Gravity safe, electroweak natural axionic solution to strong CP and SUSY μ problem

Dibyashree Sengupta

University of Oklahoma

In collaboration with : H. Baer and V. Barger

arXiv : 1810.03713

October 14, 2018

Outline

Outline

Motivation

Till today, though, the Standard Model (SM) is the most celebrated and established theory, there are several reasons to expect new physics beyond SM. Some of these are as follows :

- The Higgs mass instability problem in the EW sector
- The strong CP problem in the QCD sector
- The lack of a DM candidate

and several others. Here, in this paper, we aim to solve the above three problems while remaining in a **gravity safe** and **natural** domain.

- The Higgs mass instability problem in EW sector can be solved by introducing weak scale supersymmetry where the Higgs mass quadratic divergences all cancel leaving only mild log divergences
- However, due to lack of appearance of superpartners in LHC, it seems that the superpartners are too heavy to be visible and that might mean that SUSY is unnatural/fine-tuned.
- But before declaring SUSY to be in a fine-tuning crisis, it was pointed out that if $\Delta_{EW} < 30$, then we can still dwell in the natural domain. The Electroweak fine-tuning parameter (Δ_{EW}) is defined as

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

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

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

- The Higgs mass instability problem in EW sector can be solved by introducing weak scale supersymmetry where the Higgs mass quadratic divergences all cancel leaving only mild log divergences
- However, due to lack of appearance of superpartners in LHC, it seems that the superpartners are too heavy to be visible and that might mean that SUSY is unnatural/fine-tuned.
- But before declaring SUSY to be in a fine-tuning crisis, it was pointed out that if $\Delta_{EW} < 30$, then we can still dwell in the natural domain. The Electroweak fine-tuning parameter (Δ_{EW}) 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 :

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

- $\mu \approx$ **100 - 350 GeV**

- The MSSM superpotential contains term $\mu H_u H_d$ which leads to $\mu \approx m_p$.
- A promising approach to solve the strong CP problem is to introduce a spontaneously broken global Peccei-Quinn (PQ) symmetry which also forbids the μ term in the DFSZ axionic extensions of the MSSM.
- Besides, since the PQ symmetry gets broken, it gives rise to a pseudo goldstone boson (called the axion) which serves as a good CDM candidate.
- However, global symmetries are violated by the inclusion of gravity into the theory.
- Thus the PQ symmetry cannot be an exact global symmetry, rather it must be an approximate global symmetry in order to be gravity safe.
- According to *Kamionkowski and March-Russell*, the requirement for gravity safety is that the PQ violating terms in the scalar potential must be at least suppressed by $1/m_p^8$

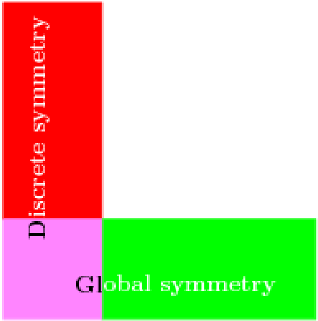


FIG 1: Kim diagram where the column represents an infinite sequence of lagrangian terms obeying gravity-safe discrete symmetry while the row represents an infinite sequence of terms obeying the global symmetry. The green region terms are gravity-unsafe while red region violates the global symmetry. The lavender terms are gravity-safe and obey the global symmetry.

Fundamental R symmetries

- One way to get PQ symmetry as an approximate global symmetry (so that the model does not suffer the gravity spoliation problem) is to assume a discrete R symmetry– which may emerge from compactification of 10-d Lorentzian spacetime in string theory– as a more fundamental symmetry of which the PQ symmetry emerges as an accidental approximate global symmetry.

Fundamental R symmetries

- One way to get PQ symmetry as an approximate global symmetry (so that the model does not suffer the gravity spoliation problem) is to assume a discrete R symmetry– which may emerge from compactification of 10-d Lorentzian spacetime in string theory– as a more fundamental symmetry of which the PQ symmetry emerges as an accidental approximate global symmetry.
- R-symmetries are characterized by the fact that superspace co-ordinates θ carry non-trivial R-charge : +1 being the simplest case.
- For the Lagrangian $\mathcal{L} \ni \int W d^2\theta$ to be invariant under Z_N^R symmetry, the superpotential W must carry R-charge :

$$Q_R(W) = 2 \text{ mod } |N|$$

Fundamental R symmetries

multiplet	Z_4^R	Z_6^R	Z_8^R	Z_{12}^R	Z_{24}^R
H_u	0	4	0	4	16
H_d	0	0	4	0	12
Q	1	5	1	5	5
U^c	1	5	1	5	5
E^c	1	5	1	5	5
L	1	3	5	9	9
D^c	1	3	5	9	9
N^c	1	1	5	1	1

These R-symmetries were shown to be anomaly-free by *Lee et al.* in *arXiv : 1102.3595*

Outline

Radiative PQ breaking scenarios

- **MSY Model** (H. Murayama, H. Suzuki and T. Yanagida)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{MSY}}{m_P} X Y H_u H_d \tag{3}$$

Radiative PQ breaking scenarios

- **MSY Model** (H. Murayama, H. Suzuki and T. Yanagida)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{MSY}}{m_P} X Y H_u H_d \qquad (3)$$

- **CCK Model** (K.Choi, E.J. Chun and J.E. Kim)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{CCK}}{m_P} X^2 H_u H_d \qquad (4)$$

Radiative PQ breaking scenarios

- **MSY Model** (H. Murayama, H. Suzuki and T. Yanagida)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{MSY}}{m_P}XYH_uH_d \tag{3}$$

- **CCK Model** (K.Choi, E.J. Chun and J.E. Kim)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{CCK}}{m_P}X^2H_uH_d \tag{4}$$

- **SPM Model** (S.P. Martin)

$$W_{PQ} \ni \frac{1}{2}h_{ij}XN_i^cN_j^c + \frac{f}{m_P}X^3Y + \frac{g_{SPM}}{m_P}Y^2H_uH_d \tag{5}$$

Radiative PQ breaking scenarios

- **MSY Model** (H. Murayama, H. Suzuki and T. Yanagida)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{MSY}}{m_P} XY H_u H_d \qquad (3)$$

- **CCK Model** (K.Choi, E.J. Chun and J.E. Kim)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{CCK}}{m_P} X^2 H_u H_d \qquad (4)$$

- **SPM Model** (S.P. Martin)

$$W_{PQ} \ni \frac{1}{2} h_{ij} X N_i^c N_j^c + \frac{f}{m_P} X^3 Y + \frac{g_{SPM}}{m_P} Y^2 H_u H_d \qquad (5)$$

Unfortunately, none of these radiative PQ breaking theories are consistent with the above mentioned R symmetries and hence suffer from the gravity spoilation problem.

- Either the Z_N^R charges of the multiplets are such that all the three terms in W_{PQ} are not allowed OR the model is not gravity-safe i.e., some PQ violating terms arise in the superpotential, just because they are allowed under the Z_N^R fundamental symmetry and the contribution of these terms in the scalar potential are suppressed by $1/m_p^7$ or less.

- Either the Z_N^R charges of the multiplets are such that all the three terms in W_{PQ} are not allowed OR the model is not gravity-safe i.e., some PQ violating terms arise in the superpotential, just because they are allowed under the Z_N^R fundamental symmetry and the contribution of these terms in the scalar potential are suppressed by $1/m_p^7$ or less.
- Let such a PQV term in W_{PQ} be $\lambda_3\ X^p Y^q / m_p^{p+q-3}$. Then the most dangerous PQV term in the scalar potential comes from the interference between $\lambda_3\ X^p Y^q / m_p^{p+q-3}$ and $f\ X^3 Y / m_p$ when constructing the scalar potential as follows :

$$V_F = \left|\frac{\partial W}{\partial X}\right|^2_{X=\phi_X;Y=\phi_Y} + \left|\frac{\partial W}{\partial Y}\right|^2_{X=\phi_X;Y=\phi_Y} \quad (6)$$

Hence, to obtain the PQV term in the scalar potential to be suppressed by $1/m_p^8$ or more, we need p+q ≥ 10

- Either the Z_N^R charges of the multiplets are such that all the three terms in W_{PQ} are not allowed OR the model is not gravity-safe i.e., some PQ violating terms arise in the superpotential, just because they are allowed under the Z_N^R fundamental symmetry and the contribution of these terms in the scalar potential are suppressed by $1/m_p^7$ or less.
- Let such a PQV term in W_{PQ} be $\lambda_3\ X^pY^q/m_p^{p+q-3}$. Then the most dangerous PQV term in the scalar potential comes from the interference between $\lambda_3\ X^pY^q/m_p^{p+q-3}$ and $f\ X^3Y/m_p$ when constructing the scalar potential as follows :

$$V_F = \left|\frac{\partial W}{\partial X}\right|^2_{X=\phi_X;Y=\phi_Y} + \left|\frac{\partial W}{\partial Y}\right|^2_{X=\phi_X;Y=\phi_Y} \tag{6}$$

  Hence, to obtain the PQV term in the scalar potential to be suppressed by $1/m_p^8$ or more, we need p+q $\geq$ 10
- For eg : SPM under Z_6^R symmetry : A PQV term like M^2Y is always present, thereby making the model gravity unsafe.

MBGW Model

This model was proposed by K.S. Babu, I. Gogoladze and K. Wang (mentioned previously by S.P. Martin and thus labelled **MBGW Model**)

$$W_{PQ} \ni \lambda_\mu \frac{X^2 H_u H_d}{m_P} + \lambda_2 \frac{X^2 Y^2}{m_P} \tag{7}$$

- This model turns out to be gravity-safe if the fundamental symmetry is considered to be a **$\mathbf{Z}_{22}$ discrete gauge symmetry**.

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{22}Charges	3	19	1	11	15	11	22	18	13	20
PQ Charges	1	0	0	1	0	0	-1	-1	1	-1

- However, the disadvantage of using a discrete gauge symmetry is that the charge assignments are inconsistent with SU(5) or SO(10) GUTs which may be expected at some level as a more ultimate theory.
- According to *Krauss and Wilczek*, a discrete gauge symmetry $\mathbf{Z}_M$ might arise if a field of charge Me condenses at some very high mass scale and condensation of a field having charge as high as 22 might not be very plausible because the resulting theory might be inconsistent with a UV completion in string theory.

- However, the disadvantage of using a discrete gauge symmetry is that the charge assignments are inconsistent with SU(5) or SO(10) GUTs which may be expected at some level as a more ultimate theory.
- According to *Krauss and Wilczek*, a discrete gauge symmetry $\mathbf{Z}_M$ might arise if a field of charge Me condenses at some very high mass scale and condensation of a field having charge as high as 22 might not be very plausible because the resulting theory might be inconsistent with a UV completion in string theory.
- This model does not turn out to be gravity safe under any of the R symmetries mentioned before.

Outline

Hybrid Models

- These Models are obtained by adopting a hybrid approach between the radiative breaking models and the MBGW model.
- In the radiative breaking models a Majorana neutrino scale is generated as the PQ field X gets VEV, however in these hybrid models the see saw term MN^cN^c is allowed but it is not generated through PQ breaking– similar to MBGW model.
- In the radiative breaking models intermediate PQ and Majorana neutrino scales develop as a consequence of intermediate scale SUSY breaking, while in the MBGW model and in these hybrid models PQ breaking is triggered by large negative soft terms instead of radiative breaking.

Hybrid CCK

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} X^2 H_u H_d \tag{8}$$

multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{24}^RCharges	5	5	9	9	5	1	16	12	-1	5
PQ Charges	1	0	0	1	0	0	-1	-1	1	-3

$$V = [fA_f \frac{\phi_X^3 \phi_Y}{m_P} + h.c.] + m_X^2 |\phi_X|^2 + m_Y^2 |\phi_Y|^2 + \frac{f^2}{m_P^2} [9\phi_X^4 \phi_Y^2 + \phi_X^6] \tag{9}$$

The lowest order PQ violating terms in the superpotential are $\mathbf{X^8 Y^2/m_P^7}$, $\mathbf{X^4 Y^6/m_P^7}$ and $\mathbf{Y^{10}/m_P^7}$ which implies the lowest order PQ breaking term in the scalar potential is suppressed by $\mathbf{1/m_P^8}$.

Hence, this model is gravity-safe.

Hybrid CCK

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} X^2 H_u H_d \quad (8)$$

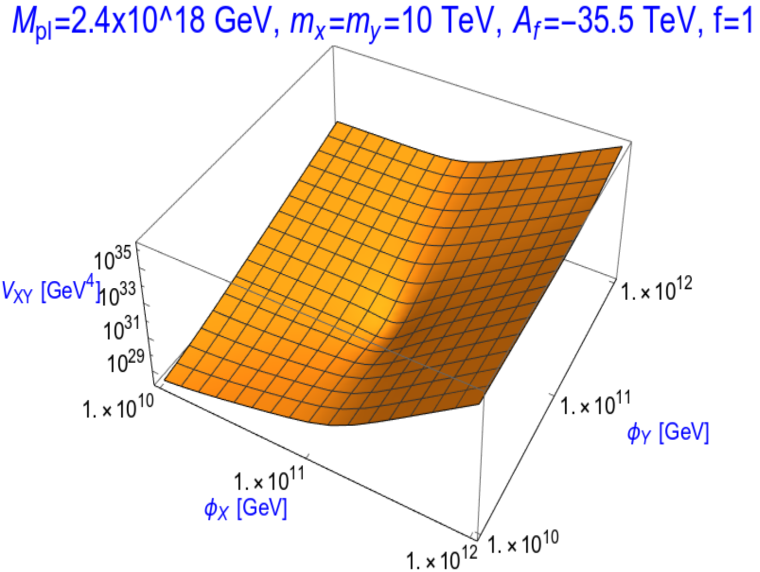
multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{24}^RCharges	5	5	9	9	5	1	16	12	-1	5
PQ Charges	1	0	0	1	0	0	-1	-1	1	-3

$$V = [f A_f \frac{\phi_X^3 \phi_Y}{m_P} + h.c.] + m_X^2 |\phi_X|^2 + m_Y^2 |\phi_Y|^2 + \frac{f^2}{m_P^2} [9\phi_X^4 \phi_Y^2 + \phi_X^6] \quad (9)$$

The lowest order PQ violating terms in the superpotential are $\mathbf{X^8Y^2/m_P^7}$, $\mathbf{X^4Y^6/m_P^7}$ and $\mathbf{Y^{10}/m_P^7}$ which implies the lowest order PQ breaking term in the scalar potential is suppressed by $\mathbf{1/m_P^8}$.
Hence, this model is gravity-safe.

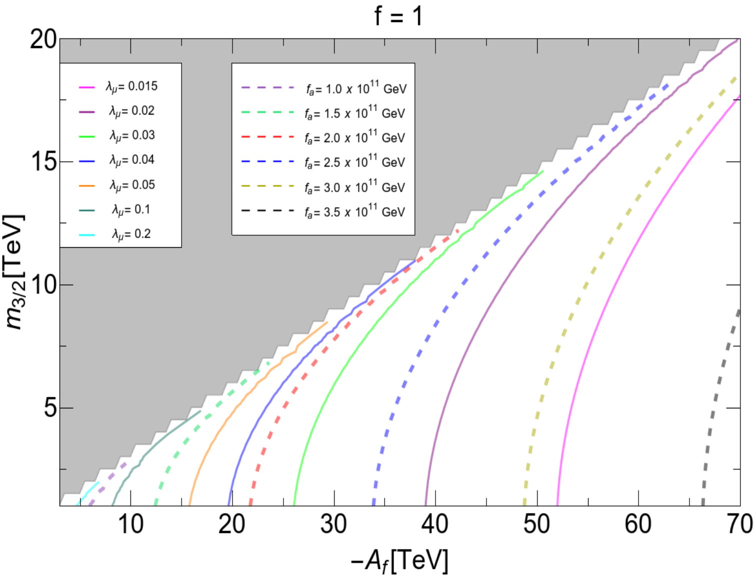
This has been mentioned earlier by *Lee et al.* in *arXiv : 1102.3595*, but the PQ breaking mechanism was radiative. Here PQ symmetry is broken through a large negative soft term A_f.

Hybrid CCK



M_{pl}=2.4x10^18 GeV, m_x=m_y=10 TeV, A_f=−35.5 TeV, f=1
V_{XY} [GeV^4]
10^{35}
10^{33}
10^{31}
10^{29}
1. × 10^{10}
1. × 10^{11}
ϕ_X [GeV]
1. × 10^{12}
1. × 10^{10}
1. × 10^{11}
ϕ_Y [GeV]
1. × 10^{12}

Hybrid CCK



f = 1
λ_μ= 0.015
λ_μ= 0.02
λ_μ= 0.03
λ_μ= 0.04
λ_μ= 0.05
λ_μ= 0.1
λ_μ= 0.2
f_a= 1.0 x 10^{11} GeV
f_a= 1.5 x 10^{11} GeV
f_a= 2.0 x 10^{11} GeV
f_a= 2.5 x 10^{11} GeV
f_a= 3.0 x 10^{11} GeV
f_a= 3.5 x 10^{11} GeV
$m_{3/2}$[TeV]
$-A_f$[TeV]
20
15
10
5
10
20
30
40
50
60
70

Hybrid SPM

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} Y^2 H_u H_d \tag{10}$$

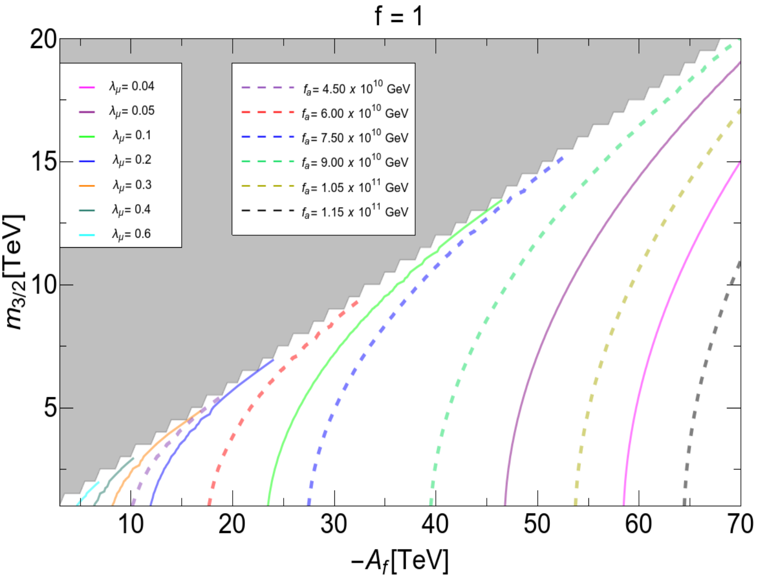
multiplet	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	Y
Z_{24}^RCharges	5	5	9	9	5	1	16	12	5	-13
PQ Charges	1	0	0	1	0	0	-1	-1	-1/3	1

$$V = [f A_f \frac{\phi_X^3 \phi_Y}{m_P} + h.c.] + m_X^2 |\phi_X|^2 + m_Y^2 |\phi_Y|^2 + \frac{f^2}{m_P^2} [9\phi_X^4 \phi_Y^2 + \phi_X^6] \tag{11}$$

The lowest order PQ violating terms in the superpotential are $\mathbf{Y^8 X^2/m_P^7}$, $\mathbf{Y^4 X^6/m_P^7}$ and $\mathbf{X^{10}/m_P^7}$ which implies the lowest order PQ breaking term in the scalar potential is suppressed by $\mathbf{1/m_P^8}$.

Hence, this model is gravity-safe.

Hybrid SPM


f = 1
λ_μ= 0.04
λ_μ= 0.05
λ_μ= 0.1
λ_μ= 0.2
λ_μ= 0.3
λ_μ= 0.4
λ_μ= 0.6
f_a= 4.50 x 10^{10} GeV
f_a= 6.00 x 10^{10} GeV
f_a= 7.50 x 10^{10} GeV
f_a= 9.00 x 10^{10} GeV
f_a= 1.05 x 10^{11} GeV
f_a= 1.15 x 10^{11} GeV
$m_{3/2}$[TeV]
$-A_f$[TeV]
20
15
10
5
10
20
30
40
50
60
70

Hybrid MSY

- Hybrid MSY

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} XY H_u H_d \tag{12}$$

Hybrid MSY

- Hybrid MSY

$$W_{PQ} \ni \frac{f}{m_P} X^3 Y + \frac{\lambda_\mu}{m_P} XYH_uH_d \qquad (12)$$

Unfortunately, The hybrid MSY model is not gravity-safe under any of the above mentioned R symmetries

Outline

Summary

- The MBGW model and the several DFSZ axionic extensions of the MSSM which generate PQ breaking radiatively as a consequence of SUSY breaking are inconsistent with gravity-safe Z_N^R symmetries which are consistent with GUTs.
- The MBGW model does turn out to be gravity safe under Z_{22} discrete gauge symmetry but this fundamental symmetry is inconsistent with GUTs.
- We have found two models : **hybrid CCK model** and **hybrid SPM model** which are gravity-safe under Z_{24}^R symmetry.
- In these models, we are able to obtain $\mu \approx 150$ GeV as required by naturalness and $f_a \approx 10^{11}$ GeV as required by mixed axion-higgsino dark matter.
- The Z_{24}^R symmetry forbids the μ term, the RPV operators and the proton decay operators. Besides, the global PQ symmetry emerges accidentally as an approximate global symmetry from the Z_{24}^R symmetry.

THANK YOU

QUESTIONS ?

Back Up Slides

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.

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

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{13}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{14}$$

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

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)tan^2\beta}{(tan^2\beta - 1)} - \mu^2 \tag{13}$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \tag{14}$$

Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \tag{15}$$

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \tag{16}$$

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.

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \quad (16)$$

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 :

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

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