The Higgs boson and new physics

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ROMA TRE UNIVERSITÀ DEGLI STUDI

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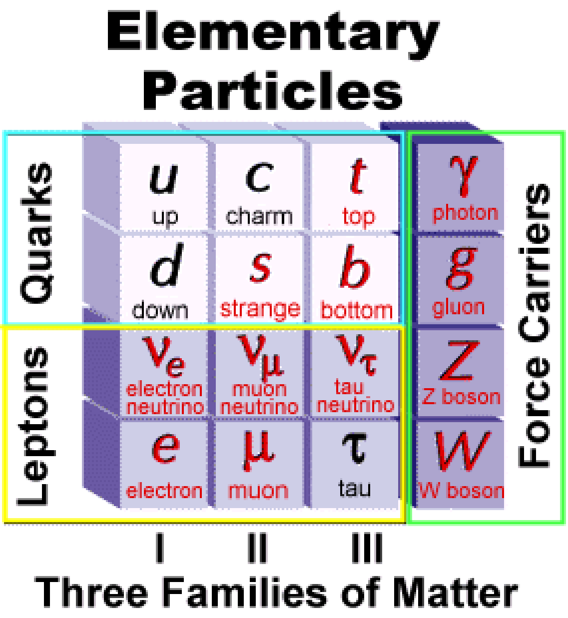
Outline

- Status of the SM
- Past and present informations on the Higgs boson
- Implications of $M_h \sim 125$ GeV for New Physics
  vacuum stability, MSSM
- Implication of $\sigma \sim \sigma_{SM}$ for the MSSM
- Conclusions

Present view: The Standard Model

Strong, electromagnetic and weak interactions (not gravity) are described by a *renormalizable* Quantum Field Theory based on the principle of local gauge invariance with gauge symmetry group $SU(3)_c \times SU(2)_W \times U(1)_Y$ spontaneously broken to $SU(3)_c \times U(1)_{em}$. The quanta of the gauge fields (W,Z) acquire mass via the Higgs mechanism. The left-over of the EWSB process is (at least) a spin 0 particle, the Higgs particle, whose coupling to gauge bosons and to fermions is determined by their masses.



"The Higgs mechanism is just a reincarnation of the Comunist Party: it controls the masses"
Anonymous

$$\mathcal{L}_{SM} = -\frac{1}{4}\underbrace{F^{a\mu\nu}F^{a}_{\mu\nu} + i\bar{\psi}\not{D}\psi}_{\text{gauge}} + \underbrace{\underbrace{(\lambda_{ij}\bar{\psi}_i\psi_j\phi + h.c)}_{\text{flavor}} + \underbrace{|D^{\mu}\phi|^2 - V(\phi)}_{\text{EWSB}}}_{\text{Renormalizable interactions}} + \underbrace{\bar{N}_i M_{ij} N_j}_{\nu\text{-mass (Majorana)}}$$

Symmetry principle
Gauge + flavor symmetry

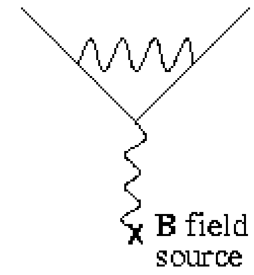
Renormalizable interactions
~~Principle of~~ minimality
Needed to give mass to the particles

Neutrinos are special

After spontaneous symmetry breaking the Lagrangian is still renormalizable

Renormalizable lagrangian $\Longrightarrow$ predictivity at the quantum level

The sector known best: the gauge part QED (unbroken)



$$\frac{(g-2)_e}{2} \equiv a_e = a_e^{QED} + \underbrace{\cancel{a_e^{weak}} + \cancel{a_e^{had}}}_{\lesssim 1 \times 10^{-12}}$$

$$a_e^{exp} \quad = \quad 1159652180.73(0.28) \times 10^{-12} \quad [0.24\ ppb]$$

Hanneke, Fogwell, Gabrielse (08)

$$a_e^{QED} = \sum_{n=1}^{\infty} \left(\frac{\alpha}{\pi}\right)^n a_e^{(2n)} \qquad (n=5)$$

need α

$$\alpha^{-1}(Rb) = 137.035999049(90) \quad [0.66\ ppb]$$

$$a_e^{th} \quad = \quad 1159652181.78(77) \times 10^{-12} \quad [0.66\ ppb]$$

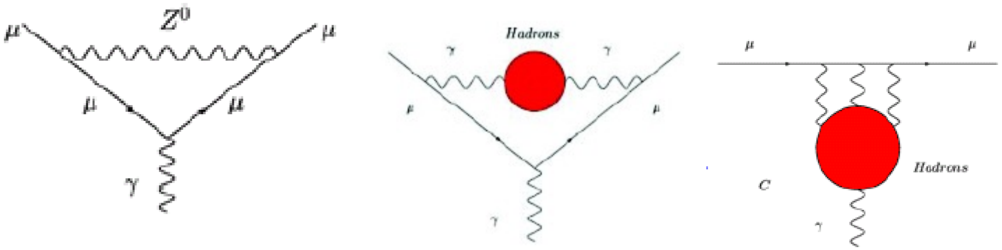
$$\alpha^2 = \frac{2R_\infty}{c} \frac{m_{\mathrm{Rb}}}{m_e} \frac{h}{m_{\mathrm{Rb}}},$$

$$a_e^{exp} - a_e^{th} = -1.05(0.82) \times 10^{-12}$$

best determination of α is from a_e

$$\alpha^{-1}(a_e) = 137.035999173(8)(33) \quad [0.25\ ppb]$$

$$a_\mu = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$



sensitivity to hadronic, weak and NP contributions increased in a_μ by a factor $(m_\mu/m_e)^2 \sim 4 \cdot 10^4$ with respect to a_e

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}$$

0.5 parts per million.
Muon g-2 Coll. (06)

$$a_\mu^{th} = 116\,592\,840(59) \times 10^{-11}$$

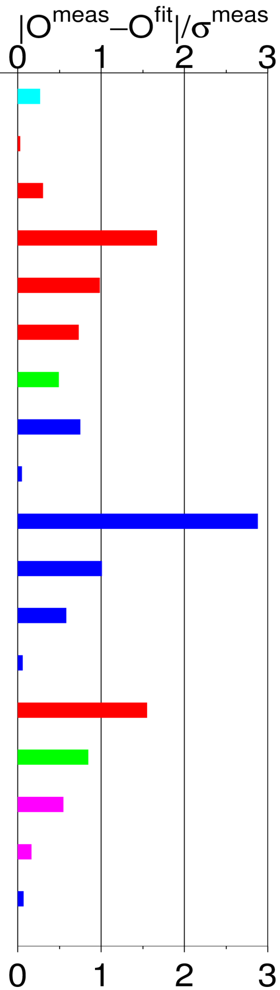
$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = 249(87) \times 10^{-11}$$

$$a_\mu^{weak} = 154(2) \times 10^{-11}$$

Δa_μ in the ballpark for a NP explanation

The sector known best: the gauge part
Electroweak (broken, W and Z physics)

		Measurement	Fit
	$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
★	m_Z [GeV]	91.1875 ± 0.0021	91.1874
★	Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
★	σ_{had}^0 [nb]	41.540 ± 0.037	41.478
	R_l	20.767 ± 0.025	20.742
	$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
	$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
	R_b	0.21629 ± 0.00066	0.21579
	R_c	0.1721 ± 0.0030	0.1723
	$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
	$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
	A_b	0.923 ± 0.020	0.935
	A_c	0.670 ± 0.027	0.668
	A_l(SLD)	0.1513 ± 0.0021	0.1481
	$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
	m_W [GeV]	80.385 ± 0.015	80.377
	Γ_W [GeV]	2.085 ± 0.042	2.092
★	m_t [GeV]	173.20 ± 0.90	173.26

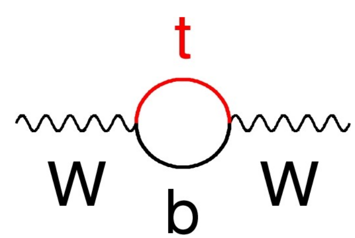


March 2012

precision $\sim 5 - 1 \times 10^{-3}$

★ better than 10^{-3}

Sensitivity to quantum effects

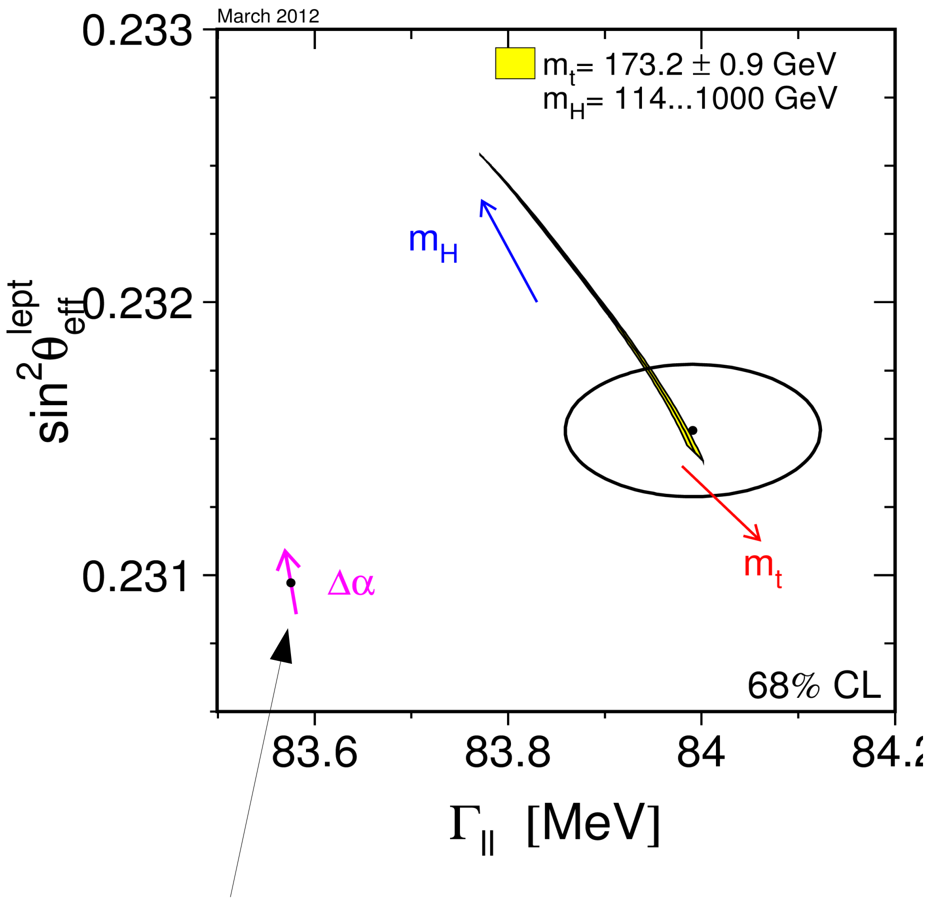


$$\sim \alpha \frac{M_t^2}{M_W^2}$$

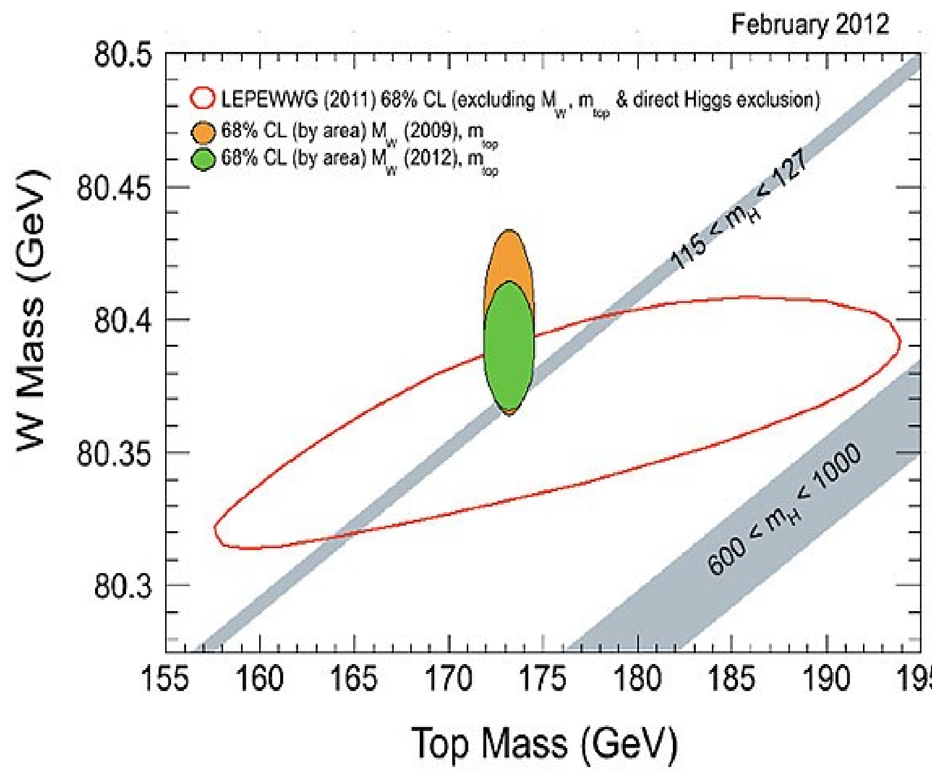
$$\sim \alpha \log \frac{M_h^2}{M_Z^2}$$

Purely EW corrections established

indirect vs. direct M_t, M_W determination

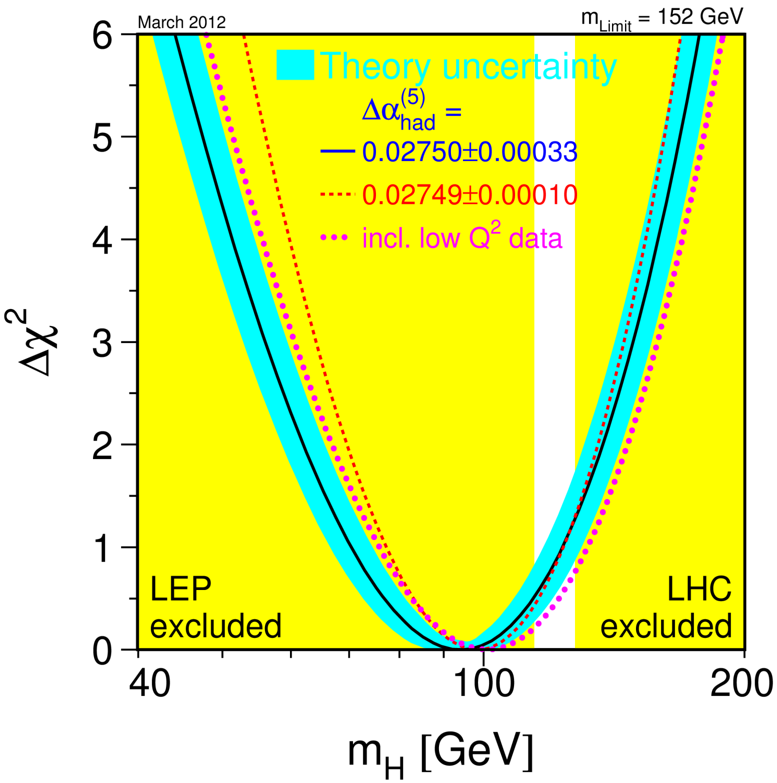


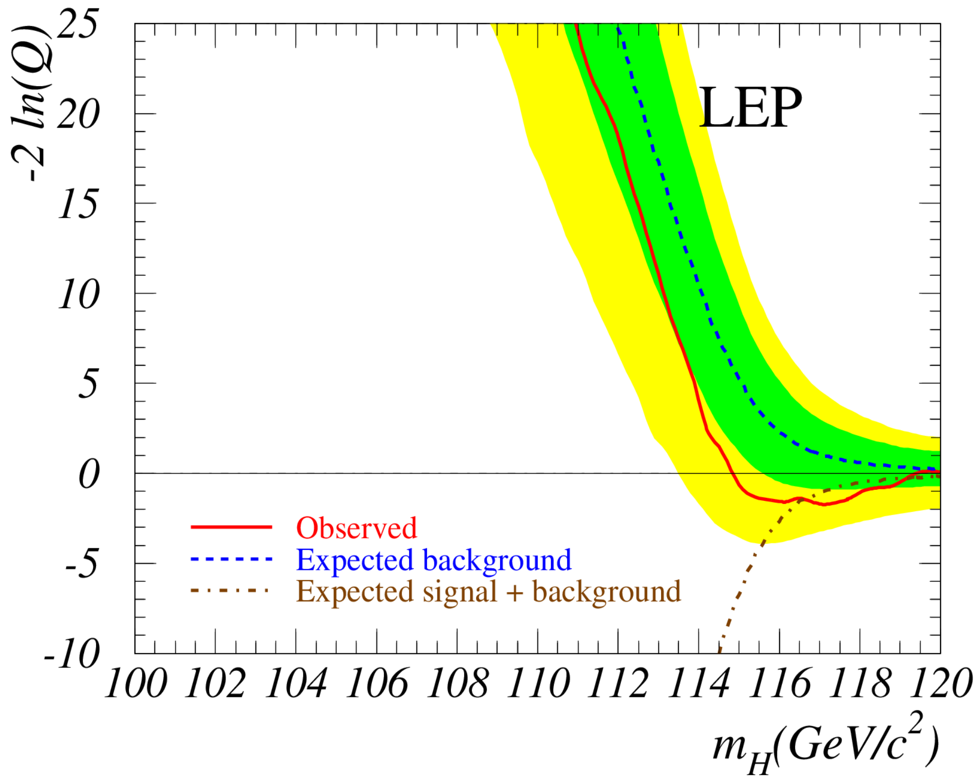
only QED corrections



The Higgs sector: pre-LHC
LEP

Known $M_t,\ M_W \Longrightarrow M_h$



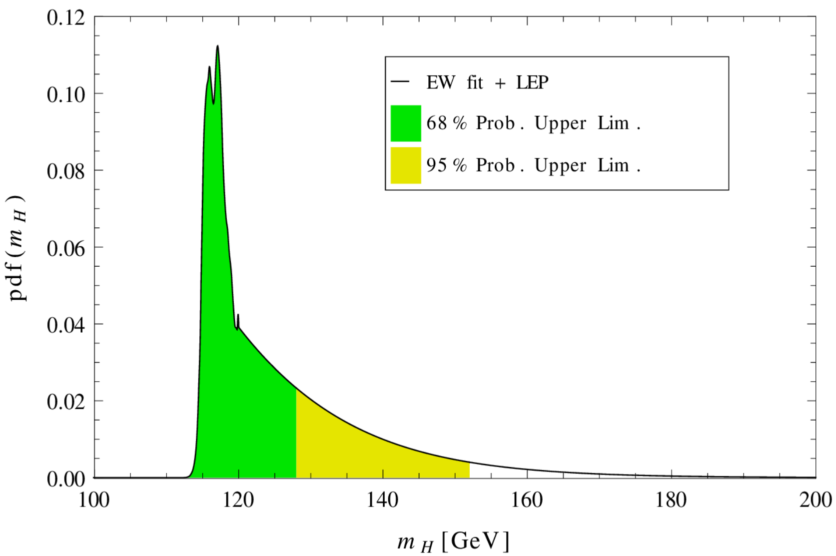


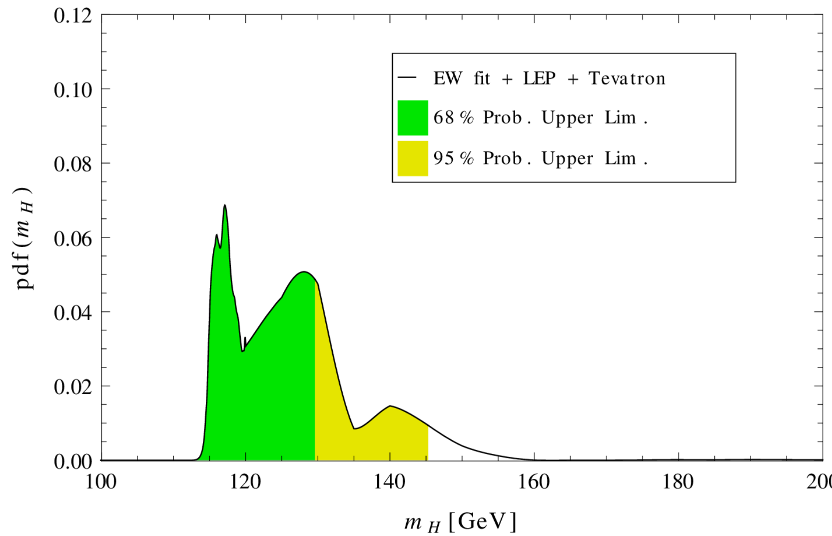
$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

The Higgs sector: pre-LHC
LEP + Tevatron

Combining direct and indirect information: $\mathrm{pdf}(M_h) \propto \frac{\mathcal{Q}(M_h) e^{-(\chi^2/2)}}{M_h}$

D'Agostini, G.D.1999

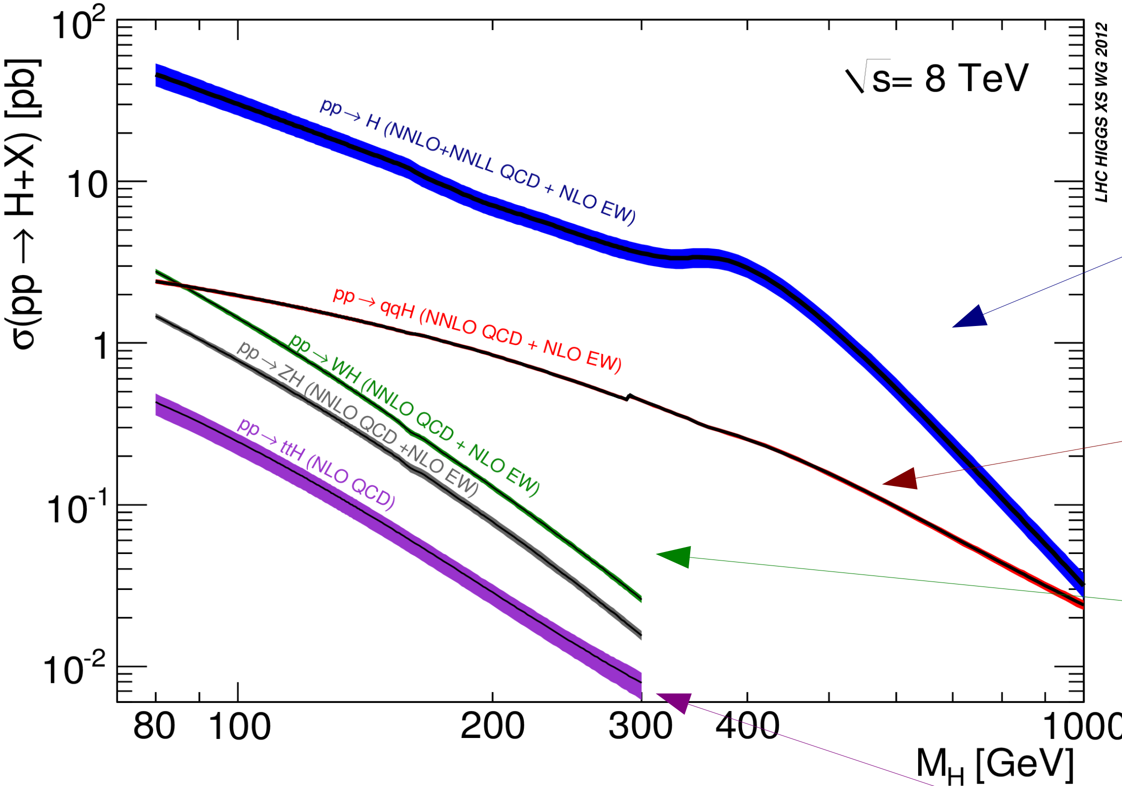


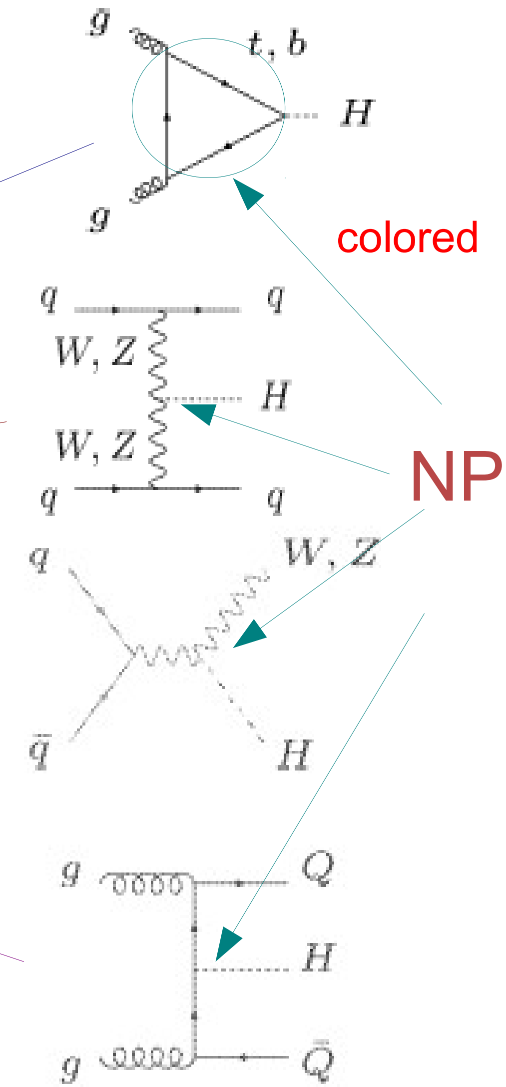


courtesy of S. Di Vita

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

The Higgs sector: LHC
Production mechanisms





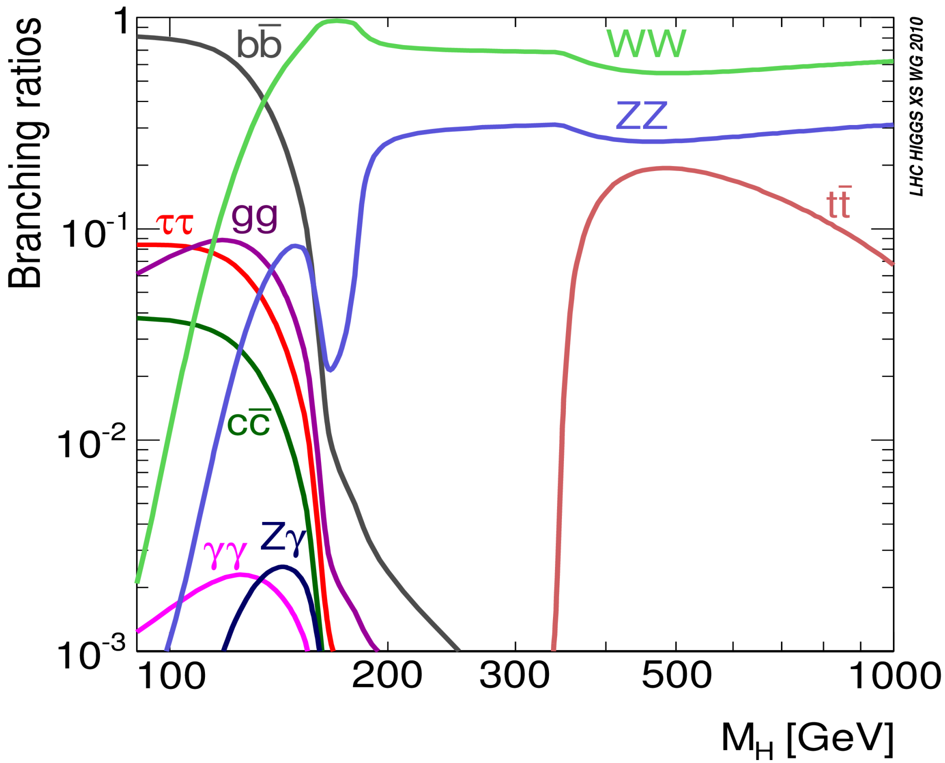
Gluon-fusion process dominant

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

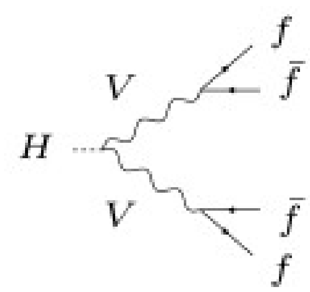
Bands include: PDF + α_s + scale uncertainties

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

The Higgs sector: LHC Decays

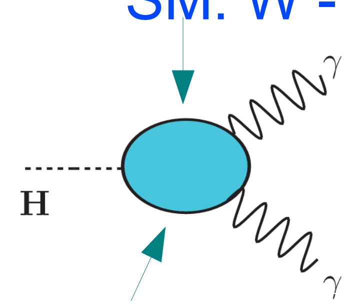


Golden Channel V=Z



Low Higgs mass

SM: W - t

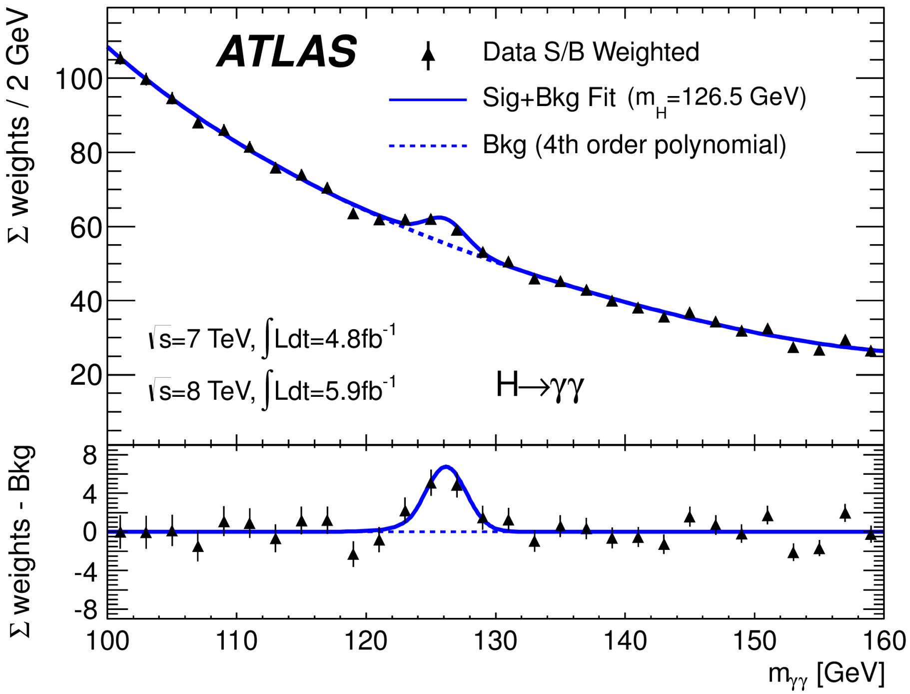


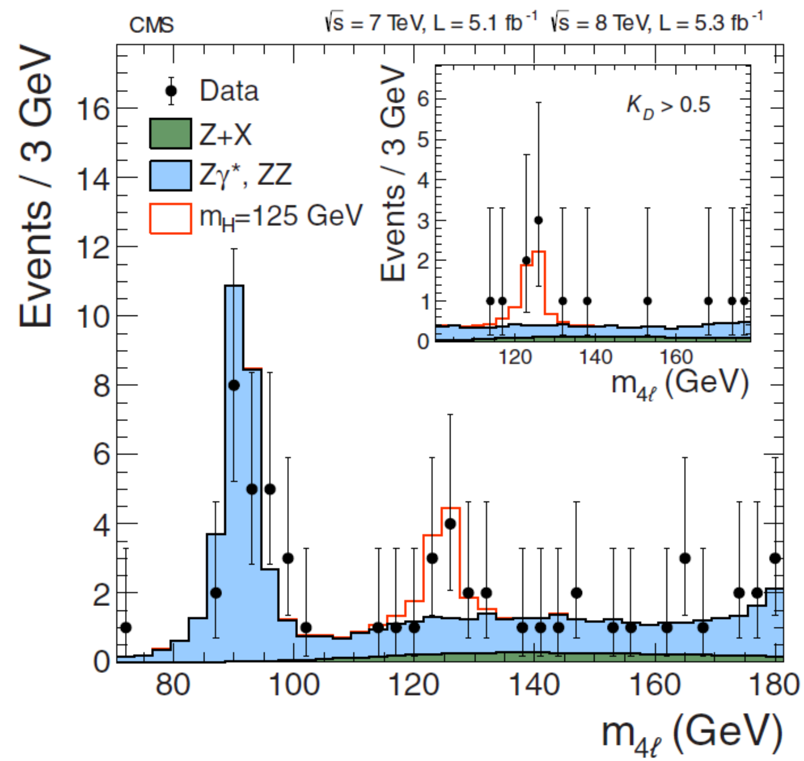
NP: white + colored

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

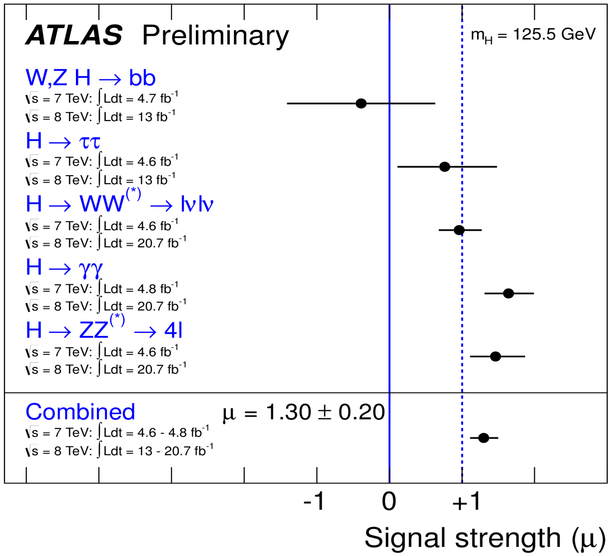
The Higgs sector: LHC
4th of July 2012

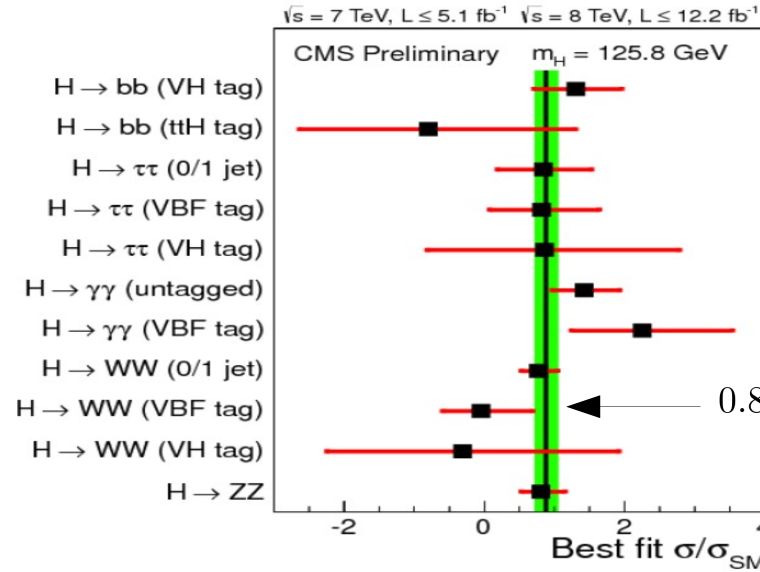




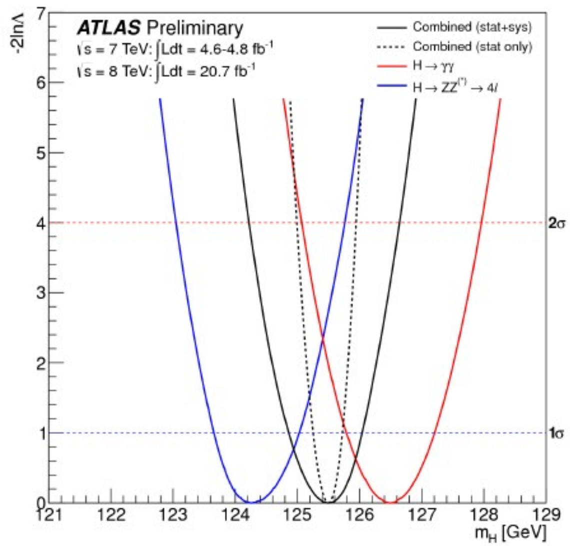
Clear evidence of a new particle
with properties compatible with those of the SM Higgs boson

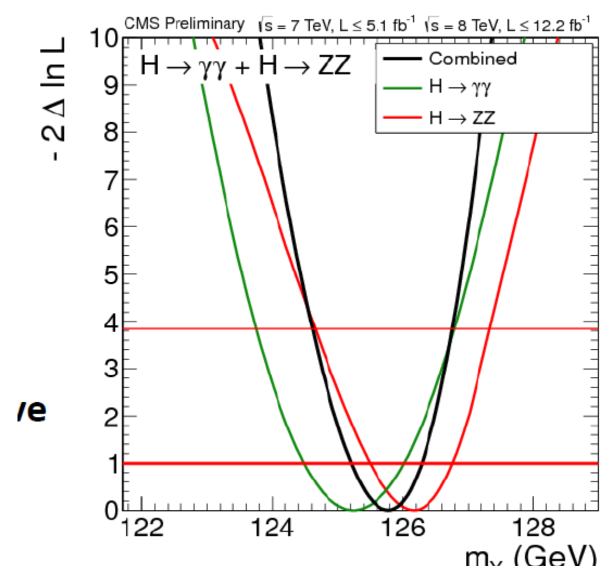
The Higgs sector: LHC
Studying the properties of the new particle





0.88 ± 0.21

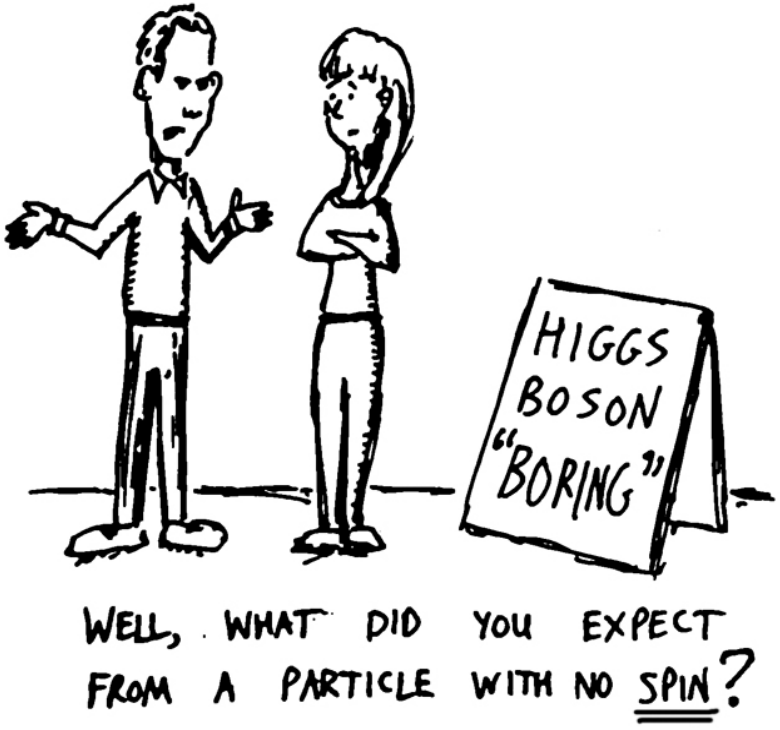




$M_h = 125.5 \pm 0.2(stat)\ ^{+0.5}_{-0.6}(syst)\ \ \mathrm{GeV}$

$M_h = 125.8 \pm 0.4(stat) \pm 0.4(syst)\ \ \mathrm{GeV}$

Implications of $M_h \sim 125$ GeV



Reversing the heavy Higgs argument

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

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

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

$c_i > 0$

To increase the fitted M_H : $\left\{ \begin{array}{l} \hat{\rho} > 1 \rightarrow \left\{ \begin{array}{l} \rho_0 > 1 \leftarrow \text{Extra Z} \\ \delta\rho > 0 \leftarrow \text{Isosplitt (s)fermions, Multi Higgs models,} \end{array} \right. \\ \Delta\hat{r}_W < 0 \end{array} \right.$

Light sleptons

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

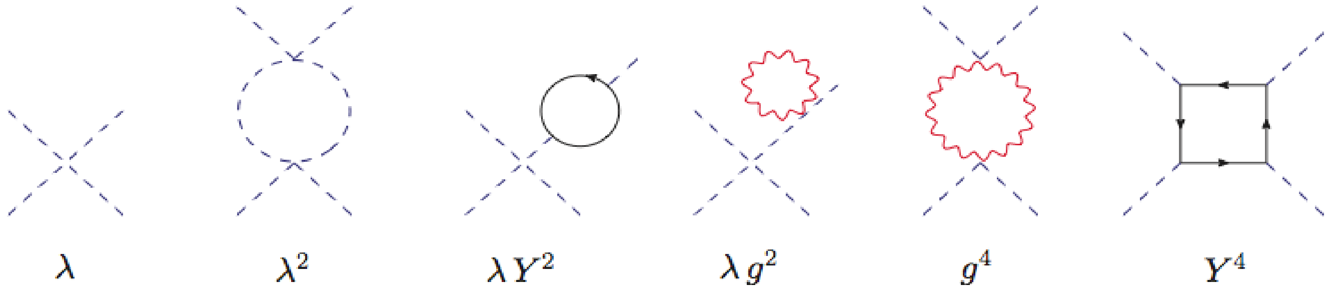
(Meta)Stability bound

Quantum corrections to the classical Higgs potential can modify its shape

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

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

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 - 2N_c Y_t + \ldots\right]$$

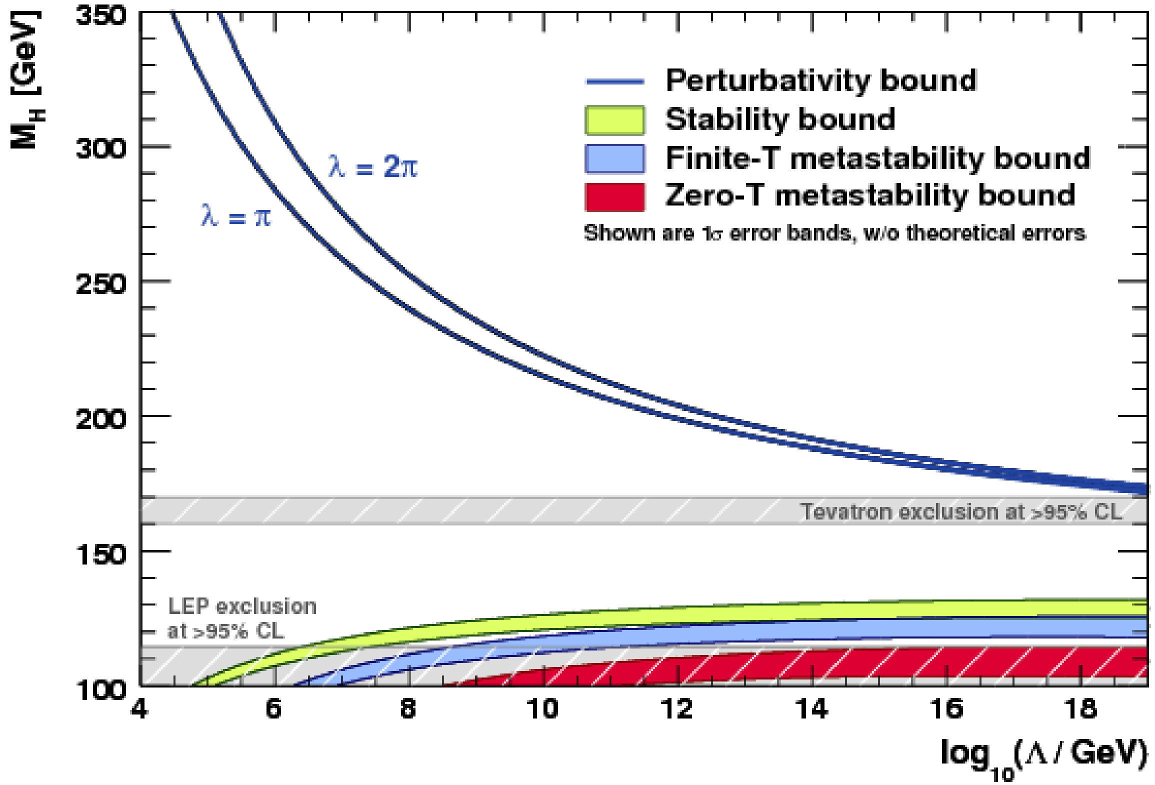
M_H large: λ^2 wins $\qquad \lambda(M_t) \rightarrow \lambda(\mu) \gg 1 \qquad$ non-perturbative regime, Landau pole

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

Ellis et al. 09

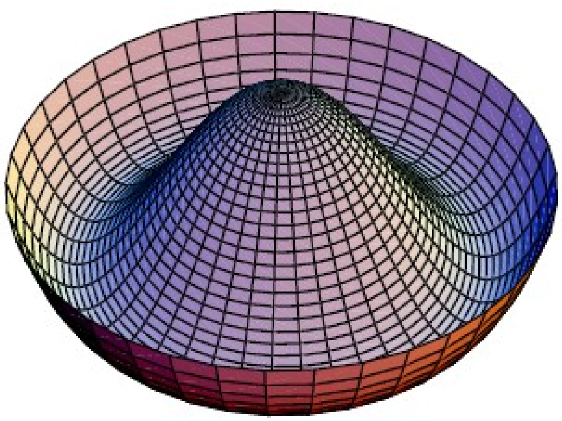
M_H ~ 125-126 GeV: $-Y_t^4$ wins
no problem with the Landau pole

Running depends on M_T, α_s ….

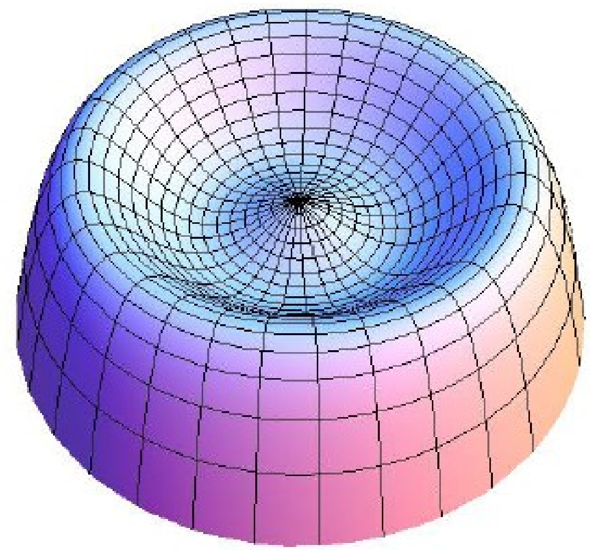


M_H ~ 125-126 GeV: $-Y_t^4$ wins: $\lambda(M_t)$ ~ 0.14 runs towards smaller values and can eventually become negative. If so the potential is either unbounded from below or can develop a second (deeper) minimun at large field values

Illustrative



$\rightarrow$

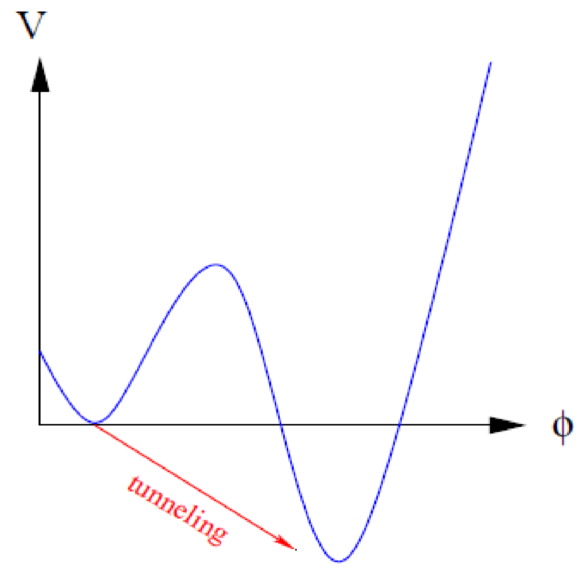


If your mexican hat turns out to be a dog bowl you have a problem...

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

Vacuum stability at NNLO

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

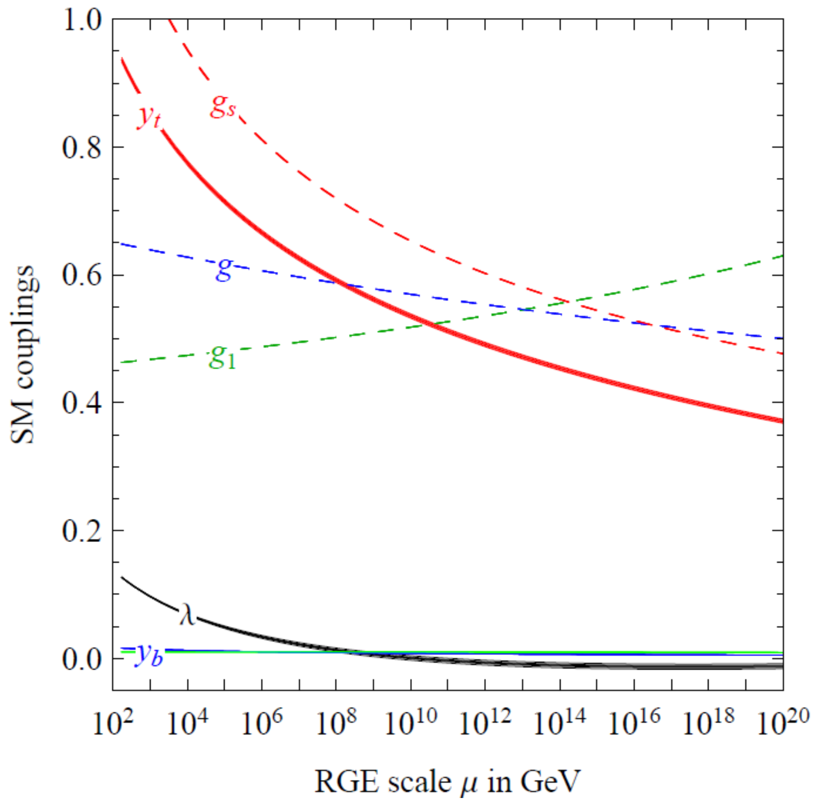
- Three-loop beta functions
  gauge Mihaila, Salomon, Steinhauser (12)
  Yukawa, Higgs Chetyrkin, Zoller (12, 13)

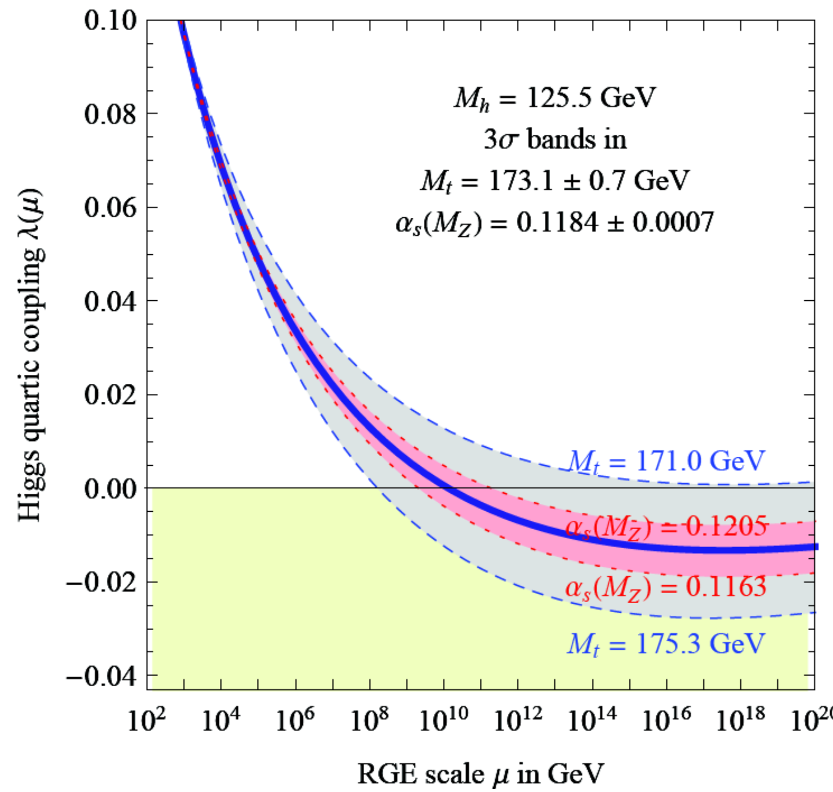
- Two-loop threshold corrections at the weak scale
  λ: Yuk x QCD Bezrukov et al. (12)
  Yuk x QCD
  SM gaugeless Di Vita, Elias-Miro', Espinosa, Giudice
  Isidori, Strumia, G.D. (12)

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

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

$$\begin{aligned}
\lambda(\mu) &= \frac{G_\mu}{\sqrt{2}}M_h^2 - \delta\lambda^{(1)} - \delta\lambda^{(2)} \\
\delta\lambda^{(2)} &= \frac{G_\mu}{\sqrt{2}}M_h^2\left\{\Delta r_0^{(2)} + \frac{1}{M_h^2}\left[\frac{T^{(2)}}{v_{\rm ren}} + \mathrm{Re}\,\Pi_{hh}^{(2)}(M_h^2)\right]\right. \\
&\quad \left. - \frac{\Delta r_0^{(1)}}{M_h^2}\left[M_h^2\Delta r_0^{(1)} + \frac{3\,T^{(1)}}{2\,v_{\rm ren}} + \mathrm{Re}\,\Pi_{hh}^{(1)}(M_h^2)\right]\right\}
\end{aligned}$$



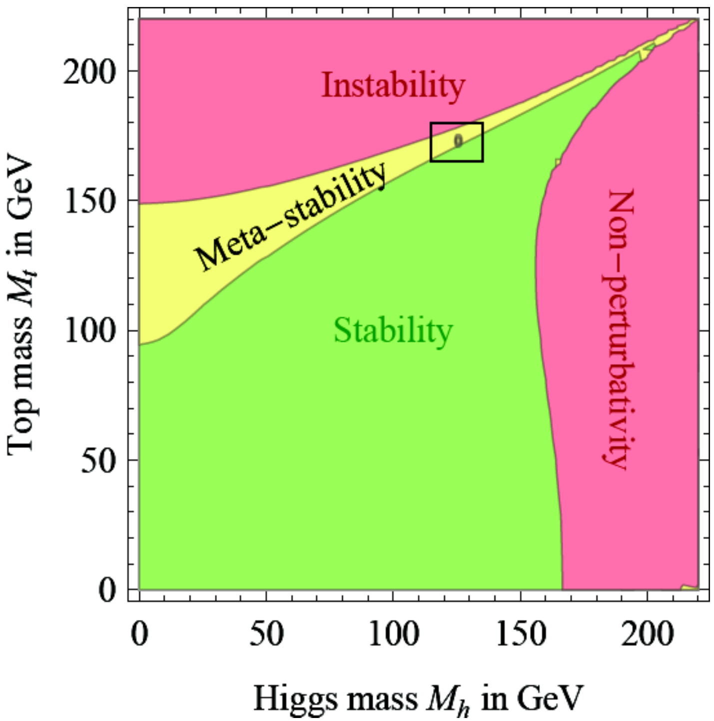


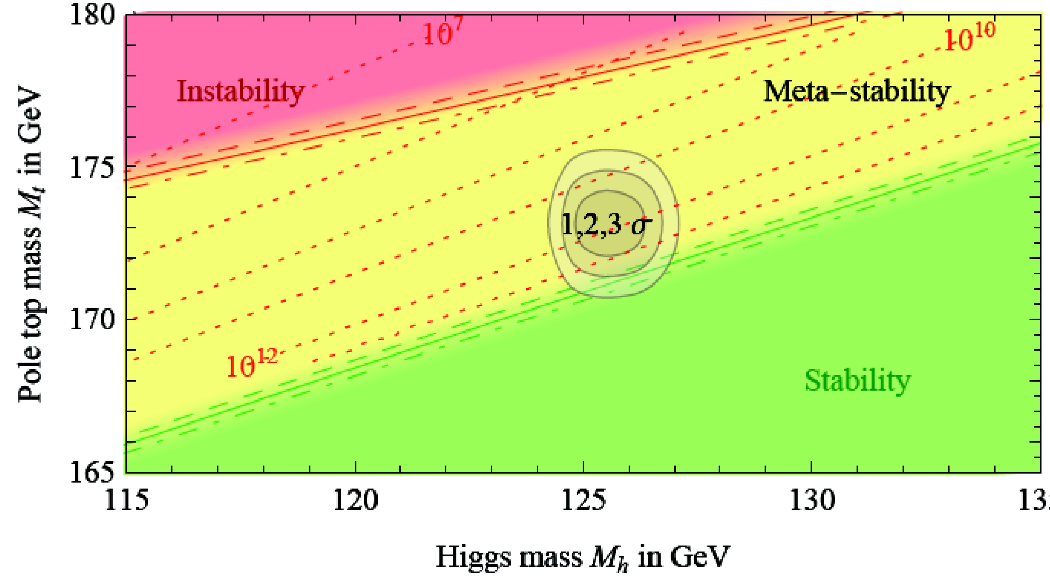
Full stability is lost at $\Lambda \sim 10^{11}$ GeV. but λ never becomes too negative

$$\lambda(M_{Pl.}) = -0.0144 + 0.0028\left(\frac{M_h}{\text{GeV}} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s(M_Z)} \pm 0.0028_{\text{th}}$$

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

Are they vanishing there?





$$M_h\,[\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\,[\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

We live in a metastable universe close to the border with the stability region.
If the top pole mass would be ~ 171 GeV we were in the stable region.
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 form total production cross section and the corresponding pole mass is consistent with the standard value albeit with a larger error

$M_h \sim 125$ GeV and Supersymmetry

Supersymmetry:
chiral fermion $\Longleftrightarrow$ complex scalar
vector boson $\Longleftrightarrow$ Majorana fermion

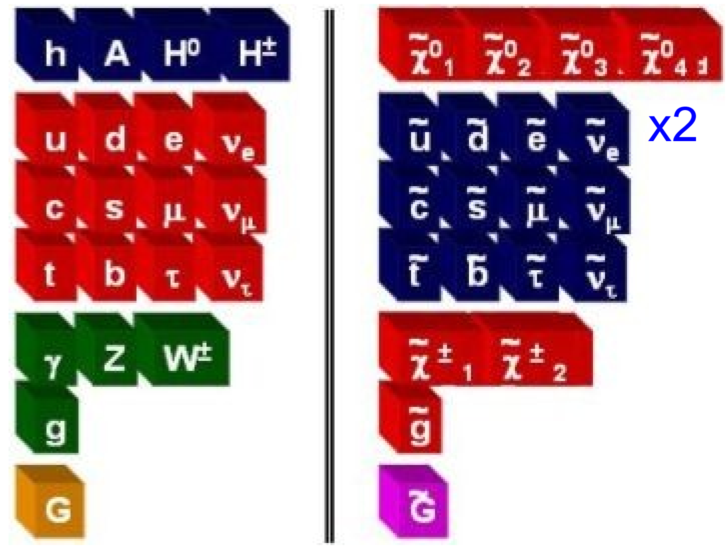
<EWSB> $\Longrightarrow$ $M_P = M_{\tilde{P}}$

In the minimal model the quartic coupling in the Higgs potential is related to the gauge couplings

$\longrightarrow$ prediction for the Higgs mass

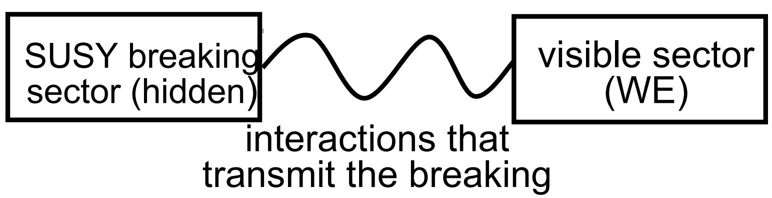
Standard fields (2HDM)

SUSY fields



SUSY must be broken!

It is not possible using SM (super)fields to break SUSY in a realistic way. The breaking of SUSY should come form somewhere else and communicated to the particles we see.



Left-over $\mathcal{L}^{soft}_{SUSY}$ (may be with some kind of universal features at the scale of the breaking transmission)

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 $(A_t, A_b, \mu \ldots)$

$$M_h \lesssim 135\,\mathrm{GeV} \qquad \xrightarrow{\text{decoupling}} \qquad h \ \text{SM-like}$$

$$M_{A,H,H^{\pm}} \sim 100 \ldots \mathrm{TeV} \qquad M_A \sim M_H \sim M_H^{\pm} > \mathcal{O}(200\mathrm{GeV})$$

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 ~ 125 GeV in the MSSM ?

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

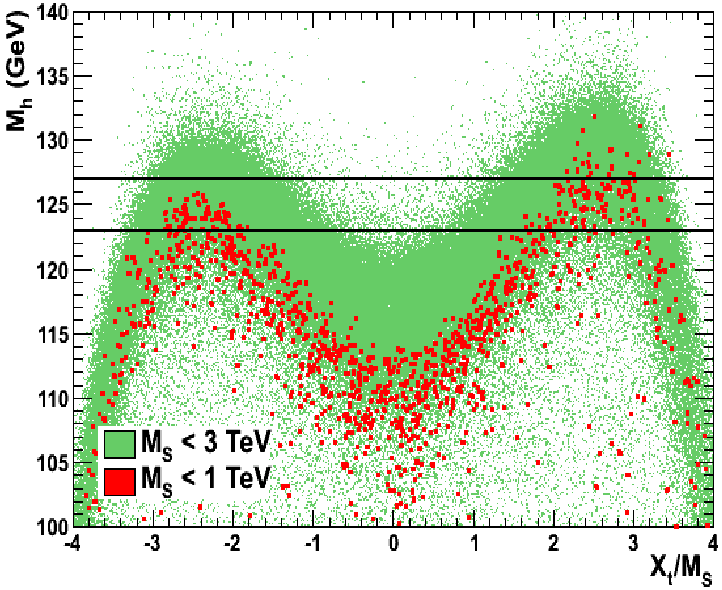
SUSY breaking parameters

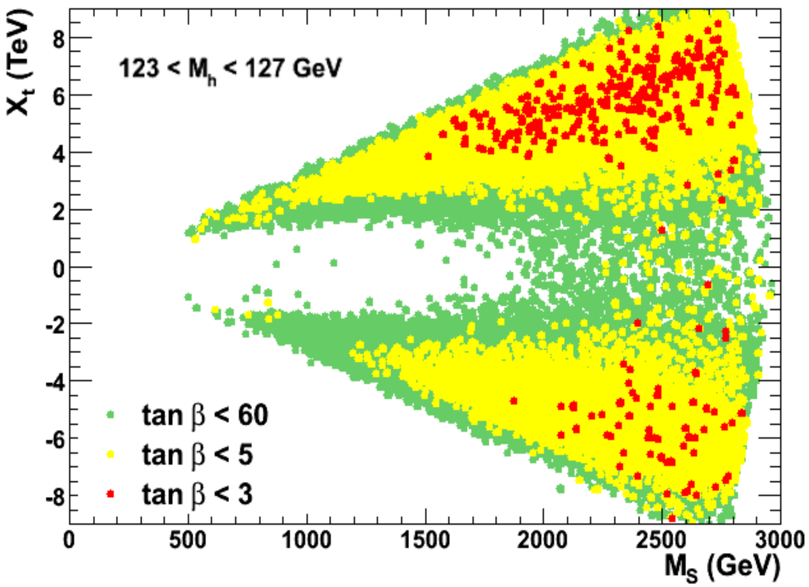
$$X_t = A_t - \mu \cot\beta, \;\; M_S = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}})$$

To get M_H ~ 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 ~ 125 GeV pMSSM: minimal assumptions on SUSY-breaking parameters





Arbey et al., 2011

22 input parameters varying in the domains:

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

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 :

$m_0 \approx -A_0$

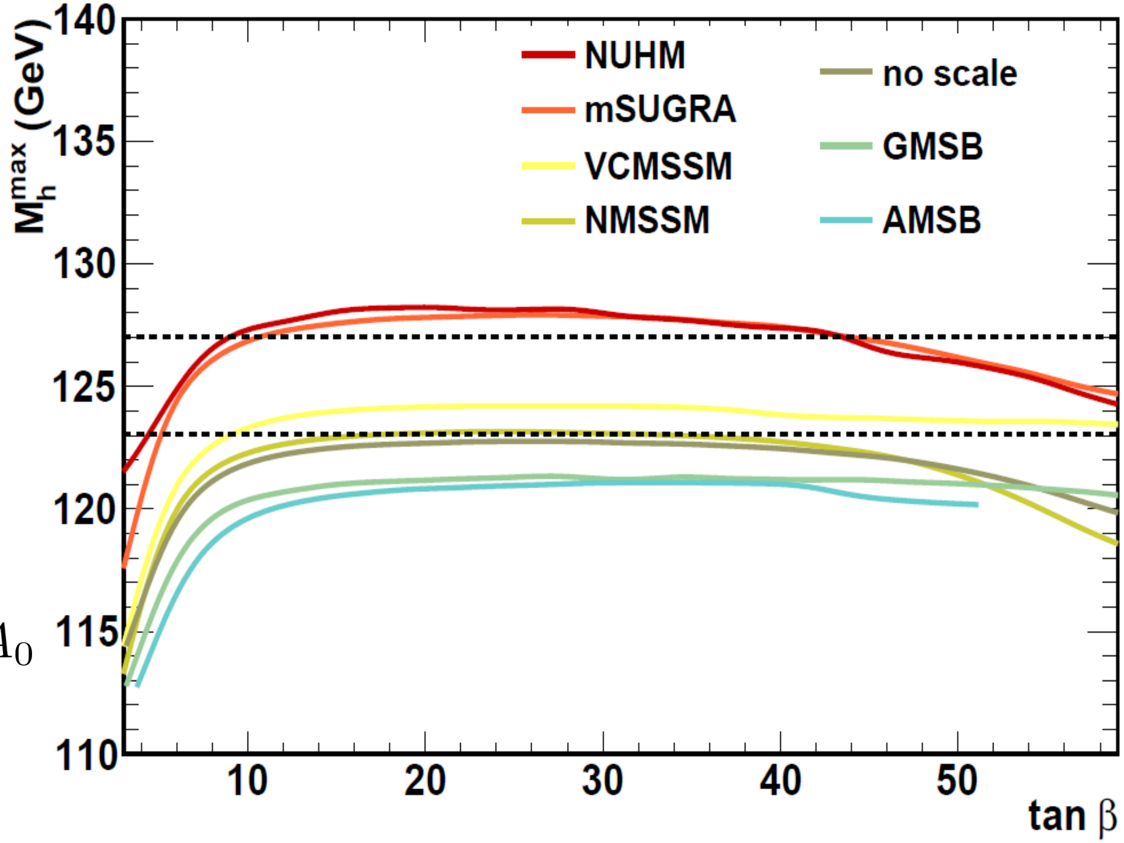
(no) NMSSM :

$m_0 \approx 0,$

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

(yes) NUHM:

non universal m_0



Arbey et al., 2011

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

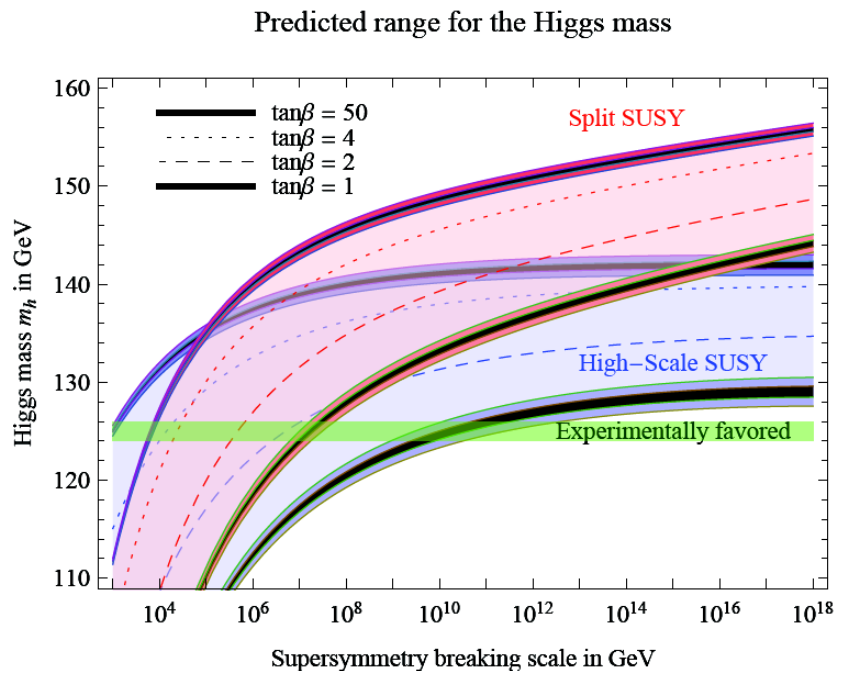
M_h ~ 125 GeV and the SUSY breaking scale

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 $\tilde{m}$

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



Supersymmetyry broken at a very large scale is disfavored

$\sigma \sim \sigma_{SM}$ and the MSSM

Squarks and gluinos contribute to the loop-induced gluon fusion production cross section

$\sigma(g\,g \to h)$ is fully known at NLO QCD (standard + SUSY contributions)

$\sigma(g\,g \to h)$ implemented in the event generator POWHEG.

E. Bagnaschi, P. Slavich, A. Vicini,G.D. (11)

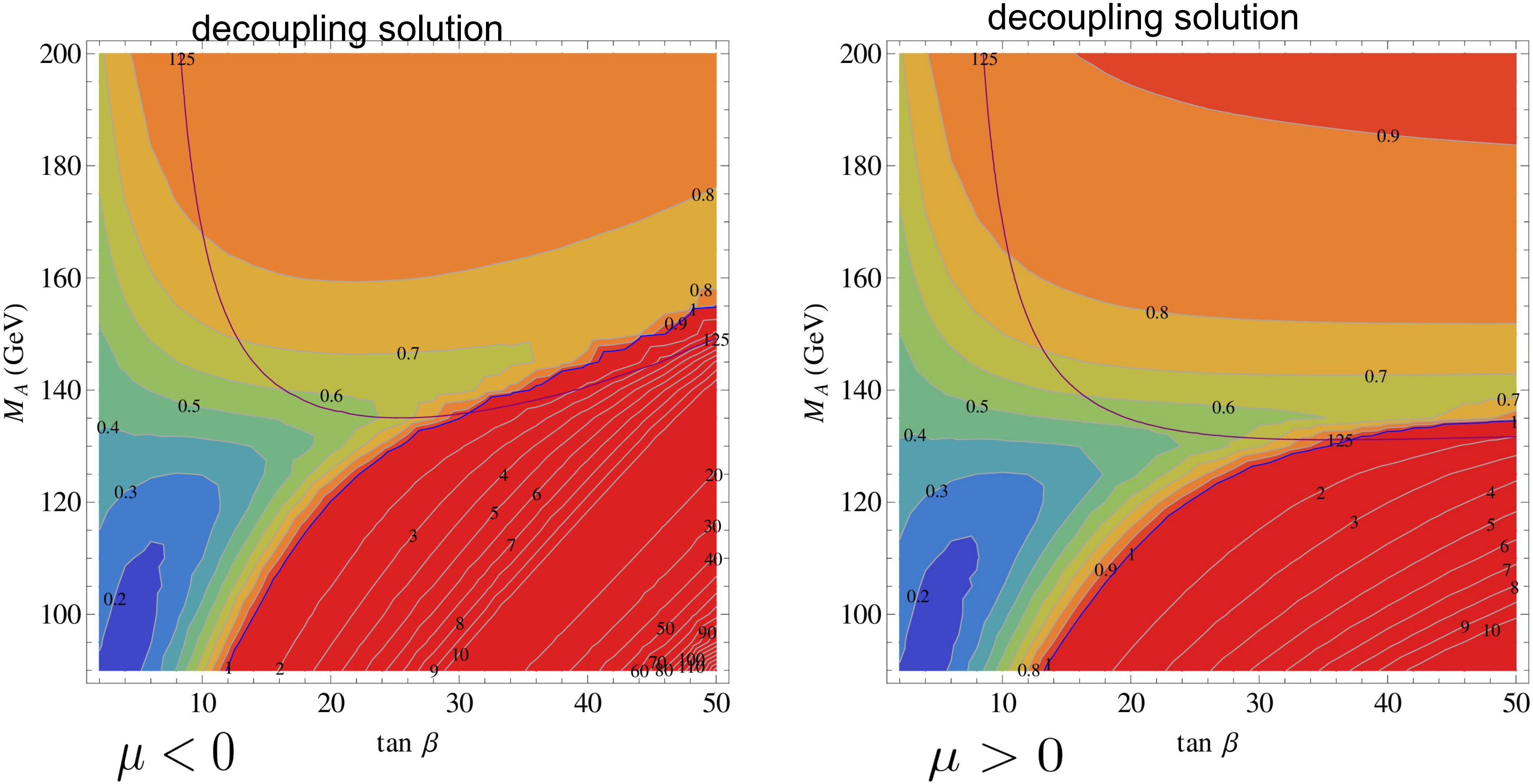
a) Interface POWHEG with a mass spectrum generator that provides Higgs masses and couplings.
b) Rescale the SM contribution.
c) insert the SUSY correction

PO(sitive)W(eight)H(ardest)E(mission)G(enerator)

Nason et al. (04--)

Matching NLO-QCD matrix elements with Parton Showers
Generate the hardest emission first, with NLO accuracy, independently of the PS
Can be interfaces to several SMC programs (HERWIG/PHYTIA)
Generate events with positive weights
NLO accuracy of the total cross-section preserved

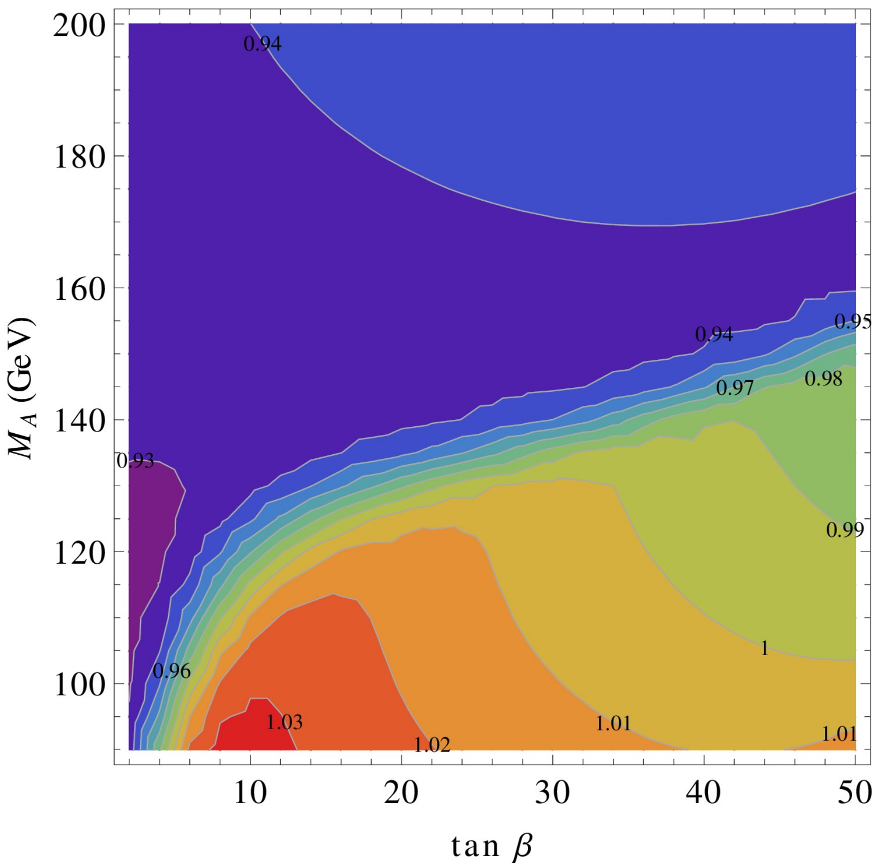
$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})}$$



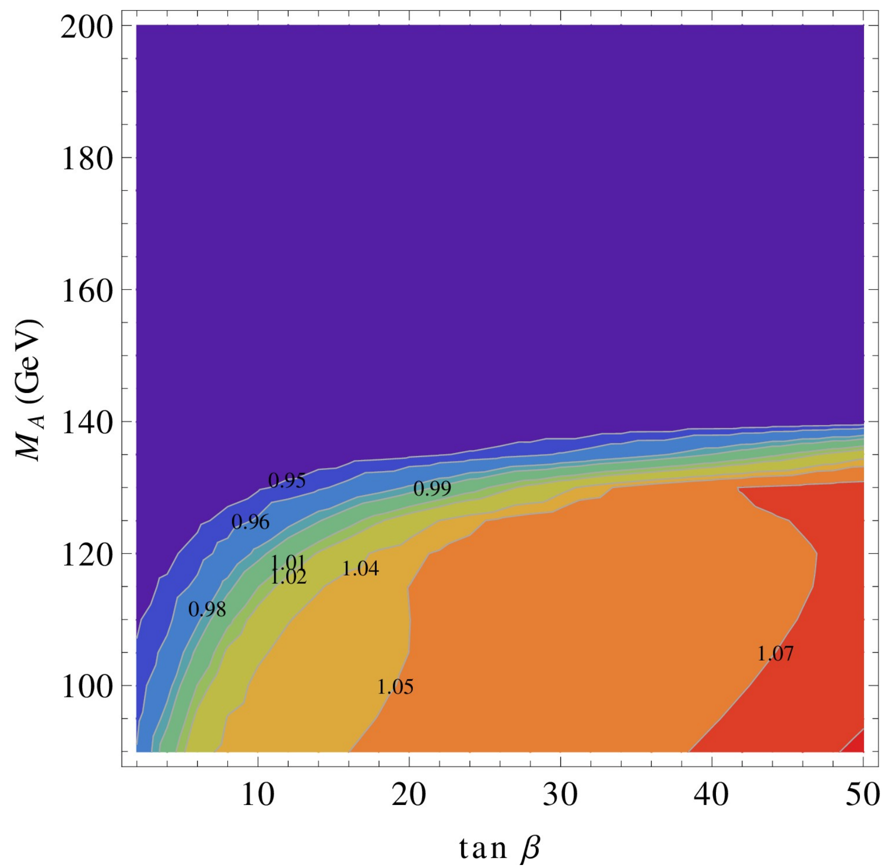
m_Q=m_U=m_D= 1000 GeV, X_t= A_t-μ cot β=2500 GeV, M_3= 800 GeV, M_2 = 2 M_1 =200 GeV, |μ| = 200 GeV

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})_{\text{rescaled}}}$$

$\mu < 0$



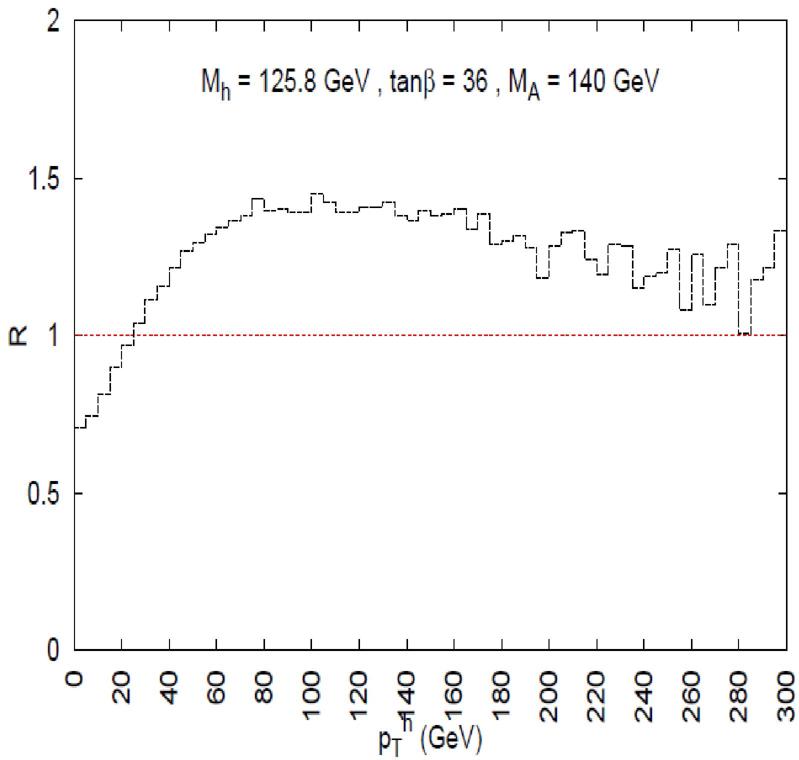
$\mu > 0$



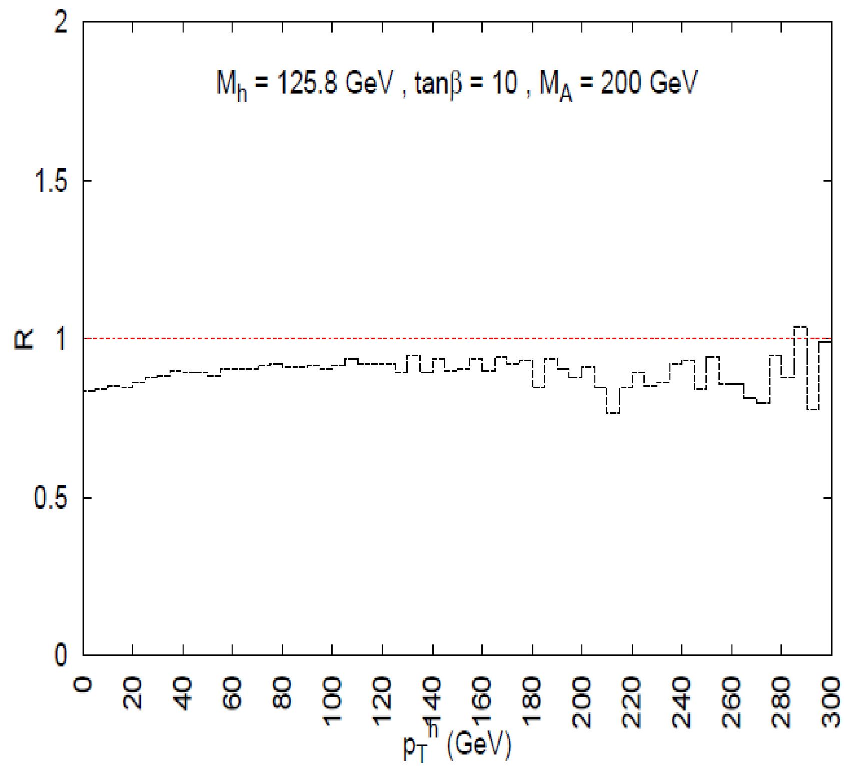
Squarks are heavy: corrections up to 10%

Using the p_t^h to disentangle between SM and MSSM

$\mu < 0$



$\mu > 0$

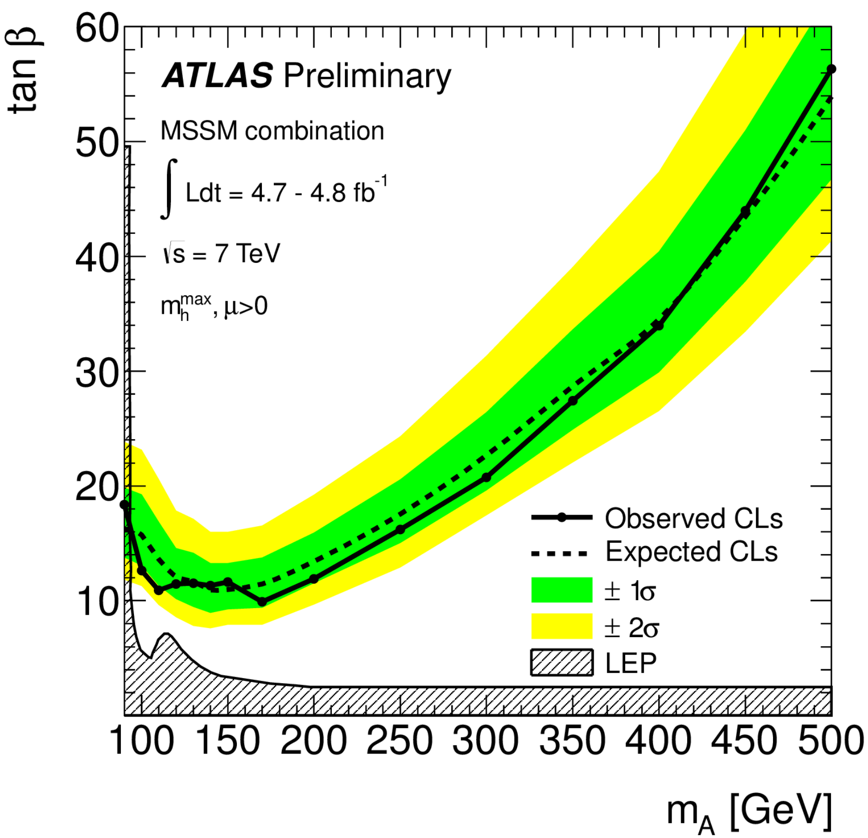


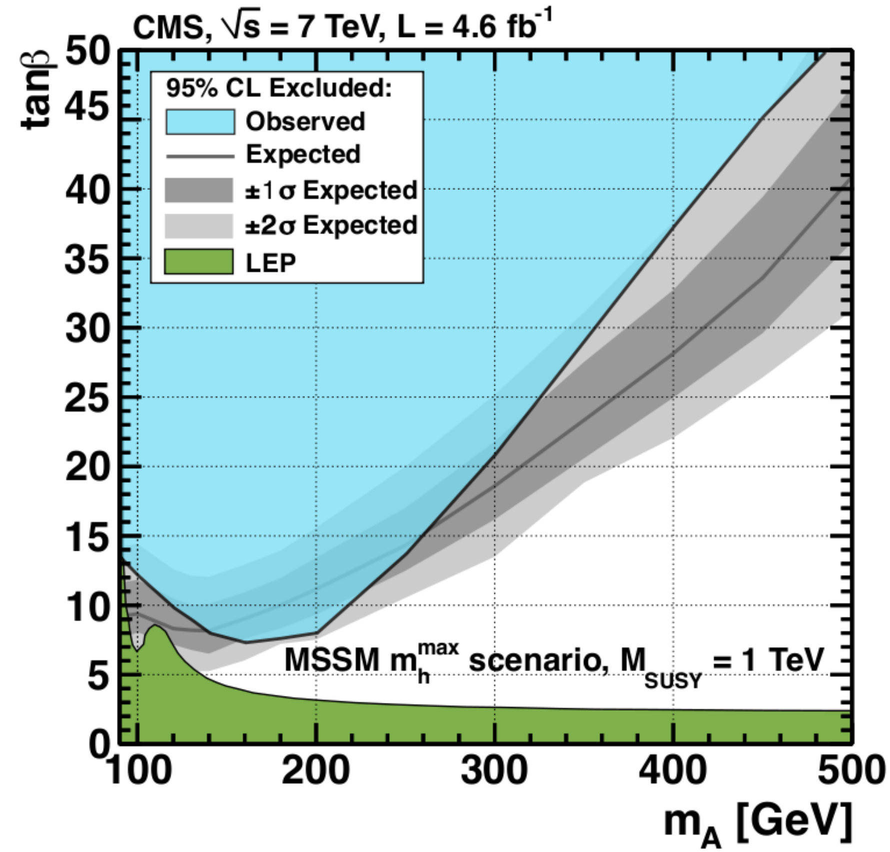
R= ratio $\frac{d\,\sigma}{d\,p_t^h}$ MSSM over SM

obtained using POWHEG + HERWIG

(Bagnaschi et al.)

$\phi \to \tau\tau \; (\phi = h, H, A)$ kills the non-decoupling solution



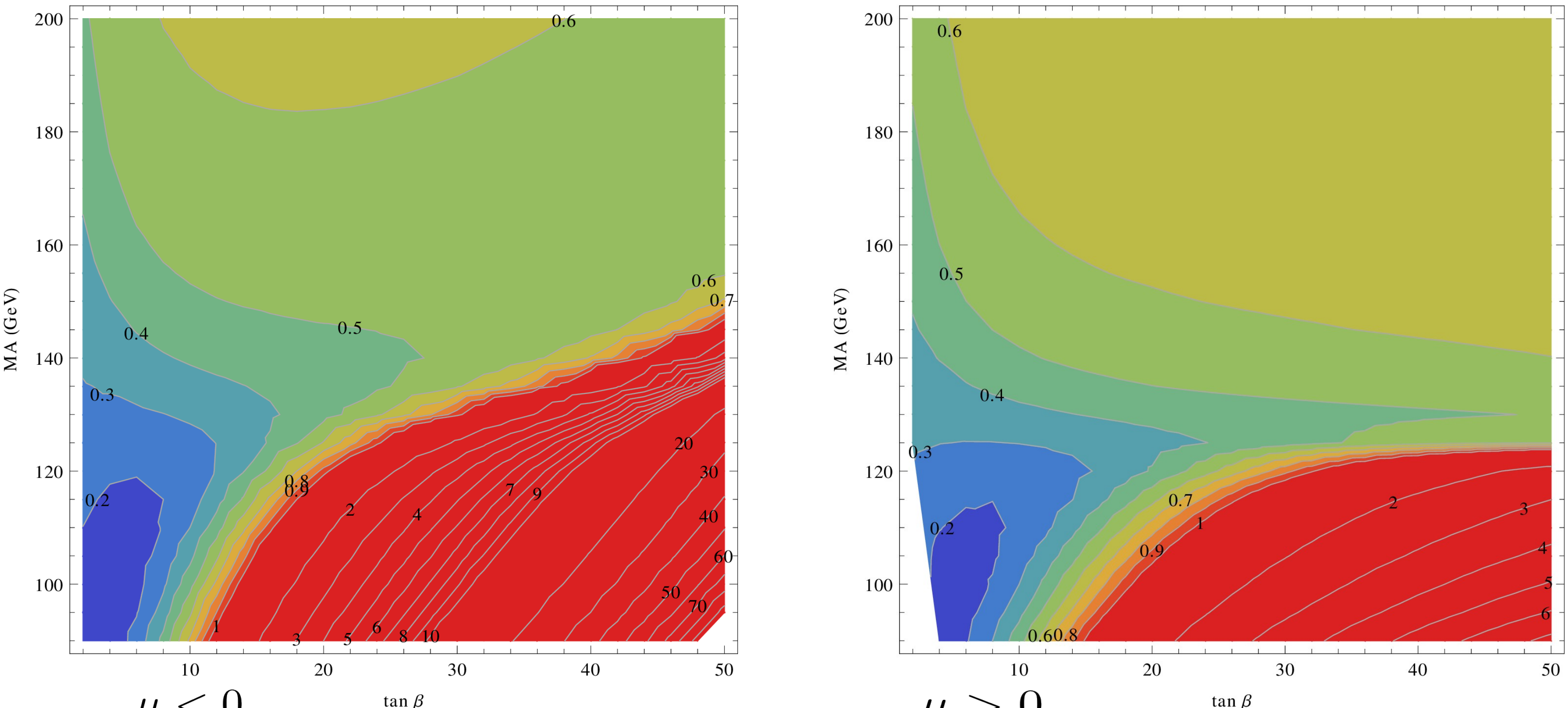


The ATLAS, CMS plots represent points in the MSSM parameter space different from ours, the SUSY corrections are not included in these plots, but with these limits ……

$M_H \sim 125$ GeV: Large M_A , to be in the decoupling regime

Light Stops

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})}$$



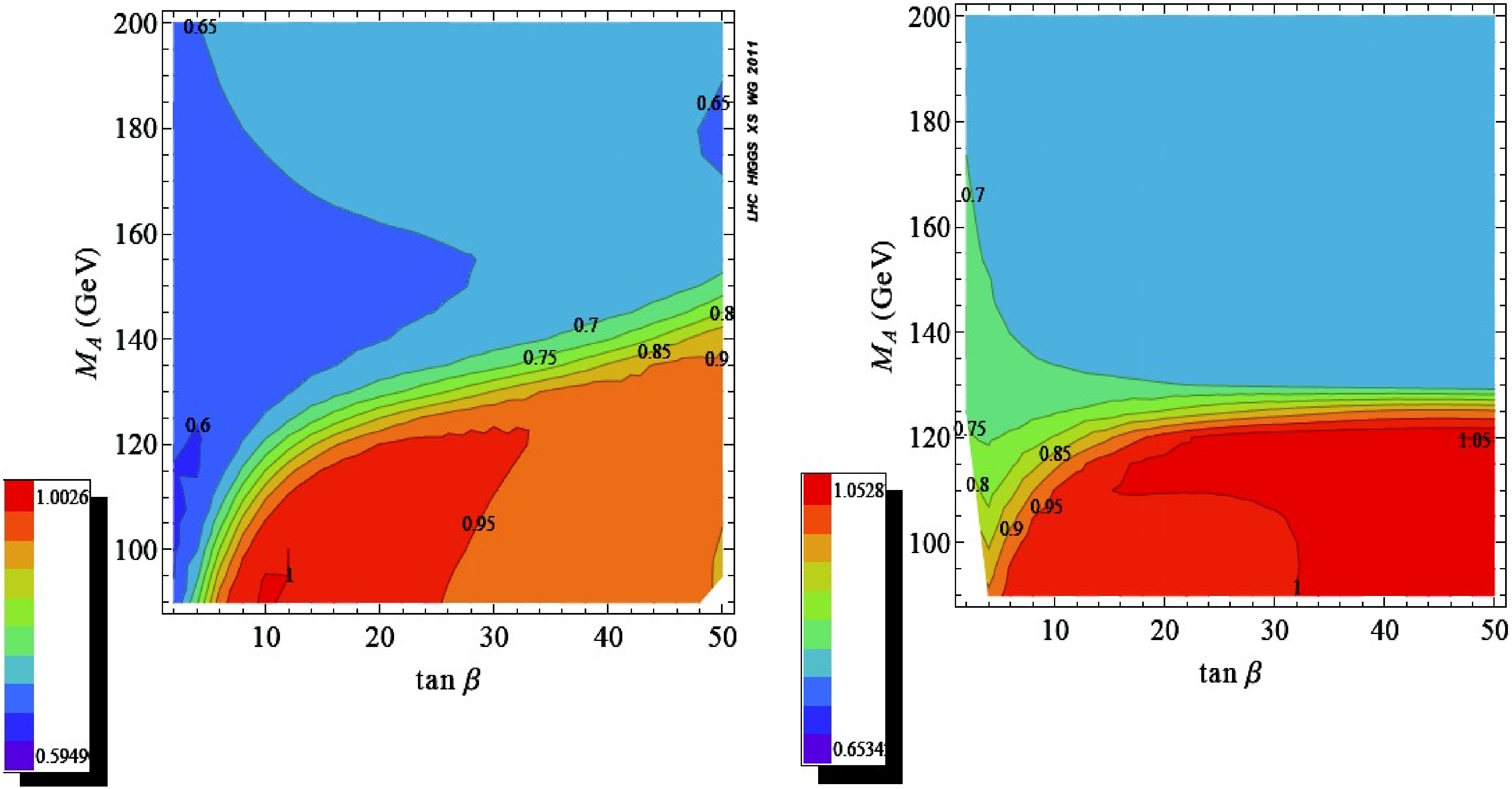
$\mu < 0$ $\qquad\qquad$ $\mu > 0$

$m_Q = m_U = m_D = 500$ GeV, $X_t = A_t - \mu \cot\beta = 1250$ GeV, $M_3 = 2\,M_2 = 4\,M_1 = 400$ GeV, $|\mu| = 200$ GeV

$$M_{\tilde{t}_1} \sim 280\,\mathrm{GeV},\; M_{\tilde{t}_2} \sim 660\,\mathrm{GeV},\; M_h^{max} < 123\,\mathrm{GeV}$$

$$\frac{\sigma(g\,g \to h)}{\sigma(g\,g \to h_{SM})_{\text{rescaled}}}$$

$\mu < 0$ $\mu > 0$



For M_A ~ 200 GeV squarks corrections are large (30–40%) and genuine SUSY

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.

THE END