SUSY 2021

High-Scale SUSY Models in Light of Recent Muon g-2 experiment

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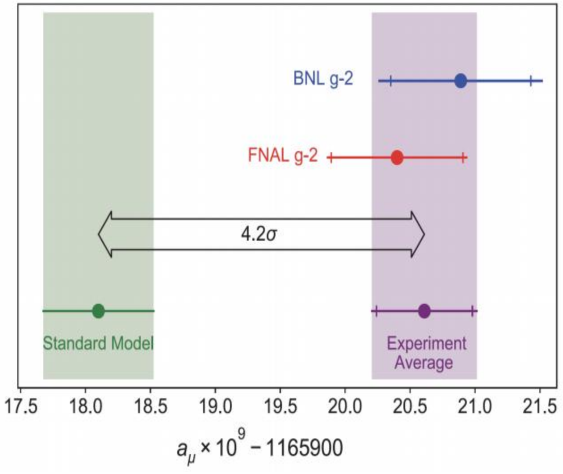
Based on 2104.03262 by Fei Wang, Lei Wu, Yang Xiao, Jin Min Yang, Yang Zhang,
Nucl.Phys.B 970 (2021) 115486
2106.04466, Zhuang Li, Guo-li Liu, Fei Wang, Jin Min Yang, Yang Zhang,

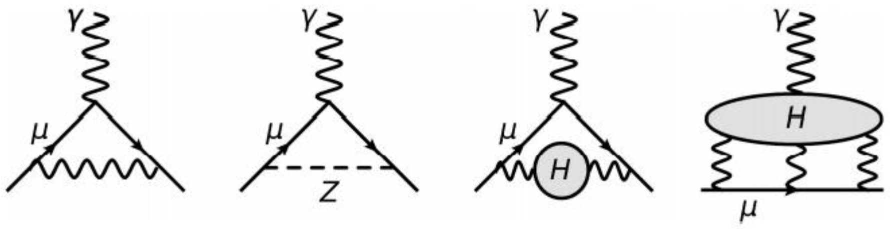
Muon g-2 Anomaly

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP} + a_\mu^{\rm HLbL},$$

$$a_\mu^{\rm SM} = (116\,591\,810 \pm 43) \times 10^{-11}$$

$$\Delta a_\mu^{2021} = (25.1 \pm 5.9) \times 10^{-10}$$





Direct Dim-6 contributions to a_mu

$$L_{eff} = \frac{C_1}{\Lambda^2} O_1 + \frac{C_2}{\Lambda^2} O_2.$$

$$O_1 = (\bar{l}\sigma^{\mu\nu}\tau_a \mu_R)\phi W^a_{\mu\nu} + h.c.$$

$$= -\frac{1}{\sqrt{2}}(\bar{\mu}\sigma^{\mu\nu}\mu)(c_w Z_{\mu\nu} + s_w F_{\mu\nu})(v+H) + ..$$

$$O_2 = (\bar{l}\sigma^{\mu\nu}\mu_R)\phi B_{\mu\nu}$$

$$= \frac{1}{\sqrt{2}}(c_w F_{\mu\nu} - s_w Z_{\mu\nu})(v+H) + ..$$

$$\frac{s_W}{\sqrt{2}} C_1, \frac{c_W}{\sqrt{2}} C_2 \sim e \frac{g^2}{16\pi^2} \frac{m_F}{v}$$

$$\Delta a_\mu \sim \frac{g^2}{8\pi^2} \frac{m_\mu m_F}{\Lambda^2}$$

Naively, we can use the estimation: $\Delta a_\mu^{\rm BSM} = C_{\rm BSM} \frac{m_\mu^2}{M_{\rm BSM}^2} \lesssim \mathcal{O}(1) \frac{m_\mu^2}{M_{\rm BSM}^2}$

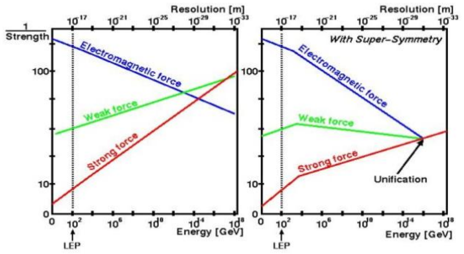
BNL: $\Delta a_\mu^{\rm BSM} = 27.9 \times 10^{-10} \quad \Rightarrow \quad M_{\rm BSM} \lesssim \mathcal{O}(2)\,{\rm TeV}$

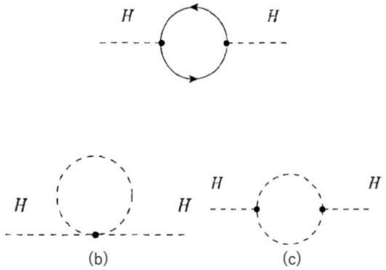
Including FNAL: $\Delta a_\mu^{\rm BSM} = 25.1 \times 10^{-10} \quad \Rightarrow \quad M_{\rm BSM} \lesssim \mathcal{O}(2.1)\,{\rm TeV}$

BSM Explanations: Always require some light new states. Dark Phton, 2HDM, scalar leptoquark,... SUSY
see [2104.03691] by Peter Athron , Csaba Balazs,...and Stöckinger’s talk

Why Supersymmetry

- Hierarchy problems. Quadratic divergence of higgs mass eliminated by introducing various superpartners.



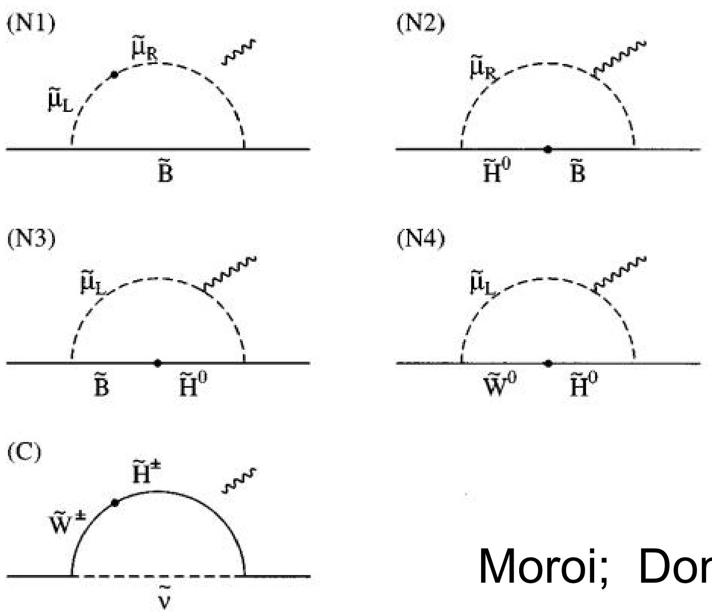


- SUSY GUT--Genuine gauge coupling unification.
- Vacuum stability naturally in SUSY at tree-level.
- Possible dark matter candidate.

  Natural dark matter candidates, many possible baryogenesis mechanism.

  Coincidence of DM and Baryon density.
- Radiative EW symmetry breaking-driven by RGE.
- Predictive-the 125 GeV Higgs lies in the '115-135' window favored by SUSY.
- Muon g-2 experiments favors new physics beyond the Standard Model.
- Good properties: holomorphic in superpotential...

SUSY Explanation To muon g-2 anomaly



$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\nu}_\mu) \simeq \quad 15 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\mu}_L) \simeq -2.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_L) \simeq \quad 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_R) \simeq -1.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L,\tilde{\mu}_R,\tilde{B}) \simeq \quad 1.5 \quad \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}/M_1\mu}\right)\left(\frac{f_N}{1/6}\right)$$

Moroi; Dominik Stöckinger,hep-ph/0609168; Endo et. al 1303.4256

Chirality Flipping

1. Breaking of chiral symmetry.
 proportional to y_mu

2. Spontaneously Broken of EW symmetry.

 propotional to v_u

 So involving a factor tan beta.

1. Light Sleptons ----O(100 GeV)
2. Light electroweakino
3. Large tan beta
4. 1,2 generation squarks heavy

Difficulties of global picture of SUSY theory on muon g-2

Howard Baer et al, 2104.07597

- LHC sparticle search limits:

Requires light sleptons, while heavy gluino and squarks are required by LHC,

in general both should be heavy in GUT theory.

- Higgs boson mass: Requires heavy stop of order O(10) TeV without large stop mixing.
- Higgs couplings: 125 Higgs SM-like, most plausible from decoupling.
- Flavor-changing B decays:

  b->s gamma et al require multi-TeV stop and charged Higgs.

- FCNCs from SUSY: gravity-mediated SUSY breaking models always favor flavor non-universality.

The decoupling solution or Typical SUSY breaking?

- SUSY CP violation: CP violating processes are all suppressed by heavy scalar
- Cosmological gravitino problem: If the gravitino mass, which set the scale of soft spectrum, too light– below the TeV scale– it can be long-lived to cause a problem for BBN
- Naturalness

SUSY Breaking Mechanism

SUGRA	GMSB	AMSB
• Order parameter：<F_X>≠0 • Non-renormaliable contact term • Neutralino LSP • Flavor violation	• Order parameter：<F_X>≠0 • Gauge interactions • Gravitino LSP • Flavor invariant	• Order parameter： <F_phi~m_{3/2}>≠0 • SuperWeyl anomaly • wino LSP • Flavor invariant • UV insensitivity

$$\mathcal{L}_{\rm SUSY} = \int d^2\theta d^2\bar{\theta}\left(Z_{\bar{I}J}\Phi_I^* e^{-V}\Phi_J + ...\right)$$
$$+\left[\int d^2\theta\left(\frac{1}{4}f_a \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha + \frac{1}{2}\mu_{IJ}\Phi_I\Phi_J + \frac{1}{6}y_{IJK}\Phi_I\Phi_J\Phi_K + ...\right) + {\rm c.c}\right]$$

$$Z_{\bar{I}J} = \delta_{\bar{I}J} \;\to\; Z_{\bar{I}J}(X, X^*, V_A) = \delta_{\bar{I}J} + \frac{XX^*}{M_{\rm mess}^2} + \frac{X}{M_{\rm mess}} + \frac{X^*}{M_{\rm mess}} + V_A$$
$$f_a = \frac{1}{g_a^2} + i\frac{\theta_{\rm vac}}{8\pi^2} \;\to\; f_a(X) = \frac{1}{g_a^2} + i\frac{\theta_{\rm vac}}{8\pi^2} + \frac{X}{M_{\rm mess}}$$

Difficulty of mSUGRA/CMSSM models

- Universal gaugino mass at the GUT scale $M_1=M_2=M_3$ will predict the gaugino ratio

  $M_1:M_2:M_3 \sim 1: 2: 6$

  LHC exclusion bounds on gluino: 2.2 TeV imply bino heavier than 360 GeV, wino heavier than 720 GeV.

- Universal m_0 at the GUT scale:

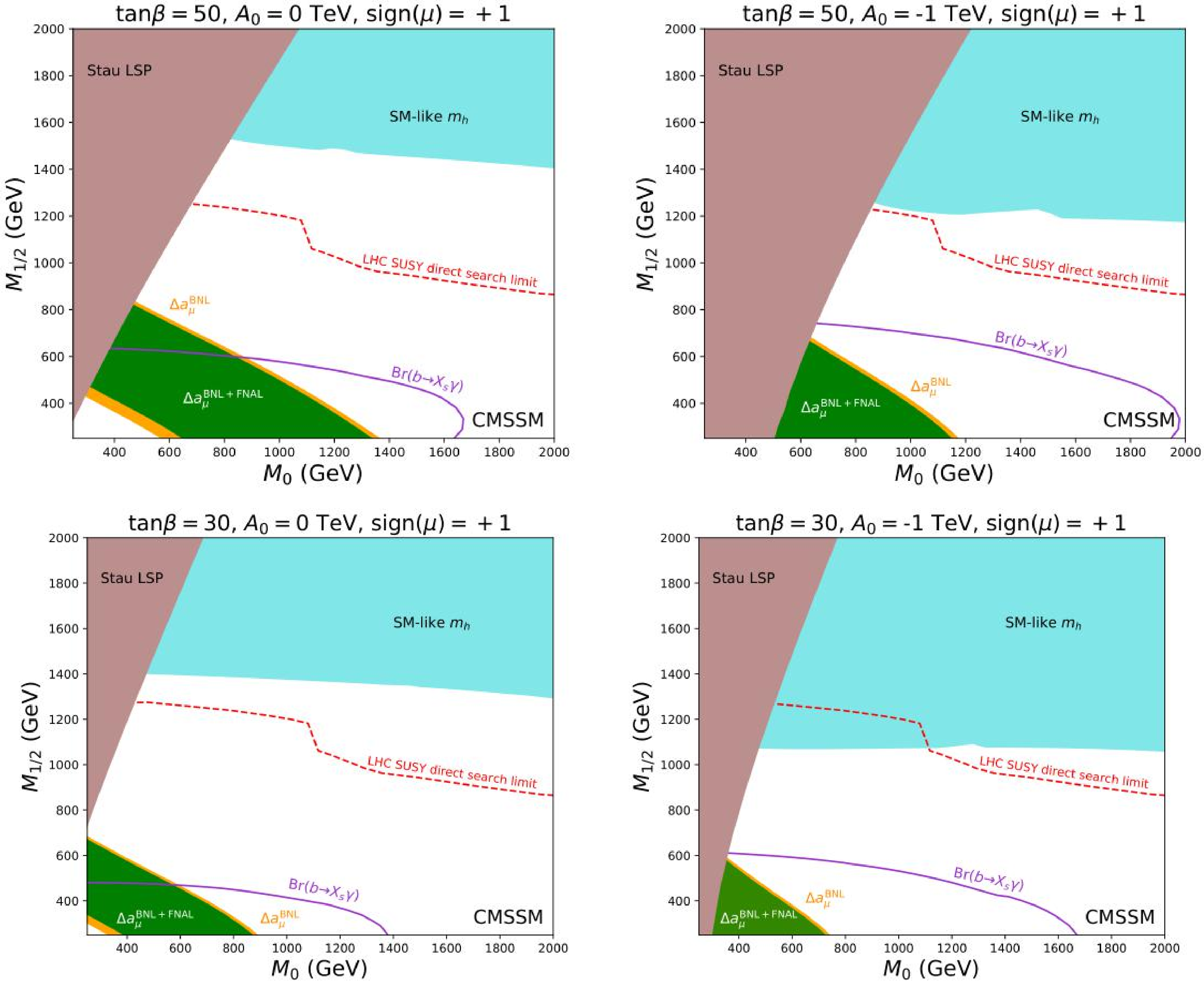
  Squark exclusion limits by LHC: multi TeV for 1,2 generation squarks

  125 GeV Higgs needs stop mass O(TeV) even with large A_t

  muon g-2 needs O(100) GeV sleptons

- Suppressed Br ($B \to X_s \gamma$) requires top-squarks and charged Higgs bosons in the multi-TeV regime

- SUSY CP, Higgs coupling..., naturalness problem....



Based on 2104.03262 by Fei Wang, Lei Wu, Yang Xiao, Jin Min Yang, Yang Zhang

Difficulty of mSUGRA/CMSSM models

- The searches for squarks and gluinos in final states of multi-jets and missing transverse momentum, which are insensitive to tanβ and A_0, have fully excluded parameter space in the CMSSM for explanation of the muon g − 2 discrepancy.

- To obtain the 125 GeV SM-like Higgs boson cause lower bounds of order1 TeV on M_1/2.

---With maximal mixing, where X_t /M_S ~√ 6, the contributions are maximised and

the bounds on M_1/2 can be relaxed to about 800 GeV, however too small tanβ

to account for muon g-2.

- BR(B → X_s γ) limit: SUSY contributions to this decay are dominated by loops involving stop, wino and heavy charged Higgs. The required suppressed SUSY loop contributions turn into bounds on M 0 and M_1/2.

- DM constraints: bino-slepton coannhiliation, bino-wino coannihilation, direct detection bounds; DM itself does not conflict with the muon g−2 explanation.

- Constraints on the mu parameter: Vacuum stability bounds on the mass of mu.

In general setting, stringent constraints on mu with the assumption $M_{\tilde{\tau}_L} = M_{\tilde{\tau}_R}$ can be relaxed.

Non-Universal Gaugino Masses

1. Previous difficulties can be relaxed by adopt non-universal gaugino masses. especially to split the gluino mass/electroweakino mass ratios
2. Try to relax some of the universal boundary conditions of mSUGRA. for example, naively only in the gaugino sector via F-term VEV of high dimensional Higgs

		$M_{\rm GUT}$			M_Z		
group	F_h	M_3	M_2	M_1	M_3	M_2	M_1
SU(5)	**1**	1	1	1	~ 6	~ 2	~ 1
SU(5)	**24**	2	-3	-1	~ 12	~ -6	~ -1
SU(5)	**75**	1	3	-5	~ 6	~ 6	~ -5
SU(5)	**200**	1	2	10	~ 6	~ 4	~ 10
$\mathrm{SO}(10) \to G_{442}$	**54**	1	-1.5	-1	~ 3	~ -1.3	~ -1
$\mathrm{SO}(10) \to \mathrm{SU}(2) \times \mathrm{SO}(7)$	**54**	1	$-7/3$	1	~ 3	~ -2.1	~ 0.42
$\mathrm{SO}(10) \to H_{51}$	**210**	1	1	$-96/25$	~ 3	~ 0.88	~ -1.6

☑

Many papers, example, see Ilia Gogoladzeet al, 1403.2337

Other contributions, see Csaba Balazs, Tianjun Li, Dimitri V. Nanopoulos and Fei Wang, JHEP09(2010)003

Gluino(driven) SUGRA Models

Sujeet Akula & Pran Nath
1304.5526

- A typical Non-universal gaugino mass extension of mSUGRA
- $M_3 \gg m_0, M_1, M_2$ at the GUT scale
- Sqarks are driven to be heavy

  from RGE by heavy M_3
- All colored particle heavy
- Sleptons and electrweakinoes light

Naturally account for various constraints:

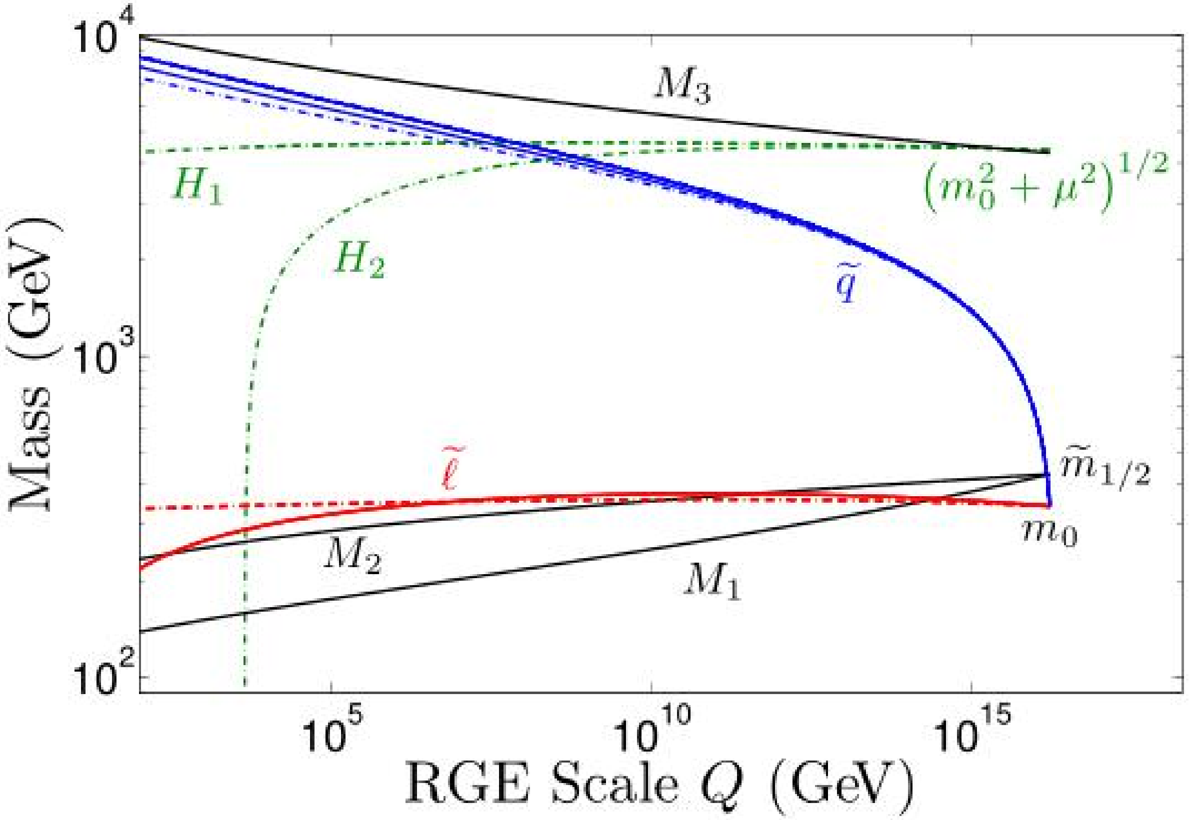
① Null search results of sparticles by LHC-

heavy colored particles

① accommodate 125 GeV Higgs mass

② Rare B meson decay

$\mathcal{B}r\left(B_s^0 \to \mu^+\mu^-\right)$ $\mathcal{B}r\left(B \to X_s\gamma\right)$



Naturally muon g-2 !!

Gluino Hierarchy in Gluino- SUGRA Models

a) Key: How to generate large hierarchy among the gauginos?

$$-\frac{\langle F \rangle_{ab}}{M_{\rm Pl}} \frac{1}{2} \lambda_a \lambda_b + {\rm H.c.}$$

Sujeet Akula & Pran Nath
1304.5526

Orignial proposal: Combining singlet and non-singlet breaking of SU(5) or SO(10)

$$\mathbf{1} + a\, \mathbf{24} + b\, \mathbf{75}$$

Choosing $a = -8/11$ and $b = -1/11$

$$M_1 : M_2 : M_3 = 1 : 1 : 10$$

Choosing $a = -3/4$ and $b = 3/2$ for SO(10)

$$\mathbf{1} + a\, \mathbf{210}_{(\mathbf{1},\mathbf{1})} + b\, \mathbf{210}_{(\mathbf{15},\mathbf{1})}$$

$$M_1 : M_2 : M_3 = 1 : 1 : 10$$

Hierarchical Gaugino Mass Pattern from GUT

- Froggatt-Nielsen type realization:

Introducing additional horizontal U(1)_H symmetry

$$Q_H : S(\mathbf{1}) = n, \quad Q_H : \Phi(\mathbf{24}) = -1, \quad Q_H : T(\mathbf{1}) = -1.$$

$$\mathcal{L} \supseteq \int d^2\theta \left(W^a W^a + c_S \frac{S}{\Lambda^{n+1}} W^a \left(c_0 T \delta_{ab} + c_1 \Phi_{ab} \right)^n W^b \right)$$

$$\langle T \rangle \delta_{ab} - \langle \Phi_{ab} \rangle$$
$$\sim \ \mathrm{diag}\left(v_T + \frac{v_U}{\sqrt{15}}, v_T + \frac{v_U}{\sqrt{15}}, v_T + \frac{v_U}{\sqrt{15}}, v_T - \frac{\sqrt{15} v_U}{10}, v_T - \frac{\sqrt{15} v_U}{10} \right)$$
$$+\theta^2 \mathrm{diag}\left(F_T + \frac{F_U}{\sqrt{15}}, F_T + \frac{F_U}{\sqrt{15}}, F_T + \frac{F_U}{\sqrt{15}}, F_T - \frac{\sqrt{15} F_U}{10}, F_T - \frac{\sqrt{15} F_U}{10} \right)$$

$$M_3 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} (v_T + \frac{v_U}{\sqrt{15}})^{n-1} (F_T + \frac{F_U}{\sqrt{15}}),$$

$$M_2 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} (v_T - \frac{\sqrt{15} v_U}{10})^{n-1} (F_T - \frac{\sqrt{15} F_U}{10}),$$

$$M_1 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} \frac{6}{5} \left[\frac{1}{3} (v_T + \frac{v_U}{\sqrt{15}})^{n-1} (F_T + \frac{F_U}{\sqrt{15}}) + \frac{1}{2} (v_T - \frac{\sqrt{15} v_U}{10})^{n-1} (F_T - \frac{\sqrt{15} F_U}{10}) \right]$$

$$F_T \gtrsim F_U$$

$$1 \gg \left(\frac{v_T + \frac{v_U}{\sqrt{15}}}{\Lambda} \right)^{n-1} \gg \left(\frac{v_T - \frac{\sqrt{15} v_U}{10}}{\Lambda} \right)^{n-1}$$

→

$$M_3 \simeq \tfrac{5}{2} M_1 \gg M_2$$

Based on 2106.04466, Zhuang Li, Guo-li Liu, Fei Wang, Jin Min Yang, Yang Zhang

Hierarchical Gaugino Mass Pattern from GUT

$$\langle c_0 T + c_1 \Phi_{\mathbf{24}} + c_2 \Phi_{\mathbf{75}} \rangle = \left(v_0 + \theta^2 F_0\right) diag(\underbrace{a, \cdots, a,}_{3} \underbrace{b, \cdots, b,}_{6} c)$$

$$M_3 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} \frac{1}{18} \left\{6a^{n-1} + 12b^{n-1}\right\} F_0,$$

$$M_2 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} \frac{1}{6} \left\{6b^{n-1}\right\} F_0,$$

$$M_1 = \frac{n\langle S \rangle}{(\Lambda)^{n+1}} \frac{1}{90} \left\{48a^{n-1} + 6b^{n-1} + 36c^{n-1}\right\} F_0.$$

$4a^{n-1} = -3c^{n-1}$ and $a > b$ ⟹ $M_3 \gg M_2 \simeq 15 M_1$

Can be generalized to other SU(5) combinations, for example, involving 200 representation of SU(5)

Hierarchical Gaugino Mass Pattern from GUT

- Wavefunction normalization:

F. Wang, W. Wang and J. M. Yang, JHEP **06**, 079 (2015), arXiv:1504.00505.

F. Wang, K. Wang, J. M. Yang and J. Zhu, JHEP **12** (2018), 041 arXiv:1808.10851.

$$\mathcal{L} \supseteq \int d^2\theta \left[W^a W^a + c_S \frac{S}{\Lambda} W^a W^a + \frac{c_\Phi}{\Lambda} W^a \Phi_{ab} W^b \right]$$

$$\langle \Phi_{\mathbf{24}} \rangle = (v_U + \theta^2 F_U) \sqrt{\frac{3}{5}} \,\mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2} \right)$$

$$1 + c_S \frac{\langle S \rangle}{\Lambda} - c_{\Phi_{\mathbf{24}}} \frac{v_U}{\Lambda} \frac{2}{\sqrt{15}} = \frac{\epsilon}{\sqrt{15}} \ll 1.$$

$$M_1 : M_2 : M_3 = \frac{\frac{1}{\sqrt{15}}}{Z_{U(1)_Y}} : \frac{\frac{3}{\sqrt{15}}}{Z_{SU(2)_L}} : \frac{-\frac{2}{\sqrt{15}}}{Z_{SU(3)_c}}$$

$$Z_{U(1)_Y} : Z_{SU(2)_L} : Z_{SU(3)_c} = \frac{3}{\sqrt{15}} : \frac{5}{\sqrt{15}} : \frac{\epsilon}{\sqrt{15}}$$

$$M_1 : M_2 : M_3 = \frac{1}{3} : \frac{3}{5} : -\frac{1}{\epsilon}$$

24 represenatation Higgs

$$M_1 : M_2 : M_3 = \frac{10}{9} : \frac{2}{1} : \frac{1}{\epsilon}$$

$$M_1 : M_2 : M_3 = \frac{20}{24} : \frac{12}{8} : -\frac{1}{\epsilon}$$

75 represenatation Higgs

200 represenatation Higgs

Hierarchical Gaugino Mass Pattern from GUT

$$\mathcal{L} \supseteq \int d^2\theta \left[W^a W^a + c_S \frac{S}{\Lambda} W^a W^a + \frac{c_{\Phi_1}}{\Lambda} W^a \Phi_{1,ab} W^b + \frac{c_{\Phi,2}}{\Lambda} W^a \Phi_{2,ab} W^b \right]$$

$$\langle \Phi_{\mathbf{24}} \rangle = v_{\mathbf{24}} \sqrt{\frac{3}{5}} \, \mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2} \right) ,$$

$$\langle \Phi_{\mathbf{75}} \rangle = \theta^2 \frac{F_{\mathbf{75}}}{2\sqrt{3}} \mathrm{diag} \left(\underbrace{1, \cdots, 1}_{3}, \underbrace{-1, \cdots, -1}_{6}, 3 \right)$$

$$M_1 : M_2 : M_3 = \frac{\frac{20}{5\sqrt{3}}}{Z_1} : -\frac{\frac{12}{5\sqrt{3}}}{Z_2} : -\frac{\frac{4}{5\sqrt{3}}}{Z_3} = \frac{5}{3} : -\frac{3}{5} : -\frac{1}{\epsilon},$$

$$Z_1 : Z_2 : Z_3 = \frac{3}{\sqrt{15}} : \frac{5}{\sqrt{15}} : \frac{\epsilon}{\sqrt{15}}.$$

The wavefunction normalization methods can be generalized to include additional higher dimensional Higgs.

The F-term VEV can be replaced by various combinations to generate more possibilities.

Constraints on Gluino-SUGRA from muon g-2

Based on 2106.04466, Zhuang Li, Guo-li Liu, Fei Wang, Jin Min Yang, Yang Zhang

Inputs:

$$m_0, M_1, M_2, M_3, A_0, \tan\beta, sign(\mu)$$

we require $M_3 \gtrsim 3\max(M_1, M_2)$ at the GUT scale

Constraints:

① 125 GeV Higgs: 125 ± 2 GeV

② Upper bounds for DM relic density&& Direct Detection $0 < \Omega h^2 < 0.1188$

③ LHC searches

④ B-meson decay

⑤ Muon g-2

⑥ Vacuum stabiity bounds on mu

$$m_0 \in [50, 2000]\ \text{GeV}, \quad A_0 \in [-5000, 5000]\ \text{GeV}, \quad \tan\beta \in [2, 60].$$

Subscenarios by DM species: M_1/M_2> (<) 1.5

Constraints on Gluino-SUGRA from muon g-2

$M_1 = M_2, \qquad M_1 \in [50, 1000]\ \mathrm{GeV}$ The lightest gaugino at the EW scale is the bino

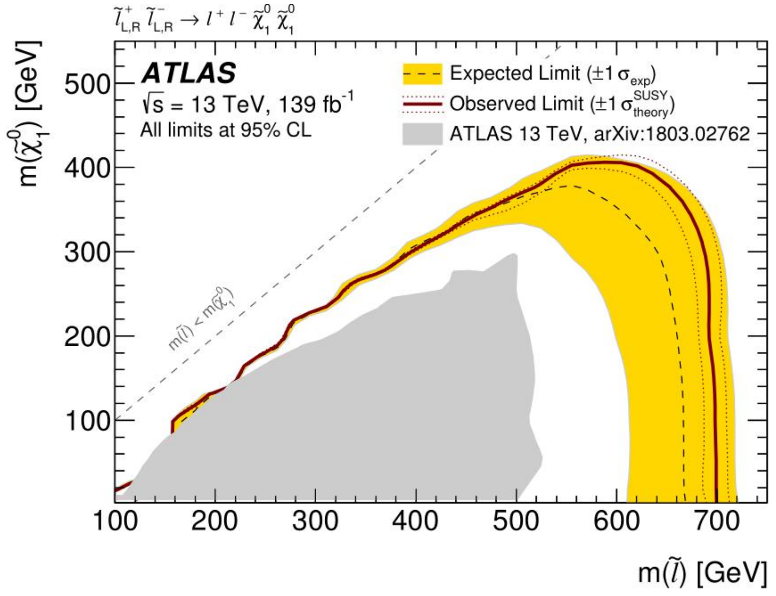
Central value for gaugino ratio at EW scale $M_1 : M_2 : M_3 \approx 1 : 2 : 45$

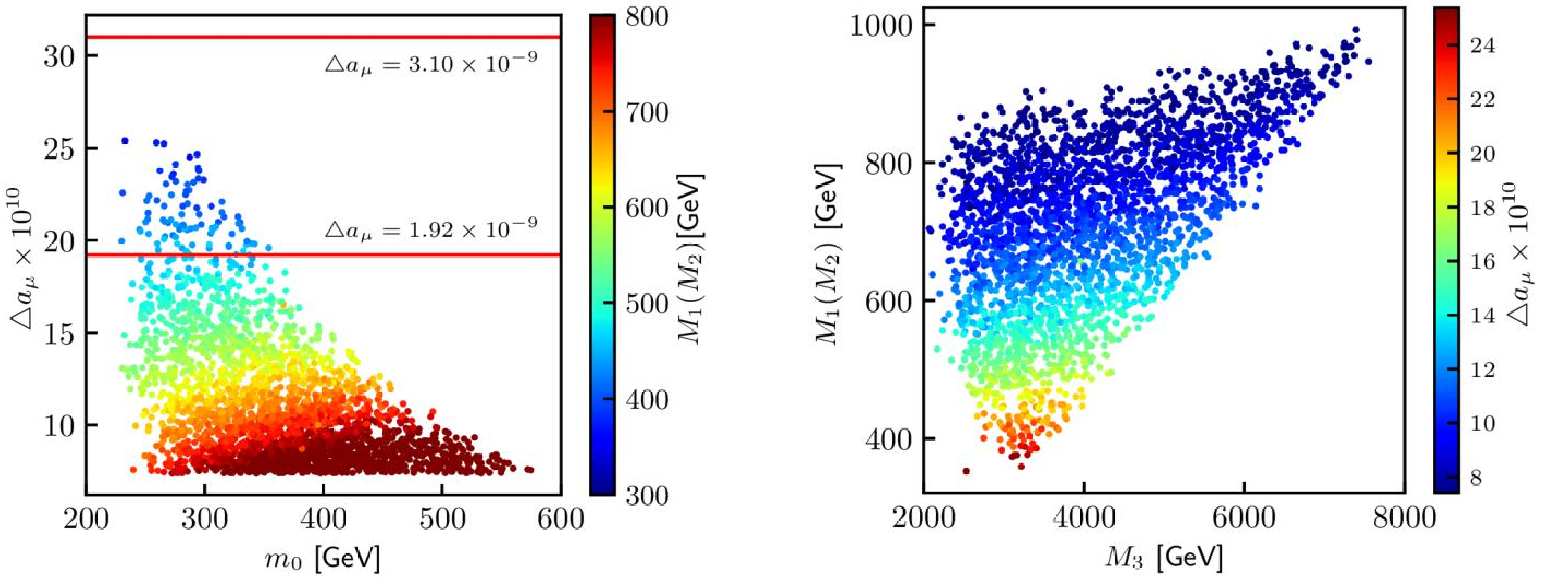
Bino DM always overabundance unless coannihilation or resonant annihilating

Colord sparticles are heavy, so only slepton-coannihilation is possible.

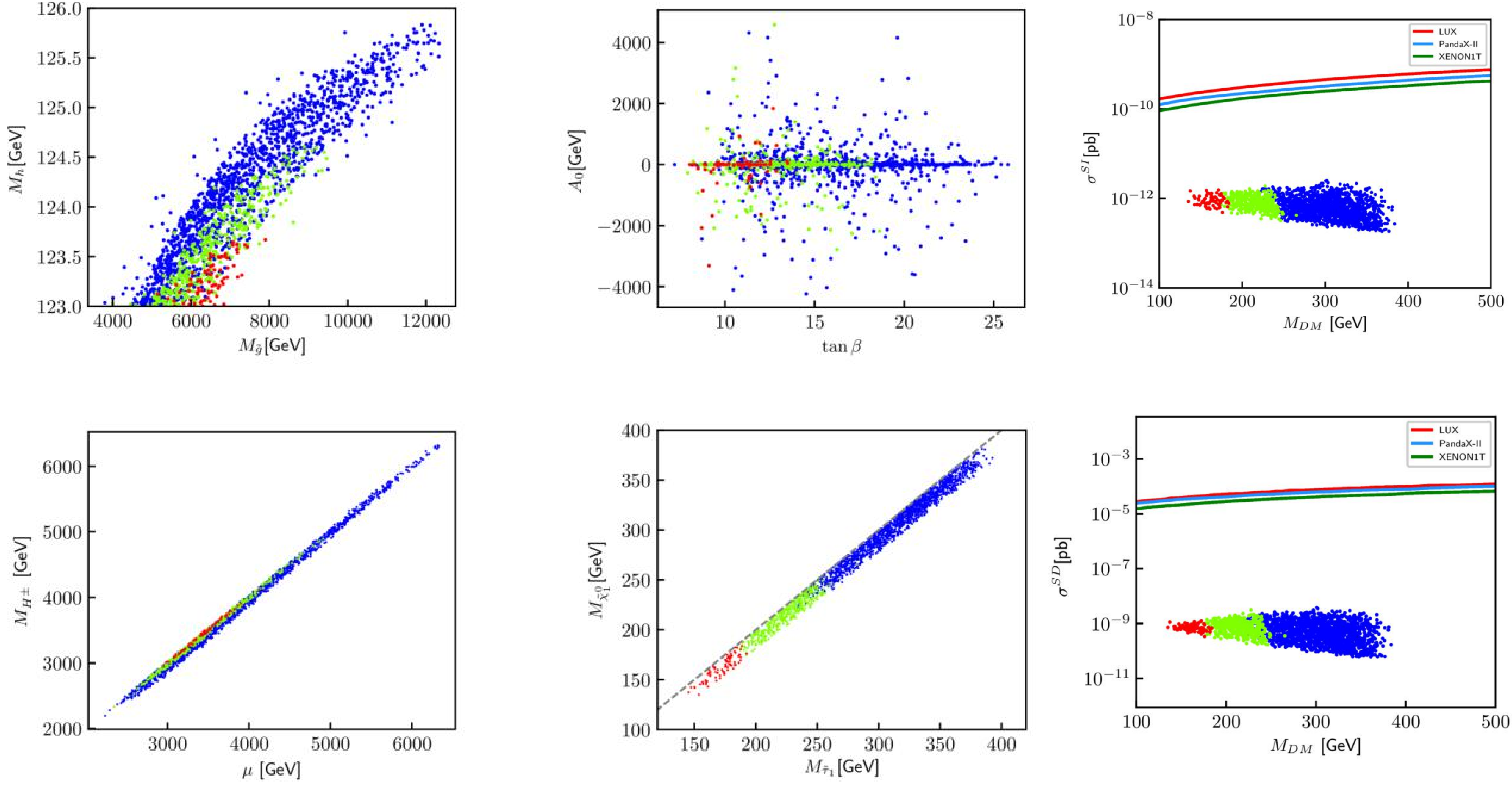
Bino-Slepton co-annihilation: efficiently reduce the DM relic density.

Non-trivial to check the LHC exclusion limits--
stau-compressed region
1,2 generation sleptons, chargino decay constraints.





$\triangle a_\mu = 3.10 \times 10^{-9}$
$\triangle a_\mu = 1.92 \times 10^{-9}$
$\triangle a_\mu \times 10^{10}$
m_0 [GeV]
$M_1(M_2)$[GeV]
$M_1(M_2)$ [GeV]
M_3 [GeV]
$\triangle a_\mu \times 10^{10}$



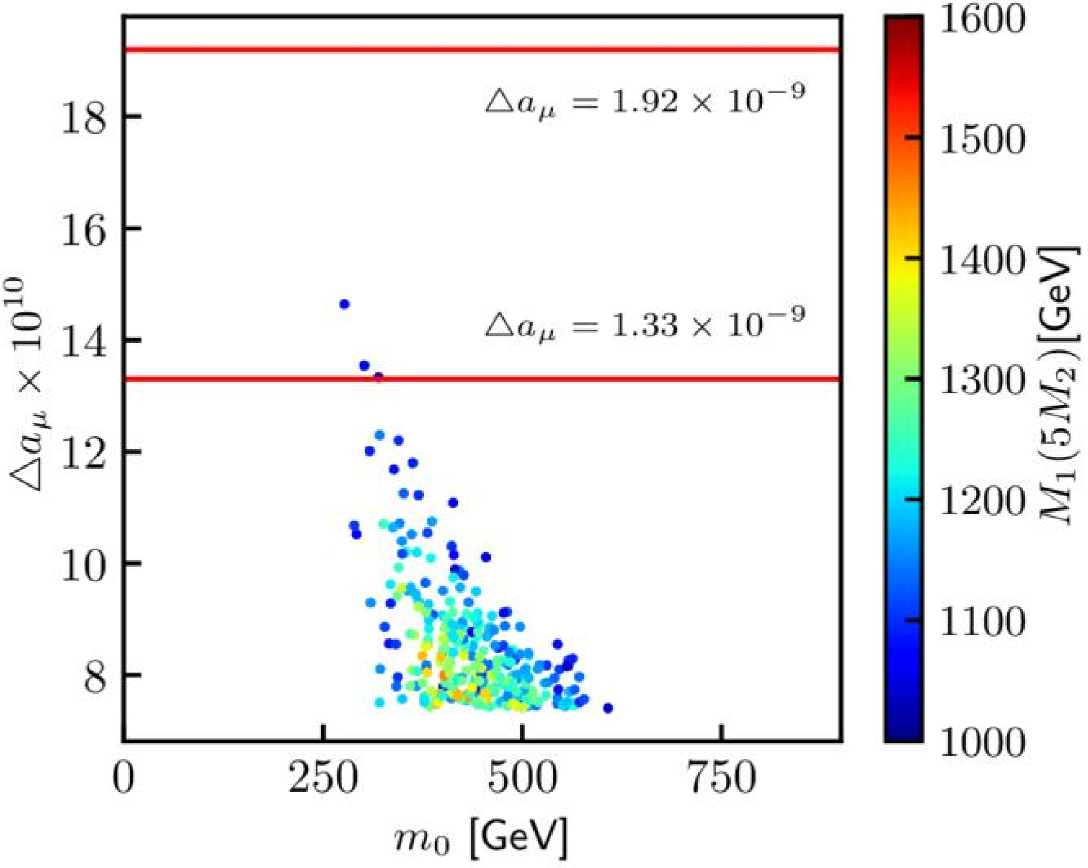
M_h [GeV]
126.0
125.5
125.0
124.5
124.0
123.5
123.0
4000
6000
8000
10000
12000
$M_{\tilde{g}}$ [GeV]
A_0 [GeV]
4000
2000
0
−2000
−4000
10
15
20
25
$\tan\beta$
σ^{SI} [pb]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
LUX
PandaX-II
XENON1T
100
200
300
400
500
M_{DM} [GeV]
$M_{H^\pm}$ [GeV]
6000
5000
4000
3000
2000
3000
4000
5000
6000
μ [GeV]
$M_{\tilde{\chi}_1^0}$ [GeV]
400
350
300
250
200
150
100
150
200
250
300
350
400
$M_{\tilde{\tau}_1}$ [GeV]
σ^{SD} [pb]
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
LUX
PandaX-II
XENON1T
100
200
300
400
500
M_{DM} [GeV]

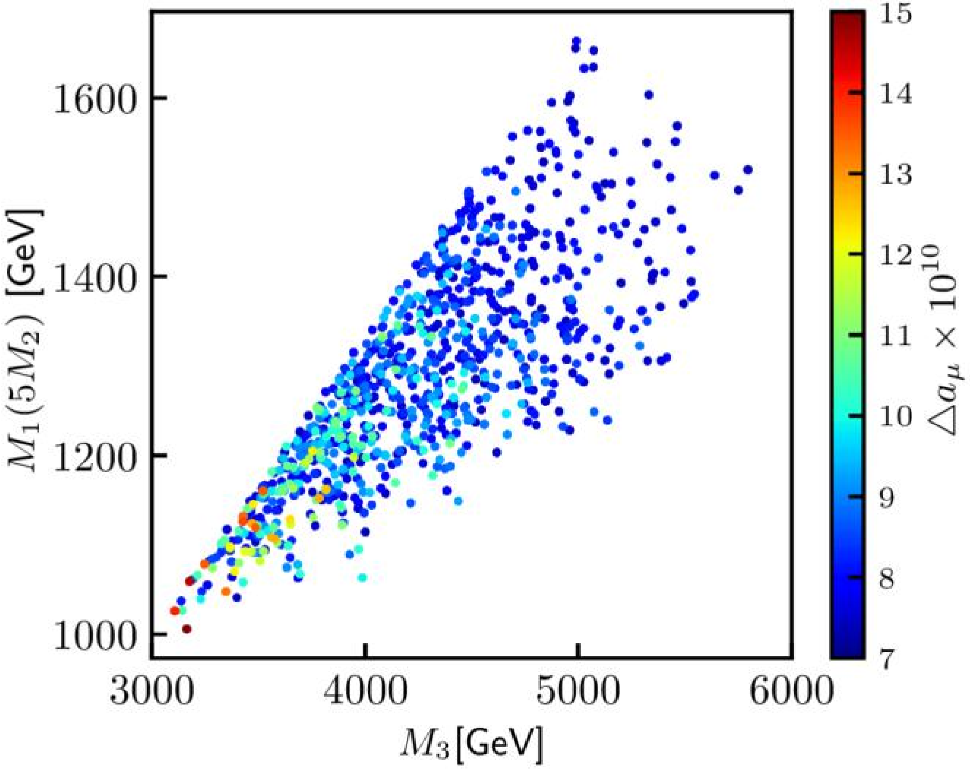
$M_1 : M_2 = 5 : 1, \qquad M_1 \in [50, 2000]$ GeV.

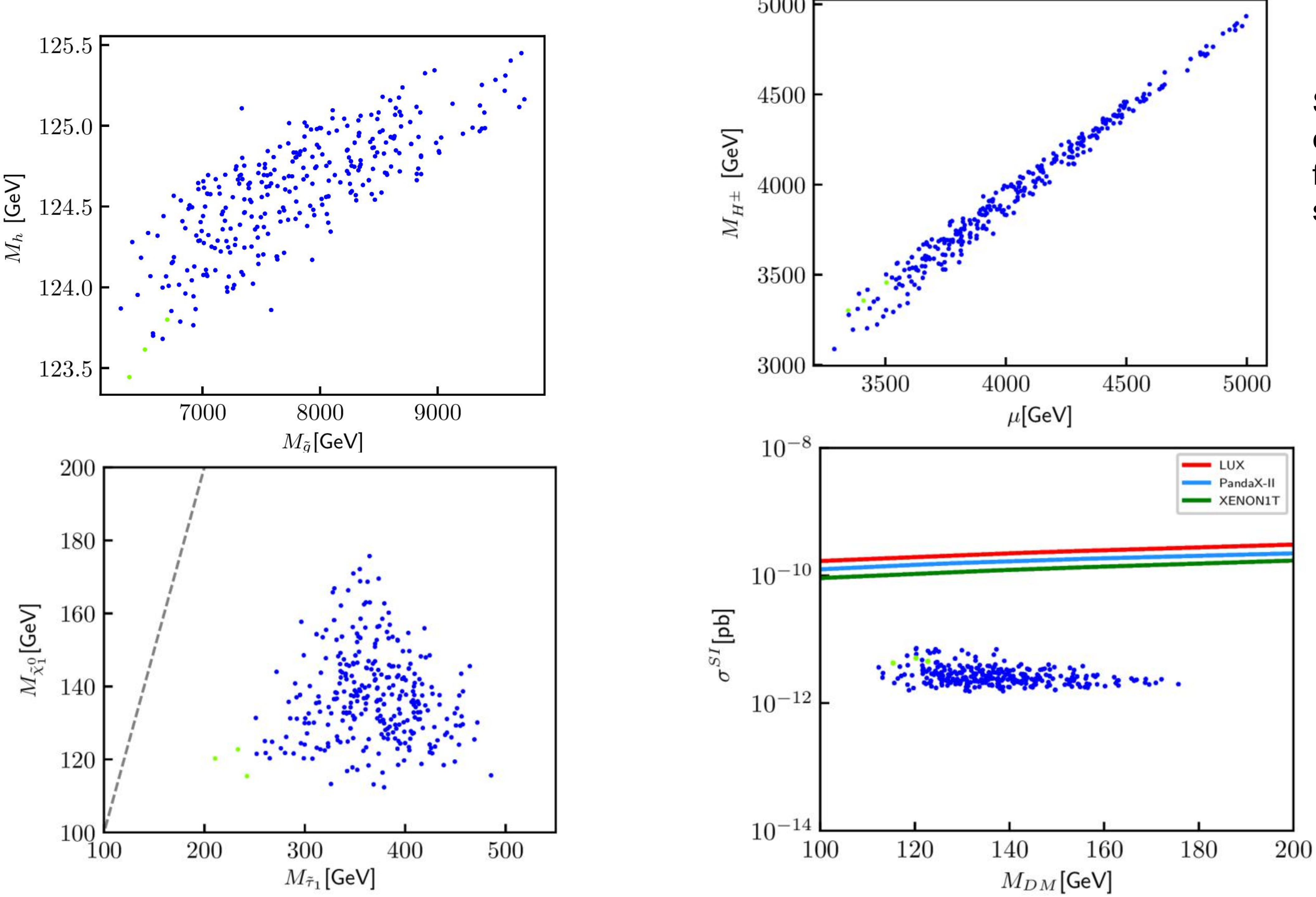
Central value: $M_1 : M_2 : M_3 \approx 5 : 2 : 105$ at EW scale

Adopting 200 representation Higgs, 24 representation and singlet Higgs

So the DM is almost pure Wino



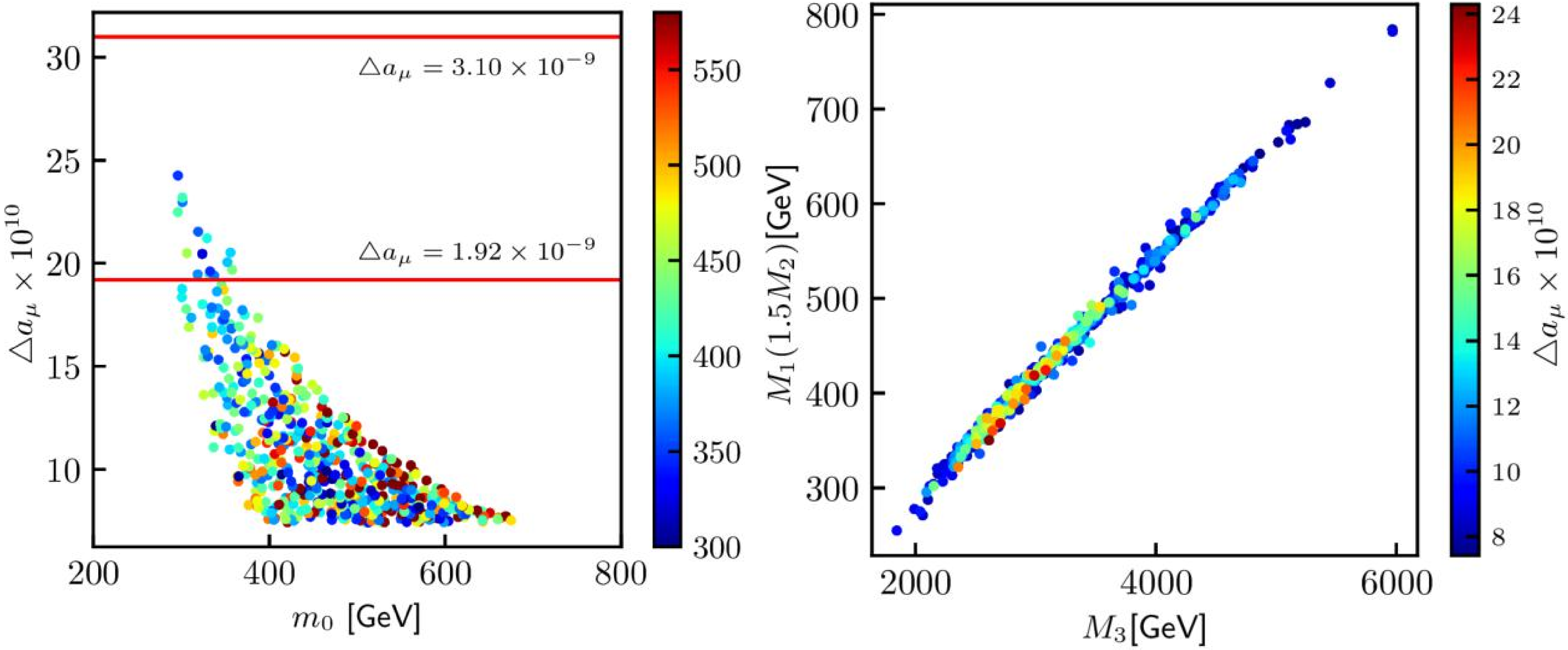


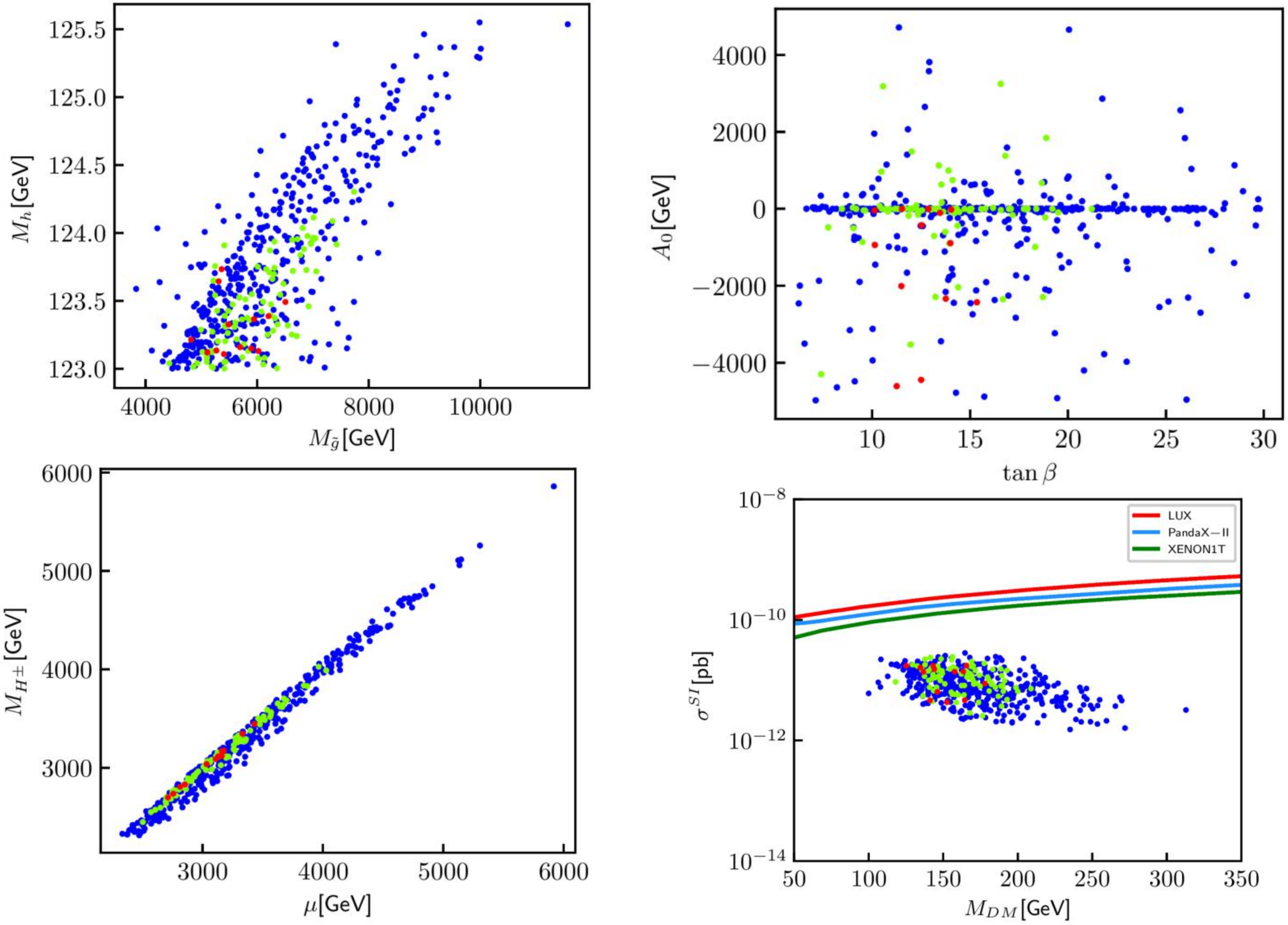


Stringent constraints from Vaccum stability

$M_1 : M_2 = 3 : 2, \quad M_1 \in [50, 2000]$ GeV

Central value: $M_1 : M_2 : M_3 \approx 3 : 4 : 130$ at EW scale





M_h[GeV]
$M_{\tilde{g}}$[GeV]
A_0[GeV]
$\tan\beta$
$M_{H^\pm}$[GeV]
μ[GeV]
σ^{SI}[pb]
M_{DM}[GeV]
LUX
PandaX−II
XENON1T

Alternative GUT-scale SUSY models

- NUHM: Briefly reviewed in our work 2104.03262

◆ NUHM1: Higgs soft SUS breaking masses can take an additional universal value

$m_{H_u}^2=m_{H_d}^2=m_1^2, m_0^2$ Not possible

◆ NUHM2: Higgs soft SUS breaking masses can be independent.

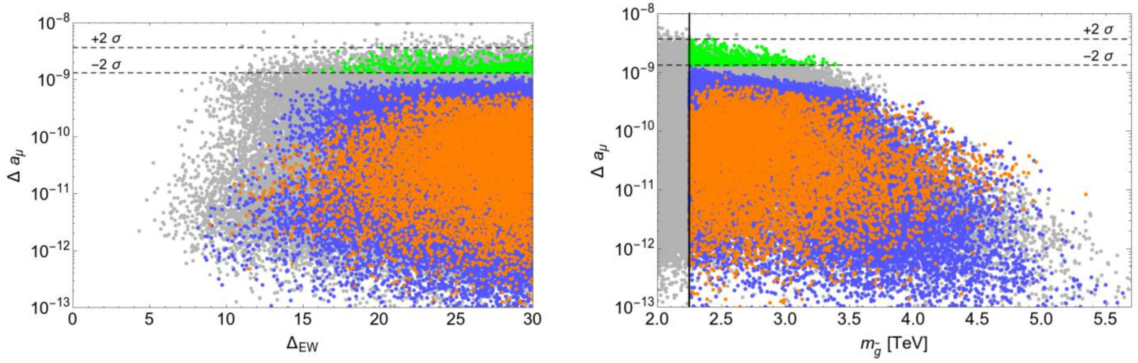
$m_{H_u}^2, m_{H_d}^2, m_0^2$ Not possible

◆ NUHM3: Higgs Higgs soft SUS breaking masses can be independent and 1,2 sfermion masses different to that of the third generation.

$m_{H_u}^2=m_{H_d}^2=m_1^2, m_{0;1,2}^2, m_{0;3}^2$

Possible

1. gaugino ratio not relaxed,
2. LHC exclusion limits-very stringent.
3. 125 GeV Higgs still not easiy to accommodate with Delta a_mu in 2sigma range.



2104.07597 by Howard Baer et al

Deflected Anomaly Mediation SUSY Breaking

1. To solve the tachyonic slepton needs to deflect the AMSB trajectory.

2. Most simple possibility: heavy threshold 。

Evading the decoupling theorem?

Simple heavy thresholds not works

Pseudo-moduli in the superpotential?

$$\phi = 1 + F_\phi \theta^2$$

Holomorphic terms in the Kahler potential?

$$W = \lambda X \Psi \bar{\Psi} + \frac{X^n}{\Lambda^{n-3}\phi^{n-3}},$$

$$\int d^2\theta \frac{\lambda m_{3/2}}{\phi} \Xi \bar{\Xi}.$$

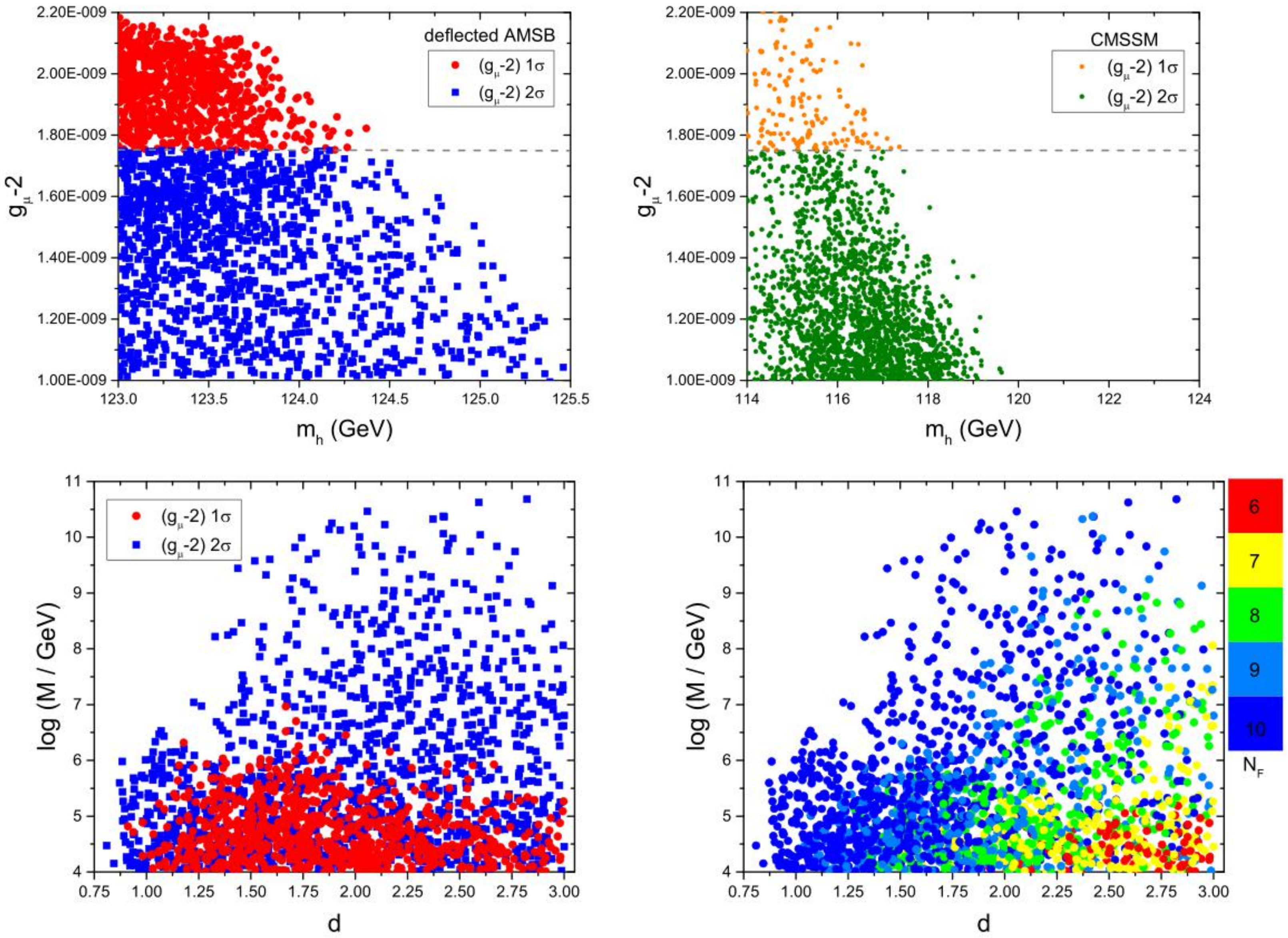
A.Nelsen, Wenner

Vanishing second term: anti-GMSB

$$m_\lambda(\mu) = \frac{\alpha(\mu)}{4\pi}(b - N)F_\phi,$$

$$M_i = -\frac{b_i + 2n}{4\pi}\alpha_i m_{3/2},$$

Explanation in deflected Anomaly Mediation



Superpotential deflection with positive deflection parameters

Fei Wang,
Wenyu Wang,
Jin Min Yang,
Yang Zhang,

JHEP07(2015)138

GMSB in light of muon g-2

Status of GMSB explanation:

Gaugino ratio: $M_1 : M_2 : M_3 \approx 1 : 2 : 6$ preserved at the EW scale

$$M_i = \frac{\alpha_i}{4\pi}\frac{F}{M}N_5 \Rightarrow \frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2}\ .$$

LHC exclusion bounds 2.2 TeV gluino------->not very light electroweakino

Minimal GMSB predict A_t=0 at the messenger scale. Hard to generate 125 GeV Higgs with light stop.

Stop heavier than 5 TeV--> heavy sleptons-----> constrained by muon g-2

Solution:

1. introduce messenger-matter mixings--> large A_t-> relax heavy stop requirements by 125 Higgs
2. introduce incomplete GUT representation messengers--> relax the gaugino ratio
3. EGM extension
4. Other realizaion of non-universal gaugino mass in GMSB

Explanation in ExtraOrdinarily Gauge Mediation

Try to relax the squark-slepton mass relations:

$$W = (\lambda_{ij}^{(k)} X_k + M_{ij})\phi_i\widetilde{\phi}_j = (\lambda_{2ij}^{(k)} X_k + M_{2ij})\ell_i\widetilde{\ell}_j + (\lambda_{3ij}^{(k)} X_k + M_{3ij})q_i\widetilde{q}_j$$

$$W = (\lambda_{ij} X + m_{ij})\phi_i\widetilde{\phi}_j = (\lambda_{2ij} X + m_{2ij})\ell_i\widetilde{\ell}_j + (\lambda_{3ij} X + m_{3ij})q_i\widetilde{q}_j$$

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\widetilde{f}}^2 = 2\sum_{r=1}^{3} C_{\widetilde{f}}^{\,r}\left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_G^2 N_{\text{eff},r}^{-1}$$

$$N_{\text{eff},r} \equiv N_{\text{eff}}(X, m_r, \lambda_r) \qquad (r = 2,\, 3)$$

$$N_{\text{eff},1}^{-1} \equiv \tfrac{3}{5}N_{\text{eff},2}^{-1} + \tfrac{2}{5}N_{\text{eff},3}^{-1}$$

Choosing N_{eff,3} << N_{eff,2}, squarks can be much heavier than sleptons.

N_{eff} can be less than 1.

$$N_{\text{eff}}(X, m, \lambda) \equiv \frac{\Lambda_G^2}{\Lambda_S^2} = \left[\frac{1}{2n^2}|X|^2 \frac{\partial^2}{\partial X \partial X^*}\sum_{i=1}^{N}\left(\log\frac{|\mathcal{M}_i|^2}{\mu^2}\right)^2\right]^{-1}$$

Imposing non-trivial R-symmetry

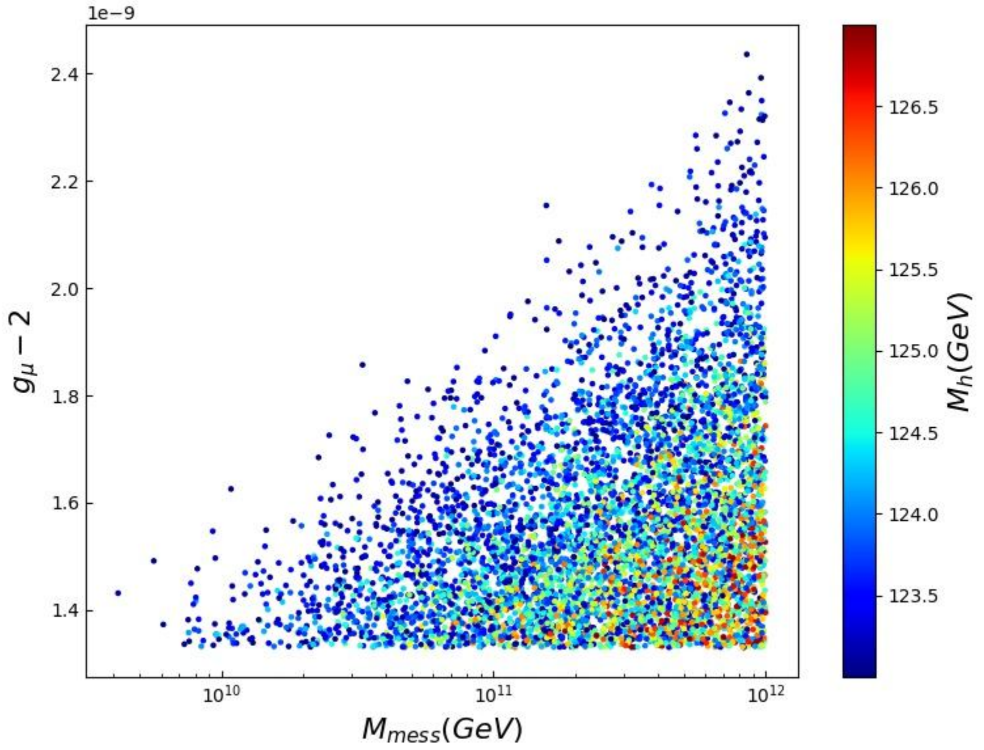
$$\lambda_{ij} \neq 0 \quad \text{only if} \quad R(\phi_i) + R(\widetilde{\phi}_j) = 2 - R(X)$$

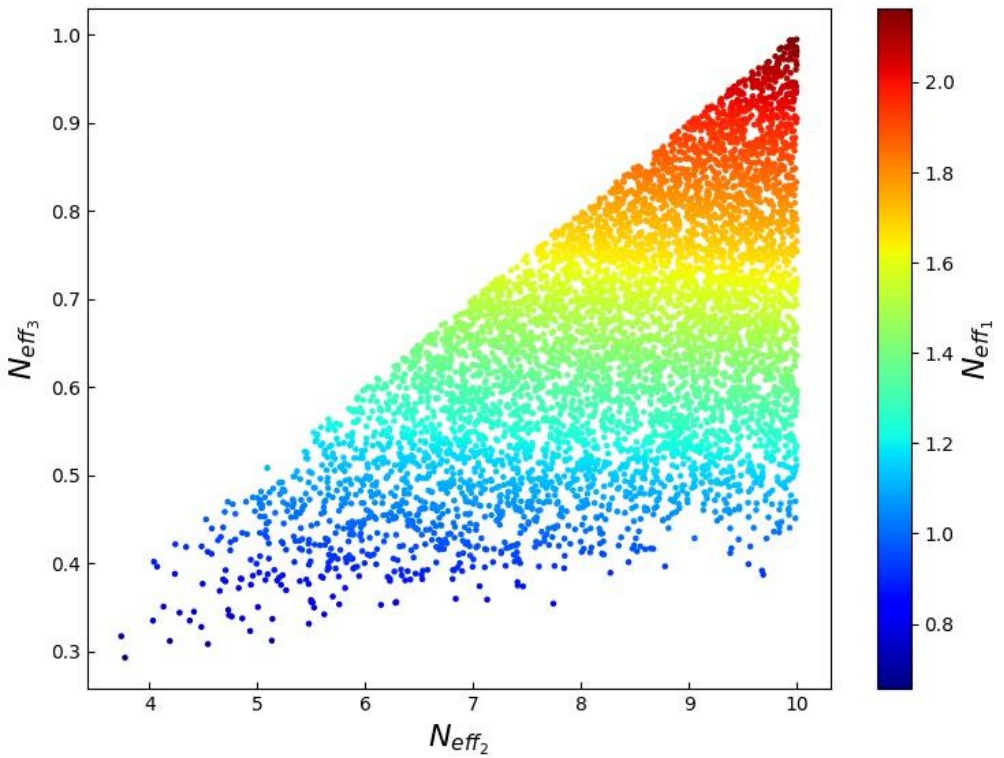
$$m_{ij} \neq 0 \quad \text{only if} \quad R(\phi_i) + R(\widetilde{\phi}_j) = 2$$

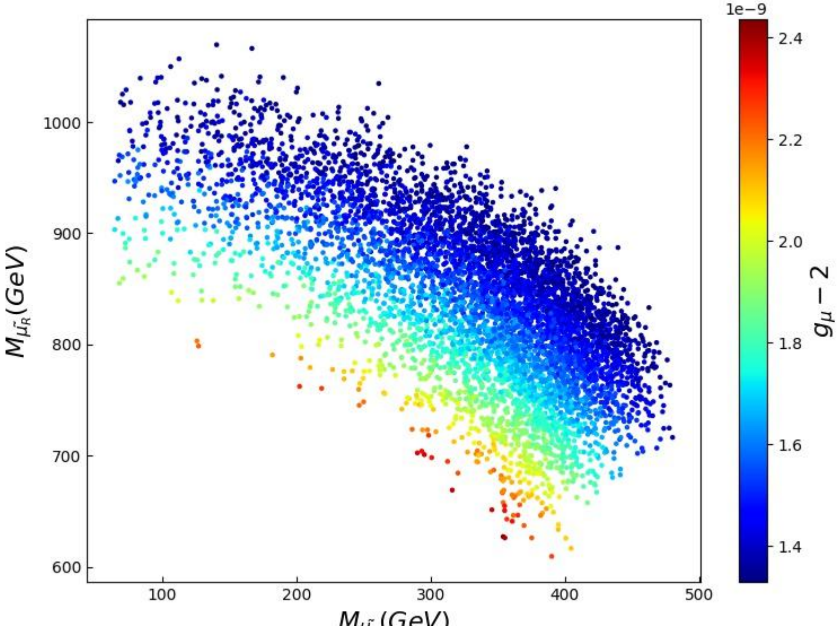
Adopt the case

$$\det\lambda = \det m = 0$$

$$0 < n < N \quad \text{and} \quad \det(\lambda X + m) = X^n G(m, \lambda)$$







Xiao kang Du, Fei Wang, Yin
Kai Zhang, To appear soon

Conclusion:

mSUGRA can not account for the recent observed muon g-2 anomaly. It needs to be extended:

- Gluino-SUGRA is the best SUGRA-type extension: simple, elegant.
- Other non-universal gaugino extension
- GMSB- (EGM extension, non-universal gaugino extension)
- AMSB (surely not minimal) very easily explain the muon g-2 anomaly.