See-saw mediators in t-channel

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BSM direct searches at CLIC, 21 February 2018
Outline

1. Introduction: the doubly charged scalar
2. Low energy: EFT and current limits
3. High energy: LHC searches
4. High energy: future colliders
5. Summary
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The doubly charged scalar from the $SU(2)_L$-triplet scalar

Type-II see-saw model

$$S = \begin{pmatrix} S^+ & \sqrt{2} S^{++} \\ \sqrt{2} S^0 & -S^+ \end{pmatrix}$$

$$<S>_0 = \begin{pmatrix} 0 & 0 \\ w & 0 \end{pmatrix}$$

Yukawa term with the triplet:

$$\Delta \mathcal{L}_Y = f_{ij} L^T_i C^{-1} i \tau_2 S L_j + \text{h.c.}$$

Majorana mass term for neutrinos:

$$m_{ij} \bar{\nu}_{iL} \nu_{jL} \quad m_{ij} = w f_{ij} = m_{ji}$$

Introduction: the doubly charged scalar

The doubly Charged $SU(2)_L$-singlet scalar

Zee-Babu model

SM + 2 $SU(2)_L$-singlet scalars:

- a singly charged scalar which couples to left-handed leptons: $h^\pm$
- a doubly charged scalar which couples to right-handed leptons: $k^{\pm\pm}$

It generates mass terms for the neutrinos at two loops:

The doubly Charged $SU(2)_L$-singlet scalar

Minimal model for neutrino masses

$\text{SM} + 1 \, SU(2)_L$-singlet doubly charged scalar: $S^\pm R$

It couples only with right-handed charged leptons:

$$\mathcal{L}_{UV} = \mathcal{L}_{\text{SM}} + (D_\mu S^{++})^\dagger (D^\mu S^{++})$$

$$+ \left( \lambda_{ab} (\ell_R a) \ell_R b \, S^{++} + \text{h.c.} \right)$$

$\lambda_{ab}$ consist of 6 independent parameters and allow for LFV processes

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124
Neutrino mass terms are generated at three loop:

\[ \nu_{La} \rightarrow l_a \rightarrow (l_b)^c \rightarrow (\nu_{Lb})^c \]

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124
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Low-energy effective Lagrangian and the matching

Feynman diagrams representing the UV-complete contributions that match to the dipole and four-fermion operators.

- Diagrams in Fig. (b) match into the diagram in Fig. (a) (dipole interaction)
- Diagram in Fig. (d) matches into the diagram in Fig. (c) (contact interaction)

Crivellin, MG, Panizzi, Pruna, Signer, work in progress
### Low-energy effective Lagrangian and the matching

<table>
<thead>
<tr>
<th>Dipole</th>
<th>Scalar/Tensorial</th>
<th>Vectorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{e\gamma}$</td>
<td>$e\mu r (\bar{l}<em>p \sigma^{\mu\nu} P_L l_r) F</em>{\mu\nu} + \text{H.c.}$</td>
<td></td>
</tr>
<tr>
<td>$Q_S$</td>
<td>$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \text{H.c.}$</td>
<td>$Q_{VLL}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{VLR}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{VRR}$</td>
</tr>
<tr>
<td>$Q_{Slq(1)}$</td>
<td>$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \text{H.c.}$</td>
<td>$Q_{VlqLL}$</td>
</tr>
<tr>
<td>$Q_{Slq(2)}$</td>
<td>$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \text{H.c.}$</td>
<td>$Q_{VlqLR}$</td>
</tr>
<tr>
<td>$Q_{Tlq}$</td>
<td>$(\bar{l}_p \sigma^{\mu\nu} P_L l_r)(\bar{q}<em>s \sigma</em>{\mu\nu} P_L q_t) + \text{H.c.}$</td>
<td>$Q_{VlqRL}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_{VlqRR}$</td>
</tr>
</tbody>
</table>

Dimension-six operators that allow for effective leptonic transitions below the EW scale
Current low-energy experimental limits

\[
\begin{align*}
\text{Br} \left[ \tau^\mp \rightarrow e^\mp e^\pm e^\mp \right] & \leq 1.4 \times 10^{-8} \\
\text{Br} \left[ \tau^\mp \rightarrow \mu^\mp \mu^\pm \mu^\mp \right] & \leq 1.2 \times 10^{-8} \\
\text{Br} \left[ \tau^\mp \rightarrow e^\mp \mu^\pm \mu^\mp \right] & \leq 1.6 \times 10^{-8} \\
\text{Br} \left[ \tau^\mp \rightarrow \mu^\mp e^\pm \mu^\mp \right] & \leq 9.8 \times 10^{-9} \\
\text{Br} \left[ \tau^\mp \rightarrow \mu^\mp e^\pm e^\mp \right] & \leq 1.1 \times 10^{-8} \\
\text{Br} \left[ \tau^\mp \rightarrow e^\mp \mu^\pm e^\mp \right] & \leq 8.4 \times 10^{-8} \\
\text{Br} \left[ \mu^\mp \rightarrow e^\mp e^\pm e^\mp \right] & \leq 1.0 \times 10^{-12}
\end{align*}
\]

\[
\text{BR} \left( l_p^\pm \rightarrow l_r^\pm \gamma \right) \simeq \frac{\alpha m_p^5}{(24\pi^2)^2 m^4_\phi \Gamma_p} \left| \sum_{w=1}^{3} \lambda_{pw} \lambda^*_w \right|^2
\]

\[
\text{BR} \left( l_p^\pm \rightarrow l_r^\pm l_s^\mp l_t^\pm \right) \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6(4\pi)^3 m^4_\phi \Gamma_p}
\]
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1. Introduction: the doubly charged scalar
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Events with two high-$p_T$, isolated, prompt leptons with the same electric charge (same-sign leptons) are produced very rarely in a proton-proton collision according to the predictions of the Standard Model (SM), but they may occur with a higher rate in various beyond the Standard Model (BSM) theories. This analysis aims to study BSM theories that contain a doubly-charged Higgs particle, and in the absence of evidence for a signal, set limits through the observed invariant mass of same-sign leptons.

Doubly-charged Higgs bosons (DCH) can arise in a large variety of BSM theories, namely in left-right symmetric models [1–4], Higgs triplet models [5–7], the little Higgs model [8], Type II seesaw models [9–13], and the Zee-Babu neutrino mass model [14–16]. Theoretical studies indicate [17,18] that the doubly-charged Higgs is predominantly pair produced via the Drell-Yan process at the LHC. The Feynman diagram of the pair production is shown in Figure 1.

Doubly-charged Higgs particles can couple to either left-handed or right-handed leptons. In LRSM the two cases are distinguished and denoted $H^{±±}_L$ and $H^{±±}_R$. The cross-section for $H^{±±}_L H^{±±}_L$ production is larger than that for $H^{±±}_R H^{±±}_R$, because of different couplings to the $Z$ boson [19]. Along with the leptonic decay, the doubly-charged Higgs particle can decay into a pair of $W$ bosons as well. The branching ratio for the doubly-charged Higgs particle to decay into a pair of $W$ bosons compared to the branching ratio to a pair of leptons depends on the vacuum expectation value ($v$) of the Higgs triplet [9,12]. For low values of $v$ it decays almost exclusively to leptons and for high values of $v$ mostly to a pair of $W$ bosons. This analysis studies the case where the $H^{±±}$ particle decays only into electrons.

The ATLAS collaboration has already published similar results and the most stringent constraints originate from Ref. [20], where the lower mass limit of $H^{±±}_R$ ($H^{±±}_L$) was observed to be 370 GeV (550 GeV) at a confidence level (C.L.) of 95% and with the assumption that $Br(H^{±±} → e^+ e^-) = 100\%$. Similar searches were also performed by the CMS collaboration [21].
Current limits from LHC

CMS searches

Search for a scalar triplet \( S = \begin{pmatrix} S^+ \\ \sqrt{2} S^0 \\ -S^+ \end{pmatrix} \) with degenerate masses.

12.9 fb\(^{-1}\) of integrated luminosity at 13 TeV

Channels:
- Pair production with decays \( S^{++} S^{--} \rightarrow \ell^+ \ell^+ \ell^- \ell^- \)
- Associated production with decays \( S^{\pm\pm} S^\mp \rightarrow \ell^\pm \ell^\pm \ell^{\mp} \nu \)
Current limits from LHC

CMS searches

- $S_L^{\pm\pm}$ decaying at 100% to $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$;
- Benchmark points:

<table>
<thead>
<tr>
<th>Benchmark Point</th>
<th>ee</th>
<th>$e\mu$</th>
<th>$e\tau$</th>
<th>$\mu\mu$</th>
<th>$\mu\tau$</th>
<th>$\tau\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.30</td>
<td>0.38</td>
<td>0.30</td>
</tr>
<tr>
<td>BP2</td>
<td>1/2</td>
<td>0</td>
<td>0</td>
<td>1/8</td>
<td>1/4</td>
<td>1/8</td>
</tr>
<tr>
<td>BP3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>1/3</td>
<td>0</td>
<td>1/3</td>
</tr>
<tr>
<td>BP4</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
</tr>
</tbody>
</table>

Lower bounds on the mass of the $S_L^{\pm\pm}$ - observed (expected) 95% CL:

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\Phi^{\pm\pm} \rightarrow ee$</th>
<th>$\Phi^{\pm\pm} \rightarrow e\mu$</th>
<th>$\Phi^{\pm\pm} \rightarrow e\tau$</th>
<th>$\Phi^{\pm\pm} \rightarrow \mu\mu$</th>
<th>$\Phi^{\pm\pm} \rightarrow \mu\tau$</th>
<th>$\Phi^{\pm\pm} \rightarrow \tau\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>734 (720)</td>
<td>750 (729)</td>
<td>746 (774)</td>
<td>568 (582)</td>
<td>518 (613)</td>
<td>479 (483)</td>
</tr>
<tr>
<td>Combined</td>
<td>800 (785)</td>
<td>820 (810)</td>
<td>816 (843)</td>
<td>714 (658)</td>
<td>643 (708)</td>
<td>535 (544)</td>
</tr>
</tbody>
</table>

$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.
36.1 fb$^{-1}$ of integrated luminosity at 13 TeV.

Scenarios:

- $\sum_{i,j=e,\mu} B(S^{\pm\pm} \rightarrow \ell_i \ell_j) = 100\%$
  - $m(S_L^{\pm\pm})$ between 770 GeV and 870 GeV @ 95% C.L.
  - $m(S_R^{\pm\pm})$ between 660 GeV and 760 GeV @ 95% C.L.

- $B(S^{\pm\pm} \rightarrow \ell_i \ell_j) > 10\%$ (decays to $\tau$ and $W$ are possible)
  - $m(S_L^{\pm\pm})$ larger than 450 GeV @ 95% C.L.
  - $m(S_R^{\pm\pm})$ larger than 320 GeV @ 95% C.L.
Expected discovery power of HiLumi-LHC

Expected lower limits on the mass - projections at 3000 fb$^{-1}$

CMS 12.9 fb$^{-1}$

- $S_{L}^{\pm\pm}$, $B_{\ell\ell} = 100\%$ → $[600, 800]$ GeV → $[2400, 3200]$ GeV
- $S_{L}^{\pm\pm}$, $B_{\ell\ell} > 10\%$ → $\sim 800$ GeV → $\sim 2400$ GeV
- $S_{R}^{\pm\pm}$, $B_{\ell\ell} = 100\%$ → $\sim 700$ GeV → $\sim 2100$ GeV
- $S_{R}^{\pm\pm}$, $B_{\ell\ell} > 10\%$ → $\sim 300$ GeV → $\sim 900$ GeV

ATLAS 36.1 fb$^{-1}$

- $S_{L}^{\pm\pm}$, PP only → $[400, 700]$ GeV → $[1600, 2800]$ GeV

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See-saw mediators in t-channel
Width effects

- No production × decay approximation;
- some topologies that are negligible in the NWA can become relevant;
- assumption: gauge sector not modified, i.e. $S_{R}^{\pm \pm}$ coupling to $Z$ is not a free coupling;
- $\Gamma_{S}$ is considered as a free parameter and $\sum_{ab,cd} \Gamma_{S}^{part} \leq \Gamma_{S}$

$$\sigma_{PP \rightarrow l_{a}^{+}l_{b}^{+}l_{c}^{-}l_{d}^{-}}(M_{S}, \Gamma_{S}, \lambda_{ab}, \lambda_{cd}) = \lambda_{ab}^{2} \lambda_{cd}^{2} \hat{\sigma}_{(M_{S}, \Gamma_{S})}$$

Crivellin, MG, Panizzi, Pruna, Signer, work in progress
Width effects: results

Very good approximation for light leptons:

\[
\sigma_{PP\rightarrow l_a^+ l_b^+ l_c^- l_d^-}(M_S, \Gamma_S, \lambda_{ij}) = \kappa_{ab,cd} \lambda_{ab}^2 \lambda_{cd}^2 \hat{\sigma}_{PP\rightarrow 2e^+2e^-}(M_S, \Gamma_S),
\]

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Width effects: results

- Cross-section corresponding to the maximum coupling values;
- Relative ratio between cross-sections in the FW regime and NWA.
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Perspective of searches at future colliders

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S = \frac{N_s}{\sqrt{N_s + N_b}}

Beamstrahlung

Standard acceptance cuts:

E(\mu^\pm) > 10 \text{ GeV}

|\cos(\theta)| < 0.95

Muon pair production at CLIC

Significance = 5
Perspective of searches at future colliders

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Electron beam polarization:

\[ P_{e^-} = 0.4 \]
\[ P_{e^+} = 0 \]

Angular cut:

\[ |\cos(\theta)| < 0.5 \]

Integrated luminosity:

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Integrated Luminosity (fb^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>1500</td>
</tr>
<tr>
<td>3 TeV</td>
<td>3000</td>
</tr>
</tbody>
</table>

(Preliminary plot)
Limits from low energy and discovery power of CLIC

(Preliminary plot)
Limits from low energy and discovery power of CLIC

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Direct production
Single production at ILC

(Preliminary plot)

\[ e^+ e^- \rightarrow \phi^{++} e^- e^- \quad \text{(Boson Fusion, 1 TeV)} \]

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Summary

- Doubly charged scalars arise in many BSM models, in triplets or singlets under $SU(2)_L$, often in connection with the neutrino masses;
- LFV low energy processes set strong limits on combination of the DCS couplings to leptons;
- future $e^+e^-$ colliders can provide complementary bounds;
- due to the production of the DCS in the t-channel, future $e^+e^-$ colliders can be sensitive to mass scales of several TeV;
- direct searches have been performed at LHC by both ATLAS and CMS, setting limits on the DCS mass in the range (320, 870) GeV depending on the assumptions;
- a moderately large width ($\Gamma_S/m_S \sim$ few%) can have 10-20% effect on the cross section compared to the NWA;
- further investigations of the DCS phenomenology are ongoing and the results will be published soon.