Muon g-2 in SUSY GUTs with Flavor (Non)Universality

Cem Salih Ün

Department of Physics, Bursa Uludağ University, Bursa, Turkey;

Departamento de Ciencias Integradas
y Centro de Estudios Avanzados en Física Matemáticas y Computación,
Universidad de Huelva, Huelva, Spain

in collaboration with Mario Gómez, Qaisar Shafi and Amit Tiwari

19^{th} MultiDark Consolider Workshop – May 24th, 2022, Cristalera UAM, Madrid

Outline

- Standard Model (Pros & Cons)
- SUSY and MSSM
- Muon $g-2$ in MSSM
- SUSY GUT - $SO(10)$
- Run3 Probe for Muon $g-2$
- Dark Matter Implications
- Conclusion

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 $g-2$)

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

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

$$a_\mu^{\mathrm{FNAL}} = 11659204(5.4) \times 10^{-10}$$

$$a_\mu^{\mathrm{BNL}} = 11659208(5.4) \times 10^{-10}$$

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

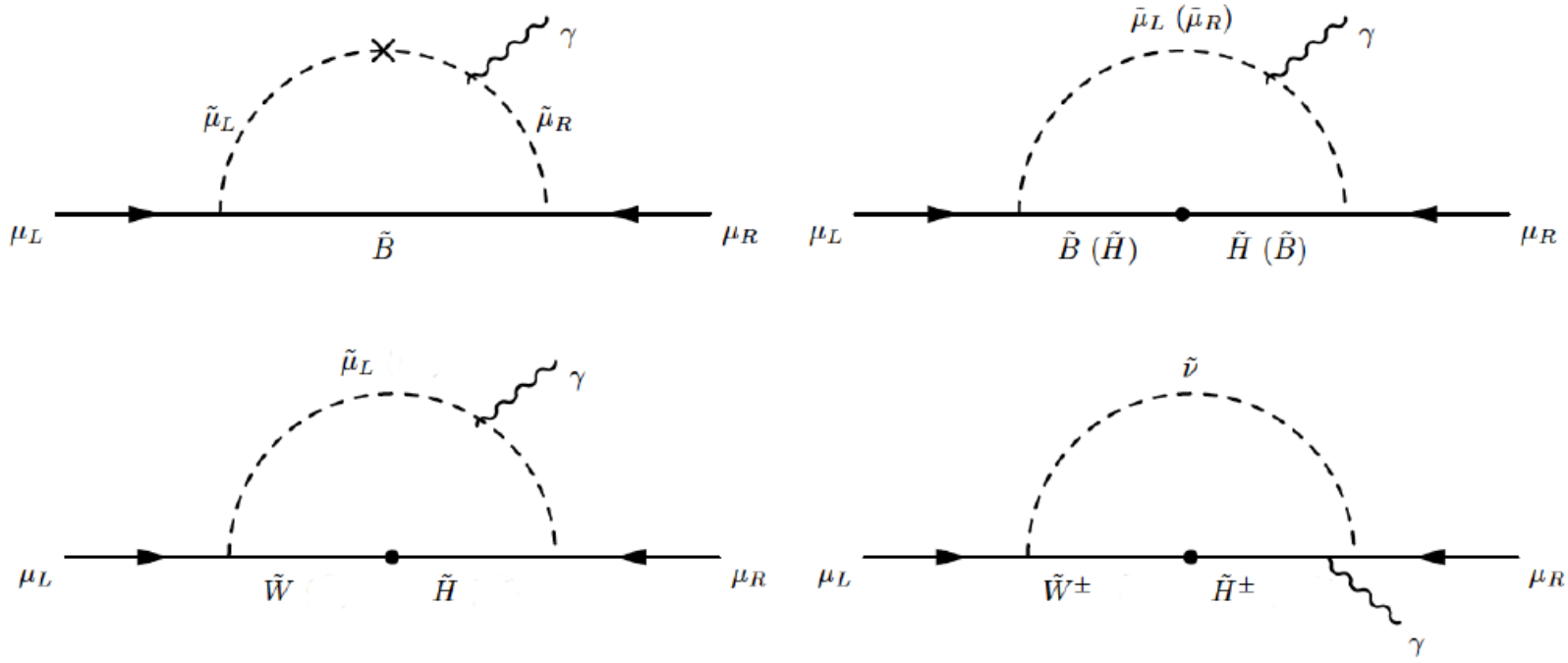
$$\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$$

SUSY and MSSM

- Resolution to the gauge hierarchy problem
- R-Parity: $R = (-1)^{3B+L+2S} \Rightarrow$ Stable LSP

  sneutrino, gravitino, neutralino
- Radiative Electroweak Symmetry Breaking
- Rich electroweak sector
- Gauge Coupling Unification $\rightarrow$ SUSY GUTs
  - Neutrino masses and mixing
  - Gauged B-L symmetry
  - Fewer free parameters

Muon $g-2$ in MSSM



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

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
  - $SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R$

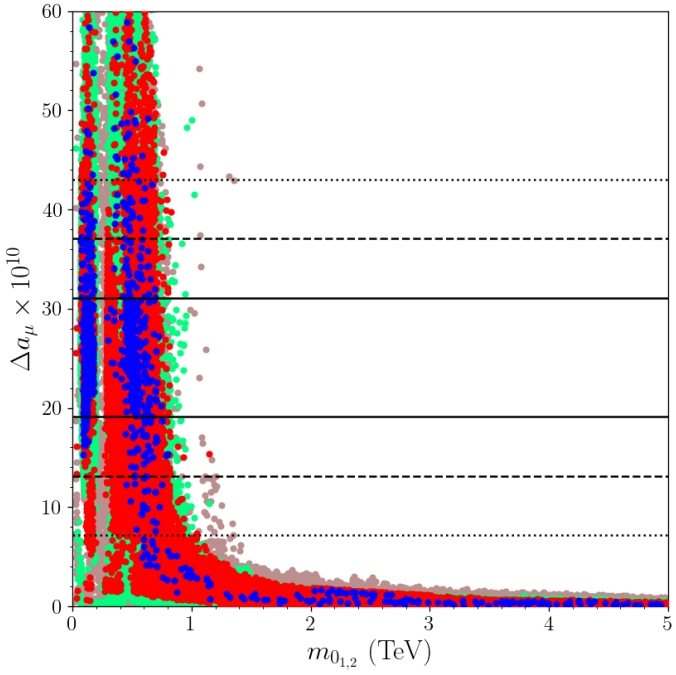
Fundamental Parameters

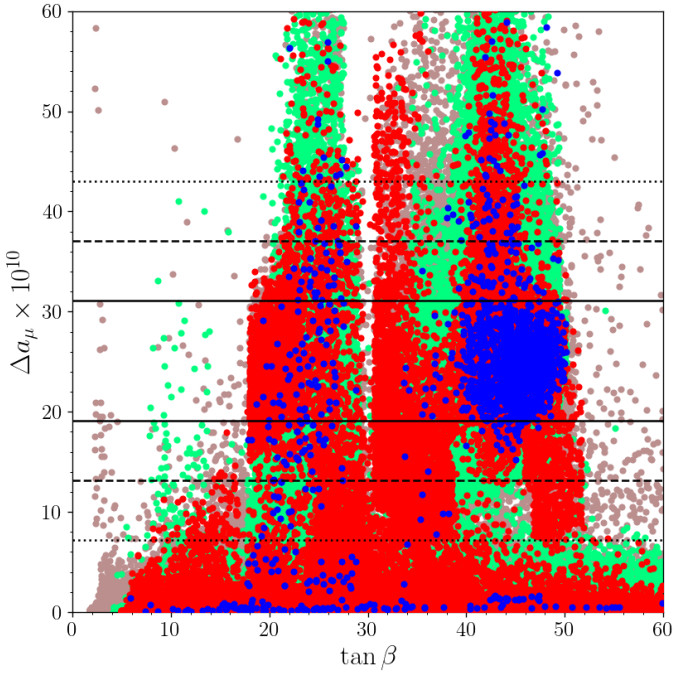
Flavor Symmetry			Pati – Salam		
$0 \leq$	$m_{0_{1,2}}, m_{0_3}$	≥ 5 TeV	$0.1 \leq$	m_L, m_R	$\leq 5, 15$ TeV
$0 \leq$	M_1, M_2	≥ 2 TeV	$0.1 \leq$	M_{2L}, M_{2R}	$\leq 5, 15$ TeV
$-5 \leq$	M_3	≥ 5 TeV	$-3 \leq$	M_3	≤ 5 TeV
$-3 \leq$	A_0/m_{0_3}	≥ 3	$-3 \leq$	A_0/m_L	≤ 3
$1.2 \leq$	$\tan\beta$	≤ 60	$1.2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

Experimental Constraints

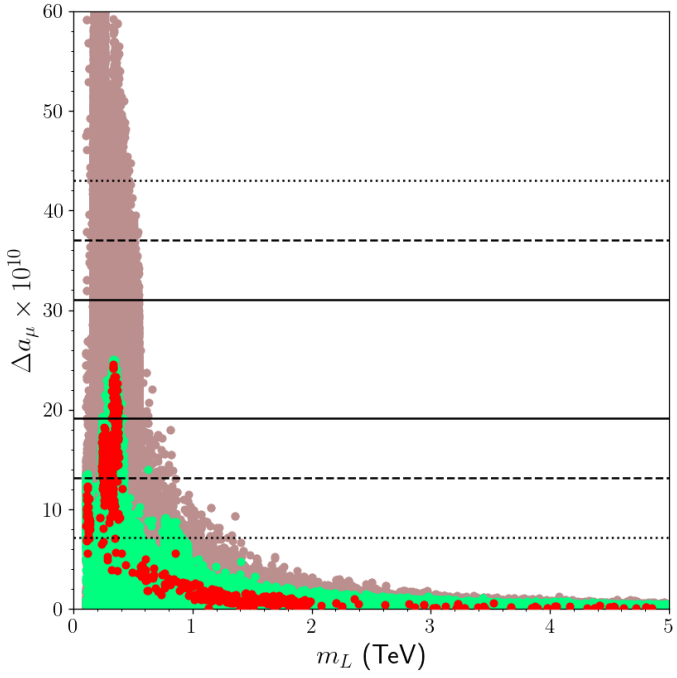
$$
\begin{array}{lcl}
123 \leq & m_h & \leq 127\ \mathrm{GeV} \\
 & m_{\tilde{g}} & \geq 2100\ \mathrm{GeV} \\
0.8 \times 10^{-9} \leq & \mathrm{BR}(B_s \to \mu^+\mu^-) & \leq 6.2 \times 10^{-9} \\
2.9 \times 10^{-4} \leq & \mathrm{BR}(b \to s\gamma) & \leq 6.2 \times 10^{-9} \\
0.114 \leq & \Omega h^2(\mathrm{Planck})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

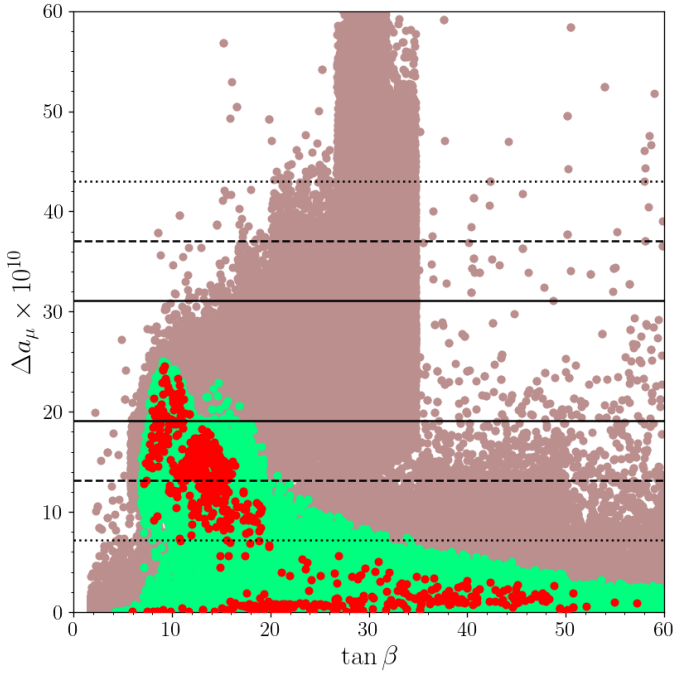
Flavor Symmetry



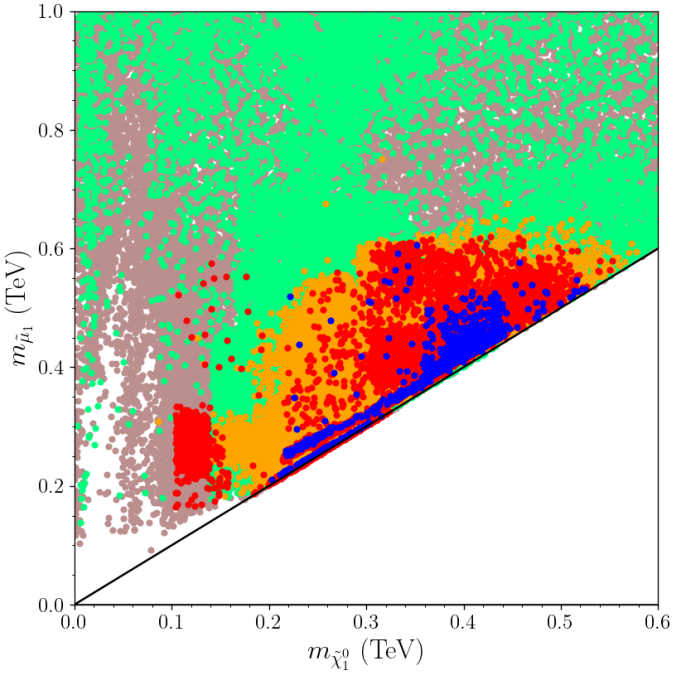


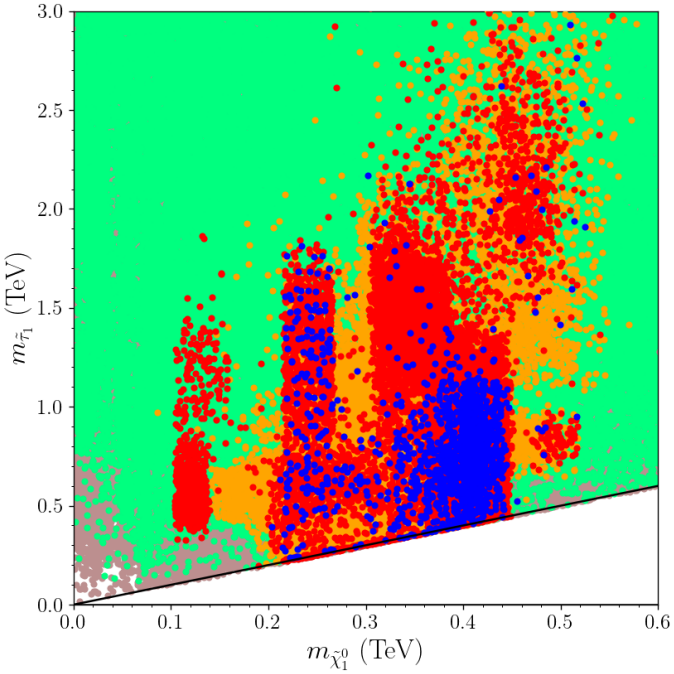
Pati-Salam



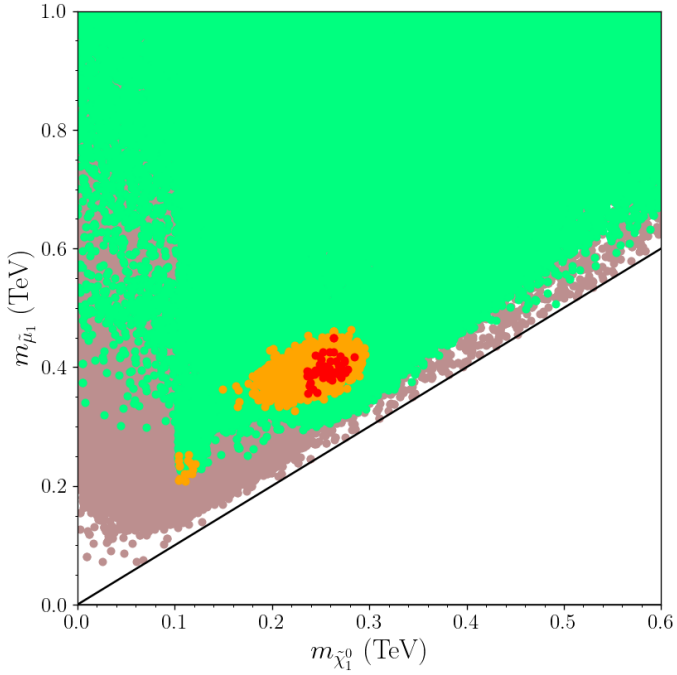


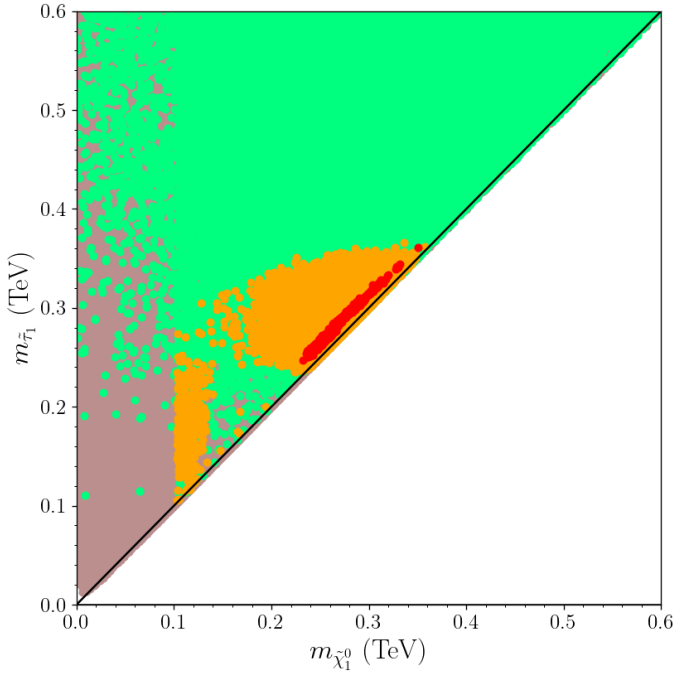
Flavor Symmetry





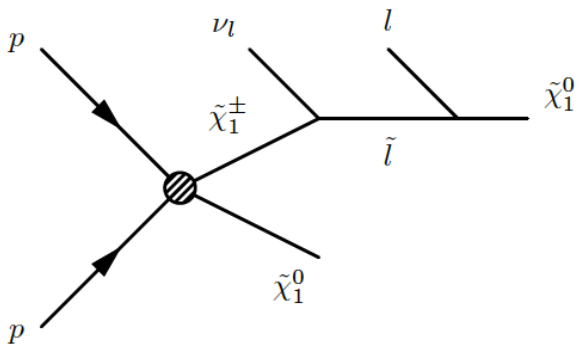
Pati-Salam



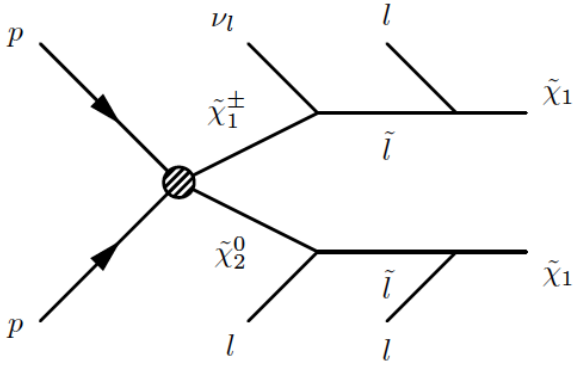


Probing muon $g-2$ in Run3

- $200 \lesssim m_{\tilde{\mu}} \lesssim 700$ 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]



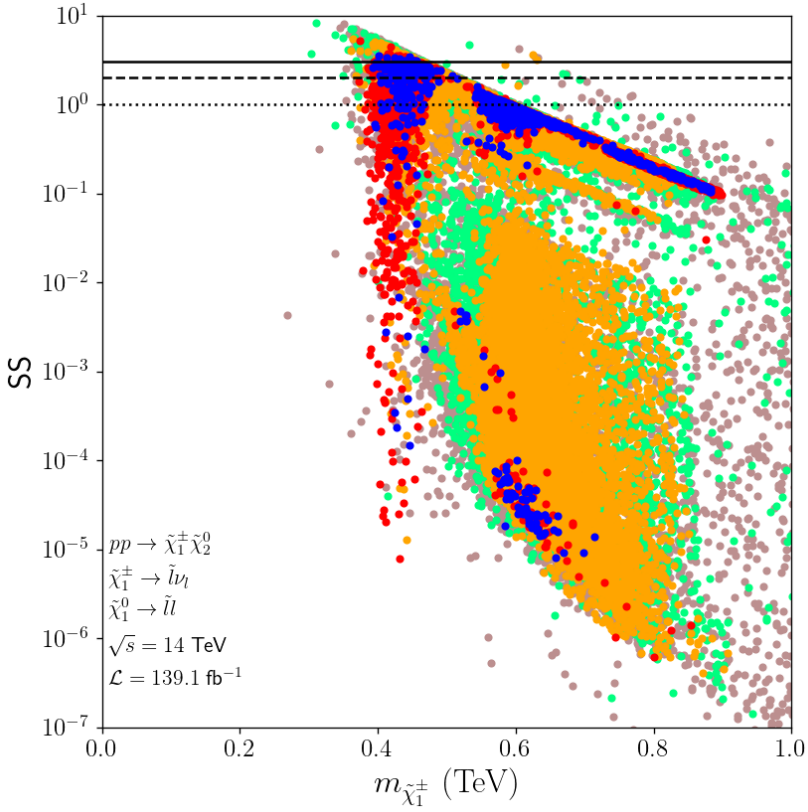
(a) Signal 1

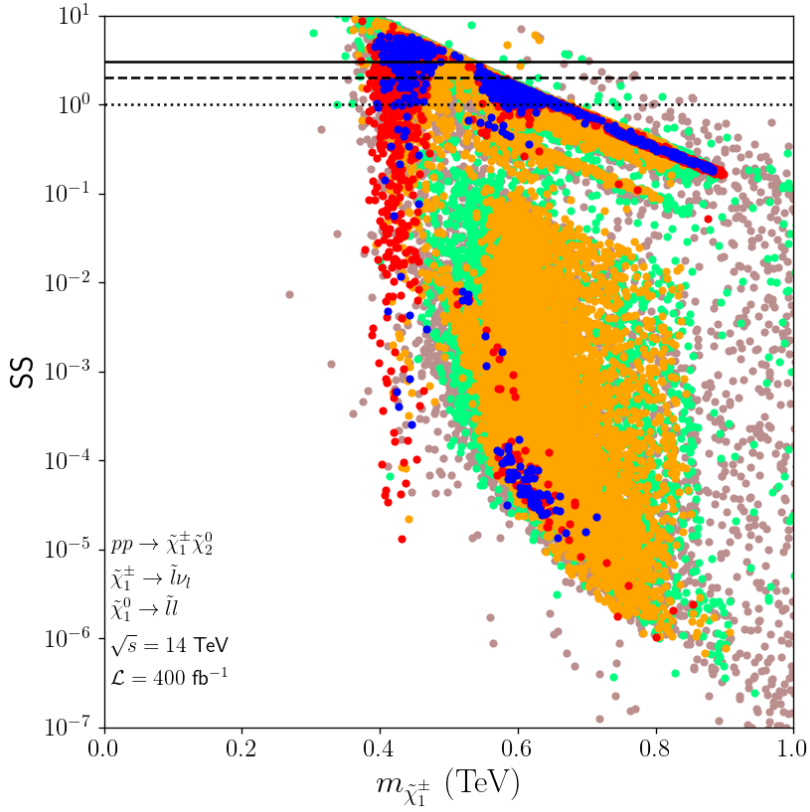


(b) Signal 2

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)





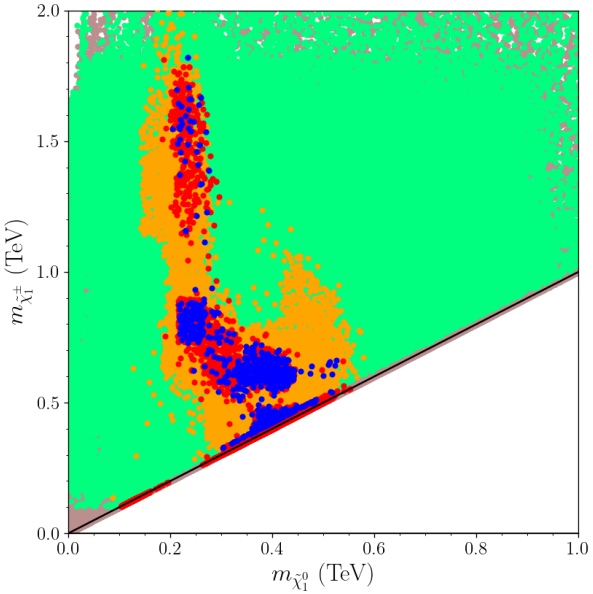
If $\tilde{\mu}_1$ is mostly left-handed

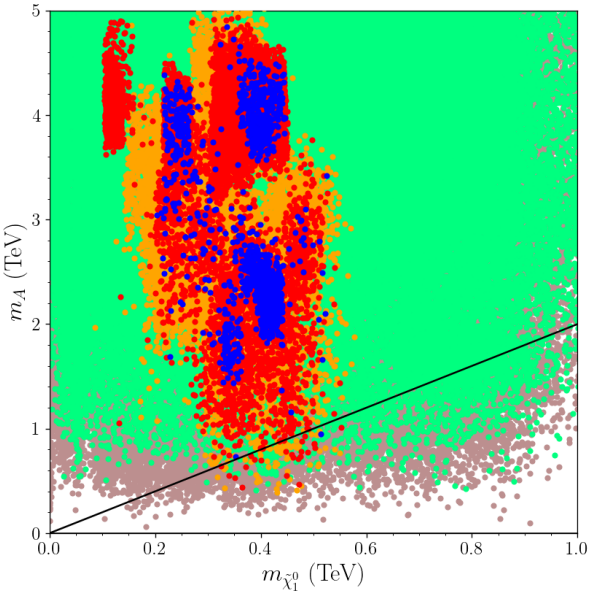
- $m_{\tilde{\chi}_1^\pm} \gtrsim 600$ GeV at 68% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 500$ GeV at 95% CL
- $m_{\tilde{\chi}_1^\pm} \gtrsim 450$ GeV excluded

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

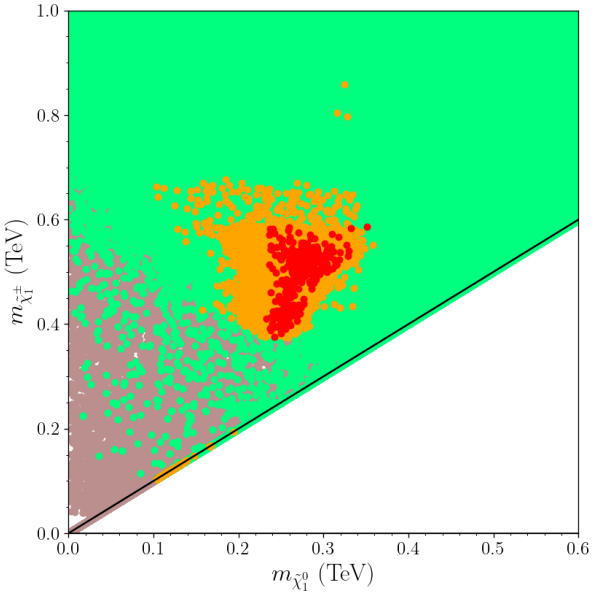
Dark Matter

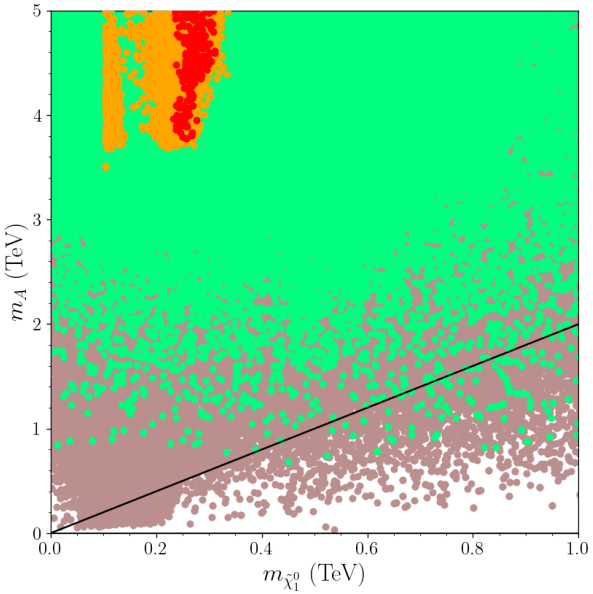
Flavor Symmetry





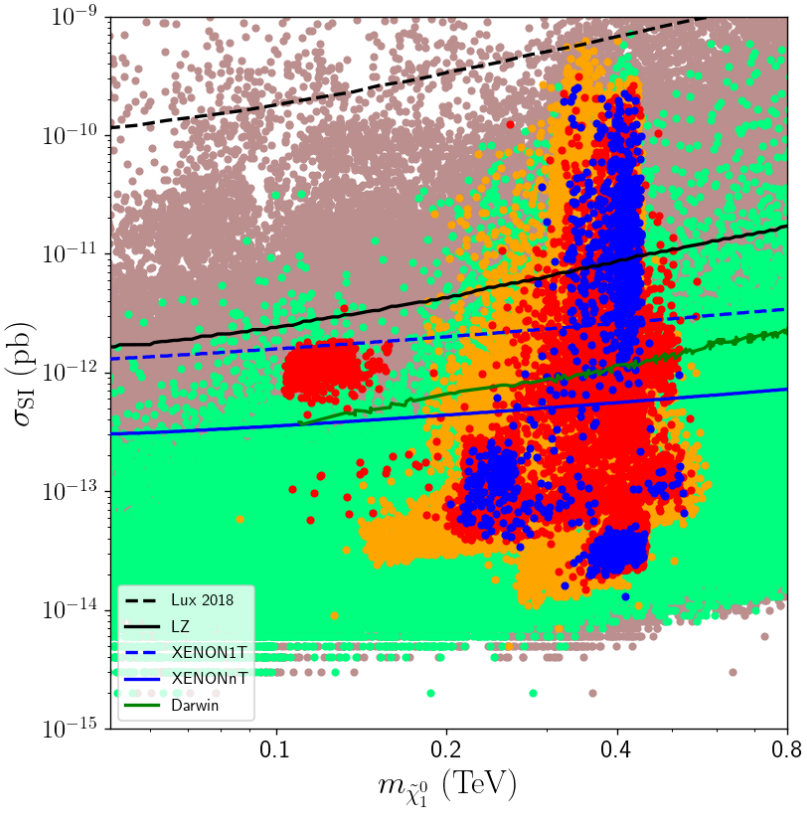
Pati-Salam



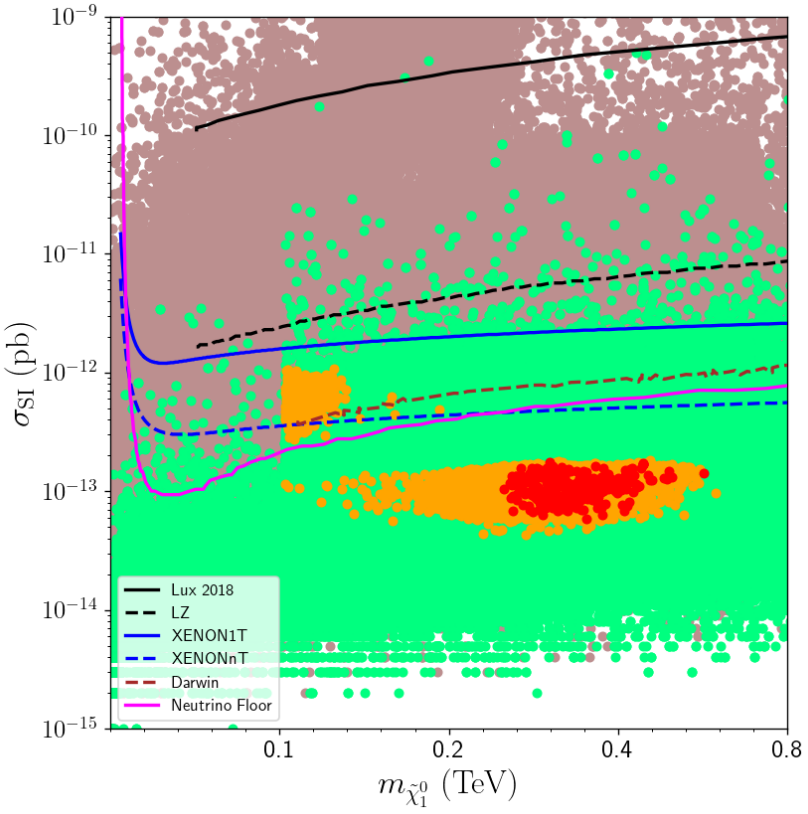


Dark Matter

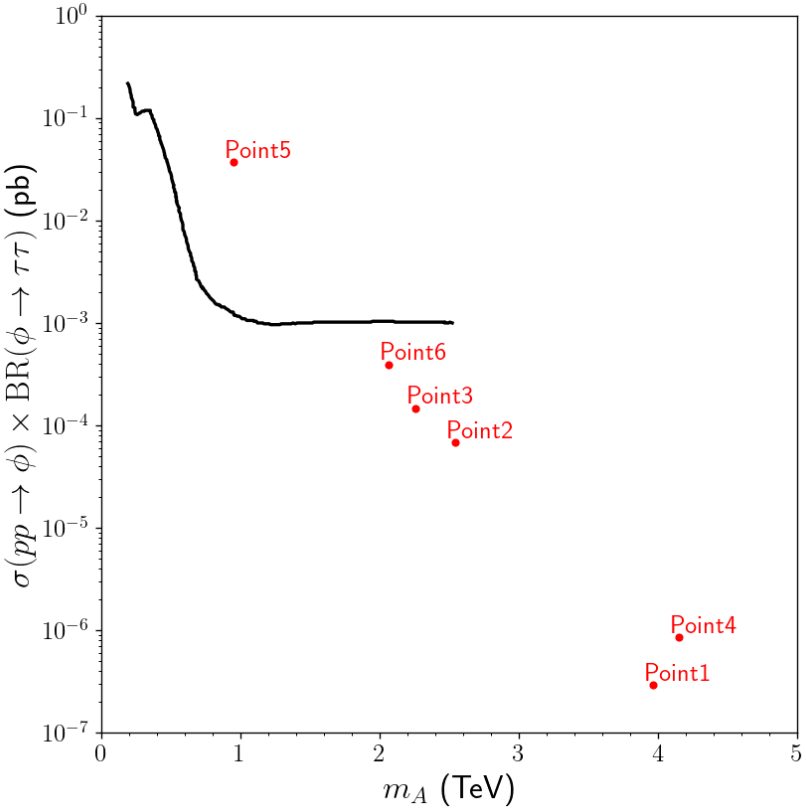
Flavor Symmetry

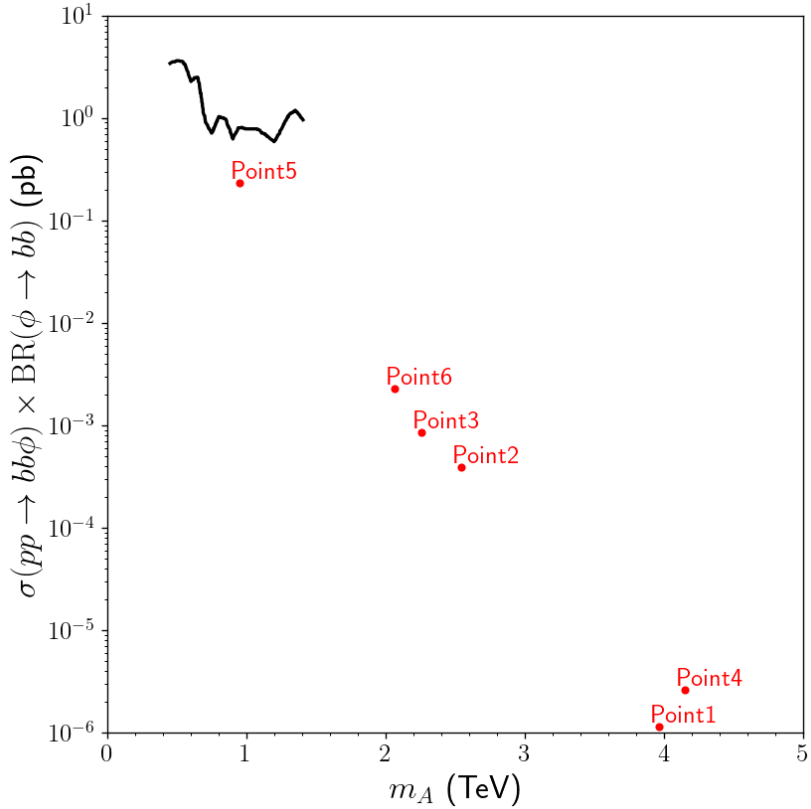


Pati-Salam



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