Reproducing an E_6SSM from its Signatures

The LHC Inverse Problem:

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- LHC-IA - What is the new physics?
- LHC-IB - What is the spectrum and effective Lagrangian of the new physics at the weak scale?
- LHC-IC - How can we begin to study what the underlying theory is, perhaps at a high scale and/or in extra dimensions?

In this talk we discuss the LHC Inverse problem from the perspective of an E_6 Supersymmetric Standard Model (shortly defined)

The μ problem

- Although MSSM solves "technical hierarchy problem" (loops) it does not address "tree-level hierarchy problem" of why Higgs masses are low
- In particular no reason why μ parameter (which respects SUSY) should be same order as soft masses → the "μ problem".
- In M-theory this cannot be resolved a la Guidice-Masiero using the Kahler term H_uH_d if H_u and H_d come from 27's of E_6 since 27×27 is not invariant
- In the NMSSM $\mu=0$ but an effective μ-term is generated from a singlet: S Hu Hd → <S> Hu Hd where singlet VEV <S> plays role of μ parameter
- A coupling S^3 is required to avoid a massless axion due to global U(1) PQ symmetry which broken at weak scale.
- With S^3 term the symmetry is reduced to Z_3 -- broken at the weak scale resulting in cosmological domain walls (or tadpoles if broken)

The E_6SSM solution

- We would like to solve μ problem of MSSM using a singlet as in the NMSSM, but avoiding the domain wall/ tadpole problems of NMSSM

- The idea is to use the superpotential coupling $W=\lambda$ S Hu Hd (without the extra S^3 term) and gauge the U(1) PQ symmetry so that the dangerous axion is eaten to form a massive Z' gauge boson → U(1)' model

- Anomaly cancellation in low energy gauged U(1)' models always implies either extra low energy exotic matter or family-nonuniversal U(1)' charges

- The E_6SSM is an example of a U(1)' model with extra low energy exotic matter with anomalies are cancelled elegantly using complete 27's of E_6

E_6SSM is discussed in SFK, Moretti and Nevzorov

Other related references (very incomplete – apologies)

Cvetic, Demir, Espinosa, Everett, Langacker; J.Wang;

Keith, Ma;

Daikoku, Suematsu;

Demir, Everett;

Hewett, Rizzo;

Demir, Kane, T.Wang;

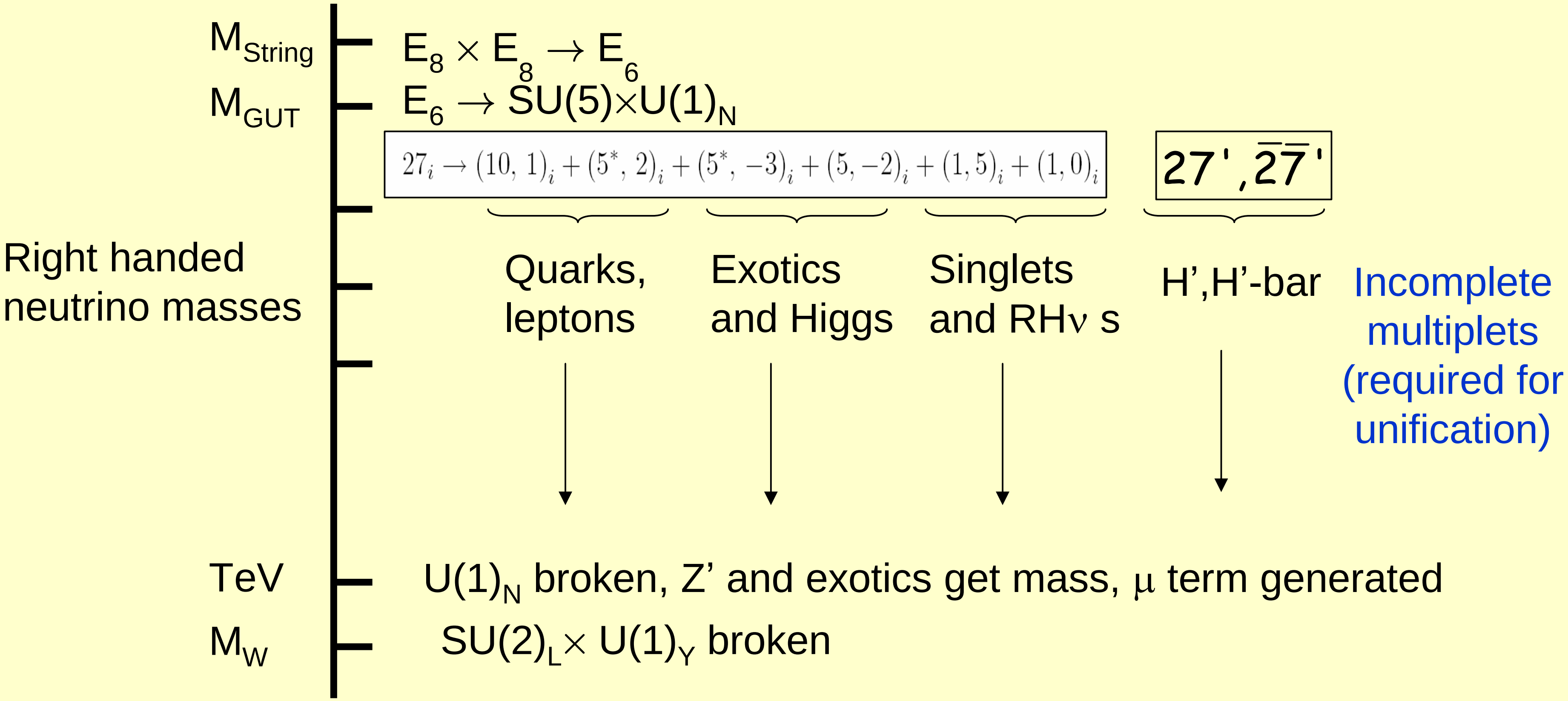
Morrissey, Wells;

Barger, Langacker, Lee, Shaughnessy;

Sketch of the E_6SSM

$$E_6 \to SO(10)\times U(1)_\psi \qquad SO(10)\to SU(5)\times U(1)_\chi$$

Right handed neutrinos are neutral under: $U(1)_N = \frac{\sqrt{15}}{4}U(1)_\psi + \frac{1}{4}U(1)_\chi$



M_{String} — $E_8 \times E_8 \to E_6$

M_{GUT} — $E_6 \to SU(5)\times U(1)_N$

$$27_i \to \underbrace{(10,1)_i + (5^*,2)_i}_{\text{Quarks, leptons}} + \underbrace{(5^*,-3)_i + (5,-2)_i}_{\text{Exotics and Higgs}} + \underbrace{(1,5)_i + (1,0)_i}_{\text{Singlets and RH}\nu\text{ s}} \qquad \underbrace{\boxed{27', \overline{27}'}}_{\text{H',H'-bar}}$$

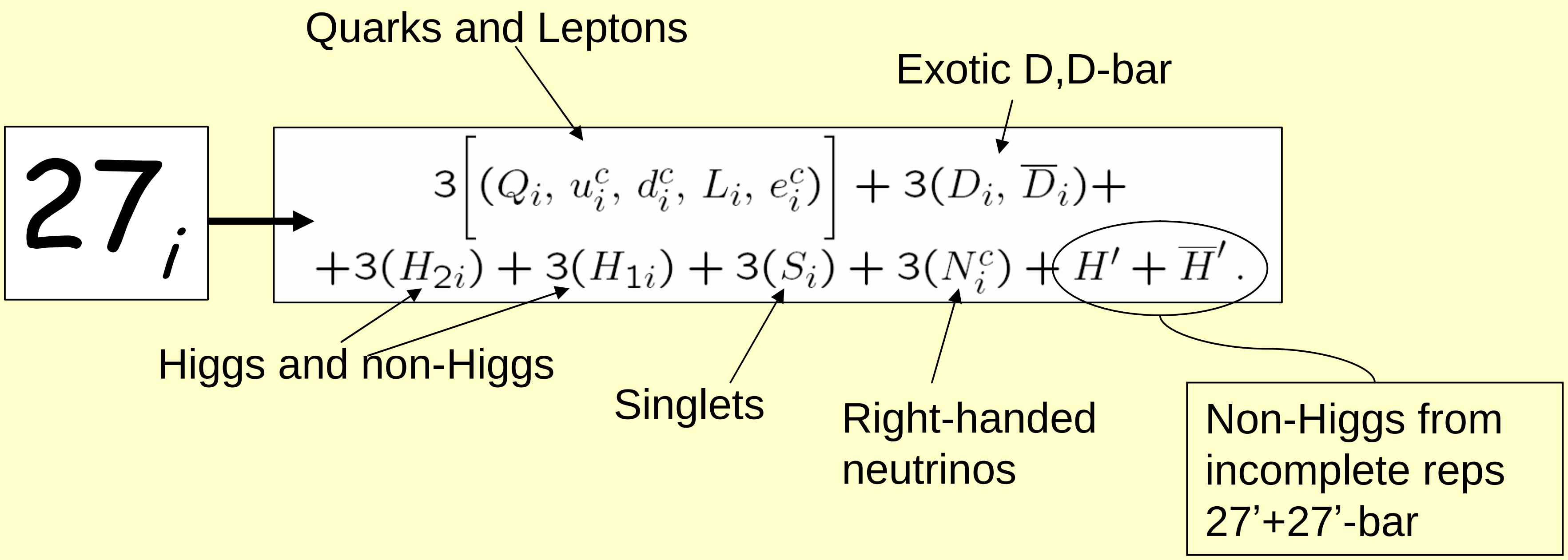
Right handed neutrino masses

Incomplete multiplets (required for unification)

TeV — $U(1)_N$ broken, Z' and exotics get mass, μ term generated

M_W — $SU(2)_L\times U(1)_Y$ broken

Low energy matter content of E_6SSM



$$27_i \rightarrow 3\left[(Q_i,\, u^c_i,\, d^c_i,\, L_i,\, e^c_i)\right] + 3(D_i,\, \overline{D}_i) + \\ +3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N^c_i) + H' + \overline{H}'\,.$$

Quarks and Leptons

Exotic D,D-bar

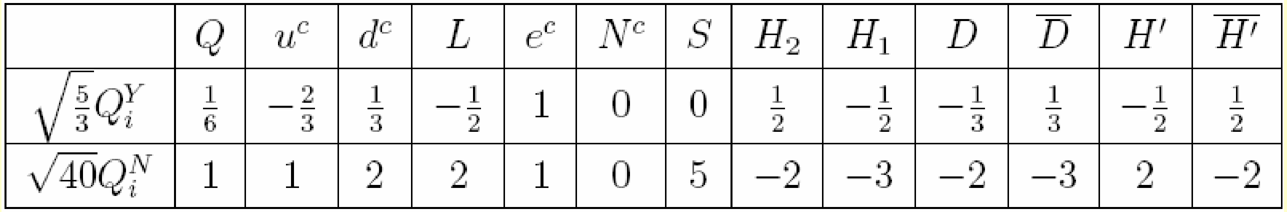
Higgs and non-Higgs

Singlets

Right-handed neutrinos

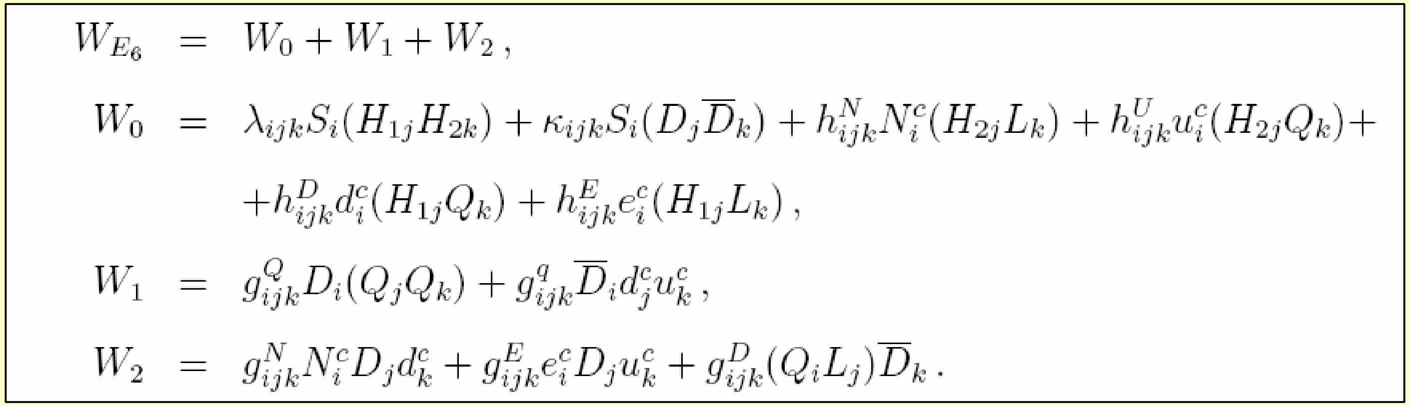
Non-Higgs from incomplete reps 27’+27’-bar

Family Universal Anomaly Free Charges:



	Q	u^c	d^c	L	e^c	N^c	S	H_2	H_1	D	$\overline{D}$	H'	$\overline{H'}$
$\sqrt{\frac{5}{3}}Q_i^Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{2}$
$\sqrt{40}Q_i^N$	1	1	2	2	1	0	5	-2	-3	-2	-3	2	-2

Most general E_6 allowed couplings from 27^3:



$$
\begin{aligned}
W_{E_6} &= W_0 + W_1 + W_2\,, \\
W_0 &= \lambda_{ijk} S_i (H_{1j} H_{2k}) + \kappa_{ijk} S_i (D_j \overline{D}_k) + h^N_{ijk} N^c_i (H_{2j} L_k) + h^U_{ijk} u^c_i (H_{2j} Q_k) + \\
&\quad + h^D_{ijk} d^c_i (H_{1j} Q_k) + h^E_{ijk} e^c_i (H_{1j} L_k)\,, \\
W_1 &= g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \overline{D}_i d^c_j u^c_k\,, \\
W_2 &= g^N_{ijk} N^c_i D_j d^c_k + g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} (Q_i L_j) \overline{D}_k\,.
\end{aligned}
$$

→ Rapid proton decay! Need generalization of R-parity→ two possibilities:

I. Z_2^L under which leptons are odd → forbids W_2→ exotic D,D-bar are diquarks

II. Z_2^B with leptons & D,D-bar odd → forbids W_1 → exotic D,D-bar are leptoquarks

Including RH neutrino masses have two models:

$$\begin{aligned} W_{ESSMI} &= \tfrac{1}{2}M_{ij}N_i^cN_j^c + W_0 + W_1\,, \\ W_{ESSMII} &= \tfrac{1}{2}M_{ij}N_i^cN_j^c + W_0 + W_2. \end{aligned}$$

To suppress FCNCs we further assume an approximate Z_2^H symmetry under which only $H_d = H_{1,3}$, $H_u=H_{2,3}$ $S=S_3$ are even (all else=odd)

Suppresses W_1, W_2 and restricts W_0 as follows (e.g. only one pair of Higgs doublets couple to quarks and leptons as in the MSSM and will get radiative VEVs):

$$\begin{aligned} W_{\mathrm{ESSM\,I,\,II}} \;\longrightarrow\;& \lambda_i S(H_{1i}H_{2i}) + \kappa_i S(D_i\overline{D}_i) + \\ & + f_{\alpha\beta}S_\alpha(H_dH_{2\beta}) + \tilde{f}_{\alpha\beta}S_\alpha(H_{1\beta}H_u) + W_{\mathrm{MSSM}}(\mu=0) \end{aligned}$$

In phenomenological studies we keep only terms with large Yukawa couplings:

$$W_{\mathrm{ESSM\,I,\,II}} \approx \lambda S(H_dH_u) + \kappa_i S(D_i\overline{D}_i) + h_t(H_uQ)t^c + h_b(H_dQ)b^c + h_\tau(H_dL)\tau^c\,.$$

However terms with small Yukawa couplings arising from W_1 or $W_{2.}$ are required for exotic decays.

The origin of bilinear masses

Right-handed neutrino masses arise from the coupling to the Higgs 27_H which breaks E_6

$$\boxed{\frac{\kappa_{ij}}{M_{Pl}}(\overline{27}_H\, 27_i)(\overline{27}_H\, 27_j) \qquad \Longrightarrow \qquad M_{ij} = \frac{2\kappa_{ij}}{M_{Pl}} < \overline{N}^c_H >^2}$$

•We also need to generate a TeV mass term μ H’ H’-bar

•The simplest possibility is to use the Guidice-Masiero mechanism

•The Kahler potential permits H’ H’-bar since H’ comes from 27’ and H’-bar comes from 27’-bar

•Unlike H_u H_d which is forbidden since 27× 27 is not invariant

•Note that H’,H’-bar are irrelevant for Higgs phenomenology since they do not develop VEVs – they are ``non-Higgs’’

Higgs Phenomenology of E_6SSM @ LHC

With $\mathbf{Z_2^H}$ only three Higgs multiplets $\mathbf{H_u}$, $\mathbf{H_d}$, **S** get VEVs

W=λ S $\mathbf{H_d}$ $\mathbf{H_d}$ as in the NMSSM but without the $\mathbf{S^3}$ term (simpler!)

This leads to the Higgs potential:

$$
\begin{aligned}
V &= V_F + V_D + V_{soft} + \Delta V \,, \\
V_F &= \lambda^2|S|^2(|H_d|^2 + |H_u|^2) + \lambda^2|(H_d H_u)|^2 \,, \\
V_D &= \frac{g_2^2}{8}\left(H_d^{+}\sigma_a H_d + H_u^{+}\sigma_a H_u\right)^2 + \frac{g'^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 \\
&\quad + \frac{g_1'^2}{2}\left(\tilde{Q}_1|H_d|^2 + \tilde{Q}_2|H_u|^2 + \tilde{Q}_S|S|^2\right)^2 \,, \\
V_{soft} &= m_S^2|S|^2 + m_1^2|H_d|^2 + m_2^2|H_u|^2 + \\
&\qquad + \left[\lambda A_\lambda S(H_u H_d) + h.c.\right] \,,
\end{aligned}
$$

where $g' = \sqrt{3/5} \cdot g_1(M_Z)$; $\tilde{Q}_1, \tilde{Q}_2$ and $\tilde{Q}_S$ are $U(1)_N$ charges of H_d, H_u and S.

- Thus the Higgs sector of the ESSM involves

  - one pseudoscalar $$m_A^2 = \frac{2\lambda^2 s^2 x}{\sin^2 2\beta} + O(M_Z^2)\,,$$

    As in the MSSM (unlike the NMSSM since the axion is eaten by the Z')

  - two charged states $$m_{H^\pm}^2 = m_A^2 + O(M_Z^2)\,,$$

    As in the MSSM and NMSSM

  - three scalars

    Extra scalar state compared to MSSM – as in the NMSSM.

$$m_{h_3}^2 = m_A^2 + O(M_Z^2)\,,$$

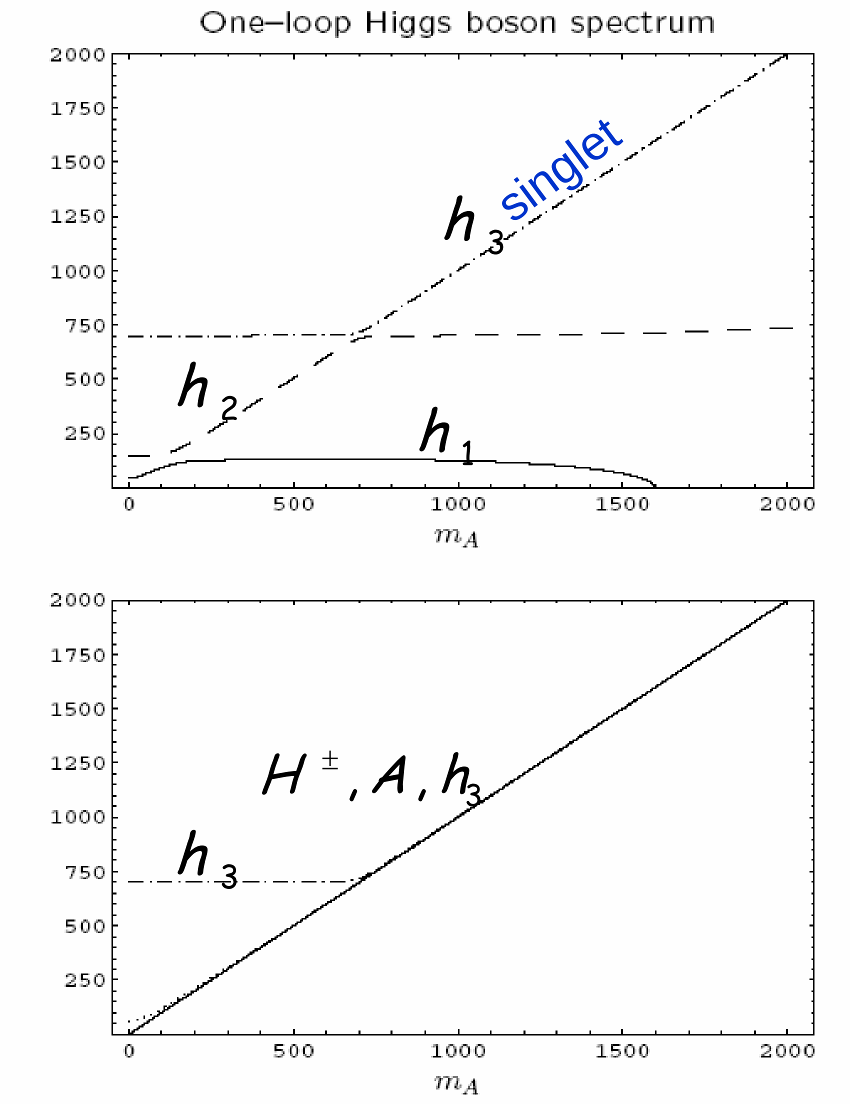
$$m_{h_2}^2 = g_1'^2 \tilde{Q}_S^2 s^2 + O(M_Z^2) \simeq M_{Z'}^2\,,$$

$$m_{h_1}^2 \simeq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + \frac{\bar{g}^2}{4} v^2 \cos^2 2\beta + + g_1'^2 v^2 \left(\tilde{Q}_1 \cos^2\beta + \tilde{Q}_2 \sin^2\beta\right)^2 - - \frac{\lambda^4 v^2}{g_1'^2 Q_S^2} \left(1 - x + \frac{g_1'^2}{\lambda^2}\left(\tilde{Q}_1 \cos^2\beta + Q_2 \sin^2\beta\right) Q_S\right)^2\,,$$

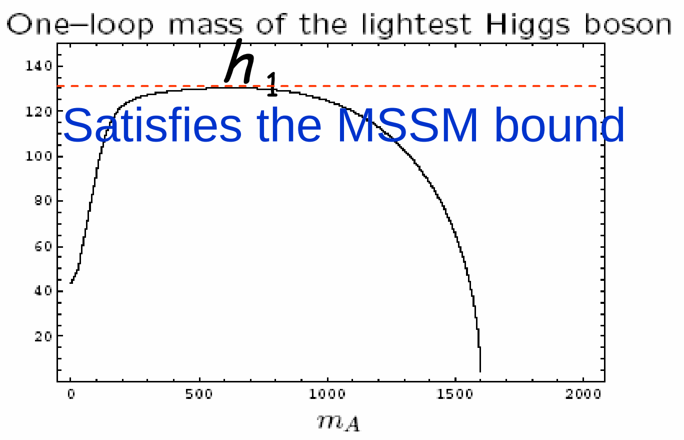
where $x = \dfrac{A_\lambda}{\sqrt{2}\lambda s}\sin 2\beta\,.$ $\dfrac{g_1(M_Z)}{g_1'(M_Z)} \simeq 0.99\,,$ $g_{11}(M_Z) \simeq 0.020\,,$ $g_1(M_Z) \simeq 0.46\,.$

Can the Higgs sector of the E$_6$SSM be distinguished from that of the MSSM and NMSSM?

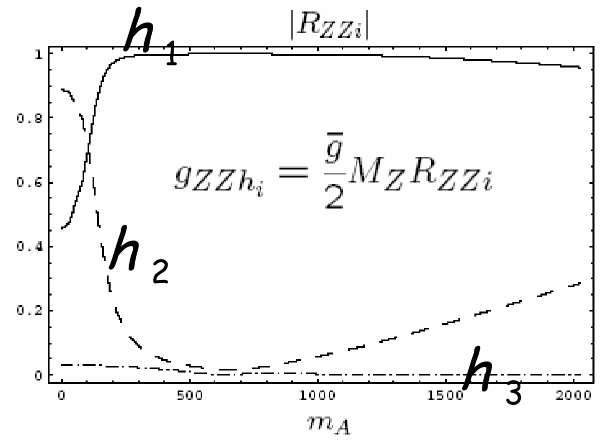
Small $\lambda < g_1$ gives an MSSM-like spectrum @ LHC (unfortunately!)


One–loop Higgs boson spectrum

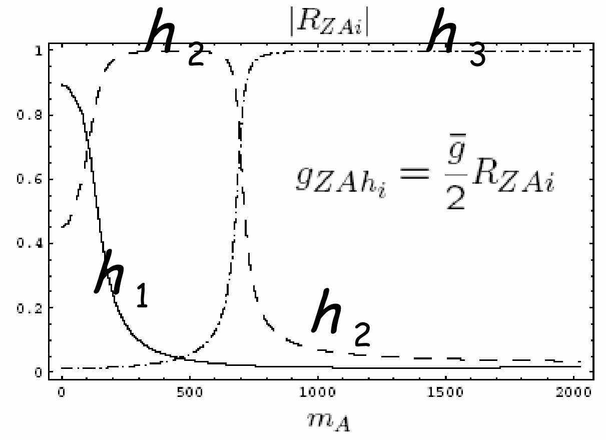
$\lambda = 0.3,\ \tan\beta = 2,\ X_t = \sqrt{6} M_S,\ M_{Z'} = M_S = 700$ GeV


One–loop mass of the lightest Higgs boson

Satisfies the MSSM bound

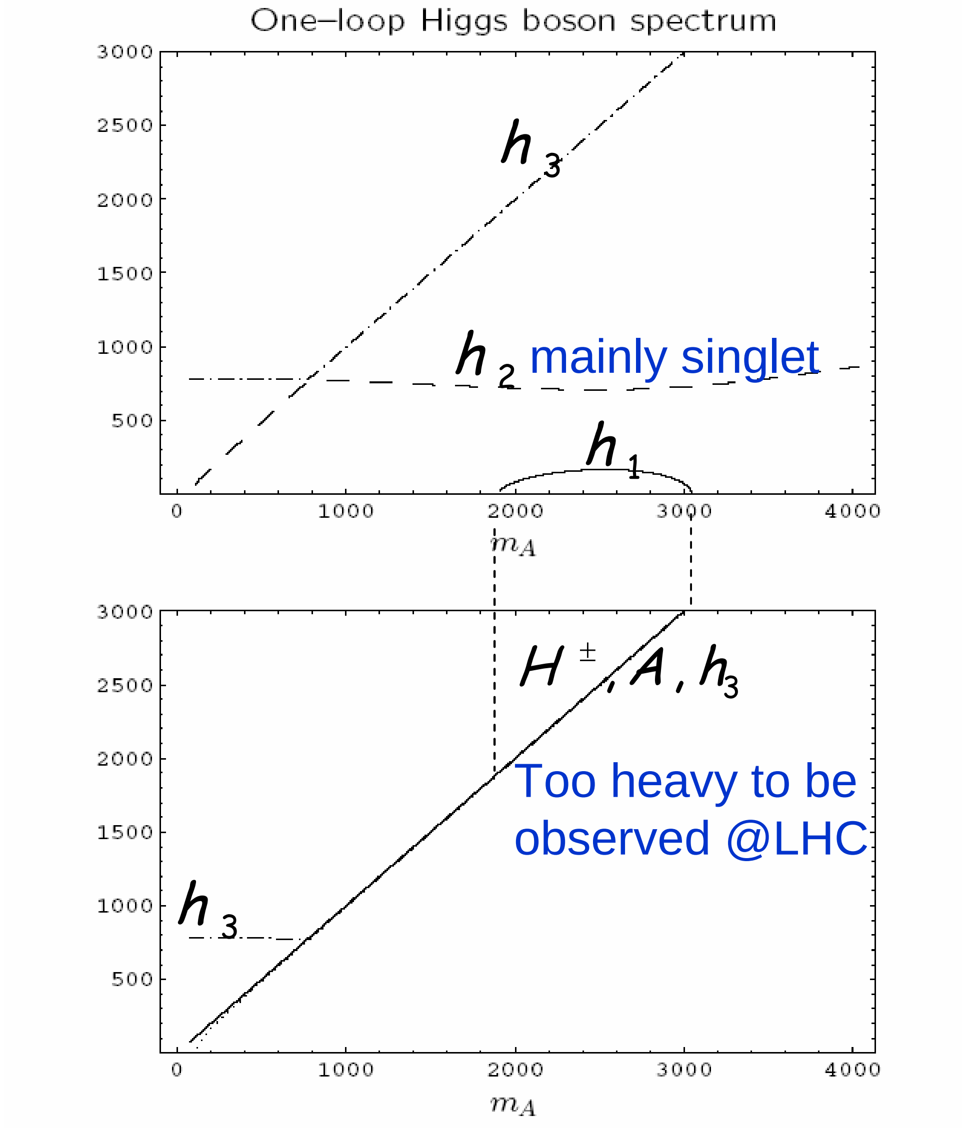

$|R_{ZZi}|$

$g_{ZZh_i} = \frac{\bar{g}}{2} M_Z R_{ZZi}$


$|R_{ZAi}|$

$g_{ZAh_i} = \frac{\bar{g}}{2} R_{ZAi}$

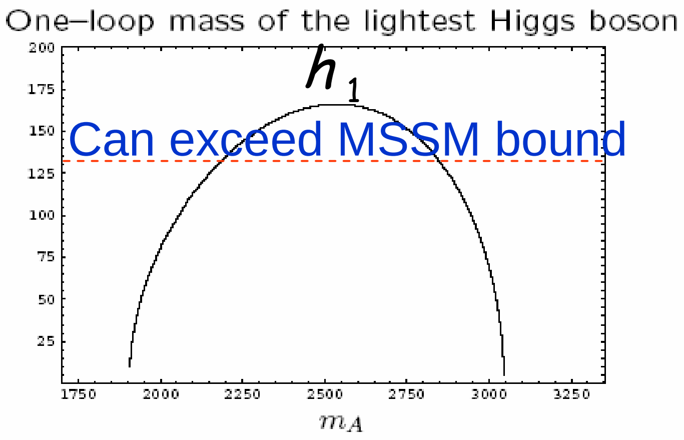
Large $\lambda > g_1$ leads to only h_1 @ LHC



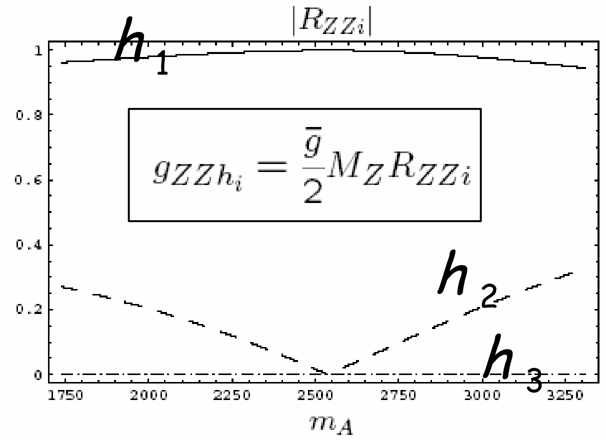
h_2 mainly singlet

Too heavy to be observed @LHC

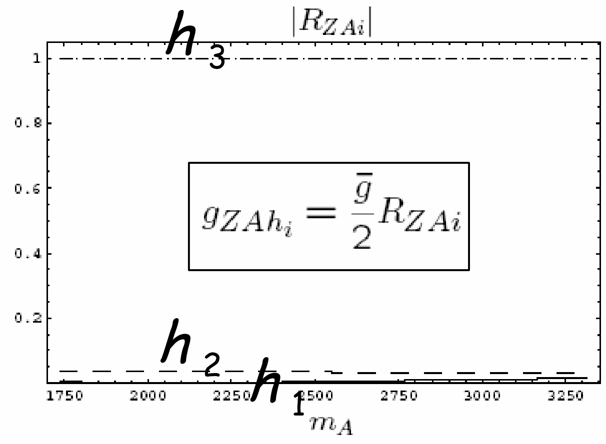
$\lambda = 0.79,\ \tan\beta = 2,\ X_t = \sqrt{6}M_S,\ M_{Z'} = M_S = 700\ \text{GeV}$



Can exceed MSSM bound



$$g_{ZZh_i} = \frac{\bar{g}}{2} M_Z R_{ZZi}$$



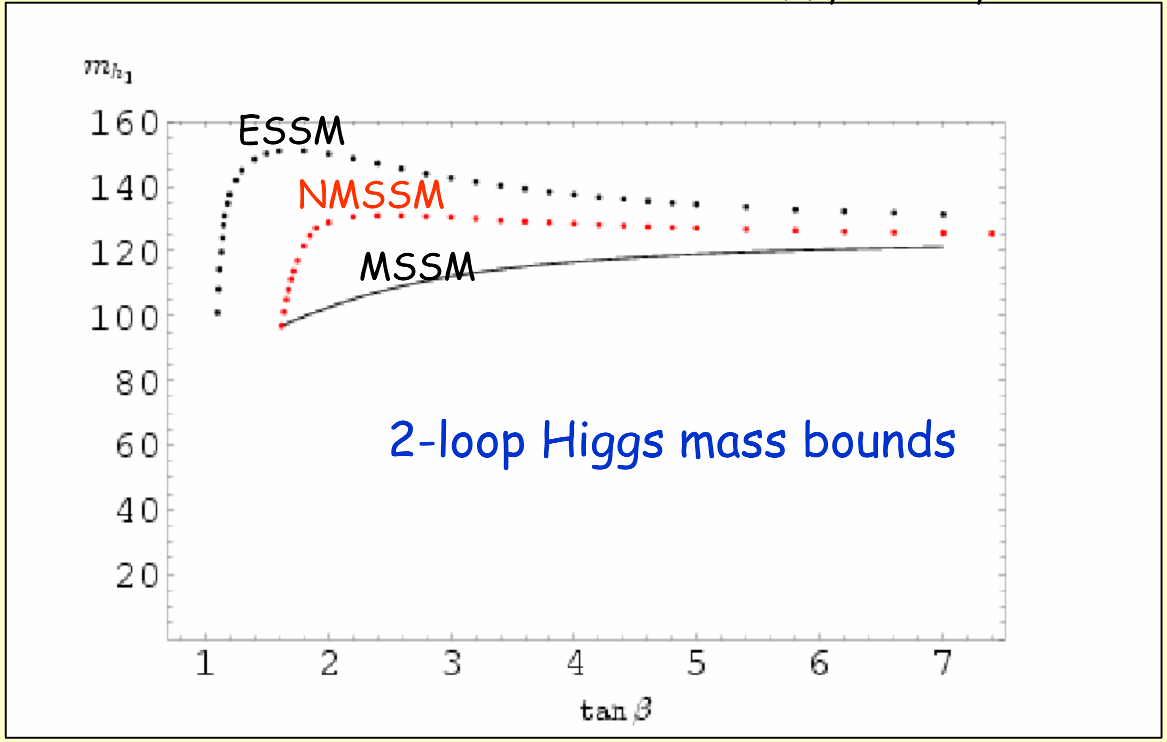
$$g_{ZAh_i} = \frac{\bar{g}}{2} R_{ZAi}$$

E_6SSM Higgs h_1 mass bound

$$m_h^2 \le \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \tfrac{1}{4} M_Z^2 \left(1+\tfrac{1}{4}\cos 2\beta\right)^2 + \Delta \le \left(160\, GeV\right)^2$$

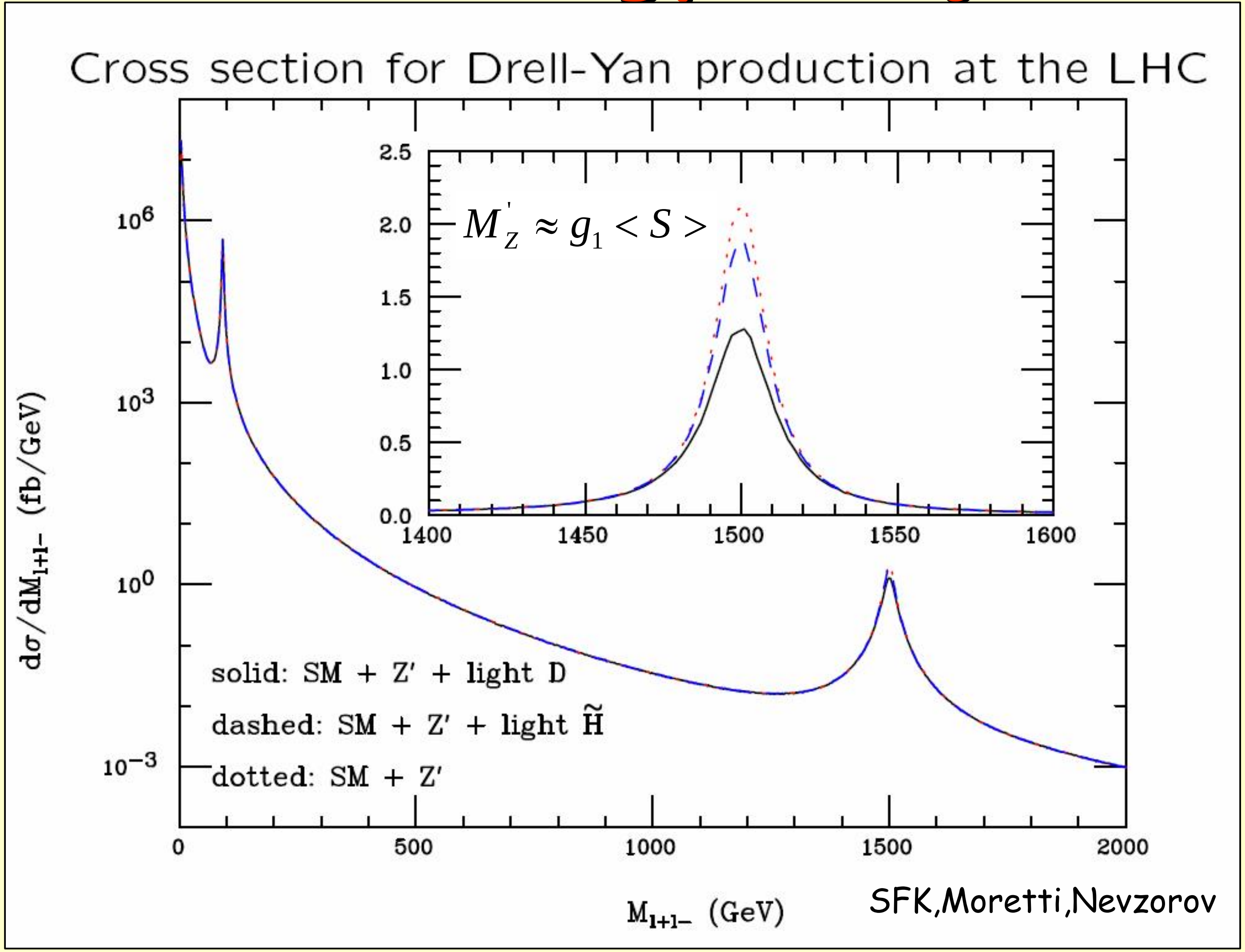
SFK,Moretti,Nevzorov

Observing a heavy Higgs boson @ LHC is one way (only way!) to distinguish the E_6SSM from the NMSSM or MSSM Higgs sectors



2-loop Higgs mass bounds

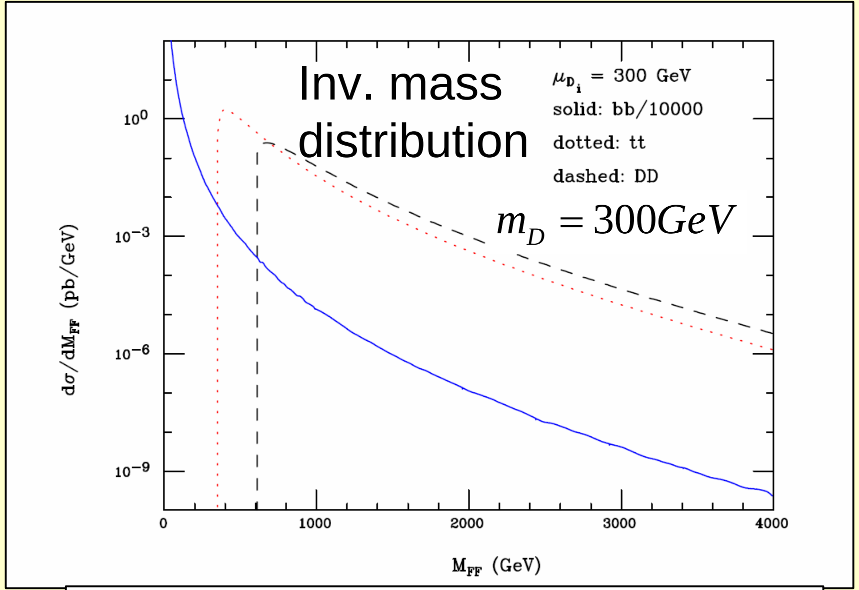
Z' Phenomenology in E_6SSM

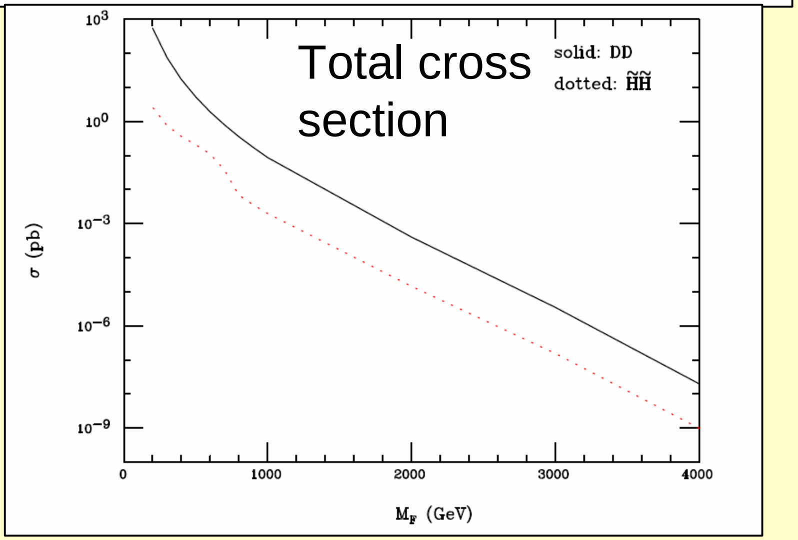


SFK,Moretti,Nevzorov

SFK,Moretti,Nevzorov

Exotic D-quarks in E$_6$SSM @ LHC





The exotic quarks decay either via

$$\overline{D} \to t + \tilde{b}\,, \qquad \overline{D} \to b + \tilde{t}$$

if exotic quarks $\overline{D}_i$ are diquarks or via

$$\begin{array}{ll} D \to t + \tilde{\tau}\,, & D \to \tau + \tilde{t}\,, \\ D \to b + \tilde{\nu}_\tau\,, & D \to \nu_\tau + \tilde{b}\,, \end{array}$$

if exotic quarks D_i are leptoquarks.

Since $\sigma(pp \to D\overline{D} + X)$ may be comparable with $\sigma(pp \to t\bar{t} + X)$ the presence of light exotic quark will result in appreciable enhancement of the cross section of either

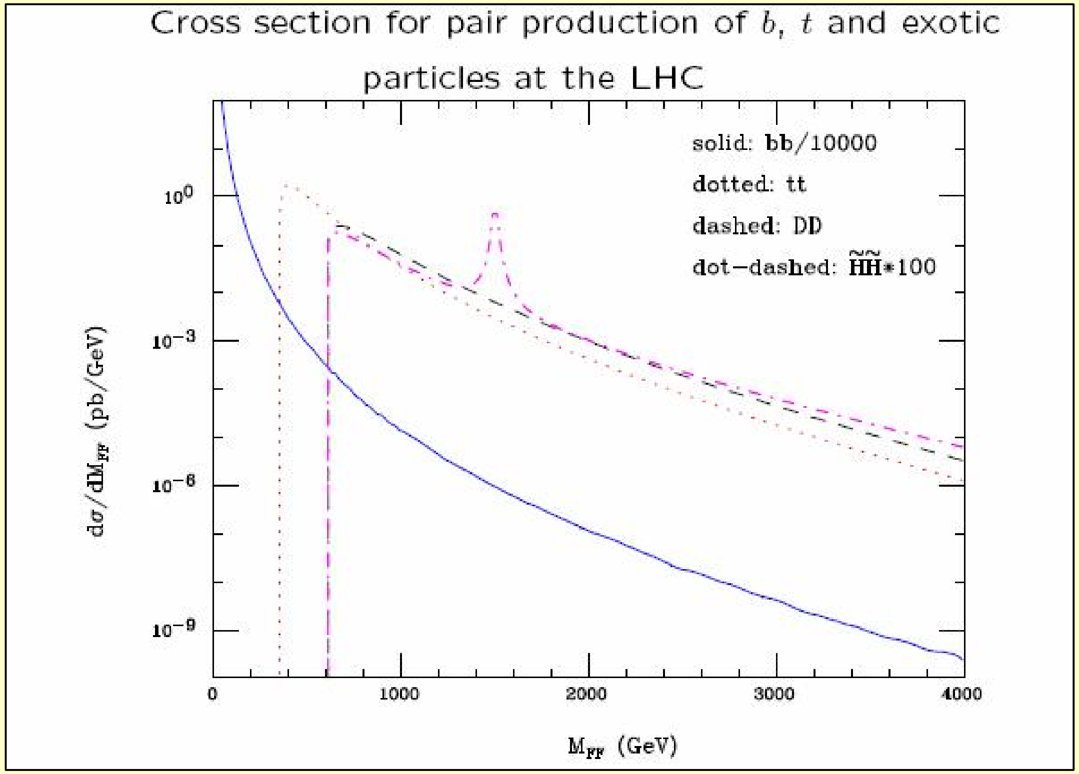
$$pp \to t\bar{t}b\bar{b} + X\,, \qquad pp \to b\bar{b}b\bar{b} + X$$

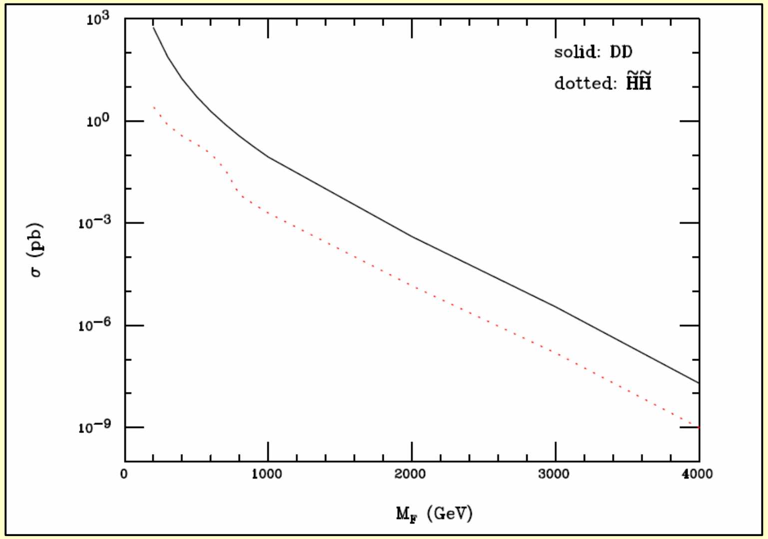
if exotic quarks are diquarks or

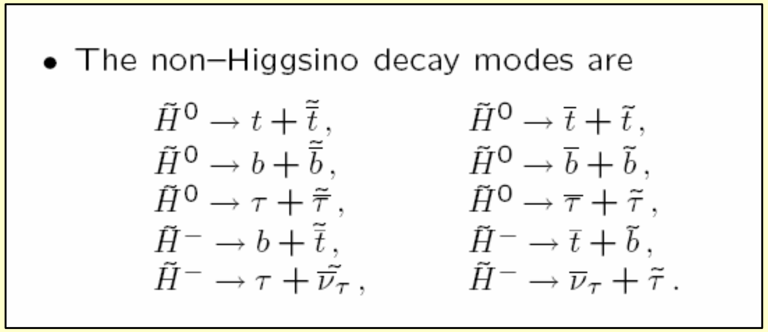
$$pp \to t\bar{t}l\bar{l} + X\,, \qquad pp \to b\bar{b}l\bar{l} + X$$

if new quark states are leptoquarks.

Non-Higgsino discovery difficult due to small cross-section @ LHC


Cross section for pair production of b, t and exotic particles at the LHC




- The non–Higgsino decay modes are

$$
\begin{array}{ll}
\tilde{H}^0 \to t + \tilde{\bar{t}}\,, & \tilde{H}^0 \to \bar{t} + \tilde{t}\,, \\
\tilde{H}^0 \to b + \tilde{\bar{b}}\,, & \tilde{H}^0 \to \bar{b} + \tilde{b}\,, \\
\tilde{H}^0 \to \tau + \tilde{\bar{\tau}}\,, & \tilde{H}^0 \to \bar{\tau} + \tilde{\tau}\,, \\
\tilde{H}^- \to b + \tilde{\bar{t}}\,, & \tilde{H}^- \to \bar{t} + \tilde{b}\,, \\
\tilde{H}^- \to \tau + \tilde{\bar{\nu}}_\tau\,, & \tilde{H}^- \to \bar{\nu}_\tau + \tilde{\tau}\,.
\end{array}
$$

Some E_6SSM Challenges for the LHC Inverse Problem

Discover:

- the Z’, SUSY, the Higgs, the exotic D-quarks, the non-Higginos (Pythia needs to be extended -- Brent Nelson)

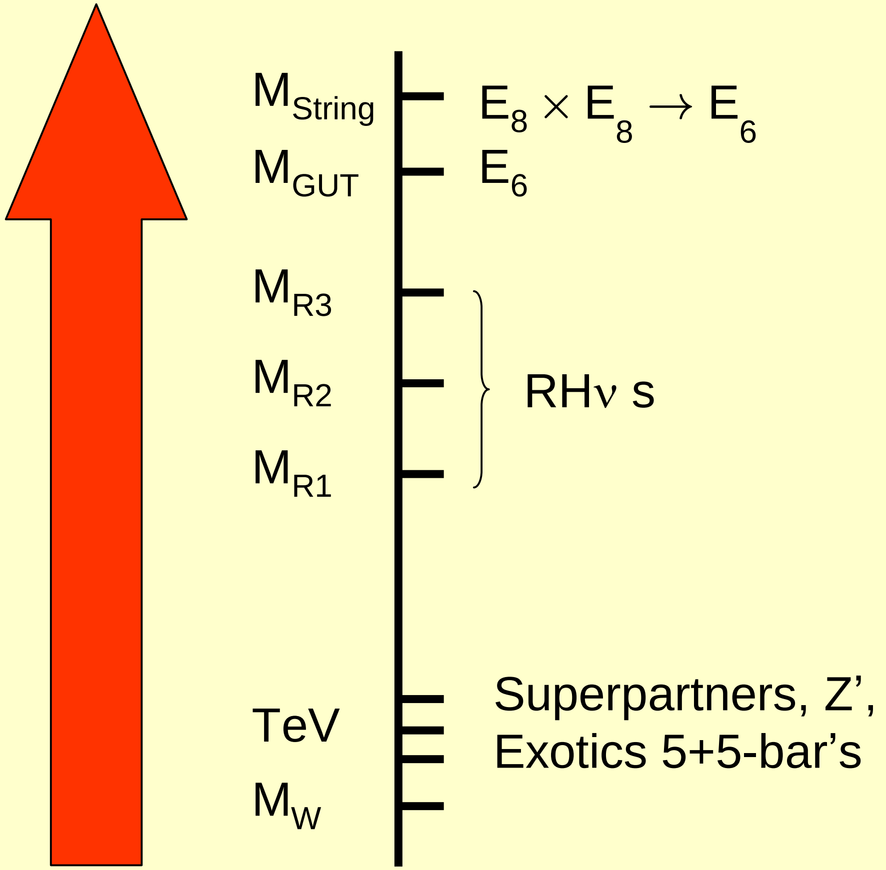
Measure:

- the Z’ mass and width and show that it is from $U(1)_N$ of the E_6SSM with $g' \approx g_1$
- the lightest Higgs boson mass and see if it exceeds the NMSSM limit
- the SUSY and exotic fermion spectrum

Deduce:

- the exotic couplings and SUSY soft masses at low energy
- the SUSY masses at the GUT scale

Running up



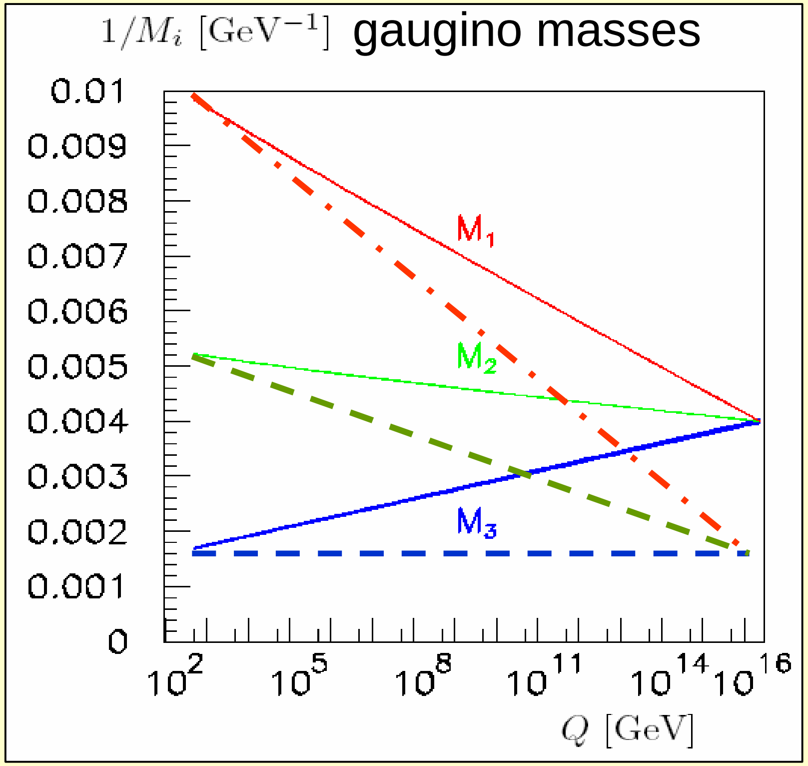
M_{String} — $E_8 \times E_8 \rightarrow E_6$

M_{GUT} — E_6

M_{R3}, M_{R2}, M_{R1} — RHν s

TeV — Superpartners, Z’, Exotics 5+5-bar’s

M_W



Final remarks

Running up the soft scalar masses will be tricky due to:

•Large exotic fermion masses which must be disentangled

•Exotic thresholds in the TeV region

•Extra U(1)$_N$ leading to additional D-term contribution to soft masses (see next talk by David Morrissey)

Such issues are presently under discussion at this workshop (with Gordy Kane, Lisa Everett,..)