Phenomenology of a doubly charged scalar

Margherita Ghezzi

PAUL SCHERRER INSTITUT

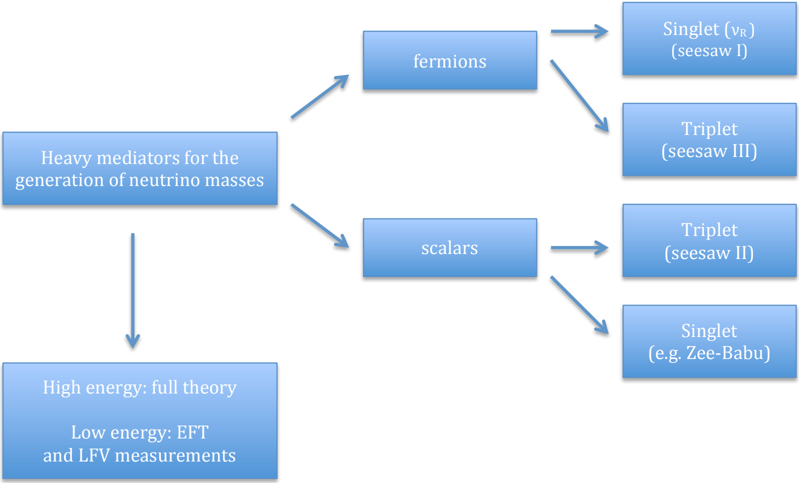
Mainly based on:

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

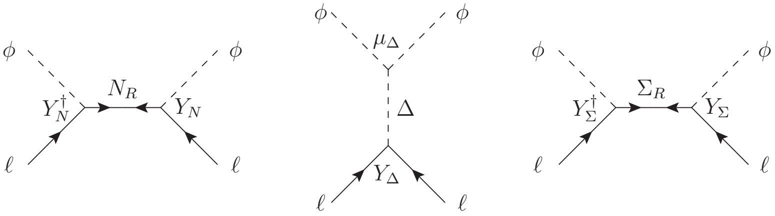
LTP Seminar, PSI, 25.06.2018

Outline

Introduction: masses for the neutrinos



The seesaw mechanism



Type I

SM singlet fermions

Type II

SM triplet scalars

Type III

SM triplet fermions

Fig. from Abada, Biggio, Bonnet, Gavela and Hambye JHEP 0712 (2007) 061

The doubly charged scalar from the $SU(2)_L$-triplet scalar

Type-II see-saw model

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

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

Yukawa term with the triplet:

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

Majorana mass term for neutrinos:

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

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

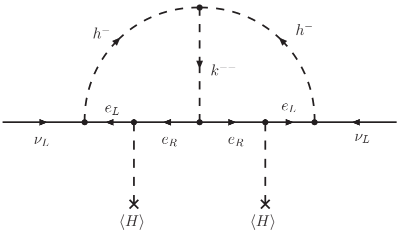
The doubly Charged $SU(2)_L$-singlet scalar

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:

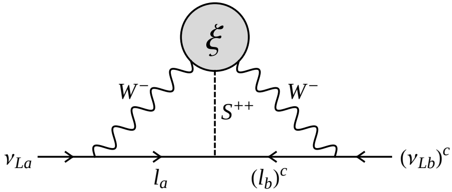
$$\begin{aligned} \Delta\mathcal{L} &= \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) + \left(\lambda_{ab}\,\overline{(\ell_R)^c_a}\ell_{Rb}\,S^{++} + \mathrm{h.c.}\right) \\ &+ \lambda_2 \left(H^\dagger H\right)\left(S^{--}S^{++}\right) + \lambda_4 \left(S^{--}S^{++}\right)^2 + [\text{inv.}]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

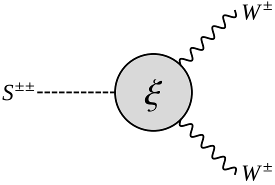
λ_{ab} consist of 6 independent complex parameters and allow for LFV processes.

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:

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

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

Outline

The Effective Field Theory approach to BSM: SMEFT

The SM can be seen as an effective theory valid up to some high scale Λ and it can be extended to include higher dimensional operators:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \sum_k c_k^{(5)} \mathcal{Q}_k^{(5)} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} \mathcal{Q}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Assumptions:

- The dynamical degrees of freedom at the EW scale are those of the SM
- The $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group must be contained in the EFT
- New Physics appears at some high scale $\Lambda >> v$ (decoupling)
- Absence of mixing of new heavy scalars with the SM Higgs doublet

The SMEFT

Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

- 15 bosonic operators
- 19 single-fermionic-current operators
- 25 four-fermion operators (assuming baryonic number conservation)

15+19+25=59 independent operators (for 1 fermion generation)

Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 1010 (2010) 085

The SMEFT beyond the tree level

Running and mixing of Wilson coefficients

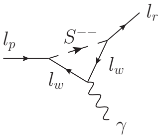
$$\bar{c}_i(\mu) = \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{g_{SM}^2}{16\pi^2} \log\left(\frac{\mu}{M}\right)\right) \bar{c}_j(M)$$

- Compared to the SM, additional logarithmic divergences are present;
- these divergences are absorbed by the running of the coefficients of the local operators;
- the matrix $\gamma_{ij}^{(0)}$ mixes the coefficients;
- the only one-loop diagrams which generate logarithmic divergences are the ones containing one insertion of effective vertices;
- a selection of the operators *a priori* is not possible;
- the coefficients must be evaluated at the scale of the experiment!

Outline

The low-energy Effective Field Theory

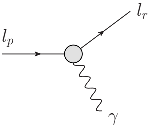
UV model



EW Scale

Matching

EFT



Running

Low Energy Scale (i.e. m_μ)

The low-energy effective Lagrangian

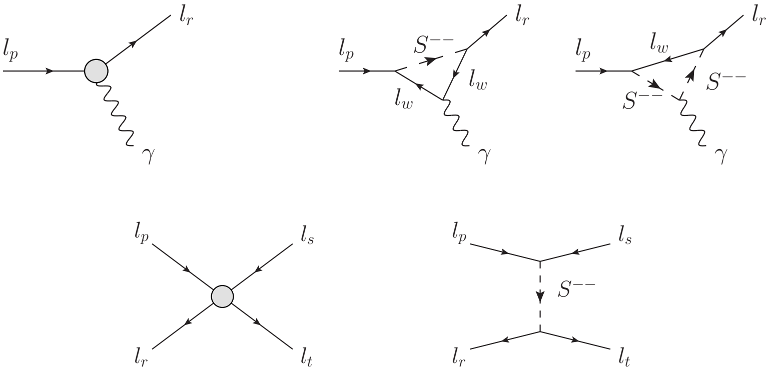
Dipole			
$Q_{e\gamma}$	$em_r(\bar{l}_p \sigma^{\mu\nu} P_L l_r) F_{\mu\nu} + \mathrm{H.c.}$		

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:



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}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_R q_t)$

$$
\begin{aligned}
C_{VRR}^{prst}(m_W) &= \frac{\lambda_{rt}\lambda_{ps}^*}{2} \\
C_{e\gamma}^{pr}(m_W) &= \frac{1}{24\pi^2}\sum_{w=1}^{3}(\lambda_{rw}\lambda_{pw}^*)
\end{aligned}
$$

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}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_R q_t)$

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

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

Low-energy effective Lagrangian and the matching

Branching ratios at the physical scale

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

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

$$\mathrm{Br}^{\mathrm{N}}_{\mu\to e} = \frac{m_\mu^5}{4\, m_S^4 \Gamma^N_{\mathrm{capt}}} \left| e(m_\mu) C_{e\gamma}^{12}(m_\mu)\, D_N + 4 \left(\tilde{C}_{VR}^{(p)}(m_\mu)\, V_N^{(p)} + p \to n \right) \right|^2$$

$$\tilde{C}_{VR}^{(p/n)} = \sum_{q=u,d} \left(C_{VlqRR}^{12qq} + C_{VlqRL}^{12qq} \right) f_{V\,p/n}^{(q)}$$

$$f_{V\,p}^{(u)} = 2 \qquad f_{V\,n}^{(u)} = 1 \qquad f_{V\,p}^{(d)} = 1 \qquad f_{V\,n}^{(d)} = 2$$

$$D_{\mathrm{Au}} = 0.189 \qquad V_{\mathrm{Au}}^{(p)} = 0.0974 \qquad V_{\mathrm{Au}}^{(n)} = 0.146$$

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)

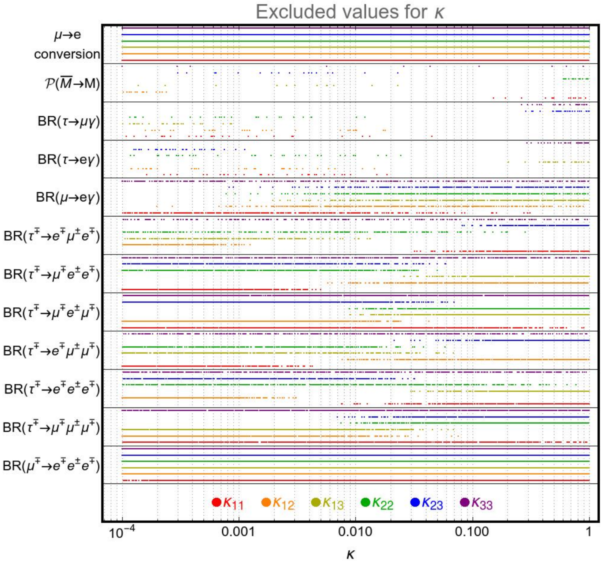
$$\mathrm{Br}^{\mathrm{Au}}_{\mu \to e} \leq 7 \times 10^{-13}$$

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

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

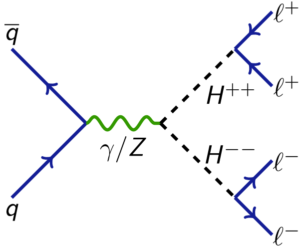
Current low-energy experimental limits

$$\lambda_{ab} = \begin{pmatrix} \kappa_{11} & \kappa_{12} & \kappa_{13} \\ \kappa_{12} & \kappa_{22} & \kappa_{23} \\ \kappa_{13} & \kappa_{23} & \kappa_{33} \end{pmatrix}$$



Outline

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:

- Eur.Phys.J. C78 (2018) no.3, 199

CMS 13 TeV:

- CMS-PAS-HIG-16-036

Current limits from LHC

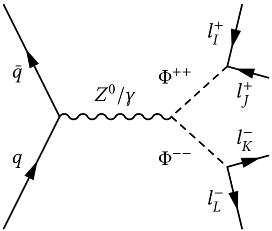
CMS searches

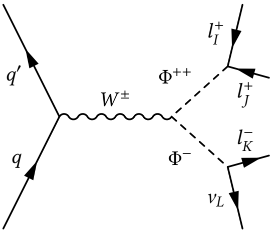
Search for a scalar triplet $S = \begin{pmatrix} S^+ & \sqrt{2}S^{++} \\ \sqrt{2}S^0 & -S^+ \end{pmatrix}$ with degenerate masses.

$12.9\,\mathrm{fb}^{-1}$ 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)

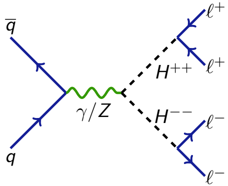
$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.

CMS-PAS-HIG-16-036

Current limits from LHC

ATLAS searches

$36.1\,\mathrm{fb}^{-1}$ 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.

Eur.Phys.J. C78 (2018) no.3, 199

Width effects

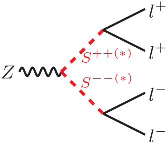
- No *production* × *decay* approximation;
- some topologies that are negligible in the NWA can become relevant;

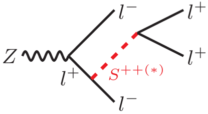
Assumptions:

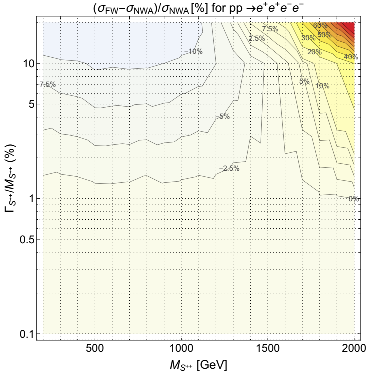
- gauge sector not modified;
- Γ_S free parameter:

$$\sum_{ab,cd} \Gamma_S^{\rm part} \leq \Gamma_S$$

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



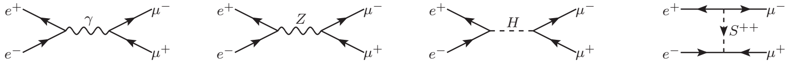


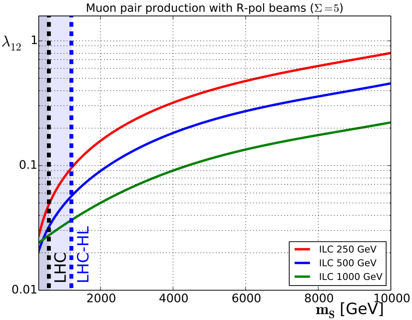


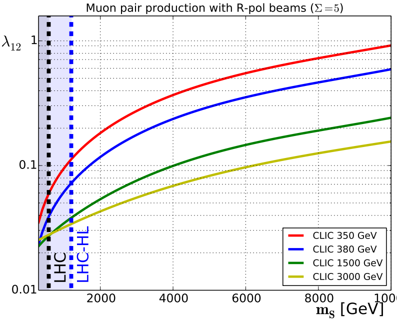
Outline

Perspective of searches at future colliders

DCS exchange in the t-channel







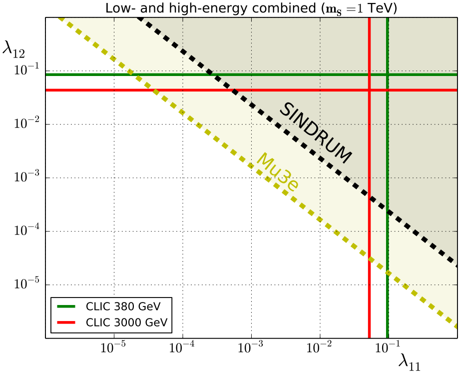
- Integrated luminosities at ILC:

250 GeV	500 GeV	1 TeV
250 fb^{-1}	500 fb^{-1}	1000 fb^{-1}

- Integrated luminosities at CLIC:

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

Limits from low energy and discovery power of LC

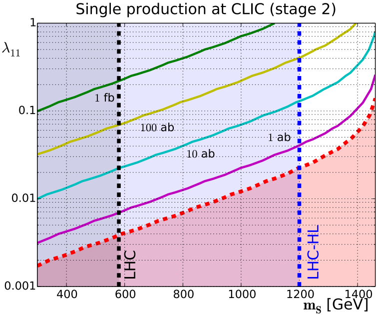


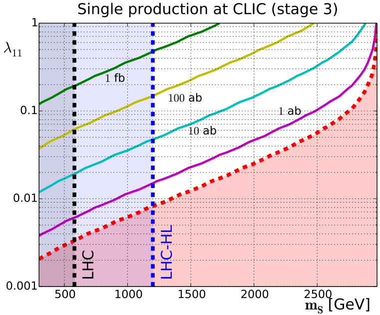
$\lambda_{11}\,, \quad \lambda_{12}$ dominant

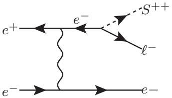
$\lambda_{13} = \lambda_{22} = \lambda_{23} = \lambda_{33} = 0$

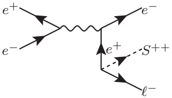
Direct production

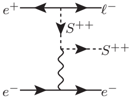
Single production at CLIC

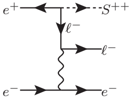






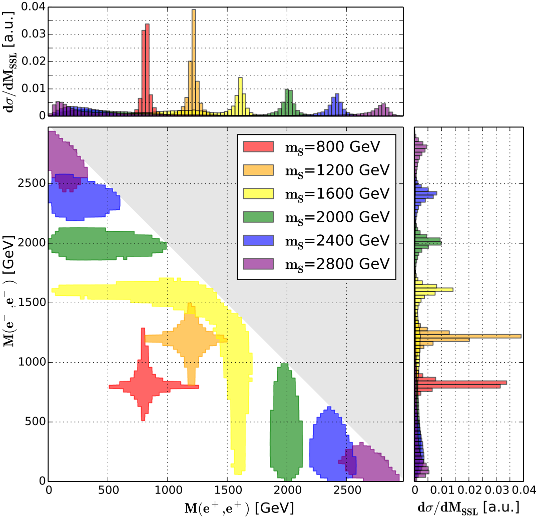






Direct production

Single production at CLIC



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;
- Direct single production of the DCS is also possible at linear colliders
- 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.