

Perspectives on the pMSSM11 in light of current LHC results

Emanuele A. Bagnaschi (DESY Hamburg)



15 May 2018

4th workshop on (Re)interpreting LHC results
CERN, Switzerland

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

Eur.Phys.J. C78 (2018) no.3, 256



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^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

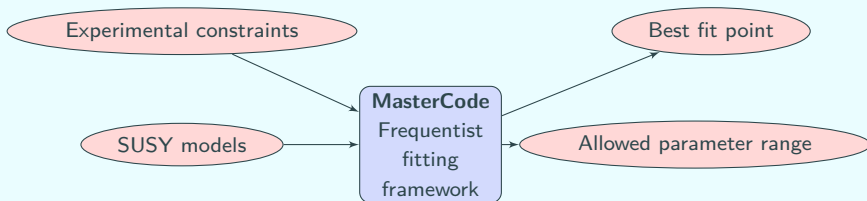
Gauge supermultiplets

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 scenario

The pMSSM11

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

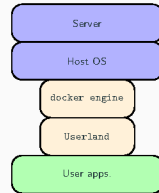
- Sampled a total of 2×10^9 points.
- We thank DESY for the resources provided by the NAF2/BIRD cluster.

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



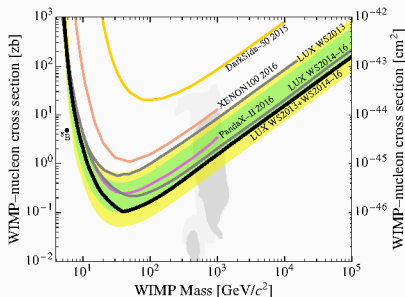
- Middleware suite developed in the context of the INDIGO data-cloud project to run docker containers in userspace, without requiring root privileges (**both for installation and execution**).

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

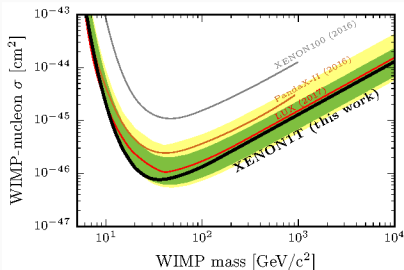
EWPOs

- 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.

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.



[1705.06655]

Flavor observables

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

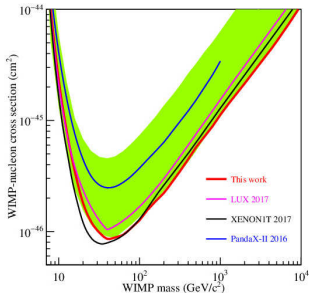
EWPOs

- 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.

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.



[1708.06917]

Flavor observables

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

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.

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

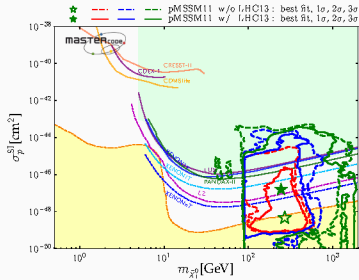
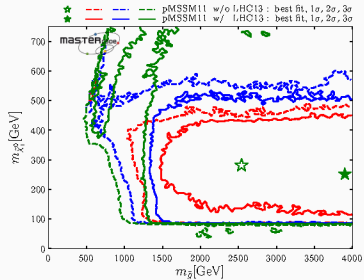
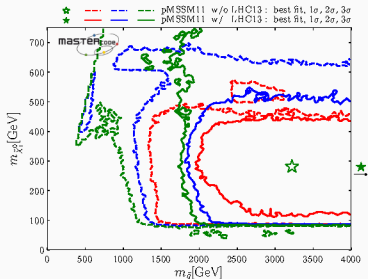
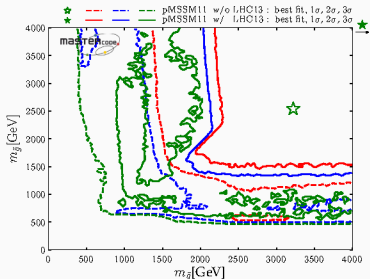
- Fastlim approach.

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

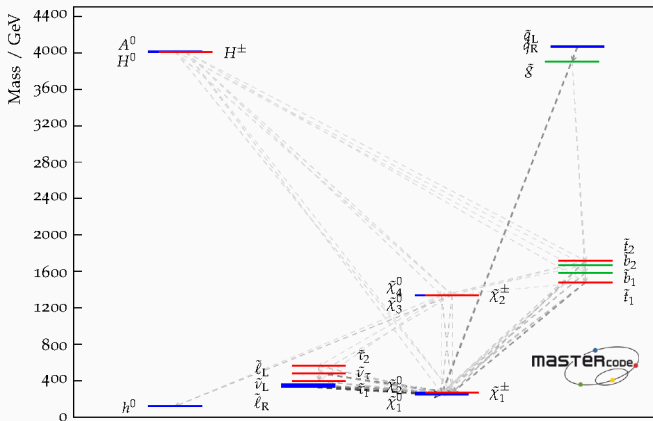
Topology	Analysis	Ref.
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow [\nu \ell^\pm \tilde{\chi}_1^0][\ell^\mp \ell^\mp \tilde{\chi}_1^0]$ (via $\tilde{\ell}^\pm$)	multileptons with $\cancel{E}_T$	[CMS-SUS-16-039, 1709.05406]
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow [\nu \tau^\pm \tilde{\chi}_1^0][\tau^\mp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

Results

From 2015 to 2017 (LHC+DD)



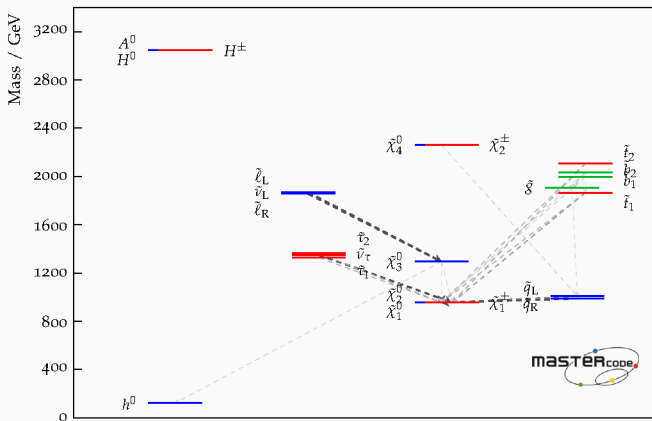
pMSSM11 best fit point



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
$m_{\tilde{\tau}_1}$	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.

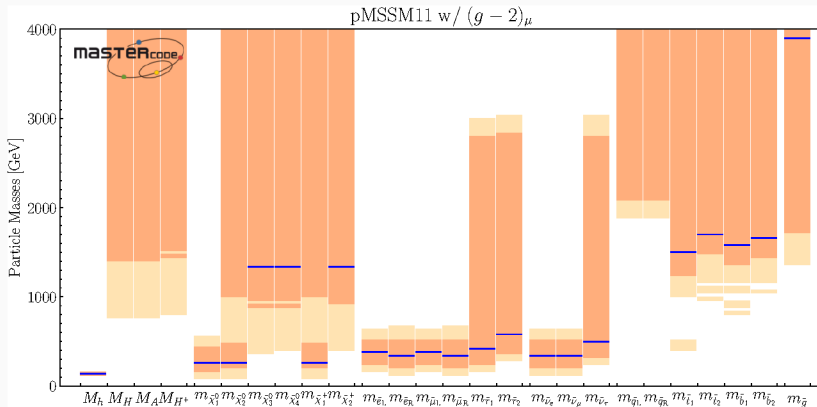
pMSSM11 best fit point w/o $(g-2)_\mu$



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

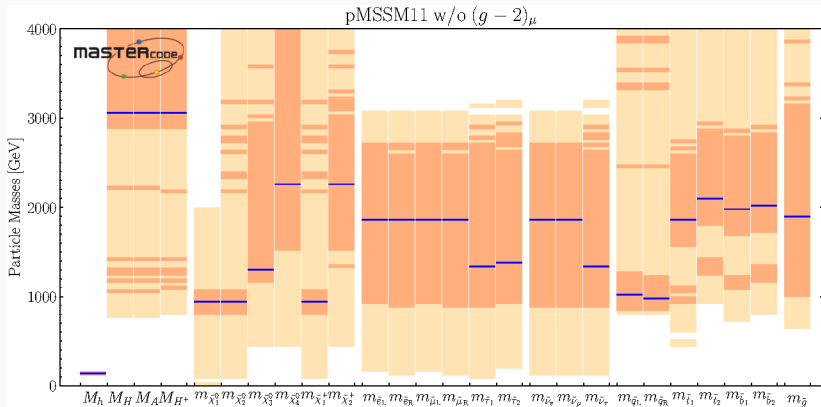
- Neutralino is Higgsino-like, at around 1 TeV.
- Heavier spectrum, with first two generation squarks around 1 TeV.

pMSSM11 mass spectrum



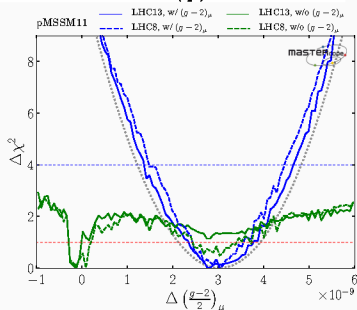
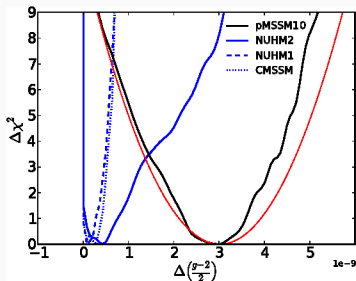
- Poor determination of the mass of colored particles (only lower bound from LHC searches).
- Larger freedom allow to fulfill the $(g-2)_\mu$ constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.

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.

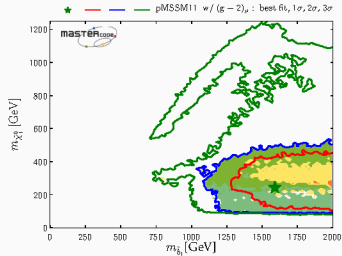
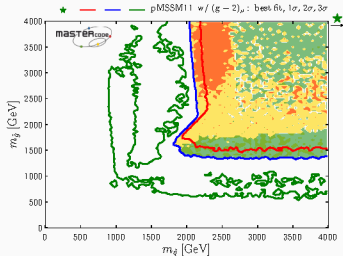
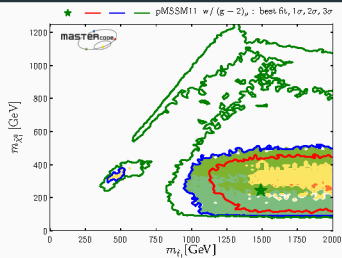
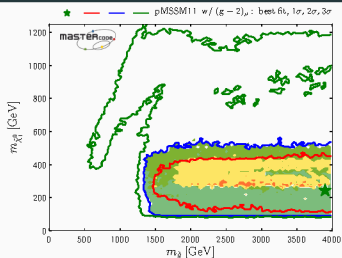
The $(g-2)_\mu$ constraint



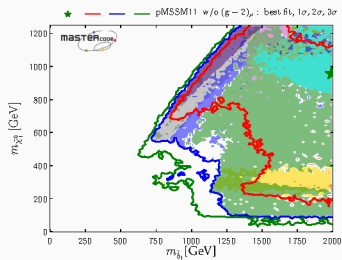
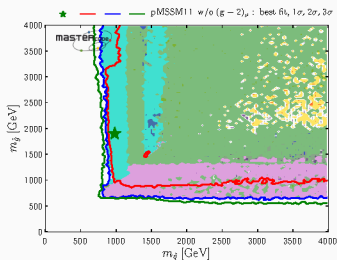
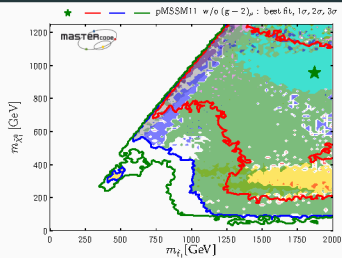
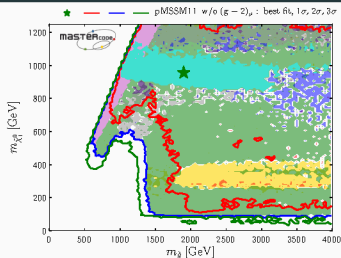
Model	χ^2/n_{dof}	χ^2 probability
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %
pMSSM11	22.21/20	33 %
pMSSM11	20.88/19	34 %
w/o $(g-2)_\mu$		

- $\simeq 3.5 \sigma$ 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 $(g-2)_\mu$.

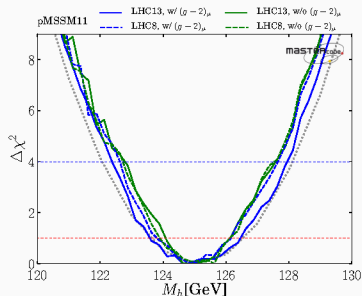
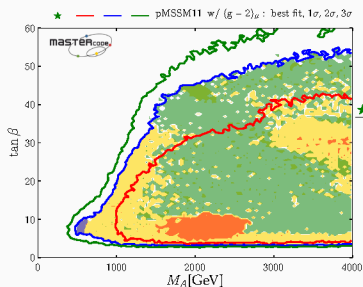
Physical mass planes for the colored sparticles



Physical mass planes for the colored sparticles

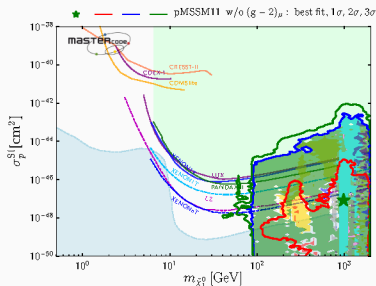
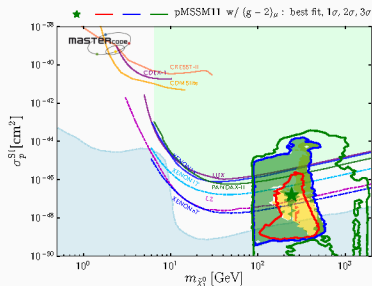


Higgs physics



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

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.

Conclusions

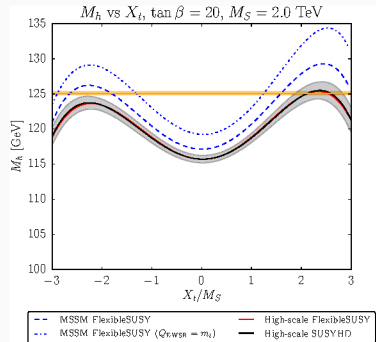
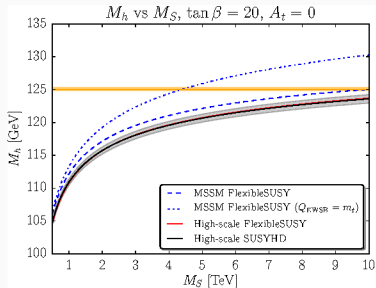
Conclusions

- We performed what is the first global likelihood analysis of the pMSSM11 using a frequentist approach including all the relevant 36 fb^{-1} constraints.
- The new results from LHC @ 13 TeV and from direct-detection 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 $(g - 2)_\mu$.
- Recently we also published a study of the subGUT-CMSSM, see [\[1711.00458\]](#) if you are interested.
- Looking *forward* to improve our constraint sets and to study new SUSY and non-SUSY scenarios.



Backup slides

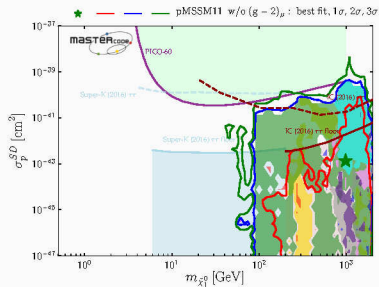
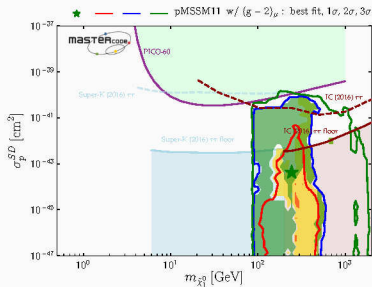
Uncertainty in the Higgs mass prediction



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

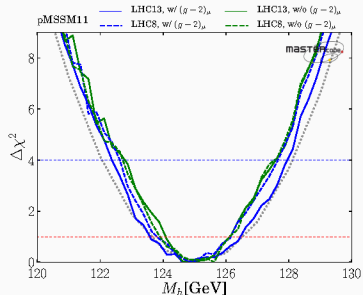
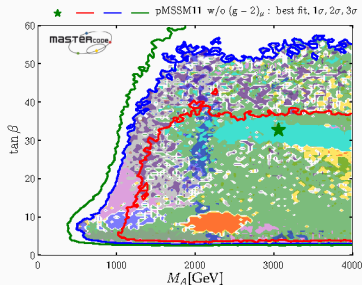
[SusyHD 1504.05200] [FlexibleSUSY Bagnaschi, Weiglein, Voigt 1806.yyyyy]
[FeynHiggs 1312.4937]

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.

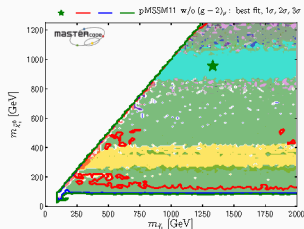
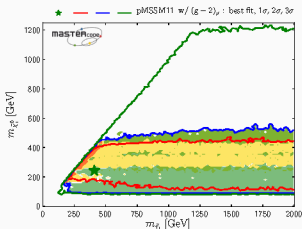
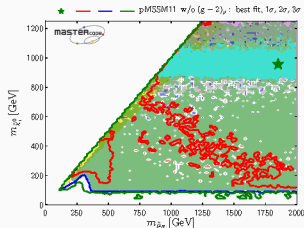
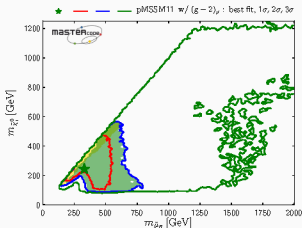
Higgs physics



■ $\tilde{\chi}_1^\pm$ 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, $\sigma_{theo} = 1.5 \text{ GeV}$)
- Slightly different contours when relieving the $(g-2)_\mu$ constraint.
- Different DM mechanisms in the two cases.

Sleptons planes



■ $\tilde{\chi}_1^\pm$ coann.

■ slep coann.

■ gluino coann.

■ stop coann.

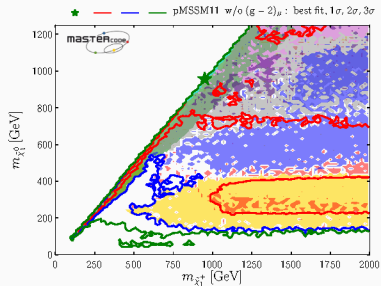
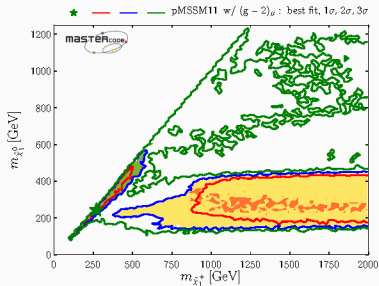
■ A/H funnel

■ stau coann.

■ squark coann.

■ sbot coann.

EWKino planes



$\tilde{\chi}_1^\pm$ coann.

slep coann.

gluino coann.

stop coann.

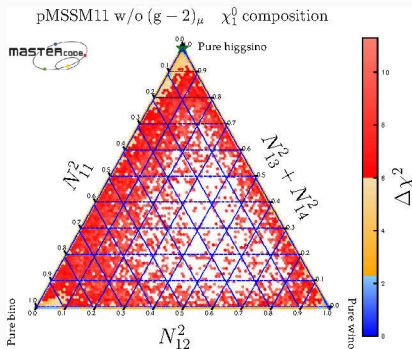
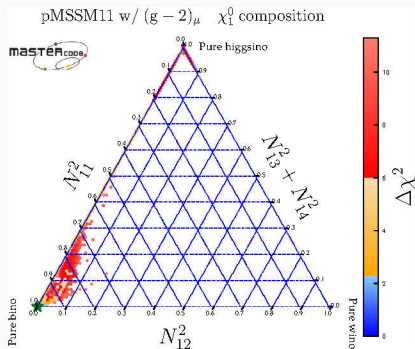
A/H funnel

stau coann.

squark coann.

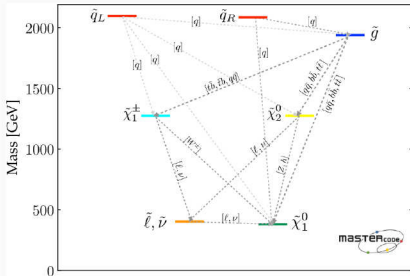
sbot coann.

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

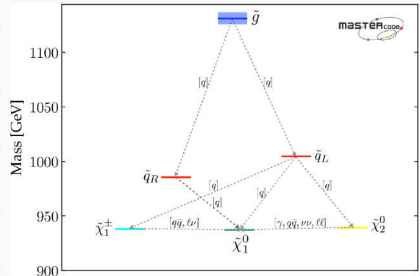


- Bi-component/pure neutralinos always preferred.
- $(g-2)_\mu$ implies preference for Bino, Bino-Higgsino.

Nose regions

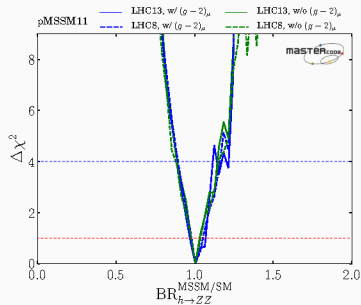
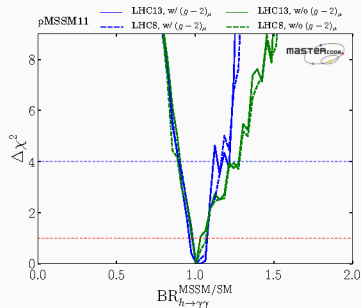


- Loss of search sensitivity when $\tilde{q}_R \rightarrow \tilde{g} + q$, the q jet is soft, and $\tilde{g} \rightarrow q\bar{q} + \tilde{\chi}^*$ compared to a high sensitivity for $\tilde{q}_R \rightarrow q\tilde{\chi}_1^0$ in the $m_{\tilde{g}} > m_{\tilde{q}}$ case.



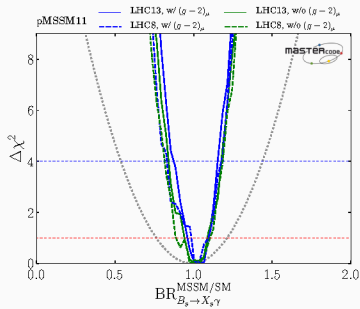
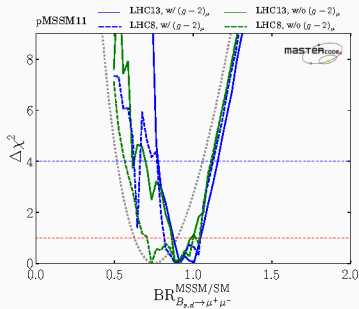
- Heavy neutralino allows for more compressed spectra, which reduced the efficiency of experimental searches.

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

