The Higgs boson and the scale of new physics

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LHC- The First Part of the Journey
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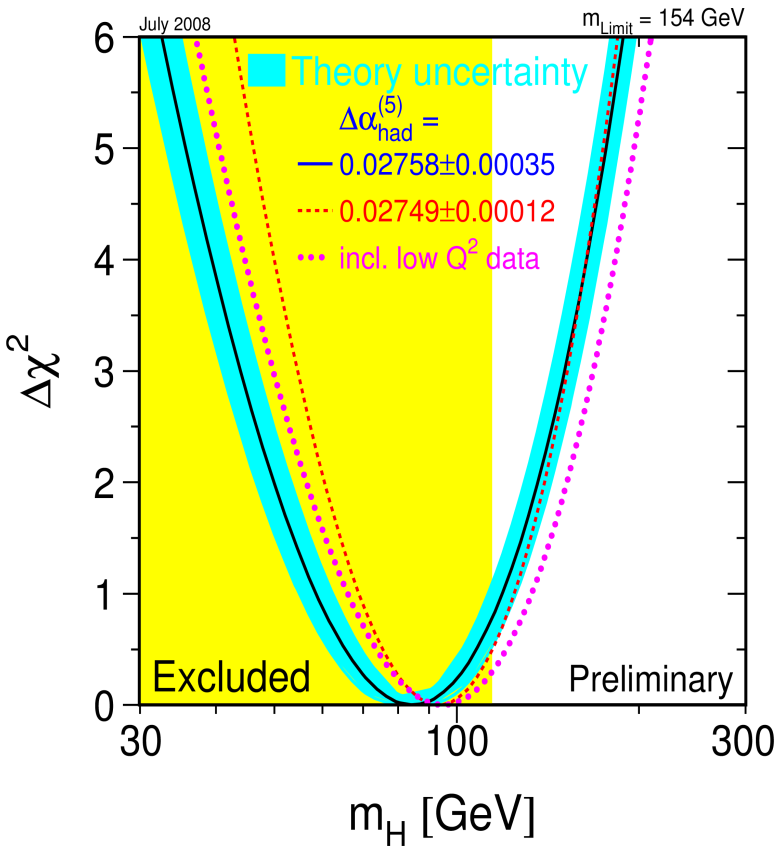
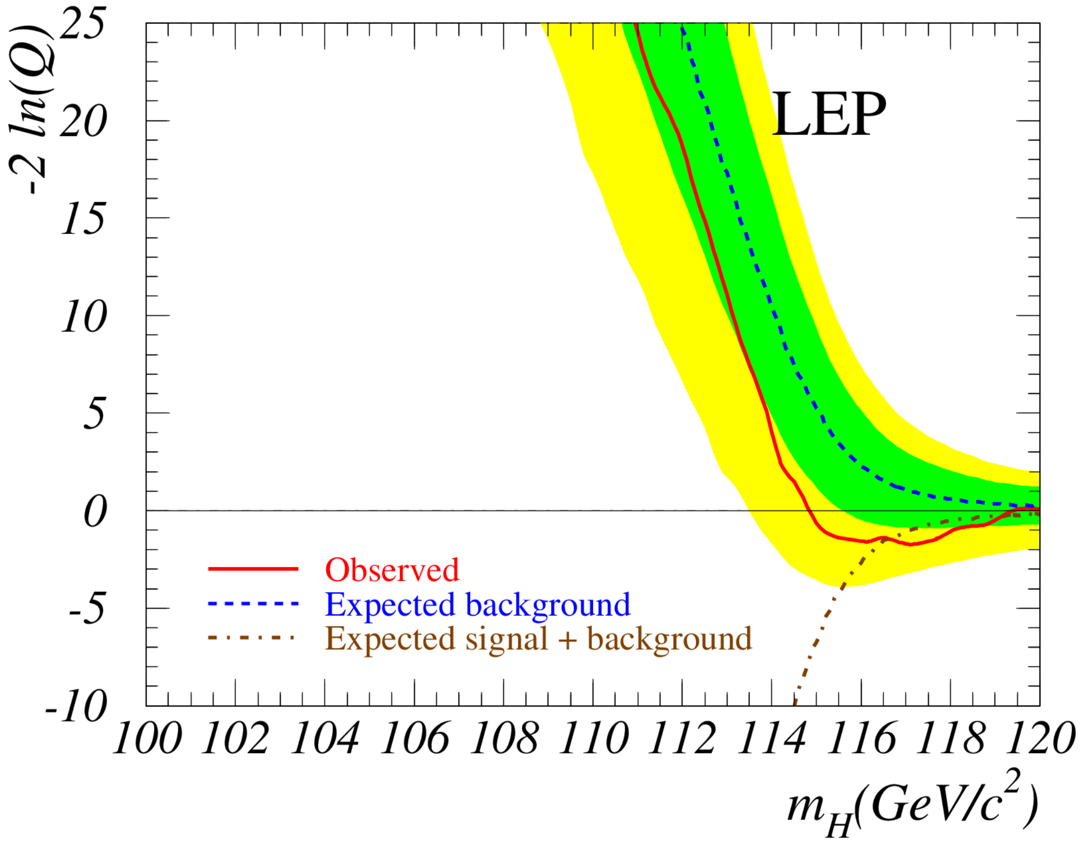
Outline

- Past and present informations on the Higgs boson
- Implications of $M_h \sim 125$ GeV for New Physics: vacuum stability, MSSM
- Conclusions

The past: LEP





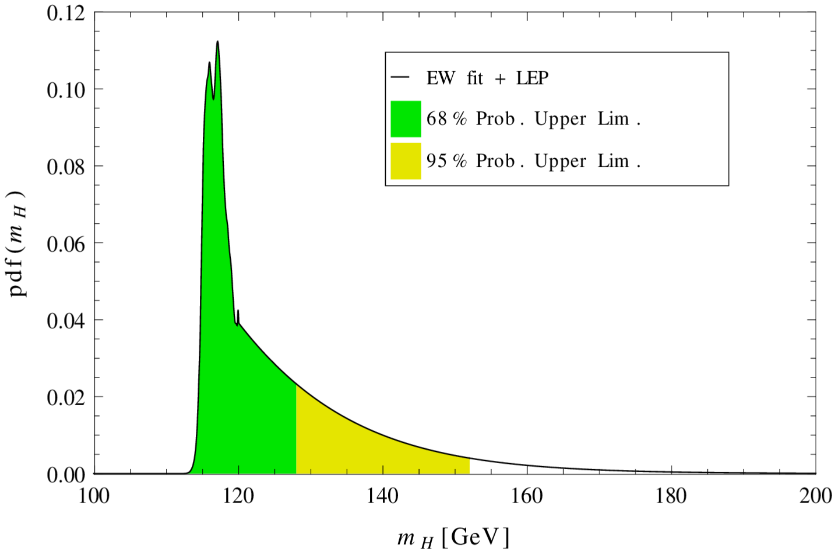
$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

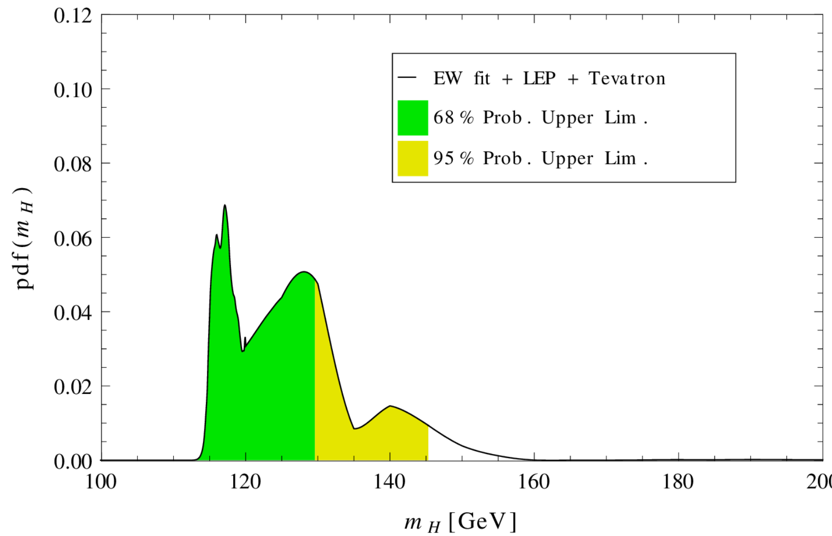
The past: LEP+ Tevatron

Combining direct and indirect information:

D'Agostini, G.D.1999

$$\mathrm{pdf}(M_h) \propto \frac{Q(M_h)e^{-(\chi^2/2)}}{M_h}$$

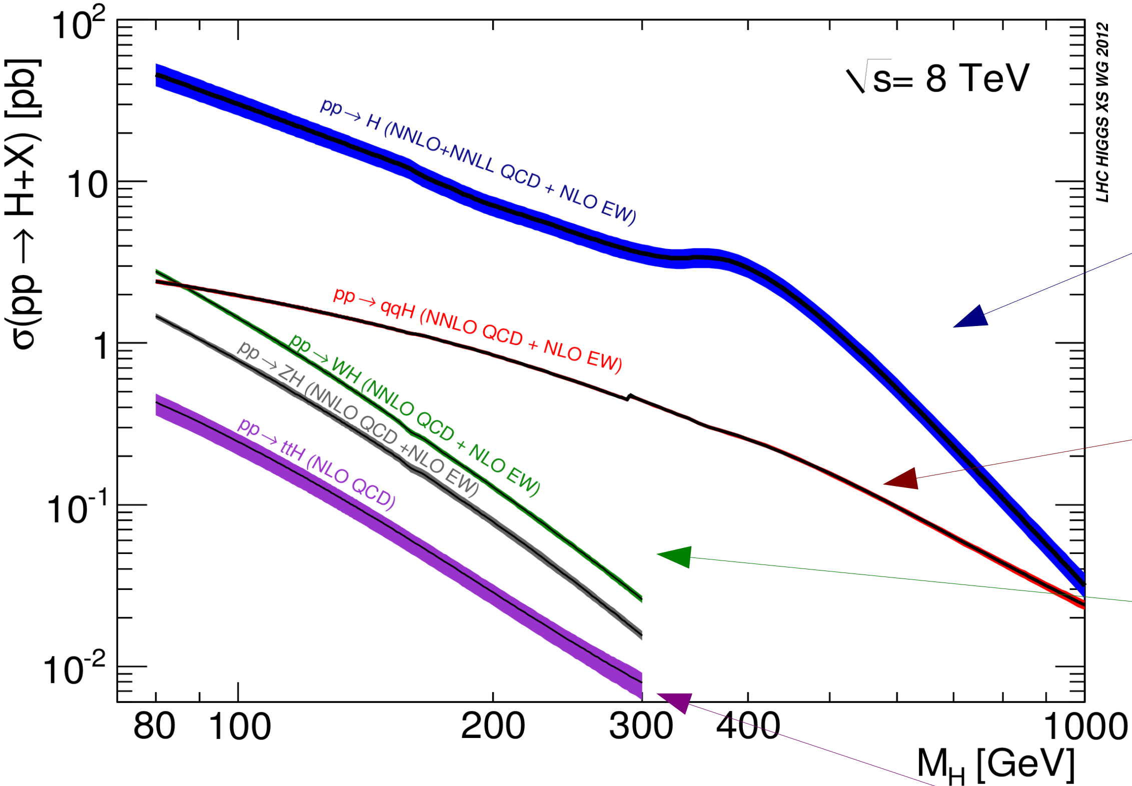


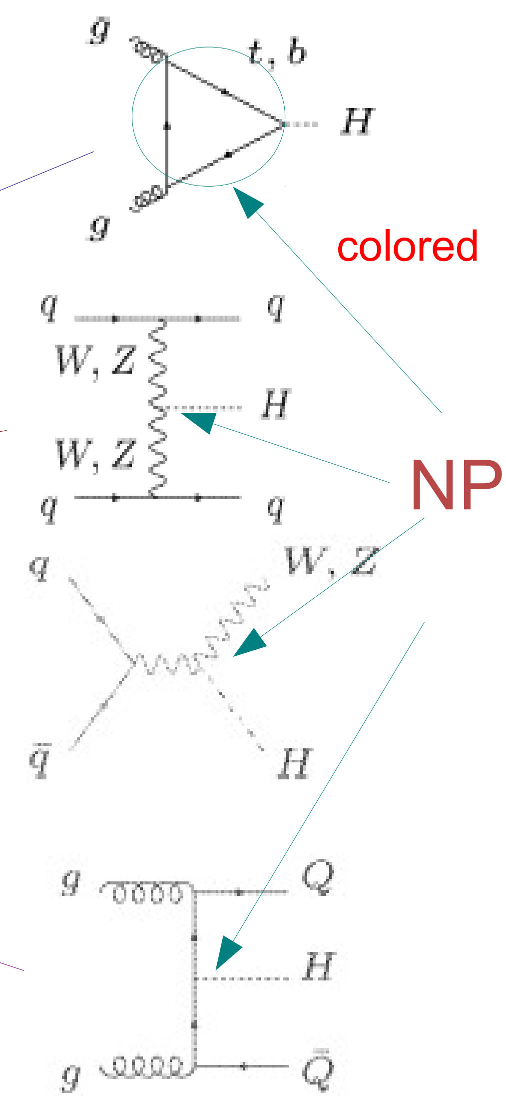


courtesy of S. Di Vita

The consistency of the (minimal) SM at the quantum level predicts a Higgs boss with mass between 110 and 160 GeV

The present: LHC Higgs Production





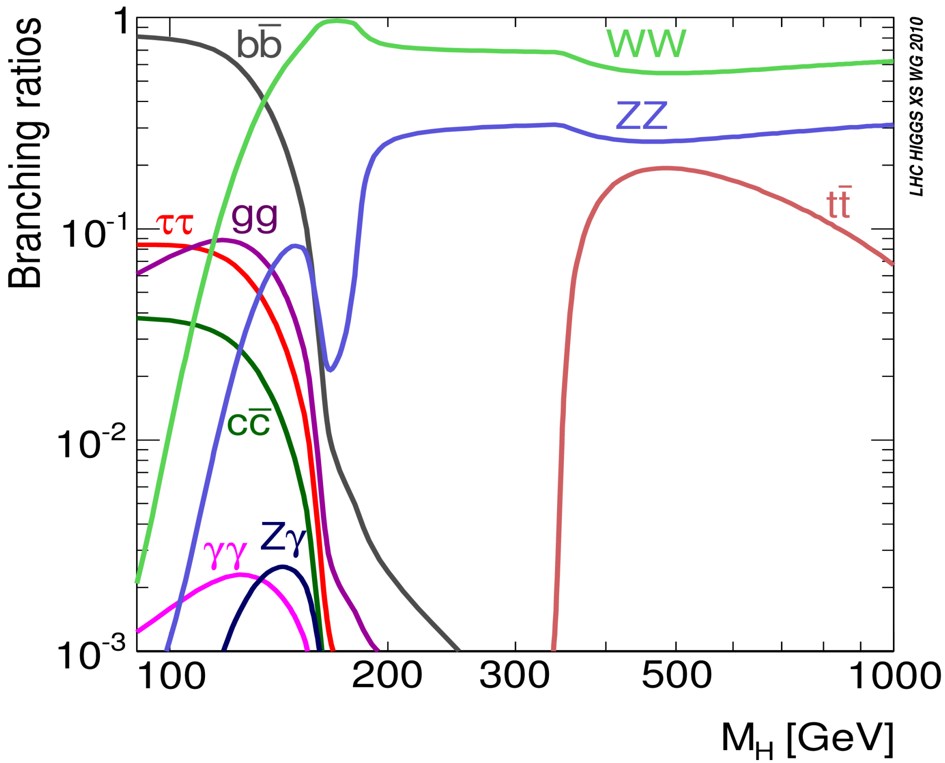
Gluon-fusion process dominant

Weak-boson fusion has a very good-signal/background ratio

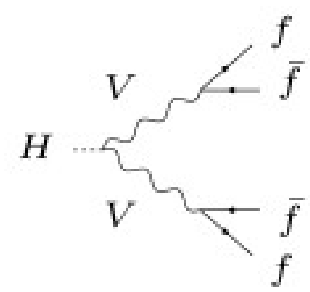
Bands include: PDF + α_s + scale uncertainties

Heavy replicas of SM particles contribute to gluon-fusion: ex. 4th generation

The present: LHC Higgs Decays

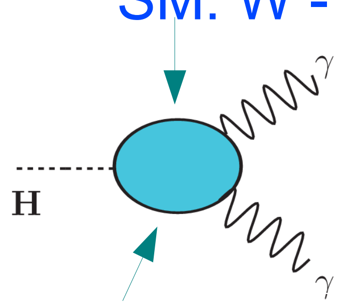


Golden Channel V=Z



Low Higgs mass

SM: W - t

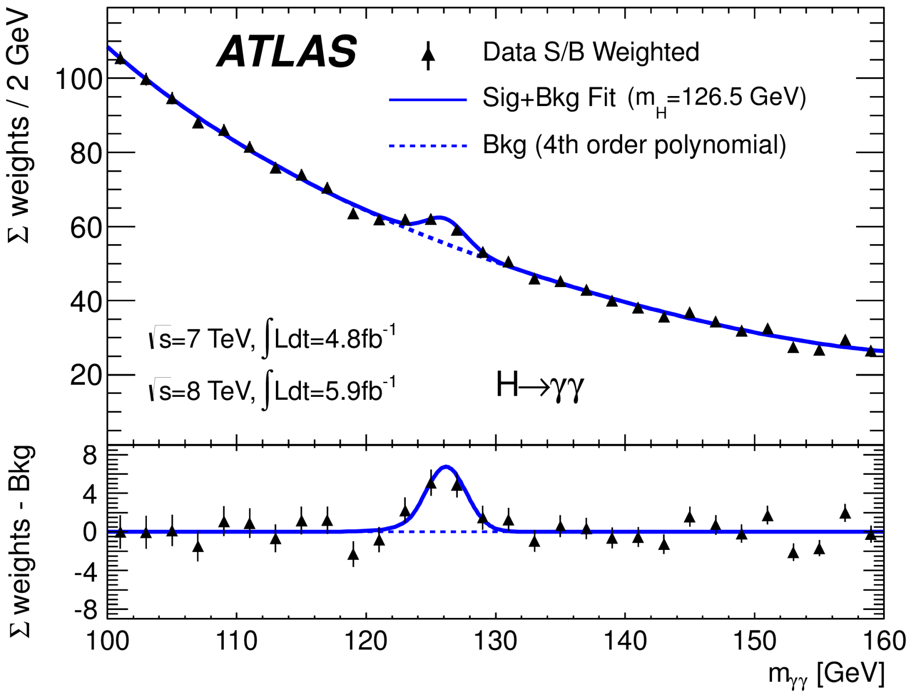


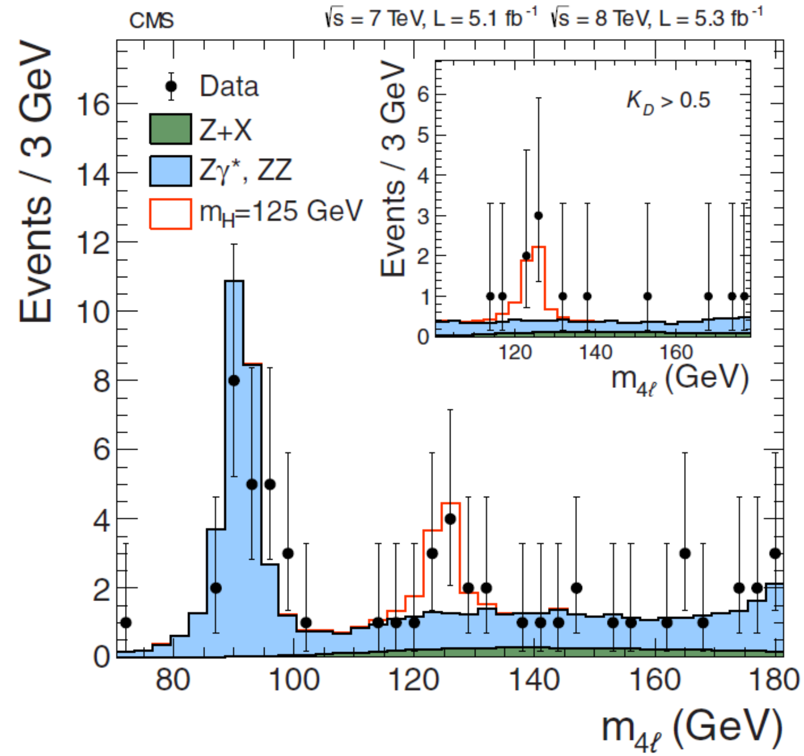
NP: white + colored

A NP increase in gluon-fusion X-sect. often corresponds to a decrease of BR$(H \to \gamma\gamma)$

The BR $(H \to \gamma\gamma)$ can increase if NP reduces the other BR's

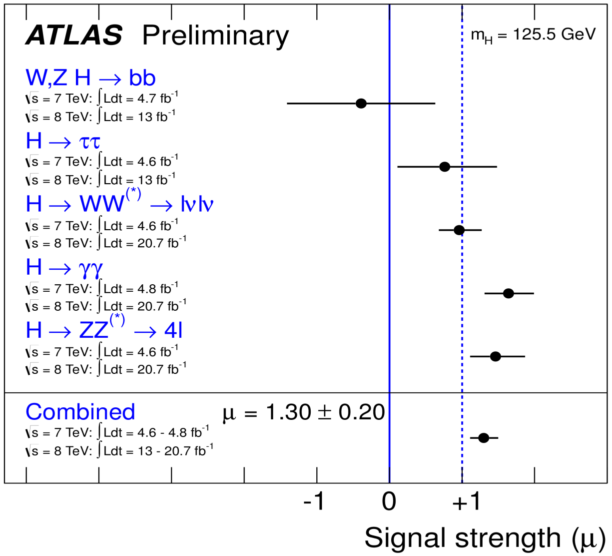
The present: LHC 4th of July 2012 news

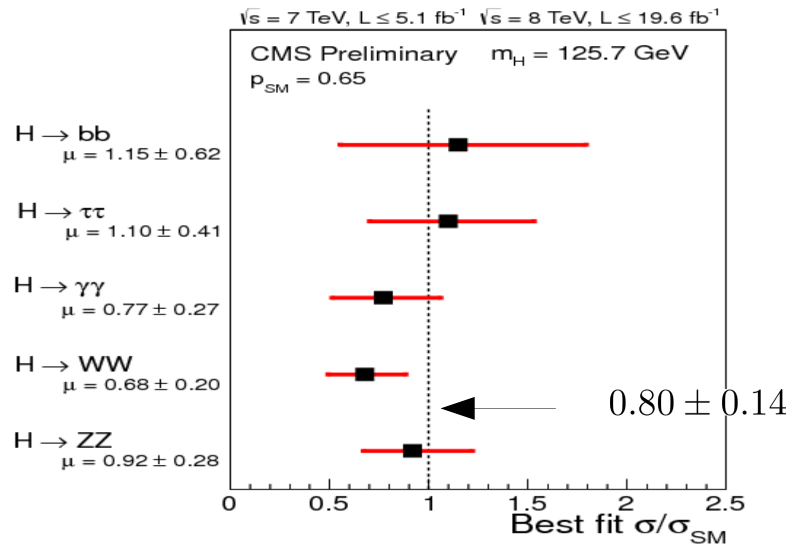


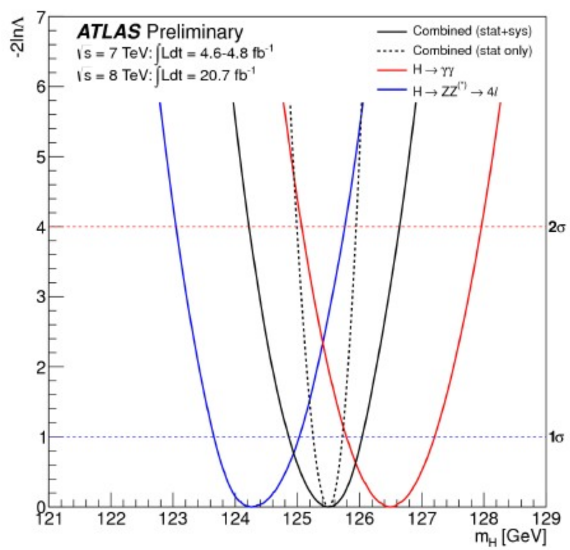


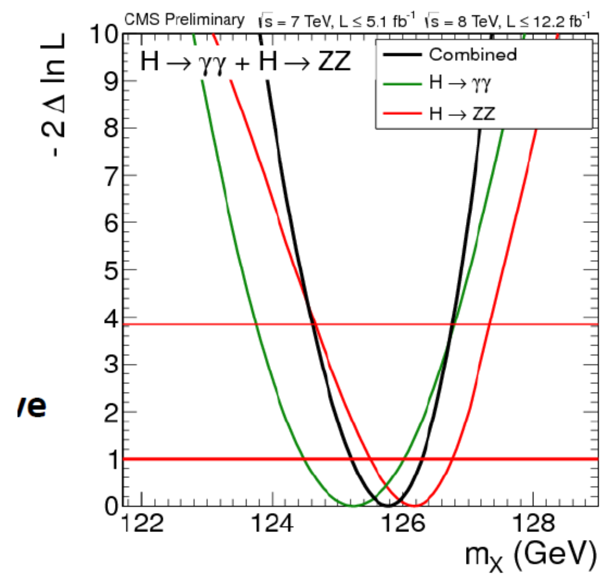
Clear evidence of a new particle
with properties compatible with those of the SM Higgs boson

The present: LHC
Studying the properties of the new particle





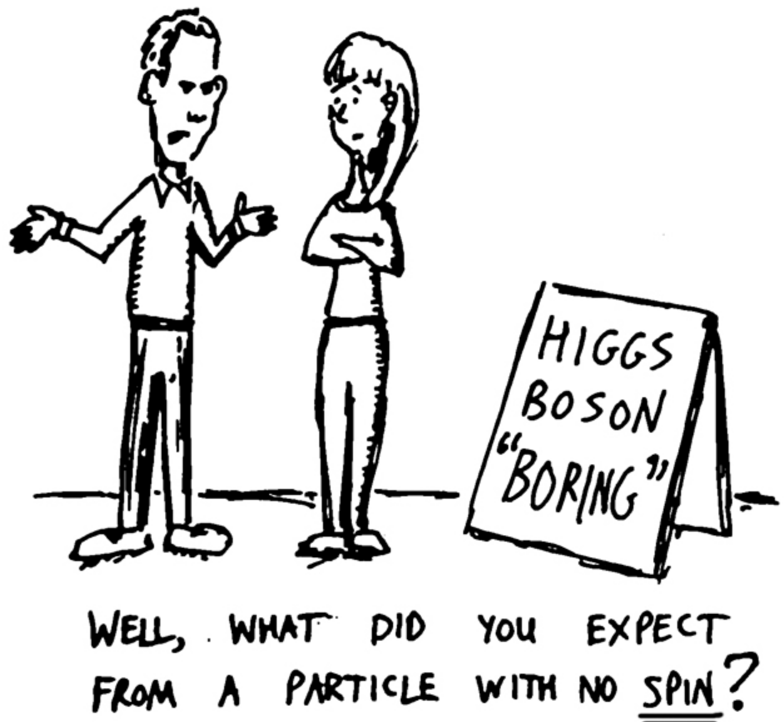




$$M_h = 125.5 \pm 0.2(stat)\ ^{+0.5}_{-0.6}(syst)\ \ \mathrm{GeV}$$

$$M_h = 125.7 \pm 0.3(stat) \pm 0.3(syst)\ \ \mathrm{GeV}$$

Implications of M_h ~ 125 GeV



Reversing the heavy Higgs argument

Specific type of NP could allow a heavy Higgs in the EW fit ("conspiracy"). Take

$$\begin{aligned} \hat{\rho} &= \rho_0 + \delta\rho \, (\rho_0^{\rm SM} = 1, \delta\rho \leftrightarrow (\epsilon_1, T)) \\ \Delta\hat{r}_W &\leftrightarrow (\epsilon_3, S) \end{aligned}$$

$$\begin{aligned} \sin^2\theta_{eff}^{lept} &\sim \frac{1}{2}\left\{1 - \left[1 - \frac{4A^2}{M_Z^2\,\hat{\rho}\,(1-\Delta\hat{r}_W)}\right]^{1/2}\right\} \\ &\sim (\sin^2\theta_{eff}^{lept})^\circ + c_1 \ln\left(\frac{M_H}{M_H^\circ}\right) + c_2\left[\frac{(\Delta\alpha)_h}{(\Delta\alpha)_h^\circ} - 1\right] - c_3\left[\left(\frac{M_t}{M_t^\circ}\right)^2 - 1\right] + \ldots \end{aligned}$$

$c_i > 0$

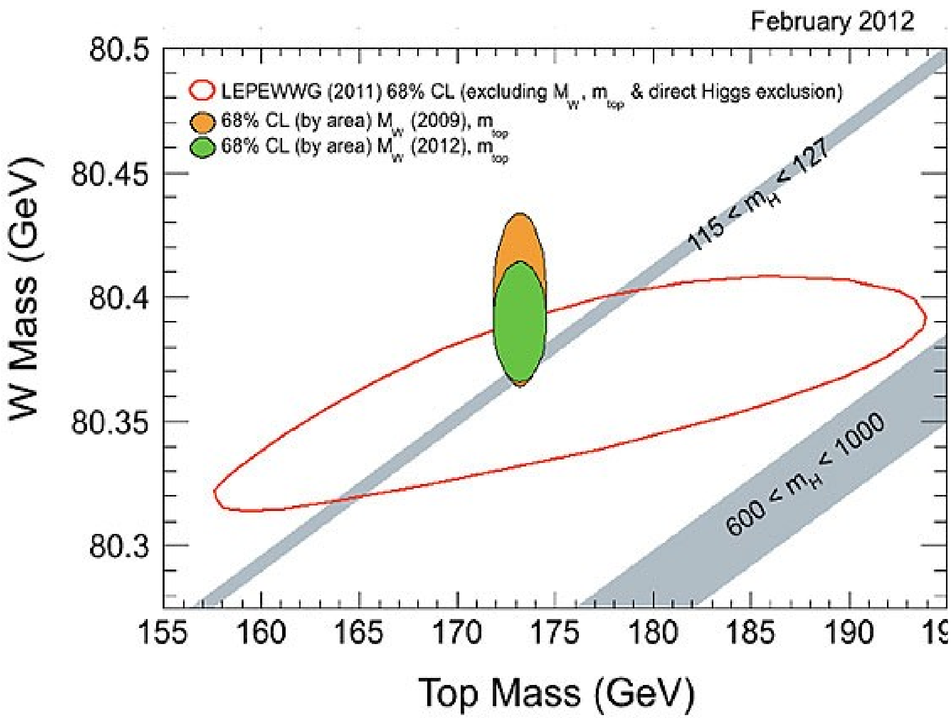
To increase the fitted M_H : $\left\{ \begin{array}{l} \hat{\rho} > 1 \rightarrow \left\{ \begin{array}{l} \rho_0 > 1 \leftarrow \\ \delta\rho > 0 \leftarrow \end{array} \right. \\ \Delta\hat{r}_W < 0 \end{array} \right.$

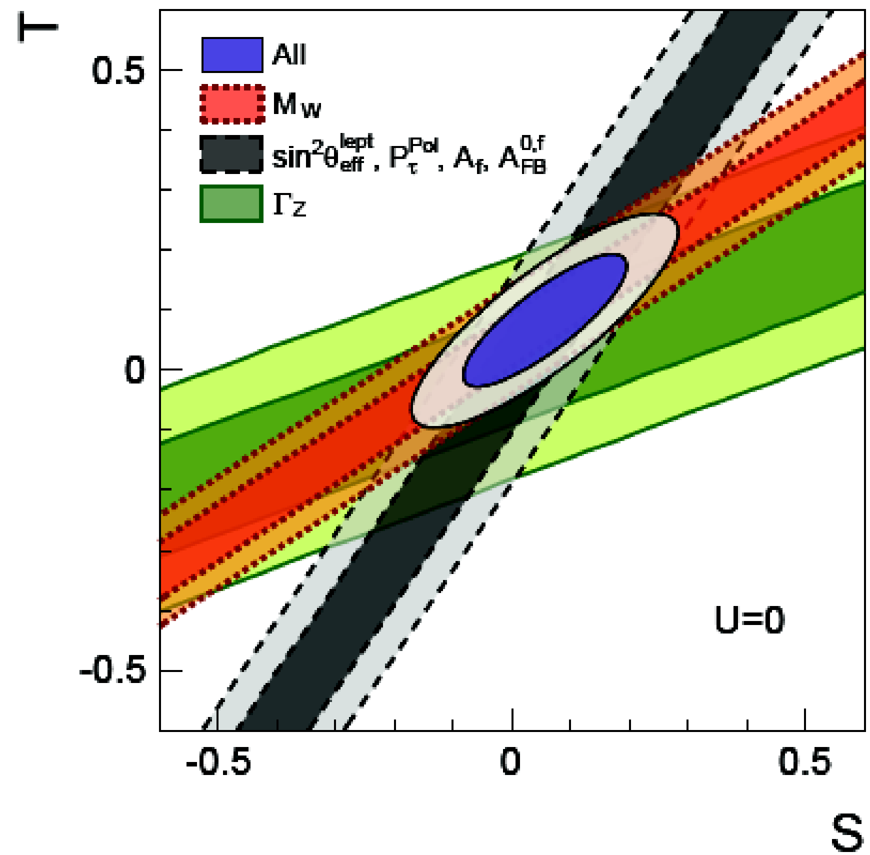
Extra Z

Isosplitt (s)fermions, Multi Higgs models,

Light sleptons

NP (if there) seems to be of the decoupling type





Ciuchini, Franco, Mishima, Silvestrini (13)

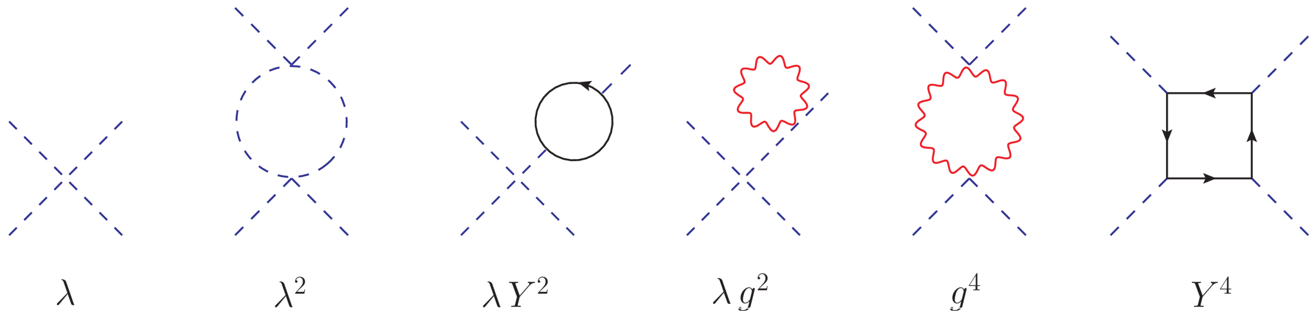
(Meta)Stability bound

Quantum corrections to the classical Higgs potential can modify its shape

$$V^{class}(\phi) = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4 \longrightarrow V^{\text{eff}} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu)$$

$$\phi \sim \mu \gg v$$

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) - 2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2 + \ldots\right]$$

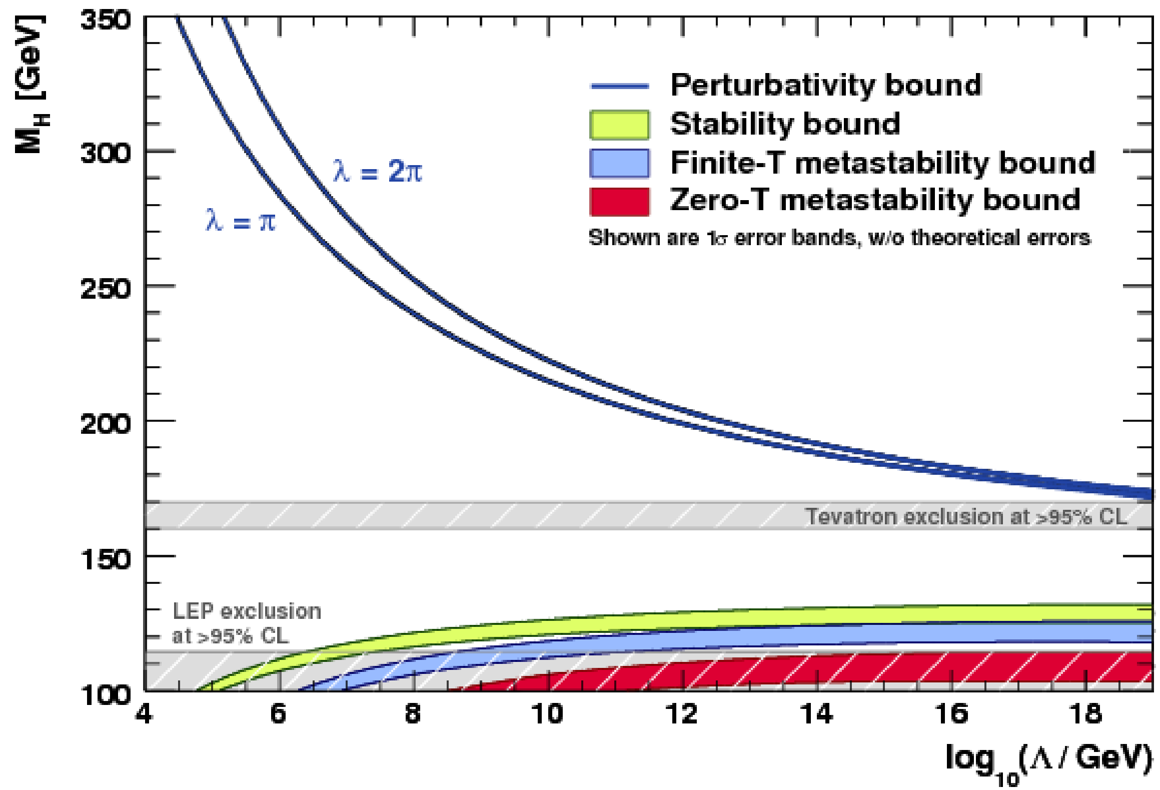
M_H large: λ^2 wins $\quad \lambda(M_t) \rightarrow \lambda(\mu) \gg 1 \quad$ non-perturbative regime, Landau pole

M_H small: $-Y_t^4$ wins $\quad \lambda(M_t) \rightarrow \lambda(\mu) \ll 1$

Ellis et al. 09

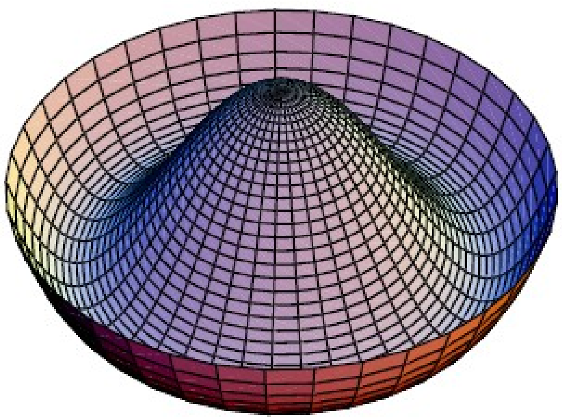
M_H ~ 125-126 GeV: $-Y_t^4$ wins
no problem with the Landau pole

Running depends on
M_t, α_s ....



M_H ~ 125-126 GeV: $-Y_t^4$ wins: $\lambda(M_t)$ ~ 0.14 runs towards smaller values and can eventually become negative. If so the potential is either unbounded from below or can develop a second (deeper) minimun at large field values

Illustrative



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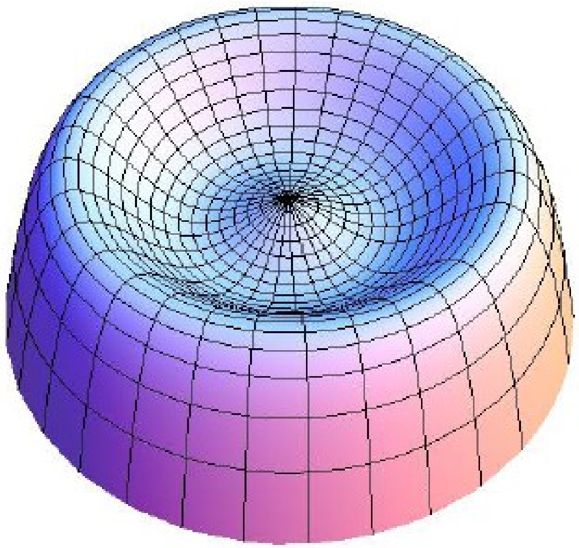
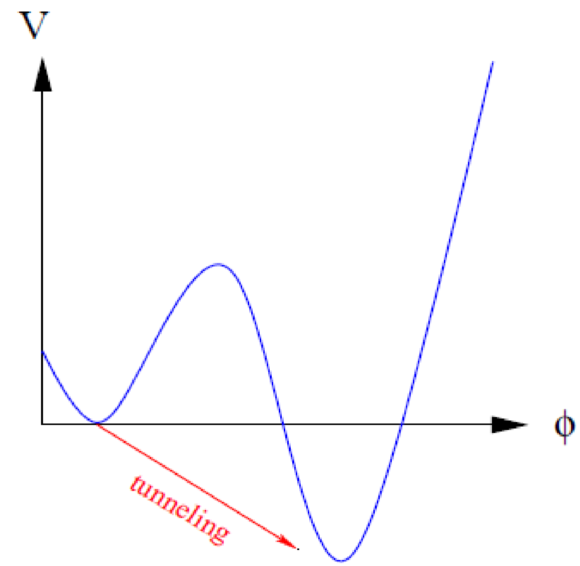


If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

The problem



There is a transition probability between the false and true vacua

It is really a problem ?

It is a problem that must be cured via the appearance of New Physics at a scale below that where the potential become unstable ONLY if the transition probability is smaller than the life of the universe.

Metastability condition: if λ becomes negative provided it remains small in absolute magnitude the SM vacuum is unstable but sufficiently long-lived compared to the age of the Universe

Transition probability: $p \sim e^{-\frac{8\pi^2}{3|\lambda|}}$

Vacuum stability at NNLO

- Two-loop effective potential
  (complete) Ford, Jack, Jones 92,97; Martin (02)

- Three-loop beta functions
  gauge Mihaila, Salomon, Steinhauser (12)
  Yukawa, Higgs Chetyrkin, Zoller (12, 13,); Bednyakov et al. (13)

- Two-loop threshold corrections at the weak scale
  y_t: gauge x QCD Bezrukov, Kalmykov, Kniehl, Shaposhnikov (12)
  λ: Yuk x QCD, Bezrukov et al. (12), Di Vita et al. (12)
  SM gaugeless Di Vita, Elias-Miro', Espinosa, Giudice, Isidori, Strumia, G.D. (12)

Dominant theory uncertainty on the Higgs mass value that ensures vacuum stability comes from the residual missing two-loop threshold corrections for λ at the weak scale

Full SM two-loop threshold corrections to λ, y_t and m

Buttazzo,Giardino, Giudice, Sala, Salvio, Strumia, G.D. (13)

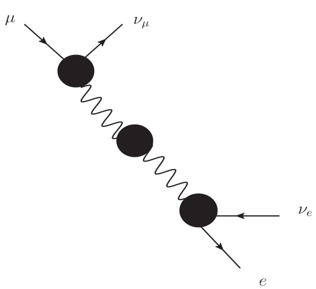
$\lambda(\mu)$ in terms of G_μ, $\alpha(M_Z)$, M_h, M_t, M_z,M_w (pole masses)

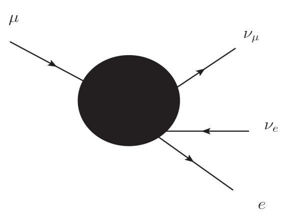
$$\lambda(\mu) = \frac{G_\mu}{\sqrt{2}} M_h^2 - \delta\lambda^{(1)}(\mu) - \delta\lambda^{(2)}(\mu)$$

Sirlin, Zucchini (86)

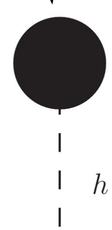
$$\frac{G_\mu}{\sqrt{2}} = \frac{1}{2v_0^2}(1+\Delta r_0)$$

$$\delta\lambda^{(2)}(\mu) \;=\; \frac{G_\mu}{\sqrt{2}} M_h^2 \left\{ -\frac{\Delta r_0^{(1)}}{M_h^2}\left[M_h^2 \Delta r_0^{(1)} + \frac{3\,T^{(1)}}{2\,v_{\rm ren}} + \mathrm{Re}\,\Pi^{(1)}_{hh}(M_h^2)\right] + \Delta r_0^{(2)} + \frac{1}{M_h^2}\left[\frac{T^{(2)}}{v_{\rm ren}} + \mathrm{Re}\,\Pi^{(2)}_{hh}(M_h^2)\right]\right\}_{\rm fin} + \Delta_\lambda$$

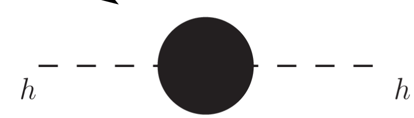




analytical



analytical

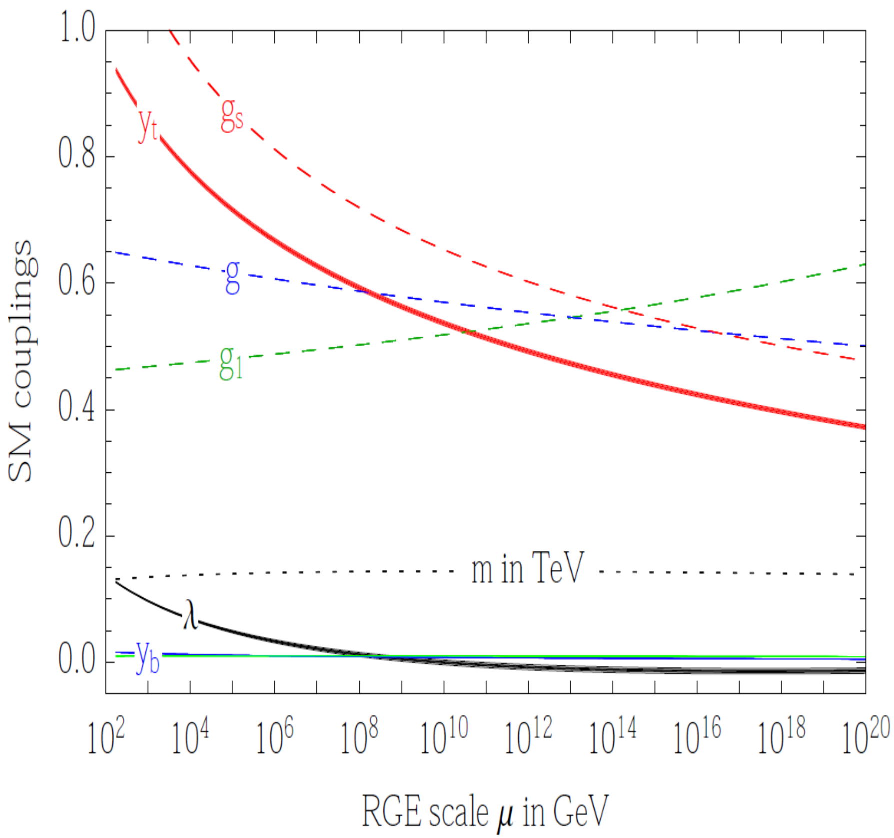


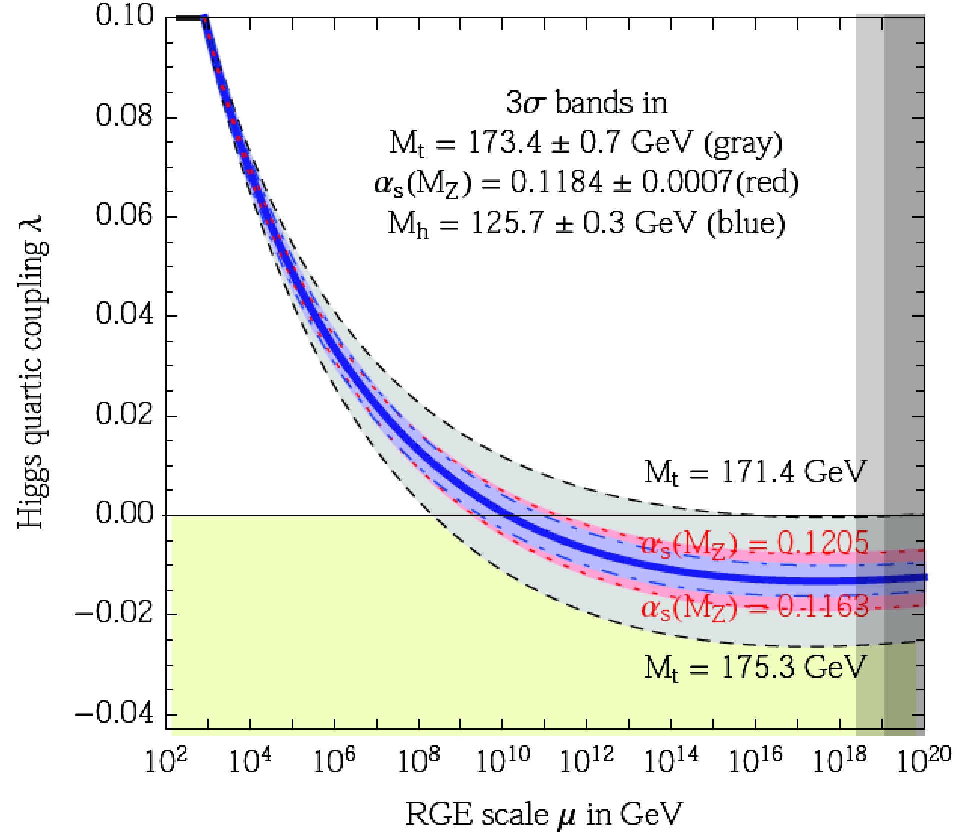
numerical,
Martin's loop functions

Martin (02,03)

$$\delta\lambda^{(2)}_{SM}(\mu = M_t) = -\frac{9.545}{(4\pi)^4}, \qquad \delta\lambda^{(2)}_{G.L.}(\mu = M_t) = -\frac{9.605}{(4\pi)^4}$$

$$\lambda(\mu = M_t) = 0.12709 + 0.00206\left(\tfrac{M_h}{\rm GeV} - 125.66\right) - 0.00004\left(\tfrac{M_t}{\rm GeV} - 173.15\right) \pm 0.00035_{\rm th}$$



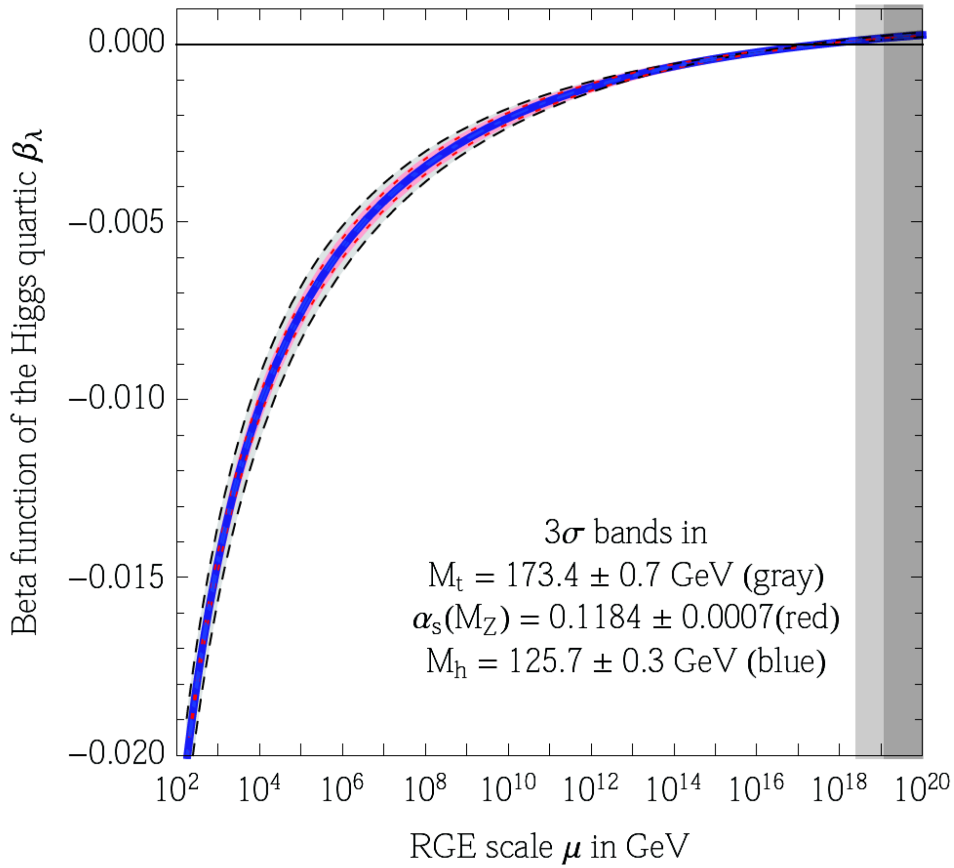


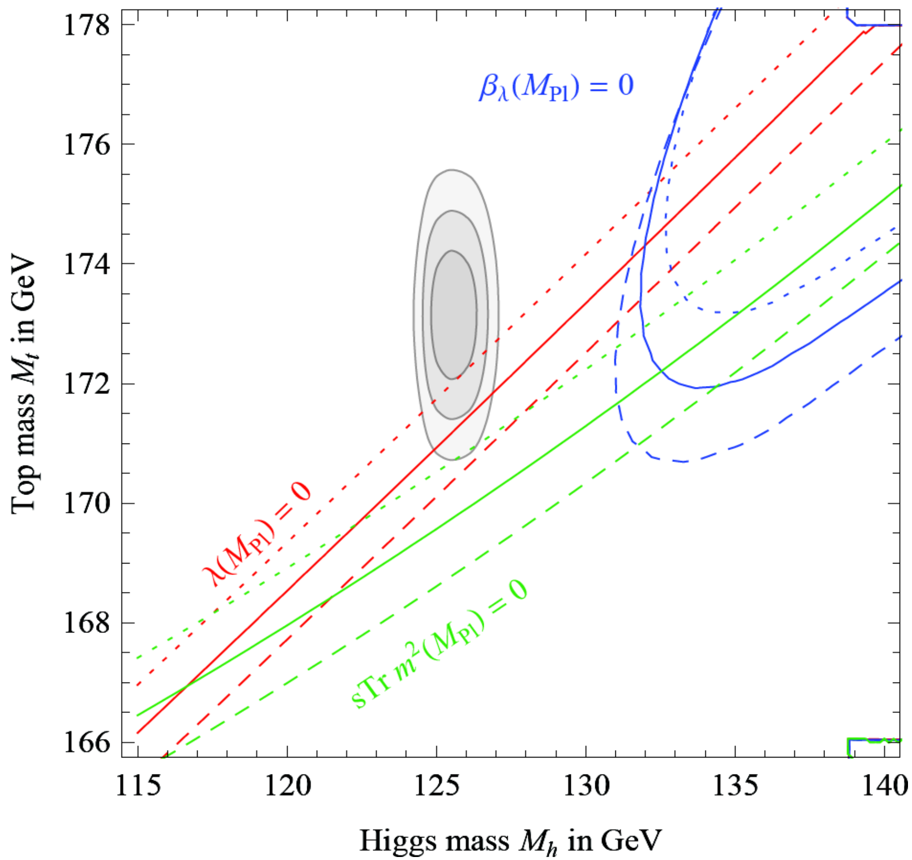
Full stability is lost at $\Lambda \sim 10^{10}$-10^{11} GeV but λ never becomes too negative

$$\lambda(M_{Pl.}) = -0.0128 + 0.0010\left(\frac{M_h - 125.66\,\text{GeV}}{0.34\,\text{GeV}}\right) - 0.0043\left(\frac{M_t - 173.35\,\text{GeV}}{0.65\,\text{GeV}}\right) + 0.0018\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right)$$

Both λ and β_λ are very close to zero around the Planck mass

Are they vanishing there?





$\lambda(M_{Pl})$=0 → M_t ~ 171 GeV

Veltman's condition →M_t ~ 169 GeV

M_t = 173.4 ± 0.7 GeV

Pole mass

Top pole vs. $\overline{\text{MS}}$ mass

Is the Tevatron number really the "pole" (what is?) mass?
Monte Carlo are used to reconstruct the top pole mass form its decays products
that contain jets, missing energy and initial state radiation.

$M_t^{\overline{MS}}$ can be extracted from total production cross section

$$M_t^{\overline{MS}}(M_t) = 163.3 \pm 2.7\,\mathrm{GeV} \rightarrow M_t = 173.3 \pm 2.8\,\mathrm{GeV}$$

Alekhin, Djouadi, Moch, 12

Consistent with the standard value albeit with a larger error.

N.B.

Fermion masses are parameters of the QCD Lagrangian, not of the EW one, Yukawas are.
$\overline{\text{MS}}$ masses are gauge invariant objects in QCD, not in EW, Yukawas are.
The vacuum is not a parameter of the EW Lagrangian. Its definition is not unique:

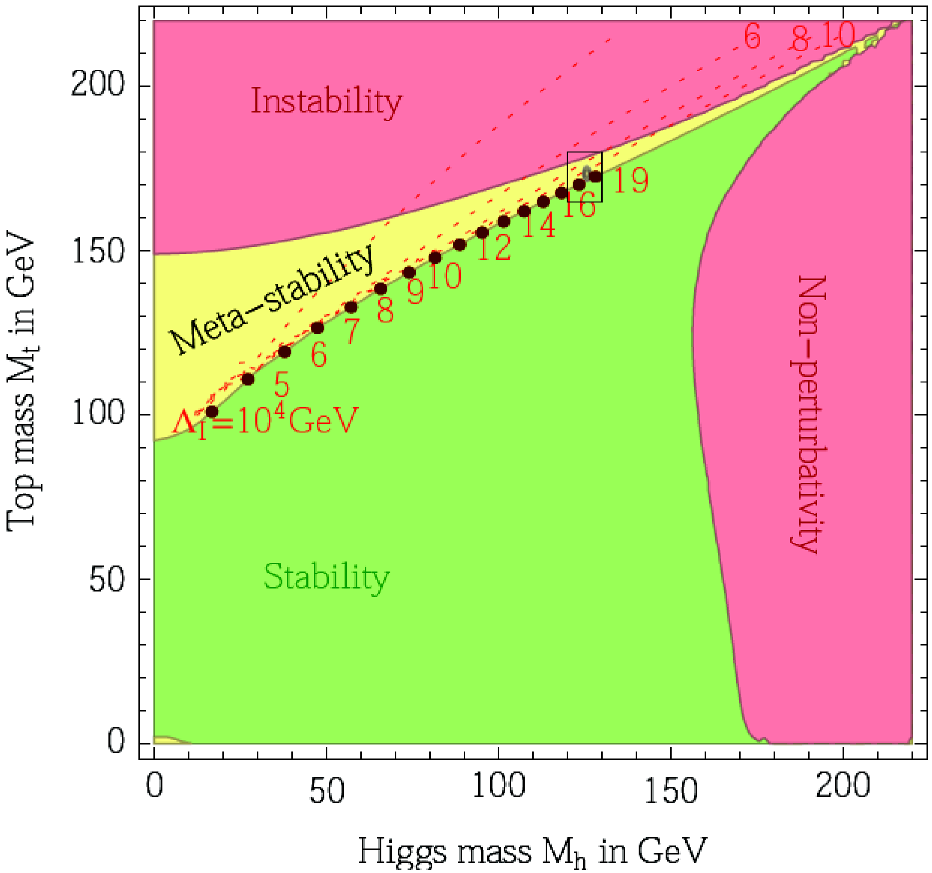
- Minimum of the tree-level potential
  $\rightarrow$ $M_t^{\overline{MS}}$ g.i. but large EW corrections in the relation pole-$\overline{\text{MS}}$ mass (~ M_t^4)

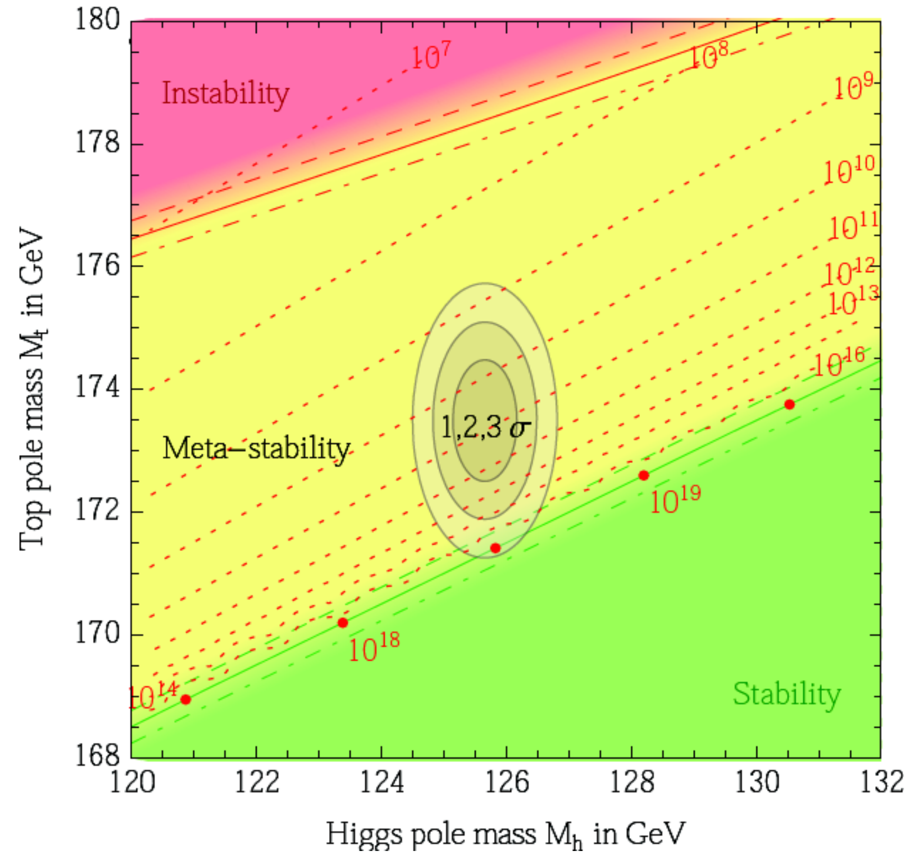
  Jegerlehner, Kalmykov, Kniehl, 12

  But direct extraction of $M_t^{\overline{MS}}$ requires EW correction

- Minimum of the radiatively corrected potential
  $\rightarrow$ $M_t^{\overline{MS}}$ not g.i. (problem? $\overline{\text{MS}}$ mass is not a physical quantity)
  no large EW corrections in the relation pole-$\overline{\text{MS}}$ mass

SM phase diagram





We live in a metastable universe close to the border with the stability region.

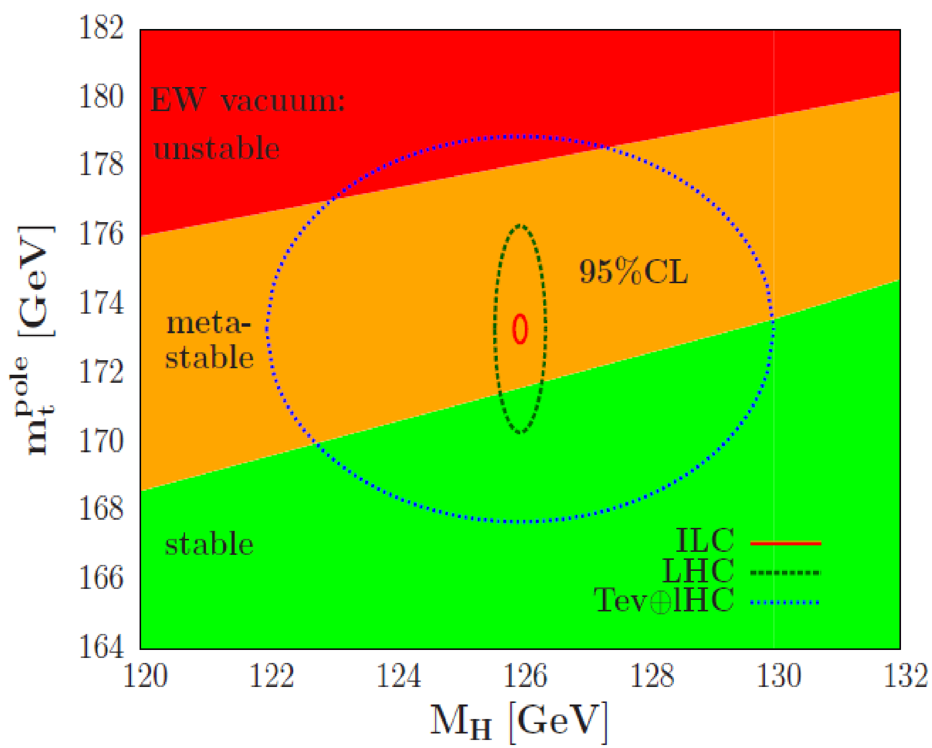
Stability condition:

$$\frac{M_h}{\text{GeV}} > 129.6 + 1.3\left(\frac{M_t - 173.35\,\text{GeV}}{0.65\,\text{GeV}}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{\text{pert.}} \pm 0.6_{\text{non-pert.}}$$

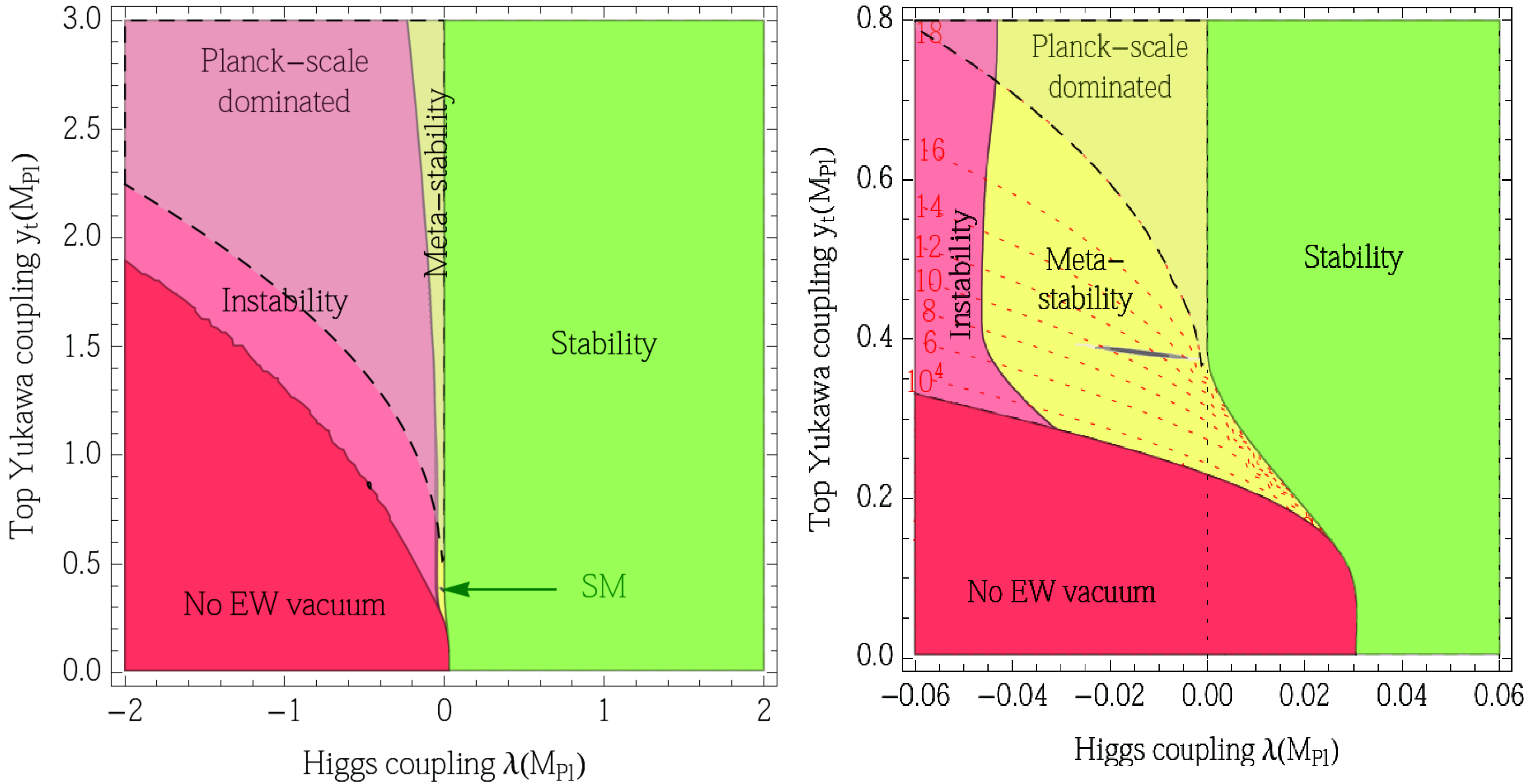
$$M_t < (171.36 \pm 0.15_{\text{pert.}} \pm 0.30_{\text{non-pert.}} \pm 0.25_{\alpha_s} \pm 0.17_{M_h})\,\text{GeV}$$

reduced

Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	**Total combined in quadrature**	± 1.5 GeV
λ	scale variation in λ	~~± 0.7 GeV~~
h_t	$\mathcal{O}(\Lambda_{\rm QCD})$ correction to M_t	± 0.6 GeV
h_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	~~± 0.2 GeV~~
Theory	**Total combined in quadrature**	~~± 1.0 GeV~~ ±0.7 GeV



Alekhin, Djouadi, Moch, 12



$\lambda(M_{Pl})$ and $y_t(M_{Pl})$ almost at the minimum of the funnel

An accident or deep meaning?

The MSSM Higgs sector

$$\beta,\ \alpha$$

Higgs sector: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \Longrightarrow h, H, A, H^\pm$

Higgs masses: predicted at the tree level in terms of M_A, tan β, $M_h < M_Z$

Including radiative corrections: dependence on all SUSY(-breaking) parameters $(A_t, A_b, \mu \ldots)$

$$M_h \lesssim 135\,\mathrm{GeV} \qquad M_{A,H,H^\pm} \sim 100\ldots\mathrm{TeV}$$

$\xrightarrow{\text{decoupling}}$ h SM-like

$$M_A \sim M_H \sim M_H^\pm > \mathcal{O}(200\mathrm{GeV})$$

ϕ	$g^\phi_{u\bar{u}}$	$g^\phi_{d\bar{d}}$	g^ϕ_{VV}
h	$\cos\alpha\,/\sin\beta \to 1$	$-\sin\alpha\,/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\sin\alpha\,/\sin\beta \to 1/\tan\beta$	$\cos\alpha\,/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

Large tanβ

$g^\phi_{d\bar{d}} \uparrow$

decoupling

$$g^\phi_{d\bar{d}} \to \frac{0}{0}$$

delayed decoupling

How easy is to get $M_H \sim 125$ GeV in the MSSM ?

$$M_h^2 \simeq M_Z c_{2\beta}^2 + \frac{3\, m_t^4}{4\,\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \dots$$

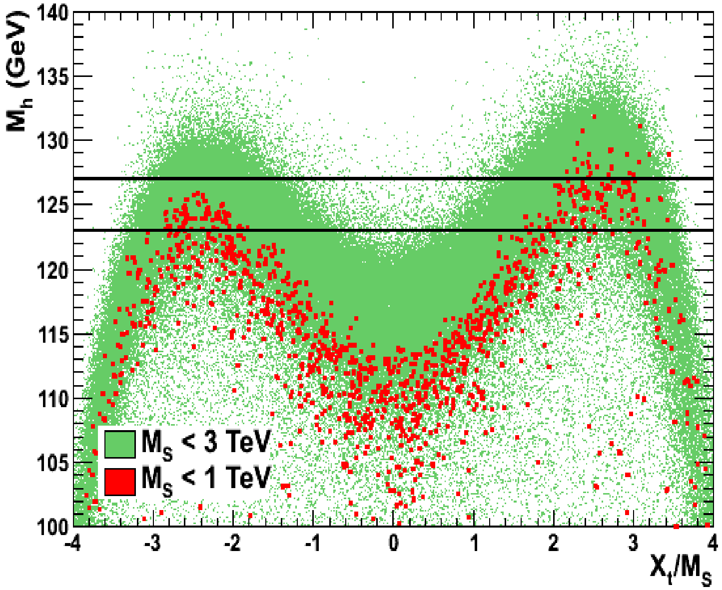
SUSY breaking parameters

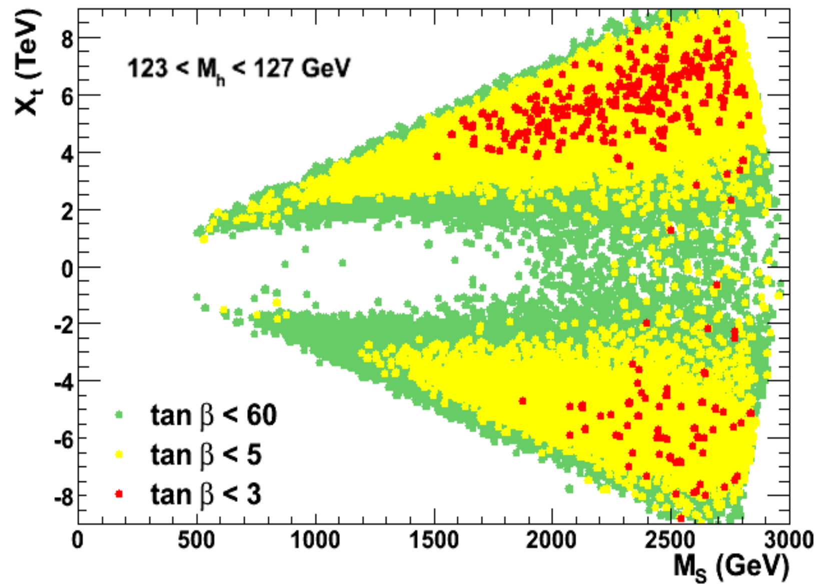
$$X_t = A_t - \mu \cot\beta, \;\; M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}})$$

To get $M_H \sim 125$ GeV:

- Large tan β, tan β > 10 (increase the tree-level)
- Heavy stops, i.e. large M_S (increase the ln)
- Large stop mixing, i.e. large X_t

The more assumptions we take on the mechanism of SUSY-breaking, the more difficult becomes to get $M_H \sim 125$ GeV pMSSM: minimal assumptions on SUSY-breaking parameters





Arbey et al., 2011

22 input parameters varying in the domains:

$$1 \leq \tan\beta \leq 60\,,\;\; 50\text{ GeV} \leq M_A \leq 3\text{ TeV}\,,\;\; -9\text{ TeV} \leq A_f \leq 9\text{ TeV}\,,$$
$$50\text{ GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3\text{ TeV}\,,\;\; 50\text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5\text{ TeV}.$$

Costrained scenarios:

(no) GMSB:

$\tan\beta,\ sign(\mu),\ M_{mess},\ N_{mess}, \Lambda$

(no) AMSB:

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

(yes) MSUGRA:

$\tan\beta,\ sign(\mu),\ m_0,\ m_{1/2},\ A_0$

(no) no-scale:

$m_0 \approx A_0 \approx 0$

(yes) VCMSSM :

$m_0 \approx -A_0$

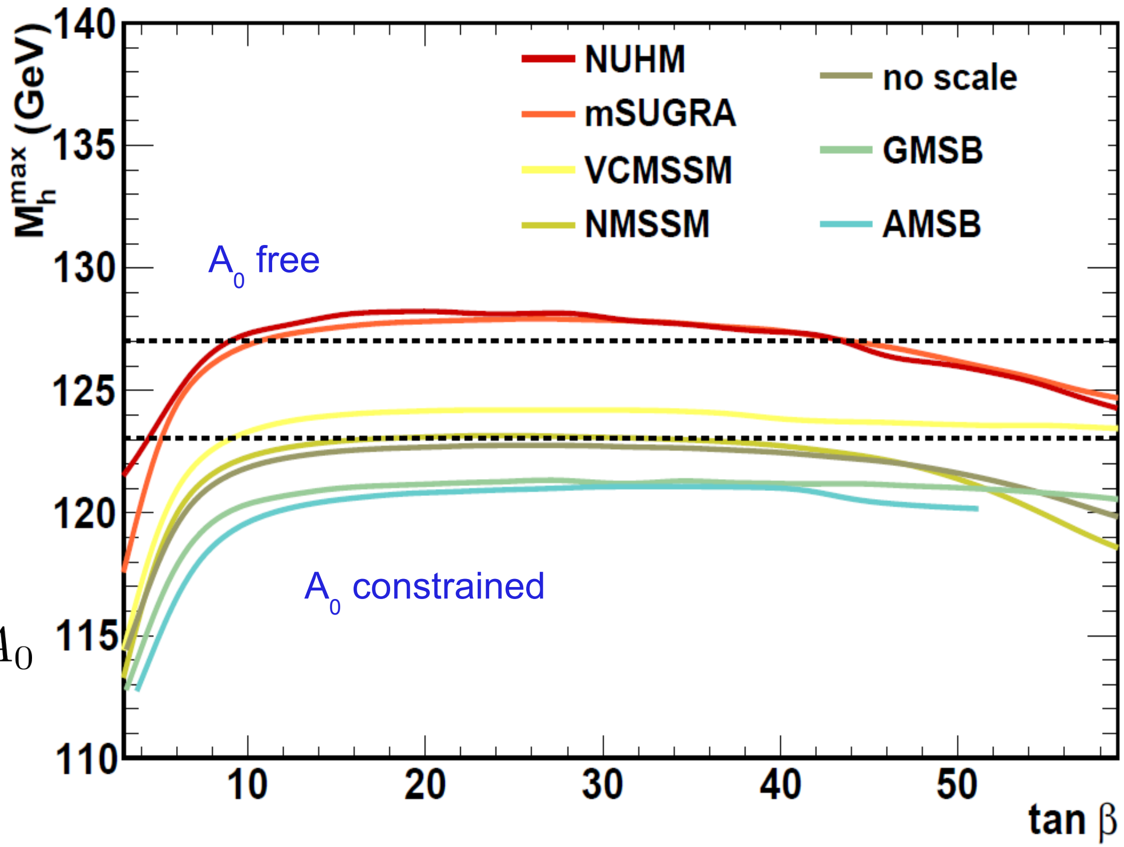
(no) NMSSM :

$m_0 \approx 0,$

$A_0 \approx -1/4 m_{1/2}$

(yes) NUHM:

non universal m_0



Arbey et al., 2011

$$\begin{array}{rlll} \text{mSUGRA:} & 50\text{ GeV} \le m_0 \le 3\text{ TeV}, & 50\text{ GeV} \le m_{1/2} \le 3\text{ TeV}, & |A_0| \le 9\text{ TeV}; \\ \text{GMSB:} & 10\text{ TeV} \le \Lambda \le 1000\text{ TeV}, & 1 \le M_{\text{mess}}/\Lambda \le 10^{11}, & N_{\text{mess}} = 1; \\ \text{AMSB:} & 1\text{ TeV} \le m_{3/2} \le 100\text{ TeV}, & 50\text{ GeV} \le m_0 \le 3\text{ TeV}. & \end{array}$$

M_h ~ 125 GeV and the SUSY breaking scale

MSSM variant: ($\tilde{m}$: Supersymmetry breaking scale)

High-Scale Supersymmetry

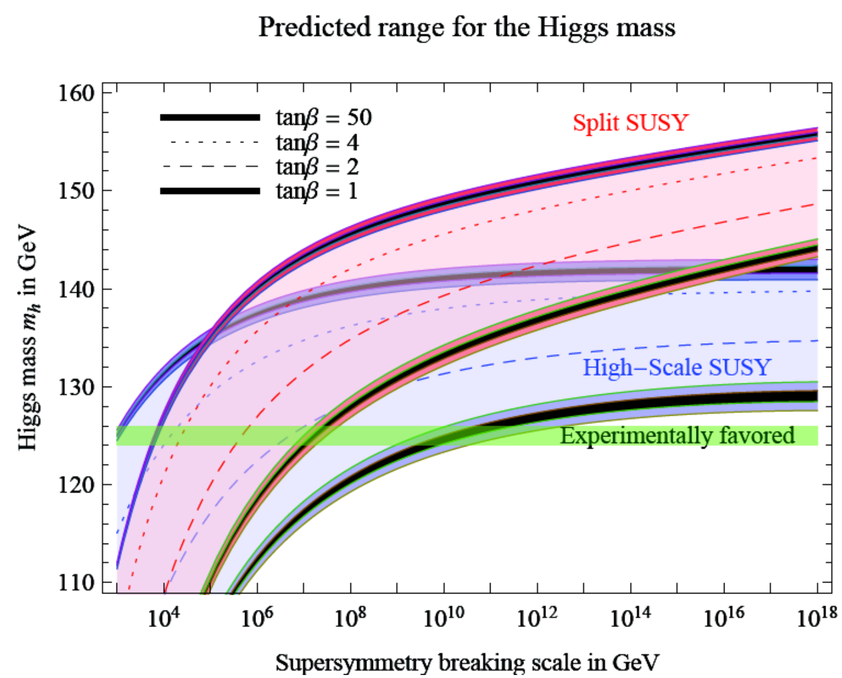
All SUSY particle with mass $\tilde{m}$

Split SUSY:

Susy fermions at the weak scale

Susy scalars with mass $\tilde{m}$

$$\lambda(\tilde{m}) = \frac{1}{8}\left[g^2(\tilde{m}) + g'^2(\tilde{m})\right]\cos^2 2\beta$$



Supersymmetry broken at a very large scale is disfavored

Conclusions

SM is quite OK

M_h−125/6   GeV is a very intriguing value.

The SM potential is metastable, at the “border” of the stability region.
Model-independent conclusion about the scale of NP cannot be derived.
λ is small at high energy: NP (if exists) should have a *weakly interacting* Higgs particle
λ and β_λ are very close to zero around the Planck mass: deep meaning or coincidence?

In the MSSM M_h−125/6 it is at the ”border” of the mass-predicted region.
CMSSM models suffer. However, if SUSY exists its scale of breaking cannot be too high.