# Prospects for SUSY discovery after the LHC Run 1

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On behalf of the Mastercode collaboration

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References: hep-ph/1312.5250, hep-ph/1408.4060 and hep-ph/1504.03260.

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

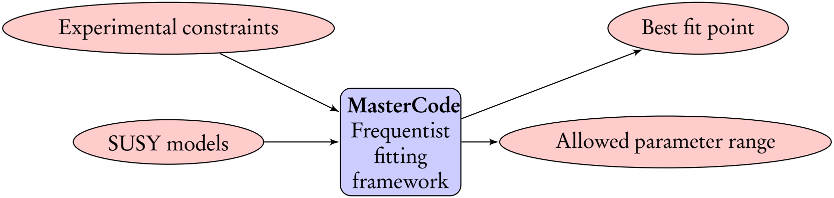
## Gauge supermultiplets

| 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 | $\widetilde{W}^\pm \quad \widetilde{W}^0$ | $W^\pm \quad W^0$ | $(\mathbf{1}, \mathbf{3}, 0)$ |
| bino, B boson | $\widetilde{B}^0$ | $B^0$ | $(\mathbf{1}, \mathbf{1}, 0)$ |

# 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 |
|---|
| $M_1, M_2, M_3$<br>$m_{\tilde{q}_{1,2}}, m_{\tilde{q}_3}, m_{\tilde{l}}$<br>$A$<br>$M_A, \tan\beta, \mu$ |

- 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 |
| $m_{\tilde{q}_3}$ | ( 0 , 4 ) TeV | 2 |
| $m_{\tilde{l}}$ | ( 0 , 2 ) TeV | 1 |
| $M_A$ | ( 0 , 4 ) TeV | 2 |
| $A$ | (-5 , 5 ) TeV | 1 |
| $\mu$ | (-5 , 5 ) TeV | 1 |
| $\tan\beta$ | ( 1 , 60) | 1 |
| Total number of boxes | | 128 |

| Codes |
|---|
| **Spectrum generation**<br>`SoftSUSY` |
| **Higgs sector and** $(g-2)_\mu$<br>`FeynHiggs, Higgssignals, Higgsbounds` |
| **B-Physics**<br>`SuFla, SuperIso` |
| **EW precision observables**<br>`FeynWZ` |
| **Dark matter**<br>`MicroOMEGAs, SSARD` |

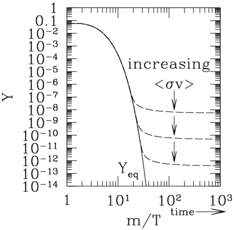
# The constraints

## Indirect measurements

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

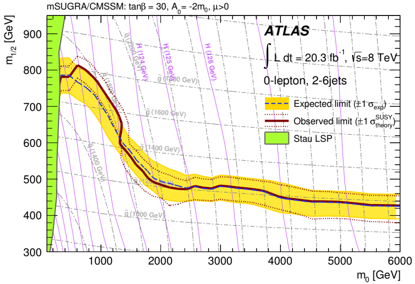
## Dark matter

- Relic density and direct detection.




## Collider – GUT models

- Limits are independent of $A_0, \tan\beta, m^2_{H_u}$ and $m^2_{H_d}$.
- 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 $\text{fb}^{-1}$):

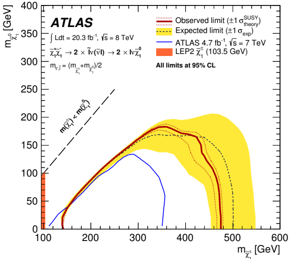
- 0-lepton $M_{T2}$
- 1-lepton $M_{T2}^{W}$
- 2-lepton OS/SS
- $\geq 3$ leptons.

### Compressed stop region

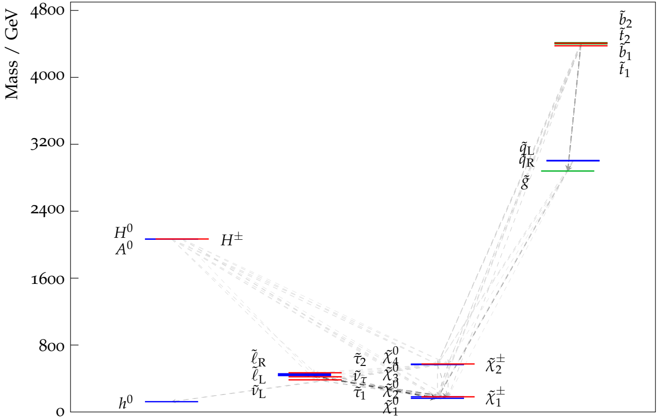
This region is separately. The stop cross-section is set to zero in the other constraints.

### 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.



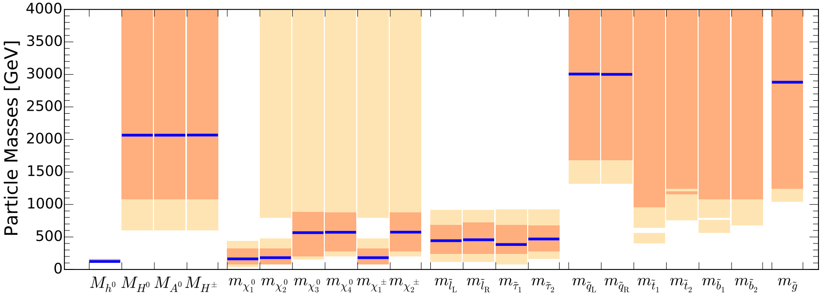
# pMSSM10 best fit point




| 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 |
| $\mu$ | 550 GeV |
| $\tan\beta$ | 37.6 |

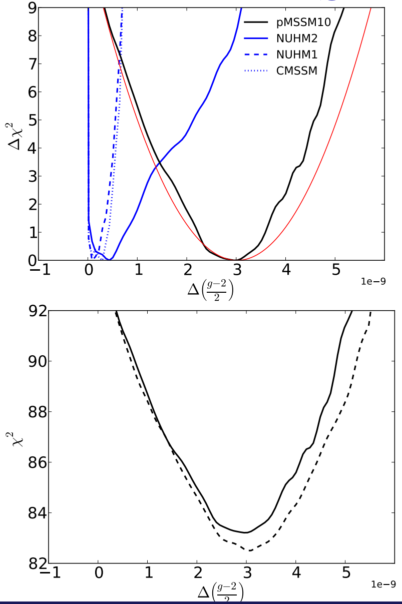
- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$.
- Sleptons are at less than 1 TeV.

# 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.

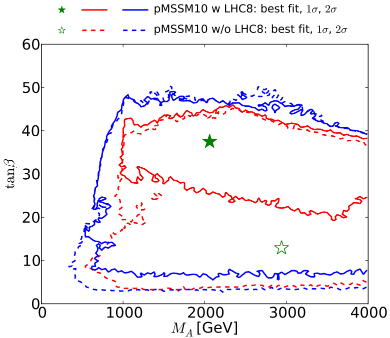
# The $(g-2)_\mu$ constraint

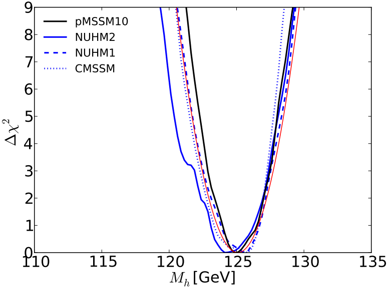



| Model | $\chi^2/n_{\mathrm{dof}}$ | p-value |
|---|---|---|
| CMSSM | 32.8/24 | 11 % |
| NUHM1 | 31.1/23 | 12 % |
| NUHM2 | 30.3/22 | 11 % |
| pMSSM10 | 20.5/18 | 31 % |

- $3.5\sigma$ 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 $\mathrm{LHC8}_{\mathrm{EWK}}$ constraint limited.

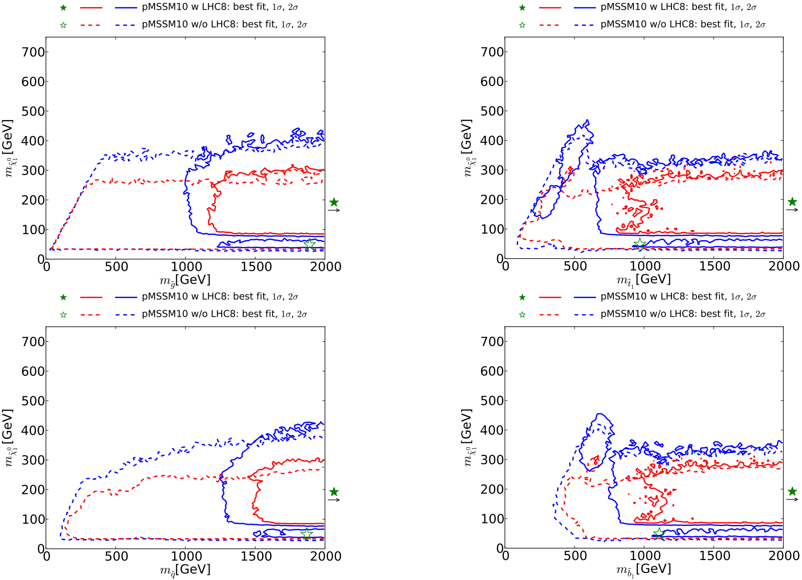
# Higgs physics



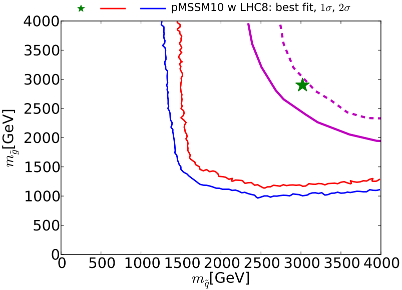



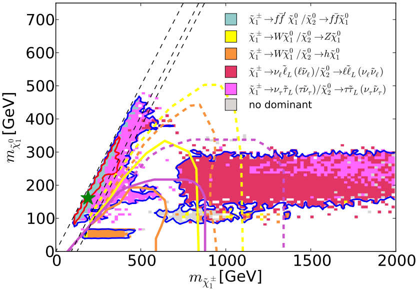

- pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by `FeynHiggs`.
- Lower value of $\tan\beta$ are disfavored at the 68% CL by LHC8$_{EWK}$, $(g-2)_\mu$ and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking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

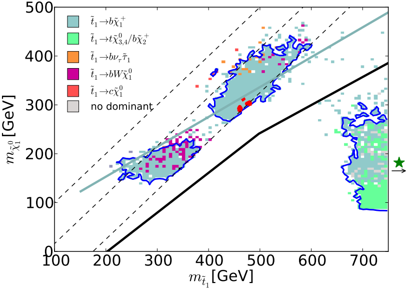
# Physical mass planes for the colored sparticles

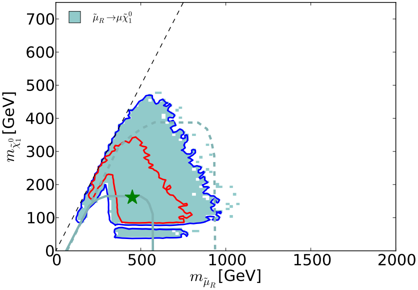


# Perspectives for discovery at LHC run 2

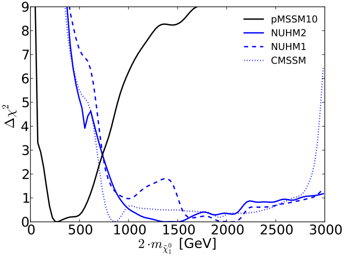


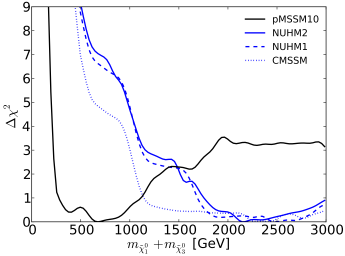



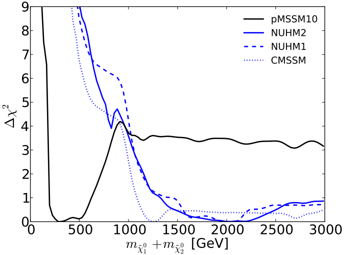



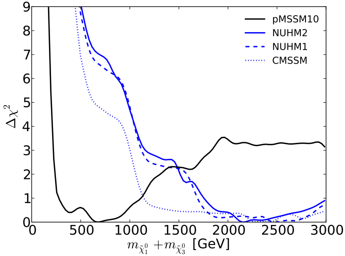



# Perspectives for discovery at $e^+e^-$ colliders



# 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