Prospects for Supersymmetry after current LHC results

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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	$(\tilde{\nu}, \tilde{e}_L)$	(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^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

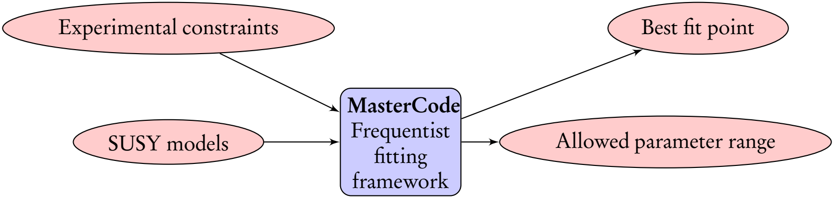
Gauge supermultiplets

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	$\widetilde{W}^\pm \quad \widetilde{W}^0$	$W^\pm \quad W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
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 scenarios

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 unification assumptions for the soft-SUSY breaking mass terms.
- Introduce correlation between the colored and uncolored sectors.

[1312.5250,1408.4060]

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

- 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.

[1504.03260]

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`

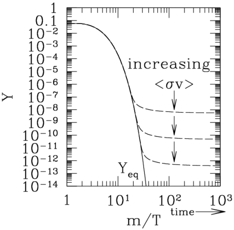
The constraints

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 ($B_s \to \mu\mu$, $b \to s\gamma$).

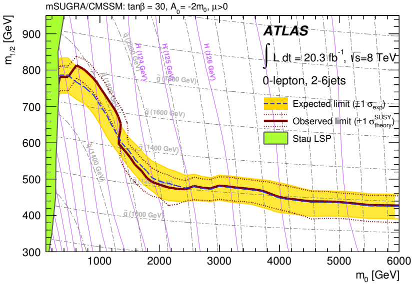
Dark matter

- 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:

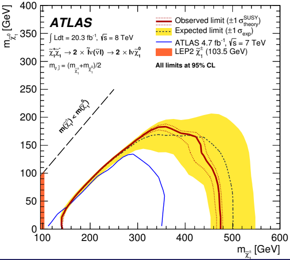
- 0-lepton M_{T2}
- 1-lepton M_{T2}^{W}
- 2-lepton OS/SS
- ≥ 3 leptons.

Compressed stop scenarios

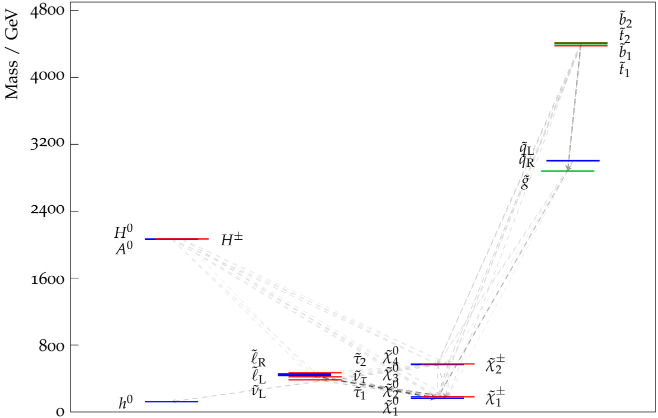
This scenario is separately in a way similar to the EWK SMS. The stop cross-section is set to zero.

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.



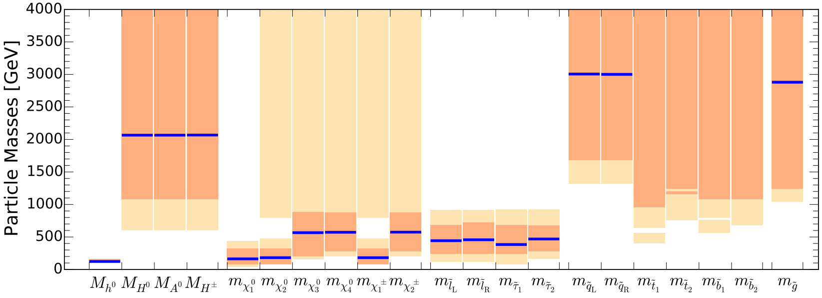
pMSSM10 best fit point



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

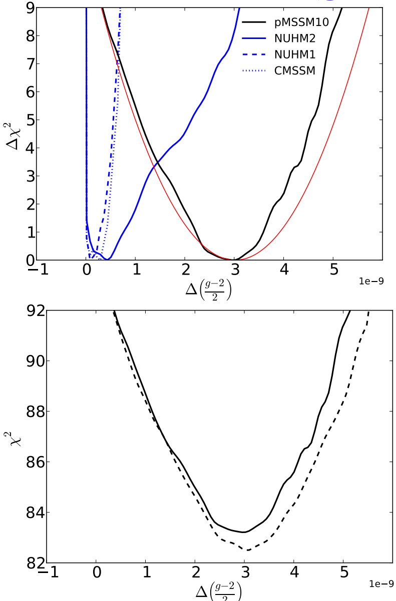
- Heavy Higgses, squarks, gluinos are relatively unconstrained.
- Left-handed fermion decay chains evolve via $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$.
- Sleptons are at less than 1 TeV.

pMSSM10 mass spectrum



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

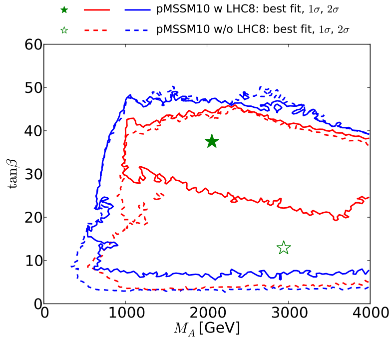
The $(g-2)_\mu$ constraint

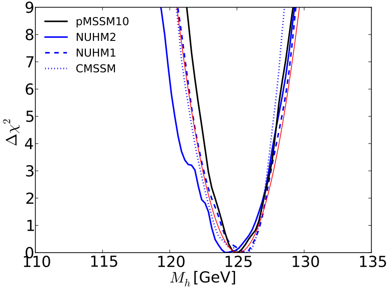


Model	$\chi^2/n_{\rm dof}$	χ^2 probability
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %

- 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_{EWK} constraint limited.

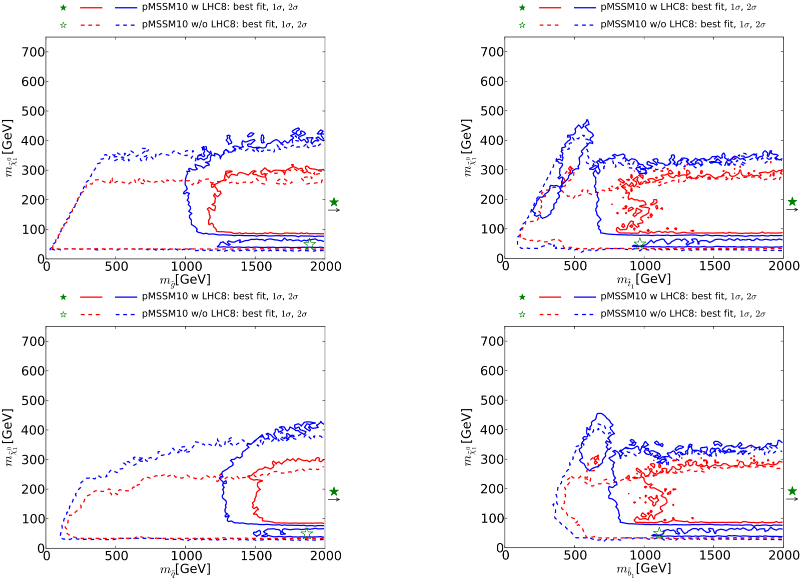
Higgs physics



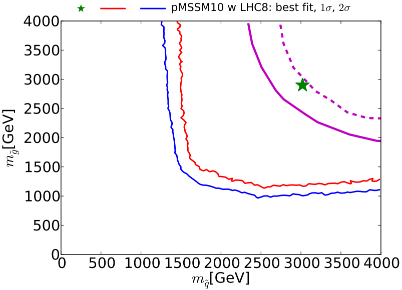


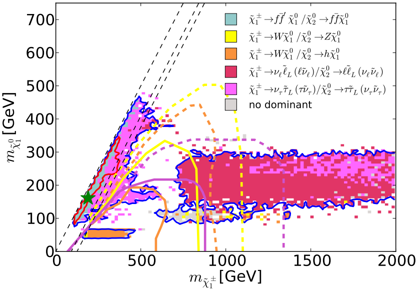
- pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by `FeynHiggs`.
- Lower value of $\tan\beta$ are disfavored at the 68% CL by LHC8_{EWK}, $(g-2)_\mu$ and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking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

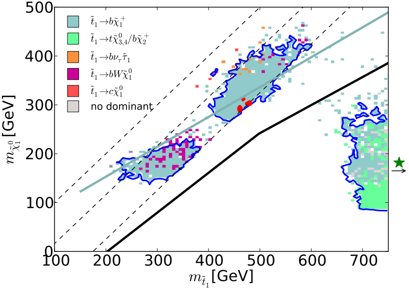
Physical mass planes for the colored sparticles

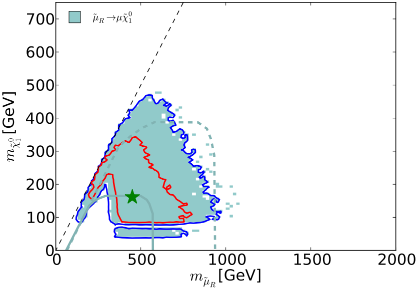


Perspectives for discovery at LHC run 2

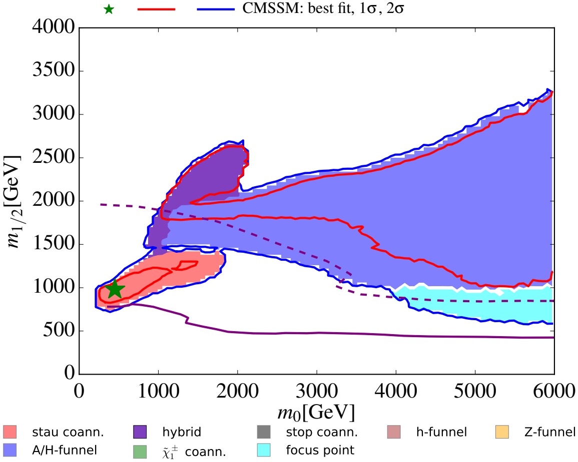






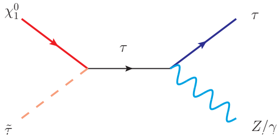


CMSSM



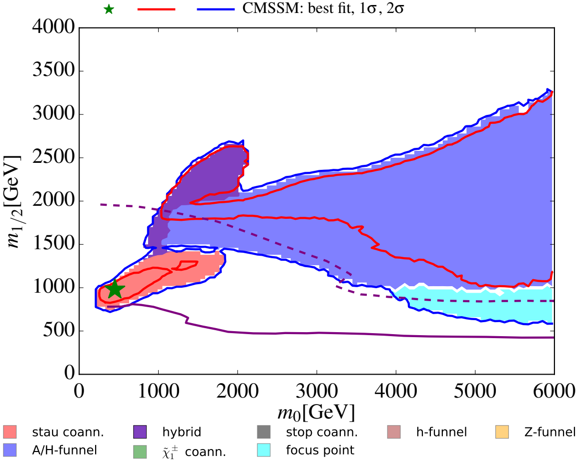
We have several different mechanism at play.

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



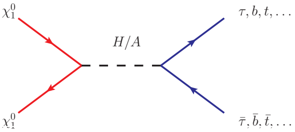
- Leading mechanism when the mass difference between the $\tilde{\tau}$ and the $\tilde{\chi}_1^0$ is of the order of a few GeV.
- $\tilde{\chi}_1^0$ is Bino-like.
- Also $\tilde{\tau} - \tilde{\tau}$ annihilation important in this scenario.

CMSSM



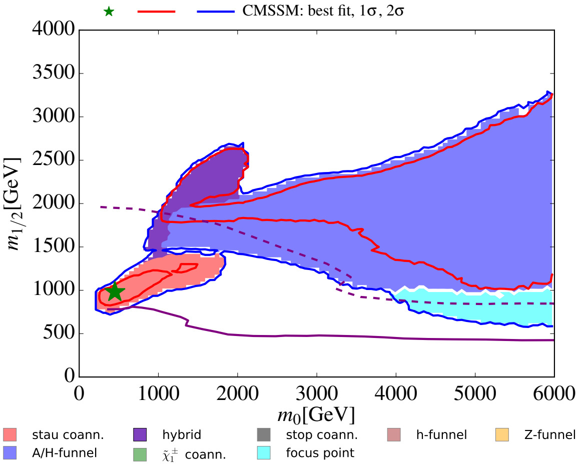
We have several different mechanism at play.

2. H/A-funnel.



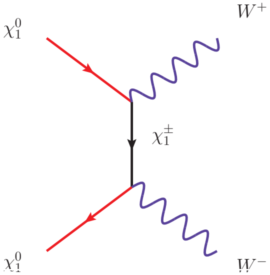
- $\tilde{\chi}_1^0$ is Bino-like.
- Mass degeneracy condition: $2 \cdot \tilde{\chi}_1^0 \approx M_A / M_H$.

CMSSM



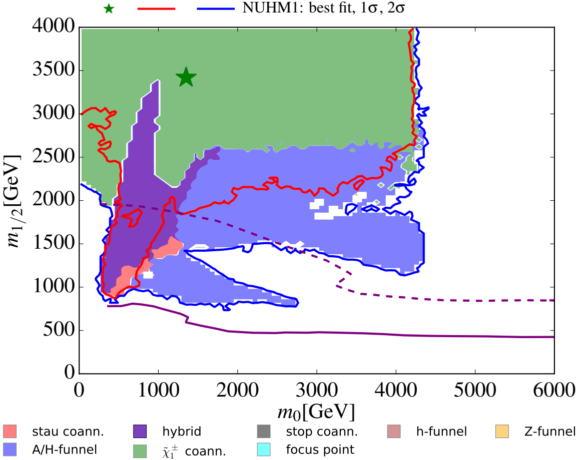
We have several different mechanism at play.

3. Focus point.



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

NUHM1

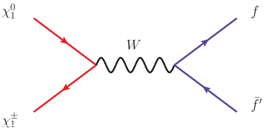


In the NUHM1, we have

- $m^2_{H_u} = m^2_{H_d} \neq m^2_0$.
- $\mu < M_1 \rightarrow$ Higgsino $\tilde{\chi}^0_1/\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$.

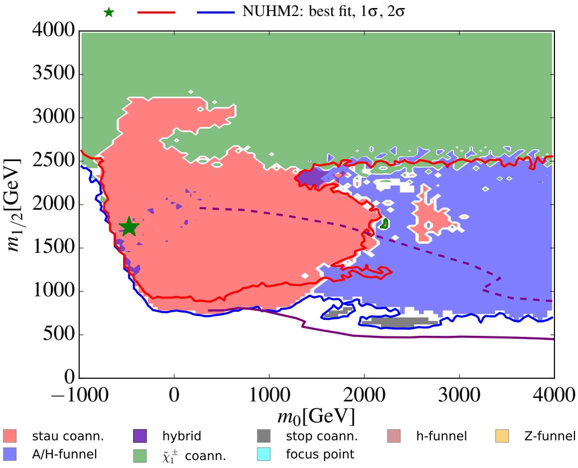
Another DM annihilation mechanism comes into play.

4 Chargino coannihilation.



- Dominant when $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ are nearly degenerate with $\tilde{\chi}^0_1$.
- $\tilde{\chi}^0_1$ is Bino-like or, if Higgsino-like, it must be that $m_{\tilde{\chi}^0_1}$, otherwise the DM annihilation mechanism is too efficient.

NUHM2

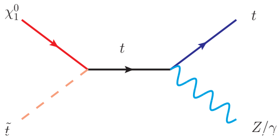


In the NUHM2, we have

- $m^2_{H_u} = m^2_{H_d} \neq m^2_0$.
- $\mu < M_1 \rightarrow$ Higgsino $\tilde{\chi}^0_1 / \tilde{\chi}^\pm_1 / \tilde{\chi}^0_2$.

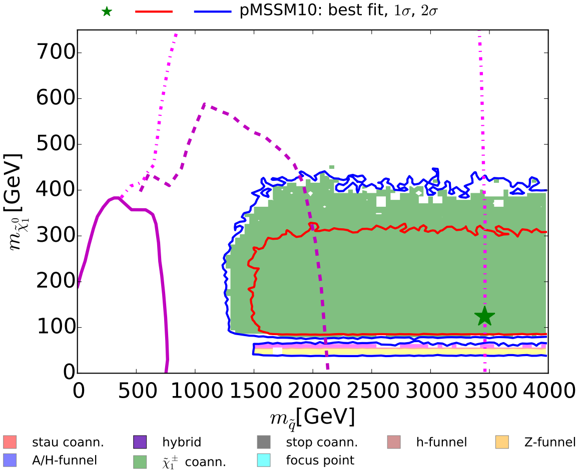
In this model we see also

5 Stop coannihilation.



- As $\tilde{\tau}$ coannihilation but degeneracy still leading even if the mass degeneracy condition is satisfied up to $\mathcal{O}(50)$ GeV.

pMSSM10

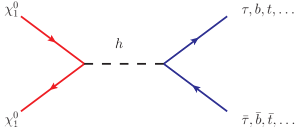


In the pMSSM10 we have

- $M_1 \simeq M_2$, so that Bino $\tilde{\chi}^0_1$, Wino $\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$.

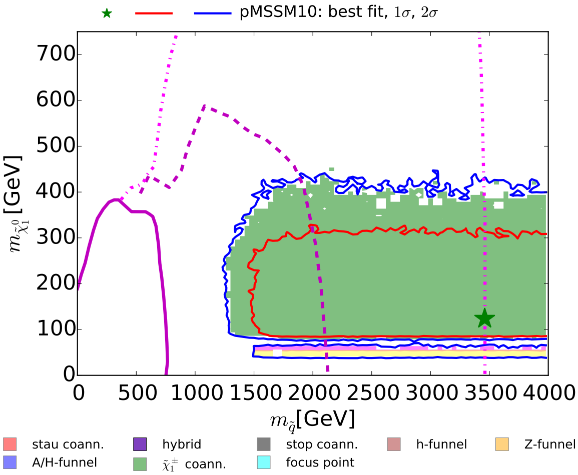
New annihilation channels appear to be part of the relevant mechanism for the pMSSM10.

5 h-funnel



- Mass degeneracy condition: $2 \cdot \tilde{\chi}^0_1 \approx M_h$.
- Allowed only in the pMSSM10, excluded by gluino searches in the GUT models.

pMSSM10

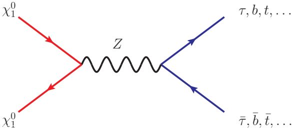


In the pMSSM10 we have

- $M_1 \simeq M_2$, so that Bino $\tilde{\chi}_1^0$, Wino $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$.

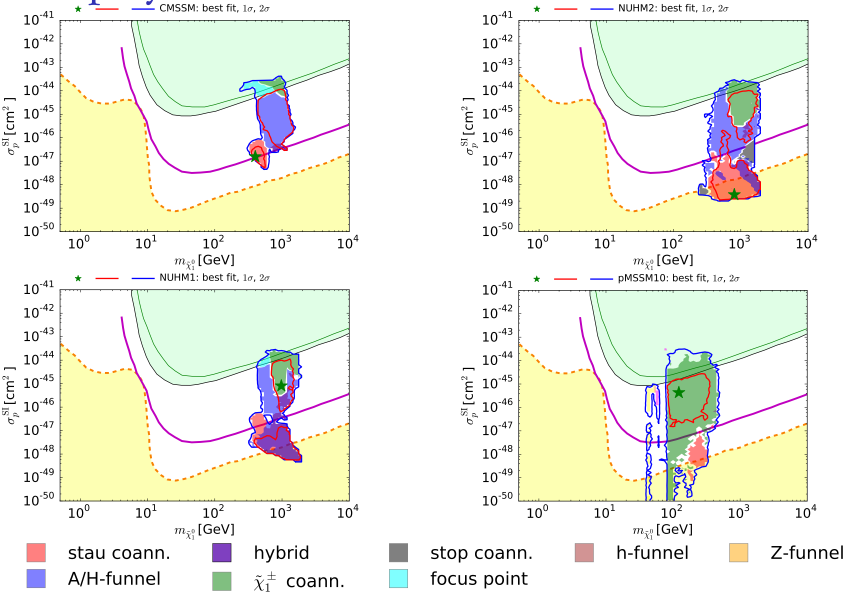
New annihilation channels appear to be part of the relevant mechanism for the pMSSM10.

6 *Z*-funnel



- Mass degeneracy condition: $2 \cdot \tilde{\chi}_1^0 \approx M_Z$.
- Allowed only in the pMSSM10, excluded by gluino searches in the GUT models.

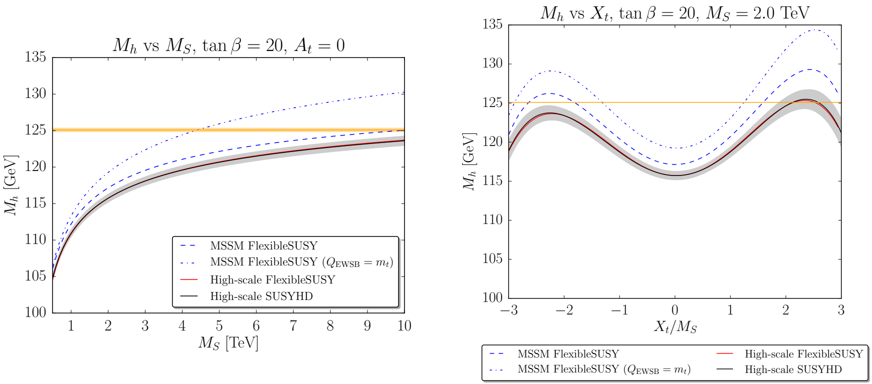
Interplay between collider and direct detection



Conclusions

- We performed what was at the time 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 $\tilde{\chi}_1^0$ and the slepton masses are effectively constrained, mainly defined by the $(g-2)_\mu$ and DM constraints.
- LHC13 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 $\tilde{\mu}$.
- We are finalizing our analyses of new MSSM scenarios, including the 13 TeV constraints presented at ICHEP.

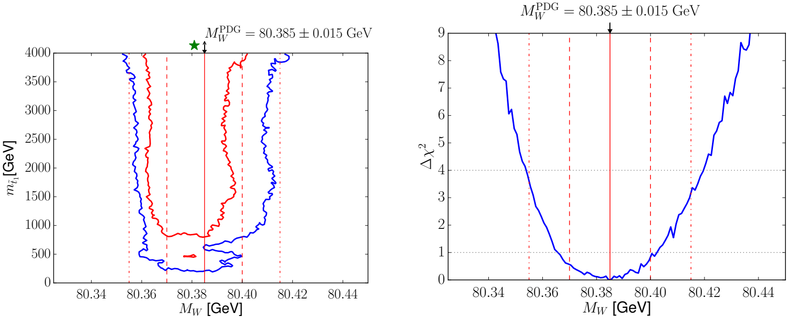
Uncertainty in the Higgs mass prediction



- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

[SusyHD 1504.05200] [FlexibleSUSY Bagnaschi, Weiglein, Voigt 16xx.yyyyy] [FeynHiggs 1312.4937]

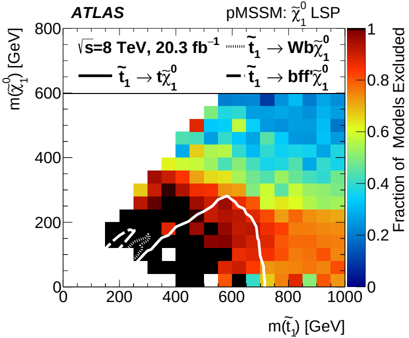
W boson mass

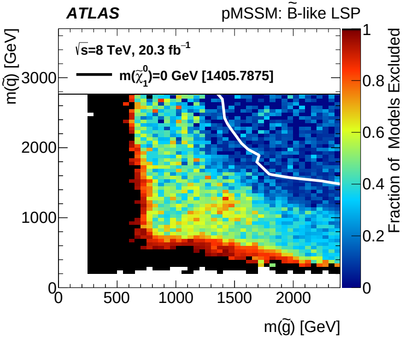


- Perfect fit of M_W around it's measured values.
- Another example where it is relevant to have accurate theoretical predictions.

Other efforts

- `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].

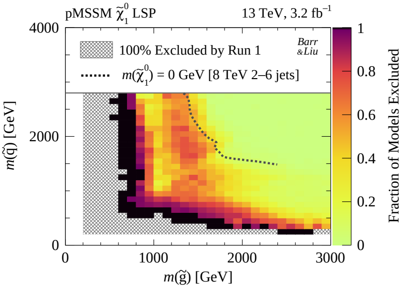


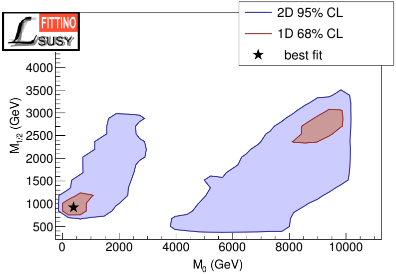


- `SUSY-AI` : use results from the `ATLAS` scan to implement the constraints from the available searches using machine-learning method [1605.02797].

Other efforts

- 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.





- Fittino: last paper on the CMSSM [1508.05951]. They find it excluded at the 90% C.L. .
- SuperBayesS: Bertone at al [1507.07008], global analysis of the pMSSM, including constraints coming from indirect detection (Fermi GeV excess).
- GAMBIT: new collaboration, no publication available yet.