Implications of the Higgs discovery

Abdelhak DJOUADI (LPT Paris-Sud)

- **Before the 4th of July**
- **The 4th of July and after**
- **Implications for the Standard Model**
- **Impliications for the MSSM**
- **Perspectives**

1. Before the 4th of July

A longstanding and most crucial problem in particle physics:

how to generate particle masses in an SU(2)$\times$U(1) gauge invariant way?

in the Standard Model $\Rightarrow$ the Higgs–Englert–Brout mechanism

Introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ with $\langle 0|\Phi^0|0\rangle \neq 0$:

fields/interactions symmetric under SU(2)$\times$U(1) but vaccum not.

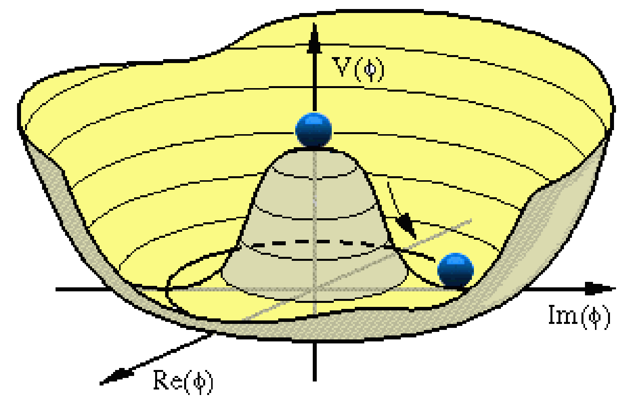
$$\mathcal{L}_S = D_\mu\Phi^\dagger D^\mu\Phi - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

$$v = (-\mu^2/\lambda)^{1/2} = 246\ \mathrm{GeV}$$

$\Rightarrow$ **three d.o.f. for $M_{W^\pm}$ and M_Z.**

For fermion masses, use <u>same</u> Φ:

$$\mathcal{L}_{Yuk} = -f_e(\bar{e},\bar{\nu})_L \Phi e_R + \ldots$$



Residual d.o.f corresponds to spin–0 H particle.

- **The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers (CP–even).**
- **Masses and self–couplings from V : $M_H^2 = 2\lambda v^2, g_{H^3} = 3\frac{M_H^2}{v}, \ldots$**
- **Higgs couplings $\propto$ particle masses: $g_{Hff} = \frac{m_f}{v}, g_{HVV} = 2\frac{M_V^2}{v}$**

Since v is known, the only free parameter in the SM is M_H (or λ).

Once M_H known, all properties of the Higgs are fixed (modulo QCD).

1. Before the 4th of July

Since v is known, the only free parameter in the SM is M_H (or λ).

Once M_H known, all properties of the Higgs are fixed (modulo QCD).

Example: Higgs decays in the SM

- **As $g_{HPP} \propto m_P$, H will decay into heaviest particle phase-space allowed:**
- $M_H \lesssim 130$ GeV :

– $H \to b\bar{b}$: **dominant decay**

– $H \to cc, \tau^+\tau^-, gg = \mathcal{O}(\text{few}\,\%)$

– $H \to \gamma\gamma, Z\gamma = \mathcal{O}(0.1\%)$

- $M_H \gtrsim 130$ GeV:

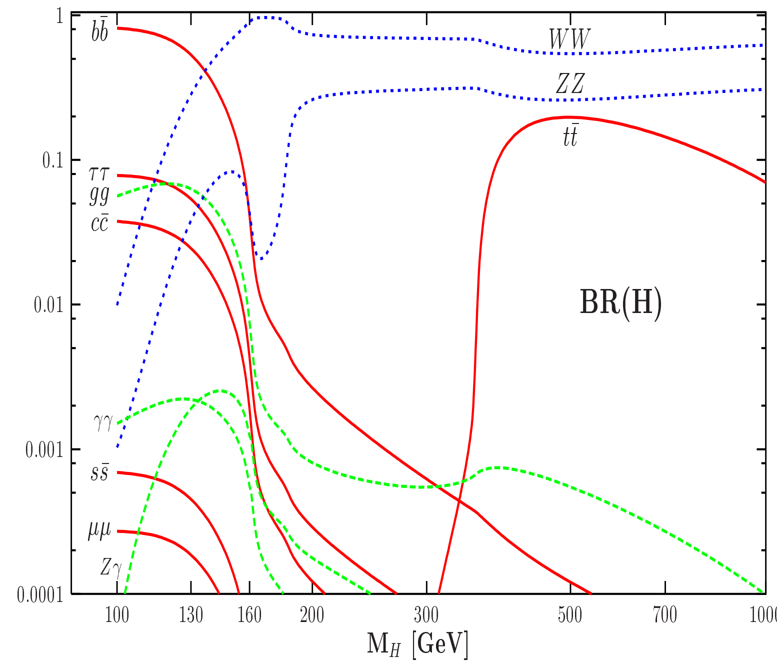
– $H \to WW, ZZ$ **dominant**

– **decays into $t\bar{t}$ for heavy Higgs**

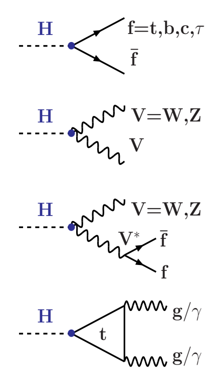
- **Total Higgs decay width:**

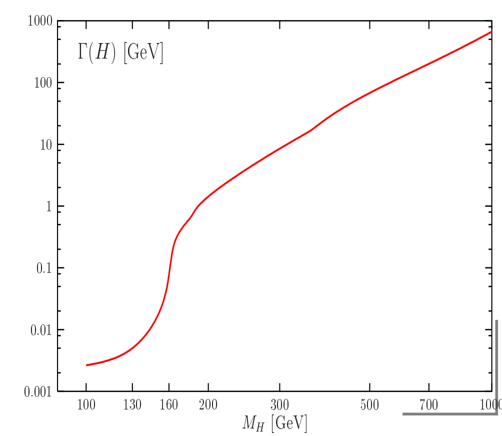
– **very small for a light Higgs**

– **comparable to mass if heavy**



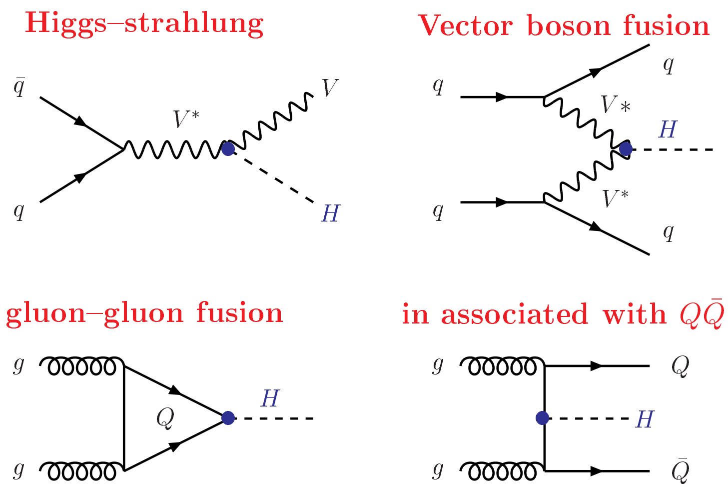
HDECAY $\Rightarrow$

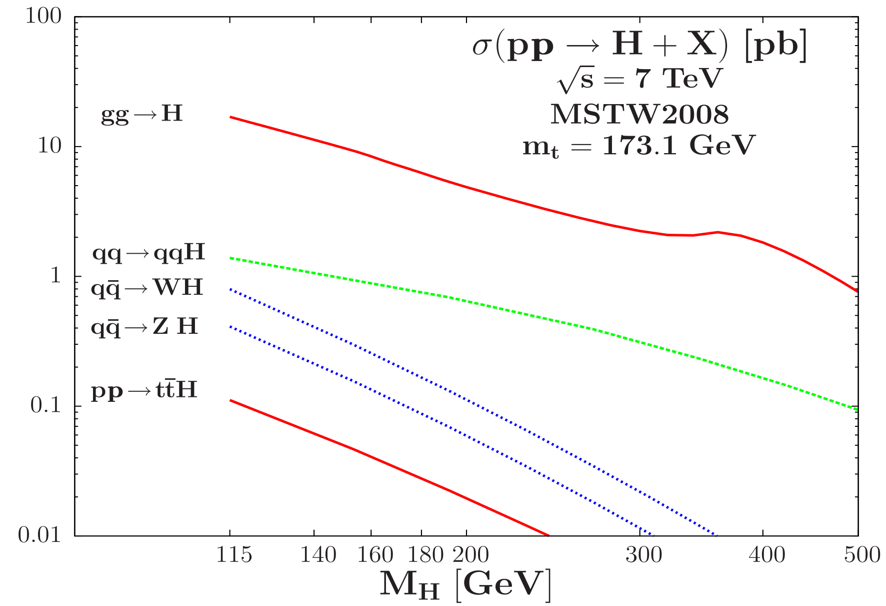




1. Before the 4th of July

Main Higgs production channels





Large production cross sections

with gg$\to$ H by far dominant process

1 $\mathrm{fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ events@LHC

$\Rightarrow \mathcal{O}(10^3)$ events@Tevatron

but eg BR(H$\to \gamma\gamma, ZZ \to 4\ell) \approx 10^{-3}$

... a small # of events at the end...

with a huge QCD-jet background.

$\Rightarrow$ an extremely challenging task!

Main sensitive channels:

$gg \to H \to \gamma\gamma$

$gg \to H \to ZZ \to 4\ell, 2\ell 2\nu, 2\ell 2$

$gg \to H \to WW \to \ell\nu\ell\nu + 0, 1j$

also help from other channels:

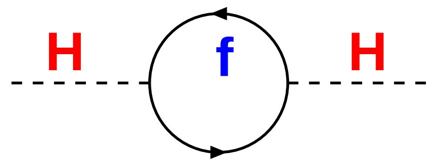
– VBF+$gg \to H \to \tau\tau$

– $q\bar{q} \to HV \to b\bar{b}\ell X$

1. Before the 4th of July

But a major problem in the SM: the hierarchy/naturalness problem

Radiative corrections to M_H^2 in SM with a cut–off $\Lambda = M_{NP} \sim M_{Pl}$

$\Delta M_H^2 \equiv$ 

$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$

M_H prefers to be close to the high scale than to the EWSB scale...

Three main avenues for solving the hierarchy problem:

Supersymmetry: a set of new/light SUSY particles cancel the divergence.

– MSSM $\equiv$ two Higgs doublet model $\Rightarrow$ 5 physical states $h, H, A, H^\pm$

– very predictive: only two free parameters at tree–level ($\tan\beta, M_A$)

– upper bound on light Higgs $M_h \lesssim 130$ GeV and $M_{H,H^\pm} \approx M_A \lesssim$ TeV

Extra dimensions: there is a cut–off at TeV scale where gravity sets in.

– in most cases: SM–like Higgs sector but properties possibly affected

– but in some cases, there might be no Higgs at all (Higgsless models)....

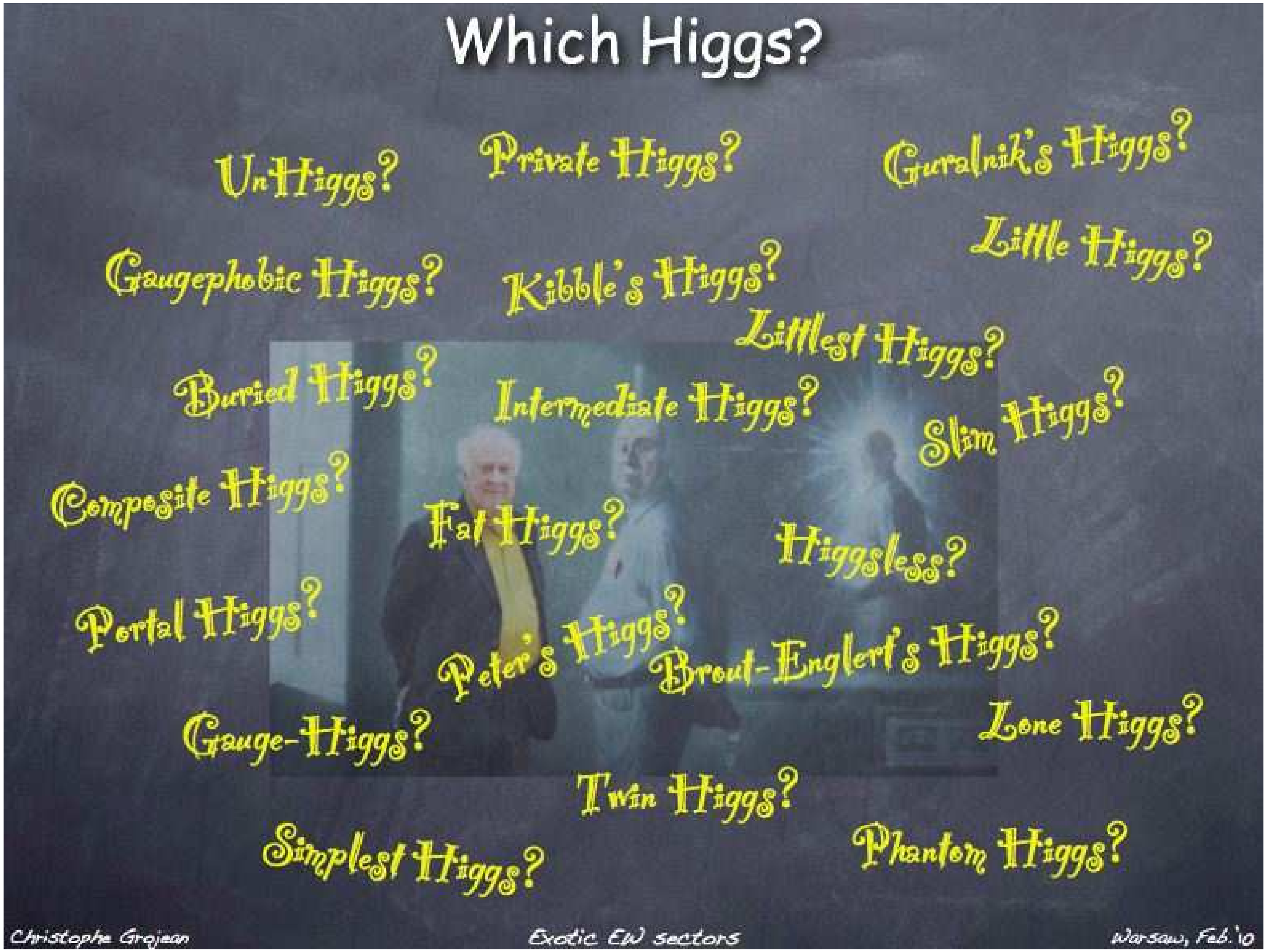
Strong interactions/compositness: the Higgs is not an elementary scalar.

– H is a bound state of fermions like for the pions in QCD...

– H emerges as a Nambu–Goldstone of a strongly interacting sector..

1. Before the 4th of July

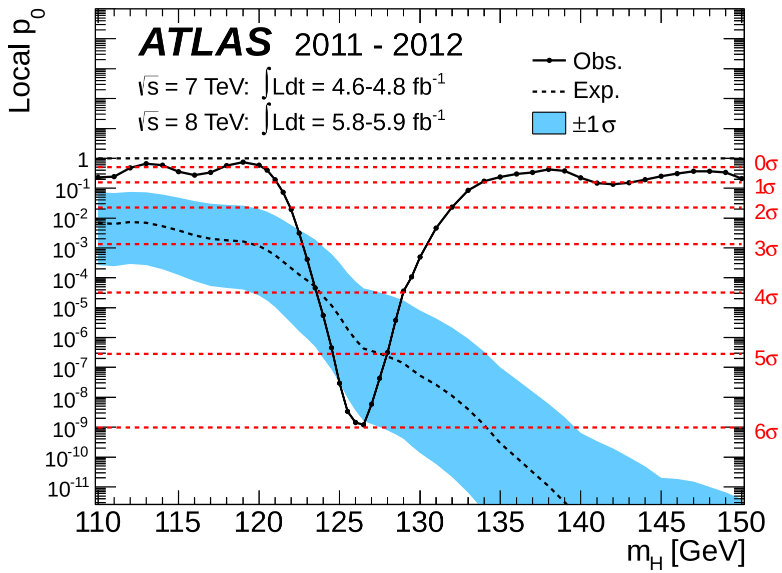
and along the avenues, many possible streets, paths, corners...

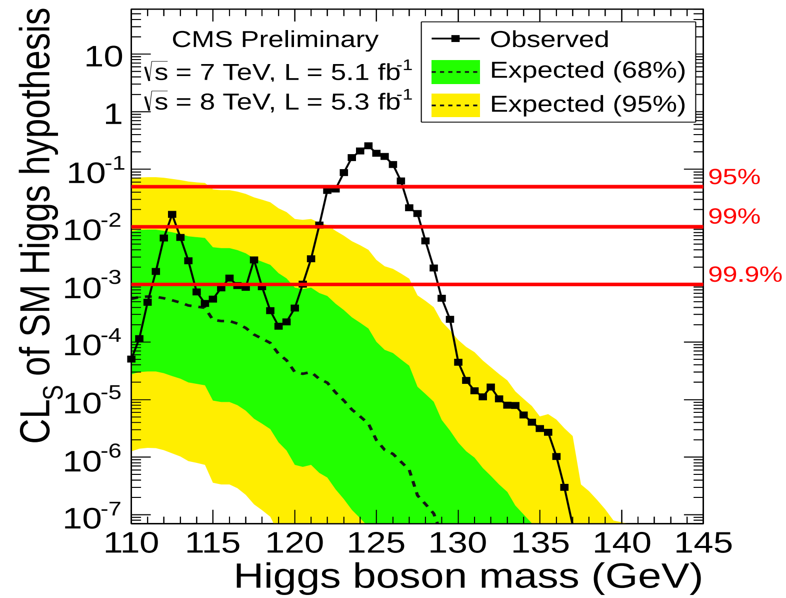


Which scenario chosen by Nature? The LHC was supposed to tell!

2. The 4th of July and after

After 48 years of postulat, 30 years of search (and a few heart attacks), the Higgs is discovered at LHC on the 4th of July: Higgstorical day!





2. The 4th of July and after

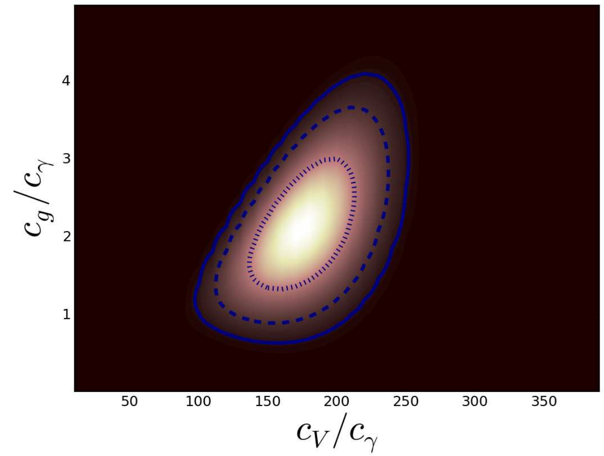
The particle decays into $\gamma\gamma$

- **not spin–1: Landau–Yang**
- **could be spin–2 like graviton?**

– miracle that rates/distributions fit that of a scalar Higgs boson,

$\Rightarrow$ "prima facie" evidence against it.

Ellis, Sanz, You

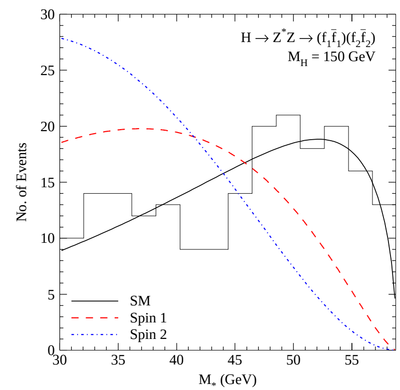


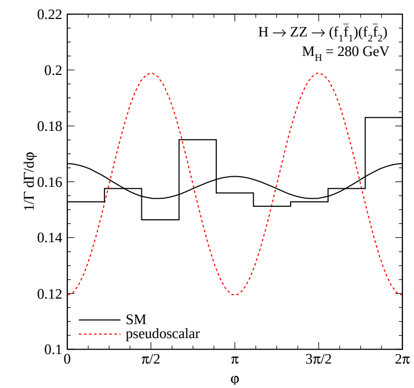
Is it CP–even or CP–odd?

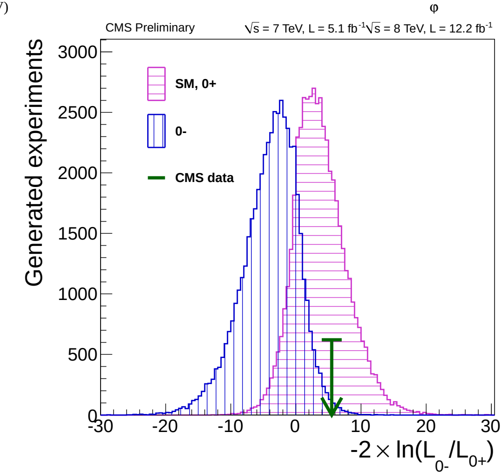
$$\mathbf{H V_\mu V^\mu \ \text{vs} \ H \epsilon^{\mu\nu\rho\sigma} Z_{\mu\nu} Z_{\rho\sigma}}$$

$$\Rightarrow \frac{d\Gamma(H \to ZZ^*)}{dM_*} \ \text{and} \ \frac{d\Gamma(H \to ZZ)}{d\phi}$$

CMS: 2.5σ for CP–even..







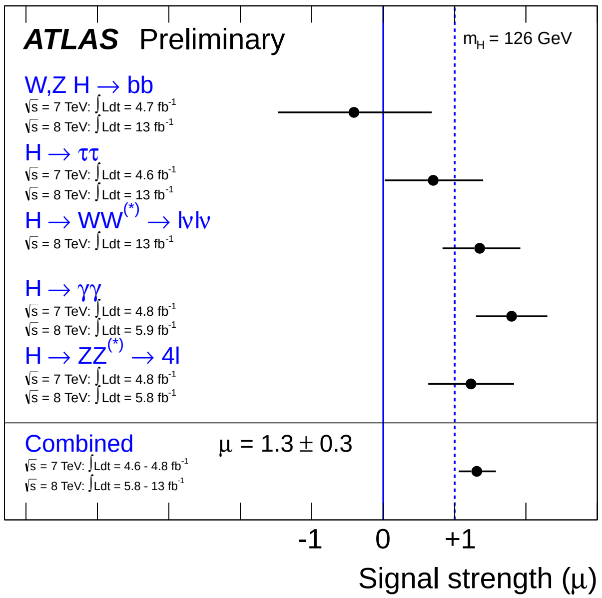
Problem: if H is CP mixture, only 0^+ component is projected out!

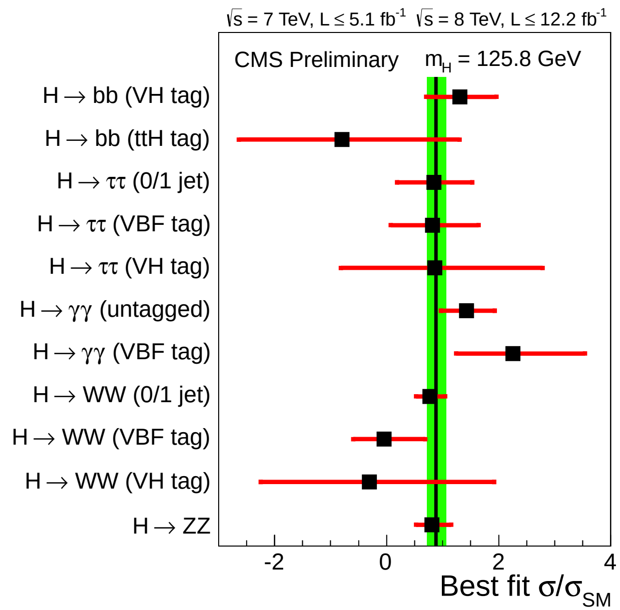
(or very large 0^-VV loop coupling).

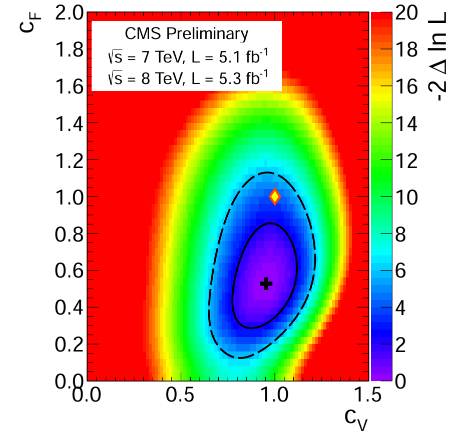
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 0.95 \pm 0.3$?

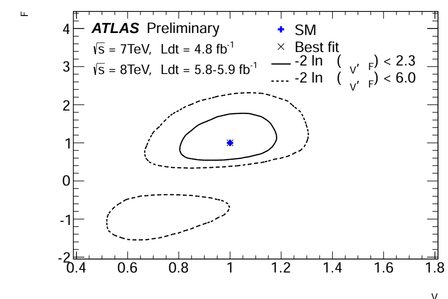
2. The 4th of July and after

Rates compatible with those expected in the SM









Higgs couplings to gauge bosons and fermions as dictated by unitarity:

- **fermiophobic, gauge-phobic scenarios ruled out**
- **still two solutions for fermion cplgs: non–SM–like is non unitary...**

SM particle spectrun now complete: no 4th generation fermions

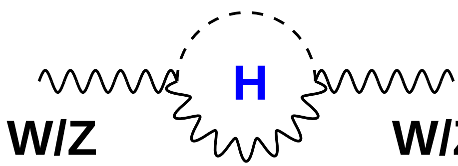
- **Rates in $\mathrm{ZZ}, \mathrm{WW}, \gamma\gamma, \mathrm{b\bar{b}}$ incomplatible with SM4**
- **direct searches and precision data against it**

3. Implications for the SM

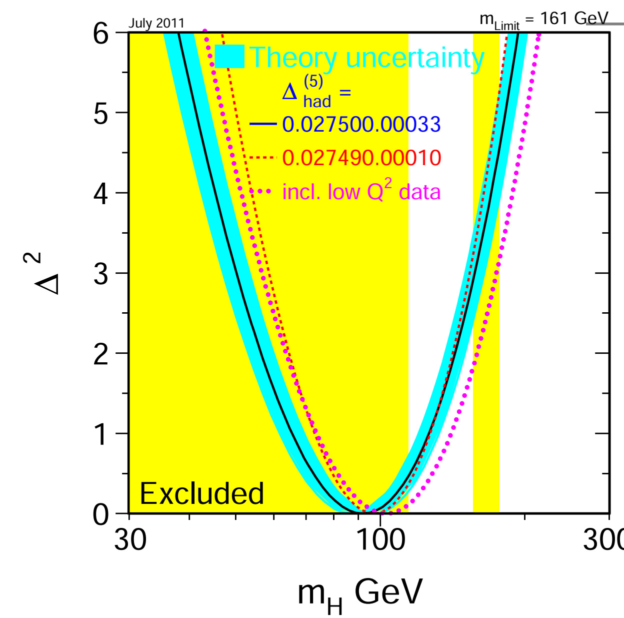
So its looks like expected in SM ⇒
a triumph for high-energy physics!

Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



$$\propto \frac{\alpha}{\pi} \log \frac{M_H}{M_W} + \cdots$$

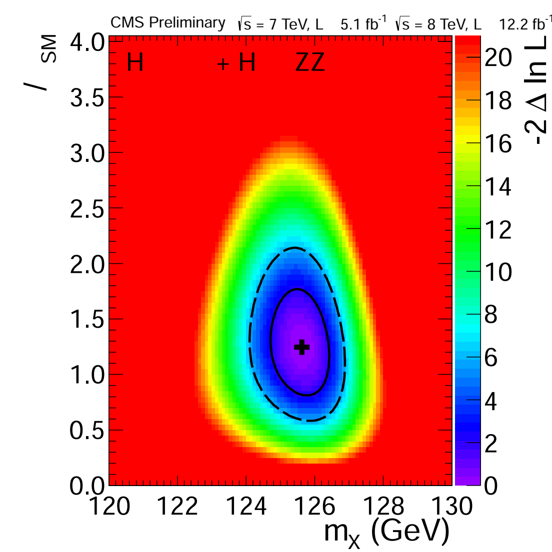


Fit the EW precision measurements, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

$$M_H \lesssim 160 \text{ GeV at 95\% CL}$$

compared with the measured mass

$$M_H \approx 126 \text{ GeV.}$$



A very non–trivial consistency check!
(remember the stop of the top quark!).
The SM is a very successfull theory!

---

[a] Still some problems with A_{FB}^{b} (LEP), A_{FB}^{t} (TeV) and $g-2$ but not severe...

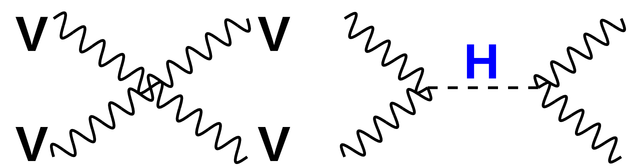
3. Implications in the SM

- **The theory preserves unitarity:**

without H: $|A_0(VV \to VV)| \propto E^2$

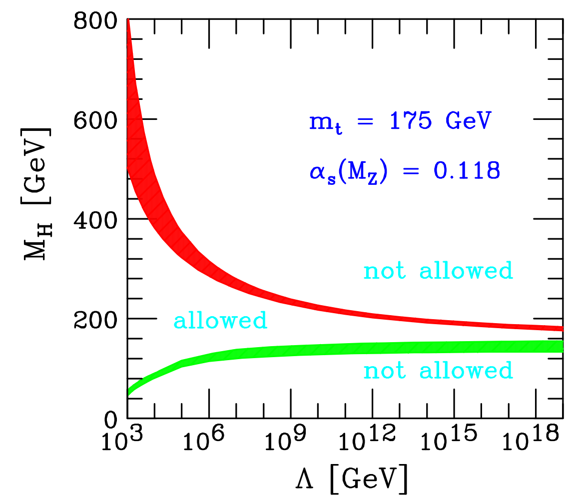
including H: $|A_0| \propto M_H^2/v^2$

theory unitary if $M_H \lesssim 700$ **GeV...**



- **Extrapolable up to highest scales.**

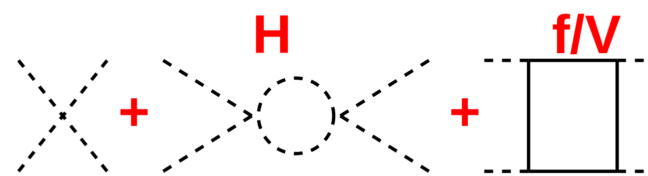
Stability of the EW vaccum?



- $\lambda = M_H^2/2v^2$ **evolves with Q:**

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx 1 + 3\,\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4} \log\frac{Q^2}{v^2}$$

tops make $\lambda(0) < \lambda(v)$: **unstable vacuum**



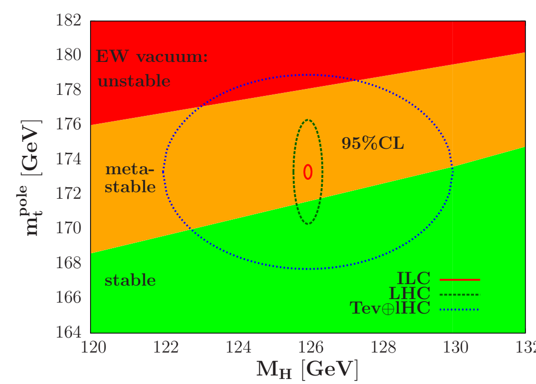
- **SM valid only if v≡EW-min, ie** $\lambda(Q^2) > 0$

$\Lambda_C \sim M_{Planck} \Rightarrow M_H \gtrsim 129\ \mathrm{GeV}!$

for $m_t = 173$ **GeV; but what is** m_t^{TEV}**??**

- **Unambiguous** m_t **only from** $\sigma(t\bar{t})$:

but value at TEV/LHC not precise...

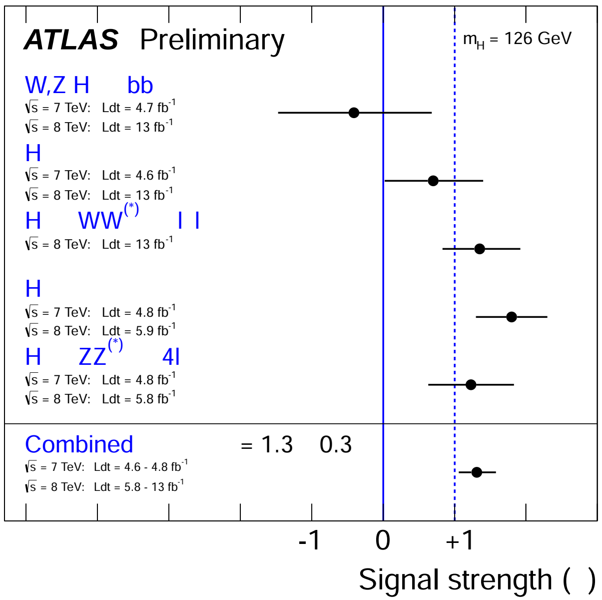


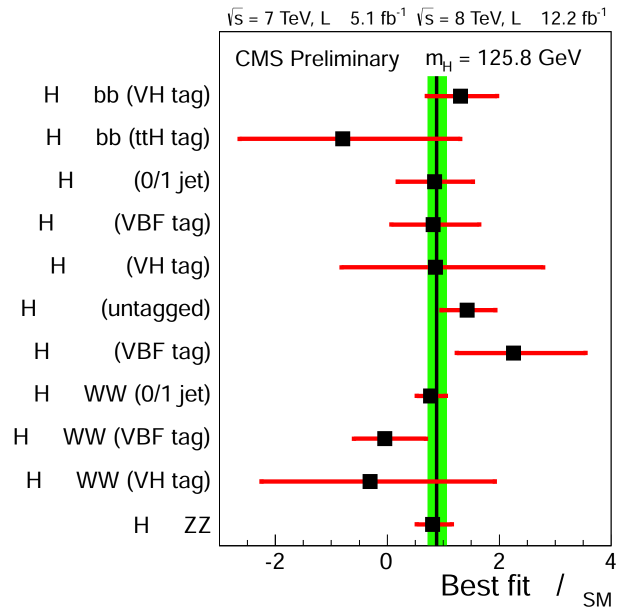
- **SM = TOE? Maybe not (?):**

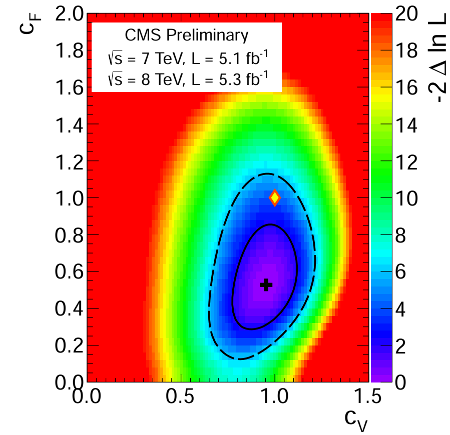
m_ν, **DM, GUT, hierarchy...**

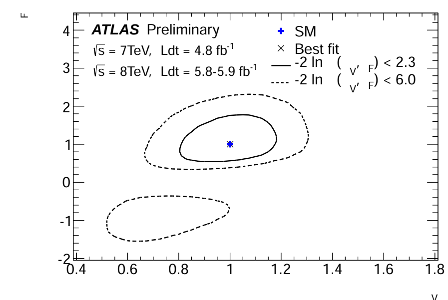
4. Implications for BSM

Rates compatible with those expected in the SM









Some beyond the SM scenarios are ruled out:

- **Higgsless models, extreme Technicolor and composite scenarios, ..**
- **fermiophobic Higgs, gauge-phobic Higgs, 4th generation, ...**

Some beyond the SM scenarios are in “hospital”:

Other BSM scenarios are strongly constrained...

Here, I discuss the example of Supersymmetry and the MSSM:

4. Implications for the MSSM

In MSSM with two Higgs doublets: $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$,

- to cancel the chiral anomalies introduced by the new $\tilde{h}$ field,
- give separately masses to d and u fermions in SUSY invariant way.

After EWSB (which can be made radiative: more elegant than in SM):
three dof to make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: $h, H, A, H^\pm$
Only two free parameters at the tree level: $\tan\beta, M_A$; others are:

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$\tan 2\alpha = \tan 2\beta\,(M_A^2 + M_Z^2)/(M_A^2 - M_Z^2)$$

We have important constraint on the MSSM Higgs boson masses:

$$M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z,\ M_{H^\pm} > M_W, M_H > M_A \ldots$$

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except for h:

$$M_h \sim M_Z |\cos 2\beta| \leq M_Z!\ ,\ M_H \sim M_{H^\pm} \sim M_A\ ,\ \alpha \sim \frac{\pi}{2} - \beta$$

$\Rightarrow$ Inclusion of radiative corrections to M_h important and necessary.

4. Implications for MSSM: mass

The mass value 126 GeV is rather large for the MSSM h boson,

$\Rightarrow$ one needs from the very beginning to almost maximize it...

Maximizing M_h is maximizing the radiative corrections; at 1-loop:

$$M_h \overset{M_A \gg M_Z}{\longrightarrow} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

- **decoupling regime with $M_A \sim \mathcal{O}$(TeV);**
- **large values of tan$\beta \gtrsim 10$ to maximize tree-level value;**
- **maximal mixing scenario: $X_t = \sqrt{6} M_S$;**
- **heavy stops, i.e. large $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$;**

we choose at maximum $M_S \lesssim 3$ TeV, not to have too much fine-tuning....

- **Do the complete job: two-loop corrections and full SUSY spectrum**
- **Use RGE codes (Suspect) with RC in $\overline{\rm DR}$/compare with FeynHiggs (OS**

Perform a full scan of the phenomenological MSSM with 22 free parameter

- **determine the regions of parameter space where $123 \leq M_h \leq 129$ GeV**

(3 GeV uncertainty includes both “experimental” and “theoretical” error)

- **require h to be SM–like: $\sigma(h) \times BR(h) \approx H_{SM}$ ($H = H_{SM)}$ later)**

Many anlayses! Here, the one from Arbey et al. 1112.3028+1207.1348

4. Implications for pMSSM: mass

Main results:

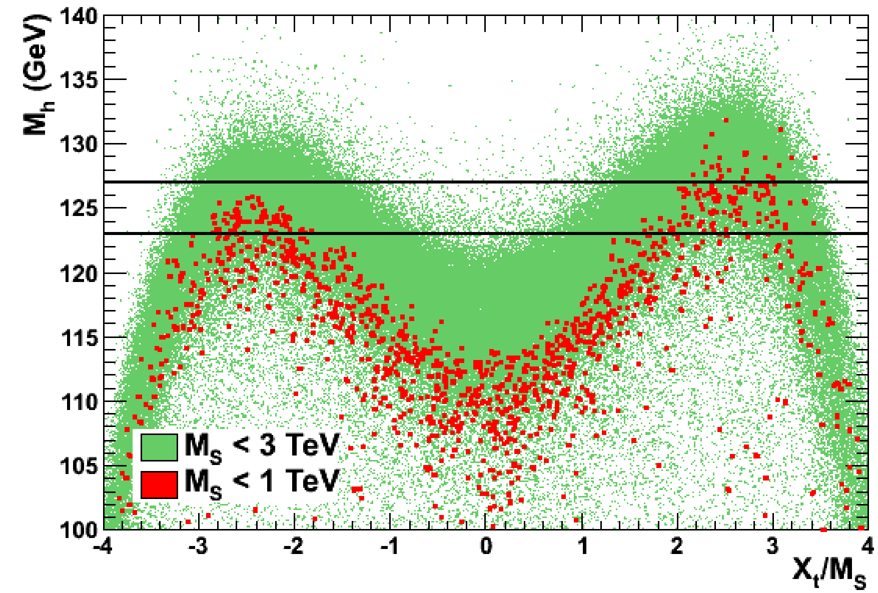
● **Large $\mathrm{M_S}$ values needed:**

– $\mathrm{M_S} \approx 1$ **TeV: only maximal mixing**

– $\mathrm{M_S} \approx 3$ **TeV: only typical mixing.**

● **Large tanβ values favored**

but tan$\beta \approx 3$ possible if $\mathrm{M_S} \approx 3$TeV



How light sparticles can be with the constraint $\mathrm{M_h} = 126$ GeV?

● **1s/2s gen. $\tilde{\mathrm{q}}$ should be heavy...**

But not main player here: the stops:

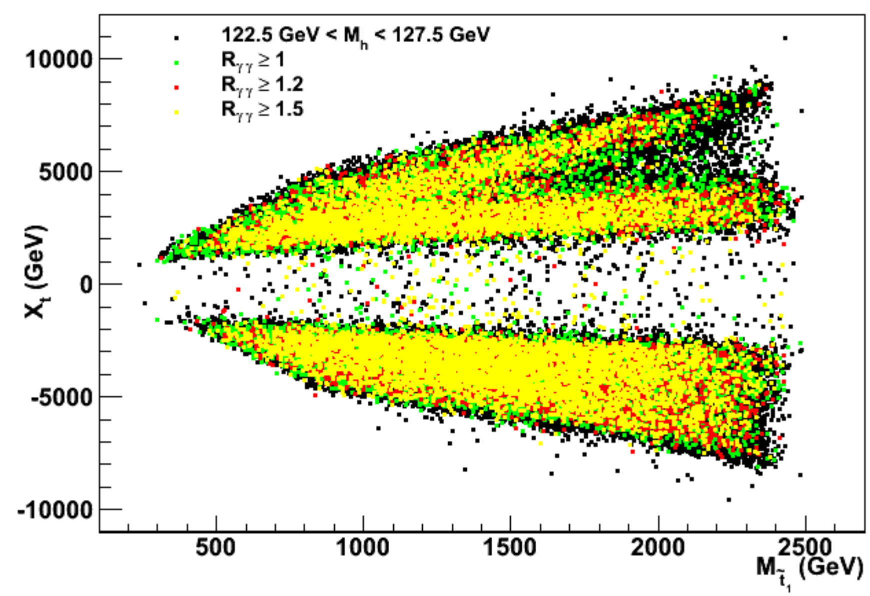
$\Rightarrow \mathrm{m}_{\tilde{\mathrm{t}}_1} \lesssim 500$ **GeV still possible!**

●$\mathrm{M_1}, \mathrm{M_2}$ **and μ unconstrained,**

● **non-univ. $\mathrm{m}_{\tilde{\mathrm{f}}}$: decouple $\tilde{\ell}$ from $\tilde{\mathrm{q}}$**

EW sparticles can be still very light

but watch out the new limits..



4. Implications for the cMSSM

Constrained MSSMs are interesting from model building point of view:

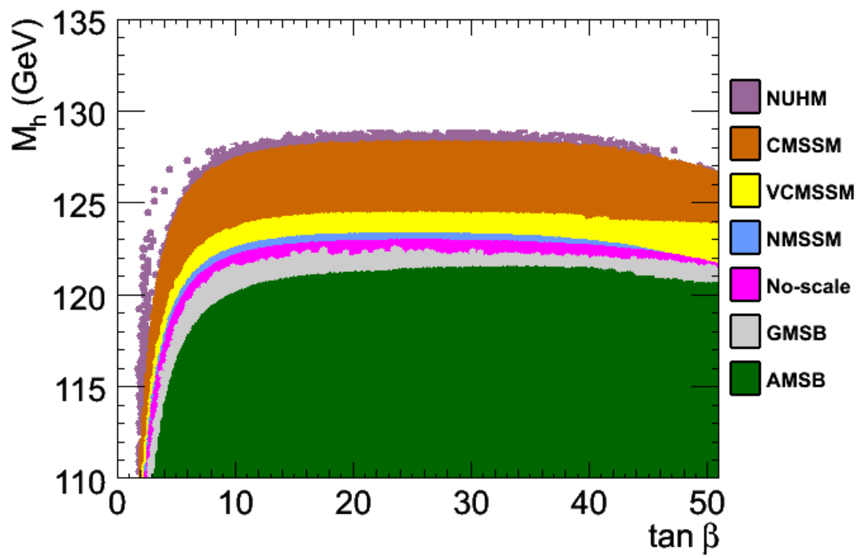
– concrete schemes: SSB occurs in hidden sector $\stackrel{\text{gravity,..}}{\longrightarrow}$ MSSM fields

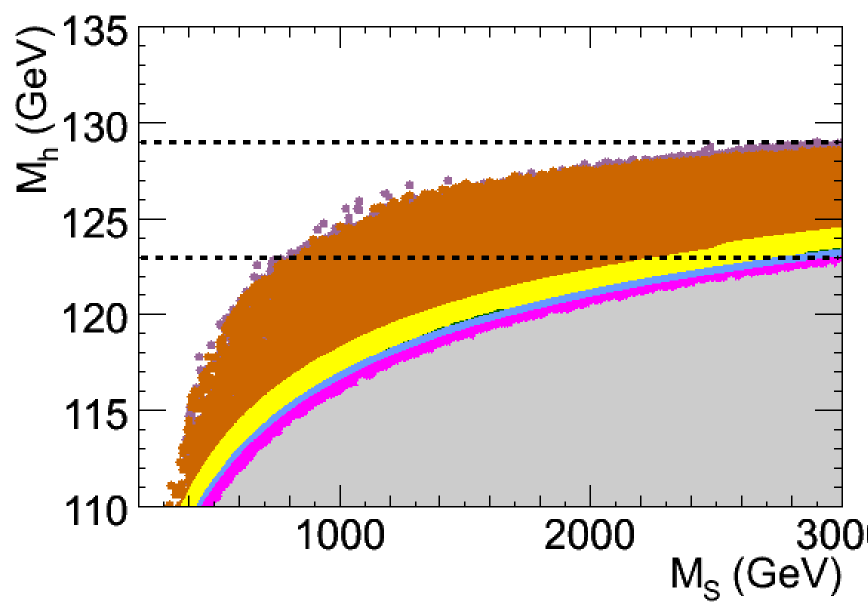
– provide solutions to some MSSM problems: CP, flavor, etc..

– parameters obey boundary conditions $\Rightarrow$ small number of inputs...

- **mSUGRA**: $\tan\beta\ ,\ \mathbf{m_{1/2}}\ ,\ \mathbf{m_0}\ ,\ \mathbf{A_0}\ ,\ \text{sign}(\mu)$
- **GMSB:** $\mathbf{tan}\beta\ ,\ \mathbf{sign}(\mu)\ ,\ \mathbf{M}_{\rm mes}\ ,\ \mathbf{\Lambda_{SSB}}\ ,\ \mathbf{N_{mess\ fields}}$
- **AMSB:**, $\mathbf{m_0}\ ,\ \mathbf{m_{3/2}}\ ,\ \tan\beta\ ,\ \text{sign}(\mu)$

full scans of the model parameters with $\mathbf{123\ GeV \le M_h \le 129\ GeV}$



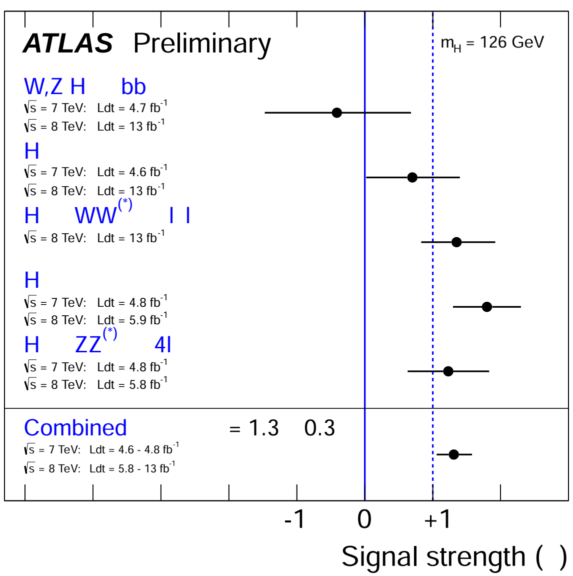


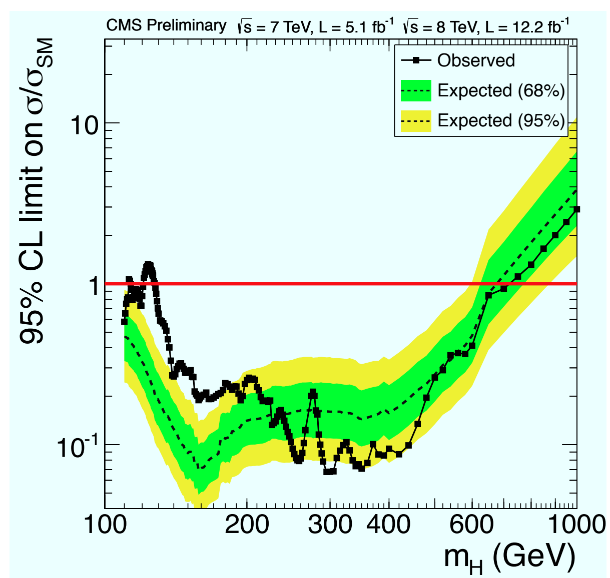
very strong constraints and some (minimal) models ruled out...

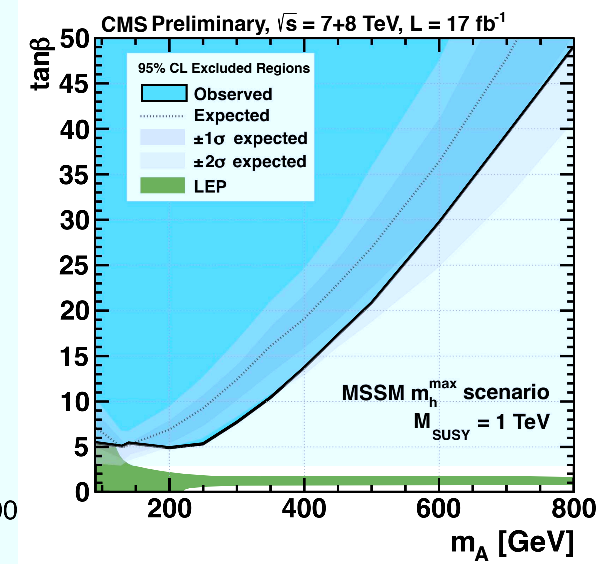
4. Implications for MSSM: other searches

There are other (stringent) constraints on pMSSM to be included:

- **production/decay rates of the observed Higgs particle;**
- **the observation of heavier Higgsses in the ZZ,WW signal channels;**
- **CMS and ATLAS $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ and $\mathrm{t} \to \mathrm{bH^+}$ searches;**
- **constraints from sparticle searches and eventually Dark Matter,**
- **constraints from flavor: at least (direct!) limits from $\mathrm{B_s} \to \mu\mu$...**



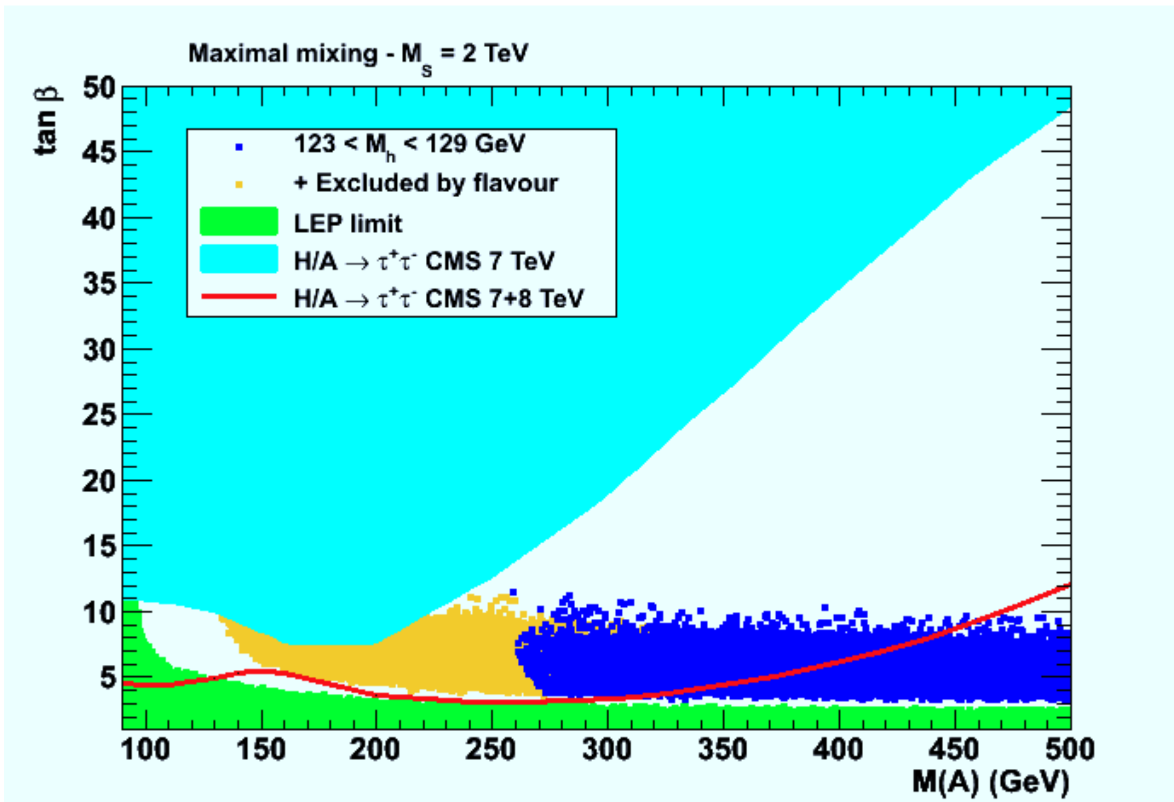




4. Implications for MSSM: other searches

There are other (stringent) constraints on pMSSM to be included:

- **production/decay rates of the observed Higgs particle;**
- **the observation of heavier Higgsses in the ZZ,WW signal channels;**
- **CMS and ATLAS $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ and $\mathrm{t} \to \mathrm{bH^+}$ searches;**
- **constraints from sparticle searches and eventually Dark Matter,**
- **constraints from flavor: at least (direct!) limits from $\mathrm{B_s} \to \mu\mu$...**



4. Implications for MSSM: rates

Sets stingent constraints on pMSSM regimes/benchmark scenarios?

- Heavier H being the observed Higgs is now excluded..
- Close $\mathrm{h, H, A, H^\pm}$ (intense coupling regime) excluded..
- Small $\alpha_{\rm eff}$ scenario with $g_{\rm hbb} \approx 0$ and thus small $\Gamma_{\rm h}$:

ruled out by LHC/Tevatron data: ex: loose Wh$\to \ell\nu b\bar{b}$ signal..

- gluophobic h with $g_{\rm hgg} \ll g_{\rm H_{SM}gg}$ due to squark loops?

ruled out by $\mathrm{ZZ, WW}, \gamma\gamma$ signals at LHC (and also the h mass)

But some difference with the SM!

a $\gtrsim 2\sigma$ excess in $\mathrm{H} \to \gamma\gamma$.

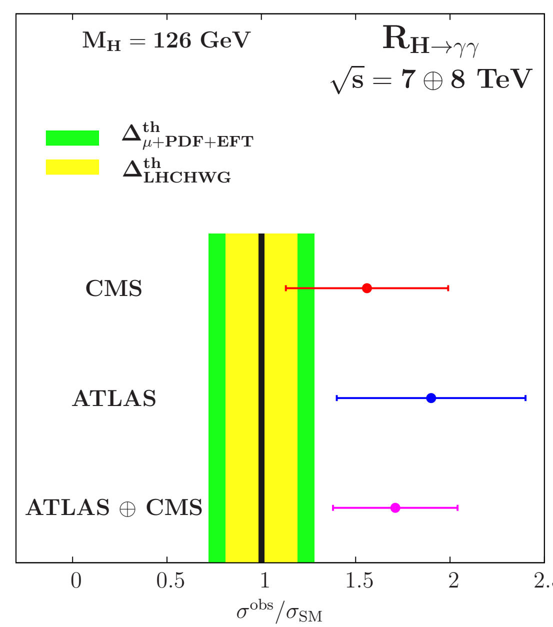
- Statistical fluctuation?
- Systematics problem?
- Maybe QCD uncertainties?

Baglio+Godbole+AD$\Rightarrow$

Hope it is due to SUSY!

– total Higgs width suppressed?

– SUSY effects in h$\gamma\gamma$ loop?



4. Implications for pMSSM: rates

Pretty hard to change tree-level Higgs couplings and loop hgg vertex

Can SUSY contributions significantly enhance the $h \to \gamma\gamma$ rate?

- **light stau's and large $\mu \tan\beta$**

  Carena+Gori+Shah+Wagner

- **light $\tilde{\chi}_1^{\pm}$ in non-univ MSSM**

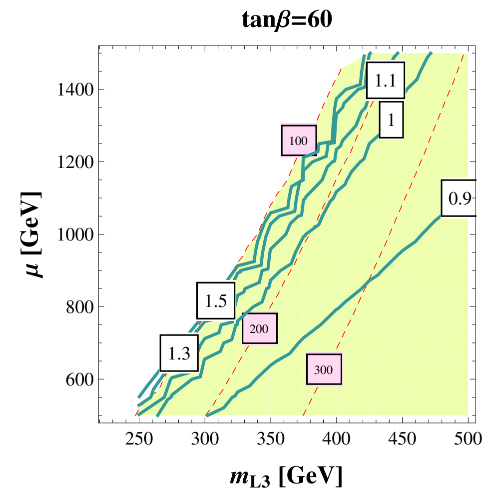
  Driesen+Illana+Hollik+AD

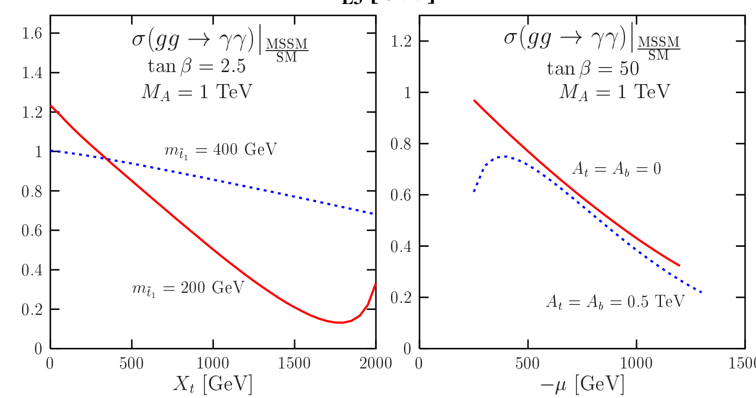
- **possibility of light $\tilde{t}$:**

$\Rightarrow$ **max-mixing: $\sigma(gg \to h)$ suppressed.**

$\Rightarrow$ **no mixing: yes, but stops too heavy.**

Arvanitaki+Villadoro,AD





- **BMSSM? One example is the NMSSM:**

Ellwanger etal, King etal., Gunion etal,..

– **stops lighter as M_h^{max} larger,**

– **additional singlet for couplings,**

– **less severe non-H constraints.**

Common features: some light sparticles are around the corner!

Data also OK with non SUSY extensions; ex: 2HDM (G. Branco et al.)

5. Conclusions: MSSM

A 126 GeV Higgs provides information on BSM and SUSY in particular:

- $M_H = 119$ **GeV would have been a boring value: everybody OK..**
- $M_H = 145$ **GeV would be a devastating value: mass extinction..**
- $M_H \approx 126$ **GeV is Darwinian: (natural) selection among models..**

SUSY spectrum heavy; except maybe for weakly interacting sparticles and also stops $\Rightarrow$ more focus on them in SUSY searches!

One has to include other Higgs/SUSY searches in particular:

- $H/A/H^{\pm}$ **searches at the LHC are becoming very constraining..**
- **SUSY searches and flavor constraints are to be taken into account.**
- **Little room for other Higgs searches at the LHC.**
- **Need to start thinking bout changing the benchmark scenarios....**

My personal feeling or bet: maybe the rather optimistic scenario?

– a stop and a chargino in 2015: my favorite/best–guess SUSY signal:

$$pp \to \tilde{t}_1 \tilde{t}_1 \to b\chi_1^+ \bar{b}\chi_1^- \to b\bar{b}e\mu + \not{E}_T$$

– following years, search for $gg \to \tilde{t}_1 \tilde{t}_1 h$ and measurement of A_t...

5. Conclusions: SM

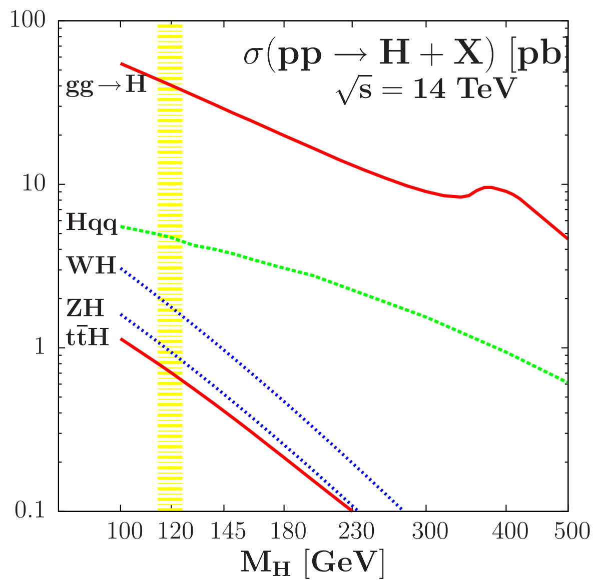
Now that Higgs is found (and nothing else yet): is Particle Physics "closed"?

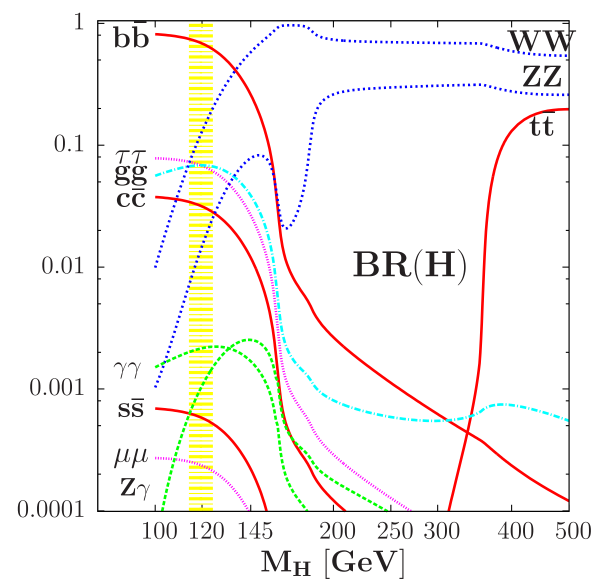
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

Measure its fundamental properties in the most precise way:

- **its mass and total decay width (invisible width due to dark matter?),**
- **its spin–parity quantum numbers and check SM prediction for them,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential V_H that makes EWSB.**

Possible for $M_H \approx$ 126 GeV as all production/decay channels useful!





5. Conclusion

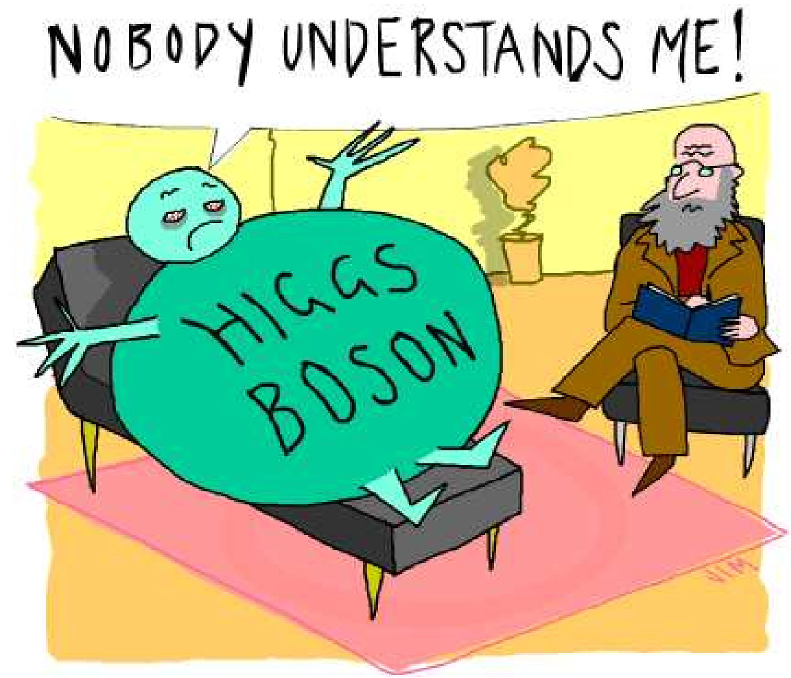
Now, this is not the end.

It is not even the beginning to the end.

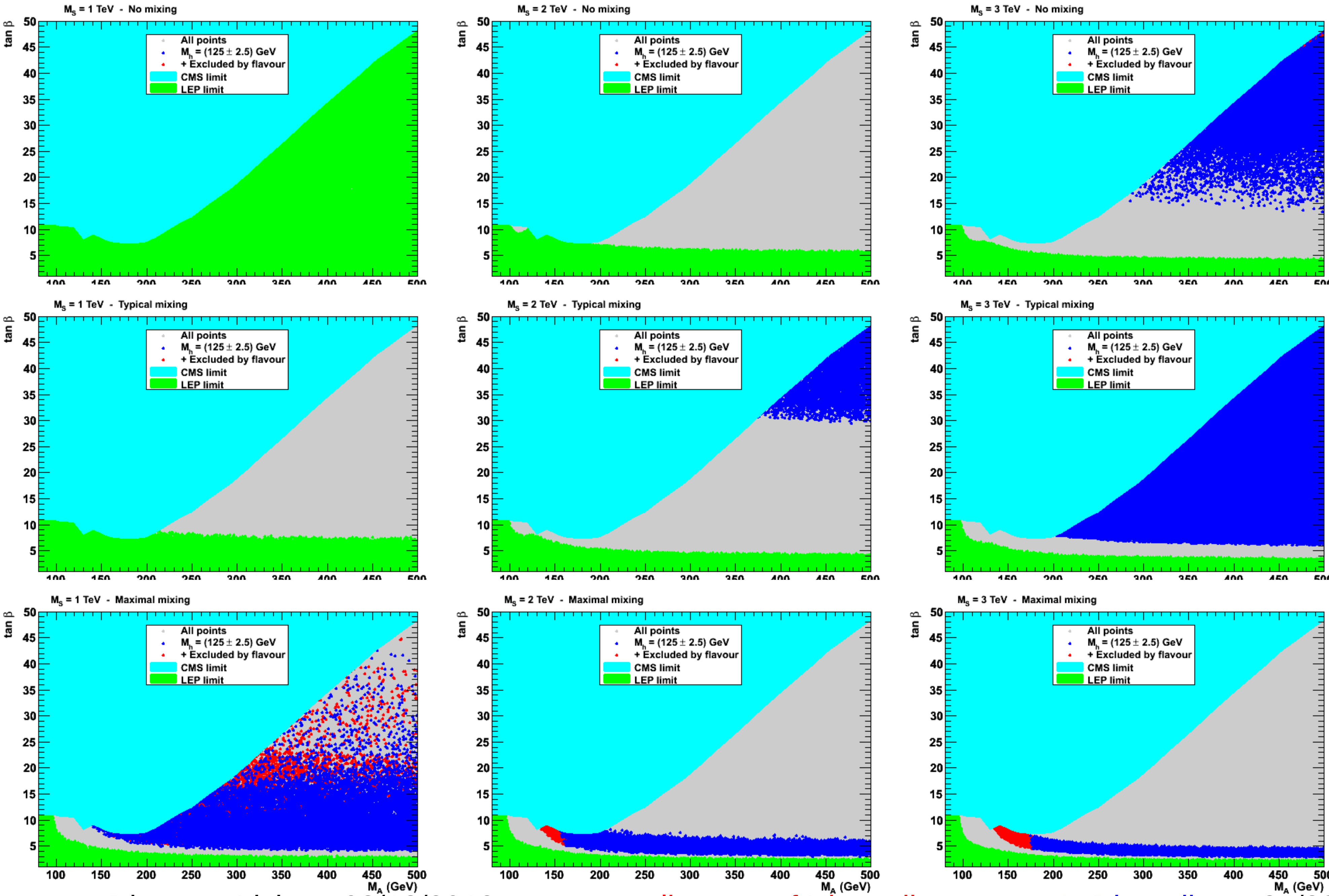
But it is, perhaps, the end of the beginning.

Sir Winston Churchill, November 1942

We hope that at the end we finally understand the EWSB mechanism, but there is a long way untill then.... and there might be many surprises!



Backup: implications for other scenarios



Backup: implications for MSSM: is H observed?

It looks like in decoupling regime. True ?

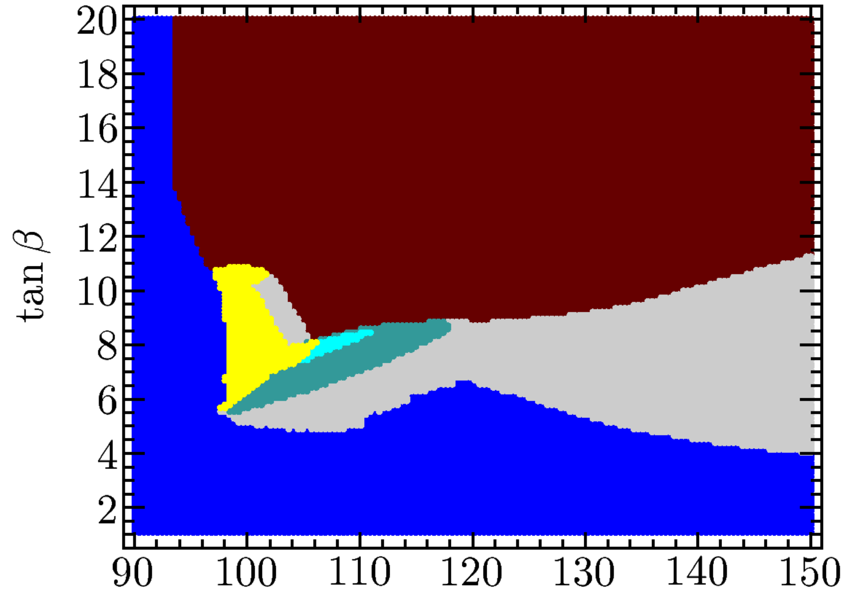
- are small values of M_A allowed?
- can H be the SM-like Higgs boson?

YES!, if no other constraints than:

– $M_H \approx 126 \pm 3$ GeV

– $g_{HVV} \approx g_{H_{SM}VV}$

Heinemeyer+Stal+Weiglein



$M_A \approx 100$ GeV, $\tan\beta \approx 6-10$,
$M_S \approx \mu \approx 1$ TeV, $X_t \approx \sqrt{6} M_S$,
$\Rightarrow M_H \approx 126$ GeV ; $M_h \approx 98$ GeV!

[ABDM scan: only few points, 10^{-6} OK
but they are all ruled out by flavor data
$\Rightarrow$ only h SM–like is likely...

With new CMS update, $\tan\beta \lesssim 5$:
$\Rightarrow$ H$\equiv$ observed is now excluded...