Safe Jet Vetoes

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Central jet vetoes are powerful tools for reducing QCD background in measurements and searches for electroweak and colorless new physics processes in hadron collisions. In this letter, we report the key findings of investigating the theoretical and phenomenological consequences of setting the jet veto scale to the transverse momentum of the leading charged lepton $\ell$ on an event-by-event basis in multi-lepton processes. We consider the case of a TeV-scale heavy neutrino $N$ decaying to the trilepton final state and find the following: (i) Perturbative uncertainties associated with the veto greatly reduce due to tying the veto scale to the hard process scale. (ii) The signal efficiency for passing the veto jumps to $\gtrsim 95\%$ and exhibits little-to-no dependence on the neutrino mass scale. (iii) Background rejection capabilities also improve when compared to vetoing only heavy flavor-tagged jets. This results in an increased sensitivity to active-sterile neutrino mixing by approximately an order of magnitude over the LHC’s lifetime. Due to the color structures of the heavy $N$ production mechanisms considered, we argue that our results hold broadly for other color-singlet processes.

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I. INTRODUCTION

Jet vetoes, i.e., the rejection of events with jets above a transverse momentum threshold ($p_T^{\ell\text{Veto}}$), are incredibly powerful tools for reducing QCD backgrounds in measurements and searches for electroweak (EW) and colorless new physics processes at hadron colliders. In conjunction with heavy quark flavor-tagging, jet vetoes are among the most widely used techniques by experiments at the Large Hadron Collider (LHC).

Theoretically, however, jet vetoes are, simply put, complicated. Foremost, known proofs of the Collinear Factorization Theorem [1–4], i.e., the master equation for computing hadronic scattering rates, do not hold in the presence of a veto; see Refs. [2–5] and references therein. In addition, for color-singlet processes occurring at a mass scale $Q$, vetoes give rise to logarithmic dependences on $p_T^{\ell\text{Veto}}$ of the form $\alpha_s(p_T^{\ell\text{Veto}}) \log(Q^2/p_T^{\ell\text{Veto}})$. While usually perturbative in practice, such contributions and uncertainties are sufficiently large that high-accuracy resummation, either analytically [6–8] or by parton showers means [9], is necessary to reproduce EW data. Moreover, the effectiveness of vetoes in searches for new high-mass particles is considerably hindered by the predisposition of higher mass objects to generate QCD radiation.

In this letter, we report on a particular jet veto implementation, which we describe as a “safe jet veto,” that addresses the latter two concerns. Specifically, for final states with multiple charged leptons, $pp \to n\ell + X$, $\ell \in \{e, \mu, \tau\}$, we set on an event-by-event basis the value of $p_T^{\ell\text{Veto}}$ to be the $p_T$ of the leading (highest-$p_T$) charged lepton. Dynamical jet vetoes, such as the one we propose, have been considered previously in the context of SM diboson production [10]. Here, we demonstrate that they can be successfully used in a much broader class of experimental searches, including searches for new, high-mass colorless particles as well as events with $\tau$ leptons decaying hadronically, and find impressive improvement over traditional, fixed-$p_T$ jet vetoes.

We report three general key findings: (i) Perturbative QCD uncertainties associated with the veto greatly reduce due to tying the veto scale to the hard process scale, i.e., by effectively converting a two-scale problem into a one-scale problem. (ii) The signal efficiency for passing the dynamical veto is very high and exhibits little-to-no dependence on the signal mass scale, unlike with static vetoes, where efficiency drops with increasing mass scale. (iii) Background rejection capabilities also improve.

To illustrate these results, we have investigated the production in proton collisions of a hypothetical, heavy colorless particle, namely a heavy neutrino $(N)$, that decays to the trilepton final state, $pp \to \ell_N N \to \ell_N \ell_W W \to \ell_N \ell_W \ell_{e\nu}$, as shown in Fig. 1. Due to the color structure of the heavy neutrino production mechanisms considered, this case study is broadly representative of many new physics scenarios.

This letter continues in the following manner: We first briefly summarize the relevant ingredients of our heavy neutrino model in Sec. II and computational inputs in Sec. III. We define and discuss our signal processes in Sec. IV. In Sec. V, we discuss how the proposed veto scheme impacts differently the signal and backgrounds processes, which leads to our findings (i)-(iii). The impact of the veto on searches for heavy neutrinos at the LHC, as well as a brief outlook, are then presented in Sec. VI. Finally, we conclude in Sec. VII. For a more extensive collection of results, we refer readers to Ref. [12].

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The above should be understood as applying to the left-handed components of spinors. For TeV-scale heavy $N$, global fits to precision EW precision and low-energy observables, such as tests of lepton universality and CKM unitarity, constrain $|V_{t4}| \lesssim 0.021 - 0.075$ [17, 18] at 2$s$. After EWSB and in the mixed basis at first order in $V_{t4}$, the relevant couplings of $N$ to SM fields are given by $^1$

$$\mathcal{L}_{\text{Int.}} = - \frac{g}{\sqrt{2}} W^\pm \sum_{\ell=e} Z^\tau_{\ell} V_{\ell4}^* \gamma^\mu P_L \ell^- - \frac{g}{2 \cos \theta_W} Z_{\mu} \sum_{\ell=e} Z^\tau_{\ell} V_{\ell4}^* \gamma^\mu P_L \nu_\ell - \frac{g m_N}{2 M_W} \sum_{\ell=e} Z^\tau_{\ell} V_{\ell4}^* P_L \nu_\ell + \text{H.c.} ,$$

with $g$ being the usual SU(2)$_L$ coupling constant. For the impact of jet vetoes on the larger particle spectrum of a full neutrino mass model, see Ref. [12].

III. COMPUTATIONAL SETUP

To compute our signal and background processes, we use a Dirac neutrino variant of the NLO in QCD-accurate [19, 20] HeavyNlo [21, 22] FeynRules [23–25] model file. LO(PS) and NLO(PS) event generation is performed by MadGraph5_aMC@NLO v2.6.2β [26], with parton shower matching (including QED effects) via Pythia8 v230 [27] using the CUETP8M1 “Monash” tune [28], and particle-level reconstruction to standard [29] Les Houches Event files by MadAnalysis5 v1.6.33 [30]. Jets are clustered according to the anti-$k_T$ algorithm [31] with $R = 1$ (unless otherwise specified), as implemented in FastJet v3.2.0 [32]. Computations at these accuracies are matched to the NNPDF 3.1 NLO+LUXqed PDF set [33] due to its LUXqed-based γ-PDF [34, 35]. As argued in Refs. [21, 22, 36, 37], such a formalism provides the most appropriate description of the $W^\gamma \rightarrow N^\ell \ell^-$ fusion process. NLO+NNLL(veto) rates are calculated within the framework of Soft-Collinear Effective Field Theory (SCET) [38–40], using Ref. [26, 41], matched with the NNPDF 3.1 NNLO+LUXqed PDF set. Approximate NNNLL(threshold) rates use the SCET-based calculation of Ref. [42], following Refs. [43, 44], and the NNPDF 3.1 NNLO+LUXqed PDF set.

Where reported, we show the dependence on the factorization and renormalization scales, as well as the hard and soft scale scales if applicable, by varying the default scales discretely by $0.5 \times$ and $2.0 \times$. We evolve PDFs and $\alpha_s(\mu)$ using the LHAPDF 6 v1.6 [45].

IV. HEAVY NEUTRINO SIGNAL PROCESS

In $pp$ collisions, heavy neutrinos can be produced through a variety of mechanisms that exhibit a nontrivial dependence on the heavy $N$ mass $m_N$ and collider energy $\sqrt{s}$. The leading [42] processes include: charged current (CC) Drell-Yan (DY), $q\bar{q} \rightarrow N\ell\ell^-$; neutral current (NC) DY, $q\bar{q} \rightarrow N\nu\ell^-$; $W\gamma$ fusion (VBF), $q\bar{q} \rightarrow N\ell\ell^\gamma$; and gluon fusion (GF), $gg \rightarrow N\nu_\ell$. Following the procedure of Refs. [22, 42], we plot in the upper panel of Fig. 2 the production cross sections of these mechanisms at various accuracies, with their residual QCD scale uncertainty (band thickness) and divided by the mixing quantity $|V_{t4}|^2$, as a function of $m_N$ at the $\sqrt{s} = 14$ TeV LHC. In the lower panel is the QCD $K$-factor, defined with respect to the lowest-order cross section: $K = \sigma/\sigma^{\text{LO}}$.

For $m_N \approx 150$ GeV – 1 TeV, we see that the sum of the CC DY and VBF production rates span about 6 pb–5 fb before mixing, and translate to 6 fb–5 ab after taking $|V_{t4}|^2 \approx 10^{-3}$, in agreement with the global fit constraints. In light of the $\mathcal{L} = 3 - 5$ ab$^{-1}$ of data

FIG. 1: Born-level diagram of heavy neutrino $N$ production via the DY process with subsequent decay to the trilepton final-state. Drawn with JaxoDraw [11].

II. SIMPLIFIED HEAVY NEUTRINO MODEL

TeV-scale neutrino mass models are well-motivated and typically assume the existence of singlet massive fermions which mix with the active ones. At colliders they commonly predict new colorless resonances that decay readily to multiple charged leptons; see, for example, references therein. Hence, to demonstrate the power of dynamical jet vetoes and how they improve searches for new particles, we consider a simplified model that extends the SM by a single colorless fermion, a heavy neutrino. In this simplified (3+1) model with Dirac neutrinos, and working in a basis where the charged lepton mass and flavor eigenstates coincide, neutrino flavor eigenstates ($\nu_\ell$) are related to light ($\nu_{\ell e}$) and heavy ($N$) mass eigenstates by $^1$

$$\nu_\ell = \sum_{m=1}^3 U_{\ell m} \nu_m + V_{4\ell} N. \quad (1)$$

$^1$ This form of the mixing and of the interaction Lagrangian, in particular the Higgs coupling is inspired by low-scale seesaw models.
that will be collected over the LHC’s lifetime, including its high-luminosity phase, the rates indicate considerable sensitivity to the mass range under discussion. However, to date, one of the main experimental factors limiting sensitivity of multi-lepton searches for heavy neutrinos (aside from the obvious potential to not exist) is the SM background [13, 46, 47]. In what follows, we report how a jet veto, and specifically one where the $p_T^{\text{Veto}}$ threshold is set on an event-by-event basis, can alleviate this issue.

In particular, we investigate the inclusive production of a heavy neutrino and charged lepton via the CC DY and VBF production modes, with the subsequent decay of $N$ to only leptons, i.e.,

$$pp \to \ell_N N + X \to \ell_N \ell_W W + X \to \ell_N \ell_W \ell \nu + X.$$  \hspace{1cm} (3)

Here, the subscript labels the particle produced in association with the charged lepton. As a benchmark hypothesis, we assuming the flavor mixing scenario,

$$|V_{e4}| = |V_{\tau 4}| \neq 0 \text{ and } |V_{\mu 4}| = 0,$$  \hspace{1cm} (4)

and choose the following collider signatures:

**Signal I:** $pp \to \tau_h^+ e^- \ell_X + \text{MET}$.  \hspace{1cm} (5)

**Signal II:** $pp \to \tau_h^+ \tau_h^- \ell_X + \text{MET}$, $\ell_X \in \{e, \mu, \tau_\ell\}$.  \hspace{1cm} (6)

Here, $\tau_\ell$ denotes a hadronically decaying $\tau$. Due to leptonic $\tau$ decays, charged lepton flavor violation (cLFV) cannot be unambiguously established by the simple observation of both signal processes alone. On the other hand, the branching rates of the $W$ and $\tau$ are known precisely. Therefore, it is possible to falsify the no-cLFV hypothesis, thus deducing that $N$ couples to both electrons and $\tau$ leptons, by accounting for how many $\tau_h^+ e^- \ell_X$ events one predicts given an observed $\tau_h^+ \tau_h^- \ell_X$ rate. Notably, the $\tau_h^+ e^- \ell_X$ rate in the flavor-violating case is relatively enhanced compared to the no-flavor-violating case.

We now turn to how jet vetoes impact the signal processes in Eqs. (5)-(6) and their leading SM backgrounds.

**V. SAFE JET VETEOS**

Central jet vetoes are premised [48–51] on the observation that color-singlet processes, such as Drell-Yan and EW vector boson scattering, possess characteristically different QCD radiation patterns than hard QCD processes themselves. Color-singlet processes give rise to jets that are predominantly forward (high $p_T$) and soft (low $p_T$) compared to those from hard QCD processes, which are central (low $p_T$) and hard (high $p_T$).

In SM measurements, vetoes on central jets with $p_T^j > p_T^{Veto} = 25 – 40$ GeV are known to yield relatively high selection efficiencies, with the efficiencies reaching, as for example in SM Z or $W^+W^-$ production [9],

$$\varepsilon(p_T^{\text{Veto}}) = \sigma(p_T^j < p_T^{\text{Veto}})/\sigma_{\text{Tot.}} \sim 75 – 90\%.$$  \hspace{1cm} (7)

Here, $\sigma(p_T^j < p_T^{\text{Veto}})$ is the cross section of a signal process after the veto is applied, and $\sigma_{\text{Tot.}}$ is the total cross section of the process before the veto. For searches of high-mass, colorless BSM particles, however, efficiencies are known [52, 53] to be much lower due to the higher likelihood to radiate high-$p_T$ gluons compared to processes with lower mass objects. This is visible in Fig. 3(a) where we plot the predicted $\varepsilon(p_T^{\text{Veto}})$ as a function of heavy neutrino mass $m_N$ for the process $pp \to N\ell_N$, along with their total scale uncertainties (band thickness). We evaluate the veto at NLO+NNLL(veto) with $p_T^{\text{Veto}} = 30$ GeV for representative jet radii $R$ and the total cross section at NLO. One sees that $\varepsilon(p_T^{\text{Veto}} \sim 30$ GeV) drops below the 80% efficiency threshold for $R = 0.1 (0.4)$ [1] at $m_N \gtrsim 700 (150)$ [100] GeV, with scale uncertainties spanning (roughly) $\pm 10$ (5) [2]%. Due to the inclusive nature of larger $R$ jets, one also sees that uncertainties are acutely sensitivity to the choice of jet radius [54–57], despite the relatively high precision of this NLO+NNLL Drell-Yan calculation. Hence, vetoes with static choices of $p_T^{\text{Veto}}$ result in discouraging efficiencies and uncertainties for otherwise sensible values of $p_T^{\text{Veto}}$.

Interestingly, were one to consider the characteristic $p_T$ scales of the charged leptons in the process in Eq. (3) one would find that each charged lepton $p_T$ scales with the mass of $N$. Namely, that [12]

$$p_T^\ell_N \sim m_N r_\star, \text{ with } r_\star \approx 0.336 \approx \frac{1}{3},$$  \hspace{1cm} (8)

$$p_T^W \sim \frac{m_N}{2} (1 - M_W^2/m_N^2) \sim \frac{m_N}{2},$$  \hspace{1cm} (9)

$$p_T^\ell \sim \frac{m_N}{4} (1 + M_W^2/m_N^2)/4 \sim \frac{m_N}{4},$$  \hspace{1cm} (10)
where the last approximations are in the $(M_W/m_N)^2 \to 0$ limit. Hence, setting $p_T^{\text{Veto}}$ to the leading, subleading, or trailing charged lepton $p_T$ (or potentially MET) does two things: (i) It foremost guarantees that the Sudakov logs $\alpha_s(p_T^{\text{Veto}}) \log(m_N^2/p_T^{\text{Veto}})^2$ are much less than 1 on an event-by-event basis, thereby reducing the need for resummation beyond LL or NLL precision. (ii) It raises the veto threshold with increasing $m_N$, thereby countering the drop in signal efficiency due to higher jet activity.

In Fig. 3(b) we show again the veto efficiency for the $pp \to N\ell_N$ process but take instead $p_T^{\text{Veto}} = m_N/2$. Remarkably, efficiencies jump to $\varepsilon(p_T^{\text{Veto}}) > 90 - 95\%$ over the $m_N$ range considered, with uncertainties reducing to the few percent level and exhibiting a much smaller dependence on $R$. When $p_T^{\text{Veto}} = m_N/4$ and $R = 1$, we have checked that efficiencies span $\varepsilon(p_T^{\text{Veto}}) > 90 - 95\%$ for $m_N \gtrsim 200$ GeV, but drop to $\varepsilon(p_T^{\text{Veto}}) \sim 80 - 85\%$ for $m_N = 150 - 200$ GeV. As one may anticipate, this is comparable to the static veto since for such masses $p_T^{\text{Veto}} = m_N/4 \sim 38 - 50$ GeV. Briefly we note that veto efficiencies above unity originate from a mismatch of input PDFs: the inclusive NLO cross-section uses an NLO PDF while the NLO+NNLL veto resummation employs an NNLO PDF. In light of these properties and since the dynamical veto can be experimentally implemented using the ratio of two measurable quantities, i.e., imposing $p_T^{\text{Veto}}/p_T \lesssim 1$, we describe this veto scheme as experimentally and theoretically safe.

It is now necessary to address whether it is justifiable to exclude hadronically decaying $\tau$ leptons from the jet veto. Experimentally, $\tau_N$ are reconstructed first as jets before $\tau$-tagging/classification [58, 59]. Theoretically, at some intermediate point $\tau$ leptons decay to quarks in the full, un-approximated trilepton process. Arguably, such partons may be color-connected to the rest of the hadronic system or interfere with initial-state radiation. Formally, though, for the DY and VBF processes, such contributions appears first at $\mathcal{O}(\alpha_s^3)$, and hence is beyond the claimed accuracy of our calculations. In spite of that, we note that for resonant heavy $N$ the $\tau$'s effective life time (ignoring abuse of notation) is $\tau_{\gamma\gamma} \sim (1/\Gamma_{\gamma\tau})(E_{\tau}/m_\tau) \sim m_N/(\Gamma_{\gamma\tau})$, where $\Gamma_{\gamma\tau} \sim 2 \times 10^{-12}$ GeV. This is much longer than the time scale of the hard process, $\tau_{\text{hard}} \sim 1/m_N$. Hence, under the narrow width approximation (NWA), which color disconnects the $\tau$ lepton to all orders of $\alpha_s$, one neglects contributions of the size $\tau_{\text{hard}}/(\tau_{\gamma\gamma}) ~ (\Gamma_{\gamma\tau}/m_N^2) \ll 1$. In the absence of the NWA for non-resonant $N$, however, the $\tau$'s effective life time may only be $\tau_{\gamma\gamma} \sim 1/\Gamma_{\gamma\tau}$. This too is much longer than the hadronization/non-perturbative scale, which is $\tau_{\text{NP}} \sim 1/\Lambda_{\text{NP}}$ with $\Lambda_{\text{NP}} \sim 1 - 2$ GeV. Hence, the $\tau$ lepton outlives the primary hadronization and exchanges between $\tau$ and the remainder of the hadronic system are long range color-singlet exchanges [60-62], i.e. beyond twist-2, and beyond the accuracy of the Factorization Theorem itself.

Legitimately, one may question if such a veto also dramatically and incidentally increases the acceptance rates of QCD backgrounds. As we now discuss, it does not.

**Top Quark Production**

Due to their inherent mass scales and rates, single and pair production of top quarks are major backgrounds to any measurement and search for EW and colorless BSM processes in TeV-scale hadron collisions. However, as investigated in Ref. [53], the $p_T$ distribution of the leading jet for top quark and Drell-Yan processes are qualitatively different, even after the application of a veto on b-jets. This implies that flavor-inclusive vetoes can generically [53] improve signal-to-background ratios over flavor-exclusive vetoes, a conclusion that also holds for the types of vetoes considered here: While the characteristic $p_T$ of
a charged lepton in the $t \rightarrow W b \rightarrow \ell \nu b$ transition scales as $p_T^b \sim E_T/W = m_t (1 + M_W^2/m_t^2)/4 \approx 50 - 55$ GeV, the $b$'s $p_T$ scale is larger with $p_T^b \approx m_t (1 - M_W^2/m_t^2)/2 \approx 65 - 70$ GeV. The issue is more extreme for $tT$, with $V \in \{W, Z\}$, where sub-leading and trailing leptons possess momenta that scale as $p_T^\ell \sim M_V/2 \sim 40 - 45$ GeV, which is again lower than $p_T^b$.

**EW Triboson Production**

The production of three (or more) EW bosons represents the main background that survives after traditional selection cuts but actually is particularly vulnerable to the veto. NLO corrections reveal 63, 64 that $O(30\%)$ of the inclusive $pp \rightarrow 3W + X$ process is made of the $3W + 1j$ subprocess; the remaining is Born-like. Hence, the veto imposes a non-negligible selection cut and restricts the intermediate $W$s to be largely at rest since recoiling against jets must by split six ways amongst the $W$s' decay products. The scalar sum over the charged lepton $p_T^\ell$ therefore possesses a characteristic value of

$$S_T^{3W} \equiv \sum_\ell |p_T^\ell| \sim 3 M_W/2 \sim 120$ GeV. \hspace{1cm} (11)$$

For the $N$ mass range we consider, one sees that the signal process characteristically exceeds this, with

$$S_T^N \sim m_N/3 + m_N/2 + m_N/4 = 13/12 m_N. \hspace{1cm} (12)$$

Therefore, a jet veto in conjunction with $S_T > 120$ GeV will suppress such backgrounds.

**EW Diboson Production**

Resonant EW diboson production can be stymied by standard invariant mass cuts,

$$m_{\ell \ell_j} > 10 \, \text{GeV}, \quad |m_{\ell \ell_j} - M_Z| > 15 \, \text{GeV},$$

and

$$|m_{3\ell} - M_Z| > 15 \, \text{GeV}, \hspace{1cm} (13)$$
on any combination of analysis-level charged leptons. Indiscriminate application to all $\ell, \ell_j$ helps suppress charm mis-measurement and fake lepton backgrounds. Highly non-negligible, non-resonant contribution to the inclusive $pp \rightarrow \ell^+ \ell^- \tau^+ \tau^- \nu$ and $\ell^+ \ell^- \ell^+ \ell^-$ processes can be sufficiently reined in by the veto+$S_T$ selections.

**Fake Leptons**

Non-prompt leptons from heavy quark decays, light jets mis-tagged as hadronic decays of $\tau$ leptons, and light jets misidentified as electrons, collectively labeled as "fake leptons," represent the second most important background in searches for heavy neutrinos at the LHC 47. In most instances of fake leptons, however, a degree high-$p_T$ QCD activity is required. Invariably, the presence of a central, energetic jet implies, by color conservation, that its progenitor parton is color-connected to some other part of the collision. Hence, whether the additional colored particles constitute the beam remnant or hard process, there is a high likelihood that the fake lepton is accompanied by a real jet of comparable $p_T$. This is especially true for semi-leptonic decays of heavy flavor hadrons, e.g., $B \rightarrow D \ell \nu$, where the hadronic and leptonic decay products carry a comparable momenta 65, 66.
VI. RESULTS AND OUTLOOK

In Sec. V we discussed the signal and background phenomenology for the heavy $N$ trilepton process under a dynamical jet veto. We now report quantitatively how a search analysis built around a dynamical jet veto can improve LHC sensitivity compared to a more traditional analysis built around the presence of high-$p_T$ charged leptons and vetoes only $b$-tagged jets, e.g., Refs [13, 47].

For further details and motivation of the following selection analysis, see Ref. [12]. We define analysis-quality charged leptons and jets as isolated objects satisfying the following fiducial and kinematic cuts:

\[
p_T^{(μ, τ)} > 15 (15) [30] \, \text{GeV with } |\eta| > 2.4, \text{ and } |\eta^{μ, τ}| < 1.4 \text{ or } 1.6 < |\eta^{μ, τ}| < 2.4. \quad (14)
\]

Charged leptons and jets are then labeled according to $p_T$, with $p_T^k > p_T^{k+1}$, and the missing transverse momentum vector $\vec{p}_T$ is built from all visible momenta above 1 GeV in the fiducial region. To simulate detector effects, momentum smearing is done as in Ref. [53]; similarly, $p_T$-based (mis)tagging, (mis)identification, and fake lepton efficiencies are based on the Detector Performance (DP) and dedicated studies of Refs. [67–71]. We require events to contain exactly three analysis-quality charged leptons with flavor composition according to Eqs. (5)-(6). We next apply the invariant mass cuts of Eq. (13). After imposing a jet veto set to the $p_T$ of the leading charged lepton, i.e., $p_T^{\text{Veto}} = p_T^{l_1}$, we impose that $S_T > 120$ GeV.

As a proxy to the invariant mass of the multi-body transverse mass $M_{T,i}$, we build a version of the leading charged lepton in the trilepton final-state. Of the two permutations of $M_{T,i}$, we choose the one $(M_T)$ closest to our mass hypothesis and select for events satisfying

\[
M_{T,i}^2 = \left( \sqrt{p_T^2(ℓ_{k}^{\text{OS}}) + m_{ℓ, k}^2} + \sqrt{p_T^2(ℓ_{l}^{\text{SS}} + \vec{p}_T) + M_W^2} \right)^2
\]

\[
- \left( p_T^{(OS)} + p_T^{(SS)} \right)^2, \quad i = 1, 2. \quad (15)
\]

Here, $p_T^{(OS)}$ ($p_T^{(SS)}$) is the one opposite-sign (either same-sign) charged lepton in the trilepton final-state. Of the two permutations of $M_{T,i}$, we choose the one $(M_T)$ closest to our mass hypothesis and select for events satisfying

\[
-0.15 < \frac{(M_T - m_N^{\text{hypothesis}})}{m_N^{\text{hypothesis}}} < 0.1. \quad (16)
\]

As a benchmark, we base the “standard analysis” on the 13 TeV CMS search for heavy neutrinos [47]. Starting from Eqs. (14) and (13), and assuming the same flavor combinations above, we require that

\[
p_T^{l_1} > 55 \text{ GeV, } p_T^{l_2} > 15 \text{ GeV, } m_{3\ell} > 80 \text{ GeV}. \quad (17)
\]

Events with at least one $b$-tagged jet are vetoed. The results of our traditional analysis are in line with Ref. [47].

Assuming Gaussian statistics and a background systematic weighting of $B \rightarrow (1 + δB)_B$, with $δB = 10\%$, we show in Fig. 4 the $95\%$ CL sensitivity to the active-sterile mixing quantity $|V_{e\ell}|^2$, $|V_{τ\ell}|^2$ in the (a) $τ_N^+ τ_N^- τ_X$ and (b) $τ_N^± e^± τ_X$ final state, for the veto (solid-star) and standard (dash-diamond) analyses, at the 14 TeV LHC with $L = 150$ fb$^{-1}$ and 3 ab$^{-1}$ of data. The improvement in sensitivity when applying the jet veto is unambiguous. We find that the veto can increase the reach of $|V_{44}|^2$ by up to a factor of 7-8 with 150 fb$^{-1}$ and up to a factor of 10-11 with 3 ab$^{-1}$. Hence, with 3 ab$^{-1}$, LHC searches can surpass indirect limits on the active-heavy mixing obtained from global fits to EW precision observables and low-energy data. We stress that the improvement at high $m_N$ stems both from an increase in signal rate and a decrease in background rate. At low $m_N$, however, small improvement is observed, in part, due to the stringent $p_T$ requirements for $τ_N$ tagging, which depletes signal strength despite improved efficiencies.

Reporting the impact on other flavor combinations is beyond our present scope and refer readers to Ref. [12].

VII. SUMMARY AND CONCLUSION

Due to inherently different radiation patterns, jet vetoes are powerful techniques to reduce QCD backgrounds in measurements and searches for electroweak and color-singlet new physics processes in hadron collisions. In this letter, we report key findings when vetoing events with jets possessing transverse momenta ($p_T$) greater than the highest $p_T$ charged lepton in the event. While such dynamical jet vetoes have been considered in the context of SM diboson production [10], we demonstrate that they can be successfully used in a much broader class of experimental searches, including searches for new high-mass particles as well as events with $τ$ leptons decaying hadronically. We find an impressive improvement over traditional, fixed-$p_T$ jet vetoes.

As a representative case study, we focused on the impact of jet vetoes in searches for heavy Dirac neutrinos ($N$) participating in the trilepton process $pp \rightarrow ℓ_N N \rightarrow ℓ_N ℓ_W ℓ_W \rightarrow ℓ_N ℓ_W ℓ_W ν$. The phenomenological consequences of such a jet veto on the signal and background processes are summarized in Sec. V. We find the following: (i) As shown in Fig. 3, perturbative uncertainties associated with the veto greatly reduce due to tying the veto scale to the hard process scale. (ii) Also shown in the figure is that the signal efficiency for passing the veto exceeds $90 – 95\%$ for $N$ with masses in the range $m_N = 150 – 1000$ GeV, and exhibits little-to-no dependence on the neutrino mass scale. (iii) Background rejection capabilities also improve when compared to vetoing only heavy flavor-tagged jets. Subsequently, as shown in Fig. 4, this results in an improved sensitivity to the heavy neutrino mixing quantity $|V_{44}|^2$ up to an order of magnitude over the LHC’s lifetime; see Sec. VI. Further investigations into the impact on heavy neutrino searches in different flavor channels is left to future work [12]. We anticipate that sensitivity could be further improved if combined with advanced multivariate techniques, and encourage future work on the topic.
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