

## MIT Open Access Articles

*Search for new physics in the # lepton plus missing transverse momentum final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** Journal of High Energy Physics. 2023 Sep 08;2023(9):51

**As Published:** [https://doi.org/10.1007/JHEP09\(2023\)051](https://doi.org/10.1007/JHEP09(2023)051)

**Publisher:** Springer Berlin Heidelberg

**Persistent URL:** <https://hdl.handle.net/1721.1/152258>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of use:** Creative Commons Attribution



# Search for new physics in the $\tau$ lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

---



## The CMS collaboration

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

**ABSTRACT:** A search for physics beyond the standard model (SM) in the final state with a hadronically decaying tau lepton and a neutrino is presented. This analysis is based on data recorded by the CMS experiment from proton-proton collisions at a center-of-mass energy of 13 TeV at the LHC, corresponding to a total integrated luminosity of  $138 \text{ fb}^{-1}$ . The transverse mass spectrum is analyzed for the presence of new physics. No significant deviation from the SM prediction is observed. Limits are set on the production cross section of a  $W'$  boson decaying into a tau lepton and a neutrino. Lower limits are set on the mass of the sequential SM-like heavy charged vector boson and the mass of a quantum black hole. Upper limits are placed on the couplings of a new boson to the SM fermions. Constraints are put on a nonuniversal gauge interaction model and an effective field theory model. For the first time, upper limits on the cross section of  $t$ -channel leptoquark (LQ) exchange are presented. These limits are translated into exclusion limits on the LQ mass and on its coupling in the  $t$ -channel. The sensitivity of this analysis extends into the parameter space of LQ models that attempt to explain the anomalies observed in B meson decays. The limits presented for the various interpretations are the most stringent to date. Additionally, a model-independent limit is provided.

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

ARXIV EPRINT: [2212.12604](https://arxiv.org/abs/2212.12604)

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>The CMS detector</b>	<b>3</b>
<b>3</b>	<b>Physics models</b>	<b>4</b>
3.1	The SSM heavy charged vector boson	4
3.2	Varying coupling strength	4
3.3	Nonuniversal gauge interaction model	5
3.4	Quantum black holes	6
3.5	Leptoquarks	6
3.6	Effective field theory description	7
<b>4</b>	<b>Data and simulated events</b>	<b>8</b>
4.1	Data	8
4.2	Event simulation	8
4.2.1	Signal simulation	8
4.2.2	Simulation of the background	9
<b>5</b>	<b>Event selection and particle identification</b>	<b>10</b>
<b>6</b>	<b>Jet background estimation</b>	<b>11</b>
<b>7</b>	<b>Systematic uncertainties</b>	<b>12</b>
<b>8</b>	<b>Results</b>	<b>13</b>
8.1	Model-independent cross section limit	14
8.2	Mass limit for a heavy vector boson	15
8.3	The NUGIM and coupling sensitivity	16
8.4	The QBH limits	16
8.5	Leptoquark limits	17
8.6	The EFT limits	18
8.7	Overview of the exclusion limits	19
<b>9</b>	<b>Summary</b>	<b>21</b>
	<b>The CMS collaboration</b>	<b>30</b>

---

## 1 Introduction

A search for new phenomena is conducted in the final state with a high transverse-momentum ( $p_T$ ) tau lepton ( $\tau$ ) and large missing transverse momentum due to the neutrino ( $\nu$ ). This search uses proton-proton (pp) collision data at  $\sqrt{s} = 13$  TeV recorded by the CMS experiment at the CERN LHC in 2016–2018, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ .

Due to its short lifetime, the  $\tau$  lepton itself is not detected directly, but via its decay products. The hadronic decays of the  $\tau$  lepton constitute about  $2/3$  of all its decays. The hadronic decay products,  $\tau_h$ , of the tau lepton are distinctive because they result in jets with a lower charged-hadron multiplicity compared to the jets originating from the hadronization of partons produced in the hard scattering process. The selection of the hadronic  $\tau$  decay mode also allows for discrimination against the leptonic  $\tau$  decays, which cannot be distinguished from prompt decays to light leptons, such as those examined in the most recent searches by the ATLAS and CMS Collaborations for  $W'$  in the final states with an electron or muon plus a neutrino [1, 2].

The transverse mass,  $m_T$ , of the  $\tau$ - $p_T^{\text{miss}}$  system is the primary discriminating variable in this analysis. It is defined as

$$m_T = \sqrt{2p_T^{\tau_h} p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})]}, \quad (1.1)$$

where  $p_T^{\tau_h}$  is the magnitude of the transverse momentum of the reconstructed  $\tau_h$  candidate,  $\vec{p}_T^{\text{miss}}$  is the vector of transverse momentum misbalance in the event,  $p_T^{\text{miss}}$  is its magnitude, and  $\Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})$  is the azimuthal opening angle between the directions of  $\vec{p}_T^{\text{miss}}$  and the tau lepton. We perform the search in a kinematic region where the  $\vec{p}_T^{\tau_h}$  and the  $\vec{p}_T^{\text{miss}}$  are approximately balanced and back-to-back in the azimuthal plane.

A new charged gauge boson ( $W'$ ) is one possible signature of the sequential SM (SSM) [3]. In this model, the  $W'$  boson couplings to fermions are similar to those of the SM  $W$ , while the additional decay mode of the  $W'$  boson to top and bottom quarks is allowed for a sufficiently high boson mass. Searches for an SSM-like  $W'$  boson decaying to the  $\tau + \nu_\tau$  final state have previously been reported by the CMS Collaboration at 8 TeV [4] and 13 TeV [5], as well as by the ATLAS Collaboration at 13 TeV [6]. These searches by the ATLAS and CMS experiments excluded  $W'$  bosons with masses up to 3.7 TeV and 4.0 TeV, respectively. The  $W'$  coupling strengths may differ from that of the SM  $W$  or the SSM  $W'$  bosons. Therefore, we also consider the case where the ratio  $g_{W'}/g_W$  of the  $W'$  boson coupling strength to that of the SM  $W$  boson is not unity. The nonuniversal gauge interaction model (NUGIM) predicts an enhanced branching fraction for decays into third-generation fermions. We also place upper exclusion limits on the ratio of the  $W'$  boson coupling strength to the  $W$  boson coupling strength and on the NUGIM.

Some models of leptoquarks (LQs) are particularly interesting in light of the significant deviations from the SM predictions in measurements in the flavor sector of the  $B \rightarrow D^{(*)} \ell \nu$  transitions, by the BaBar [7, 8], Belle [9–12], and LHCb [13–16] Collaborations. Separate measurements of the  $B \rightarrow K^{(*)} \ell^+ \ell^-$  transitions by the LHCb Collaboration [17–20], which

previously found deviations, have recently been superseded by an updated result that is compatible with the SM predictions within uncertainties [21]. The postulate of TeV-scale LQs with dominant couplings to third-generation fermions is among the favored theoretical attempts to explain these anomalies [22–44]. While numerous searches for single or pair production of LQs with dominant couplings to third-generation fermions at the LHC have yielded null results [45–55], the first search for LQ  $t$ -channel exchange in the  $\tau + \nu$  final state is presented here.

If the excess seen in the  $B \rightarrow D_s$  transitions is indeed due to new physics, the mass scale of its manifestation is expected to be at the TeV scale or not far beyond [56]. To provide a different test for the presence of new physics, a description based on an effective field theory (EFT) [57] with different types of coupling coefficients referred to as Wilson coefficients is also considered.

An open issue in modern particle physics is the large relative difference between the energy scale of electroweak symmetry breaking and that of gravity. This large discrepancy is often referred to as the hierarchy problem [58, 59], and is addressed in various ways in beyond-the-SM theories. In models with extra spatial dimensions, the hierarchy problem can be solved by lowering the fundamental Planck scale to the TeV range, which implies that gravity is strongly coupled at the LHC energies. In this case, the production of microscopic black holes may be possible at the LHC [60, 61]. In some models [62], these black holes would decay nonthermally into pairs of particles. Such black holes are often called quantum black holes (QBHs).

The shape of the  $m_T$  distribution is interpreted using a binned-likelihood method for the SSM, QBH, and EFT descriptions. We set upper exclusion limits on the cross section times branching fraction ( $\sigma\mathcal{B}$ ) for the SSM description as a function of the mass of the new resonance ( $m_{W'}$ ) and for the QBH model as a function of the mass scale of the QBH ( $m_{\text{QBH}}$ ). In the case of the EFT description, upper exclusion limits are placed on the Wilson coefficients. Additionally, a model independent limit setting method is considered and discussed.

The paper is structured as follows: the CMS detector is briefly described in section 2. The models examined in this analysis are outlined in section 3. The data and simulated samples used are presented in section 4, while section 5 describes the event reconstruction and the kinematic selection of the signal region. The specific determination of the background from misidentified  $\tau$  leptons is described in section 6. Section 7 reviews the most important sources of systematic uncertainties and their impact on the measurements. The results and achieved sensitivity for all the models are detailed in section 8 and summarized in section 9. The results are also documented in HEPData [63].

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and silicon strip tracker, measuring the charged particle trajectories inside a pseudo-rapidity ( $\eta$ ) acceptance of  $|\eta| < 2.5$ . Also within the solenoid volume are a lead tungstate

crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Each subdetector is composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about  $4 \mu\text{s}$  [64]. 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 [65].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [66].

### 3 Physics models

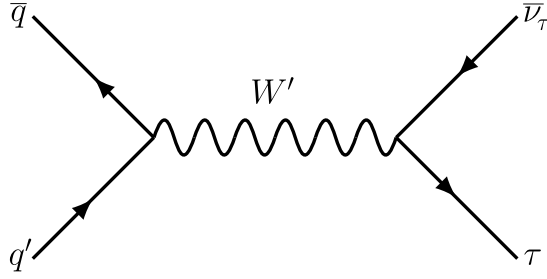
This section describes the different signal models used in this paper. All of these models predict physics beyond the SM that would be detectable in a final state with a  $\tau$  lepton and missing transverse momentum.

#### 3.1 The SSM heavy charged vector boson

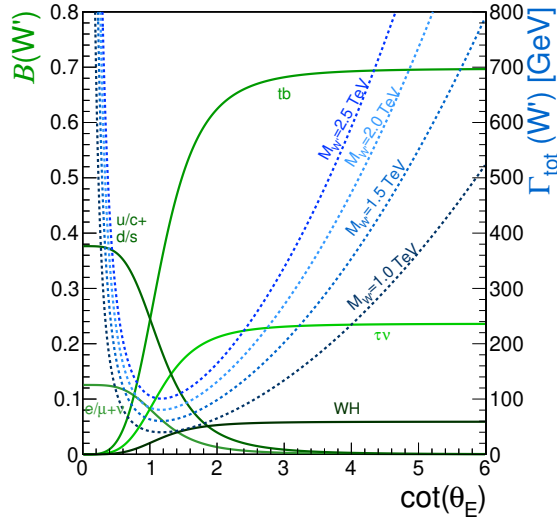
In the SSM, the  $W'$  boson is a heavy analogue of the  $W$  boson. The experimental signature would be a resonance with fermionic decay modes and branching fractions similar to those of the SM  $W$  boson. For  $W'$  boson masses larger than 180 GeV the additional  $W' \rightarrow t\bar{b}$  decay mode becomes relevant. If this decay is considered, the branching fraction for the  $W' \rightarrow \tau\nu$  decay in the SSM is 8.5% [3]. Under these assumptions, the relative decay width of a 1 TeV  $W'$  boson is  $\Gamma/M \approx 3.3\%$ . Decays to  $W$  and  $Z$  bosons are assumed to be suppressed in the SSM. No interference between the production of the new particle and the production of the SM  $W$  boson is assumed. This is justified by the fact that the subsequent hadronic decay of the  $\tau$  lepton leads to two neutrinos being present in the final state, significantly lowering the effect an interference of  $W'$  and  $W$  might have. The leading order (LO) Feynman diagram for this specific process is given in figure 1.

#### 3.2 Varying coupling strength

In the SSM, the  $W'$  boson coupling strength,  $g_{W'}$  is assumed to be identical to the SM  $W$  boson coupling,  $g_W$ . However, we also consider cases where  $g_{W'} \neq g_W$ . Because the  $W'$  boson width and cross section also depend on  $g_{W'}$ , we can interpret the kinematic distributions with respect to  $W'$  particles as described by various coupling values. The  $W'$  boson coupling strength is given in terms of the SM weak coupling strength  $g_W = e/\sin^2 \theta_W \approx 0.65$ , where  $e$  is the electron charge and  $\theta_W$  is the weak mixing angle.



**Figure 1.** Leading order Feynman diagram for the production and decay of a new heavy charged vector boson,  $W'$ , decaying to  $\tau\bar{\nu}_\tau$ .



**Figure 2.** Branching fractions  $\mathcal{B}(W')$  as function of the mixing angle  $\cot\theta_E$  (solid lines), for  $W'$  boson decays in the NUGIM G(221) framework, as calculated in refs. [67–69]. The total decay width  $\Gamma_{\text{tot}}$  (dotted lines) can also be determined as a function of the mixing angle. When re-scaled to accommodate the WH decay channel, the values associated with  $\cot\theta_E = 1$  correspond to those in the SSM.

### 3.3 Nonuniversal gauge interaction model

Models with nonuniversal couplings predict an enhanced branching fraction for decays into the third generation of SM fermions. These models could offer an explanation as to why the mass of the top quark is so large [67–69]. The NUGIM exhibits an  $SU(2)_\ell \times SU(2)_h \times U(1)$  symmetry. The symmetry groups  $SU(2)_\ell$  and  $SU(2)_h$  govern the couplings of the gauge bosons to the light fermions of the first two generations and to the heavy fermions of the third generation, respectively. Models of this type are often called G(221) models. The weak SM  $SU(2)_L$  group is a low-energy limit of two gauge groups:  $SU(2)_\ell$  and  $SU(2)_h$ .

These groups combine via a mixing angle  $\theta_E$ , resulting in an SM-like  $SU(2)_L$  group and an additional extended group  $SU(2)_E$ . This extended group gives rise to additional heavy gauge bosons such as the  $W'$  boson. The mixing angle directly affects the cross section

and decay width of such particles, as shown in figure 2. As can be seen, for  $\cot \theta_E = 1$  the branching fractions are equal for all lepton flavors, which would correspond to an SSM-like feature. When re-scaled to accommodate the WH decay channel, the values associated with  $\cot \theta_E = 1$  correspond to those in the SSM. For values larger than one, the decay to  $\tau$  leptons becomes dominant. The mixing angle changes the production cross section and the branching fractions of the  $W'$  boson. In the NUGIM, decays to W and Z bosons are negligible by construction, while decays to WH bosons typically have a branching fraction  $<6\%$ .

In the NUGIM G(221), neglecting the small contribution from the WH decay, the ratio of the couplings,  $g_{W'}/g_W$ , is related to the parameter  $\cot \theta_E$  by the following equation [69]:

$$\Gamma_{W'} = \Gamma_{W'}^{\text{SSM}} \frac{(4 + \frac{1}{4}) \cot^2 \theta_E + 8 \tan^2 \theta_E}{12 + \frac{1}{4}} = \Gamma_{W'}^{\text{SSM}} \left( \frac{g_{W'}}{g_W} \right)^2. \quad (3.1)$$

Because of this functional relationship, a reinterpretation of the limits on the coupling strength yields limits on the parameters of NUGIM G(221). Therefore, the SSM  $W'$  signal samples mentioned in section 4.1 can be used to probe this model. The product of the cross section and branching fraction,  $\sigma\mathcal{B}$ , scales with  $\Gamma_{\text{SSM}}/\Gamma_{\text{NUGIM}}$ .

### 3.4 Quantum black holes

Theories that invoke extra spatial dimensions often permit a fundamental Planck scale in the TeV region. Such theories also provide the possibility of producing microscopic black holes at LHC energies [60, 61]. In models with QBHs [62], the regime at which gravity becomes strongly coupled to SM particles causes the theory to become non-perturbative. This creates unavoidable limitations. When working in these regimes, usage of the model and its predictions should be viewed as a dimensional analysis in which some extrapolations from the classical domain carry over to the QBHs. In contrast to semiclassical thermal black holes that can decay to high-multiplicity final states, QBHs are nonthermal objects, expected to decay predominantly to pairs of particles. Despite not having a complete theory of quantum gravity, it is still possible to gain insight into the signatures of QBHs at the LHC based on some fundamental principles and a few assumptions. The cross section for QBH production depends on the threshold mass,  $m_{\text{th}}$ , in  $n$  additional spatial dimensions. The  $n > 1$  cases correspond to the Arkani-Hamed-Dimopoulos-Dvali model [70]. In this search the number of extra dimensions is assumed to be  $n=4$ . The  $m_{\text{th}}$  distribution of the QBH signal is characterized by a sharp edge at the threshold of QBH production, followed by a monotonic decrease at larger masses.

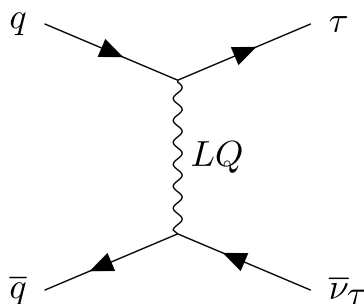
### 3.5 Leptoquarks

Leptoquarks are hypothetical new scalar or vector bosons carrying both baryon and lepton numbers and an electric charge in multiples of  $(1/3)e$ . The postulation of TeV-scale LQs with dominant couplings to third-generation fermions is a popular theoretical explanation of the observed anomalies in the ratio of the widths of semileptonic B meson decays

$$R_{D^{(*)}} = \frac{\Gamma(B \rightarrow D^{(*)} \tau \nu)}{\Gamma(B \rightarrow D^{(*)} \ell \nu)} \quad (3.2)$$

where  $\ell = e$  or  $\mu$ .





**Figure 3.** Leading order Feynman diagram of the process  $pp \rightarrow \tau \bar{\nu}_\tau$  mediated via a leptoquark in the  $t$ -channel.

Under the assumption that their couplings to the SM fermions are renormalizable and gauge invariant, the possible quantum numbers of LQs are restricted to those given in the Buchmüller-Rückl-Wyler model [71].

At the LHC, the final state with one  $\tau$  lepton and  $p_T^{\text{miss}}$  can be produced by an LQ appearing as a  $t$ -channel propagator, leading to a nonresonant enhancement of events with large values of  $m_T$ . The LO Feynman diagram of this process is shown in figure 3. The cross section of this process depends on the mass of the LQ ( $m_{LQ}$ ) and its coupling  $g_U$  to SM fermions. While the dependence of the cross section on  $m_{LQ}$  is weaker for a LQ in the  $t$ -channel compared to single or pair LQ production, it scales with  $g_U^4$  at LO.

In models addressing the tension in the flavor sector, LQs are often predicted to have flavor-nonuniversal couplings to left- (LH) and right-handed (RH) fermions, effectively modifying the LQ coupling to LH and RH SM fermions to be  $g_U \beta_L^{ij}$  and  $g_U \beta_R^{ij}$ , respectively. Here,  $\beta_L^{ij}$  and  $\beta_R^{ij}$  are complex  $3 \times 3$  matrices with  $i$  and  $j$  denoting the down-type quarks and leptons, respectively. The normalization of  $g_U$  is chosen such that  $\beta_L^{b\tau} = 1$ .

Three coupling benchmark scenarios are considered in this analysis, two of which have been proposed in ref. [44]. The first two scenarios are the result of a fit of the parameters of a U(1) vector LQ of charge  $(-1/3)e$  to explain the flavor anomalies in  $R_{D^{(*)}}$  (eq. (3.2)) and other related observables. The first benchmark scenario considers only couplings to LH SM fermions (i.e.,  $\beta_R^{ij} = 0$ ) and is referred to as “best fit LH” in the following. The second benchmark, referred to as “best fit LH+RH”, additionally considers  $|\beta_R^{b\tau}| = 1$  with all other  $\beta_R^{ij} = 0$ . In the third “democratic” benchmark, equal couplings only to LH fermions are assumed, i.e.  $|\beta_L^{ij}| = 1$  and  $\beta_R^{ij} = 0$  for all  $i$  and  $j$ .

### 3.6 Effective field theory description

As mentioned above, the ratio in eq. (3.2) appears to be enhanced with respect to the SM expectation by approximately 30%. If this enhancement originates from new physics, the corresponding mass scale of this physics is expected to be at, or near, the TeV scale [56]. The aim of this model is to search for any prescription that is able to address the  $R_{D^{(*)}}$  anomalies with new heavy mediators. It uses a low-energy EFT of new physics in semi-leptonic ( $b \rightarrow \ell \nu c$ ) transitions and translates this into a predictive theory at the TeV

scale [57]. This EFT model introduces three Wilson coefficients — one for the LH vector coupling  $\epsilon_L^{\text{cb}}$ , one for tensor like coupling  $\epsilon_T^{\text{cb}}$ , and one for scalar-tensor like coupling  $\epsilon_{\text{SL}}^{\text{cb}}$ .

## 4 Data and simulated events

### 4.1 Data

In this search, we analyze a data set from pp collisions at a center-of-mass energy of 13 TeV that was recorded by the CMS experiment in 2016–2018 and corresponds to an integrated luminosity of  $138 \text{ fb}^{-1}$ . Events were selected with an isolated single  $\tau$  trigger with  $|\eta| < 2.1$  and with  $p_T$  thresholds of 120 GeV in 2016 and 180 GeV in 2017–2018. The  $\tau$  trigger is complemented with a  $p_T^{\text{miss}}$  trigger with a 120 GeV threshold. The trigger efficiency for simulated signal events that pass the offline selection criteria is about 95%. The efficiency of the  $\tau$  trigger estimated using Monte Carlo simulations typically differs from that measured with data by approximately 10% (depending on the particular  $p_T$  bin) across all data-taking years. The estimated  $p_T^{\text{miss}}$  trigger efficiency from simulation is only 1–4% above or below data depending on the  $p_T^{\text{miss}}$  bin. We correct these differences in trigger efficiency between simulation and data using efficiency correction factors, which are henceforth referred to as scale factors. The scale factors range from 0.88–0.99 (0.87–1.08) for the 2016 (2017–2018) datasets.

### 4.2 Event simulation

Generated events are processed through a simulation of the detector geometry and response using GEANT4 [72]. The same reconstruction software is applied to both data and simulated events. Backgrounds are simulated using an expected distribution of the number of additional pp interactions within the same or nearby bunch crossings (pileup). All simulated backgrounds are reweighted such that the distribution of the number of collisions per bunch crossing matches the data, with an average of approximately 23 (32) interactions per bunch crossing [73–75] in 2016 (2017–2018). Unless otherwise noted, simulated samples use the underlying event tune CUETP8M1 [76] in 2016 and the CP5 tune [77] in 2017–2018.

#### 4.2.1 Signal simulation

The SSM  $W'$  boson signal samples ( $q'\bar{q} \rightarrow W'$ ) are generated at LO using PYTHIA 8.2.05 [78] for each data-taking year, and employing the NNPDF2.3 [79] (NNPDF3.1 [80]) parton distribution function (PDF) set for the 2016 (2017–2018) configurations. These samples are generated for mass points ranging from 0.6 to 6.0 TeV. To interpret the results in terms of the coupling ratio of the SSM  $W'$  boson and the SM  $W$  boson, signal samples are simulated at LO using MADGRAPH5\_aMC@NLO version 2.6.5 [81, 82] for different coupling ratios  $g_{W'}/g_W$  for coupling ratio values of [0.001, 0.01, 0.1, 1.0, 2.0, 3.0, 5.0], for all mass points.

Signal samples of LQ  $t$ -channel exchange at LO using MADGRAPH5\_aMC@NLO are generated for LQ masses between 0.1 and 10 TeV neglecting interference with SM processes. Interference is expected to be negligible in the phase space sensitive to this signal [83]. The parton shower, hadronization, and underlying event are modelled with PYTHIA 8. The

underlying event tune CP2 [77] is used for 2017 and 2018. The NNPDF2.3 and NNPDF3.1 PDF sets are used for 2016 and 2017–2018, respectively.

The QBH signal samples are generated with the QBH 3.0 generator [84]. We consider the  $q\bar{q}$  production of a singly positively charged QBH with its subsequent decay to a  $\tau$  lepton and a neutrino. Signal samples with minimum threshold masses from 400 to 11000 GeV are employed. The CTEQ6L1 PDF set [85], which is the recommended PDF for QBHs, is used. The definition of the  $Q$  scale for PDFs is taken to be the inverse of the gravitational radius.

Signal samples for the EFT model are generated using MADGRAPH5\_aMC@NLO at LO, while simulation of the hadronization and  $\tau$  lepton decay is performed using PYTHIA 8. The signal samples are generated with MADGRAPH5\_aMC@NLO using the values 0.3, 1.0, and 0.3 for the Wilson coefficients ( $\epsilon_L^{\text{cb}}$ ,  $\epsilon_T^{\text{cb}}$ ,  $\epsilon_{S_L}^{\text{cb}}$ ), respectively, which are obtained by fitting them to the current values of  $R_{\text{D}^{(*)}}$  [86]. The event content of these signal samples can be rescaled to cover a wider range of coupling values. The CP2 tune is used in conjunction with NNPDF3.1 PDF set for generation of signal samples.

#### 4.2.2 Simulation of the background

Background processes for this analysis include off-shell SM  $W$  production, processes coming from the decay of top quarks ( $t\bar{t}$ ), the Drell-Yan (DY) process, and diboson (ZZ, WW, WZ) processes. These samples are produced with PYTHIA 8 (for SM  $W$ ), MADGRAPH5\_aMC@NLO (for DY, ZZ, and WZ), and POWHEG 2.0 [87–89] (for  $t\bar{t}$  and WW). Backgrounds are simulated using the NNPDF3.0 (NNPDF3.1) NNLO [90] PDF set for 2016 (2017–2018). The simulated SM samples were validated in the low-mass region ( $m_{\text{T}} < 1$  TeV).

The SM background expected in this search consists of two different types of events: those where the  $\tau$  candidate originates from a gluon- or quark-initiated jet, and others where the  $\tau$  originates from a genuine  $\tau$  lepton decay. The former is derived from data, while the latter is estimated using simulation.

The dominant irreducible background for this analysis comes from SM  $W \rightarrow \tau\nu$  production. This background is generated at LO precision in quantum chromodynamics (QCD) with PYTHIA 8 for high-mass off-shell production. On-shell production is generated at LO precision in QCD with MADGRAPH5\_aMC@NLO, and the simulated jets are matched to the matrix element and parton shower produced by PYTHIA using MLM [81] merging. The differential cross section is reweighted as a function of the invariant mass of the SM  $W$  boson, incorporating next-to-LO (NLO) electroweak (EW) and next-to-NLO (NNLO) QCD corrections. The EW and QCD corrections can be combined by two different mathematical approaches: additive and multiplicative [91]. These approaches differ by approximately 5%. The applied correction factor uses the recommended additive approach [92], which is parametrized using a fit of a fourth order polynomial function. Differences between this approach and the multiplicative approach are taken as a systematic uncertainty. The calculation uses the FEWZ 3.1 and MCSANC 1.01 [93, 94] generators for the QCD and EW corrections, respectively.

## 5 Event selection and particle identification

The particle-flow algorithm [95] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various subsystems of the CMS detector. We obtain the photon energy from the ECAL measurement. Electron energy is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum from all bremsstrahlung photons spatially compatible with originating from the electron track. Muon energy is obtained from the curvature of the corresponding track. Charged-hadron energy is determined from a combination of the momentum of the hadron measured in the tracker and matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Neutral-hadron energy is obtained from the energy deposits in the ECAL and HCAL corrected in a similar way to that of the charged hadrons.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti- $k_T$  algorithm [96] in the FASTJET software package [97] with a distance parameter of 0.4. The jet momentum is determined as the vectorial momentum sum of each particle contained within the jet. From simulation, we find the jet momentum to be, on average, within 5–10% of the true momentum over the entire  $p_T$  spectrum and detector acceptance. Pileup can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, we discard charged particles identified to be originating from pileup vertices and apply an offset to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to be similar to that of particle-level jets, on average. In situ measurements of the momentum balance in dijet, photon+jet, Z +jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [98]. The jet energy resolution, obtained from a dijet balance technique, is found to be 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [98]. We apply additional selection criteria to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [99].

The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector  $p_T$  sum of all of the particle-flow candidates in an event, and its magnitude is denoted as  $p_T^{\text{miss}}$ . The  $\vec{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event [99]. Anomalous high- $p_T^{\text{miss}}$  events can occur due to a variety of reconstruction failures, detector malfunctions, or non-collision backgrounds. We reject such events by using event filters designed to identify more than 85% of the spurious high- $p_T^{\text{miss}}$  events, with a mistagging rate less than 0.1% [99].

The  $\tau_h$  candidates are reconstructed using the Hadron-plus-Strip (HPS) algorithm [100] starting from a jet. To reconstruct the  $\tau_h$  decay mode and its four momentum, we consider all particles in an  $\eta$ - $\phi$  cone of radius  $\Delta R = 0.5$  around the jet axis. This candidate is subsequently compared with quark or gluon-initiated jets, electrons, and muons. We apply corrections for the small differences in the  $\tau_h$  energy between simulation and data.

To distinguish between  $\tau_h$  candidates originating from genuine  $\tau$  leptons and other objects, we use the DEEPTAU identification [101]. This identification method consists of a convolutional deep neural network that uses machine learning techniques and image recognition methods in order to discriminate genuine  $\tau_h$  candidates from light leptons and jets. It combines high-level variables, such as the  $\tau$  lepton isolation, with low-level variables such as specific energy deposits in CMS subdetectors. This method has been shown to provide excellent discrimination against these jets, electrons, and muons while retaining a high efficiency for genuine  $\tau$  leptons. The identification efficiency of genuine  $\tau_h$  candidates ( $p_T > 100$  GeV) provided by the chosen identification method in this analysis is approximately 75%, while the probability of a jet being misidentified as a  $\tau$  lepton is less than 0.7%. Differences between data and simulation arising from the application of the identification method are corrected for using scale factors. Corrections due to differences in  $\tau$  identification performance and energy scale measurements are less than 5%.

We select  $\tau_h$  candidates with a  $p_T^{\tau_h} > 130$  (190) GeV for data recorded in 2016 (2017–2018). The  $\tau_h$  candidate is required to be in the range  $|\eta| < 2.1$ . Additionally, we require  $\tau_h$  candidates to pass anti-jet, anti-electron, and anti-muon discriminators of the DEEPTAU algorithm in order to reduce their corresponding misidentification probabilities [101]. The  $p_T^{\text{miss}}$  associated with these events is required to be at least 200 GeV.

In order to reduce the number of misidentified light leptons and to reduce background, we reject events containing loosely identified electrons [102] or muons [103] with  $p_T \approx > 20$  GeV within the detector acceptance. Events containing more than one  $\tau_h$  candidate fulfilling the identification criteria are also rejected. The  $\tau_h$  decay products and the neutrino are expected to be back-to-back to each other for all signal processes. The neutrino created during the  $\tau$  lepton decay is emitted in a similar direction to that of the  $\tau$  lepton in the laboratory frame and therefore only slightly reduces the overall magnitude of the expected  $\vec{p}_T^{\text{miss}}$ . Thus, we require  $0.7 < p_T^{\tau_h}/p_T^{\text{miss}} < 1.3$  and  $|\Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})| > 2.4$ . The variable used to determine the signal yields for this analysis is the transverse mass,  $m_T$ , as shown in eq. (1.1).

## 6 Jet background estimation

We use data to estimate the backgrounds due to jets misidentified as  $\tau_h$  candidates. In this analysis, this background contribution originates mostly from QCD multijet and Drell-Yan events. The signal-free control region comprises events with one well reconstructed light lepton and a  $\tau_h$  candidate. These events are selected using single light lepton triggers. The misidentification rate is defined as the number of  $\tau$  lepton candidates passing the full selection criteria divided by the number of those candidates that do not fulfill the isolation requirement. This rate is calculated as a function of the  $\tau$  lepton candidate  $p_T$  and the number of charged hadrons within the  $\tau$  lepton candidate isolation cone ( $\Delta R = 0.5$ ). Events where a  $\tau$  lepton is matched to a generator-level  $\tau$  lepton in simulation are subtracted from data. The ratio is estimated at approximately 5% for  $\tau$  lepton decays involving three charged hadrons and up to 30% for  $\tau$  leptons that decay into one charged hadron. The rate is then applied as an event-weight to signal-like events where a  $\tau$  lepton candidate does not fulfill the isolation requirement. This application region primarily contains events

originating from misidentified jets, with a small contamination of genuine  $\tau_h$  candidates. This contamination is subtracted from the application region using input from simulation.

This method is validated by estimating the ratio of simulated events in which jets are misidentified as  $\tau_h$  candidates, applying it to signal-like events where a  $\tau$  lepton candidate does not fulfill the isolation requirement, and comparing the results to the background prediction from simulation in the signal region. In order to account for the differences found with this validation, and to cover uncertainties arising from differences in the misidentification rate measurements from the individual sideband regions, corresponding uncertainties are applied.

## 7 Systematic uncertainties

There are various sources of uncertainties that can affect the normalization or the shape of the  $m_T$  distribution. These affect either the signal or the background estimates. We consider three types of systematic uncertainties: normalization, shape-based, and statistical.

The dominant uncertainty that affects the shape of the  $m_T$  distribution arises from the PDF sets used in simulating the background processes. We calculate this uncertainty with the PDF4LHC procedure [104], using replicas of the NNPDF3.0 (NNPDF3.1) PDF set for 2016 (2017–2018). This uncertainty grows with increasing  $m_T$  and becomes as large as 50% in the highest bin ( $> 1.8$  TeV) of the  $m_T$  distribution.

Another source of uncertainty comes from corrections to the measured  $\tau$  lepton energy scale (1.5–4.0% for  $p_T^{\tau_h} > 100$  GeV, depending on the decay mode),  $\tau$  identification efficiency (up to 5% for 1 TeV  $\tau$  leptons), and  $\tau$  trigger scale factors ( $\approx 10\%$ ). Uncertainties coming from shifting the jet energy scale and resolution are propagated to the calculation of  $\vec{p}_T^{\text{miss}}$ .

For all backgrounds estimated at NLO, factorization and renormalization scales are each multiplied by three factors (0.5, 1.0, 2.0), with the combination (1.0, 1.0) being the nominal. The largest deviations in the resulting event yield predictions, both up and down from the nominal value, are taken as systematic uncertainty. Variations where one scale is multiplied by 0.5 and the other by 2 are considered unphysical and are not considered.

Events in simulation are reweighted based on pileup differences between measured data and simulation. The total inelastic cross section of 69.2 mb [105] is varied by  $\pm 5\%$  and the resulting final  $m_T$  distribution is recalculated to estimate the uncertainty.

Uncertainties that affect the normalization of the background modeling arise from the measurement of the integrated luminosity, as well as from uncertainties in the cross sections of specific backgrounds. For the integrated luminosity, we apply an uncertainty of 1.2%/2.3%/2.5% for the year 2016/2017/2018, respectively, which correspond to the combined uncertainty of 1.6% for the full data-taking period. The cross section uncertainties are evaluated as 4% for the diboson background and 2% for the Drell-Yan background. The background from misidentified  $\tau$  lepton candidates is estimated with a normalization uncertainty of 100%. Additionally, we estimate the systematic uncertainty in the calculated ratio arising from the statistical uncertainties in the control and application regions. For the dominant W boson background, we apply the W boson mass-dependent uncertainties as explained in section 4.2.2. Uncertainties in the jet background estimation include uncer-

tainties from the misidentification ratio measurement, as well as the statistical uncertainties from both control and application regions of the method. Statistical uncertainties arise from data and from the limited event count in simulated background samples, and are taken into account [106]. These uncertainties are treated as uncorrelated between the bins of the final  $m_T$  distribution. The combination of all uncertainties shows an increasing trend with increasing  $m_T$ . Because the number of total expected background events becomes small, this does not affect the sensitivity by a significant amount for high-mass objects.

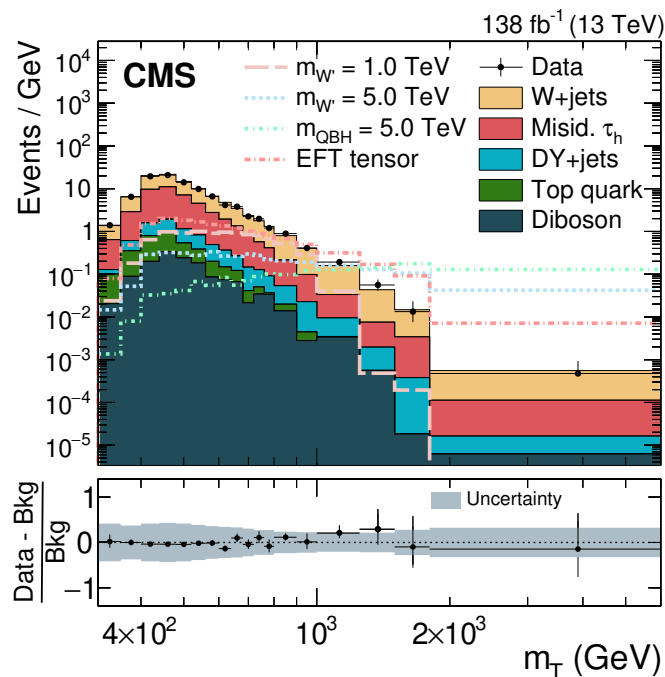
All systematic uncertainties are treated as fully correlated across years, except for those where the uncertainty arises from statistically independent sources. The uncertainties of the data-driven background are treated as uncorrelated across years. Correction uncertainties related to  $\tau_h$  and  $p_T^{\text{miss}}$  and the luminosity uncertainties are treated as partially correlated since they include some components that are considered correlated between years and some others that are not.

## 8 Results

Figure 4 displays the distribution for hadronically decaying  $\tau$  lepton events with missing transverse momentum, for the combined 2016–2018 data set. To illustrate signal distributions for the models described in this analysis, simulated SSM  $W'$  boson samples, as well as simulated QBH and EFT samples are included in the figure. The  $W'$  boson masses,  $m_{W'}$ , of 1.0 and 5.0 TeV are used for the SSM samples, a QBH mass,  $m_{\text{QBH}}$ , of 5.0 TeV is used for the QBH sample, and a tensor-type EFT sample is used to show the expected effect of the Wilson coefficients on the  $m_T$  distribution. The main background contribution comes from off-shell  $W$  boson production, followed by events with misidentified  $\tau$  leptons. Backgrounds from misidentified  $\tau$  leptons are estimated using the data-driven technique described in section 6. Other backgrounds are estimated using simulation. Example signal distributions are normalized to a cross section of 10 fb. The bin width increases with transverse mass.

The data agree with the expected background yields within statistical and systematic uncertainties. No significant deviation from the SM prediction is observed. We calculate limits at 95% confidence level (CL) from the  $m_T$  distribution using Bayesian methods known to have good frequentist coverage properties [107]. A software framework designed specifically to combine Higgs boson searches [108], based on the ROOSTATS package [109], is used to calculate the limits. For these limit calculations, we use a Bayesian method with a uniform positive prior probability density for the signal cross section. The nuisance parameters connected to shape-based uncertainties are modeled using a template-morphing technique, while those affecting the normalization of the distribution are included using a log-normal prior. To search for resonances in the  $m_T$  spectrum, a binned maximum likelihood fit is performed.

We calculate upper exclusion limits on  $\sigma\mathcal{B}$  for each model described in section 3. We further translate these into lower exclusion limits on  $m_{W'}$  and  $m_{\text{QBH}}$  for the SSM  $W'$  and QBH models, respectively. However, for the studies focused on coupling strengths, these are left as upper exclusion limits, unless otherwise specified.



**Figure 4.** The transverse mass distribution of the  $\tau_h + p_T^{\text{miss}}$  system observed in the 2016–2018 data (black dots with statistical uncertainty) as well as the expectation from SM processes (stacked histograms). The horizontal lines of the data points reflect the varying bin sizes. Different signal hypotheses normalized to  $10 \text{ fb}^{-1}$  are illustrated as dashed lines for exemplary SSM  $W'$  boson, QBH, and EFT signal hypotheses. The ratios of the background-subtracted data yield to the expected background yield are presented in the lower panel. The combined statistical and systematic uncertainties in the background are represented by the grey shaded band in the ratio panel.

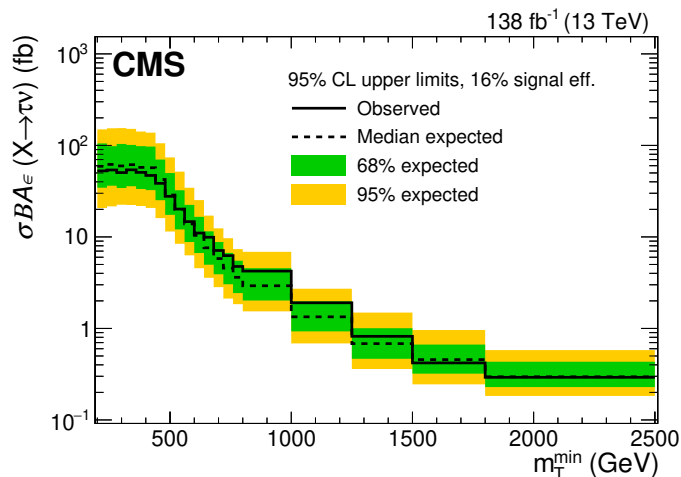
### 8.1 Model-independent cross section limit

New physics might produce signal shapes that are different from those expected for any of the above-mentioned signal models. Therefore, a model-independent (MI) cross section limit on  $(\sigma\mathcal{B}A\epsilon)_{\text{MI}}$  is provided in figure 5. This limit is obtained by calculating a single bin limit, where we integrate from a lower  $m_T$  threshold to infinity. This procedure results in an exclusion limit with a step-like behavior that originates from the binning of the  $m_T$  distribution. For the estimation of this exclusion limit, a constant product of acceptance times efficiency of 16% is assumed. This value includes the branching fraction of hadronic  $\tau$  lepton decays and experimental efficiencies for the signal. An exclusion limit on a specific model calculated using the presented MI limit can be obtained by applying the model-dependent part of  $A\epsilon$ .

To reflect the effect of the threshold,  $m_T^{\text{min}}$  on a new physics signal, we determine a factor  $f_{m_T}$  by counting the number of events with  $m_T > m_T^{\text{min}}$  and dividing this result by the number of generated events. The reconstruction efficiency is nearly constant over the entire  $m_T$  range scanned in this analysis; therefore  $f_{m_T}$  can be evaluated at the generator level.

A limit on the product of the production cross section and branching fraction  $(\sigma\mathcal{B}A\epsilon)_{\text{excl}}$  together with the acceptance  $A$  and the efficiency  $\epsilon$  can be obtained as a func-





**Figure 5.** Bayesian 95% CL model-independent upper limit on the product of signal cross section and branching fraction for the  $\tau + \nu$  decay for a back-to-back  $\tau$  lepton plus  $p_T^{\text{miss}}$  topology. To calculate this limit, all events for signal, background, and data are summed starting from a minimum  $m_T$  threshold and then divided by the total number of events. No assumption on the signal shape is included in this limit, however a signal selection efficiency of 16% is assumed. The expected (dashed line) and observed (solid line) limits are shown as well as the 68% and 95% CL uncertainty bands (green and yellow, respectively). The uncertainty bands correspond to the sum in quadrature of PDF and scale variations.

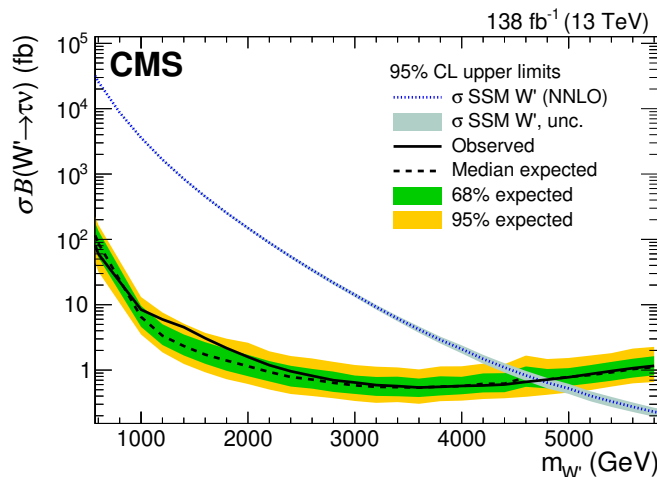
tion of  $m_T^{\text{min}}$  by dividing the excluded cross section of the MI limit  $(\sigma \mathcal{B} A \epsilon)_{\text{MI}}$  given in figure 5 by the calculated fraction  $f_{m_T}(m_T^{\text{min}})$ :

$$(\sigma \mathcal{B} A \epsilon)_{\text{excl}} = \frac{(\sigma \mathcal{B} A \epsilon)_{\text{MI}}(m_T^{\text{min}})}{f_{m_T}(m_T^{\text{min}})} \quad (8.1)$$

Here,  $\mathcal{B}$  is the branching fraction of the new particle decaying to  $\tau + \nu$ . A new physics model can be interpreted using the MI limit by scanning  $m_T^{\text{min}}$  for the minimum value of  $(\sigma \mathcal{B} A \epsilon)_{\text{excl}}$ . When accounting for the model-dependent part of  $A \epsilon$ ,  $(\sigma \mathcal{B})_{\text{excl}}$  can be extracted. Models with a theoretical cross section  $(\sigma \mathcal{B})_{\text{theo}} > (\sigma \mathcal{B})_{\text{excl}}$  can be excluded. The procedure described here can be applied to all models involving the two-body decay of a massive system to a  $\tau$  lepton and  $p_T^{\text{miss}}$ , which exhibit back-to-back kinematics similar to those of a generic  $W'$  boson. If the kinematic properties are different, the fraction of events  $f_{m_T}(m_T^{\text{min}})$  must be determined for the particular model considered.

## 8.2 Mass limit for a heavy vector boson

When calculating the limit in the SSM, the parameter of interest is the product of the signal production cross section and the branching fraction  $\sigma \mathcal{B}(W' \rightarrow \tau \nu)$ . Figure 6 shows the exclusion limit on this product as a function of the SSM  $m_{W'}$ . The SSM  $W'$  boson production is excluded for masses between 0.6 TeV and 4.8 TeV by comparison with the theoretical NNLO cross section. The observed limit is in agreement with the expected mass limit of 4.8 TeV. Previous CMS searches in this channel already exclude the lower



**Figure 6.** Bayesian upper exclusion limits at 95% CL on the product of the cross section and branching fraction of a  $W'$  boson decaying to a  $\tau$  lepton and a neutrino in the SSM model. For this model,  $W'$  boson masses of up to 4.8 TeV can be excluded. The limit is given by the intersection of the observed (solid) limit and the theoretical cross section (blue dotted curve). The 68 and 95% quantiles of the limits are represented by the green and yellow bands, respectively. The  $\sigma\mathcal{B}$  for an SSM  $W'$  boson, along with its associated uncertainty, calculated at NNLO precision in QCD is shown.

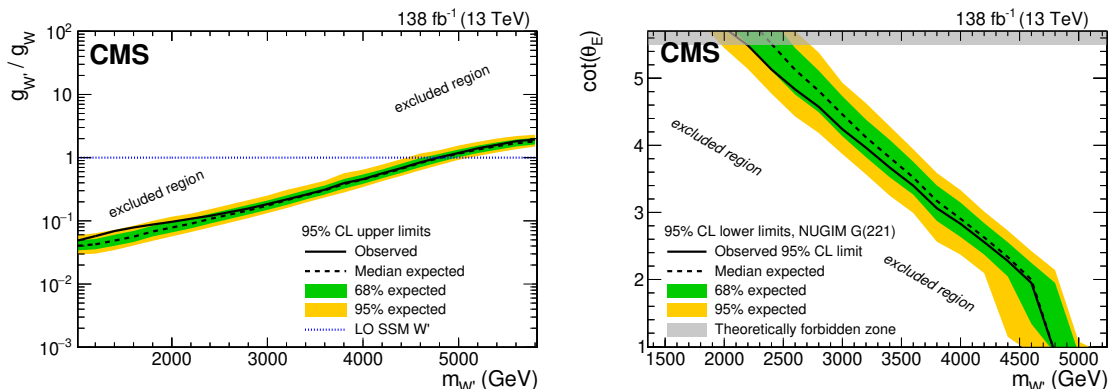
SSM mass hypotheses [4]. The lower bound is mainly determined by the trigger thresholds and the upper bound by the available data. In the high mass region, off-shell production of  $W'$  bosons becomes dominant, shifting the signal  $m_T$  distribution towards lower  $m_T$  values.

### 8.3 The NUGIM and coupling sensitivity

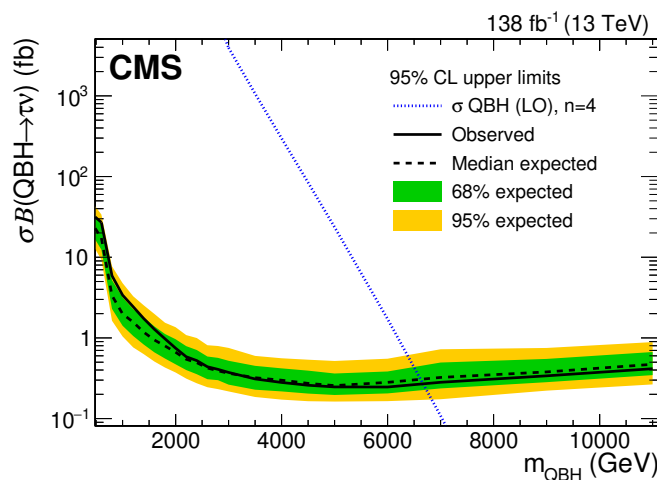
The limits for the coupling-dependent  $W'$  boson model and the NUGIM G(221) model are calculated in a two-dimensional plane that depends on the mass of the new mediator particle and its width. The  $W'$  boson width is affected by the coupling. We extract the limits shown in figure 7 by finding the intersection of the LO cross section theory plane of the corresponding model with the experimental result. The upper limits on the coupling strength in the case of SSM-like  $W'$  bosons, and on the mixing parameter  $\cot\theta_E$  in the case of the NUGIM G(221) model are provided as functions of  $m_{W'}$ . In the latter case, for  $\cot(\theta_E) > 5.5$ , the width becomes so large that the model is no longer valid. We exclude coupling values above  $g_{W'}/g_W = 0.05$  for masses of 1 TeV. For a mass hypothesis of 6 TeV, coupling values above 2 are excluded. For NUGIM G(221) models, we can exclude all theoretically allowed values of  $\cot\theta_E$  for masses below 2.2 TeV. For values of  $\cot\theta_E = 1$ , masses of up to 4.8 TeV are excluded.

### 8.4 The QBH limits

The QBH model has the same  $m_T$  sensitive observable as the SSM model. However, it differs with respect to its production mechanism. Its signal shape in the generator mass distribution is characterized by a threshold mass with a rising edge, followed by a monotonic



**Figure 7.** Bayesian upper exclusion limits on the ratio  $g_{W'}/g_W$  for an SSM-like  $W'$  boson are shown on the left. The unity coupling ratio (blue dotted curve) corresponds to the SSM common benchmark. The lower exclusion limits on the NUGIM G(221) mixing angle  $\cot\theta_E$  are shown on the right as a function of the  $W'$  boson mass. The theoretically excluded region is shaded in grey. The 68 and 95% quantiles of the limits are represented by the green and yellow bands, respectively.

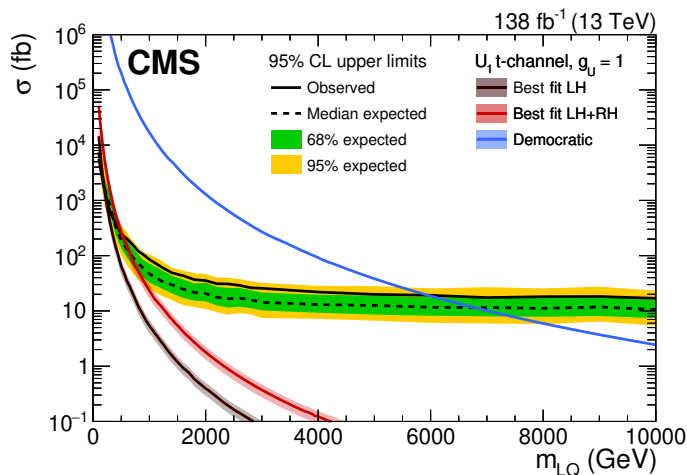


**Figure 8.** Bayesian upper exclusion limits at 95% CL on the product of the production cross section and branching fraction of a QBH in an associated  $\tau$  lepton and neutrino final state. The 68 and 95% quantiles of the limits are represented by the green and yellow bands, respectively. Masses of up to 6.6 TeV are excluded at 95% CL. The limit is given by the intersection of the observed (solid) limit and the theoretical cross section (blue dotted curve).

decrease towards higher masses. This shape is less sharp in the  $m_T$  distribution and, in parts, extends towards lower masses because of the  $\tau$  lepton decay. We exclude this model for threshold masses of up to 6.6 TeV, as shown in figure 8.

### 8.5 Leptoquark limits

We also place upper limits on the cross section of the process  $pp \rightarrow \tau\nu$  mediated by LQ exchange in the  $t$ -channel. These limits are presented in figure 9. Masses up to 205/ 515 / 5900 GeV are excluded for the best-fit LH / best-fit LH+RH / democratic scenarios.



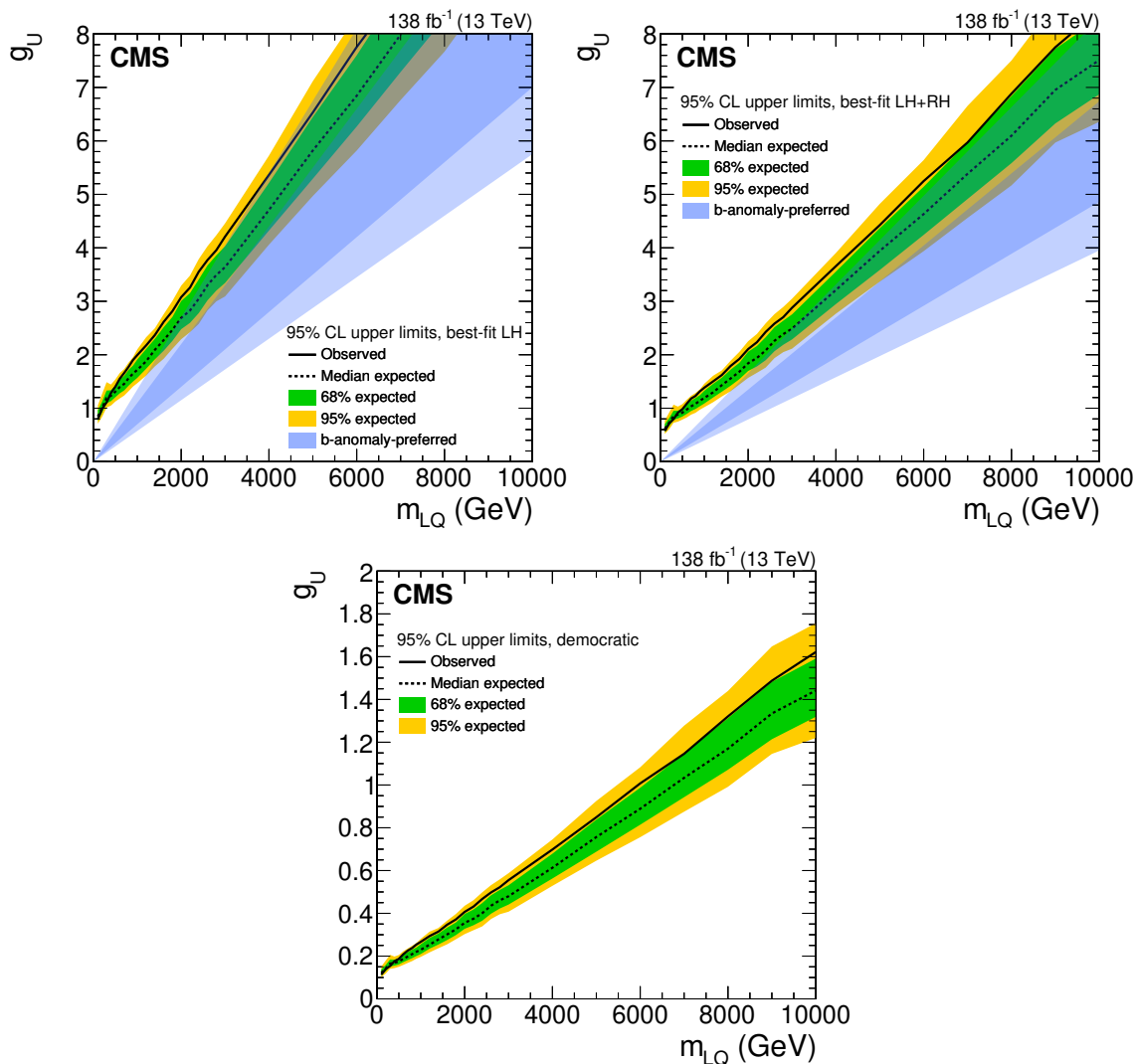
**Figure 9.** Bayesian upper limits at 95% CL on the cross section of the process  $pp \rightarrow \tau\nu$  mediated by LQ exchange in the  $t$ -channel. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The predicted LQ cross section at LO in the three coupling benchmark scenarios is depicted in different colors for  $g_U = 1$ . The uncertainty bands correspond to the sum in quadrature of PDF and scale variations. The first benchmark scenario considers only couplings to LH SM fermions (i.e.  $\beta_R^{ij} = 0$ ) and is referred to as “best fit LH”. The second benchmark, referred to as “best fit LH+RH”, considers  $|\beta_R^{b\tau}| = 1$  and all other  $\beta_R^{ij} = 0$ . In the third “democratic” benchmark, equal couplings only to LH fermions are assumed, i.e.,  $|\beta_L^{ij}| = 1$  and  $\beta_R^{ij} = 0$  for all  $i$  and  $j$ .

Figure 10 shows lower limits on the LQ mass for varying LQ couplings  $g_U$  to SM fermions. The limits are compared to the values of  $g_U$  that are obtained in the fit [44] to the flavor anomaly data in the two best fit scenarios for only LH couplings (left) and LH+RH couplings (right).

In both best-fit scenarios, we exclude a significant part of the LQ parameter space. LQ masses up to 10 TeV and couplings  $g_U$  of up to 8 are probed. In comparison to the values of  $g_U$  preferred to explain the flavor anomalies, this analysis has direct sensitivity to LQs, as predicted by the model of ref. [44]. The exclusion limits at 95% CL just reach the preferred phase space at large values of  $m_{LQ}$  and  $g_U$ . In addition to exclusion limits probing the couplings as predicted in the best fit scenarios, limits that are not motivated by the b anomalies are presented as well. They are obtained using the benchmark of democratic LH couplings. The lower limits on  $m_{LQ}$  are shown for varying values of  $g_U$  in figure 10 (lower) for this scenario.

### 8.6 The EFT limits

In the EFT description, we calculate limits in terms of the three Wilson coefficients used in this model. For each available signal hypothesis, the event yield is scaled with the square of the corresponding Wilson coefficient to probe a range between 0.05 and 2.0 for each coupling type, and the direct limit on the maximum allowed coupling value is extracted. The results are shown in figure 11. The excluded values are 0.32 (0.27) / 0.51 (0.41) / 0.27

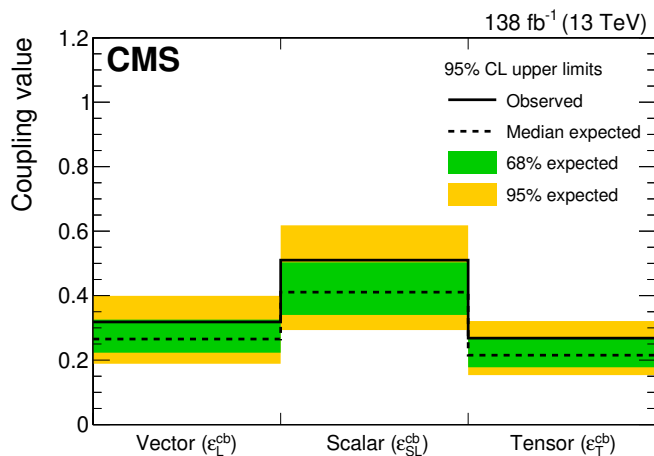


**Figure 10.** Expected and observed upper limits of the LQ coupling  $g_U$  as a function of the mass in the LH (left), LH+RH (right), and democratic (lower) scenarios. The blue band shows the 68 and 95% regions of  $g_U$  preferred by the fit to the b anomalies data [44].

(0.22) observed (expected) for  $\epsilon_L / \epsilon_{SL} / \epsilon_T$ , respectively. The small difference originates from the shape of the signals, for which the  $m_T$ -region between 1.0 and 1.5 TeV has the most impact on the exclusion limits [57].

### 8.7 Overview of the exclusion limits

A summary of mass exclusion limits calculated at 95% CL is shown in table 1. The limits presented in this analysis are the most stringent to date for all the models considered.



**Figure 11.** Bayesian upper exclusion limits at 95% CL on each of the Wilson coefficients described by the EFT model in section 3 based on 2016–2018 data. The three different coupling types represent a LH vector coupling ( $\epsilon_L^{\text{cb}}$ ), scalar-tensor-like coupling ( $\epsilon_{\text{SL}}^{\text{cb}}$ ), and tensor-like coupling ( $\epsilon_T^{\text{cb}}$ ). The 68 and 95% quantiles of the limits are represented by the green and yellow bands, respectively.

Model	Parameter	Expected Limit	Observed Limit
SSM $W' \rightarrow \tau + \nu$	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E)=1$	$m_{W'}$	4.8 TeV	4.8 TeV
NUGIM $\cot(\theta_E)=5.5$	$m_{W'}$	2.4 TeV	2.2 TeV
QBH	$m_{\text{QBH}}$	6.6 TeV	6.6 TeV
LQ democratic, $g_U=1.0$	$m_{\text{LQ}}$	6.7 TeV	5.9 TeV
LQ best-fit LH, $g_U=1.0$	$m_{\text{LQ}}$	145 GeV	205 GeV
LQ best-fit LH, $g_U=2.5$	$m_{\text{LQ}}$	1.8 TeV	1.5 TeV
LQ best-fit LH+RH, $g_U=1.0$	$m_{\text{LQ}}$	645 GeV	515 GeV
LQ best-fit LH+RH, $g_U=2.5$	$m_{\text{LQ}}$	3.0 TeV	2.5 TeV
EFT	$\epsilon_L^{\text{cb}}$	0.27	0.32
EFT	$\epsilon_{\text{SL}}^{\text{cb}}$	0.41	0.51
EFT	$\epsilon_T^{\text{cb}}$	0.22	0.27

**Table 1.** Summary of 95% CL exclusion limits (expected and observed) derived from 2016–2018 data, for the physics models studied in this analysis: sequential standard model (SSM), nonuniversal gauge interaction model (NUGIM), a quantum black hole (QBH) interpretation,  $t$ -channel leptoquark (LQ), and effective field interpretation (EFT).

## 9 Summary

A search for new resonant phenomena in the transverse mass distribution of a hadronically decaying  $\tau$  lepton and missing transverse momentum final state has been performed. The analysis uses 2016–2018 data collected with the CMS detector in proton-proton collisions with  $\sqrt{s} = 13$  TeV at the LHC, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . The newly developed DEEPTAU algorithm is used to identify  $\tau$  lepton candidates and to separate signal from background. Background from jets being misidentified as hadronically decaying  $\tau$  lepton candidates is derived from data.

No significant deviation from the standard model expectations is observed. Upper limits are set at 95% confidence level on the product of the production cross section and branching fraction  $\sigma\mathcal{B}$  of a new resonance gauge boson ( $W'$ ) decaying to a  $\tau$  lepton and a neutrino. Lower limits are derived on the mass of a  $W'$  boson in the sequential standard model and on the mass of a quantum black hole. In the case of the generalized coupling model, upper limits on  $\sigma\mathcal{B}$  are translated into upper exclusion limits on the ratio of the couplings of the  $W'$  boson to that of the standard model  $W$  boson,  $g_{W'}/g_W$ . Similarly, limits are obtained on the mixing angle  $\theta_E$  for the nonuniversal gauge interaction model and on the Wilson coefficients for an effective field theory model.

The process of  $t$ -channel leptoquark (LQ) exchange is targeted explicitly in this analysis. For the first time, upper limits are placed on the cross section of the  $pp \rightarrow \tau\nu$  process mediated by  $t$ -channel LQ exchange. Three benchmark coupling scenarios are tested that correspond to the best fits to the flavor anomaly data and to a generic democratic flavor structure. Significant portions of the LQ parameter space are excluded by placing upper limits on the LQ coupling  $g_U$  as a function of the LQ mass, including parts of the region preferred by a vector LQ explanation of the anomalies. Additionally, a model-independent limit is provided. The limits obtained for the various interpretations presented are the most stringent to date.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NK-

FIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science — EOS” — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany’s Excellence Strategy — EXC 2121 “Quantum Universe” — 390833306, and under project number 400140256 — GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program — ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

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



## References

- [1] ATLAS collaboration, *Search for a heavy charged boson in events with a charged lepton and missing transverse momentum from pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Rev. D* **100** (2019) 052013 [[arXiv:1906.05609](#)] [[INSPIRE](#)].
- [2] CMS collaboration, *Search for new physics in the lepton plus missing transverse momentum final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2022) 067 [[arXiv:2202.06075](#)] [[INSPIRE](#)].
- [3] G. Altarelli, B. Mele and M. Ruiz-Altaba, *Searching for new heavy vector bosons in  $p\bar{p}$  colliders*, *Z. Phys. C* **45** (1989) 109 [*Erratum ibid.* **47** (1990) 676] [[INSPIRE](#)].
- [4] CMS collaboration, *Search for  $W'$  decaying to tau lepton and neutrino in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, *Phys. Lett. B* **755** (2016) 196 [[arXiv:1508.04308](#)] [[INSPIRE](#)].
- [5] CMS collaboration, *Search for a  $W'$  boson decaying to a  $\tau$  lepton and a neutrino in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Lett. B* **792** (2019) 107 [[arXiv:1807.11421](#)] [[INSPIRE](#)].
- [6] ATLAS collaboration, *Search for high-mass resonances decaying to  $\tau\nu$  in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Rev. Lett.* **120** (2018) 161802 [[arXiv:1801.06992](#)] [[INSPIRE](#)].
- [7] BABAR collaboration, *Evidence for an excess of  $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$  decays*, *Phys. Rev. Lett.* **109** (2012) 101802 [[arXiv:1205.5442](#)] [[INSPIRE](#)].
- [8] BABAR collaboration, *Measurement of an excess of  $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$  decays and implications for charged Higgs bosons*, *Phys. Rev. D* **88** (2013) 072012 [[arXiv:1303.0571](#)] [[INSPIRE](#)].
- [9] BELLE collaboration, *Measurement of the branching ratio of  $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$  relative to  $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$  decays with hadronic tagging at Belle*, *Phys. Rev. D* **92** (2015) 072014 [[arXiv:1507.03233](#)] [[INSPIRE](#)].
- [10] BELLE collaboration, *Measurement of the  $\tau$  lepton polarization and  $R(D^*)$  in the decay  $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$* , *Phys. Rev. Lett.* **118** (2017) 211801 [[arXiv:1612.00529](#)] [[INSPIRE](#)].
- [11] BELLE collaboration, *Measurement of the  $\tau$  lepton polarization and  $R(D^*)$  in the decay  $\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau$  with one-prong hadronic  $\tau$  decays at Belle*, *Phys. Rev. D* **97** (2018) 012004 [[arXiv:1709.00129](#)] [[INSPIRE](#)].
- [12] BELLE collaboration, *Measurement of  $\mathcal{R}(D)$  and  $\mathcal{R}(D^*)$  with a semileptonic tagging method*, *Phys. Rev. Lett.* **124** (2020) 161803 [[arXiv:1910.05864](#)] [[INSPIRE](#)].
- [13] LHCb collaboration, *Measurement of the ratio of branching fractions  $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$* , *Phys. Rev. Lett.* **115** (2015) 111803 [*Erratum ibid.* **115** (2015) 159901] [[arXiv:1506.08614](#)] [[INSPIRE](#)].
- [14] LHCb collaboration, *Measurement of the ratio of the  $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$  and  $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$  branching fractions using three-prong  $\tau$ -lepton decays*, *Phys. Rev. Lett.* **120** (2018) 171802 [[arXiv:1708.08856](#)] [[INSPIRE](#)].
- [15] LHCb collaboration, *Test of lepton flavor universality by the measurement of the  $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$  branching fraction using three-prong  $\tau$  decays*, *Phys. Rev. D* **97** (2018) 072013 [[arXiv:1711.02505](#)] [[INSPIRE](#)].
- [16] LHCb collaboration, *Measurement of the ratios of branching fractions  $\mathcal{R}(D^*)$  and  $\mathcal{R}(D^0)$* , [[arXiv:2302.02886](#)] [[INSPIRE](#)].

- [17] LHCb collaboration, *Search for lepton-universality violation in  $B^+ \rightarrow K^+ \ell^+ \ell^-$  decays*, *Phys. Rev. Lett.* **122** (2019) 191801 [[arXiv:1903.09252](#)] [[INSPIRE](#)].
- [18] LHCb collaboration, *Test of lepton universality with  $B^0 \rightarrow K^{*0} \ell^+ \ell^-$  decays*, *JHEP* **08** (2017) 055 [[arXiv:1705.05802](#)] [[INSPIRE](#)].
- [19] LHCb collaboration, *Test of lepton universality in beauty-quark decays*, *Nature Phys.* **18** (2022) 277 [[arXiv:2103.11769](#)] [[INSPIRE](#)].
- [20] LHCb collaboration, *Tests of lepton universality using  $B^0 \rightarrow K_S^0 \ell^+ \ell^-$  and  $B^+ \rightarrow K^{*+} \ell^+ \ell^-$  decays*, *Phys. Rev. Lett.* **128** (2022) 191802 [[arXiv:2110.09501](#)] [[INSPIRE](#)].
- [21] LHCb collaboration, *Measurement of lepton universality parameters in  $B^+ \rightarrow K^+ \ell^+ \ell^-$  and  $B^0 \rightarrow K^{*0} \ell^+ \ell^-$  decays*, [arXiv:2212.09153](#) [[INSPIRE](#)].
- [22] M. Tanaka and R. Watanabe, *New physics in the weak interaction of  $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$* , *Phys. Rev. D* **87** (2013) 034028 [[arXiv:1212.1878](#)] [[INSPIRE](#)].
- [23] Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe, *Testing leptoquark models in  $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$* , *Phys. Rev. D* **88** (2013) 094012 [[arXiv:1309.0301](#)] [[INSPIRE](#)].
- [24] I. Doršner, S. Fajfer, N. Košnik and I. Nišandžić, *Minimally flavored colored scalar in  $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$  and the mass matrices constraints*, *JHEP* **11** (2013) 084 [[arXiv:1306.6493](#)] [[INSPIRE](#)].
- [25] B. Dumont, K. Nishiwaki and R. Watanabe, *LHC constraints and prospects for  $S_1$  scalar leptoquark explaining the  $\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}$  anomaly*, *Phys. Rev. D* **94** (2016) 034001 [[arXiv:1603.05248](#)] [[INSPIRE](#)].
- [26] I. Doršner, S. Fajfer, D.A. Faroughy and N. Košnik, *The role of the  $S_3$  GUT leptoquark in flavor universality and collider searches*, *JHEP* **10** (2017) 188 [[arXiv:1706.07779](#)] [[INSPIRE](#)].
- [27] D. Bečirević et al., *Scalar leptoquarks from grand unified theories to accommodate the  $B$ -physics anomalies*, *Phys. Rev. D* **98** (2018) 055003 [[arXiv:1806.05689](#)] [[INSPIRE](#)].
- [28] A. Crivellin, D. Müller and T. Ota, *Simultaneous explanation of  $R(D^{(*)})$  and  $b \rightarrow s \mu^+ \mu^-$ : the last scalar leptoquarks standing*, *JHEP* **09** (2017) 040 [[arXiv:1703.09226](#)] [[INSPIRE](#)].
- [29] B. Gripaios, M. Nardecchia and S.A. Renner, *Composite leptoquarks and anomalies in  $B$ -meson decays*, *JHEP* **05** (2015) 006 [[arXiv:1412.1791](#)] [[INSPIRE](#)].
- [30] M. Bauer and M. Neubert, *Minimal leptoquark explanation for the  $R_{D^{(*)}}$ ,  $R_K$ , and  $(g-2)_\mu$  anomalies*, *Phys. Rev. Lett.* **116** (2016) 141802 [[arXiv:1511.01900](#)] [[INSPIRE](#)].
- [31] E. Coluccio Leskow, G. D'Ambrosio, A. Crivellin and D. Müller,  *$(g-2)_\mu$ , lepton flavor violation, and  $Z$  decays with leptoquarks: correlations and future prospects*, *Phys. Rev. D* **95** (2017) 055018 [[arXiv:1612.06858](#)] [[INSPIRE](#)].
- [32] D. Bečirević and O. Sumensari, *A leptoquark model to accommodate  $R_K^{\text{exp}} < R_K^{\text{SM}}$  and  $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$* , *JHEP* **08** (2017) 104 [[arXiv:1704.05835](#)] [[INSPIRE](#)].
- [33] G. Hiller and I. Nišandžić,  *$R_K$  and  $R_{K^*}$  beyond the standard model*, *Phys. Rev. D* **96** (2017) 035003 [[arXiv:1704.05444](#)] [[INSPIRE](#)].
- [34] G. Hiller, D. Loose and I. Nišandžić, *Flavorful leptoquarks at hadron colliders*, *Phys. Rev. D* **97** (2018) 075004 [[arXiv:1801.09399](#)] [[INSPIRE](#)].
- [35] L. Di Luzio, A. Greljo and M. Nardecchia, *Gauge leptoquark as the origin of  $B$ -physics anomalies*, *Phys. Rev. D* **96** (2017) 115011 [[arXiv:1708.08450](#)] [[INSPIRE](#)].

- [36] L. Di Luzio et al., *Maximal flavour violation: a Cabibbo mechanism for leptoquarks*, *JHEP* **11** (2018) 081 [[arXiv:1808.00942](#)] [[INSPIRE](#)].
- [37] L. Calibbi, A. Crivellin and T. Li, *Model of vector leptoquarks in view of the B-physics anomalies*, *Phys. Rev. D* **98** (2018) 115002 [[arXiv:1709.00692](#)] [[INSPIRE](#)].
- [38] M. Bordone, C. Cornella, J. Fuentes-Martin and G. Isidori, *A three-site gauge model for flavor hierarchies and flavor anomalies*, *Phys. Lett. B* **779** (2018) 317 [[arXiv:1712.01368](#)] [[INSPIRE](#)].
- [39] R. Barbieri and A. Tesi, *B-decay anomalies in Pati-Salam SU(4)*, *Eur. Phys. J. C* **78** (2018) 193 [[arXiv:1712.06844](#)] [[INSPIRE](#)].
- [40] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, *B-physics anomalies: a guide to combined explanations*, *JHEP* **11** (2017) 044 [[arXiv:1706.07808](#)] [[INSPIRE](#)].
- [41] D. Marzocca, *Addressing the B-physics anomalies in a fundamental composite Higgs model*, *JHEP* **07** (2018) 121 [[arXiv:1803.10972](#)] [[INSPIRE](#)].
- [42] M.J. Baker, J. Fuentes-Martín, G. Isidori and M. König, *High- $p_T$  signatures in vector-leptoquark models*, *Eur. Phys. J. C* **79** (2019) 334 [[arXiv:1901.10480](#)] [[INSPIRE](#)].
- [43] C. Cornella, J. Fuentes-Martin and G. Isidori, *Revisiting the vector leptoquark explanation of the B-physics anomalies*, *JHEP* **07** (2019) 168 [[arXiv:1903.11517](#)] [[INSPIRE](#)].
- [44] C. Cornella et al., *Reading the footprints of the B-meson flavor anomalies*, *JHEP* **08** (2021) 050 [[arXiv:2103.16558](#)] [[INSPIRE](#)].
- [45] CMS collaboration, *Constraints on models of scalar and vector leptoquarks decaying to a quark and a neutrino at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. D* **98** (2018) 032005 [[arXiv:1805.10228](#)] [[INSPIRE](#)].
- [46] ATLAS collaboration, *Search for a scalar partner of the top quark in the all-hadronic  $t\bar{t}$  plus missing transverse momentum final state at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **80** (2020) 737 [[arXiv:2004.14060](#)] [[INSPIRE](#)].
- [47] ATLAS collaboration, *Search for new phenomena in final states with b-jets and missing transverse momentum in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector*, *JHEP* **05** (2021) 093 [[arXiv:2101.12527](#)] [[INSPIRE](#)].
- [48] CMS collaboration, *Search for singly and pair-produced leptoquarks coupling to third-generation fermions in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Lett. B* **819** (2021) 136446 [[arXiv:2012.04178](#)] [[INSPIRE](#)].
- [49] ATLAS collaboration, *Search for pair production of scalar leptoquarks decaying into first- or second-generation leptons and top quarks in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 313 [[arXiv:2010.02098](#)] [[INSPIRE](#)].
- [50] CMS collaboration, *Search for leptoquarks coupled to third-generation quarks in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **121** (2018) 241802 [[arXiv:1809.05558](#)] [[INSPIRE](#)].
- [51] ATLAS collaboration, *Search for pair production of third-generation scalar leptoquarks decaying into a top quark and a  $\tau$ -lepton in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *JHEP* **06** (2021) 179 [[arXiv:2101.11582](#)] [[INSPIRE](#)].

- [52] CMS collaboration, *Search for third-generation scalar leptoquarks decaying to a top quark and a  $\tau$  lepton at  $\sqrt{s} = 13$  TeV*, *Eur. Phys. J. C* **78** (2018) 707 [[arXiv:1803.02864](#)] [[INSPIRE](#)].
- [53] ATLAS collaboration, *Search for new phenomena in pp collisions in final states with tau leptons, b-jets, and missing transverse momentum with the ATLAS detector*, *Phys. Rev. D* **104** (2021) 112005 [[arXiv:2108.07665](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Search for heavy neutrinos and third-generation leptoquarks in hadronic states of two  $\tau$  leptons and two jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **03** (2019) 170 [[arXiv:1811.00806](#)] [[INSPIRE](#)].
- [55] CMS collaboration, *Search for a singly produced third-generation scalar leptoquark decaying to a  $\tau$  lepton and a bottom quark in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2018) 115 [[arXiv:1806.03472](#)] [[INSPIRE](#)].
- [56] L. Di Luzio and M. Nardecchia, *What is the scale of new physics behind the B-flavour anomalies?*, *Eur. Phys. J. C* **77** (2017) 536 [[arXiv:1706.01868](#)] [[INSPIRE](#)].
- [57] A. Greljo, J. Martin Camalich and J.D. Ruiz-Álvarez, *Mono- $\tau$  signatures at the LHC constrain explanations of B-decay anomalies*, *Phys. Rev. Lett.* **122** (2019) 131803 [[arXiv:1811.07920](#)] [[INSPIRE](#)].
- [58] R.N. Mohapatra and J.C. Pati, *A natural left-right symmetry*, *Phys. Rev. D* **11** (1975) 2558 [[INSPIRE](#)].
- [59] R.N. Mohapatra and J.C. Pati, *Left-right gauge symmetry and an isoconjugate model of CP violation*, *Phys. Rev. D* **11** (1975) 566 [[INSPIRE](#)].
- [60] S. Dimopoulos and G.L. Landsberg, *Black holes at the LHC*, *Phys. Rev. Lett.* **87** (2001) 161602 [[hep-ph/0106295](#)] [[INSPIRE](#)].
- [61] S.B. Giddings and S.D. Thomas, *High-energy colliders as black hole factories: the end of short distance physics*, *Phys. Rev. D* **65** (2002) 056010 [[hep-ph/0106219](#)] [[INSPIRE](#)].
- [62] P. Meade and L. Randall, *Black holes and quantum gravity at the LHC*, *JHEP* **05** (2008) 003 [[arXiv:0708.3017](#)] [[INSPIRE](#)].
- [63] *HEPData record for this analysis*, (2022) [[DOI:10.17182/hepdata.135472](#)].
- [64] CMS collaboration, *Performance of the CMS level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *2020 JINST* **15** P10017 [[arXiv:2006.10165](#)] [[INSPIRE](#)].
- [65] CMS collaboration, *The CMS trigger system*, *2017 JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [66] CMS collaboration, *The CMS experiment at the CERN LHC*, *2008 JINST* **3** S08004 [[INSPIRE](#)].
- [67] C.-W. Chiang, N.G. Deshpande, X.-G. He and J. Jiang, *The family  $SU(2)_l \times SU(2)_h \times U(1)$  model*, *Phys. Rev. D* **81** (2010) 015006 [[arXiv:0911.1480](#)] [[INSPIRE](#)].
- [68] Y.G. Kim and K.Y. Lee, *Early LHC bound on the  $W'$  boson mass in the nonuniversal gauge interaction model*, *Phys. Lett. B* **706** (2012) 367 [[arXiv:1105.2653](#)] [[INSPIRE](#)].
- [69] L. Edelhäuser and A. Knochel, *Observing nonstandard  $W'$  and  $Z'$  through the third generation and Higgs lens*, [arXiv:1408.0914](#) [[INSPIRE](#)].
- [70] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The hierarchy problem and new dimensions at a millimeter*, *Phys. Lett. B* **429** (1998) 263 [[hep-ph/9803315](#)] [[INSPIRE](#)].

- [71] W. Buchmüller, R. Rückl and D. Wyler, *Leptoquarks in lepton-quark collisions*, *Phys. Lett. B* **191** (1987) 442 [Erratum *ibid.* **448** (1999) 320] [INSPIRE].
- [72] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].
- [73] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [arXiv:2104.01927] [INSPIRE].
- [74] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at  $\sqrt{s} = 13$  TeV*, CMS-PAS-LUM-17-004, CERN, Geneva, Switzerland (2018).
- [75] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at  $\sqrt{s} = 13$  TeV*, CMS-PAS-LUM-18-002, CERN, Geneva, Switzerland (2019).
- [76] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 tune*, *Eur. Phys. J. C* **74** (2014) 3024 [arXiv:1404.5630] [INSPIRE].
- [77] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [arXiv:1903.12179] [INSPIRE].
- [78] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].
- [79] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [arXiv:1207.1303] [INSPIRE].
- [80] NNPDF collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663 [arXiv:1706.00428] [INSPIRE].
- [81] J. Alwall et al., *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [arXiv:1106.0522] [INSPIRE].
- [82] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].
- [83] CMS collaboration, *Search for a third-generation leptoquark coupled to a  $\tau$  lepton and a  $b$  quark through single, pair, and nonresonant production in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, submitted to *JHEP* [arXiv:2308.07826] [INSPIRE].
- [84] D.M. Gingrich, *Quantum black holes with charge, colour, and spin at the LHC*, *J. Phys. G* **37** (2010) 105008 [arXiv:0912.0826] [INSPIRE].
- [85] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [hep-ph/0201195] [INSPIRE].
- [86] R. Alonso, A. Kobach and J. Martin Camalich, *New physics in the kinematic distributions of  $\bar{B} \rightarrow D^{(*)} \tau^- (\rightarrow \ell^- \bar{\nu}_\ell \nu_\tau) \bar{\nu}_\tau$* , *Phys. Rev. D* **94** (2016) 094021 [arXiv:1602.07671] [INSPIRE].
- [87] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [hep-ph/0409146] [INSPIRE].
- [88] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [arXiv:0709.2092] [INSPIRE].

- [89] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
- [90] A. Buckley et al., *LHAPDF6: parton density access in the LHC precision era*, *Eur. Phys. J. C* **75** (2015) 132 [[arXiv:1412.7420](#)] [[INSPIRE](#)].
- [91] G. Balossini et al., *Combination of electroweak and QCD corrections to single W production at the Fermilab Tevatron and the CERN LHC*, *JHEP* **01** (2010) 013 [[arXiv:0907.0276](#)] [[INSPIRE](#)].
- [92] J.R. Andersen et al., *Les Houches 2013. Physics at TeV colliders: standard model working group report*, [arXiv:1405.1067](#) [[INSPIRE](#)].
- [93] A. Arbuzov et al., *Update of the MCSANC Monte Carlo integrator, v.1.20*, *JETP Lett.* **103** (2016) 131 [[arXiv:1509.03052](#)] [[INSPIRE](#)].
- [94] S.G. Bondarenko and A.A. Saproinov, *NLO EW and QCD proton-proton cross section calculations with MCSANC-v1.01*, *Comput. Phys. Commun.* **184** (2013) 2343 [[arXiv:1301.3687](#)] [[INSPIRE](#)].
- [95] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, *2017 JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].
- [96] M. Cacciari, G.P. Salam and G. Soyez, *The anti- $k_t$  jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [97] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [98] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, *2017 JINST* **12** P02014 [[arXiv:1607.03663](#)] [[INSPIRE](#)].
- [99] CMS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the CMS detector*, *2019 JINST* **14** P07004 [[arXiv:1903.06078](#)] [[INSPIRE](#)].
- [100] CMS collaboration, *Reconstruction and identification of  $\tau$  lepton decays to hadrons and  $\nu_\tau$  at CMS*, *2016 JINST* **11** P01019 [[arXiv:1510.07488](#)] [[INSPIRE](#)].
- [101] CMS collaboration, *Identification of hadronic tau lepton decays using a deep neural network*, *2022 JINST* **17** P07023 [[arXiv:2201.08458](#)] [[INSPIRE](#)].
- [102] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, *2021 JINST* **16** P05014 [[arXiv:2012.06888](#)] [[INSPIRE](#)].
- [103] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *2018 JINST* **13** P06015 [[arXiv:1804.04528](#)] [[INSPIRE](#)].
- [104] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys. G* **43** (2016) 023001 [[arXiv:1510.03865](#)] [[INSPIRE](#)].
- [105] CMS collaboration, *Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2018) 161 [[arXiv:1802.02613](#)] [[INSPIRE](#)].
- [106] R.J. Barlow and C. Beeston, *Fitting using finite Monte Carlo samples*, *Comput. Phys. Commun.* **77** (1993) 219 [[INSPIRE](#)].























- [107] PARTICLE DATA GROUP collaboration, *Review of particle physics*, [PTEP \*\*2022\*\* \(2022\) 083C01](#) [[INSPIRE](#)].
- [108] ATLAS, CMS and LHC HIGGS COMBINATION GROUP collaboration, *Procedure for the LHC Higgs boson search combination in Summer 2011*, [CMS-NOTE-2011-005](#), CERN, Geneva, Switzerland (2011).
- [109] L. Moneta et al., *The RooStats project*, [PoS \*\*ACAT2010\*\* \(2010\) 057](#) [[arXiv:1009.1003](#)] [[INSPIRE](#)].

## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan <sup>1</sup>














### Institut für Hochenergiephysik, Vienna, Austria

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














### Universiteit Antwerpen, Antwerpen, Belgium

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

### Vrije Universiteit Brussel, Brussel, Belgium

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

















### Université Libre de Bruxelles, Bruxelles, Belgium

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

### Ghent University, Ghent, Belgium

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






















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

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

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








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

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

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



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

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

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

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

**University of Sofia, Sofia, Bulgaria**

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





**Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**

S. Thakur 
















**Beihang University, Beijing, China**

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











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

M. Ahmad , G. Bauer<sup>9</sup>, Z. Hu , S. Lezki , K. Yi <sup>9,10</sup>

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

G.M. Chen <sup>8</sup>, H.S. Chen <sup>8</sup>, M. Chen <sup>8</sup>, F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao ,  
Z.-A. Liu <sup>11</sup>, V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker ,  
J. Wang , H. Zhang , J. Zhao 

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

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



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

M. Lu , Z. You 

**University of Science and Technology of China, Hefei, China**






















N. Lu 

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

















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

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

Z. Lin , C. Lu , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga **Universidad de Antioquia, Medellin, Colombia**J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**D. Giljanovic , N. Godinovic , D. Lelas , I. Puljak **University of Split, Faculty of Science, Split, Croatia**Z. Antunovic, M. Kovac , T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov <sup>12</sup>, T. Susa **University of Cyprus, Nicosia, Cyprus**A. Attikis , K. Christoforou , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov **Charles University, Prague, Czech Republic**M. Finger <sup>12</sup>, M. Finger Jr. <sup>12</sup>, A. Kveton **Escuela Politecnica Nacional, Quito, Ecuador**E. Ayala **Universidad San Francisco de Quito, Quito, Ecuador**E. Carrera Jarrin **Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**H. Abdalla <sup>13</sup>, Y. Assran<sup>14,15</sup>**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M. Abdullah Al-Mashad , M.A. Mahmoud **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 
















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

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,  
T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen ,  
M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 





























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

P. Luukka , H. Petrow , T. Tuuva












**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri ,  
S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander,  
A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro <sup>16</sup>, P. Simkina , M. Titov 


















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

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



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

J.-L. Agram <sup>17</sup>, J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom ,  
E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan ,  
P. Van Hove 

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

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo ,  
P. Depasse , C. Dozen <sup>18</sup>, H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch ,  
G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot ,  
M. Vander Donckt , P. Verdier , S. Viret























**Georgian Technical University, Tbilisi, Georgia**





A. Khvedelidze <sup>12</sup>, I. Lomidze , Z. Tsamalaidze <sup>12</sup>

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










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

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






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

S.C. Schuler, A. Sharma , A. Stein , F. Torres Da Silva De Araujo <sup>19</sup>, L. Vigilante,  
S. Wiedenbeck , S. Zaleski








































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

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
































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

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou ,  
O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman <sup>21</sup>,  
K. Borrás <sup>22</sup>, D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina ,  
S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin,  
D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo <sup>21</sup>, A. Geiser , A. Giraldi ,  
G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari <sup>23</sup>, N.Z. Jomhari ,  
B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm ,  
D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka <sup>24</sup>, W. Lohmann <sup>25</sup>, R. Mankel ,  
I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella ,  
M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otarid, D. Pérez Adán , A. Raspereza ,  
B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham <sup>26,22</sup>,  
V. Scheurer, S. Schnake <sup>22</sup>, P. Schütze , C. Schwanenberger <sup>21</sup>, M. Shchedrolosiev ,  
R.E. Sosa Ricardo , D. Stafford, N. Tonon <sup>†</sup>, M. Van De Klundert , F. Vazzoler ,  
A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann,  
L. Wiens <sup>22</sup>, C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

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

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









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

S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll,  
N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann <sup>27</sup>, M. Horzela ,  
U. Husemann , M. Klute , R. Koppenhöfer , M. Link, A. Lintuluoto , S. Maier ,  
S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , J. Rauser,  
M. Schnepf, I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden ,  
R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniewski , S. Wunsch,  
X. Zuo 


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

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








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

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








**National Technical University of Athens, Athens, Greece**

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






**University of Ioánnina, Ioánnina, Greece**

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

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

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


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

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

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

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


















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

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









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

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










**Panjab University, Chandigarh, India**

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















**University of Delhi, Delhi, India**

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , M. Naimuddin ,  
K. Ranjan , S. Saumya 


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

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

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

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










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

K. Naskar <sup>40</sup>








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

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

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

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




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

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

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

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

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

H. Bakhshiansohi <sup>43,44</sup>, E. Khazaie <sup>44</sup>, M. Zeinali <sup>45</sup>
































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

S. Chenarani <sup>46</sup>, S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





















**University College Dublin, Dublin, Ireland**









M. Grunewald 

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

M. Abbrescia <sup>a,b</sup>, R. Aly <sup>a,c,47</sup>, C. Aruta <sup>a,b</sup>, A. Colaleo <sup>a</sup>, D. Creanza <sup>a,c</sup>,  
N. De Filippis <sup>a,c</sup>, M. De Palma <sup>a,b</sup>, A. Di Florio <sup>a,b</sup>, W. Elmetenawee <sup>a,b</sup>, F. Errico <sup>a,b</sup>,  
L. Fiore <sup>a</sup>, G. Iaselli <sup>a,c</sup>, G. Maggi <sup>a,c</sup>, M. Maggi <sup>a</sup>, I. Margjeka <sup>a,b</sup>, V. Mastrapasqua <sup>a,b</sup>,  
S. My <sup>a,b</sup>, S. Nuzzo <sup>a,b</sup>, A. Pellecchia <sup>a,b</sup>, A. Pompili <sup>a,b</sup>, G. Pugliese <sup>a,c</sup>, R. Radogna <sup>a</sup>,  
D. Ramos <sup>a</sup>, A. Ranieri <sup>a</sup>, G. Selvaggi <sup>a,b</sup>, L. Silvestris <sup>a</sup>, F.M. Simone <sup>a,b</sup>, Ü. Sözbilir <sup>a</sup>,  
A. Stamerra <sup>a</sup>, R. Venditti <sup>a</sup>, P. Verwilligen <sup>a</sup>

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


















G. Abbiendi <sup>a</sup>, C. Battilana <sup>a,b</sup>, D. Bonacorsi <sup>a,b</sup>, L. Borgonovi <sup>a</sup>, L. Brigliadori <sup>a</sup>,  
R. Campanini <sup>a,b</sup>, P. Capiluppi <sup>a,b</sup>, A. Castro <sup>a,b</sup>, F.R. Cavallo <sup>a</sup>, M. Cuffiani <sup>a,b</sup>,  
G.M. Dallavalle <sup>a</sup>, T. Diotallevi <sup>a,b</sup>, F. Fabbri <sup>a</sup>, A. Fanfani <sup>a,b</sup>, P. Giacomelli <sup>a</sup>,  
L. Giommi <sup>a,b</sup>, C. Grandi <sup>a</sup>, L. Guiducci <sup>a,b</sup>, S. Lo Meo <sup>a,48</sup>, L. Lunerti <sup>a,b</sup>,

S. Marcellini <sup>a</sup>, G. Masetti <sup>a</sup>, F.L. Navarria <sup>a,b</sup>, A. Perrotta <sup>a</sup>, F. Primavera <sup>a,b</sup>,  
A.M. Rossi <sup>a,b</sup>, T. Rovelli <sup>a,b</sup>, G.P. Siroli <sup>a,b</sup>

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

S. Costa <sup>a,b,49</sup>, A. Di Mattia <sup>a</sup>, R. Potenza <sup>a,b</sup>, A. Tricomi <sup>a,b,49</sup>, C. Tuve <sup>a,b</sup>






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

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

























### INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi <sup>b</sup>, S. Bianco <sup>b</sup>, S. Meola <sup>b,50</sup>, D. Piccolo <sup>b</sup>











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

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



























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

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












### INFN Sezione di Napoli<sup>a</sup>, Università di Napoli ‘Federico II’<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy

S. Buontempo <sup>a</sup>, F. Carnevali <sup>a,b</sup>, N. Cavallo <sup>a,c</sup>, A. De Iorio <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>,  
A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a,b,51</sup>, P. Paolucci <sup>a,27</sup>, B. Rossi <sup>a</sup>, C. Sciacca <sup>a,b</sup>
















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

P. Azzi <sup>a</sup>, N. Bacchetta <sup>a,52</sup>, D. Bisello <sup>a,b</sup>, P. Bortignon <sup>a</sup>, A. Bragagnolo <sup>a,b</sup>,  
R. Carlin <sup>a,b</sup>, T. Dorigo <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, A. Gozzelino <sup>a</sup>, G. Grosso <sup>a</sup>,  
L. Layer <sup>a,53</sup>, E. Lusiani <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, J. Pazzini <sup>a,b</sup>,  
P. Ronchese <sup>a,b</sup>, R. Rossin <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, G. Strong <sup>a</sup>, M. Tosi <sup>a,b</sup>, H. Yarar <sup>a,b</sup>,  
M. Zanetti <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>




































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

S. Abu Zeid <sup>a,54</sup>, C. Aimè <sup>a,b</sup>, A. Braghieri <sup>a</sup>, S. Calzaferri <sup>a,b</sup>, D. Fiorina <sup>a,b</sup>,  
P. Montagna <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a</sup>, P. Vitulo <sup>a,b</sup>


















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

P. Asenov <sup>a,55</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, M. Magherini <sup>a,b</sup>,  
G. Mantovani <sup>a,b</sup>, V. Mariani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Moscatelli <sup>a,55</sup>, A. Piccinelli <sup>a,b</sup>,  
M. Presilla <sup>a,b</sup>, A. Rossi <sup>a,b</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga <sup>a</sup>, T. Tedeschi <sup>a,b</sup>







































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

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








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

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














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

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

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

S. Belforte , V. Candelise , M. Casarsa , F. Cossutti , A. Da Rold ,  
 G. Della Ricca , G. Sorrentino 


**Kyungpook National University, Daegu, Korea**

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

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

H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

E. Asilar , T.J. Kim , J. Park 




















**Korea University, Seoul, Korea**

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

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

J. Goh 



**Sejong University, Seoul, Korea**H. S. Kim , Y. Kim, S. Lee**Seoul National University, Seoul, Korea**J. Almond, J.H. Bhyun, J. Choi , S. Jeon , J. Kim , J.S. Kim, S. Ko , H. Kwon , H. Lee , S. Lee, B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon **University of Seoul, Seoul, Korea**W. Jang , D.Y. Kang, Y. Kang , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin, I.C. Park , Y. Roh, D. Song, I.J. Watson , S. Yang **Yonsei University, Department of Physics, Seoul, Korea**S. Ha , H.D. Yoo **Sungkyunkwan University, Suwon, Korea**M. Choi , M.R. Kim , H. Lee, Y. Lee , Y. Lee , I. Yu **College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait**T. Beyrouthy, Y. Maghrbi **Riga Technical University, Riga, Latvia**K. Dreimanis , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns **Vilnius University, Vilnius, Lithuania**M. Ambrozias , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis **National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**N. Bin Norjoharuddeen , S.Y. Hoh <sup>56</sup>, I. Yusuff <sup>56</sup>, Z. Zolkapli**Universidad de Sonora (UNISON), Hermosillo, Mexico**J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo **Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz <sup>57</sup>, R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández **Universidad Iberoamericana, Mexico City, Mexico**C. Oropeza Barrera , F. Vazquez Valencia **Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**I. Pedraza , H.A. Salazar Ibarquen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**I. Bujanja, J. Mijuskovic<sup>58</sup>, N. Raicevic**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

**AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**

V. Avati, L. Grzanka, M. Malawski

**National Centre for Nuclear Research, Swierk, Poland**

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

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

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

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

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

**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**P. Adzic<sup>59</sup>, M. Dordevic, P. Milenovic, J. Milosevic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

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

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


















J.F. de Trocóniz

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

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon

C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote ,  
C. Vico Villalba 

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

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








































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

M.K. Jayananda , B. Kailasapathy <sup>60</sup>, D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

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























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















D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon<sup>†</sup>, D. Barney ,  
J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol ,  
T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury,  
M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck ,  
M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita<sup>61</sup>,  
A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi,  
K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman ,  
V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil ,  
S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli ,  
A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli,  
L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer ,  
M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz,  
G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi ,  
A. Sharma , P. Silva , P. Sphicas <sup>62</sup>, A.G. Stahl Leiton , S. Summers , K. Tatar ,  
V.R. Tavolaro , D. Treille , P. Tropea , A. Tsiros, J. Wanczyk <sup>63</sup>, K.A. Wozniak ,  
W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**
























L. Caminada <sup>64</sup>, A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram ,  
H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli <sup>64</sup>, L. Noehte <sup>64</sup>, T. Rohe 

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

T.K. Aarrestad , K. Androsov <sup>63</sup>, M. Backhaus , P. Berger, A. Calandri , K. Datta ,  
A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia ,  
F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon ,  
R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani <sup>63</sup>, F. Nessi-Tedaldi 

J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann ,  
C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra ,  
J. Steggemann <sup>63</sup>, D. Valsecchi <sup>27</sup>, R. Wallny 











### Universität Zürich, Zurich, Switzerland

C. AMSLER <sup>65</sup>, P. Bärtschi , C. Botta , D. Brzdechko, M.F. Canelli , K. Cormier ,  
A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei ,  
B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni ,  
U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger ,  
M. Senger , Y. Takahashi 



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

C. Adloff<sup>66</sup>, C.M. Kuo, W. Lin, P.K. Rout , S.S. Yu 





















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

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

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

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu <sup>67</sup>, E. Eskut ,  
Y. Guler <sup>68</sup>, E. Gurpinar Guler <sup>68</sup>, C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,  
G. Onengut , K. Ozdemir <sup>69</sup>, A. Polatoz , A.E. Simsek , B. Tali <sup>70</sup>, U.G. Tok ,  
S. Turkcapar , E. Uslan , I.S. Zorbakir 

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

G. Karapinar<sup>71</sup>, K. Ocalan <sup>72</sup>, M. Yalvac <sup>73</sup>



### Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya <sup>74</sup>, O. Kaya <sup>75</sup>, S. Tekten <sup>76</sup>


### Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak <sup>67</sup>, Y. Komurcu , S. Sen <sup>67</sup>

### Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci <sup>70</sup>, B. Haciasahinoglu , I. Hos <sup>77</sup>, B. Isildak <sup>78</sup>, B. Kaynak ,  
S. Ozkorucuklu , C. Simsek , D. Sunar Cerci <sup>70</sup>
















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

B. Grynyov 



















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

L. Levchuk 



































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

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans ,  
H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , B. Krikler ,  
S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou <sup>79</sup>, K. Walkingshaw Pass,  
R. White 




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

A.H. Ball, K.W. Bell , A. Belyaev <sup>80</sup>, C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg <sup>81</sup>, Sh. Jain , J. Linacre ,  
K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh,  
C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 













**Imperial College, London, United Kingdom**

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio,  
V. Cepaitis , G.S. Chahal <sup>82</sup>, D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies,  
M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles ,  
J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen ,  
D.G. Monk , J. Nash <sup>83</sup>, M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards,  
A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley ,  
L.H. Vage, T. Virdee <sup>27</sup>, M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom 

**Brunel University, Uxbridge, United Kingdom**

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








**Baylor University, Waco, Texas, U.S.A.**

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

















**Catholic University of America, Washington, DC, U.S.A.**

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



















**The University of Alabama, Tuscaloosa, Alabama, U.S.A.**

S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio <sup>84</sup>,  
C. West 


















**Boston University, Boston, Massachusetts, U.S.A.**

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















**Brown University, Providence, Rhode Island, U.S.A.**

G. Benelli , B. Burkle , X. Coubez<sup>22</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan <sup>85</sup>,  
 T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan ,  
 S. Sagir <sup>86</sup>, F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

**University of California, Davis, Davis, California, U.S.A.**

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
























**University of California, Los Angeles, California, U.S.A.**

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





















**University of California, Riverside, Riverside, California, U.S.A.**

R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long ,  
 N. Manganeli , W. Si , S. Wimpenny 












**University of California, San Diego, La Jolla, California, U.S.A.**

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








**University of California, Santa Barbara — Department of Physics, Santa Barbara, California, U.S.A.**

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













**California Institute of Technology, Pasadena, California, U.S.A.**

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


















**Carnegie Mellon University, Pittsburgh, Pennsylvania, U.S.A.**

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






































































**University of Colorado Boulder, Boulder, Colorado, U.S.A.**

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



















**Cornell University, Ithaca, New York, U.S.A.**

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











**Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.**

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry ,  
J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati ,  
H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng ,  
J. Freeman , A. Gandrakota , Z. Gece , L. Gray , D. Green, S. Grünendahl ,  
D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer ,  
L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma ,  
B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid ,  
K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn ,  
J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena <sup>87</sup>,  
F. Ravera , A. Reinsvold Hall <sup>88</sup>, L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha ,  
L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger ,  
E.W. Vaandering , I. Zoi 

**University of Florida, Gainesville, Florida, U.S.A.**

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



















**Florida State University, Tallahassee, Florida, U.S.A.**

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg ,  
G. Martinez, H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang












**Florida Institute of Technology, Melbourne, Florida, U.S.A.**

M.M. Baarmand , S. Butalla , T. Elkafray <sup>54</sup>, M. Hohlmann , R. Kumar Verma ,  
M. Rahmani, F. Yumiceva 












**University of Illinois at Chicago (UIC), Chicago, Illinois, U.S.A.**

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























**The University of Iowa, Iowa City, Iowa, U.S.A.**

M. Alhusseini , K. Dilsiz <sup>89</sup>, L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo,  
A. Mestvirishvili <sup>90</sup>, J. Nachtman , O. Neogi, H. Ogul <sup>91</sup>, Y. Onel , A. Penzo , C. Snyder,  
E. Tiras <sup>92</sup>

**Johns Hopkins University, Baltimore, Maryland, U.S.A.**

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

**The University of Kansas, Lawrence, Kansas, U.S.A.**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers ,  
T. Isidori , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey,  
J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico ,  
S. Sanders , C. Smith , Q. Wang , G. Wilson 


















**Kansas State University, Manhattan, Kansas, U.S.A.**

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























**Lawrence Livermore National Laboratory, Livermore, California, U.S.A.**

F. Rebassoo , D. Wright 















**University of Maryland, College Park, Maryland, U.S.A.**

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

**Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.**

D. Abercrombie, W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans ,  
C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , D. Kovalskyi ,  
J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland ,  
G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 














**University of Minnesota, Minneapolis, Minnesota, U.S.A.**

R.M. Chatterjee, B. Crossman , A. Evans , J. Hiltbrand , B.M. Joshi , C. Kapsiak ,  
M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy ,  
N. Schroeder , N. Strobbe , M.A. Wadud 












**University of Mississippi, Oxford, Mississippi, U.S.A.**

L.M. Cremaldi 

**University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.**




















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

**State University of New York at Buffalo, Buffalo, New York, U.S.A.**



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





























**Northeastern University, Boston, Massachusetts, U.S.A.**

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












**Northwestern University, Evanston, Illinois, U.S.A.**

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

















**University of Notre Dame, Notre Dame, Indiana, U.S.A.**

R. Band , R. Bucci , M. Cremonesi , A. Das , R. Goldouzian , M. Hildreth ,  
K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton ,  
J. Mariano , N. Marinelli , I. Mcalister , T. McCauley , C. Mcgrady , K. Mohrman ,  
C. Moore , Y. Musienko <sup>12</sup>, R. Ruchti , A. Townsend , M. Wayne , H. Yockey ,  
M. Zarucki , L. Zygala 

**The Ohio State University, Columbus, Ohio, U.S.A.**

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






















**Princeton University, Princeton, New Jersey, U.S.A.**

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

**University of Puerto Rico, Mayaguez, Puerto Rico, U.S.A.**

S. Malik , S. Norberg 



















**Purdue University, West Lafayette, Indiana, U.S.A.**

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay , M. Jones , A.W. Jung ,  
D. Kondratyev , A.M. Koshy , M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,  
S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , F. Wang ,  
R. Xiao , W. Xie 
















**Purdue University Northwest, Hammond, Indiana, U.S.A.**




















































































J. Dolen , N. Parashar 

**Rice University, Houston, Texas, U.S.A.**

D. Acosta , A. Baty , T. Carnahan , S. Dildick , K.M. Ecklund ,  
P.J. Fernández Manteca , S. Freed , P. Gardner , F.J.M. Geurts , A. Kumar , W. Li ,  
B.P. Padley , R. Redjimi , J. Rotter , S. Yang , E. Yigitbasi , L. Zhang<sup>93</sup> , Y. Zhang 

**University of Rochester, Rochester, New York, U.S.A.**

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

**The Rockefeller University, New York, New York, U.S.A.**K. Goulianos **Rutgers, The State University of New Jersey, Piscataway, New Jersey, U.S.A.**B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl ,  
D. Jaroslawski , O. Karacheban <sup>25</sup>, I. Laflotte , A. Lath , R. Montalvo, K. Nash,  
M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone ,  
S.A. Thayil , S. Thomas, H. Wang **University of Tennessee, Knoxville, Tennessee, U.S.A.**H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier **Texas A&M University, College Station, Texas, U.S.A.**O. Bouhali <sup>94</sup>, M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon <sup>95</sup>, H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,  
A. Safonov **Texas Tech University, Lubbock, Texas, U.S.A.**N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke,  
S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck **Vanderbilt University, Nashville, Tennessee, U.S.A.**E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon ,  
S. Tuo , J. Velkovska , J. Viinikainen **University of Virginia, Charlottesville, Virginia, U.S.A.**B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovsky , A. Li ,  
C. Neu , C.E. Perez Lara , B. Tannenwald **Wayne State University, Detroit, Michigan, U.S.A.**P.E. Karchin , N. Poudyal **University of Wisconsin — Madison, Madison, Wisconsin, U.S.A.**S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni,  
H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless ,  
J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,  
D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,  
W. Vetens **Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN**S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,  
A. Belyaev , V. Blinov <sup>96</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev ,  
V. Chekhovsky, R. Chistov <sup>96</sup>, M. Danilov <sup>96</sup>, A. Dermenev , T. Dimova <sup>96</sup>, I. Dremin ,  
M. Dubinin <sup>87</sup>, L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov 

S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin ,  
 Y. Ivanov , V. Kachanov , L. Kardapoltsev <sup>96</sup>, V. Karjavine , A. Karneyeu , V. Kim <sup>96</sup>,  
 M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova <sup>97</sup>,  
 D. Konstantinov , V. Korenkov , A. Kozyrev <sup>96</sup>, N. Krasnikov , A. Lanev ,  
 P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov ,  
 V. Matveev <sup>96</sup>, V. Murzin , A. Nikitenko <sup>98</sup>, S. Obraztsov , A. Oskin, I. Ovtin <sup>96</sup>,  
 V. Palichik , V. Pereygin , S. Polikarpov <sup>96</sup>, V. Popov, O. Radchenko <sup>96</sup>, M. Savina ,  
 V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen <sup>96</sup>, S. Slabospitskii ,  
 V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov ,  
 O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov , A. Vorobyev,  
 N. Voytishin , B.S. Yuldashev<sup>99</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

<sup>†</sup> Deceased

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

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

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

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

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

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

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

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

<sup>9</sup> Also at Nanjing Normal University Department of Physics, Nanjing, China

<sup>10</sup> Now at The University of Iowa, Iowa City, Iowa, U.S.A.

<sup>11</sup> Also at University of Chinese Academy of Sciences, Beijing, China

<sup>12</sup> Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>13</sup> Also at Cairo University, Cairo, Egypt

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

<sup>15</sup> Now at British University in Egypt, Cairo, Egypt

<sup>16</sup> Also at Purdue University, West Lafayette, Indiana, U.S.A.

<sup>17</sup> Also at Université de Haute Alsace, Mulhouse, France

<sup>18</sup> Also at Department of Physics, Tsinghua University, Beijing, China

<sup>19</sup> Also at The University of the State of Amazonas, Manaus, Brazil

<sup>20</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey

<sup>21</sup> Also at University of Hamburg, Hamburg, Germany

<sup>22</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>23</sup> Also at Isfahan University of Technology, Isfahan, Iran

<sup>24</sup> Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

<sup>25</sup> Also at Brandenburg University of Technology, Cottbus, Germany

<sup>26</sup> Also at Forschungszentrum Jülich, Juelich, Germany

<sup>27</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

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

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

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

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

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

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

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

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

- <sup>37</sup> Also at *University of Visva-Bharati, Santiniketan, India*
- <sup>38</sup> Also at *University of Hyderabad, Hyderabad, India*
- <sup>39</sup> Also at *Indian Institute of Science (IISc), Bangalore, India*
- <sup>40</sup> Also at *Indian Institute of Technology (IIT), Mumbai, India*
- <sup>41</sup> Also at *IIT Bhubaneswar, Bhubaneswar, India*
- <sup>42</sup> Also at *Institute of Physics, Bhubaneswar, India*
- <sup>43</sup> Also at *Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- <sup>44</sup> Now at *Department of Physics, Isfahan University of Technology, Isfahan, Iran*
- <sup>45</sup> Also at *Sharif University of Technology, Tehran, Iran*
- <sup>46</sup> Also at *Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
- <sup>47</sup> Also at *Helwan University, Cairo, Egypt*
- <sup>48</sup> Also at *Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
- <sup>49</sup> Also at *Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
- <sup>50</sup> Also at *Università degli Studi Guglielmo Marconi, Roma, Italy*
- <sup>51</sup> Also at *Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy*
- <sup>52</sup> Also at *Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
- <sup>53</sup> Also at *Università di Napoli ‘Federico II’, Napoli, Italy*
- <sup>54</sup> Also at *Ain Shams University, Cairo, Egypt*
- <sup>55</sup> Also at *Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
- <sup>56</sup> Also at *Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
- <sup>57</sup> Also at *Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
- <sup>58</sup> Also at *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>59</sup> Also at *Faculty of Physics, University of Belgrade, Belgrade, Serbia*
- <sup>60</sup> Also at *Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
- <sup>61</sup> Also at *INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
- <sup>62</sup> Also at *National and Kapodistrian University of Athens, Athens, Greece*
- <sup>63</sup> Also at *Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
- <sup>64</sup> Also at *Universität Zürich, Zurich, Switzerland*
- <sup>65</sup> Also at *Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
- <sup>66</sup> Also at *Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
- <sup>67</sup> Also at *Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
- <sup>68</sup> Also at *Konya Technical University, Konya, Turkey*
- <sup>69</sup> Also at *Izmir Bakircay University, Izmir, Turkey*
- <sup>70</sup> Also at *Adiyaman University, Adiyaman, Turkey*
- <sup>71</sup> Also at *Istanbul Gedik University, Istanbul, Turkey*
- <sup>72</sup> Also at *Necmettin Erbakan University, Konya, Turkey*
- <sup>73</sup> Also at *Bozok Universitetesi Rektörlüğü, Yozgat, Turkey*
- <sup>74</sup> Also at *Marmara University, Istanbul, Turkey*
- <sup>75</sup> Also at *Milli Savunma University, Istanbul, Turkey*
- <sup>76</sup> Also at *Kafkas University, Kars, Turkey*
- <sup>77</sup> Also at *Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
- <sup>78</sup> Also at *Ozyegin University, Istanbul, Turkey*
- <sup>79</sup> Also at *Vrije Universiteit Brussel, Brussel, Belgium*
- <sup>80</sup> Also at *School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
- <sup>81</sup> Also at *University of Bristol, Bristol, United Kingdom*
- <sup>82</sup> Also at *IPPP Durham University, Durham, United Kingdom*
- <sup>83</sup> Also at *Monash University, Faculty of Science, Clayton, Australia*
- <sup>84</sup> Also at *Università di Torino, Torino, Italy*
- <sup>85</sup> Also at *Bethel University, St. Paul, Minnesota, U.S.A.*

- <sup>86</sup> Also at *Karamanoğlu Mehmetbey University, Karaman, Turkey*
- <sup>87</sup> Also at *California Institute of Technology, Pasadena, California, U.S.A.*
- <sup>88</sup> Also at *United States Naval Academy, Annapolis, Maryland, U.S.A.*
- <sup>89</sup> Also at *Bingol University, Bingol, Turkey*
- <sup>90</sup> Also at *Georgian Technical University, Tbilisi, Georgia*
- <sup>91</sup> Also at *Sinop University, Sinop, Turkey*
- <sup>92</sup> Also at *Erciyes University, Kayseri, Turkey*
- <sup>93</sup> Also at *Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China*
- <sup>94</sup> Also at *Texas A&M University at Qatar, Doha, Qatar*
- <sup>95</sup> Also at *Kyungpook National University, Daegu, Korea*
- <sup>96</sup> Also at *another institute or international laboratory covered by a cooperation agreement with CERN*
- <sup>97</sup> Also at *Yerevan Physics Institute, Yerevan, Armenia*
- <sup>98</sup> Also at *Imperial College, London, United Kingdom*
- <sup>99</sup> Also at *Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*