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The Constrained E_6SSM

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The 2009 Europhysics Conference on High Energy Physics

17th July 2009

Based on:

P. Athron, S.F. King, DJM, S. Moretti, R. Nevzorov

arXiv:0901.1192

arXiv:0904.2169

The E_6SSM

[S.F.King, S.Moretti & R. Nevzorov, Phys.Rev. D73 (2006) 035009 ; Phys.Lett. B634 (2006) 278-284]

“Inspired” by the gauge group E_6 , breaking to the SM via

$$E_6 \to SO(10) \times U(1)_\psi$$
$$\hookrightarrow SU(5) \times U(1)_\chi$$
$$\hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y$$

where only one linear superposition of the extra *U(1)* symmetries survives to low energies:

$$U(1)_N = \tfrac{1}{4} U(1)_\chi + \frac{\sqrt{15}}{4} U(1)_\psi$$

This combination is required in order to keep the right handed neutrinos sterile.

So the E_6SSM is really a $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge theory.

Matter Content

All the SM matter fields are contained in one 27-plet of E_6 per generation.

$$27_i \Rightarrow (10, 1)_i + (5^*, 2)_i + (5^*, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i$$

$(10, 1)_i$: $Q_i,\ u^c_i,\ e^c_i$

$(5^*, 2)_i$: $L_i,\ d^c_i$

$(5^*, -3)_i$: $H_{1i} = \begin{pmatrix} H^0_{1i} \\ H^-_{1i} \end{pmatrix},\ \bar{D}_i$

$(5, -2)_i$: $H_{2i} = \begin{pmatrix} H^+_{2i} \\ H^0_{2i} \end{pmatrix},\ D_i$

$(1, 5)_i$: S_i

$(1, 0)_i$: N^c_i

3 generations of "Higgs"

exotic quarks

singlets

right handed neutrino

SU(5) reps.

$U(1)_N$ charge $\times \sqrt{40}$

New exotic states

Placing each generation in a 27-plet forces us to have new particle states.:

- Now have 3 generations of Higgs bosons.
  Only the third generation Higgs boson gains a VEV.
  The others are neutral and charged scalars - we call them **"inert Higgs"**.

- Three generations of singlets, S_i with $\langle S_3 \rangle \neq 0$

- New coloured triplets of "exotic quarks" D_i and $\bar{D}_i$ with charge $\pm{}^1/_3$.

[+ right handed neutrinos]

New gauge group structure, with unification:

- Extra U(1) $\rightarrow$ extra gauge boson, Z'.
  After ewsb this will become massive (after eating the imaginary part of S_3)

- Additional SU(2) doublets H' and $\bar{H}'$, relics of an additional 27$'$ and 27$'$ which survive down to low energies, and are required for gauge unification.

Discrete Symmetries

- Z_2^B or Z_2^L Symmetries

  To prevent proton decay, we need a baryon or lepton symmetry
  This is analogous to R-parity in the MSSM
  Note that the exotic D is odd, so must decay to a susy particle

  $Z_2^B \Rightarrow$ D is a leptoquark $\quad Z_2^L \Rightarrow$ D is a diquark

- Approximate Z_2^H Symmetry

  To evade large Flavour Changing Neutral Currents, we need another Z_2

  Make the 3rd generation Higgs and singlet superfields even, all other fields odd.

  Must only be approximate to allow exotic particles to decay.

  For a Renormalisation Group analysis and mass spectra, Z_2^H violating couplings can be neglected.

E_6SSM Superpotential

To simplify the model a little:

- Impose $Z_2^{B/L}$ and (approximate) Z_2^H symmetries,
- Integrate out heavy right-handed Majorana neutrinos,
- Assume a hierarchical structure of Yukawas, and keep only large ones.

$$\begin{aligned} W_{\mathrm{E_6SSM}} \quad \simeq \quad & \lambda S(H_d H_u) + \lambda_\alpha S(H_{1,\alpha} H_{2,\alpha}) + \kappa_i S(D_i \overline{D}_i) \\ & + h_t (H_u Q) t^c + h_b (H_d Q) b^c + h_\tau (H_d L) \tau^c + \mu' (H^{'} \overline{H'}) \end{aligned}$$

Note: this is really an oversimplification – we have lots of very small Z_2^H violating couplings such as $g_{ijk} D_i \left(Q_j Q_k\right)$ which are unimportant for production, but may be important for decays.

Also need lots of new SUSY breaking parameters.

The Constrained E6SSM

The E_6SSM has 43 new parameters compared with the MSSM (14 are phases).

But if we apply constraints at the GUT scale, this is drastically reduced.

Set:

$$g_1(M_X) = g_2(M_X) = g_3(M_X) = g_1'(M_X)$$

soft scalar masses $\longrightarrow$ m_0

gaugino masses $\longrightarrow$ $M_{1/2}$

$$A_{\lambda_i}(M_X) = A_{\kappa_i}(M_X) = A_{t,b,\tau}(M_X) = A(M_X)$$

Important parameters: $\lambda_i,\ \kappa_i,\ h_t,\ h_b,\ h_\tau,\ m_0,\ M_{1/2},\ A$

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Renormalisation Group Running

We derived Renormalisation Group Equations, and modified SoftSuSY [Allanach, arXiv:hep-ph/0104145] to run down the GUT scale parameters to low energies.

- Gauge and Yukawa couplings (2 loop),
- Soft breaking gaugino and trilinear masses (2 loop),
- Soft scalar masses (1 loop).

Gauge and Yukawa couplings $\rightarrow$ Soft SUSY breaking parameters

The evolution of Gauge and Yukawa couplings doesn't depend on the soft SUSY breaking so they can be done separately and fed into the

- Sensitive to thresholds.
- At one-loop $\beta_3 \approx 0$, so need two loops.

Gauge and Yukawa couplings

$$g_1 = g_2 = g_3 = g_1'$$ unification constraint

$$\lambda_i,\ \kappa_i$$ scenario inputs

iterate

M_X

E_6SSM running

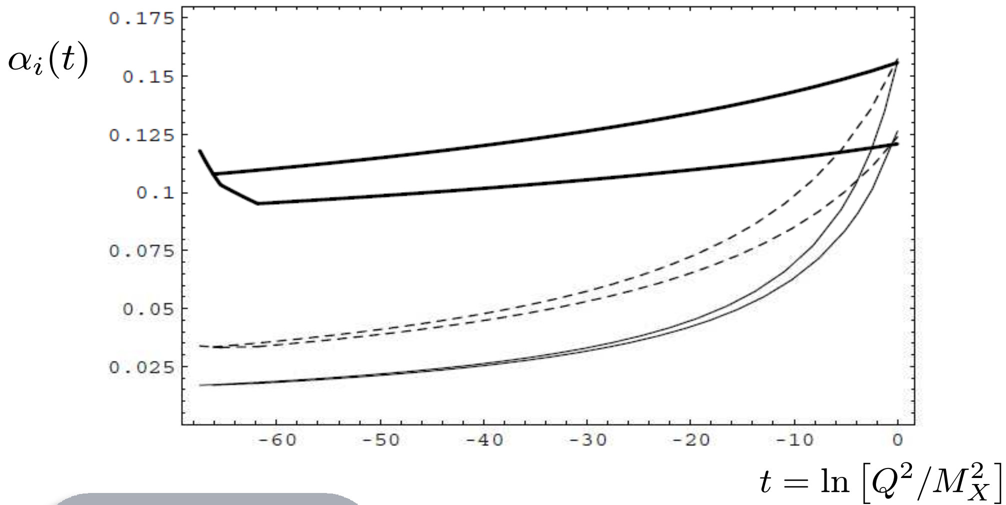
T_{E_6SSM}

MSSM running

T_{MSSM}

SM running

M_Z



$$\langle S \rangle,\ \tan\beta$$ scenario inputs

$$g_1,\ g_2,\ g_3$$

$$h_t,\ h_b,\ h_\tau$$

experimental values

$$\lambda_i,\ \kappa_i$$ first guess

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Soft SUSY breaking parameters

Generically, we can write

$$\begin{aligned} m_i^2(Q) &= a_i(Q)M_{1/2}^2 + b_i(Q)A_0^2 + c_i(Q)A_0M_{1/2} + d_i(Q)m_0^2, \\ A_i(Q) &= e_i(Q)A_0 + f_i(Q)M_{1/2}, \\ M_i(Q) &= p_i(Q)A_0 + q_i(Q)M_{1/2}. \end{aligned}$$

coefficients depend on gauge and Yukawa running

Set two of $m_0^2,\ M_{1/2},\ A_0$ to zero at M_X → run down to the low scale (full RGEs) → determine low scale coefficients numerically

- Fix $m_0^2,\ M_{1/2},\ A_0$ using ewsb constraints
- Calculate the mass spectrum
- Apply experimental constraints

$$\frac{\partial V}{\partial s} = \frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = 0$$

including one-loop stop contributions

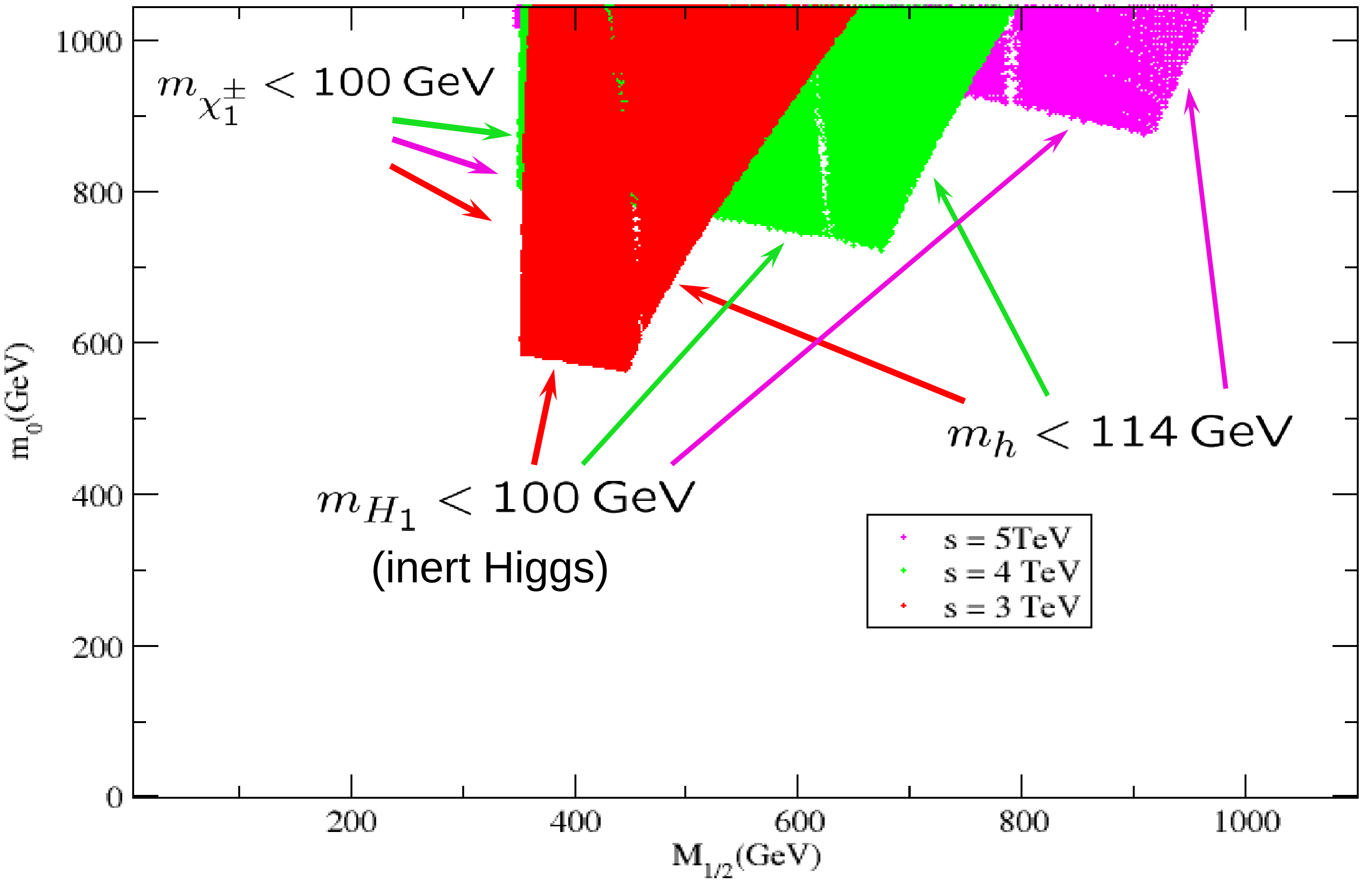
Phenomenological constraints

To ensure phenomenologically acceptable solutions, we require

- squarks and gluinos $\gtrsim$ 300 GeV
- exotic quarks and squarks $\gtrsim$ 300 GeV [HERA]
- $M_{Z'} \gtrsim$ 700 GeV
- Insist on neutralino LSP (sort of)
- Keep Yukawa couplings $\lesssim$ 3
- Inert Higgs and Higgsinos $\gtrsim$ 100 GeV

Allowed regions in the m_0 - $M_{½}$ plane

Set $\tan\beta = 10$, $s = 3, 4, 5$ TeV, $\lambda_{1,2} = 0.1$, and vary λ_3 and $\kappa = \kappa_{1,2,3}$



Particle Spectra

Firstly, notice that for most allowed scenarios $m_0 \gtrsim M_{1/2}$, so squarks tend to be heavier than the gluino

Neutralinos, charginos and gluino

$$m_{\tilde{\chi}_1^0} \approx M_1 \qquad m_{\tilde{g}} \approx M_3$$

$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2$$

$$m_{\tilde{\chi}_{3,4}^0} \approx m_{\tilde{\chi}_2^\pm} \approx \mu = \lambda \langle S \rangle$$

$$m_{\tilde{\chi}_{5,6}^0} \approx M_{Z'}$$

Higgs bosons

$$m_{h_1} \approx M_Z + \Delta$$

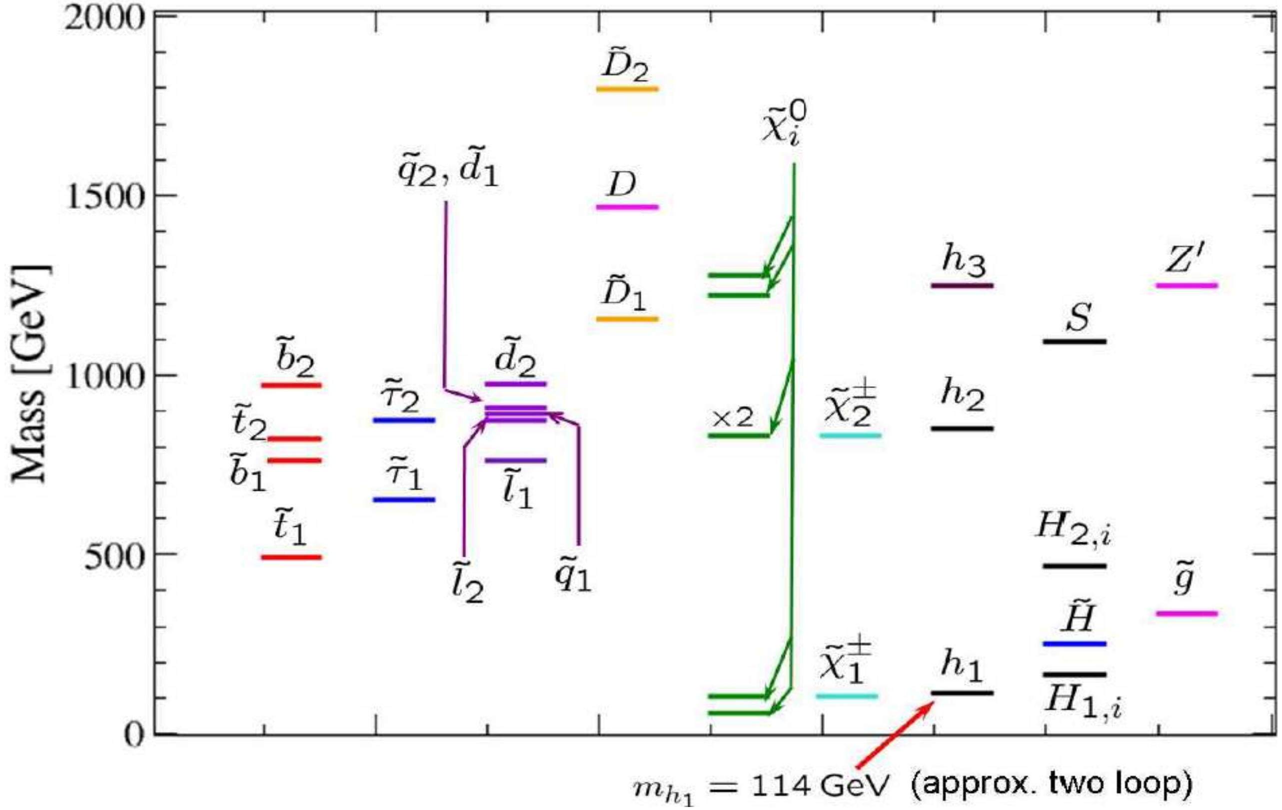
$$m_{h_2} \approx m_{H^\pm} \approx m_A$$

$$m_{h_3} \approx M_{Z'}$$

exotic quarks	$\approx \kappa_i \langle S \rangle$	
exotic squarks	$\approx m_{D_i}^2 + \kappa_i^2 \langle S \rangle^2$	+ mixing and auxiliary D-terms
inert Higgs	$\approx m_{H_i}^2 + \lambda_i^2 \langle S \rangle^2$	+ auxiliary D-terms
inert higgsino	$\approx \lambda_i \langle S \rangle$	

Benchmark A

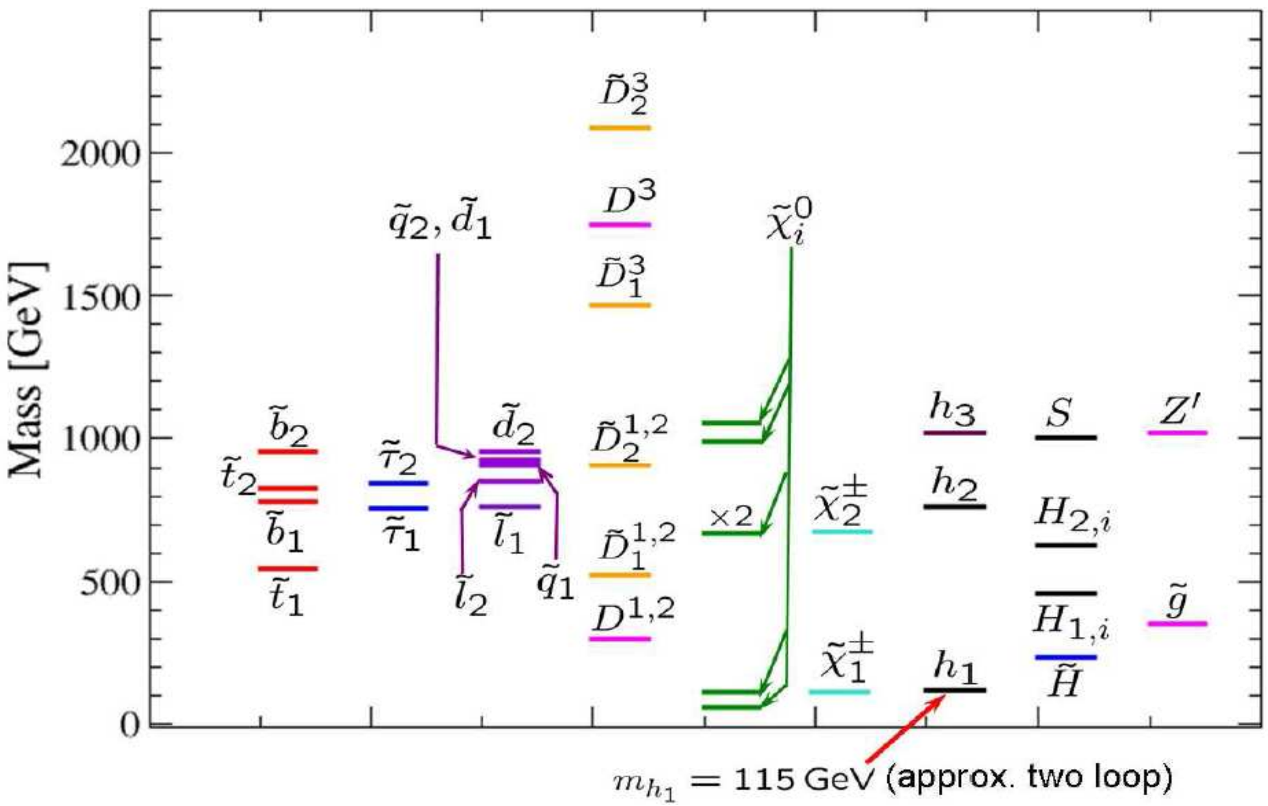
$$
\begin{aligned}
\tan\beta &= 3\\
\lambda_3(M_X) &= -0.465\\
\lambda_{1,2}(M_X) &= 0.1\\
\kappa_3(M_X) &= 0.3\\
\kappa_{1,2}(M_X) &= 0.3\\
\sqrt{2}\langle S\rangle &= 3.3\,\mathrm{TeV}\\
M_{1/2} &= 365\,\mathrm{GeV}\\
m_0 &= 640\,\mathrm{GeV}\\
A_0 &= 798\,\mathrm{GeV}
\end{aligned}
$$



- gluino rather light
- light Higgs and Bino
- $\kappa_1 = \kappa_2 = \kappa_3$ so Ds are degenerate and rather heavy

Benchmark C

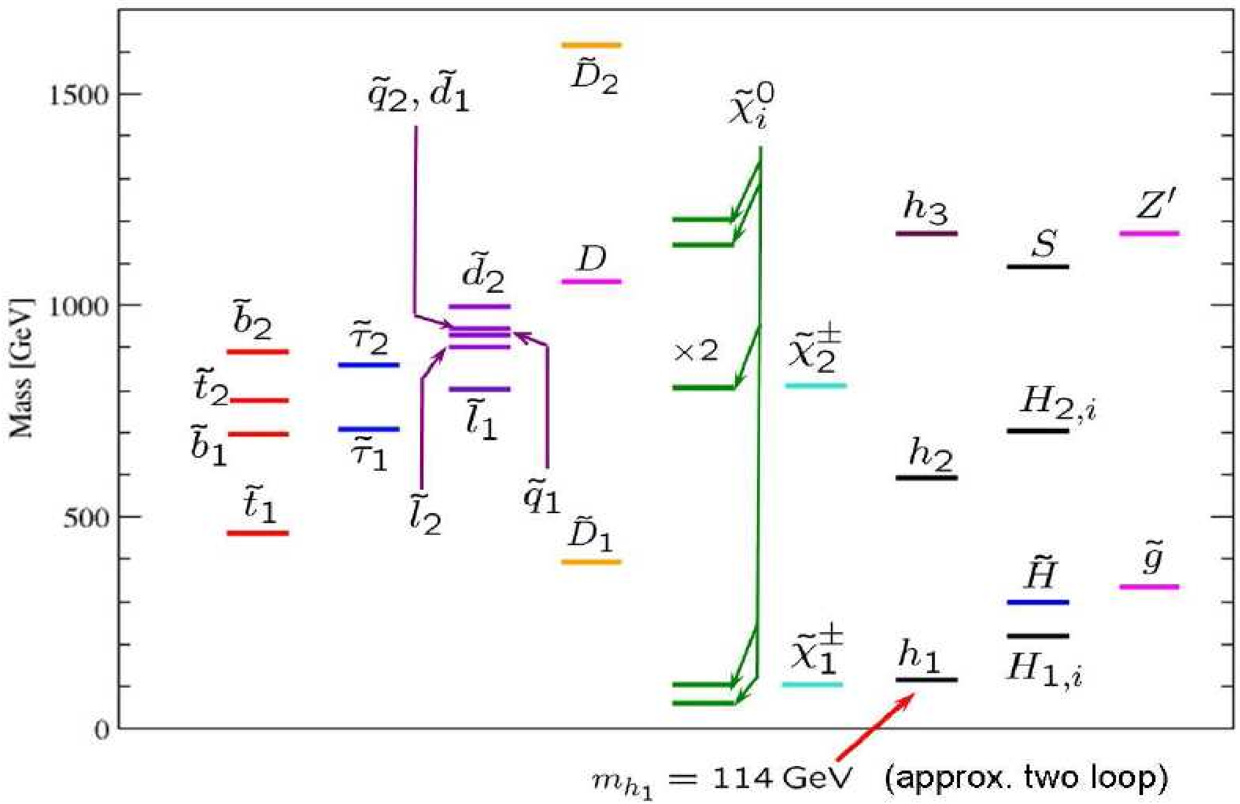
$$
\begin{aligned}
\tan\beta &= 10\\
\lambda_3(M_X) &= -0.378\\
\lambda_{1,2}(M_X) &= 0.1\\
\kappa_3(M_X) &= 0.42\\
\kappa_{1,2}(M_X) &= 0.06\\
\sqrt{2}\langle S\rangle &= 2.7\,\mathrm{TeV}\\
M_{1/2} &= 388\,\mathrm{GeV}\\
m_0 &= 681\,\mathrm{GeV}\\
A_0 &= 645\,\mathrm{GeV}
\end{aligned}
$$



- $\kappa_1 = \kappa_2 \neq \kappa_3$ so degeneracy of Ds is lifted.
- lightest exotic quark is 300 GeV

Benchmark E

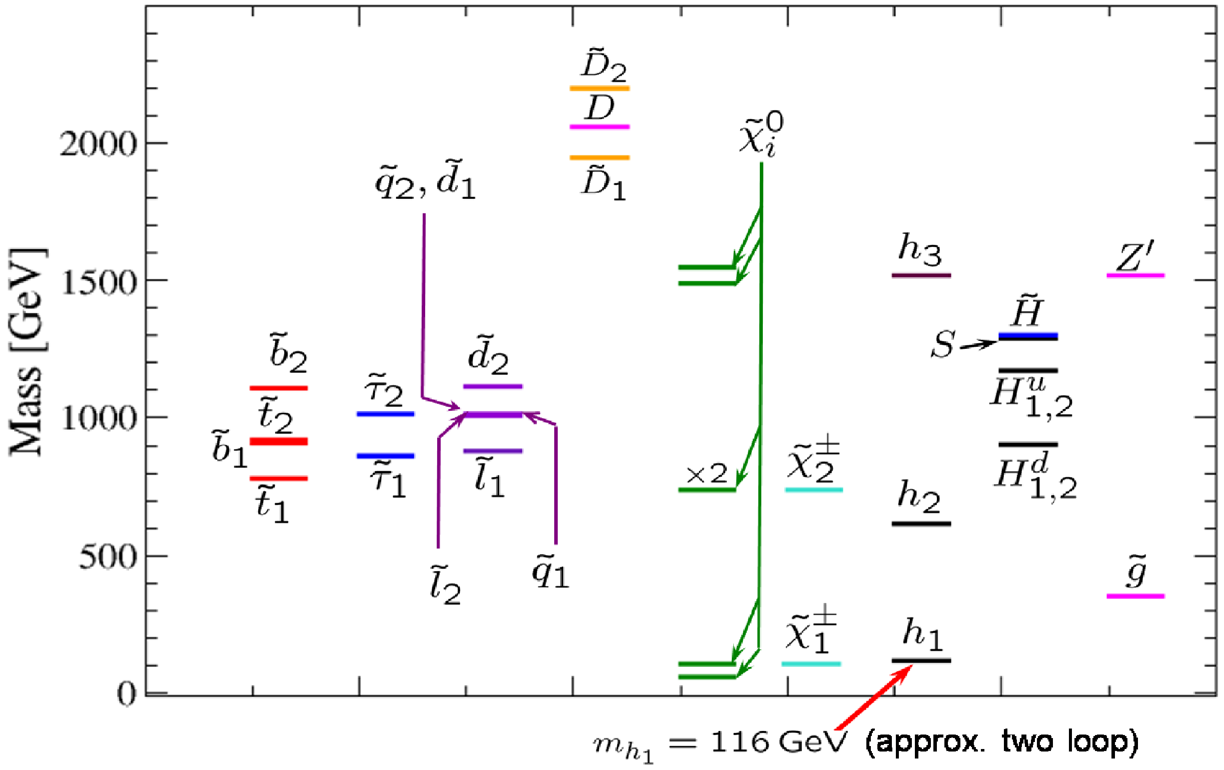
$$
\begin{aligned}
\tan\beta &= 30 \\
\lambda_3(M_X) &= -0.38 \\
\lambda_{1,2}(M_X) &= 0.1 \\
\kappa_3(M_X) &= 0.17 \\
\kappa_{1,2}(M_X) &= 0.17 \\
\sqrt{2}\langle S\rangle &= 3.1\,\mathrm{TeV} \\
M_{1/2} &= 365\,\mathrm{GeV} \\
m_0 &= 702\,\mathrm{GeV} \\
A_0 &= 1148\,\mathrm{GeV}
\end{aligned}
$$



- mixing causes a rather light $\tilde{D}$ (393 GeV)

Heavy Exotics

$$
\begin{aligned}
\tan\beta &= 10\\
\lambda_3(M_X) &= -2.0\\
\lambda_{1,2}(M_X) &= 2.6\\
\kappa_3(M_X) &= 2.5\\
\kappa_{1,2}(M_X) &= 2.5\\
\sqrt{2}\langle S\rangle &= 4.0\,\mathrm{TeV}\\
M_{1/2} &= 389\,\mathrm{GeV}\\
m_0 &= 725\,\mathrm{GeV}\\
A_0 &= -1528\,\mathrm{GeV}
\end{aligned}
$$

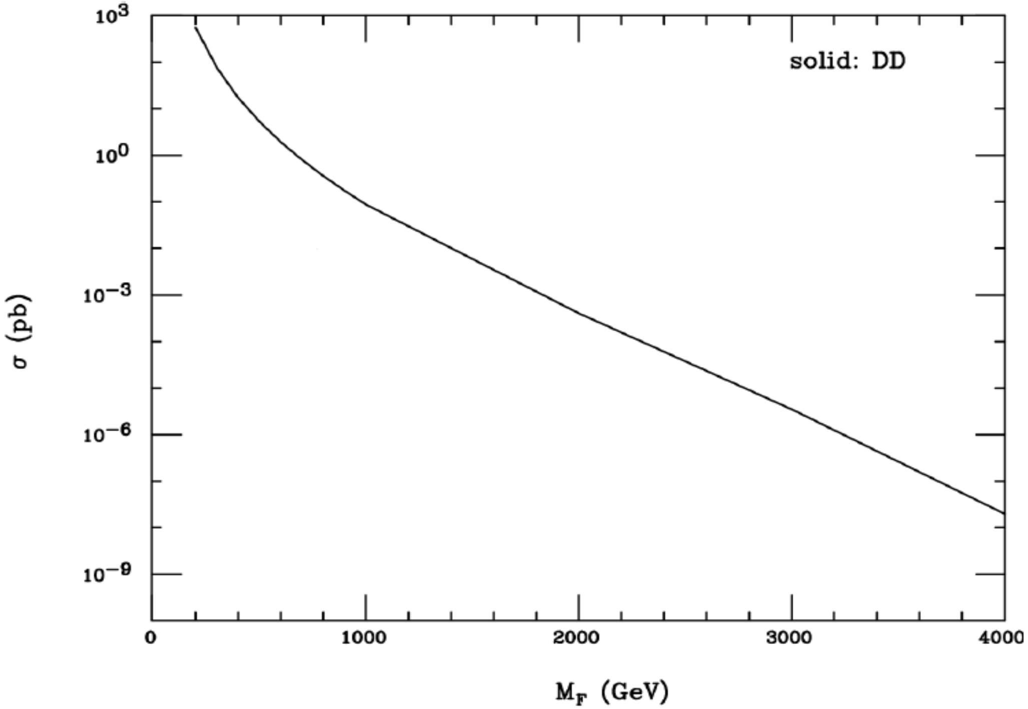


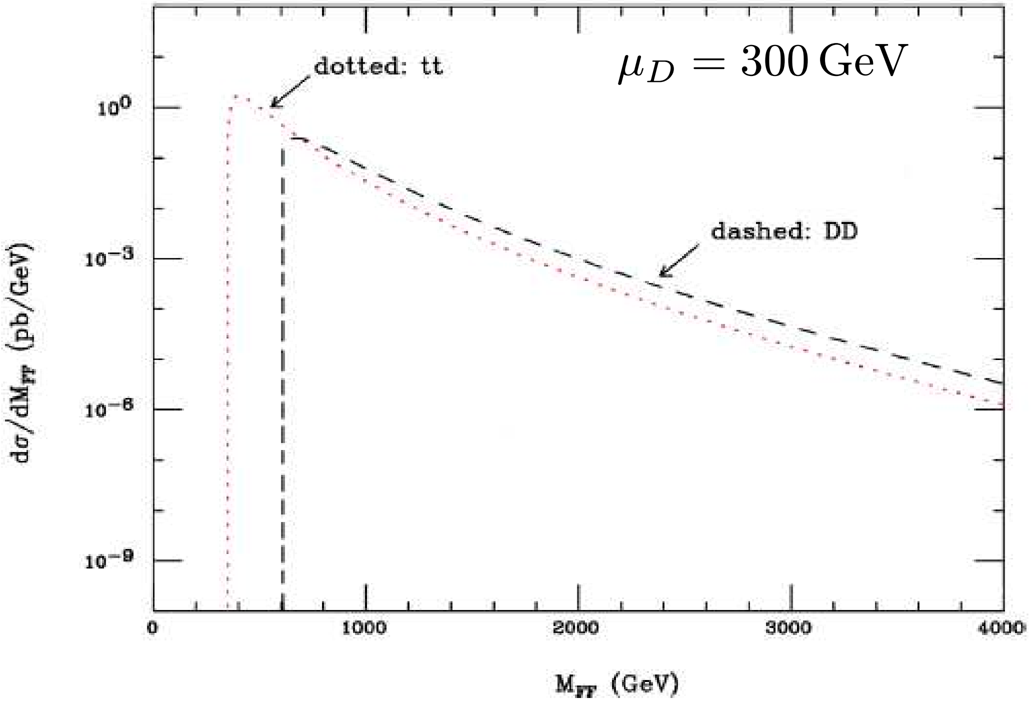
- it is possible to construct scenarios where all exotic particles are heavy
- gluino is still lighter than the squarks

LHC signatures

If the exotic quarks are light, their discovery at the LHC should be rather straightforward.

Since the exotic quarks are colored, their production cross-sections are very large

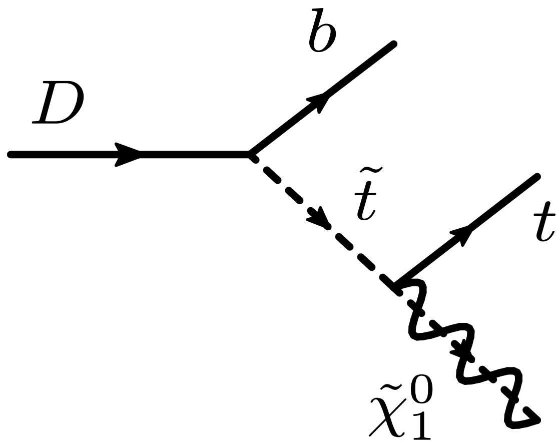




μ_D[GeV]	300	400	500	700	1000	1500	2000	3000
$\sigma(pp \to D\bar{D})$[pb]	76.4	17.4	5.30	0.797	0.0889	$4.94 \cdot 10^{-3}$	$4.09 \cdot 10^{-4}$	$3.51 \cdot 10^{-6}$

LHC signatures: Exotic quarks

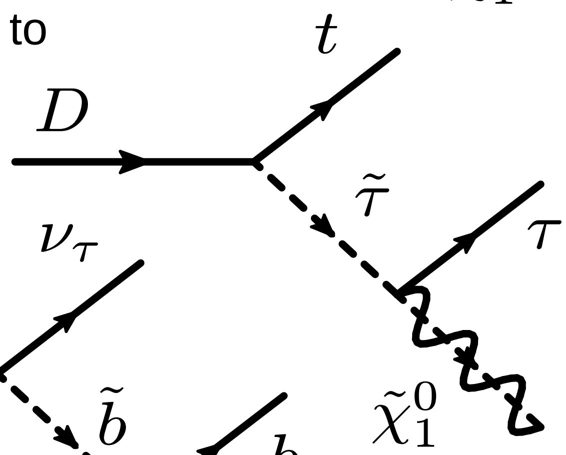
Assuming Ds couple predominantly to the 3rd generation:



- Diquarks decay to $\tilde{t}b,\ t\tilde{b}$, so would give an enhancement to

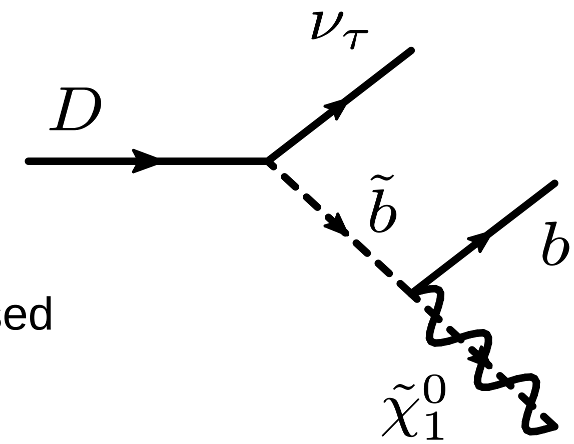
$$pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$$

- Leptoquarks decay to $\tilde{t}\tau,\ t\tilde{\tau},\ \tilde{b}\nu_\tau,\ b\tilde{\nu}_\tau$ so give enhancements to



$$pp \to t\bar{t}\tau^+\tau^- + E_T^{miss} + X$$

$$pp \to b\bar{b} + E_T^{miss} + X$$



Notice that SM production of $t\bar{t}\tau^+\tau^-$ is suppressed by $(\alpha_W/\pi)^2$ in comparison.

LHC signatures: Exotic quarks and squarks

If the Z_2^H violating coupling, e.g. $g_{ijk} D_i \left(Q_j Q_k \right)$ is very small, D quarks may hadronize before they decay leading to spectacular signatures.

- The exotic squarks $\tilde{D}$ are $Z_2^{B/L}$ even, so don't need to decay to the LSP.

  They give an enhancement to, e.g. $pp \to t\bar{t}\tau\bar{\tau} + X$

  Note that the Tevatron rules out the scalar diquarks lighter than about 630 GeV and scalar leptoquarks lighter than about 300 GeV.

- Inert Higgs decays are similar to their MSSM counterparts

$$H^0_{1,\,i} \longrightarrow b\bar{b} \qquad H^-_{1,\,i} \longrightarrow \tau\bar{\nu}_\tau$$

$$\tilde{H}^0_i \longrightarrow t\tilde{\bar{t}}^* \qquad \tilde{H}^0_i \longrightarrow \tau\tilde{\bar{\tau}}^* \qquad \tilde{H}^+_i \longrightarrow t\tilde{\bar{b}}^* \qquad \tilde{H}^-_i \longrightarrow \tau\tilde{\bar{\nu}}^*_\tau$$

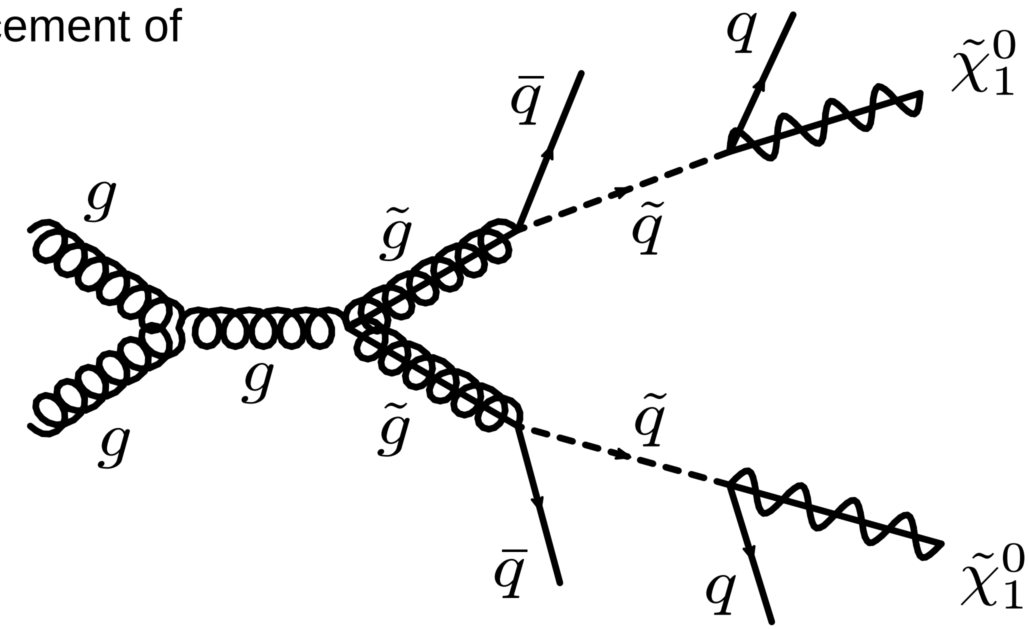
Scenarios with heavy exotics

Even if all the exotic particles are heavy, the cE_6SSM still makes striking predictions.

- light gluino, much lighter than the squarks
- light neutralinos $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$
- light chargino $\tilde{\chi}_1^\pm$

Gluino decays will provide an enhancement of

$$pp \longrightarrow q\bar{q}q\bar{q} + E_T^{\mathrm{miss}} + X$$



Conclusions and Summary

- The E_6SSM provides a credible example of a model which could arise from a GUT, where each generation forms a complete 27-plet of E_6.
- We have examined a constrained E_6SSM, using RGEs to construct realistic, phenomenologically reasonable scenarios at LHC energies.
- The model predicts a light gluino, much lighter than the squarks, light neutralinos, $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$, and a light chargino $\tilde{\chi}_1^{\pm}$.
- It also predicts new exotic quarks and squarks, “inert” Higgs bosons, and a Z'.
- If the new exotic quarks are light, they will give striking signatures, such as a significant enhancement to $pp \to t\bar{t}b\bar{b} + E_T^{miss} + X$ which should be easily observable at the LHC.