The scale-invariant NMSSM after the 125 GeV scalar discovery

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OUTLINE

- INTRODUCTION

- HOW TO RAISE THE HIGGS MASS IN SUSY

- THE NMSSM

- NATURALNESS OF THE EW SCALE AND OF THE HIGGS MASS

- REGIONS OF INTEREST IN THE PARAMETERS SPACE

- CONCLUSIONS
Standard model $\rightarrow$ SU(2) $\times$ U(1) gauge theory

$\rightarrow$ dynamics of a gauge theory (LEP era)

$\rightarrow$ in overall great agreement with data

$\rightarrow$ unlike QCD $M_{3,W} \neq 0$
The electro weak symmetry is broken

- Spontaneous breaking

- Higgs model \( \mathcal{L} = |D_\mu \phi|^2 \)

\[ \langle \phi \rangle = v \] breaks EW symmetry

\[ V(\phi) = \mu^2 \phi^2 + \lambda \phi^4 \]

\[ \langle \phi \rangle = v = \sqrt{-\frac{\mu^2}{2\lambda}} \geq \frac{|\mu|}{4\pi} \]

\[ m_w^2 \sim g^2 v^2 \]
The potential could have been different

\[ V(\phi) \]

\[ \mu^2 > 0 \]

\[ \langle \phi \rangle = 0 \quad \text{Unbroken Symmetry} \]

\[ V(\phi) \]

\[ \langle \phi \rangle >> m_w \]

\( \mu^2 \) is sensitive to UV corrections

And in general, \( \mu^2 \sim \Lambda^2 \) at the cutoff

\( \langle \phi \rangle \) is expected much larger than \( m_w \)
PLANCK-WEAK HIERARCHY PROBLEM

\[ \langle \phi \rangle \sim \frac{m_w}{g} \]

Can be attained in the Standard Model

but seems unnatural

or at least poses a question

\[ \langle \phi \rangle = 0 \]

\[ \langle \phi \rangle \sim M_{\phi} \]

\[ \langle \phi \rangle = m_w \]
• TeV may be the dynamical scale of a strongly interacting theory

$$TeV \sim \Lambda_{qcd}$$

The EW scale is generated by dimensional transmutation

$$\mathcal{L} + \lambda \phi \mathcal{L}_{\text{breaking}} \quad \lambda = \lambda_0 \text{ at high-energy, dim } 6\lambda = 4-\varepsilon$$

$$\lambda(\mathcal{E}) = \lambda_0 \left( \frac{\Lambda_{\text{UV}}}{\mathcal{E}} \right)^\varepsilon \quad \Lambda_{\text{IR}} \sim \Lambda_{\text{UV}} \lambda_0^{\varepsilon} \quad \text{(hierarchy of scales)}$$

• TeV is a mass scale controlled by a symmetry

$$m_f \sim \text{Chiral Symmetry} \rightarrow \text{SUSY}$$
Higgs Mass in SUSY

SUSY restricts the form of the Higgs potential

\[ V_h \supset \text{"D-terms" from gauge interactions} \]

\[ V_D \sim \frac{s^2}{2}(|H_1|^2 - |H_2|^2)^2 \]

In the MSSM there is no other source of \( H_4 \)

As a result \( m_h \leq m_Z \) at tree-level
LEP-CRISIS

AFTER LEP \( m_h \geq 114 \) GeV

\[ \downarrow \]

A LOT OF WORK TO "SAVE SUSY"

(next slides)

A LOT OF WORK ON NON-SUSY BSM
NEW CONTRIBUTIONS TO THE HIGGS MASS

- "F-terms" from new interactions (non-gauge)

\[ W = \lambda S H_1 \cdot H_2 \Rightarrow V_h = \lambda^2 |H_1 H_2|^2 \]

new interaction  
new field  
\[ \frac{d\lambda}{dt} \sim \lambda (\lambda^2 - g^2) \]

- new gauge interactions \( \Rightarrow "D-terms" \)

\[ 8V = 8^2 (1|H_1|^2 - 1|H_2|^2)^2 \frac{m_f}{m_f + m_\Sigma} \]

- loop corrections

\[ \sim \frac{\gamma t^4}{16 \pi^2} \]
STRUCTURE of the LOOP CORRECTION

**SUSY-limit**

**SMALL STOP MIXING**

**LARGE STOP MIXING**

\[ b(H^4) \sim \frac{3y_t^4}{\pi^2} \left( \ln \frac{m_{\tilde{t}_L}}{m_t} + X_t \right) \]

\[ X_t \sim \frac{1}{m_{\tilde{t}_L}^2} \left( A_{\tilde{t}} - \frac{m_{\tilde{t}_L}}{\tan \beta} \right)^2 \left( 6 - \frac{1}{m_{\tilde{t}_L}^2} \left( A_{\tilde{t}} - \frac{m_{\tilde{t}_L}}{\tan \beta} \right)^2 \right) \]
Without extras on top of the MSSM...

- Large stop mass and mixing are needed

\[ m_Z^2 = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{\tan^2 \beta - 1} \]

Cancellations among parameters are required \( \Rightarrow m_Z << m_{\text{susy}} \)
Next to minimal (NMSSM)

\[ W = \lambda \hat{S} \hat{A}_1 \hat{A}_2 + \frac{k}{3} \hat{S}^3 \]

\[ \mathcal{L}_{\text{soft}} \sim m_{h_u}^2 |H_u|^2 + m_{h_d}^2 |H_d|^2 + m_s^2 |S|^2 + \lambda A_\lambda \hat{S} h_u h_d + \frac{k}{3} A_k S^3 \]

\[ m_h^2 = m_e^2 \cos^2 2\beta + \delta m_{\text{loop}} \]

\[ \lambda^2 v^2 \sin^2 2\beta + \delta m_{\text{mix}} \]

**TREE-LEVEL**
Motivations

\[ W = \lambda \hat{H}_1 \hat{H}_2 \hat{S} \]

- Once \( \langle H_1 \rangle = v_1 \), \( \langle H_2 \rangle = v_2 \), \( \langle S \rangle = s \)
  generates a \( \mu \) term \( \mu H_1 H_2 \)
  \( \mu = \lambda s \)

- \( \frac{k^3}{3} \hat{S}^3 \)
  \( k \) is the only other interaction with dimensionless coupling (scale invariance? discrete \( \mathbb{Z}_3 \)?)

Other variants are possible

\[ W = m_s^2 \hat{S}^2 + \lambda \hat{S} \hat{H}_1 \hat{H}_2 \]

Hall, Pinner, Ruderman - arXiv:1112.2703
H, H_2S

They contain CP-even scalar states.

So there are 3 mass eigenstates: s_1, s_2, s_3.

\[ m_{s_2} \]
\[ m_{s_1} \]

One combination is gauge singlet. One combination couples to W^+W^-.

The orthogonal does not.

There is a charged Higgs as in the MSSM and two pseudo-scalars.
\[ m_{\phi_1} \sim 125 \text{ GeV} \]

All the Higgs sector is light

One charged light Higgs

Two pseudo-scalar

LEP, \( b \to s \gamma \), ...
PUSH-UP SCENARIO

- ONE LIGHT SCALAR
  (in the reach of LEP?)

- CHARGED HIGGS MAY BE HEAVY

- ONLY ONE PSEUDO-SCALAR COULD BE LIGHT

\[ h_i = \sum_j c_{ij} s_j \]

\[ H^2 \sim \begin{pmatrix} m_i^2 & 0 \\ 0 & m_j^2 \end{pmatrix} \]

HIGGS MASS IS PUSHED UP BY THE MIXING

\[ m_i = m_{s_2} \]

\[ m_j = m_{s_1} \]
PUSH-UP SCENARIO

\[ m_{S_2} \sim 125 \text{ GeV} \]

\[ m_{S_1} \]

\[ \text{LEP: } S_1 \approx S \text{ GAUGE SINGLET} \]

\[ \text{GUAGE INTERACTIONS} \]

\[ 0 < m < 80 \text{ GeV} \quad \sin^2 \theta \approx 10^{-2} \]

\[ 80 \text{ GeV} < m < 100 \text{ GeV} \quad \sin^2 \theta \approx 0.1 \]

\[ 100 \text{ GeV} < m < 110 \text{ GeV} \quad \sin^2 \theta \approx 0.4 \]
Figure 2: The 95% CL upper bounds, $S_{95}$ (see text), for various topological cross-sections motivated by the Higgsstrahlung process $e^+e^- \rightarrow HZ$, as a function of the Higgs boson mass (the figure is reproduced from Ref. [3]). The full lines represent the observed limits. The dark (green) and light (yellow) shaded bands around the median expectations (dashed lines) correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model cross-sections. In part (a) the Higgs boson decay branching ratios are assumed to be those predicted by the Standard Model; in part (b) the Higgs boson is assumed to decay exclusively to $b\bar{b}$ and in part (c) exclusively to $\tau^+\tau^-$. 
PULL-DOWN SCENARIO

$m_{3/2} \leq m_3^2 \cos^2 2\theta + \lambda^2 \sigma^2 \sin^2 2\rho$

$m_{s_1} \sim 125 \text{ GeV}$

$\mathcal{L}^2 \sim \left( \frac{m_i^2}{s} \right) \left( \frac{m_j^2}{s} \right)$

$\frac{d\lambda}{d\cos \mu} \sim \lambda \left( \lambda^2 - 1 \right)$

HIGGS MASS IS PULLED DOWN BY THE MIXING

AT THE WEAK SCALE:

$\lambda \leq 0.7$
\[ \tan\beta = 1.5 \]

Graph showing the relationship between \( m_h^{\text{max}} \) [GeV] and \( \lambda \) with a shaded area indicating the non-perturbative region.
\( m_{s_2} \sim 125 \text{ GeV} \)

\( m_{s_1} \sim 125 \text{ GeV} \)

**PERTURBATIVITY** till GUT

**LEP SEARCHES**

**CONSTRAIN THE TWO SCENARIOS**

\[
m_h = m_{e}^2 \cos^2 2\beta + 6m_{\text{loop}}^2
\]

\[
\lambda^2 v^2 \sin^2 2\beta + \delta m_{\text{mix}}^2
\]

**CONSTRAINED**

\[
\delta m_{\text{mix}}^2 \sim 2\lambda \sin (\lambda - k) + \lambda A_{\lambda} v
\]
\[ m_h^2 = m_q^2 \cos^2 2\beta + \delta m_{\text{loop}} \]
\[ \lambda^2 \sin^2 2\beta + \delta m_{\text{mix}}^2 \]

\( \delta m_{\text{mix}} \) \text{ needs to be small } \lesssim 0.1

\[ \delta m_{\text{mix}}^2 \approx 2 \lambda s_u (\lambda - \kappa) + \lambda A_{\lambda u} \]

In general many parameters participate

\[ \Delta_{\text{mix}} = \max_i \left. \frac{d \log \delta m_{\text{mix}}^2}{d \log p_i} \right|_{p_i = \lambda, \kappa, A_\lambda, A_u, \mu} \]
\[ (\text{Push-Up}) \otimes (\lambda < v_f) \otimes (A_{\lambda k} \leq m_Z) \]

- Other light states at LEP/LHC?
- Perturbative up to GUT?
- SUSY breaking scenario

\[ (\lambda = k) \]

\[ \lambda \ll k \]

\[ k \ll \lambda \]

- What kind of UV completion?
- Higgs sector phenomenology
\[ m_Z^2 = -1\mu^2 - \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{\tan^2 \beta - 1} \]

\[ \delta m_{H_u}^2 \bigg|_{\text{step}} \leq -\frac{3Y_t^2 \cos \beta}{8\pi^2} \frac{\Lambda_{\text{susy}}}{\text{TeV}} \left( m_{H_d}^2 + m_{A_d}^2 + 1\alpha_t l^2 \right) \]

\[ m_{\tilde{t}} < 500 \text{ GeV TO NOT REQUIRE LARGE CANCELLATIONS} \]

\[ m_h^2 = m^2_e \cos^2 2\beta + 6m^2_{\text{loop}} + \lambda^2 u^2 \sin^2 2\beta + \delta m^2_{\text{mix}} \]

\[ = m^2_{\text{tree}} + m^2_{\text{loop}} \]

\[ m_{\text{tree}} \geq 110 \text{ GeV} \]
PULL-DOWN

1) \( A_{\lambda,k} \approx 0 \)

2) \( A_{\lambda,k} \) FREE
μ = 200 GeV \, \tan β = 1.5 \, A_λ = 50 \, \text{GeV} \, \, A_k = 0 \, \text{GeV}
NEGUGIBLE A-terms $A_{\lambda,k}$

- NO REGION IS COMPATIBLE WITH PERTURBATIVITY UP TO GUT SCALE

- $\lambda \leq k$ or $\lambda \leq k$
  - non-tuned regions exist
  - Higgs couplings may deviate significantly from SM-like
  - lower Landau pole (NLSP phase in GM)
\[ \sin^2 \theta_{\text{mix}} \approx 2 \lambda \sin(\lambda - \kappa) + \lambda A_\lambda \nu \]

**Small mixing by** \( A_\lambda \approx 2 \mu \)
\( \mu = 200 \text{ GeV} \tan \beta = 1.5 \ A_\lambda = 370 \text{ GeV} \ A_k = 0 \text{ GeV} \)
SMALL MIXING BY $A_\lambda \approx 2\mu$

- TENSION BETWEEN PERTURBATIVITY UP TO GUT AND $m_h$
- TUNED BY $A_\lambda \approx 2\mu$ UP TO 1%.
- $k, \lambda, A_\lambda, A_\mu, \mu$ QUITE FIXED
PUSH-UP

$\begin{align*}
& m_3 \\
& m_{s_2} \sim 125 \text{ GeV} \\
& m_{s_1}
\end{align*}$

BEST SCENARIO FOR PERTURBATIVITY

$A_{\lambda, \kappa} \text{ FREE (to be ok with LEP)}$
$A_{\lambda, \kappa} \to 0$  \textbf{PUSH-UP}

- \textbf{NON-TUNED REGION}

- \textbf{SOME TENSION WITH PERTURBATIVITY}

- $\kappa, \lambda, A\lambda, A\kappa, \mu$ \underline{QUITE FIXED}
$\mu = 120$ GeV $\tan \beta = 1.5$ $A_\lambda = 250$ GeV $A_k = 0$ GeV
$\mu = 110$ GeV $\tan \beta = 1.5$ $A_\lambda = 50$ GeV $A_k = -250$ GeV

$\Delta_{\text{mix}}$

GUT
$A_{\chi^0}$ PUSH-UP

- SIGNIFICANT TUNING TO GET $m_{\chi}$
- NON-PERTURBATIVE
- $\lambda \propto k$
YELLOW, LIGHT YELLOW, RED ...

When the NMSSM soft masses or couplings are large $A_λ, A_κ, λ, κ$, the Higgs potential can develop extra minima where EWSB is not correct.

$\nu \neq \frac{m_ν}{g} \quad s + \frac{κ}{λ}$

- Require more work (lifetime)
- Push-up can be OK
- Pull-down can have troubles (large $λ$)
CONCLUSIONS

• Both pull-down and push-up are viable. Push-up better for perturbativity.

• Lighter and heavier Higgs bosons with observable LHC PHENO + Higgs couplings.

• Parameters space is reduced to few regions of interest \( \lambda \sim \kappa \) \( A_\lambda \sim 2\mu \).

• Vacuum stability may be an issue.
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