Perspectives on the pMSSM11 in light of current LHC results

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CERN, Switzerland

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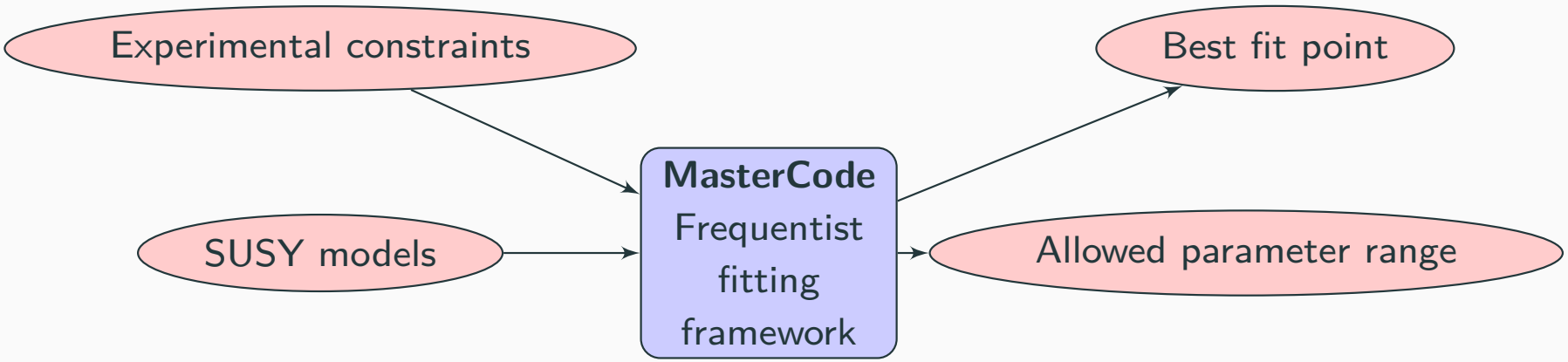
Introduction

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` 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`

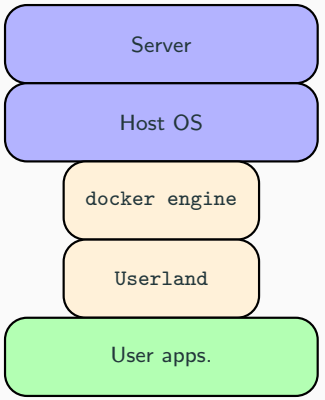
Dark matter

`MicrOMEGAs, SSARD`

- Sampled a total of $\simeq 2 \times 10^9$ 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.



- 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).

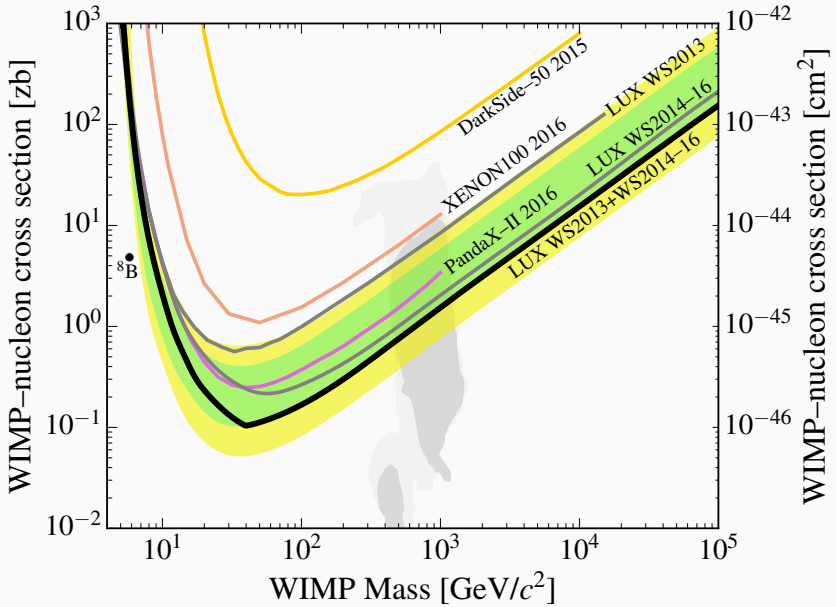
[Gomes at al., 1711.01758, submitted to CPC]

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 `PICO60`.



[1608.07648]

Flavor observables

- We include $\mathrm{BR}_{B\to X_s ll}$,$\mathrm{BR}_{K\to l\nu}$, $\mathrm{BR}_{B\to\pi\nu\bar{\nu}}$, $\mathrm{BR}_{B\to X_s\gamma}$, $\mathrm{BR}_{B\to\tau\nu}$ $\mathrm{BR}_{B_{s,d}\to\mu^+\mu^-}$,$\Delta M_{B_s}$, $\Delta M_{B_s}/\Delta M_{B_d}$, ϵ_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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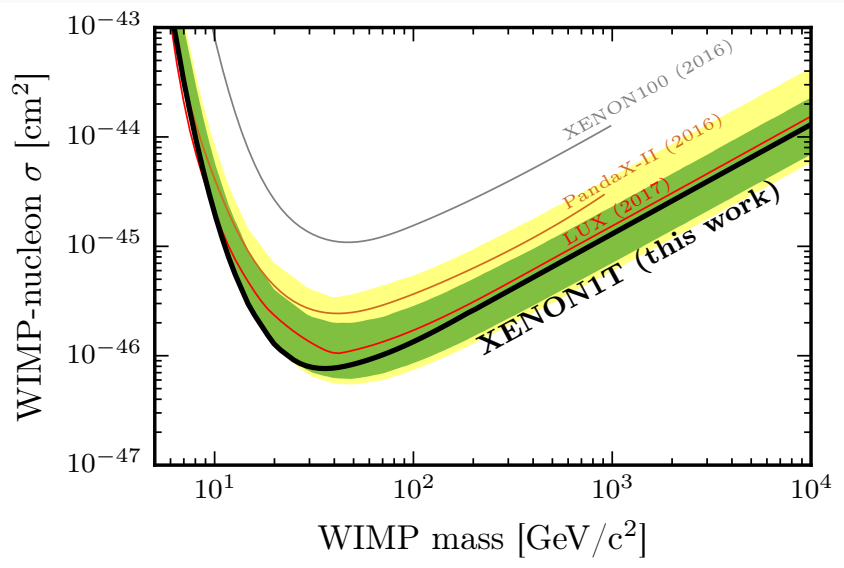

[1705.06655]

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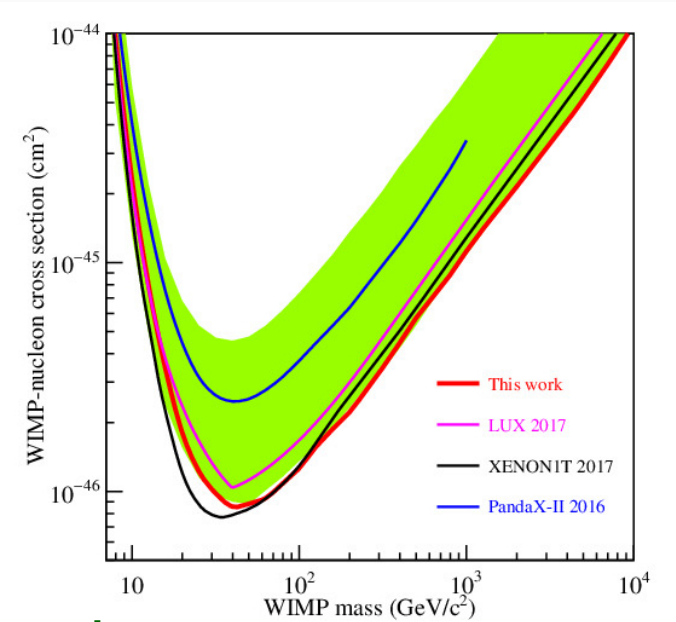

[1708.06917]

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LHC13 colored sparticle constraints

Colored sparticle production

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

Likelihood modelling

- `Fastlim` approach.

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

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

Topology	Analysis	Ref.
$\tilde{g}\tilde{g} \to [\, q\bar{q}\tilde{\chi}^0_1\,]^2,\ [\, b\bar{b}\tilde{\chi}^0_1\,]^2$	0 leptons + jets with $\not{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{g}\tilde{g} \to [\, t\bar{t}\tilde{\chi}^0_1\,]^2$	1 lepton + jets with $\not{E}_T$	[CMS-SUS-16-037, 1705.04673]
$\tilde{q}\bar{\tilde{q}} \to [\, q\tilde{\chi}^0_1\,][\, \bar{q}\tilde{\chi}^0_1\,]$	0 leptons + jets with $\not{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{b}\bar{\tilde{b}} \to [\, b\tilde{\chi}^0_1\,][\, \bar{b}\tilde{\chi}^0_1\,]$	0 leptons + jets with $\not{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{t}_1\bar{\tilde{t}}_1 \to [\, t\tilde{\chi}^0_1\,][\, \bar{t}\tilde{\chi}^0_1\,],\ [\, c\tilde{\chi}^0_1\,][\, \bar{c}\tilde{\chi}^0_1\,]$	0 leptons + jets with $\not{E}_T$	[CMS-SUS-16-036, 1705.04650]
$\tilde{t}_1\bar{\tilde{t}}_1 \to [\, \bar{b}\tilde{\chi}^+_1\,][\, \bar{b}\tilde{\chi}^-_1\,] \to [\, \bar{b}W^+\tilde{\chi}^0_1\,][\, \bar{b}W^-\tilde{\chi}^0_1\,]$	0 leptons + jets with $\not{E}_T$	[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.

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

Likelihood modelling

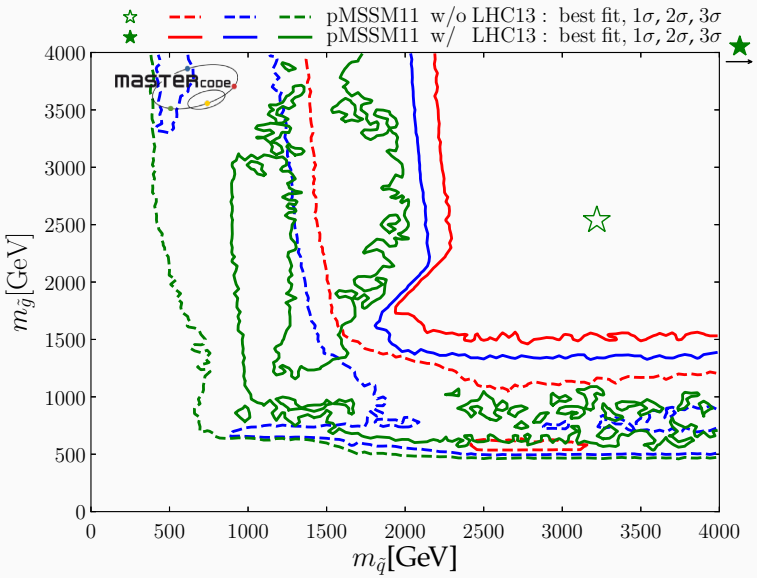
- `Fastlim` approach.

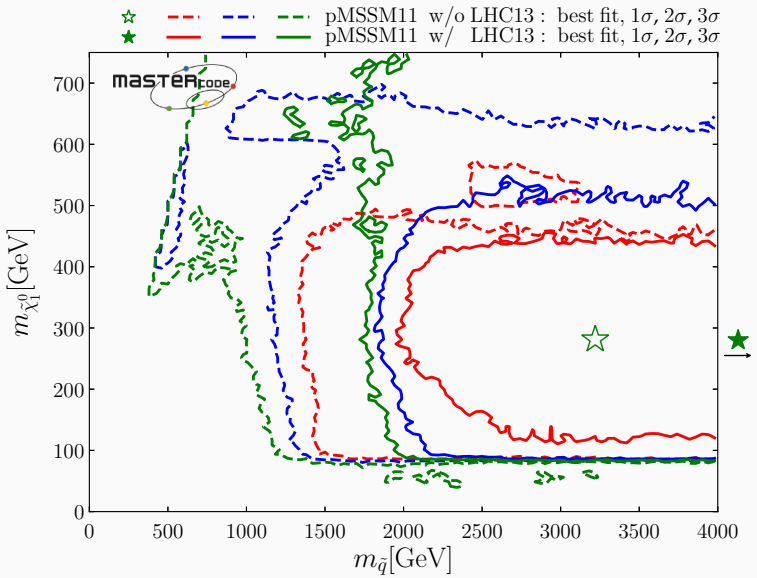
$$\chi^2_{\tilde{\chi}_1^\pm \to \mathrm{SM}\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to \mathrm{SM}\tilde{\chi}_1^0} \simeq 5.99 \cdot \left[\frac{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_2^0}^{\mathrm{BR}_{\tilde{\chi}_1^\pm \to \mathrm{SM}\tilde{\chi}_1^0}^{\mathrm{BR}_{\tilde{\chi}_2^0 \to \mathrm{SM}\tilde{\chi}_1^0}}}}{\sigma_{\mathrm{UL}}^{(\tilde{\chi}_1^\pm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

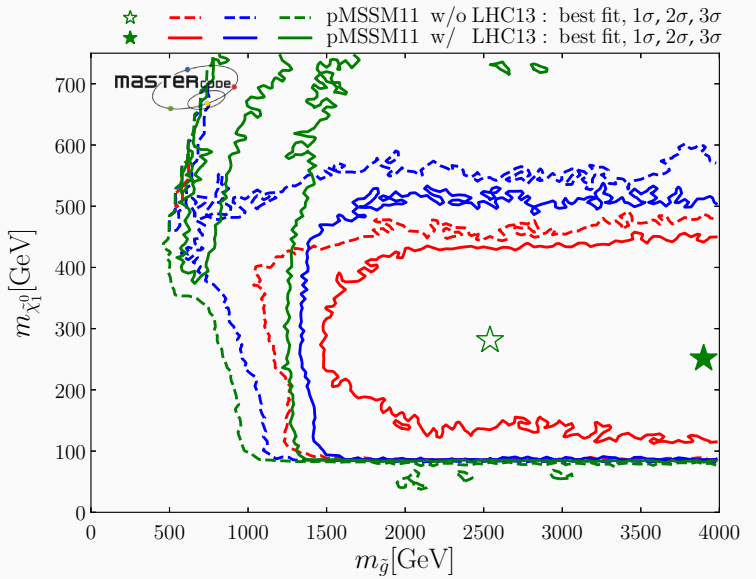
Topology	Analysis	Ref.
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to [\nu\ell^\pm \tilde{\chi}_1^0][\ell^+\ell^- \tilde{\chi}_1^0]$ (via $\tilde{\ell}^\pm$)	multileptons with $\not{E}_T$	[CMS-SUS-16-039, 1709.05406]
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to [\nu\tau^\pm \tilde{\chi}_1^0][\tau^+\tau^- \tilde{\chi}_1^0]$ (via $\tilde{\tau}^\pm$)	multileptons with $\not{E}_T$	[CMS-SUS-16-039, 1709.05406]
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to [W^\pm \tilde{\chi}_1^0][Z\tilde{\chi}_1^0]$	multileptons with $\not{E}_T$	[CMS-SUS-16-039, 1709.05406]

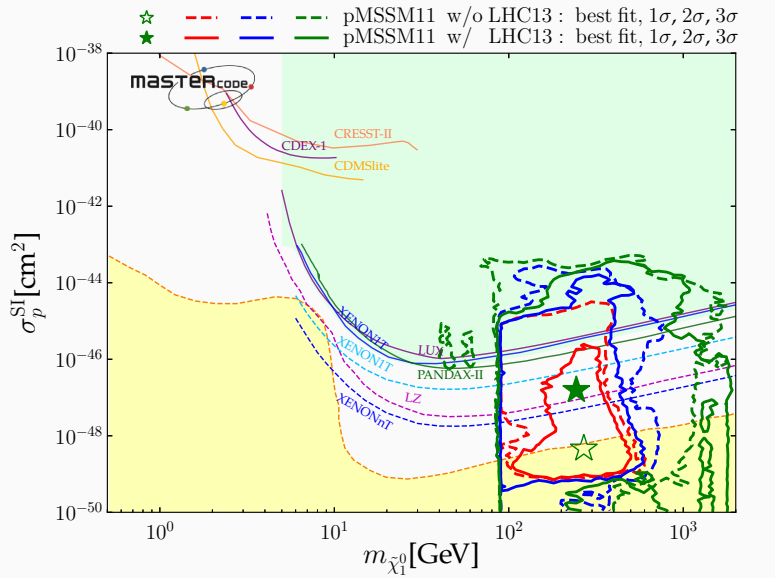
Results

From 2015 to 2017 (LHC+DD)

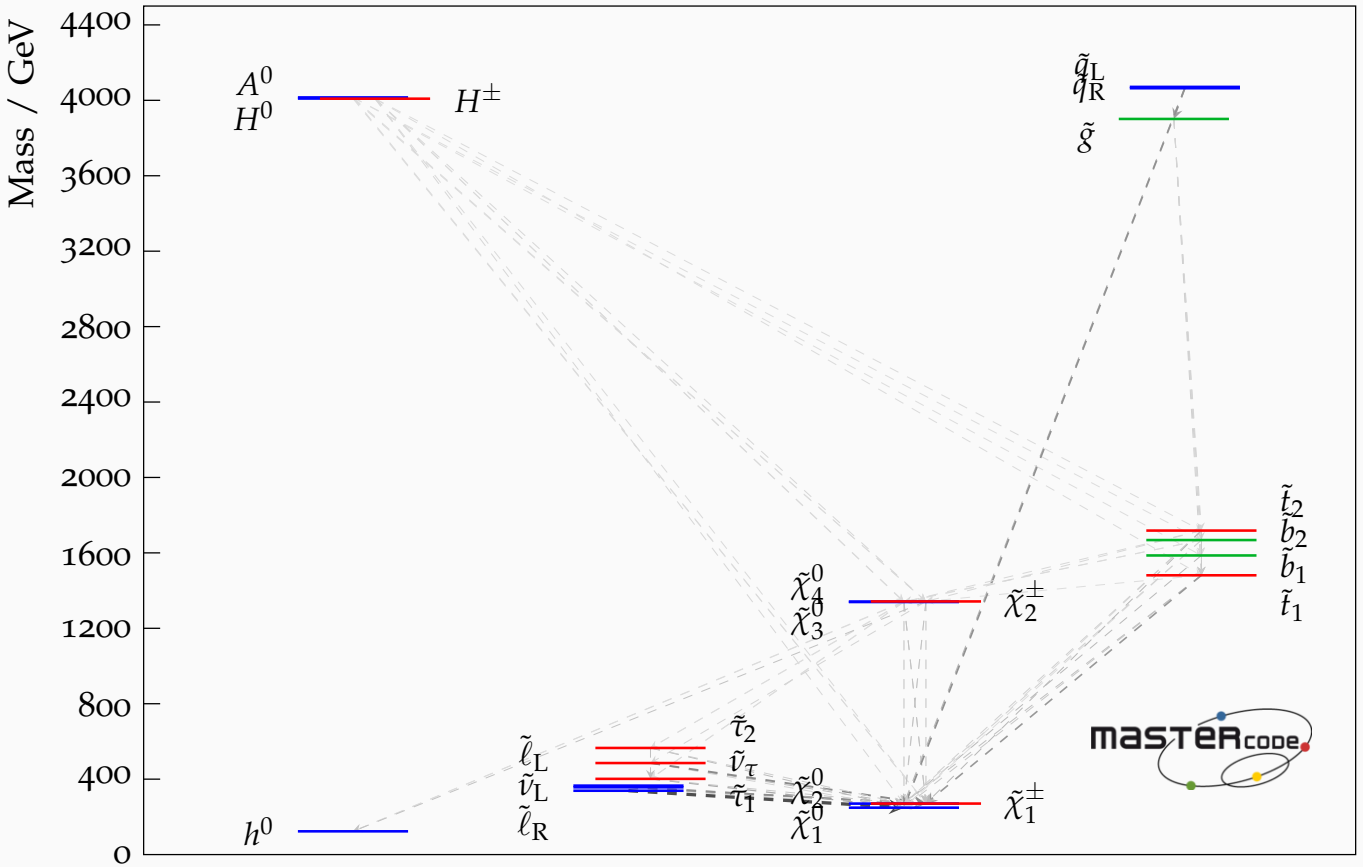








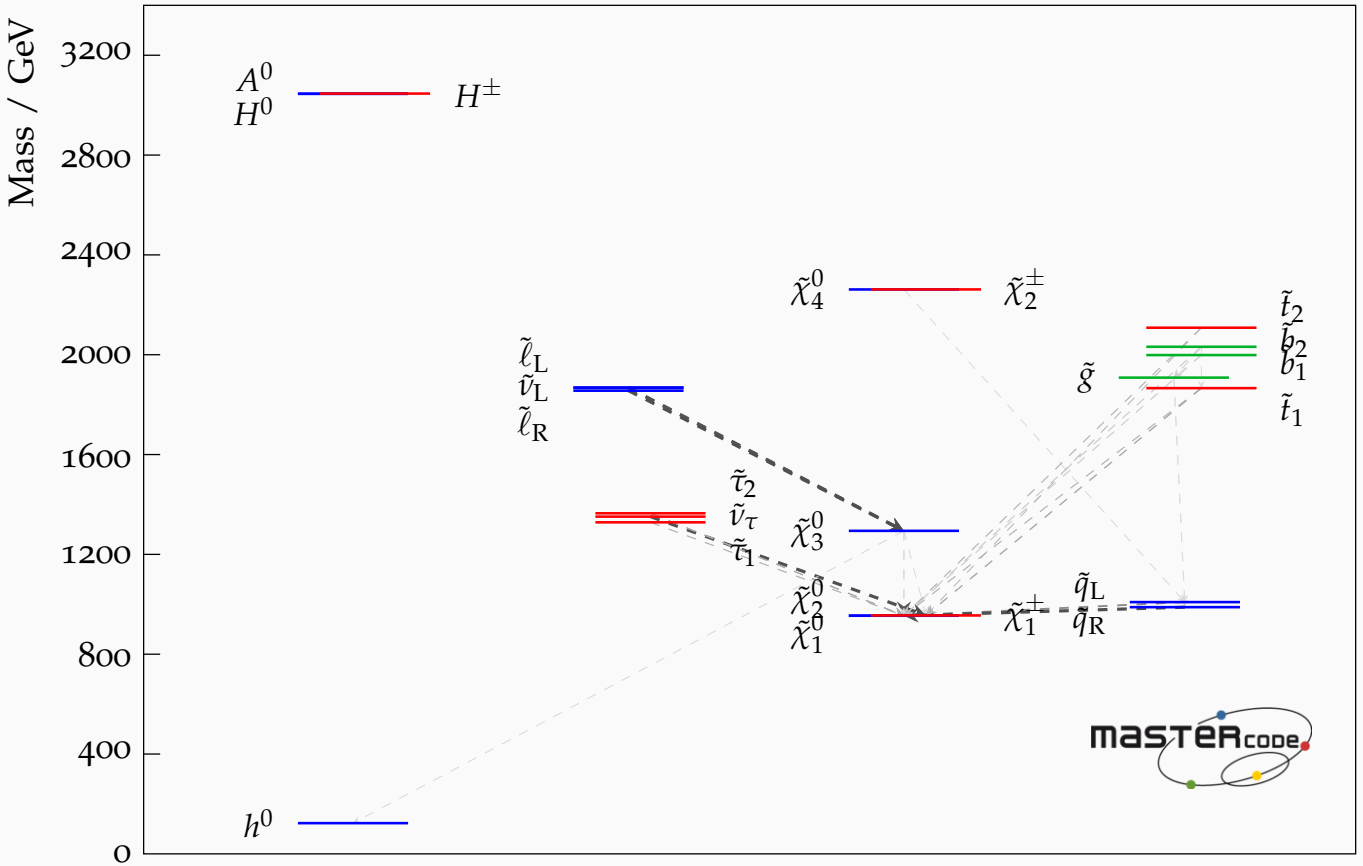
pMSSM11 best fit point



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
$m_{\tilde{l}}$	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.

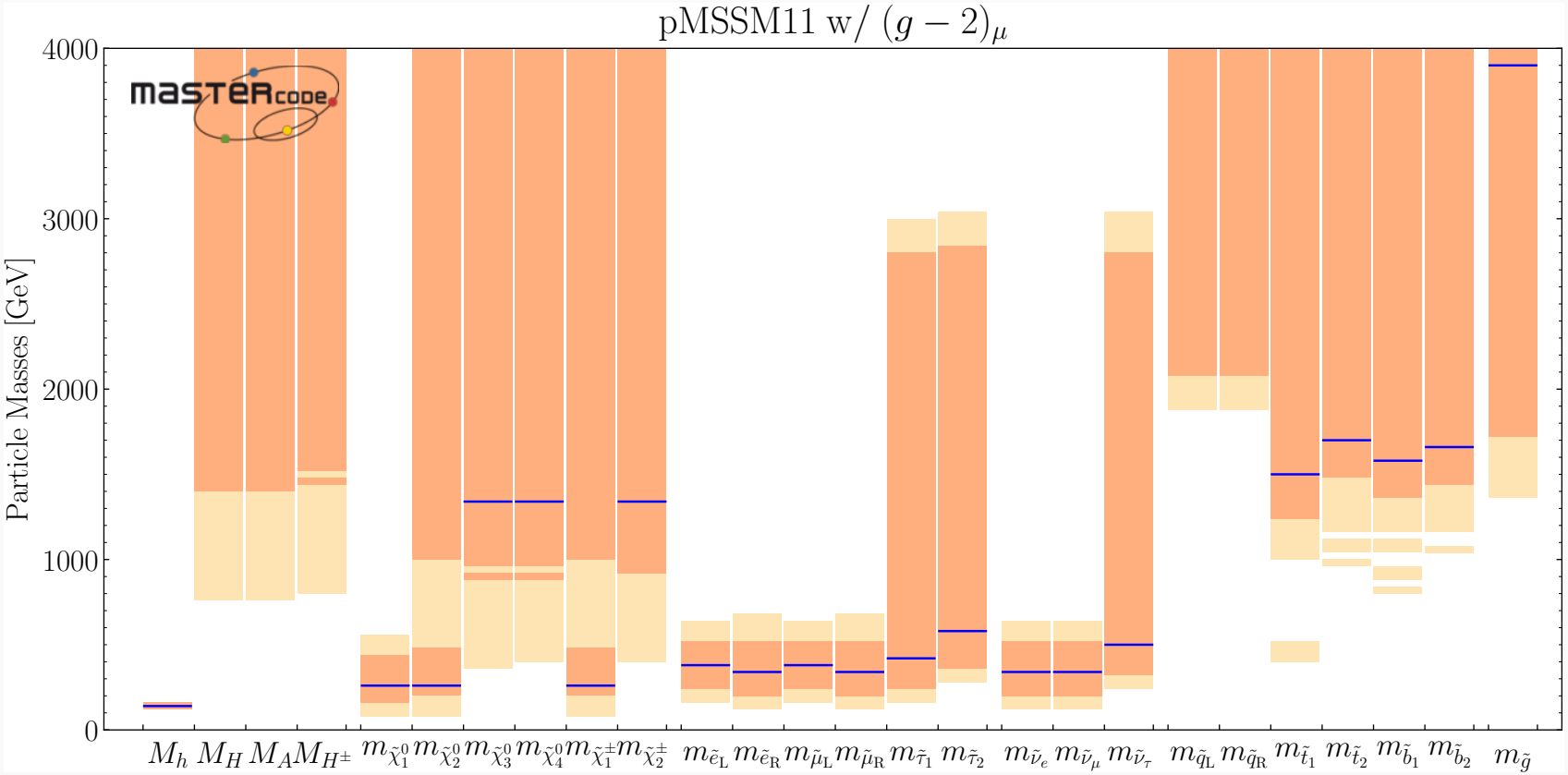
pMSSM11 best fit point w/o $(g-2)_\mu$



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

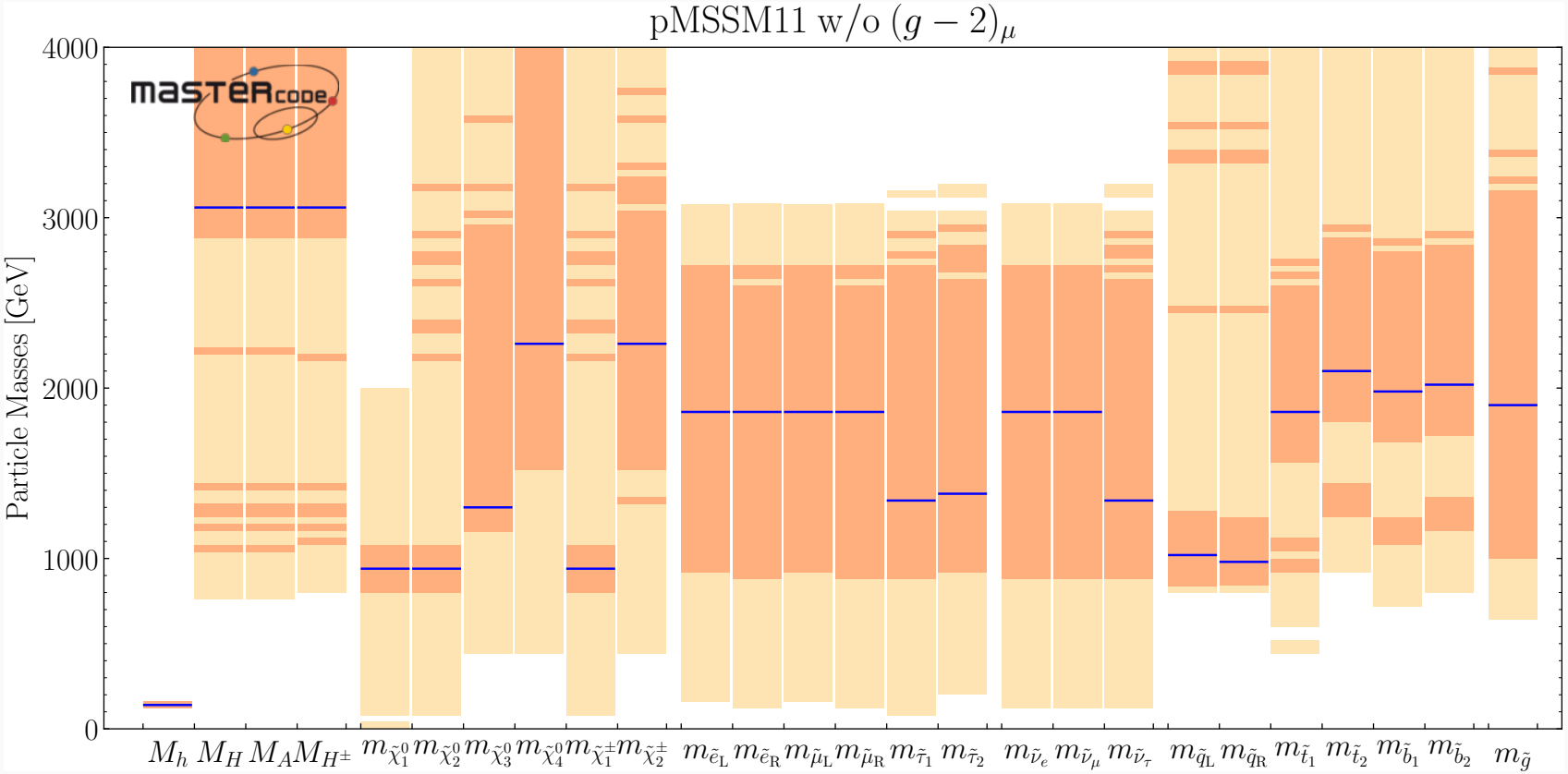
- Neutralino is Higgsino-like, at around 1 TeV.
- Heavier spectrum, with first two generation squarks around 1 TeV.

pMSSM11 mass spectrum



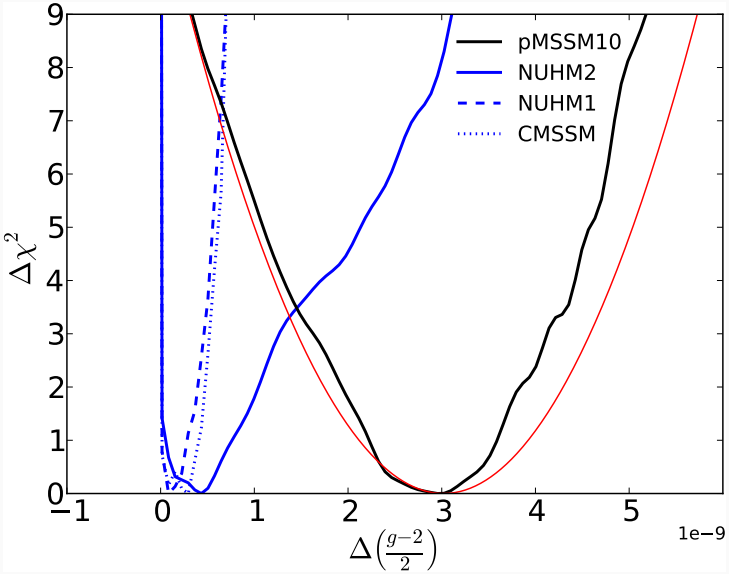
- Poor determination of the mass of colored sparticles (only lower bound from LHC searches).
- Larger freedom allow to fulfill the $(g-2)_\mu$ constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.

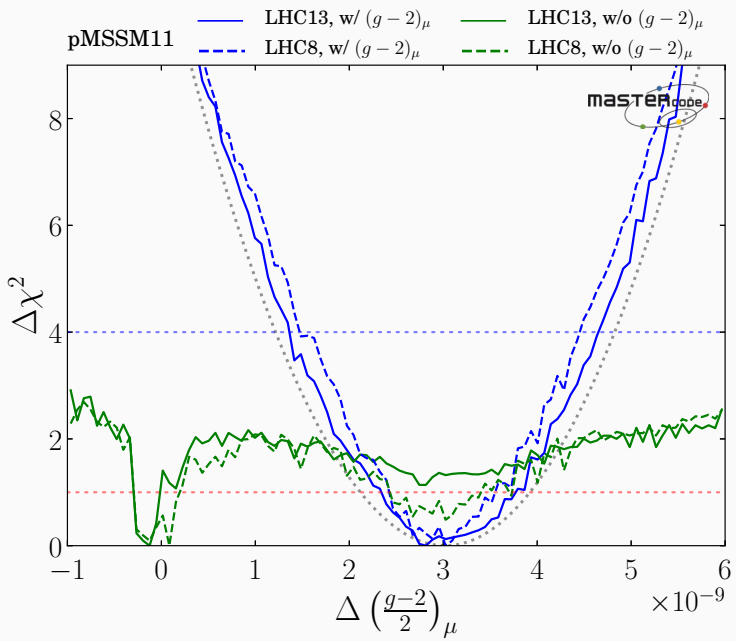
pMSSM11 mass spectrum w/o $(g-2)_\mu$



- 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

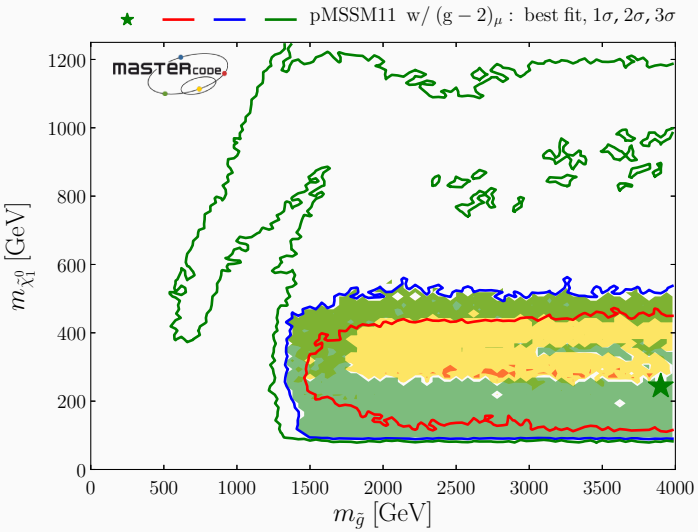


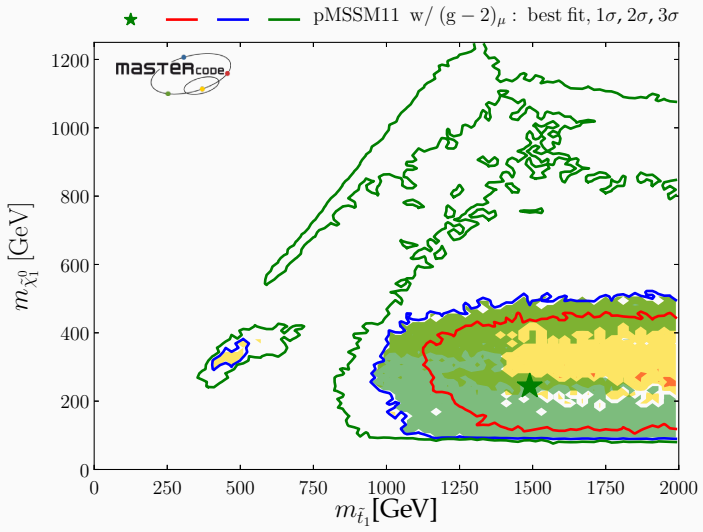


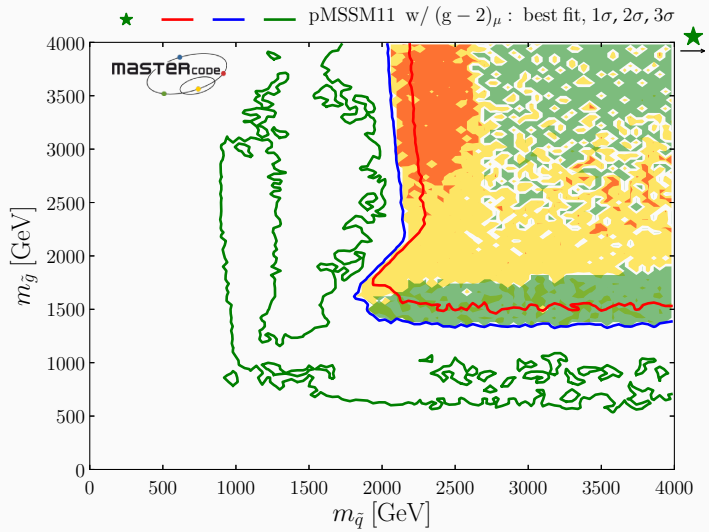
Model	$\chi^2/n_{\rm dof}$	χ^2 probability
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	20.5/18	31 %
pMSSM11	22.21/20	33 %
pMSSM11 w/o $(g-2)_\mu$	20.88/19	34 %

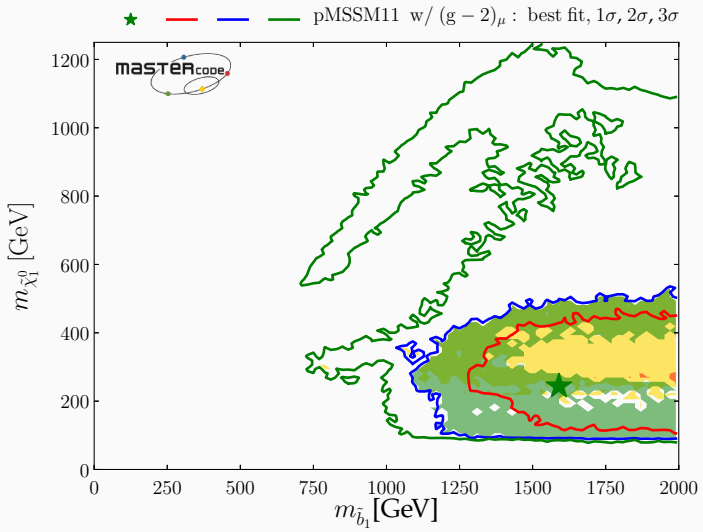
- $\simeq 3.5\ \sigma$ discrepancy between the SM $(g-2)_\mu$ value and the measured one.
- In the GUT scenarios there is a tension between the $(g-2)_\mu$ and LHC constraint.
- In the pMSSM it is possible to fit $(g-2)_\mu$.

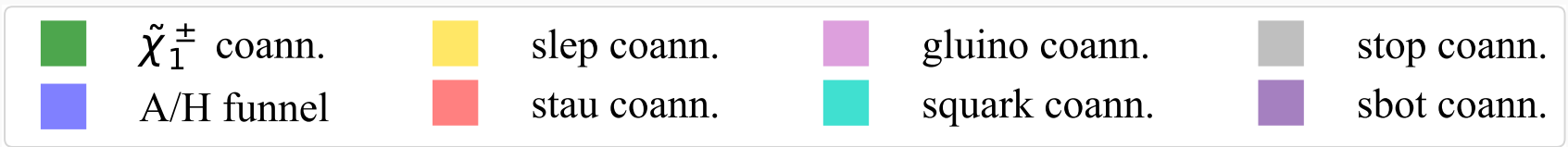
Physical mass planes for the colored sparticles











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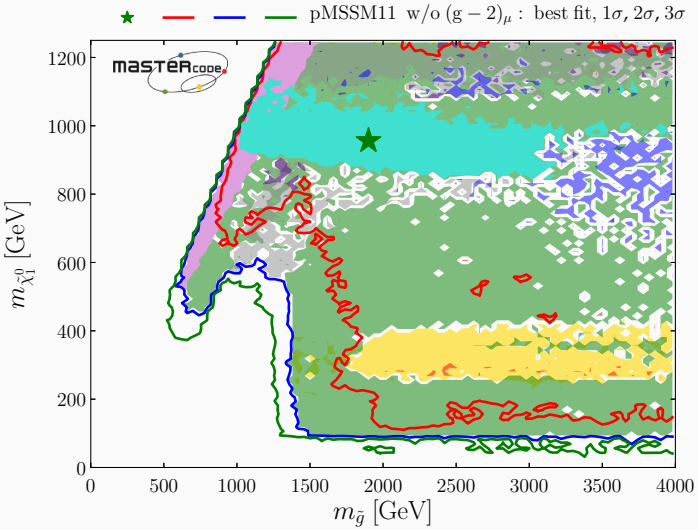
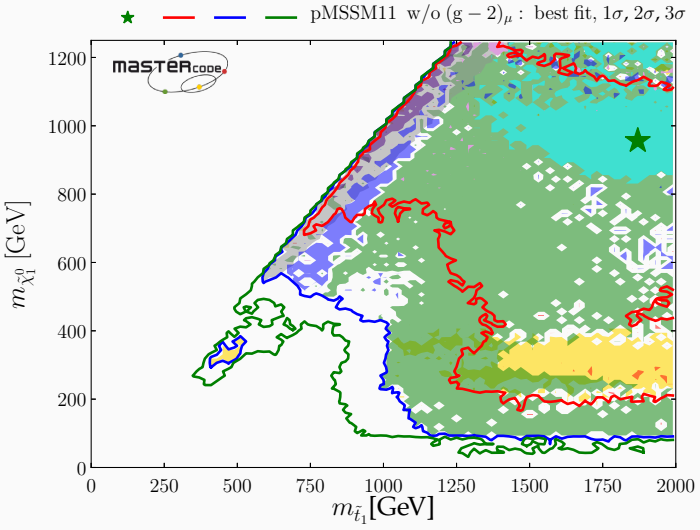
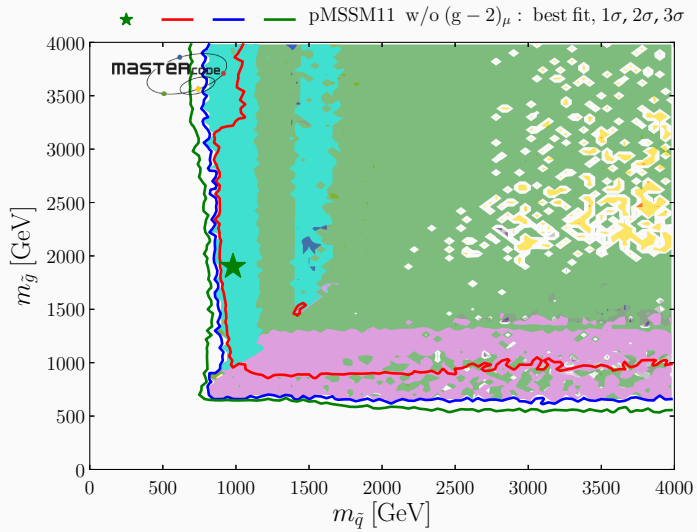
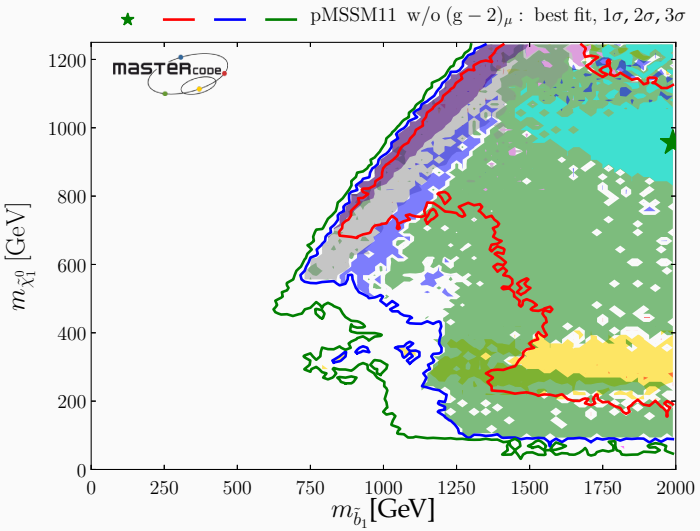
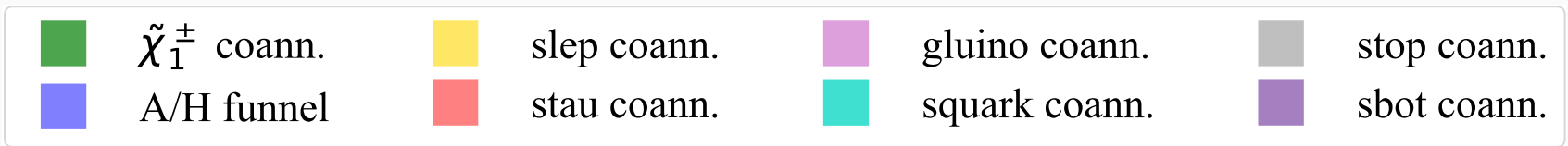


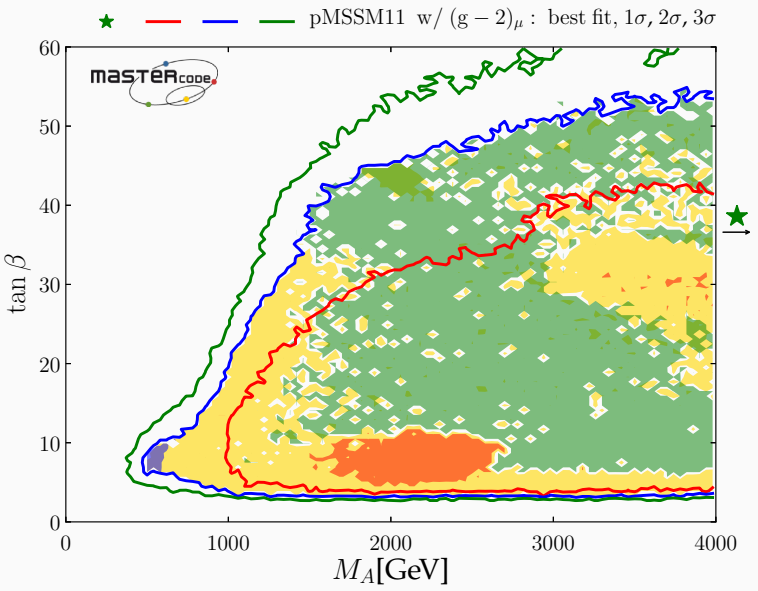


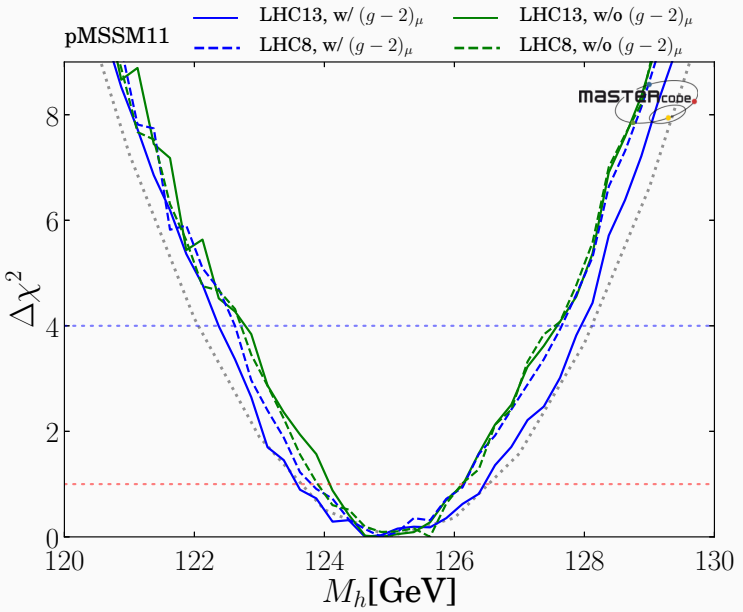






Higgs physics

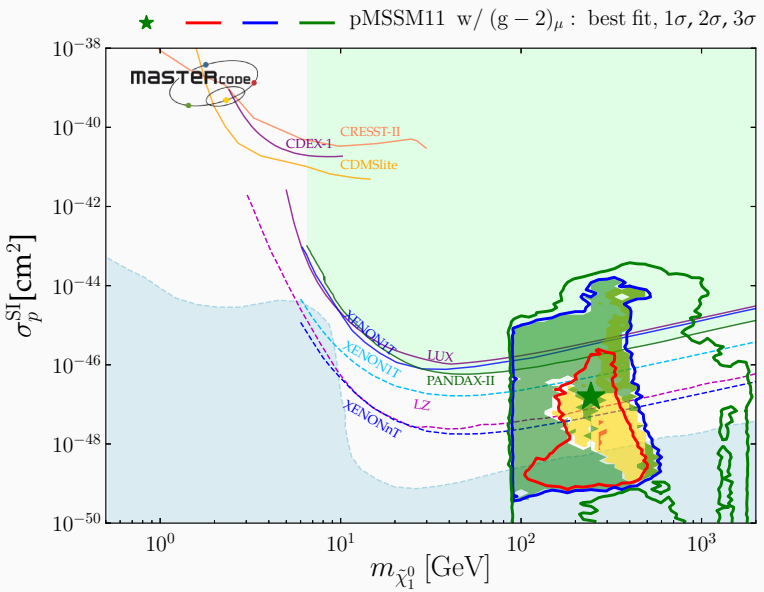


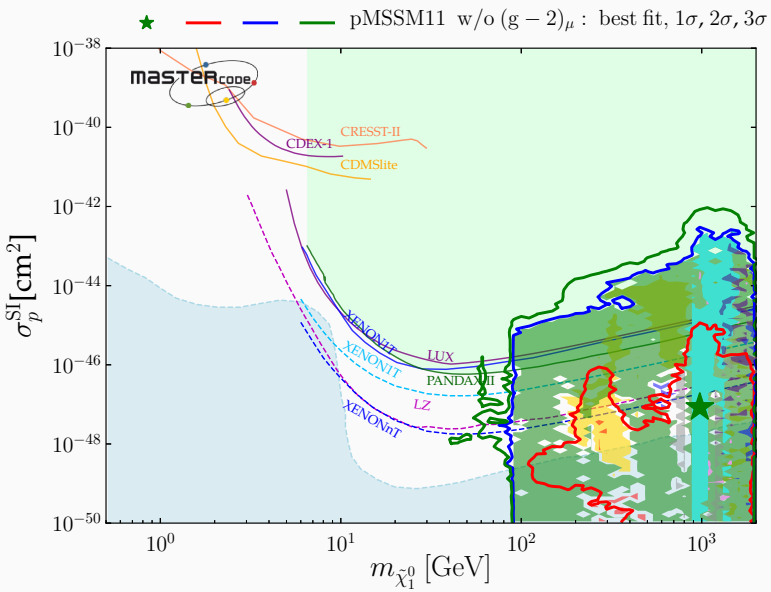


$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

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

Spin-independent scattering cross-section





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

- 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.

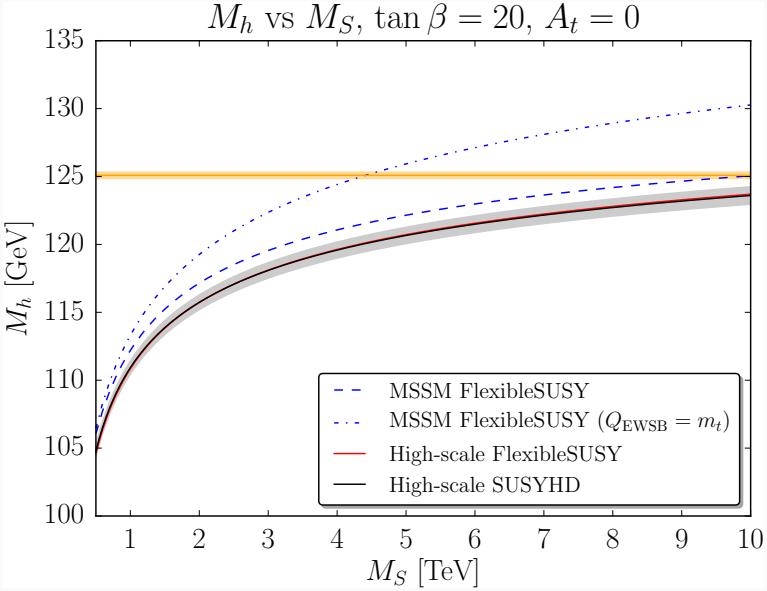
Conclusions

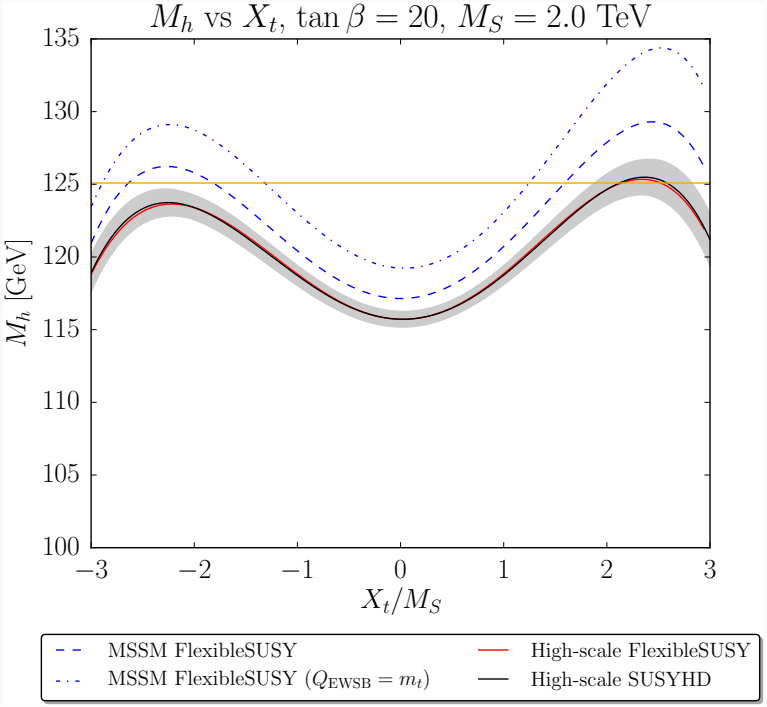
Conclusions

- 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-dection 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

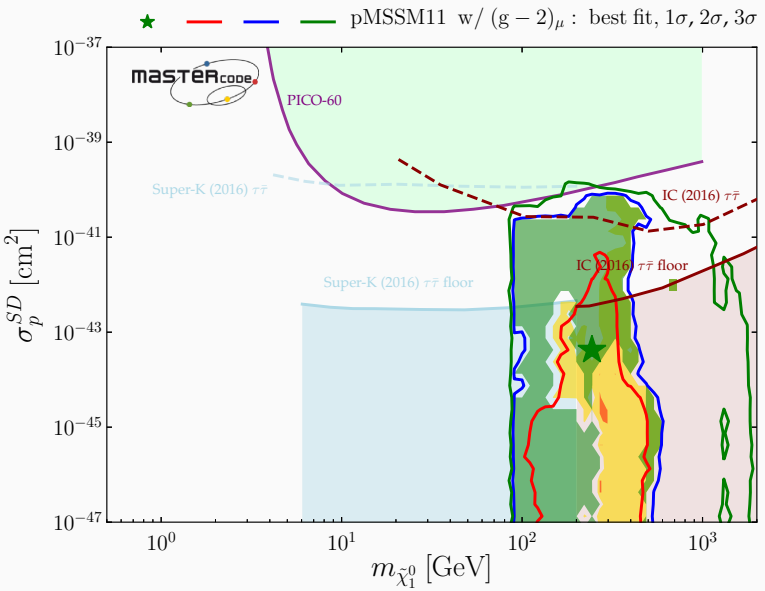


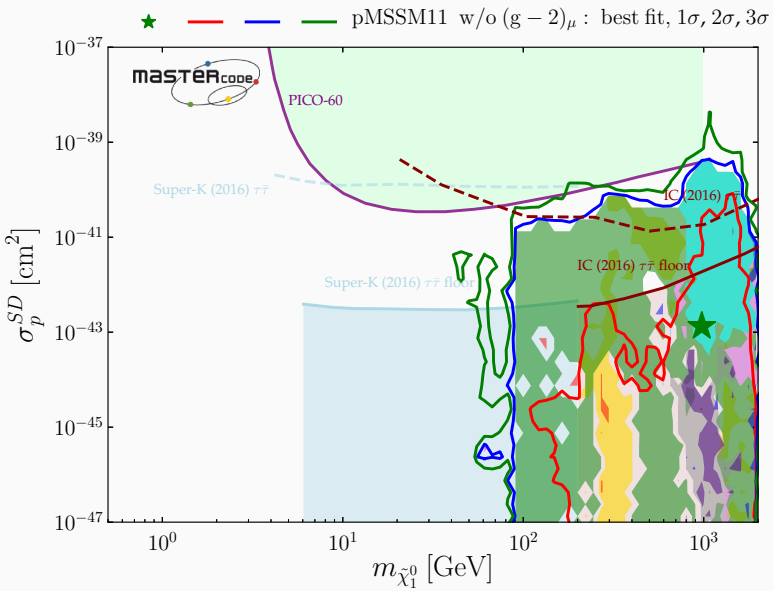


- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

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

Spin-dependent scattering cross-section

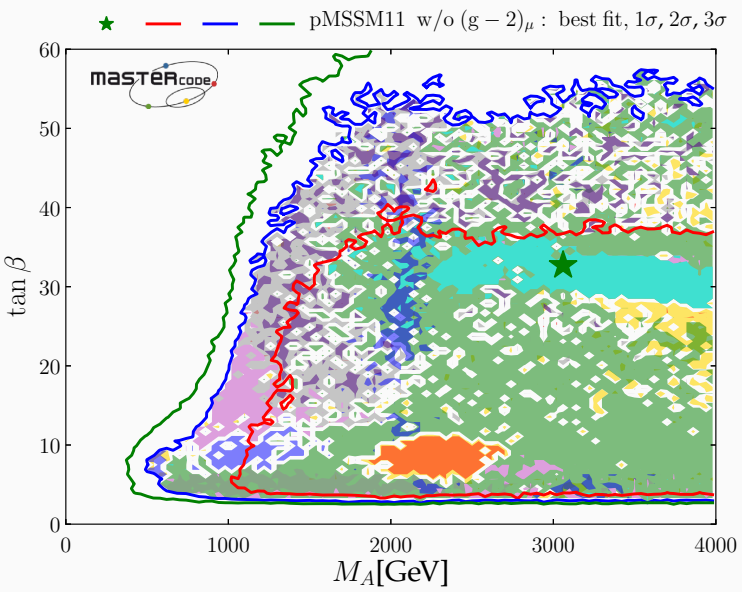


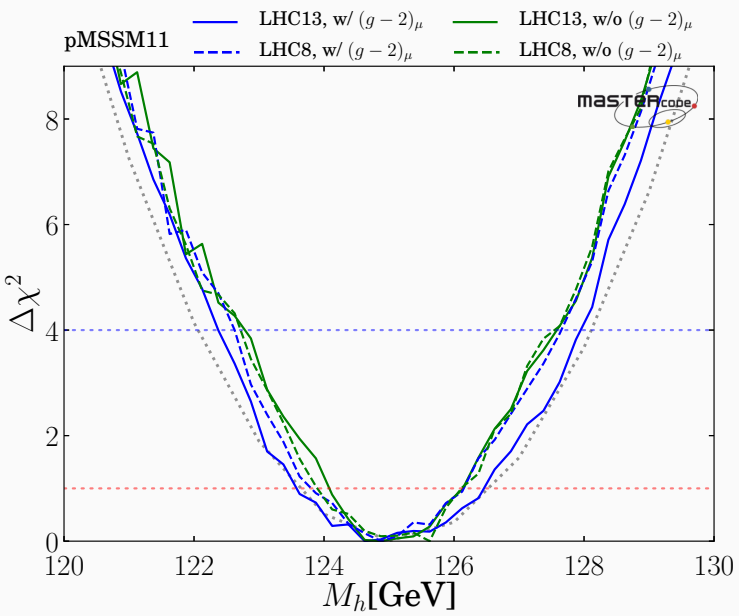


$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

- 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

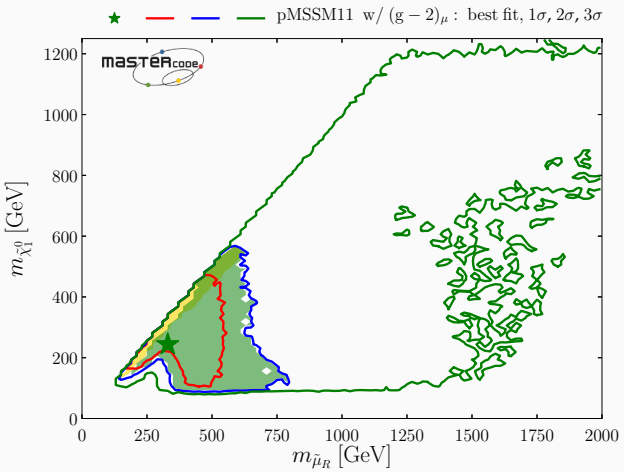


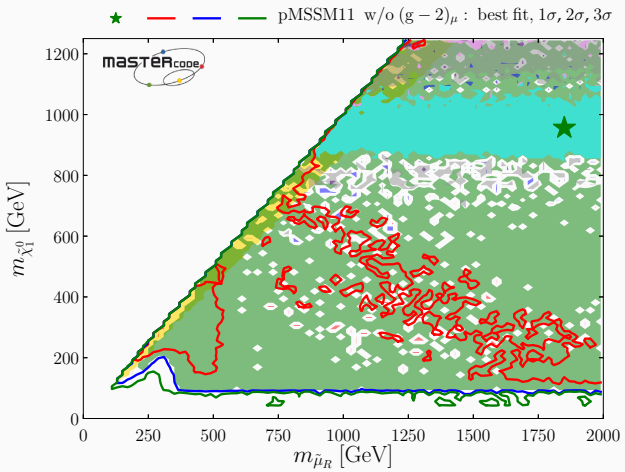


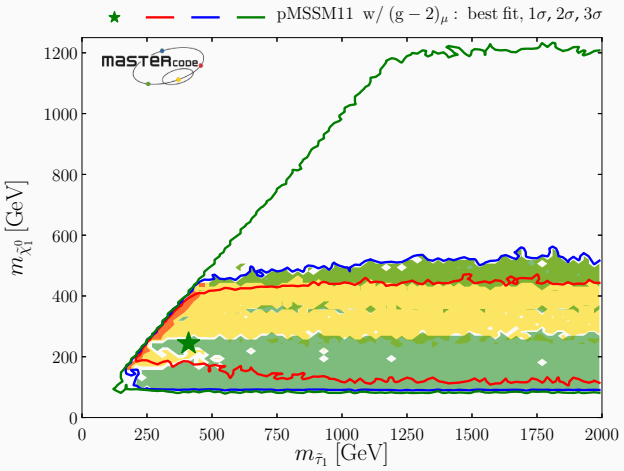
$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

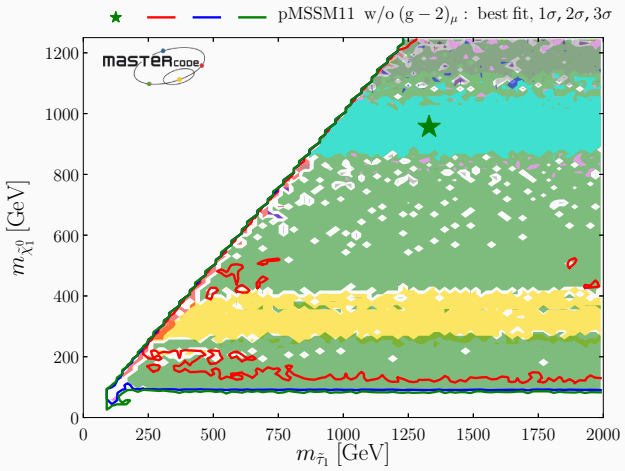
- pMSSM11 likelihood close to the experimental one smeared by theoretical uncertainty that we assume (Gaussian, $\sigma_{theo} = 1.5$ GeV)
- Slightly different contours when relieving the $(g-2)_\mu$ constraint.
- Different DM mechanisms in the two cases.

Sleptons planes



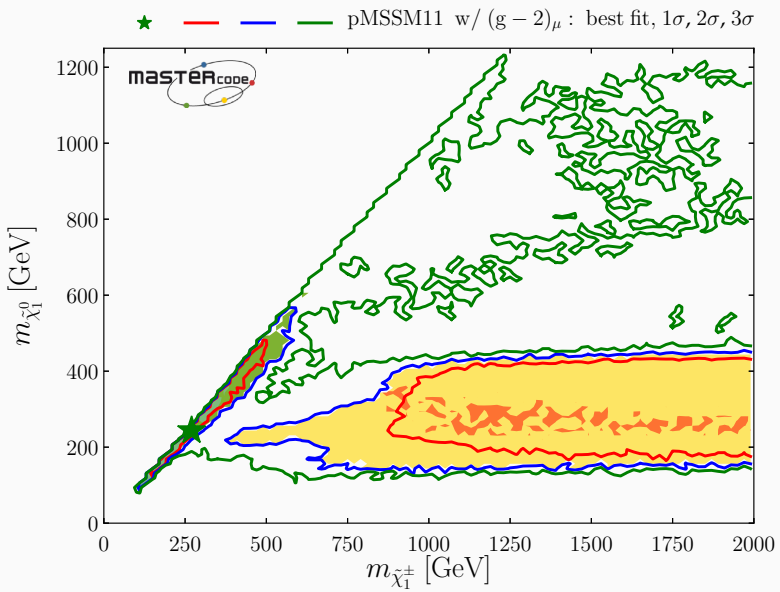


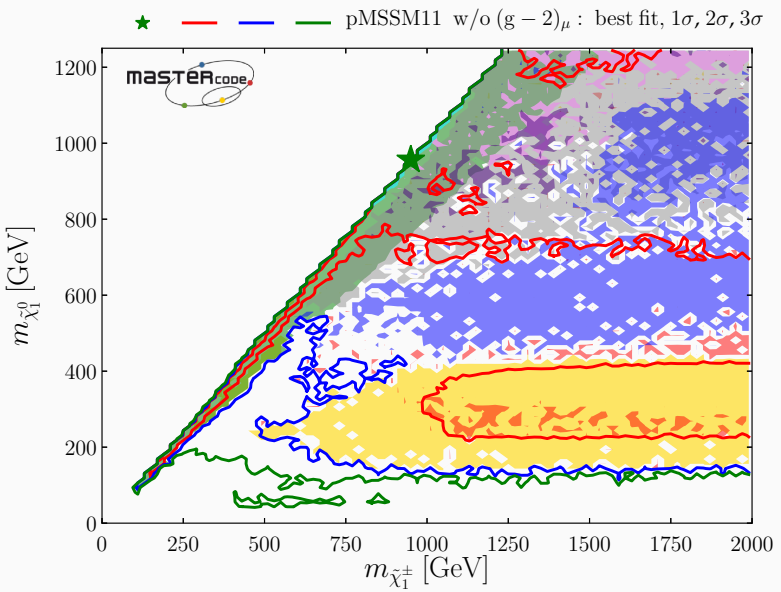




$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

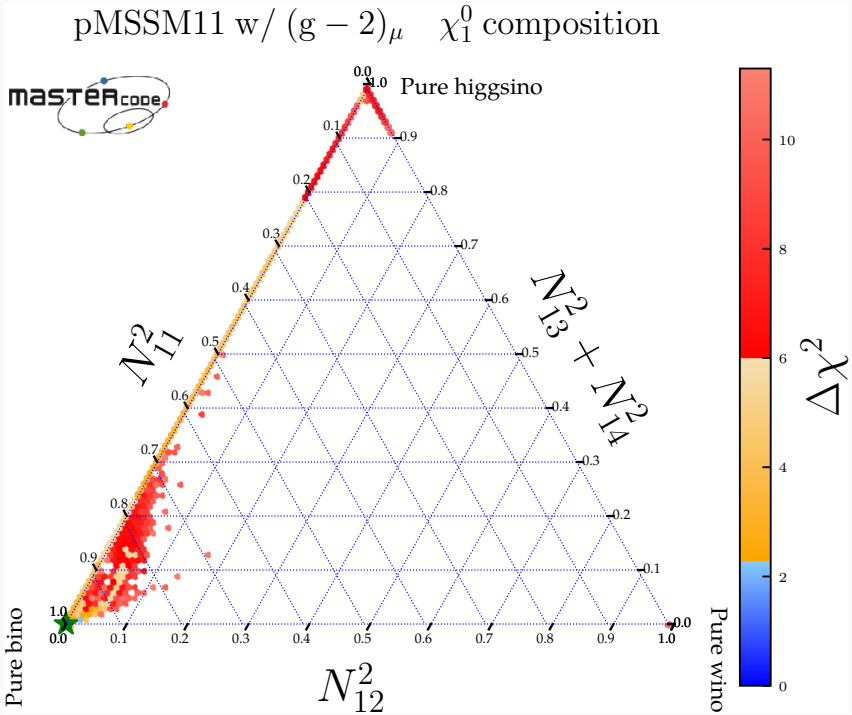
EWKino planes

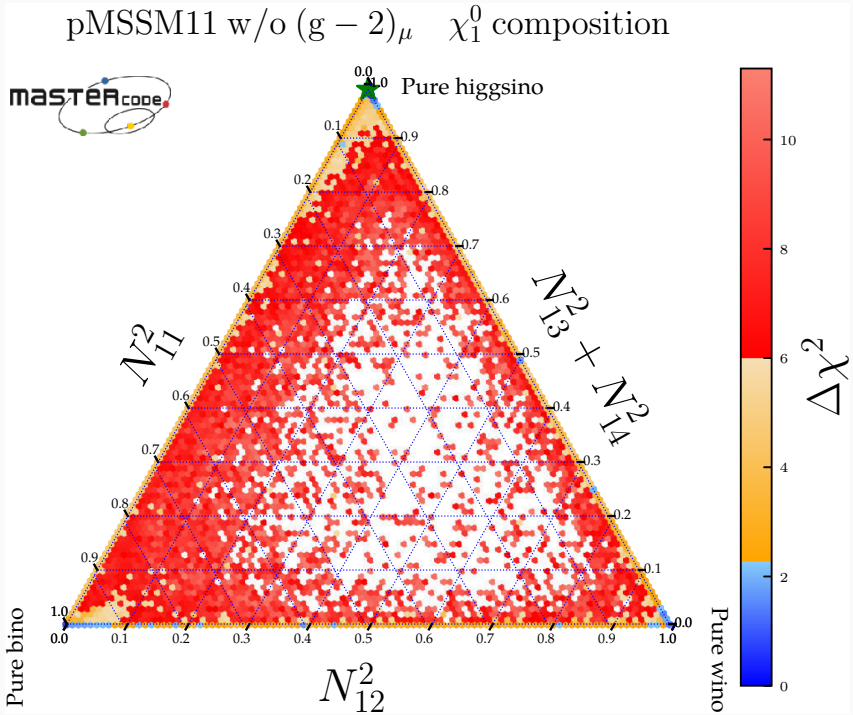




$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

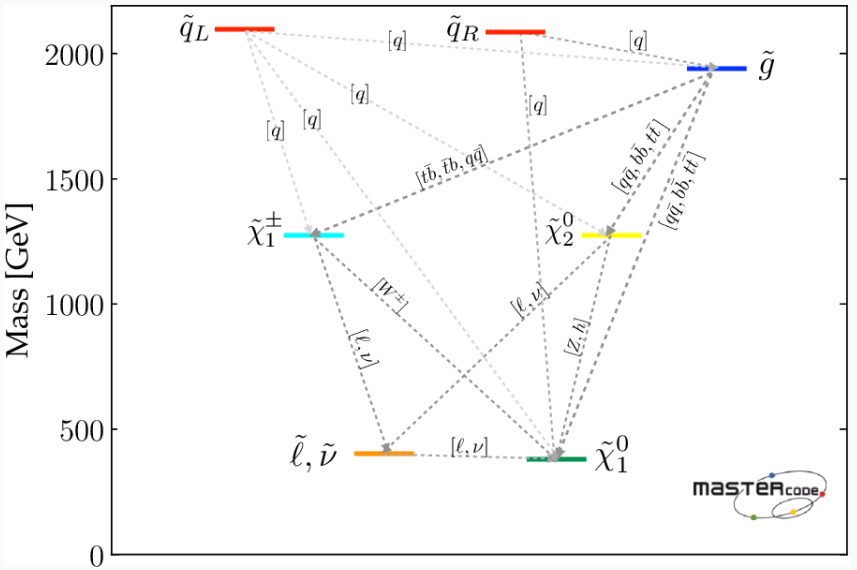
$\tilde{\chi}_1^0$ composition

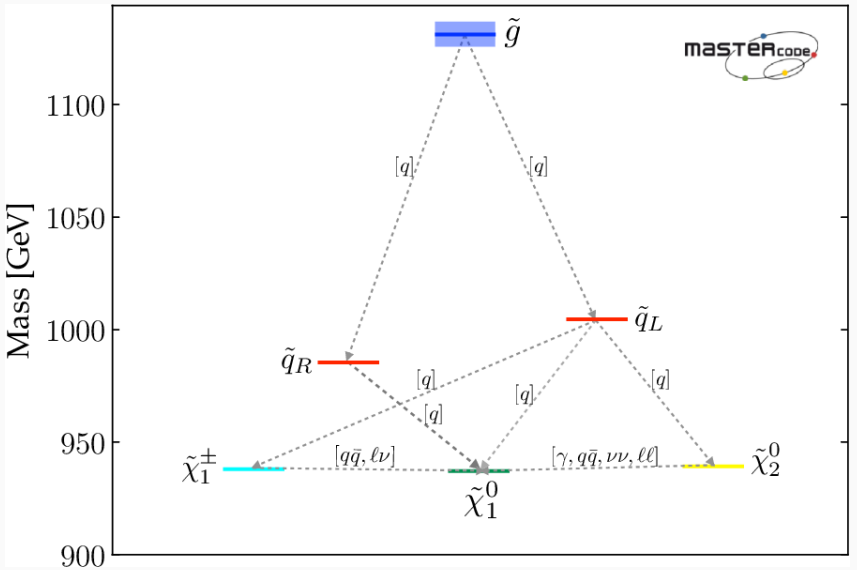




- Bi-component/pure neutralinos always preferred.
- $(g-2)_\mu$ implies preference for Bino, Bino-Higgsino.

Nose regions

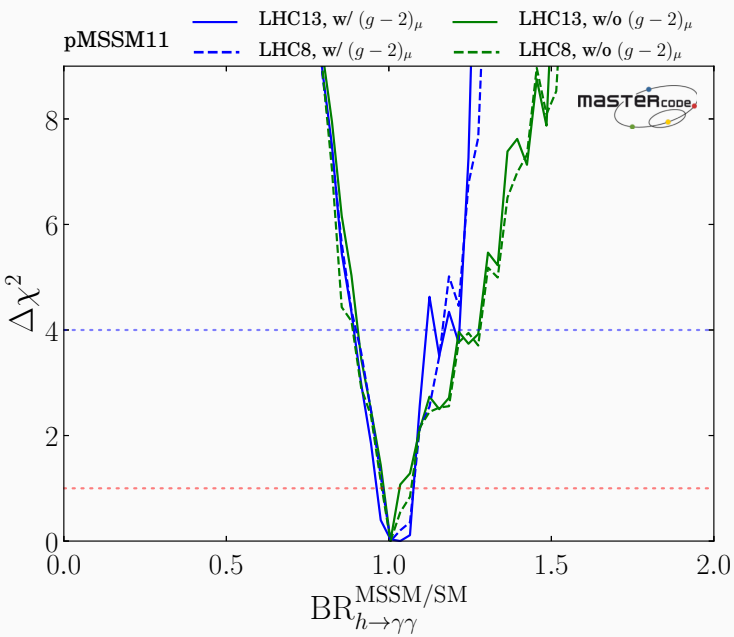


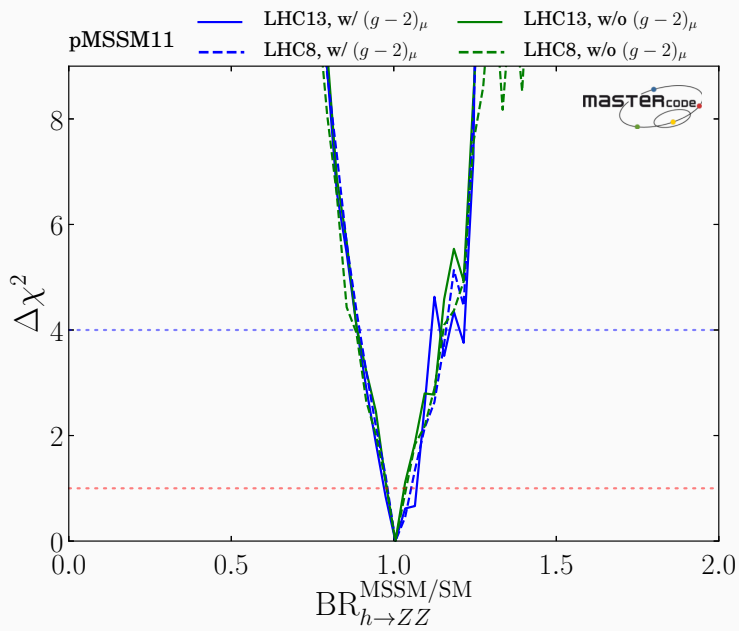


- Loss of search sensitivity when $\tilde{q}_R \to \tilde{g} + q$, the q jet is soft, and $\tilde{g} \to q\bar{q} + \tilde{\chi}^*$ compared to a high sensitivity for $\tilde{q}_R \to q\tilde{\chi}_1^0$ in the $m_{\tilde{g}} > m_{\tilde{q}}$ case.

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

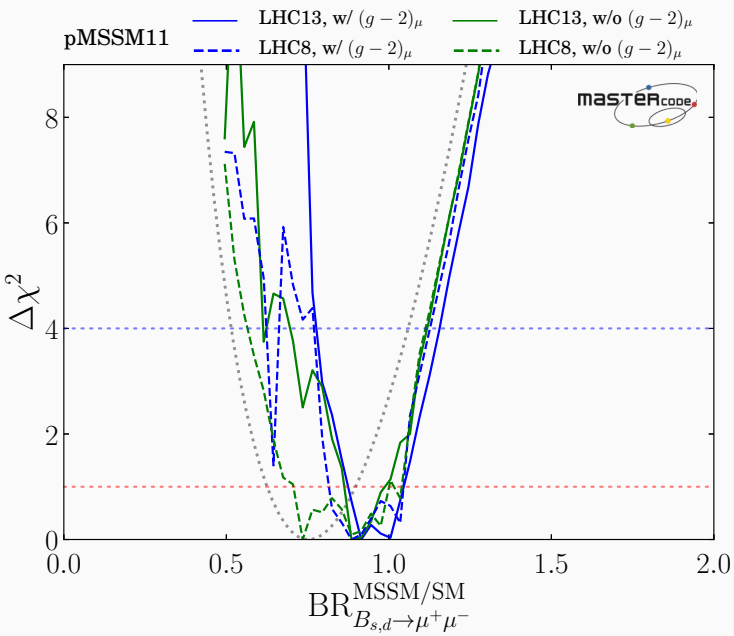
Higgs decays

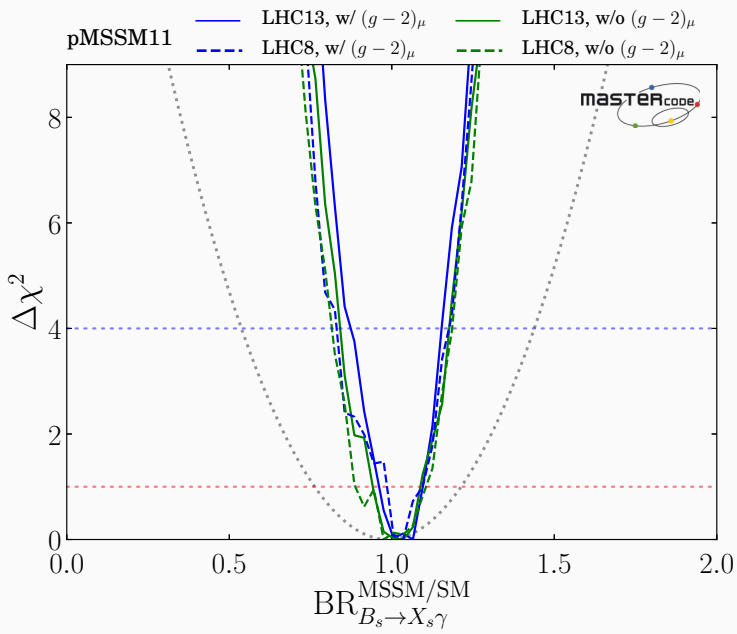




- At 68%CL no significant deviation from the SM, as expected.

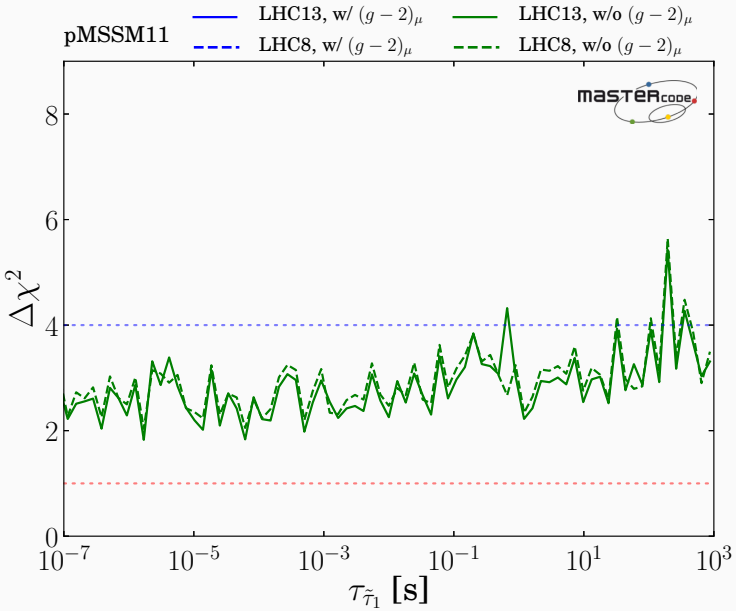
Flavor constraints

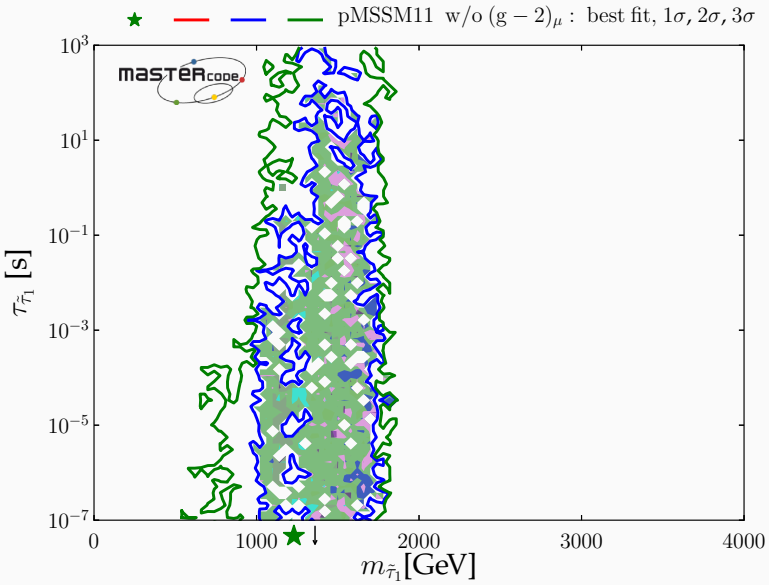


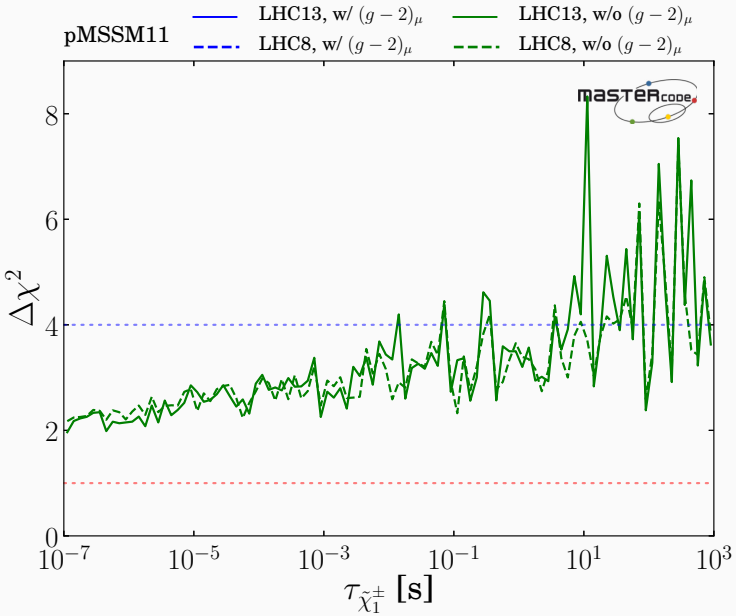


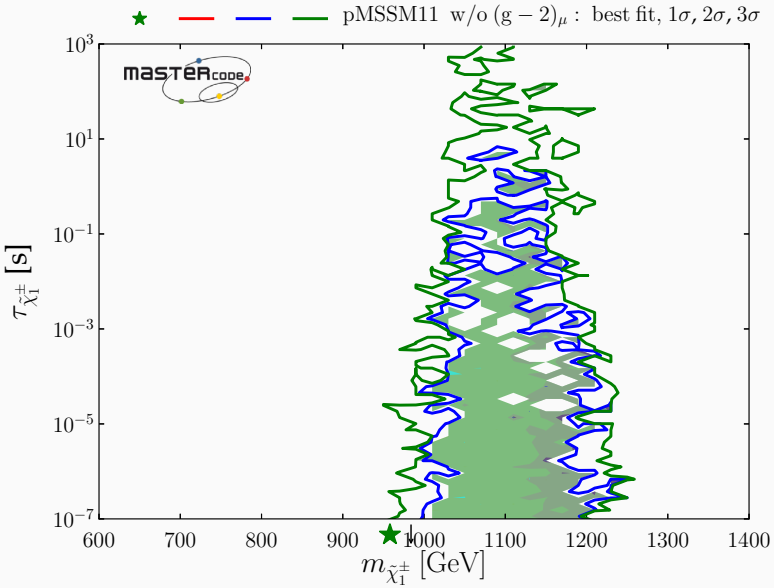
- Removing the $(g-2)_\mu$ allows for an improved fit of $B_{s,d} \to \mu^+\mu^-$.

Long lived staus and charginos









Constraint list (1)

Observable	Source Th./Ex.	Constraint
M_W [GeV]	[1]/[2, 3]	$80.379 \pm 0.012 \pm 0.010_{\rm MSSM}$
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[4]/[5]	$(30.2 \pm 8.8 \pm 2.0_{\rm MSSM}) \times 10^{-10}$
m_t [GeV]	[6]	173.34 ± 0.76
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[7]	0.02771 ± 0.00011
M_Z [GeV]	[2, 3]	91.1875 ± 0.0021
Γ_Z [GeV]	[1]/[2, 3]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
$\sigma^0_{\rm had}$ [nb]	[1]/[2, 3]	41.540 ± 0.037
R_l	[1]/[2, 3]	20.767 ± 0.025
$A_{\rm FB}(\ell)$	[1]/[2, 3]	0.01714 ± 0.00095
$A_\ell(P_\tau)$	[1]/[2, 3]	0.1465 ± 0.0032
$R_{\rm b}$	[1]/[2, 3]	0.21629 ± 0.00066
$R_{\rm c}$	[1]/[2, 3]	0.1721 ± 0.0030
$A_{\rm FB}(b)$	[1] /[2, 3]	0.0992 ± 0.0016
$A_{\rm FB}(c)$	[1]/[2, 3]	0.0707 ± 0.0035
A_b	[1] /[2, 3]	0.923 ± 0.020
A_c	[1]/[2, 3]	0.670 ± 0.027
$A^e_{\rm LR}$	[1]/[2, 3]	0.1513 ± 0.0021
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[1]/[2, 3]	0.2324 ± 0.0012

Constraint list (2)

Observable	Source Th./Ex.	Constraint
$R_{\mu\mu}$	[8, 9, 10]	2D likelihood, MFV
$\tau(B_s \to \mu^+\mu^-)$	[10]	$2.04 \pm 0.44(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$ ps
$\mathrm{BR}^{\mathrm{EXP}/\mathrm{SM}}_{b\to s\gamma}$	[11]/[12]	$0.988 \pm 0.045_{\mathrm{EXP}} \pm 0.068_{\mathrm{TH,SM}} \pm 0.050_{\mathrm{TH,SUSY}}$
$\mathrm{BR}^{\mathrm{EXP}/\mathrm{SM}}_{B\to\tau\nu}$	[12, 13]	$0.883 \pm 0.158_{\mathrm{EXP}} \pm 0.096_{\mathrm{SM}}$
$BR^{\mathrm{EXP}/\mathrm{SM}}_{B\to X_s\ell\ell}$	[14]/[12]	$0.966 \pm 0.278_{\mathrm{EXP}} \pm 0.037_{\mathrm{SM}}$
$\Delta M^{\mathrm{EXP}/\mathrm{SM}}_{B_s}$	[15, 16] /[12]	$0.968 \pm 0.001_{\mathrm{EXP}} \pm 0.078_{\mathrm{SM}}$
$\frac{\Delta M^{\mathrm{EXP}/\mathrm{SM}}_{B_s}}{\Delta M^{\mathrm{EXP}/\mathrm{SM}}_{B_d}}$	[15, 16] /[12]	$1.007 \pm 0.004_{\mathrm{EXP}} \pm 0.116_{\mathrm{SM}}$
$BR^{\mathrm{EXP}/\mathrm{SM}}_{K\to\mu\nu}$	[16, 17] /[18]	$1.0005 \pm 0.0017_{\mathrm{EXP}} \pm 0.0093_{\mathrm{TH}}$
$BR^{\mathrm{EXP}/\mathrm{SM}}_{K\to\pi\nu\bar{\nu}}$	[19]/[20]	$2.01 \pm 1.30_{\mathrm{EXP}} \pm 0.18_{\mathrm{SM}}$
$\Delta\epsilon^{\mathrm{EXP}/\mathrm{SM}}_{K}$	[15, 16] /[7]	$1.14 \pm 0.10_{\mathrm{EXP+TH}}$

Constraint list (3)

Observable	Source Th./Ex.	Constraint
$\Omega_{CDM}h^2$	[21, 22]/[23]	$0.1186 \pm 0.0020_{\mathrm{EXP}} \pm 0.0024_{\mathrm{TH}}$
σ_p^{SI}	[24, 25, 26]	Combined likelihood in the $(m_{\tilde{\chi}_1^0}, \sigma_p^{\mathrm{SI}})$ plane
σ_p^{SD}	[27]	Likelihood in the $(m_{\tilde{\chi}_1^0}, \sigma_p^{\mathrm{SD}})$ plane
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0, b\bar{b}\tilde{\chi}_1^0, t\bar{t}\tilde{\chi}_1^0$	[28, 29]	Combined likelihood in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ plane
$\tilde{q} \to q\tilde{\chi}_1^0$	[28]	Likelihood in the $(m_{\tilde{q}}, m_{\tilde{\chi}_1^0})$ plane
$\tilde{b} \to b\tilde{\chi}_1^0$	[28]	Likelihood in the $(m_{\tilde{b}}, m_{\tilde{\chi}_1^0})$, plane
$\tilde{t}_1 \to t\tilde{\chi}_1^0, c\tilde{\chi}_1^0, b\tilde{\chi}_1^{\pm}$	[28]	Likelihood in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$, plane
$\tilde{\chi}_1^{\pm} \to \nu\ell^{\pm}\tilde{\chi}_1^0, \nu\tau^{\pm}\tilde{\chi}_1^0, W^{\pm}\tilde{\chi}_1^0$	[30]	Likelihood in the $(m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_1^0})$ plane
$\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0, \tau^+\tau^-\tilde{\chi}_1^0, Z\tilde{\chi}_1^0$	[30]	Likelihood in the $(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0})$ plane
Heavy stable charged particles	[31]	Fast simulation based on [31, 32]
$H/A \to \tau^+\tau^-$	[33, 34, 35, 36]	Likelihood in the $(M_A, \tan\beta)$ plane
h_{125}	[37]	Likelihood from `HiggsSignals`
M_h [GeV]	[38, 39] / [40]	$125.09 \pm 0.24 \pm 1.5_{\mathrm{SUSY}}$

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