Search for High-Mass Resonances Decaying to $\tau\nu$ in pp Collisions at $\sqrt{s}$=13 TeV with the ATLAS Detector

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Search for High-Mass Resonances Decaying to $\tau\nu$ in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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A search for high-mass resonances decaying to $\tau\nu$ using proton-proton collisions at $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider is presented. Only τ-lepton decays with hadrons in the final state are considered. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb^{-1}. No statistically significant excess above the standard model expectation is observed; model-independent upper limits are set on the visible $\tau\nu$ production cross section. Heavy W' bosons with masses less than 3.7 TeV in the sequential standard model and masses less than 2.2–3.8 TeV depending on the coupling in the nonuniversal $G(221)$ model are excluded at the 95% credibility level.

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Heavy charged gauge bosons (W') appear frequently in theories of physics beyond the standard model (SM). They are often assumed to obey lepton universality, such as in the sequential standard model (SSM) [1], which predicts a W'_{SSM} boson with couplings identical to those of the SM W boson. However, this assumption is not required. In particular, models in which the W' boson couples preferentially to third-generation fermions may be linked to the high mass of the top quark [2–5] or to recent indications of lepton flavor universality violation in B meson decays [6,7]. An example is the nonuniversal $G(221)$ model (NU) [4,5], which exhibits a $SU(2)_l \times SU(2)_h \times U(1)$ gauge symmetry, where $SU(2)_l$ couples to *light* fermions (first two generations), $SU(2)_h$ couples to *heavy* fermions (third generation), and ϕ_{NU} is the mixing angle between them. The model predicts W'_{NU} and Z'_{NU} bosons which are approximately degenerate in mass and couple only to left-handed fermions. At leading order and neglecting sign, the W'_{NU} couplings to heavy (light) fermions are scaled by $\cot\phi_{\mathrm{NU}}$ ($\tan\phi_{\mathrm{NU}}$) relative to those of W'_{SSM}. Thus $\cot\phi_{\mathrm{NU}} > 1$ corresponds to enhanced couplings to tau leptons while $\cot\phi_{\mathrm{NU}} = 1$ yields W'_{NU} couplings identical to those of W'_{SSM}. For Z'_{NU}, the coupling to heavy (light) fermions is given by $g\cot\phi_{\mathrm{NU}}$ ($g\tan\phi_{\mathrm{NU}}$), where g is the SM weak coupling constant. At high values of $\cot\phi_{\mathrm{NU}}$, the branching fraction of W'_{NU} to a tau lepton (τ) and a neutrino (ν) approaches 26%.

In this Letter, a search for high-mass resonances (0.5–5 TeV) decaying to $\tau\nu$ using proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider (LHC) is presented. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb^{-1}. Only τ decays with hadrons in the final state are considered; these account for 65% of the total τ branching fraction. A counting experiment is performed from events that pass a high transverse-mass threshold, optimized separately for each of the signal mass hypotheses.

A direct search for high-mass resonances decaying to $\tau\nu$ has been performed by the CMS Collaboration using 19.7 fb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV [8]. The search excludes W'_{SSM} with a mass below 2.7 TeV at the 95% credibility level and W'_{NU} with a mass below 2.7–2.0 TeV for $\cot\phi_{\mathrm{NU}}$ in the range 1.0–5.5. The most stringent limit on W'_{SSM} from searches in the $e\nu$ and $\mu\nu$ final states is 5.1 TeV from ATLAS [9] using 36.1 fb^{-1} of integrated luminosity at $\sqrt{s} = 13$ TeV.

The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry [10,11]. It consists of an inner detector for charged-particle tracking in the pseudorapidity region $|\eta| < 2.5$, electromagnetic and hadronic calorimeters that provide energy measurements up to $|\eta| = 4.9$, and a muon spectrometer that covers $|\eta| < 2.7$. A two-level trigger system is used to select events [12].

Hadronic τ decays are composed of a neutrino and a set of visible decay products ($\tau_{\text{had-vis}}$), typically one or three charged pions and up to two neutral pions. The reconstruction of the visible decay products [13] is seeded by jets reconstructed from topological clusters of energy depositions [14] in the calorimeter. The $\tau_{\text{had-vis}}$ candidates must have a transverse momentum $p_T > 50$ GeV, $|\eta| < 2.4$

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(excluding $1.37 < |\eta| < 1.52$), one or three associated tracks, and an electric charge of ± 1. Only the candidate with the highest p_T in each event is selected. Hadronic τ decays are identified using boosted decision trees that exploit calorimetric shower shape and tracking information [15,16]. Loose criteria are used, which offer adequate rejection against quark- and gluon-initiated jets. Very loose criteria, with about one quarter of the rejection power, are used to create control regions. An additional dedicated veto is used to reduce the number of electrons misidentified as $\tau_{\text{had-vis}}$. The total efficiency for $\tau_{\text{had-vis}}$ is ~60% at $p_T = 100$ GeV and decreases to ~30% at $p_T = 2$ TeV, where the large boost and collimation of the decay products causes inefficiencies in the track reconstruction and association.

Events containing electron or muon candidates are rejected. Electron candidates [17–19] must have $p_T > 20$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$) and must pass a loose likelihood-based identification selection. Muon candidates [20] are required to have $p_T > 20$ GeV, $|\eta| < 2.5$ and to pass a very loose muon identification requirement. The missing transverse momentum, with magnitude E_T^{miss}, is calculated as the negative vectorial sum of the p_T of all reconstructed and calibrated $\tau_{\text{had-vis}}$ candidates and jets [21–23]. A correction that accounts for momentum not associated with these reconstructed objects is calculated using inner-detector tracks that originate from the hard-scattering vertex [23]. The correction contributes no more than 5% on average in signal events.

Events are selected by triggers that require E_T^{miss} above thresholds of 70, 90, or 110 GeV depending on the data-taking period. To minimize uncertainties in the trigger efficiency, the offline reconstructed E_T^{miss} is required to be at least 150 GeV. At this threshold the trigger efficiency is 80% and increases to more than 98% above 250 GeV. This behavior is determined by the E_T^{miss} resolution of the trigger, which is lower than in the offline reconstruction. The events must satisfy criteria designed to reduce backgrounds from cosmic rays, single-beam-induced events and calorimeter noise [24] and they must contain a loose $\tau_{\text{had-vis}}$ candidate. To further suppress single-beam-induced background, the $\tau_{\text{had-vis}}$ must have at least one associated track with $p_T > 10$ GeV. The multijet background is further suppressed by requiring that the $\tau_{\text{had-vis}}$ p_T and the E_T^{miss} are balanced: $0.7 < p_T^\tau / E_T^{\text{miss}} < 1.3$. The azimuthal angle between the $\tau_{\text{had-vis}}$ and the missing momentum, $\Delta\phi$, is required to be larger than 2.4. Finally, thresholds ranging from 0.25 to 1.8 TeV in steps of 0.05 TeV are placed on the transverse mass, m_T, where $m_T^2 \equiv 2 p_T^\tau E_T^{\text{miss}} (1 - \cos\Delta\phi)$.

The background is divided into events where the selected $\tau_{\text{had-vis}}$ originates from a quark- or gluon-initiated jet (jet background) and those where it does not (nonjet background). The jet background originates primarily from $W/Z+$jets and multijet production and is estimated using a data-driven technique. The nonjet background is estimated using simulation and originates primarily from $W \to \tau\nu$ production with additional minor contributions from $W/Z/\gamma^*$, $t\bar{t}$, single top-quark, and diboson (WW, WZ and ZZ) production (collectively called *others*).

The event generators and other software packages used to produce the simulated samples are summarized in Table I. The $W/Z/\gamma^*$ sample is artificially enhanced in high-mass events to improve statistical coverage in the scanned mass range. Particle interactions with the ATLAS detector are simulated with GEANT 4 [25,26] and contributions from additional pp interactions (pileup) are simulated using PYTHIA 8.186 and the MSTW2008LO parton distribution function (PDF) set [27]. Finally, the simulated events are processed through the same reconstruction software as the data. Corrections are applied to account for mismodeling of the momentum scales and resolutions of reconstructed objects, the $\tau_{\text{had-vis}}$ reconstruction and identification efficiency, the electron to $\tau_{\text{had-vis}}$ misidentification rate, and the E_T^{miss} trigger efficiency.

The simulated samples are normalized using the integrated luminosity of the collected data set and their theoretical cross sections. The $W/Z/\gamma^*$ cross sections are calculated as a function of the boson mass at next-to-next-to-leading order (NNLO) [49] using the CT14NNLO PDF set, including electroweak corrections at next-to-leading order (NLO) [50] using the MRST2004QED PDF set [51]. Uncertainties are taken from Ref. [52] and include variations of the PDF sets, scale, α_S, beam energy, and electroweak corrections. The variations amount to a ~5% total uncertainty in the $W/Z/\gamma^*$ cross section at low mass, increasing to 34% at 2 TeV. The $t\bar{t}$ and single top-quark production cross sections are

TABLE I. The event generators and other software packages used to generate the matrix-element process and model nonperturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

Process	Matrix element	Nonperturbative	Refs.
$W/Z/\gamma^*$	POWHEG-BOX 2, CT10, PHOTOS++ 3.52	PYTHIA 8.186, AZNLO, CTEQ6L1, EVTGEN 1.2.0	[28–36]
$t\bar{t}$	POWHEG-BOX 2, CT10	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0	[37–39]
Single top	POWHEG-BOX 1, CT10f4, MADSPIN	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0	[40–43]
Diboson	SHERPA 2.1.1, CT10	SHERPA 2.1.1	[44–48]

calculated to at least NLO with an uncertainty of 3%–6% [53–56]. The diboson cross sections are calculated to NLO with an uncertainty of 10% [44,57].

The simulated samples are affected by uncertainties associated with the generation of the events, the detector simulation, and the determination of the integrated luminosity. Uncertainties related to the modeling of the hard scatter, radiation, and fragmentation are at most 2% of the total background estimate. Uncertainties in the detector simulation manifest themselves through the efficiency of reconstruction, identification and triggering algorithms, and through particle energy scales and resolutions. The effects of energy uncertainties are propagated to E_T^{miss}. The uncertainty in the $\tau_{\text{had-vis}}$ identification efficiency is 5%–6%, as determined from measurements of $Z \to \tau\tau$ events. An additional uncertainty that increases by 20%–25% per TeV is assigned to $\tau_{\text{had-vis}}$ candidates with $p_T > 150$ GeV in accord with studies of high-p_T jets [58]. The uncertainty in the $\tau_{\text{had-vis}}$ energy scale is 2%–3%. The probability for electrons to be misidentified as $\tau_{\text{had-vis}}$ is measured with a precision of 3%–14% [16]. The uncertainty in the E_T^{miss} trigger efficiency is negligible for $E_T^{\text{miss}} > 300$ GeV and can be as large as 10% for $E_T^{\text{miss}} < 300$ GeV. Uncertainties associated with reconstructed electrons, muons, and jets are found to have a very small impact. The uncertainty in the combined $2015 + 2016$ integrated luminosity is 2.1%, derived following a methodology similar to that used in Ref. [59], and has a minor impact. The uncertainty related to the simulation of pileup is ~1%.

The W' signal events are modeled by reweighting the W sample using a leading-order matrix-element calculation. Electroweak corrections for the W cross section and interference between W and W' are not included as they are model dependent. Uncertainties in the W' cross section are estimated in the same way as for W bosons. They are not included in the fitting procedure used to extract experimental cross-section limits, but are instead included when overlaying predicted model cross sections. Uncertainties in the W' acceptance due to PDF, scale, and α_S variations are negligible. In the NU model, the total decay width increases to 35% of the pole mass for large values of $\cot\phi_{\text{NU}}$, which decreases the signal acceptance as more events are produced at low mass. Decays to WZ and Wh are not considered in the calculation of the total W'_{NU} decay width as their impact is small ($< 7\%$) and model dependent. Values of $\cot\phi_{\text{NU}} > 5.5$ are not considered as the model is nonperturbative in this range.

The jet background contribution is estimated using events in three control regions (CR1, CR2, and CR3). The events must pass the selection for the signal region, except in CR1 and CR3 they must fail loose but pass very loose $\tau_{\text{had-vis}}$ identification and in CR2 and CR3 they must have $E_T^{\text{miss}} < 100$ GeV and the requirement on $p_T^\tau/E_T^{\text{miss}}$ is removed. The low-E_T^{miss} requirement yields high multijet purity in CR2 and CR3, while the very loose identification preferentially rejects gluon-initiated jets over quark-initiated jets. This produces a similar fraction of quark-initiated jets in all control regions, which ensures minimal correlation between the identification and E_T^{miss}. The estimated jet contribution is defined as $N_{\text{jet}} = N_{\text{CR1}}N_{\text{CR2}}/N_{\text{CR3}}$. The nonjet contamination in CR1 (10%), CR2 (3.7%), and CR3 (0.5%) is subtracted using simulation. The transfer factor, $N_{\text{CR2}}/N_{\text{CR3}}$, is parametrized in $\tau_{\text{had-vis}}$ p_T and track multiplicity and is in the range 0.4–0.7 (0.15–0.3) for 1-track (3-track) $\tau_{\text{had-vis}}$. Systematic uncertainties are assigned to account for any residual correlation between the transfer factor and the E_T^{miss} and $p_T^\tau/E_T^{\text{miss}}$ selection criteria, which would arise if the jet composition was different in CR1 and CR3. They are evaluated by repeating the jet estimate with the following modified control region definitions: (a) altered very loose $\tau_{\text{had-vis}}$ identification criteria, (b) modified E_T^{miss} and $p_T^\tau/E_T^{\text{miss}}$ selection, and (c) CR2 and CR3 replaced by alternative control regions rich in $W(\to \mu\nu) + \text{jets}$ events. The corresponding variations define the dominant uncertainty in the jet background contribution, which ranges from 20% at $m_T = 0.2$ TeV to ${}^{+200\%}_{-60\%}$ at $m_T = 2$ TeV, where the jet background is subdominant. The uncertainty due to the subtraction of nonjet contamination in the control regions is negligible.

To reduce the impact of statistical fluctuations in the jet background estimate, a function $f(m_T) = m_T^{a+b\log m_T}$, where a and b are free parameters, is fitted to the estimate in the range $400 < m_T < 800$ GeV and is used to evaluate the jet background in the range $m_T > 500$ GeV. The impact of altering the fit range leads to an uncertainty that increases with m_T, reaching 50% at $m_T = 2$ TeV. The statistical uncertainty from the control regions is propagated using pseudoexperiments and also reaches 50% at $m_T = 2$ TeV.

Figure 1 shows the observed m_T distribution of the data after event selection, including the estimated SM background contributions and predictions for W'_{SSM} and W'_{NU} ($\cot\phi_{\text{NU}} = 5.5$) bosons with masses of 3 TeV. The number of observed events is consistent with the expected SM background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau\nu$. The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Fig. 2 as a function of the m_T threshold.

Limits are set at the 95% credibility level (C.L.) using the Bayesian Analysis Toolkit [60]. Figure 3 shows the

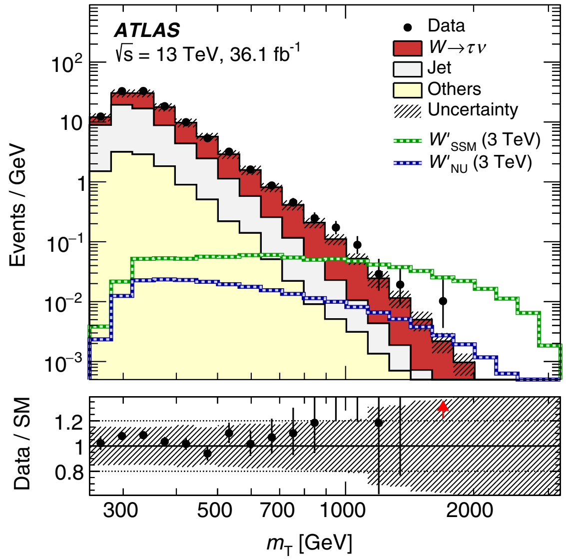


FIG. 1. Transverse mass distribution after the event selection. The total impact of the statistical and systematic uncertainties on the SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is shown in the lower panel. The prediction for W'_{SSM} and W'_{NU} ($\cot\phi_{\mathrm{NU}} = 5.5$) bosons with masses of 3 TeV are superimposed.

model-independent upper limits on the visible $\tau\nu$ production cross section, $\sigma(pp \to \tau\nu + X)\mathcal{A}\varepsilon$, as a function of the m_T threshold, where $\mathcal{A}$ is the fiducial acceptance (including the m_T threshold) and ε is the reconstruction efficiency. Model-specific limits can be derived by evaluating σ, $\mathcal{A}$, and ε for the model in question and checking if the corresponding visible cross section is excluded at any m_T threshold. This allows the results to be reinterpreted for a broad range of models, regardless of their m_T distribution. Good agreement between the generated and reconstructed m_T distributions is found, indicating that a reliable calculation of the m_T threshold acceptance can be made at generator level. The reconstruction efficiency depends on m_T, $\varepsilon(m_T[\mathrm{TeV}]) = 0.633 - 0.313m_T + 0.0688m_T^2 - 0.00575m_T^3$, ranging from 60% at 0.2 TeV to 7% at 5 TeV, and must be appropriately integrated out given the m_T distribution of the model. The relative uncertainty in the parametrized efficiency due to the choice of signal model is ∼10%. With these inputs the visible cross sections for W'_{SSM} and W'_{NU} bosons could be reproduced within 10% using only generator-level information. Data and details to facilitate reinterpretations can be found at Ref. [61].

Limits are also set on benchmark models by selecting the most sensitive m_T threshold for each W' mass hypothesis ($\sim 0.6 m_{W'}$ up to a maximum of 1.45 TeV). The chosen threshold is found to have little dependence on the W' width. Figure 4(a) shows the 95% C.L. upper limit on the cross section times branching fraction as a function of $m_{W'}$ in the SSM. Heavy W'_{SSM} bosons with a mass lower than 3.7 TeV are excluded, with an expected exclusion limit of 3.8 TeV. Figure 4(b) shows the excluded region in the parameter space of the nonuniversal $G(221)$ model. Heavy W'_{NU} bosons with a mass lower than 2.2–3.8 TeV are excluded depending on $\cot\phi_{\mathrm{NU}}$, thereby probing a significantly larger region of parameter space than previous searches [8]. The W'_{NU} limits are typically weaker than the W'_{SSM} limits as the increased W' width yields lower acceptances, while the enhancement in the decay rate cancels with the suppression in the production via first- and second-generation quarks. Limits from the ATLAS ee, $\mu\mu$, and $\tau\tau$ searches [58,62] are

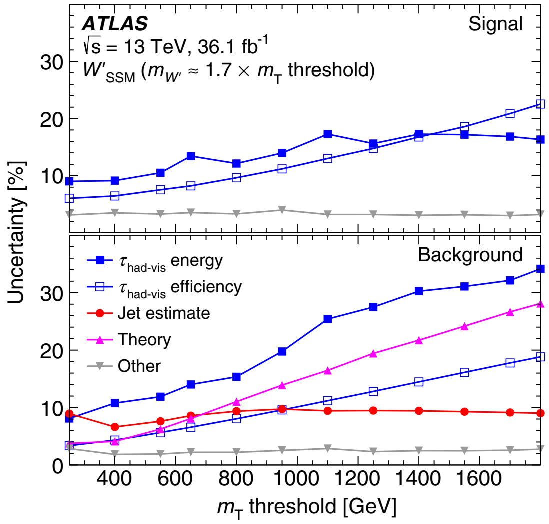


FIG. 2. Dominant relative uncertainties in the expected signal and background contributions as a function of the m_T threshold. For each threshold a W'_{SSM} boson with a mass of approximately 1.7 times the threshold is chosen. *Theory* includes uncertainties in the cross sections used to normalize the simulated samples and uncertainties associated with the modeling provided by the event generators. *Other* is the impact of all other uncertainties added in quadrature.

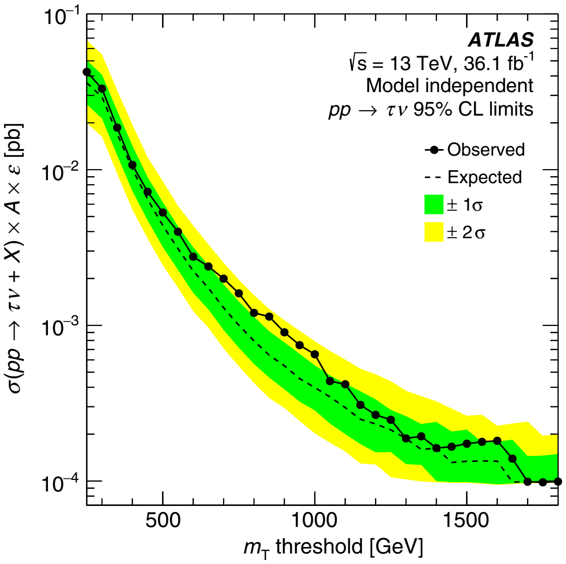
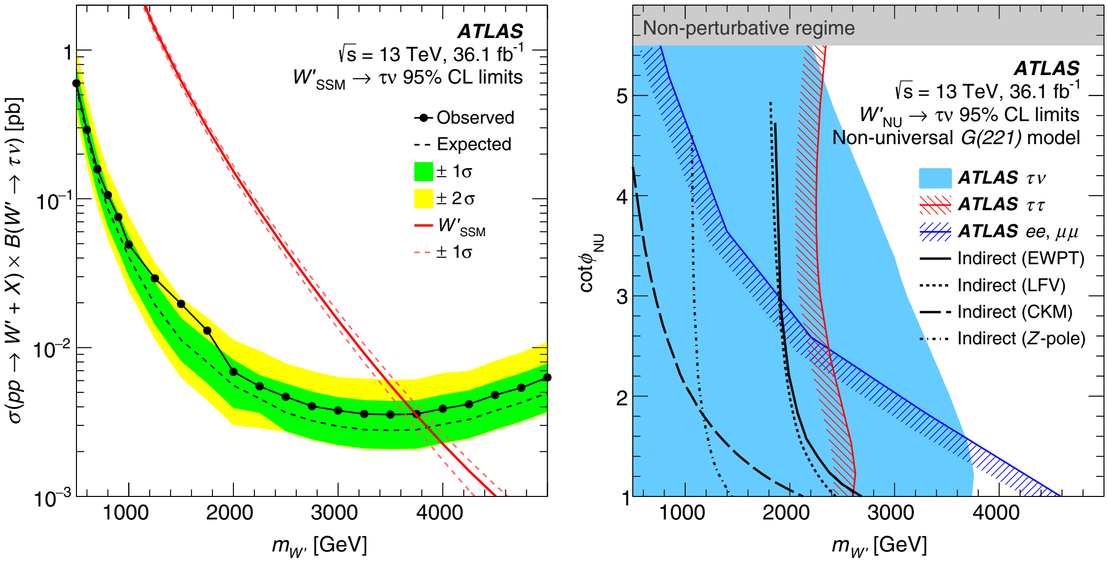


FIG. 3. The 95% C.L. upper limit on the visible $\tau\nu$ production cross section as a function of the m_T threshold.



(a) (b)

FIG. 4. (a) The 95% C.L. upper limit on the cross section times $\tau\nu$ branching fraction for W'_{SSM}. The W'_{SSM} cross section is overlaid where the additional lines represent the total theoretical uncertainty. (b) Excluded region for W'_{NU}. The 95% C.L. limits from the ATLAS ee, $\mu\mu$ [62], and $\tau\tau$ [58] searches and indirect limits at 95% C.L. from fits to electroweak precision measurements (EWPT) [63], lepton flavor violation (LFV) [64], CKM unitarity [65], and the original Z-pole data [2] are overlaid.

also overlaid, showing that the $\tau\nu$ search is complementary and extends the sensitivity over a large fraction of the parameter space. These results suggest that the $\tau\nu$ searches should be considered when placing limits on nonuniversal extended gauge groups, such as those seeking to explain lepton flavor violation in B meson decays.

In summary, a search for $W' \to \tau\nu$ in 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC is presented. The channel where the τ decays hadronically is analyzed and no significant excess over the SM expectation is found. Upper limits are set on the visible cross section for $\tau\nu$ production, allowing interpretation in a broad range of models. Sequential standard model W'_{SSM} bosons with masses less than 3.7 TeV are excluded at 95% C.L., while nonuniversal $G(221)$ W'_{NU} bosons with masses less than 2.2–3.8 TeV are excluded depending on the model parameters.

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