Global fits with MasterCode

pMSSM11 & Sub-GUT MSSM in light of 13 TeV LHC data

Likelihood Analysis of the pMSSM11 in Light of LHC 13-TeV Data

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Likelihood Analysis of the Sub-GUT MSSM in Light of LHC 13-TeV Data

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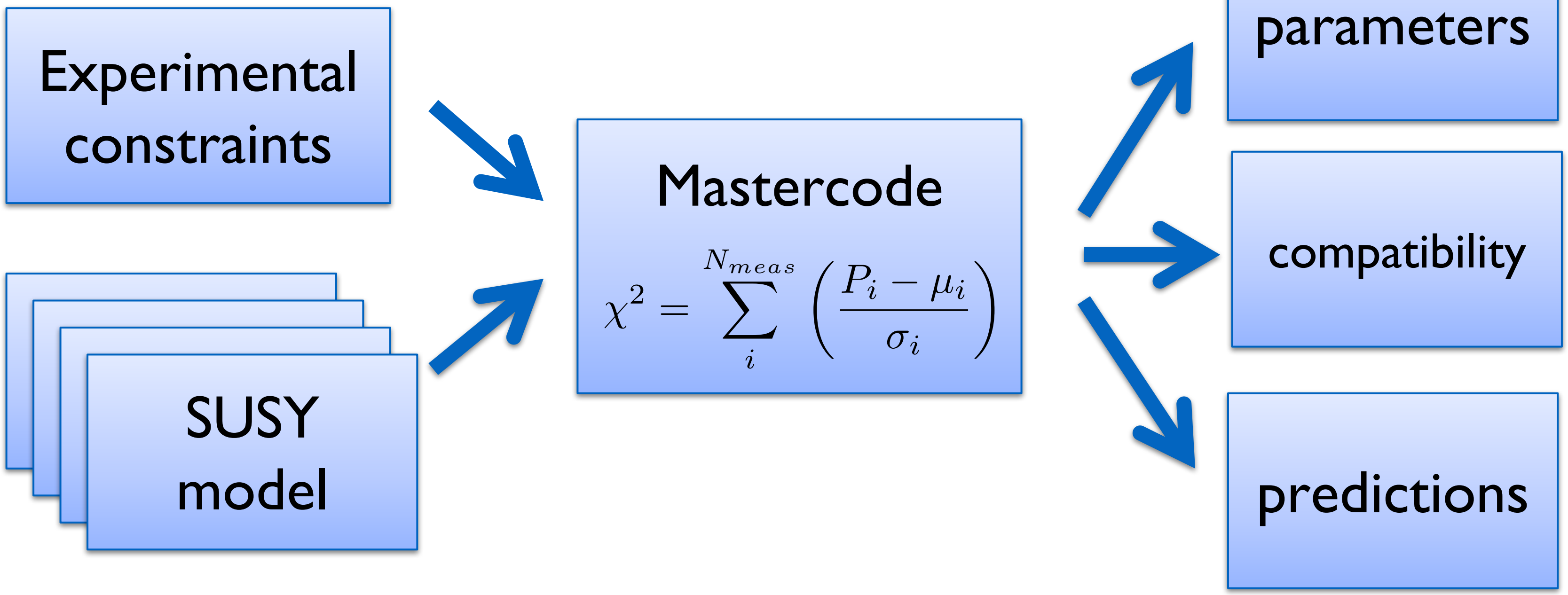
On behalf of the MasterCode collaboration

Overview

- As we know the Standard Model has several shortcomings, several of which are addressed by Supersymmetry
  - hierarchy problem, gauge unification and dark matter
- Whatever extension to SM we propose, we need to make sure this model is in agreement with existing measurements
  - and hopefully can describe some of the tantalizing deviations we see in selected measurements (think g-2)

- Aim to confront theory models with as many experimental measurements as possible
- Use state of the art calculations of physical observables
- Explore/Scan parameter space of models with multinest algorithm
  - $O(10^8\text{-}10^9)$ points per model
- Carry our frequentist interpretation by calculating an overall χ^2 and relative $\Delta\chi^2$
- Fit model parameters in different MSSM scenarios
  - Explore sensitivity of different observables to parameter space
  - Make predictions for observables

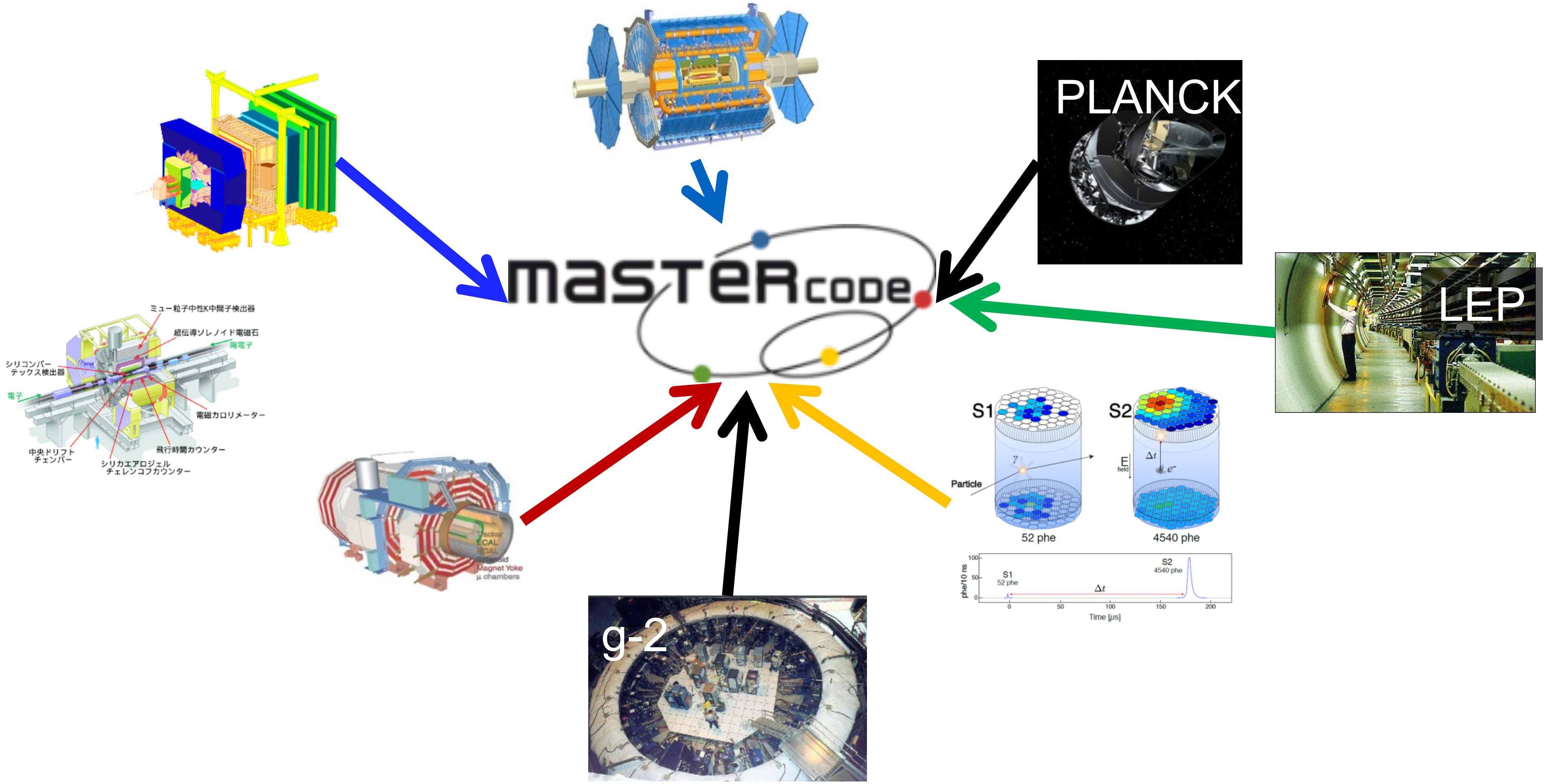
Global fit of SUSY



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`

Experimental Constraints

Global analyses of experimental data in constrained versions of the Minimal Supersymmetric Standard Model (MSSM)



Experimental Constraints

	Observable	Source Th./Ex.	Constraint
LHC	$\rightarrow$ $\mathbf{m_t}$ [GeV]	[39]	$\mathbf{173.34 \pm 0.76}$
LEP/SLD EWPO	$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	[40]	0.02771 ± 0.00011
	M_Z [GeV]	[41,42]	91.1875 ± 0.0021
	Γ_Z [GeV]	[43] / [41,42]	$2.4952 \pm 0.0023 \pm 0.001_{\rm SUSY}$
	$\sigma^0_{\rm had}$ [nb]	[43] / [41,42]	41.540 ± 0.037
	R_l	[43] / [41,42]	20.767 ± 0.025
	$A_{\rm FB}(\ell)$	[43] / [41,42]	0.01714 ± 0.00095
	$A_\ell(P_\tau)$	[43] / [41,42]	0.1465 ± 0.0032
	R_b	[43] / [41,42]	0.21629 ± 0.00066
	R_c	[43] / [41,42]	0.1721 ± 0.0030
	$A_{\rm FB}(b)$	[43] / [41,42]	0.0992 ± 0.0016
	$A_{\rm FB}(c)$	[43] / [41,42]	0.0707 ± 0.0035
	A_b	[43] / [41,42]	0.923 ± 0.020
	A_c	[43] / [41,42]	0.670 ± 0.027
	$A^e_{\rm LR}$	[43] / [41,42]	0.1513 ± 0.0021
	$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$	[43] / [41,42]	0.2324 ± 0.0012
LHC	M_W [GeV]	[43] / [41,42]	$80.385 \pm 0.015 \pm 0.010_{\rm SUSY}$
BNL	$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$	[44] / [45]	$(30.2 \pm 8.8 \pm 2.0_{\rm SUSY}) \times 10^{-10}$
LHC	$\rightarrow$ $\mathbf{M_h}$ [GeV]	[46,47] / [48]	$\mathbf{125.09 \pm 0.24 \pm 1.5_{\rm SUSY}}$
	$\rightarrow$ $\mathbf{\Delta\epsilon_K^{\rm EXP/SM}}$	[54,58] / [40]	$\mathbf{1.14 \pm 0.10_{\rm EXP+TH}}$
Planck	$\rightarrow$ $\mathbf{\Omega_{\rm CDM}h^2}$	[59,60]/ [28]	$\mathbf{0.1186 \pm 0.0020_{\rm EXP} \pm 0.0024_{\rm TH}}$

LHC	M_W [GeV]	[31] / [42,43]	$80.379 \pm 0.012 \pm 0.010_{\rm MSSM}$
LHCb & B-Factories rare B decays & mixing	$R_{\mu\mu}$	[46–48]	2D likelihood, MFV
	$\tau(B_s \to \mu^+\mu^-)$	[48]	2.04 ± 0.44(stat.) ± 0.05(syst.) ps
	${\rm BR}^{\rm EXP/SM}_{b\to s\gamma}$	[49]/ [50]	$0.988 \pm 0.045_{\rm EXP} \pm 0.068_{\rm TH,SM} \pm 0.050_{\rm TH,SUSY}$
	${\rm BR}^{\rm EXP/SM}_{B\to\tau\nu}$	[50,51]	$0.883 \pm 0.158_{\rm EXP} \pm 0.096_{\rm SM}$
	$BR^{\rm EXP/SM}_{B\to X_s\ell\ell}$	[52]/ [50]	$0.966 \pm 0.278_{\rm EXP} \pm 0.037_{\rm SM}$
	$\Delta M^{\rm EXP/SM}_{B_s}$	[34,53] / [50]	$0.968 \pm 0.001_{\rm EXP} \pm 0.078_{\rm SM}$
	$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$	[34,53] / [50]	$1.007 \pm 0.004_{\rm EXP} \pm 0.116_{\rm SM}$
	$BR^{\rm EXP/SM}_{K\to\mu\nu}$	[34,54] / [55]	$1.0005 \pm 0.0017_{\rm EXP} \pm 0.0093_{\rm TH}$
	$BR^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$	[56]/ [57]	$2.01 \pm 1.30_{\rm EXP} \pm 0.18_{\rm SM}$
Direct Detection	$\sigma_p^{\rm SI}$	[3,4,6]	Combined likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SI})$ plane
	$\sigma_p^{\rm SD}$	[5]	Likelihood in the $(m_{\tilde\chi^0_1}, \sigma_p^{\rm SD})$ plane
LHC 13TeV searches gluinos, squarks, charginos	$\tilde g \to q\bar q\tilde\chi^0_1, b\bar b\tilde\chi^0_1, t\bar t\tilde\chi^0_1$	[11,12]	Combined likelihood in the $(m_{\tilde g}, m_{\tilde\chi^0_1})$ plane
	$\tilde q \to q\tilde\chi^0_1$	[11]	Likelihood in the $(m_{\tilde q}, m_{\tilde\chi^0_1})$ plane
	$\tilde b \to b\tilde\chi^0_1$	[11]	Likelihood in the $(m_{\tilde b}, m_{\tilde\chi^0_1})$, plane
	$\tilde t_1 \to t\tilde\chi^0_1, c\tilde\chi^0_1, b\tilde\chi^\pm_1$	[11]	Likelihood in the $(m_{\tilde t_1}, m_{\tilde\chi^0_1})$, plane
	$\tilde\chi^\pm_1 \to \nu\ell^\pm\tilde\chi^0_1, \nu\tau^\pm\tilde\chi^0_1, W^\pm\tilde\chi^0_1$	[13]	Likelihood in the $(m_{\tilde\chi^\pm_1}, m_{\tilde\chi^0_1})$ plane
	$\tilde\chi^0_2 \to \ell^+\ell^-\tilde\chi^0_1, \tau^+\tau^-\tilde\chi^0_1, Z\tilde\chi^0_1$	[13]	Likelihood in the $(m_{\tilde\chi^0_2}, m_{\tilde\chi^0_1})$ plane
	Heavy stable charged particles	[58]	Fast simulation based on [58,59]
	$H/A \to \tau^+\tau^-$	[60–63]	Likelihood in the $(M_A, \tan\beta)$ plane

- + constraints from HiggsSignals for h125 properties and
- HiggsBounds for heavy MSSM Higgs boson searches

Models investigated

- The general MSSM has > 100 free parameters (masses, mixing angles, etc.)
  - Impossible to all leave free and constrain parameter space, need to make a choice

- pMSSM11 2×10^9 scan points

$$
\begin{aligned}
\text{3 gaugino masses}: &\ M_{1,2,3}\,, \\
\text{2 squark masses}: &\ m_{\tilde{q}} \equiv m_{\tilde{q}_1}, m_{\tilde{q}_2} \\
&\neq m_{\tilde{q}_3} = m_{\tilde{t}}, m_{\tilde{b}}, \\
\text{2 slepton masses}: &\ m_{\tilde{\ell}} \equiv m_{\tilde{\ell}_1} = m_{\tilde{\ell}_2} = m_{\tilde{e}}, m_{\tilde{\mu}} \\
&\neq m_{\ell_3} = m_{\tilde{\tau}}, \\
\text{1 trilinear coupling}: &\ A\,, \\
\text{Higgs mixing parameter}: &\ \mu\,, \\
\text{pseudoscalar Higgs mass}: &\ M_A\,, \\
\text{ratio of vevs}: &\ \tan\beta\,,
\end{aligned}
$$

arXiv:1710:11091

- Sub-GUT MSSM 112×10^6 scan points
  - Universality of SUSY breaking parameters not at GUT scale but some lower scale M_{in}
  - Study Sub-GUT generalization of CMSSM
  - Free parameters:
    - M_{in}
    - Common scalar mass: m_0
    - Common gaugino mass: $m_{1/2}$
    - Common trilinear mixing parameter: A
    - Ratio of MSSM Higgs vev's: tan β
    - assume Higgs mixing parameter μ > 0 (motivated by g-2)

arXiv:1711:00458

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Constraints on M_{in} - SubGUT

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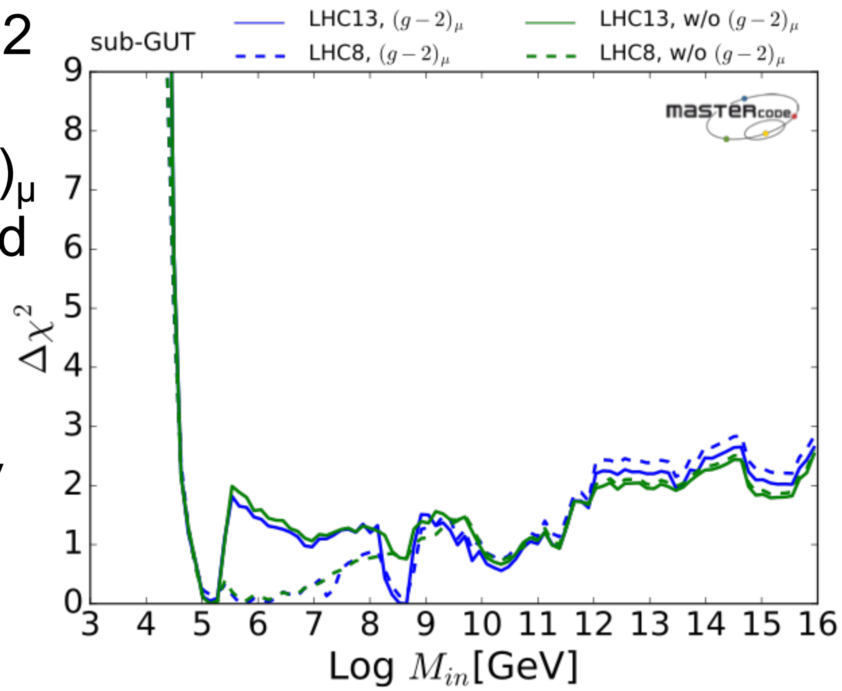
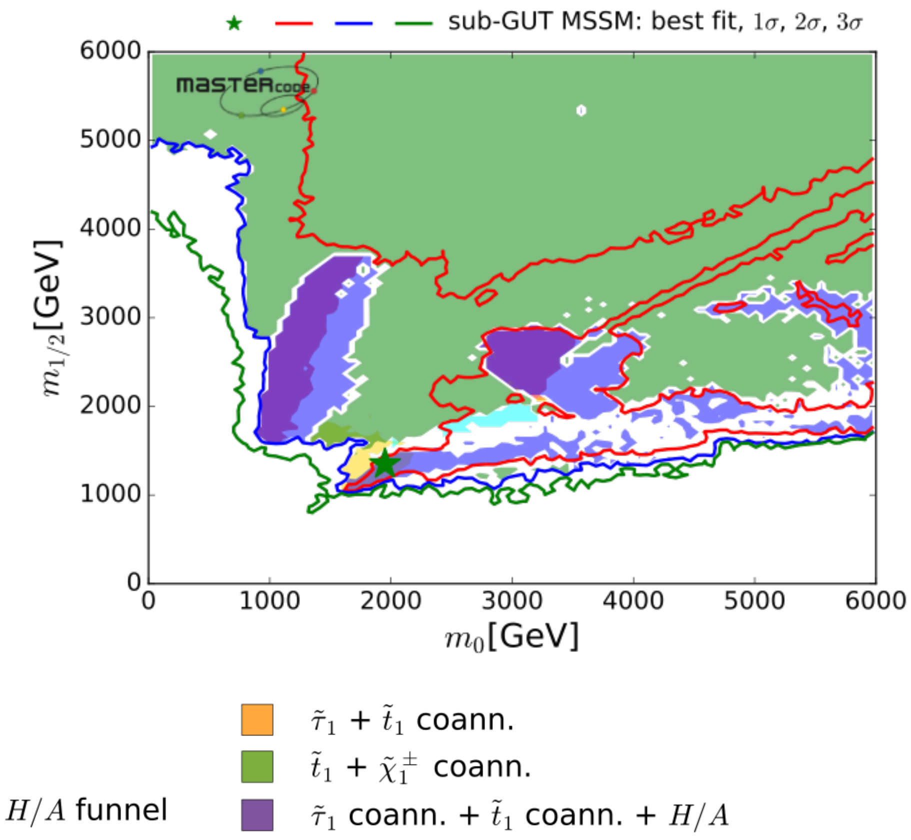
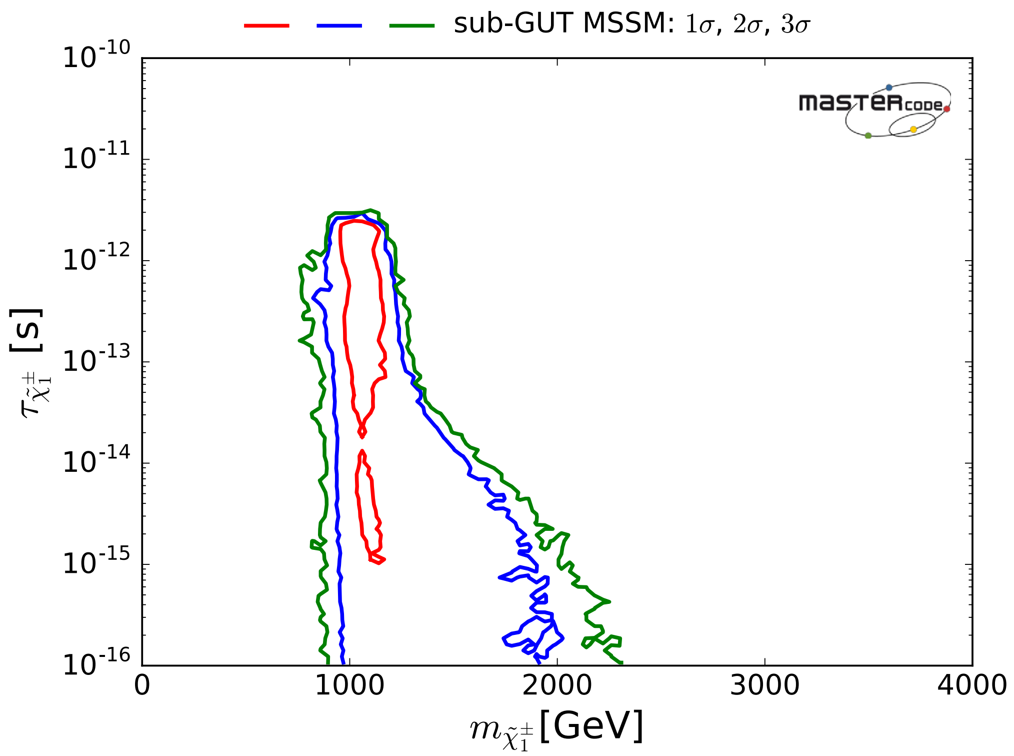
- Preference for $M_{in} \simeq 4.2 \times 10^8$ GeV when LHC 13-TeV data and $(g-2)_\mu$ are both included (solid blue line)
- falling to $M_{in} \simeq 5.9\times10^5$ GeV when the 13-TeV data are dropped (dashed blue line).
- Little difference between the global χ^2 values at these two minima, but values of M_{in} < 105 GeV are strongly disfavoured.

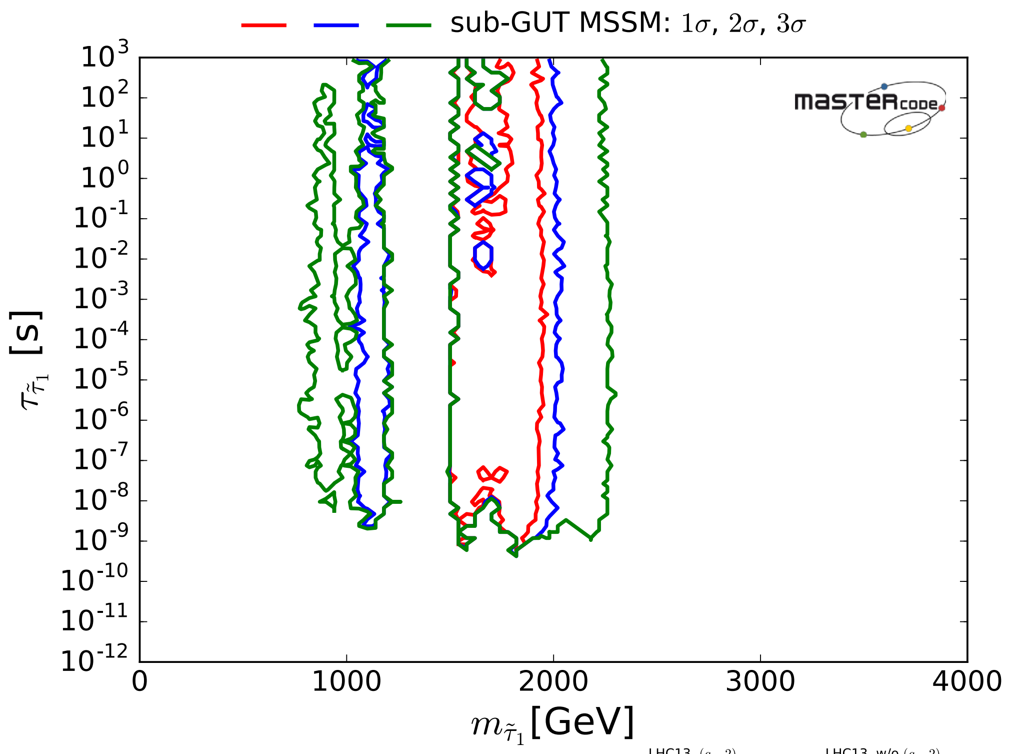




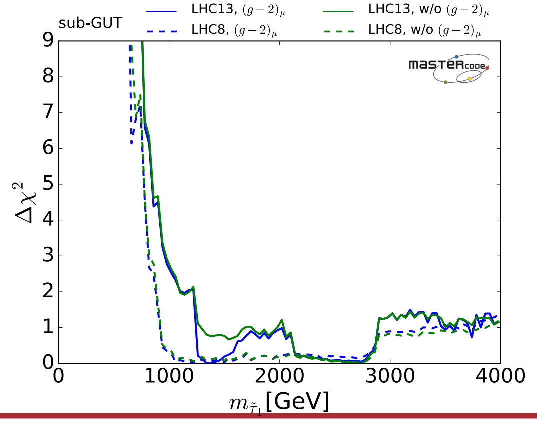
- Chargino coannihilation is important for large $m_{1/2}$
- rapid annihilation via the H/A bosons becomes important for lower m1/2, often hybridized with other mechanisms including stop and stau coannihilation.
- Smaller regions with $m_{1/2}$ ~ 1.5 to 3 TeV where stop coannihilation and focus-point mechanisms are dominant.

Chargino and stau lifetimes – Sub-GUT



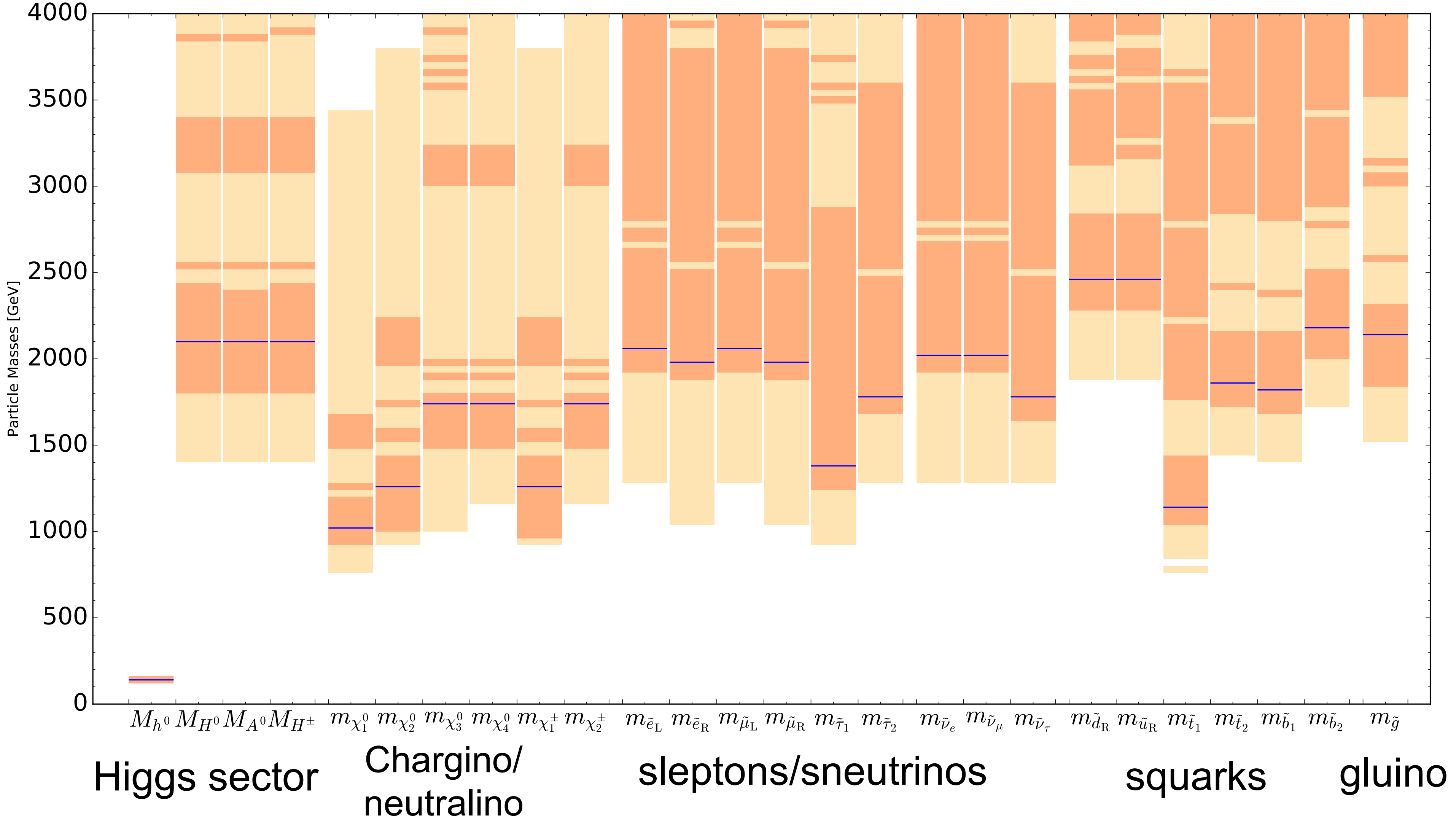


- Preference for quite heavy chargino and stau
  - impact of LHC searches
- Lifetimes of up to femto seconds for chargino
- Lifetimes of 10's of seconds allowed for stau



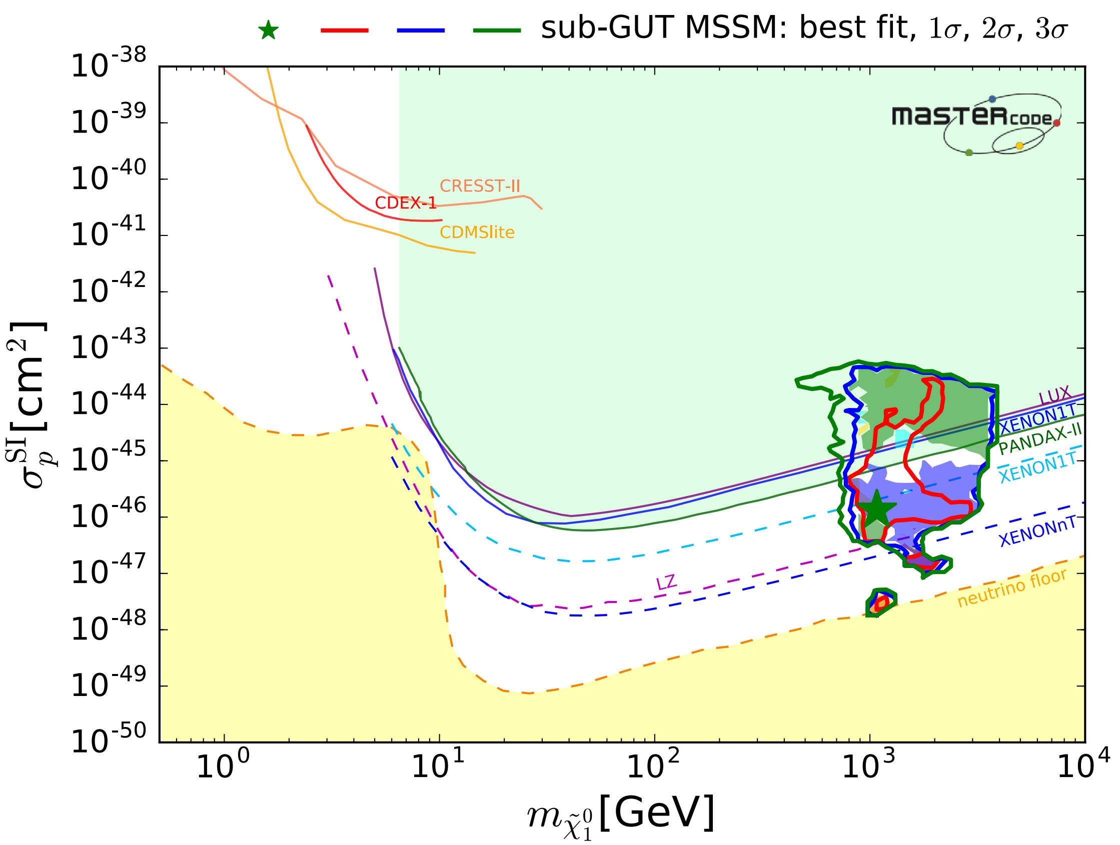
Mass Spectra

- Sub-GUTmodel:
- Very heavy sparticle spectrum
- Neutralinos/ charginos 1-1.5 TeV
- Higgs sector at 2 TeV
- Sleptons and squarks at 1.5-2 TeV

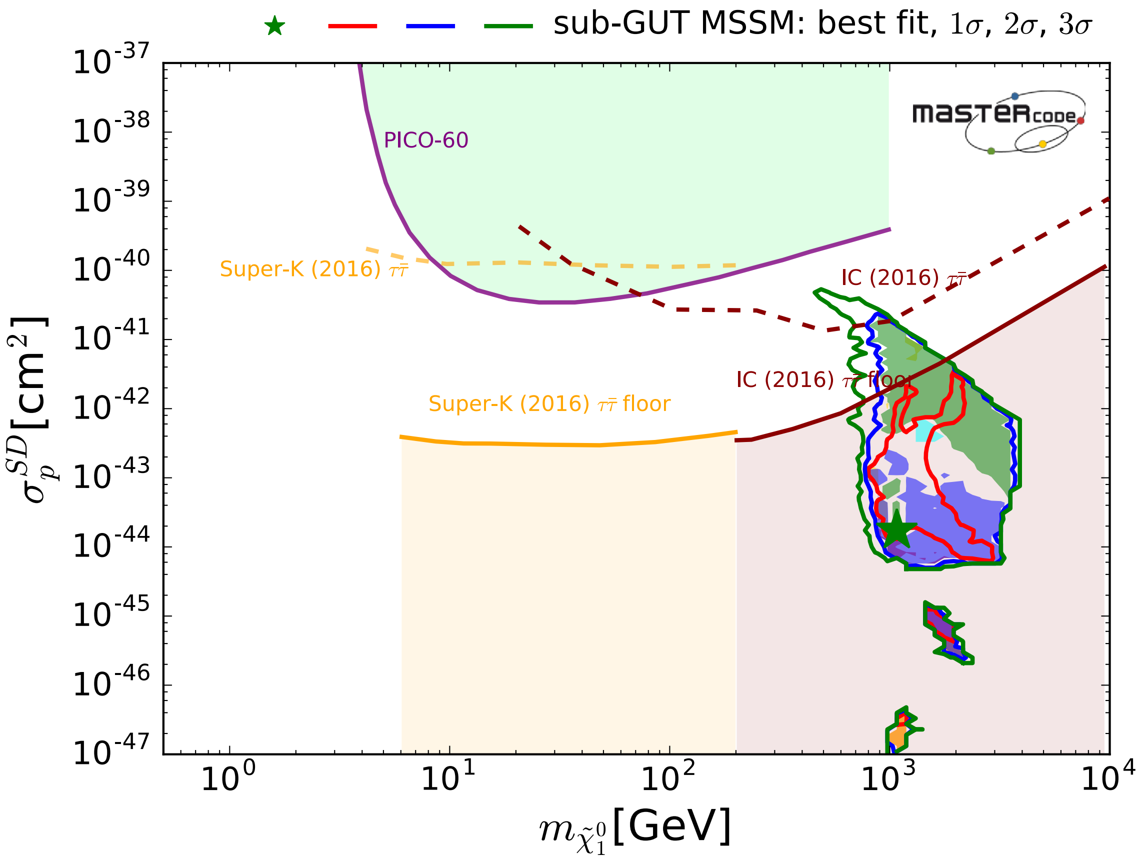


DM constraints – Sub-GUT

Spin-independent



Spin-dependent

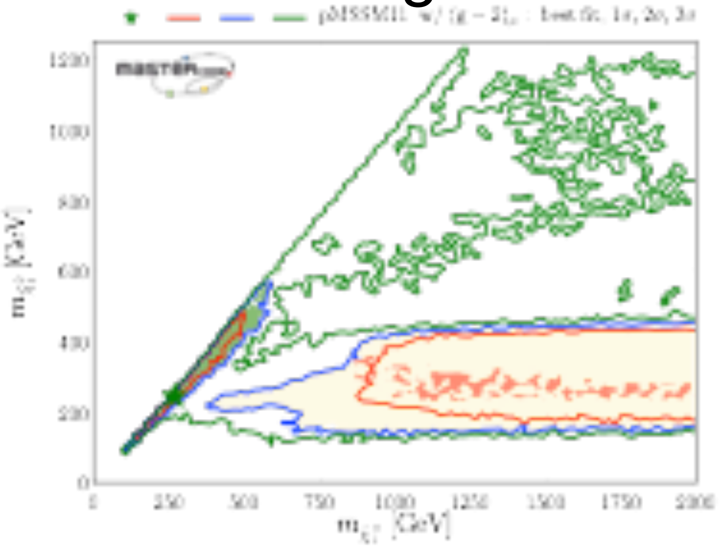


- $\tilde{\chi}_1^\pm$ coann.
- A/H funnel
- $\tilde{t}_1$ coann.
- $\tilde{\tau}_1$ coann.
- focus point
- $\tilde{t}_1$ coann. + H/A funnel
- $\tilde{\tau}_1$ + $\tilde{t}_1$ coann.
- $\tilde{t}_1$ + $\tilde{\chi}_1^\pm$ coann.
- $\tilde{\tau}_1$ coann. + $\tilde{t}_1$ coann. + H/A

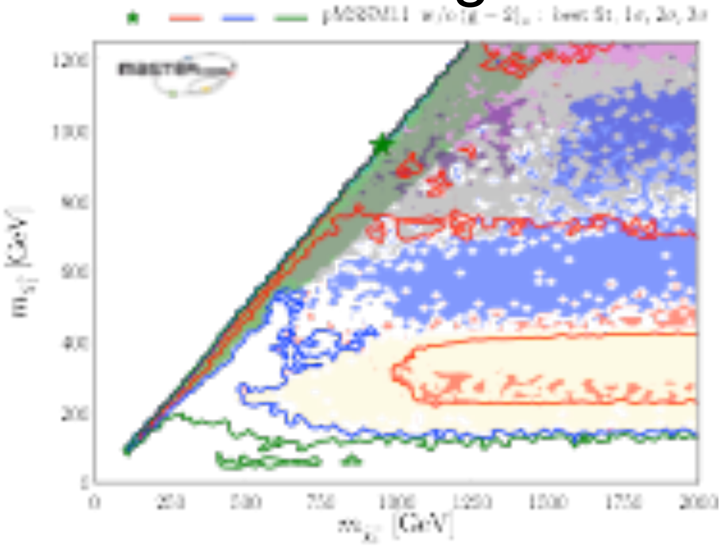
Impact of g-2 – pMSSM11

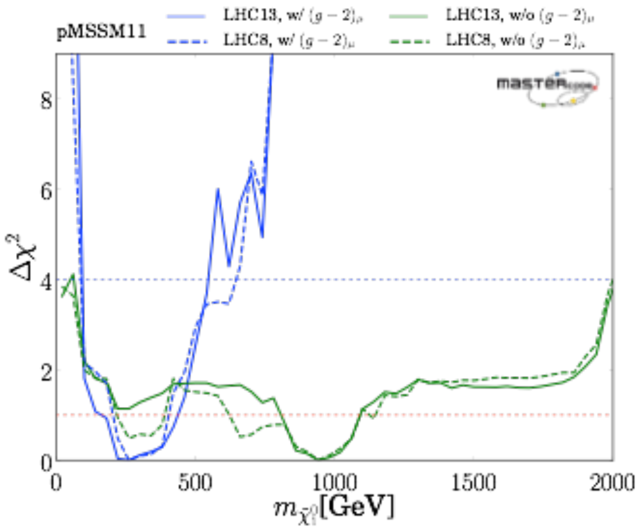
- pMSSM11
- Lightest chargino vs neutralino mass
- Likelihood fcnt for lightest neutralino and chargino mass

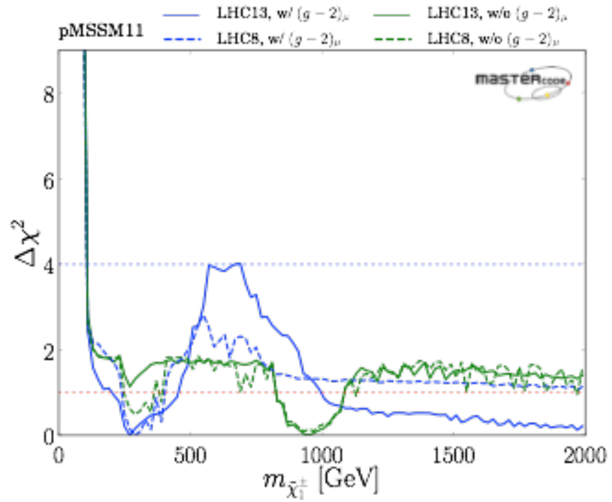
with g-2



without g-2

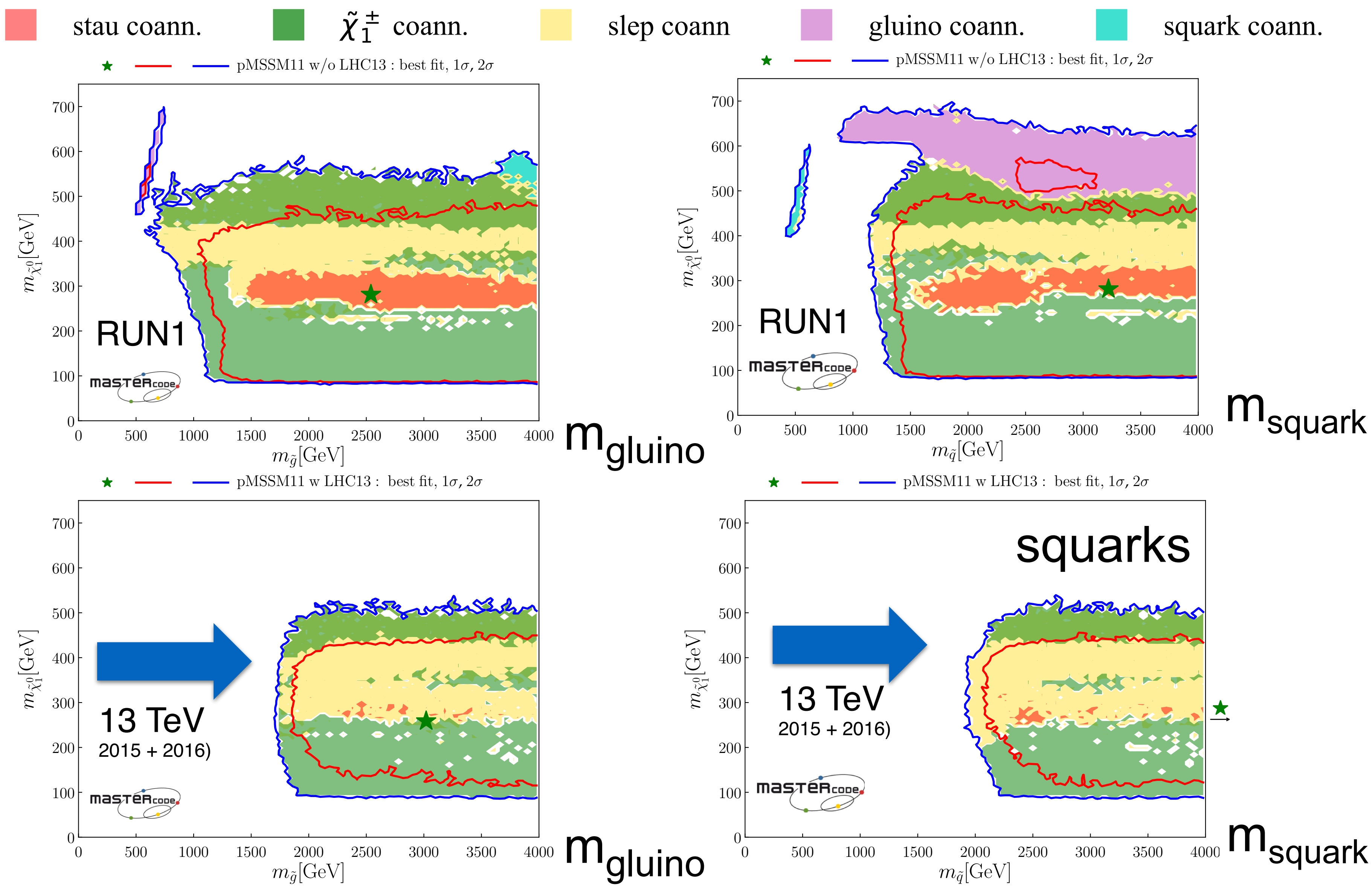






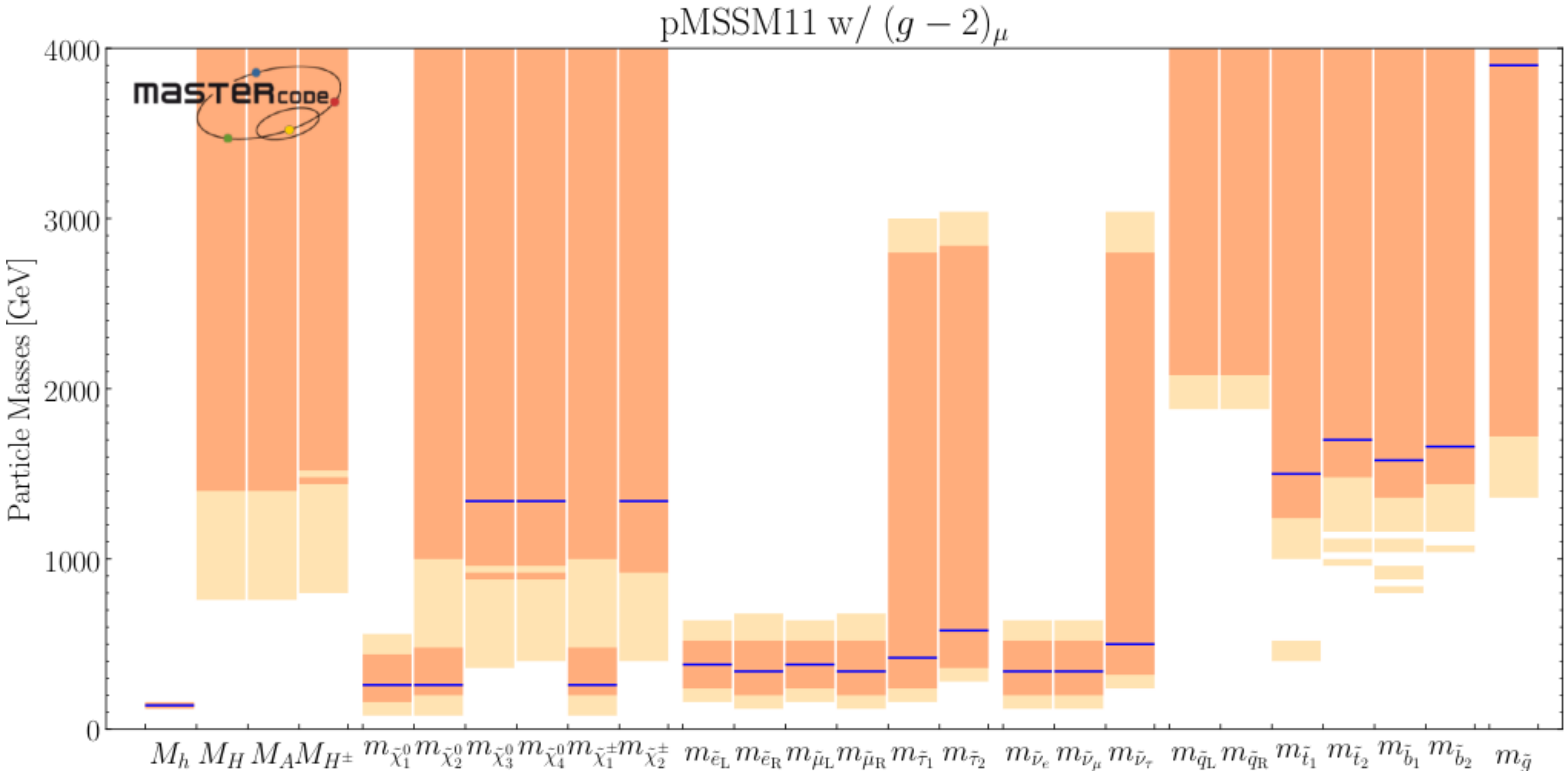
Impact of LHC@13 TeV – pMSSM11

- pMSSM11
- Gluino and squark mass vs neutralino mass



Mass Spectra – pMSSM11

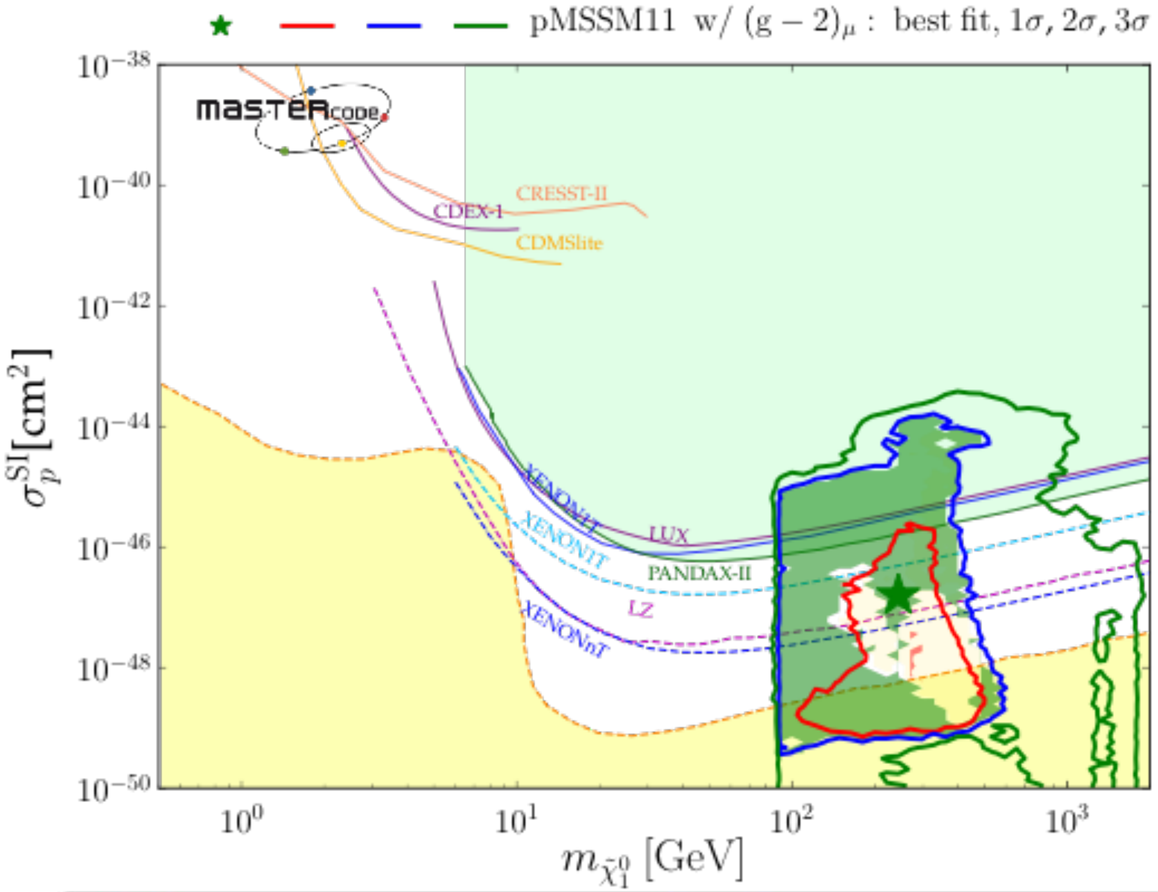
- pMSSM11
- Much lighter sparticle spectrum
- Relatively light sleptons and charginos
- Very heavy squarks and gluino with exception of 3rd generation



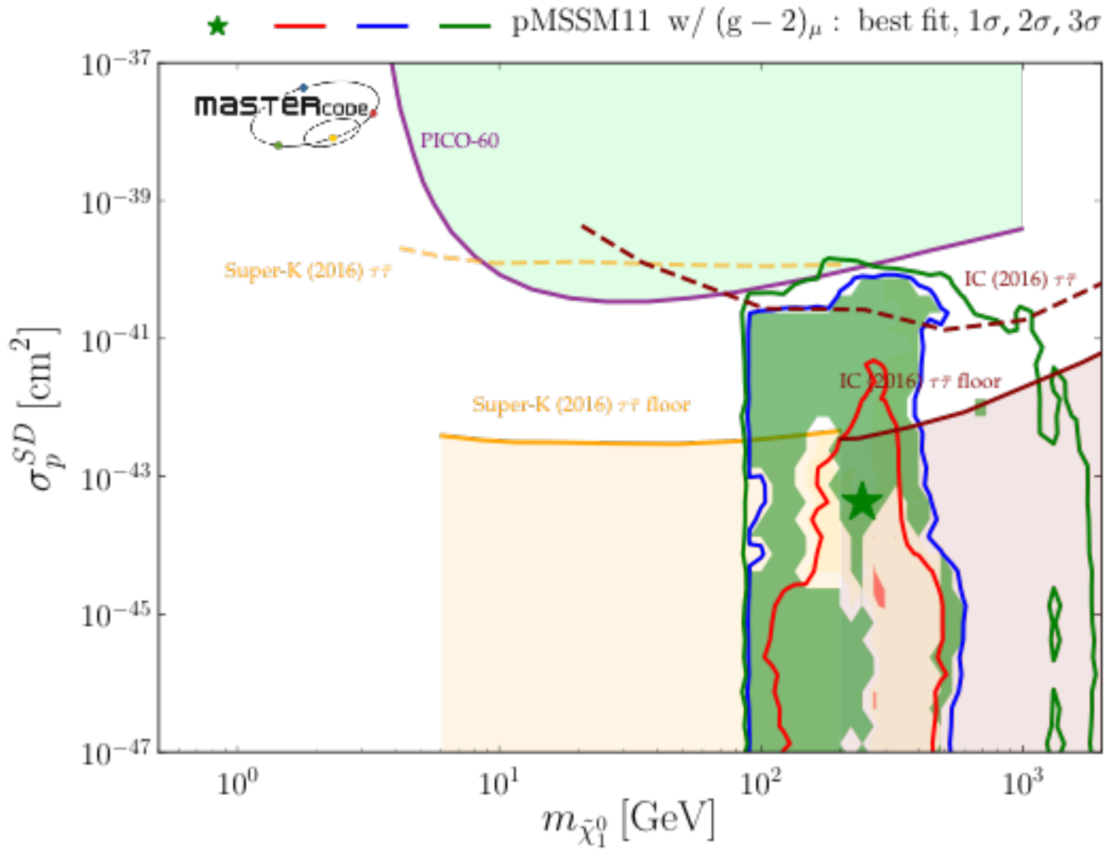
Higgs sector | Chargino/ neutralino | sleptons/sneutrinos | squarks | gluino

DM constraints - pMSSM11

Spin-independent



Spin-dependent



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Summary

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- Sub-GUT model

- Very heavy sparticle spectrum
  - Neutralinos/charginos 1-1.5 TeV
  - Higgs sector at 2 TeV
  - Sleptons and squarks at 1.5-2 TeV

- Compared to best fits with $M_{in} = M_{GUT}$, χ^2 reduced by $\Delta\chi^2 \sim 2$ in the sub-GUT model

- sub-GUT model is able to provide a better fit to the measured value of $BR(B_{s,d} \to \mu^+\mu^-)$ than in the CMSSM

- pMSSM11 scan
  - freedom for $m_{\tilde{\ell}} \neq m_{\tilde{\tau}}$ plays important role for allowed parameter range
  - Main mechanisms for bringing DM density in the right range are chargino coannihilation, slepton coannihilation and rapid annihilation via H/A funnels
  - LHC 13-TeV constraints have largest impact on strongly-interacting sparticles
  - $(g-2)_\mu$ most important for charged slep- ton masses and electroweakinos

- Backup

DM mechanisms:

To satisfy cosmological DM density constraint requires, in general, specific relations between sparticle masses that suppress the relic density via coannihilation effects and/or rapid annihilations through direct channel resonances.

Define indicative measures to highlight different DM mechanisms in the preferred regions of the fit:

$$\left(\frac{M_{\tilde{\tau}}}{m_{\chi_1^0}} - 1\right) < 0.15$$ **Stau coannihilation**

$$\left(\frac{M_{\tilde{l}}}{m_{\chi_1^0}} - 1\right) < 0.15$$ **Slepton Co-annihilation**

$$\left(\frac{M_{\chi_1^\pm}}{m_{\chi_1^0}} - 1\right) < 0.25$$ **Chargino Co-annihilation**

$$\left(\frac{M_{\tilde{g}}}{m_{\chi_1^0}} - 1\right) < 0.25$$ **Gluino Co-annihilation**

$$\left(\frac{M_{\tilde{q}}}{m_{\chi_1^0}} - 1\right) < 0.20$$ **Squark Co-annihilation**

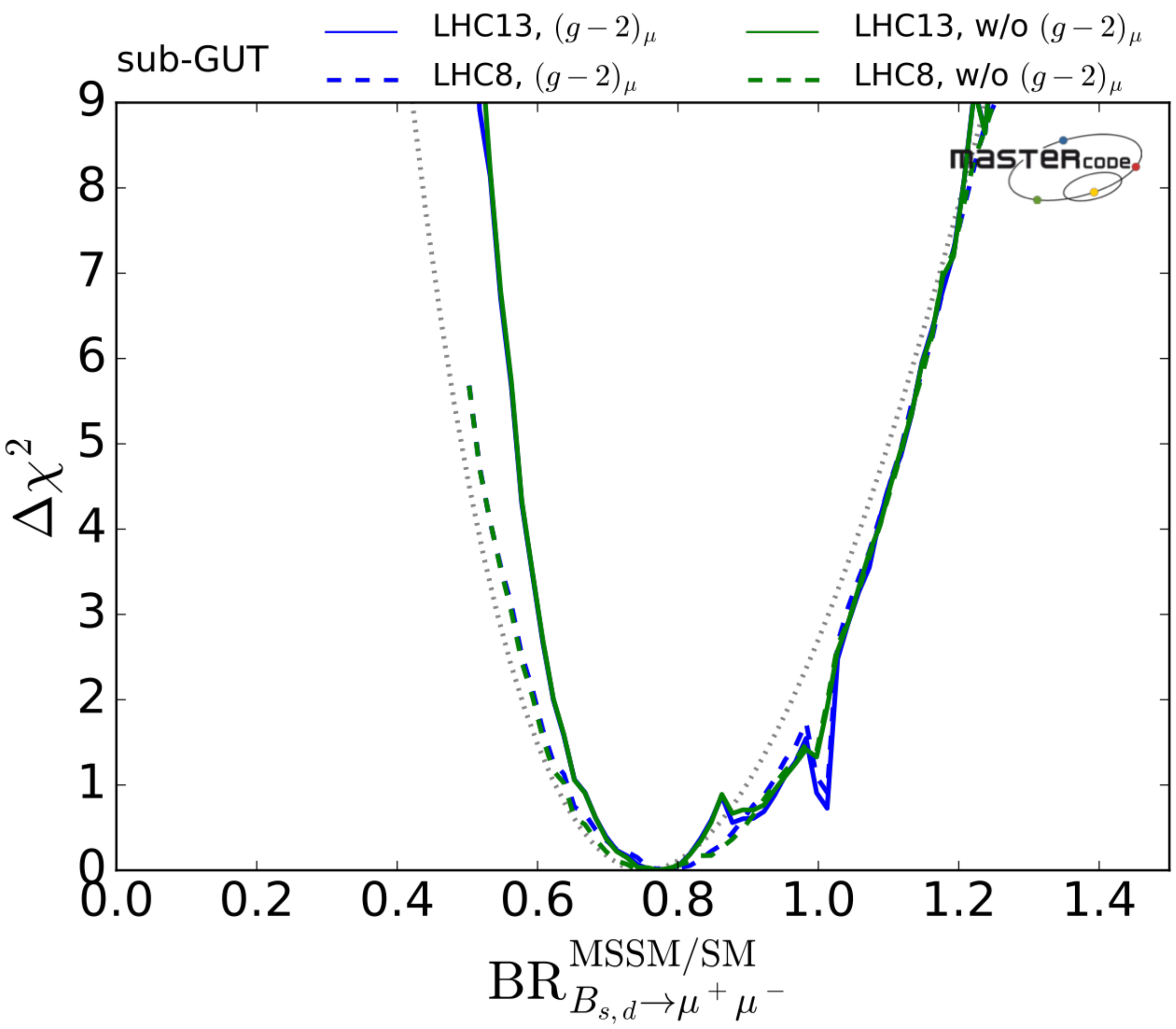
$$\left|\frac{M_B}{m_{\chi_1^0}} - 2\right| < 0.4$$ **B = h, Z or H/A funnel**

$$\left|\frac{\mu}{m_{\chi_1^0}} - 1\right| < 0.30$$ **Higgsino enriched “focus-point” like**

Hybrid regions:
In addition to the `primary' regions where only one of the conditions is satisfied, there can also be `hybrid' regions where more than one condition is satisfied. If present, these are indicated using combined colours.

See also arXiv:1508.01173 for further details

$B_{s,d}$ -> mu+mu-

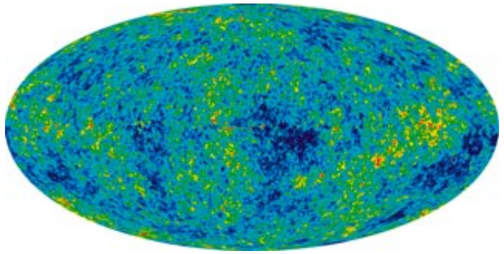


sub-GUT
LHC13, $(g-2)_\mu$
LHC8, $(g-2)_\mu$
LHC13, w/o $(g-2)_\mu$
LHC8, w/o $(g-2)_\mu$
MasterCode
$\Delta\chi^2$
9
8
7
6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$\mathrm{BR}^{\mathrm{MSSM/SM}}_{B_{s,d}\to\mu^+\mu^-}$

Experimental constraints

$$\chi^2 = \sum_i^{N_{meas}} \left(\frac{P_i - C_i}{\sigma_i} \right)^2$$

Dark matter	Indirect searches	Direct searches

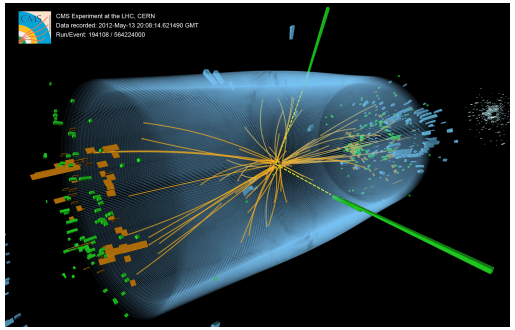


relic density

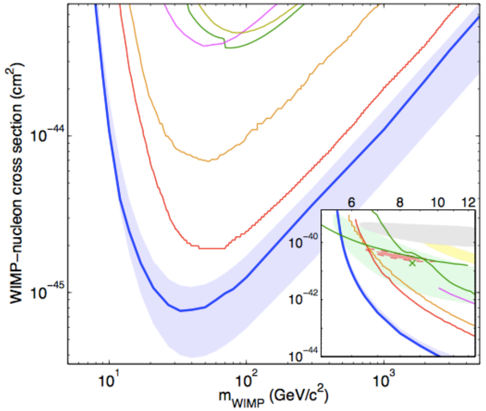
$$M_W, \ \Gamma_Z, \ A_{fb}(b), \ \ldots$$

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

Electroweak observables



Lightest Higgs



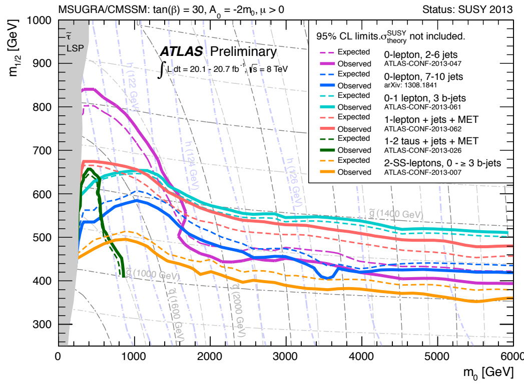
Direct Detection

LHCb

BELLE

$$B_s \to \mu\mu, \ b \to s\gamma, \ \ldots$$

Flavour observables



LHC SUSY searches

13 TeV LHC constraints