

Status of the (p)MSSM Higgs sector

Alexandre Arbey

Lyon University & CERN TH

Thanks to M. Battaglia, A. Djouadi, F. Mahmoudi, M. Mühlleitner,
G. Robbins & M. Spira

ICHEP 2018

Seoul, Korea – July 6th, 2018

Where to look for Supersymmetry?

Direct searches at high energy collider

- Direct SUSY searches
- Higgs boson searches

Indirect searches through low energy observables

- Higgs coupling measurements
- Flavour physics
- Muon $g - 2$
- Electric dipole moments
- ...

In space

- Relic density
- Direct detection
- Indirect detection
- ...

Where to look for Supersymmetry?

Direct searches at high energy collider

- Direct SUSY searches
- Higgs boson searches

Indirect searches through low energy observables

- Higgs coupling measurements
- Flavour physics
- Muon $g - 2$
- Electric dipole moments
- ...

In space

- Relic density
- Direct detection
- Indirect detection
- ...

Direct searches at high energy collider

- Direct SUSY searches
- Higgs boson searches

Indirect searches through low energy observables

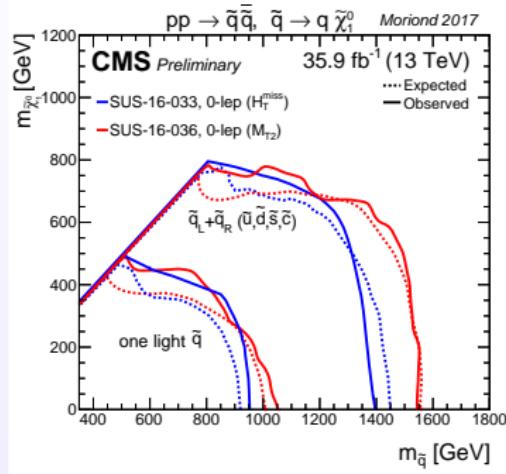
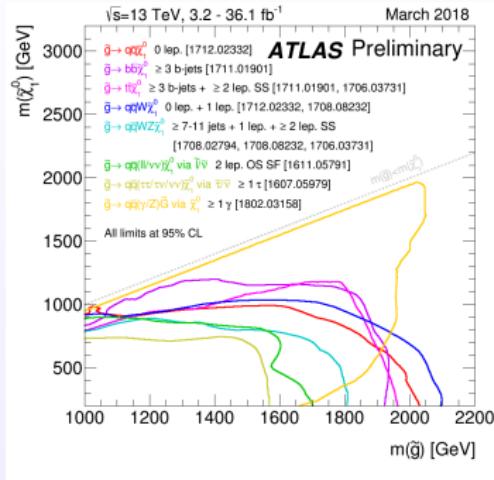
- Higgs coupling measurements
- Flavour physics
- Muon $g - 2$
- Electric dipole moments
- ...

In space

- Relic density
- Direct detection
- Indirect detection
- ...

SUSY? Is she dead? Or too heavy?

ATLAS and CMS set very strong constraints on the MSSM strongly interacting sector



$$M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \quad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV}$$

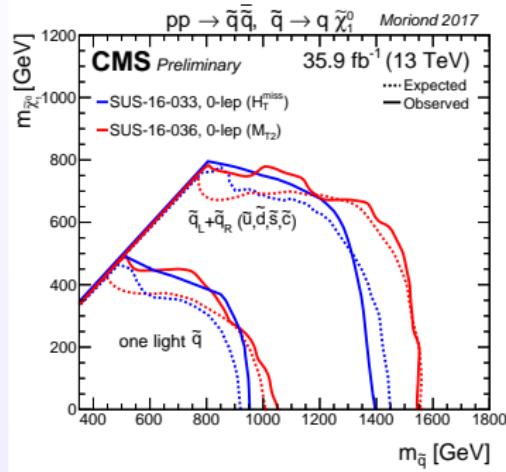
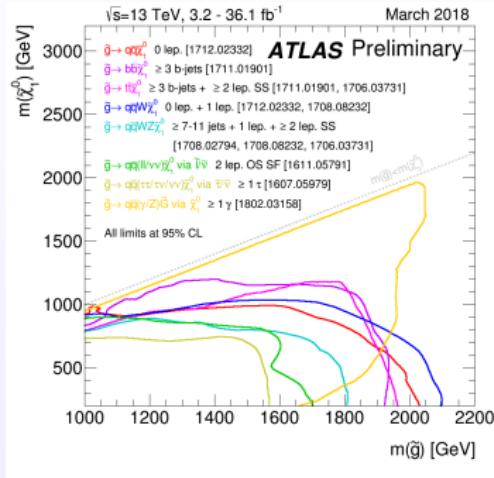
Squarks and gluinos are getting heavier and heavier...

But these limits are valid only in very simple MSSM scenarios...

While such studies are useful, they are NOT representative of the whole MSSM!

SUSY? Is she dead? Or too heavy?

ATLAS and CMS set very strong constraints on the MSSM strongly interacting sector



$$M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \quad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV}$$

Squarks and gluinos are getting heavier and heavier...

But these limits are valid only in very simple MSSM scenarios...

While such studies are useful, they are NOT representative of the whole MSSM!

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](#)

In the following, neutralino LSP

Random scans of the 19 pMSSM parameters with neutralino dark matter

Parameter	Range (in GeV)
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 5000]
$A_d = A_s = A_b$	[-15000, 15000]
$A_u = A_c = A_t$	[-15000, 15000]
$A_e = A_\mu = A_\tau$	[-15000, 15000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 5000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 5000]
$M_{\tilde{\tau}_L}$	[0, 5000]
$M_{\tilde{\tau}_R}$	[0, 5000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 5000]
$M_{\tilde{q}_{3L}}$	[0, 5000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 5000]
$M_{\tilde{t}_R}$	[0, 5000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 5000]
$M_{\tilde{b}_R}$	[0, 5000]
$\tan \beta$	[1, 60]

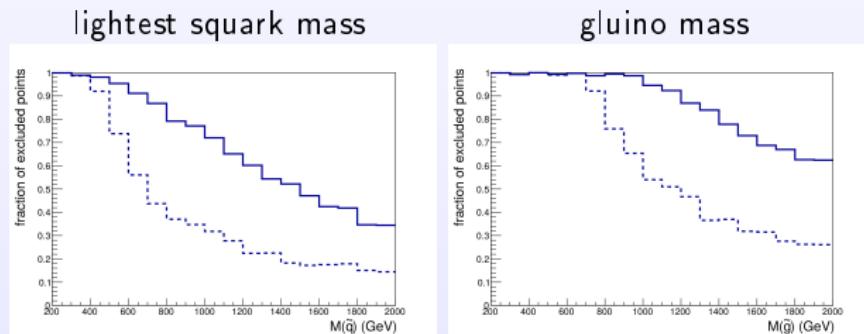
- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables and Z widths (SuperIso)
- Computation of dark matter observables (SuperIso Relic, Micromegas)
- Determination of SUSY and Higgs mass limits (SuperIso, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, SusHi)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino, MadGraph)
- Implementation of ATLAS and/or CMS SUSY and monoX search results
- Determination of detectability with fast detector simulation (Delphes)

(ATLAS) direct SUSY and monojet searches at 8 and 13 TeV (up to 36 fb^{-1}):

- squark and gluino direct searches (jets + \cancel{E}_T) [1711.03301](#)
- stop and sbottom direct searches (t, b -jets (+ leptons) + \cancel{E}_T) [1708.09266](#)
- chargino and neutralino direct searches (leptons (+ b -jets) + \cancel{E}_T) [ATLAS-CONF-2017-039](#)
- monojet searches (at least one hard jet + \cancel{E}_T) [1502.01518](#)

We generate events with MadGraph/Pythia and simulate the detector with Delphes

Fraction of excluded points as a function of the



Dotted: 8 TeV only – Solid: 8+13 TeV

Squark masses below ~ 1 TeV are still allowed in pMSSM!

Implications of the Higgs mass measurement for the MSSM

- In the MSSM light CP-even Higgs is bounded from above: $M_h^{\max} \lesssim 110 - 135 \text{ GeV}$

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

M_S : averaged stop mass and X_t the stop mixing parameter

→ Imposing M_h places very strong constraints on the MSSM parameters

- Modified couplings with respect to the SM Higgs boson (→ decoupling limit):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi e\bar{e}}$	$g_{\phi VV}$
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

ATLAS and CMS measurements:

Signal strength:

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

CMS-PAS-HIG-17-031, ATLAS-CONF-2017-047

→ The results are compatible with the SM Higgs

Implications of the Higgs mass measurement for the MSSM

- In the MSSM light CP-even Higgs is bounded from above: $M_h^{\max} \lesssim 110 - 135 \text{ GeV}$

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

M_S : averaged stop mass and X_t the stop mixing parameter

→ Imposing M_h places very strong constraints on the MSSM parameters

- Modified couplings with respect to the SM Higgs boson (→ 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

ATLAS and CMS measurements:

Signal strength:

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

CMS-PAS-HIG-17-031, ATLAS-CONF-2017-047

→ The results are compatible with the SM Higgs

Implications of the Higgs mass measurement for the MSSM

- In the MSSM light CP-even Higgs is bounded from above: $M_h^{\max} \lesssim 110 - 135 \text{ GeV}$

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

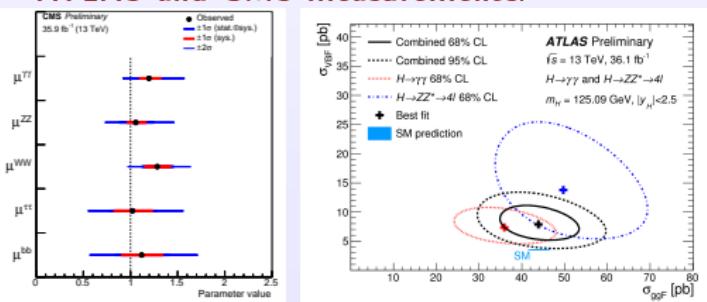
M_S : averaged stop mass and X_t the stop mixing parameter

→ Imposing M_h places very strong constraints on the MSSM parameters

- Modified couplings with respect to the SM Higgs boson (→ 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

ATLAS and CMS measurements:



Signal strength:

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

CMS-PAS-HIG-17-031, ATLAS-CONF-2017-047

→ The results are compatible with the SM Higgs

Combination of the ATLAS and CMS results in the effective coupling models

Effective couplings of the light Higgs to photons, gluons, vector bosons, top quarks, bottom quarks, tau leptons: κ_γ , κ_g , κ_V , κ_t , κ_b , κ_τ

Theorist's combination (= weighted average) of ATLAS and CMS results at 8 and 13 TeV

(Combination at 8 TeV: 1606.02266 ; 13 TeV: CMS-PAS-HIG-17-031, ATLAS 1802.04146)

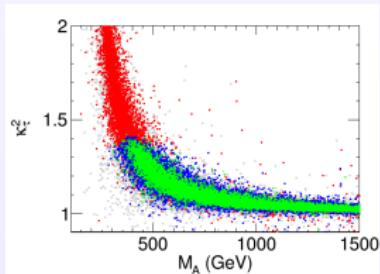
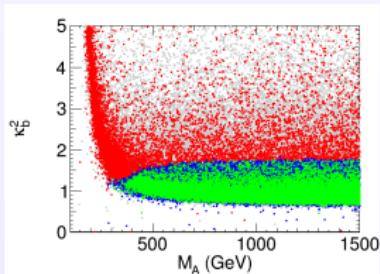
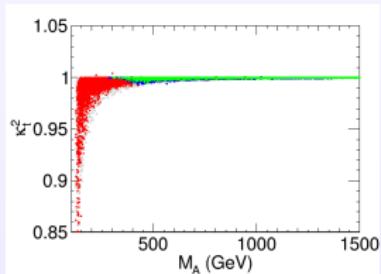
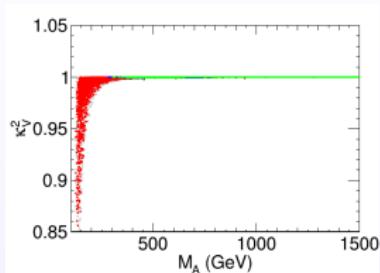
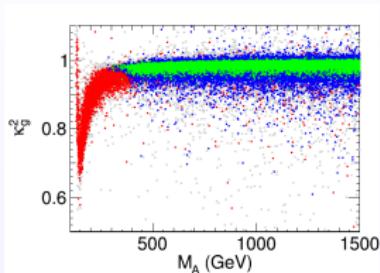
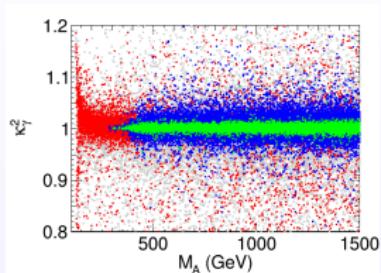
In absence of BSM decays	
Coupling	Exp. combination
$ \kappa_\gamma $	1.01 ± 0.08
$ \kappa_g $	0.89 ± 0.08
$ \kappa_V $	0.99 ± 0.06
$ \kappa_t $	1.17 ± 0.12
$ \kappa_b $	0.76 ± 0.20
$ \kappa_\tau $	0.90 ± 0.11

In presence of BSM decays	
Coupling	Exp. combination
$ \kappa_\gamma $	0.98 ± 0.06
$ \kappa_g $	0.89 ± 0.08
$ \kappa_V $	0.96 ± 0.03
$ \kappa_t $	1.23 ± 0.14
$ \kappa_b $	0.73 ± 0.12
$ \kappa_\tau $	0.89 ± 0.09
BR_{BSM}	$0.02^{+0.10}_{-0.00}$

Compatibility with experimental data assessed through χ^2 combination

Effective couplings and MSSM parameters

Preliminary



Grey: all points with $M_h \sim 125$ GeV

Red: + passing LEP constraints

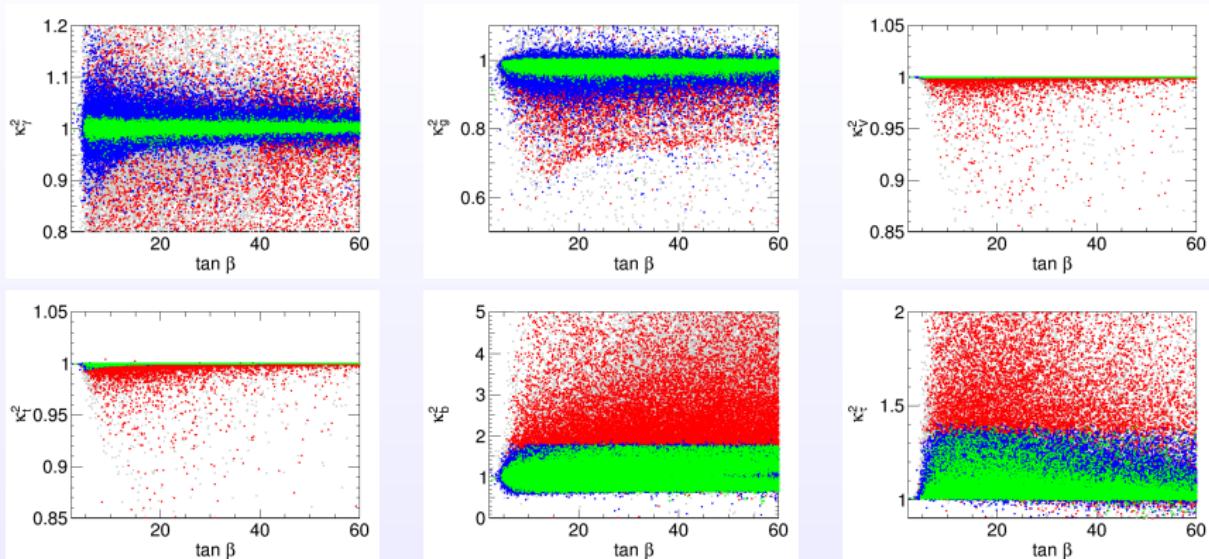
Blue: + compatible with effective coupling measurements

Green: + compatible with LHC direct searches

Main dependence on M_A and $\tan\beta$

Effective couplings and MSSM parameters

Preliminary



Grey: all points with $M_h \sim 125$ GeV

Red: + passing LEP constraints

Blue: + compatible with effective coupling measurements

Green: + compatible with LHC direct searches

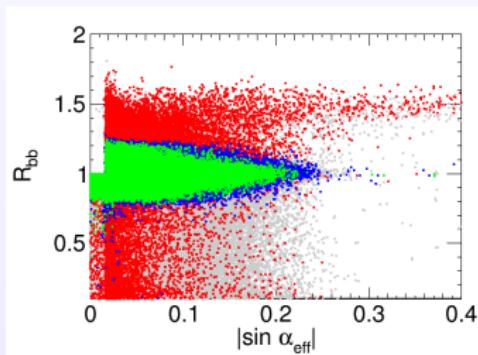
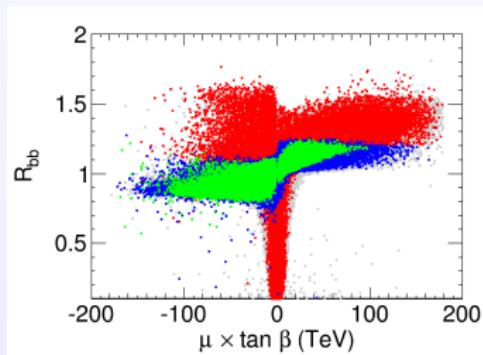
Main dependence on M_A and $\tan \beta$

Effective couplings and MSSM parameters

Dependence on other SUSY parameters especially important in the light Higgs coupling to bottom quarks:

$$\kappa_b \propto \frac{1}{1 + \Delta_b} \quad , \quad \Delta_b \approx \frac{2\alpha_s}{3\pi} \frac{m_{\tilde{g}} \mu \tan \beta}{\max(m_{\tilde{g}}^2, m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2)} + \frac{m_t^2}{8\pi^2 v^2 \sin^2 \beta} \frac{A_t \mu \tan \beta}{\max(\mu^2, m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)}$$

Preliminary



Grey: all points with $M_h \sim 125$ GeV

Red: + passing LEP constraints

Blue: + compatible with effective coupling measurements

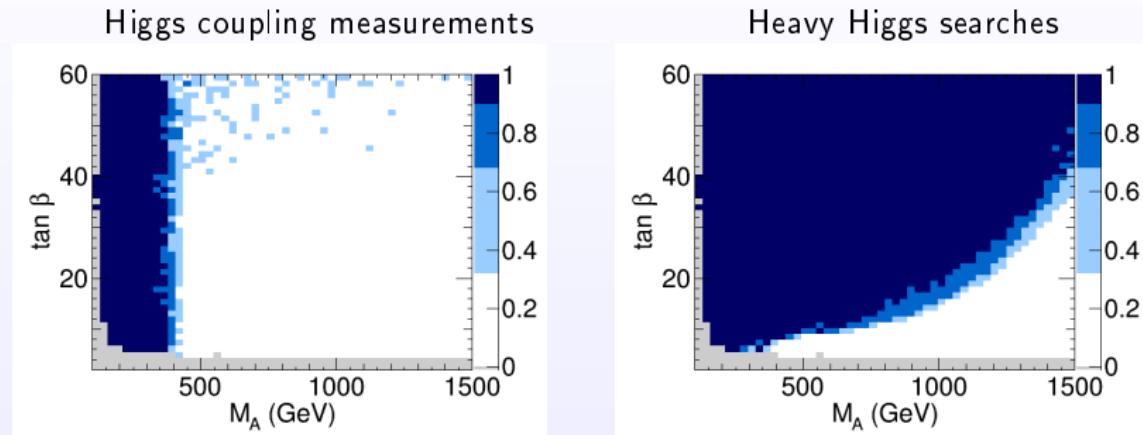
Green: + compatible with LHC direct searches

$$R_{bb} \equiv \frac{BR(h \rightarrow b\bar{b})}{BR(h \rightarrow b\bar{b})_{SM}}$$

Strong dependence on $\mu \tan \beta$ and $\sin \alpha_{eff}$

Complementarities of effective coupling measurements and heavy Higgs searches

Heavy Higgs searches: [1707.04147](#), [1707.06025](#), [1709.07242](#), [1710.01123](#), [1712.06386](#), [1803.06553](#), [1804.01939](#), [1805.12191](#)



Color scale: fraction of excluded points – Grey: points excluded by Higgs mass, EW or LEP constraints

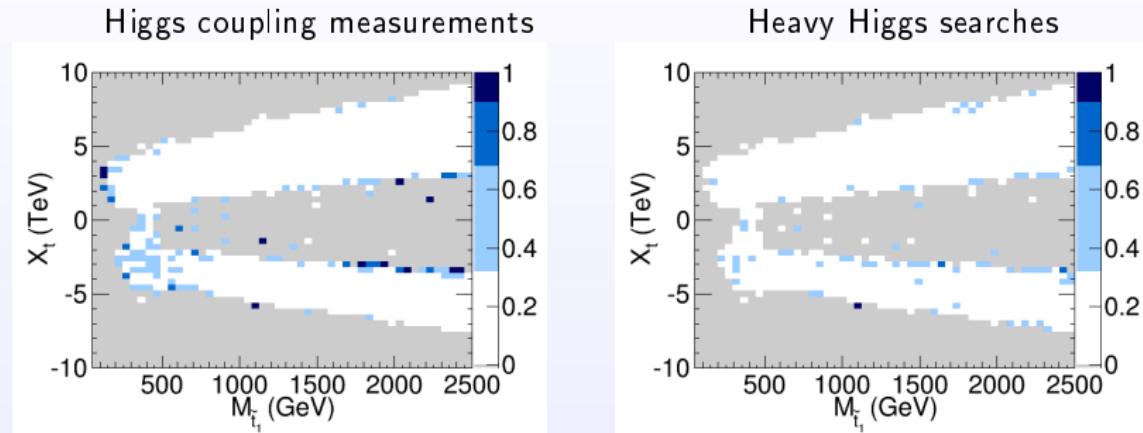
$\tan \beta$ vs. M_A parameter space

Very strong constraints in this parameter plane

Light Higgs couplings exclude $M_A \lesssim 400$ GeV independent of $\tan \beta$

Complementarities of effective coupling measurements and heavy Higgs searches

Heavy Higgs searches: [1707.04147](#), [1707.06025](#), [1709.07242](#), [1710.01123](#), [1712.06386](#), [1803.06553](#), [1804.01939](#), [1805.12191](#)



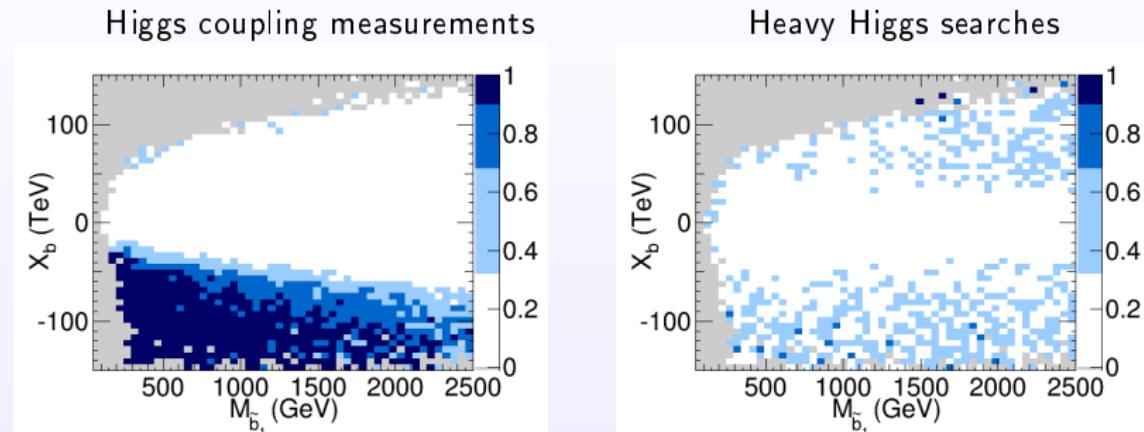
Color scale: fraction of excluded points – Grey: points excluded by Higgs mass, EW or LEP constraints

X_t vs. $M_{\tilde{t}_1}$ parameter space

Parameter plane already strongly constrained by the 125 GeV Higgs mass
→ hardly more constrained by coupling measurements or heavy Higgs searches

Complementarities of effective coupling measurements and heavy Higgs searches

Heavy Higgs searches: [1707.04147](#), [1707.06025](#), [1709.07242](#), [1710.01123](#), [1712.06386](#), [1803.06553](#), [1804.01939](#), [1805.12191](#)



Color scale: fraction of excluded points – Grey: points excluded by Higgs mass, EW or LEP constraints

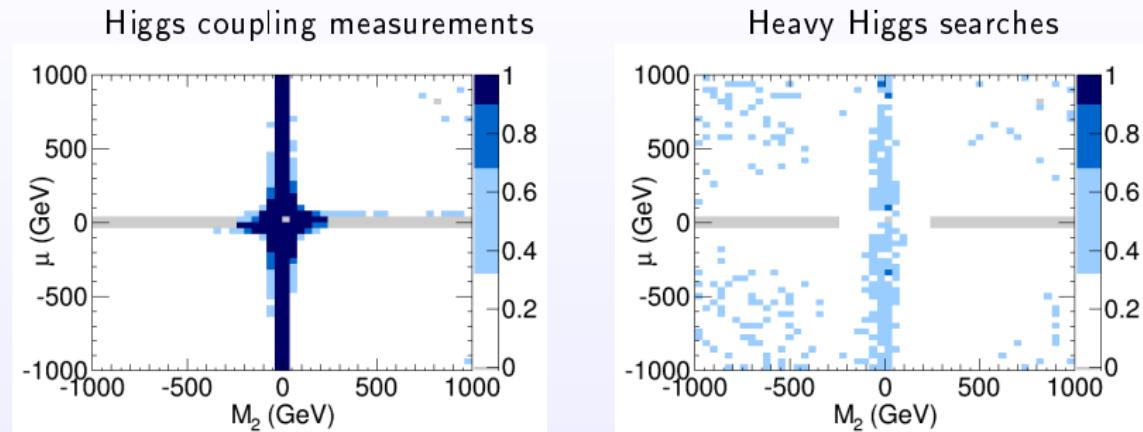
X_b vs. $M_{\tilde{b}_1}$ parameter space
Main constraints from κ_g and κ_γ

$$\kappa_g = f(\kappa_t, \kappa_b, \kappa_{\tilde{t}}, \kappa_{\tilde{b}}), \quad \kappa_\gamma = g(\kappa_t, \kappa_b, \kappa_V, \kappa_{\tilde{t}}, \kappa_{\tilde{b}}, \kappa_{\tilde{\tau}}, \kappa_{H^\pm}, \kappa_{\tilde{\chi}^\pm})$$

$$\delta\kappa_{\tilde{b}} \approx -\frac{m_b^2 X_b^2}{4m_{b_1}^2 m_{b_2}^2}$$

Complementarities of effective coupling measurements and heavy Higgs searches

Heavy Higgs searches: [1707.04147](#), [1707.06025](#), [1709.07242](#), [1710.01123](#), [1712.06386](#), [1803.06553](#), [1804.01939](#), [1805.12191](#)



μ vs. M_2 parameter space

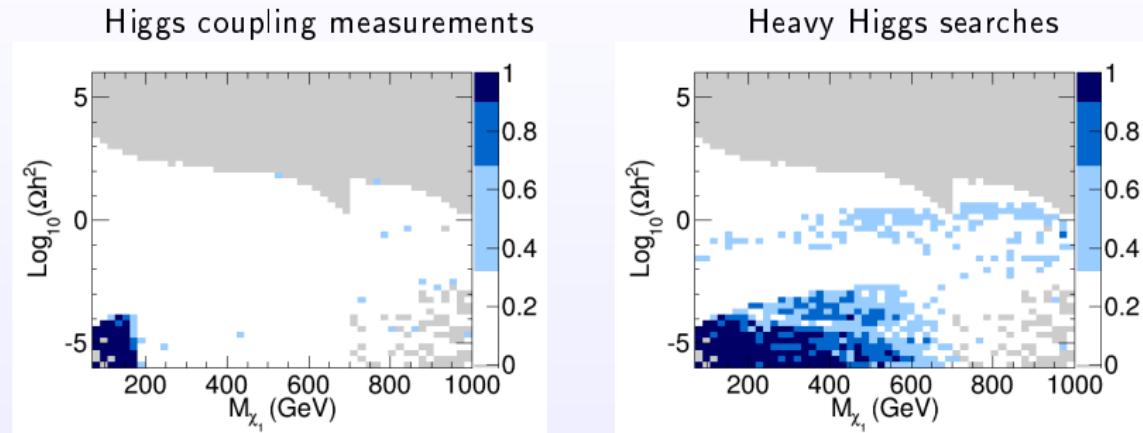
Main constraints from κ_γ (+ Higgs mass)

$$\kappa_\gamma = g(\kappa_t, \kappa_b, \kappa_V, \kappa_{\tilde{t}}, \kappa_{\tilde{b}}, \kappa_{\tilde{\tau}}, \kappa_{H^\pm}, \kappa_{\tilde{\chi}^\pm})$$

$$\delta\kappa_{\tilde{\chi}^\pm} \approx \pm \frac{2M_W^2}{m_{\tilde{\chi}_1^\pm} m_{\tilde{\chi}_2^\pm}}$$

Complementarities of effective coupling measurements and heavy Higgs searches

Heavy Higgs searches: [1707.04147](#), [1707.06025](#), [1709.07242](#), [1710.01123](#), [1712.06386](#), [1803.06553](#), [1804.01939](#), [1805.12191](#)



Color scale: fraction of excluded points – Grey: points excluded by Higgs mass, EW or LEP constraints

Ωh^2 vs. $M_{\tilde{\chi}_1}$ parameter space

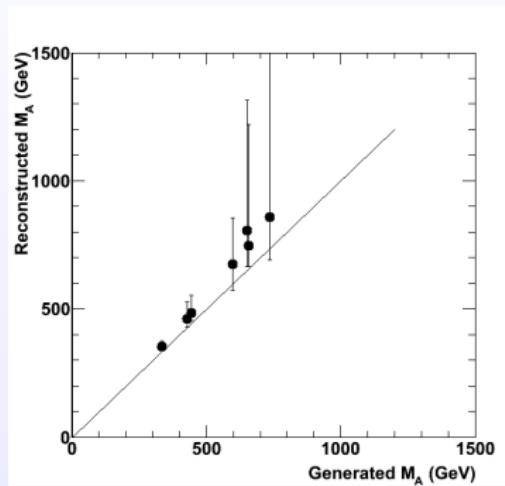
$$\Omega_{\text{Planck}} h^2 = 0.1188 \pm 0.0010$$

Small Ωh^2 obtained when strong co-annihilation or resonance through heavy Higgs bosons

Determination of SUSY parameters at LHC and ILC

Most optimistic case: HL-LHC: 3 ab^{-1} + ILC 1 TeV 1 ab^{-1}

MSSM scenarios where the Higgs coupling constraints are driven by $\tan \beta$ and M_A :



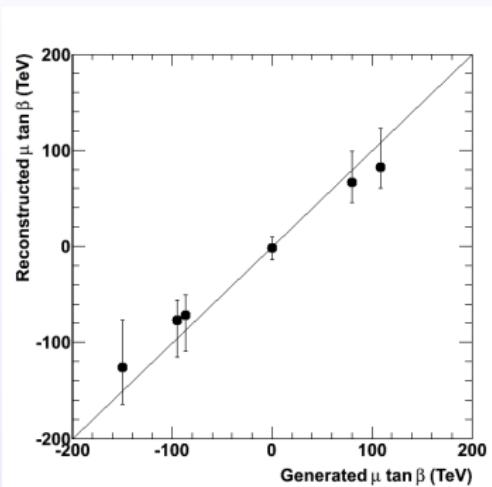
Scenario	M_A (GeV)	$\tan \beta$
1 HL-LHC	334.9	9.9
	394 ± 40	9.6 ± 4.0
	351 ± 23	9.2 ± 1.9
2 HL-LHC	427.3	5.7
	471^{+341}_{-56}	-
	460^{+54}_{-45}	10.4^{+6}_{-4}
3 ILC	443.5	10.1
	484^{+57}_{-48}	9.8^{+8}_{-2}
4 ILC	598.7	23.7
	664.7^{+158}_{-98}	14.3^{+15}_{-6}
5 ILC	657.2	12.7
	747.7^{+302}_{-97}	10.2^{+20}_{-4}
6 ILC	735.3	8.5
	795.7^{+380}_{-134}	9.2^{+21}_{-4}

The potential of reconstruction will strongly depend on the MSSM scenario

Determination of SUSY parameters at LHC and ILC

Most optimistic case: HL-LHC: 3 ab^{-1} + ILC 1 TeV 1 ab^{-1}

MSSM scenarios where the Higgs coupling constraints are driven by $\mu \tan \beta$



	$\mu \tan \beta$ (TeV)
7	-86.6
ILC	-73.5^{+29}_{-39}
8	-95.3
ILC	-77.5^{+28}_{-39}
9	-149.9
ILC	-76.3^{+28}_{-39}
10	108.6
ILC	82.5^{+40}_{-22}
11	79.6
ILC	67.2^{+39}_{-22}
12	107.5
ILC	56.3^{+31}_{-21}
SM	0
ILC	-2.2 ± 11

The potential of reconstruction will strongly depend on the MSSM scenario

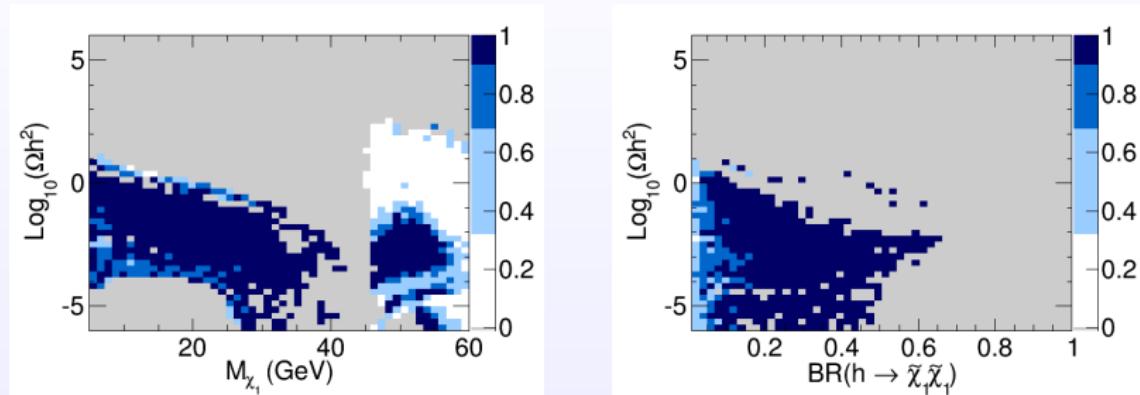
Conclusions

- Light Higgs couplings related to many MSSM parameters
- Higgs coupling measurements can provide interesting constraints on other sectors of the MSSM
- Useful interplay of Higgs coupling measurements with Higgs and SUSY direct searches
- Also complementarity of the Higgs coupling measurements with dark matter constraints
- Precise Higgs coupling measurements will allow the reconstruction of MSSM parameters

Backup

Light neutralinos and Higgs coupling measurements

$m_{\tilde{\chi}_1} < 60 \text{ GeV} + \text{invisible Higgs decays}$



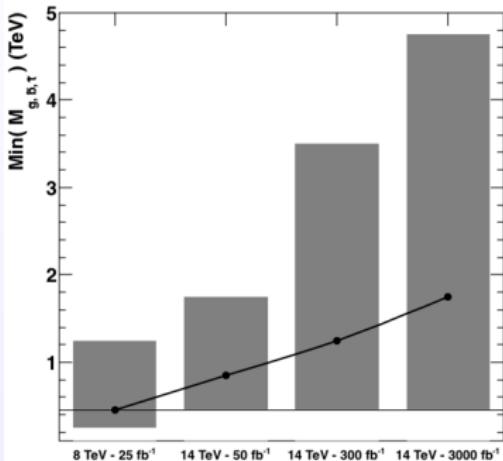
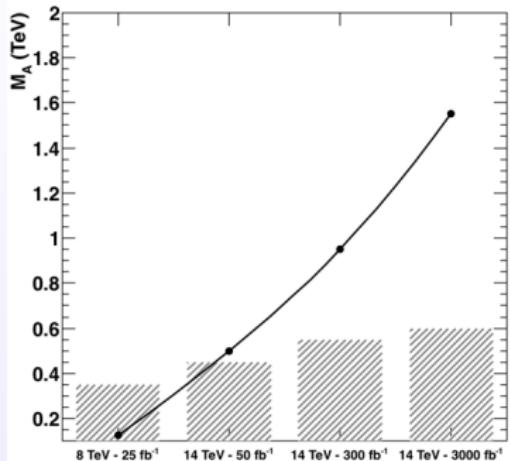
Color scale: fraction of excluded points – Grey: points excluded by Higgs mass, EW or LEP constraints

$$\Omega_{\text{Planck}} h^2 = 0.1188 \pm 0.0010$$

Strong exclusion by the $\text{BR}(h \rightarrow \text{invisible})$ constraint

Still possible to have light neutralinos with $\Omega h^2 \sim 0.1$, but specific investigation needed

Sensitivity to effective coupling measurements and heavy Higgs searches



AA, M. Battaglia, F. Mahmoudi, Ann. Phys. 528 (2016) 179

continuous line: 95% C.L. exclusion bounds by the LHC direct searches
grey bars: indirect constraints from the Higgs signal strength measurements

Higgs searches complementary to the direct searches!