Probing Radiative Neutrino Mass Generation through Monotop Production

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Outline

• Motivation

• Model
  • Dark Matter
  • Neutrinos masses

• Constraints

• Monotop Probe

• Summary
• Two important questions in the field of High Energy physics:
  • **Neutrino mass generation.**
  
• **Nature of Dark Matter.**

• **Cosmological results based on Planck’s measurements of the CMB:**
  • $\Omega_c h^2 = 0.1199 \pm 0.0027$
  
• $N_{eff} = 3.30 \pm 0.27$  Planck Collaboration arXiv:1303.5076
Introduce a model of physics beyond the Standard Model which can naturally generate small neutrino masses while providing a viable candidate for the dark matter present in our universe.
Model

- Use the top quark as a dark portal and for neutrino mass generation:
Dark Matter:

• **Extension of the Standard Model:**
  • $Z_2$ yields a viable dark matter candidate.

\[
\mathcal{L}_{BSM} = \sum_{i=u,c,t} y^u_i \bar{u}_i P_L N^c \psi + \text{h.c.}
\]

Y. Bai and J. Berger
S. Chang, R. Edezhath, J. Hutchinson, and M. Luty
M. Garny, A. Ibarra, S. Rydbeck, and S. Vogl
Dark Matter:

- **Extension of the Standard Model:**
  - $Z_2$ yields a viable dark matter candidate: $M_{NR} < m_\psi$

- Annihilation only into lights quarks is p-wave suppressed.
- Non-zero coupling to the top quark leads to an s-wave contribution.
The green region corresponds to the grey region corresponds to a thermalized cross section in the $t$-channel exchanges of the coloured electroweak-singlet, while for annihilation mainly into $\nu\bar{\nu}$. Within our framework, the region consistent with the co-annihilation channel becomes important if the mass difference $\Delta M = M_{R\psi} - M_N$ is small compared to the freeze-out temperature of the Majorana fermion $T_{\text{fo}}$. We would also like to emphasize that co-annihilation effects become important. The co-annihilation channels contribute to the relic abundance calculation are neglected.

Co-annihilation effects can be safely neglected:

$$N_R\psi^\dagger \rightarrow u/c/t, g, \psi\psi^\dagger$$

- **c-quark**
- **t-quark**
Direct Detection:

- **Majorana fermion has chiral symmetric interactions:**
- **Scattering is dominated by spin dependent interactions.**

\[ M = \frac{(y^u_\psi)^2}{4(m_\psi^2 - M_{N_R}^2)} N_R \gamma^\mu \gamma^5 N_R \langle \bar{u} \gamma_\mu \gamma^5 u \rangle \]
Neutrino mass generation:

- Conserved $Z_2$ prevents Dirac neutrino mass terms for the active neutrinos.
- Incorporate two coloured electroweak-triplet scalars.

$$
\chi = \begin{pmatrix} \chi_2 / \sqrt{2} & \chi_1 \\ \chi_3 & -\chi_2 / \sqrt{2} \end{pmatrix} : (3, 3, -1/3)
$$

$$
\omega = \begin{pmatrix} \omega_2 / \sqrt{2} & \omega_1 \\ \omega_3 & -\omega_2 / \sqrt{2} \end{pmatrix} : (3, 3, 2/3)
$$
Neutrino mass generation:

- Conserved $Z_2$ prevents Dirac neutrino mass terms for the active neutrinos.
- Incorporate two coloured electroweak-triplet scalars.

\[
\mathcal{L}_{BSM} = \sum_{i=u,c,t} y^u_{\psi} \bar{u}_i P_L N^c_i \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_{\ell} \left[ \bar{t} P_R (\chi_1 \nu^c_{\ell} + \chi_2 \ell^c) + \bar{b} P_R (\chi_3 \ell^c - \chi_2 \nu^c_{\ell}) \right] \right\} + \frac{1}{2} M_{N_R} \bar{N}^c N + \text{h.c.}
\]

\[
V(H, \psi, \chi, \omega) = -\mu^2 H^\dagger H + \frac{\lambda}{4!} (H^\dagger H)^2 + m^2_T r (\chi^\dagger \chi) + m^2_T r (\psi^\dagger \psi) + \lambda_T (Tr \chi^\dagger \chi)^2 + \lambda_\omega (Tr \omega^\dagger \omega)^2 + \lambda_\psi (\psi^\dagger \psi)^2 + \kappa_1 H^\dagger H (Tr \chi^\dagger \chi) + \kappa_2 H^\dagger \chi^\dagger \chi H + \kappa_3 H^\dagger H \psi^\dagger \psi + \kappa_4 H^\dagger H \omega^\dagger \omega H + \kappa_5 H^\dagger \omega^\dagger \omega H + \kappa_1 (Tr \chi^\dagger \chi) \psi^\dagger \psi + \kappa_2 (Tr \omega^\dagger \omega) \psi^\dagger \psi + \kappa_3 (Tr \omega^\dagger \omega) \psi^\dagger \psi + \kappa_4 (Tr \omega^\dagger \omega) \psi^\dagger \psi + \rho_1 (Tr \chi^\dagger \chi) \psi^\dagger \psi + \rho_2 (Tr \omega^\dagger \omega) \psi^\dagger \psi + \rho_3 (Tr \omega^\dagger \omega) \psi^\dagger \psi + \alpha T r H^T \sigma_2 \chi \omega^\dagger H + \tilde{V}(\chi, \omega) + \text{h.c}
\]
Neutrino mass generation:

- Conserved $Z_2$ prevents Dirac neutrino mass terms for the active neutrinos.

\[
\begin{align*}
\mathcal{L}_{BSM} &= \bar{u}_i \psi (\chi_1 \nu_c + \chi_2 \nu_c) + \bar{t} \lambda (\chi_1 \nu_c - \chi_2 \nu_c) + \frac{1}{2} M_{\nu_R} \bar{N} c N c + h.c. \\
V(H, \psi, \chi, \omega) &= -\mu^2 H^\dagger H + \frac{\lambda}{4!} (H^\dagger H)^2 + m^2 \chi \text{Tr} \chi^\dagger \chi + m^2 \omega \text{Tr} \omega^\dagger \omega + m^2 \psi \psi^\dagger \psi + \lambda \chi \text{Tr} \chi^\dagger \chi^2 + \lambda \omega (\text{Tr} \omega^\dagger \omega)^2 + \lambda \psi \psi^\dagger \psi^2 + \kappa_1 H^\dagger H \text{Tr} \chi^\dagger \chi + \kappa_2 H^\dagger \chi^\dagger c \chi H + \kappa_3 H^\dagger H \psi \psi^\dagger + \kappa_4 H^\dagger H \text{Tr} \omega^\dagger \omega + \kappa_5 H^\dagger \omega^\dagger \omega H + \rho_1 \text{Tr} \chi^\dagger \chi \psi^\dagger \psi + \rho_2 \text{Tr} \omega^\dagger \omega \psi^\dagger \psi + \rho_3 \text{Tr} \omega^\dagger \omega \psi^\dagger \omega + \alpha \text{Tr} H^\dagger \sigma^2 \chi \omega^\dagger H + \tilde{V}(\chi, \omega) + h.c.
\end{align*}
\]
Neutrino mass generation:

- Conserved $Z_2$ prevents Dirac neutrino mass terms for the active neutrinos.
- Incorporate two coloured electroweak-triplet scalars.

$$L_{BSM} = \sum_{i=u,c,t} y_{\psi}^{u_i} \bar{u}_i P_L N^c \psi + \sum_{\ell=e,\mu,\tau} \{ \lambda_\ell \left[ \bar{t} P_R (\chi_1 \nu^c_\ell - \chi_2 \nu^c_\ell) + \bar{b} P_R (\chi_3 \nu^c_\ell - \chi_2 \nu^c_\ell) \right] \} + \frac{1}{2} M_{N_R} \bar{N}^c N + \text{h.c.}$$

$$V(H, \psi, \chi, \omega) = -\mu^2 H^\dagger H + \frac{\lambda}{4!} (H^\dagger H)^2 + m_\chi^2 \text{Tr} (\chi^\dagger \chi) + m_\omega^2 \text{Tr} (\omega^\dagger \omega) + m_\psi^2 \psi^\dagger \psi + \lambda_\chi (\text{Tr} \chi^\dagger \chi)^2$$

$$+ \lambda_\omega (\text{Tr} \omega^\dagger \omega)^2 + \lambda_\psi (\psi^\dagger \psi)^2 + \kappa_1 H^\dagger H (\text{Tr} \chi^\dagger \chi) + \kappa_2 H^\dagger \chi^\dagger \chi H$$

$$+ \kappa_3 H^\dagger H \psi^\dagger \psi + \kappa_4 H^\dagger H T \omega^\dagger \omega + \kappa_5 H^\dagger \omega^\dagger \omega H + \rho_1 (\text{Tr} \chi^\dagger \chi) \psi^\dagger \psi$$

$$+ \rho_2 (\text{Tr} \omega^\dagger \omega) \psi^\dagger \psi + \rho_3 \text{Tr} (\omega^\dagger \psi \omega^\dagger \psi) + \chi \text{Tr} H^T \sigma_2 \omega^\dagger \omega H + \tilde{V}(\chi, \omega) + \text{h.c.}$$
Figure 2: 3-loop generation of a Majorana mass for active neutrinos. The crosses on the fermion lines indicate mass insertions following general structure

\[ M_{\nu} = K \sum_{i,j} \chi_i \chi_j \]

where \( K \) is a common factor that arises from the 3-loop integral and controls the scale of neutrino masses. Explicitly

\[ K = \frac{y_{\psi}^i y_{\psi}^j \rho (16\pi^2)^3}{(m_\chi^2 - m_i^2)(m_\chi^2 - m_j^2)} I(m_\chi^2, m_\psi^2, m_i^2, m_j^2), \]

\[ (M_{\nu})_{\ell \ell'} = \sum_{i,j} K^{i,j} \chi_i \chi_j \]

\[ (M^\nu)_{\ell \ell'} = \sum_{i,j} K^{i,j} \chi_i \chi_j \]

As seen previously in order to get the correct relic density for \( N_R \) we have \( M_{NR} \approx m_t \) and \( y_\psi \sim 0.5 \). We have conservatively taken \( M_\chi = 1 \text{ TeV} \). Using these values we estimate \( K \sim 1 \text{ eV} \) for \( \rho = 0 \) and \( I \sim M_{NR}^2 \). Thus, a millivolt active neutrino mass is quite natural in this model.
• Rare muon and b decays: Sensitive to coloured electroweak-triplets.

\[
\mathcal{L}_{BSM} = \sum_{i=u,c,t} y^{ui}_\psi \bar{u}_iP_L N^c_i \psi + \sum_{\ell=e,\mu,\tau} \left\{ \lambda_\ell \left[ \bar{t}P_R (\chi_1 \nu_\ell^c + \chi_2 \ell^c) + \bar{b}P_R (\chi_3 \ell^c - \chi_2 \nu_\ell^c) \right] + \text{h.c.} \right\}
\]

\[
\text{Br} (\mu \rightarrow e\gamma) = 7.2 \times 10^{-6} \left( \frac{m_{e\mu}}{K_{t,t}} \right)
\]

\[
m_{e\mu} = 1.5 - 8.8 \text{ meV}
\]
- **D meson oscillations:**

\[
\Delta M_D = \left( y_u^u y_c^c \right)^2 \frac{f_D M_D}{64\pi^2 m_\psi} \frac{2}{3} B_D \beta(m_c, m_m_\psi) |L(\eta)|
\]

\[
x_D = \frac{\Delta M_D}{\Gamma_D} = 0.43^{+0.15}_{-0.16}\%.
\]

*arXiv:1207.1158*
**Collider constraints:** SUSY searches (stop pair-production), monojet+MET and jets+MET
• **Collider constraints:** SUSY searches (stop pair-production), monojet+MET and jets+MET

![Feynman diagrams](image)
In order to show the available parameter space consistent with the present dark matter abundance and all of the constraints discussed in the previous section, we present our results in the $M_\psi - M_N$ plane.

**FIG. 10.** Allowed region of parameter space consistent with the density of dark matter as measured by Planck [6] (red solid line) after taking into account all constraints discussed in Section V for $y_t^{\psi} = 1$ and $y_c,u^{\psi} = 0.1$.

The dark grey region is excluded since we have assumed that $m_\psi > M_N R$ in order for $N_R$ to be the lightest stable particle under the dark parity. The region below the green solid line is excluded by searches for pair produced top squarks at the LHC. This is consistent with what we discussed in Section V E 3 where in the limit $y_t^{\psi} \rightarrow 1$ and $y_c,u^{\psi} \rightarrow 0$, the branching ratio $BR(\psi \rightarrow N_R t) \approx 1$, thus the coloured electroweak-singlet resembles a top squark that decays to a top quark and a neutralino as in supersymmetric extensions of the Standard Model.
Monotop probe

- Single top quark production in association with missing energy (MET) at the LHC.

- Apply search strategy for the semi-leptonic decay modes of the top quark at 8 and 14 TeV.
Semi-leptonic mode signal 8 TeV:

\[ t + N_R N_R \rightarrow b l \nu + N_R N_R \]

- Main Backgrounds:
  - \( tt \)
  - \( tj + tW \)
  - \( Wj \) and \( Zj \)
  - Di-boson
  - Less likely to be contaminated by QCD multijet background. Little contamination from mis-reconstructed jet (\( p_T \) cut).
Semi-leptonic mode signal 8 TeV:

\[ t + N_R N_R \rightarrow bl\nu + N_R N_R \]

- **Pre-selection:**
  - Require events with a lepton: \( p_T > 20 \text{ GeV}, \ |\eta| < 2.5 \)
  - Require one b-jet to with \( p_T > 20 \text{ GeV}, \ |\eta| < 2.5 \).
  - At most one light jet.

arXiv:1310.7600
Semi-leptonic mode signal 8 TeV:

- Two signal regions defined by the amount of missing energy and the transverse mass of the charged lepton, $M_T$, to probe the small and large $m_\psi$ regions.

$s_1 : m_\psi = 150$ GeV, $M_{NR} = 80$ GeV
$s_2 : m_\psi = 700$ GeV, $M_{NR} = 210$ GeV
Semi-leptonic mode signal 8 TeV (20 fb⁻¹):

<table>
<thead>
<tr>
<th>SM background</th>
<th>( N^{E&gt;90 \text{ GeV}, M_T&gt;110 \text{ GeV}} ) (( \sigma ) [pb])</th>
<th>( N^{E&gt;200 \text{ GeV}, M_T&gt;120 \text{ GeV}} ) (( \sigma ) [pb])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W \rightarrow l\nu ) + jets</td>
<td>212 (0.011)</td>
<td>&lt; 7 (&lt; 3.41 \times 10^{-4})</td>
</tr>
<tr>
<td>( Z ) + jets</td>
<td>&lt; 3 (&lt; 1.54 \times 10^{-4})</td>
<td>&lt; 3 (&lt; 1.54 \times 10^{-4})</td>
</tr>
<tr>
<td>( t\bar{t} ) + jets</td>
<td>1327 (0.066)</td>
<td>49 (2.46 \times 10^{-3})</td>
</tr>
<tr>
<td>( t , j + t \ W )</td>
<td>242 (0.012)</td>
<td>&lt; 2 (&lt; 1.15 \times 10^{-4})</td>
</tr>
<tr>
<td>( WW )</td>
<td>2 (1.15 \times 10^{-4})</td>
<td></td>
</tr>
<tr>
<td>( WZ )</td>
<td>1 (6.86 \times 10^{-5})</td>
<td></td>
</tr>
<tr>
<td>( ZZ )</td>
<td>*** (&lt; 7.94 \times 10^{-6})</td>
<td></td>
</tr>
</tbody>
</table>

- Missing energy from mis-reconstructed jets.

- 1 b-jet
- 0-1 light jets with \( p_{T,j} < 70, 120 \text{ GeV} \).

arXiv:1310.7600
Semi-leptonic mode signal 8 TeV (20 fb⁻¹):

- MET > 200 GeV, M_T > 120 GeV
- MET > 90 GeV, M_T > 110 GeV
Semi-leptonic mode signal 14 TeV:

- SM backgrounds using \textit{k-factors} from 8 TeV cross sections.
- Wj and Zj backgrounds suppressed by a combination of lepton isolation, b-tagging and M_T cuts.
- However, for large collider energies, a large MET cut is necessary.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Process & \sigma [pb] \\
\hline
W + jets & $2.19 \times 10^5$ \\
Z + jets & $6.66 \times 10^4$ \\
tt+ jets & 1052.93 \\
tj+tW & 347.42 \\
WW & 119.84 \\
WZ & 48.87 \\
ZZ & 17.09 \\
\hline
\end{tabular}
\end{table}

$y^t_\psi = 1$, $y^u_\psi = 0.5$, $m_\psi = 700$ GeV, $M_{NR} = 210$ GeV

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
$\mathcal{L}$ [fb^{-1}] & $\sigma (tt + \text{jets})$ [pb], N & $\sigma (tj + tW)$ [pb], N & $\sigma_{signal}$ [pb], N \\
\hline
30 & $6.31 \times 10^{-3}$, 189 & $1.39 \times 10^{-3}$, 42 & $6.85 \times 10^{-4}$, 21 \\
300 & 1892 & 417 & 205 \\
\hline
\end{tabular}
\end{table}

- MET > 200 GeV, M_T > 120 GeV and $p_{T,j} < 120$ GeV
In addition, over the whole range of contributions from the up and charm quarks are proportional to $t$ Equation 47. The black dashed line corresponds to the signal with tagging boosted tops. Within our framework, the relic abundance can match the latest experimental results over a wide range of boosted tops and how they are tagged is an active field of research. Nonetheless, one can start to better discriminate the signal SM backgrounds. Simulating these backgrounds will require the combined effects on models that predict a monotop signal at large centre of mass energies, together with a full implementation of the QCD multijet background.

In Figure 24 we show the fraction of events as a function of the transverse momentum of the reconstructed top quark, $p_T$, with three, four and five sigma are depicted by the dashed black, blue and green lines respectively. The signal strength is also shown for $(1 - y^u_y, y^u_y) = (0.5, 0.5)$.

**VIII. DISCUSSION**

Concerning the relic abundance of dark matter in the universe. The constraints from experimentalists and theorists ch [71–76] and it would be very interesting to see its interesting since this region of parameter space is consistent with the well established SM backgrounds by treating the dark matter and nuclei. The constraints on models that predict a monotop signal at large centre of mass energies, together with a full implementation of the QCD multijet background.
• A weakly interacting massive particle is still a very attractive candidate to address the nature of dark matter.
• We must use not only astrophysical resources to address the nature of dark matter but the power of hadron colliders.
• The existence of dark matter may be inferred through exotic processes as well as properties of SM particles.
• Next run at the LHC may begin to probe monotop production.
• It may lead to evidence of the underlying mechanism the bestows neutrinos with mass.
Back-up Slides
Dark matter - nucleon scattering: $y_{\psi}^{u} = 0.5$

protons

neutrons

![Graphs showing cross-sections for dark matter-nucleon scattering for protons and neutrons.](Image)
$\rho = 0.1, \ m_\chi = 1 \text{ TeV}$

$y^t_\psi \approx 1$

$y^t_\psi \approx 0$