Implications of a 125 GeV Higgs for the MSSM

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1. **The MSSM Higgs sector**
2. **Implications for the pMSSM**
3. **Implications for the cMSSM**
4. **Conclusion**

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Mainly based on Arbey+Battaglia+Mahmoudi+Quevillon+AD, arXiv:1112.3028 and work in preparation.

1. The MSSM Higgs sector

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

- to cancel the chiral anomalies introduced by the new $\tilde{h}$ 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 $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: $h, H, A, H^\pm$

Only two free parameters at the tree level: $\tan\beta, M_A$; others are:

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

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

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

We have important constraint on the MSSM Higgs boson masses:

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

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

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

$\Rightarrow$ **Inclusion of radiative corrections to M_h important and necessary.**

1. The MSSM Higgs sector

Radiative corrections very important in the MSSM Higgs sector.

a huge effort from early 1990s up to now to calculate them...

- **Dominant corrections are due to top (s)quark at the one-loop level**

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

Okada+Yamaguchi+Yanagida, Ellis+Ridolfi+Zwirner, Haber+Hempfling (1991)

depending on $\mathbf{\tan\beta, M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_1}}, X_t = A_t - \mu/\tan\beta}$**:**

$\mathbf{M_h^{max} \to M_Z + 30 - 50}$ **GeV...**

- **Full one-loop including all contributions** $\tilde{t}, \tilde{b}, \tilde{q}, \Phi, \tilde{\ell}, \chi, \mathrm{etc.}.$

Brignole, Chankowski+Rosiek+Pokorski, Dabelstein, Pierce+Bagger+Matchev+Zhang (92-96)

- **RGE improved one–loop corrections**

Carena+Espinosa+Quiros+Wagner, Haber+Hempfling+Hoang (95–96)

- **Dominant two–loop corrections:** $\mathcal{O}(\alpha_t \alpha_s), \mathcal{O}(\alpha_b \alpha_s), \mathcal{O}(\alpha_t^2), \mathcal{O}(\alpha_b^2)$

Heinemeyer+Hollik+Weiglein, Brignole+Degrassi+Slavich+Zwirner (98–02)

- **Dominant three–loop corrections:** $\mathcal{O}(\alpha_t \alpha_s^2)$ **contributes** $\approx$ **0.5 GeV**

Harlander+Kant+Mihaila+Steinhauser (2010)

Impact of missing corrections estimated below 1 GeV (HKMS)!

1. The MSSM Higgs sector

Radiative corrections implemented in two different ways in general:

- **On–shell scheme (OS) as in the MSSM Higgs code FeynHiggs**

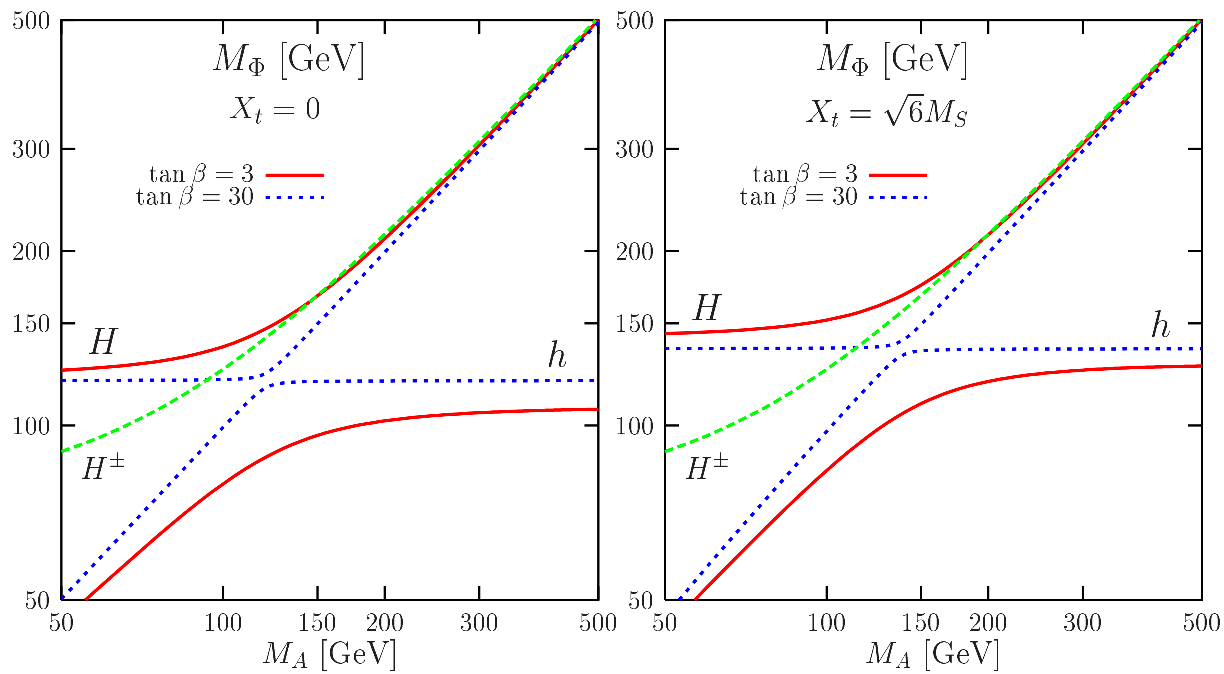
  Heinemeyer+Hollik+Weiglein+Han+....

- **$\overline{\rm DR}$ scheme à la BDSZ as in RGE codes Softsusy, Spheno, Suspect**

  Slavich, Allanach, Porod, Kneur+Moultaka+AD

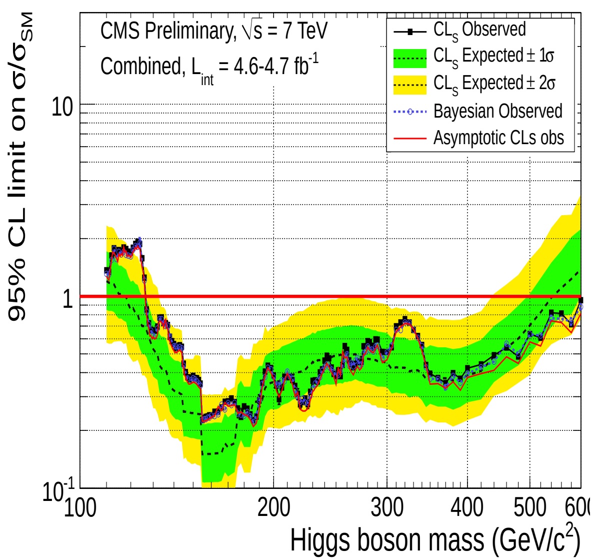
Difference between the two approaches: $\Delta M_h \approx 2$ GeV in general,
assumed to be the theoretical+"experimental" uncertainty on M_h....

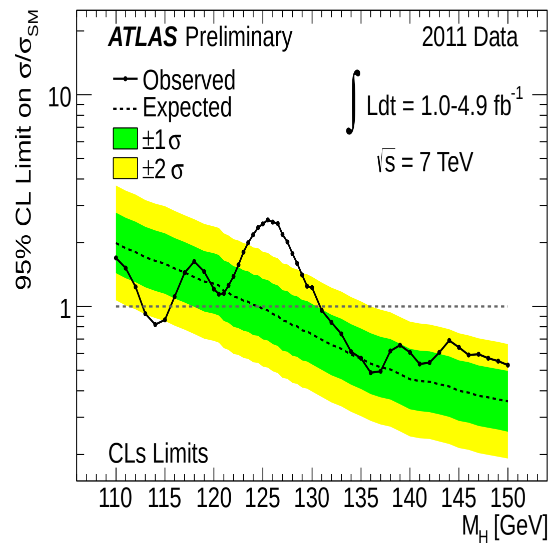
no–mixing case: $M_H \lesssim 120$ GeV; max–mixing case: $M_H \lesssim 135$ GeV

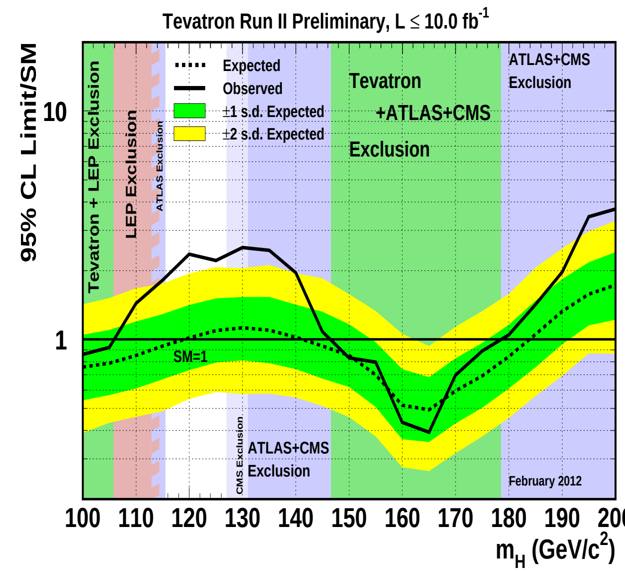


1. The MSSM Higgs sector

In the following, I assume that a 125 ± 2 GeV Higgs has been observed,
(no choice anyway as only $122.5 \leq M_h \leq 127.5$ GeV is now allowed...)







and that it is the one of the MSSM... I will ask the following questions:

- **what are the implications in unconstrained and constrained MSSMs?**
- **what happens to MSSM Higgs sector if one includes other constraints?**
- **could one increase the rate for the $h \to \gamma\gamma$ signal?**
- **what are the implications for sparticle searches (mainly stops)?**

2. Implications for the pMSSM

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:

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

- 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 Kneur+Moultaka+AD and Softsusy Allanach which implement the known radiative corrections in the $\overline{\rm DR}$ scheme.

2. Implications for the pMSSM

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:

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

- determine the regions of parameter space where $123 \leq M_h \leq 127$ GeV

(2 GeV uncertainty includes both "experimental" and "theoretical" error)

- require h to be SM–like: $\sigma(h) \times BR(h \to VV) \gtrsim 0.9 H_{SM}$

(we will also consider the possibility that H is the H_{SM}, see later).

2. Implications for the pMSSM

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

- **What about other benchmarks?**

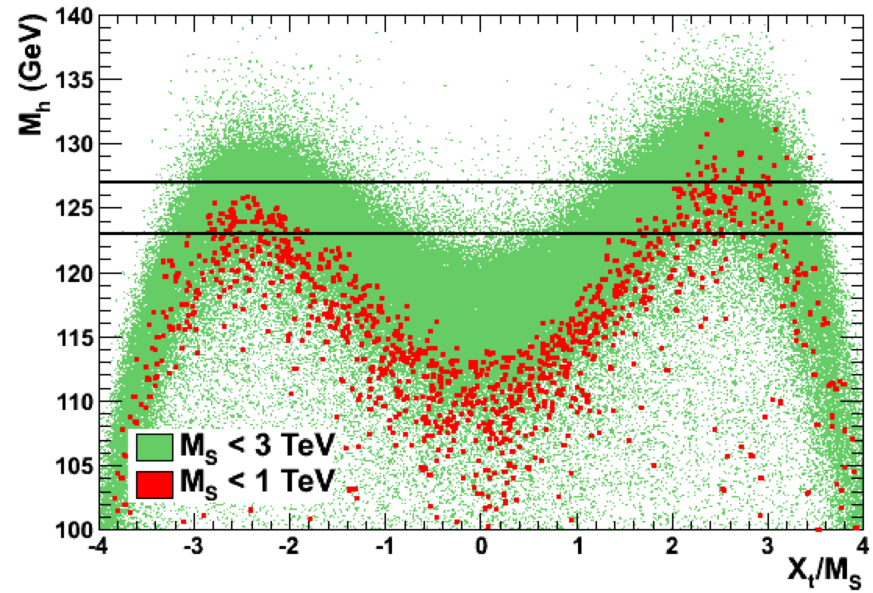
Carena+Heinemeyer+Wagner+Weiglein

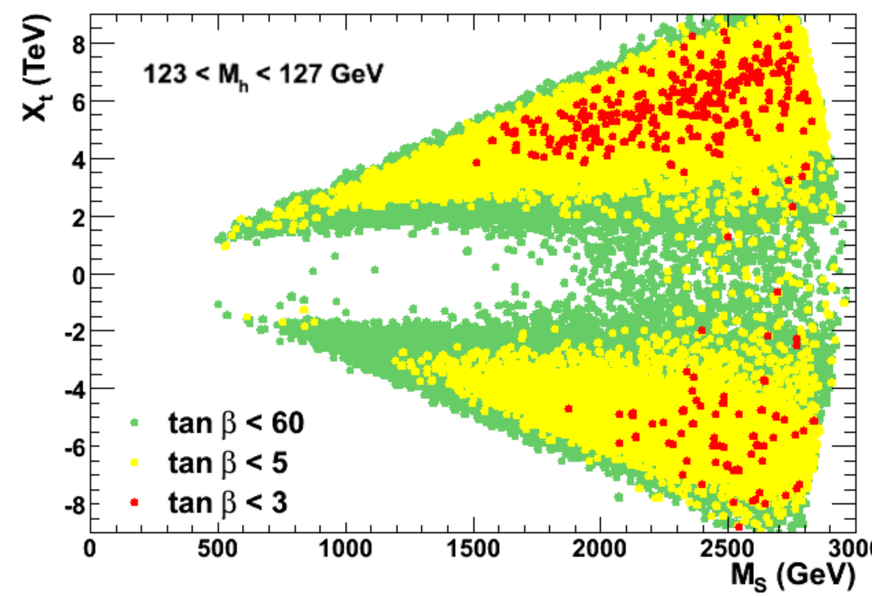
– small $\alpha_{\rm eff}$ scenario with $g_{hbb} \approx 0$: ruled out by LHC/Tevatron data.

– gluophobic h with $g_{hgg} \ll g_{H_{SM}gg}$ ruled out by $4\ell^+, \gamma\gamma$ signals at LHC (difficult to achieve as $\tilde{t}_1$ heavy..).

– no SUSY regime with light sparticles: BR($h \to \chi_1^0 \chi_1^0$) should be small...

– max and no-mix need to be updated!



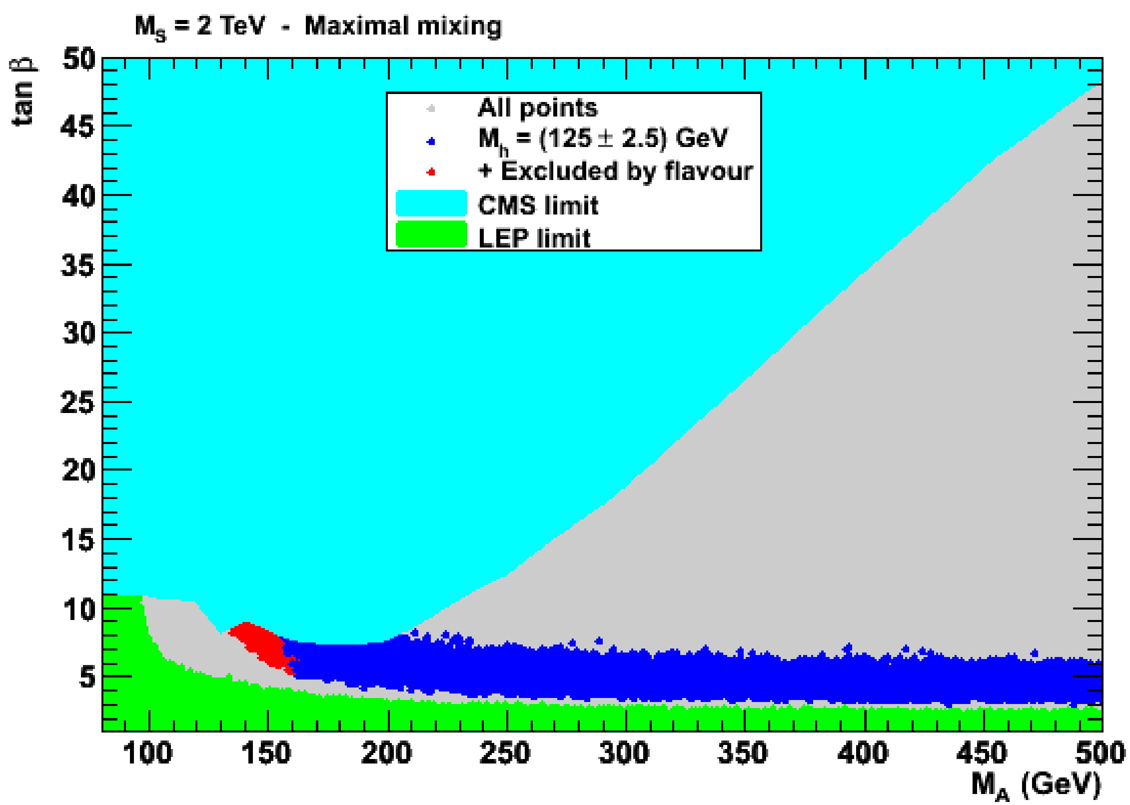


2. Implications for the pMSSM

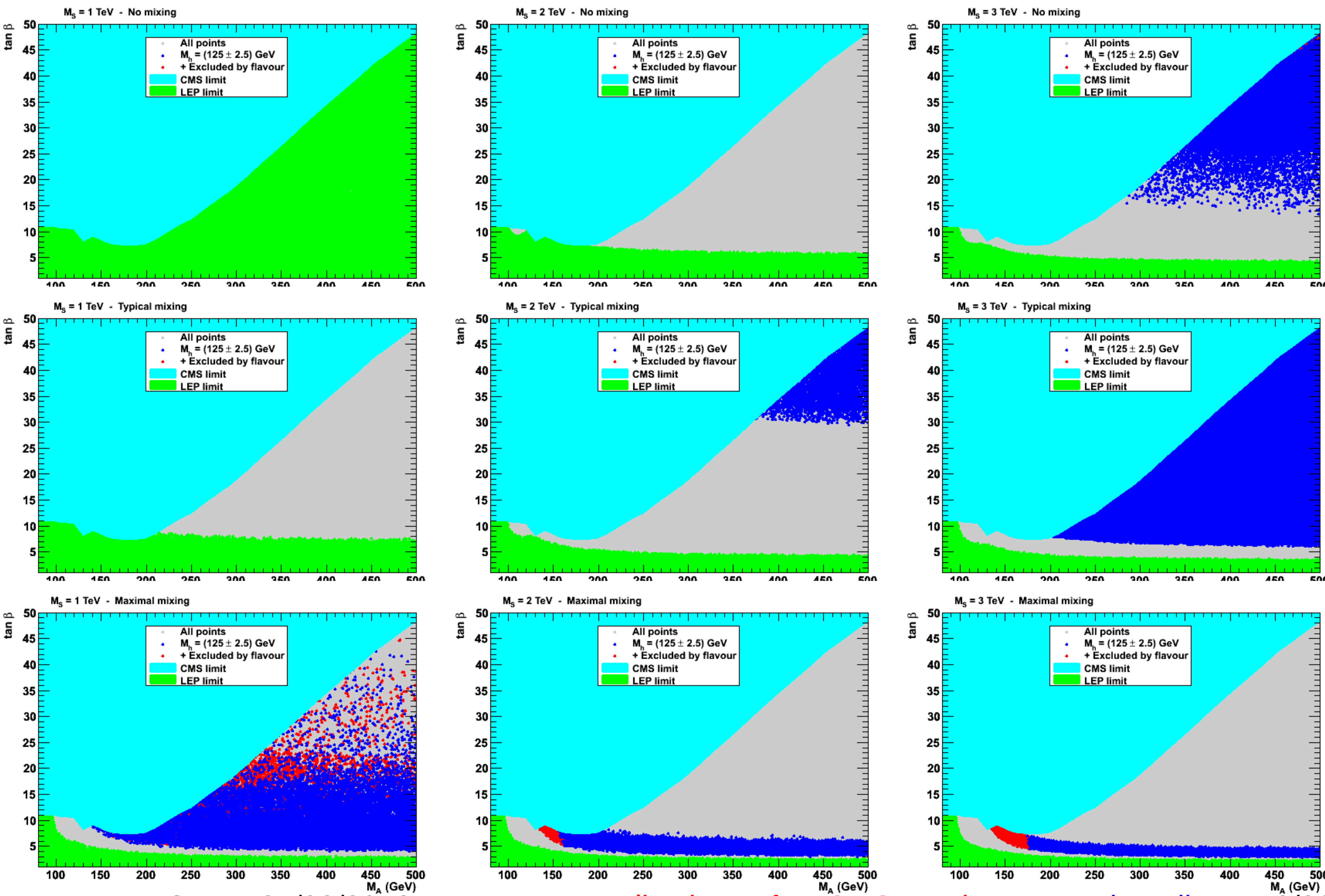
update of $[\mathrm{M_A}, \tan\beta]$ propaganda plot is desperately needed!

Besides LEP2 and $\mathrm{A/H/h} \to \tau\tau$ searches, one must now include:

- **combined ATLAS+CMS of $\tau\tau$ and $\mathrm{t} \to \mathrm{bH^+}$ searches at low $\mathrm{M_A}$**
- **the limit $122.5 \leq \mathrm{M_h} \leq 127.5$ GeV from $\mathrm{H_{SM}}$ searches**
- **constraints from flavor: at least (direct!) limits from $\mathrm{B_s} \to \mu\mu$...**



2. Implications for the pMSSM



2. Implications for the pMSSM

Are we really in decoupling regime?

- are small values of M_A allowed?
- can H be the SM-like Higgs boson?

YES!, if no other constraints than:

– $M_H \approx 125 \pm 2$ GeV

– $g_{HVV} \approx g_{H_{SM}VV}$

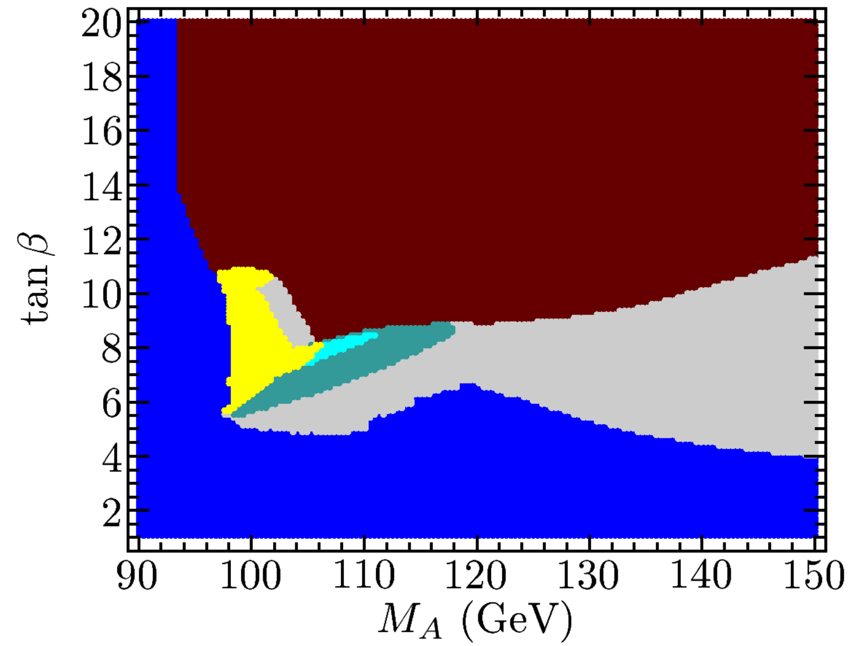
Heinemeyer+Stal+Weiglein

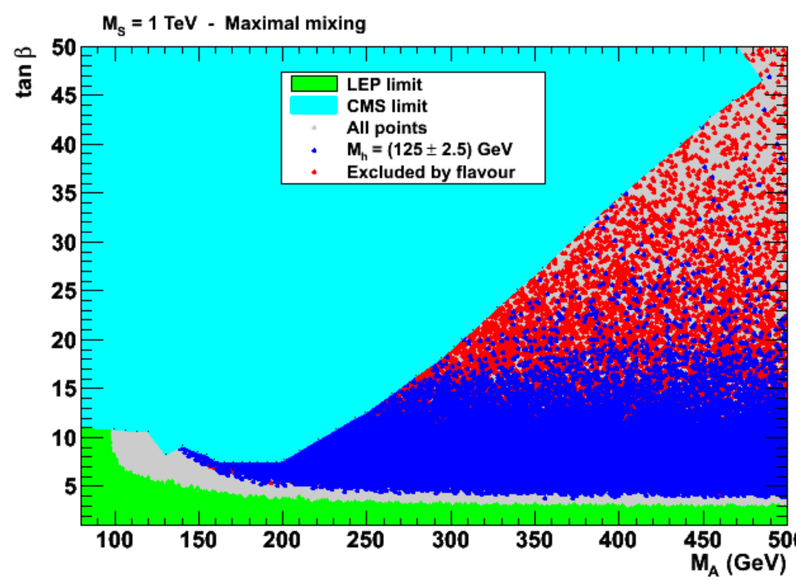
$M_A \approx 100$ GeV, $\tan\beta \approx 6-10$,
$M_S \approx \mu \approx 1$ TeV, $X_t \approx \sqrt{6} M_S$,
$\Rightarrow M_H \approx 125$ GeV ; $M_h \approx 98$ GeV!

[in ABDMQ scan, only very few points (20 out of 10^6 valid) satisfy conditions but they are all ruled out by $b \to s\gamma$

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

maybe needs more detailed studies?]





2. Implications for the pMSSM

Can one change the h prod rates?

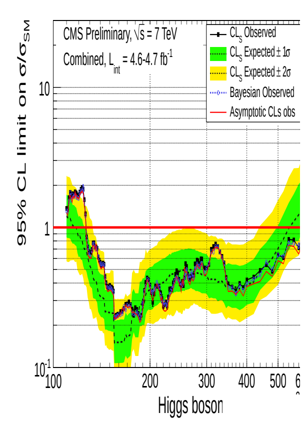
- **suppress g_{hWW} or g_{hbb} couplings**

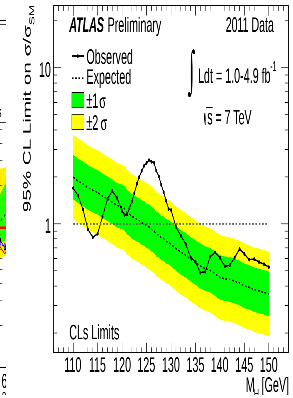
$\Rightarrow$ loose Wh$\to \ell\nu b\bar{b}$ Tevatron signal

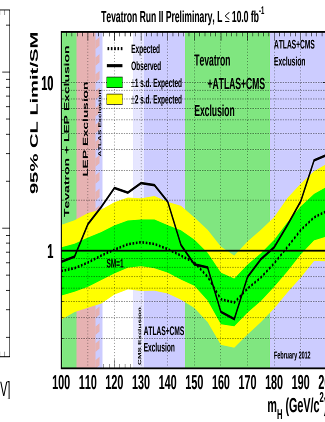
- **suppress g_{hZZ} or g_{htt} (incr. g_{hbb})**

$\Rightarrow$ loose $h \to ZZ \to 4\ell$ ATLAS signal

hard to change tree-level couplings







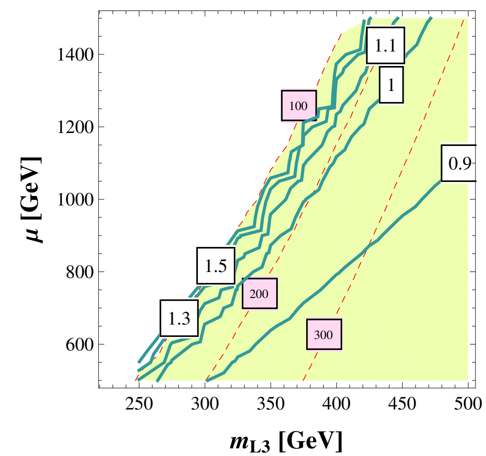
Only change is the $h\gamma\gamma$ coupling:

increase to explain $\gamma\gamma$ LHC excess?

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

Carena+Gori+Shah+Wagner

$\tan\beta$=60



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

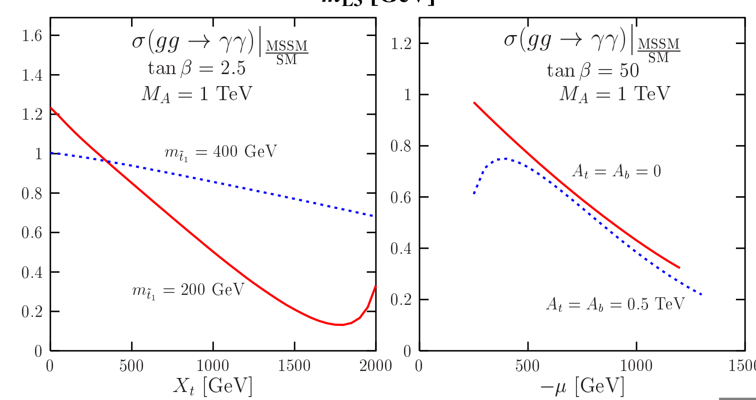
Driesen+Illana+Hollik+AD

- **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?** **Ellwanger etal, King etal., Kraml+Jiang+Gunion $\cdots$ see J. Gunion's talk**

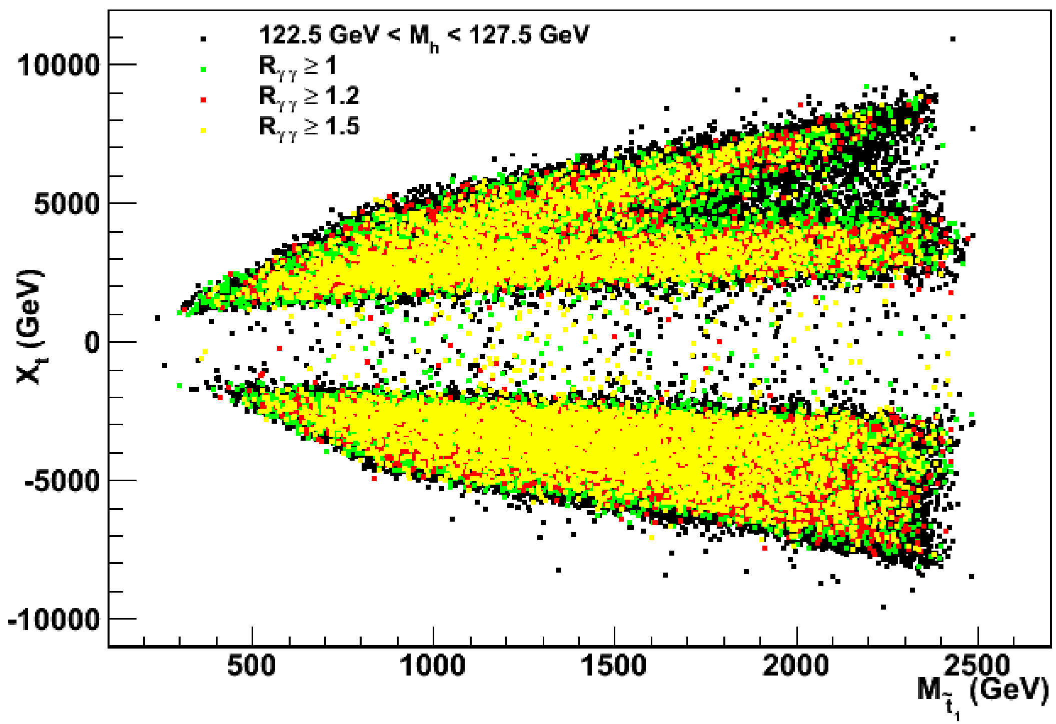
2. Implications for the pMSSM

How light superparticles can be in pMSSM with a 125 GeV Higgs?

- non-universal gaugino masses and μ parameter unconstrained,
- non-universal sfermions masses: decouple sleptons from squarks

  do not affect $M_h \Rightarrow$ light $\chi^{\pm}_{1,2}, \chi^0_{1...4}, \tilde{\ell}^{\pm}, \tilde{\nu}$ beyond LEP2 possible!
- first/second gen. squarks as well as gluinos can be very heavy...

But not main player stop! How light or heavy can the stops be?



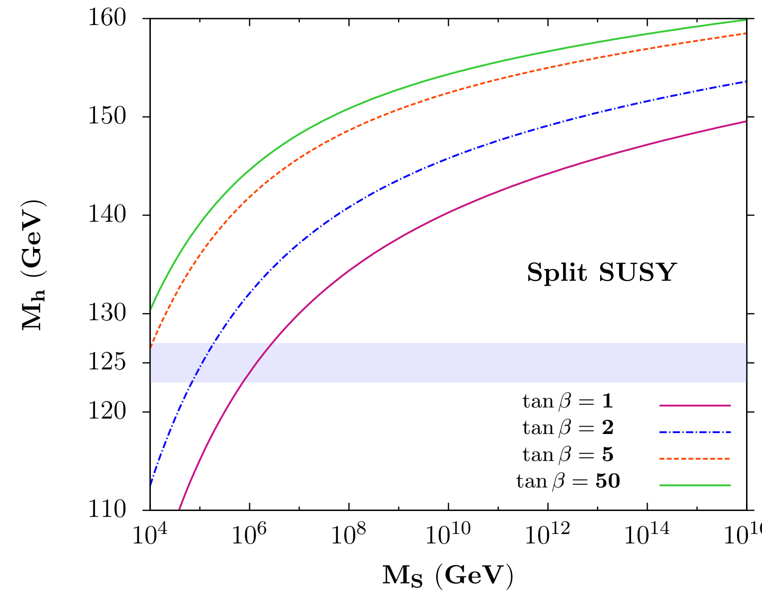
2. Implications in pMSSM: high scale SUSY

The scale M_S seems to be large. There are 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**

Arkani-Hamed+Dimopoulos
Giudice, Romanino



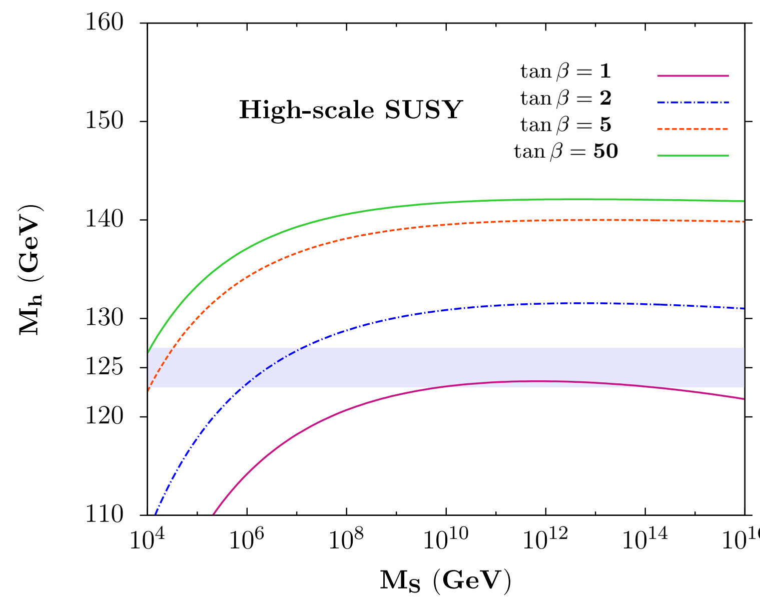
- **SUSY broken at the GUT scale...**

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 ...

Hall+Nomura, Giudice+Strumia
Bernal+Slavich+AD



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

3. Implications for the cMSSMs

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

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 $123\ \mathrm{GeV} \le M_h \le 127\ \mathrm{GeV}$

3. Implications for the cMSSMs

The following ranges are considered for the model input parameters besides $1 \leq \tan\beta \leq 60$ and sign(μ)$=\pm 1$ that are common to all:

mSUGRA: 50GeV $\leq m_0 \leq$2TeV, 50GeV $\leq m_{1/2} \leq$3TeV, $|A_0| \leq 9$TeV;

mGMSB: 10TeV$\leq \Lambda \leq$1000 TeV, 1 $\leq M_{mes}/\Lambda \leq 10^{11}$, $N_{mess} =$1;

mAMSB: 1 TeV$\leq m_{\frac{3}{2}} \leq$ 100TeV,50 GeV $\leq m_0 \leq$ 2 TeV.

In mSUGRA we further consider the following (over–constrained) cases:

- no–scale: $m_0 = A_0 = 0$
- cNMSSM: $m_0 = 0, A_0 = -\frac{1}{4} m_{1/2}$
- vcMSSM: $m_0 = A_0$

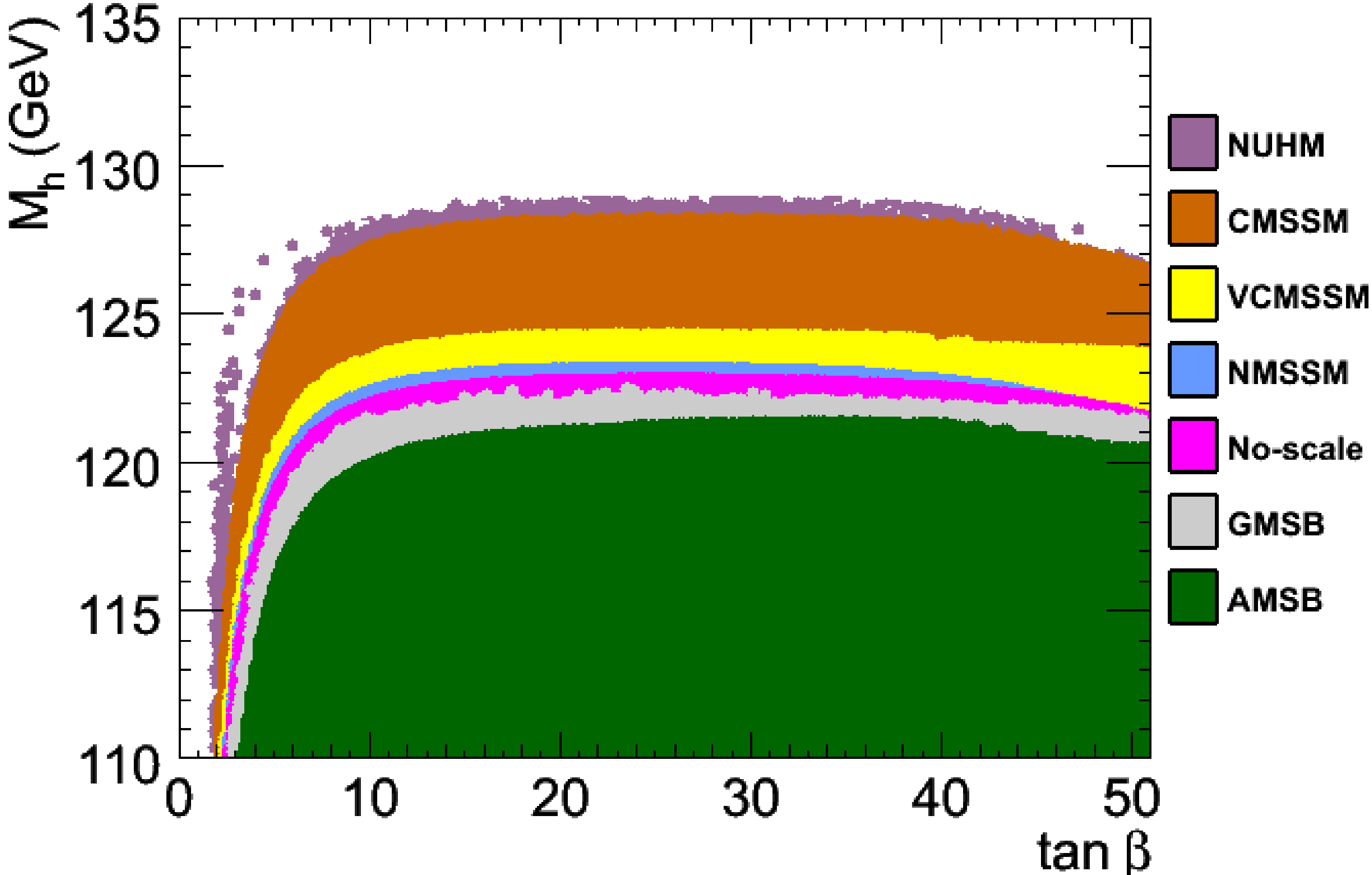
as well as as the less constrained non–universal Higgs mass model:

- NUHM: $m_{1/2}, m_0, A_0$ and m_{H_u}, m_{H_d}

In mSUGRA case and its variants, we impose in addition bounds from:
– correct relic density of DM neutralino as measured by WMAP,
– constraints from flavor physics: $b \to s\gamma, B_s \to \mu\mu$,
– constraints from heavy MSSM Higgs production at the LHC.

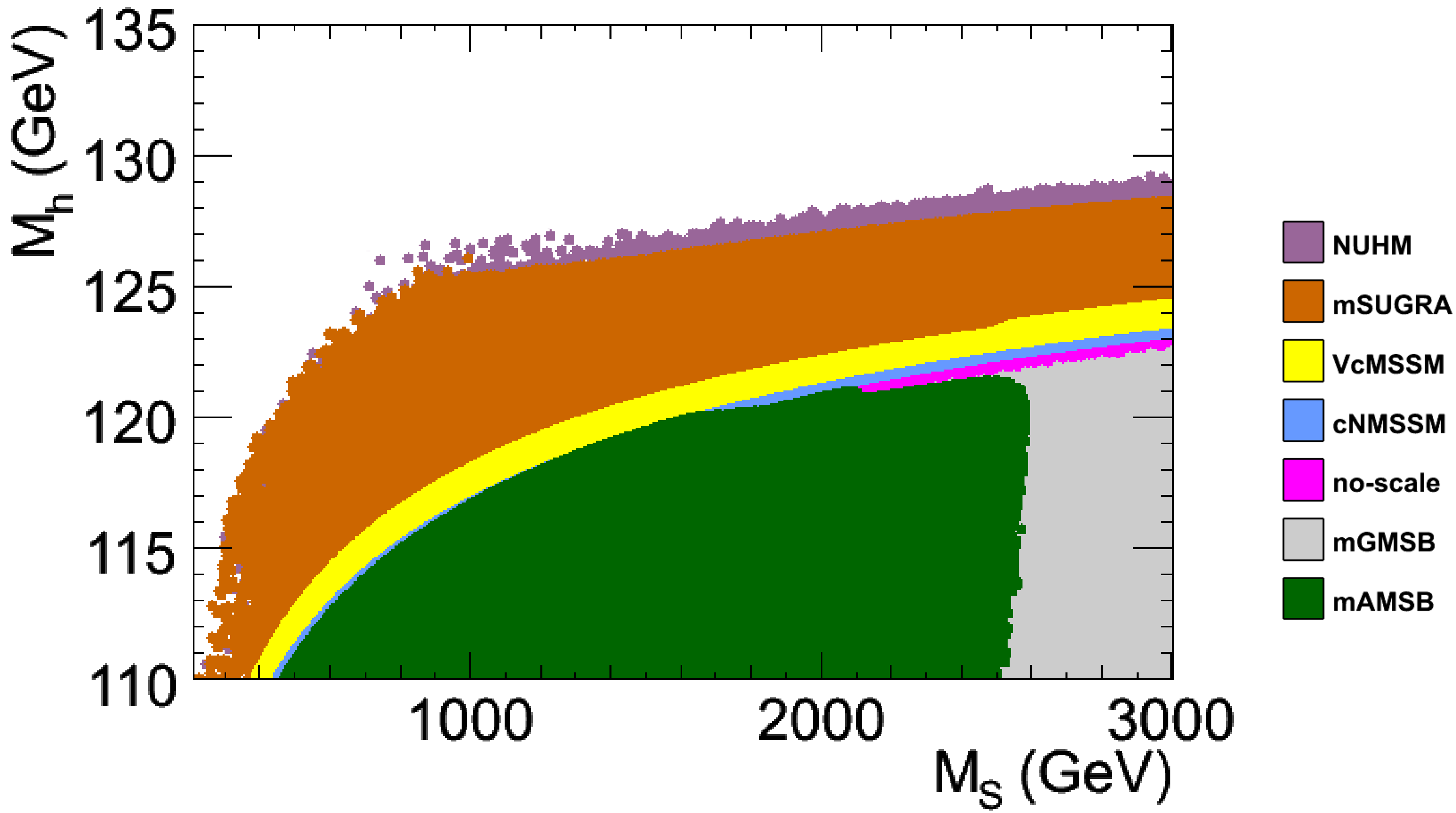
Less freedom for $A_t \Rightarrow M_h$ is much more constraining!

3. Implications for the cMSSMs



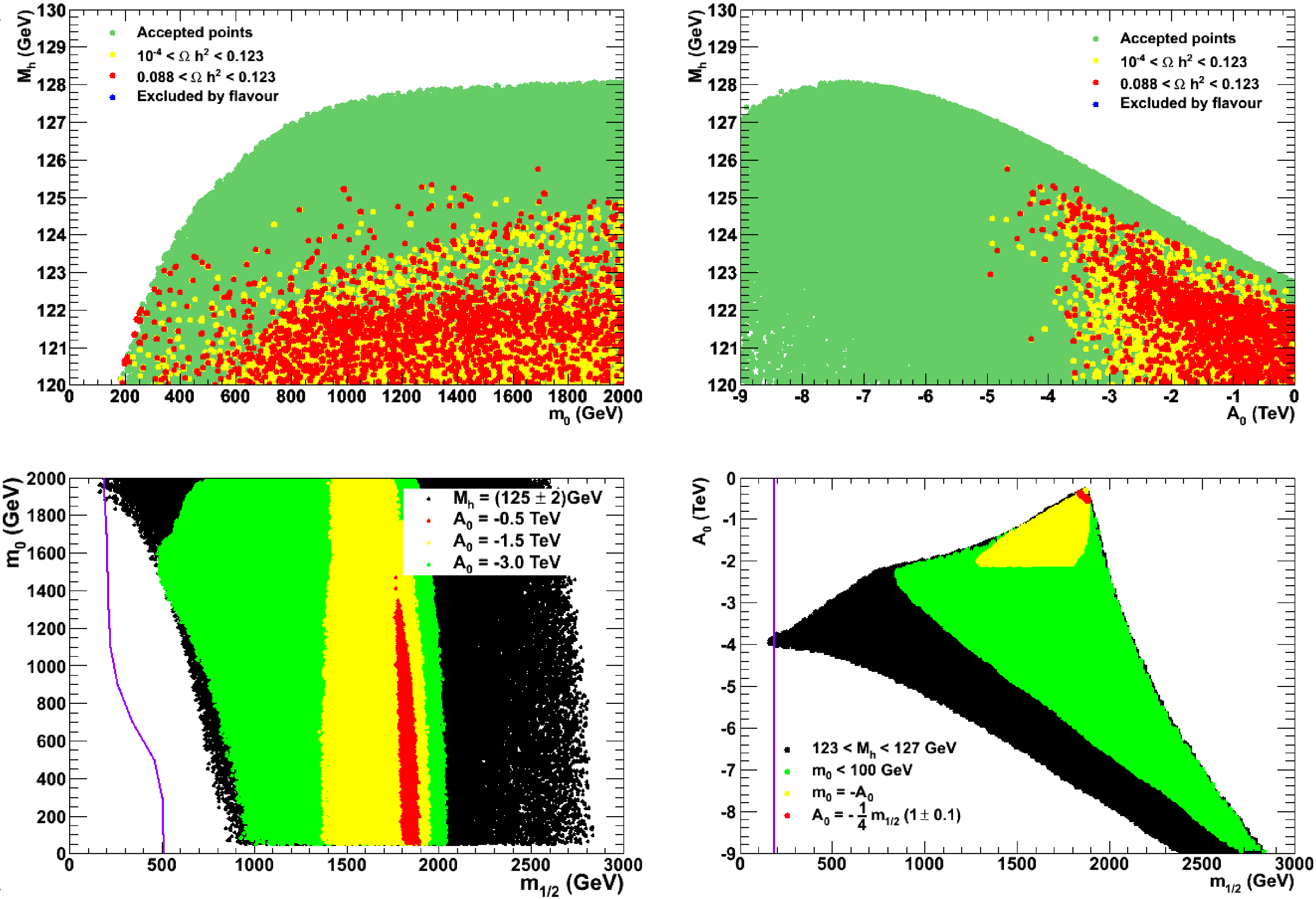
model	amsb	gmsb	sugra	noscale	cnmssm	vcmssm	nuhm
M_h^{max}	120	121	128	123	123	126	128

3. Implications for the cMSSMs



also: Buchmuller etal, Drapper etal., Baer etal., Raidal etal., Li etal, Roszkowski etal...
and in other (many!!) BMSSM including NMSSM scenarios, talk of Jack Gunion....

3. Implications for the cMSSMs



4. Conclusions

A 125 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: everybody dead**
- $M_H \approx 125$ **GeV is Darwinian: (natural) selection among models..**

Many questions remain:

– is the 125 GeV Higgs really there? any wrong cable connection?
– if yes, is it really SM–like? What about the $\gamma\gamma, 4\ell^\pm, b\bar{b}$ rates?
– if yes, SUSY spectrum heavy; except maybe for weakly interacting sparticles and also stops $\Rightarrow$ more focus on them in SUSY searches!

Some answers in July or December. More complete answer later!

My personal feeling or bet:

– a (7.3σ) Higgs in 2012, Higgstoric year!
– a stop and a chargino in 2015: my favorite/best–guess SUSY signal:

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

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