

Sensitivity of W -boson measurements to low-mass right-handed neutrinos

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A low-mass right-handed neutrino could interact with electroweak bosons via mixing, a mediator particle, or loop corrections. Using an effective field theory, we determine constraints on these interactions from W -boson measurements at hadron colliders. Due to the difference in the initial states at the Tevatron and the LHC, W -boson decays to a right-handed neutrino would artificially increase the mass measured at the Tevatron while only affecting the difference between W^+ and W^- mass measurements at the LHC. Measurements from CDF and the LHC are used to infer the corresponding parameter values, which are found to be inconsistent between the two. The LHC experiments can improve sensitivity to these interactions by measuring the cosine of the helicity angle using W bosons produced with transverse momentum above ≈ 50 GeV.

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I. INTRODUCTION

The discovery of the Higgs boson [1,2] completed the observed particle content of the Standard Model (SM), and subsequent measurements [3,4] are consistent with its prediction that all electrically charged particles and the Z boson receive their mass from the vacuum expectation value (v) in the Higgs mechanism [5–7]. However, the source of neutrino mass remains elusive, and there is no evidence that it is due to a Dirac or Majorana term, or both. Introducing a singlet right-handed neutrino ν_R would allow for a Dirac mass term, in which case the new field would provide a new spin state rather than a new particle. The SM neutrinos could instead attain a Majorana mass via the sole dimension-5 operator [8] in the SM effective field theory (SMEFT) [9]. This operator could be generated in the renormalizable seesaw mechanism [8,12–14] by the exchange of a heavy neutrino ($m_N > v$) or a heavy scalar triplet. The presence of a singlet ν_R field can thus accommodate both Majorana and Dirac masses for active neutrinos.

The introduction of ν_R fields need not be tied to active neutrino masses. Thus, in this work, we consider the

existence of ν_R states leading to one or more low-mass neutrinos ($m_N \lesssim 1$ GeV). Such neutrinos could be the source of the observed dark matter in the Universe [15] and could give a rich phenomenology at particle colliders [16–20], particularly if they are associated with other new states at the electroweak scale. We focus on possible new effective interactions of the ν_R states with W bosons, which could be generated by a small mixing of this state with active neutrinos, the exchange of another mediator particle, or loop corrections.

Regardless of its origin, this interaction will produce the phenomenologically relevant decay $W \rightarrow \ell \nu_R$, where ℓ is an electron or muon. This decay would affect measurements of the W boson mass at the Tevatron and LHC, and could be further probed through measurements of angular distributions in the W boson decay.

We determine constraints from existing and potential measurements using a ν_R -augmented SM effective field theory, the ν SMEFT [21], which captures all the aforementioned possibilities for the generation of the interaction. The relevant Lagrangian terms with dimension-6 operators are

$$\begin{aligned} \Delta\mathcal{L} = & \frac{c_{LNH}^i}{\Lambda^2} \bar{L}_i \nu_R \tilde{H} H^\dagger H + \frac{c_{HNe}^i}{\Lambda^2} \bar{\nu}_R \gamma^\mu e_{iR} \tilde{H}^\dagger i D_\mu H \\ & + \frac{c_{NW}^i}{\Lambda^2} \bar{L}_i \sigma^{\mu\nu} \nu_R \sigma_I \tilde{H} W_{\mu\nu}^I + \text{H.c.}, \end{aligned} \quad (1)$$

where c_{LNH}^i , c_{HNe}^i , and c_{NW}^i are effective couplings, $i = e, \mu$, τ , the mass scale of the new particles is Λ , L is the left-handed

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lepton doublet, H is the Higgs doublet, and $\tilde{H} = i\sigma_2 H^*$. Assuming real couplings, a nonzero c_{HNe}^i causes a parity-violating $V + A$ interaction, whereas the other two couplings cause chirality-flipping interactions [22].

Focusing on the $V + A$ interaction, a Dirac neutrino with a mass larger than 1 MeV will decay into an electron, positron, and a neutrino with a lifetime

$$\Gamma = \frac{m_N^5 G_F^2}{192\pi^3} v^4 \frac{\sum_i |c_{HNe}^i|^2}{4\Lambda^4}. \quad (2)$$

while a Majorana neutrino has twice this decay rate due to the CP -conjugate channel.

Perturbative unitarity provides an upper bound on the coupling of order

$$\frac{c_{HNe} E^2}{\Lambda^2} \lesssim 4\pi, \quad (3)$$

which also gives an upper bound on the mass scale at which new states should appear. For consistency, this scale should be greater than v , so the perturbative bound is here taken to be

$$\left| \frac{c_{HNe}}{\Lambda^2} \right| \leq \frac{4\pi}{v^2}. \quad (4)$$

For a value of $c_{HNe}^i/\Lambda^2 = 1/v^2$ and a mass of 100 MeV, the vast majority of neutrinos decay outside the fiducial volume of a typical detector ($\gamma c\tau \approx 100$ m). These decays can thus be collected with a standard W boson selection at a collider. We find that existing W boson measurements have sensitivity to values of c_{HNe}^i as low as $0.1/v^2$ and are valid for neutrino masses up to ≈ 1 GeV. Additional ν SMEFT operators could affect these results by reducing the neutrino lifetime, in particular by allowing $\nu_R \rightarrow \nu\gamma$ decay [25]. Here, we assume the associated Wilson coefficients are small enough for ν_R to dominantly decay outside the detector.

Prior measurements and searches constrain W boson couplings to low-mass right-handed neutrinos. The electron angular distributions in nuclear beta decay constrain couplings to electron neutrinos [26], and those in muon decay additionally constrain couplings to muon neutrinos [27]. The τ -lepton lifetime constrains couplings to all neutrino flavors, and direct searches for GeV-scale neutrinos at ATLAS [28] and CMS [29–32] constrain couplings to electron and muon neutrinos. All constraints are at the few-percent level relative to the coupling to left-handed neutrinos. Upper bounds have also been placed on ν_L - ν_R mixing [23]. Our results rely on a potential $V + A$ interaction in the decay of W bosons and are given in terms of the coupling c_{HNe}^i . We consider scenarios where there is one nonzero coefficient c_{HNe}^i ($i = e$) or $c_{HN\mu}$ ($i = \mu$), or where the electron and muon coefficients are the same value, c_{HNe} .

This paper is structured as follows: Sec. II quantifies the impact of $W \rightarrow \ell \nu_R$ decays on existing and potential

Tevatron and LHC W boson measurements in terms of c_{HNe}^i ; Sec. III discusses ν_L - ν_R mixing and presents the competitive constraints on c_{HNe}^i from pion and muon decay; and Sec. IV summarizes our conclusions.

II. W BOSON MEASUREMENTS

Measurements of the W boson at the Tevatron and LHC [33–40] are performed assuming that its production and decay follow the predictions of the Standard Model. Decays to right-handed neutrinos would affect these measurements, with a different impact at each collider due to differences between up-quark, down-quark, and sea-quark momentum distributions in the proton. We quantify the c_{HNe}^i dependence of existing and potential measurements of the W boson mass (m_W), cross section, and cosine of the helicity angle in the W boson decay [41].

A. CDF m_W measurement

The CDF measurement of the W boson mass [38] was performed using template fits to distributions of final-state kinematic quantities projected transverse to the beamline. The templates were produced at different values of m_W , assuming SM production and decay. The measured mass is 76 MeV higher than the SM prediction, a difference that cannot be explained currently [43–50].

W boson decays to right-handed neutrinos would artificially increase the measured value of m_W at the Tevatron due to the effects of parton momentum distributions, lepton decay angles, and detector acceptance. On average, the valence up quark in the proton has a higher momentum than the valence down quark. This leads to an average momentum along the proton direction for W^+ bosons, and vice versa for W^- bosons (see Fig. 1). For $V - A$ ($V + A$) decays, the direction of the charged lepton is along (opposite to) that of the W^+ boson. Consequently, the charged lepton has a lower average $|p_z|$ for the SM decay than for the decay to ν_R .

The lepton p_z distribution affects the measured m_W through detector acceptance. The CDF measurement used charged leptons with absolute pseudorapidity ($|\eta|$) less than 1. Increasing p_z increases the fraction of accepted leptons that decay perpendicular to the beamline. These decays correspond to the peak transverse momentum. The resulting p_T and m_T distributions, shown in Fig. 2, lead to a larger measured m_W if one assumes SM decay.

To determine the bias in m_W as a function of c_{HNe}/Λ^2 , we separately generate leading-order $W \rightarrow e \nu_L$ SM decays and $W \rightarrow e \nu_R$ decays with $c_{HNe} = 1$ and $\Lambda = v$, for $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions using the MADGRAPH5_AMC@NLO generator [51]. We apply the CDF event selection and model the detector effects by approximately reproducing the measured kinematic distributions. The inclusion of higher orders and an improved detector modeling would affect the details of these distributions, but would not

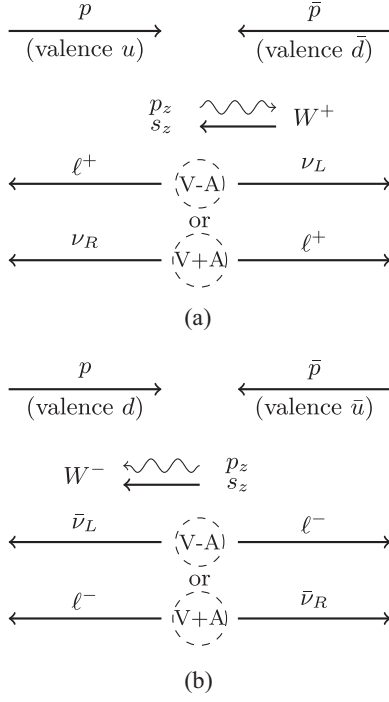


FIG. 1. The production and decay of $W^\pm$ bosons at the Tevatron for the final state containing either ν_L or ν_R . On average the $W^\pm$ boson p_z is in the direction of the interacting (anti) u quark, since $\langle p_z^u \rangle > \langle p_z^d \rangle$. Due to the $V - A$ interaction, the initial spin is along the antiproton direction, so the left-handed neutrino is produced in the direction of the W boson. In the case of ν_R , the W -boson interaction with the charged lepton is $V + A$, so the direction is reversed. (a) W^+ production and decay at the Tevatron. (b) W^- production and decay at the Tevatron.

significantly affect the difference between SM decays and decays to $\ell\nu_R$.

We estimate the measured m_W bias from a nonzero c_{HNe} using a template fit to the m_T distribution (Fig. 2), where the simulated data contain the sum of SM decays and decays to ν_R , and the template contains SM decays only. The total yields of the simulated data and the templates are normalized to the number of events observed by CDF. The m_W bias is determined as a function of the signal strength μ , defined as $N_{\text{sig}} = \mu N_{\text{gen}}$, where N_{sig} is the number of signal events in the simulated data and N_{gen} is the number of events for the generated parameter values $c_{HNe} = 1$ and $\Lambda = v$. The measured m_W value corresponds to $|c_{HNe\ell}|v^2/\Lambda^2 = 1.2 \pm 0.1$, near the perturbativity limit for a new-physics scale equal to the vacuum expectation value.

A caveat to our estimated bias on m_W is the impact a nonzero $c_{HNe\ell}$ value would have on the charge asymmetry of the W boson cross section as a function of W boson rapidity. Tevatron charge asymmetry measurements [52–54] are used

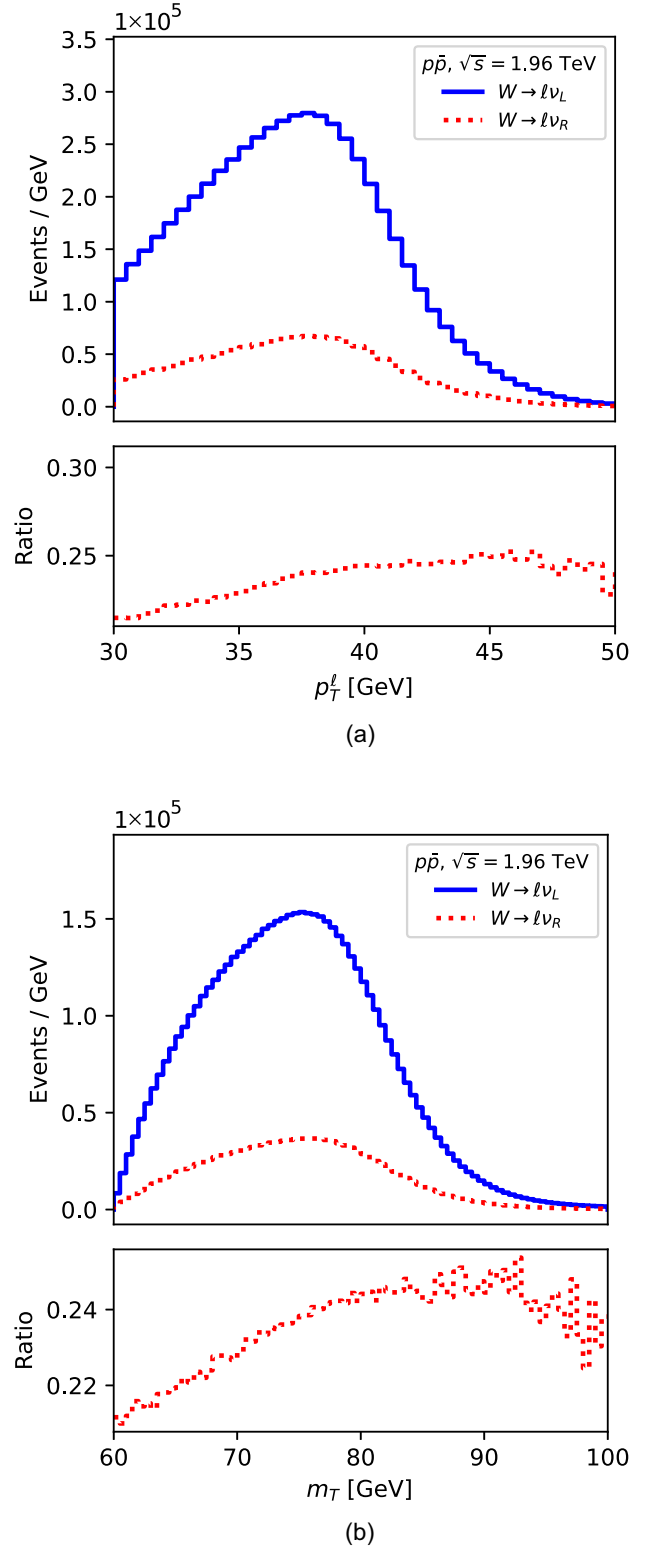


FIG. 2. The lepton p_T (a) and m_T (b) distributions for SM production and decay of the W boson ($W \rightarrow \ell\nu_L$) at CDF, and for the W boson decaying to a right-handed neutrino ($W \rightarrow \ell\nu_R$) with effective coupling $c_{HNe}/\Lambda^2 = 1/v^2$.

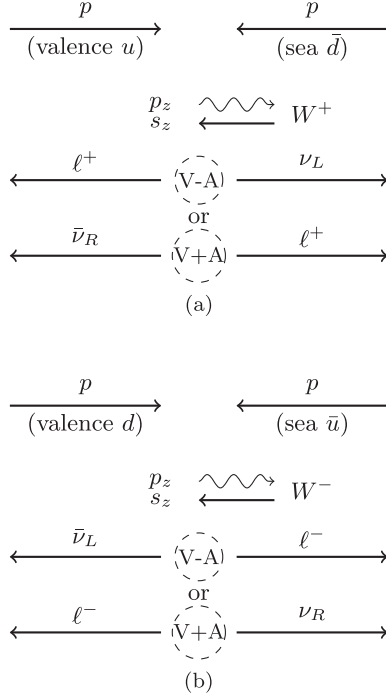


FIG. 3. The production and decay of $W^\pm$ bosons at the LHC for the final state containing either ν_L or ν_R . The $W^\pm$ boson momentum projected along the z -axis is in the direction of the proton contributing a valence quark. The decay to ν_L is V-A, so the ν_L direction is opposite to that of the W^+ boson. In the case of ν_R , the decay is V + A, and the direction is reversed. (a) W^+ production and decay at the LHC. (b) W^- production and decay at the LHC.

in fits for parton distribution functions, and these fits would be affected by a nonzero $c_{HN\ell}$. To estimate the impact on the m_W bias, we reweight the u/d ratio in the generated events such that the charge asymmetry is unchanged for the SM distribution. The reweighting suppresses the m_W bias by about 30%, so one would have to divide the estimated μ value by about 0.7 to account for this effect. In practice, the charge asymmetry measurements are just one component of a global PDF fit, and the obtained μ value is inconsistent with those derived from ATLAS and CMS below, so we do not attempt to refine our μ estimate.

B. ATLAS and CMS m_W measurements

The m_W measurements with the ATLAS [35,36] and CMS [34] experiments are sensitive to the $W \rightarrow \ell \nu_R$ decay dominantly through the difference between the W^+ and W^- boson mass measurements. W bosons tend to be produced with p_z in the direction of the interacting valence quark, so W^- bosons are generally produced at the LHC in the direction of the d valence quark, rather than the $\bar{u}$ quark at

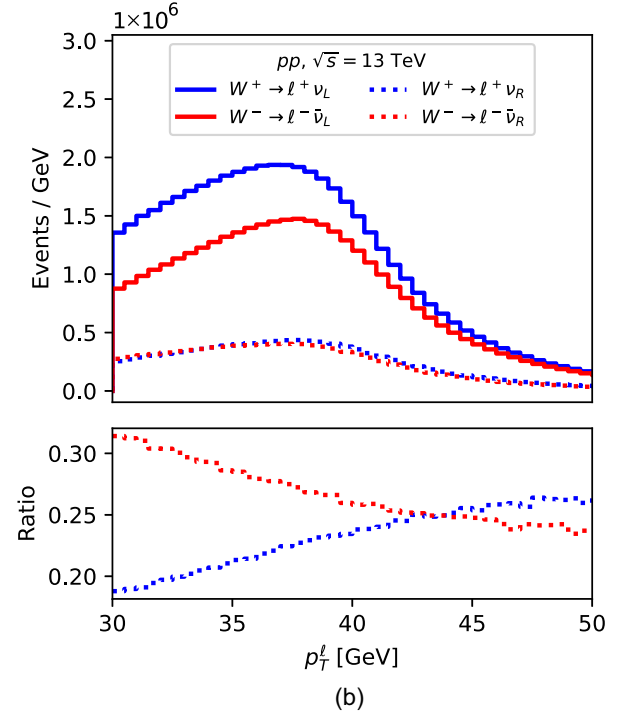
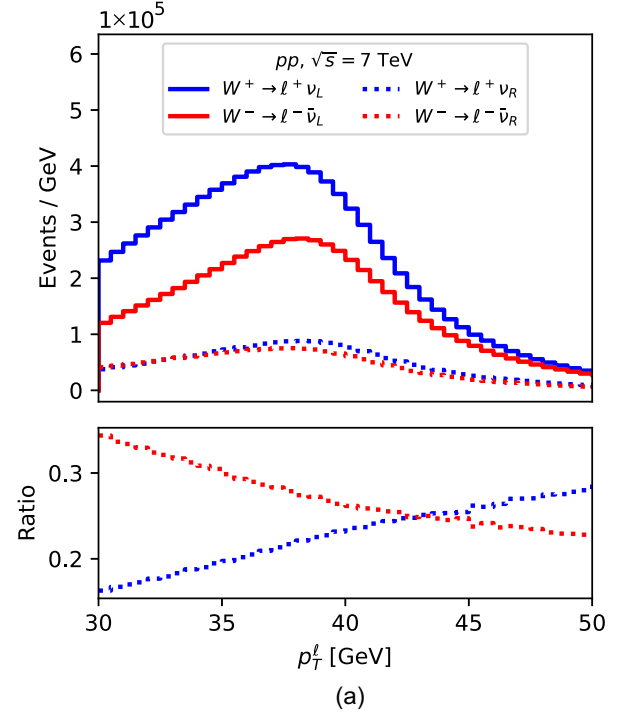


FIG. 4. The lepton p_T distribution for SM production and decay of the W^+ and W^- bosons to a given lepton ($W^\pm \rightarrow \ell \nu_L$) at the LHC with a center-of-mass energy of (a) 7 TeV or (b) 13 TeV, and for the corresponding decays to a right-handed neutrino ($W^\pm \rightarrow \ell \nu_R$) with effective coupling $c_{HN\ell}/\Lambda^2 = 1/v^2$.

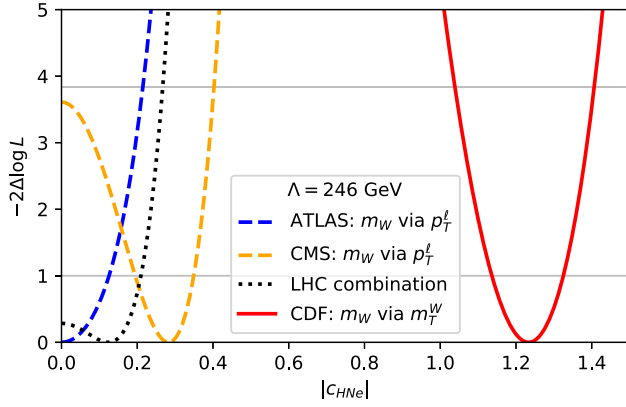


FIG. 5. The negative log likelihood as a function of $|c_{HNe}|$ inferred from the CDF m_W measurement and the ATLAS and CMS $m_{W^+} - m_{W^-}$ measurements. Also shown is the likelihood from a combination of the LHC measurements, neglecting correlations.

the Tevatron. This is represented pictorially in Fig. 3, and the impact on the p_T^ℓ distribution is shown in Fig. 4.

The measurement biases at ATLAS and CMS are evaluated in the same way as for CDF, i.e., by applying momentum resolution functions to generated $W \rightarrow \ell \nu_L$ and $W \rightarrow \ell \nu_R$ decays at the appropriate center-of-mass energy, and performing a fit to the p_T^ℓ distribution for the W^+ and W^- boson masses as a function of c_{HNe}/Λ^2 . The results are compared to the measured mass differences, $m_{W^+} - m_{W^-} = -29.2 \pm 28.0$ and 57.0 ± 30.3 MeV from ATLAS and CMS, respectively. The corresponding best-fit values for $|c_{HNe}|$ are $0_{-0}^{+0.13}$ and 0.28 ± 0.09 for $\Lambda = v$. The mass differences at ATLAS and CMS have only a small correlation through the subleading PDF uncertainty. Neglecting this correlation gives a combined value of $|c_{HNe}|v^2/\Lambda^2 = 0.12_{-0.12}^{+0.15}$, or a 95% confidence-level interval of $[0, 0.27]$. For $\Lambda = 1$ TeV the value is $|c_{HNe}| = 2_{-2}^{+2.5}$. These values are incompatible with those obtained from the CDF m_W result, as shown in Fig. 5.

The CMS W boson mass measurement constrains PDF uncertainties *in situ* using the total event yields of $W^+ \rightarrow \mu^+ \nu_L$ and $W^- \rightarrow \mu^- \bar{\nu}_L$. These event yields would also be affected by the presence of $W \rightarrow \mu^- \nu_R$ decays due to the different acceptances of these decays. To understand the sensitivity of the event yield to c_{HNe}/Λ^2 , we use the ATLAS W boson cross section measurements at 7 TeV to fit for c_{HNe}/Λ^2 , and find an uncertainty of ≈ 0.2 on c_{HNe} for $\Lambda = v$. This is approximately twice the uncertainty obtained from $m_{W^+} - m_{W^-}$, so we expect the *in situ* PDF constraint to not significantly affect the extracted constraint on $c_{HNe}^2 v^4/\Lambda^4$.

C. W boson angular measurement

The most directly sensitive observable to $V + A$ decay is the lepton decay angle in the W boson rest frame, θ^* .

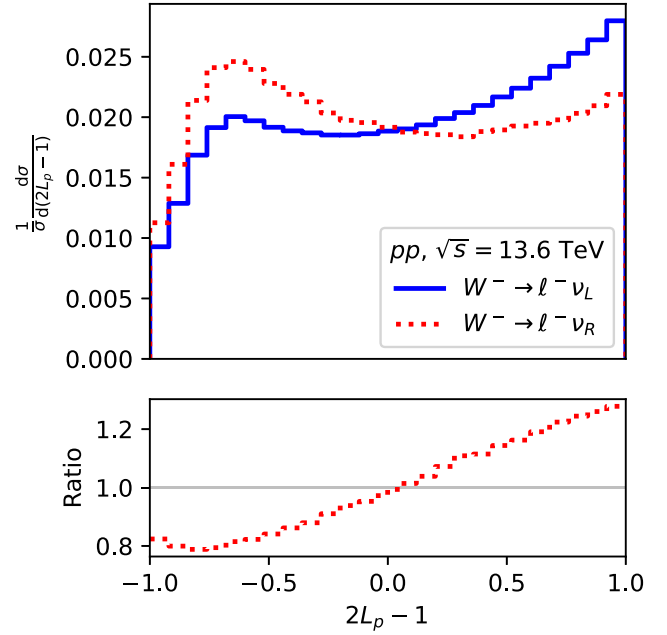


FIG. 6. The $2L_p - 1$ distribution for SM production and decay of the W^- boson to a given lepton ($W^- \rightarrow \ell^- \nu_L$) at the LHC with a center-of-mass energy of 13.6 TeV, and for the corresponding decay to a right-handed neutrino ($W^- \rightarrow \ell^- \nu_R$). The W^+ distributions are the same when plotted as a function of $-(2L_p - 1)$.

Because of the unobserved neutrino, this angle can only be determined up to a two-fold ambiguity, and the resulting distribution is symmetric for $V - A$ and $V + A$ decay. However, the ambiguity can be partially resolved if one considers W bosons boosted in the transverse plane [55,56]. At high p_T^W , the projection of the lepton onto the W boson in the transverse plane [55],

$$L_p \equiv \frac{\vec{p}_T^\ell \cdot \vec{p}_T^W}{|p_T^W|^2}, \quad (5)$$

allows θ^* to be approximated by $\cos \theta^* \approx 2L_p - 1$. Projection variables have been used to measure the helicity fractions of the W -boson, and can alternatively be used to constrain $V + A$ interactions in its decay directly.

Figure 6 shows the $2L_p - 1$ distribution for W^- bosons decaying to left-handed or right-handed neutrinos for events with $p_T^W > 50$ GeV, lepton $p_T > 25$ GeV, and $m_T > 50$ GeV. Given the good discrimination between the two cases, we estimate the expected ν_R sensitivity of a $2L_p - 1$ measurement of $W^\pm$ decays in the Run 3 data (300 fb $^{-1}$ of integrated luminosity at $\sqrt{s} = 13.6$ TeV). In this dataset, the statistical uncertainty will be below the percent level in the discriminating region of $2L_p - 1$. We thus expect systematic uncertainties to be relevant and do not project to the larger HL-LHC dataset.

Assuming equal contributions of statistical and systematic uncertainties, the expected 95% CL constraint from

Run 3 data is $|c_{HNe}| < 0.08$ (and the same for $|c_{HN\mu}|$). These constraints are tighter than those from existing measurements of $m_{W^+} - m_{W^-}$, though future measurements of the mass difference should give competitive sensitivity.

III. OTHER CONSTRAINTS

A nonzero c_{HNe} would impact various other phenomena, of which we explicitly consider pion decay, nuclear beta decay, and muon decay [57]. To compare limits arising from these measurements, we determine the effective mixing caused by c_{HNe} between the active neutrinos and a fourth singlet neutrino. The leptonic W -boson couplings are

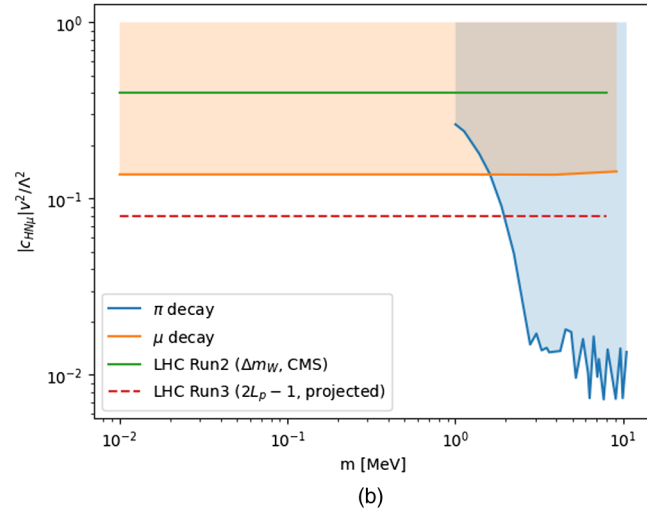
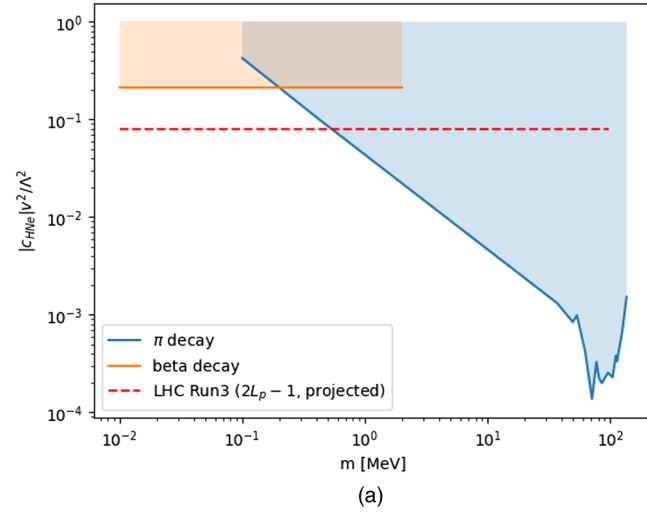


FIG. 7. 95% CL bounds on the probed Wilson coefficient from low-energy probes and from present and possible collider measurements. (a) Constraint on $|c_{HNe}|$ from nuclear β decay (orange) and $\pi \rightarrow e\nu$ (blue). (b) Constraint on $|c_{HN\mu}|$ from muon (orange) and pion (blue) decays, and from the CMS measurement of $\Delta m_W \equiv m_{W^+} - m_{W^-}$ (green). In both panels, the projected LHC Run 3 constraints from lepton angular measurements are shown as red dashed lines.

$$\mathcal{L}_{CC}^\ell = -\frac{g}{\sqrt{2}} W_\mu^- \left(\bar{\nu}_L^i \gamma_\mu e_L^i + \frac{c_{HNe}^i v^2}{2\Lambda^2} \bar{\nu}_R \gamma_\mu e_R^i \right) + \text{H.c.}, \quad (6)$$

which when taken as the couplings of an array of four neutrinos with three charged leptons gives a mixing of

$$U_{i4} = \frac{c_{HNe}^i v^2}{2\Lambda^2}. \quad (7)$$

Using this relation, Ref. [24] translated various mixing bounds to bounds on c_{HNe}^i . From their analysis, we conclude that various other experimental constraints are stronger than the bounds from W -boson measurements for neutrino masses higher than a few MeV.

For the c_{HNe} coupling, the strongest bound transitions from $\pi \rightarrow \nu + e$ searches [59] interpreted as constraints on U_{e4} [23] to nuclear β decays [26] near a neutrino mass of 0.2 MeV. In the notation of Ref. [26], $\tilde{\epsilon}_L = c_{HNe} v^2 / 2\Lambda^2$ and the β decay constraints extend to masses up to typical nuclear reaction energies of a few MeV.

Correspondingly, the strongest bound on the $c_{HN\mu}$ coupling transitions from the pion decay $\pi^+ \rightarrow \mu^+ + \nu_R$ [60] to the muon decay $\mu^- \rightarrow \nu_R + \bar{\nu} + e^-$ [24] for neutrino masses around 2 MeV.

These constraints are summarized in Fig. 7. Current constraints from W -boson mass measurements are not competitive due to the 2σ difference between m_{W^+} and m_{W^-} observed by CMS, for which a $c_{HN\mu}$ coupling interpretation is excluded by muon decay measurements.

Future measurements should become more competitive, particularly if the mass difference is provided separately for each decay channel. A measurement of the lepton decay angle in Run 3 of the LHC would improve on the constraints from muon decay by about a factor of two for right-handed neutrino masses below a couple of MeV.

IV. CONCLUSIONS

We have investigated the collider phenomenology of a right-handed neutrino that has a mass below a GeV and interacts with the Standard Model through the dimension-six operator $\frac{c_{HNe}}{\Lambda^2} \bar{\nu}_R \gamma^\mu e_R \tilde{H}^\dagger i D_\mu H$. This interaction induces a parity-violating $V + A$ component in $W \rightarrow \ell \nu$ decays, modifying both the kinematic distributions and the precision observables associated with the W boson. Working within the framework of the ν SMEFT, we provided a quantitative analysis of the impact of such interactions on current and future collider measurements.

Revisiting the CDF Run II analysis showed that the presence of a $W \rightarrow \ell \nu_R$ decay would shift the fitted W -boson mass upward by +76 MeV for a Wilson coefficient near the perturbative bound, $c_{HNe} v^2 / \Lambda^2 \simeq 1.2$. Such a coefficient would also induce differences between measurements of m_{W^+} and m_{W^-} at ATLAS and CMS. No such deviations are observed, and a 95% CL bound of

$|c_{HNe}|v^2/\Lambda^2 < 0.27$ is inferred, thereby excluding this interpretation of the CDF measurement.

We have proposed a probe of the ν SMEFT using an angular observable based on the projection variable $2L_p - 1 \approx \cos\theta^*$, evaluated in the boosted regime where $p_T^W > 50$ GeV. The reversed angular correlation induced by the $V + A$ interaction relative to the Standard Model provides strong sensitivity to the model. With the Run 3 dataset at $\sqrt{s} = 13.6$ TeV and an integrated luminosity of 300 fb^{-1} , we find an expected limit of $c_{HNe}^i v^2/\Lambda^2 < 0.08$.

These bounds are competitive with those derived from low-energy probes such as nuclear β decay, Michel parameters in muon decay, and pion decay. Importantly, for right-handed neutrino masses below a few MeV, future W -boson measurements can have dominant sensitivity.

We have also assessed the potential impact on parton distribution functions, in particular through modifications to the W -charge asymmetry data used in PDF extractions. Our analysis indicates that the inclusion of the $V + A$ component introduces only a modest shift in the relevant charge asymmetries relative to the shift in m_W .

Looking forward, extending the angular analysis to the full HL-LHC dataset with 3 ab^{-1} could further improve sensitivity. Additional gains could be achieved by moving

to a higher p_T^W regime and by constraining systematic uncertainties with a profile likelihood fit.

In summary, the right-handed neutrino interpretation of the CDF W -mass measurement is ruled out by existing LHC measurements. Measurements of the lepton decay angle could sharpen the constraints significantly in the near future. Together, our results outline a strategy for testing $V + A$ interactions arising from light sterile neutrinos through W -boson measurements at current and future hadron colliders.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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- [1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* **716**, 1 (2012).
 - [2] CMS Collaboration, A new boson with a mass of 125 GeV observed with the CMS experiment at the Large Hadron Collider, *Science* **338**, 1569 (2012).
 - [3] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, *Nature (London)* **607**, 60 (2022).
 - [4] ATLAS Collaboration, Characterising the Higgs boson with ATLAS data from Run 2 of the LHC, *Phys. Rep.* **11**, 001 (2024).
 - [5] F. Englert and R. Brout, Broken symmetry and the mass of gauge vector mesons, *Phys. Rev. Lett.* **13**, 321 (1964).
 - [6] P. W. Higgs, Broken symmetries and the masses of gauge bosons, *Phys. Rev. Lett.* **13**, 508 (1964).
 - [7] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global conservation laws and massless particles, *Phys. Rev. Lett.* **13**, 585 (1964).
 - [8] R. N. Mohapatra and G. Senjanović, Neutrino mass and spontaneous parity nonconservation, *Phys. Rev. Lett.* **44**, 912 (1980).
 - [9] See [10,11] for reviews of the SMEFT.
 - [10] I. Brivio and M. Trott, The standard model as an effective field theory, *Phys. Rep.* **793**, 1–98 (2019).
 - [11] G. Isidori, F. Wilsch, and D. Wyler, The standard model effective field theory at work, *Rev. Mod. Phys.* **96**, 015006 (2024).
 - [12] P. Minkowski, $\mu \rightarrow e\gamma$ at a rate of one out of 109 muon decays?, *Phys. Lett.* **67B**, 421 (1977).
 - [13] T. Yanagida, Horizontal gauge symmetry and masses of neutrinos, *Conf. Proc. C* **7902131**, 95 (1979).
 - [14] M. Gell-Mann, P. Ramond, and R. Slansky, Complex spinors and unified theories, *Conf. Proc. C* **790927**, 315 (1979).
 - [15] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, and O. Ruchayskiy, Sterile neutrino dark matter, *Prog. Part. Nucl. Phys.* **104**, 1 (2019).
 - [16] J. Alcaide, S. Banerjee, M. Chala, and A. Titov, Probes of the standard model effective field theory extended with a right-handed neutrino, *J. High Energy Phys.* **08** (2019) 031.
 - [17] J. M. Butterworth, M. Chala, C. Englert, M. Spannowsky, and A. Titov, Higgs phenomenology as a probe of sterile neutrinos, *Phys. Rev. D* **100**, 115019 (2019).
 - [18] R. Beltrán, G. Cottin, J. Günther, M. Hirsch, A. Titov, and Z. S. Wang, Heavy neutral leptons and top quarks in effective field theory, *J. High Energy Phys.* **05** (2025) 238.
 - [19] M. Mitra, S. Mandal, R. Padhan, A. Sarkar, and M. Spannowsky, Reexamining right-handed neutrino EFTs up to dimension six, *Phys. Rev. D* **106**, 113008 (2022).

- [20] M. Mitra, S. Saha, M. Spannowsky, and M. Takeuchi, Probing right-handed neutrinos via trilepton signals at the HL-LHC, *Phys. Rev. D* **111**, 015005 (2025).
- [21] F. del Águila, S. Bar-Shalom, A. Soni, and J. Wudka, Heavy majorana neutrinos in the effective lagrangian description: Application to hadron colliders, *Phys. Lett. B* **670**, 399 (2009).
- [22] A renormalizable Yukawa term $Y^i \bar{L}_i \nu_R \tilde{H}$ (as well as the operator with coefficient c_{LNH}^i) generates neutrino mixing and produces the opposite-chirality interactions that we do not consider in our phenomenological study. This mixing is constrained to be small ($Yv/m_N \ll 1$), see, e.g., [23,24]. The c_{NW}^i term is loop-generated in weakly coupled renormalizable UV completions, and is thus small in general.
- [23] D. A. Bryman and R. Shrock, Constraints on sterile neutrinos in the MeV to GeV mass range, *Phys. Rev. D* **100**, 073011 (2019).
- [24] E. Fernández-Martínez, M. González-López, J. Hernández-García, M. Hostert, and J. López-Pavón, Effective portals to heavy neutral leptons, *J. High Energy Phys.* **09** (2023) 001.
- [25] L. Duarte, J. Peressutti, and O. A. Sampayo, Majorana neutrino decay in an effective approach, *Phys. Rev. D* **92**, 093002 (2015).
- [26] A. Falkowski, M. González-Alonso, and O. Naviliat-Cuncic, Comprehensive analysis of beta decays within and beyond the standard model, *J. High Energy Phys.* **04** (2020) 126.
- [27] W. Fetscher, Muon decay, *SciPost Phys. Proc.* **5**, 006 (2021).
- [28] G. Aad *et al.* (ATLAS Collaboration), Search for heavy neutral leptons in decays of W bosons using leptonic and semileptonic displaced vertices in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, *J. High Energy Phys.* **07** (2025) 196.
- [29] A. Tumasyan *et al.* (CMS Collaboration), Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2022) 081.
- [30] H. Kanda, M. Sato, Y.-k. Suzuki, T. Takayanagi, and Z. Wei, Search for long-lived heavy neutral leptons with lepton flavour conserving or violating decays to a jet and a charged lepton, *J. High Energy Phys.* **03** (2023) 105.
- [31] H. Minakata, Search for long-lived heavy neutral leptons in proton-proton collision events with a lepton-jet pair associated with a secondary vertex at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **02** (2024) 036.
- [32] A. Hayrapetyan *et al.* (CMS Collaboration), Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV at the CMS experiment, *Phys. Rep.* **1115**, 570 (2025).
- [33] S. Amoroso *et al.* (LHC-TeV MW Working Group), Compatibility and combination of world W -boson mass measurements, *Eur. Phys. J. C* **84**, 451 (2024).
- [34] V. Chekhovsky *et al.* (CMS Collaboration), High-precision measurement of the W boson mass with the CMS experiment at the LHC, [arXiv:2412.13872](https://arxiv.org/abs/2412.13872).
- [35] G. Aad *et al.* (ATLAS Collaboration), Measurement of the W -boson mass and width with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV, *Eur. Phys. J. C* **84**, 1309 (2024).
- [36] M. Aaboud *et al.* (ATLAS Collaboration), Measurement of the W -boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *Eur. Phys. J. C* **78**, 110 (2018); **78**, 898(E) (2018).
- [37] M. Levi, S. Mougiakakos, and M. Vieira, Measurement of the W boson mass, *J. High Energy Phys.* **01** (2021) 036.
- [38] T. Aaltonen *et al.* (CDF Collaboration), High-precision measurement of the W boson mass with the CDF II detector, *Science* **376**, 170 (2022).
- [39] V. M. Abazov *et al.* (D0 Collaboration), Measurement of the W boson mass with the D0 detector, *Phys. Rev. D* **89**, 012005 (2014).
- [40] V. M. Abazov *et al.* (D0 Collaboration), Measurement of the W boson mass, *Phys. Rev. Lett.* **103**, 141801 (2009).
- [41] The W boson width is also affected by c_{HNe}^i , however its current value of 2014 ± 50 MeV [42] corresponds to a 95% confidence-level constraint of $c_{HNe}^i < 1.6$ for $\Lambda = v$ [17]. This is significantly weaker than the constraints we consider. Interpreting the recent ATLAS width measurement [35] in terms of c_{HNe}^i would give $c_{HNe}^i = 1.4 \pm 0.6$, in agreement with the value we obtain from the CDF m_W measurement but in tension with that obtained from LHC measurements of $m_{W^+} - m_{W^-}$.
- [42] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [43] S. Biswas, V. P. K., and A. Thapa, Connecting pseudo-Nambu-Goldstone dark matter with pseudo-Dirac neutrinos in a left-right symmetry model, *Phys. Rev. D* **111**, 075007 (2025).
- [44] K. Agashe, S. Airen, R. Franceschini, D. Kim, A. V. Kotwal, L. Ricci, and D. Sathyan, “Unification” of BSM searches and SM measurements: The case of lepton + E_T and m_W , *J. High Energy Phys.* **02** (2024) 139.
- [45] R. Alonso, D. Dimakou, and M. West, Fractional-charge hadrons and leptons to tell the standard model group apart, *Phys. Lett. B* **863**, 139354 (2025).
- [46] A. de Giorgi, F. Koutroulis, L. Merlo, and S. Pokorski, Flavour and Higgs physics in Z2-symmetric 2HD models near the decoupling limit, *Nucl. Phys. B* **994**, 116323 (2023).
- [47] A. Giannetti, J. Herrero-Garcia, S. Marciano, D. Meloni, and D. Vatsyayan, Neutrino masses from new Weinberg-like operators: Phenomenology of TeV scalar multiplets, *J. High Energy Phys.* **05** (2023) 055.
- [48] T. A. Chowdhury, K. Ezzat, S. Khalil, E. Ma, and D. Nanda, Higgs quadruplet impact on W mass shift, dark matter, and LHC signatures, *Phys. Rev. D* **109**, 075039 (2024).
- [49] A. Ahriche, M. L. Bellilet, M. O. Khojali, M. Kumar, and A.-T. Mulaudzi, Scale invariant scotogenic model: CDF-II W -boson mass and the 95 GeV excesses, *Phys. Rev. D* **110**, 015025 (2024).
- [50] K. Agashe, S. Airen, R. Franceschini, D. Kim, A. V. Kotwal, L. Ricci, and D. Sathyan, A new purpose for the W -boson mass measurement: Searching for new physics in lepton + MET, *Phys. Lett. B* **855**, 138774 (2024).
- [51] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading

- order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [52] V. M. Abazov *et al.* (D0 Collaboration), Measurement of the electron charge asymmetry in $p\bar{p} \rightarrow W + X \rightarrow e\nu + X$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. D* **91**, 032007 (2015); **91**, 079901(E) (2015).
- [53] V. M. Abazov *et al.* (D0 Collaboration), Measurement of the muon charge asymmetry in $p\bar{p} \rightarrow W + X \rightarrow \mu\nu + X$ events at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. D* **88**, 091102 (2013).
- [54] T. Aaltonen *et al.* (CDF Collaboration), Direct measurement of the W production charge asymmetry in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **102**, 181801 (2009).
- [55] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the polarization of W bosons with large transverse momenta in $W + \text{jets}$ events at the LHC, *Phys. Rev. Lett.* **107**, 021802 (2011).
- [56] G. Aad *et al.* (ATLAS Collaboration), Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment, *Eur. Phys. J. C* **72**, 2001 (2012).
- [57] We only discuss the most constraining measurements in the mass range 0.1–100 MeV. We have also investigated the constraint arising from $e^+e^- \rightarrow W^+W^-$ production at LEP [58], and find it to be weaker than the others ($|c_{HN\ell}| < 0.51$).
- [58] S. Schael *et al.* (ALEPH, DELPHI, L3, OPAL, LEP Electroweak Collaborations), Electroweak measurements in electron-positron collisions at W -boson-pair energies at LEP, *Phys. Rep.* **532**, 119 (2013).
- [59] A. Aguilar-Arevalo *et al.* (PIENU Collaboration), Improved measurement of the $\pi \rightarrow e\nu$ branching ratio, *Phys. Rev. Lett.* **115**, 071801 (2015).
- [60] M. Daum, P.-R. Kettle, B. Jost, R. M. Marshall, R. C. Minehart, W. A. Stephens, and K. O. H. Ziock, Search for admixtures of massive neutrinos in the decay $\pi^+ \rightarrow \mu^+ + \nu$, *Phys. Rev. D* **36**, 2624 (1987).