

Search for direct pair production of supersymmetric partners of τ leptons in the final state with two hadronically decaying τ 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 τ sleptons, the supersymmetric partners of τ leptons, is presented. Each τ slepton is assumed to decay to a τ 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 τ leptons, each decaying to one or more hadrons and a neutrino, and significant transverse momentum imbalance. In addition to scenarios in which the τ sleptons decay promptly, the search also addresses scenarios in which the τ sleptons have sufficiently long lifetimes to give rise to nonprompt τ 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 fb^{-1} . No significant excess is seen with respect to standard model expectations. Upper limits on cross sections for the pair production of τ sleptons are obtained in the framework of simplified models. In a scenario in which the τ sleptons are superpartners of left-handed τ leptons, and each undergoes a prompt decay to a τ lepton and a nearly massless LSP, τ slepton masses between 115 and 340 GeV are excluded. In a scenario in which the lifetime of the τ sleptons corresponds to $c\tau_0 = 0.1$ mm, where τ_0 represents the mean proper lifetime of the τ slepton, masses between 150 and 220 GeV are excluded.

Published in Physical Review D as doi:10.1103/PhysRevD.108.012011.

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 τ slepton ($\tilde{\tau}$), the superpartner of the τ 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 τ leptons in collider experiments [23–25]. Here, we study events with two τ lepton candidates, both undergoing hadronic decays (τ_h), and having significant transverse momentum imbalance resulting from the presence of LSPs and to a lesser extent, neutrinos from the τ 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 τ_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 τ 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 τ 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 τ 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 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 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 τ_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 τ_h candidates and missing transverse momentum (p_T^{miss}), and also include scenarios with long-lived τ 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 fb^{-1} . Improved techniques are used to describe the SM background with τ leptons through a method called “embedding” [42], which estimates the background with two genuine τ lepton candidates by selecting dimuon events in data, removing reconstructed muons, and replacing them with simulated τ lepton decays. Updated methods are used for the τ_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].

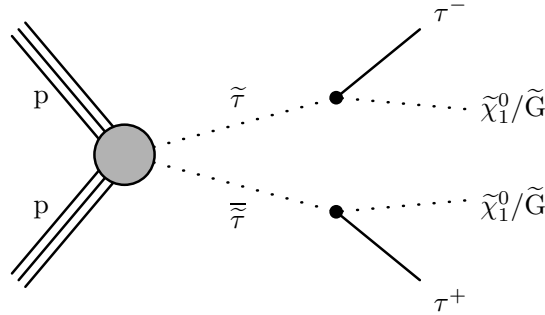


Figure 1: Diagram for direct $\tilde{\tau}$ pair production, followed by decay of each $\tilde{\tau}$ to a τ lepton and an LSP. For models with promptly decaying τ sleptons, the LSP is assumed to be $\tilde{\chi}_1^0$, the lightest neutralino. For models with long-lived τ sleptons, it is assumed to be 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 (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. 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 μ 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^{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^{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^{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 τ_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 η and azimuthal angle (ϕ) by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ from τ_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 τ_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 τ_h decay modes. Decay modes with one or three charged hadrons, with or without neutral pions, are considered in this search. To distinguish genuine τ_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 τ_h axis is combined with properties of the τ_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 ≈ 80 and $\approx 40\%$ for a genuine τ_h decay in the case of prompt τ_h production, respectively, and misidentification rates of ≈ 0.5 and $\approx 0.06\%$, respectively, for quark and gluon jets. Since the DEEPTAU algorithm was optimized for promptly produced τ_h candidates, the efficiency is reduced in the case of τ_h candidates originating from long-lived τ slepton decays. The efficiency of the “VVTight” working point, which is used to select signal τ_h candidates, ranges between 20% and 30% for the largest $\tilde{\tau}$ lifetimes considered in the search regions that explicitly target displaced τ_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 τ leptons, for simulated event samples corresponding to the 2016 and 2017–2018 data sets, respectively. The τ 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 τ 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 τ lepton pairs. Other backgrounds, originating from processes that give rise to two genuine τ_h decays, or to one or more jets that are misidentified as τ_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 τ_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, τ_h identification efficiencies, jet and τ_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^{ISR} distribution, where p_T^{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 τ 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^{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 τ_h candidates, each with $p_T > 35$ (>40) GeV in 2016 (2017–2018) data, and a p_T^{miss} -based trigger, with a threshold varying between 100 and 140 GeV, depending on the data-taking period. The di- τ_h trigger efficiency reaches its plateau, which ranges between 75% and 95% depending on the τ_h decay mode and the data-taking period, for τ_h p_T values above 80 GeV. The di- τ_h trigger is used for events with $p_T^{\text{miss}} < 200$ GeV, while the p_T^{miss} -based trigger is used for events with $p_T^{\text{miss}} > 200$ GeV. The offline p_T^{miss} threshold is chosen to be close to the range of approximately 250–300 GeV in which the efficiency of the p_T^{miss} -based trigger reaches its plateau of ~ 95 – 98% , depending on the data-taking period.

After the trigger selection, we impose a baseline event selection requiring the presence of exactly two τ_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 τ_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- τ_h system is boosted, resulting in a smaller angular separation between the τ_h candidates. Finally, we require $p_T^{\text{miss}} > 50$ GeV to suppress the background with two misidentified τ_h candidates. To avoid effects related to jet mismeasurement that can contribute to spurious p_T^{miss} , we require the \vec{p}_T^{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^{miss} . Consequently, we expect the correlations between \vec{p}_T^{miss} and the reconstructed τ_h candidates to be different between signal and background events. Mass observables calculated from \vec{p}_T^{miss} and the \vec{p}_T of the τ_h can be used to exploit these differences and discriminate signal from background.

One of the discriminants used is Σm_T , the sum of the transverse masses (m_T) calculated for each τ_h candidate with p_T^{miss} , given by

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

where the transverse mass for each τ_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^{miss} can originate from neutrinos from τ_h decays, as well as from LSPs. However, the predominant contribution to the p_T^{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^{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 τ_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 τ_h that does not satisfy the “displaced τ_h ” criteria described below for the displaced SRs. Events are then subdivided into bins of m_{T2} and Σm_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 Σm_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) τ_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 τ_h in signal events tend to have higher p_T .

The displaced category is defined by imposing the following “displaced τ_h ” criteria for both τ_h candidates. We require the significance of the τ_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) τ_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 Σm_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 Σm_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 Σm_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	Σm_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

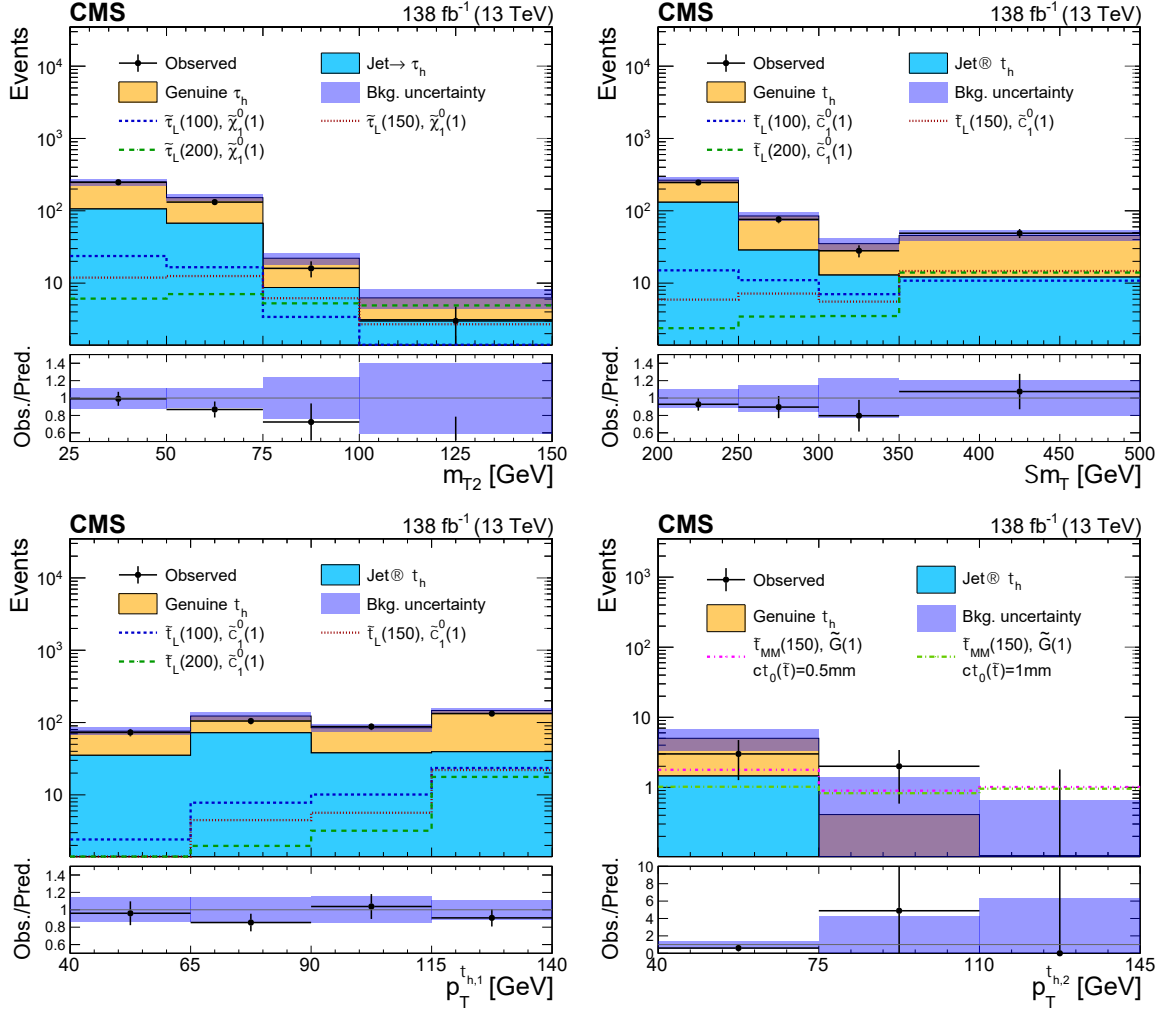


Figure 2: Distributions of m_{T2} (upper left), Σm_T (upper right), and $p_T^{\tau_{h,1}}$ (lower left) for events passing the selection criteria common to all prompt SRs, and of $p_T^{\tau_{h,2}}$ (lower right) for those passing the criteria common to all displaced SRs. The last bin includes overflow 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 τ_h candidates are misidentified jets. Contributions from backgrounds with electrons or muons misidentified as τ_h candidates are negligible. We use a method known as “embedding” for modeling backgrounds with two genuine τ_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 τ_h candidates.

5.1 Estimation of background from misidentified jets

Events with misidentified τ_h candidates, originating predominantly from QCD multijet and W +jets production, constitute the dominant background after the requirement of two τ_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 τ_h identification requirement, namely the Loose working point of the DEEPTAU discriminant. We measure the fraction of misidentified τ_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 ≈ 10 – 15% , and depends on the p_T and decay mode of the τ_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 τ_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 τ_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 τ_h decays

The background contribution with two genuine τ_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 τ leptons with the same kinematic properties as the original muons. This generates a set of hybrid events that rely on simulation only for the τ 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 τ lepton decays are simulated, we apply scale factors to match the τ_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 τ 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 τ 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 τ leptons are required to decay hadronically. We use an opposite-charge di- τ_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 τ_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- τ_h system to improve the purity of genuine τ_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 τ_h events in this sample, we measure scale factors of 1.24 ± 0.03 , 1.21 ± 0.03 , and 1.16 ± 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 τ_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 τ_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 τ_h misidentification rate that accounts for its dependence on jet flavor.

Because we use embedded events to estimate the background with two genuine τ_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, τ_h identification efficiency, and τ_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, τ_h identification efficiency, τ_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 ± 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 $m(\tilde{\tau}_L) = 150$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV.

Source	Uncertainty [%]		
	Genuine τ_h	Misidentified τ_h	Signal
Statistical	8.3–141	5.0–100	6.3–52
τ_h ID efficiency	7.2–7.8	—	6.2–6.4
τ_h ID vs. displacement	—	—	3.0
τ_h trigger efficiency	3.1–4.2	—	6.9–14
τ_h energy scale	0.1–35	—	1.6–44
τ_h misidentification rate	—	30–56	—
p_T^{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 τ_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 τ leptons, do not account for the dependence of the τ_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 τ_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 τ_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 $c\tau_0 = 2.5$ 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 $m(\tilde{\tau}_L) = 150$ GeV, $m(\tilde{\chi}_1^0) = 1$ 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 τ_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 τ sleptons in the degenerate scenario, in which we assume that both left- and right-handed τ 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 τ_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 τ 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 ≈ 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 τ 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 τ_h	Misidentified τ_h	Total SM	Observed	Prompt signal	Displaced τ_h signal
1	18.8 ± 4.4	39.6 ± 8.5	58.4 ± 9.6	65	0.6 ± 0.1	0.1 ± 0.1
2	25.9 ± 6.2	21.8 ± 5.5	47.7 ± 8.2	40	1.7 ± 0.3	0.6 ± 0.2
3	21.4 ± 4.9	26.1 ± 6.0	47.5 ± 7.7	38	1.4 ± 0.3	0.3 ± 0.1
4	$1.3^{+1.0}_{-0.6}$	$2.1^{+1.5}_{-1.4}$	$3.4^{+1.8}_{-1.5}$	4	0.5 ± 0.1	0.1 ± 0.1
5	$0.5^{+0.5}_{-0.3}$	$0.1^{+0.7}_{-0.1}$	$0.6^{+0.9}_{-0.4}$	1	0.0 ± 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 ± 0.0	<0.6
7	14.6 ± 3.9	3.7 ± 3.0	18.3 ± 4.9	28	1.8 ± 0.3	0.4 ± 0.2
8	$2.5^{+1.1}_{-0.9}$	2.7 ± 1.5	$5.2^{+1.9}_{-1.8}$	7	0.6 ± 0.1	0.1 ± 0.0
9	$2.1^{+1.3}_{-1.0}$	2.2 ± 1.6	$4.3^{+2.1}_{-1.9}$	4	1.9 ± 0.3	0.4 ± 0.1
10	$1.8^{+0.9}_{-0.7}$	$2.7^{+1.3}_{-1.1}$	$4.5^{+1.6}_{-1.3}$	0	0.8 ± 0.2	0.1 ± 0.1
11	$5.2^{+2.1}_{-1.8}$	4.2 ± 2.2	$9.4^{+3.1}_{-2.9}$	7	1.2 ± 0.2	0.3 ± 0.1
12	$1.5^{+1.3}_{-0.9}$	$1.7^{+1.4}_{-1.2}$	$3.2^{+1.9}_{-1.5}$	3	1.4 ± 0.3	0.4 ± 0.1
13	$1.1^{+1.1}_{-0.6}$	$0.1^{+1.0}_{-0.1}$	$1.1^{+1.5}_{-0.6}$	3	1.3 ± 0.2	0.3 ± 0.1
14	$0.2^{+0.5}_{-0.2}$	$0.5^{+0.8}_{-0.4}$	$0.7^{+0.9}_{-0.5}$	0	0.2 ± 0.1	0.0 ± 0.0
15	$8.9^{+2.9}_{-2.6}$	2.2 ± 2.6	$11.1^{+3.9}_{-3.7}$	17	3.0 ± 0.4	0.6 ± 0.2
16	$3.2^{+1.6}_{-1.3}$	<1.0	$3.2^{+1.9}_{-1.3}$	4	3.1 ± 0.5	0.7 ± 0.2
17	$2.5^{+1.4}_{-1.1}$	$3.0^{+1.5}_{-1.3}$	$5.5^{+2.1}_{-1.7}$	0	2.3 ± 0.4	0.6 ± 0.2
18	$0.7^{+1.0}_{-0.5}$	$0.9^{+0.8}_{-0.5}$	$1.6^{+1.3}_{-0.7}$	0	1.9 ± 0.3	0.4 ± 0.1
19	34.6 ± 7.9	23.8 ± 5.5	58.4 ± 9.6	45	0.9 ± 0.2	0.3 ± 0.1
20	35.7 ± 7.7	17.7 ± 4.8	53.4 ± 9.0	53	0.6 ± 0.1	0.3 ± 0.1
21	19.5 ± 4.9	5.4 ± 2.6	24.9 ± 5.5	15	0.7 ± 0.2	0.2 ± 0.1
22	11.4 ± 3.0	8.0 ± 3.0	19.4 ± 4.2	15	0.9 ± 0.2	0.2 ± 0.1
23	$4.5^{+1.5}_{-1.3}$	2.3 ± 1.6	$6.8^{+2.2}_{-2.1}$	6	0.3 ± 0.1	0.0 ± 0.0
24	$7.3^{+2.7}_{-2.4}$	4.7 ± 2.4	$12.0^{+3.6}_{-3.4}$	10	0.5 ± 0.1	0.2 ± 0.1
25	$4.6^{+1.9}_{-1.6}$	$2.3^{+1.4}_{-1.2}$	$6.9^{+2.3}_{-2.0}$	2	0.6 ± 0.1	0.1 ± 0.1
26	$2.3^{+1.3}_{-1.0}$	<1.3	$2.3^{+1.9}_{-1.0}$	3	0.4 ± 0.1	0.2 ± 0.1
27	15.8 ± 4.1	2.8 ± 3.1	18.6 ± 5.2	23	2.8 ± 0.4	0.8 ± 0.2
28	$0.9^{+0.9}_{-0.5}$	$1.4^{+1.1}_{-0.9}$	$2.3^{+1.5}_{-1.0}$	2	1.0 ± 0.2	0.4 ± 0.1
29	$1.5^{+1.2}_{-0.8}$	$1.9^{+1.4}_{-1.1}$	$3.4^{+1.9}_{-1.4}$	3	0.6 ± 0.1	0.1 ± 0.1
30	$3.6^{+1.5}_{-1.3}$	$0.7^{+1.3}_{-0.7}$	$4.3^{+2.0}_{-1.5}$	5	0.9 ± 0.2	2.6 ± 0.7
31	<0.5	<0.4	$0.0^{+0.7}_{-0.0}$	0	0.2 ± 0.1	1.0 ± 0.3

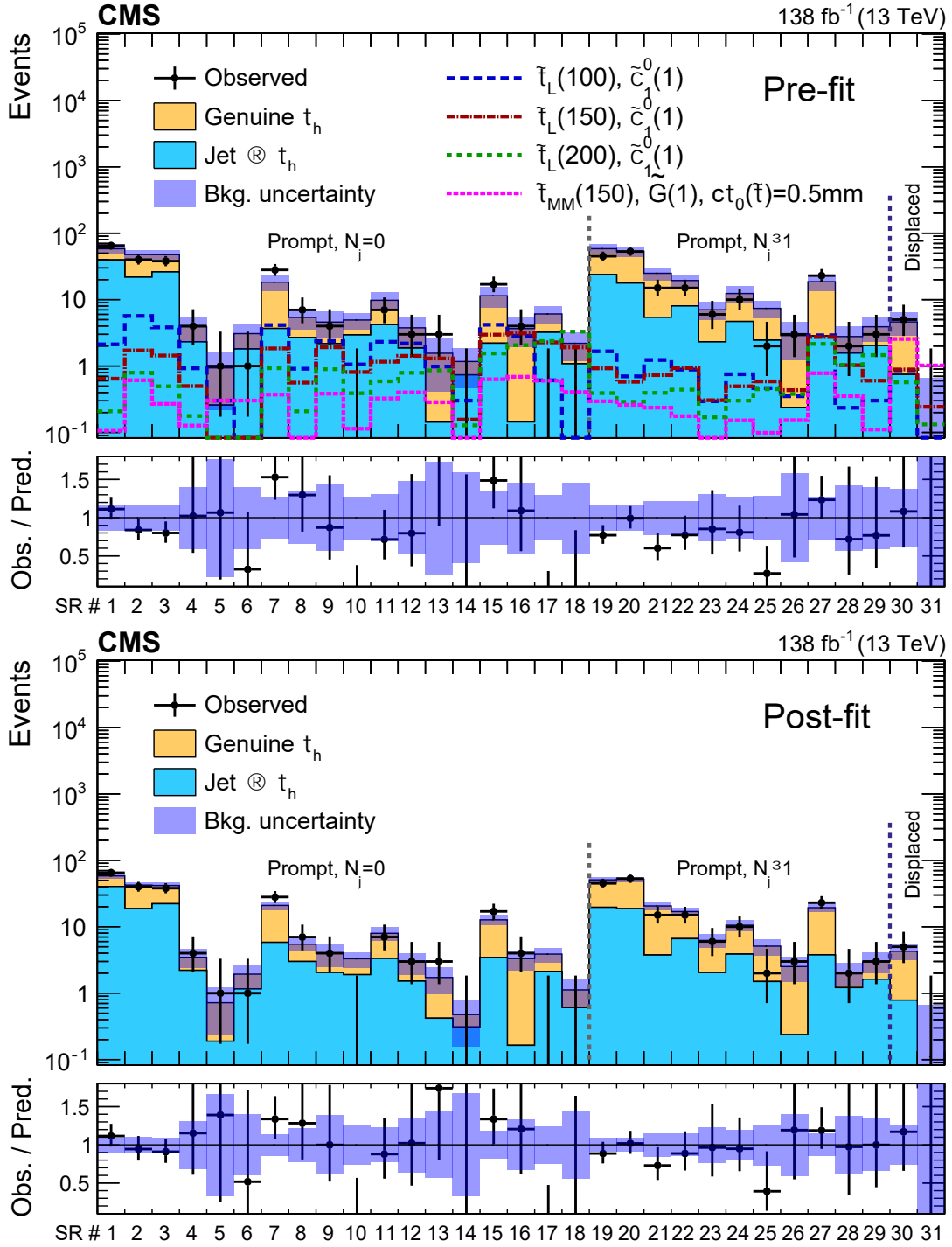


Figure 3: Event counts and predicted yields in each SR for the SM background before (upper) and after (lower) a maximum likelihood fit to the data under the background-only hypothesis. The yields expected for 3 benchmark models of left-handed $\tilde{\tau}$ pair production assuming prompt $\tilde{\tau}$ 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.

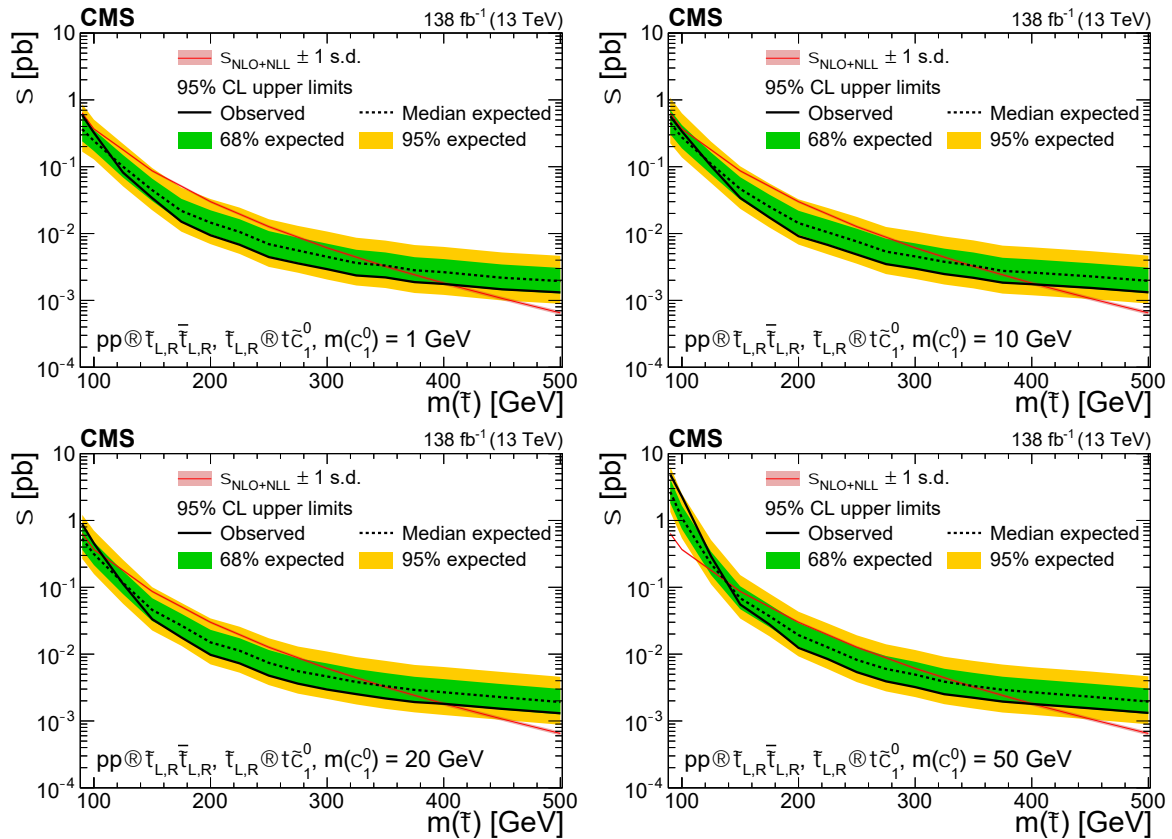


Figure 4: Expected and observed 95% CL cross section upper limits as functions of the $\tilde{\tau}$ mass in the degenerate $\tilde{\tau}$ scenario for $\tilde{\chi}_1^0$ masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the regions 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 τ_h candidates and is less efficient for more significantly displaced τ_h candidates.

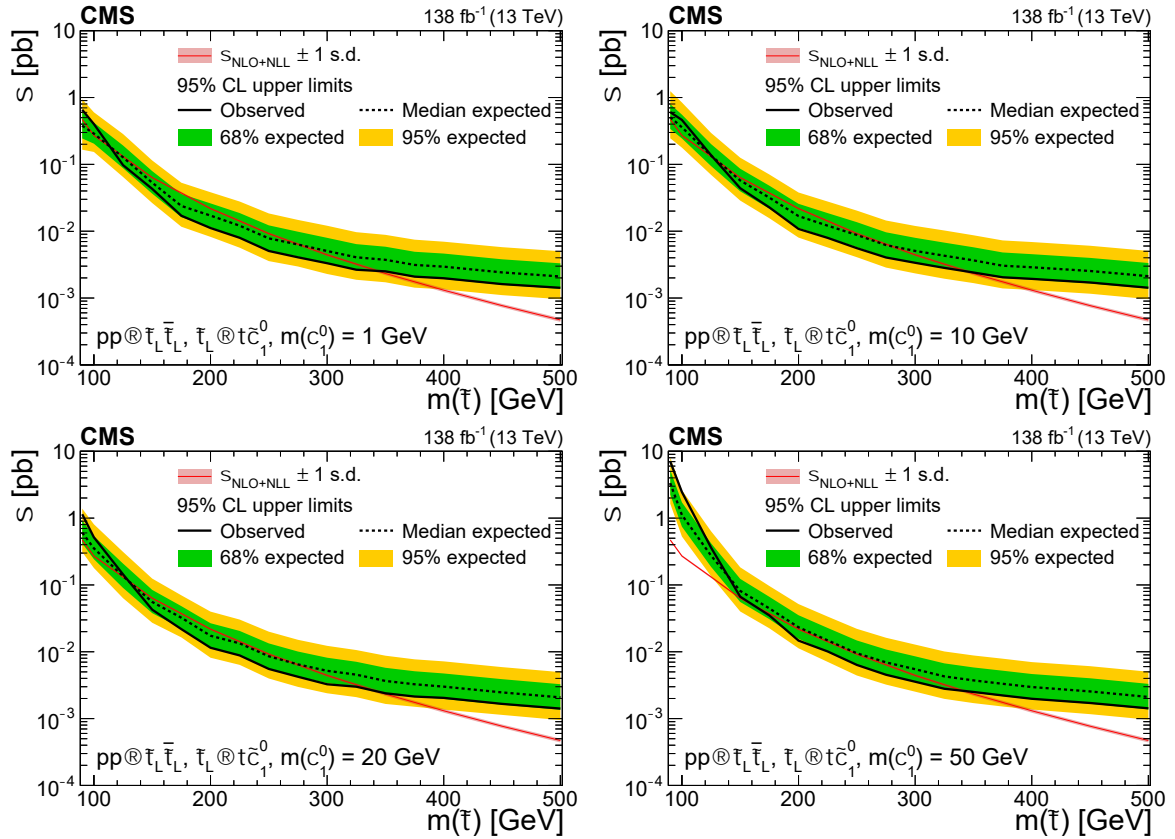


Figure 5: Expected and observed 95% CL cross section upper limits as functions of the $\tilde{\tau}$ mass in the purely left-handed $\tilde{\tau}$ scenario for $\tilde{\chi}_1^0$ masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate the 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.

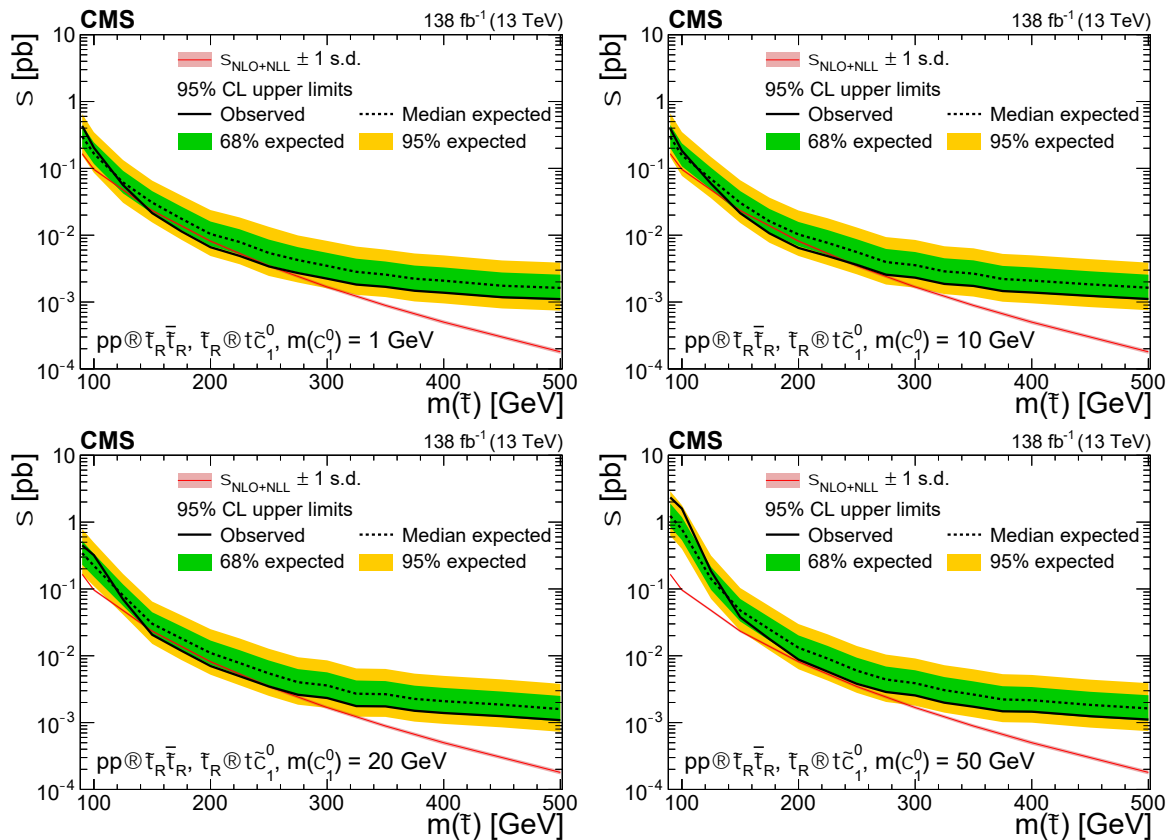


Figure 6: Expected and observed 95% CL cross section upper limits as functions of the $\tilde{\tau}$ mass in the purely right-handed $\tilde{\tau}$ scenario for $\tilde{\chi}_1^0$ masses of 1, 10, 20, and 50 GeV (upper left to lower right). The inner (green) band and the outer (yellow) band indicate 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.

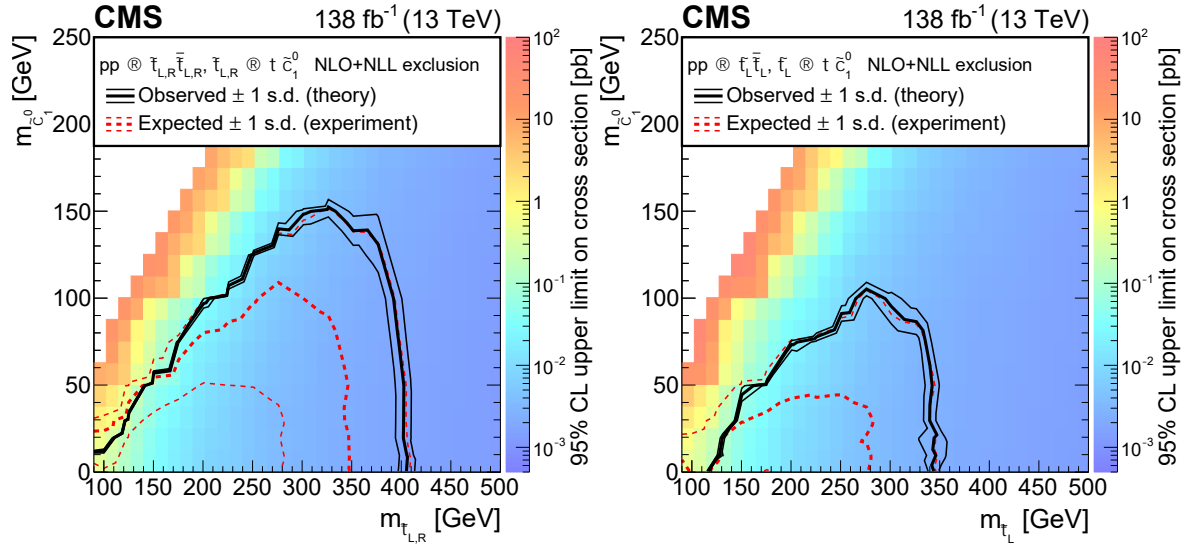


Figure 7: Upper limits at 95% CL on the cross section for degenerate (left) and purely left-handed (right) $\tilde{\tau}$ pair production in the $m(\tilde{\tau})$ - $m(\tilde{\chi}_1^0)$ plane. The thick black (red) curves show the observed (expected) exclusion limits assuming NLO+NLL predictions for the signal cross sections. The thin black curves represent the variations in the observed limits obtained when these cross sections are varied by their ± 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.

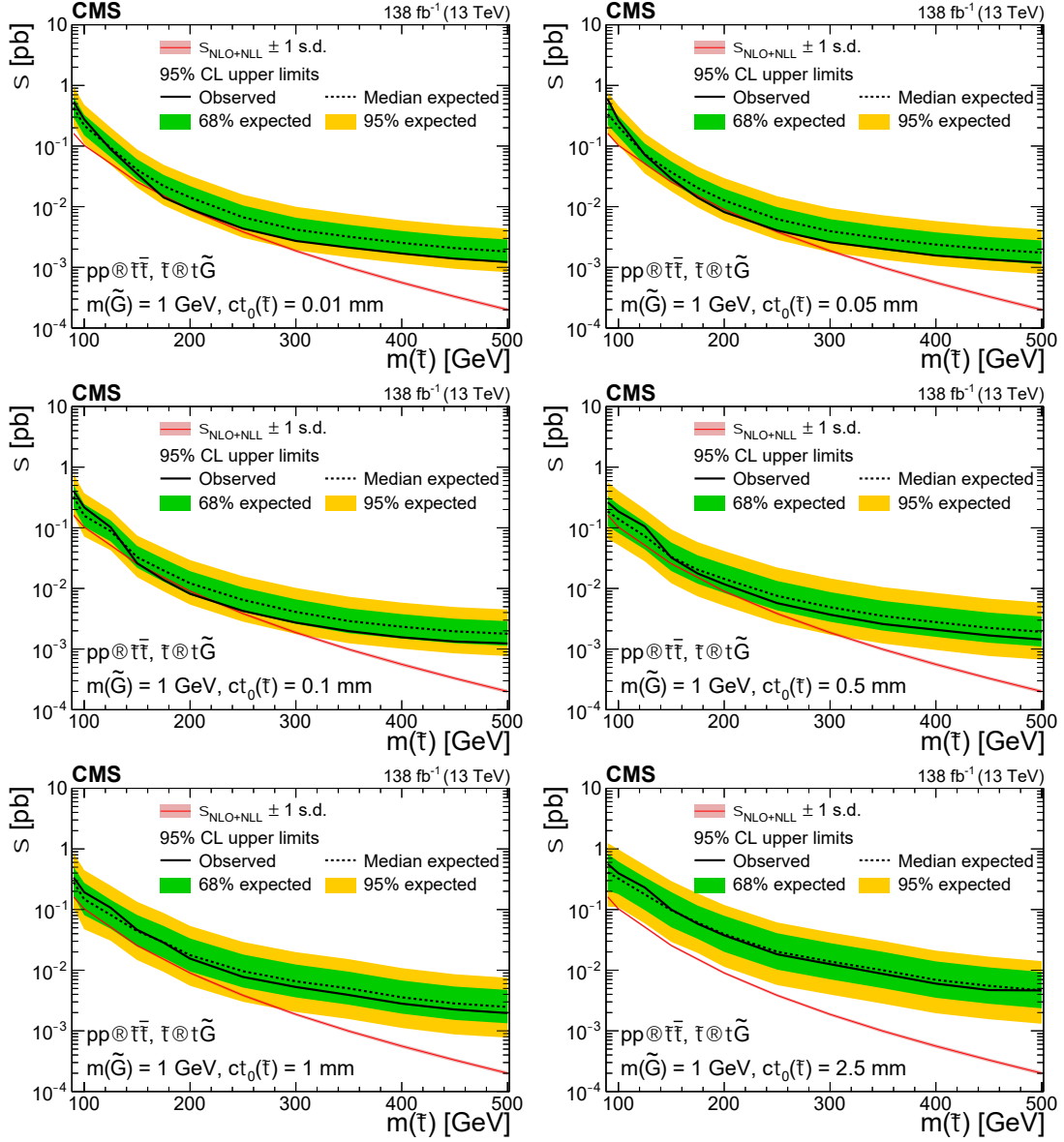


Figure 8: Expected and observed 95% CL cross section upper limits as functions of the $\tilde{\tau}$ mass for long-lived $\tilde{\tau}$ in the maximally mixed scenario for an LSP mass of 1 GeV, and for $\tau\tau_0$ values of 0.01, 0.05, 0.1, 0.5, 1, and 2.5 mm (upper left to lower right). The inner (green) 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 τ 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 τ leptons and significant missing transverse momentum. The data used for this search correspond to an integrated luminosity of 138 fb^{-1} collected in 2016–2018 with the CMS detector. Both prompt and displaced decays of the τ 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 τ 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 τ sleptons, final states with displaced τ_h candidates are investigated for the first time. In a scenario with $c\tau_0(\tilde{\tau}) = 0.1 \text{ mm}$, where τ_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.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans

l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NK-FIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] P. Ramond, "Dual theory for free fermions", *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.
- [2] Y. A. Gol'fand and E. P. Likhtman, "Extension of the algebra of Poincaré group generators and violation of P invariance", *JETP Lett.* **13** (1971) 323.
- [3] A. Neveu and J. H. Schwarz, "Factorizable dual model of pions", *Nucl. Phys. B* **31** (1971) 86, doi:10.1016/0550-3213(71)90448-2.
- [4] D. V. Volkov and V. P. Akulov, "Possible universal neutrino interaction", *JETP Lett.* **16** (1972) 438, doi:10.1007/BFb0105270.
- [5] J. Wess and B. Zumino, "A Lagrangian model invariant under supergauge transformations", *Phys. Lett. B* **49** (1974) 52, doi:10.1016/0370-2693(74)90578-4.
- [6] J. Wess and B. Zumino, "Supergauge transformations in four dimensions", *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.
- [7] P. Fayet, "Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino", *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.
- [8] H. P. Nilles, "Supersymmetry, supergravity and particle physics", *Phys. Rep.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5.

-
- [9] E. Gildener, "Gauge symmetry hierarchies", *Phys. Rev. D* **14** (1976) 1667, doi:10.1103/PhysRevD.14.1667.
- [10] M. J. G. Veltman, "Second threshold in weak interactions", *Acta Phys. Polon. B* **8** (1977) 475, doi:10.1016/B978-0-444-88807-5.50087-X.
- [11] G. 't Hooft, "Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking", *NATO Sci. Ser. B* **59** (1980) 135.
- [12] E. Witten, "Dynamical breaking of supersymmetry", *Nucl. Phys. B* **188** (1981) 513, doi:10.1016/0550-3213(81)90006-7.
- [13] G. R. Farrar and P. Fayet, "Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry", *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.
- [14] H. Goldberg, "Constraint on the photino mass from cosmology", *Phys. Rev. Lett.* **50** (1983) 1419, doi:10.1103/PhysRevLett.50.1419. [Erratum: doi:10.1103/PhysRevLett.103.099905].
- [15] J. R. Ellis et al., "Supersymmetric relics from the Big Bang", *Nucl. Phys. B* **238** (1984) 453, doi:10.1016/0550-3213(84)90461-9.
- [16] G. Jungman, M. Kamionkowski, and K. Griest, "Supersymmetric dark matter", *Phys. Rept.* **267** (1996) 195, doi:10.1016/0370-1573(95)00058-5, arXiv:hep-ph/9506380.
- [17] G. Hinshaw et al., "Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological parameter results", *Astrophys. J. Suppl.* **208** (2013) 19, doi:10.1088/0067-0049/208/2/19, arXiv:1212.5226.
- [18] K. Griest and D. Seckel, "Three exceptions in the calculation of relic abundances", *Phys. Rev. D* **43** (1991) 3191, doi:10.1103/PhysRevD.43.3191.
- [19] D. Albornoz Vásquez, G. Bélanger, and C. Boehm, "Revisiting light neutralino scenarios in the MSSM", *Phys. Rev. D* **84** (2011) 095015, doi:10.1103/PhysRevD.84.095015, arXiv:1108.1338.
- [20] S. F. King, J. P. Roberts, and D. P. Roy, "Natural dark matter in SUSY GUTs with non-universal gaugino masses", *JHEP* **10** (2007) 106, doi:10.1088/1126-6708/2007/10/106, arXiv:0705.4219.
- [21] M. Battaglia et al., "Proposed post-LEP benchmarks for supersymmetry", *Eur. Phys. J. C* **22** (2001) 535, doi:10.1007/s100520100792, arXiv:hep-ph/0106204.
- [22] R. L. Arnowitt et al., "Determining the dark matter relic density in the minimal supergravity stau-neutralino coannihilation region at the Large Hadron Collider", *Phys. Rev. Lett.* **100** (2008) 231802, doi:10.1103/PhysRevLett.100.231802, arXiv:0802.2968.
- [23] G. Bélanger, S. Biswas, C. Boehm, and B. Mukhopadhyaya, "Light neutralino dark matter in the MSSM and its implication for LHC searches for staus", *JHEP* **12** (2012) 076, doi:10.1007/JHEP12(2012)076, arXiv:1206.5404.

- [24] E. Arganda, V. Martín-Lozano, A. D. Medina, and N. Mileo, “Potential discovery of staus through heavy Higgs boson decays at the LHC”, *JHEP* **09** (2018) 056, doi:10.1007/JHEP09(2018)056, arXiv:1804.10698.
- [25] E. Arganda, V. Martín-Lozano, A. D. Medina, and N. I. Mileo, “Discovery and exclusion prospects for staus produced by heavy Higgs boson decays at the LHC”, *Adv. High Energy Phys.* **2022** (2022) 2569290, doi:10.1155/2022/2569290, arXiv:2102.02290.
- [26] J. A. Evans and J. Shelton, “Long-lived staus and displaced leptons at the LHC”, *JHEP* **04** (2016) 056, doi:10.1007/JHEP04(2016)056, arXiv:1601.01326.
- [27] J. Alwall, P. C. Schuster, and N. Toro, “Simplified models for a first characterization of new physics at the LHC”, *Phys. Rev. D* **79** (2009) 075020, doi:10.1103/PhysRevD.79.075020, arXiv:0810.3921.
- [28] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, “Model-independent jets plus missing energy searches”, *Phys. Rev. D* **79** (2009) 015005, doi:10.1103/PhysRevD.79.015005, arXiv:0809.3264.
- [29] LHC New Physics Working Group, “Simplified models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.
- [30] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Revisiting slepton pair production at the Large Hadron Collider”, *JHEP* **01** (2014) 168, doi:10.1007/JHEP01(2014)168, arXiv:1310.2621.
- [31] ALEPH Collaboration, “Search for scalar leptons in e^+e^- collisions at center-of-mass energies up to 209 GeV”, *Phys. Lett. B* **526** (2002) 206, doi:10.1016/S0370-2693(01)01494-0, arXiv:hep-ex/0112011.
- [32] DELPHI Collaboration, “Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM”, *Eur. Phys. J. C* **31** (2003) 421, doi:10.1140/epjc/s2003-01355-5, arXiv:hep-ex/0311019.
- [33] L3 Collaboration, “Search for scalar leptons and scalar quarks at LEP”, *Phys. Lett. B* **580** (2004) 37, doi:10.1016/j.physletb.2003.10.010, arXiv:hep-ex/0310007.
- [34] OPAL Collaboration, “Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s} = 183$ GeV to 209 GeV”, *Eur. Phys. J. C* **32** (2004) 453, doi:10.1140/epjc/s2003-01466-y, arXiv:hep-ex/0309014.
- [35] ATLAS Collaboration, “Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **10** (2014) 96, doi:10.1007/JHEP10(2014)096, arXiv:1407.0350.
- [36] ATLAS Collaboration, “Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **93** (2016) 052002, doi:10.1103/PhysRevD.93.052002, arXiv:1509.07152.
- [37] CMS Collaboration, “Search for electroweak production of charginos in final states with two tau leptons in pp collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **04** (2017) 018, doi:10.1007/JHEP04(2017)018, arXiv:1610.04870.

-
- [38] ATLAS Collaboration, “Search for direct stau production in events with two hadronic τ -leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **101** (2020) 032009, doi:10.1103/PhysRevD.101.032009, arXiv:1911.06660.
- [39] CMS Collaboration, “Search for direct pair production of supersymmetric partners to the τ lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **80** (2020) 189, doi:10.1140/epjc/s10052-020-7739-7, arXiv:1907.13179.
- [40] OPAL Collaboration, “Searches for gauge-mediated supersymmetry breaking topologies in e^+e^- collisions at centre-of-mass energies up to $\sqrt{s} = 209$ GeV”, *Eur. Phys. J. C* **46** (2006) 307, doi:10.1140/epjc/s2006-02524-8, arXiv:hep-ex/0507048.
- [41] ATLAS Collaboration, “Search for displaced leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. Lett.* **127** (2021) 051802, doi:10.1103/PhysRevLett.127.051802, arXiv:2011.07812.
- [42] CMS Collaboration, “An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data”, *JINST* **14** (2019) P06032, doi:10.1088/1748-0221/14/06/P06032, arXiv:1903.01216.
- [43] CMS Collaboration, “Identification of hadronic tau lepton decays using a deep neural network”, 2022. arXiv:2201.08458. Submitted to *JINST*.
- [44] HEPData record for this analysis, 2022. doi:10.17182/hepdata.131308.
- [45] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [46] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [47] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [48] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [49] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.
- [50] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [51] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [52] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [53] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

- [54] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [55] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [56] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [57] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [58] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [59] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [60] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [61] A. Kalogeropoulos and J. Alwall, “The SysCalc code: A tool to derive theoretical systematic uncertainties”, 2018. arXiv:1801.08401.
- [62] W. Beenakker et al., “Production of charginos, neutralinos, and sleptons at hadron colliders”, *Phys. Rev. Lett.* **83** (1999) 3780, doi:10.1103/PhysRevLett.83.3780, arXiv:hep-ph/9906298. [Erratum: doi:10.1103/PhysRevLett.100.029901].
- [63] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [64] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [65] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [66] E. Re, “Single-top Wt -channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [67] CMS Collaboration, “Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C* **73** (2013) 2677, doi:10.1140/epjc/s10052-013-2677-2, arXiv:1308.1586.
- [68] C. G. Lester and D. J. Summers, “Measuring masses of semi-invisibly decaying particle pairs produced at hadron colliders”, *Phys. Lett. B* **463** (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349.



















- [69] A. Barr, C. Lester, and P. Stephens, “ m_{T2} : the truth behind the glamour”, *J. Phys. G* **29** (2003) 2343, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226.
- [70] C. G. Lester and B. Nachman, “Bisection-based asymmetric m_{T2} computation: a higher precision calculator than existing symmetric methods”, *JHEP* **03** (2015) 100, doi:10.1007/JHEP03(2015)100, arXiv:1411.4312.
- [71] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [72] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [73] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [74] CMS Collaboration, “Interpretation of searches for supersymmetry with simplified models”, *Phys. Rev. D* **88** (2013) 052017, doi:10.1103/PhysRevD.88.052017, arXiv:1301.2175.
- [75] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [76] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [77] ATLAS and CMS Collaborations, and the LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.
- [78] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth² , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck² , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz² 

















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , E.A. De Wolf, T. Janssen , T. Kello⁴, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte , N. Van Remortel 










Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, D. Vannerom 


















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. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , 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 Araujo⁷ , A. Vilela Pereira 

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

C.A. Bernardes⁶ , 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. Javaid⁸ , M. Mittal , L. Yuan 









Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer, C. Dozen , Z. Hu , J. Martins⁹ , Y. Wang, K. Yi^{10,11} 

Institute of High Energy Physics, Beijing, China

E. Chapon , G.M. Chen⁸ , H.S. Chen⁸ , M. Chen , F. Iemmi , A. Kapoor , D. Leggat, H. Liao , Z.-A. Liu¹² , 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. Gao⁴ , 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

Z. Antunovic, M. Kovac , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic , A. Starodumov¹³ , 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. Finger¹³ , M. Finger Jr.¹³ , A. Kveton 

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 











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

S. Abu Zeid¹⁴ , Y. Assran^{15,16}

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 ,
M. Myllymäki , J. Ott , H. Siikonen , E. Tuominen , J. Tuominiemi 



























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 ,
E. Locci , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷ ,
M. Titov , G.B. Yu 


















Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, 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. Agram¹⁸ , J. Andrea , D. Apparú , D. Bloch , G. Bourgatte , J.-M. Brom ,
E.C. Chabert , C. Collard , D. Darej, J.-C. Fontaine¹⁸ , 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. Khvedelidze¹³ , I. Lomidze , Z. Tsamalaidze¹³ 

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 Ahmad¹⁹ , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , D. Roy , A. Stahl²⁰ , 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. Borras²¹ , 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. Gallo²² , A. Geiser , A. Giraldi , A. Grohsjean , M. Guthoff , A. Jafari²³ , N.Z. Jomhari , A. Kasem²¹ , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , D. Krücker , W. Lange, K. Lipka , W. Lohmann²⁴ , 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. Scham²⁵ , V. Scheurer, S. Schnake , P. Schütze , C. Schwanenberger²² , 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[†], A. Dierlamm , A. Droll, K. El Morabit , N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann²⁰ , 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. Gadallah²⁶ , S. Lökös²⁷ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl , O. Surányi , G.I. Veres 



Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁸ , G. Bencze, C. Hajdu , D. Horvath^{29,30} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, D. Fasanello , F. Fienga , J. Karancsi²⁸ , J. Molnar, Z. Szillasi, D. Teyssier 

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³¹ , B. Ujvari 














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

T. Csorgo³² , F. Nemes³² , 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. Dhingra³³ , 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. Bharti³⁴, R. Bhattacharya , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁵ , M. Maity³⁶, P. Palit , P.K. Rout , G. Saha , B. Sahu , S. Sarkar, M. Sharan, S.Thakur³⁴ 



Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri³⁷ , D. Kumar³⁷ , A. Muhammad , L. Panwar³⁷ , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari³⁷ 









Bhabha Atomic Research Centre, Mumbai, India

D. Dutta , V. Jha, V. Kumar , D.K. Mishra, K. Naskar³⁸ , 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. Bahinipati³⁹ , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁰ ,
A. Nayak⁴⁰ , P. Saha , N. Sur , S.K. Swain, D. Vats⁴⁰ 

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. Bakhshiansohi⁴¹ , E. Khazaie , M. Zeinali⁴² 


































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

S. Chenarani⁴³ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





























University College Dublin, Dublin, Ireland

M. Grunewald 






INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

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
















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

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

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

S. Albergo^{a,b,46} , S. Costa^{a,b,46} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,46} ,
C. Tuve^{a,b} 

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

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

























INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , D. Piccolo 

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

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

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


















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

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della












Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy

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
















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

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


















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

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


















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

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


















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

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








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

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













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

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

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

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




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 Cruz⁵⁰ , 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. Mijuskovic⁵¹, 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. Adzic⁵² , 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. Kailasapathy⁵³ , 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[†], 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. Fallavollita⁵⁴, 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. Sphicas⁵⁵ , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk⁵⁶ , K.A. Wozniak , W.D. Zeuner
























Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁵⁷ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , M. Missiroli⁵⁷ , L. Noehte⁵⁷ , T. Rohe 

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

K. Androsov⁵⁶ , 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. Steggemann⁵⁶ , R. Wallny , D.H. Zhu 















Universität Zürich, Zurich, Switzerland

C. Amsler⁵⁸ , 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. Adloff⁵⁹, C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁶ , 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. Damarseekin⁶⁰ , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶¹ , E. Eskut , Y. Guler⁶² , E. Gurpinar Guler⁶² , C. Isik , O. Kara , A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶³ , A. Polatoz , A.E. Simsek , B. Tali⁶⁴ , U.G. Tok , S. Turkcapar , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar , K. Ocalan⁶⁵ , M. Yalvac⁶⁶ 









Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁶⁷ , O. Kaya⁶⁸ , Ö. Özçelik , S. Tekten⁶⁹ , E.A. Yetkin⁷⁰ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶¹ , Y. Komurcu , S. Sen⁷¹ 

Istanbul University, Istanbul, Turkey

S. Cerci⁶⁴ , I. Hos⁷² , B. Isildak⁷³ , B. Kaynak , S. Ozkorucuklu , H. Sert , D. Sunar Cerci⁶⁴ , 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. Stylianou⁷⁴ , K. Walkingshaw Pass , R. White 




Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell , A. Belyaev⁷⁵ , 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. Chahal⁷⁶ , 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. Nash⁷⁷ , M. Pesaresi , B.C. Radburn-Smith , D.M. Raymond , A. Richards , A. Rose , E. Scott , C. Seez , A. Shtipliyski , A. Tapper , K. Uchida , T. Virdee²⁰ , 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

Baylor University, Waco, Texas, USA

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. Rumerio⁷⁸ , 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. Coubez²¹, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁷⁹ , T. KWON , G. Landsberg , K.T. Lau , D. Li , M. Lukasik, J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁰ , 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. Manganello , 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. Pena⁸¹ , O. Prokofyev, F. Ravera , A. Reinsvold Hall⁸² , 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. Elkafrawy¹⁴ , 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. Dilsiz⁸³ , L. Emediato , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁴ , J. Nachtman , H. Ogul⁸⁵ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁸⁶ 




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[†], 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. Musienko¹³ , 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 







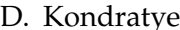












Princeton University, Princeton, New Jersey, USA

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 ,
D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,
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 
















Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , M. Decaro, S. Dildick , K.M. Ecklund , S. Freed,
P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter ,
W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang⁸⁷, 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 














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

B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart ,
M. Heindl , O. Karacheban²⁴ , 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. Bouhali⁸⁸ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,
T. Kamon⁸⁹ , 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 

Vanderbilt University, Nashville, Tennessee, USA


E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , H. Ni, K. Padeken ,
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. Blinov⁹⁰, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , O. Bychkova, M. Chadeeva⁹⁰ , V. Chekhovsky, A. Dermenev , T. Dimova⁹⁰ , I. Dremin , M. Dubinin⁸¹ , 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. Kardapoltsev⁹⁰ , V. Karjavine , A. Karneyeu , V. Kim⁹⁰ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁰ , N. Krasnikov , E. Kuznetsova⁹¹ , A. Lanev , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev^{90,92} , V. Murzin , A. Nikitenko⁹³ , S. Obraztsov , V. Okhotnikov , V. Oreshkin , A. Oskin, I. Ovtin⁹⁰ , V. Palichik , P. Parygin , A. Pashenkov, V. Perelygin , M. Perfilov, G. Pivovarov , V. Popov, E. Popova , O. Radchenko⁹⁰ , V. Rusinov, M. Savina , V. Savrin , D. Seitova, V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁰ , 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. Yuldashev⁹⁴, A. Zarubin , I. Zhizhin , A. Zhokin

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

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

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at The University of the State of Amazonas, Manaus, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at UFMS, Nova Andradina, Brazil

¹⁰Also at Nanjing Normal University Department of Physics, Nanjing, China

¹¹Now at The University of Iowa, Iowa City, Iowa, USA

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁴Also at Ain Shams University, Cairo, Egypt

¹⁵Also at Suez University, Suez, Egypt

¹⁶Now at British University in Egypt, Cairo, Egypt

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

Turkey

⁶²Also at Konya Technical University, Konya, Turkey

⁶³Also at Izmir Bakircay University, Izmir, Turkey

⁶⁴Also at Adiyaman University, Adiyaman, Turkey

⁶⁵Also at Necmettin Erbakan University, Konya, Turkey

⁶⁶Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

⁶⁷Also at Marmara University, Istanbul, Turkey

⁶⁸Also at Milli Savunma University, Istanbul, Turkey

⁶⁹Also at Kafkas University, Kars, Turkey

⁷⁰Also at Istanbul Bilgi University, Istanbul, Turkey

⁷¹Also at Hacettepe University, Ankara, Turkey

⁷²Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁷³Also at Yildiz Technical University, Istanbul, Turkey

⁷⁴Also at Vrije Universiteit Brussel, Brussel, Belgium

⁷⁵Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁷⁶Also at IPPP Durham University, Durham, United Kingdom

⁷⁷Also at Monash University, Faculty of Science, Clayton, Australia

⁷⁸Also at Università di Torino, Torino, Italy

⁷⁹Also at Bethel University, St. Paul, Minnesota, USA

⁸⁰Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸¹Also at California Institute of Technology, Pasadena, California, USA

⁸²Also at United States Naval Academy, Annapolis, Maryland, USA

⁸³Also at Bingol University, Bingol, Turkey

⁸⁴Also at Georgian Technical University, Tbilisi, Georgia

⁸⁵Also at Sinop University, Sinop, Turkey

⁸⁶Also at Erciyes University, Kayseri, Turkey

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

⁸⁸Also at Texas A&M University at Qatar, Doha, Qatar

⁸⁹Also at Kyungpook National University, Daegu, Korea

⁹⁰Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹¹Also at University of Florida, Gainesville, Florida, USA

⁹²Now at another institute or international laboratory covered by a cooperation agreement with CERN

⁹³Also at Imperial College, London, United Kingdom

⁹⁴Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan