The doubly charged scalar: current status and perspectives

Margherita Ghezzi

PAUL SCHERRER INSTITUT

Moriond QCD, 17-24 March 2018
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:

\[ \Delta \mathcal{L}_Y = f_{ij} L_i^T C^{-1} i\tau_2 S L_j + \text{h.c.} \]

Majorana mass term for neutrinos:

\[ m_{ij} \bar{\nu}^c_{iL} \nu_{jL} \quad m_{ij} = w f_{ij} = m_{ji} \]


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:

![Diagram](image)

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

**Minimal model for neutrino masses**

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

It couples only with right-handed charged leptons:

$$\Delta \mathcal{L} = (D_\mu S^{++})^\dagger (D^\mu S^{++}) + \left( \lambda_{ab} (\ell_R)^c_a \ell_R b S^{++} + h.c. \right)$$

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

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124
**The doubly charged $SU(2)_L$-singlet scalar**

Neutrino mass terms are generated at three loop:

$$
\begin{align*}
\frac{\xi}{\Lambda^3} S^{--} & \left[ H^+ H^+ (D_\mu H^0) (D^\mu H^0) - 2 H^+ H^0 (D_\mu H^+) (D^\mu H^0) + H^0 H^0 (D_\mu H^+) (D^\mu H^+) \right] + \text{h.c.}
\end{align*}
$$

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124
Current low-energy experimental limits

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

\[
\mathcal{P} \left( \bar{M} - M \right) = 2.4 \times 10^{-10}
\]

\[
\begin{align*}
\text{Br} \left[ \tau \to e\gamma \right] & \leq 3.3 \times 10^{-8} \\
\text{Br} \left[ \tau \to \mu\gamma \right] & \leq 4.4 \times 10^{-8} \\
\text{Br} \left[ \mu \to e\gamma \right] & \leq 4.2 \times 10^{-13}
\end{align*}
\]

\[
\begin{align*}
\text{BR}(l_p^\pm \to l_r^\pm \gamma) & \simeq \frac{\alpha m_p^5}{(24\pi^2)^2 m_\phi^4 \Gamma_p} \left| \sum_{w=1}^3 \lambda_{pw} \lambda_{rw}^* \right|^2 \\
\text{BR}(l_p^\pm \to l_r^\pm l_s^\mp l_t^\pm) & \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6(4\pi)^3 m_\phi^4 \Gamma_p}
\end{align*}
\]
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 \([1–4]\) (LRSM), 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 $\text{Br}(H^{±±} \rightarrow e^± e^±) = 100\%$. Similar searches were also performed by the CMS collaboration \([21]\).

**Signature:** same-sign lepton pairs

**Assumptions on the branching ratios**

**Narrow width approximation**

---

**ATLAS 7 TeV:**

**CMS 7 TeV:**

**ATLAS 13 TeV:**

**CMS 13 TeV:**
- CMS-PAS-HIG-16-036
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></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow ee$</td>
<td>734 (720)</td>
<td>652 (639)</td>
<td>800 (785)</td>
</tr>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow e\mu$</td>
<td>750 (729)</td>
<td>665 (660)</td>
<td>820 (810)</td>
</tr>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow \mu\mu$</td>
<td>746 (774)</td>
<td>712 (712)</td>
<td>816 (843)</td>
</tr>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow e\tau$</td>
<td>568 (582)</td>
<td>481 (543)</td>
<td>714 (658)</td>
</tr>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow e\tau$</td>
<td>518 (613)</td>
<td>537 (591)</td>
<td>643 (708)</td>
</tr>
<tr>
<td>100% $\Phi^{\pm\pm} \rightarrow \mu\tau$</td>
<td>479 (483)</td>
<td>396 (419)</td>
<td>535 (544)</td>
</tr>
<tr>
<td>Benchmark 1</td>
<td>613 (649)</td>
<td>519 (548)</td>
<td>723 (715)</td>
</tr>
<tr>
<td>Benchmark 2</td>
<td>670 (671)</td>
<td>465 (554)</td>
<td>716 (723)</td>
</tr>
<tr>
<td>Benchmark 3</td>
<td>706 (682)</td>
<td>531 (562)</td>
<td>761 (732)</td>
</tr>
<tr>
<td>Benchmark 4</td>
<td>639 (639)</td>
<td>496 (539)</td>
<td>722 (704)</td>
</tr>
</tbody>
</table>

$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.
High energy: LHC searches

Current limits from LHC

ATLAS searches

36.1 fb$^{-1}$ of integrated luminosity at 13 TeV.

Scenarios:

- $\sum_{i,j=e,\mu} B(S^{\pm\pm} \to \ell_i\ell_j) = 100$
  - $m(S^{\pm\pm}_L)$ between 770 GeV and 870 GeV @ 95% C.L.
  - $m(S^{\pm\pm}_R)$ between 660 GeV and 760 GeV @ 95% C.L.
- $B(S^{\pm\pm} \to \ell_i\ell_j) > 10\%$ (decays to $\tau$ and $W$ are possible)
  - $m(S^{\pm\pm}_L)$ larger than 450 GeV @ 95% C.L.
  - $m(S^{\pm\pm}_R)$ larger than 320 GeV @ 95% C.L.
Width effects

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

$$σ_{PP→l_a^+l_b^-l_c^-l_d^-}(M_S, Γ_S, λ_{ab}, λ_{cd}) = λ_{ab}^2λ_{cd}^2\hat{σ}(M_S, Γ_S)$$

Crivellin, MG, Panizzi, Pruna, Signer, in preparation
Width effects: results

Very good approximation for light leptons:

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

(Preliminary plot)

- Cross-section corresponding to the maximum coupling values;
- relative ratio between cross-sections in the FW regime and NWA.

Crivellin, MG, Panizzi, Pruna, Signer, in preparation
Perspective of searches at future colliders

- \[ S = \frac{N_s}{\sqrt{N_s+N_b}} \]
- Beamstrahlung
- Standard acceptance cuts:
  \[ E(\mu^\pm) > 10 \text{ GeV} \]
  \[ |\cos(\theta)| < 0.95 \]
- Integrated luminosities:

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

Crivellin, MG, Panizzi, Pruna, Signer, in preparation
The polarization of the beams increases the sensitivity.

CLIC will have the option to polarize the electron beam.

\[ P_{e^-} = 0.4 \]
\[ P_{e^+} = 0 \]
Perspective of searches at future colliders

Measurements with polarized beams allow to distinguish between $S_{L}^{\pm\pm}$ and $S_{R}^{\pm\pm}$


$e^+ e^- \rightarrow e^+ e^-$: $\lambda_{11}$
- $P_{e^-} = 0.4$, $P_{e^+} = 0$
- $|\cos(\theta)| < 0.5$

$e^+ e^- \rightarrow e^\pm \mu^\mp$: $\lambda_{12}, \lambda_{11}$
- No SM background

(Preliminary plot)

Crivellin, MG, Panizzi, Pruna, Signer, in preparation
Limits from low energy and discovery power of LC

(Preliminary plot)

Crivellin, MG, Panizzi, Pruna, Signer, in preparation
Direct production
Single production at ILC

(Preliminary plot)

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