Stop and Gluino Searches at the LHC and Future Colliders

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Outline

SUSY and MSSM

- R-Parity: $R = (-1)^{3B+L+2S} \Rightarrow$ Stable LSP

  sneutrino, gravitino, neutralino

- Radiative Electroweak Symmetry Breaking
- Gauge Coupling Unification $\rightarrow$ SUSY GUTs
  - Neutrino masses and mixing
  - Gauged B-L symmetry
  - Fewer free parameters

SUSY GUT - $SO(10)$

- 16-D Spinorial Representation for the matter fields

  $(15+\nu_R)$

- Neutrino masses and oscillations
- $U(1)_{B-L} \in SO(10)$

  R-Parity, Proton decay ...

- Non-Universality in SSB masses through
  - Symmetry breaking pattern: $SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R$
  - $\langle F \rangle \neq 0$ from different SO(10) representations
  - Multiple sectors breaking SUSY

Fundamental Parameters

$0 \leq$	m_{16}	≤ 5 TeV	Universal mass of matter fields
$0 \leq$	M_1, M_2, M_3	≤ 5 TeV	Gaugino masses
$-3 \leq$	A_0/m_{16}	≤ 3	Tri – linearscalar coupling
$1.2 \leq$	$\tan\beta$	≤ 60	VEV of MSSM Higgs Doublets

SARAH:	Generating the SPheno and MicrOmegas Interfaces
SPheno:	Generating the low scale predictions
MicrOmegas:	Calculating the Dark Matter predictions
MadGraph:	Calculating the signal cross-sections

Experimental Constraints

$$
\begin{aligned}
123 \leq & \quad m_h & \leq 127 \text{ GeV} \\
& \quad m_{\tilde{g}} & \geq 2100 \text{ GeV} \\
0.8 \times 10^{-9} \leq & \quad \mathrm{BR}(B_s \to \mu^+\mu^-) & \leq 6.2 \times 10^{-9} \\
2.9 \times 10^{-4} \leq & \quad \mathrm{BR}(b \to s\gamma) & \leq 6.2 \times 10^{-9} \\
0.0913 \leq & \quad \Omega h^2(\mathrm{WMAP}) & \leq 0.1363 \\
0.114 \leq & \quad \Omega h^2(\mathrm{Planck}) & \leq 0.126 \\
\mu > 0 & \quad m_t = 173.3 \text{ GeV} &
\end{aligned}
$$

$$\sigma(\text{Signal 1}) \approx \sigma(pp \to \tilde{t}_1^* \tilde{t}_1) \times \text{BR}(\tilde{t}_1 \to t\tilde{\chi}_1^0)^2$$

$$\sigma(\text{Signal 2}) \approx \sigma(pp \to \tilde{t}_1^* \tilde{t}_1) \times \text{BR}(\tilde{t}_1 \to b\tilde{\chi}_1^\pm)^2 \times \text{BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0)^2$$

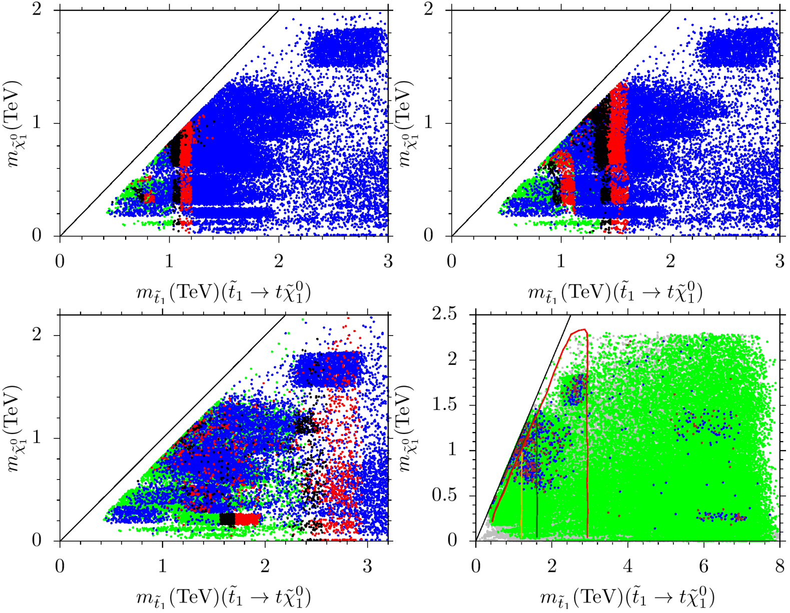
$$\sigma(\text{Signal 3}) \approx \sigma(pp \to \tilde{t}_1^* \tilde{t}_1) \times \text{BR}(\tilde{t}_1 \to b\tilde{\chi}_1^\pm)^2 \times \text{BR}(\tilde{\chi}_1^\pm \to q\bar{q}' \tilde{\chi}_1^0)^2$$

$$\frac{\text{Approximation}}{\text{Full Calculation}} \lesssim 0.7\%$$

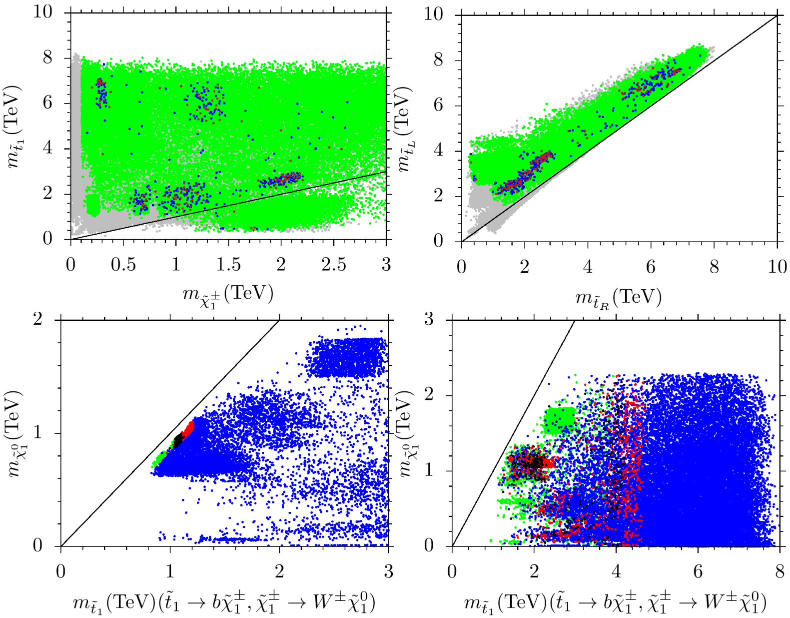
Signal Strength : $SS = \dfrac{S}{\sqrt{S+B}}$, S : number of signal processes, B : number of background processes

$0 < SS < 1$	escape	**blue**
$1 < SS < 2$	68% CL	**red**
$2 < SS < 3$	95% CL	**black**

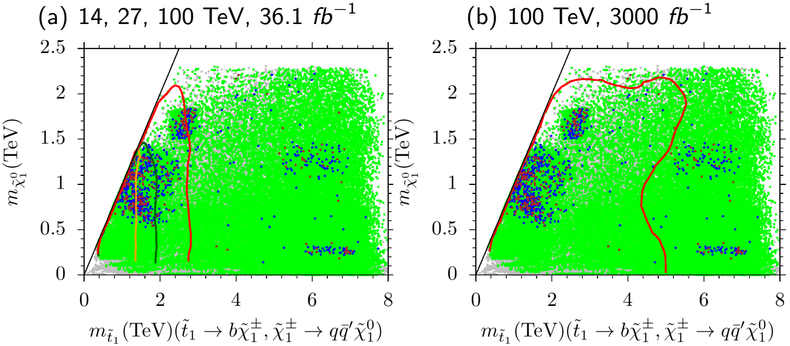
Stop Signal 1: $\tilde{t} \rightarrow t\tilde{\chi}^0$



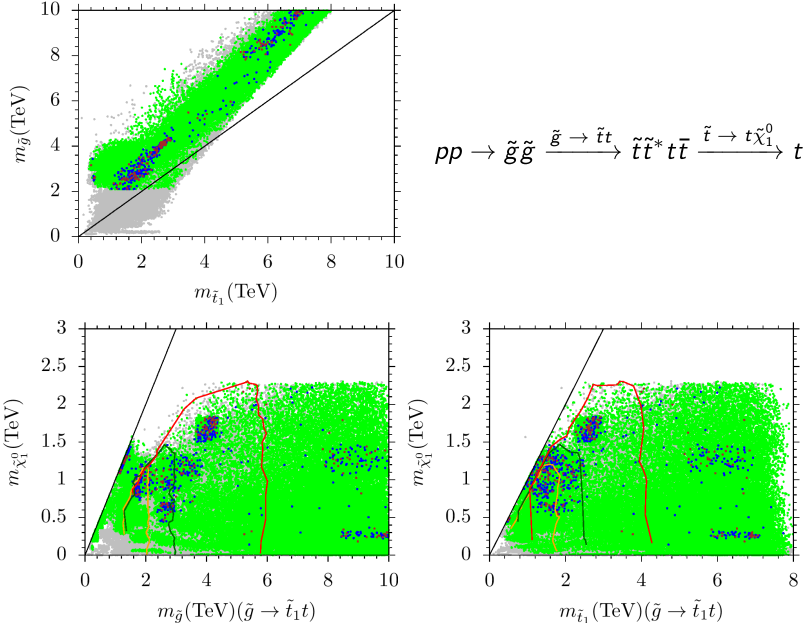
Stop Signal 2: $\tilde{t} \to b\tilde{\chi}^{\pm}, \tilde{\chi}^{\pm} \to W^{\pm}\tilde{\chi}^{0}$



Stop Signal 2: $\tilde{t} \to b\tilde{\chi}^{\pm}, \tilde{\chi}^0 \to q\bar{q}'\tilde{\chi}^0$



Gluino Signal: $\tilde{g} \to t\tilde{t}$



$$pp \to \tilde{g}\tilde{g} \xrightarrow{\tilde{g} \to \tilde{t}t} \tilde{t}\tilde{t}^* t\bar{t} \xrightarrow{\tilde{t} \to t\tilde{\chi}_1^0} t\bar{t}t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 ,$$

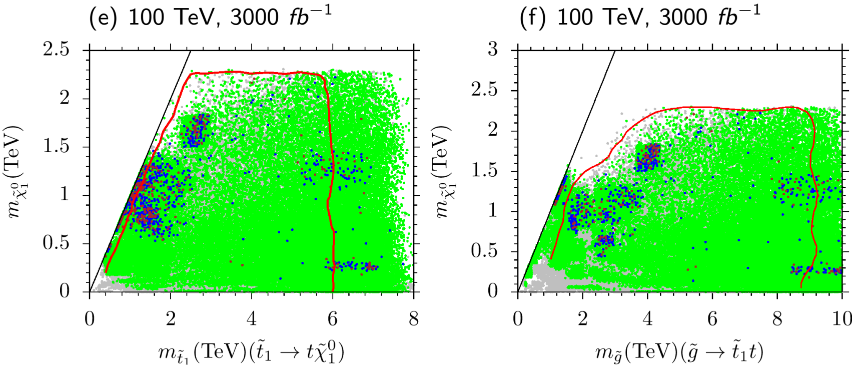
Conclusion

- ATLAS and CMS results mostly hold for SUSY GUT - MSSM

	$\tilde{t} \to t\tilde{\chi}_1^0$	$\tilde{t} \to b\tilde{\chi}_1^\pm$
14 TeV	$m_{\tilde{t}} \gtrsim 1.2$ TeV	$m_{\tilde{t}} \gtrsim 1.2$
27 TeV	$m_{\tilde{t}} \gtrsim 1.8$ TeV	$m_{\tilde{t}} \gtrsim 2$ TeV
100 TeV	$m_{\tilde{t}} \gtrsim 3$ TeV	$m_{\tilde{t}} \gtrsim 2.4$ TeV

- $\tilde{g} \to \tilde{t}t$:
  - $m_{\tilde{g}} \lesssim 2$ TeV,
  - $m_{\tilde{g}} \lesssim 3$ TeV,
  - $m_{\tilde{g}} \lesssim 6$ TeV,
  - $m_{\tilde{t}} \lesssim 1.9$ TeV is excluded at 14 TeV;
  - $m_{\tilde{t}} \lesssim 2.3$ TeV is excluded at 27 TeV;
  - $m_{\tilde{t}} \lesssim 4.4$ TeV is excluded at 100 TeV.

Back Up Slides


(e) 100 TeV, 3000 fb^{-1}
$m_{\tilde{\chi}_1^0}$(TeV)
$m_{\tilde{t}_1}$(TeV)($\tilde{t}_1 \to t\tilde{\chi}_1^0$)
0
0.5
1
1.5
2
2.5
0
2
4
6
8
(f) 100 TeV, 3000 fb^{-1}
$m_{\tilde{\chi}_1^0}$(TeV)
$m_{\tilde{g}}$(TeV)($\tilde{g} \to \tilde{t}_1 t$)
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10

Non-Universal Gauginos

$SO(10)$	$SU(5)$	$M_1 : M_2 : M_3$
1	**1**	$1:1:1$
54	**24**	$-\frac{1}{2} : -\frac{3}{2} : 1$
210	**1**	$1:1:1$
	24	$-\frac{1}{2} : -\frac{3}{2} : 1$
	75	$-5:3:1$
770	**1**	$1:1:1$
	24	$-\frac{1}{2} : -\frac{3}{2} : 1$
	75	$-5:3:1$
	200	$10:2:1$

$SO(10)$	$[SU(5)' \times U(1)]_{\text{flipped}}$	$M_1 : M_2 : M_3$
1	$(\mathbf{1}, 0)$	$1:1:1$
54	$(\mathbf{24}, 0)$	$-\frac{1}{2} : -\frac{3}{2} : 1$
210	$(\mathbf{1}, 0)$	$-\frac{19}{5} : 1 : 1$
	$(\mathbf{24}, 0)$	$\frac{7}{10} : -\frac{3}{2} : 1$
	$(\mathbf{75}, 0)$	$-\frac{1}{5} : 3 : 1$
770	$(\mathbf{1}, 0)$	$\frac{77}{5} : 1 : 1$
	$(\mathbf{24}, 0)$	$-\frac{101}{10} : -\frac{3}{2} : 1$
	$(\mathbf{75}, 0)$	$-\frac{1}{5} : 3 : 1$
	$(\mathbf{200}, 0)$	$\frac{2}{5} : 2 : 1$

$SO(10)$	$SU(4) \times SU(2)_R$	$M_1 : M_2 : M_3$
1	$(\mathbf{1}, \mathbf{1})$	$1:1:1$
54	$(\mathbf{1}, \mathbf{1})$	$-\frac{1}{2} : -\frac{3}{2} : 1$
210	$(\mathbf{1}, \mathbf{1})$	$-\frac{3}{5} : 1 : 0$
	$(\mathbf{15}, \mathbf{1})$	$-\frac{4}{5} : 0 : 1$
	$(\mathbf{15}, \mathbf{3})$	$1:0:0$
770	$(\mathbf{1}, \mathbf{1})$	$\frac{19}{10} : \frac{5}{2} : 1$
	$(\mathbf{1}, \mathbf{5})$	$1:0:0$
	$(\mathbf{15}, \mathbf{3})$	$1:0:0$
	$(\mathbf{84}, \mathbf{1})$	$\frac{32}{5} : 0 : 1$

S. P. Martin, Phys. Rev. D**79**,095019 (2009)

$SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R$: (Pati-Salam Model)

Anomaly Mediation, Gauge Mediation, Mirage Mediation

Standard Model

SM is not a fundamental theory!

- Gauge Hierarchy problem: $\delta m_h^2 \propto \Lambda^2$
- The gauge symmetry
- The Higgs vacuum stability: $\lambda < 0$ for $\Lambda \gtrsim 10^{10}$ GeV

  Stability Condition: $m_h > (129.6 \pm 1.5)$ GeV
- Neutrino masses and mixings
- Dark matter

SUSY and MSSM

SUSY is a symmetry that relates fermions and bosons

$$Q\,|fermion\rangle = |boson\rangle\,,\quad Q\,|boson\rangle = |fermion\rangle$$

Superpotential

$$W = y_u \tilde{Q} H_u \bar{\tilde{u}} + y_d \tilde{Q} H_d \bar{\tilde{d}} + y_e \tilde{L} H_d \bar{\tilde{e}} + \mu H_u H_d$$

SUSY Breaking

$$\begin{aligned}\mathcal{L}_{\not{\mathrm{SUSY}}} = &-\tfrac{1}{2}(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g}) + \mathrm{h.c.} \\ &- m_{H_u}^2 h_u^\dagger h_u - m_{H_d}^2 h_d^\dagger h_d - (b h_u h_d + \mathrm{h.c.}) \\ &- m_Q^2 \tilde{q}^\dagger \tilde{q} - m_L^2 \tilde{l}^\dagger \tilde{l} - m_u^2 \tilde{u}_R^\dagger \tilde{u}_R - m_d^2 \tilde{d}_R^\dagger \tilde{d}_R - m_e^2 \tilde{e}_R^\dagger \tilde{e}_R \\ &- (A_u \tilde{u}_R \tilde{q} h_u + A_d \tilde{d}_R \tilde{q} h_d + A_e \tilde{e}_R \tilde{l} h_d)\end{aligned}$$

A Benchmark Study

m_h	123.05	122.81	123.11	124.39	124.89
m_H	2571	2750	2812	3625	3782
m_A	2571	2750	2812	3625	3782
$m_{H^\pm}$	2572	2751	2812	3626	3783
$m_{\tilde{\chi}^0_{1,2}}$	**66.76, 1380**	**55.82, 743.2**	**131.52, 1135**	**376.2, 808.9**	**459.2, 1055**
$m_{\tilde{\chi}^0_{3,4}}$	1383, 2369	744.3, 3023	1136, 3247	810.1, 5063	1056, 5186
$m_{\tilde{\chi}^\pm_{1,2}}$	**1380, 2369**	**742.3, 3024**	**1134, 3247**	**807.9, 5063**	**1054, 5185**
$m_{\tilde{g}}$	1919	1962	2150	3403	3498
$m_{\tilde{u}_{L,R}}$	2938, 2322	3498, 2641	3875, 3006	5468, 3951	5664, 4145
$m_{\tilde{t}_{1,2}}$	**287.15, 2313**	**396.17, 2637**	**490.29, 3013**	**583.81, 3960**	**683.82, 4162**
$m_{\tilde{d}_{L,R}}$	2938, 2323	3498, 2642	3875, 3006	5468, 3949	5664, 4142
$m_{\tilde{b}_{1,2}}$	2129, 2313	2334, 2637	2477, 3012	3216, 3957	3369, 4157
$m_{\tilde{\nu}_{e,\mu}}$	2536, 2536	3186, 3186	3548, 3547	4828, 4827	5022, 5021
$m_{\tilde{\nu}_\tau}$	2461	3069	3357	4579	4759
$m_{\tilde{e}_{L,R}}$	2536, 1770	3186, 2189	3548, 2548	4828, 2965	5022, 3178
$m_{\tilde{\tau}_{1,2}}$	1570, 1770	1863, 2189	1996, 2548	2101, 2965	2285, 3178
$BR(\tilde{t}_1 \to \tilde{\chi}^0_1 t)$	1	1	1	1	1
$BR(\tilde{t}_1 \to \tilde{\chi}^\pm_1 b)$	0	0	0	0	0
$BR(\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 W^\pm)$	3.4×10^{-2}	5.86×10^{-2}	4.6×10^{-2}	1.2×10^{-1}	8.7×10^{-2}
σ(signal)	$\mathbf{2.46 \times 10^{-1}}$	$\mathbf{4.544 \times 10^{-2}}$	$\mathbf{1.375 \times 10^{-2}}$	$\mathbf{4.883 \times 10^{-3}}$	$\mathbf{1.855 \times 10^{-3}}$
$\sigma(pp \to \tilde{t}\tilde{t}^*)$	**7.115**	**1.314**	$\mathbf{4.018 \times 10^{-1}}$	$\mathbf{1.545 \times 10^{-1}}$	$\mathbf{5.523 \times 10^{-2}}$
Exclusion CL%	49.7	59.5	46.6	5.5	3.6