Doubly-charged scalars

phenomenology and perspectives at CLIC

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based on

A. Crivellin, M. Ghezzi, **LP**, G. M. Pruna and A. Signer
Low- and high-energy phenomenology of a doubly charged scalar
arXiv:1807.10224 [hep-ph], accepted by PRD

and

M. Ghezzi, **LP**, G. M. Pruna
SU(2) singlets and neutrino mass from higher dimensional operators
section 7.3 of J. de Blas *et al.*,"The CLIC Potential for New Physics," arXiv:1812.02093 [hep-ph]

The Standard Model is complete
but are we happy with it?

Observations

Dark Matter	Matter-antimatter asymmetry	Neutrino masses

Theoretical issues

Fermion mass hyerarchies	Origin of flavour families	Gauge coupling unification	. . .

There must be new physics

and most probably it's already in our reach or within the reach of future colliders!

And if there's new physics we should be able to observe new particles (hopefully soon!)

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Let's focus on mechanisms for neutrino mass generation!

Neutrino mass generation mechanisms

and which BSM states they predict

Type-II see saw

$$\mathcal{L}_Y = -f_{ij} \left(l_i^T C i \tau_2 \boldsymbol{\tau} l_j \right) \cdot \boldsymbol{\Sigma} = -f_{ij} \left(l_i^T C i \tau_2 \boldsymbol{\Delta} l_j \right) \quad \text{with} \quad \boldsymbol{\Delta} \equiv \boldsymbol{\tau} \cdot \boldsymbol{\Sigma} = \begin{pmatrix} S^+ & \sqrt{2}\, S^{++} \\ \sqrt{2}\, S^0 & -S^+ \end{pmatrix}$$

The triplet vev $\langle \boldsymbol{\Delta} \rangle = \begin{pmatrix} 0 & 0 \\ w & 0 \end{pmatrix}$ leads to Majorana mass for neutrinos $m_{ij}^{\nu} \propto f_{ij} w$

Neutral, charged and doubly-charged scalars as part of a triplet

T. P. Cheng and L. F. Li, Phys. Rev. D **22** (1980) 2860

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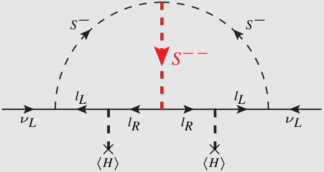
Zee-Babu



Neutrino mass at two loops

$$\mathcal{M}_{\nu,ab} \sim f_{ac}\, f^*_{db}\, h_{cd}\, m_c\, m_d \cdot \tilde{\mathcal{I}}(M_{S^+}, M_{S^{++}}, \mu)$$

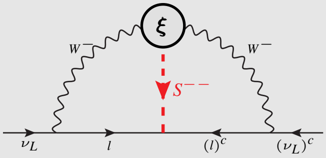
Charged and doubly-charged singlet scalars

A. Zee, Nucl. Phys. B **264** (1986) 99
K. S. Babu, Phys. Lett. B **203** (1988) 132

Neutrino mass generation mechanisms

and which BSM states they predict

Minimal effective model

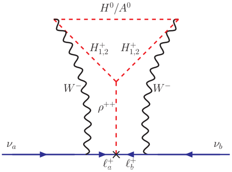


Neutrino mass at two loops in the effective theory
(three loops in UV realisations)

$$\mathcal{M}_{\nu,ab}^{\text{2-loop}} = \frac{2\,\xi\, m_a\, m_b\, M_S^2\, f_{ab}(1+\delta_{ab})}{\Lambda^3} \cdot \tilde{\mathcal{I}}(M_W, M_S, \mu)$$

One doubly-charged singlet scalar

S. F. King, A. Merle and **LP**, JHEP **1411** (2014) 124
T. Geib, S. F. King, A. Merle, J. M. No and **LP**, Phys. Rev. D **93** (2016) no.7, 073007



Example of UV realisation: the "cocktail model"

M. Gustafsson, J. M. No and M. A. Rivera, Phys. Rev. Lett. **110** (2013) no.21, 211802

Further scenarios:

- Left-right symmetric models (triplet) — J. C. Pati and A. Salam, Phys. Rev. D **10** (1974) 275
- Georgi-Machacek (triplet) — H. Georgi and M. Machacek, Nucl. Phys. B **262** (1985) 463
- Little Higgs (triplet) — N. Arkani-Hamed *et al*, JHEP **0208** (2002) 021
- Neutrinos and dark matter (quadruplet) — S. Bhattacharya *et al*, Phys. Rev. D **95** (2017) no.5, 055003

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Doubly-charged scalars are predicted in various models of new physics

embedded in different representations $\rightarrow$ different phenomenological consequences

- Different **production channels**, and for the same channel, different **cross-sections**
- Different dominant **interactions** $\longrightarrow$ different dominant **decay modes**

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Considering **singlet representation**:

$$(D_\mu S^{++})^\dagger (D^\mu S^{++}) + (\lambda_{ab} \overline{(l_R)}^c_a (l_R)_b S^+ + +h.c.)$$

1) Bounds from **low energy**
2) Bounds at the **LHC** and perspectives for higher luminosity
3) **What is the potential of CLIC for discovering them?**

Is it possible to **reinterpret** results for different representations?

Constraints from low energy

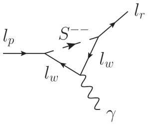
$l_a \to l_b \gamma$

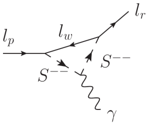
$l_a \to l_b l_c l_d$

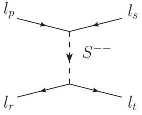
$\mu^- e^+ \to \mu^+ e^-$

lepton dipole moment

μ to e conversion in nuclei

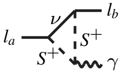






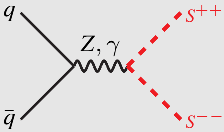
$$BR(l_p \to l_r \gamma) \simeq \frac{\alpha m_p^5}{(24\pi^2)^2 m_S^4 \Gamma_p} \left| \sum_{w=1}^{3} \lambda_{pw} \lambda_{rw}^* \right| \qquad BR(l_p \to l_r l_s l_t) \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6 (4\pi)^3 m_S^4 \Gamma_p}$$

But some low-energy bounds are affected also by singly-charged scalars!

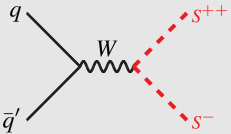


Current searches at LHC

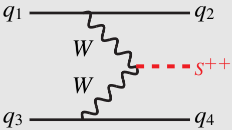
Topologies



Pair production
Any representation



Associate production
Only non-trivial representations



Single production
Only at EFT level for singlet

ATLAS (only 13 TeV)

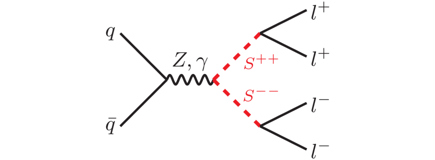
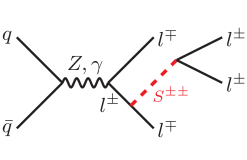
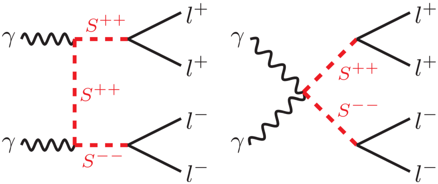
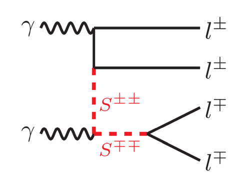
- Pair production with decay into e or μ
  Bounds for BRs = 100%:
  singlet around $\sim$600 GeV
  triplet around $\sim$700 GeV
  Eur. Phys. J. C **78** (2018) no.3, 199
- Pair production with decay into WW
  Bound above $\sim$200 GeV (triplet)
  arXiv:1808.01899 [hep-ex]

CMS (only 13 TeV)

- Pair and associate production with decay into leptons
  Pair production bounds (triplet):
  above $\sim$650 GeV (decays into e/μ)
  above $\sim$400 GeV (decays with τ)
  Associate production bounds:
  above $\sim$700 GeV (decays into e/μ)
  above $\sim$450 GeV (decays with τ)
  CMS-PAS-HIG-16-036

Photon contribution and width effects

Singlet case

	narrow-width approximation	finite width
quark-initiated		
photon-initiated		

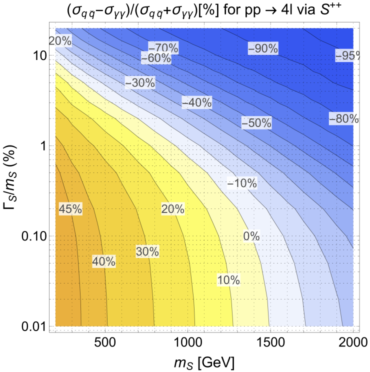
- **Photon contribution** included in the LUXQED PDFs
- no gluon-initiated topologies for S^{++} singlet
- Allowing for **non-resonant contributions** and **new topologies** which are negligible in the NWA

Photon contribution and width effects

Singlet case

Parametrisation of the cross-section:

$$\sigma_{pp\to l_a^+ l_b^+ l_c^- l_d^-}(m_S, \Gamma_S, \lambda_{ab,cd}) = \lambda_{ab}^2 \lambda_{cd}^2 \left(\hat{\sigma}_{qq}(m_S, \Gamma_S, g_{ZSS}) + \hat{\sigma}_{\gamma\gamma}(m_S, \Gamma_S)\right)$$

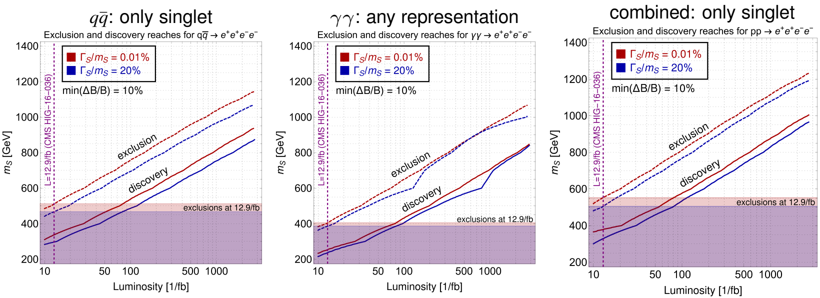


- Width as a free parameter ($\sum_{ab,cd} \Gamma_S^{\text{part}} \leq \Gamma_S$)
- Photon contribution can be sizable, especially in the large width regime
- Not possible to factorise g_{ZSS}: total results only valid for singlet S^{++}

Bounds and projections at LHC

Recasting of CMS-PAS-HIG-16-036

Results for decay into $e+e-$



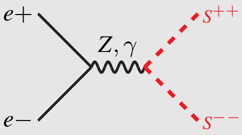
- **Current combined recast bound** above ∼500 GeV
- **Projected combined bound** for high-luminosity around ∼1200 GeV
- **Projected combined discovery reach** aroud ∼1000 GeV
- Weak width dependence (due to cut on invariant mass window of SS dileptons)

For non-trivial representations bounds and discovery slightly higher due to larger ZSS coupling

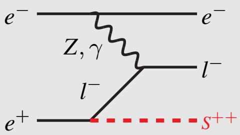
Signatures at CLIC

	Stage I		Stage II	Stage III
$\sqrt{s}$	380 GeV	350 GeV	1.5 TeV	3 TeV
$\mathcal{L}$	0.9/ab	0.1/ab	2.5/ab	5/ab

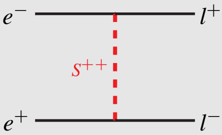
Topologies



Pair production



Single production



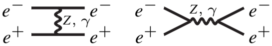
t-channel

- Pair production limited by phase space to probe $M_S < 1500$ GeV
- Single production can probe twice as much (in principle)
- The t-channel probes the dependence of mass-Yukawa up to any mass, but requires S^{++} to interact with electrons

t-channel

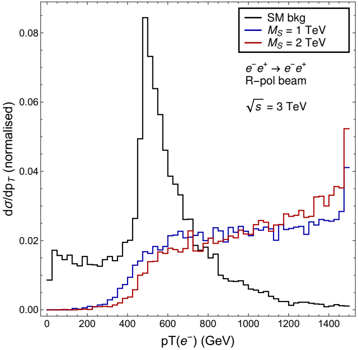
Cross-sections and distributions for $e^- e^+$ final state @ $\sqrt{s} = 3$ TeV

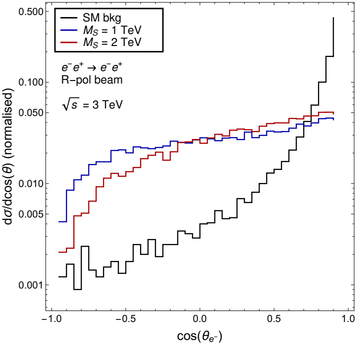
- Simulation with CALCHEP including ISR and beamstrahlung
- Standard acceptance cuts: $E(l) \geq 10$ GeV and $|\cos(\theta)| \leq 0.95$
- SM background (not showing Higgs):



- Peak at $p_T \sim 500$ GeV due to ISR+beamstrahlung

$\|\cos(\theta_e)\| \leq 0.95$	
SM	~ 1370 fb
M_S = 1 TeV	$\sim 2320/\lambda^4_{ee}$ fb
M_S = 2 TeV	$\sim 771/\lambda^4_{ee}$ fb





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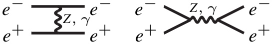
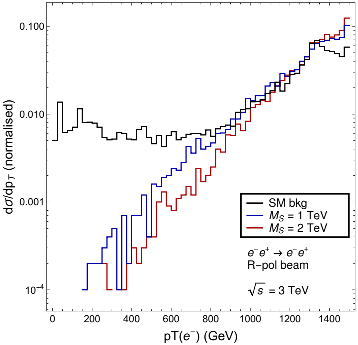
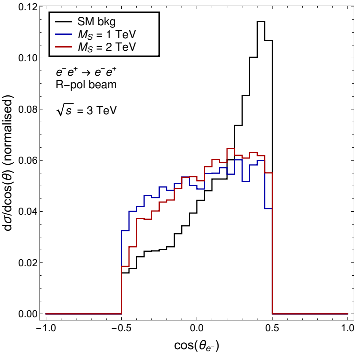


- $|\cos(\theta)| \leq 0.5$ for e to reduce the bkg

$\lvert\cos(\theta_e)\rvert \leq 0.95$	
SM	~ 1370 fb
M_S = 1 TeV	$\sim 2320/\lambda_{ee}^4$ fb
M_S = 2 TeV	$\sim 771/\lambda_{ee}^4$ fb
$\lvert\cos(\theta_e)\rvert \leq 0.5$	
SM	$\sim$30 fb
M_S = 1 TeV	$\sim 890/\lambda_{ee}^4$ fb
M_S = 2 TeV	$\sim 320/\lambda_{ee}^4$ fb

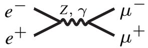




t-channel

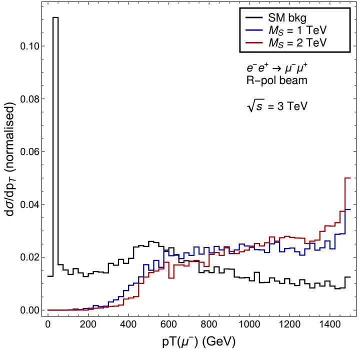
Cross-sections and distributions for $\mu^-\mu^+$ final state @ $\sqrt{s} = 3$ TeV

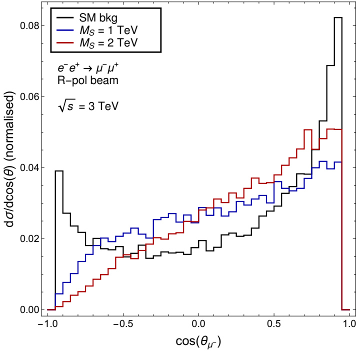
- Simulation with CALCHEP including ISR and beamstrahlung
- Standard acceptance cuts: $E(l) \geq 10$ GeV and $|\cos(\theta)| \leq 0.95$
- SM background (not showing Higgs):



and no t-channel diagrams

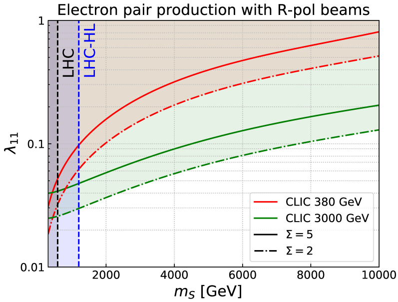
SM	$\sim$ 30 fb
M_S = 1 TeV	$\sim 2320/\lambda^4_{e\mu}$ fb
M_S = 2 TeV	$\sim 771/\lambda^4_{e\mu}$ fb

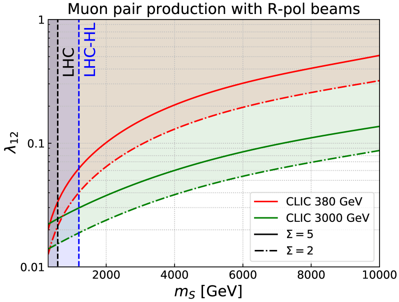


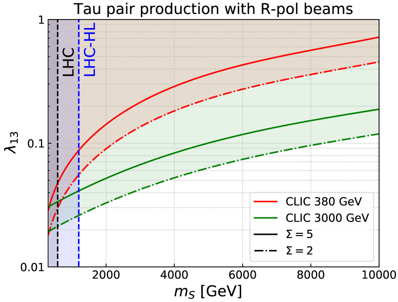


t-channel

- Simulation with CALCHEP including ISR and beamstrahlung
- Standard acceptance cuts: $E(l) \geq 10$ GeV and $|\cos(\theta)| \leq 0.95$ for μ and τ or 0.5 for e
- For τ_h final states, assuming a reconstruction efficiency of 70%
- Significance without systematic errors: $S/\sqrt{S+B}$
- Singlet/Triplet difference at x-sect. level and propagation of neutral scalar

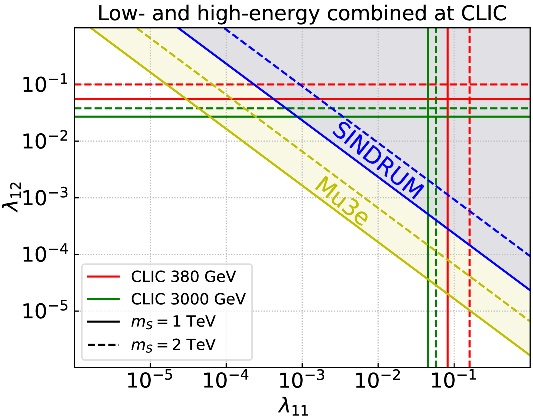






Complementarity with low energy

Yukawa couplings with electrons and muons

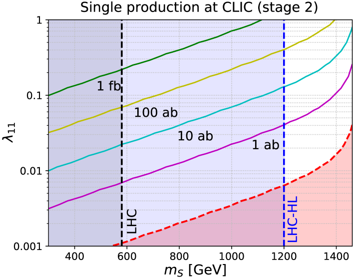


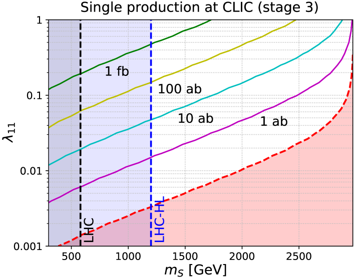
- At CLIC the two Yukawas are mostly explored independently
- Through $\mu \to 3e$ the product of the Yukawa is constrained: $BR(l_p \to l_r l_s l_t) \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6 (4\pi)^3 m_S^4 \Gamma_p}$

$$BR(\mu \to 3e)_{SINDRUM} < 10^{-12} \text{ and } BR(\mu \to 3e)_{Mu3e} < 5 \times 10^{-15}$$

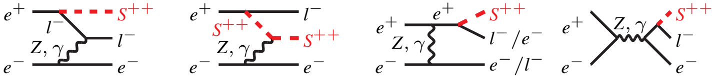
Single production

Cross-section, unpolarised beams





Contributions from different topologies with different kinematics



- Interference between topologies with Yukawa and gauge couplings
- After decay of S^{++}, same signature as pair production topologies (relevant for large width)

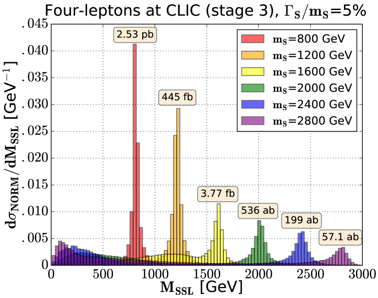
Results for singlet cannot be easily reinterpreted for triplet

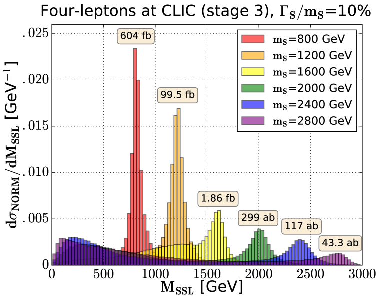
Single production

Invariant mass of same-sign leptons

$$e^+e^- \to 4e$$

Cross-sections for $\lambda_{11} = 1$ and binning of 30 GeV

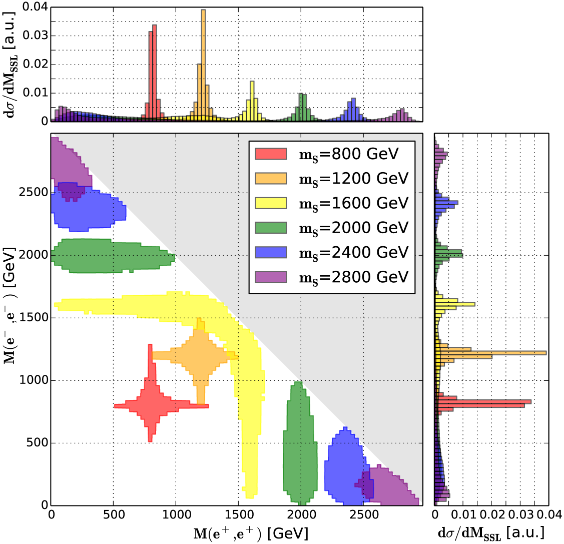




Shoulder at low invariant mass appearing when $\sqrt{s}$ is below the threshold for pair production

Single production

Invariant mass of same-sign leptons



Conclusions

- Doubly-charged scalars can play a role in the mechanism for neutrino mass generation and are predicted by various BSM models
- Constraints on couplings and masses from both low energy and LHC
- Room for further improvement of the bounds (or hopefully a discovery) with current experiments

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- Room for further improvement of the bounds (or hopefully a discovery) with current experiments

Perspectives at CLIC

- Direct production (pair and single) and contributions to SM processes (t-channel)
- Potentially larger sensitivity to masses and couplings than LHC and its upgrades
- Results with minimal setup: more realistic treatment is needed