Exotic Particles at LHC and Future Linear Colliders

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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, $H^{\pm}$, $H^{\pm\pm}$)

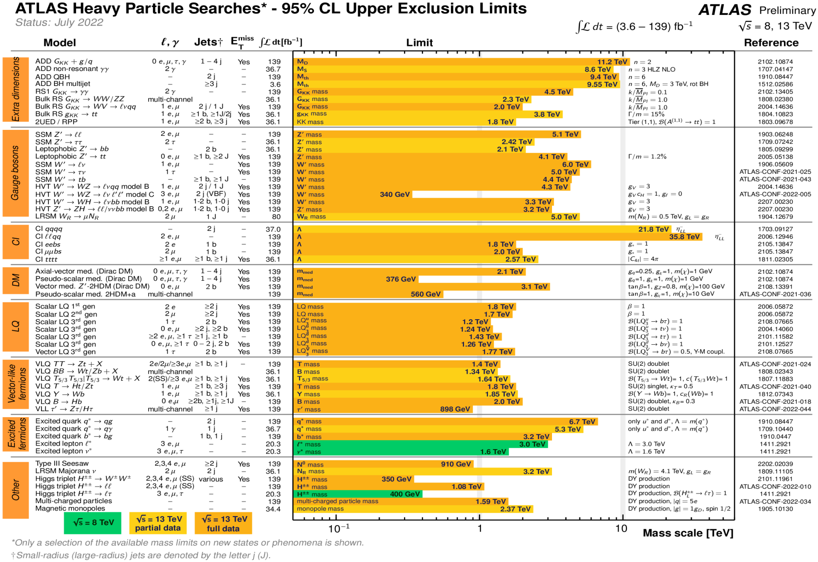
  Models: MSSM, 2HDM, 2HDM+S, GM Model etc

  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 Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	$1-4$ j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH \to \ell\nu bb$ model B	$1\ e, \mu$	1-2 b, 1-0 j	Yes	139	W' mass 3.3 TeV	$g_V = 3$	2207.00230
	HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	$0{,}2\ e, \mu$	1-2 b, 1-0 j	Yes	139	Z' mass 3.2 TeV	$g_V = 3$	2207.00230
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	$\geq 1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	$1-4$ j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	$1-4$ j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	m_{med} 3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu$, $\geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu$, $\geq 1\ \tau$	$0-2$ j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^V mass 1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Vector-like fermions	VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.0447
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$2{,}3{,}4\ e, \mu$	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2{,}3{,}4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2{,}3{,}4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Alternative Signatures

Simple/phenomenological extensions of SM:

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

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

Assumptions: X decays to the the SM particles directly.

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

BUT $\boxed{\text{X} \to YY, Y \to \text{SM}\ \ \text{SM}}$ 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)*

Search for Exotic Fermions Decaying in Exotic Scalars

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

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

$$M_\Sigma > M_\phi$$

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

<u>Our Model</u>: 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

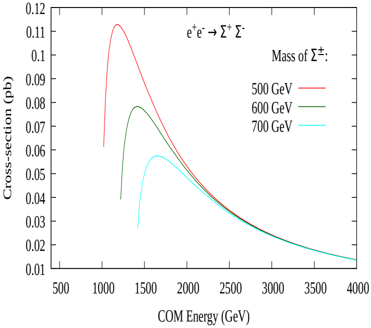
$$-\mathcal{L}_Y = (y_\ell)_{ii} \bar{L}_{L_i} H e_{R_i} + (y_\nu)_{ij} [\bar{L}_{L_i} \tilde{\Phi} \Sigma_{R_j}] + (M_R)_i [\bar{\Sigma}^c_{R_i} \Sigma_{R_i}] + \mathrm{h.c.},$$

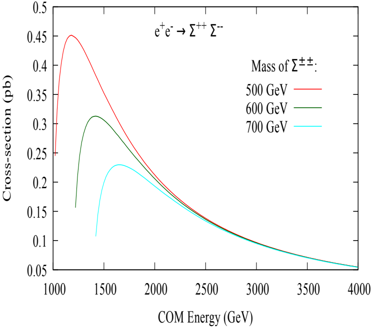
$$\boxed{\mathrm{M}_\Sigma > M_\phi,\ \Delta M = 100\ \mathrm{GeV},\ y_\nu = 0.1}$$

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 $\Sigma^+\Sigma^-$.

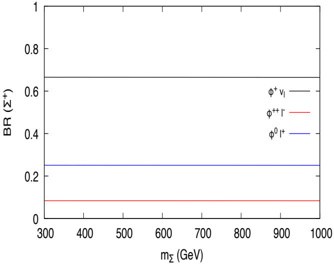
At ILC we study $e^+e^- \rightarrow \Sigma^+\Sigma^-/\Sigma^{++}\Sigma^{--}$



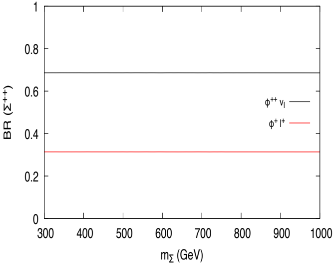


NK,V. Sahdev, Phys.Rev.D 105 (2022) 11, 115016

Decay of the Quintuplet Fermions



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



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

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

$$\Sigma^{\pm} \to \phi_2^{\pm}\nu(\bar{\nu}) \qquad \Sigma^{\pm\pm}\to\phi^{\pm\pm}\nu(\bar{\nu})$$

$$\Sigma^{\pm} \to \phi^{\pm\pm}\ell^{\mp} \qquad \Sigma^{\pm\pm}\to\phi^{\pm}\ell^{\pm}$$

$$\Sigma^{\pm} \to \phi^{0}\ell^{\pm}$$

Decay of the Scalars

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

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

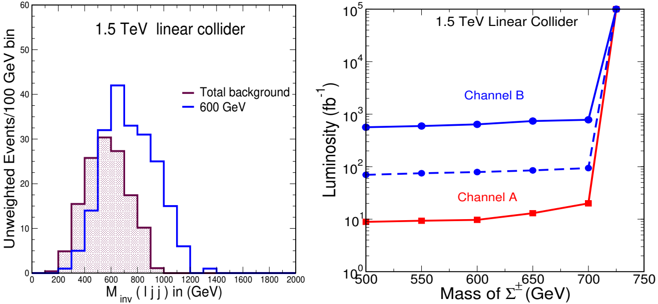
The decay of Z to jets is preferred due to large Branching Ratio compared to the leptonic decay modes. Leptons are well isolated from the jets, and the dilepton invariant mass is chosen to be grater than 100 GeV.

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) Four body invariant mass M_{inv}(lljj) 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.*

Search for Exotic Scalars Decaying in Exotic Fermions

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

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

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)

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

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

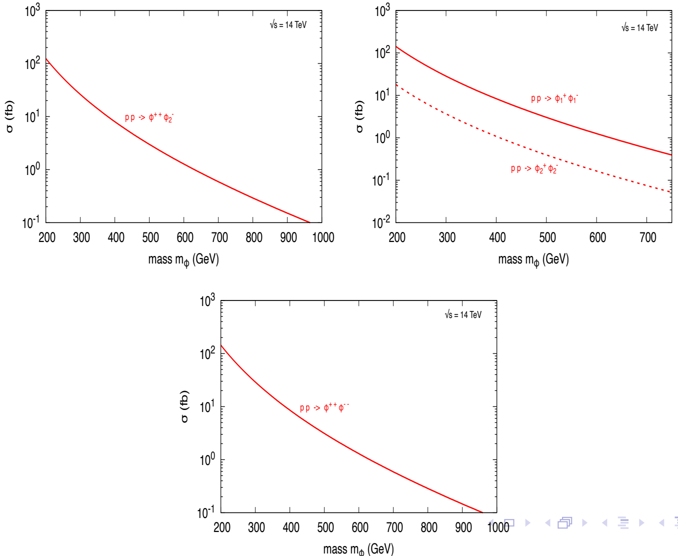
Yukawa interaction: Interaction between Σ and Φ

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

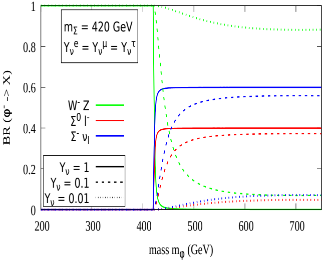
$$\boxed{\mathrm{M}_\Sigma < M_\phi,\ \Delta M = 100\ \mathrm{GeV},\ y_\nu = 0.1}$$

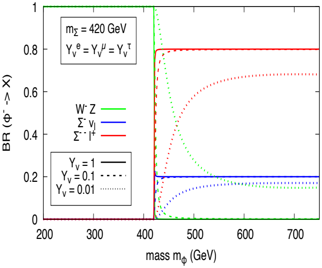
Production of the Scalars

Production cross section of the scalar multiplets at 14 *TeV* LHC



Decay of the Exotic Scalars





$$\phi_1^\pm \to W^\pm Z$$
$$\phi_1^\pm \to \Sigma^\pm$$
$$\phi_1^\pm \to \Sigma^0 l^\pm$$

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

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**.

Decay of the Quintuplet Fermions

Quintuplet fermions decay via the following modes dominantly:

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

$y_\nu = 1$ and for $M_\Phi > M_\Sigma$, following **fermiophilic modes** modes will be the dominating ones:

$$\begin{array}{rcl}pp \ \rightarrow \ \phi_1^+ \phi_1^- & \rightarrow & \Sigma^+ \nu \ \Sigma^- \bar{\nu} (60\%) \\ pp \ \rightarrow \ \phi_1^+ \phi_1^- & \rightarrow & \Sigma^0 l^+ \ \Sigma^0 l^- (40\%) \\ pp \ \rightarrow \ \phi_2^+ \phi_2^- & \rightarrow & \Sigma^{++} l^- \ \Sigma^{--} l^+ (80\%) \\ pp \rightarrow \phi^{++} \phi^{--} & \rightarrow & \Sigma^{++} \nu \ \Sigma^{--} \bar{\nu} (80\%) \\ pp \rightarrow \phi^{++} \phi_2^- & \rightarrow & \Sigma^{++} \nu \ \Sigma^{--} l^+ (80\%)\end{array}$$

We are looking at multilepton channels with W tagging.

Production of Vectorlike Leptons via the Leptoquarks

$$\boxed{\text{X} \to Y \quad SM, Y \to \text{SM} \quad \text{SM}}$$

X =Leptoquark (S_1), Y =VLL (τ')

(Ongoing work: NK,T. Mandal, S.Mitra, R.Sharma)

Standard Searches of Vectorlike Leptons (VLL)

- **Vectorlike leptons decay directly to SM particles**.
- **Singlet VLL (τ')**: Only EW pair production possible. Hence the signal cross section is very small. High luminosity required for discovery and exclusion. (NK,S. Martin arXiv: 1510.03456)

  Decay: $\tau' \to W\nu$, $\tau' \to Z\tau$, $\tau' \to H\tau$

- **Doublet VLL (τ', ν')**: Offers better discovery prospects. But, VLL coupling to third-generation SM leptons are *excluded in the mass range from 130 GeV to 900 GeV at the 95% CL*.

  Decay: $\tau' \to Z\tau$, $\tau' \to H\tau$

- Only EW couplings contribute in the production cross section of VLL. Higher Luminosity required at LHC. arXiv 1905.00498

  Time to look for alternative scenarios!!

Production of VLL via the Leptoquarks (LQ)

- LQ are color triplet bosons (scalar or vector), carry L quantum number. Leptoquark → (lepton) (quark). Higher crosssection at LHC.

- In Pati Salam, the SM fermions being $SO(4)$ singlets, do not couple with the LQ, instead they talk to the Vectorlike fermions, and they decay to the SM particles.
  Leptoquark → (VLL) (quark), VLL → (SM) (SM)

- For the LQ's, the production cross section is very large compared to VLL. LHC limits on LQ is above 1 TeV.
- Single production mode wins over pair production as large mass of LQ due to the phase space suppression in the pair production.

Minimal Model

Scalar LQ $S_1 = (\bar{3}, 1, 1/3)$, VLL Singlet $\tau' = (1, 1, 1)$

** Remember that the Singlet τ' suffers from low cross section

Yukawa Lagrangian,

$$-\mathcal{L}_Y = \alpha\ \bar{L}_L H \tau_R + \beta\ \bar{L}_L H \tau'_R + \gamma\ \bar{\tau}'_L \tau'_R + h.c. \tag{1}$$

Interaction Term:

$$\mathcal{L}_{int} \subset y^L_{ij} \bar{Q}^{Ci,a}_L S_1 \epsilon^{ab} L^{j,b}_l + y^L_{ij} \bar{u}^C_{Ri} S_1 e_{Rj} + \lambda^R_{i\tau'} \bar{u}^C_{Ri} S_1 \tau'_R$$

For simplicity we choose y^L_{ij} to be zero, that is no direct coupling of the LQ with SM particles.

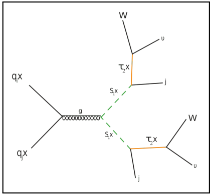
$$\mathcal{L}_{int} \subset s_R(\lambda^R_{u\tau'} \bar{u}^c_R S_1 \tau_{1R} + \lambda^R_{c\tau'} \bar{c}^c_R S_1 \tau_{1R} + \lambda^R_{t\tau'} \bar{t}^c_R S_1 \tau_{1R}) + \tag{2}$$

$$c_R(\lambda^R_{u\tau'} \bar{u}^c_R S_1 \tau_{2R} + \lambda^R_{c\tau'} \bar{c}^c_R S_1 \tau_{2R} + \lambda^R_{t\tau'} \bar{t}^c_R S_1 \tau_{2R}) \tag{3}$$

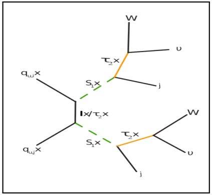
Feynman Diagrams of the LQ Production

Contribution of λ is non negligible in the NLO production cross-section.

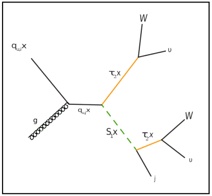
(arXiv 1503.04689)



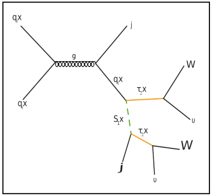
Pair Production ($\sim g_s^2$)



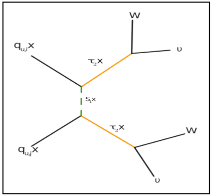
Pair Production ($\sim \lambda^2$)



2-Body Single ($\sim g_s^2\lambda$)



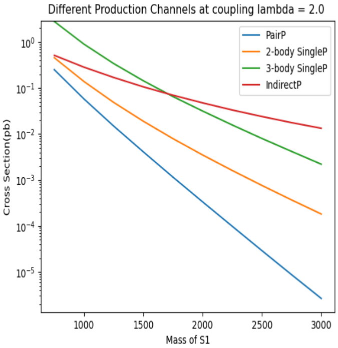
3-Body Single($\sim g_s^2\lambda$)

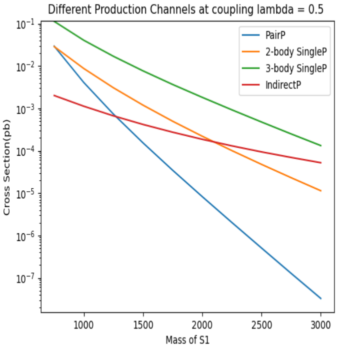


Indirect(λ^2)

Production Cross-section of S_1 Leptoquark

For Large LQ mass, if $\lambda \sim 0.5$, single production modes dominate the pair production.





Potential Channels at LHC and future colliders

For Singlet VLL, BR $(\tau' \to W\nu) = 50\%$

Main Signal at LHC: MET + 2 jets + 2 W Bosons.

- MET $+ > 2$ jets
- MET + 2 jets + 2 Leptons
- MET + 4 jets + 1 Lepton
- MET + 2 jets + 2 Fatjets (J_W)
- MET + 2 jets + 1 Fatjet (J_W) + 1 lepton

Multijet signatures for LQ mass less than 1 TeV can be studied at Linear Colliders as well.

The inclusion of the single production mode changes the bound on the LQ mass, also it impacts the search for the VLL.

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.
- Models with both fermionic and scalar multiplets can address the DM relic.

  –*Next talk on Boosted Dark matter by Soumya and talk in the parallel session by Arindam.*

Backup Slide

Collider analysis:

- **SM Backgrounds**: Inclusive production of di-boson (WW, ZZ), $t\bar{t}$, $t\bar{V}$, Triboson (VVV=ZZZ, ZWW) and HZ.
- The jets are reconstructed in FastJet with distance parameter $R = 0.4$ using anti-K_t algorithm. Delphes ILD detector (arXiv: 1306.6329) card for detector simulation.

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