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Khachatryan, V.

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# Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV

V. Khachatryan *et al.*\*

(CMS Collaboration)

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Results are presented of a search for heavy stable charged particles produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV using a data sample corresponding to an integrated luminosity of  $2.5 \text{ fb}^{-1}$  collected in 2015 with the CMS detector at the CERN LHC. The search is conducted using signatures of anomalously high energy deposits in the silicon tracker and long time-of-flight measurements by the muon system. The data are consistent with the expected background, and upper limits are set on the cross sections for production of long-lived gluinos, top squarks, tau sleptons, and leptonlike long-lived fermions. These upper limits are equivalently expressed as lower limits on the masses of new states; the limits for gluinos, ranging up to 1610 GeV, are the most stringent to date. Limits on the cross sections for direct pair production of long-lived tau sleptons are also determined.

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## I. INTRODUCTION

Many extensions of the standard model (SM) include heavy long-lived charged particles that might have high momentum, but speed significantly smaller than the speed of light [1–3] and/or charge,  $Q$ , not equal to the elementary charge  $\pm 1e$  [4–7]. Those particles with lifetimes greater than a few nanoseconds can travel distances larger than the size of a typical collider detector and appear quasistable like the pion or kaon. These particles are generally referred to as heavy stable charged particles (HSCPs) and can be singly ( $|Q| = 1e$ ), fractionally ( $|Q| < 1e$ ), or multiply ( $|Q| > 1e$ ) charged. Without dedicated searches, HSCPs may be misidentified or unobserved, since charged particle identification algorithms at hadron collider experiments generally assume that particles have speeds close to the speed of light and charges of  $\pm 1e$ . Additionally, HSCPs may be charged during only a part of their passage through detectors [8] further limiting the ability of standard algorithms to identify them.

For HSCP masses greater than about 100 GeV, a significant fraction of particles produced at the LHC will have a relative velocity  $\beta \equiv v/c < 0.9$ . It is possible to distinguish  $|Q| \geq 1e$  particles with  $\beta < 0.9$  from light SM particles traveling close to the speed of light through their higher rate of energy loss via ionization ( $dE/dx$ ) or through their longer time of flight (TOF) to the outer detectors. This paper describes a search for HSCPs using the CMS detector in two ways: (i) requiring tracks to be reconstructed only in the silicon detectors, the *tracker-only* analysis; (ii) requiring

tracks to be reconstructed in both the silicon detectors and the muon system, referred to as the *tracker+TOF* analysis.

The dependence of  $dE/dx$  on the particle momentum is described by the Bethe-Bloch formula [9]. This dependence can be seen in Fig. 1, which shows the  $dE/dx$  estimator versus momentum for good quality (Sec. IV) high transverse momentum ( $p_T > 55$  GeV) tracks from data and the generated Monte Carlo (MC) samples for HSCP signals with various charges. In the momentum range of interest at the LHC (10–1000 GeV), SM particles have nearly uniform

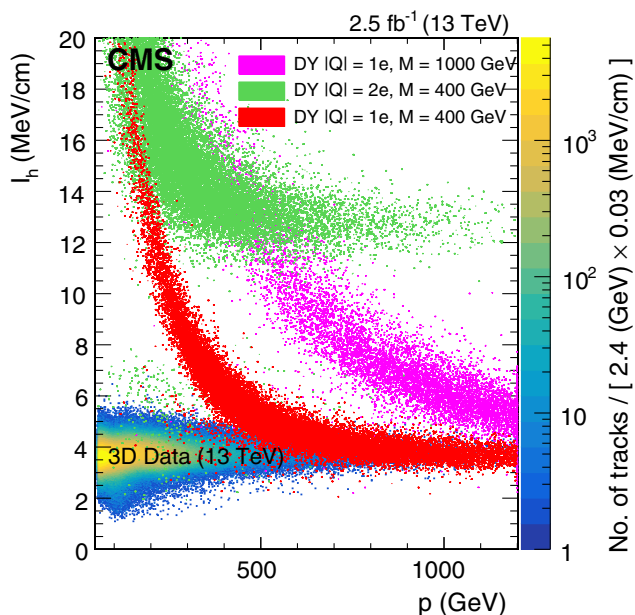


FIG. 1. Distribution of the  $dE/dx$  estimator,  $I_h$  (see Sec. III A), versus particle momentum for tracks in the 13 TeV data, and for simulation of HSCP for singly or multiply charged particles with masses of 400 and 1000 GeV. The vertical scale shows the density of entries for data only.

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

ionization energy loss ( $\approx 3$  MeV/cm). Searching for candidates with larger  $dE/dx$  gives sensitivity to massive particles with  $|Q| \geq 1e$ .

Previous collider searches for HSCPs have been performed at LEP [10–13], HERA [14], the Tevatron [15–18] and the CERN LHC during Run 1 (proton-proton collisions with  $\sqrt{s}$  up to 8 TeV) [19–27]. The results from these searches have placed significant bounds on theories beyond the SM [28,29], such as lower limits at 95% confidence level (CL) on the mass of long-lived gluinos (1300 GeV), top squarks (900 GeV), and directly pair-produced tau sleptons (330 GeV).

In the present paper, results of searches for singly and multiply charged HSCPs in  $2.5 \text{ fb}^{-1}$  of data collected with the CMS detector at  $\sqrt{s} = 13$  TeV in 2015 are presented. Similar limits on HSCPs were recently obtained by the ATLAS experiment [30,31] using  $3.2 \text{ fb}^{-1}$  of 13 TeV data collected in 2015.

## II. SIGNAL BENCHMARKS

The analyses described in this paper employ several HSCP models as benchmarks, to account for a range of signatures that are experimentally accessible.

The first type of signal consists of HSCPs that interact via the strong force and hadronize with SM quarks to form  $R$ -hadrons [2,3]. As in Ref. [27], events involving direct pair production of gluinos ( $\tilde{g}$ ) and top squarks ( $\tilde{t}_1$ ), with mass values in the range 300–2600 GeV, are generated according to the Split Supersymmetry (Split SUSY) scenarios [32–35]. Gluinos are generated assuming the squark mass is 10 TeV [32,36]. In the region of parameter space where squarks are too heavy to be produced at the LHC, the gluino-gluino production cross section and kinematic distributions depend only on the gluino mass, thus the cross section limits are model-independent. PYTHIA 8.153 [37], with the underlying event tune CUETP8M1 [38], is used to generate the 13 TeV MC samples. The fraction,  $f$ , of produced  $\tilde{g}$  hadronizing into a  $\tilde{g}$ -gluon state is an arbitrary value of the hadronization model. It determines the fraction of  $R$ -hadrons that are neutral at production. For this search, results are obtained for two different values of  $f$ , 0.1 and 0.5. As in Ref. [27], two scenarios of  $R$ -hadron strong interactions with nuclear matter are considered. The first scenario follows the cloud model in Refs. [8,39], which assumes that the  $R$ -hadron is surrounded by a cloud of colored, light constituents that interact during scattering. Therefore, the  $R$ -hadron interacting inside the detector may change its charge sign. The second scenario adopts a model of complete charge suppression [40] where the  $R$ -hadron becomes a neutral particle before it enters the muon system. Both the *tracker-only* and *tracker+TOF* analyses are used to search for these signals, although only the *tracker-only* analysis is expected to have sensitivity in the charge-suppressed scenario. In the case of a discovery, a comparison of the numbers of events found in the two analyses

could give a hint about the nature of the new long-lived particle.

The second type of signal consists of HSCPs that behave like leptons. The minimal gauge mediated supersymmetry breaking (mGMSB) model [41] is selected as a benchmark for leptonlike HSCPs. Production of quasistable sleptons at the LHC can proceed either directly or via production of heavier supersymmetric particles (mainly squarks and gluinos) that decay and lead to two sleptons at the end of the decay chain. This latter process is dominant because the direct production process is electroweak. Direct production is relevant only if squarks and gluinos are too heavy to be produced at the LHC. The mGMSB model is explored using the SPS7 slope [42], which has the tau slepton (stau  $\tilde{\tau}_1$ ) as the next-to-lightest supersymmetric particle (NLSP). The particle mass spectrum and the decay table are produced with the program ISASUGRA 7.69 [43]. The mGMSB model is characterized by six fundamental parameters. The mGMSB parameter  $\Lambda$ , which corresponds to the effective supersymmetry breaking scale, is varied from 31 to 510 TeV. It is proportional to the sparticle masses. The range of its values gives a tau slepton mass of 100 to 1600 GeV. Other parameters are fixed to the following values. The number of the messenger SU(5) multiplets  $N_{\text{mes}} = 3$  and their mass scale  $M$  is set as  $M_{\text{mes}}/\Lambda = 2$ . The ratio of the vacuum expectation values of the Higgs doublets is  $\tan\beta = 10$ , and a positive sign of the higgsino mass term,  $\mu > 0$ , is assumed. The large value of the scale factor of the gravitino coupling,  $C_{\text{grav}} = 10000$ , results in a long-lived  $\tilde{\tau}_1$ . The SUSY mass spectrum produced is input to PYTHIA 6.4 [37] with the Z2\* tune [44] as the generator for a MC simulation at 13 TeV. Two tau slepton samples are generated for each SUSY point: one with all processes (labeled “GMSB stau”) and one with only direct pair production (labeled “Pair prod. stau”). The pair-produced stau includes only  $\tilde{\tau}_1$ , which is predominantly  $\tilde{\tau}_R$  for these model parameters. The direct production of long-lived stau is model independent. Both cross section and kinematics depend only on the stau mass and the scan over the stau mass parameter shows the effect of variations in center-of-mass energy and integrated luminosity. The *tracker-only* and *tracker+TOF* analyses are both used to search for these signals.

The last type of signal is based on modified Drell–Yan (DY) production of long-lived leptonlike fermions. In this scenario, new massive spin-1/2 particles have arbitrary electric charge but are neutral under  $SU(3)_{\text{Color}}$  and  $SU(2)_{\text{Left}}$ , and therefore couple only to the photon and the Z boson. PYTHIA v6.4 [37] with the Z2\* tune [44] is used to generate these 13 TeV MC signal samples. Simulations of events with leptonlike fermions are generated with masses ranging from 100 to 2600 GeV and for electric charges  $|Q| = 1e$  and  $2e$ .

Different PYTHIA tunes were studied and the effects on the kinematic distribution were negligible for the HSCPs

considered. The *tracker-only* and *tracker+TOF* analyses are both expected to have sensitivity to  $|Q| = 2e$  HSCPs.

In all signal samples, simulated minimum bias events are overlaid with the primary collision to produce the effect of additional interactions in the same LHC beam crossing (pileup).

### III. THE CMS DETECTOR

The central feature of the CMS [45] apparatus is a 3.8 T superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Outside the solenoid, forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid. The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection on the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as  $E_T^{\text{miss}}$ .

The silicon tracker, consisting of 1440 silicon pixel and 15 148 silicon strip detector modules, measures charged particles within the pseudorapidity range  $|\eta| < 2.5$ . Isolated particles of transverse momentum  $p_T = 100$  GeV and with  $|\eta| < 1.4$  have track resolutions of 2.8% in  $p_T$  and 10 (30)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [46]. Muons are measured in the pseudorapidity range  $|\eta| < 2.4$ , using three technologies: drift tubes (DTs), cathode strip chambers (CSCs), and resistive-plate chambers (RPCs). Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with  $20 < p_T < 100$  GeV of 1.3%–2.0% in the barrel and better than 6% in the endcaps. The  $p_T$  resolution in the barrel is better than 10% for muons with  $p_T$  up to 1 TeV [47].

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest within a fixed time interval of less than 4  $\mu\text{s}$ . The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [45].

#### A. $dE/dx$ measurements

For the reconstructed track, information about  $dE/dx$  can be gained from measurements of ionization deposited in layers of the pixel and silicon tracker. The ionization charge measured is compared with that expected from a minimum-ionizing particle (MIP), and its level of

compatibility can provide a probability, using a  $dE/dx$  discriminator. As in Ref. [24], to distinguish SM particles from HSCP candidates the  $I_{\text{as}}$  discriminator is used and is given by

$$I_{\text{as}} = \frac{3}{N} \left( \frac{1}{12N} + \sum_{i=1}^N \left[ P_i \left( P_i - \frac{2i-1}{2N} \right)^2 \right] \right), \quad (1)$$

where  $N$  is the number of measurements in the silicon-tracker detectors,  $P_i$  is the probability for a MIP to produce a charge smaller or equal to that of the  $i$ th measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing  $P_i$ .

In addition, the  $dE/dx$  of a track is estimated using a harmonic-2 estimator

$$I_h = \left( \frac{1}{N_{85\%}} \sum_i^{N_{85\%}} c_i^{-2} \right)^{-1/2}, \quad (2)$$

where  $c_i$  is the charge per unit path length in the sensitive part of the silicon detector of the  $i$ th track measurement. The harmonic-2 estimator has units MeV/cm and the summation includes just the top 85% of the charge measurements. Ignoring the low charge measurements increases the resilience of the estimator against instrumental biases. This procedure is not necessary for  $I_{\text{as}}$  which is, by construction, robust against that type of bias.

The mass of a candidate particle can be calculated [27] from its momentum and its  $I_h$   $dE/dx$  estimate, based on the relation

$$I_h = K \frac{m^2}{p^2} + C, \quad (3)$$

where the empirical parameters  $K = 2.684 \pm 0.001$  MeV cm $^{-1}$  and  $C = 3.375 \pm 0.001$  MeV cm $^{-1}$  are determined from data using a sample of low-momentum protons. As the momentum reconstruction is done assuming  $|Q| = 1e$  particles, Eq. (3) leads to an accurate mass reconstruction only for singly charged particles.

The HSCP candidates are preselected using the  $I_{\text{as}}$  discriminator because it has a better signal-to-background discriminating power compared to the  $I_h$  estimator or the mass. Nonetheless, the mass is used at the last stage of the analysis, after the  $I_{\text{as}}$  selection, to further discriminate between signal and backgrounds since the latter tend to have a low reconstructed mass.

#### B. Time of flight measurements

The time of flight to the muon system can be used to discriminate between particles traveling at near the speed of light and slower candidates. Both the DT and the CSC muon systems measure the time of each hit. In the DT, the precision position is obtained from this time measurement.

The synchronization works in a such a way that a relativistic muon produced at the interaction point gives an aligned pattern of hits in consecutive DT layers. For a slower HSCP particle, hits in each DT layer will be reconstructed as shifted with respect to its true position and will form a zigzag pattern with an offset proportional to the particle delay,  $\delta_i$ . In the CSC the delay is measured for each hit separately. Each  $\delta_i$  measurement can be used to determine the track  $\beta$  via the equation

$$\beta^{-1} = 1 + \frac{c\delta_i}{L} \quad (4)$$

where  $L$  is the flight distance. The track  $\beta^{-1}$  value is calculated as the weighted average of the  $\beta^{-1}$  measurements from the DT and CSC systems associated with the track. The weight for the  $i^{\text{th}}$  DT measurement is given by

$$w_i = \frac{(n-2)}{n} \frac{L_i^2}{\sigma_{\text{DT}}^2} \quad (5)$$

where  $n$  is the number of  $\phi$  projection measurements found in the muon chamber producing the measurement and  $\sigma_{\text{DT}}$  is the time resolution of the DT measurements, for which the measured value of 3 ns is used. The factor  $(n-2)/n$  accounts for residuals computed using the two parameters of a straight line determined from the same  $n$  measurements. The minimum number of hits in a given DT chamber that allows for at least one residual calculation is  $n=3$ . The weight for the  $i^{\text{th}}$  CSC measurement is given by

$$w_i = \frac{L_i^2}{\sigma_i^2} \quad (6)$$

where  $\sigma_i$ , the measured time resolution, is 7.0 ns for cathode strip measurements and 8.6 ns for anode wire measurements.

The resolution on the weighted average  $\beta^{-1}$  measurement is approximately 0.065 in both the DT and CSC subsystems.

#### IV. DATA SELECTION

All events pass a trigger requiring either a reconstructed muon with high transverse momentum or large  $E_T^{\text{miss}}$ , calculated using an online particle-flow algorithm [48–50].

The muon trigger is more efficient than the  $E_T^{\text{miss}}$  trigger for all HSCP models considered with the exception of the charge-suppressed  $R$ -hadron model, but it is not efficient for particles that are slow ( $\beta < 0.6$ ).

The  $E_T^{\text{miss}}$  trigger can recover some events in which the HSCP is charged in the tracker and neutral in the muon subsystem. The particle-flow algorithm rejects tracks reconstructed only in the tracker and having a track  $p_T$  significantly greater than the matched energy deposited in

the calorimeter [49], as would be the case for HSCPs that become neutral in the calorimeter. Thus only an HSCP's energy deposit in the calorimeter, roughly 10–20 GeV, will be included in the  $E_T^{\text{miss}}$  calculation. Where one or more HSCPs fail to be reconstructed as muon candidates, the events may appear to have significant  $E_T^{\text{miss}}$ .

For both the *tracker-only* and the *tracker+TOF* analyses, the muon high-level trigger requires a muon candidate with  $p_T > 50$  GeV and the  $E_T^{\text{miss}}$  trigger requires  $E_T^{\text{miss}} > 170$  GeV. Using these two triggers for both analyses allows for increased sensitivity to HSCP candidates that arrive in

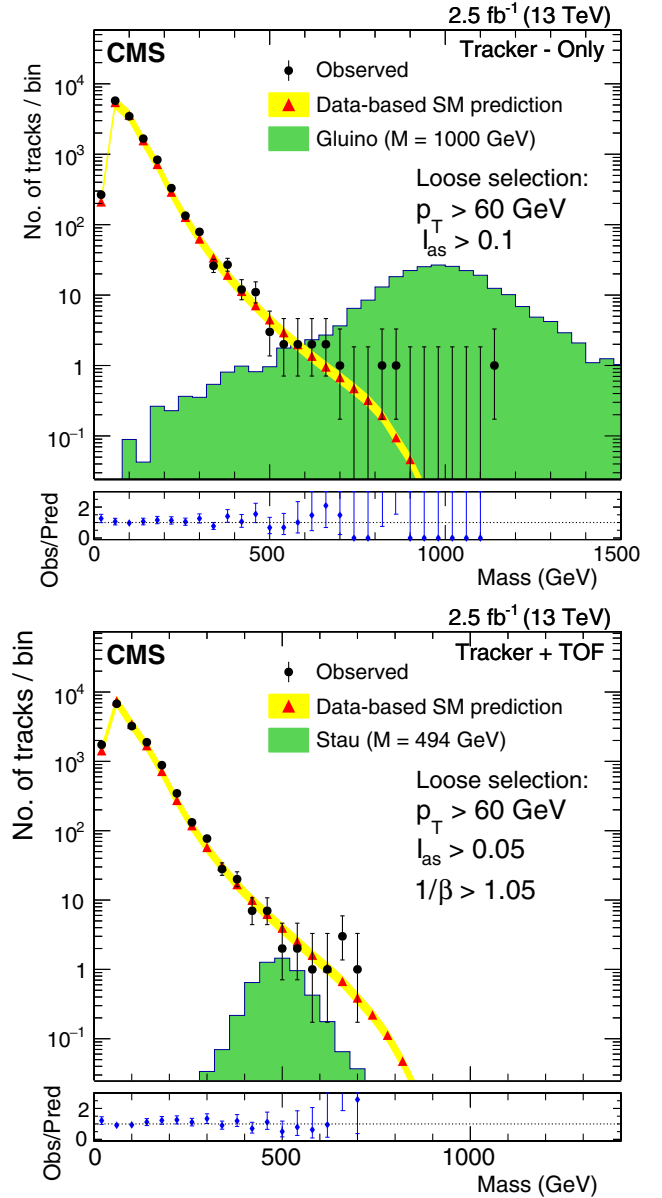


FIG. 2. Observed and predicted mass spectra for loose selection candidates in the *tracker-only* (top) and *tracker+TOF* (bottom) analyses. The expected distributions for representative signals are shown as histograms.

the muon system very late, as well as for hadronlike HSCPs, which may be charged only in the tracker.

Off-line, for the *tracker-only* analysis, all events are required to have a candidate track with  $p_T > 55$  GeV as measured in the tracker, relative uncertainty in  $p_T$  ( $\sigma_{p_T}/p_T$ ) less than 0.25,  $|\eta| < 2.1$ , and the track fit  $\chi^2/\text{dof} < 5$ . The magnitudes of the impact parameters  $d_z$  and  $d_{xy}$  must both be less than 0.5 cm, where  $d_z$  and  $d_{xy}$  are the longitudinal and transverse impact parameters with respect to the vertex with the smallest  $d_z$ . The requirements on the impact parameters are very loose compared to the resolutions for tracks in the tracker. Candidates must pass isolation requirements in the tracker and calorimeter. The tracker isolation criterion is  $\sum p_T < 50$  GeV, where the sum is over all tracks (except the candidate) within  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  of the candidate track. The calorimeter isolation criterion is  $E/p = 0.3$ , where  $E$  is the sum of energy deposited in the calorimeter towers within  $\Delta R = 0.3$  and  $p$  is the track momentum reconstructed from the tracker. Candidate tracks must have at least two measurements in the silicon pixel detector and at least six measurements in the strip detectors. In addition, there must be measurements in at least 80% of the silicon layers between the first and last measurements of the track. To reduce the contamination from clusters with a large energy deposition due to overlapping tracks, a filtering procedure is applied to remove clusters in the silicon strip tracker that are not consistent with the passage of a singly charged particle (i.e., a narrow cluster with most of the energy deposited in one or two strips). After cluster filtering, there must be at least six measurements in the silicon tracker that are used for the  $dE/dx$  calculation.

The *tracker+TOF* analysis applies the same criteria, but additionally requires a reconstructed muon matched to the track in the inner detectors. At least eight independent time measurements are needed for the TOF computation. Finally,  $1/\beta > 1$  and  $\sigma_{1/\beta} < 0.15$  are required.

## V. BACKGROUND ESTIMATION

For background estimation we follow the procedure described in our previous work [27]. Candidates passing the preselection (Sec. IV) are subject to either two or three additional criteria to improve the signal-to-background discrimination. By choosing two uncorrelated criteria it is possible to predict the background using the ABCD (matrix) method. In this approach, the expected background in the signal region,  $D$ , is estimated by  $BC/A$ , where  $B$  and  $C$  are the number of candidates that fail the first or second criterion, respectively, while  $A$  is the number of candidates that fail both criteria.

Results are based upon a comparison of the number of candidates passing the selection criteria defining the signal region with the number of predicted background events in that region. Fixed selections on the appropriate set of  $I_{as}$ ,  $p_T$ , and  $1/\beta$  are used to define the final signal region (and the regions for the background prediction). The values are chosen to give the best discovery potential over the signal mass regions of interest.

For the *tracker-only* analysis, the two criteria are  $p_T > 65$  GeV and  $I_{as} > 0.3$ . The candidates passing only the  $I_{as}$  requirement fall into the  $B$  region and those passing only the  $p_T$  requirement fall into the  $C$  region. The  $B$  and  $C$  candidates are then used to form binned probability density functions in  $I_h$  and  $p$ , respectively, such that, using the mass value [Eq. (3)], the full mass spectrum of the background in the signal region  $D$  can be predicted. However, the  $\eta$  distribution of candidates with low  $dE/dx$  differs from the distribution of candidates with high  $dE/dx$ . To correct for this, events in the  $C$  region are weighted such that the  $\eta$  distribution matches that in the  $B$  region.

For the *tracker+TOF* analysis, a three-dimensional matrix method is used with  $p_T > 65$  GeV,  $I_{as} > 0.175$ , and  $1/\beta > 1.25$ , creating eight regions labeled  $A$ – $H$ . Region  $D$  represents the signal region, with events passing

TABLE I. Selection criteria for the two analyses with the number of predicted and observed events. In the background prediction, the statistical and systematic uncertainties are added in quadrature.

	Selection requirements				Numbers of events $\sqrt{s} = 13$ TeV	
	$p_T$ (GeV)	$I_{as}$	$1/\beta$	Mass (GeV)	Predicted	Observed
<i>tracker-only</i>	>65	>0.3	...	>0	$28.7 \pm 6.0$	24
				>100	$20.7 \pm 4.4$	15
				>200	$3.8 \pm 0.8$	2
				>300	$0.82 \pm 0.18$	0
				>400	$0.25 \pm 0.05$	0
<i>tracker+TOF</i>	>65	>0.175	>1.250	>0	$18.2 \pm 3.7$	14
				>100	$5.4 \pm 1.1$	4
				>200	$0.90 \pm 0.19$	0
				>300	$0.06 \pm 0.04$	0

all three criteria. The candidates in the  $A$ ,  $F$ , and  $G$  regions pass only the  $1/\beta$ ,  $I_{as}$ , and  $p_T$  criteria, respectively, while the candidates in the  $B$ ,  $C$ , and  $H$  regions fail only the  $p_T$ ,  $I_{as}$ , and  $1/\beta$  criteria, respectively. The  $E$  region contains events that fail all three criteria. Background estimates can be made from several different combinations of these regions. The combination  $D = AGF/E^2$  is used because it yields the smallest statistical uncertainty. As in the *tracker-only* analysis, events in the  $G$  region are reweighted to match the  $\eta$  distribution in the  $B$  region. The spread in background estimated from the other combinations is less

than 20%, which is taken as the systematic uncertainty in the collision background estimate. The same 20% systematic uncertainty is used for the *tracker-only* analysis.

In order to check the background prediction, samples with a loose selection, which would be dominated by background tracks, are used for the *tracker-only* and *tracker+TOF* analyses. The loose selection sample for the *tracker-only* analysis is defined as  $p_T > 60$  GeV and  $I_{as} > 0.10$ . The loose selection sample for the *tracker+TOF* analysis is defined by  $p_T > 60$  GeV,  $I_{as} > 0.05$ , and  $1/\beta > 1.05$ . Figure 2 shows the observed and estimated mass spectra for these samples.

For both analyses, an additional requirement on the reconstructed mass is applied. The specific requirement is adapted to each HSCP model. For a given signal mass and model, the mass requirement is  $M \geq M_{reco} - 2\sigma$ , where  $M_{reco}$  is the average reconstructed mass for the given mass  $M_{HSCP}$  and  $\sigma$  is the expected resolution. Simulation is used to determine  $M_{reco}$  and  $\sigma$ .

Table I lists the final selection criteria, the predicted number of background events, and the number of events observed in the signal region. Agreement between prediction and observation is seen for both the *tracker-only* and the *tracker+TOF* analyses. Figure 3 shows the predicted and observed mass distributions for the *tracker-only* and the *tracker+TOF* analyses with the final selection.

## VI. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainty considered are those related to the background prediction, the signal acceptance, and the integrated luminosity. The uncertainty in the integrated luminosity is 2.7% at  $\sqrt{s} = 13$  TeV [51]. The uncertainties in the collision background predictions are estimated to be at the level of 20% for the *tracker-only* and the *tracker+TOF* analyses, as described in Sec. V.

The signal acceptance is obtained from MC samples of the various signals processed through the full detector simulation (Sec. II). Systematic uncertainties are derived by comparing the response of the detector in the data and simulation. The relevant sources of uncertainty are discussed below.

The signal trigger efficiency is dominated by the muon triggers efficiency, for all the models except the charge-suppressed ones. The uncertainty in the muon trigger efficiency has many contributions. It is estimated from the difference between the trigger efficiency in data and that seen in simulation, using  $Z(\mu\mu)$  data. For genuine muons, the trigger efficiency uncertainty is 3%.

For slow moving particles, the effect of the timing synchronization of the muon system is tested by shifting the arrival times in simulation by the synchronization accuracy observed in data, resulting in an efficiency change of less than 4% for most samples but up to 8% for the 2.4 TeV gluino sample. The uncertainty in the  $E_T^{miss}$  trigger efficiency is found by varying the jet energy scale in the

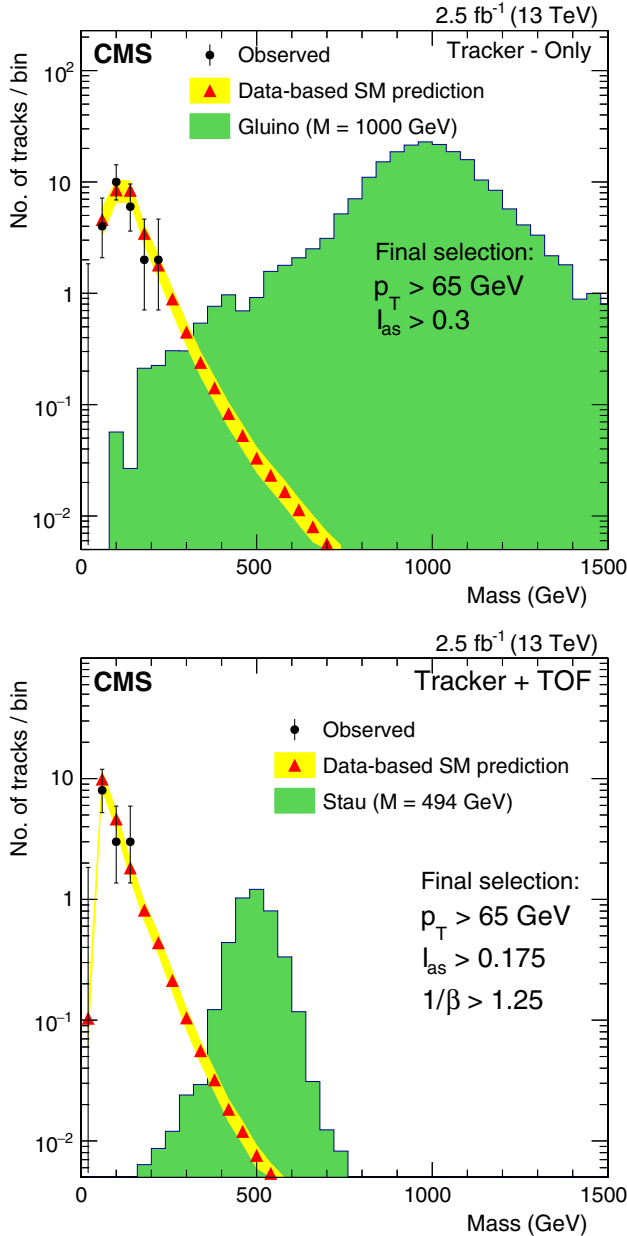


FIG. 3. Observed and predicted mass spectra for candidates passing the final selection in the *tracker-only* (top) and *tracker+TOF* (bottom) analyses. The expected distributions for representative signals are shown as histograms.

simulation of the high-level trigger by its uncertainty in data. The  $E_T^{\text{miss}}$  uncertainty is found to be less than 12% for all samples. The total trigger uncertainty is found to be less than 13% for all the samples, since the muon trigger inefficiencies are often compensated by the  $E_T^{\text{miss}}$  trigger and vice versa.

Low-momentum protons are used to compare the observed and simulated distributions of  $I_h$  and  $I_{\text{as}}$  that reflect the energy loss in the silicon tracker. The  $dE/dx$  distributions of signal samples are varied by the observed differences in order to estimate the systematic uncertainty. The uncertainty in the signal acceptance is usually less than 10% and is at most 15%.

Bias in the energy loss measurement due to highly ionizing particles (HIP), such as low-momentum protons produced in pp collisions earlier than the triggering collision, was also considered as a source of uncertainty in the  $I_h$  estimate. In 2015, the LHC collision frequency was doubled, with bunches colliding every 25 ns compared to collisions every 50 ns in 2012, causing an increase of the HIP rate. The contribution of HIPs was included in simulations with the rate observed during the 2015 data taking. The uncertainty in this rate is found to be 25% and 80% for pixel and strip sensors, respectively. Varying the HIP rate in the simulation by these amounts leads to a change in signal acceptance of at most 4% for both analyses.

Dimuon events are used to test the MC simulation of  $1/\beta$  by comparing with data. An offset of at most 1.5% is found for the muon system. The resulting uncertainty (labeled “Time of flight” in Table II) in the signal acceptance is found to be less than 5% by shifting  $1/\beta$  by this amount.

As in Ref. [26], the uncertainties in the efficiencies for muon [47] and track [52] reconstruction are each less than 2%. The track momentum uncertainty is estimated by shifting the momentum of the inner track, as in Ref. [26].

TABLE II. Systematic uncertainties for the two HSCP searches. All values are relative uncertainties in the signal acceptance for the *tracker-only* and *tracker+TOF* analyses.

Source of systematic uncertainty	Relative uncertainty (%)	
	<i>tracker-only</i>	<i>tracker+TOF</i>
Signal acceptance		
- Trigger efficiency	13	13
- Track momentum scale	< 20	< 20
- Track reconstruction	< 2	< 2
- Ionization energy loss	< 15	< 15
- HIP background effect	< 3	< 4
- Time of flight	...	< 5
- Muon reconstruction	...	2
- Pileup	< 1	< 1
Total uncert. in signal acceptance	< 20	< 25
Collision background uncert.	20	20
Luminosity uncertainty	2.7	2.7

This uncertainty is found to be less than 5% for most of the samples, increasing to 20% for masses above 2 TeV.

The uncertainty in the number of pileup events is evaluated by varying  $\pm 5\%$  the minimum bias cross section used to calculate the weights applied to signal events in order to reproduce the pileup observed in data. The uncertainties due to pileup estimated with this procedure are less than 1%.

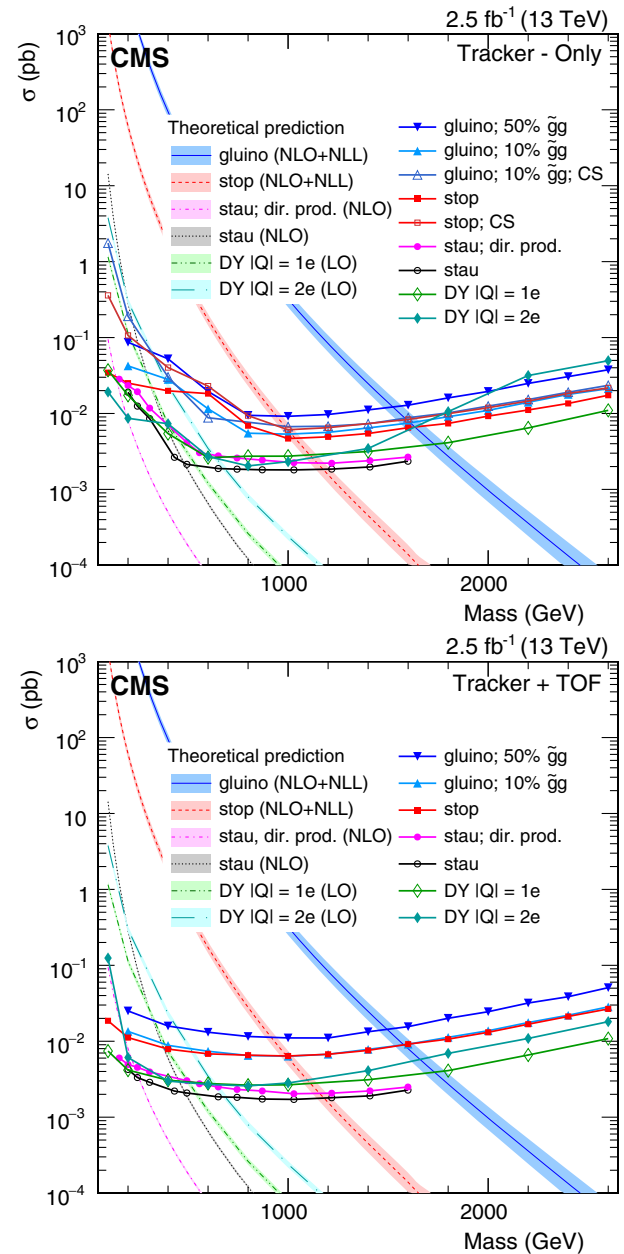


FIG. 4. Results of the HSCP search as the cross section upper limits at 95% CL for various signal models for the *tracker-only* analysis (top) and *tracker+TOF* analysis (bottom) at  $\sqrt{s} = 13$  TeV. In the legend, “CS” stands for charge-suppressed interaction model.



TABLE III. Summary of the search for long-lived gluinos: the  $p_T$  (GeV),  $I_{as}$ ,  $1/\beta$ , and mass thresholds  $M$  (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass (GeV)	$p_T$	Requirements		M	Yields		Signal		$\sigma$ (pb)	
		$I_{as}$	$1/\beta$		SM predicted	data	eff.	theo.	exp.	obs.
Gluino ( $f = 0.1$ ) with the <i>tracker-only</i> analysis										
400	65	0.3	...	60	$28.000 \pm 5.880$	23	0.167	$9.5 \times 10^{+1}$	$3.7 \times 10^{-2}$	$2.8 \times 10^{-2}$
800	65	0.3	...	350	$0.435 \pm 0.093$	0	0.223	1.5	$5.5 \times 10^{-3}$	$5.5 \times 10^{-3}$
1200	65	0.3	...	590	$0.046 \pm 0.010$	0	0.220	$8.4 \times 10^{-2}$	$5.6 \times 10^{-3}$	$5.6 \times 10^{-3}$
1600	65	0.3	...	720	$0.017 \pm 0.004$	0	0.166	$8.0 \times 10^{-3}$	$7.5 \times 10^{-3}$	$7.5 \times 10^{-3}$
2000	65	0.3	...	770	$0.012 \pm 0.003$	0	0.112	$9.7 \times 10^{-4}$	$1.1 \times 10^{-2}$	$1.1 \times 10^{-2}$
2400	65	0.3	...	800	$0.012 \pm 0.002$	0	0.072	$1.3 \times 10^{-4}$	$1.8 \times 10^{-2}$	$1.8 \times 10^{-2}$
Gluino charge-suppressed ( $f = 0.1$ ) with the <i>tracker-only</i> analysis										
400	65	0.3	...	120	$15.600 \pm 3.300$	10	0.092	$9.5 \times 10^{+1}$	$4.9 \times 10^{-2}$	$3.0 \times 10^{-2}$
600	65	0.3	...	250	$1.690 \pm 0.369$	0	0.141	9.1	$1.2 \times 10^{-2}$	$8.8 \times 10^{-3}$
1200	65	0.3	...	580	$0.050 \pm 0.011$	0	0.183	$8.4 \times 10^{-2}$	$6.8 \times 10^{-3}$	$6.8 \times 10^{-3}$
1600	65	0.3	...	680	$0.023 \pm 0.005$	0	0.142	$8.0 \times 10^{-3}$	$8.8 \times 10^{-3}$	$8.8 \times 10^{-3}$
2000	65	0.3	...	670	$0.024 \pm 0.005$	0	0.099	$9.7 \times 10^{-4}$	$1.3 \times 10^{-2}$	$1.3 \times 10^{-2}$
2400	65	0.3	...	680	$0.023 \pm 0.005$	0	0.066	$1.3 \times 10^{-4}$	$1.9 \times 10^{-2}$	$1.9 \times 10^{-2}$
Gluino ( $f = 0.5$ ) with the <i>tracker-only</i> analysis										
400	65	0.3	...	50	$28.700 \pm 6.030$	24	0.094	$9.5 \times 10^{+1}$	$6.6 \times 10^{-2}$	$5.2 \times 10^{-2}$
800	65	0.3	...	340	$0.491 \pm 0.105$	0	0.129	1.5	$9.5 \times 10^{-3}$	$9.5 \times 10^{-3}$
1200	65	0.3	...	580	$0.050 \pm 0.011$	0	0.127	$8.4 \times 10^{-2}$	$9.7 \times 10^{-3}$	$9.7 \times 10^{-3}$
1600	65	0.3	...	710	$0.018 \pm 0.004$	0	0.096	$8.0 \times 10^{-3}$	$1.3 \times 10^{-2}$	$1.3 \times 10^{-2}$
2000	65	0.3	...	760	$0.013 \pm 0.003$	0	0.063	$9.7 \times 10^{-4}$	$2.0 \times 10^{-2}$	$2.0 \times 10^{-2}$
2400	65	0.3	...	740	$0.014 \pm 0.003$	0	0.040	$1.3 \times 10^{-4}$	$3.1 \times 10^{-2}$	$3.1 \times 10^{-2}$

The total systematic uncertainty in the signal acceptance is the sum in quadrature of the uncertainties due to the sources discussed above. For almost all signal models, it is less than 20% for both analyses. Only for the *tracker+TOF* analysis of the gluino ( $f = 0.5$ ) sample it is larger, but does not exceed 25%.

Table II summarizes the systematic uncertainties for the two analyses. As the uncertainty often depends on the

model and HSCP mass, the largest systematic uncertainty is reported for each source.

## VII. RESULTS

No significant excess of events is observed above the predicted background. Cross section limits are placed at 95% CL using a  $CL_s$  approach [53–55] where a profile

TABLE IV. Summary of the search for long-lived top squarks: the  $p_T$  (GeV),  $I_{as}$ ,  $1/\beta$ , and mass thresholds  $M$  (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass (GeV)	$p_T$	Requirements		M	Yields		Signal		$\sigma$ (pb)	
		$I_{as}$	$1/\beta$		SM predicted	data	eff.	theo.	exp.	obs.
Top squark with the <i>tracker-only</i> analysis										
200	65	0.3	...	0	$28.700 \pm 6.030$	24	0.195	$6.1 \times 10^{+1}$	$3.3 \times 10^{-2}$	$2.5 \times 10^{-2}$
600	65	0.3	...	40	$28.700 \pm 6.030$	24	0.266	$1.7 \times 10^{-1}$	$2.4 \times 10^{-2}$	$1.8 \times 10^{-2}$
1000	65	0.3	...	320	$0.632 \pm 0.136$	0	0.260	$6.0 \times 10^{-3}$	$4.7 \times 10^{-3}$	$4.7 \times 10^{-3}$
1800	65	0.3	...	660	$0.026 \pm 0.006$	0	0.163	$4.6 \times 10^{-5}$	$7.4 \times 10^{-3}$	$7.4 \times 10^{-3}$
2200	65	0.3	...	690	$0.021 \pm 0.005$	0	0.109	$6.0 \times 10^{-6}$	$1.1 \times 10^{-2}$	$1.1 \times 10^{-2}$
Top squark charge-suppressed with the <i>tracker-only</i> analysis										
200	65	0.3	...	0	$28.700 \pm 6.030$	24	0.046	$6.1 \times 10^{+1}$	$1.4 \times 10^{-1}$	$1.1 \times 10^{-1}$
600	65	0.3	...	90	$22.500 \pm 4.710$	16	0.169	$1.7 \times 10^{-1}$	$3.1 \times 10^{-2}$	$2.3 \times 10^{-2}$
1000	65	0.3	...	320	$0.632 \pm 0.136$	0	0.195	$6.0 \times 10^{-3}$	$7.4 \times 10^{-3}$	$6.1 \times 10^{-3}$
1800	65	0.3	...	550	$0.063 \pm 0.014$	0	0.124	$4.6 \times 10^{-5}$	$9.9 \times 10^{-3}$	$9.9 \times 10^{-3}$
2200	65	0.3	...	580	$0.050 \pm 0.011$	0	0.087	$6.0 \times 10^{-6}$	$1.5 \times 10^{-2}$	$1.5 \times 10^{-2}$

TABLE V. Summary of the search for long-lived tau sleptons: the  $p_T$  (GeV),  $I_{as}$ ,  $1/\beta$ , and mass thresholds  $M$  (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass (GeV)	$p_T$	Requirements		M	Yields		Signal		$\sigma$ (pb)	
		$I_{as}$	$1/\beta$		SM predicted	Data	Eff.	Theo.	Exp.	Obs.
Inclusive tau slepton with the <i>tracker+TOF</i> analysis										
200	65	0.175	1.25	50	$0.861 \pm 0.174$	0	0.290	$2.8 \times 10^{-1}$	$6.0 \times 10^{-3}$	$4.3 \times 10^{-3}$
308	65	0.175	1.25	130	$0.081 \pm 0.016$	0	0.431	$2.5 \times 10^{-2}$	$2.9 \times 10^{-3}$	$2.9 \times 10^{-3}$
494	65	0.175	1.25	260	$0.008 \pm 0.002$	0	0.592	$1.9 \times 10^{-3}$	$2.1 \times 10^{-3}$	$2.1 \times 10^{-3}$
651	65	0.175	1.25	380	$0.002 \pm 0.000$	0	0.662	$4.1 \times 10^{-4}$	$1.9 \times 10^{-3}$	$1.9 \times 10^{-3}$
1029	65	0.175	1.25	610	$0.000 \pm 0.000$	0	0.710	$2.2 \times 10^{-5}$	$1.7 \times 10^{-3}$	$1.7 \times 10^{-3}$
1599	65	0.175	1.25	910	$0.000 \pm 0.000$	0	0.549	$1.0 \times 10^{-6}$	$2.3 \times 10^{-3}$	$2.3 \times 10^{-3}$
Direct pair production of tau slepton with the <i>tracker+TOF</i> analysis										
200	65	0.175	1.25	40	$0.924 \pm 0.187$	0	0.242	$8.0 \times 10^{-3}$	$7.1 \times 10^{-3}$	$4.9 \times 10^{-3}$
308	65	0.175	1.25	110	$0.130 \pm 0.026$	0	0.315	$1.5 \times 10^{-3}$	$3.9 \times 10^{-3}$	$3.9 \times 10^{-3}$
494	65	0.175	1.25	230	$0.013 \pm 0.003$	0	0.415	$1.9 \times 10^{-4}$	$3.0 \times 10^{-3}$	$3.0 \times 10^{-3}$
651	65	0.175	1.25	330	$0.003 \pm 0.001$	0	0.496	$4.9 \times 10^{-5}$	$2.5 \times 10^{-3}$	$2.5 \times 10^{-3}$
1029	65	0.175	1.25	590	$0.000 \pm 0.000$	0	0.592	$4.0 \times 10^{-6}$	$2.0 \times 10^{-3}$	$2.0 \times 10^{-3}$
1599	65	0.175	1.25	930	$0.000 \pm 0.000$	0	0.504	0.0	$2.5 \times 10^{-3}$	$2.5 \times 10^{-3}$

likelihood technique [56] is used. It utilizes a log-normal model [57,58] for the nuisance parameters, which are the integrated luminosity, the signal acceptance, and the expected background in the signal region. The observed limits are shown in Fig. 4 for both the *tracker-only* and the *tracker+TOF* analyses along with the theoretical predictions. The theoretical cross sections are computed at NLO or NLO + NLL [59–62] using PROSPINO [63] with CTEQ6.6M PDFs [64]. The uncertainty bands of the theoretical cross sections include the PDF uncertainty, the renormalization and factorization scale uncertainties,

and the uncertainty in  $\alpha_s$ . The 95% CL limits on the production cross sections are shown in Tables III, IV, V, and VI for long-lived gluino, top squark, tau slepton, and modified Drell–Yan signals, respectively. The limits were determined from the numbers of events passing all final criteria (including the mass criteria).

Mass limits are obtained from the intersection of the observed limit and the central value of the theoretical cross section. The *tracker-only* analysis excludes  $f = 0.1$  gluino masses below 1610 (1580) GeV for the cloud interaction model (charge-suppressed model). Top squark masses

TABLE VI. Summary of the search for long-lived particles from modified Drell–Yan models of various charge: the  $p_T$  (GeV),  $I_{as}$ ,  $1/\beta$ , and mass thresholds  $M$  (GeV) requirements, the predicted and observed yields passing these criteria, and the resulting expected (exp.) and observed (obs.) cross section limits. The signal efficiencies and theoretical (theo.) cross sections are also listed.

Mass (GeV)	$p_T$	Requirements		M	Yields		Signal		$\sigma$ (pb)	
		$I_{as}$	$1/\beta$		SM predicted	data	eff.	theo.	exp.	obs.
Modified Drell–Yan $ Q  = 1e$ particles with the <i>tracker+TOF</i> analysis										
200	65	0.175	1.25	80	$0.319 \pm 0.065$	0	0.303	$1.1 \times 10^{-1}$	$4.2 \times 10^{-3}$	$4.2 \times 10^{-3}$
400	65	0.175	1.25	210	$0.018 \pm 0.004$	0	0.417	$7.3 \times 10^{-3}$	$3.1 \times 10^{-3}$	$3.1 \times 10^{-3}$
600	65	0.175	1.25	350	$0.002 \pm 0.000$	0	0.461	$1.2 \times 10^{-3}$	$2.8 \times 10^{-3}$	$2.8 \times 10^{-3}$
800	65	0.175	1.25	480	$0.001 \pm 0.000$	0	0.485	$2.6 \times 10^{-4}$	$2.6 \times 10^{-3}$	$2.6 \times 10^{-3}$
1000	65	0.175	1.25	610	$0.000 \pm 0.000$	0	0.485	$7.6 \times 10^{-5}$	$2.7 \times 10^{-3}$	$2.7 \times 10^{-3}$
1800	65	0.175	1.25	1020	$0.000 \pm 0.000$	0	0.312	$1.0 \times 10^{-6}$	$4.1 \times 10^{-3}$	$4.1 \times 10^{-3}$
2600	65	0.175	1.25	1270	$0.000 \pm 0.000$	0	0.114	0.0	$1.1 \times 10^{-2}$	$1.1 \times 10^{-2}$
Modified Drell–Yan $ Q  = 2e$ particles with the <i>tracker+TOF</i> analysis										
200	65	0.175	1.25	0	$0.930 \pm 0.188$	0	0.212	$3.0 \times 10^{-1}$	$8.0 \times 10^{-3}$	$6.1 \times 10^{-3}$
400	65	0.175	1.25	90	$0.230 \pm 0.047$	0	0.409	$2.3 \times 10^{-2}$	$3.0 \times 10^{-3}$	$3.0 \times 10^{-3}$
600	65	0.175	1.25	200	$0.021 \pm 0.004$	0	0.481	$3.5 \times 10^{-3}$	$2.7 \times 10^{-3}$	$2.7 \times 10^{-3}$
800	65	0.175	1.25	300	$0.004 \pm 0.001$	0	0.487	$8.0 \times 10^{-4}$	$2.6 \times 10^{-3}$	$2.6 \times 10^{-3}$
1000	65	0.175	1.25	360	$0.002 \pm 0.000$	0	0.449	$2.4 \times 10^{-4}$	$2.8 \times 10^{-3}$	$2.8 \times 10^{-3}$
1800	65	0.175	1.25	410	$0.001 \pm 0.000$	0	0.182	$4.0 \times 10^{-6}$	$6.9 \times 10^{-3}$	$6.9 \times 10^{-3}$
2600	65	0.175	1.25	480	$0.001 \pm 0.000$	0	0.069	0.0	$1.8 \times 10^{-2}$	$1.8 \times 10^{-2}$

TABLE VII. Mass limits obtained at  $\sqrt{s} = 13$  TeV for various HSCP candidate models compared with earlier results for  $\sqrt{s} = 7 + 8$  TeV [27]. In the model name, “CS” stands for charged suppressed interaction model and “DY” for Drell–Yan. The limits for doubly charged particles are also compared to the earlier CMS results obtained with the “*multiply charged*” analysis, which was specifically designed to search for multiply charged particles.

Model	Analysis used	$\sqrt{s} = 7 + 8$ TeV	$\sqrt{s} = 13$ TeV
Gluino $f = 0.1$	<i>tracker-only</i>	$M > 1320$ GeV	$M > 1610$ GeV
	<i>tracker+TOF</i>	$M > 1290$ GeV	$M > 1580$ GeV
Gluino $f = 0.1$ CS	<i>tracker-only</i>	$M > 1230$ GeV	$M > 1580$ GeV
Gluino $f = 0.5$	<i>tracker-only</i>	$M > 1250$ GeV	$M > 1520$ GeV
	<i>tracker+TOF</i>	$M > 1220$ GeV	$M > 1490$ GeV
Gluino $f = 0.5$ CS	<i>tracker-only</i>	$M > 1150$ GeV	$M > 1540$ GeV
Top squark	<i>tracker-only</i>	$M > 930$ GeV	$M > 1040$ GeV
	<i>tracker+TOF</i>	$M > 910$ GeV	$M > 990$ GeV
Top squark CS	<i>tracker-only</i>	$M > 810$ GeV	$M > 1000$ GeV
GMSB tau slepton	<i>tracker+TOF</i>	$M > 430$ GeV	$M > 490$ GeV
	<i>tracker-only</i>	$M > 389$ GeV	$M > 480$ GeV
Pair prod. tau slepton	<i>tracker+TOF</i>	$M > 330$ GeV	$M > 240$ GeV
	<i>tracker-only</i>	$M > 180$ GeV	...
DY $ Q  = 1e$	<i>tracker-only</i>	$M > 640$ GeV	$M > 510$ GeV
	<i>tracker+TOF</i>	$M > 650$ GeV	$M > 550$ GeV
DY $ Q  = 2e$	<i>multiply charged</i>	$M > 720$ GeV	...
	<i>tracker-only</i>	$M > 520$ GeV	$M > 680$ GeV
	<i>tracker+TOF</i>	$M > 520$ GeV	$M > 660$ GeV

below 1040 (1000) GeV are excluded for the cloud (charge-suppressed) models. In addition, the *tracker+TOF* analysis excludes  $\tilde{\tau}_1$  masses below 490 (240) GeV for the GMSB (direct pair production) model. Drell–Yan signals with  $|Q| = 1e$  ( $2e$ ) are excluded below 550 (680) GeV.

The mass limits obtained at  $\sqrt{s} = 13$  TeV for various HSCP signal models are summarized in Table VII and compared with earlier results at  $\sqrt{s} = 7$  and 8 TeV [27]. A significant increase in mass limit is obtained for all models with large QCD production cross section (gluinos, top squarks, and inclusive production of GMSB tau sleptons), arising from the higher center-of-mass energy pp collisions delivered by the LHC. For scenarios with much smaller cross sections, directly pair-produced tau sleptons and Drell–Yan signals with  $|Q| = 1e$ , the results do not improve, because the larger integrated luminosity at 7 and 8 TeV with respect to that at 13 TeV prevails over the effect of the increase of the center-of-mass energy. For the  $|Q| = 2e$  analysis, results from the previous analysis optimized for multiply charged signals [27] are also provided.

### VIII. SUMMARY

A search for heavy stable charged particles produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the CMS detector is presented. Two complementary analyses were performed: using only the tracker and using both the tracker and the muon system. The data are found to be compatible with the expected background. Mass limits for long-lived gluinos, top squarks, tau sleptons, and multiply charged

particles are calculated. The models for  $R$ -hadronlike HSCPs include a varying fraction of  $\tilde{g}$ -gluon hadronization and two different interaction models leading to a variety of exotic experimental signatures. The limits are significantly improved over those from Run 1 of the LHC, and the limits on long-lived gluinos, ranging up to 1610 GeV, are the most stringent to date.

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Dogra,<sup>12a</sup> T. R. Fernandez Perez Tomei,<sup>12a</sup> E. M. Gregores,<sup>12b</sup> P. G. Mercadante,<sup>12b</sup> C. S. Moon,<sup>12a</sup> S. F. Novaes,<sup>12a</sup> Sandra S. Padula,<sup>12a</sup> D. Romero Abad,<sup>12b</sup> J. C. Ruiz Vargas,<sup>12a</sup> A. Aleksandrov,<sup>13</sup> R. Hadjiiska,<sup>13</sup> P. Iaydjiev,<sup>13</sup> M. Rodozov,<sup>13</sup> S. Stoykova,<sup>13</sup> G. Sultanov,<sup>13</sup> M. Vutova,<sup>13</sup> A. Dimitrov,<sup>14</sup> I. Glushkov,<sup>14</sup> L. Litov,<sup>14</sup> B. Pavlov,<sup>14</sup> P. Petkov,<sup>14</sup> W. Fang,<sup>15,g</sup> M. Ahmad,<sup>16</sup> J. G. Bian,<sup>16</sup> G. M. Chen,<sup>16</sup> H. S. Chen,<sup>16</sup> M. Chen,<sup>16</sup> Y. Chen,<sup>16,h</sup> T. Cheng,<sup>16</sup> C. H. Jiang,<sup>16</sup> D. Leggat,<sup>16</sup> Z. Liu,<sup>16</sup> F. Romeo,<sup>16</sup> S. M. Shaheen,<sup>16</sup> A. Spiezia,<sup>16</sup> J. Tao,<sup>16</sup> C. Wang,<sup>16</sup> Z. Wang,<sup>16</sup> H. 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Bloch,<sup>32</sup> J.-M. Brom,<sup>32</sup> M. Buttignol,<sup>32</sup> E. C. Chabert,<sup>32</sup> N. Chanon,<sup>32</sup> C. Collard,<sup>32</sup> E. Conte,<sup>32,n</sup> X. Coubez,<sup>32</sup> J.-C. Fontaine,<sup>32,n</sup> D. Gelé,<sup>32</sup> U. Goerlach,<sup>32</sup> A.-C. Le Bihan,<sup>32</sup> K. Skovpen,<sup>32</sup> P. Van Hove,<sup>32</sup> S. Gadrat,<sup>33</sup> S. Beauceron,<sup>34</sup> C. Bernet,<sup>34</sup> G. Boudoul,<sup>34</sup> E. Bouvier,<sup>34</sup> C. A. Carrillo Montoya,<sup>34</sup> R. Chierici,<sup>34</sup> D. Contardo,<sup>34</sup> B. Courbon,<sup>34</sup> P. Depasse,<sup>34</sup> H. El Mamouni,<sup>34</sup> J. Fan,<sup>34</sup> J. Fay,<sup>34</sup> S. Gascon,<sup>34</sup> M. Gouzevitch,<sup>34</sup>

G. Grenier,<sup>34</sup> B. Ille,<sup>34</sup> F. Lagarde,<sup>34</sup> I. B. Laktineh,<sup>34</sup> M. Lethuillier,<sup>34</sup> L. Mirabito,<sup>34</sup> A. L. Pequegnot,<sup>34</sup> S. Perries,<sup>34</sup> A. Popov,<sup>34,o</sup> D. Sabes,<sup>34</sup> V. Sordini,<sup>34</sup> M. Vander Donckt,<sup>34</sup> P. Verdier,<sup>34</sup> S. Viret,<sup>34</sup> T. Toriashvili,<sup>35,p</sup> Z. Tsamalaidze,<sup>36,i</sup> C. Autermann,<sup>37</sup> S. Beranek,<sup>37</sup> L. Feld,<sup>37</sup> A. Heister,<sup>37</sup> M. K. Kiesel,<sup>37</sup> K. Klein,<sup>37</sup> M. Lipinski,<sup>37</sup> A. Ostapchuk,<sup>37</sup> M. Preuten,<sup>37</sup> F. Raupach,<sup>37</sup> S. Schael,<sup>37</sup> C. Schomakers,<sup>37</sup> J. F. Schulte,<sup>37</sup> J. Schulz,<sup>37</sup> T. Verlage,<sup>37</sup> H. Weber,<sup>37</sup> V. Zhukov,<sup>37,o</sup> A. Albert,<sup>38</sup> M. Brodski,<sup>38</sup> E. Dietz-Laursonn,<sup>38</sup> D. Duchardt,<sup>38</sup> M. Endres,<sup>38</sup> M. Erdmann,<sup>38</sup> S. Erdweg,<sup>38</sup> T. Esch,<sup>38</sup> R. Fischer,<sup>38</sup> A. Güth,<sup>38</sup> M. Hamer,<sup>38</sup> T. Hebbeker,<sup>38</sup> C. Heidemann,<sup>38</sup> K. Hoepfner,<sup>38</sup> S. Knutzen,<sup>38</sup> M. Merschmeyer,<sup>38</sup> A. Meyer,<sup>38</sup> P. Millet,<sup>38</sup> S. Mukherjee,<sup>38</sup> M. Olschewski,<sup>38</sup> K. Padeken,<sup>38</sup> T. Pook,<sup>38</sup> M. Radziej,<sup>38</sup> H. Reithler,<sup>38</sup> M. Rieger,<sup>38</sup> F. Scheuch,<sup>38</sup> L. Sonnenschein,<sup>38</sup> D. Teyssier,<sup>38</sup> S. Thüer,<sup>38</sup> V. Cherepanov,<sup>39</sup> G. Flügge,<sup>39</sup> W. Haj Ahmad,<sup>39</sup> F. Hoehle,<sup>39</sup> B. Kargoll,<sup>39</sup> T. Kress,<sup>39</sup> A. Künsken,<sup>39</sup> J. Lingemann,<sup>39</sup> T. Müller,<sup>39</sup> A. Nehr Korn,<sup>39</sup> A. Nowack,<sup>39</sup> I. M. Nugent,<sup>39</sup> C. Pistone,<sup>39</sup> O. Pooth,<sup>39</sup> A. Stahl,<sup>39,q</sup> M. 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Lobanov,<sup>40</sup> W. Lohmann,<sup>40,t</sup> R. Mankel,<sup>40</sup> I.-A. Melzer-Pellmann,<sup>40</sup> A. B. Meyer,<sup>40</sup> G. Mittag,<sup>40</sup> J. Mnich,<sup>40</sup> A. Mussgiller,<sup>40</sup> E. Ntomari,<sup>40</sup> D. Pitzl,<sup>40</sup> R. Placakyte,<sup>40</sup> A. Raspereza,<sup>40</sup> B. Roland,<sup>40</sup> M. Ö. Sahin,<sup>40</sup> P. Saxena,<sup>40</sup> T. Schoerner-Sadenius,<sup>40</sup> C. Seitz,<sup>40</sup> S. Spannagel,<sup>40</sup> N. Stefaniuk,<sup>40</sup> G. P. Van Onsem,<sup>40</sup> R. Walsh,<sup>40</sup> C. Wissing,<sup>40</sup> V. Blobel,<sup>41</sup> M. Centis Vignali,<sup>41</sup> A. R. Draeger,<sup>41</sup> T. Dreyer,<sup>41</sup> E. Garutti,<sup>41</sup> D. Gonzalez,<sup>41</sup> J. Haller,<sup>41</sup> M. Hoffmann,<sup>41</sup> A. Junkes,<sup>41</sup> R. Klanner,<sup>41</sup> R. Kogler,<sup>41</sup> N. Kovalchuk,<sup>41</sup> T. Lapsien,<sup>41</sup> T. Lenz,<sup>41</sup> I. Marchesini,<sup>41</sup> D. Marconi,<sup>41</sup> M. Meyer,<sup>41</sup> M. Niedziela,<sup>41</sup> D. Nowatschin,<sup>41</sup> F. Pantaleo,<sup>41,q</sup> T. Peiffer,<sup>41</sup> A. Pericaneu,<sup>41</sup> J. Poehlsen,<sup>41</sup> C. Sander,<sup>41</sup> C. Scharf,<sup>41</sup> P. Schleper,<sup>41</sup> A. Schmidt,<sup>41</sup> S. Schumann,<sup>41</sup> J. Schwandt,<sup>41</sup> H. Stadie,<sup>41</sup> G. Steinbrück,<sup>41</sup> F. M. Stober,<sup>41</sup> M. Stöver,<sup>41</sup> H. Tholen,<sup>41</sup> D. Troendle,<sup>41</sup> E. Usai,<sup>41</sup> L. Vanelderen,<sup>41</sup> A. Vanhoefer,<sup>41</sup> B. Vormwald,<sup>41</sup> C. Barth,<sup>42</sup> C. Baus,<sup>42</sup> J. Berger,<sup>42</sup> E. Butz,<sup>42</sup> T. Chwalek,<sup>42</sup> F. Colombo,<sup>42</sup> W. De Boer,<sup>42</sup> A. Dierlamm,<sup>42</sup> S. Fink,<sup>42</sup> R. Friese,<sup>42</sup> M. Giffels,<sup>42</sup> A. Gilbert,<sup>42</sup> P. Goldenzweig,<sup>42</sup> D. Haitz,<sup>42</sup> F. Hartmann,<sup>42,q</sup> S. M. Heindl,<sup>42</sup> U. Husemann,<sup>42</sup> I. Katkov,<sup>42,o</sup> P. Lobelle Pardo,<sup>42</sup> B. Maier,<sup>42</sup> H. Mildner,<sup>42</sup> M. U. Mozer,<sup>42</sup> Th. Müller,<sup>42</sup> M. Plagge,<sup>42</sup> G. Quast,<sup>42</sup> K. Rabbertz,<sup>42</sup> S. Röcker,<sup>42</sup> F. Roscher,<sup>42</sup> M. Schröder,<sup>42</sup> I. Shvetsov,<sup>42</sup> G. Sieber,<sup>42</sup> H. J. Simonis,<sup>42</sup> R. Ulrich,<sup>42</sup> J. Wagner-Kuhr,<sup>42</sup> S. Wayand,<sup>42</sup> M. Weber,<sup>42</sup> T. Weiler,<sup>42</sup> S. Williamson,<sup>42</sup> C. Wöhrmann,<sup>42</sup> R. Wolf,<sup>42</sup> G. Anagnostou,<sup>43</sup> G. Daskalakis,<sup>43</sup> T. Geralis,<sup>43</sup> V. A. Giakoumopoulou,<sup>43</sup> A. Kyriakis,<sup>43</sup> D. Loukas,<sup>43</sup> I. Topsis-Giotis,<sup>43</sup> S. Kesisoglou,<sup>44</sup> A. Panagiotou,<sup>44</sup> N. Saoulidou,<sup>44</sup> E. Tziaferi,<sup>44</sup> I. Evangelou,<sup>45</sup> G. Flouris,<sup>45</sup> C. Foudas,<sup>45</sup> P. Kokkas,<sup>45</sup> N. Loukas,<sup>45</sup> N. Manthos,<sup>45</sup> I. Papadopoulos,<sup>45</sup> E. Paradas,<sup>45</sup> N. Filipovic,<sup>46</sup> G. Bencze,<sup>47</sup> C. Hajdu,<sup>47</sup> P. Hidas,<sup>47</sup> D. Horvath,<sup>47,u</sup> F. Sikler,<sup>47</sup> V. Veszpremi,<sup>47</sup> G. Vesztergombi,<sup>47,v</sup> A. J. Zsigmond,<sup>47</sup> N. Beni,<sup>48</sup> S. Czellar,<sup>48</sup> J. Karancsi,<sup>48,w</sup> A. Makovec,<sup>48</sup> J. Molnar,<sup>48</sup> Z. Szillasi,<sup>48</sup> M. Bartók,<sup>49,v</sup> P. Raics,<sup>49</sup> Z. L. Trocsanyi,<sup>49</sup> B. Ujvari,<sup>49</sup> S. Bahinipati,<sup>50</sup> S. Choudhury,<sup>50,x</sup> P. Mal,<sup>50</sup> K. Mandal,<sup>50</sup> A. Nayak,<sup>50,y</sup> D. K. Sahoo,<sup>50</sup> N. Sahoo,<sup>50</sup> S. K. Swain,<sup>50</sup> S. Bansal,<sup>51</sup> S. B. Beri,<sup>51</sup> V. Bhatnagar,<sup>51</sup> R. Chawla,<sup>51</sup> U. Bhawandeep,<sup>51</sup> A. K. Kalsi,<sup>51</sup> A. Kaur,<sup>51</sup> M. Kaur,<sup>51</sup> R. Kumar,<sup>51</sup> A. Mehta,<sup>51</sup> M. Mittal,<sup>51</sup> J. B. Singh,<sup>51</sup> G. Walia,<sup>51</sup> Ashok Kumar,<sup>52</sup> A. Bhardwaj,<sup>52</sup> B. C. Choudhary,<sup>52</sup> R. B. Garg,<sup>52</sup> S. Keshri,<sup>52</sup> S. Malhotra,<sup>52</sup> M. Naimuddin,<sup>52</sup> N. Nishu,<sup>52</sup> K. Ranjan,<sup>52</sup> R. Sharma,<sup>52</sup> V. Sharma,<sup>52</sup> R. Bhattacharya,<sup>53</sup> S. Bhattacharya,<sup>53</sup> K. Chatterjee,<sup>53</sup> S. Dey,<sup>53</sup> S. Dutt,<sup>53</sup> S. Dutta,<sup>53</sup> S. Ghosh,<sup>53</sup> N. Majumdar,<sup>53</sup> A. Modak,<sup>53</sup> K. Mondal,<sup>53</sup> S. Mukhopadhyay,<sup>53</sup> S. Nandan,<sup>53</sup> A. Purohit,<sup>53</sup> A. Roy,<sup>53</sup> D. Roy,<sup>53</sup> S. Roy Chowdhury,<sup>53</sup> S. Sarkar,<sup>53</sup> M. Sharan,<sup>53</sup> S. Thakur,<sup>53</sup> P. K. Behera,<sup>54</sup> R. Chudasama,<sup>55</sup> D. Dutta,<sup>55</sup> V. Jha,<sup>55</sup> V. Kumar,<sup>55</sup> A. K. Mohanty,<sup>55,q</sup> P. K. Netrakanti,<sup>55</sup> L. M. Pant,<sup>55</sup> P. Shukla,<sup>55</sup> A. Topkar,<sup>55</sup> T. Aziz,<sup>56</sup> S. Dugad,<sup>56</sup> G. Kole,<sup>56</sup> B. Mahakud,<sup>56</sup> S. Mitra,<sup>56</sup> G. B. Mohanty,<sup>56</sup> B. Parida,<sup>56</sup> N. Sur,<sup>56</sup> B. Sutar,<sup>56</sup> S. Banerjee,<sup>57</sup> S. Bhowmik,<sup>57,z</sup> R. K. Dewanjee,<sup>57</sup> S. Ganguly,<sup>57</sup> M. Guchait,<sup>57</sup> Sa. Jain,<sup>57</sup> S. Kumar,<sup>57</sup> M. Maity,<sup>57,z</sup> G. Majumder,<sup>57</sup> K. Mazumdar,<sup>57</sup> T. Sarkar,<sup>57,z</sup> N. Wickramage,<sup>57,aa</sup> S. Chauhan,<sup>58</sup> S. Dube,<sup>58</sup> V. Hegde,<sup>58</sup> A. Kapoor,<sup>58</sup> K. Kotheekar,<sup>58</sup> A. Rane,<sup>58</sup> S. Sharma,<sup>58</sup> H. Behnamian,<sup>59</sup> S. Chenarani,<sup>59,bb</sup> E. Eskandari Tadavani,<sup>59</sup> S. M. Etesami,<sup>59,bb</sup> A. Fahim,<sup>59,cc</sup> M. Khakzad,<sup>59</sup> M. Mohammadi Najafabadi,<sup>59</sup> M. Naseri,<sup>59</sup> S. Paktinat Mehdiabadi,<sup>59,dd</sup> F. Rezaei Hosseinabadi,<sup>59</sup> B. Safarzadeh,<sup>59,ee</sup> M. Zeinali,<sup>59</sup> M. Felcini,<sup>60</sup> M. Grunewald,<sup>60</sup> M. Abbrescia,<sup>61a,61b</sup> C. Calabria,<sup>61a,61b</sup> C. Caputo,<sup>61a,61b</sup> A. Colaleo,<sup>61a</sup> D. Creanza,<sup>61a,61c</sup> L. Cristella,<sup>61a,61b</sup> N. De Filippis,<sup>61a,61c</sup> M. De Palma,<sup>61a,61b</sup> L. Fiore,<sup>61a</sup> G. Iaselli,<sup>61a,61c</sup> G. Maggi,<sup>61a,61c</sup> M. Maggi,<sup>61a</sup> G. Miniello,<sup>61a,61b</sup> S. My,<sup>61a,61b</sup> S. Nuzzo,<sup>61a,61b</sup> A. Pompili,<sup>61a,61b</sup> G. Pugliese,<sup>61a,61c</sup> R. Radogna,<sup>61a,61b</sup> A. Ranieri,<sup>61a</sup> G. Selvaggi,<sup>61a,61b</sup> L. Silvestris,<sup>61a,q</sup> R. Venditti,<sup>61a,61b</sup> P. Verwilligen,<sup>61a</sup> G. Abbiendi,<sup>62a</sup> C. Battilana,<sup>62a</sup> D. Bonacorsi,<sup>62a,62b</sup>

- S. Braibant-Giacomelli,<sup>62a,62b</sup> L. Brigliadori,<sup>62a,62b</sup> R. Campanini,<sup>62a,62b</sup> P. Capiluppi,<sup>62a,62b</sup> A. Castro,<sup>62a,62b</sup> F. R. Cavallo,<sup>62a</sup>  
 S. S. Chhibra,<sup>62a,62b</sup> G. Codispoti,<sup>62a,62b</sup> M. Cuffiani,<sup>62a,62b</sup> G. M. Dallavalle,<sup>62a</sup> F. Fabbri,<sup>62a</sup> A. Fanfani,<sup>62a,62b</sup>  
 D. Fasanella,<sup>62a,62b</sup> P. Giacomelli,<sup>62a</sup> C. Grandi,<sup>62a</sup> L. Guiducci,<sup>62a,62b</sup> S. Marcellini,<sup>62a</sup> G. Masetti,<sup>62a</sup> A. Montanari,<sup>62a</sup>  
 F. L. Navarria,<sup>62a,62b</sup> A. Perrotta,<sup>62a</sup> A. M. Rossi,<sup>62a,62b</sup> T. Rovelli,<sup>62a,62b</sup> G. P. Siroli,<sup>62a,62b</sup> N. Tosi,<sup>62a,62b,q</sup> S. Albergo,<sup>63a,63b</sup>  
 M. Chiorboli,<sup>63a,63b</sup> S. Costa,<sup>63a,63b</sup> A. Di Mattia,<sup>63a</sup> F. Giordano,<sup>63a,63b</sup> R. Potenza,<sup>63a,63b</sup> A. Tricomi,<sup>63a,63b</sup> C. Tuve,<sup>63a,63b</sup>  
 G. Barbagli,<sup>64a</sup> V. Ciulli,<sup>64a,64b</sup> C. Civinini,<sup>64a</sup> R. D'Alessandro,<sup>64a,64b</sup> E. Focardi,<sup>64a,64b</sup> V. Gori,<sup>64a,64b</sup> P. Lenzi,<sup>64a,64b</sup>  
 M. Meschini,<sup>64a</sup> S. Paoletti,<sup>64a</sup> G. Sguazzoni,<sup>64a</sup> L. Viliani,<sup>64a,64b,q</sup> L. Benussi,<sup>65</sup> S. Bianco,<sup>65</sup> F. Fabbri,<sup>65</sup> D. Piccolo,<sup>65</sup>  
 F. Primavera,<sup>65,q</sup> V. Calvelli,<sup>66a,66b</sup> F. Ferro,<sup>66a</sup> M. Lo Vetere,<sup>66a,66b</sup> M. R. Monge,<sup>66a,66b</sup> E. Robutti,<sup>66a</sup> S. Tosi,<sup>66a,66b</sup>  
 L. Brianza,<sup>67a,q</sup> M. E. Dinardo,<sup>67a,67b</sup> S. Fiorendi,<sup>67a,67b</sup> S. Gennai,<sup>67a</sup> A. Ghezzi,<sup>67a,67b</sup> P. Govoni,<sup>67a,67b</sup> M. Malberti,<sup>67a</sup>  
 S. Malvezzi,<sup>67a</sup> R. A. Manzoni,<sup>67a,67b,q</sup> B. Marzocchi,<sup>67a,67b</sup> D. Menasce,<sup>67a</sup> L. Moroni,<sup>67a</sup> M. Paganoni,<sup>67a,67b</sup> D. Pedrini,<sup>67a</sup>  
 S. Pigazzini,<sup>67a</sup> S. Ragazzi,<sup>67a,67b</sup> T. Tabarelli de Fatis,<sup>67a,67b</sup> S. Buontempo,<sup>68a</sup> N. Cavallo,<sup>68a,68c</sup> G. De Nardo,<sup>68a</sup>  
 S. Di Guida,<sup>68a,68d,q</sup> M. Esposito,<sup>68a,68b</sup> F. Fabozzi,<sup>68a,68c</sup> A. O. M. Iorio,<sup>68a,68b</sup> G. Lanza,<sup>68a</sup> L. Lista,<sup>68a</sup> S. Meola,<sup>68a,68d,q</sup>  
 P. Paolucci,<sup>68a,q</sup> C. Sciacca,<sup>68a,68b</sup> F. Thyssen,<sup>68a</sup> P. Azzi,<sup>69a,q</sup> N. Bacchetta,<sup>69a</sup> L. Benato,<sup>69a,69b</sup> M. Biasotto,<sup>69a,ff</sup>  
 A. Boletti,<sup>69a,69b</sup> A. Carvalho Antunes De Oliveira,<sup>69a,69b</sup> P. Checchia,<sup>69a</sup> M. Dall'Osso,<sup>69a,69b</sup> P. De Castro Manzano,<sup>69a</sup>  
 T. Dorigo,<sup>69a</sup> F. Fanzago,<sup>69a</sup> F. Gasparini,<sup>69a,69b</sup> U. Gasparini,<sup>69a,69b</sup> A. Gozzelino,<sup>69a</sup> S. Lacaprara,<sup>69a</sup> M. Margoni,<sup>69a,69b</sup>  
 G. Maron,<sup>69a,ff</sup> A. T. Meneguzzo,<sup>69a,69b</sup> J. Pazzini,<sup>69a,69b,q</sup> N. Pozzobon,<sup>69a,69b</sup> P. Ronchese,<sup>69a,69b</sup> F. Simonetto,<sup>69a,69b</sup>  
 E. Torassa,<sup>69a</sup> M. Zanetti,<sup>69a</sup> P. Zotto,<sup>69a,69b</sup> A. Zucchetta,<sup>69a,69b</sup> G. Zumerle,<sup>69a,69b</sup> A. Braghieri,<sup>70a</sup> A. Magnani,<sup>70a,70b</sup>  
 P. Montagna,<sup>70a,70b</sup> S. P. Ratti,<sup>70a,70b</sup> V. Re,<sup>70a</sup> C. Riccardi,<sup>70a,70b</sup> P. Salvini,<sup>70a</sup> I. Vai,<sup>70a,70b</sup> P. Vitulo,<sup>70a,70b</sup>  
 L. Alunni Solostizi,<sup>71a,71b</sup> G. M. Bilei,<sup>71a</sup> D. Ciangottini,<sup>71a,71b</sup> L. Fanò,<sup>71a,71b</sup> P. Lariccia,<sup>71a,71b</sup> R. Leonardi,<sup>71a,71b</sup>  
 G. Mantovani,<sup>71a,71b</sup> M. Menichelli,<sup>71a</sup> A. Saha,<sup>71a</sup> A. Santocchia,<sup>71a,71b</sup> K. Androsov,<sup>72a,gg</sup> P. Azzurri,<sup>72a,q</sup> G. Bagliesi,<sup>72a</sup>  
 J. Bernardini,<sup>72a</sup> T. Boccali,<sup>72a</sup> R. Castaldi,<sup>72a</sup> M. A. Ciocci,<sup>72a,gg</sup> R. Dell'Orso,<sup>72a</sup> S. Donato,<sup>72a,72c</sup> G. Fedi,<sup>72a</sup> A. Giassi,<sup>72a</sup>  
 M. T. Grippo,<sup>72a,gg</sup> F. Ligabue,<sup>72a,72c</sup> T. Lomtadze,<sup>72a</sup> L. Martini,<sup>72a,72b</sup> A. Messineo,<sup>72a,72b</sup> F. Palla,<sup>72a</sup> A. Rizzi,<sup>72a,72b</sup>  
 A. Savoy-Navarro,<sup>72a,hh</sup> P. Spagnolo,<sup>72a</sup> R. Tenchini,<sup>72a</sup> G. Tonelli,<sup>72a,72b</sup> A. Venturi,<sup>72a</sup> P. G. Verdini,<sup>72a</sup> L. Barone,<sup>73a,73b</sup>  
 F. Cavallari,<sup>73a</sup> M. Cipriani,<sup>73a,73b</sup> G. D'imperio,<sup>73a,73b,q</sup> D. Del Re,<sup>73a,73b,q</sup> M. Diemoz,<sup>73a</sup> S. Gelli,<sup>73a,73b</sup> E. Longo,<sup>73a,73b</sup>  
 F. Margaroli,<sup>73a,73b</sup> P. Meridiani,<sup>73a</sup> G. Organtini,<sup>73a,73b</sup> R. Paramatti,<sup>73a</sup> F. Preiato,<sup>73a,73b</sup> S. Rahatlou,<sup>73a,73b</sup> C. Rovelli,<sup>73a</sup>  
 F. Santanastasio,<sup>73a,73b</sup> N. Amapane,<sup>74a,74b</sup> R. Arcidiacono,<sup>74a,74c,q</sup> S. Argiro,<sup>74a,74b</sup> M. Arneodo,<sup>74a,74c</sup> N. Bartosik,<sup>74a</sup>  
 R. Bellan,<sup>74a,74b</sup> C. Biino,<sup>74a</sup> N. Cartiglia,<sup>74a</sup> M. Costa,<sup>74a,74b</sup> G. Cotto,<sup>74a,74b</sup> R. Covarelli,<sup>74a,74b</sup> D. Dattola,<sup>74a</sup>  
 A. Degano,<sup>74a,74b</sup> N. Demaria,<sup>74a</sup> L. Finco,<sup>74a,74b</sup> B. Kiani,<sup>74a,74b</sup> C. Mariotti,<sup>74a</sup> S. Maselli,<sup>74a</sup> E. Migliore,<sup>74a,74b</sup>  
 V. Monaco,<sup>74a,74b</sup> E. Monteil,<sup>74a,74b</sup> M. M. Obertino,<sup>74a,74b</sup> L. Pacher,<sup>74a,74b</sup> N. Pastrone,<sup>74a</sup> M. Pelliccioni,<sup>74a</sup>  
 G. L. Pinna Angioni,<sup>74a,74b</sup> F. Ravera,<sup>74a,74b</sup> A. Romero,<sup>74a,74b</sup> M. Ruspa,<sup>74a,74c</sup> R. Sacchi,<sup>74a,74b</sup> V. Sola,<sup>74a</sup> A. Solano,<sup>74a,74b</sup>  
 A. Staiano,<sup>74a</sup> P. Traczyk,<sup>74a,74b</sup> S. Belforte,<sup>75a</sup> M. Casarsa,<sup>75a</sup> F. Cossutti,<sup>75a</sup> G. Della Ricca,<sup>75a,75b</sup> C. La Licata,<sup>75a,75b</sup>  
 A. Schizzi,<sup>75a,75b</sup> A. Zanetti,<sup>75a</sup> D. H. Kim,<sup>76</sup> G. N. Kim,<sup>76</sup> M. S. Kim,<sup>76</sup> S. Lee,<sup>76</sup> S. W. Lee,<sup>76</sup> Y. D. Oh,<sup>76</sup> S. Sekmen,<sup>76</sup>  
 D. C. Son,<sup>76</sup> Y. C. Yang,<sup>76</sup> A. Lee,<sup>77</sup> H. Kim,<sup>78</sup> J. A. Brochero Cifuentes,<sup>79</sup> T. J. Kim,<sup>79</sup> S. Cho,<sup>80</sup> S. Choi,<sup>80</sup> Y. Go,<sup>80</sup>  
 D. Gyun,<sup>80</sup> S. Ha,<sup>80</sup> B. Hong,<sup>80</sup> Y. Jo,<sup>80</sup> Y. Kim,<sup>80</sup> B. Lee,<sup>80</sup> K. Lee,<sup>80</sup> K. S. Lee,<sup>80</sup> S. Lee,<sup>80</sup> J. Lim,<sup>80</sup> S. K. Park,<sup>80</sup> Y. Roh,<sup>80</sup>  
 J. Almond,<sup>81</sup> J. Kim,<sup>81</sup> H. Lee,<sup>81</sup> S. B. Oh,<sup>81</sup> B. C. Radburn-Smith,<sup>81</sup> S. h. Seo,<sup>81</sup> U. K. Yang,<sup>81</sup> H. D. Yoo,<sup>81</sup> G. B. Yu,<sup>81</sup>  
 M. Choi,<sup>82</sup> H. Kim,<sup>82</sup> J. H. Kim,<sup>82</sup> J. S. H. Lee,<sup>82</sup> I. C. Park,<sup>82</sup> G. Ryu,<sup>82</sup> M. S. Ryu,<sup>82</sup> Y. Choi,<sup>83</sup> J. Goh,<sup>83</sup> C. Hwang,<sup>83</sup>  
 J. Lee,<sup>83</sup> I. Yu,<sup>83</sup> V. Dudenias,<sup>84</sup> A. Juodagalvis,<sup>84</sup> J. Vaitkus,<sup>84</sup> I. Ahmed,<sup>85</sup> Z. A. Ibrahim,<sup>85</sup> J. R. Komaragiri,<sup>85</sup>  
 M. A. B. Md Ali,<sup>85,ii</sup> F. Mohamad Idris,<sup>85,ij</sup> W. A. T. Wan Abdullah,<sup>85</sup> M. N. Yusli,<sup>85</sup> Z. Zolkapli,<sup>85</sup> H. Castilla-Valdez,<sup>86</sup>  
 E. De La Cruz-Burelo,<sup>86</sup> I. Heredia-De La Cruz,<sup>86,kk</sup> A. Hernandez-Almada,<sup>86</sup> R. Lopez-Fernandez,<sup>86</sup> R. Magaña Villalba,<sup>86</sup>  
 J. Mejia Guisao,<sup>86</sup> A. Sanchez-Hernandez,<sup>86</sup> S. Carrillo Moreno,<sup>87</sup> C. Oropeza Barrera,<sup>87</sup> F. Vazquez Valencia,<sup>87</sup>  
 S. Carpintheyro,<sup>88</sup> I. Pedraza,<sup>88</sup> H. A. Salazar Ibarguen,<sup>88</sup> C. Uribe Estrada,<sup>88</sup> A. Morelos Pineda,<sup>89</sup> D. Krofcheck,<sup>90</sup>  
 P. H. Butler,<sup>91</sup> A. Ahmad,<sup>92</sup> M. Ahmad,<sup>92</sup> Q. Hassan,<sup>92</sup> H. R. Hoorani,<sup>92</sup> W. A. Khan,<sup>92</sup> M. A. Shah,<sup>92</sup> M. Shoaib,<sup>92</sup>  
 M. Waqas,<sup>92</sup> H. Bialkowska,<sup>93</sup> M. Bluj,<sup>93</sup> B. Boimska,<sup>93</sup> T. Frueboes,<sup>93</sup> M. Górski,<sup>93</sup> M. Kazana,<sup>93</sup> K. Nawrocki,<sup>93</sup>  
 K. Romanowska-Rybinska,<sup>93</sup> M. Szleper,<sup>93</sup> P. Zalewski,<sup>93</sup> K. Bunkowski,<sup>94</sup> A. Byszuk,<sup>94,ll</sup> K. Doroba,<sup>94</sup> A. Kalinowski,<sup>94</sup>  
 M. Konecki,<sup>94</sup> J. Krolikowski,<sup>94</sup> M. Misiura,<sup>94</sup> M. Olszewski,<sup>94</sup> M. Walczak,<sup>94</sup> P. Bargassa,<sup>95</sup> C. Beirão Da Cruz E Silva,<sup>95</sup>  
 A. Di Francesco,<sup>95</sup> P. Faccioli,<sup>95</sup> P. G. Ferreira Parracho,<sup>95</sup> M. Gallinaro,<sup>95</sup> J. Hollar,<sup>95</sup> N. Leonardo,<sup>95</sup> L. Lloret Iglesias,<sup>95</sup>  
 M. V. Nemallapudi,<sup>95</sup> J. Rodrigues Antunes,<sup>95</sup> J. Seixas,<sup>95</sup> O. Toldaiev,<sup>95</sup> D. Vadrucchio,<sup>95</sup> J. Varela,<sup>95</sup> P. Vischia,<sup>95</sup>  
 V. Alexakhin,<sup>96</sup> I. Golutvin,<sup>96</sup> I. Gorbunov,<sup>96</sup> V. Karjavin,<sup>96</sup> V. Korenkov,<sup>96</sup> A. Lanev,<sup>96</sup> A. Malakhov,<sup>96</sup> V. Matveev,<sup>96,mm,nn</sup>  
 V. V. Mitsyn,<sup>96</sup> P. Moisenz,<sup>96</sup> V. Palichik,<sup>96</sup> V. Perelygin,<sup>96</sup> M. Savina,<sup>96</sup> S. Shmatov,<sup>96</sup> S. Shulha,<sup>96</sup> N. Skatchkov,<sup>96</sup>



V. Smirnov,<sup>96</sup> E. Tikhonenko,<sup>96</sup> A. Zarubin,<sup>96</sup> L. Chtchipounov,<sup>97</sup> V. Golovtsov,<sup>97</sup> Y. Ivanov,<sup>97</sup> V. Kim,<sup>97,oo</sup>  
 E. Kuznetsova,<sup>97,pp</sup> V. Murzin,<sup>97</sup> V. Oreshkin,<sup>97</sup> V. Sulimov,<sup>97</sup> A. Vorobyev,<sup>97</sup> Yu. Andreev,<sup>98</sup> A. Dermenev,<sup>98</sup> S. Gninenko,<sup>98</sup>  
 N. Golubev,<sup>98</sup> A. Karneyev,<sup>98</sup> M. Kirsanov,<sup>98</sup> N. Krasnikov,<sup>98</sup> A. Pashenkov,<sup>98</sup> D. Tlisov,<sup>98</sup> A. Toropin,<sup>98</sup> V. Epshteyn,<sup>99</sup>  
 V. Gavrilov,<sup>99</sup> N. Lychkovskaya,<sup>99</sup> V. Popov,<sup>99</sup> I. Pozdnyakov,<sup>99</sup> G. Safronov,<sup>99</sup> A. Spiridonov,<sup>99</sup> M. Toms,<sup>99</sup> E. Vlasov,<sup>99</sup>  
 A. Zhokin,<sup>99</sup> A. Bylinkin,<sup>100,nn</sup> R. Chistov,<sup>101,qq</sup> M. Danilov,<sup>101,qq</sup> V. Rusinov,<sup>101</sup> V. Andreev,<sup>102</sup> M. Azarkin,<sup>102,nn</sup>  
 I. Dremin,<sup>102,nn</sup> M. Kirakosyan,<sup>102</sup> A. Leonidov,<sup>102,nn</sup> S. V. Rusakov,<sup>102</sup> A. Terkulov,<sup>102</sup> A. Baskakov,<sup>103</sup> A. Belyaev,<sup>103</sup>  
 E. Boos,<sup>103</sup> M. Dubinin,<sup>103,rr</sup> L. Dudko,<sup>103</sup> A. Ershov,<sup>103</sup> A. Gribushin,<sup>103</sup> V. Klyukhin,<sup>103</sup> O. Kodolova,<sup>103</sup> I. Lokhtin,<sup>103</sup>  
 I. Miagkov,<sup>103</sup> S. Obraztsov,<sup>103</sup> S. Petrushanko,<sup>103</sup> V. Savrin,<sup>103</sup> A. Snigirev,<sup>103</sup> V. Blinov,<sup>104,ss</sup> Y. Skovpen,<sup>104,ss</sup>  
 I. Azhgirey,<sup>105</sup> I. Bayshev,<sup>105</sup> S. Bitioukov,<sup>105</sup> D. Elumakhov,<sup>105</sup> V. Kachanov,<sup>105</sup> A. Kalinin,<sup>105</sup> D. Konstantinov,<sup>105</sup>  
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 P. Adzic,<sup>106,tt</sup> P. Cirkovic,<sup>106</sup> D. Devetak,<sup>106</sup> M. Dordevic,<sup>106</sup> J. Milosevic,<sup>106</sup> V. Rekovic,<sup>106</sup> J. Alcaraz Maestre,<sup>107</sup>  
 M. Barrio Luna,<sup>107</sup> E. Calvo,<sup>107</sup> M. Cerrada,<sup>107</sup> M. Chamizo Llatas,<sup>107</sup> N. Colino,<sup>107</sup> B. De La Cruz,<sup>107</sup> A. Delgado Peris,<sup>107</sup>  
 A. Escalante Del Valle,<sup>107</sup> C. Fernandez Bedoya,<sup>107</sup> J. P. Fernández Ramos,<sup>107</sup> J. Flix,<sup>107</sup> M. C. Fouz,<sup>107</sup> P. Garcia-Abia,<sup>107</sup>  
 O. Gonzalez Lopez,<sup>107</sup> S. Goy Lopez,<sup>107</sup> J. M. Hernandez,<sup>107</sup> M. I. Josa,<sup>107</sup> E. Navarro De Martino,<sup>107</sup>  
 A. Pérez-Calero Yzquierdo,<sup>107</sup> J. Puerta Pelayo,<sup>107</sup> A. Quintario Olmeda,<sup>107</sup> I. Redondo,<sup>107</sup> L. Romero,<sup>107</sup> M. S. Soares,<sup>107</sup>  
 J. F. de Trocóniz,<sup>108</sup> M. Missiroli,<sup>108</sup> D. Moran,<sup>108</sup> J. Cuevas,<sup>109</sup> J. Fernandez Menendez,<sup>109</sup> I. Gonzalez Caballero,<sup>109</sup>  
 J. R. González Fernández,<sup>109</sup> E. Palencia Cortezon,<sup>109</sup> S. Sanchez Cruz,<sup>109</sup> I. Suárez Andrés,<sup>109</sup> J. M. Vizán García,<sup>109</sup>  
 I. J. Cabrillo,<sup>110</sup> A. Calderon,<sup>110</sup> J. R. Castiñeiras De Saa,<sup>110</sup> E. Curras,<sup>110</sup> M. Fernandez,<sup>110</sup> J. Garcia-Ferrero,<sup>110</sup>  
 G. Gomez,<sup>110</sup> A. Lopez Virto,<sup>110</sup> J. Marco,<sup>110</sup> C. Martinez Rivero,<sup>110</sup> F. Matorras,<sup>110</sup> J. Piedra Gomez,<sup>110</sup> T. Rodrigo,<sup>110</sup>  
 A. Ruiz-Jimeno,<sup>110</sup> L. Scodellaro,<sup>110</sup> N. Trevisani,<sup>110</sup> I. Vila,<sup>110</sup> R. Vilar Cortabitarte,<sup>110</sup> D. Abbaneo,<sup>111</sup> E. Auffray,<sup>111</sup>  
 G. Auzinger,<sup>111</sup> M. Bachtis,<sup>111</sup> P. Baillon,<sup>111</sup> A. H. Ball,<sup>111</sup> D. Barney,<sup>111</sup> P. Bloch,<sup>111</sup> A. Bocci,<sup>111</sup> A. Bonato,<sup>111</sup> C. Botta,<sup>111</sup>  
 T. Camporesi,<sup>111</sup> R. Castello,<sup>111</sup> M. Cepeda,<sup>111</sup> G. Cerminara,<sup>111</sup> M. D'Alfonso,<sup>111</sup> D. d'Enterria,<sup>111</sup> A. Dabrowski,<sup>111</sup>  
 V. Daponte,<sup>111</sup> A. David,<sup>111</sup> M. De Gruttola,<sup>111</sup> A. De Roeck,<sup>111</sup> E. Di Marco,<sup>111,uu</sup> M. Dobson,<sup>111</sup> B. Dorney,<sup>111</sup>  
 T. du Pree,<sup>111</sup> D. Duggan,<sup>111</sup> M. Dünser,<sup>111</sup> N. Dupont,<sup>111</sup> A. Elliott-Peisert,<sup>111</sup> S. Fartoukh,<sup>111</sup> G. Franzoni,<sup>111</sup> J. Fulcher,<sup>111</sup>  
 W. Funk,<sup>111</sup> D. Gigi,<sup>111</sup> K. Gill,<sup>111</sup> M. Girone,<sup>111</sup> F. Glege,<sup>111</sup> D. Gulhan,<sup>111</sup> S. Gundacker,<sup>111</sup> M. Guthoff,<sup>111</sup> J. Hammer,<sup>111</sup>  
 P. Harris,<sup>111</sup> J. Hegeman,<sup>111</sup> V. Innocente,<sup>111</sup> P. Janot,<sup>111</sup> J. Kieseler,<sup>111</sup> H. Kirschenmann,<sup>111</sup> V. Knünz,<sup>111</sup> A. Kornmayer,<sup>111,q</sup>  
 M. J. Kortelainen,<sup>111</sup> K. Kousouris,<sup>111</sup> M. Kramer,<sup>111,b</sup> C. Lange,<sup>111</sup> P. Lecoq,<sup>111</sup> C. Lourenço,<sup>111</sup> M. T. Lucchini,<sup>111</sup>  
 L. Malgeri,<sup>111</sup> M. Mannelli,<sup>111</sup> A. Martelli,<sup>111</sup> F. Meijers,<sup>111</sup> J. A. Merlin,<sup>111</sup> S. Mersi,<sup>111</sup> E. Meschi,<sup>111</sup> F. Moortgat,<sup>111</sup>  
 S. Morovic,<sup>111</sup> M. Mulders,<sup>111</sup> H. Neugebauer,<sup>111</sup> S. Orfanelli,<sup>111</sup> L. Orsini,<sup>111</sup> L. Pape,<sup>111</sup> E. Perez,<sup>111</sup> M. Peruzzi,<sup>111</sup>  
 A. Petrilli,<sup>111</sup> G. Petrucciani,<sup>111</sup> A. Pfeiffer,<sup>111</sup> M. Pierini,<sup>111</sup> A. Racz,<sup>111</sup> T. Reis,<sup>111</sup> G. Rolandi,<sup>111,vv</sup> M. Rovere,<sup>111</sup>  
 M. Ruan,<sup>111</sup> H. Sakulin,<sup>111</sup> J. B. Sauvan,<sup>111</sup> C. Schäfer,<sup>111</sup> C. Schwick,<sup>111</sup> M. Seidel,<sup>111</sup> A. Sharma,<sup>111</sup> P. Silva,<sup>111</sup>  
 P. Sphicas,<sup>111,ww</sup> J. Steggemann,<sup>111</sup> M. Stoye,<sup>111</sup> Y. Takahashi,<sup>111</sup> M. Tosi,<sup>111</sup> D. Treille,<sup>111</sup> A. Triossi,<sup>111</sup> A. Tsiros,<sup>111</sup>  
 V. Veckalns,<sup>111,xx</sup> G. I. Veres,<sup>111,v</sup> N. Wardle,<sup>111</sup> H. K. Wöhri,<sup>111</sup> A. Zagozdinska,<sup>111,ll</sup> W. D. Zeuner,<sup>111</sup> W. Bertl,<sup>112</sup>  
 K. Deiters,<sup>112</sup> W. Erdmann,<sup>112</sup> R. Horisberger,<sup>112</sup> Q. Ingram,<sup>112</sup> H. C. Kaestli,<sup>112</sup> D. Kotlinski,<sup>112</sup> U. Langenegger,<sup>112</sup>  
 T. Rohe,<sup>112</sup> F. Bachmair,<sup>113</sup> L. Bäni,<sup>113</sup> L. Bianchini,<sup>113</sup> B. Casal,<sup>113</sup> G. Dissertori,<sup>113</sup> M. Dittmar,<sup>113</sup> M. Donegà,<sup>113</sup>  
 C. Grab,<sup>113</sup> C. Heidegger,<sup>113</sup> D. Hits,<sup>113</sup> J. Hoss,<sup>113</sup> G. Kasieczka,<sup>113</sup> P. Lecomte,<sup>113,a</sup> W. Lustermaan,<sup>113</sup> B. Mangano,<sup>113</sup>  
 M. Marionneau,<sup>113</sup> P. Martinez Ruiz del Arbol,<sup>113</sup> M. Masciovecchio,<sup>113</sup> M. T. Meinhard,<sup>113</sup> D. Meister,<sup>113</sup> F. Micheli,<sup>113</sup>  
 P. Musella,<sup>113</sup> F. Nessi-Tedaldi,<sup>113</sup> F. Pandolfi,<sup>113</sup> J. Pata,<sup>113</sup> F. Pauss,<sup>113</sup> G. Perrin,<sup>113</sup> L. Perrozzi,<sup>113</sup> M. Quittnat,<sup>113</sup>  
 M. Rossini,<sup>113</sup> M. Schönenberger,<sup>113</sup> A. Starodumov,<sup>113,yy</sup> V. R. Tavolaro,<sup>113</sup> K. Theofilatos,<sup>113</sup> R. Wallny,<sup>113</sup>  
 T. K. Aarrestad,<sup>114</sup> C. Amsler,<sup>114,zz</sup> L. Caminada,<sup>114</sup> M. F. Canelli,<sup>114</sup> A. De Cosa,<sup>114</sup> C. Galloni,<sup>114</sup> A. Hinzmann,<sup>114</sup>  
 T. Hreus,<sup>114</sup> B. Kilminster,<sup>114</sup> J. Ngadiuba,<sup>114</sup> D. Pinna,<sup>114</sup> G. Rauco,<sup>114</sup> P. Robmann,<sup>114</sup> D. Salerno,<sup>114</sup> Y. Yang,<sup>114</sup>  
 V. Candelise,<sup>115</sup> T. H. Doan,<sup>115</sup> Sh. Jain,<sup>115</sup> R. Khurana,<sup>115</sup> M. Konyushikhin,<sup>115</sup> C. M. Kuo,<sup>115</sup> W. Lin,<sup>115</sup> Y. J. Lu,<sup>115</sup>  
 A. Pozdnyakov,<sup>115</sup> S. S. Yu,<sup>115</sup> Arun Kumar,<sup>116</sup> P. Chang,<sup>116</sup> Y. H. Chang,<sup>116</sup> Y. W. Chang,<sup>116</sup> Y. Chao,<sup>116</sup> K. F. Chen,<sup>116</sup>  
 P. H. Chen,<sup>116</sup> C. Dietz,<sup>116</sup> F. Fiori,<sup>116</sup> W.-S. Hou,<sup>116</sup> Y. Hsiung,<sup>116</sup> Y. F. Liu,<sup>116</sup> R.-S. Lu,<sup>116</sup> M. Miñano Moya,<sup>116</sup>  
 E. Paganis,<sup>116</sup> A. Psallidas,<sup>116</sup> J. f. Tsai,<sup>116</sup> Y. M. Tzeng,<sup>116</sup> B. Asavapibhop,<sup>117</sup> G. Singh,<sup>117</sup> N. Srimanobhas,<sup>117</sup>  
 N. Suwonjandee,<sup>117</sup> S. Cerci,<sup>118,aaa</sup> S. Damarseckin,<sup>118</sup> Z. S. Demiroglu,<sup>118</sup> C. Dozen,<sup>118</sup> I. Dumanoglu,<sup>118</sup> S. Girgis,<sup>118</sup>  
 G. Gokbulut,<sup>118</sup> Y. Guler,<sup>118</sup> E. Gurpinar,<sup>118</sup> I. Hos,<sup>118</sup> E. E. Kangal,<sup>118,bbb</sup> O. Kara,<sup>118</sup> A. Kayis Topaksu,<sup>118</sup> U. Kiminsu,<sup>118</sup>  
 M. Oglakci,<sup>118</sup> G. Onengut,<sup>118,ccc</sup> K. Ozdemir,<sup>118,ddd</sup> D. Sunar Cerci,<sup>118,aaa</sup> H. Topakli,<sup>118,eee</sup> S. Turkapar,<sup>118</sup> I. S. Zorbakir,<sup>118</sup>  
 C. Zorbilmez,<sup>118</sup> B. Bilin,<sup>119</sup> S. Bilmis,<sup>119</sup> B. Isildak,<sup>119,fff</sup> G. Karapinar,<sup>119,ggg</sup> M. Yalvac,<sup>119</sup> M. Zeyrek,<sup>119</sup> E. Gülmez,<sup>120</sup>

M. Kaya,<sup>120,hhh</sup> O. Kaya,<sup>120,iii</sup> E. A. Yetkin,<sup>120,jjj</sup> T. Yetkin,<sup>120,kkk</sup> A. Cakir,<sup>121</sup> K. Cankocak,<sup>121</sup> S. Sen,<sup>121,III</sup> B. Grynyov,<sup>122</sup> L. Levchuk,<sup>123</sup> P. Sorokin,<sup>123</sup> R. Aggleton,<sup>124</sup> F. Ball,<sup>124</sup> L. Beck,<sup>124</sup> J. J. Brooke,<sup>124</sup> D. Burns,<sup>124</sup> E. Clement,<sup>124</sup> D. Cussans,<sup>124</sup> H. Flacher,<sup>124</sup> J. Goldstein,<sup>124</sup> M. Grimes,<sup>124</sup> G. P. Heath,<sup>124</sup> H. F. Heath,<sup>124</sup> J. Jacob,<sup>124</sup> L. Kreczko,<sup>124</sup> C. Lucas,<sup>124</sup> D. M. Newbold,<sup>124,mmm</sup> S. Paramesvaran,<sup>124</sup> A. Poll,<sup>124</sup> T. Sakuma,<sup>124</sup> S. Seif El Nasr-storey,<sup>124</sup> D. Smith,<sup>124</sup> V. J. Smith,<sup>124</sup> K. W. Bell,<sup>125</sup> A. Belyaev,<sup>125,nnn</sup> C. Brew,<sup>125</sup> R. M. Brown,<sup>125</sup> L. Calligaris,<sup>125</sup> D. Cieri,<sup>125</sup> D. J. A. Cockerill,<sup>125</sup> J. A. Coughlan,<sup>125</sup> K. Harder,<sup>125</sup> S. Harper,<sup>125</sup> E. Olaiya,<sup>125</sup> D. Petyt,<sup>125</sup> C. H. Shepherd-Themistocleous,<sup>125</sup> A. Thea,<sup>125</sup> I. R. Tomalin,<sup>125</sup> T. Williams,<sup>125</sup> M. Baber,<sup>126</sup> R. Bainbridge,<sup>126</sup> O. Buchmuller,<sup>126</sup> A. Bundock,<sup>126</sup> D. Burton,<sup>126</sup> S. Casasso,<sup>126</sup> M. Citron,<sup>126</sup> D. Colling,<sup>126</sup> L. Corpe,<sup>126</sup> P. Dauncey,<sup>126</sup> G. Davies,<sup>126</sup> A. De Wit,<sup>126</sup> M. Della Negra,<sup>126</sup> R. Di Maria,<sup>126</sup> P. Dunne,<sup>126</sup> A. Elwood,<sup>126</sup> D. Futyan,<sup>126</sup> Y. Haddad,<sup>126</sup> G. Hall,<sup>126</sup> G. Iles,<sup>126</sup> T. James,<sup>126</sup> R. Lane,<sup>126</sup> C. Laner,<sup>126</sup> R. Lucas,<sup>126,mmm</sup> L. Lyons,<sup>126</sup> A.-M. Magnan,<sup>126</sup> S. Malik,<sup>126</sup> L. Mastrolorenzo,<sup>126</sup> J. Nash,<sup>126</sup> A. Nikitenko,<sup>126,yy</sup> J. Pela,<sup>126</sup> B. Penning,<sup>126</sup> M. Pesaresi,<sup>126</sup> D. M. Raymond,<sup>126</sup> A. Richards,<sup>126</sup> A. Rose,<sup>126</sup> C. Seez,<sup>126</sup> S. Summers,<sup>126</sup> A. Tapper,<sup>126</sup> K. Uchida,<sup>126</sup> M. Vazquez Acosta,<sup>126,ooo</sup> T. Virdee,<sup>126,q</sup> J. Wright,<sup>126</sup> S. C. Zenz,<sup>126</sup> J. E. Cole,<sup>127</sup> P. R. Hobson,<sup>127</sup> A. Khan,<sup>127</sup> P. Kyberd,<sup>127</sup> D. Leslie,<sup>127</sup> I. D. Reid,<sup>127</sup> P. Symonds,<sup>127</sup> L. Teodorescu,<sup>127</sup> M. Turner,<sup>127</sup> A. Borzou,<sup>128</sup> K. Call,<sup>128</sup> J. Dittmann,<sup>128</sup> K. Hatakeyama,<sup>128</sup> H. Liu,<sup>128</sup> N. Pastika,<sup>128</sup> O. Charaf,<sup>129</sup> S. I. Cooper,<sup>129</sup> C. Henderson,<sup>129</sup> P. Rumerio,<sup>129</sup> C. West,<sup>129</sup> D. Arcaro,<sup>130</sup> A. Avetisyan,<sup>130</sup> T. Bose,<sup>130</sup> D. Gastler,<sup>130</sup> D. Rankin,<sup>130</sup> C. Richardson,<sup>130</sup> J. Rohlf,<sup>130</sup> L. Sulak,<sup>130</sup> D. Zou,<sup>130</sup> G. Benelli,<sup>131</sup> E. Berry,<sup>131</sup> D. Cutts,<sup>131</sup> A. Garabedian,<sup>131</sup> J. Hakala,<sup>131</sup> U. Heintz,<sup>131</sup> J. M. Hogan,<sup>131</sup> O. Jesus,<sup>131</sup> E. Laird,<sup>131</sup> G. Landsberg,<sup>131</sup> Z. Mao,<sup>131</sup> M. Narain,<sup>131</sup> S. Piperov,<sup>131</sup> S. Sagir,<sup>131</sup> E. Spencer,<sup>131</sup> R. Syarif,<sup>131</sup> R. Breedon,<sup>132</sup> G. Breto,<sup>132</sup> D. Burns,<sup>132</sup> M. Calderon De La Barca Sanchez,<sup>132</sup> S. Chauhan,<sup>132</sup> M. Chertok,<sup>132</sup> J. Conway,<sup>132</sup> R. Conway,<sup>132</sup> P. T. Cox,<sup>132</sup> R. Erbacher,<sup>132</sup> C. Flores,<sup>132</sup> G. Funk,<sup>132</sup> M. Gardner,<sup>132</sup> W. Ko,<sup>132</sup> R. Lander,<sup>132</sup> C. Mclean,<sup>132</sup> M. Mulhearn,<sup>132</sup> D. Pellett,<sup>132</sup> J. Pilot,<sup>132</sup> S. Shalhout,<sup>132</sup> J. Smith,<sup>132</sup> M. Squires,<sup>132</sup> D. Stolp,<sup>132</sup> M. Tripathi,<sup>132</sup> S. Wilbur,<sup>132</sup> R. Yohay,<sup>132</sup> R. Cousins,<sup>133</sup> P. Everaerts,<sup>133</sup> A. Florent,<sup>133</sup> J. Hauser,<sup>133</sup> M. Ignatenko,<sup>133</sup> D. Saltzberg,<sup>133</sup> E. Takasugi,<sup>133</sup> V. Valuev,<sup>133</sup> M. Weber,<sup>133</sup> K. Burt,<sup>134</sup> R. Clare,<sup>134</sup> J. Ellison,<sup>134</sup> J. W. Gary,<sup>134</sup> G. Hanson,<sup>134</sup> J. Heilman,<sup>134</sup> P. Jandir,<sup>134</sup> E. Kennedy,<sup>134</sup> F. Lacroix,<sup>134</sup> O. R. Long,<sup>134</sup> M. Olmedo Negrete,<sup>134</sup> M. I. Paneva,<sup>134</sup> A. Shrinivas,<sup>134</sup> W. Si,<sup>134</sup> H. Wei,<sup>134</sup> S. Wimpenny,<sup>134</sup> B. R. Yates,<sup>134</sup> J. G. Branson,<sup>135</sup> G. B. Cerati,<sup>135</sup> S. Cittolin,<sup>135</sup> M. Derdzinski,<sup>135</sup> R. Gerosa,<sup>135</sup> A. Holzner,<sup>135</sup> D. Klein,<sup>135</sup> V. Krutelyov,<sup>135</sup> J. Letts,<sup>135</sup> I. Macneill,<sup>135</sup> D. Olivito,<sup>135</sup> S. Padhi,<sup>135</sup> M. Pieri,<sup>135</sup> M. Sani,<sup>135</sup> V. Sharma,<sup>135</sup> S. Simon,<sup>135</sup> M. Tadel,<sup>135</sup> A. Vartak,<sup>135</sup> S. Wasserbaech,<sup>135,ppp</sup> C. Welke,<sup>135</sup> J. Wood,<sup>135</sup> F. Würthwein,<sup>135</sup> A. Yagil,<sup>135</sup> G. Zevi Della Porta,<sup>135</sup> R. Bhandari,<sup>136</sup> J. Bradmiller-Feld,<sup>136</sup> C. Campagnari,<sup>136</sup> A. Dishaw,<sup>136</sup> V. Dutta,<sup>136</sup> K. Flowers,<sup>136</sup> M. Franco Sevilla,<sup>136</sup> P. Geffert,<sup>136</sup> C. George,<sup>136</sup> F. Golf,<sup>136</sup> L. Gouskos,<sup>136</sup> J. Gran,<sup>136</sup> R. Heller,<sup>136</sup> J. Incandela,<sup>136</sup> N. Mccoll,<sup>136</sup> S. D. Mullin,<sup>136</sup> A. Ovcharova,<sup>136</sup> J. Richman,<sup>136</sup> D. Stuart,<sup>136</sup> I. Suarez,<sup>136</sup> J. Yoo,<sup>136</sup> D. Anderson,<sup>137</sup> A. Apresyan,<sup>137</sup> J. Bendavid,<sup>137</sup> A. Bornheim,<sup>137</sup> J. Bunn,<sup>137</sup> Y. Chen,<sup>137</sup> J. Duarte,<sup>137</sup> J. M. Lawhorn,<sup>137</sup> A. Mott,<sup>137</sup> H. B. Newman,<sup>137</sup> C. Pena,<sup>137</sup> M. Spiropulu,<sup>137</sup> J. R. Vlimant,<sup>137</sup> S. Xie,<sup>137</sup> R. Y. Zhu,<sup>137</sup> M. B. Andrews,<sup>138</sup> V. Azzolini,<sup>138</sup> T. Ferguson,<sup>138</sup> M. Paulini,<sup>138</sup> J. Russ,<sup>138</sup> M. Sun,<sup>138</sup> H. Vogel,<sup>138</sup> I. Vorobiev,<sup>138</sup> J. P. Cumalat,<sup>139</sup> W. T. Ford,<sup>139</sup> F. Jensen,<sup>139</sup> A. Johnson,<sup>139</sup> M. Krohn,<sup>139</sup> T. Mulholland,<sup>139</sup> K. Stenson,<sup>139</sup> S. R. Wagner,<sup>139</sup> J. Alexander,<sup>140</sup> J. Chaves,<sup>140</sup> J. Chu,<sup>140</sup> S. Dittmer,<sup>140</sup> K. McDermott,<sup>140</sup> N. Mirman,<sup>140</sup> G. Nicolas Kaufman,<sup>140</sup> J. R. Patterson,<sup>140</sup> A. Rinkevicius,<sup>140</sup> A. Ryd,<sup>140</sup> L. Skinnari,<sup>140</sup> L. Soffi,<sup>140</sup> S. M. Tan,<sup>140</sup> Z. Tao,<sup>140</sup> J. Thom,<sup>140</sup> J. Tucker,<sup>140</sup> P. Wittich,<sup>140</sup> M. Zientek,<sup>140</sup> D. Winn,<sup>141</sup> S. Abdullin,<sup>142</sup> M. Albrow,<sup>142</sup> G. Apollinari,<sup>142</sup> S. Banerjee,<sup>142</sup> L. A. T. Bauerdick,<sup>142</sup> A. Beretvas,<sup>142</sup> J. Berryhill,<sup>142</sup> P. C. Bhat,<sup>142</sup> G. Bolla,<sup>142</sup> K. Burkett,<sup>142</sup> J. N. Butler,<sup>142</sup> H. W. K. Cheung,<sup>142</sup> F. Chlebana,<sup>142</sup> S. Cihangir,<sup>142,a</sup> M. Cremonesi,<sup>142</sup> V. D. Elvira,<sup>142</sup> I. Fisk,<sup>142</sup> J. Freeman,<sup>142</sup> E. Gottschalk,<sup>142</sup> L. Gray,<sup>142</sup> D. Green,<sup>142</sup> S. Grünendahl,<sup>142</sup> O. Gutsche,<sup>142</sup> D. Hare,<sup>142</sup> R. M. Harris,<sup>142</sup> S. Hasegawa,<sup>142</sup> J. Hirschauer,<sup>142</sup> Z. Hu,<sup>142</sup> B. Jayatilaka,<sup>142</sup> S. Jindariani,<sup>142</sup> M. Johnson,<sup>142</sup> U. Joshi,<sup>142</sup> B. Klima,<sup>142</sup> B. Kreis,<sup>142</sup> S. Lammel,<sup>142</sup> J. Linacre,<sup>142</sup> D. Lincoln,<sup>142</sup> R. Lipton,<sup>142</sup> T. Liu,<sup>142</sup> R. Lopes De Sá,<sup>142</sup> J. Lykken,<sup>142</sup> K. Maeshima,<sup>142</sup> N. Magini,<sup>142</sup> J. M. Marraffino,<sup>142</sup> S. Maruyama,<sup>142</sup> D. Mason,<sup>142</sup> P. McBride,<sup>142</sup> P. Merkel,<sup>142</sup> S. Mrenna,<sup>142</sup> S. Nahn,<sup>142</sup> C. Newman-Holmes,<sup>142,a</sup> V. O'Dell,<sup>142</sup> K. Pedro,<sup>142</sup> O. Prokofyev,<sup>142</sup> G. Rakness,<sup>142</sup> L. Ristori,<sup>142</sup> E. Sexton-Kennedy,<sup>142</sup> A. Soha,<sup>142</sup> W. J. Spalding,<sup>142</sup> L. Spiegel,<sup>142</sup> S. Stoynev,<sup>142</sup> N. Strobbe,<sup>142</sup> L. Taylor,<sup>142</sup> S. Tkaczyk,<sup>142</sup> N. V. Tran,<sup>142</sup> L. Uplegger,<sup>142</sup> E. W. Vaandering,<sup>142</sup> C. Vernieri,<sup>142</sup> M. Verzocchi,<sup>142</sup> R. Vidal,<sup>142</sup> M. Wang,<sup>142</sup> H. A. Weber,<sup>142</sup> A. Whitbeck,<sup>142</sup> D. Acosta,<sup>143</sup> P. Avery,<sup>143</sup> P. Bortignon,<sup>143</sup> D. Bourilkov,<sup>143</sup> A. Brinkerhoff,<sup>143</sup> A. Carnes,<sup>143</sup> M. Carver,<sup>143</sup> D. Curry,<sup>143</sup> S. Das,<sup>143</sup> R. D. Field,<sup>143</sup> I. K. Furic,<sup>143</sup> J. Konigsberg,<sup>143</sup> A. Korytov,<sup>143</sup> P. Ma,<sup>143</sup> K. Matchev,<sup>143</sup> H. Mei,<sup>143</sup> P. Milenovic,<sup>143,qqq</sup> G. Mitselmakher,<sup>143</sup> D. Rank,<sup>143</sup> L. Shchutska,<sup>143</sup> D. Sperka,<sup>143</sup> L. Thomas,<sup>143</sup> J. Wang,<sup>143</sup> S. Wang,<sup>143</sup> J. Yelton,<sup>143</sup> S. Linn,<sup>144</sup> P. Markowitz,<sup>144</sup> G. Martinez,<sup>144</sup> J. L. Rodriguez,<sup>144</sup> A. Ackert,<sup>145</sup> J. R. Adams,<sup>145</sup>

T. Adams,<sup>145</sup> A. Askew,<sup>145</sup> S. Bein,<sup>145</sup> B. Diamond,<sup>145</sup> S. Hagopian,<sup>145</sup> V. Hagopian,<sup>145</sup> K. F. Johnson,<sup>145</sup> A. Khatiwada,<sup>145</sup> H. Prosper,<sup>145</sup> A. Santra,<sup>145</sup> M. Weinberg,<sup>145</sup> M. M. Baarmand,<sup>146</sup> V. Bhopatkar,<sup>146</sup> S. Colafranceschi,<sup>146,rrr</sup> M. Hohlmann,<sup>146</sup> D. Noonan,<sup>146</sup> T. Roy,<sup>146</sup> F. Yumiceva,<sup>146</sup> M. R. Adams,<sup>147</sup> L. Apanasevich,<sup>147</sup> D. Berry,<sup>147</sup> R. R. Betts,<sup>147</sup> I. Bucinskaite,<sup>147</sup> R. Cavanaugh,<sup>147</sup> O. Evdokimov,<sup>147</sup> L. Gauthier,<sup>147</sup> C. E. Gerber,<sup>147</sup> D. J. Hofman,<sup>147</sup> P. Kurt,<sup>147</sup> C. O'Brien,<sup>147</sup> I. D. Sandoval Gonzalez,<sup>147</sup> P. Turner,<sup>147</sup> N. Varelas,<sup>147</sup> H. Wang,<sup>147</sup> Z. Wu,<sup>147</sup> M. Zakaria,<sup>147</sup> J. Zhang,<sup>147</sup> B. Bilki,<sup>148,sss</sup> W. Clarida,<sup>148</sup> K. Dilsiz,<sup>148</sup> S. Durgut,<sup>148</sup> R. P. Gandrajula,<sup>148</sup> M. Haytmyradov,<sup>148</sup> V. Khristenko,<sup>148</sup> J.-P. Merlo,<sup>148</sup> H. Mermerkaya,<sup>148,ttt</sup> A. Mestvirishvili,<sup>148</sup> A. Moeller,<sup>148</sup> J. Nachtman,<sup>148</sup> H. Ogul,<sup>148</sup> Y. Onel,<sup>148</sup> F. Ozok,<sup>148,uuu</sup> A. Penzo,<sup>148</sup> C. Snyder,<sup>148</sup> E. Tiras,<sup>148</sup> J. Wetzel,<sup>148</sup> K. Yi,<sup>148</sup> I. Anderson,<sup>149</sup> B. Blumenfeld,<sup>149</sup> A. Cocoros,<sup>149</sup> N. Eminizer,<sup>149</sup> D. Fehling,<sup>149</sup> L. Feng,<sup>149</sup> A. V. Gritsan,<sup>149</sup> P. Maksimovic,<sup>149</sup> M. Osherson,<sup>149</sup> J. Roskes,<sup>149</sup> U. Sarica,<sup>149</sup> M. Swartz,<sup>149</sup> M. Xiao,<sup>149</sup> Y. Xin,<sup>149</sup> C. You,<sup>149</sup> A. Al-bataineh,<sup>150</sup> P. Baringer,<sup>150</sup> A. Bean,<sup>150</sup> S. Boren,<sup>150</sup> J. Bowen,<sup>150</sup> C. Bruner,<sup>150</sup> J. Castle,<sup>150</sup> L. Forthomme,<sup>150</sup> R. P. Kenny III,<sup>150</sup> A. Kropivnitskaya,<sup>150</sup> D. Majumder,<sup>150</sup> W. Mcbrayer,<sup>150</sup> M. Murray,<sup>150</sup> S. Sanders,<sup>150</sup> R. Stringer,<sup>150</sup> J. D. Tapia Takaki,<sup>150</sup> Q. Wang,<sup>150</sup> A. Ivanov,<sup>151</sup> K. Kaadze,<sup>151</sup> S. Khalil,<sup>151</sup> M. Makouski,<sup>151</sup> Y. Maravin,<sup>151</sup> A. Mohammadi,<sup>151</sup> L. K. Saini,<sup>151</sup> N. Skhirtladze,<sup>151</sup> S. Toda,<sup>151</sup> F. Rebassoo,<sup>152</sup> D. Wright,<sup>152</sup> C. Anelli,<sup>153</sup> A. Baden,<sup>153</sup> O. Baron,<sup>153</sup> A. Belloni,<sup>153</sup> B. Calvert,<sup>153</sup> S. C. Eno,<sup>153</sup> C. Ferraioli,<sup>153</sup> J. A. Gomez,<sup>153</sup> N. J. Hadley,<sup>153</sup> S. Jabeen,<sup>153</sup> R. G. Kellogg,<sup>153</sup> T. Kolberg,<sup>153</sup> J. Kunkle,<sup>153</sup> Y. Lu,<sup>153</sup> A. C. Mignerey,<sup>153</sup> F. Ricci-Tam,<sup>153</sup> Y. H. Shin,<sup>153</sup> A. Skuja,<sup>153</sup> M. B. Tonjes,<sup>153</sup> S. C. Tonwar,<sup>153</sup> D. Abercrombie,<sup>154</sup> B. Allen,<sup>154</sup> A. Apyan,<sup>154</sup> R. Barbieri,<sup>154</sup> A. Baty,<sup>154</sup> R. Bi,<sup>154</sup> K. Bierwagen,<sup>154</sup> S. Brandt,<sup>154</sup> W. Busza,<sup>154</sup> I. A. Cali,<sup>154</sup> Z. Demiragli,<sup>154</sup> L. Di Matteo,<sup>154</sup> G. Gomez Ceballos,<sup>154</sup> M. Goncharov,<sup>154</sup> D. Hsu,<sup>154</sup> Y. Iiyama,<sup>154</sup> G. M. Innocenti,<sup>154</sup> M. Klute,<sup>154</sup> D. Kovalskyi,<sup>154</sup> K. Krajczar,<sup>154</sup> Y. S. Lai,<sup>154</sup> Y.-J. Lee,<sup>154</sup> A. Levin,<sup>154</sup> P. D. Luckey,<sup>154</sup> A. C. Marini,<sup>154</sup> C. MCGinn,<sup>154</sup> C. Mironov,<sup>154</sup> S. Narayanan,<sup>154</sup> X. Niu,<sup>154</sup> C. Paus,<sup>154</sup> C. Roland,<sup>154</sup> G. Roland,<sup>154</sup> J. Salfeld-Nebgen,<sup>154</sup> G. S. F. Stephans,<sup>154</sup> K. Sumorok,<sup>154</sup> K. Tatar,<sup>154</sup> M. Varma,<sup>154</sup> D. Velicanu,<sup>154</sup> J. Veverka,<sup>154</sup> J. Wang,<sup>154</sup> T. W. Wang,<sup>154</sup> B. Wyslouch,<sup>154</sup> M. Yang,<sup>154</sup> V. Zhukova,<sup>154</sup> A. C. Benvenuti,<sup>155</sup> R. M. Chatterjee,<sup>155</sup> A. Evans,<sup>155</sup> A. Finkel,<sup>155</sup> A. Gude,<sup>155</sup> P. Hansen,<sup>155</sup> S. Kalafut,<sup>155</sup> S. C. Kao,<sup>155</sup> Y. Kubota,<sup>155</sup> Z. Lesko,<sup>155</sup> J. Mans,<sup>155</sup> S. Nourbakhsh,<sup>155</sup> N. Ruckstuhl,<sup>155</sup> R. Rusack,<sup>155</sup> N. Tambe,<sup>155</sup> J. Turkewitz,<sup>155</sup> J. G. Acosta,<sup>156</sup> S. Oliveros,<sup>156</sup> E. Avdeeva,<sup>157</sup> R. Bartek,<sup>157</sup> K. Bloom,<sup>157</sup> D. R. Claes,<sup>157</sup> A. Dominguez,<sup>157</sup> C. Fangmeier,<sup>157</sup> R. Gonzalez Suarez,<sup>157</sup> R. Kamalieddin,<sup>157</sup> I. Kravchenko,<sup>157</sup> A. Malta Rodrigues,<sup>157</sup> F. Meier,<sup>157</sup> J. Monroy,<sup>157</sup> J. E. Siado,<sup>157</sup> G. R. Snow,<sup>157</sup> B. Stieger,<sup>157</sup> M. Alyari,<sup>158</sup> J. Dolen,<sup>158</sup> J. George,<sup>158</sup> A. Godshalk,<sup>158</sup> C. Harrington,<sup>158</sup> I. Iashvili,<sup>158</sup> J. Kaisen,<sup>158</sup> A. Kharchilava,<sup>158</sup> A. Kumar,<sup>158</sup> A. Parker,<sup>158</sup> S. Rappoccio,<sup>158</sup> B. Roozbahani,<sup>158</sup> G. Alverson,<sup>159</sup> E. Barberis,<sup>159</sup> D. Baumgartel,<sup>159</sup> A. Hortiangtham,<sup>159</sup> A. Massironi,<sup>159</sup> D. M. Morse,<sup>159</sup> D. Nash,<sup>159</sup> T. Orimoto,<sup>159</sup> R. Teixeira De Lima,<sup>159</sup> D. Trocino,<sup>159</sup> R.-J. Wang,<sup>159</sup> D. Wood,<sup>159</sup> S. Bhattacharya,<sup>160</sup> K. A. Hahn,<sup>160</sup> A. Kubik,<sup>160</sup> A. Kumar,<sup>160</sup> J. F. Low,<sup>160</sup> N. Mucia,<sup>160</sup> N. Odell,<sup>160</sup> B. Pollack,<sup>160</sup> M. H. Schmitt,<sup>160</sup> K. Sung,<sup>160</sup> M. Trovato,<sup>160</sup> M. Velasco,<sup>160</sup> N. Dev,<sup>161</sup> M. Hildreth,<sup>161</sup> K. Hurtado Anampa,<sup>161</sup> C. Jessop,<sup>161</sup> D. J. Karmgard,<sup>161</sup> N. Kellams,<sup>161</sup> K. Lannon,<sup>161</sup> N. Marinelli,<sup>161</sup> F. Meng,<sup>161</sup> C. Mueller,<sup>161</sup> Y. Musienko,<sup>161,mmm</sup> M. Planer,<sup>161</sup> A. Reinsvold,<sup>161</sup> R. Ruchti,<sup>161</sup> G. Smith,<sup>161</sup> S. Taroni,<sup>161</sup> M. Wayne,<sup>161</sup> M. Wolf,<sup>161</sup> A. Woodard,<sup>161</sup> J. Alimena,<sup>162</sup> L. Antonelli,<sup>162</sup> J. Brinson,<sup>162</sup> B. Bylsma,<sup>162</sup> L. S. Durkin,<sup>162</sup> S. Flowers,<sup>162</sup> B. Francis,<sup>162</sup> A. Hart,<sup>162</sup> C. Hill,<sup>162</sup> R. Hughes,<sup>162</sup> W. Ji,<sup>162</sup> B. Liu,<sup>162</sup> W. Luo,<sup>162</sup> D. Puigh,<sup>162</sup> B. L. Winer,<sup>162</sup> H. W. Wulsin,<sup>162</sup> S. Cooperstein,<sup>163</sup> O. Driga,<sup>163</sup> P. Elmer,<sup>163</sup> J. Hardenbrook,<sup>163</sup> P. Hebda,<sup>163</sup> D. Lange,<sup>163</sup> J. Luo,<sup>163</sup> D. Marlow,<sup>163</sup> T. Medvedeva,<sup>163</sup> K. Mei,<sup>163</sup> M. Mooney,<sup>163</sup> J. Olsen,<sup>163</sup> C. Palmer,<sup>163</sup> P. Piroué,<sup>163</sup> D. Stickland,<sup>163</sup> C. Tully,<sup>163</sup> A. Zuranski,<sup>163</sup> S. Malik,<sup>164</sup> A. Barker,<sup>165</sup> V. E. Barnes,<sup>165</sup> S. Folgueras,<sup>165</sup> L. Gutay,<sup>165</sup> M. K. Jha,<sup>165</sup> M. Jones,<sup>165</sup> A. W. Jung,<sup>165</sup> K. Jung,<sup>165</sup> D. H. Miller,<sup>165</sup> N. Neumeister,<sup>165</sup> X. Shi,<sup>165</sup> J. Sun,<sup>165</sup> A. Svyatkovskiy,<sup>165</sup> F. Wang,<sup>165</sup> W. Xie,<sup>165</sup> L. Xu,<sup>165</sup> N. Parashar,<sup>166</sup> J. Stupak,<sup>166</sup> A. Adair,<sup>167</sup> B. Akgun,<sup>167</sup> Z. Chen,<sup>167</sup> K. M. Ecklund,<sup>167</sup> F. J. M. Geurts,<sup>167</sup> M. Guilbaud,<sup>167</sup> W. Li,<sup>167</sup> B. Michlin,<sup>167</sup> M. Northup,<sup>167</sup> B. P. Padley,<sup>167</sup> R. Redjimi,<sup>167</sup> J. Roberts,<sup>167</sup> J. Rorie,<sup>167</sup> Z. Tu,<sup>167</sup> J. Zabel,<sup>167</sup> B. Betchart,<sup>168</sup> A. Bodek,<sup>168</sup> P. de Barbaro,<sup>168</sup> R. Demina,<sup>168</sup> Y. t. Duh,<sup>168</sup> T. Ferbel,<sup>168</sup> M. Galanti,<sup>168</sup> A. Garcia-Bellido,<sup>168</sup> J. Han,<sup>168</sup> O. Hindrichs,<sup>168</sup> A. Khukhunaishvili,<sup>168</sup> K. H. Lo,<sup>168</sup> P. Tan,<sup>168</sup> M. Verzetti,<sup>168</sup> A. Agapitos,<sup>169</sup> J. P. Chou,<sup>169</sup> E. Contreras-Campana,<sup>169</sup> Y. Gershtein,<sup>169</sup> T. A. Gómez Espinosa,<sup>169</sup> E. Halkiadakis,<sup>169</sup> M. Heindl,<sup>169</sup> D. Hidas,<sup>169</sup> E. Hughes,<sup>169</sup> S. Kaplan,<sup>169</sup> R. Kunnawalkam Elayavalli,<sup>169</sup> S. Kyriacou,<sup>169</sup> A. Lath,<sup>169</sup> K. Nash,<sup>169</sup> H. Saka,<sup>169</sup> S. Salur,<sup>169</sup> S. Schnetzer,<sup>169</sup> D. Sheffield,<sup>169</sup> S. Somalwar,<sup>169</sup> R. Stone,<sup>169</sup> S. Thomas,<sup>169</sup> P. Thomassen,<sup>169</sup> M. Walker,<sup>169</sup> M. Foerster,<sup>170</sup> J. Heideman,<sup>170</sup> G. Riley,<sup>170</sup> K. Rose,<sup>170</sup> S. Spanier,<sup>170</sup> K. Thapa,<sup>170</sup> O. Bouhali,<sup>171,vvv</sup> A. Celik,<sup>171</sup> M. Dalchenko,<sup>171</sup> M. De Mattia,<sup>171</sup> A. Delgado,<sup>171</sup> S. Dildick,<sup>171</sup> R. Eusebi,<sup>171</sup> J. Gilmore,<sup>171</sup> T. Huang,<sup>171</sup> E. Juska,<sup>171</sup> T. Kamon,<sup>171,www</sup> R. Mueller,<sup>171</sup> Y. Pakhotin,<sup>171</sup> R. Patel,<sup>171</sup> A. Perloff,<sup>171</sup> L. Perniè,<sup>171</sup> D. Rathjens,<sup>171</sup> A. Rose,<sup>171</sup> A. Safonov,<sup>171</sup> A. Tatarinov,<sup>171</sup> K. A. Ulmer,<sup>171</sup> N. Akchurin,<sup>172</sup> C. Cowden,<sup>172</sup> J. Damgov,<sup>172</sup>

F. De Guio,<sup>172</sup> C. Dragoiu,<sup>172</sup> P. R. Duerdo,<sup>172</sup> J. Faulkner,<sup>172</sup> S. Kunori,<sup>172</sup> K. Lamichhane,<sup>172</sup> S. W. Lee,<sup>172</sup> T. Libeiro,<sup>172</sup> T. Peltola,<sup>172</sup> S. Undleeb,<sup>172</sup> I. Volobouev,<sup>172</sup> Z. Wang,<sup>172</sup> A. G. Delannoy,<sup>173</sup> S. Greene,<sup>173</sup> A. Gurrola,<sup>173</sup> R. Janjam,<sup>173</sup> W. Johns,<sup>173</sup> C. Maguire,<sup>173</sup> A. Melo,<sup>173</sup> H. Ni,<sup>173</sup> P. Sheldon,<sup>173</sup> S. Tuo,<sup>173</sup> J. Velkovska,<sup>173</sup> Q. Xu,<sup>173</sup> M. W. Arenton,<sup>174</sup> P. Barria,<sup>174</sup> B. Cox,<sup>174</sup> J. Goodell,<sup>174</sup> R. Hirosky,<sup>174</sup> A. Ledovskoy,<sup>174</sup> H. Li,<sup>174</sup> C. Neu,<sup>174</sup> T. Sinthuprasith,<sup>174</sup> X. Sun,<sup>174</sup> Y. Wang,<sup>174</sup> E. Wolfe,<sup>174</sup> F. Xia,<sup>174</sup> C. Clarke,<sup>175</sup> R. Harr,<sup>175</sup> P. E. Karchin,<sup>175</sup> P. Lamichhane,<sup>175</sup> J. Sturdy,<sup>175</sup> D. A. Belknap,<sup>176</sup> S. Dasu,<sup>176</sup> L. Dodd,<sup>176</sup> S. Duric,<sup>176</sup> B. Gomber,<sup>176</sup> M. Grothe,<sup>176</sup> M. Herndon,<sup>176</sup> A. Hervé,<sup>176</sup> P. Klabbers,<sup>176</sup> A. Lanaro,<sup>176</sup> A. Levine,<sup>176</sup> K. Long,<sup>176</sup> R. Loveless,<sup>176</sup> I. Ojalvo,<sup>176</sup> T. Perry,<sup>176</sup> G. Polese,<sup>176</sup> T. Ruggles,<sup>176</sup> A. Savin,<sup>176</sup> N. Smith,<sup>176</sup> W. H. Smith,<sup>176</sup> D. Taylor,<sup>176</sup> and N. Woods<sup>176</sup>

(CMS Collaboration)

<sup>1</sup>*Yerevan Physics Institute, Yerevan, Armenia*

<sup>2</sup>*Institut für Hochenergiephysik, Wien, Austria*

<sup>3</sup>*National Centre for Particle and High Energy Physics, Minsk, Belarus*

<sup>4</sup>*Universiteit Antwerpen, Antwerpen, Belgium*

<sup>5</sup>*Vrije Universiteit Brussel, Brussel, Belgium*

<sup>6</sup>*Université Libre de Bruxelles, Bruxelles, Belgium*

<sup>7</sup>*Ghent University, Ghent, Belgium*

<sup>8</sup>*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

<sup>9</sup>*Université de Mons, Mons, Belgium*

<sup>10</sup>*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

<sup>11</sup>*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

<sup>12a</sup>*Universidade Estadual Paulista, São Paulo, Brazil*

<sup>12b</sup>*Universidade Federal do ABC, São Paulo, Brazil*

<sup>13</sup>*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

<sup>14</sup>*University of Sofia, Sofia, Bulgaria*

<sup>15</sup>*Beihang University, Beijing, China*

<sup>16</sup>*Institute of High Energy Physics, Beijing, China*

<sup>17</sup>*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

<sup>18</sup>*Universidad de Los Andes, Bogota, Colombia*

<sup>19</sup>*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

<sup>20</sup>*University of Split, Faculty of Science, Split, Croatia*

<sup>21</sup>*Institute Rudjer Boskovic, Zagreb, Croatia*

<sup>22</sup>*University of Cyprus, Nicosia, Cyprus*

<sup>23</sup>*Charles University, Prague, Czech Republic*

<sup>24</sup>*Universidad San Francisco de Quito, Quito, Ecuador*

<sup>25</sup>*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

<sup>26</sup>*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

<sup>27</sup>*Department of Physics, University of Helsinki, Helsinki, Finland*

<sup>28</sup>*Helsinki Institute of Physics, Helsinki, Finland*

<sup>29</sup>*Lappeenranta University of Technology, Lappeenranta, Finland*

<sup>30</sup>*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

<sup>31</sup>*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*

<sup>32</sup>*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*

<sup>33</sup>*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

<sup>34</sup>*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3,*

*Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

<sup>35</sup>*Georgian Technical University, Tbilisi, Georgia*

<sup>36</sup>*Tbilisi State University, Tbilisi, Georgia*

<sup>37</sup>*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

<sup>38</sup>*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

<sup>39</sup>*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

<sup>40</sup>*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

- <sup>41</sup>*University of Hamburg, Hamburg, Germany*
- <sup>42</sup>*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
- <sup>43</sup>*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- <sup>44</sup>*National and Kapodistrian University of Athens, Athens, Greece*
- <sup>45</sup>*University of Ioánnina, Ioánnina, Greece*
- <sup>46</sup>*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- <sup>47</sup>*Wigner Research Centre for Physics, Budapest, Hungary*
- <sup>48</sup>*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- <sup>49</sup>*University of Debrecen, Debrecen, Hungary*
- <sup>50</sup>*National Institute of Science Education and Research, Bhubaneswar, India*
- <sup>51</sup>*Panjab University, Chandigarh, India*
- <sup>52</sup>*University of Delhi, Delhi, India*
- <sup>53</sup>*Saha Institute of Nuclear Physics, Kolkata, India*
- <sup>54</sup>*Indian Institute of Technology Madras, Madras, India*
- <sup>55</sup>*Bhabha Atomic Research Centre, Mumbai, India*
- <sup>56</sup>*Tata Institute of Fundamental Research-A, Mumbai, India*
- <sup>57</sup>*Tata Institute of Fundamental Research-B, Mumbai, India*
- <sup>58</sup>*Indian Institute of Science Education and Research (IISER), Pune, India*
- <sup>59</sup>*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- <sup>60</sup>*University College Dublin, Dublin, Ireland*
- <sup>61a</sup>*INFN Sezione di Bari, Bari, Italy*
- <sup>61b</sup>*Università di Bari, Bari, Italy*
- <sup>61c</sup>*Politecnico di Bari, Bari, Italy*
- <sup>62a</sup>*INFN Sezione di Bologna, Bologna, Italy*
- <sup>62b</sup>*Università di Bologna, Bologna, Italy*
- <sup>63a</sup>*INFN Sezione di Catania, Catania, Italy*
- <sup>63b</sup>*Università di Catania, Catania, Italy*
- <sup>64a</sup>*INFN Sezione di Firenze, Firenze, Italy*
- <sup>64b</sup>*Università di Firenze, Firenze, Italy*
- <sup>65</sup>*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- <sup>66a</sup>*INFN Sezione di Genova, Genova, Italy*
- <sup>66b</sup>*Università di Genova, Genova, Italy*
- <sup>67a</sup>*INFN Sezione di Milano-Bicocca, Milano, Italy*
- <sup>67b</sup>*Università di Milano-Bicocca, Milano, Italy*
- <sup>68a</sup>*INFN Sezione di Napoli, Roma, Italy*
- <sup>68b</sup>*Università di Napoli 'Federico II', Roma, Italy*
- <sup>68c</sup>*Università della Basilicata, Roma, Italy*
- <sup>68d</sup>*Università G. Marconi, Roma, Italy*
- <sup>69a</sup>*INFN Sezione di Padova, Trento, Italy*
- <sup>69b</sup>*Università di Padova, Trento, Italy*
- <sup>69c</sup>*Università di Trento, Trento, Italy*
- <sup>70a</sup>*INFN Sezione di Pavia, Pavia, Italy*
- <sup>70b</sup>*Università di Pavia, Pavia, Italy*
- <sup>71a</sup>*INFN Sezione di Perugia, Perugia, Italy*
- <sup>71b</sup>*Università di Perugia, Perugia, Italy*
- <sup>72a</sup>*INFN Sezione di Pisa, Pisa, Italy*
- <sup>72b</sup>*Università di Pisa, Pisa, Italy*
- <sup>72c</sup>*Scuola Normale Superiore di Pisa, Pisa, Italy*
- <sup>73a</sup>*INFN Sezione di Roma*
- <sup>73b</sup>*Università di Roma*
- <sup>74a</sup>*INFN Sezione di Torino, Novara, Italy*
- <sup>74b</sup>*Università di Torino, Novara, Italy*
- <sup>74c</sup>*Università del Piemonte Orientale, Novara, Italy*
- <sup>75a</sup>*INFN Sezione di Trieste, Trieste, Italy*
- <sup>75b</sup>*Università di Trieste, Trieste, Italy*
- <sup>76</sup>*Kyungpook National University, Daegu, Korea*
- <sup>77</sup>*Chonbuk National University, Jeonju, Korea*
- <sup>78</sup>*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- <sup>79</sup>*Hanyang University, Seoul, Korea*

- <sup>80</sup>*Korea University, Seoul, Korea*  
<sup>81</sup>*Seoul National University, Seoul, Korea*  
<sup>82</sup>*University of Seoul, Seoul, Korea*  
<sup>83</sup>*Sungkyunkwan University, Suwon, Korea*  
<sup>84</sup>*Vilnius University, Vilnius, Lithuania*  
<sup>85</sup>*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*  
<sup>86</sup>*Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*  
<sup>87</sup>*Universidad Iberoamericana, Mexico City, Mexico*  
<sup>88</sup>*Benemerita Universidad Autónoma de Puebla, Puebla, Mexico*  
<sup>89</sup>*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*  
<sup>90</sup>*University of Auckland, Auckland, New Zealand*  
<sup>91</sup>*University of Canterbury, Christchurch, New Zealand*  
<sup>92</sup>*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*  
<sup>93</sup>*National Centre for Nuclear Research, Swierk, Poland*  
<sup>94</sup>*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*  
<sup>95</sup>*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*  
<sup>96</sup>*Joint Institute for Nuclear Research, Dubna, Russia*  
<sup>97</sup>*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*  
<sup>98</sup>*Institute for Nuclear Research, Moscow, Russia*  
<sup>99</sup>*Institute for Theoretical and Experimental Physics, Moscow, Russia*  
<sup>100</sup>*Moscow Institute of Physics and Technology*  
<sup>101</sup>*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*  
<sup>102</sup>*P.N. Lebedev Physical Institute, Moscow, Russia*  
<sup>103</sup>*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*  
<sup>104</sup>*Novosibirsk State University (NSU), Novosibirsk, Russia*  
<sup>105</sup>*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*  
<sup>106</sup>*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*  
<sup>107</sup>*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*  
<sup>108</sup>*Universidad Autónoma de Madrid, Madrid, Spain*  
<sup>109</sup>*Universidad de Oviedo, Oviedo, Spain*  
<sup>110</sup>*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*  
<sup>111</sup>*CERN, European Organization for Nuclear Research, Geneva, Switzerland*  
<sup>112</sup>*Paul Scherrer Institut, Villigen, Switzerland*  
<sup>113</sup>*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*  
<sup>114</sup>*Universität Zürich, Zurich, Switzerland*  
<sup>115</sup>*National Central University, Chung-Li, Taiwan*  
<sup>116</sup>*National Taiwan University (NTU), Taipei, Taiwan*  
<sup>117</sup>*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*  
<sup>118</sup>*Cukurova University, Adana, Turkey*  
<sup>119</sup>*Middle East Technical University, Physics Department, Ankara, Turkey*  
<sup>120</sup>*Bogazici University, Istanbul, Turkey*  
<sup>121</sup>*Istanbul Technical University, Istanbul, Turkey*  
<sup>122</sup>*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*  
<sup>123</sup>*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*  
<sup>124</sup>*University of Bristol, Bristol, United Kingdom*  
<sup>125</sup>*Rutherford Appleton Laboratory, Didcot, United Kingdom*  
<sup>126</sup>*Imperial College, London, United Kingdom*  
<sup>127</sup>*Brunel University, Uxbridge, United Kingdom*  
<sup>128</sup>*Baylor University, Waco, Texas 76798, USA*  
<sup>129</sup>*The University of Alabama, Tuscaloosa, Alabama 35487, USA*  
<sup>130</sup>*Boston University, Boston, Massachusetts 02215, USA*  
<sup>131</sup>*Brown University, Providence, Rhode Island 02912, USA*  
<sup>132</sup>*University of California, Davis, Davis, California 95616, USA*  
<sup>133</sup>*University of California, Los Angeles, California 90095, USA*  
<sup>134</sup>*University of California, Riverside, Riverside, California 92521, USA*  
<sup>135</sup>*University of California, San Diego, La Jolla, California 92093, USA*  
<sup>136</sup>*University of California, Santa Barbara—Department of Physics, Santa Barbara, California 93106, USA*  
<sup>137</sup>*California Institute of Technology, Pasadena, California 91125, USA*

- <sup>138</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*  
<sup>139</sup>*University of Colorado Boulder, Boulder, Colorado 80309, USA*  
<sup>140</sup>*Cornell University, Ithaca, New York 14853, USA*  
<sup>141</sup>*Fairfield University, Fairfield, Connecticut 06430, USA*  
<sup>142</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*  
<sup>143</sup>*University of Florida, Gainesville, Florida 32611, USA*  
<sup>144</sup>*Florida International University, Miami, Florida 33199, USA*  
<sup>145</sup>*Florida State University, Tallahassee, Florida 32306, USA*  
<sup>146</sup>*Florida Institute of Technology, Melbourne, Florida 32901, USA*  
<sup>147</sup>*University of Illinois at Chicago (UIC), Chicago, Illinois 60607, USA*  
<sup>148</sup>*The University of Iowa, Iowa City, Iowa 52242, USA*  
<sup>149</sup>*Johns Hopkins University, Baltimore, Maryland 21218, USA*  
<sup>150</sup>*The University of Kansas, Lawrence, Kansas 66045, USA*  
<sup>151</sup>*Kansas State University, Manhattan, Kansas 66506, USA*  
<sup>152</sup>*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*  
<sup>153</sup>*University of Maryland, College Park, Maryland 20742, USA*  
<sup>154</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*  
<sup>155</sup>*University of Minnesota, Minneapolis, Minnesota 55455, USA*  
<sup>156</sup>*University of Mississippi, Oxford, Mississippi 38677, USA*  
<sup>157</sup>*University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA*  
<sup>158</sup>*State University of New York at Buffalo, Buffalo, New York 14260, USA*  
<sup>159</sup>*Northeastern University, Boston, Massachusetts 02115, USA*  
<sup>160</sup>*Northwestern University, Evanston, Illinois 60208, USA*  
<sup>161</sup>*University of Notre Dame, Notre Dame, Indiana 46556, USA*  
<sup>162</sup>*The Ohio State University, Columbus, Ohio 43210, USA*  
<sup>163</sup>*Princeton University, Princeton, New Jersey 08542, USA*  
<sup>164</sup>*University of Puerto Rico, Mayaguez, Puerto Rico 00681, USA*  
<sup>165</sup>*Purdue University, West Lafayette, Indiana 47907, USA*  
<sup>166</sup>*Purdue University Calumet, Hammond, Indiana 46323, USA*  
<sup>167</sup>*Rice University, Houston, Texas 77251, USA*  
<sup>168</sup>*University of Rochester, Rochester, New York 14627, USA*  
<sup>169</sup>*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA*  
<sup>170</sup>*University of Tennessee, Knoxville, Tennessee 37996, USA*  
<sup>171</sup>*Texas A&M University, College Station, Texas 77843, USA*  
<sup>172</sup>*Texas Tech University, Lubbock, Texas 79409, USA*  
<sup>173</sup>*Vanderbilt University, Nashville, Tennessee 37235, USA*  
<sup>174</sup>*University of Virginia, Charlottesville, Virginia 22904, USA*  
<sup>175</sup>*Wayne State University, Detroit, Michigan 48202, USA*  
<sup>176</sup>*University of Wisconsin—Madison, Madison, Wisconsin 53706, USA*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Vienna University of Technology, Vienna, Austria.

<sup>c</sup>Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

<sup>d</sup>Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

<sup>e</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>f</sup>Also at Universidade Federal de Pelotas, Pelotas, Brazil.

<sup>g</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>h</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

<sup>i</sup>Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>j</sup>Also at Suez University, Suez, Egypt.

<sup>k</sup>Also at British University in Egypt, Cairo, Egypt.

<sup>l</sup>Also at Ain Shams University, Cairo, Egypt.

<sup>m</sup>Also at Helwan University, Cairo, Egypt.

<sup>n</sup>Also at Université de Haute Alsace, Mulhouse, France.

<sup>o</sup>Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>p</sup>Also at Tbilisi State University, Tbilisi, Georgia.

<sup>q</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>r</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>s</sup>Also at University of Hamburg, Hamburg, Germany.

- <sup>t</sup> Also at Brandenburg University of Technology, Cottbus, Germany.
- <sup>u</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- <sup>v</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- <sup>w</sup> Also at University of Debrecen, Debrecen, Hungary.
- <sup>x</sup> Also at Indian Institute of Science Education and Research, Bhopal, India.
- <sup>y</sup> Also at Institute of Physics, Bhubaneswar, India.
- <sup>z</sup> Also at University of Visva-Bharati, Santiniketan, India.
- <sup>aa</sup> Also at University of Ruhuna, Matara, Sri Lanka.
- <sup>bb</sup> Also at Isfahan University of Technology, Isfahan, Iran.
- <sup>cc</sup> Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- <sup>dd</sup> Also at Yazd University, Yazd, Iran.
- <sup>ee</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- <sup>ff</sup> Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- <sup>gg</sup> Also at Università degli Studi di Siena, Siena, Italy.
- <sup>hh</sup> Also at Purdue University, West Lafayette, USA.
- <sup>ii</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- <sup>jj</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- <sup>kk</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- <sup>ll</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- <sup>mm</sup> Also at Institute for Nuclear Research, Moscow, Russia.
- <sup>nn</sup> Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- <sup>oo</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>pp</sup> Also at University of Florida, Gainesville, USA.
- <sup>qq</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- <sup>rr</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>ss</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>tt</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>uu</sup> Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.
- <sup>vv</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>ww</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>xx</sup> Also at Riga Technical University, Riga, Latvia.
- <sup>yy</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>zz</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>aaa</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>bbb</sup> Also at Mersin University, Mersin, Turkey.
- <sup>ccc</sup> Also at Cag University, Mersin, Turkey.
- <sup>ddd</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>eee</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>fff</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>ggg</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>hhh</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>iii</sup> Also at Kafkas University, Kars, Turkey.
- <sup>jjj</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>kkk</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>lll</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>mmm</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>nnn</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>ooo</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>ppp</sup> Also at Utah Valley University, Orem, USA.
- <sup>qqq</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>rrr</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- <sup>sss</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>ttt</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>uuu</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>vvv</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>www</sup> Also at Kyungpook National University, Daegu, Korea.