

Prospects for SUSY dark matter in light of LHC Run 2 results

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Based on E. Bagnaschi, K. Sakurai et al. [1710.11091]

and J.C. Costa, E. Bagnaschi, K. Sakurai et al. [1711.00458]



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

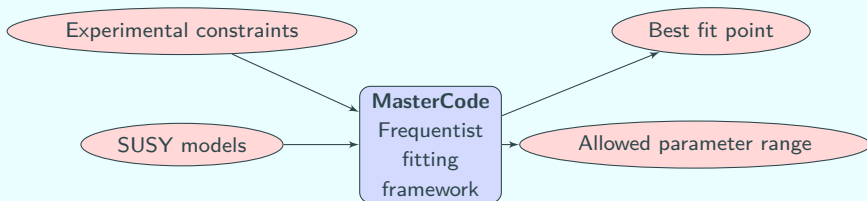
Gauge supermultiplets

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



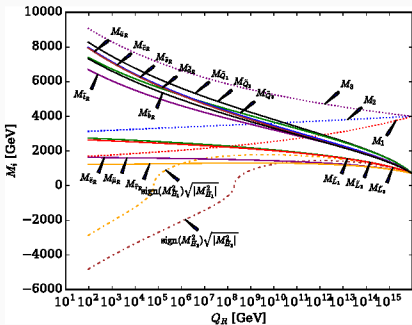
The scenarios

MSSM scenarios

GUT Models

CMSSM

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



- Introduce correlation between the colored and uncolored sectors.

GUT Models

NUHM1/NUHM2

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

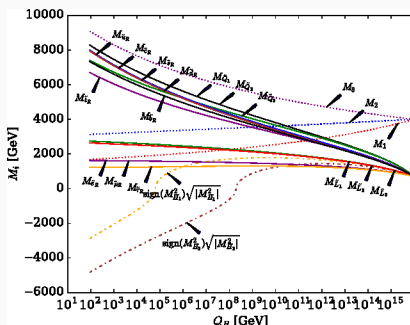
SU(5)

$$m_{1/2}, m_{\bar{5}}, m_{10}, m_{H_u}, m_{H_d}, A_0, \tan \beta$$

mAMSB

$m_0, m_{3/2}, \tan \beta$

[1312.5250, 1408.4060, 1508.01173]
[1610.10084, 1610.10084, 1612.05210]

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

- [1711.00458]

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].

pMSSM11

$$M_1, M_2, M_3$$

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

$$m_{\tilde{l}_{1,2}}, m_{\tilde{\tau}}$$

$$A$$

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

- Phenomenological model with 11 low-energy input parameters.
- We assume all left and right soft-SUSY mass breaking terms to be equal.
- All the trilinear coupling are the same.

[1710.11091]

The framework

The framework

- Frequentist fitting framework written in Python/Cython and C++.
- The Multinest algorithm is used to sample the parameter space.
- udocker also used for deployment .

Parameter	Range	Number of segments
M_1	(-4 , 4) TeV	6
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
$m_{\tilde{\tau}}$	(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		384

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

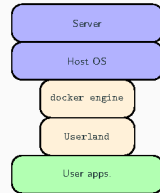
- Sampled a total of 2×10^9 points.
- We thank DESY for the resources provided by the NAF2/BIRD cluster.

Docker and udocker

- As suggested by the name, udocker uses docker containers.
- Docker: software framework to automatize the deployment of application inside Linux containers.
- Other options, such as LXC, are available to use the Linux container infrastructure.



INDIGO - DataCloud



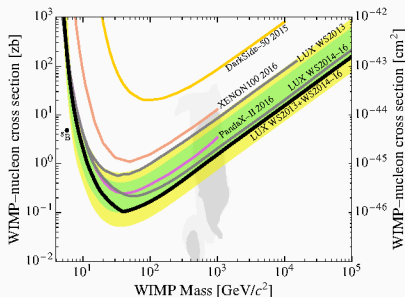
- Middleware suite developed in the context of the INDIGO data-cloud project to run docker containers in userspace, without requiring root privileges (**both for installation and execution**).

The constraints

Non-LHC constraints

Dark matter

- Relic density constraints from Planck.
- Direct detection constraints on σ_p^{SI} from LUX, XENON1T and PANDAX.
- Direct detection constraints on σ_p^{SD} from PIC060.



[1608.07648]

Flavor observables

- We include $\text{BR}_{B \rightarrow X_s l l}, \text{BR}_{K \rightarrow l \nu}, \text{BR}_{B \rightarrow \pi \nu \bar{\nu}}, \text{BR}_{B \rightarrow X_s \gamma}, \text{BR}_{B \rightarrow \tau \nu}, \text{BR}_{B_{s,d} \rightarrow \mu^+ \mu^-}, \Delta M_{B_s}, \Delta M_{B_d} / \Delta M_{B_d}, \epsilon_K$.

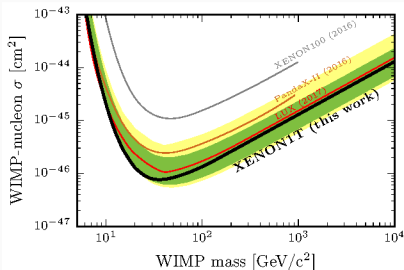
EWPOs

- Z-pole observables from LEP.
- $M_W (80.379 \pm 0.012 \pm 0.010)$, combination with the latest ATLAS results from HEPfit.
- $(g - 2)_\mu$, whose impact has been investigated in detail.

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[1705.06655]

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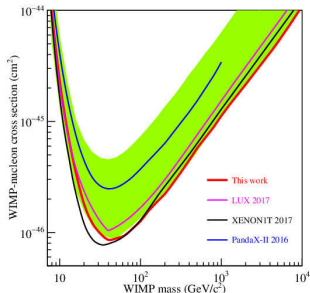
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[1708.06917]

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LHC13 colored particle constraints

Colored particle production

- Production cross-sections computed at NLO+NLL with NLL-Fast, point by point.
- Decays from SDECAY.

Likelihood modelling

- Fastlim approach.

$$\chi^2_{\tilde{g} \rightarrow \text{SM} \tilde{\chi}_1^0} = 5.99 \cdot \left[\frac{\sigma_{\tilde{g}\tilde{g}} \text{BR}_{\tilde{g} \rightarrow \text{SM} \tilde{\chi}_1^0}^2}{\sigma_{\text{UL}}^{\tilde{g} \rightarrow \text{SM} \tilde{\chi}_1^0}(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})} \right]^2$$

$$\chi^2_{\tilde{q}_3 \rightarrow \text{SM} \tilde{\chi}_1^0} = 5.99 \cdot \left[\frac{\sigma_{\tilde{q}_3 \tilde{q}_3} \text{BR}_{\tilde{q}_3 \rightarrow \text{SM} \tilde{\chi}_1^0}^2}{\sigma_{\text{UL}}^{\tilde{q}_3 \rightarrow \text{SM} \tilde{\chi}_1^0}(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})} \right]^2$$

Topology	Analysis	Ref.
$\tilde{g}\tilde{g} \rightarrow [q\bar{q}\tilde{\chi}_1^0]^2, [b\bar{b}\tilde{\chi}_1^0]^2$	0 leptons + jets with $\cancel{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{g}\tilde{g} \rightarrow [t\bar{t}\tilde{\chi}_1^0]^2$	1 lepton + jets with $\cancel{E}_T$	[CMS-SUS-16-037, 1705.04673]
$\tilde{q}\tilde{q} \rightarrow [q\tilde{\chi}_1^0][\bar{q}\tilde{\chi}_1^0]$	0 leptons + jets with $\cancel{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{b}\tilde{b} \rightarrow [b\tilde{\chi}_1^0][\bar{b}\tilde{\chi}_1^0]$	0 leptons + jets with $\cancel{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{t}_1\tilde{t}_1 \rightarrow [t\tilde{\chi}_1^0][\bar{t}\tilde{\chi}_1^0], [c\tilde{\chi}_1^0][\bar{c}\tilde{\chi}_1^0]$	0 leptons + jets with $\cancel{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{t}_1\tilde{t}_1 \rightarrow [\bar{b}\tilde{\chi}_1^+][\bar{b}\tilde{\chi}_1^-] \rightarrow [\bar{b}W^+\tilde{\chi}_1^0][\bar{b}W^-\tilde{\chi}_1^0]$	0 leptons + jets with $\cancel{E}_T$	[CMS-SUS-16-036, 1705.04650]

LHC13 EWKinos constraints

EWKino production

- Production cross-sections computed at NLO with EWK-fast, point by point.
- New code from Bagnaschi, Papucci, Sakurai, Weiler and Zeune, soon to be released.

$$\sigma(pp \rightarrow \tilde{\chi}_i \tilde{\chi}_j) = \sum_a T_a(\mathcal{U}) F_a(m_{\tilde{\chi}_i}, m_{\tilde{\chi}_j}, m_a)$$

Likelihood modelling

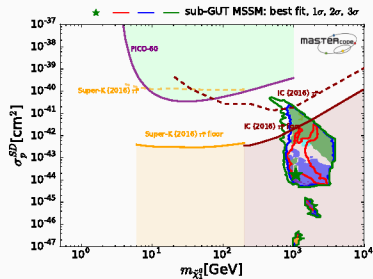
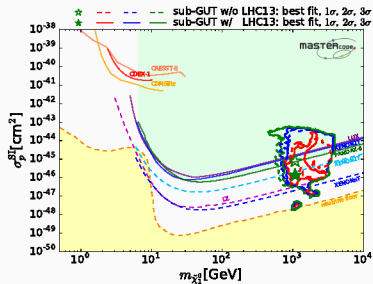
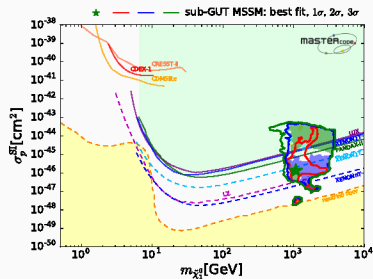
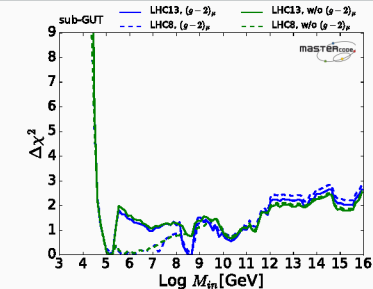
- Fastlim approach.

$$\chi^2_{\tilde{\chi}_1^\pm \rightarrow \text{SM} \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow \text{SM} \tilde{\chi}_1^0} \simeq 5.99 \cdot \left[\frac{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0}^{\text{BR}} \tilde{\chi}_1^\pm \rightarrow \text{SM} \tilde{\chi}_1^0 \text{BR} \tilde{\chi}_2^0 \rightarrow \text{SM} \tilde{\chi}_1^0}{(\tilde{\chi}_1^\pm \rightarrow \text{SM} \tilde{\chi}_1^0)(\tilde{\chi}_2^0 \rightarrow \text{SM} \tilde{\chi}_1^0)} \right]^2$$

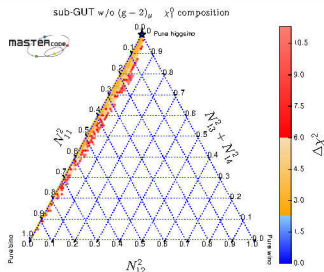
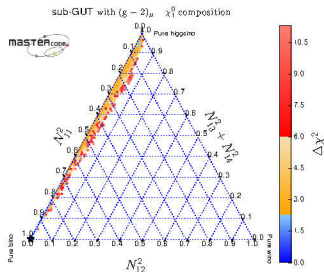
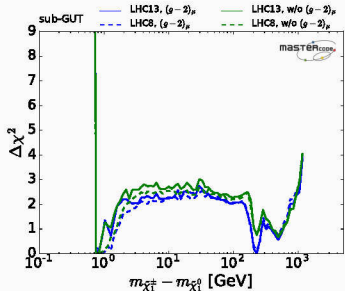
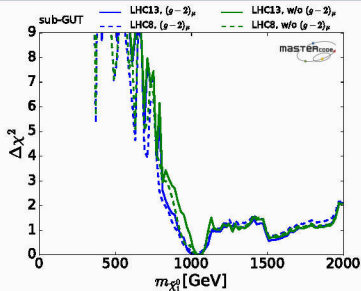
Topology	Analysis	Ref.
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow [\nu \ell^\pm \tilde{\chi}_1^0][\ell^\mp \ell^\mp \tilde{\chi}_1^0]$ (via $\tilde{\ell}^\pm$)	multileptons with $\cancel{E}_T$	[CMS-SUS-16-039, 1709.05406]
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow [\nu \tau^\pm \tilde{\chi}_1^0][\tau^\mp \tau^\mp \tilde{\chi}_1^0]$ (via $\tilde{\tau}^\pm$)	multileptons with $\cancel{E}_T$	[CMS-SUS-16-039, 1709.05406]
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow [W^\pm \tilde{\chi}_1^0][Z \tilde{\chi}_1^0]$	multileptons with $\cancel{E}_T$	[CMS-SUS-16-039, 1709.05406]

subGUT-CMSSM

Parameter Input-scale dependence

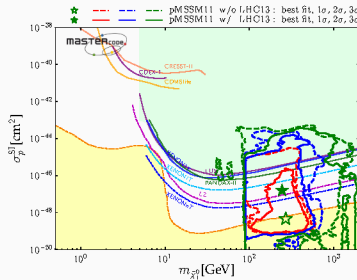
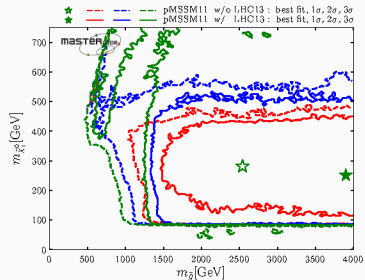
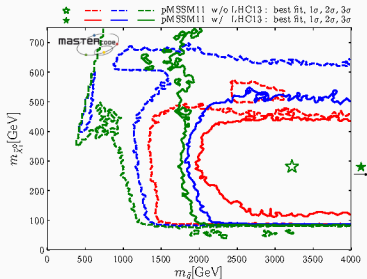
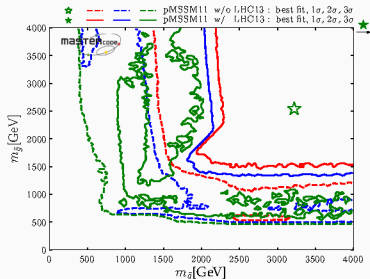


Colored sparticle mass range

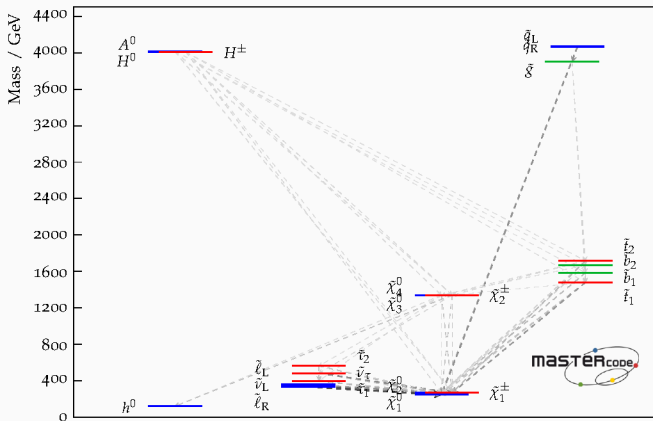


pMSSM11

From 2015 to 2017 (LHC+DD)



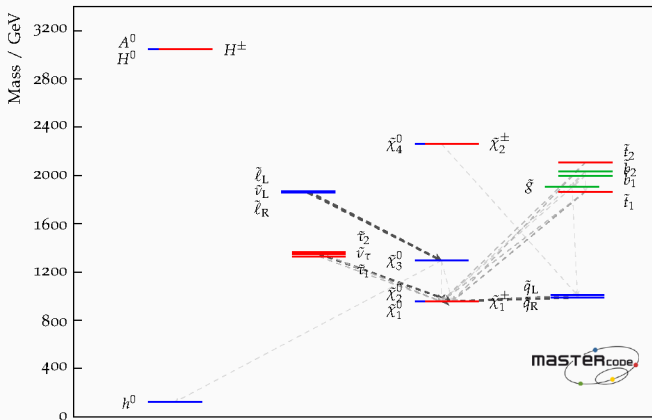
pMSSM11 best fit point



Parameter	Best-fit
M_1	250 GeV
M_2	250 GeV
M_3	3.86 TeV
$m_{\tilde{q}}$	4 TeV
$m_{\tilde{q}_3}$	1.7 TeV
$m_{\tilde{t}_1}$	350 GeV
$m_{\tilde{\tau}}$	460 GeV
M_A	4 TeV
A	2.8 TeV
μ	1.33 TeV
$\tan \beta$	36

- 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.

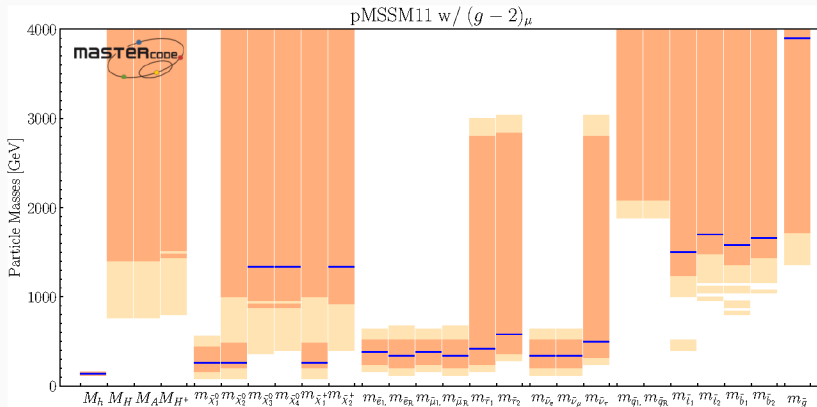
pMSSM11 best fit point w/o $(g-2)_\mu$



Parameter	Best-fit
M_1	-1.3 TeV
M_2	2.3 TeV
M_3	1.9 TeV
$m_{\tilde{q}}$	0.9 TeV
$m_{\tilde{q}_3}$	2.0 TeV
$m_{\tilde{l}}$	1.9 TeV
$m_{\tilde{\tau}}$	1.3 TeV
M_A	3.0 TeV
A	-3.4 TeV
μ	-0.95 TeV
$\tan \beta$	33

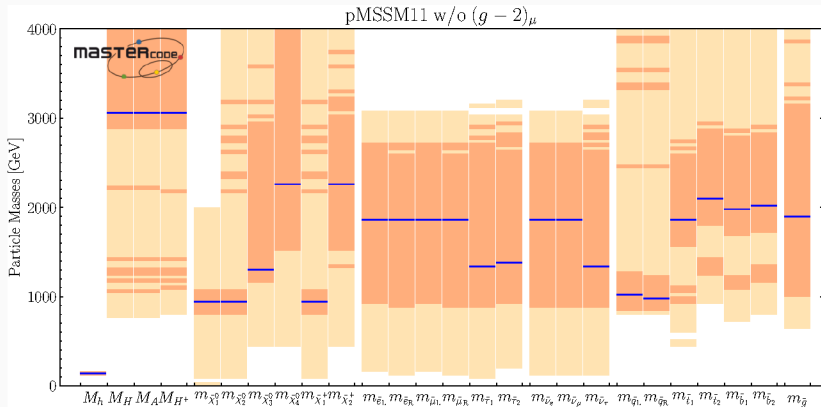
- Neutralino is Higgsino-like, at around 1 TeV.
- Heavier spectrum, with first two generation squarks around 1 TeV.

pMSSM11 mass spectrum



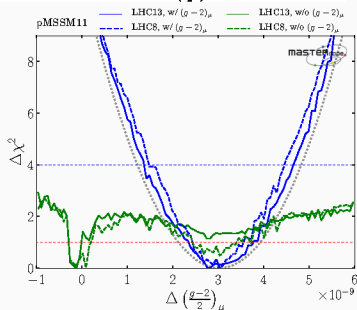
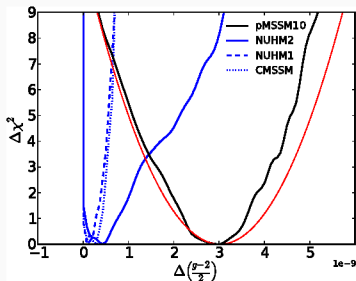
- Poor determination of the mass of colored particles (only lower bound from LHC searches).
- Larger freedom allow to fulfill the $(g-2)_\mu$ constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.

pMSSM11 mass spectrum w/o $(g-2)_\mu$



- Poor determination of the mass of colored sparticles (only lower bound from LHC searches).
- Reduced parameter range at 68% CL because of slightly improved fit of flavor observables.

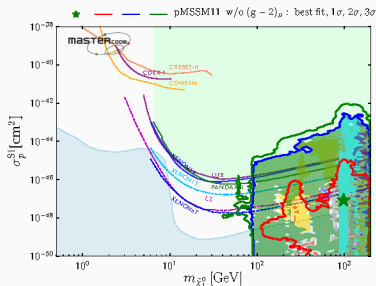
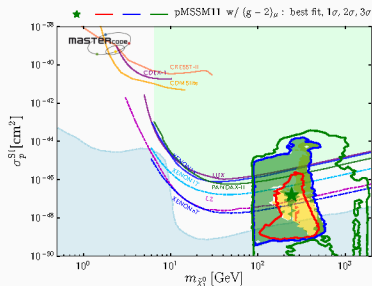
The $(g-2)_\mu$ constraint



Model	χ^2/n_{dof}	χ^2 probability
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %
pMSSM11	22.21/20	33 %
pMSSM11	20.88/19	34 %
w/o $(g-2)_\mu$		

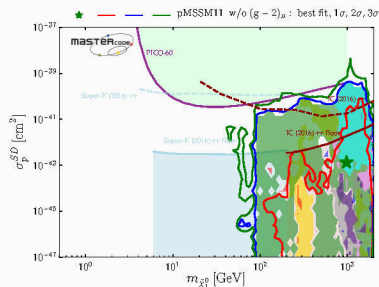
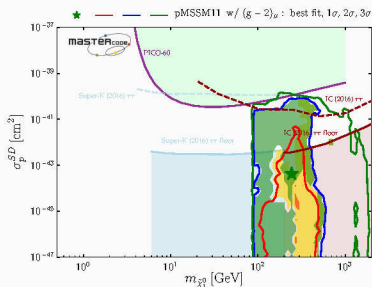
- $\simeq 3.5 \sigma$ discrepancy between the SM $(g-2)_\mu$ value and the measured one.
- In the GUT scenarios there is a tension between the $(g-2)_\mu$ and LHC constraint.
- In the pMSSM it is possible to fit $(g-2)_\mu$.

Spin-independent scattering cross-section



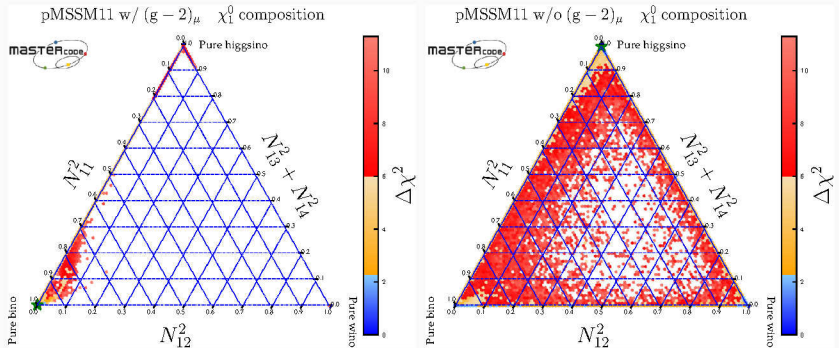
- Complementarity of collider searches vs direct-detection searches.
- Relieving $(g-2)_\mu$ allows for light higgs funnel/Z funnel/t-channel-stau regions to appear at the 2σ and 3σ level.

Spin-dependent scattering cross-section



- PICO-60 results touch the 3σ contours.
- We cross-checked for a selection of points that IC constraints are relevant only for a minority of points in our sample.

$\tilde{\chi}_1^0$ composition



- Bi-component/pure neutralinos always preferred.
- $(g-2)_\mu$ implies preference for Bino, Bino-Higgsino.

Conclusions

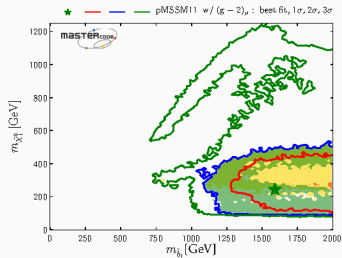
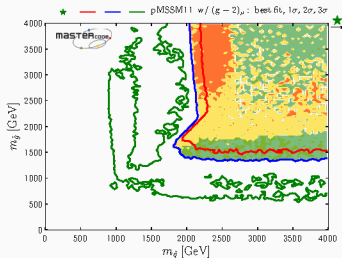
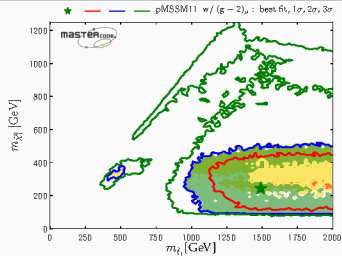
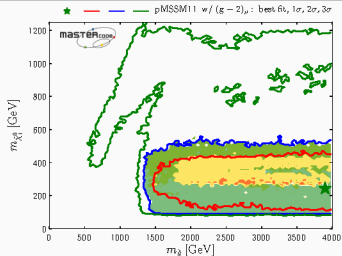
Conclusions

- We performed what is the first global likelihood analysis of the pMSSM11 and the subGUT-CMSSM using a frequentist approach including all the relevant 36 fb^{-1} constraints.
- In the case of the pMSSM11, The new results from LHC @ 13 TeV and from direct-decay DM experiments exerts a significant impact on the allowed parameter range.
- We studied in depth the interplay between $(g - 2)_\mu$ and flavor constraints. Significant change in the phenomenology when relieving $(g - 2)_\mu$.
- In the pMSSM11, still relatively low masses for sparticles appear to be allowed and in part will be probed by the future runs of the LHC.
- Looking *forward* to improve our constraint sets and to study new SUSY and non-SUSY scenarios.

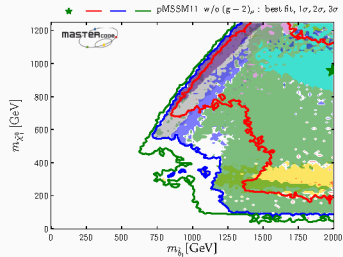
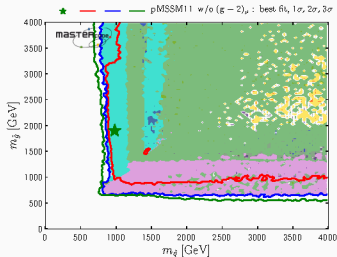
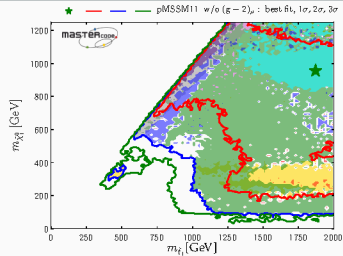
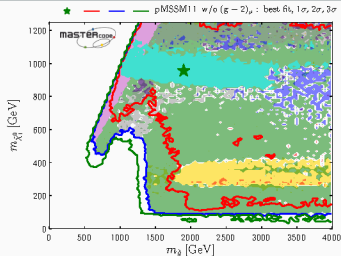


Backup slides

Physical mass planes for the colored sparticles



Physical mass planes for the colored sparticles



█ $\tilde{\chi}_1^\pm$ coann.

█ slep coann.

█ gluino coann.

█ stop coann.

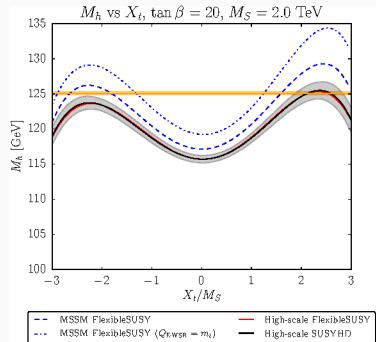
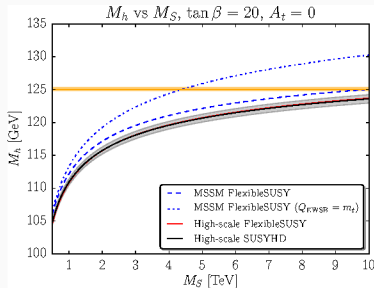
█ A/H funnel

█ stau coann.

█ squark coann.

█ sbot coann.

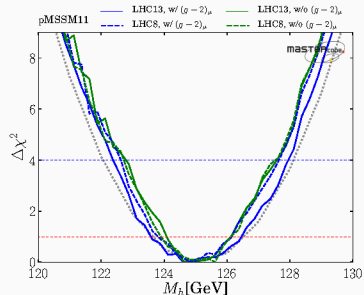
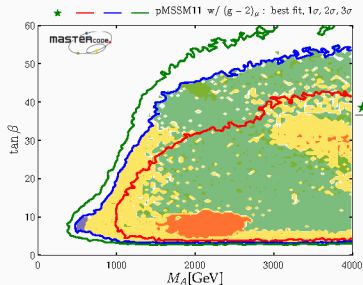
Uncertainty in the Higgs mass prediction



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

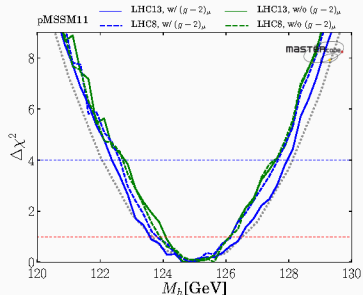
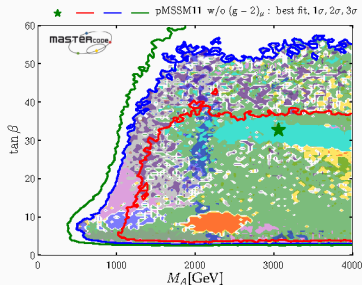
[SusyHD 1504.05200] [FlexibleSUSY Bagnaschi, Weiglein, Voigt 1808.yyyyy]
[FeynHiggs 1312.4937]

Higgs physics



- pMSSM11 likelihood close to the experimental one smeared by theoretical uncertainty that we assume (Gaussian, $\sigma_{theo} = 1.5 \text{ GeV}$)
- Slightly different contours when relieving the $(g-2)_\mu$ constraint.
- Different DM mechanisms in the two cases.

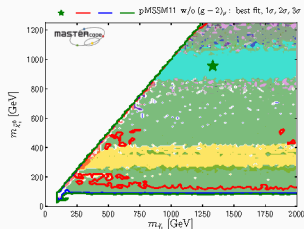
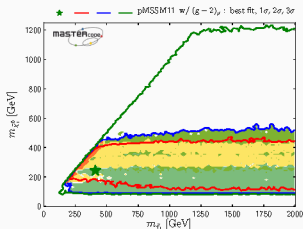
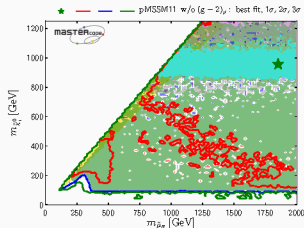
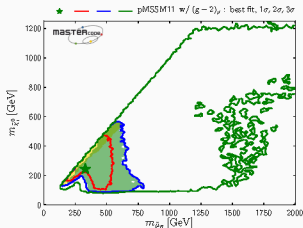
Higgs physics



■ $\tilde{\chi}_1^\pm$ coann.	■ slep coann.	■ gluino coann.	■ stop coann.
■ A/H funnel	■ stau coann.	■ squark coann.	■ sbot coann.

- pMSSM11 likelihood close to the experimental one smeared by theoretical uncertainty that we assume (Gaussian, $\sigma_{theo} = 1.5 \text{ GeV}$)
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- Different DM mechanisms in the two cases.

Sleptons planes



■ $\tilde{\chi}_1^\pm$ coann.

■ slep coann.

■ gluino coann.

■ stop coann.

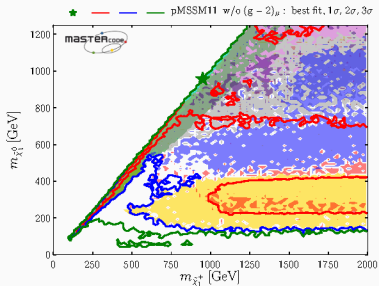
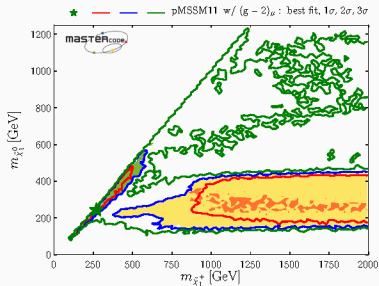
■ A/H funnel

■ stau coann.

■ squark coann.

■ sbot coann.

EWKino planes



■ $\tilde{\chi}_1^\pm$ coann.

■ slep coann.

■ gluino coann.

■ stop coann.

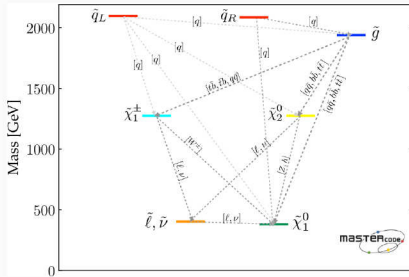
■ A/H funnel

■ stau coann.

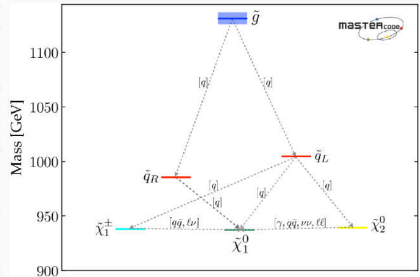
■ squark coann.

■ sbot coann.

Nose regions

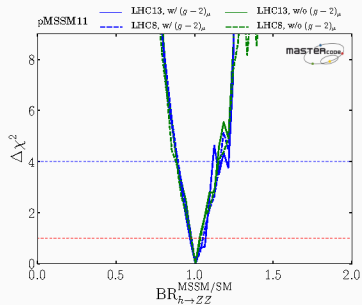
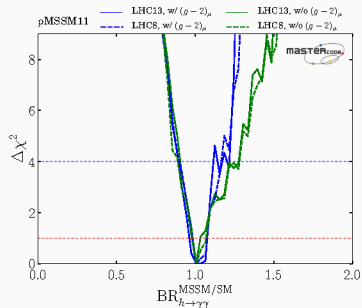


- Loss of search sensitivity when $\tilde{q}_R \rightarrow \tilde{g} + q$, the q jet is soft, and $\tilde{g} \rightarrow q\bar{q} + \tilde{\chi}^*$ compared to a high sensitivity for $\tilde{q}_R \rightarrow q\tilde{\chi}_1^0$ in the $m_{\tilde{g}} > m_{\tilde{q}}$ case.



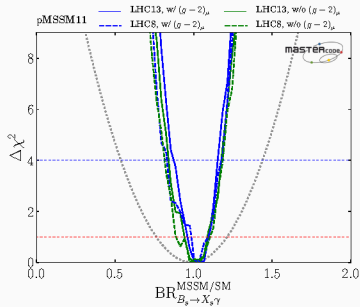
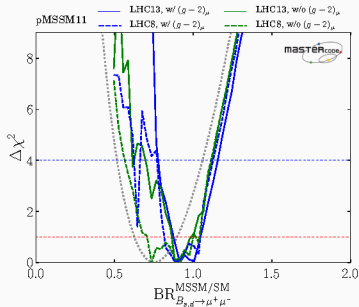
- Heavy neutralino allows for more compressed spectra, which reduced the efficiency of experimental searches.

Higgs decays



- At 68%CL no significant deviation from the SM, as expected.

Flavor constraints



- Removing the $(g-2)_\mu$ allows for an improved fit of $B_{s,d} \rightarrow \mu^+ \mu^-$.

Long lived staus and charginos

