Implications of the LHC Higgs results for Supersymmetry

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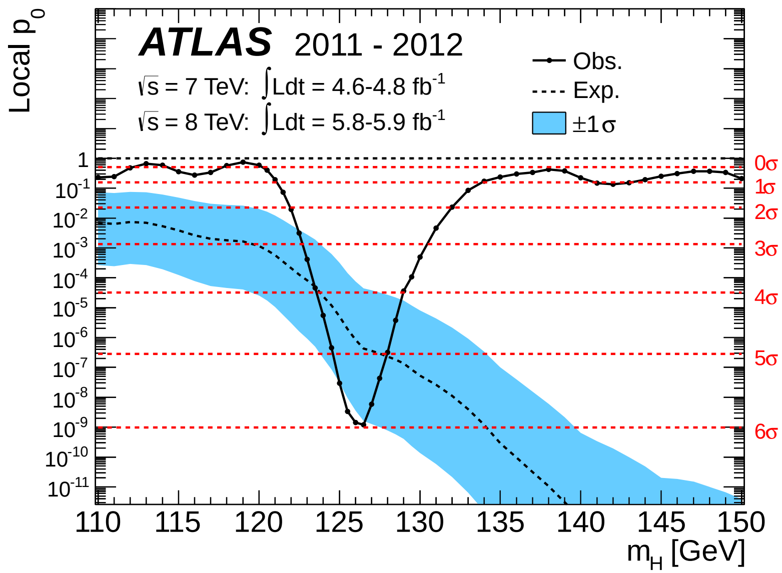
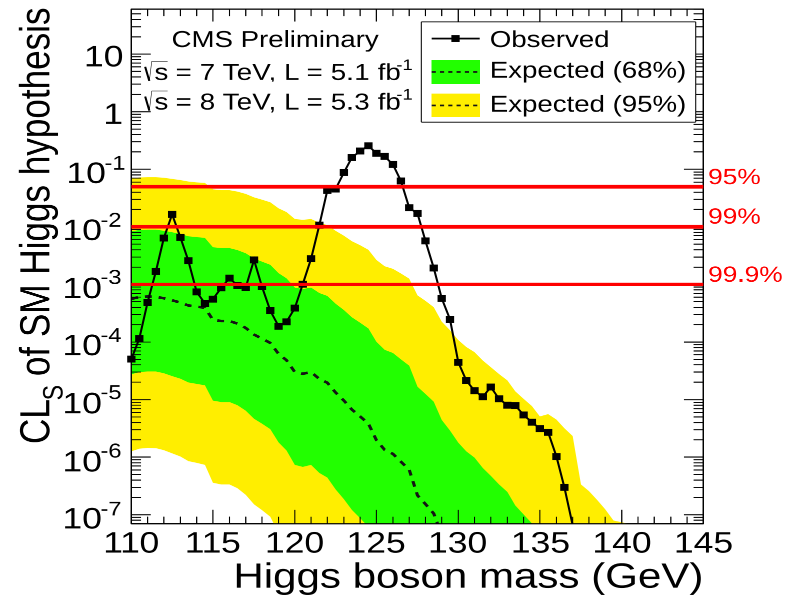
- **Is it a Higgs?**
- **Implications from the mass**
- **Implications from the rates**
- **Conclusion**

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. Is it a Higgs?

To generate particle masses in an SU(2)×U(1) gauge invariant way:
introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ with $\langle 0|\Phi^0|0\rangle \neq 0$

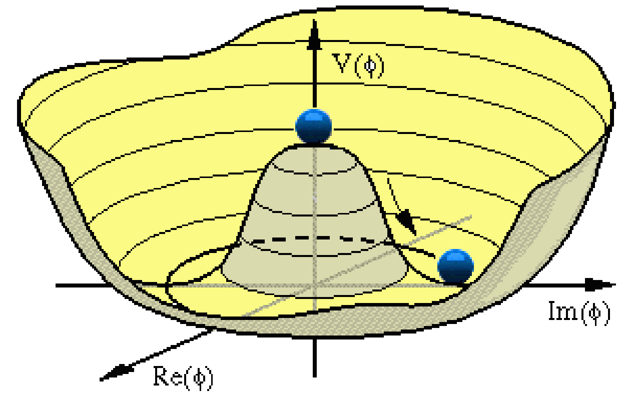
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

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

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

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

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



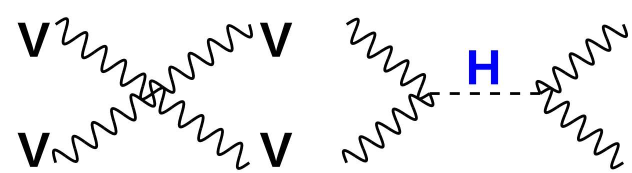
Residual dof corresponds to spin–0 H particle.

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

The Higgs unitarizes the theory:

without Higgs: $|A_0(vv \to vv)| \propto E^2/v^2$

including H with couplings as predicted:



$|A_0| \propto M_H^2/v^2 \Rightarrow$ **the theory is unitary but needs $M_H \lesssim 700$ GeV...**

In the SM: once M_H known, all properties of the Higgs are fixed.

1. Is it a Higgs?

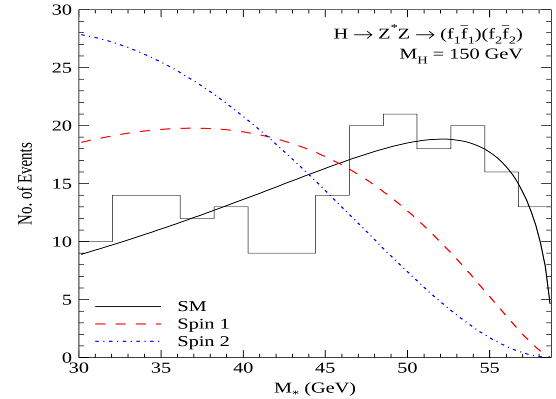
The particle decays into $\gamma\gamma$ states

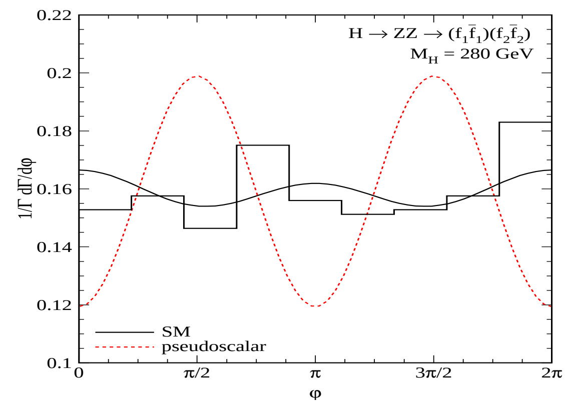
- **not spin–1: Landau–Yang...**
- **could be spin–2 like graviton?**

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

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

Many theoretical analyses...



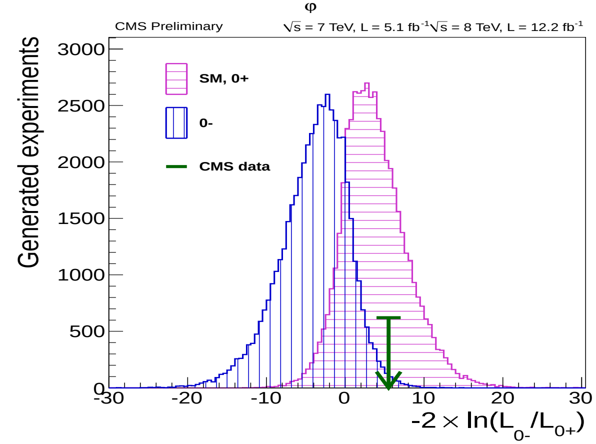


Is it a CP–even state or CP–odd?

$$\mathrm{HV}_\mu \mathrm{V}^\mu \text{ versus } \mathrm{H}\epsilon^{\mu\nu\rho\sigma}\mathrm{Z}_{\mu\nu}\mathrm{Z}_{\rho\sigma}$$

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

CMS/(ATLAS): 2.5σ for CP–even...

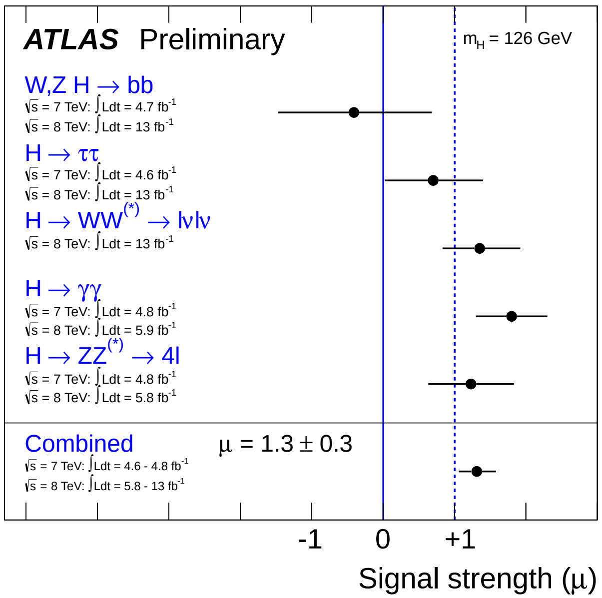


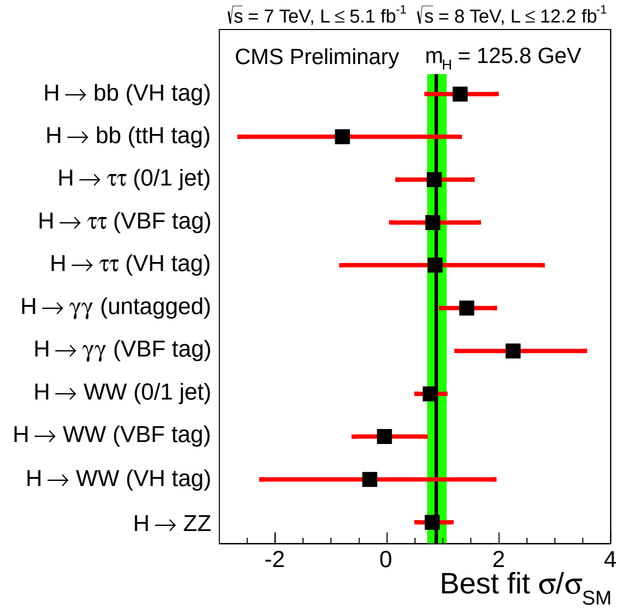
Problem: if H is CP mixture, only 0^+ component is projected out!

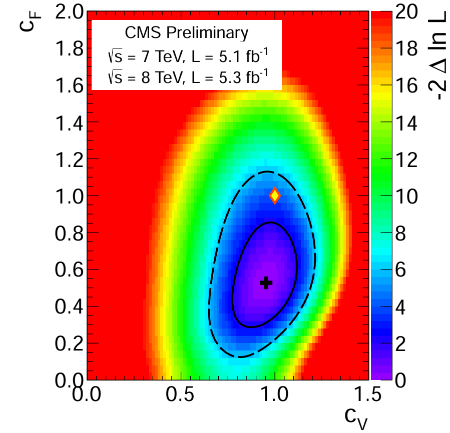
(or very large 0^-VV loop coupling).

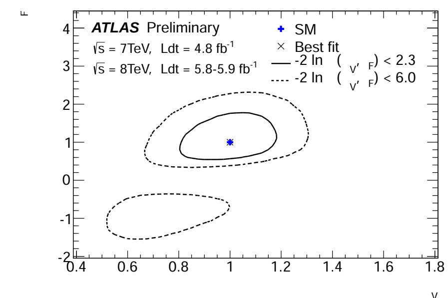
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 0.95 \pm 0.3$?

1. 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 "125 GeV boson", a "new state"...

IT IS A HIGGS BOSON!

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

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

2. Implications from the Higgs mass

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

After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states left out: $\mathbf{h, H, A, H^\pm}$

Only two free parameters at tree–level: $\tan\beta, \mathbf{M_A}$ but rad. cor. important

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

– Couplings of $\mathrm{h, H}$ 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

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

2. Implications from the Higgs 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:

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

- **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 paramete

- **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

2. Implications from the Higgs 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?

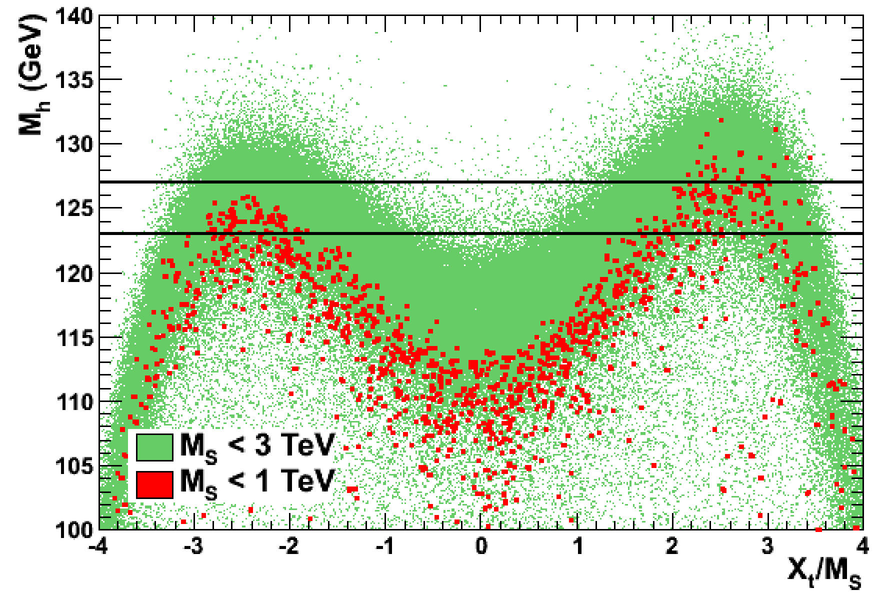
- 1s/2s gen. $\tilde{q}$ should be heavy...

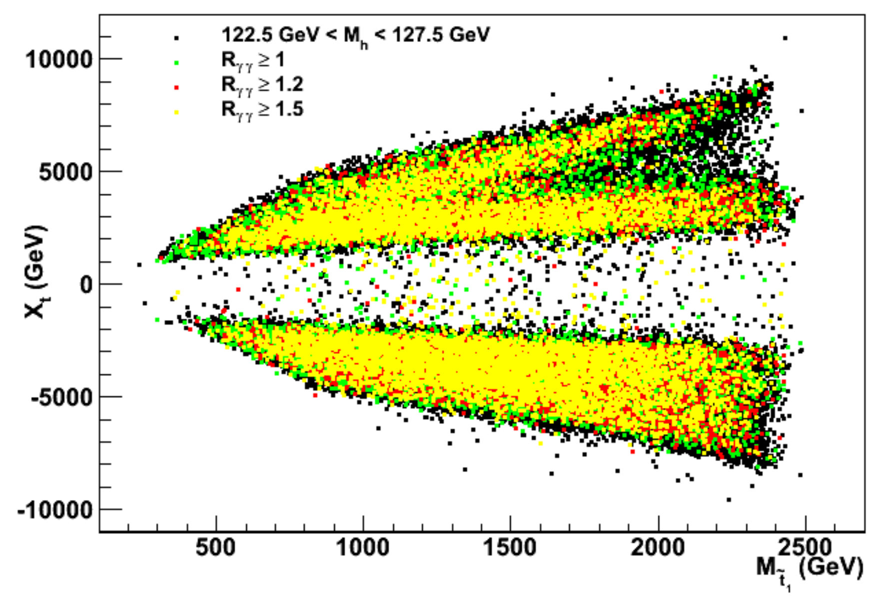
But not main player here: the stops:

$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ 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..





2. Implications from the Higgs mass

Constrained MSSMs are interesting from model building point of view:

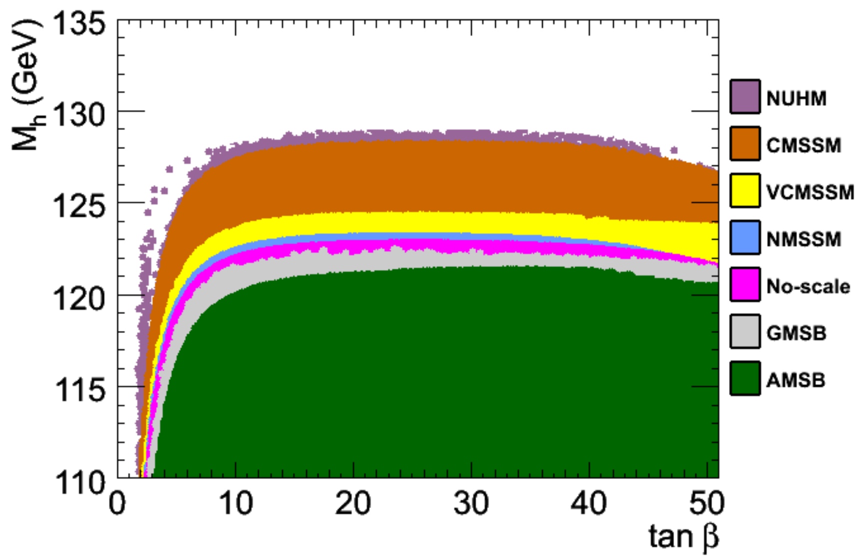
– concrete schemes: SSB occurs in hidden sector $\stackrel{\text{gravity,..}}{\longrightarrow}$ MSSM fields

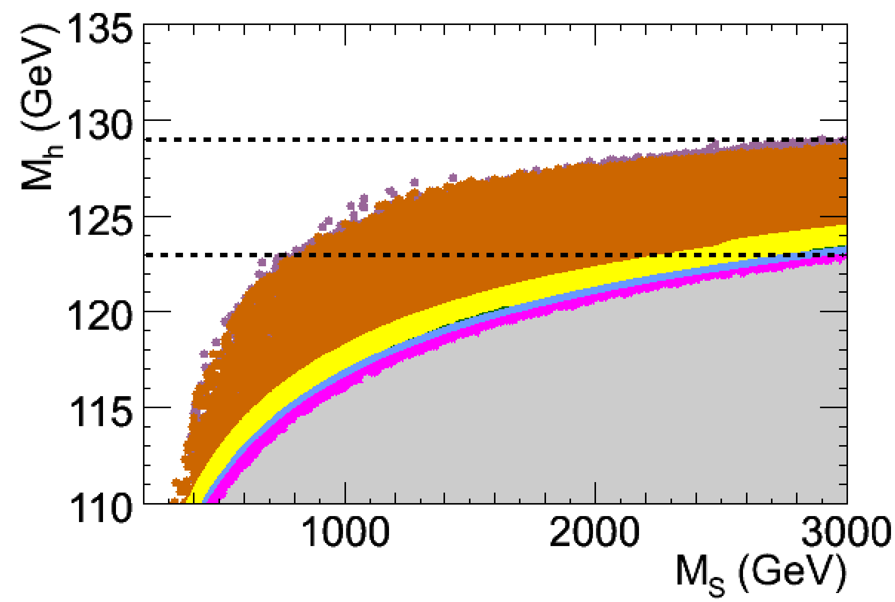
– provide solutions to some MSSM problems: CP, flavor, etc..

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

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

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





very strong constraints and some (minimal) models 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)
$M_h \propto \log(M_S/m_t) \rightarrow$ **large**

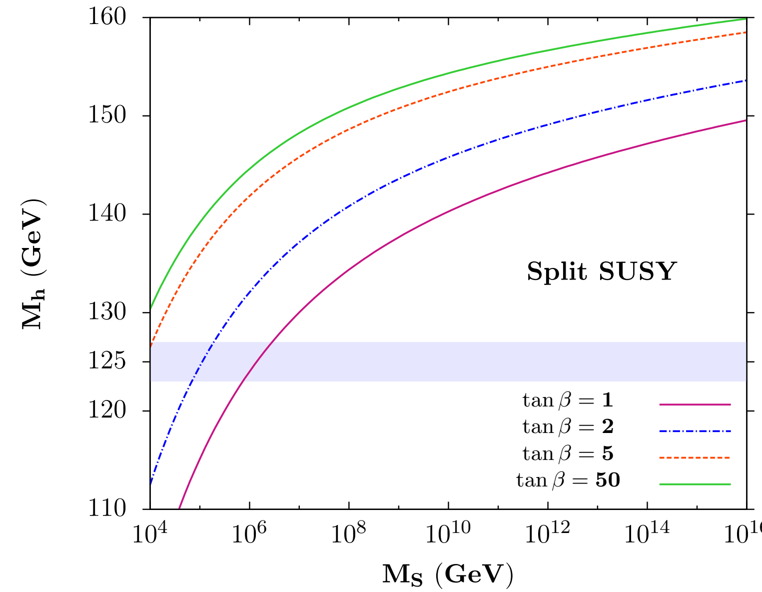
- **SUSY broken at the GUT scale...**

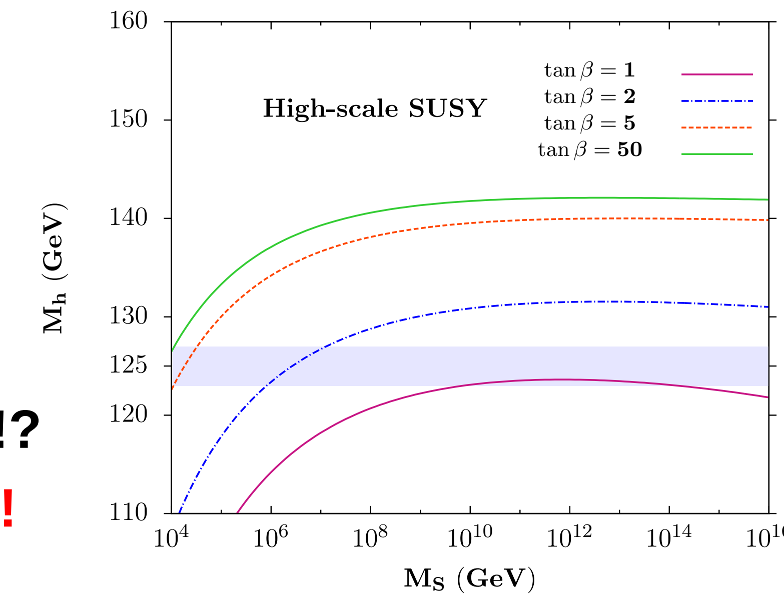
give up fine-tuning and everything else
still, $\lambda \propto M_H^2$ related to gauge cplgs

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

... leading to $M_H =$120–140 GeV ...

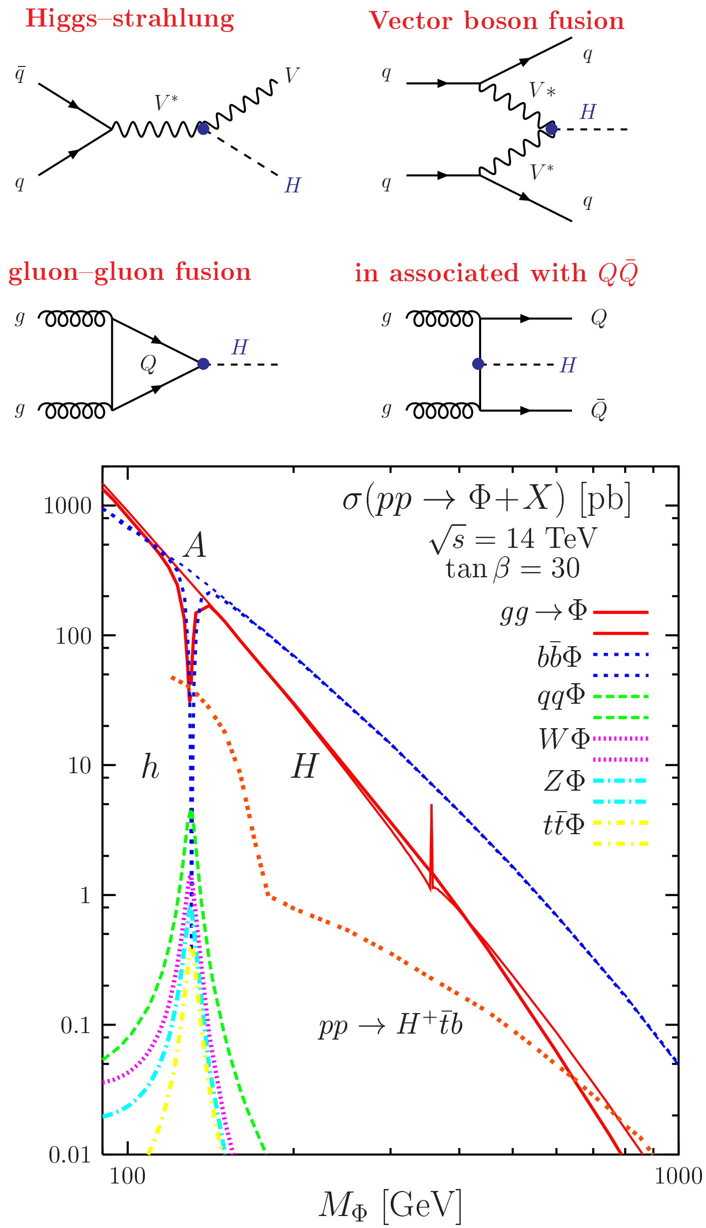
In both cases small $\tan\beta$ needed...
note 1: $\tan\beta \approx 1$ possible
note 2: M_S large and not M_A possible!?
Consider general MSSM with $\tan\beta \approx 1$!





3. Implications from the Higgs rates

Higgs searches are more complicated/challenging in the MSSM case



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

– 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 processes

(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 $M_h = 115 - 130$GeV

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

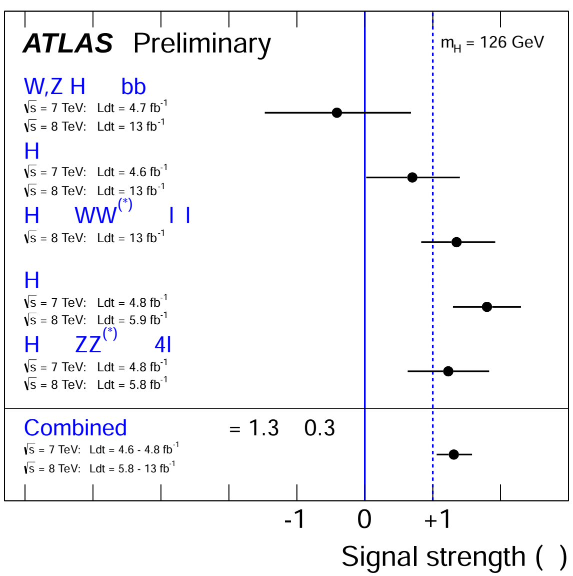
It is even more tricky in beyond MSSM!

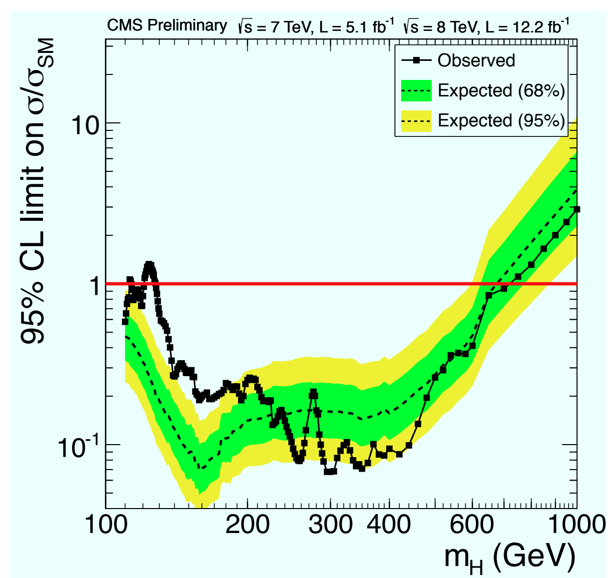
and also in some non–SUSY extensions...

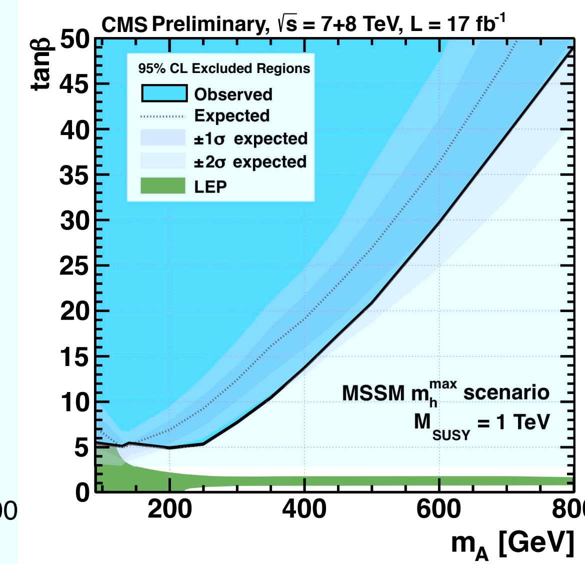
3. Implications from the Higgs rates

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

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







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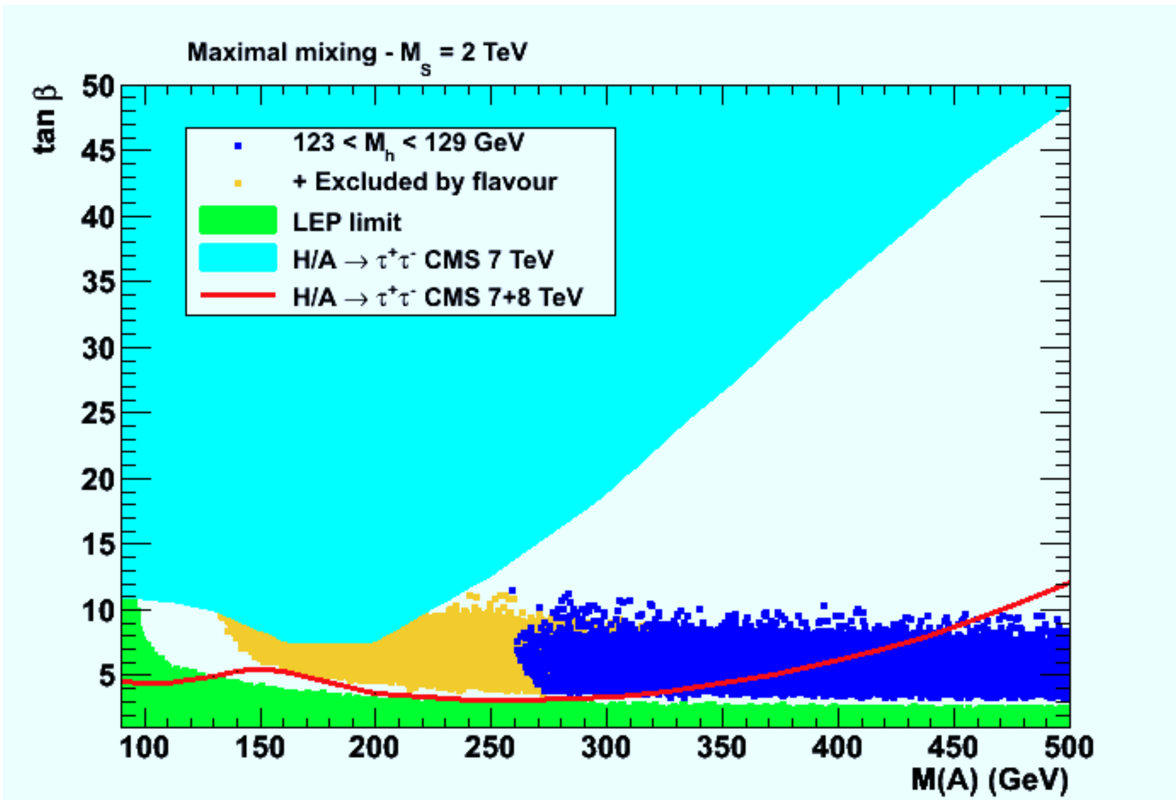
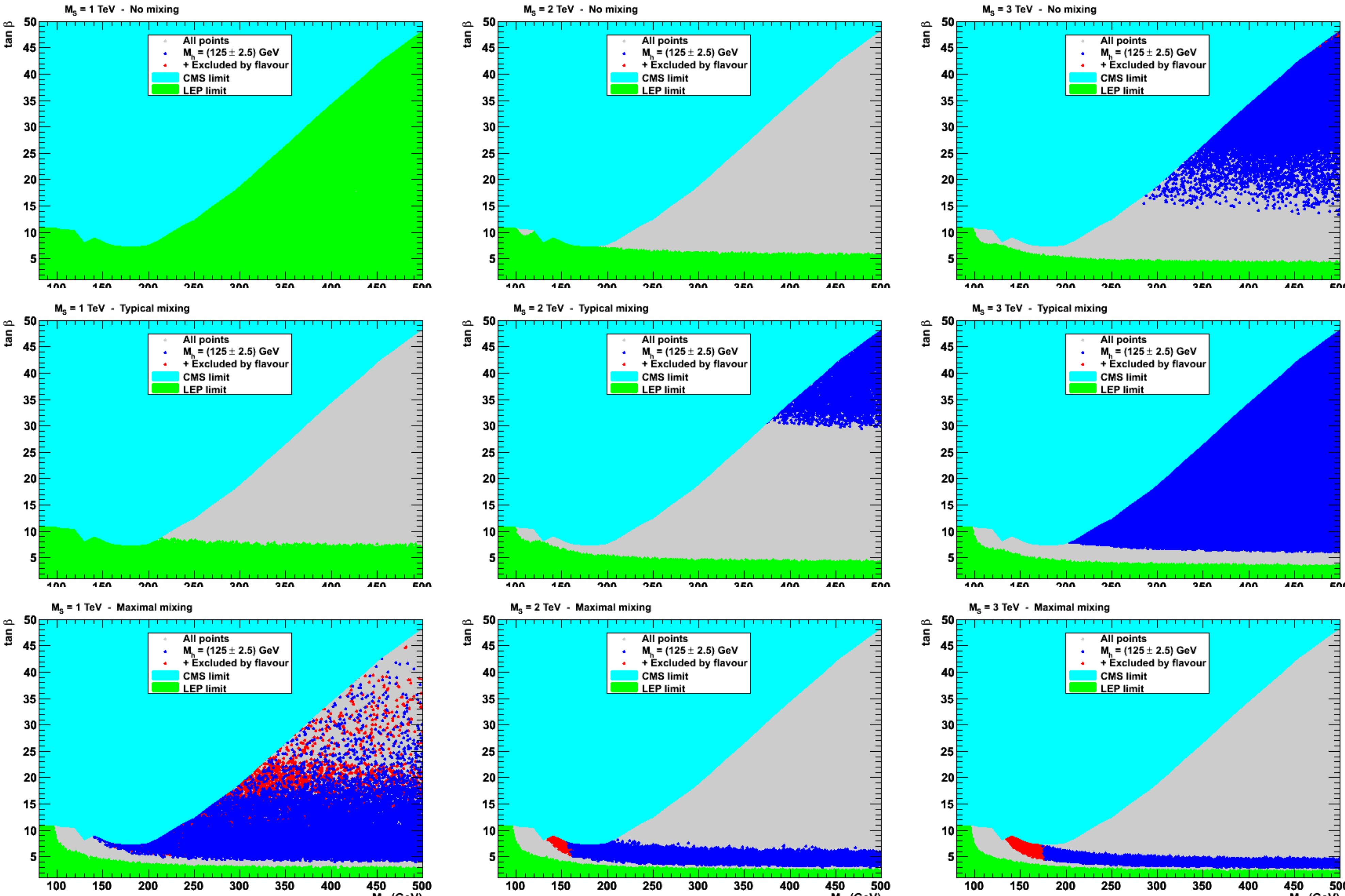


3. Implications from the Higgs rates



3. Implications from the Higgs rates

... is decoupling regime true ?

- are small values of $\mathrm{M_A}$ allowed?
- can H be the SM-like Higgs boson?

Yes, if no other constraints than:

– $\mathrm{M_H} \approx 126 \pm 3$ GeV

– $\mathrm{g_{HVV}} \approx \mathrm{g_{H_{SM}VV}}$

Heinemeyer+Stal+Weiglein

$\mathrm{M_A \approx 100\ GeV, \tan\beta \approx 6-10,}$
$\mathrm{M_S \approx \mu \approx 1\ TeV, X_t \approx \sqrt{6} M_S,}$

$\Rightarrow \mathrm{M_H} \approx 126$ GeV ; $\mathrm{M_h} \approx 98$ GeV!

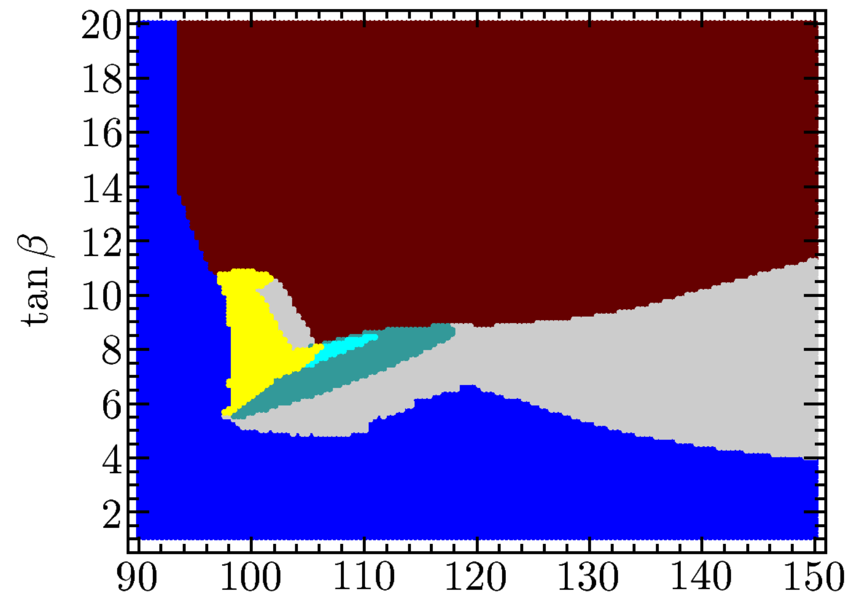
[ABDM scan: only few points, 10^{-6} OK

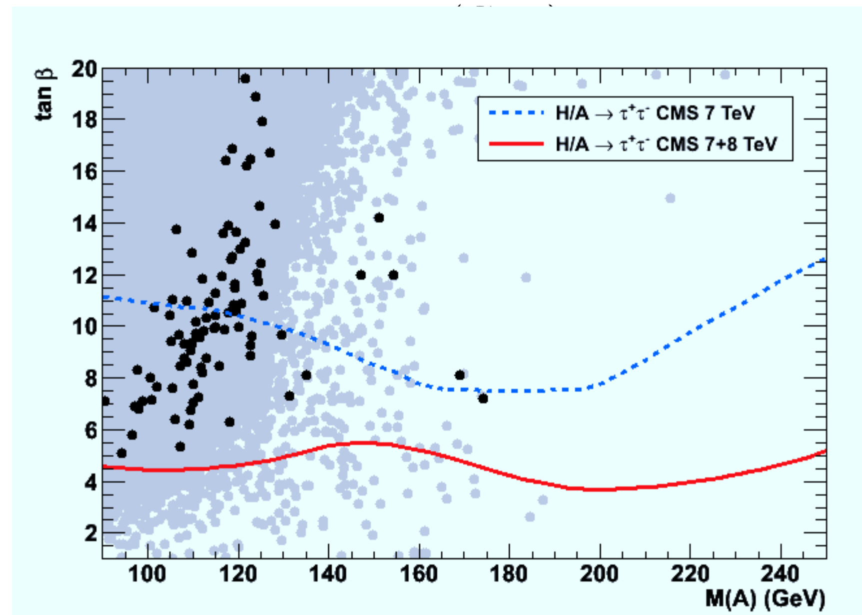
but they are all ruled out by flavor data

$\Rightarrow$ only h SM–like is likely...

With new CMS update, $\tan\beta \lesssim 5$:

$\Rightarrow$ H$\equiv$ observed is now excluded...





3. Implications from the Higgs rates

Sets stingent constraints on pMSSM regimes/benchmark scenarios?

- **Heavier CP–even 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$\to \ell \nu \mathrm{b\bar{b}}$ 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 $\mathrm{H} \to \gamma\gamma$.

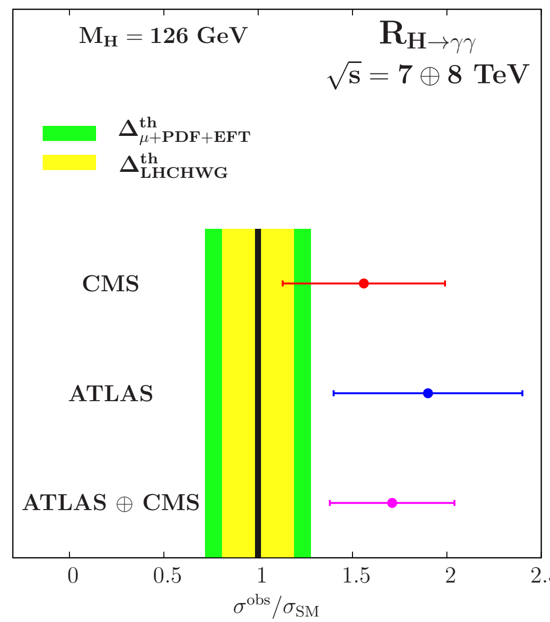
- **Statistical fluctuation?**
- **Systematics problem?**
- **Maybe QCD uncertainties?**

or a combination of the three..

Hope it is due to SUSY!

– total Higgs width suppressed?

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



Baglio, Godbole, AD

3. Implications from the Higgs rates

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

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

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

  very agressive choice of parameters...

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

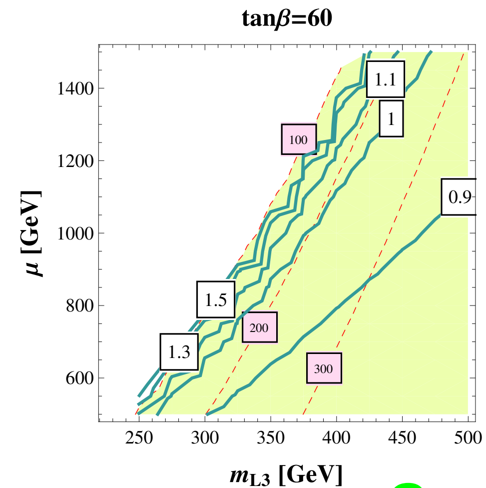
  but only O(10%) contributions...

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

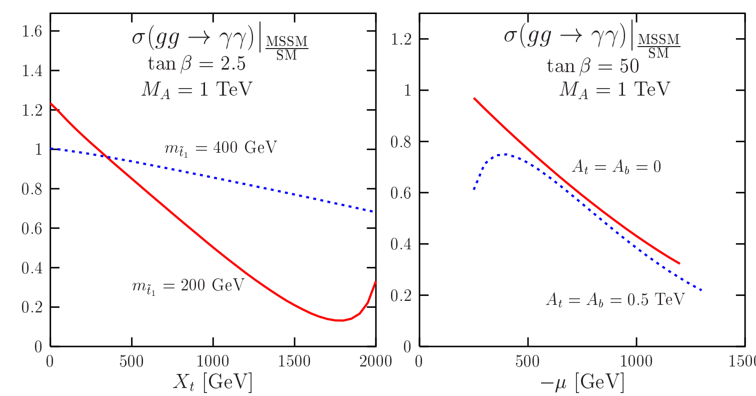
$\Rightarrow$ **max-mixing: $\sigma(gg \to h)$ suppressed.**

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

U. Haisch: highly disfavored by data



Carena et al.



AD, 1998

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

many virtues compared to MSSM:
– 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!
But let's wait for the updates of nex week.....

4. Conclusions

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$\to$ $\mu\mu$,bb,..**

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

- **Some search channels at low tanβ still relevant: H$\to$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?