Low scale seesaw models and collider phenomenology

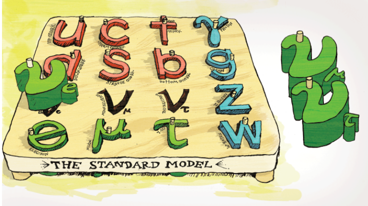
EPJC78(2018)795 – PLB786(2018)106 – arXiv:1812.08750

Cédric Weiland

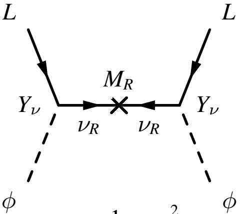
Pitt-PACC, University of Pittsburgh

SUSY 2019
Corpus Christi
22 May 2019

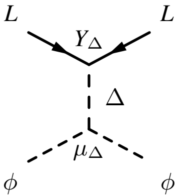
Massive neutrinos and New Physics



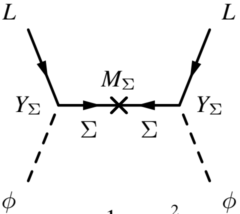
- Observation of ν oscillations
  $\Rightarrow$ at least 2 ν are massive
- BSM necessary for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed 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)

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

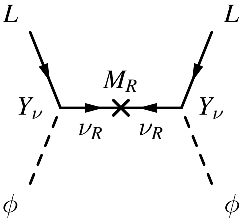
- After EWSB, mixing between active and sterile neutrinos

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

giving the relevant couplings for N production

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

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
  $\rightarrow$ Cancellation in matrix product to get large $m_D M_R^{-1}$

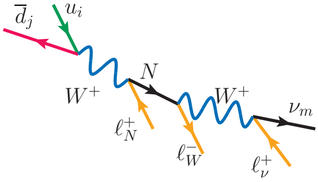
$m_\nu = 0$ equivalent to conserved lepton number for models with arbitrary number of ν_R [Moffat, Pascoli, CW, 2017]

$\Rightarrow$ Nearly conserved L symmetry ensures stability of the cancellation

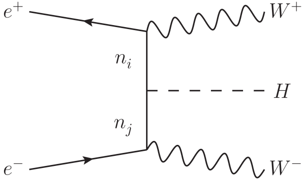
- Explicitly realised in, e.g.
  - low-scale type I [Ilakovac and Pilaftsis, 1995] and others
  - inverse seesaw [Mohapatra and Valle, 1986, Bernabéu et al., 1987]
  - linear seesaw [Akhmedov et al., 1996, Barr, 2004, Malinsky et al., 2005]

Searching for heavy neutrinos at colliders

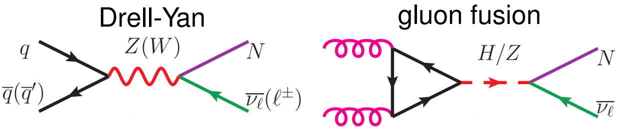
- Review talk this morning by Bhupal Dev
- Direct search at hadron colliders: $pp \to \ell N \to \ell\ell\ell + \not{E}_T$

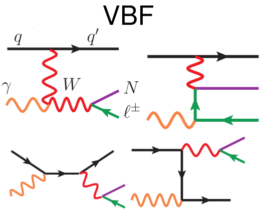


- Indirect search via modified $\sigma(ee \to WWH)$



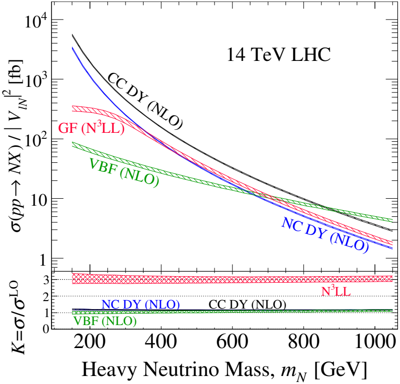
Heavy neutrino production at hadron colliders



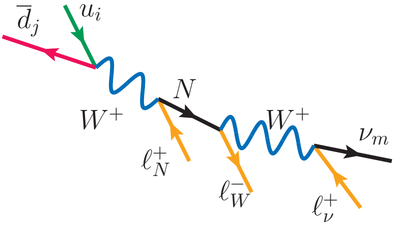


diagrams from [Degrande et al., 2016]

- 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



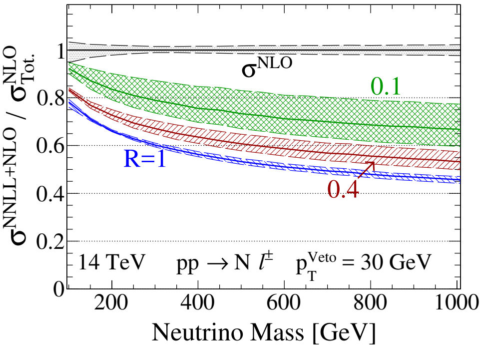
Signal: tri-lepton + MET



- Focus on lepton number conserving final state
- Produced from charged-current Drell-Yan and VBF
- Signal: $pp \to \ell_i^\pm \ell_j^\mp \ell_k^\pm + \not{E}_T$
- Purely leptonic final state → include jet veto in analysis

Jet veto with fixed p_T

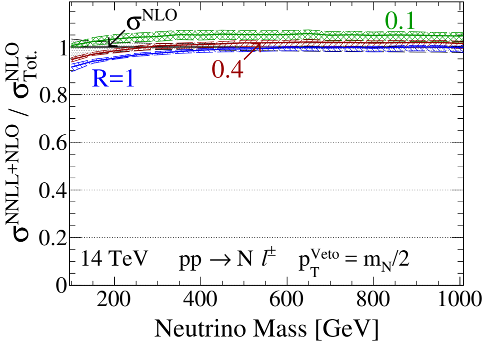
- Jets associated with colour-singlet processes mostly forward and soft
  → veto central and hard jets associated with coloured backgrounds
  [Barger et al., 1990, Barger et al., 1991, Fletcher and Stelzer, 1993, Barger et al., 1995]



- 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

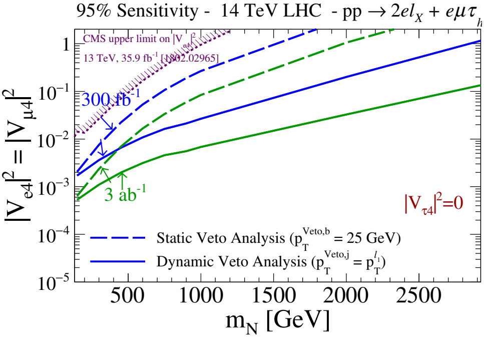
- Idea: Tie the veto scale to the hard scale
- Previously used for EW multiboson production
  [Denner et al., 2009, Nhung et al., 2013, Frye et al., 2016]



- $p_T^{\text{Veto}} = m_N/2 \Rightarrow Q^2/p_T^{\text{Veto}\,2} \sim 4$
- Logs under control → No need for NNLL resummation any more
- 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

Results



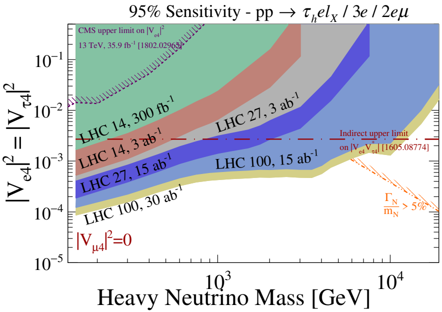
- $p_T^{\ell\ [\tau_h]\ \{j\}} > 15\ [30]\ \{25\}$ GeV, $|\eta^{\mu,\tau_h}| < 2.4$, $|\eta^j| < 2.5$ $|\eta^e| < 1.4$ or $1.6 < |\eta^e| < 2.4$
- Top background: killed by jet veto $p_T^{\text{Veto}} = p_T^{\ell_1}$
- EW triboson: $S_T > 125 - 175\,\text{GeV}$

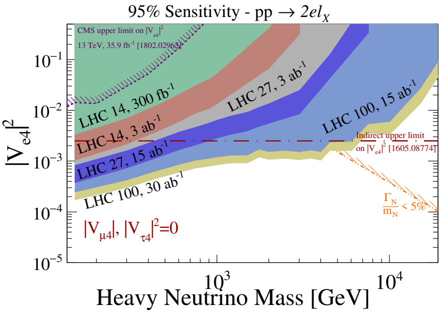
$$S_T^{3W} \equiv \sum_\ell |\vec{p_T}^\ell| \sim 3\frac{M_W}{2} \sim 120\,\text{GeV}$$
$$S_T^N \sim \frac{m_N}{5} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{19}{20} m_N.$$

- EW diboson: $M_{\ell\ell} > 10\,\text{GeV}$, $|M_{\ell\ell}\text{ or }M_{3\ell} - M_Z| < 15\,\text{GeV}$
- Fake leptons: killed by jet veto

- Proxy for m_N: multi-body transverse mass [Barger et al., 1983, Barger et al., 1988]
- $\mathcal{O}(10)$ improvement in $|V_{\ell4}|^2$ reach
- Above 400 GeV, dynamic veto with 300fb^{-1} performs better than standard analysis with 3ab^{-1}

Future sensitivities

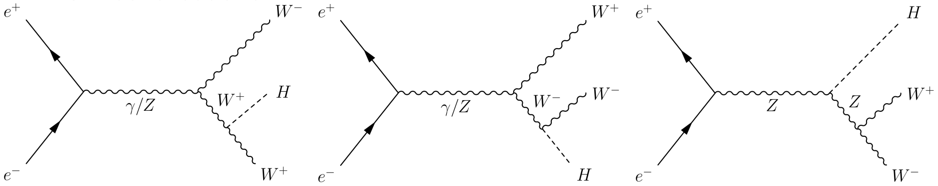




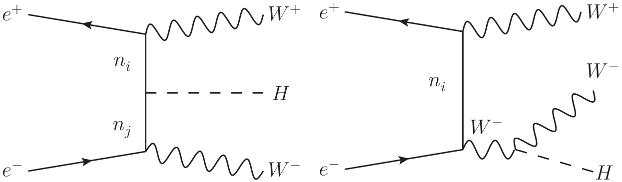
- Able to improve on indirect EWPO constraints at the (HL-)LHC (Run 3 up to 250 GeV, HL-LHC up to 600 GeV)
- Future colliders can probe the $\mathcal{O}(10)$ TeV regime
- Ratios of cross-sections in different final states sensitive to the flavour structure

WWH production

- Idea: Probe Y_ν at tree-level with off-shell N $\Rightarrow$ t-channel $e^+e^- \to W^+W^-H$
- Good detection prospects in SM [Baillargeon et al., 1994]
- SM contributions:

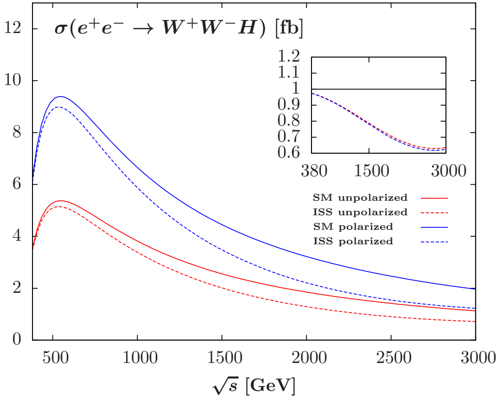


- SM+ISS contributions:



- SM electroweak corrections negligible for $\sqrt{s} > 600\,\mathrm{GeV}$ [Mao et al., 2009]
  $\Rightarrow$ neglected in our analysis

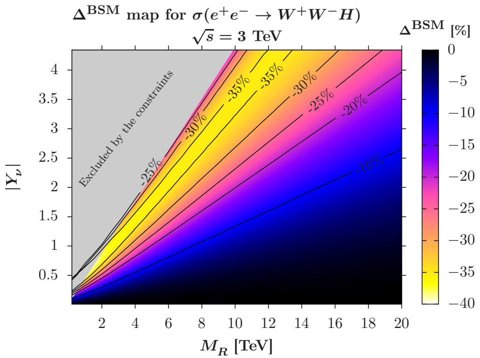
CoM energy dependence



- LO calculation, neglecting m_e
- Calculation done with `FeynArts`, `FormCalc`, `BASES`
- Deviation from the SM in the insert
- Polarized: $P_{e^-} = -80\%$, $P_{e^+} = 0$
- $\sigma(e^+e^- \to W^+W^-H)_{\text{pol}} \sim 2\sigma(e^+e^- \to W^+W^-H)_{\text{unpol}}$
- $Y_\nu = \mathbb{1}$, $M_{R_1} = 3.6\,\text{TeV}$, $M_{R_2} = 8.6\,\text{TeV}$, $M_{R_3} = 2.4\,\text{TeV}$

- Destructive interference between SM and heavy neutrino contributions
- Maximal deviation of -38% close to $3\,\text{TeV}$

Results in the inverse seesaw



- $\Delta^{\rm BSM} = (\sigma^{\rm ISS} - \sigma^{\rm SM})/\sigma^{\rm SM}$
- Polarization $P_{e^-} = -80\%$

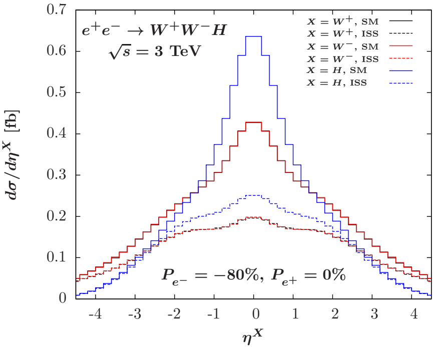
$$\mathcal{A}^{\rm ISS}_{\rm approx} = \frac{(1\ \text{TeV})^2}{M_R^2}\mathrm{Tr}(Y_\nu Y_\nu^\dagger) \times \left(17.07 - \frac{19.79\ \text{TeV}^2}{M_R^2}\right)$$

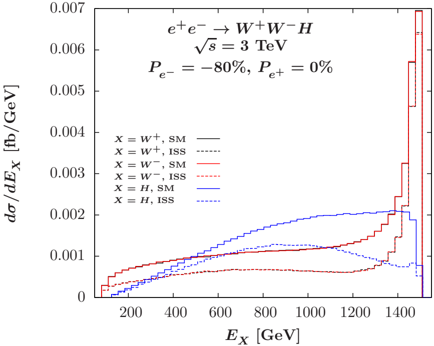
$$\Delta^{\rm BSM}_{\rm approx} = (\mathcal{A}^{\rm ISS}_{\rm approx})^2 - 11.94\,\mathcal{A}^{\rm ISS}_{\rm approx}$$

- Fit agrees within 1% for $M_R > 3\,\mathrm{TeV}$

- Maximal deviation of -38%, $\sigma^{\rm ISS}_{\rm pol} = 1.23\,\mathrm{fb}$
  → ISS induces sizeable deviations in large part of the parameter space
- Provide a new probe of the $\mathcal{O}(10)\,\mathrm{TeV}$ region
  ⇒ Complementary to existing observables

Enhancing the deviations





- Stronger destructive interference from ISS for: – central production
  – larger Higgs energy
- Cuts: $|\eta_H| < 1$, $|\eta_{W^\pm}| < 1$ and $E_H > 1$ TeV

	Before cuts	After cuts
σ_{SM} (fb)	1.96	0.42
σ_{ISS} (fb)	1.23	0.14
Δ^{BSM}	-38%	-66%

Conclusions

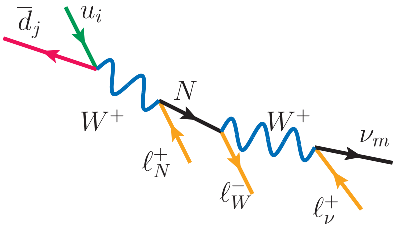
- ν oscillations $\rightarrow$ New physics is needed to generate masses and mixing
- Higgs sector allows new measurement to probe neutrino mass models
- Dynamical jet veto:
  - reduces QCD uncertainties
  - improve signal efficiencies
  - improve background rejection
- $\mathcal{O}(10)$ improvement in $|V_{\ell 4}|$ sensitivity in tri-lepton searches for heavy N
- Broadly applicable to other color singlet processes
- Corrections to W^+W^-H production as large as -66% after cuts at CLIC
- Maximal for diagonal Y_ν and provide new probes of the $\mathcal{O}(10)$ TeV region
- Complementarity with flavor observables

Backup slides

Signal definition

- Characteristic p_T scales:

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



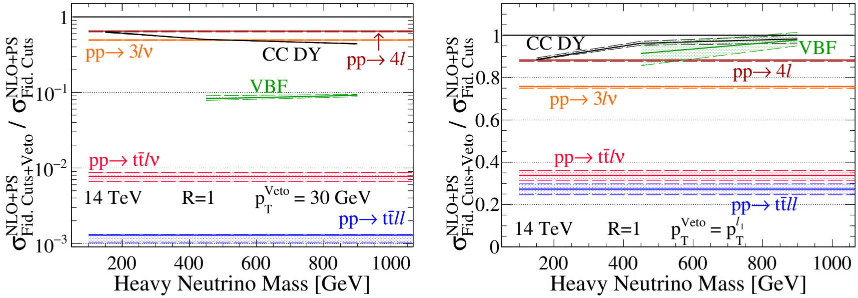
- Selection cuts at the LHC
  - Analysis quality objects + divergences regulation

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

  - 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: $-0.15 < \frac{(\tilde{M}_T - m_N^{\text{hypothesis}})}{m_N^{\text{hypothesis}}} < 0.1$

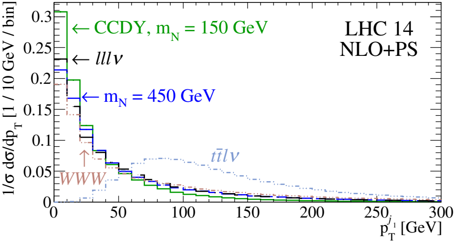
$$\tilde{M}_{T,i}^2 = \left[\sqrt{p_T^2(\ell^{\text{OS}}) + m_{\ell\text{OS}}^2} + \sqrt{p_T^2(\ell_i^{\text{SS}}, \not{\vec{p}}_T) + M_W^2}\right]^2 - \left[\vec{p}_T(\ell^{\text{OS}}, \ell_i^{\text{SS}}) + \not{\vec{p}}_T\right]^2, \quad i = 1, 2$$

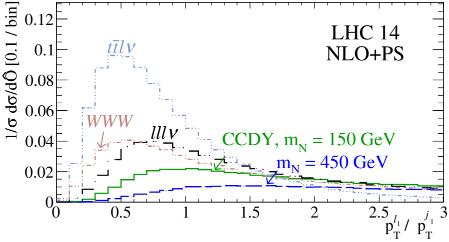
Jet veto efficiencies



- CCDY efficiencies: $45 - 65\%$ vs $90 - 98\%$
  VBF efficiencies: $\mathcal{O}(10)\%$ vs $90 - 98\%$
- 2% CCDY scale uncertainty and behaviour comparable to NLO+NNLL
  $\rightarrow$ NLO+PS is sufficient for discovery searches
- Jet veto useful for rejecting EW background
- Degraded top background rejection from $\ell\nu$ $(\ell\ell)$ recoiling against $t\bar{t}$

Top background

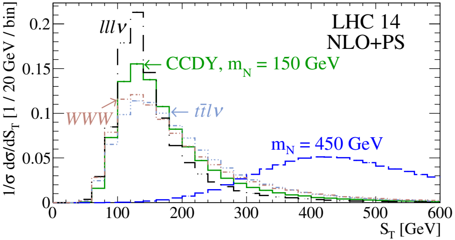


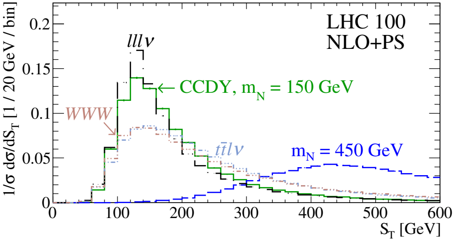


- Single top and top pair + W or Z (e.g $\bar{t}tW$ with $t \to Wb \to \ell\nu b$)
  - $t \to Wb \to \ell\nu b$: $p_T^{\ell} \sim E_W/2 \approx 50 - 55$ GeV
  - $W \to \ell\nu$ or $Z \to \ell\ell$: $p_T^{\ell} \sim M_V/2 \sim 40 - 45$ GeV
  - $t \to Wb \to \ell\nu b$: $p_T^{b} \sim m_t(1 - M_W^2/m_t^2)/2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

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

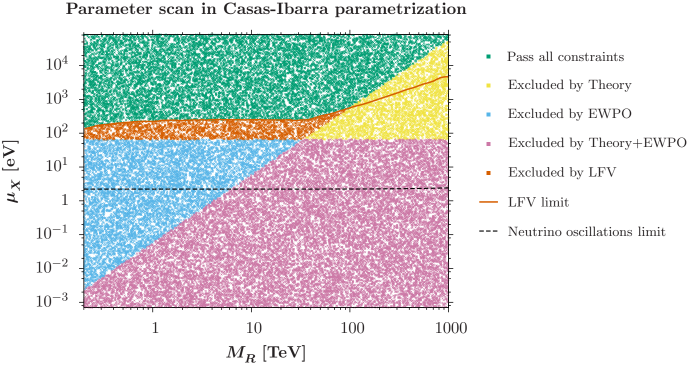
Most relevant constraints for the ISS

- Accommodate neutrino oscillation data using parametrization
  [Casas and Ibarra, 2001; Arganda, Herrero, Marcano, **CW**, 2015; Baglio and **CW**, 2017]

$$\begin{aligned} \mathrm{v} Y_\nu^T &= V^\dagger \mathrm{diag}(\sqrt{M_1}\,, \sqrt{M_2}\,, \sqrt{M_3})\; R\; \mathrm{diag}(\sqrt{m_1}\,, \sqrt{m_2}\,, \sqrt{m_3}) U_{PMNS}^\dagger \\ M &= M_R \mu_X^{-1} M_R^T \\ &\quad \text{or} \\ \mu_X &= M_R^T\; Y_\nu^{-1}\; U_{\mathrm{PMNS}}^* m_\nu U_{\mathrm{PMNS}}^\dagger\; {Y_\nu^T}^{-1} M_R \mathrm{v}^2 \qquad \text{and beyond} \end{aligned}$$

- Charged lepton flavour violation
  → For example: $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
- Global fit to EWPO and low-energy data [Fernandez-Martinez et al., 2016]
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: $M_R > m_H$, does not apply
- Yukawa perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5$

Impact of constraints



- Y_ν increases when M_R increases and/or μ_X decreases
- Strongest constraints:
  - Lepton flavour violation, mainly $\mu \to e\gamma$
  - Yukawa perturbativity (and neutrino width)
- Larger Y_ν (and effects) necessarily excluded by LFV constraints ?
  $\to$ Switch to μ_X-parametrization and use diagonal Y_ν