Search for lepton flavour violating decays of a neutral heavy Higgs boson to $\mu\tau$ and $e\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for lepton flavour violating decays of a neutral non-standard-model Higgs boson in the $\mu\tau$ and $e\tau$ decay modes is presented. The search is based on proton-proton collisions at a center of mass energy $\sqrt{s} = 13$ TeV collected with the CMS detector in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The $\tau$ leptons are reconstructed in the leptonic and hadronic decay modes. No signal is observed in the mass range 200–900 GeV. At 95% confidence level, the observed (expected) upper limits on the production cross section multiplied by the branching fraction vary from 51.9 (57.4) fb to 1.6 (2.1) fb for the $\mu\tau$ and from 94.1 (91.6) fb to 2.3 (2.3) fb for the $e\tau$ decay modes.

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1 Introduction

The discovery of the 125 GeV Higgs boson, $H(125)$, at the CERN LHC in 2012 \cite{1-3} was a major breakthrough in particle physics. A combined study of data from collisions at $\sqrt{s} = 7$ and 8 TeV collected by the ATLAS and CMS Collaborations shows the particle to have properties consistent with the standard model (SM) Higgs boson \cite{4-9} including the spin, couplings, and charge-parity assignment \cite{10, 11}. Lepton flavour violating (LFV) decays of the $H(125)$ are forbidden in the SM. However, the presence of new physics in the Higgs sector is not excluded \cite{12} and there exist many possible extensions of the SM that allow LFV decays of the $H(125)$. These include the two Higgs doublet model \cite{13}, supersymmetric models \cite{14-20}, composite Higgs models \cite{21, 22}, models with flavour symmetries \cite{23}, Randall–Sundrum models \cite{24-26}, and others \cite{27-35}. A common feature of many of these models is the presence of additional neutral Higgs bosons (H and A) that would also have LFV decays \cite{36, 37}.

The most recent search for LFV decays of the $H(125)$ was performed by the CMS Collaboration in the $\mu\tau$ and $e\tau$ channels, using proton-proton (pp) collision data recorded at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, and corresponding to an integrated luminosity of $35.9 \text{ fb}^{-1}$ \cite{38}. The observed (expected) upper limits set on the branching fractions were $B(H(125) \to \mu\tau) < 0.25 \ (0.25)\%$ and $B(H(125) \to e\tau) < 0.61 \ (0.37)\%$ at 95% confidence level (CL). These constraints were a significant improvement over the previously set limits by the CMS and ATLAS Collaborations using the 8 TeV pp collision data set, corresponding to an integrated luminosity of $20 \text{ fb}^{-1}$ \cite{39-42}. Results from the previous CMS H(125) $\to \mu\tau$ search, performed using 8 TeV pp collision data, were used to set limits on high mass LFV H decays in a phenomenological study \cite{12}. Limits on the product of the production cross section with branching fraction for the $H \to \mu\tau$ channel were obtained for $H$ mass, $m_H$, less than 300 GeV.

This paper describes the first direct search for LFV $H \to \mu\tau$ and $H \to e\tau$ decays for an $H$ mass in the range $200 < m_H < 900$ GeV. The search is performed in four decay channels, $H \to \mu\tau_h$, $H \to e\tau_h$, and $H \to e\mu$, where $\tau_h$, $\tau_e$, and $\tau_\mu$ correspond to the hadronic, electronic and muonic decay channels of $\tau$ leptons, respectively. The final-state signatures are very similar to those of the $H \to \tau\tau$ decays, studied by CMS \cite{43-46} and ATLAS \cite{47}. However, there are some significant kinematic differences. The primary difference is that the muon (electron) in the LFV $H \to \mu(e)\tau$ decay is produced promptly, and tends to have a higher momentum than in the $H \to \tau\mu(e)\tau$ decay. Only the gluon fusion production process is considered in this search and the signal is modelled assuming a narrow width of the Higgs boson. The strategy is similar to the previous LFV $H(125)$ searches performed by the CMS Collaboration, but optimised for higher mass Higgs boson decays.

This paper is organized as follows. After a brief overview of the CMS detector in Section 2 and the description of the collision data and simulated samples used in the analysis in Section 3, the event reconstruction is described in Section 4. The event selection is outlined in Section 5 and the background processes are described in Section 6. This is followed by a description of the systematic uncertainties in Section 7. Finally, the results are presented in Section 8 and the paper is summarized in Section 9.

2 The CMS detector

A 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. \cite{48}. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate
crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system \[49\]. 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 $\mu$s. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimised for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 Collision data and event simulation

The data used in this analysis have been collected in pp collisions at the LHC, at a centre-of-mass energy of 13 TeV, with the CMS detector in 2016, and correspond to an integrated luminosity of 35.9 fb$^{-1}$ \[50\]. A trigger requiring at least one muon is used to collect the data sample in the $H \rightarrow \mu \tau_h$ and $H \rightarrow \mu \tau_\mu$ channels. Triggers requiring at least one electron, or a combination of an electron and a muon are used for the $H \rightarrow e \tau_h$ and $H \rightarrow e \tau_\mu$ channels respectively. Simulated samples of signal and background events are produced with different event generators. The $H \rightarrow \mu \tau$ and $H \rightarrow e \tau$ decay samples are generated with POWHEG 2.0 \[51–56\] at next-to-leading-order (NLO) in perturbative quantum chromodynamics. Only the gluon fusion (ggH) \[57\] production mode has been considered in this analysis. These scalar boson samples are generated assuming the narrow width approximation for a range of masses from 200 to 900 GeV. The $Z +$jets and $W +$jets processes are simulated using the MADGRAPH5_aMC@NLO 2.2.2 \[58\] generator at leading order with the MLM jet matching and merging \[59\]. The MADGRAPH5_aMC@NLO generator is also used for diboson production which is simulated at NLO with the FxFx jet matching and merging scheme \[60\]. The POWHEG 2.0 and 1.0 at NLO are used for top quark-antiquark (t$\bar{t}$) and single top quark production, respectively. The POWHEG and MADGRAPH5_aMC@NLO generators are interfaced with PYTHIA 8.212 \[61\] for parton showering and fragmentation. The PYTHIA parameters for the underlying event description are set to the CUETP8M1 tune \[62\]. The set of parton distribution functions (PDFs) used is NNPDF30nnloas0118 \[63\]. The CMS detector response is modelled using GEANTA4 \[64\]. Because of the high instantaneous luminosities attained during data taking, events have multiple pp interactions per bunch crossing (pileup). This effect is taken into account in simulated samples, by generating concurrent minimum bias events, and overlapping them with simulated hard events. All simulated samples are weighted to match the pileup distribution observed in data, which has an average of approximately 23 interactions per bunch crossing.

4 Event reconstruction

The event reconstruction is performed using a particle-flow (PF) algorithm, which aims to reconstruct and identify each individual particle in an event (PF candidate), with an optimised combination of information from the various elements of the CMS detector \[65\]. In this process, the identification of the particle type for each PF candidate (photon, electron, muon, charged or neutral hadron) plays an important role in the determination of the particle direction and energy. The primary pp vertex of the event is identified as the reconstructed vertex with the largest value of summed physics-object $p_T^2$, where $p_T$ is the transverse momentum. The physics objects are the jets, clustered using the jet finding algorithm \[66,67\] with the tracks assigned to
the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the $p_T$ of those jets.

A muon is identified as a track in the silicon detectors, consistent with the primary pp vertex and with either a track or several hits in the muon system, associated with an energy deposit in the calorimeters compatible with the expectations for a muon [65, 68]. Identification is based on the number of spatial points measured in the tracker and in the muon system, the track quality, and its consistency with the event vertex location. The identification working point chosen for this analysis reconstructs muons with an efficiency above 98% and a hadron misidentification rate of 0.1% for pions and 0.3% for kaons. The energy is obtained from the corresponding track momentum. An important aspect of muon reconstruction is the lepton isolation that is described later in this section.

An electron is identified as a charged-particle track from the primary pp vertex in combination with one or more ECAL energy clusters. These clusters are matched with the track extrapolation to the ECAL and with possible bremsstrahlung photons emitted when interacting with the material of the tracker [69]. Electron candidates are accepted in the pseudorapidity range $|\eta| < 2.5$, with the exception of the region $1.44 < |\eta| < 1.57$ where service infrastructure for the detector is located. They are identified using a multivariate-analysis (MVA) discriminator that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the geometric and momentum matching between the electron trajectory and associated clusters, as well as various shower shape observables in the calorimeters. Electrons from photon conversions are removed. The chosen working point for selecting the electrons assures an average identification efficiency of 80% with a misidentification probability of 5%. The energy of electrons is determined from a combination of the track momentum at the primary vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons associated with the track.

Charged hadrons are identified as charged-particle tracks neither identified as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged hadron energy deposit. All the PF candidates are clustered into hadronic jets using the infrared- and collinear-safe anti-$k_T$ algorithm [66], implemented in the FASTJET package [70], with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the whole $p_T$ spectrum and detector acceptance. Additional proton-proton interactions within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation studies so that the average measured response of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, $Z + $ jets, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [71]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures.

Hadronically decaying $\tau$ leptons ($\tau_h$) are reconstructed and identified using the hadrons-plus-strips algorithm [72, 73]. The reconstruction starts from a jet and searches for the products of the main $\tau$ lepton decay modes: one charged hadron and up to two neutral pions, or three charged hadrons. To improve the reconstruction efficiency in the case of conversion of the
photons from a neutral-pion decay, the algorithm considers the PF photons and electrons from a strip along $\phi$. The sign of the $\tau_h$ candidate is determined through its decay products.

An MVA discriminator, based on variables such as lifetime information, decay mode, multiplicity of neutral, charged and pileup particles in a cone around the reconstructed $\tau_h$, is used to reduce the rate for quark- and gluon-initiated jets identified as $\tau_h$ candidates. The working point used in the analysis is a “tight” one, with an efficiency of about 50% for a genuine $\tau_h$, and approximately a 0.2% misidentification rate for quark and gluon jets \cite{73}. Additionally, muons and electrons misidentified as $\tau_h$ are rejected by considering the consistency between the measurements in the tracker, calorimeters, and muon detectors. The specific identification criteria depend on the final state studied and on the background composition. The $\tau$ leptons that decay to muons and electrons are reconstructed in the same manner as prompt muons and electrons, respectively, as described above.

The variable $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ is used to measure the separation between reconstructed objects in the detector, where $\eta$ and $\phi$ are the pseudorapidity and azimuthal directions, respectively.

Jets misidentified as muons or electrons are suppressed by imposing isolation requirements. The muon (electron) isolation is measured relative to its $p_T(\ell = \mu, e)$ by summing over the $p_T$ of PF particles in a cone with $\Delta R = 0.4 (0.3)$ around the lepton, excluding the lepton itself:

$$I_{\ell_{\text{rel}}} = \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^{\gamma} - p_T^{\text{PU}}(\ell) \right],$$

where $p_T^{\text{charged}}$, $p_T^{\text{neutral}}$, and $p_T^{\gamma}$ indicate the $p_T$ of a charged and of a neutral particle, and a photon within the cone, respectively. The neutral particle contribution to isolation from pileup, $p_T^{\text{PU}}(\ell)$, is estimated from the $p_T$ sum of charged hadrons not originating from the primary vertex scaled by a factor of 0.5 \cite{68} for the muons. For the electrons, this contribution is estimated from the area of the jet and the average energy density of the event \cite{74,75}. The charged-particle contribution to isolation from pileup is rejected by requiring the tracks to originate from the primary vertex. Jet arising from a b quark are identified by the combined secondary vertex b tagging algorithm \cite{76} using the working point characterised by a b jet identification efficiency around 65% and a misidentification probability around 1% for light quark and gluon jets.

All the reconstructed particles in the event are used to estimate the missing transverse momentum, $\vec{p}_T^{\text{miss}}$, which is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF candidates in an event \cite{77}. The effect of the jet energy corrections described earlier in this section is then propagated to this $\vec{p}_T^{\text{miss}}$. The magnitude of the final vector is referred to as $p_T^{\text{miss}}$. The transverse mass $m_T(\ell)$ is a variable formed from the lepton transverse momentum and the missing transverse momentum vectors: $m_T(\ell) = \sqrt{2 |p_T^\ell| |\vec{p}_T^{\text{miss}}| (1 - \cos \Delta \phi_{\ell - p_T^{\text{miss}}})}$, where $\Delta \phi_{\ell - p_T^{\text{miss}}}$ is the angle between the lepton transverse momentum and the missing transverse momentum. The collinear mass, $M_{\text{col}}$, provides an estimate of $m_T$ using the observed decay products of the Higgs boson candidate. It is reconstructed using the collinear approximation based on the observation that, since $m_T \gg m_\ell$, the $\tau$ lepton decay products are highly boosted in the direction of the $\tau$ candidate \cite{78}. The neutrino momenta can be approximated to have the same direction as the other visible decay products of the $\tau$ lepton ($\vec{x}^{\text{vis}}$) and the component of the $\vec{p}_T^{\text{miss}}$ in the direction of the visible $\tau$ lepton decay products is used to estimate the transverse component of the neutrino momentum ($p_T^{\nu,\text{est}}$). The collinear mass is then $M_{\text{col}} = M_{\text{vis}} / \sqrt{x_T^{\text{vis}}}$, where $x_T^{\text{vis}}$ is the fraction of
momentum carried by the visible decay products of the $\tau$ lepton, $x_{\tau}^{\text{vis}} = p_{\text{T}}^{\text{vis}} / (p_{\text{T}}^{\text{vis}} + p_{\text{T}}^{\nu_{\text{est}}})$, and $M_{\text{vis}}$ is the visible mass of the $\tau - e$ or $\tau - \mu$ system.

Dedicated performance studies on data validate the reconstruction and identification techniques described in this section. When necessary, corrections have been applied to the simulated samples to ensure they correctly describe the behaviour of the data [68, 69, 71, 73, 76, 77].

5 Event selection

The event selection is performed in two steps. An initial selection is followed by another, final, set of requirements on kinematic variables that exploit the distinct event topology of the signal. The event sample defined by the initial selection is used in the background estimation described in Section 6. The event selection begins by requiring two isolated leptons of opposite charge, different flavour, and separated by $\Delta R > 0.3$. The isolation of the $\tau_h$ candidates is included in the MVA discriminator described in Section 4. Events with additional $\mu$, $e$, or $\tau_h$ candidates respectively with $p_T > 10, 5, \text{ or } 20\text{ GeV}$ are discarded. The kinematic requirements applied are dictated by the triggers or detector acceptance and are summarized in Table 1.

The events are then divided into two categories according to the number of jets in the event. The jets are required to have $p_T > 30\text{ GeV}$ and $|\eta| < 4.7$. Events with no jets form the 0-jet category while events with exactly one jet form the 1-jet category. The 1-jet category includes ggH production with initial state radiation. Events with more than one jet are discarded.

Table 1: Initial selection criteria applied to the kinematic variables for the $H \rightarrow \mu \tau$ and $H \rightarrow e \tau$ analyses. The selected sample is used in the background estimation from control samples in data.

| $H \rightarrow \mu \tau_h$ | $H \rightarrow \mu \tau_e$ | $H \rightarrow e \tau_h$ | $H \rightarrow e \tau_{\mu}$ |
|--------------------------|--------------------------|--------------------------|--------------------------|
| $p_T^{\mu}$              | $>53\text{ GeV}$         | $>53\text{ GeV}$         | $>$10 GeV                |
| $p_T^{\tau}$             | $-$                       | $>$10 GeV                | $>$26 GeV                | $>$26 GeV                |
| $p_T$                    | $>$30 GeV                 | $-$                      | $>$30 GeV                | $-$                      |
| $|\eta|^{\mu}$            | $<2.4$                    | $<2.4$                   | $-$                      | $<2.4$                   |
| $|\eta|^{e}$              | $-$                       | $<2.4$                   | $<2.1$                   | $<2.4$                   |
| $|\eta|^{\tau}$           | $<2.3$                    | $-$                      | $<2.3$                   | $-$                      |
| $P_T^{\text{rel}}$       | 0.15                      | $<0.15$                  | $-$                      | $<0.15$                  |
| $\Delta R(\mu, e)$      | $-$                       | $>0.3$                   | $-$                      | $>0.3$                   |
| $\Delta R(\mu, \tau)$  | $>0.3$                    | $-$                      | $-$                      | $-$                      |
| $\Delta R(e, \tau)$     | $-$                       | $-$                      | $>$0.3                   | $-$                      |

The final selection is given in Table 2. It begins by tightening the $p_T$ requirement of the prompt lepton from the Higgs boson decay, as it provides a powerful discriminant against the background. The $\tau$ lepton in the $H$ decay is highly boosted, leading to a collimation of the decay products. This can be exploited by either limiting the azimuthal separation of the decay products including the $\vec{p}_{\text{T}}^{\text{miss}}$, or imposing a requirement on the transverse mass $m_T(\tau)$, which is strongly correlated with the azimuthal separation. These selection criteria are optimised for each decay mode in two $m_H$ ranges to obtain the most stringent expected upper limits. The low- and high-mass regions are defined to be $200 < m_H < 450\text{ GeV}$ and $450 < m_H < 900\text{ GeV}$, respectively. A binned likelihood fit to the $M_{\text{col}}$ distributions is then used to extract signal and background contributions. The $M_{\text{col}}$ approximates the Higgs mass better than the widely used $M_{\text{vis}}$, and therefore improves the separation of the signal from the background. This improve-
ment is larger in the high mass regime, with up to a factor of three gain in sensitivity when compared to the use of $M_{\text{vis}}$.

Table 2: Final event selection criteria for the low-mass range, $200 < m_H < 450$ GeV, and the high-mass range, $450 < m_H < 900$ GeV, considered in the $H \to \mu \tau$ and $H \to e \tau$ analyses.

|                  | Low-mass range | High-mass range |
|------------------|----------------|-----------------|
|                  | $p_T^\ell > 60$ GeV | $p_T^\mu > 150$ GeV |
| 0-jet $H \to \mu \tau_h$ | $p_T^\mu > 45$ GeV | $p_T^\mu > 45$ GeV |
|                  | $m_{\tau_h} < 105$ GeV | $m_{\tau_h} < 200$ GeV |
| 1-jet $H \to \mu \tau_h$ | $p_T^\mu > 60$ GeV | $p_T^\mu > 150$ GeV |
|                  | $p_T^\mu > 30$ GeV | $p_T^\mu > 45$ GeV |
|                  | $m_{\tau_h} < 120$ GeV | $m_{\tau_h} < 230$ GeV |
| 0-jet $H \to e \tau_h$ | $p_T^e > 60$ GeV | $p_T^e > 150$ GeV |
|                  | $p_T^e > 30$ GeV | $p_T^e > 45$ GeV |
|                  | $m_{\tau_h} < 105$ GeV | $m_{\tau_h} < 200$ GeV |
| 1-jet $H \to e \tau_h$ | $p_T^e > 60$ GeV | $p_T^e > 150$ GeV |
|                  | $p_T^e > 30$ GeV | $p_T^e > 45$ GeV |
|                  | $m_{\tau_h} < 120$ GeV | $m_{\tau_h} < 230$ GeV |
| 0-jet $H \to e \tau_\mu$ | $p_T^e > 60$ GeV | $p_T^e > 150$ GeV |
|                  | $p_T^\mu > 150$ GeV | $p_T^\mu > 45$ GeV |
|                  | $\Delta \phi(e, \mu) < 0.7$ rad | $\Delta \phi(e, \mu) < 0.3$ rad |
| 1-jet $H \to e \tau_\mu$ | $\Delta \phi(e, \mu) > 2.2$ rad | $\Delta \phi(e, \mu) > 2.2$ rad |

6 Background estimation

The most significant background in the $\mu \tau_h$ and $e \tau_h$ channels comes from the $W +$ jets process and from events comprised uniquely of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events. In these processes, jets are misidentified as electrons, muons or $\tau$ leptons. This background is estimated with the collected data. The main background in the $\mu \tau_e$ and $e \tau_\mu$ channels is $t \bar{t}$ production. It is estimated using simulations. Other smaller backgrounds include electroweak diboson ($WW, WZ$, and $ZZ$), Drell-Yan ($DY \to \ell \ell$ ($\ell = e, \mu$) + jets, $DY \to \tau \tau +$ jets, SM Higgs boson ($H \to \tau \tau, WW$), $W \gamma^{(*)} +$ jets, and single top quark production processes. These are estimated using simulations. Gluon fusion,
vector boson fusion, and associated production mechanisms are considered for the SM Higgs boson background. The background estimation techniques are described in detail below, and are validated with control regions that are enhanced with the dominant backgrounds.

The DY→ ℓℓ, ττ background is estimated from simulation. A reweighting is applied to the generator-level Z boson pT and invariant mass, m_{ℓℓ,ττ}, distributions to correct for a shape discrepancy between data and simulation. The reweighting factors, extracted from a control region enriched in Z → μμ events, are applied in bins of Z boson pT and m_{ℓℓ,ττ} as explained in [45]. Additional corrections for e → τ and μ → τ misidentification rates are applied to the simulated DY sample when the reconstructed τ candidate is matched to an electron for the H → eτ channel or a muon for the H → μτ channel, respectively, at the generator level. These corrections depend on the lepton η and are measured in Z → ℓℓ data events.

The tt background is also estimated using simulation. The overall normalisation of this estimate in the signal region is corrected with a rescaling factor derived from a control region enriched in t jets. A technique fully based on control samples in data is used to estimate the misidentified-lepton background in the τ channel. In QCD multijet events, both lepton candidates are misidentified as a jet. In W+jets events, one lepton candidate is expected to be a genuine lepton from the W decay and the other a jet misidentified as a lepton. In QCD multijet events, both lepton candidates are misidentified jets. A technique fully based on control samples in data is used to estimate the misidentified lepton background in the μτ channel. In the μτ channels, this background is estimated using a combination of simulated samples and control regions in data. These methods have been used in Refs. [38] and [45], and a detailed description can be found in those publications. However, we are briefly describing the techniques in the following subsections.

6.1 Misidentified lepton background estimation from control samples in data

The misidentified-lepton background is estimated from data. The misidentification probabilities, f_i, where i = μ, e, or τ, are evaluated with independent Z+jets data sets and then applied to a control sample. The control sample is obtained by relaxing the signal selection requirements, the μ, e, or τ isolation, and excluding events passing the signal selection. The f_i are estimated using events with a Z boson candidate and one jet that can be misidentified as μ, e, or τ. The Z boson candidate is formed requiring two muons with pT > 26 GeV, |η| < 2.4, and l^0_{rel} < 0.15. The muons are required to have opposite charges and the dimuon invariant mass, m_{μμ}, must satisfy 76 < m_{μμ} < 106 GeV. The contribution from diboson events, where the third lepton candidate corresponds to a genuine μ, e, or τ, is subtracted using simulation. Two Z+jets samples are defined: a signal-like one, in which the jet satisfies the same μ, e, or τ selection criteria used in the H → μτ or H → eτ selections, and a background-enriched Z+jets sample with relaxed identification on the jet misidentified as μ, e, or τ, but excluding events selected in the signal-like sample. The requirements on the third candidate, i.e. the misidentified jet, depend on the lepton flavour. The two samples are used to estimate f_i as

\[ f_i = \frac{N_i(Z\text{-jets signal-like})}{N_i(Z\text{-jets background-enriched}) + N_i(Z\text{-jets signal-like})}, \]

where N_i(Z+jets signal-like) is the number of events with a third candidate (μ, e, or τ) that passes the signal-like sample selection, and N_i(Z+jets background-enriched) is the number of
Figure 1: The $M_{col}$ distribution in the $t\bar{t}$ enriched (upper left), like-sign lepton (upper right), and $W+\text{jets}$ enriched (lower) control samples defined in the text. The uncertainty bands include both statistical and systematic uncertainties from Section 7. No fit is performed for these distributions. The different background processes shown are normalised to the luminosity of the data either using the theoretical prediction of the corresponding production cross section or directly from the data driven technique described in the text.
6.2 W+jets and QCD background estimation in $\mu\tau_e$ and $e\tau_\mu$ channels

Events in the background-enriched sample. The background-enriched selection used to estimate the misidentified $\mu$ and $e$ contribution requires an isolation of $0.15 < I_{rel}^\mu < 0.25$ and $0.1 < I_{rel}^e < 0.5$, respectively. In both cases the misidentification rate is computed and applied as a function of the lepton $p_T$. The lepton selection for the $\tau_h$ background-enriched sample requires that the $\tau_h$ lepton candidates are identified using a loose $\tau_h$ identification and isolation working point but are not identified by the tight working point used for the signal selection. The loose and tight working points have efficiencies of 70 and 50% for genuine $\tau_h$ candidates, respectively.

The $\tau_h$ misidentification rates have a $p_T$ dependence that varies with the number of charged pions in the decay. They are estimated and applied as a function of $p_T$ and for either one or three charged pions in the decay. The misidentified background in the signal sample is obtained from control samples for each lepton flavour. The selection requirements for these samples are the same as for the signal sample except that the $\mu$, $e$, or $\tau$ should pass the identification and isolation criteria used for the $Z$+jets background-enriched sample, but not those defining the $Z$+jets signal-like sample. To estimate the misidentified background in the signal sample, each event in this background enriched sample is weighted by a factor $f_i/(1-f_i)$. The background from misidentified muons and electrons is estimated to be less than 5% of the misidentified $\tau_h$ lepton background and is neglected.

The background estimate is validated in a like-sign sample by applying the misidentification rate $f_i$ to events selected by requiring the $\mu$, $e$, or $\tau$ in the pairs having the same charge in both the background-enriched and the signal-like samples. This validation is performed after the initial selection described in Section 5. Figure 1 (upper right) shows the data compared to the background estimate in the like-sign control region for the $H \rightarrow \mu\tau_h$ channel. The like-sign selection enhances the misidentified-lepton background, and this sample is expected to be composed of a similar fraction of $W$+jets and QCD multijet events. The background estimate is also validated in a $W$ boson enriched control sample. This data sample is obtained by applying the signal sample requirements and $m_T$ cuts, $50 < m_T(\ell) < 110$ GeV ($\ell = \mu$ or $e$) and $m_T(\tau) > 50$ GeV. The misidentified background in the signal region and $W$ boson enriched control sample are both dominated by $W$+jets events, with QCD multijet events forming a small fraction of the samples. Figure 1 (lower) shows the data compared to the background estimate in the $W$+jets enriched sample for the $H \rightarrow \mu\tau_h$ channel. The background expectation for the $H \rightarrow e\tau_h$ channel is also validated with the same samples and gives similar agreement.

6.2 W+jets and QCD background estimation in $\mu\tau_e$ and $e\tau_\mu$ channels

The $W$+jets background contribution to the misidentified background is estimated with simulations. The QCD multijet contribution is estimated with like-sign data events that pass all the other signal requirements. The remaining non-QCD background is estimated using simulation. The resulting sample is then rescaled to account for the differences between the background composition in the like and opposite sign samples. The scaling factors are extracted from QCD multijet enriched control samples, composed of events where the lepton candidates satisfy inverted isolation requirements, as explained in Ref. [45]. This background contribution accounts for a negligible fraction of the total yield after selection in both $\mu\tau_e$ and $e\tau_\mu$ channels.

7 Systematic uncertainties

Systematic uncertainties arise from both experimental and theoretical sources and can affect the normalisation and the shape of the collinear mass distribution. They are summarized in
Table 3: The systematic uncertainties for the four channels. All uncertainties are treated as correlated between the categories, except those with more values separated by the $\oplus$ symbol. In the case of two values, the first value is the correlated uncertainty and the second value is the uncorrelated uncertainty for each individual category. In the case of three values, the first and second values correspond to the uncertainties arising from factorisation and renormalisation scales and PDF variations and are correlated between categories, while the third value is the uncorrelated uncertainty for each individual category. Two values separated by the “$-$” sign represent the range of the uncertainties from the different sources and/or in the different jet categories.

| Systematic uncertainty                        | $H \rightarrow \mu \tau_h$ | $H \rightarrow \mu \tau_e$ | $H \rightarrow e \tau_h$ | $H \rightarrow e \tau_\mu$ |
|-----------------------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Muon trigger/ID/isolation                     | 2%                          | 2%                          | 2%                          | 2%                          |
| Electron trigger/ID/isolation                 | 2%                          | 2%                          | 2%                          | 2%                          |
| Hadronic $\tau_h$ efficiency                  | 5%                          | —                           | 5%                          | —                           |
| High $p_T \tau_h$ efficiency                  | $^{+5 \% \times p_T\times 0.001}_{-35 \% \times p_T\times 0.001}$ | —                           | $^{+5 \% \times p_T\times 0.001}_{-35 \% \times p_T\times 0.001}$ | —                           |
| b tagging veto                                | 2.0–2.5%                    | 2.0–2.5%                    | 2.0–2.5%                    | 2.0–2.5%                    |
| $\mu \rightarrow \tau_h$ background          | 25%                         | —                           | —                           | —                           |
| $e \rightarrow \tau_h$ background             | —                           | 12%                         | —                           | —                           |
| jet $\rightarrow \tau_h$ background           | 30%±10%                     | 30%±10%                     | —                           | —                           |
| QCD multijet background                        | —                           | 30%                         | —                           | 30%                         |
| $Z \rightarrow \mu \mu/ee +$ jets background | 0.1%±2%±5%                  | 0.1%±2%±5%                  | 0.1%±2%±5%                  | 0.1%±2%±5%                  |
| $Z \rightarrow \tau \tau +$ jets background   | 0.1%±2%±5%                  | 0.1%±2%±5%                  | 0.1%±2%±5%                  | 0.1%±2%±5%                  |
| W+jets background                              | 0.8%±3.8%±5%                | —                           | 0.8%±3.8%±5%                | —                           |
| WW, ZZ, WZ background                          | 3.5%±5%±5%                  | 3.5%±5%±5%                  | 3.5%±5%±5%                  | 3.5%±5%±5%                  |
| W+$\gamma$ background                         | 10%±5%                      | 10%±5%                      | —                           | 10%±5%                      |
| Single top quark background                    | 3%±5%±5%                    | 3%±5%±5%                    | 3%±5%±5%                    | 3%±5%±5%                    |
| $t\bar{t}$ background                          | 10%±5%                      | 10%±5%                      | 10%±5%                      | 10%±5%                      |
| SM Higgs fact./renorm. scales                  | 3.9 %                       | 3.9 %                       | 3.9 %                       | 3.9 %                       |
| SM Higgs PDF+$\alpha_S$                       | 3.2 %                       | 3.2 %                       | 3.2 %                       | 3.2 %                       |
| Jet energy scale                               | 3–20%                       | 3–20%                       | 3–20%                       | 3–20%                       |
| $\tau_h$ energy scale                         | 1.2%                       | —                           | 1.2%                       | —                           |
| $\mu, e \rightarrow \tau_h$ energy scale      | 1.5%                       | 3%                           | —                           | 0.2%                       |
| $\mu$ energy scale                             | 0.2%                       | 0.2%                       | —                           | 0.2%                       |
| $e$ energy scale                               | —                           | 0.1-0.5%                    | 0.1-0.5%                    | 0.1-0.5%                    |
| Unclustered energy scale                       | $\pm 1\sigma$              | $\pm 1\sigma$              | $\pm 1\sigma$              | $\pm 1\sigma$              |
| IntegRated luminosity                          | 2.5%                       | 2.5%                       | 2.5%                       | 2.5%                       |

The uncertainties in the muon, electron and $\tau$ lepton selection including the trigger, identification (ID), and isolation efficiencies are estimated from collision data sets of $Z$ bosons decaying to $ee, \mu\mu, \tau_\mu \tau_h$ [68, 69, 73]. They result in changes of normalisation, with the exception of the uncertainty on high $p_T$ lepton efficiency that changes both yield and $M_{col}$ distribution shape. The $b$ tagging efficiency is measured in collision data, and the simulation is adjusted accordingly to match with it. The uncertainty in this measurement is taken as the systematic error affecting the normalisation of the simulation [76].

The uncertainties in the estimate of the misidentified-lepton backgrounds ($\mu \rightarrow \tau_h$, $e \rightarrow \tau_h$, jet $\rightarrow \tau_h$, $\mu, e$) are extracted from the validation tests in control samples, as described in Section 3, they affect both the normalisation and the shape of the $M_{col}$ distribution. The uncertainty in the QCD multijet background yield is 30%, and corresponds to the uncertainty in the extrapolation factor from the same-sign to the opposite-sign region, as determined in Ref. [45].
The uncertainties in the background contributions from $Z$, $WW$, $ZZ$, $W\gamma$, $t\bar{t}$ and single-top quark arise predominantly from those in the measured cross sections of these processes and are applied as uncertainties in sample normalisation.

The uncertainties in the Higgs boson production cross sections due to the factorisation and the renormalisation scales, as well as the PDFs and the strong coupling constant ($\alpha_S$), result in changes in normalisation. They are taken from Ref. [79] and summarized in Table 3 for the SM Higgs boson and Table 4 for heavy Higgs bosons. Only effects on the total rate are considered. Effects on the acceptance have been neglected.

Table 4: Theoretical uncertainties from [79] are applied to the Higgs boson production cross sections for the different masses. In the reference, the PDF and $\alpha_S$ uncertainties are computed following the recommendation of the PDF4LHC working group. The remaining Gaussian uncertainty accounts for additional intrinsic sources of theory uncertainty described in detail in the reference.

| $m_H$ (GeV) | Cross section (pb) | Theory, Gaussian (%) | PDF+$\alpha_S$ (%) |
|------------|-------------------|---------------------|--------------------|
| 200        | 16.94 ±1.8        | ±1.8                | ±3.0               |
| 300        | 6.59 ±1.8         | ±1.8                | ±3.0               |
| 450        | 2.30 ±2.0         | ±2.0                | ±3.1               |
| 600        | 1 ±2.1            | ±2.1                | ±3.5               |
| 750        | 0.50 ±2.1         | ±2.1                | ±4.0               |
| 900        | 0.27 ±2.2         | ±2.2                | ±4.6               |

Shape and normalization uncertainties arising from the uncertainty in the jet energy scale are computed by propagating the effect of altering each source of jet energy scale uncertainty by ±1 standard deviation to the fit templates of each process. There are 27 independent sources of jet energy scale uncertainty, fully correlated between categories and $\tau \ell$ lepton decay channels.

The uncertainty in the $\tau_h$ energy scale is treated equally for the two independent channels: $H \to \mu \tau_h$ and $H \to e \tau_h$. It is propagated to the collinear mass distributions. Also, the uncertainty in the energy scale of electrons and muons misidentified as $\tau_h$ is propagated to the $M_{col}$ distributions and produces changes in the distribution shape and normalization. Systematic uncertainties in the electron energy scale and resolution include the effects of electron selection efficiency, pseudorapidity dependence and categorisation, summed in quadrature. They impact both the normalization and shape of the $M_{col}$ distribution. The systematic uncertainties in the energy resolution have negligible effect. The uncertainty in muon energy scale and resolution is also treated in the same manner. Scale uncertainties on the energy from jets with $p_T$ below 15 GeV and PF candidates not clustered inside jets (unclustered energy scale uncertainty) are also considered [77]. They are estimated independently for four particle categories: charged particles, photons, neutral hadrons, and very forward particles which are not contained in jets. The effect of shifting the energy of each particle by its uncertainty is propagated to $p_T^{miss}$ and leads to both changes in shape of the distribution and in overall predicted yields. The different systematic uncertainties from the four particle categories, for the unclustered energy scale, are considered uncorrelated.

The bin-by-bin uncertainties [80] account for the statistical uncertainties in every bin of the template distributions of every process. They are uncorrelated between bins, processes, and categories.

Shape uncertainties related to the pileup have been considered by varying the weights applied to simulation. This weight variation is obtained changing by 5% the total inelastic cross section used in the estimate of the pileup events in data [81]. The new values are then applied, event by
event, to produce alternative collinear mass distributions used as shape uncertainties in the fit. Other minimum bias event modelling and simulation uncertainties are estimated to be much smaller and are therefore neglected. The uncertainty on the integrated luminosity affects all processes with normalization taken directly from simulation.

8 Results

After all selection criteria have been applied, a binned maximum likelihood fit is performed on the $M_{\text{col}}$ distributions in the range 0–1400 GeV, looking for a signal-like excess on top of the estimated background. No fit on the control region is performed. The systematic uncertainties are represented by nuisance parameters, assuming a log normal prior for normalisation parameters, and Gaussian priors for $M_{\text{col}}$ shape uncertainties. The uncertainties that affect the shape of the $M_{\text{col}}$ distribution, mainly those corresponding to the energy scales, are represented by nuisance parameters whose variation results in a modification of the distribution \cite{82, 83}. A profile likelihood ratio is used as test statistic. The 95% CL upper limits on the H production cross section times branching fraction to LFV lepton channels, $\sigma(gg \rightarrow H)B(H \rightarrow \mu\tau)$ and $\sigma(gg \rightarrow H)B(H \rightarrow e\tau)$, are set using the CL\textsubscript{s} criterion \cite{84, 85} and the asymptotic approximation of the distributions of the LHC test-statistic \cite{86}, in a combined fit to the $M_{\text{col}}$ distributions. The limits are also computed per channel and category. The upper limits are derived in the analysed mass range in steps of 50 GeV. Where simulated samples are not available, shapes and yields are interpolated from the neighbouring samples with a moment morphing algorithm that derive the $M_{\text{col}}$ distribution from the two closest simulated mass points.

8.1 $H \rightarrow \mu\tau$ results

The distributions of the collinear mass $M_{\text{col}}$ compared to the signal and background contributions in the $H \rightarrow \mu\tau_h$ and $H \rightarrow \mu\tau_e$ channels, in each jet category, are shown in Figs. 2 and 3. No excess over the background expectation is observed. The observed and median expected 95% CL upper limits on $\sigma(gg \rightarrow H)B(H \rightarrow \mu\tau)$ range from 51.9 (57.4) fb to 1.6 (2.1) fb, and are given for each category in Table 5. The limits are also summarized graphically in Fig. 4 for the individual categories, and in Fig. 5 for the combination of the two $\tau$ decay channels.

8.2 $H \rightarrow e\tau$ results

The distributions of the collinear mass $M_{\text{col}}$ compared to the signal and background contributions in the $H \rightarrow e\tau_h$ and $H \rightarrow e\tau_\mu$ channels, in each category, are shown in Figs. 6 and 7. No excess over the background expectation is observed. The observed and median expected 95% CL upper limits on $\sigma(gg \rightarrow H)B(H \rightarrow e\tau)$ range from 94.1 (91.6) fb to 2.3 (2.3) fb, and are given for each category in Table 6. The limits are also summarized graphically in Fig. 8 for the individual categories, and in Fig. 9 for the combination of both two $\tau$ decay channels.

9 Summary

The first direct search for lepton flavour violating decays of a neutral non-standard-model Higgs boson (H) in the $\mu\tau$ and $e\tau$ channels is presented in this paper. The analyzed data set corresponds to an integrated luminosity of 35.9 fb$^{-1}$ of proton-proton collision data recorded at $\sqrt{s} = 13$ TeV. The results are extracted from a fit to the collinear mass distributions. No evidence is found for lepton flavour violating decays of H in the investigated mass range. The observed (expected) upper limits at 95% confidence level on the product of production cross
Figure 2: The $M_{\text{col}}$ distribution in the signal region, for the $\mu\tau_h$ (upper) and $\mu\tau_e$ (lower) channels for the Higgs boson mass in the range 200–450 GeV for 0-jet (left) and 1-jet (right) categories. The uncertainty bands include both statistical and systematic uncertainties. The plotted values are number of events per bin using a variable bin size. The background is normalised to the best fit values from a binned likelihood fit, discussed in the text, to the background only hypothesis. For depicting the signals a branching fraction of 1% and BSM cross sections from Ref. [79] are assumed.
Figure 3: The $M_{col}$ distribution in the signal region, for the $\mu \tau_h$ (upper) and $\mu \tau_e$ (lower) channels for the Higgs boson mass in the range 450–900 GeV for 0-jet (left) and 1-jet (right) categories. The uncertainty bands include both statistical and systematic uncertainties. The plotted values are number of events per bin using a variable bin size. The background is normalised to the best fit values from a binned likelihood fit, discussed in the text, to the background only hypothesis. For depicting the signals a branching fraction of 1% and BSM cross sections from Ref. [79] are assumed.
Table 5: The observed and median expected 95% CL upper limits on $\sigma(gg \rightarrow H)B(H \rightarrow \mu\tau)$.

| $m_H$ (GeV) | 0 jet $\mu\tau_e$ | 1 jet $\mu\tau_e$ comb | 0 jet $\mu\tau_h$ | 1 jet $\mu\tau_h$ comb | 0 jet $\mu\tau$ | 1 jet $\mu\tau$ comb |
|-------------|-------------------|------------------------|------------------|------------------------|----------------|---------------------|
| 200         | 147.8             | 262.1                  | 159.4            | 53.1                   | 136.9          | 46.4                |
| 300         | 30.1              | 100.8                  | 29.3             | 57.4                   | 49.4           | 51.4                |
| 450         | 31.1              | 35.3                   | 23.7             | 9.1                    | 14.2           | 7.3                 |
| 600         | 8.1               | 15.2                   | 6.8              | 7.5                    | 7.4            | 5.3                 |
| 750         | 6.5               | 7.8                    | 4.7              | 4.8                    | 4.8            | 3.2                 |
| 900         | 4.4               | 5.6                    | 2.9              | 4.6                    | 2.6            | 2.3                 |

Median expected 95% CL upper limit on $\sigma(gg \rightarrow H)B(H \rightarrow \mu\tau)$ (fb)

| $m_H$ (GeV) | 0 jet $\mu\tau_e$ | 1 jet $\mu\tau_e$ comb | 0 jet $\mu\tau_h$ | 1 jet $\mu\tau_h$ comb | 0 jet $\mu\tau$ | 1 jet $\mu\tau$ comb |
|-------------|-------------------|------------------------|------------------|------------------------|----------------|---------------------|
| 200         | 107.5             | 209.8                  | 95.6             | 79.7                   | 151.6          | 72.5                |
| 300         | 49.8              | 108.6                  | 45.2             | 31.0                   | 54.8           | 27.7                |
| 450         | 17.5              | 32.8                   | 20.4             | 9.4                    | 15.3           | 8.0                 |
| 600         | 10.4              | 17.9                   | 8.9              | 6.2                    | 8.3            | 4.9                 |
| 750         | 8.0               | 11.1                   | 6.1              | 4.3                    | 5.4            | 3.1                 |
| 900         | 6.9               | 8.0                    | 4.9              | 3.3                    | 4.3            | 2.4                 |

Table 6: The observed and median expected 95% CL upper limits on $\sigma(gg \rightarrow H)B(H \rightarrow e\tau)$.

| $m_H$ (GeV) | 0 jet $e\tau_\mu$ | 1 jet $e\tau_\mu$ comb | 0 jet $e\tau_h$ | 1 jet $e\tau_h$ comb | 0 jet $e\tau$ | 1 jet $e\tau$ comb |
|-------------|-------------------|------------------------|------------------|------------------------|----------------|---------------------|
| 200         | 119.2             | 365.3                  | 117.8            | 179.4                  | 197.8          | 139.6               |
| 300         | 85.1              | 208.7                  | 94.5             | 56.4                   | 56.4           | 43.2                |
| 450         | 14.0              | 25.1                   | 11.7             | 7.6                    | 16.9           | 6.8                 |
| 600         | 17.4              | 13.9                   | 11.7             | 9.3                    | 9.1            | 6.3                 |
| 750         | 5.1               | 9.5                    | 4.1              | 4.7                    | 5.6            | 3.3                 |
| 900         | 7.7               | 8.3                    | 5.3              | 3.8                    | 5.0            | 2.7                 |

Median expected 95% CL upper limit on $\sigma(gg \rightarrow H)B(H \rightarrow e\tau)$ (fb)

| $m_H$ (GeV) | 0 jet $e\tau_\mu$ | 1 jet $e\tau_\mu$ comb | 0 jet $e\tau_h$ | 1 jet $e\tau_h$ comb | 0 jet $e\tau$ | 1 jet $e\tau$ comb |
|-------------|-------------------|------------------------|------------------|------------------------|----------------|---------------------|
| 200         | 158.2             | 366.6                  | 142.3            | 135.7                  | 238.9          | 120.1               |
| 300         | 57.9              | 123.0                  | 52.3             | 42.9                   | 70.3           | 37.5                |
| 450         | 20.4              | 32.6                   | 17.2             | 10.1                   | 18.0           | 8.7                 |
| 600         | 14.7              | 22.1                   | 11.9             | 8.6                    | 11.6           | 6.8                 |
| 750         | 8.6               | 10.5                   | 6.2              | 4.9                    | 6.5            | 3.7                 |
| 900         | 8.5               | 9.0                    | 5.7              | 4.0                    | 4.7            | 2.6                 |
Figure 4: The observed and median expected 95% CL upper limits on $\sigma(gg \rightarrow H)B(H \rightarrow \mu\tau)$, for the $\mu\tau_{h}$ (upper) and $\mu\tau_{e}$ (lower) channels, for 0-jet (left) and 1-jet (right) categories. The dashed line shows the transition between the two investigated mass ranges.
Figure 5: The combined observed and median expected 95% CL upper limits on $\sigma(gg \to H) B(H \to \mu\tau)$, for $\mu\tau_h$ (upper left) and $\mu\tau_e$ (lower right) channels, and their combination $\mu\tau$ (lower). The dashed line shows the transition between the two investigated mass ranges.
Figure 6: The $M_{col}$ distribution in the signal region, for the $e\tau_h$ (upper) and $e\tau_\mu$ (lower) channels for the Higgs boson mass in the range 200–450 GeV for 0-jet (left) and 1-jet (right) categories. The uncertainty bands include both statistical and systematic uncertainties. The plotted values are number of events per bin using a variable bin size. The background is normalised to the best fit values from a binned likelihood fit, discussed in the text, to the background only hypothesis. For depicting the signals a branching fraction of 1% and BSM cross sections from Ref. [79] are assumed.
Figure 7: The $M_{col}$ distribution in the signal region, for the $e\tau_h$ (upper) and $e\tau_\mu$ (lower) channels for the Higgs boson mass in the range 450–900 GeV for 0-jet (left) and 1-jet (right) categories. The uncertainty bands include both statistical and systematic uncertainties. The plotted values are number of events per bin using a variable bin size. The background is normalised to the best fit values from a binned likelihood fit, discussed in the text, to the background only hypothesis. For depicting the signals a branching fraction of 1% and BSM cross sections from Ref. [79] are assumed.
Figure 8: The observed and median expected 95% CL upper limits on $\sigma(gg \to H)B(H \to e\tau)$, for the $e\tau_h$ (upper) and $e\tau_\mu$ (lower) channels, for 0-jet (left) and 1-jet (right) categories. The dashed line shows the transition between the two investigated mass ranges.
Figure 9: The combined observed and median expected 95% CL upper limits on \( \sigma(gg \rightarrow H)B(H \rightarrow e\tau) \), for \( e\tau_h \) (upper left) and \( e\tau_\mu \) (upper right) channels, and their combination \( e\tau \) (lower). The dashed line shows the transition between the two investigated mass ranges.
section with branching fraction, for H mass in the range 200–900 GeV, decaying to $\mu\tau$ and $e\tau$
 vary from 51.9 (57.4) fb to 1.6 (2.1) fb and from 94.1 (91.6) fb to 2.3 (2.3) fb, respectively.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan1, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth1, M. Jeitler1, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck1, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz1, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D’Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Vandenbroucke, 1, 1

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, J. Luetic, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vandersyde, P. Vanlaer, D. Vannerom

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, I. Khvastunov2, M. Niedziela, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, A. Magitteri, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato3, E. Coelho, E.M. Da Costa, G.G. Da Silveira4, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins5, D. Matos Figueiredo, M. Medina Jaime6, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nagima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Szajder, M. Thiel, E.J. Tonelli Manganote3, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahujaa, C.A. Bernardesa, L. Calligarisa, T.R. Fernandez Perez Tomeia, E.M. Gregoresb, D.S. Lemos, P.G. Mercadanteb, S.F. Novaesa, Sandras Padulaa

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
M. Ahmad, G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla, E. Salama

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro\textsuperscript{14}, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris
C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram\textsuperscript{15}, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte\textsuperscript{15}, J.-C. Fontaine\textsuperscript{15}, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, S. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze\textsuperscript{10}

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze\textsuperscript{10}

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, J. Roemer, A. Schmidt, S.C. Schüler, A. Sharma, S. Thüer, S. Wiedenbeck

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, W. Haj Ahmad\textsuperscript{16}, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkor, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl\textsuperscript{17}
Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Deffranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, D. Marconi, J. Multhaup, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann, U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, T. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

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

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak, D.K. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarami, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinebad

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, R. Aly, C. Calabria, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis, M. De Palma, A. Di Florio, L. Fiore, A. Gelmi, G. Iaselli,
M. Inceab, b, S. Lezkiab, b, G. Maggia, c, M. Maggna, G. Miniellaa, b, S. Myaa, b, S. Nuzzoa, b, A. Pontillia, b, G. Pugliesie, c, R. Radogna, a, A. Ranieria, G. Selvaggiab, L. Silvestria, R. Venditta, a, P. Verwillinga

**INFN Sezione di Bologna a, Università di Bologna b, Bologna, Italy**
G. Abbenci, c, C. Battilanaab, b, D. Bonacorsiab, b, L. Borgonovia, b, S. Braibant-Giacomelliab, b, R. Campaninia, b, P. Capiluppia, b, A. Castra, b, F.R. Cavalloa, C. Cioccia, G. Codispotiab, b, M. Cuffianiab, b, G.M. Dallavallea, F. Fabbria, A. Fanfania, b, E. Fontanesi, P. Giacomelliab, C. Grandia, L. Guiducciab, b, F. Iemminia, b, S. Lo Meoa, b, S. Marcellinia, G. Masettiab, F.L. Navariaab, A. Perrottia, F. Primaverab, a, A.M. Rossia, b, T. Rovellia, b, G.P. Siroliab, b, N. Tosis

**INFN Sezione di Catania a, Università di Catania b, Catania, Italy**
S. Albergob, 31, S. Costaab, a, A. Di Mattiaa, R. Potenzaab, b, A. Tricomib, a, 31, C. Tuvedab

**INFN Sezione di Firenze a, Università di Firenze b, Firenze, Italy**
G. Barbagli, a, R. Ceccarelli, K. Chatterjeeab, b, V. Ciullib, c, C. Cивиниа, R. D’Alessandroab, b, E. Focardiab, b, G. Latino, P. Lenzb, b, M. Meschinib, S. Paoletti, G. Sguazzonib, D. Stromab, L. Vilianab

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**
L. Benussi, S. Bianco, D. Piccoloa

**INFN Sezione di Genova a, Università di Genova b, Genova, Italy**
M. Bozzoa, b, F. Ferroa, R. Mulargiaab, b, E. Robuttia, N. Tosis

**INFN Sezione di Milano-Bicocca a, Università di Milano-Bicocca b, Milano, Italy**
A. Benaglia, a, A. Beschib, b, F. Brivioc, b, V. Cirioloab, c, S. Di Guidaa, b, M.E. Dinardob, a, P. Dini, S. Fiorendia, b, S. Genniab, A. Ghezzia, b, P. Govoniab, b, L. Guzzia, b, M. Malbertib, S. Malvezziab, D. Menasceab, F. Montia, b, L. Moronib, G. Ortonaab, b, M. Paganonib, a, D. Pedrini, S. Ragazzaab, T. Tabarellia de Fatisab, b, D. Zuoab

**INFN Sezione di Napoli a, Università di Napoli ‘Federico II’ b, Napoli, Italy, Università della Basilicata c, Potenza, Italy, Università G. Marconi d, Roma, Italy**
S. Buontempoab, N. Cavalloa, c, A. De Iorioab, c, A. Di Crescenzoab, c, F. Fabozzic, c, F. Fienga, b, G. Galatia, A.O.M. Iorioab, b, L. Listaa, b, S. Meoal, a, d, 17, P. Paoluccioab, 17, B. Rossia, C. Sciaccaab, E. Voevodinab

**INFN Sezione di Padova a, Università di Padova b, Padova, Italy, Università di Trento c, Trento, Italy**
P. Azzi, N. Bacchettaab, D. Bisellia, b, A. Bolettia, a, A. Bragagnolo, R. Carlinab, b, P. Checchia, b, P. De Castro Manzana, T. Dorigoa, b, U. Dosselliab, F. Gasparinib, c, U. Gasparinib, a, A. Gozzellina, b, S.Y. Hoh, P. Lujan, M. Margonib, A.T. Meneguzzoa, b, J. Pazzinnib, M. Presilla, b, P. Ronchesea, b, R. Rossina, b, F. Simonettoab, A. Tiko, M. Tosis, b, M. Zanettia, b, P. Zottob, a, G. Zumerleab

**INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy**
A. Braghiera, P. Montagnab, b, S.P. Ratiab, b, V. Reab, M. Ressegottia, b, C. Riccardia, b, P. Salvini, a, I. Vainab, b, P. Vitulob, a

**INFN Sezione di Perugia a, Università di Perugia b, Perugia, Italy**
M. Biasiniab, b, G.M. Bileib, C. Cecchib, d, D. Ciangottianiab, L. Fanob, c, P. Laricciab, R. Leonardiab, E. Manoniab, G. Mantovania, b, V. Marianab, d, M. Menichellia, A. Rossia, a, A. Santochiaab, D. Spigaa

**INFN Sezione di Pisa a, Università di Pisa b, Scuola Normale Superiore di Pisa c, Pisa, Italy**
K. Androsov, a, P. Azzurriab, G. Bagliesi, b, V. Bertacchiab, c, L. Bianchiana, T. Boccaliana
R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,b}, R. Dell’Orso\textsuperscript{a}, G. Fedi\textsuperscript{a}, L. Giannini\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, E. Manca\textsuperscript{a,c}, G. Mandorli\textsuperscript{a,c}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, G. Rolandi\textsuperscript{32}, S. Roy Chowdhury, A. Scribano\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, N. Turini, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

\textbf{INFN Sezione di Roma} \textsuperscript{a}, Sapienza Universit`a di Roma \textsuperscript{b}, Rome, Italy
F. Cavallari\textsuperscript{a}, M. Cipriani\textsuperscript{a,b}, D. Del Re\textsuperscript{a,b}, E. Di Marco\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, E. Longo\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b}, P. Meridiani\textsuperscript{a}, G. Organtini\textsuperscript{a,b}, F. Pandolfi\textsuperscript{a}, R. Paramatti\textsuperscript{a,b}, C. Quaranta\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a,b}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}, L. Soffi\textsuperscript{a,b}

\textbf{INFN Sezione di Torino} \textsuperscript{a}, Universit`a di Torino \textsuperscript{b}, Torino, Italy, Universit`a del Piemonte Orientale \textsuperscript{c}, Novara, Italy
N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, N. Bartosik\textsuperscript{a}, R. Bellan\textsuperscript{a,b}, C. Biino\textsuperscript{a}, A. Cappati\textsuperscript{a,b}, N. Cartiglia\textsuperscript{a}, S. Cometti\textsuperscript{a}, M. Costa\textsuperscript{a,b}, R. Covarelli\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, B. Kiani\textsuperscript{a,b}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, E. Montej\textsuperscript{a,b}, M. Monteno\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Salvatico\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, D. Soldi\textsuperscript{a,b}, A. Staiano\textsuperscript{a}

\textbf{INFN Sezione di Trieste} \textsuperscript{a}, Universit`a di Trieste \textsuperscript{b}, Trieste, Italy
S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, A. Da Rold\textsuperscript{a,b}, G. Della Ricca\textsuperscript{a,b}, F. Vezzoler\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

\textbf{Kyungpook National University}, Daegu, Korea
B. Kim, D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

\textbf{Chonnam National University}, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

\textbf{Hanyang University}, Seoul, Korea
B. Francois, T.J. Kim, J. Park

\textbf{Korea University}, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh

\textbf{Kyung Hee University}, Department of Physics
J. Goh

\textbf{Sejong University}, Seoul, Korea
H.S. Kim

\textbf{Seoul National University}, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

\textbf{University of Seoul}, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, I. Watson

\textbf{Sungkyunkwan University}, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

\textbf{Riga Technical University}, Riga, Latvia
V. Veckalns\textsuperscript{33}
Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z.A. Ibrahim, F. Mohamad Idris, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Gorski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
A. Baginyan, Y. Ershov, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, V. Karjавин, A. Lanev, A. Malakhov, V. Matveev, V. Mitsyn, P. Moisenz, V. Palchik, V. Perelygin, M. Savina, S. Shmatov, V. Vovtishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chchtipounov, V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev
Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
M. Chadeeva, P. Parygin, D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M.Perfilov, S. Petrushankov, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov, V. Blinov, T. Dimova, L. Kardapoltsev, Y. Skovpen

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, Á. Alvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz
The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, Y.t. Duh, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. McColl, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang, J. Yoo

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

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee,
L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, AllisonReinsvold Hall, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Nahn, V. O’Dell, V. Papadimitriou, K. Pedo, C. Pen, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkacyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y.R. Joshi

Florida State University, Tallahassee, USA
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martine, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki3, W. Clarida, K. Dilisz20, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili71, A. Moeller, J. Nachtman, H. Ogul23, Y. Onel, F. Ozok23, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright
University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D’Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A.C. Benvenuti†, R.M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverton, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko37, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, USA
S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud,
D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

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

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, S. Luo, D. Marley, R. Mueller, D. Overton, L. Pernière, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

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

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber, H. He, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS, Nova Andradina, Brazil
6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Cairo University, Cairo, Egypt
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Purdue University, West Lafayette, USA
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at Shoolini University, Solan, India
27: Also at University of Visva-Bharati, Santiniketan, India
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Now at INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Bari, Italy
30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
31: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
32: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, USA
41: Also at Imperial College, London, United Kingdom
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at California Institute of Technology, Pasadena, USA
44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
46: Also at Università degli Studi di Siena, Siena, Italy
47: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy, Pavia, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Universität Zürich, Zurich, Switzerland
50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Şırnak University, Şırnak, Turkey
53: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
54: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
55: Also at Mersin University, Mersin, Turkey
56: Also at Piri Reis University, Istanbul, Turkey
57: Also at Gaziosmanpasa University, Tokat, Turkey
58: Also at Ozyegin University, Istanbul, Turkey
59: Also at Izmir Institute of Technology, Izmir, Turkey
60: Also at Marmara University, Istanbul, Turkey
61: Also at Kafkas University, Kars, Turkey
62: Also at Istanbul Bilgi University, Istanbul, Turkey
63: Also at Hacettepe University, Ankara, Turkey
64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
65: Also at IPPP Durham University, Durham, United Kingdom
66: Also at Monash University, Faculty of Science, Clayton, Australia
67: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
68: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
69: Also at Vilnius University, Vilnius, Lithuania
70: Also at Bingol University, Bingol, Turkey
71: Also at Georgian Technical University, Tbilisi, Georgia
72: Also at Sinop University, Sinop, Turkey
73: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
74: Also at Texas A&M University at Qatar, Doha, Qatar
75: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
76: Also at University of Hyderabad, Hyderabad, India