Low scale seesaw models and collider phenomenology

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Massive neutrinos and New Physics

- Observation of $\nu$ oscillations
  ⇒ at least 2 $\nu$ are massive

- BSM necessary for $\nu$ mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms

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

\[
\begin{align*}
\nu_R & \rightarrow Y^\nu \nu_R \\
\Delta^{\pm \pm} & \rightarrow Y^\Delta \Delta^{\pm \pm} \\
\Sigma^+ & \rightarrow Y^\Sigma \Sigma^+
\end{align*}
\]

\[
\begin{align*}
m_\nu &= -\frac{1}{2} Y^\nu \frac{v^2}{M_R} Y^\nu_T \\
m_\nu &= -2 Y^\Delta v^2 \frac{\mu \Delta}{M_\Delta^2} \\
m_\nu &= -\frac{1}{2} Y^\Sigma v^2 \frac{Y^{\Sigma T}}{M_\Sigma}
\end{align*}
\]
Properties of type I seesaw and variants

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

\[ \mathcal{L}_{\text{type I}} = -Y_\nu \mathcal{L} \bar{\nu}_R \nu_R - \frac{1}{2} M_R \bar{\nu}_R \nu_R + \text{h.c.} \]

- After EWSB, mixing between active and sterile neutrinos

\[
\begin{pmatrix}
\nu_L \\
\nu^c_R \\
\nu_R
\end{pmatrix}_{\text{gauge}} =
\begin{pmatrix}
U & V \\
W & X
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
N
\end{pmatrix}_{\text{mass}}
\]

\text{giving the relevant couplings for N production}

\[
\mathcal{L}_{\text{Int.}} = - \frac{g}{\sqrt{2}} W^+ \mathcal{N} V^* \gamma^\mu P_L \ell^-
\]
\[- \frac{g}{2 \cos \theta_W} Z \mathcal{N} V^* \gamma^\mu P_L \nu_\ell
\]
\[- \frac{g m_N}{2 M_W} h \mathcal{N} V^* P_L \nu_\ell + \text{h.c.},
\]
Towards testable Type I variants

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

$$m_\nu = -m_D M_R^{-1} m_D^T$$

$$m_\nu \sim 0.1 \text{ eV} \Rightarrow Y_\nu \sim 1 \text{ and } M_R \sim 10^{14} \text{ GeV}$$

$$Y_\nu \sim 10^{-6} \text{ and } M_R \sim 10^2 \text{ GeV}$$

- $V \sim m_D M_R^{-1}$ 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 $\nu_R$ [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] 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: \( pp \rightarrow \ell N \rightarrow \ell\ell\ell + \not{E}_T \)

![Diagram of direct search process](image)

- **Indirect** search via modified \( \sigma(ee \rightarrow WWH) \)

![Diagram of indirect search process](image)
Heavy neutrino production at hadron colliders

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 $m_N \approx 900$ GeV

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: $pp \rightarrow \ell_i^\pm \ell_j^\mp \ell_k^\pm + \not{E}_T$
- Purely leptonic final state $\rightarrow$ include jet veto in analysis
Tri-lepton searches and safe jet veto

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 $\Rightarrow$ No need for NNLL resummation any more
- $p_T^{\text{Veto}}$ increases with $m_N$
  $\Rightarrow$ No drop in efficiency
- Mismatch here due to $O(\alpha_S^2) \log R$

- Can be used for $\tau$ at NLO since they are colour-disconnected from the initial state
Tri-lepton searches and safe jet veto

Results

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

- Top background: killed by jet veto  
  $p_T^{Veto} = p_T^{\ell_1}$

- EW triboson: $S_T > 125 - 175 \text{ GeV}$  
  $S_T^{3W} \equiv \sum_\ell |p_T^{\ell}| \sim 3 \frac{M_W}{2} \sim 120 \text{ GeV}$  
  $S_T^N \sim \frac{m_N}{5} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{19}{20} m_N.$

- 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 $|V_{\ell 4}|^2$ reach

- Above 400 GeV, dynamic veto with $300 \text{ fb}^{-1}$ performs better than standard analysis with $3 \text{ ab}^{-1}$
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 $Y_\nu$ at tree-level with off-shell N $\Rightarrow$ t-channel $e^+e^- \rightarrow W^+W^-H$
- **Good detection prospects in SM** [Baillargeon et al., 1994]
- **SM contributions:**

  ![Diagram of SM contributions]

- **SM+ISS contributions:**

  ![Diagram of SM+ISS contributions]

- **SM electroweak corrections negligible for $\sqrt{s} > 600$ 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: $P_{e^-} = -80\%$, $P_{e^+} = 0$
- $\sigma(e^+e^- \to W^+ W^- H)_{\text{pol}} \sim 2\sigma(e^+e^- \to W^+ W^- H)_{\text{unpol}}$
- $Y_{\nu} = 1$, $M_{R_1} = 3.6 \text{ TeV}$, $M_{R_2} = 8.6 \text{ TeV}$, $M_{R_3} = 2.4 \text{ TeV}$

- Destructive interference between SM and heavy neutrino contributions
- Maximal deviation of $-38\%$ close to 3 TeV
Results in the inverse seesaw

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

\[
A_{approx}^{ISS} = \frac{(1 \text{ TeV})^2}{M_R^2} \text{Tr}(Y_\nu Y_\nu^\dagger) \\
\times \left( 17.07 - \frac{19.79 \text{ TeV}^2}{M_R^2} \right)
\]

- \( \Delta_{BSM}^{approx} = (A_{approx}^{ISS})^2 - 11.94 A_{approx}^{ISS} \)

- Fit agrees within 1\% for \( M_R > 3 \text{ TeV} \)

- Maximal deviation of \(-38\%\), \( \sigma_{pol}^{ISS} = 1.23 \text{ fb} \)

\( \Rightarrow \) ISS induces sizeable deviations in large part of the parameter space

- Provide a new probe of the \( \mathcal{O}(10) \) TeV region

\( \Rightarrow \) 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

<table>
<thead>
<tr>
<th></th>
<th>Before cuts</th>
<th>After cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{SM}}$ (fb)</td>
<td>1.96</td>
<td>0.42</td>
</tr>
<tr>
<td>$\sigma_{\text{ISS}}$ (fb)</td>
<td>1.23</td>
<td>0.14</td>
</tr>
<tr>
<td>$\Delta_{\text{BSM}}$</td>
<td>$-38%$</td>
<td>$-66%$</td>
</tr>
</tbody>
</table>
Conclusions

- $\nu$ 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 $Y_\nu$ and provide new probes of the $\mathcal{O}(10)$ TeV region
- Complementarity with flavor observables
Backup slides
Signal definition

- Characteristic $p_T$ scales:
  
  \[
  p_T^{\ell_N} \sim \frac{m_N}{5} \\
  p_T^{\ell_W} \sim \frac{m_N}{2} \\
  p_T^{\ell_V} \sim \frac{m_N}{4}
  \]

- Selection cuts at the LHC
  
  - Analysis quality objects + divergences regulation
  \[
  p_T^{[\tau_h]} \{j\} > 15 [30] \{25\} \text{ GeV}, \quad |\eta^{\mu, \tau_h}| < 2.4, \quad |\eta^{j}| < 2.5, \quad |\eta^{e}| < 1.4 \text{ or } 1.6 < |\eta^{e}| < 2.4
  \]
  
  - 3 analysis-quality charged lepton
  
  - Dynamical jet veto: $p_T^{\ell_1} = p_T^{\ell_{Veto}}$
  
  - Sum of $p_T$: $S_T = p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\ell_3} > 125 \text{ GeV}$
  
  - Invariant masses: $M_{\ell\ell} > 10 \text{ GeV}, \quad |M_{\ell\ell} \text{ or } M_{3\ell} - M_Z| > 15 \text{ GeV}$
  
  - Mass hypothesis: $-0.15 < \frac{(\tilde{M}_T - m_N^{\text{hypothesis}})}{m_N^{\text{hypothesis}}} < 0.1$

  \[
  \tilde{M}_{i,2}^2 = \left[ \sqrt{p_T^2(\ell^{OS}) + m_{\ell^{OS}}^2} + \sqrt{p_T^2(\ell_{i}^{SS}, \not{p_T}) + M_W^2} \right]^2 - \left[ \not{p_T}(\ell^{OS}, \ell_{i}^{SS} + \not{p_T}) \right]^2, \quad i = 1,2
  \]
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
  - 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 $\bar{t}t$

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Heavy N at colliders
Top background

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

$\Rightarrow$ Suppressed by jet veto $p^\nu V^\text{Veto}_T = p^\nu p^\ell_T$

- Additional cuts further suppress top background
**EW triboson backgrounds**

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

\[
S^3_W = \sum_\ell |p_T^\ell| \sim 3 \frac{M_W}{2} \sim 120 \text{ GeV}
\]

\[
S^N_T \sim \frac{m_N}{5} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{19}{20} m_N
\]

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

$\Rightarrow$ Suppressed by jet veto $+ S_T > 125/150/175$ GeV at $\sqrt{s} = 14/27/100$ TeV
EW diboson and fake lepton backgrounds

- **Resonant $WZ/ZZ$**
  - Standard cuts
    \[
    m_{\ell_i\ell_j} > 10 \text{ GeV}, \quad |m_{\ell_i\ell_j} - M_Z| > 15 \text{ GeV}, \\
    \text{and} \quad |m_{3\ell} - M_Z| > 15 \text{ GeV}
    \]
  - Applied to all $\ell_i\ell_j$ suppressed charge misID and fake leptons
    ⇒ **Suppressed by invariant mass cuts**

- **Continuum $\ell\ell\ell\nu/\ell\ell\ell\ell$**
  - Forced to be at rest by the jet veto
    ⇒ **Suppressed by jet veto + $S_T > 125 - 175$ GeV**

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

  \[\nu Y^T_\nu = V^\dagger \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) R \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{\text{PMNS}}^\dagger\]

  \[M = M_R \mu_X M_R^T\]

  or

  \[\mu_X = M_R^T Y^{-1}_\nu U_{\text{PMNS}}^* m_\nu U_{\text{PMNS}}^\dagger Y^{-1}_\nu M_R \nu^2\]

  and beyond

- Charged lepton flavour violation
  \[\text{For example: } \text{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \quad \text{[MEG, 2016]}\]

- 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: \(|\frac{Y^2_\nu}{4\pi}| < 1.5\)
Impact of constraints

- $Y_\nu$ increases when $M_R$ increases and/or $\mu_X$ decreases

- Strongest constraints:
  - Lepton flavour violation, mainly $\mu \rightarrow e\gamma$
  - Yukawa perturbativity (and neutrino width)

- Larger $Y_\nu$ (and effects) necessarily excluded by LFV constraints?
  - Switch to $\mu_X$-parametrization and use diagonal $Y_\nu$