EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-132
2018/06/15

CMS-SUS-17-009

Search for supersymmetric partners of electrons and muons in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search for direct production of the supersymmetric (SUSY) partners of electrons or muons is presented in final states with two opposite-charge, same-flavor leptons (electrons and muons), no jets, and large missing transverse momentum. The data sample corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, collected with the CMS detector at the LHC in 2016. The search uses the M_{T2} variable, which generalizes the transverse mass for systems with two invisible objects and provides a discrimination against standard model backgrounds containing W bosons. The observed yields are consistent with the expectations from the standard model. The search is interpreted in the context of simplified SUSY models and probes slepton masses up to approximately 290, 400, and 450 GeV, assuming right-handed only, left-handed only, and both right- and left-handed sleptons (mass degenerate selectrons and smuons), and a massless lightest supersymmetric particle. Limits are also set on selectrons and smuons separately. These limits show an improvement on the existing limits of approximately 150 GeV.

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics provides a description of the fundamental particles and their interactions, and its predictions have been confirmed experimentally with increasing precision over the last several decades. Supersymmetry (SUSY) [1–8], one of the most promising extensions of the SM, addresses several open questions for which the SM has no answer, such as the hierarchy problem and the origin of dark matter. The theory postulates a new fundamental symmetry that assigns to each SM particle a SUSY partner whose spin differs by one half, causing the SUSY partner of an SM fermion (boson) to be a boson (fermion). In addition to stabilizing the Higgs boson (H) mass via cancellations between quantum loop corrections including the top quark and its superpartner, SUSY provides a natural dark matter candidate, if R-parity [9] is conserved, in the form of the lightest SUSY particle (LSP), which is assumed to be massive and stable.

SUSY particles (sparticles) that are colored, the squarks and gluinos, are produced via the strong interaction with significantly larger cross sections than colorless sparticles of equal masses. However, if the squarks and gluinos are too heavy to be produced at the Large Hadron Collider (LHC), the direct production of colorless sparticles, such as the electroweak superpartners (charginos ($\widetilde{\chi}_1^{\pm}$), neutralinos ($\widetilde{\chi}_2^0$), and sleptons ($\widetilde{\ell}$)), would be the dominant observable SUSY process.

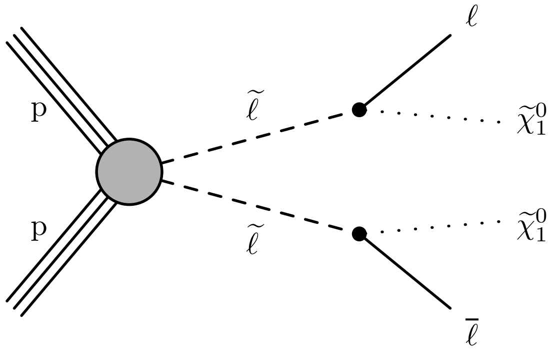

Figure 1: Diagram of slepton pair production with direct decays into leptons and the lightest neutralino.

Supersymmetric models predict charged sleptons ($\widetilde{e}_L$, $\widetilde{\mu}_L$, $\widetilde{\tau}_L$, $\widetilde{e}_R$, $\widetilde{\mu}_R$, $\widetilde{\tau}_R$), the superpartners of the charged left-handed and right-handed SM leptons, which can be produced at proton-proton (pp) colliders in direct electroweak pair production. At sufficiently heavy slepton masses, the sleptons undergo a two-body decay into one of the heavier neutralinos or a chargino, while direct decays to a neutralino LSP are favored for light slepton masses. This Letter presents a search for directly produced selectrons and smuons ($\widetilde{e}_L$, $\widetilde{\mu}_L$, $\widetilde{e}_R$, $\widetilde{\mu}_R$), under the assumption of direct decays $\widetilde{\ell} \rightarrow \ell\widetilde{\chi}_1^0$ with 100% branching ratio, as sketched in Fig. 1. The final state contains little or no hadronic activity and provides a clean signature composed of two opposite-charge (OC), same-flavor (SF) leptons (dielectron or dimuon pairs) and large missing transverse momentum (p_T^{miss}) from the two LSPs that escape detection.

The main SM backgrounds resulting in two OC SF leptons and no reconstructed jets are pp $\rightarrow$ $t\bar{t}$ (if both jets from the top decays are out of acceptance) and pp $\rightarrow$ WW $\rightarrow 2\ell 2\nu$, both of which involve W bosons that decay into an electron or a muon with equal probability, resulting in the same number of dielectron and dimuon events as electron-muon events (different flavor, DF). This flavor symmetry is used in the analysis to predict the number of background SF leptons based on the number of DF leptons in the signal region (SR) in data, after correcting for differences in trigger and lepton reconstruction efficiencies. The Drell–Yan (DY) process would also be a main background in the analysis, but is greatly suppressed by the SR requirements. The pp $\to$ ZZ $\to 2\ell 2\nu$ and pp $\to$ WZ $\to 3\ell\nu$ processes can also result in two OC SF leptons. These contributions are taken from Monte Carlo (MC) simulation after comparing data and simulation predictions in control regions (CR).

The data set of proton-proton collisions used for this search was collected in 2016 with the CMS detector at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$, and corresponds to an integrated luminosity of $35.9\,\text{fb}^{-1}$. Interpretations of the search results are given in terms of simplified SUSY model spectra [10, 11]. Searches for SUSY in these final states were performed previously by the ATLAS [12] and CMS [13] Collaborations at $\sqrt{s} = 8\,\text{TeV}$.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, that provides an axial magnetic field of 3.8 T. Within the solenoid volume are various particle detection systems. Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 < \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $-\log[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the counterclockwise-beam direction. A lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter surround the tracking volume. The calorimeters provide energy and direction measurements of electrons and hadronic jets. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing for transverse momentum (p_{T}) balance measurements, in the plane perpendicular to the beam direction. A two-tier trigger system selects events of interest for physics analysis. 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. [14].

3 Event samples

The search is based on samples of dielectron and dimuon events. As mentioned in Section 1, DF events are used to predict the contribution of background SF events in the SR. The SF and DF samples are collected with a variety of dilepton triggers. Triggers that include loose isolation criteria on both leptons require $p_{\mathrm{T}} > 23\,\text{GeV}$ (electron) or $17\,\text{GeV}$ (muon) on the highest p_{T} lepton. The other lepton is then required to have $p_{\mathrm{T}} > 12\,\text{GeV}$ (electrons) or $8\,\text{GeV}$ (muons). In addition, dilepton triggers without isolation requirements are used to increase signal efficiency. These require $p_{\mathrm{T}} > 33$ (30) GeV for both leptons in the dielectron (electron-muon) case. The dimuon trigger requires either $p_{\mathrm{T}} > 27$ (8) or $p_{\mathrm{T}} > 30$ (11) GeV for the highest (next-to-highest) p_{T} muon, depending on the data taking period. The lepton pseudorapidity coverage for the triggers is $|\eta| < 2.5$ (2.4) for electrons (muons). The trigger efficiencies are measured in data using events selected by a suite of jet triggers and are found to be 90–96%.

The main SM backgrounds are estimated using data control samples, while simulated events are used to predict backgrounds from diboson (ZZ and WZ) production. Simulated events are also used extensively in the analysis to estimate systematic uncertainties. Next-to-leading order (NLO) and next-to-next-NLO (NNLO) cross sections [15–26] are used to normalize the simulated background samples. For the signal samples we use NLO plus next-to-leading-logarithmic (NLL) calculations for left- or right-handed sleptons, with all the other sparticles except the LSP assumed to be heavy and decoupled [27–29].

The gg $\rightarrow$ ZZ process is generated at LO with MCFM 7.0 [30], and all other diboson production processes [31, 32], and $\mathrm{t\bar{t}}$ [33] and the production of single top quark associated with a W boson [34], are generated at NLO with no additional partons with POWHEG v2. Simulated samples of DY processes are generated with MADGRAPH5_aMC@NLO 2.3.3 program [15] to leading order precision with up to four additional partons in the matrix element calculation. Simulated VVV and $\mathrm{t\bar{t}V}$ ($\mathrm{V} = \mathrm{W}, \mathrm{Z}$) events are simulated with the same generator but at NLO precision. The NNPDF3.0 [35] LO (NLO) parton distribution functions (PDFs) are used for the samples generated at LO (NLO). The matrix element calculations performed with these generators are interfaced with PYTHIA [36], including the CUETP8M1 tune [37, 38] for the simulation of parton showering and hadronization. Double counting of partons generated with MADGRAPH5_aMC@NLO and PYTHIA is removed using the MLM [39] and FXFX [40] matching schemes in the LO and NLO samples, respectively. The detector response is simulated with a GEANT4 model [41] of the CMS detector. The simulation of new-physics signals is performed using the MADGRAPH5_aMC@NLO 2.2.2 program at LO precision, with up to two additional partons in the matrix element calculation. Events are then interfaced with PYTHIA for fragmentation and hadronization and simulated using the CMS fast simulation package [42]. The slepton decays are also simulated with PYTHIA. Multiple pp interactions, also known as pileup, are superimposed on the hard collision, and the simulated samples are reweighed in such a way that the number of collisions per bunch crossing accurately reflects the distribution observed in data. Corrections are applied to the simulated samples to account for differences between simulation and data in the trigger and reconstruction efficiencies.

4 Object selection

The particle-flow (PF) algorithm [43] reconstructs and identifies particle candidates in the event, referred to as PF objects. To select collision events we require at least one reconstructed vertex, and the one with the largest value of summed physics object p_{T}^2 is taken to be the primary pp interaction vertex. The physics objects used for the primary vertex selection are the objects returned by a jet finding algorithm [44, 45] applied to all charged tracks associated with the vertex, plus the corresponding associated $p_{\mathrm{T}}^{\mathrm{miss}}$. Its vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF objects in the event, and its magnitude is $p_{\mathrm{T}}^{\mathrm{miss}}$. Electrons are reconstructed by associating tracks with ECAL clusters. They are identified using a multivariate approach based on information on ECAL cluster shapes, track reconstruction quality, and the matching between the track and the ECAL cluster [46]. Electrons coming from reconstructed photon conversions are rejected. Muons are reconstructed from tracks in the muon system associated with tracks in the tracker. The identification uses the quality of the track fit and the number of associated hits in the tracking detectors [47]. For both electrons and muons, the impact parameter with respect to the primary vertex is required to be within 0.5 mm in the transverse plane and less than 1 mm along the beam direction. A lepton isolation variable is defined as the scalar p_{T} sum of all PF objects in a cone around the lepton, excluding identified electrons or muons. Additional pp interactions in the same or nearby bunch crossings (pileup) can be mitigated by only considering charged PF objects that are compatible with the primary vertex and the average expected pileup contribution is subtracted from the neutral component of the isolation. The isolation sum is required to be smaller than 10 (20)% of the electron (muon) p_{T}. A shrinking cone-size with increasing p_{T} is chosen that ensures high efficiency for leptons from Lorentz-boosted boson decays [48]. This varying cone size is chosen as the following

$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ for $p_T < 50\,\text{GeV}$, $= 10\,\text{GeV}/p_T$ for $50 < p_T < 200\,\text{GeV}$, and 0.05 for $p_T > 200\,\text{GeV}$.

Isolated charged particle tracks identified by the PF algorithm are selected with a looser criteria than the leptons defined above, and are used as a veto on the presence of additional charged leptons from vector boson decays. Isolation is evaluated by summing the p_T of all charged PF objects within a cone of $\Delta R = 0.3$ and with the longitudinal impact parameter $|\Delta z| < 0.1\,\text{cm}$ relative to the primary vertex. PF objects identified as charged hadrons (electrons or muons) are required to have $p_T > 10$ (5) GeV and an isolation value less than 10 (20)% of the object p_T.

Jets are clustered from PF objects, excluding charged hadrons not associated with the primary vertex that are assumed to be the result of pileup interactions, using the anti-k_T clustering algorithm [44] with a distance parameter of 0.4 as implemented in the FASTJET package [45, 49]. Jets are required to have $|\eta| < 2.4$ and $p_T > 35\,\text{GeV}$, where the p_T is corrected for nonuniform detector response and pileup effects [50, 51]. Jets reconstructed within $\Delta R < 0.4$ of any of the selected leptons are removed from the event. Corrections to the jet energy are propagated to p_T^{miss} using the procedure developed in Ref. [50]. At least two such jets are selected for CRs of this analysis, and a veto of jets with p_T above 25 GeV is applied in the SR.

Events are selected for the SR by requiring two OC SF leptons ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) with $p_T > 50$ (20) GeV for the highest (next-to-highest) p_T lepton and $|\eta| < 2.4$ for both leptons. For the background prediction methods a sample of lepton pairs are selected, with a p_T threshold of 25 (20) GeV for the leading (subleading) lepton. The highest minimum p_T value is chosen because it efficiently suppresses backgrounds while maintaining signal acceptance efficiency. Any additional leptons, identified with the looser requirement that the isolation sum should be less than 40% of the lepton p_T, are vetoed. Leptons must be spatially separated by $\Delta R > 0.1$ to avoid reconstruction efficiency differences between electrons and muons in events with collinear leptons. All leptons in the transition region between the barrel and endcap of the ECAL, $1.4 < |\eta| < 1.6$, are rejected to ensure similar acceptance for electrons and muons. The same lepton selection criteria are used for a control sample of OC DF pairs, $e^{\pm}\mu^{\mp}$. The selection requirements have been chosen in order to maximize the lepton selection efficiency while maintaining a similarity between electron and muon efficiencies.

5 Search strategy

The slepton SRs are designed to suppress expected backgrounds from SM processes, while maintaining sensitivity to different assumptions on the masses of the $\widetilde{\ell}$ and $\widetilde{\chi}_1^0$. To suppress backgrounds due to low-mass resonances and Z boson production, the dilepton invariant mass is required to be above 20 GeV, and to be either below 76 or above 106 GeV. Little or no hadronic activity is expected in the direct production of sleptons at pp colliders when assuming a 100% branching ratio for $\widetilde{\ell} \to \ell\widetilde{\chi}_1^0$. As a result, events are rejected if they contain jets with p_T above 25 GeV. Furthermore, events with two leptons and an additional isolated and charged PF candidate passing the selections described in Section 4 are vetoed since signal events would not include additional isolated charged particles.

The kinematic variable M_{T2} [52, 53] is used to reduce backgrounds from $t\bar{t}$ and WW processes. This variable was first introduced to measure the mass of pair-produced particles, each decaying to the same final state, consisting of a visible and an invisible particle. It is defined as:

$$M_{T2} = \min_{\vec{p}_T^{\text{miss}(1)} + \vec{p}_T^{\text{miss}(2)} = \vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right], \tag{1}$$

where $\vec{p}_{\mathrm{T}}^{\mathrm{miss}(i)}$ ($i = 1, 2$) are trial vectors obtained by decomposing $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. The transverse masses $M_{\mathrm{T}}^{(i)} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{vis}} p_{\mathrm{T}}^{\mathrm{miss}(i)} [1 - \cos(\Delta\phi)]}$ are obtained by pairing either of these trial vectors with one of the two leptons.

The $\Delta\phi$ is the angle between the p_{T} of the lepton (noted as $p_{\mathrm{T}}^{\mathrm{vis}}$) and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}(i)}$. The minimization is performed over all trial momenta satisfying the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ constraint. When building M_{T2} from the two selected leptons and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, denoted as $M_{\mathrm{T2}}(\ell\ell)$, its distribution exhibits a sharp decrease above the mass of the W boson for $\mathrm{t\bar{t}}$ and WW events and is therefore well suited to suppress these backgrounds. For this reason a requirement of $M_{\mathrm{T2}}(\ell\ell) > 90\,\mathrm{GeV}$ is imposed in this search.

The SR is divided into four bins of $p_{\mathrm{T}}^{\mathrm{miss}}$: 100–150, 150–225, 225–300, and $\geq$300 GeV. The selection results in a signal selection efficiency that ranges from 20 to 30% assuming a massless LSP. In addition to results including both flavors of SF lepton pairs, results separated in dielectron and dimuon pairs are presented, as the simplified models do not assume that smuon and selectron masses should be the same.

6 Standard model background predictions

The backgrounds from the SM processes are divided into four categories. Flavor-symmetric (FS) background processes are those processes that result in DF pairs ($\mathrm{e}^{\pm}\mu^{\mp}$) as often as SF pairs ($\mu^{\pm}\mu^{\mp}$, $\mathrm{e}^{\pm}\mathrm{e}^{\mp}$). The dominant contributions to this category are due to top quark pair production and WW production.

The subleading background contribution arises from diboson production, ZZ and WZ, and is estimated from simulation. The ZZ process can result a final state with two leptons originating from one Z boson decay and two neutrinos from the other Z boson decay. The WZ process can give rise to a final state with three leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$, which can satisfy the signal selection criteria if one of the leptons fails the identification or acceptance requirements.

The contribution from DY is small but not negligible in the SR due to the large $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement. The contribution is estimated using simulated events after relaxing the Z boson veto and a transfer factor $r_{\mathrm{out/in}}$ that gives the contribution of DY+jets events outside of the Z boson mass window of 76–106 GeV. The transfer factor $r_{\mathrm{out/in}}$ is measured in a DY enriched CR as the ratio of events outside of the Z boson mass over the events compatible with the Z boson mass. A systematic uncertainty of 50% is assumed to result from this method.

Finally, a very minor background, referred to in the following as Rare backgrounds, originates from triboson production, or processes resulting in non-FS leptons, such as $\mathrm{t\bar{t}Z}$, tZq and tWZ. The simulation is also used to estimate this contribution, with a conservative systematic uncertainty of 50% assigned in place of QCD scale and PDF variations.

6.1 Flavor-symmetric backgrounds

The data-driven prediction of SM SF backgrounds is obtained using event counts in the DF sample, multiplied by a translation factor, $R_{\mathrm{SF/DF}}$, correcting for flavor dependent reconstruction, identification and trigger efficiencies which can be different for electrons and muons, as described in Ref. [54]. The translation factor is estimated with two independent methods.

The first method estimates directly the translation factor in a data CR enriched in enriched in $\mathrm{t\bar{t}}$ events, requiring exactly two jets, $100 < p_{\mathrm{T}}^{\mathrm{miss}} < 150\,\mathrm{GeV}$ and excluding the dilepton invariant mass range $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$ to reduce contributions from DY production. Here, $R_{\mathrm{SF/DF}}$

is computed using the observed yield of the SF and DF events, $R_{\mathrm{SF/DF}} = N_{\mathrm{SF}}/N_{\mathrm{DF}}$. Data and simulation agree to within 2% in this region. A 4% systematic uncertainty on the translation factor is assigned from simulation studies, as the maximal magnitude of the systematic needed to cover discrepancies in the translation factor as a function of some SR variables.

The second method utilizes a factorized approach. The ratio of muon to electron reconstruction and identification efficiencies, $r_{\mu/\mathrm{e}}$, is measured in a CR enriched in DY events by requiring at least two jets, $p_{\mathrm{T}}^{\mathrm{miss}} < 50\,\mathrm{GeV}$, and $60 < m_{\ell\ell} < 120\,\mathrm{GeV}$. This results in a large sample of $\mathrm{e}^{\pm}\mathrm{e}^{\mp}$ and $\mu^{\pm}\mu^{\mp}$ events with similar kinematic distributions to those of the SR. Assuming factorization for the efficiencies of the two leptons, the ratio of efficiencies for muons and electrons is measured as $r_{\mu/\mathrm{e}} = \sqrt{N_{\mu^+\mu^-}/N_{\mathrm{e}^+\mathrm{e}^-}}$. This ratio depends on the lepton p_{T} due to the trigger and reconstruction efficiency differences, especially at low lepton p_{T}, and a parametrization as a function of the p_{T} of the less energetic lepton is used:

$$r_{\mu/\mathrm{e}} = r_{\mu/\mathrm{e,c}} + \frac{\alpha}{p_{\mathrm{T}}}. \qquad (2)$$

Here $r_{\mu/\mathrm{e,c}}$ and α are constants that are determined from a fit to data and cross-checked using simulation. These fit parameters are determined to be $r_{\mu/\mathrm{e,c}} = 1.140 \pm 0.005$ and $\alpha = 5.20 \pm 0.16\,\mathrm{GeV}$. In addition to the fit uncertainty, a 10% systematic uncertainty is assigned to account for remaining variations observed when studying the dependence of $r_{\mu/\mathrm{e}}$ on $p_{\mathrm{T}}^{\mathrm{miss}}$ and on the p_{T} of the more energetic lepton.

The trigger efficiencies for the three flavor combinations are used to define the factor $R_{\mathrm{T}} = \sqrt{\epsilon^{\mathrm{T}}_{\mu^{\pm}\mu^{\mp}}\epsilon^{\mathrm{T}}_{\mathrm{e}^{\pm}\mathrm{e}^{\mp}}}/\epsilon^{\mathrm{T}}_{\mathrm{e}^{\pm}\mu^{\mp}}$, which takes into account the difference between SF and DF channels. The efficiencies, $\epsilon^{\mathrm{T}}_{\mu^{\pm}\mu^{\mp}}$, $\epsilon^{\mathrm{T}}_{\mathrm{e}^{\pm}\mathrm{e}^{\mp}}$ and $\epsilon^{\mathrm{T}}_{\mathrm{e}^{\pm}\mu^{\mp}}$, are calculated as the fraction of events collected with PF HT triggers, that also passes the dimuon, dielectron and $e\mu$ triggers respectively. The measured efficiencies range between 90–96%, yielding a final value of $R_{\mathrm{T}} = 1.052 \pm 0.043$. The translation factor in the factorized approach is thus $R_{\mathrm{SF/DF}} = 0.5(r_{\mu/\mathrm{e}} + r^{-1}_{\mu/\mathrm{e}})R_{\mathrm{T}}$ where the factor of 0.5 is due to the assumption that the number of produced DF events is twice the number of produced events in each SF sample (ee and $\mu\mu$). Since $r_{\mu/\mathrm{e}}$ depends on the lepton kinematic variables, this translation factor is calculated on an event-by-event basis. A separate translation factor is determined for each SR and is combined with the translation factor from the direct measurement using a weighted average.

6.2 Diboson backgrounds

Although a Z boson veto is applied, the ZZ process can still enter the SR through an off-shell Z boson. This contribution is estimated from simulated events, validated in a data CR with four identified leptons. The selections for the CR and SR are exclusive, and the physics process in the CR (ZZ where both Z bosons decay to charged leptons) has similar kinematics as the process it is designed to validate. In order for the CR to accurately reflect the kinematics in the SR, the same jet veto as in the SR is applied in the CR. In addition, for the CR the Z boson candidate with the invariant mass best (next best) compatible with the Z boson mass is required to have $76 < m_{\ell\ell} < 106\,\mathrm{GeV}$ ($50 < m_{\ell\ell} < 130\,\mathrm{GeV}$). A generator-level p_{T} dependent NNLO/NLO K factor taking into account missing electroweak corrections [55–57] is applied to the $\mathrm{q\overline{q}} \to \mathrm{ZZ}$ process cross-sections. The smaller contribution from the $\mathrm{gg} \to \mathrm{ZZ}$ process is normalized to the NLO calculation [19]. After subtracting contributions to the CR from other processes, as determined by simulation, a simulation-to-data scale factor of 0.94 ± 0.07 is obtained. This scale factor is used to correct the ZZ background prediction from simulation in the SR, where one Z boson decays to charged leptons, and the other Z boson decays to neutrinos. A systematic uncertainty of 7% results from the limited statistics in the CR.

A difference in the $p_{\mathrm{T}}^{\mathrm{miss}}$ and $M_{\mathrm{T2}}(\ell\ell)$ distributions is observed after applying the $\mathrm{q\overline{q}} \rightarrow \mathrm{ZZ}$ NNLO/NLO K factor as a function of different generator level kinematic variables. An uncertainty is then assigned to the method based on the difference in the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape for MC events in the SR before and after the application of the K factor. Additional systematic uncertainties are considered in the background prediction, originating from the jet energy scale, the variation of the renormalization and factorization scales, the PDF choice, and the uncertainties in the lepton reconstruction and isolation efficiencies, and in the trigger modelling.

The WZ process result in SF events when one of the three leptons is not reconstructed (lost). The two detected leptons are of the SF when the lepton from W decay is lost, but they can be either SF or DF, with equal probability, when the lost lepton is from the Z boson decay. In the first case the background contribution is estimated from simulation, whereas in the second case it is covered by the data-driven FS prediction method.

Just as for the ZZ background, the prediction from simulation is validated in a CR enriched in WZ events. We select events with three leptons, with an additional jet veto and a requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 70\,\mathrm{GeV}$. The invariant mass of two SF leptons must be within $76 < m_{\ell\ell} < 106\,\mathrm{GeV}$. To reduce contributions from the DY process, events are required to have $M_{\mathrm{T}} > 50\,\mathrm{GeV}$, where M_{T} is calculated from $p_{\mathrm{T}}^{\mathrm{miss}}$ and the lepton from the W boson. After subtracting contributions from other processes, a simulation-to-data scale factor of 1.06 is obtained and applied to the prediction from simulation in SR A systematic uncertainty of 6% results from the limited statistics in the CR.

An additional uncertainty of 5% is added (in quadrature) to cover possible differences in the identification and isolation efficiencies at low lepton p_{T}. Finally, uncertainties due to the jet energy scale, the lepton efficiencies, the trigger modeling, the PDF choice, and the renormalization and factorization scales are taken into account when computing the expected WZ yields in the SR.

7 Results

The observed number of events in data in the SR are compared with the stacked SM background estimates as shown in Fig. 2 (SF events), and in Fig. 3 (dielectron and dimuon events separately). The SM background and data yields are summarized in Table 1 for SF events and in Table 2 for dielectron and dimuon events.

At high $p_{\mathrm{T}}^{\mathrm{miss}}$ values, the uncertainties in the background prediction are driven by the statistical uncertainty in the number of events in the DF sample used to derive the FS background. There is agreement between observation and SM expectation given the systematic and statistical uncertainties.

8 Interpretation

The results are interpreted in terms of the simplified model described in Section 1. Upper limits on the cross section, assuming branching ratios of 100%, have been calculated at 95% confidence level (CL) using the $\mathrm{CL_s}$ criterion and an asymptotic formulation [58–61], taking into account the statistical and systematic uncertainties in the signal yields and the background predictions. All systematic uncertainties are of the type log-normal in the limit determination, except the gamma function nuisance which is used for the FS statistical uncertainty.

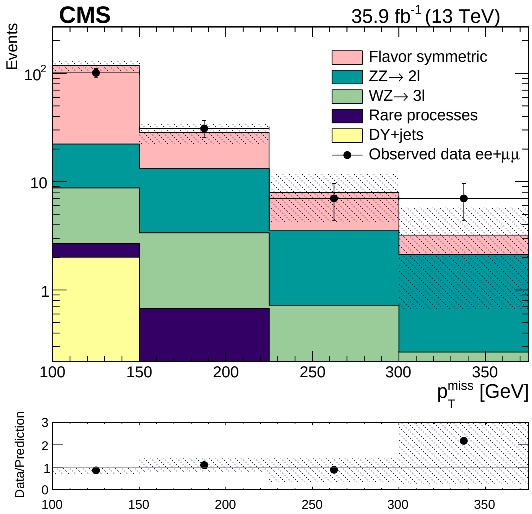

Figure 2: Upper: Distribution of $p_{\mathrm{T}}^{\mathrm{miss}}$ for the resulting SM background yields estimated in the analysis SR (colored histograms) with the corresponding event counts observed in data (black points), selecting only SF events. Lower: Ratio of data to SM prediction, with the filled band representing the statistical uncertainty on the data and the estimated backgrounds and the systematic uncertainty on the estimated backgrounds.

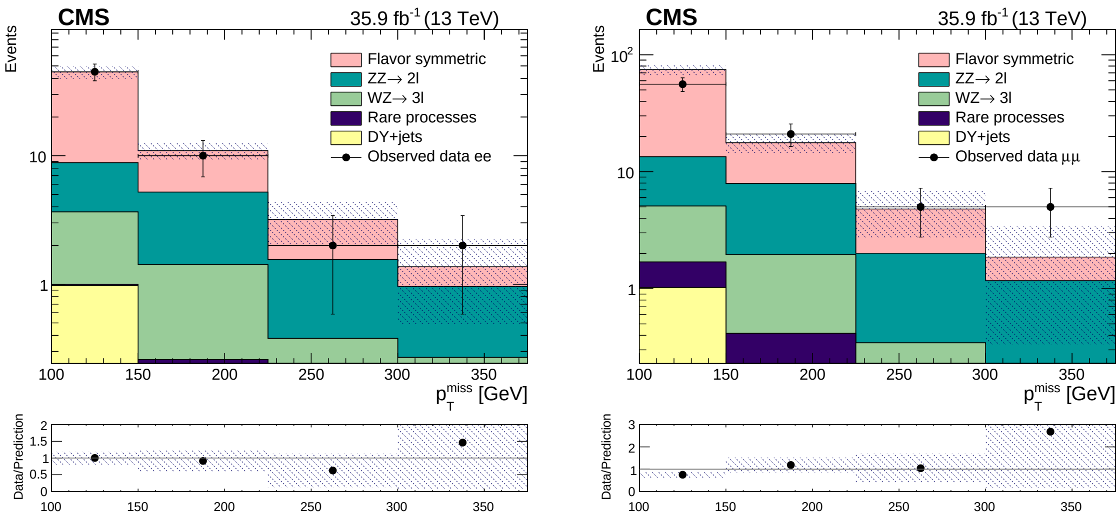

Figure 3: Upper: Distribution of $p_{\mathrm{T}}^{\mathrm{miss}}$ for the resulting SM background yields estimated in the analysis SR (colored histograms) with the corresponding event counts observed in data (black points), selecting only dielectron (left) or dimuon (right) events. Lower: Ratio of data to SM prediction, with the filled band representing the statistical uncertainty on the data and the estimated backgrounds and the systematic uncertainty on the estimated backgrounds.

8.1 Systematic uncertainty in the signal yield

The systematic uncertainties associated with the signal are shown in Table 3, and described below. The uncertainty in the measurement of the integrated luminosity is 2.5% [62]. A flat uncertainty of 5% is associated to the lepton identification and isolation efficiency in the signal acceptance and an uncertainty of 4% in the lepton efficiency of the signal using fast simulation. The uncertainty on the trigger efficiency is measured to be 3%. The uncertainty in the jet en-

Table 1: The predicted SM background contributions, their sum and the observed number of SF events in data. The yields expected for several signal scenarios are provided as a reference. The uncertainties associated with the background yields stem from statistical and systematic sources. The last bin is inclusive above 300 GeV.

p_T^{miss} [GeV]	100–150	150–225	225–300	≥300
FS bkg.	96^{+13}_{-12}	$15.3^{+5.6}_{-4.5}$	$4.4^{+3.6}_{-2.3}$	$1.1^{+2.5}_{-1.0}$
ZZ	13.5 ± 1.5	9.78 ± 1.19	2.84 ± 0.56	1.86 ± 0.12
WZ	6.04 ± 1.19	2.69 ± 0.88	0.86 ± 0.45	0.21 ± 0.20
DY+jets	$2.01^{+0.39}_{-0.23}$	$0.00 + 0.28$	$0.00 + 0.28$	$0.00 + 0.28$
Rare processes	0.69 ± 0.44	0.68 ± 0.47	$0.00 + 0.20$	0.05 ± 0.12
Total prediction	118^{+13}_{-12}	$28.4^{+5.9}_{-4.8}$	$7.9^{+3.7}_{-2.4}$	$3.2^{+2.6}_{-1.1}$
Data	101	31	7	7
$m_{\tilde{\ell}} = 450\,\text{GeV}$, $m_{\tilde{\chi}_1^0} = 40\,\text{GeV}$	0.73 ± 0.08	1.81 ± 0.12	2.39 ± 0.14	6.17 ± 0.23
$m_{\tilde{\ell}} = 375\,\text{GeV}$, $m_{\tilde{\chi}_1^0} = 160\,\text{GeV}$	2.91 ± 0.19	6.86 ± 0.29	6.06 ± 0.27	5.25 ± 0.26
$m_{\tilde{\ell}} = 250\,\text{GeV}$, $m_{\tilde{\chi}_1^0} = 180\,\text{GeV}$	14.04 ± 1.02	8.59 ± 0.80	0.91 ± 0.26	0.10 ± 0.10
$m_{\tilde{\ell}} = 100\,\text{GeV}$, $m_{\tilde{\chi}_1^0} = 1\,\text{GeV}$	159.1 ± 16.5	30.4 ± 7.26	13.0 ± 5.00	—

Table 2: The predicted SM background contributions, their sum and the observed number of dielectron (upper) and dimuon (lower) events in data. The uncertainties associated with the yields stem from statistical and systematic sources. The last bin is inclusive above 300 GeV.

Dielectron events				
p_T^{miss} [GeV]	100–150	150–225	225–300	≥300
FS bkg.	$36.1^{+6.6}_{-6.3}$	$5.7^{+2.5}_{-2.1}$	$1.6^{+1.5}_{-1.1}$	$0.41^{+1}_{-0.5}$
ZZ	5.17 ± 0.68	3.79 ± 0.58	1.18 ± 0.31	0.69 ± 0.07
WZ	2.65 ± 0.68	1.16 ± 0.45	0.39 ± 0.33	0.21 ± 0.20
DY+jets	$0.98^{+0.14}_{-0.15}$	$0.00 + 0.28$	$0.00 + 0.28$	$0.00 + 0.28$
Rare processes	0.02 ± 0.14	0.26 ± 0.21	$0.00 + 0.11$	0.06 ± 0.04
Total prediction	$45^{+6.7}_{-6.4}$	$11.0^{+2.6}_{-2.3}$	$3.2^{+1.6}_{-1.2}$	$1.4^{+1.1}_{-0.6}$
Data	45	10	2	2
Dimuon events				
p_T^{miss} [GeV]	100–150	150–225	225–300	≥300
FS bkg.	$61.3^{+9.1}_{-8.5}$	$9.8^{+3.9}_{-3.2}$	$2.8^{+2.4}_{-1.7}$	$0.70^{+1.7}_{-0.8}$
ZZ	8.33 ± 0.99	5.98 ± 0.80	1.67 ± 0.42	1.17 ± 0.10
WZ	3.40 ± 0.91	1.53 ± 0.73	0.47 ± 0.30	$0.00 + 0.06$
DY+jets	$1.03^{+0.33}_{-0.14}$	$0.00 + 0.28$	$0.00 + 0.28$	$0.00 + 0.28$
Rare processes	0.66 ± 0.41	0.42 ± 0.35	$0.00 + 0.16$	$0.00 + 0.11$
Total prediction	$75^{+9.2}_{-8.7}$	$17.7^{+4.1}_{-3.4}$	$4.8^{+2.5}_{-1.8}$	$1.9^{+1.7}_{-0.8}$
Data	56	21	5	5

ergy scale is assessed by shifting the jet energy correction factors for each jet by one standard deviation up and down and recalculating the kinematic quantities. The result varies between 1 and 16% depending on the signal kinematics. Determining the signal acceptance in high-and low-pileup regimes separately yields an uncertainty of 0.5–7%. The uncertainty in the $p_{\mathrm{T}}^{\mathrm{miss}}$ modeling is assessed by comparing the reconstructed $p_{\mathrm{T}}^{\mathrm{miss}}$ to the generator-level $p_{\mathrm{T}}^{\mathrm{miss}}$ in fast simulation and amounts to 0.5–20%. Varying the unclustered energy, and the electron and muon scales, results in systematic uncertainties of 0.5–8%, 0.5–4%, and 0.5–20% respectively. The large variation associated to the muon energy scale is due to the poor muon momentum resolution at high p_{T}, and the quoted value is driven by one signal scenario containing such a high p_{T} muon event. The theoretical uncertainties are those related to the uncertainty on the QCD renormalization (μ_{R}) and factorization (μ_{F}) scales, and of the PDF. The systematic uncertainties associated with the μ_{R} and μ_{F} scales are evaluated using weights derived from the SysCalc code applied to simulated signal events [63]. For renormalization and factorization scales the Stewart–Tackmann prescription [64] is followed, that treats the theory uncertainties in analyses with a jet selection. This procedure results in an uncertainty of 1–11%. Finally the statistical uncertainty in the number of simulated events is also considered and found to be in the range 0.5–20%, depending on the signal scenario.

Table 3: List of systematic uncertainties taken into account for the signal yields.

Source of uncertainty	Uncertainty (%)
Integrated luminosity	2.5
Lepton reconstruction/isolation eff.	5
Trigger modeling	3
Fast simulation electron efficiency	1–2.5
Fast simulation muon efficiency	1–3
Jet energy scale	1–15
Pileup	0.5–7
Fast simulation $p_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.5–20
Unclustered energy shifted $p_{\mathrm{T}}^{\mathrm{miss}}$	0.5–8
Muon energy scale shifted $p_{\mathrm{T}}^{\mathrm{miss}}$	0.5–20
Electron energy scale shifted $p_{\mathrm{T}}^{\mathrm{miss}}$	0.5–4
Renormalization/factorization scales	1–11
PDF	3
MC statistical uncertainty	0.5–20

8.2 Interpretations using simplified models

Upper limits on the direct slepton pair production cross section are displayed in Fig. 4 for three scenarios: assuming the existence of both flavor mass degenerate left- and right-handed sleptons, for only left-handed sleptons, and for only right-handed sleptons. Similarly, the limits on direct selectron and smuon production are displayed in Figs. 5 and 6, respectively. The Figs. 4-6 also show the 95% CL exclusion contours, as a function of the $\widetilde{\ell}$ and $\widetilde{\chi}_1^0$ masses. Note that the cross section at a given mass for right-handed sleptons is expected to be about one third of that for left-handed sleptons. The analysis probes slepton masses up to approximately 450, 400, or 290 GeV, assuming both left- and right-handed, left-handed only, or right-handed sleptons, and a massless LSP. In the case of selectrons (smuons), the limits corresponding to these 3 scenarios are 350, 310 and 250 GeV (310, 280, and 210 GeV). Since the dimuon data yield in the highest $p_{\mathrm{T}}^{\mathrm{miss}}$ bin is somewhat higher than predicted, the observed limits in this channel are weaker than expected in the absence of signal. These results improve the previous 8 TeV exclusion limits by 100–150 GeV in the slepton mass [13].

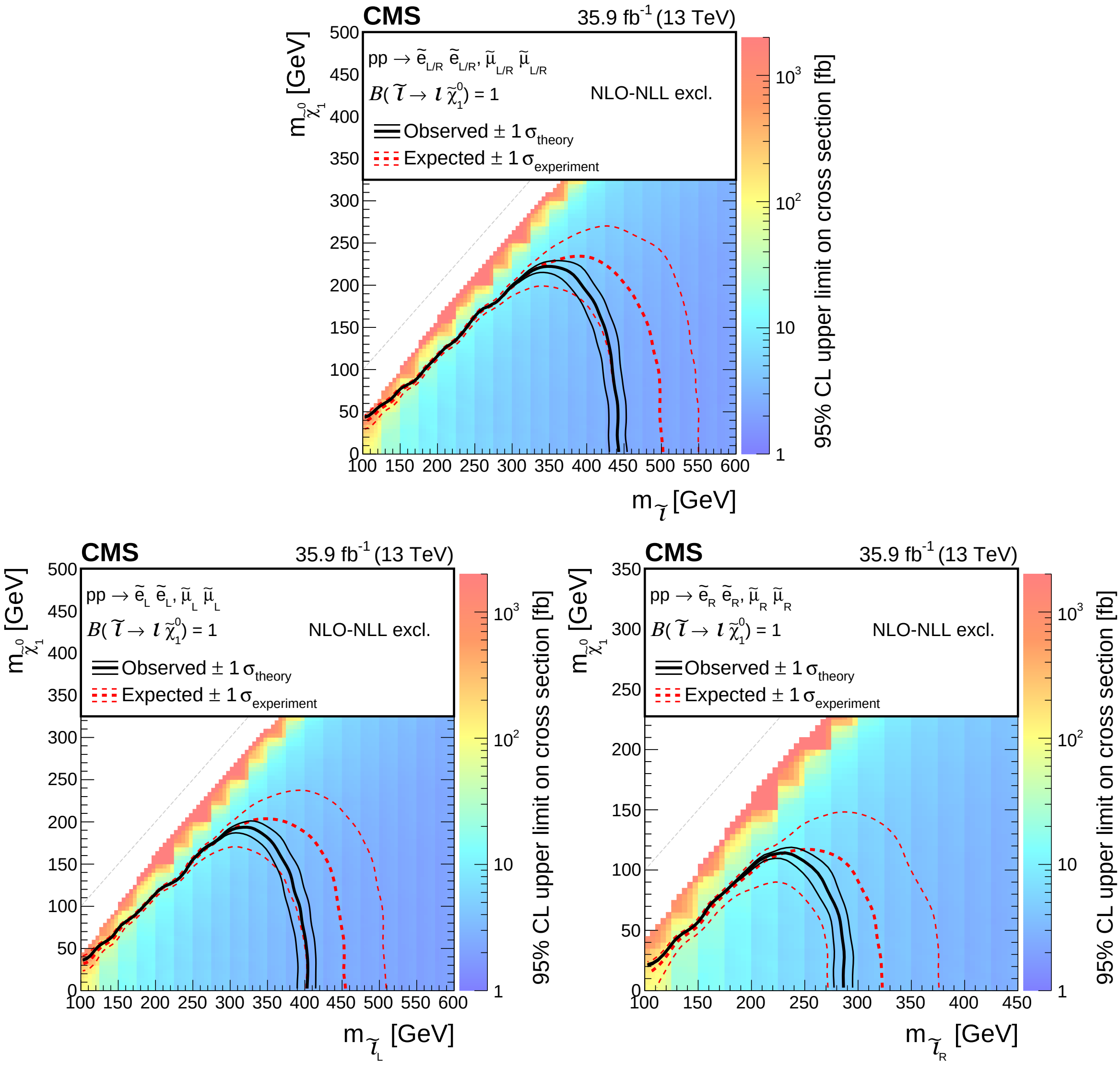

Figure 4: Cross section upper limit and exclusion contours at 95% CL for direct slepton production of two flavors, selectrons and smuons, as a function of the $\tilde{\chi}^0_1$ and $\tilde{\ell}$ masses, assuming the production of both left- and right-handed sleptons (upper) or production of only left- (lower left) or right-handed (lower right). The region under the thick red dotted (black solid) line is excluded by the expected (observed) limit. The thin red dotted curves indicate the regions containing 95% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

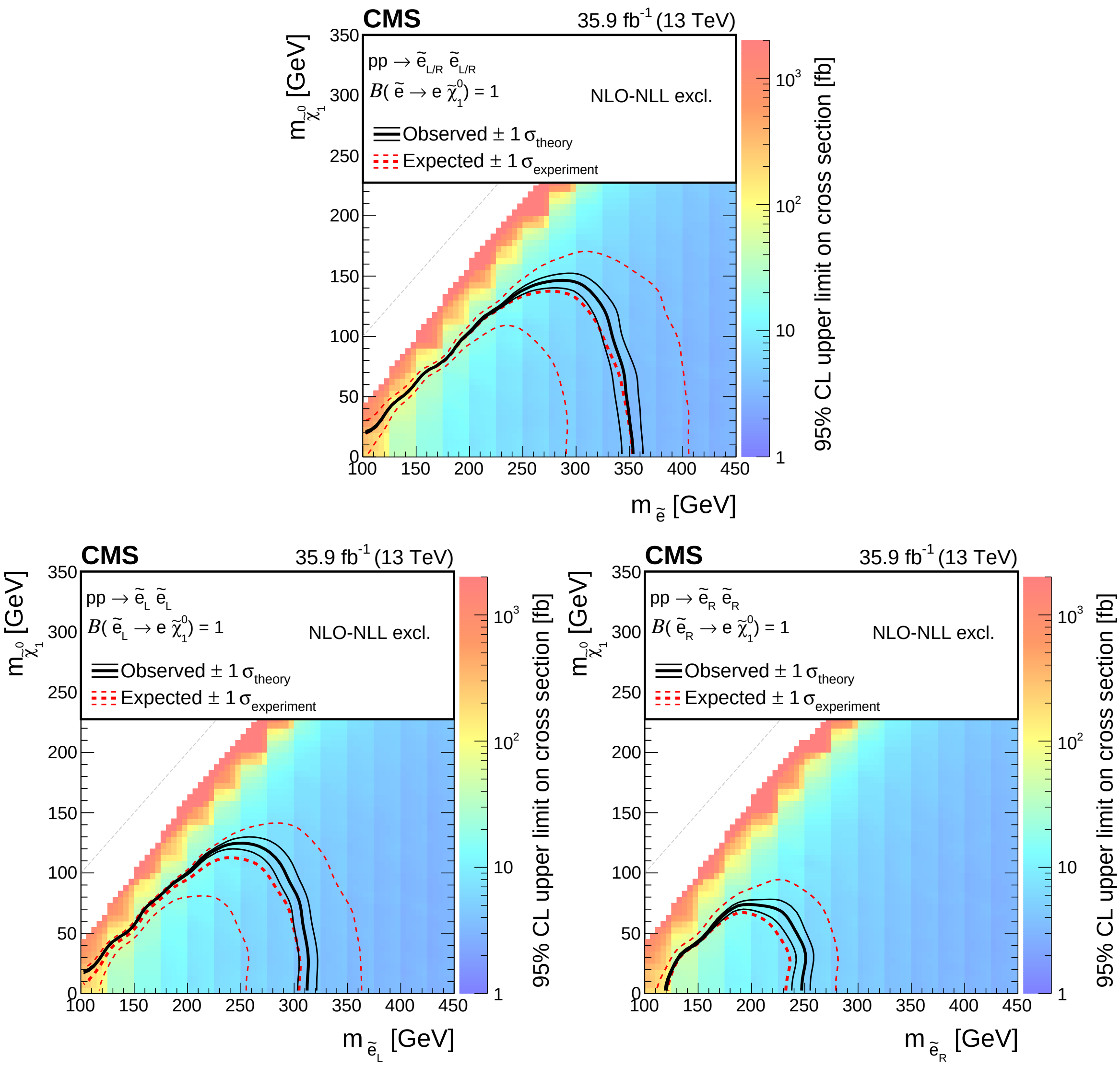

Figure 5: Cross section upper limit and exclusion contours at 95% CL for direct selectron production as a function of the $\widetilde{\chi}^0_1$ and $\widetilde{\ell}$ masses, assuming the production of both left- and right-handed selectrons (upper), or production of only left- (lower left) or right-handed (lower right) selectrons. The region under the thick red dotted (black solid) line is excluded by the expected (observed) limit. The thin red dotted curves indicate the regions containing 95% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

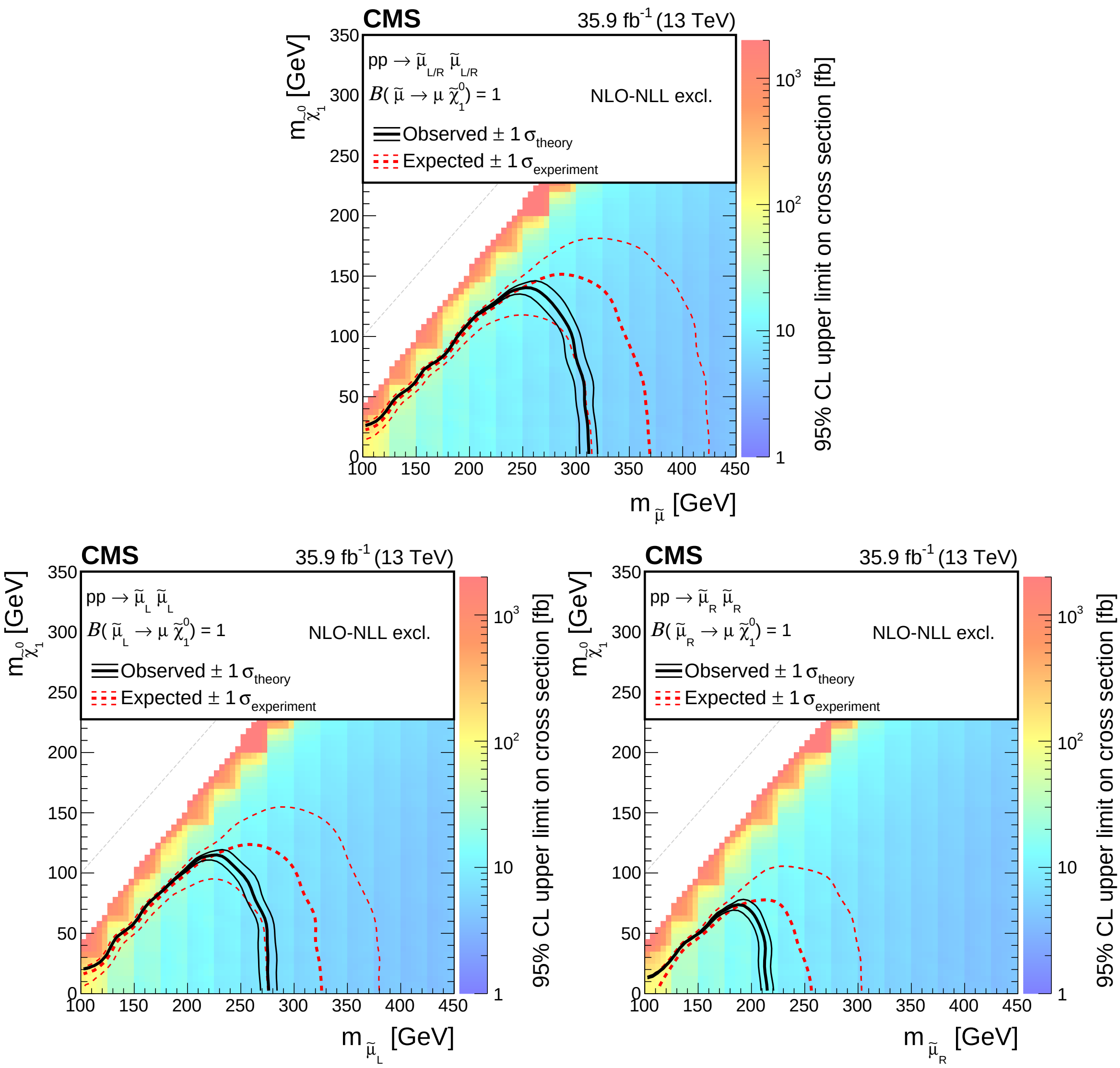

Figure 6: Cross section upper limit and exclusion contours at 95% CL for direct smuon production as a function of the $\widetilde{\chi}_1^0$ and $\widetilde{\ell}$ masses, assuming the production of both left- and right-handed smuons (upper), or production of only left- (lower left) or right-handed (lower right) smuons. The region under the thick red dotted (black solid) line is excluded by the expected (observed) limit. The thin red dotted curves indicate the regions containing 95% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

9 Summary

A search for direct slepton (selectron or smuon) production, in events with opposite-charge, same-flavor leptons, no jets, and missing transverse momentum has been presented. The data comprise a sample of proton-proton collisions collected with the CMS detector in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. Observations are in agreement with Standard Model expectations within the statistical and systematic uncertainties. Exclusion limits are provided assuming right-handed only, left-handed only and right-and left-handed two flavor slepton production scenarios (mass degenerate selectrons and smuons). Slepton masses up to 290, 400 and 450 GeV respectively are excluded at 95% confidence level. Exclusion limits are also provided assuming right-handed only, left-handed only and right-and left-handed single flavor production scenarios, excluding selectron (smuon) masses up to 250, 310 and 350 GeV (210, 280 and 310 GeV), respectively. These results improve the previous exclusion limits measured by the CMS experiment at a centerofmass energy of 8 TeV by 100-150 GeV in slepton masses.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] P. Ramond, "Dual Theory for Free Fermions", *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.

[2] Y. A. Gol'fand and E. P. Likhtman, "Extension of the algebra of Poincaré group generators and violation of P invariance", *JETP Lett.* **13** (1971) 323.

[3] A. Neveu and J. H. Schwarz, "Factorizable dual model of pions", *Nucl. Phys. B* **31** (1971) 86, doi:10.1016/0550-3213(71)90448-2.

[4] D. V. Volkov and V. P. Akulov, "Possible universal neutrino interaction", *JETP Lett.* **16** (1972) 438. [*Pisma Zh. Eksp. Teor. Fiz.* **16** (1972) 621].

[5] J. Wess and B. Zumino, "A Lagrangian model invariant under supergauge transformations", *Phys. Lett. B* **49** (1974) 52, doi:10.1016/0370-2693(74)90578-4.

[6] J. Wess and B. Zumino, "Supergauge transformations in four dimensions", *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.

[7] P. Fayet, "Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino", *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.

[8] H. P. Nilles, "Supersymmetry, supergravity and particle physics", *Phys. Rep.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5.

[9] G. R. Farrar and P. Fayet, "Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry", *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.

[10] D. Alves et al., "Simplified models for LHC new physics searches", *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.

[11] CMS Collaboration, "Interpretation of searches for supersymmetry with simplified models", *Phys. Rev. D* **88** (2013) 052017, doi:10.1103/PhysRevD.88.052017, arXiv:1301.2175.

[12] ATLAS Collaboration, "Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector", *Phys. Rev. D* **93** (2016) 052002, doi:10.1103/PhysRevD.93.052002, arXiv:1509.07152.

[13] CMS Collaboration, "Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV", *Eur. Phys. J. C* **74** (2014) 3036, doi:10.1140/epjc/s10052-014-3036-7, arXiv:1405.7570.

[14] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[15] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[16] M. Czakon and A. Mitov, "Top++: A program for the calculation of the top-pair cross-section at hadron colliders", *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[17] M. Grazzini, S. Kallweit, D. Rathlev, and M. Wiesemann, "$W^{\pm}Z$ production at the LHC: fiducial cross sections and distributions in NNLO QCD", *JHEP* **05** (2017) 139, doi:10.1007/JHEP05(2017)139, arXiv:1703.09065.

[18] F. Cascioli et al., "ZZ production at hadron colliders in NNLO QCD", *Phys. Lett. B* **735** (2014) 311, doi:10.1016/j.physletb.2014.06.056, arXiv:1405.2219.

[19] F. Caola, K. Melnikov, R. Röntsch, and L. Tancredi, "QCD corrections to ZZ production in gluon fusion at the LHC", *Phys. Rev. D* **92** (2015) 094028, doi:10.1103/PhysRevD.92.094028, arXiv:1509.06734.

[20] J. M. Campbell, R. K. Ellis, M. Czakon, and S. Kirchner, "Two loop correction to interference in gg $\to$ ZZ", *JHEP* **08** (2016) 011, doi:10.1007/JHEP08(2016)011, arXiv:1605.01380.

[21] T. Binoth, G. Ossola, C. G. Papadopoulos, and R. Pittau, "NLO QCD corrections to tri-boson production", *JHEP* **06** (2008) 082, doi:10.1088/1126-6708/2008/06/082, arXiv:0804.0350.

[22] D. T. Nhung, L. D. Ninh, and M. M. Weber, "NLO corrections to WWZ production at the LHC", *JHEP* **12** (2013) 096, doi:10.1007/JHEP12(2013)096, arXiv:1307.7403.

[23] S. Yong-Bai et al., "NLO QCD + NLO EW corrections to WZZ productions with leptonic decays at the LHC", *JHEP* **10** (2015) 186, doi:10.1007/JHEP10(2015)186, arXiv:1507.03693. [Erratum: doi:10.1007/JHEP10(2016)156].

[24] W. Hong et al., "NLO QCD+EW corrections to ZZZ production with subsequent leptonic decays at the LHC", *J. Phys. G* **43** (2016) 115001, doi:10.1088/0954-3899/43/11/115001, arXiv:1610.05876.

[25] S. Yong-Bai et al., "NLO QCD and electroweak corrections to WWW production at the LHC", *Phys. Rev. D* **95** (2017) 073005, doi:10.1103/PhysRevD.95.073005, arXiv:1605.00554.

[26] S. Dittmaier, A. Huss, and G. Knippen, "Next-to-leading-order QCD and electroweak corrections to WWW production at proton-proton colliders", *JHEP* **09** (2017) 034, doi:10.1007/JHEP09(2017)034, arXiv:1705.03722.

[27] W. Beenakker et al., "Production of charginos, neutralinos, and sleptons at hadron colliders", *Phys. Rev. Lett.* **83** (Nov, 1999) 3780–3783, doi:10.1103/PhysRevLett.83.3780.

[28] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, "Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV", *JHEP* **10** (2012) 081, doi:10.1007/JHEP10(2012)081, arXiv:1207.2159.

[29] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, "Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO", *Eur. Phys. J. C* **73** (2013) 2480, doi:10.1140/epjc/s10052-013-2480-0, arXiv:1304.0790.

[30] J. M. Campbell and R. K. Ellis, "MCFM for the Tevatron and the LHC", *Nucl. Phys. Proc. Suppl.* **205** (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.

[31] T. Melia, P. Nason, R. Röntsch, and G. Zanderighi, "W^+W^-, WZ and ZZ production in the POWHEG BOX", *JHEP* **11** (2011) 078, doi:10.1007/JHEP11(2011)078, arXiv:1107.5051.

[32] P. Nason and G. Zanderighi, "W^+W^-, WZ and ZZ production in the POWHEG-BOX-V2", *Eur. Phys. J. C* **74** (2014) 2702, doi:10.1140/epjc/s10052-013-2702-5, arXiv:1311.1365.

[33] J. M. Campbell, R. K. Ellis, P. Nason, and E. Re, "Top-pair production and decay at NLO matched with parton showers", *JHEP* **04** (2015) 114, doi:10.1007/JHEP04(2015)114, arXiv:1412.1828.

[34] E. Re, "Single-top Wt-channel production matched with parton showers using the POWHEG method", *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.

[35] NNPDF Collaboration, "Parton distributions for the LHC Run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[36] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "A Brief Introduction to PYTHIA 8.1", *Comput. Phys. Commun.* **178** (2008) 852, doi:10.1016/j.cpc.2008.01.036, arXiv:0710.3820.

[37] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 tune", *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.

[38] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[39] J. Alwall et al., "Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions", *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[40] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO", *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.

[41] GEANT4 Collaboration, "GEANT4 — a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[42] S. Abdullin et al., "The fast simulation of the CMS detector at LHC", *J. Phys. Conf. Ser.* **331** (2011) 032049, doi:10.1088/1742-6596/331/3/032049.

[43] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[44] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_T jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[45] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[46] CMS Collaboration, "Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV", *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[47] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[48] K. Rehermann and B. Tweedie, "Efficient identification of boosted semileptonic top quarks at the LHC", *JHEP* **03** (2011) 059, doi:10.1007/JHEP03(2011)059, arXiv:1007.2221.

[49] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57, doi:10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.

[50] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[51] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

[52] C. G. Lester and D. J. Summers, "Measuring masses of semi-invisibly decaying particle pairs produced at hadron colliders", *Phys. Lett. B* **463** (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349.

[53] A. Barr, C. Lester, and P. Stephens, "A variable for measuring masses at hadron colliders when missing energy is expected; m_{T2}: the truth behind the glamour", *J. Phys. G* **29** (2003) 2343, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226.

[54] CMS Collaboration, "Search for new phenomena in final states with two opposite-charge, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV", (2017). arXiv:1709.08908. Submitted to *JHEP*.

[55] A. Bierweiler, T. Kasprzik, and J. H. Kühn, "Vector-boson pair production at the LHC to $\mathcal{O}(\alpha^3)$ accuracy", *JHEP* **12** (2013) 071, doi:10.1007/JHEP12(2013)071, arXiv:1305.5402.

[56] S. Gieseke, T. Kasprzik, and J. H. Kühn, "Vector-boson pair production and electroweak corrections in HERWIG++", *Eur. Phys. J. C* **74** (2014) 2988, doi:10.1140/epjc/s10052-014-2988-y, arXiv:1401.3964.

[57] J. Baglio, L. D. Ninh, and M. M. Weber, "Massive gauge boson pair production at the LHC: A next-to-leading order story", *Phys. Rev. D* **88** (2013) 113005, doi:10.1103/PhysRevD.88.113005, arXiv:1307.4331. [Erratum: doi:10.1103/PhysRevD.94.099902].

[58] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[59] A. L. Read, "Presentation of search results: the CL_s technique", *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[60] ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in summer 2011", Technical Report ATL-PHYS-PUB-2011-011, CMS-NOTE-2011-005, CERN, 2011.

[61] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[62] CMS Collaboration, "CMS Luminosity Measurements for the 2016 Data Taking Period", CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

[63] A. Kalogeropoulos and J. Alwall, "The SysCalc code: A tool to derive theoretical systematic uncertainties", (2018). arXiv:1801.08401.

[64] I. W. Stewart and F. J. Tackmann, "Theory uncertainties for Higgs mass and other searches using jet bins", *Phys. Rev. D* **85** (2012) 034011, doi:10.1103/PhysRevD.85.034011, arXiv:1107.2117.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], V.M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], SandraS. Padula[a], D. Romero Abad[b]

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,

Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[5], X. Gao[5], L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger[7], M. Finger Jr.[7]

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
S. Elgammal[8], S. Khalil[9], A. Mahrous[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam[11], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[12], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte[12], J.-C. Fontaine[12], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[13], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[7]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[7]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov[13]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl[14]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[15], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[16], A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann[17], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Karlsruher Institut fuer Technology
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann[14], S.M. Heindl, U. Husemann, F. Kassel[14], I. Katkov[13], S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[18], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[20], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
M. Bartók[19], P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[21], C. Kar, P. Mal, K. Mandal, A. Nayak[22], D.K. Sahoo[21], S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[23], M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[23], D. Bhowmik, S. Dey, S. Dutt[23], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur[23]

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[24], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar[24]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[25], E. Eskandari Tadavani, S.M. Etesami[25], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[26], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,14], R. Venditti[a], P. Verwilligen[a], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,27], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[14]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
F. Ferro[a], F. Ravera[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[b], L. Brianza[a,b], F. Brivio[a,b], V. Ciriolo[a,b,14], S. Di Guida[a,d,14], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,14], P. Paolucci[a,14], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c],

E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], N. Daci[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], S. Cometti, M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], D. Soldi, A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J. Goh, T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[28], F. Mohamad Idris[29], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz[30], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[31], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[32,33], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[34], E. Kuznetsova[35], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin[33]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[36], P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[33], I. Dremin[33], M. Kirakosyan[33], S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[37], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[38], T. Dimova[38], L. Kardapoltsev[38], D. Shtol[38], Y. Skovpen[38]

State Research Center of Russian Federation, Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[39], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita[40], D. Fasanella,

G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban[17], J. Kieseler, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[41], F. Moortgat, M. Mulders, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo[14], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi[42], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[43], A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[44], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl[†], L. Caminada[45], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[46], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci[47], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos[48], E.E. Kangal[49], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[50], S. Ozturk[51], D. Sunar Cerci[47], B. Tali[47], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[52], G. Karapinar[53], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[54], O. Kaya[55], S. Tekten, E.A. Yetkin[56]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[57]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[58], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[59], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash[60], A. Nikitenko[6], V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[14], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[61], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir[62], R. Syarif, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli,

E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[63], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[64], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[65], W. Clarida, K. Dilsiz[66], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[67], Y. Onel, F. Ozok[68], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[32], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali[69], A. Castaneda Hernandez[69], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[70], S. Luo, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Now at British University in Egypt, Cairo, Egypt
9: Also at Zewail City of Science and Technology, Zewail, Egypt
10: Now at Helwan University, Cairo, Egypt
11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
12: Also at Université de Haute Alsace, Mulhouse, France
13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
16: Also at University of Hamburg, Hamburg, Germany
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
22: Also at Institute of Physics, Bhubaneswar, India
23: Also at Shoolini University, Solan, India
24: Also at University of Visva-Bharati, Santiniketan, India

25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
27: Also at Università degli Studi di Siena, Siena, Italy
28: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
29: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
30: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
31: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
32: Also at Institute for Nuclear Research, Moscow, Russia
33: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
34: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
35: Also at University of Florida, Gainesville, USA
36: Also at P.N. Lebedev Physical Institute, Moscow, Russia
37: Also at California Institute of Technology, Pasadena, USA
38: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
40: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
41: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
42: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
43: Also at National and Kapodistrian University of Athens, Athens, Greece
44: Also at Riga Technical University, Riga, Latvia
45: Also at Universität Zürich, Zurich, Switzerland
46: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
47: Also at Adiyaman University, Adiyaman, Turkey
48: Also at Istanbul Aydin University, Istanbul, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Gaziosmanpasa University, Tokat, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Marmara University, Istanbul, Turkey
55: Also at Kafkas University, Kars, Turkey
56: Also at Istanbul Bilgi University, Istanbul, Turkey
57: Also at Hacettepe University, Ankara, Turkey
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
60: Also at Monash University, Faculty of Science, Clayton, Australia
61: Also at Bethel University, St. Paul, USA
62: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
63: Also at Utah Valley University, Orem, USA
64: Also at Purdue University, West Lafayette, USA
65: Also at Beykent University, Istanbul, Turkey
66: Also at Bingol University, Bingol, Turkey
67: Also at Sinop University, Sinop, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar

70: Also at Kyungpook National University, Daegu, Korea