Heavy Neutrinos and (Safe) Jet Vetoes [1]

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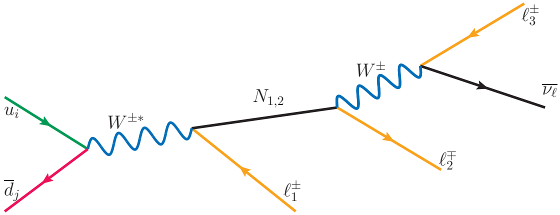
[1] with Silvia Pascoli and Cedric Weiland [1805.09335, 181X.YYYYY]

[2] IPPP $\rightarrow$ CP3, Universite Catholique de Louvain (Fall '18)

a short history

2.5 years ago asked if possible to improve LHC searches for leptonic decays of heavy neutrinos, $N \to \ell_1 W \to \ell_1 \ell_2 \nu$

- "improve" $\neq$ MVA or BDT but a qualitatively new search strategy

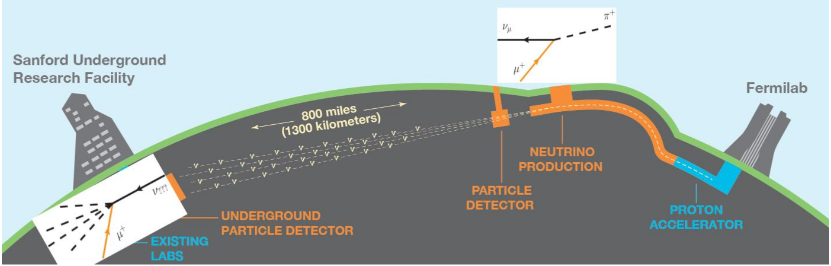


Why? new channels ($W\gamma$ fusion), new technology (automated NLO+PS), unclear lepton number-violating $\ell_1^{\pm}\ell_2^{\pm} + nj$ was viable

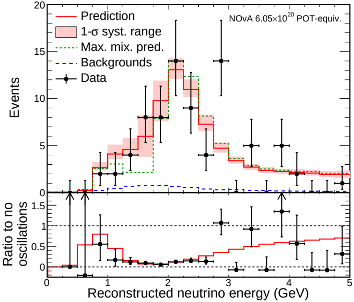
An idea: Global QCD activity in heavy N production different than backgrounds, e.g., fewer central, high-p_T jets.

The question: Can jet observables be used to improve heavy N searches?

Motivation for new physics from ν physics



In neutrino fixed-target expts, ν_μ beams from collimated $\pi^\pm$, then studied at near and far detectors (reminiscent of early SLAC DIS expts)



Deficit/disappearance of expected ν_μ (+apperance of ν_e/ν_τ) interpreted as $\nu_{\ell_1} \to \nu_{\text{mass}} \to \nu_{\ell_2}$ transitions/oscillations [E.g. NOνA ν_μ disapp., 1701.05891]

$\Longrightarrow$ ν have mass!

So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV.

Is this a problem?

Yes.

Neutrinos Masses and New Physics

To generate Dirac masses for ν ***like other*** SM fermions, we need N_R

$$\mathcal{L}_{\nu\text{ Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. = -y_\nu \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \langle\Phi\rangle + h \\ 0 \end{pmatrix} N_R + H.c.$$

$$= \underbrace{-y_\nu \langle\Phi\rangle}_{=m_D} \overline{\nu_L} N_R + H.c. + \dots$$

However, ${N_R}^i$ do not exist in the SM, implying $m_D = 0$

Significance of Neutrino Oscillations:

- Neutrino masses $\implies \mathcal{L}_{\text{Universe}} \neq \mathcal{L}_{\text{SM}} \quad (+\mathcal{L}_{\text{gravity}})$
- Instead, $\mathcal{L}_{\text{Universe}} \approx \mathcal{L}_{\text{SM}} + \underbrace{\mathcal{L}_{\nu\text{ masses}}}_{\textit{BSM physics!}} + \dots$

Neutrino masses $\implies$ existence of physics beyond the SM!

Neutrinos Masses and New Particles?

Nonzero neutrino masses implies new degrees of freedom exist [Ma'98]:

$$m_\nu \neq 0 + \text{LH currents}$$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$ and/or Dirac Mass : $m_\nu^D \overline{\nu_L} N_R$

$m_\nu^L = y\langle\Delta\rangle$ or strong dynamics

$m_\nu^D = y\langle\Phi_{\rm SM}\rangle$

$$m_\nu + \textbf{gauge inv.} + \textbf{renormalizability} \implies \textbf{new particles!}$$

- No guarantee that new particles are N_R, e.g. Type II Seesaw
- New particles might be charged under new gauge symmetries, e.g., (N_R, e_R) form $SU(2)_R$ doublet or Δ_L is scalar $SU(2)_L$ triplet

Collider Connection to Neutrino Mass Models[3]

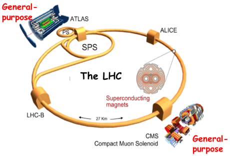
Neutrino mass models (aka Seesaw models) hypothesize new particles of all shapes, spins, charges, and color:

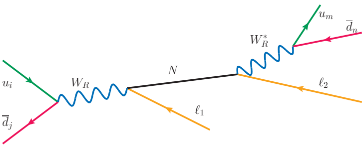
N (Type I), $T^{0,\pm}$ (Type III), Z_{B-L}, $H_R^{\pm,\pm\pm}$ (Type I+II), ...

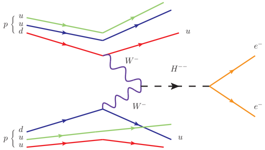
Produced in *ee*/*ep*/*pp* collisions through gauge couplings and mixing:

DY : $q\overline{q} \to \gamma^*/Z^* \to T^+T^-$ and $q\overline{q'} \to W_R^\pm \to N\ell^\pm$

VBF : $W^\pm W^\pm \to H^{\pm\pm}$ **GF** : $gg \to h^*/Z^* \to N\nu_\ell$







Identification of Seesaw particles through decays to SM particles

[3] Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, **RR** [1711.02180]

Heavy Neutrinos and Colliders

(Heavy) Neutrino Mixing for Non-experts (1/2)

After EWSB, ν_ℓ and N_R have same quantum numbers $\implies$ mixing!

Example: In a two-state system, mixing between chiral eigenstates and mass eigenstates is given by unitary transformation/rotation

$$\underbrace{\begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}}_{\text{chiral basis}} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{\text{mass matrix}} \underbrace{\begin{pmatrix} \nu_1 \\ N_2 \end{pmatrix}}_{\text{mass basis}}$$

Decompose chiral/interaction states into mass states using:

$$|\nu_L\rangle = \cos\theta \underbrace{|\nu_1\rangle}_{light} + \sin\theta \underbrace{|N_2\rangle}_{heavy} \overset{\theta \ll 1}{\approx} (1 - \tfrac{1}{2}\theta^2)|\nu_1\rangle + \theta|N_2\rangle$$

(Heavy) Neutrino Mixing for Non-experts (2/2)

Realistic neutrino mass models are much more complicated[4]. After diagonalizing mass matrix one gets two limits[5]:

- **High-scale seesaw**: $\mu_M \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\mu_M}\right), \quad m_N \sim \mu_M$
- **Low-scale seesaw**: $\mu_M \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \mu_M \left(\frac{m_D}{m_R}\right)^2, \quad m_N \sim m_R$

For ***discovery purposes***, no need to complicate life. Take agnostic/pheno. approach[6] with generic $V_{\ell N}$ parametrization and one N mass eigenstate

- This requires modifying SM interactions with the following[7]:

$$\nu_{\ell L} = \sum_{m=1}^{3} U_{\ell m} \nu_m + V_{\ell m'=4} N_{m'=4}$$

[4] See for example, C. Weiland's thesis, [1311.5860]

[5] Kersten, Smirnov [0705.3221]; Moffat, Pascoli, Weiland [1712.07611]

[6] Appropriate since other Seesaws can mimic Type I pheno. See **RR**, [1703.04669]

[7] Atre, Han, Pascoli, Zhang [0901.3589]

Heavy Neutrinos Couplings to EW Bosons

Consider left-handed (LH) $SU(2)_L$ doublets (**gauge basis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The SM W chiral coupling to **leptons** in **flavor basis** is given by

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\overline{\nu_{\ell L}} \gamma^\mu P_L \ell^-\right] \quad + \quad H.c.$$

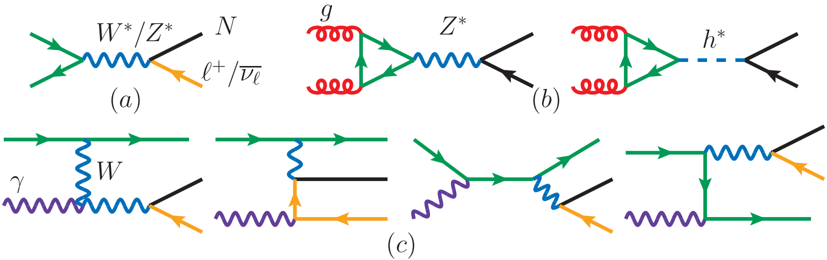
The SM W chiral coupling to **leptons** in the **mass basis**

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\sum_{m=1}^{3} \overline{\nu_m} U_{m\ell}^* + \overline{N^c} V_{N\ell}^*\right] \gamma^\mu P_L \ell^- \quad + \quad H.c.$$

$\Longrightarrow$ N is **accessible through** $W/Z/h$ currents

Heavy Neutrino Production At Hadron Colliders

Heavy N can be produced through a variety of mechanisms in pp collisions



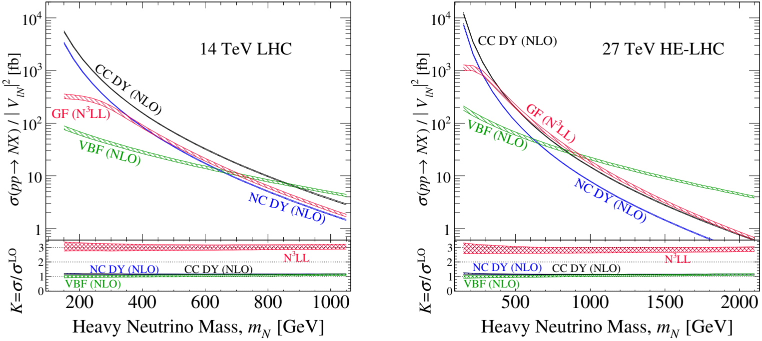
In fact, a resurgence of calculations in recent years[8]

- Clarity needed on (i) $m_N, \sqrt{s}$ dependence and (ii) conflicting claims

$\implies$ more physical collider definitions + public tools [1602.06957]

[8]DY@NLO [*1509.06375]; GF [1408.0983, *1602.06957] @NNNLL [*1706.02298]; VBF [1308.2209, *1411.7305, *1602.06957]; DY,VBF Automation@NLO [*1602.06957]; For extensive details, see review: [*1711.02180]; (*) = Pittsburgh and/or IPPP

Across different colliders, wild interplay of PDF and matrix elements



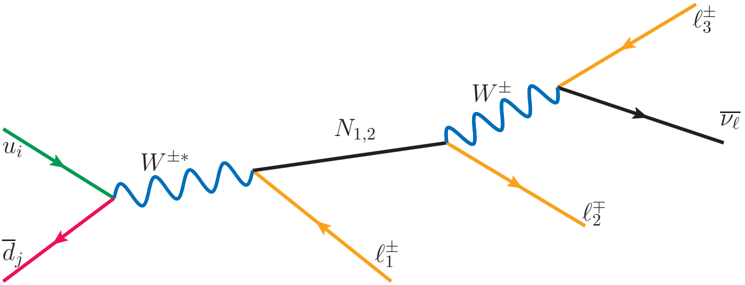
Plotted: Normalized production rate $(\sigma/|V|^2)$ vs heavy N mass (m_N)

- For $\sqrt{s} \gtrsim 25 - 27$ TeV **GF** greater than **DY** due to gg luminosity
- For $m_N \gtrsim 1 - 2$ TeV, **VBF** dominant due to large Yukawa couplings

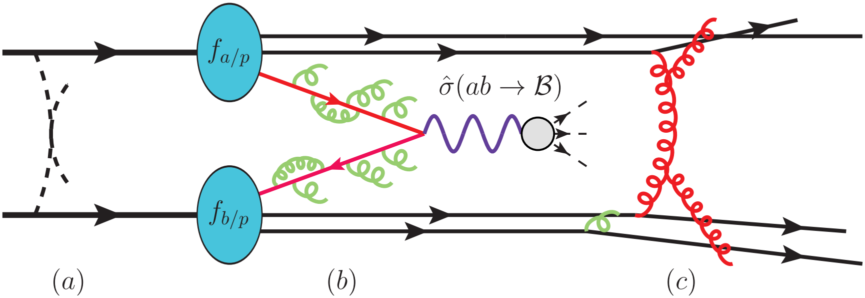
Note: For $m_N = 10$ TeV and $|V_{\ell N}|^2 \sim 10^{-3}$, then at 100 TeV, one has $\mathcal{O}(30)$ VBF events after 30 ab^{-1}! If BR$\times\varepsilon \times \mathcal{A} \sim \frac{1}{3}$, then $\sqrt{N_{Obs.}} > 3\sigma$

Heavy Neutrinos and Jet Vetoes:

The Difficulties of Jet Vetoes



1. Sources of Jets



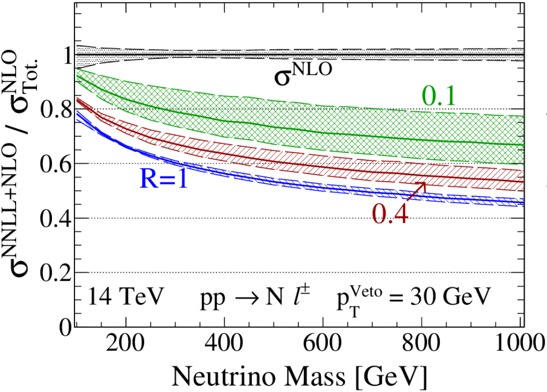
In *pp* collisions, hadronic activity has three sources:

- (a) Early, colorless, ultra-collinear/soft exchanges (suppressed)
- (b) Hard scattering (calculable)
- (c) Secondary/double/multi-parton scattering[9] (...)
  - Can contaminate jets from (b)

[9] Extremely rich physics. See, e.g., Collins, "Foundations of pQCD" (2011)

2. & 3. Poor signal Efficiencies and Uncertainties

For Drell-Yan and other color-singlet processes,
more/harder QCD radiation (jets!) for systems with larger masses[10]



Prob. for signal to survive veto:

$$\varepsilon = \frac{\sigma^{\rm NLO+NNLL}(p_T^j < p_T^{\rm Veto})}{\sigma^{\rm NLO}_{\rm Tot.}}$$

$\varepsilon \to 0$ as $(p_T^{\rm Veto}/m_N) \to 0$

Large uncertainty despite high (NLO+NNLL!) precision
(R = jet radius parameter)

Paradox: Relax $p_T^{\rm Veto}$ for increasing m_N but top background jumps!

[10] Eg., Sleptons: F. Tackmann, et al [1603.03052]; W': B. Fuks, **RR** [1701.05263]

Heavy Neutrinos and *Dynamical* Jet Vetoes

A thought:[11] *how about p_T of the leading charged lepton in the event?*

- For $pp \to N\ell \to 3\ell X$, $p_T^\ell \propto m_N \implies$ increases for larger m_N

[11]Disclosure: discovered basis of idea in an unrelated CMS paper on $WW + 0j$

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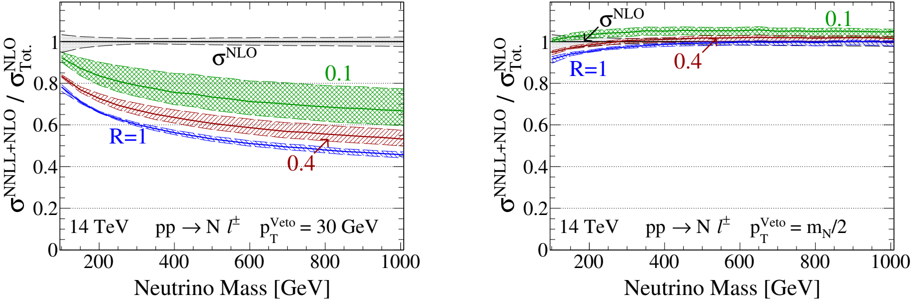


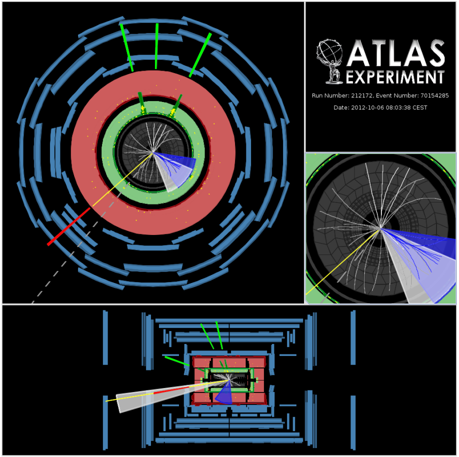
QCD uncertainties ***shrink*** since 2-scale problem converted into 1-scale

- less precise predictions, e.g., LL/parton shower, now more reliable

<u>**Question:** What about backgrounds?</u>

[11]Disclosure: discovered basis of idea in an unrelated CMS paper on $WW + 0j$

Top Quark Background vs Dynamical Jet Vetoes



$pp \to t\bar{t}Z \to 1\mu + 3e + 2j_b + \not{E}_T$ candidate event [1509.05276]

Classic kinematics:

- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

Typically,

- $p_T^{e_1} \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ GeV
- $p_T^{b_1} \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 60$ GeV

$p_T^{b_1} > p_T^{\ell_1} \implies$ event vetoed!

Setting $p_T^{\rm Veto}$ on event-by-event basis to $p_T^{\ell_1}$ can eliminate top quark background ***without*** b-jet tagging!

Jet Vetoes and SM Backgrounds

Associated Top Quark Production: $pp \to t\bar{t}\ell\ell,\ t\bar{t}\ell\nu,\ tq\ell\ell$

- Typical p_T of lepton from top: $p_T^\ell \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- Typical p_T of b from top: $p_T^b \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 65$ GeV
- $p_T^\ell < p_T^b \implies$ top events vetoed without need of b-tagging

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Fake Leptons:

- Low-p_T jet (in $t\bar{t}$ events) identified as $e^\pm$ or $\tau^\pm$
- Low-p_T charged $\ell^\pm$ from weak decays of hadrons (in $t\bar{t}$ events)
- Color conservation $\implies$ second jet with comparable p_T likely exist

Jet Vetoes and SM Backgrounds

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Electroweak Production: $pp \to 4\ell,\ 3\ell\nu, WWW,\ WW\ell\ell$

- Jet veto $\implies$ EW bosons at rest since no recoil
- Typical $S_T \equiv \sum_\ell |\vec{p}_T^\ell|$ for $3W$ or WZ: $S_T \sim \frac{3M_V}{2} \sim 120 - 130$ GeV
- Typical S_T for heavy N: $S_T \sim \frac{m_N}{3} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{13m_N}{12}$

Results[12]

[12] with Silvia Pascoli and Cedric Weiland [1805.09335, 180X.YYYYY]

Jet vetoes are nonstandard selection cuts and make MC generation tricky

- **Need**: reliable description of ***leading*** jet at all p_T for signal (color-singlet) and background
- **Need**: "jets" (resummation/parton shower + jet definition) $\Longrightarrow$ cannot apply veto at same time as other cuts
- **Need**: inclusive samples since bkg include $\ell^\pm$ outside fid. volume

Moto: "We start at NLO"

- Event Generation: HeavyN@NLO UFO[13] + MadGraph5_aMC@NLO
    - Bare-bones gen-level cuts on leptons + MadSpin for decay
- Shower: Pythia8.2 (w/ QED shower + recoil + Monash* Tune)
- Particle-level Reco (lhe output)[14]: MadAnalysis5 + $R = 1$ anti-k_T
- Smearing + offline analysis: private ROOT code

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[13] C. Degrande, O. Mattelaer, **RR**, J. Turner [1602.06957]
Available from FeynRules database: feynrules.irmp.ucl.ac.be/wiki/HeavyN

[14] See W'+jet veto analysis, Fuks, **RR** [1701.05263]

Flavor Hypothesis and Signal Definition

As a benchmark flavor mixing scenario we set:

$$|V_{e4}| = |V_{\tau 4}| \neq 0 \quad \text{and} \quad |V_{\mu 4}| = 0$$

Two complementary[15] signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \tau_h^+ \tau_h^- \ell_X$+MET and **Signal II:** $pp \to \tau_h^\pm e^\mp \ell_X$+MET

Selection Cuts: Standard ID requirements and $m_{2\ell,3\ell}$ cuts

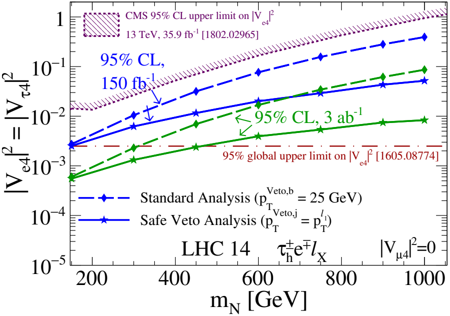
Nonstandard Cuts:

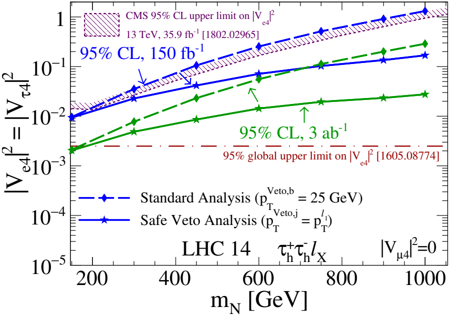
- Require $p_T^{j_1} < p_T^{\ell_1}$ (jet veto) and $S_T^\ell > 120$ GeV
- Given m_N hypothesis, cut on closest multi-body transverse mass $\tilde{M}$

$$\tilde{M}_{T,i}^2 = \left[\sqrt{p_T^2(\ell^{\rm OS}) + m_{\ell^{\rm OS}}^2} + \sqrt{p_T^2(\ell_i^{\rm SS}, \not{\vec{p}}_T) + M_W^2}\right]^2 - \left[\vec{p}_T(\ell^{\rm OS}, \ell_i^{\rm SS}) + \not{\vec{p}}_T\right]^2, \quad i = 1, 2.$$

[15] BR($\tau/W \to eX$) are well-measured $\implies$ can falsify no-LFV hypothesis if measured

Results for 14 TeV LHC: $e\tau$ Scenario





Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass

- Dash = standard search[16] with b-jet veto (13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

Improved sensitivity up to $10-11\times$ with $\mathcal{L} = 3$ ab^{-1}.

[16] More aggressive cuts on charged leptons: e.g., $p_T^{\ell_1} > 55$ GeV, $m_{3\ell} > 80$ GeV

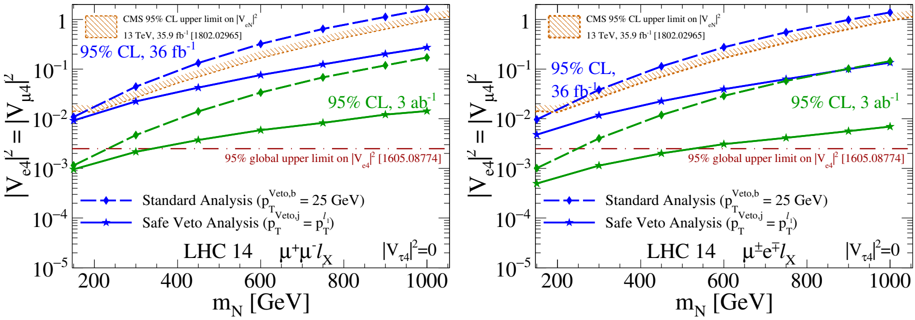
More at 14 TeV LHC: $e\mu$ Scenario

Benchmark flavor mixing scenario II:

$$|V_{e4}| = |V_{\mu4}| \neq 0 \quad \text{and} \quad |V_{\tau4}| = 0$$

Two complementary signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \mu^+\mu^-\ell_X$+MET and **Signal II:** $pp \to \mu^\pm e^\mp \ell_X$+MET



Again, improved sensitivity $> 10\times$ with $\mathcal{L} = 3\ \text{ab}^{-1}$.

Summary

Heavy neutrinos remain one of the best (but not the only!) explanations for tiny neutrino masses

Idea: *We have developed a new approach to searches for heavy* N *at pp colliders, one based on an unsual jet veto scheme* $(p_T^{\rm Veto} = p_T^{\ell_1})$

- New veto scheme reveals $> 90 - 95\%$ signal acceptance with little-to-no dependence on m_N (contrary to previous veto schemes)
- Substantial reduction in QCD theory uncertainty at NLO+NNLL(Veto) $\implies$ less need for high-precision resummation
- Redesigned search analysis with better reduction of background $\implies$ Improved LHC sensitivity by up to $10\times$ over LHC's lifetime

Remember: "*The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work*" [press.cern]

- High-Luminosity LHC and Belle II goals: 3-5 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

Thank you.