Natural anomaly-mediation from the landscape with implications for LHC SUSY searches

Dibyashree Sengupta

INFN, Laboratori Nazionali di Frascati

Istituto Nazionale di Fisica Nucleare

ICHEP 2024

Phys.Rev.D 109 (2024) 3, 035011, arXiv:2311.18120 in collaboration with

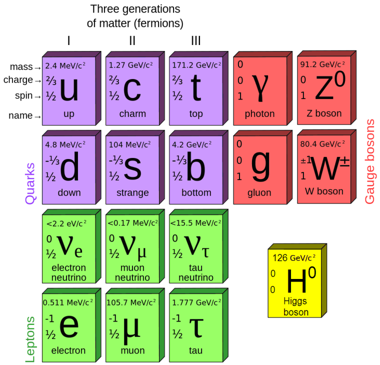
Howard Baer, Vernon Barger, Jessica Bolich and Juhi Dutta

July 18, 2024

Overview

1. The Standard Model and its drawbacks
2. Supersymmetry
   - Naturalness in SUSY
   - Soft SUSY breaking
3. Natural anomaly mediatied SUSY breaking model (nAMSB)
   - nAMSB from the Landscape
   - LHC-allowed nAMSB parameter space
   - Prospects for nAMSB AT Run3 and HL- LHC searches
4. Conclusion

The Standard Model and its drawbacks



Particle Spectrum of The Standard Model

Although the Standard Model is the most celebrated theory till today, it cannot explain nature completely. It has certain drawbacks as follows:

- The big hierarchy problem
- The lack of a DM candidate
- Radiative breakdown of electroweak symmetry

and several others.

Weak Scale Supersymmetry is one of the most attractive ways to deal with these problems.

Why Supersymmetry?

- Each Standard Model particle has a *Superpartner* whose spin vary by 1/2 with respect to its corresponding SM particle.

- Superpartner of a boson (fermion) is a fermion (boson)

- Quadratic Divergences in Higgs Mass due to each SM particle is cancelled by its *Superpartner*. This idea can be illustrated to explain the stability of scalar masses which is one of the main motivations of SUSY.

Naturalness

However, **no** sparticles have been seen in LHC yet.

$$m_{sparticles} >> m_{SMparticles} \implies \textbf{Is SUSY Unnatural?}$$

The notion of *Practical Naturalness* states that

> *An Observable $\mathcal{O}$ is natural if all independent contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.*

The measure of Naturalness is the Electroweak fine-tuning parameter (Δ_{EW}) which is defined as

$$\Delta_{EW} = max_i |C_i|/(M_Z^2/2) \quad (1)$$

Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \quad (2)$$

A SUSY model is said to be natural if $\Delta_{EW} < 30$. This choice $\Delta_{EW} < 30$ is not ad-hoc, rather it arises from anthropic requirements for life to sustain.

Soft SUSY breaking

$m_{sparticles} >> m_{SMparticles} \implies$ SUSY broken $\implies$ Soft SUSY breaking (SSB) terms $\implies$ Log divergences introduced

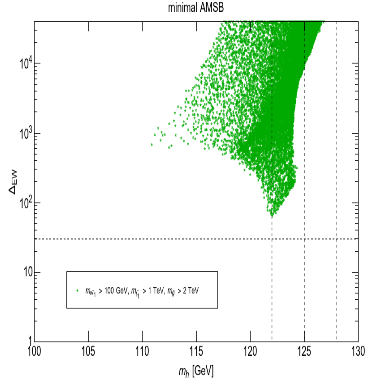
How does these SSB terms originate ?

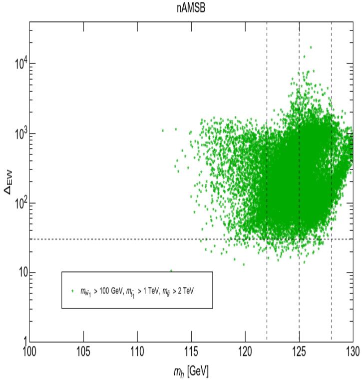
- Gravity-mediated SUSY breaking
- Anomaly-mediated SUSY breaking (AMSB)
- Gauge-mediated SUSY breaking
- Gaugino-mediated SUSY breaking

AMSB model: In this model, one-loop contribution to the SSB parameters originates in the super-Weyl anomaly always when SUSY is broken. This mechanism is called the **anomaly-mediated SUSY breaking**.

Minimal and Natural AMSB Model

Phys.Rev.D 98 (2018) 1, 015039 by H. Baer, V. Barger and **D. S.**





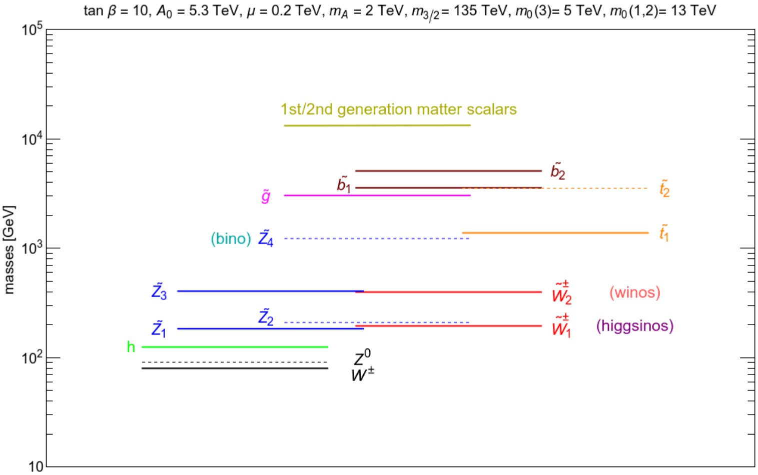
Parameter: m_0, $m_{3/2}$, tan β and sign(μ)

Parameter: $m_0(1,2)$, $m_0(3)$, $m_{3/2}$, A_0, tan β, μ and m_A

Mass spectra in nAMSB

The natural generalized AMSB (nAMSB) model parameter set :

$$m_0(1,2),\ m_0(3),\ m_{3/2},\ A_0,\ \tan\beta,\ \mu \text{ and } m_A$$



A typical superparticle mass spectrum generated from natural generalized anomaly mediation (nAMSB)

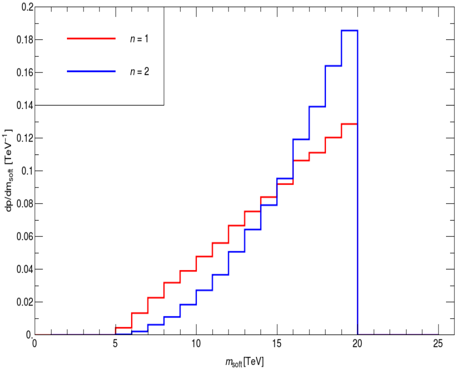
LANDSCAPE

Nature prefers the soft SUSY breaking terms to be as high as possible unless disfavored by anthropic requirements for sustaining life.

Why Landscape ? Because it has successfully explained why the experimentally measured value of cosmological constant (CC) Λ so tiny ($\Lambda \simeq 10^{-120} m_P^2$) when there is no known symmetry to suppress its magnitude.

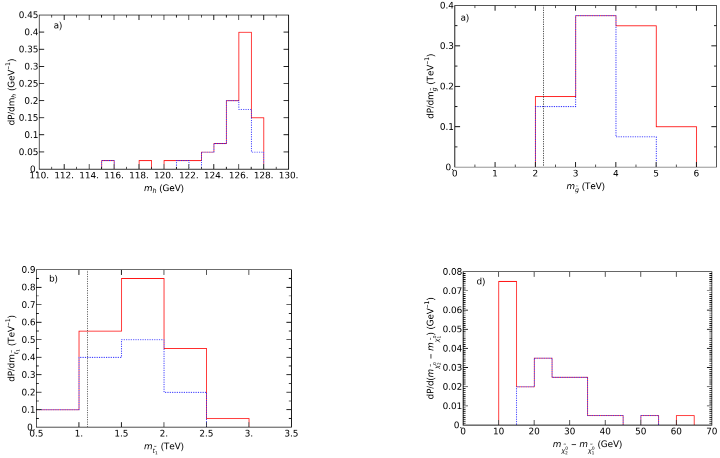
PARAMETER SPACE SCAN:

- $m_{3/2}$: 80-400 TeV
- $m_0(1,2)$: 1-20 TeV
- $m_0(3)$: 1-10 TeV
- A_0 : 0 - $\pm$20 TeV
- m_A : 0.25-10 TeV
- tan β : 3-60 (flat scan)
- $\mu = 250$ GeV



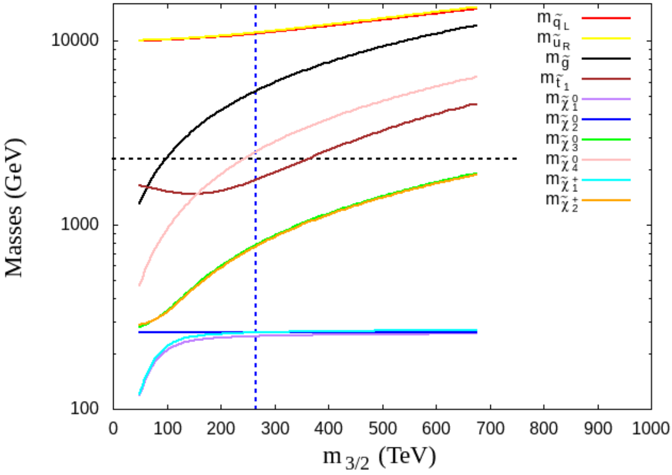
These soft terms with non-uniform distribution at the GUT scale are used to generate masses of sparticles at the weak scale through RGE running and an upper bound is obtained by requiring $\Delta_{EW} < 30$.

nAMSB from the Landscape



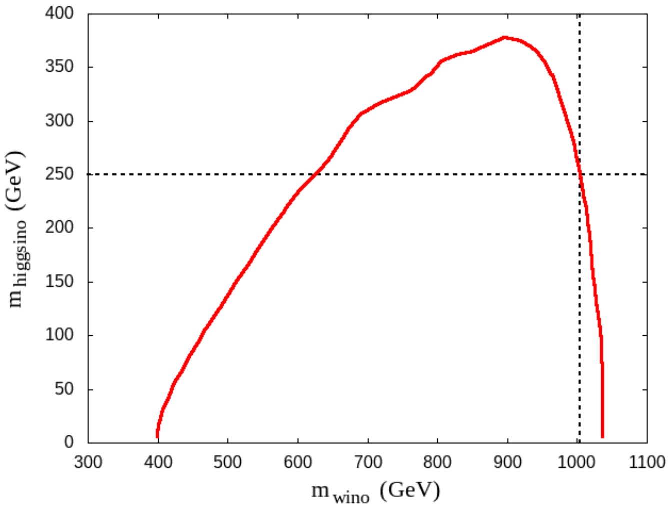
The red histogram shows the full probability distribution while the blue-dashed histogram shows the remaining distribution after LHC sparticle mass limits are imposed.

nAMSB model lines



Plot of sparticle masses vs.$m_{3/2}$ along the nAMSB model line: tan $\beta = 10$, $m_0(1,2) = 10$ TeV, $m_0(3) = 5$ TeV, $A_0 = 6$ TeV. Black dashed line: $m_{\tilde{g}} \geq 2.3$ TeV $\implies m_{3/2} \geq 90$ TeV; Blue dashed line: Upper limit on $m_{3/2}$ ($m_{3/2} \leq 265$ TeV) obtained from Naturalness($\Delta_{EW} < 30$).

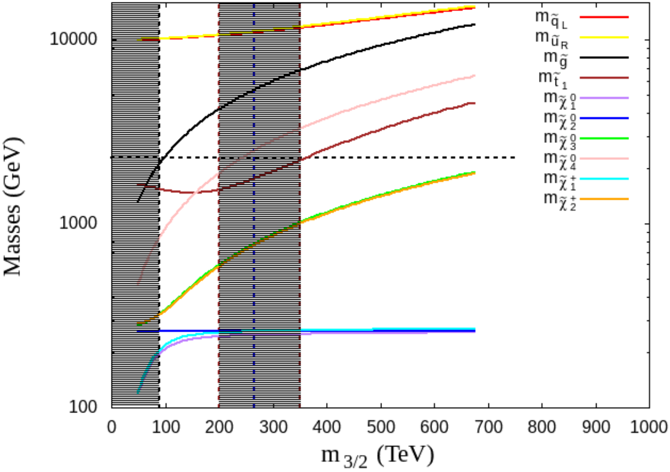
Constraints from m_{wino}



Allowed/excluded regions of m(wino) vs. m(higgsino) plane from ATLAS analysis of EWino pair production followed by decay to W, Z, h with decay to boosted dijets. From this plot we would expect that the range m_{wino} : 625 - 1000 GeV would be ruled out, corresponding to a range of $m_{3/2}$: 200 - 350 TeV.

LHC-allowed nAMSB parameter space

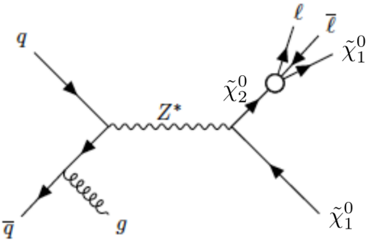
$m_{3/2}$: **90 - 200 TeV $\Longrightarrow$ Lower limit from $m_{\tilde{g}}$; Upper limit from** m_{wino}



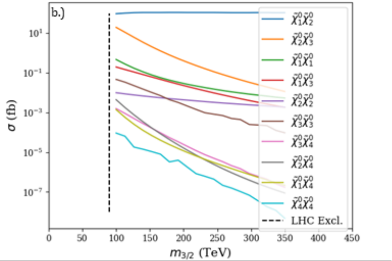
Regions of the chosen nAMSB model-line along with various sparticle masses allowed/excluded by the LHC.

Prospects for nAMSB AT Run3 and HL-LHC

Soft opposite-sign dilepton, jet+MET search: Particularly compelling signal due to large $pp \longrightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$ cross-section. What makes this signal even more compelling in nAMSB as compared to gaugino mass unification or mirage mediation is the relatively larger mass gap between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ (15-60 GeV)



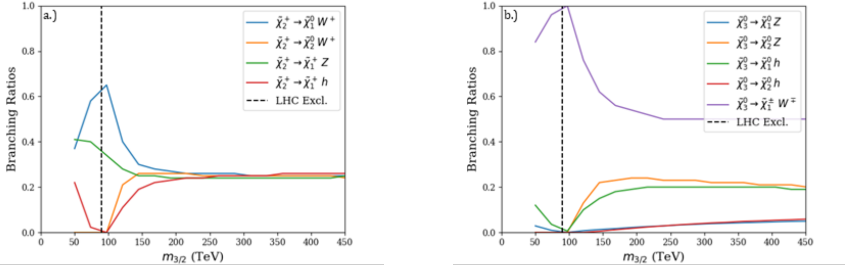
(a) Feynman diagram for opposite-sign dilepton+jets+MET signature from higgsino pair production at hadron colliders



(b) Plot for neutralino pair production vs $m_{3/2}$ along the nAMSB model line

Prospects for nAMSB AT Run3 and HL-LHC

LHC wino pair production search: In nAMSB, the winos are lighter than binos as opposed to the other types of natural SUSY models. Hence, a lucrative channel to look into would be the same-sign diboson (SSdB) signature via wino pair production ($pp \longrightarrow \tilde{\chi}_3^0 \tilde{\chi}_2^{\pm}$) where each wino decays to a higgsino($\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_1^{\pm}$) and a $W^{\pm}$ boson.



(a) (b)

Plot of charged and neutral wino branching fractions a) BF($\tilde{\chi}_2^+$) and b) BF($\tilde{\chi}_3^0$) vs $m_{3/2}$ along the nAMSB model line

Conclusion

- Anomaly-mediated SUSY breaking is extremely well-motivated.
- The minimal AMSB model is ruled out because
  - cannot simultaneously generate $m_h \sim 125$ GeV and $\Delta_{EW} \leq 30$.
  - presence of wino-like WIMP dark matter which seems excluded by direct- and indirect-dark matter detection limits
- While natural AMSB model can accommodate $m_h \sim 125$ GeV while being natural. Also, in nAMSB though wino is the lightest gaugino, the LSP and hence the dark matter is higgsino-like. The dark matter issues can be resolved by postulating mixed axion-higgsino-like WIMP dark matter which is mainly coposed of axions.

Conclusion

- In this work, we investigated some detail LHC constraints on natural AMSB models.

- LHC gluino mass limits require a gravitino mass $m_{3/2} > 90$ TeV. Recent ATLAS results from wino searches seem to rule out $m_{3/2}$: 200-350 TeV, while naturalness require $m_{3/2} < 265$ TeV. All these constraints combined yields $m_{3/2}$: 90-200 TeV.

- Such a small mass window may be either discovered or falsified at HL-LHC through:
  - OSDLJMET searches from higgsino pair production. Some excess above SM background in the OSDLJMET channel already seems to be present in both ATLAS and CMS data.
  - Same-sign diboson searches which are a characteristic signature of wino pair production followed by wino decay to W +higgsino.

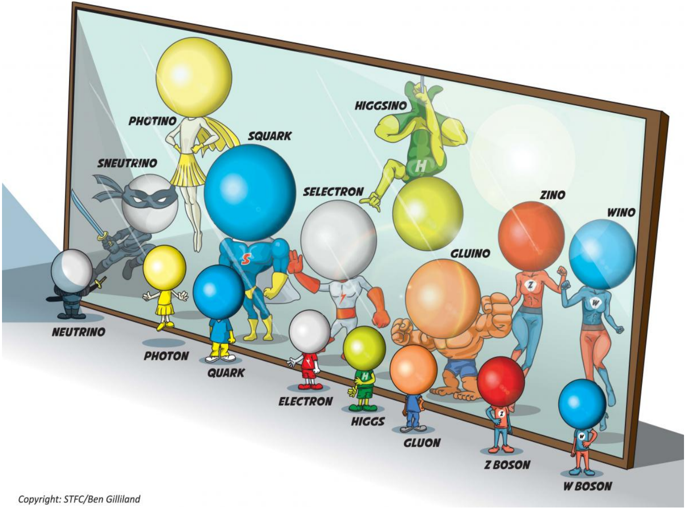
Thank You

Questions ?

Back Up Slides

Basics of Supersymmetry

- Each Standard Model particle has a *Superpartner* whose spin vary by 1/2 with respect to its corresponding SM particle.
- Superpartner of a boson (fermion) is a fermion (boson)
- Quadratic Divergences in Higgs Mass due to each SM particle is cancelled by its *Superpartner*. This idea can be illustrated to explain the stability of scalar masses which is one of the main motivations of SUSY.



SUSY Particles

http://united-states.cern/physics/supersymmetry

Naturalness

$$m_{sparticles} >> m_{SMparticles}$$

LHC Limits : $m_{\tilde{g}} > 2.3\ TeV$, $m_{\tilde{t}_1} > 1.3\ TeV \implies$ **Is SUSY Unnatural?**

The notion of *Practical Naturalness* states that

> *An Observable $\mathcal{O}$ is natural if all independent contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.*

The measure of Naturalness is the Electroweak fine-tuning parameter (Δ_{EW}) which is defined as

$$\Delta_{EW} = max_i |C_i| / (M_Z^2/2) \tag{3}$$

Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{4}$$

A SUSY model is said to be natural if $\Delta_{EW} < 30$. This choice $\Delta_{EW} < 30$ is not ad-hoc, rather it arises from anthropic requirements for life to sustain.

Naturalness

$\mathcal{O} = \mathcal{O} +$ b - b
When evaluating fine-tuning, it is not permissible to claim fine-tuning of dependent quantities one against another.
The Electroweak Measure Δ_{EW}

$$\Delta_{EW} = max_i|C_i|/(M_Z^2/2) \tag{5}$$

Where, C_i is any one of the parameters on the RHS of the following equation :

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{6}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{7}$$

Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \tag{8}$$

The weak scale SUSY parameters $m_{H_u}^2$ and μ^2 can be replaced in terms of GUT scale parameters as follows :

$$\begin{aligned}
m_Z^2 \simeq & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 \\
& - 0.42M_2^2 + 0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t \\
& - 0.15M_2A_t - 0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\
& - 1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& + 0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
& + 0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
& + 0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2
\end{aligned}$$

Then Δ_{BG} is calculated as :

$$\Delta_{BG} \equiv max_i\,[c_i] \quad \text{where} \quad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right| \tag{9}$$

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2(weak) + m_{H_u}^2(weak) + mixing + rad.corr. \qquad (10)$$

In terms of some high-energy cut-off scale Λ,

$$m_{H_u}^2(weak) = m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \qquad (11)$$

$\delta m_{H_u}^2$ is calculated from the renormalization group equation (RGE) by setting several terms in $dm_{H_u}^2/dt$ (with $t = \log Q^2$) to zero so as to integrate in a single step:

$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/m_{soft}^2\right). \qquad (12)$$

Taking $\Lambda \sim m_{GUT}$, a simplified formula to calculate Δ_{HS} is :

$$\Delta_{HS} = \delta m_{H_u}^2/m_{H_u}^2 \qquad (13)$$

Upper bounds from Δ_{BG} and Δ_{HS}

mass	upper limit	source
$m_{\tilde{g}}$	< 400 GeV	BG(1987)
$m_{\tilde{u}_R}$	< 400 GeV	BG(1987)
$m_{\tilde{e}_R}$	< 350 GeV	BG(1987)
$m_{\tilde{\chi}_1^{\pm}}$	< 100 GeV	BG(1987)
$m_{\tilde{\chi}_1^0}$	< 50 GeV	BG(1987)
m_h	< 115 GeV	CGR(2009)
$m_{\tilde{t}_{1,2},\tilde{b}_1}$	< 500 GeV	PRW,BKLS(2011)

Table: Upper bounds on sparticle and Higgs boson masses from 10% naturalness using Δ_{BG} within multi-parameter SUSY effective theories. We also include bounds from Δ_{HS}.

Δ_{EW}, Δ_{HS}, Δ_{BG}

$\mathcal{O} = \mathcal{O} +$ b - b

When evaluating fine-tuning, it is not permissible to claim fine-tuning of dependent quantities one against another.

The Electroweak Measure Δ_{EW}

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{14}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{15}$$

Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \tag{16}$$

The Large Log Measure Δ_{HS}

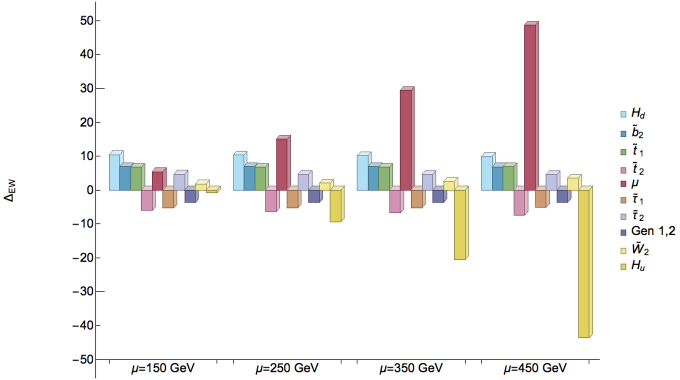
$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \quad (17)$$

where Λ is a high energy scale up to which MSSM is valid. Λ can be as high as m_{GUT} or even m_P.
A simple fix for Δ_{HS} is to regroup the dependent terms as follows :

$$m_h^2 \approx \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) \quad (18)$$

This regrouping now leads back to Δ_{EW} measure because now $(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) = m_{H_u}^2(Weak)$.

arXiv : 1702.06588 by H. Baer et. al.



Top ten contributions to Δ_{EW} from NUHM2 model benchmark points with $\mu = 150$, 250, 350 and 450 GeV.

$\Delta_{EW} < 30$ requires $\mu \sim$ 100-350 GeV.

minimal AMSB

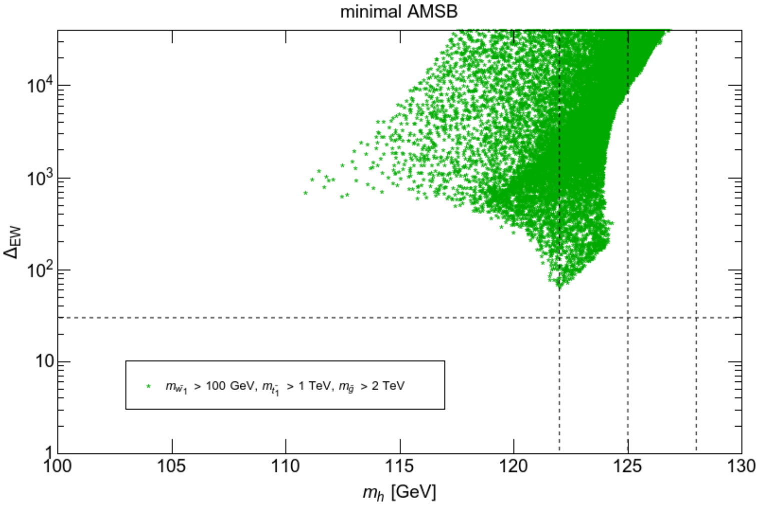
With the usual construct of the minimal AMSB model, it was seen that the slepton mass turns out to be tachyonic leading to electric charge breaking minimum for the scalar potential. To solve this problem it was suggested to add bulk contribution m_0 to scalar mass.

The minimal AMSB model is characterized by the parameter set :

$$m_0,\ m_{3/2},\ \tan\beta \text{ and } \mathrm{sign}(\mu)$$

m_0 : 1-10 TeV
$m_{3/2}$: 80-1000 TeV
tan β : 4-58
$\mu > 0$

minimal AMSB



Plot of points from a scan over mAMSB parameter space in the Δ_{EW} vs. m_h plane.

AMSB with bulk Higgs soft masses

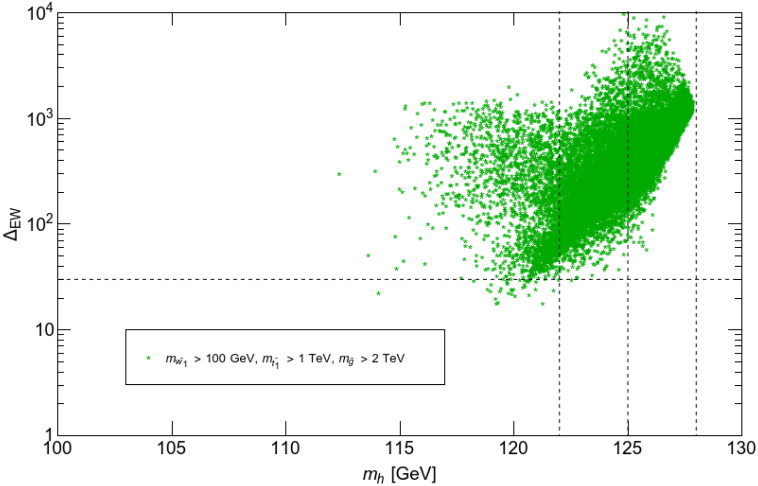
We modify the model by introducing separate bulk Higgs masses $m_{H_u}^2$ and $m_{H_d}^2$ since these live in different gut multiplets from matter superfields. Then we can trade m_{H_u} and m_{H_d} for μ and m_A at weak scale.

Thus this modified AMSB model is characterized by the parameter set :

$$m_0(1,2),\ m_0(3),\ m_{3/2},\ \text{tan}\ \beta,\ \mu\ \text{and}\ m_A$$

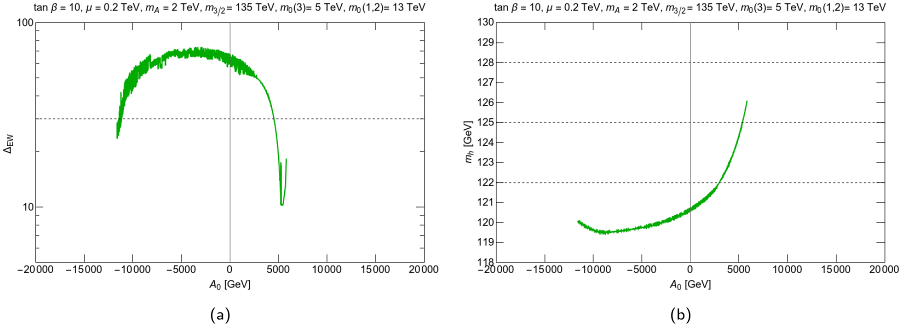
m_0(3) : 1-10 TeV
m_0(1, 2) : m_0(3)-20 TeV
$m_{3/2}$: 80-1000 TeV
tan β : 4-58
μ : 100-500 GeV
m_A : 0.25-10 TeV

AMSB with bulk Higgs soft mass



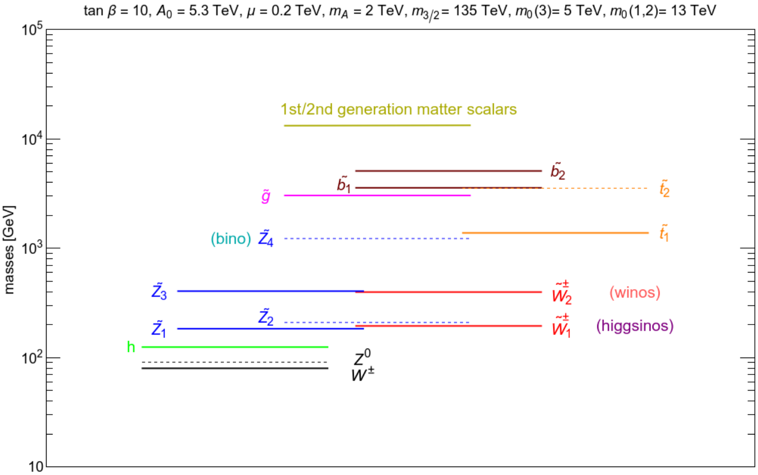
Plot of points in the Δ_{EW} vs. m_h plane from a scan over AMSB parameter space with added bulk Higgs soft terms but without bulk A_0 terms.

natural generalized AMSB (nAMSB)



Frame a): Δ_{EW} vs. A_0 for $m_{3/2} = 135$ TeV, $m_0(1,2) = 13.5$ TeV, $m_0(3) = 5$ TeV, $\mu = 200$ GeV and $m_A = 2000$ GeV. Frame b): m_h vs A_0 plot for the same parameters.

nAMSB



A typical superparticle mass spectrum generated from natural generalized anomaly mediation (nAMSB)

nAMSB

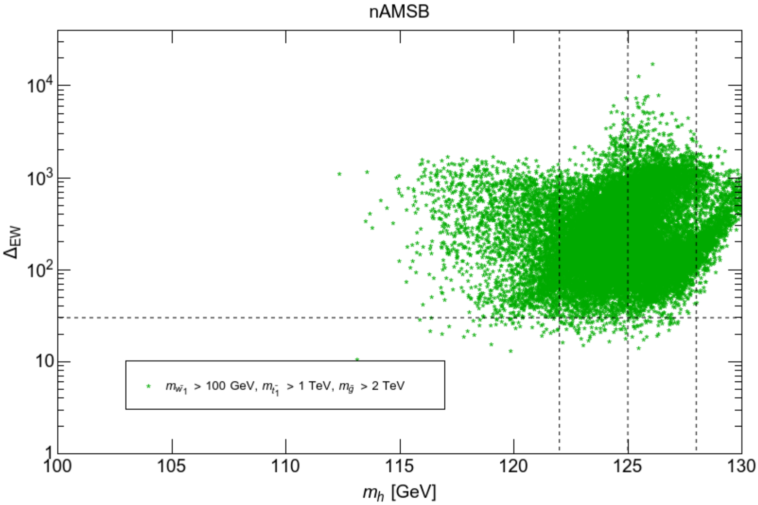
We now introduce bulk trilinear terms (A_0) which were originally proposed by Randall Sundrum but got lost in creating old AMSB model. The A_0 term allows for highly mixed stops which then allow $m_h \sim$ 125 GeV, while also improving naturalness.

The natural generalized AMSB model is characterized by the parameter set :

$$m_0(1,2),\ m_0(3),\ m_{3/2},\ A_0,\ \tan\beta,\ \mu \text{ and } m_A$$

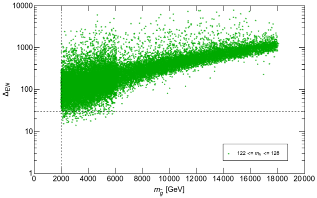
m_0(3) : 1-10 TeV
m_0(1, 2) : m_0(3)-20 TeV
$m_{3/2}$: 80-1000 TeV
tan β : 4-58
μ : 100-500 GeV
m_A : 0.25-10 TeV
A_0 : -20 - +20 TeV

nAMSB

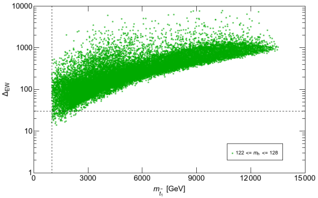


Plot of points from a scan over nAMSB parameter space in the Δ_{EW} vs. m_h plane.

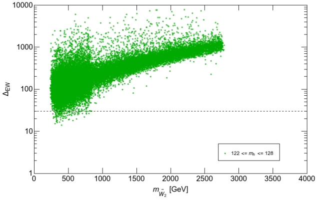
nAMSB



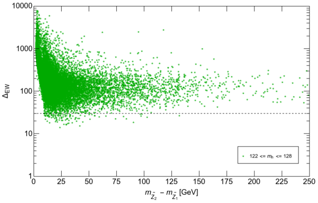
Δ_{EW} vs. $m_{\tilde{g}}$



Δ_{EW} vs. $m_{\tilde{t}_1}$

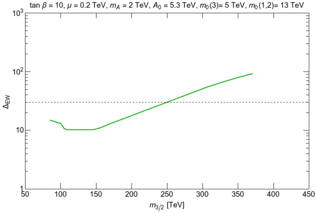


Δ_{EW} vs. $m_{\tilde{W}_2}$

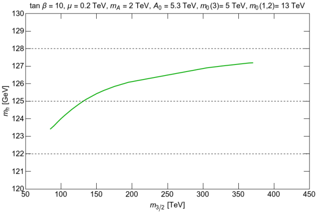


Δ_{EW} vs. $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$

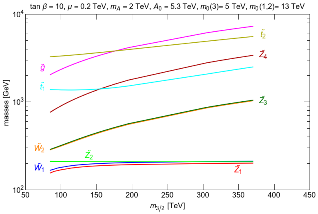
nAMSB model lines



Δ_{EW} vs. $m_{3/2}$



m_h vs. $m_{3/2}$



$masses$ vs. $m_{3/2}$