



The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence



Exploring the energy frontier with muon beams

Jun 30, 2025 - Aug 01, 2025

In this workshop we will explore the opportunities unleashed by progress in muon-based experiments, with particular focus on a multi-TeV muon collider. We will discuss both Standard Model precision physics and the search for new phenomena at the highest possible accelerator energies.

Muon beams up to multi-TeV energies hold the potential to revolutionize the exploration of the high-energy frontier. At the same time, they require the development of new methods and tools in particle theory as well as in collider experiments and accelerator physics. Our workshop will bring together experts, and early career scientists from these communities and will provide the setting to weave together the strategy to get to the next new kind of particle collider. In addition the workshop will serve as a platform to develop possible synergies between all the communities potentially interested in muon beams, and in the technologies that are necessary to develop them.

A muon collider requires an intense proton beam that produces similarly intense hadron, muon, and neutrino beams; we will discuss how those beams can enable exploration of the lepton and neutrino sector, as well as dark matter and dark sectors and other investigations at the intensity frontier. During the workshop we will organize several pedagogical activities aimed at increasing the awareness and competence in the high energy physics theoretical community on the exciting possibilities enabled by progress expected in muon beams and collider technologies. We will also organize small groups focused on further developing key tools needed for muon collider R&D.

Topics:

- Week-1 Training Week: Introduction To Muon Beams And Applications
- Week-2 Focus Week: Precision Physics (SM)
- Week-3 Focus Week: New Physics (BSM)
- Synergy Week: Physics With Muon Beams
- Public Conference: "Physics At The Highest Energies With Colliders"

with the support of



Organizing Committee:

J. Scott Berg (BNL, USA)
Dario Buttazzo (INFN Pisa)
Roberto Franceschini (Roma Tre U. and INFN)
Tova Holmes (University of Tennessee, Knoxville, USA)
Patrick Meade (Stony Brook University, USA)
Fabio Maltoni (Louvain, Bologna U. and INFN)
Federico Meloni (Deutsches Elektronen-Synchrotron, DE)

Training Week (Jun 30, 2025 - Jul 04, 2025)
Conference (Jul 28, 2025 - Aug 01, 2025)

Deadline for applications: Feb 14, 2025

SUSY beyond the TeV scale

Giovanni Villadoro



The Abdus Salam
International Centre
for Theoretical Physics

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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$$\begin{array}{ccc} \text{Poincaré} & \rightarrow & \text{SUSY} \\ \mathcal{P} & & \mathcal{S} \end{array} \quad \left\{ \begin{array}{l} [\mathcal{P}, \mathcal{P}] = \mathcal{P} \\ [\mathcal{P}, \mathcal{S}] = \mathcal{S} \\ \{\mathcal{S}, \mathcal{S}\} = \mathcal{P} \end{array} \right.$$

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Important Feature of Quantum Gravity

→ Supergravity / String Theory

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Important Feature of Quantum Gravity
→ Supergravity / String Theory

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

SUSY breaking scale?

Supersymmetry

Historical motivations for low-energy SUSY:

- Hierarchy Problem
- WIMP Miracle
- Grand Unification

1. Hierarchy Problem

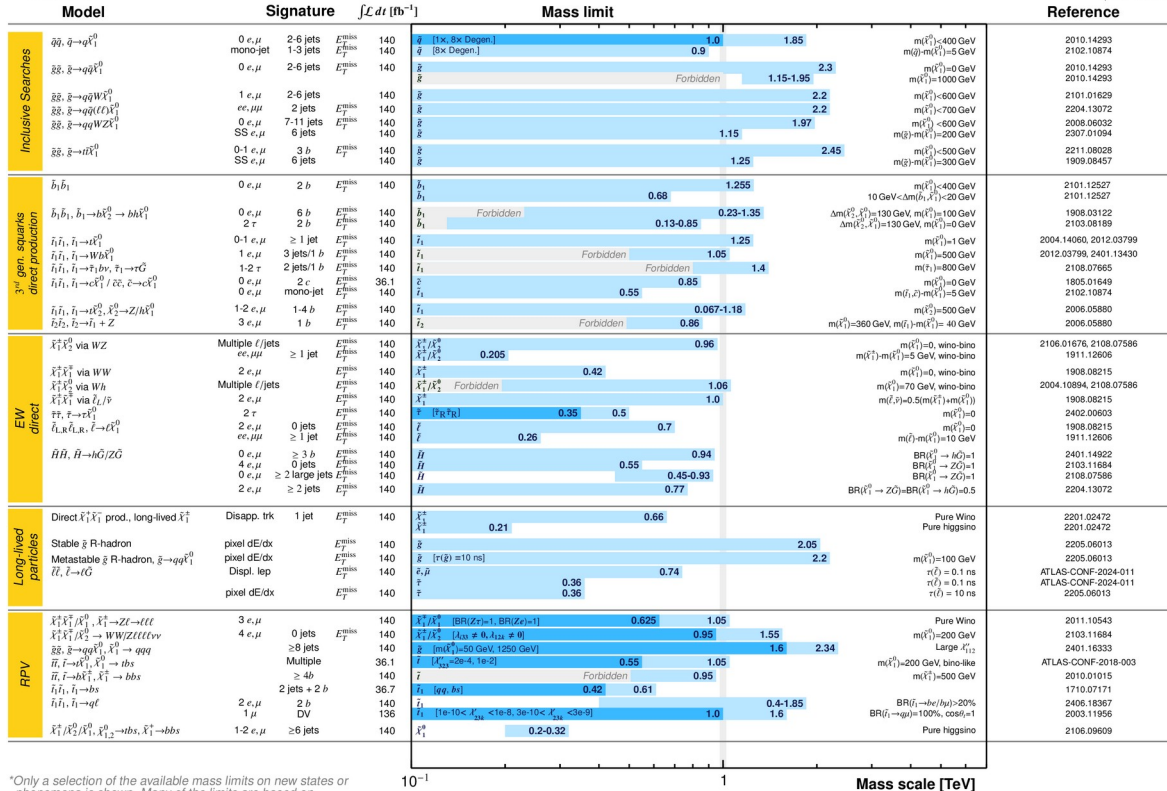
$$\delta m_Z^2 \sim m_{\text{SUSY}}^2$$

1. Hierarchy Problem

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

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2024

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$

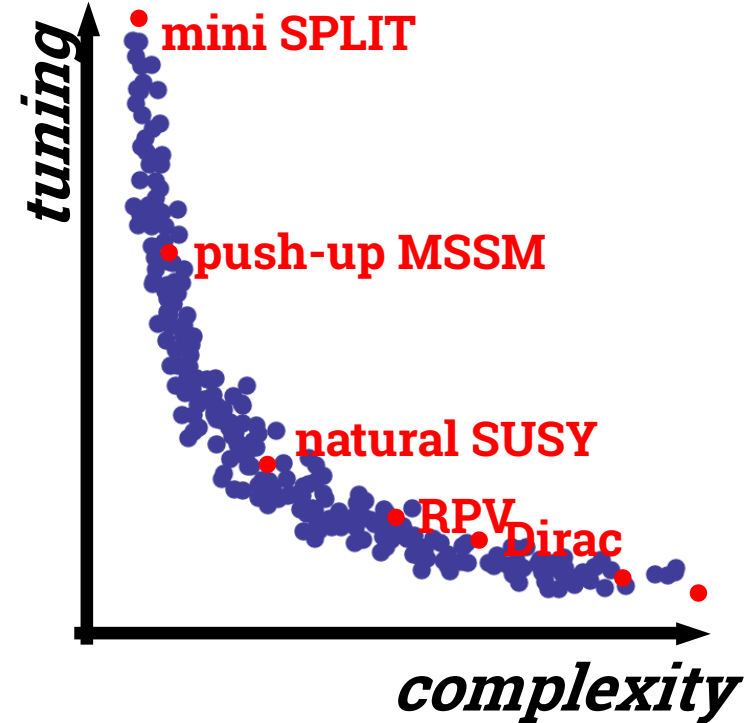
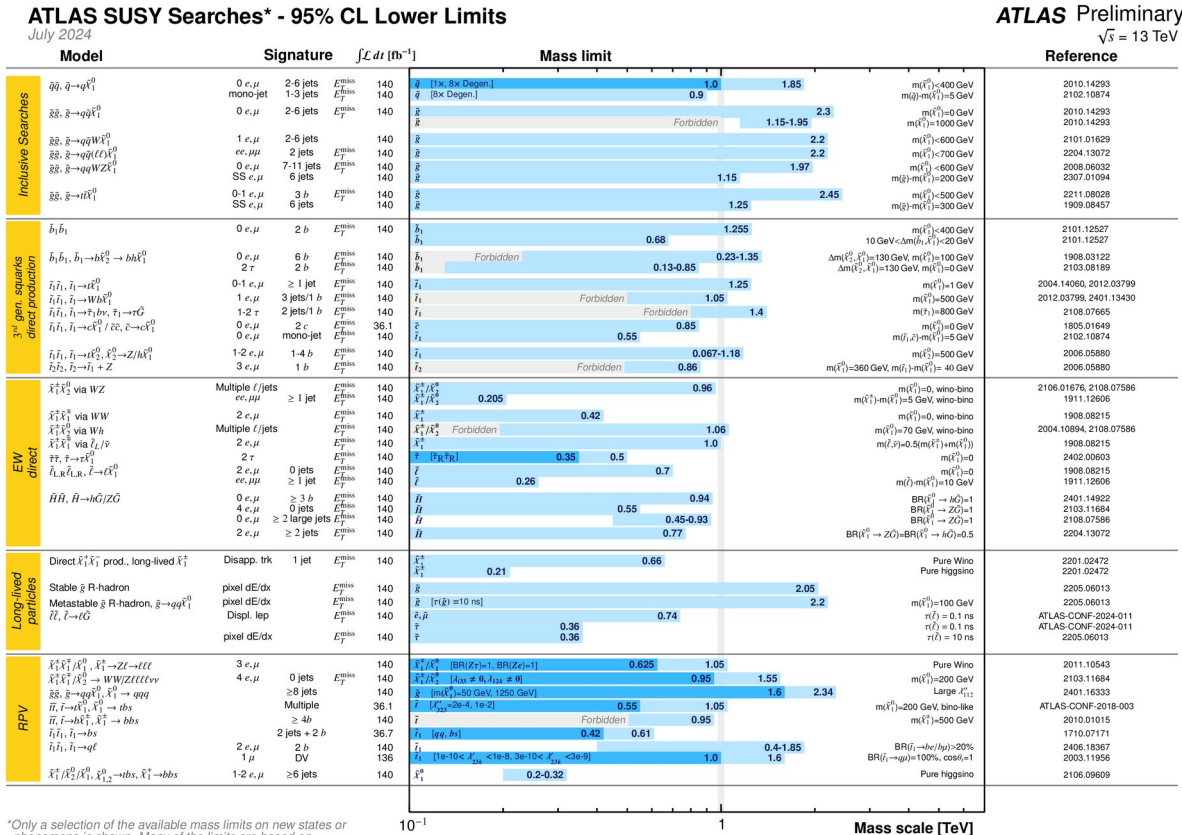


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Mass scale [TeV]

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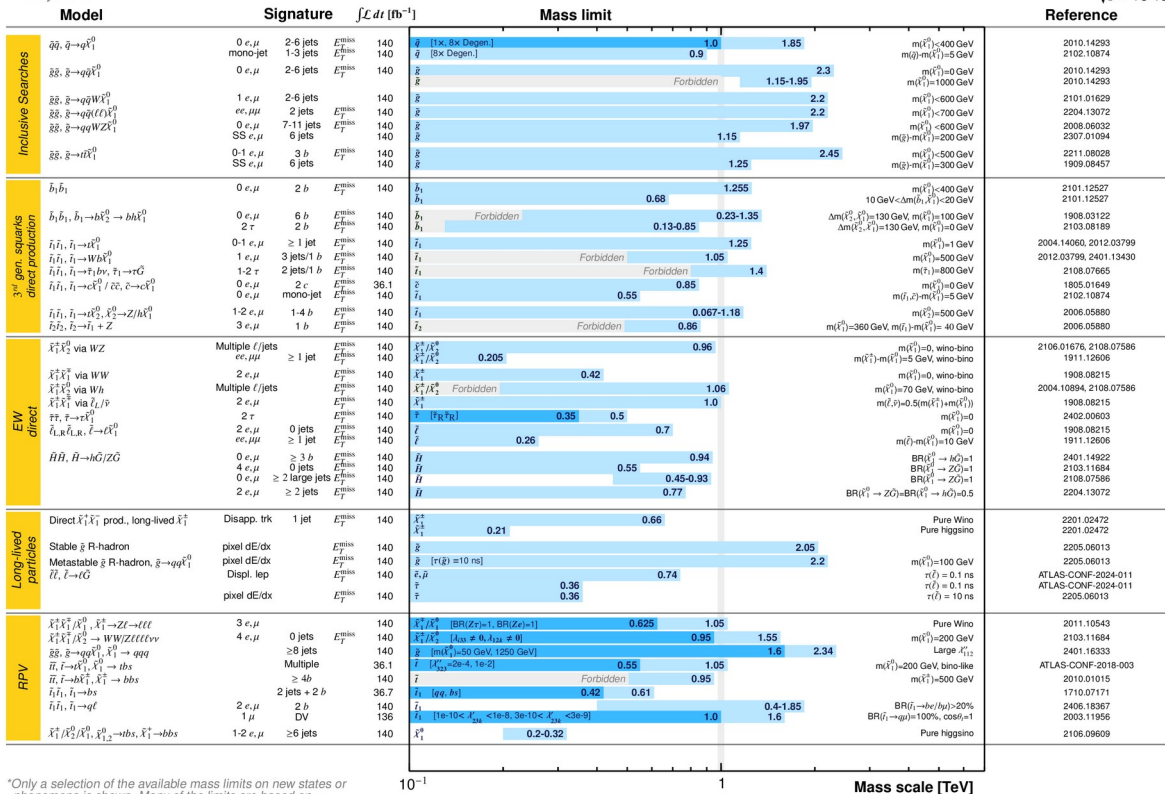
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many known alternatives to SUSY

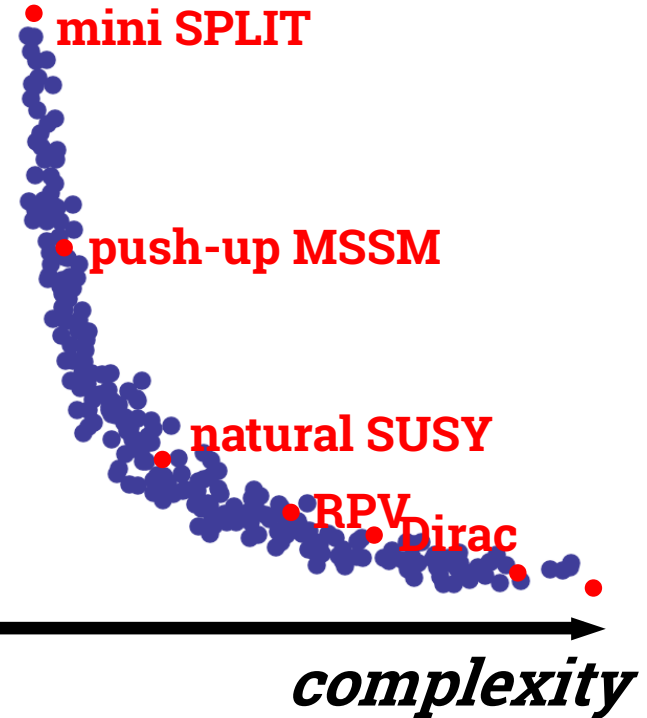
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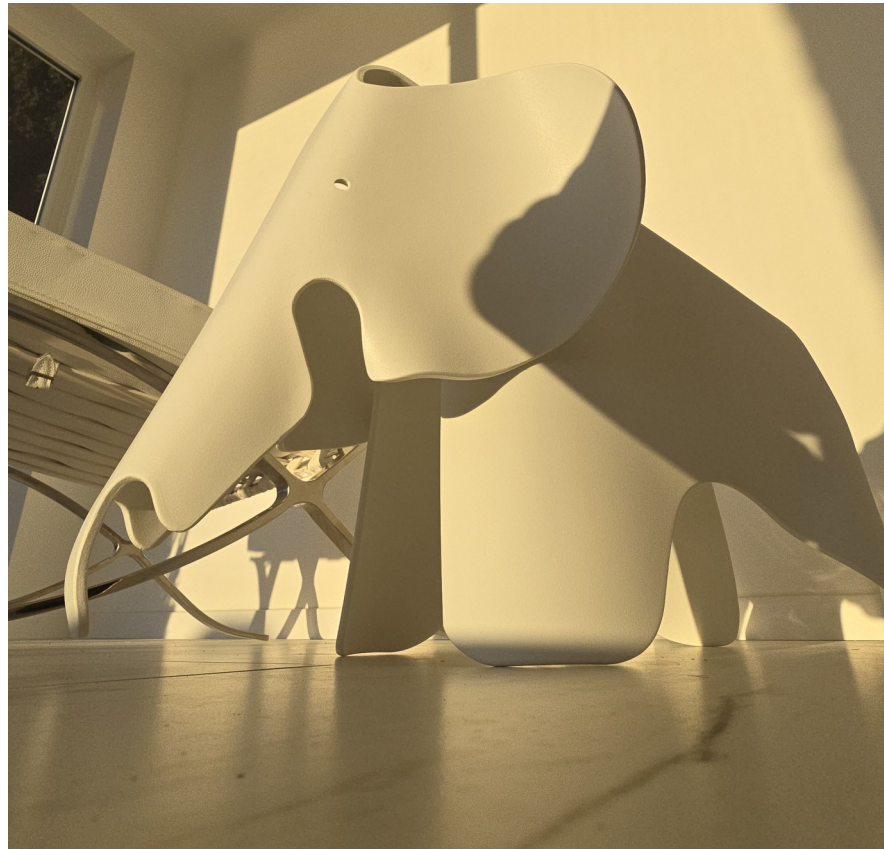
tuning



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

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

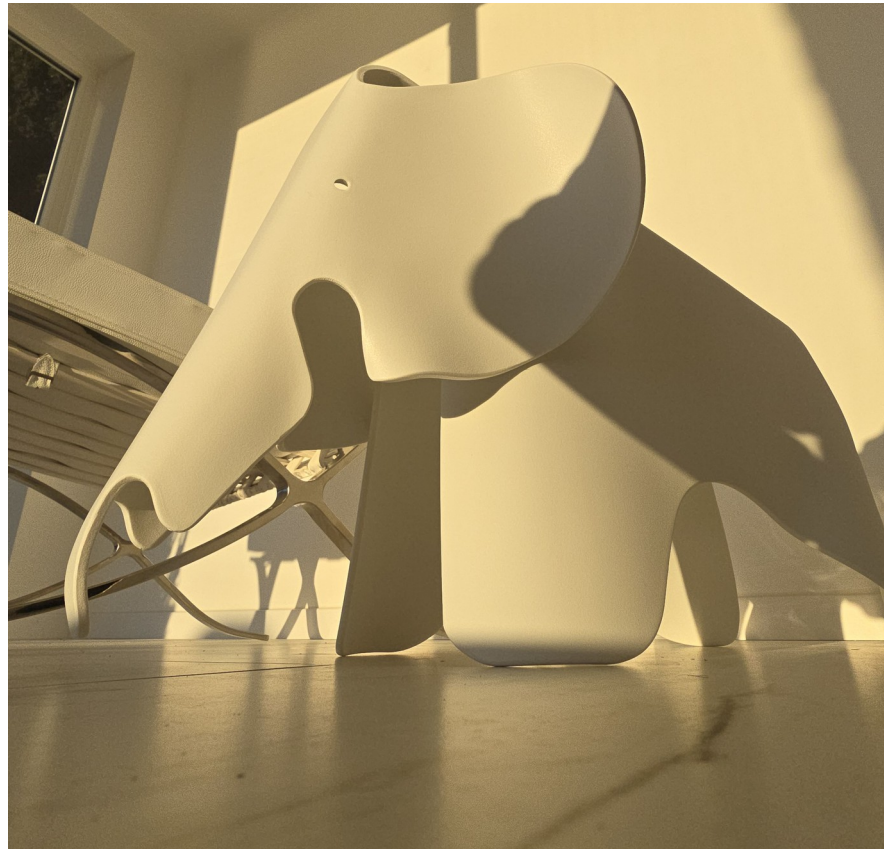


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2. WIMP Miracle

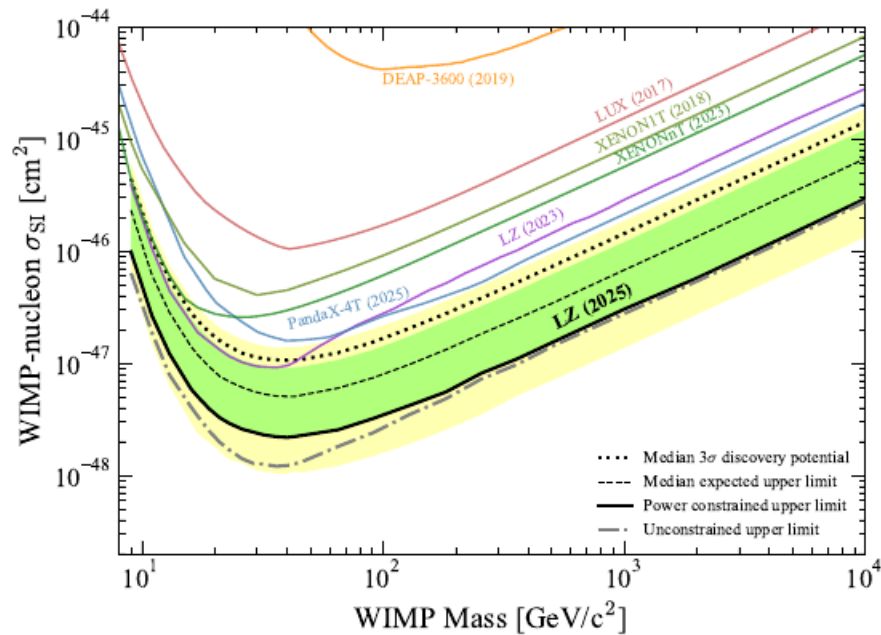
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have naturally the right thermal relic abundance

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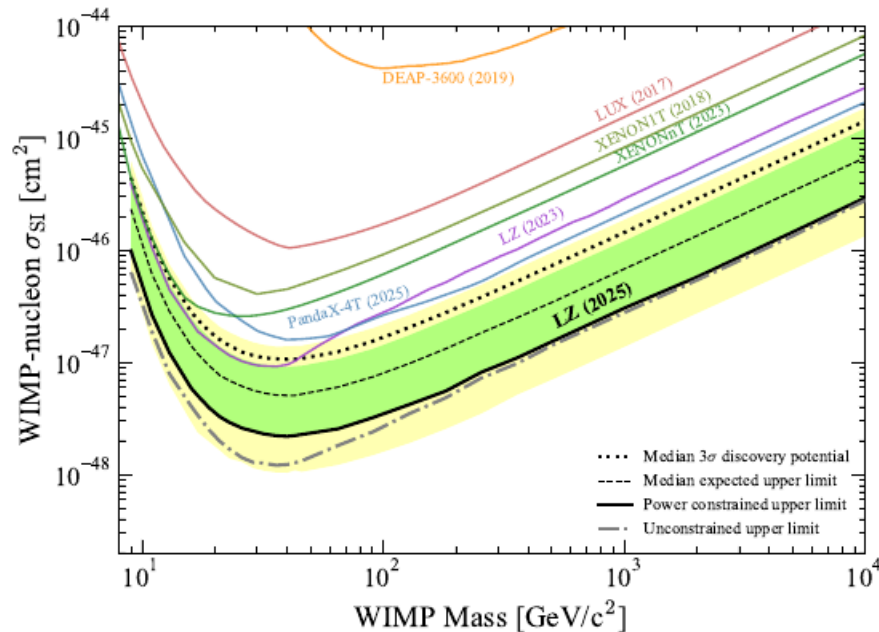


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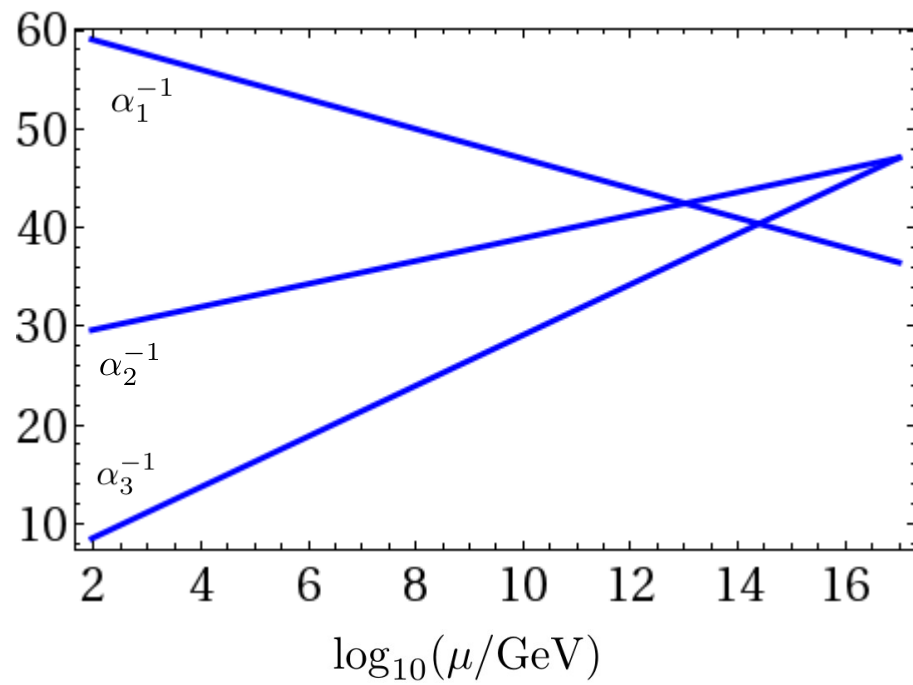


**many other equally
plausible candidates:**

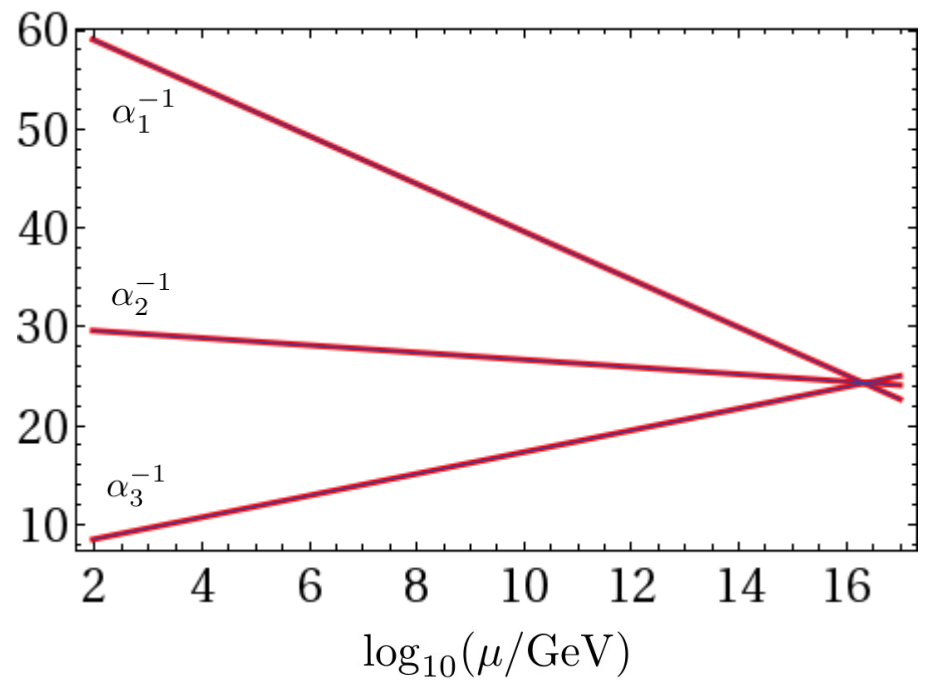
*QCD axion, ALPs, Dark Sectors,
etc...*

3. GUT

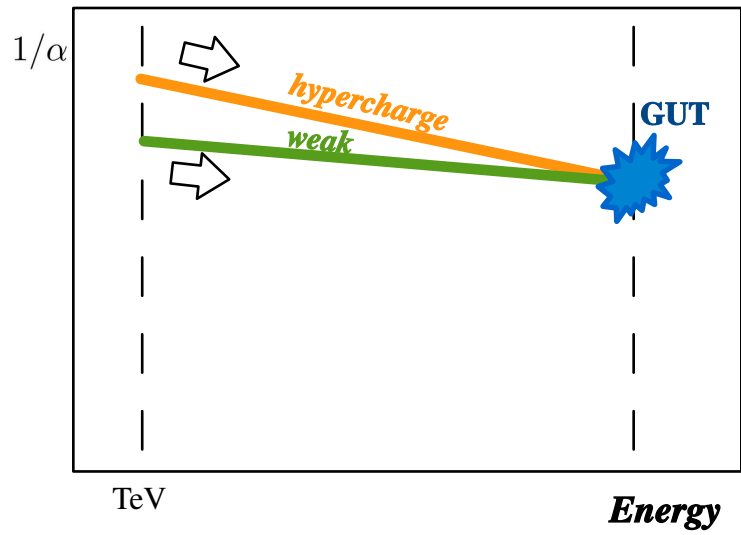
SM



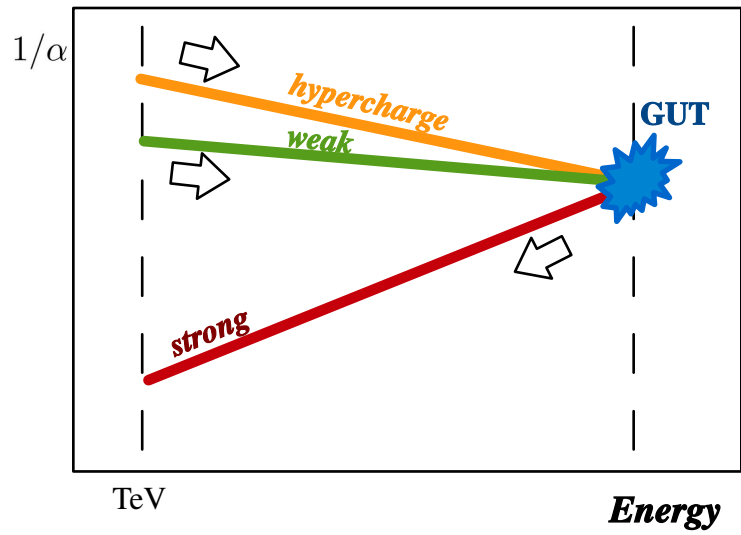
MSSM



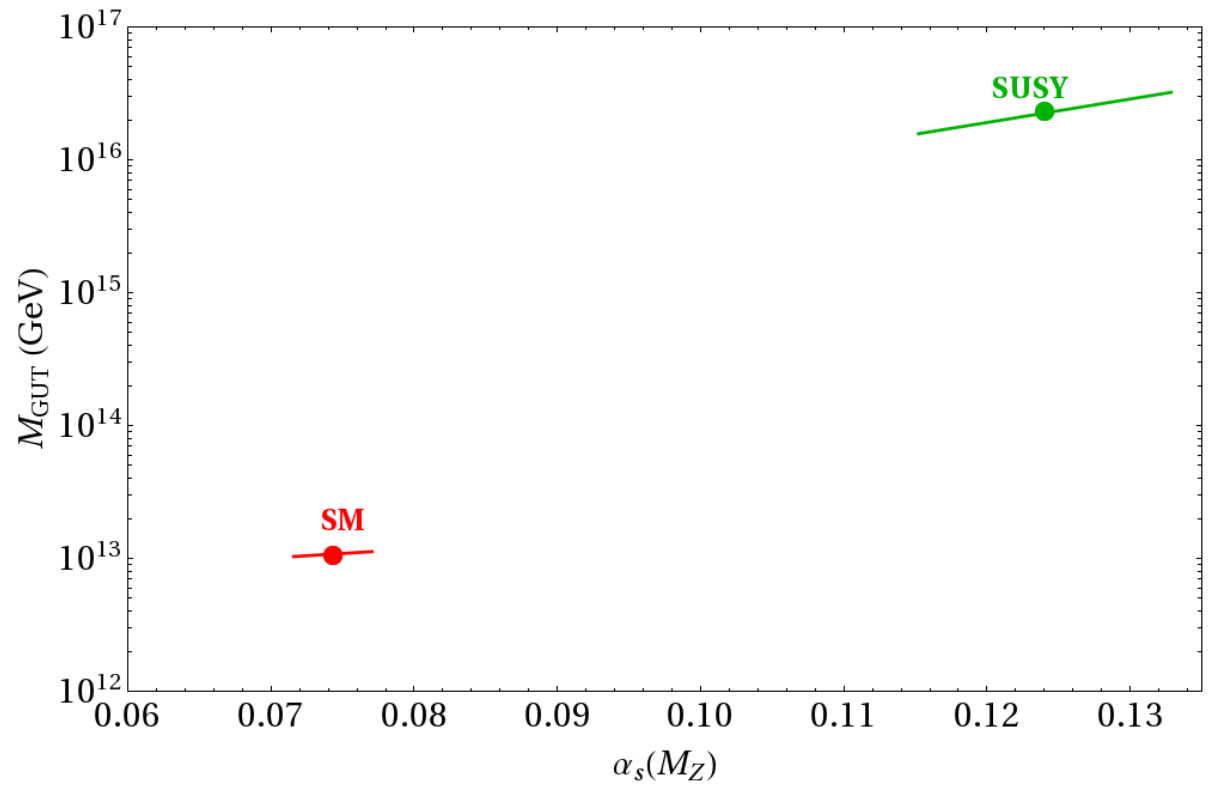
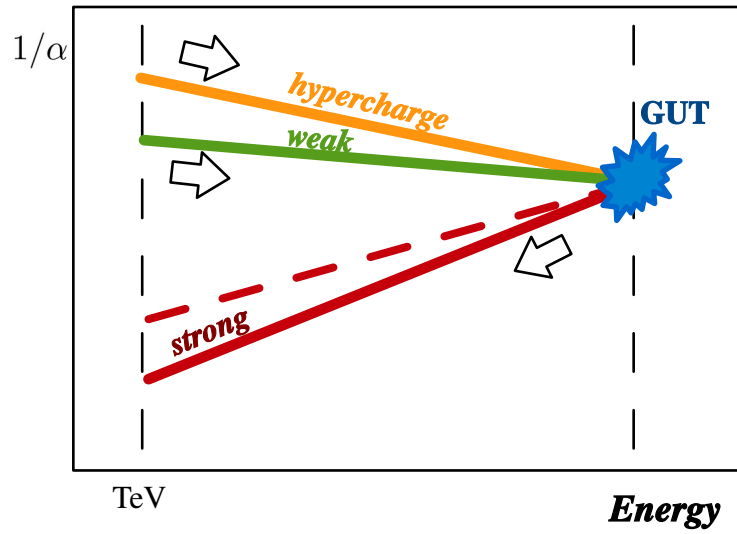
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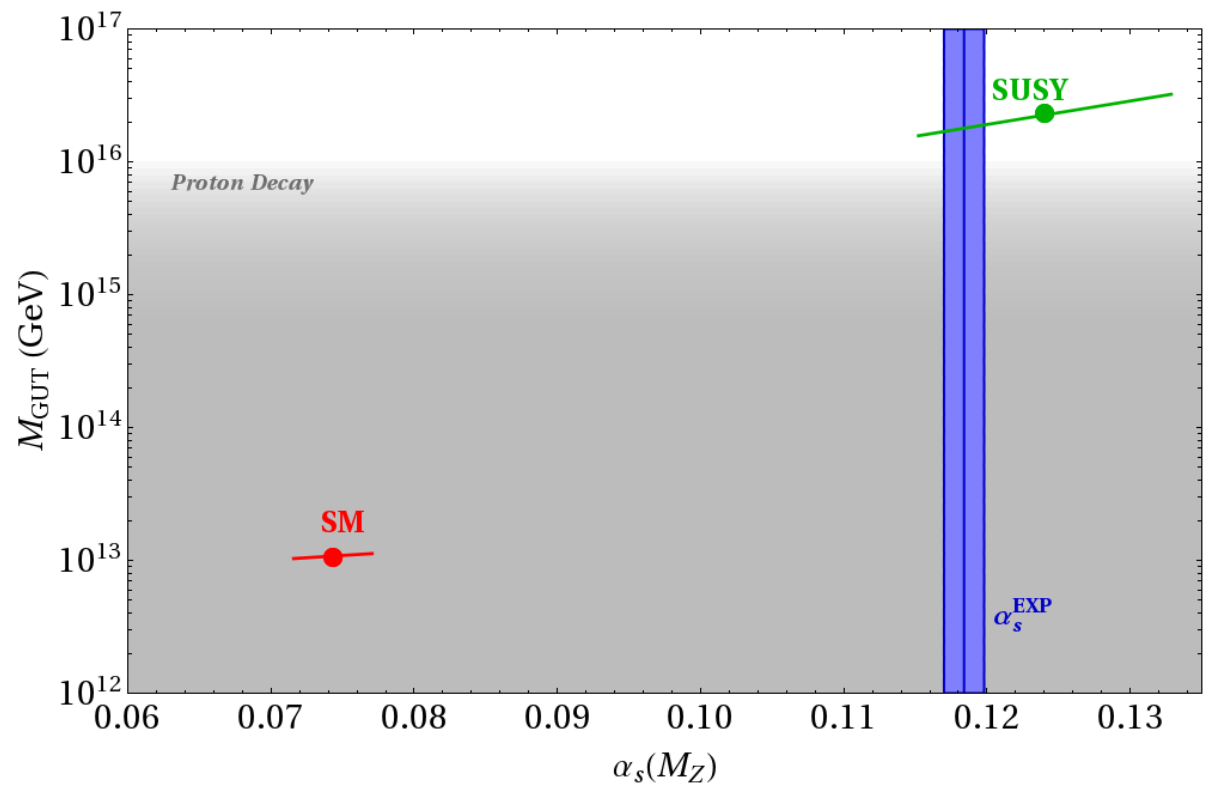
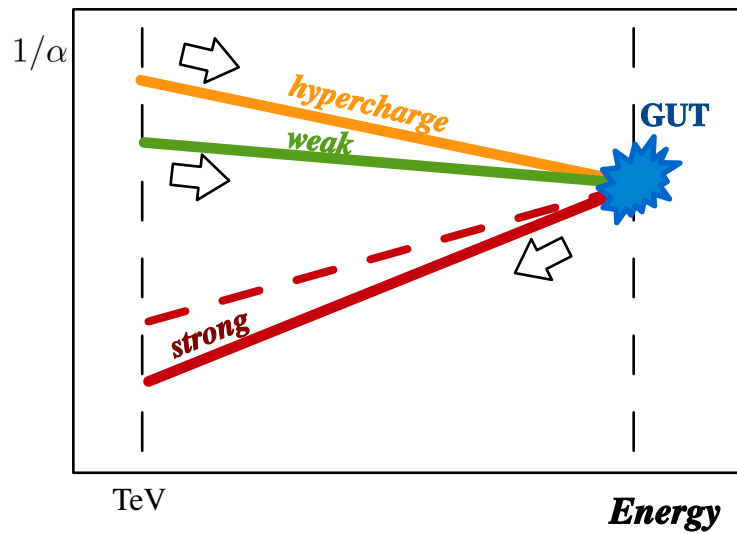
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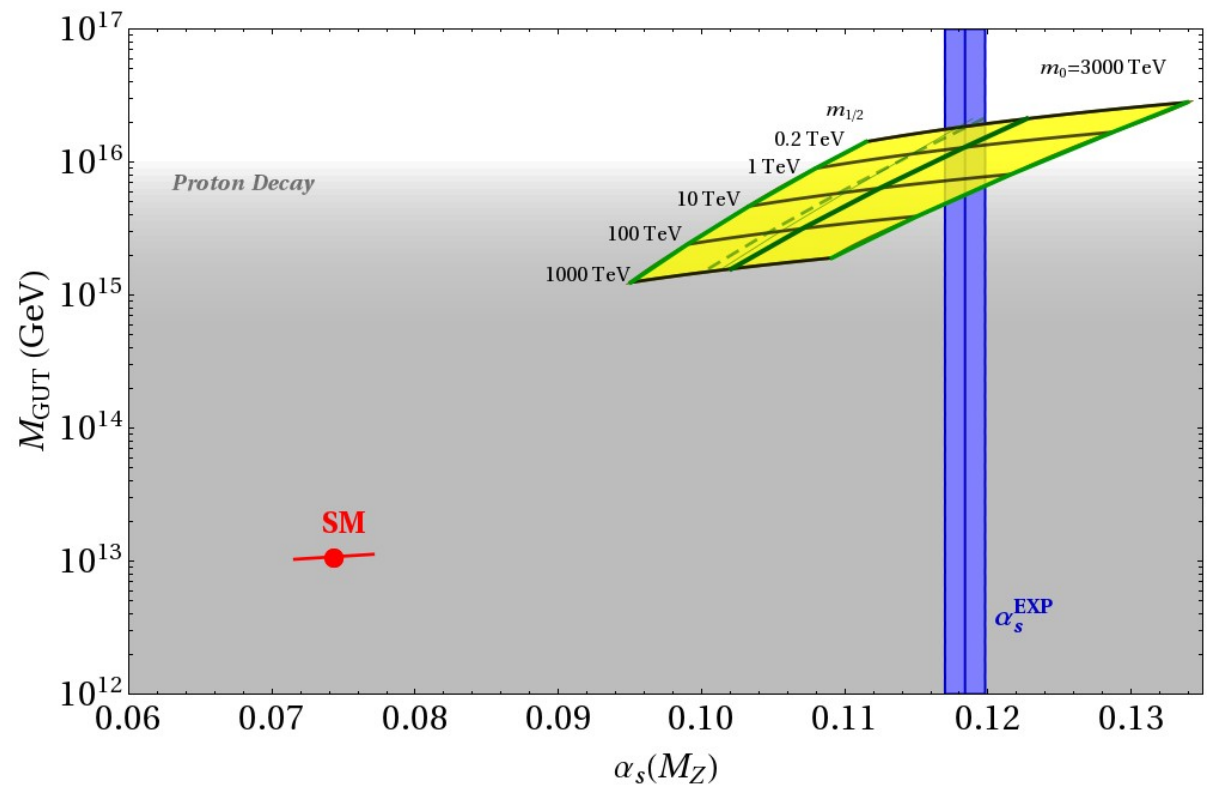
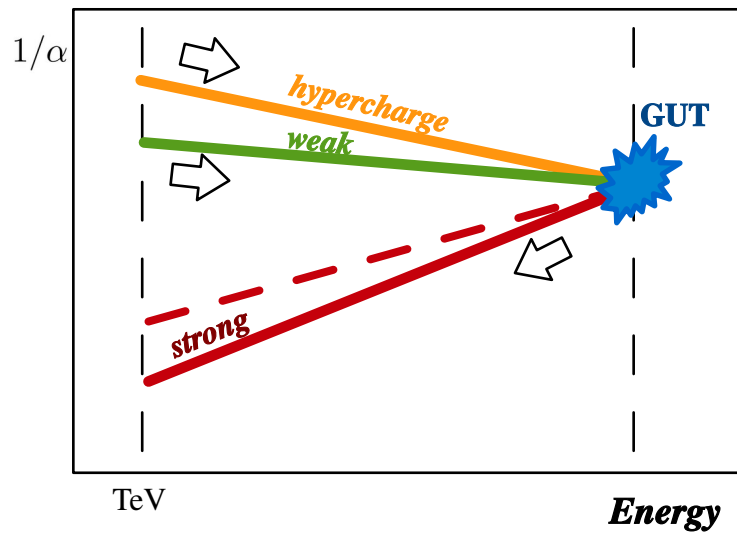
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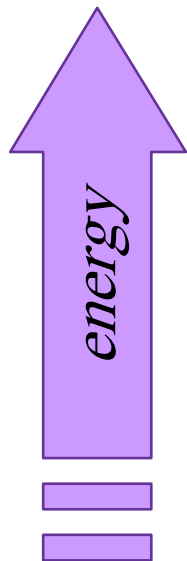


SUSY: A New Angle

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

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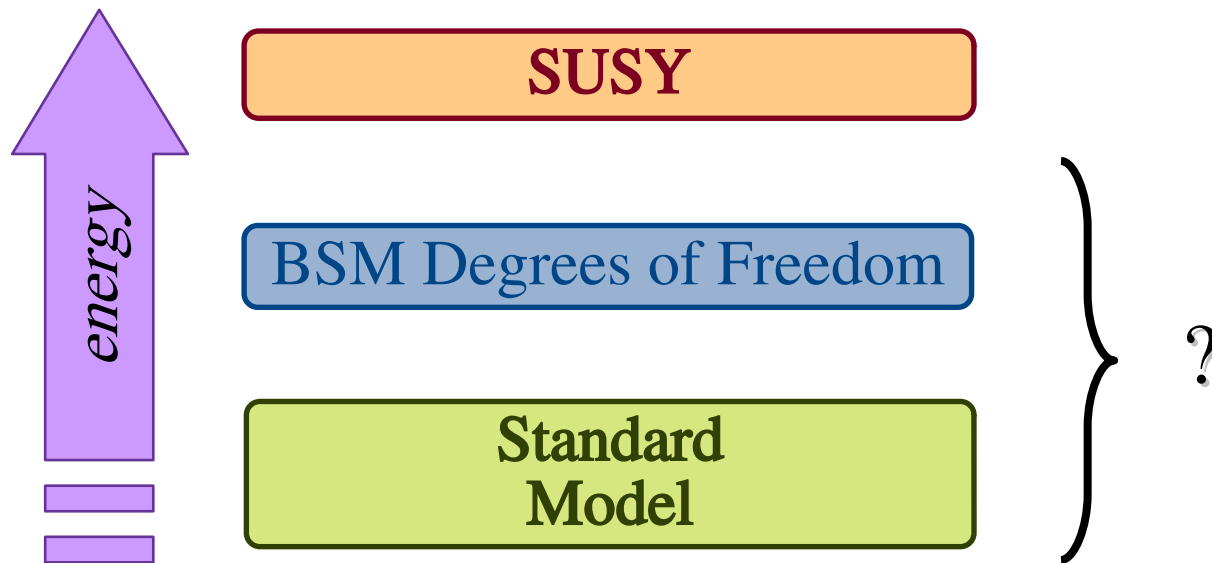
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Standard
Model

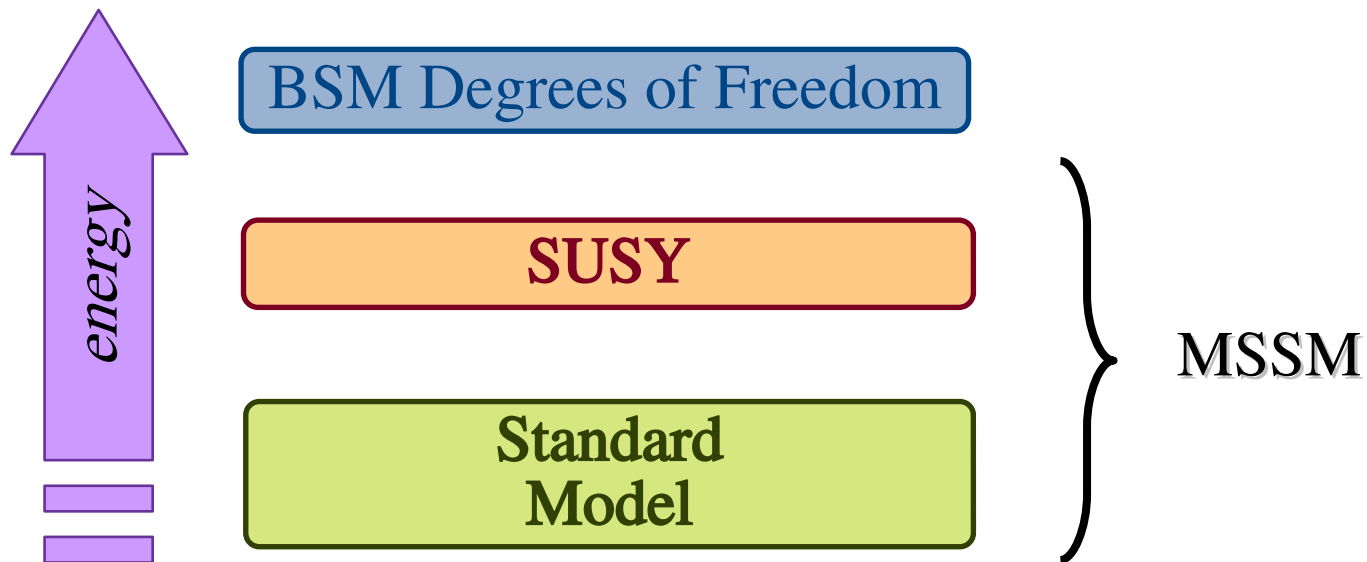
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In the MSSM the Higgs mass is predictive

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$$125^2 \sim \underbrace{90^2}_{\text{tree}} + \underbrace{90^2}_{\text{loop}}$$

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only *log*-dependence on new physics scale

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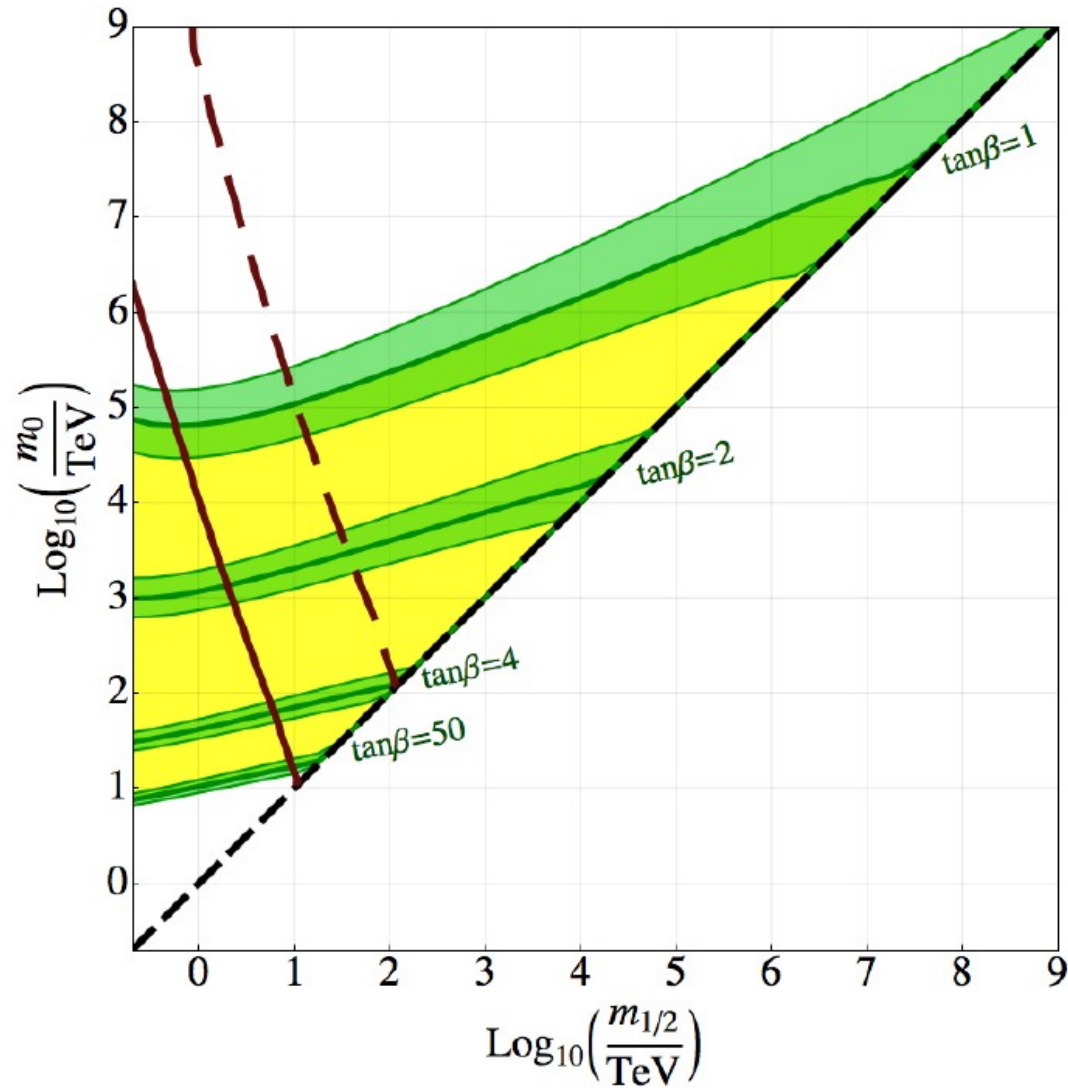
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only *log*-dependence on new physics scale

⇒ high precision to get reliable constraints

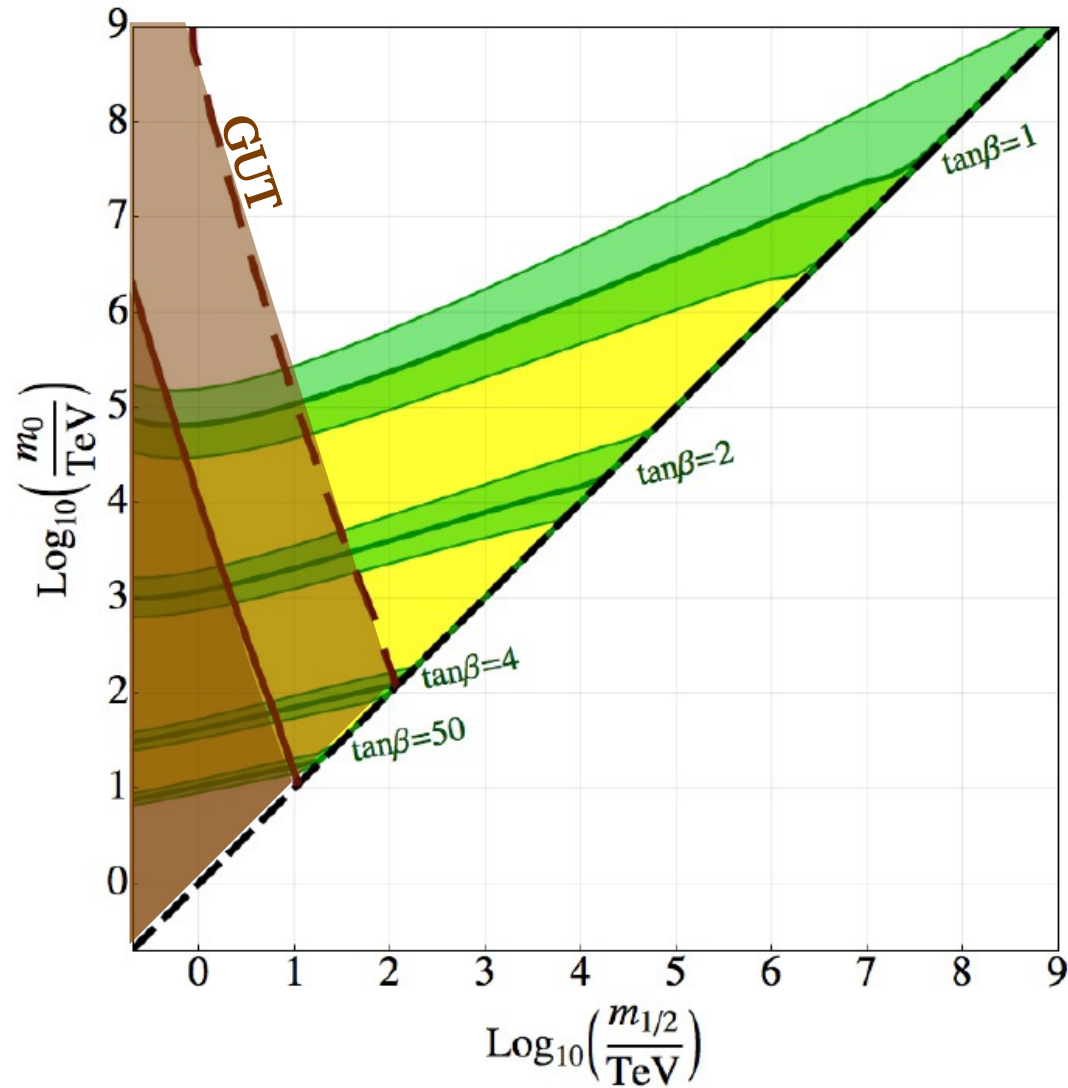
Mini - Split

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



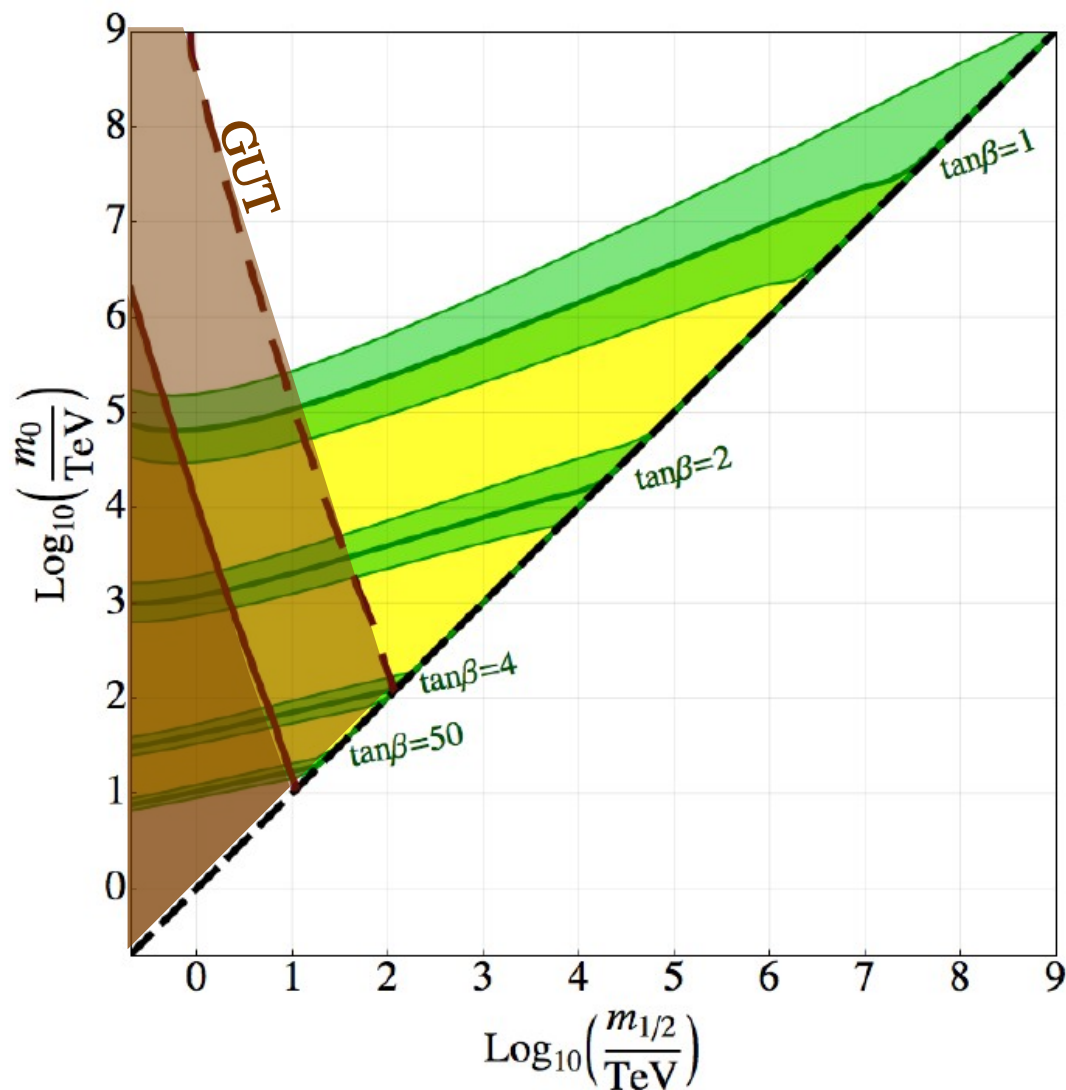
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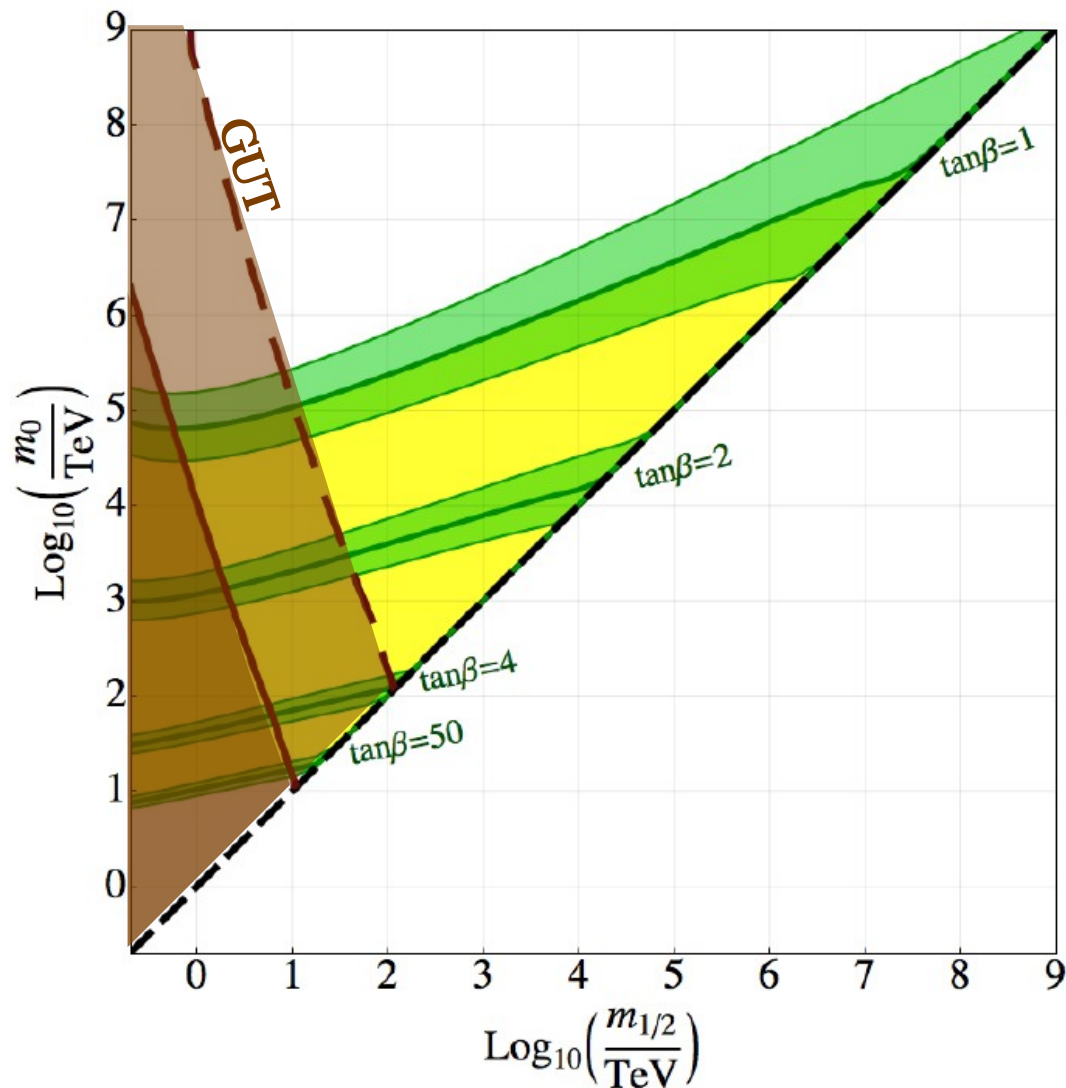


Small $\tan\beta$ and EWSB

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

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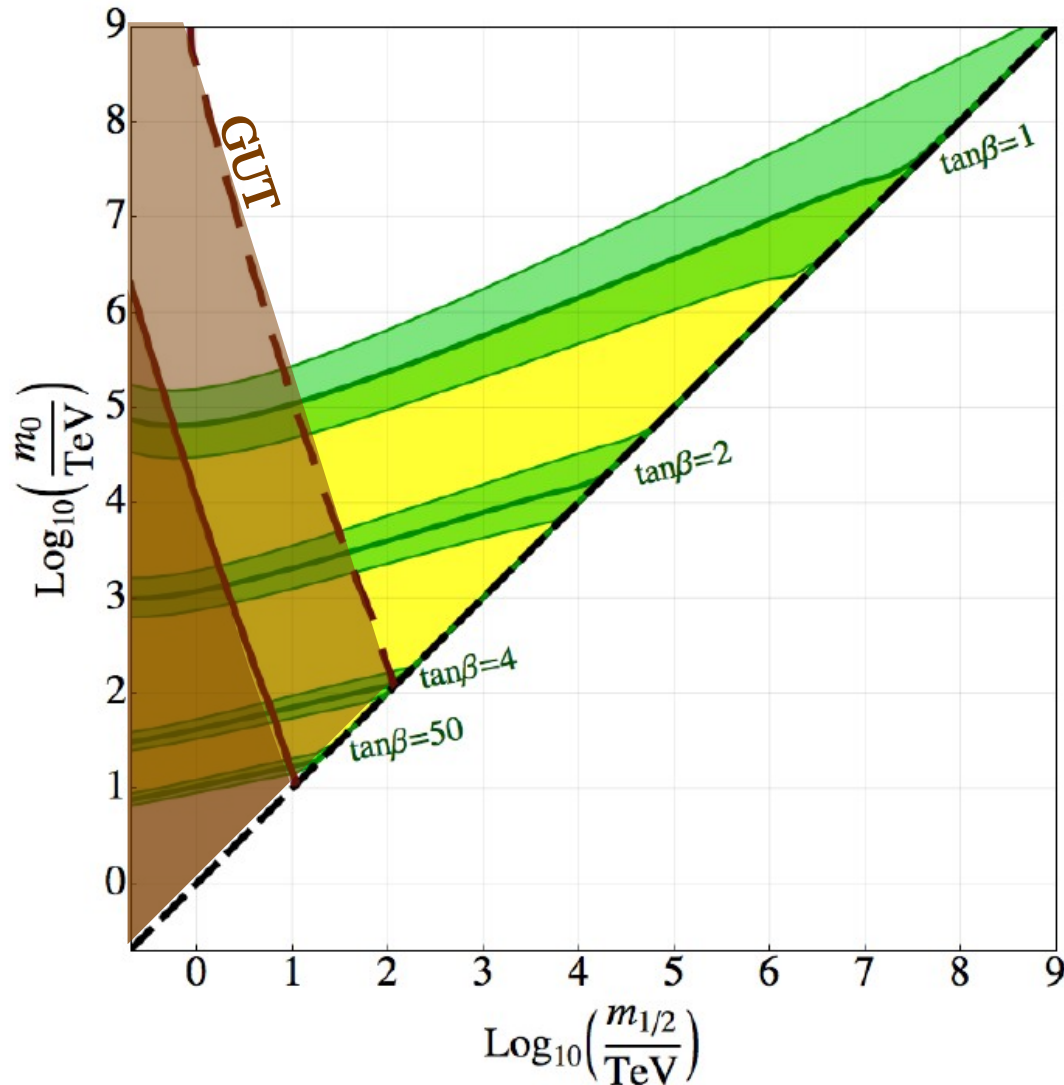
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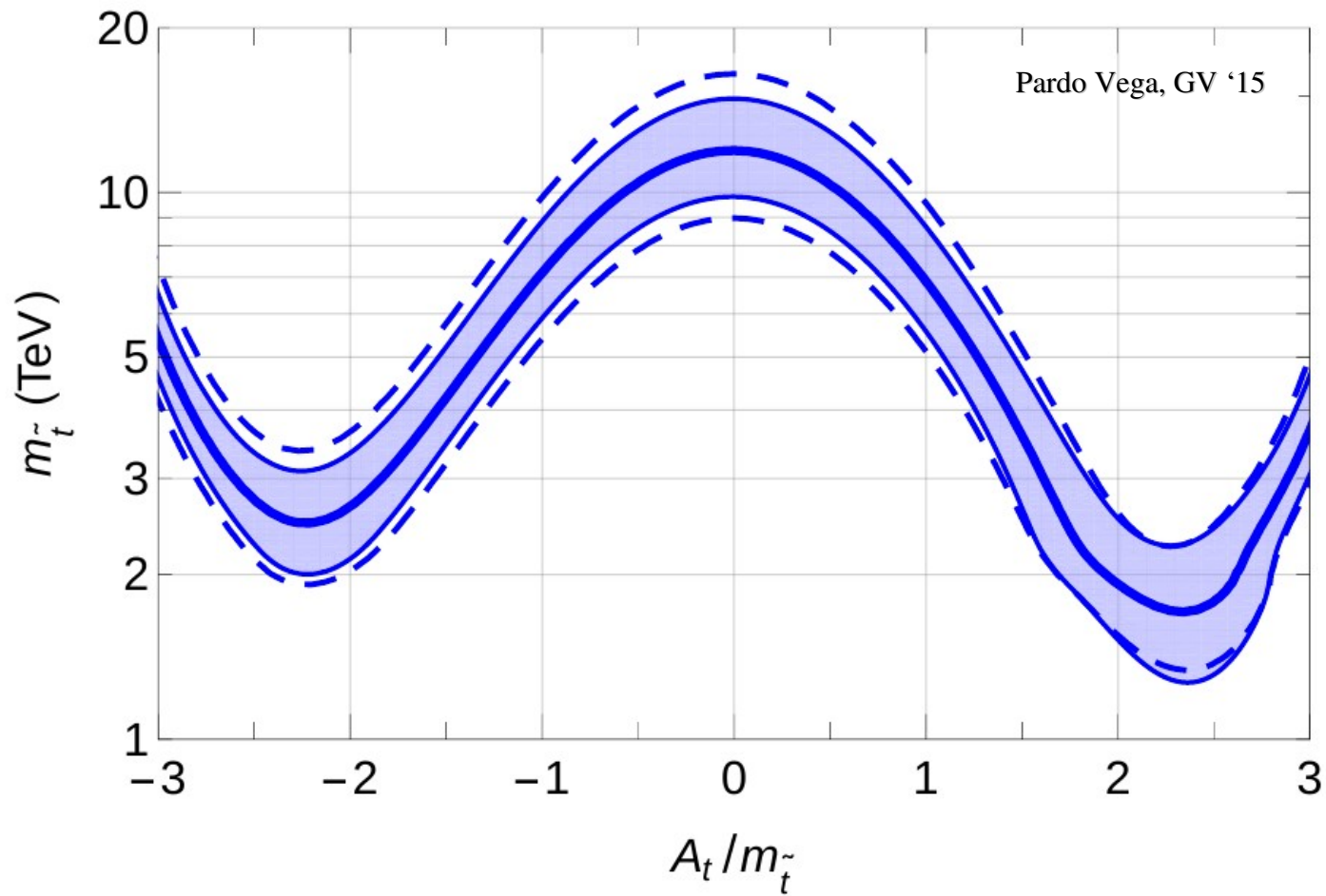


$$\tan \beta \approx \frac{m_{H_d}}{m_{H_u}}$$

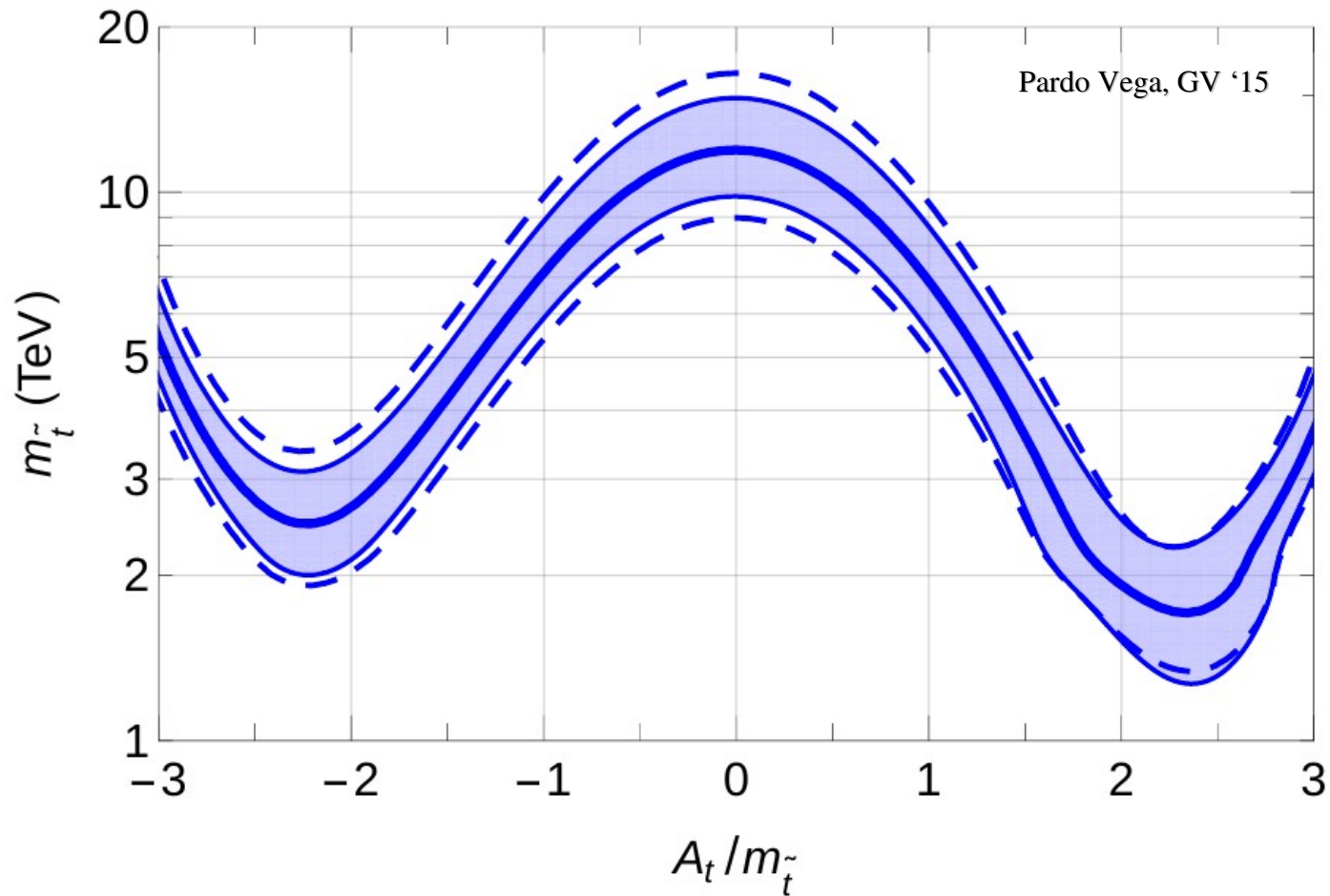
but relation: $m_{H_u}^2 \simeq m_{H_d}^2$

broken by Yukawa

MSSM Higgs @ large $\tan\beta$

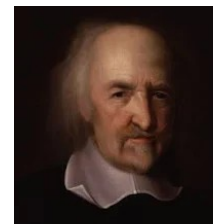


MSSM Higgs @ large $\tan\beta$



“Hell is truth seen too late.”

– Thomas Hobbes, Leviathan

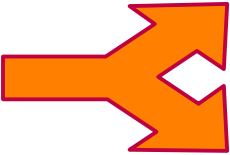


MSSM freedom

	SM	MSSM
params.	19	18

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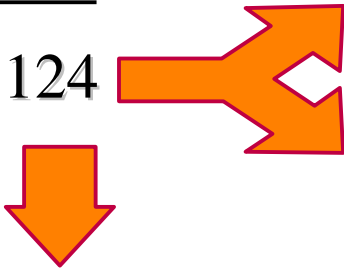
	SM	MSSM
params.	19	18 $\rightarrow$ 124



not predictive
FCNC, EDM, ...

MSSM freedom

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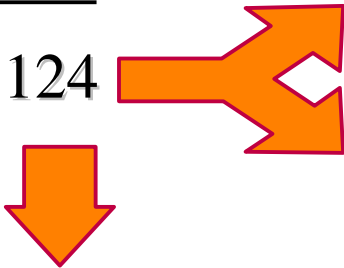
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Depend on Mediation Mechanism:

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

MSSM freedom

	SM	MSSM
params.	19	18 → 124



not predictive
FCNC, EDM, ...

Depend on Mediation Mechanism:

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Minimal Gauge Mediation

most simple + predictive + most compatible

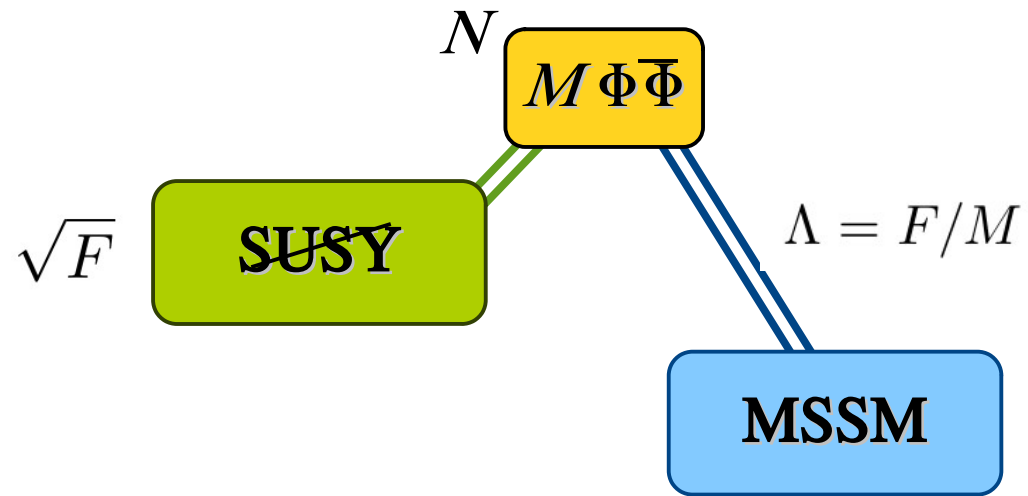
Minimal Gauge Mediation

$\sqrt{F}$

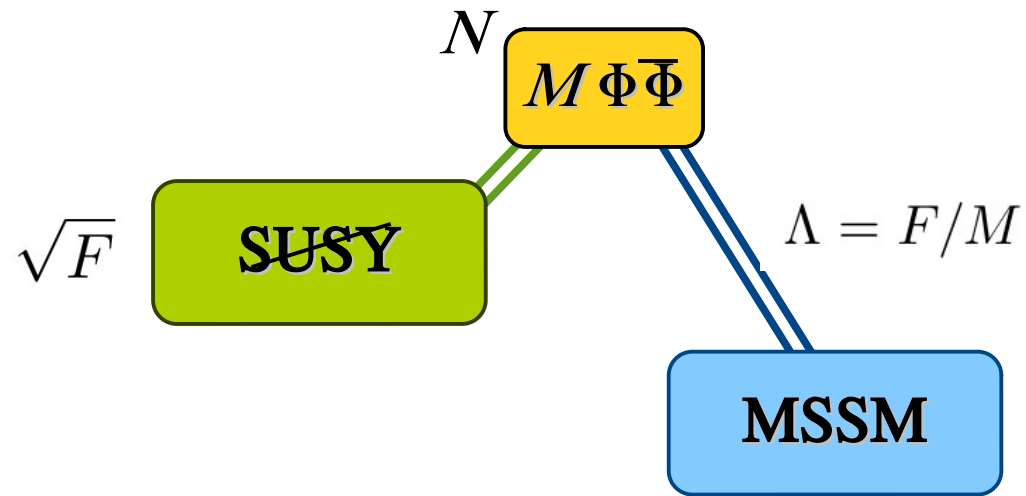
~~SUSY~~

MSSM

Minimal Gauge Mediation

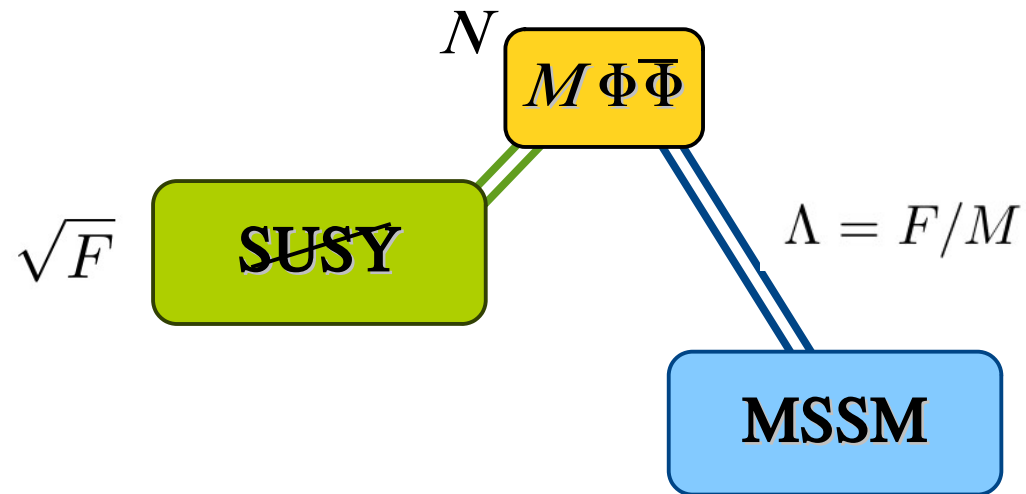


Minimal Gauge Mediation



spectrum: $\left\{ \begin{array}{l} M_j = N \frac{\alpha_j}{4\pi} \Lambda \\ m_i = 2\sqrt{N} C_{ij} \frac{\alpha_j}{4\pi} \Lambda \\ A_i = B_\mu = 0 \end{array} \right.$

Minimal Gauge Mediation

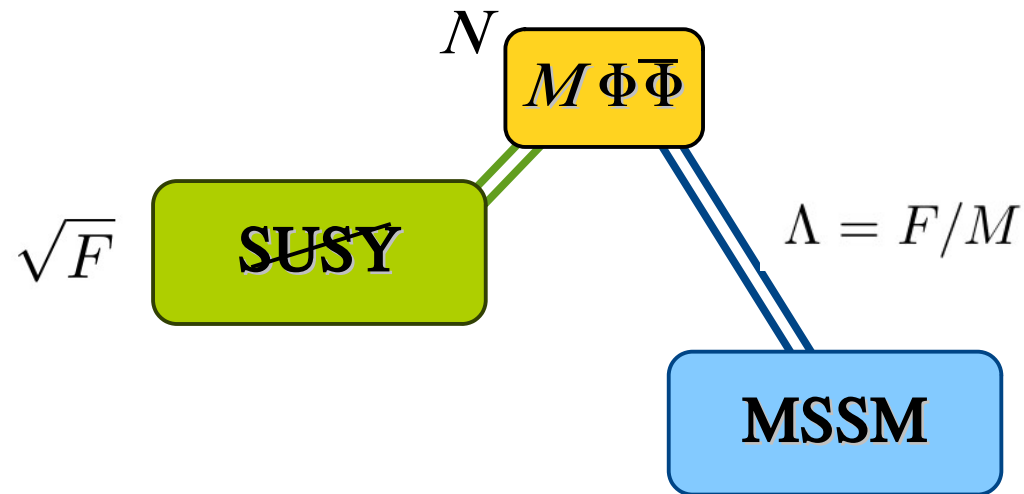


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**flavor blind (MFV) spectrum:
NO dangerous FCNC**

Minimal Gauge Mediation

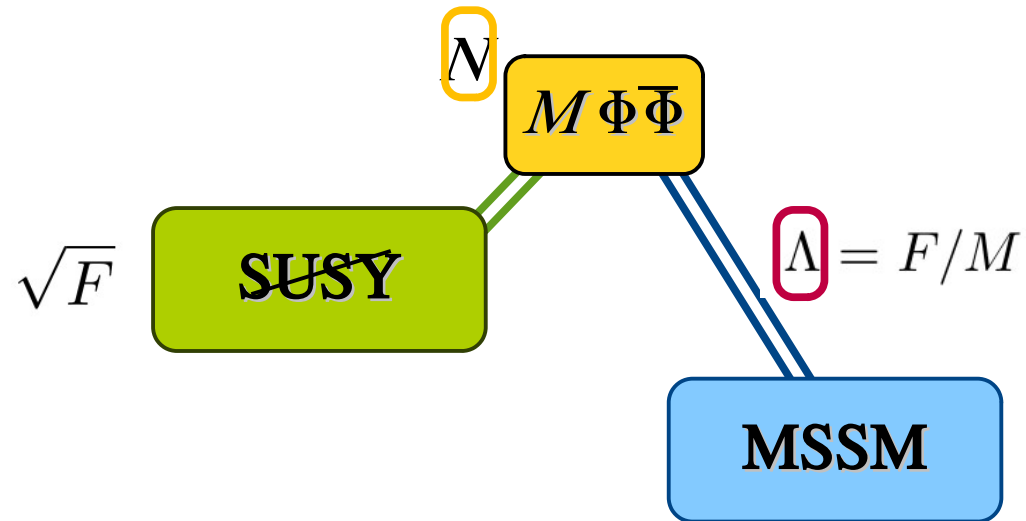


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$\Rightarrow$ flavor blind (MFV) spectrum:
 NO dangerous FCNC

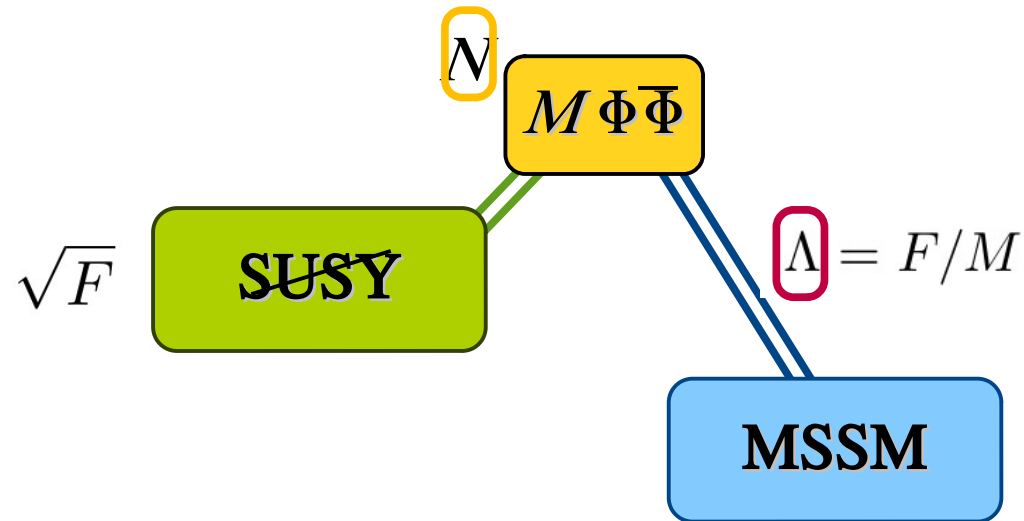
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Minimal Gauge Mediation



spectrum: $\left\{ \begin{array}{l} M_j = N \frac{\alpha_j}{4\pi} \Lambda \\ m_i = 2\sqrt{N} C_{ij} \frac{\alpha_j}{4\pi} \Lambda \\ A_i = B_\mu = 0 \end{array} \right. \quad \begin{array}{l} \Rightarrow \text{flavor blind (MFV) spectrum:} \\ \text{NO dangerous FCNC} \\ \\ \Rightarrow \text{NO CPV phases} \end{array}$

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

No naturalness $\rightarrow$ no μ problem:

$$\Lambda = F/M$$




μ

No EWSB

$$m_0, M_{1/2}$$


No naturalness $\rightarrow$ no μ problem:

$$\Lambda = F/M$$


$$m_0, M_{1/2}$$

$$m_Z$$

$$\text{EWSB} \sim m_0$$


$$\mu$$

No naturalness $\rightarrow$ no μ problem:

$$\Lambda = F/M$$


$$m_0, M_{1/2}$$

$$\mu$$
$$\text{EWSB} \ll m_0$$
$$|\mu|^2 \simeq -m_{H_u}^2 + \dots$$

$$m_Z$$


No naturalness $\rightarrow$ no μ problem:

$$\Lambda = F/M$$

$$m_0, M_{1/2} \quad \mu \quad \text{EWSB} \ll m_0 \quad |\mu|^2 \simeq -m_{H_u}^2 + \dots$$

$$m_Z$$

$$B_\mu, A = 0 \quad \text{at the scale } M$$

generated radiatively



$$A_t \lesssim m_0 \quad \text{no maximal mixing}$$



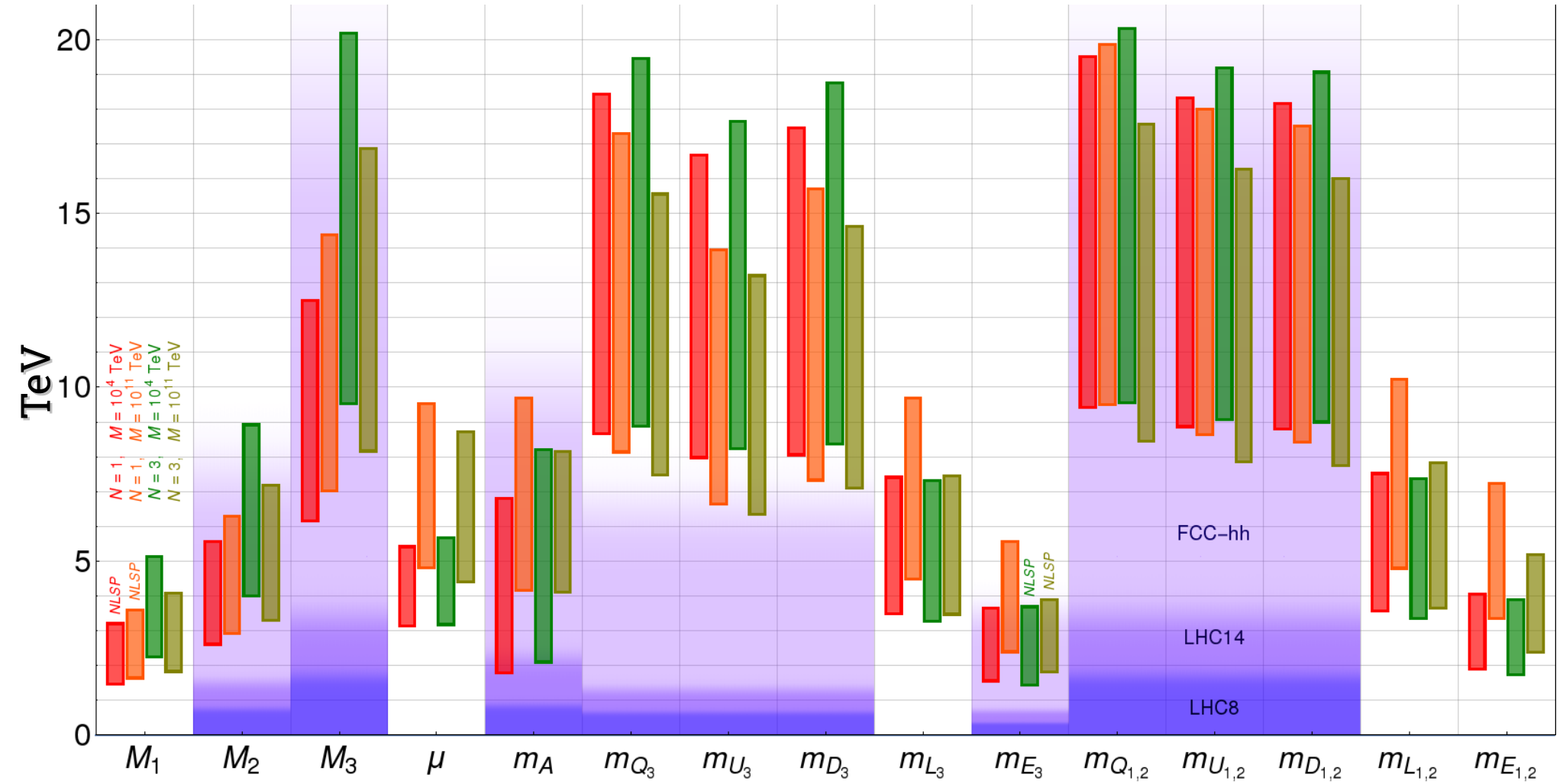
$$B_\mu \ll m_0^2 \quad \tan(\beta) \sim 30\text{-}60$$



no CP phases $\rightarrow$ no EDMs

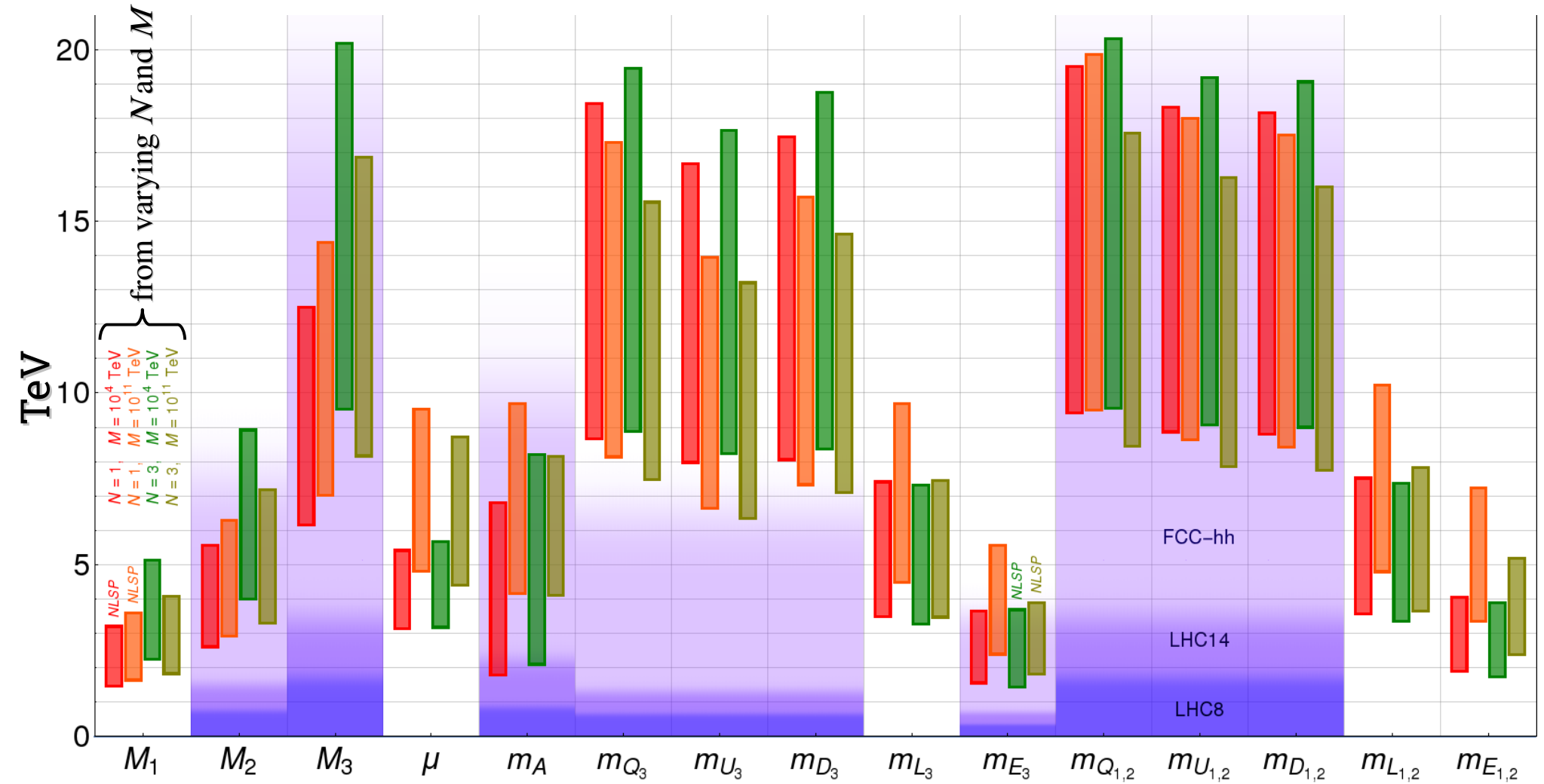
Predicting the MGM spectrum

Pardo Vega, GV '15



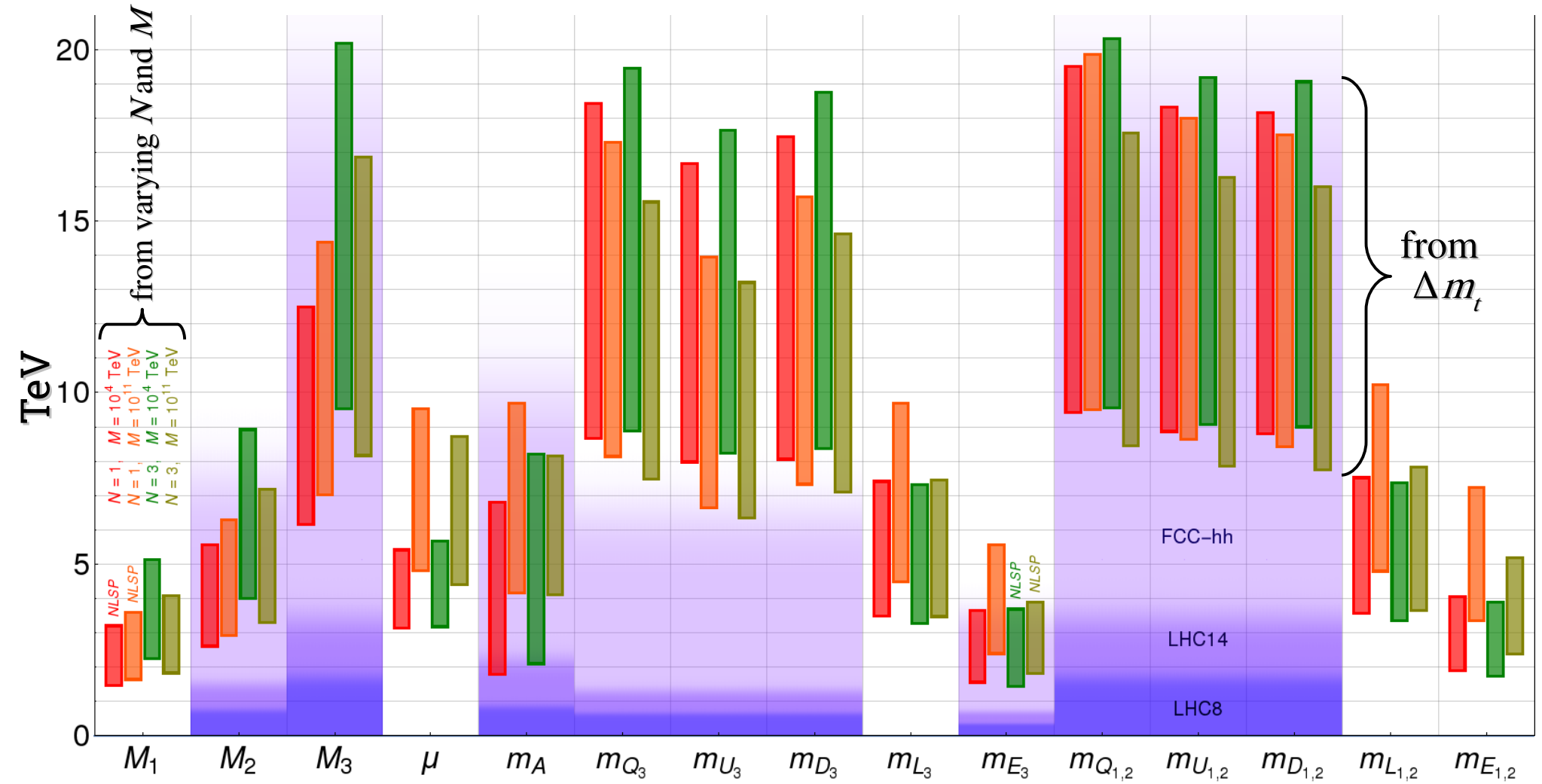
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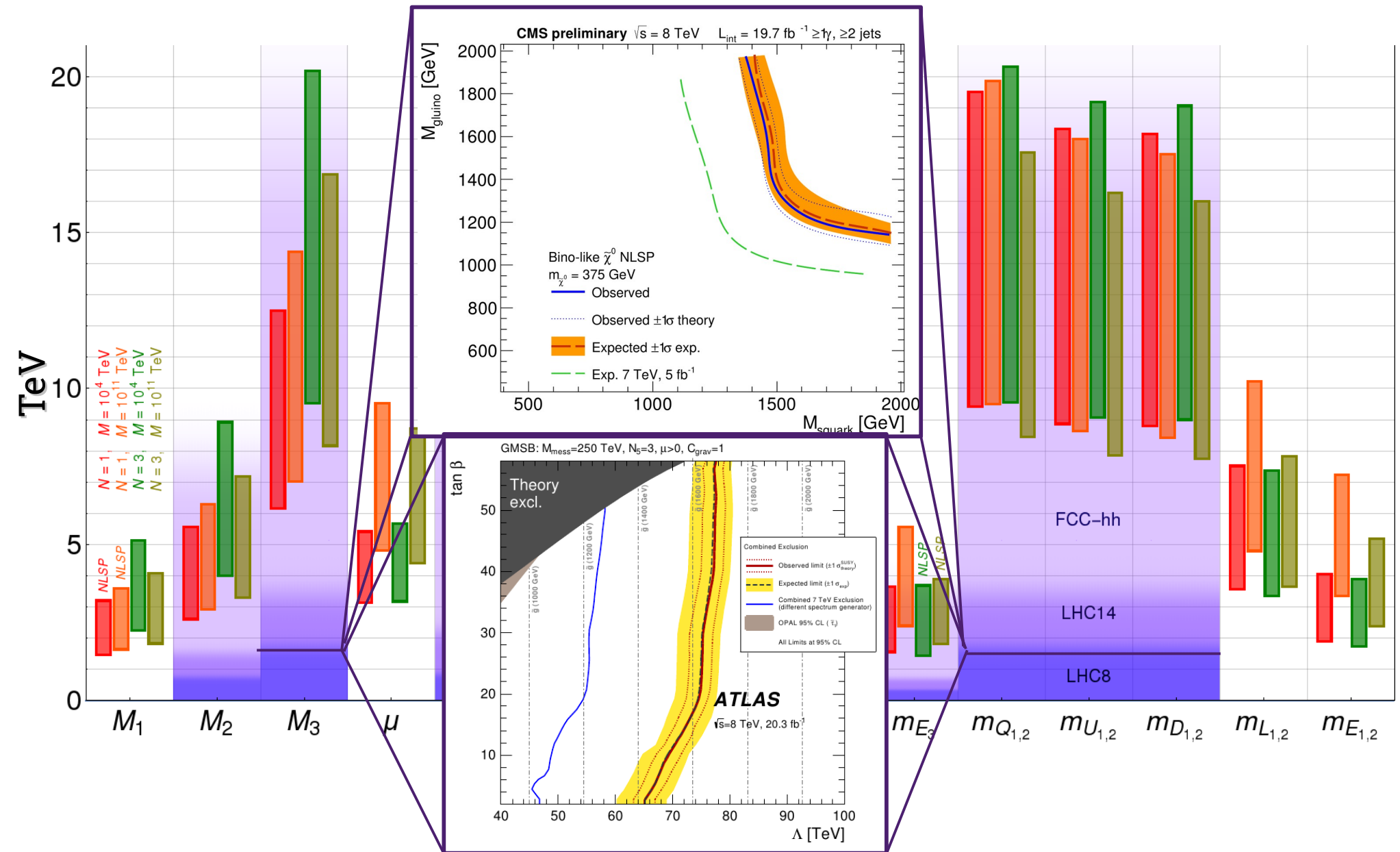
Predicting the MGM spectrum

Pardo Vega, GV '15



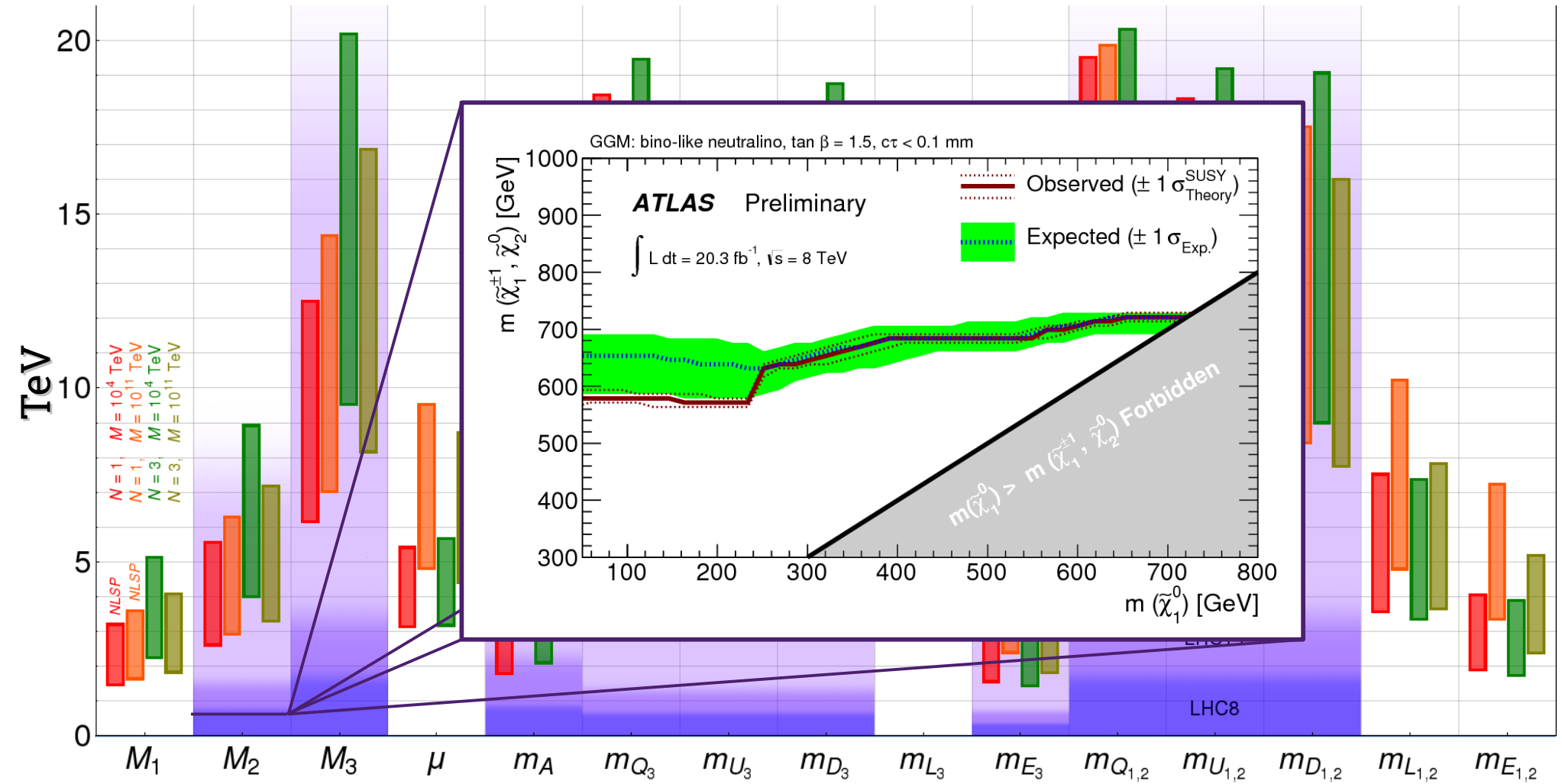
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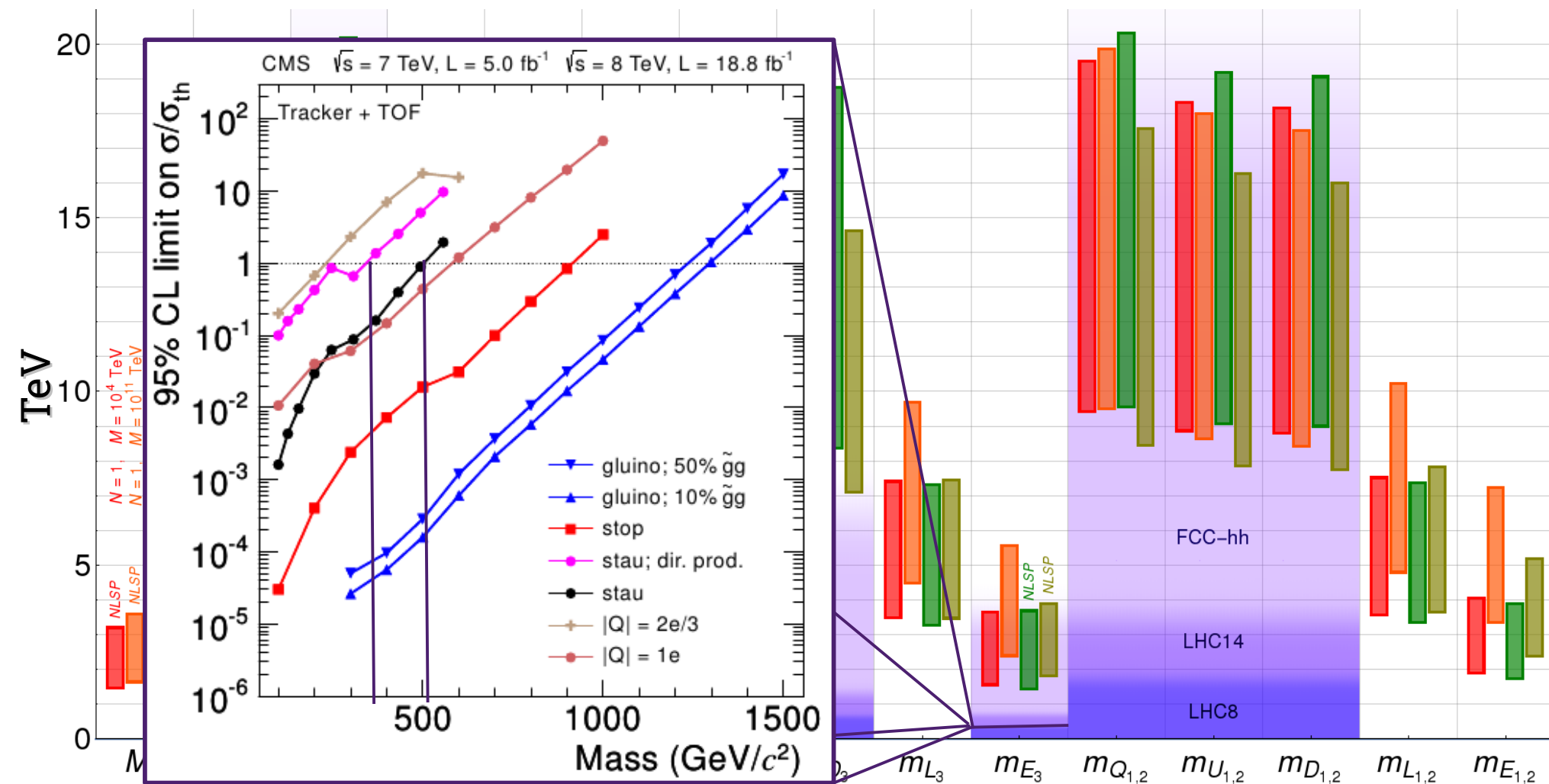


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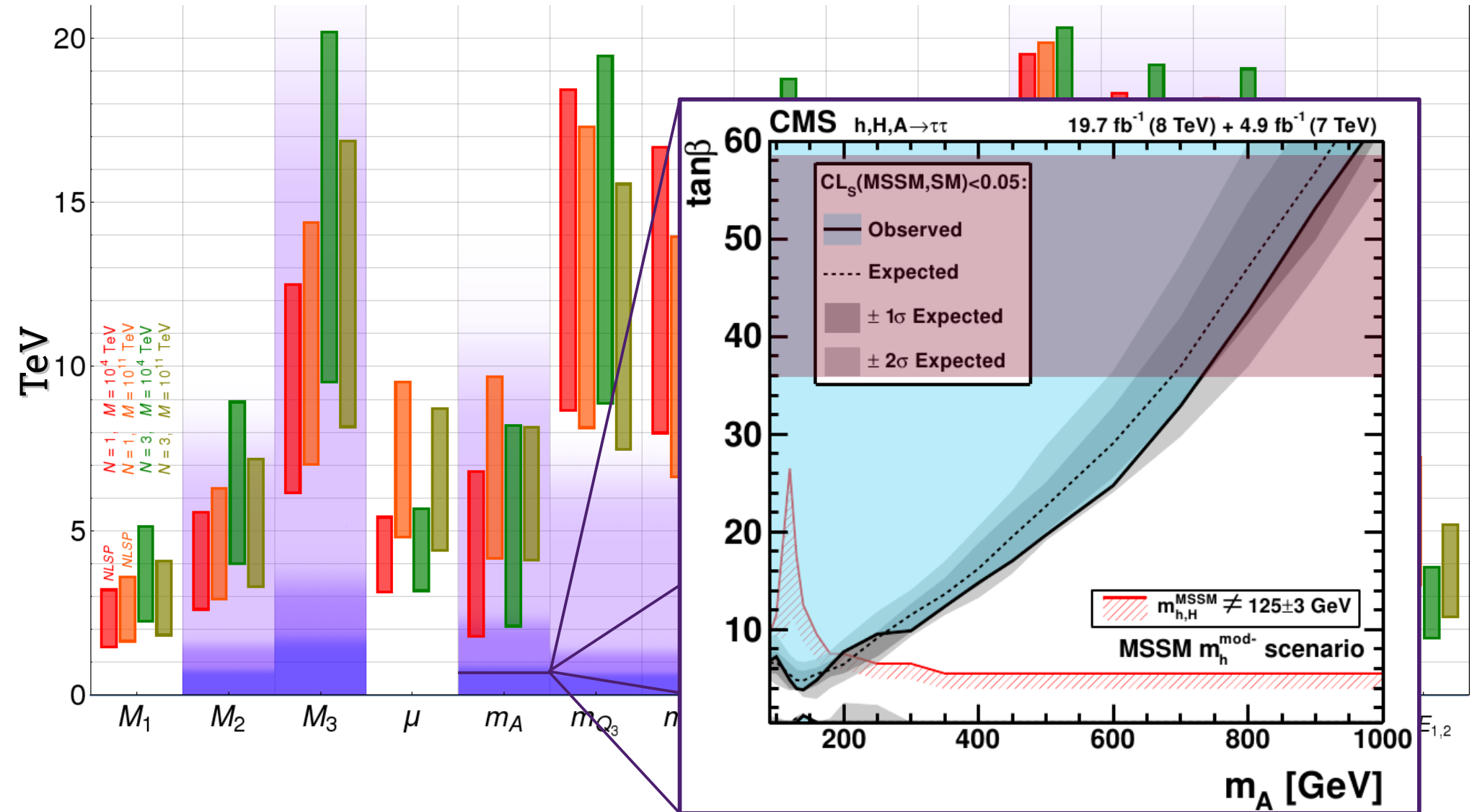


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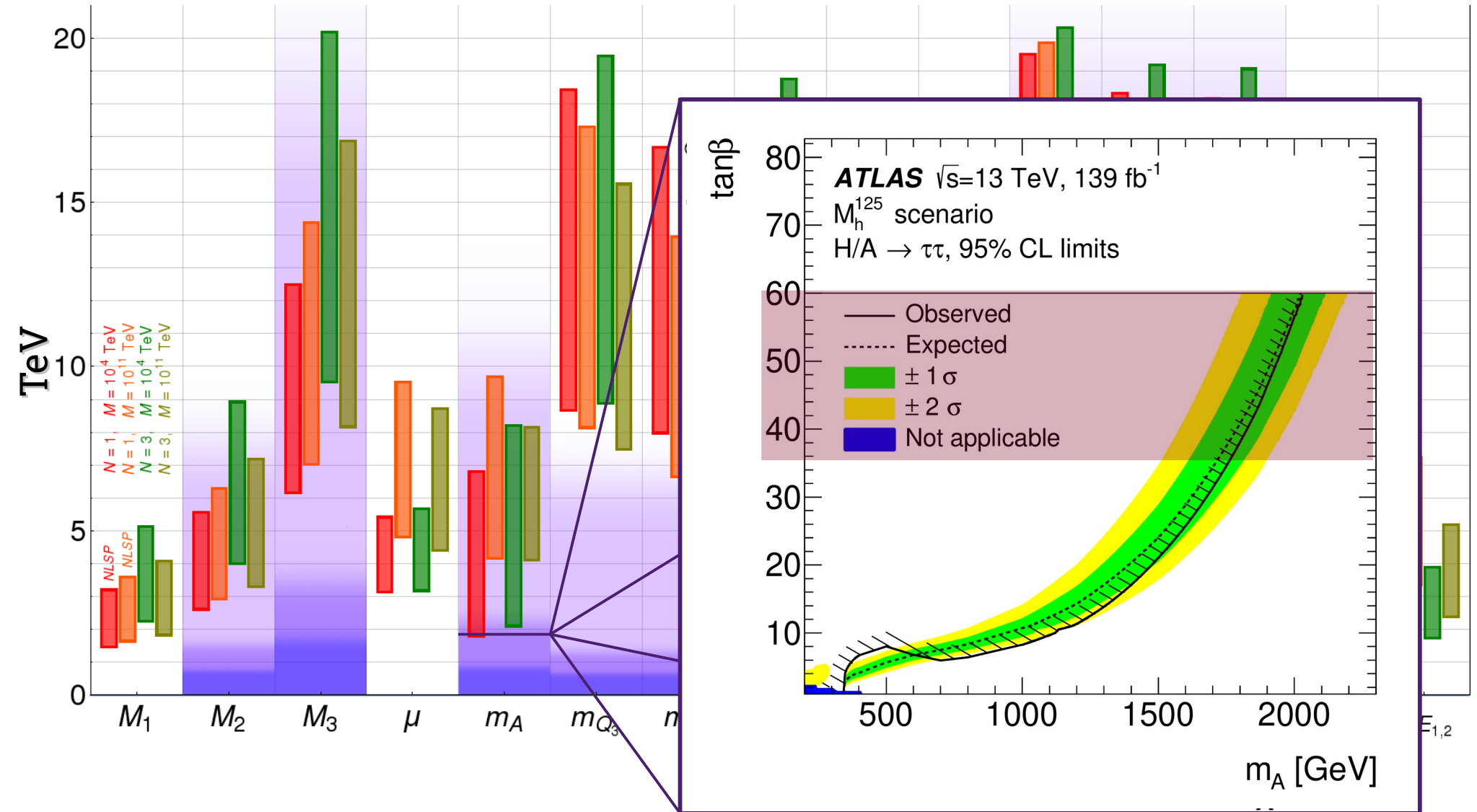
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fully compatible with: {
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MGM as benchmark for Future Collider – “*work in progress*”

- 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:

