Prospects for SUSY dark matter after the LHC Run 1

Emanuele A. Bagnaschi (DESY Hamburg)

On behalf of the Mastercode collaboration

Exp O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, H. Flacher, S. Mallik, J. Marrouche, D. Martinez-Santos and K. J. de Vries.
Theo E. Bagnaschi, M. Dolan, J. Ellis, S. Heinemeyer, G. Isidori, K. Olive, K.Sakurai and G. Weiglein.

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

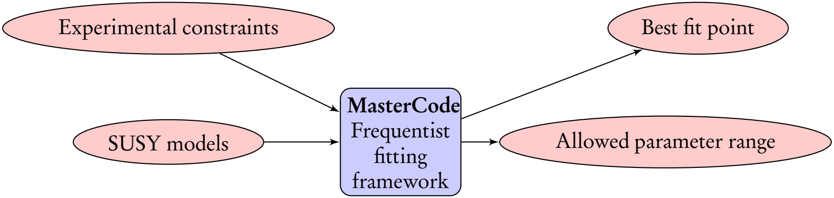
Gauge supermultiplets

Name	spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
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	$(\mathbf{1}, \mathbf{1}, 0)$

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

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`

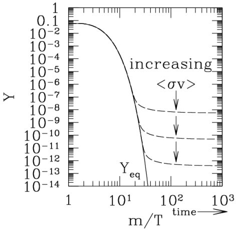
The constraints

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

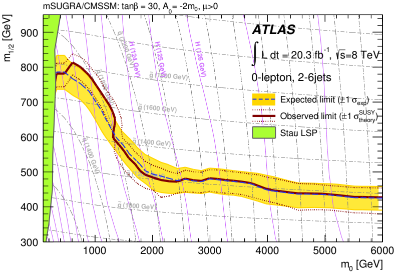
Dark matter

- 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 (8 TeV, 20 fb^{-1}:)

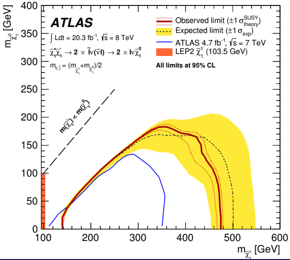
- 0-lepton M_{T2}
- 1-lepton M_{T2}^{W}
- 2-lepton OS/SS
- ≥ 3 leptons.

Compressed stop region

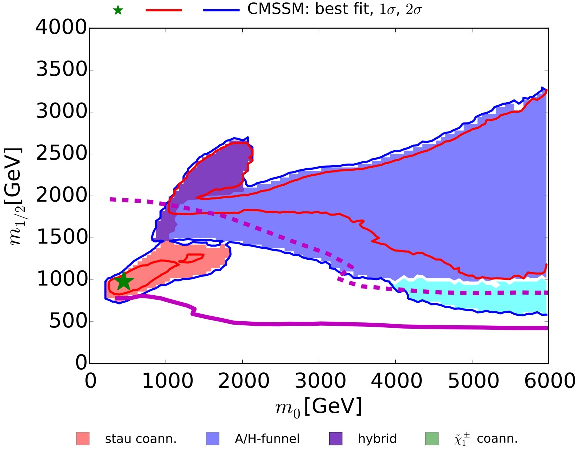
This region is separately. The stop cross-section is set to zero in the other constraints.

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.

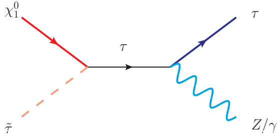


CMSSM



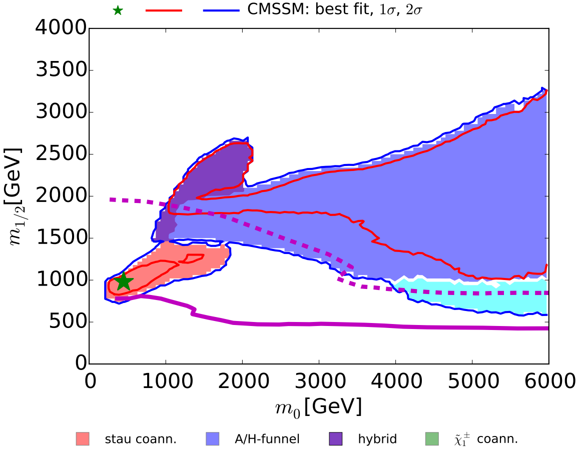
We have several different mechanism at play.

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



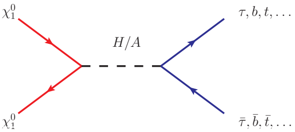
- Leading mechanism when the mass difference between the $\tilde{\tau}$ and the $\tilde{\chi}_1^0$ is of the order of a few GeV.
- $\tilde{\chi}_1^0$ is Bino-like.
- Also $\tilde{\tau}-\tilde{\tau}$ annihilation important in this scenario.

CMSSM



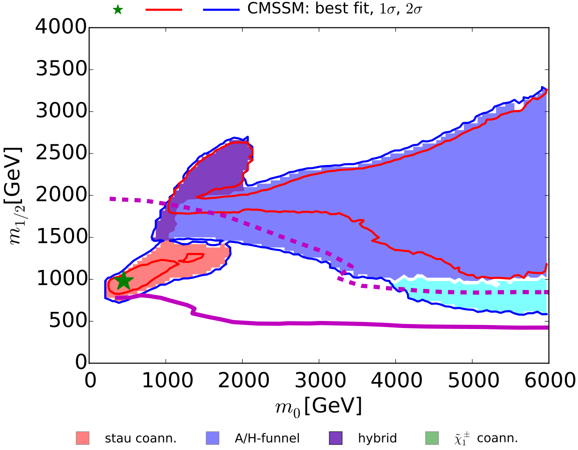
We have several different mechanism at play.

2. H/A-funnel.



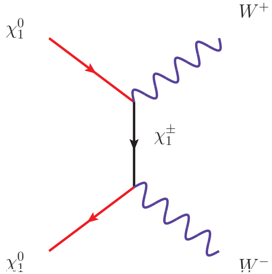
- $\tilde{\chi}_1^0$ is Bino-like.
- Mass degeneracy condition: $2 \cdot \tilde{\chi}_1^0 \approx M_A/M_H$.

CMSSM



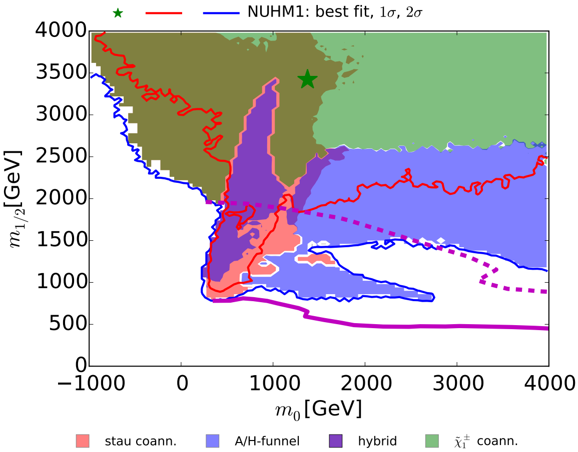
We have several different mechanism at play.

3. Focus point.



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

NUHM1

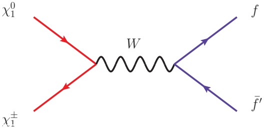


In the NUHM1, we have

- $m_{H_u}^2 = m_{H_d}^2 \neq m_0^2$.
- $\mu < M_1 \to$ Higgsino, $\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ (chargino coannihilation region).

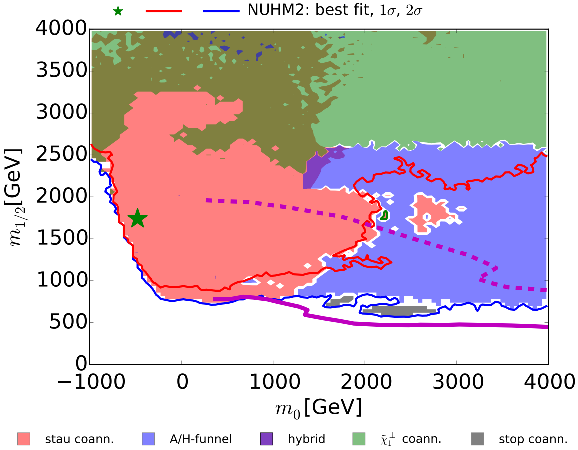
Another DM annihilation mechanism comes into play.

4 Chargino coannihilation.



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

NUHM2

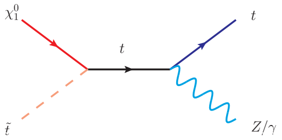


In the NUHM2, we have

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

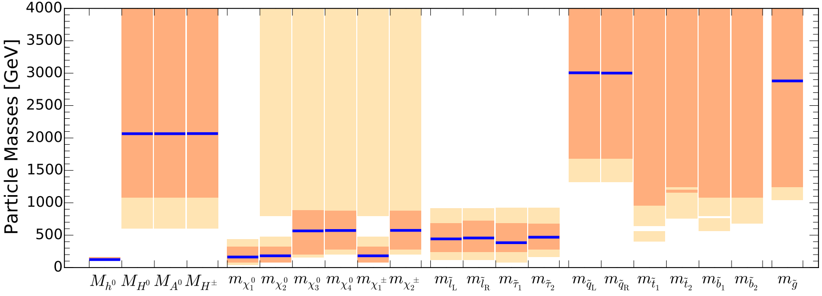
In this model we see also

5 Stop coannihilation.



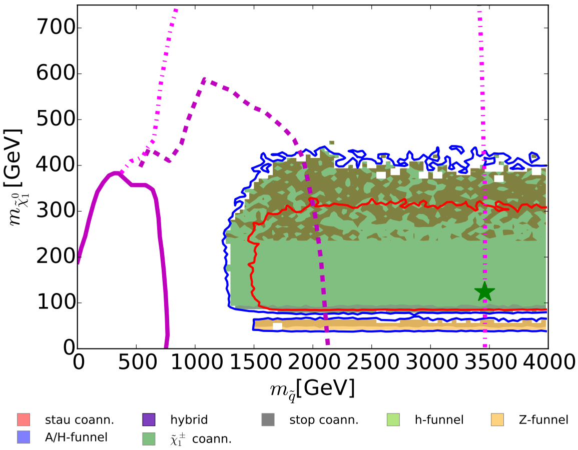
- As $\tilde{\tau}$ coannihilation but degeneracy still leading even if the mass degeneracy condition is satisfied up to $\mathcal{O}(50)$ GeV.

pMSSM10 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.

pMSSM10



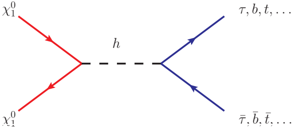
Preliminary

In the pMSSM10 we have

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

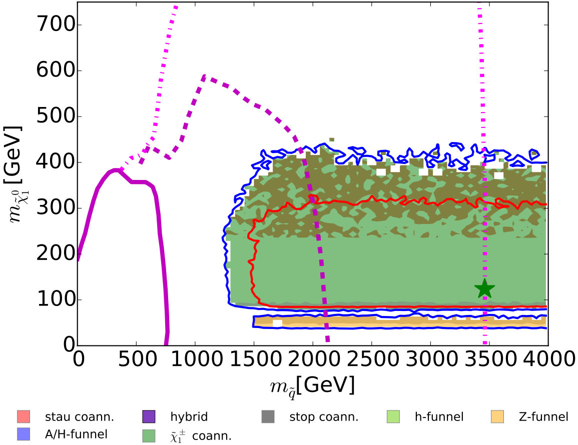
New annihilation channels appear to be part of the relevant mechanism for the pMSSM10.

5 h-funnel



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

pMSSM10



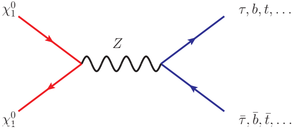
Preliminary

In the pMSSM10 we have

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

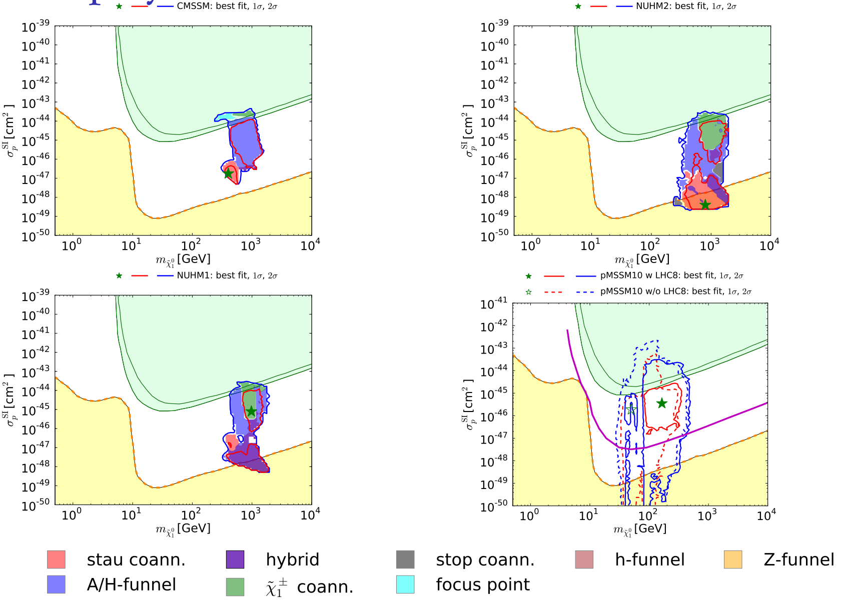
New annihilation channels appear to be part of the relevant mechanism for the pMSSM10.

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

- The tensions present in the GUT models between the $(g-2)_\mu$, sparticles searches at LHC and M_h is resolved in the pMSSM10.
- In the GUT models, stau-coannihilation, A/H-funnel and stop-coannihilation are in reach of LHC.
- The pMSSM10 is dominated by the chargino coannihilation mechanism, due to the χ_1^0 being mainly bino and the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ being mainly Wino.
- Complementarity between colliders and direct detection searches.

Backup slides