Implications of the discovery of the Higgs particle

officially called the “new particle", “125 GeV boson", “new state"

for the SM and SUSY

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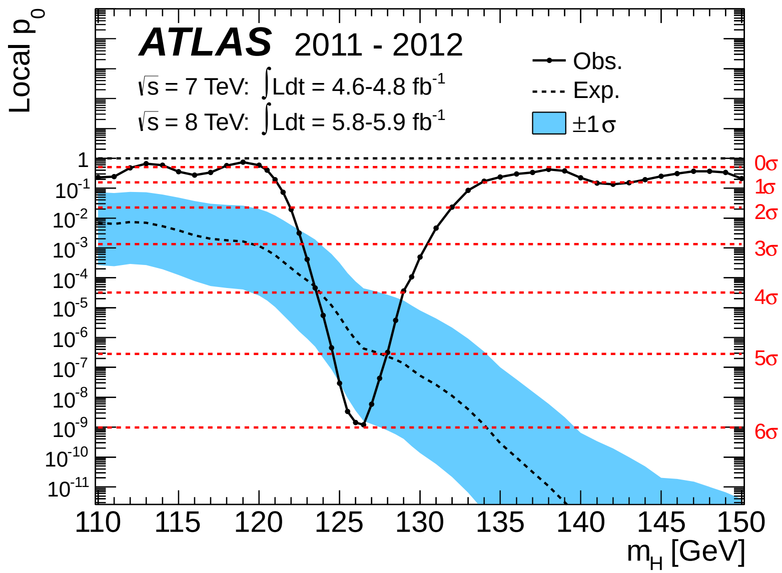
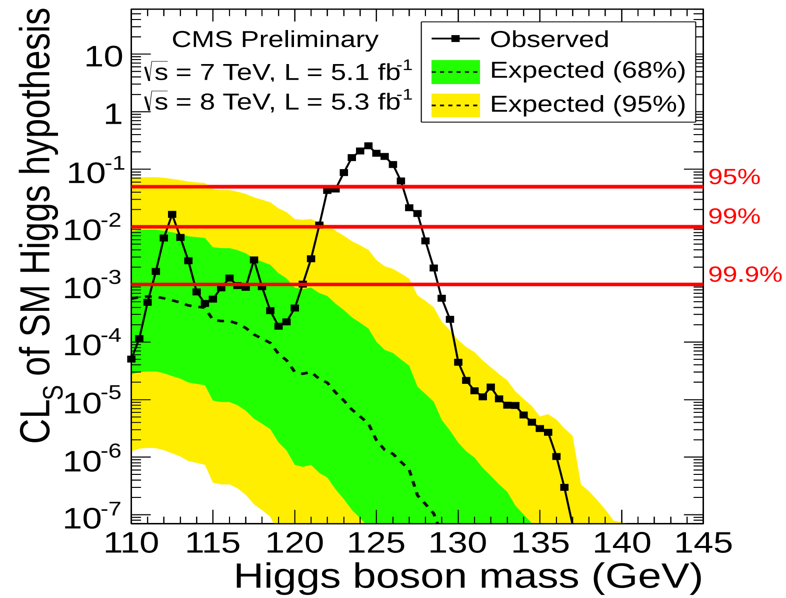
- **The 4th of July**
- **Implications for the Standard Model**
- **The Higgs sector in the MSSM**
- **Implications for the MSSM**
- **Conclusion**

1. The 4th of July

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





1. The 4th of July

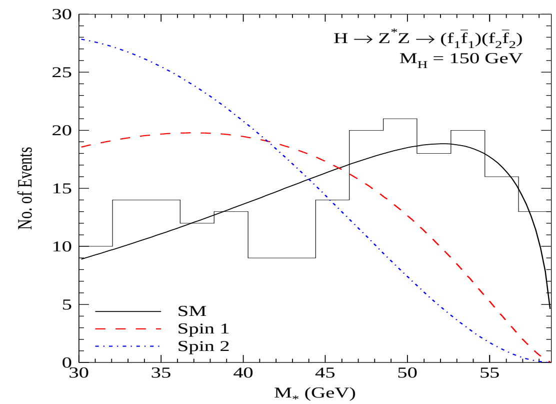
The particle decays into $\gamma\gamma$ states

- **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.

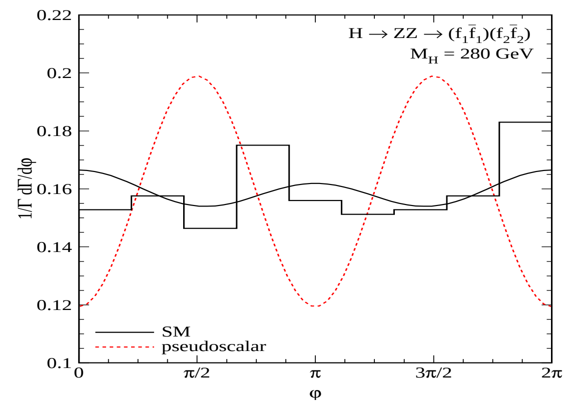
Many theoretical analyses...



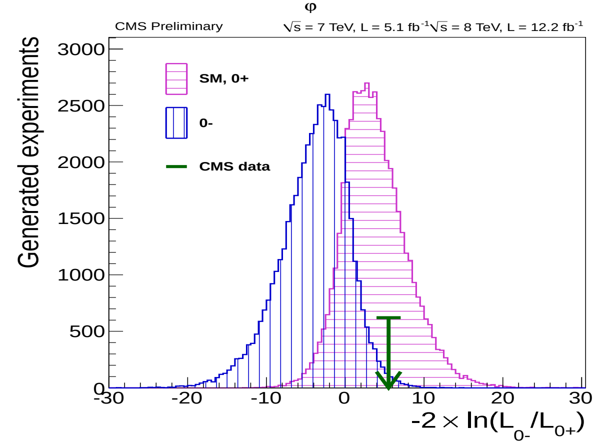
Is it a CP–even state or CP–odd?

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

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



CMS/(ATLAS): 2.5σ for CP–even...

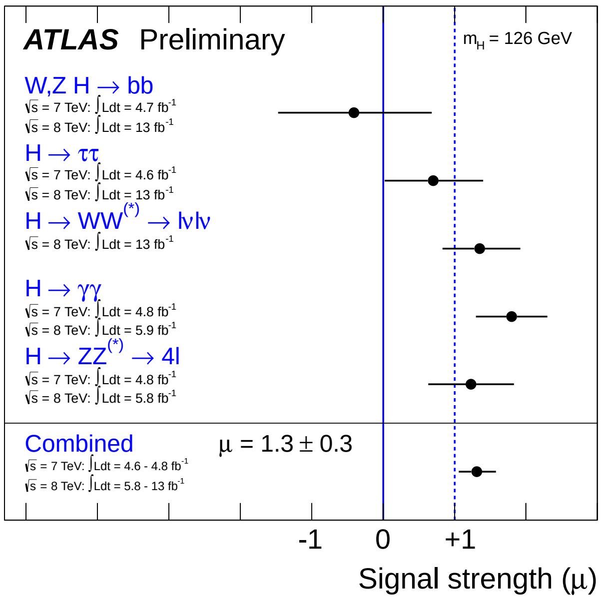


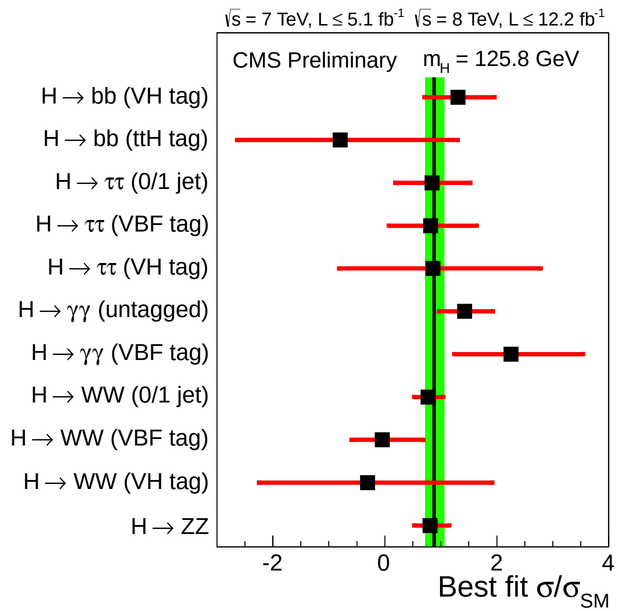
Problem: if H is CP mixture, only 0^+ component is projected out!

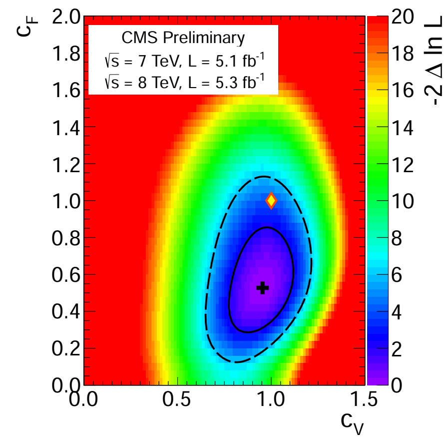
(or very large 0^-VV loop coupling).

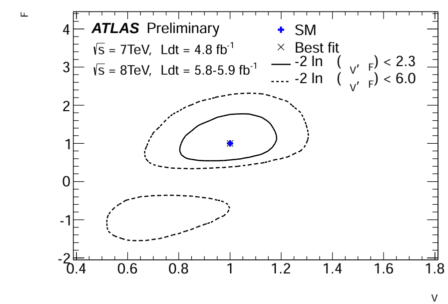
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 0.95 \pm 0.3$?

1. The 4th of July









From ATLAS/CMS results:

Higgs couplings to elementary particles as predicted by Higgs mechanism

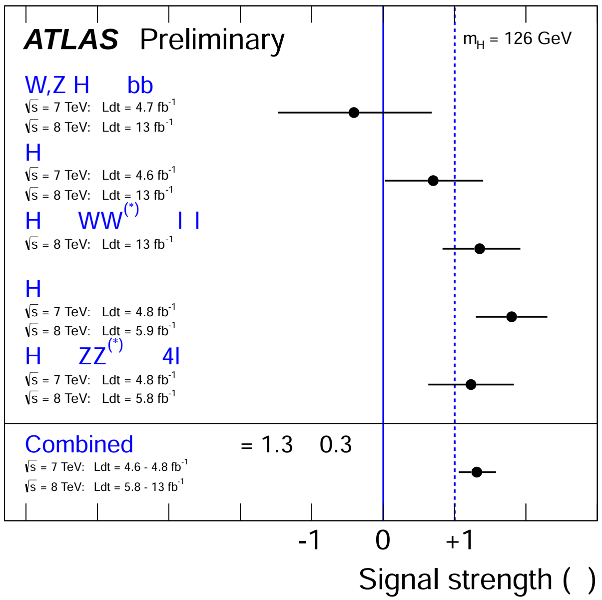
- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs**
- **couplings proportionial to masses as expected for the Higgs boson**

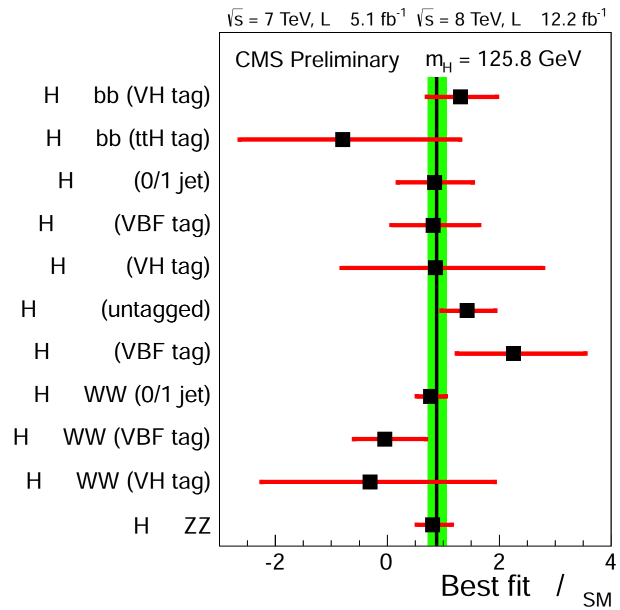
it is not only a "new particle", the "125 GeV boson", a "new state"...

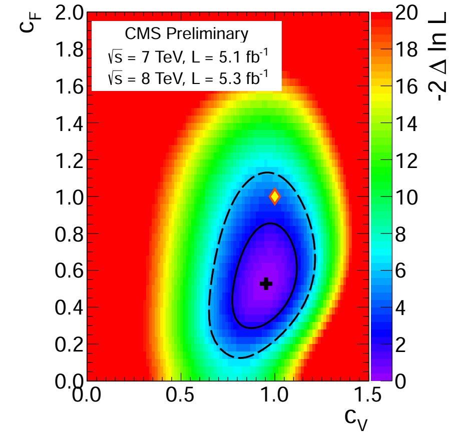
IT IS THE HIGGS BOSON!

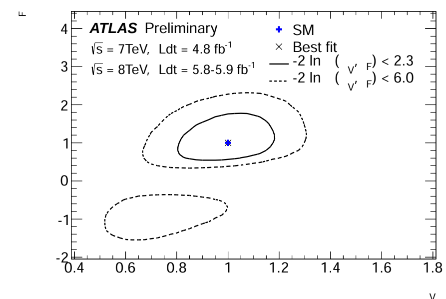
2. Implications for the SM

Rates compatible with those expected in the SM









From ATLAS/CMS results:

Higgs couplings to gauge bosons and fermions as dictated by unitarity:

- **fermiophobic, gauge-phobic completely scenarios ruled out,**
- **still two solutions for fermion cplgs: non–SM–like is non unitary...**

SM particle spectrun now complete: no 4th generation fermions

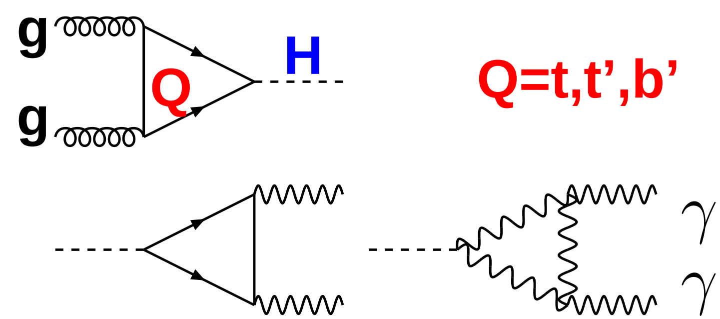
- **Rates in $ZZ, WW, \gamma\gamma, b\bar{b}$ incomplatible with SM4,**
- **direct searches and precision data against it...**

2. Implications in the SM

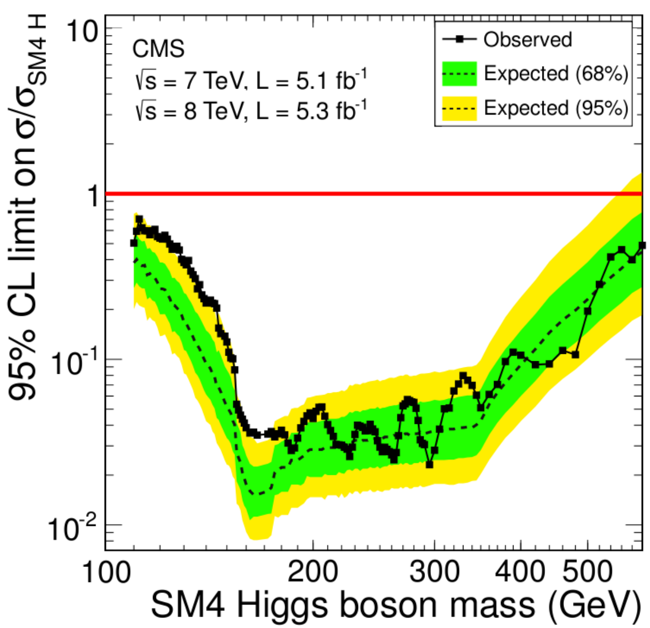
From LHC (and Tevatron) data: no room for a 4th fermionic generation!

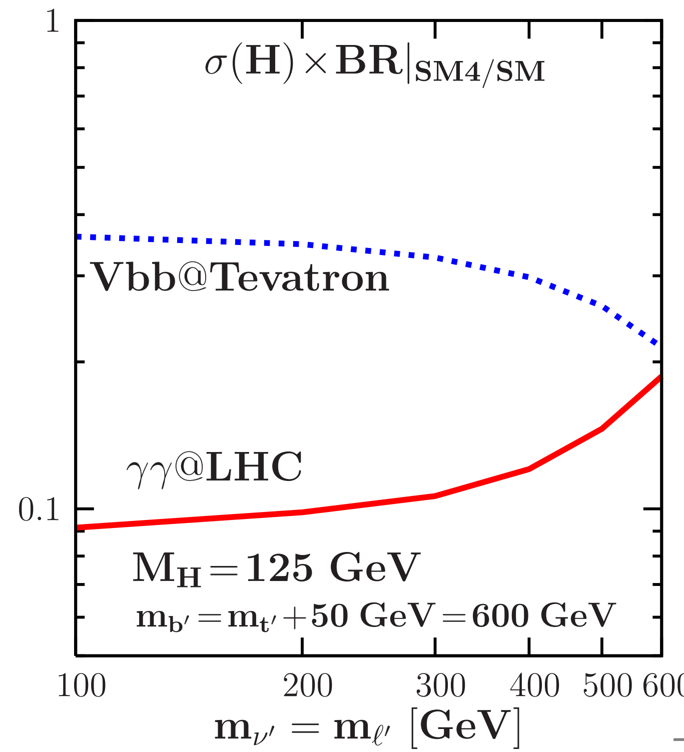
Indeed, an extra doublet of quarks and leptons (with heavy ν') would:

- **increase $\sigma(\mathrm{gg} \to \mathrm{H})$ by factor ≈ 9**
- **H$\to$gg suppresses BR(bb,VV) by $\approx$2**
- **strongly suppresses $\mathrm{BR}(\mathrm{H} \to \gamma\gamma)$**



NLO $\mathcal{O}(\mathrm{G_F m^2_{F'}})$ effects very important:





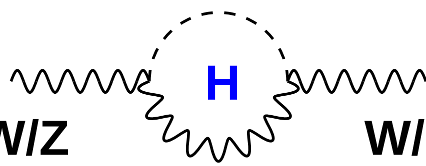
Same can be said for fermiophobic..

2. Implications for 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:



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

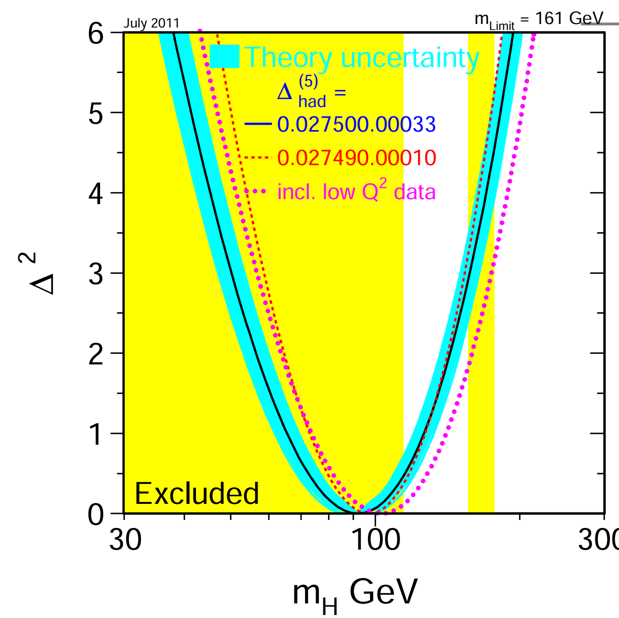
Fit the EW precision measurements,
one obtains $M_H = 92^{+34}_{-26}$ GeV, or

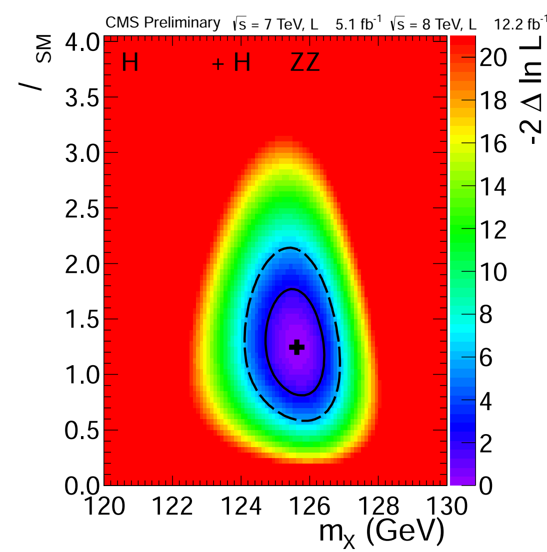
$$M_H \lesssim 160 \text{ GeV at 95\% CL}$$

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 as $M_H \ll 700$ 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 $\lambda(Q^2) > 0$**

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

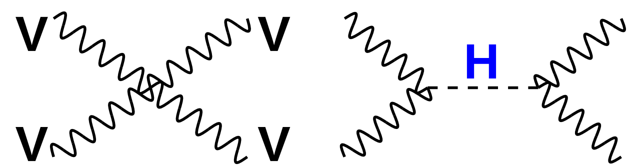
for $m_t = 173$ GeV; but what is $m_t^{\rm TEV}$??

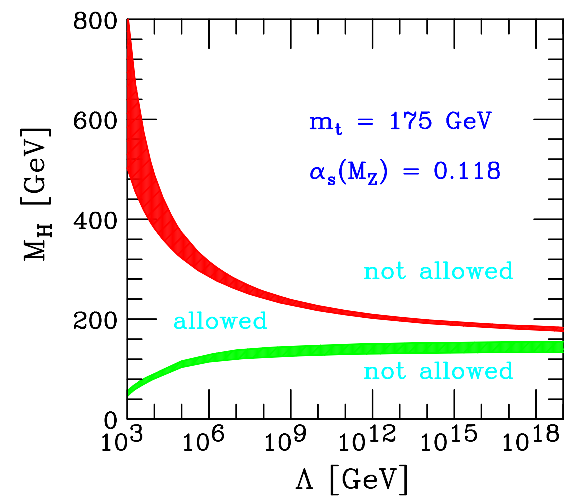
- **Unambiguous m_t only from $\sigma(t\bar{t})$:**

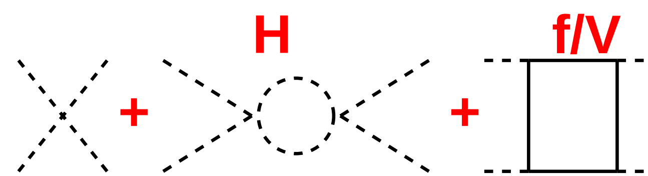
but value at TEV/LHC not precise..(ILC!)

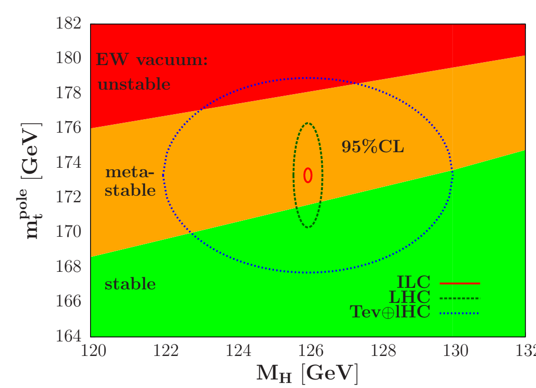
- **Standardissimo=TOE? Maybe not (?):**

  m_ν, DM, GUT, hierarchy problem...









3. MSSM Higgs at the LHC

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: $\tan\beta, \mathrm{M_A}$ 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.

Haber

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

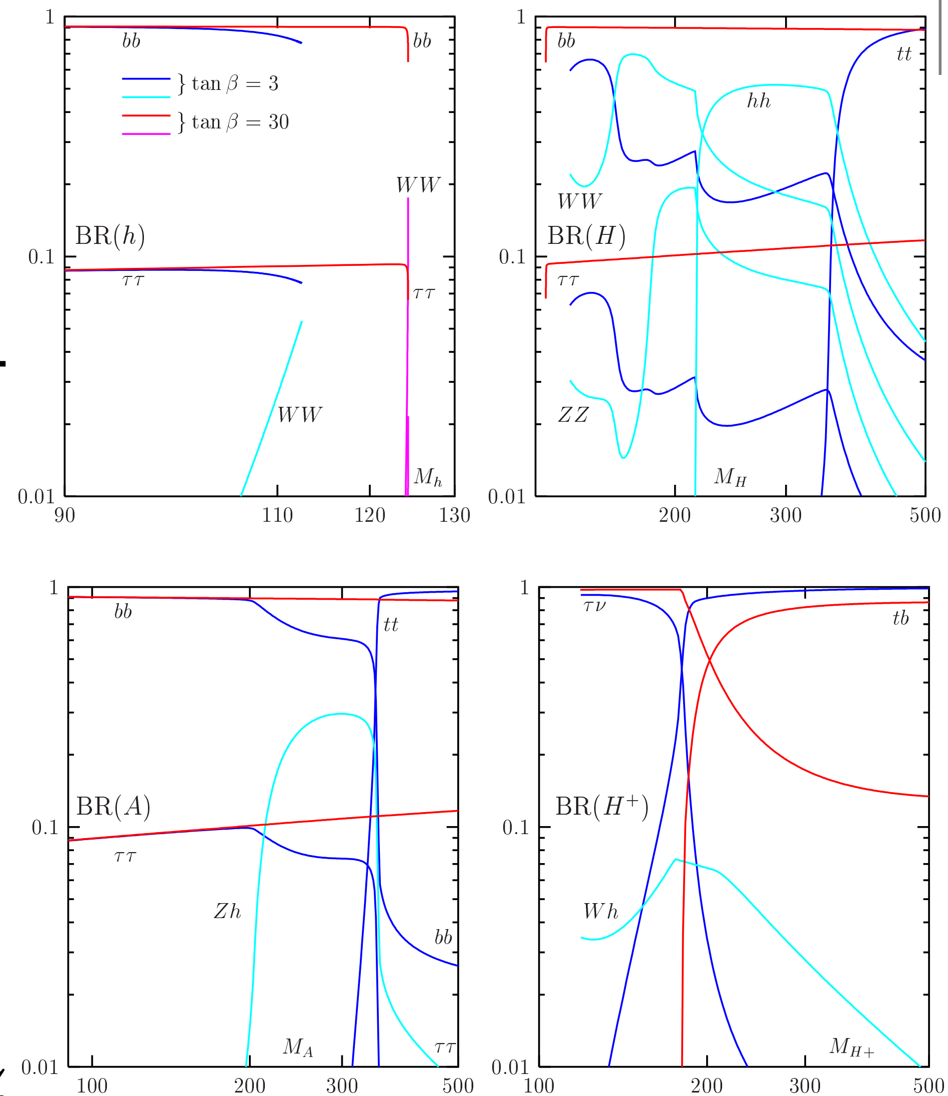
$$\mathbf{M_A \leq M_h^{max} \Rightarrow h \equiv A, H \equiv H_{SM}}\ ,\ \mathbf{M_A \geq M_h^{max} \Rightarrow H \equiv A, h \equiv H_{SM}}$$

3. MSSM Higgs at the LHC

Higgs decays in the MSSM:

General features:

- h: same as $\mathrm{H_{SM}}$ in general (esp. in decoupling limit) if not $\mathrm{h} \to \mathrm{b\bar{b}}$, $\tau^+\tau^-$ enhanced for tanβ >1
- A: only $\mathrm{b\bar{b}}$, $\tau^+\tau^-$ and $\mathrm{t\bar{t}}$ decays (no VV decays, hZ suppressed).
- H: same as A in general; tan$\beta \gg$1 $\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed.
- $\mathrm{H^\pm}$: $\tau\nu$ and tb decays (depending if $\mathrm{M_{H^\pm}} <$ or $>$ $\mathrm{m_t}$).



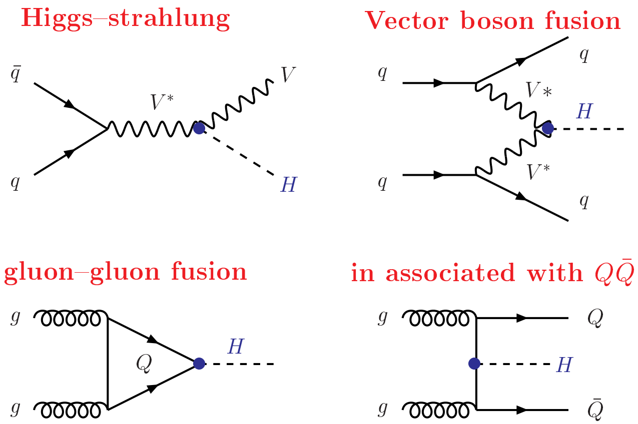
Possible new effects from SUSY!!

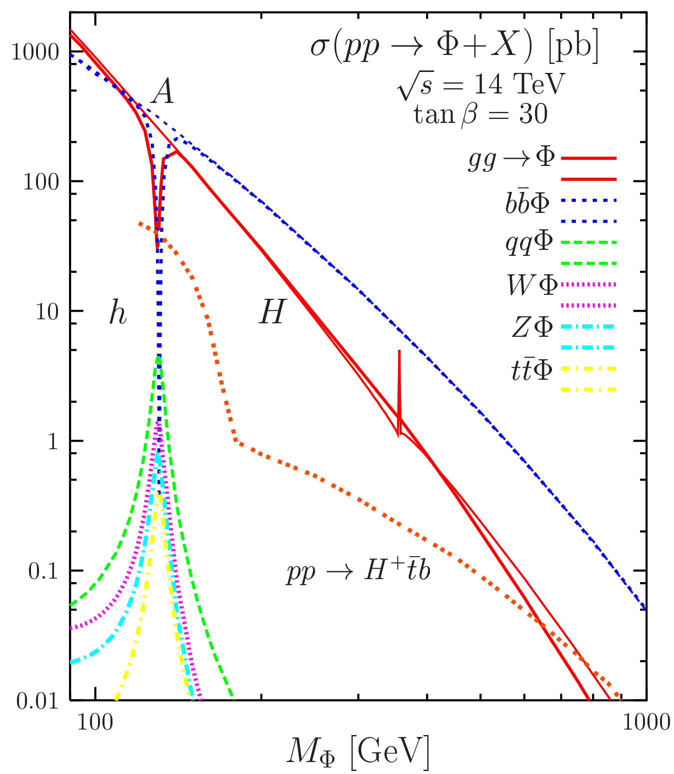
For tan$\beta \gg$1, only decays into b/τ:
BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$

For tan$\beta \approx$1, other channels need to be considered too!

3. MSSM Higgs at the LHC

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 $\longrightarrow$ 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 for the MSSM

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:

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

- 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 $123 \le M_h \le 129$ 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

4. Implications for the MSSM

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 favored**

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

How light sparticles can be with the constraint $\mathrm{M_h} = 126$ GeV?

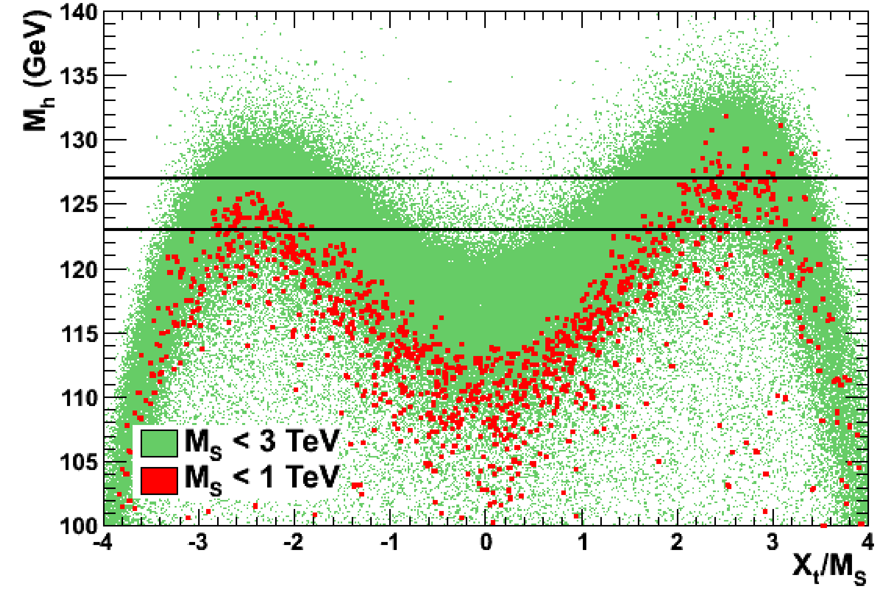
- **1s/2s gen. $\tilde{\mathrm{q}}$ should be heavy...**

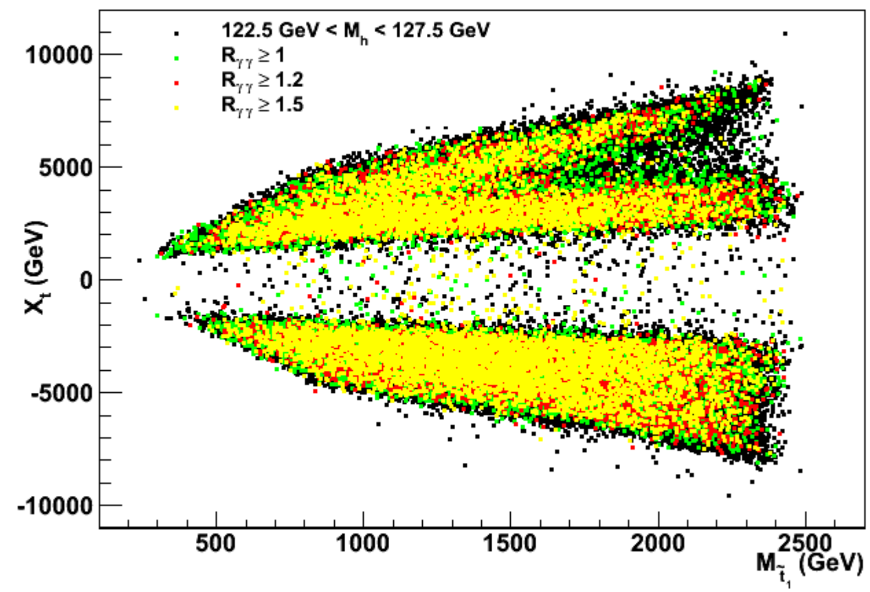
But not main player here: the stops:

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

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





4. Implications for the MSSM

Constrained MSSMs are interesting from model building point of view:

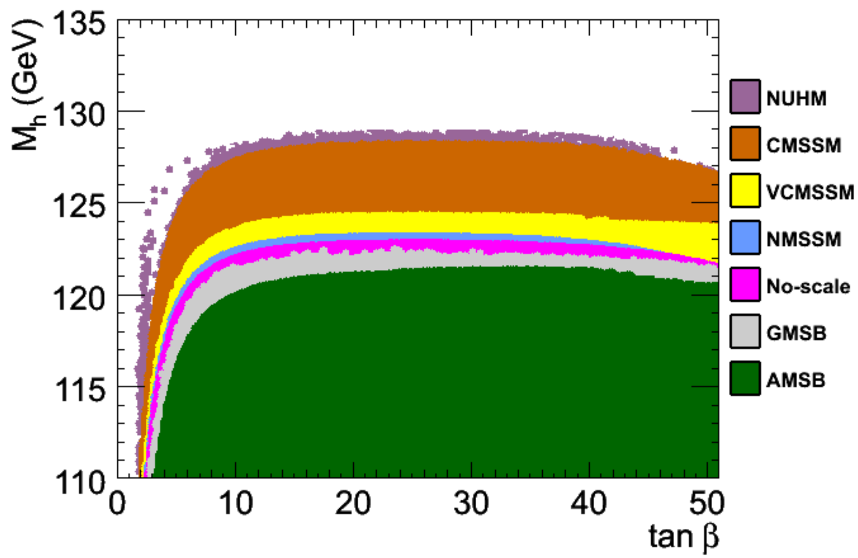
– concrete schemes: SSB occurs in hidden sector $\stackrel{\text{gravity,..}}{\longrightarrow}$ MSSM fields

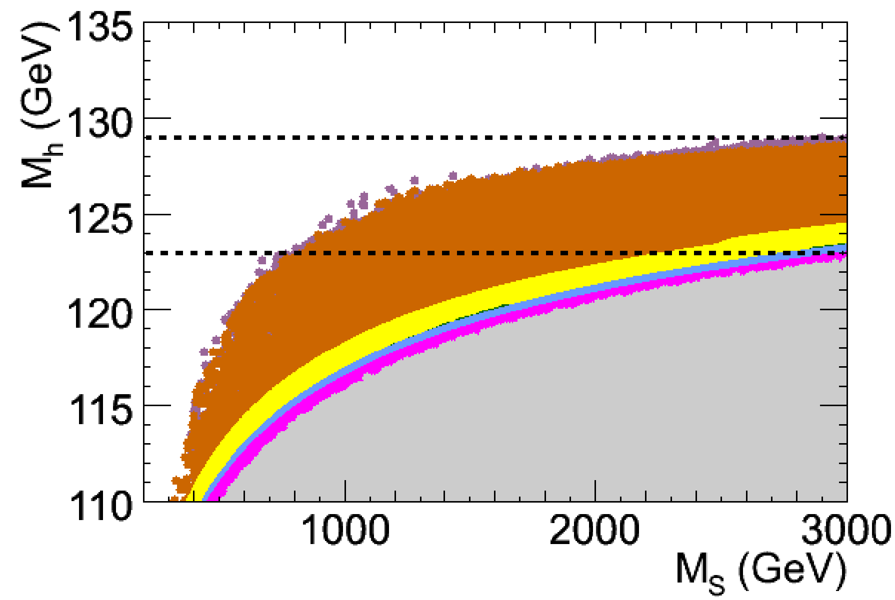
– provide solutions to some MSSM problems: CP, flavor, etc..

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

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

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





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

4. Implications for the MSSM

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

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

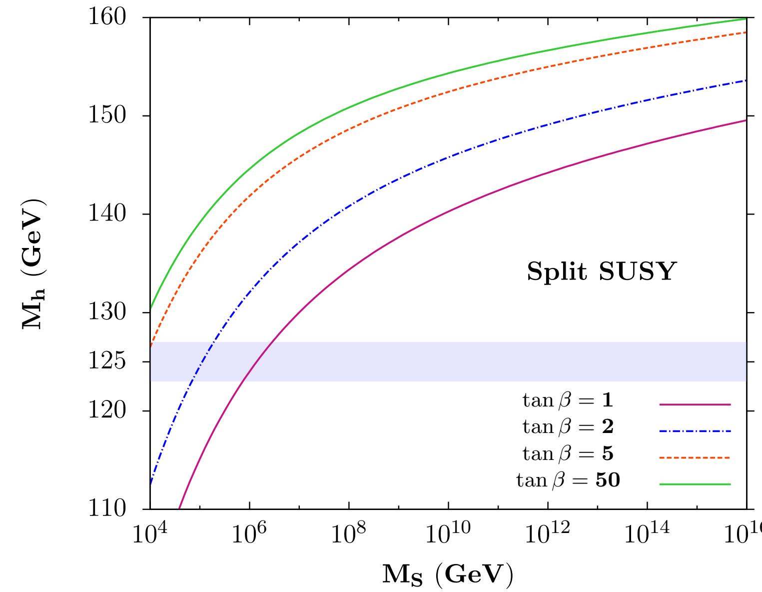
... leading to $M_H =$120–140 GeV ...

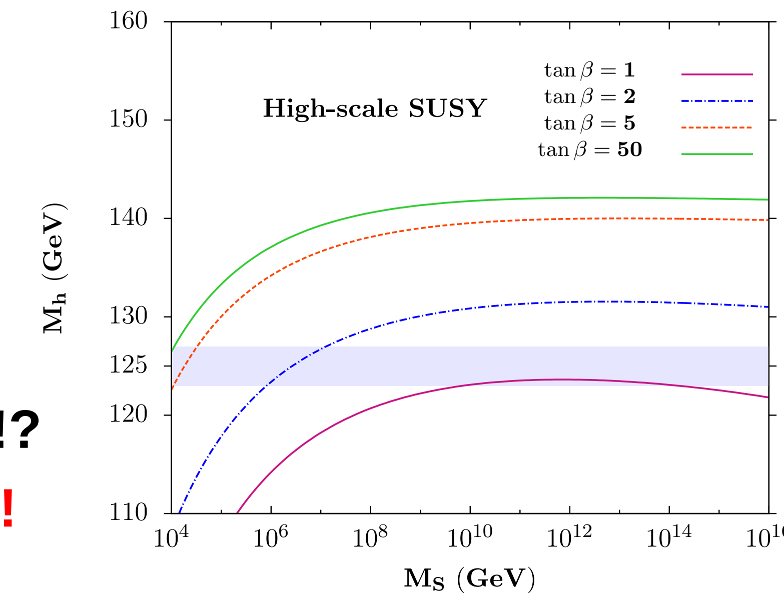
In both cases small $\tan\beta$ needed...

note 1: $\tan\beta \approx 1$ possible

note 2: M_S large and not M_A possible!?

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

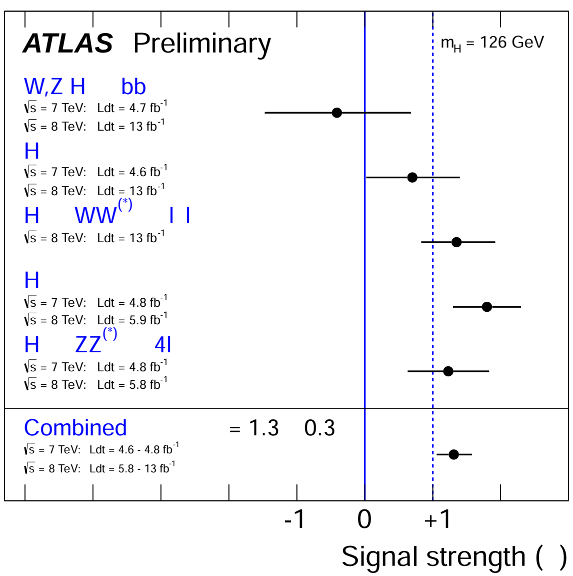


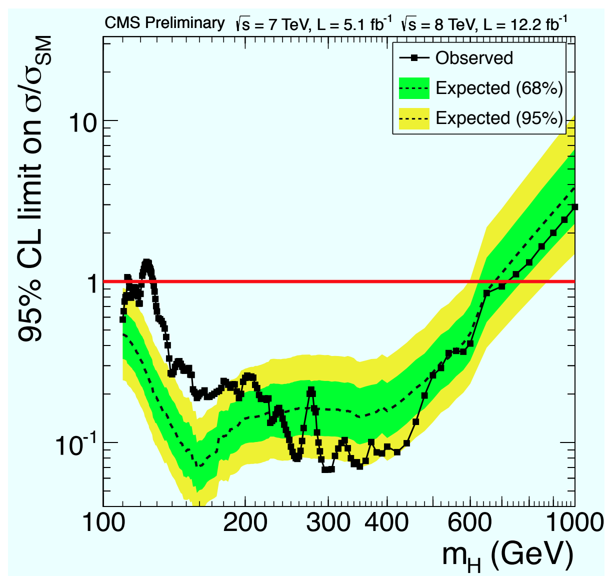


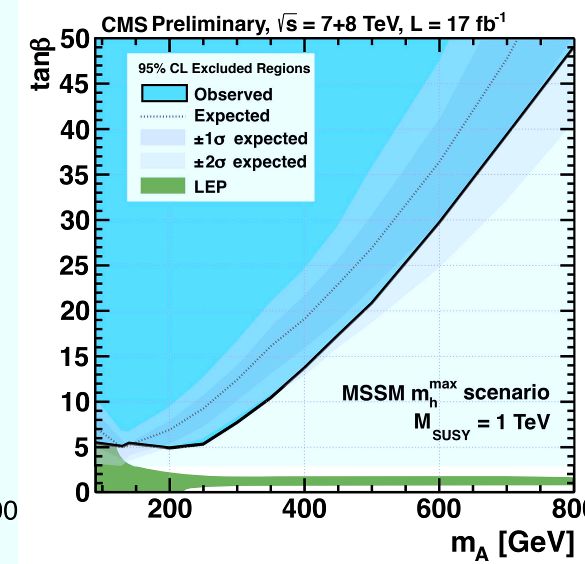
4. Implications for MSSM: other searches

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 $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ 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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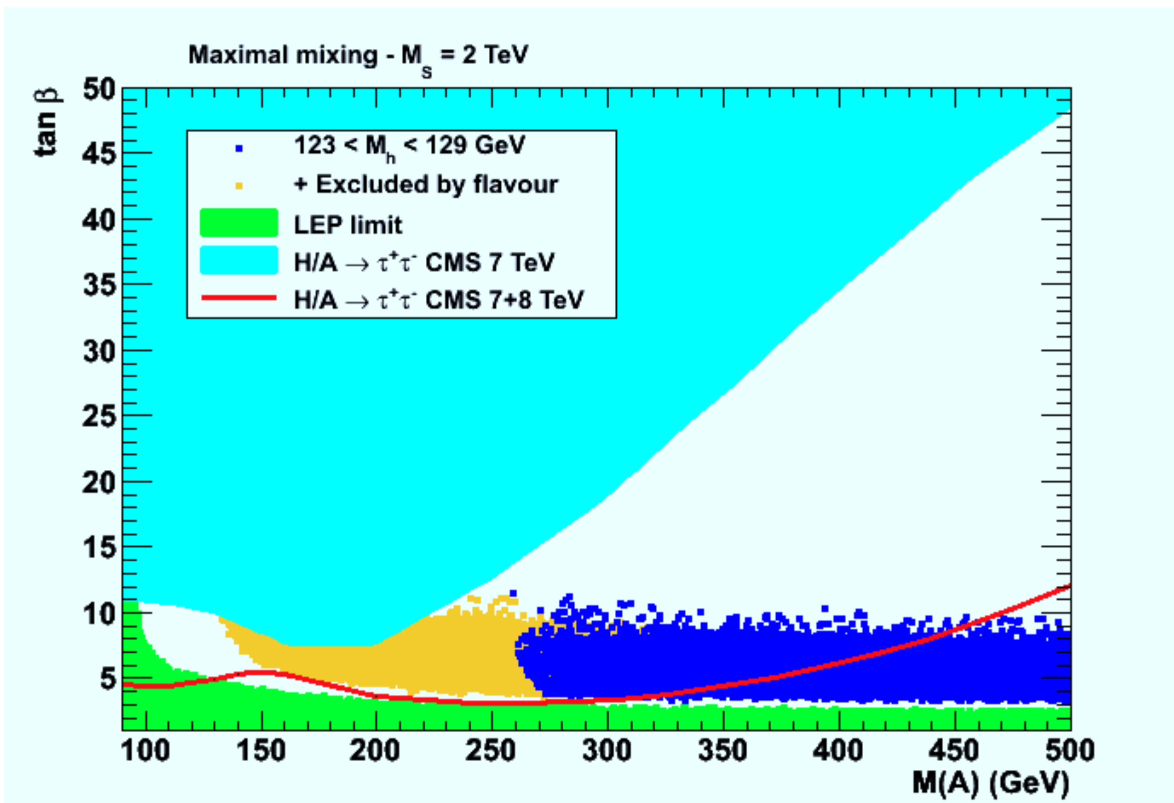

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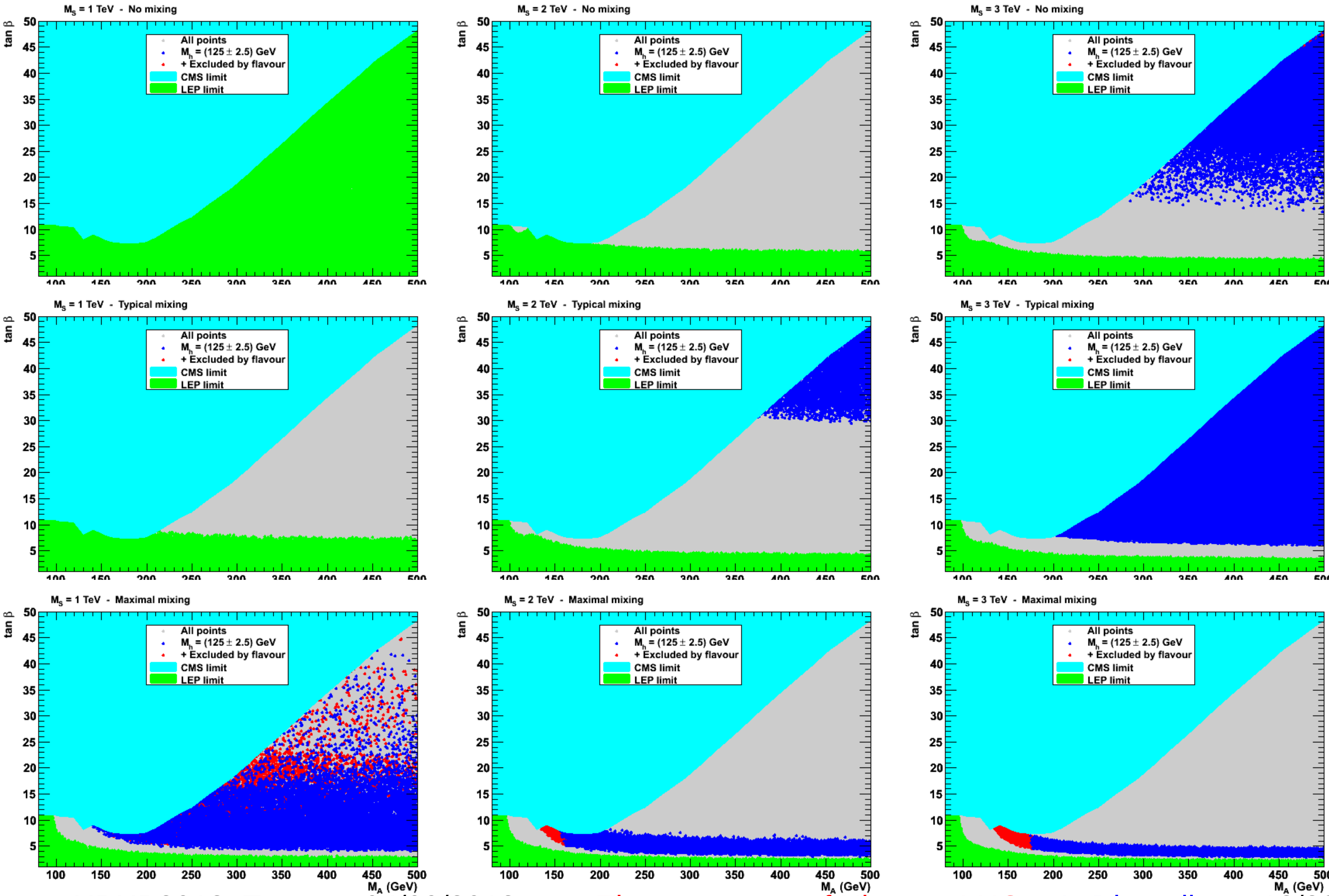


4. Implications for MSSM

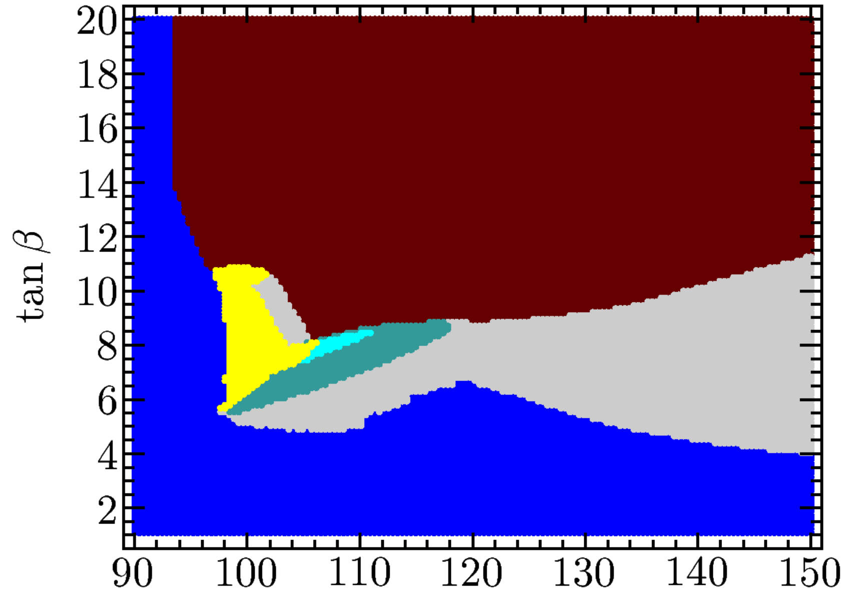
... is decoupling regime true ?

- **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

$$M_A \approx 100\ \text{GeV}, \tan\beta \approx 6-10,$$
$$M_S \approx \mu \approx 1\ \text{TeV}, X_t \approx \sqrt{6} M_S,$$
$$\Rightarrow M_H \approx 126\ \textbf{GeV}\ ;\ M_h \approx 98\ \textbf{GeV!}$$

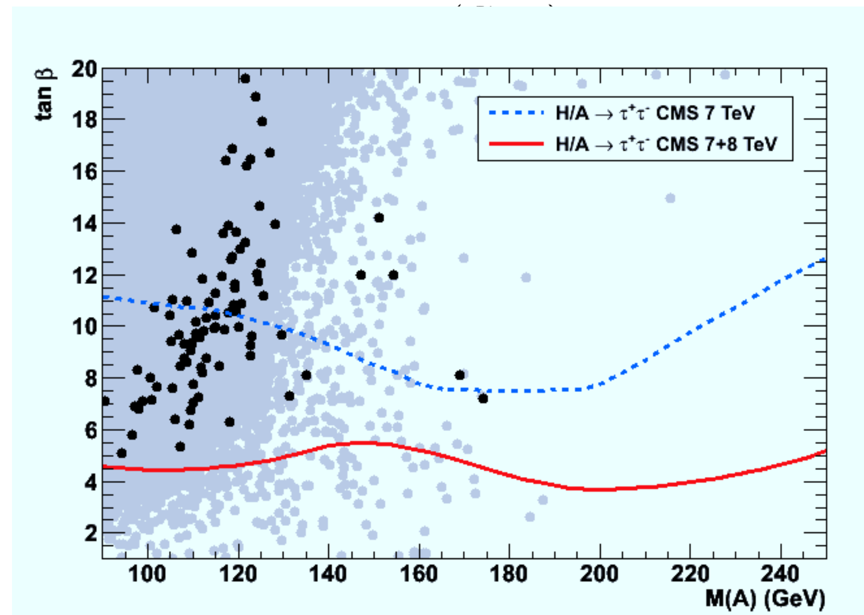
[ABDM scan: only few points, 10^{-6} OK

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...



4. Implications for MSSM: rates

Sets stingent constraints on pMSSM regimes/benchmark scenarios?

- As seen hseavier H being the observed Higgs is now excluded..
- Close $\mathrm{h,H,A,H^{\pm}}$ (intense coupling regime) excluded..
- Small α_{eff} scenario with $\mathrm{g_{hbb}} \approx 0$ and thus small Γ_{h}:

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

- gluophobic h with $\mathrm{g_{hgg}} \ll \mathrm{g_{H_{SM}gg}}$ 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 $\mathrm{H}\to\gamma\gamma$.

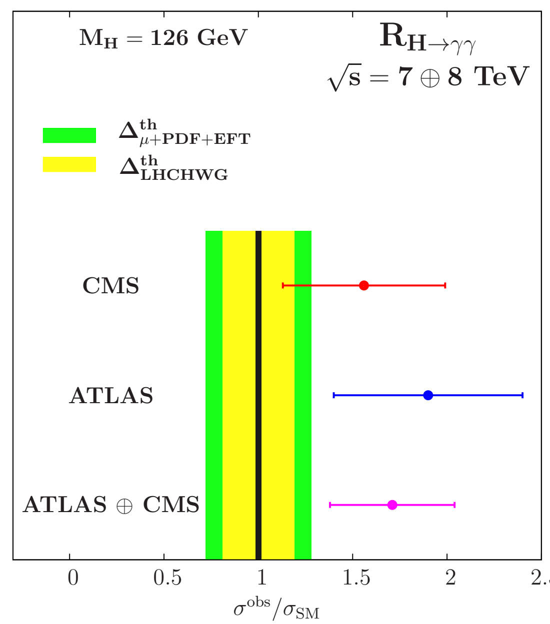
- Statistical fluctuation?
- Systematics problem?
- Maybe QCD uncertainties?

or a combination of the three..

Hope it is due to SUSY!

– total Higgs width suppressed?

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



4. Implications for pMSSM: rates

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

Can SUSY contributions significantly enhance the $\mathrm{h} \to \gamma\gamma$ 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 $\tilde{\mathrm{t}}$:**

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

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

highly disfavored by data

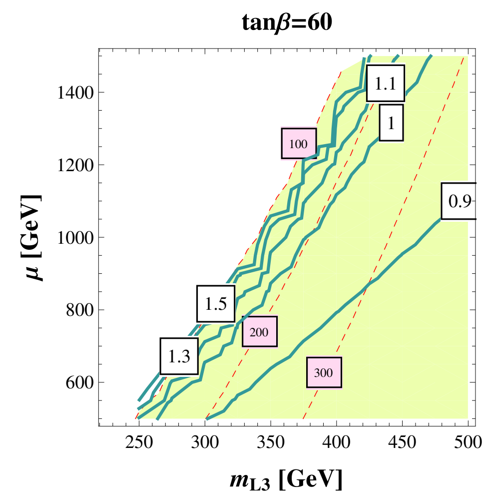
- **BMSSM? One example is the NMSSM:**

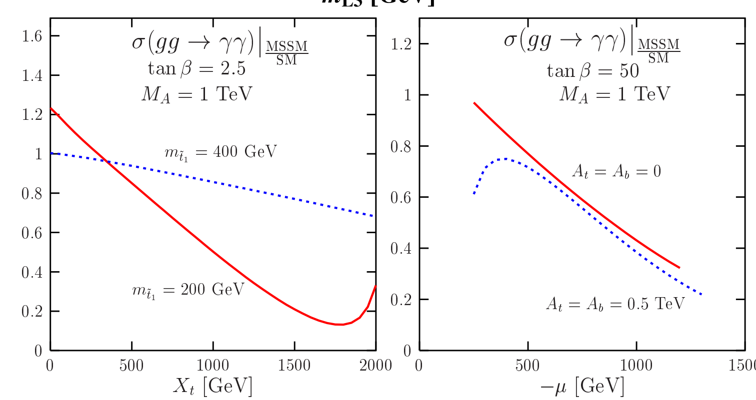
many virtues compared to MSSM:

– stops lighter as $\mathrm{M_h^{max}}$ larger,

– additional singlet for couplings,

– less severe non-H constraints.





Common features: some light sparticles are around the corner!

Data also OK with non SUSY BSM; ex: 2HDM, triplets, new fermions,..

5. Some 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 are still relevant**

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

- **Invisible Higgs decays still possible for h and also for h/H/A (DM!)...**

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?