The Higgs: SM and SUSY

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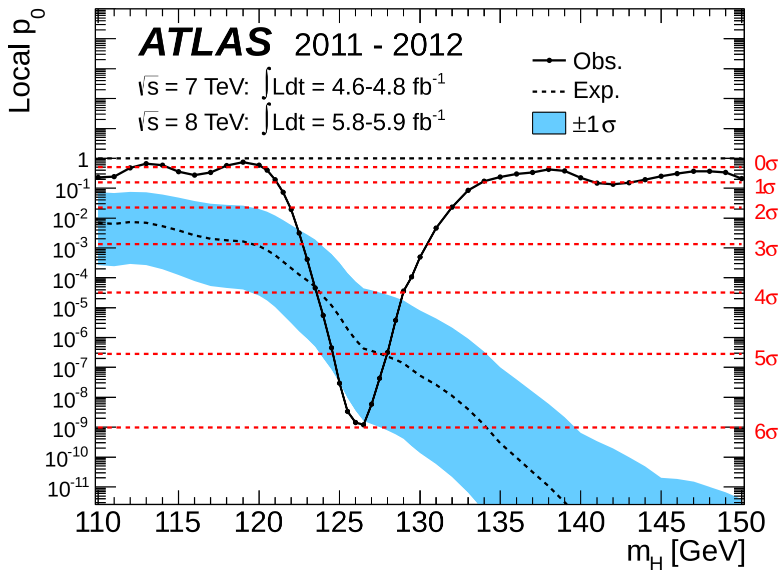
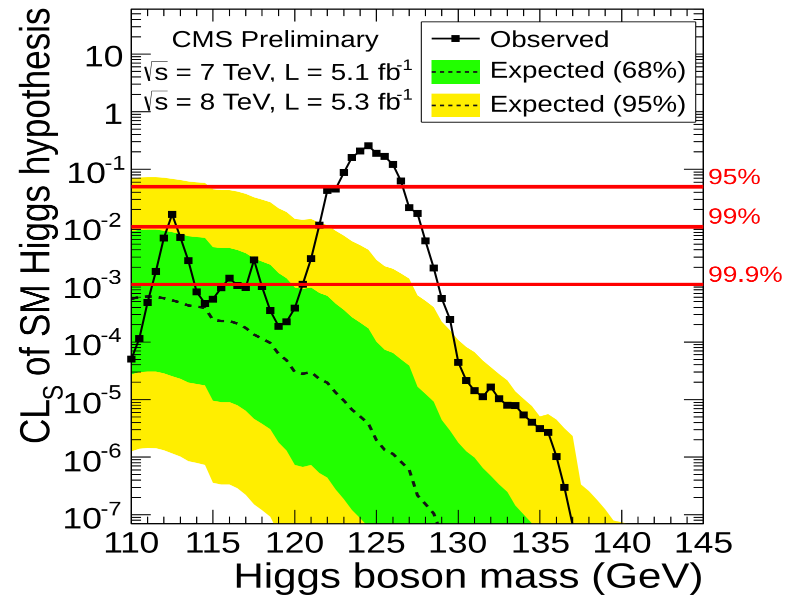
- **The 4th of July**
- **Implications for the Standard Model**
- **Impliications for the MSSM**
- **Perspectives**

1. The 4th of July

After 48 years of postulat, 37 years of search (and a few heart attacks), the Higgs is discovered at LHC on the 4th of July: Higgstorical day!





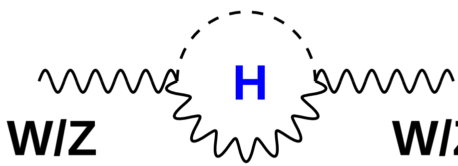
2. Implications for the SM

... and its looks like expected ⇒

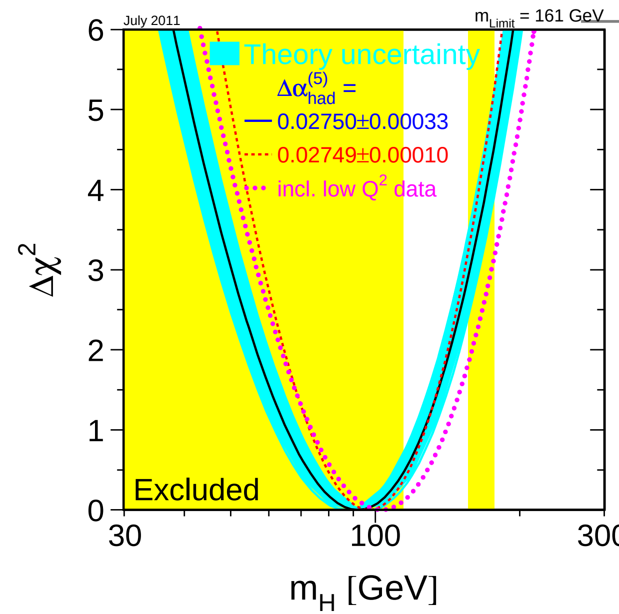
a triumph for high-energy physics!

Indirect constraints from EW data [a]

H contributes to RC to W/Z masses:



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



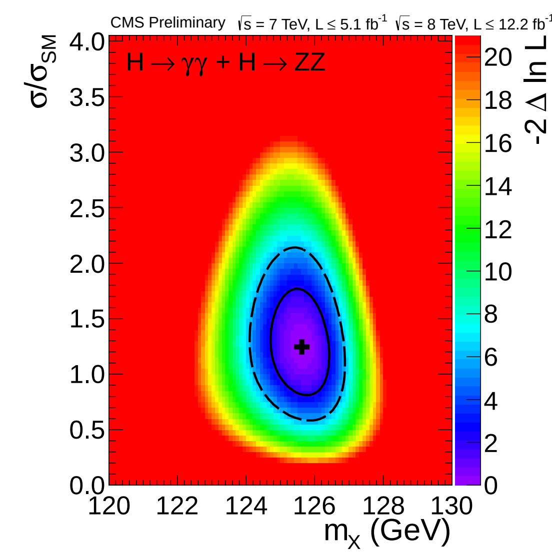
Fit the EW precision measurements,

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...

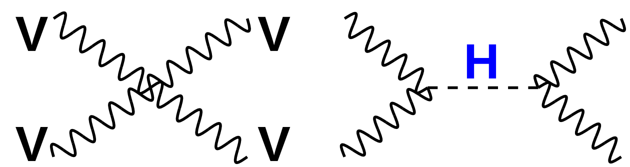
2. Implications in the SM

- **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...



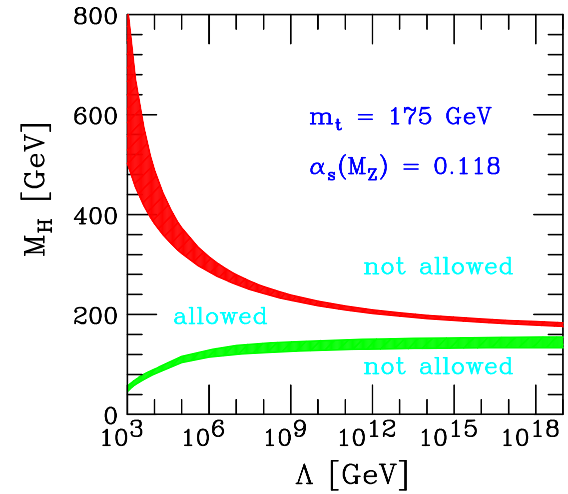
- **Extrapolable up to highest scales.**

  Stability of the EW vaccum?

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

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

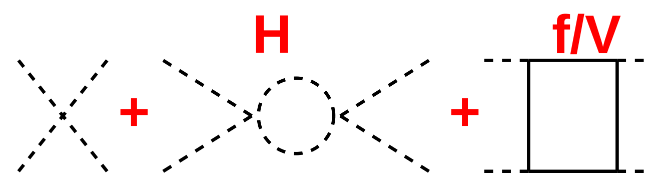
tops make $\lambda(0) < \lambda(v)$: unstable vacuum



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

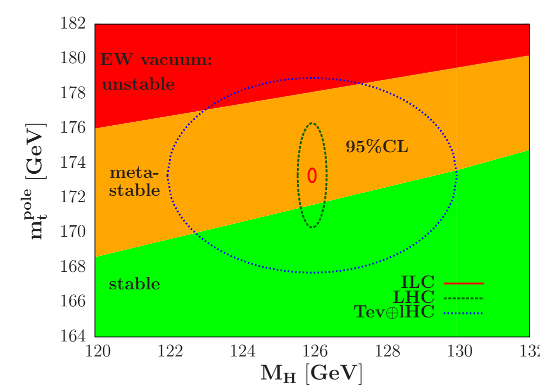
$\Lambda_C \sim M_{Planck} \Rightarrow M_H \gtrsim 129$ GeV!

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...

2. Implications for the SM

The particle decays into $\gamma\gamma$

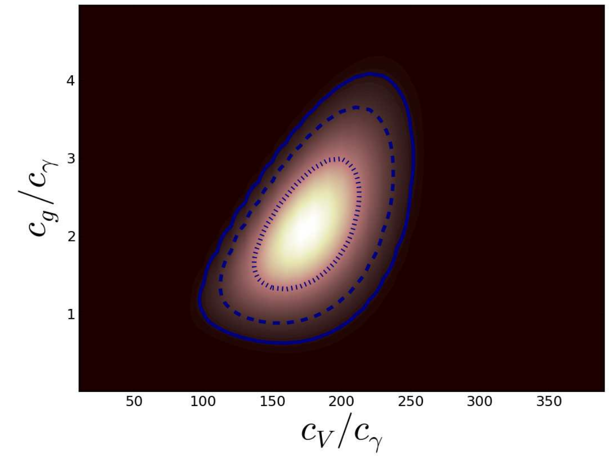
- **not spin–1: Landau–Yang**
- **could be spin–2 like graviton?**

– miracle that couplings fit that of H,

– "prima facie" evidence against it:

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

Ellis, Sanz, You

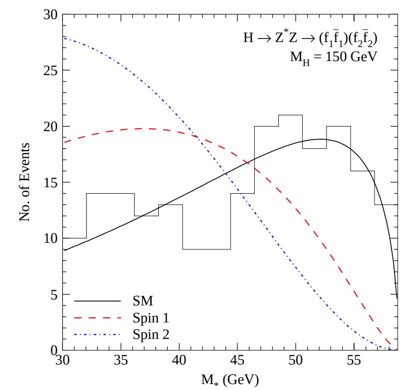


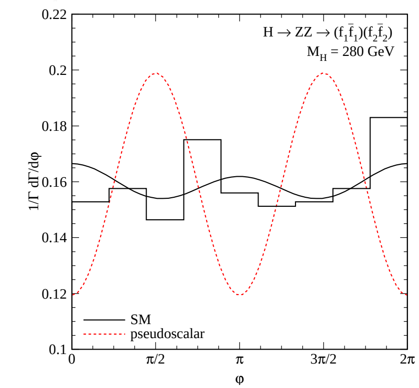
Is it CP–even or CP–odd?

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

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

CMS: 2.5σ for CP–even..



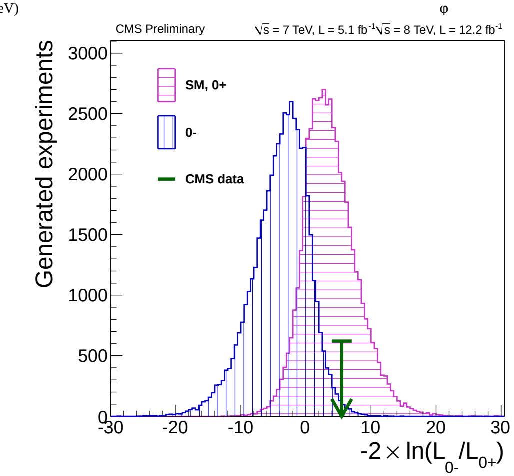


Problem: if H is CP mixture, only

0^+ component is projected out!

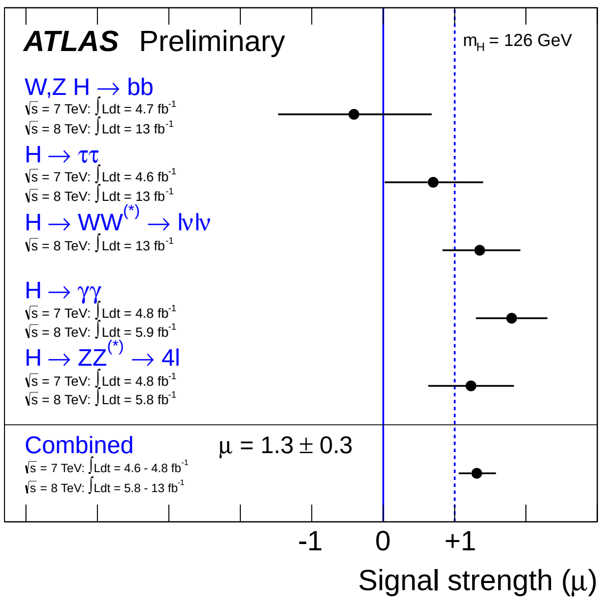
(or very large 0^-VV loop coupling).

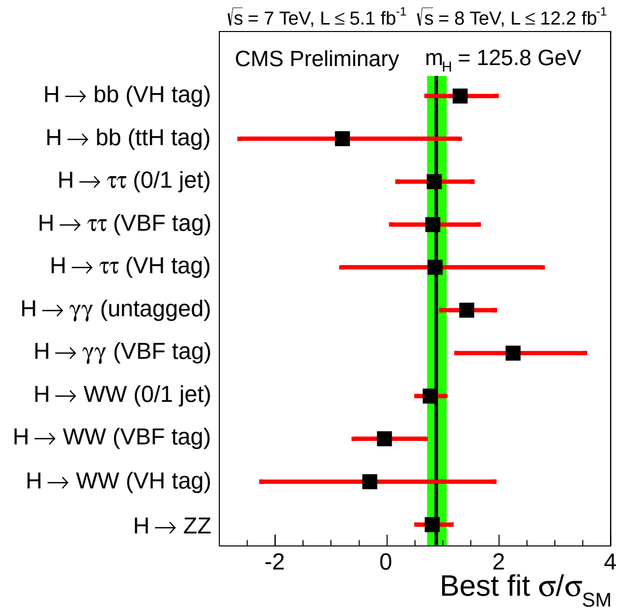
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 0.95 \pm 0.3$?

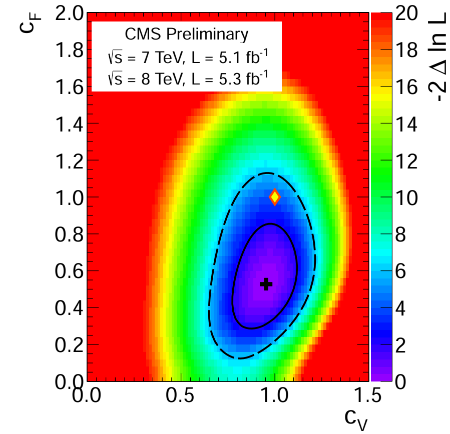


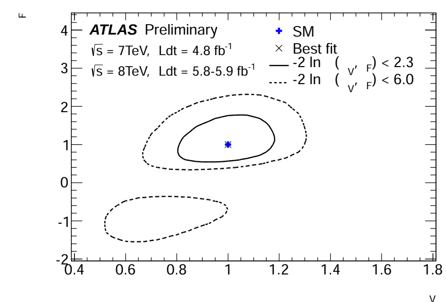
2. Implications for the SM

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 (see A. Lenz?)**

BSM scenarios: many ruled out, some "in hospital", all are constrained..

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

3. Implications for the MSSM

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

- to cancel the chiral anomalies introduced by the new $\tilde{\mathrm{h}}$ 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 $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states left out: $\mathbf{h, H, A, H^\pm}$
Only two free parameters at the tree level: $\tan\beta, \mathbf{M_A}$; others are:

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

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

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

We have important constraint on the MSSM Higgs boson masses:

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

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

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

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

3. 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:

$$M_h \xrightarrow{M_A \gg M_Z} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

- **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 as in real life:

- **small contributions of entire SUSY spectrum: $\Phi, \chi_i^{\pm}, \chi_i^0, \tilde{q}_i, \tilde{l}_i, \tilde{g}$...**
- **complete radiative corrections up to two–loops**

We use the RGE codes Suspect/Softsusy with known RC in $\overline{\rm DR}$ scheme and compare with FeynHiggs (on-shell scheme): $\Delta M_h \approx$ 2 GeV.

3. Implications for pMSSM

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

To evaluate M_h, perform a full scan of the MSSM parameter space;
too complicated in the general MSSM as there are 105 free parameters

$\Rightarrow$ **work in the phenomenological MSSM or pMSSM:**

– no CP or flavor-violation: no new phase and diagonal $\tilde{m}, A$ matrices,
– universal first and second generation sfermions to cope with flavor.

Only 22 free parameters: $\tan\beta, M_A, \mu, M_{1,2,3}, m_{\tilde{f}_L}, m_{\tilde{f}_R}, A_f$
and only a few of them will play and important role in the Higgs sector..

Perform a full and fine scan of the pMSSM parameter space:

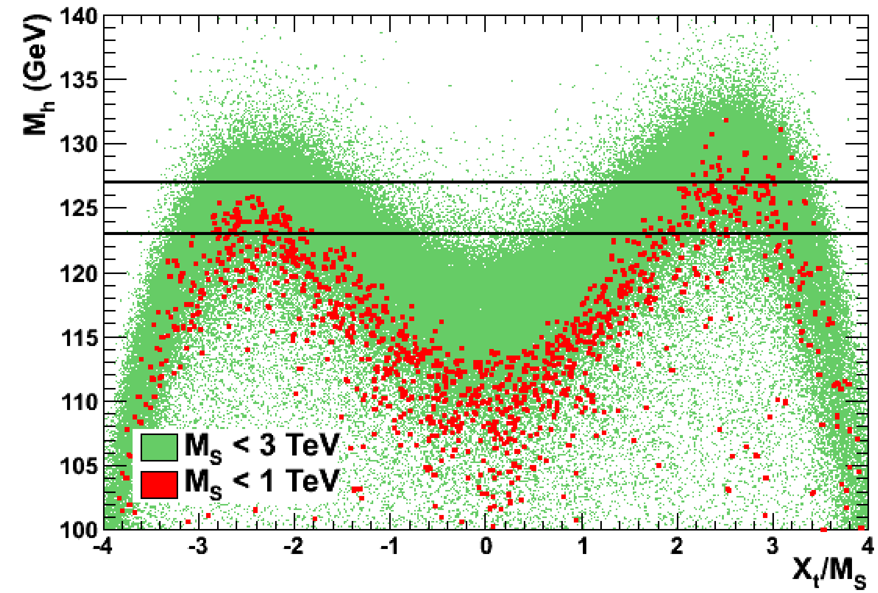
$$1 \leq \tan\beta \leq 60\,,\ 50\ \mathrm{GeV} \leq M_A \leq 3\ \mathrm{TeV},\ -9\ \mathrm{TeV} \leq A_f \leq 9\ \mathrm{TeV},$$
$$50\ \mathrm{GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3\ \mathrm{TeV}, 50\ \mathrm{GeV} \leq M_1, M_2, |\mu| \leq 1.5\ \mathrm{TeV}$$

- **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)**

3. Implications for pMSSM: mass

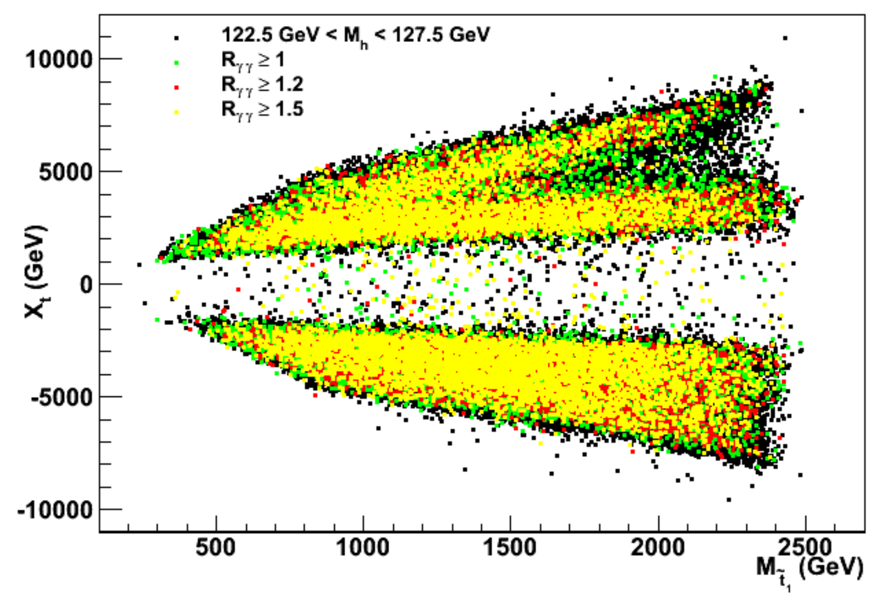
Main results:

● **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 cMSSM

Constrained MSSMs are interesting from model building point of view:

– provide concrete schemes for supersymmetry breaking

– solve some problems of unconstrained MSSM: flavor, CPV, universality, ...

– reduce number of input parameters and are thus more predictive

Prototype model: the minimal supergravity model (mSUGRA).

– Underlying assumption: SUSY–breaking occurs in a hidden sector communicating with visible sector through gravitational interactions,

– parameters obey a set of boundary conditions at $M_{GUT} \approx 10^{16}$ GeV

– universal soft terms emerge if the interactions are "flavor–blind"

$\Rightarrow$ only 4.5 inputs: $\tan\beta\ ,\ m_{1/2}\ ,\ m_0\ ,\ A_0\ ,\ \mathrm{sign}(\mu)$

In GMSB, SSB transmitted to MSSM fields via SM gauge interactions.

Minimal inputs: $\tan\beta\ ,\ \mathrm{sign}(\mu)\ ,\ M_{\rm mes}\ ,\ \Lambda_{\rm SSB}\ ,\ N_{\rm mess\ fields}$

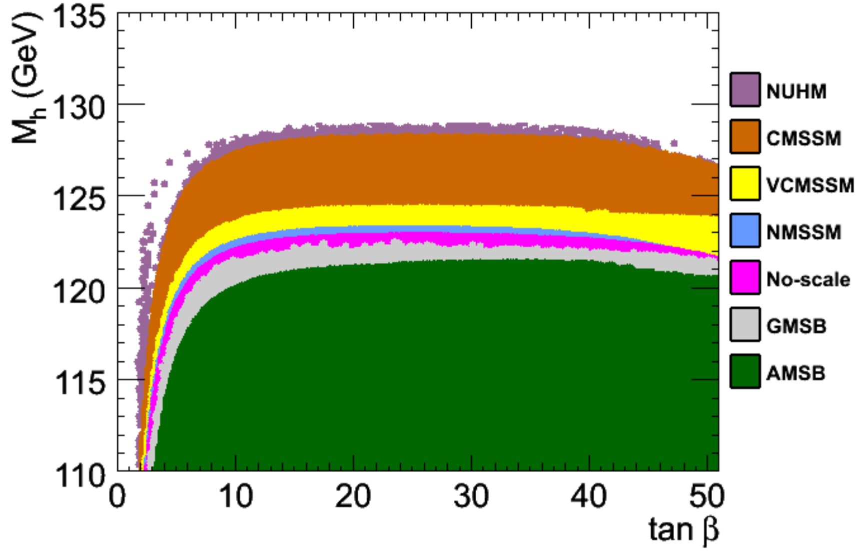
In AMSB, SSB in hidden sector transmitted via (super-Weyl) anomalies.

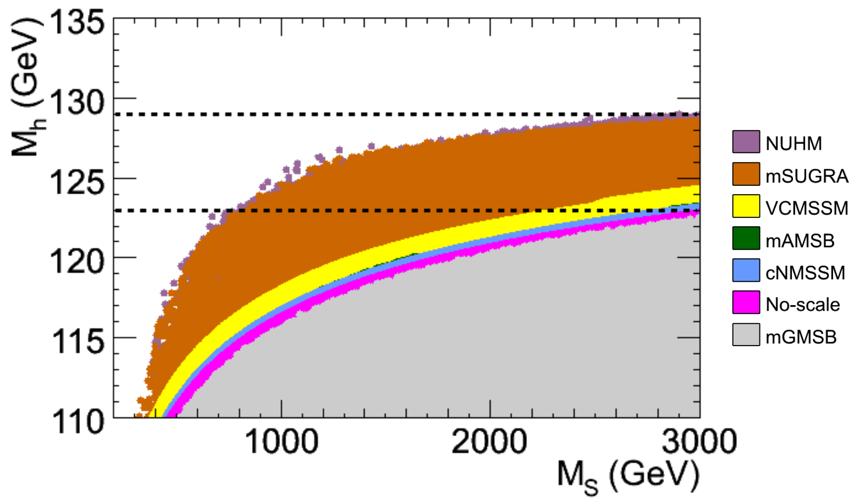
Minimal inputs: $m_0\ ,\ m_{3/2}\ ,\ \tan\beta\ ,\ \mathrm{sign}(\mu)$

Using Suspect+Softsusy, perform scans of the models parameter space and confront them with LHC constraint $123\ \mathrm{GeV} \leq M_h \leq 129\ \mathrm{GeV}$

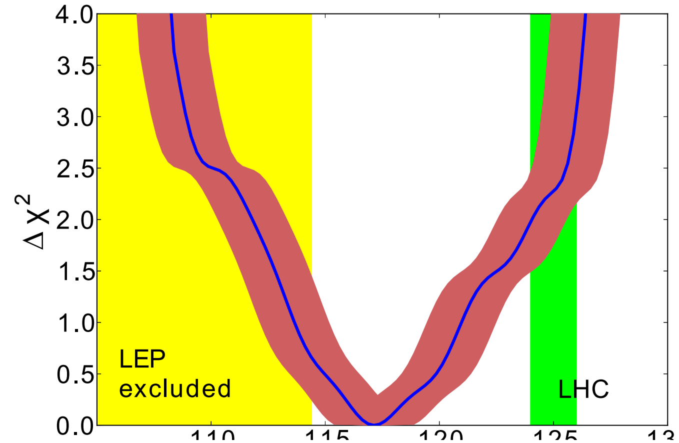
3. Implications for the cMSSM: mass

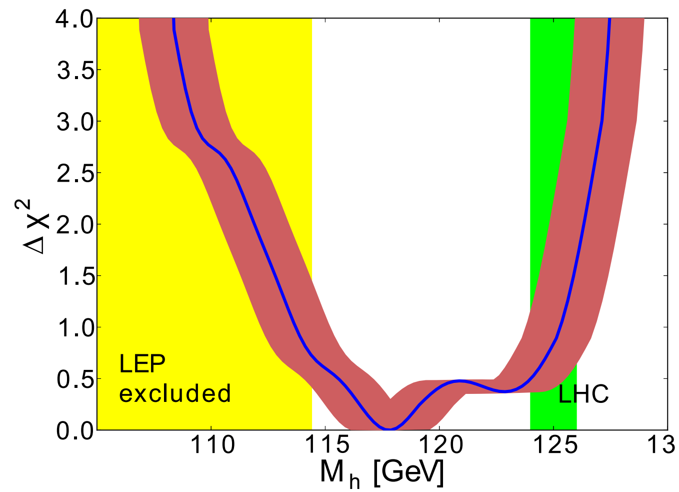
Results of our scan





Mastercode in mSUGRA and NUHM

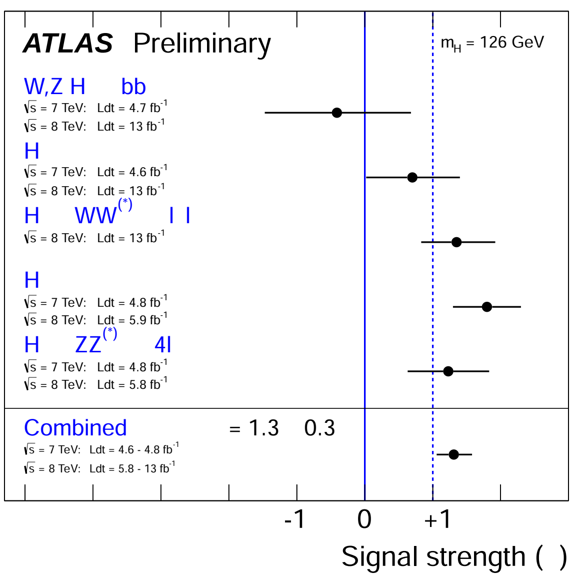


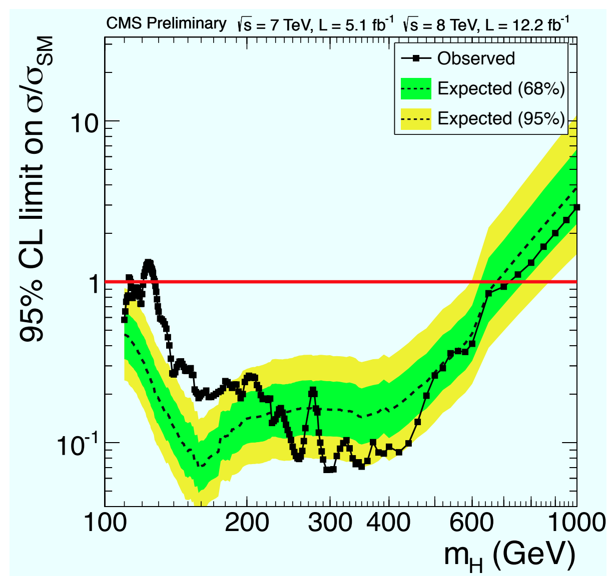


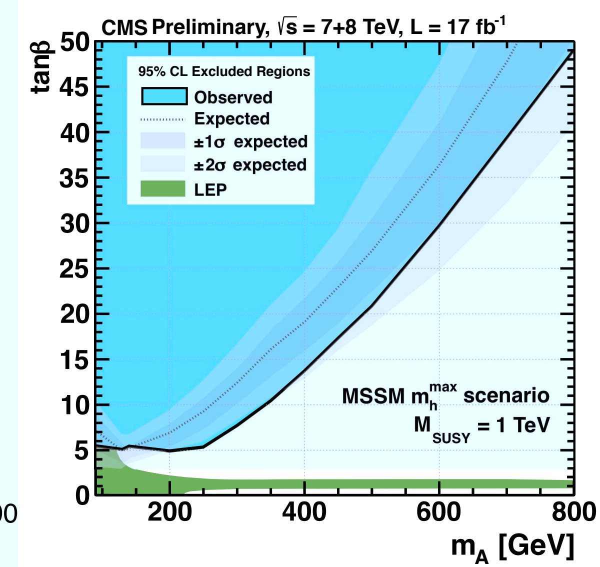
3. Implications from other searches

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 $\mathrm{B_s} \to \mu\mu$...**







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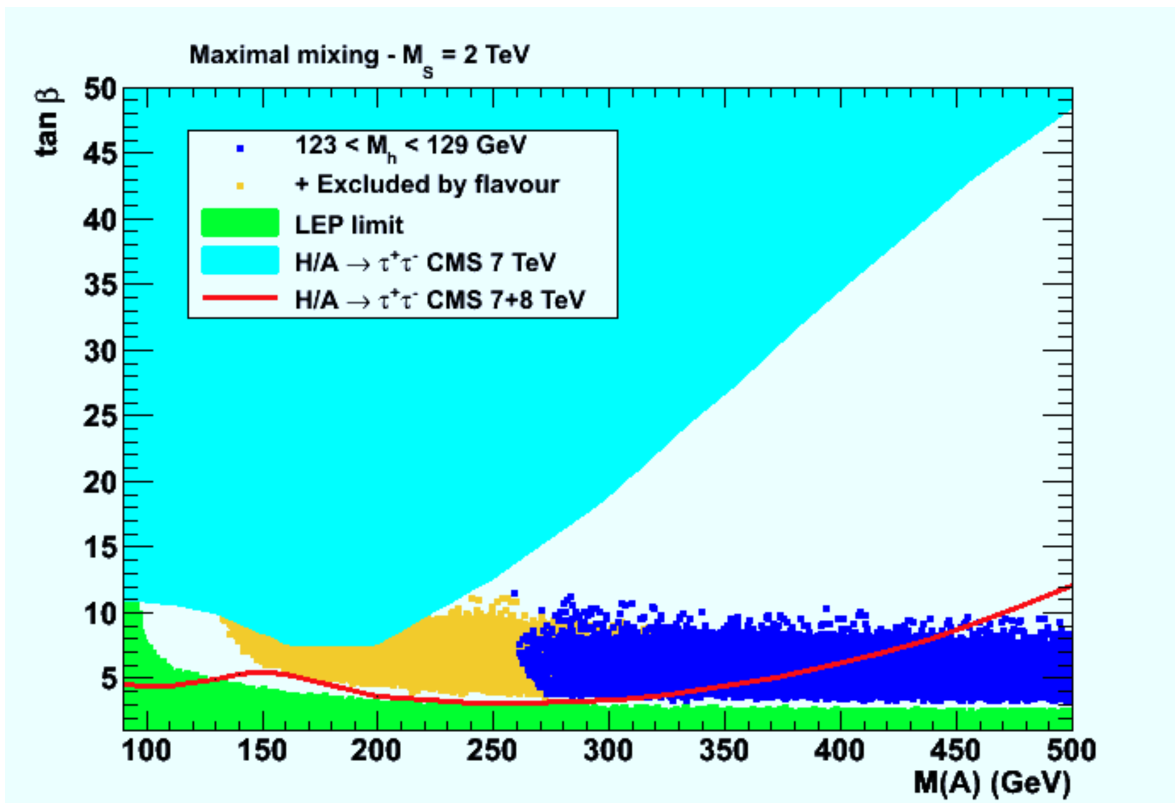

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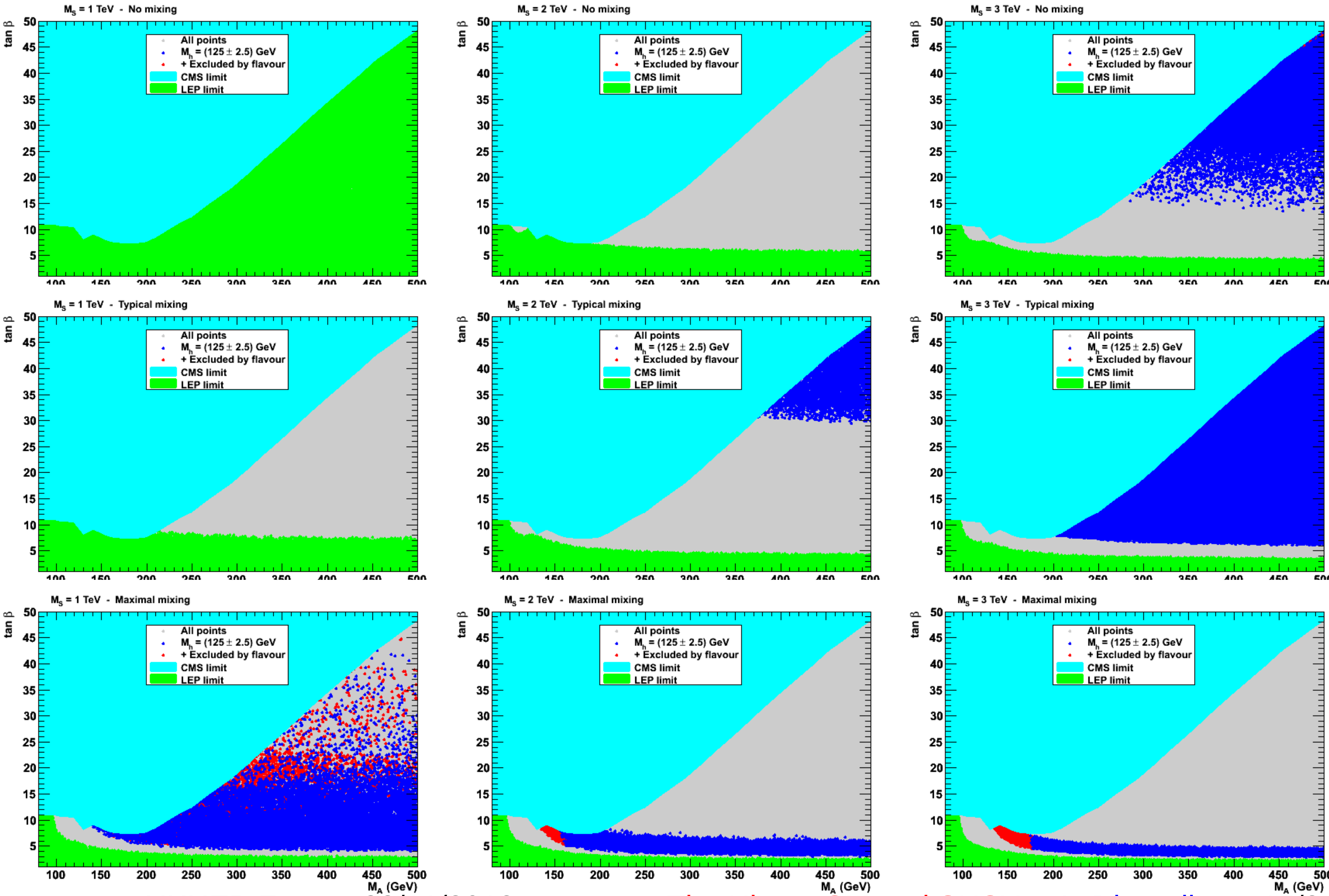


3. Implications from other searches

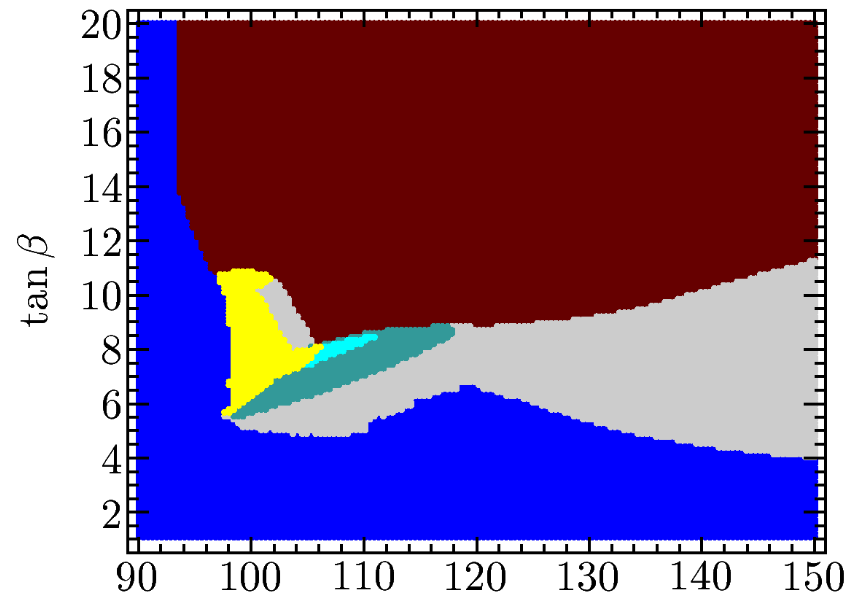
It looks like in decoupling regime. True ?

- **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

– $g_{HVV} \approx g_{H_{SM}VV}$

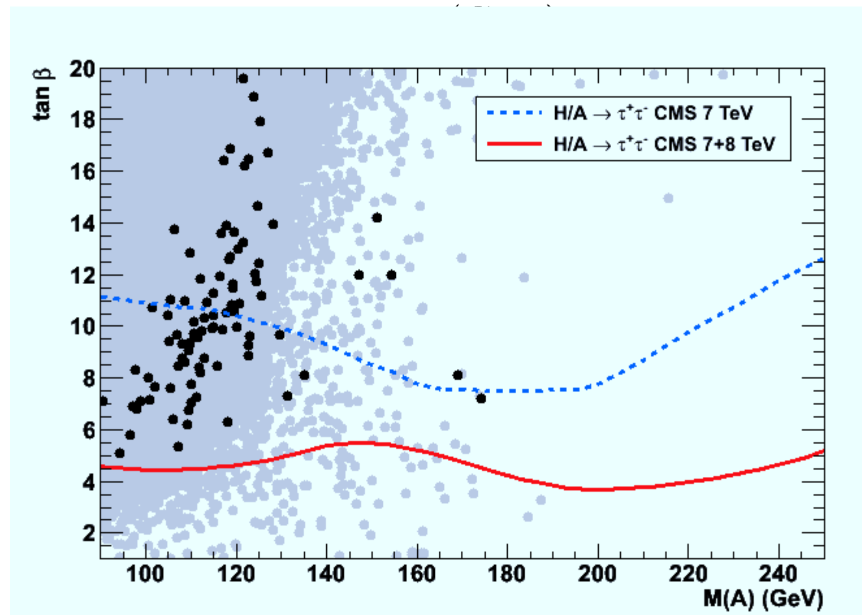


Heinemeyer+Stal+Weiglein

$M_A \approx 100$ 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...



3. Implications for MSSM: rates

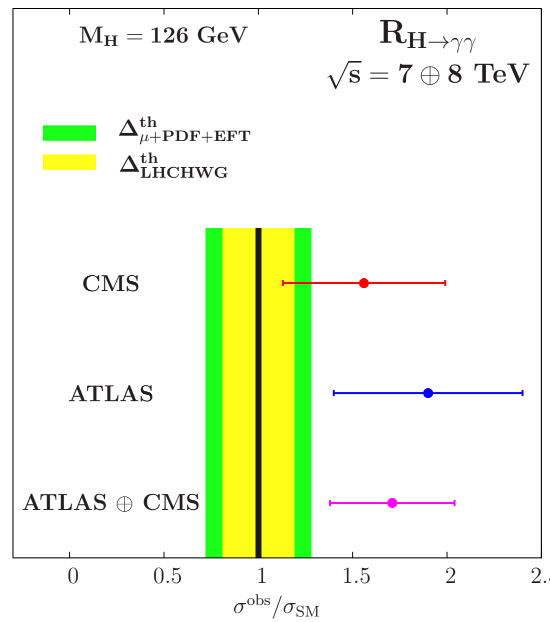
What about other pMSSM regimes/benchmark scenarios?

Carena+Heinemeyer+Wagner+Weiglein

Almost everything is driven by the $\gtrsim 2\sigma$ excess in $H \to \gamma\gamma$.

- 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?

- Light $h, H, A, H^{\pm}$ (intense coupling regime) excluded..
- Small α_{eff} scenario with $g_{hbb} \approx 0$ and thus small Γ_h: ruled out by LHC/Tevatron data: ex: loose Wh$\to \ell\nu b\bar{b}$ signal..
- gluophobic h with $g_{hgg} \ll g_{H_{SM}gg}$ due to squark loops? ruled out by $ZZ, WW, \gamma\gamma$ signals at LHC (and also the h mass)

3. Implications for pMSSM; rates

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

Only possible change is the loop induced $h\gamma\gamma$ coupling:

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

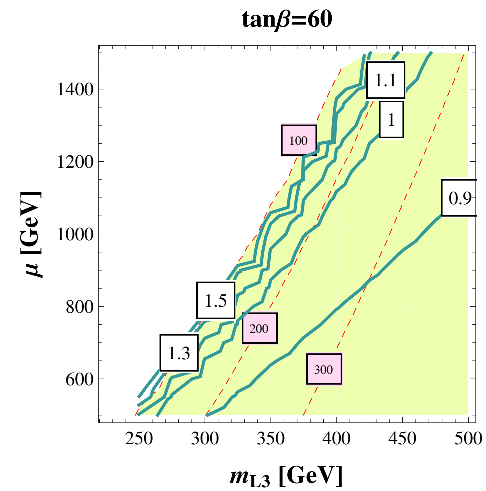
- **BMSSM? One exmple is the NMSSM:**

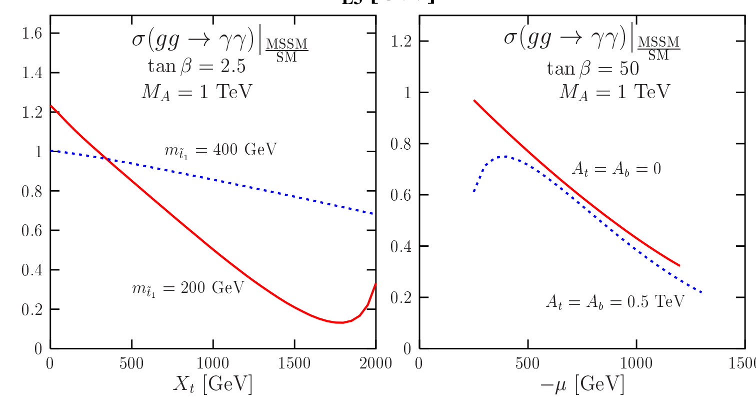
Ellwanger etal, King etal., Gunion etal,..

– stops lighter as M_h^{max} larger,

– additional singlet for cplgs,

– less severe non-H constraints.





Common features: some light sparticles are around the corner!

4. Conclusions: MSSM

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

- $\mathrm{M_H = 119}$ **GeV would have been a boring value: everybody OK..**
- $\mathrm{M_H = 145}$ **GeV would be a devastating value: mass extinction..**
- $\mathrm{M_H \approx 126}$ **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:

- $\mathrm{H/A/H^\pm}$ **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:

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

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

4. Conclusions: SM

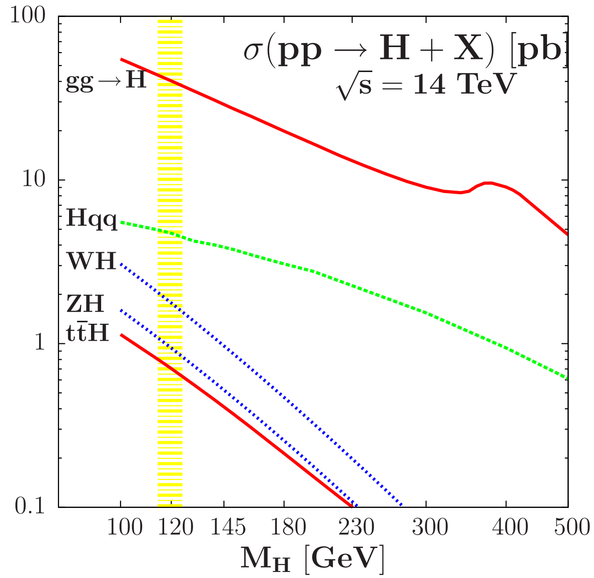
Now that Higgs is found (and nothing else yet): is Particle Physics "closed"?

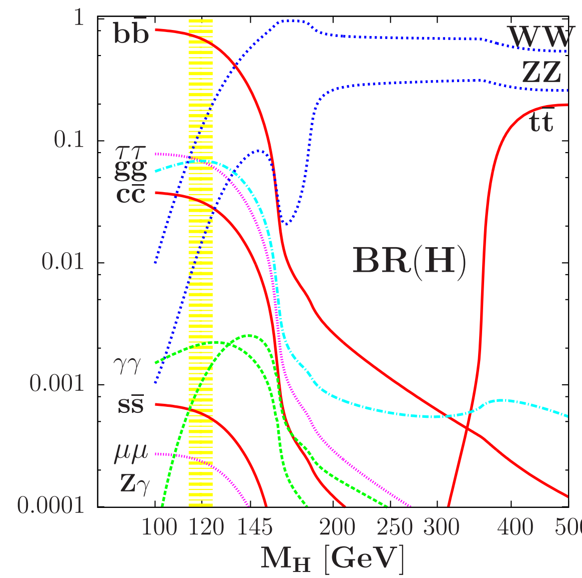
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

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!





4. 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!