The Higgs boson and the top quark

. . .

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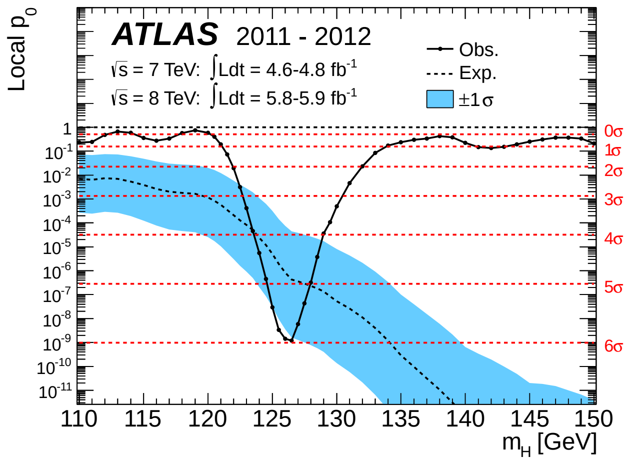
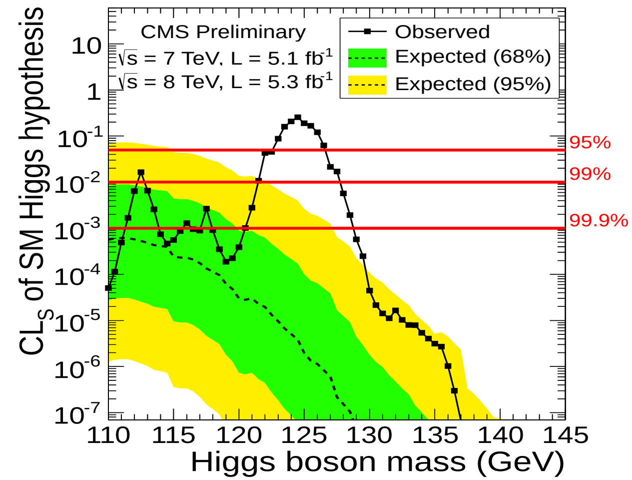
- **First implications of the discovery**
- **Probing EWSB with Higgs and tops:**
  - **– The CP texture of the Higgs**
  - **– The Higgs couplings to matter**
  - **– One example of Higss + tops in SUSY**
- **Conclusion**

1. First implications of the discovery

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!

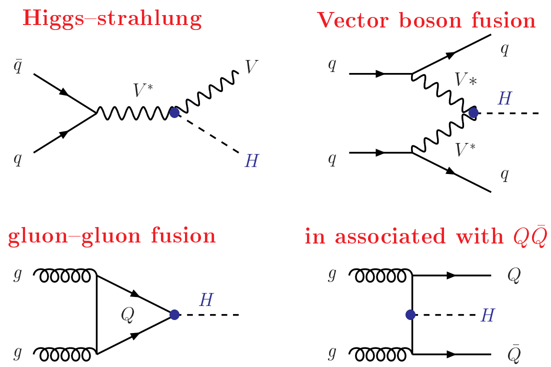


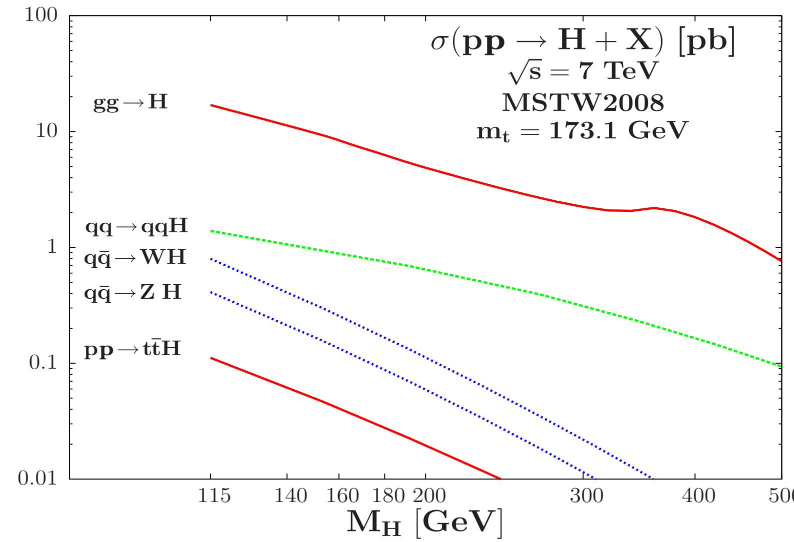


Thanks to whom? .... The top quark of course!

1. First implications of the discovery

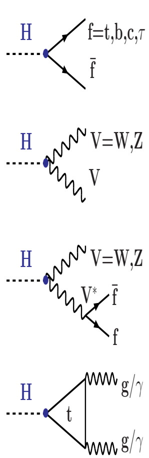
Production processes at LHC

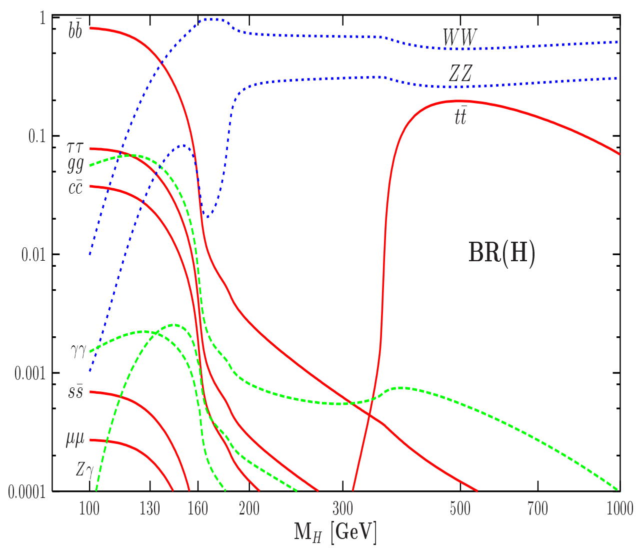




Large production cross sections with top induced gg→H dominant

Higgs detection channels:





Dominant decays: $\mathrm{H} \to \mathrm{b\bar{b}}, \mathrm{WW}^*$

Cleanest decays: $\mathrm{H} \to \gamma\gamma, \mathrm{ZZ}^* \to 4\ell^{\pm}$

(with $\mathrm{H} \to \gamma\gamma$ **induced by W+t loops).**

Most important discovery mode@LHC:

$$\mathrm{gg} \to \mathrm{H} \to \gamma\gamma(\mathrm{ZZ}^*)$$

– **thanks to the large ttH coupling...**

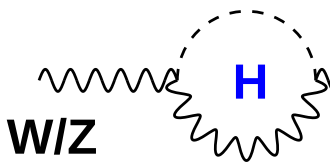
– **produced via quantum fluctuation...**

1. First implications of the discovery

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

Indirect constraints from EW data

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

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

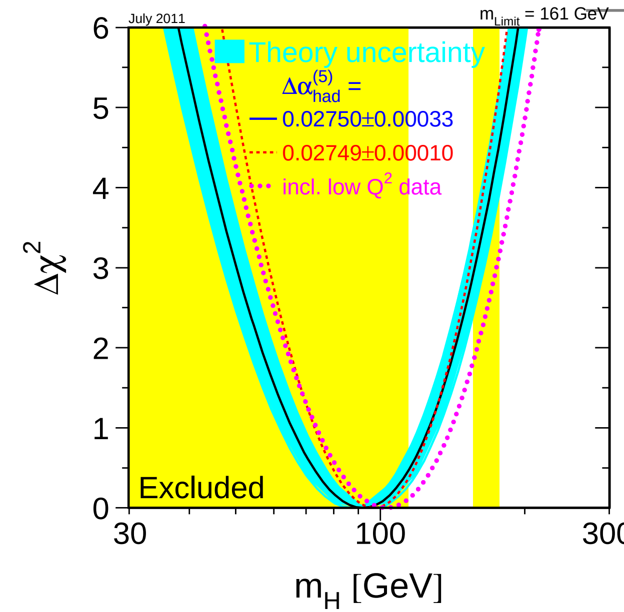
compared with the measured mass

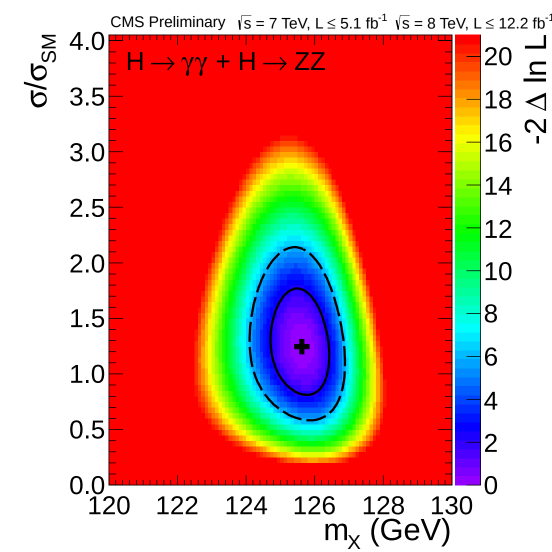
$$M_H \approx 126 \text{ GeV.}$$

A very non–trivial consistency check!

closing the story of the top quark:

1995: $m_t^{TeV} \approx m_t^{LEP} = 175$ GeV!





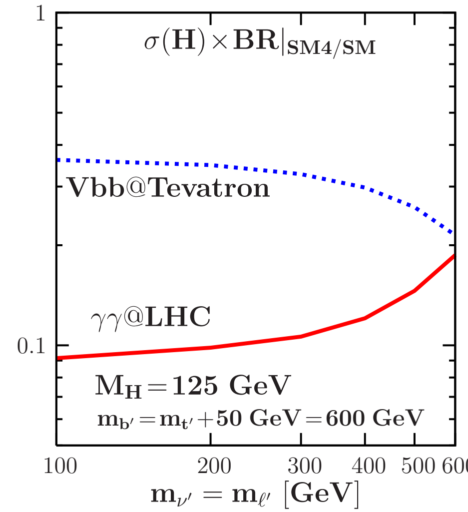
1. First implications of the discovery

- **Particle spectrum complete:**

4th family excluded by $H \to VV, ff$ rates

$\Rightarrow$ **top remains heaviest SM particle!**

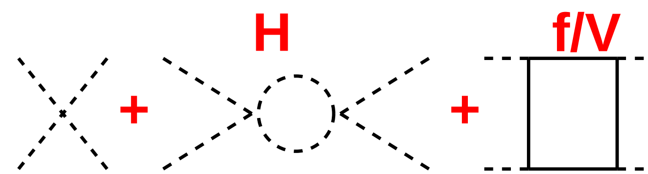
(that couples "normally" to the Higgs..)



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

$\Rightarrow$ Degrassi et al., Bezrukov et al.

but what is measured m_t at TEV/LHC

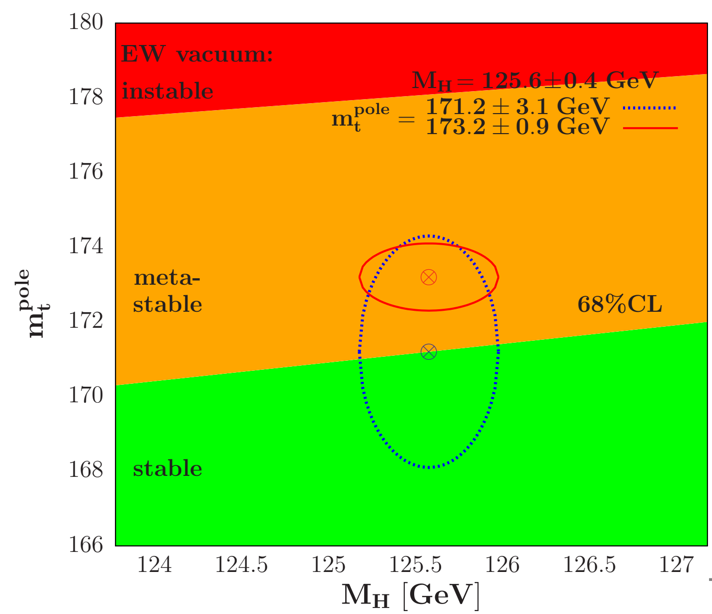
$m_t^{TeV+LHC} = 173.34 \pm 0.76$ GeV...

$m_t^{pole}?m_t^{MC}?$ not clear; much better:

$m_t = 171 \pm 3$GeV from $\sigma(pp \to t\bar{t})$

Other alternatives at TEV/LHC (tt+j rates..)?

or should we wait for $e^+e^- \to t\bar{t}$ scan?



1. First implications of the discovery

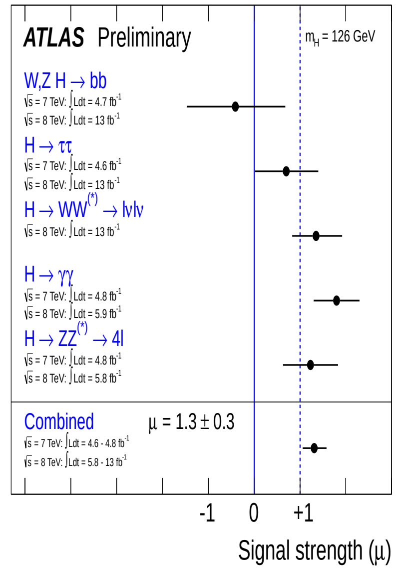
$\sigma\times$**BR rates compatible with those expected in the SM**

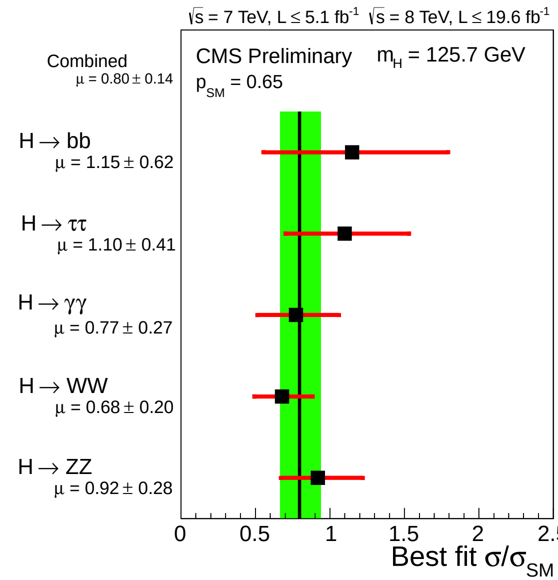
Fit of all LHC Higgs data $\Rightarrow$ agreement at 20–30% level

$$\mu^{\rm ATL}_{\rm tot} = 1.30 \pm 0.30$$

$$\mu^{\rm ATL}_{\rm tot} = 0.87 \pm 0.23$$

.... standardissimo...





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": Composite...

Other BSM scenarios are strongly constrained: SUSY ....

To go beyond: you need very precise measurements to see small deviations...

In fact, the story is a two chapters story........

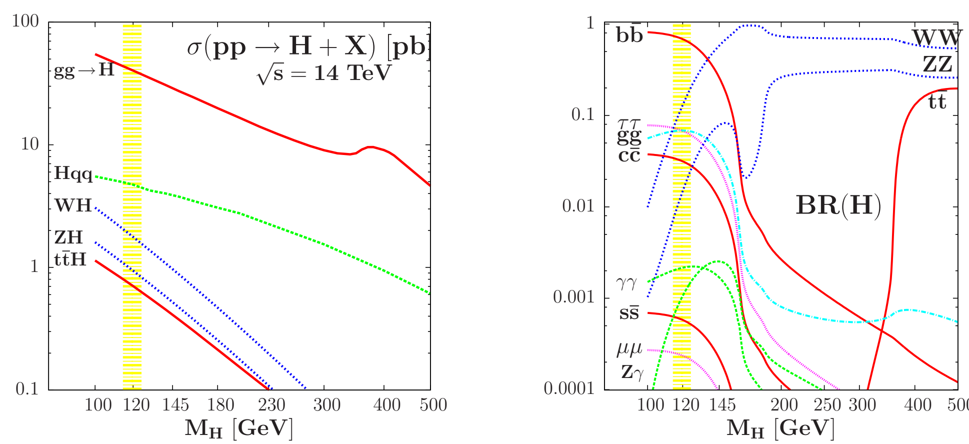
2. Probing EWSB with Higgs and tops

First: find the dof which would correspond to a scalar Higgs boson
Second: need to check that H is indeed responsible of sEWSB (SM-like?)

$\Rightarrow$ measure its fundamental properties in the most precise way:

- 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!



What kind of tests can we make with top quarks? Three examples (others are FCNC top decays, single top + Higgs, $t \to H^+ b$, ...).

2. Probing EWSB with Higgs and tops: JPC

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

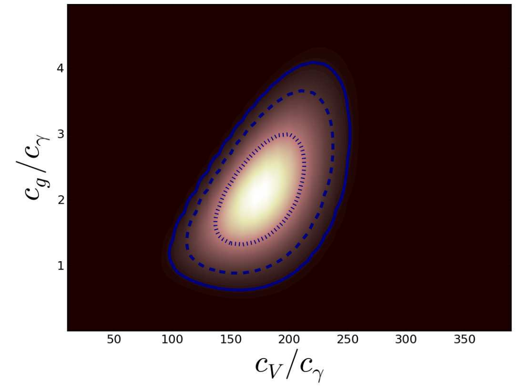
- not spin–1: Landau–Yang
- could be spin–2 like graviton? **Ellis et al.**

– miracle that couplings fit that of H,

– “prima facie” evidence against it:

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

many th. analyses (no suspense).



CP: even, odd, or mixture?

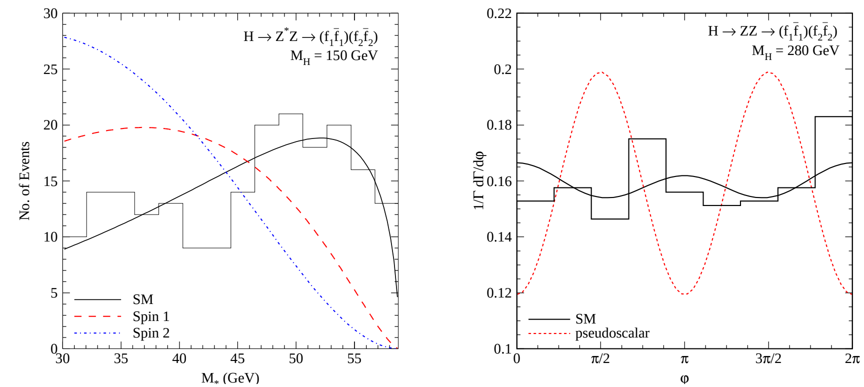
(more important; CPV in Higgs!)

ATLAS/CMS CP analyses for

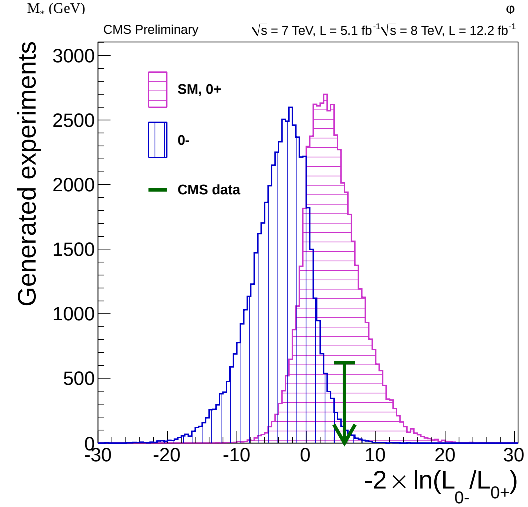
pure CP–even vs pure–CP–odd

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

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



MELA $\approx 3\sigma$ for CP-even..



2. Probing EWSB with Higgs and tops: JPC

There are however some problems with this (too simple) picture:

– a pure CP odd Higgs does not couple to VV states at tree–level

– coupling should be generated by loops or HOEF: should be small

– H CP–even with small CP–odd admixture: high precision measurement..

– in H$\to$VV only CP–even component projected out in most cases!

Indirect probe:

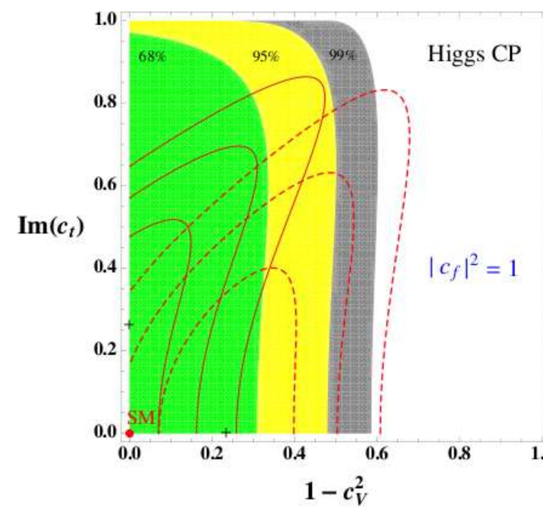
$\mathbf{g_{HVV} = c_V g_{\mu\nu}\ with\ c_V \leq 1}$

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

gives upper bound on CP mixture:

$\eta_{CP} \equiv 1 - c_V^2 \gtrsim 0.5 @ 68\% CL$

for any value of Im and Re c_f...



Direct probe: **look at processes with the Higgs decaying into fermions**

(Higgs couplings to fermions are more democratic with respect to CP.....)

Best deal at the LHC: corelations in $q\bar{q}/gg \to Ht\bar{t} \to b\bar{b}t\bar{t}$!

... extremely challenging process but maybe doable with some efforts?

2. Probing EWSB with Higgs and tops: couplings

• **Look at various H production/decay channels and measure $\mathbf{N_{ev} = \sigma \times BR}$**

• **For the moment, not much information:**

– only gg$\to$H has significant rate

– $\mathbf{c_V}$ versus universal $\mathbf{c_f}$ for simple.

– measurement at 20–30% level...

• **Not better to be expected with gg$\to$H:**

– total theory error of about 15–20%

– more when broken to jet categories

– gg$\to$Hjj contaminates VBF (now 30%).

$\Rightarrow$ ratios of σxBR: many errors out!

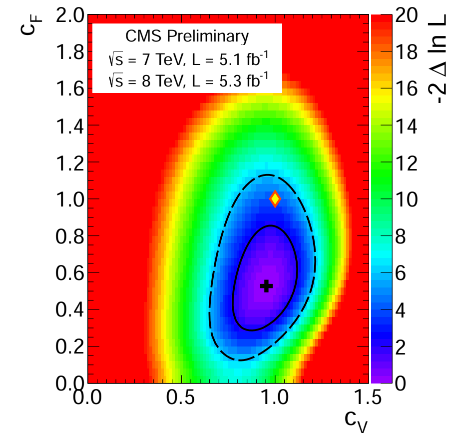
Deal with ratios of widths $\mathbf{\Gamma_X/\Gamma_Y}$, no:

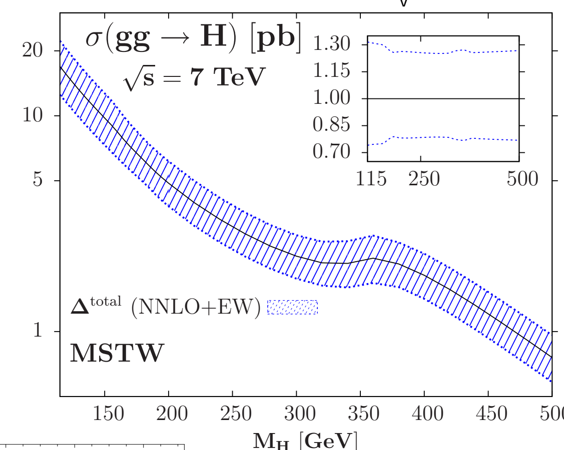
– TH error on σ and some EX errors

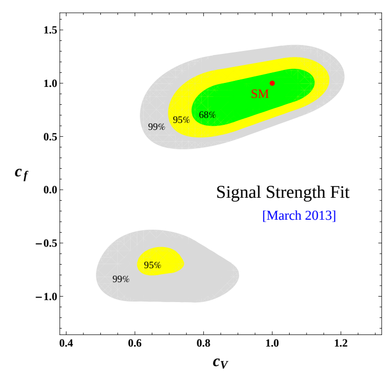
– parametric/QCD errors in BRs

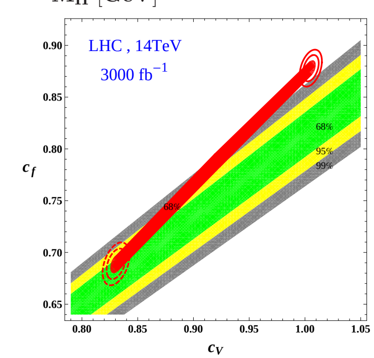
– TH ambiguities from $\mathbf{\Gamma_H^{tot}}$ (invisible?)

• **Achievable accuracy: a few %!**









2. Probing EWSB at the LHC:

Sufficient to probe BSM physics? Maybe not..

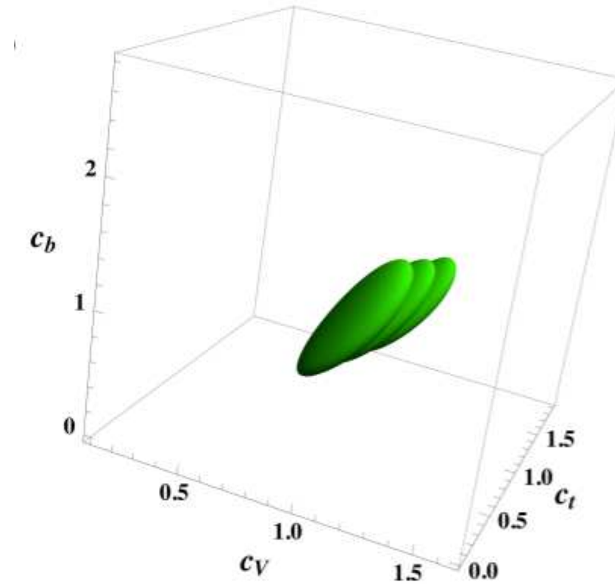
- **First of all c_V, c_f only not sufficient.**

Example of lightest (SM–like) MSSM Higgs:

$$c_V = \sin(\beta - \alpha),\ c_t = \frac{\cos\alpha}{\sin\beta},\ c_b = -\frac{\sin\alpha}{\cos\beta}$$

$\Rightarrow$ at least a 3–dimensional coupling fit.

(ideal is to probe all couplings separately..).



- **We are not really measuring the Htt coupling c_t but Hgg coupling c_g and loop induced c_g is affected by possible BSM loop contributions.**

(the other occurence of g_{Htt} is also in the loop process H$\to\gamma\gamma$...)

Example of the MSSM: stop loops also contribute to the gg$\to$H process:

$$c_t \to c_t \times \left[1 + \frac{m_t^2}{4 m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu \cot\alpha)(A_t + \mu \tan\alpha) \right) \right]$$

We therefore need a more direct probe of the important Htt coupling

$\Rightarrow$ we have to consider the $pp \to t\bar{t}H$ process!

2. Probing EWSB with Higgs and tops: MSSM

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

After EWSB and $M_{W^\pm}, M_Z :\Rightarrow$ 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

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

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

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

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

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

$M_h = 125$ GeV: $M_A \gg M_Z, \tan\beta \gg 1, M_S \gg M_Z, X_t \approx \sqrt{6} M_S$,...

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

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

At $\tan\beta \approx 1$: top plays again the major role but large M_S required...

2. Probing EWSB with Higgs and tops: MSSM

Model independent – effective – approach

- $\tan\beta \lesssim 3$ usually "excluded" by LEP2: $M_h \gtrsim 114$ GeV for BMS with $M_S \approx 1$ TeV.

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

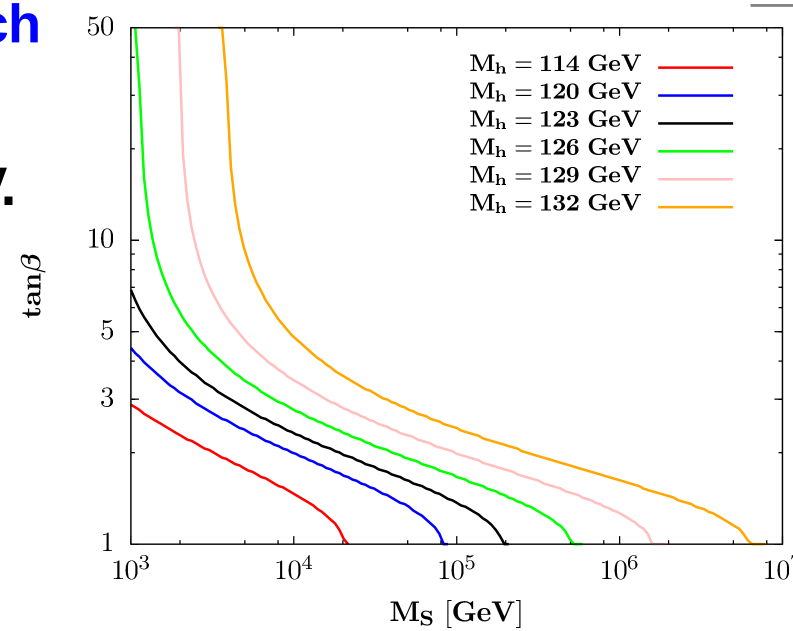
MSSM with only 2 inputs at HO: $M_A, \tan\beta$

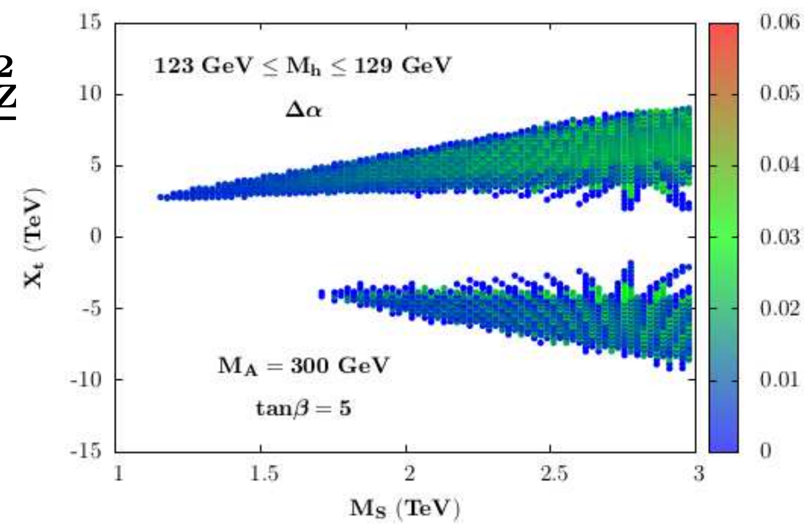
$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2+M_A^2 s_\beta^2)-M_A^2 M_Z^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right)$$

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

Habemus MSSM (hMSSSM):
AD, Maiani,Polosa,Quevillon,Riquer





2. Probing EWSB with Higgs and tops: MSSM

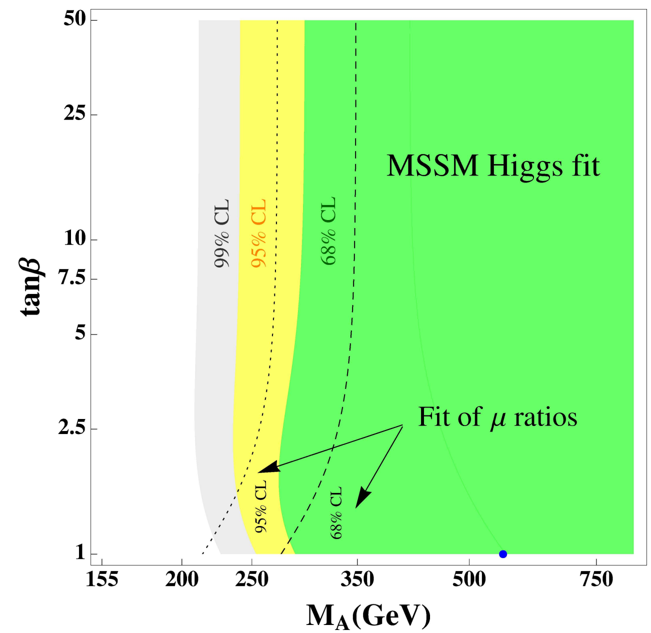
Constraints on the $[\mathrm{M_A}, \tan\beta]$ plane

- Fits of the h properties $\Rightarrow$

can be turned into MSSM constraints

h SM–like $\Rightarrow \mathrm{M_A} \gtrsim 200-500$ GeV

(best fit: $\tan\beta \approx 1, \mathrm{M_A} \approx 500$ GeV...)

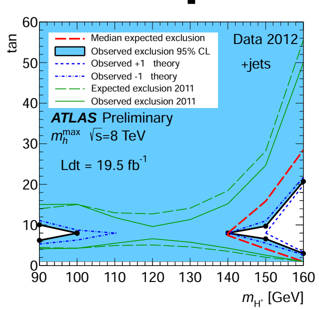


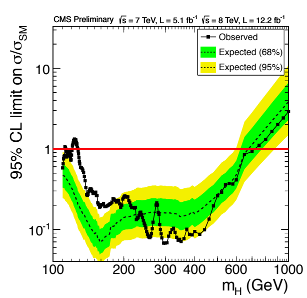
- Constraints in the high tanβ region:

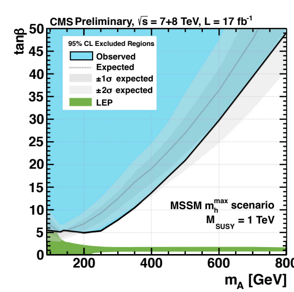
– $\mathrm{t \to H^+ b \to b\tau\nu} : \mathrm{M_A} \gtrsim 140$ GeV

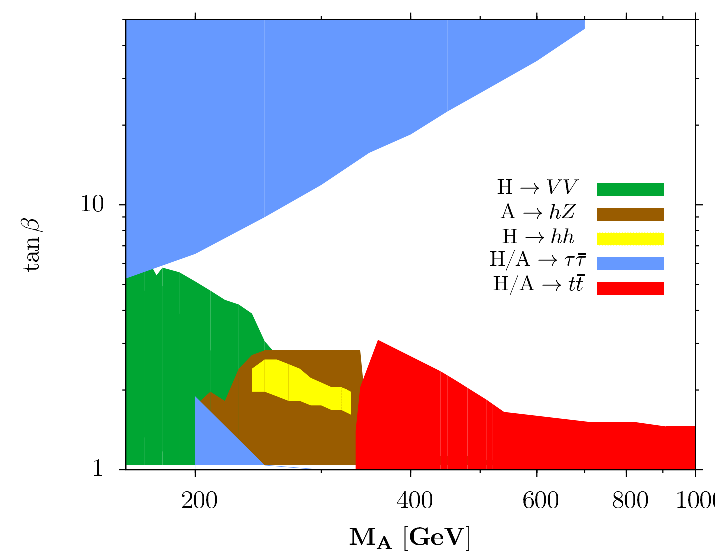
– $\mathrm{H/A} \to \tau\tau : \mathrm{M_A} \gtrsim 300$ GeV

– Extrapolate H$\to$WW,ZZ of SM









- Addtional constraints at low tanβ:

$\mathrm{gg \to H/A \to t\bar{t}}$

already discussed for heavy Z' and $\mathrm{V_{KK}}$

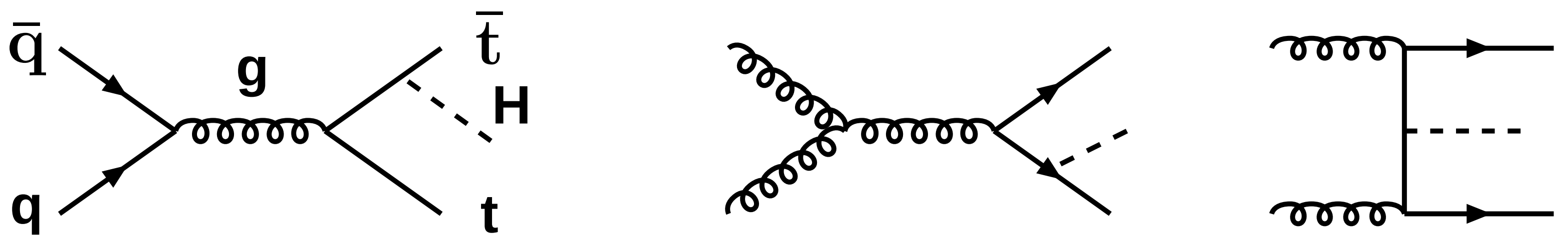
needs large mass for boosted tops (no?)...

3. Conclusion

Hence, to complete the LHC Higgs program and to probe the Higgs properties in the most complete and fairly model-independent way

$\Rightarrow$ we need to consider the $\mathrm{pp} \to \mathrm{ttH}$ process

and make the Higgs decay not only to $\gamma\gamma$ but also to bb etc.. final states.



- **extremely complicated topology**
- **very low production rates (even with high luminosity for H$\to \gamma\gamma$...)**
- **huge backgrounds (in particular if one considers H$\to$bb)**

Good luck...

and do not forget to address the other important issues related to tops: like $\mathrm{t} \to \mathrm{Hc}$, in the SM and $\mathrm{pp} \to \mathrm{H^- t}, \mathrm{pp} \to \mathrm{H/A} \to \mathrm{t\bar{t}}$ in BSM...