

RECEIVED: July 3, 2022

REVISED: November 11, 2022

ACCEPTED: December 9, 2022

PUBLISHED: September 6, 2023

# Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV



## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** A search for a charged Higgs boson  $H^\pm$  decaying into a heavy neutral Higgs boson  $H$  and a W boson is presented. The analysis targets the  $H$  decay into a pair of tau leptons with at least one of them decaying hadronically and with an additional electron or muon present in the event. The search is based on proton-proton collision data recorded by the CMS experiment during 2016–2018 at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . The data are consistent with standard model background expectations. Upper limits at 95% confidence level are set on the product of the cross section and branching fraction for an  $H^\pm$  in the mass range of 300–700 GeV, assuming an  $H$  with a mass of 200 GeV. The observed limits range from 0.085 pb for an  $H^\pm$  mass of 300 GeV to 0.019 pb for a mass of 700 GeV. These are the first limits on  $H^\pm$  production in the  $H^\pm \rightarrow HW^\pm$  decay channel at the LHC.

**KEYWORDS:** Beyond Standard Model, Hadron-Hadron Scattering, Higgs Physics

**ARXIV EPRINT:** [2207.01046](https://arxiv.org/abs/2207.01046)

---

**Contents**

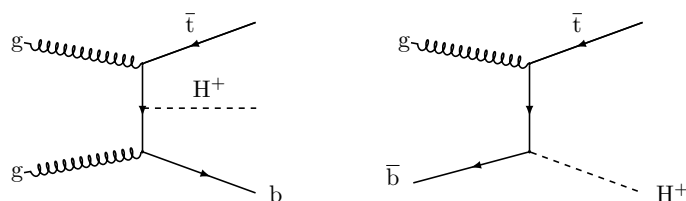
<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>The CMS detector</b>	<b>4</b>
<b>3</b>	<b>Collision data and simulated samples</b>	<b>5</b>
<b>4</b>	<b>Object reconstruction</b>	<b>6</b>
<b>5</b>	<b>Event selection</b>	<b>10</b>
<b>6</b>	<b>Background estimation</b>	<b>12</b>
<b>7</b>	<b>Search strategy</b>	<b>15</b>
<b>8</b>	<b>Systematic uncertainties</b>	<b>17</b>
	8.1 Experimental sources	18
	8.2 Theoretical sources	20
<b>9</b>	<b>Results</b>	<b>20</b>
<b>10</b>	<b>Summary</b>	<b>26</b>
	<b>The CMS collaboration</b>	<b>35</b>

---

**1 Introduction**

The experimental confirmation of the Brout–Englert–Higgs mechanism [1–6] at the CERN LHC [7–9] has provided the long-sought solution to the electroweak symmetry breaking problem. It has also further established the standard model (SM) of particle physics as a successful theory. Subsequent precision measurements of the couplings of the observed Higgs boson with the SM particles are in agreement with expectations, with an experimental precision of  $\approx 5\text{--}33\%$  [10–13]. Regardless of the success it has achieved, the SM is still considered to be an effective field theory valid only at low energies because of its inability to address various fundamental theoretical problems and compelling observations in nature such as the naturalness problem, the vacuum metastability, the conjectured cosmological inflation, the presence of dark matter and the matter-antimatter asymmetry of our universe.

Numerous theoretical models have been proposed to remedy the shortcomings of the SM, many of which predict that the Higgs sector must also be extended. Minimal extensions known as two-Higgs-doublet models (2HDMs) [14–17] include a second complex



**Figure 1.** Leading order Feynman diagrams for the production of a heavy  $H^+$  at the LHC through  $pp \rightarrow t(b)H^+$  in the 4FS (left) and 5FS (right).

doublet and are classified into four types according to the couplings of the Higgs doublets to fermions. The two-doublet structure gives rise to five physical Higgs bosons via spontaneous symmetry breaking: two neutral  $CP$ -even particles  $h$  and  $H$  with  $m_h \leq m_H$ , one neutral  $CP$ -odd particle  $A$ , and two charged Higgs bosons  $H^\pm$ . In these models the ratio of the vacuum expectation values of the two Higgs doublets,  $\tan \beta$ , and the mixing angle,  $\alpha$ , between  $h$  and  $H$  are free parameters. These can be tuned to the alignment limit  $\sin(\beta - \alpha) = 1$  whereby  $h$  aligns with the properties of the SM Higgs boson with  $m_h = 125 \text{ GeV}$  [18].

Three mass regions are conveniently defined for the classification of charged Higgs bosons: light ( $m_{H^\pm} < m_t - m_b$ ), intermediate ( $m_{H^\pm} \approx m_t$ ), and heavy ( $m_{H^\pm} > m_t + m_b$ ), where  $m_{H^\pm}$ ,  $m_t$ , and  $m_b$  represent the masses of the charged Higgs boson, the top and bottom quarks, respectively. The search described in this paper is focused on a heavy  $H^\pm$ , whose production at the LHC would take place predominantly in association with top and bottom quarks. The associated top quark production dominates and can be described in the four- and five-flavor scheme (4FS and 5FS), which yield consistent results at sufficiently high order of perturbation theory [19–22]. The corresponding leading-order (LO) Feynman diagrams are shown in figure 1, with charge-conjugate processes implied.

When considering 2HDMs, the decay branching fractions  $\mathcal{B}$  of  $H^\pm$  can vary significantly between different models. Under the enforcement of the  $Z_2$  symmetry there are four types of 2HDMs which, for  $\tan \beta = 1$ , lead to the channels  $H^\pm \rightarrow \tau^\pm \nu_\tau$  and  $H^\pm \rightarrow cs$  being dominant in the light- $H^\pm$  region. In the heavy- $H^\pm$  region, the decay mode  $H^\pm \rightarrow tb$  dominates, with some competition from the  $H^\pm \rightarrow hW^\pm$  and  $H^\pm \rightarrow HW^\pm$  decay modes. This behavior also holds in the alignment limit with the only difference being that  $\mathcal{B}(H^\pm \rightarrow HW^\pm)$  increases faster with  $m_{H^\pm}$ , while  $\mathcal{B}(H^\pm \rightarrow hW^\pm)$  vanishes completely. At larger values of  $\tan \beta$  and for  $\sin(\beta - \alpha) \neq 1$ , the interplay between the channels  $H^\pm \rightarrow HW^\pm$  and  $H^\pm \rightarrow hW^\pm$  becomes more intricate, with the former becoming important once kinematically attainable and the latter dominating because of the large phase space available.

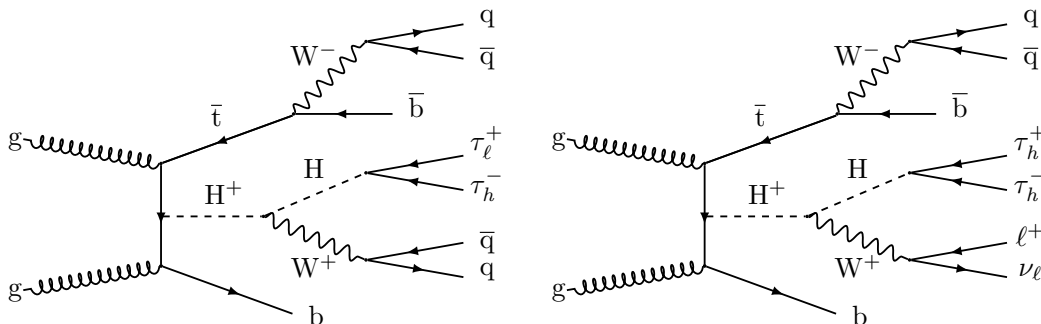
The importance of the potential interference between the  $H^\pm \rightarrow HW^\pm$  and  $H^\pm \rightarrow hW^\pm$  channels is difficult to quantify as it highly depends on the considered parameter space. In general, however, a large  $H^\pm \rightarrow hW^\pm$  coupling is always associated with a small  $H^\pm \rightarrow HW^\pm$  coupling, and vice versa. As discussed in ref. [23], assuming a misalignment

of  $\approx 0.1$  with  $\sin(\beta - \alpha) = 0.9$ ,  $\mathcal{B}(H^\pm \rightarrow hW^\pm)$  is suppressed by a factor of  $\approx 100$  with respect to  $\mathcal{B}(H^\pm \rightarrow HW^\pm)$ , while the interference between  $H^\pm \rightarrow HW^\pm$  and  $H^\pm \rightarrow hW^\pm$  is also expected to be suppressed by at least a factor of  $\approx 10$  compared to the contribution from  $H^\pm \rightarrow HW^\pm$  itself. In this paper, we focus on the  $H^\pm \rightarrow HW^\pm$  decay mode and neglect completely the  $H^\pm \rightarrow hW^\pm$  decay mode, as well as their interference. For the neutral Higgs boson, typically the most frequent final states close to the alignment limit are the  $bb$  and  $\tau\tau$ , while the  $WW$ ,  $ZZ$ , and  $\gamma\gamma$  channels are experimentally the cleanest ones. However, the aforementioned decay rates are model-dependent and are also affected, directly or indirectly, by the value of  $m_H$ .

Since no charged scalar boson exists in the SM, a discovery of a charged Higgs boson would provide unequivocal proof of physics beyond the SM. To date, various searches for an  $H^\pm$  signature have been conducted by the ATLAS and CMS Collaborations in proton-proton (pp) collisions at  $\sqrt{s} = 7, 8, \text{ and } 13$  TeV. Searches for a light  $H^\pm$  include the channels  $H^\pm \rightarrow \tau^\pm \nu_\tau$  [24–27],  $H^\pm \rightarrow cs$  [28, 29],  $H^\pm \rightarrow cb$  [30], and  $H^\pm \rightarrow W^\pm A$  [31]. In the heavy- $H^\pm$  region, the searches include the channels  $H^\pm \rightarrow tb$  [25, 32–34] and  $H^\pm \rightarrow \tau^\pm \nu_\tau$  [24–26, 35, 36]. Charged-current processes from low-energy flavor observables, such as tauonic B meson decays and the  $b \rightarrow s\gamma$  transition, have yielded indirect lower limits on  $m_{H^\pm}$  [37, 38]. Searches for  $H^\pm \rightarrow W^\pm Z$  decays predicted in Higgs triplet models [39–41] have also been conducted in the vector boson ( $V = Z$  or  $W$ ) fusion production mode [42–45]. Finally, the ATLAS Collaboration has set limits on  $H^\pm$  production with a search for dijet resonances in events with an isolated charged lepton [46]. No evidence of a charged Higgs boson has been reported in any of the aforementioned searches. Searches for additional heavy neutral Higgs bosons have also been performed at experiments at LEP [47] and the Tevatron [48–51]. These are superseded by searches performed by the ATLAS and CMS Collaborations in the  $bb$  [52–55],  $\mu\mu$  [56–59], and  $\tau\tau$  [56, 60–67] final states.

In this paper, a direct search for a heavy  $H^\pm$  is performed through the  $H^\pm \rightarrow HW^\pm$  and  $H \rightarrow \tau\tau$  decay modes, targeting the  $H^\pm \rightarrow HW^\pm$  decay channel for the first time at the LHC. In this search it is assumed that the H boson has a mass of  $m_H = 200$  GeV. This particular choice appears as a benchmark point in various scenarios such as extended Inert Doublet Models aiming to provide a viable dark matter candidate [68, 69], in 2HDM frameworks with new sources of CP-violation [70] or a strong first order electroweak phase transition [71] which are needed for a successful electroweak baryogenesis. Such heavy neutral scalars have also been proposed to address flavor puzzles such as the anomalous magnetic moment of the muon [72].

The search focuses on an associated  $H^\pm$  production with a hadronically decaying top quark, in final states with at least one tau lepton decaying hadronically ( $\tau_h$ ) and exactly one isolated lepton ( $\ell = e, \mu$ ), as shown in figure 2. Four distinct final states are targeted:  $e\tau_h$ ,  $\mu\tau_h$ ,  $e\tau_h\tau_h$ , and  $\mu\tau_h\tau_h$ . For the  $\ell\tau_h$  final states, candidate events contain one  $\tau_h$  candidate, one isolated lepton, missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ ), and three additional hadronic jets from W boson decays and b quarks. The  $\ell\tau_h$  search employs a multivariate analysis (MVA) classifier based on boosted decision tree with gradient boost (BDTG) to distinguish the signal from backgrounds. For the  $\ell\tau_h\tau_h$  final states, candidate events



**Figure 2.** Feynman diagrams showing the signal processes targeted by this analysis, with the production of a heavy  $H^+$  in the 4FS, followed by the  $H^+ \rightarrow HW^+$  and  $H \rightarrow \tau\tau$  decays, resulting in  $\ell\tau_h$  (left) and  $\ell\tau_h\tau_h$  (right) final states. Contributions to the  $\ell\tau_h$  final state may also arise from the right diagram when one  $\tau_h$  from the  $H \rightarrow \tau\tau$  decay is not reconstructed.

are selected by requiring one additional  $\tau_h$  candidate and by relaxing the hadronic jet multiplicity requirement to at least two. In these final states, the transverse mass of the charged Higgs boson,  $m_T$ , is used to distinguish signal from backgrounds. Upper limits on the product of the  $H^\pm$  production cross section,  $\sigma_{H^\pm}$ , and the branching fraction  $\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau)$  for the decay chain  $H^\pm \rightarrow HW^\pm$  with  $H \rightarrow \tau\tau$ , are presented as functions of  $m_{H^\pm}$ .

The paper is organized as follows. A brief description of the CMS detector is given in section 2, while the collision data and simulated samples are discussed in section 3. Section 4 describes the global event reconstruction and physics object identification, followed by the event selection in section 5. Background estimation, search strategy, and systematic uncertainties are described in sections 6, 7 and 8, respectively. Finally, the results are presented in section 9 and summarized in section 10.

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors up to  $|\eta| = 5$ . 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, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than  $4 \mu\text{s}$  [73]. 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 [74].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [75].

### 3 Collision data and simulated samples

The analysis presented in this paper uses pp collision data collected with the CMS experiment at  $\sqrt{s} = 13$  TeV during the years 2016, 2017, and 2018. The corresponding integrated luminosities are 36.3, 41.5, and 59.8 fb<sup>-1</sup>, respectively, amounting to a total of 138 fb<sup>-1</sup>. The aforementioned data were collected with the use of single-electron and single-muon triggers with isolation criteria. The trigger thresholds are mentioned in section 5.

Simulated events are used to model the signal and background processes using various Monte Carlo (MC) event generators. The signal samples are generated with the MADGRAPH5\_aMC@NLO generator [76] v2.2.2 for 2016 (v2.4.2 for 2017–2018) using the 4FS at next-to-LO (NLO) precision in quantum chromodynamics (QCD). The decays of the H<sup>±</sup> resonances are generated with MADSPIN [77] to preserve spin-correlation and finite-width effects. Both charge-conjugate signal processes are generated with four mass hypotheses  $m_{H^\pm} = 300, 400, 500, \text{ and } 700$  GeV and under the assumption that  $m_h = 125$  GeV and  $m_H = 200$  GeV.

The top quark-antiquark pair (t $\bar{t}$ ) production constitutes an important background that contributes significantly to all final states considered. It is simulated with NLO precision in QCD using the POWHEG v2.0 [78–83] generator. Its cross section is obtained from the TOP++ v2.0 [84] calculation that includes next-to-NLO (NNLO) corrections in QCD and resummation of the next-to-next-to-leading logarithmic soft-gluon terms. Other important sources of background include single top quark production (single t), t $\bar{t}$ X with X = W, Z, h, or t $\bar{t}$ , and electroweak processes including V+jets with V = Z or W and diboson (WZ, ZZ, WW) production. For the single t samples, the t-channel process is generated with POWHEG v2.0 at NLO precision in QCD using the 4FS [85] and interfaced with MADSPIN for simulating the top quark decay. The s-channel process is simulated using MADGRAPH5\_aMC@NLO, while the production via the tW-channel is simulated at NLO in QCD using the 5FS and POWHEG v2.0 [86]. The production of t $\bar{t}$  in association with W or Z boson is simulated with NLO precision in QCD using MADGRAPH5\_aMC@NLO. The t $\bar{t}$ h background process is generated using POWHEG v2.0 at NLO [87], with a Higgs boson mass of 125 GeV. The top quark mass is set to  $m_t = 172.5$  GeV. The V+jets samples are generated at leading-order (LO) precision using MADGRAPH5\_aMC@NLO, with up to four partons included in the matrix element (ME) calculations. Finally, the diboson processes are generated at LO precision using PYTHIA v8.212 [88].

For processes generated at LO precision in QCD, the MLM matching and merging procedure is used [89], whereby partons from the ME calculation are matched to the jets reconstructed after the perturbative shower. For processes generated at NLO precision in QCD with the MADGRAPH5\_aMC@NLO generator, the events from the ME characterized by different parton multiplicities are merged with the FxFx procedure [90]. The matching between the ME calculation and the parton shower in POWHEG v2.0 is controlled by the

damping factor  $h_{\text{damp}}$ , which has a value set to  $h_{\text{damp}} = 1.379m_t$ . It is used to limit the resummation of higher-order effects by the Sudakov form factor to below a given  $p_T$  scale.

For the generation of the above-mentioned simulated processes, the parton distribution functions (PDFs) are parameterized using NNPDF3.0 [91] for 2016 (NNPDF3.1 [92] for 2017–2018). The PDFs in the ME calculations are at NLO for NNPDF3.0 and at NNLO for NNPDF3.1. The parton shower and fragmentation are modeled with the PYTHIA generator v8.212 for 2016 samples (v8.230 for 2017–2018). The PYTHIA parameters affecting the description of the underlying event are set to the CUETP8M1 tune [93] for 2016 (CP5 tune [94] for 2017–2018). The response of the CMS detector is simulated using GEANT4 v9.4 [95] and reconstructed using the same version of the CMS software as that used for the collision data.

The effect of additional inelastic pp interactions within the same or nearby bunch crossings, henceforth referred to as pileup, is taken into account by generating concurrent minimum bias events. All simulated events are weighted to match the pileup distributions observed in the data. The average number of pileup in the 2016 data set was 23, increasing to 32 during the 2017–2018 data taking.

## 4 Object reconstruction

The global event reconstruction is based on the particle-flow (PF) algorithm [96], which uses an optimized combination of information from the elements of the CMS detector to reconstruct individual particles in an event. It categorizes these PF candidates as photons, electrons, muons, charged hadrons, and neutral hadrons. Higher-level objects are reconstructed from combinations of the PF candidates. The primary pp interaction vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone. More specifically, the individual tracks originating from the same candidate vertex are clustered using the anti- $k_T$  algorithm with a distance parameter of 0.4 [97], as implemented in the FASTJET library [98]. For each PV candidate the  $\sum p_T^2$  value is computed by considering the clustered jets, the remaining single tracks, and the neutral particle contributions inferred from the negative vector sum of the  $p_T$  of those jets. The PV with the largest  $\sum p_T^2$  is chosen as the one corresponding to the hard scattering. All other candidate vertices are attributed to pileup, with the exception of secondary vertices that are transversely displaced from the PV and indicative of decays of long-lived particles emerging from it.

Electrons are identified as charged-particle tracks that are potentially associated with ECAL energy clusters and bremsstrahlung photons emitted while traversing the tracker material. Their momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with  $p_T \approx 45$  GeV from  $Z \rightarrow ee$  decays ranges from 1.7 to 4.5%. It is generally better in the barrel region than in the endcaps, and also it depends on the bremsstrahlung energy emitted by the electron as it traverses the material in front of the ECAL. An MVA discriminant [99] is used to achieve better discrimination of prompt isolated electrons from other electron candidates, mainly originating from photon conversions, jet misidentification,

and semileptonic  $b$  hadron decays. It requires as input several variables describing the shapes of the energy deposits in the ECAL and the track quality. In this paper, a medium (loose) working point with an identification efficiency of 90 (>99)% is used for selecting (vetoing) electrons, corresponding to a rate of jets misidentified as electrons of  $\approx 1$  (20)%.

Muons are reconstructed as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. They are measured in the range of  $|\eta| < 2.4$ , with detection planes using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Their momentum is obtained from the curvature of the corresponding tracks in the silicon tracker, with a relative resolution of 1 and 3% for muons with  $p_T$  up to 100 GeV in the barrel and endcaps, respectively. The  $p_T$  resolution in the barrel is better than 7% for muons with  $p_T$  up to 1 TeV [100]. To increase the purity of prompt muons originating at the PV, a set of discriminants is employed based on the track fit quality, the number of hits per track, and the degree of compatibility of the information from the tracker and muon systems. A tight (loose) working point with an efficiency of  $\approx 95$  (99)% is used for selecting (vetoing) muons, in order to suppress muons from decays in flight and misidentified muons from hadronic punch-through.

Both prompt and displaced reconstructed leptons are used in this analysis, with the latter exclusively used in the validation of the background estimation, described in detail in section 6. In both cases the background contributions from misidentified leptons are further suppressed by applying stringent requirements on the lepton isolation. The relative lepton isolation variable  $I_{\text{rel}}$  is employed to ensure that the leptons are not associated with any significant electromagnetic or hadronic activity in the detector. It is defined as the scalar  $p_T$  sum, normalized to the lepton  $p_T$ , of all PF candidates within a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  (0.4) around the electron (muon) direction at the PV, where  $\phi$  is the azimuthal angle in radians. The lepton itself is excluded from the calculation. To mitigate any effects due to contamination from pileup, only PF candidates whose tracks are associated with the PV are taken into account. For neutral hadrons and photons, where the absence of an associated track precludes an unambiguous association with the PV, an estimate of the pileup contribution is subtracted from their energy sums [101]. A tight (loose) isolation criterion with discriminant  $I_{\text{rel}} < 0.15$  (0.25) is used in lepton selection (veto). The three-dimensional impact parameter significance, which is the impact parameter value normalized to its uncertainty, can also be used to further suppress electrons from photon conversions and muons originating from in-flight decays of hadrons. Its value is required to be less than ten for prompt electrons, or greater than three for all displaced electrons or muons.

Jets are reconstructed from PF candidates using the anti- $k_T$  algorithm [97], as implemented in the FASTJET package [98], with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet. It is found from simulation to be within 5–10% of the true momentum, over the whole  $p_T$  spectrum and detector acceptance. 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 [101]. 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 applied to simulated events [102]. After the corrections, the jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [102].

The identification of jets that originate from the hadronization of b quarks (b jets) is performed with the DEEPJET multiclass flavor-tagging algorithm, as described in refs. [103–105]. In this analysis, a medium working point of this algorithm is chosen that corresponds to a b-jet identification efficiency of  $\approx 80\%$ . The associated misidentification rate for jets originating from light quarks and gluons (c quarks) is 1 (15)% [104].

The  $\tau_h$  candidates are reconstructed with the hadrons-plus-strips algorithm, as described in ref. [106]. It uses clustered anti- $k_T$  jets as seeds to reconstruct  $\tau$  decay modes with one charged hadron and up to two neutral pions (one-prong), or three charged hadrons and up to one neutral pion (three-prong). The neutral pions, which decay promptly to a photon pair, are reconstructed as strips of  $p_T$ -dependent size in the  $\eta$ - $\phi$  plane from reconstructed electrons and photons contained in the jet. These strips are narrow in  $\eta$  but wide in  $\phi$  to allow for the broadening of ECAL energy deposits due to photon conversions. The  $\tau_h$  decay mode is then obtained by combining the charged hadrons with the strips, resulting in a reconstruction efficiency of  $\approx 80\%$ . To efficiently discriminate the  $\tau_h$  decays against jets originating from the hadronization of quarks or gluons, and against electrons or muons, the DEEPTAU [107, 108] multiclass  $\tau$  identification algorithm is used. It exploits the reconstructed event quantities by combining low-level information from the tracking, calorimeter, and muon detectors with high-level properties of the  $\tau_h$  candidate and other PF candidates in its vicinity. The multiclassification output  $y_\alpha$  represents a Bayesian probability that the  $\tau_h$  candidate originates from a lepton ( $\alpha = e, \mu$ ), the hadronization of a quark or gluon ( $\alpha = j$ ), or a genuine  $\tau_h$  ( $\alpha = \tau$ ). The aforementioned output enables the definition of three discriminators according to the ratio  $D_\alpha = y_\tau / (y_\tau + y_\alpha)$  with  $\alpha = e, \mu, j$ . For this analysis, medium and tight working points of  $D_e$  and  $D_\mu$  are used with efficiencies of 62 and 70% and misidentification rates of 0.2 and 0.03%, respectively. For  $D_j$ , the medium and loose working points are used with efficiencies of 49 and 70% for misidentification rates of 0.4 and 5%, respectively, for  $\tau_h$  candidates with  $p_T$  up to 200 GeV. The selected  $\tau_h$  candidates that pass the loose but fail the medium  $D_j$  working point are referred to as anti-isolated  $\tau_h$ 's and are solely used in the background estimation as described in section 6.

The  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector sum of the transverse momenta of all PF candidates in an event, and its magnitude is denoted as  $p_T^{\text{miss}}$  [109]. The  $\vec{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event. The scalar  $p_T$  sum of all selected leptons and  $\tau_h$  objects in an event is denoted as  $L_T$ , while the corresponding sum over all selected jets is designated as  $H_T$ . In addition, we define  $S_T$  as the scalar sum of  $p_T^{\text{miss}}$ ,  $L_T$ , and  $H_T$  in the event. The transverse mass of charged Higgs

boson candidates is calculated as:

$$m_T = \sqrt{(E_T^1 + E_T^2 + E_T^W + p_T^{\text{miss}})^2 - |\vec{p}_T^1 + \vec{p}_T^2 + \vec{p}_T^W + \vec{p}_T^{\text{miss}}|^2}, \quad (4.1)$$

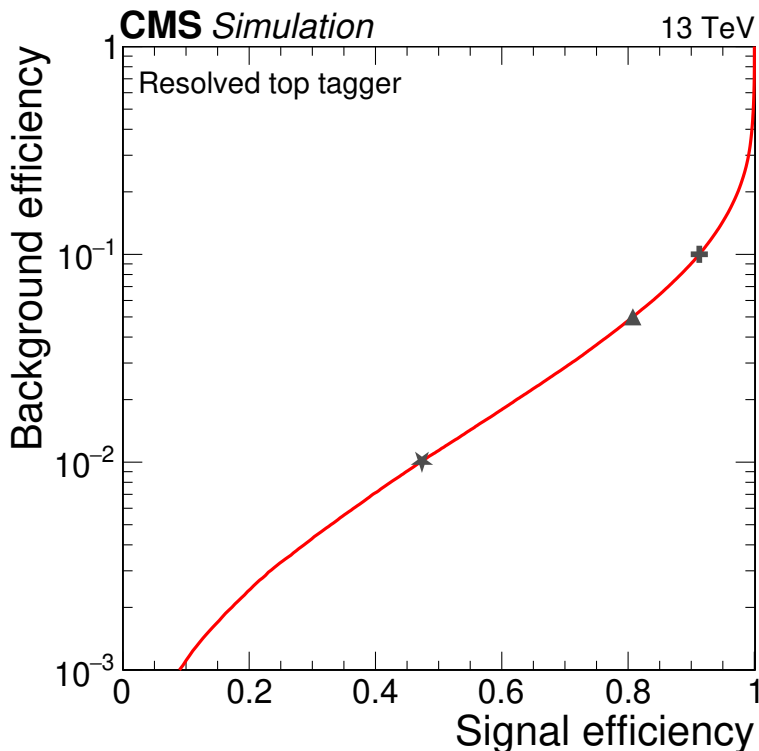
where  $E_T^1$ ,  $E_T^2$ , and  $E_T^W$  are the total visible transverse energies of the two tau lepton and W boson decay products, respectively, and  $\vec{p}_T^1$ ,  $\vec{p}_T^2$ , and  $\vec{p}_T^W$  the corresponding transverse momentum vectors.

Hadronic decays of top quarks are reconstructed and identified using a resolved top quark ( $t^{\text{res}}$ ) tagger that is based on a fully connected neural network implemented using KERAS [110] and TENSORFLOW [111] software packages. It targets top quarks whose decay products are resolved as three separate anti- $k_T$  jets with a distance parameter of 0.4. It is trained on simulated  $t\bar{t}$  events to discriminate between three-jet combinations originating from the decay of top quarks (signal) and other combinatorial three-jet systems (background). For training, the signal  $t^{\text{res}}$  candidates are matched to the generated top quark decay products with one-to-one jet-to-quark matching, while the  $t^{\text{res}}$  candidates with at least one unmatched jet are considered as combinatorial background.

This MVA classifier utilizes high-level information from each of the three seed jets, such as invariant masses, angular separations, jet flavor, and jet shape variables. All the selected variables are uncorrelated with the top quark mass to minimize possible correlations between the  $t^{\text{res}}$  candidate mass and the associated classifier output. To improve the stability and performance of the learning algorithm, the input features are transformed such that they are distributed in similar ranges and not influenced by outliers. This tagger uses the robust scaler preprocessing method via SCIKIT-LEARN tool [112]. Furthermore to prevent mass sculpting effects, the algorithm uses the sample-reweighting technique to decorrelate the classifier's output from the top quark mass. The mass information is removed from all the input features by reweighting the combinatorial background data sets so that the  $t^{\text{res}}$  candidate mass distribution matches that of the signal.

The performance of the  $t^{\text{res}}$  tagger is expressed as a receiver operating characteristic curve and it is shown in figure 3. The loose, medium, and tight working points are established at 10, 5, and 1% background misidentification probability. The corresponding identification efficiencies are 91, 81, and 47%, respectively. The loose working point is employed in this analysis.

The misidentification rate and tagging efficiency of the  $t^{\text{res}}$  tagger have been estimated and compared in data and simulation to extract data-to-simulation corrections, using a sample of lepton+jets, dominated by the semileptonic  $t\bar{t}$  events. The events are characterized by large  $p_T^{\text{miss}}$ , exactly one muon identified as tight with  $p_T > 50$  GeV and at least four jets with  $p_T > 40$  GeV and  $|\eta| < 2.4$ , of which at least one is b tagged. The jet closest to the muon is considered as the b jet from the leptonic top quark decay. The three-jet system with a mass closest to the top quark mass is selected as the hadronic  $t^{\text{res}}$  candidate. The misidentification rate is measured using events in which the  $t^{\text{res}}$  candidate mass,  $m_{t^{\text{res}}}$ , falls outside a mass window of 130–210 GeV, and the sample is dominated by the combinatorial background. Events where  $m_{t^{\text{res}}}$  is within the mass window are used to measure the  $t^{\text{res}}$  tagging efficiency, after subtracting from data the contributions from non-top quark

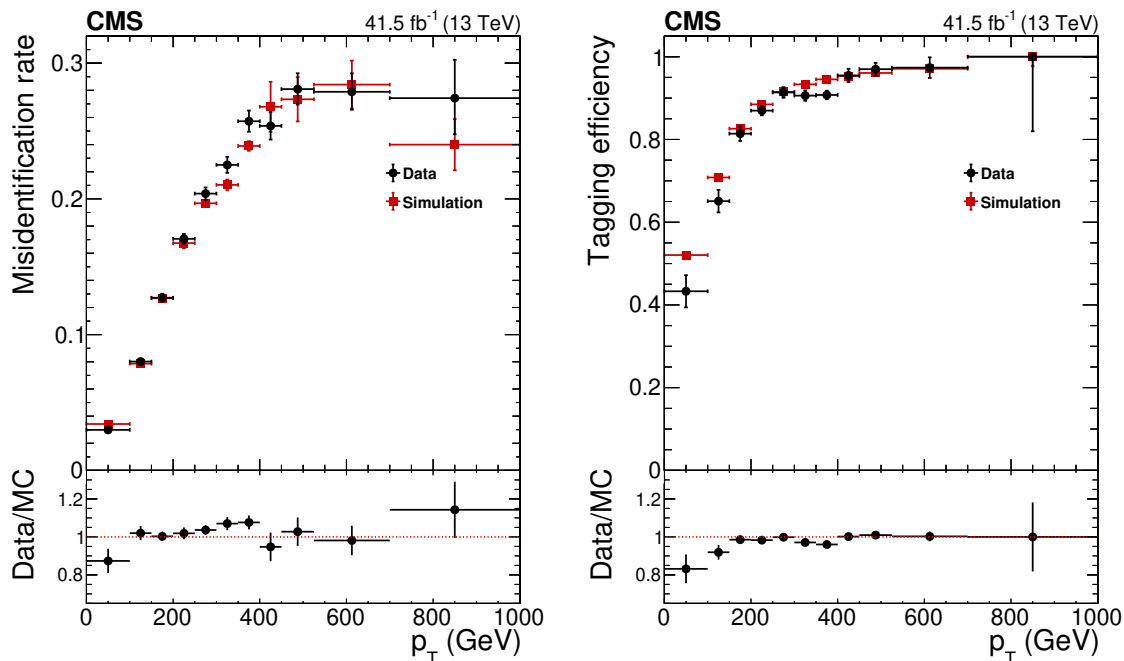


**Figure 3.** Receiver operating characteristic curve of the  $t^{\text{res}}$  tagger. The cross-, triangle-, and star-shaped markers indicate the loose, medium, and tight working points with 10, 5, and 1% background misidentification probability. The corresponding identification efficiencies are 91, 81, and 47%, respectively.

processes and the combinatorial background, as estimated from simulations. The misidentification rate and tagging efficiency for the 2017 data set are shown in figure 4 as a function of the  $t^{\text{res}}$  candidate  $p_T$  for the loose working point. The data-to-simulation corrections are defined as the ratio data/simulation, in  $p_T$  bins of the  $t^{\text{res}}$  candidate. Similar behavior was also observed for the 2016 and 2018 data.

## 5 Event selection

The analysis is conducted in the mutually exclusive  $e\tau_h$ ,  $\mu\tau_h$ ,  $e\tau_h\tau_h$ , and  $\mu\tau_h\tau_h$  final states. The event selection strategy is independently optimized for each final state to improve the suppression of backgrounds while maintaining a large signal selection efficiency. The selection of signal candidate events at the trigger level is based on the presence of at least a single isolated lepton. More specifically, for the  $e\tau_h$  and  $e\tau_h\tau_h$  channels the online HLT requires the presence of an isolated electron with a  $p_T$  threshold of 27, 32, and 32 GeV for the data-taking years 2016, 2017, and 2018, respectively. For the  $\mu\tau_h$  and  $\mu\tau_h\tau_h$  channels, an isolated muon is required, with  $p_T$  thresholds of 24, 27, and 24 GeV for the three years. The HLT objects are geometrically matched to analogous offline objects that satisfy the  $p_T$ ,  $\eta$ ,



**Figure 4.** Misidentification rate (left) and  $t^{\text{res}}$ -tagging efficiency (right) in data and simulation, as a function of the  $t^{\text{res}}$  candidate  $p_T$  for the loose working point, using the 2017 data.

$I_{\text{rel}}$  criteria described in the following, in addition to the object identification requirements given in section 4.

To ensure high trigger efficiency, the offline  $p_T$  and  $\eta$  requirements for prompt electrons (muons) are  $p_T > 30, 35, 35$  (26, 29, 26) GeV and  $|\eta| \leq 2.1$  (2.4) for the 2016, 2017, and 2018 data-taking periods. Selected electrons (muons) are also required to pass medium (tight) identification criteria and satisfy  $I_{\text{rel}} < 0.15$  for all three years. Only events with exactly one such electron (muon) are accepted. Furthermore, events with any additional electrons or muons fulfilling looser identification criteria are also discarded, provided that the electron (muon) candidates satisfy the requirements of  $p_T > 10$  GeV,  $|\eta| \leq 2.4$  (2.5), and  $I_{\text{rel}} < 0.25$ . This helps to avoid the incorrect assignment of objects in the transverse mass reconstruction and the inadvertent smearing of its Jacobian peak, and ensures the orthogonality between final states with different lepton flavors.

In both the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  final states, all  $\tau_h$  candidates are required to have  $p_T > 20$  GeV and  $|\eta| < 2.3$ . They must be well separated in  $\eta$ - $\phi$  space from the trigger lepton and other  $\tau_h$  candidates, such that  $\Delta R(\tau_h, \ell/\tau_h) > 0.5$ . To reduce the contribution of electrons, muons, or jets mimicking a  $\tau_h$  object, the medium, tight, and medium working points of the  $D_e$ ,  $D_\mu$ , and  $D_j$  discriminants are chosen, irrespective of final state, or year of data taking. In the  $\ell\tau_h$  final states, the events are classified according to the sum of the electric charge of the selected lepton and  $\tau_h$  objects,  $Q_{\ell\tau_h}$ , in units of the electron charge  $e$ . Both the opposite-sign (OS) case with  $|Q_{\ell\tau_h}| = 0$  and the same-sign (SS) case with  $|Q_{\ell\tau_h}| = 2$  are considered as separate categories. The categorisation of the  $\ell\tau_h$  final states into OS and SS significantly improves the expected sensitivity over the entire  $m_{H^\pm}$  region

considered. Events in the  $\ell\tau_h$  SS category arise when one of the tau leptons from the  $H \rightarrow \tau\tau$  decay is not reconstructed or identified. It has significantly smaller contributions from SM processes with a top quark in the final state than the  $\ell\tau_h$  OS category. In the  $\ell\tau_h\tau_h$  final states, the two  $\tau_h$  candidates are required to be OS with  $|Q_{\tau_h\tau_h}| = 0$ .

The  $\ell\tau_h$  final states are required to contain at least three jets with  $p_T > 30$  GeV and  $|\eta| < 2.4$ , for all data-taking years. Slightly modified criteria are used for the  $\ell\tau_h\tau_h$  final states, with the multiplicity requirement reduced to two and the pseudorapidity extended to  $|\eta| < 4.7$ , in order to increase the signal acceptance. All selected jets must be well separated from the reconstructed  $\tau_h$  objects such that  $\Delta R(j, \tau_h) > 0.5$ . We denote the selected jet with the highest (second-highest)  $p_T$  in each event as  $j_1$  ( $j_2$ ). For all final states considered, at least one of the selected jets is required to pass the medium working point of the DEEPJETb jet identification algorithm.

To further suppress multijet events with nonprompt leptons and jets misidentified as  $\tau_h$ , the  $\ell\tau_h$  ( $\ell\tau_h\tau_h$ ) final states require the presence of moderate magnitude of missing transverse momentum of  $p_T^{\text{miss}} \geq 40$  (30) GeV. For the  $\ell\tau_h\tau_h$  final state, the requirement  $S_T > 400$  GeV is also used as it considerably improves the expected sensitivity. A summary of the event selection criteria for all final states is shown in table 1. They result in a total of 6 signal regions (SRs) per year of data taking;  $e\tau_h$  OS,  $e\tau_h$  SS,  $\mu\tau_h$  OS,  $\mu\tau_h$  SS,  $e\tau_h\tau_h$ , and  $\mu\tau_h\tau_h$ . They are complemented by the various control regions (CRs) and validation regions (VRs) described in section 6, which are used to predict the dominant backgrounds in the statistical inference of the signal.

## 6 Background estimation

The dominant background for all the final states considered stems from  $V$ +jets and  $t\bar{t}$  productions. This can be decomposed into events with genuine  $\tau_h$  candidates, and events with leptons or jets misidentified as  $\tau_h$  candidates. Backgrounds from events with genuine  $\tau_h$  candidates, together with events involving electrons or muons misidentified as  $\tau_h$  objects ( $\ell \rightarrow \tau_h$ ) are estimated from simulation. The reconstructed  $\tau_h$  candidate is matched to a generator-level tau lepton, electron, or muon using a cone of  $\Delta R = 0.1$ . Backgrounds from jets misidentified as  $\tau_h$  candidates ( $j \rightarrow \tau_h$ ) are estimated using control samples in data by the use of misidentification rates. These misidentification rates are measured in dedicated CRs that are enriched in jets misidentified as  $\tau_h$  candidates, and mimic as closely as possible the composition and kinematic properties of the corresponding SRs. The CRs are required to be orthogonal to all SRs and have negligible signal contamination. Then, the misidentification rate is defined as:

$$\mathcal{R}_{j \rightarrow \tau_h} = \frac{N_{\text{nominal } \tau_h}^{\text{CR}}}{N_{\text{loose } \tau_h}^{\text{CR}}} \tag{6.1}$$

where  $N_{\text{nominal } \tau_h}^{\text{CR}}$  is the number of events in the CR satisfying the nominal  $\tau_h$  selection criteria, and  $N_{\text{loose } \tau_h}^{\text{CR}}$  is the corresponding number of events in the CR satisfying loose  $\tau_h$  selection criteria. For both the numerator and denominator in eq. (6.1) a correction is

Object	Selection	Signal Regions			
		$e\tau_h$	$\mu\tau_h$	$e\tau_h\tau_h$	$\mu\tau_h\tau_h$
Prompt electrons	$N$	=1	=0	=1	=0
	$p_T$	>(30, 35, 35)	>10	>(30, 35, 35)	>10
	$ \eta $	<2.1	<2.5	<2.1	<2.5
	$I_{rel}$	<0.15	<0.25	<0.15	<0.25
Prompt muons	$N$	=0	=1	=0	=1
	$p_T$	>10	>(26, 29, 26)	>10	>(26, 29, 26)
	$ \eta $	<2.4	<2.4	<2.4	<2.4
	$I_{rel}$	<0.25	<0.15	<0.25	<0.15
$\tau_h$ objects	$N$		=1		=2
	$p_T$		>20		>20
	$ \eta $		<2.3		<2.3
	$ Q_{\star\tau_h} $		=0, 2		=0
Jets	$N$		$\geq 3$		$\geq 2$
	$p_T$		>30		>30
	$ \eta $		<2.4		<4.7
b jets	$N$		$\geq 1$		$\geq 1$
	$p_T$		>30		>30
	$ \eta $		<2.4		<2.4
Event-based	$p_T^{miss}$		>40		>30
	$S_T$		—		>400

**Table 1.** Offline selections applied to the reconstructed objects to obtain the SRs of the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  final states. The  $p_T$ ,  $p_T^{miss}$ , and  $S_T$  variables are reported in units of GeV, and  $Q$  in units of  $e$ . Selection criteria that depend on the year of data taking are presented in parentheses with the order corresponding to (2016, 2017, 2018). The symbol  $\star$  is used to represent an electron (muon) for the  $e\tau_h$  ( $\mu\tau_h$ ) final states, and a  $\tau_h$  object in the  $e\tau_h\tau_h$  and  $\mu\tau_h\tau_h$  final states.

applied to remove events containing jets originating from a genuine  $\tau_h$  candidate or from a lepton misidentified as a  $\tau_h$  candidate.

The misidentification rate measurements are performed in different CRs, separately for each final state and data-taking period. In the  $\ell\tau_h$  channels, the CRs are selected with the nominal criteria used in defining the SRs, but with the following modifications. The  $p_T^{miss}$  criterion is inverted such that  $p_T^{miss} < 40$  GeV, while the requirement of exactly one  $t^{res}$  object is also introduced to suppress contributions from  $V$ +jets processes. The motivation for these selections is twofold: to enforce orthogonality with the SRs, and to ensure that the obtained regions are enriched in  $t\bar{t}$ . A second set of CRs, orthogonal to all other CRs and SRs, is also used with alternative selection criteria that are introduced to enhance electroweak contributions. More specifically, the  $p_T^{miss}$  requirement is removed, the b jet multiplicity is inverted, and the requirement of exactly one  $t^{res}$  object is also imposed.

These auxiliary CRs are used to quantify systematic uncertainties related to differences in sample composition between the SRs and the CRs, and in particular the relative contribution of  $t\bar{t}$  and electroweak processes. The misidentification rates are measured as a function of the  $\tau_h$  candidate  $p_T$ , separately for one- and three-prong decays, and individually for the central ( $|\eta| \leq 1.5$ ) and forward regions ( $|\eta| \geq 1.5$ ) of the detector.

In the  $\ell\tau_h\tau_h$  channels, the misidentification rates are measured using similar event selection as in the SRs, except that the two  $\tau_h$  objects are required to be SS with  $|Q_{\tau_h\tau_h}| = 2$ , and no requirement is imposed on the  $S_T$  variable. To compensate for the lower statistical precision relative to the  $\ell\tau_h$  final states, the misidentification rates are parametrized in the  $p_T$  and decay mode of the  $\tau_h$  objects, without separating the central and forward regions of the detector.

The predicted number of events with misidentified  $\tau_h$  objects in the SRs is derived using the fake factor method [113] by applying the misidentification rates evaluated in the CRs to events with anti-isolated  $\tau_h$  objects:

$$N_{j \rightarrow \tau_h}^{\text{SR}} = \sum_i w_i^{\text{CR}} N_{\text{one anti-isolated } \tau_h, i}^{\text{SR}} - \sum_i w_{i,1}^{\text{CR}} w_{i,2}^{\text{CR}} N_{\text{two anti-isolated } \tau_h, i}^{\text{SR}}. \quad (6.2)$$

The index  $i$  refers to each bin of the parametrization and  $w_i$  to the corresponding normalization weight. The term  $N_{\text{anti-isolated } \tau_h, i}^{\text{SR}}$  refers to number of events with anti-isolated  $\tau_h$  objects in the SR of interest, after subtracting events with jets originating from a genuine  $\tau_h$  or from a lepton misidentified as a  $\tau_h$  candidate. The normalization weight for a given parametrization bin  $i$  is given by:

$$w_i^{\text{CR}} = \frac{\mathcal{R}_{j \rightarrow \tau_h, i}}{1 - \mathcal{R}_{j \rightarrow \tau_h, i}} \quad (6.3)$$

for each event with a single anti-isolated  $\tau_h$  candidate present. In the  $\ell\tau_h\tau_h$  final states, eq. (6.3) must be applied to each of the two  $\tau_h$  candidates that are present. It thus accounts for the case where only one of the  $\tau_h$  candidate is a misidentified  $\tau_h$ , but also includes cases whereby both  $\tau_h$  candidates are misidentified and one of them passes all nominal identification criteria. In order to account for this double counting, the number of misidentified  $\tau_h$  events is predicted by the weighted sum of the number of events with one anti-isolated  $\tau_h$  candidate minus the weighted number of events with two anti-isolated  $\tau_h$  candidates.

The validity of the extracted misidentification rates is verified by defining additional VRs with either anti-isolated or isolated  $\tau_h$  candidates, mutually orthogonal to both the SRs and CRs. The misidentification rates are used to normalize the misidentified  $\tau_h$  samples from the anti-isolated VRs to a signal-depleted VR with isolated  $\tau_h$  candidates, where the obtained background prediction is compared with the observed data. This validation is performed separately for all channels and data-taking periods.

In the  $\ell\tau_h$  channels, the VRs are defined by selecting events with the same selection criteria as those used for the SRs. However, instead of requiring the presence of one b jet in the  $e\tau_h$  ( $\mu\tau_h$ ) region, a low- $p_T$  loosely identified and loosely isolated displaced muon (electron) is required. In the  $\ell\tau_h\tau_h$  channels, the validation of the background estimation

is performed using two VRs. The first VR is defined by using similar event selections to the SRs but vetoing events with identified b jets, while also removing any requirements on the  $S_T$  variable. For the second VR, events are selected with identical criteria as for the SR, except that the  $S_T$  requirement is inverted to satisfy  $S_T < 400$  GeV. A summary of the event selection criteria for the CRs and the VRs used is shown in table 2, indicating only selections that are different than their respective SRs defined in table 1.

Object	Selection	Control Regions		Validation Regions			
		$\ell\tau_h$	$\ell\tau_h\tau_h$	$e\tau_h$	$\mu\tau_h$	$\ell\tau_h\tau_h$	
Displaced electrons	$N$	—	—	—	=1	—	—
	$p_T$	—	—	—	>10	—	—
	$ \eta $	—	—	—	<2.5	—	—
	$I_{\text{rel}}$	—	—	—	<0.25	—	—
Displaced muons	$N$	—	—	=1	—	—	—
	$p_T$	—	—	>10	—	—	—
	$ \eta $	—	—	<2.4	—	—	—
	$I_{\text{rel}}$	—	—	<0.25	—	—	—
$\tau_h$ objects	$ Q_{\star\tau_h} $	—	=2	—	—	—	—
b jets	$N$	—	—	$\geq 0$	$\geq 0$	=0	—
$t^{\text{res}}$	$N$	=1	—	—	—	—	—
Event-based	$p_T^{\text{miss}}$	<40	—	—	—	—	—
	$S_T$	—	>0	—	—	>0	<400

**Table 2.** Offline selections applied to the reconstructed objects to obtain the CRs and VRs for the misidentified  $\tau_h$  candidate background estimation in the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  final states. Only differences with respect to the corresponding SRs are shown. The  $p_T$ ,  $p_T^{\text{miss}}$ , and  $S_T$  variables are reported in units of GeV, and  $Q$  in units of  $e$ . The symbol  $\star$  is used to represent an electron (muon) for the  $e\tau_h$  ( $\mu\tau_h$ ) final states, and a  $\tau_h$  object in the  $e\tau_h\tau_h$  and  $\mu\tau_h\tau_h$  final states.

## 7 Search strategy

To maximize the sensitivity of the search, the discriminating variable used to separate between the signal and background processes is chosen separately for the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  final states. For the latter, the search strategy focuses on the reconstruction of the full  $H^\pm$  decay chain in order to search for localized excesses in the  $m_T$  spectrum, as per eq. (4.1). For the hypothetical signal, the  $m_T$  distribution should possess a Jacobian peak with an endpoint at  $m_T = m_{H^\pm}$  that remains unchanged by the transverse motion of the mother particle. For the  $\ell\tau_h$  final states, the ambiguity in the selection of the jets that go into the  $m_T$  calculation results in a combinatorial background that smears the discriminating power of the variable. Thus, while still valuable, the  $m_T$  is not an optimal variable for signal extraction in the  $\ell\tau_h$  channels.



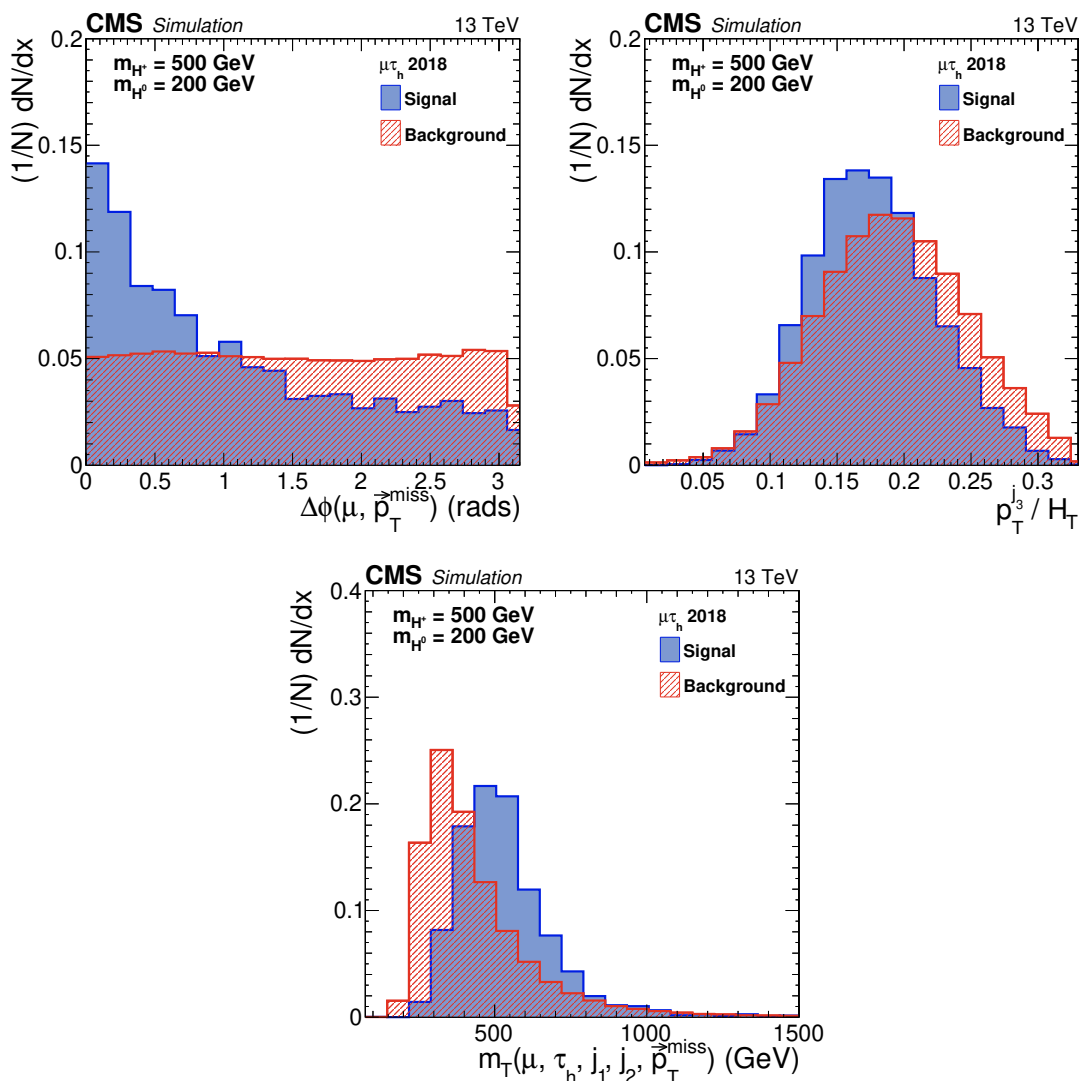
Variable	Description
$\Delta\phi(\tau_h, \vec{p}_T^{\text{miss}})$	azimuthal angle between the $\tau_h$ and $\vec{p}_T^{\text{miss}}$ objects
$\Delta\phi(\ell, \vec{p}_T^{\text{miss}})$	azimuthal angle between the $\ell$ and $\vec{p}_T^{\text{miss}}$ objects
$\frac{p_T^{j_1 j_2} - p_T^{H^\pm}}{p_T^{j_1 j_2} + p_T^{H^\pm}}$	ratio of $p_T$ sums calculated from $\ell$ , $\tau_h$ , $j_1$ , $j_2$ and $\vec{p}_T^{\text{miss}}$
$\frac{p_T^{j_1 j_2}}{H_T}$	ratio of $p_T$ of the first two leading jets and the $H_T$
$m_T(\ell, \tau_h, j_1, j_2, \vec{p}_T^{\text{miss}})$	$m_T$ reconstructed from $\ell$ , $\tau_h$ , $j_1$ , $j_2$ , and $\vec{p}_T^{\text{miss}}$
$\frac{p_T^{j_3}}{H_T}$	ratio of the $p_T$ of the third leading jet and the $H_T$
$m(\ell, \tau_h)$	invariant mass of the $\ell$ and $\tau_h$ objects
$\frac{p_T^{j_1 j_2} + L_T}{H_T}$	ratio of $p_T$ of first two leading jets plus $L_T$ and the $H_T$
$m_T(\ell, \vec{p}_T^{\text{miss}})$	$m_T$ reconstructed from the $\ell$ and $\vec{p}_T^{\text{miss}}$ objects
$p_T^{\tau_h}$	transverse momentum of $\tau_h$ object
$N_{\text{jets}}$	number of selected jets in the event
$N_{t^{\text{res}}}$	number of selected $t^{\text{res}}$ objects in the event

**Table 3.** The complete set of discriminating variables used in the training of the BDTG classifier employed in the search strategy of the  $\ell\tau_h$  final states.

In order to enhance the signal and background separation in the  $\ell\tau_h$  final states, an MVA BDTG classifier is employed using the TMVA [114] framework. The training was performed separately for each simulated signal sample, final state, and data-taking period. The inclusive  $V$ +jets and  $t\bar{t}$  simulated samples were used to train against the background, weighted according to their cross-sections. A total of 12 input variables were used for the training of the BDTG classifiers and include kinematic variables of individual physics objects, as well as event-based variables. They are summarized in table 3. All kinematic and event-based variable distributions were verified to agree in shape between data and background estimates.

Three of these variables are shown in figure 5 for the  $\mu\tau_h$  final state and the 2018 data-taking period. Figure 5 (top left) shows the azimuthal angle between the  $\mu$  and  $\vec{p}_T^{\text{miss}}$ , denoted as  $\Delta\phi(\mu, \vec{p}_T^{\text{miss}})$ . In the same figure (top right) the ratio of the  $p_T$  of the third leading jet and the  $H_T$ , denoted as  $p_T^{j_3}/H_T$  is shown. Finally, the transverse mass  $m_T(\mu, \tau_h, j_1, j_2, \vec{p}_T^{\text{miss}})$  reconstructed from the selected  $\mu$ ,  $\tau_h$ ,  $j_1$ ,  $j_2$ , and  $\vec{p}_T^{\text{miss}}$  objects is shown in figure 5 (bottom). Instead of being used as an input to the BDTG, the event-variable  $Q_{\ell\tau_h}$  is used for the categorization of  $\ell\tau_h$  events, as it increases signal sensitivity over the entire mass spectrum. In particular, the SS selection significantly suppresses the  $t\bar{t}$  contribution that dominates the OS category, leaving the misidentified  $\tau_h$  as the dominant

background.



**Figure 5.** Three of the BDTG input variables used for the  $\mu\tau_h$  final state, assuming a signal with mass  $m_{H^\pm} = 500$  GeV and 2018 data-taking conditions: the azimuthal angle between the  $\mu$  and  $\vec{p}_T^{\text{miss}}$  objects (top left), the ratio of the  $p_T$  of the third leading jet and the  $H_T$  (top right), and the transverse mass reconstructed from the  $\mu$ ,  $\tau_h$ ,  $j_1$ ,  $j_2$ , and  $\vec{p}_T^{\text{miss}}$  objects (bottom). Both signal and background distributions are normalized to unit area.

## 8 Systematic uncertainties

The systematic uncertainties from various experimental and theoretical sources can affect the expected event yield (rate uncertainties), the shape of the fit discriminant (shape uncertainties), or both. Log-normal (Gaussian) a priori distributions are assumed for rate (shape) uncertainties. Partial and complete correlations between the uncertainties in different categories and years are taken into account, depending on the way they are derived.

All experimental sources are treated as correlated across categories but as uncorrelated across years, unless otherwise specified. All theoretical sources are treated as correlated across all categories and years. A summary of all sources of systematic uncertainties discussed in this section is given in table 4.

Apart from the various experimental uncertainties, the statistical analysis of the results employs an uncertainty model that also accounts for uncertainties due to the limited population of template distributions in signal and background modeling. These statistical uncertainties can lead to fluctuations in nominal predictions and their effect is individually incorporated for each template bin with the *Barlow–Beeston lite* approach [115, 116]. Each bin is assigned a combined statistical uncertainty, and these uncertainties are treated as uncorrelated among other bins, categories, channels, and data sets.

## 8.1 Experimental sources

The integrated luminosity for each year of data taking is measured individually with an uncertainty in the 1.2–2.5% range [117–119]. The total integrated luminosity for the period 2016–2018 has an uncertainty of 1.6%. The improvement in precision reflects the uncorrelated time evolution of some systematic effects. These effects are applied as rate uncertainties to all simulated processes and thus only affect the expected yield of events, but not the individual shapes of the fit discriminants.

Uncertainties related to the electron and muon trigger efficiencies arise from the fact that simulated events are corrected to match the efficiencies measured in data. The uncertainties in the corrections, which depend on the  $p_T$  and  $\eta$  of the trigger object, lead to rate and shape effects in the fit discriminants that amount to 1–4%.

During the 2016–2017 data taking, a gradual shift in the timing of the ECAL inputs to the first-level trigger in the region of  $|\eta| > 2.0$  caused a trigger inefficiency of  $\approx 10$ –20% for events containing an electron (jet) with  $p_T \gtrsim 50$  (100) GeV and in the region  $2.5 < |\eta| < 3.0$ , depending on  $p_T$ ,  $\eta$ , and time. Corresponding correction factors were derived from data and applied to the acceptance evaluated from simulation. The related uncertainties, which are treated as correlated between the two years and all categories, are found to affect the expected event yields by  $\approx 1\%$  when propagated to the final fit discriminants.

The uncertainty due to the pileup modeling in simulated samples is estimated by varying the total inelastic pp cross section used to estimate the number of pileup events in data. The nominal value of 69.2 mb is varied by 5% [120, 121] and the effect is propagated through all event selections. The resulting uncertainty amounts to up to 5.5%, and is treated as correlated across all categories and years.

Uncertainties associated with the identification efficiency for electrons and muons are propagated as variations to the final fit discriminants. They are treated as correlated across all categories and years and result in shape-altering variations that change the total event yield by about 0.1–2.4%. The uncertainty related to the vetoing of leptons passing loose selection criteria is between 0.1 and 2.0%.

The uncertainties associated with the  $\tau_h$  identification efficiency are evaluated in  $p_T$  bins of the  $\tau_h$  object and range between 0.1 and 5.3%. The  $\tau_h$  energy scale uncertainties are found to be up to about 2.0%, depending on the decay mode of the  $\tau_h$  object. For

the energy and momentum scale of electrons and muons misidentified as  $\tau_h$  candidates, the relevant corrections depend on the  $p_T$  and decay mode of the candidate and their uncertainties are of  $\mathcal{O}(1\%)$ . The above-mentioned uncertainties lead to shape effects and are treated as uncorrelated across  $p_T$  bins and decay modes.

The jet energy scale uncertainties are specified as functions of jet  $p_T$  and  $\eta$  and are treated as correlated across all categories and years. They are estimated by shifting the energy of jets and propagating these shifts through the analysis selections. This results in rate- and shape-altering variations of  $\mathcal{O}(5\%)$ . The energy resolution of simulated jets is adjusted to match the resolution observed in data. The uncertainties in the jet energy resolution are evaluated by smearing the jet energies around their nominal values. These are treated as uncorrelated across the years and correlated across categories and result in an overall effect of  $\mathcal{O}(5\%)$ .

Jet energy uncertainties are also propagated to the  $\vec{p}_T^{\text{miss}}$  calculation to account for the fact that it primarily relies on the accurate measurement of the reconstructed physics objects. Another uncertainty in the  $\vec{p}_T^{\text{miss}}$  measurement is related to the unclustered energy in the event. It refers to jets with  $p_T < 10$  GeV and PF candidates not clustered into jets. This unclustered energy scale uncertainty impacts both the rate and the shape of the fit discriminants and has an overall effect of up to 2.4%.

The efficiency of classifying jets as b tagged is different in data than in simulation. To correct for this effect  $p_T$ -dependent corrections are incorporated. The systematic uncertainties in these tagging and mistagging efficiency corrections are treated as rate and shape altering. They are found to have an effect of  $\mathcal{O}(5\%)$  in the expected event yields.

The uncertainties associated with the  $t^{\text{res}}$  tagging and mistagging efficiency corrections are only relevant for the  $\ell\tau_h$  categories. They are evaluated in bins of  $p_T$  of the selected  $t^{\text{res}}$  and the various sources of uncertainty are treated as uncorrelated. These include effects due to the generator-level matching definition, the damping of radiation with high  $p_T$ , the modeling of the first emission, the scale radiation, the color reconnection strength, the assumed value of the top quark mass, and the tuning of the underlying event parameters. These are propagated to the fit discriminants of the  $\ell\tau_h$  final states as shape uncertainties and are found to change the total event yield by about 5% for tagging and 8% for mistagging.

For the misidentified  $\tau_h$  background estimation three distinct components of uncertainties are defined. The first component is the statistical uncertainty associated with the evaluation of the misidentification rates in the dedicated CRs. The various parametrization bins that are used in the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  channels for this measurement, as described in section 6, are treated as uncorrelated. The propagation of the statistical uncertainty in the final fit discriminants has an overall effect of  $\mathcal{O}(10\%)$ . The second component is concerned with a rate and shape-altering uncertainties implemented to address the level of agreement of closure tests in the VRs. Their impact on the expected event yield is  $\mathcal{O}(10\%)$ . The third component accounts for the difference in sample composition between the CRs in which the misidentification rates are determined, and the SRs in which they are applied. It is treated as uncorrelated between the parametrization bins and when propagated to the final fit discriminants brings about an overall effect of up to 18%.

## 8.2 Theoretical sources

The systematic uncertainties related to theoretical considerations mainly arise due to missing higher-order QCD corrections and uncertainties in the PDF sets. An additional source of uncertainty concerns the assumed values of the top quark mass  $m_t$  and that of the strong coupling  $\alpha_S$  in parton showers [122]. These affect both the total and differential cross sections of the processes, yielding uncertainties on the overall normalization of the simulated processes and the acceptance of the event selection. All effects are taken into account as rate uncertainties.

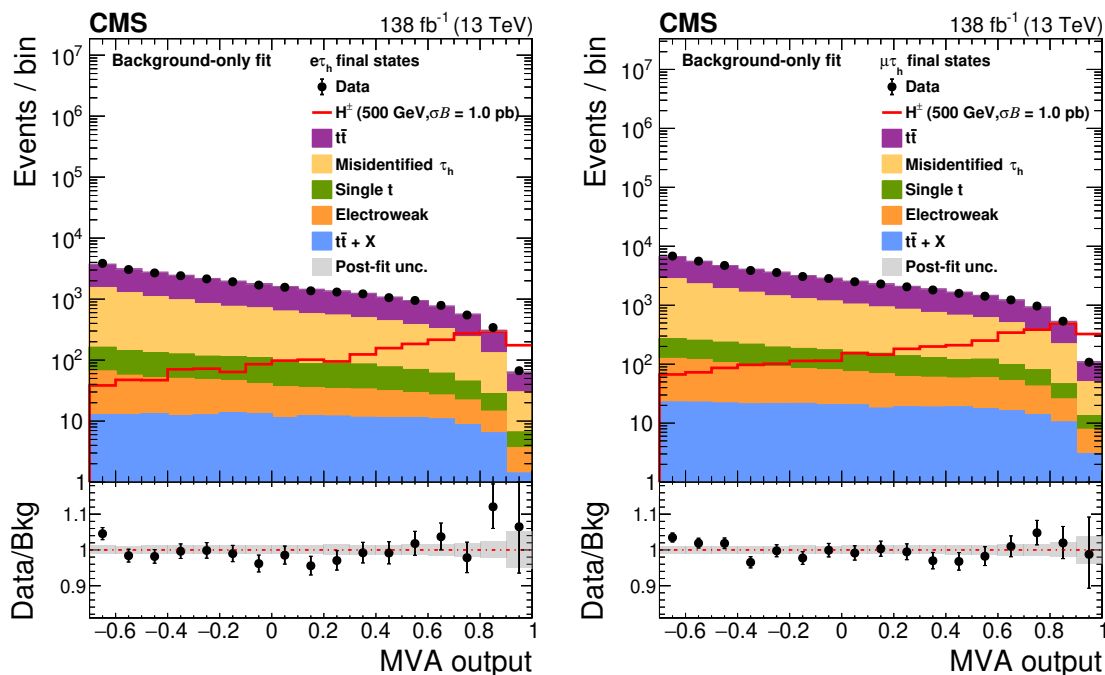
For the  $t\bar{t}$  and single  $t$  processes, the effect of  $m_t$  on the cross sections is evaluated by varying its nominal value of 172.5 GeV by 1.0 GeV. The effects from the renormalization and factorization (RF) scales on the acceptance and cross sections are evaluated by varying them independently by factors of one-half and two with respect to their nominal values, respectively. Extreme variations where one scale is varied by one-half and the other one by two are excluded. The effect on the event yield from simulated events is then calculated by enveloping the maximum variation with respect to the nominal fit discriminants, as recommended in ref. [123].

The PDF uncertainties are also treated as fully correlated for all processes and categories. They are also correlated between simulated samples that share the same dominant partons in the initial state of the ME calculations [124].

## 9 Results

Binned MVA output distributions in the  $\ell\tau_h$  analysis and  $m_T$  distributions in the  $\ell\tau_h\tau_h$  analysis are used to test the compatibility of the observed data with the presence or absence of a signal. Data are split in 6 categories determined by the lepton flavor in the final state (e or  $\mu$ ), for each of the three years of data taking. For the  $\ell\tau_h$  final states the number of categories is double due to the consideration of the sum of the electric charge of the lepton and  $\tau_h$  objects. Therefore there are 18 categories in total; 12 associated with the  $\ell\tau_h$  analysis and 6 with the  $\ell\tau_h\tau_h$  analysis. A simultaneous binned maximum likelihood fit is performed over all categories and data sets. The likelihood incorporates all the systematic uncertainties described in section 8 as nuisance parameters, with shape variations taken into account via continuous morphing [116].

No significant excess is found in any of the categories considered. The distributions for the fit performed under the background-only hypothesis are shown in figures 6 and 7 for the  $\ell\tau_h$  and  $\ell\tau_h\tau_h$  final states, respectively, whereby all categories for each individual final state are added into a single distribution. For the  $\ell\tau_h\tau_h$  final states, the distributions are binned with variable width and according to the statistical precision of the samples. In order to retain the shape of the distributions, each bin is divided by their width. The pre-fit contribution of a hypothetical  $H^\pm \rightarrow HW^\pm$  signal with masses  $m_{H^\pm} = 500$  GeV and  $m_H = 200$  GeV is also shown, normalized assuming that the product of the cross section and branching fraction  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau)$  is 1 pb. Tabulated results are provided in the HEPData record for this analysis [125].

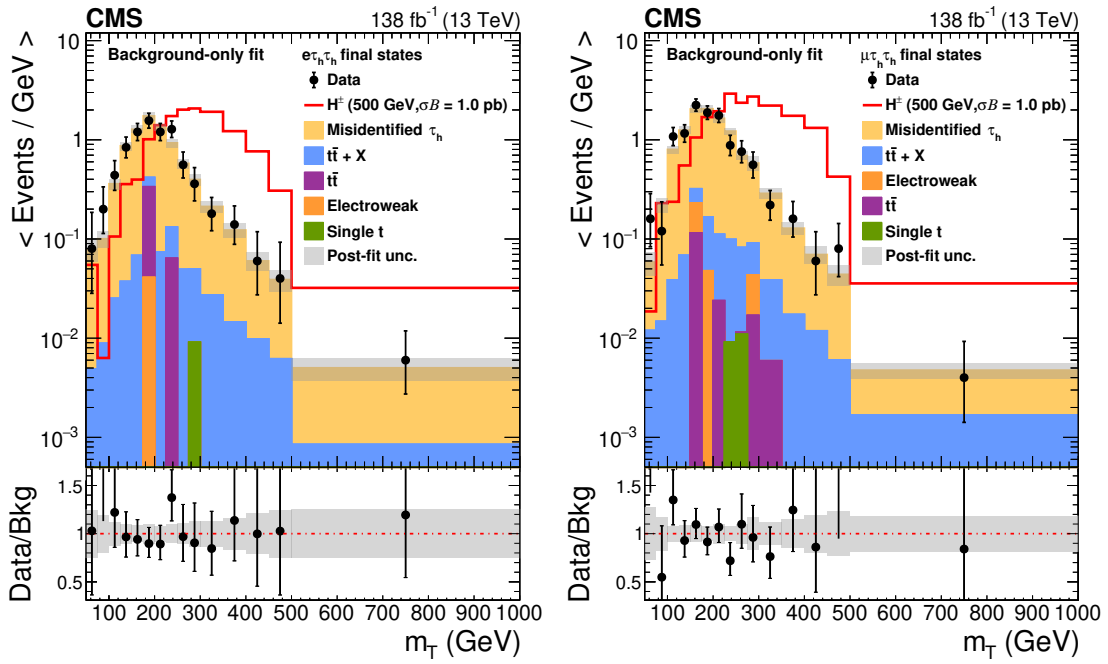


**Figure 6.** The MVA output of the BDTG for the  $e\tau_h$  (left) and  $\mu\tau_h$  (right) final states used in the limit extraction, after a background-only fit to the data. The data sets of all categories have been added. The pre-fit contribution from  $H^\pm \rightarrow HW^\pm$  with masses  $m_{H^\pm} = 500$  GeV and  $m_H = 200$  GeV and  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau) = 1$  pb is also shown.

The event rates, with the expected yields from the SM backgrounds normalized as resulting from a background-only fit to the data, are shown in figure 8, for all data sets and final states considered.

Upper limits on  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau)$  for a potential  $H^\pm$  signal are computed at the 95% CL, using the modified frequentist  $CL_s$  criterion [126, 127]. The definition of the profile likelihood test statistic is as defined in ref. [128], using the asymptotic approximation [129].

The upper limit with all final states, categories, and years combined is shown in figure 9 (left). The observed upper limit on  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau)$  varies between 0.085 pb at 300 GeV to 0.019 pb at 700 GeV. In the same figure (right), the expected sensitivity from each contributing final state is also shown. The  $\ell\tau_h\tau_h$  final states are the most sensitive in the whole  $m_{H^\pm}$  range from 300 to 700 GeV, while the  $\ell\tau_h$  final states improve the overall sensitivity by 10–35%. The dependence of these results on the assumed H mass was studied with full simulation for two additional mass points,  $m_H = 125$  GeV and  $m_H = 150$  GeV. The rate and shape of the transverse mass of the charged Higgs boson in eq. (4.1), which is the fit discriminant of the most sensitive categories,  $e\tau_h\tau_h$  and  $\mu\tau_h\tau_h$ , were shown to be unchanged. As a result, the observed upper limits are not expected to show a strong dependence on small variations to the mass of the heavy neutral Higgs boson.

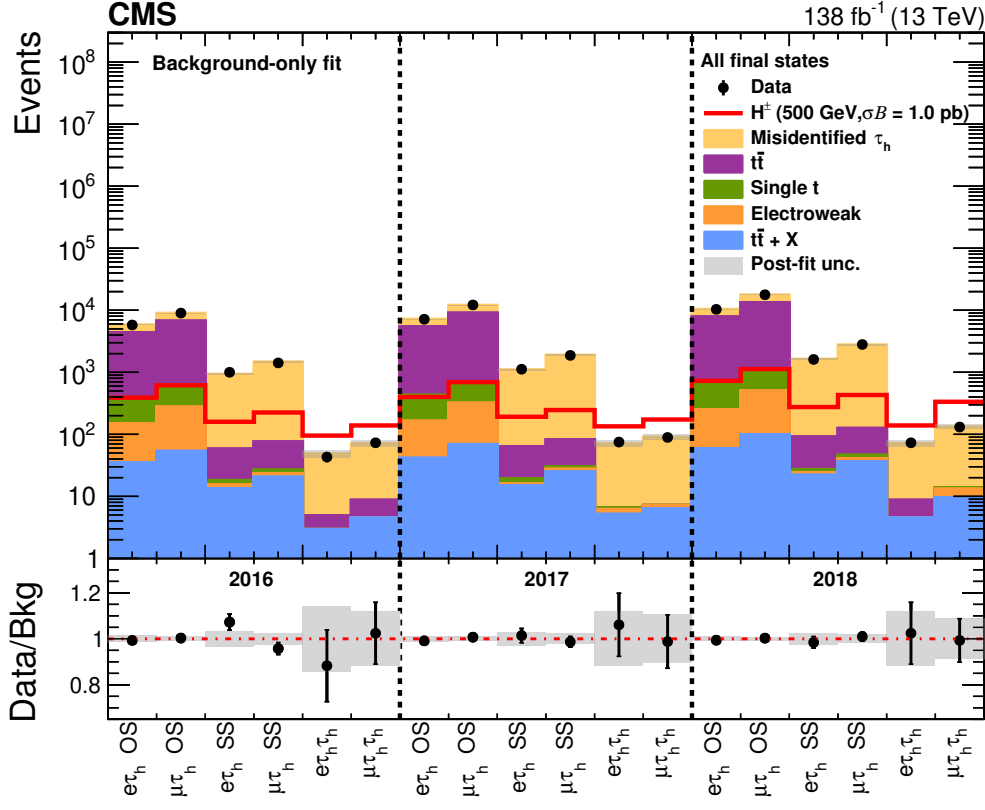


**Figure 7.** The  $m_T$  distributions for the  $e\tau_h\tau_h$  (left) and  $\mu\tau_h\tau_h$  (right) final states used in the limit extraction, after a background-only fit to the data. The data sets of all categories have been added. The pre-fit contribution from  $H^\pm \rightarrow HW^\pm$  with masses  $m_{H^\pm} = 500$  GeV and  $m_H = 200$  GeV and  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau) = 1$  pb is also shown. The brackets  $\langle \cdot \rangle$  signify that the plotted variable is averaged over an interval in which the event frequency may have changed considerably.

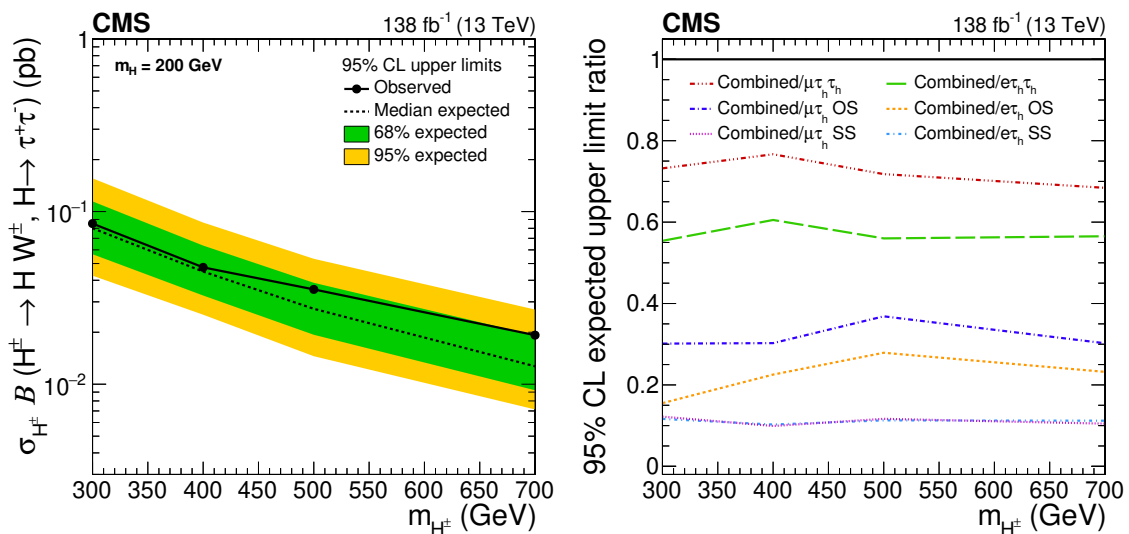
Uncertainty source	Shape	Category				Correlated across	
		$e\tau_h$	$\mu\tau_h$	$e\tau_h\tau_h$	$\mu\tau_h\tau_h$	Years	Categories
Experimental							
Integrated luminosity	—		1.2–2.5			✓ <sup>†</sup>	✓
Trigger efficiency	✓	0.9–4.2	0.5–2.9	1.2–3.0	0.1–0.3	—	✓
Trigger timing inefficiency	✓		—	0.1–0.3	0.1–0.3	—	✓
Pileup	✓	0.2–2.9	0.1–1.6	0.1–5.5	0.1–2.3	✓	✓
Electron identification	✓	0.1–2.4	—	0.1–1.9	—	✓	✓
Muon identification	✓	—	0.4–1.6	—	0.1–1.1	✓	✓
Lepton veto	—	0.1–2.0	0.1–2.0	0.1–2.0	0.1–2.0	—	✓
$\tau_h$ identification	✓	0.1–3.6	0.1–3.2	4.2–5.2	4.3–5.3	—	✓
$\tau_h$ energy scale	✓	0.2–1.8	0.2–0.4	0.8–1.5	0.8–1.2	—	✓
$e \rightarrow \tau_h$ misidentification	✓	0.2–1.5	0.1–0.4	0.3–0.6	0.2–0.6	—	✓
$\mu \rightarrow \tau_h$ misidentification	✓	0.1–1.6	0.1–0.3	0.1–0.3	0.1–0.3	—	✓
Jet energy scale	✓	1.1–4.9	1.2–4.2	1.6–3.6	1.6–2.4	✓	✓
Jet energy resolution	✓	0.3–3.1	0.3–3.1	1.1–4.6	1.2–3.1	—	✓
b jet identification	✓	2.5–5.4	2.5–5.1	2.4–4.2	3.2–4.2	—	✓
b jet misidentification	✓	2.4–4.1	2.2–4.5	1.0–2.6	1.7–2.5	—	✓
Unclustered energy scale	✓	0.1–1.9	0.2–1.5	0.5–1.7	0.3–2.4	—	✓
$t^{\text{res}}$ tagging	✓	1.5–7.6	1.3–7.5	—	—	—	✓
$t^{\text{res}}$ mistagging	✓	1.7–4.9	1.7–5.4	—	—	—	✓
$j \rightarrow \tau_h$ misidentification	✓	17.8–21.1	18.2–22.4	14.8	10.5	—	—
Theoretical							
Top quark mass ( $t\bar{t}$ )	—		2.2			✓	✓
Top quark mass (single $t$ )	—		2.8			✓	✓
Acceptance $H^\pm$ (RF scale, PDF)	—		5.3			✓	✓
Acceptance $t\bar{t}$ (RF scale, PDF)	—		–2.8 to +2.0			✓	✓
Acceptance single $t$ (RF scale, PDF)	—		–2.0 to +0.3			✓	✓
Acceptance $t\bar{t}X$ (RF scale, PDF)	—		2.0			✓	✓
Acceptance EW (RF scale, PDF)	—		<1.0			✓	✓
Cross section $t\bar{t}$ (RF scale, PDF)	—		–4.8 to 5.5			✓	✓
Cross section single $t$ (RF scale, PDF)	—		5.3			✓	✓
Cross section $t\bar{t}X$ (RF scale, PDF)	—		2.2			✓	✓
Cross section EW (RF scale, PDF)	—		5.4			✓	✓

**Table 4.** Summary of all sources of systematic uncertainties discussed in the text. The first column identifies the source of uncertainty and, where applicable, the process that it applies to. The second column indicates with a check mark ✓ or dash — whether or not the nuisance parameter also affects the shape of the fit discriminant. The third column, which is subdivided into four event categories, presents the percentage % impact of these nuisance parameters on the expected event yields, before simultaneous fitting the data for the background-only hypothesis. A range of such values represents the minimum and maximum values observed through the different samples and data eras, with apparent disparities also attributed to the limited sample size of minor backgrounds. The last two columns indicate whether or not the nuisance parameters are correlated across years and categories. A dagger † designates that a nuisance parameter is only partially correlated across years or categories.





**Figure 8.** Observed event yields (black markers) for the 18 categories considered in this analysis, grouped into data sets that are represented by vertical dashed lines. The expected event yields (stacked histograms) resulting from a background-only fit to the data are also shown, broken down into various background processes. The solid red line represents the expected signal yields from  $H^\pm \rightarrow HW^\pm$  with masses  $m_{H^\pm} = 500$  GeV and  $m_H = 200$  GeV, assuming  $\sigma_{H^\pm} \mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau) = 1$  pb.



**Figure 9.** Expected and observed upper limits at 95% CL on the product of cross section and branching fraction  $\sigma_{H^\pm}\mathcal{B}(H^\pm \rightarrow HW^\pm, H \rightarrow \tau\tau)$  as a function of  $m_{H^\pm}$  and assuming  $m_H = 200$  GeV for the combination of all final states considered (left). The observed upper limits are represented by a solid black line and circle markers. The median expected limit (dashed line), 68% (inner green band), and 95% (outer yellow band) confidence intervals are also shown. The relative expected contributions of each final state to the overall combination are also presented (right). The black solid line corresponds to the combined expected limit, while the red dash-dotted, green dashed, blue dashed-dotted, orange dashed, magenta dotted, and light blue dash-dotted lines represent the relative contributions from the  $\mu\tau_h\tau_h$ ,  $e\tau_h\tau_h$ ,  $\mu\tau_h$  OS,  $e\tau_h$  OS,  $\mu\tau_h$  SS, and  $e\tau_h$  SS categories, respectively.

## 10 Summary

Results are presented from a search for a charged Higgs boson  $H^\pm$  decaying into a heavy neutral Higgs boson  $H$  and a  $W$  boson. Events are selected with exactly one isolated electron or muon, targeting event topologies whereby the  $H$  decays into a pair of tau leptons with at least one decaying hadronically ( $\tau_h$ ). Four distinct final states are considered:  $e\tau_h$ ,  $\mu\tau_h$ ,  $e\tau_h\tau_h$ , and  $\mu\tau_h\tau_h$ . The analysis uses proton-proton collision data recorded by the CMS detector at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . No significant deviation is observed from standard model expectations. Upper limits at 95% confidence level are set on the product of the cross section and branching fraction for an  $H^\pm$  in the mass range of 300–700 GeV, assuming an  $H$  with a mass of 200 GeV. The observed limits range from 0.085 pb for an  $H^\pm$  mass of 300 GeV to 0.019 pb for a mass of 700 GeV. These are the first limits on  $H^\pm$  production in the  $H^\pm \rightarrow HW^\pm$  decay channel at the LHC.

## 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 NKFIH 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).

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] P.W. Higgs, *Broken symmetries, massless particles and gauge fields*, *Phys. Lett.* **12** (1964) 132 [[INSPIRE](#)].
- [2] P.W. Higgs, *Broken symmetries and the masses of gauge bosons*, *Phys. Rev. Lett.* **13** (1964) 508 [[INSPIRE](#)].
- [3] G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, *Global conservation laws and massless particles*, *Phys. Rev. Lett.* **13** (1964) 585 [[INSPIRE](#)].
- [4] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, *Phys. Rev. Lett.* **13** (1964) 321 [[INSPIRE](#)].
- [5] P.W. Higgs, *Spontaneous symmetry breakdown without massless bosons*, *Phys. Rev.* **145** (1966) 1156 [[INSPIRE](#)].
- [6] T.W.B. Kibble, *Symmetry breaking in non-Abelian gauge theories*, *Phys. Rev.* **155** (1967) 1554 [[INSPIRE](#)].
- [7] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](#)] [[INSPIRE](#)].

- [8] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](#)] [[INSPIRE](#)].
- [9] CMS collaboration, *Observation of a new boson with mass near 125 GeV in pp Collisions at  $\sqrt{s} = 7$  and 8 TeV*, *JHEP* **06** (2013) 081 [[arXiv:1303.4571](#)] [[INSPIRE](#)].
- [10] ATLAS and CMS collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at  $\sqrt{s} = 7$  and 8 TeV*, *JHEP* **08** (2016) 045 [[arXiv:1606.02266](#)] [[INSPIRE](#)].
- [11] CMS collaboration, *Combined measurements of Higgs boson couplings in proton–proton collisions at  $\sqrt{s} = 13$  TeV*, *Eur. Phys. J. C* **79** (2019) 421 [[arXiv:1809.10733](#)] [[INSPIRE](#)].
- [12] ATLAS collaboration, *Combined measurements of Higgs boson production and decay using up to 80 fb<sup>-1</sup> of proton–proton collision data at  $\sqrt{s} = 13$  TeV collected with the ATLAS experiment*, *Phys. Rev. D* **101** (2020) 012002 [[arXiv:1909.02845](#)] [[INSPIRE](#)].
- [13] CMS collaboration, *Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state*, *Phys. Rev. D* **99** (2019) 112003 [[arXiv:1901.00174](#)] [[INSPIRE](#)].
- [14] J.F. Gunion and H.E. Haber, *The CP conserving two Higgs doublet model: the approach to the decoupling limit*, *Phys. Rev. D* **67** (2003) 075019 [[hep-ph/0207010](#)] [[INSPIRE](#)].
- [15] A.G. Akeroyd et al., *Prospects for charged Higgs searches at the LHC*, *Eur. Phys. J. C* **77** (2017) 276 [[arXiv:1607.01320](#)] [[INSPIRE](#)].
- [16] G.C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [[arXiv:1106.0034](#)] [[INSPIRE](#)].
- [17] N. Craig and S. Thomas, *Exclusive signals of an extended Higgs sector*, *JHEP* **11** (2012) 083 [[arXiv:1207.4835](#)] [[INSPIRE](#)].
- [18] CMS collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, *Phys. Lett. B* **805** (2020) 135425 [[arXiv:2002.06398](#)] [[INSPIRE](#)].
- [19] S. Dittmaier, M. Krämer and M. Spira, *Higgs radiation off bottom quarks at the Tevatron and the CERN LHC*, *Phys. Rev. D* **70** (2004) 074010 [[hep-ph/0309204](#)] [[INSPIRE](#)].
- [20] S. Dawson, C.B. Jackson, L. Reina and D. Wackerroth, *Exclusive Higgs boson production with bottom quarks at hadron colliders*, *Phys. Rev. D* **69** (2004) 074027 [[hep-ph/0311067](#)] [[INSPIRE](#)].
- [21] R.V. Harlander and W.B. Kilgore, *Higgs boson production in bottom quark fusion at next-to-next-to leading order*, *Phys. Rev. D* **68** (2003) 013001 [[hep-ph/0304035](#)] [[INSPIRE](#)].
- [22] R. Harlander, M. Kramer and M. Schumacher, *Bottom-quark associated Higgs-boson production: reconciling the four- and five-flavour scheme approach*, [arXiv:1112.3478](#) [[INSPIRE](#)].
- [23] H. Bahl, T. Stefaniak and J. Wittbrodt, *The forgotten channels: charged Higgs boson decays to a  $W^\pm$  and a non-SM-like Higgs boson*, *JHEP* **06** (2021) 183 [[arXiv:2103.07484](#)] [[INSPIRE](#)].
- [24] ATLAS collaboration, *Search for charged Higgs bosons decaying via  $H^\pm \rightarrow \tau^\pm \nu$  in fully hadronic final states using pp collision data at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *JHEP* **03** (2015) 088 [[arXiv:1412.6663](#)] [[INSPIRE](#)].
- [25] CMS collaboration, *Search for a charged Higgs boson in pp collisions at  $\sqrt{s} = 8$  TeV*, *JHEP* **11** (2015) 018 [[arXiv:1508.07774](#)] [[INSPIRE](#)].

- [26] ATLAS collaboration, *Search for charged Higgs bosons decaying via  $H^\pm \rightarrow \tau^\pm \nu_\tau$  in the  $\tau$ +jets and  $\tau$ +lepton final states with  $36 \text{ fb}^{-1}$  of pp collision data recorded at  $\sqrt{s} = 13 \text{ TeV}$  with the ATLAS experiment*, *JHEP* **09** (2018) 139 [[arXiv:1807.07915](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *Search for charged Higgs bosons in the  $H^\pm \rightarrow \tau^\pm \nu_\tau$  decay channel in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$* , *JHEP* **07** (2019) 142 [[arXiv:1903.04560](#)] [[INSPIRE](#)].
- [28] CMS collaboration, *Search for a light charged Higgs boson decaying to  $c\bar{s}$  in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$* , *JHEP* **12** (2015) 178 [[arXiv:1510.04252](#)] [[INSPIRE](#)].
- [29] ATLAS collaboration, *Search for a light charged Higgs boson in the decay channel  $H^+ \rightarrow c\bar{s}$  in  $t\bar{t}$  events using pp collisions at  $\sqrt{s} = 7 \text{ TeV}$  with the ATLAS detector*, *Eur. Phys. J. C* **73** (2013) 2465 [[arXiv:1302.3694](#)] [[INSPIRE](#)].
- [30] CMS collaboration, *Search for a charged Higgs boson decaying to charm and bottom quarks in proton-proton collisions at  $\sqrt{s} = 8 \text{ TeV}$* , *JHEP* **11** (2018) 115 [[arXiv:1808.06575](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Search for a light charged Higgs boson decaying to a W boson and a CP-odd Higgs boson in final states with  $e\mu\mu$  or  $\mu\mu\mu$  in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$* , *Phys. Rev. Lett.* **123** (2019) 131802 [[arXiv:1905.07453](#)] [[INSPIRE](#)].
- [32] ATLAS collaboration, *Search for charged Higgs bosons in the  $H^\pm \rightarrow tb$  decay channel in pp collisions at  $\sqrt{s} = 8 \text{ TeV}$  using the ATLAS detector*, *JHEP* **03** (2016) 127 [[arXiv:1512.03704](#)] [[INSPIRE](#)].
- [33] ATLAS collaboration, *Search for charged Higgs bosons decaying into top and bottom quarks at  $\sqrt{s} = 13 \text{ TeV}$  with the ATLAS detector*, *JHEP* **11** (2018) 085 [[arXiv:1808.03599](#)] [[INSPIRE](#)].
- [34] CMS collaboration, *Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$* , *JHEP* **01** (2020) 096 [[arXiv:1908.09206](#)] [[INSPIRE](#)].
- [35] ATLAS collaboration, *Search for charged Higgs bosons produced in association with a top quark and decaying via  $H^\pm \rightarrow \tau\nu$  using pp collision data recorded at  $\sqrt{s} = 13 \text{ TeV}$  by the ATLAS detector*, *Phys. Lett. B* **759** (2016) 555 [[arXiv:1603.09203](#)] [[INSPIRE](#)].
- [36] CMS collaboration, *Search for charged Higgs bosons decaying into a top and a bottom quark in the all-jet final state of pp collisions at  $\sqrt{s} = 13 \text{ TeV}$* , *JHEP* **07** (2020) 126 [[arXiv:2001.07763](#)] [[INSPIRE](#)].
- [37] BABAR and BELLE collaborations, *The Physics of the B Factories*, *Eur. Phys. J. C* **74** (2014) 3026 [[arXiv:1406.6311](#)] [[INSPIRE](#)].
- [38] BELLE-II collaboration, *The Belle II physics book*, *PTEP* **2019** (2019) 123C01 [Erratum *ibid.* **2020** (2020) 029201] [[arXiv:1808.10567](#)] [[INSPIRE](#)].
- [39] G. Senjanovic and R.N. Mohapatra, *Exact left-right symmetry and spontaneous violation of parity*, *Phys. Rev. D* **12** (1975) 1502 [[INSPIRE](#)].
- [40] J.F. Gunion, R. Vega and J. Wudka, *Higgs triplets in the standard model*, *Phys. Rev. D* **42** (1990) 1673 [[INSPIRE](#)].
- [41] H. Georgi and M. Machacek, *Doubly charged higgs bosons*, *Nucl. Phys. B* **262** (1985) 463 [[INSPIRE](#)].
- [42] ATLAS collaboration, *Search for a charged Higgs boson produced in the vector-boson fusion mode with decay  $H^\pm \rightarrow W^\pm Z$  using pp collisions at  $\sqrt{s} = 8 \text{ TeV}$  with the ATLAS experiment*, *Phys. Rev. Lett.* **114** (2015) 231801 [[arXiv:1503.04233](#)] [[INSPIRE](#)].

- [43] CMS collaboration, *Search for charged Higgs bosons produced via vector boson fusion and decaying into a pair of W and Z bosons using pp collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **119** (2017) 141802 [[arXiv:1705.02942](#)] [[INSPIRE](#)].
- [44] CMS collaboration, *Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **120** (2018) 081801 [[arXiv:1709.05822](#)] [[INSPIRE](#)].
- [45] CMS collaboration, *Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Eur. Phys. J. C* **81** (2021) 723 [[arXiv:2104.04762](#)] [[INSPIRE](#)].
- [46] ATLAS collaboration, *Search for dijet resonances in events with an isolated charged lepton using  $\sqrt{s} = 13$  TeV proton-proton collision data collected by the ATLAS detector*, *JHEP* **06** (2020) 151 [[arXiv:2002.11325](#)] [[INSPIRE](#)].
- [47] ALEPH et al. collaborations, *Search for neutral MSSM Higgs bosons at LEP*, *Eur. Phys. J. C* **47** (2006) 547 [[hep-ex/0602042](#)] [[INSPIRE](#)].
- [48] CDF collaboration, *Search for Higgs bosons predicted in two-Higgs-doublet models via decays to tau lepton pairs in 1.96 TeV  $p\bar{p}$  collisions*, *Phys. Rev. Lett.* **103** (2009) 201801 [[arXiv:0906.1014](#)] [[INSPIRE](#)].
- [49] D0 collaboration, *Search for Neutral Higgs Bosons in the Multi-b-Jet Topology in  $5.2\text{fb}^{-1}$  of  $p\bar{p}$  Collisions at  $\sqrt{s} = 1.96$  TeV*, *Phys. Lett. B* **698** (2011) 97 [[arXiv:1011.1931](#)] [[INSPIRE](#)].
- [50] D0 collaboration, *Search for Higgs bosons decaying to  $\tau\tau$  pairs in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV*, *Phys. Lett. B* **707** (2012) 323 [[arXiv:1106.4555](#)] [[INSPIRE](#)].
- [51] CDF collaboration, *Search for Higgs bosons produced in association with b-quarks*, *Phys. Rev. D* **85** (2012) 032005 [[arXiv:1106.4782](#)] [[INSPIRE](#)].
- [52] CMS collaboration, *Search for a Higgs boson decaying into a b-quark pair and produced in association with b quarks in proton-proton collisions at 7 TeV*, *Phys. Lett. B* **722** (2013) 207 [[arXiv:1302.2892](#)] [[INSPIRE](#)].
- [53] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying into a pair of bottom quarks*, *JHEP* **11** (2015) 071 [[arXiv:1506.08329](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Search for beyond the standard model Higgs bosons decaying into a  $b\bar{b}$  pair in pp collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **08** (2018) 113 [[arXiv:1805.12191](#)] [[INSPIRE](#)].
- [55] ATLAS collaboration, *Search for heavy neutral Higgs bosons produced in association with b-quarks and decaying into b-quarks at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Rev. D* **102** (2020) 032004 [[arXiv:1907.02749](#)] [[INSPIRE](#)].
- [56] ATLAS collaboration, *Search for the neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *JHEP* **02** (2013) 095 [[arXiv:1211.6956](#)] [[INSPIRE](#)].
- [57] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to  $\mu^+\mu^-$  in pp collisions at  $\sqrt{s} = 7$  and 8 TeV*, *Phys. Lett. B* **752** (2016) 221 [[arXiv:1508.01437](#)] [[INSPIRE](#)].
- [58] CMS collaboration, *Search for MSSM Higgs bosons decaying to  $\mu^+\mu^-$  in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Lett. B* **798** (2019) 134992 [[arXiv:1907.03152](#)] [[INSPIRE](#)].
- [59] ATLAS collaboration, *Search for scalar resonances decaying into  $\mu^+\mu^-$  in events with and without b-tagged jets produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **07** (2019) 117 [[arXiv:1901.08144](#)] [[INSPIRE](#)].

- [60] ATLAS collaboration, *Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *JHEP* **11** (2014) 056 [[arXiv:1409.6064](#)] [[INSPIRE](#)].
- [61] ATLAS collaboration, *Search for minimal supersymmetric standard model Higgs bosons  $H/A$  and for a  $Z'$  boson in the  $\tau\tau$  final state produced in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 585 [[arXiv:1608.00890](#)] [[INSPIRE](#)].
- [62] ATLAS collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in  $36\text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **01** (2018) 055 [[arXiv:1709.07242](#)] [[INSPIRE](#)].
- [63] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to tau pairs in pp collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Rev. Lett.* **106** (2011) 231801 [[arXiv:1104.1619](#)] [[INSPIRE](#)].
- [64] CMS collaboration, *Search for neutral Higgs bosons decaying to tau pairs in pp collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Lett. B* **713** (2012) 68 [[arXiv:1202.4083](#)] [[INSPIRE](#)].
- [65] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions*, *JHEP* **10** (2014) 160 [[arXiv:1408.3316](#)] [[INSPIRE](#)].
- [66] CMS collaboration, *Search for additional neutral MSSM Higgs bosons in the  $\tau\tau$  final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **09** (2018) 007 [[arXiv:1803.06553](#)] [[INSPIRE](#)].
- [67] ATLAS collaboration, *Search for heavy Higgs bosons decaying into two tau leptons with the ATLAS detector using pp collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **125** (2020) 051801 [[arXiv:2002.12223](#)] [[INSPIRE](#)].
- [68] A. Cordero et al., *Dark matter signals at the LHC from a 3HDM*, *JHEP* **05** (2018) 030 [[arXiv:1712.09598](#)] [[INSPIRE](#)].
- [69] A. Cordero-Cid et al., *Lepton collider indirect signatures of dark CP-violation*, *Eur. Phys. J. C* **80** (2020) 135 [[arXiv:1812.00820](#)] [[INSPIRE](#)].
- [70] V. Keus, S.F. King, S. Moretti and K. Yagyu, *CP violating two-Higgs-doublet model: constraints and LHC predictions*, *JHEP* **04** (2016) 048 [[arXiv:1510.04028](#)] [[INSPIRE](#)].
- [71] K. Kainulainen et al., *On the validity of perturbative studies of the electroweak phase transition in the Two Higgs Doublet model*, *JHEP* **06** (2019) 075 [[arXiv:1904.01329](#)] [[INSPIRE](#)].
- [72] V. Keus, N. Koivunen and K. Tuominen, *Singlet scalar and 2HDM extensions of the Standard Model: CP-violation and constraints from  $(g - 2)_\mu$  and  $eEDM$* , *JHEP* **09** (2018) 059 [[arXiv:1712.09613](#)] [[INSPIRE](#)].
- [73] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *2020 JINST* **15** P10017 [[arXiv:2006.10165](#)] [[INSPIRE](#)].
- [74] CMS collaboration, *The CMS trigger system*, *2017 JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [75] CMS collaboration, *The CMS experiment at the CERN LHC*, *2008 JINST* **3** S08004 [[INSPIRE](#)].
- [76] 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 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [77] P. Artoisenet, R. Frederix, O. Mattelaer and R. Rietkerk, *Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations*, *JHEP* **03** (2013) 015 [[arXiv:1212.3460](#)] [[INSPIRE](#)].



- [78] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [[hep-ph/0409146](#)] [[INSPIRE](#)].
- [79] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [[arXiv:0709.2092](#)] [[INSPIRE](#)].
- [80] 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 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
- [81] S. Alioli et al., *Jet pair production in POWHEG*, *JHEP* **04** (2011) 081 [[arXiv:1012.3380](#)] [[INSPIRE](#)].
- [82] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO Higgs boson production via gluon fusion matched with shower in POWHEG*, *JHEP* **04** (2009) 002 [[arXiv:0812.0578](#)] [[INSPIRE](#)].
- [83] E. Bagnaschi, G. Degrossi, P. Slavich and A. Vicini, *Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM*, *JHEP* **02** (2012) 088 [[arXiv:1111.2854](#)] [[INSPIRE](#)].
- [84] M. Czakon and A. Mitov, *Top++: a program for the calculation of the top-pair cross-section at hadron colliders*, *Comput. Phys. Commun.* **185** (2014) 2930 [[arXiv:1112.5675](#)] [[INSPIRE](#)].
- [85] R. Frederix, E. Re and P. Torrielli, *Single-top t-channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO*, *JHEP* **09** (2012) 130 [[arXiv:1207.5391](#)] [[INSPIRE](#)].
- [86] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547 [[arXiv:1009.2450](#)] [[INSPIRE](#)].
- [87] H.B. Hartanto, B. Jager, L. Reina and D. Wackerroth, *Higgs boson production in association with top quarks in the POWHEG BOX*, *Phys. Rev. D* **91** (2015) 094003 [[arXiv:1501.04498](#)] [[INSPIRE](#)].
- [88] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [89] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J. C* **53** (2008) 473 [[arXiv:0706.2569](#)] [[INSPIRE](#)].
- [90] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [[arXiv:1209.6215](#)] [[INSPIRE](#)].
- [91] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [92] NNPDF collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663 [[arXiv:1706.00428](#)] [[INSPIRE](#)].
- [93] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [[arXiv:1512.00815](#)] [[INSPIRE](#)].
- [94] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [[arXiv:1903.12179](#)] [[INSPIRE](#)].
- [95] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [96] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, *2017 JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].

- [97] M. Cacciari, G.P. Salam and G. Soyez, *The anti- $k_t$  jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [98] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [99] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, 2021 *JINST* **16** P05014 [[arXiv:2012.06888](#)] [[INSPIRE](#)].
- [100] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV*, 2018 *JINST* **13** P06015 [[arXiv:1804.04528](#)] [[INSPIRE](#)].
- [101] CMS collaboration, *Pileup mitigation at CMS in 13 TeV data*, 2020 *JINST* **15** P09018 [[arXiv:2003.00503](#)] [[INSPIRE](#)].
- [102] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, 2017 *JINST* **12** P02014 [[arXiv:1607.03663](#)] [[INSPIRE](#)].
- [103] E. Bols et al., *Jet flavour classification using Deepjet*, 2020 *JINST* **15** P12012 [[arXiv:2008.10519](#)] [[INSPIRE](#)].
- [104] CMS collaboration, *Performance of the DeepJet b tagging algorithm using 41.9/fb of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector*, CMS-DP-2018-058 (2018).
- [105] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*, 2018 *JINST* **13** P05011 [[arXiv:1712.07158](#)] [[INSPIRE](#)].
- [106] CMS collaboration, *Performance of reconstruction and identification of  $\tau$  leptons decaying to hadrons and  $\nu_\tau$  in pp collisions at  $\sqrt{s} = 13$  TeV*, 2018 *JINST* **13** P10005 [[arXiv:1809.02816](#)] [[INSPIRE](#)].
- [107] CMS collaboration, *Identification of hadronic tau lepton decays using a deep neural network*, 2022 *JINST* **17** P07023 [[arXiv:2201.08458](#)] [[INSPIRE](#)].
- [108] CMS collaboration, *Performance of the DeepTau algorithm for the discrimination of taus against jets, electron, and muons*, CMS-DP-2019-033 (2019).
- [109] CMS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the CMS detector*, 2019 *JINST* **14** P07004 [[arXiv:1903.06078](#)] [[INSPIRE](#)].
- [110] F. Chollet et al., *Keras*, <https://keras.io>.
- [111] M. Abadi et al., *TensorFlow: large-scale machine learning on heterogeneous distributed systems*, [arXiv:1603.04467](#) [[INSPIRE](#)].
- [112] F. Pedregosa et al., *Scikit-learn: machine learning in Python*, *J. Machine Learning Res.* **12** (2011) 2825 [[arXiv:1201.0490](#)] [[INSPIRE](#)].
- [113] CMS collaboration, *Measurement of the  $Z\gamma^* \rightarrow \tau\tau$  cross section in pp collisions at  $\sqrt{s} = 13$  TeV and validation of  $\tau$  lepton analysis techniques*, *Eur. Phys. J. C* **78** (2018) 708 [[arXiv:1801.03535](#)] [[INSPIRE](#)].
- [114] H. Voss, A. Hocker, J. Stelzer and F. Tegenfeldt, *TMVA, the Toolkit for Multivariate Data Analysis with ROOT*, *PoS ACAT* (2007) 040 [[physics/0703039](#)] [[INSPIRE](#)].
- [115] R.J. Barlow and C. Beeston, *Fitting using finite Monte Carlo samples*, *Comput. Phys. Commun.* **77** (1993) 219 [[INSPIRE](#)].






















- [116] J.S. Conway, *Incorporating Nuisance Parameters in Likelihoods for Multisource Spectra*, in the proceedings of the *PHYSTAT 2011*, (2011), p. 115–120 [[DOI:10.5170/CERN-2011-006.115](#)] [[arXiv:1103.0354](#)] [[INSPIRE](#)].
- [117] 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 [[arXiv:2104.01927](#)] [[INSPIRE](#)].
- [118] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at  $\sqrt{s} = 13$  TeV*, *CMS-PAS-LUM-17-004*, CERN, Geneva (2018).
- [119] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at  $\sqrt{s} = 13$  TeV*, *CMS-PAS-LUM-18-002*, CERN, Geneva (2019).
- [120] ATLAS collaboration, *Measurement of the Inelastic Proton-Proton Cross Section at  $\sqrt{s} = 13$  TeV with the ATLAS Detector at the LHC*, *Phys. Rev. Lett.* **117** (2016) 182002 [[arXiv:1606.02625](#)] [[INSPIRE](#)].
- [121] CMS collaboration, *Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2018) 161 [[arXiv:1802.02613](#)] [[INSPIRE](#)].
- [122] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties*, [arXiv:1307.1347](#) [[DOI:10.5170/CERN-2013-004](#)] [[INSPIRE](#)].
- [123] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, [arXiv:1610.07922](#) [[DOI:10.23731/CYRM-2017-002](#)] [[INSPIRE](#)].
- [124] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001 [[arXiv:1510.03865](#)] [[INSPIRE](#)].
- [125] EPData record for this analysis, [DOI:10.17182/HEPDATA.130491](#).
- [126] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [[hep-ex/9902006](#)] [[INSPIRE](#)].
- [127] A.L. Read, *Presentation of search results: The  $CL_s$  technique*, *J. Phys. G* **28** (2002) 2693 [[INSPIRE](#)].
- [128] CMS collaboration, *Combined results of searches for the standard model Higgs boson in pp collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Lett. B* **710** (2012) 26 [[arXiv:1202.1488](#)] [[INSPIRE](#)].
- [129] 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 [*Erratum ibid.* **73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].

## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan <sup>1</sup>














### Institut für Hochenergiephysik, Vienna, Austria

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


















### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish <sup>3</sup>, T. Janssen , T. Kello <sup>4</sup>, H. Rejeb Sfar , P. Van Mechelen 

### Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , 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

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee ,  
M. Mahdavihorrani , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau ,  
E. Starling , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 

### Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , M. Niedziela , C. Rendón , C. Roskas ,  
A. Samalan , K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 























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

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








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

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

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho ,  
H. Brandao Malbouisson , W. Carvalho , J. Chinellato <sup>5</sup>, E.M. Da Costa ,  
G.G. Da Silveira <sup>6</sup>, D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza ,  
J. Martins <sup>7</sup>, C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima ,  
A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel ,  
F. Torres Da Silva De Araujo <sup>8</sup>, A. Vilela Pereira 

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

C.A. Bernardes <sup>6</sup>, L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores ,  
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, E. Shumka 
















**Beihang University, Beijing, China**

T. Cheng , T. Javaid <sup>9</sup>, M. Mittal , L. Yuan 











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

M. Ahmad , G. Bauer<sup>10</sup>, Z. Hu , S. Lezki , K. Yi <sup>10,11</sup>

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

G.M. Chen <sup>9</sup>, H.S. Chen <sup>9</sup>, M. Chen <sup>9</sup>, F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao ,  
Z.-A. Liu <sup>12</sup>, V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker ,  
J. Wang , H. Zhang , J. Zhao 




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

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

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

J. Li, M. Lu , Z. You 

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

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


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

Z. Lin , C. Lu , M. Xiao 





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

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

**Universidad de Antioquia, Medellin, Colombia**

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

**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 , B.K. Chitroda , D. Ferencek , D. Majumder , M. Roguljic ,  
A. Starodumov <sup>13</sup>, T. Susa 

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

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


**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala 

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

E. Carrera Jarrin 

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

H. Abdalla <sup>14</sup>, Y. Assran<sup>15,16</sup>

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

A. Lotfy , M.A. Mahmoud 

















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

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , 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 , M.m. Rantanen , 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 , V. Lohezic , J. Maleles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro <sup>17</sup>, P. Simkina , M. Titov 




















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

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , J. Rembser , R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche 




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

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

**Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France**

S. Beauceron , C. Bernet , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen <sup>19</sup>, H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, V. Sordini , L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret

























**Georgian Technical University, Tbilisi, Georgia**

I. Bagaturia <sup>20</sup>, I. Lomidze , Z. Tsamalaidze <sup>13</sup>










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

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










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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck , S. Zaleski

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








C. Dziwok , G. Flügge , W. Haj Ahmad <sup>21</sup>, O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , A. Stahl <sup>22</sup>, T. Ziemons , A. Zotz 

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









H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman <sup>23</sup>,

K. Borras <sup>24</sup>, D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo <sup>23</sup>, A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari <sup>25</sup>, N.Z. Jomhari , B. Kaech , A. Kasem <sup>24</sup>, M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka , W. Lohmann <sup>26</sup>, R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham <sup>27,24</sup>, V. Scheurer, S. Schnake <sup>24</sup>, P. Schütze , C. Schwanenberger <sup>23</sup>, M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon <sup>†</sup>, M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens <sup>24</sup>, C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

### University of Hamburg, Hamburg, Germany

R. Aggleton, A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , R. Klanner , W. Korcari , T. Kramer , V. Kutzner , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , M. Rieger , O. Rieger, P. Schleper , M. Schröder , J. Schwandt , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 






### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel , S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann <sup>22</sup>, M. Horzela , U. Husemann , P. Keicher, M. Klute , R. Koppenhöfer , S. Maier , S. Mitra , Th. Müller , M. Neukum, G. Quast , K. Rabbertz , J. Rauser, D. Savoie , M. Schnepf, D. Seith, I. Shvetsov , H.J. Simonis , N. Trevisani , 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, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 

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








M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , E. Vourliotis , I. Zisopoulos 

### National Technical University of Athens, Athens, Greece

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








**University of Ioánnina, Ioánnina, Greece**

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

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

M. Csanád , K. Farkas , M.M.A. Gadallah <sup>28</sup>, S. Lökös <sup>29</sup>, P. Major , K. Mandal , G. Pásztor , A.J. Rádl <sup>30</sup>, O. Surányi , G.I. Veres 


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

M. Bartók <sup>31</sup>, G. Bencze, C. Hajdu , D. Horvath <sup>32,33</sup>, F. Sikler , V. Veszpremi 

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

N. Beni , S. Czellar, J. Karancsi <sup>31</sup>, J. Molnar, Z. Szillasi, D. Teyssier 


















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

P. Raics, B. Ujvari <sup>34</sup>











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

T. Csorgo <sup>30</sup>, F. Nemes <sup>30</sup>, T. Novak 











**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra <sup>35</sup>, R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh <sup>36</sup>, A. Singla , A. K. Virdi 














**University of Delhi, Delhi, India**

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

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

S. Baradia , S. Barman <sup>37</sup>, S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber <sup>38</sup>, M. Maity <sup>37</sup>, P. Palit , P.K. Rout , G. Saha , B. Sahu , S. Sarkar

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

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri <sup>39</sup>, D. Kumar <sup>39</sup>, A. Muhammad , L. Panwar <sup>39</sup>, R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari <sup>39</sup>, S. Verma 










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

K. Naskar <sup>40</sup>










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

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

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

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

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

S. Bahinipati <sup>41</sup>, A.K. Das, C. Kar , P. Mal , T. Mishra ,  
V.K. Muraleedharan Nair Bindhu <sup>42</sup>, A. Nayak <sup>42</sup>, P. Saha , N. Sur , S.K. Swain,  
D. Vats <sup>42</sup>

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

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

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

H. Bakhshiansohi <sup>43</sup>, E. Khazaie , M. Zeinali <sup>44</sup>

































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

S. Chenarani <sup>45</sup>, S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





























**University College Dublin, Dublin, Ireland**

M. Grunewald 

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

M. Abbrescia <sup>a,b</sup>, R. Aly <sup>a,c,46</sup>, C. Aruta <sup>a,b</sup>, A. Colaleo <sup>a</sup>, D. Creanza <sup>a,c</sup>,  
N. De Filippis <sup>a,c</sup>, M. De Palma <sup>a,b</sup>, A. Di Florio <sup>a,b</sup>, W. Elmetenawee <sup>a,b</sup>, F. Errico <sup>a,b</sup>,  
L. Fiore <sup>a</sup>, G. Iaselli <sup>a,c</sup>, M. Ince <sup>a,b</sup>, G. Maggi <sup>a,c</sup>, M. Maggi <sup>a</sup>, I. Margjeka <sup>a,b</sup>,  
V. Mastrapasqua <sup>a,b</sup>, S. My <sup>a,b</sup>, S. Nuzzo <sup>a,b</sup>, A. Pellicchia <sup>a,b</sup>, A. Pompili <sup>a,b</sup>,  
G. Pugliese <sup>a,c</sup>, R. Radogna <sup>a</sup>, D. Ramos <sup>a</sup>, A. Ranieri <sup>a</sup>, G. Selvaggi <sup>a,b</sup>, L. Silvestris <sup>a</sup>,  
F.M. Simone <sup>a,b</sup>, Ü. Sözbilir <sup>a</sup>, A. Stamerra <sup>a</sup>, R. Venditti <sup>a</sup>, P. Verwilligen <sup>a</sup>

















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








































































































G. Abbiendi <sup>a</sup>, C. Battilana <sup>a,b</sup>, D. Bonacorsi <sup>a,b</sup>, L. Borgonovi <sup>a</sup>, L. Brigliadori <sup>a</sup>,  
R. Campanini <sup>a,b</sup>, P. Capiluppi <sup>a,b</sup>, A. Castro <sup>a,b</sup>, F.R. Cavallo <sup>a</sup>, M. Cuffiani <sup>a,b</sup>,  
G.M. Dallavalle <sup>a</sup>, T. Diotallevi <sup>a,b</sup>, F. Fabbri <sup>a</sup>, A. Fanfani <sup>a,b</sup>, P. Giacomelli <sup>a</sup>,  
L. Giommi <sup>a,b</sup>, C. Grandi <sup>a</sup>, L. Guiducci <sup>a,b</sup>, S. Lo Meo <sup>a,47</sup>, L. Lunerti <sup>a,b</sup>,  
S. Marcellini <sup>a</sup>, G. Masetti <sup>a</sup>, F.L. Navarria <sup>a,b</sup>, A. Perrotta <sup>a</sup>, F. Primavera <sup>a,b</sup>,  
A.M. Rossi <sup>a,b</sup>, T. Rovelli <sup>a,b</sup>, G.P. Siroli <sup>a,b</sup>












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

S. Costa <sup>a,b,48</sup>, A. Di Mattia <sup>a</sup>, R. Potenza <sup>a,b</sup>, A. Tricomi <sup>a,b,48</sup>, C. Tuve <sup>a,b</sup>


















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

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







































**INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi , S. Bianco , S. Meola <sup>22</sup>, D. Piccolo **INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**M. Bozzo <sup>a,b</sup>, F. Ferro <sup>a</sup>, R. Mulargia <sup>a</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**A. Benaglia <sup>a</sup>, G. Boldrini <sup>a</sup>, F. Brivio <sup>a,b</sup>, F. Cetorelli <sup>a,b</sup>, F. De Guio <sup>a,b</sup>,  
M.E. Dinardo <sup>a,b</sup>, P. Dini <sup>a</sup>, S. Gennai <sup>a</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, L. Guzzi <sup>a,b</sup>,  
M.T. Lucchini <sup>a,b</sup>, M. Malberti <sup>a</sup>, S. Malvezzi <sup>a</sup>, A. Massironi <sup>a</sup>, D. Menasce <sup>a</sup>,  
L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</sup>, B.S. Pinolini <sup>a</sup>, S. Ragazzi <sup>a,b</sup>, N. Redaelli <sup>a</sup>,  
T. Tabarelli de Fatis <sup>a,b</sup>, D. Zuolo <sup>a,b</sup>**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy**S. Buontempo <sup>a</sup>, F. Carnevali <sup>a,b</sup>, N. Cavallo <sup>a,c</sup>, A. De Iorio <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>,  
A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a,b,49</sup>, P. Paolucci <sup>a,22</sup>, B. Rossi <sup>a</sup>, C. Sciacca <sup>a,b</sup>**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**P. Azzi <sup>a</sup>, N. Bacchetta <sup>a,50</sup>, D. Bisello <sup>a,b</sup>, P. Bortignon <sup>a</sup>, A. Bragagnolo <sup>a,b</sup>,  
R. Carlin <sup>a,b</sup>, P. Checchia <sup>a</sup>, D. Corti <sup>a</sup>, T. Dorigo <sup>a</sup>, F. Fanzago <sup>a</sup>, F. Gasparini <sup>a,b</sup>,  
F. Gonella <sup>a</sup>, G. Grosso <sup>a</sup>, L. Layer <sup>a,51</sup>, E. Lusiani <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>,  
J. Pazzini <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, G. Strong <sup>a</sup>, M. Tosi <sup>a,b</sup>, H. Yarar <sup>a,b</sup>,  
M. Zanetti <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**S. Abu Zeid <sup>a,52</sup>, C. Aimè <sup>a,b</sup>, A. Braghieri <sup>a</sup>, S. Calzaferri <sup>a,b</sup>, D. Fiorina <sup>a,b</sup>,  
P. Montagna <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a</sup>, P. Vitulo <sup>a,b</sup>**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**P. Asenov <sup>a,53</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, M. Magherini <sup>a,b</sup>,  
G. Mantovani <sup>a,b</sup>, V. Mariani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Moscatelli <sup>a,53</sup>, A. Piccinelli <sup>a,b</sup>,  
M. Presilla <sup>a,b</sup>, A. Rossi <sup>a,b</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga <sup>a</sup>, T. Tedeschi <sup>a,b</sup>**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, V. Bertacchi <sup>a,c</sup>, R. Bhattacharya <sup>a</sup>, L. Bianchini <sup>a,b</sup>,  
T. Boccali <sup>a</sup>, E. Bossini <sup>a,b</sup>, D. Bruschini <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,b</sup>,  
V. D'Amante <sup>a,d</sup>, R. Dell'Orso <sup>a</sup>, M.R. Di Domenico <sup>a,d</sup>, S. Donato <sup>a</sup>, A. Giassi <sup>a</sup>,  
F. Ligabue <sup>a,c</sup>, E. Manca <sup>a,c</sup>, G. Mandorli <sup>a,c</sup>, D. Matos Figueiredo <sup>a</sup>, A. Messineo <sup>a,b</sup>,  
M. Musich <sup>a,b</sup>, F. Palla <sup>a</sup>, S. Parolia <sup>a,b</sup>, G. Ramirez-Sanchez <sup>a,c</sup>, A. Rizzi <sup>a,b</sup>,

G. Rolandi <sup>a,c</sup>, S. Roy Chowdhury <sup>a,c</sup>, T. Sarkar <sup>a,37</sup>, A. Scribano <sup>a</sup>, N. Shafiei <sup>a,b</sup>,  
P. Spagnolo <sup>a</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, N. Turini <sup>a,d</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>








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

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














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

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

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

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

### Kyungpook National University, Daegu, Korea

S. Dogra <sup>a</sup>, C. Huh <sup>a</sup>, B. Kim <sup>a</sup>, D.H. Kim <sup>a</sup>, G.N. Kim <sup>a</sup>, J. Kim, J. Lee <sup>a</sup>, S.W. Lee <sup>a</sup>,  
C.S. Moon <sup>a</sup>, Y.D. Oh <sup>a</sup>, S.I. Pak <sup>a</sup>, M.S. Ryu <sup>a</sup>, S. Sekmen <sup>a</sup>, Y.C. Yang <sup>a</sup>





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

H. Kim <sup>a</sup>, D.H. Moon <sup>a</sup>

### Hanyang University, Seoul, Korea

E. Asilar <sup>a</sup>, T.J. Kim <sup>a</sup>, J. Park <sup>a</sup>

### Korea University, Seoul, Korea

S. Cho, S. Choi <sup>a</sup>, S. Han, B. Hong <sup>a</sup>, K. Lee, K.S. Lee <sup>a</sup>, J. Lim, J. Park, S.K. Park, J. Yoo <sup>a</sup>















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

J. Goh <sup>a</sup>










### Sejong University, Seoul, Korea

H. S. Kim <sup>a</sup>, Y. Kim, S. Lee

### Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi <sup>a</sup>, S. Jeon <sup>a</sup>, W. Jun <sup>a</sup>, J. Kim <sup>a</sup>, J. Kim <sup>a</sup>, J.S. Kim, S. Ko <sup>a</sup>,  
H. Kwon <sup>a</sup>, H. Lee <sup>a</sup>, J. Lee <sup>a</sup>, S. Lee, B.H. Oh <sup>a</sup>, M. Oh <sup>a</sup>, S.B. Oh <sup>a</sup>, H. Seo <sup>a</sup>, U.K. Yang,  
I. Yoon <sup>a</sup>

**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang, Y. Kang , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee ,  
J.A. Merlin, I.C. Park , Y. Roh, 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 , M.R. Kim , H. Lee, Y. 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 , A. Gaile , A. Potrebko , T. Torims , V. Veckalns 







**Vilnius University, Vilnius, Lithuania**

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

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

N. Bin Norjoharuddeen , S.Y. Hoh <sup>54</sup>, I. Yusuff <sup>54</sup>, Z. Zolkapli

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

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez,  
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 , I. Heredia-De La Cruz <sup>55</sup>, R. Lopez-Fernandez ,  
C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**

C. Oropeza Barrera , F. Vazquez Valencia 








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

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

**University of Montenegro, Podgorica, Montenegro**

I. Bubanja, J. Mijuskovic<sup>56</sup>, N. Raicevic 

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

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , H.R. Hoorani , W.A. Khan ,  
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. Szleper ,  
P. Zalewski 

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

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





























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

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

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

P. Adzic <sup>57</sup>, M. Dordevic , P. Milenovic , J. Milosevic 













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

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández , M. Barrio Luna,  
Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada , N. Colino ,  
B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , 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 , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,  
J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas ,  
J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott









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










J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , 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 ,  
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 , A. García Alonso, G. Gomez , C. Lasasosa García 

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






































































### University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy <sup>58</sup>, D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

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






































### CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon<sup>†</sup>, D. Barney ,  
J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol ,  
T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury,  
M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck ,  
M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, A. Elliott-Peisert,  
F. Fallavollita<sup>59</sup>, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh ,  
S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko ,  
J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler ,  
N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , A. Lintuluoto , C. Lourenço ,  
B. Maier , L. Malgeri , 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. Rabadý , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin ,  
J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas <sup>60</sup>,  
A.G. Stahl Leitner , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea ,  
A. Tsiros, J. Wanczyk <sup>61</sup>, K.A. Wozniak , W.D. Zeuner

### Paul Scherrer Institut, Villigen, Switzerland














L. Caminada <sup>62</sup>, A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram ,  
H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli <sup>62</sup>, L. Noehte <sup>62</sup>, T. Rohe 

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

T.K. Aarrestad , K. Androsov <sup>61</sup>, M. Backhaus , P. Berger, A. Calandri , K. Datta ,  
A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia ,  
F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon ,  
R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani <sup>61</sup>, 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 , F. Riti , D. Ruini,  
D.A. Sanz Becerra , J. Stegmann <sup>61</sup>, D. Valsecchi <sup>22</sup>, R. Wallny 

### Universität Zürich, Zurich, Switzerland










C. Amsler <sup>63</sup>, P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier ,  
A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei 

B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , V.M. Mikuni ,  
U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger ,  
M. Senger , Y. Takahashi 

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

C. Adloff<sup>64</sup>, C.M. Kuo, W. Lin, S.S. Yu 


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

L. Ceard, Y. Chao , K.F. 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

C. Asawatangtrakuldee , N. Srimanobhas 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu <sup>65</sup>, E. Eskut ,  
Y. Guler <sup>66</sup>, E. Gurpinar Guler <sup>66</sup>, C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,  
G. Onengut , K. Ozdemir <sup>67</sup>, A. Polatoz , A.E. Simsek , B. Tali <sup>68</sup>, U.G. Tok ,  
S. Turkcapar , E. Uslan , I.S. Zorbakir 

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

G. Karapinar<sup>69</sup>, K. Ocalan <sup>70</sup>, M. Yalvac <sup>71</sup>

### Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya <sup>72</sup>, O. Kaya <sup>73</sup>, Ö. Özçelik , S. Tekten <sup>74</sup>


### Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak <sup>65</sup>, Y. Komurcu , S. Sen <sup>75</sup>

### Istanbul University, Istanbul, Turkey

O. Aydılek , S. Cerci <sup>68</sup>, B. Hacisahinoglu , I. Hos <sup>76</sup>, B. Isildak <sup>77</sup>, B. Kaynak ,  
S. Ozkorucuklu , C. Simsek , D. Sunar Cerci <sup>68</sup>











### 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 , J.J. Brooke , A. Bundock , E. Clement , D. Cussans ,  
H. Flacher , M. Glowacki, J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko 



































B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou <sup>78</sup>,  
K. Walkingshaw Pass, R. White 

### Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev <sup>79</sup>, C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg <sup>80</sup>, J. Linacre ,  
K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , 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, C.E. Brown , O. Buchmuller,  
V. Cacchio, V. Cepaitis , G.S. Chahal <sup>81</sup>, D. Colling , J.S. Dancu, P. Dauncey ,  
G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi ,  
A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli ,  
M. Mieskolainen , D.G. Monk , J. Nash <sup>82</sup>, M. Pesaresi, B.C. Radburn-Smith ,  
D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, R. Shukla ,  
A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee <sup>22</sup>, M. Vojinovic ,  
N. Wardle , S.N. Webb , D. Winterbottom

### Brunel University, Uxbridge, United Kingdom

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

### Baylor University, Waco, Texas, USA

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

















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

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



















### The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez ,  
P. Rumerio <sup>83</sup>, C. West 



















### Boston University, Boston, Massachusetts, USA

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

### Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez<sup>24</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan <sup>84</sup>,  
T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan ,  
S. Sagir <sup>85</sup>, F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

### University of California, Davis, Davis, California, USA

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

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

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

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

Y. Chen, R. Clare [ID](#), J.W. Gary [ID](#), M. Gordon, G. Hanson [ID](#), G. Karapostoli [ID](#), O.R. Long [ID](#),  
N. Manganeli [ID](#), W. Si [ID](#), S. Wimpenny [ID](#)

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

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

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

N. Amin, C. Campagnari [ID](#), M. Citron [ID](#), G. Collura [ID](#), A. Dorsett [ID](#), V. Dutta [ID](#),  
J. Incandela [ID](#), M. Kilpatrick [ID](#), J. Kim [ID](#), A.J. Li [ID](#), B. Marsh, P. Masterson [ID](#), H. Mei [ID](#),  
M. Oshiro [ID](#), M. Quinnan [ID](#), J. Richman [ID](#), U. Sarica [ID](#), R. Schmitz [ID](#), F. Setti [ID](#), J. Sheplock [ID](#),  
P. Siddireddy, D. Stuart [ID](#), S. Wang [ID](#)

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

A. Bornheim [ID](#), O. Cerri, I. Dutta [ID](#), J.M. Lawhorn [ID](#), N. Lu [ID](#), J. Mao [ID](#), H.B. Newman [ID](#),  
T. Q. Nguyen [ID](#), M. Spiropulu [ID](#), J.R. Vlimant [ID](#), C. Wang [ID](#), S. Xie [ID](#), R.Y. Zhu [ID](#)

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

J. Alison [ID](#), S. An [ID](#), M.B. Andrews [ID](#), P. Bryant [ID](#), T. Ferguson [ID](#), A. Harilal [ID](#), C. Liu [ID](#),  
T. Mudholkar [ID](#), S. Murthy [ID](#), M. Paulini [ID](#), A. Roberts [ID](#), A. Sanchez [ID](#), W. Terrill [ID](#)

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









































J.P. Cumalat [ID](#), W.T. Ford [ID](#), A. Hassani [ID](#), G. Karathanasis [ID](#), E. MacDonald, F. Marini [ID](#),  
R. Patel, A. Perloff [ID](#), C. Savard [ID](#), N. Schonbeck [ID](#), K. Stenson [ID](#), K.A. Ulmer [ID](#),  
S.R. Wagner [ID](#), N. Zipper [ID](#)

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



















J. Alexander [ID](#), S. Bright-Thonney [ID](#), X. Chen [ID](#), D.J. Cranshaw [ID](#), J. Fan [ID](#), X. Fan [ID](#),  
D. Gadkari [ID](#), S. Hogan [ID](#), J. Monroy [ID](#), J.R. Patterson [ID](#), D. Quach [ID](#), J. Reichert [ID](#), M. Reid [ID](#),  
A. Ryd [ID](#), J. Thom [ID](#), P. Wittich [ID](#), R. Zou [ID](#)

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









M. Albrow [ID](#), M. Alyari [ID](#), G. Apollinari [ID](#), A. Apresyan [ID](#), L.A.T. Bauerdick [ID](#), D. Berry [ID](#),  
J. Berryhill [ID](#), P.C. Bhat [ID](#), K. Burkett [ID](#), J.N. Butler [ID](#), A. Canepa [ID](#), G.B. Cerati [ID](#),  
H.W.K. Cheung [ID](#), F. Chlebana [ID](#), K.F. Di Petrillo [ID](#), J. Dickinson [ID](#), V.D. Elvira [ID](#), Y. Feng [ID](#),  
J. Freeman [ID](#), A. Gandrakota [ID](#), Z. Geese [ID](#), L. Gray [ID](#), D. Green, S. Grünendahl [ID](#),  
O. Gutsche [ID](#), R.M. Harris [ID](#), R. Heller [ID](#), T.C. Herwig [ID](#), J. Hirschauer [ID](#), L. Horyn [ID](#),

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 , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena <sup>86</sup>,  
 F. Ravera , A. Reinsvold Hall <sup>87</sup>, L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha ,  
 L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger ,  
 E.W. Vaandering , H.A. Weber , I. Zoi 

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

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field, D. Guerrero ,  
 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 



















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

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













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

M.M. Baarmand , S. Butalla , T. Elkafrawy <sup>52</sup>, M. Hohlmann , R. Kumar Verma ,  
 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.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy ,  
 S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 


























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

M. Alhusseini , K. Dilsiz <sup>88</sup>, L. Emediato , R.P. Gandrajula , G. Karaman ,  
 O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili <sup>89</sup>, J. Nachtman , O. Neogi, H. Ogul <sup>90</sup>,  
 Y. Onel , A. Penzo , C. Snyder, E. Tiras <sup>91</sup>








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
























































































































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

### The University of Kansas, Lawrence, Kansas, USA









A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers ,  
 T. Isidori , S. Khalil , J. King , G. Krintiras , 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 , Q. Wang , J. Williams , G. Wilson 

### Kansas State University, Manhattan, Kansas, USA




















B. Allmond , S. Duric, R. Gujju Gurunadha , A. Ivanov , K. Kaadze , D. Kim,  
 Y. Maravin , T. Mitchell, A. Modak, K. Nam, J. Natoli , D. Roy 

**Lawrence Livermore National Laboratory, Livermore, California, USA**F. Rebasoo , D. Wright **University of Maryland, College Park, Maryland, USA**E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M. Seidel , L. Wang , K. Wong **Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**D. Abercrombie, 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 , D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , 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, B. Crossman , A. Evans , J. Hiltbrand , Sh. Jain , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud **University of Mississippi, Oxford, Mississippi, USA**L.M. Cremaldi **University of Nebraska-Lincoln, Lincoln, Nebraska, USA**K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow<sup>†</sup>, W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli **State University of New York at Buffalo, Buffalo, New York, USA**G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams **Northeastern University, Boston, Massachusetts, USA**G. Alverson , E. Barberis , Y. Haddad , Y. Han , 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, S. Castells , M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko <sup>13</sup>, H. Nelson , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

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

B. Bylsma, M. Carrigan , L.S. Durkin , B. Francis , C. Hill , A. Lesauvage ,  
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 ,  
P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li ,  
B.P. Padley , R. Redjimi, J. Rotter , W. Shi , S. Yang , E. Yigitbasi , L. Zhang<sup>92</sup>,  
Y. Zhang , X. Zuo 
















**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 

**The Rockefeller University, New York, New York, USA**

K. Goulianos 














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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl ,  
D. Jaroslawski , O. Karacheban <sup>26</sup>, I. Laflotte , A. Lath , R. Montalvo, K. Nash,  
M. Osherson , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas,  
H. Wang 










**University of Tennessee, Knoxville, Tennessee, USA**

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

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

O. Bouhali <sup>93</sup>, M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon <sup>94</sup>, H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,  
A. Safonov 

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

N. Akchurin , J. Damgov , V. Hegde , 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 , F. Romeo , P. Sheldon ,  
S. Tuo , J. Velkovska , J. Viinikainen 






















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

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , M. Joyce ,  
A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald 

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






P.E. Karchin , 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. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless ,  
J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,  
D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,  
W. Vetens 

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

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,  
A. Belyaev , V. Blinov <sup>95</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev ,  
M. Chadeeva <sup>95</sup>, V. Chekhovsky, A. Dermenev , T. Dimova <sup>95</sup>, I. Dremin , M. Dubinin <sup>86</sup>,  
L. Dudko , V. Epshteyn , G. Gavrilo , V. Gavrilo , S. Gninenko , V. Golovtsov ,  
N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov ,  
V. Kachanov , L. Kardapoltsev <sup>95</sup>, V. Karjavine , A. Karneyeu , V. Kim <sup>95</sup>,  
M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova <sup>96</sup>,  
D. Konstantinov , V. Korenkov , A. Kozyrev <sup>95</sup>, N. Krasnikov , E. Kuznetsova <sup>97</sup>,  
A. Lanev , P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov ,  
V. Matveev <sup>95</sup>, V. Murzin , A. Nikitenko <sup>98</sup>, S. Obraztsov , V. Okhotnikov , A. Oskin,  
I. Ovtin <sup>95</sup>, V. Palichik , P. Parygin , V. Perelygin , M. Perfilov, S. Petrushanko ,  
G. Pivovarov , V. Popov, E. Popova , O. Radchenko <sup>95</sup>, M. Savina , V. Savrin ,  
D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen <sup>95</sup>, S. Slabospitskii ,  
V. Smirnov , D. Sosnov , A. Steppenov , V. Sulimov , E. Tcherniaev , A. Terkulov ,  
O. Teryaev , I. Tlisova , M. Toms , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov 

A. Vorobyev, N. Voytishin , B.S. Yuldashev<sup>99</sup>, A. Zarubin , E. Zhemchugov <sup>95</sup>, I. Zhizhin ,  
A. Zhokin 

<sup>†</sup> Deceased

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

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

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

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

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

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

<sup>7</sup> Also at UFMS, Nova Andradina, Brazil

<sup>8</sup> Also at The University of the State of Amazonas, Manaus, Brazil

<sup>9</sup> Also at University of Chinese Academy of Sciences, Beijing, China

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

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

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

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

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

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

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

<sup>17</sup> Also at Purdue University, West Lafayette, Indiana, USA

<sup>18</sup> Also at Université de Haute Alsace, Mulhouse, France

<sup>19</sup> Also at Department of Physics, Tsinghua University, Beijing, China

<sup>20</sup> Also at Ilia State University, Tbilisi, Georgia

<sup>21</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey

<sup>22</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

<sup>23</sup> Also at University of Hamburg, Hamburg, Germany

<sup>24</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>25</sup> Also at Isfahan University of Technology, Isfahan, Iran

<sup>26</sup> Also at Brandenburg University of Technology, Cottbus, Germany

<sup>27</sup> Also at Forschungszentrum Jülich, Juelich, Germany

<sup>28</sup> Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

<sup>29</sup> Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

<sup>30</sup> Also at Wigner Research Centre for Physics, Budapest, Hungary

<sup>31</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

<sup>32</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

<sup>33</sup> Now at Universitatea Babeş-Bolyai — Facultatea de Fizica, Cluj-Napoca, Romania

<sup>34</sup> Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary

<sup>35</sup> Also at Punjab Agricultural University, Ludhiana, India

<sup>36</sup> Also at UPES — University of Petroleum and Energy Studies, Dehradun, India

<sup>37</sup> Also at University of Visva-Bharati, Santiniketan, India

<sup>38</sup> Also at University of Hyderabad, Hyderabad, India

<sup>39</sup> Also at Indian Institute of Science (IISc), Bangalore, India

<sup>40</sup> Also at Indian Institute of Technology (IIT), Mumbai, India

<sup>41</sup> Also at IIT Bhubaneswar, Bhubaneswar, India

<sup>42</sup> Also at Institute of Physics, Bhubaneswar, India

<sup>43</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

<sup>44</sup> Also at Sharif University of Technology, Tehran, Iran

<sup>45</sup> Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran

<sup>46</sup> Also at Helwan University, Cairo, Egypt

<sup>47</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy

- <sup>48</sup> Also at *Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
- <sup>49</sup> Also at *Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
- <sup>50</sup> Also at *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- <sup>51</sup> Also at *Università di Napoli 'Federico II', Napoli, Italy*
- <sup>52</sup> Also at *Ain Shams University, Cairo, Egypt*
- <sup>53</sup> Also at *Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
- <sup>54</sup> Also at *Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
- <sup>55</sup> Also at *Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
- <sup>56</sup> Also at *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>57</sup> Also at *Faculty of Physics, University of Belgrade, Belgrade, Serbia*
- <sup>58</sup> Also at *Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
- <sup>59</sup> Also at *INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
- <sup>60</sup> Also at *National and Kapodistrian University of Athens, Athens, Greece*
- <sup>61</sup> Also at *Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
- <sup>62</sup> Also at *Universität Zürich, Zurich, Switzerland*
- <sup>63</sup> Also at *Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
- <sup>64</sup> Also at *Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
- <sup>65</sup> Also at *Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
- <sup>66</sup> Also at *Konya Technical University, Konya, Turkey*
- <sup>67</sup> Also at *Izmir Bakircay University, Izmir, Turkey*
- <sup>68</sup> Also at *Adiyaman University, Adiyaman, Turkey*
- <sup>69</sup> Also at *Istanbul Gedik University, Istanbul, Turkey*
- <sup>70</sup> Also at *Necmettin Erbakan University, Konya, Turkey*
- <sup>71</sup> Also at *Bozok Universitetesi Rektörlüğü, Yozgat, Turkey*
- <sup>72</sup> Also at *Marmara University, Istanbul, Turkey*
- <sup>73</sup> Also at *Milli Savunma University, Istanbul, Turkey*
- <sup>74</sup> Also at *Kafkas University, Kars, Turkey*
- <sup>75</sup> Also at *Hacettepe University, Ankara, Turkey*
- <sup>76</sup> Also at *Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
- <sup>77</sup> Also at *Yildiz Technical University, Istanbul, Turkey*
- <sup>78</sup> Also at *Vrije Universiteit Brussel, Brussel, Belgium*
- <sup>79</sup> Also at *School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
- <sup>80</sup> Also at *University of Bristol, Bristol, United Kingdom*
- <sup>81</sup> Also at *IPPP Durham University, Durham, United Kingdom*
- <sup>82</sup> Also at *Monash University, Faculty of Science, Clayton, Australia*
- <sup>83</sup> Also at *Università di Torino, Torino, Italy*
- <sup>84</sup> Also at *Bethel University, St. Paul, Minnesota, USA*
- <sup>85</sup> Also at *Karamanoğlu Mehmetbey University, Karaman, Turkey*
- <sup>86</sup> Also at *California Institute of Technology, Pasadena, California, USA*
- <sup>87</sup> Also at *United States Naval Academy, Annapolis, Maryland, USA*
- <sup>88</sup> Also at *Bingol University, Bingol, Turkey*
- <sup>89</sup> Also at *Georgian Technical University, Tbilisi, Georgia*
- <sup>90</sup> Also at *Sinop University, Sinop, Turkey*
- <sup>91</sup> Also at *Erciyes University, Kayseri, Turkey*
- <sup>92</sup> Also at *Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China*
- <sup>93</sup> Also at *Texas A&M University at Qatar, Doha, Qatar*
- <sup>94</sup> Also at *Kyungpook National University, Daegu, Korea*
- <sup>95</sup> Also at *another institute or international laboratory covered by a cooperation agreement with CERN*
- <sup>96</sup> Also at *Yerevan Physics Institute, Yerevan, Armenia*



<sup>97</sup> *Now at University of Florida, Gainesville, Florida, USA*

<sup>98</sup> *Also at Imperial College, London, United Kingdom*

<sup>99</sup> *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*