# Low-energy supersymmetry facing LHC constraints

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## Introduction

The Minimal	Supers	ymmetric	Standard	Model
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Chiral supermultiplets

Name	Symbol	spin 0	spin 1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks,quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	$(u_L, d_L)$	$(3, 2, \frac{1}{6})$
(×3 families)	ū	$\widetilde{u}_R^*$	$u_R^{\dagger}$	$\left(\overline{3},1,-\frac{2}{3}\right)$
	ā	$\widetilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{3},1,\frac{1}{3}\right)$
sleptons,leptons	L	$(\tilde{v}, \tilde{e}_L)$	$(v, e_L)$	$(1,2,-\frac{1}{2})$
(×3 families)	ē	${\widetilde e}_R^*$	$e_R^{\dagger}$	(1,1,1)
Higgses, Higgsinos	$H_{\mu}$	$(H^+_{\!\scriptscriptstyle {\cal U}},H^{\rm O}_{\!\scriptscriptstyle {\cal U}})$	$(\widetilde{H}^+_{\!\scriptscriptstyle {\cal U}}, \widetilde{H}^{\rm O}_{\!\scriptscriptstyle {\cal U}})$	$(1, 2, \frac{1}{2})$
	$H_d$	$(H^{\rm O}_d,H^d)$	$(\widetilde{H}_d^{\rm O}, \widetilde{H}_d^-)$	$(1, 2, -\frac{1}{2})$
	G	auge supermu	ltiplets	
Name		spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon		ĝ	g	(8,1,0)
winos, W bosons		$\widetilde{W}^\pm$ $\widetilde{W}^{ extsf{0}}$	$W^{\pm}$ $W^{0}$	(1,3,0)
bino, B boson		$\widetilde{B}^{O}$	$B^{0}$	(1,1,0)

### The MSSM

► Superpotential  $W = h_e H_d L \bar{e} + h_d H_d Q \bar{d} + h_u Q H_u U^c - \mu H_u H_d$ 

Soft SUSY-breaking mass and interaction terms for MSSM scalars

$$\begin{split} \mathscr{L}_{\text{soft-breaking}} &= m_{H_{u}}^{2} H_{u}^{\dagger} H_{u} + m_{H_{d}}^{2} H_{d}^{\dagger} H_{d} + m_{Q}^{2} Q^{\dagger} Q + m_{L}^{2} L^{\dagger} L \\ &+ m_{u}^{2} \tilde{u}_{R}^{*} \tilde{u}_{R} + m_{d}^{2} \tilde{d}_{R}^{*} \tilde{d}_{R} + m_{e}^{2} \tilde{c}_{R}^{*} \tilde{e}_{R} \\ &+ \left( T_{e} H_{d} L \tilde{e}_{R}^{*} + T_{d} H_{d} Q \tilde{d}_{R}^{*} + T_{u} Q H_{u} \tilde{u}_{R}^{*} + B_{\mu} H_{u} H_{d} + h.c. \right) \end{split}$$

SUSY-soft-breaking gauginos masses

$$\mathscr{L}_G = \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right) + h.c.$$

#### A few phenomenological features

- After EWSB, gauginos and higgsinos mix to form the neutralinos (χ<sup>0</sup><sub>1,2,3,4</sub>) and the charginos (χ<sup>±</sup><sub>1,2</sub>).
- Higgs sector is a two Higgs-doublet (2HDM) of type-II. Physical spectrum is composed of two neutral CP-even Higgs(h and H), one neutral CP-odd Higgs (A) and two charged Higgses (H<sup>±</sup>).
- The light Higgs mass is *predicted* in the MSSM. Tree level upper bound of m<sub>Z</sub>, however radiative corrections are very important and allow to reach the observable value.

## Patterns of soft SUSY-breaking masses

#### Unified models

- Assume a specific mechanism of soft SUSY-breaking.
- Impose universality conditions on the soft SUSY-breaking terms at some high scale, e.g. GUT scale.
- Example: CMSSM, NUHM1, mAMSB, ....



## Phenomenological scenario

- Do not impose a specific structure at the high scale, very large number of parameters.
- Consider "reasonable" assumptions based on current measurements.
- No new sources of CP-violation, no new sources of FCNC, first and second generation universality.
- phenomenological MSSMn (pMSSMn) where n is the number of parameters [hep-ph/9901246, hep-ph/0211331].

#### LHC constraints

 Intense campaign of searches for SUSY signatures both from ATLAS and CMS. See talks by F. Lacroix (CMS), T. Yamanaka (ATLAS) and F. Legger (ATLAS) for more information on the experimental searches.

ATLAS SUSY Searches* - 95% CL Lower Limits					ATLAS Preliminary				
51	Model	ε, μ, τ, γ	r Jets	E <sup>miss</sup> <sub>T</sub>	∫£ difte	·1 Mass limit	$\sqrt{s} = 7,1$	TeV vr = 13 TeV	√s = 7, 8, 13 TeV Reference
Indusive Searches	$\begin{array}{l} \label{eq:main_states} \begin{split} & \underline{MSUGRA(CMSSM)} \\ & \underline{v}_{1}^{1}, \underline{v}_{1} + \underline{v}_{1}^{2} \\ & \underline{s}_{2}^{1}, \underline{v}_{1} + \underline{v}_{1}^{2} \\ & \underline{s}_{2}^{1}, \underline{v}_{2} + \underline{v}_{1}^{2} \\ & \underline{s}_{2}^{1}, \underline{v}_{2} + \underline{v}_{1}^{2} \\ & \underline{s}_{2}^{1}, \underline{v}_{2} + \underline{v}_{1}^{2} \\ & \underline{c}_{2}^{1}, \underline{v}_{2} + \underline{v}_{2}^{2} \\ & \underline{CASB} \left( NLSP \right) \\ & \underline{CAM} \left( Ino(LSP) \\ & \underline{CAM} \left( Ino(LSP) \\ & \underline{CAM} \left( Ino(LSP) \\ & \underline{CAM} \left( Ino(Ino(LSP) \\ & \underline{CAM} \left( Ino(Ino(LSP) \right) \\ & \underline{CAM} \left( Ino(Ino(LSP) \\ & \underline{CAM} \left( Ino(Ino(LSP) \right) \\ & \underline{CAM} \left( Ino(LSP) \right) \\ & \underline{CAM} \left( Ino(LSP)$	0.3 r, µ/1.2 r 0 menojet 0 3 r, µ 2 r, µ(55) 1.2 r + 0.1 2 y 7 2 r, µ(2) 0	2-10 jets 3 2-6 jets 1-3 jets 2-6 jets 2-6 jets 4 jets 0-3 jets 1-0-2 jets - 1-0-2 jets 2 jets mono-jet	<sup>2</sup> Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 12.3 12.3 12.3 12.2 12.2 12.2 22.3 20.3 12.3 20.3 20.3 20.3	2 000 Garr 2 000 Garr 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	1.85 TeV 1.25 TeV 1.82 TeV 1.7 TeV 1.7 TeV 1.7 TeV 2.0 Te 1.65 TeV 1.25 TeV 1.27 TeV 1.27 TeV	$\begin{array}{l} m(p_{1},\ldots,p_{2}) \\ m(p_{1}',\ldots,p_{2}) \\ m(p_{2}',\ldots,p_{2}) \\ $	- 100 0000 XTULE CORE OF 914-019 1004.0777 XTULE CORE OF 914-019 XTULE CORE OF 914-017 XTULE CORE OF 914-027 XTULE CORE OF 914-027 100 00480 XTULE CORE OF 914-026 100 00480 XTULE CORE OF 914-066 150.03900 150.03900
3" gen	$\begin{array}{c} \chi_2, \chi \rightarrow th \tilde{\chi}_1^0 \\ \chi_2, \chi \rightarrow t \tilde{\chi}_1^0 \\ \chi_2, \chi \rightarrow t \tilde{\chi}_1^0 \end{array}$	0 0-1 4. µ 0-1 4. µ	3.b 3.b	Yes Yes Yes	14.8 14.8 20.1	2 2 2	1.09 TeV 1.09 TeV 1.37 TeV	m(r <sup>2</sup> <sub>1</sub> )=0 GeV m(r <sup>2</sup> <sub>1</sub> )=0 GeV m(r <sup>2</sup> <sub>1</sub> )<300 GeV	ATLAG-CONF-2016-052 ATLAG-CONF-2016-052 1407-0600
31 <sup>4</sup> gen squarts destiproduction	$\begin{array}{l} \dot{h}_1 \dot{h}_1, \dot{h}_2 \rightarrow b \dot{1}_1^0 \\ \dot{h}_1 \dot{h}_1, \dot{h}_2 \rightarrow b \dot{1}_1^0 \\ \dot{h}_1 \dot{h}_1, \dot{h}_2 \rightarrow b \dot{1}_1^0 \\ \dot{h}_1 \dot{h}_1, \dot{h}_1 \rightarrow b \dot{1}_1^0 \\ \dot{h}_1 \dot{h}_1, \dot{h}_1 \rightarrow b \dot{h}_1^0 \\ \dot{h}_1 \dot{h}_1, \dot{h}_1 \rightarrow b \dot{h}_1^0 \\ \dot{h}_1 \dot{h}_1 \dot{h}_1 \dot{h}_2 \dot{h}_2 \\ \dot{h}_2 \dot{h}_1 \dot{h}_2 \rightarrow b \dot{h}_1 + Z \\ \dot{h}_2 \dot{h}_1 \dot{h}_2 \rightarrow b \dot{h}_1 + Z \\ \dot{h}_2 \dot{h}_1 \dot{h}_2 \rightarrow b \dot{h}_1 + J \end{array}$	0 2 s, µ (55) 0-2 s, µ 0-2 s, µ 0 2 s, µ (Z) 3 s, µ (Z) 1 s, µ	2.b 1.b 1-2.b 0-2 jets/1-2 mono-jet 1.b 1.b 6 jets + 2.b	Yes Yes Yes Yes Yes Yes Yes	3.2 13.2 4.7/13.3 4.7/13.3 3.2 20.3 13.3 20.3	Her     Her <td></td> <td>ကျပို့ 1:00 GeV ကျပို့ 1:05 GeV ကျပို့ = ကျပို့ 1:00 GeV ကျပို့ - 2:00 ပို့ ကျပို _)-65 GeV ကျပို့ - 1:04 ကျပို _)-5 GeV ကျပို _)-5 GeV ကျပို _)-05 GeV ကျပို _)-05 GeV</td> <td>1666.08772 ATLAS-DOIR-027 106.31002, ATLAS-CONF-2016-077 1566.08418, ATLAS-CONF-2016-077 1566.08219 1603.5222 ATLAS-DOIR-0316-038 1566.08416</td>		ကျပို့ 1:00 GeV ကျပို့ 1:05 GeV ကျပို့ = ကျပို့ 1:00 GeV ကျပို့ - 2:00 ပို့ ကျပို _)-65 GeV ကျပို့ - 1:04 ကျပို _)-5 GeV ကျပို _)-5 GeV ကျပို _)-05 GeV ကျပို _)-05 GeV	1666.08772 ATLAS-DOIR-027 106.31002, ATLAS-CONF-2016-077 1566.08418, ATLAS-CONF-2016-077 1566.08219 1603.5222 ATLAS-DOIR-0316-038 1566.08416
EW direct	$\begin{array}{l} \hat{\ell}_{L,R}\hat{\ell}_{L,R}, \hat{\ell} \! \! \! \! \! \! \! \! \! \! \! \! \! \! \! \! \! \! \!$	2 κ.μ 2 κ.μ 2 τ 3 κ.μ 2 3 κ.μ τ/γγ κ.μ.γ 4 κ.μ 1 π.μ + γ 2 γ	0 0 0-2 jets 0-2 h 0 -	Yes Yes Yes Yes Yes Yes Yes	20.3 12.3 14.8 12.3 20.3 20.3 20.3 20.3 20.3	1     Sector GeV       1     Sec GeV	ಸರ್() ಗಾಗ ಸರ್()	$\begin{split} m(\tilde{l}_1, d, d, d, v) & \\ & M(\tilde{l}_1, d, d, d, d) m(\tilde{l}_1) + m(\tilde{l}_1) $	1002 0014 ATLAS-COMF-2014-006 ATLAS-COMF-2014-000 ATLAS-COMF-2014-000 1002 0014-0012 1002 0014 1002 00640 1020 00640
Lorg-lived particles	$\begin{array}{l} \text{Direct} \ \widehat{i}_{1}^{+}\widehat{i}_{1}^{+} \text{ prod.}, \ \text{long-load} \\ \text{Direct} \ \widehat{i}_{1}^{+}\widehat{i}_{1}^{-} \text{ prod.}, \ \text{long-load} \\ \text{Stable, integrad } \widehat{i}_{1}^{-}\text{Anderson} \\ \text{Stable } \ \widehat{i}_{1}^{-}\text{Redexon} \\ \text{Stable } \ \widehat{i}_{1}^{-}\text{Redexon} \\ \text{CMSB}, \ \widehat{i}_{1}^{-} \rightarrow i \widehat{i}_{1}^{-} \text{Redexon} \\ \text{CMSB}, \ \widehat{i}_{1}^{-} \rightarrow i \widehat{j}_{1}^{-} \text{Redexon} \\ \text{CMSB}, \ \widehat{i}_{1}^{-} \rightarrow i \widehat{j}_{2}^{-} \text{Redexon} \\ \end{array}$	<sup>(1)</sup> Disapp. t9 <sup>(1)</sup> dEids trk 0 trk dEids trk dEids trk (κ,μ) 1-2 μ 2 γ displ. κε/κμ( displ. vtx + js	k 1 jet 1-5 jets - - - - - - - - - - - - - - - - - - -	Yes Yes Yes Yes Yes	20.3 18.4 27.9 3.2 19.1 20.3 20.3 20.3	1 270 GeV 405 GeV 4 50 GeV 4 50 GeV 4 507 GeV 4 40 GeV 1 1.0 1 1.	1.50 TeV 1.57 TeV TeV	$\begin{split} m_{1}^{(1)}m_{1}^{(1)}m_{2}^{(1)}m_{2}^{(1)}m_{3}^{$	12116 3475 1526 05322 1233 8458 1666 05322 1366 05329 1666 05320 1111 3766 1668 0562 1566 05682
NH	$\begin{split} & LFV  \rho p \!$	r εμ,ετ,μτ 2 ε,μ (55) μμν 4 ε,μ τ, 3 ε,μ+τ 0 4 1 ε,μ 1 ε,μ 0 2 ε,μ		Yes Yes Yes is is is is is is is is is is is is is	3.2 20.3 10.3 20.3 14.8 14.8 14.8 14.8 14.8 15.4 20.3	5. 1. 453 GeV 2. 453 GeV 3. 453 GeV 45. 452 GeV 45. 515 GeV 45. 515 GeV 45. 515 GeV 45. 515 GeV 45. 644.9 6.444.9 1. 415 GeV 45. 644.9 1. 415 GeV 45. 644.9 1. 455 GeV 45. 645.9 1. 455 GeV	1.9 TeV 1.45 TeV 1.45 TeV 1.55 TeV 1.75 TeV 1.4 TeV TeV	$\begin{split} & \mathcal{A}_{i_1}, \mathrm{d} (3, 1, A_{i_1(i_1(i_1))} \mathrm{d} (3, 2)) \\ & \mathrm{stripset}(g_i, \mathrm{stripset}(g_i, \mathrm{stripset}(g_i))) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i, \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i), \mathrm{stripset}(g_i)) \\ & \mathrm{stripset}(g_i), \mathrm{stripset}(g$	1407.08779 1408.006 ATLAS-CORF-3914-075 1405.008 ATLAS-CORF-3914-07 ATLAS-CORF-3914-07 ATLAS-CORF-3914-07 ATLAS-CORF-3914-08 ATLAS-CORF-3914-08 ATLAS-CORF-3914-08 ATLAS-CORF-3914-08
Other	Scalar charm, $2 \rightarrow c \hat{\pi}_1^0$	0	2.0	Yes	20.3	a Stū GeV		m(l <sup>2</sup> )-200 GeV	1501.01325
	"Only a selection of it	re available n	nass limits	on n	ow 1	D-1	1	Mass scale [Te\/]	

Low-energy supersymmetry facing LHC constraints

### LHC constraints

- A proper interpretation of current results in terms of MSSM parameter space depends strongly on the hierarchy of masses between the different SUSY particles.
- Different hierarchies implies different decay rate. Some configuration results in difficult experimentally accessible region (e.g. compressed regions).
- Assumptions that results in the near degeneracy of some states (e.g. first two generation squarks), strongly influence the constraints.
- If using a simplified model, dependence on its assumptions (BRs, mass of the other sparticles etc.).



[CMS-PAS-SUS-16-05]

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## LHC constraints ... but not only

#### Indirect measurements

- (g−2)<sub>μ</sub>. 3.4σ discrepancy may be explained with O(100) GeV smuons.
- $M_W, M_Z, M_h$  and EWPO.
- Flavor physics observables  $(B_s \rightarrow \mu \mu, b \rightarrow s\gamma, \ldots)$ .

#### Dark matter

- Relic density constraint especially important, if assuming that the  $\hat{\chi}_1^{\circ}$  is the only DM component.
- Strong constraint from direct detection experiment; complementary to the LHC searches.
- Indirect detection constraints can be important according to the neutralino composition, however large uncertainties in the modeling of the signal.



## Where is SUSY now?

#### Global likelihood studies

- Define a simplified model based on reasonable assumptions and a minor number of free parameters.
- Use of the available collider data, electro-weak precision observables and DM constraint to fit the best value and the likelihood profile of the model parameters.
- Effectively implement interplay between different searches (e.g. collider vs direct detection for DM).



#### MSSM scenarios



 $\underbrace{\frac{M_1, M_2, M_3}{m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{f}}}}_{A}}_{M_A, \tan\beta, \mu}$ 

pMSSM19

$$\begin{array}{c} M_{1}, M_{2}, M_{3} \\ m_{\tilde{Q}_{1,2}}, m_{\tilde{Q}_{3}}, m_{\tilde{u}_{R}, \tilde{c}_{R}}, m_{\tilde{d}_{R}, \tilde{s}_{R}}, m_{\tilde{t}_{R}}, m_{\tilde{b}_{R}} \\ m_{\tilde{L}_{1,2}}, m_{\tilde{L}_{3}}, m_{e,\tilde{\mu}}, m_{\tilde{\tau}} \\ A_{t}, A_{b}, A_{\tau} \\ M_{A}, \tan \beta, \mu \end{array}$$

[1504.03260],[1508.06608,1605.09502, 1608.05379]

## GUT models

#### **CMSSM**



We have several different mechanism at play.

1.  $\tilde{\tau}$ -coannihilation



- Leading mechanism when the mass difference between the τ̃ and the χ̃<sup>1</sup><sub>1</sub> is of the order of a few GeV.
- $\hat{\chi}_1^0$  is Bino-like.
- Also  $\tilde{\tau} \tilde{\tau}$  annihilation important in this scenario.

GUT models

#### **CMSSM**



#### **CMSSM**



We have several different mechanism at play.

3. Focus point.



- Region where RGEs have focussing properties.
- We have that  $\mu \approx M_1$ , sizable Higgsino component of the  $\hat{\chi}_1^{\circ}$ .

GUT models

#### SU(5) boundary conditions





Phenomenological models

## Phenomenological models

#### pMSSM10 mass spectrum



- Poor determination of the mass of colored sparticles (only lower bound from LHC searches).
- Larger freedom allow to fulfill the  $(g-2)_{\mu}$  constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.



Model	$\chi^2/n_{\rm dof}$	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %

- $3.5\sigma$  discrepancy between the SM  $(g-2)_{\mu}$  value and the measured one.
- In CMSSM,NUHM1 and NUHM2 there is a tension between the  $(g-2)_{\mu}$ and LHC constraints from direct searches, due the universality relations.
- In the pMSSM10 we are able to fit perfectly the  $(g-2)_{\mu}$ .
- Impact of LHC8<sub>FWK</sub> constraint limited.

Low-energy supersymmetry facing LHC constraints



Phenomenological models

## Interplay between collider and direct detection



Low-energy supersymmetry facing LHC constraints

## pMSSM19

- ATLAS pMSSM19 scan vs 7/8 TeV searches.
- Flat-prior random-sampling. Upper and lower bound chosen to maximize coverage of the parameter space accessible to the LHC [1508.06608].





SUSY-AI : use results from the ATLAS scan to implement the constraints from the available searches using machine-learning method [1605.02797].

## pMSSM19

- Exclusion power of the 13 TeV data from Barr et al [1605.09502].
- Use the models previously found to be allowed by the ATLAS study.
- Exclude a further 15.7% model points from the set that survived from Run 1 searches.



 Barr et al [1608.05379], complementarity with DM.



### Conclusions

- Completely covering Supersymmetry at LHC is difficult, even for the simplest case of the MSSM.
- Strong dependence of the spectrum (and of the signatures) on the theoretical assumptions of the scenario.
- ► GUT models unable to fit (g-2)<sub>µ</sub> anymore due to the LHC constraints on sparticle production.
- Interesting complementarity with DM direct-detection searches.
- Countless other studies not covered in this talk.

## Appendix

### Higgs mechanism in the MSSM

► Tree level Higgs scalar potential  $(m_u^2 = m_{H_u}^2 + |\mu|^2 \text{ and } m_d^2 = m_{H_d}^2 + |\mu|^2)$ 

$$V_{0} = m_{\mu}^{2} \left| H_{\mu}^{0} \right|^{2} + m_{d}^{2} \left| H_{d}^{0} \right|^{2} + B_{\mu} (H_{d}^{0} H_{\mu}^{0} + \text{h.c.}) + \frac{g^{2} + g'^{2}}{8} \left( \left| H_{d}^{0} \right|^{2} - \left| H_{\mu}^{0} \right|^{2} \right)^{2}$$

- The two Higgs doublet are supposed to acquire a v.e.v. different from zero
- Decomposition of the fields

$$H_{\mu}^{0} = \frac{1}{\sqrt{2}} \left( v_{\mu} + S_{\mu} + iP_{\mu} \right), \quad H_{d}^{0} = \frac{1}{\sqrt{2}} \left( v_{d} + S_{d} + iP_{d} \right)$$

Diagonalization of the pseudoscalar mass matrix (rotation angle β) give a would-be Goldstone boson eaten by the Z and a pseudoscalar state with a mass

$$m_A^2 = \frac{B_\mu}{\cos\beta\sin\beta}$$

- Same diagonalization angle for the charged Higgs matrix
- Pseudoscalar couplings to quarks and leptons are given by

$$g_{Auu} = \cot \beta \frac{m_u}{v}, \quad g_{Add,Aee} = \tan \beta \frac{m_{d,e}}{v}$$

### Higgs mechanism in the MSSM

• Mass matrix for the scalar sector  $(m_{\mu}^2 \text{ and } m_d^2 \text{ replaced by a combination of } m_A^2 \text{ and } \tan \beta)$ 

$$\mathcal{M}_{0} = \begin{pmatrix} m_{A}^{2} \sin^{2}\beta + m_{Z}^{2} \cos^{2}\beta & -(m_{A}^{2} + m_{Z}^{2}) \sin\beta\cos\beta \\ -(m_{A}^{2} + m_{Z}^{2}) \sin\beta\cos\beta & m_{A}^{2} \cos^{2}\beta + m_{Z}^{2} \sin^{2}\beta \end{pmatrix}$$

► Diagonalization angle  $\alpha$ .  $m_b^2 \le m_Z^2 \cos^2(2\beta)$  at tree level.

$$\tan 2\alpha = \left(\frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}\right) \tan 2\beta$$

$$m_{b,H} = \frac{1}{2} \left( m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_Z^2 m_A^2 \sin^2(2\beta)} \right)$$

Scalar coupling to the gauge bosons: g<sub>bVV</sub> = <sup>2m<sup>2</sup><sub>V</sub></sup>/<sub>v</sub> sin(β−α), g<sub>HVV</sub> = <sup>2m<sup>2</sup><sub>V</sub></sup>/<sub>v</sub> cos(β−α)
Scalar couplings to the quarks and leptons are given by

$$g_{huu} = \frac{\cos \alpha}{\sin \beta} \frac{m_u}{v}, \quad g_{hdd,hee} = -\frac{\sin \alpha}{\cos \beta} \frac{m_{d,e}}{v}$$
$$g_{Huu} = \frac{\sin \alpha}{\sin \beta} \frac{m_u}{v}, \quad g_{Hdd,hee} = \frac{\cos \alpha}{\cos \beta} \frac{m_{d,e}}{v}$$

►

### The framework

- Frequentist fitting framework written in Python/Cython and C++.
- We use SLHA standard as an interface between the external codes that are used to compute the spectrum and the observables.
- The Multinest algorithm is used to sample the parameter space.

Parameter	Range	Number of
	_	segments
M <sub>1</sub>	(-1, 1) TeV	2
M <sub>2</sub>	(0,4)TeV	2
M <sub>3</sub>	(-4,4) TeV	4
$m_{\tilde{q}}$	(0,4)TeV	2
$m_{\tilde{q}_3}$	(0,4)TeV	2
mj	(0,2)TeV	1
M <sub>A</sub>	(0,4)TeV	2
Â	(-5,5) TeV	1
μ	(-5, 5) TeV	1
$\tan \beta$	(1,60)	1
Total number of boxes		128



Spectrum generation SoftSUSY

Higgs sector and  $(g-2)_{\mu}$  FeynHiggs, Higgssignals, Higgsbounds

**B-Physics** 

SuFla, SuperISO

EW precision observables FeynWZ

Dark matter MicrOMEGAs, SSARD

## SU(5) GUT



SUSY-breaking terms.

- $(q_L, u_L^c, e_L^c)_i \in 10_i$
- $(\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$
- $H_{u} \in \mathbf{5}_{i}, H_{u} \in \mathbf{\bar{5}}_{i}$
- Universal trilinear  $A_0$ .
- $\tan \beta$ .



## SU(5) GUT



- CMS simplified models, 100% BR  $\tilde{q} \rightarrow q \tilde{\chi}_1^{\circ}$ .
- $\tilde{u}_L$  and  $\tilde{d}_L$  decays on other hand mainly in  $\tilde{\chi}^{\pm} + q'$ .
- We implemented our own recasting of the analysis.

## SU(5) GUT



- CMS simplified models, 100% BR  $\tilde{q} \rightarrow q \tilde{\chi}_1^{\circ}$ .
- $\tilde{u}_L$  and  $\tilde{d}_L$  decays on other hand mainly in  $\hat{\chi}^{\pm} + q'$ .
- We implemented our own recasting of the analysis.

#### mAMSB



- SUSY breaking via loop-induced super-Weyl anomaly.
- Pure AMSB unrealistic (tachionic sleptons), add a term m<sub>0</sub>.
- Three parameters:  $m_0$ ,  $m_{3/2}$  and  $\tan \beta$ .
- Sign of μ is also free.



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## pMSSM10 best fit point



- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via  $\tilde{\chi}_1^{\pm}$  and  $\tilde{\chi}_2^{\circ}$ .
- Sleptons are at less than 1 TeV.



## Higgs physics



- pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by FeynHiggs.
- ► Lower value of tan  $\beta$  are disfavored at the 68% CL by LHC8<sub>*EWK*</sub>,  $(g-2)_{\mu}$  and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking mass-parameter for the sleptons.