



Search for top squark pair production using dilepton final states in pp collision data collected at $\sqrt{s} = 13$ TeV

CMS Collaboration*

CERN, Geneva, Switzerland

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Abstract A search is presented for supersymmetric partners of the top quark (top squarks) in final states with two oppositely charged leptons (electrons or muons), jets identified as originating from bquarks, and missing transverse momentum. The search uses data from proton-proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector, corresponding to an integrated luminosity of 137 fb^{-1} . Hypothetical signal events are efficiently separated from the dominant top quark pair production background with requirements on the significance of the missing transverse momentum and on transverse mass variables. No significant deviation is observed from the expected background. Exclusion limits are set in the context of simplified supersymmetric models with pair-produced lightest top squarks. For top squarks decaying exclusively to a top quark and a lightest neutralino, lower limits are placed at 95% confidence level on the masses of the top squark and the neutralino up to 925 and 450 GeV, respectively. If the decay proceeds via an intermediate chargino, the corresponding lower limits on the mass of the lightest top squark are set up to 850 GeV for neutralino masses below 420 GeV. For top squarks undergoing a cascade decay through charginos and sleptons, the mass limits reach up to 1.4 TeV and 900 GeV respectively for the top squark and the lightest neutralino.

1 Introduction

The standard model (SM) of particle physics accurately describes the overwhelming majority of observed particle physics phenomena. Nevertheless, several open questions are not addressed by the SM, such as the hierarchy problem, the need for fine tuning to reconcile the large difference between the electroweak and the Planck scales in the presence of a fundamental scalar [1–4]. Moreover, there is a lack of an SM candidate particle that could constitute the dark matter in cosmological and astrophysical observations [5, 6]. Supersymmetry (SUSY) [7–14] is a well-motivated extension of

the SM that provides a solution to both of these problems, through the introduction of a symmetry between bosons and fermions. In SUSY models, large quantum loop corrections to the mass of the Higgs boson (H), mainly arising from the top quarks, are mostly canceled by those arising from their SUSY partners, the top squarks, if the masses of the SM particles and their SUSY partners are close in value. Similar cancellations occur for other particles, resulting in a natural solution to the hierarchy problem [2, 15, 16]. Furthermore, SUSY introduces a new quantum number, R parity [17], that distinguishes between SUSY and SM particles. If R parity is conserved, top squarks are produced in pairs and the lightest SUSY particle (LSP) is stable. If neutral, the LSP provides a good candidate for the dark matter. The lighter top squark mass eigenstate \tilde{t}_1 is the lightest squark in many SUSY models and may be within the energy reach of the CERN LHC if SUSY provides a natural solution to the hierarchy problem [18]. This strongly motivates searches for top squark production.

In this paper, we present a search for top squark pair production in data from proton-proton (pp) collisions collected at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 137 fb^{-1} , with the CMS detector at the LHC from 2016 to 2018. The search is performed in final states with two leptons (electrons or muons), hadronic jets identified as originating from bquarks, and significant missing transverse momentum (p_T^{miss}). The large background from the SM top quark–antiquark pair production ($t\bar{t}$) is reduced by several orders of magnitude through the use of specially designed transverse-mass variables [19, 20]. Simulations of residual SM backgrounds in the search regions are validated in control regions orthogonal to the signal regions, using observed data.

Simplified models [21–23] of strong top squark pair production and different top squark decay modes are considered. Following the naming convention in Ref. [24], top squark decays to top quarks and neutralinos ($\tilde{\chi}_1^0$, identified as LSPs) are described by the T2tt model (Fig. 1, left). In the T2bW model (Fig. 1, center), both top squarks decay via an interme-

* e-mail: cms-publication-committee-chair@cern.ch

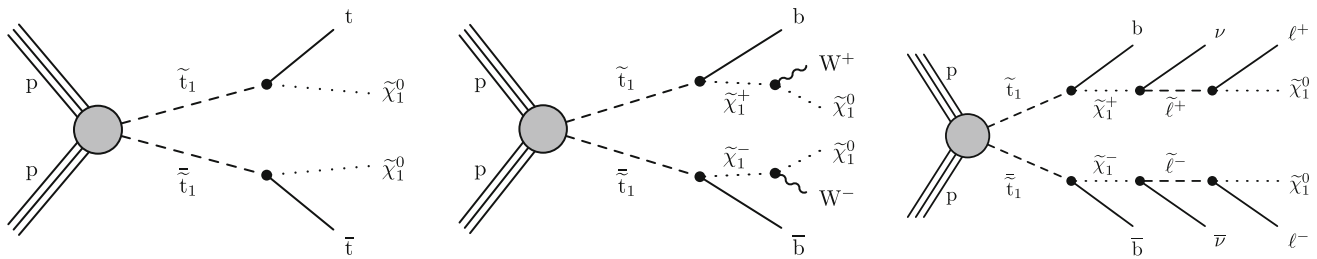


Fig. 1 Diagrams for simplified SUSY models with strong production of top squark pairs $\tilde{t}_1\tilde{t}_1$. In the T2tt model (left), the top squark decays to a top quark and a $\tilde{\chi}_1^0$. In the T2bW model (center), the top squark decays into a bottom quark and an intermediate $\tilde{\chi}_1^\pm$ that further decays

into a W boson and a $\tilde{\chi}_1^0$. The decay of the intermediate $\tilde{\chi}_1^\pm$, which yields a ν , plus a $\tilde{\chi}_1^0$ and a ℓ^\pm from the decay of an intermediate slepton $\tilde{\ell}^\pm$, is described by the T8bb $\ell\ell\nu\nu$ model (right)

intermediate chargino ($\tilde{\chi}_1^\pm$) into a bottom quark, a W boson, and an LSP. In both models, the undetected LSPs and the neutrinos from leptonic Wdecays account for significant p_T^{miss} , and the leptons provide a final state with low SM backgrounds. In the T8bb $\ell\ell\nu\nu$ model (Fig. 1, right), both top squarks decay via an intermediate chargino to a bottom quark, a slepton, and a neutrino. The branching fraction of the chargino to sleptons is assumed to be identical for the three slepton flavors. The subsequent decay of the sleptons to neutralinos and leptons leads to a final state with the same particle content as in the T2tt model, albeit without the suppression of the dilepton final state from the leptonic Wboson branching fraction.

Searches for top squark production have been performed by the ATLAS [25–32] and CMS [33–40] Collaborations using 8 and 13 TeV pp collision data. These searches disfavor top squark masses below about 1.1–1.3 TeV in a wide variety of production and decay scenarios. Here we present a search for top squark pair production in dilepton final states. With respect to a previous search in this final state [38], improved methods to suppress and estimate backgrounds from SM processes and a factor of about four larger data set increase the expected sensitivity by about 125 GeV in the \tilde{t}_1 mass. This search complements recent searches for top squark production in other final states [39,40], in particular in scenarios with a compressed mass spectrum or final states with a single lepton.

2 The 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, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors

that improve the measurement of the imbalance in transverse momentum. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tier trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events in a fixed time interval of less than $4\mu\text{s}$. The second level, called the high-level trigger, further decreases the event rate from around 100 kHz to less than 1 kHz before data storage [41]. 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. [42].

3 Event samples

The search is performed in a data set collected by the CMS experiment during the 2016–2018 LHC running periods. Events are selected online by different trigger algorithms that require the presence of one or two leptons (electrons or muons). The majority of events are selected with dilepton triggers. The thresholds of same-flavor (SF) dilepton triggers are 23 GeV (electron) or 17 GeV (muon) on the transverse momentum (p_T) of the leading lepton, and 12 GeV (electron) or 8 GeV (muon) on the subleading lepton p_T . Triggers for different-flavor (DF) dileptons have thresholds of 23 GeV on the leading lepton p_T , and 12 GeV (electron) or 8 GeV (muon) on the subleading lepton p_T . Single lepton triggers with a 24 GeV threshold for muons and with a 27 GeV threshold for electrons (32 GeV for electrons in the years 2017 and 2018) improve the selection efficiency. The efficiency of this online selection is measured using observed events that are independently selected based on the presence of jets and requirements on the p_T^{miss} . Typical efficiencies range from 95 to 99%, depending on the p_T and η of the two leptons and are accounted for by corrections applied to simulated events.

Table 1 Event generator and orders of accuracy for each simulated background process

Process	Cross section normalization	Event generator	Perturbative order
$\bar{t}t$, single t	NNLO+NNLL	POWHEG v2	NLO
tW	NNLO	POWHEG v1/v2	NLO
$\bar{t}tH$	NLO+NLL	POWHEG v2	NLO
Drell–Yan	NNLO	MADGRAPH5_aMC@NLO	LO
$\bar{t}tZ$, $\bar{t}tW$, tZq , $\bar{t}t\gamma^{(*)}$, VVV, VV	NLO	MADGRAPH5_aMC@NLO	NLO
tHW , tHq	NLO	MADGRAPH5_aMC@NLO	LO
tWZ	LO	MADGRAPH5_aMC@NLO	LO

Simulated samples matching the varying conditions for each data taking period are generated using Monte Carlo (MC) techniques. The $\bar{t}t$ production and t - and s -channel single-top-quark background processes are simulated at next-to-leading order (NLO) with the POWHEG v2 [43–50] event generator, and are normalized to next-to-next-to-leading-order (NNLO) cross sections, including soft-gluon resummation at next-to-next-to-leading-logarithmic (NNLL) accuracy [51]. Events with single top quarks produced in association with W bosons (tW) are simulated with POWHEG v1 [52] (2016) or POWHEG v2 (2017–2018), and are normalized to the NNLO cross section [53, 54]. The $\bar{t}tH$ process is generated with POWHEG v2 at NLO [55]. Drell–Yan events are generated with up to four extra partons in the matrix element calculations with MADGRAPH5_aMC@NLO v2.3.3 (2016) and v2.4.2 (2017–2018) [56] at leading order (LO), and the cross section is computed at NNLO [57]. The $\bar{t}tZ$, $\bar{t}tW$, tZq , $\bar{t}t\gamma^{(*)}$, and triboson (VVV) processes are generated with MADGRAPH5_aMC@NLO at NLO. The cross section of the $\bar{t}tZ$ process is computed at NLO in perturbative quantum chromodynamics (QCD) and electroweak accuracy [58, 59]. The $\bar{t}tH$ process is normalized to a cross section calculated at NLO+NLL accuracy [60]. The diboson (VV) processes are simulated with up to one extra parton in the matrix element calculations, using MADGRAPH5_aMC@NLO at NLO. The tWZ , tHq , and tHW processes are generated at LO with MADGRAPH5_aMC@NLO. These processes are normalized to the most precise available cross sections, corresponding to NLO accuracy in most cases. A summary of the event samples is provided in Table 1.

The event generators are interfaced with PYTHIA v8.226 (8.230) [61] using the CUETP8M1 (CP5) tune [62–64] for 2016 (2017, 2018) samples to simulate the fragmentation, parton shower, and hadronization of partons in the initial and final states, along with the underlying event. The NNPDF parton distribution functions (PDFs) at different perturbative orders in QCD are used in v3.0 [65] and v3.1 [66] for 2016 and 2017–2018 samples, respectively. Double counting of the partons generated with MADGRAPH5_aMC@NLO and

PYTHIA is removed using the MLM [67] and the FxFx [68] matching schemes for LO and NLO samples, respectively. The events are subsequently processed with a GEANT4-based simulation model [69] of the CMS detector.

The SUSY signal samples are generated with MADGRAPH5_aMC@NLO at LO precision, with up to two extra partons in the matrix element calculations, interfaced with PYTHIA v8.226 (8.230) using the CUETP8M1 (CP2) tune for 2016 (2017, 2018). For the T2tt and T2bW models, the top squark mass is varied from 200 to 1200 GeV and the mass of the LSP is scanned from 1 to 650 GeV. The mass of the chargino in the T2bW model is assumed to be equal to the mean of the masses of the top squark and the lightest neutralino. For the T8bb $\ell\ell\nu\nu$ model, the top squark mass is varied from 200 to 1600 GeV and the mass of the LSP is scanned from 1 to 1200 GeV. Similarly to the T2bW model, the mass of the chargino is assumed to be equal to the mean of the top squark and the LSP masses. For the slepton mass, three values of $x = 0.95, 0.50, 0.05$ are chosen in $m_{\tilde{\ell}} = x(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) + m_{\tilde{\chi}_1^0}$. The production cross sections of signal samples are normalized to approximate NNLO+NNLL accuracy with all other SUSY particles assumed to be heavy and decoupled [70–82]. The simulation of the detector response is performed using the CMS fast detector simulation [83, 84].

All simulated samples include the effects of additional pp collisions in the same or adjacent bunch crossings (pileup), and are reweighted according to the observed distribution of the number of interactions per bunch crossing. An additional correction is applied to account for a mismatch of the simulated samples and the observed distribution of primary vertices in the 2018 running period.

4 Object and event selection

Event reconstruction uses the CMS particle-flow (PF) algorithm [85], which provides an exclusive set of electron [86], muon [87], charged hadron, neutral hadron, and photon can-

didates. These particles are defined with respect to the primary pp interaction vertex, which is the vertex with the largest value of summed physics-object p_T^2 . The physics objects are the jets, clustered using the anti- k_T algorithm [88, 89] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets. Charged-hadron candidates not originating from the selected primary vertex in the event are discarded from the list of reconstructed particles.

Electron candidates are reconstructed using tracking and ECAL information, by combining the clusters of energy deposits in the ECAL with charged tracks [86]. The electron identification is performed using shower shape variables, track-cluster matching variables, and track quality variables. The selection is optimized to identify electrons from the decay of W and Z bosons while rejecting electron candidates originating from jets. To reject electrons originating from photon conversions inside the detector, electrons are required to have all possible measurements in the innermost tracker layers and to be incompatible with any conversion-like secondary vertices. Reconstruction of muon candidates is done by geometrically matching tracks from measurements in the muon system and tracker, and fitting them to form a global muon track. Muons are identified using the quality of the geometrical matching and the quality of the tracks [87].

In all three running periods, the selected lepton candidates are required to satisfy $p_T > 30$ (20) GeV for the leading (sub-leading) lepton, and $|\eta| < 2.4$, and to be isolated. To obtain a measure of isolation for leptons with $p_T < 50$ GeV, a cone with radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ (where ϕ is the azimuthal angle in radians) is constructed around the lepton at the event vertex. For leptons with $p_T > 50$ GeV the radius is reduced to $\Delta R = \max(0.05, 10 \text{ GeV}/p_T)$. A lepton is isolated if the scalar p_T sum of photons and neutral and charged hadrons reconstructed by the PF algorithm within this cone is less than 20% of the lepton p_T , i.e. $I_{\text{rel}} < 0.2$. The contribution of neutral particles from pileup interactions is estimated according to the method described in Ref. [86], and subtracted from the isolation sum. The remaining selection criteria applied to electrons, muons, and the reconstruction of jets and p_T^{miss} are described in Ref. [38]. Jets are clustered from PF candidates using the anti- k_T algorithm with a distance parameter of $R = 0.4$, and are required to satisfy $p_T > 30$ GeV, $|\eta| < 2.4$, and quality criteria. A multivariate btagging discriminator algorithm, DeepCSV [90], is used to identify jets arising from bquark hadronization and decay (bjets). The chosen working point has a mistag rate of approximately 1% for light-flavor jets and a corresponding btagging efficiency of approximately 70%, depending on jet p_T and η .

Scale factors are applied to simulated events to take into account differences between the observed and simulated lep-

ton reconstruction, identification, and isolation, and btagging efficiencies. Typical corrections are less than 1% per lepton and less than 10% per b-tagged jet.

5 Search strategy

We select events containing a pair of leptons with opposite charge. The invariant mass of the lepton pair $m(\ell\ell)$ is required to be greater than 20 GeV to suppress backgrounds with misidentified or nonprompt leptons from the hadronization of (heavy-flavor) jets in multijet events. Events with additional leptons with $p_T > 15$ GeV and satisfying a looser isolation criterion of $I_{\text{rel}} < 0.4$ are rejected. Events with an SF lepton pair that is consistent with the SM Drell–Yan production are removed by requiring $|m_Z - m(\ell\ell)| > 15$ GeV, where m_Z is the mass of the Z boson. To further suppress Drell–Yan and other vector boson backgrounds, we require the number of jets (N_{jets}) to be at least two and, among them, the number of b-tagged jets (N_b) to be at least one.

We use the p_T^{miss} significance, denoted as \mathcal{S} , to suppress events where detector effects and misreconstruction of particles from pileup interactions are the main source of reconstructed p_T^{miss} . In short, the \mathcal{S} observable offers an event-by-event assessment of the likelihood that the observed p_T^{miss} is consistent with zero. Using a Gaussian parametrization of the resolutions of the reconstructed objects in the event, the \mathcal{S} observable follows a χ^2 -distribution with two degrees of freedom for events with no genuine p_T^{miss} [91–93]. Figure 2 shows the distribution of \mathcal{S} in a $Z \rightarrow \ell\ell$ sample, requiring events with two SF leptons with $|m_Z - m(\ell\ell)| < 15$ GeV, $N_{\text{jets}} \geq 2$ and $N_b = 0$. Events with no genuine p_T^{miss} , such as from the Drell–Yan process, follow a χ^2 distribution with two degrees of freedom. Processes with true p_T^{miss} such as $t\bar{t}$ or production of two or more W or Z bosons populate high values of the \mathcal{S} distribution. The algorithm is described in Ref. [93] and provides stability of event selection efficiency as a function of the pileup rate. We exploit this property by requiring $\mathcal{S} > 12$ in order to suppress the otherwise overwhelming Drell–Yan background in the SF channel. We further reduce this background by placing a requirement on the azimuthal angular separation of \vec{p}_T^{miss} and the momentum of the leading (subleading) jet of $\cos \Delta\phi(p_T^{\text{miss}}, j) < 0.80$ (0.96). These criteria reject a small background of Drell–Yan events with significantly mismeasured jets.

The event preselection is summarized in Table 2. The resulting event sample is dominated by events with top quark pairs that decay to the dilepton final state.

The main search variable in this analysis is [20, 94]

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

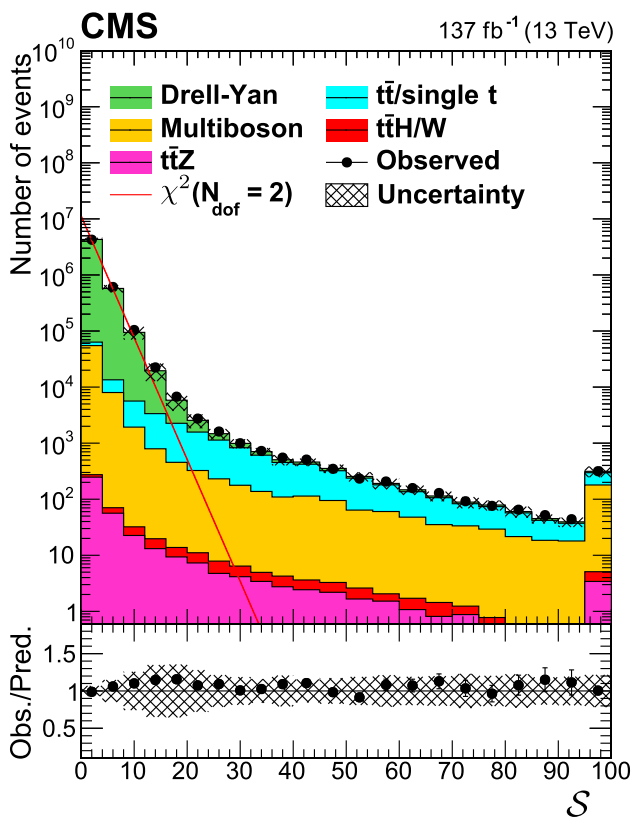


Fig. 2 Distribution of p_T^{miss} significance S in a $Z \rightarrow \ell\ell$ selection, requiring an SF lepton pair. Points with error bars represent the data, and the stacked histograms the SM backgrounds predicted as described in Sect. 6, with uncertainty in the SM prediction indicated by the hatched area. The red line represents a χ^2 distribution with two degrees of freedom. The last bin includes the overflow events. The lower panel gives the ratio between the observation and the predicted SM backgrounds. The relative uncertainty in the SM background prediction is shown as a hatched band

Table 2 Overview of the event preselection requirements

Quantity	Requirement
N_{leptons}	$= 2$ (e or μ), oppositely charged
$m(\ell\ell)$	> 20 GeV
$ m_Z - m(\ell\ell) $	> 15 GeV, SF only
N_{jets}	≥ 2
N_b	≥ 1
S	> 12
$\cos \Delta\phi(p_T^{\text{miss}}, j_1)$	< 0.80
$\cos \Delta\phi(p_T^{\text{miss}}, j_2)$	< 0.96

where the choice $\vec{p}_T^{\text{vis}1,2} = \vec{p}_T^{\ell 1,2}$ corresponds to the definition introduced in Ref. [95]. The alternative choice $\vec{p}_T^{\text{vis}1,2} = \vec{p}_T^{\ell 1,2} + \vec{p}_T^{b1,2}$ involves the b-tagged jets and defines $M_{T2}(b\ell b\ell)$. If only one b-tagged jet is found in the event, the jet with the highest p_T that does not pass the b tagging selection is taken instead. The calculation of $M_{T2}(\ell\ell)$ and

$M_{T2}(b\ell b\ell)$ is performed through the algorithm discussed in Ref. [96], assuming vanishing mass for the undetected particles, and follows the description in Ref. [38]. The key feature of the $M_{T2}(\ell\ell)$ observable is that it retains a kinematic endpoint at the Wboson mass for background events from the leptonic decays of two Wbosons, produced directly or through top quark decay. Similarly, the $M_{T2}(b\ell b\ell)$ observable is bound by the top quark mass if the leptons, neutrinos and b-tagged jets originate from the decay of top quarks. In turn, signal events from the processes depicted in Fig. 1 do not respect the endpoint and are expected to populate the tails of these distributions.

Signal regions based on $M_{T2}(\ell\ell)$, $M_{T2}(b\ell b\ell)$ and S are defined to enhance sensitivity to different signal scenarios, and are listed in Table 3. The regions are further divided into different categories based on SF or DF lepton pairs, accounting for the different SM background composition. The signal regions are defined so that there is no overlap between them, nor with the background-enriched control regions.

6 Background predictions

Events with an opposite-charge lepton pair are abundantly produced by Drell–Yan and $t\bar{t}$ processes. The event selection discussed in Sect. 4 efficiently rejects the vast majority of Drell–Yan events. Therefore, the major backgrounds from SM processes in the search regions are $t\bar{t}$ events that pass the $M_{T2}(\ell\ell)$ threshold because of severely mismeasured p_T^{miss} or a misidentified lepton. In signal regions with large $M_{T2}(\ell\ell)$ and S requirements, $t\bar{t}Z$ events with $Z \rightarrow \nu\bar{\nu}$ are the main SM background. Remaining Drell–Yan events with large p_T^{miss} from mismeasurement, multiboson production and other $t\bar{t}$ /single t processes in association with a W, a Z or a Higgs boson ($t\bar{t}W$, tqZ or $t\bar{t}H$) are sources of smaller contributions. The background estimation procedures and their corresponding control regions, listed in Table 4, are discussed in the following.

6.1 Top quark background

Events from the $t\bar{t}$ process are contained in the $M_{T2}(\ell\ell) < 100$ GeV region, as long as the jets and leptons in each event are identified and their momenta are precisely measured. Three main sources are identified that promote $t\bar{t}$ events into the tail of the $M_{T2}(\ell\ell)$ distribution. Firstly, the jet momentum resolution is approximately Gaussian [97] and jet mismeasurements propagate to p_T^{miss} , which subsequently leads to values of $M_{T2}(\ell\ell)$ and $M_{T2}(b\ell b\ell)$ that do not obey the endpoint at the mother particle mass. For events with $M_{T2}(\ell\ell) \leq 140$ GeV, this $t\bar{t}$ component is dominant, while it amounts to less than 10% for signal regions with $M_{T2}(\ell\ell) > 140$ GeV. Secondly, significant mismeas-

Table 3 Definition of the signal regions. The regions are further split into SF and DF regions. The preselection in Table 2 is applied to all regions

$M_{T2}(b\ell b\ell)$ (GeV)	\mathcal{S}	$100 < M_{T2}(\ell\ell) < 140$ GeV	$140 < M_{T2}(\ell\ell) < 240$ GeV	$M_{T2}(\ell\ell) > 240$ GeV
0–100	12–50	SR0	SR6	
	> 50	SR1	SR7	
100–200	12–50	SR2	SR8	SR12
	> 50	SR3	SR9	
> 200	12–50	SR4	SR10	
	> 50	SR5	SR11	

Table 4 Definition of the control regions. The preselection in Table 2 is applied to all regions

Name	Definition	
TTCRSF	$M_{T2}(\ell\ell) < 100$ GeV, SF leptons, $ m(\ell\ell) - m_Z > 15$ GeV	
TTCRDF	$M_{T2}(\ell\ell) < 100$ GeV, DF leptons	
TTZ2j2b	$N_{\text{jets}} = 2, N_b \geq 2$	
TTZ3j1b	$N_\ell = 3, \mathcal{S} \geq 0, \geq 1$ SF lepton pair	$N_{\text{jets}} = 3, N_b = 1$
TTZ3j2b	with $ m(\ell\ell) - m_Z < 10$ GeV	$N_{\text{jets}} = 3, N_b \geq 2$
TTZ4j1b		$N_{\text{jets}} \geq 4, N_b = 1$
TTZ4j2b		$N_{\text{jets}} \geq 4, N_b \geq 2$
CR0-CR12	Same as SR0-SR12 in Table 3 but requiring SF leptons, $ m(\ell\ell) - m_Z < 15$ GeV, $N_b = 0$, and without the $\cos \Delta\phi(p_T^{\text{miss}}, j)$ requirements given in Table 2.	

surements of the momentum of jets can be caused by the loss of photons and neutral hadrons showering in masked channels of the calorimeters, or neutrinos with high p_T within jets. For $M_{T2}(\ell\ell) > 140$ GeV, up to 50% of the top quark background falls into this category. The predicted rate and kinematic modeling of these rare non-Gaussian effects in simulation are checked in a control region requiring SF leptons satisfying $|m(\ell\ell) - m_Z| < 15$ GeV. A 30% uncertainty covers differences in the tails of the p_T^{miss} distribution observed in this control region.

Finally, an electron or a muon may fail the identification requirements, or the event may have a τ lepton produced in a Wboson decay. If there is a nonprompt lepton from the hadronization of a bottom quark or a charged hadron misidentified as a lepton selected in the same event, the reconstructed value for $M_{T2}(\ell\ell)$ is not bound by the W mass. To validate the modeling of this contribution, we select events with one additional lepton satisfying loose isolation requirements on top of the selection in Table 2. In order to mimic the lost prompt-lepton background, we recompute $M_{T2}(\ell\ell)$ by combining each of the isolated leptons with the extra lepton in both the observed and simulated samples. Since the transverse momentum balance is not significantly changed by the lepton misidentification, the p_T^{miss} and \mathcal{S} observables are not modified. Events with misidentified electrons or muons from this category constitute up to 40% of the top quark background prediction for $M_{T2}(\ell\ell) > 140$ GeV. We see good

agreement between the observed and simulated kinematic distributions, indicating that the simulation describes such backgrounds well. Based on the statistical precision in the highest $M_{T2}(\ell\ell)$ regions, we assign a 50% uncertainty to this contribution.

The $\bar{t}t$ normalization is measured in situ by including a signal-depleted control region defined by $M_{T2}(\ell\ell) < 100$ GeV in the signal extraction fit, yielding a scale factor for the $\bar{t}t$ prediction of 1.02 ± 0.04 . The region is split into DF (TTCRDF) and SF channels (TTCRSF). Events with a Zboson candidate are rejected in the latter.

6.2 Top quark + X background

Top quarks produced in association with a boson ($\bar{t}tZ$, $\bar{t}tW$, $\bar{t}tH$, tqZ) form an irreducible background, if the boson decays to leptons or neutrinos. The $Z \rightarrow \nu\bar{\nu}$ decay in the $\bar{t}tZ$ process provides genuine p_T^{miss} and is the dominant background component at high values of $M_{T2}(\ell\ell)$. The decay mode $\bar{t}tZ \rightarrow (b\ell^\pm\nu)(bjj)(\ell^\pm\ell^\mp)$ is used to measure the normalization of this contribution. The leading, subleading, and trailing lepton p_T are required to satisfy thresholds of 40, 20, and 20 GeV, respectively. The invariant mass of two SF leptons with opposite charge is required to satisfy the tightened requirement $|m(\ell\ell) - m_Z| < 10$ GeV. The shape of the distribution of $p_T(Z)$ has recently been measured in the 2016 and 2017 data sets [98] and is well described by simulation. Five

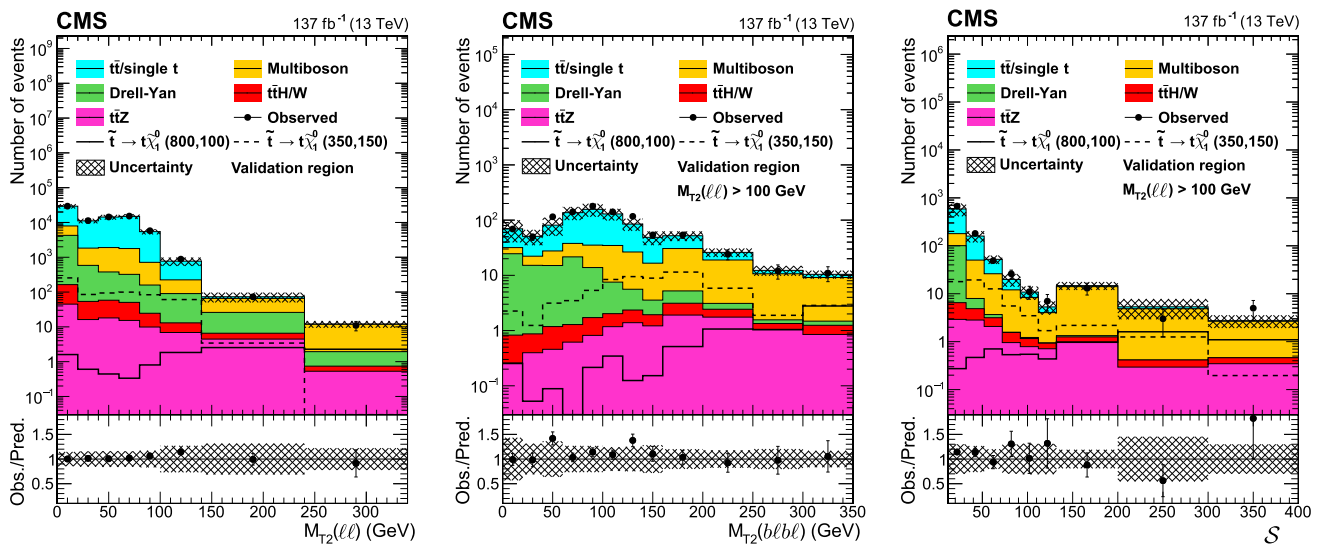


Fig. 3 The $M_{T2}(\ell\ell)$, $M_{T2}(b\ell b\ell)$, and S distributions in the validation regions requiring $N_{\text{jets}} \geq 2$ and $N_b = 0$, combining the SF and DF channels. All other event selection requirements are applied. For the $M_{T2}(b\ell b\ell)$ and S distributions, $M_{T2}(\ell\ell) > 100$ GeV is required. The individual processes are scaled using their measured respective scale factors, as described in the text. The hatched band represents the

experimental systematic uncertainties and the uncertainties in the scale factors. The last bin in each distribution includes the overflow events. The lower panel gives the ratio between the observation and the predicted SM backgrounds. The relative uncertainty in the SM background prediction is shown as a hatched band

control regions requiring different N_{jets} and N_b combinations are defined in Table 4 and labeled TTZ2j2b–TTZ4j2b. They are included in the signal extraction fit, in which the simulated number of $t\bar{t}Z$ events is found to be scaled up by a factor of 1.22 ± 0.25 , consistent with the initial prediction.

ulated distributions in Fig. 3. The hatched band includes the experimental systematic uncertainties and the uncertainties in the background normalizations.

6.3 Drell–Yan and multiboson backgrounds

7 Systematic uncertainties

In order to measure the small residual Drell–Yan contribution that passes the event selection, we select dilepton events according to the criteria listed in Table 2 except that we invert the Zboson veto, the b_{jet} requirements, and remove the angular separation requirements on jets and \vec{p}_T^{miss} . We expect from the simulation that the selection is dominated by the Drell–Yan and multiboson events. For each SF signal region, we define a corresponding control region with the selections above and the signal region requirements on $M_{T2}(\ell\ell)$, $M_{T2}(b\ell b\ell)$, and S . The regions are labeled CR0–CR12 in Table 4 and are included in the signal extraction fit. The $M_{T2}(b\ell b\ell)$ observable is calculated in these regions using the two highest p_T jets. The scale factors for the Drell–Yan and multiboson background components are found to be 1.18 ± 0.28 and 1.35 ± 0.32 , respectively.

Several experimental uncertainties affect the signal and background yield estimations. The efficiency of the trigger selection ranges from 95 to 99% with uncertainties lower than 2.3% in all signal and control regions. Offline lepton reconstruction and selection efficiencies are measured using $Z \rightarrow \ell\ell$ events in bins of lepton p_T and η . These measurements are performed separately in the observed and simulated data sets, with efficiency values ranging from 70 to 80%. Scale factors are used to correct the efficiencies measured in simulated events to those in the observed data. The uncertainties in these scale factors are less than 3% per lepton and less than 5% in most of the search and control regions.

The good modeling of the multiboson and $t\bar{t}$ processes, including potential sources of anomalous p_T^{miss} , is demonstrated in a validation region requiring $N_{\text{jets}} \geq 2$ and $N_b = 0$ and combining the SF and DF channels. The observed distributions of the search variables are compared with the sim-

Uncertainties in the event yields resulting from the calibration of the jet energy scale are estimated by shifting the jet momenta in the simulation up and down by one standard deviation of the jet energy corrections. Depending on the jet p_T and η , the resulting uncertainty in the simulated yields from the jet energy scale is typically 4%, except in the lowest regions in $M_{T2}(\ell\ell)$ close to the m_W threshold where it can be as high as 20%. In addition, the energy scale of deposits from soft particles that are not clustered in jets are varied within

Table 5 Typical values (90% quantiles) and maximum values of the systematic uncertainties in all signal regions

Systematic uncertainty	Typical (%)	Max (%)
Integrated luminosity	2	2
Pileup modeling	5	7
Jet energy scale	4	20
Jet energy resolution	3	4
b tagging efficiency	2	3
b tagging mistag rate	1	7
Trigger efficiency	1	2
Lepton identification efficiency	3	5
Modeling of unclustered energy	3	7
Non-Gaussian jet mismeasurements	6	6
Misidentified or nonprompt leptons	5	5
$t\bar{t}$ normalization	9	9
$t\bar{t}Z$ normalization	10	14
Multiboson background normalization	4	8
$t\bar{t}H/W$ background normalization	5	8
Drell–Yan normalization	3	8
Parton distribution functions	2	4
μ_R and μ_F choice	7	11

their uncertainties, and the resulting uncertainty reaches 7%. The btagging efficiency in the simulation is corrected using scale factors determined from the observed data [90], and uncertainties are propagated to all simulated events. These contribute an uncertainty of up to 7% in the predicted yields, depending on the p_T , η and origin of the b-tagged jet.

The effect of all the experimental uncertainties described above is evaluated for each of the simulated processes in all signal regions, and is considered correlated across the analysis bins and simulated processes.

The uncertainties in the normalizations of the single top and $t\bar{t}$, $t\bar{t}Z$, Drell–Yan, and multiboson backgrounds are discussed in Sect. 6. Finally, the uncertainty in the integrated luminosity is 2.3–2.5% [99–101].

Additional systematic uncertainties affect the modeling in simulation of the various processes, discussed in the following. All simulated samples are reweighted according to the distribution of the true number of interactions at each bunch crossing. The uncertainty in the total inelastic pp cross section leads to uncertainties of 5% in the expected yields.

For the $t\bar{t}$ and $t\bar{t}Z$ backgrounds, we determine the event yield changes resulting from varying the renormalization scale (μ_R) and the factorization scale (μ_F) up and down by a factor of two, while keeping the overall normalization constant. The combinations of variations in opposite directions are disregarded. We assign as the uncertainty the envelope of the considered yield variations, treated as uncorrelated among the background processes. Uncertainties in the PDFs can have a further effect on the simulated $M_{T2}(\ell\ell)$ shape. We determine the change of acceptance in the signal regions

using the PDF variations and assign the envelope of these variations—less than 4%—as a correlated uncertainty [102].

The contributions to the total uncertainty in the estimated backgrounds are summarized in Table 5, which provides the maximum uncertainties over all signal regions and the typical values, defined as the 90% quantile of the uncertainty values in all signal regions.

For the small contribution from $t\bar{t}$ production in association with a W or a Higgs boson, we take an uncertainty of 20% in the cross section based on the variations of the generator scales and the PDFs.

Most of the sources of systematic uncertainty in the background estimates affect the prediction of the signal as well, and these are evaluated separately for each mass configuration of the considered simplified models. We further estimate the effect of missing higher-order corrections for the signal acceptance by varying μ_R and μ_F [103–105] and find that those uncertainties are below 10%. The modeling of initial-state radiation (ISR) is relevant for the SUSY signal simulation in cases where the mass difference between the top squark and the LSP is small. The ISR reweighting is based on the number of ISR jets (N_J^{ISR}) so as to make the predicted jet multiplicity distribution agree with that observed. The comparison is performed in a sample of events requiring two leptons and two b-tagged jets. The reweighting procedure is applied to SUSY MC events and factors vary between 0.92 and 0.51 for N_J^{ISR} between 1 and 6. We take one half of the deviation from unity as the systematic uncertainty in these reweighting factors, correlated across search regions. It is generally found to have a small effect, but can reach 30%

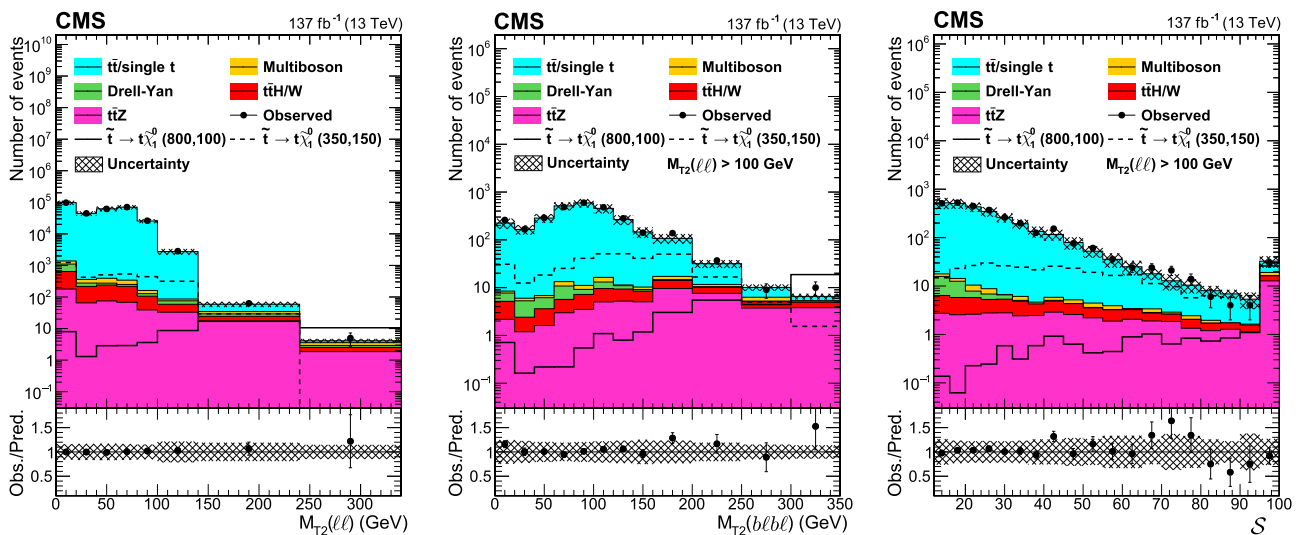


Fig. 4 Distributions of $M_{T2}(\ell\ell)$ (left), $M_{T2}(b\ell b\ell)$ (middle), and S (right) for all lepton flavors for the preselection defined in Table 2. Additionally, $M_{T2}(\ell\ell) > 100$ GeV is required for the $M_{T2}(b\ell b\ell)$ and S distributions. The last bin in each distribution includes the overflow

events. The lower panel gives the ratio between the observation and the predicted SM backgrounds and the relative uncertainty in the SM background prediction is shown as a hatched band

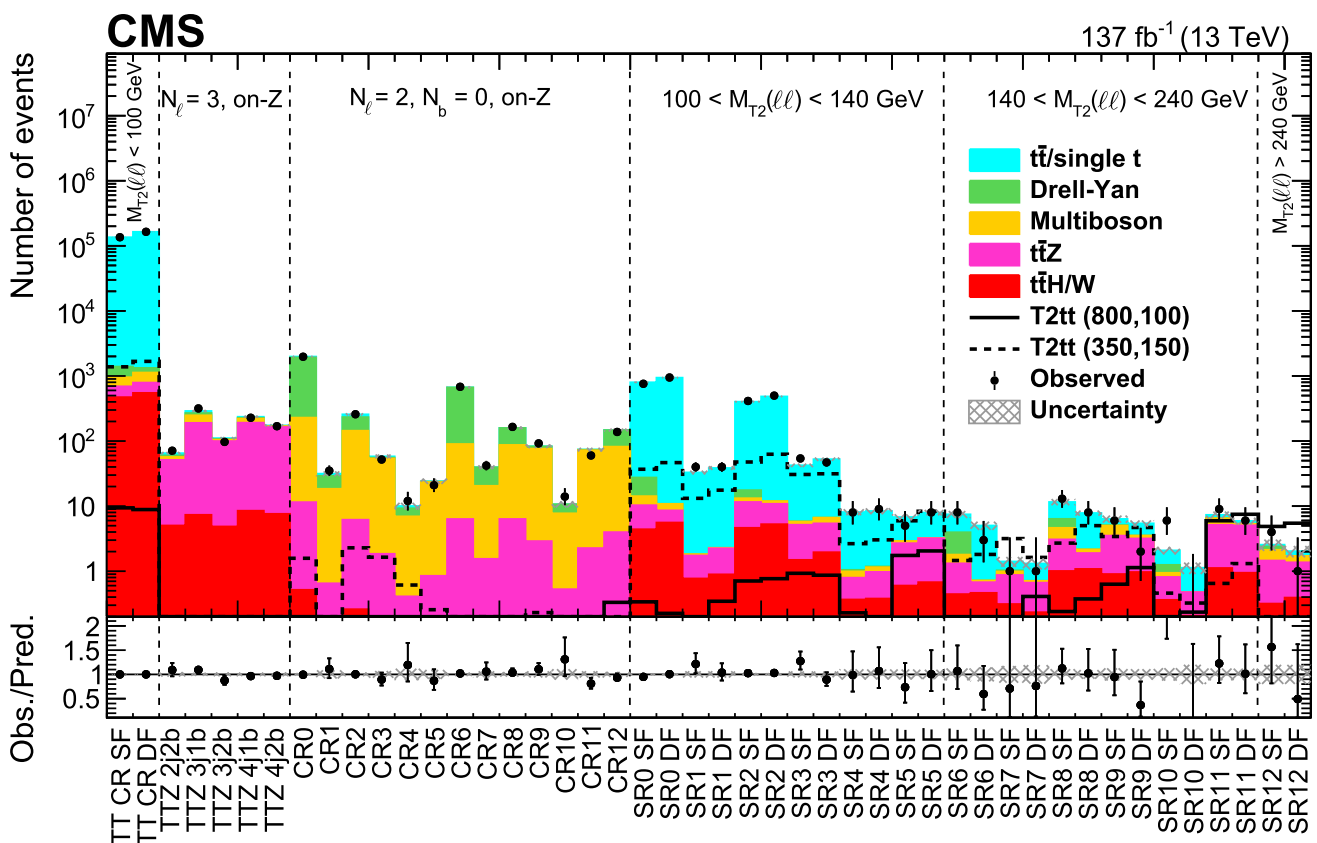


Fig. 5 Predicted and observed yields in the signal and control regions as defined in Tables 3 and 4. The control regions TTCRSF and TTCRDF are defined by $M_{T2}(\ell\ell) < 100$ GeV and are used to constrain the $t\bar{t}$ normalization. The $t\bar{t}Z$ control regions employ a 3 lepton requirement in different N_{jets} and N_b bins. The dilepton invariant mass and N_b selec-

tions are inverted for CR0–CR12 in order to constrain the Drell–Yan and multiboson normalizations, using only the SF channel. The lower panel gives the ratio between the observation and the predicted SM backgrounds. The hatched band reflects the post-fit systematic uncertainties

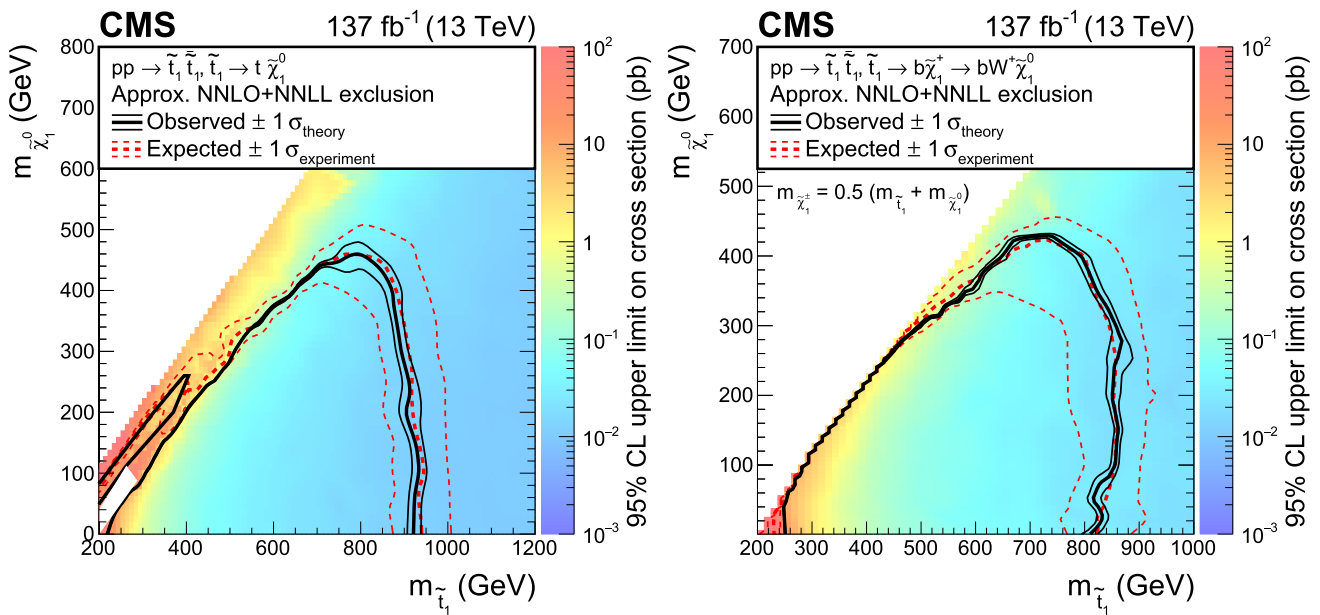


Fig. 6 Expected and observed limits for the T2tt model with $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ decays (left) and for the T2bW model with $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+ \rightarrow bW^+ \tilde{\chi}_1^0$ decays (right) in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ mass plane. The color indicates the 95% CL upper limit on the cross section at each point in the plane. The area below the thick black curve represents the observed exclusion region at 95% CL assuming 100% branching fraction for the decays of the SUSY particles, while the dashed red lines indicate the expected limits

at 95% CL and the region containing 68% of the distribution of limits expected under the background-only hypothesis. The thin black lines show the effect of the theoretical uncertainties in the signal cross section. The small white area on the diagonal in the left figure corresponds to configurations where the mass difference between \tilde{t}_1 and $\tilde{\chi}_1^0$ is very close to the top quark mass. In this region the signal acceptance strongly depends on the $\tilde{\chi}_1^0$ mass and is therefore hard to model

for compressed mass configurations. An uncertainty from potential differences of the modeling of p_T^{miss} in the fast simulation of the CMS detector is evaluated by comparing the reconstructed p_T^{miss} with the p_T^{miss} obtained using generator-level information. This uncertainty ranges up to 20% and only affects the SUSY signal samples. For these samples, the scale factors and uncertainties for the tagging efficiency of bjets and leptons are evaluated separately. Typical uncertainties in the scale factors are below 2% for b-tagged jets, and between 1 and 7% for leptons.

8 Results

Good agreement between the SM-predicted and observed $M_{T2}(\ell\ell)$, $M_{T2}(b\ell b\ell)$, and \mathcal{S} distributions is found, as shown in Fig. 4. No significant deviation from the SM prediction is observed in any of the signal regions as shown in Fig. 5. The observed excess events in SR10SF are found to be close to the signal region selection thresholds. To perform the statistical interpretations, a likelihood function is formed with Poisson probability functions for all data regions. The control and signal regions as depicted in Fig. 5 are included. The correlations of the uncertainties are taken into account as

described in Sect. 7. A profile likelihood ratio in the asymptotic approximation [106] is used as the test statistic. Upper limits on the production cross section are calculated at 95% confidence level (CL) according to the asymptotic CL_s criterion [107, 108].

The results shown in Fig. 5 are interpreted in the context of simplified SUSY models of top squark production followed by a decay to top quarks and neutralinos (T2tt), via an intermediate chargino (T2bW), and via an additional intermediate slepton (T8bbℓℓνν). These interpretations are presented on the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane in Figs. 6 and 7. The color on the z axis indicates the 95% CL upper limit on the cross section at each point in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane. The area below the thick black curve represents the observed exclusion region at 95% CL assuming 100% branching fraction for the decays of the SUSY particles. The thick dashed red lines indicate the expected limit at 95% CL, while the region containing 68% of the distribution of limits expected under the background-only hypothesis is bounded by thin dashed red lines. The thin black lines show the effect of the theoretical uncertainties in the signal cross section. In the T2tt model we exclude mass configurations with $m_{\tilde{\chi}_1^0}$ up to 450 GeV and $m_{\tilde{t}_1}$ up to 925 GeV, assuming that the top quarks are unpolarized, thus improving by approximately 125 GeV in $m_{\tilde{t}_1}$

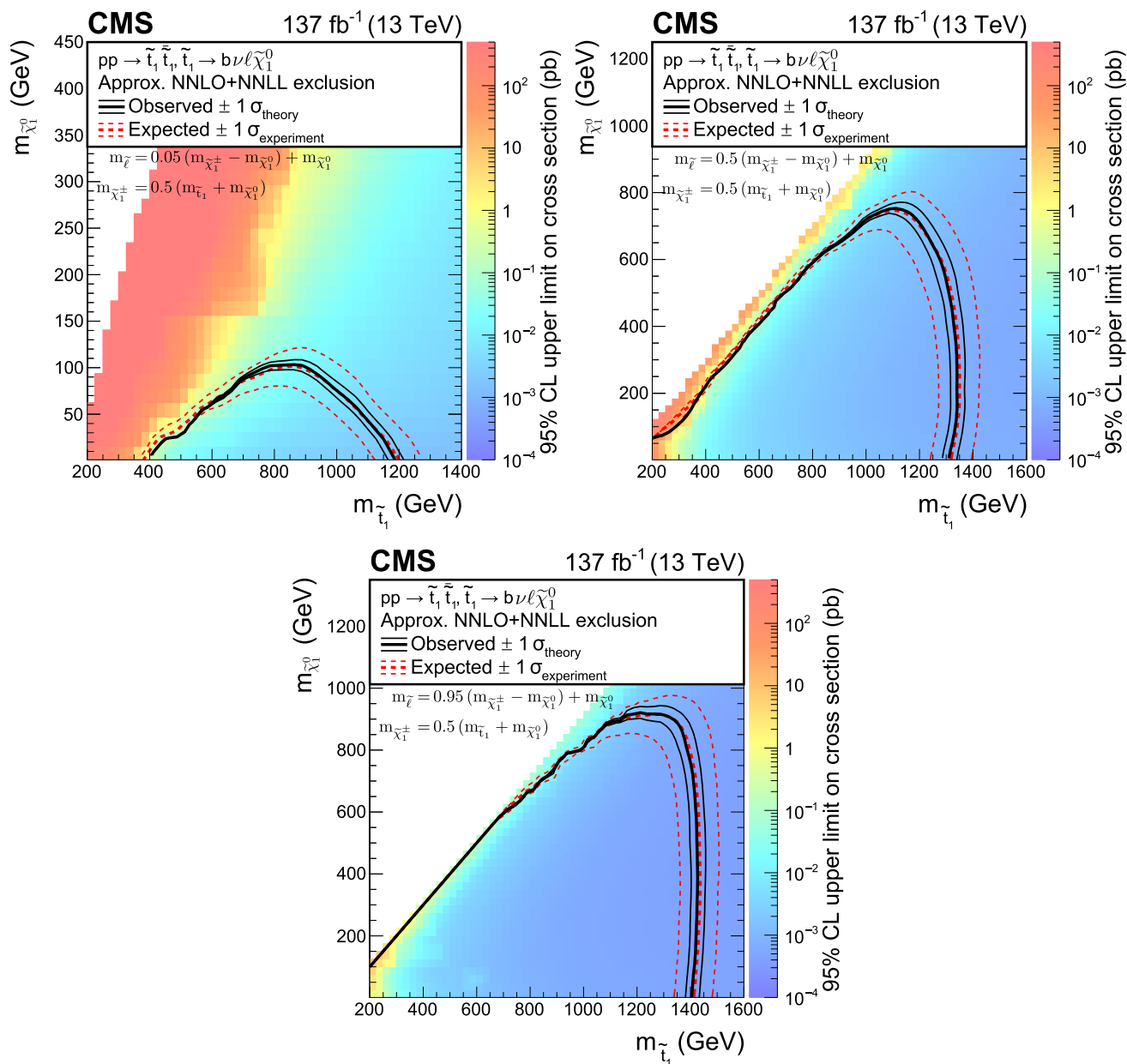


Fig. 7 Expected and observed limits for the T8bbllνν model with $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \rightarrow b\nu\tilde{\ell} \rightarrow b\nu\ell\tilde{\chi}_1^0$ decays in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ mass plane for three different mass configurations defined by $m_{\tilde{\ell}} = x(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) +$

$m_{\tilde{\chi}_1^0}$ with $x = 0.05$ (upper left), $x = 0.50$ (upper right), and $x = 0.95$ (lower). The description of curves is the same as in the caption of Fig. 6

the results presented on a partial data set in Ref. [38]. The observed upper limit on the top squark cross section improved by approximately 50% for most mass configurations. The result for the T2bW model is shown in Fig. 6 (right) and the results for T8bbllνν models are shown in Fig. 7. We exclude mass configurations with $m_{\tilde{\chi}_1^0}$ up to 420 GeV and $m_{\tilde{t}_1}$ up to 850 GeV in the T2bW model, extending the exclusion limits set in Ref. [38] by approximately 100 GeV in $m_{\tilde{t}_1}$. The sensitivity in the T8bbllνν model strongly depends on the intermediate slepton mass and is largest when $x = 0.95$ in

$m_{\tilde{\ell}} = x(m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) + m_{\tilde{\chi}_1^0}$. In this case, excluded masses reach up to 900 GeV for $m_{\tilde{\chi}_1^0}$ and 1.4 TeV for $m_{\tilde{t}_1}$. These upper limits decrease to 750 GeV for $m_{\tilde{\chi}_1^0}$ and 1.3 TeV for $m_{\tilde{t}_1}$ when $x = 0.5$ and to 100 GeV for $m_{\tilde{\chi}_1^0}$ and 1.2 TeV for $m_{\tilde{t}_1}$ when $x = 0.05$. In this model, the improvement upon previous results from Ref. [38] is approximately 100 GeV in $m_{\tilde{t}_1}$, and up to 100 GeV in $m_{\tilde{\chi}_1^0}$.

9 Summary

A search for top squark pair production in final states with two opposite-charge leptons, bjets, and significant missing transverse momentum (p_T^{miss}) is presented. The data set of proton-proton collisions corresponds to an integrated luminosity of 137 fb^{-1} and was collected with the CMS detector at a center-of-mass energy of 13 TeV. Transverse mass variables and the significance of p_T^{miss} are used to efficiently suppress backgrounds from standard model processes. No evidence for a deviation from the expected background is observed. The results are interpreted in several simplified models for supersymmetric top squark pair production and decay.

In the T2tt model with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ decays, \tilde{t}_1 masses up to 925 GeV and $\tilde{\chi}_1^0$ masses up to 450 GeV are excluded. In the T2bW model with $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \rightarrow bW^+\tilde{\chi}_1^0$ decays, \tilde{t}_1 masses up to 850 GeV and $\tilde{\chi}_1^0$ masses up to 420 GeV are excluded, assuming the chargino mass to be the mean of the \tilde{t}_1 and $\tilde{\chi}_1^0$ masses. In the T8bbll $\nu\nu$ model with decays $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \rightarrow b\nu\tilde{\ell} \rightarrow b\nu\ell\tilde{\chi}_1^0$, therefore 100% branching fraction to dilepton final states, the sensitivity depends on the intermediate particle masses. With the chargino mass again taken as the mean of the \tilde{t}_1 and $\tilde{\chi}_1^0$ masses, the strongest exclusion is obtained if the slepton mass is close to the chargino mass. In this case, excluded masses reach up to 1.4 TeV for \tilde{t}_1 and 900 GeV for $\tilde{\chi}_1^0$. When the slepton mass is taken as the mean of the chargino and neutralino masses, these numbers decrease to 1.3 TeV for \tilde{t}_1 and 750 GeV for $\tilde{\chi}_1^0$. A further reduction to 1.2 TeV for \tilde{t}_1 and to 100 GeV for $\tilde{\chi}_1^0$ is observed when the slepton mass is close to the neutralino mass.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. M. Sirunyan[†], A. Tumasyan



Institut für Hochenergiephysik, Vienna, Austria

W. Adam , F. Ambrogio , T. Bergauer, M. Dragicevic , J. Erö, A. Escalante Del Valle , R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F. M. Pitters, N. Rad, J. Schieck , R. Schöfbeck , M. Spanring, S. Tempel, W. Waltenberger , C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko , J. Suarez Gonzalez










Universiteit Antwerpen, Antwerp, Belgium

M. R. Darwish², E. A. De Wolf, D. Di Croce, X. Janssen , T. Kello³, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Havermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel 




Vrije Universiteit Brussel, Brussels, Belgium

F. Blekman , E. S. Bols , S. S. Chhibra , J. D'Hondt , J. De Clercq , D. Lontkovskiy, S. Lowette , I. Marchesini, S. Moortgat , A. Morton , Q. Python , S. Tavernier, W. Van Doninck, P. Van Mulders






Université Libre de Bruxelles, Brussels, Belgium

D. Beghin, B. Bilin , B. Clerbaux , G. De Lentdecker, B. Dorney, L. Favart , A. Grebenyuk, A. K. Kalsi , I. Makarenko , L. Moureaux, L. Pétré, A. Popov , N. Postiau, E. Starling , L. Thomas , C. Vander Velde , P. Vanlaer , D. Vannerom, L. Wezenbeek



Ghent University, Ghent, Belgium

T. Cornelis , D. Dobur, M. Gruchala, I. Khvastunov⁴, M. Niedziela, C. Roskas, K. Skovpen , M. Tytgat , W. Verbeke, B. Vermassen, M. Vit













Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G. Bruno, F. Bury, C. Caputo , P. David , C. Delaere , M. Delcourt, I. S. Donertas, A. Giammanco , V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia , S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G. A. Alves , G. Correia Silva, C. Hensel, A. Moraes 

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. L. Aldá Júnior , E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho , J. Chinellato⁵, E. Coelho, E. M. Da Costa , G. G. Da Silveira , D. De Jesus Damiao , S. Fonseca De Souza , J. Martins⁷, D. Matos Figueiredo, M. Medina Jaime⁸, M. Melo De Almeida, C. Mora Herrera , L. Mundim , H. Nogima, P. Rebello Teles , L. J. Sanchez Rosas, A. Santoro, S. M. Silva Do Amaral , A. Sznajder , M. Thiel, E. J. Tonelli Manganote⁵, F. Torres Da Silva De Araujo, A. Vilela Pereira 

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

C. A. Bernardes ^a, L. Calligaris ^a, T. R. Fernandez Perez Tomei ^a, E. M. Gregores ^b, D. S. Lemos ^a, P. G. Mercadante ^b, S. F. Novaes ^a, Sandra S. Padula ^a


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

A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov , B. Pavlov, P. Petkov, A. Petrov










Beihang University, Beijing, China

W. Fang ³, Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, Z. Hu , Y. Wang

Institute of High Energy Physics, Beijing, China

E. Chapon , G. M. Chen ⁹, H. S. Chen ⁹, M. Chen , A. Kapoor , D. Leggat, H. Liao, Z. Liu , R. Sharma , A. Spiezia, J. Tao , J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang⁹, J. Zhao 

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin , Q. Li , M. Lu, X. Lyu, Y. Mao, S. J. Qian, D. Wang , Q. Wang , J. Xiao


Sun Yat-Sen University, Guangzhou, China

Z. You 

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Shanghai, China

X. Gao³

Zhejiang University, Hangzhou, China

M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , A. Cabrera, C. Florez , J. Fraga, A. Sarkar, M. A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J. D. Ruiz Alvarez , C. A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

D. Giljanovic, N. Godinovic , D. Lelas, I. Puljak , T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic, A. Starodumov¹⁰, T. Susa 

University of Cyprus, Nicosia, Cyprus

M. W. Ather, A. Attikis, E. Erodoutou, A. Ioannou, G. Kole , M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa , C. Nicolaou, F. Ptochos , P. A. Razis, H. Rykaczewski, H. Saka , D. Tsiakkouri

Charles University, Prague, Czech Republic

M. Finger¹¹, M. Finger Jr. , A. Kveton, J. Tomsa


Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

H. Abdalla ¹², Y. Assran^{13,14}, S. Khalil¹⁵

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M. A. Mahmoud , Y. Mohammed ¹⁶


National Institute of Chemical Physics and Biophysics, Tallinn, Estonia





































































S. Bhowmik , A. Carvalho Antunes De Oliveira , R. K. Dewanjee , K. Ehataht, M. Kadastik, M. Raidal , C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland










P. Eerola , L. Forthomme , H. Kirschenmann , K. Osterberg, M. Voutilainen 

Helsinki Institute of Physics, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M. S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen , J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, FinlandP. Luukka , T. Tuuva**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**C. Amendola , M. Besancon, F. Couderc , M. Dejardin, D. Denegri, J. L. Faure, F. Ferri , S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault , P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin , A. Savoy-Navarro¹⁷, M. Titov , G. B. Yu **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris, France**S. Ahuja , F. Beaudette , M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac , A. Hakimi, I. Kucher , A. Lobanov , C. Martin Perez, M. Nguyen , C. Ochando, P. Paganini , J. Rembser, R. Salerno , J. B. Sauvan , Y. Sirois , A. Zabi, A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram ¹⁸, J. Andrea, D. Bloch , G. Bourgatte, J.-M. Brom, E. C. Chabert, C. Collard , J.-C. Fontaine¹⁸, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**E. Asilar , S. Beauceron , C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon , D. Contardo, P. Depasse , H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain , I. B. Laktineh, H. Lattaud, A. Lesavage, M. Lethuillier , L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret**Georgian Technical University, Tbilisi, Georgia**I. Bagaturia¹⁹, Z. Tsamalaidze¹¹**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**L. Feld , K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M. P. Rauch, J. Schulz, M. Teroerde **RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**D. Eliseev, M. Erdmann , P. Fackeldey, B. Fischer, S. Ghosh , T. Hebbeker , K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer , A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee , D. Noll, A. Novak, T. Pook , A. Pozdnyakov , T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt , S. C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**C. Dziwok, G. Flügge, W. Haj Ahmad ²⁰, O. Hlushchenko, T. Kress, A. Nowack , C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl ²¹, T. Ziemons**Deutsches Elektronen-Synchrotron, Hamburg, Germany**H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau , S. Baxter, O. Behnke, A. Bermúdez Martínez, A. A. Bin Anuar , K. Borrás²², V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez , V. Danilov, A. De Wit , M. M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L. I. Estevez Banos, E. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean , M. Guthoff, A. Harb , A. Jafari ²⁴, N. Z. Jomhari , H. Jung, A. Kasem²², M. Kasemann , H. Kaveh, C. Kleinwort , J. Knolle , D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁵, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A. B. Meyer, M. Meyer, M. Missiroli , J. Mnich , A. Mussgiller, V. Myronenko , Y. Otariid, D. Pérez Adán, S. K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger , A. Singh, R. E. Sosa Ricardo , N. Tonon , O. Turkot , A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen , K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev , R. Zlebcik **University of Hamburg, Hamburg, Germany**R. Aggleton, S. Bein, L. Benato , A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, J. Haller , A. Hinzmann , A. Karavdina, G. Kasieczka, R. Klanner , R. Kogler, V. Kutzner, J. Lange , T. Lange, A. Malara, C. E. N. Niemeyer, A. Nigamova, K. J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt , D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald , I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz , R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann , K. Flöh, M. Giffels, A. Gottmann, F. Hartmann ²¹, C. Heidecker, U. Husemann , M. A. Iqbal, I. Katkov²⁶, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra , D. Müller, Th. Müller, M. Musich, G. Quast , K. Rabbertz , J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder , D. Seith, I. Shvetsov, H. J. Simonis, R. Ulrich , M. Wassmer, M. Weber, R. Wolf, S. Wozniewski


Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C. K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis






National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris , I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou



University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitará, N. Manthos, I. Papadopoulos, J. Strogas 

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók ²⁷, R. Chudasama, M. Csanad , M. M. A. Gadallah²⁸, S. Lökös²⁹, P. Major, K. Mandal, A. Mehta , G. Pasztor , O. Surányi, G. I. Veres 

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu , D. Horvath³⁰, F. Sikler , V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁷, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z. L. Trocsanyi , G. Zilizi



Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

T. Csorgo, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J. R. Komaragiri , D. Kumar, L. Panwar, P. C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati³¹, D. Dash , C. Kar, P. Mal, T. Mishra, V. K. Muraleedharan Nair Bindhu, A. Nayak³², D. K. Sahoo³¹, N. Sur , S. K. Swain


Panjab University, Chandigarh, India

S. Bansal , S. B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra³³, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J. B. Singh, A. K. Viridi

University of Delhi, Delhi, India

A. Ahmed, A. Bhardwaj, B. C. Choudhary , R. B. Garg, M. Gola, S. Keshri , A. Kumar, M. Naimuddin , P. Priyanka, K. Ranjan, A. Shah 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³⁴, R. Bhattacharya, S. Bhattacharya , D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber³⁵, M. Maity³⁶, S. Nandan, P. Palit, A. Purohit, P. K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh³⁴, S. Thakur³⁴


Indian Institute of Technology Madras, Madras, India

P. K. Behera , S. C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P. R. Pujahari, A. Sharma, A. K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

D. Dutta, V. Kumar, K. Naskar³⁷, P. K. Netrakanti, L. M. Pant, P. Shukla 




Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M. A. Bhat, S. Dugad, R. Kumar Verma, G. B. Mohanty , U. Sarkar


Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India

S. Dube , B. Kansal, K. Kothekar , S. Pandey, A. Rane, A. Rastogi, S. Sharma 

Department of Physics, Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi ³⁸























Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani³⁹, S. M. Etesami, M. Khakzad, M. Mohammadi Najafabadi 
























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 , R. Aly^{a,b,40}, C. Aruta^{a,b}, A. Colaleo , D. Creanza , N. De Filippis , M. De Palma , A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee , L. Fiore , A. Gelmi^{a,b}, M. Gul , G. Iaselli , M. Ince , S. Lezki , G. Maggi , M. Maggi , I. Margjeka^{a,b}, V. Mastrapasqua^{a,b}, J. A. Merlin^a, S. My , S. Nuzzo , A. Pompili , G. Pugliese , A. Ranieri , G. Selvaggi , L. Silvestris , F. M. Simone^{a,b}, R. Venditti , P. Verwilligen 













INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi , C. Battilana , D. Bonacorsi , L. Borgonovi^{a,b}, S. Braibant-Giacomelli , R. Campanini , P. Capiluppi , A. Castro , F. R. Cavallo , M. Cuffiani , G. M. Dallavalle , T. Diotallevi^{a,b}, F. Fabbri , A. Fanfani , E. Fontanesi^{a,b}, P. Giacomelli , L. Giommi^{a,b}, C. Grandi , L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,41}, S. Marcellini , G. Masetti , F. L. Navarria , A. Perrotta , F. Primavera , A. M. Rossi , T. Rovelli , G. P. Siroli , N. Tosi 




INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo , S. Costa , A. Di Mattia , R. Potenza^{a,b}, A. Tricomi , C. Tuve 

INFN Sezione di Firenze ^a, Università di Firenze ^b, Florence, Italy

G. Barbagli , A. Cassese , R. Ceccarelli^{a,b}, V. Ciulli , C. Civinini , R. D'Alessandro , F. Fiori^a, E. Focardi , G. Latino , P. Lenzi , M. Lizzo^{a,b}, M. Meschini , S. Paoletti , R. Seidita^{a,b}, G. Sguazzoni , L. Viliani 
















INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , D. Piccolo 

INFN Sezione di Genova ^a, Università di Genova ^b, Genoa, Italy

M. Bozzo , F. Ferro , R. Mulargia^{a,b}, E. Robutti , S. Tosi 

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milan, Italy

A. Benaglia , A. Beschi^{a,b}, F. Brivio^{a,b}, F. Cetorelli^{a,b}, V. Ciriolo^{a,b,21}, F. De Guio , M. E. Dinardo , P. Dini , S. Gennai , A. Ghezzi , P. Govoni , L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi , D. Menasce , F. Monti^{a,b}, L. Moroni , M. Paganoni , D. Pedrini , S. Ragazzi , T. Tabarelli de Fatis , D. Valsecchi^{a,b,21}, D. Zuolo 

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Rome, Italy

S. Buontempo , N. Cavallo , A. De Iorio^{a,b}, F. Fabozzi , F. Fienga^a, A. O. M. Iorio , L. Lista , S. Meola , P. Paolucci , B. Rossi , C. Sciacca , E. Voevodina^{a,b}

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi , N. Bacchetta , D. Bisello , A. Boletti , A. Bragagnolo^{a,b}, R. Carlin , P. Checchia 

P. De Castro Manzano^a, T. Dorigo^{id}^a, F. Gasparini^{id}^{a,b}, U. Gasparini^{id}^{a,b}, S. Y. Hoh^{id}^{a,b}, L. Layer^a, M. Margoni^{id}^{a,b}, A. T. Meneguzzo^{id}^{a,b}, M. Presilla^b, P. Ronchese^{id}^{a,b}, R. Rossin^{a,b}, F. Simonetto^{id}^{a,b}, G. Strong, A. Tiko^{id}^a, M. Tosi^{id}^{a,b}, H. YARAR^{a,b}, M. Zanetti^{id}^{a,b}, P. Zotto^{id}^{a,b}, A. Zucchetta^{id}^{a,b}, G. Zumerle^{id}^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

C. Aime^{a,b}, A. Braghieri^{id}^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, P. Montagna^{a,b}, S. P. Ratti^{a,b}, V. Re^{id}^a, M. Ressegotti^{a,b}, C. Riccardi^{id}^{a,b}, P. Salvini^{id}^a, I. Vai^{id}^a, P. Vitulo^{id}^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

M. Biasini^{id}^{a,b}, G. M. Bilei^{id}^a, D. Ciangottini^{id}^{a,b}, L. Fanò^{id}^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^{id}^a, F. Moscatelli^{id}^a, A. Piccinelli^{a,b}, A. Rossi^{id}^{a,b}, A. Santocchia^{id}^{a,b}, D. Spiga^{id}^a, T. Tedeschi^{a,b}

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy

K. Androsov^{id}^a, P. Azzurri^{id}^a, G. Bagliesi^{id}^a, V. Bertacchi^{a,c}, L. Bianchini^{id}^a, T. Boccali^{id}^a, R. Castaldi^{id}^a, M. A. Ciocci^{id}^{a,b}, R. Dell'Orso^{id}^a, M. R. Di Domenico^{a,b}, S. Donato^{id}^a, L. Giannini^{a,c}, A. Giassi^{id}^a, M. T. Grippo^{id}^a, F. Ligabue^{id}^{a,c}, E. Manca^{id}^{a,c}, G. Mandorli^{a,c}, A. Messineo^{id}^{a,b}, F. Palla^{id}^a, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{id}^{a,b}, G. Rolandi^{id}^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b}, P. Spagnolo^{id}^a, R. Tenchini^{id}^a, G. Tonelli^{id}^{a,b}, N. Turini^a, A. Venturi^{id}^a, P. G. Verdini^{id}^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Rome, Italy

F. Cavallari^{id}^a, M. Cipriani^{id}^{a,b}, D. Del Re^{id}^{a,b}, E. Di Marco^{id}^a, M. Diemoz^{id}^a, E. Longo^{id}^{a,b}, P. Meridiani^{id}^a, G. Organtini^{id}^{a,b}, F. Pandolfi^a, R. Paramatti^{id}^{a,b}, C. Quaranta^{a,b}, S. Rahatlou^{id}^{a,b}, C. Rovelli^{id}^a, F. Santanastasio^{id}^{a,b}, L. Soffi^{id}^{a,b}, R. Tramontano^{a,b}

INFN Sezione di Torino^a, Università di Torino^b, Turin, Italy, Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{id}^{a,b}, R. Arcidiacono^{id}^{a,c}, S. Argiro^{id}^{a,b}, M. Arneodo^{id}^{a,c}, N. Bartosik^a, R. Bellan^{id}^{a,b}, A. Bellora^{a,b}, C. Biino^{id}^a, A. Cappati^{a,b}, N. Cartiglia^{id}^a, S. Cometti^{id}^a, M. Costa^{id}^{a,b}, R. Covarelli^{id}^{a,b}, N. Demaria^{id}^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^{id}^a, S. Maselli^{id}^a, E. Migliore^{id}^{a,b}, V. Monaco^{id}^{a,b}, E. Monteil^{id}^{a,b}, M. Monteno^{id}^a, M. M. Obertino^{id}^{a,b}, G. Ortona^{id}^a, L. Pacher^{id}^{a,b}, N. Pastrone^{id}^a, M. Pelliccioni^{id}^a, G. L. Pinna Angioni^{a,b}, M. Ruspá^{id}^{a,c}, R. Salvatico^{a,b}, F. Siviero^{a,b}, V. Sola^{id}^a, A. Solano^{a,b}, D. Soldi^{id}^{a,b}, A. Staiano^{id}^a, D. Trocino^{id}^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^{id}^a, V. Candolise^{id}^{a,b}, M. Casarsa^{id}^a, F. Cossutti^{id}^a, A. Da Rold^{id}^{a,b}, G. Della Ricca^{id}^{a,b}, F. Vazzoler^{id}^{a,b}

Kyungpook National University, Daegu, Korea

S. Dogra^{id}, C. Huh, B. Kim, D. H. Kim, G. N. Kim^{id}, J. Lee, S. W. Lee^{id}, C. S. Moon^{id}, Y. D. Oh^{id}, S. I. Pak, B. C. Radburn-Smith, S. Sekmen^{id}, Y. C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D. H. Moon^{id}

Hanyang University, Seoul, Korea

B. Francois, T. J. Kim^{id}, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi^{id}, Y. Go, S. Ha, B. Hong^{id}, K. Lee, K. S. Lee, J. Lim, J. Park, S. K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

J. Goh^{id}, A. Gurtu

Sejong University, Seoul, Korea

H. S. Kim^{id}, Y. Kim

Seoul National University, Seoul, Korea

J. Almond, J. H. Bhyun, J. Choi, S. Jeon, J. Kim, J. S. Kim, S. Ko, H. Kwon, H. Lee^{id}, K. Lee, S. Lee, K. Nam, B. H. Oh, M. Oh, S. B. Oh, H. Seo, U. K. Yang, I. Yoon^{id}

University of Seoul, Seoul, Korea



D. Jeon, J. H. Kim, B. Ko, J. S. H. Lee^{id}, I. C. Park, Y. Roh, D. Song, I. J. Watson^{id}

Department of Physics, Yonsei University, Seoul, Korea

H. D. Yoo

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, LatviaV. Veckalns ⁴³**Vilnius University, Vilnius, Lithuania**A. Juodagalvis , A. Rinkevicius , G. Tamulaitis**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**


W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, MexicoJ. F. Benitez , A. Castaneda Hernandez , J. A. Murillo Quijada , L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo , I. Heredia-De La Cruz ⁴⁴, R. Lopez-Fernandez, D. A. Perez Navarro, A. Sanchez-Hernandez **Universidad Iberoamericana, Mexico City, Mexico**


S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H. A. Salazar Ibarquen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, MexicoA. Morelos Pineda **University of Montenegro, Podgorica, Montenegro**J. Mijuskovic⁴, N. Raicevic**University of Auckland, Auckland, New Zealand**D. Krofcheck **University of Canterbury, Christchurch, New Zealand**S. Bheesette, P. H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad, M. I. Asghar, M. I. M. Awan, H. R. Hoorani, W. A. Khan, M. A. Shah, M. Shoaib , M. Waqas**AGH University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**




V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, PolandH. Bialkowska, M. Bluj , B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szeleper, P. Traczyk, P. Zalewski**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski, A. Byszuk⁴⁵, K. Doroba, A. Kalinowski , M. Konecki , J. Krolkowski, M. Olszewski, M. Walczak**Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**M. Araujo, P. Bargassa , D. Bastos, P. Faccioli , M. Gallinaro , J. Hollar, N. Leonardo , T. Niknejad, J. Seixas , K. Shchelina, O. Toldaiev , J. Varela **Joint Institute for Nuclear Research, Dubna, Russia**S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev⁴⁷, P. Moisev, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin


Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim⁴⁸, E. Kuznetsova⁴⁹, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev , A. Dermenev, S. Gninenko , N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov , D. Tliso[†], A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko⁵⁰, V. Popov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov , A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia

O. Bychkova, M. Danilov , D. Philippov, E. Popova, V. Rusinov


P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov



Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Belyaev, E. Boos , V. Bunichev, M. Dubinin , L. Dudko , A. Ershov, A. Gribushin, V. Klyukhin , O. Kodolova, I. Lokhtin , S. Obraztsov, M. Perfilov, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁵³, T. Dimova⁵³, L. Kardapoltsev⁵³, I. Ovtin⁵³, Y. Skovpen 

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

I. Azhgirey , I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin , N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh
















Tomsk State University, Tomsk, Russia

V. Borchsh, V. Ivanchenko , E. Tcherniaev

University of Belgrade, Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁵⁴, P. Cirkovic , M. Dordevic , P. Milenovic, J. Milosevic 








Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya , J. A. Brochero Cifuentes , C. A. Carrillo Montoya, M. Cepeda , M. Cerrada, N. Colino , B. De La Cruz, A. Delgado Peris , J. P. Fernández Ramos , J. Flix , M. C. Fouz, A. García Alonso, O. Gonzalez Lopez , S. Goy Lopez, J. M. Hernandez , M. I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , L. Romero, S. Sánchez Navas, M. S. Soares , A. Triossi , L. Urda Gómez, C. Willmott





Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J. F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas , C. Erice, J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , E. Palencia Cortezon , C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza , S. Sanchez Cruz , A. Trapote

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 

G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol , F. Matorras , J. Piedra Gomez , C. Prieels, F. Ricci-Tam , T. Rodrigo , A. Ruiz-Jimeno , L. Scodellaro , I. Vila, J. M. Vizan Garcia 












































University of Colombo, Colombo, Sri Lanka

M. K. Jayananda, B. Kailasapathy⁵⁵, D. U. J. Sonnadara, D. D. C. Wickramarathna

Department of Physics, University of Ruhuna, Matara, Sri Lanka

W. G. D. Dharmaratna , K. Liyanage, N. Perera, N. Wickramage










CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco , A. Bocci, P. Bortignon , E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella , D. d'Enterria , A. Dabrowski, N. Daci, V. Daponte, A. David , A. De Roeck , M. Deile, R. Di Maria , M. Dobson, M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁵⁶, D. Fasanella , S. Fiorendi , A. Florent , G. Franzoni , J. Fulcher , W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko , J. Hegeman , Y. Iiyama , V. Innocente, T. James, P. Janot , J. Kaspar, J. Kieseler , M. Komm , N. Kratochwil, C. Lange , P. Lecoq , K. Long, C. Lourenço , L. Malgeri , M. Mannelli, A. Massironi , F. Meijers, S. Mersi , E. Meschi , F. Moortgat , M. Mulders , J. Ngadiuba, J. Niedziela , S. Orfanelli, L. Orsini, F. Pantaleo , L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani , A. Pfeiffer , M. Pierini , D. Rabadý , A. Racz, M. Rieger , M. Rovere, H. Sakulin, J. Salfeld-Nebgen , S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva , W. Snoeys , P. Sphicas , J. Steggemann , S. Summers, V. R. Tavolaro , D. Treille, A. Tsirou, G. P. Van Onsem , A. Vartak , M. Verzetti, K. A. Wozniak, W. D. Zeuner









Paul Scherrer Institut, Villigen, Switzerland

L. Caminada , W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe


ETH Zurich, Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus , P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori , M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T. A. Gómez Espinosa , C. Grab , D. Hits, W. Lustermaun, A.-M. Lyon, R. A. Manzoni , M. T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini , M. G. Ratti , M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D. A. Sanz Becerra, M. Schönenberger , V. Stampf, M. L. Vesterbacka Olsson, R. Wallny , D. H. Zhu

Universität Zürich, Zurich, Switzerland

C. AMSler⁵⁹, C. Botta , D. Brzhechko, M. F. Canelli , R. Del Burgo, J. K. Heikkilä , M. Huwiler, A. Jofrehei, B. Kilminster , S. Leontsinis , A. Macchiolo, P. Meiring, V. M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger , Y. Takahashi , S. Wertz 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁰, C. M. Kuo, W. Lin, A. Roy, T. Sarkar , S. S. Yu




National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, P. Chang , Y. Chao, K. F. Chen, P. H. Chen, W.-S. Hou , Y. y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan 


Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop , C. Asawatangtrakuldee, N. Srimanobhas



Physics Department, Science and Art Faculty, Çukurova University, Adana, Turkey



F. Boran, S. Damarseckin⁶¹, Z. S. Demiroglu , F. Dolek, C. Dozen⁶², I. Dumanoglu⁶³, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler⁶⁴, I. Hos⁶⁵, C. Isik, E. E. Kangal⁶⁶, O. Kara, A. Kayis Topaksu, U. Kiminsu , G. Onengut, K. Ozdemir⁶⁷, A. Polatoz, A. E. Simsek, B. Tali⁶⁸, U. G. Tok, S. Turkcapar, I. S. Zorbakir , C. Zorbilmez

Physics Department, Middle East Technical University, Ankara, Turkey
















































B. Isildak⁶⁹, G. Karapinar⁷⁰, K. Ocalan , M. Yalvac⁷²

Bogazici University, Istanbul, Turkey




I. O. Atakisi, E. Gülmez , M. Kaya⁷³, O. Kaya⁷⁴, Ö. Özçelik, S. Tekten⁷⁵, E. A. Yetkin 

Istanbul Technical University, Istanbul, TurkeyA. Cakir , K. Cankocak⁶³, Y. Komurcu, S. Sen **Istanbul University, Istanbul, Turkey**F. Aydogmus Sen, S. Cerci⁶⁸, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁶⁸**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, UkraineL. Levchuk **University of Bristol, Bristol, UK**E. Bhal, S. Bologna, J. J. Brooke , E. Clement , D. Cussans, H. Flacher , J. Goldstein , G. P. Heath, H. F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran, T. Sakuma , S. Seif El Nasr-Storey, V. J. Smith, J. Taylor, A. Titterton**Rutherford Appleton Laboratory, Didcot, UK**K. W. Bell, A. Belyaev ⁷⁸, C. Brew , R. M. Brown, D. J. A. Cockerill, K. V. Ellis, K. Harder, S. Harper, J. Linacre , K. Manolopoulos, D. M. Newbold , E. Olaiya, D. Petyt, T. Reis , T. Schuh, C. H. Shepherd-Themistocleous, A. Thea , I. R. Tomalin, T. Williams**Imperial College, London, UK**R. Bainbridge , P. Bloch, S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, A. Bundock , V. Cepaitis, G. S. Chahal⁷⁹, D. Colling, P. Dauncey , G. Davies, M. Della Negra , G. Fedi , G. Hall , G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli , V. Milosevic , J. Nash ⁸⁰, V. Palladino , M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott , C. Seez, A. Shtipliyski, M. Stoye, A. Tapper , K. Uchida, T. Virdee ²¹, N. Wardle , S. N. Webb, D. Winterbottom, A. G. Zecchinelli**Brunel University, Uxbridge, UK**J. E. Cole , P. R. Hobson , A. Khan, P. Kyberd , C. K. Mackay, I. D. Reid , L. Teodorescu, S. Zahid**Baylor University, Waco, USA**A. Brinkerhoff , K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A. R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson**Catholic University of America, Washington, DC, USA**R. Bartek , A. Dominguez , R. Uniyal, A. M. Vargas Hernandez**The University of Alabama, Tuscaloosa, USA**A. Buccilli , O. Charaf, S. I. Cooper, S. V. Gleyzer, C. Henderson , P. Rumerio, C. West**Boston University, Boston, USA**A. Akpinar, A. Albert , D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart , I. Suarez, S. Yuan, D. Zou**Brown University, Providence, USA**G. Benelli, B. Burkle , X. Coubez²², D. Cutts , Y.t. Duh, M. Hadley, U. Heintz, J. M. Hogan ⁸¹, K. H. M. Kwok, E. Laird, G. Landsberg , K. T. Lau, J. Lee, M. Narain, S. Sagir ⁸², R. Syarif , E. Usai , W. Y. Wong, D. Yu, W. Zhang**University of California, Davis, Davis, USA**R. Band, C. Brainerd , R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway , R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor , K. Tos, M. Tripathi , Y. Yao, F. Zhang **University of California, Los Angeles, USA**M. Bachtis, R. Cousins , A. Dasgupta, D. Hamilton, J. Hauser , M. Ignatenko, T. Lam, N. Mccoll, W. A. Nash, S. Regnard , D. Saltzberg , C. Schnaible, B. Stone, V. Valuev




University of California, Riverside, Riverside, USA

K. Burt, Y. Chen, R. Clare , J. W. Gary , S. M. A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O. R. Long , N. Manganelli, M. Olmedo Negrete, M. I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA

J. G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte , R. Gerosa , D. Gilbert , B. Hashemi, V. Krutelyov , J. Letts , M. Masciovecchio, S. May, S. Padhi, M. Pieri , V. Sharma , M. Tadel, F. Würthwein , A. Yagil 

Department of Physics, University of California, Santa Barbara, Santa Barbara, USA

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela , B. Marsh, H. Mei, A. Ovcharova, H. Qu , M. Quinnan, J. Richman, U. Sarica , D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim , O. Cerri, I. Dutta, J. M. Lawhorn , N. Lu , J. Mao, H. B. Newman , T. Q. Nguyen , J. Pata, M. Spiropulu , J. R. Vlimant , S. Xie , Z. Zhang , R. Y. Zhu 








Carnegie Mellon University, Pittsburgh, USA

J. Alison, M. B. Andrews, T. Ferguson , T. Mudholkar, M. Paulini , M. Sun, I. Vorobiev









































University of Colorado Boulder, Boulder, USA

J. P. Cumalat, W. T. Ford , E. MacDonald, T. Mulholland, R. Patel, A. Perloff , K. Stenson , K. A. Ulmer , S. R. Wagner 







Cornell University, Ithaca, USA

J. Alexander, Y. Cheng, J. Chu, D. J. Cranshaw, A. Datta, A. Frankenthal , K. Mcdermott , J. Monroy , J. R. Patterson , D. Quach , A. Ryd, W. Sun , S. M. Tan, Z. Tao, J. Thom, 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 , D. Berry , J. Berryhill , P. C. Bhat, K. Burkett , J. N. Butler, A. Canepa, G. B. Cerati , H. W. K. Cheung , F. Chlebana, M. Cremonesi, V. D. Elvira , J. Freeman, Z. Gecse, E. Gottschalk , L. Gray, D. Green, S. Grünendahl , O. Gutsche , R. M. Harris , S. Hasegawa, R. Heller, T. C. Herwig, J. Hirschauer , B. Jayatilaka , S. Jindariani, M. Johnson, U. Joshi, P. Klabbers , T. Klijnsma, B. Klima , M. J. Kortelainen , S. Lammel , D. Lincoln , R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride , P. Merkel, S. Mrenna , S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro , C. Pena ⁵², O. Prokofyev, F. Ravera , A. Reinsvold Hall , L. Ristori , B. Schneider , E. Sexton-Kennedy , N. Smith, A. Soha , W. J. Spalding , L. Spiegel, S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk, N. V. Tran, L. Uplegger , E. W. Vaandering , H. A. Weber , A. Woodard

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov , L. Cadamuro , V. Cherepanov, F. Errico, R. D. Field, D. Guerrero, B. M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K. H. Lo, K. Matchev, N. Menendez, G. Mitselmakher , D. Rosenzweig, K. Shi , J. Wang , S. Wang , X. Zuo










Florida State University, Tallahassee, USA

T. Adams , A. Askew, D. Diaz, R. Habibullah , S. Hagopian , V. Hagopian, K. F. Johnson, R. Khurana, T. Kolberg , G. Martinez, H. Prosper, C. Schiber, R. Yohay , J. Zhang

Florida Institute of Technology, Melbourne, USA

M. M. Baarmand , S. Butalla, T. Elkafrawy ⁸³, M. Hohlmann , D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva 

University of Illinois at Chicago (UIC), Chicago, USA

M. R. Adams, L. Apanasevich , H. Becerril Gonzalez, R. Cavanaugh , X. Chen , S. Dittmer, O. Evdokimov , C. E. Gerber , D. A. Hangal, D. J. Hofman , C. Mills , G. Oh, T. Roy, M. B. Tonjes, N. Varelas, J. Viinikainen , X. Wang, Z. Wu 

The University of Iowa, Iowa City, USA

M. Alhusseini, K. Dilsiz⁸⁴, S. Durgut, R. P. Gandrajula^{ID}, M. Haytmyradov, V. Khristenko, O. K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁸⁵, A. Moeller, J. Nachtman, H. Ogul^{ID}⁸⁶, Y. Onel, F. Ozok⁸⁷, A. Penzo, C. Snyder, E. Tiras, J. Wetzel^{ID}, K. Yi⁸⁸

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld^{ID}, L. Corcodilos, M. Eminizer, A. V. Gritsan^{ID}, S. Kyriacou, P. Maksimovic, C. Mantilla^{ID}, J. Roskes^{ID}, M. Swartz, T.Á. Vámi^{ID}

The University of Kansas, Lawrence, USA

C. Baldenegro Barrera, P. Baringer^{ID}, A. Bean^{ID}, A. Bylinkin^{ID}, T. Isidori, S. Khalil^{ID}, J. King, G. Krintiras^{ID}, A. Kropivnitskaya, C. Lindsey, N. Minafra^{ID}, M. Murray, C. Rogan^{ID}, C. Royon, S. Sanders, E. Schmitz, J. D. Tapia Takaki^{ID}, Q. Wang^{ID}, J. Williams, G. Wilson^{ID}

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov^{ID}, K. Kaadze, D. Kim, Y. Maravin^{ID}, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

E. Adams, A. Baden, O. Baron, A. Belloni^{ID}, S. C. Eno^{ID}, Y. Feng, N. J. Hadley, S. Jabeen, G. Y. Jeng^{ID}, R. G. Kellogg, T. Koeth, A. C. Mignerey, S. Nabili, M. Seidel^{ID}, A. Skuja, S. C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen^{ID}, R. Bi, S. Brandt, W. Busza^{ID}, I. A. Cali, Y. Chen^{ID}, M. D'Alfonso^{ID}, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi^{ID}, J. Krupa, Y.-J. Lee^{ID}, P. D. Luckey, B. Maier, A. C. Marini^{ID}, C. Mcginn, C. Mironov, S. Narayanan^{ID}, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi^{ID}, G. S. F. Stephans^{ID}, K. Sumorok, K. Tatar^{ID}, D. Velicanu, J. Wang, T. W. Wang, Z. Wang, B. Wyslouch^{ID}

University of Minnesota, Minneapolis, USA

R. M. Chatterjee, A. Evans^{ID}, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain^{ID}, M. Krohn, Y. Kubota, Z. Lesko, J. Mans^{ID}, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe^{ID}, M. A. Wadud

University of Mississippi, Oxford, USA

J. G. Acosta, S. Oliveros^{ID}

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom^{ID}, S. Chauhan^{ID}, D. R. Claes, C. Fangmeier, L. Finco^{ID}, F. Golf^{ID}, J. R. González Fernández, I. Kravchenko^{ID}, J. E. Siado, G. R. Snow[†], B. Stieger, W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA

G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili^{ID}, A. Kharchilava, C. McLean^{ID}, D. Nguyen, J. Pekkanen, S. Rappoccio^{ID}, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson^{ID}, E. Barberis, C. Freer, Y. Haddad^{ID}, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi^{ID}, D. M. Morse^{ID}, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari^{ID}, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood^{ID}

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert^{ID}, T. Gunter, K. A. Hahn, N. Odell, M. H. Schmitt^{ID}, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev^{ID}, R. Goldouzian, M. Hildreth, K. Hurtado Anampa^{ID}, C. Jessop, D. J. Karmgard, K. Lannon, W. Li, N. Loukas^{ID}, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko⁴⁶, R. Ruchti, P. Siddireddy, S. Taroni^{ID}, M. Wayne, A. Wightman, M. Wolf^{ID}, L. Zygala

The Ohio State University, Columbus, USA

J. Alimena^{ID}, B. Bylsma, B. Cardwell, L. S. Durkin, B. Francis, C. Hill^{ID}, A. Lefeld, B. L. Winer, B. R. Yates^{ID}








Princeton University, Princeton, USA

P. Das, G. Dezoort, P. Elmer , B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos , G. Kopp, S. Kwan, D. Lange, M. T. Lucchini , 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

V. E. Barnes , R. Chawla, S. Das, L. Gutay, M. Jones, A. W. Jung , B. Mahakud, G. Negro, N. Neumeister , C. C. Peng, S. Piperov , H. Qiu, J. F. Schulte , M. Stojanovic¹⁷, N. Trevisani , F. Wang , R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar









Rice University, Houston, USA

A. Baty , S. Dildick, K. M. Ecklund , S. Freed, F. J. M. Geurts , M. Kilpatrick, A. Kumar, W. Li, B. P. Padley , R. Redjimi, J. Roberts[†], J. Rorie, W. Shi , A. G. Stahl Leiton 

University of Rochester, Rochester, USA

A. Bodek , P. de Barbaro, R. Demina, J. L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA

B. Chiarito, J. P. Chou , A. Gandrakota, Y. Gershtein , E. Halkiadakis , A. Hart, M. Heindl , E. Hughes, S. Kaplan, O. Karacheban ²⁵, I. Laflotte, A. Lath , R. Montalvo, K. Nash, M. Osherson, S. Salur , S. Schnetzer, S. Somalwar , R. Stone, S. A. Thayil, S. Thomas, H. Wang



University of Tennessee, Knoxville, USA

H. Acharya, A. G. Delannoy , S. Spanier

Texas A&M University, College Station, USA

O. Bouhali ⁸⁹, M. Dalchenko , A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹⁰, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè , D. Rathjens , A. Safonov , J. Sturdy 

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S. W. Lee , T. Mengke, S. Muthumuni, T. Peltola , S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA

E. Appelt , S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon , S. Tuo, J. Velkovska , M. Verweij 








University of Virginia, Charlottesville, USA

M. W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky , M. Joyce, A. Ledovskoy, A. Li, C. Neu , B. Tannenwald , Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

P. E. Karchin, N. Poudyal , P. Thapa

University of Wisconsin-Madison, Madison, WI, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He, M. Herndon , A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudan Sreekala , A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma , W. H. Smith , D. Teague, S. Trembath-reichert, W. Vetens

† Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at Department of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

- 3: Also at Université Libre de Bruxelles, Brussels, Belgium
- 4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 5: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 7: Also at UFMS, Nova Andradina, Brazil
- 8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 9: Also at University of Chinese Academy of Sciences, Beijing, China
- 10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
- 11: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 12: Also at Cairo University, Cairo, Egypt
- 13: Also at Suez University, Suez, Egypt
- 14: Now at British University in Egypt, Cairo, Egypt
- 15: Also at Zewail City of Science and Technology, Zewail, Egypt
- 16: Now at Fayoum University, El-Fayoum, Egypt
- 17: Also at Purdue University, West Lafayette, USA
- 18: Also at Université de Haute Alsace, Mulhouse, France
- 19: Also at Ilia State University, Tbilisi, Georgia
- 20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 23: Also at University of Hamburg, Hamburg, Germany
- 24: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
- 25: Also at Brandenburg University of Technology, Cottbus, Germany
- 26: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 28: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 29: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 31: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 32: Also at Institute of Physics, Bhubaneswar, India
- 33: Also at G.H.G. Khalsa College, Punjab, India
- 34: Also at Shoolini University, Solan, India
- 35: Also at University of Hyderabad, Hyderabad, India
- 36: Also at University of Visva-Bharati, Santiniketan, India
- 37: Also at Indian Institute of Technology (IIT), Mumbai, India
- 38: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 39: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 40: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy
- 41: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 42: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 43: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 44: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 45: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 46: Also at Institute for Nuclear Research, Moscow, Russia
- 47: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- 48: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 49: Also at University of Florida, Gainesville, USA
- 50: Also at Imperial College, London, UK
- 51: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 52: Also at California Institute of Technology, Pasadena, USA
- 53: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

- 54: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 55: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- 56: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy
- 57: Also at National and Kapodistrian University of Athens, Athens, Greece
- 58: Also at Universität Zürich, Zurich, Switzerland
- 59: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 60: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 61: Also at Şirnak University, Şirnak, Turkey
- 62: Also at Department of Physics, Tsinghua University, Beijing, China
- 63: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 64: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 65: Also at Istanbul Aydın University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
- 66: Also at Mersin University, Mersin, Turkey
- 67: Also at Piri Reis University, Istanbul, Turkey
- 68: Also at Adiyaman University, Adiyaman, Turkey
- 69: Also at Ozyegin University, Istanbul, Turkey
- 70: Also at Izmir Institute of Technology, Izmir, Turkey
- 71: Also at Necmettin Erbakan University, Konya, Turkey
- 72: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 73: Also at Marmara University, Istanbul, Turkey
- 74: Also at Milli Savunma University, Istanbul, Turkey
- 75: Also at Kafkas University, Kars, Turkey
- 76: Also at Istanbul Bilgi University, Istanbul, Turkey
- 77: Also at Hacettepe University, Ankara, Turkey
- 78: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 79: Also at IPPP Durham University, Durham, UK
- 80: Also at Monash University, Faculty of Science, Clayton, Australia
- 81: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 82: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 83: Also at Ain Shams University, Cairo, Egypt
- 84: Also at Bingol University, Bingol, Turkey
- 85: Also at Georgian Technical University, Tbilisi, Georgia
- 86: Also at Sinop University, Sinop, Turkey
- 87: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 88: Also at Department of Physics, Nanjing Normal University, Nanjing, China
- 89: Also at Texas A&M University at Qatar, Doha, Qatar
- 90: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea