The MSSM Higgs sector after LHC8

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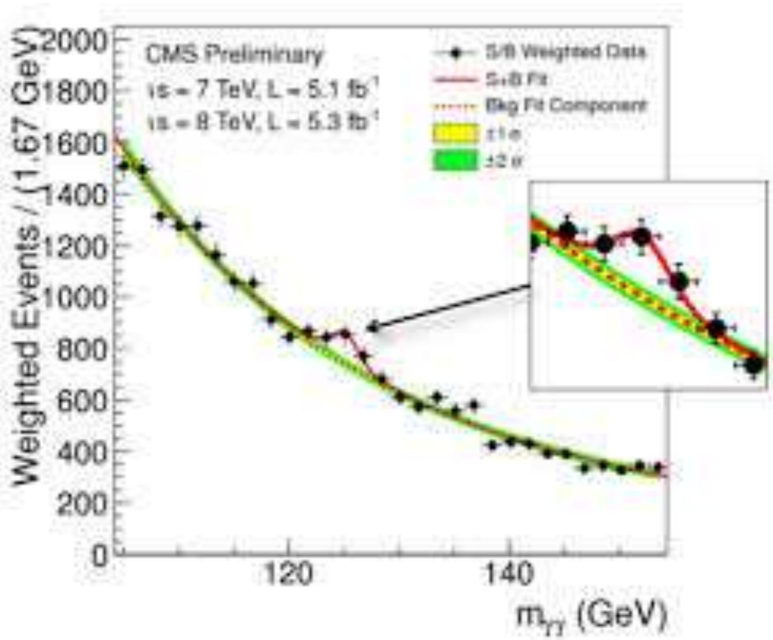
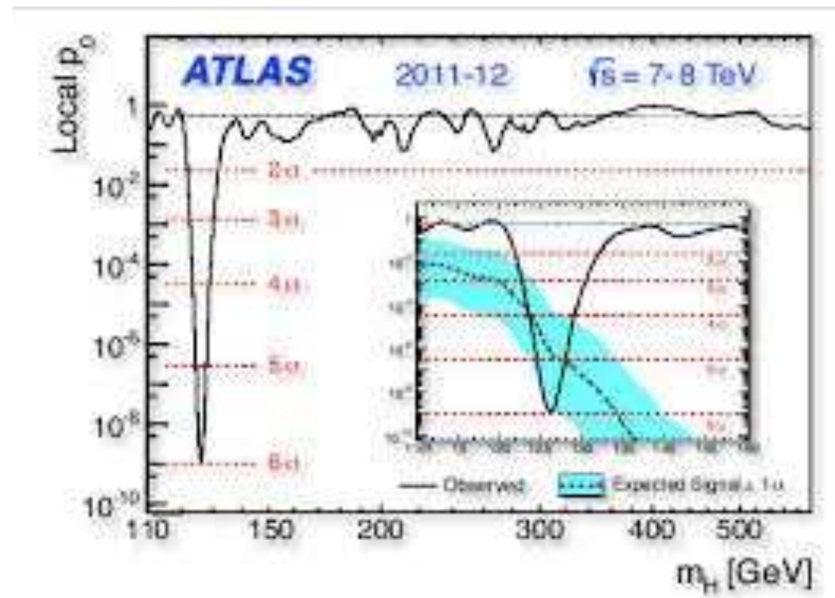
General implications of the Higgs discovery

1. The Higgs sector of (minimal) Supersymmetry
2. Implications from the Higgs boson mass
3. Implications from the Higgs properties
4. Implications from other Higgs searches
5. What next?

General implications of the Higgs discovery

... 4th of July 2012: a Higgstorical day...





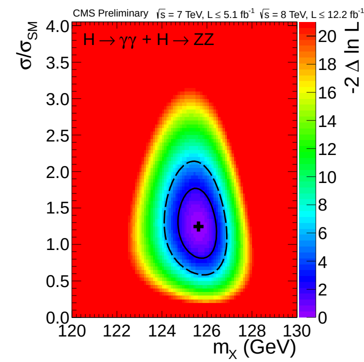
General implications of the Higgs discovery

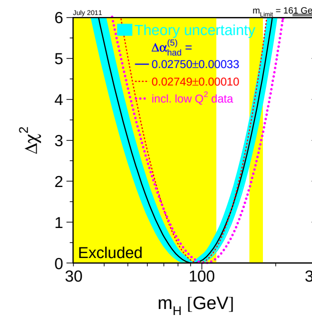
We have observed a Higgs particle with a mass in the expected range:

$M_H = 92^{+34}_{-26}$ GeV was expected

$M_h \approx 125$ GeV is measured

(no twin peaks anymore... yes?).





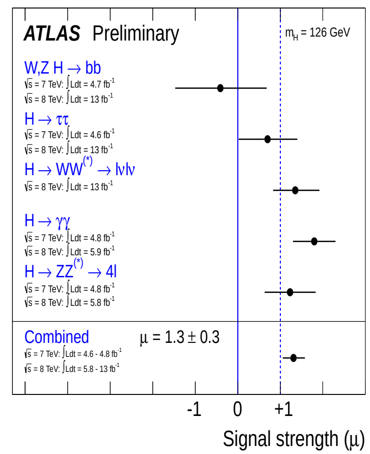
Production rates compatible with with those expected in the SM:

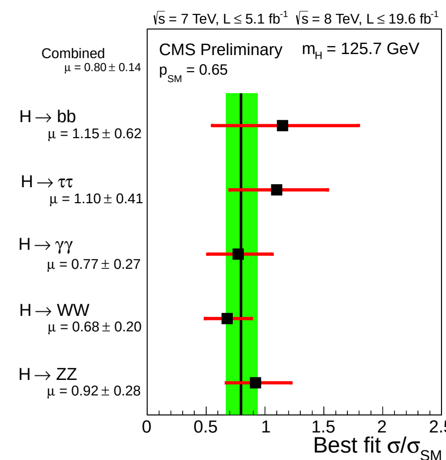
fit of all the LHC Higgs data ⇒ agreement at the 20–30% level:

$$\mu_{\rm tot}^{\rm ATLAS} = 1.30 \pm 0.30$$

$$\mu_{\rm tot}^{\rm CMS} = \ 0.87 \pm 0.23$$

combined: $\mu_{\rm tot}^{\rm lHC} \simeq 1.$



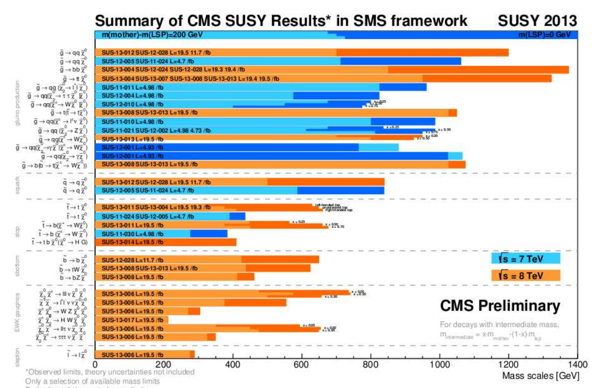


No other new particle observed:

– no other Higgs particle seen,

– no SUSY, KK, etc... new state...

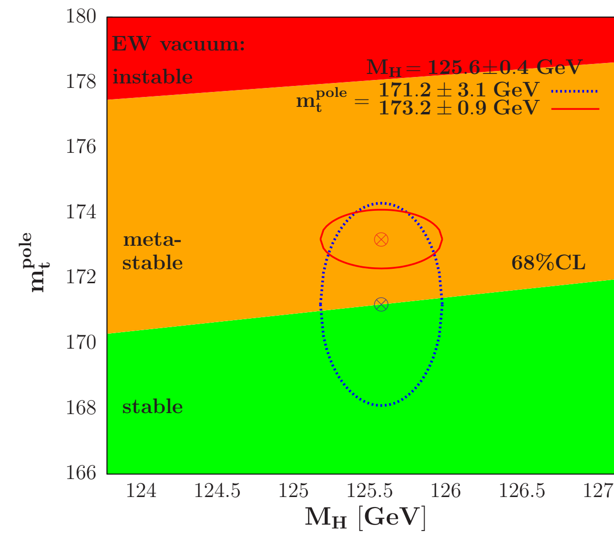
looks like standardissimo, no?



General implications of the Higgs discovery

Maybe we have the theory of everything?

- renormalisable, unitary, perturbative, ...
- extrapolable to the hightest possible scale (EW vacuum (meta)stable up to Planck scale).
- Very successful in describing present data (with all problems disappearing one by one).

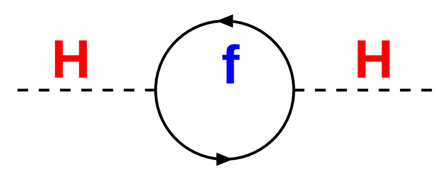


It requires some extensions though...

- dark matter: maybe Peccei-Quinn axion?
- neutrino masses, baryon asymmetry, ...
- gauge coupling unification problem:

fixed in SO(10) with $M_{inter} \approx 10^{11}$ GeV?

corrections to M_H
with cut–off $\Lambda = M_{NP}$



$$\Delta M_H^2 \propto \Lambda^2 \approx M_P^2?$$

Remains only the "mother of all problems":

hierarchy problem calls for beyond the SM.
Three most discussed beyond SM scenarii:

- spin–zero Higgs $\equiv$ bound-state $\Rightarrow$ Technicolor: in "mortuary"?
- cut–off at TeV scale $\Rightarrow$ extra space-time dimensions: in "hospital"?
- new protecting symmetry $\Rightarrow$ Supersymmetry: in "trouble"?

Here, I discuss the example of Supersymmetry and stick to the MSSM.

1. The Higgs sector of the MSSM

In the MSSM we need two Higgs doublets $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$,
to generate up/down-type fermion masses while having chiral anomalies.
after EWSB, three dof for $W_L^\pm, Z_L \Rightarrow$ 5 physical states: $h, H, A, H^\pm$.
Only two free parameters at tree-level to describe the system $\tan\beta, M_A$:

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

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

$$\tan 2\alpha = \frac{-(M_A^2+M_Z^2)\sin 2\beta}{(M_Z^2-M_A^2)\cos 2\beta} = \tan 2\beta\, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2} \quad \left(-\frac{\pi}{2} \le \alpha \le 0\right)$$

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

- 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 decoupling limit: MSSM Higgs sector reduces to SM with a light h.

1. The Higgs sector of the MSSM

Life is more complicated and radiative corrections have to be included.

The CP-even Higgses described by 2×2 matrix including corrections:

$$\mathbf{M_S^2} = \mathbf{M_Z^2} \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + \mathbf{M_A^2} \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

and the two Higgs masses and the mixing angle α are given by:

$$\mathbf{M_{h/H}^2} = \frac{1}{2}\left(\mathbf{M_A^2} + \mathbf{M_Z^2} + \mathbf{C_+} \mp \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - 2\mathbf{M_A^2}\mathbf{M_Z^2}\mathbf{c}_{4\beta} + \mathbf{C}}\right)$$

$$\alpha = \frac{2\Delta\mathcal{M}_{12}^2 - (\mathbf{M_A^2} + \mathbf{M_Z^2})\mathbf{s}_\beta}{\mathbf{C_-} + (\mathbf{M_Z^2} - \mathbf{M_A^2})\mathbf{c}_{2\beta} + \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - 2\mathbf{M_A^2}\mathbf{M_Z^2}\mathbf{c}_{4\beta} + \mathbf{C}}}$$

with

$$\mathbf{C_\pm} = \Delta\mathcal{M}_{11}^2 \pm \Delta\mathcal{M}_{22}^2$$

$$\mathbf{C} = 4\Delta\mathcal{M}_{12}^4 + \mathbf{C_-^2} - 2(\mathbf{M_A^2} - \mathbf{M_Z^2})\mathbf{C_-}\mathbf{c}_{2\beta} - 4(\mathbf{M_A^2} + \mathbf{M_Z^2})\Delta\mathcal{M}_{12}^2\mathbf{s}_{2\beta}$$

The dominant corrections come from stop/top sector with a leading term:

$$\Delta\mathcal{M}_{11/12}^2 \sim 0\,,\ \Delta\mathcal{M}_{22}^2 \sim \epsilon = \frac{3\,\bar{\mathbf{m}}_t^4}{2\pi^2 \mathbf{v}^2 \sin^2\beta}\left[\log\frac{\mathbf{M_S^2}}{\bar{\mathbf{m}}_t^2} + \frac{\mathbf{X_t^2}}{\mathbf{M_S^2}}\left(1 - \frac{\mathbf{X_t^2}}{12\,\mathbf{M_S^2}}\right)\right]$$

still a simple picture but with a few additional parameters $\mathrm{M_S}, \mathrm{X_t}$...

See talk by Howie Haber

2. Implications from the Higgs mass

The mass value 125 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:

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

- **decoupling regime with $M_A \sim \mathcal{O}$(TeV);**
- **large values of tan$\beta \gtrsim 10$ to maximize tree-level value;**
- **maximal mixing scenario: $X_t = A_t - \mu \cot\beta = \sqrt{6} M_S$;**
- **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 code (Suspect) with RC in $\overline{\rm DR}$/compare with FeynHiggs (OS).**

Perform a full scan of phenomenological MSSM with 22 free parameters:

- **determine 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.

2. Implications from the Higgs 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 are favored,

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

How light sparticles can be with the constraint $\mathrm{M_h} = 125$ GeV?

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

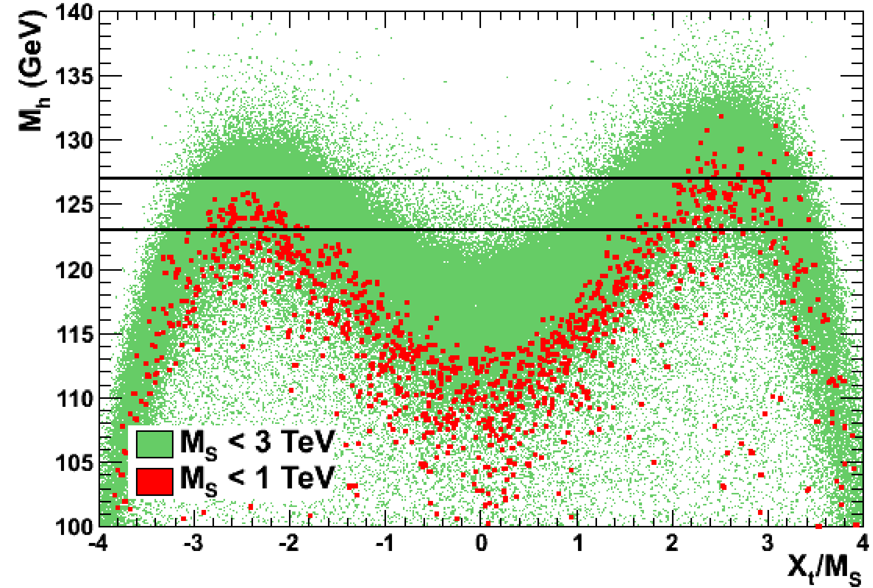
But not main player here: the stops:

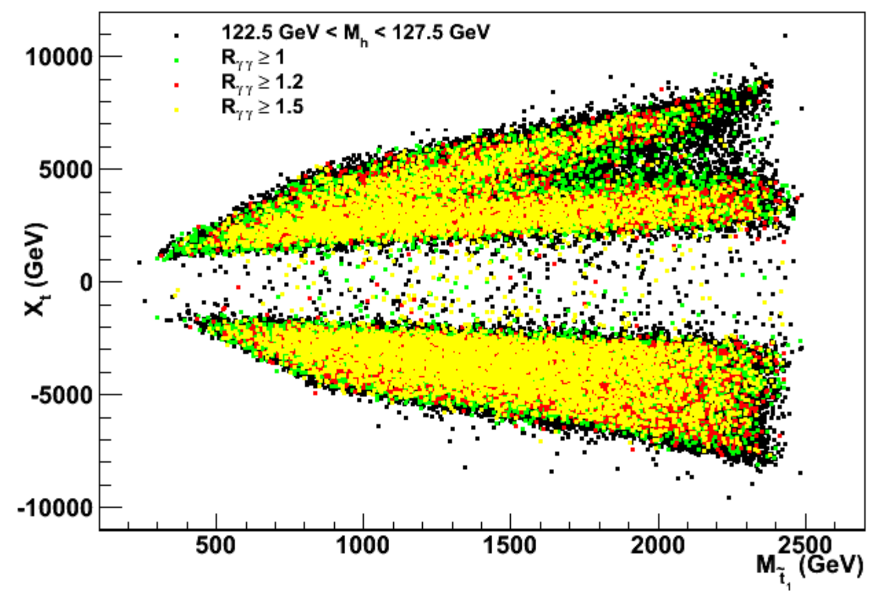
$\Rightarrow \mathrm{m}_{\tilde{\mathrm{t}}_1} \lesssim 500$ GeV still possible

(and compatible with direct limits).

- $\mathrm{M_1}, \mathrm{M_2}$ 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 LHC limits..





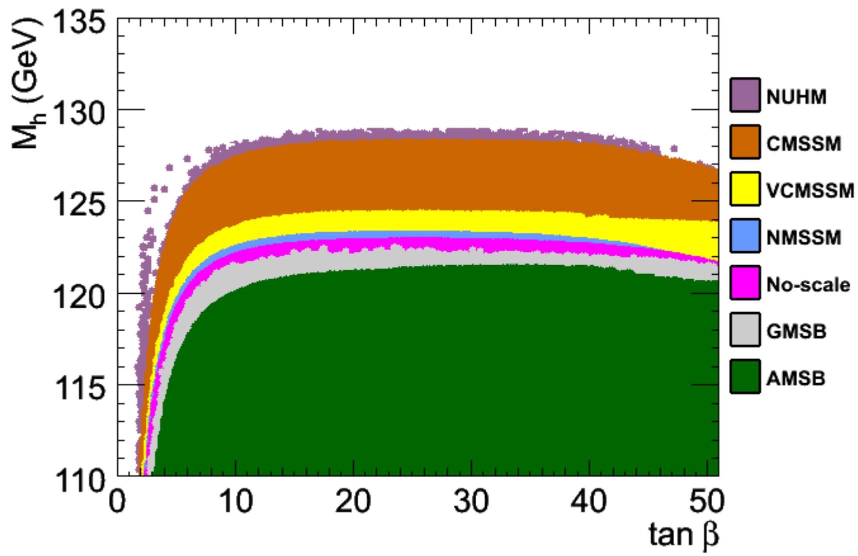
2. Implications from the Higgs mass

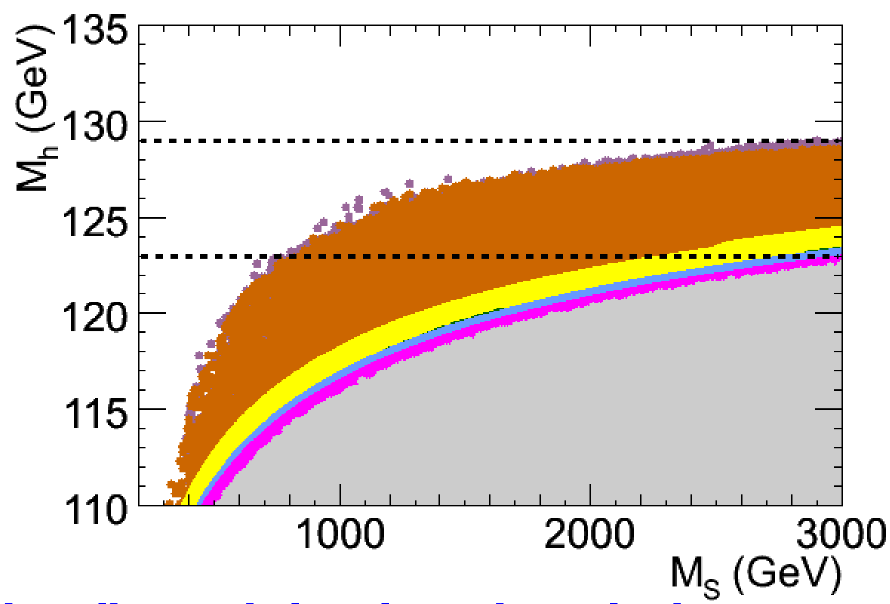
Constrained MSSMs are interesting from model building point of view:

– concrete schemes: SSB occurs in hidden sector $\stackrel{\rm gravity,..}{\longrightarrow}$ MSSM fields,
– provide solutions to many problems in general MSSM: CP, flavor, CCB,..
– parameters obey boundary conditions $\Rightarrow$ small number of basic inputs.

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

full scans of the model parameters with $123\ {\rm GeV} \leq M_h \leq 129\ {\rm GeV}$.





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

2. Implications from the Higgs 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).

$M_h \propto \log(M_S/m_t) \Rightarrow$ **larger.**

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

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

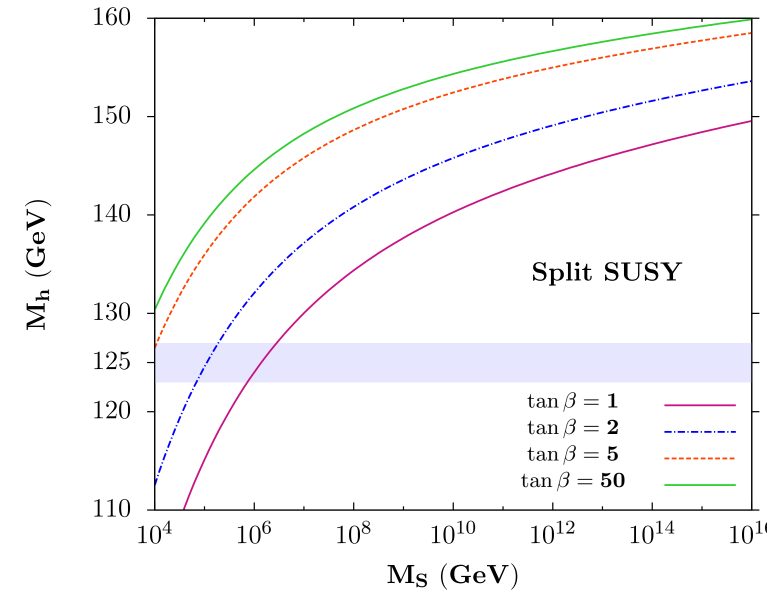
$$\lambda(\tilde{m}) = \frac{g_1^2(\tilde{m}) + g_2^2(\tilde{m})}{8}(1 + \delta_{\tilde{m}})$$

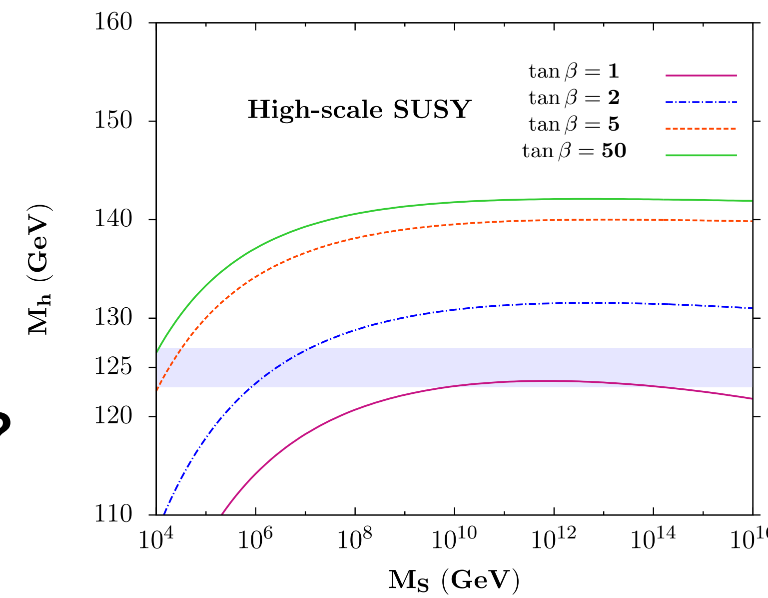
... leading to $M_H =$120–140 GeV ...

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

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

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





3. Implications from the Higgs properties

In principle, once the angles β and α known, all h couplings are fixed:

MSSM: $\mathbf{c_V^0 = \sin(\beta-\alpha)\ ,\ c_t^0 = \cos\alpha/\sin\beta\ ,\ c_b^0 = -\sin\alpha/\cos\beta}$

if only radiative corrections to masses $M_{h/H}$ and α taken into account.

However also direct/vertex corrections have to be included! $\Rightarrow$ Figure

The two important SUSY (QCD) corrections affect the t,b couplings:

$$c_b \approx c_b^0 \times [1 - \frac{\Delta_b}{1+\Delta_b} \times (1+\cot\alpha\cot\beta)] \text{ with } \tan\alpha \stackrel{M_A \gg M_Z}{\rightarrow} \frac{-1}{\tan\beta}$$

$$c_t \approx c_t^0 \times [1 + \frac{m_t^2}{4 m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu\cot\alpha)(A_t + \mu\tan\alpha))]$$

- c_τ, c_c and c_t from $pp \rightarrow Ht\bar{t}$ do not involve same vertex corrections.
- $gg \rightarrow h$ process has $\tilde{t}, \tilde{b}$ loops and $h \rightarrow \gamma\gamma$ has also $\tilde{\tau}$ and $\chi_i^\pm$ loops.

In general case, we need (at least) 7 couplings $c_g, c_\gamma, c_t, c_b, c_c, c_\tau, c_V$.

(not to mention the invisible Higgs decay width that enters all BRs...)

8 parameters fit difficult! Simpler to make reasonable approximations:

- low sensitivity on $h \rightarrow c\bar{c}$, $h \rightarrow \tau\tau$ and $pp \rightarrow ttH$ at the LHC....
- in $h \rightarrow \gamma\gamma$ additional $\tilde{b}, \tilde{\tau}, \chi_1^\pm$ contributions smaller than those of $\tilde{t}$.

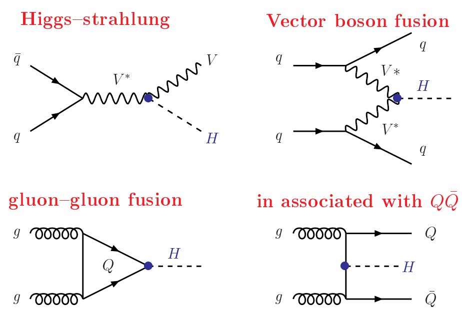
$\Rightarrow$ assume $c_c = c_t, c_\tau = c_b$ and $c_t(ttH) = c_t(ggF), c_\gamma \approx c_g \approx c_t$:

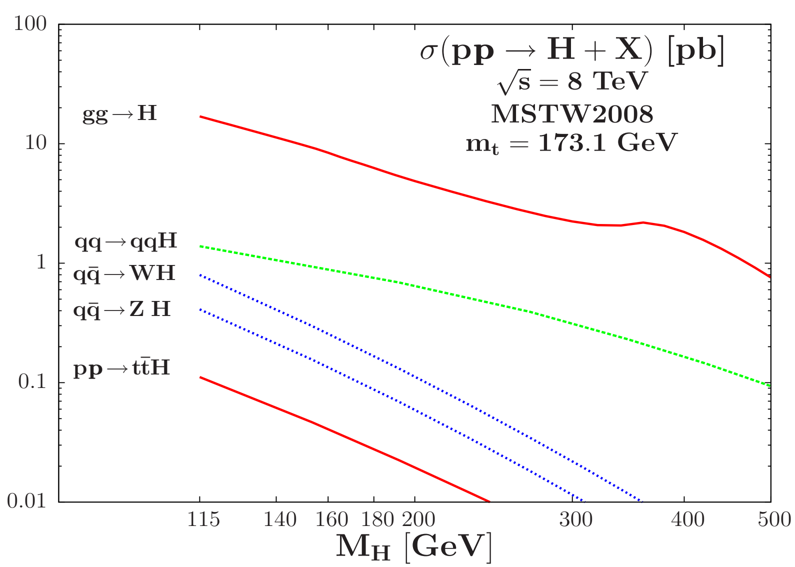
reduce the problem to a fit of three couplings: c_V, c_b, c_t.

3. Implications from the Higgs properties

Adapt the SM Higgs rates to that of h close to the decoupling limit...

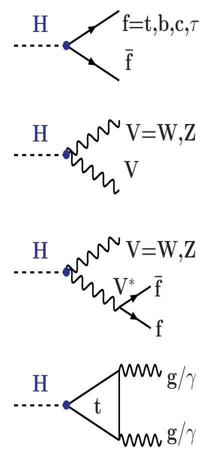
Main Higgs production channels:

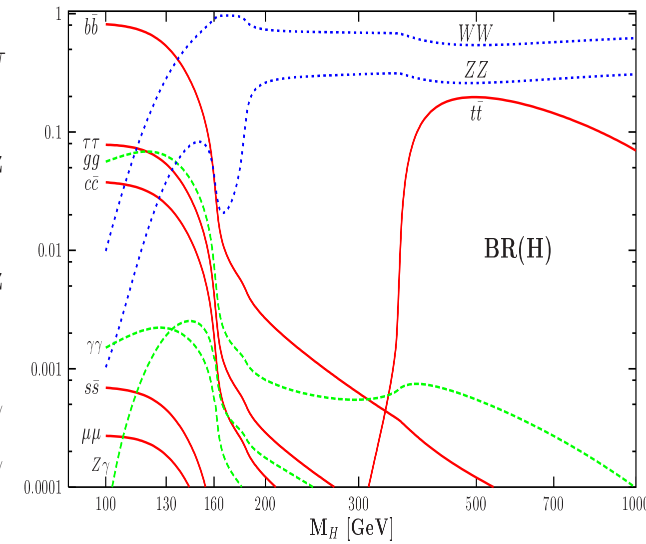




gg→ h by far dominant process proceeds via heavy quark loops!

Higg decays branching ratios:





– $h \to b\bar{b} \approx 60\%$: **dominant**

– $h \to cc, \tau\tau, gg = \mathcal{O}(\text{few }\%)$

– $h \to \gamma\gamma, ZZ^* \to 4\ell^{\pm} \propto 10^{-3}$

main points besides $\alpha, \beta \Rightarrow$

change in $h \to b\bar{b}$ drastic,

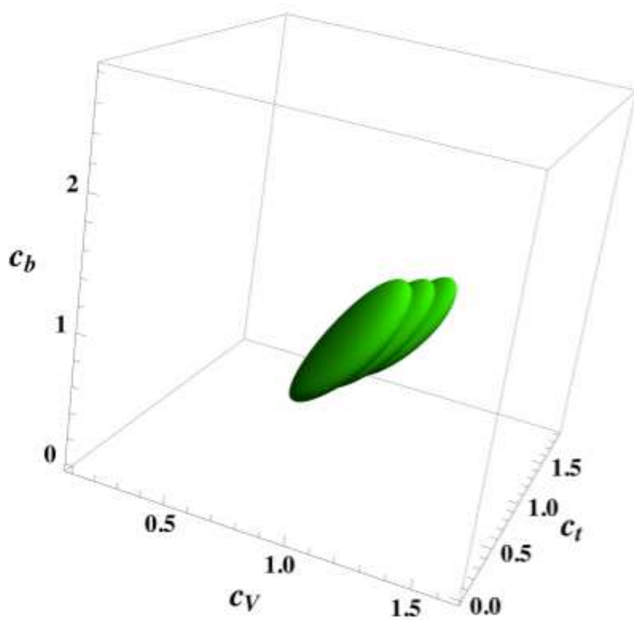
more loops in $h \to gg, \gamma\gamma$...

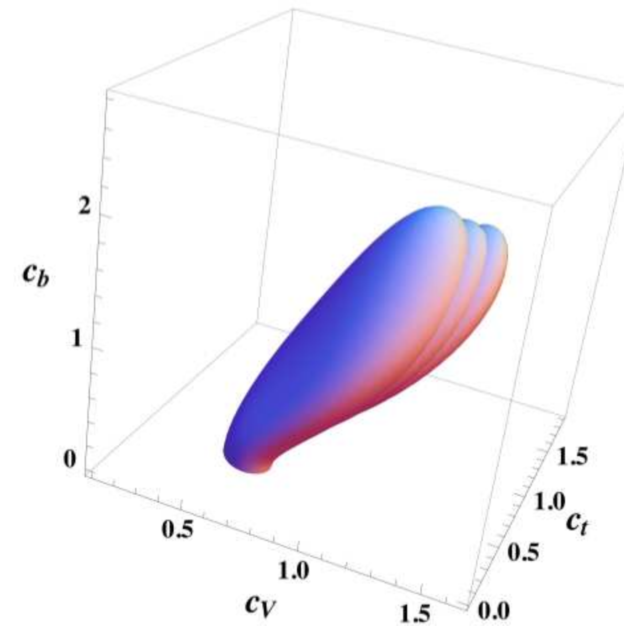
3. Implications from the Higgs properties

⇒ **general MSSM at LHC is described by M_h and c_V, c_t, c_b.**

3-dimensional fit in $[c_t, c_b, c_V]$ space: **AD, Maiani,Polosa,Quevillon,Riquer**

- **– ATLAS+CMS 2013 data for signal strengths in all channels;**
- **– consider the ($\approx$ 15–20%) theory uncertainty as a bias not nuisance;**
- **– use ratios of signal strengths where theory uncertainty cancels out.**





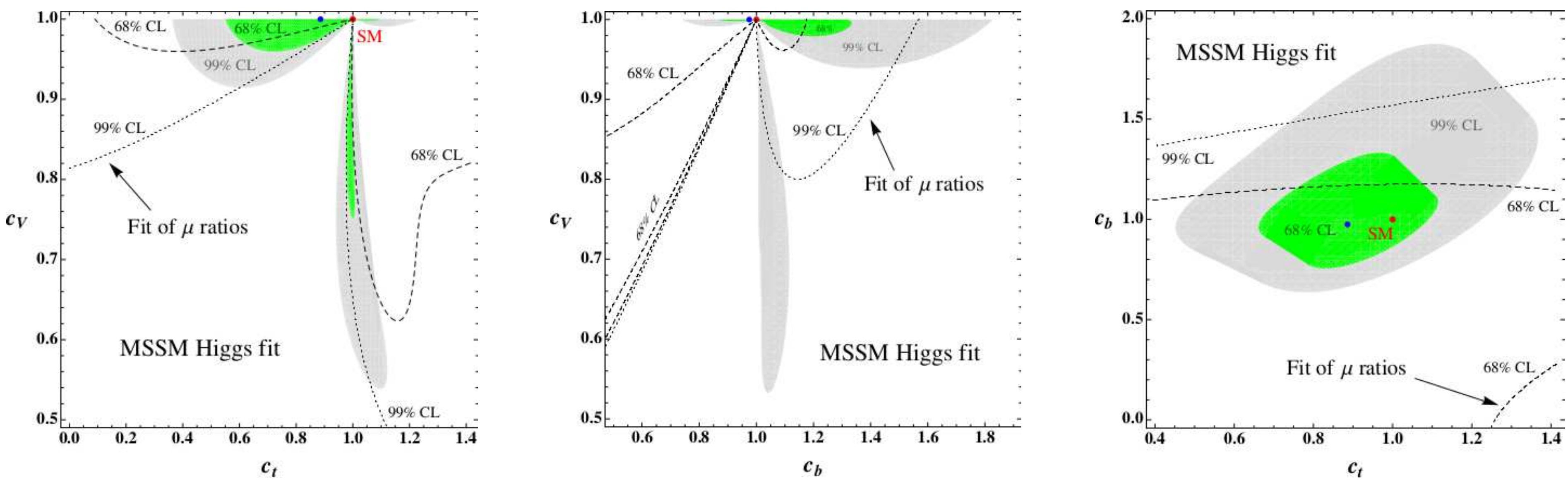
1σ 3–dimension fit **3σ 3–dimension fit**

(3 regions for central and two extreme choices of the theory prediction).

Best-fit value: $c_t = 0.894,\ c_b = 1.007, c_V = 1.02$ with χ^2 =64.80 (71).

3. Implications from the Higgs properties

Now back to MSSM relations and make a 2–dimensional fit for simplicity (the assumption is that there is no direct correction and one c_i is fixed).



$(c_t = 0.9, c_V = 1.0)$, $(c_b = 0.97, c_V = 1.0)$, $(c_t = 0.89, c_b = 0.97)$.

are now the best-fit points; combining the three possible cases, one has:

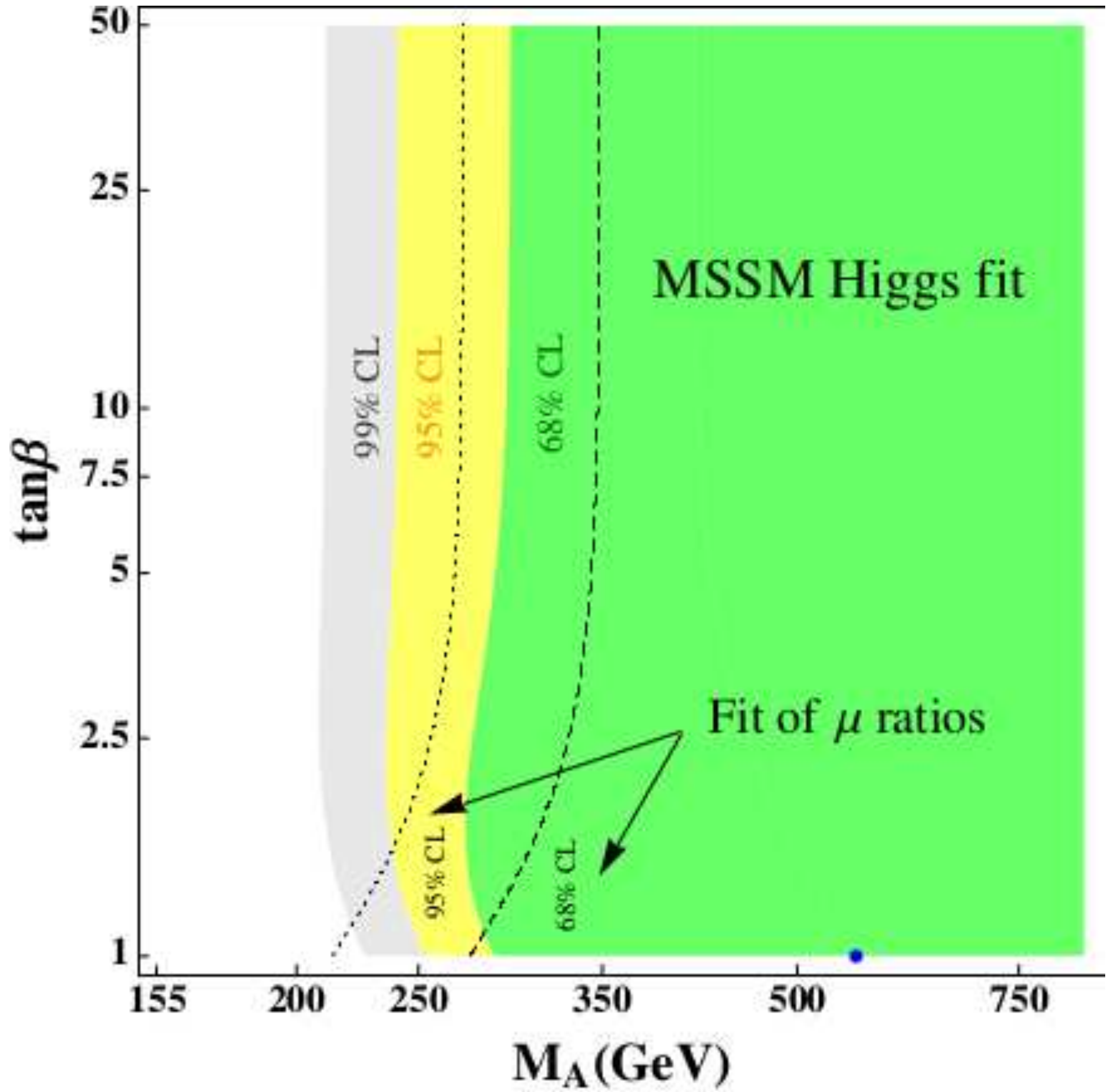
$\tan\beta = 1$ **and** $M_A = 560$ **GeV**

which, with $M_h = 125$ GeV implies $M_H = 580$ GeV, $M_{H^\pm} = 563$ GeV.

But the minimum is flat and many points (with high $\tan\beta$) are also OK...

3. Implications from the Higgs properties

Signal strengths and ratios fit turned in a $[\tan\beta, M_A]$ constraint...

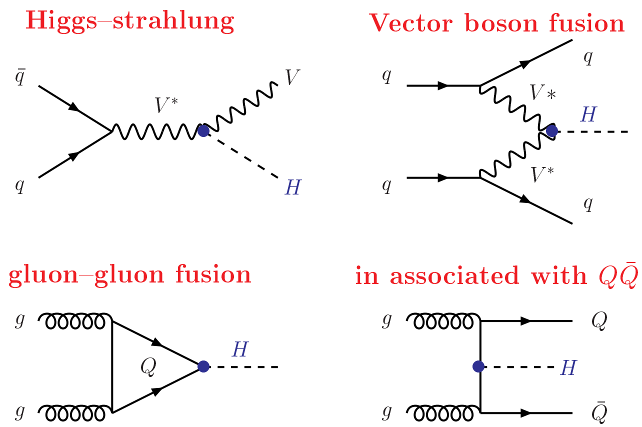


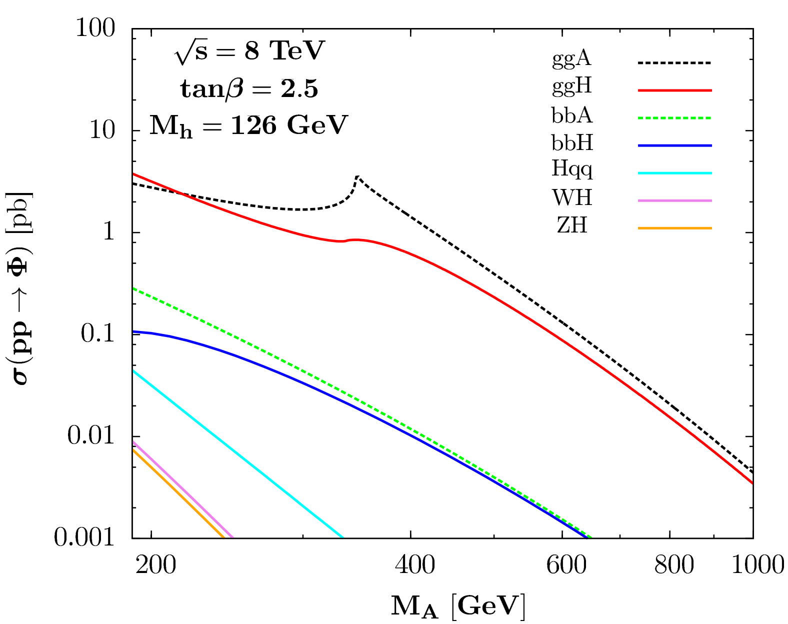
AD, Maiani, Moreau, Polosa, Quevillon, Riquer.

4. Implications from heavy Higgs searches

Besides superparticles, the heavier H/A/$H^{\pm}$ states can also be produced.

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**
  – in ΦV, $qq\Phi$ h/H complementary
  – additional mechanism: qq $\to$ A+h/H
- **For $gg \to \Phi$ and $pp \to QQ\Phi$**
  – include the contr. of b–quarks
  – dominant contr. at high tanβ!
- **For pseudoscalar A boson:**
  – CP: no ΦA and qqA processes
  – $gg \to A$ and $pp \to bbA$ dominant.
- **For charged Higgs boson:**
  – $M_H \lesssim m_t$: $pp \to t\bar{t}$ with $t \to H^+ b$
  – $M_H \gtrsim m_t$: continuum $pp \to t\bar{b}H^-$

At high tanβ values:

– h as in SM with $M_h = 115 - 130$GeV
– dominant channel: $gg, b\bar{b} \to \Phi \to \tau\tau$

4. Implications from heavy Higgs searches

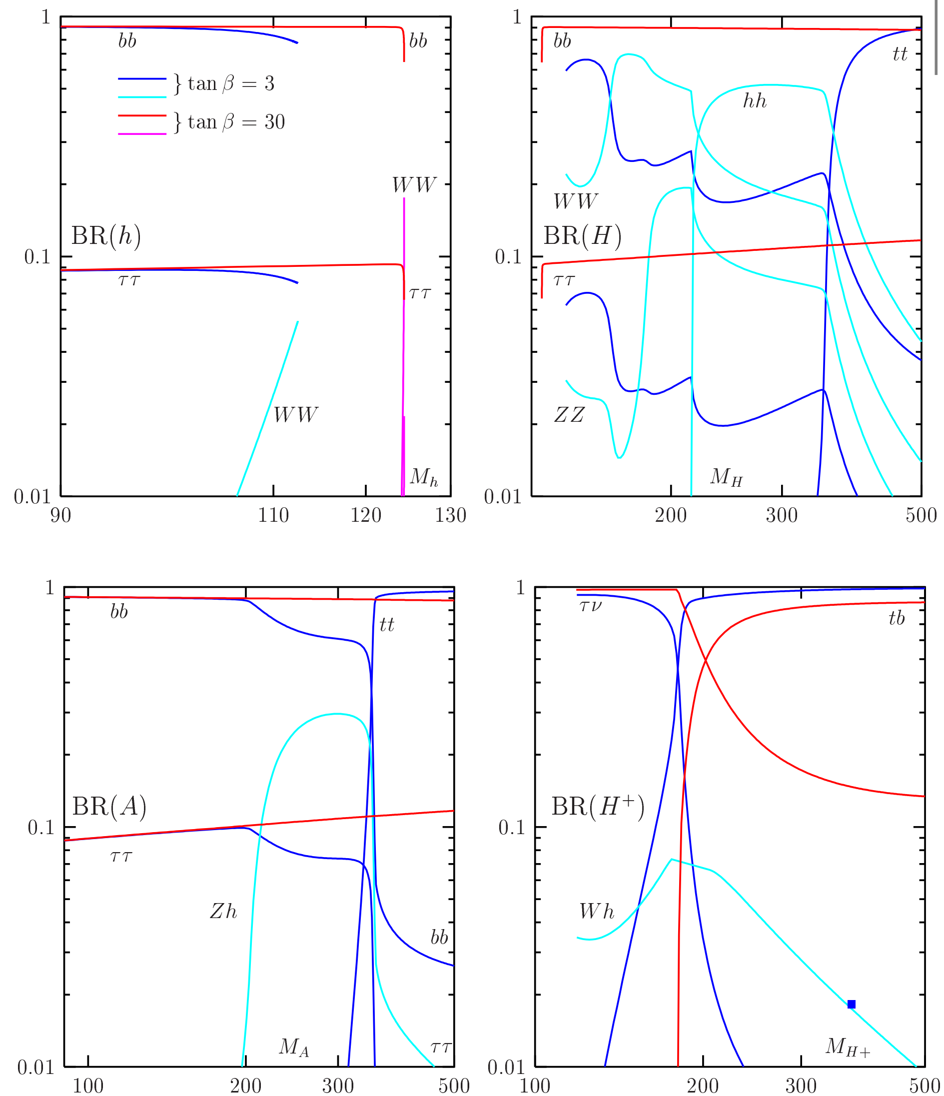
MSSM Higgs detection modes:

General features for h/H/A/$H^\pm$

- **h: same as $\mathrm{H_{SM}}$ in general (especially in decoupling limit).**
- **A: only $\mathrm{b\bar{b}}, \tau^+\tau^-$, $\mathrm{t\bar{t}}$ decays (no VV decays, hZ suppressed).**
- **H: same as A in general as $\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ modes suppressed.**
- **$\mathrm{H}^\pm : \tau\nu$ and tb decays (depending if $\mathrm{M_{H^\pm}} <$ or $> \mathrm{m_t}$).**

– loop decays strongly suppressed

– possible new effects from SUSY!?



For tan$\beta \gg 1$, only decays into b/τ:

BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$

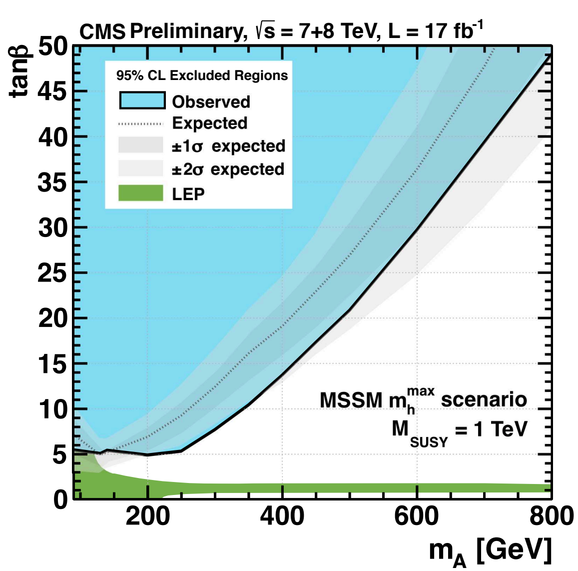
For tan$\beta \approx 1$, other good channels:

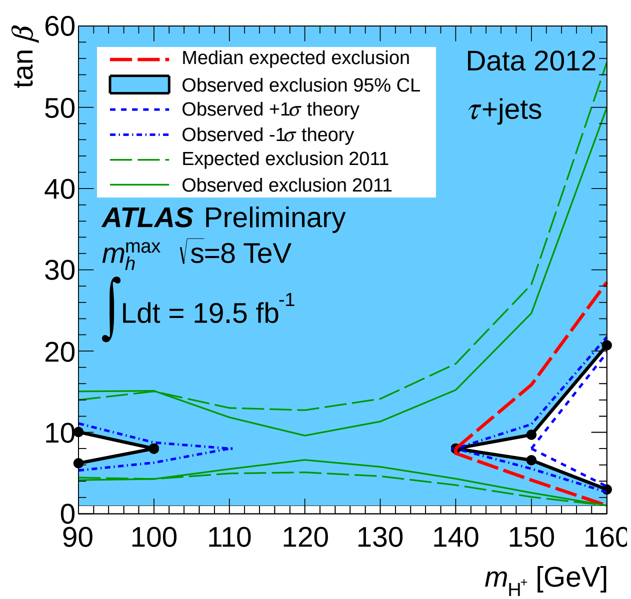
$$\mathrm{H/A \to tt, H \to WW, ZZ}$$
$$\mathrm{A \to hZ, H \to hh}$$

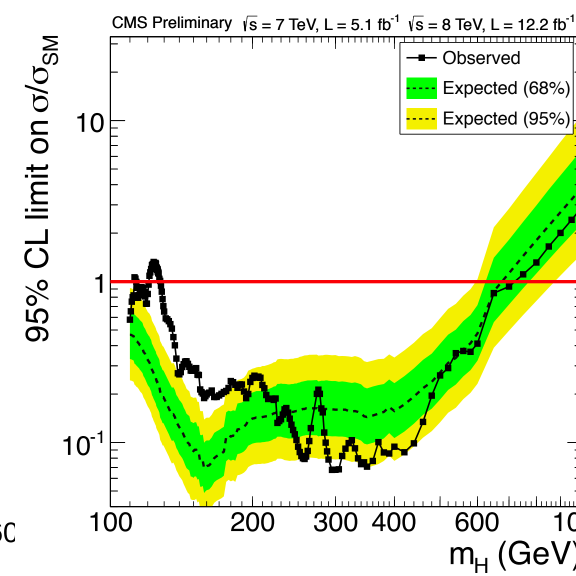
4. Implications from heavy Higgs searches

Most efficient channels for the production of the heavier MSSM Higgses.

- **Searches for the $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ resonant process:**
  $\Rightarrow$ **rules out high $\tan\beta$ for low $\mathrm{M_A}$ values.**
- **Searches for charged Higgs in $\mathrm{t} \to \mathrm{bH^+} \to \mathrm{b}\tau\nu$ decays:**
  $\Rightarrow$ **rules out almost any $\tan\beta$ value for $\mathrm{M_{H^\pm}} \lesssim 160$ GeV.**
- **Non observation of heavier Higgs bosons in H→ZZ,WW modes:**
  $\Rightarrow$ **no analysis yet!? The width is different from SM-case.**
- **Also searches for $\mathrm{A} \to \mathrm{hZ}$ and $\mathrm{H} \to \mathrm{hh}$ but not in the MSSM....**
- **Searches for heavy tt resonances but not in the MSSM ($\mathrm{KK, Z'}$)...**







4. Implications from heavy Higgs searches

The most constraining channel is by far the $pp \to \tau^+\tau^-$ process.

However, there are problems with the interpretation in the MSSM context.

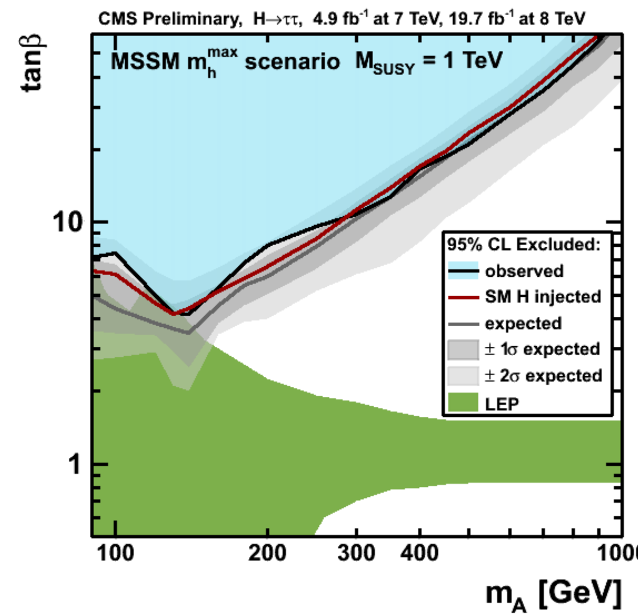
- **Derived in the “Mh-max scenario” that maximizes radiative corrections to M_h (but constraints are solid at high–tanβ).**
- **Uses the $M_S = 1$ TeV benchmark that is ruled out in most (realistic) cases.**
- **Uses LEP2 constraint $M_h \gtrsim 114$ GeV which is now superseded by the LHC (and this rules out all tan$\beta \lesssim 3$ values).**
- **Does not take into account LHC data: h has 125 GeV and SM–like couplings..**

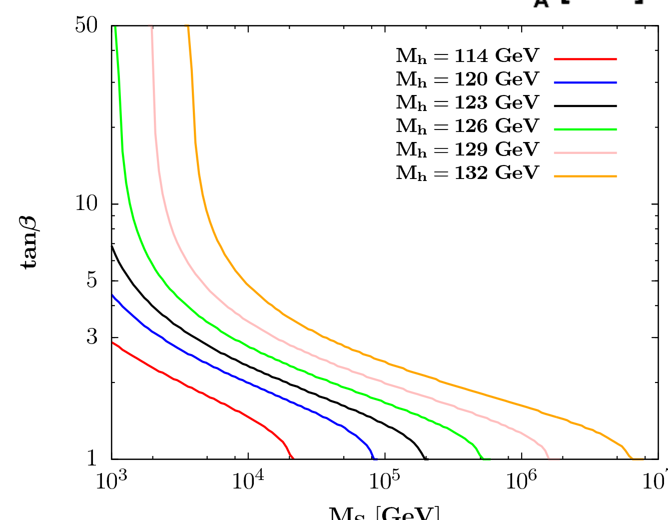
We can be more relaxed: $M_S \gg M_Z$

and choose it in order that LHC data OK:

$\Rightarrow$ more consitent/realistic approach,

$\Rightarrow$ much less model dependance.





4. Implications from heavy Higgs searches

Model independent – effective – approach

Habemus MSSM (hMSSSM):

AD, Maiani,Polosa,Quevillon,Riquer

- **We turn $M_h \approx M_Z |\cos 2\beta| +$RC to**
  RC= 125 GeV - $f(M_A, \tan\beta)$

ie. we "trade" RC with the measured M_h

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

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

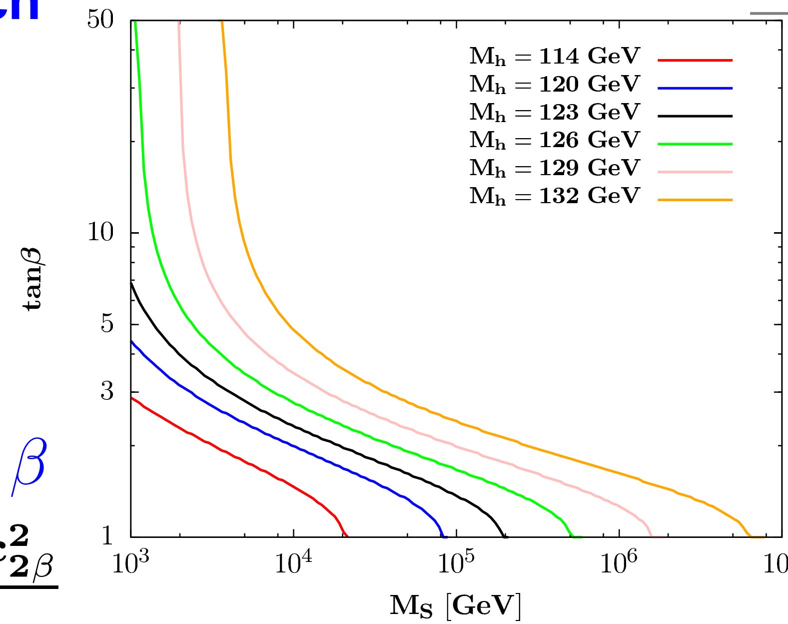
$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}\right)$$

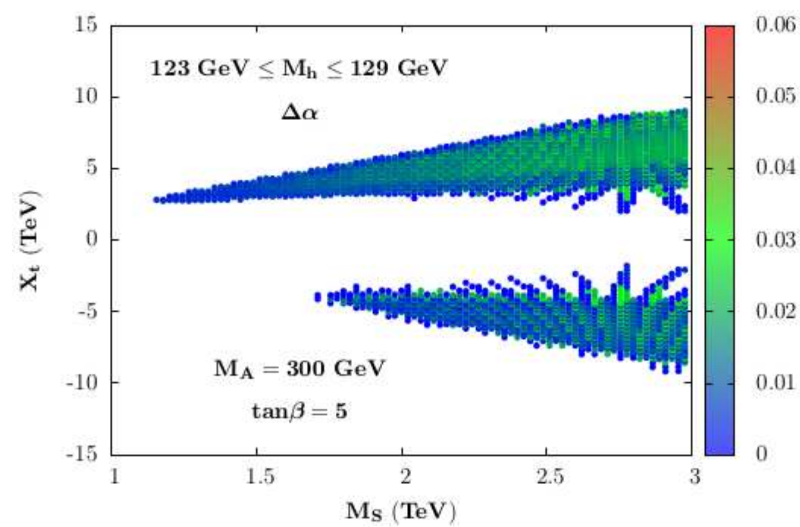
$$M_{H^\pm} \simeq \sqrt{M_A^2 + M_W^2}$$

Clearly works when leading RC only:

$$\Delta\mathcal{M}_{22}^2 = \frac{M_h^2(M_A^2+M_Z^2-M_h^2)-M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2+M_A^2 s_\beta^2-M_h^2}$$

But we checked that it is also good in general, ie for $\Delta\mathcal{M}_{11,12}^2 \neq 0$.





4. Implications from heavy Higgs searches

LHC run 1 legacy on the MSSM $[\mathrm{M_A}, \tan\beta]$ plane in the hMSSM:

- $\mathrm{pp} \to \mathrm{H/A} \to \tau\tau$
- $\mathrm{t} \to \mathrm{H^+ b} \to \mathrm{b}\tau\nu$

(also at low tanβ values

- H$\to$WW and ZZ

(but width as in SM).

- CMS A$\to$hZ analysis
- CMS H$\to$hh (to update)

(both MSSM interpreted).

- $\mathrm{pp} \to \mathrm{H/A} \to \mathrm{t\bar{t}}$

with complete analysis:

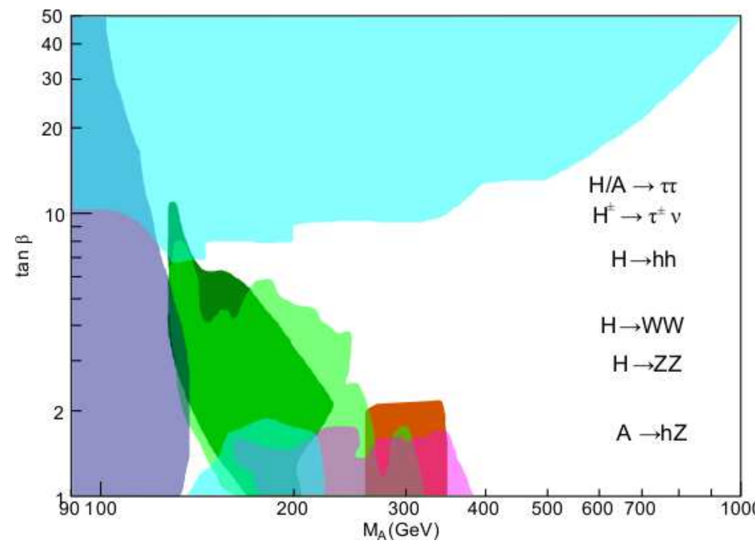
– effect of total width

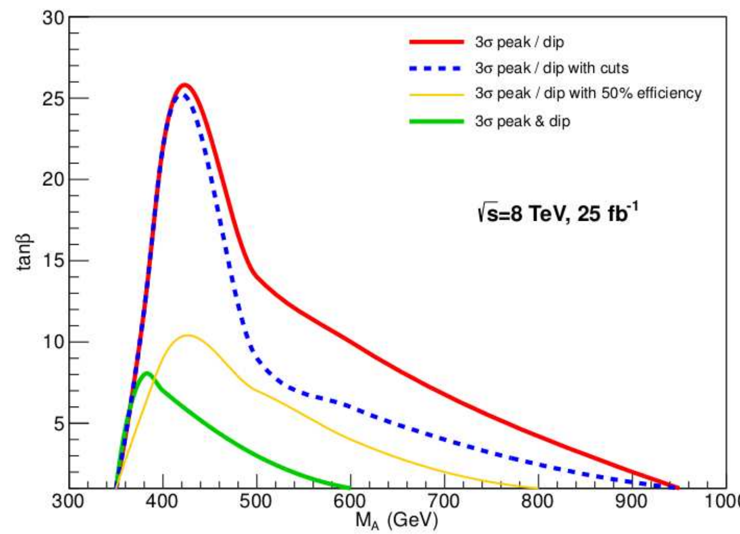
– S and B interference

– boosted top jets

the action is at low tanβ!

Quevillon in progress





5. What next?

KEEP GOING!

It is still "action" time:

- **keep measuring the Higgs properties: the devil is hidden in the details...**
- **keep searching for the heavier Higgses, some can be around the corner, ...**
- **keep searching for SUSY with more focus on stops and EW states..**

and keep an open mind towards overlooked and extended scenarios...

Thank you!