What can the Higgs teach us about UV physics?

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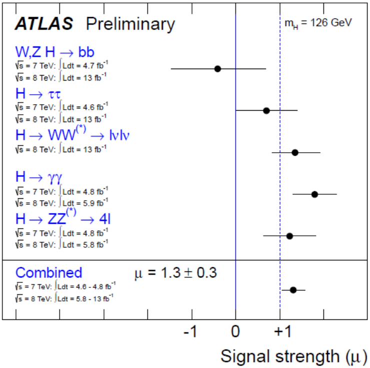
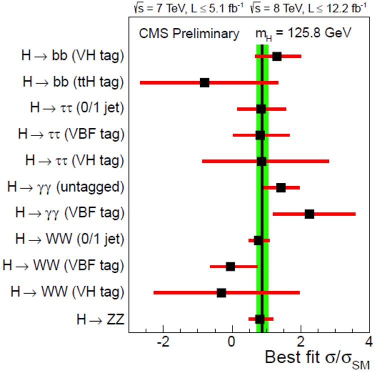
The SM-like Higgs at $m_h \sim 125$ GeV

It looks like a SM-like Higgs...



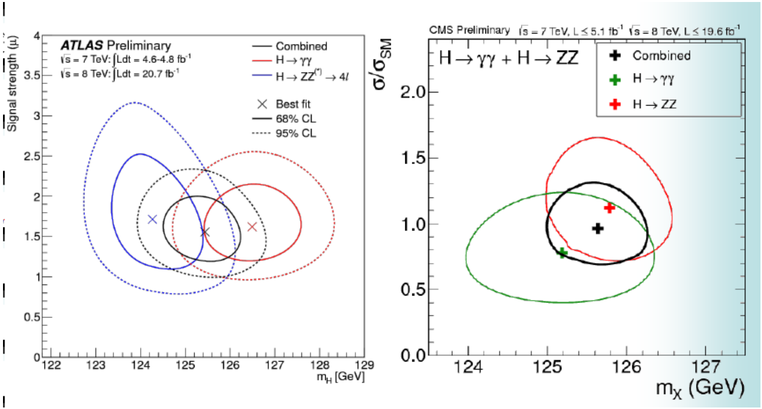


Alternatives?

- Spin 2: No reason for couplings to be at all SM-like...
- Spin 1: Landau-Yang
- Spin 0^-: $\phi F\tilde{F}$, 3σ against at LHC

Details: see Francesco Riva's talk!

LHC Higgs mass determination vs. rates

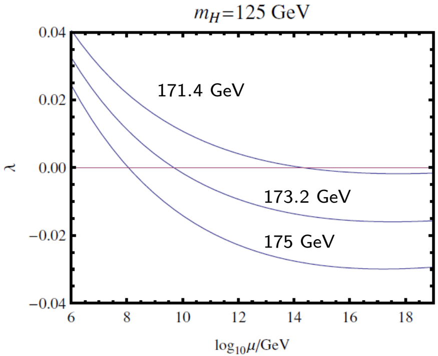


The SM Higgs in the UV

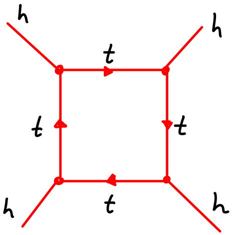
The SM Higgs in the UV

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

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



SM at 2-Loop

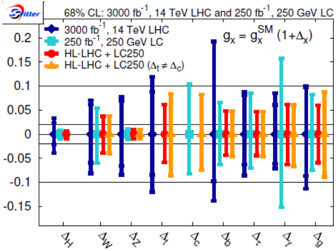


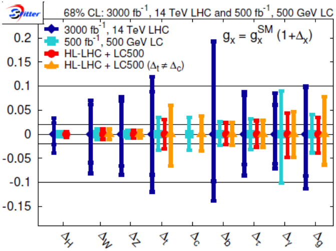
UV coupling is twice as sensitive to Δm_t than to Δm_h!

- Precise measurement of m_t crucial for QG, string pheno, cosmology!
- If no new physics @ LHC:
  LC “Top factory” + Higgs factory the future of high energy physics?

ILC TDR ’13 ($500 fb^{-1}$):

$$\Delta m_t/m_t = 0.02\% \, (34 MeV) \qquad \Delta m_h/m_h = 0.03\% \, (35 MeV)$$



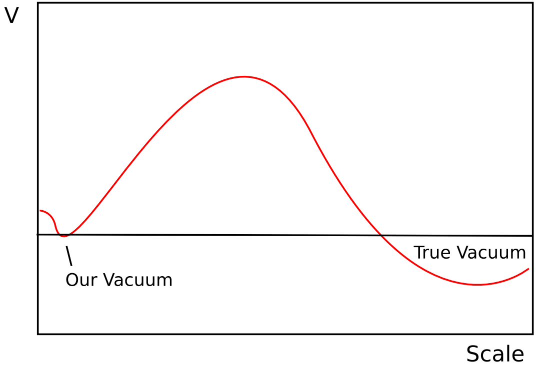


Some Resulting Questions

1. Do we end up in the correct vacuum after BB
2. Do we have to worry about instability?
3. Does this point to new physics at high scales?
4. What about the hierarchy problem?

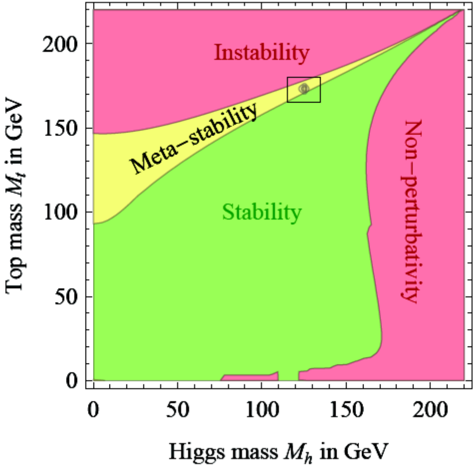
Ending up in our vacuum

Vacuum stability argument is for T=0
but where does a cooling universe settle? $V_{eff} \sim \lambda(h) h^4$



[Abel, Chu, Jaeckel, Khoze hep-th/0610334]:
Those vacua are preferred which contain more light degrees of freedom...
More detailed analysis for our model work in progress

Vacuum Stability



Degrassi et al.

- Special location in the "phase diagram" a hint against nonstandard EWSB at the TeV scale
- Generic in certain well-motivated UV completions (see this talk)

Several phenomena point towards intermediate new physics scales of $\Lambda_{NP} \gtrsim 10^9 \ldots 10^{14}$ GeV

- The Higgs potential
- Seesaw scale
- Axion DM
- $SU(2) \times U(1)$ unification

Is this a coincidence?

These scales, and our seemingly dangerous place on the $m_t - m_h$ map, may be a direct consequence of the underlying UV completion

New physics near the scale of instability

We interpret our location in the $m_t - m_h$ plane as a hint towards

- SM-*like* EWSB at the weak scale and
- new physics at a high scale $\Lambda_{NP} \gtrsim \Lambda_{\lambda=0}$.

$\Rightarrow$ Hierarchy Problem?

$$\delta m_h^2 \propto \Lambda^2 \quad \text{or} \quad \delta m_h^2 \propto M^2(const. + \log \frac{M}{\mu})?$$

- is 10^{-10} fine tuning (high scale SUSY) more problematic than 10^{-4}?
- Λ_{CC} finetuning dominates

Naturalness/fine tuning arguments may have misled us...

What is the origin of $\lambda = 0$ in the UV?

our picture

Shift symmetric High scale SUSY models

[Hebecker, AK, Weigand '12][Ibanez et al. '12][Hebecker, AK, Weigand '13]

- The SM is embedded into a supersymmetric (stringy) theory without treelevel higgs potential
- The observed quartic coupling and weak scale are generated radiatively

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The same scale choice can explain $\lambda = 0$, Axion CDM and provide a viable seesaw scale! [Ibanez et al. '13]

Shift Symmetry

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

The mechanism: 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 $F^S \neq 0 \Longrightarrow$ special relations between soft parameters!

see e.g. [Ibáñez, Muñoz]

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

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]

Shift Symmetry

Higgs mass matrix from shift symmetry:

$$V = \left[\begin{array}{c} H_u \\ \overline{H}_d \end{array}\right]^\dagger \left[\begin{array}{cc} |\mu|^2 + m_H^2 & |\mu|^2 + m_H^2 \\ |\mu|^2 + m_H^2 & |\mu|^2 + m_H^2 \end{array}\right] \left[\begin{array}{c} H_u \\ \overline{H}_d \end{array}\right]$$

SM Higgs from the light (massless) eigenstate $H^{light} = \frac{1}{\sqrt{2}}(H_u - \overline{H}_d)$

$$|\alpha| = 45^\circ, \quad \tan\beta = 1$$

Mass eigenstates $\sim$ flat directions of MSSM D-Term potential

$$V \sim (|H_u^0|^2 - |H_d^0|^2)^2$$

The quartic coupling λ_{tree} of the light Higgs vanishes at the "soft" scale

Alternative proposal: exchange symmetry [Ibáñez, Marchesano, Regalado, Valenzuela (arXiv:1206.2655)]

High scale radiative corrections to m_h

Radiative corrections

I. Violation of Higgs sector shift/exchange symmetry

$$\mathcal{W} = y_t H_u T_R Q_L$$

(remember: $\tan\beta = 1 \Rightarrow y_t \gg y_b$)

Assume the symmetry to be good at $m_C \gg m_S$ and consider RG evolution of mass matrix. This yields [A. Hebecker, AK, T. Weigand '12]

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

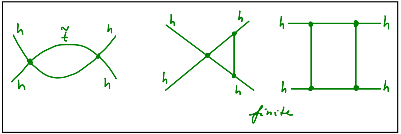
We are lucky: $y_t^4(m_S) \ll 1!$ [Hall, Nomura]

Threshold effects

Naively, λ at m_S is given by SUSY tree relation - but what is m_S?

m_S is unphysical - need 1-Loop decoupling to determine where $\lambda = \lambda_{tree}$

II. Threshold corrections to λ



$$\delta\lambda_T(m_S) = \frac{3y_t^4}{16\pi^2}\left[\frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right) + 2\log\left(\frac{m_{\tilde{t}}}{m_S}\right)\right]$$

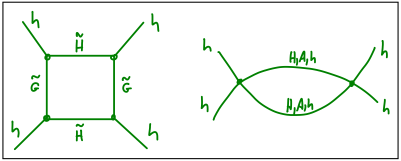
$X_t \sim A_t - \mu$

[Okada, Yamaguchi, Yanagida '91] ...

We are again lucky that $y_t^4(m_S) \ll 1$

Threshold effects

Furthermore: gauginos, Higgsinos, heavy Higgs sector



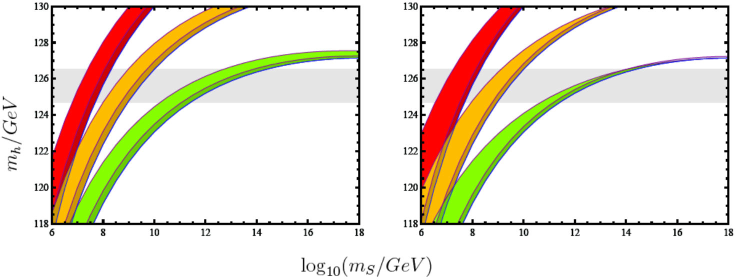
$$\delta\lambda^{LL}_{GH+A} \approx \frac{\tilde{b}_\lambda}{16\pi^2}\left[\log\frac{m_\chi}{m_S} - \frac{1}{4}\log\frac{m_A}{m_S}\right]$$

$m_\chi = \max(M,\mu)$, $\tilde{b}_\lambda < 0$ see also [Hollik et al. '02][Giudice, Strumia '11]

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 $m_C^2 \sim m_S M_{Pl}$)

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

$\Rightarrow \delta m_h < 2$ GeV for $m_S \sim 10^9$ GeV.

Effects from extended SUSY/MSSM

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

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

where e.g. $\vec{P} \sim (F_{5,6}, D)$

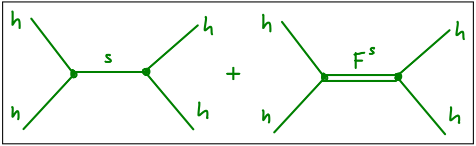
The relation
"$\tan\beta = 1 \Rightarrow \lambda = 0$"
relies on SUSY decoupling of P^1, P^2!

This might be problematic for "non-SUSY model" explanations of $\lambda = 0$
For a discussion of this see [A. Hebecker, AK, T. Weigand '13]

4D effective description as F term:

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

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



(Nice twist: make SUSY gauge sector heavy via Dirac masses and decouple D term (and F term): small λ for arbitrary $\tan\beta$!
[Fox, Nelson, Weiner '02][J. Unwin '12])

Consider soft mass term

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

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

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

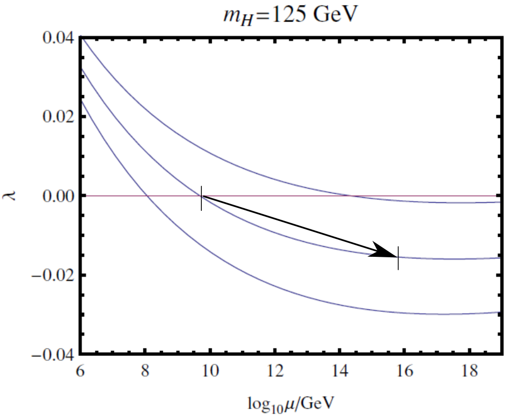
Amusing feature:

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

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

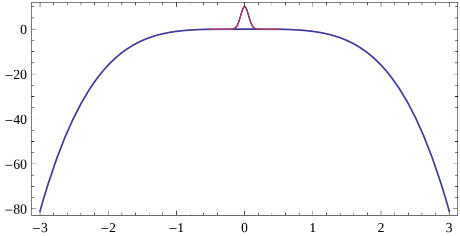
$$-M^2 < m_s^2 < 0, \quad |m_s| \sim M/10$$

would bring us to arbitrarily high scales:



UV completion in unstable regime?

Can we reliably match SM to our UV SUSY model in the $\lambda < 0$ regime?



- $\lambda < 0$ does not introduce a time scale of instability
- Localized vacuum state near $h \sim 0$ can live long compared to m_S^{-1} (limited by loop suppressed instabilities and IR cutoff)
- This should be sufficient to allow perturbative matching $\lambda \to \lambda_{SM}$
- RG running towards IR $\to$ $h = 0$ quickly becomes local minimum again

Conclusions

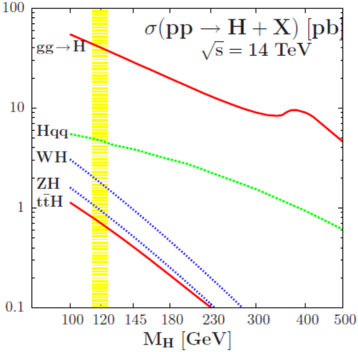
- After the Discovery: We seem to live on the verge of instability
- Nature's critical location in the $m_t - m_h$ plane can be seen as a hint *against* nonstandard EWSB
- UV completions with an approximately flat Higgs potential at an intermediate — high SUSY scale can explain the apparent metastability, neutrino masses and Axion CDM
- Several promising approaches in Het. and Type II exist
- Work remains to be done wrt. Axion phenomenology, cosmology + inflation
- Effects from the extended sector may place the UV completion in the unstable regime $\lambda < 0$ and/or alleviate the constraints on $\tan\beta = 1$

Thank you for your attention!

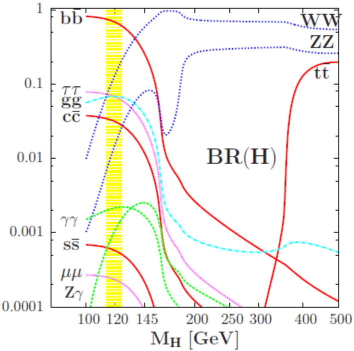
Higgs properties at future Hadron and Lepton colliders

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%



$\sigma(pp \to H + X)$ [pb]
$\sqrt{s} = 14$ TeV
100
10
1
0.1
gg→H
Hqq
WH
ZH
$t\bar{t}H$
100 120 145 180 230 300 400 500
M_H [GeV]



BR(H)
1
0.1
0.01
0.001
0.0001
$b\bar{b}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
WW
ZZ
tt
100 120 145 200 250 300 400 500
M_H [GeV]