Alternative searches for Quintuplet Fermions at International Linear Collider

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Based on arXiv:2112.09451

Motivation:

- Large fermionic multiplets are essential $\rightarrow$ small neutrino masses, muon (g-2).
- Fermion multiplet + Scalar multiplet $\rightarrow$ EW constrains, relic abundance of DM, and flavor anomalies.
- **Example**: *Seesaw-like* (Σ_R(Y=0) and Φ (Y=-1)) 1204.6599
  Left -Right Symmetric Models 1403.4902
  Little Higgs Scenario $SU(6)/Sp(6)$ 2007.15626
- If $M_\Sigma > M_\Phi$, then the quintuplet fermions can decay into the scalar components of Φ.
- Non standard decay modes $\rightarrow$ Signatures rich with multiple jets and leptons.
- Clean environment of linear collider (ILC) is better suited.

Model:

- In models with quintuplet Majorana fermion Σ_R and one or more scalar multiplets(Φ_4, Φ_5,...), small neutrino mass is achieved, proportional to v_4, v_5... and suppressed by M_Σ .
- Small neutrino mass and $\rho = 1$ is satisfied with
$$v_i \sim 1 \text{ GeV}.$$
- Addition of Φ_5, makes Φ_4 inert and neutrino mass is induced at one-loop level. Possible explanation for flavor anomalies and muon (g-2) (1912.03990).
- Irrespective of the number of scalar multiplets, charged and neutral scalars are obtained after diagonalization.

Simplistic scenario for phenomenological purpose:

$$\text{Quintuplet fermion, } \Sigma_R(Y=0) = \left[\Sigma_1^{++}, \Sigma_1^{+}, \Sigma^0, \Sigma_2^{+}, \Sigma_2^{++}\right]_R^T$$
$$\text{Quartet scalar, } \Phi_4(Y=1/2) = \left(\varphi^{++}, \varphi_2^{+}, \varphi^0, \varphi_1^{-}\right)^T$$

Model:

Gauge interaction:

$$\mathcal{L}_{gauge} = \bar{\Sigma}_R \gamma^\mu i D_\mu \Sigma_R$$

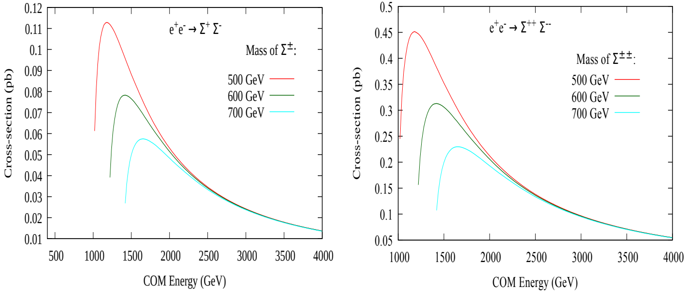
Yukawa interaction:

$$-\mathcal{L}_Y = (y_\ell)_{ii} \bar{L}_{L_i} H e_{R_i} + (y_\nu)_{ij} [\bar{L}_{L_i} \tilde{\Phi}_4 \Sigma_{R_j}] + (M_R)_i [\bar{\Sigma}^c_{R_i} \Sigma_{R_i}] + \mathrm{h.c.},$$

- Current constrains from flavor and muon(g-2) suggest, $y_\nu \sim$(0.001-1), depending on the scalar particle content of the model.(1912.03990)
- For the phenomenological purpose, we choose a very conservative limit of $y_\nu = 0.1$
- Also, $M_\Sigma > M_\phi$ is naturally implied form muon(g-2). Hence, quintuplets fermions decay via the scalars. $\Delta M \leq 100$ GeV

Production of the Quintuplet fermions:

$$e^+e^- \to \Sigma^+\Sigma^-/\Sigma^{++}\Sigma^{--}$$



Benchmark Points:

$M_\Sigma = 200$ GeV at $\sqrt{s} = 500$ GeV,

$M_\Sigma = 300, 400$ GeV at $\sqrt{s} = 1000$ GeV, and

$M_\Sigma = 500, 600, 700$ GeV for $\sqrt{s} = 1500$ GeV

Decay of the Quintuplet fermions:

$$\begin{array}{ll} \Sigma^{\pm} \rightarrow \phi_2^{\pm}\nu(\bar{\nu}) & \Sigma^{\pm\pm} \rightarrow \phi^{\pm\pm}\nu(\bar{\nu}) \\ \Sigma^{\pm} \rightarrow \phi^{\pm\pm}\ell^{\mp} & \Sigma^{\pm\pm} \rightarrow \phi^{\pm}\ell^{\pm} \\ \Sigma^{\pm} \rightarrow \phi^{0}\ell^{\pm} & \end{array}$$

$$\begin{array}{ll} \phi_2^{\pm}(\phi_1^{\pm}) & \rightarrow W^{\pm}Z \\ \phi^{\pm\pm} & \rightarrow W^{\pm}W^{\pm} \\ \phi^{0} & \rightarrow W^{+}W^{-} \end{array}$$

The decay of W/Z to jets is preferred due to large Branching Ratio compares to the leptons. But multijet states are hard to probe at LHC due to large QCD background. At ILC the final states from $e^+e^- \rightarrow \Sigma^+\Sigma^-$ are:

- Channel(A): One lepton ($\ell^{\pm}$) + 4 jets.
- Channel(B): Opposite sign lepton pair ($\ell^+\ell^-$) + 4 jets.

Collider analysis:

- **SM Backgrounds**:

  Inclusive production of di-boson (WW, ZZ),

  $t\bar{t}$, $t\bar{V}$,

  Triboson (VVV=ZZZ, ZWW) and HZ

  The contribution from the $\ell\ell+$ 2 jets, 4-jets and 4-top production are found to be small.

- The jets are reconstructed in FastJet with distance parameter $R = 0.4$ using anti-K_t algorithm. In Delphes, we use the Delphes ILD detector (1306.6329) card for detector simulation.

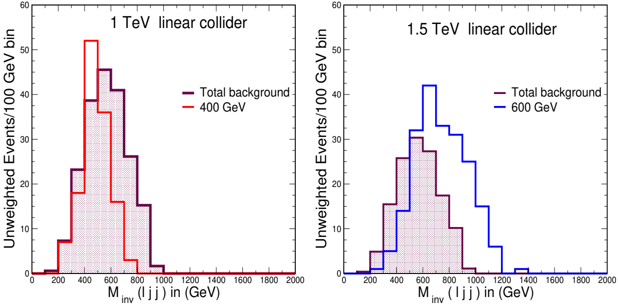
Selections:

Selections	(A) $(\ell^{\pm})$ + 4 jets	(B) $(\ell^{+}\ell^{-})$ + 4 jets
S1	$p_T(\ell) > 10$ GeV	$p_T(\ell) > 10$ GeV
	$\lvert\eta\rvert(\ell) < 2.5$	$\lvert\eta\rvert(\ell) < 2.5$
	$\Delta R(\ell, \ell/j) > 0.4$	$\Delta R(\ell, \ell) > 0.4$
	$p_T(j) > 20$ GeV	$p_T(j) > 20$ GeV
	$\lvert\eta\rvert(j) < 5.0$	$\lvert\eta\rvert(j) < 5.0$
	$\Delta R_{jj} > 0.4$	$\Delta R_{jj} > 0.4$
S2	$\Delta R(\ell, j) > 1.5$	$\Delta R(\ell, j) > 1.5$
	–	$M(\ell^{+}, \ell^{-}) > 100$ GeV

Findings: Signal cross section is comparatively small in Channel B, but the quintuplet mass (M_{Σ}) can be reconstructed.

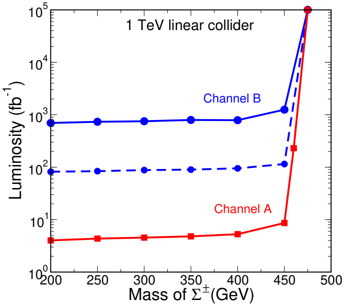
The largest contribution of SM background comes from $t\bar{t}+$ jets.

Result:



Three body invariant mass $M(\ell^{\pm}jj)$ for $M_{\Sigma} = 400$ GeV (left) and $M_{\Sigma} = 600$ GeV (right) in channel B at 1 TeV and 1.5 TeV $e^{+}e^{-}$ collider respectively. The shadowed region represents the total background.

Result:



Solid line: Integrated luminosity for discovery for channel A and B.

Dashed line: Integrated luminosity for exclusion for channel B.

Conclusion:

- Singly charged component of the quintuplet fermion ($\Sigma^{\pm}$) shows a great discovery potential 1 TeV and 1.5 TeV ILC.
- For the doubly charged component ($\Sigma^{\pm\pm}$), the final state will be much more complicated.
- For larger masses of the quintuplet, W/Z will behave as *fatjets* $\rightarrow$ need new techniques.
- If ILC Can be operated as $\gamma\gamma$ and an $e^{-}\gamma$ collider, the cross section will increase by a factor of $\sim$10.
- The component of the scalar multiplets can also be produced at ILC.
- Overall, alternative searches of these exotic particles has a great potential at ILC.

ILC Snowmass Contribution:

The discussion so far is already done in arXiv:2112.09451.

In addition to that, for the Snowmass contribution several things can be worked on:

1. Detailed discussion on the doubly charged fermion ($\Sigma^{\pm\pm}$) production and their nonstandard decays.

2. Production of multicharged scalars ($\phi^{\pm\pm}$, $\phi^{\pm}$) at ILC and its phenomenology.

3. Channels with (W/Z) Fatjets, for masses of quintuplets, larger than ~ 1 TeV.