Searches for a doubly charged scalar
at LHC and future colliders

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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:

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

Majorana mass term for neutrinos:

$$m_{ij}\bar{\nu}_{iL}^c \nu_{jL} \qquad m_{ij} = w\, f_{ij} = m_{ji}$$

T. P. Cheng and L. F. Li, Phys. Rev. D 22 (1980) 2860
W. Grimus, R. Pfeiffer and T. Schwetz, Eur. Phys. J. C 13 (2000) 125
E. Ma, M. Raidal and U. Sarkar, Nucl. Phys. B 615 (2001) 313
A. G. Akeroyd and M. Aoki, Phys. Rev. D 72 (2005) 035011

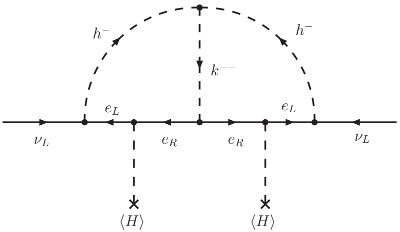
The doubly Charged $SU(2)_L$-singlet scalar

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:



A. Zee, Nucl. Phys. B **264** (1986) 99

K. S. Babu, Phys. Lett. B **203**, 132 (1988)

M. Nebot, J. F. Oliver, D. Palao and A. Santamaria, Phys. Rev. D 77 (2008) 093013

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:

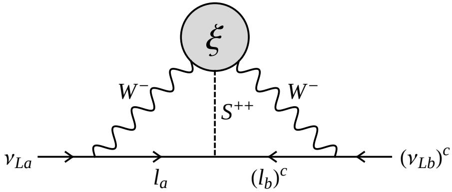
$$\begin{aligned} \Delta\mathcal{L} &= \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) + \left(\lambda_{ab}\,\overline{(\ell_R)^c_a}\ell_{Rb}\,S^{++} + \mathrm{h.c.}\right) \\ &+ \lambda_2 \left(H^\dagger H\right)\left(S^{--}S^{++}\right) + \lambda_4 \left(S^{--}S^{++}\right)^2 + [\text{inv.}] \end{aligned}$$

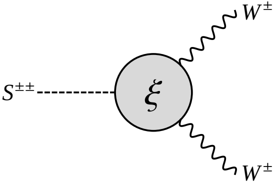
λ_{ab} consist of 6 independent complex parameters and allow for LFV processes.

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:





EFT approach:

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

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124

Current low-energy experimental limits

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

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

(for right-handed currents)

$$\mathrm{Br}^{\mathrm{Au}}_{\mu\to e} \leq 7 \times 10^{-13}$$

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

SINDRUM Collaboration, Nucl.Phys. B299 (1988) 1-6
MEG Collaboration, Eur.Phys.J. C76 (2016) no.8, 434
HFLAV Collaboration, Eur.Phys.J. C77 (2017) no.12, 895
BaBar Collaboration, Phys.Rev.Lett. 104 (2010) 021802

Low-energy effective Lagrangian and the matching

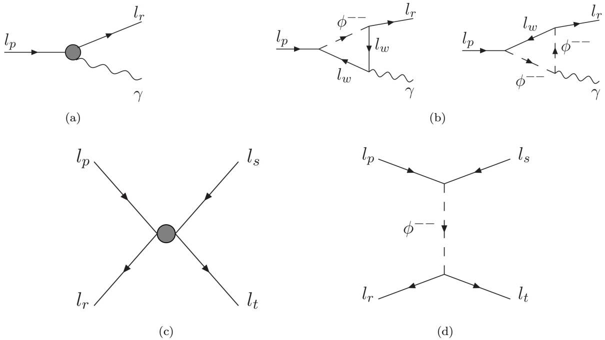
Dipole	
$Q_{e\gamma}$	$em_r(\bar{l}_p \sigma^{\mu\nu} P_L l_r) F_{\mu\nu} + \mathrm{H.c.}$

Scalar/Tensorial		Vectorial	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \mathrm{H.c.}$	Q_{VLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_L l_t)$
		Q_{VLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \mathrm{H.c.}$	Q_{VlqLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \mathrm{H.c.}$	Q_{VlqLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p \sigma^{\mu\nu} P_L l_r)(\bar{q}_s \sigma_{\mu\nu} P_L q_t) + \mathrm{H.c.}$	Q_{VlqRL}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_R q_t)$

Dimension-six operators that allow for effective leptonic transitions below the EW scale

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, in preparation

Low-energy effective Lagrangian and the matching

Dipole			
$Q_{e\gamma}$	$em_r(\bar{l}_p\sigma^{\mu\nu}P_L l_r)F_{\mu\nu} + \mathrm{H.c.}$		
Scalar/Tensorial		**Vectorial**	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \mathrm{H.c.}$	Q_{VLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_L l_t)$
		Q_{VLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \mathrm{H.c.}$	Q_{VlqLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \mathrm{H.c.}$	Q_{VlqLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p\sigma^{\mu\nu}P_L l_r)(\bar{q}_s\sigma_{\mu\nu}P_L q_t) + \mathrm{H.c.}$	Q_{VlqRL}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_R q_t)$

$$C_{VRR}^{prst}(m_W) = \frac{\lambda_{rt}\lambda^*_{ps}}{2}$$

$$C_{e\gamma}^{pr}(m_W) = \frac{1}{24\pi^2}\sum_{w=1}^{3}\left(\lambda_{rw}\lambda^*_{pw}\right)$$

Low-energy effective Lagrangian and the matching

Dipole	
$Q_{e\gamma}$	$e m_r (\bar{l}_p \sigma^{\mu\nu} P_L l_r) F_{\mu\nu} + \mathrm{H.c.}$

Scalar/Tensorial		Vectorial	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \mathrm{H.c.}$	Q_{VLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_L l_t)$
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		Q_{VRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
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$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \mathrm{H.c.}$	Q_{VlqLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p \sigma^{\mu\nu} P_L l_r)(\bar{q}_s \sigma_{\mu\nu} P_L q_t) + \mathrm{H.c.}$	Q_{VlqRL}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_R q_t)$

$$C_{VRR}^{prst}(m_W) = \frac{\lambda_{rt}\lambda_{ps}^*}{2}$$

$$C_{e\gamma}^{pr}(m_W) = \frac{1}{24\pi^2}\sum_{w=1}^{3}(\lambda_{rw}\lambda_{pw}^*)$$

Low-energy effective Lagrangian and the matching

Matching at the EW scale:

$$C_{VRR}^{prst(m_W)} = \frac{\lambda_{rt}\lambda_{ps}^*}{2}$$

$$C_{e\gamma}^{pr}(m_W) = \frac{1}{24\pi^2}\sum_{w=1}^{3}\left(\lambda_{rw}\lambda_{pw}^*\right)$$

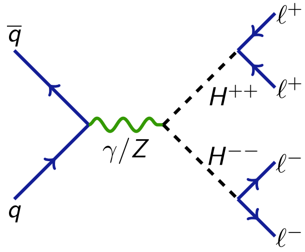
Branching ratios at the physical scale:

$$\mathrm{BR}(l_p^\pm \to l_r^\pm \gamma) = \frac{\alpha\, m_p^5}{m_\phi^4 \Gamma_p}\left|C_{e\gamma}^{rp}(m_p)\right|^2$$

$$\mathrm{BR}(l_p^\pm \to l_r^\pm l_s^\mp l_t^\pm) = \frac{m_p^5}{(1+\delta_{rt})6 m_\phi^4 \Gamma_p}\left(\frac{1}{2(4\pi)^3}\left(8\left|C_{VRR}^{prst}(m_p)\right|^2 + \left|C_{VRL}^{prst}(m_p)\right|^2\right) + \frac{\delta_{st}\alpha^2}{\pi}\left|C_{e\gamma}^{rp}(m_p)\right|^2\left(8\log(m_p/m_s) - 11\right)\right)$$

Crivellin, MG, Panizzi, Pruna, Signer, in preparation

Direct searches at LHC



- Signature: same-sign lepton pairs
- Assumptions on the branching ratios
- Narrow width approximation

ATLAS 7 TeV:

- Eur.Phys.J. C72 (2012) 2244

CMS 7 TeV:

- Eur.Phys.J. C72 (2012) 2189

ATLAS 13 TeV:

- CERN-EP-2017-198

CMS 13 TeV:

- CMS-PAS-HIG-16-036

Current limits from LHC

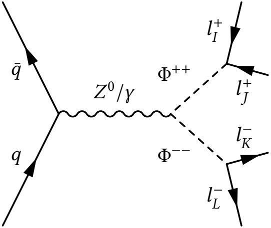
CMS searches

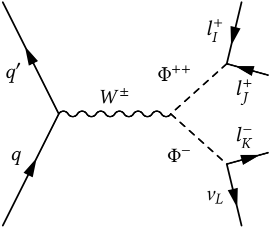
Search for a scalar triplet $S = \begin{pmatrix} S^+ & \sqrt{2}S^{++} \\ \sqrt{2}S^0 & -S^+ \end{pmatrix}$ with degenerate masses.

$12.9\,\text{fb}^{-1}$ of integrated luminosity at 13 TeV

Channels:

- Pair production with decays $S^{++}S^{--} \to \ell^+\ell^+\ell^-\ell^-$
- Associated production with decays $S^{\pm\pm}S^{\mp} \to \ell^\pm\ell^\pm\ell^\mp\nu$





CMS-PAS-HIG-16-036

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:

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

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

Benchmark	AP [GeV]	PP [GeV]	Combined [GeV]
100% $\Phi^{\pm\pm} \to ee$	734 (720)	652 (639)	800 (785)
100% $\Phi^{\pm\pm} \to e\mu$	750 (729)	665 (660)	820 (810)
100% $\Phi^{\pm\pm} \to \mu\mu$	746 (774)	712 (712)	816 (843)
100% $\Phi^{\pm\pm} \to e\tau$	568 (582)	481 (543)	714 (658)
100% $\Phi^{\pm\pm} \to \mu\tau$	518 (613)	537 (591)	643 (708)
100% $\Phi^{\pm\pm} \to \tau\tau$	479 (483)	396 (419)	535 (544)
Benchmark 1	613 (649)	519 (548)	723 (715)
Benchmark 2	670 (671)	465 (554)	716 (723)
Benchmark 3	706 (682)	531 (562)	761 (732)
Benchmark 4	639 (639)	496 (539)	722 (704)

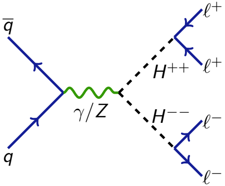
$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.

CMS-PAS-HIG-16-036

Current limits from LHC

ATLAS searches

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



Scenarios:

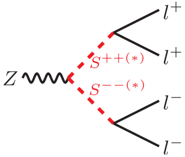
- $\sum_{i,j=e,\mu} \mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) = 100\%$
  - $m\left(S_L^{\pm\pm}\right)$ between 770 GeV and 870 GeV @ 95% C.L.
  - $m\left(S_R^{\pm\pm}\right)$ between 660 GeV and 760 GeV @ 95% C.L.
- $\mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) > 10\%$ (decays to τ and W are possible)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

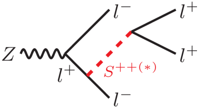
CERN-EP-2017-198

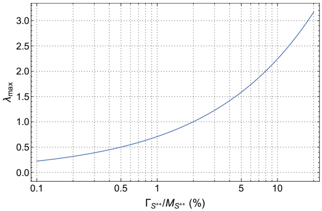
Width effects

- No *production* $\times$ *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;
- Γ_S is considered as a free parameter and $\sum_{ab,cd} \Gamma_S^{\mathrm{part}} \leq \Gamma_S$

$$\sigma_{PP\to l_a^+ l_b^+ l_c^- l_d^-}(M_S, \Gamma_S, \lambda_{ab}, \lambda_{cd}) = \lambda_{ab}^2 \lambda_{cd}^2 \hat{\sigma}(M_S, \Gamma_S)$$







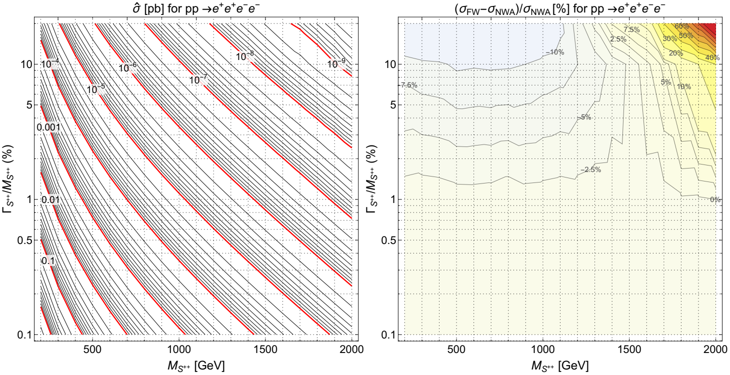
Crivellin, MG, Panizzi, Pruna, Signer, in preparation

Width effects: results

Very good approximation for light leptons:

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

(Preliminary plot)



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

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Perspective of searches at future colliders

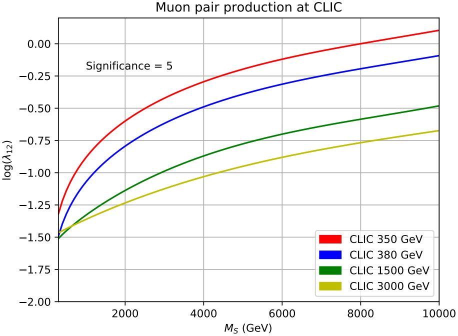
(Preliminary plot)

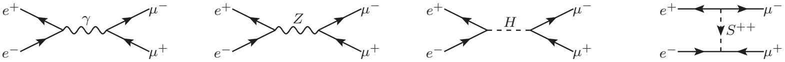
- $S = \frac{N_s}{\sqrt{N_s + N_b}}$
- Beamstrahlung
- Standard acceptance cuts:

$$E(\mu^\pm) > 10\,\text{GeV}$$
$$|\cos(\theta)| < 0.95$$

- Integrated luminosities:

350 GeV	380 GeV	1.5 TeV	3 TeV
100 fb^{-1}	500 fb^{-1}	1500 fb^{-1}	3000 fb^{-1}



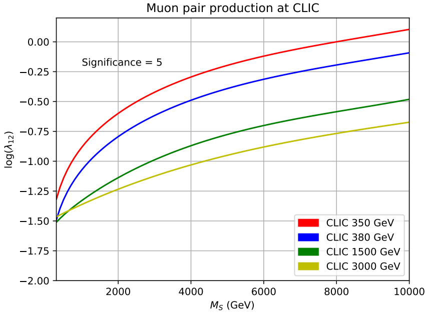


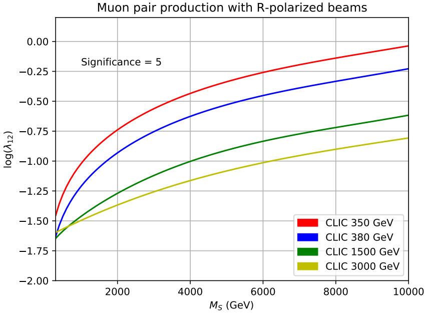
Crivellin, MG, Panizzi, Pruna, Signer, in preparation

Perspective of searches at future colliders

- The polarization of the beams increases the sensitivity
- CLIC will have the option to polarize the electron beam

$$P_{e^-} = 0.4$$
$$P_{e^+} = 0$$





(Preliminary plots)

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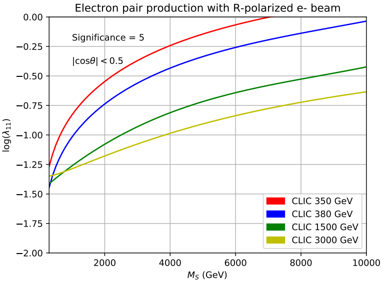
Perspective of searches at future colliders

Measurements with polarized beams allow to distinguish between $S_L^{\pm\pm}$ and $S_R^{\pm\pm}$

T. Nomura, H. Okada and H. Yokoya, Nucl. Phys. B 929 (2018) 193

(Preliminary plot)

- $e^+e^- \to e^+e^-$: λ_{11}
  - $P_{e^-} = 0.4 \quad , P_{e^+} = 0$
  - $|\cos(\theta)| < 0.5$
- $e^+e^- \to e^\pm\mu^\mp$: λ_{12}, λ_{11}
  - No SM background



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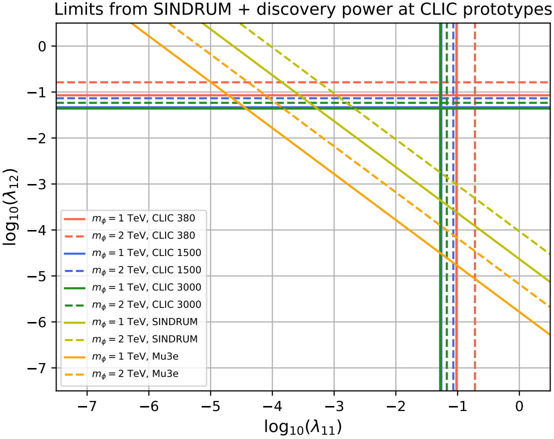
Limits from low energy and discovery power of LC

(Preliminary plot)



Crivellin, MG, Panizzi, Pruna, Signer, in preparation

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.