Supersymmetry breaking in the light of LHC

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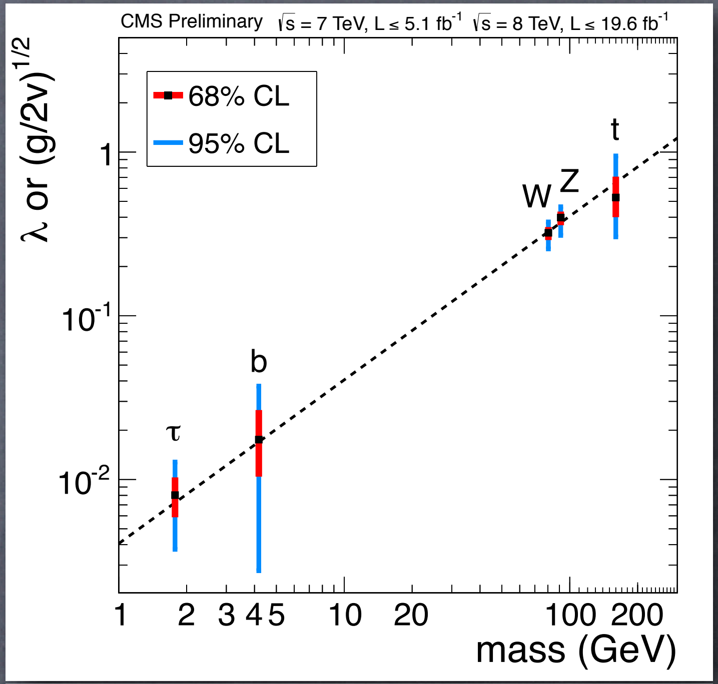
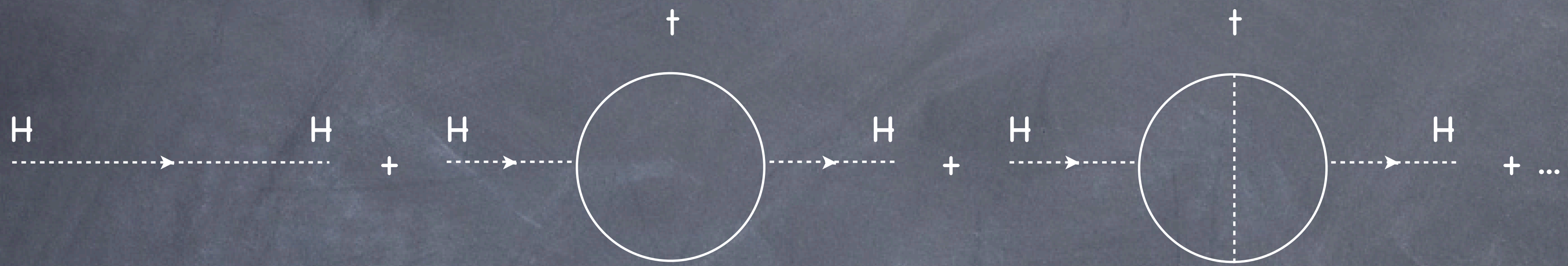
Habemus Higgs

- "h" is $SU(3)_c \times U(1)_{em}$ neutral
- "h" has S = 0 and P = 1
- "h" couplings prop. to masses



- "h" singlet under custodial symmetry

The unbearable lightness of the Higgs



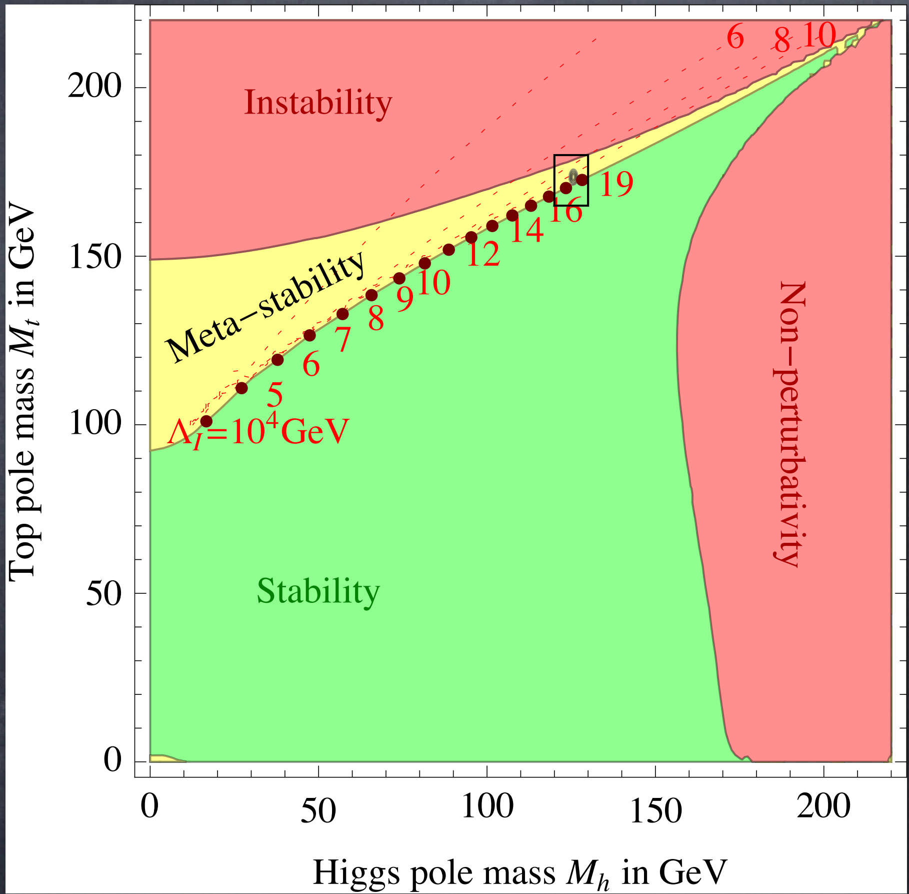
$$\delta m_h^2 \sim 12\,\lambda_t^2 \int \frac{k^3\,dk}{8\pi^2}\,\frac{1}{k^2} \xrightarrow{\text{cut-off}} 12\,\frac{\lambda_t^2}{(4\pi)^2}\,Q_{\max}^2$$

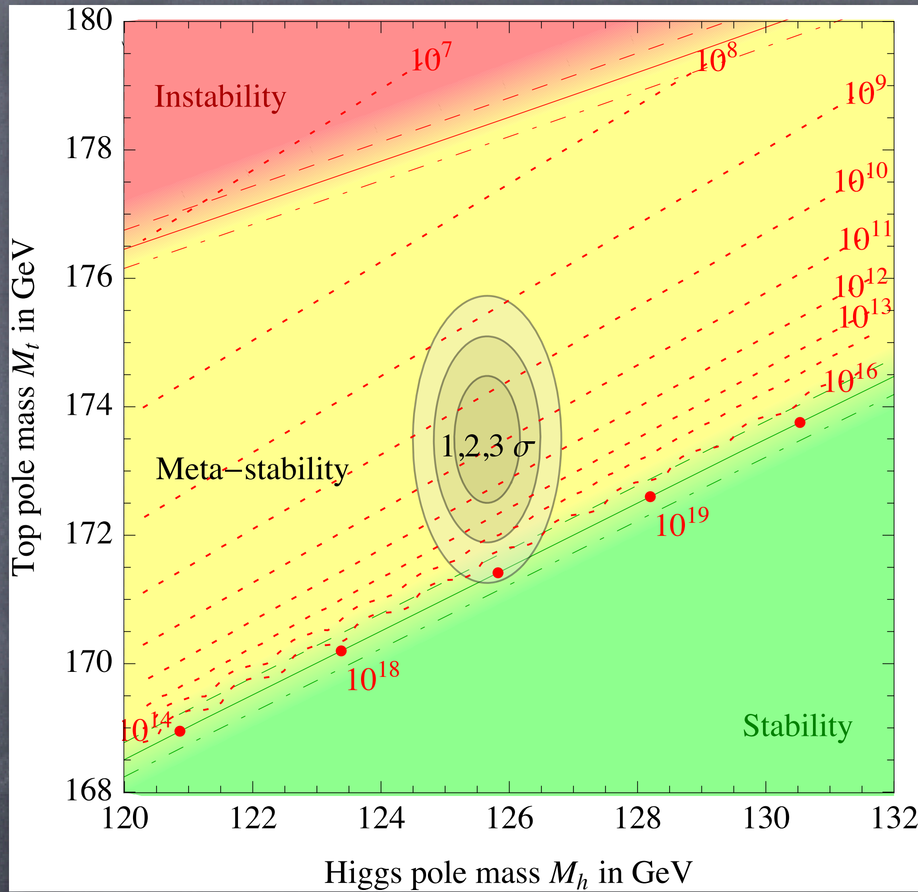
- Quadratic divergences "per se" do not mean much (e.g. disappear in dimensional regularization)
- If the SM is the ultimate (renormalizable) theory of everything: $Q_{max} \to \infty$ mathematical problem (renormalization theory)
- If the SM is the low energy limit of a more fundamental theory: $Q_{max} \to m_{NP}$ physical (calculability) problem IF $m_{NP} \gg m_H$

- μ^2 parametro del potenziale di Higgs (tree level)
- M^2 massa $O(10^{16}$ GeV) particella con accoppiamento g all'Higgs

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

The SM can be extrapolated up to M_{Pl}





Buttazzo et al

Is SM the ultimate renormalizable theory of everything?

- Experimental "problems"
  - Gravity
  - Dark matter
  - Baryon asymmetry
  - Neutrino masses

Is SM the ultimate renormalizable theory of everything?

- Experimental “hints” of physics beyond the SM
  - Neutrino masses
  - Quantum number unification

Unification

	SU(3)	SU(2)	U(1)		SO(10)
L_i	1	2	-1/2		
e^c_i	1	1	1		
Q_i	3	2	1/6	⇒	16
u^c_i	3^*	1	-2/3		
d^c_i	3^*	1	1/3		
			Y		

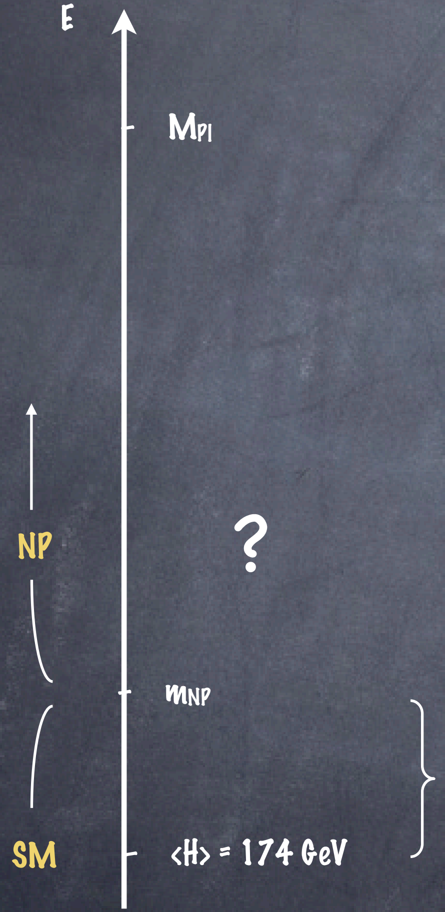
Is SM the ultimate renormalizable theory of everything?

- Theoretical puzzles of the SM
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, masses and mixings

Is SM the ultimate renormalizable theory of everything?

- Theoretical problems of the SM
  - Landau poles
  - Strong CP problem $\theta\, G_{\mu\nu}\tilde{G}^{\mu\nu} \quad D=4$
  - Naturalness problem $\alpha\, Q^2_{\rm max} H^\dagger H \quad D=2$
  - Cosmological constant problem $\beta\, Q^4_{\rm max}\sqrt{g} \quad D=0$

Naturalness problem



$$\delta m_h^2 \sim 12 \frac{\lambda_t^2}{(4\pi)^2} m_{\rm NP}^2 \approx (125\,{\rm GeV})^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)$$

Due comments

1. m_{NP} is not precisely determined: any value of m_{NP} is viable as long as a cancellation of one part out of

$$\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

is accepted.

E.g.

$m_{NP} > 1.5$ TeV $\leftrightarrow$ $\Delta > 10$

$m_{NP} > 5$ TeV $\leftrightarrow$ $\Delta > 100$

Due comments

2. The bound $\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$ is model dependent

For example:

- Supersoft theories $\delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$

- Soft theories $\delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$

(e.g. **supersymmetry** with mediation scale M)

Due comments

3. Though general, the above argument rests on assumptions

- existence of superheavy physics
- the cancellation in the Higgs mass is accidental

(dynamical mechanisms? environmental selection?)

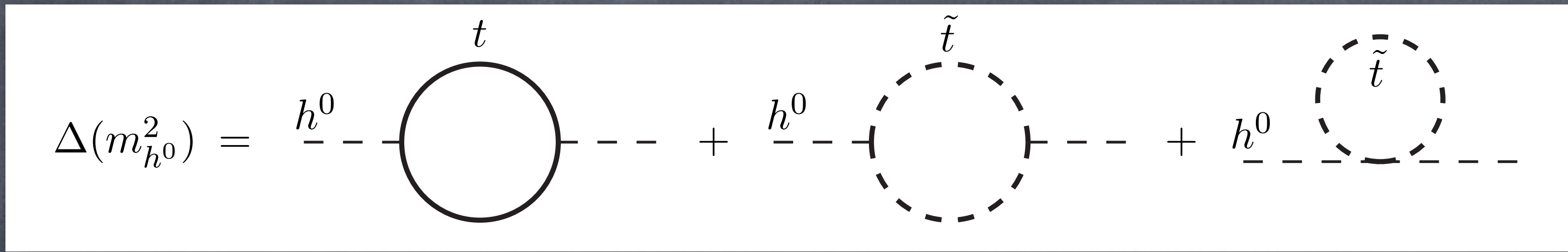
Supersymmetry

- SUSY: fermion ↔ scalars; SUSY partners much heavier

- Theoretical motivations
  - Unification of fermions and bosons (we do have a boson after all)
  - Local supersymmetry = supergravity + crucial in string theory
  - Completes the list of possible symmetries of S (under hypotheses)
  - Powerful technical tool
- Phenomenological motivations

Solves (the bulk of) the hierarchy problem

$$\frac{3}{4\pi^2}\lambda_t^2 Q^2 \qquad\qquad -\frac{3}{4\pi^2}\tilde{\lambda}_t Q^2$$

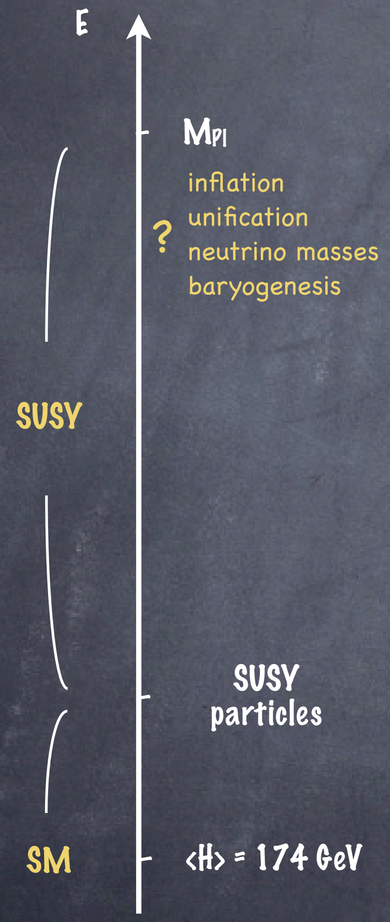


$$\lambda_t^2 = \tilde{\lambda}_t$$

Calculability $$\frac{3}{4\pi^2}\lambda_t^2 Q^2 \to \frac{3}{4\pi^2}\lambda_t^2 \tilde{m}^2 \log\frac{Q^2}{\tilde{m}^2}$$ $\tilde{m} \lesssim$ few TeV?

The cancellation of quadratic divergences holds at all orders in perturbation theory

Can be extrapolated up to the Planck scale



Unification

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
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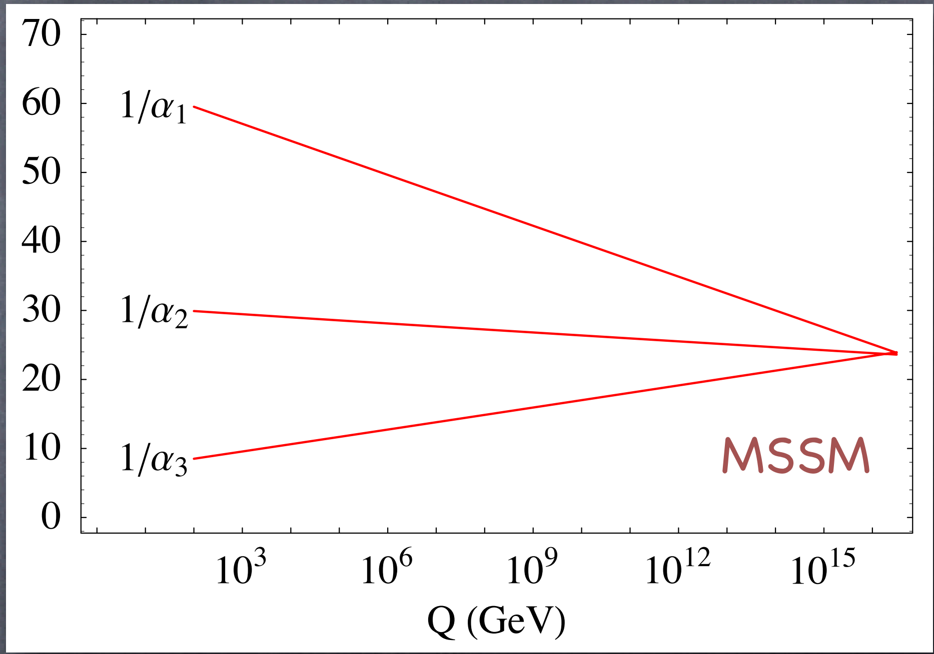
u^c_i	3^*	1	-2/3
d^c_i	3^*	1	1/3
			Y

⇒ SO(10): 16



+ M_{GUT} prediction: $\Lambda_B < M_{GUT} < M_{Pl}$

inflation scale?

However

- Not chiral (explicit, supersymmetric mass term for the Higgsinos)
  - ➥ Giudice-Masiero, NMSSM
- Correct symmetry breaking not guaranteed (CCLB minima)
  - ➥ radiative EWSB
- L, B not accidental symmetries anymore
  - ➥ R-parity
    - ➥ Lightest Supersymmetric Particle (LSP) is stable (DM, missing E_T)
    - ➥ SUSY corrections to SM processes only via loops
- Trouble with supersymmetry breaking

Supersymmetry breaking

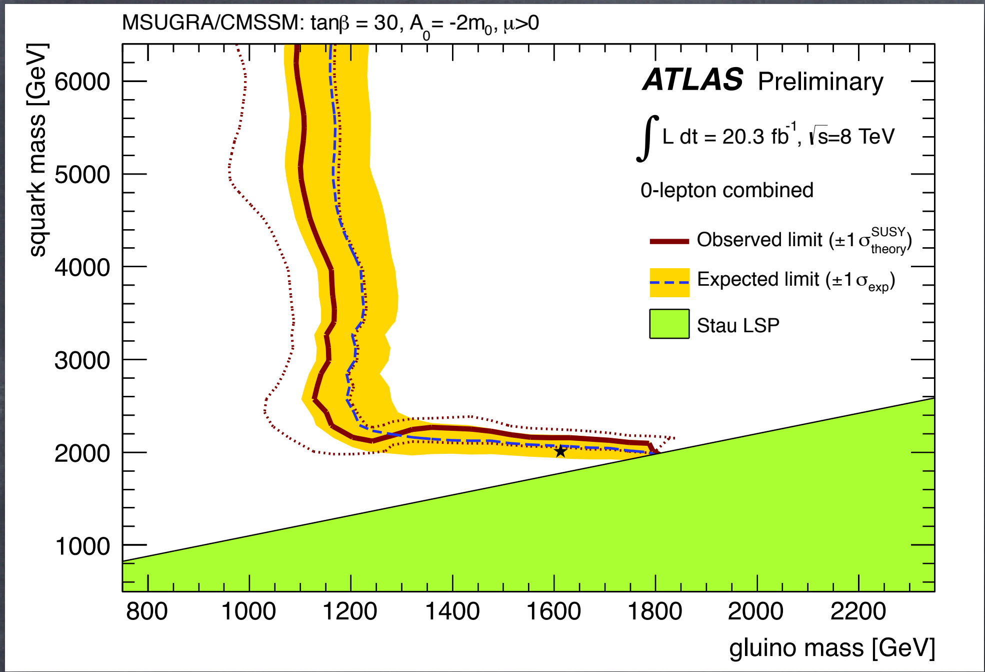
- Supersymmetry predicts m = m̃

- Needs to be broken, hopefully spontaneously

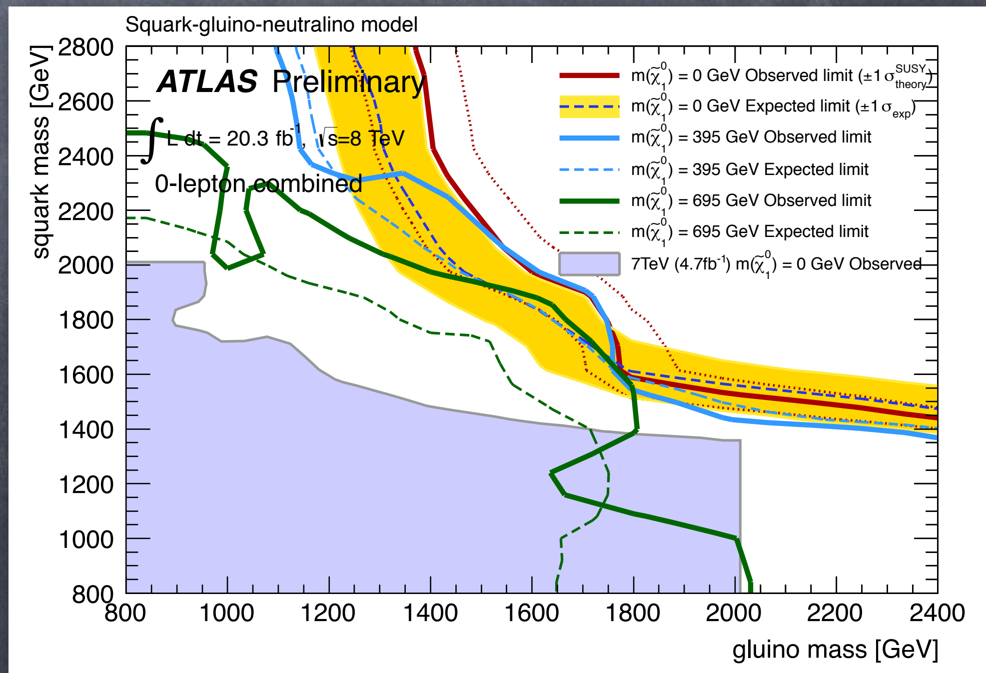
  - Effective description in terms of O(100) parameters

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} = {} & A^U_{ij}\tilde{u}^c_i\tilde{q}_j h_u + A^D_{ij}\tilde{d}^c_i\tilde{q}_j h_d + A^E_{ij}\tilde{e}^c_i\tilde{l}_j h_d + m^2_{ud}h_u h_d + \text{h.c.} \\
& + (\tilde{m}^2_q)_{ij}\tilde{q}^\dagger_i\tilde{q}_j + (\tilde{m}^2_{u^c})_{ij}(\tilde{u}^c_i)^\dagger\tilde{u}^c_j + (\tilde{m}^2_{d^c})_{ij}(\tilde{d}^c_i)^\dagger\tilde{d}^c_j + (\tilde{m}^2_l)_{ij}\tilde{l}^\dagger_i\tilde{l}_j \\
& + (\tilde{m}^2_{e^c})_{ij}(\tilde{e}^c_i)^\dagger\tilde{e}^c_j + m^2_{h_u}h^\dagger_u h_u + m^2_{h_d}h^\dagger_d h_d \\
& + \frac{M_3}{2}\tilde{g}_A\tilde{g}_A + \frac{M_2}{2}\tilde{W}_a\tilde{W}_a + \frac{M_1}{2}\tilde{B}\tilde{B} + \text{h.c.}
\end{aligned}
$$

(Vanilla) direct experimental constraints



- Based on missing E_T
- First family squarks
- One slice of the par space



How bad is it?

Supersymmetry is a soft theory

$$\delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$$

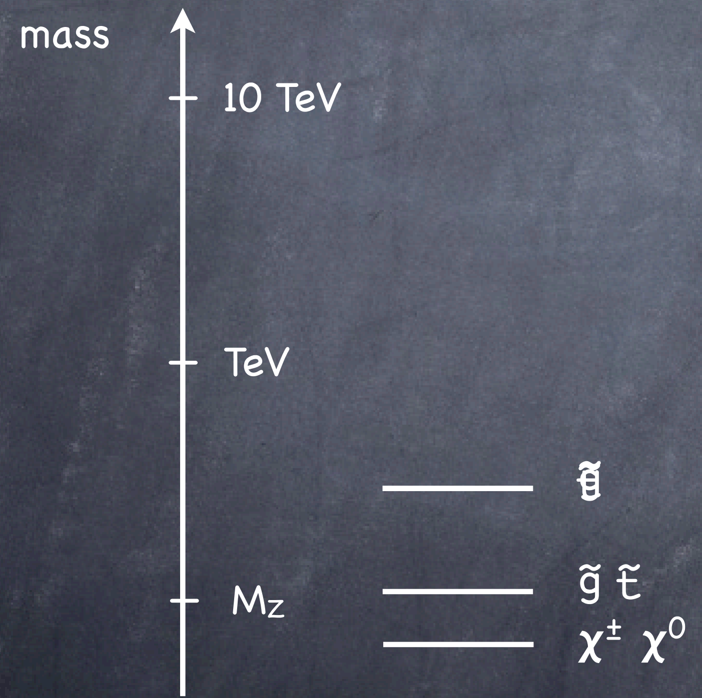
$$\approx m_h^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}/\sqrt{\log}}\right)^2$$

M = mediation scale

E.g. in supergravity M = M_{Pl}

A tale of naturalness

- Supergravity (unavoidable mediation mechanism): $\Lambda_{NP} = M = M_{Planck}$
- log = O(70) $\Longrightarrow$ natural expectation: m_{NP} around M_Z!

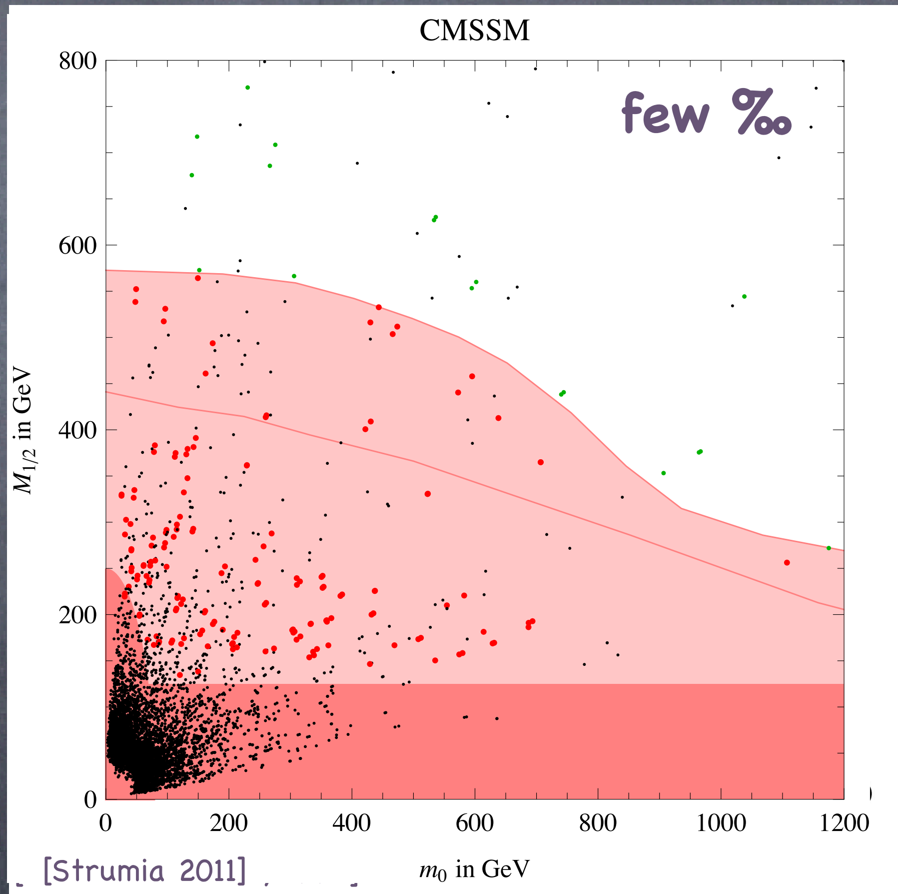


m_H = 125 GeV

LHC

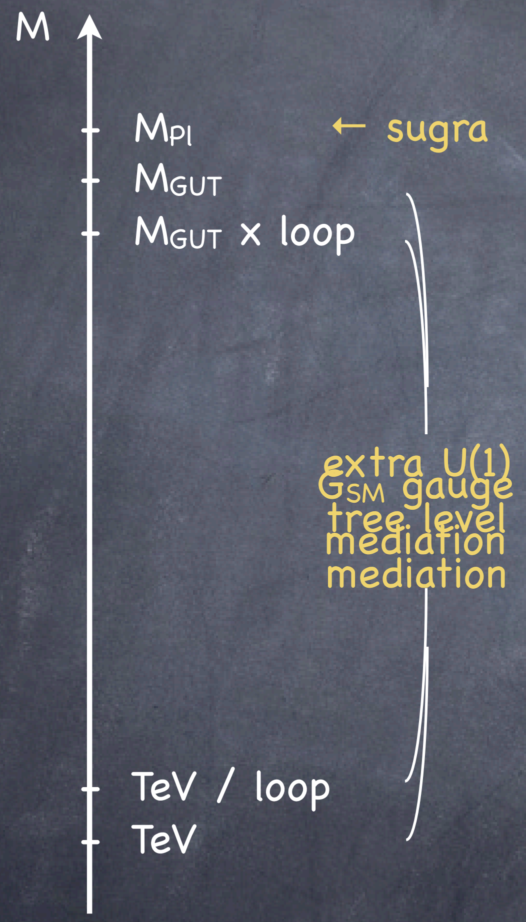
m_H > 115 GeV

LEP + Tevatron



[Strumia 2011]

Lower M: how low?



$$\tilde{m} = \frac{\alpha F}{4\pi M}$$

Where does FT come from?

$$m_Z^2 \approx -2m_{H_u}^2 - 2|\mu|^2$$

$$\downarrow$$

$$\delta m_{H_u}^2 \sim -12\frac{\lambda_t^2}{(4\pi)^2}\tilde{m}_t^2 \log\frac{M}{\tilde{m}_t}$$

$$\downarrow$$

$$\delta\tilde{m}_t^2 = \frac{32}{3}\frac{g_3^2}{(4\pi)^2}M_3^2 \log\frac{M}{M_3}$$

+ experimental constraints
+ indirect bounds from m_H

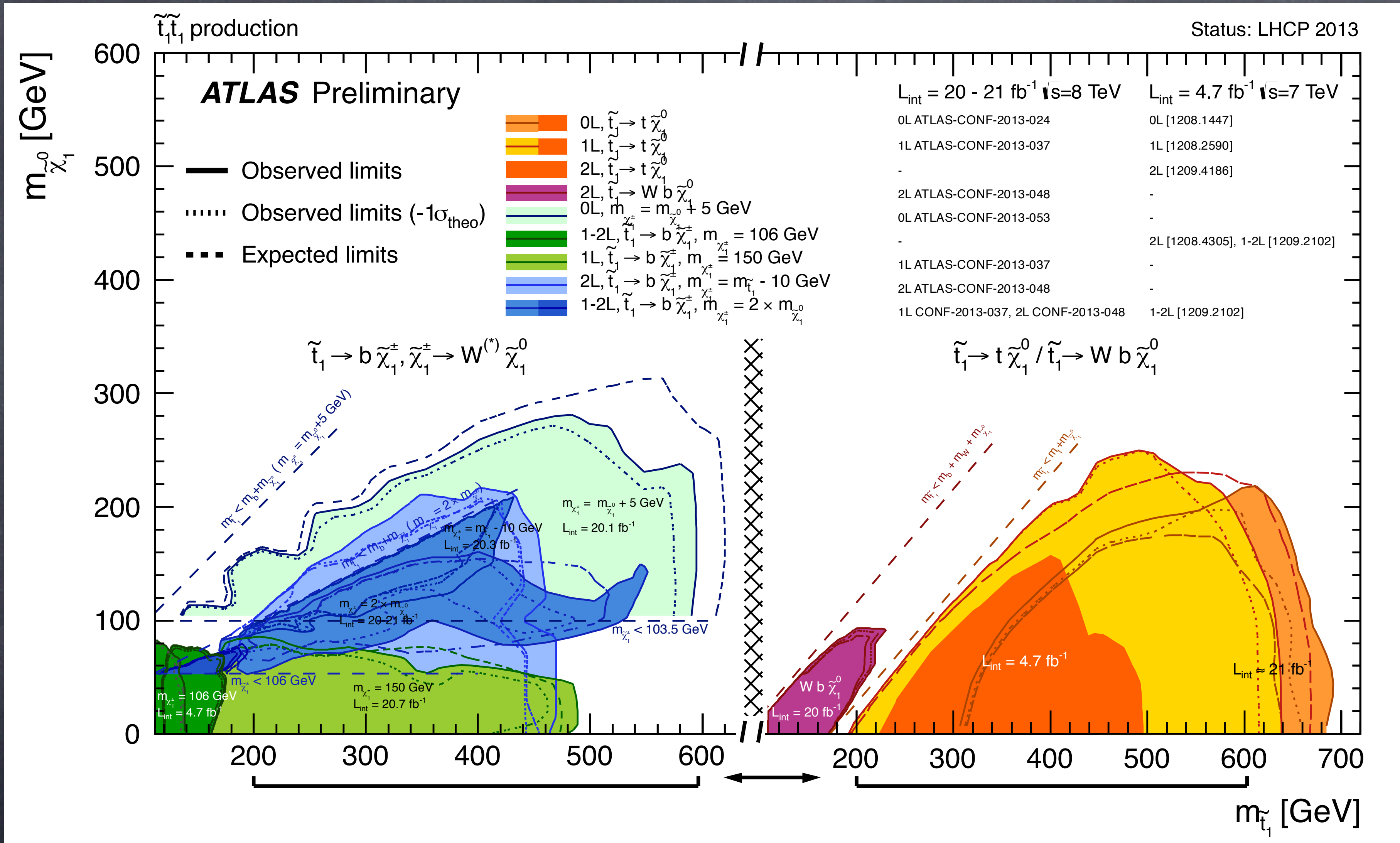
Ways out

- Lower M
- Decouple stop from sup, scharm
- NMSSM

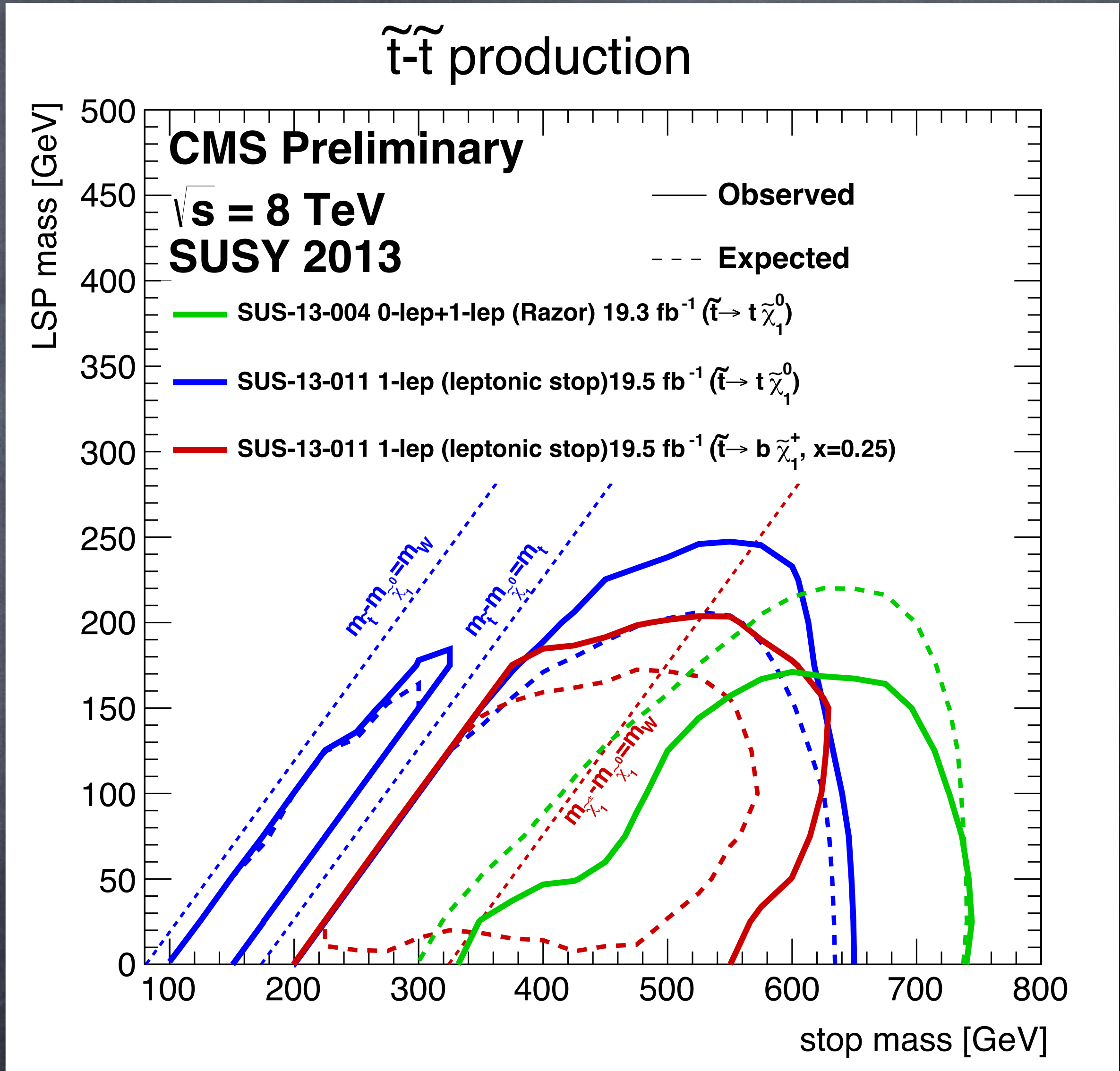
- Dirac gluinos
- Weakly constrained regions
- Give up E_T-miss signature

Give up naturalness

How light can the stop be?



How light can the stop be?

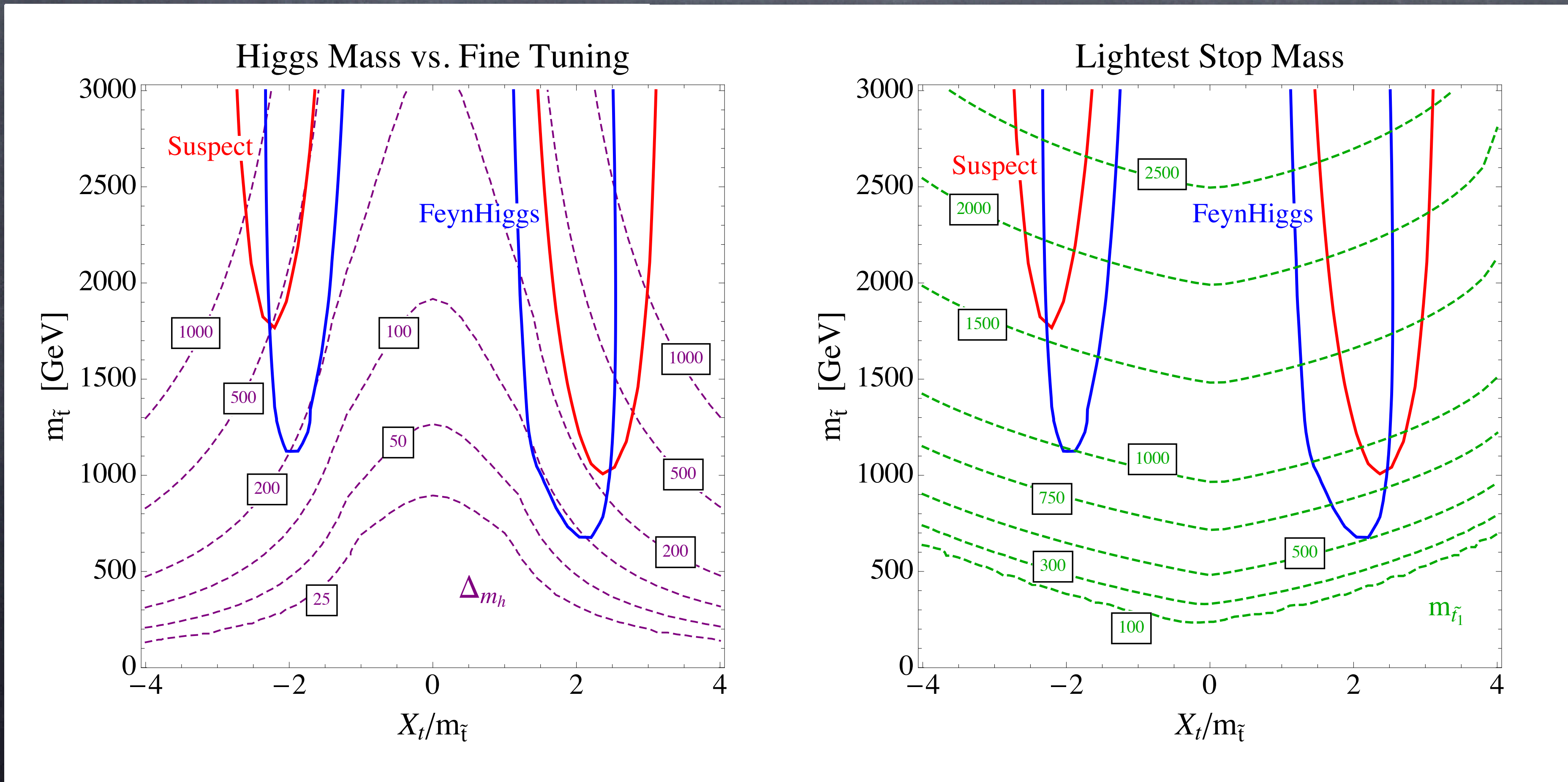


"Light" stops and m_H = 126 GeV

- In the MSSM (only SM superpartners)

$$m_h^2 \leq M_Z^2 \cos^2 2\beta \quad \text{(tree level)}$$

$$m_h^2 = M_Z^2 \cos^2 2\beta + 12 \frac{h_t^2 m_t^2}{(4\pi)^2} \left[\log \frac{\tilde{m}_t^2}{m_t^2} + \ldots \right] \quad \text{(one loop)}$$



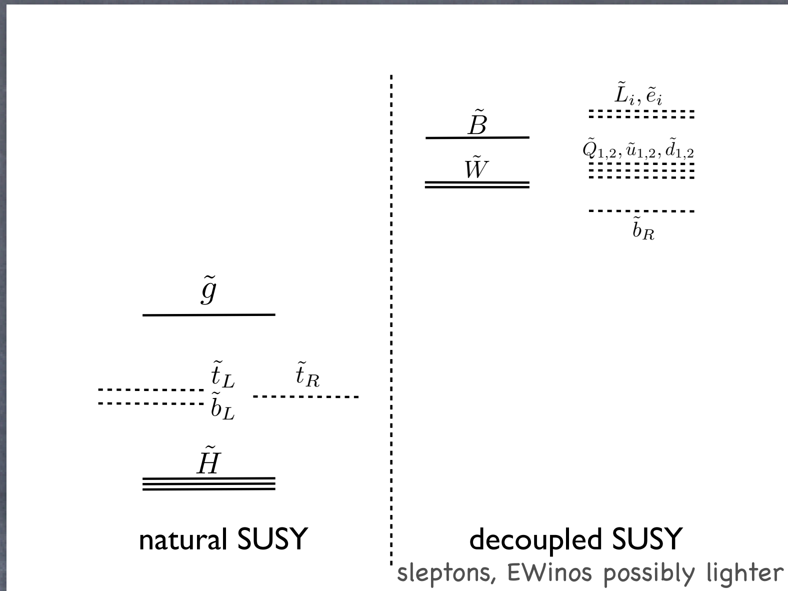
Hall Pinner Rudeman 1112.2703

"Light" stops and m_H = 126 GeV: NMSSM

- Minimal extension: $\lambda S H_u H_d$ (symmetries forbid $\mu H_u H_d$)
  - harmless (unification OK)
  - welcome ($\mu = \lambda \langle S \rangle \approx$ susy scale)
- $m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loops}$

“Natural” values of sparticle masses

- M > 10 TeV + tuning < 10%: (less un)“natural SUSY”
    - $\mu \lesssim 200$ GeV
    - $m_{stop} \lesssim 500$ GeV
    - $M_3 \lesssim 1.4$ TeV



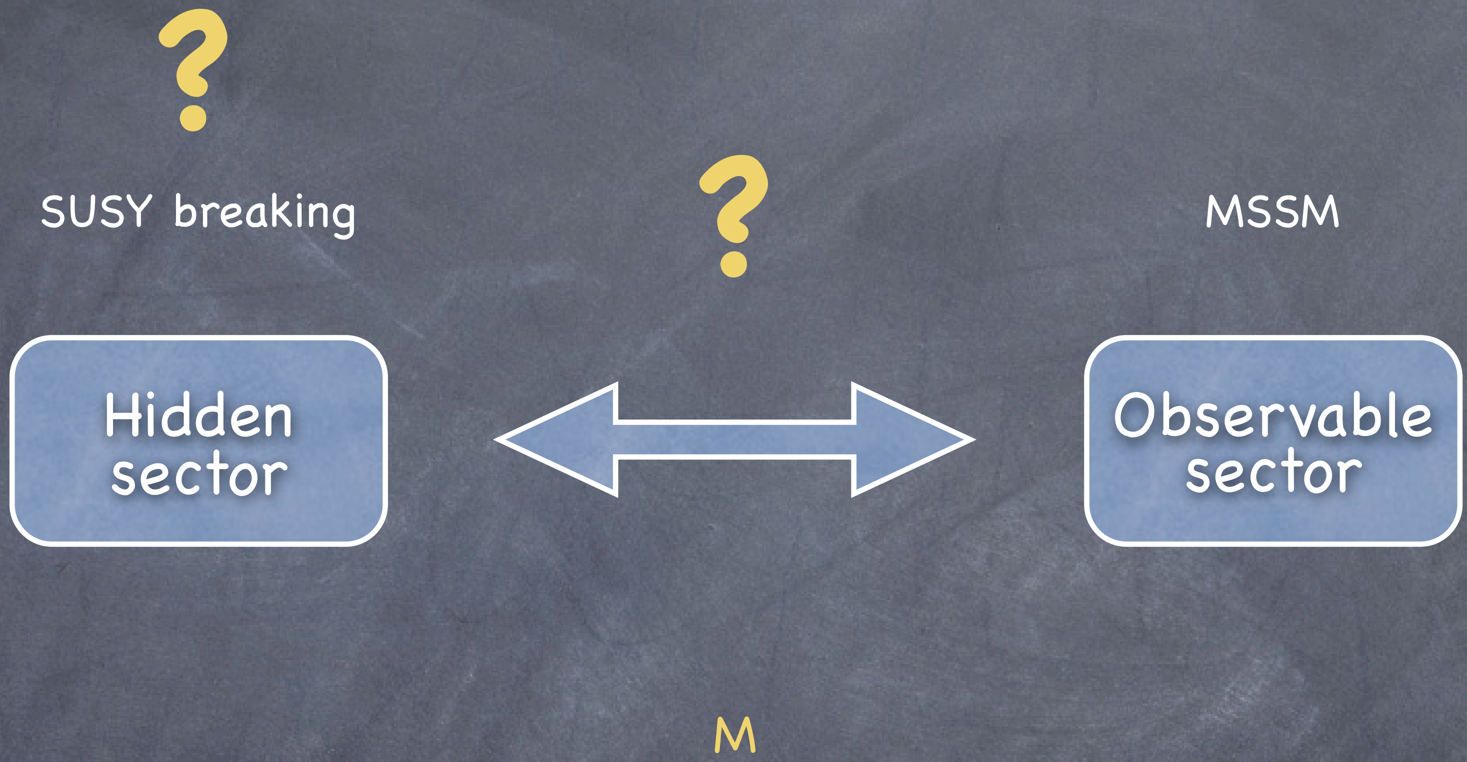
[Papucci Ruderman Weiler]

- Need
    - $(m_3)^2 \ll (m_{1,2})^2$ (by a factor about 5-10)
    - MSSM → NMSSM

A motivated framework

- NMSSM
- With supersymmetry mediated at a low scale M
- And lighter $(m_3)^2 \ll (m_{1,2})^2$ (by a factor about 5-10)

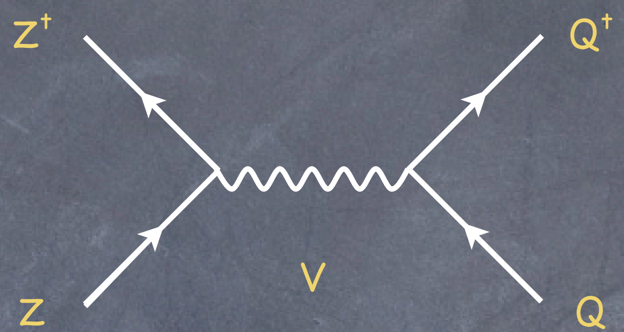
Realizing natural susy?



Tree-level extra U(1) gauge mediation for families 1,2

[Nardecchia R Ziegler]

[Anomalous case: e.g.
Barbieri Ferrara Nanopoulos
Dvali Pomarol]



↑

massive vector of a
spontaneously broken
non-anomalous U(1)
$G \supset G_{SM} \times U(1)$

$Q_{1,2}$ charged under U(1)
Q_3 H NOT charged

$$\tilde{m}^2_{1,2} = q_{1,2}\,\tilde{m}^2$$

third family, Higgs
are loop suppressed

$M \approx M_V$ scale of U(1) breaking

- Ren. Kähler + tree level + $Tr(T_a) = 0$ → $Str\ M^2 = 0$
- Supergravity: non-renormalizable Kähler: $Str \neq 0$ FCNC ?
- "Loop" gauge-mediation: loop-induced: $Str \neq 0$ FCNC OK
- Anomalous U(1)'s: $Tr(T_a) \neq 0$: $Str \neq 0$ FCNC OK
- Tree-level gauge mediation: $Str = 0$ FCNC OK

Need of extra heavy (through U(1) breaking) fields

- Masses^2 (before EWSB)

	MSSM	extra = $\Phi + \bar{\Phi}$
fermions	0	M^2
scalars	$0 + m^2$	$M^2 - m^2$

STr = 0

- Play the role of gauge mediation messengers

- Stop, gluino, and Higgs mass get a (suppressed) mass

- Light Yukawas break U(1): understanding of SM flavour

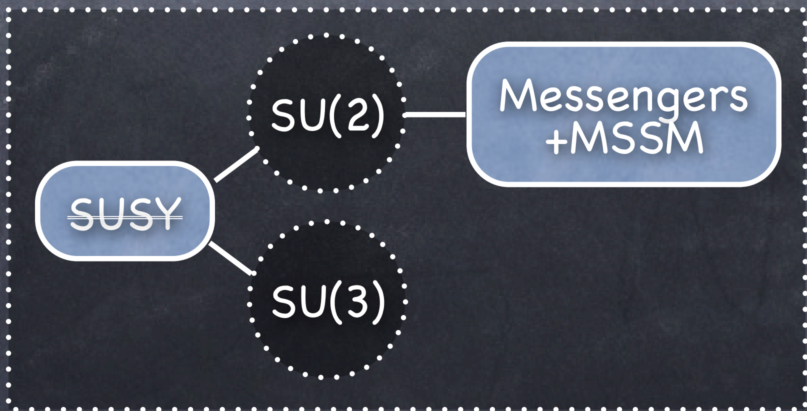
A simple and viable complete model

?

SUSY breaking

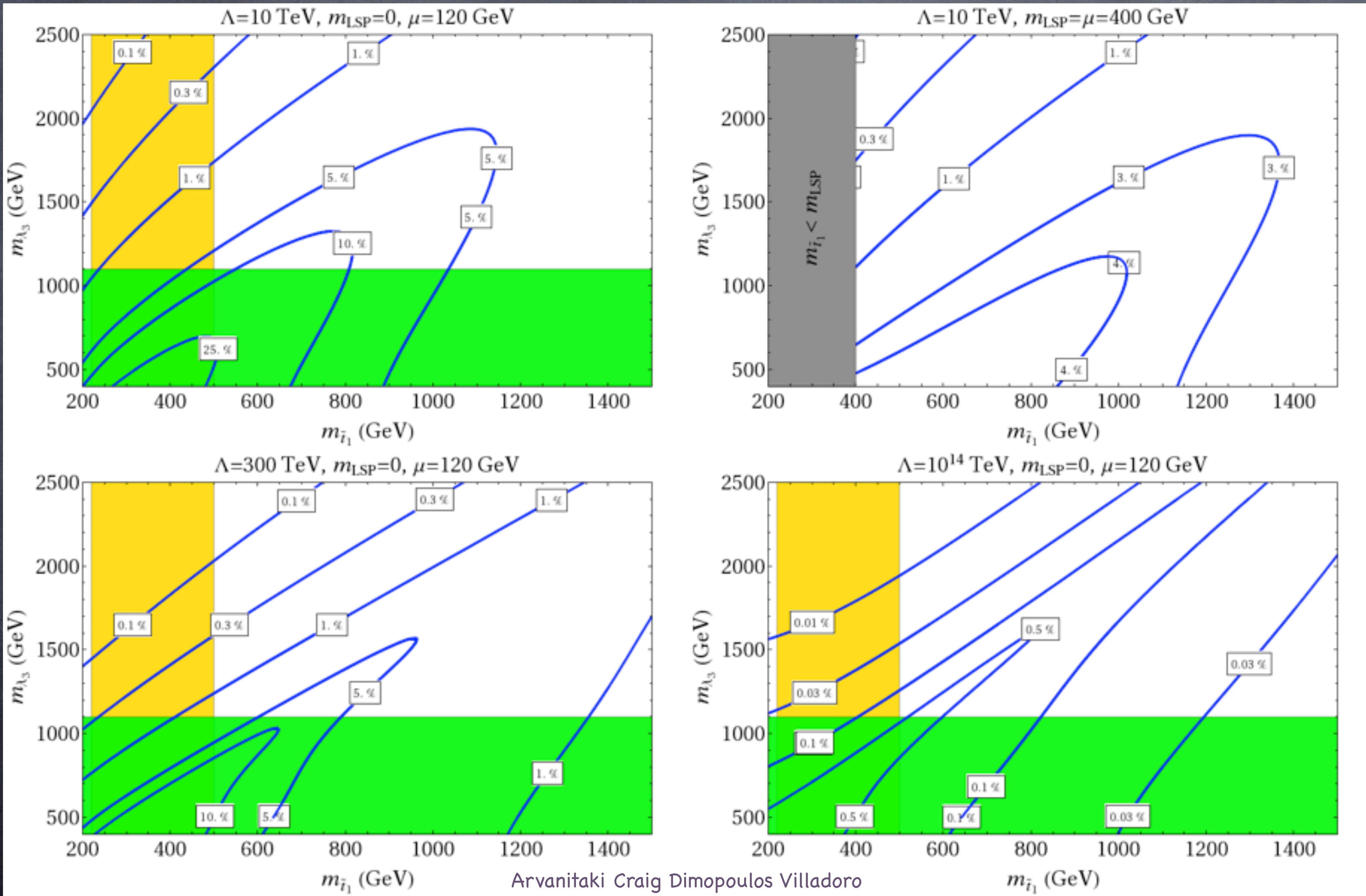
MSSM

M



[Caracciolo R]

Natural susy helps... to some extent



Arvanitaki Craig Dimopoulos Villadoro

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+ experimental constraints
+ indirect bounds from m_H

Ways out

- Lower M
- Decouple stop from sup, scharm
- NMSSM
- Dirac gluinos
- Weakly constrained regions
- Give up E_T-miss signature

Dirac gauginos

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$$\delta \tilde{m}_t^2 = \frac{32}{3}\frac{g_3^2}{(4\pi)^2}M_3^2 \cancel{\log\frac{M}{M_3}}$$

- Sfermion masses super-soft (larger natural M_3)
- Suppress flavour violation
- R-symmetry conserved (useful for theory of susy breaking)
- From N=2 in gauge sector

Dirac gauginos

$$\int d^2\theta \sqrt{2} \frac{W'_\alpha W_j^\alpha A_j}{M} \qquad m_D \sim \frac{\alpha}{4\pi} \frac{D}{M}$$

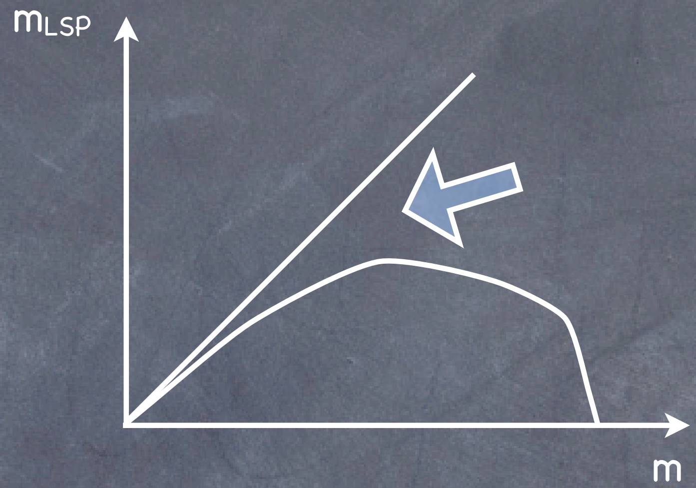
$$\int d^2\theta \frac{W'_\alpha W'^\alpha}{M^2} A_j^2 \qquad \delta \tilde{m}_A^2 \sim \pm \frac{\alpha}{4\pi} \left(\frac{D}{M} \right)$$

- Sfermion masses super-soft (larger natural M_3)
- Suppress flavour violation, prod.
- R-symmetry conserved (useful for theory of susy breaking)
- From N=2 in gauge sector

- μ/Bμ-like issue reintroduces a log(loop) enhancement
- Tachyons?
- Unification prediction spoiled
- Higgs quartic forbidden (extra model-building needed)

Weakly constrained regions of parameter space

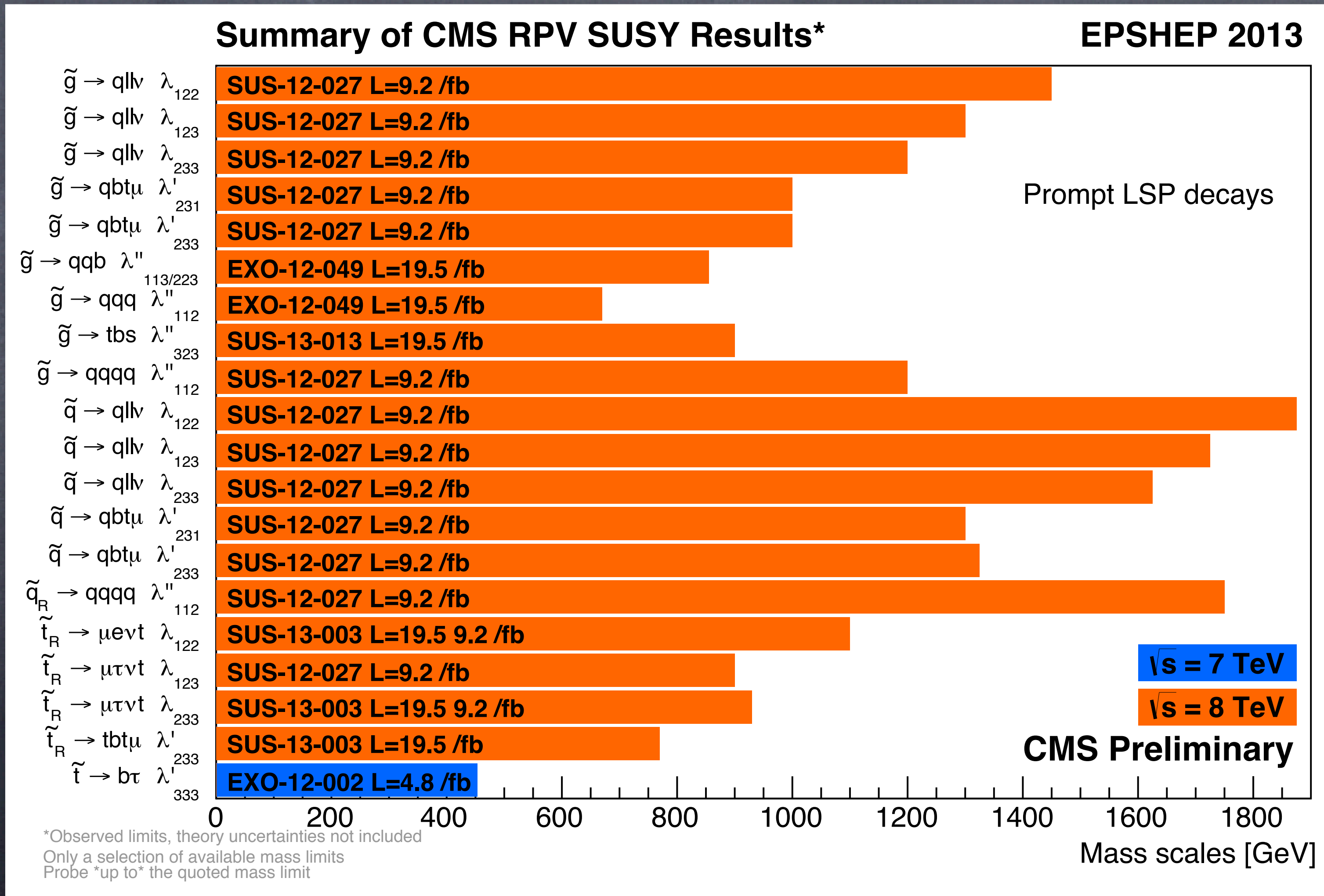
- Compressed spectra



  - reduced activity (small phase space)
  - LSP back to back
  - theory?

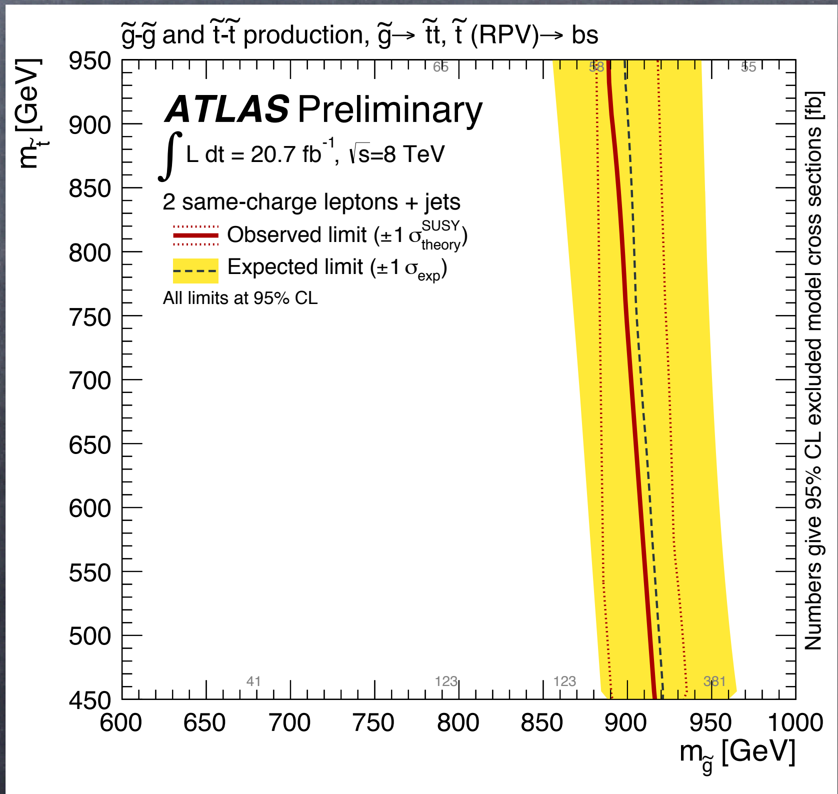
Giving up the E_T-miss signature: RPV

- Baryonic RPV + Leptonic RPV = proton decay
- Leptonic RPV well constrained



Giving up the E_T-miss signature: RPV

- Use baryonic RPV Forbid leptonic RPV
- Need also
  - $m_{3/2}$ > 1 GeV (p-decay) and $m_{3/2}$ < 10 GeV (flavour)
  - $\lambda'' < 10^{-5}$ ($\Delta B = 2$) and $\lambda'' > 10^{-7}$ (prompt decay)
  - M_3 > 0.9 TeV



- Need $$W_{\rm eff}^{\rm ren} = W_{\rm MSSM} + \lambda''_{ijk} u_i^c d_j^c d_k^c,$$

- Unification? $10_i \overline{5}_j \overline{5}_k = u_i^c d_j^c d_k^c + Q_i d_j^c L_k + Q_i L_j d_k^c + E_i^c L_j L_k$

- A solution in SO(10) $$16_i \oplus 16 \oplus \overline{16} \oplus 10$$

$$W_1 = \lambda 16\,16\,10 + \alpha_a \overline{16}\,45_H 16_a + \beta_a 16_H 16_a 10 + M_{16} \overline{16} 16$$

[Di Luzio Nardecchia R]

Giving up the E_T-miss signature: stealth susy

- R_P is conserved
- Lightest Visible Supersymmetric Particle decays into a "hidden sector" singlet with small splitting $\tilde{S} \to S$ + LSP (gravitino)
- Small E_T-miss because of small Δm

How does SUSY compares with competitors?

- Generic composite Higgs is supersoft

$$m_h^2 = \delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

if m_{NP} = mass of first resonances ≈ compositeness scale, as expected

- Compositeness scale > 5 TeV
  - ➥ 1% fine-tuning (comparable with natural susy)

- But $m_h^2 = \delta m_h^2$ needs $(m_{NP})^2 \ll (5\text{TeV})^2$
  - ➥ soft, with M = compositeness scale (better)
  - ➥ tension moves to smallness of $(m_{NP})^2$

Is the naturalness criterium really relevant?

Though general, the naturalness argument rests on assumptions

- the cancellation in the Higgs mass is accidental
  - environmental selection
  - only understanding available for cosmological constant
- existence of superheavy physics
  - maybe there are no dofs much heavier than TeV
  - then quadratic corrections do not matter

No superheavy physics?

Strumia

Neutrino mass models add extra particles with mass M

$$M \lesssim \begin{cases} 0.7\ 10^7\,\text{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model.} \end{cases}$$

Leptogenesis is compatible with FN only in type I.

Axion and LHC usually are like fish and bicycle because $f_a \gtrsim 10^9\,\text{GeV}$. Axion models can satisfy FN, e.g. KSVZ models employ heavy quarks with mass M

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\,\text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\,\text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\,\text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

Inflation does not need big scales and anyhow flatness implies small couplings. Absolute gravitational limit on H_I and on any mass [Arvinataki, Dimopoulos..]

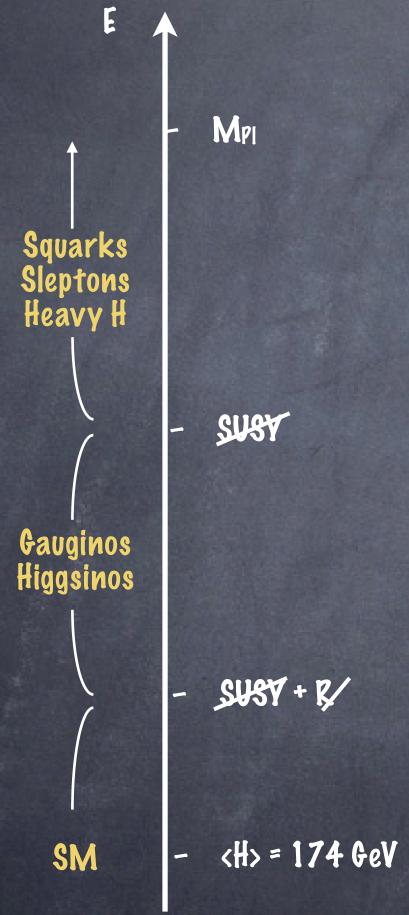
$$\delta m^2 \sim \frac{y_t^2 M^6}{M_{\text{Pl}}^4 (4\pi)^6} \qquad \text{so} \qquad M \lesssim \Delta^{1/6} \times 10^{14}\,\text{GeV}$$

Dark Matter: extra scalars/fermions with/without weak gauge interactions.

- What about gravity? → Adimensional gravity
  - renormalizable gravity + no mass scale inducing physical quadratic corrections
  - (but a ghost)
  - r ≈ 1.3

Giving up naturalness: Split Supersymmetry

[Arkani-Hamed Dimopoulos
Giudice R
Arkani-Hamed Dimopoulos Giudice R]



- $m^2_h \ll \delta m^2_h$ accidentally or because of unspeakable reasons
- Dark matter and unification keep part of spectrum near TeV

An (almost) troubleless MSSM

- Issues
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs (SUSY breaking mechanism, symmetries)
  - Proton decay from dimension 5 operators (non minimal models)
  - Gravitino and moduli problem (low reheating T)
  - Fine-tuning (NMSSM)

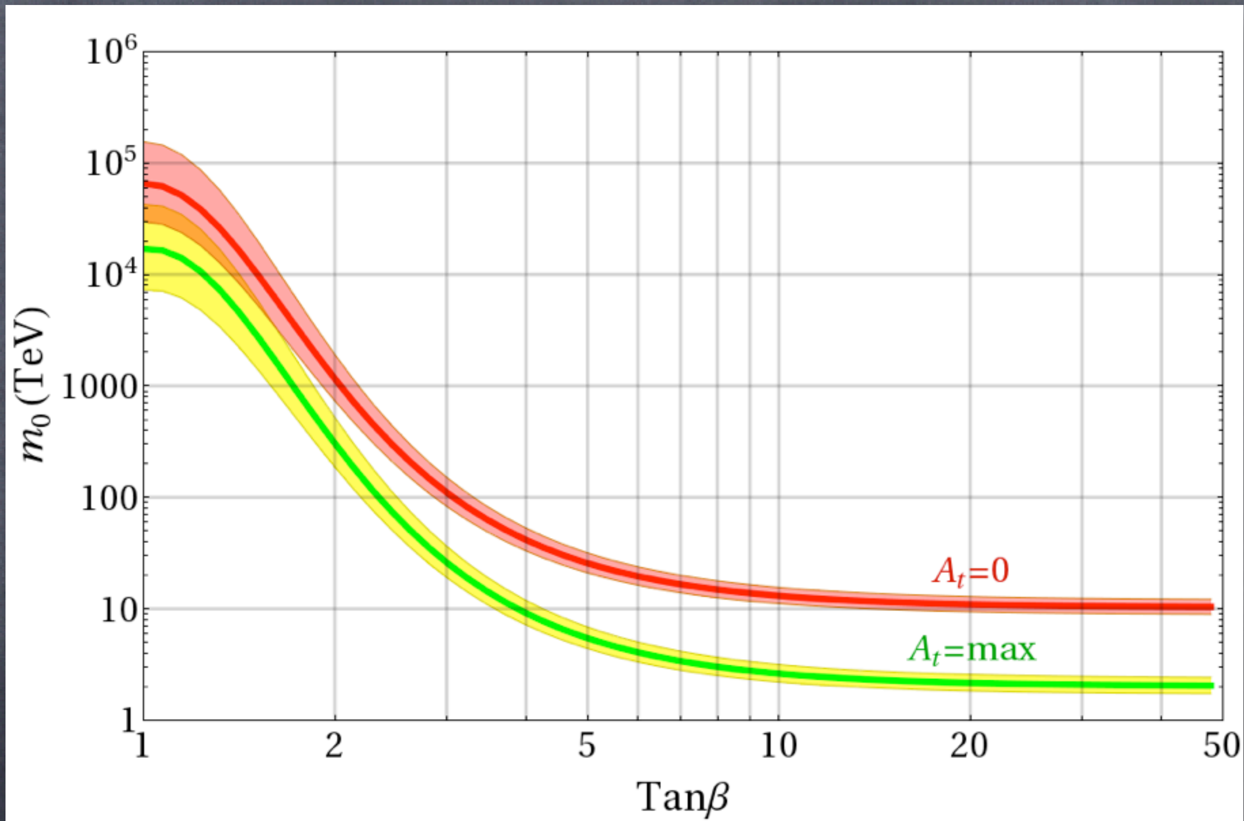
  } scalars

- Successes of the MSSM
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)

  } fermions

Back to the MSSM

Sfermion (stop) masses from m_H = 126 GeV

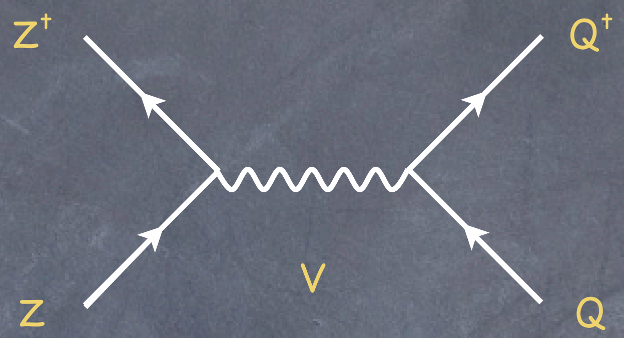


Arvanitaki Craig Dimopoulos Villadoro

Tree-level extra U(1) gauge mediation for ALL families

[Nardecchia R Ziegler]

[Anomalous case: e.g. Barbieri Ferrara Nanopoulos Dvali Pomarol]



↑

massive vector of a spontaneously broken non-anomalous U(1)

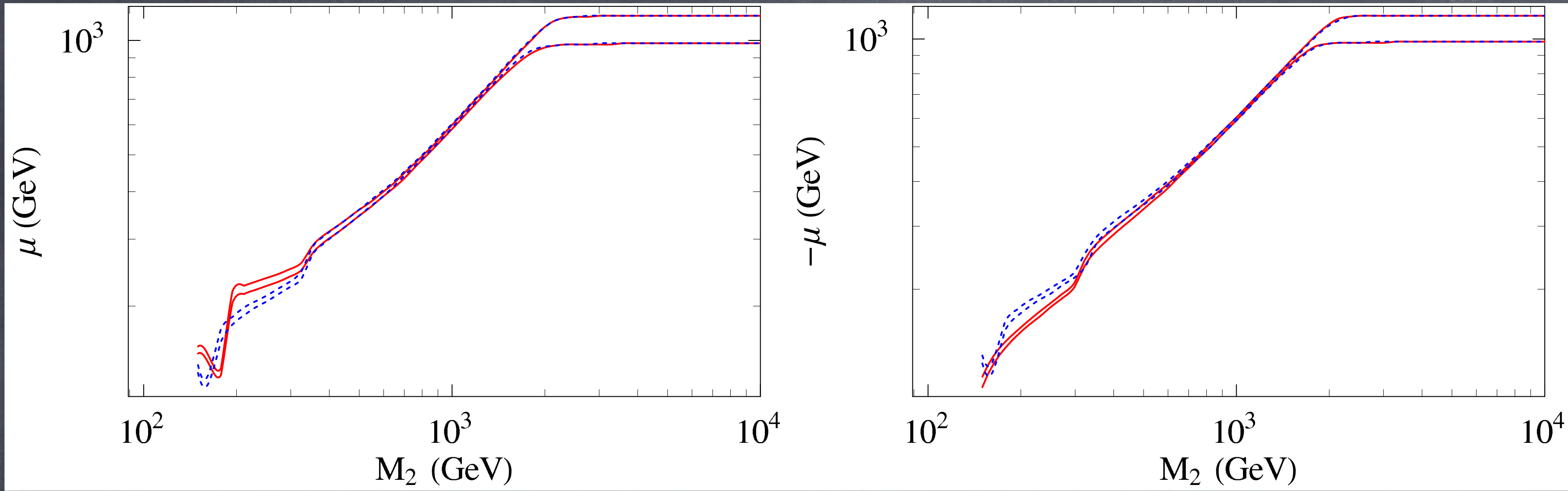
$G \supset G_{SM} \times U(1)$

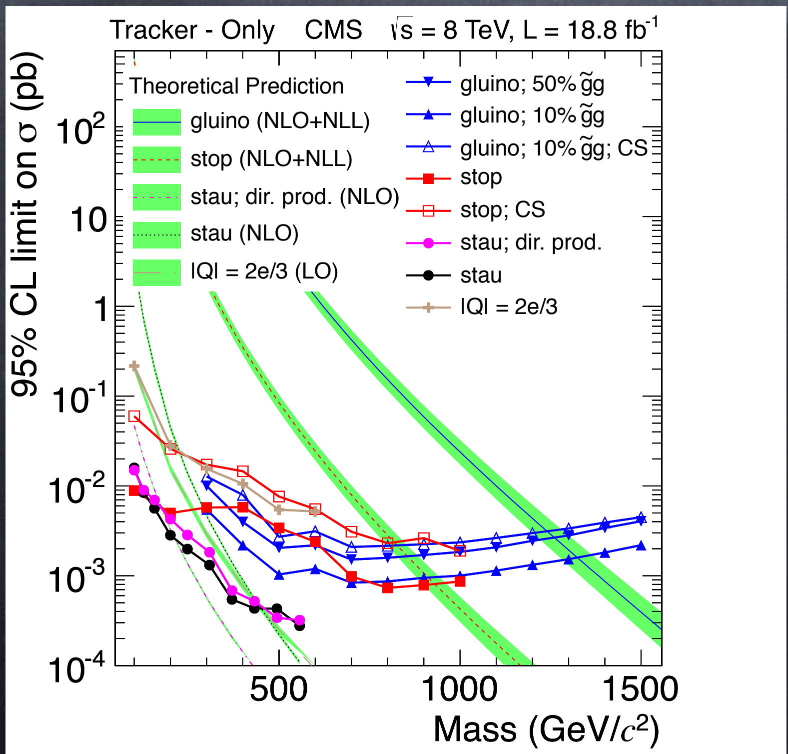
$$\tilde{m}_f^2 = q_f\, \tilde{m}^2$$

$$M_g \sim \frac{\alpha}{4\pi} \frac{k}{h} \frac{F}{M}$$

$M \approx M_V$ scale of U(1) breaking

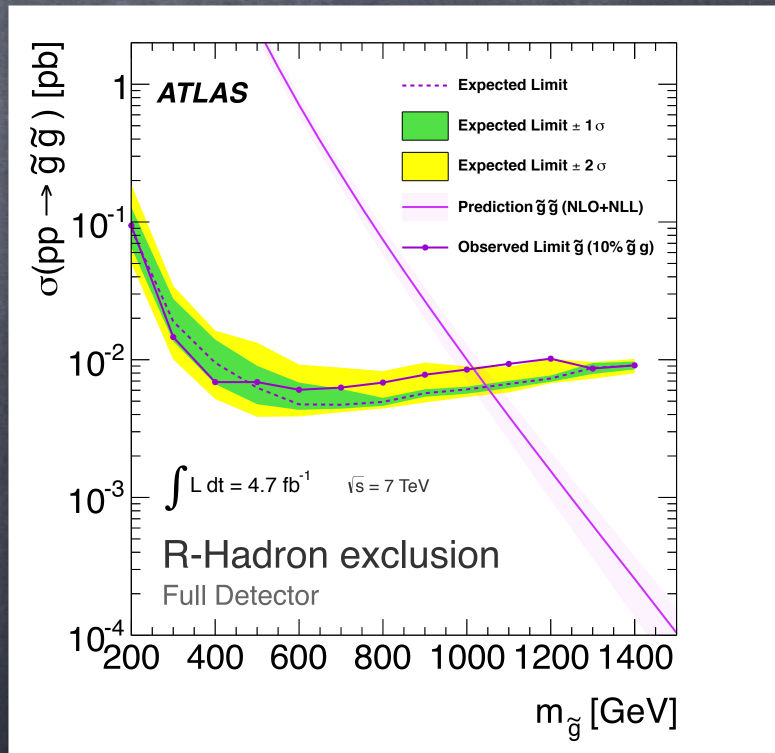
Expectations and constraints





Gaugino unification

$M_3 \approx 3.5\ M_2$



In conclusion

- Maybe Nature is telling us something about NP and SUSY in particular...
- At least, NP is not vanilla supersymmetry
- Perhaps NP is not natural
- Hopefully, unlike the Higgs, is unexpected
- Looking forward to 8 TeV → 13/14 TeV