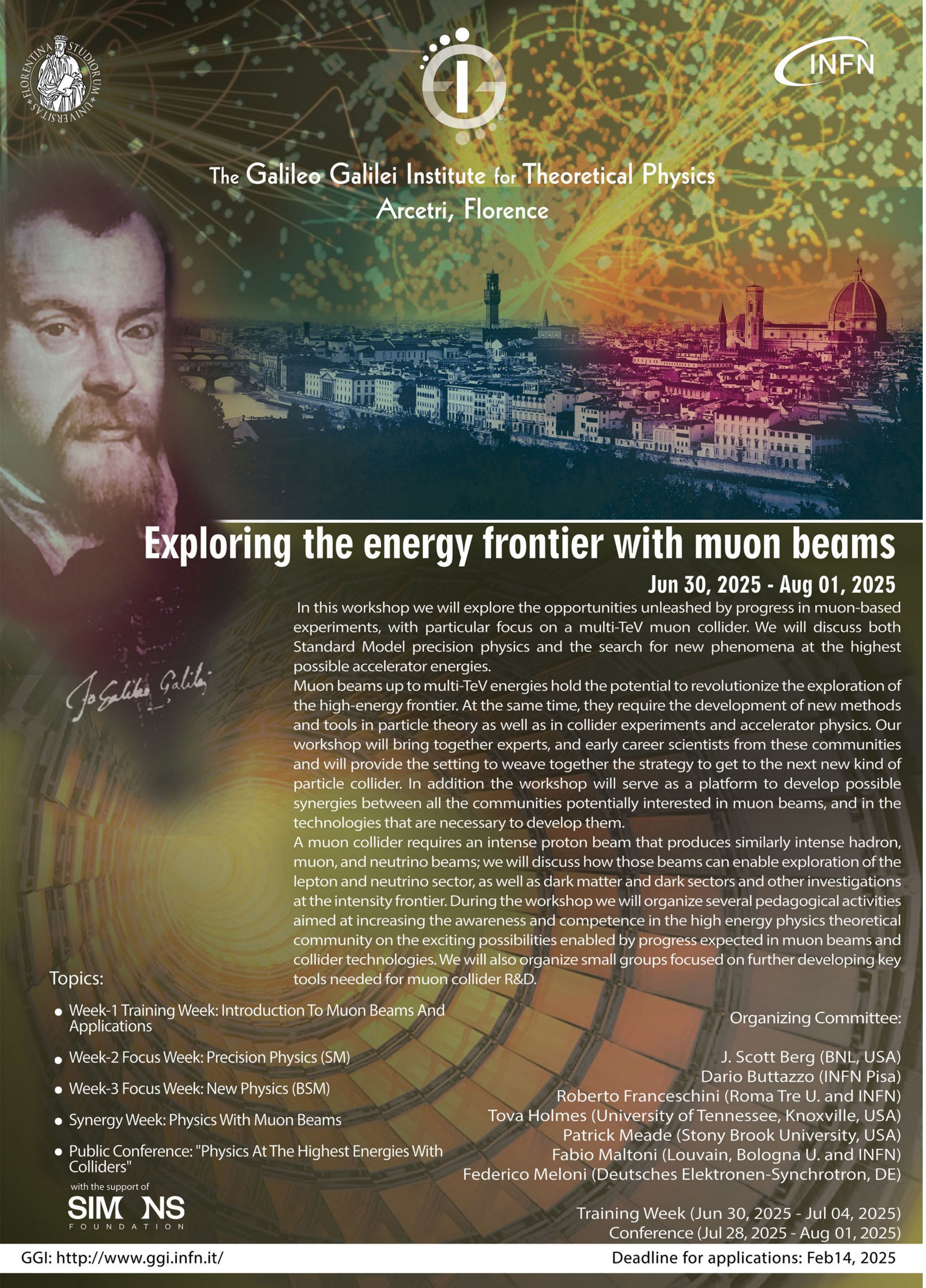

SUSY beyond the TeV scale

Giovanni Villadoro

The Abdus Salam International Centre for Theoretical Physics (ICTP)

based on:

Arvanitaki, Craig, Dimopoulos and GV – ‘12

Pardo Vega and GV – ‘15

Chen, Redigolo, GV – *work in progress*

Supersymmetry

$$|\text{boson}\rangle \quad \leftrightarrow \quad |\text{fermion}\rangle$$

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Poincaré $\rightarrow$ SUSY

$\mathcal{P}$ $\qquad$ $\mathcal{S}$

$$\begin{cases} [\mathcal{P},\mathcal{P}] = \mathcal{P} \\ [\mathcal{P},\mathcal{S}] = \mathcal{S} \\ \{\mathcal{S},\mathcal{S}\} = \mathcal{P} \end{cases}$$

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Important Feature of Quantum Gravity

$\rightarrow$ Supergravity / String Theory

Supersymmetry

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$$\mathcal{P} \qquad\qquad \mathcal{S}$$

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Important Feature of Quantum Gravity

→ Supergravity / String Theory

$$\mathcal{P}|0\rangle = 0 \qquad \mathcal{S}|0\rangle \neq 0$$

SUSY breaking scale?

Supersymmetry

Historical motivations for low-energy SUSY:

- Hierarchy Problem
- WIMP Miracle
- Grand Unification

1. Hierarchy Problem

$$\delta m_Z^2 \sim m_{\rm SUSY}^2$$

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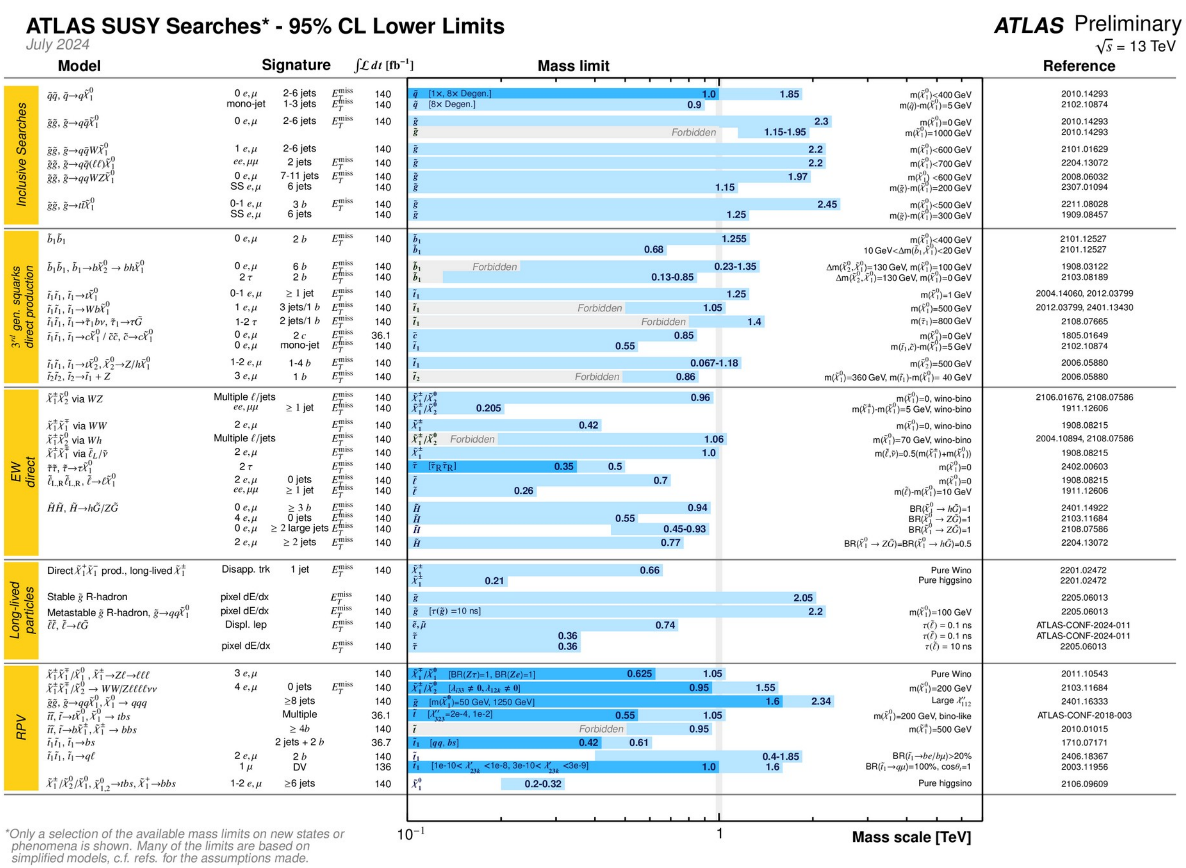
$$\delta m_Z^2 \sim m_{\rm SUSY}^2 \sim 10^2 m_Z^2 \left(\frac{m_{\rm SUSY}}{\rm TeV}\right)^2$$



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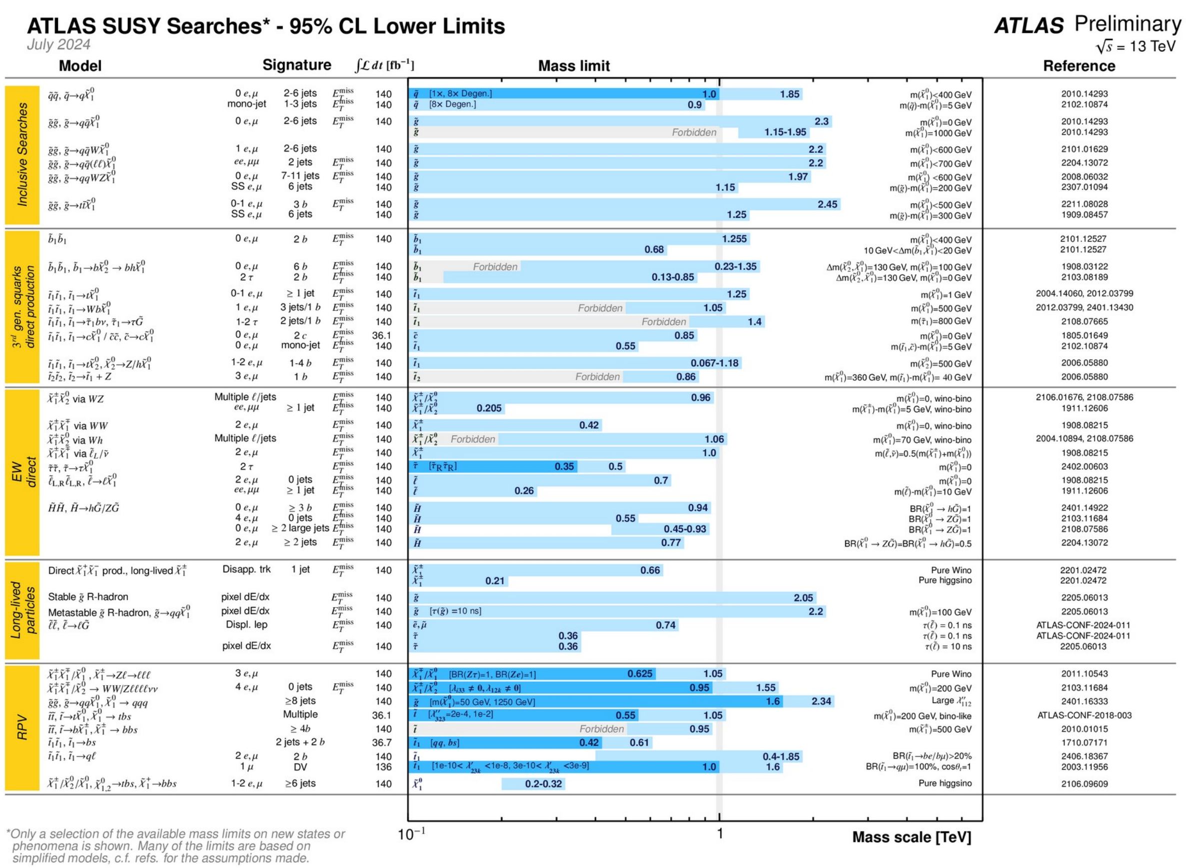

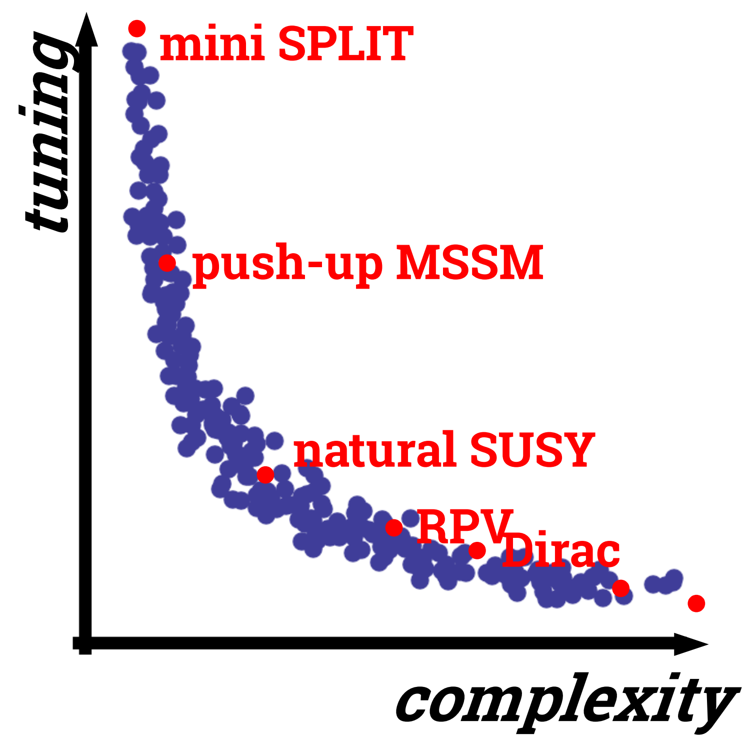

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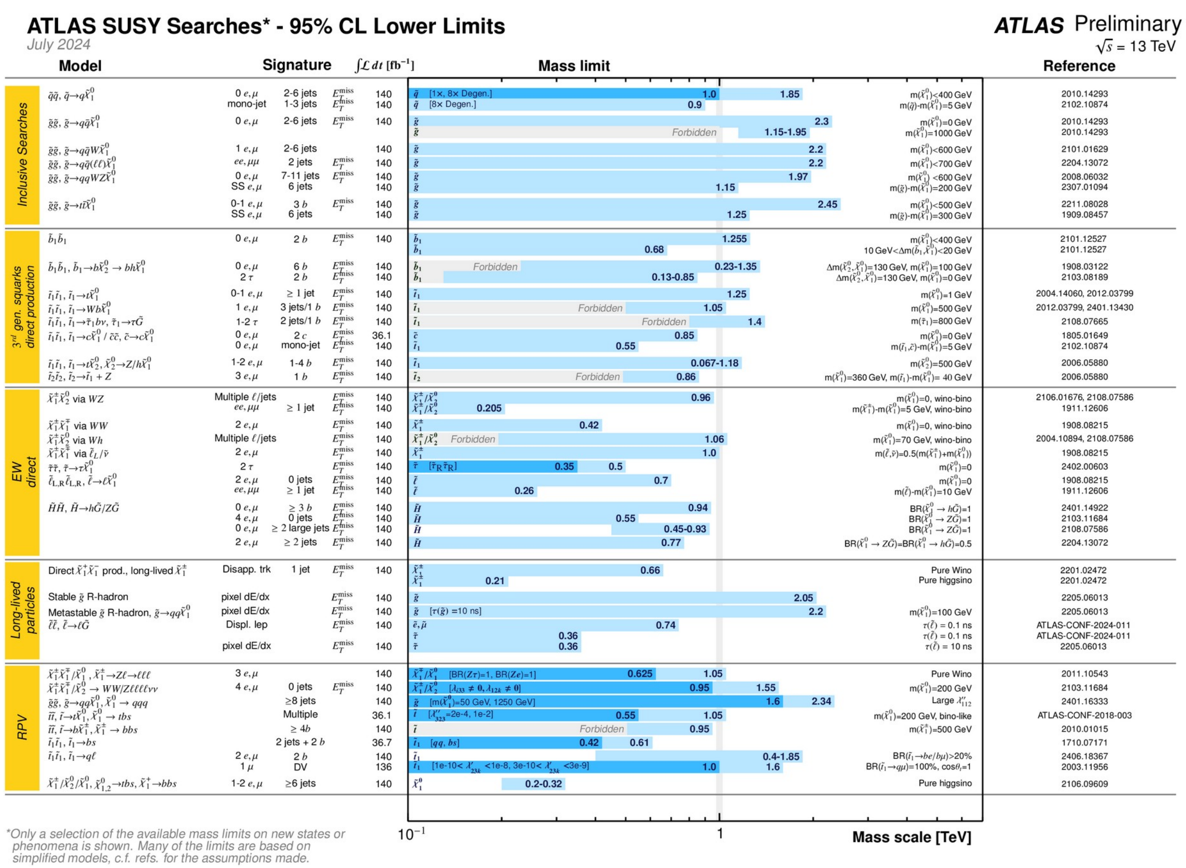
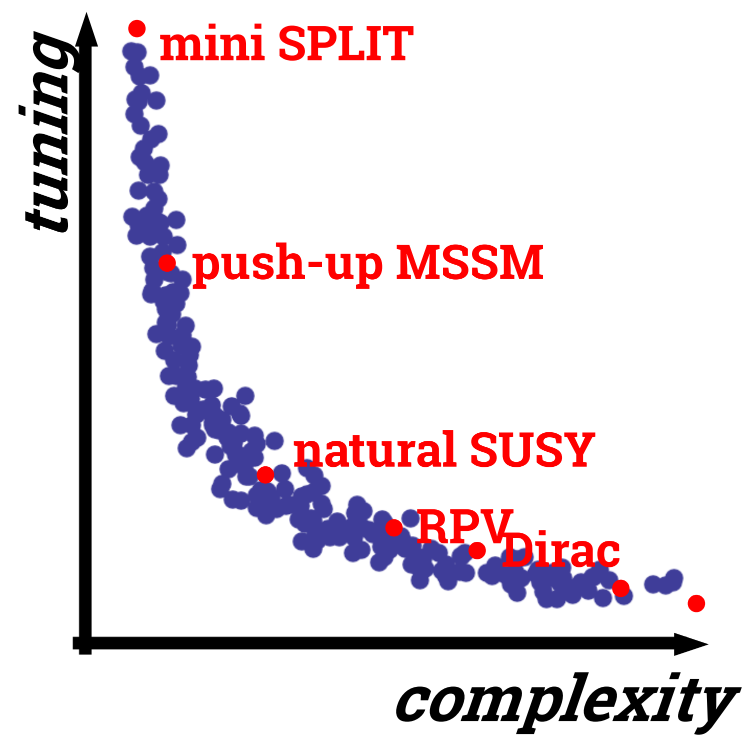
many known alternatives to SUSY





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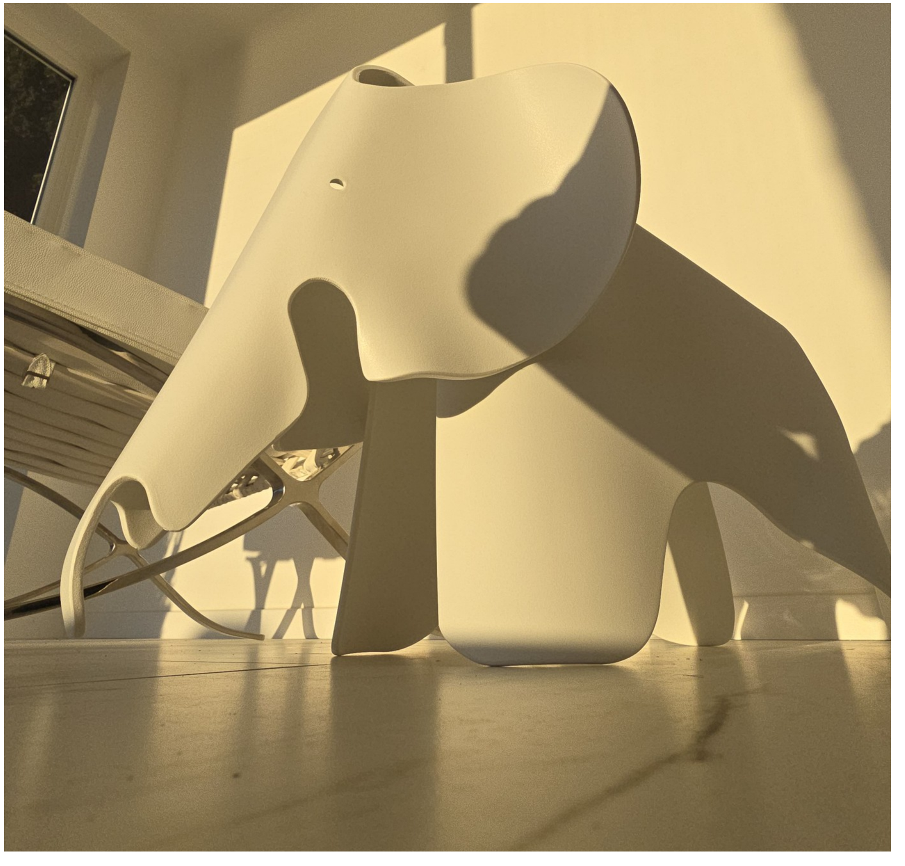
$$\delta \Lambda_{cc} \sim m_{\rm SUSY}^4 \sim 10^{62} \Lambda_{\rm cc} \left(\frac{m_{\rm SUSY}}{\rm TeV}\right)^4$$



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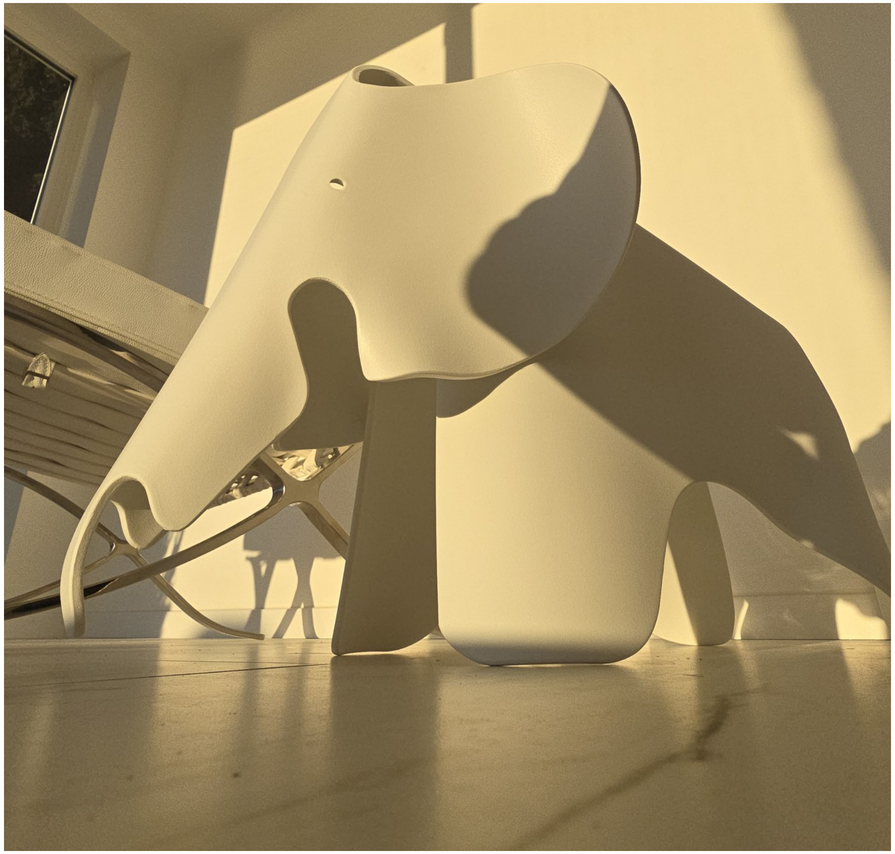
no known alternatives to SUSY



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LSP (typically Neutralino) :

have naturally the right thermal relic abundance

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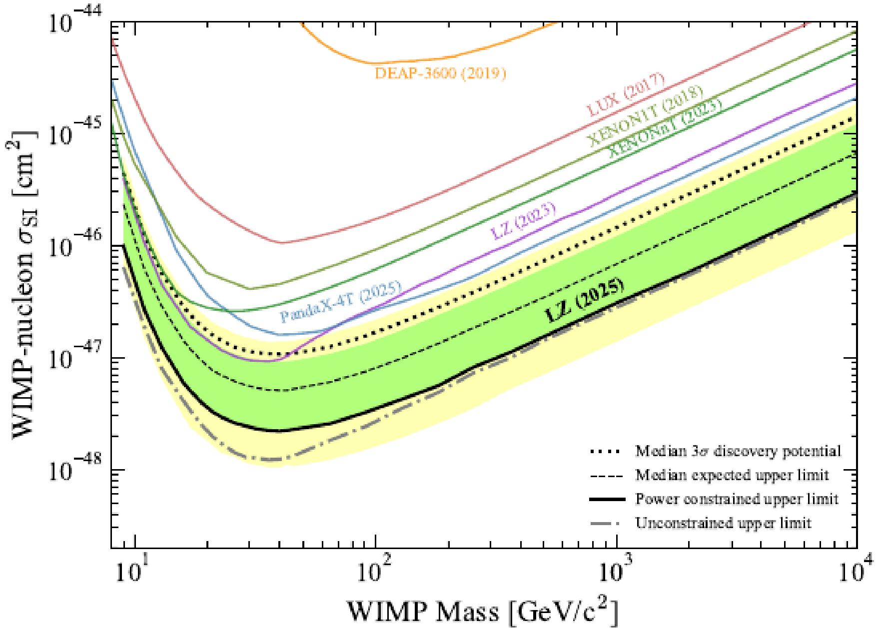

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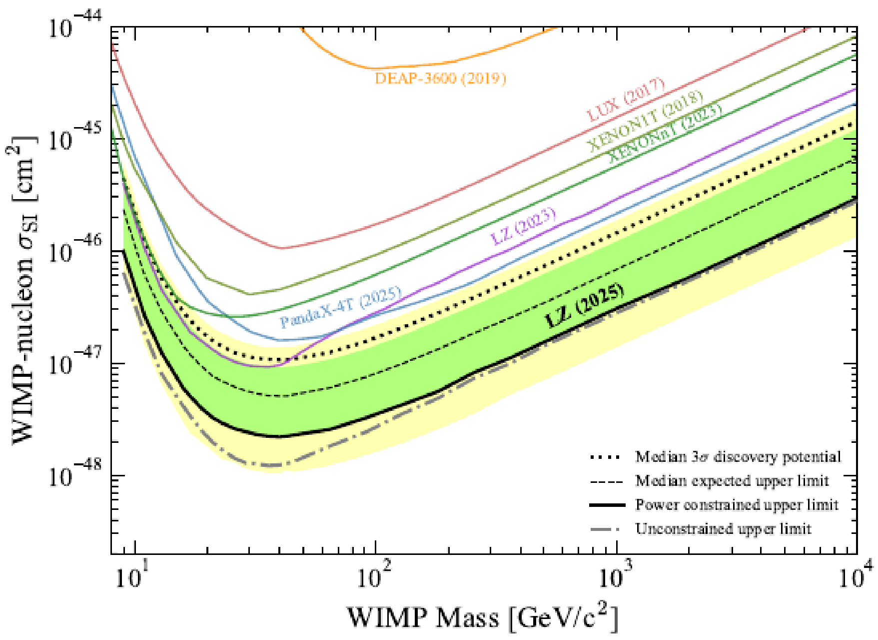
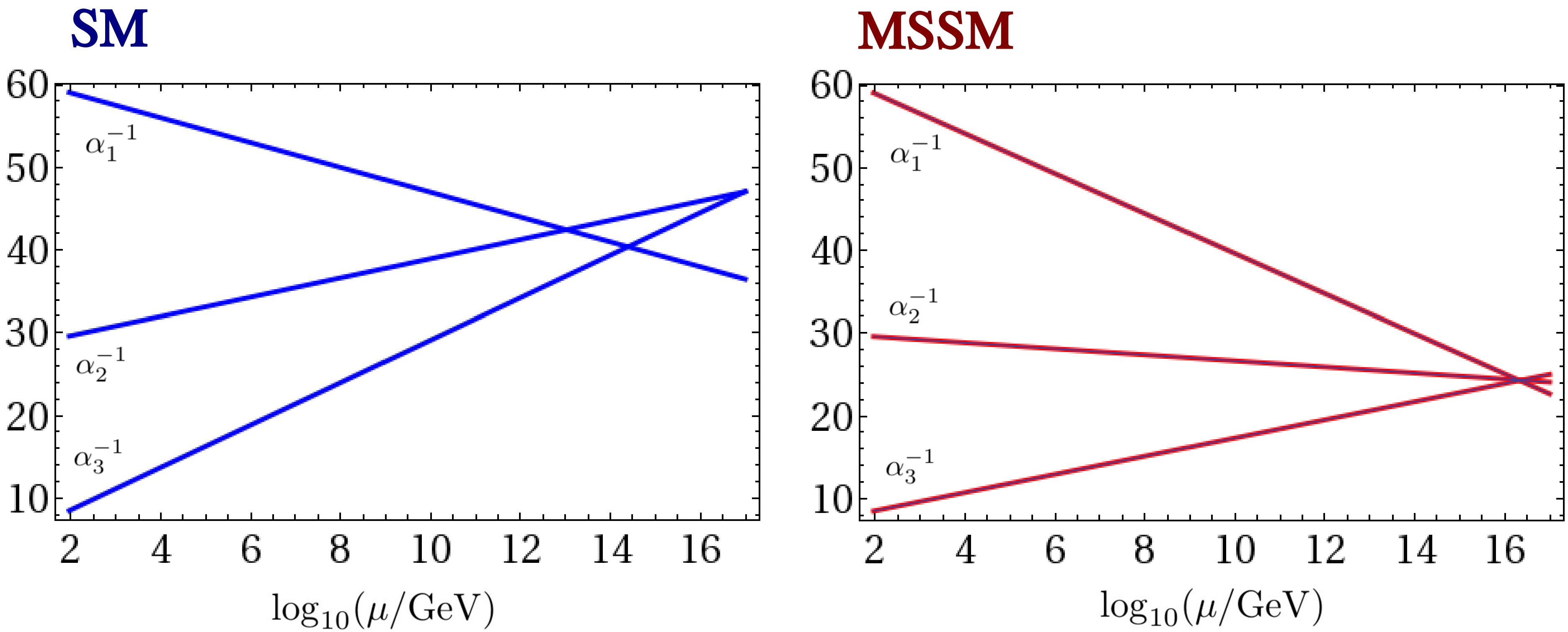


many other equally plausible candidates:

QCD axion, ALPs, Dark Sectors, etc...

3. GUT


SM
60
50
40
30
20
10
α_1^{-1}
α_2^{-1}
α_3^{-1}
2 4 6 8 10 12 14 16
$\log_{10}(\mu/\mathrm{GeV})$
MSSM
60
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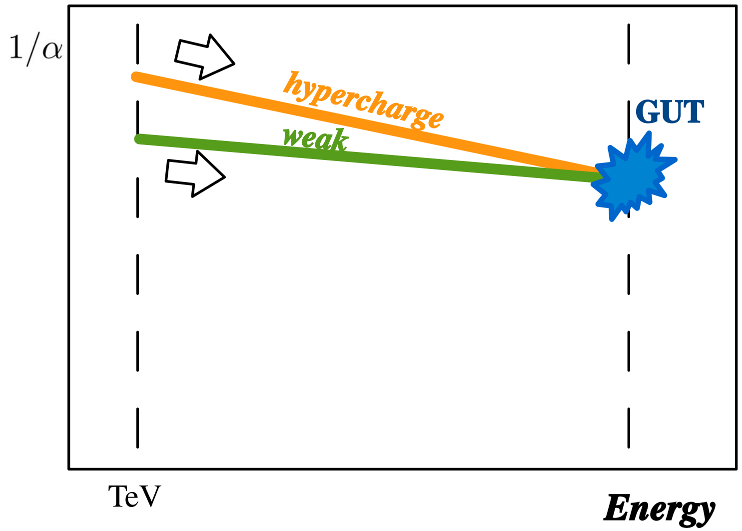

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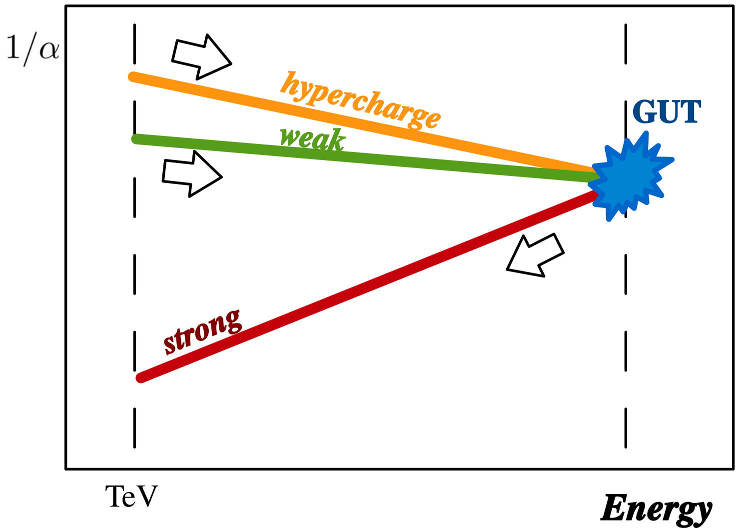

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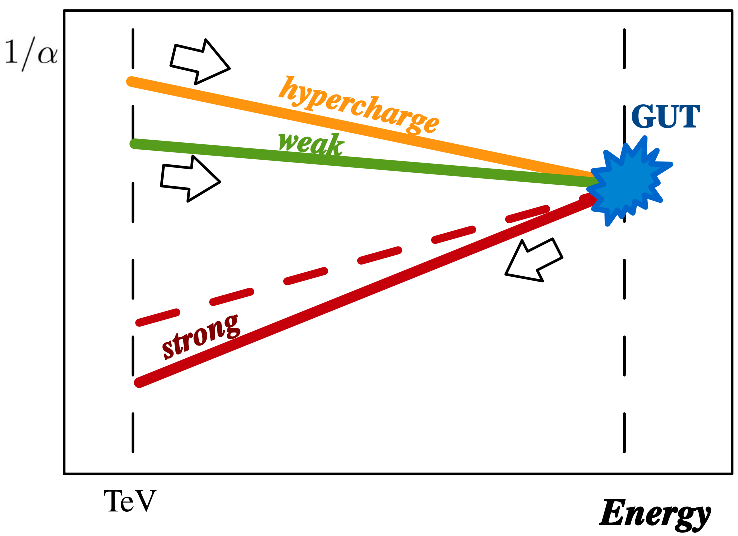
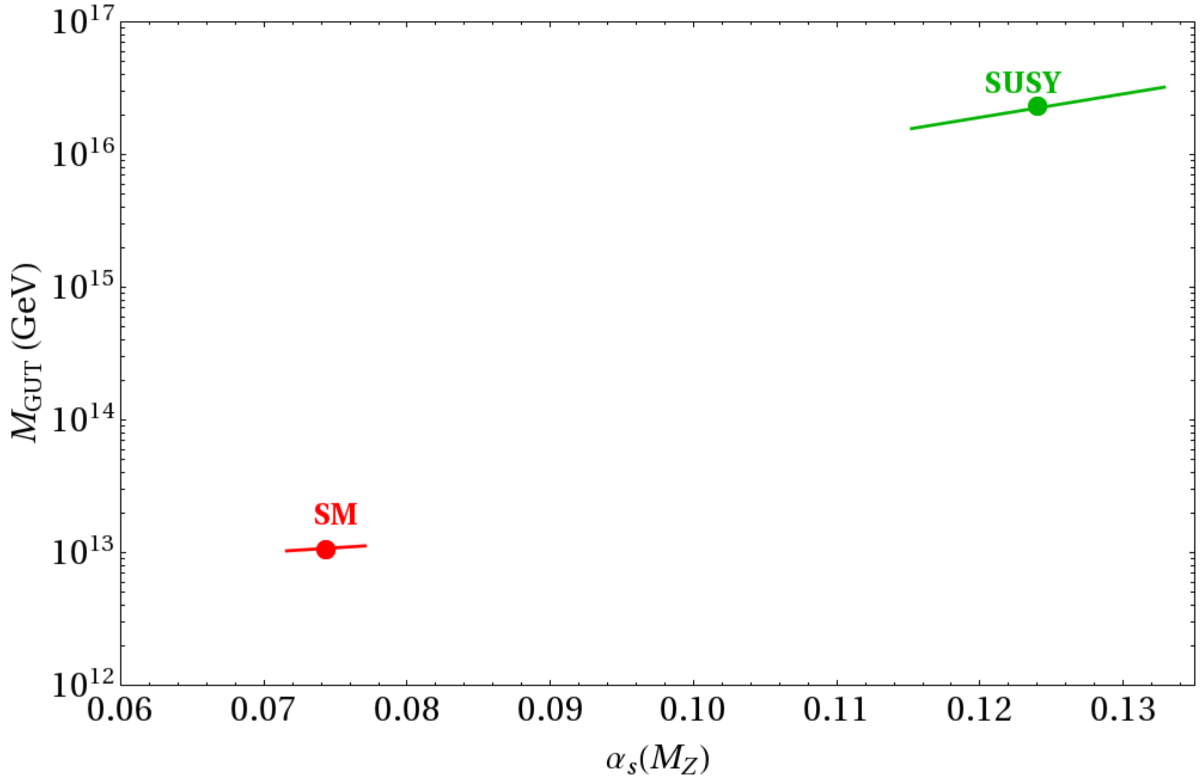
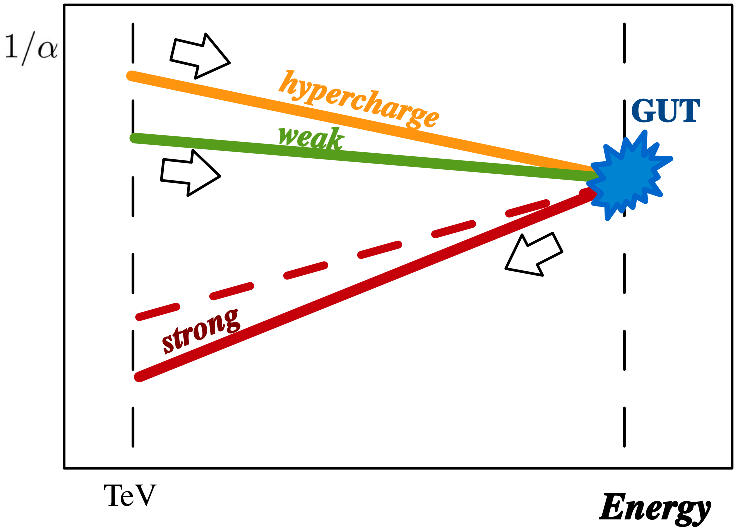


1/α
hypercharge
weak
GUT
strong
TeV
Energy

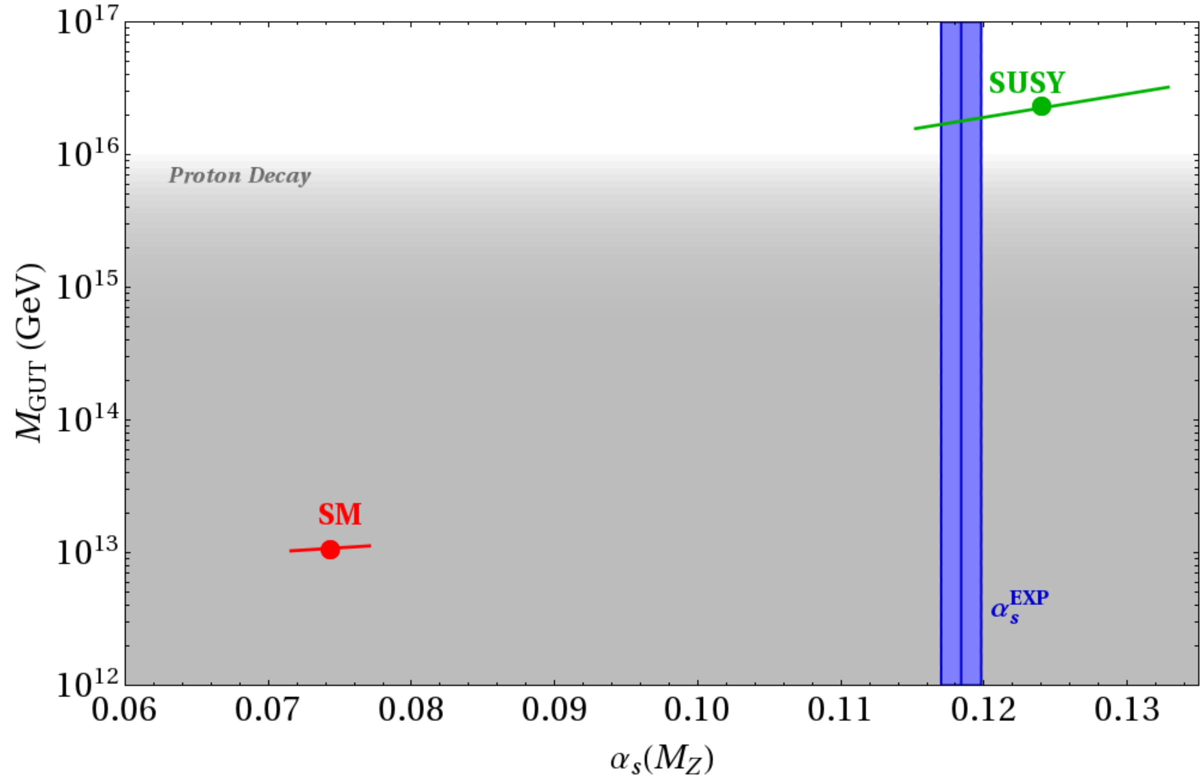


SUSY
SM
$M_{\rm GUT}$ (GeV)
$\alpha_s(M_Z)$
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13

3. GUT

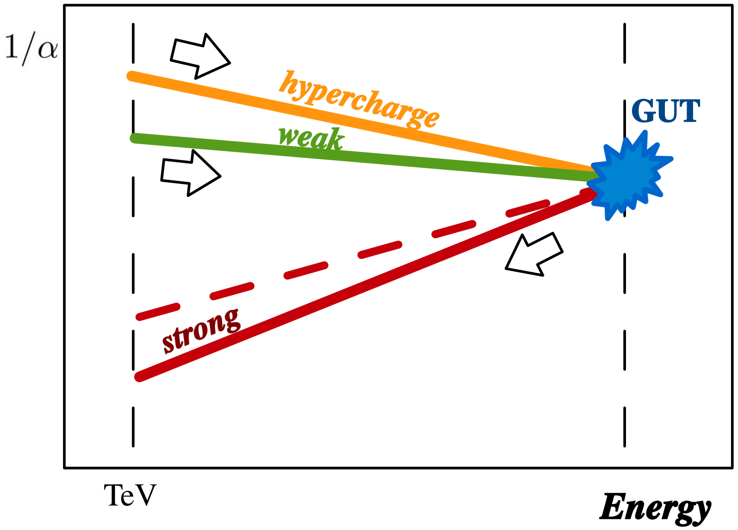


$1/\alpha$
hypercharge
weak
GUT
strong
TeV
Energy

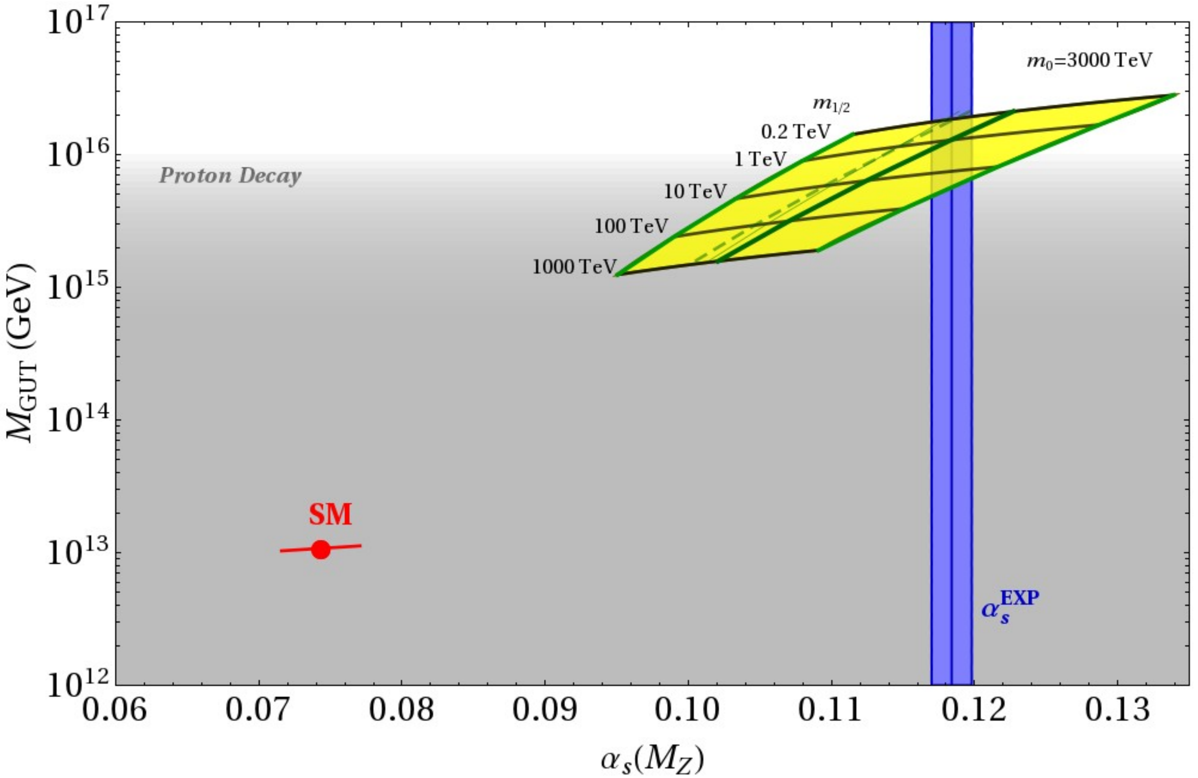


SUSY
Proton Decay
SM
α_s^{EXP}
M_{GUT} (GeV)
$\alpha_s(M_Z)$
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13

3. GUT



$1/\alpha$
hypercharge
weak
strong
GUT
TeV
Energy



10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
M_{GUT} (GeV)
Proton Decay
m_0=3000 TeV
$m_{1/2}$
0.2 TeV
1 TeV
10 TeV
100 TeV
1000 TeV
SM
α_s^{EXP}
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
$\alpha_s(M_Z)$

SUSY: A New Angle

- assume SUSY
- take seriously GUT
- use exp. to determine SUSY scale

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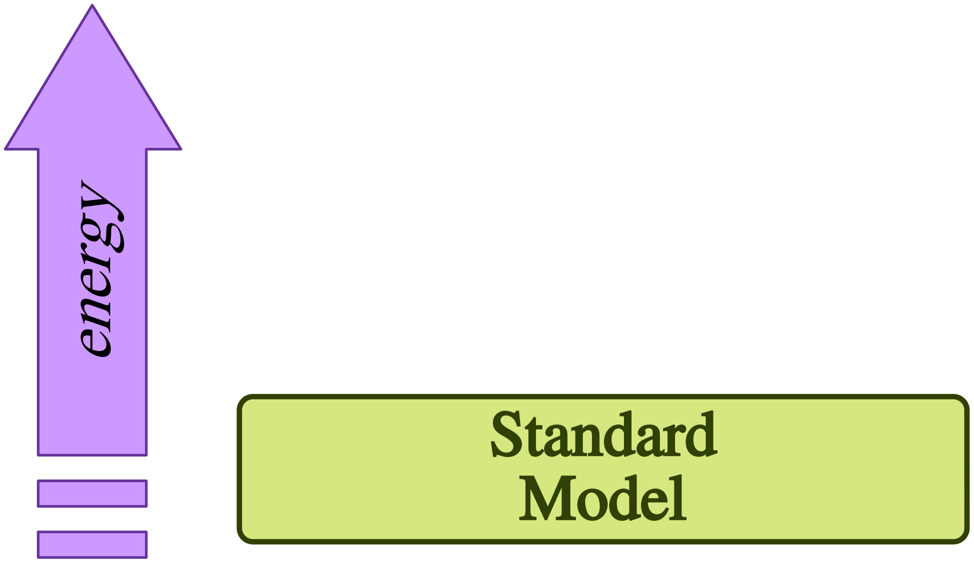

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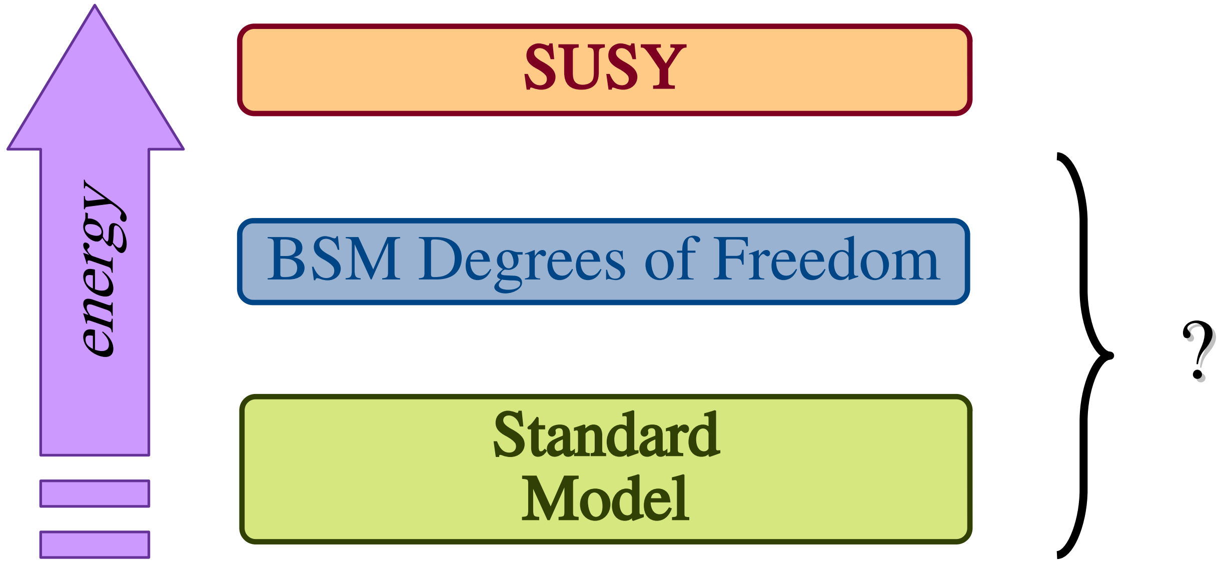

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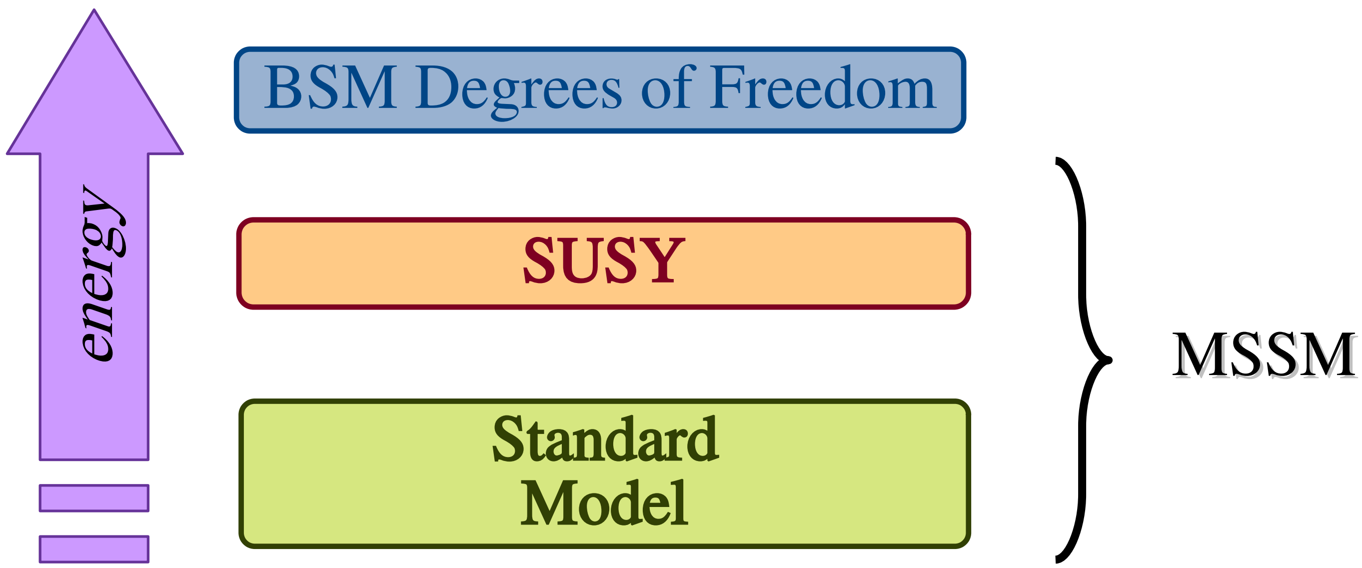

In the MSSM the Higgs mass is predictive

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta \,.$$

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$125^2 \sim 90^2 + 90^2$

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only *log*-dependence on new physics scale

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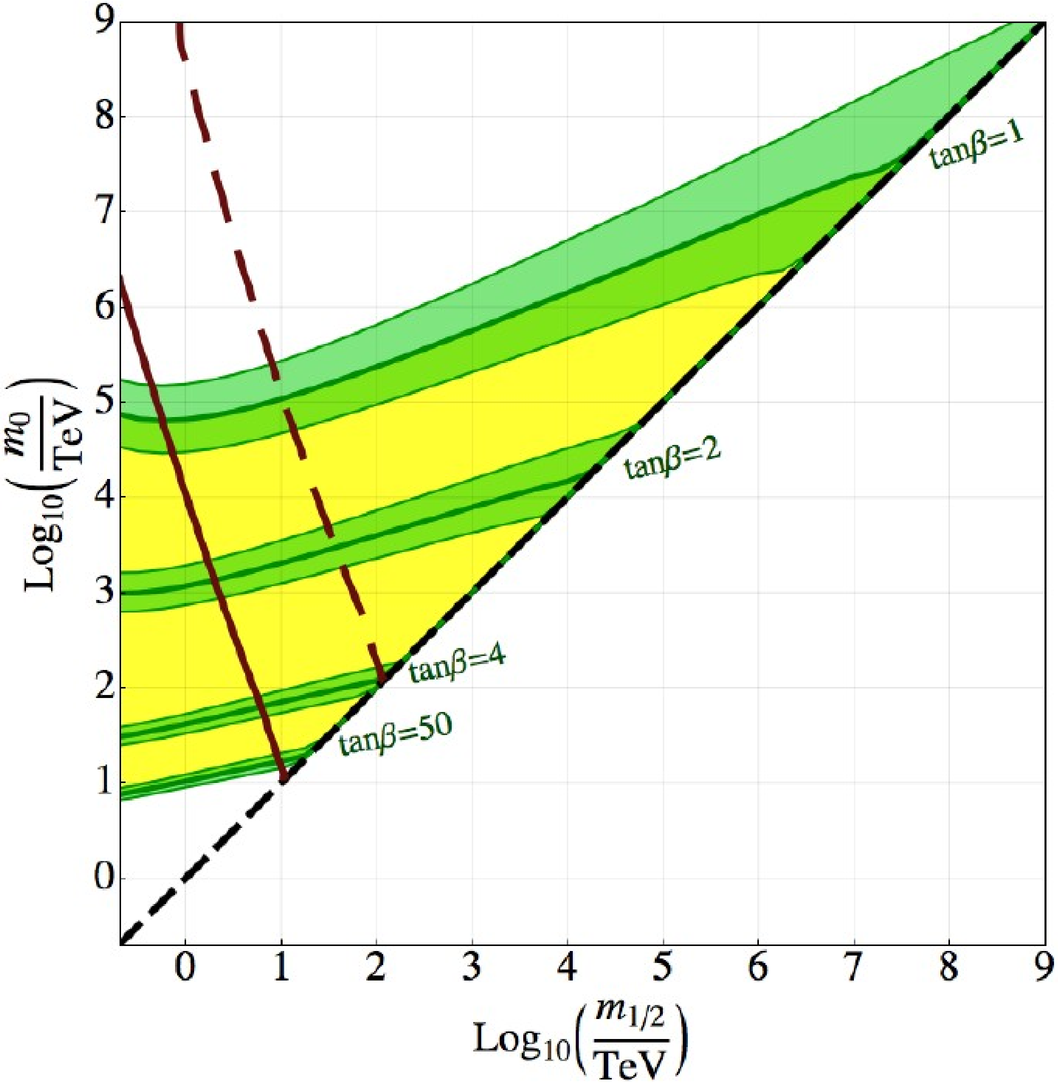
only *log*-dependence on new physics scale

⇒ high precision to get reliable constraints

Mini - Split

Arvanitaki et al. ‘12
Arkani-Hamed et al. ‘12



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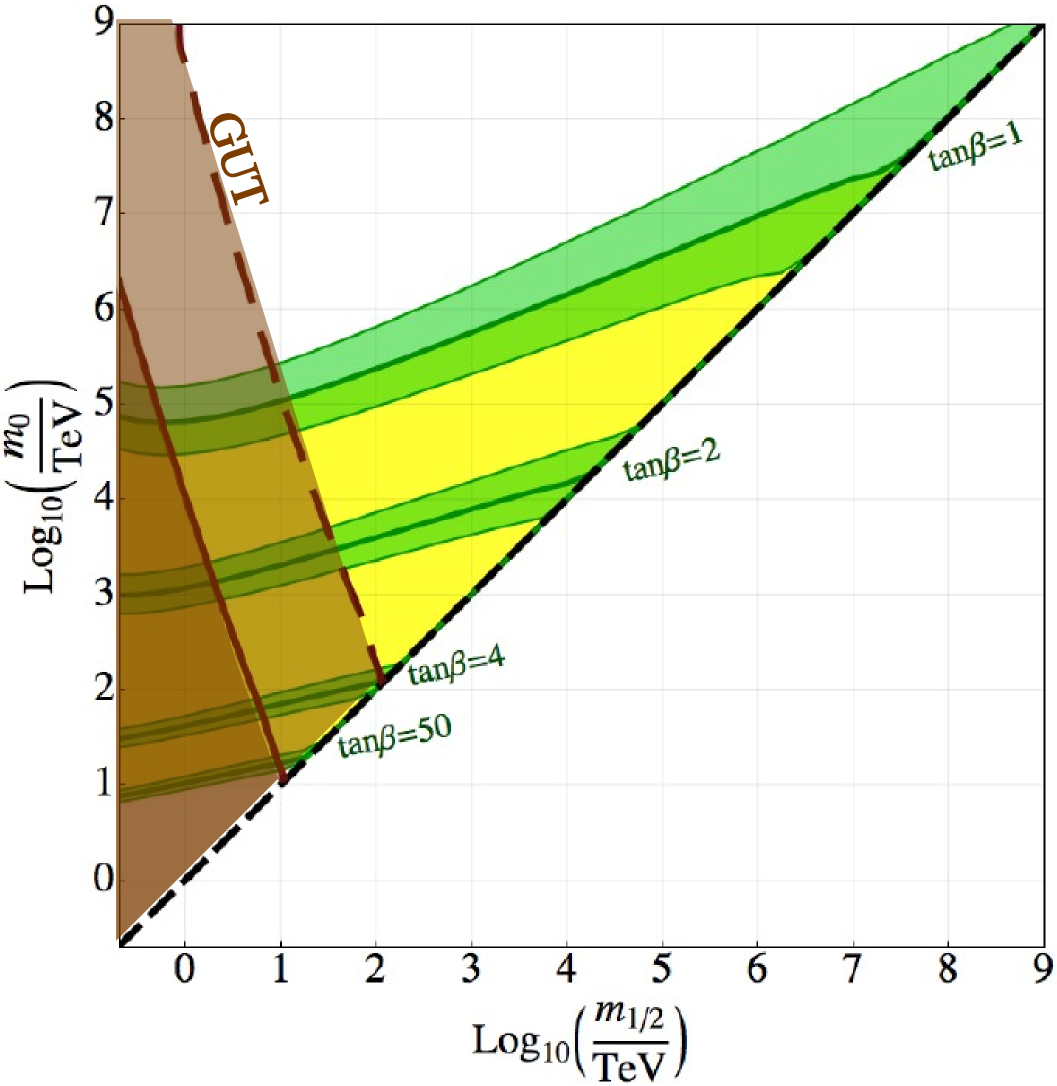

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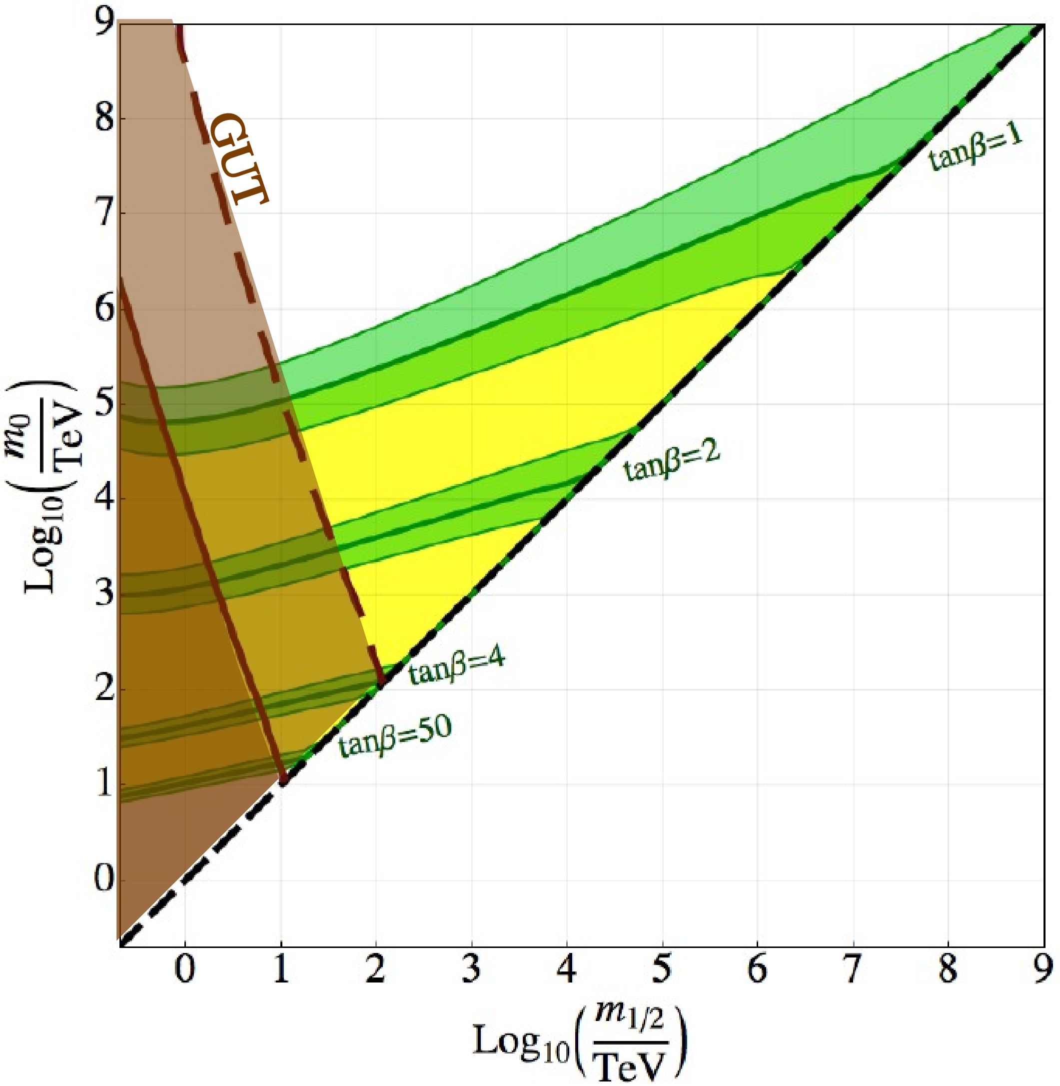

Small tanβ and EWSB

$$\det\begin{pmatrix} |\mu|^2+m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2+m_{H_d}^2 \end{pmatrix}\approx 0$$

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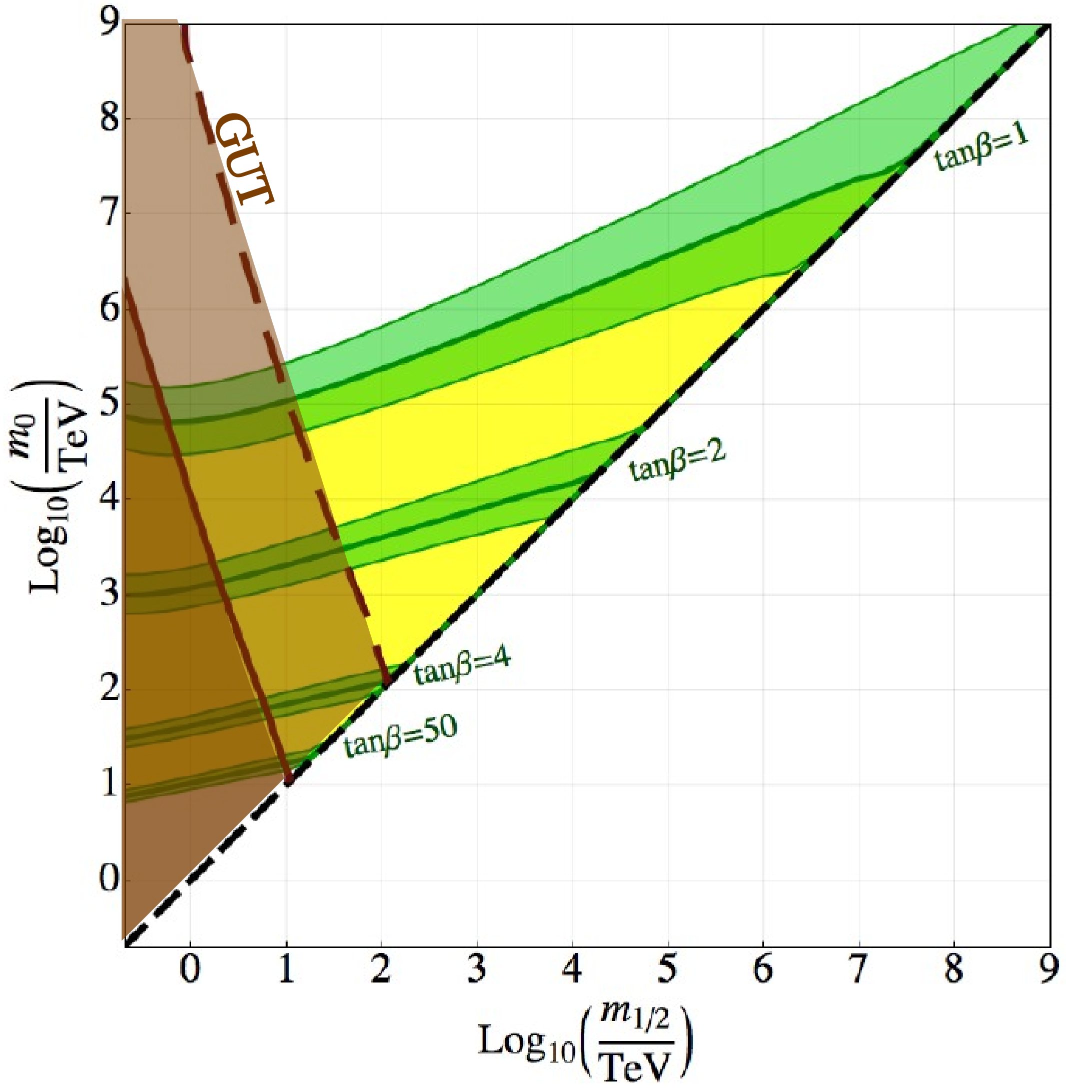

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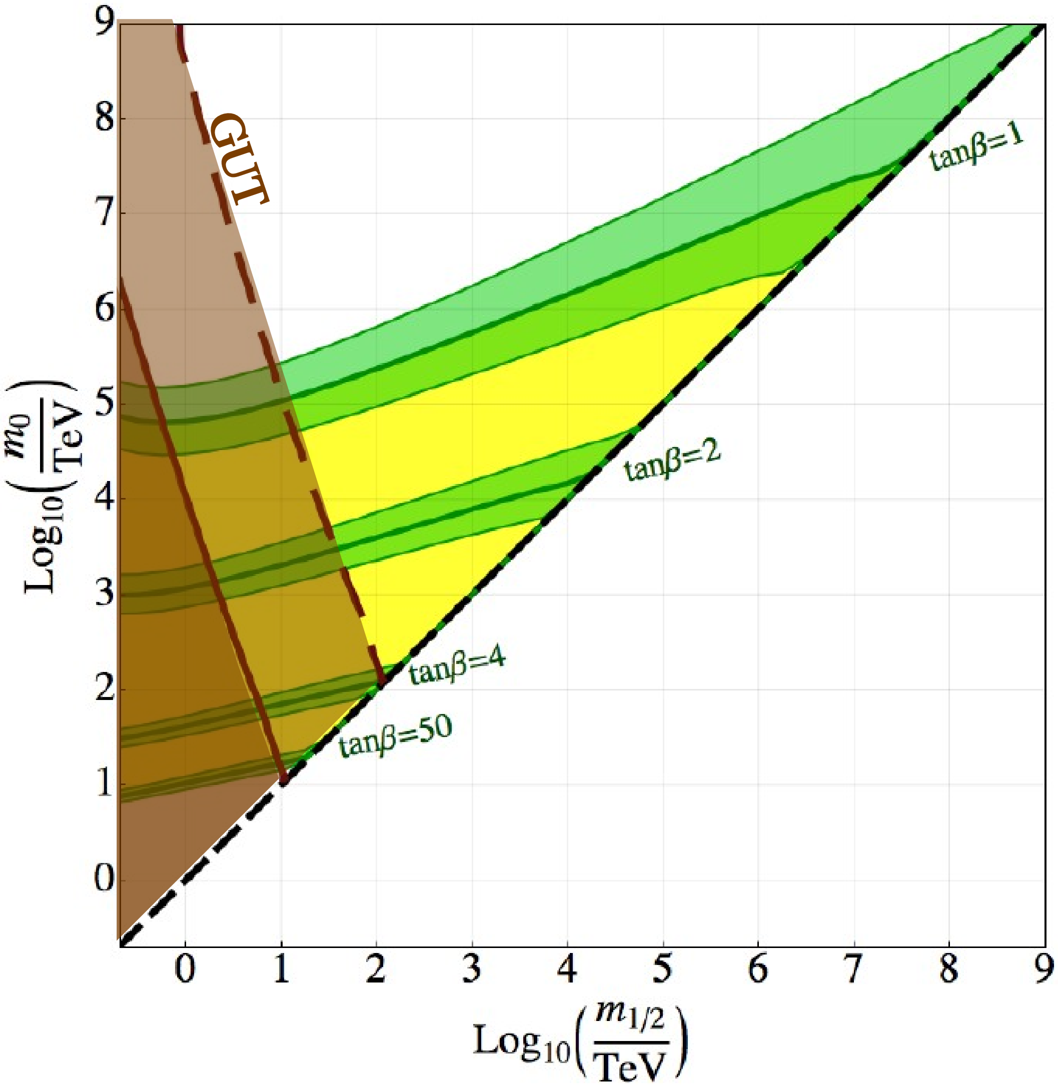

Small tanβ and EWSB

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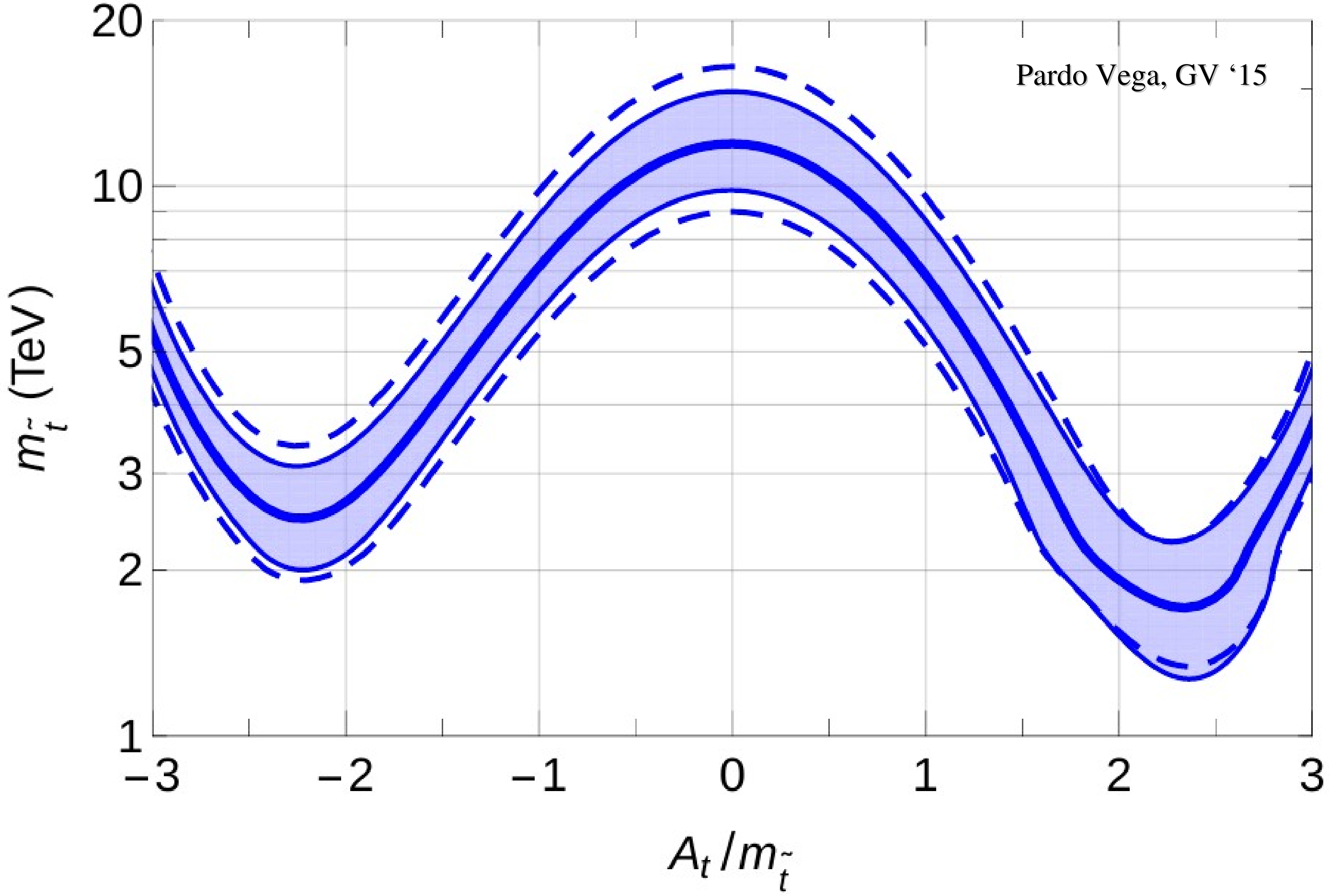
$$|B_\mu|^2 \approx m_{H_u}^2 m_{H_d}^2$$

$$\tan\beta \approx \frac{m_{H_d}}{m_{H_u}}$$

but relation: $m_{H_u}^2 \simeq m_{H_d}^2$

broken by Yukawa

MSSM Higgs @ large tanβ



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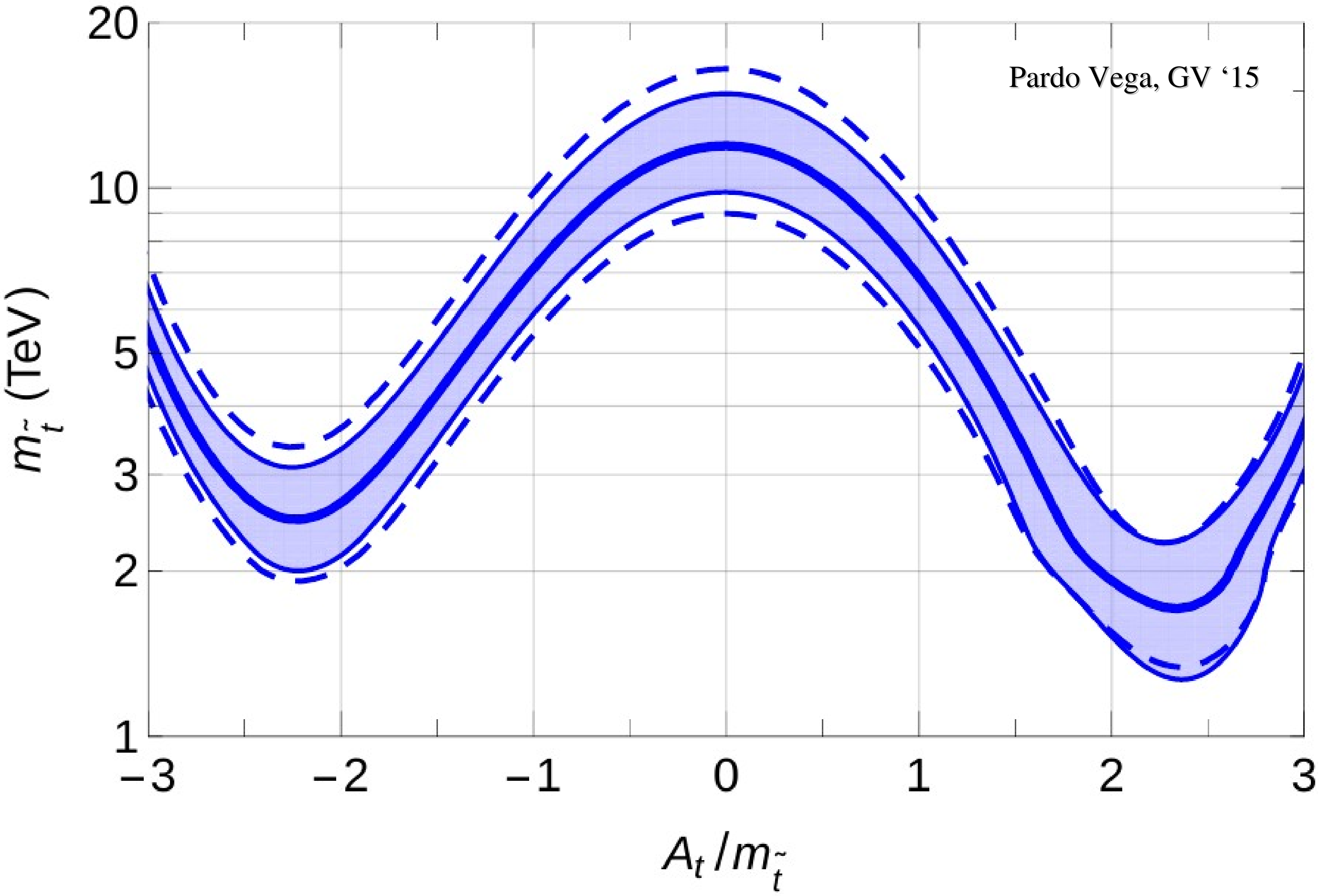
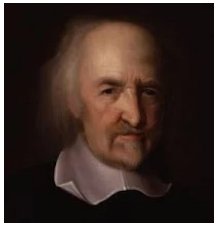


"Hell is truth seen too late."

– Thomas Hobbes, Leviathan



MSSM freedom

	SM	MSSM
params.	19	18

MSSM freedom

	SM	**MSSM**
params.	19	18 → 124

not predictive

FCNC, EDM, ...

MSSM freedom

	SM	MSSM
params.	19	18 → 124

not predictive

FCNC, EDM, ...

Depend on Mediation Mechanism:

Gravity / Anomaly / (Generalized) Gauge / Gaugino / Moduli / …

MSSM freedom

	SM	MSSM
params.	19	$18 \rightarrow 124$

not predictive

FCNC, EDM, ...

Depend on Mediation Mechanism:

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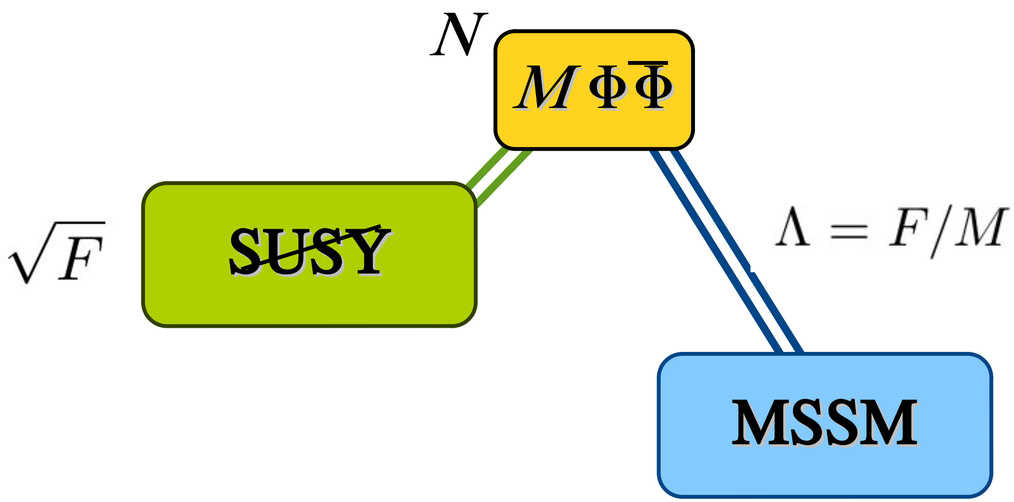
Minimal Gauge Mediation

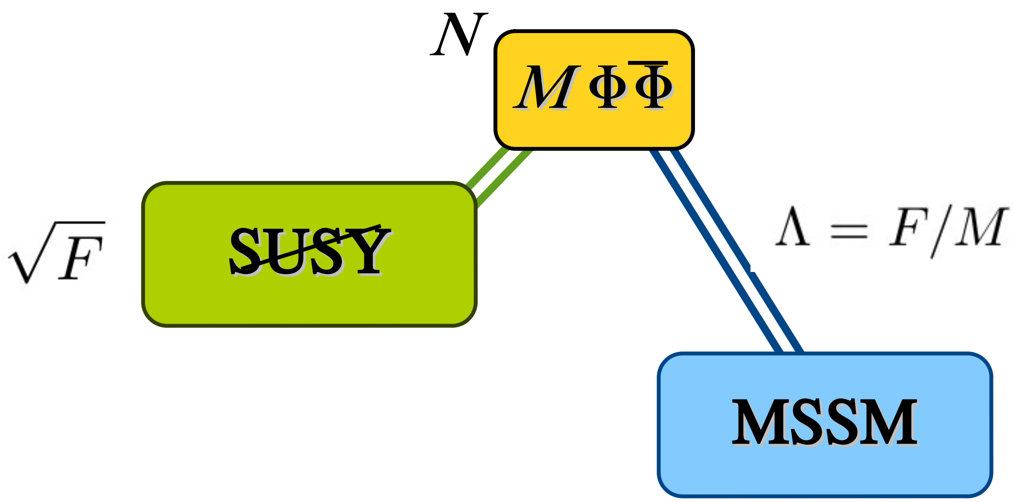
most simple + predictive + most compatible

Minimal Gauge Mediation

Minimal Gauge Mediation



Minimal Gauge Mediation



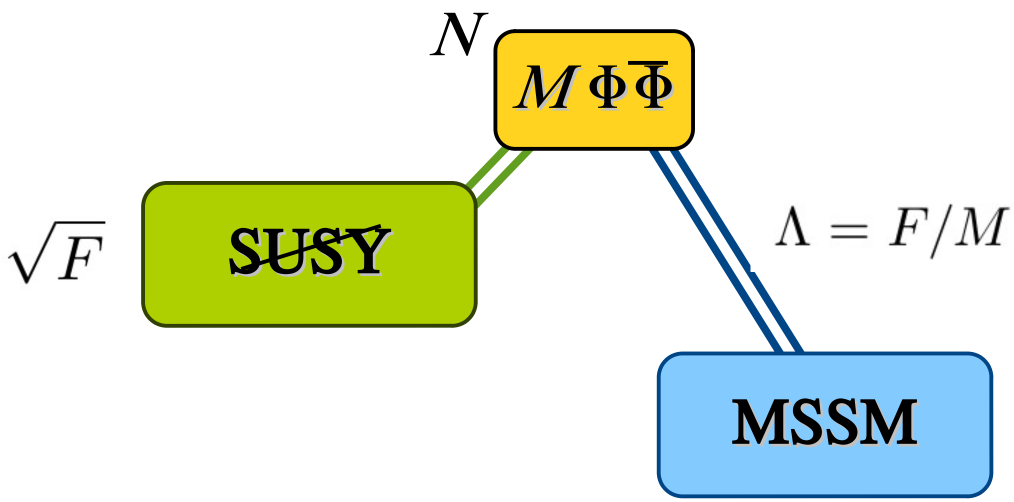
spectrum:

$$M_j = N\frac{\alpha_j}{4\pi}\Lambda$$

$$m_i = 2\sqrt{N}C_{ij}\frac{\alpha_j}{4\pi}\Lambda$$

$$A_i = B_\mu = 0$$

Minimal Gauge Mediation

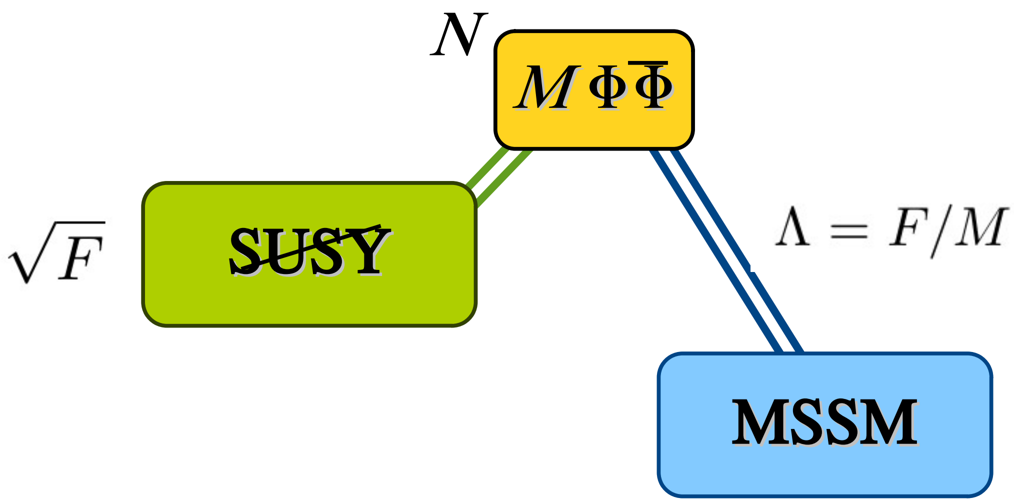


spectrum:

$$
\begin{cases}
M_j = N \dfrac{\alpha_j}{4\pi} \Lambda \\
m_i = 2\sqrt{N} C_{ij} \dfrac{\alpha_j}{4\pi} \Lambda \\
A_i = B_\mu = 0
\end{cases}
$$

⇒ **flavor blind (MFV) spectrum:**
NO dangerous FCNC

Minimal Gauge Mediation



spectrum:

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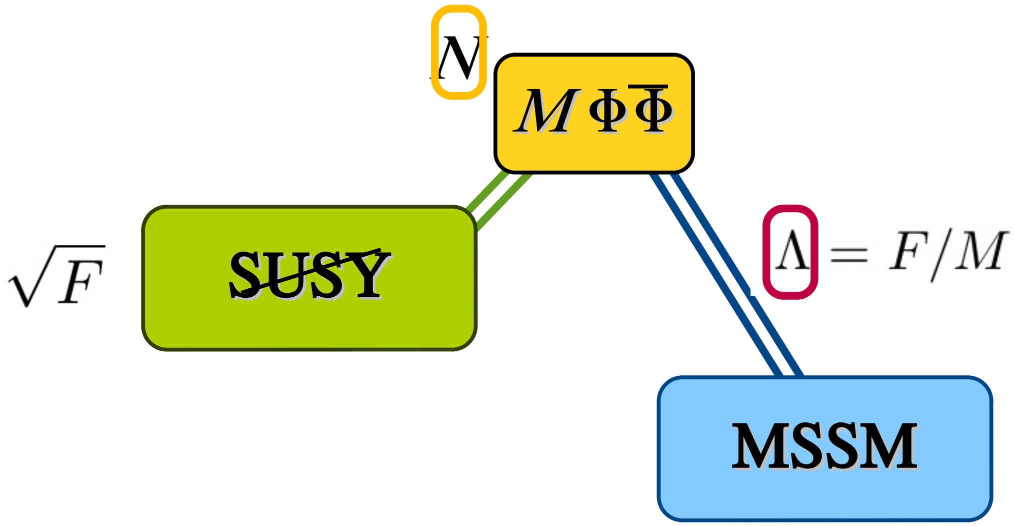
⇨ flavor blind (MFV) spectrum: NO dangerous FCNC

⇨ NO CPV phases

Minimal Gauge Mediation



spectrum:

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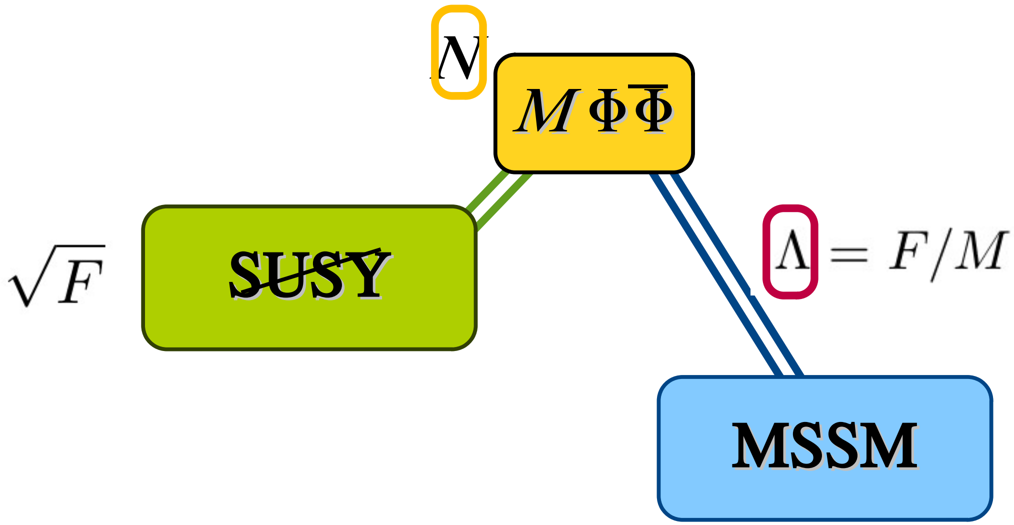


spectrum:

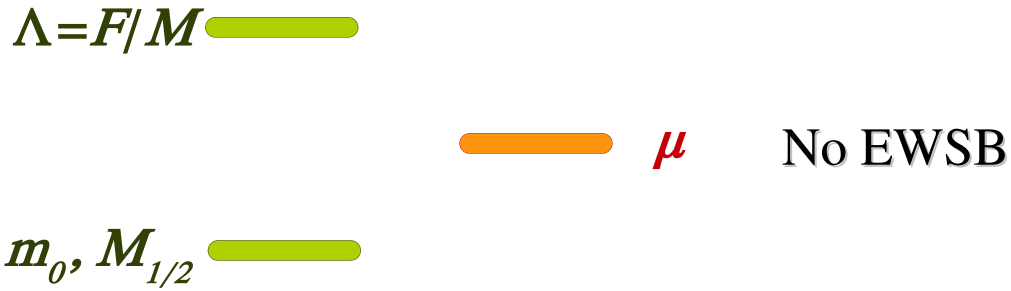
$$
\begin{cases}
M_j = N \frac{\alpha_j}{4\pi} \Lambda \\
m_i = 2\sqrt{N} C_{ij} \frac{\alpha_j}{4\pi} \Lambda \\
A_i = B_\mu = 0
\end{cases}
$$

⇨ **flavor blind (MFV) spectrum: NO dangerous FCNC**

⇨ **NO CPV phases**

\# parameters = # parameters of SM
+ weak dependence on N and $\log(M)$

No naturalness → no μ problem:



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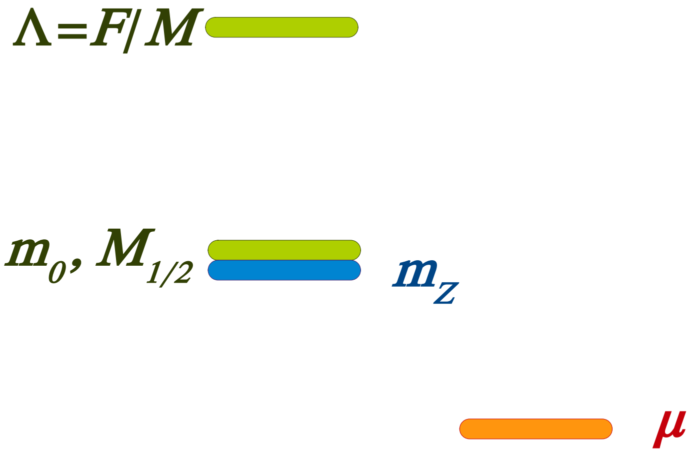


EWSB ~ m_0

No naturalness → no μ problem:

$\Lambda = F/M$

$m_0, M_{1/2}$ — μ — EWSB $\ll m_0$ — $|\mu|^2 \simeq -m_{H_u}^2 + \ldots$

m_Z

No naturalness → no μ problem:

$\Lambda = F/M$

$m_0, M_{1/2}$ — μ — EWSB $\ll m_0$ — $|\mu|^2 \simeq -m_{H_u}^2 + \ldots$

m_Z

$B_\mu, A = 0$ at the scale M

<u>generated radiatively</u>

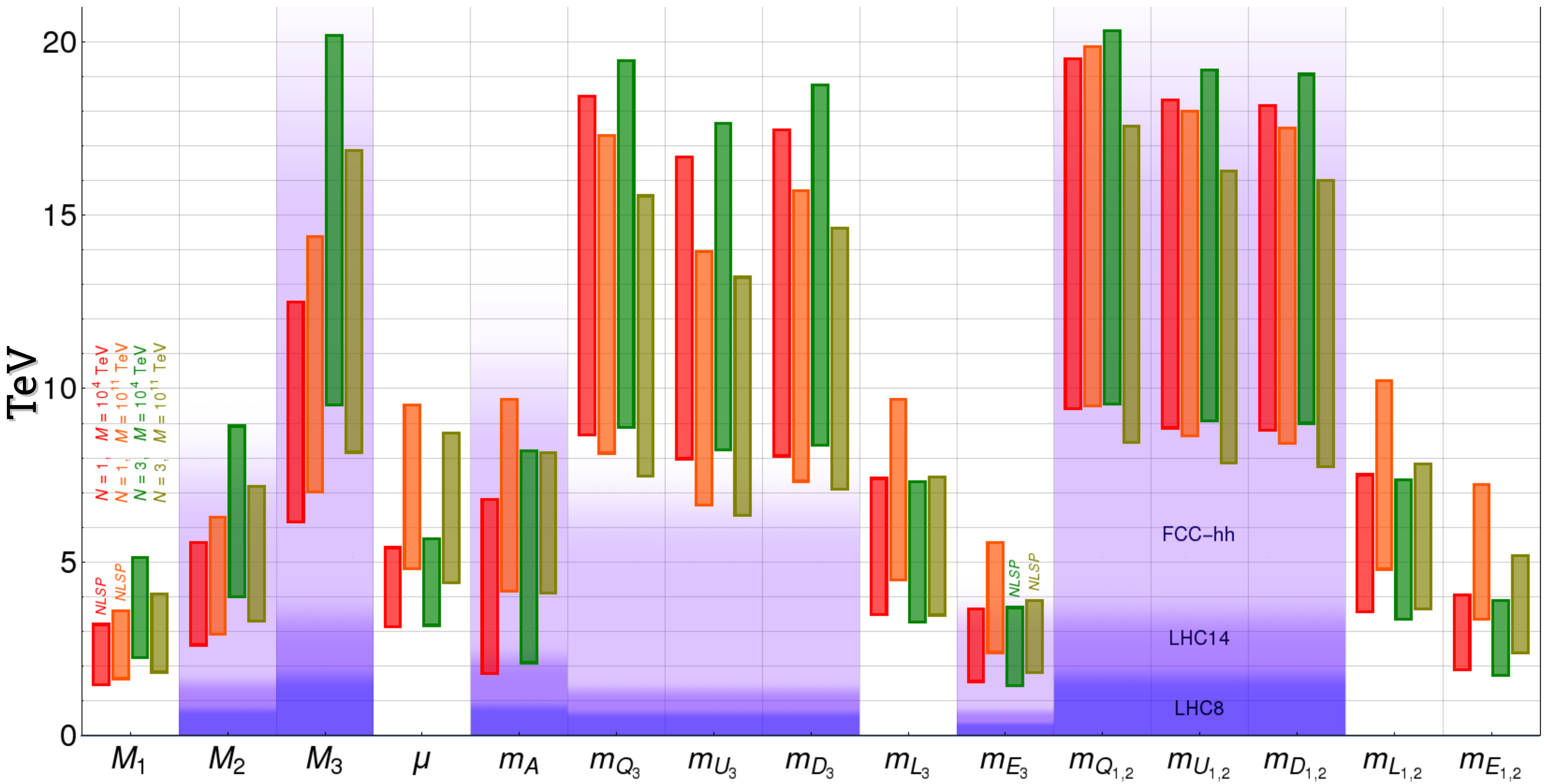
→ $A_t \lesssim m_0$ *no maximal mixing*

→ $B_\mu \ll m_0^2$ $\tan(\beta) \sim$ 30-60

→ *no CP phases → no EDMs*

Predicting the MGM spectrum

Pardo Vega, GV '15



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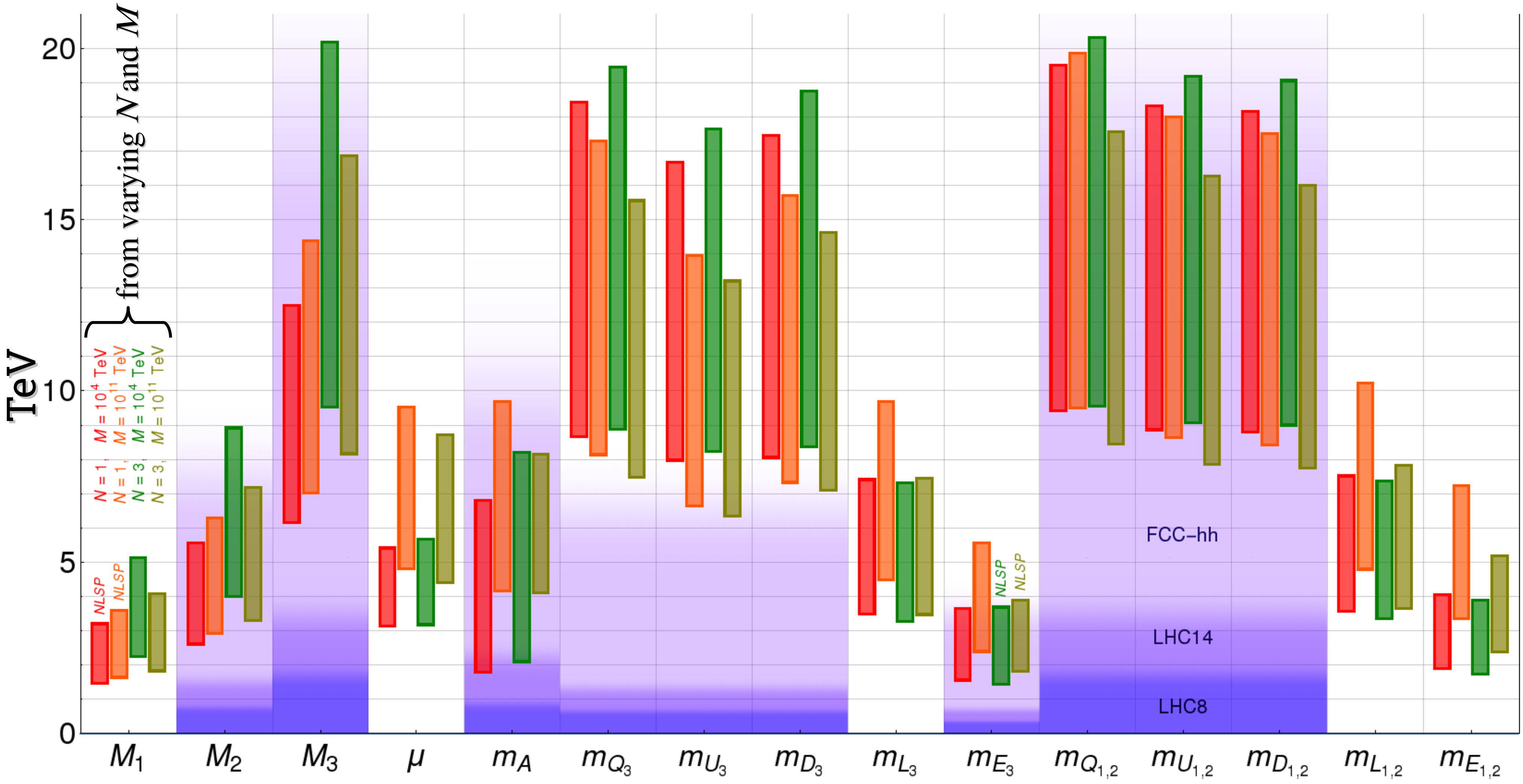
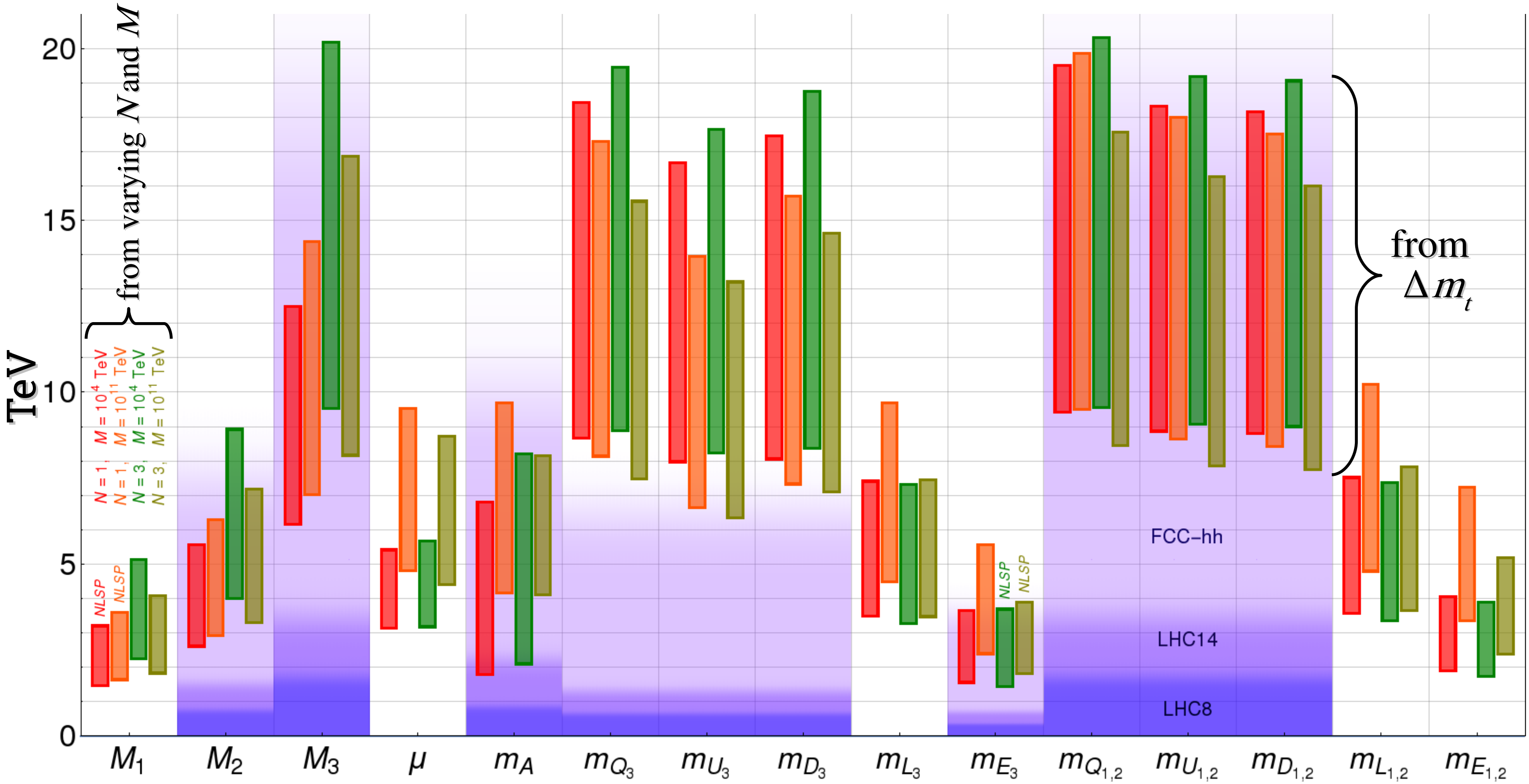


Predicting the MGM spectrum

Pardo Vega, GV '15



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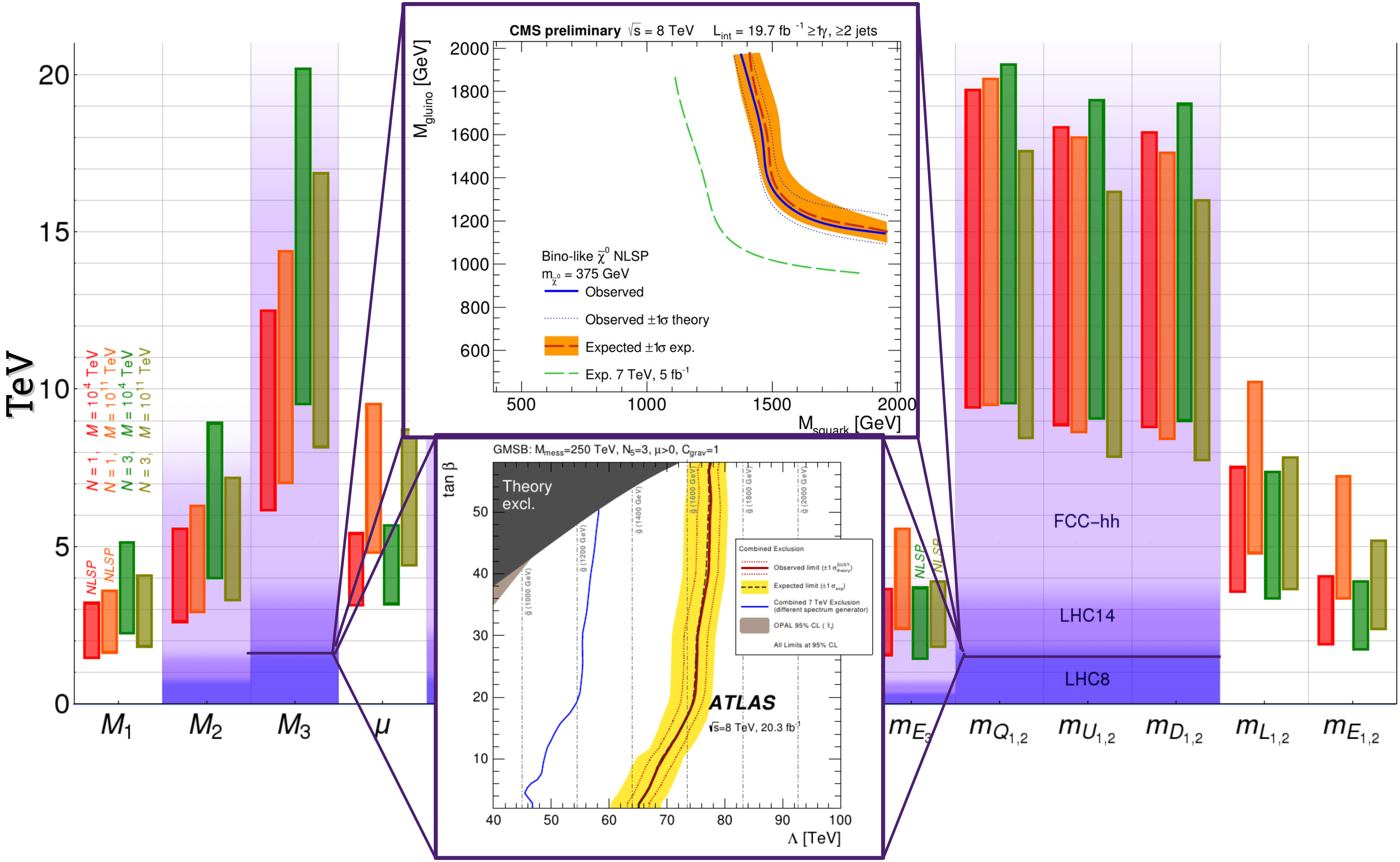

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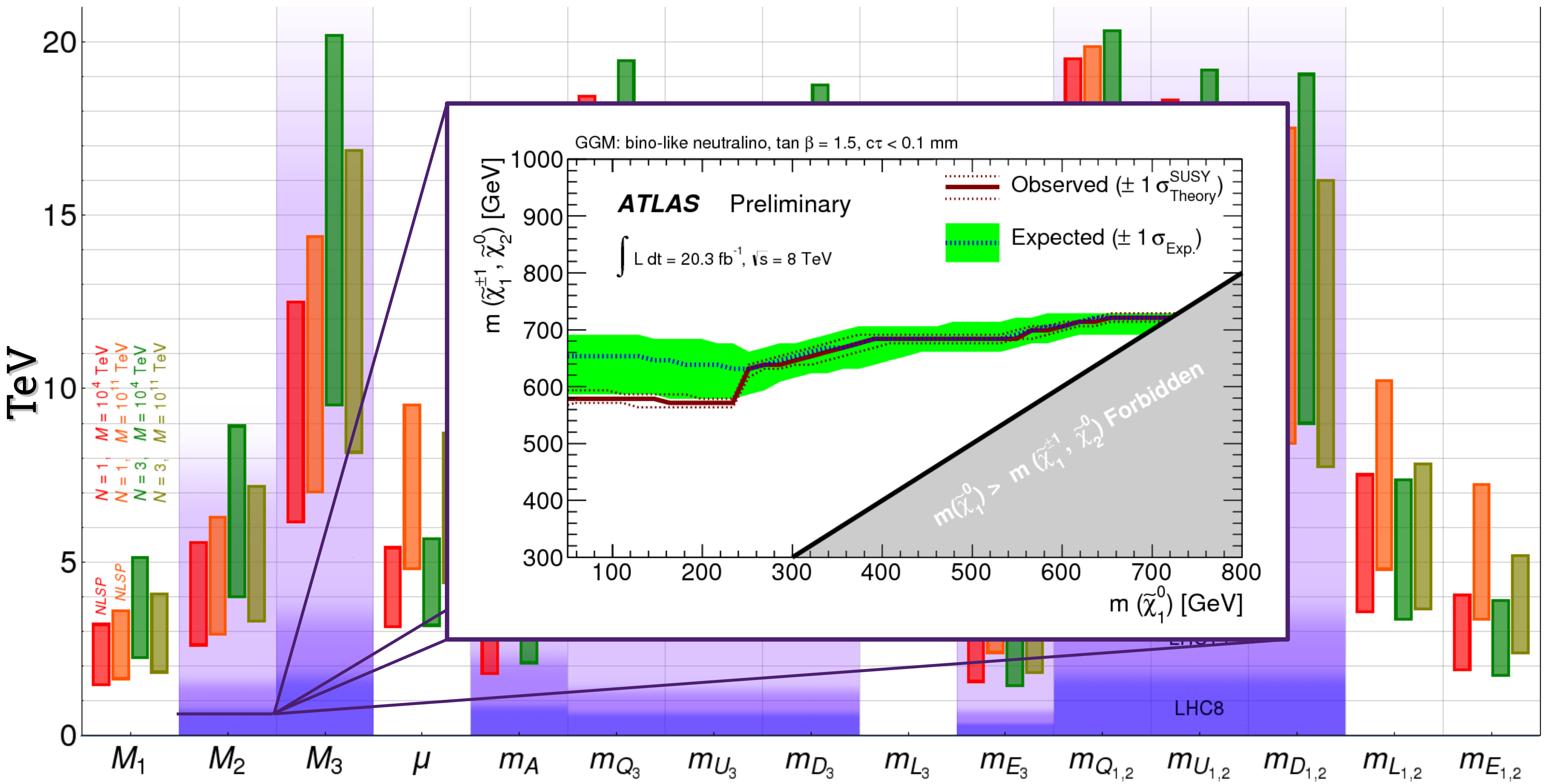

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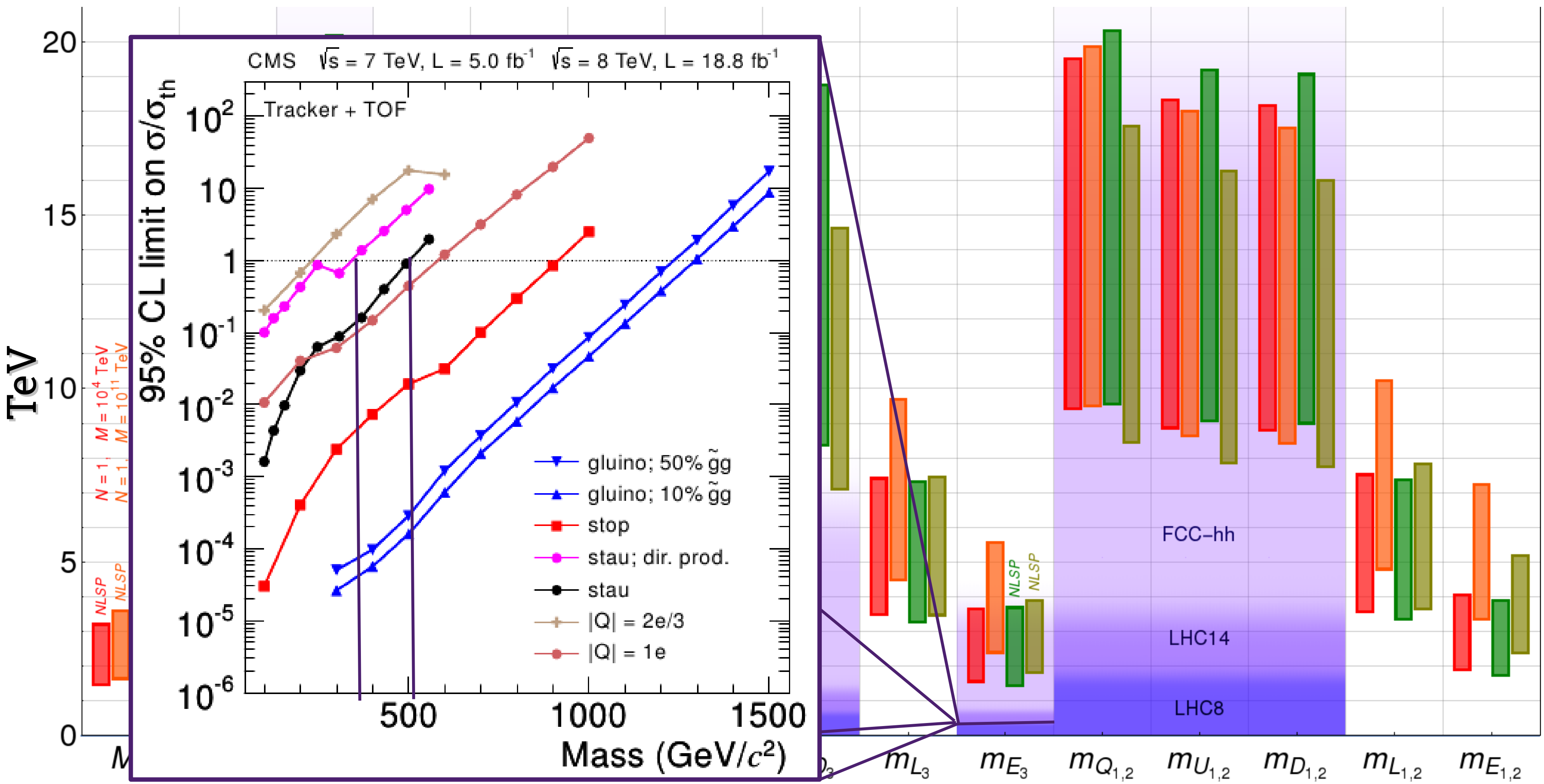

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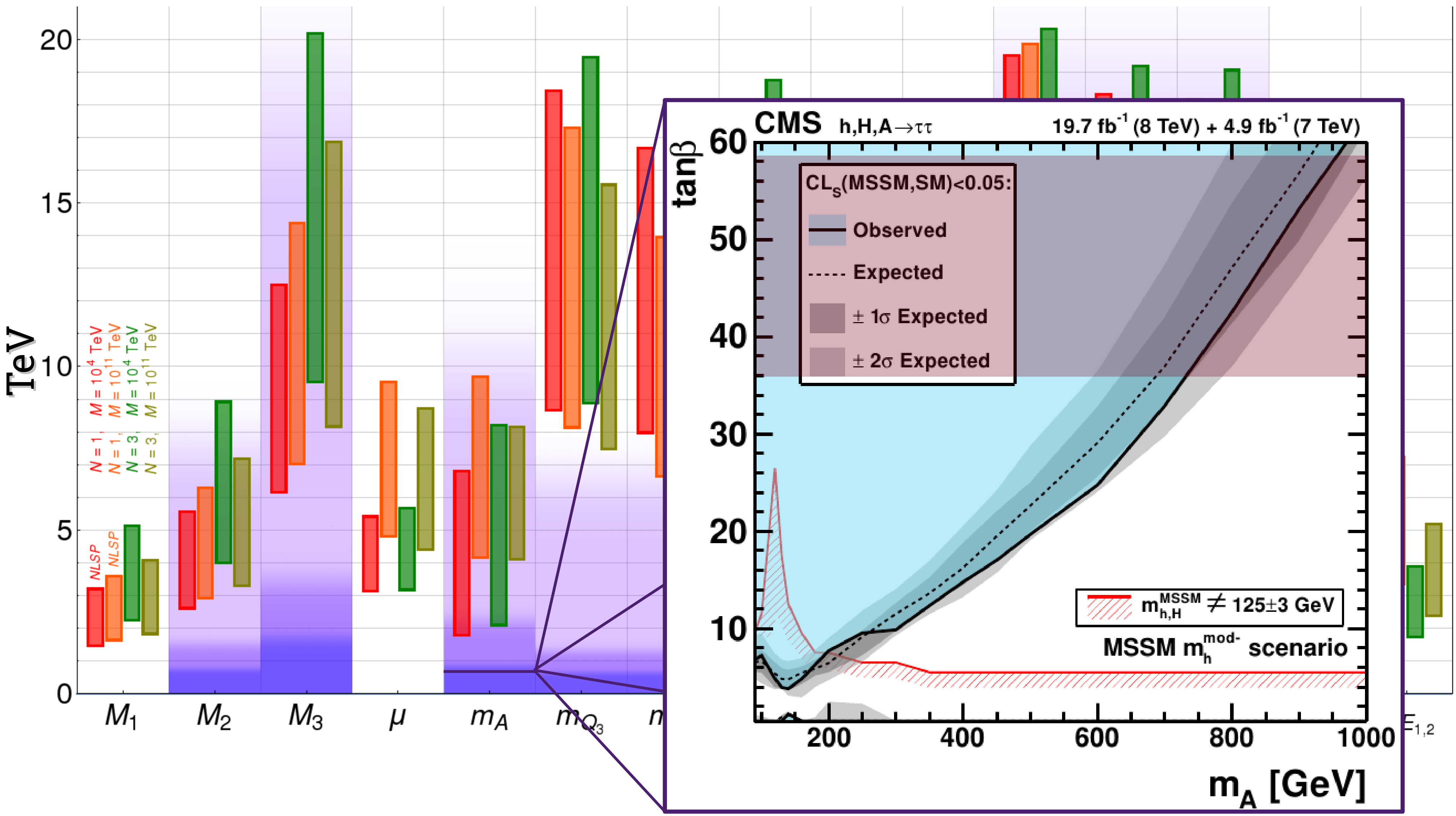

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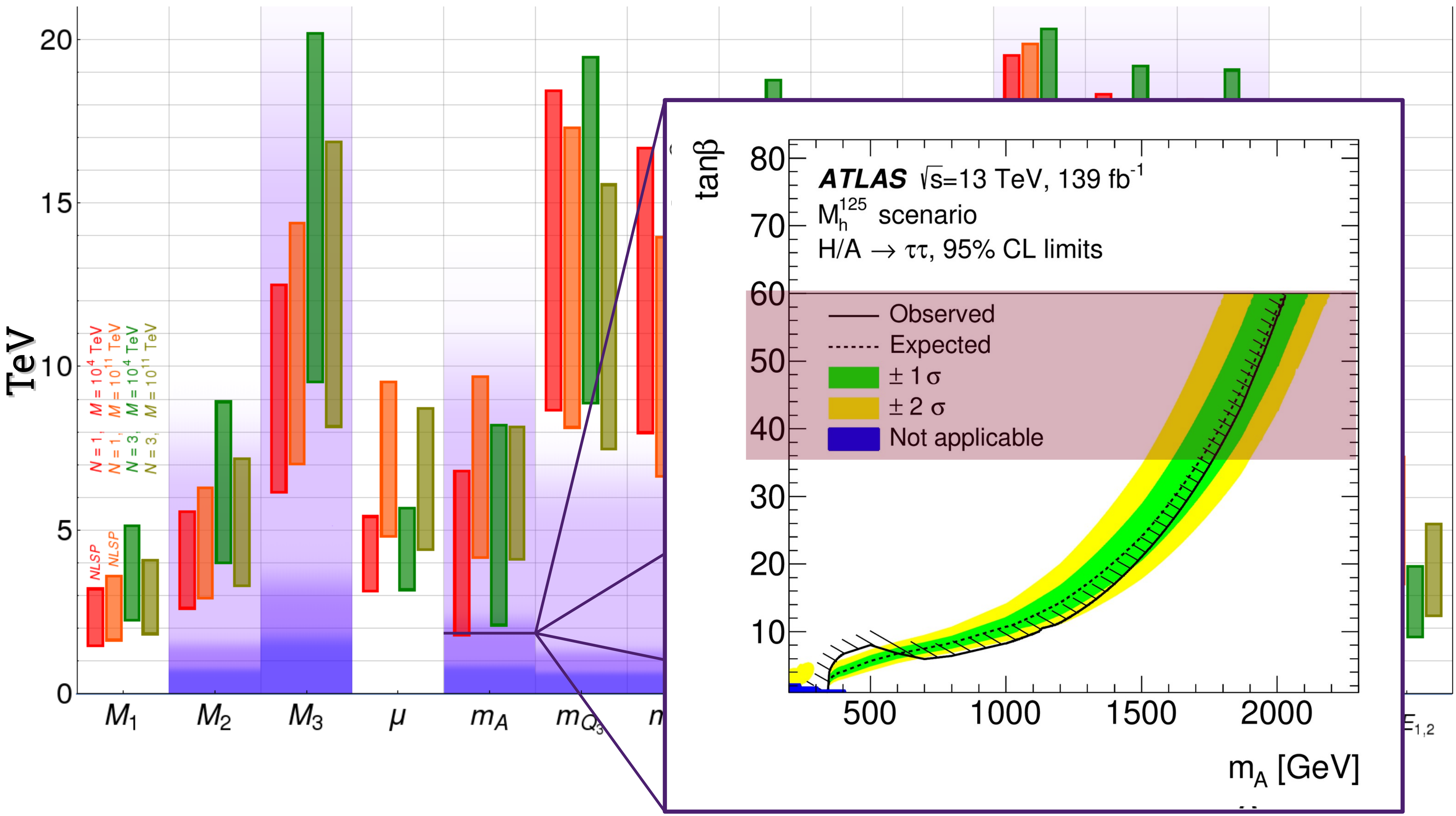

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MGM as benchmark for Future Collider – *"work in progress"*
- Muon Collider (and FCC) reach / parameters
- Constraints from cosmology and SUSY breaking sectors

more in general

O(10) TeV SUSY still well motivated
and plausible scenario for BSM

Thank You!

Backup

Estimate of the Uncertainties: