BEYOND THE STANDARD MODEL*

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After giving a brief overview of the Standard Model status, I survey physics beyond the Standard Model at the TeV scale, focusing on Technicolour, Little Higgs, Extra Dimensions and Supersymmetry including the MSSM, NMSSM and ESSM.

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1. Standard Model status

The Standard Model (SM) contains one Higgs doublet

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \tag{1.1}$$

with the Higgs potential

$$V = m_H^2 |H|^2 + \tfrac{1}{2}\lambda |H|^2 \,. \tag{1.2}$$

If $m_H^2 < 0$ and $\lambda > 0$ (both conditions not explained in the SM) then the potential is minimised by

$$\langle |H|^2 \rangle = v^2 = -\frac{m_H^2}{\lambda} = (246 \text{ GeV})^2 \,, \tag{1.3}$$

where without loss of generality we may suppose that $\langle \mathrm{Re}(H^0) \rangle = v = 246$ GeV. The 4 degrees of freedom $H^+, H^-, A^0 \equiv \mathrm{Im}(H^0)$ become the longitudinal components of the gauge bosons $W_{\rm L}^+, W_{\rm L}^-, Z_{\rm L}^0$ leaving one physical Higgs boson $h = \mathrm{Re}(H^0)$ with mass squared $m_h^2 = \frac{1}{2}\lambda v^2$.

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The SM suffers acutely from the *hierarchy problem.* Note the tree level relation from Eq. (1.3),

$$m_H^2 = -\lambda v^2 = -\lambda(246\ \text{GeV})^2 \tag{1.4}$$

which at one-loop becomes

$$m_H^2 + \delta m_H^2 = -\lambda(246\ \text{GeV})^2\,. \tag{1.5}$$

The largest correction comes from the top quark loop correction to the Higgs mass (the first diagram in Fig. 3) which gives

$$\delta m_H^2|_{\text{top}} = -\frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = -(900\ \text{GeV})^2 \left(\frac{\Lambda}{3\ \text{TeV}}\right)^2 , \tag{1.6}$$

where fine-tuning is required if the cut-off $\Lambda \gg 1\text{TeV}$. This implies that new physics must show up at the TeV scale, which is still the best motivation for physics beyond the SM (BSM) since the weak scale cannot be explained by anthropic arguments [1]. However there is no firm indication of new physics in precision LEP measurements, which are consistent with a light SM Higgs boson as shown in Fig. 1.

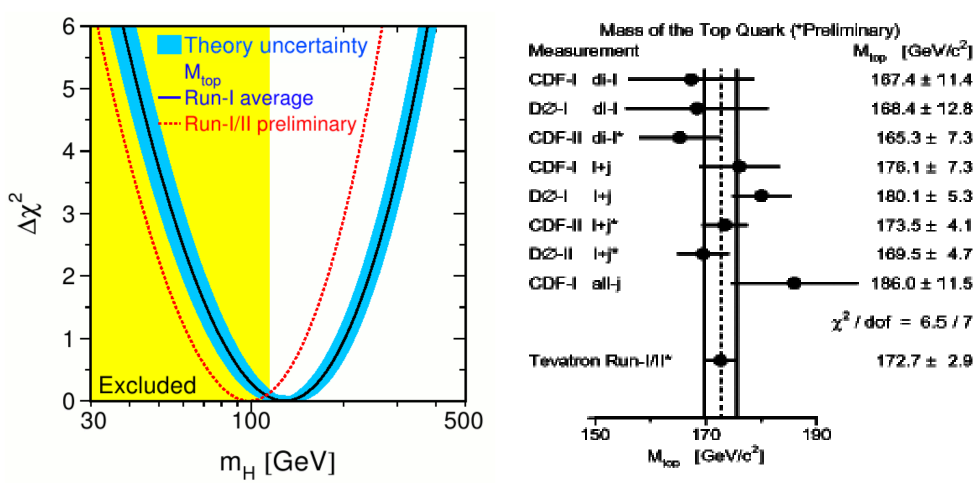


Fig. 1. The latest top quark measurements (right-hand panel) shift the preferred Higgs mass to the left (dotted line in left-hand panel).

Optimistically there are two mild indications of new physics, the first from the measured value of the W boson mass M_W (as a function of the top mass m_t) which seems a bit too high compared to the SM prediction [2], being more consistent with the minimal supersymmetric standard model

(MSSM). The second indication for new physics is from the anomalous magnetic moment of the muon $(g-2)_\mu$ whose average measured value is higher than the theoretical expectation. Both these indicators are shown in Fig. 2 [3].

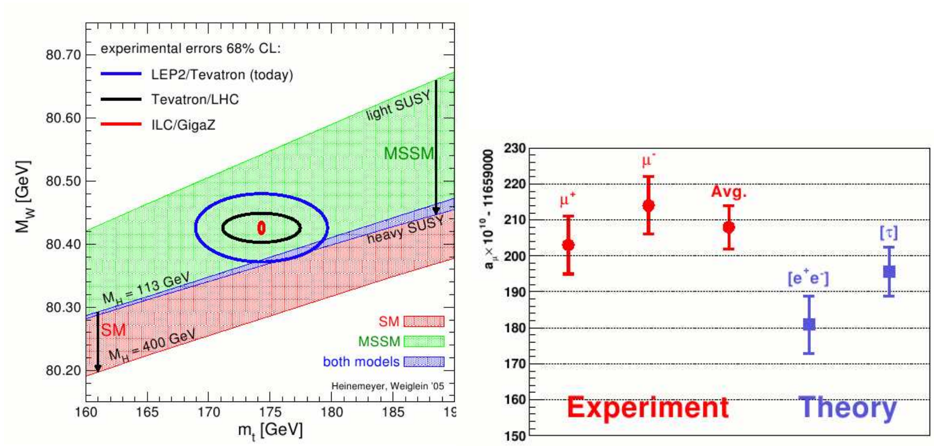


Fig. 2. Two indications for new physics. In the left-hand panel the measured M_W is about one standard deviation too high compared to the SM prediction. In the right-hand panel the measured $(g-2)_\mu$ is two to three standard deviations too high compared to the SM prediction. Both effects can be accounted for in SUSY.

From the bottom-up point of view the hierarchy problem provides the best motivation for new physics at the TeV scale. However the absence of any strong indication for new physics from precision measurements leads to the "LEP Paradox" [4]. A solution to the LEP paradox is to only allow new particles associated with the solution to the hierarchy problem to couple in pairs to the SM particles, and so only appear in loops suppressed by a loop factor of $1/(4\pi)^2$. An example of this would be the MSSM, or indeed any supersymmetric (SUSY) theory with conserved R-parity. However not all theories BSM have a built in solution to the LEP paradox. For example Technicolour theories, Little Higgs models and in general theories with Extra Dimensions at a low scale can all be subject to the LEP paradox, unless they are supplemented by some additional symmetry that only allows the new states to couple in pairs to the SM states. Of these possibilities, shortly to be discussed, it is worth mentioning that there is a quite independent motivation for Supersymmetry and Extra Dimensions from top-down perspective since these are necessary ingredients of string theory [5].

2. Technicolour

Naive Technicolour (TC) is just a scaled-up version of QCD as shown in Fig. 3 (for a review see *e.g.* [6]). The basic starting point is the gauge group (ignoring QCD):

$$\mathrm{SU}(N)_{\mathrm{TC}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}} \tag{2.1}$$

under which one introduces a doublet of technifermions:

$$T = \begin{pmatrix} P \\ M \end{pmatrix}_{\mathrm{L}} = (N, 2, 0), \quad P_{\mathrm{R}} = (N, 1, \tfrac{1}{2}), \quad M_{\mathrm{R}} = (N, 1, -\tfrac{1}{2}) \tag{2.2}$$

The approximate global chiral symmetry is broken at the TeV scale by techniquark condensates $\langle \bar{T}T \rangle \neq 0$:

$$\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \to \mathrm{SU}(2)_{\mathrm{L+R}} \tag{2.3}$$

resulting in three Goldstone bosons (GBs), the technipions, $\Pi^{+}_{\mathrm{TC}}, \Pi^{-}_{\mathrm{TC}}, \Pi^{0}_{\mathrm{TC}}$ which become the longitudinal components of the gauge bosons $W^{+}_{\mathrm{L}}, W^{-}_{\mathrm{L}}, Z^{0}_{\mathrm{L}}$. Unlike the SM there is no left over physical state analogous to the Higgs boson below the TeV scale.

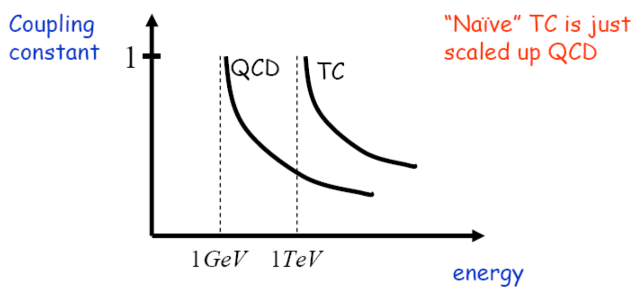


Fig. 3. Naive technicolour.

The major successes of naive TC are that it accounts for the masses of the W, Z and also that it solves the hierarchy problem since there are no elementary scalars.

The major failings of naive TC is that it does not account for fermion masses (for which extended TC is required, leading to complications and problems with flavour changing processes) and also that it conflicts with the precision measurements (the "LEP paradox").

The major predictions of naive TC are technimeson resonances in longitudinal $W_{\mathrm{L}}W_{\mathrm{L}}$ or $W_{\mathrm{L}}Z_{\mathrm{L}}$ scattering at the LHC or ILC. Examples of such resonances are the "heavy Higgs" 0^{-+} resonance η^0_{TC} at about 1.5 TeV, and the "technirho" 1^{--} resonance ρ^0_{TC} at about 2.0 TeV. Technihadrons can also be produced in $\gamma\gamma$ scattering at the PLC.

Some of the problems of naive TC may be addressed in Walking TC, where some of the predictions are also modified (for a review see *e.g.* [6]).

3. Little Higgs

The basic idea of the Little Higgs approach is that the Higgs boson is composite on a scale of say $f \sim 10$ TeV and a light physical Higgs boson emerges as a GB of some usually rather complicated (TC?) theory at $f \sim 10$ TeV. The simplest example I know is due to Martin Schmaltz [9] in which an extra SU(2) singlet quark of charge 2/3 is added, $T_{\mathrm{L}}, T_{\mathrm{R}}$, with a mass $\lambda_t f \bar{T}_{\mathrm{L}} T_{\mathrm{R}}$. A global SU(3) symmetry is broken to SU(2) at the scale f such that:

$$\begin{pmatrix} t_{\mathrm{L}} \\ b_{\mathrm{L}} \\ T_{\mathrm{L}} \end{pmatrix} \rightarrow \begin{pmatrix} t_{\mathrm{L}} \\ b_{\mathrm{L}} \end{pmatrix} + T_{\mathrm{L}} \tag{3.1}$$

and the Higgs doublet H emerges as a GB with GB-like couplings to fermions,

$$\lambda_t \begin{pmatrix} \bar{t}_{\mathrm{L}} & \bar{b}_{\mathrm{L}} & \bar{T}_{\mathrm{L}} \end{pmatrix} e^{iH/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} T_{\mathrm{R}} \,. \tag{3.2}$$

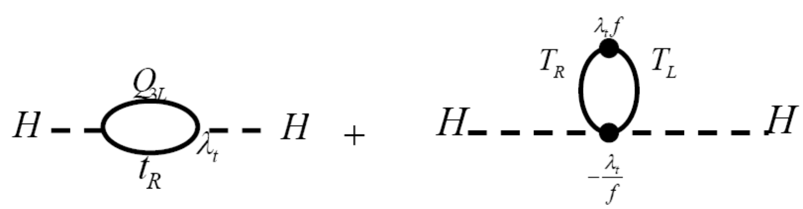
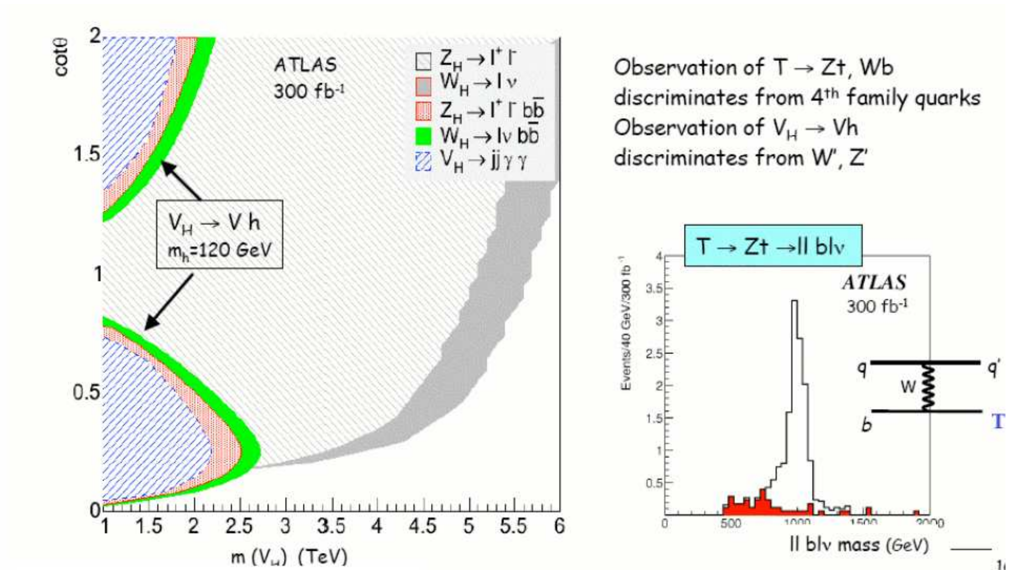


Fig. 4. The T contribution to the Higgs mass cancels the top loop at one-loop. Note the minus sign in the $TTHH$ vertex coming from the second order expansion of the exponential in Eq. (3.2).

The expansion of the exponential in Eq. (3.2) leads to a coupling between T_{L}, T_{R} and two Higgs H fields, which gives a contribution to the Higgs mass radiative correction which cancels the top correction at one-loop order, as seen in Fig. 4, and below,

$$\delta m_H^2|_{\mathrm{top}+T} = -\frac{3}{8\pi^2}\lambda_t^2 \Lambda^2 - \frac{3}{8\pi^2}\left(-\frac{\lambda_t}{f}\right)\lambda_t f \Lambda^2 = 0\,. \tag{3.3}$$

This solves the most severe hierarchy problem from top quark 1-loop diagrams. Additional gauge bosons W_H, Z_H, A_H are required to cancel 1-loop gauge boson contributions. Even with these particles present, the theory cannot cancel two-loop contributions to the Higgs mass, however it is sufficient to stabilise the mini-hierarchy up to the scale f. At the LHC the T quarks can be distinguished from a fourth family of quarks, and the W_H, Z_H can be distinguished from the more usual W', Z' as shown in Fig. 5.



F.Gianotti, Lepton-Photon 2005

Fig. 5. Distinctive signatures of T and W_H, Z_H which provide smoking gun signatures for Little Higgs models at the LHC.

4. Extra dimensions

The existence of extra dimensions is motivated by string/D-brane theory as shown in Fig. 6. The physics of extra dimensions depends on whether the extra dimensions are *flat* or *warped*, and we shall consider each possibility in turn.

In the Arkani-Hamed, Dimopoulos, Dvali (ADD) scenario [7], the extra dimensions are *flat* and only gravity is in the bulk (*i.e.* feels the extra dimensions). The Planck mass $M_{\rm Planck}$ is a derived quantity given in terms of the basic scale of the theory $M_{\rm D}$ (roughly speaking the "string scale") and the compactification scale of the δ extra dimensions R as:

$$M^2_{\rm Planck} = M_{\rm D}^{2+\delta} R^{\delta} \,. \tag{4.1}$$

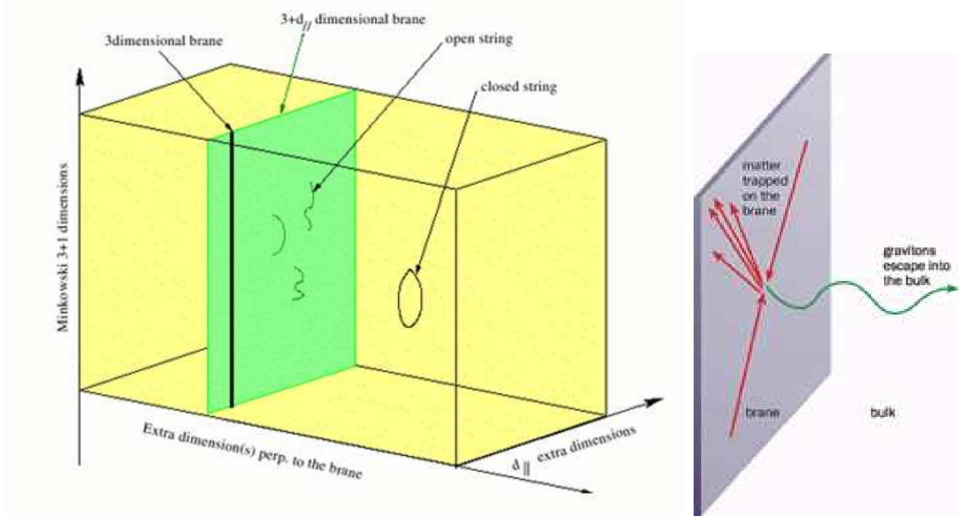


Fig. 6. Typical string/D-brane set ups involve extra dimensions (left panel), and can lead to collider signals with missing energy due to gravitons (closed strings) escaping into the bulk (right panel).

Gravitons in extra dimensions get quantized in mass $m_k \sim k/R$, $k = 1, \ldots, \infty$, leading to a mass splitting $\Delta m \sim 1/R$, with a continuous Kaluza–Klein (KK) tower of massive graviton excitations of typical mass splitting $\Delta m \sim 400$ eV for $\delta = 3$, $m_{\rm D} = 1$ TeV. The collider signal is for two SM particles to collide to give a final state including a graviton G which can escape into the bulk, *e.g.* $qg \to qG$ giving an event topology of jet(s) plus missing E_T (with no final state leptons unlike SUSY), as shown in Fig. 6. The cross section is suppressed the gravitational coupling of G to SM particles, but is enhanced by the multiplicity $N_{\rm KK}$ of gravitons in the KK tower, $\sigma \sim N_{\rm KK}/M^2_{\rm Planck}$, where $N_{\rm KK} \sim (\sqrt{s}/\Delta m)^\delta$ or $N_{\rm KK} \sim (\sqrt{s}R)^\delta$ leading to a cross section of electroweak strength $\sigma \sim \sqrt{s}^\delta/M_{\rm D}^{\delta+2}$. ADD may also be tested at the PLC as shown in Fig. 7.

In the Randall–Sundrum (RS) scenario [7] the extra dimensions are *warped* with again only gravity in the bulk. For example RS1 involves warped extra dimensions with two branes, a Planck brane and a TeV brane on which we live and observe that the strength of gravity is exponentially suppressed, as depicted in Fig. 8. The experimental signal in RS1 consists of TeV graviton resonances as seen on the TeV brane, with KK modes split by the TeV scale. The TeV graviton resonances have spin-2 and may be distinguished from a spin-1 Z' resonance by the angular distribution of their decay products as shown in Fig. 8.

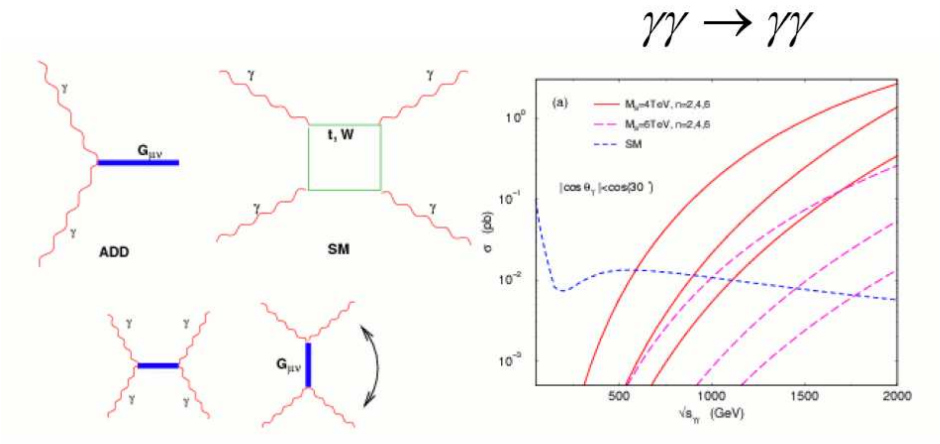


Fig. 7. ADD may also tested at the PLC [8].

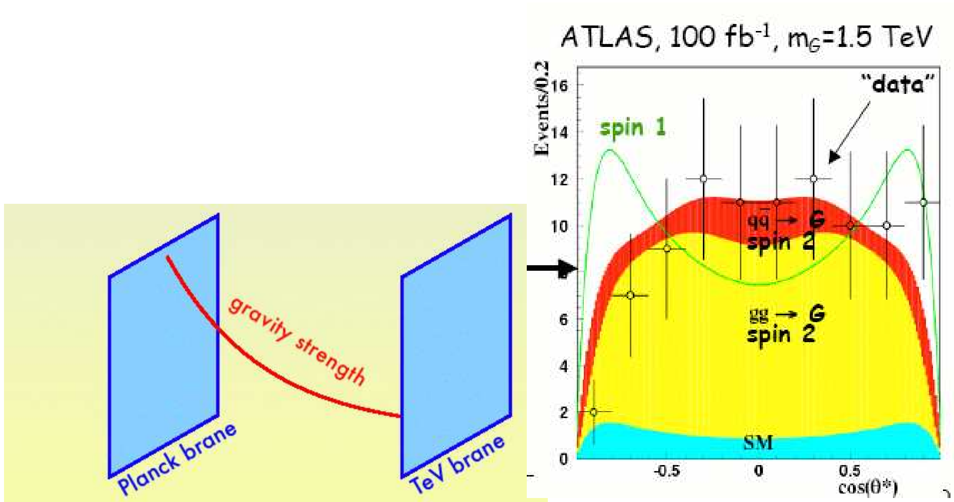


Fig. 8. The RS1 set-up (left panel) predicts spin-2 TeV graviton resonances which can be distinguished from a spin-1 Z' from the angular distribution of the decay products (right panel).

5. SUSY

This was the subject of a dedicated talk [10] so here I only briefly comment on three different SUSY standard models, the MSSM, the NMSSM and the Exceptional SSM. Amongst BSM theories SUSY holds a special place since with conserved R-parity it solves the LEP Paradox. It turns out that MSSM leads to a 2% fine tuning which however can be eliminated in non-minimal models such as the NMSSM and Exceptional SSM.

5.1. MSSM

The particle content of the MSSM [11] contains three families plus a pair of Higgs doublets H_u, H_d with the mass term:

$$W = \mu H_u H_d \tag{5.1}$$

which together with soft mass terms leads to the tree-level Higgs potential

$$\begin{aligned} V \ = \ & \left(m_{H_u}^2 + \mu^2\right)|H_u|^2 + \left(m_{H_d}^2 + \mu^2\right)|H_d|^2 - b(H_u H_d + \text{h.c.}) \\ & + \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u|^2 - |H_d|^2\right) , \end{aligned} \tag{5.2}$$

where the quartic Higgs coupling λ in the SM potential in Eq. (1.2) is now replaced by gauge couplings in Eq. (5.2) leading to a prediction for the Higgs boson mass which including radiative corrections is given by:

$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \Delta \leq (130 \text{ GeV})^2 , \tag{5.3}$$

where $\tan\beta = v_u/v_d$ where $v_i = \langle H_i \rangle$ as usual. A nice feature of the MSSM is radiative electroweak symmetry breaking due to stop and top loops which drives $m_{H_u}^2$ negative at low energies, but leads to a fine tuning of about 2%. The fine tuning and Higgs mass bound in the MSSM are shown in Fig. 9.

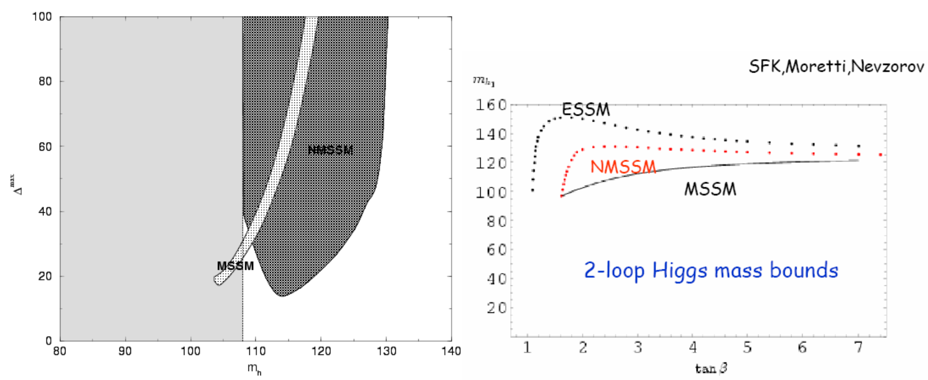


Fig. 9. The left panel shows the fine tuning in the NMSSM compared to the MSSM as a function of the Higgs mass for $\tan\beta = 5$ [12]. The right panel shows the comparison of the Higgs mass bound in the MSSM, NMSSM and ESSM at the two-loop level [13].

5.2. NMSSM

The next-to-minimal SSM (NMSSM) [11] has the particle content of the MSSM plus an extra Higgs singlet S whose vacuum expectation value (VEV) generates the μ term effectively. However to avoid an axion one requires a cubic S^3 term which subsequently leads to a domain wall problem when S develops its VEV. Thus the superpotential is:

$$W = \lambda S H_u H_d + \tfrac{1}{3} k S^3 \,. \tag{5.4}$$

The singlet coupling gives rise to an extra tree-level contribution to the Higgs mass whose lower bound is increased to:

$$m_h^2 \leq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta \leq (140\ \text{GeV})^2 \,, \tag{5.5}$$

where the Higgs mass bound in the NMSSM is shown in Fig. 9. This also leads to a reduction in the fine-tuning to about 10% as compared to the MSSM tuning of about 2% as also shown in Fig. 9.

5.3. ESSM

The Exceptional SSM (ESSM) [13] has a low energy particle content of three families in the 27 of E_6 plus a pair of Higgs doublets plus an extra Z' which eats the axion solving all the problems of the NMSSM. The anomalies associated with the extra $\mathrm{U}(1)'$ are cancelled family by family since E_6 is anomaly free, and the $\mathrm{U}(1)'$ here is a subgroup of E_6 defined uniquely by the requirement that right-handed neutrinos are singlets. The Higgs superpotential is then just:

$$W = \lambda S H_u H_d \tag{5.6}$$

assuming that only one pair of Higgs doublets and one singlet develop VEVs, the remaining states being "non-Higgs". The Higgs mass bound has an additional contribution from the extra $\mathrm{U}(1)'$ associated with the Z'

$$\begin{aligned} m_h^2 &\leq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \frac{1}{4} M_Z^2 \left(1 + \frac{1}{4}\cos 2\beta\right)^2 + \Delta \\ &\leq (160\ \text{GeV})^2 \,. \end{aligned} \tag{5.7}$$

The main effect in increasing the Higgs mass bound is due to the increased allowed value of λ at low energies, due to the extra matter contained in the three 27's which increases the gauge couplings at high energies (for example the QCD coupling now has a zero one-loop beta function). The bounds on the lightest CP-even Higgs boson mass in the MSSM, NMSSM and ESSM are compared in Fig. 9.

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