The Higgs and High Scale SUSY

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Partly based on 1304.2767 and 1204.2551 (with A. Hebecker and T. Weigand)

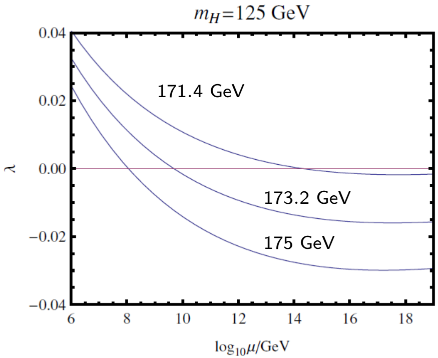
The new boson at $m \sim 125$ GeV looks like the SM Higgs

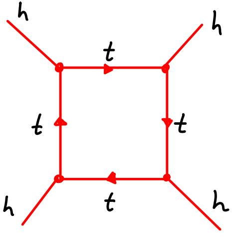
- alternative spin/parity disfavored theoretically+experimentally
- correct production rates + branchings (including $\gamma\gamma$)
- no BSM physics @ LHC8
- m_h is in a special range

The SM Higgs in the UV

Assuming an SM(-like) Higgs, we have now measured λ via $m_h \sim v\sqrt{\lambda}$!

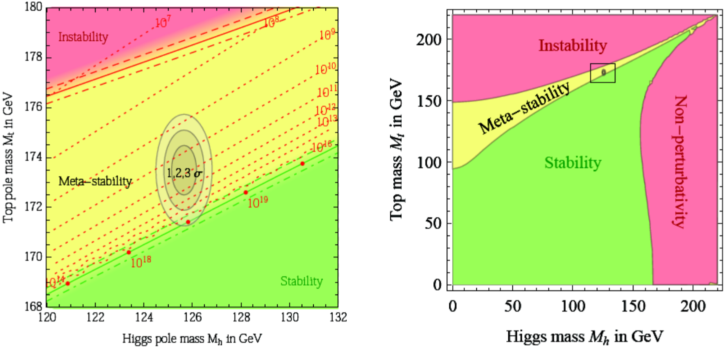
$$16\pi^2 \frac{\partial \lambda}{\partial \log \mu} \sim \lambda(-9g_2^2 - 3g_1^2 + 12y_t^2) + 24\lambda^2 + \frac{3}{4}g_2^4 + \frac{3}{8}(g_1^2 + g_2^2)^2 - 6y_t^4$$





$$V(\phi) \sim \lambda(\phi)\,(\phi^\dagger\phi)^2$$

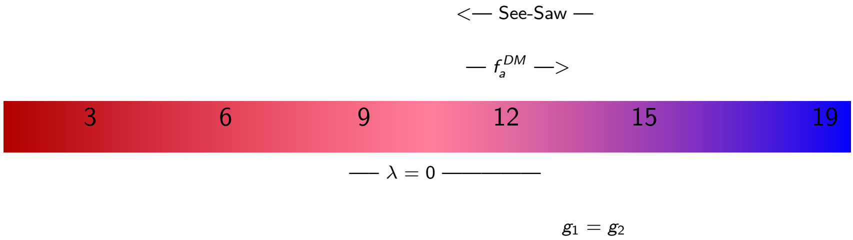
The Near-Critical Higgs



[Degrassi et al.][Buttazzo et al. '13]

- Special location in the "phase diagram" a hint *against* non-standard EWSB at the TeV scale?
- modified by high scale new physics

Wo spielt die Musik?



Is this a coincidence?

Intermediate scale SUSY

$\lambda = 0$ has generated predictions and attracted some interest

- Gogoladze, Okada Shafi '07 (high scale GHU)
- Shaposhnikov, Wetterich '10 ($\lambda = \beta_\lambda = 0$)
- Holthausen, Lim, Lindner '11

[Hebecker, AK, Weigand '12][Hebecker, AK, Weigand '13]

- We embed the SM into a supersymmetric stringy model with flat treelevel Higgs potential

  (compare [Hall, Nomura '09] where λ is maximal - ruled out)

- The observed quartic coupling and weak scale are generated radiatively (the latter probably finetuned)
- Objective: unified description of $\lambda = 0$, Axion CDM, Seesaw, gauge unification [Ibanez, Marchesano, Regalado, Valenzuela '12][Hebecker, Unwin '14][Hall, Nomura '13]

Shift Symmetry

[A. Hebecker, AK, T. Weigand: A Shift Symmetry in the Higgs Sector (arXiv:1204.2551)]

Mechanism (4D FT): a shift symmetry *in the Higgs sector*

$$H_u \longrightarrow H_u + c, \quad H_d \longrightarrow H_d - \overline{c}$$

This gives us $\mu(\mathcal{W}) = 0$ and $\mathcal{K} = \mathcal{K}(H_u + \overline{H}_d)$,

$$\mathcal{K} = f(S, \overline{S})|H_u + \overline{H}_d|^2 + \dots$$

SUSY breaking $F^S \neq 0 \Longrightarrow$ "shift symmetry relations" in soft parameters

see e.g. [Ibáñez, Muñoz], [Choi et al '04][Hebecker et al. '09][Brümmer et al. '09]

$$B\mu \quad = \quad |\mu|^2 + m^2_{H_u} \quad = \quad |\mu|^2 + m^2_{H_d}$$

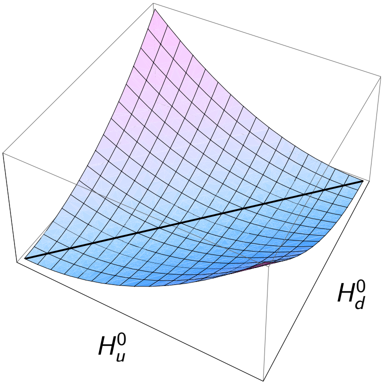
Realizations known in Heterotic [Lopes Cardoso et al '94][Antoniadis et al. '94][Brignole et al. '97]..., IIA [Hebecker, AK, Weigand '12][Ibanez et al '12], IIB/F-Theory [Hebecker, AK, Weigand '12,'13]

Higgs mass matrix from shift symmetry:

$$V = \begin{bmatrix} H_u \\ \overline{H}_d \end{bmatrix}^\dagger \begin{bmatrix} |\mu|^2 + m_H^2 & |\mu|^2 + m_H^2 \\ |\mu|^2 + m_H^2 & |\mu|^2 + m_H^2 \end{bmatrix} \begin{bmatrix} H_u \\ \overline{H}_d \end{bmatrix} \sim |H_u + \overline{H}_d|^2$$

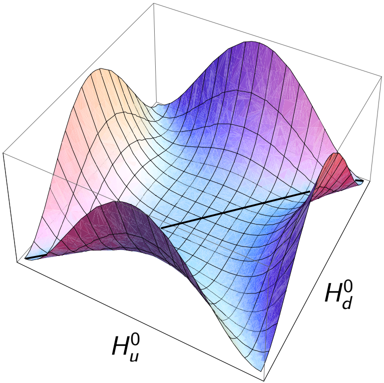
"shift-symmetric" mass matrix

$|H_u^0 + \overline{H}_d^0|^2$



electroweak D-Term

$(|H_u^0|^2 - |H_d^0|^2)^2$



Mass eigenstates $\sim$ flat directions of EW D-Term: $\sin 2\beta = 0 \Rightarrow \lambda = 0$

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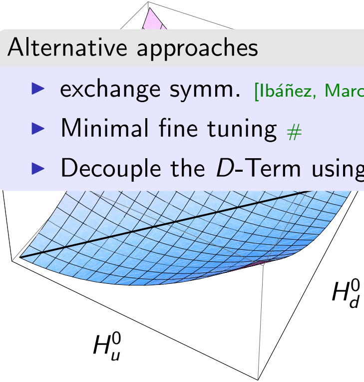

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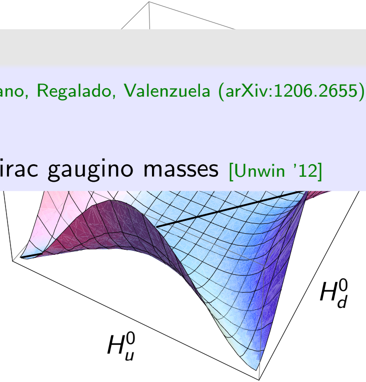


Alternative approaches

- exchange symm. [Ibáñez, Marchesano, Regalado, Valenzuela (arXiv:1206.2655)]
- Minimal fine tuning #
- Decouple the D-Term using Dirac gaugino masses [Unwin '12]

Mass eigenstates $\sim$ flat directions of EW D-Term: $\sin 2\beta = 0 \Rightarrow \lambda = 0$

How stable is this scenario against (MSSM) radiative corrections?

Radiative corrections

I. Violation of Higgs sector shift/exchange symmetry

[Hebecker, AK, Weigand '12] (remember: $\tan\beta = 1 \Rightarrow y_t \gg y_b$)

$$\mathcal{W} = y_t H_u T_R Q_L \qquad \longrightarrow \qquad \delta\mathcal{K} \sim |H|^2$$

RG evolution of Kähler Potential/quadratic thresholds

- perturbs $\tan\beta = 1$
- lifts massless mode

This is where the m_w fine tuning happens:

$$LL: \quad \left[2m_{\tilde{t}}^2 + (A_t - \mu)^2\right]\epsilon_y + 2\left[2M_{1/2}^2 - m_H^2 + 2\mu M_{1/2} + \mu^2\right]\epsilon_g \approx 0\,.$$

$$\cos 2\beta = \epsilon_y \frac{m_H^2 + m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2}{2(|\mu|^2 + m_H^2)}$$

This yields

$$\lambda_{tree}(m_S) = \delta\lambda_{SV}(m_S) \approx \frac{g_2^2 + g_1^2}{8}\left|\frac{6\overline{y_t^2}}{16\pi^2}\log\left(\frac{m_S}{m_C}\right)\right|^2.$$

So we predict $\lambda \approx 0$!

... but at what scale?

Radiative corrections

II. Threshold corrections to λ [Hebecker, AK, Weigand '13]

m_S is unphysical and arbitrary at tree level $\longrightarrow$ 1-Loop matching

Integrating out $\tilde{G}, \tilde{H}, A, H, \tilde{f}$

$$\begin{aligned} \delta\lambda &= \frac{3y_t^4}{16\pi^2}\left[\frac{X_t^2}{m_{\tilde{t}}^2}\left(1-\frac{X_t^2}{12m_{\tilde{t}}^2}\right)+2\log\left(\frac{m_{\tilde{t}}}{m_S}\right)\right]-\frac{1}{16\pi^2}\frac{1}{4}\tilde{b}_\lambda\log\frac{m_A}{m_S} \\ &+ \frac{\tilde{b}_\lambda}{16\pi^2}\left[\log\frac{\mu}{m_S}+\frac{(r-1)(r+1)^2+2(r-3)r^2\log r}{2(r-1)^3}\right] \end{aligned}$$

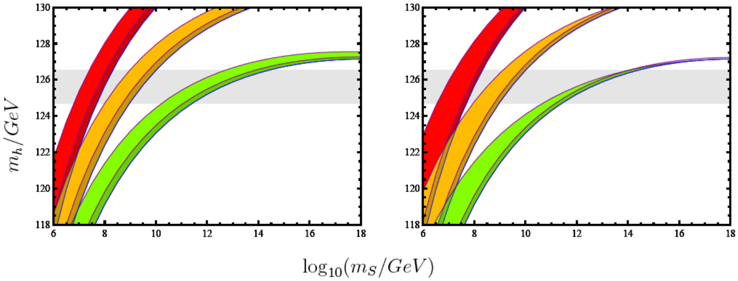
$X_t \sim A_t - \mu$

[Okada, Yamaguchi, Yanagida '91][Hollik et al. '96][Giudice, Strumia '12,'14] ...

m_h independent of m_S at LL, can give effective SUSY scale at leading log:

$$m_S^{eff} = \left[m_A^{-\tilde{b}_\lambda/3}\, m_{\tilde{t}}^{8y_t^4}\, m_\chi^{4\tilde{b}_\lambda/3}\right]^{1/(\tilde{b}_\lambda+8y_t^4)}$$

Results for m_h (Thresholds/SV effects)



(fat bands: worst cases $X_t = \sqrt{6} m_{\tilde{t}}$ and $m_C^2 \sim m_S^{eff} M_{Pl}$)

Various $\delta\lambda$ thresholds and "stop mixing" effects tend to cancel in scenarios where $M \sim m_0 \sim \mu$

$\Rightarrow \delta m_h \lesssim$ GeV for $m_S^{eff} \sim 10^9$ GeV.

Dark Matter, Unification and Proton Decay

Unification and Proton Decay

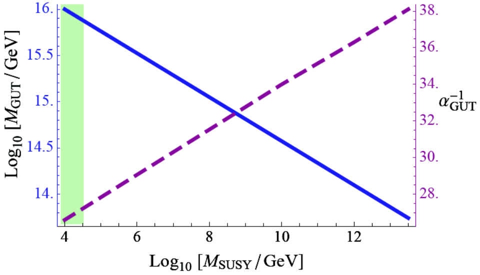
In High Scale SUSY, unification from classical IIB/F-Theory corrections: [Blumenhagen '09]

$$S_{DBI} \sim \frac{1}{g_s} \int d^8x Tr_f \left\{ \sqrt{-det(g_{\mu\nu} + F_{\mu\nu})} \right\} \quad \ni \quad F^4 \xrightarrow{\langle F^2_{z\bar{z}} \rangle} \langle F^2 \rangle F^2$$

... but the unification scale is reduced! [Hebecker, Unwin '14]

$$M_{GUT} = 4.25 \times 10^{15}\ \text{GeV} \left(\frac{10^5\ \text{GeV}}{M_{SUSY}} \right)^{2/9} \left(\frac{3.3}{\Lambda / M_{KK}} \right)^{1/3}$$

Generically, KK modes induce proton decay - require new suppression mechanism.



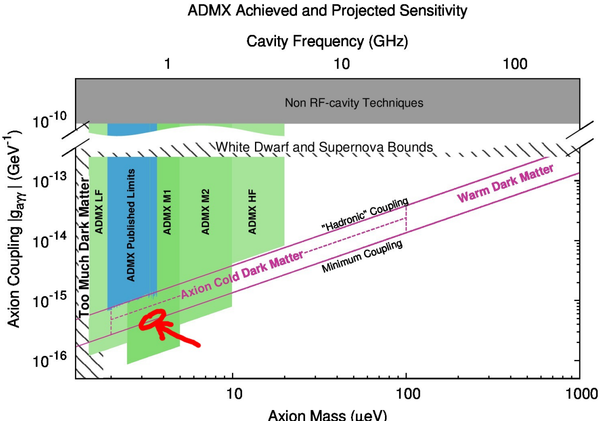
Axion Dark Matter and Unification

Gauge unification allows a concrete connection $m_{GUT} \leftrightarrow m_S \leftrightarrow F_a$

Stringy proposal by Ibanez et al '12: axion= ImT of an $SU(5)$ GUT in a large volume scenario.

$$T\mathcal{W}\mathcal{W} \longrightarrow Re(t)FF + Im(a)F\tilde{F}$$

$$F_a = \left(\frac{18}{\pi^2}\right)^{1/4} \frac{M_c}{16\pi^2}, \quad \text{e.g. } F_a = 2\times 10^{12}\ \text{GeV}, \quad m_a = 2.7\mu\text{eV}$$



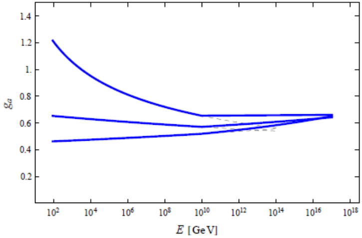
Unification and Proton Decay

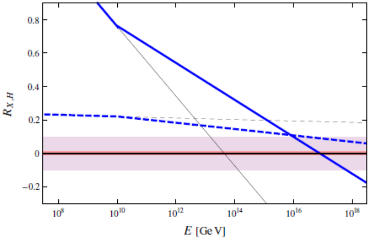
More optimistic: 4D field theoretic models ([Hall, Nomura '13]):

- GUT-breaking multiplets Σ can fix gauge unification
- Require higher-dimension effects and Σ_3, Σ_8 to keep $M_{HiggsTriplet} < M_{Pl}$

$$Tr[\mathcal{W}\mathcal{W}] + \frac{c_1}{\Lambda} Tr[\langle\Sigma\rangle\mathcal{W}\mathcal{W}] + \frac{c_2}{\Lambda} Tr[\langle\Sigma\rangle\mathcal{W}]\, Tr[\langle\Sigma\rangle\mathcal{W}]$$

- $M_X > 6 \times 10^{15}$ GeV for $M_{SUSY} \lesssim 2 \times 10^{11}$ GeV [Hall, Nomura '13]





- For High Scale SUSY and lowish T_R: pure axion DM, but connection $M_{SUSY} \leftrightarrow F_a$ less clear

Effects from extended sectors

[A. Hebecker, AK, T. Weigand '13]

Effects from extended SUSY

If Higgs originates from higher dimensional bulk or some sector with $\mathcal{N}=2$ locally such as a non-generic D6 system

$$\mathcal{L} \supset \cdots + \frac{1}{2}\vec{P}^2 + g\phi^A \vec{P}\cdot\vec{\sigma}_A{}^B\,\phi_B^\dagger + \cdots$$

where e.g. $\vec{P} \sim (ReF, ImF, D)$

The relation "$\tan\beta = 1 \Rightarrow \lambda = 0$" relies on SUSY decoupling of F!

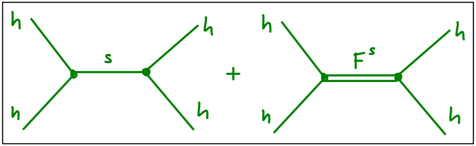
Consider $P^+ \sim S|_{\theta^2}$,

$$\begin{aligned} V_{\Lambda>M} \quad = \quad & |\kappa H_u H_d + MS|^2 + |\kappa S H_u|^2 + |\kappa S H_d|^2 + \left\{\kappa\overline{\mu}S(|H_u|^2 + |H_d|^2) + \text{h.c.}\right\} \\ & + m_1^2|H_u + H_d^\dagger|^2 + \frac{g_2^2+g_1^2}{8}(|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2}|H_u\epsilon H_d^\dagger|^2 + m_s^2|S|^2 \end{aligned}$$

In terms of 4D superfields:

$$\mathcal{W} \sim \kappa S H_u H_d + \frac{M}{2} S^2$$

Below scale M, S and in particular F^s decouple.



Consider soft mass term

$$\mathcal{L}_{soft} = -m_s^2 s^\dagger s$$

$m_s \neq 0$: decoupling of F^s is not exact:

$$V_{\Lambda=M} = \kappa^2 \frac{m_s^2}{m_s^2 + M^2} |H_u H_d|^2$$

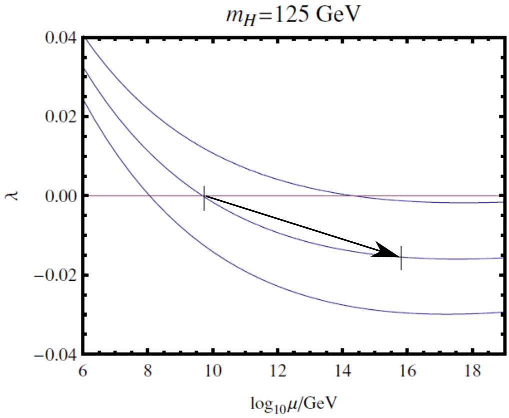
Amusing feature:

- negative mass squared results in quartic (not tachyonic!) instability

$\kappa \sim \sqrt{2}g \sim 1$, so a small hierarchy

$$-M^2 < m_s^2 < 0, \quad |m_s| \sim M/10$$

would bring us to arbitrarily high scales:



Conclusions

- After the Discovery: We *seem* to live on the verge of instability
- Nature's critical location in the $m_t - m_h$ plane can be seen as a hint *against* nonstandard EWSB near weak scale.
- Intermediate scale SUSY with flat LO potential (DM, Neutrinos,Unification!)
- Several promising approaches in Het. and Type II exist
- Effects from the extended sector may induce UV completion in the metastable regime $\lambda < 0$!
- Depending on BSM@LHC13, intermediate SUSY can be *the* (string) model building avenue to pursue.

Thank you for your attention!