Muon $g-2$ in MSSM and BLSSM

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in collaboration with

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Outline

- Standard Model
- MSSM
- CMSSM and NUHM, GMSB
- Non-Universality
  - Flavor symmetry based MSSM (sMSSM)
  - Non-universal Gauginos (NUGM)
- Non-Minimality
  - B-L extended MSSM with inverse seesaw (BLSSM-IS)

Standard Model

- Spontaneous Symmetry Breaking
  * Higgs Boson, Particle masses
  * Gauge Hierarchy Problem

$$\delta m_h^2 \propto \Lambda^2$$

- Rare B-meson Decays

$B_s \to \mu^+\mu^-$:

$$Exp : 3.2^{+1.5}_{-1.2} \times 10^{-9}$$
$$SM : (3.2 \pm 0.2) \times 10^{-9}$$

$b \to s\gamma$:

$$Exp : (3.43 \pm 0.22) \times 10^{-4}$$
$$SM : (3.15 \pm 0.23) \times 10^{-4}$$

- Muon Anomalous Magnetic Moment (muon $g-2$)

$$\vec{\mu} = g_\mu \left(\frac{q}{2m}\right) \vec{S}, \;\; g_\mu = 2$$

$$a_\mu = \frac{1}{2}(g_\mu - 2) \Rightarrow a_\mu = 0$$

$$a_\mu^{exp} = 11659208.9(6.3) \times 10^{-10}$$

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{SM}$$

$$\Delta a_\mu = (28.7 \pm 8.0) \times 10^{-10}$$

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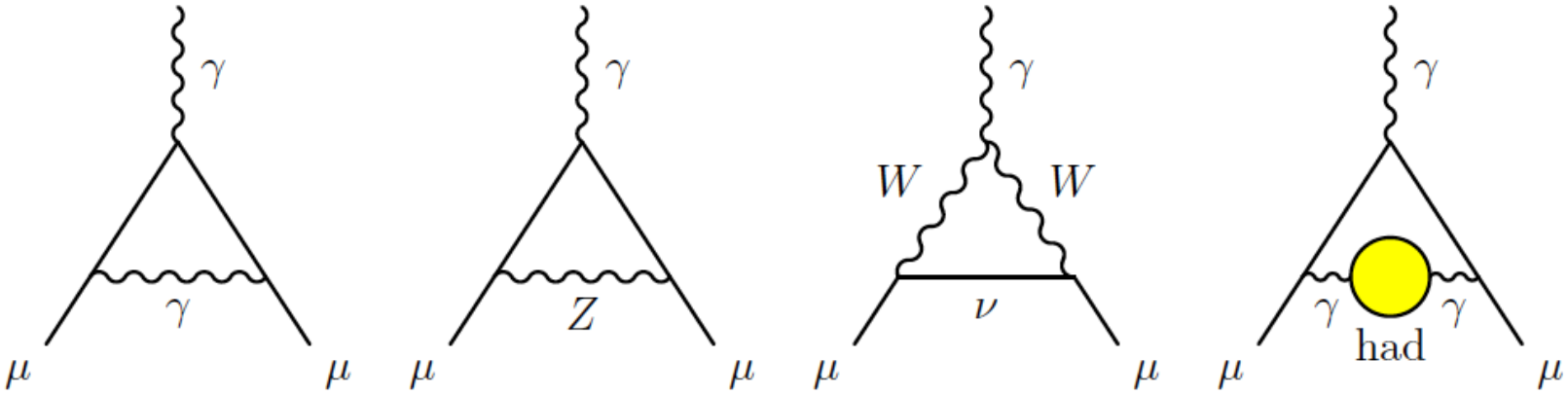
Muon $g-2$ in the SM



$$a_\mu^{QED} \approx 11658471.895 \times 10^{-10}$$

$$a_\mu^{EW} \approx 15.36 \times 10^{-10}$$

$$a_\mu^{had} \approx 10.5 \times 10^{-10}$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$

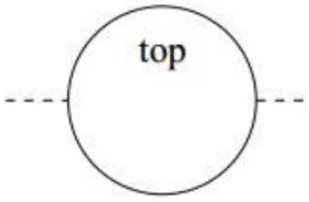
$$a_\mu^{SM} \approx 11659182 \times 10^{-10}$$

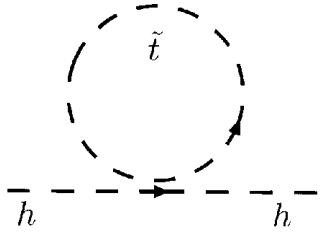
MSSM

- Gauge hierarchy problem

MSSM

- Gauge hierarchy problem





MSSM

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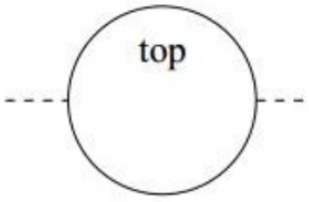
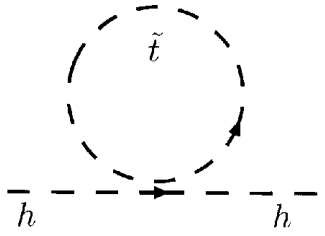
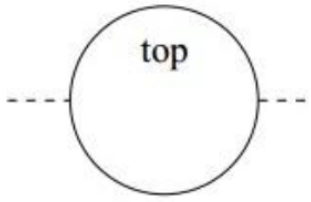


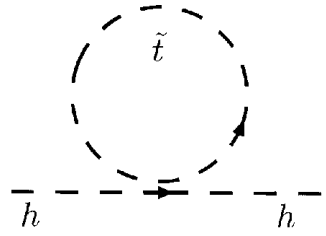


- Gauge coupling unification

MSSM

- Gauge hierarchy problem





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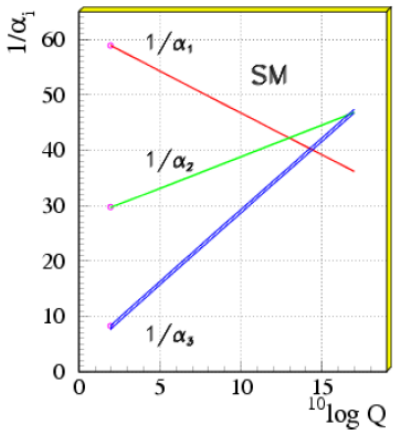
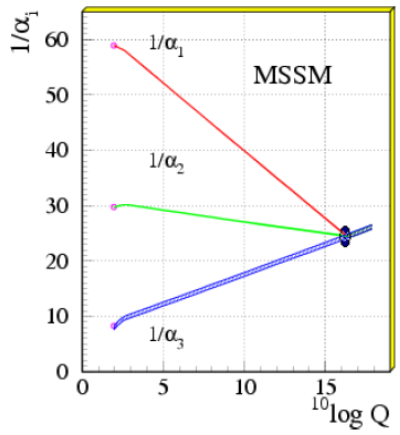
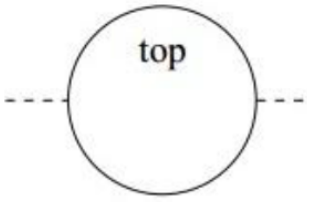
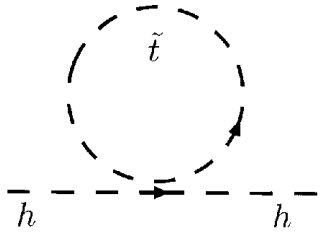




MSSM

- Gauge hierarchy problem





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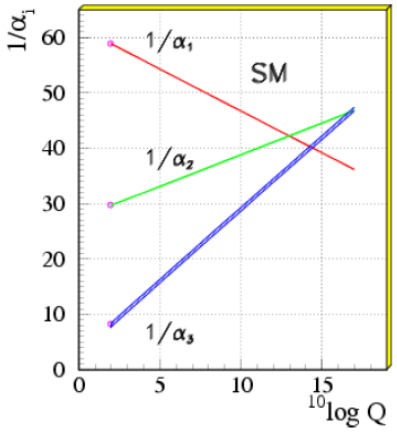
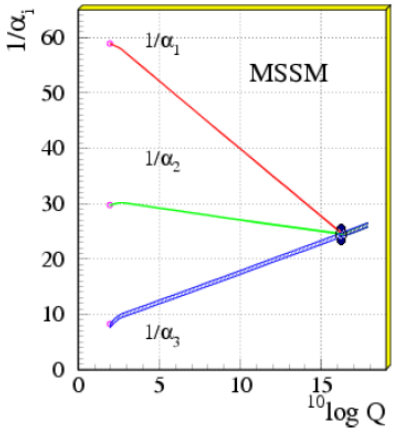
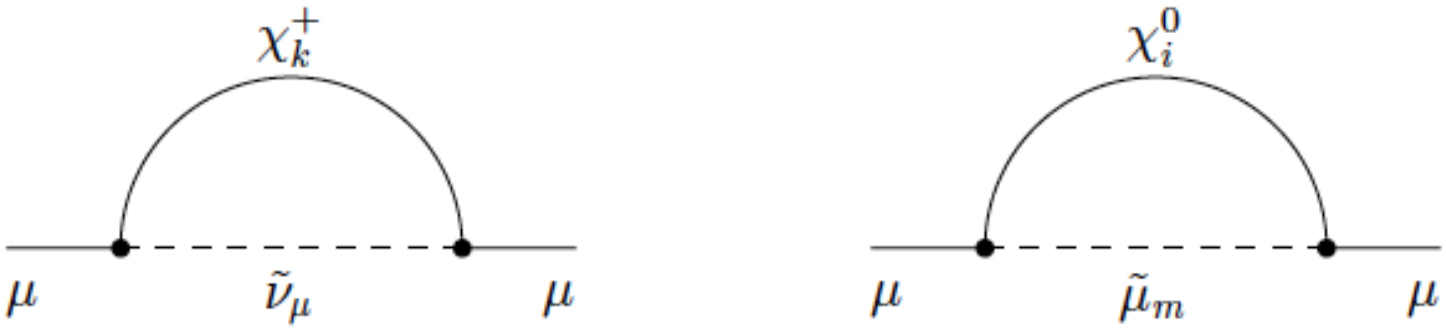




- $R-$parity

$$R = (-1)^{2S+3B-L}$$

Muon $g-2$ in MSSM



$$\Delta a_\mu = \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\mu}_L}^2}\left[\frac{f_\chi(M_2^2/m_{\tilde{\mu}_L}^2) - f_\chi(\mu^2/m_{\tilde{\mu}_L}^2)}{M_2^2-\mu^2}\right]$$

$$+\frac{\alpha m_\mu^2 \mu M_1 \tan\beta}{4\pi \cos^2\theta_W (m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_R}^2)}\left[\frac{f_N(M_1/m_{\tilde{\mu}_R}^2)}{m_{\tilde{\mu}_R}^2} - \frac{f_N(M_1^2/m_{\tilde{\mu}_L}^2)}{m_{\tilde{\mu}_L}^2}\right]$$

$$\{M_1, M_2, \mu, \tan\beta, m_{\tilde{\mu}_L}, m_{\tilde{\mu}_R}\}$$

CMSSM and NUHM

CMSSM: $\{m_{16} = m_{10} = m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)\}$

NUHM : $\{m_{16},\ m_{10},\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)\}$

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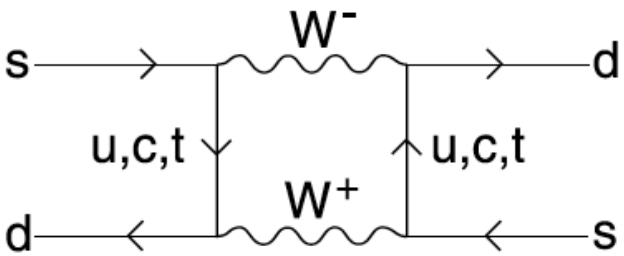

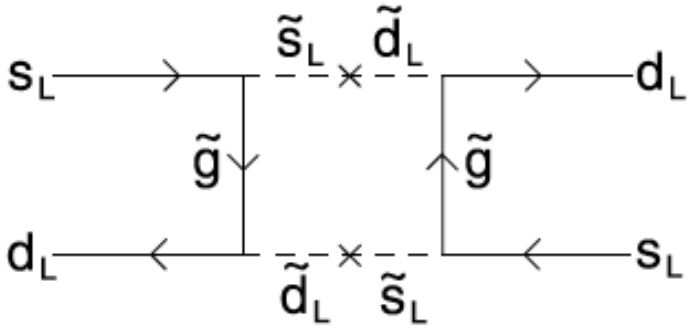

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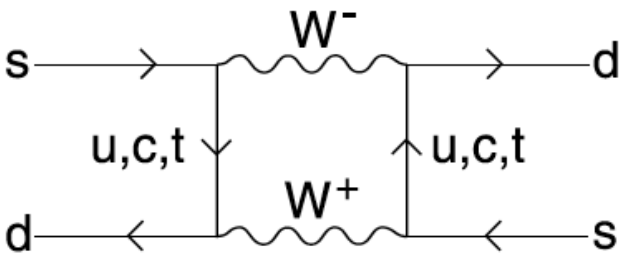
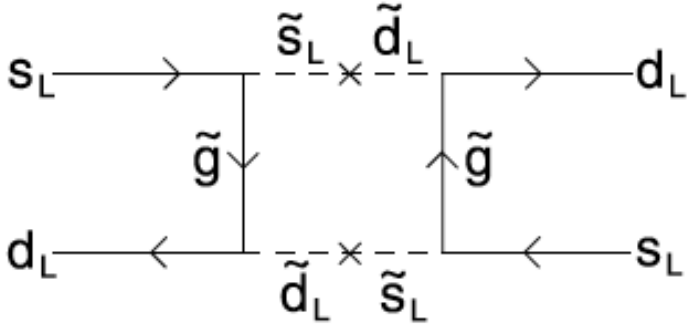




$\Delta m_K / m_K = (7.01 \pm 0.01) \times 10^{-5}$

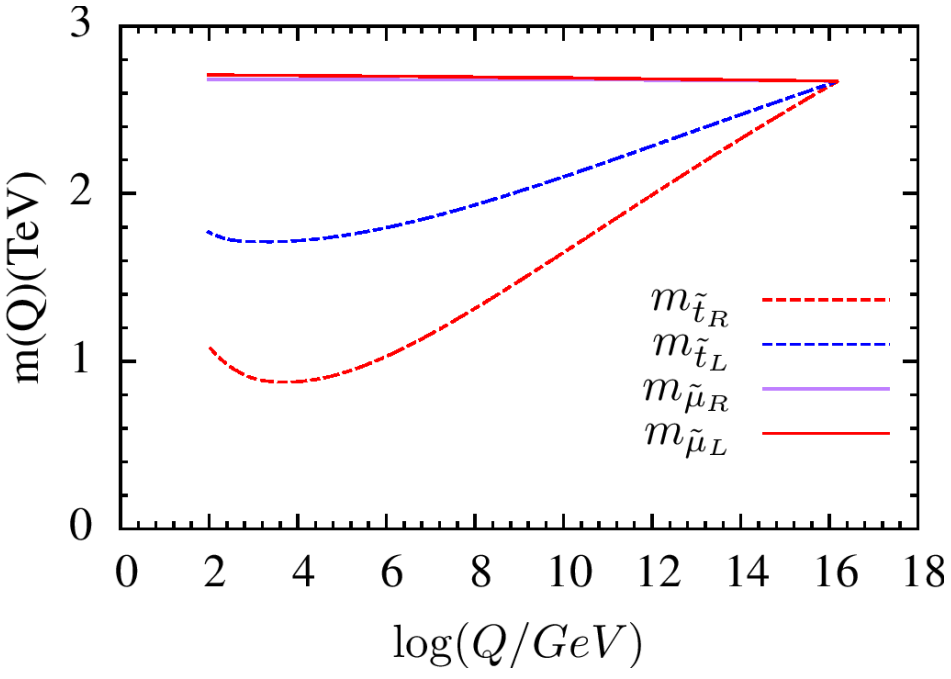
$\Delta m_K \sim \Delta m_{\tilde{q}_1 \tilde{q}_2}$

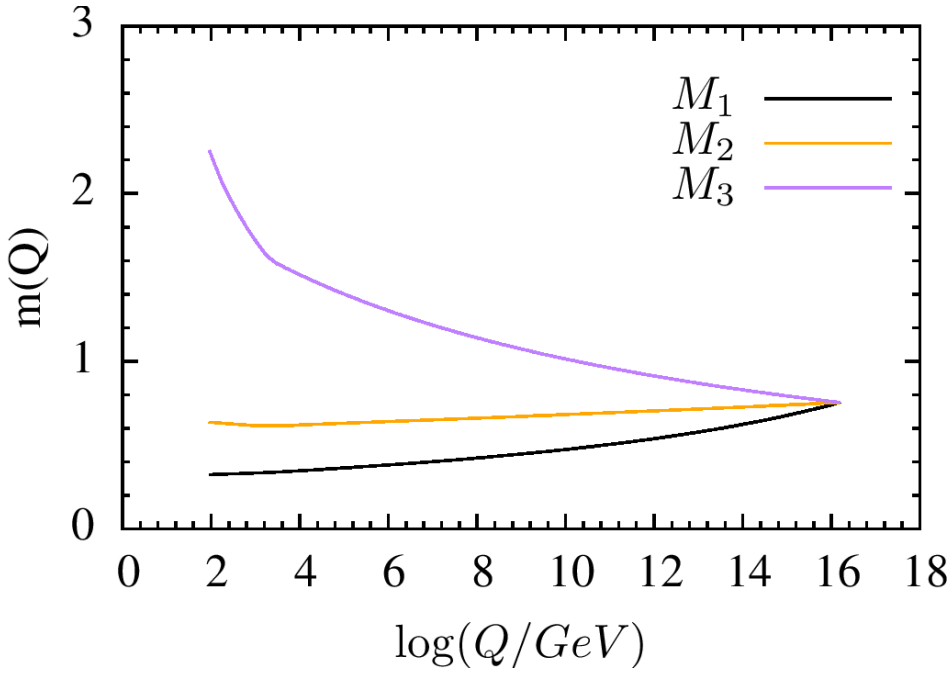
$m_{\tilde{q}_1} \approx m_{\tilde{q}_2}$

$V_{td}, V_{ts} \ll V_{ds}$

CMSSM and NUHM

$m_0 = 2671$ GeV, $M_{1/2} = 754$ GeV, $A_0 = -5800$ GeV, $\tan\beta = 46.1$





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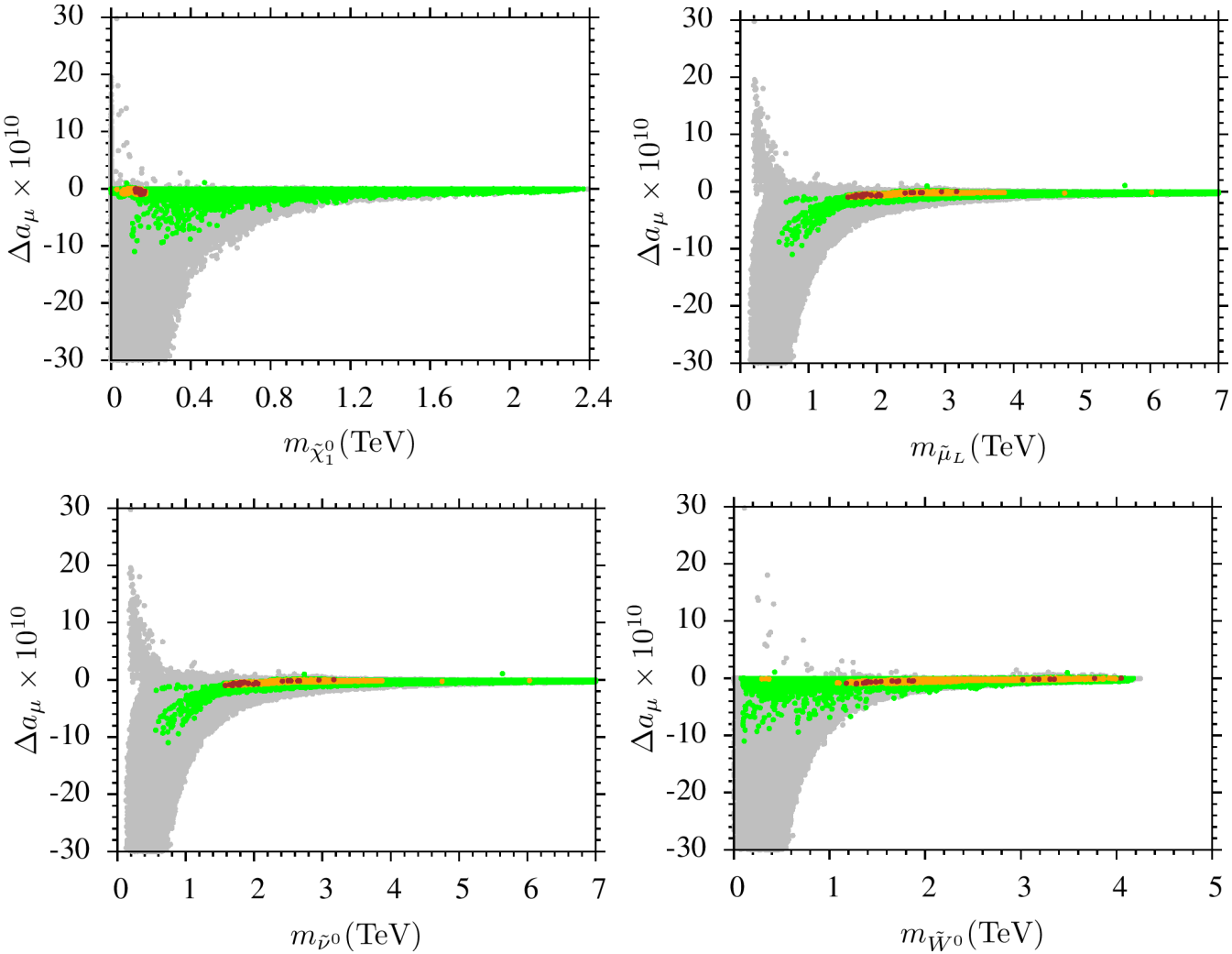
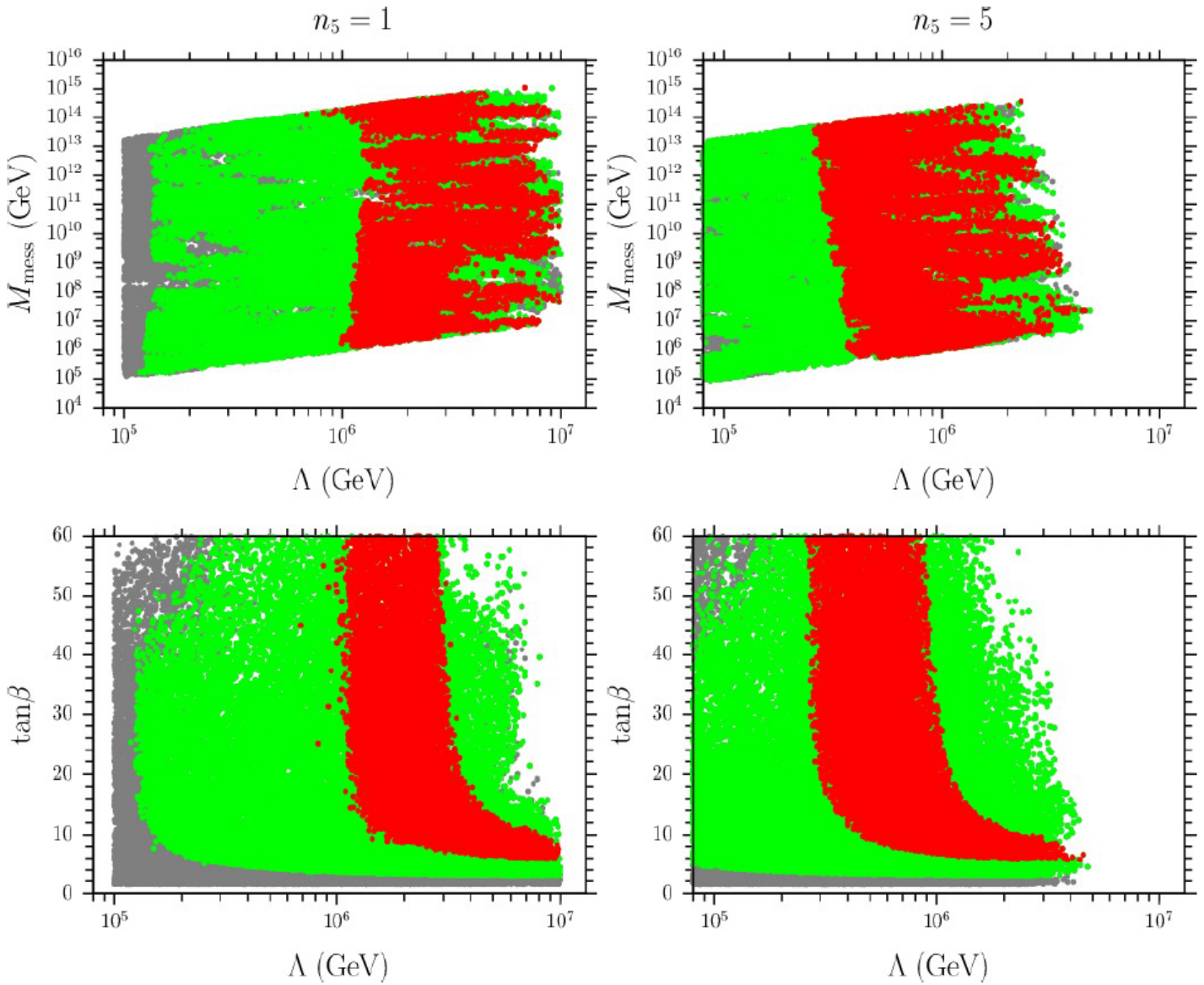


Demir, D. and Un, C.S., Phys. Rev. D**90**, 095015 (2014)

Minimal GMSB[1]



[1] Ajaib, Gogoladze, Nasir, Shafi, Phys. Lett. B **713**, 462 (2012)

Minimal GMSB

	Point 1	Point 2	Point 3
Λ	1×10^6	4.22×10^5	1.5×10^6
M_{mess}	1.74×10^{14}	9.02×10^{12}	1.9×10^6
n_5	1	5	1
$\tan\beta$	42	60	46
μ	7873	5802	3678
m_h	**125**	**125.2**	**125.1**
m_H	9930	4865	5141
m_A	9865	4833	5107
$m_{H^\pm}$	9930	4866	5142
$m_{\tilde{\chi}^0_{1,2}}$	**1398**, 2619	2924, 5307	2405, 3732
$m_{\tilde{\chi}^0_{3,4}}$	7775, 7775	5833, 5836	3735, 4449
$m_{\tilde{\chi}^\pm_{1,2}}$	2624, 7711	5315, 5840	3811, 4364
$m_{\tilde{g}}$	6689	12312	10613
$m_{\tilde{u}_{L,R}}$	15956, 14113	12014, 11276	14064, 13301
$m_{\tilde{t}_{L,R}}$	13637, 9847	10289, 8994	13027, 11873
$m_{\tilde{d}_{L,R}}$	15956, 13540	12015, 11151	14064, 13213
$m_{\tilde{b}_R}$	12233	9720	12421
$m_{\tilde{\nu}_1}$	9281	4885	5112
$m_{\tilde{\nu}_3}$	8722	4424	5009
$m_{\tilde{e}_{L,R}}$	9290, 6774	4900, 2962	5133, 2640
$m_{\tilde{\tau}_{L,R}}$	8706, 5109	4407, **783**	4991, 2306
$m_{\tilde{G}}$	42	0.916	$\mathbf{6.86 \times 10^{-7}}$

Non-Universality

- $SU(2)$, $SO(3)$, $SU(3)^2$
- D-term Contribution $= 0$:
  - $SU(2) : \phi \leftrightarrow \bar{\phi}$
  - $SO(3) : \text{Real VEV or } Z_2 \times Z_2$
- $SU(2)$: $(q_1, q_2, q_3) \equiv \mathbf{2} + \mathbf{1}$, $m_{q_1} = m_{q_2} \neq m_{q_3}$
- $SO(3) : (q_1, q_2, q_3) \equiv \mathbf{3} \xrightarrow{\text{Heavy top}} \mathbf{2} + \mathbf{1}$

$$m_{q_1} \approx m_{q_2} \neq m_{q_3}$$

[2] Babu, Gogoladze, Shafi, Un, Phys. Rev. D **90**, 116002 (2014)
Babu, Gogoladze, Raza, Shafi, Phys. Rev. D **90**, 056001 (2014)

Non-Universality

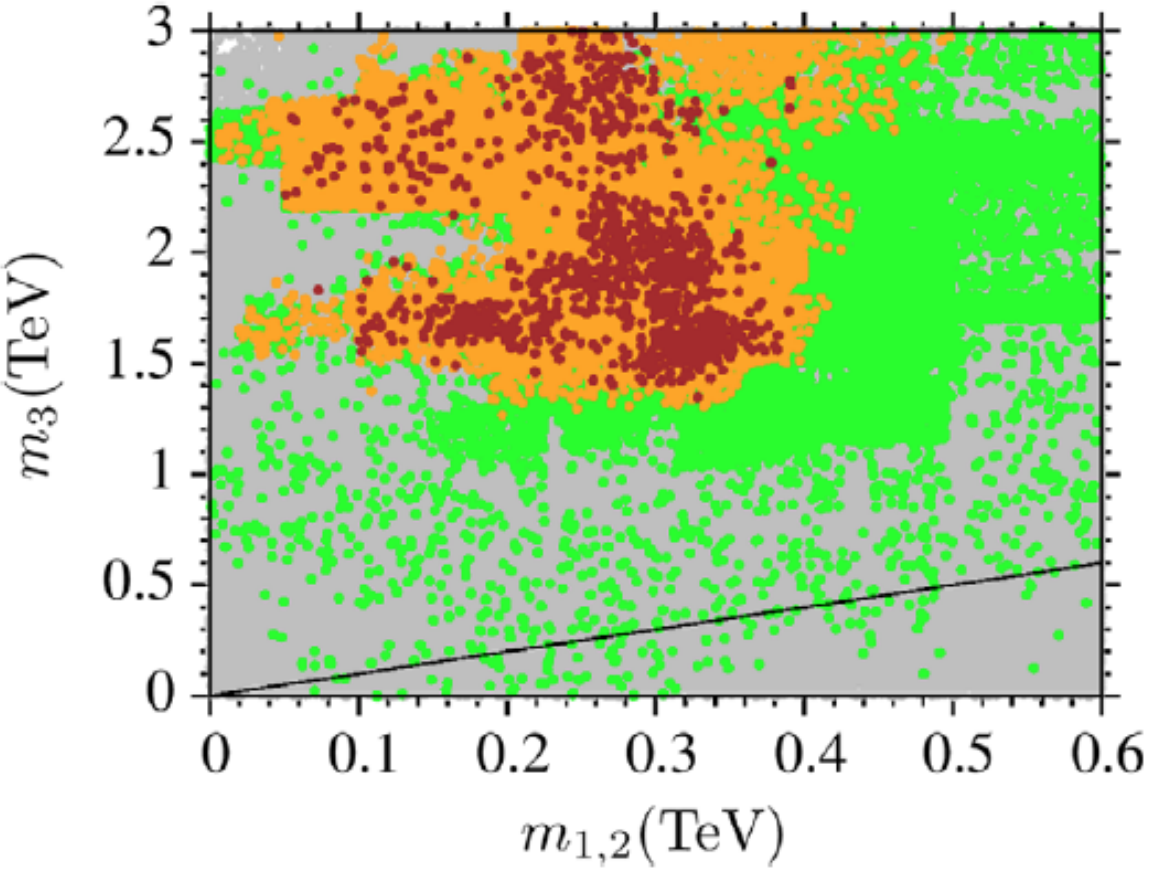
3. Family SSB Mass Term	m_3	$0 \longrightarrow 3$ TeV
1. ve 2. Family SSB Mass Term	$m_{1,2}$	$0 \longrightarrow 3$ TeV
CP – odd Higgs Mass	m_A	$0 \longrightarrow 3$ TeV
Bilineer Higgs Mixing	μ	$0 \longrightarrow 3$ TeV
Gaugino SSB Mass	$M_{1/2}$	$0 \longrightarrow 2$ TeV
SSB Trilinear Scalar Term	A_0/m_3	$-3 \longrightarrow 3$ TeV
Higgs VEV Ratio	$\tan\beta$	$2 \longrightarrow 60$

Experimental Constraints

$$m_{\tilde{\chi}_1^\pm}\ (\text{chargino}) \geq 103.5\ \text{GeV},$$
$$123 \leq m_h\ (\text{lightest Higgs boson}) \leq 127\ \text{GeV},$$
$$m_{\tilde{\tau}}\ (\text{stau}) \geq 105\ \text{GeV},$$
$$m_{\tilde{g}}\ (\text{gluino}) \geq 1000\ \text{GeV},$$
$$m_{\tilde{t}_1}\ (\text{light stop}) \geq 175\ \text{GeV},$$
$$0.8 \times 10^{-9} \leq BR(B_s \to \mu^+\mu^-) \leq 6.2 \times 10^{-9}(2\sigma),$$
$$2.99 \times 10^{-4} \leq BR(b \to s\gamma) \leq 3.87 \times 10^{-4}(2\sigma),$$
$$0.15 < \frac{BR(B_u \to \tau\nu_\tau)MSSM}{BR(B_u \to \tau\nu_\tau)SM} < 2.41\ (3\sigma),$$
$$,$$
$$0.0913 \leq \Omega_{\text{CDM}} h^2 \leq 0.1363$$

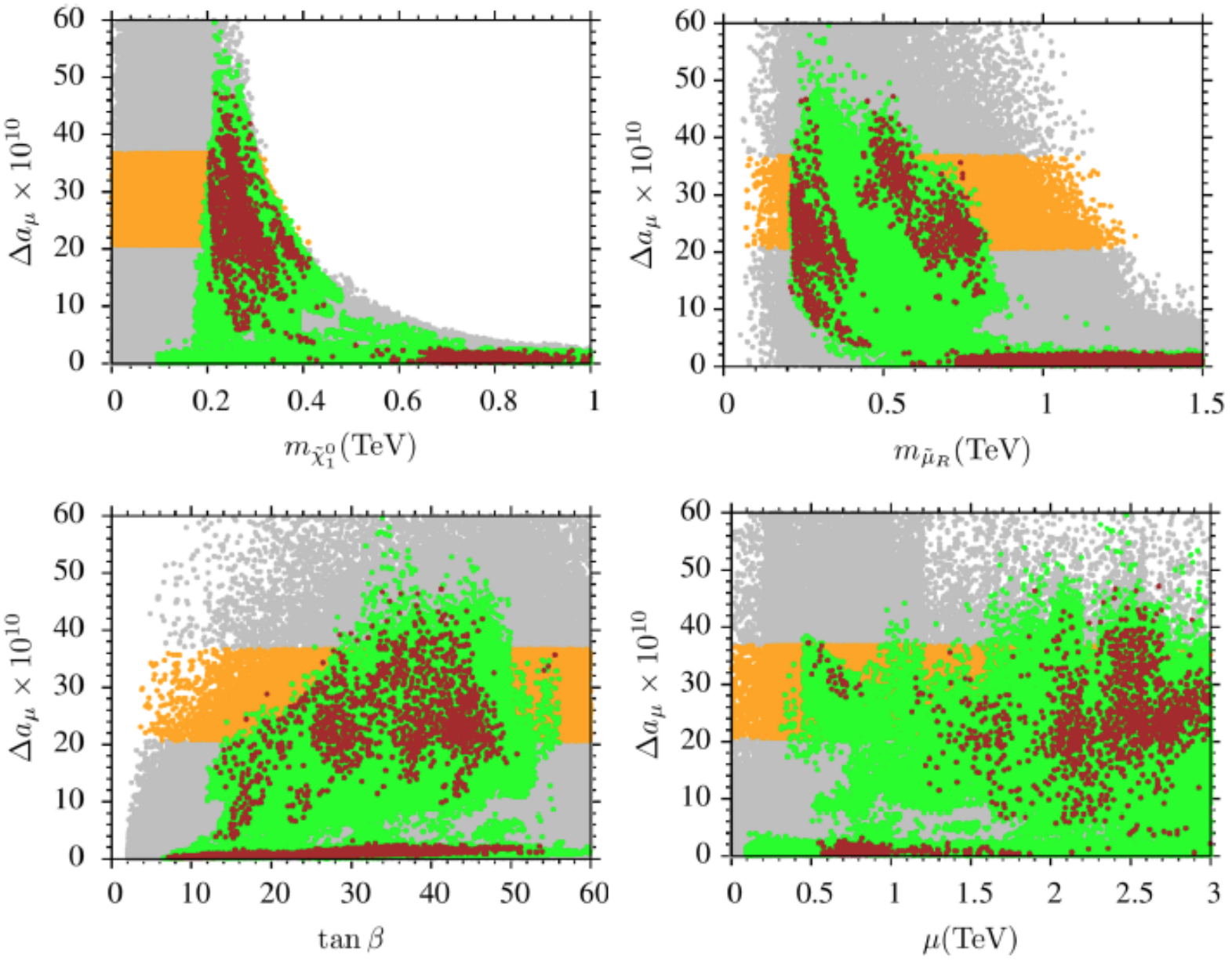
REWSB, LSP neutralino

Non-Universality



All points are consistent with REWSB and Neutralino LSP. Green points satisfy mass bounds and B-Physics constraints, yellow points form a subset of green, and they are compatible with muon $g-2$. Brown points are a subset of yellow and they are consistent with the WMAP bound.

Non-Universality



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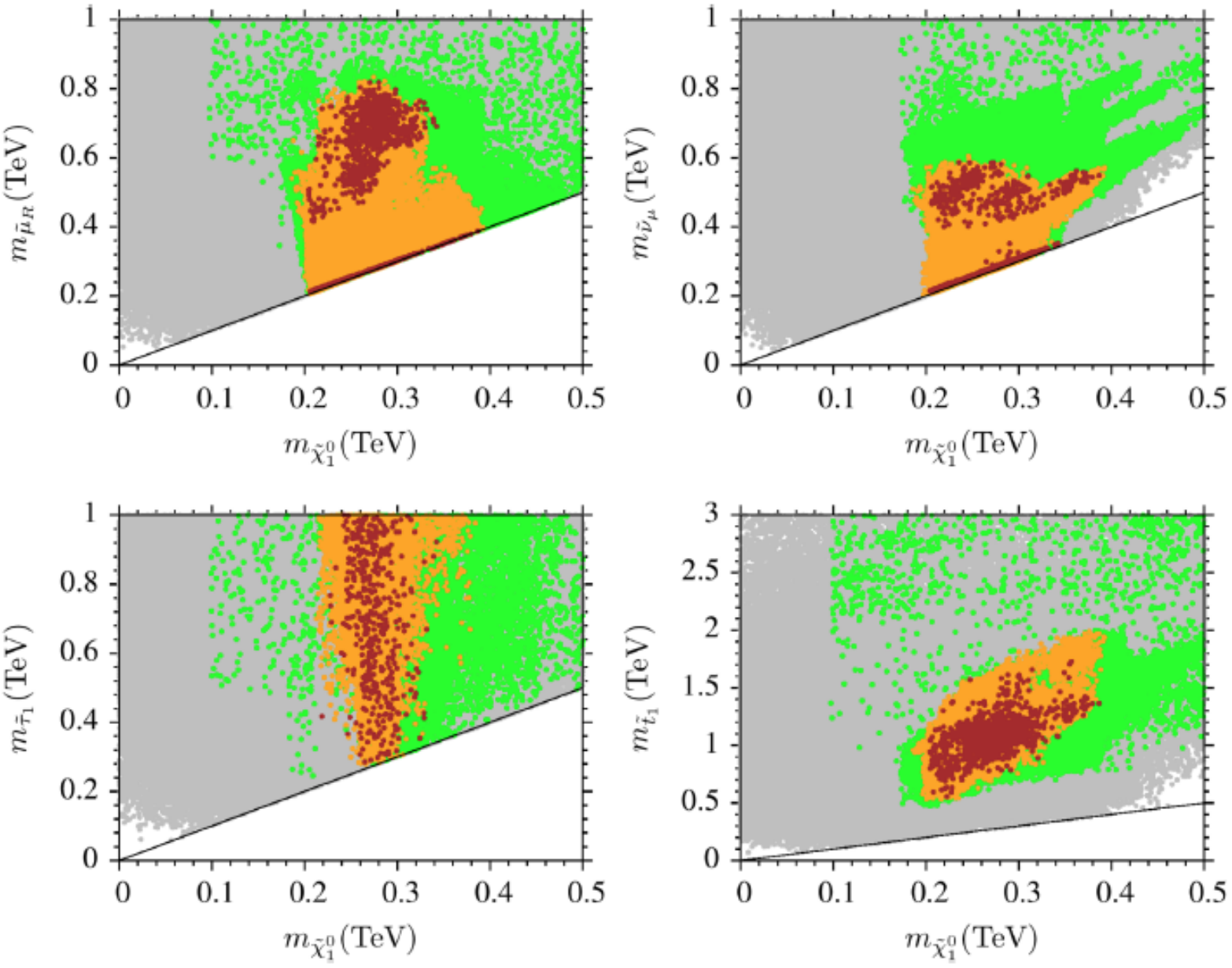

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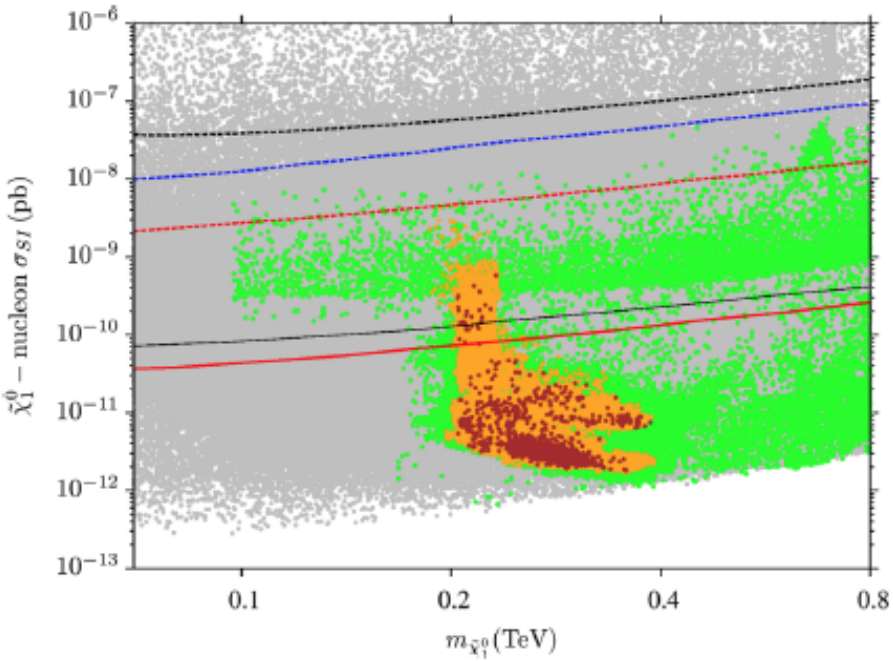
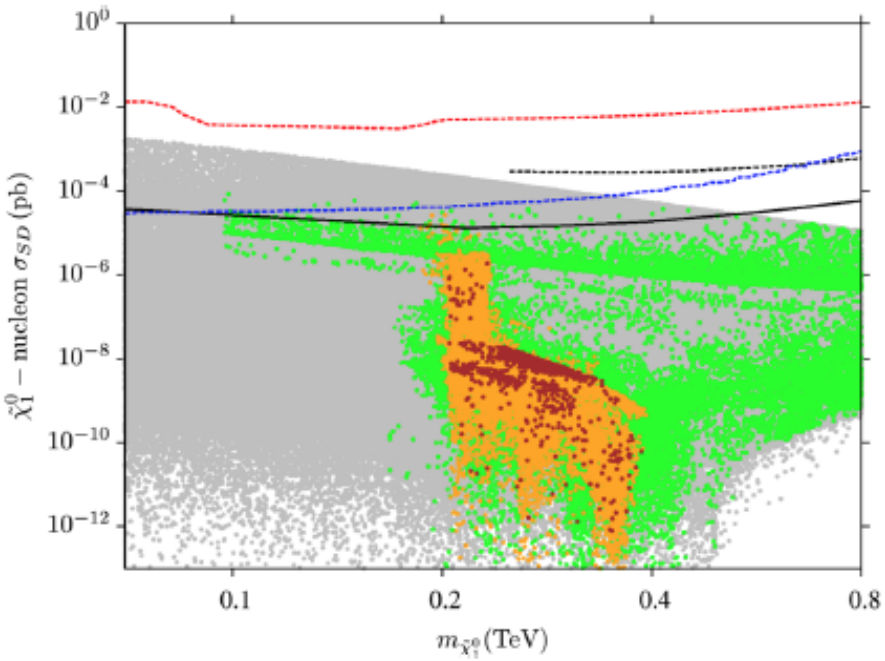
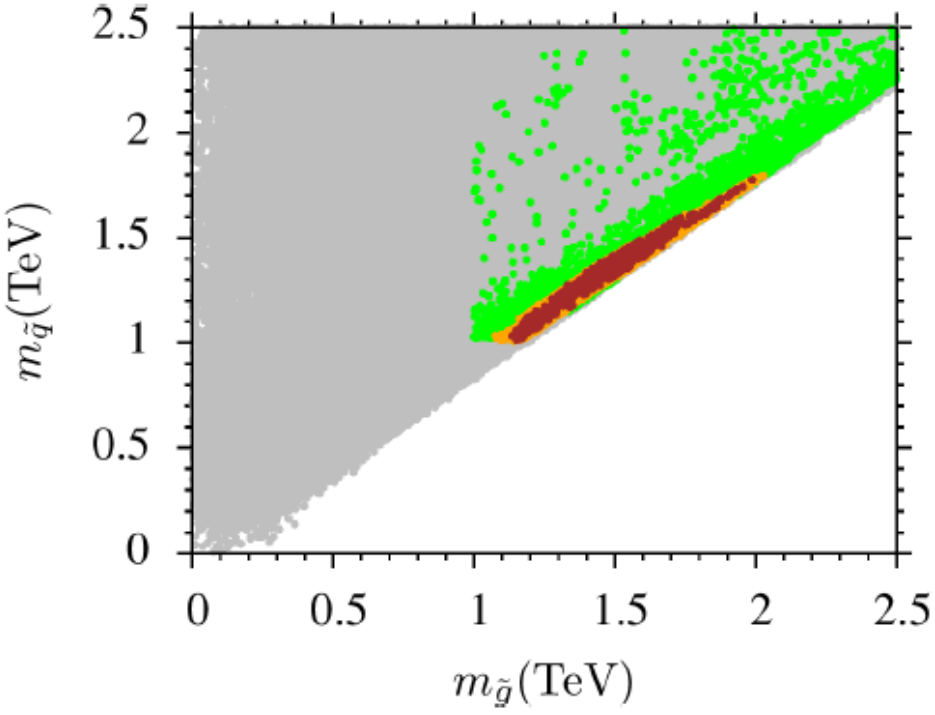
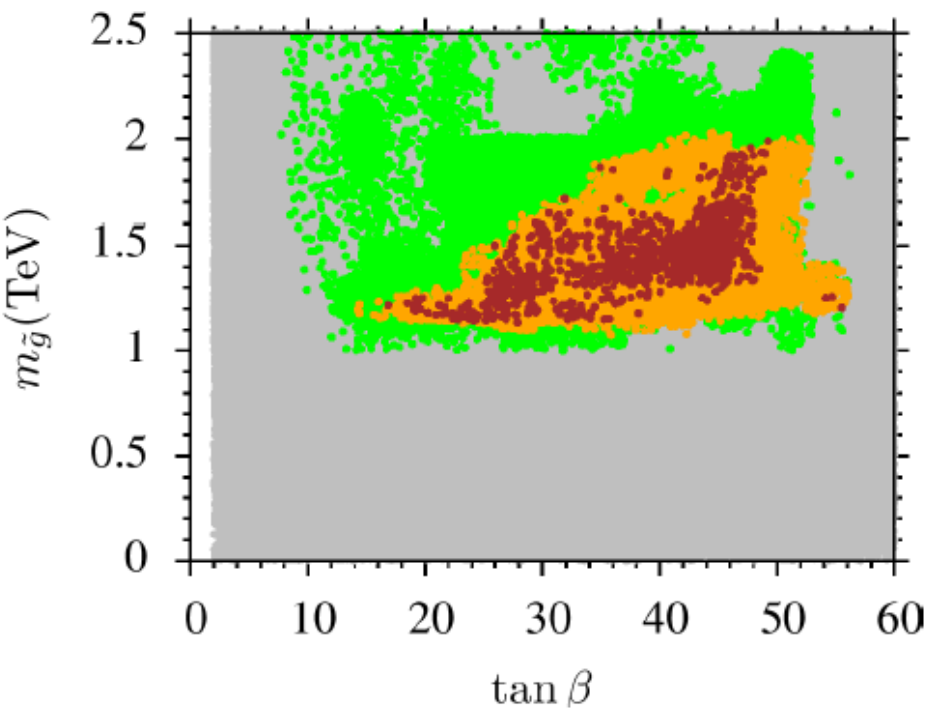




Black dashed (solid) lines represents the current (future) CDMS results, while red dashed (solid) displays the current (future) XENON results

Non-Universality





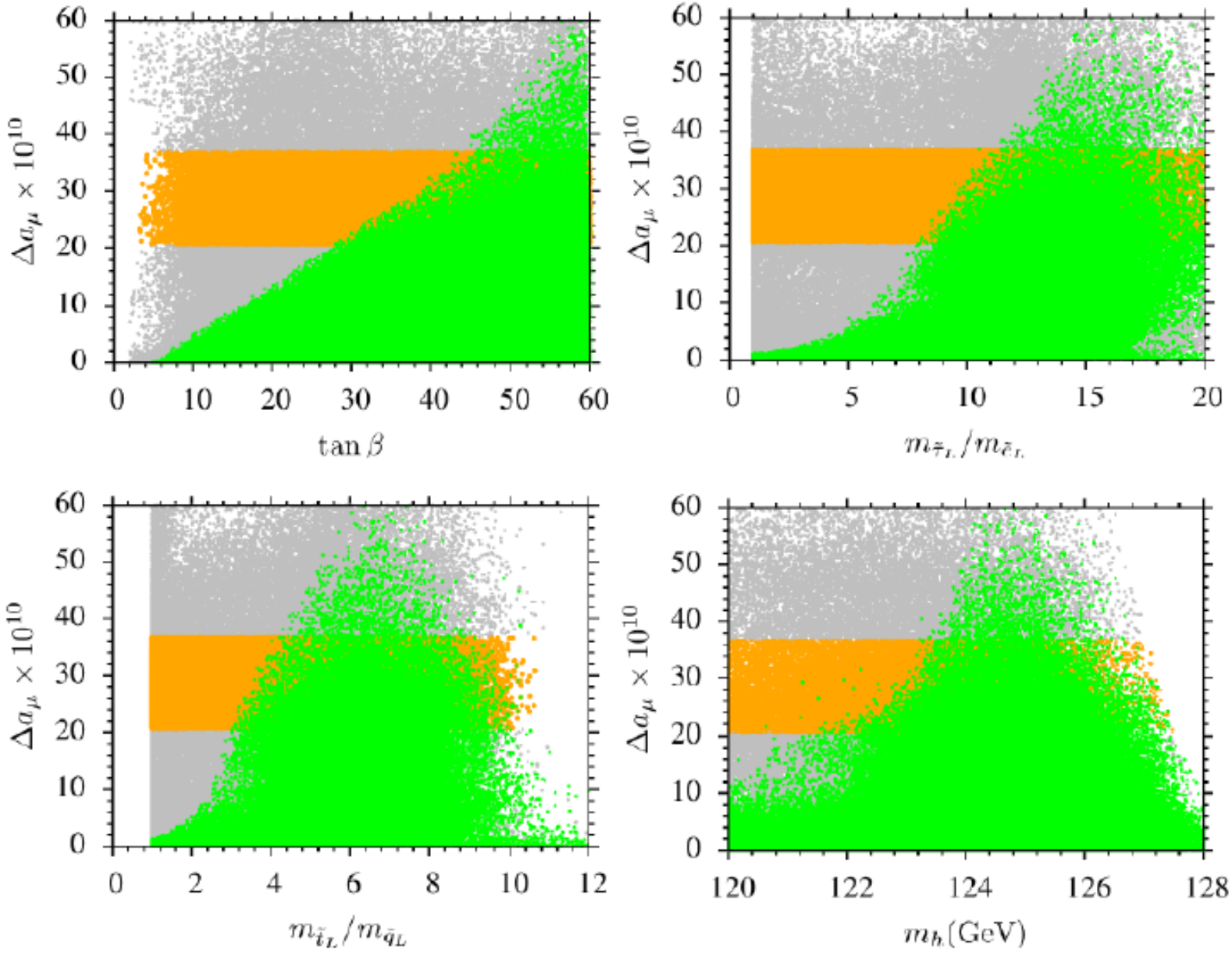
GMSB[3]

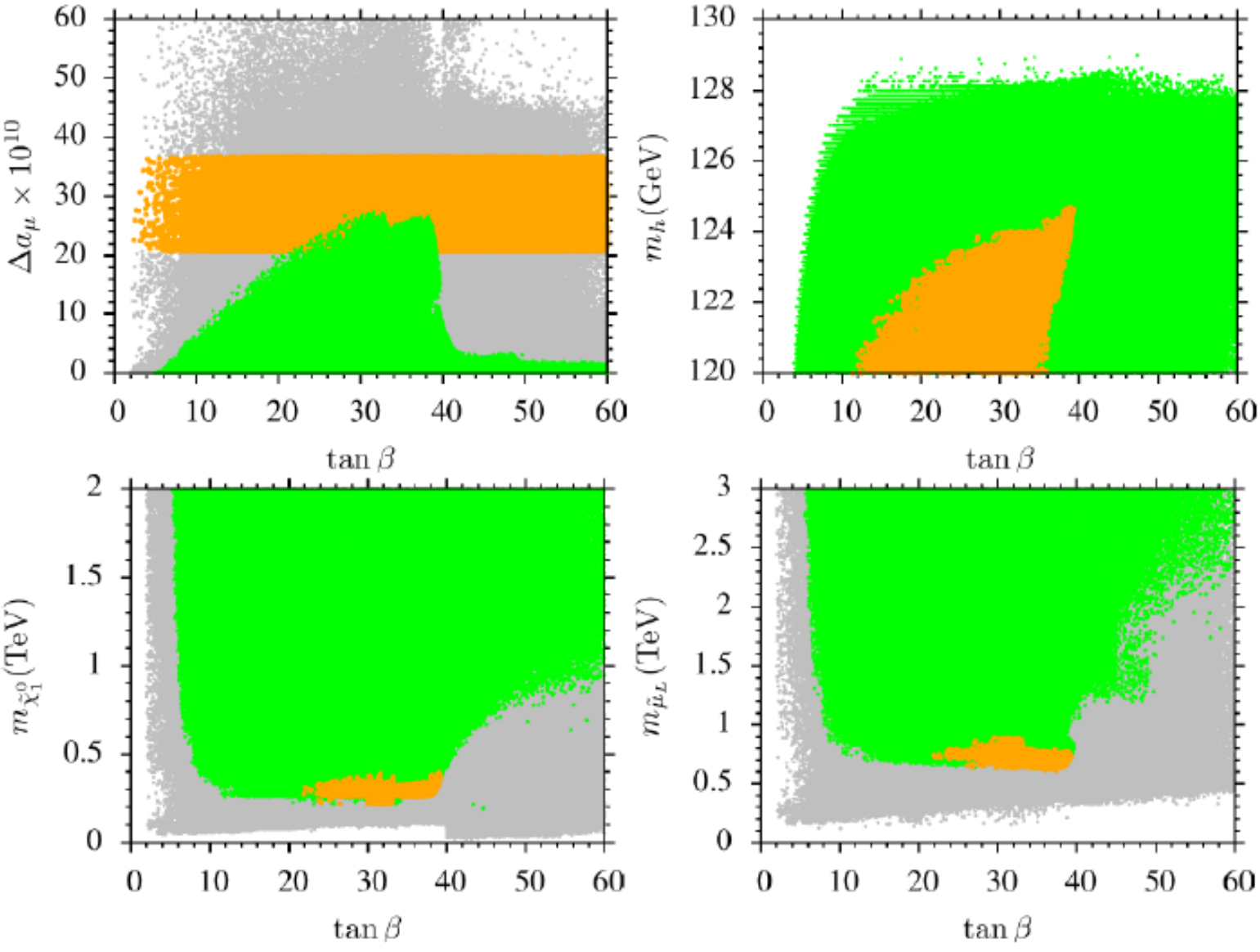
		Q_3	U_3^c	d_3^c	L_3	e_3^c	$\nu_{\tau 3}$
	$U(1)_Y$	$1/6$	$-2/3$	$1/3$	$-1/2$	1	0
Model I	$U(1)_1$	$-\eta$	η	η	$-\eta$	η	η
Model II	$U(1)_2$	η	$-\eta$	$-\eta$	-3η	3η	3η

$$M_i = N_5 \Lambda \frac{\alpha_i}{4\pi}, \quad m^2 = 2N_5\Lambda^2 \sum_i C_i \left(\frac{\alpha_i}{4\pi}\right)^2$$

$$C_1 = \frac{4}{3}, \quad C_2 = \frac{3}{4}, C_3 = \frac{3}{5}\frac{Y}{2}, \quad C_4 = 0, \ \eta^2$$

[3] Gogoladze, Shafi, Un, arXiv:1509.07906 [hep-ph]


$\Delta a_\mu \times 10^{10}$
$\tan\beta$
$m_{\tilde{\tau}_L}/m_{\tilde{e}_L}$
$m_{\tilde{t}_L}/m_{\tilde{q}_L}$
m_h(GeV)


$\Delta a_\mu \times 10^{10}$
$\tan\beta$
m_h(GeV)
$\tan\beta$
$m_{\tilde{\chi}_1^0}$(TeV)
$\tan\beta$
$m_{\tilde{\mu}_L}$(TeV)
$\tan\beta$

Non-Minimality: BLSSM[4]

- Gauged $B - L$ symmetry

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

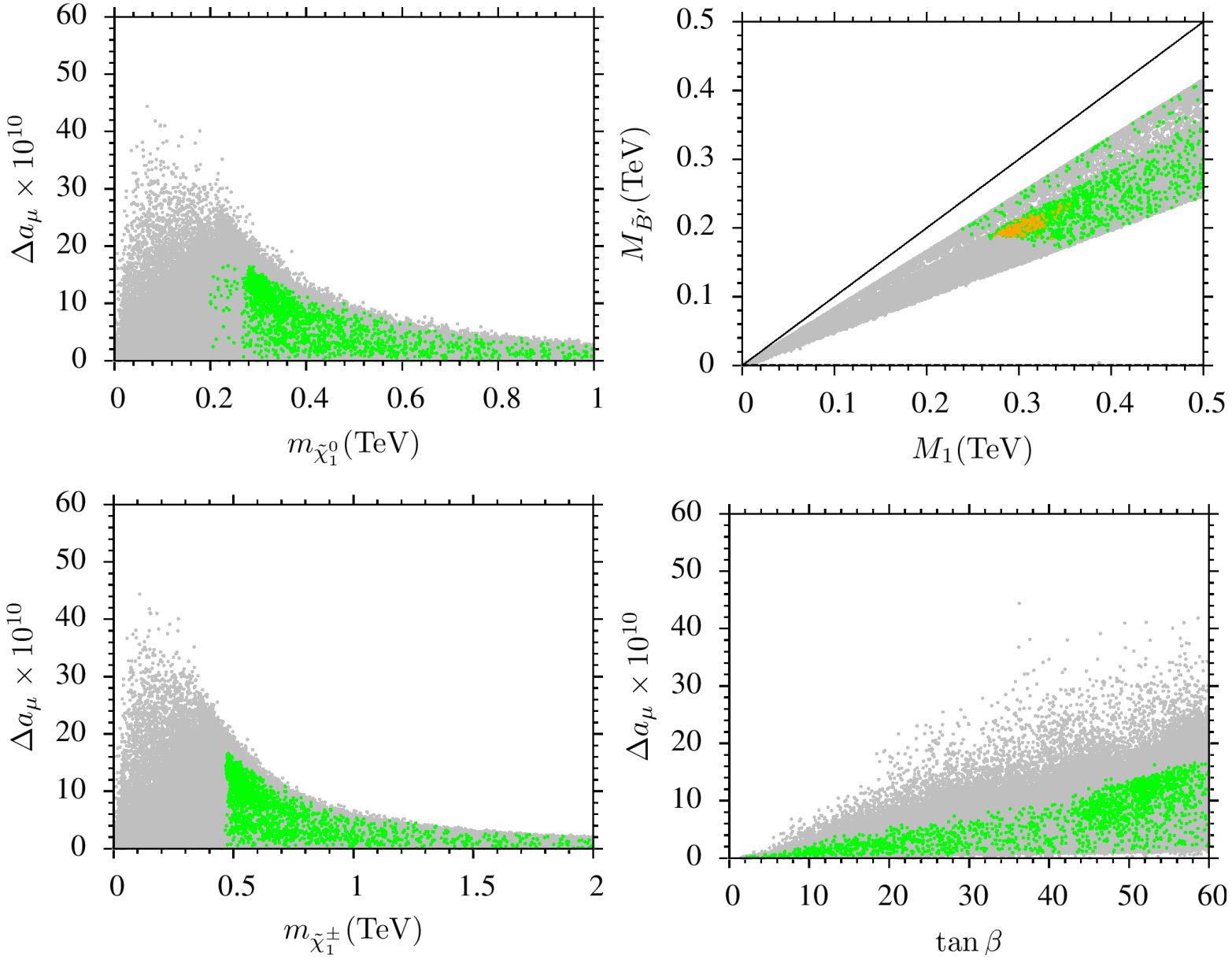
- R-parity connection
- Spontaneous symmetry breaking

SM singlet Higgs fields: $\mathcal{X}_{1,2}$

- Right-handed neutrinos

Seesaw, Inverse Seesaw

[4] Khalil and Un, arXiv:1509.05391 [hep-ph]


$\Delta a_\mu \times 10^{10}$
$m_{\tilde{\chi}_1^0}$(TeV)
$M_{\tilde{B}'}$(TeV)
M_1(TeV)
$m_{\tilde{\chi}_1^\pm}$(TeV)
tan β

Conclusion

- The tension between muon $g-2$ and the Higgs boson mass:

  Minimality, Universality!

- Non-universality in scalars and gauginos
- sMSSM, BLSSM, ...