Search for a $W'$ boson decaying to a $\tau$ lepton and a neutrino in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

CERN, Switzerland

A R T I C L E  I N F O

Article history:
Received 30 July 2018
Received in revised form 30 January 2019
Accepted 31 January 2019
Available online 15 March 2019

Editor: M. Doser

Keywords:
CMS
Physics
Tau
MET

A B S T R A C T

A search for a new high-mass resonance decaying to a $\tau$ lepton and a neutrino is reported. The analysis uses proton-proton collision data collected by the CMS experiment at the LHC at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The search utilizes hadronically decaying $\tau$ leptons. No excess in the event yield is observed at high transverse masses of the $\tau$ and missing transverse momentum. An interpretation of results within the sequential standard model excludes $W'$ boson masses below 4.0 TeV at 95% confidence level. Existing limits are also improved on models in which the $W'$ boson decays preferentially to fermions of the third generation. Heavy $W'$ bosons with masses less than 1.7–3.9 TeV, depending on the coupling in the non-universal G(221) model, are excluded at 95% confidence level. These are the most stringent limits on this model to date.

© 2019 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP$^3$.

1. Introduction

New charged heavy gauge bosons, generally referred to as $W'$ bosons, are predicted by various extensions of the standard model (SM). An example is the sequential standard model (SSM) [1], featuring an extended gauge sector, which is often used as a benchmark model. Lepton universality holds in the SSM; however, there exist models without this assumption. Nonuniversal gauge interaction models (NUGIMs) [2–6] predict an enhanced $W'$ boson branching fraction to the third generation fermions. In this approach, the top quark mass is associated with the large vacuum expectation value of the corresponding Higgs field.

The analysis presented in this Letter searches for $W' \rightarrow \tau \nu$ events, where the $\tau$ lepton decays hadronically. The leading order Feynman diagram is shown in Fig. 1. In this Letter, the symbol $\tau_h$ will be used to denote the visible part of the hadronic decay of the $\tau$, which is reconstructed as a $\tau$ jet in the detector. The hadronic decays of the $\tau$ lepton are experimentally distinctive because they result in low charged-hadron multiplicity, unlike jets originating from the hadronization of partons produced in the hard scattering process, which have high charged-hadron multiplicity. The signature of a $W'$ boson event is similar to that of a $W$ boson event in which the $W$ boson is produced “off-shell” with a high mass.

Searches for a $W'$ boson decaying to a $\tau$ lepton and a neutrino have been performed previously by the CMS [7] and ATLAS [8] collaborations at the CERN LHC. Searches for a $W'$ boson have been performed also in $e + p_T^{miss}$, $\mu + p_T^{miss}$ [9,10], $WZ$ [11,12], $qq'$ [13,14] and $tb$ [15,16] channels. The ATLAS experiment has excluded an SSM $W'$ for masses below 3.7 TeV in the $\tau_h + p_T^{miss}$ channel. The CMS experiment has excluded an SSM $W'$ for masses below 5.2 TeV in the combination of electron and muon channels. This Letter describes a search for a $W'$ boson in the $\tau_h + p_T^{miss}$ channel using proton-proton (pp) collisions collected in 2016 at a center-of-mass energy of 13 TeV. The data set corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The results are interpreted in the context of two models, the SSM and the NUGIM.

2. Physics models

2.1. The sequential standard model $W'$ boson

In the SSM, the $W'$ boson is a heavy analog of the $W$ boson. It is a resonance with fermionic decay modes and branching frac-
tions similar to those of the SM W boson, with the addition of the decay $W' \to tb$, which becomes relevant for $W'$ boson masses larger than 180 GeV. If the $W'$ boson is heavy enough to decay to top and bottom quarks, the SM branching fraction for the decay $W' \to \tau v$ is 8.5% [1]. Under these assumptions, the relative width $\Gamma/W$ of the $W'$ boson is $\sim 3.3\%$. With increasing mass, a growing fraction of events is produced off-shell and shifted to lower mass values. Assuming events within a window of $\pm 10\%$ around the actual mass to be on-shell, the off-shell fractions are approximately 9, 22 and 66% for $W'$ masses of 1, 3 and 5 TeV, respectively. Decays into WZ depend on the specific model assumptions and are usually considered to be suppressed in the SSM, as assumed by the current search.

In accordance with previous analyses, it is assumed that there is no interference between the production of the new particle and the production of the SM W boson. Such an absence of interference would occur, for example, if the $W'$ interacts via V+A coupling [17].

Signal events for the SSM $W'$ boson are simulated at leading order (LO) with PYTHIA 8.212 [18], using the NNPDF 2.3 [19,20] parton distribution function (PDF) set and tune CUETP8M1 [21]. The $W'$ samples are normalized to next-to-next-to-leading-order (NNLO) cross sections from FEWZ [22,23].

2.2. Coupling strength

The $W'$ boson coupling strength, $g_{WW'}$, is given in terms of the SM weak coupling strength $g_W = e/\sin^2\theta_W \approx 0.65$. Here, $\theta_W$ is the weak mixing angle. If the $W'$ is a heavier copy of the SM W boson, their coupling ratio is $g_{WW'}/g_W = 1$ and the SSM $W'$ theoretical cross sections, signal shapes, and widths apply. However, different couplings are possible. Because of the dependence of the width of a particle on its coupling, and the consequent effect on the transverse mass distribution, a limit can also be set on the coupling strength for this study. For this reason, a reweighting procedure is used. Some selected signal samples are simulated at LO with MADGRAPH (version 1.5.11) [24], for a range of coupling ratios $g_{WW'}/g_W$ from 0.01 to 3. These signals exhibit different widths as well as different cross sections. The generated distributions of the SSM PYTHIA samples with $g_{WW'}/g_W = 1$ are reweighted to take into account the decay width dependence, thus providing the appropriate reconstructed transverse mass distributions for $g_{WW'}/g_W \neq 1$. For $g_{WW'}/g_W = 1$, the theoretical LO cross sections apply and this coupling strength is used to compare the standard SSM samples with the reweighted ones, allowing the reweighting method to be verified.

2.3. Nonuniversal gauge interaction model

Models with nonuniversal couplings predict an enhanced branching fraction for the third generation of fermions and explain the large mass of the top quark. The nonuniversal gauge interaction models (NUIGMs) exhibit a $SU(2)_L \times SU(2)_R \times U(1)$ symmetry, and thus are often called G(221) models. Here the indices l and h refer to light and heavy, respectively. The weak SM $SU(2)_W$ group is a low-energy limit of two gauge groups, a light $SU(2)_L$ and a heavy $SU(2)_h$, which govern the couplings to the light fermions of the first two generations and to the heavy fermions of the third generation, respectively. These two groups mix, resulting in an SM-like $SU(2)_{W'}$ and an extended group $SU(2)_E$. The $SU(2)_E$ extended gauge group gives rise to additional gauge bosons such as a $W'$. The mixing of the two gauge groups involves a mixing angle of the extended group, $\theta_h$, which modifies the couplings to the heavy boson. Consequently, the mixing modifies the production cross section and, as illustrated in Fig. 2, the branching fractions of the $W'$. For $\cot \theta_h \gtrsim 3$ the $W'$ decays predominantly to third generation fermions. The branching fraction to WH is smaller than the branching fraction to third generation fermions, as shown in Fig. 2. For $\cot \theta_h = 1$ the branching fractions are the same as those of the SSM, and the $W'$ boson couples democratically to all fermions. For $\cot \theta_h < 1$ the decays into light fermions are dominant.

In the NUGIM G(221), the ratio of the couplings $g_{WW'}/g_W$ is related to the parameter $\cot \theta_h$ by the following equation [26]:

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

Because of this functional relationship, a reinterpretation of limits on coupling strength will yield limits on NUGIM G(221), and thus it was not necessary to generate a signal sample for this model.

3. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15148 silicon strip detector modules. For nonisolated particles with transverse momentum $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically $1.5\%$ in $p_T$ and $25–90\mu$m in the transverse impact parameter and $45–150\mu$m in the longitudinal impact parameter. The ECAL consists of 75 848 lead tungstate crystals, which provide coverage of $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). The HCAL is a sampling calorimeter, which utilizes alternating layers of brass as an absorber and plastic scintillator as active material, covering the range $|\eta| < 3$. In the forward region, the calorimetric coverage is extended to $|\eta| < 5$ by a steel and quartz fiber Cherenkov hadron forward calorimeter. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers,
and resistive plate chambers. Events of interest are selected using
a two-tiered trigger system [27].

A more detailed description of the CMS detector, together with
a definition of the coordinate system used and the relevant kine-
natic variables, can be found in Ref. [28].

4. Background simulation

The dominant SM background is the production of W+ jets. This
background is generated at LO using MadGraph5_AMC@NLO
version 2.2.2 with the MLM merging [24,29] and the NNPDF 3.0 [19,
20,30] PDF set for on-shell W boson production and using Pythia
8.212 with the NNPDF 2.3 PDF set for off-shell production.
The differential cross section is reweighted as a function of the
invariant mass of the SM W boson decay products, incorporating
NNLO quantum chromodynamics (QCD) and next-to-leading-order
(NLO) electroweak (EW) corrections. The effect with respect to the
LO calculation corresponds to a correction factor (K factor) for the
W boson transverse mass spectrum. To combine the QCD and EW
differential cross sections, two different mathematical approaches
could be taken [31]: an additive or a multiplicative combination.
Their effects differ by around 5%. The K factor assumed in this
analysis is obtained by taking the additive combination as recom-
manded by Ref. [32] and the difference from the multiplicative
combination is treated as a systematic uncertainty. The K factor is
1.15 at a W mass of 0.3 TeV and drops monotonically for higher
masses down to 0.6 for a mass of 6 TeV. The calculation uses the
generators FW2X 3.1 and MC@NLO 1.01 [33] for the QCD and elec-
troneutral corrections.

Other background processes are: Z/γ∗ → ℓℓ generated with
MadGraph5_AMC@NLO version 2.3.2.2 [24] with the NNPDF 3.0
PDF set, diboson processes generated with Pythia 8.212 and with
the NNPDF 2.3 PDF set, and top quark processes generated with
POWHEG 2.0 [34–39] and the NNPDF 3.0 PDF set. Background from
jets that are falsely identified as τν candidates is dominated by
Z → τντν+jets events, which are simulated with MadGraph5_ 
AMC@NLO version 2.3.2.2 and with the NNPDF 3.0 PDF set.

Parton fragmentation and hadronization are performed with
Pythia 8.212 with the underlying event tune CUETP8M1. The
detector response is simulated using a detailed description of the
CMS detector implemented with the GEANT4 package [40]. All sim-
ulated event samples are normalized to the integrated luminosity of
the recorded data, using the theoretical cross section values.
Additional pp collisions during the same bunch crossing (pileup)
is taken into account by superimposing simulated minimum bias
interactions onto all simulated events. The simulated events are
weighted so that the pileup distribution matches that of the data,
with an average of about 27 interactions per bunch crossing.

5. Reconstruction and identification of physics objects

A particle-flow (PF) algorithm [41] is used to combine informa-
tion from all CMS subdetectors in order to reconstruct and identify
individual particles in the event: muons, electrons, photons, and
charged and neutral hadrons. The resulting set of particles is used
to reconstruct the τν candidates, missing transverse momentum
(pTmiss), and jets. The vector pTmiss is defined as the negative vector
pT sum of all PF candidates reconstructed in the event. The mag-
nitude of this vector is referred to as pTmiss. The raw pTmiss value is
modified to account for corrections to the energy scale of all the
reconstructed jets in the event [42]. The jets are clustered using
the anti-kT jet finding algorithm [43,44]. The reconstructed vertex
with the largest value of summed physics-object pT is taken as the
primary vertex.

Electrons [45,46] are reconstructed by matching energy deposits in
the ECAL with track segments in the inner tracker. Muon recon-
struction [47] is performed by matching a track segment recon-
structed in the inner tracker with a track segment reconstructed in
the muon detector and performing a global fit of the charge de-
posits from the two track segments.

The τν reconstruction in CMS starts from jets clustered from PF
candidates, using the anti-kT algorithm with a distance parameter
of 0.4. The τν candidates are reconstructed using the hadrons-
plus-strips algorithm [48,49], which is designed to optimize the
performance of τν reconstruction and identification by consider-
ing specific τ lepton decay modes. Individual τν decay modes are
reconstructed separately. The signatures distinguished by the algo-
rium are: a single charged hadron, a charged hadron and up to
two neutral pions, and three charged hadrons.

Requiring τν candidates to pass isolation requirements reduces the
jet → τν misidentification probability. The multivariate-based
(MVA-based) τν identification discriminant combine isolation and
other variables with sensitivity to the τ lifetime, to provide the
best possible discrimination for τν decays against quark and gluon
jets. Hadronically decaying τ leptons in this analysis are required
to satisfy the very loose working point of the MVA-based iso-
lation [50]. This working point has an efficiency of about 70% for
genuine τν, with about 0.4% misidentification rate for quark- and
gluon-initiated jets, for a pT range typical of τν originating from a
W boson of mass of 2 TeV. Isolated electrons have a high proba-
ability to be misidentified as τν objects that decay to a single charged
hadron (hν and hν′ν). Electrons can emit energetic bremsstrahlung
photons as they traverse the material of the silicon tracker. When
this occurs, the electron and accompanying photons may be mis-
takenly reconstructed as a hadronically decaying τ. Muons can
also be reconstructed as τν objects in the hν decay mode. The
τν candidates in this analysis are required to pass the loose work-
ning point of the antielectron discriminator, which has an efficiency
of about 85% for genuine τν events and a misidentification rate of
about 1.5% for electrons. The τν candidates are further required to
pass the loose working point of the antimuon discriminator, which
has an efficiency of >99% for genuine τν events, with a misiden-
ification rate of about 0.3% for muons [50,51].

6. Analysis strategy

The discriminating variable used in this analysis is the trans-
verse mass, defined as follows:

\[
mt = \sqrt{2p_T^e p_T^{\text{miss}} [1 - \cos \Delta\phi(p_T^e, p_T^{\text{miss}})]},
\]

where pT^e is the magnitude of the transverse momentum vector
of the τν candidate p_T^e, and Δφ is the difference in the azimuthal
angle between p_T^e and p_T^{\text{miss}}.

The strategy of this analysis is to select a heavy boson candidate
decaying almost at rest to a hadronic jet consistent with a τν
candidate and neutrinos, the latter manifesting themselves as p_T^{\text{miss}}.
Signal events are selected online with a τν + p_T^{\text{miss}} trigger that
requires the p_T of the τν candidate to be greater than 50 GeV and
the value of p_T^{\text{miss}} to be greater than 90 GeV. To ensure that the
trigger is maximally efficient for selected events, the offline selec-
tion requires one isolated τν candidate to have p_T^e greater than
80 GeV and p_T^{\text{miss}} to be greater than 200 GeV.

Although there are two neutrinos in the final state, p_T^{\text{miss}} and
the isolated τν candidate are largely produced in opposite direc-
tions, which helps to distinguish signal from background events
especially those coming from QCD multijet production. Two selec-
tion criteria exploit this behavior to reduce the background: the
ratio of the p_T^e to p_T^{\text{miss}} is required to satisfy 0.7 < p_T^e/p_T^{\text{miss}} < 1.3;
and the angle $\Delta \phi(\vec{p}_T^\tau, \vec{p}_T^{miss})$ has to be greater than 2.4 radians. Consequently, the lowest $m_T$ value is about 300 GeV. To avoid an overlap with the $W^\prime$ boson search in the electron channel, events are rejected if they contain a loosely identified electron with $p_T > 20$ GeV and $|\eta| < 2.5$, where the loose working point is $\approx 90\%$ efficient for real electrons. For similar reasons, events containing a loosely identified muon with $p_T > 20$ GeV and $|\eta| < 2.4$ are not considered in this analysis, where the loose working point is $> 99\%$ efficient for real muons.

After all selections, the $m_T$ distributions for the observed data and expected background events are presented in Fig. 3 (left). Fig. 3 (right) shows the integral distribution, which is formed by filling each bin of the histogram with the sum of that bin and all following bins. The systematic uncertainties, which are detailed in Section 7, are shown as a gray band in the lower panels of the plots. The product of the signal efficiency and acceptance for simulated $W^\prime \rightarrow \tau \nu$ events depends on the $W^\prime$ boson mass. The total signal efficiency for the studied range of $m_T > 300$ GeV varies from 14% to about 24% as $M_{W^\prime}$ increases from 1 to 3 TeV. For higher $W^\prime$ boson masses, events shift to lower $m_T$ because of the increasing fraction of off-shell production (as shown in Fig. 3 for a few signal mass points). For example, for a $W^\prime$ boson with a mass of 5 TeV, the total signal efficiency is around 17%. The trigger threshold affects the signal efficiency in the low-mass range. These efficiency values are obtained assuming the $W^\prime \rightarrow \tau \nu$ branching fraction to be unity. The efficiency values are estimated using simulated events where the $\tau$ lepton decays hadronically.

The dominant background is from the off-shell tail of the $m_T$ distribution of the SM $W$ boson, and is obtained from simulation. The background contributions from $Z(\rightarrow \nu\nu) + \text{jets}$ and QCD multijet events are also obtained from simulation. These backgrounds primarily arise as a consequence of jets misidentified as $\tau_h$ candidates. The contribution of QCD multijet background is small compared to $Z(\rightarrow \nu\nu) + \text{jets}$ in the signal region. Following the strategy in Ref. [52], to ensure that the misidentified $\tau$ background is simulated properly, the agreement between data and simulation is checked in a control region dominated by $Z(\rightarrow \mu\mu) + \text{jets}$ events, where a jet is misidentified as a $\tau_h$ candidate. The $p_T^{miss}$ is recalculated excluding the muons from the $Z$ decay in order to reproduce the $p_T^{miss}$ distribution of $Z \rightarrow \nu\nu$ events. Specifically, the control region is defined as follows. Events are selected online using a dimuon trigger with $p_T$ thresholds of 17 and 8 GeV. They must contain two oppositely charged $\nu$s with $p_T > 20$ GeV and $|\eta| < 2.4$, both passing loose identification and isolation requirements. The invariant mass of the dimuon system is required to be between 81 and 101 GeV. In addition, the events are required to contain exactly one $\tau_h$ candidate passing the same selection requirements as in the signal region, with $p_T > 20$ GeV and $|\eta| < 2.1$. To remove the overlap between muon and $\tau_h$ candidates, the separation between them must fulfill $\Delta R(\mu, \tau_h) > 0.1$, where $\Delta R$ is defined as $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$. Data and simulation are compared using distributions of the dimuon mass, $p_T^{miss}$, $p_T/p_T^{miss}$, $m_T$, $\eta$ and $p_T^\tau$. Fig. 4 shows the $p_T^\tau$ distribution in the control region. Data and simulation agree within 50% in all bins except in one bin in the tail of the $p_T^\tau$ distribution, giving confidence that the misidentified $\tau_h$ background source—about 22% of the total background—is correctly modeled in the simulation.

7. Systematic uncertainties

The uncertainty in the modeling of the $m_T$ distribution can be split into three categories: uncertainties affecting shape and normalization, uncertainties affecting only normalization, and an uncertainty due to limited numbers of events in simulated samples.

The dominant uncertainty of the first category comes from the $\tau_h$ reconstruction and identification, affecting background and a potential signal in the same way. The uncertainty associated with the $\tau_h$ identification is 5% [48]. An additional systematic uncertainty, which dominates for high-$p_T$ $\tau_h$ candidates, is related to the degree of confidence that the MC simulation correctly models the identification efficiency. This additional uncertainty increases linearly with $p_T^\tau$ and amounts to $\sim 5\%$ at $p_T^\tau = 1$ TeV. The uncertainty is asymmetric because studies indicate that the $\tau$ identification efficiency is smaller in data than in simulation, and the difference increases as the $p_T$ of the $\tau$ increases. The uncertainty in the $\tau_h$ energy scale amounts to $\sim 3\%$ [48]. The main sources of
$p_T^\text{miss}$ uncertainty from jets are the jet energy scale and jet energy resolution [53]. For the energy measurements of other objects the following uncertainties are applied: 3% [48] for $t\bar{t}$, 0.6% in EB and 1.5% in EE, respectively, for electrons and photons [54]; and 0.2% for muons [47]. The contribution to the uncertainty in $p_T^\text{miss}$ associated with unclustered energy is estimated by varying this energy by ±10%. For the $\tau$ plus $p_T^\text{miss}$ trigger, a scale factor of 0.9 is applied. The scale factor has an uncertainty of 10%. The uncertainty associated with the choice of the PDF in the simulation is evaluated according to the PDF4LHC prescription [55–57]. The values increase with $m_T$, ranging from an uncertainty of 1 to 10% at $m_T = 0.5$ to 4.0 TeV. For the $K$ factor of the $W$ boson background, the difference between additive and multiplicative combination, which is around 5%, is taken to be the systematic uncertainty. The simulated events are weighted so that the pileup distribution matches the measured one, using a value for the total inelastic cross section of 69.2 mb, which has an uncertainty of ±4.6% [58].

Uncertainties of the second category only influence the normalization of the $m_T$ distribution. Kinematic distributions in the $Z(\rightarrow \mu\mu) +$ jets control region demonstrate that data and simulation agree within 50% for misidentified $t\bar{t}$ background, which is composed of $Z(\rightarrow \nu\nu) +$ jets and QCD multijet events. This guides the assignment of a 50% systematic uncertainty in the normalization of this backgrounds. The uncertainty in the electron identification efficiency (veto) is 2% and the uncertainty in the integrated luminosity measurement is 2.5% [59].

Uncertainties in the third category arise from limited sizes of event samples in the simulation of background processes. In contrast to all other uncertainties, they are not correlated between the bins of the invariant mass distribution.

In the high-mass region, where both the expected and the observed numbers of events are consistent with zero, the effect of the systematic uncertainty on the exclusion limits is negligible.

The relevant systematic uncertainties taken into account in the estimation of potential signals include those associated with $t\bar{t}$ identification and energy scale, $p_T^\text{miss}$, trigger, pile-up simulation, and integrated luminosity. The uncertainty in the signal $K$ factor arises from the choices of PDF and $\alpha_S$. The combined uncertainty is evaluated using the PDF4LHC prescription, where in the computation of each PDF set, the strong coupling constant is varied. Uncertainties from different PDF sets and $\alpha_S$ variation are added in quadrature.

### 8. Results

The transverse mass distribution in Fig. 3 shows no significant deviations from the expected SM background. Signal events are expected to be particularly prominent at the upper end of the $m_T$ distribution, where the expected SM background is low. The expected and measured yields are summarized in Table 1 together with the detailed systematic uncertainties described in Section 7.

#### 8.1. Statistical analysis

Upper limits on the product of the production cross section and branching fraction, $\sigma(pp \rightarrow W^+\ell\nu)(W^+ \rightarrow \tau\nu)$, are determined using a Bayesian method [60,61] with a uniform positive prior probability density for the signal cross section (known to have excellent frequentist properties when used as a technical device for generating frequentist upper limits). All limits presented here are at 95% confidence level (CL). The nuisance parameters associated with the systematic uncertainties are modeled through log-normal distributions for uncertainties in the normalizations. Uncertainties in the shape of the distributions are modeled through “template morphing” techniques [62]. The limits are obtained from the entire $m_T$ spectrum for $m_T > 320$ GeV, as displayed in Fig. 3. This procedure is performed for different values of parameters of each signal, to obtain limits in terms of these parameters, such as the $W$ boson mass.

#### Table 1

<table>
<thead>
<tr>
<th>Range of $m_T$</th>
<th>$m_T &lt; 0.5$ TeV</th>
<th>$0.5 &lt; m_T &lt; 1$ TeV</th>
<th>$m_T &gt; 1$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W +$ jets</td>
<td>786 ± 110</td>
<td>355 ± 68</td>
<td>21.8 ± 6.2</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu +$ jets</td>
<td>238 ± 120</td>
<td>68 ± 35</td>
<td>0.9 ± 0.5</td>
</tr>
<tr>
<td>Multijet</td>
<td>68 ± 35</td>
<td>18 ± 10</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>68 ± 15</td>
<td>145 ± 4.5</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell +$ jets</td>
<td>35.8 ± 8.7</td>
<td>10.4 ± 5.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Diboson (WW, WZ, Z Z)</td>
<td>24.9 ± 6.4</td>
<td>9.6 ± 3.5</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>Single top quark</td>
<td>21.5 ± 6.5</td>
<td>7.0 ± 2.9</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total background</td>
<td>1243 ± 160</td>
<td>485 ± 77</td>
<td>23.4 ± 6.2</td>
</tr>
<tr>
<td>SSM $W^+M = 600$ GeV</td>
<td>28229 ± 4388</td>
<td>14012 ± 2798</td>
<td>45.6 ± 7.7</td>
</tr>
<tr>
<td>SSM $W^+M = 1$ TeV</td>
<td>3767 ± 590</td>
<td>10079 ± 1581</td>
<td>355 ± 98</td>
</tr>
<tr>
<td>SSM $W^+M = 4$ TeV</td>
<td>0.7 ± 0.1</td>
<td>3.0 ± 1.8</td>
<td>11.4 ± 3.9</td>
</tr>
</tbody>
</table>

Data

|            | 1203 | 452 | 15 |
To determine a model-independent upper limit on the product of the cross section and branching fraction, all events above a threshold \( m_{W'}^{\text{min}} \) are summed. From the number of background events, signal events, and observed data events, the cross section limit can be calculated. The resulting limit can be reinterpreted in the framework of other models with a \( \tau_h \) and \( p_T^{\text{miss}} \) in the final state.

### 8.2. The sequential standard model \( W' \)

The parameter of interest is the product of the signal cross section and the branching fraction, \( \sigma \cdot B(W' \to \tau \nu) \). The branching fraction includes all \( \tau \) lepton decay modes, to allow a direct comparison with the \( W' \) searches in the electron and muon channels [9].

The upper limit on \( \sigma \cdot B(W' \to \tau \nu) \) as a function of the SSM \( W' \) boson mass is shown in Fig. 5. The observed limit is consistent with the expected limit. The SSM \( W' \) boson is excluded for masses \( 0.4 < M_{W'} < 4.0 \text{ TeV} \) at 95% CL where the lower limit is mainly determined by the trigger threshold and the upper one by the available data. This result in the \( \tau \) channel may be compared with the lower mass limit of 5.2 TeV for an SSM \( W' \) boson, obtained from the combination of electron and muon channels [9, 10].

### 8.3. Limits on the coupling strength

The upper limits on the cross section depend not only on the mass of a potential excess, but also on the width. Because of the relation between the coupling of a particle and its width, a limit can also be set on the coupling strength. In order to compute the limit for couplings \( g_W/g_W \neq 1 \), reweighted samples are used that take into account the appropriate signal width and the differences in reconstructed \( m_T \) shapes. For \( g_W/g_W = 1 \) the theoretical LO cross sections apply. For a given mass, the cross section limit as a function of the coupling strength \( g_W/g_W \) is determined.

For each simulated \( W' \) boson mass, the excluded cross section is determined from the intersection of the theoretical cross section curve with the observed cross section limit. The resulting intersection points provide the input for the exclusion limit in a two-dimensional plane made of \( g_W/g_W \) and \( M_{W'} \), as depicted in Fig. 6.

The phase space above the observed limit contour is excluded. For low masses, \( g_W/g_W \) values down to \( 7 \times 10^{-2} \) are excluded.

### 8.4. The nonuniversal gauge interaction model limits

In the NUGIM G(221) framework, the ratio of the couplings \( g_W/g_W \) is related to the parameter \( \cot \theta_k \) through Eq. (1). Thus \( \cot \theta_k \) can be extracted for each value of \( g_W/g_W \). Based on the limits on coupling strengths presented in Fig. 6, the two-dimensional limit on \( \cot \theta_k \) is shown as a function of \( W' \) boson mass. Fig. 7 (left) shows the width of the \( W' \) boson as a function of \( \cot \theta_k \) and \( M_{W'} \). For \( \cot \theta_k > 6.5 \), the width becomes so large that the model is no longer valid. The limit, shown in Fig. 7 (right), focuses on the parameter space \( \cot \theta_k \geq 1 \) where the \( \tau_h \) channel sets the most stringent bounds, as illustrated in Fig. 2. For lower values of \( \cot \theta_k \), other channels are more sensitive. Depending on the value of \( \cot \theta_k \), the mass of the \( W' \) boson can be excluded at 95% CL up to 3.9 TeV in the NUGIM G(221) framework.

### 8.5. The model-independent cross section limit

The shape analysis assumes a certain signal shape in \( m_T \). However, alternative new physics processes yielding a \( \tau_h + p_T^{\text{miss}} \) final state could cause an excess of a different shape. A model-independent cross section limit is determined using a single bin ranging from a lower threshold on \( m_T \) to infinity. No assumptions on the shape of the signal \( m_T \) distribution have to be made other than that of a flat product of acceptance times efficiency, \( A_e \), as a function of \( W' \) mass. The model-independent cross section limit shown here, only the model-dependent part of the efficiency needs to be applied. The experimental efficiencies for the signal are already taken into account, including the effect of the kinematic selection of events containing \( \tau_h \) and \( p_T^{\text{miss}} \) (the selections on \( p_T/p_T^{\text{miss}} \) and \( \Delta \phi \), the geometrical acceptance (selection on \( \eta \)), and the trigger threshold.

A factor \( f_m \) that reflects the effect of the threshold \( m_T^{\text{min}} \) on the signal is determined by counting the events with \( m_T > m_T^{\text{min}} \) and dividing the result by the number of generated events. The reconstruction efficiency is nearly constant over the entire \( m_T \) range.
probed here, therefore \( f_{m_{\tau}} \) can be evaluated at generator level. A limit on the product of the cross section and branching fraction \((\sigma B A e)_{\text{excl}} \) can be obtained by dividing the excluded cross section of the model-independent limit \((\sigma B A e)_{\text{ML}} \) given in Fig. 8 by the calculated fraction \( f_{m_{\tau}} (m_{\tau}^{\text{min}}) \):

\[
(\sigma B A e)_{\text{excl}} = \frac{(\sigma B A e)_{\text{ML}} (m_{\tau}^{\text{min}})}{f_{m_{\tau}} (m_{\tau}^{\text{min}})}
\]

(3)

Here, \( B \) is the branching fraction of the new particle decaying to \( \tau + \nu \). Models with a theoretical cross section \((\sigma B)_{\text{theo}} \) larger than \((\sigma B)_{\text{excl}} \) can be excluded. The procedure described here can be applied to all models involving the two-body decay of a massive state, which exhibit back-to-back kinematics similar to those of a generic \( W' \). If the kinematic properties are different, the fraction of events \( f_{m_{\tau}} (m_{\tau}^{\text{min}}) \) must be determined for the particular model considered.

The resulting cross section limit as a function of \( m_{\tau}^{\text{min}} \) is shown in Fig. 8. The highest \( m_{\tau} \) event in data was found at 1.65 TeV, after which the limit becomes flat. The results depend strongly on the threshold \( m_{\tau}^{\text{min}} \). Values of the product \( \sigma B A e \) between 50 fb \((m_{\tau}^{\text{min}} > 400\,\text{GeV})\) and 0.4 fb \((m_{\tau}^{\text{min}} > 2\,\text{TeV})\) are excluded for the \( m_{\tau}^{\text{min}} \) thresholds given in brackets.

9. Summary

A search for new physics in final states with a hadronically decaying \( \tau \) lepton and missing transverse momentum has been performed by the CMS experiment, using proton-proton collision data at the center-of-mass energy \( \sqrt{s} = 13\,\text{TeV} \) with an integrated luminosity of \( 35.9\,\text{fb}^{-1} \). No significant excess compared to the standard model expectation is observed in the transverse mass of the \( \tau \) and missing transverse momentum. A sequential standard model \( W' \) boson is excluded in the mass range \( 0.4 < m_{W'} < 4.0\,\text{TeV} \) at 95% confidence level. Couplings that are weaker than assumed in the sequential standard model can be excluded down to values of \( 7 \times 10^{-2} \) for \( m_{W'} = 1\,\text{TeV} \). Within the nonuniversal gauge interaction \( SU(2) \times SU(2) \times U(1) \) model, the lower limit on the \( W' \) boson mass depends on the coupling constant and varies from 1.7 to 3.9 TeV at 95% confidence level. For \( \cot \theta_{W} > 1 \), these results obtained in the \( \tau \) channel provide the most stringent constraints on this model to date. In addition, a model-independent limit is provided allowing the results to be interpreted in other models giving the same final state with similar kinematic distributions.

Acknowledgements

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 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 and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RFPI (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NPI (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); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka);


The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia


Institut für Hochenergiephysik, Wien, Austria

V. Chekhnovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus


Universiteit Antwerpen, Antwerpen, Belgium


Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium


Ghent University, Ghent, Belgium


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


Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil


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


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

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang, X. Gao, L. Yuan

Beihang University, Beijing, China


Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia


University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran, S. Elgammal, S. Khalil

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland


Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland


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


Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France


Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze 8

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze 8

Tbilisi State University, Tbilisi, Georgia


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


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


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


Deutsches Elektronen-Synchrotron, Hamburg, Germany


University of Hamburg, Hamburg, Germany


Karlsruher Institut fuer Technologie, Karlsruhe, Germany


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


National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece


University of Ioánnina, Ioánnina, Greece


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

G. Bencze, C. Hajdu, D. Horvath 20, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi†

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi 21, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India


National Institute of Science Education and Research, HBNI, Bhubaneswar, India


Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India


Tata Institute of Fundamental Research-A, Mumbai, India


Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland


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


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

t S. Albergo, A. Di Mattia, R. Potenza, A. Tricomi, C. Tuve

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


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

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro, F. Ravera, E. Robutti, S. Tosi

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea


Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea


Seoul National University, Seoul, Republic of Korea


University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania


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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico


Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

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

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
D. Krofcheck
University of Auckland, Auckland, New Zealand

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lyakhkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin
Institute for Theoretical and Experimental Physics, Moscow, Russia

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

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov
PN. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhina, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Barnyakov 40, V. Blinov 40, T. Dimova 40, L. Kardapoltsev 40, Y. Skovpen 40

Novosibirsk State University (NSU), Novosibirsk, Russia


State Research Center of Russian Federation, Institute for High Energy Physics of NRC “Kurchatov Institute”, Protvino, Russia

A. Babaev, S. Baidali, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic 41, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia


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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain


Universidad de Oviedo, Oviedo, Spain


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

N. Wickramage

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


CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland


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


Universität Zürich, Zurich, Switzerland


National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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


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

B. Isildak 54, G. Karapinar 55, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya 56, O. Kaya 57, S. Ozkorucuklu 58, S. Tekten, E.A. Yetkin 59

Bogazici University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cancakac, Y. Komurcu, S. Sen 60

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine


University of Bristol, Bristol, United Kingdom

California Institute of Technology, Pasadena, USA


Carnegie Mellon University, Pittsburgh, USA


University of Colorado Boulder, Boulder, USA


Cornell University, Ithaca, USA


Fermi National Accelerator Laboratory, Batavia, USA


University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA


Florida Institute of Technology, Melbourne, USA


University of Illinois at Chicago (UIC), Chicago, USA
Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

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

Purdue University, West Lafayette, USA

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

Rice University, Houston, USA

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

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

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

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA


Wayne State University, Detroit, USA


University of Wisconsin – Madison, Madison, WI, USA
48 Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
49 Also at Gaziosmanpasa University, Tokat, Turkey.
50 Also at Adiyaman University, Adiyaman, Turkey.
51 Also at Istanbul Aydin University, Istanbul, Turkey.
52 Also at Mersin University, Mersin, Turkey.
53 Also at Piri Reis University, Istanbul, Turkey.
54 Also at Ozyegin University, Istanbul, Turkey.
55 Also at Gaziosmanpasa University, Tokat, Turkey.
56 Also at Marmara University, Istanbul, Turkey.
57 Also at Kafkas University, Kars, Turkey.
58 Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
59 Also at Istanbul Bilgi University, Istanbul, Turkey.
60 Also at Hacettepe University, Ankara, Turkey.
61 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
62 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
63 Also at Monash University, Faculty of Science, Clayton, Australia.
64 Also at Bethel University, St. Paul, USA.
65 Also at Karamano˘glu Mehmetbey University, Karaman, Turkey.
66 Also at Utah Valley University, Orem, USA.
67 Also at Purdue University, West Lafayette, USA.
68 Also at Beykent University, Istanbul, Turkey.
69 Also at Bingol University, Bingol, Turkey.
70 Also at Sinop University, Sinop, Turkey.
71 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
72 Also at Texas A&M University at Qatar, Doha, Qatar.
73 Also at Kyungpook National University, Daegu, Republic of Korea.