Doubly Charged Leptons and The Higgs Portal

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Motivation

- Higgs portal is very simple model that connects the dark matter sector to the SM via a SM singlet scalar Φ
- It is simple and independent of the details of the dark sector.
- It also very useful for electroweak baryogensis.
- Being a SM singlet it is very difficult to probe.
- Need a systematic study to enhance its signal in both higher energy collider experiments as well as precision measurements and searches.

Higgs Portal Lagrangian

The scalar potential for the scalar portal is

$$V = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + \lambda_\phi(\Phi^\dagger\Phi)^2 + M_\phi^2\Phi^\dagger\Phi + \lambda_{\phi h}\Phi^\dagger\Phi H^\dagger H$$
$$+ \alpha\Phi + \beta\Phi^\dagger\Phi\Phi + \kappa_H\Phi H^\dagger H + h.c.$$

where H is the SM Higgs field.

- κ_H will induce a mixing with the Higgs
- If Φ picks up a VeV $\lambda_{\phi H}$ term will also gives rise to mixing with Higgs

$\phi - h$ mixing

If Φ is not Higgssed then the mixing is given by

$$\frac{1}{2}\begin{pmatrix} h & \phi \end{pmatrix}\begin{pmatrix} 2v^2\lambda & \frac{v\kappa_H}{\sqrt{2}} \\ \frac{v\kappa_H}{\sqrt{2}} & \bar{M_\phi}^2 \end{pmatrix}\begin{pmatrix} h \\ \phi \end{pmatrix},$$

where $\bar{M_\phi}^2 = M_\phi^2 + \lambda_{\phi h} v^2/2$. (h, ϕ) is related to the mass eigenstates (h', ϕ') by the usual 2×2 rotation matrix define by the mixing angle θ which is given by

$$\tan 2\theta = \frac{\sqrt{2} v\kappa_H}{\bar{M_\phi}^2 - v^2\lambda}.$$

From Higgs measurement we get $\sin^2\theta < .04$.
Very small signature in Higgs measurements

di-Higgs Boson Prouction

Use the process

$$g + g \to \phi \to h + h$$

This gives a possible enhancement over SM di-Higgs production for $\phi \sim 300 - 400$ GeV. Needs high luminosity LHC.

Enhance ϕ signature by vectorlike fermions

We need new states that carry SM qauntum numbers and also couple to Φ

- Fermions are obvious candidates. Due to anomaly cancellations they have to be vectorlike
- Simplest are vectorlike leptons
- To go even further in simplicity examine $SU(2)_l$ singlets.
- They need $Y > 1$ in order not to mix with e_R
- They narrows to $E^{\pm\pm}$
- They can couple to Φ by $\bar{E}E\Phi$ coupling.
- They can also be searched for in e^+e^- colliders.

$E^{\pm\pm}$ is not enough

As is written the lepton $E^{\pm\pm}$ is stable.
We have to make it decay.

$$E^{\pm\pm} \to W^{\pm}\ell^{\pm}, \quad \ell = e, \mu, \text{or} \tau$$

is allowed by charge and angular momentum conservation.
Forbidden by $SU(2)$
Simplest solution is to add a $SU(2)_L$ singlet with $Y = 1$ scalar.
Decay modes are

- If $M_E > M_s$ 2-body decay $E^{++} \to S + \ell^+$
- If $M_E < M_s$ 3-body decay $E^{++} \to \ell^+ + \ell'^+ + \nu$

Particle Content of Minimal Model

The quantum numbers of the new particles together with the relevant SM fields are given in Table (1) below

Table : Quantum numbers of the SM Higgs H, leptons L, ℓ and E, S, ϕ

Field	$SU(2)$	$U(1)_Y$
H	$\mathbf{2}$	$\frac{1}{2}$
L	$\mathbf{2}$	$-\frac{1}{2}$
ℓ_R	$\mathbf{1}$	-1
E	$\mathbf{1}$	-2
S	$\mathbf{1}$	1
Φ	$\mathbf{1}$	0

where standard notations are used.

New Lagrangian

$$
\begin{aligned}
&\mathcal{L}' \\
&= \overline{E} i\gamma^\mu(\partial_\mu - 2ig_1 B_\mu)E + [(\partial^\mu + ig_1 B^\mu)S]^\dagger(\partial_\mu + ig_1 B_\mu)S \\
&- \left[f_{e\mu}(\overline{\nu_e^c}\mu_L - \overline{\nu_\mu^c}e_L) + f_{e\tau}(\overline{\nu_e^c}\tau_L - \overline{\nu_\tau^c}e_L)\right. \\
&\left.+ f_{\mu\tau}(\overline{\nu_\mu^c}\tau_L - \overline{\nu_\tau^c}\mu_L)\right] S - y_E \overline{E} E \Phi - M_E \overline{E} E \\
&- \sum_a^{e,\mu,\tau} y_a \overline{E} \ell_{Ra} S^\dagger - V(H, S, \Phi) + h.c.
\end{aligned}
$$

The scalar Potential

The scalar potential $V(H, S, \Phi)$ is

$$\begin{aligned} V = & -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + M_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 \\ & + \lambda_{SH} S^\dagger S H^\dagger H + \lambda_\phi (\Phi^\dagger \Phi)^2 + M_\phi^2 \Phi^\dagger \Phi + \lambda_{\phi h} \Phi^\dagger \Phi H^\dagger H \\ & + \lambda_{\phi S} \Phi^\dagger \Phi S^\dagger S + \alpha \Phi + \beta \Phi^\dagger \Phi \Phi + \kappa_H \Phi H^\dagger H \\ & + \kappa_S \Phi S^\dagger S \end{aligned}$$

Constraints from universality

- Exchange of S in muon decays will modify G_F. It interfers with SM
- Since new physics in the leptonic sector we assume unitarity of quark mixing and extract G_F from nuclear, Kaon and B-meson decays and compare with G_μ. This gives

$$\mathcal{L} = \frac{if_{e\mu}^2}{2M_S^2}\left(\overline{\nu_\mu}\gamma^\alpha \hat{L}\nu_e\right)\left(\bar{e}\gamma_\alpha \hat{L}\mu\right)$$

whereas the SM has $-\frac{ig^2}{2M_W^2}$ in front of the 4-fermi operator. Here $\hat{L} = (1-\gamma_5)/2$.

- We get

$$f_{e\mu} \leq 1.502 \times 10^{-1}\left(\frac{M_S}{400\mathrm{GeV}}\right).$$

τ leptonic decays

Use the leptonic τ decays ratio into μ, e we get

$$\frac{\Gamma(\tau \to \mu + \nu' s)}{\Gamma(\tau \to e + \nu' s)} = \frac{\left(1 - \frac{f_{\mu\tau}^2 M_W^2}{g^2 M_S^2}\right)^2 + \cdots}{\left(1 - \frac{f_{e\tau}^2 M_W^2}{g^2 M_S^2}\right)^2 + \cdots}$$

$$\simeq 1 + 2(f_{e\tau}^2 - f_{\mu\tau}^2)\left(\frac{M_W^2}{g^2 M_S^2}\right)$$

where $\cdots$ denotes terms such as $f_{\mu e}^2 f_{\tau e}^2$ which come from diagrams that interfere incoherently with the SM ones. They are of order f^4 which we neglect.

$$f_{e\tau}^2 - f_{\mu\tau}^2 \leq \pm 2.25 \times 10^{-2}\left(\frac{M_S}{400\mathrm{GeV}}\right)^2 .$$

Experimental value of $\frac{\Gamma(\tau \to \mu^- \bar{\nu_\mu} \nu_\tau)}{\Gamma(\tau \to e^- \bar{\nu_e} \nu_\tau)} = 0.979 \pm 0.004$ has been used

$\mu \to e + \gamma$

The diagrams are

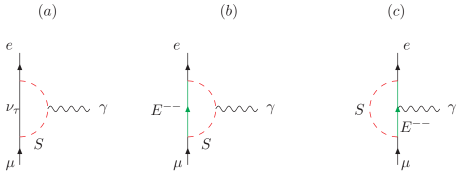


Figure : Diagrams leading to $\mu \to e\gamma$. Wavefunction renormalization graphs are not shown

Note that (a) has different chiral structure than (b) and (c) We get

$$f_{e\tau}^2 f_{\mu\tau}^2 + \left(\frac{y_e y_\mu x^2}{(1-x)^4}\right)^2 \left[(-4+9x-5x^3)+6x(2x-1)\ln x\right]^2$$
$$\leq 2.235 \times 10^{-12} \left(\frac{M_s}{400\mathrm{GeV}}\right)^4,$$

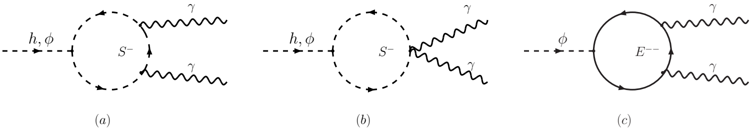
where $x = \frac{M_S^2}{M_E^2}$.

contd.

- Similar diagrams yields constraint from anomalous magnetic moment of the muon, a_μ.
- The constraint is not as strong as the above

How do $E^{\pm\pm}$ and S^pm held with ϕ signals?

Since we do not know the masses and first look at the case $M_\phi < 2M_E(2M_s)$. The signature is then the diphoton resonance



The effective Lagrangian is

$$\mathcal{L} = \frac{1}{f_\gamma}\phi(F_{\mu\nu})^2$$

The production is via photon fusion.

Calculation of f_γ

$$f_\gamma^{-1} =$$

$$\frac{\alpha}{4\pi M_\phi}\left(Q^2 N y_E \sqrt{\tau_E} F_{\frac{1}{2}}(\tau_E) + \frac{2(\lambda_{\phi S} w + \kappa_S)}{M_S}\sqrt{\tau_s} F_0(\tau_s)\right).$$

We define $\tau_i = M_\phi^2/(4M_i^2)$ and the 1-loop functions are

$$F_0(\tau) = -[\tau - f(\tau)]\tau^{-2}; \;\; F_{\frac{1}{2}}(\tau) = 2[\tau + (\tau - 1)f(\tau)]\tau^{-2}$$

with

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \leq 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1. \end{cases}$$

From the limits of event rates for a 800 GeV ϕ one can deduce that $f_\gamma \sim 8 - 9$ TeV. The above give strong constraints on the model parameters since the F functions are known.

contd

- $\kappa_s << v$. The E-loop will be the dominant contribution. We obtain

$$y_E N \leq 16.8$$

where N is the number of E.

- $\kappa_s >> v$ the S loop can assist. Then the constraint is

$$N y_E \sqrt{\tau_E} F_{\frac{1}{2}}(\tau_E) + \frac{\kappa_S}{2M_S}\sqrt{\tau_s} F_0(\tau_s) \lesssim 34$$

For $\kappa_s \sim 10$ TeV the scalar loop dominates.

more results

- di-boson widths

$$\Gamma_{\gamma\gamma} : \Gamma_{\gamma Z} : \Gamma_{ZZ} = 1 : \frac{2s_w^2}{c_w^2} : \frac{s_w^4}{c_w^4}$$
$$\approx 1 : 0.54 : 0.07$$
$$\Gamma_{WW} = 0.$$

- Limits from $h \to \gamma\gamma$

$$R = \left|1 + \frac{\lambda_{SH} v^2}{2M_S^2} \frac{F_0(\tau')}{F_1(\tau_w) + \frac{4}{3} F_{\frac{1}{2}}(\tau_t)}\right|^2$$

where $R \equiv \Gamma^{new}/\Gamma^{SM}$,$\tau' = M_h^2/4M_S^2$ and
$F_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\tau^{-2}$. The current bound on R is
1.17 ± 0.27 This yields the constraint: $|\lambda_{SH}| < 8.1$.

Production of E and S

- At hadron colliders S can be produced via Drell-Yan

$$q + \bar{q} \to S^+ S^- \to \ell^+ \nu \ell^{-\prime} \nu^c$$

  The SM background is enormous

- For E we have

$$q + \bar{q} \to E + \bar{E} \to S^- + \ell_a^- + S^+ + \ell_b^+ \to \ell_a^- + \ell_c^- + \ell_b^+ + \ell_d^+ + \not{E}_T$$

  where a, b, c, d denote the flavors of the charged leptons. Here the signal is four leptons plus $\not{E}_T$ with no associated jets.Furthermore, the charged leptons do not form invariant mass peaks. Interestingly if the couplings f's and y's are very small i.e. $< O(10^{-6})$ we will have displaced vertices.

- $e^+ e^-$ colliders will be better since the signals are cleaner.

Conclusions

- The singlet Higgs portal can have enhanced signals with the aid of vectorlike $E^{\pm}\pm$
- Since E must not be stable a singlet charged scalar must be added
- The leading signal for the Higgs portal is $\phi \to \gamma\gamma$.
- E and S will greatly enhanced this signal.
- Displayed vertices are important tools for these kind of new states.
- LHC can be very effective in probing very small couplings which to date are restricted to high precision low energy measurements.
- The best search for these are a high energy lepton collider