Physics Beyond the SM

Under The Higgs Lamppost

Tao Han

Pitt PACC, Univ. of Pittsburgh

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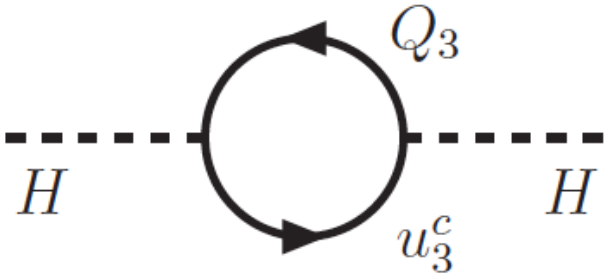
Physics Beyond the SM

Under The Higgs Lamppost

1. The Quest for the SM & Beyond
2. A Strongly-coupled EW Sector
3. A Weakly-coupled Extension
4. Flavors of Matter Fields & EFT

The BIG Hierarchy Problem



Why the weak scale M_W is so much smaller than M_{Pl}?

1. Dynamical generation: dimensional transmutation
2. Controlled by symmetry:

- Shift symmetry (Nambu-Goldstone boson)
- Super-symmetry (elementary particles)
- Discrete symmetries

Supersymmetry: an elegant formalism

Julius Wess & Bruno Zumino (in 1974)

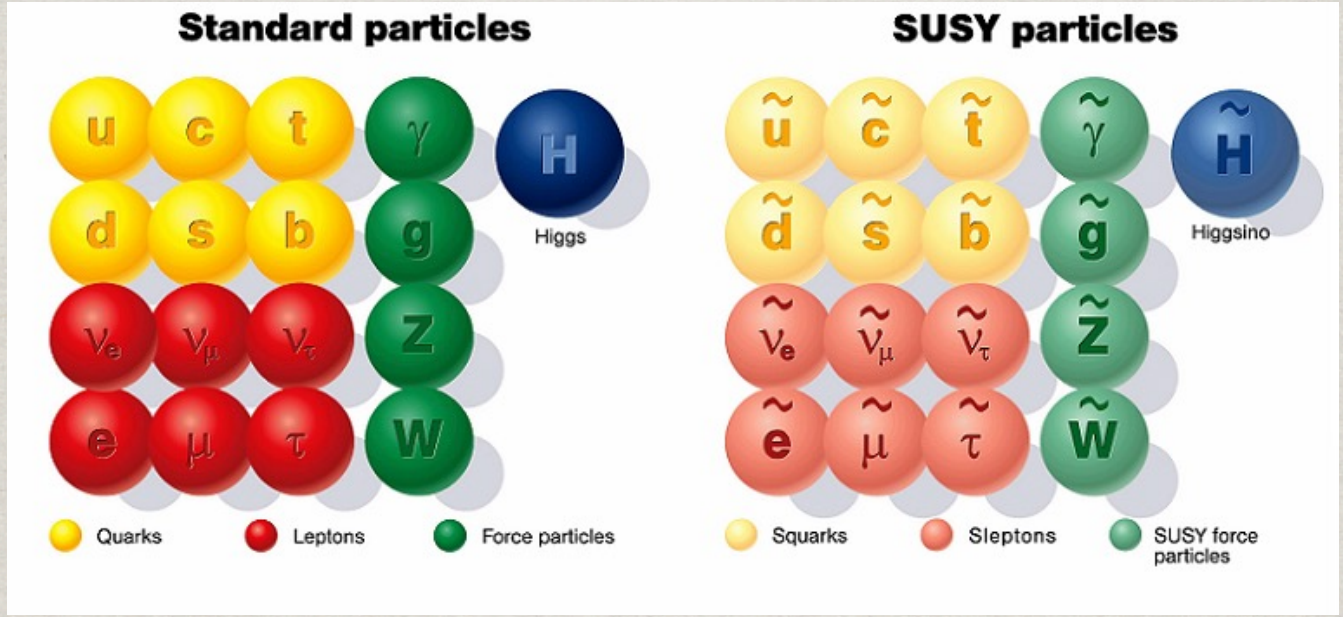
- Generalized extension of Poincare group of spacetime symmetry
- Critical ingredients for string theory: World sheet/Spacetime SUSY
- Low energy effective field theory from compactification

- Eliminate the cosmological constant upto symmetry breaking
- Stabilizes weak scale at all orders
- Potential Grand Unification of EW & QCD
- Natural WIMP dark matter candidate

Supersymmetry: fermion <-> boson

The SUSY generators $\mathcal{Q}$ transform fermions into bosons and vice–versa

$$\mathcal{Q}|\text{Fermion}\rangle >= |\text{Boson}\rangle \quad , \quad \mathcal{Q}|\text{Boson}\rangle = |\text{Fermion}\rangle$$



Under SUSY, the two partners must

- Have the same mass, the same coupling
- Spin different by ½

Since we have not seen a partner of same mass, SUSY must be broken, at a higher scale.

Minimal Supersymmetric Standard-Model (MSSM)

Extended symmetry between *opposite* spin & statistics

particles	symbol	spin	mass param.
gluino	$\tilde{g}$	1/2	M_3
charginos	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$	1/2	M_2
neutralinos	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	1/2	M_1, μ, B $m^2_{H_u}$, $m^2_{H_d}$
sleptons	$\tilde{e}_L$, $\tilde{\nu}_{e_L}$, $\tilde{e}_R$	0	$m^2_{\ell L}$
	$\tilde{\mu}_L$, $\tilde{\nu}_{\mu_L}$, $\tilde{\mu}_R$	0	
	$\tilde{\tau}_1$,$\tilde{\tau}_2$, $\tilde{\nu}_{\tau_L}$	0	$m^2_{\ell R}$
squarks	$\tilde{u}_L$, $\tilde{d}_L$, $\tilde{u}_R$,$\tilde{d}_R$	0	$m^2_{q_L}$
	$\tilde{c}_L$,$\tilde{s}_L$, $\tilde{c}_R$,$\tilde{s}_R$	0	
	$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$,$\tilde{b}_2$	0	$m^2_{q_R}$
Higgs	h^0, H^0, A^0, $H^{\pm}$	0	m^2_A, $\tan\beta$

$\tilde{t}$ versus t; $\tilde{W}$ versus W; $\tilde{H}$ versus H; H_d versus H_u,

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\frac{\lambda_f^2}{16\pi^2}\ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

only if the "soft-SUSY breaking": $M_{SUSY} \sim \mathcal{O}(M_{SM})$.

→ "Weak scale" supersymmetry!

What about M_{SUSY} (in a hidden sector)?

× Supersymmetry breaking mechanism is unknown.

Fermionic masses:

$$M_1,\ M_2,\ M_3,\ \mu\ \rightarrow M_{\chi^{\pm}_{1,2}},\ M_{\chi^{0}_{1,2,3,4}};$$

Scalar masses:

$$M_{\tilde{q}_{L,R}},\ M_{\tilde{l}_{L,R}};$$

Mixings:

$$\tan\beta,\ \sin\alpha\ \ldots\ \ldots$$

CP Phases:

$$\phi_{1,2,3\mu}\ \ldots\ \ldots$$

Parameter count in the SM and MSSM (no $m'_\nu s$ yet)

model	masses and mixing ang.	CP-viol. phases	TOTAL
SM	17	2	19
MSSM	79	45	124
$(\text{MSSM})_{\text{BV}}$	97	62	159
$(\text{MSSM})_{\text{LV}}$	157	122	279
$(\text{MSSM})_{\text{BLV}}$	175	140	315

Based on observation:

* Proton stability:

  $\Rightarrow$ R-parity conservation; or B, L not broken simultaneously (in $1^{st}, 2^{nd}$ generations).

* No excessively large CP-violation/FCNC:

  $\Rightarrow$ no (or small) phases; sfermion mass degenerate (or heavy).

General parameter selection: Phenomenological MSSM (pMSSM)

The 20 dimensional pMSSM parameter space then includes

$$M_1,\ M_2,\ M_3,$$
$$m_{Q_1},\ m_{U_1},\ m_{D_1},\ m_{L_1},\ m_{E_1},$$
$$m_{Q_3},\ m_{U_3},\ m_{D_3},\ m_{L_3},\ m_{E_3},$$
$$A_t,\ A_b,\ A_\tau,$$
$$m^2_{H_u},\ m^2_{H_d},\ \mu,\ B.$$

scan over parameters

SUSY *is* still relevant!

Hitoshi Murayama (Berkeley, Kavli IPMU)

SUSY 2025, Santa Cruz, Aug 23, 2025

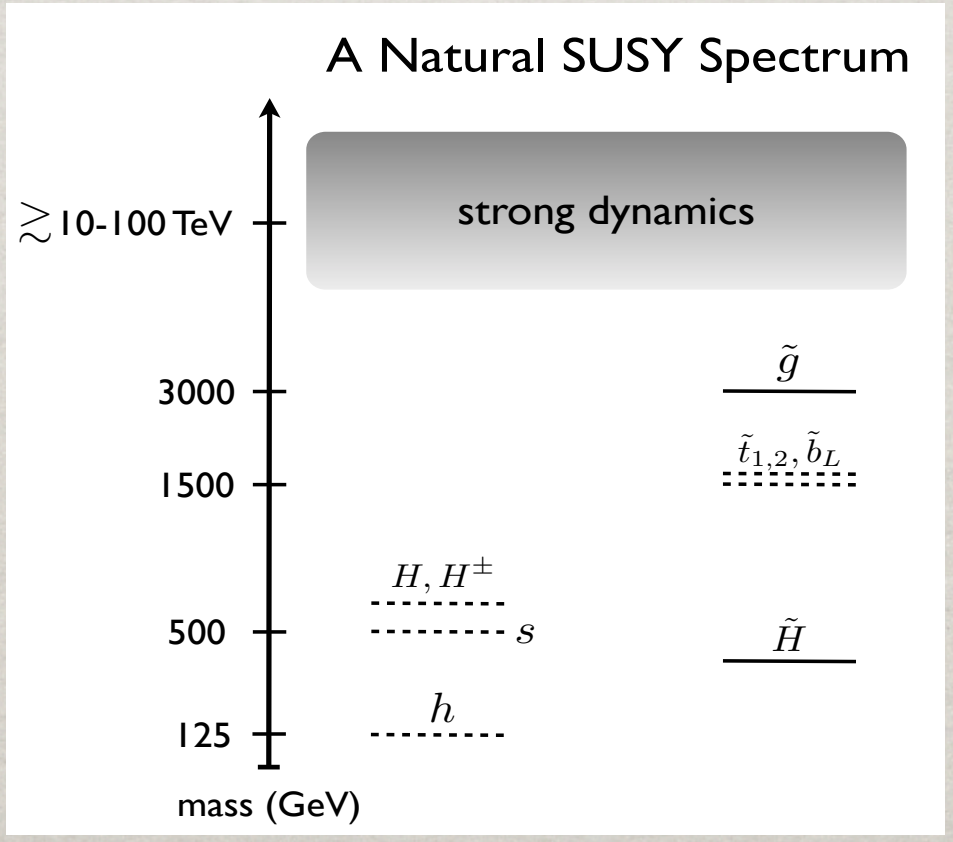
"Natural SUSY": Radiative EWSB

√ radiative EWSB by the large top Yukawa coupling:

$$M_Z^2/2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2.$$

Assume higher scales correlated , only insist on light Higgsinos:

Cohen, Kaplan, Nelson, 1996
Hall, Pinner, Ruderman, 2012
Baer, Barger, Huang, Tata, 2012



Higgs mass corrections & Heavy Higgs bosons

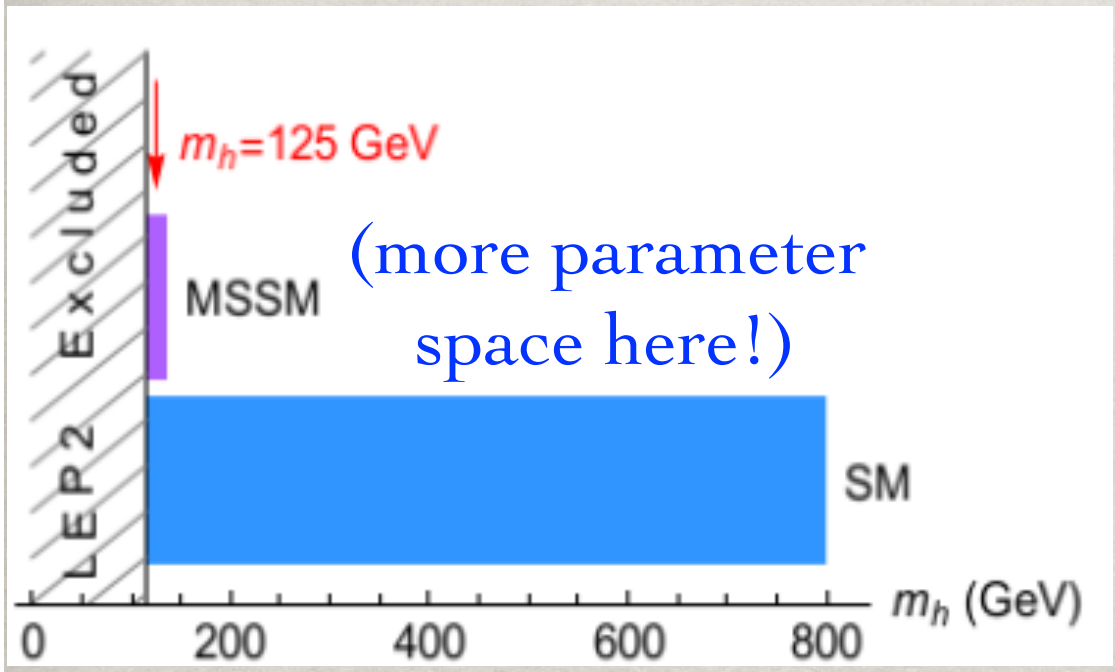
$$m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m^2_{SUSY}$$

Tree-level $<(80\ \text{GeV})^2$ + loop-level: $>(45\ \text{GeV})^2$

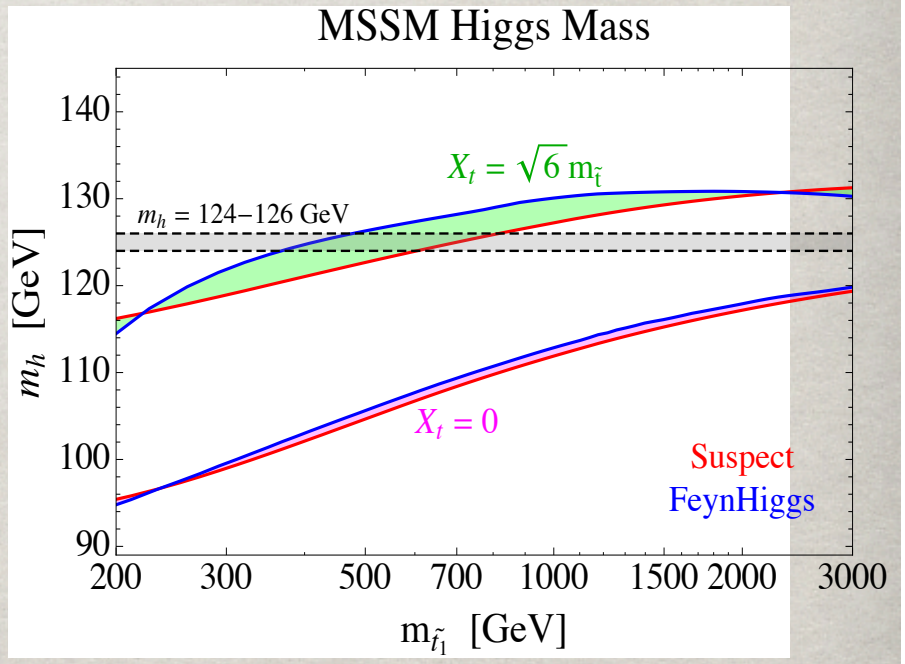
→ Need large tanβ;

m_{stop} & mixing $X_t >> m_t$

sensitive to **μ**, the Higgsino parameter

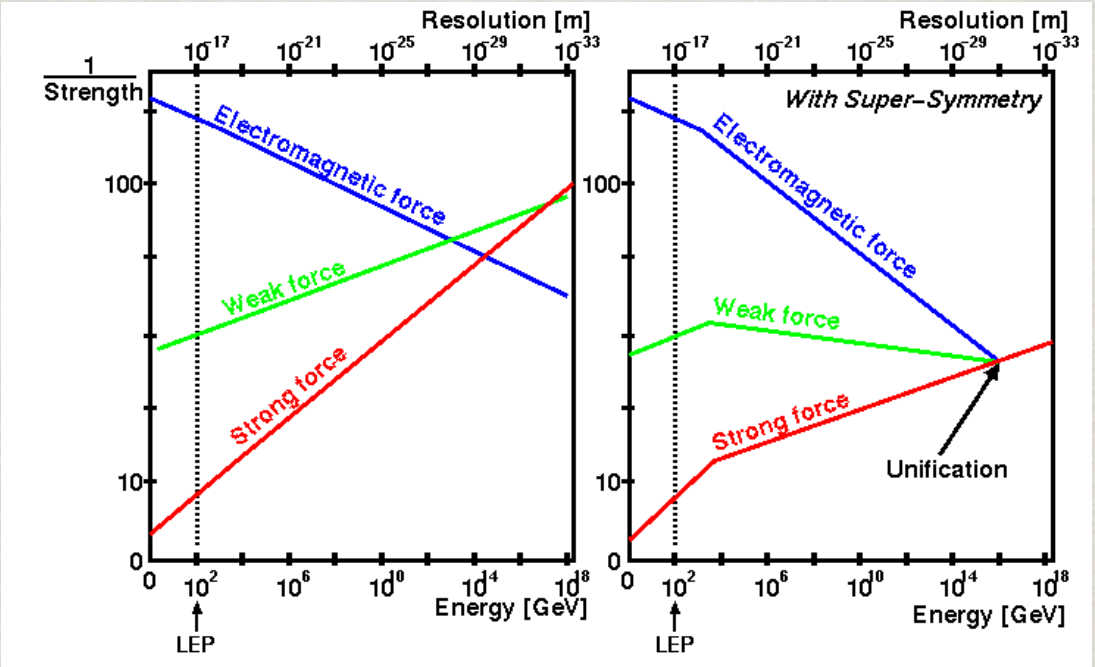


(more parameter space here!)

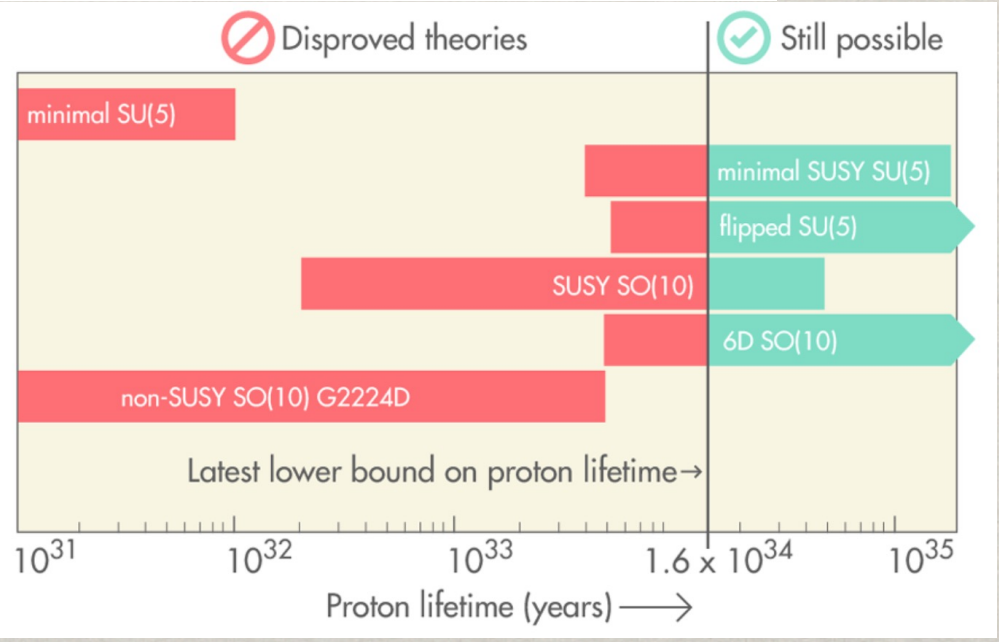


"Little hierarchy problem"

SUSY Grand Unification



Proton decay bounds
--- SUSY helps!

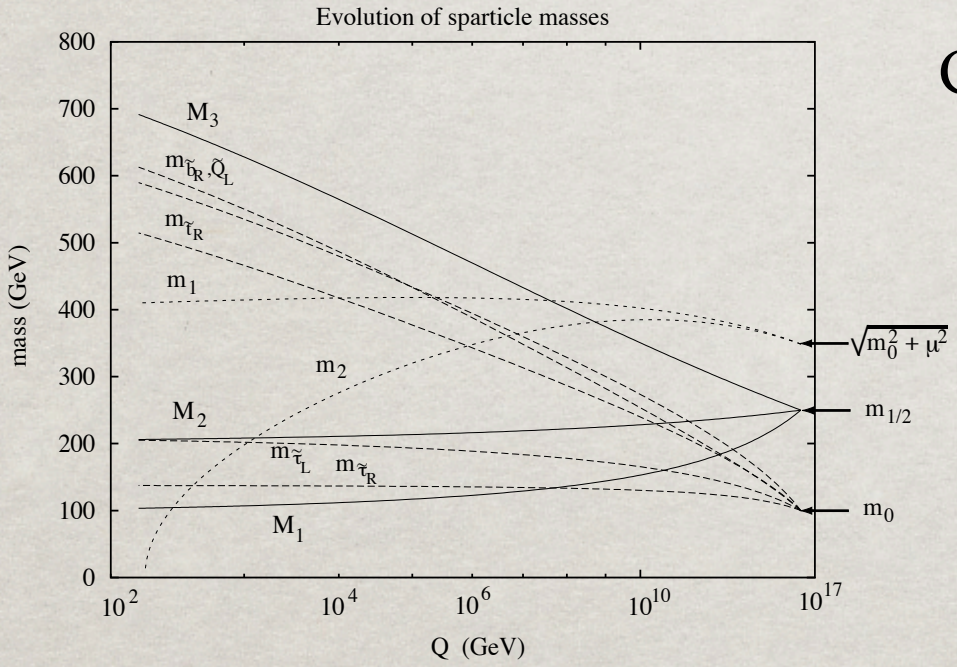


SUSY breaking/mediation scenarios:

(*) "Minimal Super-gravity" (mSUGRA) scenario:

Gravity mediates the SUSY breaking from M_{GUT} to M_{EW}.

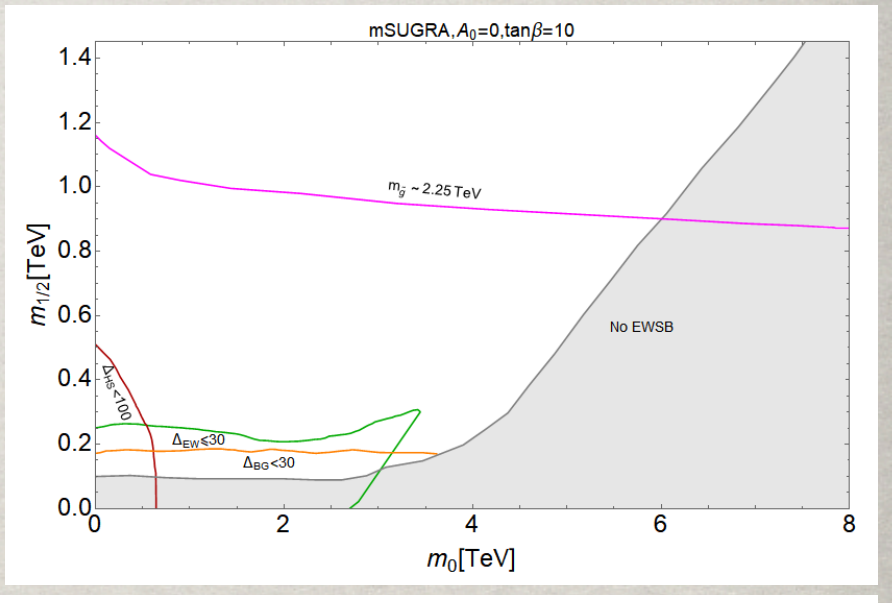
At the high scale: $m_0,\ m_{1/2},\ A,\ \tan\beta$, and $sign(\mu)$



All masses at the EW scale predicted.

However,

Currently, $\Delta_{BG}(\text{mSUGRA}) > 1000$



mSUGRA/CMSSM highly unnatural under all measures: ruled out by LHC!

(*) "Gauge mediation" scenario: *

parameters: Λ, M_m, N, $\tan\beta$, $sign(\mu)$

N: no. of messengers,

M_m (10 – 100 TeV) :
messenger mass scale,

$\Lambda = F/M_m$ (10 – 100 TeV):
SUSY breaking scale.

Spin-$\frac{1}{2}$ Goldstino LSP:

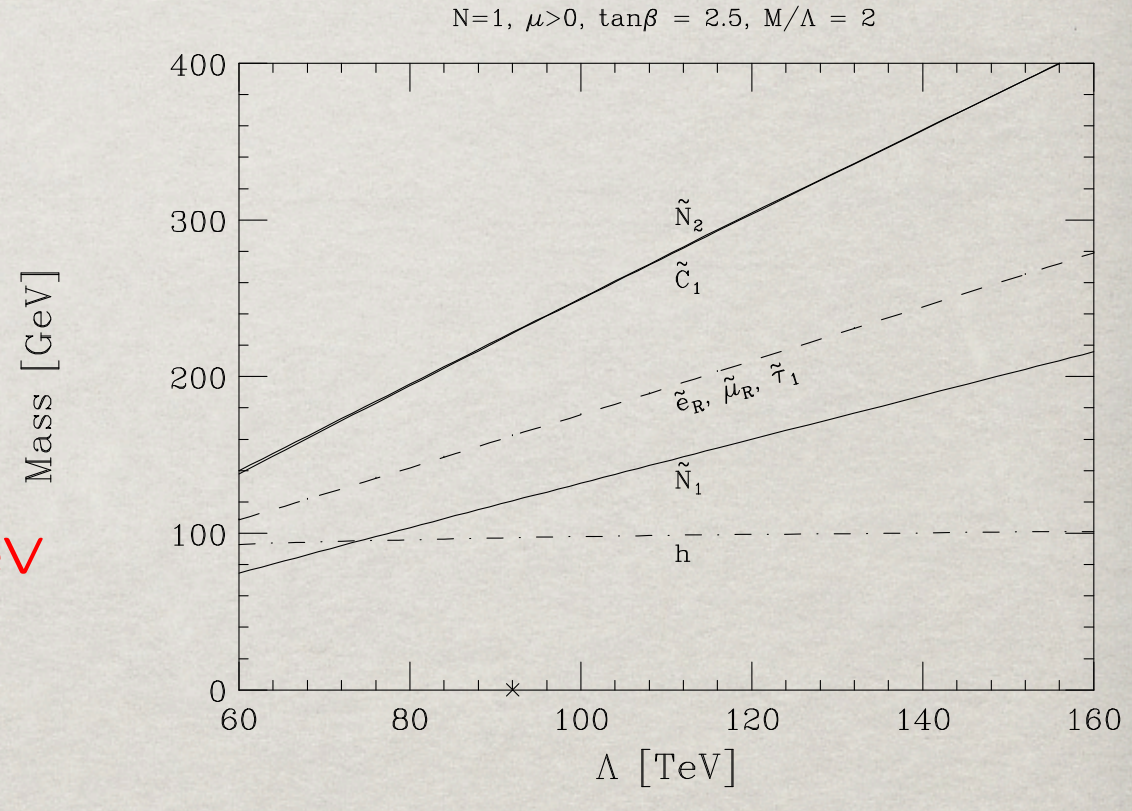
$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{pl}} \approx \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^2\ \text{eV}$$

leading to missing energy.

Sparticle masses:

$\tilde{M}_{\tilde{\chi}} \sim \kappa N \frac{\alpha_a}{4\pi}\Lambda$,

$\tilde{m}^2_{\tilde{f}} \sim \kappa' N \sum_i C_i \frac{\alpha_i}{4\pi}\Lambda^2$.



$$\tilde{e} \to e^+ \chi_1^0, \quad \chi_1^0 \to \gamma \tilde{G}$$

(*) "Anomaly mediation" scenario: †

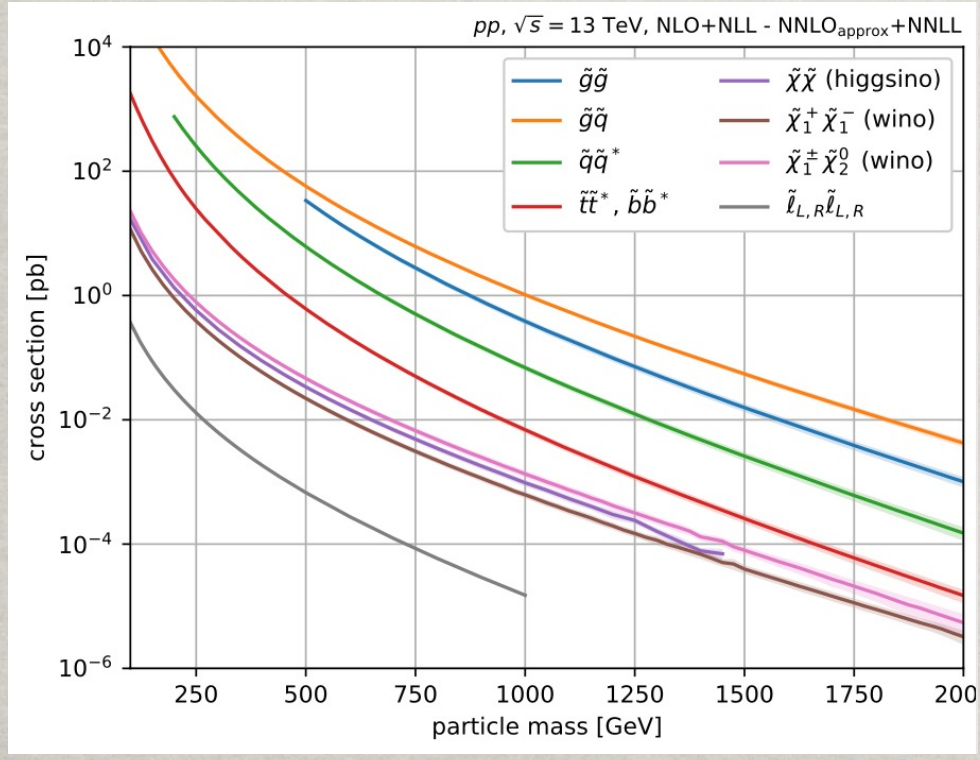
Scalar and gaugino masses generated by one-loop Super-Weyl anomaly (Gravity as bluk messengers).

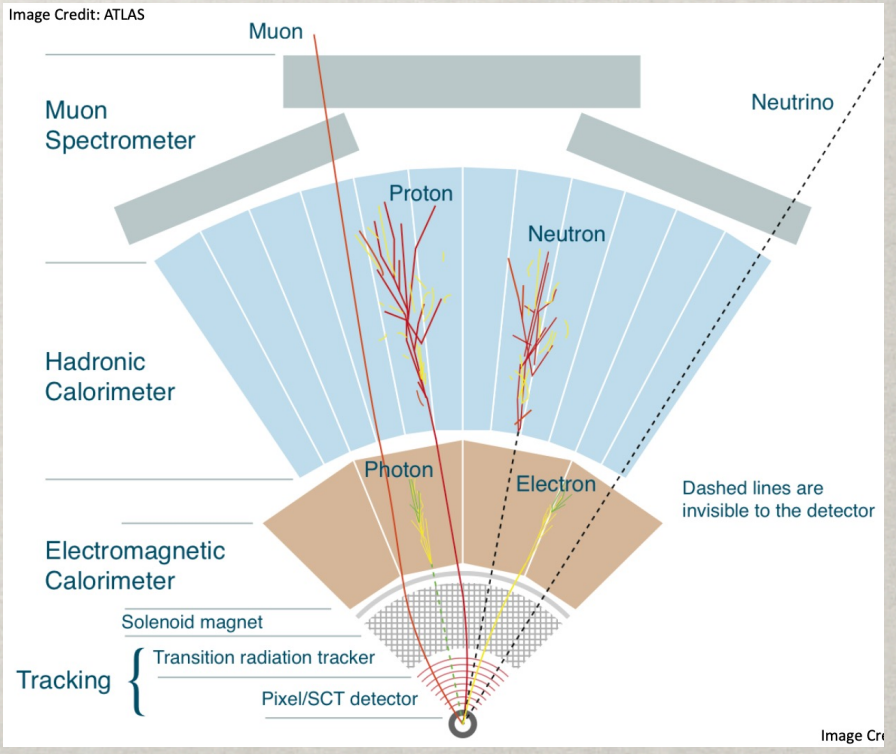
(*) "Gaugino mediation" scenario: †

Gauginos as bulk messengers.

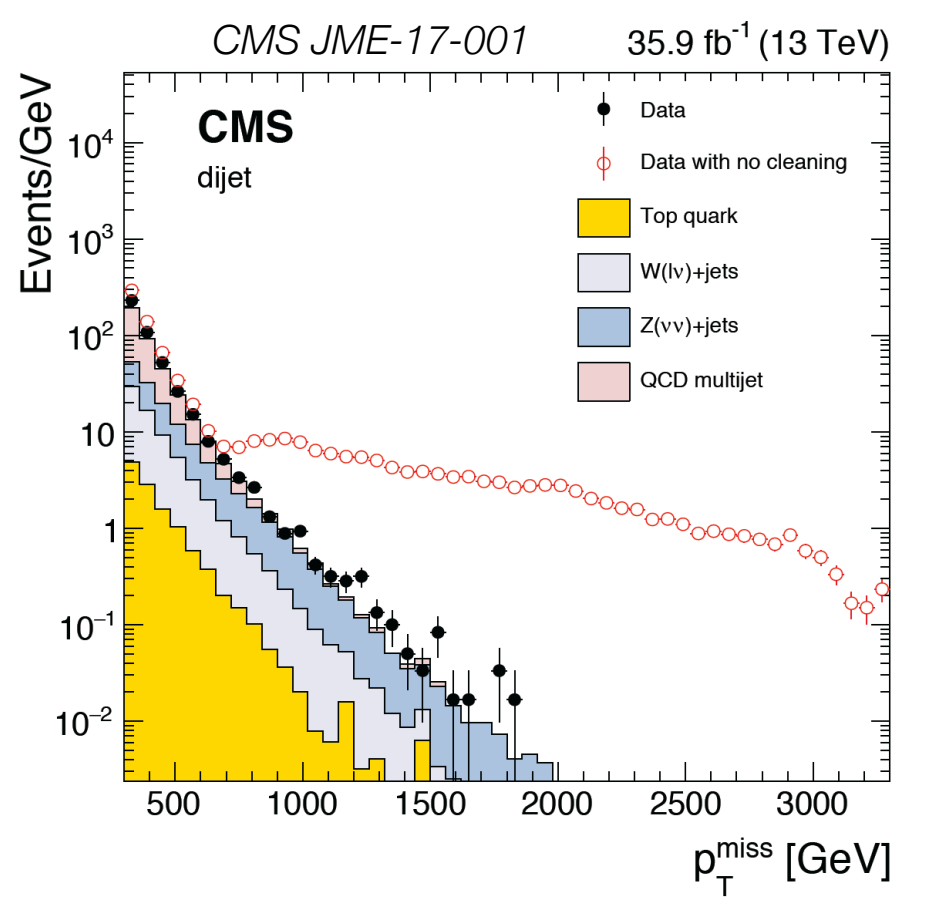
(*) "Mixed Modulus-Anomaly mediation" scenario: ‡

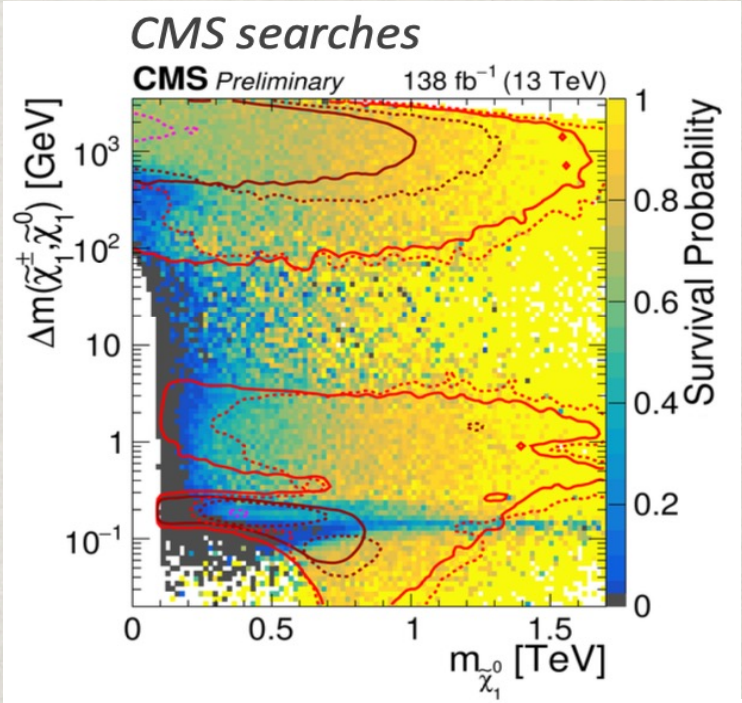
Only experiments can tell: A real challenge!

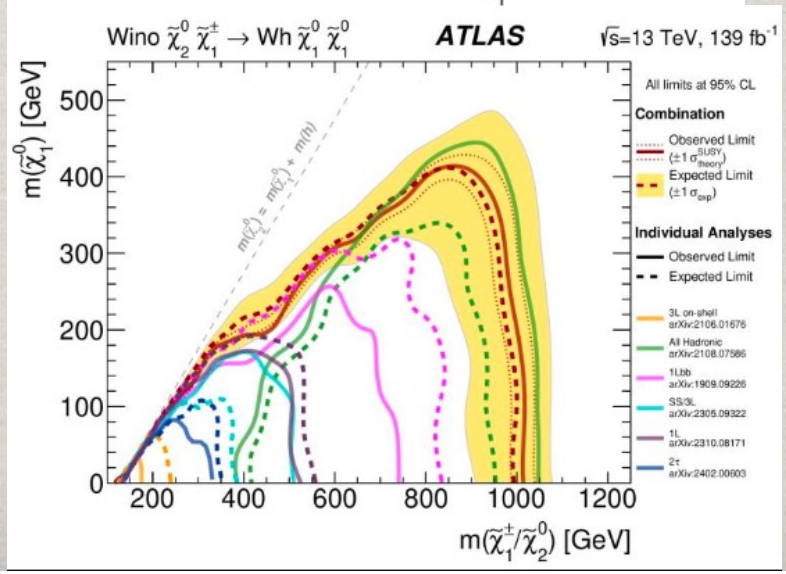




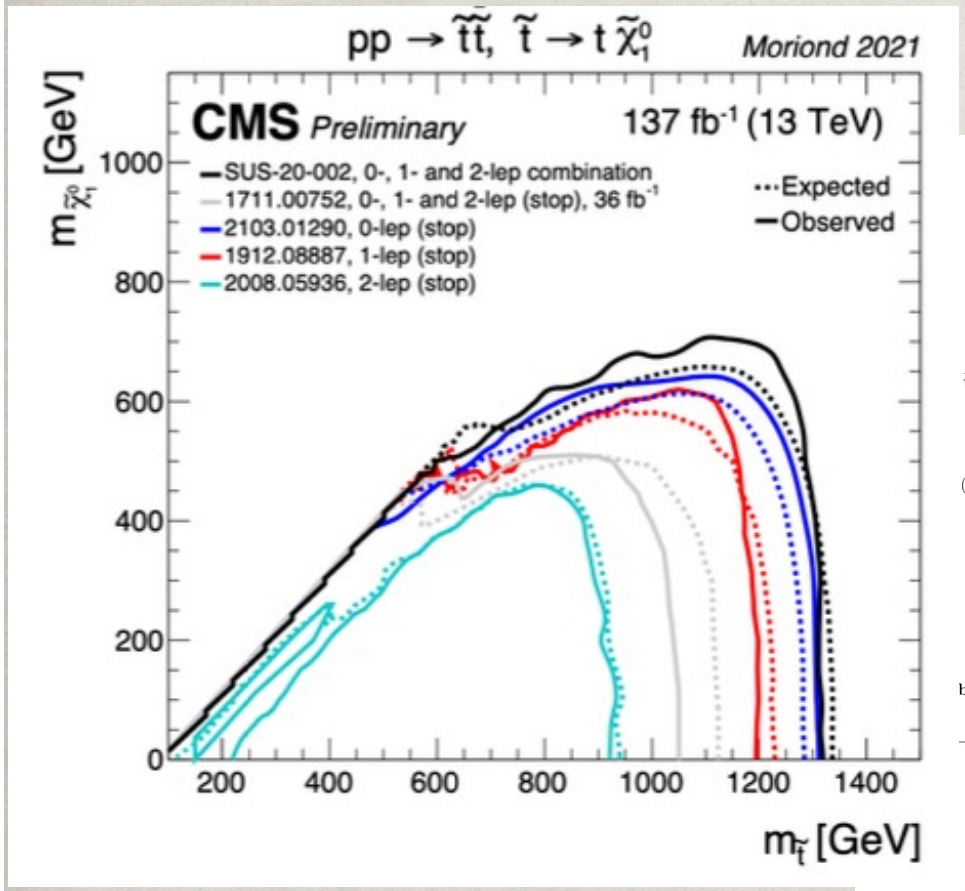
Smoking gun signal for SUSY --- Large missing transverse momentum:

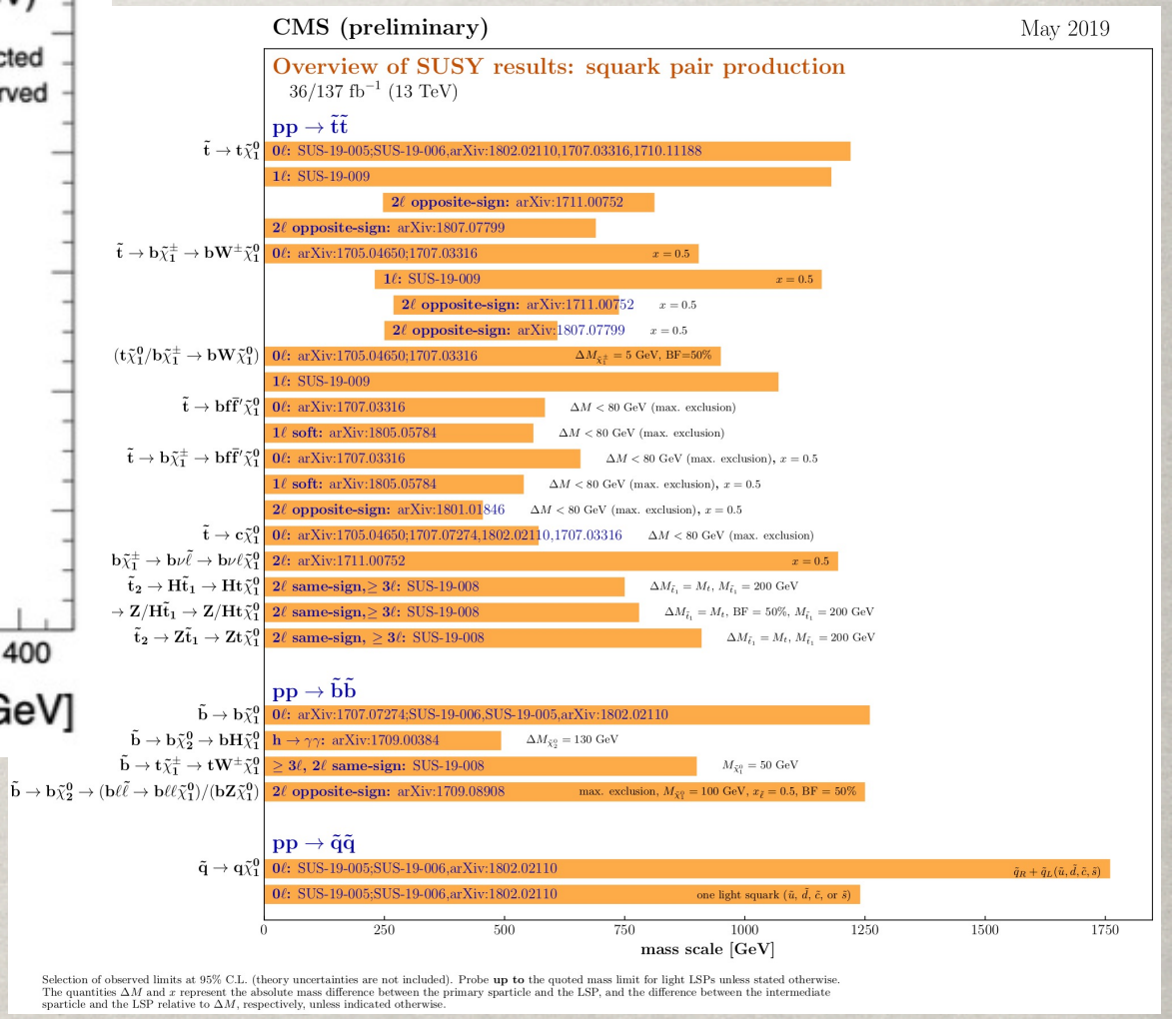




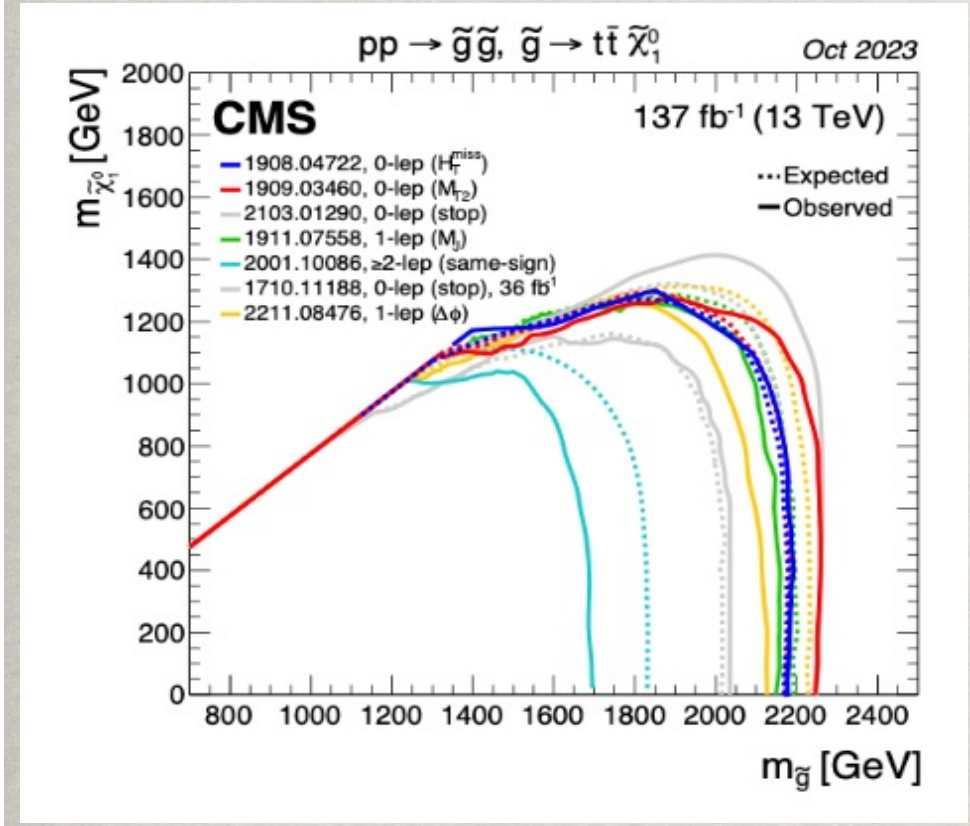


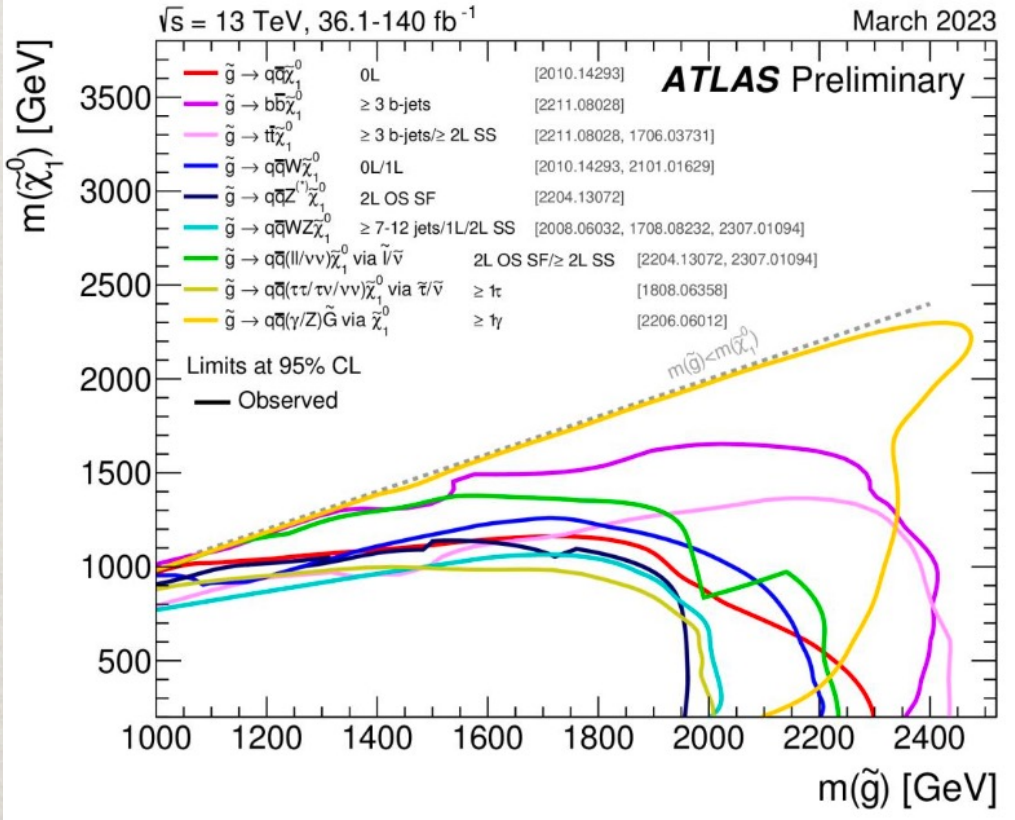
Top-partner is the most likely suspect SUSY on Trial:



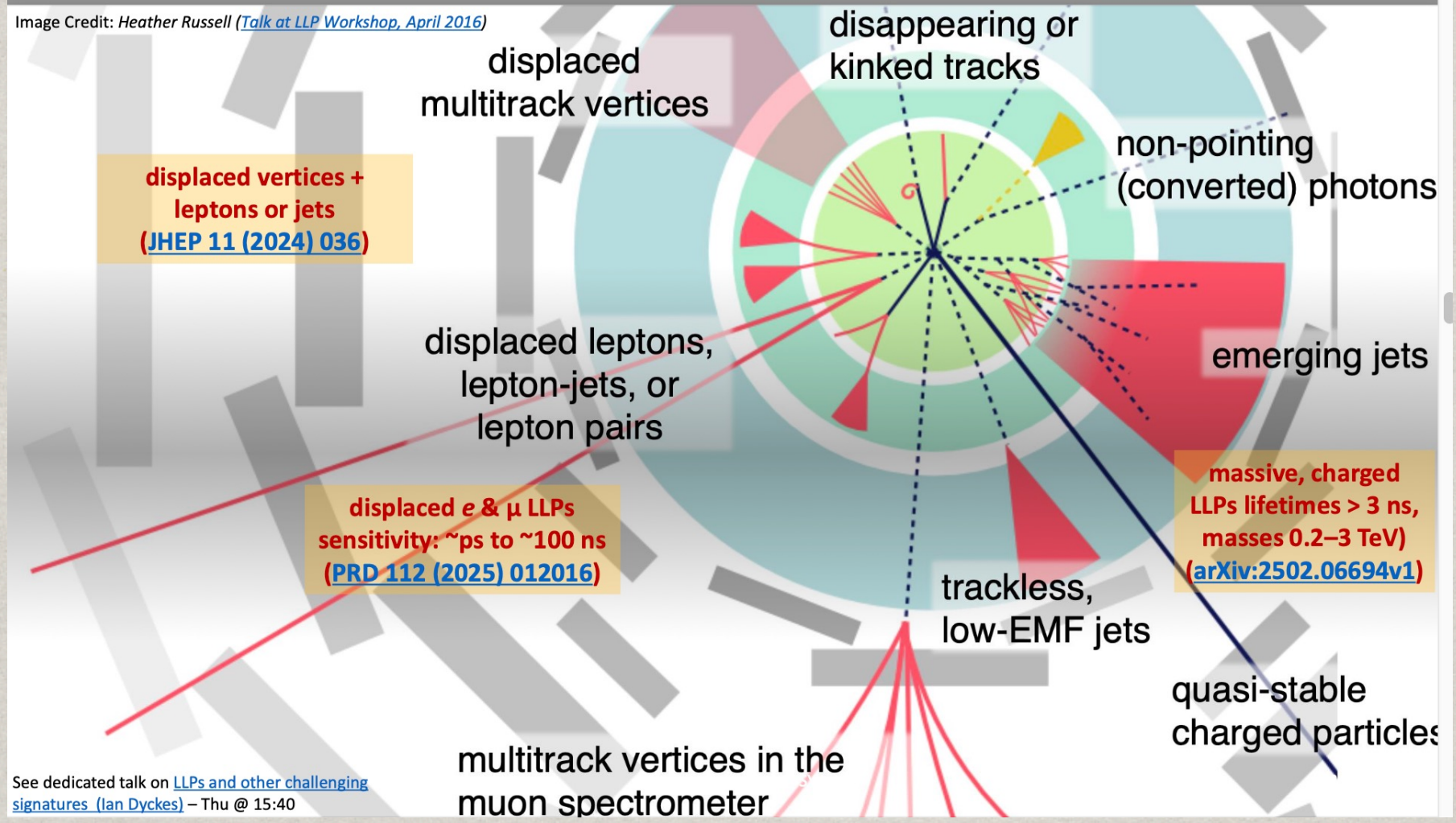


Gluinos are the next candidate!





Long-lived particles (LLP)



Missing siblings:

Two Higgs-Doublet Model

5 Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

Tree-level mass given by:

$M_A,\ \tan\beta$

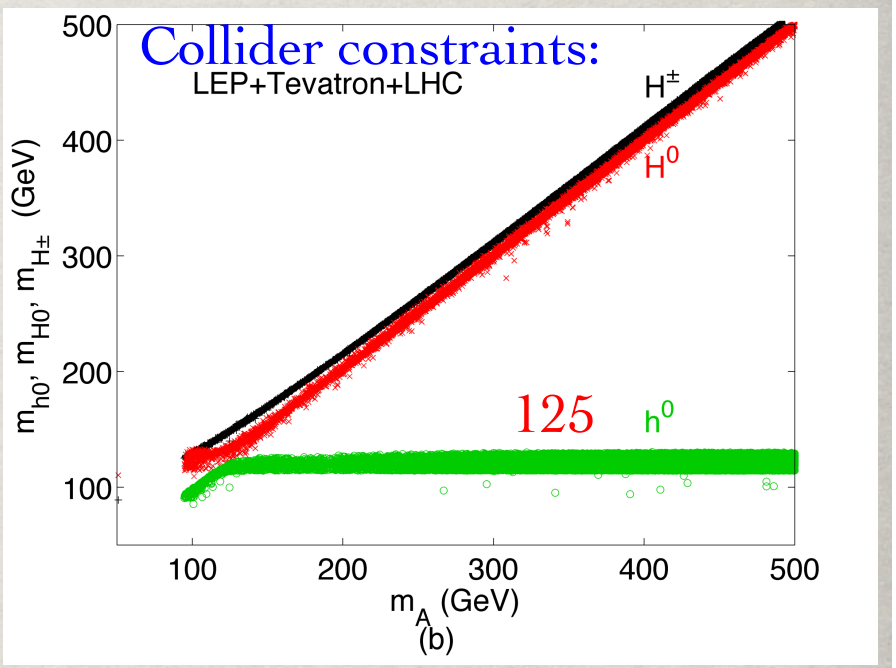
General 2HDM with Z_2 symm

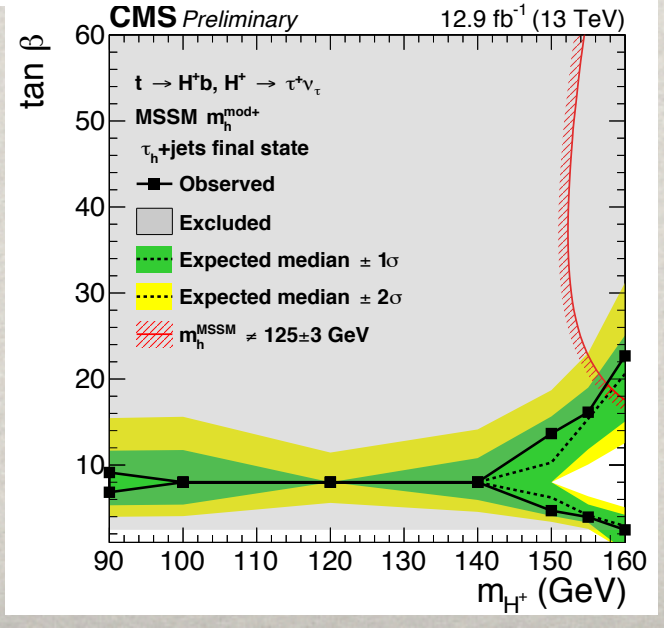
Types	Φ_1	Φ_2	u_R	d_R	ℓ_R	$Q_L,\ L_L$	Φ_1	Φ_2
Type-I	+	−	−	−	−	+		$u,\ d,\ \ell$
Type-II	+	−	−	+	+	+	$d,\ \ell$	u
Type-L	+	−	−	−	+	+	ℓ	$u,\ d,$
Type-F	+	−	−	+	−	+	d	$u,\ \ell$

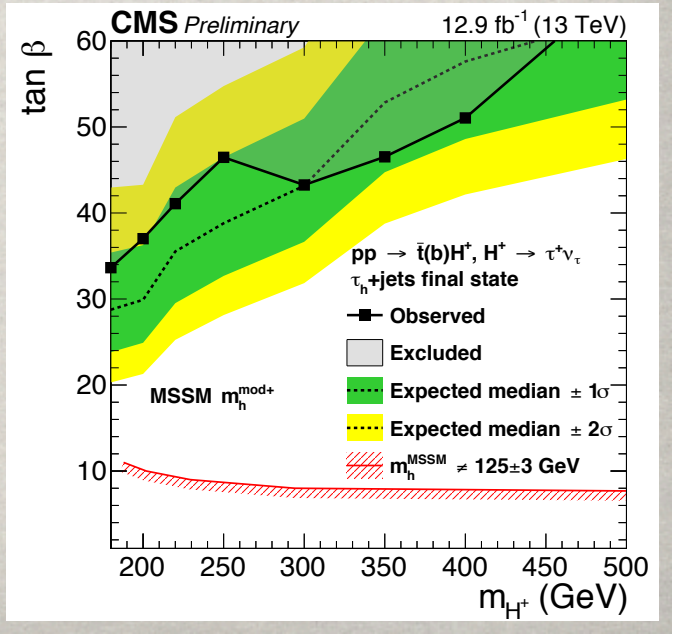
$$\begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_2^\pm \\ \phi_1^\pm \end{pmatrix}$$

$$\begin{pmatrix} A^0 \\ G^0 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G_2^0 \\ G_1^0 \end{pmatrix}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_2^0 \\ \phi_1^0 \end{pmatrix}$$







"Naturally speaking":

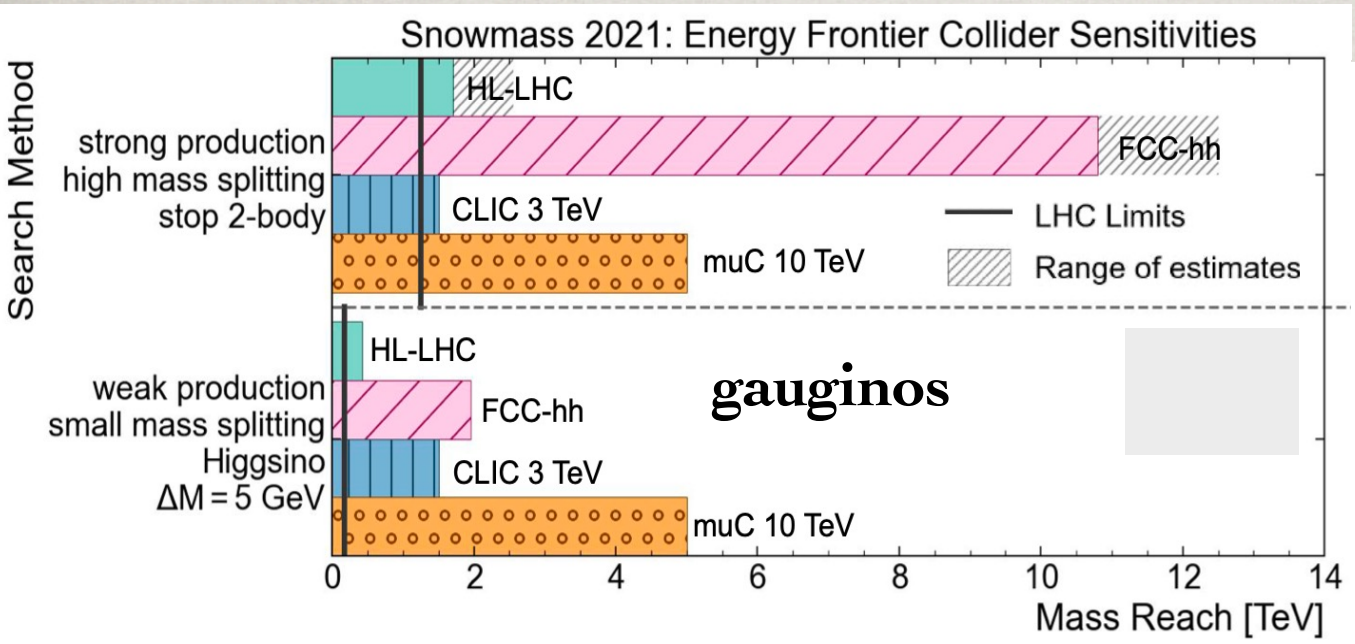
H^0 should not be a lonely particle; has an "interactive friend circle": $t,\ W^{\pm},\ Z$ and partners $\tilde{t},\ \tilde{W}^{\pm},\ \tilde{Z},\ \tilde{H}^{\pm,0}$ ...

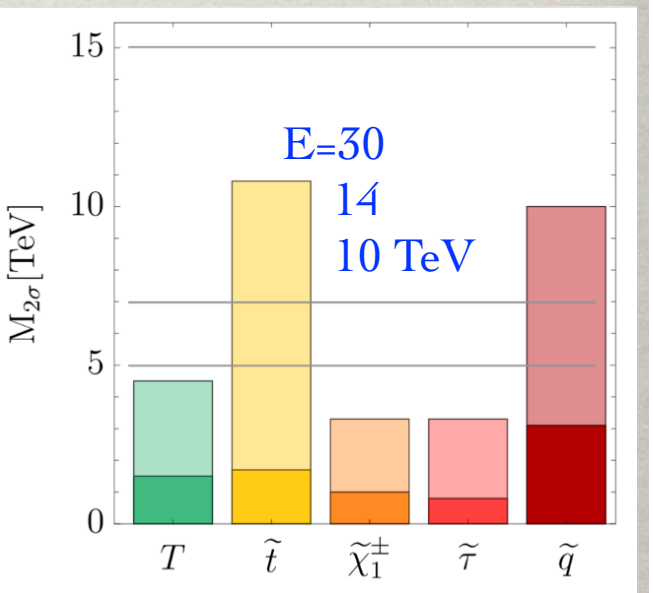
"Little hierarchy problem"

The Jury is still out (again) ...

Future prospects:
pushing the "Naturalness" limit

The searches for top quark partners & gluinos, gauginos …



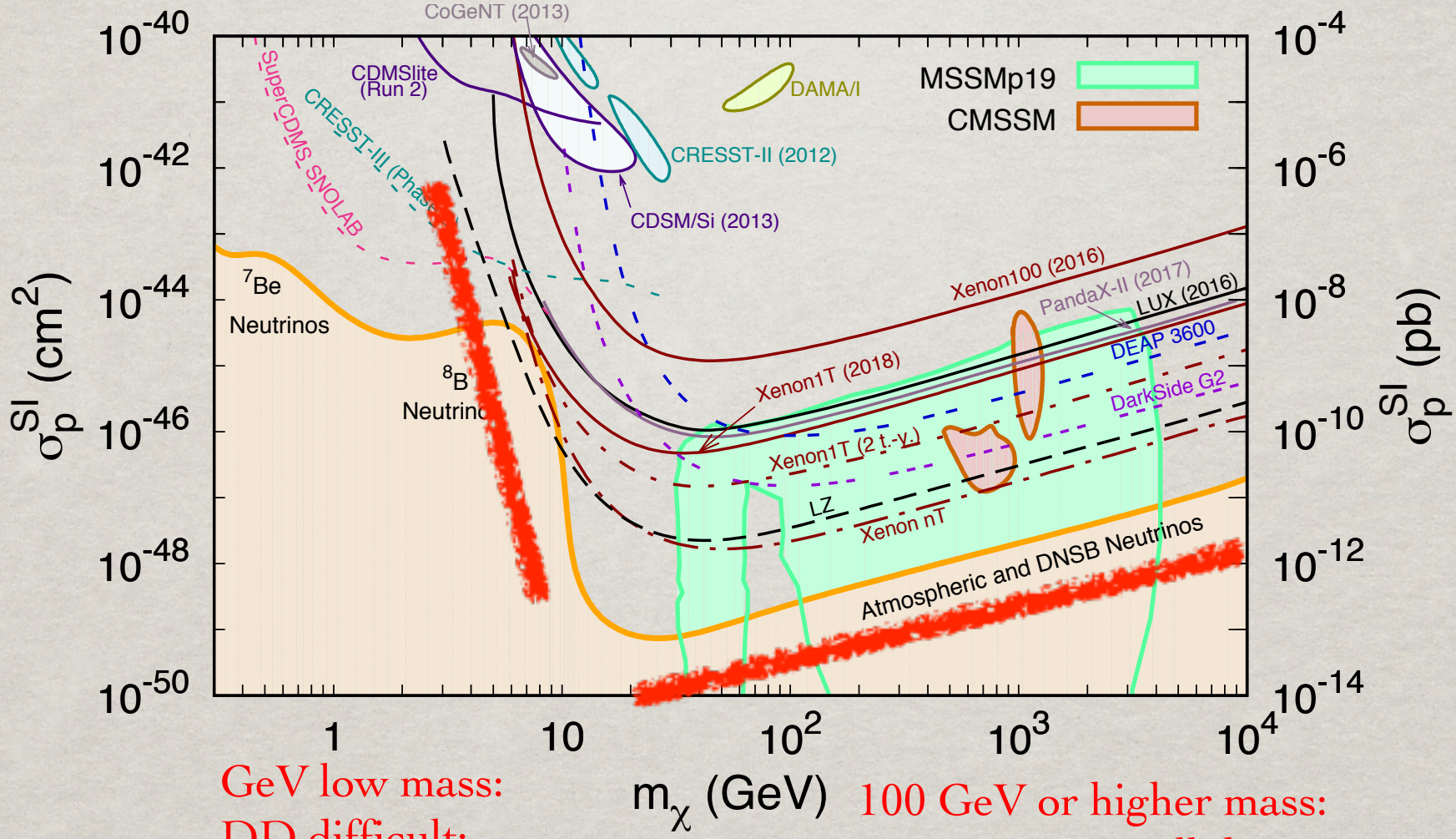


→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \ (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

SUSY WIMP DM

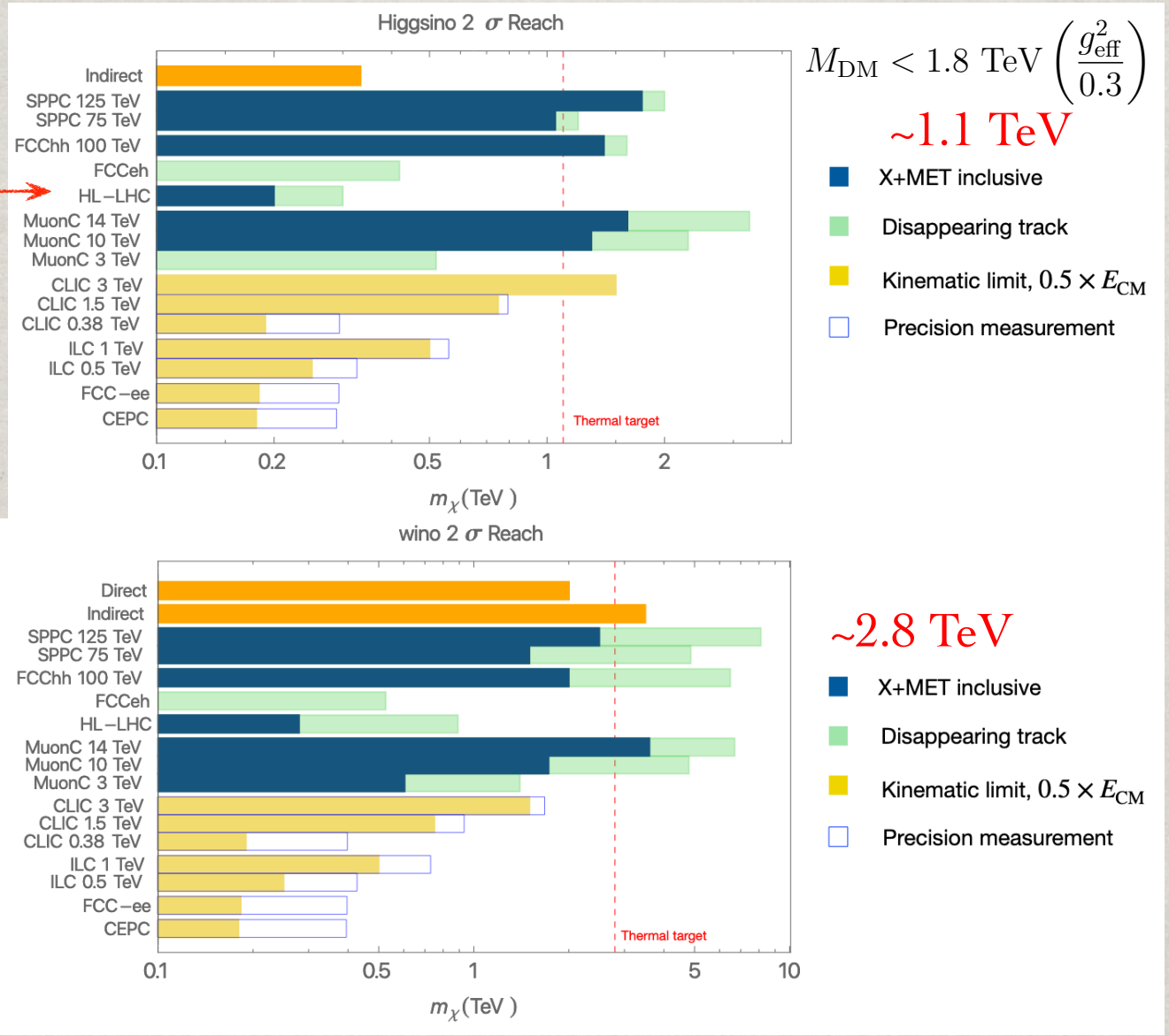
The lightest neutralino could be a natural WIMP dark matter candidate!



GeV low mass:
DD difficult;
Collider complementary

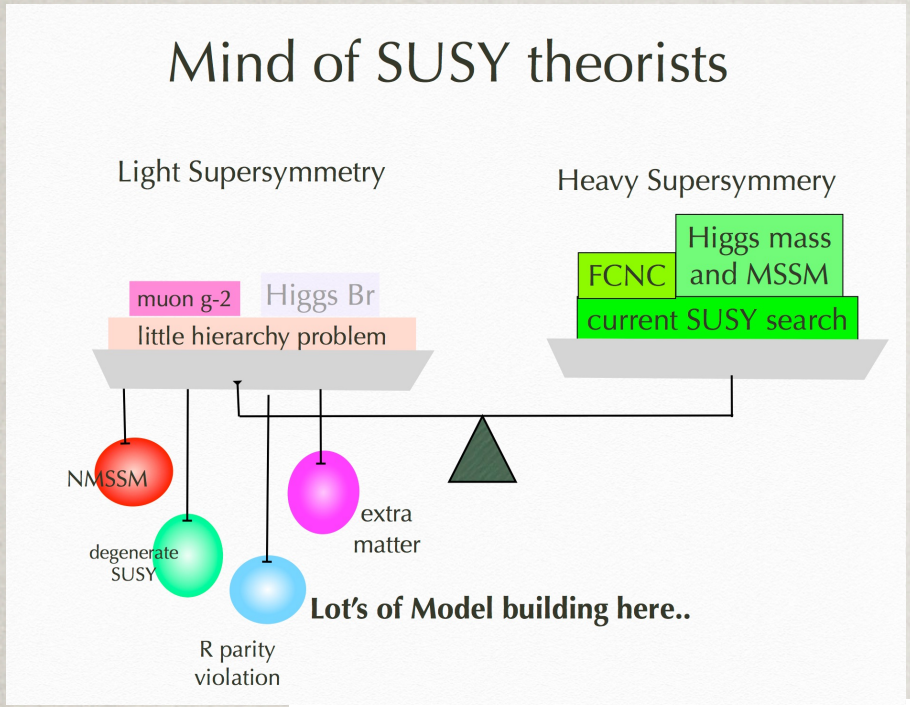
100 GeV or higher mass:
DD + ID + HE Collider

Utilizing the missing-mass technique for DM search, covering the thermal target



TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

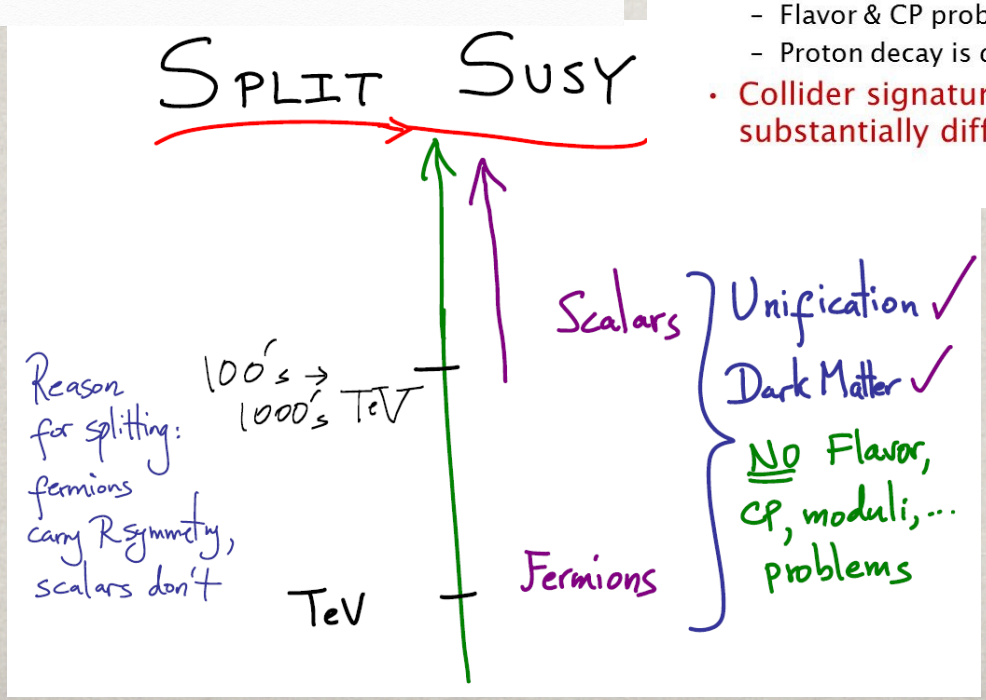
Alternative to "Naturalness": SUSY "splitted"?



Nima Arkani-Hamed, Giudice, Delgado, …

Split Supersymmetry: Philosophy

- SUSY is irrelevant to the hierarchy problem
  - Cosmological constant problem suggests fine-tuning mechanism → may also apply to the gauge hierarchy
- Break SUSY at the GUT scale
  - Scalars become ultra-heavy (except 1 light Higgs): $m_S \sim 10^{9\text{-}12}$ GeV
  - Fermions protected by chiral symmetry
- Phenomenological Successes:
  - Retain gauge coupling unification
  - Higgs mass predicted to be `heavier': $m_H \sim 120\text{-}150$ GeV
  - Flavor & CP problems are automatically solved
  - Proton decay is delayed (occurs via dimension-6 operator)
- Collider signatures & Dark Matter implications substantially different!



Alternatives to "Naturalness"?

- Anthropic Landscape– not a *dynamical* explanation

String theory predicts: there are at least $10^{272,000}$ vacau!
And we just so happen to live here …(Don't ask why!)

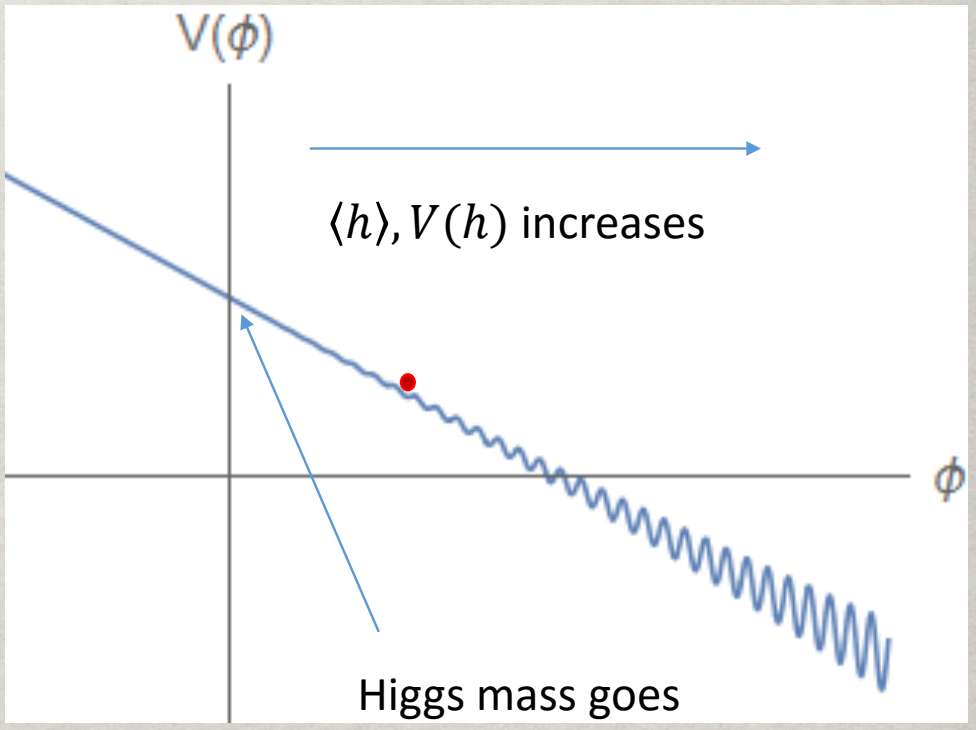
- Cosmological Relaxation (Graham, Kaplan, Rajendran 2015)

$$\mathcal{L} \supset g\Lambda^3\phi - \left(M^2 - g\Lambda\phi\right)|h|^2$$

Λ is the EFT cutoff scale; "bare" Higgs mass is $M \sim \Lambda$

Technically natural-- shift symmetry for ϕ broken only by small coupling g

ϕ must vary over a range $\Delta\phi \sim \Lambda/g$ to scan the Higgs mass by $O(1)$



``…settling the ultimate fate of naturalness is perhaps the most profound theoretical question of our time''

-- Nima Arkani-Hamed

The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory