

# Search for direct pair production of supersymmetric partners of $\tau$ leptons in the final state with two hadronically decaying $\tau$ leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

A search for the direct production of a pair of  $\tau$  sleptons, the supersymmetric partners of  $\tau$  leptons, is presented. Each  $\tau$  slepton is assumed to decay to a  $\tau$  lepton and the lightest supersymmetric particle (LSP), which is assumed to be stable and to not interact in the detector, leading to an imbalance in the total reconstructed transverse momentum. The search is carried out in events identified as containing two  $\tau$  leptons, each decaying to one or more hadrons and a neutrino, and significant transverse momentum imbalance. In addition to scenarios in which the  $\tau$  sleptons decay promptly, the search also addresses scenarios in which the  $\tau$  sleptons have sufficiently long lifetimes to give rise to nonprompt  $\tau$  leptons. The data were collected in proton-proton collisions at a center-of-mass energy of 13 TeV at the CERN LHC with the CMS detector in 2016–2018, and correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$ . No significant excess is seen with respect to standard model expectations. Upper limits on cross sections for the pair production of  $\tau$  sleptons are obtained in the framework of simplified models. In a scenario in which the  $\tau$  sleptons are superpartners of left-handed  $\tau$  leptons, and each undergoes a prompt decay to a  $\tau$  lepton and a nearly massless LSP,  $\tau$  slepton masses between 115 and 340 GeV are excluded. In a scenario in which the lifetime of the  $\tau$  sleptons corresponds to  $c\tau_0 = 0.1$  mm, where  $\tau_0$  represents the mean proper lifetime of the  $\tau$  slepton, masses between 150 and 220 GeV are excluded.

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# 1 Introduction

Supersymmetry (SUSY) [1–8] is appealing because it could address some of the shortcomings of the standard model (SM) of particle physics. It features superpartners, i.e., new particles with the same quantum numbers as their SM counterparts, with the exception of their spin, which is shifted by half a unit. The superpartner loop contributions in the radiative corrections to the Higgs boson mass could cancel quadratic divergences, thus solving the fine-tuning problem [9–12]. In SUSY models with  $R$ -parity conservation [13], the lightest supersymmetric particle (LSP) is stable and could be a dark matter (DM) candidate [14–16].

In this paper, we report the results of a search for the  $\tau$  slepton ( $\tilde{\tau}$ ), the superpartner of the  $\tau$  lepton, in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, with the CMS detector. Early universe  $\tilde{\tau}$ -neutralino coannihilation models provide a mechanism that can explain the observed DM relic density [17–22]. These models motivate the existence of a light  $\tilde{\tau}$  as the next-to-lightest supersymmetric particle (NLSP), which would lead to an enhanced rate of production of final states with  $\tau$  leptons in collider experiments [23–25]. Here, we study events with two  $\tau$  lepton candidates, both undergoing hadronic decays ( $\tau_h$ ), and having significant transverse momentum imbalance resulting from the presence of LSPs and to a lesser extent, neutrinos from the  $\tau$  lepton decays. While previous searches in this final state have largely focused on prompt decays of the parent particles, the present search also addresses scenarios in which the  $\tilde{\tau}$  is long-lived, which can arise in theories of gauge-mediated SUSY breaking (GMSB) that in many cases predict a  $\tilde{\tau}$  as the NLSP [26]. This search is the first to target final states in which reconstructed  $\tau_h$  candidates are identified as having production vertices that are significantly displaced from the primary interaction point as expected for long-lived  $\tilde{\tau}$  decays.

Figure 1 shows a diagram of direct  $\tilde{\tau}$  pair production, with the  $\tilde{\tau}$  decaying to a  $\tau$  lepton and LSP, which we study in this paper within the framework of simplified models [27–29]. For models featuring prompt decays of the  $\tilde{\tau}$ , we assume  $\tilde{\chi}_1^0$ , the lightest neutralino, to be the LSP, and consider a range of  $\tilde{\chi}_1^0$  masses up to 200 GeV. We use the symbols  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$  to refer to the superpartners of left- and right-handed  $\tau$  leptons, respectively. We consider cases in which only  $\tilde{\tau}_L$  or only  $\tilde{\tau}_R$  pairs are produced, as well as a degenerate case in which both  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$  pairs are produced. The cross section for  $\tilde{\tau}_L$  pair production is expected to be approximately three times larger than for  $\tilde{\tau}_R$  pair production [30], while the experimental acceptance is expected to be higher in the right-handed case than in the left-handed because of differences in the polarization of the  $\tau$  leptons that are produced. The small production cross section expected for the signal and the significant SM backgrounds make this search challenging.

Previous searches for direct  $\tilde{\tau}$  pair production in prompt decay scenarios were performed at the CERN LEP collider [31–34] and excluded  $\tilde{\tau}$  masses at 95% confidence level (CL) up to about 90 GeV for neutralino masses up to 80 GeV, in some models. The ATLAS [35, 36] and CMS [37] Collaborations performed searches for direct  $\tilde{\tau}$  pair production using 8 TeV CERN LHC data. The ATLAS Collaboration has reported the results of a search for direct  $\tilde{\tau}$  pair production using 13 TeV data corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$  [38] that excludes  $\tilde{\tau}$  masses between 155 and 310 GeV at 95% CL, for the case of a nearly massless LSP. The CMS Collaboration has previously reported the results of a search for direct  $\tilde{\tau}$  pair production using data collected in 2016–2017 at  $\sqrt{s} = 13 \text{ TeV}$ , corresponding to an integrated luminosity of  $77.2 \text{ fb}^{-1}$  [39], and placed upper limits on the cross section for  $\tilde{\tau}$  pair production.

We also target scenarios where the  $\tilde{\tau}$  has a short but finite lifetime, decaying within a few cm of the primary interaction point. These signatures are sensitive to GMSB SUSY models in which

a nearly massless gravitino ( $\tilde{G}$ ) is the LSP and the  $\tilde{\tau}$  is the NLSP that can become long-lived as a result of its suppressed coupling to the gravitino. We consider models involving the pair production of  $\tilde{\tau}_1$ , a mixture of  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$ , for  $c\tau_0$  up to 2.5 mm, where  $\tau_0$  is the mean proper lifetime of the  $\tilde{\tau}_1$ . For these models, we assume a scenario with maximal mixing, i.e., with a mixing angle of  $\frac{\pi}{4}$ , for which the cross section is very similar to that for purely right-handed  $\tilde{\tau}$  pair production [30]. This scenario is therefore consistent with GMSB SUSY models, in which the  $\tilde{\tau}$  is typically right-handed. Previously, the LEP experiments set limits on GMSB SUSY models with  $\tilde{\tau}_1$  as the NLSP, with the strongest limits coming from the OPAL experiment [40]. The OPAL limits excluded masses up to 87.4 GeV at 95% CL, for all  $\tilde{\tau}_1$  lifetimes. The ATLAS Collaboration recently reported the results of a search for long-lived sleptons, including  $\tilde{\tau}_{1,2}$ , a combination of mixed states of  $\tilde{\tau}_L$  and  $\tilde{\tau}_R$ , in final states with nonprompt electrons or muons. The degenerate production of the two mixed states  $\tilde{\tau}_1$  and  $\tilde{\tau}_2$  results in a larger cross section than the production of  $\tilde{\tau}_1$  alone. The search excluded  $\tilde{\tau}_{1,2}$  masses up to 340 GeV for a proper lifetime of 0.1 ns, i.e., for a  $c\tau_0$  of 30 mm, within the simplified GMSB SUSY model considered [41], under the assumption of a nearly massless LSP.

The results presented in this paper supersede those of the search reported in Ref. [39], for final states with two  $\tau_h$  candidates and missing transverse momentum ( $p_T^{\text{miss}}$ ), and also include scenarios with long-lived  $\tau$  sleptons. The LHC pp collision data collected with the CMS detector in 2018 have been analyzed, and the data collected in 2016–2017 have been re-analyzed, resulting in a sample corresponding to a total integrated luminosity of  $138 \text{ fb}^{-1}$ . Improved techniques are used to describe the SM background with  $\tau$  leptons through a method called “embedding” [42], which estimates the background with two genuine  $\tau$  lepton candidates by selecting dimuon events in data, removing reconstructed muons, and replacing them with simulated  $\tau$  lepton decays. Updated methods are used for the  $\tau_h$  candidate selection [43] and the search region definitions have been re-optimized. Overall, we obtain a significant improvement in the search sensitivity. Tabulated results are provided in the HEPData record for this analysis [44].

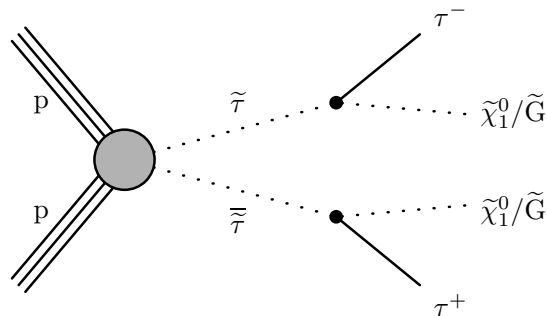


Figure 1: Diagram for direct  $\tilde{\tau}$  pair production, followed by decay of each  $\tilde{\tau}$  to a  $\tau$  lepton and an LSP. For models with promptly decaying  $\tau$  sleptons, the LSP is assumed to be  $\tilde{\chi}_1^0$ , the lightest neutralino. For models with long-lived  $\tau$  sleptons, it is assumed to be the gravitino,  $\tilde{G}$ .

## 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. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections, reside within the solenoid volume. Forward calorimeters

extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4  $\mu$ s [45]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [46].

### 3 Event reconstruction and simulation

The event reconstruction uses the particle-flow (PF) algorithm [47], which aims to reconstruct and identify individual particles in an event, with an optimized combination of information from the various elements of the CMS detector. The vector  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector sum of the transverse momenta,  $\vec{p}_T$ , of all PF-reconstructed particles in an event. Its magnitude,  $p_T^{\text{miss}}$ , is used in the search as a discriminator between signal and SM background. Events selected for the search are required to pass selection criteria [48] designed to remove anomalous high- $p_T^{\text{miss}}$  events that can occur due to a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds, and must have at least one reconstructed pp interaction vertex. The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [49].

Reconstructed particles are clustered into jets using the anti- $k_T$  algorithm [50, 51] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the whole  $p_T$  spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [52]. Jets considered in this analysis, other than those from which  $\tau_h$  candidates are reconstructed, are required to be within the tracker volume,  $|\eta| < 2.4$ , and to satisfy the condition  $p_T > 30 \text{ GeV}$ . They are required to be separated in the plane of  $\eta$  and azimuthal angle ( $\phi$ ) by  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$  from  $\tau_h$  candidates to avoid the double counting of objects. The deep neural network (DNN) based combined secondary vertex algorithm (DEEPCSV) [53] is used to identify, or “tag”, jets originating from the hadronization of b quarks. A high-efficiency (“Loose”) working point of this algorithm is used to reject events with b quark jets that are likely to have originated from SM backgrounds with top quarks. This working point corresponds to an efficiency of  $\approx 84\%$  for identifying b quarks originating from top quark decays, and misidentification rates of about 41 and 11%, respectively, for jets from charm quarks and from light quarks or gluons.

In order to suppress SM backgrounds, such as those originating from diboson production, or  $t\bar{t}$  production in association with a vector boson, we veto events with isolated electron or muon candidates. We identify these charged leptons using the same selection criteria as those described in [39]. The  $\tau_h$  candidates are reconstructed from jets, using the hadrons-plus-strips

algorithm [54], which combines 1 or 3 tracks with energy deposits in the calorimeters, to identify the  $\tau_h$  decay modes. Decay modes with one or three charged hadrons, with or without neutral pions, are considered in this search. To distinguish genuine  $\tau_h$  decays from electrons, muons, or jets originating from the hadronization of quarks or gluons, the multi-class DNN-based DEEPTAU [43] algorithm is used. Information from all individual reconstructed particles near the  $\tau_h$  axis is combined with properties of the  $\tau_h$  candidate and event activity. We employ both a relaxed (“Loose”) and a more stringent (“VVTight”) working point of the anti-jet DEEPTAU discriminant. These have efficiencies of  $\approx 80$  and  $\approx 40\%$  for a genuine  $\tau_h$  decay in the case of prompt  $\tau_h$  production, respectively, and misidentification rates of  $\approx 0.5$  and  $\approx 0.06\%$ , respectively, for quark and gluon jets. Since the DEEPTAU algorithm was optimized for promptly produced  $\tau_h$  candidates, the efficiency is reduced in the case of  $\tau_h$  candidates originating from long-lived  $\tau$  slepton decays. The efficiency of the “VVTight” working point, which is used to select signal  $\tau_h$  candidates, ranges between 20% and 30% for the largest  $\tilde{\tau}$  lifetimes considered in the search regions that explicitly target displaced  $\tau_h$  decays.

Monte Carlo (MC) simulation is used to model the signal. The MADGRAPH5\_aMC@NLO version 2.3.3 and 2.4.2 event generators [55] are used at leading order (LO) precision to generate models of direct  $\tilde{\tau}$  pair production for promptly decaying  $\tilde{\tau}$  up to the production of  $\tau$  leptons, for simulated event samples corresponding to the 2016 and 2017–2018 data sets, respectively. The  $\tau$  lepton decays are modeled by PYTHIA 8.2 (8.212 for 2016, or 8.230 for 2017–2018) [56]. For signal models in which the  $\tilde{\tau}$  undergoes nonprompt decays, the  $\tilde{\tau}$  pair production process is generated with MADGRAPH5\_aMC@NLO at LO precision, with the  $\tilde{\tau}$  decays being subsequently carried out by PYTHIA, using a specified  $\tilde{\tau}$  lifetime. We consider models with  $c\tau_0$  ranging from 0.01 to 2.5 mm. In the case of both prompt and long-lived  $\tau$  sleptons, we consider  $\tilde{\tau}$  masses ranging from 90 to 500 GeV. The CUETP8M1 underlying event tune [57] is used with PYTHIA for simulated event samples corresponding to the 2016 data set, and the CP5 tune [58] is used for 2017 and 2018 samples. The NNPDF3.0LO [59] set of parton distribution functions (PDFs) is used in generating the 2016 simulation samples, while the NNPDF3.1 next-to-leading order (NLO) PDFs are used for 2017–2018. Showering and hadronization of partons are carried out using PYTHIA, while a detailed simulation of the CMS detector is based on the GEANT4 [60] package. Finally, uncertainties in the renormalization and factorization scales have been obtained using the SYSCALC package [61]. The signal production cross sections are calculated at NLO using next-to-leading logarithmic (NLL) soft-gluon resummation [30, 62].

We also use MC simulation to model the background from SM production of Higgs bosons. The POWHEGv2 [63–66] generator is used to produce samples of Higgs boson events with decays to  $\tau$  lepton pairs. Other backgrounds, originating from processes that give rise to two genuine  $\tau_h$  decays, or to one or more jets that are misidentified as  $\tau_h$  candidates, are estimated from data, as described in Section 5. The background from events in which an electron or muon is misidentified as a  $\tau_h$  candidate is found from simulation to be negligible.

Simulated events are weighted to match the pileup profile observed in data. Scale factors are applied to simulated events to account for differences with respect to data in trigger efficiencies,  $\tau_h$  identification efficiencies, jet and  $\tau_h$  energy scales, and b tagging efficiency. We improve the modeling of initial-state radiation (ISR) in the 2016 signal simulation samples by reweighting the  $p_T^{\text{ISR}}$  distribution, where  $p_T^{\text{ISR}}$  corresponds to the magnitude of the total transverse momentum of the system of parent SUSY particles, obtained in our case by calculating the vector sum of the  $p_T$  of the two  $\tau$  sleptons at generator level. This reweighting procedure is based on studies of the  $p_T$  of Z bosons in data and simulation [67]. No corrections were found to be necessary for the  $p_T^{\text{ISR}}$  distribution in 2017 and 2018 simulation samples, as the ISR modeling was improved in the simulation with the updated underlying-event tune.

## 4 Event selection

The data used in this search are selected with two sets of triggers: a trigger requiring the presence of two  $\tau_h$  candidates, each with  $p_T > 35$  ( $>40$ ) GeV in 2016 (2017–2018) data, and a  $p_T^{\text{miss}}$ -based trigger, with a threshold varying between 100 and 140 GeV, depending on the data-taking period. The di- $\tau_h$  trigger efficiency reaches its plateau, which ranges between 75% and 95% depending on the  $\tau_h$  decay mode and the data-taking period, for  $\tau_h$   $p_T$  values above 80 GeV. The di- $\tau_h$  trigger is used for events with  $p_T^{\text{miss}} < 200$  GeV, while the  $p_T^{\text{miss}}$ -based trigger is used for events with  $p_T^{\text{miss}} > 200$  GeV. The offline  $p_T^{\text{miss}}$  threshold is chosen to be close to the range of approximately 250–300 GeV in which the efficiency of the  $p_T^{\text{miss}}$ -based trigger reaches its plateau of  $\sim 95$ – $98\%$ , depending on the data-taking period.

After the trigger selection, we impose a baseline event selection requiring the presence of exactly two  $\tau_h$  candidates of opposite charge with  $p_T > 40$  GeV,  $|\eta| < 2.1$ , and satisfying the “VVTight” DEEPTAU selection and other criteria described in Section 3. Backgrounds originating from diboson production or  $t\bar{t}$  production in association with a vector boson are suppressed by vetoing events with electron or muon candidates with  $p_T > 20$  GeV and  $|\eta| < 2.5$  or  $< 2.4$  for electrons and muons respectively, or additional  $\tau_h$  candidates with  $p_T > 30$  GeV satisfying the “Loose” DEEPTAU selection. We reject any events with a b-tagged jet to suppress top quark backgrounds, and we require  $|\Delta\phi(\tau_h^{(1)}, \tau_h^{(2)})| > 1.5$ . This requirement retains high signal efficiency while reducing the background from  $Z/\gamma^* \rightarrow \tau\tau$ +jets events in which the di- $\tau_h$  system is boosted, resulting in a smaller angular separation between the  $\tau_h$  candidates. Finally, we require  $p_T^{\text{miss}} > 50$  GeV to suppress the background with two misidentified  $\tau_h$  candidates. To avoid effects related to jet mismeasurement that can contribute to spurious  $p_T^{\text{miss}}$ , we require the  $\vec{p}_T^{\text{miss}}$  to have a minimum separation of 0.25 in  $|\Delta\phi|$  from reconstructed jets.

The search strategy relies on a simultaneous maximum likelihood fit of the event yields observed in 31 search regions (SRs), which are described below and summarized in Table 1. We use a number of discriminants to subdivide events satisfying the baseline selection criteria into exclusive SRs. For signal events, we expect the two stable LSPs in the final state to contribute to the  $p_T^{\text{miss}}$ . Consequently, we expect the correlations between  $\vec{p}_T^{\text{miss}}$  and the reconstructed  $\tau_h$  candidates to be different between signal and background events. Mass observables calculated from  $\vec{p}_T^{\text{miss}}$  and the  $\vec{p}_T$  of the  $\tau_h$  can be used to exploit these differences and discriminate signal from background.

One of the discriminants used is  $\Sigma m_T$ , the sum of the transverse masses ( $m_T$ ) calculated for each  $\tau_h$  candidate with  $p_T^{\text{miss}}$ , given by

$$\Sigma m_T = m_T(\tau_h^{(1)}) + m_T(\tau_h^{(2)}), \quad (1)$$

where the transverse mass for each  $\tau_h$  candidate is

$$m_T(\tau_h) \equiv \sqrt{2p_T^{\tau_h} p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})]}. \quad (2)$$

For our signal models,  $p_T^{\text{miss}}$  can originate from neutrinos from  $\tau_h$  decays, as well as from LSPs. However, the predominant contribution to the  $p_T^{\text{miss}}$  is expected to come from the LSPs, which we assume to be massless in the calculation of  $m_T$ .

We also use the “stransverse mass”  $m_{T2}$  [68–70], given by

$$m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} \left[ \max \left( m_T^{(1)}, m_T^{(2)} \right) \right], \quad (3)$$

where  $\vec{p}_T^{X(i)}$  (with  $i=1, 2$ ) are the unknown transverse momenta of the two invisible particles,  $X(1)$  and  $X(2)$ , corresponding to the LSPs in our signal models, and  $m_T^{(i)}$  are the transverse masses calculated from the assigned LSP transverse momenta. The latter are obtained by associating either of the two LSPs, assumed to be massless, to one of the two parent  $\tilde{\tau}$  decays. The minimization of Eq. (3) is performed over all possible LSP 2-vector momenta, which are constrained to add up to the  $\vec{p}_T^{\text{miss}}$  in the event. We expect large values of  $m_{T2}$  to occur more frequently in signal events for models with larger  $\tilde{\tau}$  masses, and to occur relatively rarely in SM background events.

For the selection of events in the SRs, requirements of  $m_{T2} > 25 \text{ GeV}$  and  $\Sigma m_T > 200 \text{ GeV}$  are imposed. Two sets of SRs are defined: the ‘‘prompt’’ SRs, targeting models in which the  $\tilde{\tau}$  decays promptly, and the ‘‘displaced’’ SRs, targeting long-lived  $\tilde{\tau}$  models in which nonprompt  $\tau_h$  candidates are expected.

In order to ensure that the prompt and displaced SRs are disjoint, we require that events in the prompt SRs have at least one  $\tau_h$  that does not satisfy the ‘‘displaced  $\tau_h$ ’’ criteria described below for the displaced SRs. Events are then subdivided into bins of  $m_{T2}$  and  $\Sigma m_T$ , which provides sensitivity to a range of  $\tilde{\tau}$  masses. We further subdivide events into two categories based on the number of reconstructed jets ( $N_j$ ):  $N_j = 0$ , and  $N_j \geq 1$ . Since background events that satisfy the SR kinematic selection criteria usually contain additional jets, the 0-jet category provides SRs with improved signal-to-background ratios. Signal events with ISR or pileup jets may populate the  $N_j \geq 1$  SRs, and so we also retain these to avoid losing signal sensitivity. Finally, we gain additional sensitivity in bins with lower  $\Sigma m_T$  and  $m_{T2}$  values ( $\Sigma m_T < 300 \text{ GeV}$  and  $m_{T2} < 75 \text{ GeV}$ ) in the 0-jet category, which have relatively high background, by further subdividing them into two bins based on the  $p_T$  of the leading (higher- $p_T$ )  $\tau_h$  candidate,  $p_T^{\tau_{h,1}}$  ( $p_T^{\tau_{h,1}} < 90 \text{ GeV}$ , and  $p_T^{\tau_{h,1}} \geq 90 \text{ GeV}$ ). This further improves the discrimination of signal from background as  $\tau_h$  in signal events tend to have higher  $p_T$ .

The displaced category is defined by imposing the following ‘‘displaced  $\tau_h$ ’’ criteria for both  $\tau_h$  candidates. We require the significance of the  $\tau_h$  impact parameter relative to the PV in the transverse plane ( $d_{xy}$ ), defined as the quantity divided by its uncertainty, to have an absolute value above 5, and the absolute value of its three-dimensional impact parameter (IP3D) to exceed  $100 \mu\text{m}$ . We also require  $|\Delta\phi(\tau_h^{(1)}, \tau_h^{(2)})| > 1.75$  to further suppress the background in the displaced category. For events satisfying these selection criteria, the  $p_T$  of the subleading (lower- $p_T$ )  $\tau_h$  candidate,  $p_T^{\tau_{h,2}}$ , provides additional discrimination between signal and the remaining background. Accordingly, we define two SR bins for events in this category, with  $p_T^{\tau_{h,2}} < 110 \text{ GeV}$  and  $p_T^{\tau_{h,2}} \geq 110 \text{ GeV}$ .

The SR binning was chosen to optimize the search sensitivity, with statistical and systematic uncertainties in the signal and background predictions being taken into account in the optimization procedure. Table 1 summarizes the  $\Sigma m_T$ ,  $m_{T2}$ , and  $p_T^{\tau_{h,1}}$  criteria used to define the prompt SRs, and the  $p_T^{\tau_{h,2}}$  criteria used to define the displaced SRs. Figure 2 shows distributions of  $\Sigma m_T$ ,  $m_{T2}$ , and  $p_T^{\tau_{h,1}}$  for events satisfying the selection criteria that are common to all prompt SRs in data, along with the corresponding background estimates that are obtained using the methods described in Section 5. Predicted signal distributions are shown for three benchmark models of purely left-handed  $\tilde{\tau}$  pair production with prompt decays with  $\tilde{\tau}_L$  masses of 100, 150, and 200 GeV and an LSP mass of 1 GeV. The distribution of  $p_T^{\tau_{h,2}}$  is also shown for events satisfying the common selection criteria of the displaced SRs for data, the predicted background, and two benchmark models of long-lived  $\tilde{\tau}$  pair production in the maximally-mixed scenario ( $\tilde{\tau}_{\text{MM}}$ ) with a  $\tilde{\tau}_{\text{MM}}$  mass of 150 GeV, an LSP mass of 1 GeV, and  $c\tau_0$  values of 0.5 and 1 mm.



Table 1: Ranges of  $\Sigma m_T$ ,  $m_{T2}$ , and  $p_T^{\tau_{h,1}}$  used to define the prompt SRs for the  $N_j = 0$  and  $N_j \geq 1$  event categories, and ranges of  $p_T^{\tau_{h,2}}$  used to define the displaced SRs.

Prompt SRs			
SR bin	$\Sigma m_T$ [GeV]	$m_{T2}$ [GeV]	$p_T^{\tau_{h,1}}$ [GeV]
$N_j = 0$			
1	200 – 250	25 – 50	<90
2	200 – 250	25 – 50	>90
3	200 – 250	50 – 75	<90
4	200 – 250	50 – 75	>90
5	200 – 250	>75	—
6	250 – 300	25 – 50	<90
7	250 – 300	25 – 50	>90
8	250 – 300	50 – 75	<90
9	250 – 300	50 – 75	>90
10	250 – 300	>75	—
11	300 – 350	25 – 50	—
12	300 – 350	50 – 75	—
13	300 – 350	75 – 100	—
14	300 – 350	>100	—
15	>350	25 – 50	—
16	>350	50 – 75	—
17	>350	75 – 100	—
18	>350	>100	—
$N_j \geq 1$			
19	200 – 250	25 – 50	—
20	200 – 250	>50	—
21	250 – 300	25 – 50	—
22	250 – 300	50 – 75	—
23	250 – 300	>75	—
24	300 – 350	25 – 50	—
25	300 – 350	50 – 75	—
26	300 – 350	>75	—
27	>350	25 – 75	—
28	>350	75 – 100	—
29	>350	>100	—
Displaced SRs			
SR bin	$p_T^{\tau_{h,2}}$ [GeV]		
30	<110		
31	>110		

## 5 Background estimation

Significant contributions to the SM background in this search originate from  $Z/\gamma^* \rightarrow \tau\tau$ +jets,  $W$ +jets,  $t\bar{t}$ , and diboson processes, as well as from events exclusively comprising jets produced through the strong interaction of quantum chromodynamics (QCD), which we refer to as QCD multijet events. Smaller contributions arise from single top quark production and rare SM processes, such as triboson and Higgs boson production, and top quark pair production in association with vector bosons. We rely on a method based on control samples in data to estimate

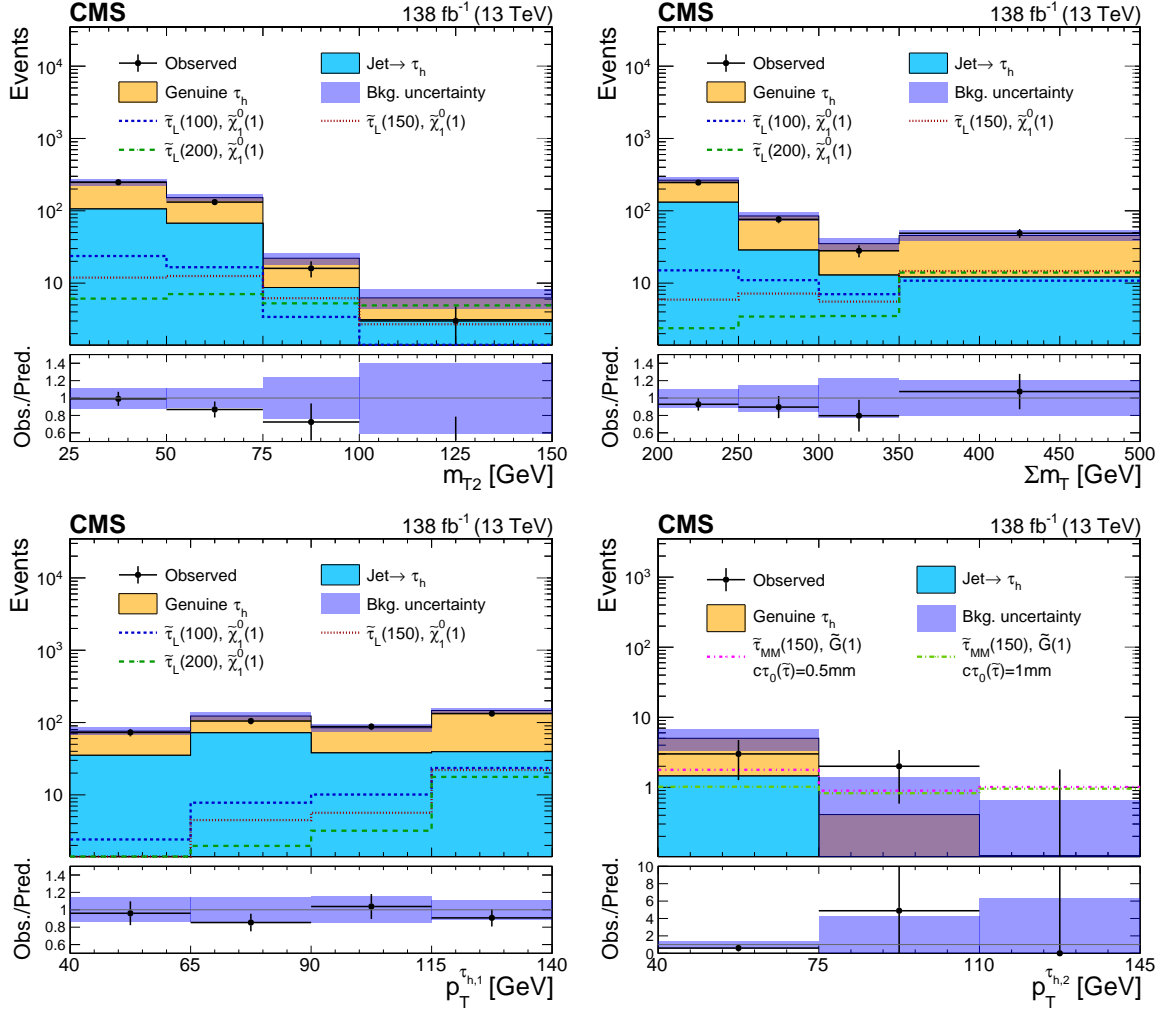


Figure 2: Distributions of  $m_{T2}$  (upper left),  $\Sigma m_T$  (upper right), and  $p_T^{\tau_{h,1}}$  (lower left) for events passing the selection criteria common to all prompt SRs, and of  $p_T^{\tau_{h,2}}$  (lower right) for those passing the criteria common to all displaced SRs. The last bin includes overflow events in all cases. The shaded band indicates the combined statistical and systematic uncertainty in the total SM background prediction. The lower panels show the ratio of the observed event counts to the total background prediction. Signal distributions are shown for benchmark models of  $\tilde{\tau}$  pair production that are described in the text. The numbers in parentheses correspond to the masses of the  $\tilde{\tau}$  and LSP in units of GeV for the different signal models.

the contributions of backgrounds in which one or both  $\tau_h$  candidates are misidentified jets. Contributions from backgrounds with electrons or muons misidentified as  $\tau_h$  candidates are negligible. We use a method known as “embedding” for modeling backgrounds with two genuine  $\tau_h$  decays [42], which has the advantage that many event quantities are described by data. The background estimation methods described below are validated in dedicated background-enriched data samples that are similar in many respects but disjoint to the SRs. Separate samples are used to validate the modeling of backgrounds with prompt and displaced  $\tau_h$  candidates.

## 5.1 Estimation of background from misidentified jets

Events with misidentified  $\tau_h$  candidates, originating predominantly from QCD multijet and  $W$ +jets production, constitute the dominant background after the requirement of two  $\tau_h$  candidates with high  $p_T$ . We estimate this background by extrapolating the event count in a control data sample into the SR, following the same approach as that described in [39]. The control sample is selected with a relaxed  $\tau_h$  identification requirement, namely the Loose working point of the DEEPTAU discriminant. We measure the fraction of misidentified  $\tau_h$  candidates selected with the Loose working point that also satisfy the VVTight requirement in a QCD multijet-enriched sample of same-charge  $\tau_h\tau_h$  events. The fraction is found to be  $\approx 10$ – $15\%$ , and depends on the  $p_T$  and decay mode of the  $\tau_h$  candidate, as well as on the additional activity in an event from the presence of pileup. We parameterize the measurement by the  $p_T$  and decay mode of the  $\tau_h$  candidate as well as the number of reconstructed primary vertices to take these effects into account. The misidentification rate also depends on the jet flavor, i.e., whether the misidentified jet originates from the hadronization of light- or heavy-flavor quarks, or gluons, which cannot be reliably determined in data. We assign a systematic uncertainty of 30% based on studies of the variation of the misidentification rate with jet flavor, performed with simulated samples, to account for the flavor dependence of the misidentification rate. The contribution of genuine  $\tau_h$  candidates in the sideband regions selected with the relaxed identification requirement is taken into account when determining the background prediction, as described in [39].

## 5.2 Estimation of backgrounds with two genuine $\tau_h$ decays

The background contribution with two genuine  $\tau_h$  decays originates mainly from the  $Z/\gamma^* \rightarrow \tau\tau$ +jets process, with smaller contributions originating from diboson production or processes with top quarks. We estimate this background using an embedding method [42] in which the reconstructed muons in a selected data sample of dimuon events are replaced by simulated  $\tau$  leptons with the same kinematic properties as the original muons. This generates a set of hybrid events that rely on simulation only for the  $\tau$  lepton decays. Consequently, they provide a better description of the underlying event, pileup, additional jets, detector noise and resolution effects compared to pure simulation samples. Since the embedded samples rely on the data for the description of these effects, no additional corrections for the pileup profile, jet energy scale, or  $b$  tagging efficiency are needed. Correction factors are applied to account for the efficiencies of the dimuon triggers and muon identification and isolation criteria used to select events. As the  $\tau$  lepton decays are simulated, we apply scale factors to match the  $\tau_h$  identification efficiency and energy scale in data. Correction factors are also applied to match the efficiencies of triggers used to select events for the search in data. Since the tracking efficiency in embedded events is higher than in data, scale factors are applied to account for this discrepancy. In order to save processing time, the sample selected for the detector simulation of  $\tau$  lepton decays is restricted to events that will subsequently satisfy the selection criteria applied in analyses. This is done by applying a kinematic filter on the  $p_T$  and  $|\eta|$  of the visible  $\tau$  lepton decay products. Event weights are applied to account for the bias arising from the filter requirements. These corrections are described in more detail in [42].

We use a set of embedded samples in which both  $\tau$  leptons are required to decay hadronically. We use an opposite-charge di- $\tau_h$  region in data to derive residual scale factors for the normalization of the embedded samples after all other correction factors are applied. These scale factors are designed to measure any remaining differences in the  $\tau_h$  identification and trigger efficiencies between data and the embedded samples in a region that is kinematically similar to the SRs. This region consists of events passing the baseline selection, with the following ad-

ditional requirements imposed on the mass and  $p_T$  of the di- $\tau_h$  system to improve the purity of genuine  $\tau_h$  decays and enhance the contribution from  $Z/\gamma^* \rightarrow \tau\tau$ +jets:  $50 < m_{\tau_h\tau_h} < 90$  GeV and  $p_T^{\tau_h\tau_h} > 50$  GeV. In order to ensure there is no overlap with the SRs and to suppress signal contamination, we require that events in this region have  $m_{T2} < 25$  GeV or  $\Sigma m_T < 200$  GeV. After subtracting the estimated contributions from misidentified  $\tau_h$  events in this sample, we measure scale factors of  $1.24 \pm 0.03$ ,  $1.21 \pm 0.03$ , and  $1.16 \pm 0.02$  for 2016, 2017, and 2018 data, respectively, for the embedded events, with the uncertainties listed being statistical. We apply these scale factors, along with a conservative uncertainty corresponding to the full size of their deviations from unity, to the normalization of the embedded sample.

The genuine  $\tau_h$  background prediction from the embedded sample accounts for SM events originating from processes in which the branching fractions for  $\tau\tau$  and dimuon decays are identical, i.e.,  $Z/\gamma^* \rightarrow \tau\tau$ +jets,  $t\bar{t}$  (with or without extra vector bosons), single top quark, and diboson processes. Small contributions from top quark events in which the  $W$  boson from the top quark decay does not decay directly into a muon and a neutrino, e.g., from  $W \rightarrow \tau\nu_\tau$ , may be included in the sample selected to undergo the embedding process, resulting in a possible overestimation of the fraction of top quark events. In order to account for this effect, we check the normalization of top quark events estimated from the embedded sample in a control region selected by requiring at least one b-tagged jet,  $m_{\tau_h\tau_h} > 100$  GeV, and  $p_T^{\text{miss}} > 50$  GeV to enrich the proportion of top quark events. Based on the level of agreement observed between data and the prediction from the embedded sample in this region, we assign an uncertainty of 10% in the expected fraction of top quark events in the embedded sample.

The embedded sample does not account for contributions from SM Higgs boson (H) events, for which the  $\tau\tau$  and dimuon branching fractions are very different. We therefore include the estimated contribution from SM  $H \rightarrow \tau\tau$  events from simulation in the total estimate of the genuine  $\tau_h$  background. We find that the background contribution from SM  $H \rightarrow \tau\tau$  events is small compared to the other backgrounds.

## 6 Systematic uncertainties

The dominant uncertainties in the background estimates are the statistical uncertainty driven by the limited event counts in the data sidebands or embedded samples used to obtain the estimates, and the systematic uncertainty (30%) assigned to the estimate of the  $\tau_h$  misidentification rate that accounts for its dependence on jet flavor.

Because we use embedded events to estimate the background with two genuine  $\tau_h$  decays, the prediction is less affected by systematic uncertainties than in the case of wholly simulated samples. For this background, we propagate uncertainties related to the trigger efficiency,  $\tau_h$  identification efficiency, and  $\tau_h$  energy scale. We also assign additional uncertainties as discussed in Section 5.2: a 10% uncertainty in the expected fraction of top quark events in the embedded samples estimated from simulation, and a normalization uncertainty determined by the full size of the deviations from unity of the normalization scale factors derived from the  $Z/\gamma^* \rightarrow \tau\tau$ +jets control region, weighted over the three years by the fractions of the integrated luminosity collected in each year. A 20% normalization uncertainty is assigned to the small contribution from SM  $H \rightarrow \tau\tau$  events.

For the signal prediction obtained from simulation, we propagate uncertainties in the trigger efficiency,  $\tau_h$  identification efficiency,  $\tau_h$  energy scale, b tagging efficiency, pileup reweighting, jet energy scale and resolution, and unclustered energy. We also take into account the uncertainty in the integrated luminosity measurement. The integrated luminosities for the 2016, 2017, and

Table 2: Uncertainties in the analysis affecting signal and the SM backgrounds. The numbers indicate the percentage effect of propagating  $\pm 1$ -standard deviation variations of the respective sources of uncertainty on the predicted signal and background yields, prior to a fit to the data. The ranges shown for signal refer to a representative benchmark model of  $\tilde{\tau}_L$  pair production with  $m(\tilde{\tau}_L) = 150 \text{ GeV}$ ,  $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ .

Source	Uncertainty [%]		
	Genuine $\tau_h$	Misidentified $\tau_h$	Signal
Statistical	8.3–141	5.0–100	6.3–52
$\tau_h$ ID efficiency	7.2–7.8	—	6.2–6.4
$\tau_h$ ID vs. displacement	—	—	3.0
$\tau_h$ trigger efficiency	3.1–4.2	—	6.9–14
$\tau_h$ energy scale	0.1–35	—	1.6–44
$\tau_h$ misidentification rate	—	30–56	—
$p_T^{\text{miss}}$ trigger efficiency	1.0	—	1.5
Embedded normalization	19	—	—
Embedded top quark fraction	1.0–3.8	—	—
Jet energy scale	—	—	0.7–32
Jet energy resolution	—	—	1.3–55
Unclustered energy	—	—	0.5–32
b tagging	—	—	0.2–1.1
Pileup	—	—	1.0–28
Integrated luminosity	—	—	1.6
ISR	—	—	0.1–16
Renormalization/factorization scales	—	—	0.4–3.6

2018 data-taking years have 1.2–2.5% individual uncertainties [71–73], while the overall uncertainty for the 2016–2018 period is 1.6%. Uncertainties related to the renormalization and factorization scales, and to the modeling of ISR, are propagated to the signal prediction as well. Since the  $\tau_h$  identification and trigger efficiency correction factors applied to simulation, which are obtained from samples of  $Z/\gamma^* \rightarrow \tau\tau$ +jets events with promptly produced  $\tau$  leptons, do not account for the dependence of the  $\tau_h$  candidate selection on the displacement of the decay position, we assign an additional uncertainty for this effect in signal events. The uncertainty is assessed via a comparison of  $\tau_h$  impact parameter distributions between data and simulation in a control region that is mainly populated by  $Z/\gamma^* \rightarrow \tau\tau$ +jets events, and the expected displacement of signal events for different  $\tilde{\tau}$  lifetimes. In order to probe the tails of the  $\tau_h$  impact parameter distributions, which we expect to be populated by signal events with significant displacement, the data-to-simulation ratios observed in the control region at lower values of  $d_{xy}$  significance and IP3D are extrapolated to higher values via a linear fit when deriving this uncertainty. The size of the uncertainty ranges from 3% for promptly decaying  $\tilde{\tau}$ , to 45% for  $\tilde{\tau}$  with  $c\tau_0 = 2.5 \text{ mm}$ .

We treat statistical uncertainties as uncorrelated, while systematic uncertainties related to the same modeling effect are taken to be correlated across processes and data-taking periods. Table 2 lists the ranges of the uncertainty in the predicted yields for background and a benchmark signal model of  $\tilde{\tau}_L$  pair production with  $m(\tilde{\tau}_L) = 150 \text{ GeV}$ ,  $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$  across all SRs corresponding to different sources.

## 7 Results and interpretation

Observed and predicted event yields for each SR are shown in Fig. 3 (upper) and summarized in Table 3 for the combined 2016–2018 data set. Figure 3 (lower) shows the background predictions after a maximum likelihood fit to the data under the background-only hypothesis. The likelihood function is constructed from the observed and predicted event yields in all 31 SRs, with the uncertainties in the predicted yields incorporated as nuisance parameters in the fit. The normalization uncertainties affecting background and signal predictions are generally assumed to be log-normally distributed. For statistical uncertainties limited by small event counts in the embedded or simulation samples, or in the sideband regions in the data used to estimate the misidentified  $\tau_h$  background, we use a Poisson distribution. The nuisance parameters are allowed to vary within their uncertainties in the fit. The uncertainties in the background predictions are reduced after the fit to the data. In general, the data are consistent with the prediction for the SM background. The most significant discrepancies between the data and the predicted background occur in SR bins 10 and 17, where we observe a deficit at approximately the 2-standard deviation level with respect to the pre-fit predictions, while a smaller deficit, at about the 1.2-standard deviation level, is observed in SR bin 18. Signal predictions are also shown in Fig. 3 (upper) for three benchmark models of left-handed prompt  $\tilde{\tau}$  pair production with  $\tilde{\tau}$  masses of 100, 150, and 200 GeV for an LSP mass of 1 GeV, and for one of long-lived  $\tilde{\tau}$  pair production in the maximally mixed scenario with a  $\tilde{\tau}$  mass of 150 GeV, an LSP mass of 1 GeV, and  $c\tau_0(\tilde{\tau}) = 0.5$  mm.

We use the results to set upper limits on the cross section for the production of  $\tilde{\tau}$  pairs in the context of simplified models [27–29, 74] using all of the 31 exclusive SRs in a full statistical combination. The 95% CL upper limits on SUSY production cross sections are calculated using a modified frequentist approach with the  $CL_s$  criterion [75–77]. An asymptotic approximation is used for the test statistic [78].

Expected and observed 95% CL cross section upper limits as a function of the  $\tilde{\tau}$  mass for 4 choices of LSP mass are shown in Fig. 4 for  $\tilde{\tau}$  pair production with promptly decaying  $\tau$  sleptons in the degenerate scenario, in which we assume that both left- and right-handed  $\tau$  sleptons are produced with the same mass, and in Figs. 5 and 6, in the purely left- and right-handed scenarios, respectively. Also shown is the theoretical prediction for the cross section of  $\tilde{\tau}$  pair production in each scenario, as a function of the  $\tilde{\tau}$  mass. In general, the cross section limits become less stringent for higher values of the  $\tilde{\chi}_1^0$  mass as a result of smaller experimental acceptance, caused in particular by the decreasing probability of the  $\tau_h$  candidate to exceed the 40 GeV  $p_T^{\tau_h}$  threshold. Exclusion limits in the  $\tilde{\tau}$  vs  $\tilde{\chi}_1^0$  mass plane are presented in Fig. 7 for promptly decaying  $\tau$  sleptons in the degenerate and purely left-handed scenarios. In the degenerate scenarios  $\tilde{\tau}$  masses up to 400 GeV are excluded at 95% CL under the hypothesis of a nearly massless LSP, while in the purely-left handed scenario,  $\tilde{\tau}$  masses between 115 and 340 GeV are excluded under the same hypothesis. For values of the  $\tilde{\tau}$  mass above  $\approx 175$ –200 GeV, we generally observe exclusion limits that are approximately 1-standard deviation stronger than the expected exclusion limits, with the difference being largely driven by the deficits observed in SR bins 17 and 18. Exclusion limits for the purely right-handed scenario are not shown, because our sensitivity in this scenario is not yet sufficient to exclude a sizeable region in the  $\tilde{\tau}$  vs  $\tilde{\chi}_1^0$  mass plane.

Expected and observed 95% CL cross section upper limits are shown in Fig. 8 for long-lived  $\tau$  sleptons in the maximally mixed scenario, under the hypothesis of a nearly massless LSP. For a  $\tilde{\tau}$  lifetime corresponding to  $c\tau_0 = 0.1$  mm,  $\tilde{\tau}$  masses between 150 and 220 GeV are excluded in this scenario, with the mass limits being assessed from the intersection of the observed exclusion curve with the theoretical prediction. The search sensitivity is reduced for longer  $\tilde{\tau}$

Table 3: Predicted SM background yields, observed event counts, and predicted signal yields for two benchmark models with a  $\tilde{\tau}$  mass of 150 GeV and an LSP mass of 1 GeV, in all prompt and displaced SRs as labeled in Table 1. For the prompt signal model shown, we assume left-handed  $\tilde{\tau}$  pair production, while for the displaced signal model we assume a maximally mixed scenario and  $c\tau_0(\tilde{\tau}) = 0.5$  mm. The uncertainties listed are the sum in quadrature of the statistical and systematic components. For any estimate with no events in the data sideband, embedded, or simulation sample corresponding to a given SR selection, we provide the one standard deviation upper bound evaluated for that estimate.

SR bin	Genuine $\tau_h$	Misidentified $\tau_h$	Total SM	Observed	Prompt signal	Displaced $\tau_h$ signal
1	$18.8 \pm 4.4$	$39.6 \pm 8.5$	$58.4 \pm 9.6$	65	$0.6 \pm 0.1$	$0.1 \pm 0.1$
2	$25.9 \pm 6.2$	$21.8 \pm 5.5$	$47.7 \pm 8.2$	40	$1.7 \pm 0.3$	$0.6 \pm 0.2$
3	$21.4 \pm 4.9$	$26.1 \pm 6.0$	$47.5 \pm 7.7$	38	$1.4 \pm 0.3$	$0.3 \pm 0.1$
4	$1.3^{+1.0}_{-0.6}$	$2.1^{+1.5}_{-1.4}$	$3.4^{+1.8}_{-1.5}$	4	$0.5 \pm 0.1$	$0.1 \pm 0.1$
5	$0.5^{+0.5}_{-0.3}$	$0.1^{+0.7}_{-0.1}$	$0.6^{+0.9}_{-0.4}$	1	$0.0 \pm 0.0$	$<0.6$
6	$1.0^{+0.9}_{-0.6}$	$1.6^{+1.1}_{-0.9}$	$2.5^{+1.5}_{-1.1}$	1	$0.0 \pm 0.0$	$<0.6$
7	$14.6 \pm 3.9$	$3.7 \pm 3.0$	$18.3 \pm 4.9$	28	$1.8 \pm 0.3$	$0.4 \pm 0.2$
8	$2.5^{+1.1}_{-0.9}$	$2.7 \pm 1.5$	$5.2^{+1.9}_{-1.8}$	7	$0.6 \pm 0.1$	$0.1 \pm 0.0$
9	$2.1^{+1.3}_{-1.0}$	$2.2 \pm 1.6$	$4.3^{+2.1}_{-1.9}$	4	$1.9 \pm 0.3$	$0.4 \pm 0.1$
10	$1.8^{+0.9}_{-0.7}$	$2.7^{+1.3}_{-1.1}$	$4.5^{+1.6}_{-1.3}$	0	$0.8 \pm 0.2$	$0.1 \pm 0.1$
11	$5.2^{+2.1}_{-1.8}$	$4.2 \pm 2.2$	$9.4^{+3.1}_{-2.9}$	7	$1.2 \pm 0.2$	$0.3 \pm 0.1$
12	$1.5^{+1.3}_{-0.9}$	$1.7^{+1.4}_{-1.2}$	$3.2^{+1.9}_{-1.5}$	3	$1.4 \pm 0.3$	$0.4 \pm 0.1$
13	$1.1^{+1.1}_{-0.6}$	$0.1^{+1.0}_{-0.1}$	$1.1^{+1.5}_{-0.6}$	3	$1.3 \pm 0.2$	$0.3 \pm 0.1$
14	$0.2^{+0.5}_{-0.2}$	$0.5^{+0.8}_{-0.4}$	$0.7^{+0.9}_{-0.5}$	0	$0.2 \pm 0.1$	$0.0 \pm 0.0$
15	$8.9^{+2.9}_{-2.6}$	$2.2 \pm 2.6$	$11.1^{+3.9}_{-3.7}$	17	$3.0 \pm 0.4$	$0.6 \pm 0.2$
16	$3.2^{+1.6}_{-1.3}$	$<1.0$	$3.2^{+1.9}_{-1.3}$	4	$3.1 \pm 0.5$	$0.7 \pm 0.2$
17	$2.5^{+1.4}_{-1.1}$	$3.0^{+1.5}_{-1.3}$	$5.5^{+2.1}_{-1.7}$	0	$2.3 \pm 0.4$	$0.6 \pm 0.2$
18	$0.7^{+1.0}_{-0.5}$	$0.9^{+0.8}_{-0.5}$	$1.6^{+1.3}_{-0.7}$	0	$1.9 \pm 0.3$	$0.4 \pm 0.1$
19	$34.6 \pm 7.9$	$23.8 \pm 5.5$	$58.4 \pm 9.6$	45	$0.9 \pm 0.2$	$0.3 \pm 0.1$
20	$35.7 \pm 7.7$	$17.7 \pm 4.8$	$53.4 \pm 9.0$	53	$0.6 \pm 0.1$	$0.3 \pm 0.1$
21	$19.5 \pm 4.9$	$5.4 \pm 2.6$	$24.9 \pm 5.5$	15	$0.7 \pm 0.2$	$0.2 \pm 0.1$
22	$11.4 \pm 3.0$	$8.0 \pm 3.0$	$19.4 \pm 4.2$	15	$0.9 \pm 0.2$	$0.2 \pm 0.1$
23	$4.5^{+1.5}_{-1.3}$	$2.3 \pm 1.6$	$6.8^{+2.2}_{-2.1}$	6	$0.3 \pm 0.1$	$0.0 \pm 0.0$
24	$7.3^{+2.7}_{-2.4}$	$4.7 \pm 2.4$	$12.0^{+3.6}_{-3.4}$	10	$0.5 \pm 0.1$	$0.2 \pm 0.1$
25	$4.6^{+1.9}_{-1.6}$	$2.3^{+1.4}_{-1.2}$	$6.9^{+2.3}_{-2.0}$	2	$0.6 \pm 0.1$	$0.1 \pm 0.1$
26	$2.3^{+1.3}_{-1.0}$	$<1.3$	$2.3^{+1.9}_{-1.0}$	3	$0.4 \pm 0.1$	$0.2 \pm 0.1$
27	$15.8 \pm 4.1$	$2.8 \pm 3.1$	$18.6 \pm 5.2$	23	$2.8 \pm 0.4$	$0.8 \pm 0.2$
28	$0.9^{+0.9}_{-0.5}$	$1.4^{+1.1}_{-0.9}$	$2.3^{+1.5}_{-1.0}$	2	$1.0 \pm 0.2$	$0.4 \pm 0.1$
29	$1.5^{+1.2}_{-0.8}$	$1.9^{+1.4}_{-1.1}$	$3.4^{+1.9}_{-1.4}$	3	$0.6 \pm 0.1$	$0.1 \pm 0.1$
30	$3.6^{+1.5}_{-1.3}$	$0.7^{+1.3}_{-0.7}$	$4.3^{+2.0}_{-1.5}$	5	$0.9 \pm 0.2$	$2.6 \pm 0.7$
31	$<0.5$	$<0.4$	$0.0^{+0.7}_{-0.0}$	0	$0.2 \pm 0.1$	$1.0 \pm 0.3$

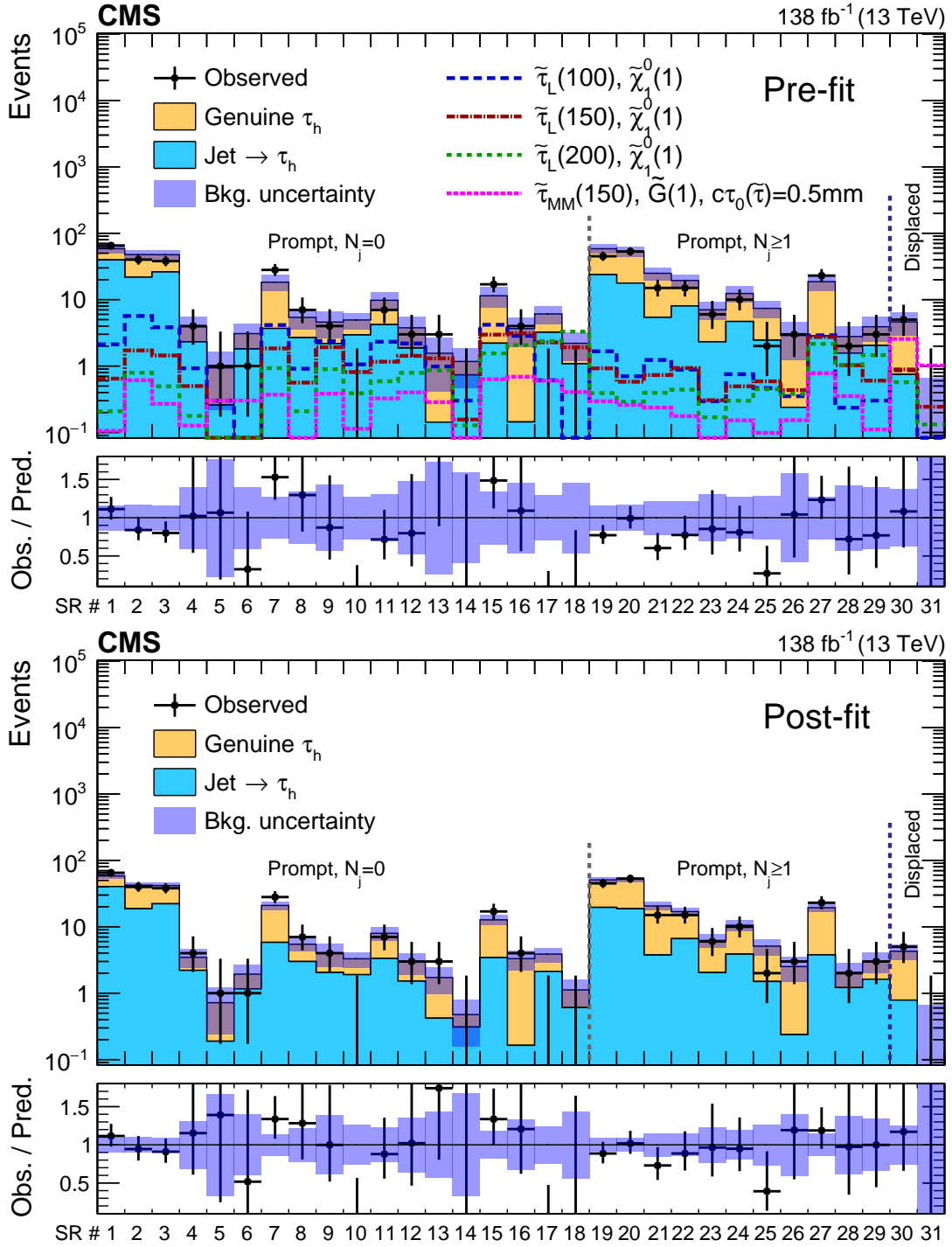


Figure 3: Event counts and predicted yields in each SR for the SM background before (upper) and after (lower) a maximum likelihood fit to the data under the background-only hypothesis. The yields expected for 3 benchmark models of left-handed  $\tilde{\tau}$  pair production assuming prompt  $\tilde{\tau}$  decays, and one model of long-lived  $\tilde{\tau}$  pair production in the maximally mixed scenario ( $\tilde{\tau}_{MM}$ ) are overlaid in the pre-fit case. The numbers in parentheses correspond to the masses of the  $\tilde{\tau}$  and LSP in units of GeV for the different signal models. The lower panels show the ratio of the observed event counts to the total SM background prediction. The first 29 bins correspond to the prompt SRs, while bins 30 and 31 correspond to the displaced SRs, as labeled in Table 1.



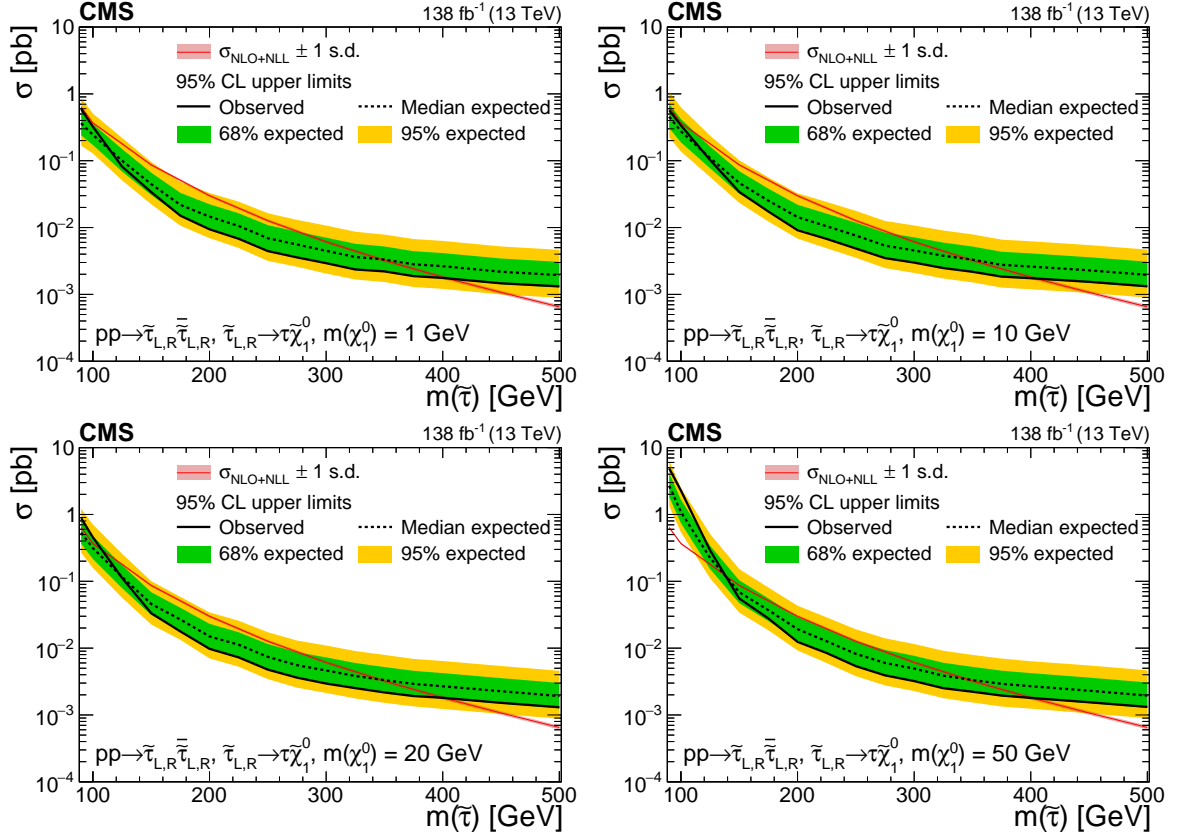


Figure 4: Expected and observed 95% CL cross section upper limits as functions of the  $\tilde{\tau}$  mass in the degenerate  $\tilde{\tau}$  scenario for  $\tilde{\chi}_1^0$  masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line and thin shaded band indicate the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [30, 62], and its uncertainty.

lifetimes because the DEEPTAU algorithm is currently optimized for promptly produced  $\tau_h$  candidates and is less efficient for more significantly displaced  $\tau_h$  candidates.

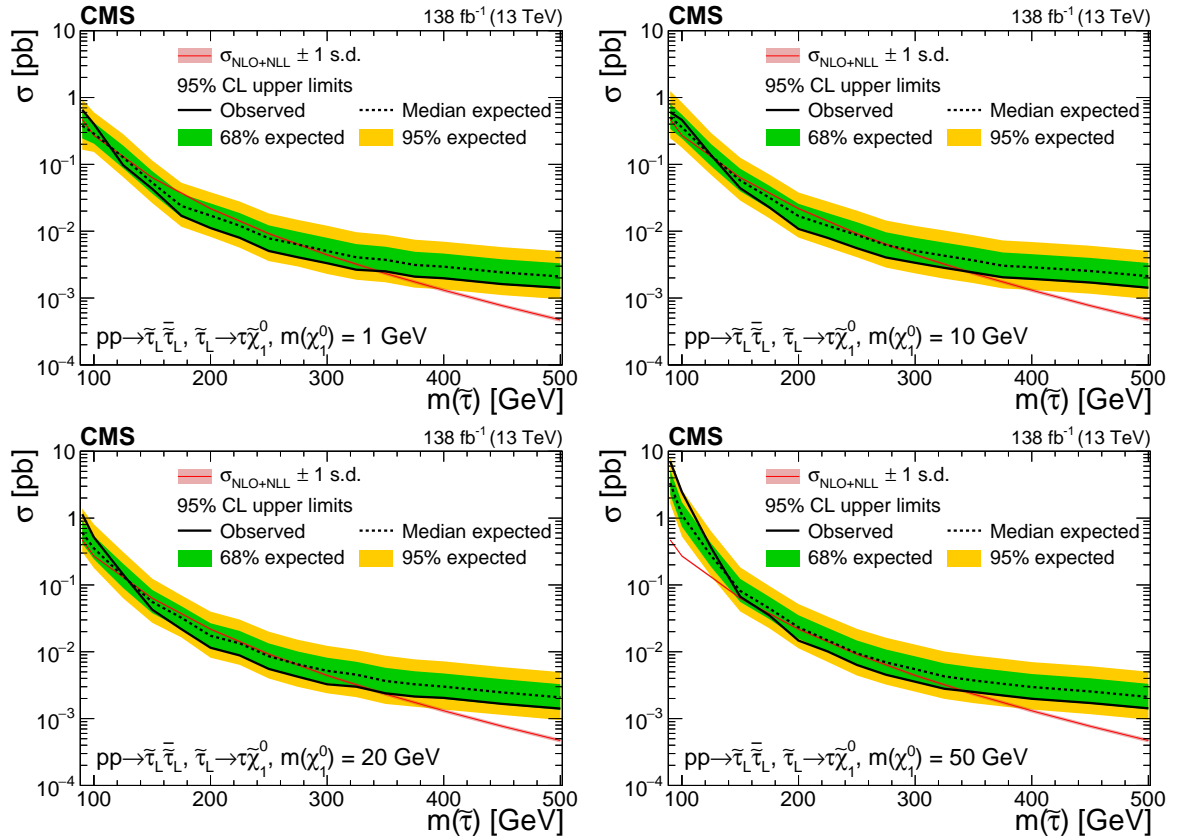


Figure 5: Expected and observed 95% CL cross section upper limits as functions of the  $\tilde{\tau}$  mass in the purely left-handed  $\tilde{\tau}$  scenario for  $\tilde{\chi}_1^0$  masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line and thin shaded band indicate the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [30], and its uncertainty.

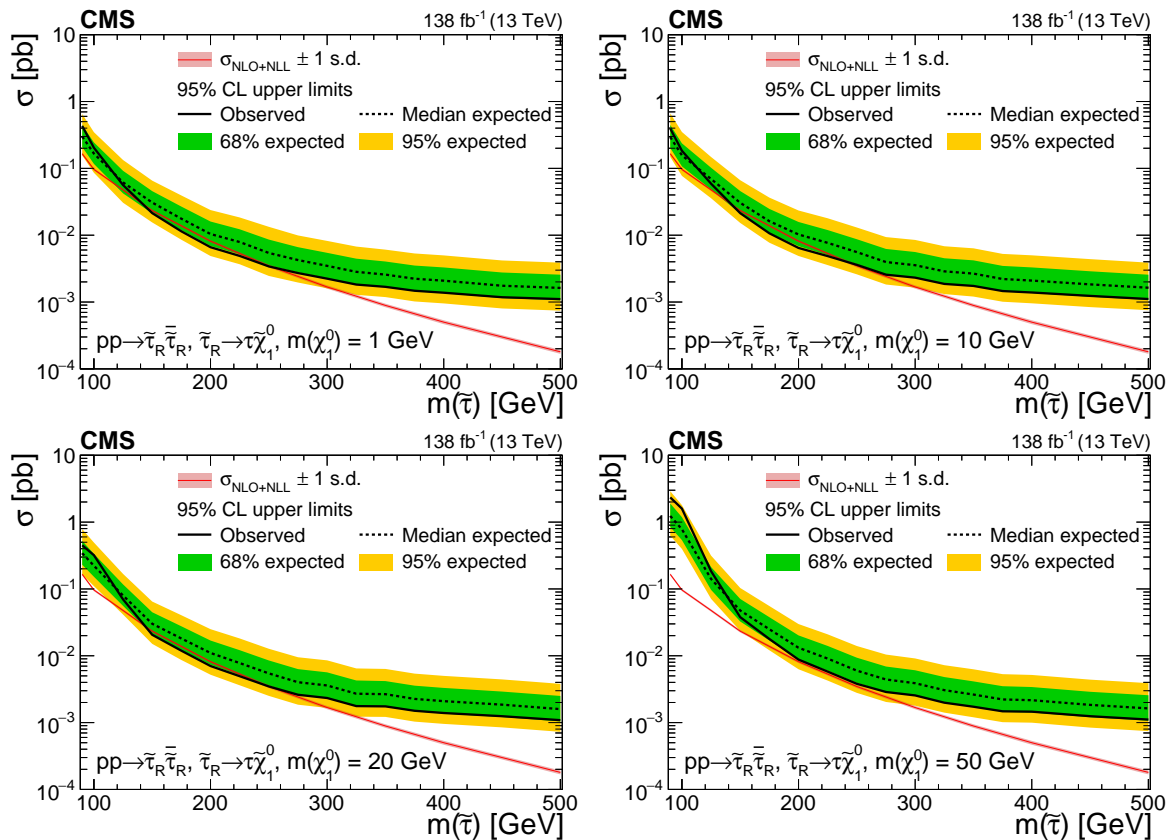


Figure 6: Expected and observed 95% CL cross section upper limits as functions of the  $\tilde{\tau}$  mass in the purely right-handed  $\tilde{\tau}$  scenario for  $\tilde{\chi}_1^0$  masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line and thin shaded band indicate the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [30], and its uncertainty.

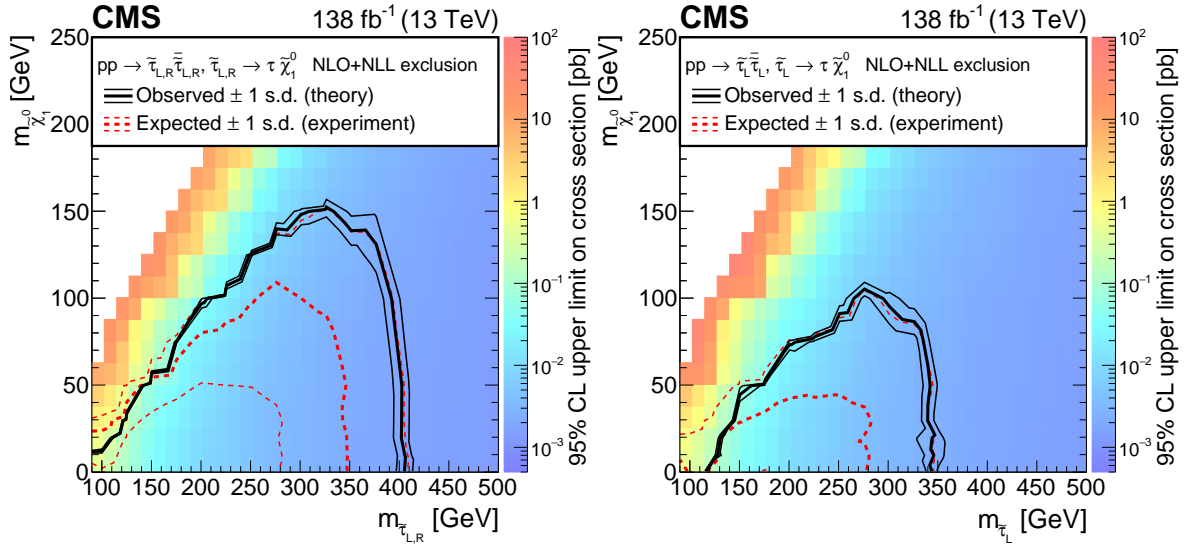


Figure 7: Upper limits at 95% CL on the cross section for degenerate (left) and purely left-handed (right)  $\tilde{\tau}$  pair production in the  $m(\tilde{\tau})$ - $m(\tilde{\chi}_1^0)$  plane. The thick black (red) curves show the observed (expected) exclusion limits assuming NLO+NLL predictions for the signal cross sections. The thin black curves represent the variations in the observed limits obtained when these cross sections are varied by their  $\pm 1$  standard deviation uncertainties. The thin dashed red curves indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis.

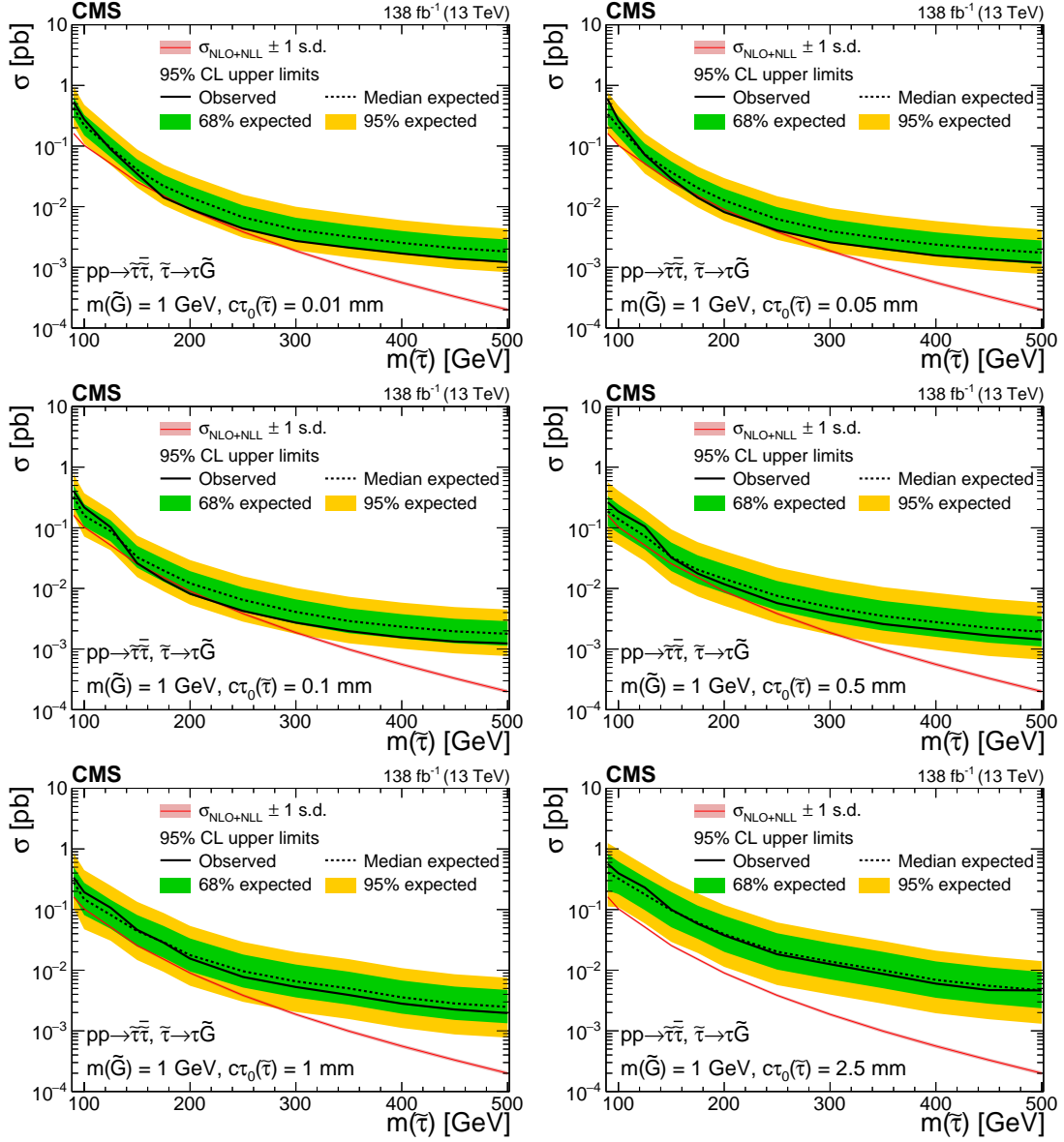


Figure 8: Expected and observed 95% CL cross section upper limits as functions of the  $\tilde{\tau}$  mass for long-lived  $\tilde{\tau}$  in the maximally mixed scenario for an LSP mass of 1 GeV, and for  $c\tau_0$  values of 0.01, 0.05, 0.1, 0.5, 1, and 2.5 mm (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line and thin shaded band indicate the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [30], and its uncertainty.

## 8 Summary

A search for direct  $\tau$  slepton ( $\tilde{\tau}$ ) pair production has been performed in proton-proton collisions at a center-of-mass energy of 13 TeV in events with two hadronically decaying  $\tau$  leptons and significant missing transverse momentum. The data used for this search correspond to an integrated luminosity of  $138 \text{ fb}^{-1}$  collected in 2016–2018 with the CMS detector. Both prompt and displaced decays of the  $\tau$  slepton are studied. Thirty-one different search regions are used in the analysis, based on kinematic observables that exploit expected differences between signal and background. No significant excess of events above the expected standard model background has been observed. Upper limits have been set on the cross section for direct  $\tilde{\tau}$  pair production for simplified models in which each  $\tilde{\tau}$  decays to a  $\tau$  lepton and the lightest supersymmetric particle (LSP). For purely left-handed  $\tilde{\tau}$  pair production with prompt decays,  $\tilde{\tau}$  masses between 115 and 340 GeV are excluded at 95% confidence level for the case of a nearly massless LSP, while for the degenerate production of left- and right-handed  $\tilde{\tau}$  pairs,  $\tilde{\tau}$  masses up to 400 GeV are excluded under the same hypothesis. The limits observed are the most stringent obtained thus far in the case of direct  $\tilde{\tau}$  pair production with prompt  $\tilde{\tau}$  decays, for both the purely left-handed and degenerate production scenarios. They represent a considerable improvement in sensitivity with respect to the previous CMS search reported in Ref. [39]. In the context of long-lived  $\tau$  sleptons, final states with displaced  $\tau_h$  candidates are investigated for the first time. In a scenario with  $c\tau_0(\tilde{\tau}) = 0.1 \text{ mm}$ , where  $\tau_0$  denotes the mean proper lifetime of the  $\tilde{\tau}$ , masses between 150 and 220 GeV are excluded for the case that the LSP is nearly massless.

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













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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan<sup>1</sup> 

### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth<sup>2</sup> , M. Jeitler<sup>2</sup> , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck<sup>2</sup> , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz<sup>2</sup> 

















### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>3</sup> , E.A. De Wolf, T. Janssen , T. Kello<sup>4</sup>, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte , N. Van Remortel 










### Vrije Universiteit Brussel, Brussel, Belgium

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










### Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin , B. Clerbaux , G. De Lentdecker , L. Favart , A.K. Kalsi , K. Lee , M. Mahdavihorrani , I. Makarenko , L. Moureaux , S. Paredes , L. Pétré , A. Popov , N. Postiau, E. Starling , L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer 

### Ghent University, Ghent, Belgium

T. Cornelis , D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach, M. Niedziela , C. Rendón, C. Roskas , A. Samalan, K. Skovpen , M. Tytgat , B. Vermassen, L. Wezenbeek 





















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

A. Benecke , A. Bethani , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaître, K. Mondal , J. Prisciandaro, A. Taliercio , M. Teklishyn , T.T. Tran , P. Vischia , S. Wertz 

### Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , C. Hensel , A. Moraes , P. Rebello Teles 

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>5</sup>, E.M. Da Costa , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo<sup>7</sup> , A. Vilela Pereira 

### Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes<sup>6</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D. S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

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

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






### University of Sofia, Sofia, Bulgaria

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

**Beihang University, Beijing, China**

T. Cheng , T. Javaid<sup>8</sup> , M. Mittal , L. Yuan 









**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad , G. Bauer, C. Dozen , Z. Hu , J. Martins<sup>9</sup> , Y. Wang, K. Yi<sup>10,11</sup> 

**Institute of High Energy Physics, Beijing, China**

E. Chapon , G.M. Chen<sup>8</sup> , H.S. Chen<sup>8</sup> , M. Chen , F. Iemmi , A. Kapoor , D. Leggat, H. Liao , Z.-A. Liu<sup>12</sup> , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 

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

A. Agapitos , Y. An , Y. Ban , C. Chen, A. Levin , Q. Li , X. Lyu, Y. Mao, S.J. Qian , D. Wang , J. Xiao , H. Yang

**Sun Yat-Sen University, Guangzhou, China**

M. Lu , Z. You 

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

X. Gao<sup>4</sup> , H. Okawa , Y. Zhang 





**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , M. Xiao 





**Universidad de Los Andes, Bogota, Colombia**

C. Avila , A. Cabrera , C. Florez , J. Fraga 



**Universidad de Antioquia, Medellin, Colombia**

J. Mejia Guisao , F. Ramirez , J.D. Ruiz Alvarez , C.A. Salazar González 

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

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

**University of Split, Faculty of Science, Split, Croatia**

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

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic , A. Starodumov<sup>13</sup> , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , A. Ioannou, G. Kole , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka 

**Charles University, Prague, Czech Republic**

M. Finger<sup>13</sup> , M. Finger Jr.<sup>13</sup> , A. Kveton 

**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala 

**Universidad San Francisco de Quito, Quito, Ecuador**

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






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

S. Abu Zeid<sup>14</sup> , Y. Assran<sup>15,16</sup>

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

M.A. Mahmoud , Y. Mohammed 

















**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik , S. Nandan , C. Nielsen ,  
J. Pata , M. Raidal , L. Tani , C. Veelken 

**Department of Physics, University of Helsinki, Helsinki, Finland**

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




















**Helsinki Institute of Physics, Helsinki, Finland**

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,  
T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti , L. Martikainen ,  
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























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow , 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 , P. Gras , G. Hamel de Monchenault , P. Jarry , B. Lenzi ,  
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






















**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

S. Ahuja , F. Beaudette , M. Bonanomi , A. Buchot Perraguin , P. Busson ,  
A. Cappati , C. Charlot , O. Davignon , B. Diab , G. Falmagne , S. Ghosh ,  
R. Granier de Cassagnac , A. Hakimi , I. Kucher , J. Motta , M. Nguyen ,  
C. Ochando , P. Paganini , J. Rembser , R. Salerno , U. Sarkar , J.B. Sauvan ,  
Y. Sirois , A. Tarabini , A. Zabi , A. Zghiche 




**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>18</sup> , J. Andrea , D. Apparú , D. Bloch , G. Bourgatte , J.-M. Brom ,  
E.C. Chabert , C. Collard , D. Darej , J.-C. Fontaine<sup>18</sup> , U. Goerlach , C. Grimault , A.-  
C. Le Bihan , E. Nibigira , P. Van Hove 










**Institut de Physique des 2 Infinis de Lyon (IP2I), 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 , I.B. Laktineh , H. Lattaud , A. Lesauvage , M. Lethuillier , L. Mirabito , S. Perries,  
K. Shchablo , V. Sordini , L. Torterotot , G. Touquet , M. Vander Donckt , S. Viret













**Georgian Technical University, Tbilisi, Georgia**











A. Khvedelidze<sup>13</sup> , I. Lomidze , Z. Tsamalaidze<sup>13</sup> 

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**











V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert ,  
J. Schulz , M. Teroerde 

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Dodonova , D. Eliseev , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker ,  
K. Hoepfner , F. Ivone , L. Mastrolorenzo , M. Merschmeyer , A. Meyer , G. Mocellin 

S. Mondal , S. Mukherjee , D. Noll , A. Novak , T. Pook , A. Pozdnyakov , Y. Rath, H. Reithler , J. Roemer, A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck , S. Zaleski










### **RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

C. Dziwok , G. Flügge , W. Haj Ahmad<sup>19</sup> , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , D. Roy , A. Stahl<sup>20</sup> , T. Ziemons , A. Zotz 































### **Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman , K. Borras<sup>21</sup> , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , V. Danilov, M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>22</sup> , A. Geiser , A. Giraldi , A. Grohsjean , M. Guthoff , A. Jafari<sup>23</sup> , N.Z. Jomhari , A. Kasem<sup>21</sup> , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , D. Krücker , W. Lange, K. Lipka , W. Lohmann<sup>24</sup> , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , M. Meyer , J. Mnich , A. Mussgiller , Y. Otariid, D. Pérez Adán , D. Pitzl, A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham<sup>25</sup> , V. Scheurer, S. Schnake , P. Schütze , C. Schwanenberger<sup>22</sup> , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon , M. Van De Klundert , F. Vazzoler , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens , C. Wissing , S. Wuchterl 

### **University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Albrecht , S. Bein , L. Benato , P. Connor , K. De Leo , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, M. Hajheidari, J. Haller , A. Hinzmann , G. Kasieczka , R. Klanner , T. Kramer , V. Kutzner , J. Lange , T. Lange , A. Lobanov , A. Malara , A. Mehta , A. Nigamova , K.J. Pena Rodriguez , M. Rieger , O. Rieger, P. Schleper , M. Schröder , J. Schwandt , J. Sonneveld , H. Stadie , G. Steinbrück , A. Tews, I. Zoi 










### **Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

J. Bechtel , S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , W. De Boer<sup>†</sup>, A. Dierlamm , A. Droll, K. El Morabit , N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann<sup>20</sup> , C. Heidecker, U. Husemann , P. Keicher, R. Koppenhöfer , S. Maier , M. Metzler, S. Mitra , Th. Müller , M. Neukum, A. Nürnberg , G. Quast , K. Rabbertz , J. Rauser, D. Savoie , M. Schnepf, D. Seith, I. Shvetsov , H.J. Simonis , R. Ulrich , J. Van Der Linden , R.F. Von Cube , M. Wassmer , M. Weber , S. Wieland , R. Wolf , S. Wozniewski , S. Wunsch




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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Stakia 

### **National and Kapodistrian University of Athens, Athens, Greece**







M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , C.K. Koraka , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , 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**

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Giannelios , P. Katsoulis, P. Kokkas , N. Manthos , I. Papadopoulos , J. Strologas 

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

M. Csanád , K. Farkas , M.M.A. Gadallah<sup>26</sup> , S. Lökös<sup>27</sup> , P. Major , K. Mandal , G. Pásztor , A.J. Rádl , O. Surányi , G.I. Veres 



**Wigner Research Centre for Physics, Budapest, Hungary**

M. Bartók<sup>28</sup> , G. Bencze, C. Hajdu , D. Horvath<sup>29,30</sup> , F. Sikler , V. Veszpremi 




**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

S. Czellar, D. Fasanello , F. Fienga , J. Karancsi<sup>28</sup> , J. Molnar, Z. Szillasi, D. Teyssier 

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

P. Raics, Z.L. Trocsanyi<sup>31</sup> , B. Ujvari 














**Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary**

T. Csorgo<sup>32</sup> , F. Nemes<sup>32</sup> , T. Novak 









**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury










**Panjab University, Chandigarh, India**

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>33</sup> , R. Gupta, A. Kaur , H. Kaur , M. Kaur , P. Kumari , M. Meena , K. Sandeep , J.B. Singh , A. K. Viridi 













**University of Delhi, Delhi, India**

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





**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

M. Bharti<sup>34</sup>, R. Bhattacharya , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber<sup>35</sup> , M. Maity<sup>36</sup>, P. Palit , P.K. Rout , G. Saha , B. Sahu , S. Sarkar, M. Sharan, S.Thakur<sup>34</sup> 



**Indian Institute of Technology Madras, Madras, India**

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri<sup>37</sup> , D. Kumar<sup>37</sup> , A. Muhammad , L. Panwar<sup>37</sup> , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari<sup>37</sup> 








**Bhabha Atomic Research Centre, Mumbai, India**

D. Dutta , V. Jha, V. Kumar , D.K. Mishra, K. Naskar<sup>38</sup> , P.K. Netrakanti, L.M. Pant, P. Shukla 





**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, M. Kumar , G.B. Mohanty 








**Tata Institute of Fundamental Research-B, Mumbai, India**

S. Banerjee , R. Chudasama , M. Guchait , S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Mukherjee 

**National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**

S. Bahinipati<sup>39</sup> , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>40</sup> ,  
A. Nayak<sup>40</sup> , P. Saha , N. Sur , S.K. Swain, D. Vats<sup>40</sup> 

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

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 

**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>41</sup> , E. Khazaie , M. Zeinali<sup>42</sup> 


































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

S. Chenarani<sup>43</sup> , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





























**University College Dublin, Dublin, Ireland**

M. Grunewald 






**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup> , R. Aly<sup>a,c,44</sup> , C. Aruta<sup>a,b</sup> , A. Colaleo<sup>a</sup> , D. Creanza<sup>a,c</sup> ,  
N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , A. Di Florio<sup>a,b</sup> , A. Di Pilato<sup>a,b</sup> ,  
W. Elmetenawee<sup>a,b</sup> , L. Fiore<sup>a</sup> , A. Gelmi<sup>a,b</sup> , M. Gul<sup>a</sup> , G. Iaselli<sup>a,c</sup> , M. Ince<sup>a,b</sup> ,  
S. Lezki<sup>a,b</sup> , G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a,b</sup> , V. Mastrapasqua<sup>a,b</sup> ,  
S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , D. Ramos<sup>a</sup> ,  
A. Ranieri<sup>a</sup> , G. Selvaggi<sup>a,b</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,b</sup> , Ü. Sözbilir<sup>a</sup> ,  
R. Venditti<sup>a</sup> , P. Verwilligen<sup>a</sup> 
















**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , L. Borgonovi<sup>a</sup> , L. Brigliadori<sup>a</sup>,  
R. Campanini<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>a,b</sup> , F.R. Cavallo<sup>a</sup> , C. Ciocca<sup>a</sup> ,  
M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</sup> ,  
P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,45</sup> ,  
L. Lunerti<sup>a,b</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarria<sup>a,b</sup> , A. Perrotta<sup>a</sup> ,  
F. Primavera<sup>a,b</sup> , A.M. Rossi<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b,46</sup> , S. Costa<sup>a,b,46</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,46</sup> ,  
C. Tuve<sup>a,b</sup> 

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a,b</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> ,  
R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a,b</sup> ,  
M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , R. Seidita<sup>a,b</sup> , G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 

























**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi , S. Bianco , D. Piccolo 

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**

M. Bozzo<sup>a,b</sup> , F. Ferro<sup>a</sup> , R. Mulargia<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**


















A. Benaglia<sup>a</sup> , G. Boldrini<sup>a</sup> , F. Brivio<sup>a,b</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> ,  
M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a,b</sup> ,  
M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> ,  
L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , D. Pedrini<sup>a</sup> , B.S. Pinolini<sup>a</sup>, S. Ragazzi<sup>a,b</sup> , N. Redaelli<sup>a</sup> ,  
T. Tabarelli de Fatis<sup>a,b</sup> , D. Valsecchi<sup>a,b,20</sup> , D. Zuolo<sup>a,b</sup> 

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della**












**Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup> , N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,47</sup> , S. Meola<sup>a,d,20</sup> , P. Paolucci<sup>a,20</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 
















**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup> , N. Bacchetta<sup>a</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> , A. Bragagnolo<sup>a,b</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , U. Dosselli<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , G. Grosso<sup>a</sup> , S.Y. Hoh<sup>a,b</sup> , L. Layer<sup>a,48</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , G. Strong<sup>a</sup> , M. Tosi<sup>a,b</sup> , H. Yarar<sup>a,b</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> 


















**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

C. Aimè<sup>a,b</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup> , D. Fiorina<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , S.P. Ratti<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a</sup> , P. Vitulo<sup>a,b</sup> 


















**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

P. Asenov<sup>a,49</sup> , G.M. Bilei<sup>a</sup> , D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , G. Mantovani<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,49</sup> , A. Piccinelli<sup>a,b</sup> , M. Presilla<sup>a,b</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 


















**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**

P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , V. Bertacchi<sup>a,c</sup> , L. Bianchini<sup>a</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a,b</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , M.R. Di Domenico<sup>a,d</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , E. Manca<sup>a,c</sup> , G. Mandorli<sup>a,c</sup> , D. Matos Figueiredo<sup>a</sup> , A. Messineo<sup>a,b</sup> , F. Palla<sup>a</sup> , S. Parolia<sup>a,b</sup> , G. Ramirez-Sanchez<sup>a,c</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a,c</sup> , A. Scribano<sup>a</sup> , N. Shafiei<sup>a,b</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> 








**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**

P. Barria<sup>a</sup> , M. Campana<sup>a,b</sup> , F. Cavallari<sup>a</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a</sup> , M. Diemoz<sup>a</sup> , E. Longo<sup>a,b</sup> , P. Meridiani<sup>a</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> , R. Tramontano<sup>a,b</sup> 













**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , J. Berenguer Antequera<sup>a,b</sup> , C. Biino<sup>a</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> , R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> , C. Mariotti<sup>a</sup> , S. Maselli<sup>a</sup> , E. Migliore<sup>a,b</sup> , E. Monteil<sup>a,b</sup> , M. Monteno<sup>a</sup> , M.M. Obertino<sup>a,b</sup> , G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> , K. Shchelina<sup>a</sup> , F. Siviero<sup>a,b</sup> , V. Sola<sup>a</sup> , A. Solano<sup>a,b</sup> , D. Soldi<sup>a,b</sup> , A. Staiano<sup>a</sup> , M. Tornago<sup>a,b</sup> , D. Trocino<sup>a</sup> , A. Vagnerini<sup>a,b</sup> 

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , A. Da Rold<sup>a,b</sup> , G. Della Ricca<sup>a,b</sup> , G. Sorrentino<sup>a,b</sup> 




**Kyungpook National University, Daegu, Korea**

S. Dogra , C. Huh , B. Kim , D.H. Kim , G.N. Kim , J. Kim, J. Lee , S.W. Lee , C.S. Moon , Y.D. Oh , S.I. Pak , S. Sekmen , Y.C. Yang 





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

H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

B. Francois , T.J. Kim , J. Park 

**Korea University, Seoul, Korea**

S. Cho, S. Choi , B. Hong , K. Lee, K.S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo 

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

J. Goh , A. Gurtu 

**Sejong University, Seoul, Korea**

H. S. Kim , 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 , S. Lee, B.H. Oh , M. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 




**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin, I.C. Park , Y. Roh, M.S. Ryu , D. Song, Watson, I.J. , S. Yang 

**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha , H.D. Yoo 

**Sungkyunkwan University, Suwon, Korea**

M. Choi , H. Lee, Y. Lee , I. Yu 

**College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait**

T. Beyrouthy, Y. Maghrbi 


**Riga Technical University, Riga, Latvia**

K. Dreimanis , V. Veckalns 

**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

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

**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez , A. Castaneda Hernandez , M. León Coello , J.A. Murillo Quijada , A. Sehrawat , 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<sup>50</sup> , R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 


**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera , F. Vazquez Valencia 

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**

J. Mijuskovic<sup>51</sup>, N. Raicevic 







**University of Auckland, Auckland, New Zealand**

D. Krofcheck 

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler 

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad , M.I. Asghar, A. Awais , 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, Poland**

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeleper ,  
P. Zalewski 

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 


























**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,  
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , O. Toldaiev , J. Varela 



**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

P. Adzic<sup>52</sup> , 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 , 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 ,  
O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. León Holgado ,  
D. Moran , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,  
J. Puerta Pelayo , I. Redondo , L. Romero, S. Sánchez Navas , L. Urda Gómez ,  
C. Willmott


















**Universidad Autónoma de Madrid, Madrid, Spain**

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 , J.R. González Fernández , E. Palencia Cortezon ,  
C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote ,  
N. Trevisani , C. Vico Villalba 

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , P.J. Fernández Manteca , A. García Alonso, G. Gomez , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , J. Piedra Gomez , C. Prieels, A. Ruiz-Jimeno , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

**University of Colombo, Colombo, Sri Lanka**

M.K. Jayananda , B. Kailasapathy<sup>53</sup> , D.U.J. Sonnadara , D.D.C. Wickramarathna 

**University of Ruhuna, Department of Physics, 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 , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon<sup>†</sup>, D. Barney , J. Bendavid , M. Bianco , A. Bocci , C. Caillol , T. Camporesi , M. Capeans Garrido , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defran- chis , M. Deile , M. Dobson , M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>54</sup>, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Gi- ani, D. Gigi, K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , M. Komm , N. Kratochwil , C. Lange , S. Laurila , P. Lecoq , A. Lintuluoto , K. Long , C. Lourenço , B. Maier , L. Malgeri , S. Mallios, M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , C. Schäfer, M. Selvaggi , A. Sharma , P. Silva , W. Snoeys , P. Sphicas<sup>55</sup> , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk<sup>56</sup> , K.A. Wozniak , W.D. Zeuner
























**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>57</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , M. Missiroli<sup>57</sup> , L. Noehte<sup>57</sup> , T. Rohe 




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

K. Androsov<sup>56</sup> , M. Backhaus , P. Berger, A. Calandri , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , C. Dorfer , F. Eble , K. Gedia , F. Glessgen , T.A. Gómez Es- pinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , M.T. Meinhard , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , D. Ruini, D.A. Sanz Becerra , V. Stampf, J. Steggemann<sup>56</sup> , R. Wallny , D.H. Zhu 











**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>58</sup> , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofre- hei , B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 




**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>59</sup>, C.M. Kuo, W. Lin, A. Roy , T. Sarkar<sup>36</sup> , S.S. Yu 




















**National Taiwan University (NTU), Taipei, Taiwan**

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

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

B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 

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

F. Boran , S. Damarseekin<sup>60</sup> , Z.S. Demiroglu , F. Dolek , I. Dumanoglu<sup>61</sup> , E. Eskut , Y. Guler<sup>62</sup> , E. Gurpinar Guler<sup>62</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir<sup>63</sup> , A. Polatoz , A.E. Simsek , B. Tali<sup>64</sup> , U.G. Tok , S. Turkcapar , I.S. Zorbakir 

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Karapinar, K. Ocalan<sup>65</sup> , M. Yalvac<sup>66</sup> 









**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>67</sup> , O. Kaya<sup>68</sup> , Ö. Özçelik , S. Tekten<sup>69</sup> , E.A. Yetkin<sup>70</sup> 


**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>61</sup> , Y. Komurcu , S. Sen<sup>71</sup> 

**Istanbul University, Istanbul, Turkey**

S. Cerci<sup>64</sup> , I. Hos<sup>72</sup> , B. Isildak<sup>73</sup> , B. Kaynak , S. Ozkorucuklu , H. Sert , D. Sunar Cerci<sup>64</sup> , C. Zorbilmez 
















**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine**

B. Grynyov 
















**National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine**

L. Levchuk 






























**University of Bristol, Bristol, United Kingdom**

D. Anthony , E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou<sup>74</sup> , K. Walkingshaw Pass, R. White 




**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell , A. Belyaev<sup>75</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin, T. Williams 













**Imperial College, London, United Kingdom**

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G.S. Chahal<sup>76</sup> , D. Colling , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , D.G. Monk , J. Nash<sup>77</sup> , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, A. Tapper , K. Uchida , T. Virdee<sup>20</sup> , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

**Brunel University, Uxbridge, United Kingdom**

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid , L. Teodorescu

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S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti , B. McMaster , N. Pastika , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 
















**Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez 



















**The University of Alabama, Tuscaloosa, Alabama, USA**

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio<sup>78</sup> , C. West 


















**Boston University, Boston, Massachusetts, USA**

A. Akpınar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , E. Fontanesi , D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan , D. Zou














**Brown University, Providence, Rhode Island, USA**

G. Benelli , B. Burkle , X. Coubez<sup>21</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>79</sup> , T. KWON , G. Landsberg , K.T. Lau , D. Li , M. Lukasik, J. Luo , M. Narain , N. Pervan , S. Sagir<sup>80</sup> , F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

**University of California, Davis, Davis, California, USA**

J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , R. Lander, M. Mulhearn , D. Pellett , B. Regnery , D. Taylor , Y. Yao , F. Zhang 





















**University of California, Los Angeles, California, USA**

M. Bachtis , R. Cousins , A. Datta , D. Hamilton , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , W.A. Nash , S. Regnard , D. Saltzberg , B. Stone , V. Valuev 









**University of California, Riverside, Riverside, California, USA**

K. Burt, Y. Chen, R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganeli , M. Olmedo Negrete, W. Si , S. Wimpenny , Y. Zhang









**University of California, San Diego, La Jolla, California, USA**

J.G. Branson, P. Chang , S. Cittolin, S. Cooperstein , N. Deelen , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel , F. Würthwein , Y. Xiang , A. Yagil 

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

N. Amin, C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , B. Marsh, H. Mei , M. Oshiro , M. Quinnan , J. Richman , U. Sarica , F. Setti , J. Sheplock , P. Siddireddy, D. Stuart , S. Wang 

**California Institute of Technology, Pasadena, California, USA**












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

**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**



















J. Alison , S. An , M.B. Andrews , P. Bryant , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , M. Paulini , A. Sanchez , W. Terrill 

































































#### **University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald, R. Patel, A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 























#### **Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , X. Chen , Y. Cheng , D.J. Cranshaw , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd , W. Sun , J. Thom , P. Wittich , R. Zou 









#### **Fermi National Accelerator Laboratory, Batavia, Illinois, USA**

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , A. Apyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , V.D. Elvira , Y. Feng , J. Freeman , Z. Gece , L. Gray , D. Green, S. Grünendahl , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , V. O'Dell, V. Papadimitriou , K. Pedro , C. Pena<sup>81</sup> , O. Prokofyev, F. Ravera , A. Reinsvold Hall<sup>82</sup> , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber 








#### **University of Florida, Gainesville, Florida, USA**

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



















#### **Florida State University, Tallahassee, Florida, USA**

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












#### **Florida Institute of Technology, Melbourne, Florida, USA**

M.M. Baarmand , S. Butalla , T. Elkafrawy<sup>14</sup> , M. Hohlmann , R. Kumar Verma , D. Noonan , M. Rahmani, F. Yumiceva 












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

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





























#### **The University of Iowa, Iowa City, Iowa, USA**

M. Alhusseini , K. Dilsiz<sup>83</sup> , L. Emediato , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>84</sup> , J. Nachtman , H. Ogul<sup>85</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>86</sup> 




#### **Johns Hopkins University, Baltimore, Maryland, USA**

O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , M. Eminizer , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , M. Swartz , T.Á. Vámi 

**The University of Kansas, Lawrence, Kansas, USA**

A. Abreu , J. Anguiano , C. Baldenegro Barrera , P. Baringer , A. Bean , A. Bylinkin , Z. Flowers , T. Isidori , S. Khalil , J. King , G. Krintiras , A. Kropivnitskaya , M. Lazarovits , C. Le Mahieu , C. Lindsey, J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , E. Schmitz , C. Smith , J.D. Tapia Takaki , Q. Wang , Z. Warner, J. Williams , G. Wilson 


















**Kansas State University, Manhattan, Kansas, USA**

S. Duric, A. Ivanov , K. Kaadze , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam






















**Lawrence Livermore National Laboratory, Livermore, California, USA**

F. Rebassoo , D. Wright 













**University of Maryland, College Park, Maryland, USA**

E. Adams , A. Baden , O. Baron, A. Belloni , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , M. Seidel , A. Skuja , L. Wang , K. Wong 
















**Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

D. Abercrombie, G. Andreassi, R. Bi, W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , M. Klute , D. Kovalskyi , J. Krupa , Y.-J. Lee , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch 

**University of Minnesota, Minneapolis, Minnesota, USA**

R.M. Chatterjee, A. Evans , J. Hiltbrand , Sh. Jain , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 





















**University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , M. Bryson, S. Chauhan , D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , I. Kravchenko , M. Musich , I. Reed , J.E. Siado , G.R. Snow<sup>†</sup>, W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 









**State University of New York at Buffalo, Buffalo, New York, USA**

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 






















**Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Hortiangtham , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 

**Northwestern University, Evanston, Illinois, USA**

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , T. Gunter , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco




















**University of Notre Dame, Notre Dame, Indiana, USA**

R. Band , R. Bucci, M. Cremonesi, A. Das , N. Dev , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko<sup>13</sup> , R. Ruchti , A. Townsend , M. Wayne , M. Zarucki , L. Zygala 

**The Ohio State University, Columbus, Ohio, USA**

B. Bylsma, L.S. Durkin , B. Francis , C. Hill , M. Nunez Ornelas , K. Wei, B.L. Winer ,  
B. R. Yates 







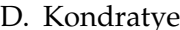












#### **Princeton University, Princeton, New Jersey, USA**

F.M. Addesa , B. Bonham , P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,  
B. Greenberg , N. Haubrich , S. Higginbotham , A. Kalogeropoulos , G. Kopp ,  
S. Kwan , D. Lange , D. Marlow , K. Mei , I. Ojalvo , J. Olsen , D. Stickland ,  
C. Tully 



#### **University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik , S. Norberg










#### **Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung ,  
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S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , F. Wang ,  
R. Xiao , W. Xie 












#### **Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar 
















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W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang<sup>87</sup>, Y. Zhang 





#### **University of Rochester, Rochester, New York, 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 ,  
G.P. Van Onsem 














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B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart ,  
M. Heindl , O. Karacheban<sup>24</sup> , 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, Tennessee, USA**

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , S. Spanier 










#### **Texas A&M University, College Station, Texas, USA**

O. Bouhali<sup>88</sup> , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon<sup>89</sup> , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,  
A. Safonov 

#### **Texas Tech University, Lubbock, Texas, USA**








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

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F. Romeo , P. Sheldon , S. Tuo , J. Velkovska 

#### **University of Virginia, Charlottesville, Virginia, USA**



















M.W. Arenton , B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky 

M. Joyce , A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald , S. White 

**Wayne State University, Detroit, Michigan, USA**

N. Poudyal 

**University of Wisconsin - Madison, Madison, Wisconsin, USA**

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

**Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN**

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov<sup>90</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , O. Bychkova, M. Chadeeva<sup>90</sup> , V. Chekhovsky, A. Dermenev , T. Dimova<sup>90</sup> , I. Dremin , M. Dubinin<sup>81</sup> , L. Dudko , V. Epshteyn , G. Gavrilo , V. Gavrilo , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov , V. Kachanov , L. Kardapoltsev<sup>90</sup> , V. Karjavine , A. Karneyeu , V. Kim<sup>90</sup> , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova , D. Konstantinov , V. Korenkov , A. Kozyrev<sup>90</sup> , N. Krasnikov , E. Kuznetsova<sup>91</sup> , A. Lanev , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev<sup>90,92</sup> , V. Murzin , A. Nikitenko<sup>93</sup> , S. Obraztsov , V. Okhotnikov , V. Oreshkin , A. Oskin, I. Ovtin<sup>90</sup> , V. Palichik , P. Parygin , A. Pashenkov, V. Perelygin , M. Perfilov, G. Pivovarov , V. Popov, E. Popova , O. Radchenko<sup>90</sup> , V. Rusinov, M. Savina , V. Savrin , D. Seitova, V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen<sup>90</sup> , S. Slabospitskii , I. Smirnov, V. Smirnov , A. Snigirev , D. Sosnov , A. Stepenov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , M. Toms , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov , S. Volkov, A. Vorobyev, N. Voytishin , B.S. Yuldashev<sup>94</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup>Also at TU Wien, Vienna, Austria

<sup>3</sup>Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

<sup>4</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium

<sup>5</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup>Also at The University of the State of Amazonas, Manaus, Brazil

<sup>8</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>9</sup>Also at UFMS, Nova Andradina, Brazil

<sup>10</sup>Also at Nanjing Normal University Department of Physics, Nanjing, China

<sup>11</sup>Now at The University of Iowa, Iowa City, Iowa, USA

<sup>12</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>13</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>14</sup>Also at Ain Shams University, Cairo, Egypt

<sup>15</sup>Also at Suez University, Suez, Egypt

<sup>16</sup>Now at British University in Egypt, Cairo, Egypt

- 
- <sup>17</sup>Also at Purdue University, West Lafayette, Indiana, USA
- <sup>18</sup>Also at Université de Haute Alsace, Mulhouse, France
- <sup>19</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>20</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>21</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>22</sup>Also at University of Hamburg, Hamburg, Germany
- <sup>23</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>24</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>25</sup>Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>26</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>27</sup>Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- <sup>28</sup>Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- <sup>29</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- <sup>30</sup>Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>31</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- <sup>32</sup>Also at Wigner Research Centre for Physics, Budapest, Hungary
- <sup>33</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>34</sup>Also at Shoolini University, Solan, India
- <sup>35</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>36</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>37</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>38</sup>Also at Indian Institute of Technology (IIT), Mumbai, India
- <sup>39</sup>Also at IIT Bhubaneswar, Bhubaneswar, India
- <sup>40</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>41</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>42</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>43</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>44</sup>Also at Helwan University, Cairo, Egypt
- <sup>45</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>46</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>47</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>48</sup>Also at Università di Napoli 'Federico II', Napoli, Italy
- <sup>49</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>50</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>51</sup>Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- <sup>52</sup>Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- <sup>53</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>54</sup>Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- <sup>55</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>56</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>57</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>58</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>59</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- <sup>60</sup>Also at Şırnak University, Sirnak, Turkey
- <sup>61</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin,

Turkey

<sup>62</sup>Also at Konya Technical University, Konya, Turkey

<sup>63</sup>Also at Izmir Bakircay University, Izmir, Turkey

<sup>64</sup>Also at Adiyaman University, Adiyaman, Turkey

<sup>65</sup>Also at Necmettin Erbakan University, Konya, Turkey

<sup>66</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

<sup>67</sup>Also at Marmara University, Istanbul, Turkey

<sup>68</sup>Also at Milli Savunma University, Istanbul, Turkey

<sup>69</sup>Also at Kafkas University, Kars, Turkey

<sup>70</sup>Also at Istanbul Bilgi University, Istanbul, Turkey

<sup>71</sup>Also at Hacettepe University, Ankara, Turkey

<sup>72</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

<sup>73</sup>Also at Yildiz Technical University, Istanbul, Turkey

<sup>74</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium

<sup>75</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

<sup>76</sup>Also at IPPP Durham University, Durham, United Kingdom

<sup>77</sup>Also at Monash University, Faculty of Science, Clayton, Australia

<sup>78</sup>Also at Università di Torino, Torino, Italy

<sup>79</sup>Also at Bethel University, St. Paul, Minnesota, USA

<sup>80</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

<sup>81</sup>Also at California Institute of Technology, Pasadena, California, USA

<sup>82</sup>Also at United States Naval Academy, Annapolis, Maryland, USA

<sup>83</sup>Also at Bingol University, Bingol, Turkey

<sup>84</sup>Also at Georgian Technical University, Tbilisi, Georgia

<sup>85</sup>Also at Sinop University, Sinop, Turkey

<sup>86</sup>Also at Erciyes University, Kayseri, Turkey

<sup>87</sup>Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

<sup>88</sup>Also at Texas A&M University at Qatar, Doha, Qatar

<sup>89</sup>Also at Kyungpook National University, Daegu, Korea

<sup>90</sup>Also at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>91</sup>Also at University of Florida, Gainesville, Florida, USA

<sup>92</sup>Now at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>93</sup>Also at Imperial College, London, United Kingdom

<sup>94</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan