

Implications of LHC Higgs and SUSY searches for MSSM

Nazila Mahmoudi

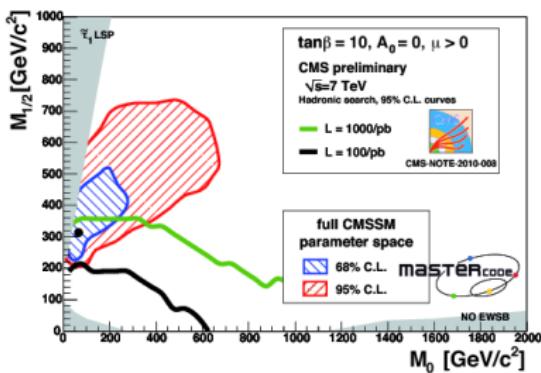
CERN TH & LPC Clermont-Ferrand

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

**GDR Terascale @ Paris
LPNHE, November 5-7, 2012**

Before the start of the LHC:

high expectation for an early discovery of SUSY particles



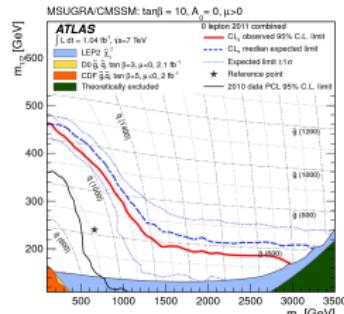
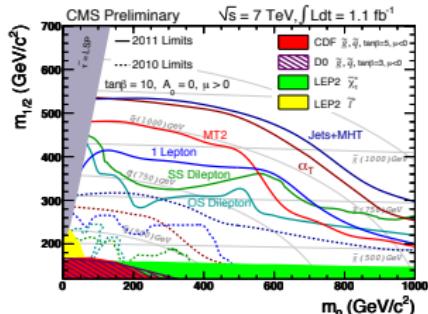
O. Buchmueller et al., JHEP 0809 (2008) 117

SUSY could be discovered even before the Higgs!

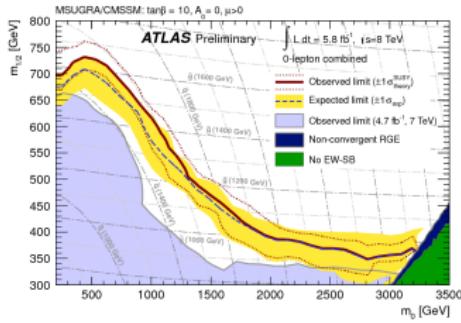
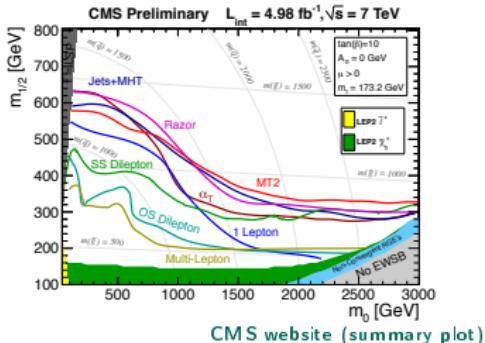


SUSY searches

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

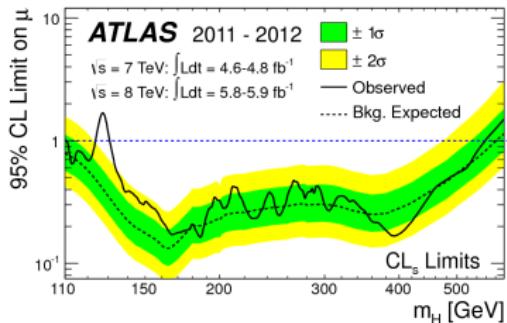


Summer 2012 (with $\sim 5 \text{ fb}^{-1}$ of data at 7 and 8 TeV):

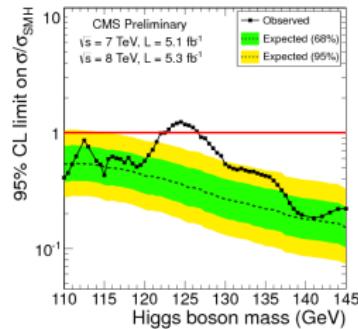


Higgs searches

Discovery of a new boson announced in July 2012!



ATLAS-CONF-2012-091



CMS PAS HIG-2012-015

Compatible with the SM Higgs



Interpretation of the results

Two categories of studies:

- Constrained SUSY scenarios (CMSSM, mSUGRA,...)
handful number of free parameters, useful for benchmarking,...
→ Most of the experimental limits are given for constrained MSSM scenarios
But CMSSM is NOT representative of the whole MSSM!
- General SUSY scenarios: pMSSM
much richer features, signatures and phenomenology!

Limits are pushed higher and higher

But still a lot of solutions compatible with all present bounds!

→ Not possible to falsify MSSM!

Alternative path to tightly constrain and test the MSSM at the LHC:
through the Higgs sector!



Implications of the Higgs mass determination

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above:
 $M_h^{\max} \approx M_Z |\cos 2\beta| + \text{radiative corrections} \lesssim 110 - 135 \text{ GeV}$
- 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. $X_t \approx 0$.



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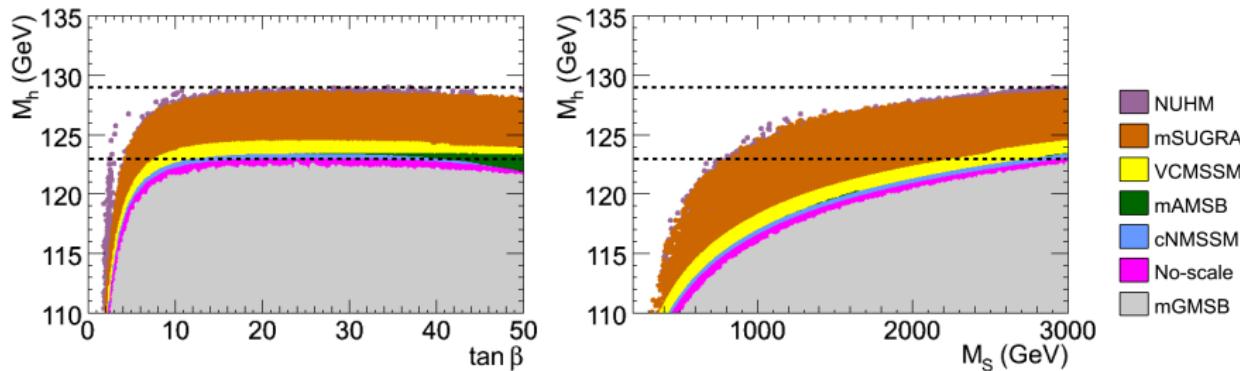
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Implications of the Higgs mass determination

Maximal Higgs mass in constrained MSSM scenarios



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

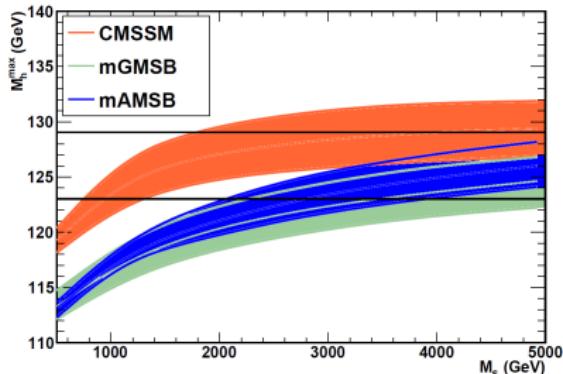
Several constrained models are excluded or about to be!



Sensitivity to the top mass

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!



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

→ 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)
- 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 $\text{BR}(B \rightarrow X_s \gamma)$, $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$, $\text{BR}(B \rightarrow \tau \nu)$
- 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:

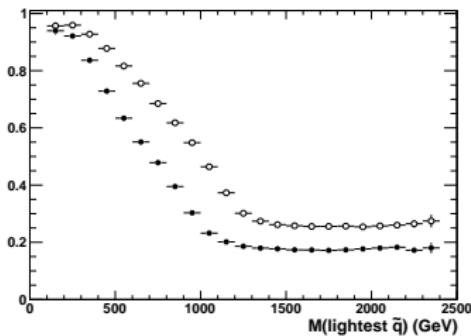
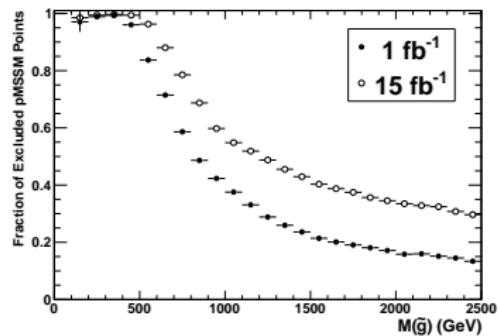
- more than 100M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.



Consequences on sparticle masses

Strongly Interacting Sparticle Spectra of Allowed pMSSM Points



A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847

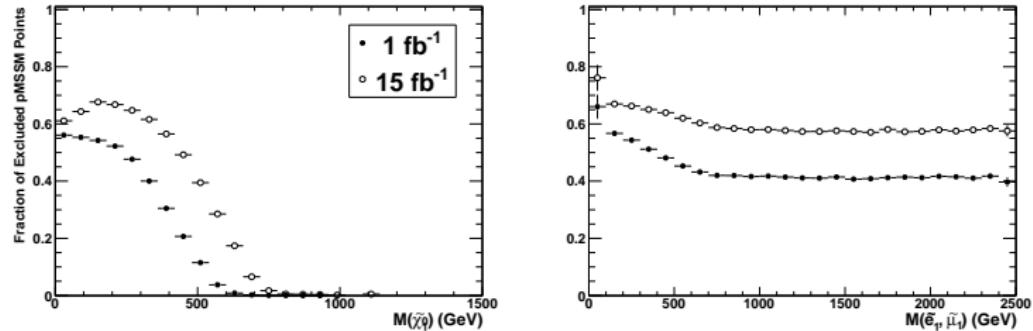
For the gluino, LHC data can exclude more than 85% of the points up to a mass of 520 (700) GeV for 1 (15) fb^{-1}

For the squarks, 85% of the points can be excluded up to mass values of 320 (510) GeV for 1 (15) fb^{-1}



Consequences on sparticle masses

Weakly Interacting Sparticle Spectra of Allowed pMSSM Points

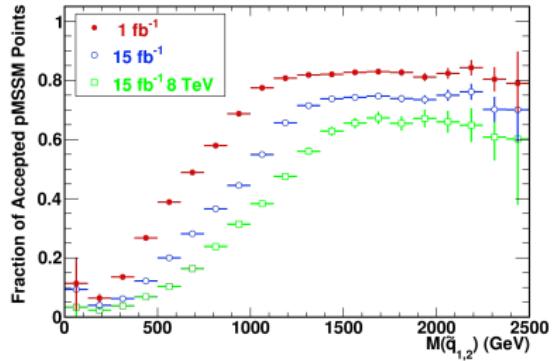


A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847

The domain of SUSY weakly-interacting particle masses above 500 GeV is relatively unaffected by the present LHC data



Consequences of a 125 GeV Higgs



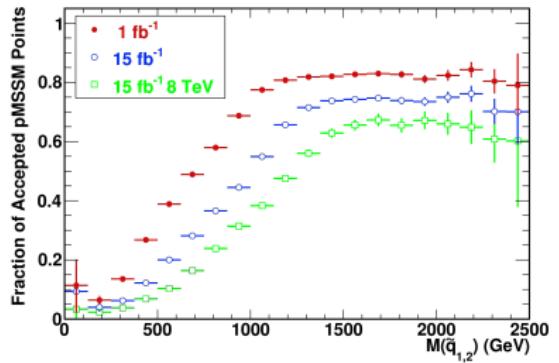
With $M_h > 111 \text{ GeV}$

A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847

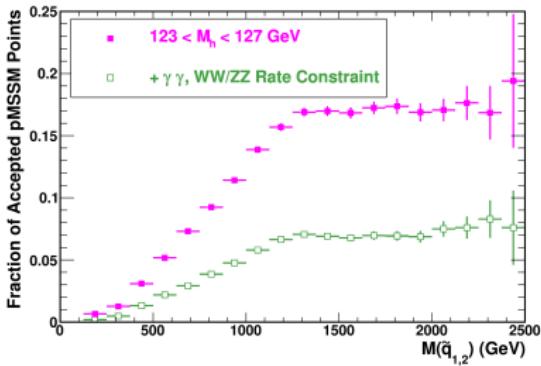
A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1906



Consequences of a 125 GeV Higgs



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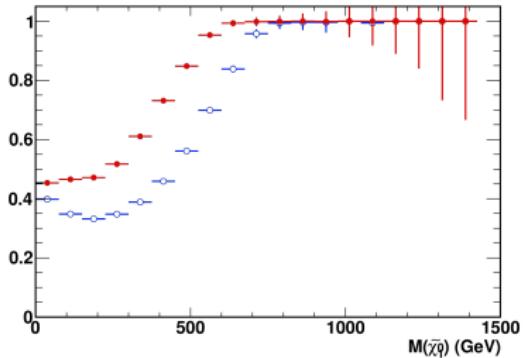
With $123 < M_h < 127$ GeV

A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847

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Consequences of a 125 GeV Higgs



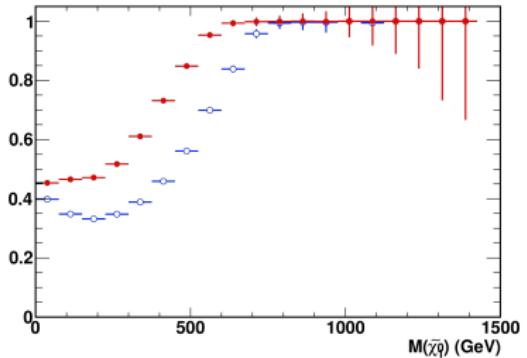
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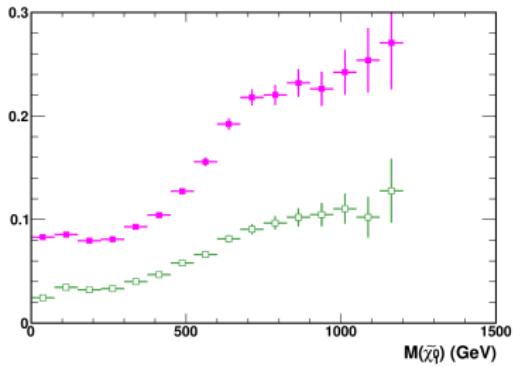
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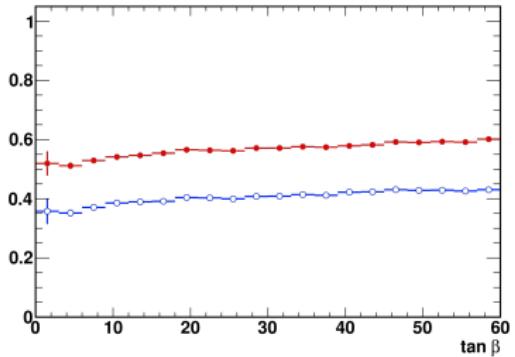
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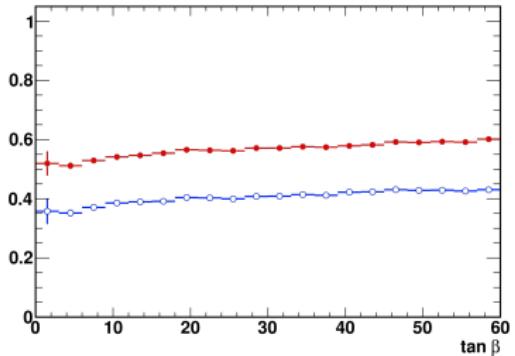
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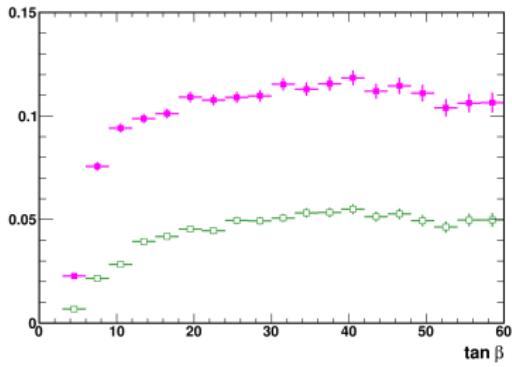
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Consequences of a 125 GeV Higgs



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Higgs decay rates

Signal strength is defined as:

$$\mu_{XX} = \frac{\sigma(pp \rightarrow h) \text{BR}(h \rightarrow XX)}{\sigma(pp \rightarrow h)_{\text{SM}} \text{BR}(h \rightarrow XX)_{\text{SM}}}$$

LHC results:

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

- diphoton decay mode ⇒ massive neutral boson with spin $\neq 1$
- compatible with the SM Higgs
- too early for conclusive information from couplings/rates



Higgs couplings

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

ϕ	$g_{\phi u \bar{u}}$	$g_{\phi d \bar{d}} = g_{\phi \ell \bar{\ell}}$	$g_{\phi v v}$
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:

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



Benchmark scenarios

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:

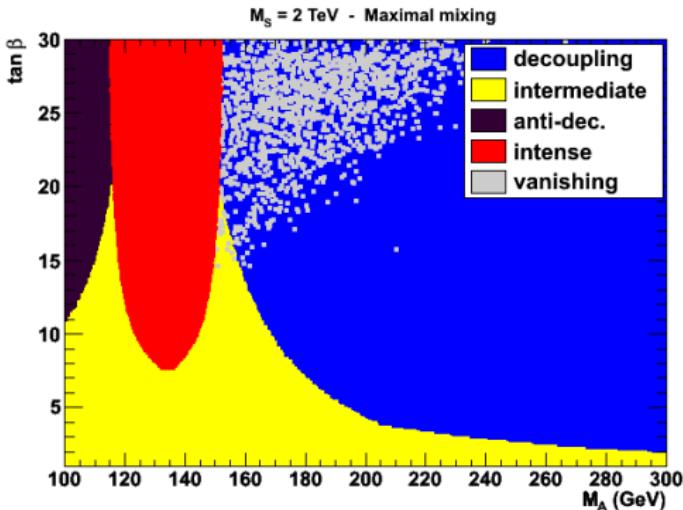
small M_A , $\cos^2(\beta - \alpha) \geq 0.95$

Intense coupling:

h, A, H rather close in mass,
 g_{hbb}^2 and $g_{Hbb}^2 \geq 50$

Vanishing coupling:

g_{hbb}^2 or $g_{hVV}^2 \leq 0.05$



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Green: LEP Higgs search limit

Solid cyan line: CMS $A/H \rightarrow \tau^+\tau^-$ search limit at 7 TeV with 4.6/fb

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



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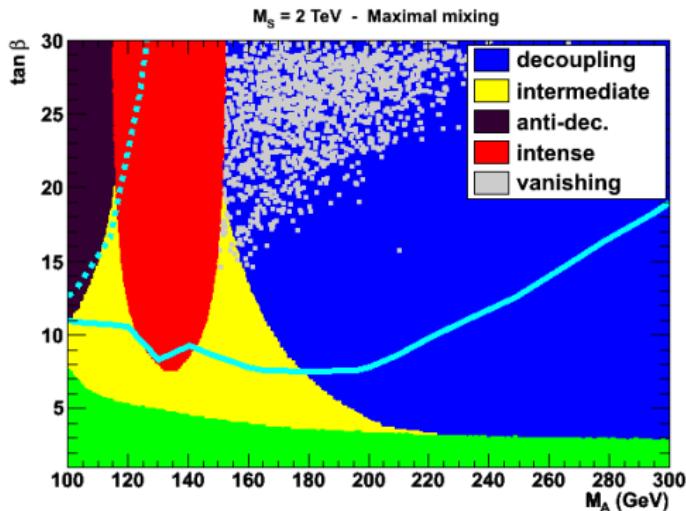
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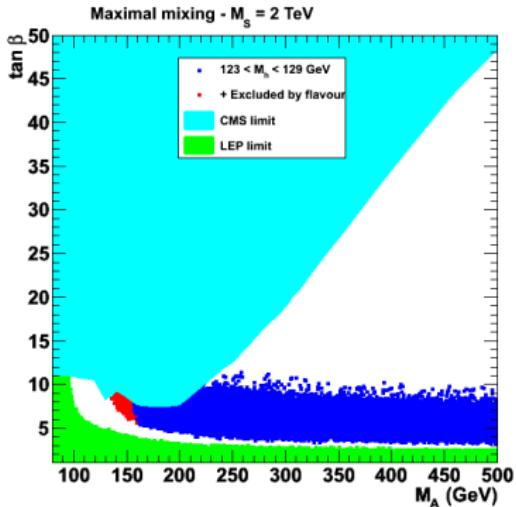
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Cyan: CMS limit from $A/H \rightarrow \tau\tau$ with 4.6/fb

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

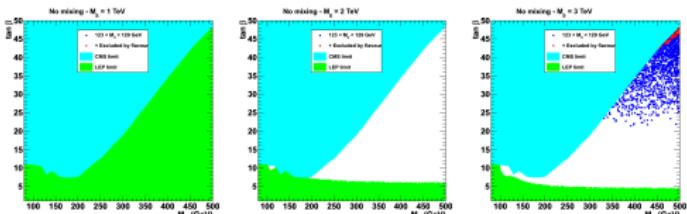
Strong constraints from the neutral Higgs searches!



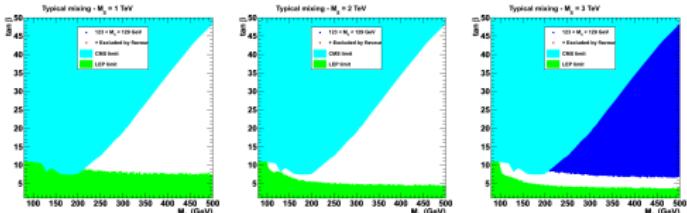
Benchmark scenarios

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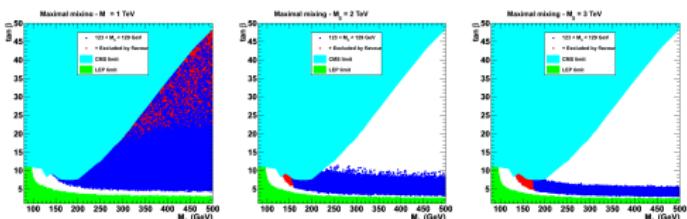
No mixing: $X_t \approx 0$



Typical mixing:
 $X_t \approx M_S$



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



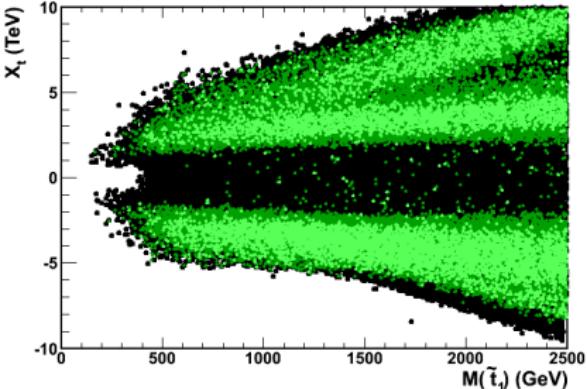
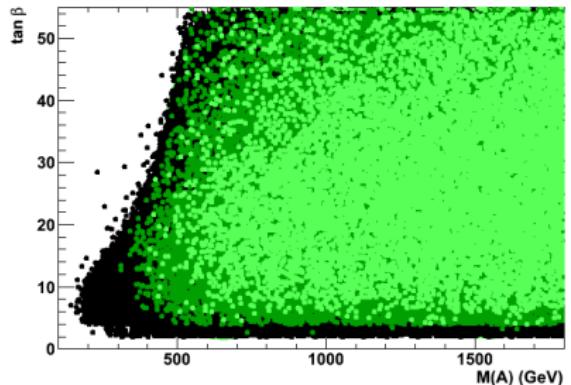
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Strong constraints from the neutral Higgs searches for individual scenarios!



Consequences in pMSSM

Consequences of the cross-section and decay rate measurements



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

→ $M_A < 400$ GeV disfavoured by the Higgs signal strengths (→ decoupling regime)

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

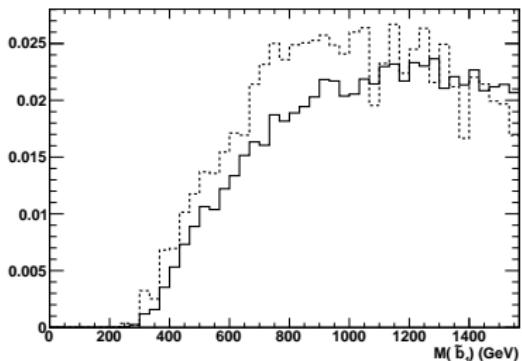
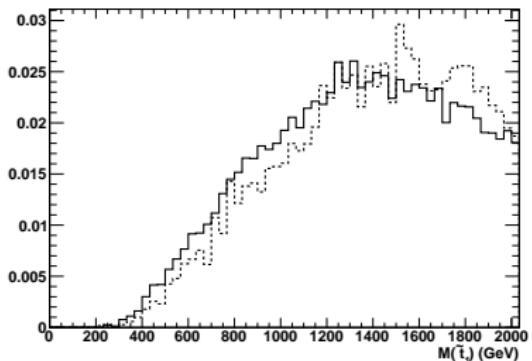
Black: all accepted points (including the LEP Higgs mass limit)

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 in pMSSM

Favoured region: χ^2 analysis and normalized distributions



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Solid lines: accepted pMSSM points with $123 < M_h < 129$ GeV

Dashed lines: points favoured at 90% C.L. by M_h , $\text{BR}(h^0 \rightarrow \gamma\gamma)$, $\text{BR}(h^0 \rightarrow ZZ)$ and $\text{BR}(h^0 \rightarrow b\bar{b})$

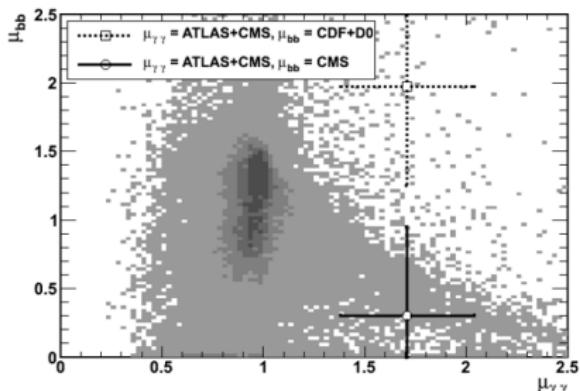
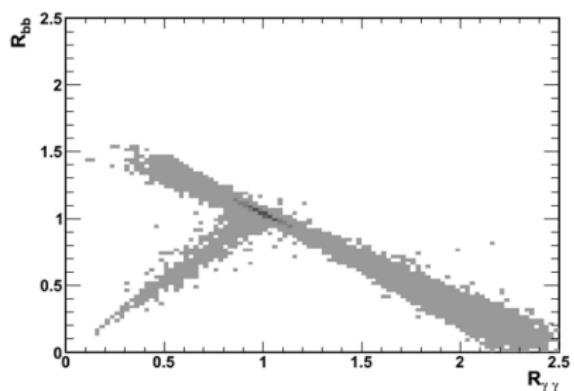
$R_{\gamma\gamma} = 1.71 \pm 0.33$, $R_{ZZ} = 0.95 \pm 0.40$ (ATLAS+CMS), $R_{b\bar{b}} = 1.06 \pm 0.50$ (CMS+Tevatron)

→ Heavy stops and light sbottoms favoured by the LHC Higgs results!



Consequences in pMSSM

Correlation between $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$



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

Invisible Higgs decays can modify the correlation

Correlation washed out in the signal strengths



- 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
- Still too early for conclusive information from couplings/rates



Backup

Backup



Constraints

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

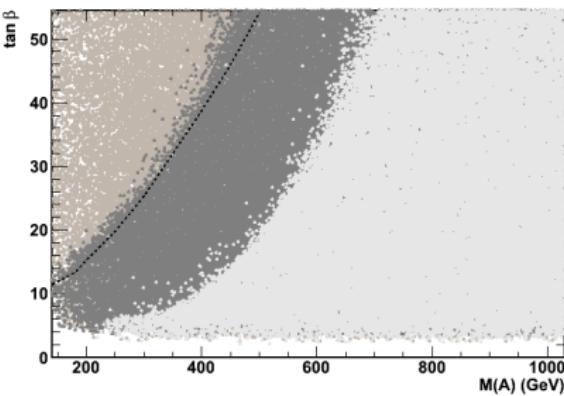
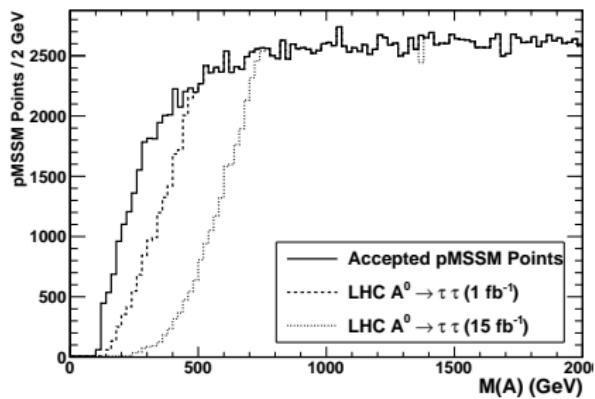


Higgs searches

Direct searches for $A \rightarrow \tau\tau$

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



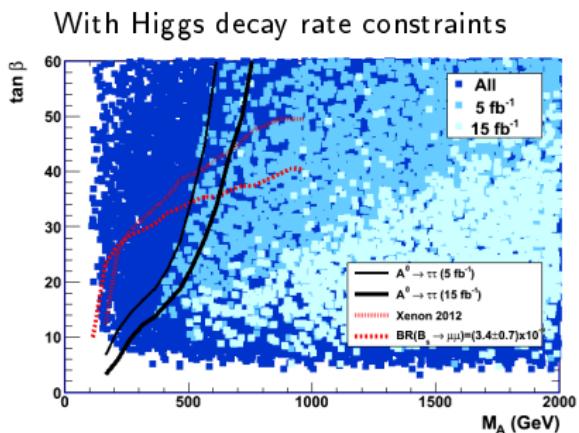
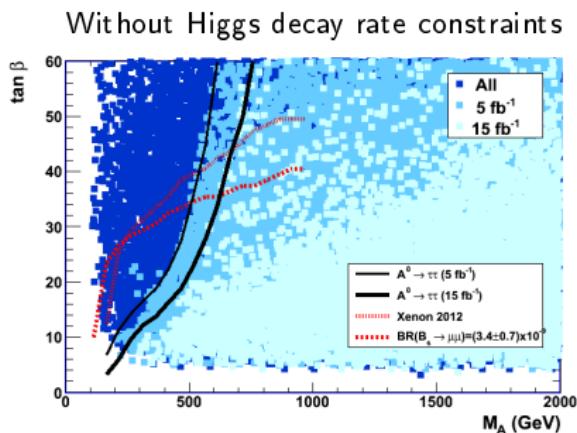
A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

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



Constraints on the MSSM

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

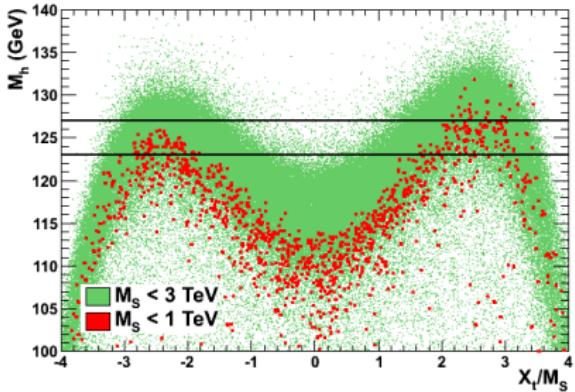


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Once putting everything together the allowed region is really squeezed!



Consequences of a 125 GeV Higgs



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

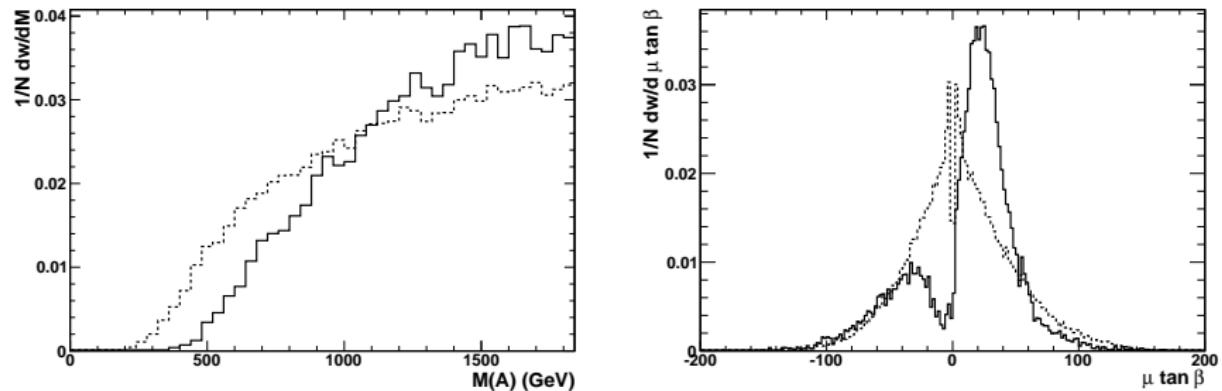
A large part of the pMSSM still survives

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



Consequences in pMSSM

Consequences of the cross-section and decay rate measurements



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

Solid line: all accepted points (including the LEP Higgs mass limit)

Dotted line: including constraints from M_h , $\mu_{\gamma\gamma}$, μ_{ZZ} and μ_{WW}

→ $M_A < 400$ GeV and $\mu \tan \beta < 0$ disfavoured by the Higgs signal strengths

