Unconventional Searches of Exotic particles at Future Linear Colliders

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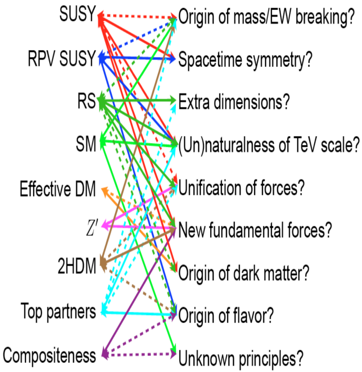
New Theories Beyond Standard Model



SM is a part of a Larger theory (BSM) at a very large scale.

BSM may alter the prediction of coupling strength, B Physics, muon (g-2) etc and give DM candidate.

BSM predicts exotic particles which can be discovered at LHC.

What are Exotic Particles?

Exotic particles are predicted in Beyond Standard Model theories. **ATLAS** and **CMS** search for exotic particles at Large Hadron Collider. The search Categories are:

- Higgs Physics, Standard Model, Top Quark
- Supersymmetry, Heavy Ion
- Higgs and Diboson searches (Exotic Higgs: H, $H^{\pm}$, $H^{\pm\pm}$)

  Models: MSSM, 2HDM, 2HDM+S, GM Model etc

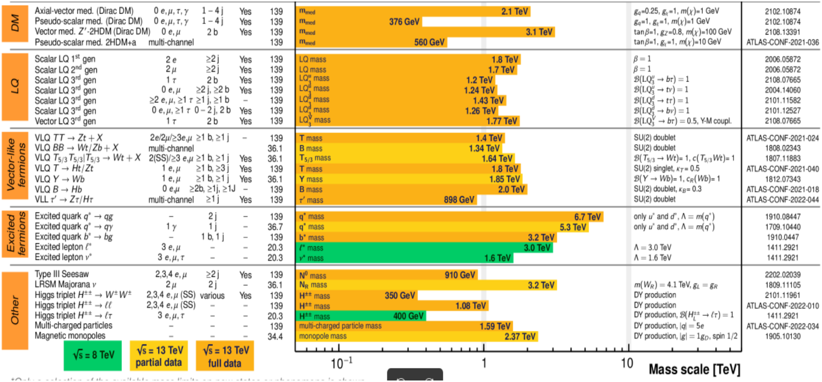
  Exotic higgs decay into diboson (VV), Vh, hh, aa leading to the final states with lepton, jets, radiation and MET.

- Exotic searches:

  Multicharged Particles (MCP), Leptoquarks, DM searches, LLP, W', Z', Vectorlike Quark, Vectorlike Lepton...

Non SUSY Collider Searches

ATLAS 13 TeV



For CMS check https://twiki.cern.ch/twiki/bin/view/CMSPublic SummaryPlotsEXO13TeVOverallsummaryplot

Standard Signatures

Simple/phenomenological extensions of SM:

- SM + Exotic Scalar (Singlet/Doublet/Triplet)
- SM + Exotic Fermion (Vectorlike/Multicharged multiplets)
- SM + Leptoquarks

LHC is pushing the exotic particles (X) beyond 1 TeV !!

Assumptions: X decays to the the SM particles directly.

$$X \to \text{SM SM}$$

Alternative Signatures

BUT $\boxed{X \to YY, Y \to \text{SM} \;\; \text{SM}}$ is also possible.

- If Exotic particles (X, Y) both exist in a Model
- If interaction among X and Y are allowed by the theory

Models:*Seesaw-like(1204.6599), LRSM(1403.4902), Little Higgs(2007.15626), Composite Higgs(1506.01961), GUT (0608183)*

Recent Studies: arXiv: 2206.11718, 2208.09700 and many more.

Search for Exotic Fermions Decaying in Exotic Scalars

$$\boxed{\mathrm{X} \to YY, Y \to \mathrm{SM}\ \ \mathrm{SM}}$$

$X = \Sigma$ (Fermion multiplet) $Y = \Phi$ (Scalar multiplet)

$$M_\Sigma > M_\phi$$

Based on:

NK,V. Sahdev, Phys.Rev.D 105 (2022) 11, 115016

NK, T. Nomura and H. Okada, Eur. Phys. J. C **80**, no.8, 801 (2020)

Search for Exotic/Heavy Fermions

Large fermionic multiplets are essential to satisfy small neutrino masses (type-III seesaw), muon (g-2). In these models, the allowed decays are:

$$\Sigma^0 \to Z\nu / H\nu / W^\pm l^\mp$$
$$\Sigma^\pm \to Hl^\pm / Zl^\pm / W^\pm \nu$$

The observed limit on M_Σ from multilepton searches is $\sim$ **900GeV**.

ATLAS:Eur. Phys. J. C 82 (2022) 988

Our Model: Fermion multiplet (Σ) + Scalar multiplet (Φ)
Address EW constrains, DM, flavor anomalies and muon (g-2).

$$\Sigma \to \Phi \to \text{SM}$$

Signatures rich with multiple jets and leptons.

Model

Fermion and Scalar multiplets: arXiv:1204.6599,1708.03204

$\Sigma = (\Sigma_1^{++}, \Sigma_1^{+}, \Sigma^0, \Sigma_2^{-}, \Sigma_2^{--})$ (1,5,0)

$\Phi = (\phi^{++}, \phi_1^{+}, \phi^0, \phi_2^{-})$ (1,4,1/2)

Gauge interaction: The production and decay of the fermion and scalar multiplets to the gauge bosons are given by the Lagrangian

$$\mathcal{L}_{gauge} = \bar{\Sigma}_R \gamma^\mu i D_\mu \Sigma_R + |D_\mu \Phi|^2$$

Yukawa interaction: Interaction between Σ and Φ

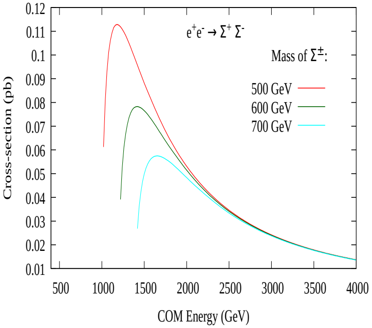
$$-\mathcal{L}_Y = (y_\ell)_{ii} \bar{L}_{L_i} H e_{R_i} + (y_\nu)_{ij} [\bar{L}_{L_i} \tilde{\Phi} \Sigma_{R_j}] + (M_R)_i [\bar{\Sigma}^c_{R_i} \Sigma_{R_i}] + \mathrm{h.c.},$$

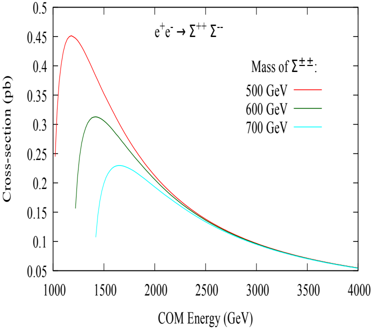
$M_\Sigma > M_\phi$, $\Delta M = 100$ GeV, $y_\nu = 0.1$

Production of the Quintuplet Fermions

The production cross section of $\Sigma^+\Sigma^-$ is very small compared to the production of $\Sigma^{++}\Sigma^{--}$. Hence no good S/B ratio $\Sigma^+\Sigma^-$.

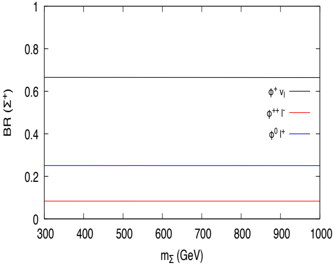
At ILC we study $e^+e^- \to \Sigma^+\Sigma^-/\Sigma^{++}\Sigma^{--}$



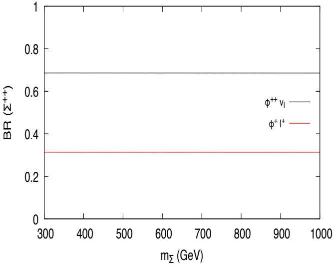


NK,V. Sahdev, Phys.Rev.D 105 (2022) 11, 115016

Decay of the Quintuplet Fermions



$\mathrm{BR}(\Sigma^{\pm})$



$\mathrm{BR}(\Sigma^{\pm\pm})$

$$M_\Sigma > M_\phi,\ \Delta M = 100\ \text{GeV},\ y_\nu = 0.1$$

$$\Sigma^{\pm} \rightarrow \phi_2^{\pm}\nu(\bar{\nu})$$
$$\Sigma^{\pm} \rightarrow \phi^{\pm\pm}\ell^{\mp}$$
$$\Sigma^{\pm} \rightarrow \phi^{0}\ell^{\pm}$$

$$\Sigma^{\pm\pm} \rightarrow \phi^{\pm\pm}\nu(\bar{\nu})$$
$$\Sigma^{\pm\pm} \rightarrow \phi^{\pm}\ell^{\pm}$$

Decay of the Scalars

$$\begin{aligned} \phi_2^\pm &\to W^\pm Z \\ \phi^{\pm\pm} &\to W^\pm W^\pm \\ \phi^0 &\to W^+ W^- \end{aligned}$$

Channel B:

$\Sigma^+\Sigma^- \to \phi_2^+\nu \;\; \phi_2^-\bar{\nu} \to W^+Z\nu \;\; W^-Z\bar{\nu} \to (l^+jj) \;\; (l^-jj) \; + \text{MET}$

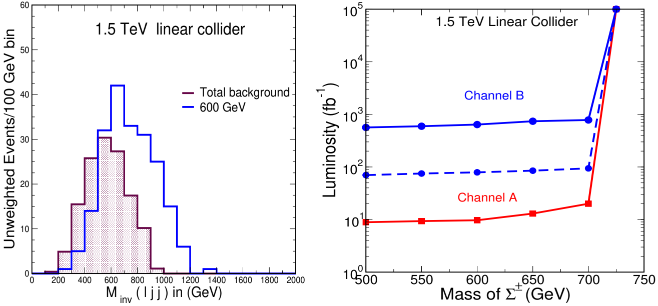
The decay of Z to jets is preferred due to large Branching Ratio compared to the leptonic decay modes. Leptons are well isolated from the jets, and the dilepton invariant mass is chosen to be grater than 100 GeV.

Mulltijet states are hard to probe at LHC due to large QCD background. ILC is better to study the multijet final states.

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

Result

NK,V. Sahdev, Phys.Rev.D 105 (2022) 11, 115016



(Left) Three body invariant mass M_{inv}(ljj) for $M_\Sigma = 600$ GeV (right) in channel $(\ell^+\ell^-) + 4$ jets.(right) 5σ discovery and 95% exclusion plot. Channel(A): One lepton $(\ell^\pm) + 4$ jets. Channel(B): Opposite sign lepton pair $(\ell^+\ell^-) + 4$ jets.

$\Sigma^\pm$ *shows a great discovery potential 1 TeV and 1.5 TeV ILC which is other wise not possible to observe at 13/14 TeV LHC via alternative decay modes.*

Quintuplet Fermions at $\gamma\gamma$ *Collider*

Improve in the cross section, specially for the doubly charged fermions compared to e^+e^- colliders.

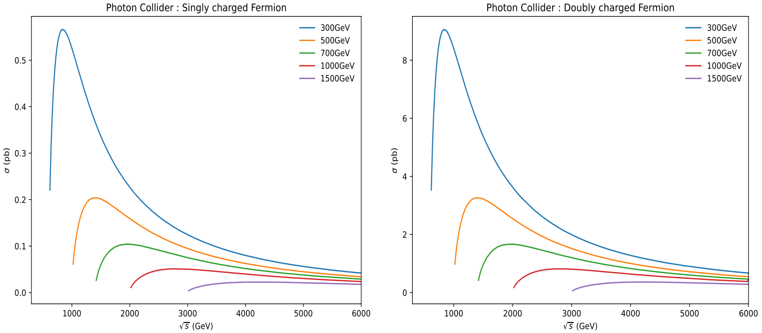


Figure: Pair production cross-sections for the singly and doubly charged fermions at $\gamma\gamma$ collider via **photon induced** processes. The production cross section via Laser induced process and IWW approximation is relatively smaller.

Quintuplet Fermions at Muon Collider

Muon collider offers higher mass reach for the exotic fermions.

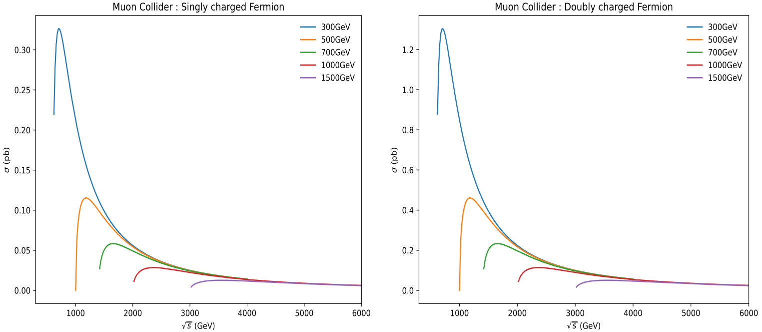


Figure: Pair production cross-sections for the singly and doubly charged fermions at $\mu^+\mu^-$ collider.

Search for Exotic Scalars Decaying in Exotic Fermions

$$\boxed{X \to YY, Y \to \text{SM} \;\; \text{SM}}$$

$$X = \Phi, Y = \Sigma$$

Based on:

Ongoing work, A. Chakraborty, NK, V. Sahdev

Same Model

Fermion and Scalar multiplets: arXiv:1204.6599,1708.03204

$\Sigma = (\Sigma_1^{++}, \Sigma_1^{+}, \Sigma^{0}, \Sigma_2^{-}, \Sigma_2^{--})$ (1,5,0)

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Gauge interaction: The production and decay of the fermion and scalar multiplets to the gauge bosons are given by the Lagrangian

$$\mathcal{L}_{gauge} = \bar{\Sigma}_R \gamma^\mu i D_\mu \Sigma_R + |D_\mu \Phi_4|^2$$

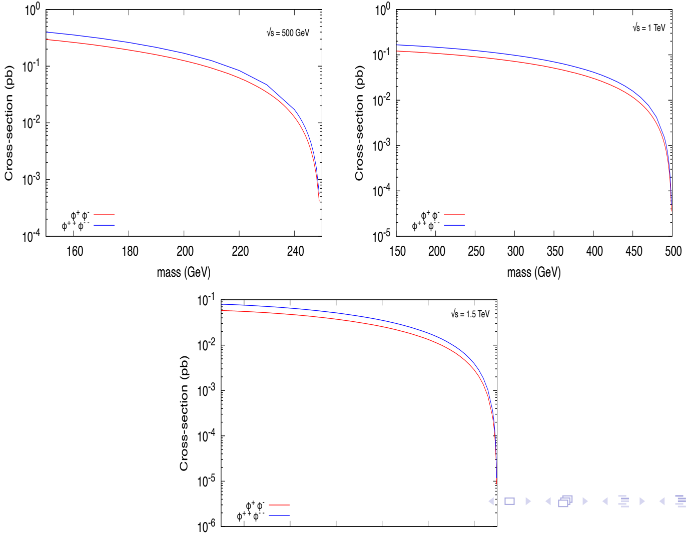
Yukawa interaction: Interaction between Σ and Φ

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

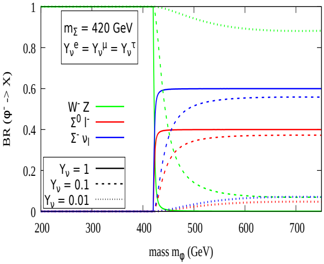
$$\boxed{\mathrm{M}_\Sigma < M_\phi,\ \Delta M = 100\ \mathrm{GeV},\ y_\nu = 0.1}$$

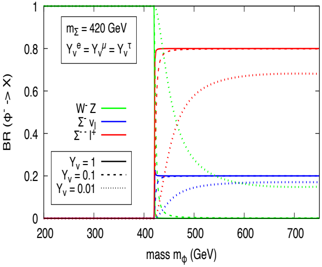
Production at e^+e^- Collider

Multijet channels are harder to probe at LHC. Linear colliders offer better prospects.



Decay of the Scalars





$$\phi_1^\pm \to W^\pm Z \qquad \phi_2^\pm \to W^\pm Z$$
$$\phi_1^\pm \to \Sigma^\pm \qquad \phi_2^\pm \to \Sigma^\pm \nu$$
$$\phi_1^\pm \to \Sigma^0 l^\pm \qquad \phi_2^\pm \to \Sigma^{\pm\pm} l^\pm$$

Note that the decay modes of the two singly charged scalars are different.

In the region $M_\Sigma < M_\phi$, ϕ_1 is **fermiophilic** and **fermiophobic** both but ϕ_2 is mostly **fermiophilic**.

Mixing With SM Leptons

Combine the similarly charged components to form Dirac fermion. Neutral component Σ_R^0 remains Majorana.

$$\Sigma^{+(++)} = \Sigma_{1,R}^{+(++)} + (\Sigma_{2,R}^{-(--)})^C \equiv \Sigma_R^{+(++)} + \Sigma_L^{+(++)}.$$

If Φ develops a vev, $v_4/\sqrt{2}$, Dirac mass term connecting the SM neutrinos and Σ_R^0 will act as a off diagonal entry in the mass matrix.

$$\mathcal{L}_{mass,N} \supset -\begin{pmatrix} \bar{\nu}_L & (\bar{\Sigma_R^0})^C \end{pmatrix} \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} y_\nu \frac{v_4}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} y_\nu^T \frac{v_4}{\sqrt{2}} & M_\Sigma \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \Sigma_R^0 \end{pmatrix} + h.c.,$$

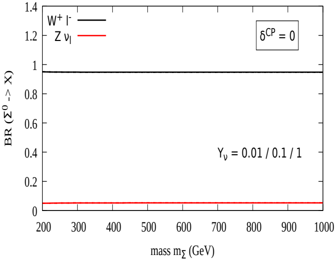
$$\mathcal{L}_{NC} \sim \frac{g}{cw} \left\{ \bar{\nu}\gamma^\mu \left[U^\dagger V P_L - U^T V^* P_R \right] \Sigma^0 Z_\mu + \left[\bar{\ell^C} \gamma^\mu V^* P_R \Sigma^+ Z_\mu \right] \right\}$$

U= PMNS Matrix

Decay of the Quintuplet Fermions

Quintuplet fermions decay via the following modes dominantly:

$$\begin{aligned} \Sigma^0 &\rightarrow l^- W^+ \\ \Sigma^\pm &\rightarrow \nu W^\pm \\ \Sigma^{\pm\pm} &\rightarrow W^\pm l^\pm \end{aligned}$$



Fermiophilic Channels

For $y_\nu = 1$ and for $M_\Phi > M_\Sigma$, following **fermiophilic modes** modes will dominate:

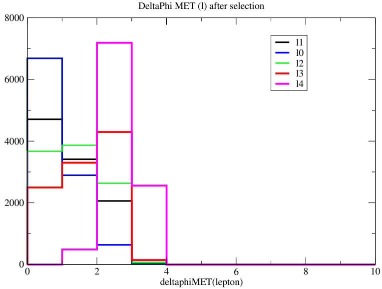
$$
\begin{aligned}
(1)\phi_1^+\phi_1^- &\rightarrow \Sigma^+\nu\ \Sigma^-\bar{\nu} \rightarrow W^+\nu\bar{\nu}W^-\bar{\nu}\nu \\
(2)\phi_1^+\phi_1^- &\rightarrow \Sigma^0 l^+\ \Sigma^0 l^- \rightarrow W^+l^-l^+W^-l^+l^- \\
(3)\phi_2^+\phi_2^- &\rightarrow \Sigma^{++}l^-\ \Sigma^{--}l^+ \rightarrow W^+l^+l^-W^-l^-l^+ \\
(4)\phi^{++}\phi^{--} &\rightarrow \Sigma^{++}\nu\ \Sigma^{--}\bar{\nu} \rightarrow W^+l^+\bar{\nu}W^-l^-\nu \\
(5)\phi^{++}\phi_2^- &\rightarrow \Sigma^{++}\nu\ \Sigma^{--}l^+ \rightarrow W^+l^+\bar{\nu}W^-l^-l^+ \\
(6)\phi_1^+\phi_1^- &\rightarrow \Sigma^+\bar{\nu}\Sigma^{0*}l^- \rightarrow W^+\nu\bar{\nu}W^-l^+l^-
\end{aligned}
$$

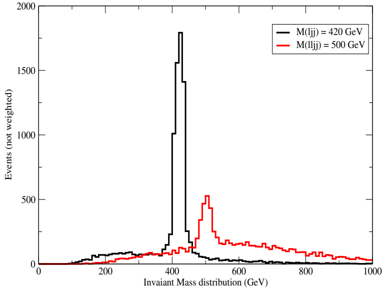
Multilepton Channel: Process 3, Process 2, Process 6

$2(\ell^+\ell^-) + \ell^\pm + jj$: Process 2, Process 3 $\rightarrow$ Unique signature

Analysis of $2(\ell^+\ell^-) + \ell^\pm + jj$

Reconstruction of $\Sigma^{\pm\pm}$ and $\phi^\pm$ are possible in this channel.





Select the Opposite sign lepton pair by requiring large $\Delta\phi_{MET}(\ell)$ and small angular separation $\Delta R(\ell^+, \ell^-)$ among the pairs. Total charge of the dilepton system is zero.

ℓ_0 is the isolated lepton. (ℓ_1, ℓ_2) is the nearest OS lepton pair. (ℓ_3, ℓ_4) is the farthest OS lepton pair.

Fermiophobic Channels

For $y_\nu = 0.1$ and for $M_\Phi < M_\Sigma$, following **fermiophobic modes** modes will dominate:

$$\begin{aligned}
(1)\phi_1^+\phi_1^- &\rightarrow W^+Z\ W^-Z \\
(2)\phi_2^+\phi_2^- &\rightarrow \Sigma^{++}l^-\ \Sigma^{--}l^+ \quad \rightarrow W^+l^+\ l^-W^-l^-l^+ \\
(3)\phi^{++}\phi^{--} &\rightarrow W^+W^+W^-W^- \\
(4)\phi^{++}\phi_2^- &\rightarrow W^+W^+\ \Sigma^{--}l^+ \rightarrow W^+W^+W^-W^-l^+
\end{aligned}$$

As ϕ_2 still prefers to decay to Σ, some interesting channels are possible.
For example, Process 4 will contribute in the $(\ell^+\ell^-) + (\ell^+\ell^+) + jj$ channel which is unique.

Many more possible final states with 4 or more jets possible.

Conclusion

- Alternative decay modes of exotic particles may lead to the discovery of new particles which are otherwise excluded by CMS and ATLAS.
- Simplified assumptions are necessary but might overlook important channels to search the exotic particles at the colliders.
- Linear colliders such as ILC gives more control over multijet backgrounds. Muon colliders are also great alternative for the alternative channels.
- The coupling between two types of exotic particles is very unique. Linear colliders can shed light on this coupling, which is otherwise difficult to probe at LHC.