] K. Wichmann,[43] L. Wiens,[43,w] C. Wissing,[43] S. Wuchterl,[43] Y. Yang,[43] A. Zimermmane Castro Santos,[43] R. Aggleton,[44] A. Albrecht,[44] S. Albrecht,[44] M. Antonello,[44] S. Bein,[44] L. Benato,[44] M. Bonanomi,[44] P. Connor,[44] K. De Leo,[44] M. Eich,[44] K. El Morabit,[44] F. Feindt,[44] A. Fröhlich,[44] C. Garbers,[44] E. Garutti,[44] M. Hajheidari,[44] J. Haller,[44] A. Hinzmann,[44] H. R. Jabusch,[44] G. Kasieczka,[44] R. Klanner,[44] W. Korcari,[44] T. Kramer,[44] V. Kutzner,[44] J. Lange,[44] A. Lobanov,[44] C. Matthies,[44] A. Mehta,[44] L. Moureaux,[44] M. Mrowietz,[44] A. Nigamova,[44] Y. Nissan,[44] A. Paasch,[44] K. J. Pena Rodriguez,[44] M. Rieger,[44] O. Rieger,[44] P. Schleper,[44] M. Schröder,[44] J. Schwandt,[44] H. Stadie,[44] G. Steinbrück,[44] A. Tews,[44] M. Wolf,[44] J. Bechtel,[45] S. Brommer,[45] M. Burkart,[45] E. Butz,[45] R. Caspart,[45] T. Chwalek,[45] A. Dierlamm,[45] A. Droll,[45] N. Faltermann,[45]

M. Giffels,[45] J. O. Gosewisch,[45] A. Gottmann,[45] F. Hartmann,[45,u] M. Horzela,[45] U. Husemann,[45] P. Keicher,[45] M. Klute,[45] R. Koppenhöfer,[45] S. Maier,[45] S. Mitra,[45] Th. Müller,[45] M. Neukum,[45] G. Quast,[45] K. Rabbertz,[45] J. Rauser,[45] D. Savoiu,[45] M. Schnepf,[45] D. Seith,[45] I. Shvetsov,[45] H. J. Simonis,[45] N. Trevisani,[45] R. Ulrich,[45] J. van der Linden,[45] R. F. Von Cube,[45] M. Wassmer,[45] M. Weber,[45] S. Wieland,[45] R. Wolf,[45] S. Wozniewski,[45] S. Wunsch,[45] G. Anagnostou,[46] P. Assiouras,[46] G. Daskalakis,[46] A. Kyriakis,[46] A. Stakia,[46] M. Diamantopoulou,[47] D. Karasavvas,[47] P. Kontaxakis,[47] A. Manousakis-Katsikakis,[47] A. Panagiotou,[47] I. Papavergou,[47] N. Saoulidou,[47] K. Theofilatos,[47] E. Tziaferi,[47] K. Vellidis,[47] E. Vourliotis,[47] I. Zisopoulos,[47] G. Bakas,[48] T. Chatzistavrou,[48] K. Kousouris,[48] I. Papakrivopoulos,[48] G. Tsipolitis,[48] A. Zacharopoulou,[48] K. Adamidis,[49] I. Bestintzanos,[49] I. Evangelou,[49] C. Foudas,[49] P. Gianneios,[49] C. Kamtsikis,[49] P. Katsoulis,[49] P. Kokkas,[49] P. G. Kosmoglou Kioseoglou,[49] N. Manthos,[49] I. Papadopoulos,[49] J. Strologas,[49] M. Csanád,[50] K. Farkas,[50] M. M. A. Gadallah,[50,aa] C. Komjáti,[50] S. Lökös,[50,bb] P. Major,[50] K. Mandal,[50] G. Pásztor,[50] A. J. Rádl,[50,cc] O. Surányi,[50] G. I. Veres,[50] M. Bartók,[51,dd] G. Bencze,[51] C. Hajdu,[51] D. Horvath,[51,ee,ff] F. Sikler,[51] V. Veszpremi,[51] N. Beni,[52] S. Czellar,[52] J. Karancsi,[52,dd] J. Molnar,[52] Z. Szillasi,[52] D. Teyssier,[52] P. Raics,[53] B. Ujvari,[53,gg] T. Csorgo,[54,cc] F. Nemes,[54,cc] T. Novak,[54] J. Babbar,[55] S. Bansal,[55] S. B. Beri,[55] V. Bhatnagar,[55] G. Chaudhary,[55] S. Chauhan,[55] N. Dhingra,[55,hh] R. Gupta,[55] A. Kaur,[55] A. Kaur,[55] H. Kaur,[55] M. Kaur,[55] S. Kumar,[55] P. Kumari,[55] M. Meena,[55] K. Sandeep,[55] T. Sheokand,[55] J. B. Singh,[55,ii] A. Singla,[55] A. K. Virdi,[55] A. Ahmed,[56] A. Bhardwaj,[56] B. C. Choudhary,[56] M. Gola,[56] S. Keshri,[56] A. Kumar,[56] M. Naimuddin,[56] P. Priyanka,[56] K. Ranjan,[56] S. Saumya,[56] A. Shah,[56] S. Baradia,[57] S. Barman,[57,jj] S. Bhattacharya,[57] D. Bhowmik,[57] S. Dutta,[57] S. Dutta,[57] B. Gomber,[57,kk] M. Maity,[57,jj] P. Palit,[57] P. K. Rout,[57] G. Saha,[57] B. Sahu,[57] S. Sarkar,[57] P. K. Behera,[58] S. C. Behera,[58] P. Kalbhor,[58] J. R. Komaragiri,[58,ll] D. Kumar,[58,ll] A. Muhammad,[58] L. Panwar,[58,ll] R. Pradhan,[58] P. R. Pujahari,[58] A. Sharma,[58] A. K. Sikdar,[58] P. C. Tiwari,[58,ll] S. Verma,[58] K. Naskar,[59,mm] T. Aziz,[60] I. Das,[60] S. Dugad,[60] M. Kumar,[60] G. B. Mohanty,[60] P. Suryadevara,[60] S. Banerjee,[61] R. Chudasama,[61] M. Guchait,[61] S. Karmakar,[61] S. Kumar,[61] G. Majumder,[61] K. Mazumdar,[61] S. Mukherjee,[61] A. Thachayath,[61] S. Bahinipati,[62,nn] A. K. Das,[62] C. Kar,[62] P. Mal,[62] T. Mishra,[62] V. K. Muraleedharan Nair Bindhu,[62,oo] A. Nayak,[62,oo] P. Saha,[62] N. Sur,[62] S. K. Swain,[62] D. Vats,[62,oo] A. Alpana,[63] S. Dube,[63] B. Kansal,[63] A. Laha,[63] S. Pandey,[63] A. Rastogi,[63] S. Sharma,[63] H. Bakhshiansohi,[64,pp] E. Khazaie,[64] M. Zeinali,[64,qq] S. Chenarani,[65,rr] S. M. Etesami,[65] M. Khakzad,[65] M. Mohammadi Najafabadi,[65] M. Grunewald,[66] M. Abbrescia,[67a,67b] R. Aly,[67a,67c,ss] C. Aruta,[67a,67b] A. Colaleo,[67a] D. Creanza,[67a,67c] N. De Filippis,[67a,67c] M. De Palma,[67a,67b] A. Di Florio,[67a,67b] W. Elmetenawee,[67a,67b] F. Errico,[67a,67b] L. Fiore,[67a] G. Iaselli,[67a,67c] M. Ince,[67a,67b] G. Maggi,[67a,67c] M. Maggi,[67a] I. Margjeka,[67a,67b] V. Mastrapasqua,[67a,67b] S. My,[67a,67b] S. Nuzzo,[67a,67b] A. Pellecchia,[67a,67b] A. Pompili,[67a,67b] G. Pugliese,[67a,67c] R. Radogna,[67a] D. Ramos,[67a] A. Ranieri,[67a] G. Selvaggi,[67a,67b] L. Silvestris,[67a] F. M. Simone,[67a,67b] Ü. Sözbilir,[67a] A. Stamerra,[67a] R. Venditti,[67a] P. Verwilligen,[67a] G. Abbiendi,[68a] C. Battilana,[68a,68b] D. Bonacorsi,[68a,68b] L. Borgonovi,[68a] L. Brigliadori,[68a] R. Campanini,[68a,68b] P. Capiluppi,[68a,68b] A. Castro,[68a,68b] F. R. Cavallo,[68a] M. Cuffiani,[68a,68b] G. M. Dallavalle,[68a] T. Diotalevi,[68a,68b] F. Fabbri,[68a] A. Fanfani,[68a,68b] P. Giacomelli,[68a] L. Giommi,[68a,68b] C. Grandi,[68a] L. Guiducci,[68a,68b] S. Lo Meo,[68a,tt] L. Lunerti,[68a,68b] S. Marcellini,[68a] G. Masetti,[68a] F. L. Navarria,[68a,68b] A. Perrotta,[68a] F. Primavera,[68a,68b] A. M. Rossi,[68a,68b] T. Rovelli,[68a,68b] G. P. Siroli,[68a,68b] S. Costa,[69a,69b,uu] A. Di Mattia,[69a] R. Potenza,[69a,69b] A. Tricomi,[69a,69b,uu] C. Tuve,[69a,69b] G. Barbagli,[70a] B. Camaiani,[70a,70b] A. Cassese,[70a] R. Ceccarelli,[70a,70b] V. Ciulli,[70a,70b] C. Civinini,[70a] R. D'Alessandro,[70a,70b] E. Focardi,[70a,70b] G. Latino,[70a,70b] P. Lenzi,[70a,70b] M. Lizzo,[70a,70b] M. Meschini,[70a] S. Paoletti,[70a] R. Seidita,[70a,70b] G. Sguazzoni,[70a] L. Viliani,[70a] L. Benussi,[71] S. Bianco,[71] S. Meola,[71,u] D. Piccolo,[71] M. Bozzo,[72a,72b] F. Ferro,[72a] R. Mulargia,[72a] E. Robutti,[72a] S. Tosi,[72a,72b] A. Benaglia,[73a] G. Boldrini,[73a] F. Brivio,[73a,73b] F. Cetorelli,[73a,73b] F. De Guio,[73a,73b] M. E. Dinardo,[73a,73b] P. Dini,[73a] S. Gennai,[73a] A. Ghezzi,[73a,73b] P. Govoni,[73a,73b] L. Guzzi,[73a,73b] M. T. Lucchini,[73a,73b] M. Malberti,[73a] S. Malvezzi,[73a] A. Massironi,[73a] D. Menasce,[73a] L. Moroni,[73a] M. Paganoni,[73a,73b] D. Pedrini,[73a] B. S. Pinolini,[73a] S. Ragazzi,[73a,73b] N. Redaelli,[73a] T. Tabarelli de Fatis,[73a,73b] D. Zuolo,[73a,73b] S. Buontempo,[74a] F. Carnevali,[74a,74b] N. Cavallo,[74a,74c] A. De Iorio,[74a,74b] F. Fabozzi,[74a,74c] A. O. M. Iorio,[74a,74b] L. Lista,[74a,74b,vv] P. Paolucci,[74a,u] B. Rossi,[74a] C. Sciacca,[74a,74b] P. Azzi,[75a] N. Bacchetta,[75a,ww] P. Bortignon,[75a] A. Bragagnolo,[75a,75b] R. Carlin,[75a,75b] P. Checchia,[75a] U. Gasparini,[75a,75b]

G. Grosso,[75a] L. Layer,[75a,xx] E. Lusiani,[75a] M. Margoni,[75a,75b] A. T. Meneguzzo,[75a,75b] M. Passaseo,[75a] J. Pazzini,[75a,75b] P. Ronchese,[75a,75b] R. Rossin,[75a,75b] M. Sgaravatto,[75a] F. Simonetto,[75a,75b] G. Strong,[75a] M. Tosi,[75a,75b] S. Ventura,[75a] H. Yarar,[75a,75b] M. Zanetti,[75a,75b] P. Zotto,[75a,75b] A. Zucchetta,[75a,75b] G. Zumerle,[75a,75b] S. Abu Zeid,[76a,yy] C. Aimè,[76a,76b] A. Braghieri,[76a] S. Calzaferri,[76a,76b] D. Fiorina,[76a,76b] P. Montagna,[76a,76b] V. Re,[76a] C. Riccardi,[76a,76b] P. Salvini,[76a] I. Vai,[76a] P. Vitulo,[76a,76b] P. Asenov,[77a,zz] G. M. Bilei,[77a] D. Ciangottini,[77a,77b] L. Fanò,[77a,77b] M. Magherini,[77a,77b] G. Mantovani,[77a,77b] V. Mariani,[77a,77b] M. Menichelli,[77a] F. Moscatelli,[77a,zz] A. Piccinelli,[77a,77b] M. Presilla,[77a,77b] A. Rossi,[77a,77b] A. Santocchia,[77a,77b] D. Spiga,[77a] T. Tedeschi,[77a,77b] P. Azzurri,[78a] G. Bagliesi,[78a] V. Bertacchi,[78a,78c] R. Bhattacharya,[78a] L. Bianchini,[78a,78b] T. Boccali,[78a] E. Bossini,[78a,78b] D. Bruschini,[78a,78c] R. Castaldi,[78a] M. A. Ciocci,[78a,78b] V. D'Amante,[78a,78d] R. Dell'Orso,[78a] M. R. Di Domenico,[78a,78d] S. Donato,[78a] A. Giassi,[78a] F. Ligabue,[78a,78c] E. Manca,[78a,78c] G. Mandorli,[78a,78c] D. Matos Figueiredo,[78a] A. Messineo,[78a,78b] M. Musich,[78a,78b] F. Palla,[78a] S. Parolia,[78a,78b] G. Ramirez-Sanchez,[78a,78c] A. Rizzi,[78a,78b] G. Rolandi,[78a,78c] S. Roy Chowdhury,[78a,78c] T. Sarkar,[78a,jj] A. Scribano,[78a] N. Shafiei,[78a,78b] P. Spagnolo,[78a] R. Tenchini,[78a] G. Tonelli,[78a,78b] N. Turini,[78a,78d] A. Venturi,[78a] P. G. Verdini,[78a] P. Barria,[79a] M. Campana,[79a,79b] F. Cavallari,[79a] D. Del Re,[79a,79b] E. Di Marco,[79a] M. Diemoz,[79a] E. Longo,[79a,79b] P. Meridiani,[79a] G. Organtini,[79a,79b] F. Pandolfi,[79a] R. Paramatti,[79a,79b] C. Quaranta,[79a,79b] S. Rahatlou,[79a,79b] C. Rovelli,[79a] F. Santanastasio,[79a,79b] L. Soffi,[79a] R. Tramontano,[79a,79b] N. Amapane,[80a,80b] R. Arcidiacono,[80a,80c] S. Argiro,[80a,80b] M. Arneodo,[80a,80c] N. Bartosik,[80a] R. Bellan,[80a,80b] A. Bellora,[80a,80b] J. Berenguer Antequera,[80a,80b] C. Biino,[80a] N. Cartiglia,[80a] M. Costa,[80a,80b] R. Covarelli,[80a,80b] N. Demaria,[80a] M. Grippo,[80a,80b] B. Kiani,[80a,80b] F. Legger,[80a] C. Mariotti,[80a] S. Maselli,[80a] A. Mecca,[80a,80b] E. Migliore,[80a,80b] E. Monteil,[80a,80b] M. Monteno,[80a] M. M. Obertino,[80a,80b] G. Ortona,[80a] L. Pacher,[80a,80b] N. Pastrone,[80a] M. Pelliccioni,[80a] M. Ruspa,[80a,80c] K. Shchelina,[80a] F. Siviero,[80a,80b] V. Sola,[80a] A. Solano,[80a,80b] D. Soldi,[80a,80b] A. Staiano,[80a] M. Tornago,[80a,80b] D. Trocino,[80a] G. Umoret,[80a,80b] A. Vagnerini,[80a,80b] S. Belforte,[81a] V. Candelise,[81a,81b] M. Casarsa,[81a] F. Cossutti,[81a] A. Da Rold,[81a,81b] G. Della Ricca,[81a,81b] G. Sorrentino,[81a,81b] S. Dogra,[82] C. Huh,[82] B. Kim,[82] D. H. Kim,[82] G. N. Kim,[82] J. Kim,[82] J. Lee,[82] S. W. Lee,[82] C. S. Moon,[82] Y. D. Oh,[82] S. I. Pak,[82] M. S. Ryu,[82] S. Sekmen,[82] Y. C. Yang,[82] H. Kim,[83] D. H. Moon,[83] E. Asilar,[84] T. J. Kim,[84] J. Park,[84] S. Cho,[85] S. Choi,[85] S. Han,[85] B. Hong,[85] K. Lee,[85] K. S. Lee,[85] J. Lim,[85] J. Park,[85] S. K. Park,[85] J. Yoo,[85] J. Goh,[86] H. S. Kim,[87] Y. Kim,[87] S. Lee,[87] J. Almond,[88] J. H. Bhyun,[88] J. Choi,[88] S. Jeon,[88] W. Jun,[88] J. Kim,[88] J. Kim,[88] J. S. Kim,[88] S. Ko,[88] H. Kwon,[88] H. Lee,[88] J. Lee,[88] S. Lee,[88] B. H. Oh,[88] M. Oh,[88] S. B. Oh,[88] H. Seo,[88] U. K. Yang,[88] I. Yoon,[88] W. Jang,[89] D. Y. Kang,[89] Y. Kang,[89] D. Kim,[89] S. Kim,[89] B. Ko,[89] J. S. H. Lee,[89] Y. Lee,[89] J. A. Merlin,[89] I. C. Park,[89] Y. Roh,[89] D. Song,[89] I. J. Watson,[89] S. Yang,[89] S. Ha,[90] H. D. Yoo,[90] M. Choi,[91] M. R. Kim,[91] H. Lee,[91] Y. Lee,[91] Y. Lee,[91] I. Yu,[91] T. Beyrouthy,[92] Y. Maghrbi,[92] K. Dreimanis,[93] A. Gaile,[93] A. Potrebko,[93] T. Torims,[93] V. Veckalns,[93] M. Ambrozas,[94] A. Carvalho Antunes De Oliveira,[94] A. Juodagalvis,[94] A. Rinkevicius,[94] G. Tamulaitis,[94] N. Bin Norjoharuddeen,[95] S. Y. Hoh,[95,aaa] I. Yusuff,[95,aaa] Z. Zolkapli,[95] J. F. Benitez,[96] A. Castaneda Hernandez,[96] H. A. Encinas Acosta,[96] L. G. Gallegos Maríñez,[96] M. León Coello,[96] J. A. Murillo Quijada,[96] A. Sehrawat,[96] L. Valencia Palomo,[96] G. Ayala,[97] H. Castilla-Valdez,[97] I. Heredia-De La Cruz,[97,bbb] R. Lopez-Fernandez,[97] C. A. Mondragon Herrera,[97] D. A. Perez Navarro,[97] A. Sánchez Hernández,[97] C. Oropeza Barrera,[98] F. Vazquez Valencia,[98] I. Pedraza,[99] H. A. Salazar Ibarguen,[99] C. Uribe Estrada,[99] I. Bubanja,[100] J. Mijuskovic,[100,ccc] N. Raicevic,[100] A. Ahmad,[101] M. I. Asghar,[101] A. Awais,[101] M. I. M. Awan,[101] M. Gul,[101] H. R. Hoorani,[101] W. A. Khan,[101] M. Shoaib,[101] M. Waqas,[101] V. Avati,[102] L. Grzanka,[102] M. Malawski,[102] H. Bialkowska,[103] M. Bluj,[103] B. Boimska,[103] M. Górski,[103] M. Kazana,[103] M. Szleper,[103] P. Zalewski,[103] K. Bunkowski,[104] K. Doroba,[104] A. Kalinowski,[104] M. Konecki,[104] J. Krolikowski,[104] M. Araujo,[105] P. Bargassa,[105] D. Bastos,[105] A. Boletti,[105] P. Faccioli,[105] M. Gallinaro,[105] J. Hollar,[105] N. Leonardo,[105] T. Niknejad,[105] M. Pisano,[105] J. Seixas,[105] O. Toldaiev,[105] J. Varela,[105] P. Adzic,[106,ddd] M. Dordevic,[106] P. Milenovic,[106] J. Milosevic,[106] M. Aguilar-Benitez,[107] J. Alcaraz Maestre,[107] A. Álvarez Fernández,[107] M. Barrio Luna,[107] Cristina F. Bedoya,[107] C. A. Carrillo Montoya,[107] M. Cepeda,[107] M. Cerrada,[107] N. Colino,[107] B. De La Cruz,[107] A. Delgado Peris,[107] D. Fernández Del Val,[107] J. P. Fernández Ramos,[107] J. Flix,[107] M. C. Fouz,[107] O. Gonzalez Lopez,[107] S. Goy Lopez,[107] J. M. Hernandez,[107] M. I. Josa,[107] J. León Holgado,[107] D. Moran,[107] C. Perez Dengra,[107] A. Pérez-Calero Yzquierdo,[107] J. Puerta Pelayo,[107] I. Redondo,[107] D. D. Redondo Ferrero,[107] L. Romero,[107]

S. Sánchez Navas,[107] J. Sastre,[107] L. Urda Gómez,[107] J. Vazquez Escobar,[107] C. Willmott,[107] J. F. de Trocóniz,[108] B. Alvarez Gonzalez,[109] J. Cuevas,[109] J. Fernandez Menendez,[109] S. Folgueras,[109] I. Gonzalez Caballero,[109] J. R. González Fernández,[109] E. Palencia Cortezon,[109] C. Ramón Álvarez,[109] V. Rodríguez Bouza,[109] A. Soto Rodríguez,[109] A. Trapote,[109] C. Vico Villalba,[109] J. A. Brochero Cifuentes,[110] I. J. Cabrillo,[110] A. Calderon,[110] J. Duarte Campderros,[110] M. Fernandez,[110] C. Fernandez Madrazo,[110] A. García Alonso,[110] G. Gomez,[110] C. Lasaosa García,[110] C. Martinez Rivero,[110] P. Martinez Ruiz del Arbol,[110] F. Matorras,[110] P. Matorras Cuevas,[110] J. Piedra Gomez,[110] C. Prieels,[110] A. Ruiz-Jimeno,[110] L. Scodellaro,[110] I. Vila,[110] J. M. Vizan Garcia,[110] M. K. Jayananda,[111] B. Kailasapathy,[111,eee] D. U. J. Sonnadara,[111] D. D. C. Wickramarathna,[111] W. G. D. Dharmaratna,[112] K. Liyanage,[112] N. Perera,[112] N. Wickramage,[112] D. Abbaneo,[113] J. Alimena,[113] E. Auffray,[113] G. Auzinger,[113] J. Baechler,[113] P. Baillon,[113,a] D. Barney,[113] J. Bendavid,[113] M. Bianco,[113] B. Bilin,[113] A. Bocci,[113] E. Brondolin,[113] C. Caillol,[113] T. Camporesi,[113] G. Cerminara,[113] N. Chernyavskaya,[113] S. S. Chhibra,[113] S. Choudhury,[113] M. Cipriani,[113] L. Cristella,[113] D. d'Enterria,[113] A. Dabrowski,[113] A. David,[113] A. De Roeck,[113] M. M. Defranchis,[113] M. Deile,[113] M. Dobson,[113] M. Dünser,[113] N. Dupont,[113] A. Elliott-Peisert,[113] F. Fallavollita,[113,fff] A. Florent,[113] L. Forthomme,[113] G. Franzoni,[113] W. Funk,[113] S. Ghosh,[113] S. Giani,[113] D. Gigi,[113] K. Gill,[113] F. Glege,[113] L. Gouskos,[113] E. Govorkova,[113] M. Haranko,[113] J. Hegeman,[113] V. Innocente,[113] T. James,[113] P. Janot,[113] J. Kaspar,[113] J. Kieseler,[113] N. Kratochwil,[113] S. Laurila,[113] P. Lecoq,[113] E. Leutgeb,[113] A. Lintuluoto,[113] C. Lourenço,[113] B. Maier,[113] L. Malgeri,[113] M. Mannelli,[113] A. C. Marini,[113] F. Meijers,[113] S. Mersi,[113] E. Meschi,[113] F. Moortgat,[113] M. Mulders,[113] S. Orfanelli,[113] L. Orsini,[113] F. Pantaleo,[113] E. Perez,[113] M. Peruzzi,[113] A. Petrilli,[113] G. Petrucciani,[113] A. Pfeiffer,[113] M. Pierini,[113] D. Piparo,[113] M. Pitt,[113] H. Qu,[113] T. Quast,[113] D. Rabady,[113] A. Racz,[113] G. Reales Gutiérrez,[113] M. Rovere,[113] H. Sakulin,[113] J. Salfeld-Nebgen,[113] S. Scarfi,[113] M. Selvaggi,[113] A. Sharma,[113] P. Silva,[113] P. Sphicas,[113,ggg] A. G. Stahl Leiton,[113] S. Summers,[113] K. Tatar,[113] V. R. Tavolaro,[113] D. Treille,[113] P. Tropea,[113] A. Tsirou,[113] J. Wanczyk,[113,hhh] K. A. Wozniak,[113] W. D. Zeuner,[113] L. Caminada,[114,iii] A. Ebrahimi,[114] W. Erdmann,[114] R. Horisberger,[114] Q. Ingram,[114] H. C. Kaestli,[114] D. Kotlinski,[114] C. Lange,[114] M. Missiroli,[114,iii] L. Noehte,[114,iii] T. Rohe,[114] T. K. Aarrestad,[115] K. Androsov,[115,hhh] M. Backhaus,[115] P. Berger,[115] A. Calandri,[115] K. Datta,[115] A. De Cosa,[115] G. Dissertori,[115] M. Dittmar,[115] M. Donegà,[115] F. Eble,[115] M. Galli,[115] K. Gedia,[115] F. Glessgen,[115] T. A. Gómez Espinosa,[115] C. Grab,[115] D. Hits,[115] W. Lustermann,[115] A.-M. Lyon,[115] R. A. Manzoni,[115] L. Marchese,[115] C. Martin Perez,[115] A. Mascellani,[115,hhh] M. T. Meinhard,[115] F. Nessi-Tedaldi,[115] J. Niedziela,[115] F. Pauss,[115] V. Perovic,[115] S. Pigazzini,[115] M. G. Ratti,[115] M. Reichmann,[115] C. Reissel,[115] T. Reitenspiess,[115] B. Ristic,[115] F. Riti,[115] D. Ruini,[115] D. A. Sanz Becerra,[115] J. Steggemann,[115,hhh] D. Valsecchi,[115,u] R. Wallny,[115] C. Amsler,[116,jjj] P. Bärtschi,[116] C. Botta,[116] D. Brzhechko,[116] M. F. Canelli,[116] K. Cormier,[116] A. De Wit,[116] R. Del Burgo,[116] J. K. Heikkilä,[116] M. Huwiler,[116] W. Jin,[116] A. Jofrehei,[116] B. Kilminster,[116] S. Leontsinis,[116] S. P. Liechti,[116] A. Macchiolo,[116] P. Meiring,[116] V. M. Mikuni,[116] U. Molinatti,[116] I. Neutelings,[116] A. Reimers,[116] P. Robmann,[116] S. Sanchez Cruz,[116] K. Schweiger,[116] M. Senger,[116] Y. Takahashi,[116] C. Adloff,[117,kkk] C. M. Kuo,[117] W. Lin,[117] S. S. Yu,[117] L. Ceard,[118] Y. Chao,[118] K. F. Chen,[118] P. s. Chen,[118] H. Cheng,[118] W.-S. Hou,[118] Y. y. Li,[118] R.-S. Lu,[118] E. Paganis,[118] A. Psallidas,[118] A. Steen,[118] H. y. Wu,[118] E. Yazgan,[118] P. r. Yu,[118] C. Asawatangtrakuldee,[119] N. Srimanobhas,[119] D. Agyel,[120] F. Boran,[120] Z. S. Demiroglu,[120] F. Dolek,[120] I. Dumanoglu,[120,lll] E. Eskut,[120] Y. Guler,[120,mmm] E. Gurpinar Guler,[120,mmm] C. Isik,[120] O. Kara,[120] A. Kayis Topaksu,[120] U. Kiminsu,[120] G. Onengut,[120] K. Ozdemir,[120,nnn] A. Polatoz,[120] A. E. Simsek,[120] B. Tali,[120,ooo] U. G. Tok,[120] S. Turkcapar,[120] E. Uslan,[120] I. S. Zorbakir,[120] G. Karapinar,[121,ppp] K. Ocalan,[121,qqq] M. Yalvac,[121,rrr] B. Akgun,[122] I. O. Atakisi,[122] E. Gülmez,[122] M. Kaya,[122,sss] O. Kaya,[122,ttt] Ö. Özçelik,[122] S. Tekten,[122,uuu] A. Cakir,[123] K. Cankocak,[123,lll] Y. Komurcu,[123] S. Sen,[123,vvv] O. Aydilek,[124] S. Cerci,[124,ooo] B. Hacisahinoglu,[124] I. Hos,[124,www] B. Isildak,[124,xxx] B. Kaynak,[124] S. Ozkorucuklu,[124] C. Simsek,[124] D. Sunar Cerci,[124,ooo] B. Grynyov,[125] L. Levchuk,[126] D. Anthony,[127] E. Bhal,[127] J. J. Brooke,[127] A. Bundock,[127] E. Clement,[127] D. Cussans,[127] H. Flacher,[127] M. Glowacki,[127] J. Goldstein,[127] G. P. Heath,[127] H. F. Heath,[127] L. Kreczko,[127] B. Krikler,[127] S. Paramesvaran,[127] S. Seif El Nasr-Storey,[127] V. J. Smith,[127] N. Stylianou,[127,yyy] K. Walkingshaw Pass,[127] R. White,[127] A. H. Ball,[128] K. W. Bell,[128] A. Belyaev,[128,zzz] C. Brew,[128] R. M. Brown,[128] D. J. A. Cockerill,[128] C. Cooke,[128] K. V. Ellis,[128] K. Harder,[128] S. Harper,[128] M.-L. Holmberg,[128,aaaa] J. Linacre,[128] K. Manolopoulos,[128] D. M. Newbold,[128]

E. Olaiya,[128] D. Petyt,[128] T. Reis,[128] G. Salvi,[128] T. Schuh,[128] C. H. Shepherd-Themistocleous,[128] I. R. Tomalin,[128] T. Williams,[128] R. Bainbridge,[129] P. Bloch,[129] S. Bonomally,[129] J. Borg,[129] S. Breeze,[129] C. E. Brown,[129] O. Buchmuller,[129] V. Cacchio,[129] V. Cepaitis,[129] G. S. Chahal,[129,bbbb] D. Colling,[129] J. S. Dancu,[129] P. Dauncey,[129] G. Davies,[129] J. Davies,[129] M. Della Negra,[129] S. Fayer,[129] G. Fedi,[129] G. Hall,[129] M. H. Hassanshahi,[129] A. Howard,[129] G. Iles,[129] J. Langford,[129] L. Lyons,[129] A.-M. Magnan,[129] S. Malik,[129] A. Martelli,[129] M. Mieskolainen,[129] D. G. Monk,[129] J. Nash,[129,cccc] M. Pesaresi,[129] B. C. Radburn-Smith,[129] D. M. Raymond,[129] A. Richards,[129] A. Rose,[129] E. Scott,[129] C. Seez,[129] A. Shtipliyski,[129] R. Shukla,[129] A. Tapper,[129] K. Uchida,[129] G. P. Uttley,[129] L. H. Vage,[129] T. Virdee,[129,u] M. Vojinovic,[129] N. Wardle,[129] S. N. Webb,[129] D. Winterbottom,[129] K. Coldham,[130] J. E. Cole,[130] A. Khan,[130] P. Kyberd,[130] I. D. Reid,[130] S. Abdullin,[131] A. Brinkerhoff,[131] B. Caraway,[131] J. Dittmann,[131] K. Hatakeyama,[131] A. R. Kanuganti,[131] B. McMaster,[131] M. Saunders,[131] S. Sawant,[131] C. Sutantawibul,[131] J. Wilson,[131] R. Bartek,[132] A. Dominguez,[132] R. Uniyal,[132] A. M. Vargas Hernandez,[132] A. Buccilli,[133] S. I. Cooper,[133] D. Di Croce,[133] S. V. Gleyzer,[133] C. Henderson,[133] C. U. Perez,[133] P. Rumerio,[133,dddd] C. West,[133] A. Akpinar,[134] A. Albert,[134] D. Arcaro,[134] C. Cosby,[134] Z. Demiragli,[134] C. Erice,[134] E. Fontanesi,[134] D. Gastler,[134] S. May,[134] J. Rohlf,[134] K. Salyer,[134] D. Sperka,[134] D. Spitzbart,[134] I. Suarez,[134] A. Tsatsos,[134] S. Yuan,[134] G. Benelli,[135] B. Burkle,[135] X. Coubez,[135,w] D. Cutts,[135] M. Hadley,[135] U. Heintz,[135] J. M. Hogan,[135,eeee] T. Kwon,[135] G. Landsberg,[135] K. T. Lau,[135] D. Li,[135] J. Luo,[135] M. Narain,[135] N. Pervan,[135] S. Sagir,[135,ffff] F. Simpson,[135] E. Usai,[135] W. Y. Wong,[135] X. Yan,[135] D. Yu,[135] W. Zhang,[135] J. Bonilla,[136] C. Brainerd,[136] R. Breedon,[136] M. Calderon De La Barca Sanchez,[136] M. Chertok,[136] J. Conway,[136] P. T. Cox,[136] R. Erbacher,[136] G. Haza,[136] F. Jensen,[136] O. Kukral,[136] G. Mocellin,[136] M. Mulhearn,[136] D. Pellett,[136] B. Regnery,[136] D. Taylor,[136] Y. Yao,[136] F. Zhang,[136] M. Bachtis,[137] R. Cousins,[137] A. Datta,[137] D. Hamilton,[137] J. Hauser,[137] M. Ignatenko,[137] M. A. Iqbal,[137] T. Lam,[137] W. A. Nash,[137] S. Regnard,[137] D. Saltzberg,[137] B. Stone,[137] V. Valuev,[137] Y. Chen,[138] R. Clare,[138] J. W. Gary,[138] M. Gordon,[138] G. Hanson,[138] G. Karapostoli,[138] O. R. Long,[138] N. Manganelli,[138] W. Si,[138] S. Wimpenny,[138] J. G. Branson,[139] P. Chang,[139] S. Cittolin,[139] S. Cooperstein,[139] D. Diaz,[139] J. Duarte,[139] R. Gerosa,[139] L. Giannini,[139] J. Guiang,[139] R. Kansal,[139] V. Krutelyov,[139] R. Lee,[139] J. Letts,[139] M. Masciovecchio,[139] F. Mokhtar,[139] M. Pieri,[139] B. V. Sathia Narayanan,[139] V. Sharma,[139] M. Tadel,[139] F. Würthwein,[139] Y. Xiang,[139] A. Yagil,[139] N. Amin,[140] C. Campagnari,[140] M. Citron,[140] G. Collura,[140] A. Dorsett,[140] V. Dutta,[140] J. Incandela,[140] M. Kilpatrick,[140] J. Kim,[140] A. J. Li,[140] B. Marsh,[140] P. Masterson,[140] H. Mei,[140] M. Oshiro,[140] M. Quinnan,[140] J. Richman,[140] U. Sarica,[140] R. Schmitz,[140] F. Setti,[140] J. Sheplock,[140] P. Siddireddy,[140] D. Stuart,[140] S. Wang,[140] A. Bornheim,[141] O. Cerri,[141] I. Dutta,[141] J. M. Lawhorn,[141] N. Lu,[141] J. Mao,[141] H. B. Newman,[141] T. Q. Nguyen,[141] M. Spiropulu,[141] J. R. Vlimant,[141] C. Wang,[141] S. Xie,[141] R. Y. Zhu,[141] J. Alison,[142] S. An,[142] M. B. Andrews,[142] P. Bryant,[142] T. Ferguson,[142] A. Harilal,[142] C. Liu,[142] T. Mudholkar,[142] S. Murthy,[142] M. Paulini,[142] A. Roberts,[142] A. Sanchez,[142] W. Terrill,[142] J. P. Cumalat,[143] W. T. Ford,[143] A. Hassani,[143] G. Karathanasis,[143] E. MacDonald,[143] F. Marini,[143] R. Patel,[143] A. Perloff,[143] C. Savard,[143] N. Schonbeck,[143] K. Stenson,[143] K. A. Ulmer,[143] S. R. Wagner,[143] N. Zipper,[143] J. Alexander,[144] S. Bright-Thonney,[144] X. Chen,[144] D. J. Cranshaw,[144] J. Fan,[144] X. Fan,[144] D. Gadkari,[144] S. Hogan,[144] J. Monroy,[144] J. R. Patterson,[144] D. Quach,[144] J. Reichert,[144] M. Reid,[144] A. Ryd,[144] J. Thom,[144] P. Wittich,[144] R. Zou,[144] M. Albrow,[145] M. Alyari,[145] G. Apollinari,[145] A. Apresyan,[145] L. A. T. Bauerdick,[145] D. Berry,[145] J. Berryhill,[145] P. C. Bhat,[145] K. Burkett,[145] J. N. Butler,[145] A. Canepa,[145] G. B. Cerati,[145] H. W. K. Cheung,[145] F. Chlebana,[145] K. F. Di Petrillo,[145] J. Dickinson,[145] V. D. Elvira,[145] Y. Feng,[145] J. Freeman,[145] A. Gandrakota,[145] Z. Gecse,[145] L. Gray,[145] D. Green,[145] S. Grünendahl,[145] O. Gutsche,[145] R. M. Harris,[145] R. Heller,[145] T. C. Herwig,[145] J. Hirschauer,[145] L. Horyn,[145] B. Jayatilaka,[145] S. Jindariani,[145] M. Johnson,[145] U. Joshi,[145] T. Klijnsma,[145] B. Klima,[145] K. H. M. Kwok,[145] S. Lammel,[145] D. Lincoln,[145] R. Lipton,[145] T. Liu,[145] C. Madrid,[145] K. Maeshima,[145] C. Mantilla,[145] D. Mason,[145] P. McBride,[145] P. Merkel,[145] S. Mrenna,[145] S. Nahn,[145] J. Ngadiuba,[145] D. Noonan,[145] V. Papadimitriou,[145] N. Pastika,[145] K. Pedro,[145] C. Pena,[145,gggg] F. Ravera,[145] A. Reinsvold Hall,[145,hhhh] L. Ristori,[145] E. Sexton-Kennedy,[145] N. Smith,[145] A. Soha,[145] L. Spiegel,[145] J. Strait,[145] L. Taylor,[145] S. Tkaczyk,[145] N. V. Tran,[145] L. Uplegger,[145] E. W. Vaandering,[145] H. A. Weber,[145] I. Zoi,[145] P. Avery,[146] D. Bourilkov,[146] L. Cadamuro,[146] V. Cherepanov,[146] R. D. Field,[146] D. Guerrero,[146] M. Kim,[146] E. Koenig,[146] J. Konigsberg,[146] A. Korytov,[146]

K. H. Lo,[146] K. Matchev,[146] N. Menendez,[146] G. Mitselmakher,[146] A. Muthirakalayil Madhu,[146] N. Rawal,[146] D. Rosenzweig,[146] S. Rosenzweig,[146] K. Shi,[146] J. Wang,[146] Z. Wu,[146] T. Adams,[147] A. Askew,[147] R. Habibullah,[147] V. Hagopian,[147] R. Khurana,[147] T. Kolberg,[147] G. Martinez,[147] H. Prosper,[147] C. Schiber,[147] O. Viazlo,[147] R. Yohay,[147] J. Zhang,[147] M. M. Baarmand,[148] S. Butalla,[148] T. Elkafrawy,[148,yy] M. Hohlmann,[148] R. Kumar Verma,[148] M. Rahmani,[148] F. Yumiceva,[148] M. R. Adams,[149] H. Becerril Gonzalez,[149] R. Cavanaugh,[149] S. Dittmer,[149] O. Evdokimov,[149] C. E. Gerber,[149] D. J. Hofman,[149] D. S. Lemos,[149] A. H. Merrit,[149] C. Mills,[149] G. Oh,[149] T. Roy,[149] S. Rudrabhatla,[149] M. B. Tonjes,[149] N. Varelas,[149] X. Wang,[149] Z. Ye,[149] J. Yoo,[149] M. Alhusseini,[150] K. Dilsiz,[150,iiii] L. Emediato,[150] R. P. Gandrajula,[150] G. Karaman,[150] O. K. Köseyan,[150] J.-P. Merlo,[150] A. Mestvirishvili,[150,jjjj] J. Nachtman,[150] O. Neogi,[150] H. Ogul,[150,kkkk] Y. Onel,[150] A. Penzo,[150] C. Snyder,[150] E. Tiras,[150,llll] O. Amram,[151] B. Blumenfeld,[151] L. Corcodilos,[151] J. Davis,[151] A. V. Gritsan,[151] L. Kang,[151] S. Kyriacou,[151] P. Maksimovic,[151] J. Roskes,[151] S. Sekhar,[151] M. Swartz,[151] T. Á. Vámi,[151] A. Abreu,[152] L. F. Alcerro Alcerro,[152] J. Anguiano,[152] P. Baringer,[152] A. Bean,[152] Z. Flowers,[152] T. Isidori,[152] S. Khalil,[152] J. King,[152] G. Krintiras,[152] M. Lazarovits,[152] C. Le Mahieu,[152] C. Lindsey,[152] J. Marquez,[152] N. Minafra,[152] M. Murray,[152] M. Nickel,[152] C. Rogan,[152] C. Royon,[152] R. Salvatico,[152] S. Sanders,[152] E. Schmitz,[152] C. Smith,[152] Q. Wang,[152] J. Williams,[152] G. Wilson,[152] B. Allmond,[153] S. Duric,[153] R. Gujju Gurunadha,[153] A. Ivanov,[153] K. Kaadze,[153] D. Kim,[153] Y. Maravin,[153] T. Mitchell,[153] A. Modak,[153] K. Nam,[153] J. Natoli,[153] D. Roy,[153] F. Rebassoo,[154] D. Wright,[154] E. Adams,[155] A. Baden,[155] O. Baron,[155] A. Belloni,[155] A. Bethani,[155] S. C. Eno,[155] N. J. Hadley,[155] S. Jabeen,[155] R. G. Kellogg,[155] T. Koeth,[155] Y. Lai,[155] S. Lascio,[155] A. C. Mignerey,[155] S. Nabili,[155] C. Palmer,[155] C. Papageorgakis,[155] M. Seidel,[155] L. Wang,[155] K. Wong,[155] D. Abercrombie,[156] R. Bi,[156] W. Busza,[156] I. A. Cali,[156] Y. Chen,[156] M. D'Alfonso,[156] J. Eysermans,[156] C. Freer,[156] G. Gomez-Ceballos,[156] M. Goncharov,[156] P. Harris,[156] M. Hu,[156] D. Kovalskyi,[156] J. Krupa,[156] Y.-J. Lee,[156] K. Long,[156] C. Mironov,[156] C. Paus,[156] D. Rankin,[156] C. Roland,[156] G. Roland,[156] Z. Shi,[156] G. S. F. Stephans,[156] J. Wang,[156] Z. Wang,[156] B. Wyslouch,[156] R. M. Chatterjee,[157] B. Crossman,[157] A. Evans,[157] J. Hiltbrand,[157] Sh. Jain,[157] B. M. Joshi,[157] C. Kapsiak,[157] M. Krohn,[157] Y. Kubota,[157] J. Mans,[157] M. Revering,[157] R. Rusack,[157] R. Saradhy,[157] N. Schroeder,[157] N. Strobbe,[157] M. A. Wadud,[157] L. M. Cremaldi,[158] K. Bloom,[159] M. Bryson,[159] D. R. Claes,[159] C. Fangmeier,[159] L. Finco,[159] F. Golf,[159] C. Joo,[159] I. Kravchenko,[159] I. Reed,[159] J. E. Siado,[159] G. R. Snow,[159,a] W. Tabb,[159] A. Wightman,[159] F. Yan,[159] A. G. Zecchinelli,[159] G. Agarwal,[160] H. Bandyopadhyay,[160] L. Hay,[160] I. Iashvili,[160] A. Kharchilava,[160] C. McLean,[160] M. Morris,[160] D. Nguyen,[160] J. Pekkanen,[160] S. Rappoccio,[160] A. Williams,[160] G. Alverson,[161] E. Barberis,[161] Y. Haddad,[161] Y. Han,[161] A. Krishna,[161] J. Li,[161] J. Lidrych,[161] G. Madigan,[161] B. Marzocchi,[161] D. M. Morse,[161] V. Nguyen,[161] T. Orimoto,[161] A. Parker,[161] L. Skinnari,[161] A. Tishelman-Charny,[161] T. Wamorkar,[161] B. Wang,[161] A. Wisecarver,[161] D. Wood,[161] S. Bhattacharya,[162] J. Bueghly,[162] Z. Chen,[162] A. Gilbert,[162] T. Gunter,[162] K. A. Hahn,[162] Y. Liu,[162] N. Odell,[162] M. H. Schmitt,[162] M. Velasco,[162] R. Band,[163] R. Bucci,[163] S. Castells,[163] M. Cremonesi,[163] A. Das,[163] R. Goldouzian,[163] M. Hildreth,[163] K. Hurtado Anampa,[163] C. Jessop,[163] K. Lannon,[163] J. Lawrence,[163] N. Loukas,[163] L. Lutton,[163] J. Mariano,[163] N. Marinelli,[163] I. Mcalister,[163] T. McCauley,[163] C. Mcgrady,[163] K. Mohrman,[163] C. Moore,[163] Y. Musienko,[163,n] H. Nelson,[163] R. Ruchti,[163] A. Townsend,[163] M. Wayne,[163] H. Yockey,[163] M. Zarucki,[163] L. Zygala,[163] B. Bylsma,[164] M. Carrigan,[164] L. S. Durkin,[164] B. Francis,[164] C. Hill,[164] A. Lesauvage,[164] M. Nunez Ornelas,[164] K. Wei,[164] B. L. Winer,[164] B. R. Yates,[164] F. M. Addesa,[165] B. Bonham,[165] P. Das,[165] G. Dezoort,[165] P. Elmer,[165] A. Frankenthal,[165] B. Greenberg,[165] N. Haubrich,[165] S. Higginbotham,[165] A. Kalogeropoulos,[165] G. Kopp,[165] S. Kwan,[165] D. Lange,[165] D. Marlow,[165] K. Mei,[165] I. Ojalvo,[165] J. Olsen,[165] D. Stickland,[165] C. Tully,[165] S. Malik,[166] S. Norberg,[166] A. S. Bakshi,[167] V. E. Barnes,[167] R. Chawla,[167] S. Das,[167] L. Gutay,[167] M. Jones,[167] A. W. Jung,[167] D. Kondratyev,[167] A. M. Koshy,[167] M. Liu,[167] G. Negro,[167] N. Neumeister,[167] G. Paspalaki,[167] S. Piperov,[167] A. Purohit,[167] J. F. Schulte,[167] M. Stojanovic,[167] J. Thieman,[167] F. Wang,[167] R. Xiao,[167] W. Xie,[167] J. Dolen,[168] N. Parashar,[168] D. Acosta,[169] A. Baty,[169] T. Carnahan,[169] M. Decaro,[169] S. Dildick,[169] K. M. Ecklund,[169] P. J. Fernández Manteca,[169] S. Freed,[169] P. Gardner,[169] F. J. M. Geurts,[169] A. Kumar,[169] W. Li,[169] B. P. Padley,[169] R. Redjimi,[169] J. Rotter,[169] W. Shi,[169] S. Yang,[169] E. Yigitbasi,[169] L. Zhang,[169,mmmm] Y. Zhang,[169] X. Zuo,[169] A. Bodek,[170] P. de Barbaro,[170] R. Demina,[170] J. L. Dulemba,[170] C. Fallon,[170] T. Ferbel,[170] M. Galanti,[170] A. Garcia-Bellido,[170] O. Hindrichs,[170]

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[dddd]Also at Università di Torino, Torino, Italy.
[eeee]Also at Bethel University, St. Paul, Minnesota, USA.
[ffff]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[gggg]Also at California Institute of Technology, Pasadena, California, USA.
[hhhh]Also at United States Naval Academy, Annapolis, Maryland, USA.
[iiii]Also at Bingol University, Bingol, Turkey.
[jjjj]Also at Georgian Technical University, Tbilisi, Georgia.
[kkkk]Also at Sinop University, Sinop, Turkey.
[llll]Also at Erciyes University, Kayseri, Turkey.
[mmmm]Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China.
[nnnn]Also at Texas A&M University at Qatar, Doha, Qatar.
[oooo]Also at Kyungpook National University, Daegu, Korea.
[pppp]Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[qqqq]Also at Yerevan Physics Institute, Yerevan, Armenia.
[rrrr]Also at University of Florida, Gainesville, Florida, USA.
[ssss]Also at Imperial College, London, United Kingdom.
[tttt]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.