Heavy Neutrino Searches at the LHC

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Cédric Weiland

with Silvia Pascoli and Richard Ruiz

Pitt-PACC, University of Pittsburgh

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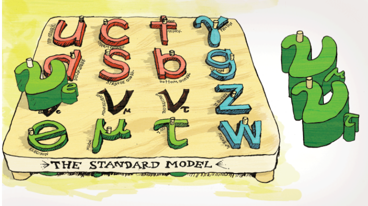
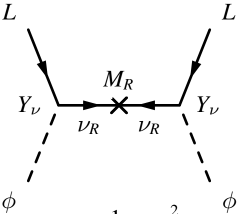
Massive neutrinos and New Physics

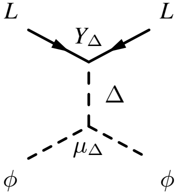
- Observation of ν oscillations
  $\Rightarrow$ at least 2 ν are massive
- BSM necessary for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms



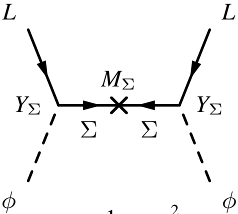
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets $\rightarrow \nu_R$
  - type II: scalar triplets $\rightarrow \Delta^{\pm\pm},\ \Delta^{\pm},\ \Delta^0$
  - type III: fermionic triplets $\rightarrow \Sigma^+,\ \Sigma^0,\ \Sigma^-$



$$m_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$



$$m_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$



$$m_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

Properties of type I seesaw and variants

- Generic field content: SM + fermionic gauge singlets (a.k.a. right-handed neutrinos / sterile neutrinos)

$$\mathcal{L}_{\text{type I}} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - \frac{1}{2} M_R \overline{\nu_R^c}\nu_R + \text{h.c.}$$

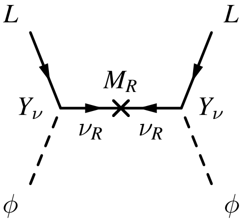
- After EWSB, mixing between active and sterile neutrinos

$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}_{\text{gauge}} = \begin{pmatrix} U & V \\ W & X \end{pmatrix} P_L \begin{pmatrix} \nu \\ N \end{pmatrix}_{\text{mass}}$$

giving the relevant couplings for N production

$$\begin{aligned} \mathcal{L}_{\text{Int.}} = & - \frac{g}{\sqrt{2}} W_\mu^+ \, \overline{N} \, V^* \, \gamma^\mu P_L \ell^- \\ & - \frac{g}{2\cos\theta_W} Z_\mu \, \overline{N} \, V^* \, \gamma^\mu P_L \nu_\ell \\ & - \frac{g m_N}{2 M_W} h \, \overline{N} \, V^* P_L \nu_\ell + \text{h.c.} \,, \end{aligned}$$

Towards testable Type I variants



- Taking $M_R \gg m_D$ gives the "vanilla" type 1 seesaw

$$\mathrm{m}_\nu = -m_D M_R^{-1} m_D^T$$

$$\mathrm{m}_\nu \sim 0.1\,\mathrm{eV} \Rightarrow \left| \begin{array}{l} Y_\nu \sim 1 \quad \text{and} \quad M_R \sim 10^{14}\,\mathrm{GeV} \\ Y_\nu \sim 10^{-6}\,\text{and} \;\; M_R \sim 10^{2}\;\;\mathrm{GeV} \end{array} \right.$$

- $V \sim m_D M_R^{-1}$ controls the phenomenology of the heavy neutrinos too
  → Cancellation in matrix product to get large $m_D M_R^{-1}$

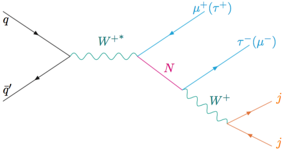
> $m_\nu = 0$ equivalent to conserved lepton number for models with arbitrary number of ν_R [Moffat, Pascoli, CW, 2017]

⇒ Nearly conserved L symmetry ensures stability of the cancellation

- Explicitly realised in, e.g.
  - low-scale type I [Ilakovac and Pilaftsis, 1995]...
  - inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]
  - linear seesaw [Akhmedov et al., 1996, Barr, 2004, Malinsky et al., 2005]

Heavy ν searches at hadron colliders

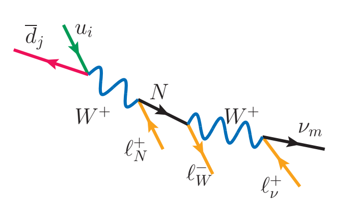
- Theorem motivates a focus on L conserving observables at the LHC (or a broader interpretation of LNV searches such as $pp \to \ell^\pm \ell^\pm jj$)
- Below m_W: displaced vertices [Gronau et al., 1984, Helo et al., 2014, Abada et al., 2019]...
  Below m_H: modified Higgs decays [Bhupal Dev et al., 2012, Banerjee et al., 2013]...
- Above m_H: LFV dilepton + dijet



100+ events expected at LHC after run 3

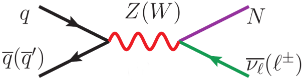
[Arganda, Herrero, Marcano and **CW**, 2016]

Above m_H: tri-lepton + missing E_T

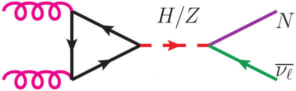


Heavy neutrino production at the LHC

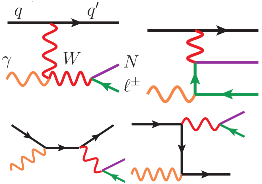
Drell-Yan



gluon fusion

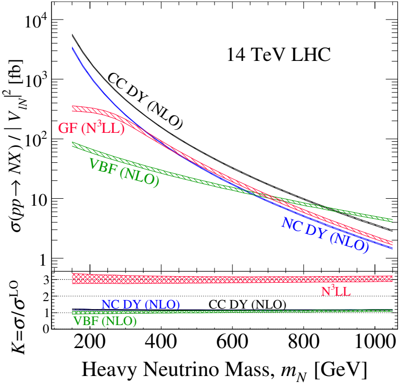


VBF

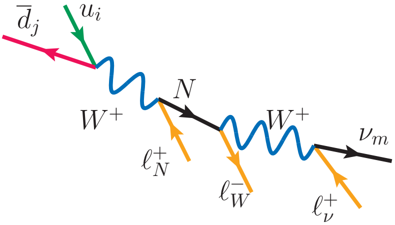


diagrams from [Degrande et al., 2016]

- Model file available for automated NLO calculation → Use Dirac version
- Jets clustered using anti-k_T with $R = 1$
- Drell-Yan channel dominates at low masses
- VBF dominates above $m_N \simeq 900$ GeV
  [Dev et al., 2014, Alva et al., 2015]
- Flat K-factors, typical of colour-singlet processes
- Band width = scale uncertainty



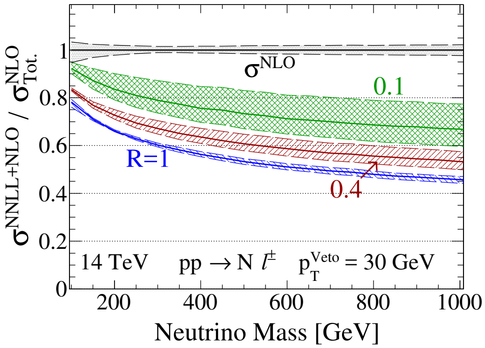
Signal: tri-lepton + MET



- Focus on lepton number conserving final state
- Produced from charged-current Drell-Yan and VBF
- Signal: $pp \to \ell_i^\pm \ell_j^\mp \ell_k^\pm +$ MET
- Purely leptonic final state → include jet veto in analysis

Jet veto with fixed p_T

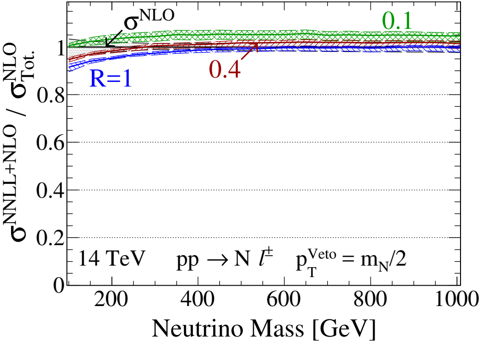
- Jets associated with colour-singlet processes mostly forward and soft
  → veto central and hard jets associated with coloured backgrounds
  [Barger et al., 1990, Barger et al., 1991, Fletcher and Stelzer, 1993, Barger et al., 1995]



- Major issues:
  - Signal efficiency drops with m_N
  - $\alpha_s(p_T^{\text{Veto}}) \log(Q^2/p_T^{\text{Veto}\,2})$ corrections
- Jet veto: NLO + NNLL(veto) resummation within SCET formalism [Alwall et al., 2014, Becher et al., 2015]
- Residual scale uncertainties: $\pm 10/5/2\%$

Dynamical jet veto

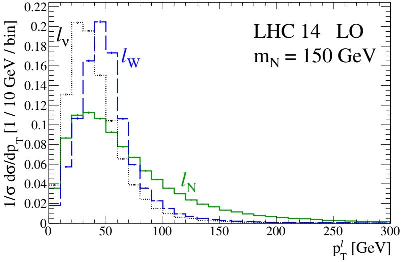
- Idea: Tie the veto scale to the hard scale
- Previously used for EW multiboson production
  [Denner et al., 2009, Nhung et al., 2013, Frye et al., 2016]

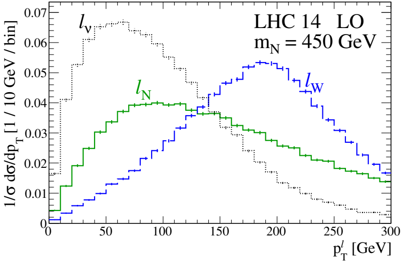


- $p_T^{\text{Veto}} = m_N/2 \Rightarrow Q^2/p_T^{\text{Veto}\,2} \sim 4$
- Logs under control → NLO+PS sufficient for discovery searches
- p_T^{Veto} increases with m_N → No drop in efficiency
- Mismatch here due to $\mathcal{O}(\alpha_S^2)\log R$

- Can be used for τ at NLO since they are colour-disconnected from the initial state

Effective jet veto implementation





- Lepton p_T depends on m_N: $p_T^{\ell_N} \sim \frac{m_N}{5}$

$$p_T^{\ell_W} \sim \frac{m_N}{2}\left(1 - \frac{M_W^2}{m_N^2}\right)$$

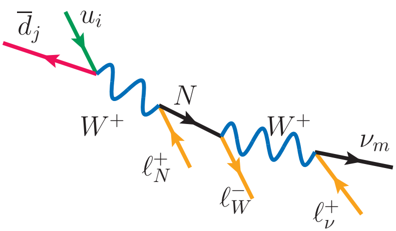
$$p_T^{\ell_W} \sim \frac{m_N}{4}\left(1 + \frac{M_W^2}{m_N^2}\right)$$

- Dominant contributions from on-shell particles
  $\Rightarrow$ Shape largely independent from $\sqrt{s}$
- Use p_T of the leading lepton to define p_T^{Veto}

Signal definition

- Characteristic p_T scales:

$$p_T^{\ell_N} \sim \frac{m_N}{5}$$
$$p_T^{\ell_W} \sim \frac{m_N}{2}$$
$$p_T^{\ell_\nu} \sim \frac{m_N}{4}$$



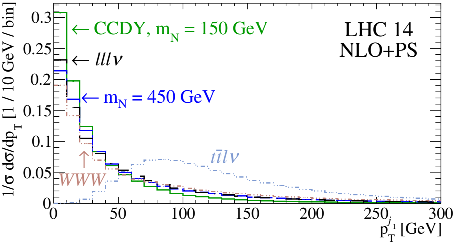
- Selection cuts at the LHC
  - Analysis quality objects + divergences regulation

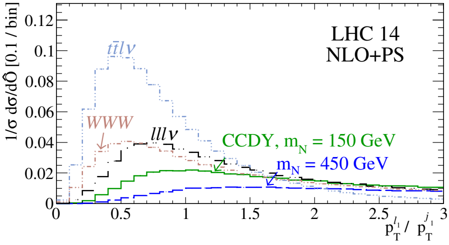
$$p_T^{\ell\ [\tau_h]\ \{j\}} > 15\ [30]\ \{25\}\ \text{GeV}\,,\ |\eta^{\mu,\tau_h}| < 2.4\,,\ |\eta^j| < 2.5\,,\ |\eta^e| < 1.4 \text{ or } 1.6 < |\eta^e| < 2.4$$

  - 3 analysis-quality charged lepton
  - Dynamical jet veto: $p_T^{\text{Veto}} = p_T^{\ell_1}$
  - Sum of p_T: $S_T = p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\ell_3} > 125\ \text{GeV}$
  - Invariant masses: $M_{\ell\ell} > 10\ \text{GeV}$, $|M_{\ell\ell} \text{ or } M_{3\ell} - M_Z| > 15\ \text{GeV}$
  - Mass hypothesis: $-0.15 < \frac{(\tilde{M}_T - m_N^{\text{hypothesis}})}{m_N^{\text{hypothesis}}} < 0.1$

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

Top background

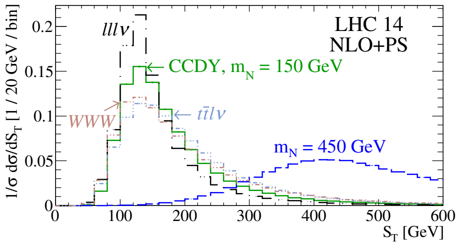


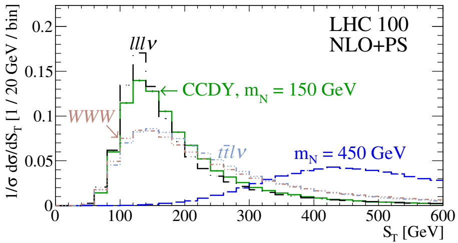


- Single top and top pair + W or Z (e.g $\bar{t}tW$ with $t \to Wb \to \ell\nu b$)
  - $t \to Wb \to \ell\nu b$: $p_T^\ell \sim E_W/2 \approx 50 - 55$ GeV
  - $W \to \ell\nu$ or $Z \to \ell\ell$: $p_T^\ell \sim M_V/2 \sim 40 - 45$ GeV
  - $t \to Wb \to \ell\nu b$: $p_T^b \sim m_t(1 - M_W^2/m_t^2)/2 \approx 60 - 70$ GeV

  $\Rightarrow$ Suppressed by jet veto $p_T^{\text{Veto}} = p_T^{\ell_1}$
- Additional cuts further suppress top background

EW triboson backgrounds





- *WWW* and $WW\ell\ell$
  - Main background that survives cuts in traditional analysis
  - $\mathcal{O}(30\%)$ of inclusive $pp \to WWW$ is $+1j \to$ Taken care of by the jet veto
  - Jet veto forces W to be mostly at rest

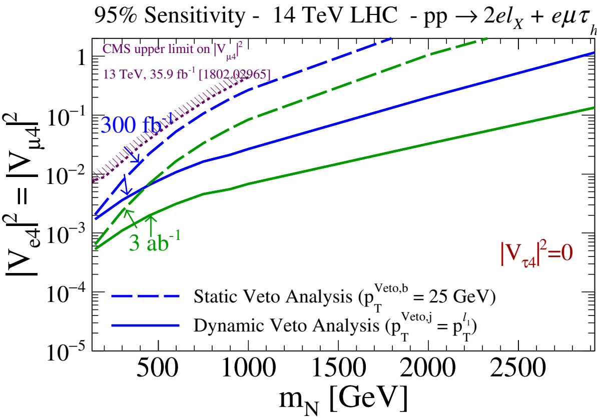
$$S_T^{3W} \equiv \sum_\ell |\vec{p_T}^\ell| \sim 3\frac{M_W}{2} \sim 120\ \text{GeV}$$

$$VS \qquad S_T^N \sim \frac{m_N}{5} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{19}{20}m_N$$

  - Broadening of the distribution at higher $\sqrt{s}$

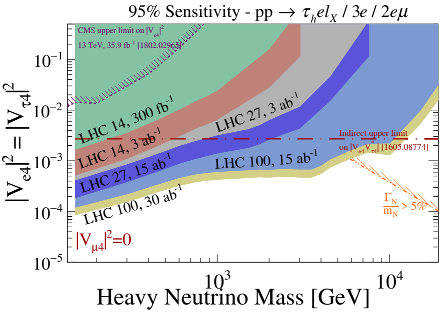
$\Rightarrow$ Suppressed by jet veto + $S_T > 125/150/175\ \text{GeV}$ at $\sqrt{s} = 14/27/100$ TeV

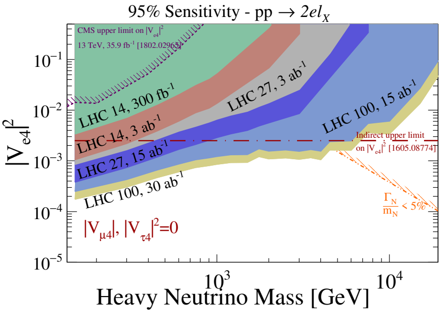
Results



- At low masses, cuts converge to the traditional analysis → similar results
- $\mathcal{O}(10)$ improvement in $|V_{\ell 4}|^2$ reach at high masses
- Above 400 GeV, dynamic veto with 300fb^{-1} performs better than standard analysis with 3ab^{-1}

Future sensitivities





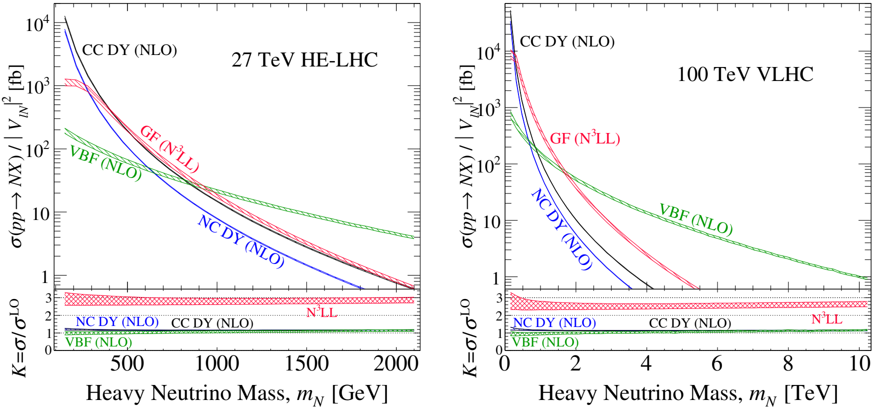
- Able to improve on indirect EWPO constraints at the (HL-)LHC (Run 3 up to 250 GeV, HL-LHC up to 600 GeV)
- Future colliders can probe the $\mathcal{O}(10)$ TeV regime
- Ratios of cross-sections in different final states sensitive to the flavour structure

Conclusions

- ν oscillations → New physics is needed to generate masses and mixing
- One of the simplest ideas: Add right-handed, sterile neutrinos
- Nearly conserved L is a cornerstone of low-scale type I seesaw variants
- Dynamical jet veto:
  - reduces QCD uncertainties
  - improve signal efficiencies
  - improve background rejection
- $\mathcal{O}(10)$ improvement in $|V_{\ell 4}|$ sensitivity in tri-lepton searches for heavy N
- Broadly applicable to other colour singlet processes

Backup slides

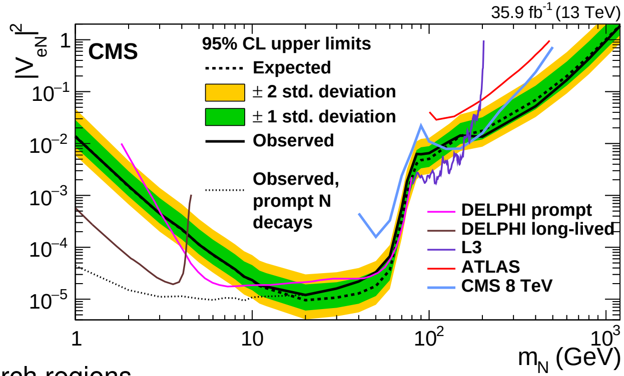
Heavy neutrino production at future colliders



- Gluon fusion larger at higher $\sqrt{s}$ from increased gg luminosity
  $\to$ At 27 TeV, dominates for $m_N \simeq 450 - 900$ GeV
  $\to$ At 100 TeV, dominates for $m_N \simeq 250 - 1750$ GeV
- VBF remains above 1 fb for $m_N = 2(10)$ TeV at $\sqrt{s} = 27(100)$ TeV

Tri-lepton + missing E_T searches

- CMS results on tri-lepton searches [1802.02965]



- 33 search regions
- High mass regime: Cuts on flavour, charge, lepton $p_T > 55, 15, 10\,\mathrm{GeV}$, OSSF $M_{\ell\ell} > 5\,\mathrm{GeV}$, $|M_{\ell\ell}\,\mathrm{or}\,M_{3\ell} - M_Z| < 15\,\mathrm{GeV}$, b jet veto, bins of $M_{2\ell\mathrm{OS}}^{\mathrm{min}}$, $M_{3\ell}$ and M_{T}
- Jets: anti-k_T, $R = 0.4$, $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.4$

EW diboson and fake lepton backgrounds

- Resonant WZ/ZZ
  - Standard cuts

$$m_{\ell_i\ell_j} > 10~\text{GeV}, \qquad |m_{\ell_i\ell_j} - M_Z| > 15~\text{GeV},$$
$$\text{and} \qquad |m_{3\ell} - M_Z| > 15~\text{GeV}$$

  - Applied to all $\ell_i\ell_j$ suppressed charge misID and fake leptons

$\Rightarrow$ Suppressed by invariant mass cuts

- Continuum $\ell\ell\ell\nu/\ell\ell\ell\ell$
  - Forced to be at rest by the jet veto

$\Rightarrow$ Suppressed by jet veto + $S_T > 125 - 175\,\text{GeV}$

- Fake leptons
  - misID rate for low-p_T QCD jet as $e^{\pm}$: $\sim 10^{-4}$
  - misID rate for QCD jet as τ_h: $\sim 10^{-4}$–10^{-2}
  - misIDed jet has to be colour connected to the rest of the event $\rightarrow$ high probability to have additional jets with similar p_T

$\Rightarrow$ Suppressed by jet veto + invariant mass cuts