EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2017-336
2018/01/08

CMS-SUS-16-048

Search for new physics in events with two soft oppositely charged leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for new physics in events with two low-momentum, oppositely charged leptons (electrons or muons) and missing transverse momentum in proton-proton collisions at a centre-of-mass energy of 13 TeV. The data collected using the CMS detector at the LHC correspond to an integrated luminosity of $35.9\,\text{fb}^{-1}$. The observed event yields are consistent with the expectations from the standard model. The results are interpreted in terms of pair production of charginos and neutralinos ($\widetilde{\chi}^{\pm}_{1}$ and $\widetilde{\chi}^{0}_{2}$) with nearly degenerate masses, as expected in natural supersymmetry models with light higgsinos, as well as in terms of the pair production of top squarks ($\widetilde{\mathrm{t}}$), when the lightest neutralino and the top squark have similar masses. At 95% confidence level, wino-like $\widetilde{\chi}^{\pm}_{1}/\widetilde{\chi}^{0}_{2}$ masses are excluded up to 230 GeV for a mass difference of 20 GeV relative to the lightest neutralino, a region constrained thus far only by the LEP experiments. For $\widetilde{\mathrm{t}}$ pair production, top squark masses up to 450 GeV are excluded for a mass difference of 40 GeV relative to the lightest neutralino.

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

Supersymmetry (SUSY) [1–5] is a widely considered extension of the standard model (SM) of particle physics, as it can provide solutions to several open questions in the SM, in particular those related to the hierarchy problem [6–8] and the nature of dark matter. SUSY predicts superpartners of SM particles whose spins differ by one-half unit with respect to their SM partners. In R-parity conserving models [9], SUSY particles are pair-produced and their decay chains end in the stable, lightest SUSY particle (LSP), which in many models corresponds to the lightest neutralino ($\widetilde{\chi}_1^0$). A stable LSP would escape undetected, yielding a characteristic signature of a large magnitude of missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) in collisions at the CERN LHC. As a stable, neutral and weakly interacting particle, the neutralino matches the properties required of a dark matter candidate.

The absence of SUSY signals in previous experiments, as well as at the LHC, can be interpreted as an indication that SUSY particles have very large mass, leading to the expectation that SUSY events have large visible energy and momentum. As a result, the many searches that yield the most stringent limits on the masses of the SUSY particles are based on events with large $p_{\mathrm{T}}^{\mathrm{miss}}$ and energetic final-state objects such as leptons and jets. These searches, however, are less sensitive to scenarios with a compressed mass spectrum, in which the mass splitting between the next-to-LSP and the LSP is small. When the mass splittings between SUSY particles are small, the visible energy in the event, and also potentially the $p_{\mathrm{T}}^{\mathrm{miss}}$, is relatively low, which motivates searches in events with low-momentum objects.

Compressed mass spectra arise in several SUSY models, including natural SUSY, i.e. SUSY models that solve the hierarchy problem with little fine tuning. It has been pointed out in several studies, for example in Refs. [6–8, 10–14], that naturalness imposes constraints on the masses of higgsinos, top squarks, and gluinos. Natural SUSY is generally considered to require at least one coloured SUSY particle of mass below approximately one TeV. Further, it is often assumed that this particle is the top squark ($\widetilde{\mathrm{t}}$). More recently, however, the hypothesis of natural SUSY requiring a light top squark has been disputed as arising from oversimplified assumptions [15]. Irrespective of the top squark, higgsinos remain a complementary window to natural SUSY as they are generally expected to be light. As pointed out in Refs. [15–18], light higgsinos are likely to have a compressed mass spectrum, potentially leading to signatures with soft leptons and moderate $p_{\mathrm{T}}^{\mathrm{miss}}$. Thus far, the most sensitive searches in this model have been carried out by experiments at LEP [19, 20].

The search described in this letter is designed for neutralinos and charginos, which are collectively referred to as "electroweakinos", in a model where these electroweakinos form a compressed mass spectrum [16–18, 21]. The search has discovery potential also when a light top squark and the LSP are nearly degenerate in mass and the top squark decays to four fermions. A more detailed discussion of such models can be found in Ref. [22]. The near-degeneracy in mass of the top squark and the LSP is typical of the so-called "co-annihilation region", in which the LSP is the sole source of dark matter [23].

In the models considered in this analysis, the visible decay products in the SUSY signal have low momentum, which can be distinguished from SM processes when a jet with large transverse momentum (p_{T}) from initial-state radiation (ISR) leads to a large boost of the SUSY particle pair. This boost also enhances the $p_{\mathrm{T}}^{\mathrm{miss}}$ in the event. A similar search has previously been reported by the ATLAS Collaboration [24]. The search strategy based on the presence of an ISR jet was also used to search for two-body decays in the monojet topology by the ATLAS [25] and CMS [26] experiments. Two ISR jets are requested in searches for topologies involving vector-boson fusion by CMS [27]. For the signal studied in this letter, SUSY particles can decay leptonically, and the presence of low-p_{T} leptons can be used to discriminate against otherwise dominant SM backgrounds, such as multijet production through quantum chromodynamics (QCD) and Z+jets events with invisible Z boson decays.

The current strategy is similar to that in the previous publication based on 8 TeV data [28], with the main difference being the deployment of a new trigger selection that improves the sensitivity of the search in events with two muons and low $p_{\mathrm{T}}^{\mathrm{miss}}$. In addition, the selection has further been optimized for electroweakinos with a compressed mass spectrum. At least one jet is required in the final state; in the case of the signal, this jet must arise from ISR, which provides the final-state particles with a boost in the transverse plane, and thereby the potential for moderate or large $p_{\mathrm{T}}^{\mathrm{miss}}$ in the event. Unlike the 8 TeV analysis, there is no upper limit on the number of jets in the event.

2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$ from $\mathrm{Z} \to \mathrm{ee}$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps. The dielectron mass resolution for $\mathrm{Z} \to \mathrm{ee}$ decays when both electrons are in the ECAL barrel is 1.9%, and is 2.9% when both electrons are in the endcaps [29].

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution of 1.3–2.0% in the barrel and better than 6% in the endcaps for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$, and of better than 10% in the barrel for muons with p_{T} up to 1 TeV [30].

Events of interest are selected using a two-tiered trigger system [31]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [32].

3 Data and simulated samples

The data used in this search correspond to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ of proton-proton (pp) collisions at a centre-of-mass energy of 13 TeV, recorded in 2016 using the CMS detector. The data are selected using two triggers: an inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger, with a threshold that changed over the year from an initial value of 90 GeV up to 120 GeV as the instantaneous luminosity of the LHC increased; and a subsequently introduced trigger with the requirement of a muon pair having $p_{\mathrm{T}} > 3\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$. The inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$ triggers correspond to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$, whereas the events recorded with the dimuon+$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger correspond to $33.2\,\mathrm{fb}^{-1}$.

Simulated signal and major background processes, such as $\mathrm{t\bar{t}}$, W+jets, and Z+jets are generated with the MADGRAPH5_aMC@NLO 2.2.2 [33, 34] event generator at leading order (LO) precision in perturbative quantum chromodynamics using the MLM merging scheme [35]. Additional partons are modelled in these samples. The diboson processes WW, Z Z, and Wγ are generated with the MADGRAPH5_aMC@NLO 2.2.2 event generator at next-to-leading order (NLO) precision using the FxFx merging scheme [34], while the WZ process is generated at NLO with POWHEG v2.0 [36–40]. Rare background processes (e.g. $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, WWW, ZZZ, WZZ, and WWZ are also generated at NLO precision with MADGRAPH5_aMC@NLO2.2.2 (2.3.2.2 for $\mathrm{t\bar{t}Z}$) [33, 34]. The rare background from single top quarks produced in association with a W boson is generated at NLO precision with POWHEG v1.0 [41]. The NNPDF3.0 [42] LO and NLO parton distribution functions (PDF) are used for the simulated samples generated at LO and NLO. Showering, hadronization and the underlying event description are carried out using the PYTHIA 8.212 package [43] with the CUETP8M1 underlying event tune [44, 45]. A detailed simulation of the CMS detector is based on the GEANT4 [46] package. A fast detector simulation [47] is used for the large number of signal samples, corresponding to different SUSY particle masses. The trigger, lepton identification, and b tagging efficiencies are corrected in the simulation through application of scale factors measured in dedicated data samples. Corrections for the use of the fast detector simulation are also applied.

For the signal, we consider the neutralino-chargino ($\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$) pair production where the mass degenerate $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ are assumed to decay to the LSP via virtual Z and W bosons. The decays of electroweakinos are carried out using PYTHIA, assuming a constant matrix element. The simplified models do not include any spin correlations in the decays. The SM branching fractions are assumed for the decays of the virtual Z and W bosons. The simulation of the $\widetilde{\chi}_2^0$ ($\widetilde{\chi}_1^{\pm}$) decay takes into account the Breit–Wigner shape of the Z (W) boson mass. The production cross sections correspond to those of pure wino production [48–50] computed at NLO plus next-to-leading-logarithmic (NLL) precision. A second mass scan simulates a simplified model of $\widetilde{\mathrm{t}}$-pair production, in which a heavy chargino mediates the decay of the $\widetilde{\mathrm{t}}$ into leptons and $\widetilde{\chi}_1^0$, namely $\widetilde{\mathrm{t}} \to \mathrm{b}\widetilde{\chi}_1^{\pm} \to \mathrm{bW}^*\widetilde{\chi}_1^0$. The mass of the $\widetilde{\chi}_1^{\pm}$ is set to $(m_{\widetilde{\mathrm{t}}} + m_{\widetilde{\chi}_1^0})/2$, and the mass difference between $\widetilde{\mathrm{t}}$ and $\widetilde{\chi}_1^0$ is set to be less than 80 GeV, thus b jets are expected to be soft. Figure 1 shows diagrams for these two simplified models. We denote the left diagram in Fig. 1 as TChi and the right diagram as T2tt. The masses are given with the model name, i.e. TChi150/20 (T2tt150/20) denotes a $\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$ ($\widetilde{\mathrm{t}}$ pair) production, where the produced particles have a mass of 150 GeV and a mass difference to the LSP of 20 GeV.

In addition to the electroweakino model, we interpret the results in a phenomenological minimal supersymmetric model (pMSSM) [51], in which the mass parameters for the higgsino (μ), bino (M_1), and wino (M_2) mass parameters are varied. There is only a small dependency on $\tan\beta$, which is set to 10. All other mass parameters are assumed to be decoupled. To reduce the parameter space to a two-dimensional grid, M_2 is set to $2M_1$. This convention is inspired by electroweakino mass unification at the grand unified theory scale. Since the focus is on electroweak production only, the gluino mass parameter M_3 is assumed to be decoupled. All trilinear couplings are discarded. Events for this “higgsino pMSSM” are generated with MADGRAPH5_aMC@NLO [52]. The NLO cross sections are computed using Prospino 2 [53]. Several additional packages [54–58] are used to calculate mass spectra and particle decays.

We also interpret the results of this search in two variations of the electroweakino model. While the model described above uses pure wino cross sections with the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ mass degenerate, these additional models resemble a scenario where the electroweakinos are of higgsino nature. The first of these higgsino simplified models features associated $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ production and as such corresponds to the same diagram as the one shown in in Fig. 1 (left). The second higgsino model considers associated $\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^0$ production. In both cases, the mass of the chargino is given as $m_{\widetilde{\chi}_1^{\pm}} = (m_{\widetilde{\chi}_2^0} + m_{\widetilde{\chi}_1^0})/2$, and the $\widetilde{\chi}_2^0$ decays via an off-shell Z boson, and if applicable, the $\widetilde{\chi}_1^{\pm}$ decays via an off-shell W boson.

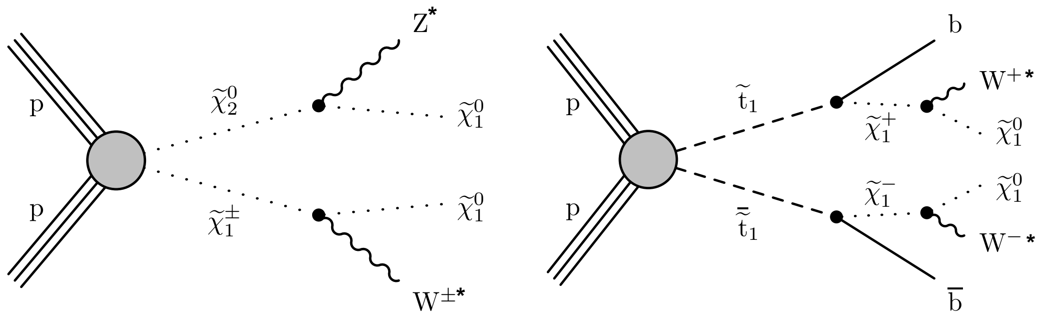

Figure 1: Production and decay of an electroweakino pair (left) and of a chargino-mediated $\widetilde{t}$ pair (right).

4 Object reconstruction

The analysis makes use of the particle-flow (PF) algorithm [59], which reconstructs and identifies each individual particle through an optimized combination of information from the various elements of the CMS detector. The difficulties in reconstructing the event of interest, because of the presence of the large average number of interactions per bunch crossing (pileup), are mitigated by a primary vertex selection and other methods described below. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [60, 61] with the tracks assigned to the vertex as inputs, and the associated p_T^{miss}, taken as the negative vector p_T sum of those jets.

Leptons are required to have p_T and η within the trigger acceptance and within the boundaries of the inner tracker. The leading and subleading muon (electron) are thus required to satisfy $p_T > 5\,\text{GeV}$, $|\eta| < 2.4$ (2.5). A requirement of $p_T < 30\,\text{GeV}$ on the leptons is also applied; this threshold is identified as the p_T value below which the current analysis is more sensitive in the compressed regions compared to other CMS analyses. To increase the sensitivity in the compressed mass regime, the lower threshold on the p_T of the subleading muon is set to 3.5 GeV in the high-p_T^{miss} regions of the $\widetilde{t}$ search.

Muons are required to satisfy standard identification criteria [30], and to be isolated within a cone in η–ϕ space of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$: the p_T sum of other charged particle tracks within the cone, Iso_{abs}, is required to be less than 5 GeV. In addition, the quantity Iso_{rel}, which is the ratio of Iso_{abs} and the p_T of the muon, is required to be less than 0.5. Contamination from pileup within the isolation cone is subtracted using techniques that utilize charged particle deposits within the cone itself [30].

Electrons from prompt decays are selected using a multivariate discriminant based on the energy distribution in the shower and track quality variables. The loose working point employed by the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ analysis [62] is used for $p_{\mathrm{T}} < 10\,\mathrm{GeV}$, and a tighter one for $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. The same definition of isolation and the same isolation criteria are applied for electrons as used for muons.

To suppress nonprompt leptons, requirements on the three-dimensional impact parameter [63] relative to the primary vertex, $\mathrm{IP}_{3\mathrm{D}}$, and its significance, $\mathrm{SIP}_{3\mathrm{D}}$, are applied. Leptons are required to have $\mathrm{IP}_{3\mathrm{D}} < 0.01\,\mathrm{cm}$ and $\mathrm{SIP}_{3\mathrm{D}} < 2$ standard deviations (s.d.).

Jets are clustered using the anti-k_{T} algorithm [60] with a distance parameter of 0.4 [64], as implemented in the FASTJET package [61]. The momentum of a jet, which is determined by the vectorial sum of all particle momenta in the jet, is found from simulation to be within 5 to 10% of the true momentum over the full p_{T} spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from pileup [65]. Jet energy corrections are obtained from simulation, and confirmed through in situ measurements of the energy balance in dijet and photon+jet events [66]. Jets are selected with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$. In the following, the transverse hadronic energy, H_{T}, is defined as the scalar p_{T} sum of the selected jets.

Jets arising from the hadronization of b quarks are identified through the combined secondary vertex (CSV) tagger [67, 68], which employs both secondary vertex and track-based information. In this analysis, a loose working point corresponding to a b tagging efficiency of about 80% is used with misidentification rates of 10% and 40% for light-quark or gluon jets and for c quark jets, respectively [67].

The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is determined using the PF-reconstructed objects. A variety of event filters are applied to remove detector- and beam related noise [69].

5 Event selection

The analysis requires two oppositely charged leptons ($N_\ell = 2$), of either same (ee, $\mu\mu$) or different flavour (eμ), and moderate $p_{\mathrm{T}}^{\mathrm{miss}}$ in the final state, together with at least one jet in the event.

The main backgrounds arise from events in which one of the leptons is not prompt (mainly from W+jets events), events from fully leptonic $\mathrm{t\bar{t}}$ decays ($\mathrm{t\bar{t}}(2\ell)$), and Drell–Yan (DY) processes with subsequent decays $\gamma/\mathrm{Z}^* \to \tau\tau \to \ell\ell\nu_\ell\nu_\ell\nu_\tau\nu_\tau$. Smaller backgrounds are from tW production (tW) and the diboson processes WW and ZZ^*, with $\mathrm{Z}^* \to \ell\ell$ and $\mathrm{Z} \to \nu\nu$ (VV). Processes such as $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, WWW, ZZZ, WZZ and WWZ have very small contributions, grouped together as “Rare”. The following event selection shown in Table 1 includes a number of requirements designed to reduce these backgrounds:

- $0.6 < p_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}} < 1.4$: this criterion is effective in rejecting SM events comprised uniquely of jets produced through the strong interaction, referred to as QCD multijet events, while remaining efficient for events with ISR, as in the case of the signal. The bounds on the ratio $p_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}$ is determined from a study of a control region (CR) at low-$p_{\mathrm{T}}^{\mathrm{miss}}$ and dimuon mass close to that of the J/ψ meson. This requirement rejects such events while leaving the signal unaffected.
- b jet event veto: requiring events where no jet is tagged as originating from b quarks significantly reduces the $\mathrm{t\bar{t}}$ background in which b jets originate from the decay of the top quarks. This requirement is applied to all jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and uses the

b tagging selection criteria described in Section 4. The efficiency for a potential signal from $\widetilde{t}$ decays is not affected significantly since in the compressed $\widetilde{t}$-LSP model, the b jets are expected to have small p_T and are therefore not tagged.

- $M(\tau\tau) < 0$ or $M(\tau\tau) > 160\,\text{GeV}$: this requirement on the estimate of the ditau mass is designed to reject the large background from $Z \to \tau\tau$ decays, with the τ leptons decaying leptonically. The quantity $M(\tau\tau)$ [18] is computed as follows: since the τ leptons from the decay of a Z boson have large p_T compared to their mass, the direction of the outgoing lepton is approximately the same as that of the τ lepton (i.e. $\Delta R(\ell, \tau) \approx 0$). The magnitudes of the lepton momentum vectors are then rescaled so that the lepton pair balances the hadronic recoil. For $Z \to \tau\tau$ events, this leads to a fairly good approximation of the original τ momenta. The invariant mass of the two τ leptons, $M(\tau\tau)$, is estimated by the invariant mass of the two scaled leptons. In some events, the estimate of the magnitude of the τ momentum results in a negative value when the flight direction is opposite to the direction of the lepton. In such cases, $M(\tau\tau)$ is set to its negative value.
- $M_T(\ell_i, p_T^{\text{miss}}) < 70\,\text{GeV}$, for $i = 1, 2$: the transverse mass M_T is defined as

$$M_T(\ell, p_T^{\text{miss}}) = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} \left(1 - \cos\left[\Delta\phi\left(\ell, p_T^{\text{miss}}\right)\right]\right)},$$

  and ℓ_1 and ℓ_2 are the leading and subleading leptons, respectively. For the signal, the leading lepton is typically aligned with the boost direction of the LSP ($\Delta\phi(\ell, p_T^{\text{miss}}) \approx 0$). This requirement is effective in further suppressing the $t\bar{t}$ background for the electroweakino search, but not for the $\widetilde{t}$ search. It is therefore only applied in the electroweakino search.
- J/ψ, and Υ veto: to suppress background contributions from J/ψ, low-mass γ^*, and Υ decays, the dilepton invariant mass $M(\ell\ell)$ is required to satisfy $M(\ell\ell) > 4\,\text{GeV}$ and to also lie outside the range $9 < M(\ell\ell) < 10.5\,\text{GeV}$. This veto is only applied to same flavour lepton pairs.
- $p_T^{\text{miss}} > 125\,\text{GeV}$: to ensure high trigger efficiency, both the p_T^{miss} and the muon corrected p_T^{miss}, which is computed from the vectorial sum of the p_T^{miss} and the p_T of the muons selected in the event, is required to be larger than 125 GeV.
- Trigger acceptance: in the online selection, the lepton pair is required to have a small boost of $p_T > 3\,\text{GeV}$, together with an upper bound on the dimuon invariant mass $M(\ell\ell) < 60\,\text{GeV}$, to limit the trigger rate. To remain fully efficient after offline reconstruction, an upper bound of 50 GeV on $M(\ell\ell)$ and a lower requirement on the dilepton transverse momentum $p_T(\ell\ell) > 3\,\text{GeV}$ are imposed.
- $H_T > 100\,\text{GeV}$: this requirement suppresses backgrounds with low hadronic activity in the event.

For the selected events, a set of signal regions (SRs) is defined, based on the dilepton invariant mass and p_T^{miss}. For events with leptons of same flavour and opposite charge, four SRs are defined in $M(\ell\ell)$ ranges of 4–9, 10.5–20, 20–30, and 30–50 GeV. These SRs are intended for searches for $\widetilde{\chi}_2^0 \to Z^* \widetilde{\chi}_1^0$ events, where $M(\ell\ell)$ is related to the mass difference between the two electroweakinos. For events with leptons of different flavour and opposite charge, three SRs are defined in the leading lepton p_T ranges of 5–12, 12–20, and 20–30 GeV. The definition of the bins of the SRs can be found in Table 2.

To exploit the potential of the dimuon plus p_T^{miss} trigger, events are separated according to the value of p_T^{miss}: in total three ranges are used for the signal regions, namely $p_T^{\text{miss}} \in$ 125–200, 200–300, and >300 GeV for the $\widetilde{t}$ search, and $p_T^{\text{miss}} \in$ 125–200, 200–250, and >250 GeV

Table 1: Common selection requirements for the signal regions. The subleading lepton p_{T} threshold is reduced to 3.5 GeV for muons in the high-$p_{\mathrm{T}}^{\mathrm{miss}}$, $\widetilde{\mathrm{t}}$-like signal region.

Variable	SR selection criteria
N_ℓ	2 ($\mu\mu$, μe, ee)
$\mathrm{q}(\ell_1)\mathrm{q}(\ell_2)$	-1
$p_{\mathrm{T}}(\ell_1)$, $p_{\mathrm{T}}(\ell_2)$	$[5, 30]$ GeV
$p_{\mathrm{T}}(\mu_2)$ for high-$p_{\mathrm{T}}^{\mathrm{miss}}$ $\widetilde{\mathrm{t}}$-like SR	$[3.5, 30]$ GeV
$\lvert\eta_\mu\rvert$	$<$2.4
$\lvert\eta_{\mathrm{e}}\rvert$	$<$2.5
$\mathrm{IP}_{\mathrm{3D}}$	$<$0.01 cm
$\mathrm{SIP}_{\mathrm{3D}}$	$<$2
$\mathrm{Iso}_{\mathrm{rel}}(\ell_{1,2})$	$<$0.5
$\mathrm{Iso}_{\mathrm{abs}}(\ell_{1,2})$	$<$5 GeV
$p_{\mathrm{T}}(\mathrm{jet})$	$>$25 GeV
$\lvert\eta\rvert(\mathrm{jet})$	$<$2.4
N_{b} (p_{T} $>$25 GeV, CSV)	0
$M(\ell\ell)$	$[4, 9]$ or $[10.5, 50]$ GeV (for $\mu\mu$ and ee)
$p_{\mathrm{T}}(\ell\ell)$	$>$3 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>$125 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$ (muon corrected)	$>$125 GeV
$p_{\mathrm{T}}^{\mathrm{miss}} / H_{\mathrm{T}}$	$[0.6, 1.4]$
H_{T}	$>$100 GeV
$M(\tau\tau)$	veto $[0, 160]$ GeV
$M_{\mathrm{T}}(\ell_i, p_{\mathrm{T}}^{\mathrm{miss}}), i = 1, 2$	$<$70 GeV (electroweakino selection only)

Table 2: Definition of bins in the two SRs.

electroweakino search region		$\widetilde{\mathrm{t}}$ search region	
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$M(\ell\ell)$ [GeV]	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{lepton}}$ [GeV]
$[125, 200]$	$[4, 9]$ $[10.5, 20]$ $[20, 30]$ $[30, 50]$	$[125, 200]$	$[5, 12]$ $[12, 20]$ $[20, 30]$
$[200, 250]$	$[4, 9]$ $[10.5, 20]$ $[20, 30]$ $[30, 50]$	$[200, 300]$	$[5, 12]$ $[12, 20]$ $[20, 30]$
$>$250	$[4, 9]$ $[10.5, 20]$ $[20, 30]$ $[30, 50]$	$>$300	$[5, 12]$ $[12, 20]$ $[20, 30]$

for the electroweakino search. Since the low-$p_{\mathrm{T}}^{\mathrm{miss}}$ region contains events accessible only via the dimuon+$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger, only $\mu\mu$ pairs are considered. The muons need to be of opposite charge. Conversely, in the high-$p_{\mathrm{T}}^{\mathrm{miss}}$ regions, both electron and muon flavours are considered. The electroweakino SRs are populated by ee and $\mu\mu$ pairs, where the leptons are oppositely charged. For the $\widetilde{\mathrm{t}}$ SRs, eμ pairs are also considered. For the latter, the p_{T} threshold on the trailing lepton is reduced to 3.5 GeV for muons in the high-$p_{\mathrm{T}}^{\mathrm{miss}}$ region to gain sensitivity in the search for $\widetilde{\mathrm{t}}$ signal.

6 Background estimation

Backgrounds with two prompt leptons are estimated using CRs chosen to be mostly free from signal but when possible, with similar kinematic characteristics as the events in the signal regions. Different CRs are employed for each SM process that contributes significantly to the signal region, i.e. the $\mathrm{t\bar{t}}$ dilepton background, the DY+jets background, and the diboson background.

For each background, the number of events in each SR is estimated using the number of events observed in the corresponding CR, and a transfer factor that is used to describe the expected ratio of events in the SR and CR for the process in question. The transfer factor for a specific process, F_{process}, is determined from Monte Carlo (MC) simulation of the process through the ratio

$$F_{\text{process}} = \frac{N^{\text{SR}}_{\text{MC process}}}{N^{\text{CR}}_{\text{MC process}}}.$$

Since a CR typically contains contributions from other physics processes, they need to be subtracted from $N^{\text{CR}}_{\text{data}}$. These contributions, $N^{\text{CR}}_{\text{MC other}}$, are small compared to the main process for which the CR is defined, and are thus estimated using MC simulation. The estimate of the background from a specific physics process in the SR is then given by

$$N^{\text{SR}}_{\text{process}} = \left(N^{\text{CR}}_{\text{data}} - N^{\text{CR}}_{\text{MC other}}\right) F_{\text{process}}.$$

Systematic uncertainties in the value of F_{process} are included when determining the full uncertainty in $N^{\text{SR}}_{\text{process}}$. The total background in the SR is given as the sum of the backgrounds expected from each process.

The different CRs are binned in $p_{\mathrm{T}}^{\mathrm{miss}}$, but not in $M(\ell\ell)$ or lepton p_{T}. A summary of all the CRs for prompt leptons is given in Table 3. For the diboson background, a validation region enriched in VV (mainly WW events) is added. This region is used to establish how well the simulation agrees with data in order to validate the uncertainty assigned to the diboson simulation.

6.1 The DY+jets control region

The main difference between the CR for the DY+jets background and the SR lies in the requirement imposed on the $M_{\tau\tau}$ variable; the CR consists of events that are vetoed in the SR selection, namely those events with $M_{\tau\tau}$ in the range 0–160 GeV. To increase the efficiency for leptons from τ decays, the impact parameter requirements are relaxed to $\mathrm{IP_{3D}} < 0.0175$ cm and $\mathrm{SIP_{3D}} < 2.5$ s.d. In addition, the 30 GeV upper bound on the lepton p_{T} is removed, and the region with lepton $p_{\mathrm{T}} < 20$ GeV, $\mathrm{IP_{3D}} < 0.01$ cm, and $\mathrm{SIP_{3D}} < 2$ is also removed to reduce the presence of potential signal. The distributions in kinematic quantities of these events, including the variables used to define the signal regions, $M(\ell\ell)$ and the leading lepton p_{T}, are well

Table 3: Summary of changes in selection criteria relative to Table 1 for CRs and the VV validation region (VR).

DY CR	$t\bar{t}$ (2ℓ) CR	VV VR
No upper requirement on p_T (ℓ) $\mathrm{Iso}_{rel} < 0.1$ as an or condition with the SR isolation		
$0 < M(\tau\tau) < 160\,\mathrm{GeV}$ $\mathrm{IP}_{3D} < 0.0175\,\mathrm{cm}$, $\mathrm{SIP}_{3D} < 2.5$ s.d.		
$p_T(\ell_1) > 20\,\mathrm{GeV}$, or $\mathrm{IP}_{3D} > 0.01\,\mathrm{cm}$, or $\mathrm{SIP}_{3D} > 2$ s.d. M_T as for electroweakino SR	No requirements on M_T	$p_T(\ell_1) > 20\,\mathrm{GeV}$ $\lvert$same flavour $M(\ell\ell) - M(Z)\rvert > 10\,\mathrm{GeV}$ $M_T > 90\,\mathrm{GeV}$
	At least one b-tagged jet with $p_T > 40\,\mathrm{GeV}$	

described in simulation. The event yields estimated from simulation and the observed event yields are listed in Table 4.

Table 4: Data and simulation yields for the DY and $t\bar{t}$ (2ℓ) CRs, corresponding to integrated luminosities of $35.9\,\mathrm{fb}^{-1}$ (high-p_T^{miss} region) and $33.2\,\mathrm{fb}^{-1}$ (low-p_T^{miss} region). The SR scale factors are derived by subtracting the other processes from the observed data count, and dividing this number by the expected event yields from simulation for the process in question. The uncertainties are statistical only.

	DY CR		$t\bar{t}$ (2ℓ) CR	
p_T^{miss}	125–200 GeV	>200 GeV	125–200 GeV	>200 GeV
DY+jets or $t\bar{t}$	70.1 ± 5.1	64.5 ± 3.3	1053.7 ± 9.4	535.7 ± 7.1
All SM processes	82.6 ± 5.5	75.2 ± 3.6	1170.0 ± 11.0	710.4 ± 11.1
Data	84	75	1157	680
SR scale factor	1.02 ± 0.13	0.99 ± 0.13	0.99 ± 0.03	0.94 ± 0.05

6.2 The $t\bar{t}$ (2ℓ) control region

To obtain a sample enriched in $t\bar{t}$ events, one or two jets are required to be identified as originating from b quarks. To reduce potential signal contamination, the leading b-tagged jet is required to satisfy $p_T > 40\,\mathrm{GeV}$. To increase the number of events in the CR, while still avoiding potentially large signal contamination, the upper bound on the lepton p_T is also removed. The event yields estimated from simulation and the observed event yields are also shown in Table 4.

6.3 Nonprompt background

The background from nonprompt or misidentified leptons is evaluated using a "tight-to-loose" method. Events where at least one lepton fails the tight identification and isolation criteria but passes a looser selection define the "application region". Events in this region are weighted by a transfer factor based on the probability that nonprompt leptons passing the loose requirements also satisfy the tight ones. The resulting estimate is corrected for the presence of prompt leptons in the application region.

The probability for nonprompt or misidentified leptons to pass the tight selection criteria is referred to as the misidentification probability, which is determined as a function of lepton p_T and η. This probability is measured using a dedicated data sample, the "measurement region" (MR), which is enriched in the background from SM events containing only jets produced via strong interaction, referred to as QCD multijet events. This method has been used in several multilepton analyses at CMS and is described in more detail in Ref. [70]. The MR is defined through the presence of one loose lepton, obtained by relaxing the isolation and impact parameter requirements, and through a jet with $p_T > 30\,\mathrm{GeV}$, separated from the lepton by $\Delta R > 0.7$.

For muons, events are selected through prescaled single-lepton triggers with no isolation requirements. For electrons, a mixture of prescaled jet triggers is used. The method includes a correction for the presence of prompt leptons in the MR, mostly due to W and Z boson production in association with jets. The probability for prompt leptons to pass the tight selection criteria is taken from simulation and is corrected with a data-to-simulation scale factor extracted from data enriched in $Z \rightarrow \ell\ell$ decays.

In this analysis, the misidentification probability measured in QCD multijet events is applied to loosely identified leptons in events that are dominated by W+jets and $t\bar{t}$ production. The latter can have both a different composition in terms of the flavour of the jets that give rise to the nonprompt leptons, as well as different kinematic properties, potentially resulting in a different effective misidentification probability. These effects are studied by comparing the misidentification probabilities measured in simulated events of these two processes in the kinematic regions probed by this analysis. A closure test is then performed by applying the misidentification probability measured in the QCD simulated multijet events to a sample of W+jets events. The yield of events passing the tight identification criteria is compared with the estimate obtained by applying the misidentification probability to events in the application region. The method is found to close within a level of <40%; this value is used as a systematic uncertainty in the estimate of the reducible background.

To further constrain the contribution of the nonprompt lepton background in the SR, a dedicated CR consisting of same-sign (SS) leptons is defined. Requiring the two lepton candidates to have the same sign increases significantly the probability that at least one of the two is a nonprompt or misidentified lepton. The SS CR is defined using the $\widetilde{t}$ selection in the $p_T^{miss} > 200$ GeV region, where the opposite charge requirement of the two leptons is modified to same-sign. Agreement within uncertainties is observed between data and the data-driven prediction of the background from misidentified leptons in this SS CR. Also visible in Fig. 2, is the near absence of a signal from prompt leptons. The distribution of the leading lepton p_T is used as input to the final fit that performs the signal extraction, as its constraining power is significant, given the significant uncertainty on the measured misidentification probability.

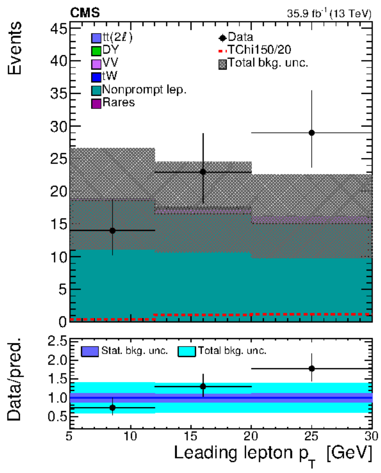

Figure 2: Same-sign CR for $\widetilde{t}$ selection and $p_T^{miss} > 200$ GeV. The distribution of the leading lepton p_T is used as input to the final signal extraction. A signal from neutralino-chargino ($\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$) production is superimposed.

7 Systematic uncertainty in the predicted background

This section summarizes the systematic uncertainties in the estimate of the background from the various SM processes. For each source of systematic uncertainty, we present both the effect on the corresponding specific background and the overall effect on the total background predictions are listed in Table 5.

Table 5: Relative uncertainties in the final predictions for each individual systematic source of uncertainty.

Systematic source of uncertainty	Typical uncertainty (%)
VV background normalization	3–25
Nonprompt lepton background normalization	4–20
DY+jets background normalization	4–20
$t\bar{t}$ background normalization	2–8
Rare background normalization	1–3
Jet energy scale	2–12
b tagging	2–6
Pileup	1–5
Lepton selection	1–4
Integrated luminosity	2.5
Trigger	1–2
$t\bar{t}$ modelling	$<$1

The uncertainty in the predicted nonprompt lepton background is dominated by the statistical uncertainty in the application region event yield, it ranges from 10% to 50%. When applied in the SR, the uncertainty is 4% to 20%. Another source of statistical uncertainty arises from limited statistics in data and simulation in the DY+jets and $t\bar{t}$ (2ℓ) CRs. The effect on the predicted yields in the SR, obtained using the transfer factor described in Section 6, is approximately 13% for the DY+jets background and 3% for the $t\bar{t}$ background.

For the $t\bar{t}$ background, we have considered a set of systematic uncertainties arising from the modelling of the kinematic distributions in the simulation of this process. The spin correlation of the top quarks has been varied by 20%, based on the ATLAS and CMS [71, 72] measurements and a comparison between different generators (MADGRAPH5_aMC@NLO versus POWHEG). The helicity amplitudes of the W boson in top quark decays have been varied by 5%. A top quark p_T modelling uncertainty has also been derived by reweighting the simulated $t\bar{t}$ events based on the number of ISR jets ($N_{\text{jets}}^{\text{ISR}}$), so as to make the jet multiplicity agree with data. The reweighting factors range from 0.92 to 0.51 for $N_{\text{jets}}^{\text{ISR}}$ between 1 and 6. The systematic uncertainty in these reweighting factors is taken to be equal to one half of the deviation of the factor from unity. The combined effect of this set of $t\bar{t}$ modelling uncertainties on the total number of predicted $t\bar{t}$ background events is found to be in the range 3–5%.

For the DY+jets background, the uncertainty in the resolution of the p_T of the system recoiling against the two leptons is obtained from data dominated by $Z \to \mu\mu$ events. The uncertainty affects the DY estimate, which uses the efficiency of the requirements on $M_{\tau\tau}$ from simulation. The effect on the estimated yields of DY+jets is found to be negligible ($<$1%).

As presented in Section 6, the method used to estimate the background from nonprompt and misidentified leptons leads to a 40% uncertainty on the normalization.

A 50% uncertainty is assigned for the diboson background normalization, which is checked in the dedicated region described in Section 6. In this region, which is enriched in WW events with similar kinematic properties as the events in the SR, the simulation is found to agree, within the given uncertainty, with the data.

A conservative 100% uncertainty is assigned to the very small rare backgrounds that are dominated by the tW process.

The experimental uncertainties related to b tagging, trigger, lepton reconstruction, identification, and isolation criteria have been propagated and their effect on the final results ranges from 2% up to 12%. The jet energy scale corrections (JEC) are applied to match jet energies measured in data and simulation. The JEC are affected by an intrinsic uncertainty, which affects all simulated background, leading to typically 2–12% uncertainties in the final predictions.

An uncertainty of 2.5% is assigned to the integrated luminosity measured by CMS for the 2016 data taking period [73]. This affects the estimate of the rare SM backgrounds that rely on the measured data luminosity.

Finally, the uncertainty related to pileup has been estimated by varying the minimum-bias cross section by $\pm 5\%$ and reweighting the pileup distribution accordingly. The systematic uncertainty is found to be in the range 1–5%.

As the signal yields are from simulation, additional systematic uncertainties are applied in two categories. One arises from the systematic uncertainty in the inclusive NLO+NLL [48–50] cross section used for the normalization, determined by varying the renormalization and factorization scales and the PDF. The dependence on these QCD scales yields a total uncertainty of 3%. The other category arises from the uncertainty in the product of the signal acceptance and efficiency.

It is important to properly model the ISR that leads to the boost of the produced SUSY particles in the transverse plane. In particular, for the electroweakino benchmark, the modelling of the ISR with MADGRAPH5_aMC@NLO affects the total transverse momentum $p_{\mathrm{T}}^{\mathrm{ISR}}$ of the system of SUSY particles, which can be improved by reweighting $p_{\mathrm{T}}^{\mathrm{ISR}}$ in the simulated signal events. This reweighting is based on p_{T} studies of events containing a Z boson [28], in which the factors range between 1.18 at $p_{\mathrm{T}}^{\mathrm{ISR}}$ of 125 GeV, and 0.78 for $p_{\mathrm{T}}^{\mathrm{ISR}} > 600$ GeV. The deviation from 1.0 is taken as the systematic uncertainty of the reweighting procedure. For the $\widetilde{\mathrm{t}}$ benchmark to improve the modelling of the multiplicity of additional jets from ISR, the events are reweighted based on the $N_{\mathrm{jets}}^{\mathrm{ISR}}$, as described in Section 7. The typical uncertainties on the final results from the ISR modelling are found to be in the range 2–7%.

We account for differences observed in $p_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction effects in full and fast simulation used for signal. The uncertainties vary between 3 and 5%. The uncertainties related to potential differences in b tagging between the full and fast simulation and in the JEC vary in the range 1–2%.

These uncertainties, together with those related to the predicted backgrounds described in Section 6, are included as log-normal distributed nuisance parameters in the likelihood approach.

8 Results

The estimated yields of the SM background processes and the data observed in the SRs are shown in Figs. 3 and 4. No significant excess has been observed. The estimates in the SR bins are extracted from a maximum likelihood fit of the data using the expected yields described in Section 6, namely the DY+jets, $\mathrm{t\bar{t}}$ (2ℓ), and SS CRs. Log-normal distributions for nuisance parameters are used to describe the systematic uncertainties of Section 7. The uncertainties in the predicted yields quoted in the following are those determined from the fit.

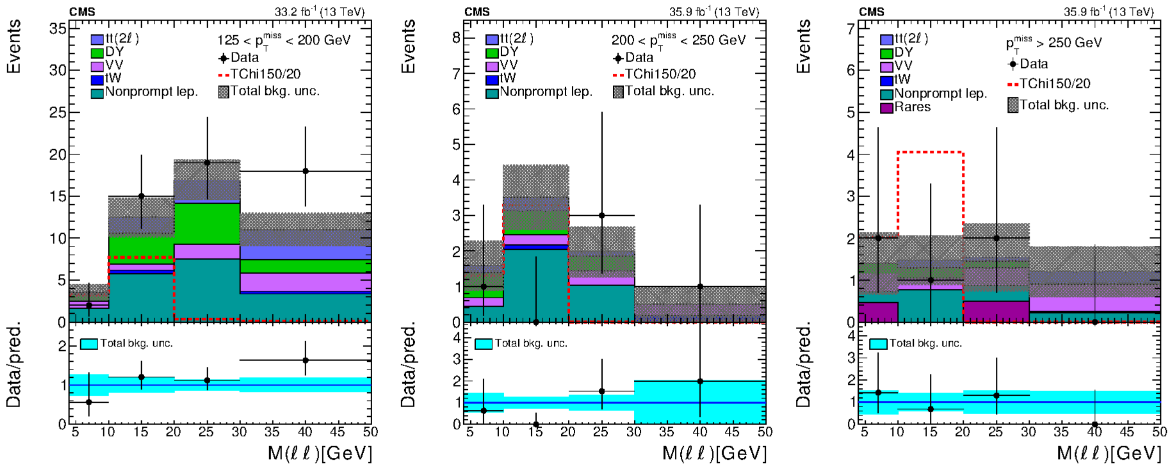

Figure 3: Left: electroweakino search regions in bins of $M(\ell\ell)$ for $125 < p_{\mathrm{T}}^{\mathrm{miss}} < 200\,\mathrm{GeV}$ (muon only channel) for $33.2\,\mathrm{fb}^{-1}$; middle: $200 < p_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$ (muon and electron channel) for $35.9\,\mathrm{fb}^{-1}$; right: $p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ (muon and electron channel) for $35.9\,\mathrm{fb}^{-1}$. A signal from neutralino-chargino ($\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$) production is superimposed.

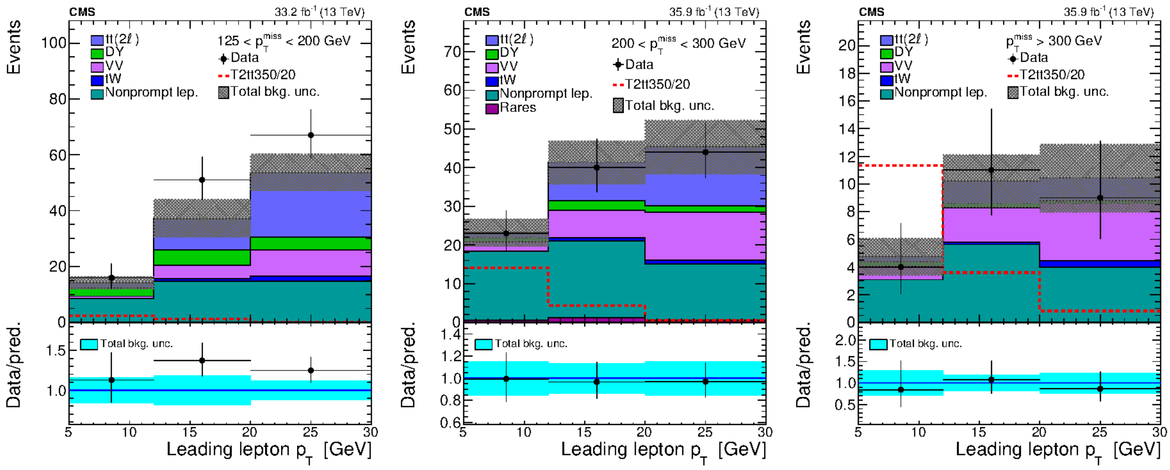

Figure 4: Left: $\widetilde{\mathrm{t}}$ search regions in bins of leading lepton p_{T} for $125 < p_{\mathrm{T}}^{\mathrm{miss}} < 200\,\mathrm{GeV}$ (muon only channel) for $33.2\,\mathrm{fb}^{-1}$; middle: $200 < p_{\mathrm{T}}^{\mathrm{miss}} < 300\,\mathrm{GeV}$ (muon and electron channel) for $35.9\,\mathrm{fb}^{-1}$; right: $p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$ (muon and electron channel) for $35.9\,\mathrm{fb}^{-1}$. A signal from $\widetilde{\mathrm{t}}$ pair production is superimposed.

The predicted yields along with the data are also summarized in Tables 6 and 7 for each bin of the SR.The total uncertainty in the yield for each SM process includes the systematic and statistical uncertainties described in Section 7, added in quadrature. In the lowest $p_{\mathrm{T}}^{\mathrm{miss}}$ range of the electroweakino and $\widetilde{\mathrm{t}}$ regions, 6 out of 7 bins show a possible over fluctuation. However, the bins of the two search regions are not orthogonal. The largest deviation from the SM expectation is seen in a bin of the electroweakino search region. The bin with $p_{\mathrm{T}}^{\mathrm{miss}} \in [200, 250]$ GeV and $M(\ell\ell) \in [10.5, 20]$ GeV has 3.5 ± 0.9 expected events but 0 observed. This amounts to a negative significance slightly above 2σ. Overall, there is good agreement between expectation and observation.

Table 6: The number of events observed in the data and the result of the fit of the backgrounds to the data in the electroweakino search regions. The uncertainty indicated is determined from the fit to the 33.2 and 35.9 fb^{-1} integrated luminosities. Values for the $M(\ell\ell)$ ranges are in GeV. Rare background event yields are omitted when they do not contribute to the SR bin.

$125 < p_{\mathrm{T}}^{\mathrm{miss}} < 200\,\mathrm{GeV}$	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$\mathrm{t\bar{t}}(2\ell)$	0.23 ± 0.16	1.9 ± 0.52	2.80 ± 0.65	3.60 ± 0.75
DY+jets	0.83 ± 0.63	3.7 ± 1.5	4.9 ± 1.5	1.60 ± 0.99
VV	0.82 ± 0.48	0.71 ± 0.65	1.7 ± 1.0	2.2 ± 1.2
Nonprompt lepton	1.7 ± 0.7	5.7 ± 1.5	7.5 ± 1.7	3.3 ± 1.1
tW	—	$0.46^{+0.64}_{-0.45}$	—	$0.33^{+0.49}_{-0.32}$
Total SM prediction	3.5 ± 1.0	12.0 ± 2.3	17.0 ± 2.4	11.0 ± 2.0
Data	2	15	19	18

$200 < p_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$\mathrm{t\bar{t}}(2\ell)$	0.21 ± 0.17	0.38 ± 0.18	$0.11^{+0.11}_{-0.10}$	—
DY+jets	0.69 ± 0.62	0.67 ± 0.32	0.42 ± 0.27	—
VV	$0.26^{+0.28}_{-0.25}$	$0.29^{+0.32}_{-0.28}$	0.42 ± 0.33	0.33 ± 0.29
Nonprompt lepton	0.44 ± 0.32	2.0 ± 0.7	1.0 ± 0.6	$0.03^{+0.14}_{-0.02}$
tW	—	$0.14^{+0.39}_{-0.13}$	—	$0.17^{+0.37}_{-0.16}$
Total SM prediction	1.6 ± 0.7	3.5 ± 0.9	2.0 ± 0.7	$0.51^{+0.52}_{-0.50}$
Data	1	0	3	1

$p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$\mathrm{t\bar{t}}(2\ell)$	—	0.19 ± 0.14	0.091 ± 0.091	0.27 ± 0.14
DY+jets	0.24 ± 0.19	0.24 ± 0.17	0.17 ± 0.16	$0.014^{+0.019}_{-0.013}$
VV	0.43 ± 0.35	$0.29^{+0.29}_{-0.28}$	0.41 ± 0.29	0.66 ± 0.45
Nonprompt lepton	$0.28^{+0.33}_{-0.27}$	0.77 ± 0.44	0.38 ± 0.30	0.23 ± 0.18
tW	—	—	—	$0.04^{+0.28}_{-0.03}$
Rare	$0.6^{+0.6}_{-0.5}$	—	$0.6^{+0.6}_{-0.5}$	—
Total SM prediction	1.4 ± 0.7	1.5 ± 0.6	1.5 ± 0.8	1.2 ± 0.6
Data	2	1	2	0

9 Interpretation

The results are interpreted in terms of the simplified models with compressed mass spectra for $\widetilde{\chi}^0_2\widetilde{\chi}^\pm_1 \to \mathrm{Z}^*\mathrm{W}^{\pm *}\widetilde{\chi}^0_1\widetilde{\chi}^0_1$ and for $\widetilde{\mathrm{t}}\widetilde{\mathrm{t}} \to \mathrm{b}\widetilde{\chi}^\pm_1\mathrm{b}\widetilde{\chi}^\mp_1$ with the subsequent decay $\widetilde{\chi}^\pm_1 \to \mathrm{W}^{\pm *}\widetilde{\chi}^0_1$ as discussed in Section 3. A binned likelihood fit of signal and the background expectations to the data is performed. This fit takes as input the yields in the SRs (12 for the electroweakino interpretation and 9 for the top squark interpretation), together with those in the two CRs ($125 < p_{\mathrm{T}}^{\mathrm{miss}} < 200\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$) for the $\mathrm{t\bar{t}}$ and DY+jets estimates, and the three p_{T} bins for same-sign leptons for the $p_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$ CR. These background-dominated bins also help to constrain the uncertainties in the background taken from simulation and the one predicted by the "tight-to-loose" method.

Upper limits on the cross sections in the benchmark models at 95% confidence level (CL) are extracted. We use asymptotic formulae [74] to derive the results. To set limits, the $\mathrm{CL_s}$ criterion, as described in [75, 76], is used. Figure 6 shows the expected upper limits on the electroweakino

Table 7: The number of events observed in the data and the result of the fit of the backgrounds to the data in the $\widetilde{t}$ search regions. The uncertainty indicated is determined from the fit to the 33.2 and 35.9 fb^{-1} integrated luminosities. Values for the $p_T(\ell_1)$ ranges are in GeV. Rare background event yields are omitted when they do not contribute to the SR bin.

	$125 < p_T^{miss} < 200$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	1.9 ± 0.4	11.0 ± 1.9	23.0 ± 3.5
DY+jets	2.9 ± 1.4	5.6 ± 1.9	4.6 ± 1.7
VV	0.8 ± 0.7	$4.9^{+6.3}_{-4.8}$	9.4 ± 5.4
Nonprompt lepton	8.5 ± 1.9	15.0 ± 2.6	15.0 ± 2.6
tW	$0.10^{+0.16}_{-0.09}$	$0.93^{+1.0}_{-0.92}$	1.8 ± 1.7
Total SM prediction	14.0 ± 2.3	37.0 ± 6.8	54.0 ± 6.5
Data	16	51	67

	$200 < p_T^{miss} < 300$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	1.3 ± 0.35	9.9 ± 1.2	15 ± 2.2
DY+jets	0.92 ± 0.83	2.4 ± 0.9	1.6 ± 0.6
VV	2.5 ± 1.4	7.1 ± 4.0	12.0 ± 6.2
Nonprompt lepton	18.0 ± 3.2	20.0 ± 3.4	15.0 ± 2.7
tW	—	$0.79^{+0.77}_{-0.78}$	$0.89^{+0.96}_{-0.88}$
Rare	$0.52^{+0.54}_{-0.51}$	1.2 ± 1.2	$0.57^{+0.59}_{-0.56}$
Total SM prediction	23.0 ± 3.5	41.0 ± 5.6	45.0 ± 7.0
Data	23	40	44

	$p_T^{miss} > 300$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	0.39 ± 0.25	1.6 ± 0.5	1.6 ± 0.4
DY+jets	0.33 ± 0.26	0.28 ± 0.18	0.19 ± 0.07
VV	0.93 ± 0.53	2.5 ± 1.4	4.2 ± 2.2
Nonprompt lepton	3.1 ± 1.1	5.6 ± 1.3	4.0 ± 1.3
tW	—	$0.15^{+0.18}_{-0.14}$	$0.45^{+0.50}_{-0.44}$
Total SM prediction	4.7 ± 1.3	10.0 ± 1.9	10.0 ± 2.5
Data	4	11	9

and $\widetilde{t}$ pair production cross sections for the benchmarks considered in this search.

For the electroweakino simplified model, the production cross sections are computed at NLO+NLL precision in the limit of a mass degenerate wino $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^{\pm}_1$, a light bino $\widetilde{\chi}^0_1$, and assuming all other SUSY particles to be heavy and decoupled [48–50]. Masses of $\widetilde{\chi}^0_2$ up to 230 GeV for a $\Delta m(\widetilde{\chi}^0_2, \widetilde{\chi}^0_1)$ of 20 GeV are excluded. The existence of $\widetilde{t}$ masses up to 450 GeV with a $\Delta m(\widetilde{t}, \widetilde{\chi}^0_1)$ of 40 GeV is ruled out for this specific model.

The expected and observed exclusion contours for the higgsino pMSSM are shown in Fig. 7. The higgsino mass parameter μ is excluded up to 160 GeV, when the bino mass parameter M_1 is 300 GeV and the wino mass parameter M_2 is 600 GeV. For larger values of M_1 and M_2, the mass splitting $\Delta m(\widetilde{\chi}^0_2, \widetilde{\chi}^0_1)$ becomes smaller and the sensitivity is reduced. For $M_1 = 700$ GeV, μ is excluded up to 100 GeV.

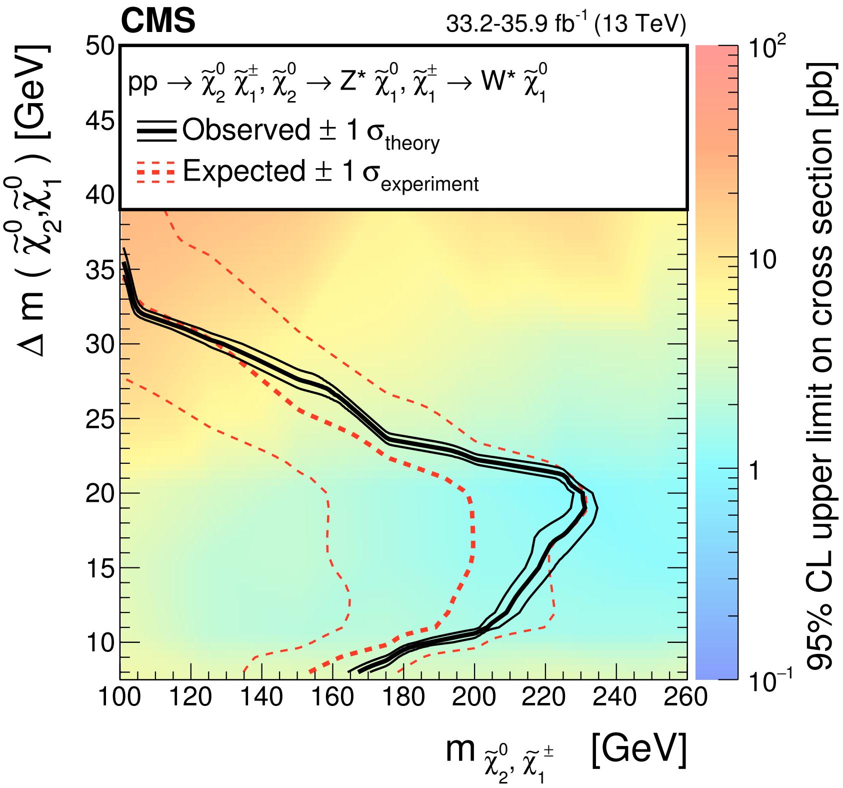

Figure 5: The observed 95% CL exclusion contours (black curves) assuming the NLO+NLL cross sections, with the variations corresponding to the uncertainty in the cross section for electroweakino. The dashed (red) curves present the 95% CL expected limits with the band covering 68% of the limits in the absence of signal. Results are based on a simplified model of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \mathrm{Z}^*\mathrm{W}^*\tilde{\chi}_1^0\tilde{\chi}_1^0$ process with a pure wino production cross section.

Figure 8 shows the expected and observed exclusion contours and upper limits on cross sections at 95% CL in a higgsino simplified model. To calculate the cross sections in this model, a scan in $|\mu|$, M_1, M_2 and $\tan\beta$ is carried out. All parameters are required to be real, M_2 to be positive and $\tan\beta \in [1, 100]$. The remaining SUSY particle masses are decoupled, and all trilinear couplings are discarded. The parameter space is then scanned to achieve the maximum higgsino content for $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ [77]. For a Δm between 15 and 20 GeV, the production model of $\mathrm{pp} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm$ and $\mathrm{pp} \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ is excluded for masses up to $\tilde{\chi}_2^0 \sim 167$ GeV.

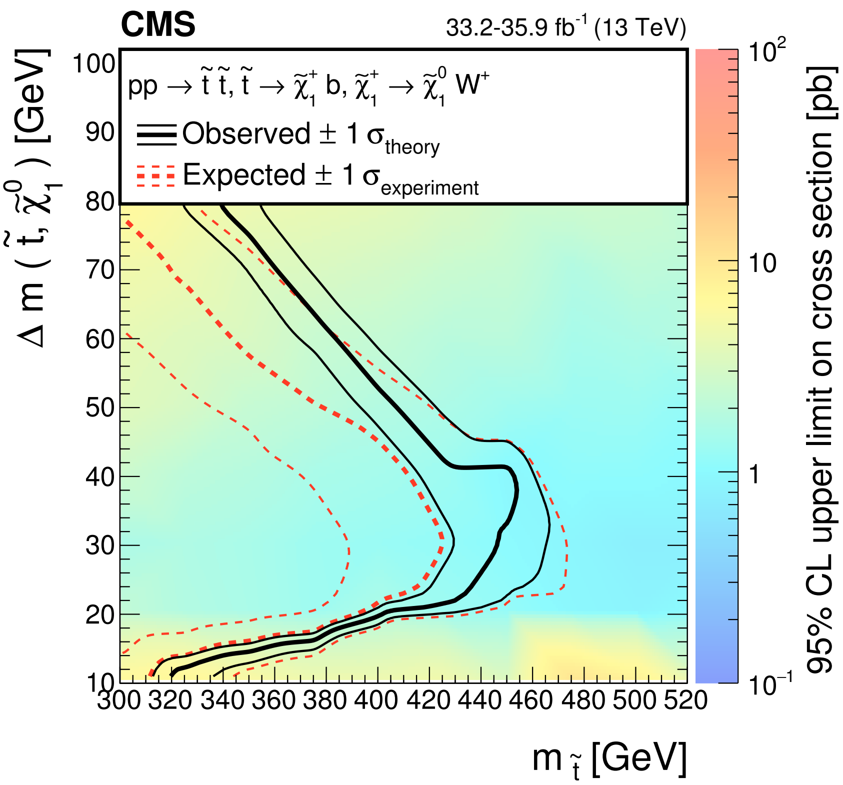

Figure 6: The observed 95% CL exclusion contours (black curves) assuming the NLO+NLL cross sections, with the variations corresponding to the uncertainty in the cross section for $\widetilde{t}$. The dashed (red) curves present the 95% CL expected limits with the band covering 68% of the limits in the absence of signal. A simplified model of the $\widetilde{t}$ pair production, followed by the $\widetilde{t} \to b\widetilde{\chi}_1^{\pm}$ and the subsequent $\widetilde{\chi}_1^{\pm} \to W^*\widetilde{\chi}_1^0$ decay is used for the $\widetilde{t}$ search. In this latter model, the mass of the $\widetilde{\chi}_1^{\pm}$ is set to be $(m_{\widetilde{t}} + m_{\widetilde{\chi}_1^0})/2$.

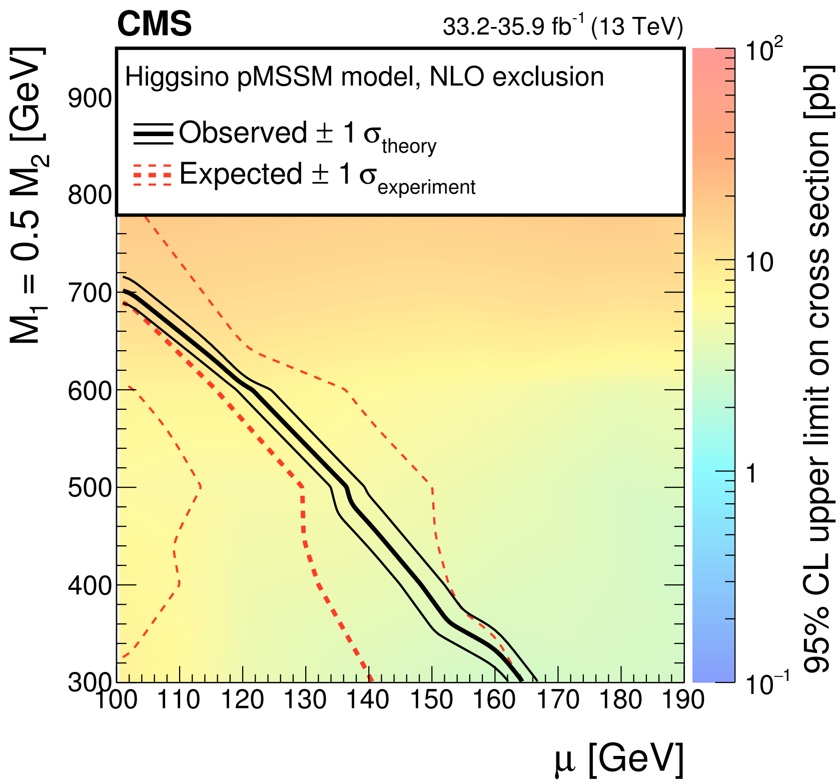

Figure 7: The observed 95% CL exclusion contours (black curve) assuming the NLO cross sections, with the variations corresponding to the uncertainty in the cross sections for the higgsino pMSSM, which has been introduced in the text. The dashed (red) curves present the band covering 68% of the limits in the absence of signal. The model considers all possible production processes.

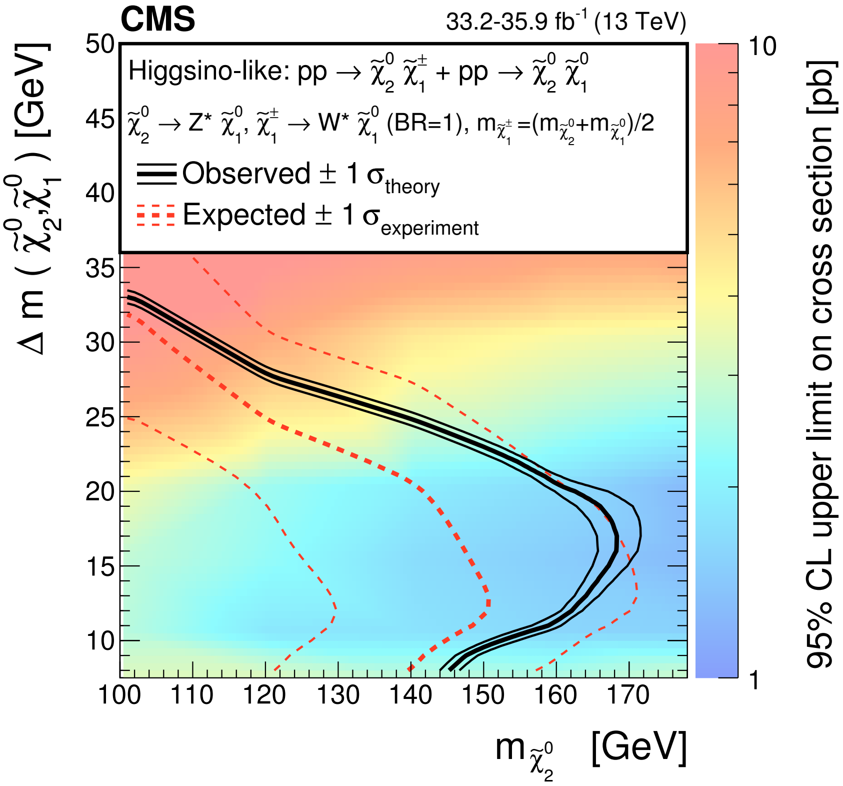

Figure 8: The observed 95% CL exclusion contours (black curves) assuming the NLO+NLL cross sections, with the variations corresponding to the uncertainty in the cross sections for the higgsino simplified models. The dashed (red) curves present the expected limits with the associated band covering 68% of the limits in the absence of signal.

10 Summary

A search is presented for new physics in events with two low-momentum leptons of opposite charge and missing transverse momentum in data collected by the CMS experiment at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of up to 35.9 fb^{-1}. The data are found to be consistent with standard model expectations. The results are interpreted in the framework of supersymmetric simplified models targeting electroweakino mass-degenerate spectra and $\widetilde{\mathrm{t}}$-$\widetilde{\chi}^0_1$ mass-degenerate benchmark models. For the $\widetilde{\mathrm{t}}$ chargino-mediated decay into $\mathrm{bW}^*\widetilde{\chi}^0_1$, top squark masses of up to 450 GeV are excluded in a simplified model for $\Delta m(\widetilde{\mathrm{t}},\widetilde{\chi}^0_1) = 40\,\mathrm{GeV}$. The search further probes the $\widetilde{\chi}^0_2\widetilde{\chi}^{\pm}_1 \to \mathrm{Z}^*\mathrm{W}^*\widetilde{\chi}^0_1\widetilde{\chi}^0_1$ process for mass differences (Δm) between $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^0_1$ of less than 20 GeV. Assuming wino production cross sections, $\widetilde{\chi}^0_2$ masses up to 230 GeV are excluded for Δm of 20 GeV. The search is also sensitive to higgsino production; in a simplified higgsino model, $\widetilde{\chi}^0_2$ masses up to 167 GeV are excluded for Δm of 15 GeV, while in a higgsino pMSSM, limits in the higgsino-bino mass parameters μ-M_1 plane are extracted.

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 centres 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, 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); OTKA and NIH (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 RAEP (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 programme 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 Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme 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 Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes 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] J. Wess and B. Zumino, "Supergauge transformations in four dimensions", *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.

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

[3] H. E. Haber and G. L. Kane, "The search for supersymmetry: Probing physics beyond the standard model", *Phys. Rept.* **117** (1985) 75, doi:10.1016/0370-1573(85)90051-1.

[4] R. Barbieri, S. Ferrara, and C. A. Savoy, "Gauge models with spontaneously broken local supersymmetry", *Phys. Lett. B* **119** (1982) 343, doi:10.1016/0370-2693(82)90685-2.

[5] S. Dawson, E. Eichten, and C. Quigg, "Search for supersymmetric particles in hadron-hadron collisions", *Phys. Rev. D* **31** (1985) 1581, doi:10.1103/PhysRevD.31.1581.

[6] R. Barbieri and G. Giudice, "Upper bounds on supersymmetric particle masses", *Nucl. Phys. B* **306** (1988) 63, doi:10.1016/0550-3213(88)90171-X.

[7] E. Witten, "Dynamical breaking of supersymmetry", *Nucl. Phys. B* **188** (1981) 513, doi:10.1016/0550-3213(81)90006-7.

[8] S. Dimopoulos and H. Georgi, "Softly broken supersymmetry and SU(5)", *Nucl. Phys. B* **193** (1981) 150, doi:10.1016/0550-3213(81)90522-8.

[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] B. de Carlos and J. Casas, "One-loop analysis of the electroweak breaking in supersymmetric models and the fine-tuning problem", *Phys. Lett. B* **309** (1993) 320, doi:10.1016/0370-2693(93)90940-J, arXiv:hep-ph/9303291.

[11] M. Dine, W. Fischler, and M. Srednicki, "Supersymmetric technicolor", *Nucl. Phys. B* **189** (1981) 575, doi:10.1016/0550-3213(81)90582-4.

[12] S. Dimopoulos and S. Raby, "Supercolor", *Nucl. Phys. B* **192** (1981) 353, doi:10.1016/0550-3213(81)90430-2.

[13] N. Sakai, "Naturalness in supersymmetric GUTS", *Z. Phys. C* **11** (1981) 153, doi:10.1007/BF01573998.

[14] R. K. Kaul and P. Majumdar, "Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories", *Nucl. Phys. B* **199** (1982) 36, doi:10.1016/0550-3213(82)90565-X.

[15] H. Baer, A. Mustafayev, and X. Tata, "Monojet plus soft dilepton signal from light higgsino pair production at LHC14", *Phys. Rev. D* **90** (2014) 115007, doi:10.1103/PhysRevD.90.115007, arXiv:1409.7058.

[16] G. F. Giudice, T. Han, K. Wang, and L.-T. Wang, "Nearly degenerate gauginos and dark matter at the LHC", *Phys. Rev. C* **81** (2010) 115011, doi:10.1103/PhysRevD.81.115011, arXiv:1004.4902.

[17] C. Han et al., "Probing light higgsinos in natural SUSY from monojet signals at the LHC", *JHEP* **02** (2014) 049, doi:10.1007/JHEP02(2014)049, arXiv:1310.4274.

[18] Z. Han, G. D. Kribs, A. Martin, and A. Menon, "Hunting quasidegenerate Higgsinos", *Phys. Rev. D* **89** (2014) 075007, doi:10.1103/PhysRevD.89.075007, arXiv:1401.1235.

[19] ALEPH Collaboration, "Search for charginos nearly mass degenerate with the lightest neutralino in e^+e^- collisions at center-of-mass energies up to 209 GeV", *Phys. Lett. B* **533** (2002) 223, doi:10.1016/S0370-2693(02)01584-8, arXiv:hep-ex/0203020.

[20] DELPHI Collaboration, "Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM", *Eur. Phys. J. C* **31** (2003) 421, doi:10.1140/epjc/s2003-01355-5, arXiv:hep-ex/0311019.

[21] P. Schwaller and J. Zurita, "Compressed electroweakino spectra at the LHC", *JHEP* **03** (2014) 060, doi:10.1007/JHEP03(2014)060, arXiv:1312.7350.

[22] R. Gröber, M. M. Mühlleitner, E. Popenda, and A. Wlotzka, "Light stop decays: implications for LHC searches", *Eur. Phys. J. C* **75** (2015) 420, doi:10.1140/epjc/s10052-015-3626-z, arXiv:1408.4662.

[23] C. Balázs, M. Carena, and C. E. M. Wagner, "Dark matter, light stops and electroweak baryogenesis", *Phys. Rev. D* **70** (2004) 015007, doi:10.1103/PhysRevD.70.015007, arXiv:hep-ph/0403224.

[24] ATLAS Collaboration, "Search for electroweak production of supersymmetric states in scenarios with compressed mass spectra at $\sqrt{s} = 13$ TeV with the ATLAS detector", (2017). arXiv:1712.08119.

[25] ATLAS Collaboration, "Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s}$ =8 TeV with the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 299, doi:10.1140/epjc/s10052-015-3517-3, arXiv:1502.01518. [Erratum: *Eur. Phys. J. C* **75** (2015) 408, doi:10.1140/epjc/s10052-015-3639-7].

[26] CMS Collaboration, "Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8$ TeV", *Eur. Phys. J. C* **75** (2015) 235, doi:10.1140/epjc/s10052-015-3451-4, arXiv:1408.3583.

[27] CMS Collaboration, "Search for dark matter and supersymmetry with a compressed mass spectrum in the vector boson fusion topology in proton-proton collisions at $\sqrt{s}$ = 8 TeV", *Phys. Rev. Lett.* **118** (2017) 021802, doi:10.1103/PhysRevLett.118.021802, arXiv:1605.09305.

[28] CMS Collaboration, "Search for supersymmetry in events with soft leptons, low jet multiplicity, and missing transverse energy in proton-proton collisions at $\sqrt{s}$=8 TeV", *Phys. Lett. B* **759** (2016) 9, doi:10.1016/j.physletb.2016.05.033, arXiv:1512.08002.

[29] 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.

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

[31] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

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

[33] 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.

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

[35] 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.

[36] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[37] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with parton shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[38] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[39] 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.

[40] 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.

[41] 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.

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

[43] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[44] 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.

[45] 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.

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

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

[48] W. Beenakker et al., "Production of charginos, neutralinos, and sleptons at hadron colliders", *Phys. Rev. Lett.* **83** (1999) 3780, doi:10.1103/PhysRevLett.83.3780, arXiv:hep-ph/9906298. [Erratum: *Phys. Rev. Lett.* **100** (2008) 029901, doi:10.1103/PhysRevLett.100.029901].

[49] 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.

[50] 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.

[51] MSSM Working Group, "The minimal supersymmetric standard model: Group summary report", (1998). arXiv:hep-ph/9901246.

[52] J. Alwall et al., "MadGraph5: going beyond", *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.

[53] W. Beenakker, R. Hopker, and M. Spira, "PROSPINO: A program for the production of supersymmetric particles in next-to-leading order QCD", (1996). arXiv:hep-ph/9611232.

[54] A. Djouadi, J.-L. Kneur, and G. Moultaka, "SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM", *Comput. Phys. Commun.* **176** (2007) 426, doi:10.1016/j.cpc.2006.11.009, arXiv:hep-ph/0211331.

[55] M. Mühlleitner, A. Djouadi, and Y. Mambrini, "SDECAY: A Fortran code for the decays of the supersymmetric particles in the MSSM", *Comput. Phys. Commun.* **168** (2005) 46, doi:10.1016/j.cpc.2005.01.012, arXiv:hep-ph/0311167.

[56] A. Djouadi, J. Kalinowski, and M. Spira, "HDECAY: A program for Higgs boson decays in the standard model and its supersymmetric extension", *Comput. Phys. Commun.* **108** (1998) 56, doi:10.1016/S0010-4655(97)00123-9, arXiv:hep-ph/9704448.

[57] M. M. Mühlleitner, A. Djouadi, and M. Spira, "Decays of supersymmetric particles: The Program SUSY-HIT", in *Physics at LHC. Proceedings, 3rd Conference*, volume 38, p. 635. Cracow, Poland, July, 2006. `arXiv:hep-ph/0609292`. Acta Phys. Polon. B 38 (2007) 635.

[58] P. Z. Skands et al., "SUSY Les Houches accord: Interfacing SUSY spectrum calculators, decay packages, and event generators", *JHEP* **07** (2004) 036, `doi:10.1088/1126-6708/2004/07/036`, `arXiv:hep-ph/0311123`.

[59] 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`.

[60] 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`.

[61] 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`.

[62] CMS Collaboration, "Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **11** (2017) 047, `doi:10.1007/JHEP11(2017)047`, `arXiv:1706.09936`.

[63] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, `doi:10.1088/1748-0221/9/10/P10009`, `arXiv:1405.6569`.

[64] 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`.

[65] 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`.

[66] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, `doi:10.1088/1748-0221/12/02/P02014`, `arXiv:1607.03663`.

[67] CMS Collaboration, "Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV", (2017). `arXiv:1712.07158`. Submitted to *JINST*.

[68] CMS Collaboration, "Identification of b-quark jets with the CMS experiment", *JINST* **8** (2013) P04013, `doi:10.1088/1748-0221/8/04/P04013`, `arXiv:1211.4462`.

[69] CMS Collaboration, "Performance of missing energy reconstruction in 13 TeV pp collision data using the CMS detector", CMS Physics Analysis Summary CMS-PAS-JME-16-004, 2016.

[70] CMS Collaboration, "Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy at the LHC", *JHEP* **06** (2011) 077, `doi:10.1007/JHEP06(2011)077`, `arXiv:1104.3168`.

[71] ATLAS Collaboration, "Measurement of spin correlation in top-antitop quark events and search for top squark pair production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector", *Phys. Rev. Lett.* **114** (2015) 142001, `doi:10.1103/PhysRevLett.114.142001`, `arXiv:1412.4742`.

[72] CMS Collaboration, "Measurements of $t\bar{t}$ spin correlations and top quark polarization using dilepton final states in pp collisions at $\sqrt{s} = 8$ TeV", *Phys. Rev. D* **93** (2016) 052007, doi:10.1103/PhysRevD.93.052007, arXiv:1601.01107.

[73] CMS Collaboration, "CMS luminosity measurement for the 2016 data taking period", CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

[74] 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: *Eur. Phys. J. C* **73** (2013) 2501, doi:10.1140/epjc/s10052-013-2501-z].

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

[76] 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.

[77] B. Fuks, M. Klasen, S. Schmiemann, and M. Sunder, "Realistic simplified gaugino-higgsino models in the MSSM", (2017). arXiv:1710.09941. Submitted to EPJC.

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, M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler[1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, 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. 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, T. Maerschalk, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, 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, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, 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], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

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, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang[5]

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, J.D. Ruiz Alvarez, 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, P.M. Ribeiro Cipriano, 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]

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
A.A. Abdelalim[8,9], S. Khalil[9], A. Mohamed[9]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, M. Kadastik, L. Perrini, 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, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, M. Machet, 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[10], C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram[11], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, C. Collard, E. Conte[11], X. Coubez, F. Drouhin[11], J.-C. Fontaine[11], B. Fuks[12], D. Gelé, U. Goerlach, M. Jansová, P. Juillot, 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, 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, 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, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[15], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[16], J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[17], H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann[17], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, 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, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[14], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
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, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann[14], S.M. Heindl, U. Husemann, F. Kassel[14], S. Kudella, H. Mildner, 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

Universität Münster
M. Klasen, M. Sunder

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

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

National Technical University of Athens, Athens, Greece
K. Kousouris

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, G. Pasztor, O. Surányi, G.I. Veres[18]

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[19], Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi[18]

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[18], P. Raics, Z.L. Trocsanyi, B. Ujvari

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

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

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[23], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[23], D. Bhowmik, S. Dey, S. Dutt[23], S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, 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, A.K. Mohanty[14], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

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, T. Sarkar[24], N. Wickramage[25]

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[26], E. Eskandari Tadavani, S.M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[27], F. Rezaei Hosseinabadi, B. Safarzadeh[28], 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], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], 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], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a],

C. Grandi[a], L. Guiducci[a,b], F. Iemmi, 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], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], 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,29], 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
V. Calvelli[a,b], 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], 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], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], K. Pauwels[a,b], D. Pedrini[a], S. Pigazzini[a,b,30], 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], S. Di Guida[a,d,14], F. Fabozzi[a,c], F. Fienga[a,b], 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], F. Thyssen[a]

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], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Fanzago[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], N. Pozzobon[a,b], P. Ronchese[a,b], R. Rossin[a,b], A. Tiko, E. Torassa[a], M. Zanetti[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], R. Leonardi[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,14], 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,29], F. Ligabue[a,c], T. Lomtadze[a], 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], F. Margaroli[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], 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], R. Castello[a,b], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[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], A. Staiano[a], P. Traczyk[a,b]

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

Kyungpook National University, Daegu, Korea
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.A. Brochero Cifuentes, J. Goh, T.J. Kim

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

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
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[31], F. Mohamad Idris[32], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[33], Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, 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
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, 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. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[34], 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
S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[35,36], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim[37], E. Kuznetsova[38], 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[36]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[39], P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[36], I. Dremin[36], M. Kirakosyan[36], S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin[40], L. Dudko, A. Ershov, A. Gribushin,

V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[41], D. Shtol[41], Y. Skovpen[41]

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, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[42], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, I. Bachiller, M. Barrio Luna, 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, A. Álvarez Fernández

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

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, 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, J. Garcia-Ferrero, A. García Alonso, 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, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, 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, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[43], F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, 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[44], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[45], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[46], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl†, L. Caminada[47], 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, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, 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[48], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
V. Candelise, 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
Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[49], E.E. Kangal[50], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[51], S. Ozturk[52], A. Polatoz, B. Tali[53], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar[54], K. Ocalan[55], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[56], O. Kaya[57], S. Tekten, E.A. Yetkin[58]

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

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[59], S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[60], C. Brew, R.M. Brown, L. Calligaris, 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, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash[61], A. Nikitenko[6], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[62], 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, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, 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, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[63], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, 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, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang

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. Ellison, 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[64], 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, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J. Bunn, I. Dutta, J.M. Lawhorn, H.B. Newman, T. Q. Nguyen, C. Pena, 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, J. Russ, M. Sun, H. Vogel, 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, S. Dittmer, 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, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[65], 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, W. Wu

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

Florida International University, Miami, USA
Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

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, 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, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki[66], W. Clarida, K. Dilsiz[67], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[68], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[69], Y. Onel, F. Ozok[70], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, 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, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, 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

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, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

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
J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, 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[35], 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, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, 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, S. Folgueras, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, 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, 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, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA
R. Ciesielski, K. Goulianos, C. Mesropian

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[71], A. Castaneda Hernandez[71], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[72], 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, J. Faulkner, E. Gurpinar, 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, P. Sheldon, S. Tuo, J. Velkovska, 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, V. Rekovic, 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: Also at Helwan University, Cairo, Egypt
9: Now at Zewail City of Science and Technology, Zewail, Egypt
10: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
11: Also at Université de Haute Alsace, Mulhouse, France
12: Also at Laboratoire de Physique Théorique et Hautes Energies, PARIS, 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 MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, 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 University of Ruhuna, Matara, Sri Lanka
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Yazd University, Yazd, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Istanbul Aydin University, Istanbul, Turkey
50: Also at Mersin University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Gaziosmanpasa University, Tokat, Turkey
53: Also at Adiyaman University, Adiyaman, Turkey
54: Also at Izmir Institute of Technology, Izmir, Turkey
55: Also at Necmettin Erbakan University, Konya, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Monash University, Faculty of Science, Clayton, Australia
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Bethel University, ST. PAUL, USA
64: Also at Utah Valley University, Orem, USA
65: Also at Purdue University, West Lafayette, USA
66: Also at Beykent University, Istanbul, Turkey
67: Also at Bingol University, Bingol, Turkey
68: Also at Erzincan University, Erzincan, Turkey
69: Also at Sinop University, Sinop, Turkey
70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
71: Also at Texas A&M University at Qatar, Doha, Qatar
72: Also at Kyungpook National University, Daegu, Korea