Charged Higgs in view of the LHC constraints in the phenomenological MSSM

Nazila Mahmoudi

CERN TH & LPC Clermont-Ferrand

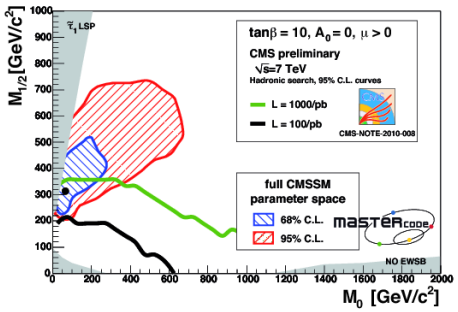
In collaboration with A. Arbey, M. Battaglia & A. Djouadi

cH$^{\pm}$arged 2012
Uppsala, October 8-11, 2012

Before the start of the LHC:

High expectation for an early discovery of SUSY particles

SUSY could be discovered even before the Higgs!



O. Buchmueller et al., JHEP 0809 (2008) 117

It appears not to be the case:

So far we have only limits which are pushing the masses to higher and higher values

Not enough to confirm/exclude SUSY

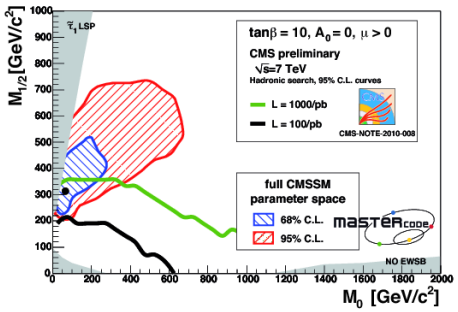
BUT:

- Supersymmetry is more than just the CMSSM!
- An alternative path to constrain SUSY efficiently is through the Higgs sector!

Before the start of the LHC:

High expectation for an early discovery of SUSY particles

SUSY could be discovered even before the Higgs!



O. Buchmueller et al., JHEP 0809 (2008) 117

It appears not to be the case:
So far we have only limits which are pushing the masses to higher and higher values

Not enough to confirm/exclude SUSY

BUT:

- Supersymmetry is more than just the CMSSM!
- An alternative path to constrain SUSY efficiently is through the Higgs sector!

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: M_1, M_2, M_3

3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$

3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

A. Djouadi et al., hep-ph/9901246

Pioneer study:
SUSY without prejudice, C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo, JHEP 0902 (2009) 023

Our pMSSM studies:
Implications of LHC SUSY searches: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1847
Higgs, DM and $B_s \rightarrow \mu\mu$ searches: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906
Light χ_1^0 and DM direct detection: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 2169
Implications of Higgs searches: A. Arbey, M. Battaglia, A. Djouadi, FM, J. Quevillon, PLB708 (2012) 162
Implications of Higgs discovery: A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: M_1, M_2, M_3

3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$

3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

A. Djouadi et al., hep-ph/9901246

Pioneer study:
SUSY without prejudice, C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo, JHEP 0902 (2009) 023

Our pMSSM studies:
Implications of LHC SUSY searches: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1847
Higgs, DM and $B_s \rightarrow \mu\mu$ searches: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906
Light χ_1^0 and DM direct detection: A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 2169
Implications of Higgs searches: A. Arbey, M. Battaglia, A. Djouadi, FM, J. Quevillon, PLB708 (2012) 162
Implications of Higgs discovery: A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Complete analysis in pMSSM:

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables (**SuperIso**)
- Computation of dark matter observables (**SuperIso Relic**, Micromegas)
- Determination of SUSY and Higgs mass limits (**SuperIso**, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, ...)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino)
- Determination of detectability with fast detector simulation (Delphes)

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
M_3	[50, 2500]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 2500]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 2500]
$M_{\tilde{\tau}_L}$	[0, 2500]
$M_{\tilde{\tau}_R}$	[0, 2500]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 2500]
$M_{\tilde{q}_{3L}}$	[0, 2500]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 2500]
$M_{\tilde{t}_R}$	[0, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 2500]
$M_{\tilde{b}_R}$	[0, 2500]

Constraints from:

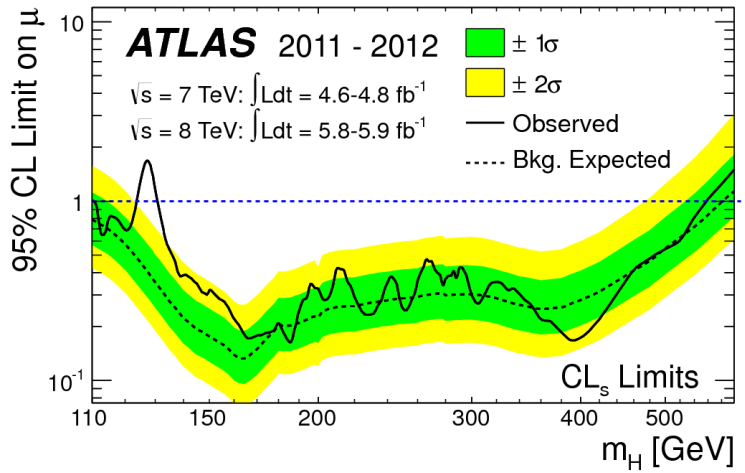
- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search limits
- Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct search limits
- LHC monojet limits

Statistics:

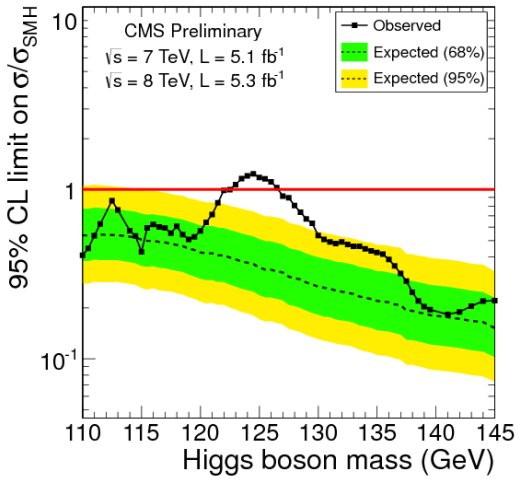
- more than 100M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

ATLAS and CMS discovery of a scalar compatible with the Higgs



ATLAS-CONF-2012-091



CMS PAS HIG-2012-015

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 2.1	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.66 ± 0.33	ATLAS+CMS
μ_{ZZ}	0.99 ± 0.38	ATLAS+CMS
μ_{WW}	0.95 ± 0.35	ATLAS+CMS
$\mu_{b\bar{b}}$	< 1.64 (95% CL)	CMS
$\mu_{\tau\tau}$	< 1.06 (95% CL)	CMS

$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

$\to$ diphoton decay mode $\Rightarrow$ massive neutral boson with spin $\neq 1$

$\to$ compatible with the SM Higgs

$\to$ too early for conclusive information from couplings/rates

Higgs mass

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above:
  $M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\lesssim 110 - 135$ GeV
- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right] + \frac{3m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t \approx \sqrt{6} M_S$
- In contrast, much smaller M_h^{max} values for the no-mixing scenario, *i.e.* $X_t \approx 0$.

Higgs mass

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above:
  $M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\lesssim 110 - 135$ GeV
- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right] + \frac{3m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t \approx \sqrt{6} M_S$
- In contrast, much smaller M_h^{max} values for the no-mixing scenario, *i.e.* $X_t \approx 0$.

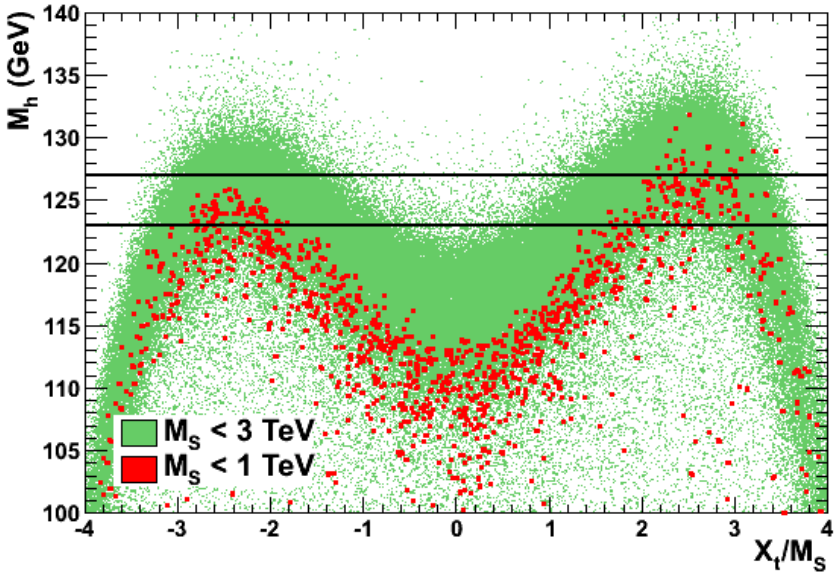
Higgs mass

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above: $M_h^{max} \approx M_Z |\cos 2\beta| + \text{radiative corrections} \lesssim 110 - 135$ GeV
- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right] + \frac{3m_t^4}{2\pi^2 v^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t \approx \sqrt{6} M_S$
- In contrast, much smaller M_h^{max} values for the no-mixing scenario, *i.e.* $X_t \approx 0$.

Consequences of a 125 GeV Higgs



A. Arbey, M. Battaglia, A. Djouadi, FM, J. Quevillon, Phys.Lett. B708 (2012) 162

A large part of the pMSSM still survives

No mixing cases ($X_t \approx 0$) excluded for $M_S < 1$ TeV

Modified couplings with respect to the SM Higgs boson ($\rightarrow$ decoupling limit):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$\cot\beta$	$\tan\beta$	0

where:

$$\alpha = \frac{1}{2}\arctan\left(\tan(2\beta)\,\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\right)$$

Higher order corrections to the tree level couplings can be large for light SUSY particles

Also at tree level:

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

Particular benchmark scenario: maximal mixing ($X_t \approx \sqrt{6} M_S$):

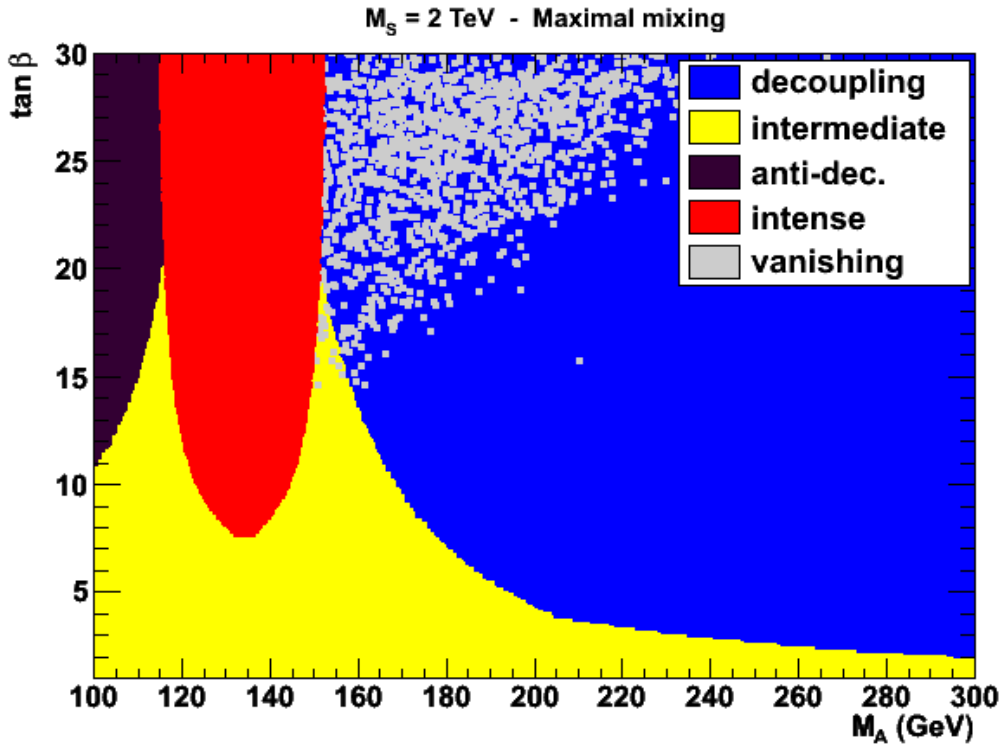
Decoupling regime:
large M_A, $\cos^2(\beta - \alpha) \leq 0.05$

Intermediate regime:
intermediate M_A

Anti-decoupling regime:
small M_A, $\cos^2(\beta - \alpha) \geq 0.95$

Intense coupling:
h, A, H rather close in mass,
g^2_{hbb} and $g^2_{Hbb} \geq 50$

Vanishing coupling:
g^2_{hbb} or $g^2_{hVV} \leq 0.05$



A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Green: LEP Higgs search limit
Solid cyan line: CMS $A/H \to \tau^+\tau^-$ search limit at 7 TeV with 4.6/fb
Dotted cyan line: ATLAS $t \to H^+ b$ search limit at 7 TeV with 4.6/fb

Particular benchmark scenario: maximal mixing ($X_t \approx \sqrt{6} M_S$):

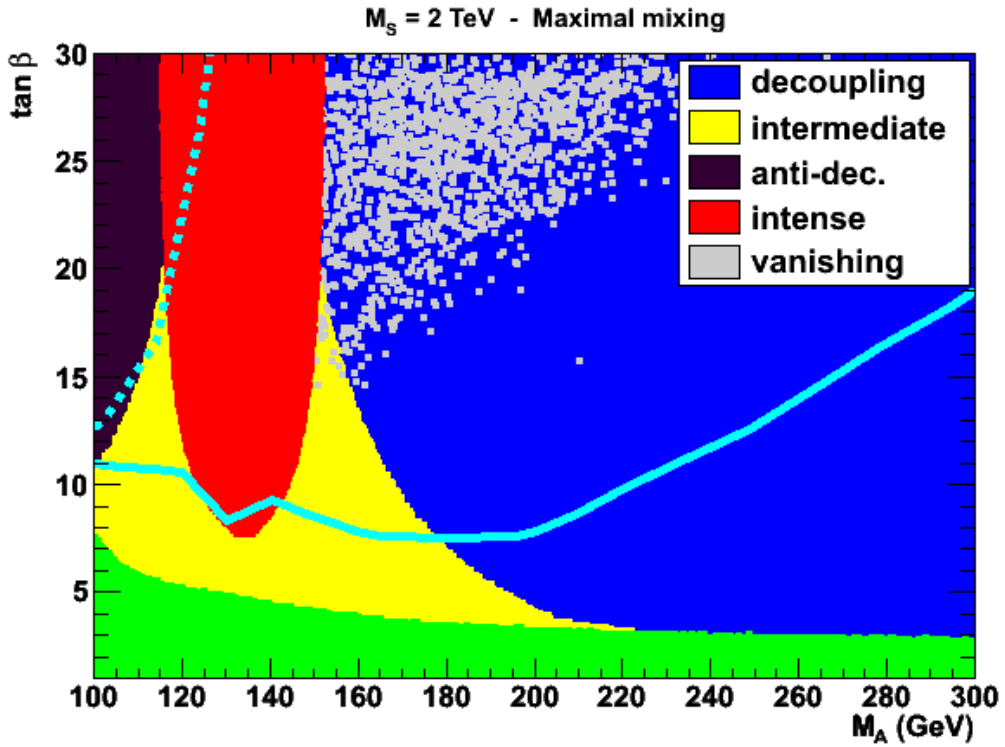
Decoupling regime:
large M_A, $\cos^2(\beta - \alpha) \leq 0.05$

Intermediate regime:
intermediate M_A

Anti-decoupling regime:
small M_A, $\cos^2(\beta - \alpha) \geq 0.95$

Intense coupling:
h, A, H rather close in mass,
g^2_{hbb} and $g^2_{Hbb} \geq 50$

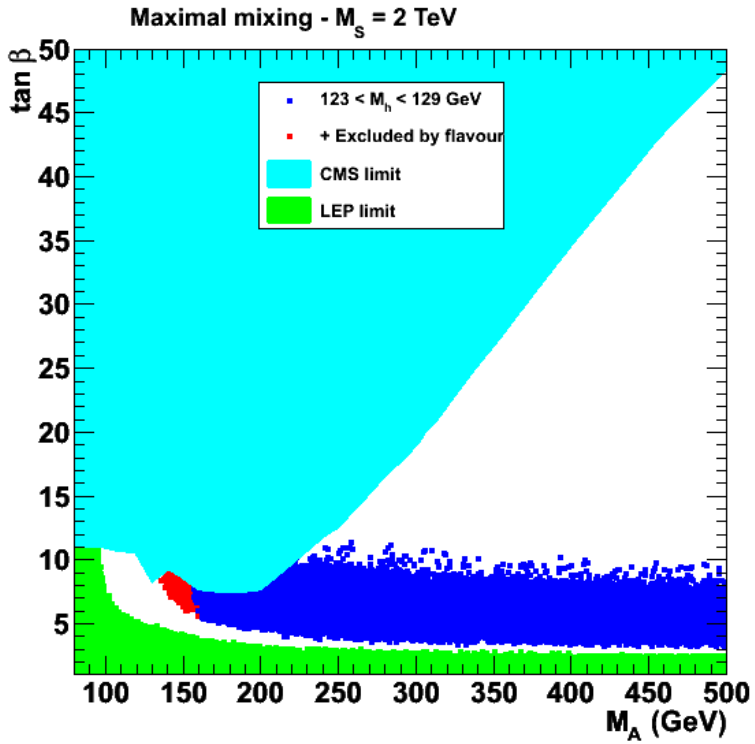
Vanishing coupling:
g^2_{hbb} or $g^2_{hVV} \leq 0.05$



A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Green: LEP Higgs search limit
Solid cyan line: CMS $A/H \to \tau^+\tau^-$ search limit at 7 TeV with 4.6/fb
Dotted cyan line: ATLAS $t \to H^+ b$ search limit at 7 TeV with 4.6/fb

Particular benchmark scenario: maximal mixing ($X_t \approx \sqrt{6} M_S$):



A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Cyan: CMS limit from $A/H \to \tau\tau$ with 4.6/fb

Red: flavour constraints: $b \to s\gamma$, $B \to \tau\nu$ and $B_s \to \mu\mu$

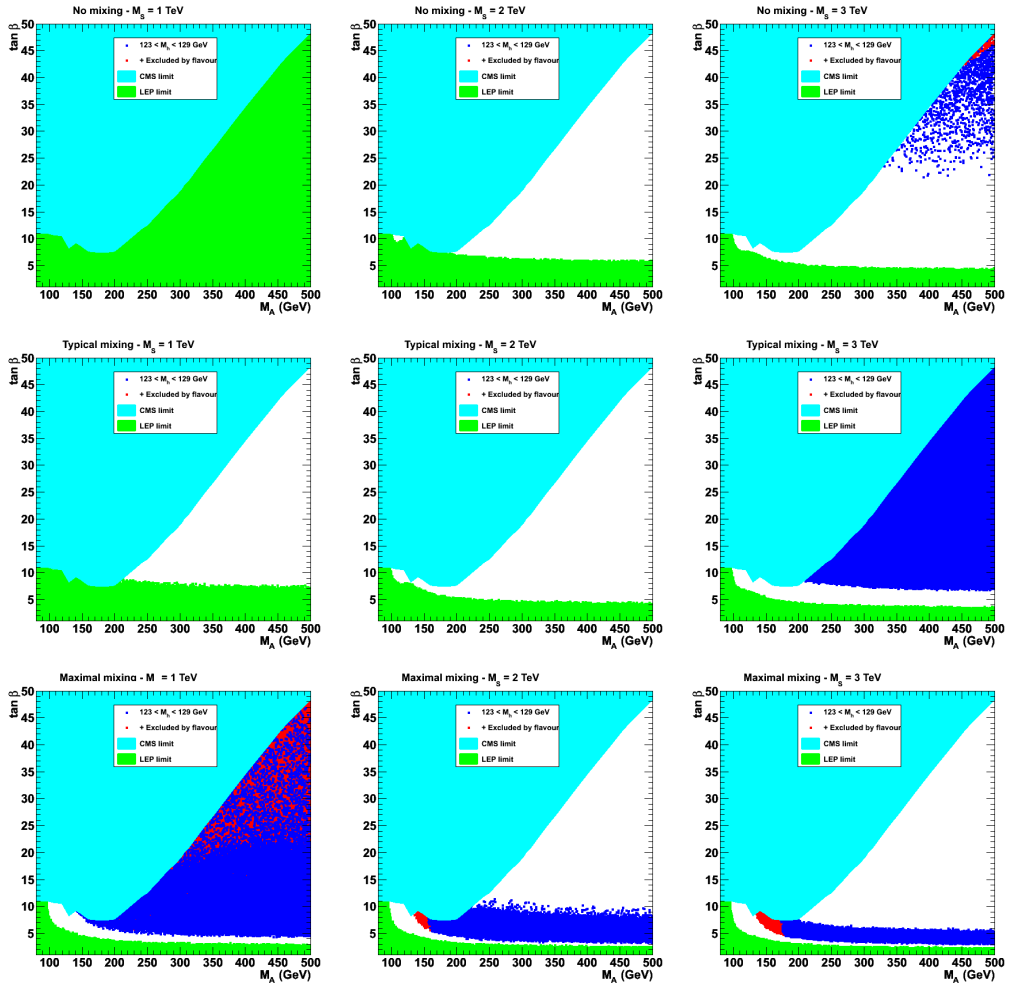
Strong constraints from the neutral Higgs searches!

Particular benchmark scenarios:

No mixing: $X_t \approx 0$

Typical mixing:
$X_t \approx M_S$

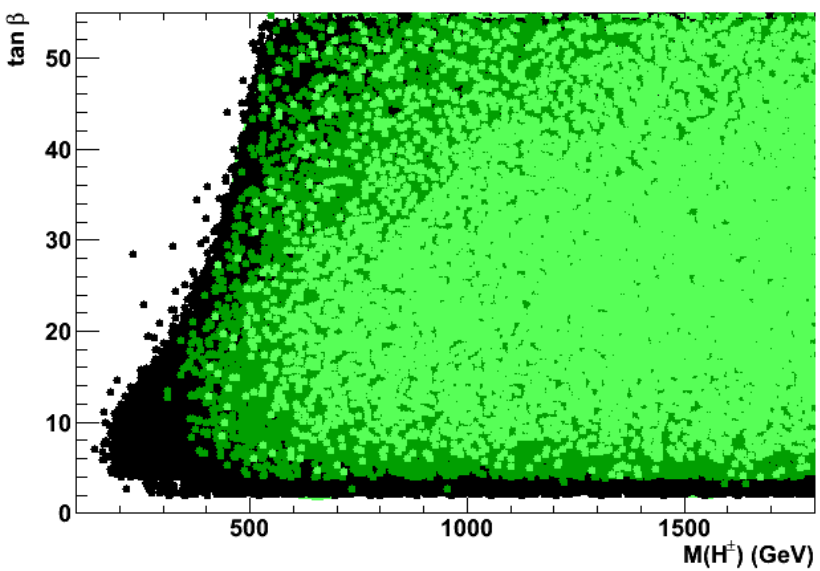
Maximal mixing:
$X_t \approx \sqrt{6} M_S$

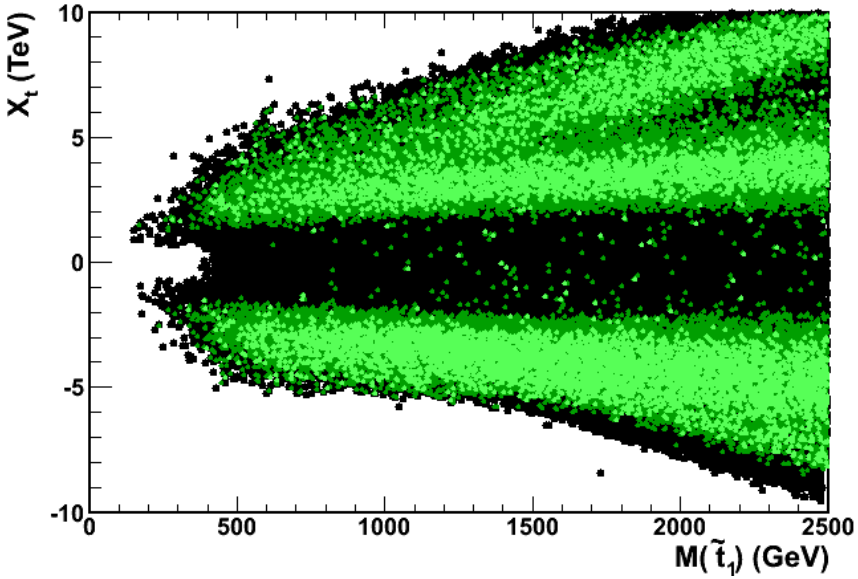


A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Strong constraints from the neutral Higgs searches for individual scenarios!

Consequences of the cross-section and decay rate measurements





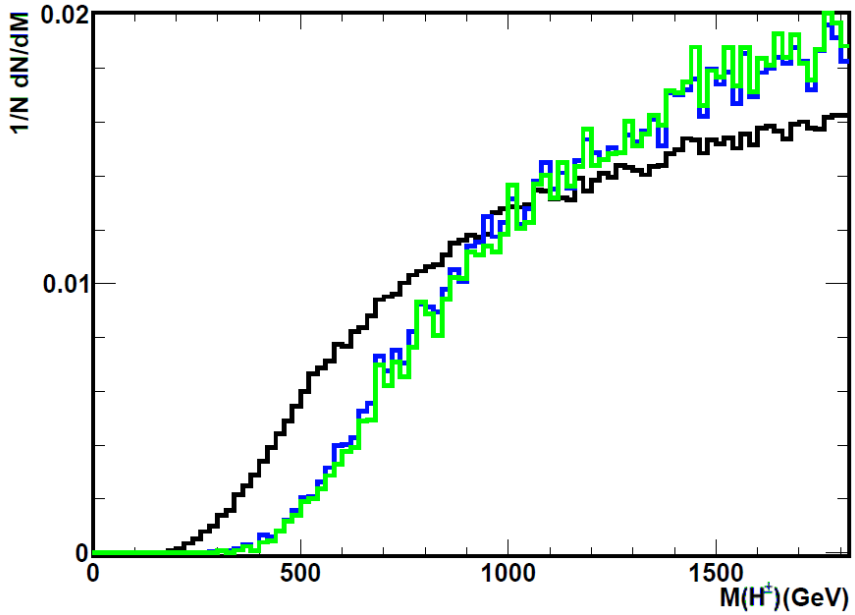
A. Arbey, M. Battaglia, A. Djouadi, FM, to appear

$\rightarrow M_{H^\pm} < 400$ GeV disfavoured by the Higgs signal strengths ($\rightarrow$ decoupling regime)

$\rightarrow |X_t| < 1.5$ TeV strongly disfavoured by the Higgs data

Black: all accepted points (including the LEP Higgs mass limit)
Dark green: points compatible at 90% C.L. with the Higgs mass and rates
Light green: points compatible at 68% C.L. with the Higgs mass and rates

Consequences of the cross-section and decay rate measurements



A. Arbey, M. Battaglia, A. Djouadi, FM, to appear

Black line: all accepted points (including the LEP Higgs mass limit)
Blue line: including constraints from M_h, $\mu_{\gamma\gamma}$, μ_{ZZ} and μ_{WW}
Green line: including constraints from M_h, $\mu_{\gamma\gamma}$, μ_{ZZ}, μ_{WW}, $\mu_{b\bar{b}}$ and $\mu_{\tau\tau}$

$\rightarrow M_{H^\pm} < 400$ GeV disfavoured by the Higgs signal strengths ($\rightarrow$ decoupling regime)

Summary

- Constrained MSSM was a nice case in hand, but now it is mandatory to go beyond!
- Understanding the LHC results in a general formulation of the MSSM: complex yet feasible!
- There still exists plenty of room for MSSM!
- Impressive impact of the Higgs searches on SUSY scenarios
- Light charged Higgs already strongly constrained
- Still too early for conclusive information from couplings/rates

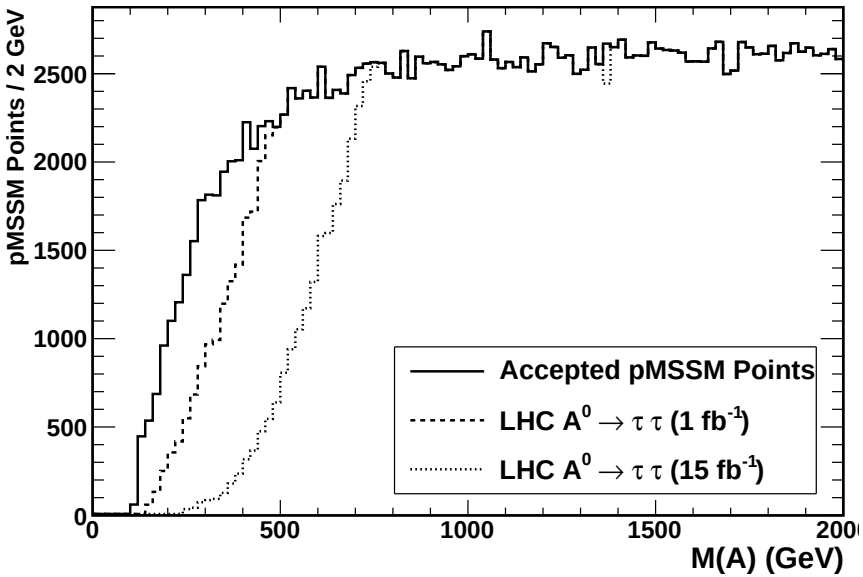
Backup

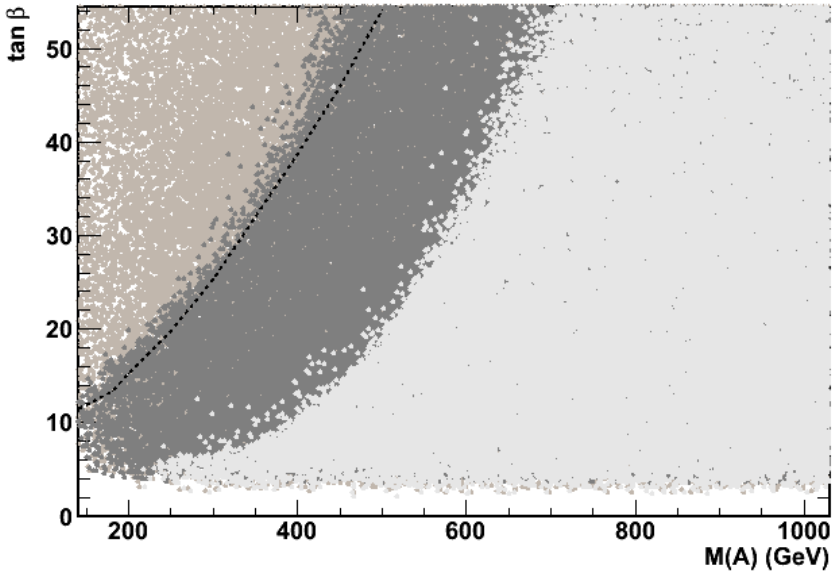
Constraints

$2.16 \times 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.93 \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-8}$
$0.56 < \mathrm{R}(B \to \tau\nu) < 2.70$
$4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau\nu) < 6.1 \times 10^{-2}$
$2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0\tau\nu) < 14.2 \times 10^{-3}$
$0.985 < \mathrm{R}_{\mu 23}(K \to \mu\nu) < 1.013$
$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
$10^{-4} < \Omega_\chi h^2 < 0.155$
+ sparticle mass upper bounds
+ Higgs search limits

Direct searches for $A \to \tau\tau$ CMS-PAS-HIG-11-009

Allowed region of $(M_A, \tan\beta)$ from full pMSSM scans for 1.1 and 15 fb^{-1} compared to published CMS expected limit

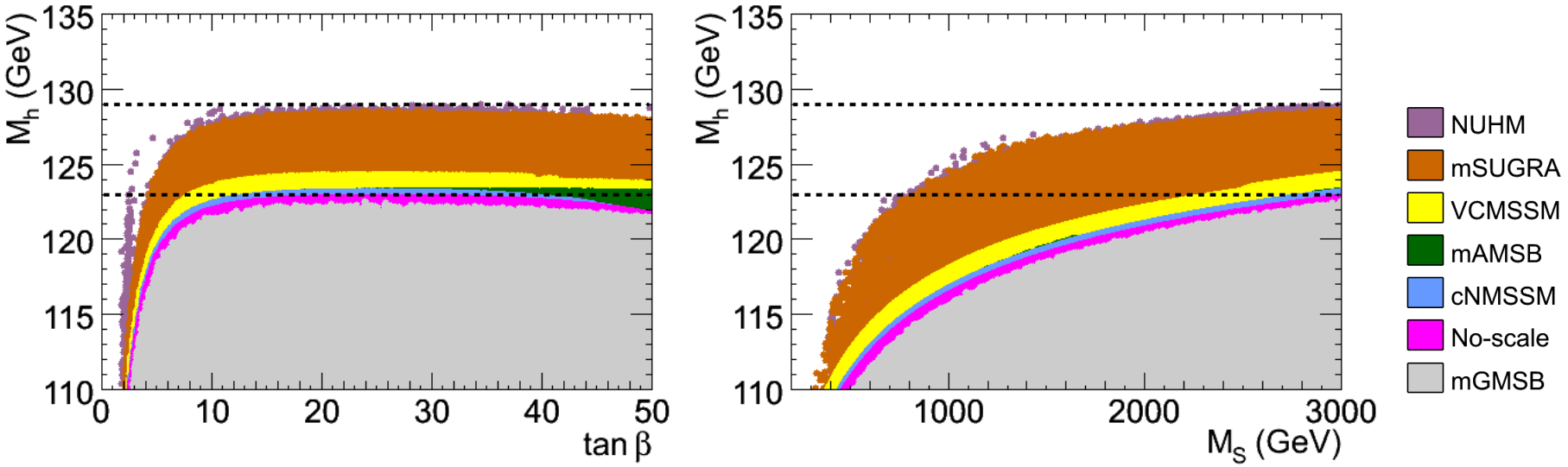




A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

Low M_A region below 350 GeV can be explored and excluded if no signal except a narrow strip around $\tan\beta$ =5.

Maximal Higgs mass

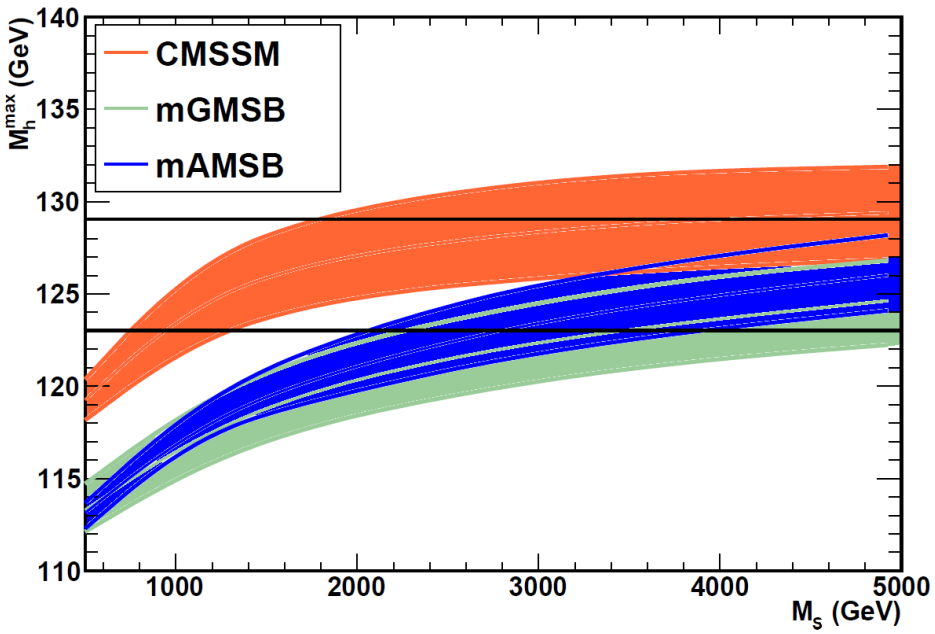


A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Several constrained models are excluded or about to be!

Impact of m_t on the Higgs mass:

m_t =170, 173 and 176 GeV



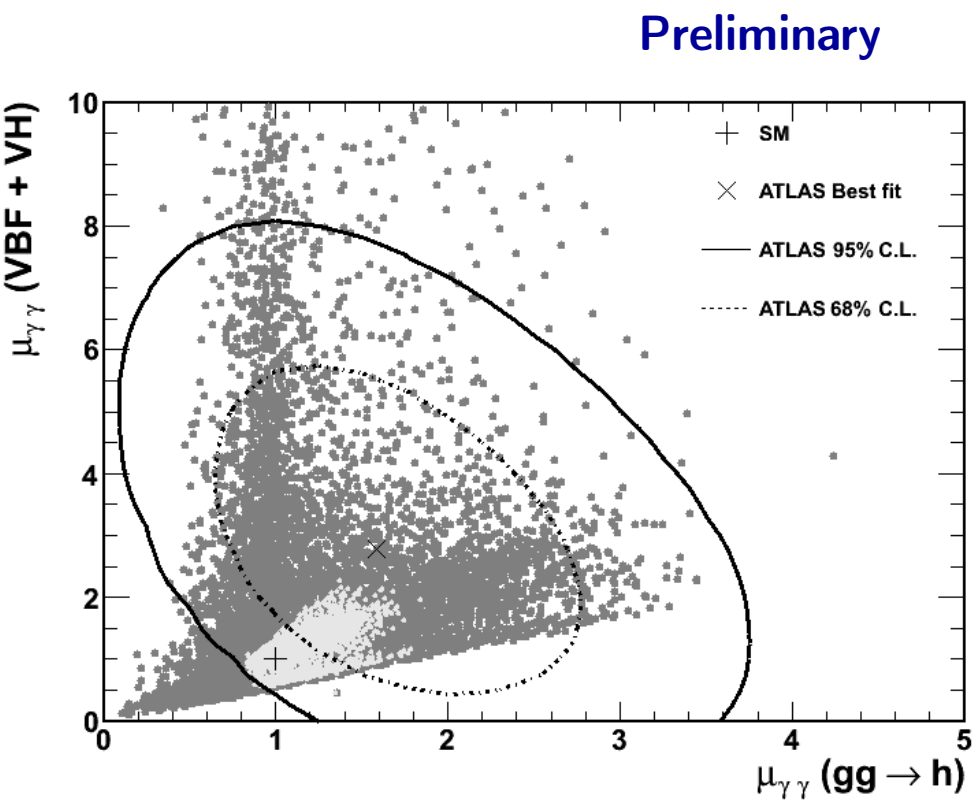
A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

The variations in the top mass is directly transmitted to the Higgs mass!

That can even resurrect mGMSB!

Consequences of the cross-section and decay rate measurements

ATLAS measurements: VBF and VH production vs. gluon fusion



A. Arbey, M. Battaglia, A. Djouadi, FM, to appear

Dark grey: compatible at 90% CL with the Higgs data

Light grey: compatible at 68% CL with the Higgs data

→ Accuracy of the data not yet sufficient to perform a meaningful fit...

→ Need for more statistics