Implications of the Higgs discovery

. . .

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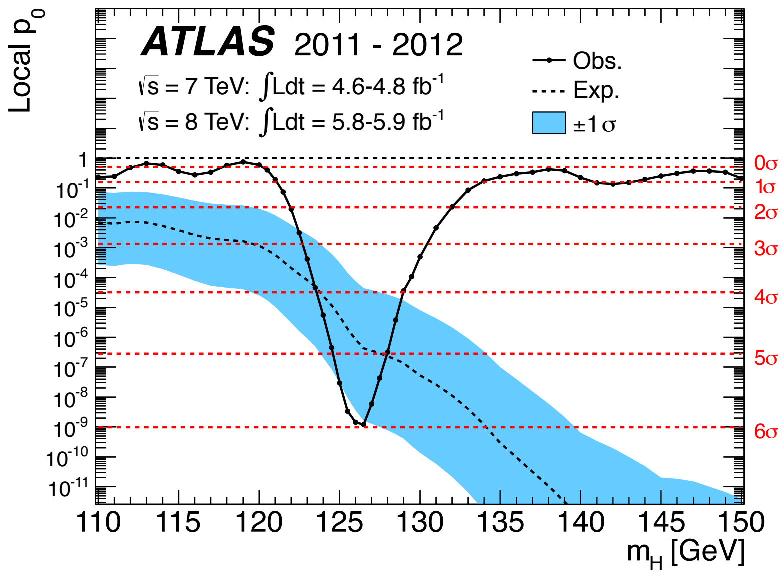
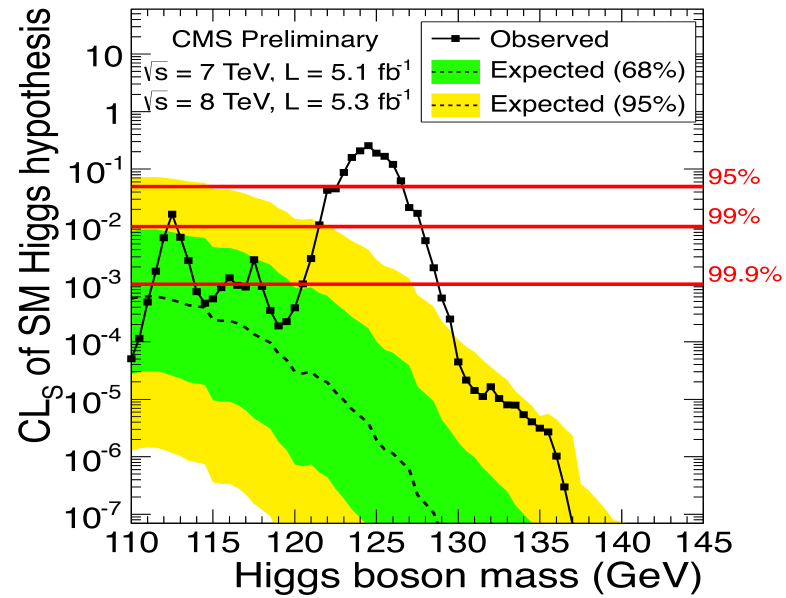
- First, is it a Higgs?
- Implications for the SM
- Implications for the MSSM: mass
- Other implications for the MSSM
- What next?

1. Is it a Higgs?

After 48 years of postulat, 30 years of search (and a few heart attacks), "a boson" is discovered at LHC on the 4th of July: Hi(gg)storical day!





1. First, is it a Higgs?

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.

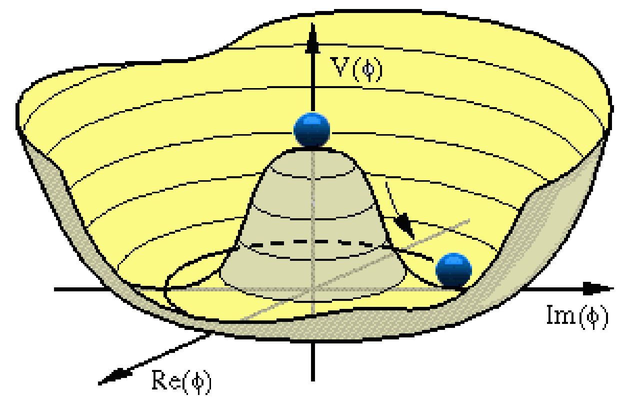
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

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

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

For fermion masses, use same Φ:

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



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

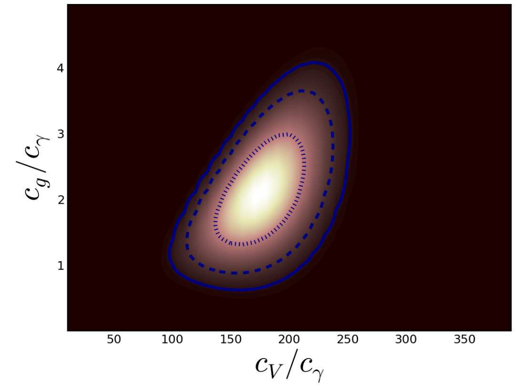
- **The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers (CP–even).**
- **Masses and self–couplings from V : $M_H^2 = 2\lambda v^2, g_{H^3} = 3\frac{M_H^2}{v}, \ldots$**
- **Higgs couplings $\propto$ particle masses: $g_{Hff} = \frac{m_f}{v}, g_{HVV} = 2\frac{M_V^2}{v}$**

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

1. First, is it a Higgs?

Spin: the state decays into $\gamma\gamma$

- **not spin–1: Landau–Yang**
- **could be spin–2 like graviton?** **Ellis et al.**



– miracle that couplings fit that of H,

– “prima facie” evidence against it:

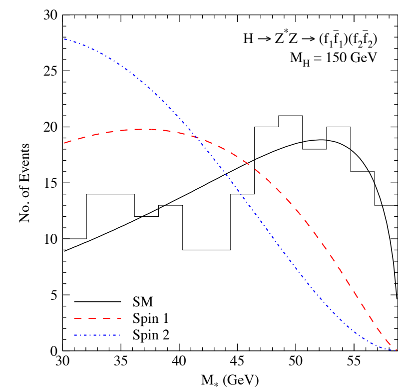
e.g.: $\mathbf{c_g \neq c_\gamma, c_V \gg 35 c_\gamma}$

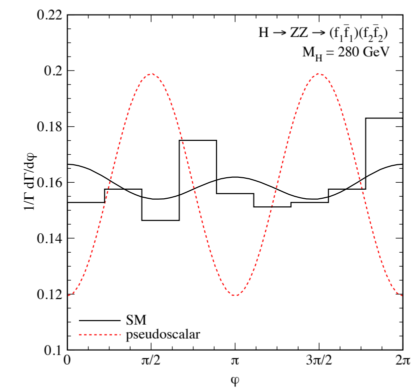
many th. analyses (no suspense).

CP: is it CP–even or CP–odd?

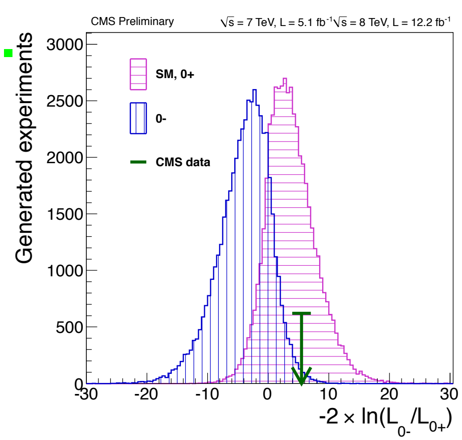
$$\mathrm{HV_\mu V^\mu \ vs \ H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}}$$

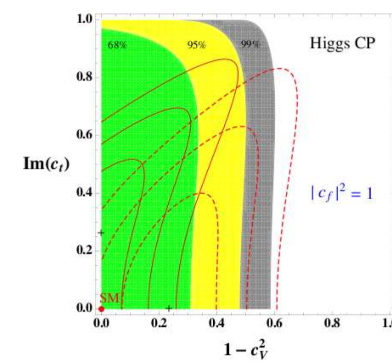
$$\Rightarrow \frac{\mathrm{d\Gamma(H\to ZZ^*)}}{\mathrm{dM_*}} \text{ and } \frac{\mathrm{d\Gamma(H\to ZZ)}}{\mathrm{d}\phi}$$





ATLAS/CMS: $\approx 3\sigma$ for CP-even.



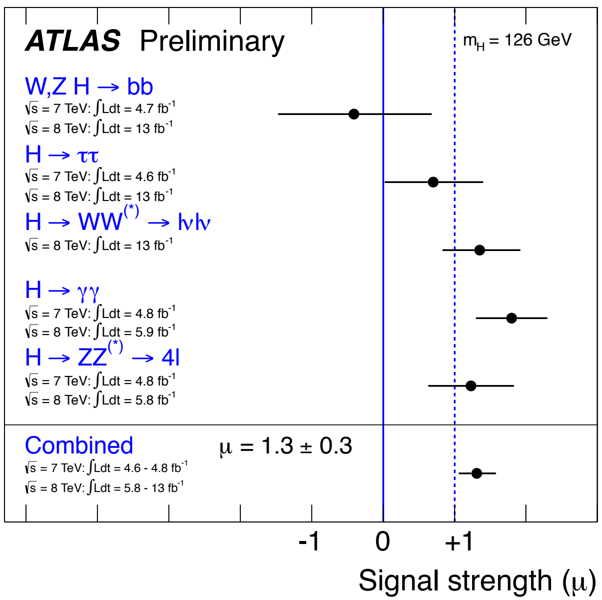


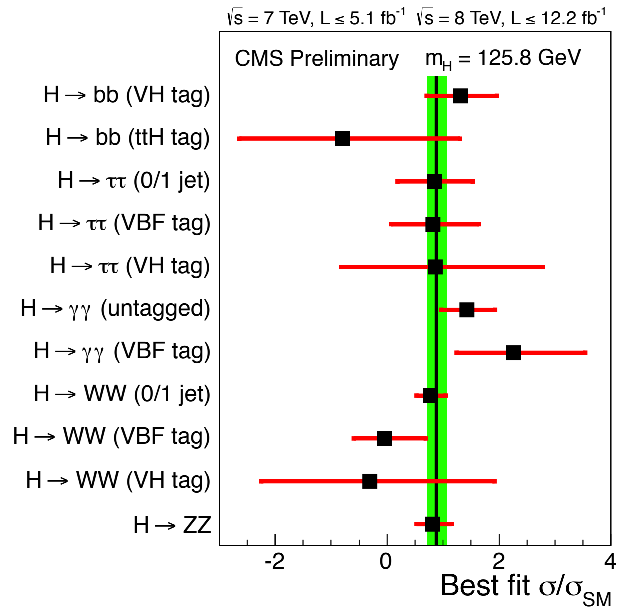
Problem: if H is CP mixture, only 0^+ component is projected out!

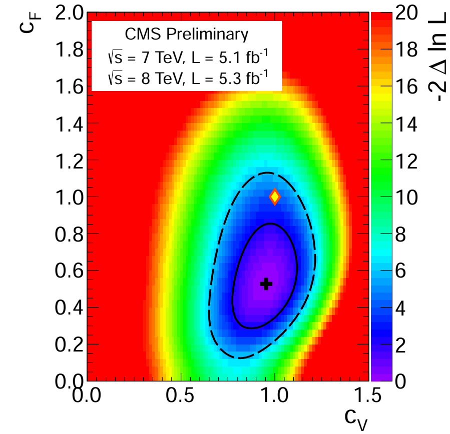
(or very large 0^-VV loop cplg).

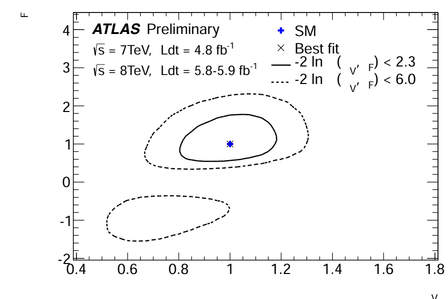
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4$!

1. First, is it a Higgs?









From ATLAS/CMS results:

Higgs couplings to elementary particles as predicted by Higgs mechanism

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs**
- **couplings proportionial to masses as expected for the Higgs boson**

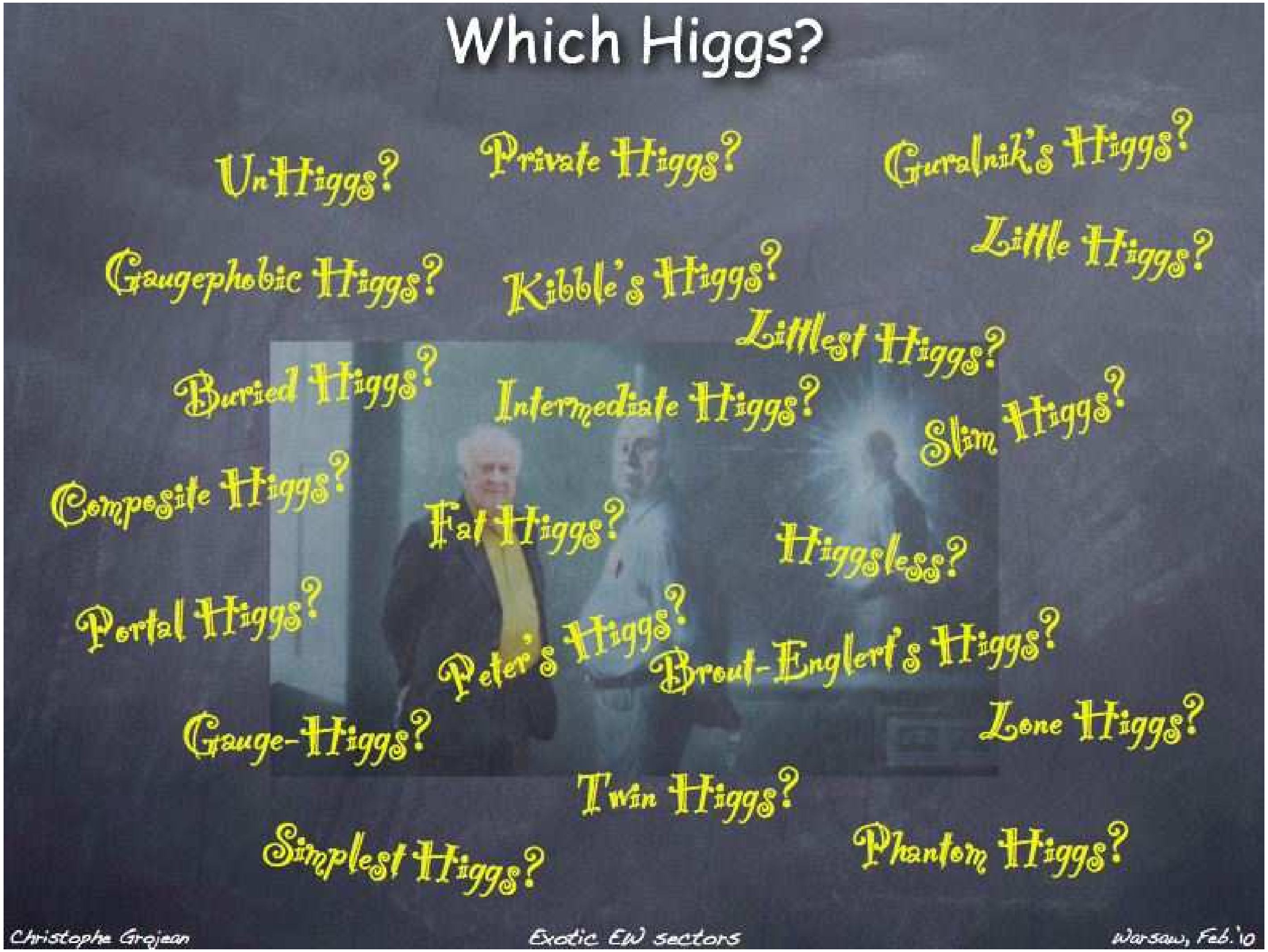
So, it is not only a "new particle", the "126 GeV boson", a "new state"...

IT IS A HIGGS BOSON!

But is it THE SM Higgs boson or A Higgs boson from some extension?

1. First, is it a Higgs?

a SM or a BSM Higgs?



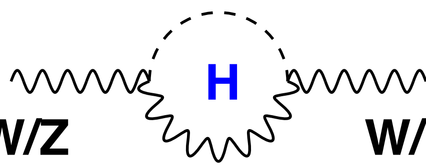
To check this you need very precise measurements to see small deviations...

2. Implications in the SM

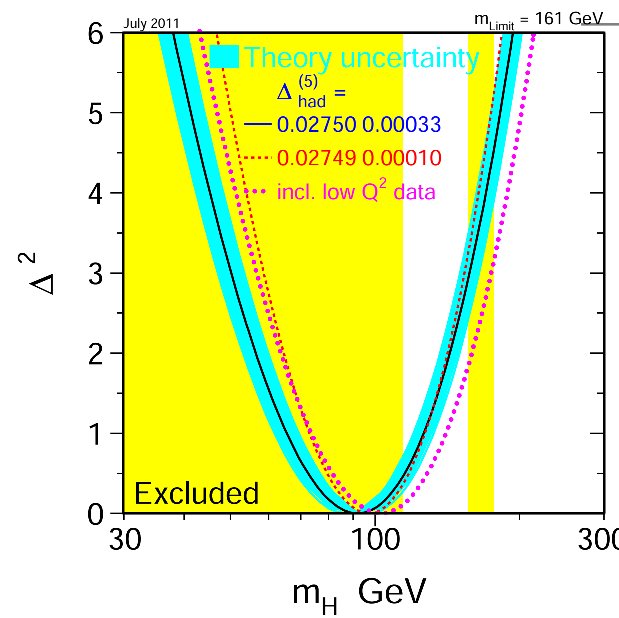
So its looks like expected in SM $\Rightarrow$
a triumph for high-energy physics!

Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



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

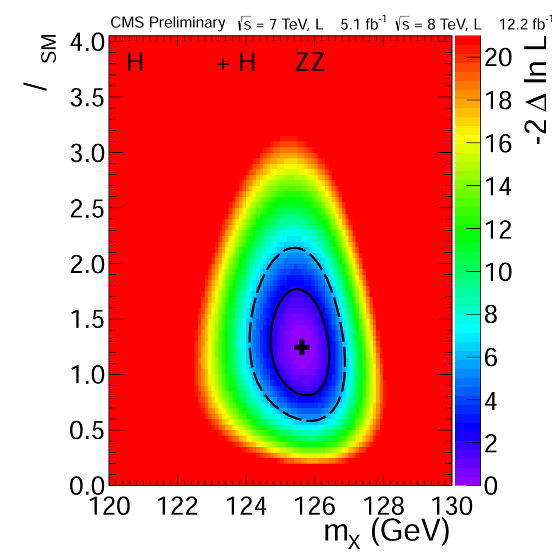


Fit the EW precision measurements, one obtains $M_H = 92^{+34}_{-26}$ GeV, or

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

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!

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

2. 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...

- **Particle spectrum complete:**

Fourth generation excluded by

$H \to ZZ, WW, \gamma\gamma, bb$ rates...

- **Extrapolable up to highest scales.**

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

tops make $\lambda < 0$: unstable vacuum

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

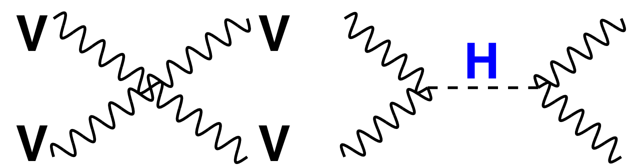
at 2loops for $m_t^{pole} = 173$ GeV.....

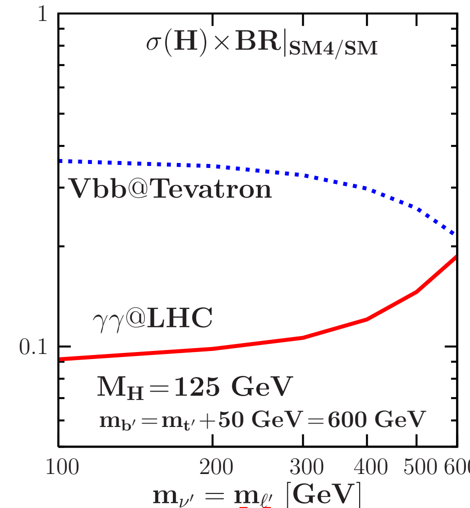
Degrassi et al., Bezrukov et al.

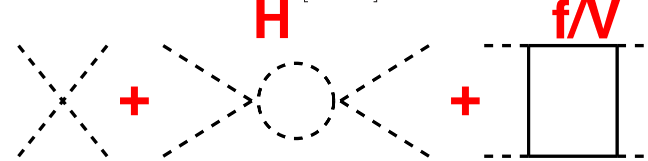
but what is measured m_t value?

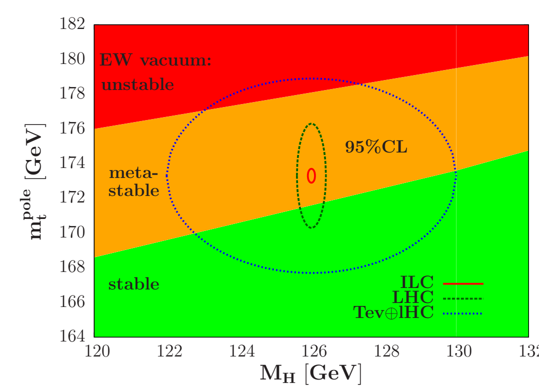
- **SM = TOE? Maybe not (?):**

m_ν, DM, GUT, hierarchy...









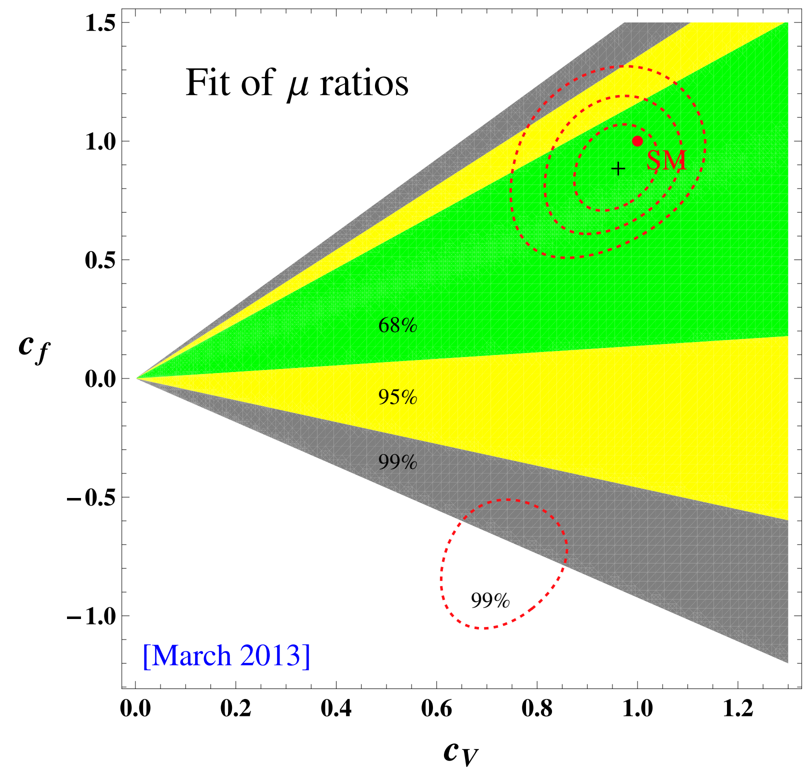
2. Implications in the SM

Rates compatible with those expected in the SM

Fit of all LHC Higgs data $\Rightarrow$,

agreement at 20–30% level with SM predictions!

Moreau+AD and $>$20 TH+EXP analyses



Some beyond the SM scenarios are in ‘mortuary”:

- 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:

3. Implications for the MSSM: mass

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

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 tree–level: $\tan\beta, M_A$ but rad. cor. important

$$M_h \lesssim M_Z |\cos 2\beta| + RC \lesssim 130 \text{ GeV} \;,\; M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}$$

– Couplings of h, H to VV are suppressed; no AVV couplings (CP).

– For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light SM Higgs.

this decoupling limit occurs in many extensions....

At tan$\beta \gg$1, one SM–like and two CP–odd like Higgses with cplg to b,τ

$$M_A \le M_h^{max} \Rightarrow h \equiv A, H \equiv H_{SM} \;,\; M_A \ge M_h^{max} \Rightarrow H \equiv A, h \equiv H_{SM}$$

3. Implications for the 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:

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

- 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

3. Implications for the MSSM: mass

Main results:

• Large M_S values needed:

– $M_S \approx 1$ TeV: only maximal mixing

– $M_S \approx 3$ TeV: only typical mixing.

• Large tanβ values favored

but tan$\beta \approx 3$ possible if $M_S \approx 3$TeV

How light sparticles can be with the constraint $M_h = 126$ GeV?

• 1s/2s gen. $\tilde{q}$ should be heavy...

But not main player here: the stops:

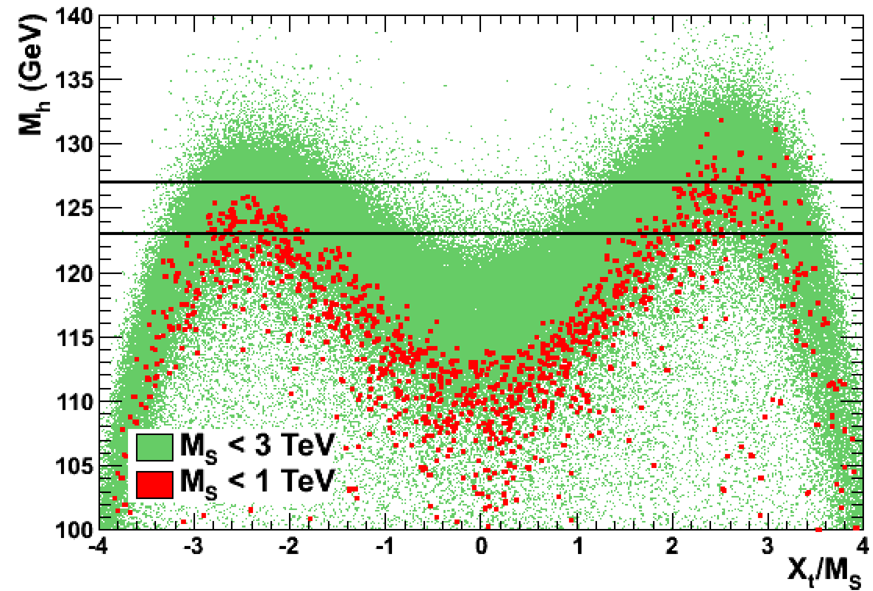
$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ GeV still possible!

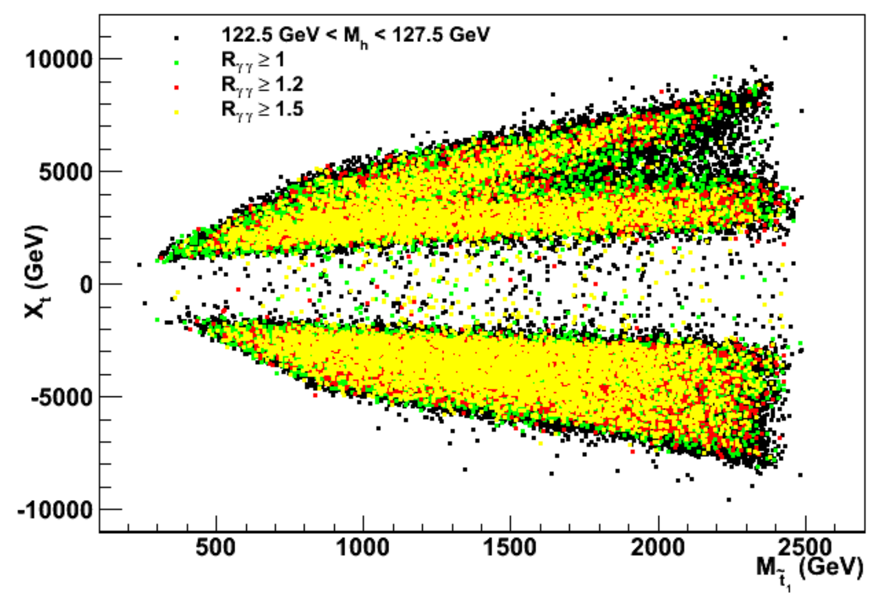
•M_1, M_2 and μ unconstrained,

• non-univ. $m_{\tilde{f}}$: decouple $\tilde{\ell}$ from $\tilde{q}$

EW sparticles can be still very light

but watch out the new limits..





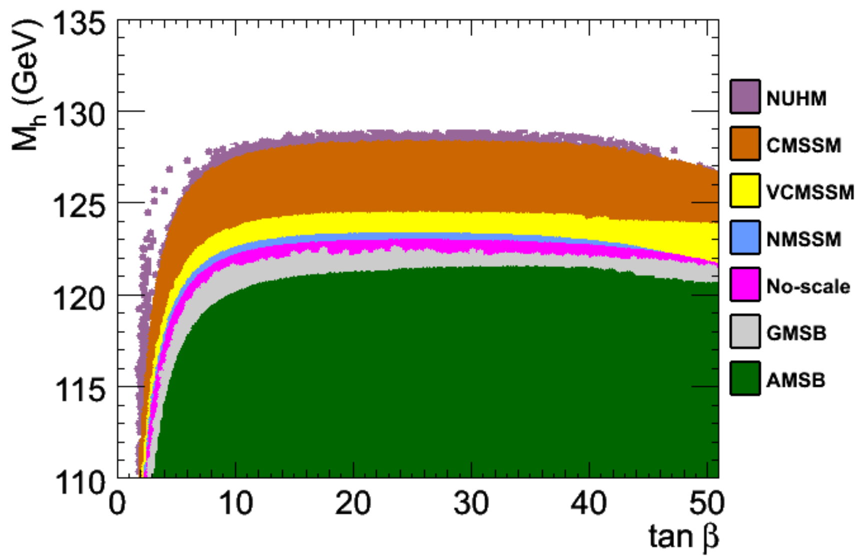
3. Implications for the MSSM: mass

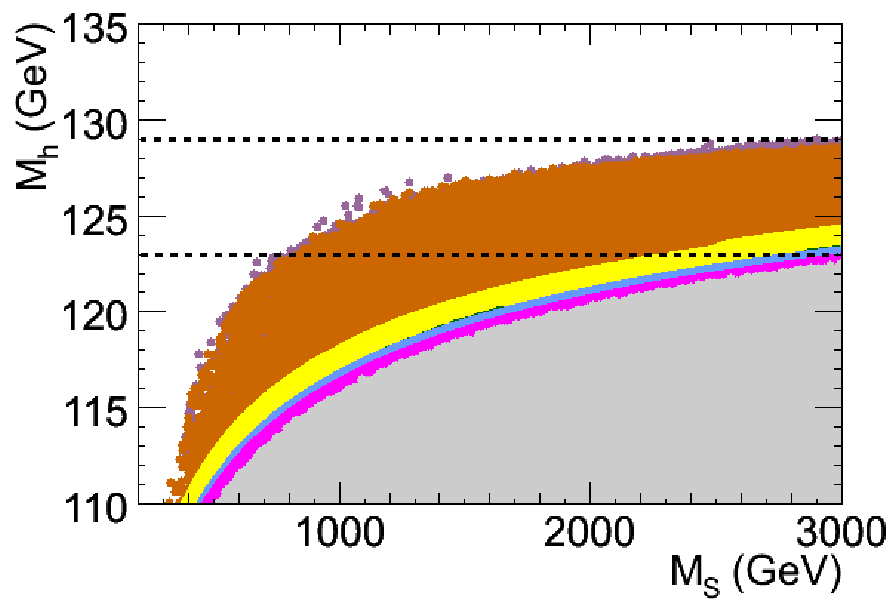
Constrained MSSMs are interesting from model building point of view:

– concrete schemes: SSB occurs in hidden sector $\stackrel{\text{gravity,..}}{\rightarrow}$ 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:** $\mathbf{tan}\beta$, $\mathbf{sign}(\mu)$, $\mathbf{M_{mes}}$, $\mathbf{\Lambda_{SSB}}$, $\mathbf{N_{mess\ fields}}$
- **AMSB:**, $\mathbf{m_0}$, $\mathbf{m_{3/2}}$, $\tan\beta$, $\text{sign}(\mu)$

full scans of the model parameters with $123\ \text{GeV} \leq \text{M}_\text{h} \leq 129\ \text{GeV}$





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

3. Implications for the MSSM: mass

As the scale M_S seems to be large, consider two extreme possibilities

- **Split SUSY: allow fine–tuning**

scalars (including H_2) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK)
$M_h \propto \log(M_S/m_t) \to$ large

- **SUSY broken at the GUT scale...**

give up fine-tuning and everything else
still, $\lambda \propto M_H^2$ related to gauge cplgs

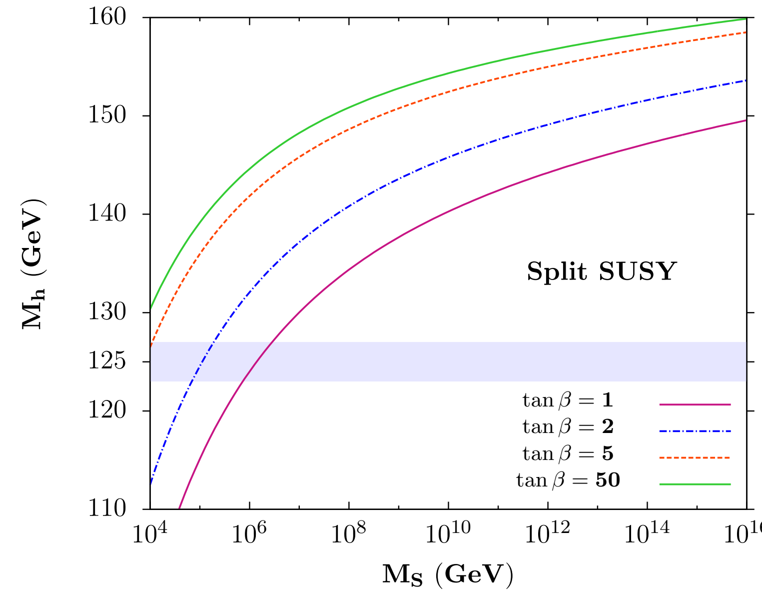
$$\lambda(\tilde{m}) = \frac{g_1^2(\tilde{m}) + g_2^2(\tilde{m})}{8}(1 + \delta_{\tilde{m}})$$

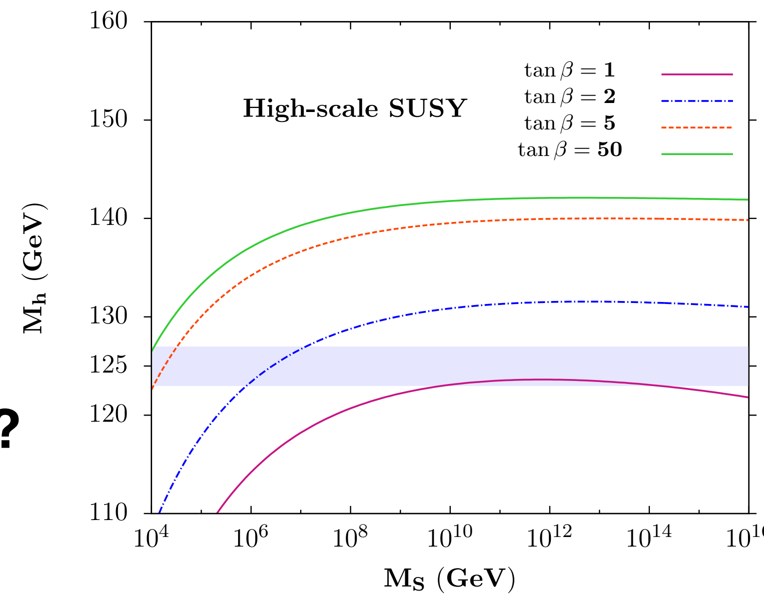
... leading to $M_H =$120–140 GeV ...

In both cases small $\tan\beta$ needed...

note 1: $\tan\beta \approx 1$ possible
note 2: M_S large and not M_A possible!?

Consider general MSSM with $\tan\beta \approx 1$!

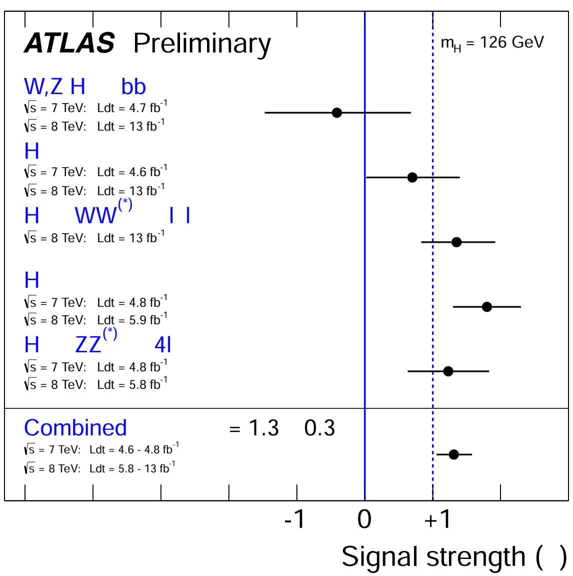


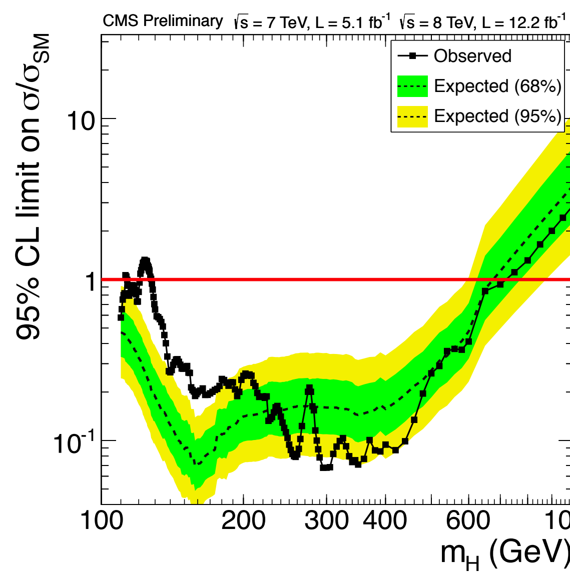


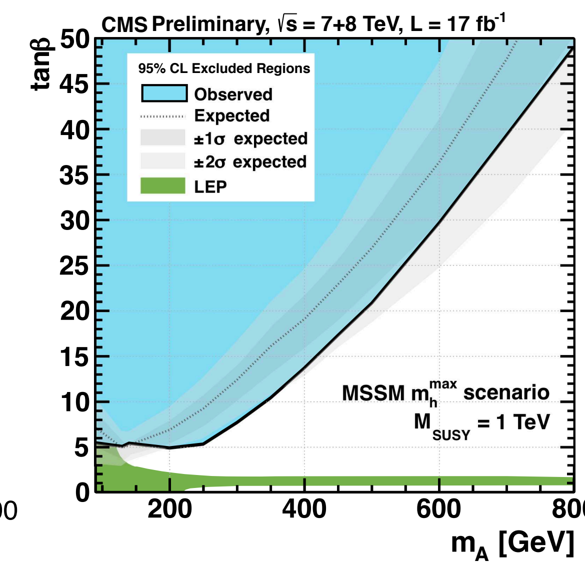
4. Other implications for the MSSM

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

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

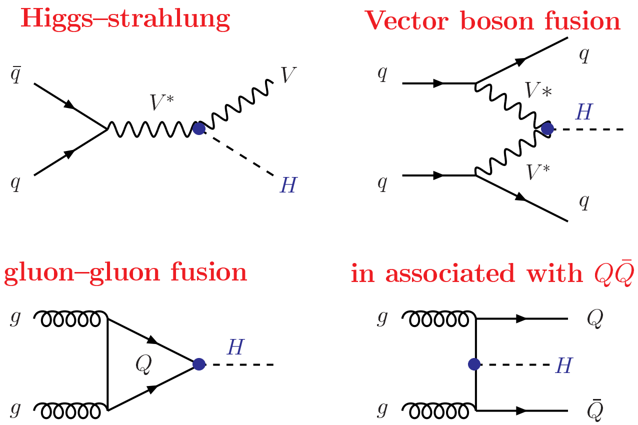


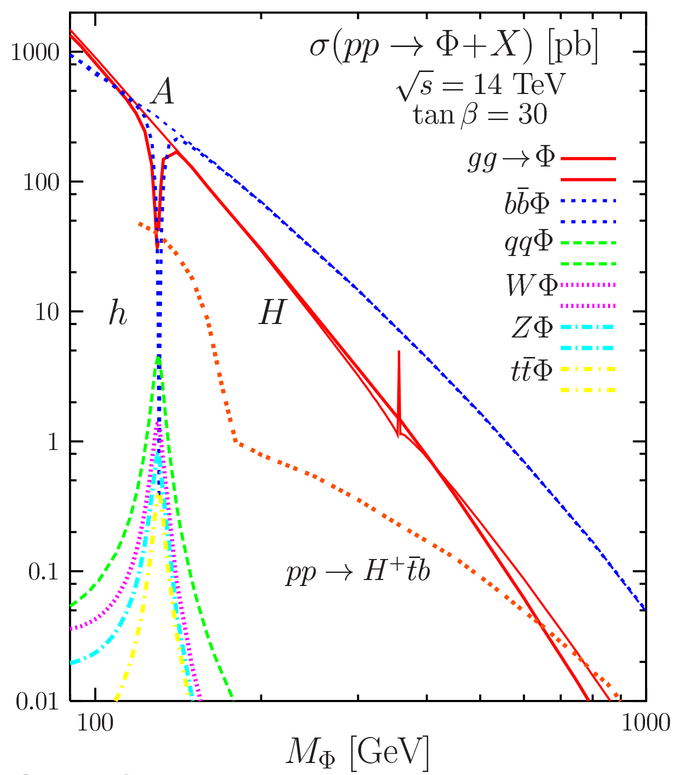




4. Other implications for the MSSM

Higgs searches are more complicated/challenging in the MSSM case





- **More Higgs particles: $\Phi = \mathrm{h, H, A, H^{\pm}}$**

– some couple almost like the SM Higgs,

– but some are more weakly coupled.

- **In general same production as in SM**

but also new/more complicated processse

(rates can be smaller or larger than in SM)

- **Possibility of different decay modes**

(and clean decays eg into $\gamma\gamma$ suppressed

- **Impact of light SUSY particles?**

$\Rightarrow$ In general very complicated situation!

But simpler in the decoupling regime:

– h as in SM with $\mathrm{M_h = 115 - 130}$GeV

– dominant mode: $\mathrm{gg, b\bar{b} \to H/A \to \tau\tau}$

It is even more tricky in beyond MSSM!

and also in some non–SUSY extensions...

4. Other implications for the MSSM

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- **production/decay rates of the observed Higgs particle;**
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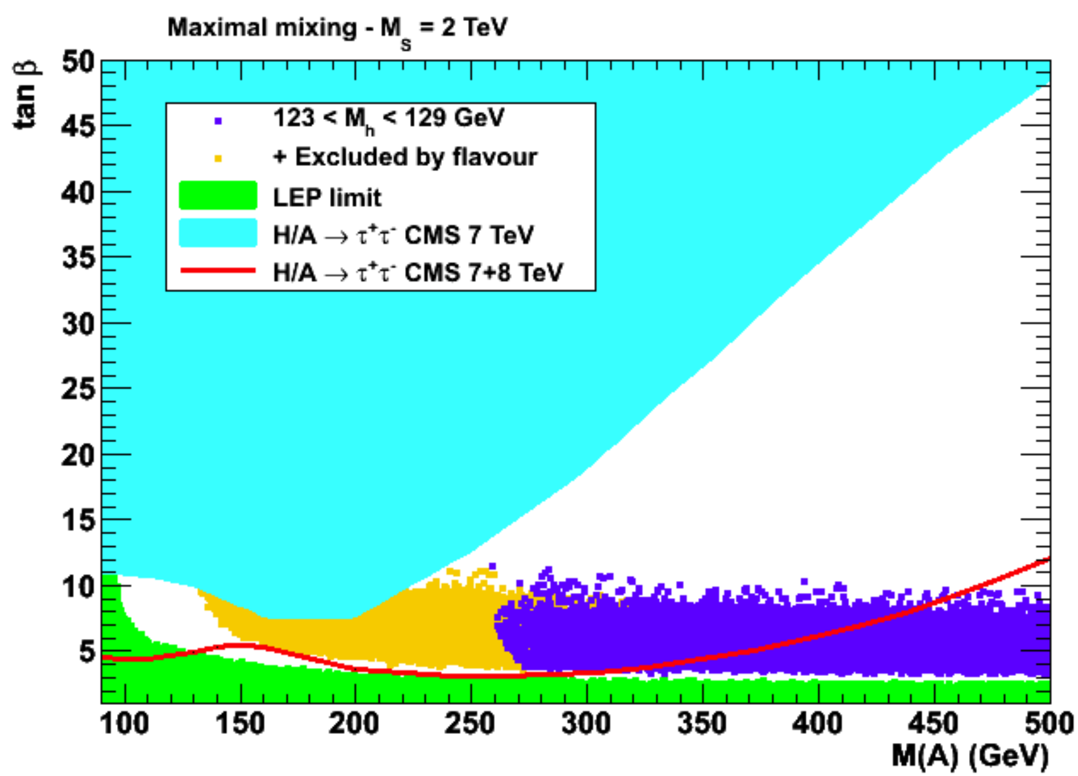


4. Other implications for the MSSM

What about the low tanβ regime?

- tan$\beta \lesssim 3$ usually "excluded" by LEP2:

$M_h \gtrsim 114$ GeV for BMS with $M_S \approx 1$ TeV.

Be we can be more relaxed: $M_S \gg M_Z$

$\Rightarrow$ tanβ as low as 1 could be allowed!

- We turn $M_h \approx M_Z |\cos 2\beta|$+RC to

  RC= 126 GeV - $f(M_A, \tan\beta)$

ie. we "trade" RC with the measured M_h

MSSM with only 2 inputs at HO: $M_A, \tan\beta$

$\Rightarrow$ **model indep. effective approach!**

- Constraints on the low tanβ region:

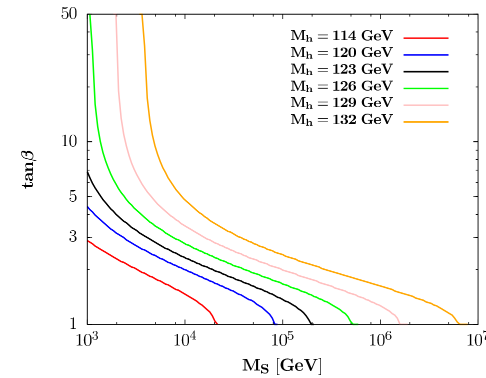
– H$\rightarrow$WW,ZZ in SM

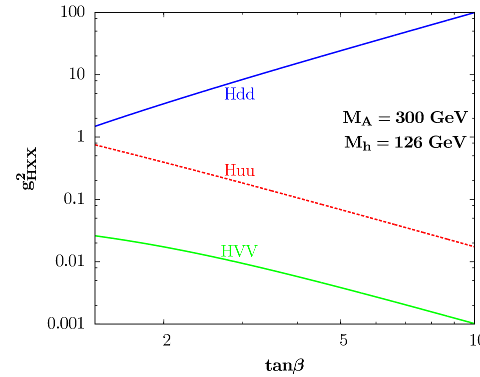
– H$\rightarrow$tt in BSM scenarios

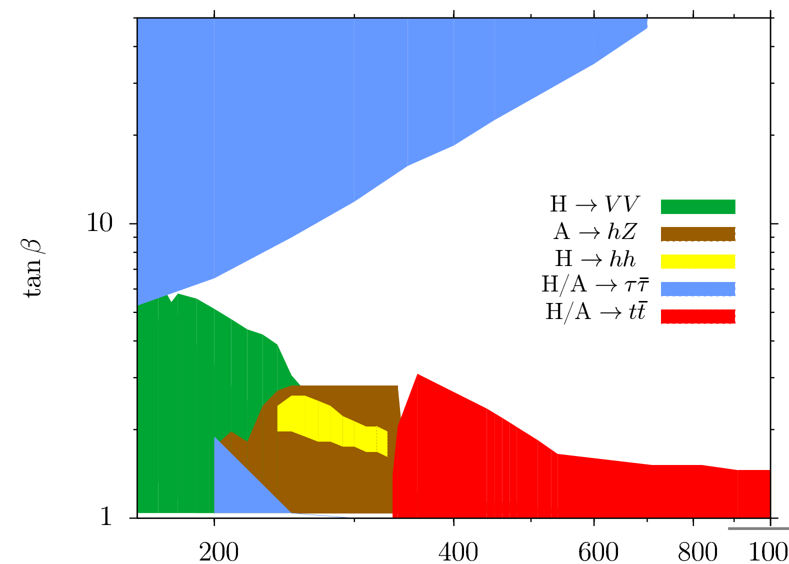
– H$\rightarrow$hh and A$\rightarrow$hZ..

Use current data for constraints...

Quevillon+AD







4. Other implications from the MSSM

Sets stingent constraints on pMSSM regimes/benchmark scenarios?

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

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

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

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

But some difference with the SM!

a $\gtrsim 2\sigma$ excess in $\rm H \to \gamma\gamma$.

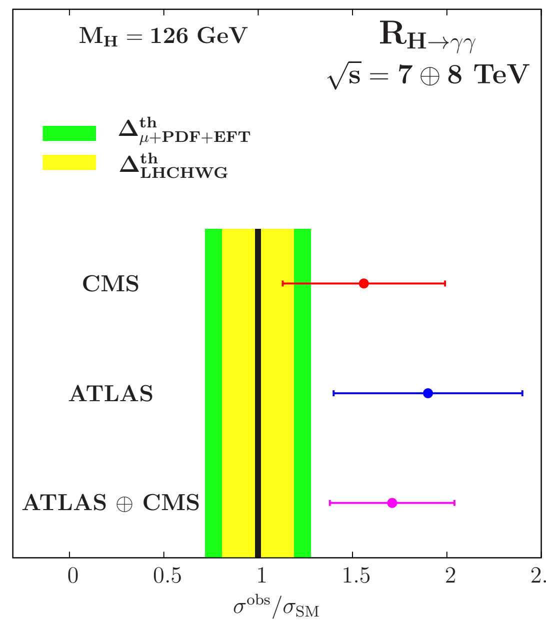
- Statistical fluctuation?
- Systematics problem?
- Maybe QCD uncertainties?

or a combination of the three..

Hope it is due to SUSY!

– total Higgs width suppressed?

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



4. Other implications for the 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.
- No more room for some search channels such as H/A$\rightarrow \mu\mu$,bb,..

(need to start thinking bout changing the benchmark scenarios....)

- Some search channels at low tanβ still relevant: H$\rightarrow$WW,ZZ,tt,hh,..

(need to continue/adapt the SM Higgs searches at high masses!)

7–8 TeV LHC for the lightest h and 13–14 TeV LHC for H/A/H^{+}?
and maybe some supersymmetric particles will show up?

5. What next?

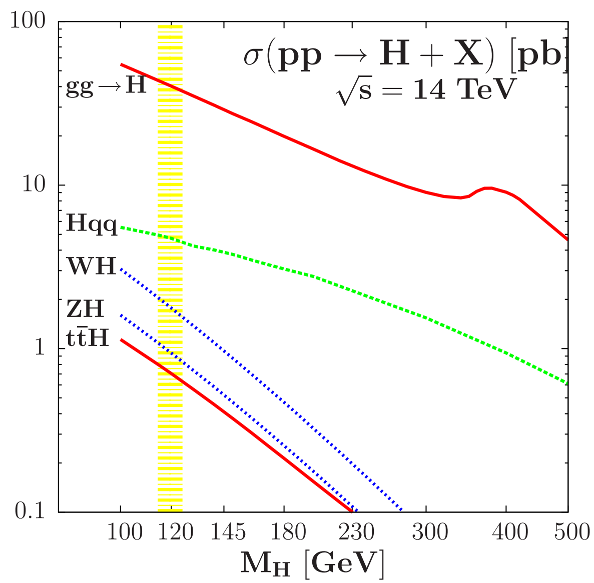
Even if no sign of BSM physics is seen: is Particle Physics “closed”?

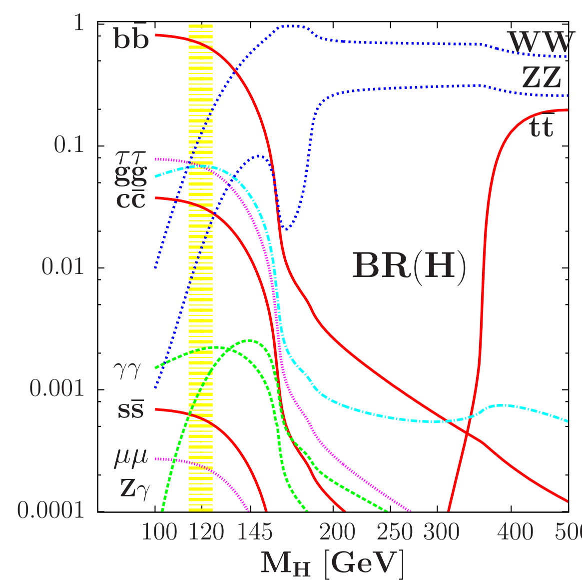
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

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. What next?

- **Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$**
- **But large errors mainly due to:**

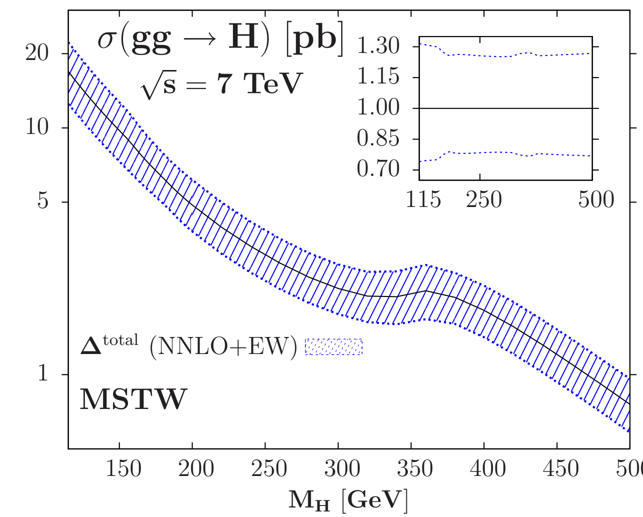
– experimental: stats, system., lumi...
– theory: PDFs, HO/scale, jetology...
total error about 20–30% in $\mathrm{gg} \to \mathrm{H}$
Hjj contaminates VBF (now 30%)..
$\Rightarrow$ ratios of σxBR: many errors out!
Deal with width ratios $\Gamma_{\mathrm{X}}/\Gamma_{\mathrm{Y}}$
– TH on σ and some EX errors
– parametric errors in BRs
– TH ambiguities from $\Gamma_{\mathrm{H}}^{\mathrm{tot}}$

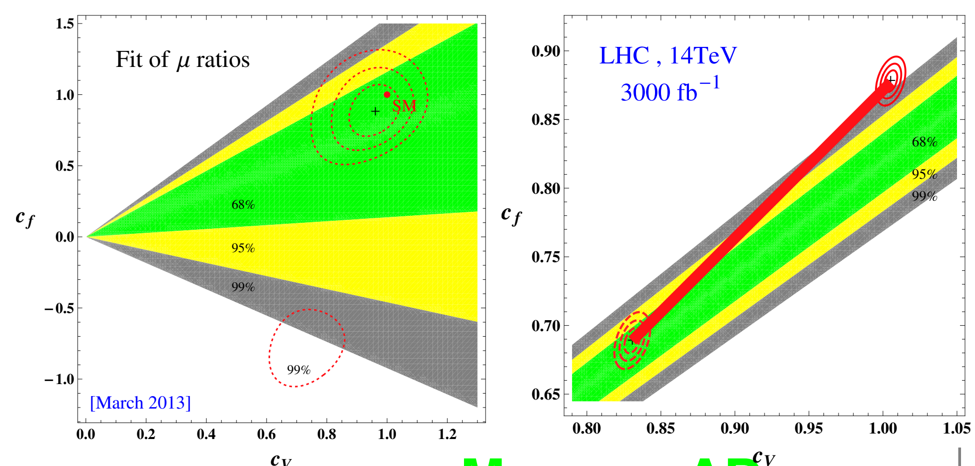
- **Achievable accuracy:**

– now: 20–30% on $\gamma\gamma/\mathrm{VV}, \tau\tau/\mathrm{VV}$
– future: few % at HL–LHC!

Sufficient to probe BSM physics?

Baglio+AD





Moreau+AD

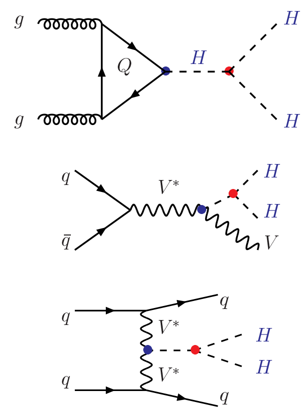
5. What next?

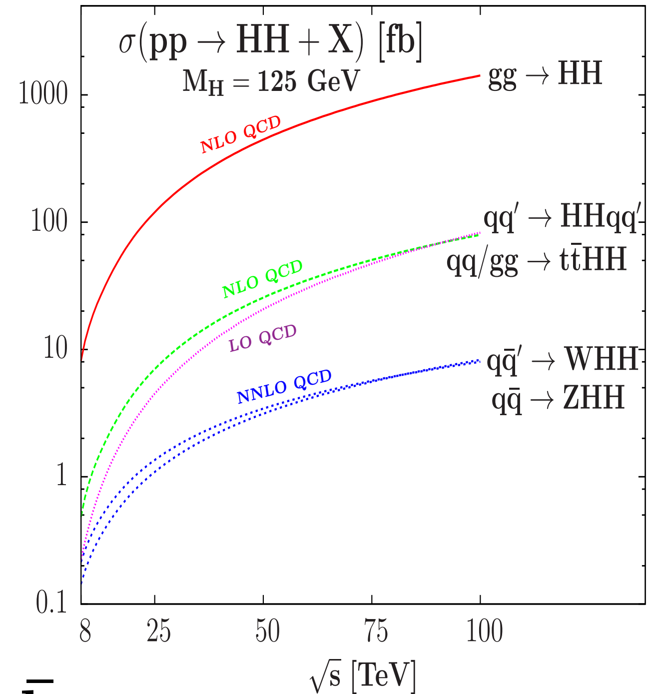
Challenge: measurement of Higgs self-couplings and access to V_H.

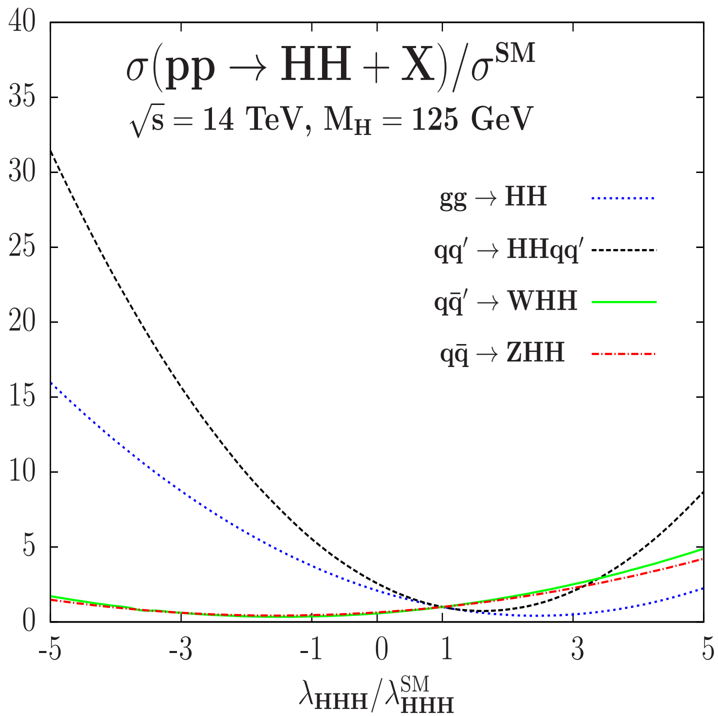
- g_{H^3} **from** $pp \to HH + X \Rightarrow$
- g_{H^4} **from pp→3H+X, hopeless.**

Various processes for HH prod:

only $gg \to HHX$ **relevant...**







- $H \to b\bar{b}$ **decay alone not clean**
- $H \to \gamma\gamma$ **decay very rare,**
- $H \to \tau\tau$ **would be possible?**
- $H \to WW$ **not useful?**

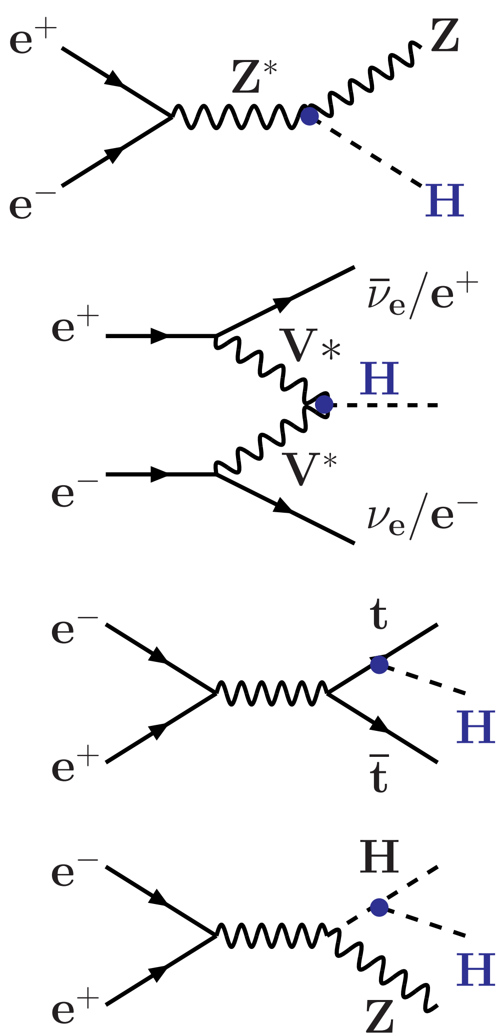
– $bb\tau\tau, bb\gamma\gamma$ **viable?**

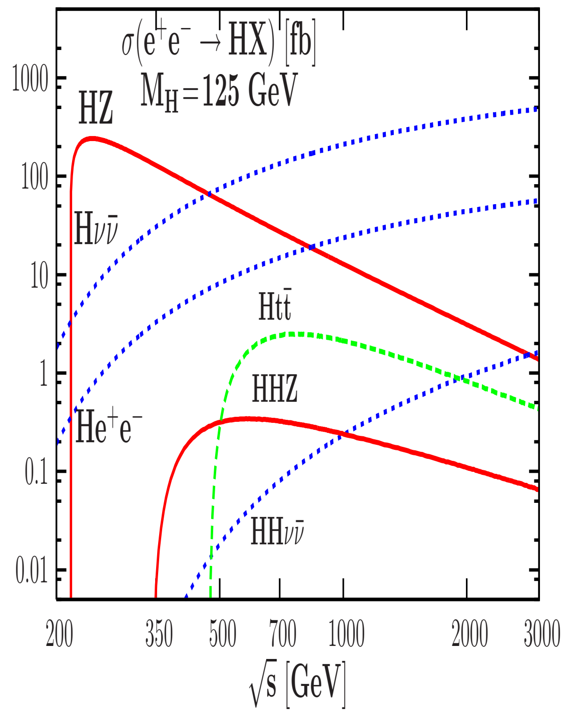
– **but needs very large luminosity.**

Baglio et al., arXiv:1212.5581

Maybe even needs an ILC.....

5. What next?





Very precise measurements mostly at $\sqrt{s} \lesssim$ 500 GeV and mainly in $e^+e^- \to ZH$ (with $\sigma \propto 1/s$) and ZHH, ttH

g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

$\Rightarrow$ difficult to be beaten by anything else for $\approx$ 125 GeV Higgs

$\Rightarrow$ welcome to the ILC!

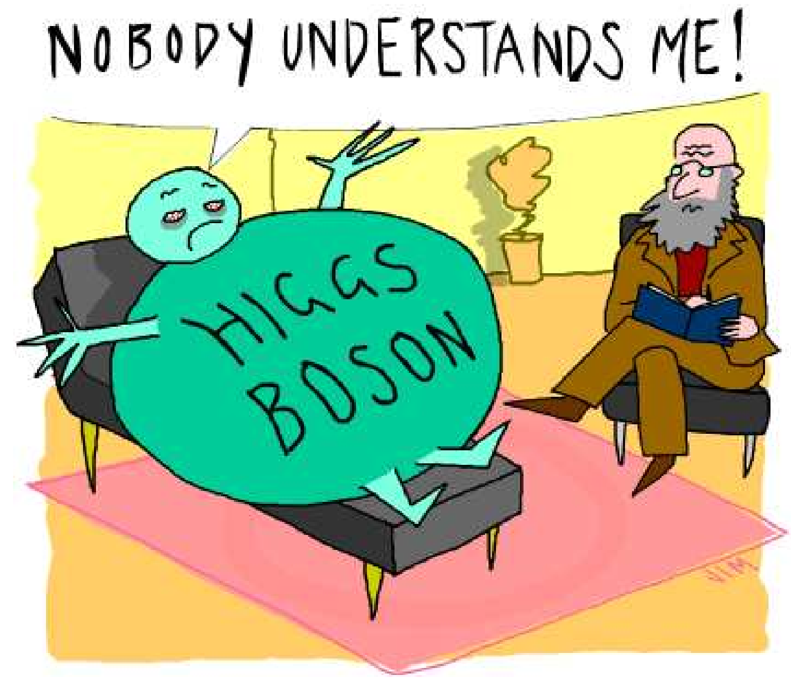
5. What next?

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!