

Prospects for SUSY discovery after the LHC Run 1

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On behalf of the Mastercode collaboration

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

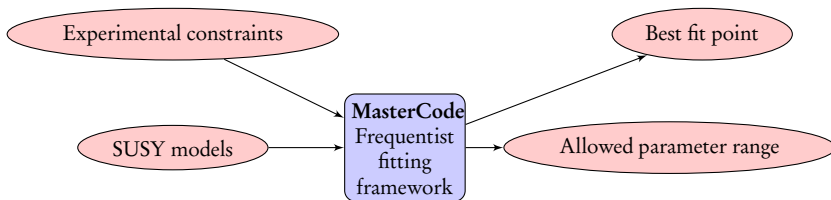
Gauge supermultiplets

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

Physical motivations

Global fits

- ▶ In the unconstrained MSSM 105 new free parameters (masses, mixing angles and phases). Impossible/uninteresting to probe.
- ▶ 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).



The models

GUT Models

CMSSM

$$m_0, m_{1/2}, A_0, \tan \beta$$

NUHM1

$$m_0, m_{1/2}, A_0, \tan \beta, m_H$$

NUHM2

$$m_0, m_{1/2}, A_0, \tan \beta, m_{H_u}, m_{H_d}$$

- ▶ Based on unifications assumptions for the soft-SUSY breaking mass terms.
- ▶ Introduce correlation between the colored and uncolored sectors.

pMSSM10

$$M_1, M_2, M_3$$

$$m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{t}}$$

$$A$$

$$M_A, \tan \beta, \mu$$

- ▶ Phenomenological model with 10 low-energy input parameters.
- ▶ We assume all left and right soft-SUSY mass breaking terms to be equal.
- ▶ We assume that the first two generations of squarks have the same soft-SUSY breaking term.
- ▶ All the trilinear coupling are the same.

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
$m_{\tilde{g}}$	(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

MicroOMEGAs, SSARD

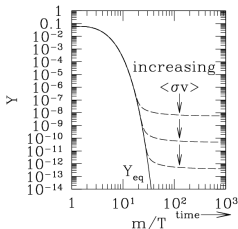
The constraints

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 observables ($B_s \rightarrow \mu\mu, b \rightarrow s\gamma$).

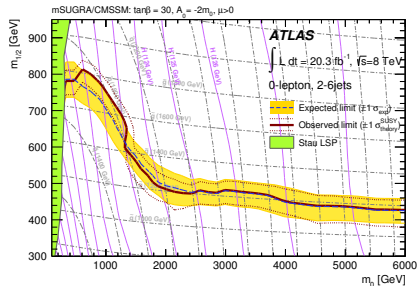
Dark matter

- ▶ Relic density and direct detection.



Collider – GUT models

- ▶ Limits are independent of $A_0, \tan\beta, m_{H_u}^2$ and $m_{H_d}^2$.
- ▶ Due to unification, limits on squarks and gluinos are relevant also for sleptons and electroweakinos.



The constraints – collider pMSSM10

Three classes of constraints

Colored sparticle production

We have combined the following CMS searches (8 TeV, 20 fb⁻¹):

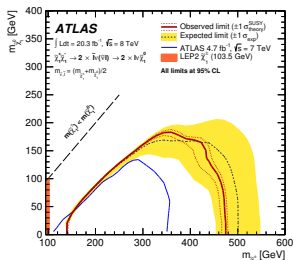
- ▶ 0-lepton M_{T2}
- ▶ 1-lepton M_{T2}^W
- ▶ 2-lepton OS/SS
- ▶ ≥ 3 leptons.

Compressed stop region

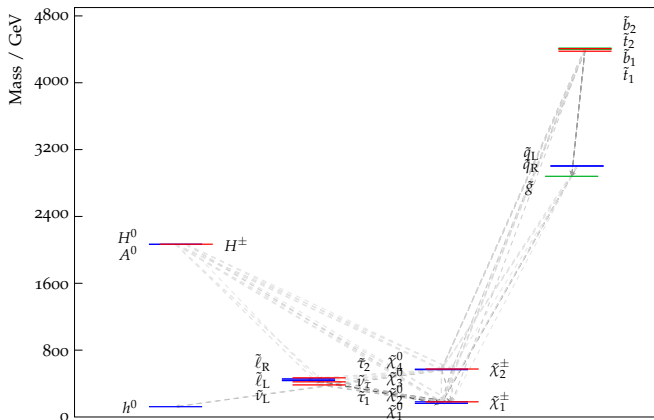
This region is separately. The stop cross-section is set to zero in the other constraints.

Electroweakinos production

- ▶ Simplified ModelS (SMS) approach. Limited mass hierarchies.
- ▶ Slepton production.
- ▶ $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via sleptons.
- ▶ $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ.



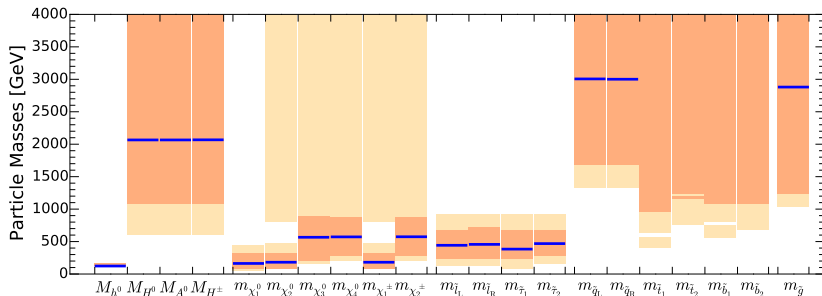
pMSSM10 best fit point



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

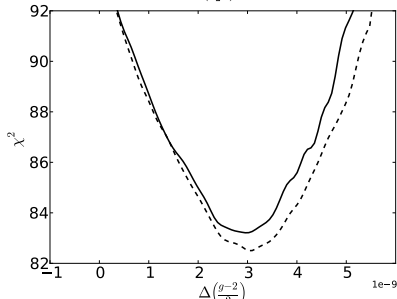
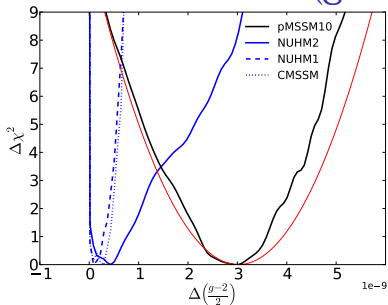
- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$.
- Sleptons are at less than 1 TeV.

pMSSM10 mass spectrum



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

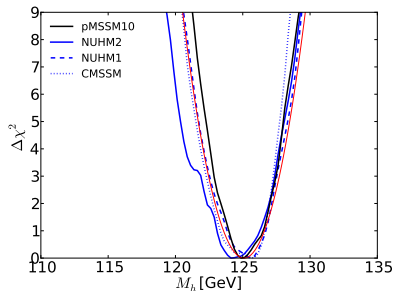
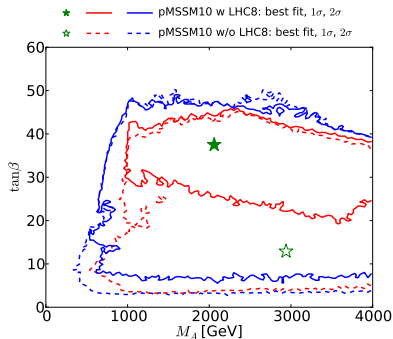
The $(g-2)_\mu$ constraint



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

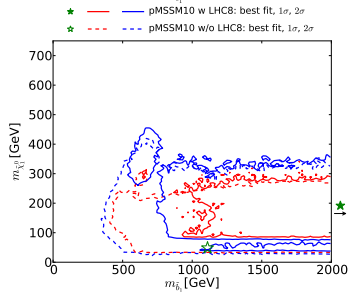
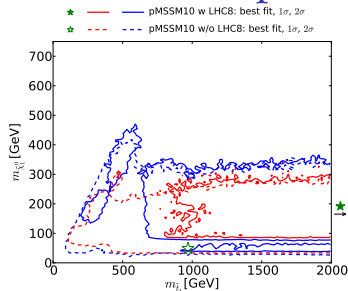
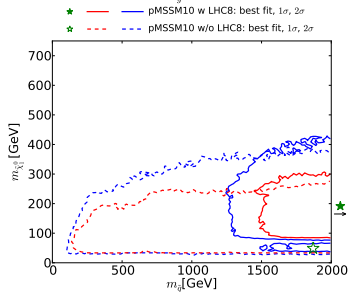
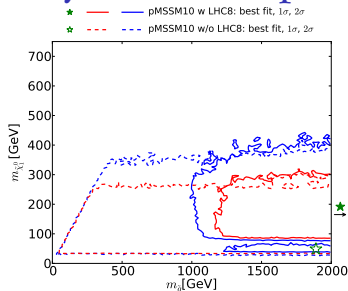
- ▶ 3.5 σ discrepancy between the SM $(g-2)_\mu$ value and the measured one.
- ▶ In CMSSM, NUHM1 and NUHM2 there is a tension between the $(g-2)_\mu$ and LHC constraints from direct searches, due the universality relations.
- ▶ In the pMSSM10 we are able to fit **perfectly** the $(g-2)_\mu$.
- ▶ Impact of LHC8_{EWK} constraint limited.

Higgs physics

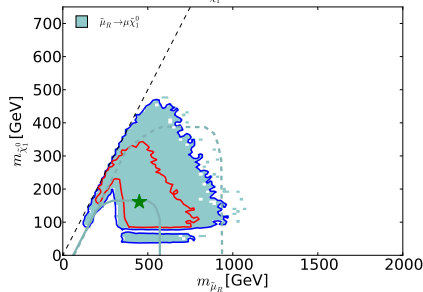
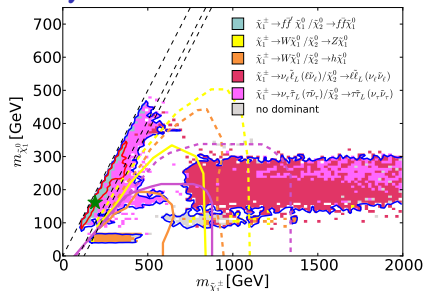
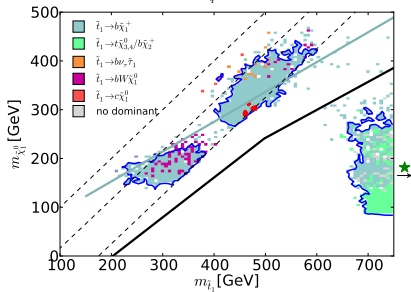
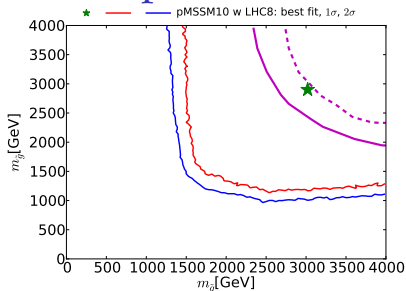


- ▶ pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by `FeynHiggs`.
- ▶ Lower value of $\tan\beta$ are disfavored at the 68% CL by LHC8_{EWK}, $(g-2)_\mu$ and DM constraints
- ▶ The constraints interplay with the choice of a single soft SUSY-breaking mass-parameter for the sleptons.

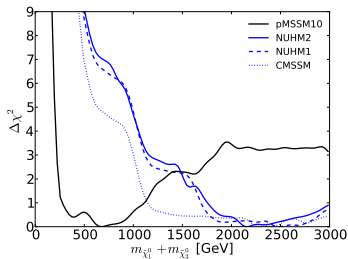
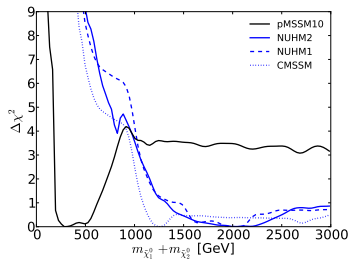
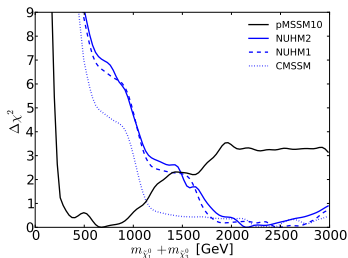
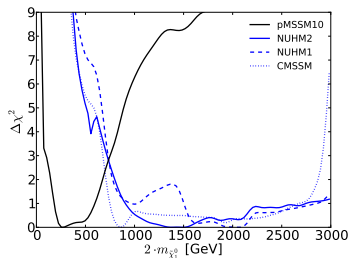
Physical mass planes for the colored sparticles



Perspectives for discovery at LHC run 2



Perspectives for discovery at e^+e^- colliders



Conclusions

- ▶ We performed the first global likelihood analysis of the pMSSM using a frequentist approach including LHC8 constraints.
- ▶ Some model parameter, like the squark or the gluino mass, are poorly constrained by the fit.
- ▶ Others, like the $\tilde{\chi}^0_1$ and the slepton masses are effectively constrained, mainly defined by the $(g-2)_\mu$ and DM constraints.
- ▶ LHC14 searches have a good prospect of exploring the preferred regions of $m_{\tilde{q}}$ and $m_{\tilde{g}}$, as well as light $\tilde{t}_1$, $\tilde{e}$ and $\tilde{\mu}$.
- ▶ Production threshold for various particles in the preferred fit region accessible with a 500-1000 GeV collider.

Backup slides