How constrained is the MSSM?

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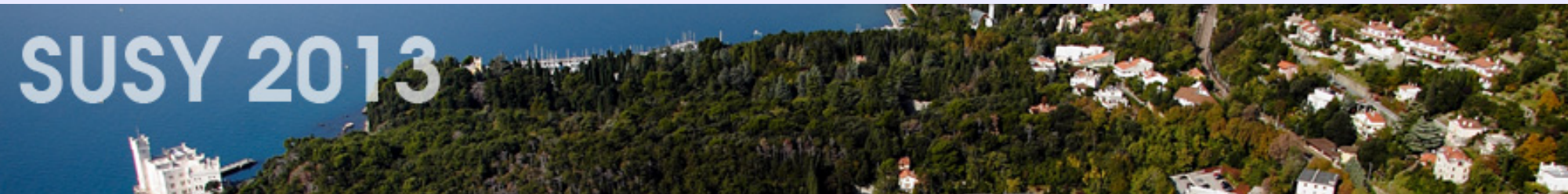
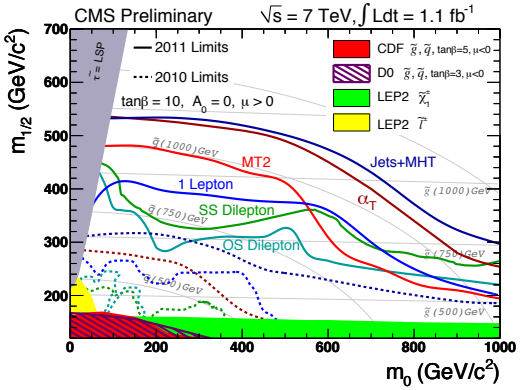
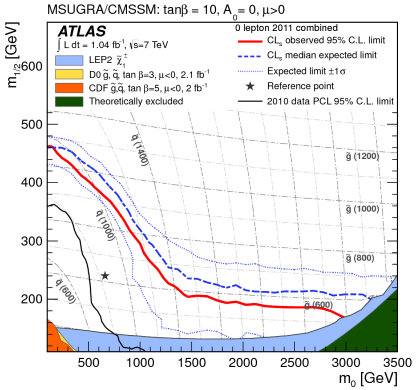
SUSY 2013, ICTP, Trieste, August 26-31, 2013



Summer 2011
(with $\sim$1 fb^{-1} of data
at 7 TeV)





SUSY searches

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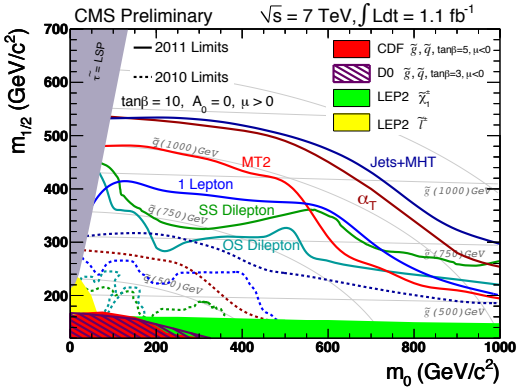
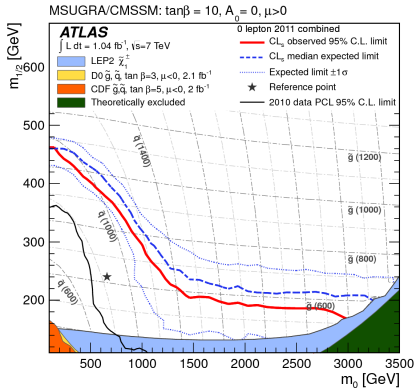
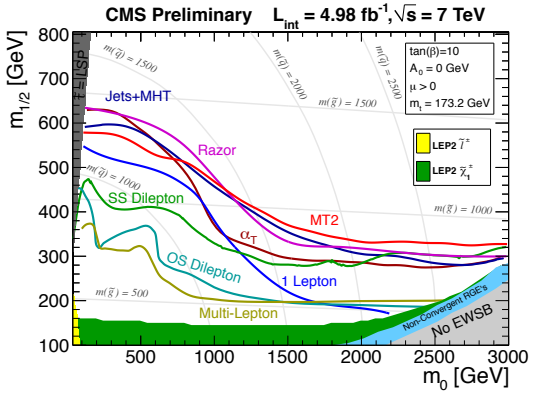
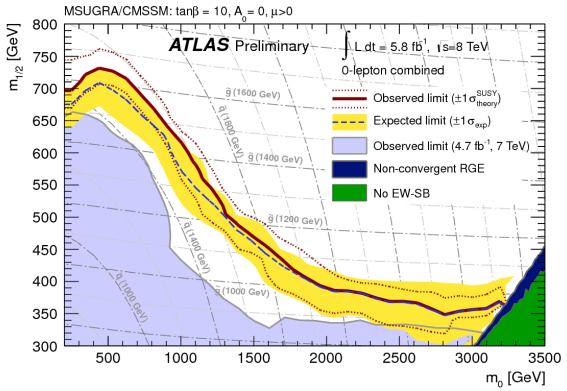




Summer 2012
(with $\sim$5 fb^{-1} of data
at 7 and 8 TeV)





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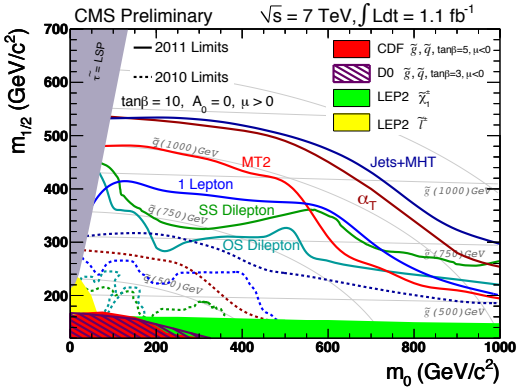

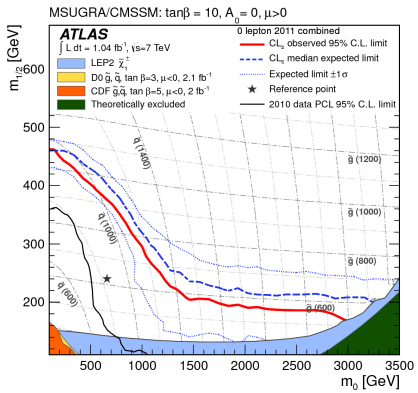

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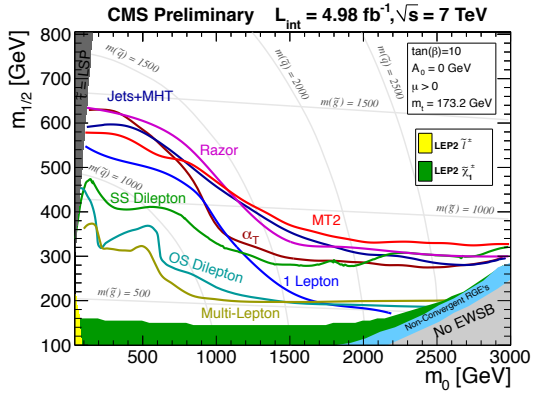
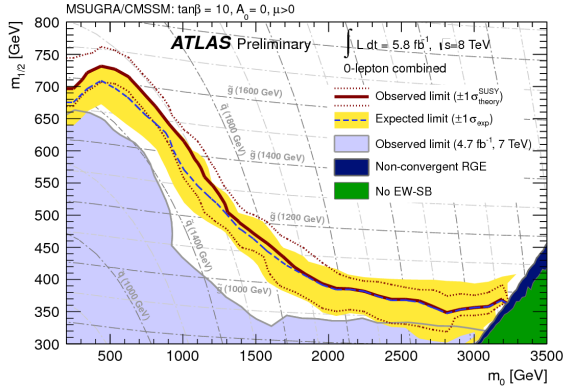
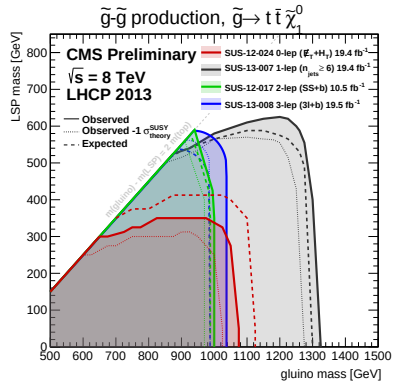
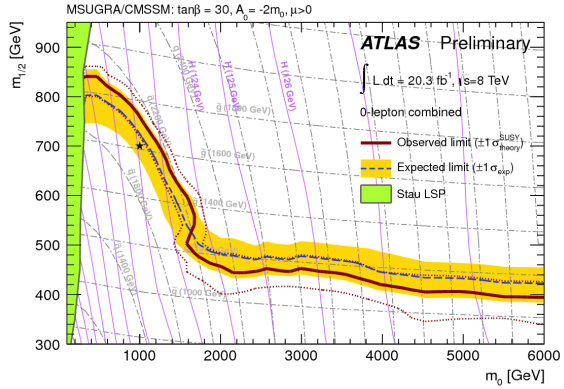




Summer 2013
(with $\sim$25 fb^{-1} of data
at 7 and 8 TeV)





SUSY masses pushed to larger and larger values!

Two important points:

- What do these limits mean exactly?

  Is low energy SUSY excluded??

  Most of the experimental limits are given for constrained or simplified MSSM scenarios

  Useful, but NOT representative of the whole MSSM!

- As a result of the current searches: the limits are pushed to larger masses

  This does not provide any conclusive idea!

  The only way to point to a specific SUSY scenario, or exclude SUSY would be to take advantage of **interplay with other sectors**

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

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, DarkSUSY)
- Determination of SUSY and Higgs mass limits (**SuperIso**, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, SusHi...)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino, MadGraph)
- 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]
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$M_{\tilde{t}_R}$	[0, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 2500]
$M_{\tilde{b}_R}$	[0, 2500]

Constraints from:

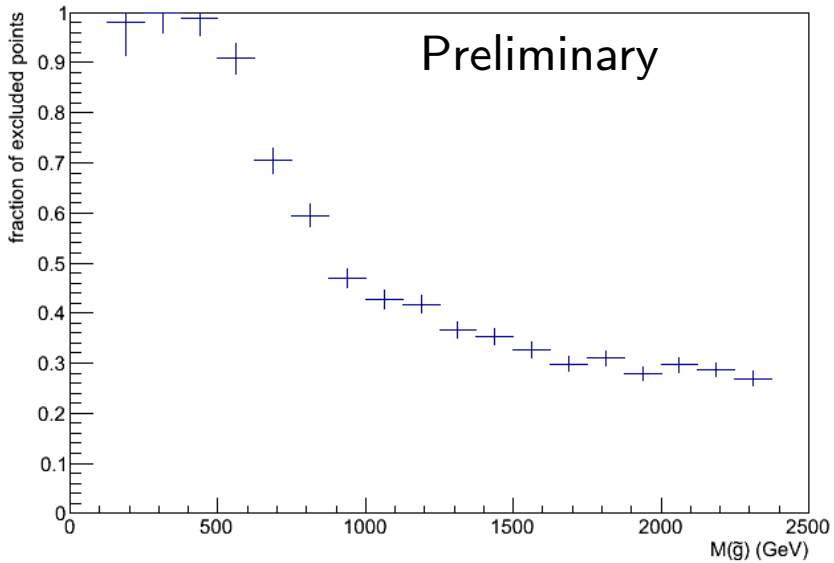
- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search limits
- Higgs mass limits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

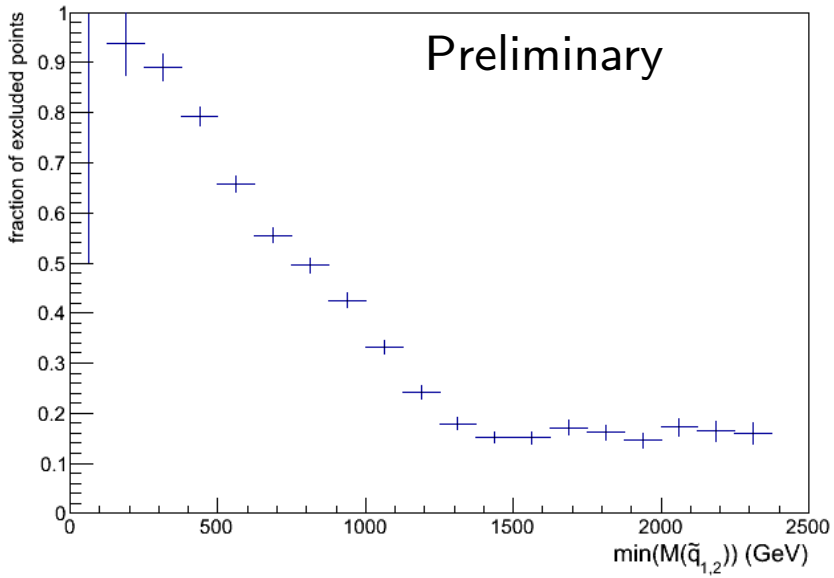
Statistics:

- more than 200M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

How the limits on squark and gluino masses change in the pMSSM?





Squarks and gluinos below 1 TeV are still allowed!

The CMSSM results cannot be applied directly to general MSSM!

Alternative path to really constrain SUSY:

Using interplay with other sectors, in particular:

- Higgs searches at the LHC
- flavour physics
- dark matter searches

The Higgs search results play a crucial role in pointing to specific MSSM scenarios!

- 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

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

- 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 $X_t = A_t - \mu / \tan\beta$

- 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.* $X_t \approx \sqrt{6} M_S$

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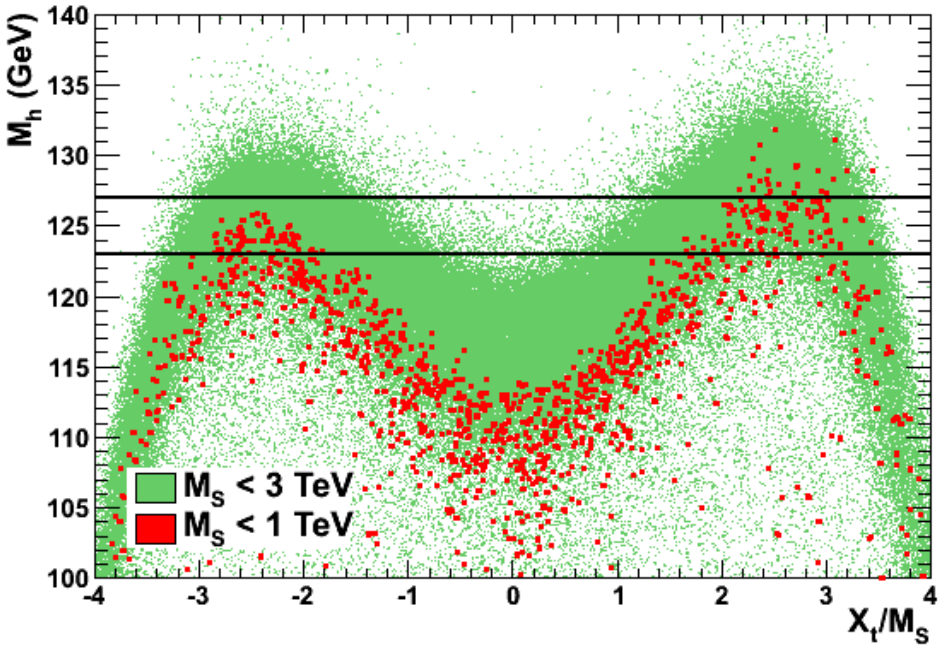


A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

$M_h \sim 125$ GeV is easily satisfied in pMSSM

No mixing cases ($X_t \approx 0$) excluded for small M_S

Signal strength is defined as:

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

LHC results:

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 2.1	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.20 ± 0.30	ATLAS+CMS
μ_{ZZ}	1.10 ± 0.22	ATLAS+CMS
μ_{WW}	0.77 ± 0.21	ATLAS+CMS
$\mu_{b\bar{b}}$	1.12 ± 0.45	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	1.01 ± 0.36	ATLAS+CMS

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

$\to$ rates are compatible with the SM Higgs

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 ($X_t \approx \sqrt{6} M_S$):

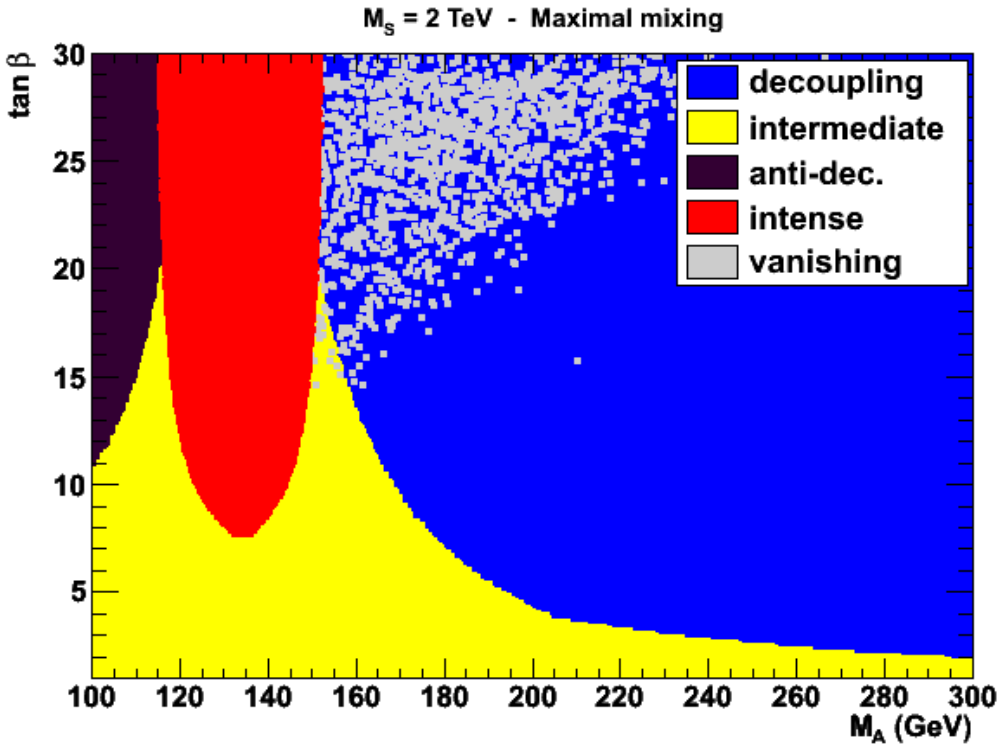
Decoupling regime:
large M_A, $\cos^2(\beta - \alpha) \leq 0.05$

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 $g^2_{hVV} \leq 0.05$



Green: LEP Higgs search limit

Solid black line: CMS $A/H \to \tau^+\tau^-$ search limit at 7+8 TeV with 17/fb

Dotted cyan line: ATLAS $t \to H^+ b$ search limit at 7 TeV with 4.6/fb

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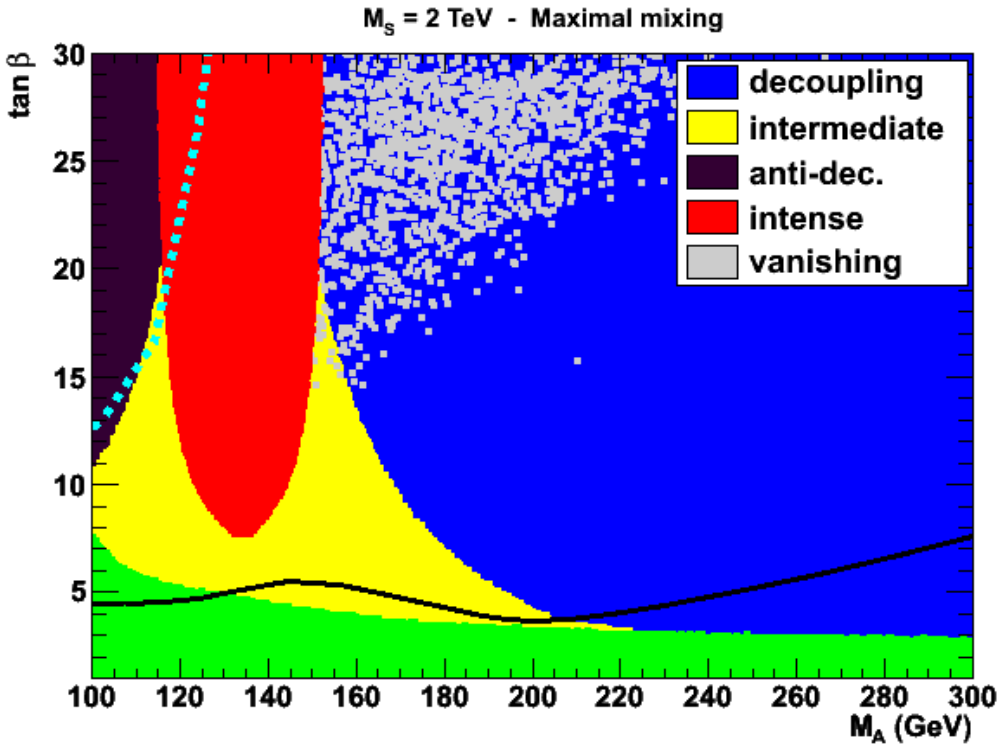

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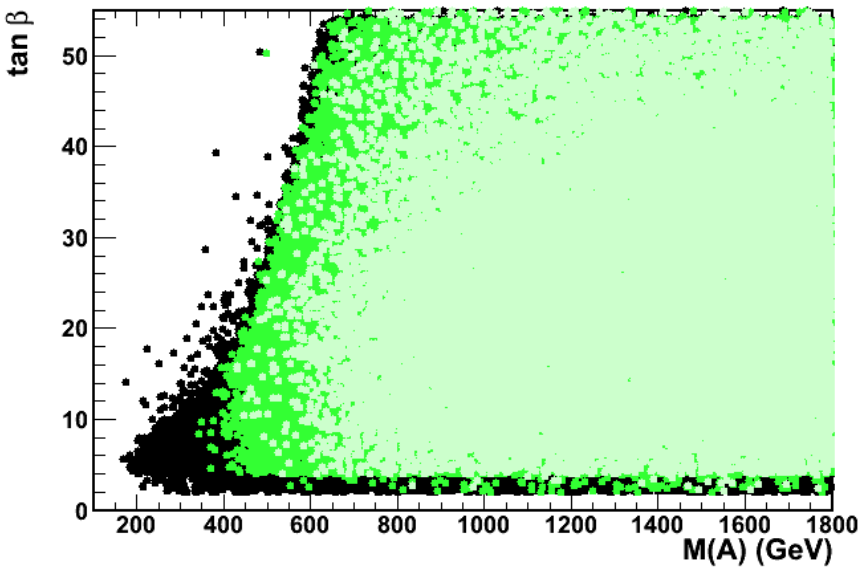
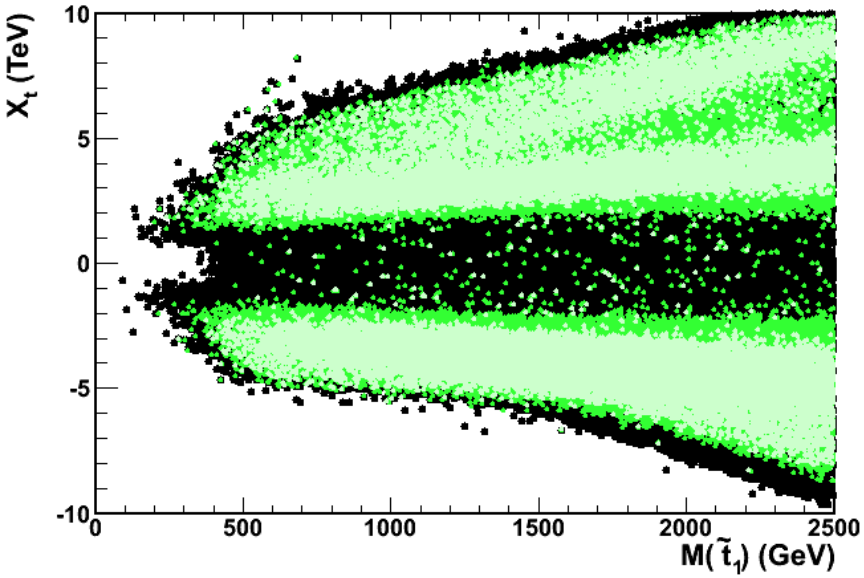
Consequences of the Higgs rate measurements in pMSSM



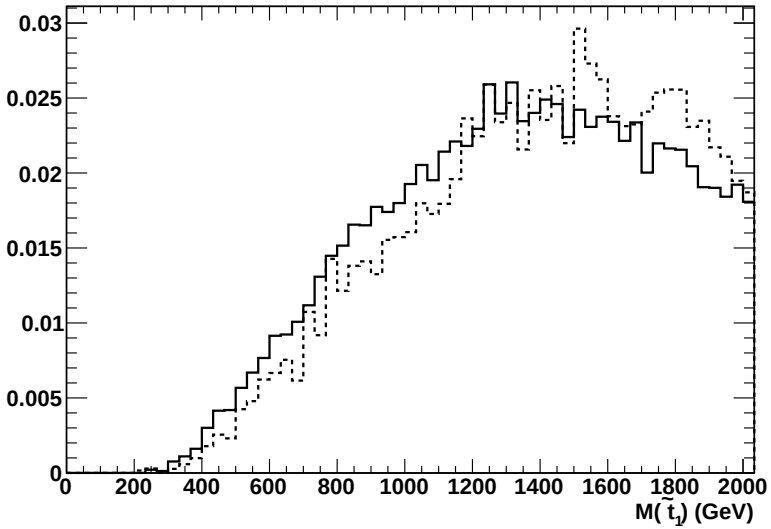


A. Arbey, M. Battaglia, A. Djouadi, FM, Phys. Lett. B720 (2013) 153

Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

$\rightarrow$ $M_A < 350$ GeV disfavoured by the Higgs signal strengths ($\rightarrow$ decoupling regime)
$\rightarrow$ Still possible to have $M_{\tilde{t}} < 500$ GeV!
$\rightarrow$ $|X_t| < 1.5$ TeV strongly disfavoured by the Higgs data

Favoured region: χ^2 analysis and normalized distributions



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

Solid lines: accepted pMSSM points with $123 < M_{\boldsymbol{h}} < 129$ GeV

Dashed lines: points favoured at 90% C.L. by $M_{\boldsymbol{h}}$, BR($h \to \gamma\gamma$), BR($h \to ZZ$) and BR($h \to b\bar{b}$)

$\to$ Heavy stops favoured by the LHC Higgs results,
but stops as light as 400 GeV still possible!

MSSM can be strongly constrained also by Heavy Higgs searches

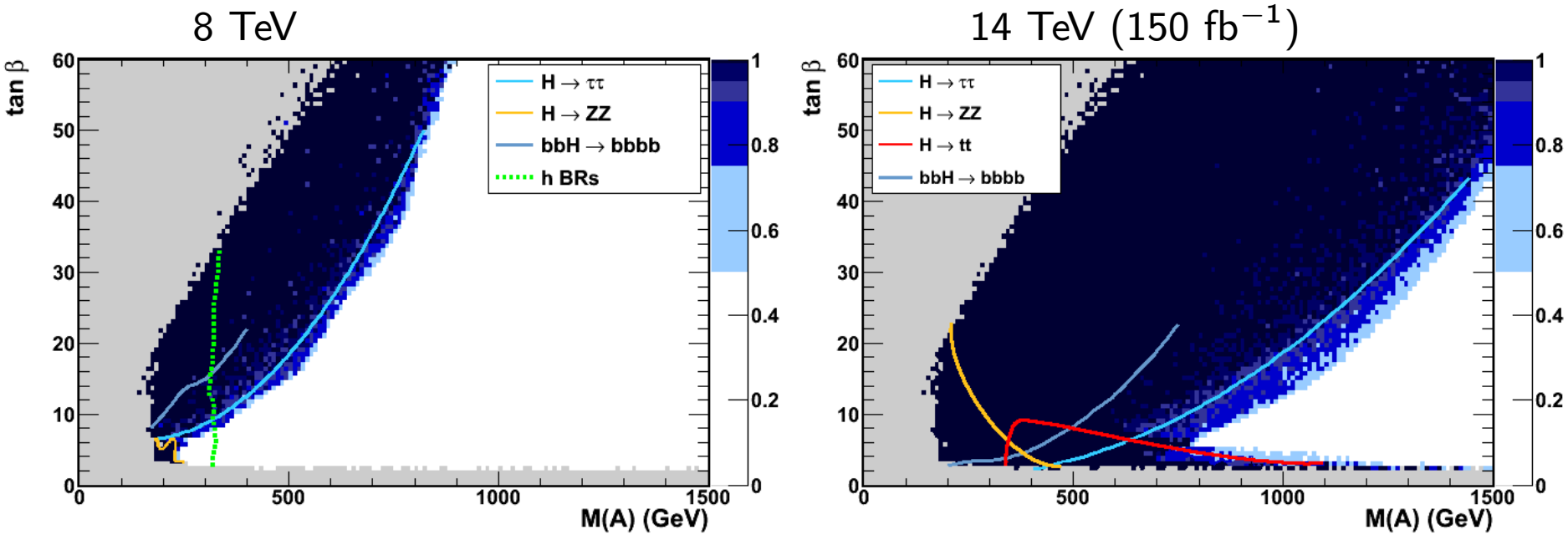
$\rightarrow$ LHC experiments focussed mainly on $H/A \rightarrow \tau^+\tau^-$ so far

However:

- limits are given for the M_h^{max} scenario
- They can be falsified in case of light SUSY particles
  $\rightarrow$ Higgs decays to MSSM particles open (i.e. decays to light staus)
- Important to use several channels

$\rightarrow$ **Look for other channels, with the largest strengths**

Complementarity channels: $H \to ZZ, bb, tt, hZ, hh$



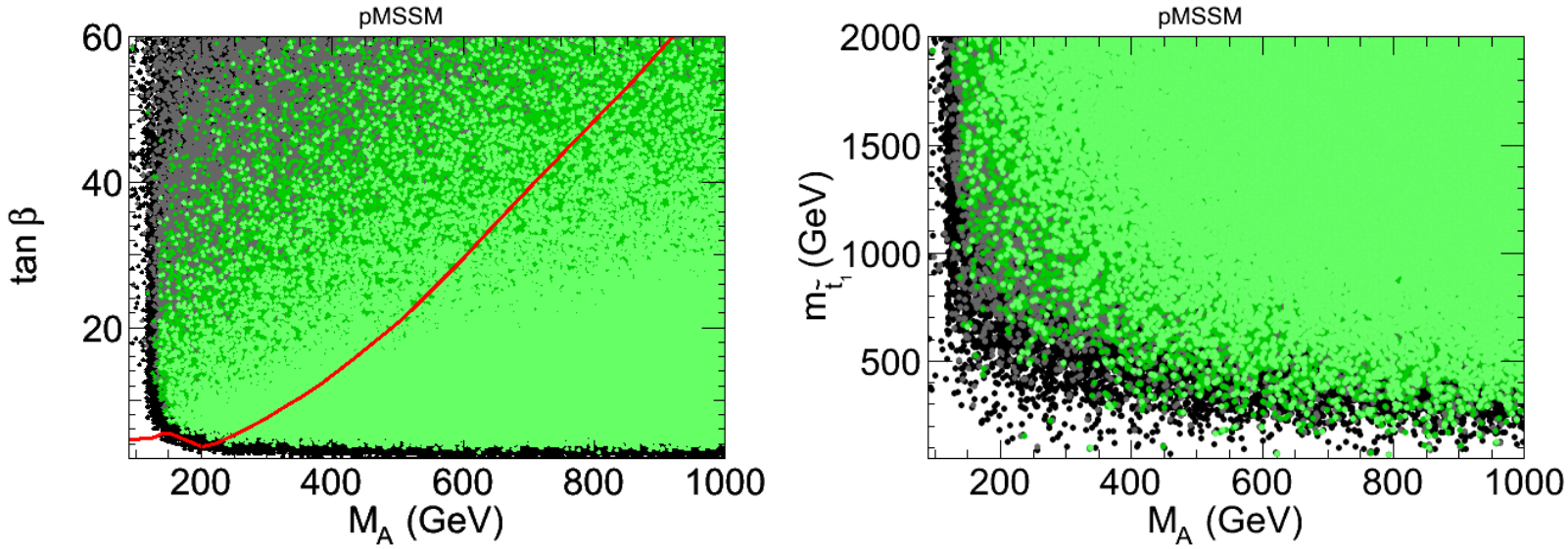
A. Arbey, M. Battaglia, FM, Phys.Rev. D88 (2013) 015007

lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
colour (blue) scale: fraction of excluded points

→ Some points inside the $H \to \tau\tau$ excluded region still survive

→ Other channels ($H \to ZZ$, $H \to t\bar{t}$, ...) will help probing the small $\tan\beta$ region

Same region also probed by BR($B_s \to \mu^+\mu^-$)...

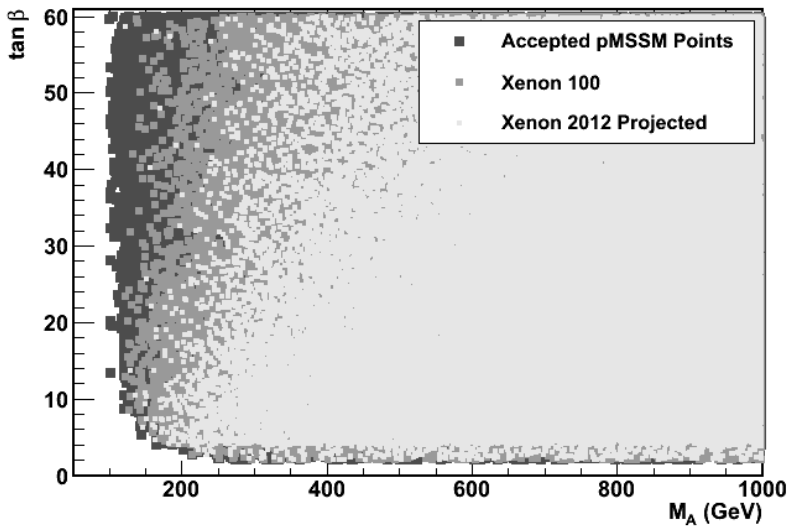


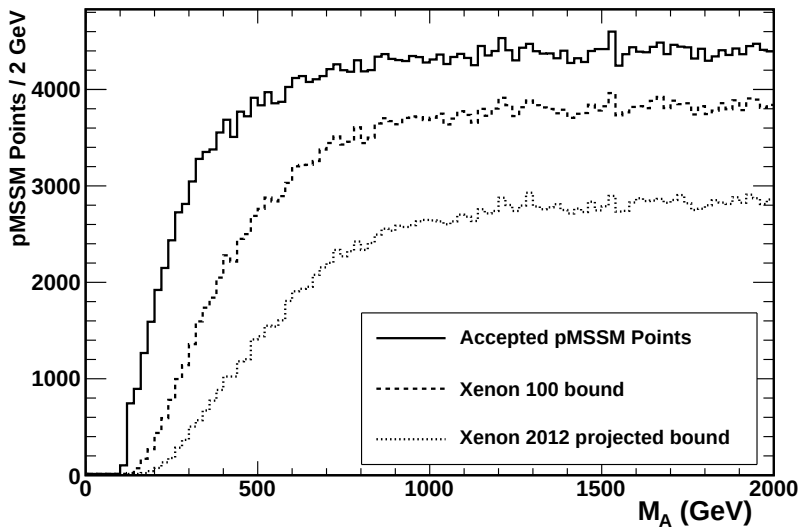
A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

Black points: all the valid pMSSM points
Gray points: $123 < M_h < 129$ GeV
Dark green points: in agreement with the latest BR($B_s \to \mu^+\mu^-$)
Light green points: in agreement with the ultimate LHCb BR($B_s \to \mu^+\mu^-$) measurement
Red line: excluded at 95% C.L. by the latest CMS $A/H \to \tau^+\tau^-$ searches

$\to$ Strong constraints for small M_A and large $\tan\beta$

... Same region also probed by dark matter direct detection





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

Results and sensitivity similar to those from $B_s \to \mu^+\mu^-$ and $A/H \to \tau^+\tau^-$, with different couplings/sectors probed

$\to$ **Strong constraints for small M_A and large** $\tan\beta$

Summary

- SUSY searches alone are not sufficient to exclude SUSY or to point to a specific scenario
- Alternative path to test the MSSM at the LHC is through the Higgs sector!
- Complementarity of the light and heavy Higgs searches
- Of importance are also consistency checks using data from flavour and dark matter sectors
- So far MSSM is doing fine!

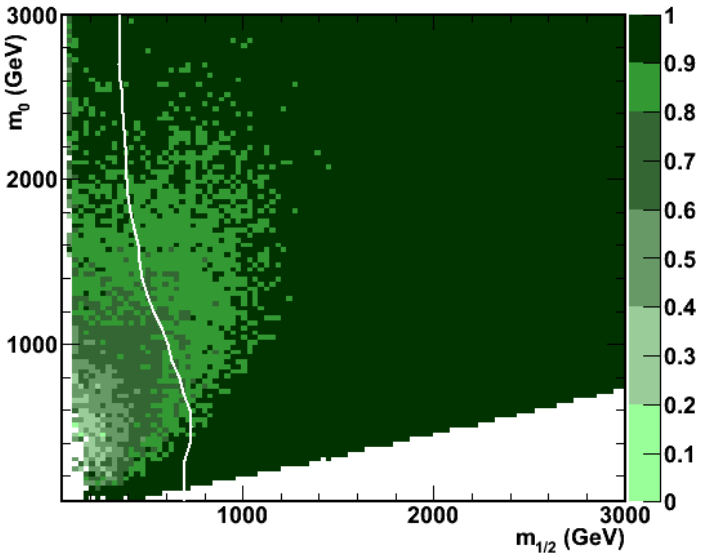
$\rightarrow$ **low energy SUSY is still alive!**

Backup

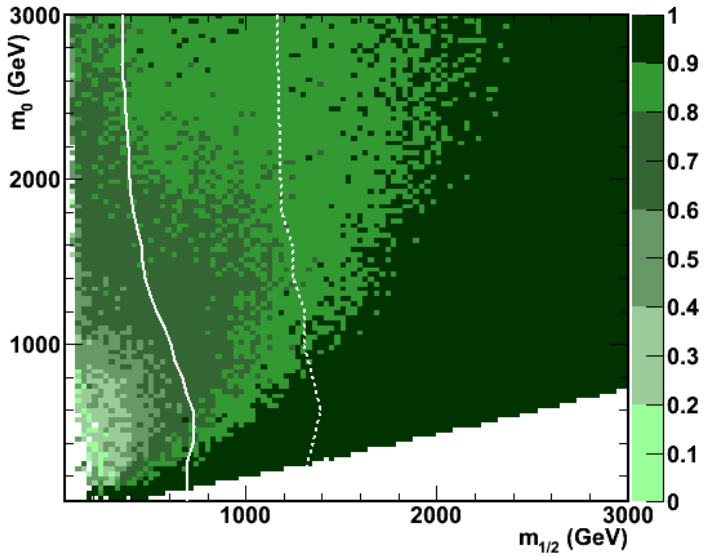
$2.63 \times 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.23 \times 10^{-4}$
$0.99 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-) < 6.47 \times 10^{-9}$
$0.40 \times 10^{-4} < \mathrm{BR}(B \to \tau\nu) < 1.88 \times 10^{-4}$
$4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau\nu) < 6.1 \times 10^{-2}$
$2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0\tau\nu) < 14.2 \times 10^{-3}$
$0.985 < \mathrm{R}_{\mu 23}(K \to \mu\nu) < 1.013$
$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
$10^{-4} < \Omega_\chi h^2 < 0.155$
+ sparticle mass upper bounds
+ Higgs search limits

Fraction of CMSSM points compatible with BR($B_s \to \mu^+\mu^-$)

Current constraints



Ultimate constraints

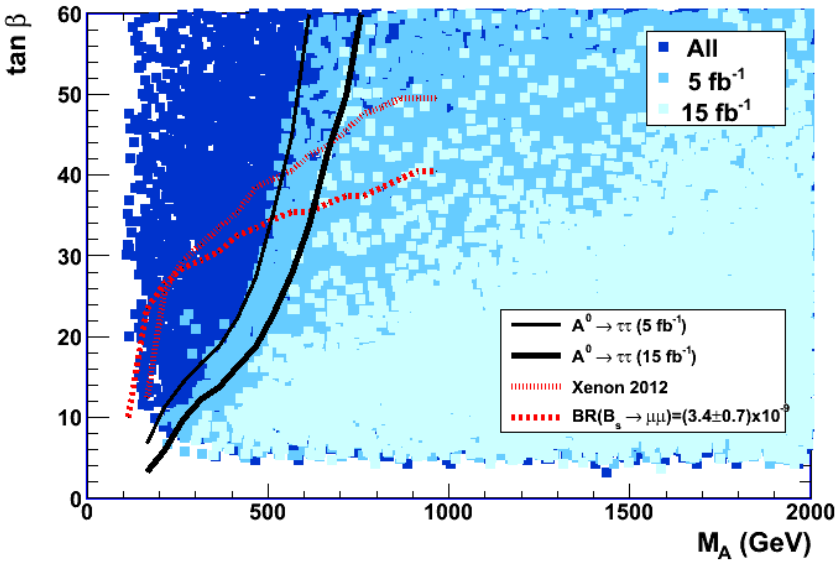


A. Arbey, M. Battaglia, FM, D. Martinez Santos, Phys.Rev. D87 (2013) 035026

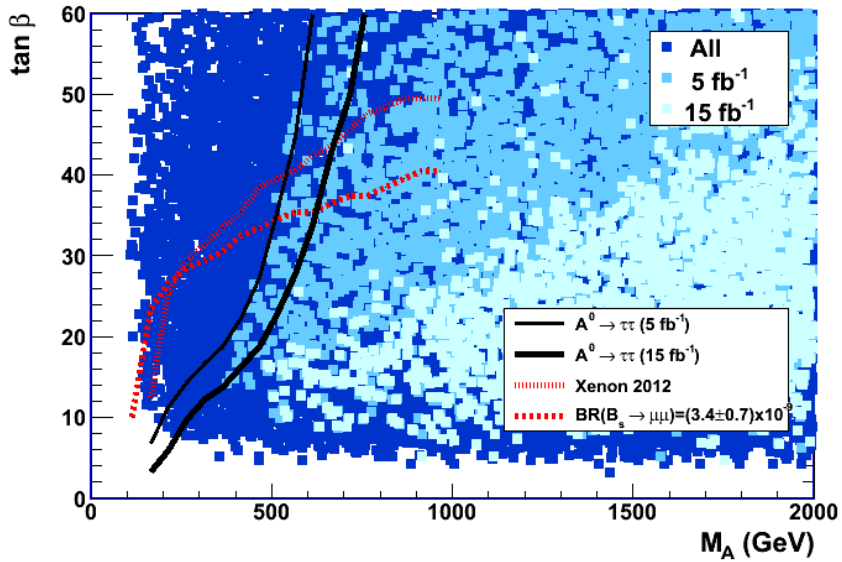
Continuous line: ATLAS SUSY searches at 8 TeV with 5.8 fb^{-1} of data
Dotted line: reach estimated at 14 TeV with 300 fb^{-1}

Constraints from flavour physics, dark matter direct detection, SUSY and Higgs searches

Without Higgs decay rate constraints



With Higgs decay rate constraints

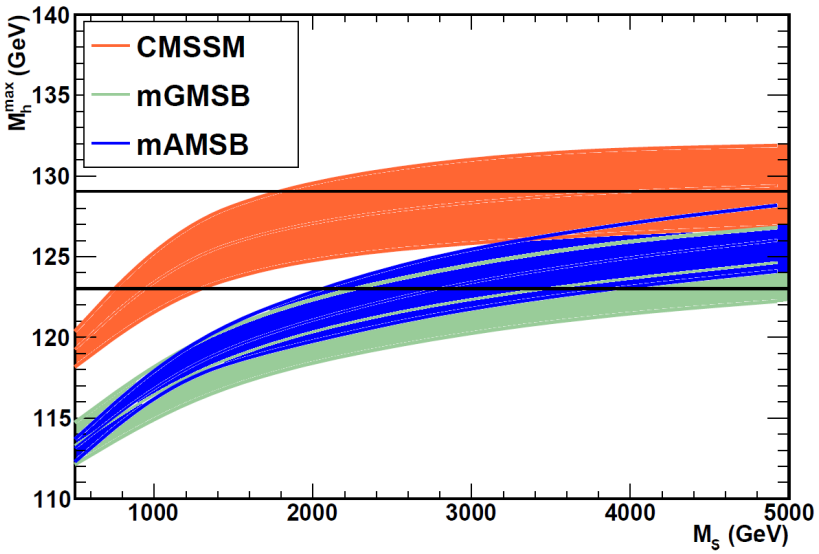


A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

Once putting everything together the allowed region is really squeezed!

Impact of m_t on the Higgs mass:

m_t =170, 173 and 176 GeV



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

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

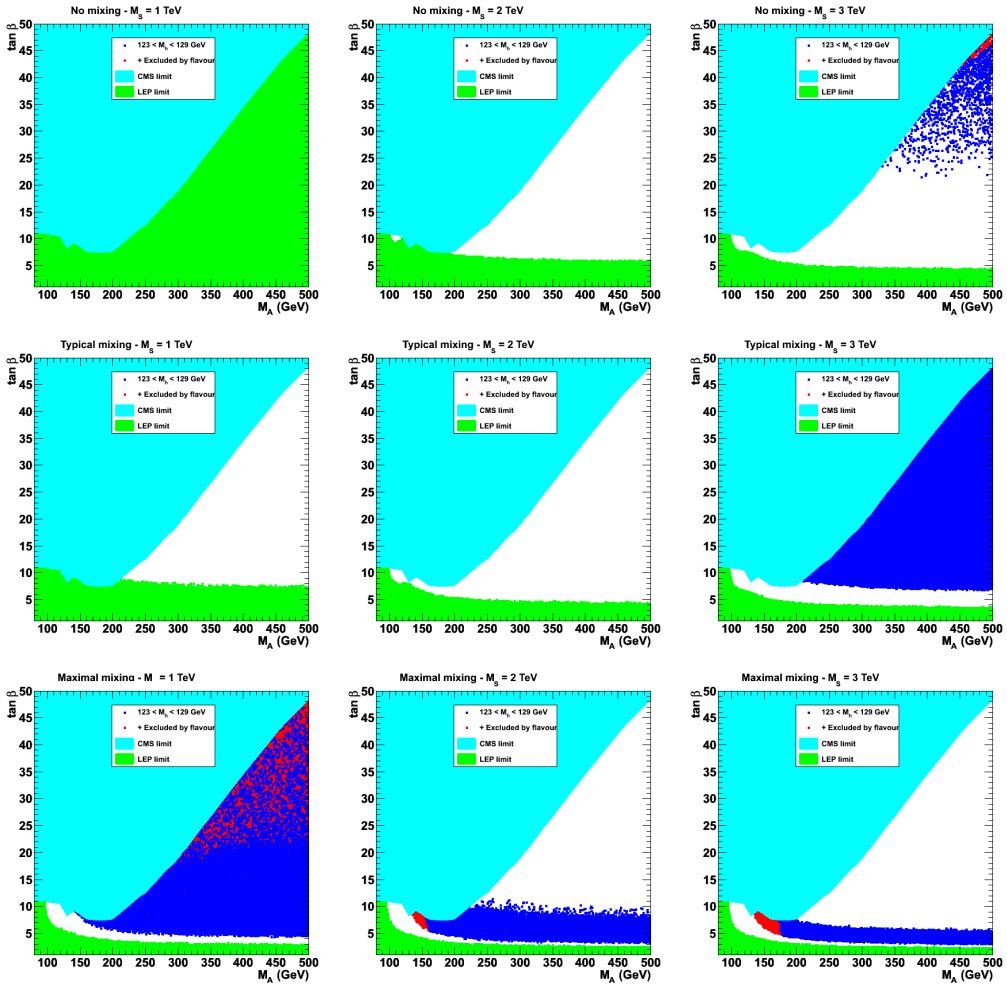
That can even resurrect mGMSB!

Particular benchmark scenarios:

No mixing: $X_t \approx 0$

Typical mixing:
$X_t \approx M_S$

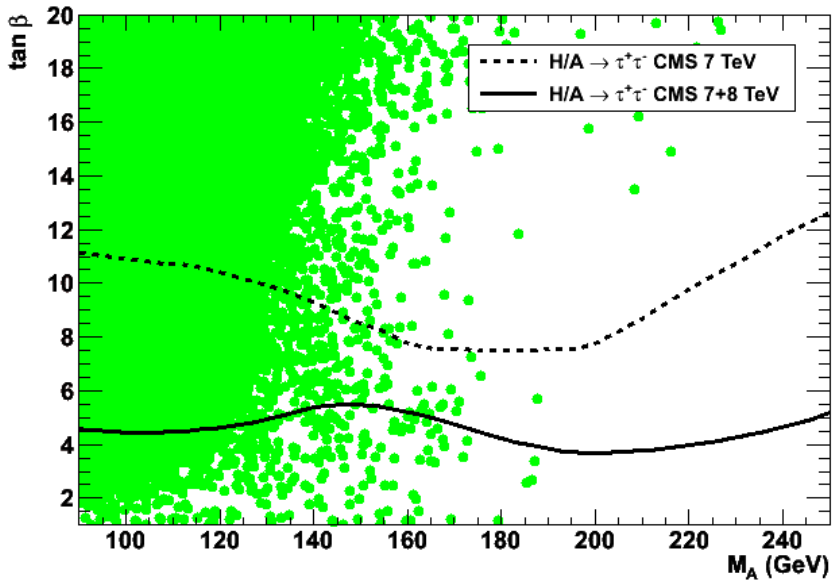
Maximal mixing:
$X_t \approx \sqrt{6} M_S$



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

Strong constraints from the neutral Higgs searches for individual scenarios!

Light or heavy Higgs at 126 GeV??



A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

Green: $122 < M_{\boldsymbol{H}} < 129$ GeV

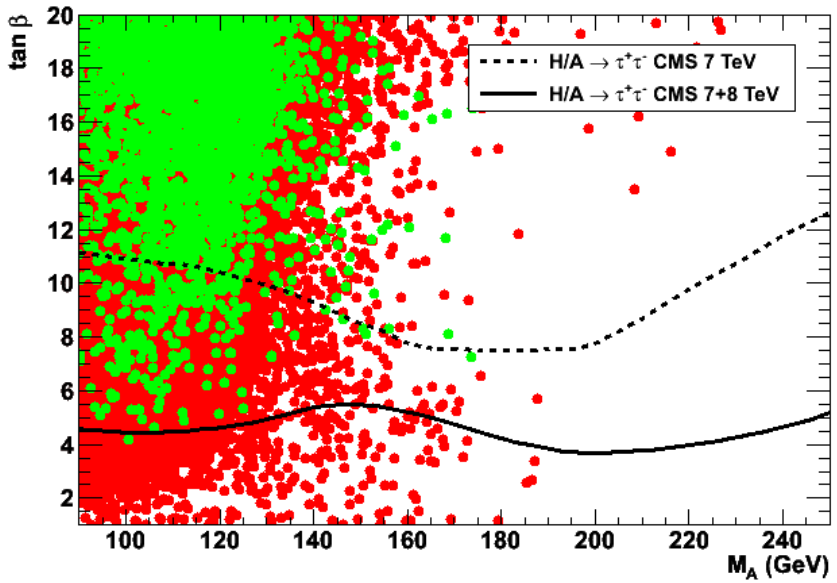
Red: + excluded by BR($B \to X_{\boldsymbol{s}}\gamma$)

Blue: + excluded by BR($B \to \tau\nu$)

Yellow: + excluded by BR($B_{\boldsymbol{s}} \to \mu^+\mu^-$)

$\to$ 126 GeV heavy Higgs scenario excluded by flavour constraints

Light or heavy Higgs at 126 GeV??



A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

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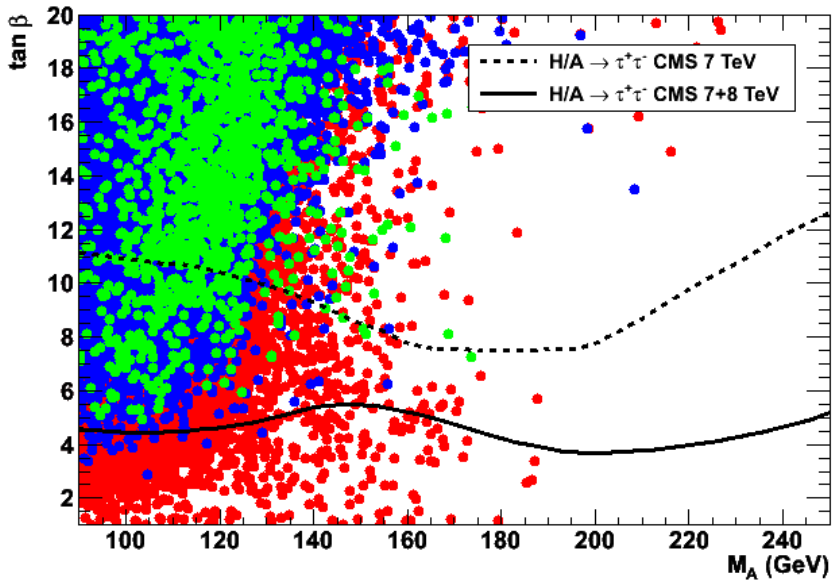

A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

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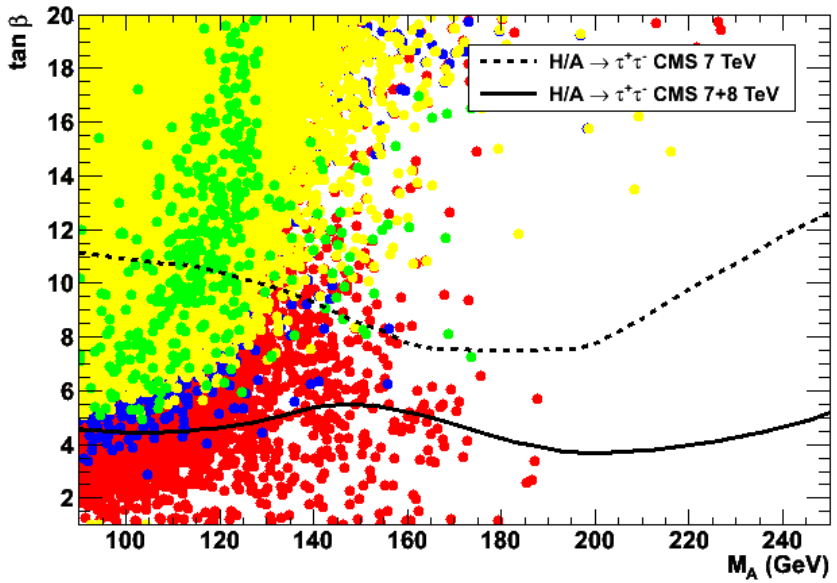

A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

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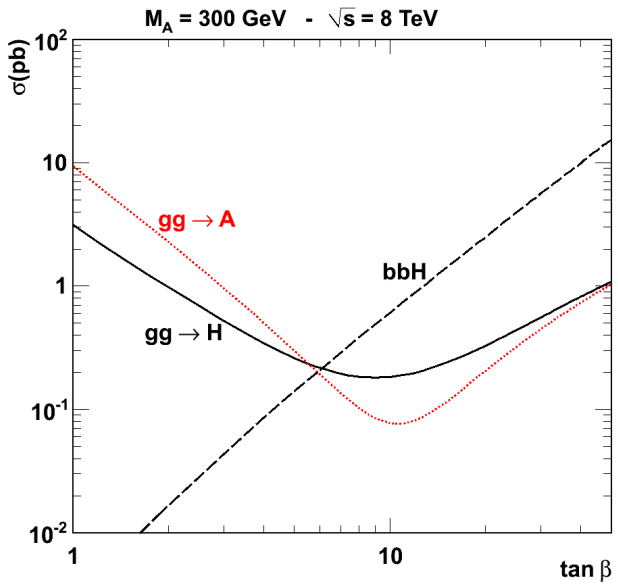
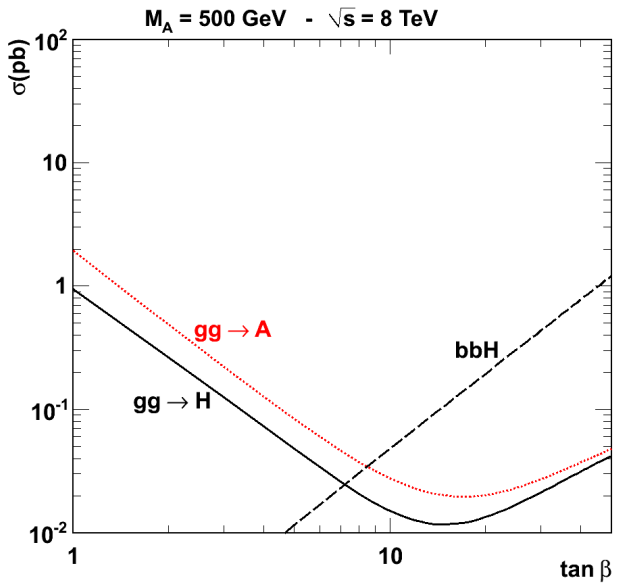
Blue: + excluded by BR($B \to \tau\nu$)

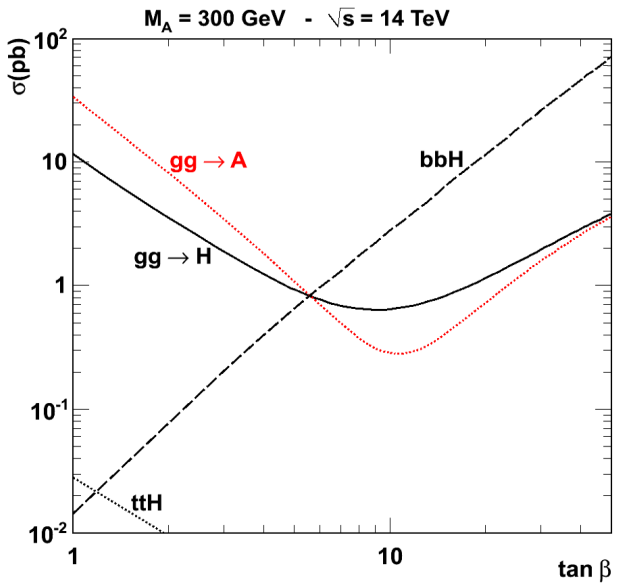
Yellow: + excluded by BR($B_{\boldsymbol{s}} \to \mu^+\mu^-$)

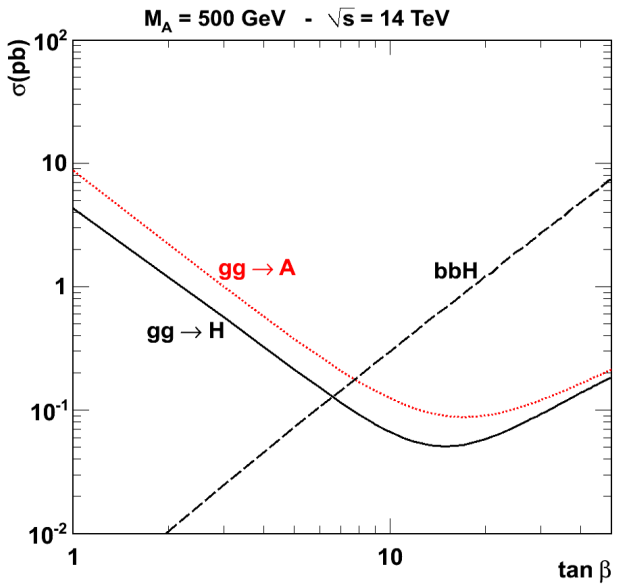
$\to$ 126 GeV heavy Higgs scenario excluded by flavour constraints

Heavy Higgs production



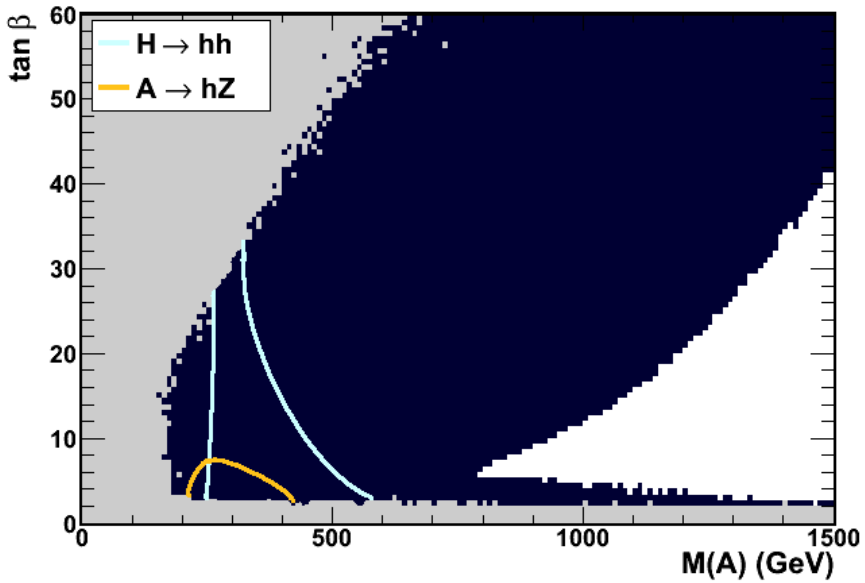






Other future searches of interest: light Higgs production

14 TeV (150 fb^{-1})



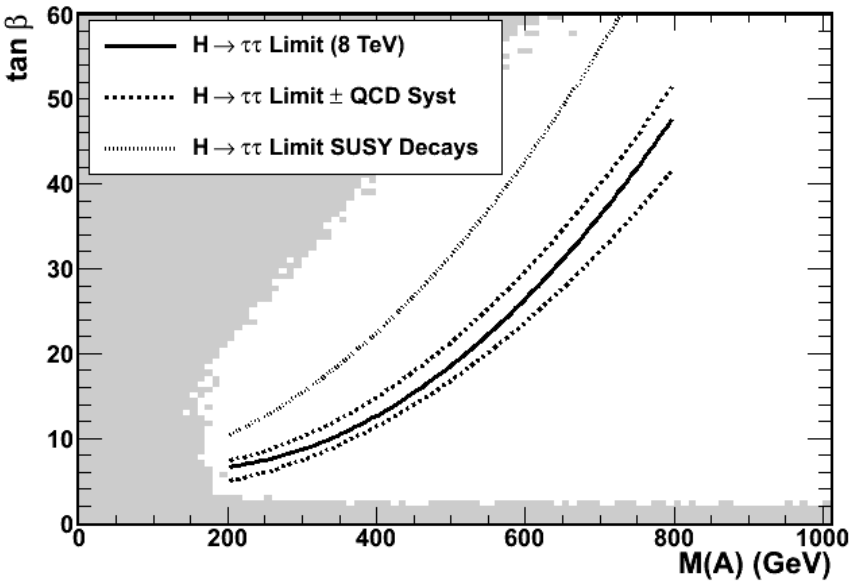
lines: limits corresponding to an exclusion of 99.9% of the points
grey points: excluded by dark matter, flavour physics and Higgs mass constraints
dark blue points: excluded by the other heavy Higgs searches

$\rightarrow$ These channels will probe the small to intermediate tan β region

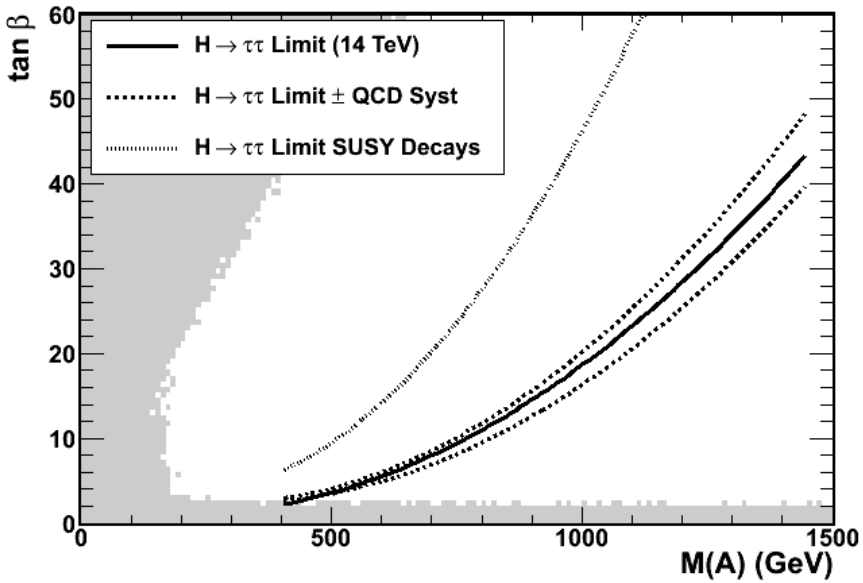
QCD uncertainties (PDF, α_s, m_t, ...) limiting factor for the $H/A \to \tau^+\tau^-$ constraints

Additional H to SUSY particle decays also limiting factor

8 TeV



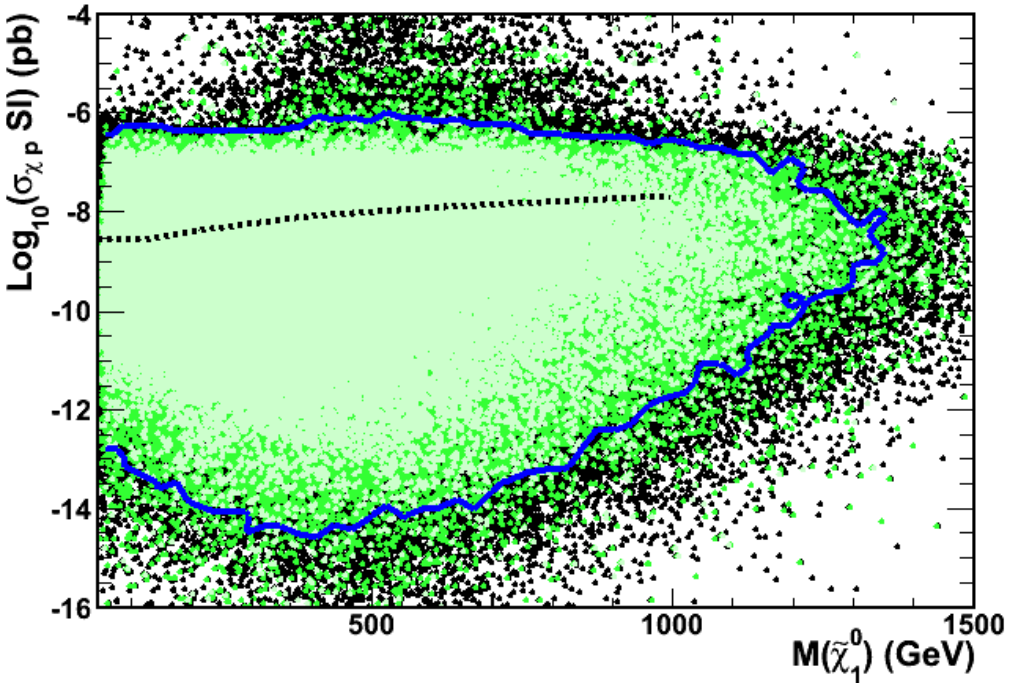
14 TeV



Existence of SUSY decays much more limiting than QCD uncertainties

→ **Exclusion limits should not be blindly applied**

pMSSM points and XENON dark matter exclusion limit



A. Arbey, M. Battaglia, A. Djouadi, FM, Phys.Lett. B720 (2013) 153

Black: all valid points
Dark green: points compatible at 90% C.L. with the LHC Higgs search results
Light green: points compatible at 68% C.L. with the LHC Higgs search results

Dotted line: 2012 XENON-100 limit at 95% C.L.

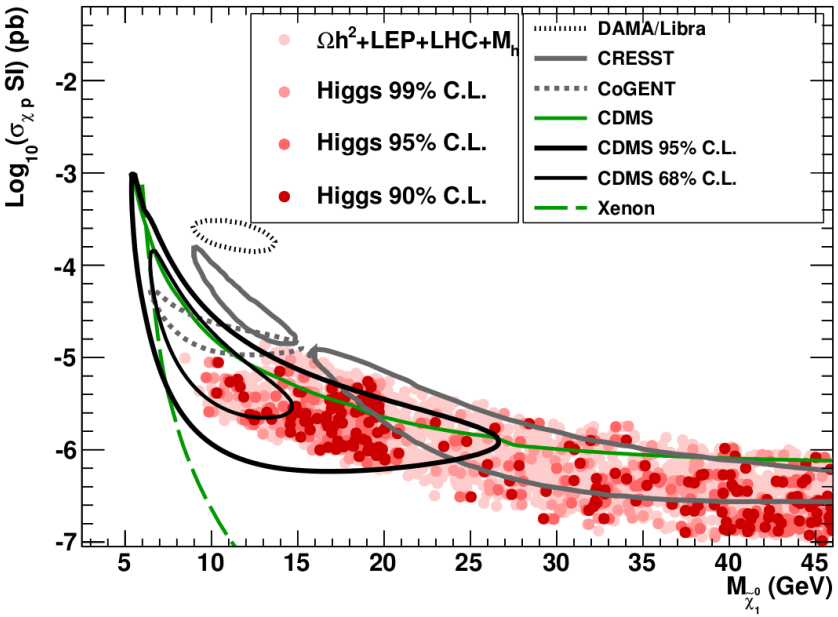
28% of the valid points are excluded by XENON-100

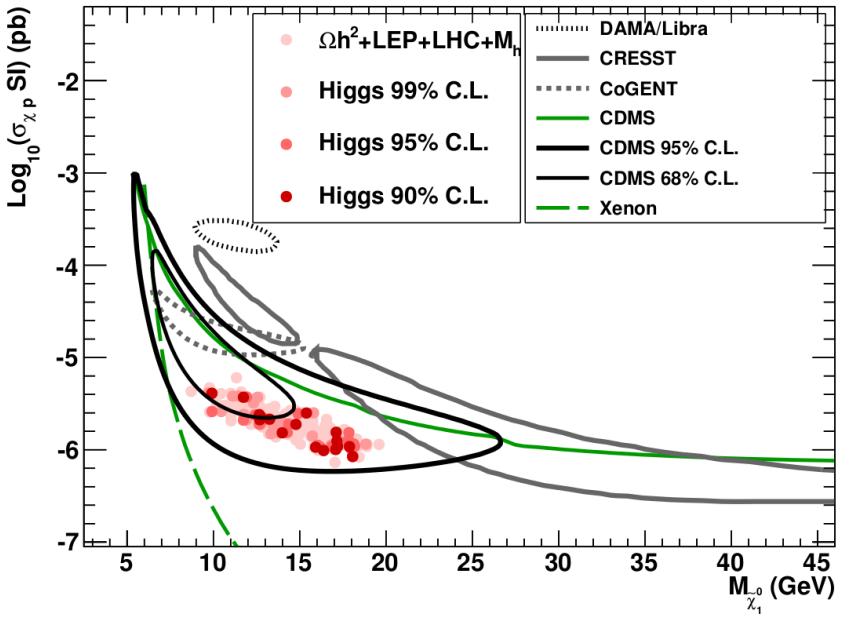
Can pMSSM provide solutions compatible with CoGeNT/CRESST/DAMA/CDMS data?

→ **Low mass neutralino of mass ~ 10 GeV?**

Not possible in constrained MSSM...

Dedicated scans focusing on a region with $m_{\tilde{\chi}^0} < 50$ GeV





A. Arbey, M. Battaglia, FM, arXiv:1308.2153

loose relic density constraint:
$10^{-4} < \Omega_\chi h^2 < 0.163$

tight relic density constraint:
$0.076 < \Omega_\chi h^2 < 0.163$