A Collider Signature of the Supersymmetric Golden Region

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Two Strategies for SUSY Collider Studies

How can we set 105 parameters in MSSM for a collider study?

1. Top-down approach (the usual):
   - Pick favorite SUSY breaking scheme (mSUGRA *etc*) to reduce dimensionality of parameter space
   - Find phenomenologically "interesting" benchmark points
2. Bottom-up approach (this talk):
   - Parameterize ignorance by considering weak scale superpotential and soft SUSY breaking terms
   - Apply existing experimental bounds (non-observation of particles, SM precision measurements)
   - Reduce fine tuning as much as possible (after all the original motivation for SUSY!)

Relevant Parameters: Higgs and Top Sector

Strongest constraints from data and naturalness: Higgs sector
$\Rightarrow$ relevant soft SUSY breaking Lagrangian:

$$
\begin{aligned}
\mathcal{L} = & - m_u^2 |H_u|^2 - m_d^2 |H_d|^2 - \left(b H_u^T H_d + \mathrm{c.c.} \right) \\
& - m_{Q^3}^2 Q^{3\dagger} Q^3 - m_{u^3}^2 |u^3|^2 - \left(y_t A_t Q^{3\dagger} H_u u^3 + \mathrm{c.c.} \right)
\end{aligned}
$$

where $y_t = y_t^{\mathrm{SM}} / \sin\beta$.

How can we parameterize this parameter space?

- μ-term + six additional free parameters
- Higgs VEV fixes one combination
- Six remaining can be choosen as $\tan\beta, \mu, m_A, \tilde{m}_1, \tilde{m}_2, \theta_t$

Quantifying Naturalness: Higgs Sector

Tree level Z boson mass in the MSSM:

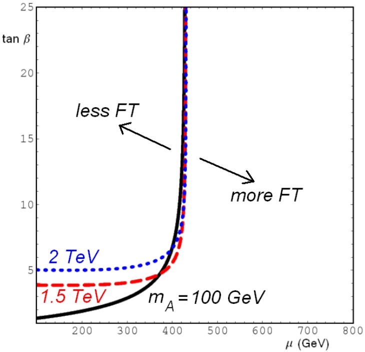
$$m_Z^2 = -m_{H_u}^2\left(1-\frac{1}{\cos 2\beta}\right) - m_{H_d}^2\left(1+\frac{1}{\cos 2\beta}\right) - 2|\mu|^2$$

Quantify fine-tuning by

$$A(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right| .$$

Overall tree-level fine tuning Δ:

Add $A(\mu)$, $A(b)$, $A(m_u^2)$ and $A(m_d^2)$ in quadrature



Quantifying Naturalness: Top Sector

In these variables the stop loop contributions to $\delta m_{H_u}^2$ are

$$\frac{3}{16\pi^2}\left(y_t^2\left(\tilde{m}_1^2+\tilde{m}_2^2-2m_t^2\right)+\frac{(\tilde{m}_2^2-\tilde{m}_1^2)^2}{4v^2}\sin^2 2\theta_t\right)\log\frac{2\Lambda^2}{\tilde{m}_1^2+\tilde{m}_2^2}$$

where Λ is the scale at which the divergence is cut off.

$$\Rightarrow \qquad \delta_t m_Z^2 \approx -\delta m_{H_u}^2\left(1-\frac{1}{\cos 2\beta}\right).$$

Renormalization of the angle β is subdominant and neglected. We measure fine-tuning in the stop sector by introducing

$$\Delta_t = \left|\frac{\delta_t m_Z^2}{m_Z^2}\right|.$$

Experimental Constraints - Higgs Mass

To one loop order the Higgs mass is given by

$$m^2(h^0) = m_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2}\log\frac{M^2}{m_t^2}\right) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{a^2}{M^2}\left(1 - \frac{a^2}{12M^2}\right) + \log\frac{M^2}{m_t^2}\right]$$

where

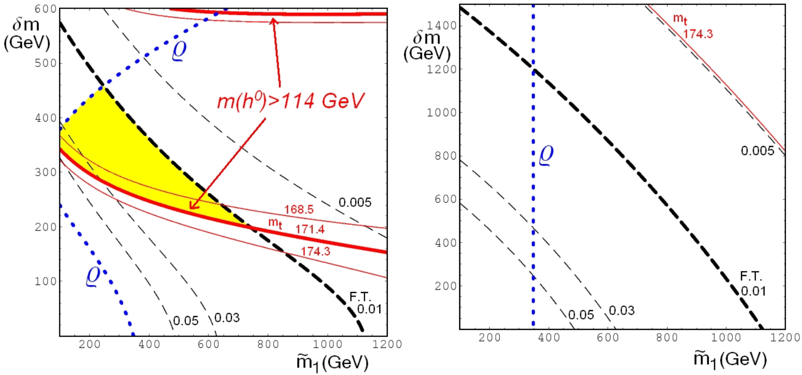
$$M^2 = \frac{1}{2}(\tilde{m}_1^2 + \tilde{m}_2^2) \qquad a = \frac{\tilde{m}_2^2 - \tilde{m}_1^2}{2v\sin 2\theta_t}$$

$\Rightarrow$ Pushing the Higgs mass over the experimentally excluded limit (114.4 GeV) requires significant stop mass splitting.

Other Experimental Constraints

1. Direct Collider Bounds: LEP2 & Tevatron searches for chargino and stop production $\Rightarrow \mu, \tilde{m}_1 \gtrsim 100$ GeV
2. Loop corrections to the ρ parameter $\Rightarrow$ eliminate part of parameter space with low $\tilde{m}_1$ and large δm
3. $b \to s\gamma$ decay rate:
    - Large contributions from $\tilde{t} - \tilde{H}$ loop
    - Can be cancelled by top-charged Higgs loop
    - Consistent value of m_A can be found for any μ
4. $g_\mu - 2$: Most sensitive to slepton and weak gaugino masses, no critical dependence on stop and Higgs sectors

Plot of the Golden Region for $\theta_t = \pi/4$ and $\theta_t = 0$



- In this plots $\tan\beta = 10$ and $\Lambda_t = 100$ TeV
- Shape of the Golden Region is approximately independent of $\tan\beta$ for values between 3 and 35

Signature of the Golden Region

How can this hypothesis be tested?

1. $\tilde{t}_1$ and $\tilde{t}_2$ have masses below 1 TeV
   $\Rightarrow$ stop sector is directly accessible at the LHC
2. Substantial mass splitting between the two stops
   $\Rightarrow$ decay mode $\tilde{t}_2 \to \tilde{t}_1 Z$ is kinematically allowed
3. Stop mixing angle is large $\Rightarrow$ $\tilde{t}_2\tilde{t}_1 Z$-vertex is non-zero, the decay occurs with substantial BR
4. Independently of the spectrum, all stop decays will eventually produce a b-jet

Inclusive Signature at the LHC

$Z(\ell^+, \ell^-) + 2j_b + \not{E}_T + X$

Golden Region Benchmark Point

- Weak scale MSSM input parameters:

m_{Q^3}	m_{u^3}	m_{d^3}	A_t	μ	m_A	$\tan\beta$	$M_{1,2,3}$	$m_{\tilde{q},\tilde{\ell}}$
548.7	547.3	1000	1019	250	200	10	1000	1000

- Mass spectrum of superpartners and Higgs sector:

$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_L$	χ_1^0	χ_2^0	$\chi_1^\pm$	h^0	H^0	A	$H^\pm$
400	700	552	243	253	247	128.6	201	200	250

(stop mixing $\theta_t = \pi/4$; at the LHC $\sigma(pp \to \tilde{t}_2\tilde{t}_2^*) \approx 50$ fb)

- $\tilde{t}_2$ decay branching ratios (in %):

$\tilde{t}_1 Z$	$\chi_1^0 t$	$\chi_2^0 t$	$\chi_1^+ b$	$\tilde{b} W^+$	$\tilde{t}_1 A$	$\tilde{t}_1 h^0$	$\tilde{t}_1 H^0$
31	19	13	18	15	3	3×10^{-3}	3×10^{-4}

Tools, Backgrounds and Cuts

Simulation and analysis chain:

Madgraph 4.0 $\Rightarrow$ Pythia 6.4 $\Rightarrow$ PGS 3.9 $\Rightarrow$ ROOT
(advantage: identical treatment of signal and all BGs)

Use rectangular cuts to isolate signal from irreducible SM backgrounds ($jjZZ$, $t\bar{t}$, $t\bar{t}Z$):

- Two OSSF leptons with $\sqrt{s(\ell^+\ell^-)} = M_Z \pm 2$ GeV
- $p_t > 125$ GeV for the hardest jet, 50 GeV for the second jet
- one of the two hardest jet must be b-tagged
- minimal Z boost factor: $\gamma(Z) > 2.0$
- missing E_T cut: $\not{E}_T > 225$ GeV

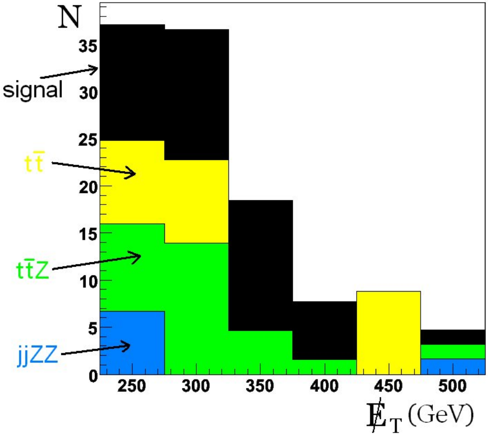
Can probably be improved by using neural networks, decision trees, ...

Event Numbers and Oberservability

	$\tilde{t}_2\tilde{t}_2^*$	$jjZZ$	$t\bar{t}Z$	$t\bar{t}$
σ_{prod}(pb)	0.051	0.888	0.616	552
total simulated	9964	159672	119395	3745930
1. leptonic Z(s)	1.4	4.5	2.6	0.04
2(a). $p_t(j_1) > 125$ GeV	89	67	55	21
2(b). $p_t(j_2) > 50$ GeV	94	93	92	76
3. b-tag	64	8	44	57
4. $\gamma(Z) > 2.0$	89	66	69	26
5. $\not{E}_T > 225$ GeV	48	2.2	4.4	1.7
$N_{\text{exp}}(100\ \text{fb}^{-1})$	16.4	2.8	10.8	8.8

We also simulated 1.4×10^6 jjZ events. All that survive cuts 1-4 have $\not{E}_T < 50$ GeV.

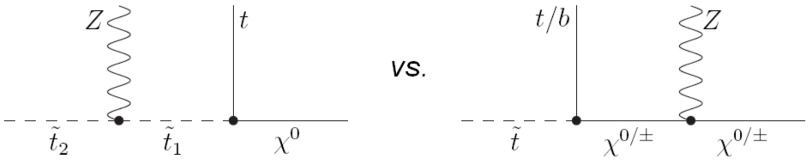
Missing Energy Distribution



Other backgrounds:

- *jjZ*: large σ with high $\not{E}_T$ tail, exponential fit $\Rightarrow$ negligible?
- $t\bar{t}j$: comparable to $t\bar{t}$, shoulder subtraction
- ZZZ, ZZW, ZWW, tZj, $\bar{t}Zj$: event rates $\times$ BR: $\Rightarrow$ not a problem

SUSY Background: Confusion with $\chi^{0/\pm}$ Decay



Possible strategies to distinguish decay chains:

- B-tags: Zs from $\tilde{t}_2$ decays are always accompanied by a b-jet (but 3rd generation squarks could just have low mass)
- Spin correlation: event rate for chargino (not neutralino) decays have linear dependence on $s_{bZ} = (p_b + p_Z)^2$
- Related decays: $\tilde{t}_2 \to \tilde{b}_L W^+$ and $\tilde{b}_L \to \tilde{t}_1 W^-$ would be easier to interpret (but harder to observe)

Summary

1. Naturalness and data point to a Golden Region in the MSSM parameter space
2. We expect stops with large mixing angle, split by 300-400 GeV
3. The decay mode $\tilde{t}_2 \to \tilde{t}_1 + Z$ has a substantial branching ratio
4. The detector signature of this decay is $Z(\ell^+\ell^-) + 2\ j_b + \not{E}_T + X$
5. Evidence can be observed with $\sim 100\ \mathrm{fb}^{-1}$ at the LHC