SUSY GUTs from Muon $g-2$ Window

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in collaboration with
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Outline

- The Standard Model
- SUSY and MSSM
- Muon $g-2$ in MSSM
- SUSY GUTs - SO(10)
- Flavor Symmetry vs. Left-Right Symmetry
- Probing Muon $g-2$
  - Chargino-Neutralino
  - Dark Matter
  - CP-odd Higgs Boson
- Conclusion and Perspectives

The Standard Model

- The SM is a gauge theory of fields of spin 0, 1/2 and 1 based on $SU(3)_c \times SU(2)_L \times U(1)_Y$

  $SU(3)_c \rightarrow$ QCD, confinement

  $SU(2)_L \times U(1)_Y \rightarrow$ electroweak interactions, chiral, spontaneous symmetry breaking

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\mathrm{em}}$$

- The SM is one of the most successful theories in physics. It has been tested rigorously.

  $W^{\pm}, Z$ bosons

  Rare B-meson decays: $B_s \rightarrow \mu^+\mu^-$, $b \rightarrow s\gamma$

  The Higgs Boson

The Standard Model

SM is not a fundamental theory!

- Gauge Hierarchy problem: $\delta m_h^2 \propto \Lambda^2$
- The Higgs vacuum stability: $\lambda < 0$ for $\Lambda \gtrsim 10^{10}$ GeV

  Stability Condition: $m_h > (129.6 \pm 1.5)$ GeV
- The gauge symmetry
- Neutrino masses and mixings
- Dark matter

The Standard Model

- Muon $g-2$

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = \begin{cases} (25.1 \pm 5.1) \times 10^{-10} & 2021 \\ (24.5 \pm 4.9) \times 10^{-10} & 2023 \end{cases}$$

★ *BMW Collaboration*!

$$a_\mu({\rm HVP}) = 711 \times 10^{11} \qquad \sim 3\sigma \text{ from SM}$$

- Lepton Flavor Universality

$$\Delta a_e = \begin{cases} (0.48 \pm 0.30) \times 10^{-12} & (1.7\sigma) \\ (-0.88 \pm 0.36) \times 10^{-12} & (-2.5\sigma) \end{cases}$$

SUSY is a symmetry that relates fermions and bosons

$$Q\,|fermion\rangle = |boson\rangle\,, \quad Q\,|boson\rangle = |fermion\rangle$$

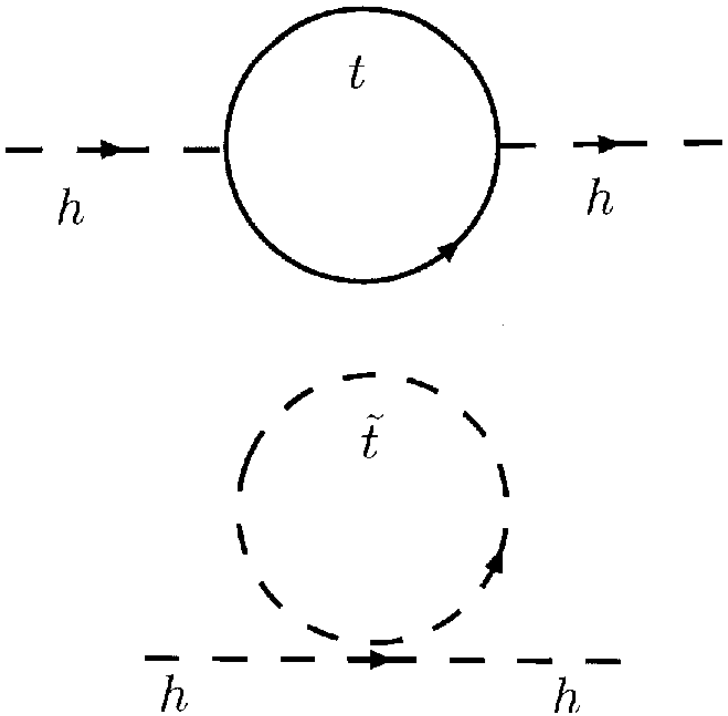
Holomorphy Condition

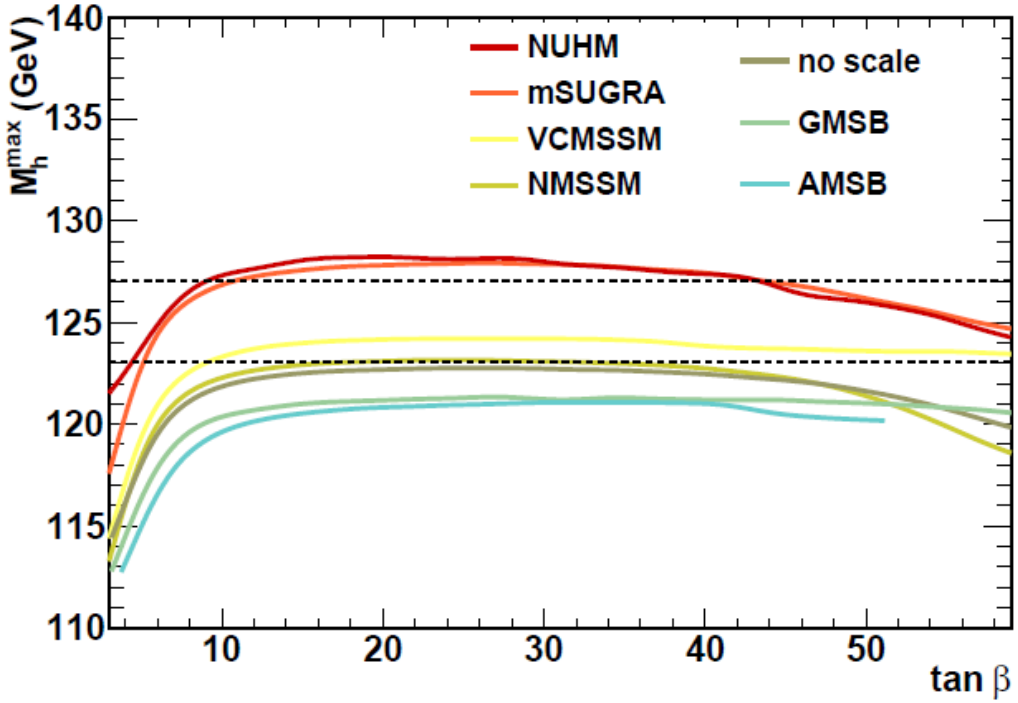
Two Higgs doublets $H_u, H_d \Rightarrow h, H, A, H^{\pm}$

$h \sim H_{\mathrm{SM}}$ when $m_h \ll m_H \sim m_A$ (Decoupling Limit)

SUSY and MSSM

Resolution to the gauge hierarchy problem





$m_h \lesssim 130$ GeV

$$\Delta m_h^2 \simeq \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta}\frac{\mu A_t}{M_{\rm SUSY}^2}\left[\frac{A_t^2}{M_{\rm SUSY}^2}-6\right]+$$

$$\frac{y_b^4 v^2}{16\pi^2}\sin^2\beta\frac{\mu^3 A_b}{M_{\rm SUSY}^4}+\frac{y_\tau^4 v^2}{48\pi^2}\sin^2\beta\frac{\mu^3 A_\tau}{m_{\tilde\tau}^4}\ .$$

SUSY and MSSM

- R-Parity: $R = (-1)^{3B+L+2S} \Rightarrow$ Stable LSP

  sneutrino, gravitino, neutralino

- Radiative Electroweak Symmetry Breaking

$$V_H = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_u^d|^2 - (bH_u^0 H_d^0 + \text{c.c.})$$

$$+\frac{1}{8}(g + g')(|H_u^0|^2 - |H_d^2|)^2$$

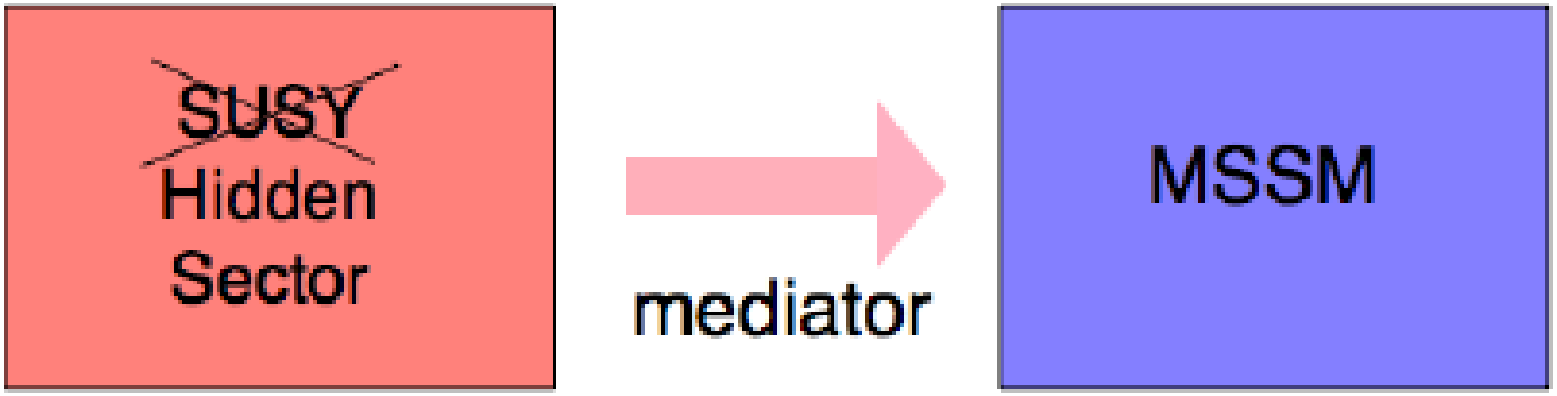
$$2b < (|\mu|^2 + m_{H_u}^2) + (|\mu|^2 + m_{H_d}^2)$$

$$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2)$$

$$m_{H_u} \neq m_{H_d}$$

$$m_{H_u} < 0, \; m_{H_u} \ll m_{H_d}$$

SUSY BREAKING



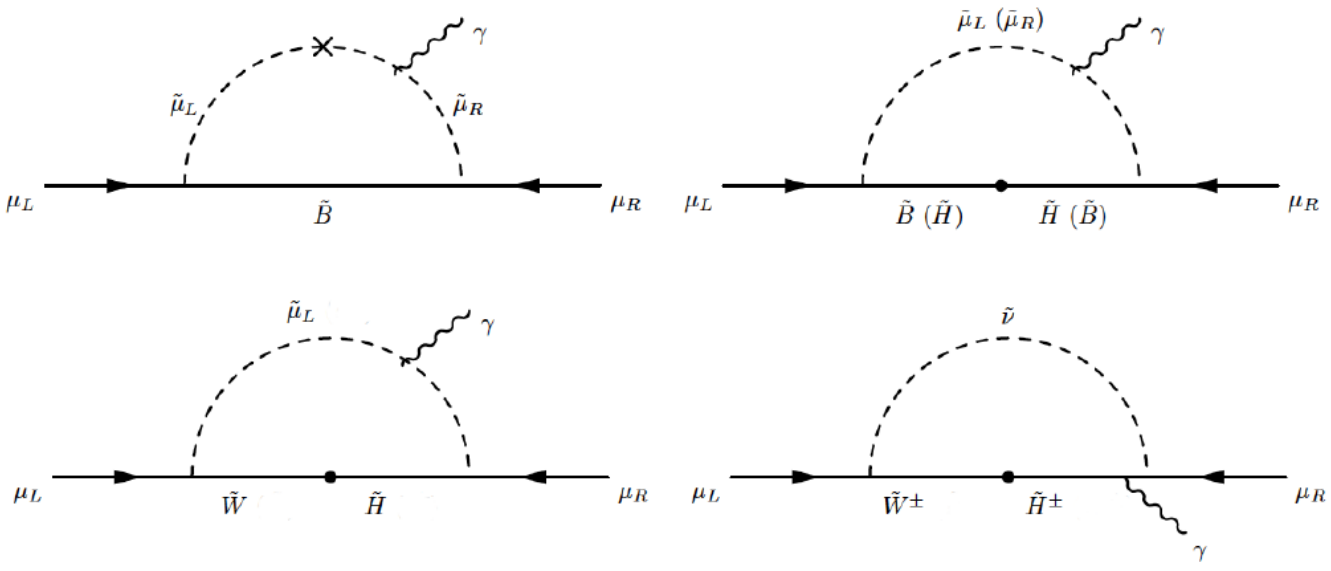
- Gravity Mediated SUSY Breking ($\Lambda \gtrsim M_{\mathrm{GUT}}$)
- Gauge Mediated SUSY Breaking ($\mathcal{O}(\mathrm{TeV}) \leq \Lambda \leq M_{\mathrm{GUT}}$)
- Anomaly Mediated SUSY Breaking ($\Lambda \gtrsim M_{\mathrm{GUT}}$)

Soft Supersymmetry breaking

$$\begin{aligned}\mathcal{L}_{\cancel{\mathrm{SUSY}}} = &-\tfrac{1}{2}(M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g}) + \mathrm{h.c.} \\ &-m_{H_u}^2 h_u^\dagger h_u - m_{H_d}^2 h_d^\dagger h_d - (b h_u h_d + \mathrm{h.c.}) \\ &-m_Q^2 \tilde{q}^\dagger \tilde{q} - m_L^2 \tilde{l}^\dagger \tilde{l} - m_u^2 \tilde{u}_R^\dagger \tilde{u}_R - m_d^2 \tilde{d}_R^\dagger \tilde{d}_R - m_e^2 \tilde{e}_R^\dagger \tilde{e}_R \\ &-(A_u \tilde{u}_R \tilde{q} h_u + A_d \tilde{d}_R \tilde{q} h_d + A_e \tilde{e}_R \tilde{l} h_d)\end{aligned}$$

MSSM + SSB = 124 parameter

Muon $g-2$ in MSSM



Low Scale	GUT Scale
$m_{\tilde{\mu}_L}, m_{\tilde{\nu}}$	m_L
$m_{\tilde{\mu}_R}$	m_R
$M_{\tilde{B}}$	M_1
$M_{\tilde{W}}$	M_2
μ	m_{H_u}, m_{H_d}
A_μ	A_0
$\tan\beta$	$\tan\beta$

$$\Delta a_\mu \approx C_\mu \ \mathrm{sign}(\mu M_i) \left(\frac{500\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right) \frac{\tan\beta}{40}\ , \qquad C_\mu = \begin{cases} \dfrac{2.4\mu}{500\ \mathrm{GeV}} \times 10^{-10} & \text{for BLR}\ , \\ 1.2 \times 10^{-10} & \text{for BHL}\ , \\ -2.4 \times 10^{-10} & \text{for BHR}\ , \\ 21 \times 10^{-10} & \text{for WHL}\ . \end{cases}$$

SUSY GUT - $SO(10)$

- 16-D Spinorial Representation for the matter fields

$$(15+\nu_R)$$

$$\mathcal{L}_{\cancel{SUSY}} = m_{16}^2 16_i 16_i + m_{10}^2 10_H 10_H + M_{1/2}\lambda_j\lambda_j$$

- Neutrino masses and oscillations
- $U(1)_{B-L} \in SO(10)$

R-Parity, Proton decay ...

- Non-Universality in SSB masses through
  - Flavor symmetries
  - $\langle F \rangle \neq 0$ from different SO(10) representations
  - Multiple sectors breaking SUSY: Gravity mediation, Gauge mediation, Mirage mediation, Anomaly mediation
  - $SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R$

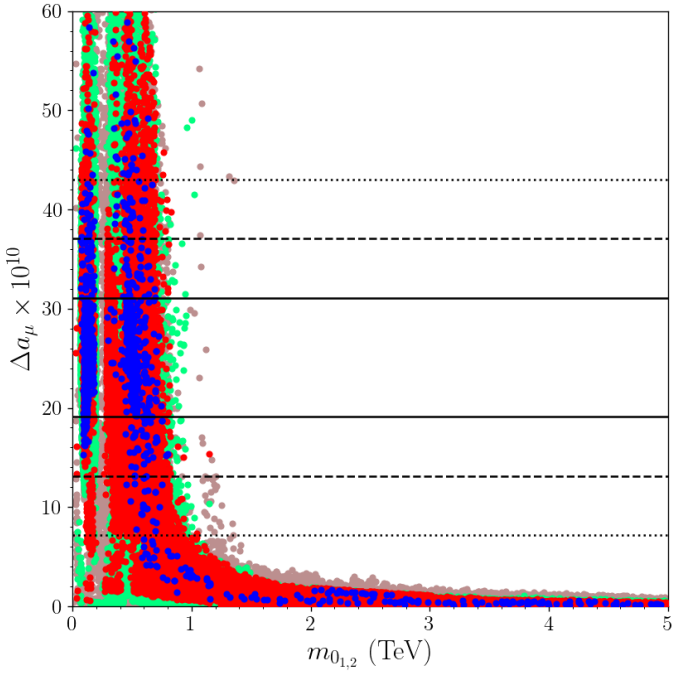
Fundamental Parameters

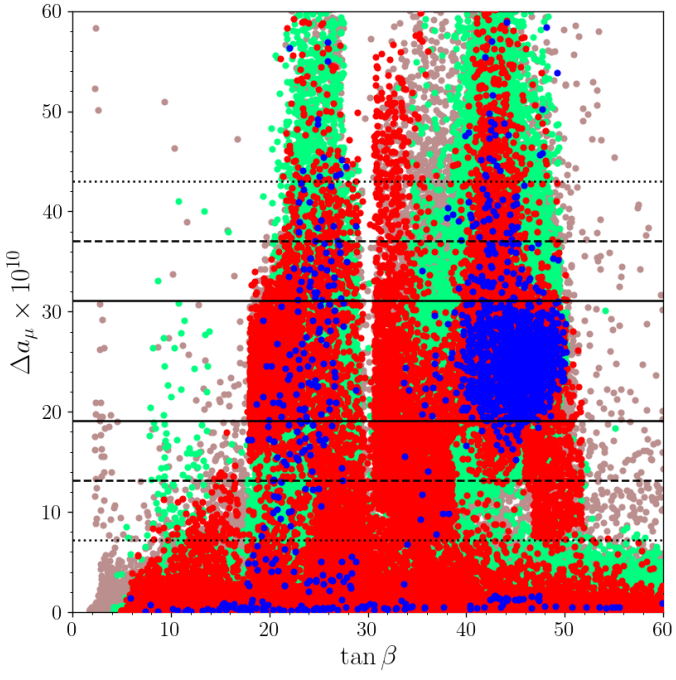
Flavor Symmetry			Pati – Salam		
$0 \leq$	$m_{0_{1,2}}, m_{0_3}$	≥ 5 TeV	$0.1 \leq$	m_L, m_R	$\leq 5, 15$ TeV
$0 \leq$	M_1, M_2	≥ 2 TeV	$0.1 \leq$	M_2	≤ 5 TeV
$-5 \leq$	M_3	≥ 5 TeV	$-3 \leq$	M_3	≤ 5 TeV
$-3 \leq$	A_0/m_{0_3}	≥ 3	$-3 \leq$	A_0/m_L	≤ 3
$1.2 \leq$	$\tan\beta$	≤ 60	$1.2 \leq$	$\tan\beta$	≤ 60
$0 \leq$	m_{H_d}, m_{H_u}	≤ 5 TeV	$0 \leq$	m_{H_d}, m_{H_u}	≤ 15 TeV

Experimental Constraints

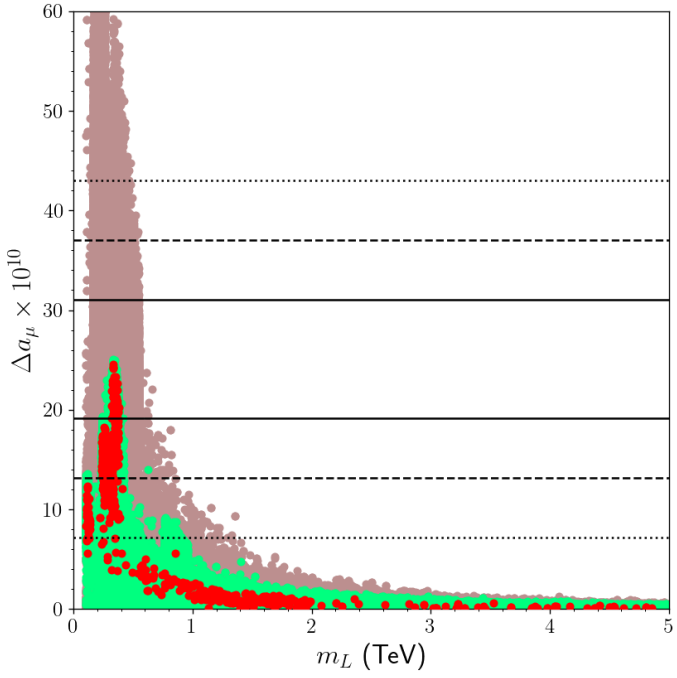
$$
\begin{array}{lcl}
123 \leq & m_h & \leq 127\ \mathrm{GeV} \\
 & m_{\tilde{g}} & \geq 2100\ \mathrm{GeV} \\
0.8 \times 10^{-9} \leq & \mathrm{BR}(B_s \to \mu^+ \mu^-) & \leq 6.2 \times 10^{-9} \\
2.9 \times 10^{-4} \leq & \mathrm{BR}(b \to s\gamma) & \leq 6.2 \times 10^{-9} \\
0.114 \leq & \Omega h^2(\mathrm{Planck}) & \leq 0.126 \\
\mu > 0 & m_t = 173.3\ \mathrm{GeV} &
\end{array}
$$

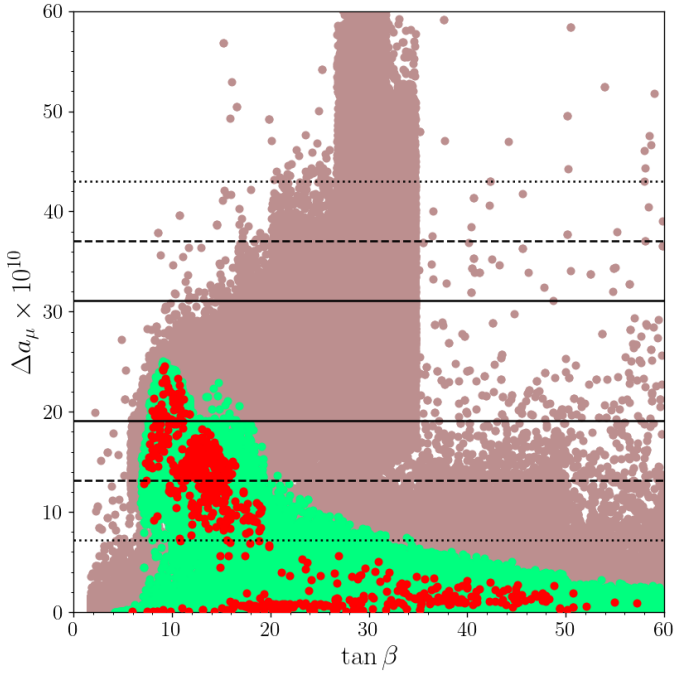
Flavor Symmetry



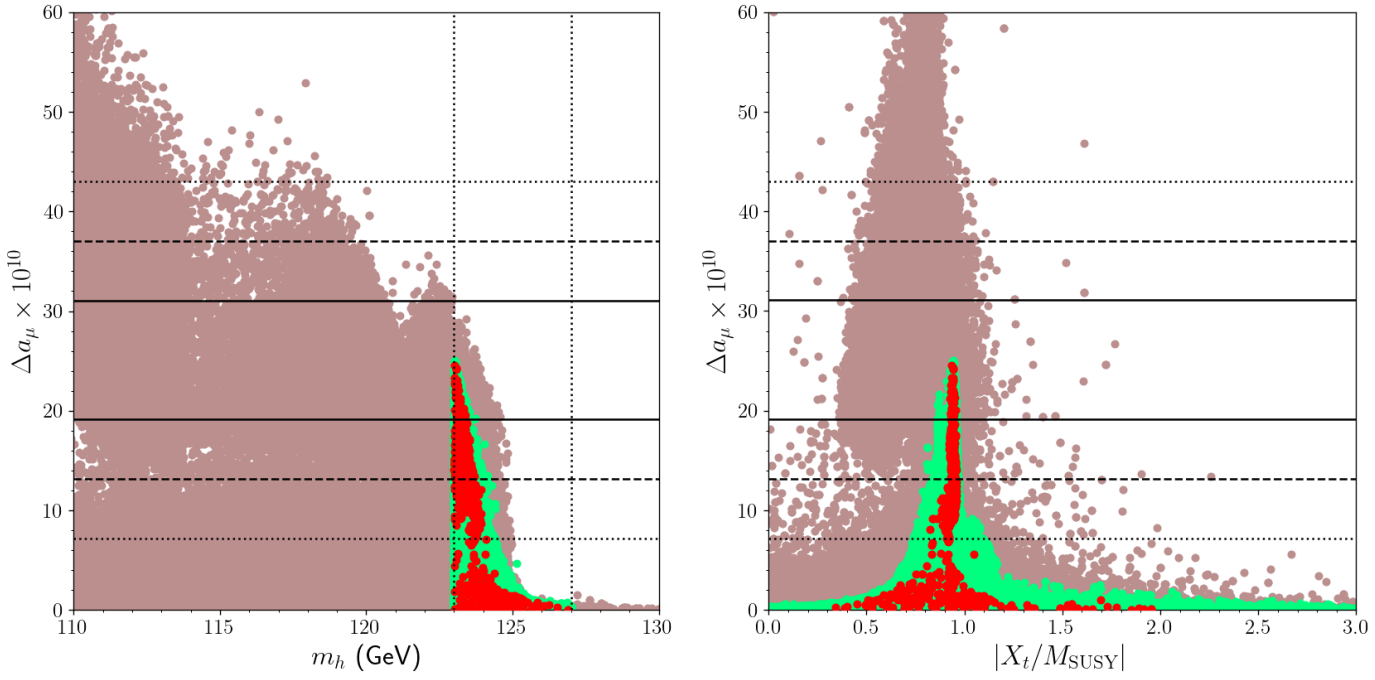


Pati-Salam





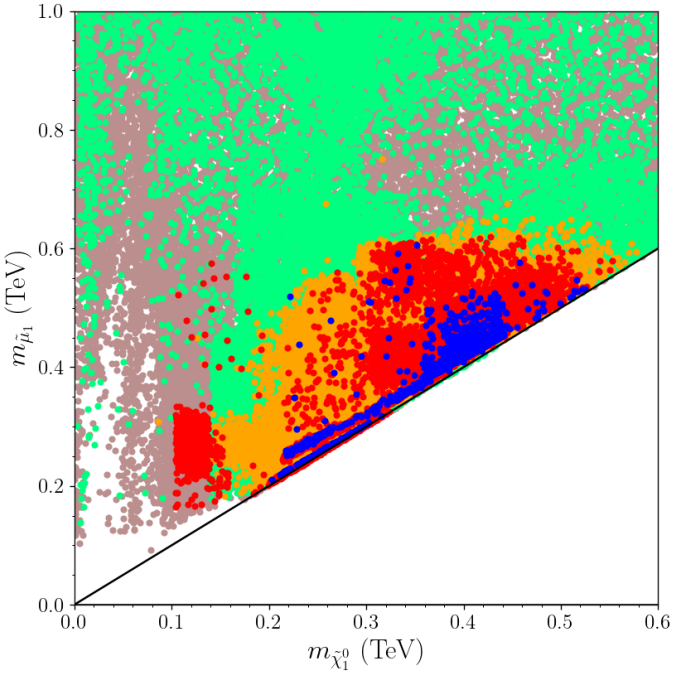
Higgs Mass in Pati-Salam

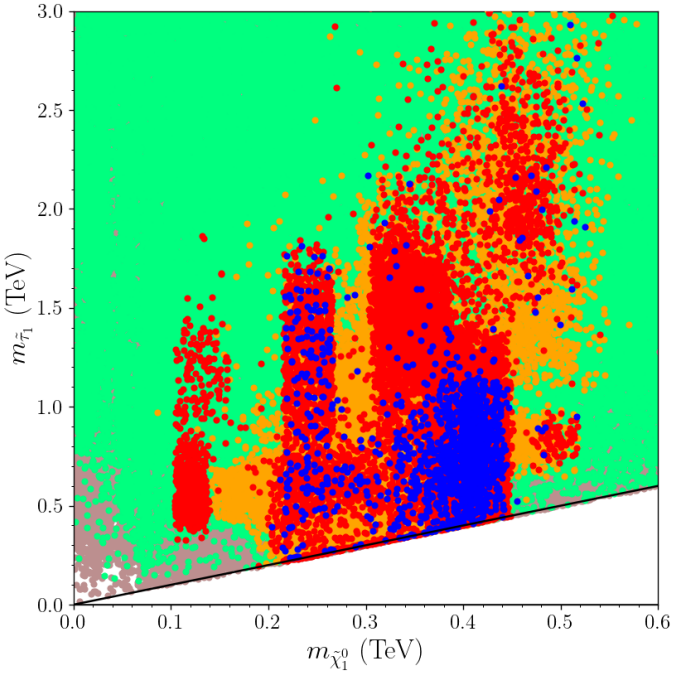


$$\Delta m_h^2 \simeq \frac{m_t^4}{16\pi^2 v^2 \sin^2\beta}\frac{\mu A_t}{M_{\rm SUSY}^2}\left[\frac{A_t^2}{M_{\rm SUSY}^2}-6\right]+ \qquad X_t = A_t - \mu\cot\beta \ ,$$

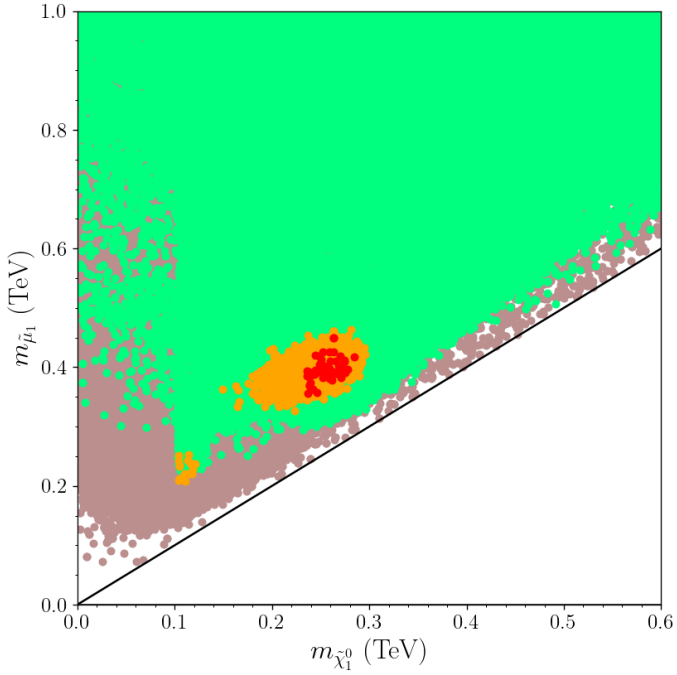
$$\frac{y_b^4 v^2}{16\pi^2}\sin^2\beta\frac{\mu^3 A_b}{M_{\rm SUSY}^4}+\frac{y_\tau^4 v^2}{48\pi^2}\sin^2\beta\frac{\mu^3 A_\tau}{m_{\tilde\tau}^4} \ , \qquad M_{\rm SUSY} = \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$$

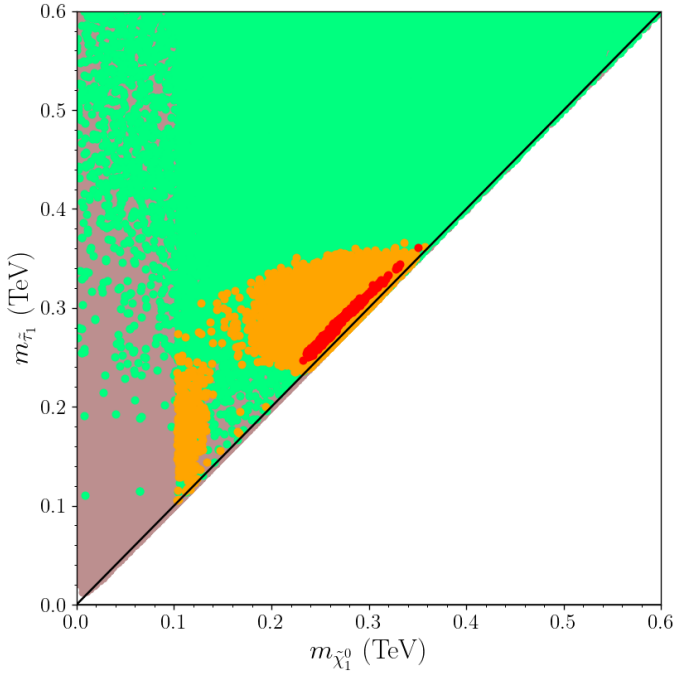
Flavor Symmetry





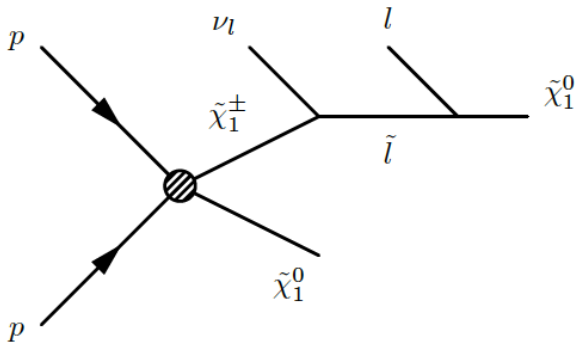
Pati-Salam



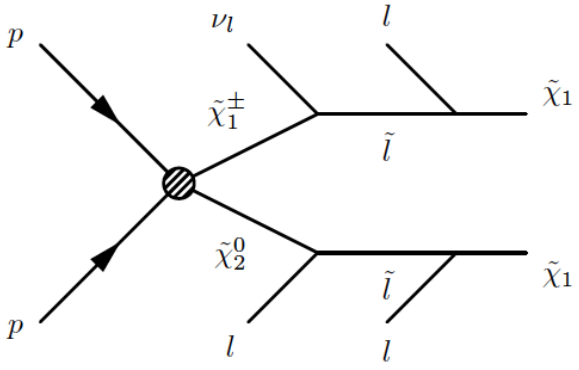


Probing muon $g-2$ in Run3

- $200 \lesssim m_{\tilde{\mu}} \lesssim 700$ GeV, $m_{\tilde{\chi}_1^\pm} \lesssim 1$ TeV
- LHC: $m_{\tilde{\chi}_1^\pm} \gtrsim 1100$ GeV, $m_{\tilde{l}} \gtrsim 350$ GeV [1]



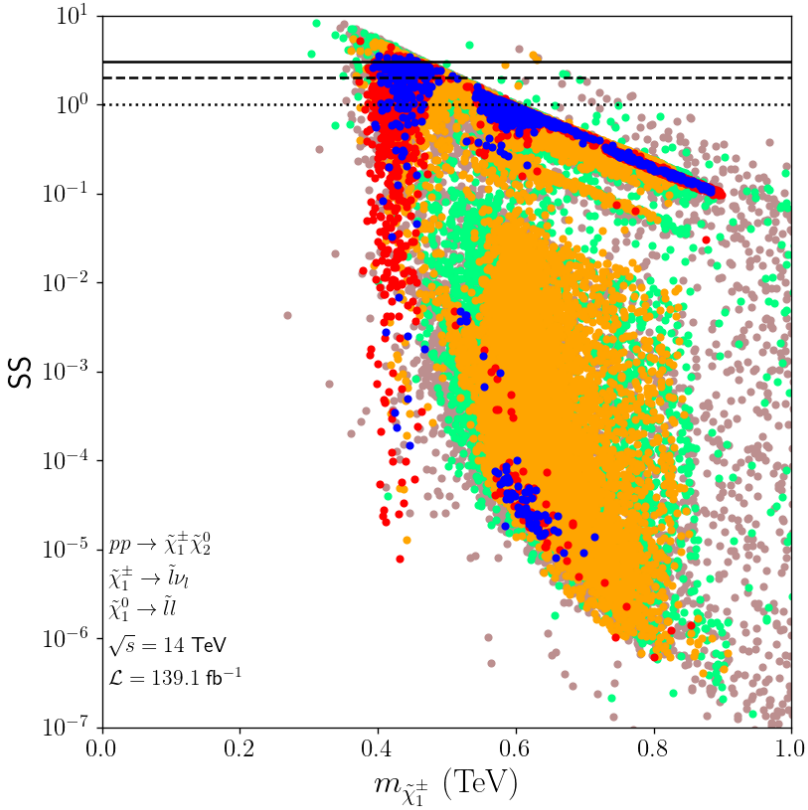
(c) Signal 1

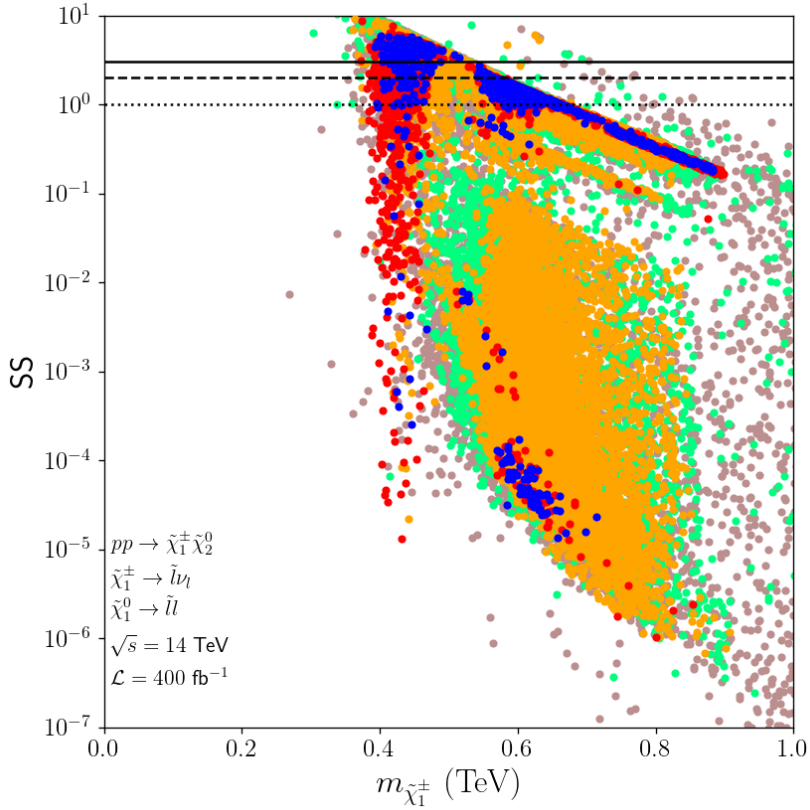


(d) Signal 2

The SM background:

- $\bar{t}t$: $\sigma(pp \to \bar{t}t) \simeq 830$ pb (2006.13076)
- WW: $\sigma(pp \to WW) \simeq 115.3$ pb (CMS-PAS-SMP-16-006)
- WZ: $\sigma(pp \to WZ) \simeq 48.1$ pb (1901.03428)
- ZZ: $\sigma(pp \to ZZ) \simeq 39.9$ pb (1709.08601)





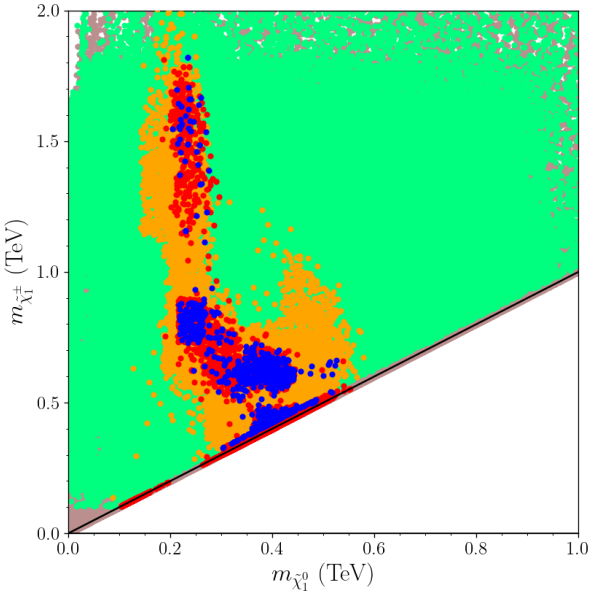
If $\tilde{\mu}_1$ is mostly left-handed

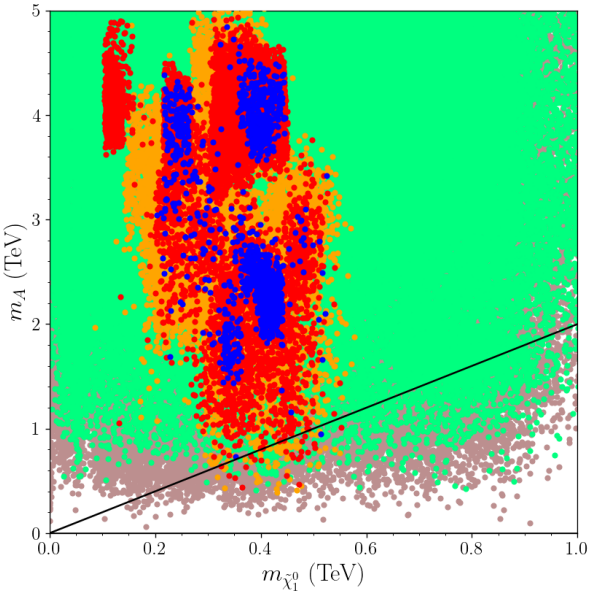
- $m_{\tilde{\chi}_1^\pm} \gtrsim 600$ GeV at 68% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 500$ GeV at 95% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 450$ GeV excluded

- $m_{\tilde{\chi}_1^\pm} \gtrsim 700$ GeV at 68% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 600$ GeV at 95% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 550$ GeV excluded

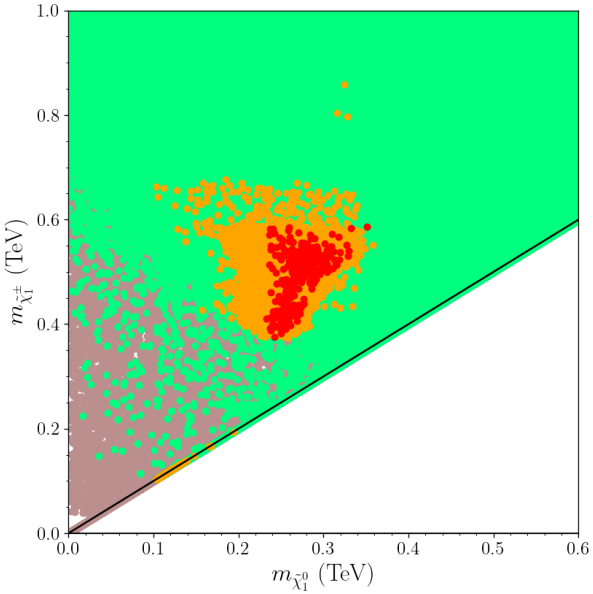
Dark Matter

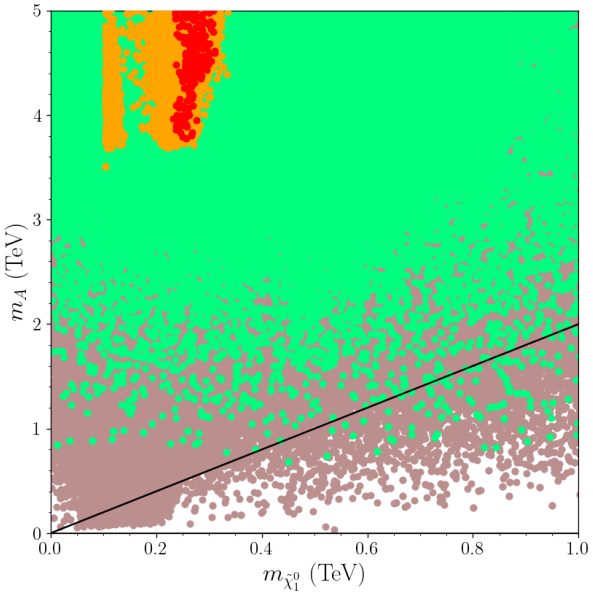
Flavor Symmetry





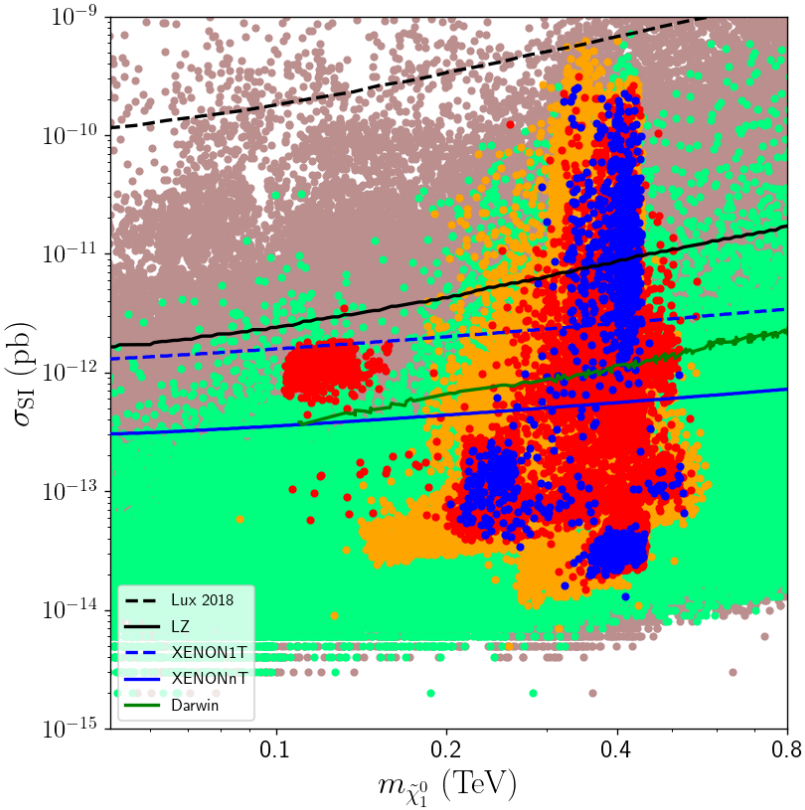
Pati-Salam



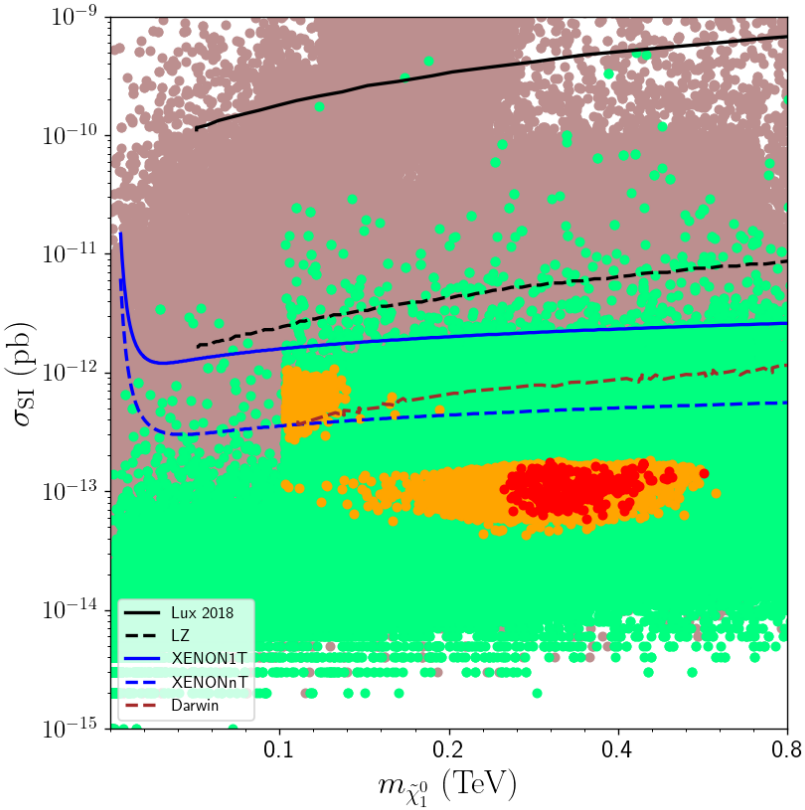


Dark Matter

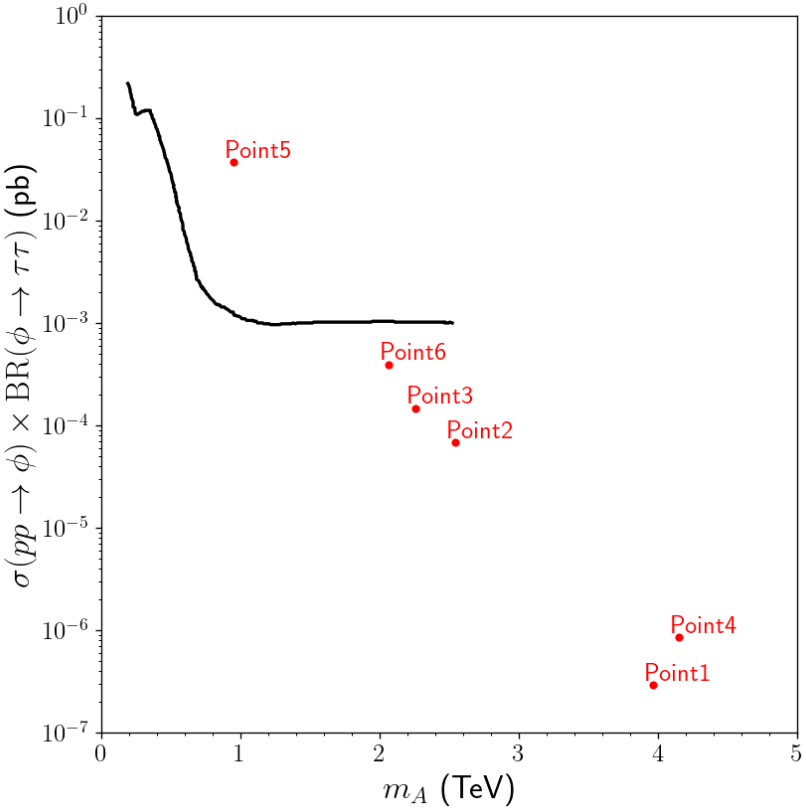
Flavor Symmetry

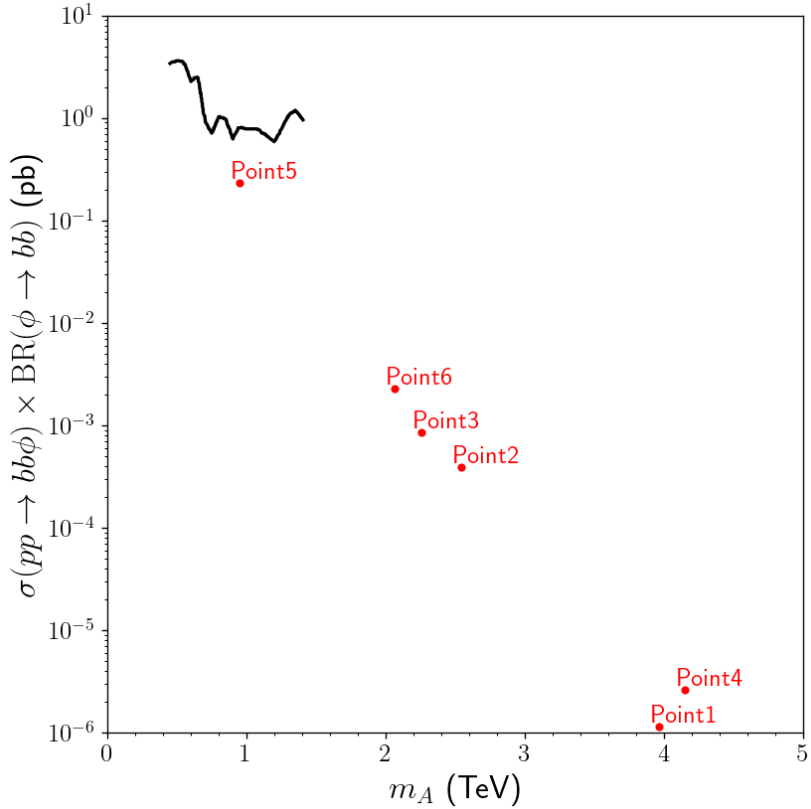


Pati-Salam



Flavor Symmetry	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
$m_{0_{1,2}}$	325	112.3	160.3	499.5	444.7	120.7
m_{0_3}	1989	2166	2000	3025	2472	1893
M_1	854.8	1010	817.8	885	1073	977.9
M_2	483.4	759.4	721.1	523	514	745.6
M_3	2139	2079	1764	2691	-3891	1956
A_0/m_{0_3}	-3.0	-2.0	-2.2	-2.7	-1.4	-1.3
$\tan\beta$	20.2	44.9	43.5	43.3	44.4	47.8
μ	4508	1861	1537	5039	4080	468.9
$\Delta a_\mu \times 10^{10}$	24.6	25.6	28.9	26.1	24.3	22.3
m_h	125.6	124.4	124.4	125.6	123.1	123.4
m_H	3963	2540	2255	4148	946.8	2062
m_A	3964	2540	2255	4148	946.8	2062
$m_{H^\pm}$	3967	2542	2258	4150	951.1	2065
$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$	365.2, 387	433.1, 617.7	348.8, 587.4	380.6, 419.9	513.7, 540.5	411.2, 562.8
$m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}$	4495, 4495	1909, 1911	1576, 1578	5028, 5029	4160, 4160	639.2, 682
$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$	387.2, 4496	617.9, 1912	587.6, 1579	420.1, 5029	540.7, 4160	561.5, 680.8
$m_{\tilde{g}}$	4470	4344	3724	5560	7841	4108
$m_{\tilde{u}_1}, m_{\tilde{u}_2}$	3843, 3849	3719, 3740	3202, 3224	4732, 4759	6634, 6637	3518, 3545
$m_{\tilde{t}_1}, m_{\tilde{t}_2}$	2272, 3323	2755, 3246	2218, 2740	3671, 4346	6190, 6274	2778, 3104
$m_{\tilde{d}_1}, m_{\tilde{d}_2}$	3840, 3844	3726, 3741	3206, 3225	4760, 4767	6634, 6636	3530, 3546
$m_{\tilde{b}_1}, m_{\tilde{b}_2}$	3298, 4096	3218, 3582	2709, 3077	4321, 4873	6230, 6324	3076, 3287
$m_{\tilde{\nu}_e}, m_{\tilde{\nu}_\mu}$	467.9, 470.6	434.4, 442	444.1, 450.8	385.6, 400.1	520.7, 522.4	414.4, 420.3
$m_{\tilde{l}_1}, m_{\tilde{l}_2}$	378.9, 475.7	435.5, 460.7	370, 452.3	392.4, 812.6	522.8, 596.9	422, 482.2
$m_{\tilde{\tau}_1}, m_{\tilde{\tau}_2}$	1512, 1809	502.4, 1608	351.2, 1484	1128, 2228	1937, 2251	551.8, 1418
$\sigma_{\rm SI}$	7.9×10^{-14}	1.28×10^{-12}	2.02×10^{-12}	2.9×10^{-14}	9.56×10^{-13}	2.25×10^{-10}
$\sigma_{\rm SD}$	7.08×10^{-12}	8.25×10^{-9}	1.85×10^{-8}	3.09×10^{-13}	2.57×10^{-10}	3.22×10^{-6}
Ωh^2	0.115	0.117	0.121	0.118	0.115	0.12


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\sigma(pp \to \phi) \times \mathrm{BR}(\phi \to \tau\tau)$ (pb)
Point5
Point6
Point3
Point2
Point4
Point1
0
1
2
3
4
5
m_A (TeV)


10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sigma(pp \to bb\phi) \times \mathrm{BR}(\phi \to bb)$ (pb)
Point5
Point6
Point3
Point2
Point4
Point1
0
1
2
3
4
5
m_A (TeV)

Conclusion

	Flavor Blind	Flavor Symmetry
•	muon $g-2$ ✓	muon $g-2$ ✓
•	Higgs mass problematic for $tan\beta \gtrsim 17$	No tension with the Higgs boson mass
•	Stau and/or chargino NLSP	Stau, smuon, chargino NLSP
•	Light sparticles can escape from LHC	$m_{\tilde{\chi}_1^\pm} \gtrsim 600$ GeV $\xrightarrow{\text{Run 3}}$ 700 GeV $m_{\tilde{\mu}} \gtrsim 350$ GeV
•	Stau-neutralino Coannihilation Chargino-neutralino coannihilation	Stau-smuon-chargino coannihilations A-resonance (Testable in Run3)
	Direct Detection DM experiments	
•	Testable in near future	Testable currently and in near future

Perspectives

- Higgsino Mass $\neq \mu$: Higgsino DM compatible with muon $g-2$
- Seesaw Mechanisms $\Rightarrow$ Lepton Non-Universality:
  - Type I Seesaw: ✗
  - Inverse Seesaw: ✓
- Non-Holomorphic Terms

$$A'_u \bar{Q} H_d u,\ A'_d \bar{Q} H_u d,\ A'_e \bar{L} H_u e$$

  - New contributions to the SM-like Higgs boson
  - Non-Universal $A'_e \to \Delta a_\mu \not\Longleftrightarrow \Delta a_e$