

TOP-DOWN BEYOND THE STANDARD MODEL REVIEW

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The recent discovery of the Standard Model boson (SMS) and direct searches place new constraints and a new perspective on New Physics models. I mostly review supersymmetric model building, with special emphasizes on predictions of flavor models on superpartner spectra and inverted hierarchy models, mini-split models, low-scale supersymmetry breaking scenario and some string theory inspired low-energy spectra.

1 Introduction

Hierarchy problem guided, or maybe misguided, depending on its own perspective, the physics beyond the Standard Model for the last thirty years. Traditional solutions fall into three categories:

- Low-energy supersymmetry with superpartner masses in the TeV range $M_{\text{SUSY}} \sim \text{TeV}$
 - Strong dynamics like technicolor, Randall-Sundrum models, composite SMS models
 - Low-scale (TeV) strings /quantum gravity with or without supersymmetry $M_{\text{SUSY}} \sim M_* \sim \text{TeV}$.
- Notice that in string theory the scale of supersymmetry breaking is not really predicted to be in the TeV range and it could be much higher. Is is even possible that $M_{\text{SUSY}} \sim M_s \sim 10^{16} - 10^{17} \text{ GeV}$, see the talk of A. Sagnotti¹.

Starting in reverse order, extra dimensions provide spectacular low-energy physics: (sub)mm size gravitational (perpendicular) dimensions, TeV-size and possibly unification of gauge couplings from parallel dimensions, Kaluza-Klein dark matter, etc. Current constraints from micro-gravity experiments set limits on perpendicular dimensions $R_{\perp} < 0.02 \text{ mm}$, whereas direct searches in colliders and indirect precision test sets current limits on parallele dimensions $R_{\parallel}^{-1} > 1.5 - 2 \text{ TeV}$ ². Due to lack of time, I will not discuss further extra dimensional models in what follows.

The second solution to the hierarchy problem, strong dynamics, has its modern incarnation in holographic models. There is a conjectured holographic dictionary³ inspired by the AdS/CFT correspondence :

- 5d states localized on the TeV/infrared brane are composite from a 4d viewpoint. For example the 5d KK states are interpeted as resonances of a four-dimensional strongly-coupled theory.
- 5d states localized on the Planck/UV brane are elementary from a 4d perspective.

In such a framework, geometric localization leads to flavor structure. Current limits from electroweak precision tests and flavor changing neutral current (FCNC) effects put bounds on the infrared (IR) scale of the order of $\Lambda_{\text{IR}} > 3 \text{ TeV}$. A more severe bound $\Lambda_{\text{IR}} > 10 \text{ TeV}$ arises

if there is CP violation in the Yukawa sector. Most of the recent activity in this field was focused on composite models for the scalar model boson⁴, in which gauge symmetry is typically enhanced in the bulk to a higher one, the minimal example being $SU(3) \times SO(5) \times U(1)'$. In this example, the gauge symmetry is broken by boundary conditions to the Standard Model on the Planck brane and to $SU(3) \times SO(4) \times U(1)'$ on the TeV/IR brane. The $SO(4)$ factor on the IR brane contains the custodial symmetry, which will survive as an approximate global symmetry. The SMS is the fifth component of a gauge boson and is a pseudo-goldstone of the coset $SO(5)/SO(4)$. Since it is localized on the IR brane, it behaves as a composite state. The lightest KK states in the model are colored fermions with electric charges $-1/3, 2/3$ and $5/3$, with masses between 0.5 and 1.5 TeV. The electrically charged state with charge $5/3$ decays mainly into $W^+ t \rightarrow W^+ W^+ b$, giving a pair of same sign leptons in the final state.

1.1 SUSY hints from LHC searches and BEH scalar mass

LHC direct supersymmetry searches, the mass and the couplings of the recently discovered Standard Model scalar set new limits on superpartner masses for simple (simplified) supersymmetric models⁵. I think it is fair to say that popular models like minimal supergravity (mSUGRA), constrained Minimal Supersymmetric Standard Model (CMSSM) or minimal gauge mediation with TeV superpartner masses have some difficulties in accomodating the experimental data in a natural way⁶. However, from a ultraviolet (UV) point of view (supergravity, string theory) popular models are rather unpopular, i.e. they are difficult to obtain in specific string models with broken supersymmetry and which address flavor problems and moduli stabilization. It is therefore important to theoretically propose and analyze and to experimentally search for non-minimal supersymmetric models. In what follows we display some non-minimal models; the first of them is motivated by flavor models for fermion mass hierarchies the second by models of moduli stabilization, the third by pushing to the extreme lowest values the scale of supersymmetry breaking and the last one is inspired by local models in recent F-theory constructions.

2 Inverted hierarchy / Natural SUSY models

One old possibility⁷ which became popular recently because of LHC constraints is that of inverted hierarchy or, in its more extreme version, natural SUSY models. In such scenarios, the third generation squarks and gauginos have masses in the TeV range, in particular stops are light. On the other hand, the first two generation squarks are much heavier, typically 10 – 15 TeV. They affect little however the tuning of the electroweak scale, since their contribution to the electroweak scale is multiplied by their corresponding Yukawa couplings. Inverted hierarchy was invented in order to ease the FCNC and CP constraints in supersymmetric models. Early ideas did invoke horizontal non-abelian symmetries for explaining fermion mass hierarchies like $U(2)$ under which first two generations transform as a doublet, whereas the third generation is a singlet⁷. Whereas $U(2)$ models do explain the difference and therefore can accomodate an hierarchy between the first two and the third generation of scalars, they do not actually predict it. To our knowledge, the first class of models in which the inverted hierarchy is really predicted are supersymmetric generalisations of abelian flavor models of the Froggatt-Nielsen type⁸. These models contain an additional abelian gauge symmetry $U(1)_X$ under which the three fermion generations have different charges (therefore the name horizontal or flavor symmetry), spontaneously broken at a high energy scale by the vev of (at least) one scalar field Φ , such that $\epsilon = \langle \Phi \rangle / M \ll 1$, where M is the Planck scale or more generically the scale where Yukawa couplings are generated. Quark mass matrices for example, in such models are given, order of magnitude wise, by

$$h_{ij}^U \sim \epsilon^{q_i + u_j + h_u} \quad , \quad h_{ij}^D \sim \epsilon^{q_i + d_j + h_d} \quad , \quad (1)$$

where q_i (u_i, d_i, h_u, h_d) denote the $U(1)_X$ charges of the left-handed quarks (right-handed up-quarks, right-handed down-quarks, H_u and H_d , respectively). Quark masses and mixings in the

simplest models are given as

$$\begin{aligned} \frac{m_u}{m_t} &\sim \epsilon^{q_{13}+u_{13}} \quad , \quad \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \quad , \quad \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \quad , \quad \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}} \quad , \\ \sin \theta_{12} &\sim \epsilon^{q_{12}} \quad , \quad \sin \theta_{13} \sim \epsilon^{q_{13}} \quad , \quad \sin \theta_{23} \sim \epsilon^{q_{23}} \quad . \end{aligned} \quad (2)$$

A successful fit of the experimental data requires larger charges for the lighter generations

$$q_1 > q_2 > q_3 \quad , \quad u_1 > u_2 > u_3 \quad , \quad d_1 > d_2 > d_3 \quad , \quad (3)$$

one simple example, using as small parameter the Cabibbo angle $\epsilon = \sin \theta_c$, being defined by the charges

$$q_1 = 3 \quad , \quad q_2 = 2 \quad , \quad q_3 = 0 \quad , \quad u_1 = 5 \quad , \quad u_2 = 2 \quad , \quad u_3 = 0 \quad , \quad d_1 = 1 \quad , \quad d_2 = 0 \quad , \quad d_3 = 0 \quad . \quad (4)$$

Scalar soft masses in abelian flavor models are typically of the form

$$m_{ij}^2 = X_i \langle D \rangle + (m_{ij}^F)^2 \quad , \quad (5)$$

where $X_i \langle D \rangle$ are D-term contribution for the scalar of charge X_i , whereas $(m_{ij}^F)^2$ are F-term contributions. D-term contributions were argued to be naturally generated in effective string models, to be positive and, in certain circumstances, to be dominant over the F-term contributions. It is then clear from (3),(4) that precisely because the first generations of fermions are lighter than the third one, the corresponding scalars are *predicted to be heavier*⁹.

Abelian and non-abelian flavor models are complementary in one respect: whereas abelian models naturally predict the inverted hierarchy, which is just an option in the non-abelian case, they do not generically predict approximate degeneracy among the first two generations, unlike their non-abelian cousins. This leads to possible tension with FCNC constraints, which were analyzed in some details in the literature. This means that inverted hierarchy models do generically predict $m_{Q_i} \neq m_{U_i} \neq m_{D_i}$. Since the first two generations are very heavy, we could expect much larger RGE effects than in the universal case $m_{Q_i} = m_{U_i} = m_{D_i}$. Indeed, the RGE's of all scalar soft masses and in particular of the third generation of squarks and of the Higgs scalars depend to some extent of the combination

$$S = \text{Tr}(Y m^2) = m_{H_u}^2 - m_{H_d}^2 + \sum_{i=1}^3 [m_{Q_i}^2 - 2m_{U_i}^2 + m_{D_i}^2 - m_{L_i}^2 + m_{E_i}^2] \quad , \quad (6)$$

which is zero at high-energy in the universal case, where the trace is over the whole spectrum of MSSM states. Interestingly enough, in abelian flavor models with D-term dominance of the type discussed here, the quantity S is equal to

$$S = \text{Tr}(YX) \langle D \rangle \quad . \quad (7)$$

However, $\text{Tr}(YX)$ has to vanish (or to be very small) for phenomenological reasons, as argued in various papers. The running of soft terms and the fine-tuning of the electroweak scale was discussed in¹⁰. It was noticed there that there is a region in parameter space where the stop becomes light and the stop mixing becomes large due to the RG effect coming from the first two generation squarks. Indeed, due to their heavy mass, at two-loops they affect significantly the stop running and have the tendency to render the stop light and even tachyonic.

3 Mini-split SUSY models

Mini-split models are version of split supersymmetry¹¹, with scalar and higgsino masses in the mass range 30 – 500 TeV and gaugino masses in the TeV range, due to a loop suppression. Natural realizations of mini-split scenario arise in "pure gravity mediation"¹³ or "strong moduli

stabilization” models¹⁴, in which scalar masses are fixed by the gravitino mass $m_0 \sim m_{3/2}$, whereas gaugino masses and A-terms are fixed by anomaly mediation

$$M_{1/2}^a = \frac{b_a g_a^2}{16\pi^2} m_{3/2} . \quad (8)$$

Models with strong moduli stabilization were initially proposed in order to solve cosmological problems like vacuum destabilization during inflation and moduli problem in models of moduli stabilization in string theory¹². In such models, moduli masses T and the mass of the field breaking supersymmetry S are much higher than the gravitino mass $m_{3/2}$, which is in the range 30 – 500 TeV. Moduli T have a very small contribution to supersymmetry breaking, which is almost entirely provided by S . If S has a small coupling to MSSM fields in the Kahler potential and superpotential, then the mini-split spectrum with scalar masses close to the gravitino mass and gaugino masses given by anomaly mediation arises naturally. The LSP in this case is the wino, as in anomaly mediation.

In such models, there are strong correlations between:

- the SMS mass and the gravitino mass. For a fixed Standard Model mass, there is an upper limit on the scalar superpartner masses and therefore the gravitino mass. For example, an SMS mass of 125 GeV implies a limit of 50 – 100 TeV on scalar masses.
- the relic density of wino LSP and the gravitino mass, which determine an upper bound $m_{3/2} < 650$ TeV. In this upper limit case, the Higgs mass is on the heavy side, around 128.5 GeV, which is by now disfavored well off the central SMS mass value. For lower scalar masses, compatible with the central value for the SMS mass, the relic density of the LSP winos is too small compared to the needed value $\Omega_\chi h^2 \simeq 0.11$. In this case, one needs other options to increase relic density. One option is simply another dark matter component, for example axions. The second logical option is a non-thermal production of LSP through decays of moduli fields or gravitinos.

4 Low-scale SUSY breaking dynamics

Spontaneous breaking of global supersymmetry leads, through the goldstone theorem, to the existence of a massless fermion, the goldstino. In its gauged version (supergravity), analogously to the Higgs mechanism, the goldstino provides the longitudinal components and is absorbed by the gravitino, which therefore becomes massive. The goldstino is part of a supersymmetric multiplet, which can be chiral or vector. In what follows we consider goldstino to be part of a chiral multiplet $X = (x, G, F_X)$, where its scalar superpartner is called sgoldstino in what follows. The sgoldstino mass m_x depends on the microscopic theory of supersymmetry breaking. In a SUSY theory well below the scale of SUSY breaking $E \ll \sqrt{f}$, SUSY is non-linearly realized. For low scale of supersymmetry breaking $\langle |F_X| \rangle \simeq f \ll m_{sparticles}^2$, where $m_{sparticles}$ is the typical mass scale of superpartner masses, there is always one light fermion in the effective theory, the goldstino G or more precisely the gravitino which couples to matter through its helicity 1/2 components, of mass

$$m_G \sim \frac{f}{M_P} \quad (9)$$

In the decoupling limit $M_P, m_x \rightarrow \infty$, with fixed scale of supersymmetry breaking f , the transverse polarizations of the gravitino decouple, whereas its longitudinal component (goldstino) couplings scale as $1/f$.

There are three qualitatively different cases of goldstino couplings to matter, depending on the masses of superpartners and sgoldstino versus the energy of the process :

- i) Non-SUSY matter spectrum, for example the Standard Model coupled to the goldstino, if

$$E \ll m_{sparticles} , m_x , \sqrt{f} . \quad (10)$$

In this case, there is a non-linear realization of supersymmetry in the matter sector. This is the straightforward generalization of the original Volkov-Akulov lagrangian. All models of

supersymmetry breaking at energies below the scale of supersymmetry breaking enter into this category. If one wants a low-scale of supersymmetry breaking $\sqrt{f} \sim 5\text{--}10$ TeV, one expects the underlying microscopic degrees of freedom, superpartners for field theory models or string states for string theory, to have similar masses. Explicit realizations of models in this class include string models with non-linear supersymmetry with low string scale $M_s \sim \text{TeV}$ ¹⁵. This is not the regime that will be discussed in what follows.

ii) SUSY matter multiplets like in MSSM: quarks-squarks, gauge fields-gauginos, etc, but with non-linear supersymmetry in the goldstino multiplet sector, i.e. heavy sgoldstino

$$m_{\text{particles}} \sim E \ll \sqrt{f}, m_x. \quad (11)$$

In this case, the matter sector has a linearly realized supersymmetry, coupled to the goldstino. This is one energy regime we will consider in what follows, dubbed non-linear MSSM¹⁷. This framework leads, in addition to the standard MSSM soft terms and known goldstino couplings, to new MSSM couplings, and in particular to correction to the SMS potential.

iii) Linear supersymmetric multiplets, for energies such that all superpartners and the goldstino are accessible

$$E \sim m_{\text{particles}}, m_x < \sqrt{f}. \quad (12)$$

This regime corresponds to standard linear realization of supersymmetry in all sectors, with non-renormalizable couplings of the supersymmetry (X) breaking sector to the MSSM sector. The origin of these couplings should be related to strong dynamics at low-energy, coupling the supersymmetric breaking sector to the observable one.

In both cases ii) and iii), not much is known about the explicit construction of such models with low fundamental scale. The minimal ingredients for explicit construction of such models should include a supersymmetry breaking sector at TeV low-energy and a mediation of supersymmetry breaking via strongly-coupled messengers. This is needed in order to overcome the usual lower-bound on supersymmetry breaking scale $\sqrt{f} > 50 - 100$ TeV in gauge mediation models, based on perturbative loop-induced soft terms.

Let us start with the case ii) above, in which supersymmetry is non-linearly realized only in the goldstino sector. In what follows we are using the superfield approach of Rocek¹⁶, in which the Goldstino G can be described by a chiral superfield X , subject to the superfield constraint

$$X^2 = 0. \quad (13)$$

The constraint is solved by

$$X = \frac{GG}{2F_X} + \sqrt{2} \theta G + \theta\theta F_X, \quad (14)$$

where the auxiliary field F_X is to be eliminated via its field equations.

Usually we parameterize SUSY breaking in supersymmetric extensions of the Standard Model by coupling matter fields to a spurion with no dynamics $S = \theta^2 m_{\text{soft}}$. The main difference in the context of the non-linear MSSM is the replacement of the spurion with a dynamical constrained superfield $S \rightarrow \frac{m_{\text{soft}}}{f} X$. This reproduces the MSSM soft terms, but it contains simultaneously the goldstino couplings to matter. Moreover, it adds new dynamics. The fact that F_X is a dynamical auxiliary field, determined as usual through its algebraic field equations, generates new couplings :

$$-\bar{F}_X = f + \frac{B}{f} h_1 h_2 + \frac{A_u}{f} \tilde{q} \tilde{u} h_2 + \dots \quad (15)$$

The formalism contains in a very compact, superfield form, the goldstino couplings to matter. The one-goldstino couplings are on-shell equivalent to the standard couplings based on the original supercurrent coupling of the goldstino $\frac{1}{f} \partial_\mu G J^\mu$. For processes in which some particles

are off-shell, comparison with standard approach was checked in some instances but, to my knowledge, not completely.

In this formalism, all couplings to the Goldstino are proportional to soft-terms. The lagrangian is schematically

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_X + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g \quad , \quad \text{where} \quad (16)$$

$$\begin{aligned} \mathcal{L}_H &= \sum_{i=1,2} \frac{m_i^2}{f^2} \int d^4\theta \, X^\dagger X \, H_i^\dagger e^{V_i} H_i \, , \\ \mathcal{L}_m &= \sum_{\Phi} \frac{m_\Phi^2}{f^2} \int d^4\theta \, X^\dagger X \Phi^\dagger e^V \Phi \, , \quad \Phi = Q, U_c, D_c, L, E_c \\ \mathcal{L}_{AB} &= \frac{B}{f} \int d^2\theta \, X H_1 H_2 + \left(\frac{A_u}{f} \int d^2\theta \, X Q U_c H_2 + \dots \right) \\ \mathcal{L}_g &= \sum_{i=1}^3 \frac{1}{16 g_i^2 \kappa} \frac{2 m_{\lambda_i}}{f} \int d^2\theta \, X \, \text{Tr} [W^\alpha W_\alpha]_i + h.c. \end{aligned} \quad (17)$$

This lagrangian is still a parametrization and not an explicit model of supersymmetry breaking. The origin of soft terms is not specified and their values are just parametrized, like in MSSM with a spurion. But such lagrangian contains more than the MSSM lagrangian with soft terms. In addition to goldstino couplings, matter terms coming from solving for F_X are new; they do not come from a standard Volkov-Akulov non-linear supersymmetry realization prescription. The most interesting example of a new coupling is the scalar potential, which is modified compared to MSSM and is given by:

$$\begin{aligned} V &= (|\mu|^2 + m_1^2) |h_1|^2 + (|\mu|^2 + m_2^2) |h_2|^2 + (B h_1 \cdot h_2 + \text{h.c.}) \\ &+ \frac{g_1^2 + g_2^2}{8} [|h_1|^2 - |h_2|^2]^2 + \frac{g_2^2}{2} |h_1^\dagger h_2|^2 + \frac{1}{f^2} \left| m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B h_1 \cdot h_2 \right|^2 . \end{aligned} \quad (18)$$

The last term in (18) is new compared to MSSM. It contains new quartic couplings not related to gauge couplings like in the usual MSSM potential, but rather related to the soft terms and the scale of supersymmetry breaking. It is generated by integrating out the sgoldstino multiplet and its physical interpretation should be related to new couplings of the Higgs multiplet to the (low-scale) supersymmetry breaking sector.

It was shown¹⁷ that this framework can raise the Standard Model boson mass up to the ATLAS and CMS values by the tree-level contributions of the goldstino auxiliary field displayed in (18). On the other hand, the one-goldstino couplings to the MSSM fields that one finds contain the usual supercurrent couplings. This is obtained in the minimal setup containing MSSM plus the minimal set of operators needed to parameterize the soft-breaking terms¹⁷. One show that the effect of additional higher-dimensional/derivative operators is to correct existing MSSM couplings λ in the following generic way¹⁸,

$$\lambda = \lambda_{MSSM} \left(1 + \sum_n c_n \left(\frac{M_{SUSY}}{\sqrt{f}} \right)^n \right) , \quad (19)$$

where $M_{SUSY} \sim M_{sparticles}$ is the scale of supersymmetry breaking in the observable sector, generating particle masses. Since by consistency $M_{sparticles} < \sqrt{f}$, the correction to an existent tree-level MSSM coupling is small. Some couplings however, which are loop-generated or small at tree-level can receive important corrections, such as the SMS self-coupling or the SMS decay into two photons $h \rightarrow \gamma\gamma$. The renormalizable tree level SMS couplings can be parametrized as

$$\mathcal{L}_{ren} = -c_t \frac{m_t}{v} h t \bar{t} - c_c \frac{m_c}{v} h c \bar{c} - c_b \frac{m_b}{v} h b \bar{b} - c_\tau \frac{m_\tau}{v} h \tau \bar{\tau} + c_Z \frac{m_Z^2}{v} h Z^\mu Z_\mu + c_W \frac{2m_W^2}{v} h W^{+\mu} W_\mu^- . \quad (20)$$

In the MSSM decoupling limit: $c = 1$ and the c^{loop} -coefficients equals the SM ones. In case iii) above with light sgoldstino scalar, there is an interesting phenomenon, a sgoldstino-higgs mass mixing, which leads to possible enhancement in $h \rightarrow \gamma\gamma$ ^{19,18}. It comes from

$$\mathcal{L} \supset x \left(-\frac{m_i^2}{f^2} F_X^\dagger h_i^\dagger F_i + \frac{B}{f} (F_1 h_2 + h_1 F_2) - \frac{M_a}{4f} (F^{k\mu\nu} F_{\mu\nu}^k)_a \right) + h.c. - |x|^2 \left(\frac{m_i^2}{f^2} |F_i|^2 + m_X^2 \right). \quad (21)$$

If sgoldstino x is heavy we can use its e.o.m. (zero-momentum limit), to integrate it out. We obtain

$$-\frac{M_a}{4m_X^2 f^2} (F^{k\mu\nu} F_{\mu\nu}^k)_a \left(m_i^2 h_i^\dagger F_i + B(F_1 h_2 + h_1 F_2) \right) + h.c. \quad (22)$$

This generates an effective interactions between h and the gauge field strengths. Then

$$c_\gamma = c_\gamma^{\text{loop}} + c_\gamma^{\text{sgold}}, \quad c_g = c_g^{\text{loop}} + c_g^{\text{sgold}}, \quad c_{Z\gamma} = c_{Z\gamma}^{\text{loop}} + c_{Z\gamma}^{\text{sgold}}, \quad (23)$$

where,

$$\begin{aligned} c_\gamma^{\text{sgold}} &= -\frac{4\pi v^2 \mu}{f^2 m_X^2 \alpha_{\text{EM}}} (M_1 \cos^2 \theta_w + M_2 \sin^2 \theta_w) \Delta \\ c_{Z\gamma}^{\text{sgold}} &= -\frac{4\pi v^2 \mu \cos \theta_w \sin^2 \theta_w}{f^2 m_X^2 \alpha_{\text{EM}}} (M_1 - M_2) \Delta, \quad c_g^{\text{sgold}} = -\frac{6\pi v^2 \mu}{f^2 m_X^2 \alpha_S} M_3 \Delta. \end{aligned} \quad (24)$$

The factor Δ is written explicitly in ¹⁸ and equals $\Delta \rightarrow \mu^2 \sin 2\beta$ in the MSSM decoupling limit. We can then use the experimental bound on the gluino mass, which enters the c_g^{sgold} to estimate how much the Higgs couplings to $\gamma\gamma$ and $Z\gamma$ can be enhanced. If we do not want gluon fusion to deviate from SM value by more than around 30%, i.e. $|c_g^{\text{sgold}}| \leq 0.14 \cdot |c_g^{\text{SM}}|$, then there is a lower limit on the supersymmetry breaking scale. By combining this with the expression for c_γ^{sgold} gives the bound $|c_\gamma^{\text{sgold}}| \leq 1.37 \left| \frac{M_{12}}{M_3} \right|$, where $M_{12} = M_1 \cos^2 \theta_w + M_2 \sin^2 \theta_w$. Assuming the signs of μ and M_{12} are such that the sgoldstino mixing contribution is constructive, this implies

$$\frac{\Gamma_{h\gamma\gamma}}{\Gamma_{h\gamma\gamma}^{\text{SM}}} = \left| \frac{c_\gamma}{c_\gamma^{\text{SM}}} \right|^2 \leq \left| 1 + 0.21 \frac{M_{12}}{M_3} \right|^2. \quad (25)$$

5 String and F-theory inspired SUSY spectra

Recently there was an intense activity in constructing F-theory models of particle physics, especially in building $SU(5)$ GUT models with additional $U(1)$ gauge symmetries ²⁰. In such models, the GUT gauge group is localized on a D7 brane wrapping a four space called the GUT divisor. Typically there are magnetic type fluxes in the internal space along the hypercharge generator and in the additional $U(1)$ gauge factors. Hypercharge flux is needed to break $SU(5)$ down to the Standard Model gauge group, whereas $U(1)$ fluxes generate the chirality necessary in order to reproduce the MSSM spectrum. The internal volume of the GUT brane is described by a modulus field, called GUT modulus in what follows. The hypothesis made by the recent papers ²¹ is that this modulus is responsible for breaking supersymmetry. In this case, scanning over one parameter flux, they found that soft terms generated at the string scale satisfy the relations:

$$M_{1/2} = m_0 = -\frac{2}{3}A = -B. \quad (26)$$

In particular, $A \simeq -2m_0$ and, after running from the fundamental string scale down to the TeV scale, this pattern of soft masses generate a nearly maximal stop mixing needed in order to increase the Higgs mass to 125 GeV with relatively light stop masses. This example shows that it is possible to get a nearly maximal stop mixing naturally from a microscopic theory like string theory.

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