Low-energy supersymmetry facing LHC constraints

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Introduction

The Minimal Supersymmetric Standard Model

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)	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$
(×3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
sleptons,leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$
(×3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgses, Higgsinos	H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)$
	H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

Gauge supermultiplets

Name	spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm$ $\widetilde{W}^0$	$W^\pm$ W^0	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

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

$$
\begin{aligned}
\mathscr{L}_{\text{soft—breaking}} = {} & m^2_{H_u} H_u^\dagger H_u + m^2_{H_d} H_d^\dagger H_d + m^2_Q Q^\dagger Q + m^2_L L^\dagger L \\
& + m^2_u \tilde{u}^*_R \tilde{u}_R + m^2_d \tilde{d}^*_R \tilde{d}_R + m^2_e \tilde{e}^*_R \tilde{e}_R \\
& + \left(T_e H_d L \tilde{e}^*_R + T_d H_d Q \tilde{d}^*_R + T_u Q H_u \tilde{u}^*_R + B_\mu H_u H_d + h.c. \right)
\end{aligned}
$$

- SUSY-soft-breaking gauginos masses

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

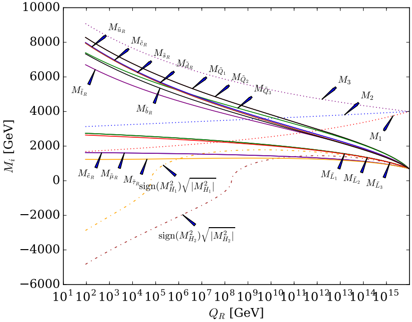
A few phenomenological features

- After EWSB, gauginos and higgsinos mix to form the neutralinos ($\tilde{\chi}^0_{1,2,3,4}$) and the charginos ($\tilde{\chi}^\pm_{1,2}$).
- 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 ($H^\pm$).
- The light Higgs mass is *predicted* in the MSSM. Tree level upper bound of m_Z, 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, ...

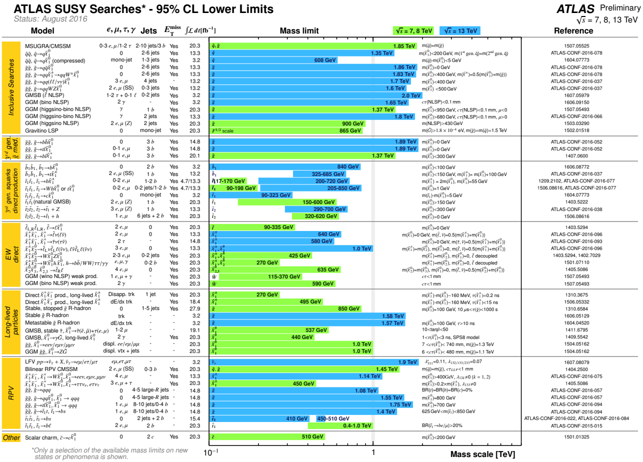


Phenomenological scenario

- 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].

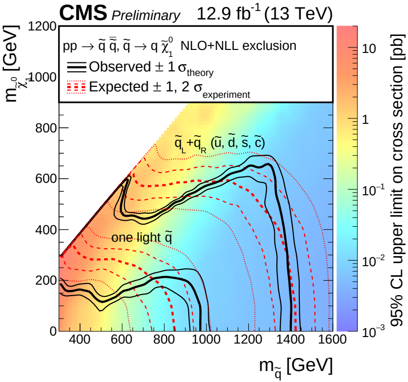
LHC constraints

- 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.



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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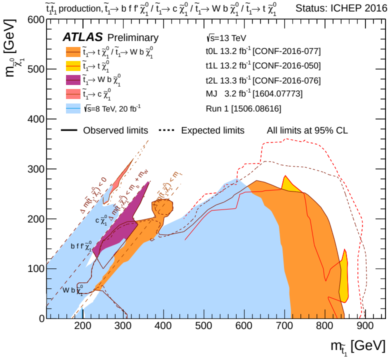
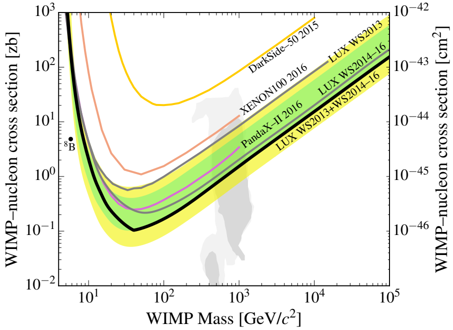


[ATLAS summary plot]

LHC constraints ... but not only

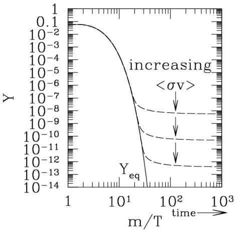
Indirect measurements

- $(g-2)_\mu$. 3.4σ discrepancy may be explained with $\mathcal{O}(100)$ GeV smuons.
- M_W,M_Z, M_h and EWPO.
- Flavor physics observables ($B_s \to \mu\mu$, $b \to s\gamma$, ...).



Dark matter

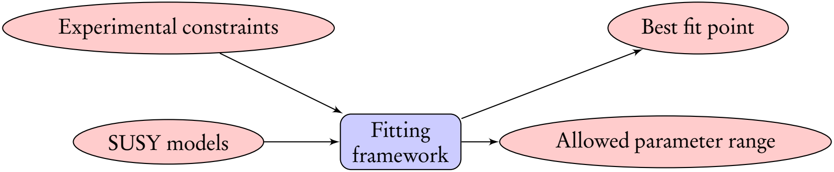
- Relic density constraint especially important, if assuming that the $\tilde{\chi}_1^0$ is the only DM component.
- Strong constraint from direct detection experiment; complementary to the LHC searches.
- Indirect detection constraints can be important according to the neutralino composition, however 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

GUT Models
CMSSM
$m_0, m_{1/2}, A_0, \tan\beta$
SU(5)
$m_{1/2}, m_{\bar{5}}, m_{10}, m_{H_u}, m_{H_d}, A_0, \tan\beta$
mAMSB
$m_0, m_{3/2}, \tan\beta$
others, e.g NUHM1, NUHM2, ...

- Introduce correlation between the colored and uncolored sectors.

[1312.5250,1408.4060,1610.10084,1610.10084]

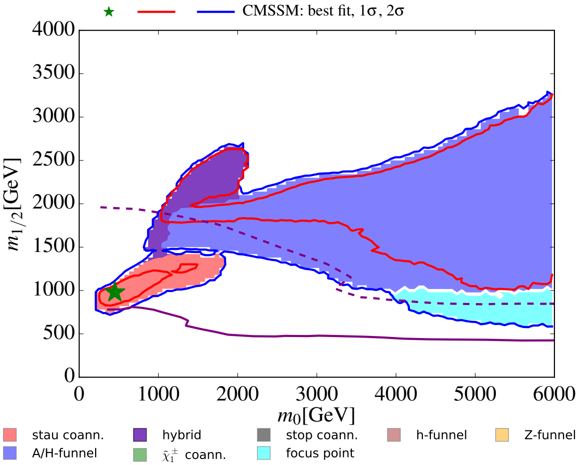
pMSSM10
M_1, M_2, M_3
$m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{l}}$
A
$M_A, \tan\beta, \mu$

pMSSM19
M_1, M_2, M_3
$m_{\tilde{Q}_{1,2}}, m_{\tilde{Q}_3}, m_{\tilde{u}_R,\tilde{c}_R}, m_{\tilde{d}_R,\tilde{s}_R}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$
$m_{\tilde{L}_{1,2}}, m_{\tilde{L}_3}, m_{\tilde{e},\tilde{\mu}}, m_{\tilde{\tau}}$
A_t, A_b, A_τ
$M_A, \tan\beta, \mu$

[1504.03260],[1508.06608,1605.09502, 1608.05379]

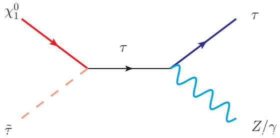
GUT models

CMSSM



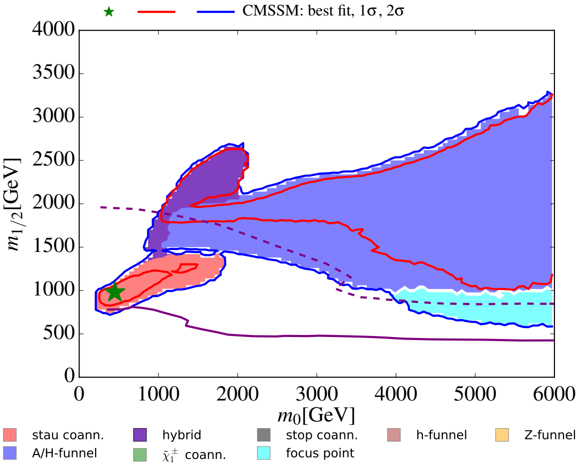
We have several different mechanism at play.

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



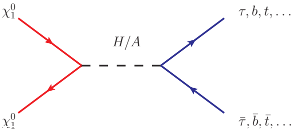
- Leading mechanism when the mass difference between the $\tilde{\tau}$ and the $\tilde{\chi}_1^0$ is of the order of a few GeV.
- $\tilde{\chi}_1^0$ is Bino-like.
- Also $\tilde{\tau} - \tilde{\tau}$ annihilation important in this scenario.

CMSSM



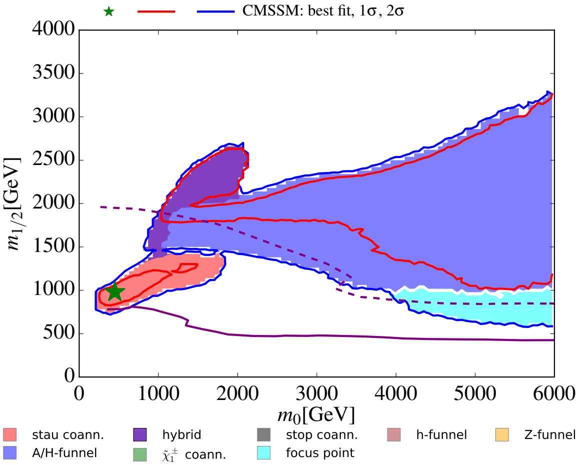
We have several different mechanism at play.

2. H/A-funnel.



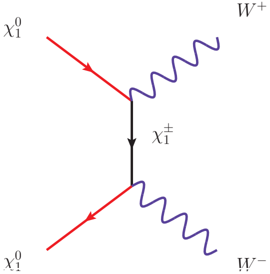
- $\tilde{\chi}_1^0$ is Bino-like.
- Mass degeneracy condition: $2 \cdot \tilde{\chi}_1^0 \approx M_A/M_H$.

CMSSM



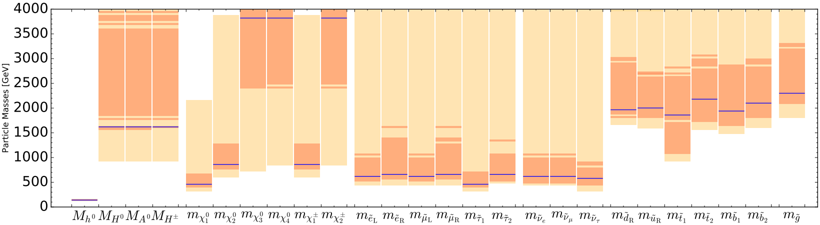
We have several different mechanism at play.

3. Focus point.

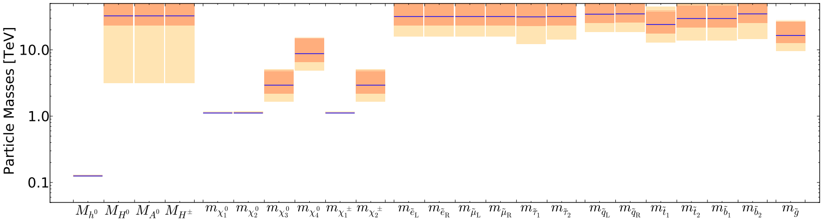


- Region where RGEs have focussing properties.
- We have that $\mu \approx M_1$, sizable Higgsino component of the $\tilde{\chi}_1^0$.

SU(5) boundary conditions

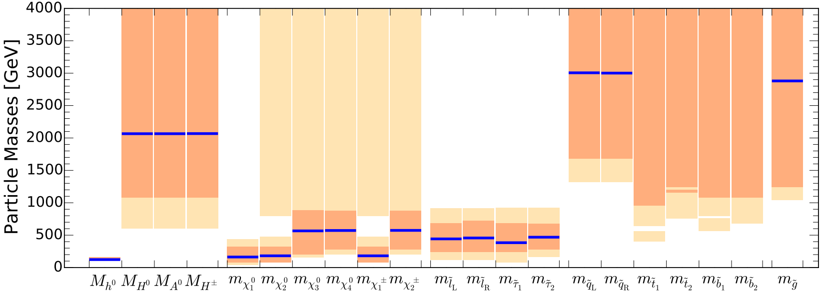


mAMSB



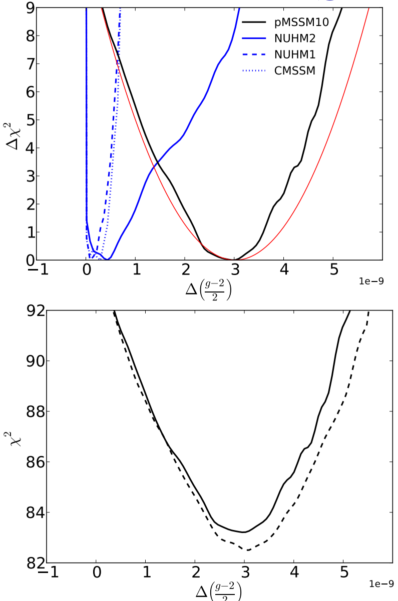
Phenomenological models

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.

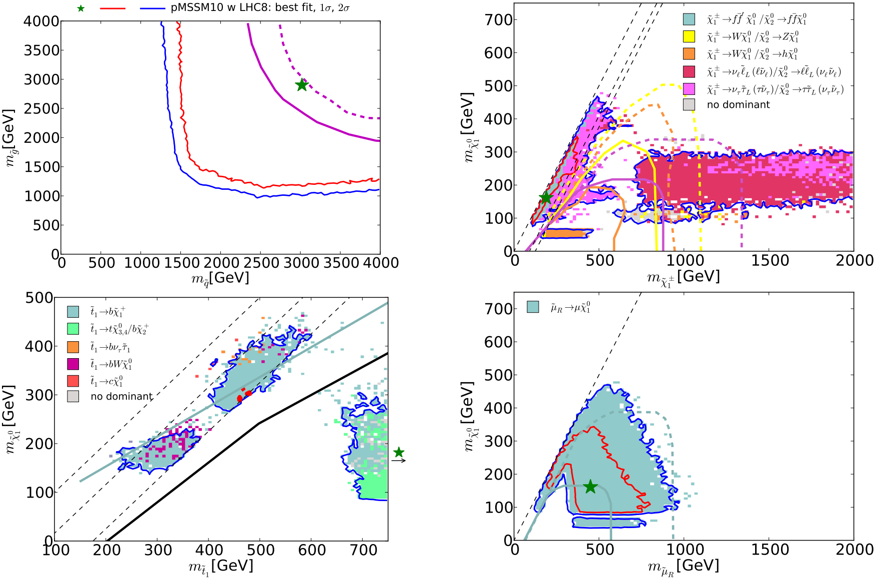
The $(g-2)_\mu$ constraint



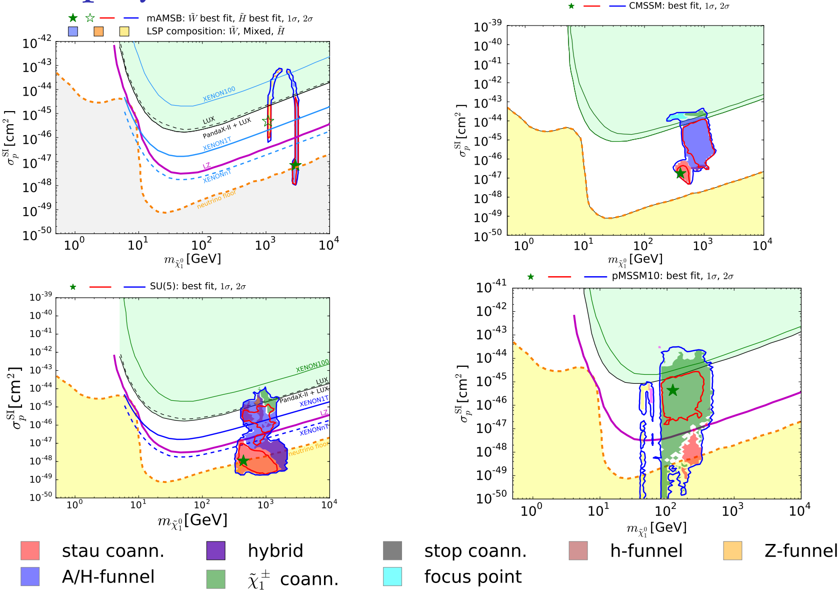
Model	$\chi^2/n_{\rm dof}$	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %

- 3.5σ 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$_{\rm EWK}$ constraint limited.

Perspectives for discovery at LHC run 2

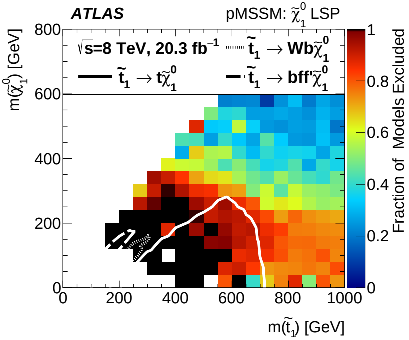


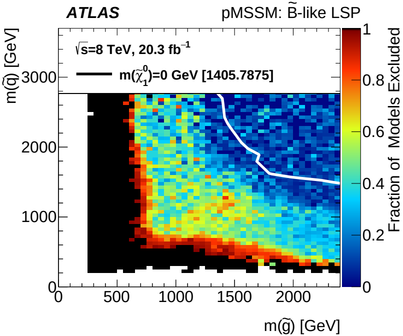
Interplay between collider and direct detection



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].

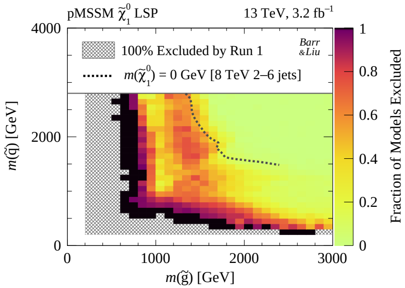




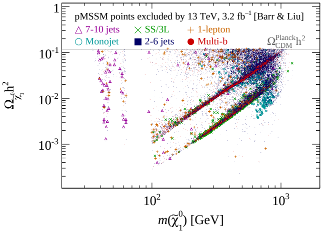
- SUSY-AI : use results from the ATLAS scan to implement the constraints from the available searches using machine-learning method [1605.02797].

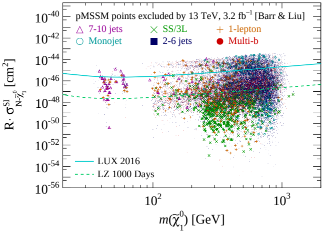
pMSSM19

- 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 $(g-2)_\mu$ 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 ($m_u^2 = m_{H_u}^2 + |\mu|^2$ and $m_d^2 = m_{H_d}^2 + |\mu|^2$)

$$V_0 = m_u^2 \left|H_u^0\right|^2 + m_d^2 \left|H_d^0\right|^2 + B_\mu (H_d^0 H_u^0 + \text{h.c.}) + \frac{g^2 + g'^2}{8} \left(\left|H_d^0\right|^2 - \left|H_u^0\right|^2\right)^2$$

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

$$H_u^0 = \frac{1}{\sqrt{2}}(v_u + S_u + iP_u), \quad H_d^0 = \frac{1}{\sqrt{2}}(v_d + S_d + iP_d)$$

- 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_u^2 and m_d^2 replaced by a combination of m_A^2 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 α. $m_h^2 \leq m_Z^2 \cos^2(2\beta)$ at tree level.

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

-

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

- Scalar coupling to the gauge bosons: $g_{hVV} = \frac{2m_V^2}{v}\sin(\beta - \alpha)$, $\quad g_{HVV} = \frac{2m_V^2}{v}\cos(\beta - \alpha)$
- Scalar couplings to the quarks and leptons are given by

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

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

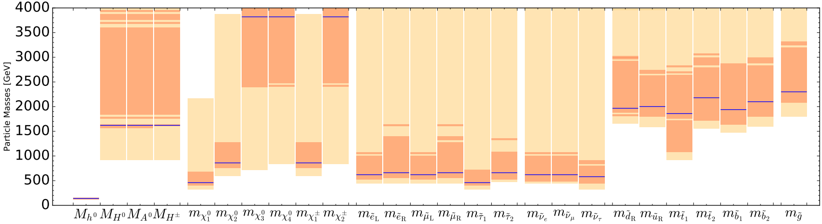
The framework

- 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.

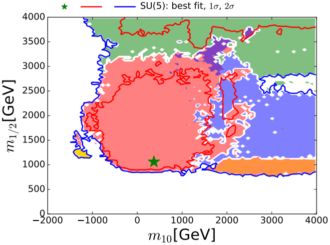
Parameter	Range	Number of segments
M_1	(-1 , 1) TeV	2
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}3}$	(0 , 4) TeV	2
$m_{\tilde{l}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		128

Codes
Spectrum generation `SoftSUSY`
Higgs sector and $(g-2)_\mu$ `FeynHiggs, Higgssignals, Higgsbounds`
B-Physics `SuFla, SuperISO`
EW precision observables `FeynWZ`
Dark matter `MicrOMEGAs, SSARD`

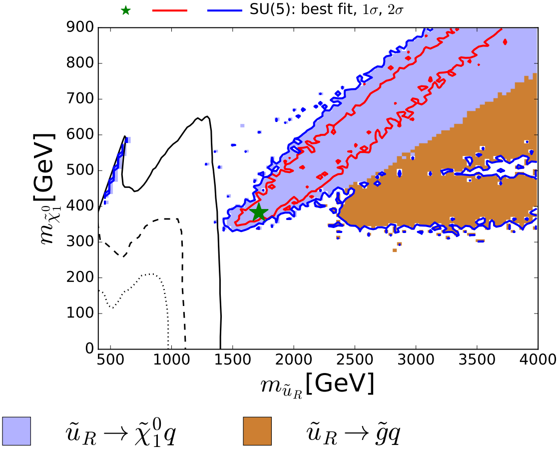
SU(5) GUT



- SU(5) boundary conditions for soft SUSY-breaking terms.
  - $(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i$
  - $(\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$
  - $H_u \in \mathbf{5}_i, H_u \in \bar{\mathbf{5}}_i$
  - Universal trilinear A_0.
  - $\tan\beta$.

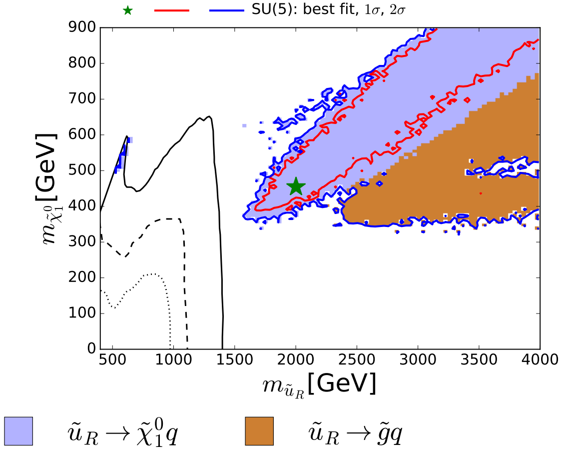


SU(5) GUT



- CMS simplified models, 100% BR $\tilde{q} \to q\tilde{\chi}_1^0$.
- $\tilde{u}_L$ 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



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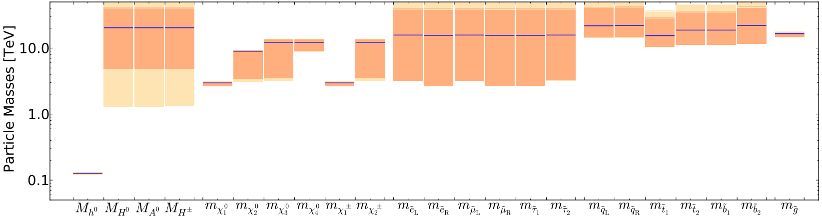
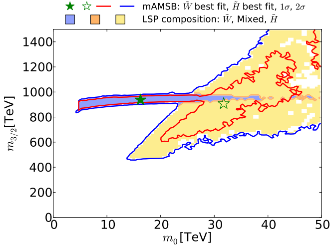
mAMSB



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



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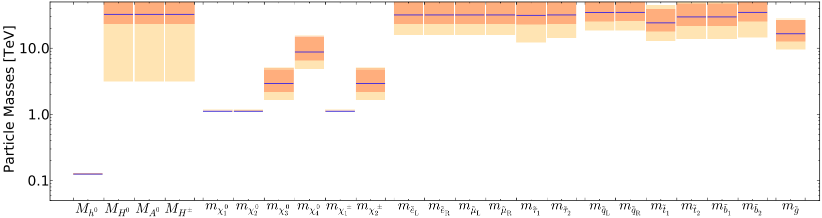

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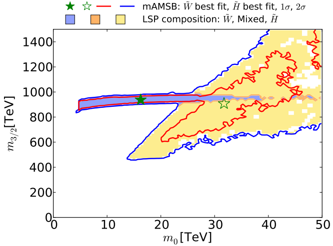
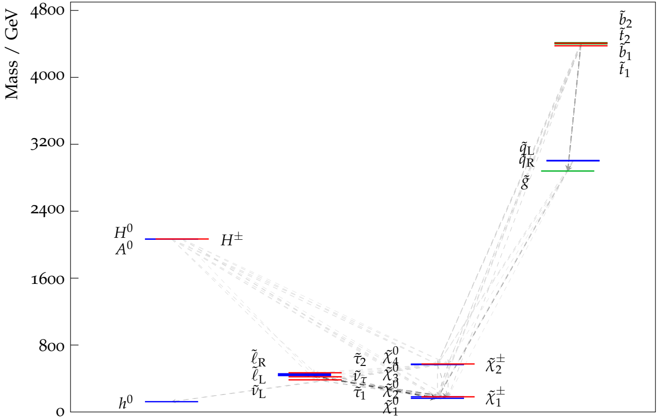


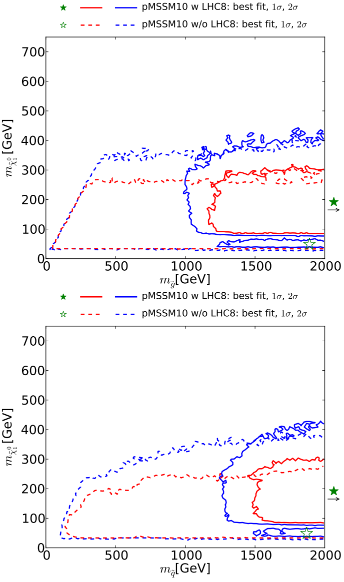
pMSSM10 best fit point



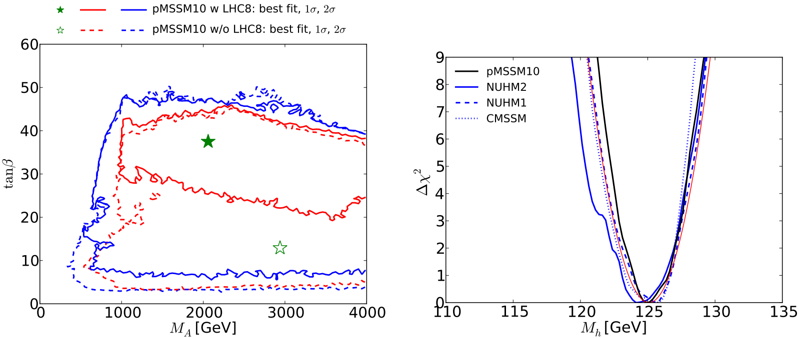
Parameter	Best-fit
M_1	170 GeV
M_2	170 GeV
M_3	2600 GeV
$m_{\tilde{q}}$	2880 GeV
$m_{\tilde{q}_3}$	4360 GeV
$m_{\tilde{l}}$	440 GeV
M_A	2070 GeV
A	790 GeV
μ	550 GeV
$\tan\beta$	37.6

- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$.
- Sleptons are at less than 1 TeV.

Physical mass planes for the colored sparticles



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$_{EWK}$, $(g-2)_\mu$ and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking mass-parameter for the sleptons.