What would an E6 GUT look like at the LHC?

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Outline:

- Introduction: Why do we need a new model?
- The E_6SSM
- The Constrained E_6SSM
- Particle Spectra and Benchmarks
- Conclusions and Summary

1. Introduction: Why do we need a new model?

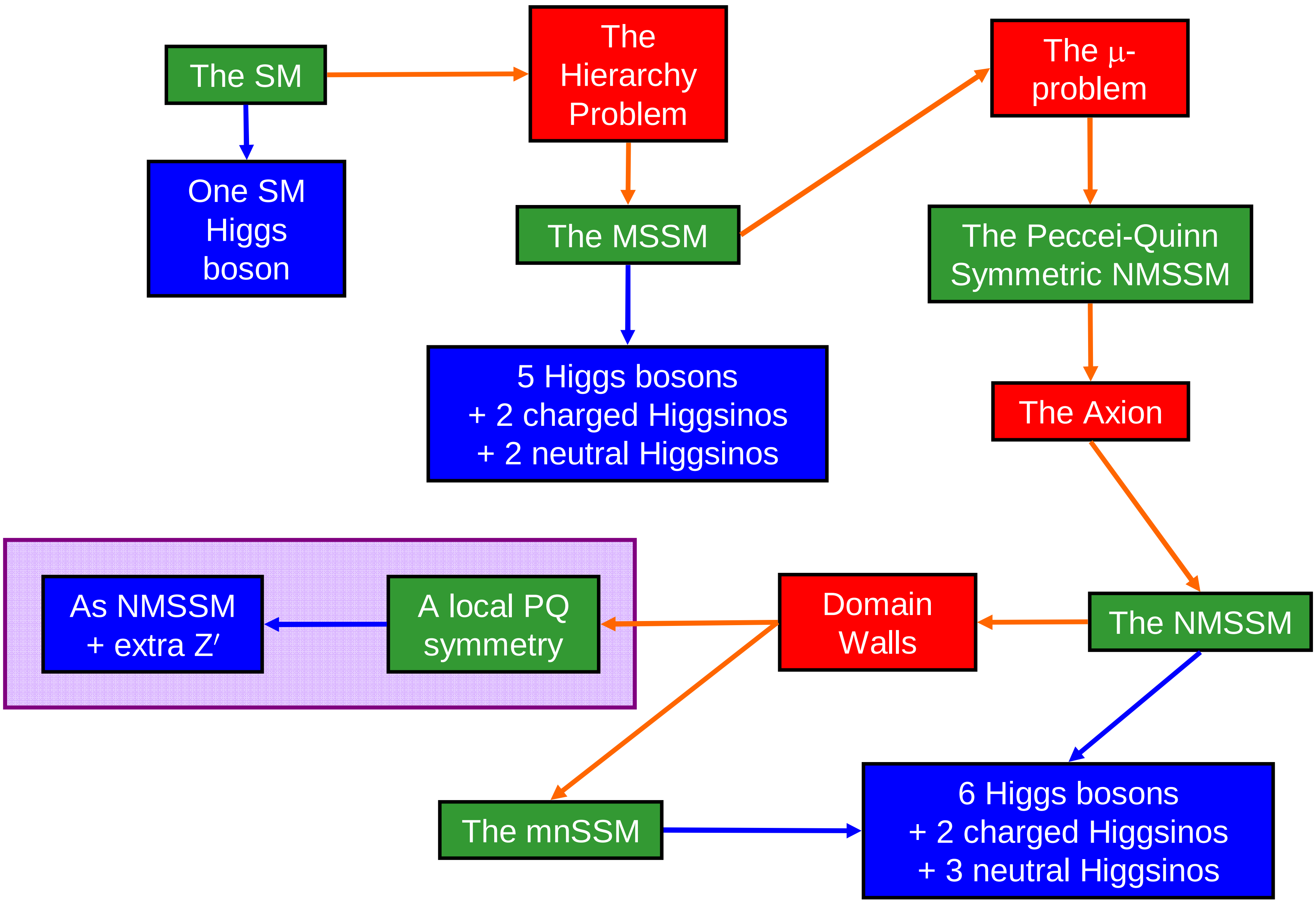
Physics will be extremely boring if we turn on the LHC and only find a SM Higgs.

Most theorists think this will not happen. We have good motivation for believing that something new exists at the TeV scale.

- The hierarchy problem (why is the Higgs so light?)
- Dark Matter (need a WIMP at the TeV scale)
- Gauge coupling unification (making the gauge coupling meet)
- Vacuum stability/triviality (causing a SM with “wrong” Higgs mass to break down by well below the GUT scale)

+ many more

We clearly need new physics and many people think that new physics will be **supersymmetry**.


The SM
The Hierarchy Problem
The μ-problem
One SM Higgs boson
The MSSM
The Peccei-Quinn Symmetric NMSSM
5 Higgs bosons
+ 2 charged Higgsinos
+ 2 neutral Higgsinos
The Axion
As NMSSM
+ extra Z′
A local PQ symmetry
Domain Walls
The NMSSM
The mnSSM
6 Higgs bosons
+ 2 charged Higgsinos
+ 3 neutral Higgsinos

Technical issues aside, there is a powerful aesthetic argument for new physics:

We want a unified model of all the forces (including gravity!)

While a unified theory is probably well beyond us still (especially gravity) we can ask what low energy phenomenology we might expect to see at the LHC as a consequence of unification.

This talk will discuss the E_6 inspired **Exceptional Supersymmetric Standard Model** (E_6SSM)

[S.F. King, S. Moretti, R. Nevzrov, Phys.Rev. D73 (2006) 035009]

Confession:

My title is really a bit of a con. The E_6SSM is **not** really a GUT model, since it contains no mechanism of unification.

However, it does provide us with a glimpse of how a GUT model may affect the low energy phenomenology.

2. The E_6SSM

"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 down to low energies:

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

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.

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

$$[27]_i \Rightarrow [10, 1/\sqrt{40}]_i + [5^*, 2/\sqrt{40}]_i + [5^*, -3/\sqrt{40}]_i + [5, -2/\sqrt{40}]_i + [1, 5]_i + [1, 0]_i$$

- $[10, 1/\sqrt{40}]_i$: $Q_i,\ u_i^c,\ e_i^c$
- $[5^*, 2/\sqrt{40}]_i$: $L_i,\ d_i^c$
- $[5^*, -3/\sqrt{40}]_i$: $H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix},\ \bar{D}_i$
- $[5, -2/\sqrt{40}]_i$: $H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix},\ D_i$
- $[1, 5]_i$: S_i
- $[1, 0]_i$: N_i^c

3 generations of "Higgs" ($H_{1\,i}$, $H_{2\,i}$)

exotic quarks ($\bar{D}_i$, D_i)

singlets (S_i)

right handed neutrino (N_i^c)

SU(5) reps. (first entry in each bracket)

$U(1)_N$ charge (second entry in each bracket)

New 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 will gain a VEV, due to the large top Yukawa coupling. The others are neutral and charged scalars -- we will call them **"inert Higgs"**.

- New "exotic quarks" D_i and $\bar{D}_i$. These are colored SU(2) singlets, with charge $\pm^1/_3$.

- Three generations of singlets w.r.t. all SM groups, S_i (gen 3 becomes "Higgs-like").

(+ right handed neutrinos)

- Also require an additional SU(2) doublet H' and antidoublet $\bar{H}'$. These are the only part of an additional $27'$ and $\overline{27}'$ which survive down to low energies.

  They are needed for gauge coupling unification, just as the normal Higgs doublets are needed for gauge unification in the MSSM.

  These extra states have a mass term $\mu' H' \bar{H}'$ which is not related to EWSB, so can in principle be anything. However, their masses should be less that about 100TeV for gauge unification.

- Extra U(1) $\rightarrow$ extra gauge boson, Z'.

  After electroweak symmetry breaking this will become massive (after eating the imaginary part of S_3)

Extra Symmetries

We have two potential problems:

- Rapid proton decay (just like most SuSy models)
- Large flavour changing neutral currents (FCNC)

Need extra symmetries to solve these problems.

For **proton decay**, we introduce Z_2^B or Z_2^L symmetries. This works just like R-parity except for the slightly surprising result that D has R_P = -1 while $\tilde{D}$ has R_P = +1 (so they are more like the Higgs/Higgsinos where the scalar has R_P =+1)

For **FCNC**, we must introduce an extra **approximate** "Z_2^H" symmetry, under which all superfields except the third generation of Higgs bosons and scalars are odd.

Writing $H_d \equiv H_{1,3}$, $H_u \equiv H_{2,3}$ and $S \equiv S_3$, the superpotential becomes:

$$\begin{aligned} W_{\rm ESSM} &= \sum_{i=1}^{3}\left(\lambda_i \hat{S}(\hat{H}_{1i}\hat{H}_{2i}) + \kappa_i \hat{S}(\hat{D}_i\hat{\overline{D}}_i)\right) + \sum_{\alpha,\,\beta=1,2}\left[f_{\alpha\beta}\hat{S}_\alpha(\hat{H}_d\hat{H}_{2\beta})\right. \\ &+ \left.\tilde{f}_{\alpha\beta}\hat{S}_\alpha(\hat{H}_{1\beta}\hat{H}_u)\right] + \mu'(\hat{H}'\hat{\overline{H}}') + g_i\hat{e}^c_i(\hat{H}_d\hat{H}') + W_{\rm MSSM}(\mu=0), \end{aligned}$$

Notice that H′ have interactions like leptons

New parameters: $\lambda_i,\ \kappa_i,\ f_{\alpha\beta},\ \tilde{f}_{\alpha\beta},\ g_i \quad (i = 1\ldots3,\ \alpha,\ \beta = 1,\ 2)$

Electroweak symmetry breaking

The third generation Higges H_d, H_u, gain VEVs and cause electroweak symmetry breaking, giving masses to quarks and leptons through Yukawa couplings.

The third generation S also gains a VEV:

- breaks $U(1)_N$, giving the Z' a mass
- provides an effective μ-term

The first and second generation remain "VEVless" (inert).

To achieve VEVs for only the third generation: $\lambda_3 \gtrsim \lambda_{1,2} \gg f_{\alpha\beta},\, \tilde{f}_{\alpha\beta},\, g_i$

$$W_{\text{ESSM}} \simeq \lambda \hat{S}(\hat{H}_d \hat{H}_u) + \lambda_1 \hat{S}(\hat{H}_{1,1}\hat{H}_{2,1}) + \lambda_2 \hat{S}(\hat{H}_{1,2}\hat{H}_{2,2}) + \kappa \hat{S}(\hat{D}_3 \hat{\overline{D}}_3) + \kappa_1 \hat{S}(\hat{D}_1 \hat{\overline{D}}_1)$$
$$+\kappa_2 \hat{S}(\hat{D}_2 \hat{\overline{D}}_2) + h_t(\hat{H}_u \hat{Q})\hat{t}^c + h_b(\hat{H}_d \hat{Q})\hat{b}^c + h_\tau(\hat{H}_d \hat{L})\hat{\tau}^c + \mu'(\hat{H}' \hat{\overline{H}'}) \,,$$

$$\left[\lambda \equiv \lambda_3,\ \kappa \equiv \kappa_3\right]$$

We also need to include soft SuSy breaking.

Scalar potential: $V = V_F + V_D + V_{\text{soft}}$

with: $$V_{soft} = \sum_{i=1}^{3}\Big(m_{S_i}^2|S_i|^2 + m_{H_{2\,i}}^2|H_{2\,i}|^2 + m_{H_{1\,i}}^2|H_{1\,i}|^2 + m_{D_i}^2|D_i|^2 + m_{\overline{D}_i}^2|\overline{D}_i|^2$$
$$+m_{Q_i}^2|Q_i|^2 + m_{u_i^c}^2|u_i^c|^2 + m_{d_i^c}^2|d_i^c|^2 + m_{L_i}^2|L_i|^2 + m_{e_i^c}^2|e_i^c|^2\Big) + m_{H'}^2|H'^2| + m_{\overline{H'}}^2|\overline{H'}|^2$$
$$+\Big[B'\,\mu'(H'\overline{H'}) + h.c.\Big] + \Big[\sum_{i=1}^{3}\Big(\lambda_i A_{\lambda_i} S(H_{1\,i}H_{2\,i}) + \kappa_i A_{\kappa_i} S(D_i\overline{D}_i)\Big)$$
$$+h_t A_t(H_u Q)t^c + h_b A_b(H_d Q)b^c + h_\tau A_\tau(H_d L)\tau^c + h.c.\Big].$$

Extra soft trilinear scalar couplings (e.g. $A_{\lambda_i},\ A_{\kappa_i}$) and 15 extra soft masses

3. 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:

$\lambda_i,\ \kappa_i,\ h_t,\ h_b,\ h_\tau,\ m_0,\ M_{1/2},\ A$ (at M_X)

Renormalisation Group Running

We have derived the RGEs to 2 loops, and modified a verison of SoftSuSY [B. Allanach] to run down the GUT scale parameters to low energies.

Procedure:

Run in two stages, first for gauge and Yukawa couplings and later for soft parameters

Gauge and Yukawa couplings:

- Fix tanβ at EW scale and derive EW scale quark/lepton Yakawas

  (e.g. $m_t(M_t) = \frac{h_t(M_t)v}{\sqrt{2}} \sin\beta$)

- Fix λ_i and κ_i (a guess) at SuSy scale and run all Yukawas and gauge couplings to M_X

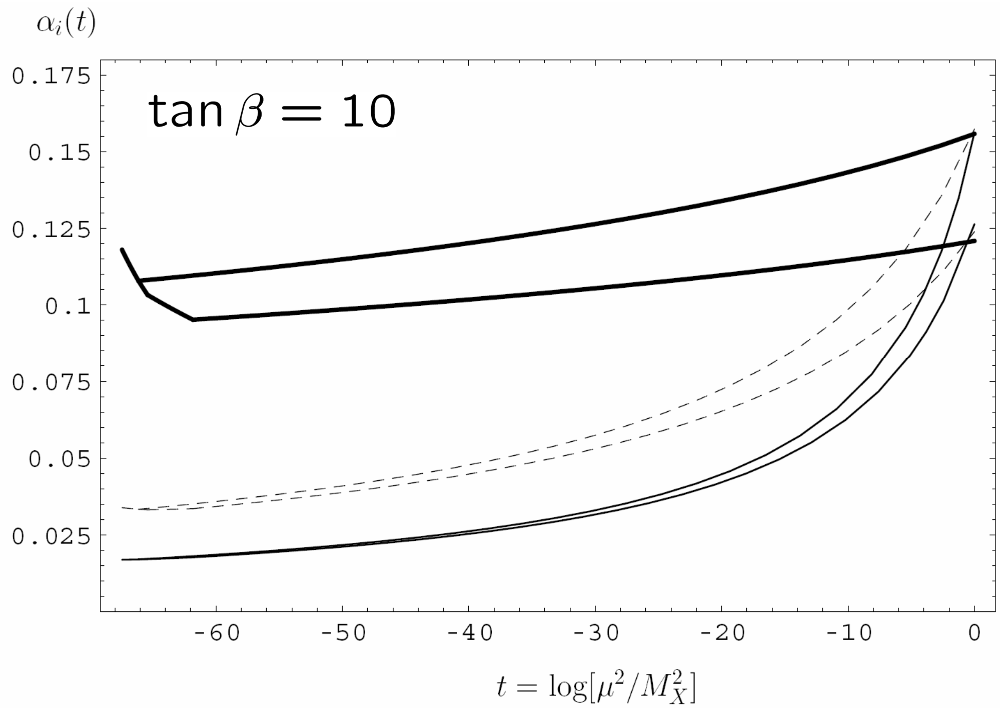
- Choose λ_i and κ_i at the High scale and fix gauge coupling unification
- Iterate until everything is consistent

Note:

Two loop running is essential since at one loop there is an accidental cancellation

making $\beta_3 \approx 0$

Running is very sensitive to thresholds



Soft SuSy breaking parameters

Since the gauge and Yukawa coupling RGEs don't involve soft SuSy breaking parameters, we can evolve these separately once we know the gauge and Yukawa couplings.

- For a particular scenario, put gauge and Yukawa coulpings into the soft SuSy RGEs
- This results in equations of the form, e.g.

$$M_3(\mu_S) = 0.705\, M_{1/2} + 0.0046\, A, \qquad M_2(\mu_S) = 0.274\, M_{1/2} + 0.0015\, A,$$

$$M_1(\mu_S) = 0.155\, M_{1/2} + 0.00088\, A, \qquad M_1'(\mu_S) = 0.159\, M_{1/2} + 0.0016\, A,$$

$$\begin{aligned} m_S^2(\mu_S) &= -0.535\, m_0^2 - 1.578\, M_{1/2}^2 - 0.085\, A^2 - 0.264\, AM_{1/2}, \\ m_{H_u}^2(\mu_S) &= 0.128\, m_0^2 - 1.145\, M_{1/2}^2 - 0.124\, A^2 - 0.481\, AM_{1/2}, \\ m_{H_d}^2(\mu_S) &= 0.940\, m_0^2 + 0.296\, M_{1/2}^2 - 0.013\, A^2 - 0.025\, AM_{1/2}, \end{aligned}$$

+ many more

- Use EWSB constraints to replace soft parameters with $\langle S \rangle = \frac{s}{\sqrt{2}}$, M_Z, $\tan\beta$

$$
\begin{aligned}
\frac{\partial V}{\partial s} &= m_S^2 s - \frac{\lambda A_\lambda}{\sqrt{2}} v_1 v_2 + \frac{\lambda^2}{2}(v_1^2+v_2^2)s + \\
&\quad + \frac{g_1^{\prime 2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_S s + \frac{\partial \Delta V}{\partial s} = 0\,, \\
\frac{\partial V}{\partial v_1} &= m_1^2 v_1 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_2 + \frac{\lambda^2}{2}(v_2^2+s^2)v_1 + \frac{\bar{g}^2}{8}\left(v_1^2 - v_2^2\right)v_1 + \\
&\quad + \frac{g_1^{\prime 2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_1 v_1 + \frac{\partial \Delta V}{\partial v_1} = 0\,, \\
\frac{\partial V}{\partial v_2} &= m_2^2 v_2 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_1 + \frac{\lambda^2}{2}(v_1^2+s^2)v_2 + \frac{\bar{g}^2}{8}\left(v_2^2 - v_1^2\right)v_2 + \\
&\quad + \frac{g_1^{\prime 2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_2 v_2 + \frac{\partial \Delta V}{\partial v_2} = 0\,,
\end{aligned}
$$

Note: only s is free choice now

solve at tree-level → gives tree-level m_0, $M_{1/2}$, A

- Iterate to include higher orders (ΔV)

Restrictions on solutions

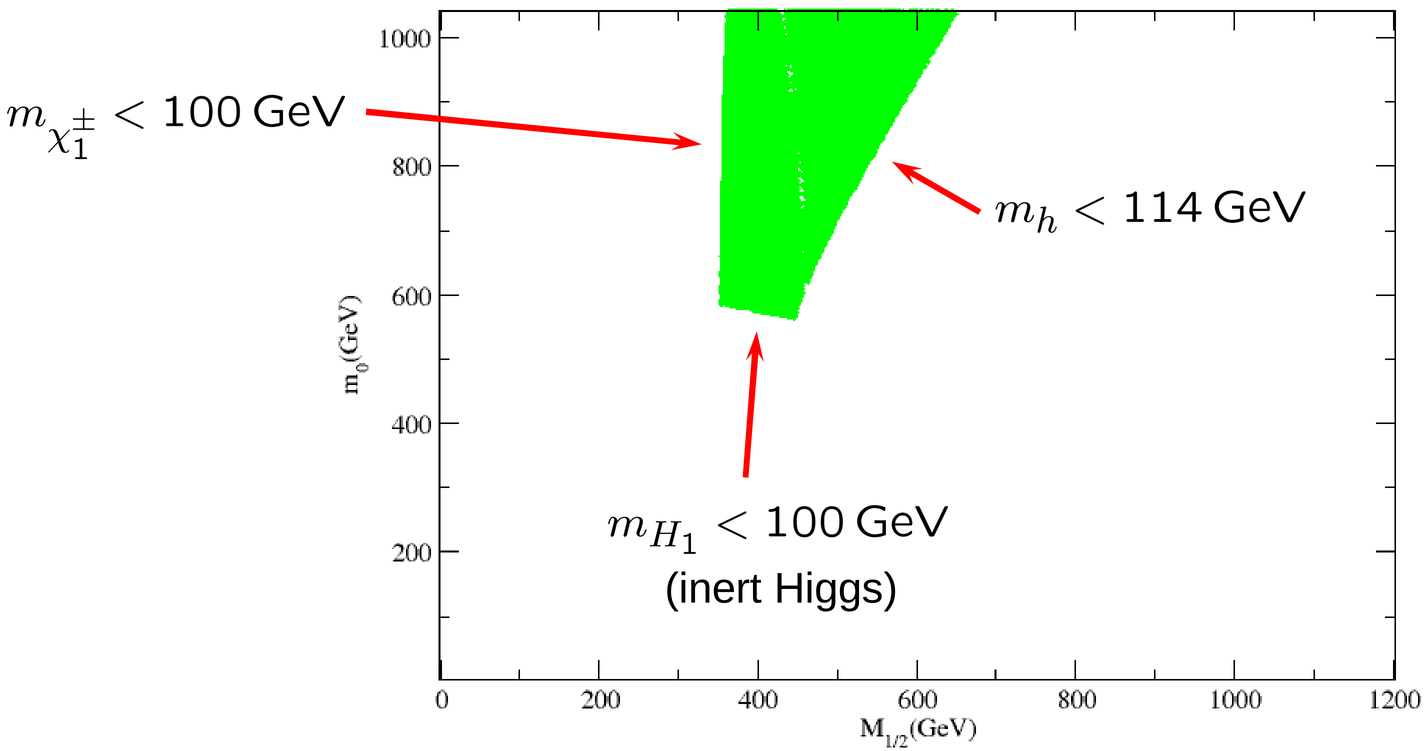
To ensure phenomenologically acceptable solutions, we require

- squarks and gluinos $\gtrsim$ 300 GeV
- exotic quarks and squarks $\gtrsim$ 300 GeV [HERA]
- $M_{Z'} \gtrsim$ 700 GeV (considering increasing to 900 GeV)
- Insist on neutralino LSP
- Keep Yukawa couplings $\lesssim$ 3
- Inert Higgs and Higgsinos $\gtrsim$ 100 GeV

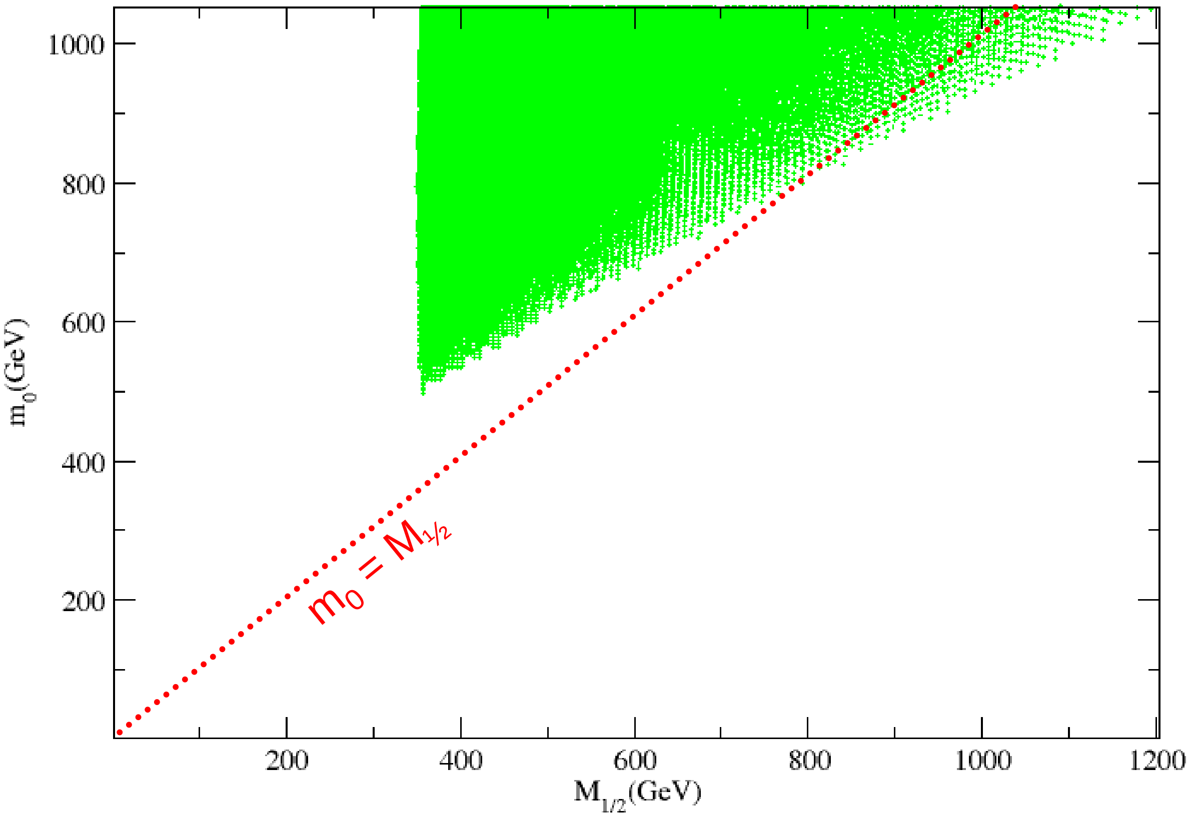
Allowed regions in the m_0 - $M_{½}$ plane

Fix $\tan\beta = 10,\ s = 3\,\text{TeV}$ and allow everything else to vary

Allowed points are in green.



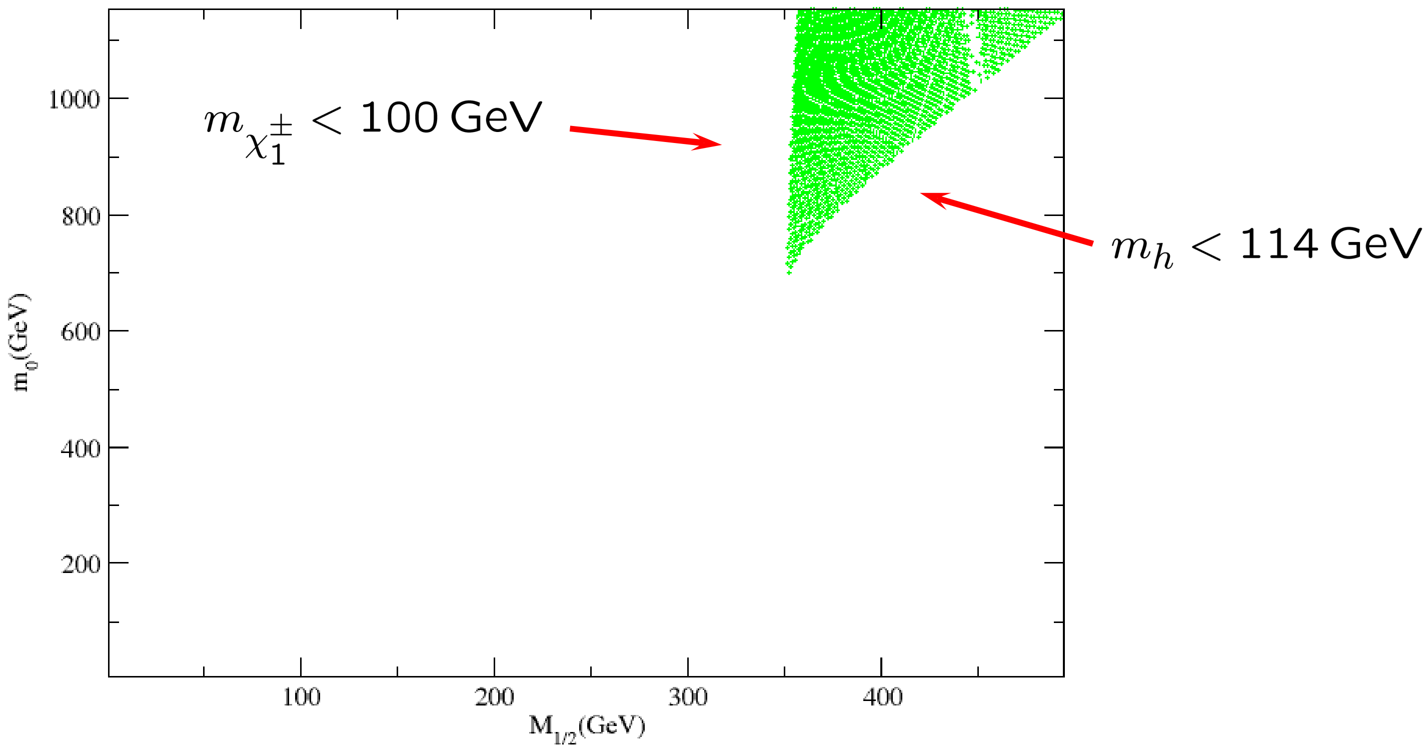
As previous, but now allowing s to vary too, i.e. only $\tan\beta = 10$ fixed



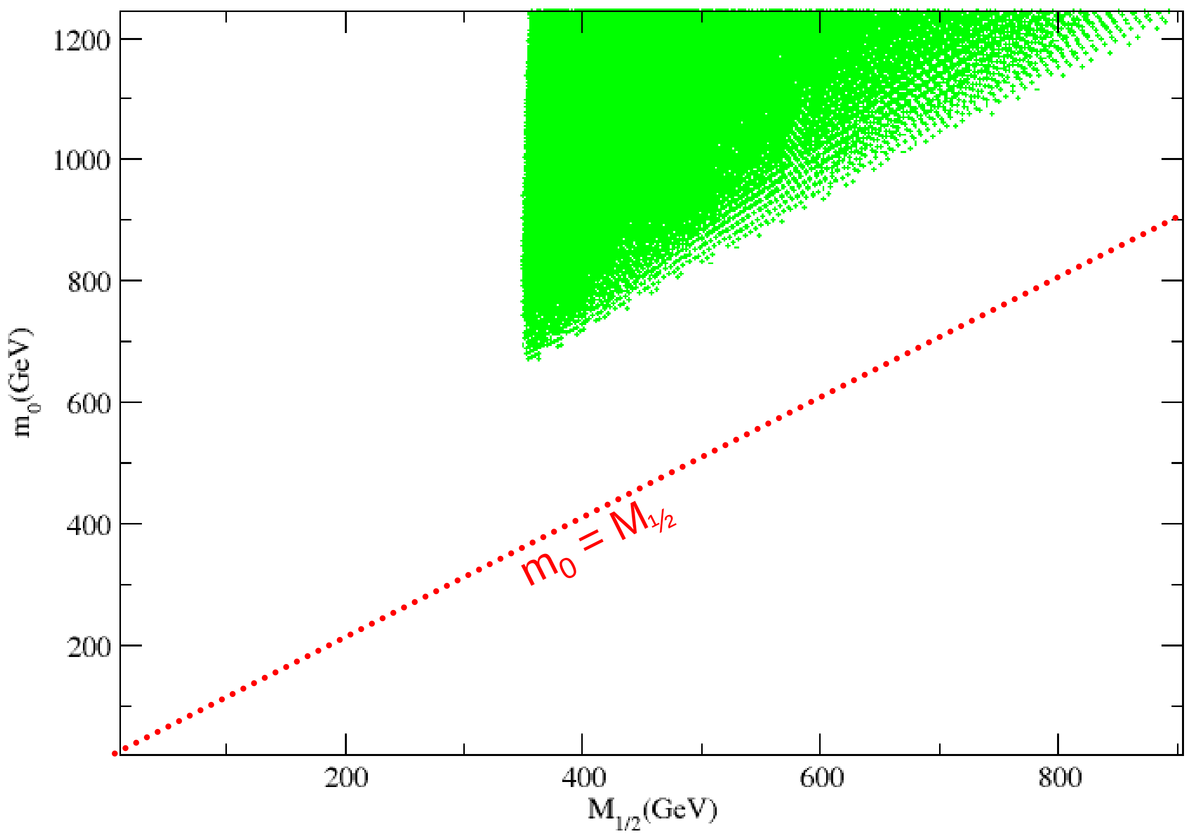
Note: since m_0, $M_{1/2}$ are derived, some possible regions are sparsely populated

Fix $\tan\beta = 30,\ s = 3\,\text{TeV}$ and allow everything else to vary

Allowed points are in green.



As previous, but now allowing s to vary too, i.e. only $\tan\beta = 30$ fixed



4. Particle Spectra and Benchmarks

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

- Neutralinos, charginos and gluino:

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

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

$$m_{\tilde{\chi}_{3,4}^0} \approx m_{\tilde{\chi}_2^\pm} \approx \mu = \frac{\lambda s}{\sqrt{2}}$$

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

$$m_{\tilde{g}} \approx M_3$$

- 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 have their mass set by $\frac{\kappa_i(M_S)}{\sqrt{2}}s$

  Exotic squarks are similar, but also have a contribution from the soft SuSy mass

  $$m^2_{\tilde{D}_i} \approx m^2_{D_i} + \frac{\kappa_i^2(M_S)}{2}\, s^2 \qquad \text{+ mixing and auxiliary D-terms}$$

- Inert Higgses have contributions from the soft mass, auxiliary D-terms and $\frac{\lambda_i(M_S)}{\sqrt{2}}s$

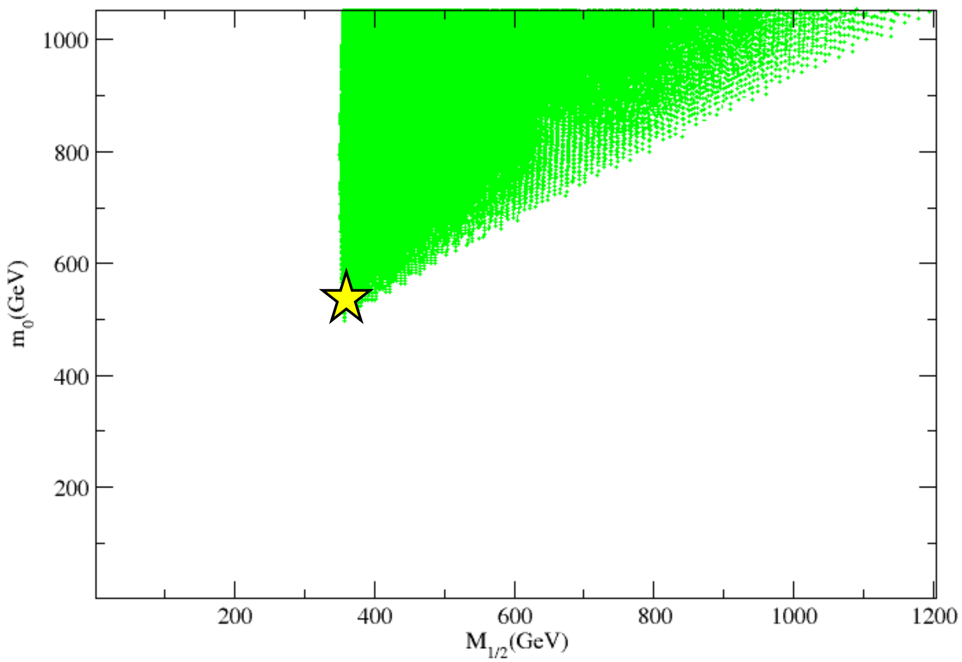
  Inert Higgsinos are much simpler, $m_{\tilde{H}_i} \approx \frac{\lambda_i(M_S)}{\sqrt{2}}s$

  can be negative

Benchmark 1 (light spectra)

$$\tan\beta = 10, \quad s = 2.7\,\text{TeV},$$
$$M_{1/2} = 363\,\text{GeV}, \quad m_0 = 537\,\text{GeV}, \quad A = 711\,\text{GeV}$$
$$\lambda(M_X) = -0.368, \quad [\lambda(M_S) = -0.355]\,, \quad \lambda_{1,2}(M_X) = 0.1$$
$$\kappa_{1,2,3}(M_X) = 0.207, \quad \left[\kappa_{1,2,3}(M_S) = 0.538\right]$$

- κ's all equal, so exotic squarks all degenerate

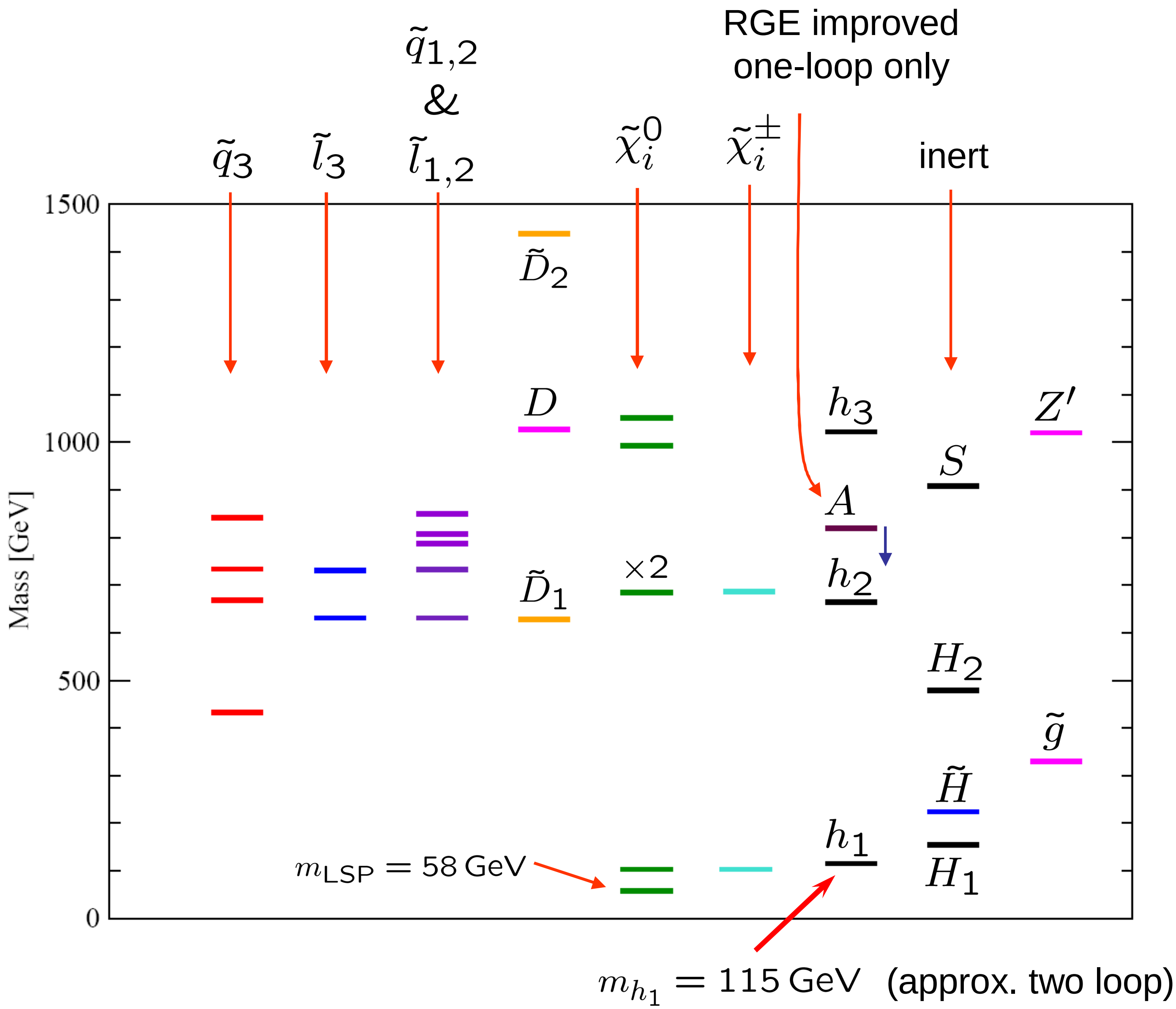


- Light Higgs and inert Higgs

$$m_{h_1} = 115\,\text{GeV}$$
$$m_{H_1} = 154\,\text{GeV}$$

- Light gluino and chargino

$$m_{\tilde{g}} = 330\,\text{GeV}$$
$$m_{\tilde{\chi}_1^\pm} = 103\,\text{GeV}$$

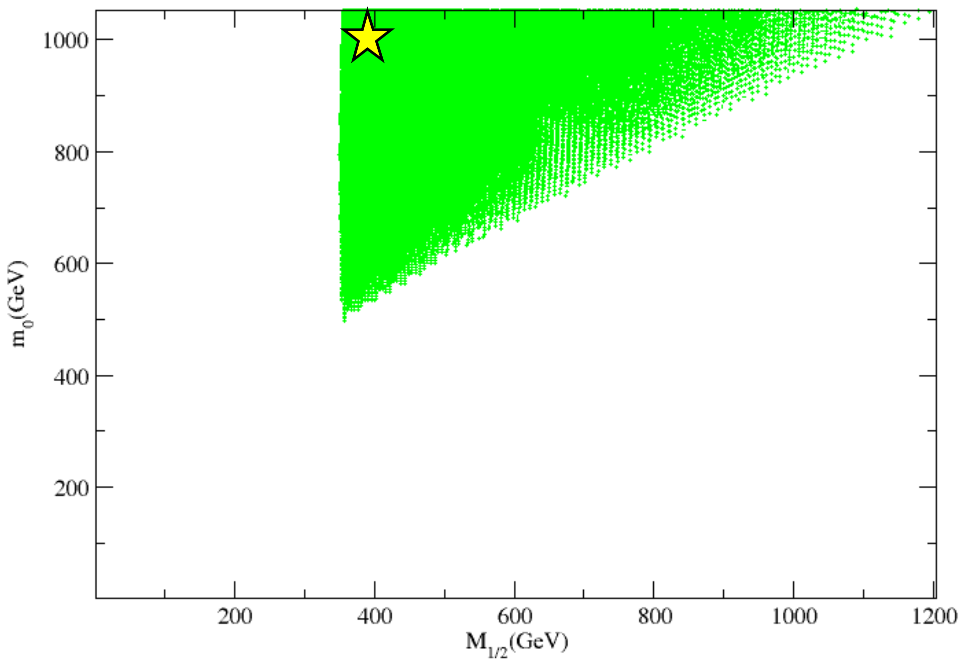


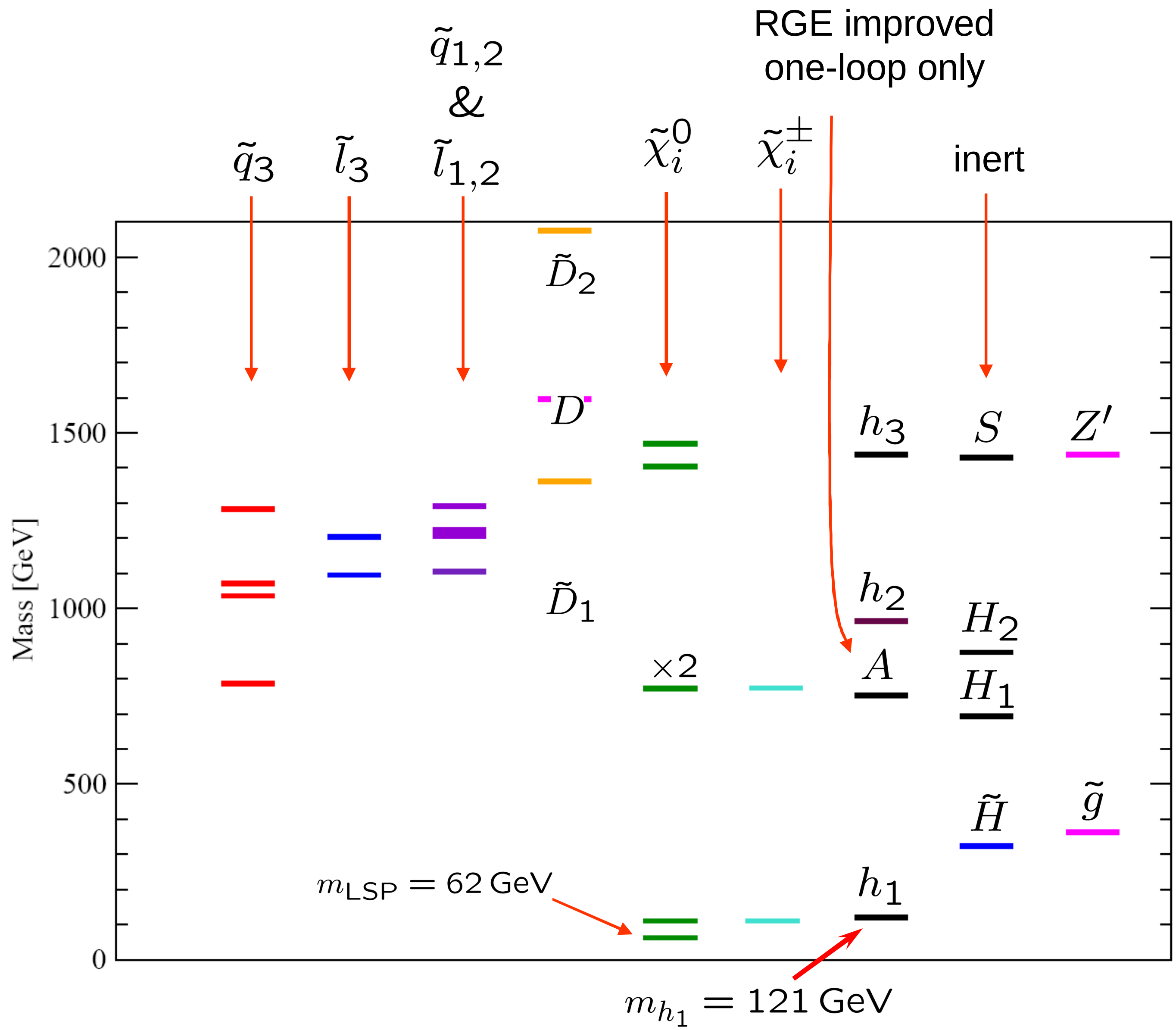
RGE improved
one-loop only
$\tilde{q}_{1,2}$
&
$\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
1500
1000
500
0
Mass [GeV]
$\tilde{D}_2$
D
$\tilde{D}_1$
$\times 2$
h_3
A
h_2
h_1
Z'
S
H_2
$\tilde{g}$
$\tilde{H}$
H_1
$m_{\rm LSP} = 58$ GeV
$m_{h_1} = 115$ GeV (approx. two loop)

Benchmark 2 $\left(m_0 \gg M_{1/2}\right)$

$$\tan\beta = 10, \quad s = 3.8\,\text{TeV},$$
$$M_{1/2} = 390\,\text{GeV}, \quad m_0 = 998\,\text{GeV}, \quad A = 768\,\text{GeV}$$
$$\lambda(M_X) = -0.307, \quad [\lambda(M_S) = -0.285], \quad \lambda_{1,2}(M_X) = 0.1$$
$$\kappa_{1,2,3}(M_X) = 0.246, \quad \left[\kappa_{1,2,3}(M_S) = 0.594\right]$$

- Very split spectrum with light neutralinos/gauginos but very heavy scalars




RGE improved
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$\tilde{q}_{1,2}$ & $\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
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Mass [GeV]
$\tilde{D}_2$
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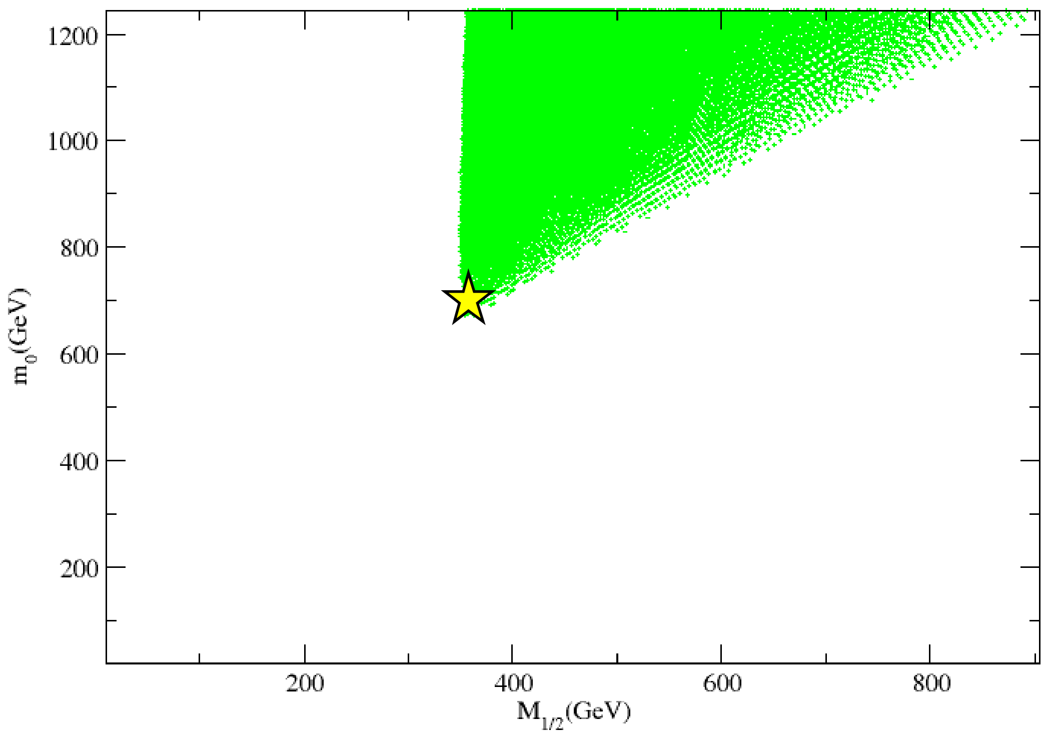
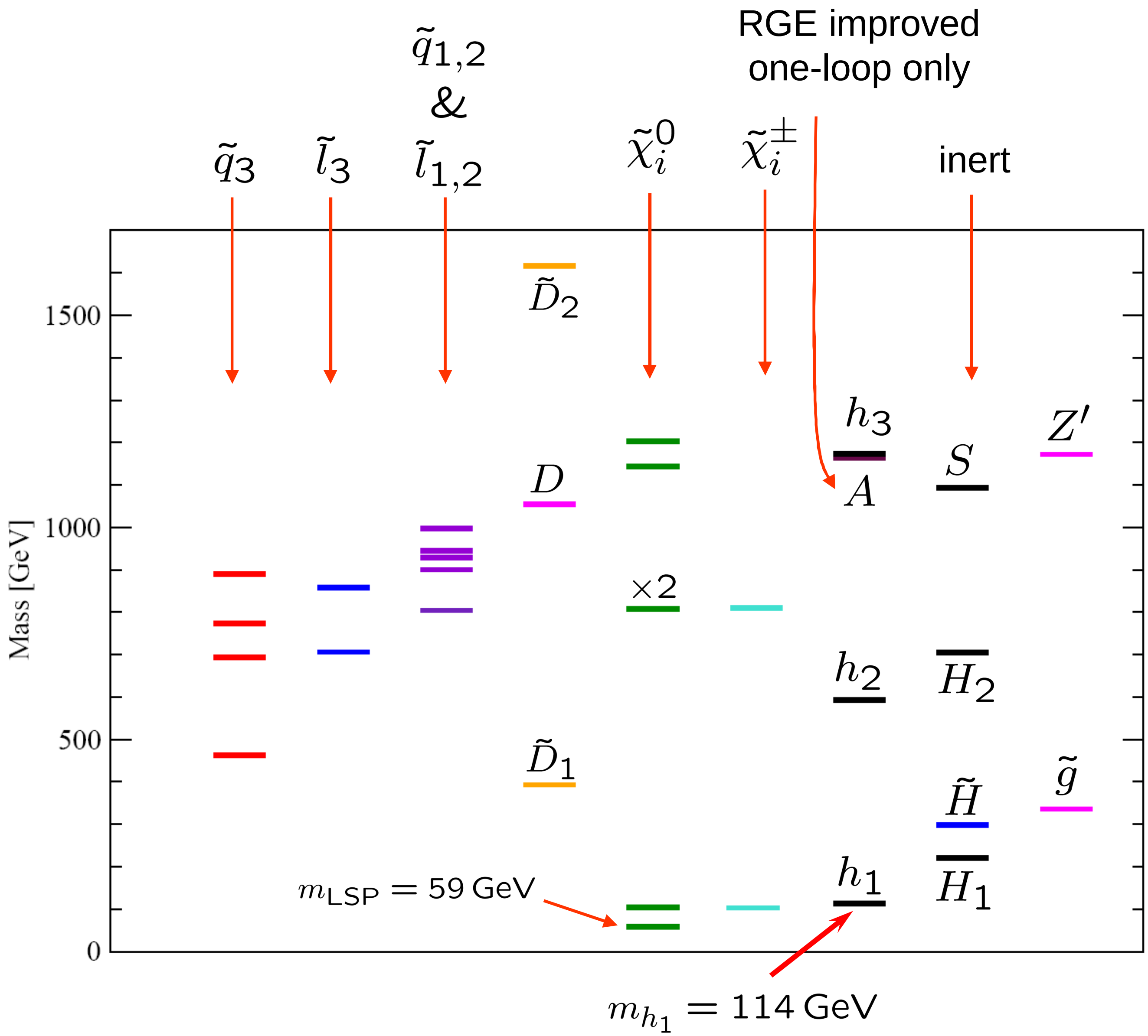
$\times 2$
h_3
S
Z'
h_2
H_2
A
H_1
$\tilde{H}$
$\tilde{g}$
h_1
$m_{\mathrm{LSP}} = 62$ GeV
$m_{h_1} = 121$ GeV

Benchmark 3 (high $\tan\beta$ with light spectra)

$\tan\beta = 30, \quad s = 3.1\,\text{TeV},$
$M_{1/2} = 365\,\text{GeV}, \quad m_0 = 702\,\text{GeV}, \quad A = 1148\,\text{GeV}$
$\lambda(M_X) = -0.378, \quad [\lambda(M_S) = -0.366]\,, \quad \lambda_{1,2}(M_X) = 0.1$
$\kappa_{1,2,3}(M_X) = 0.171, \quad [\kappa(M_S) = 0.481]$





RGE improved
one-loop only
$\tilde{q}_{1,2}$ & $\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
1500
1000
500
0
Mass [GeV]
$\tilde{D}_2$
D
$\tilde{D}_1$
$\times 2$
h_3
A
S
Z'
h_2
H_2
$\tilde{H}$
$\tilde{g}$
h_1
H_1
$m_{\rm LSP} = 59$ GeV
$m_{h_1} = 114$ GeV

5. Conclusions and Summary

- The E_6SSM provides a credible example of a model which could arise from a GUT
- As well as the usual SuSy partner particles, it contains exotic quarks, “inert” Higgs bosons, extra scalars and a Z'.
- Each generation forms a complete 27-plet of E_6.
- The model contains 43 new parameters compared to the MSSM (incl. 14 phases)
- We have calculated the E_6SSM RGEs to two-loop accuracy and used them to study a constrained version of the model where soft SuSy breaking parameters (and gauge couplings) are unified at some high scale.
- We find that a large portion of the parameter space is open to phenomenologically reasonable scenarios, although they tend to require that $m_0 \gtrsim M_{1/2}$, causing a rather split spectrum.
- We presented some interesting benchmarks, with new exotic particle states within reach of the LHC
- The next step is to calculate production cross-sections and branching ratios for these new exotic particles.