Naturalness after the first run of the LHC

Galileo Galilei Institute
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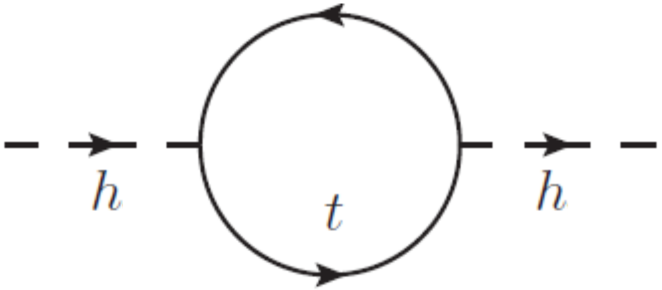
Naturalness in trouble?

Naturalness is now in trouble, two measurements:

- top is heavy $M_t \approx 173\,\mathrm{GeV}$
- Higgs is light $M_h \approx 126\,\mathrm{GeV}$



$$\delta m_h^2 \approx \delta m_h^2(\text{top loop}) \approx \frac{12\lambda_t^2}{(4\pi)^2}\Lambda_{\rm NP}^2 \times \begin{cases} 1 \\ \ln M_{\rm Pl}^2/\Lambda_{\rm NP}^2 \end{cases}$$

$$\delta m_h^2 \lesssim M_h^2 \times \Delta \qquad\qquad \Lambda_{\rm NP} \lesssim \sqrt{\Delta} \times \begin{cases} 400\,\mathrm{GeV} \\ 50\,\mathrm{GeV} \end{cases}$$

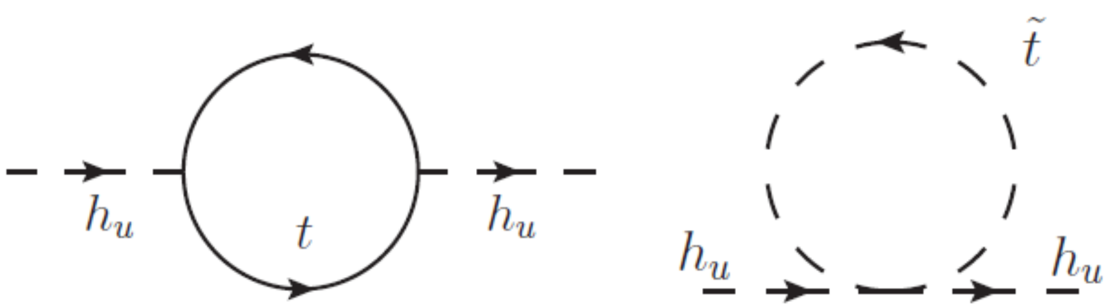
Top partners?

The biggest issue is in the third generation.
Bottom up approach with Higgs+top+top partners:

- Assume mass of the form $m^2(T_i) = m_{0,i}^2 + c_i h^2 + \cdots$

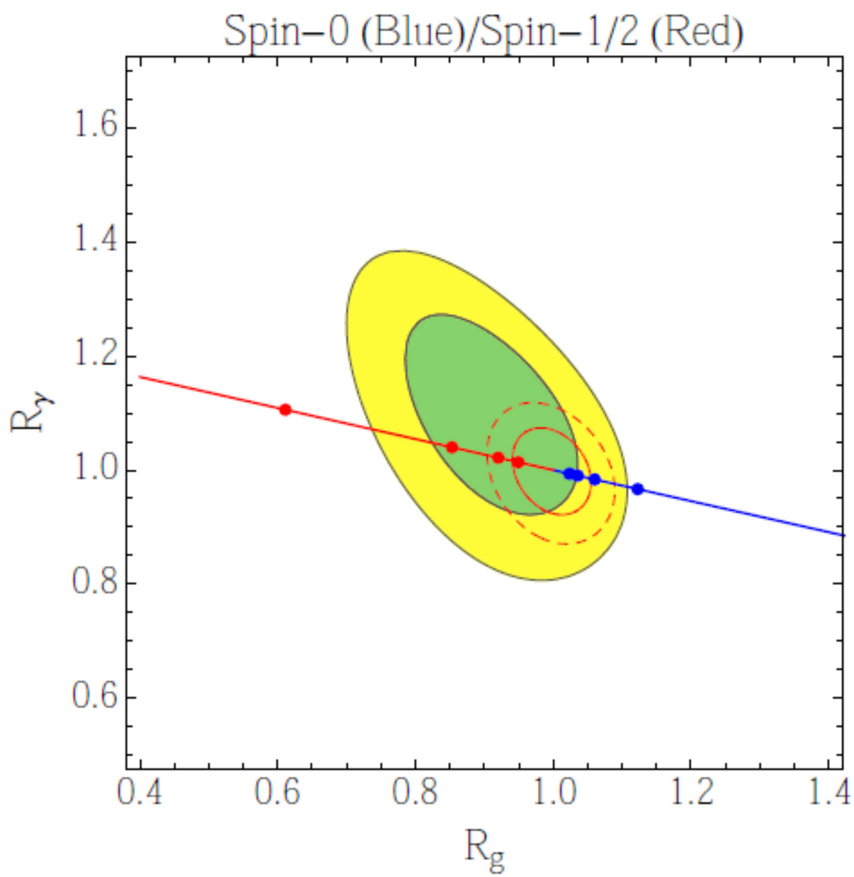
  Can be spin-0 (SUSY), spin-1/2 (Little Higgs, etc.)

- Cancelling quadratic divergences ⇨ $6y_t^2 = \sum_i g_i(-1)^{F_i} c_i$



Top partners?

Low-Energy Theorems relate to Higgs couplings:



$$\mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v} C_\gamma h F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} C_g h G_{\mu\nu} G^{\mu\nu}$$

$$C_\gamma \approx 1 + \frac{3}{4}\sum_f \frac{N_{c,f} Q_f^2 c_f v^2}{m_{0,f}^2 + c_f v^2} + \frac{3}{16}\sum_s \frac{N_{c,s} Q_s^2 c_s v^2}{m_{0,s}^2 + c_s v^2}$$

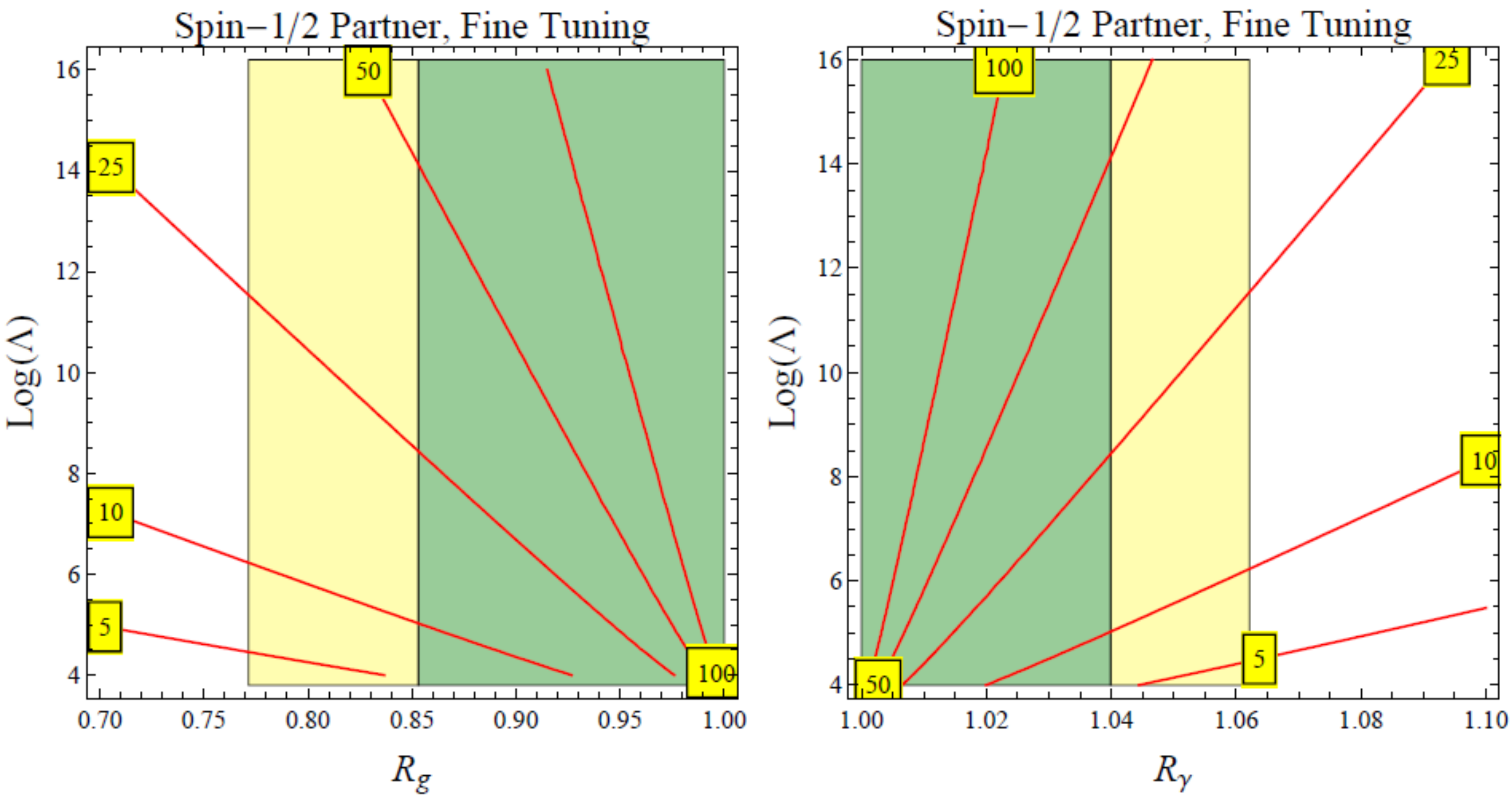
$$C_g \approx 1 + 2\sum_f \frac{C(r_f) c_f v^2}{m_{0,f}^2 + c_f v^2} + \frac{1}{2}\sum_f s\frac{C(r_s) c_s v^2}{m_{0,s}^2 + c_s v^2}$$

14 TeV Data from Peskin 1207.2516

MF, M. Perelstein, N. Rey-Le Lorier 1305.6068

Top partners

We can now put together (log) FT and Higgs couplings. E.g. spin-1/2 partner



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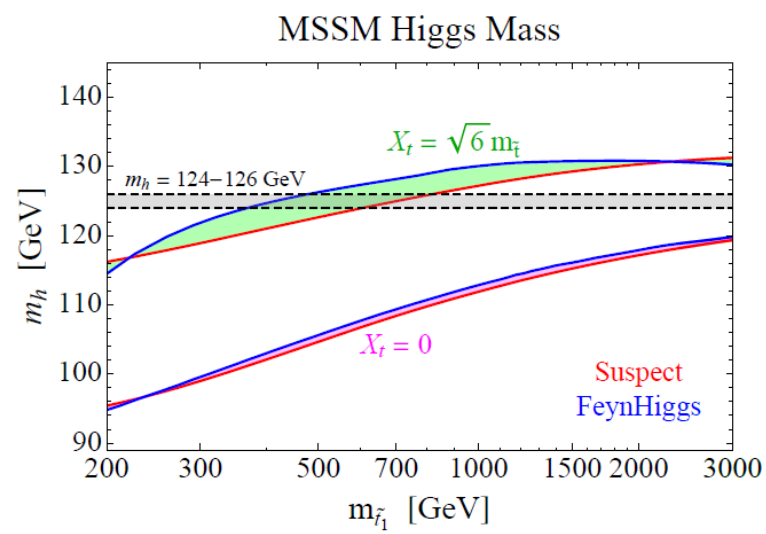
SUSY and the Higgs mass

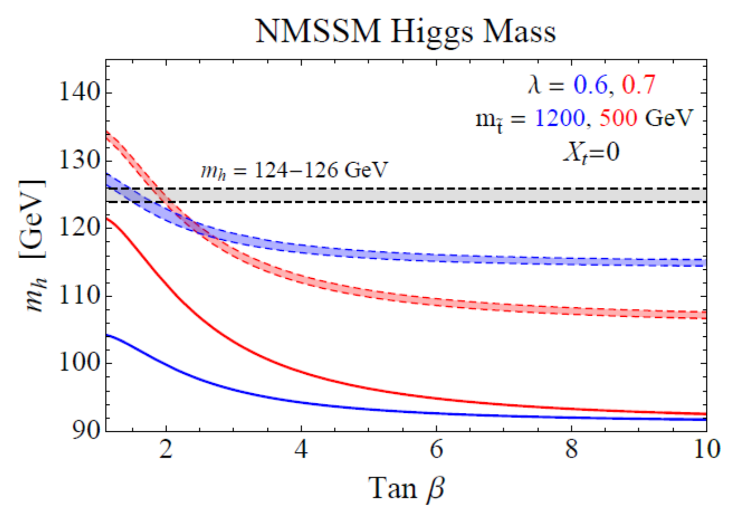
$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

Different ways to get 125 GeV:

- heavy stops
- large stop mixing
- extended scalar sector (NMSSM)

$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|$$





Hall, Pinner, Ruderman 1112.2703

Stops and Naturalness

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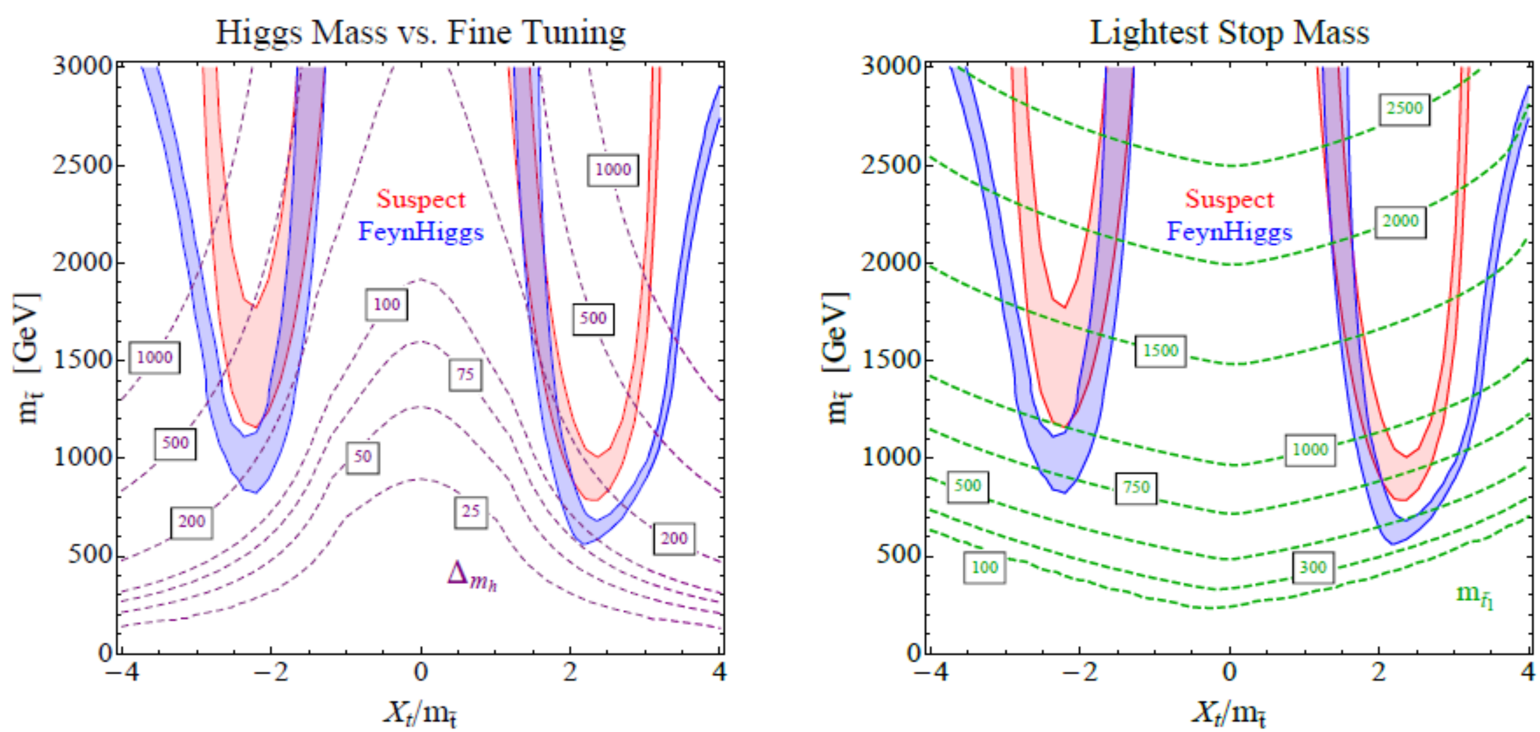
If too large ⇨ tuned parameters to get correct EWSB scale

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$



Hall, Pinner, Ruderman
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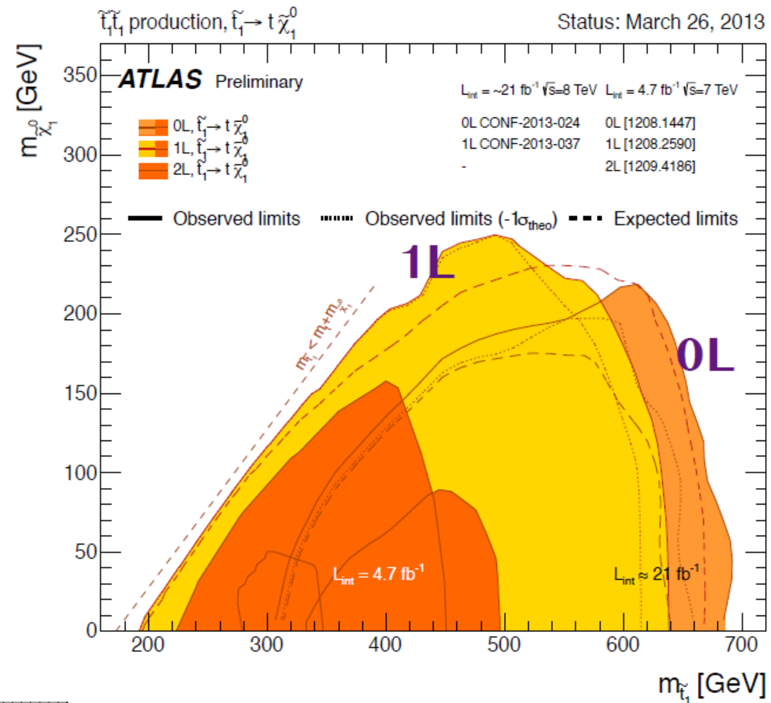
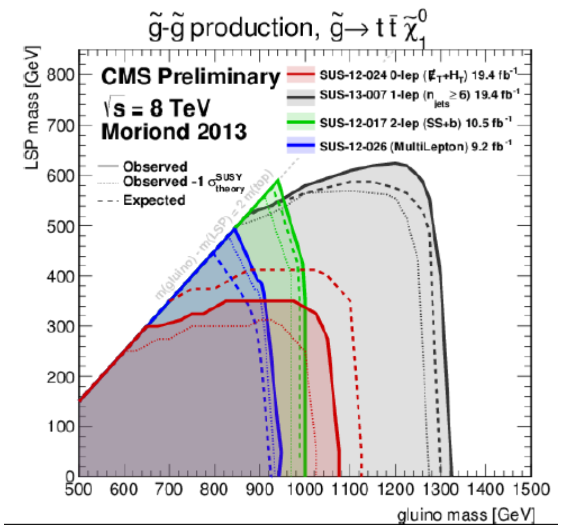
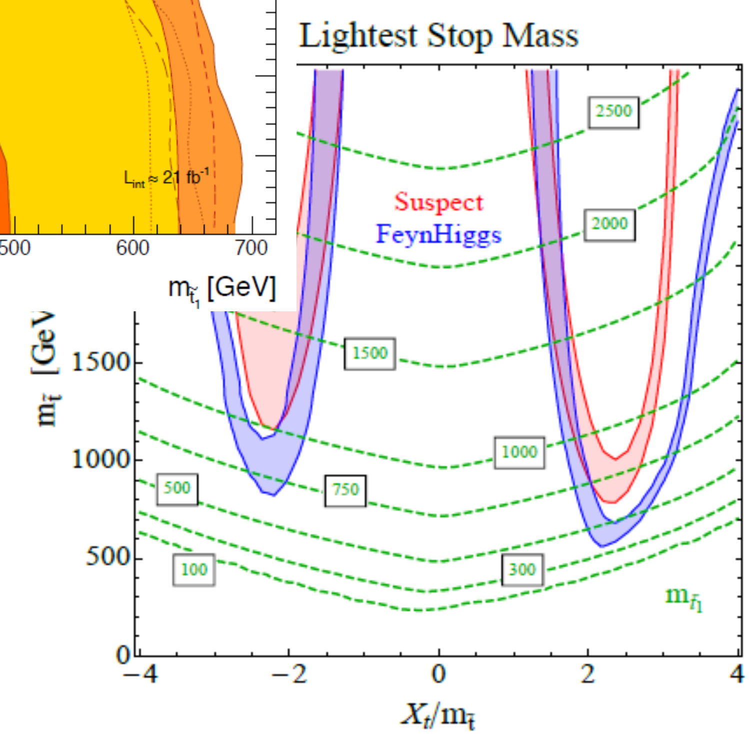
Stops and Naturalness



$$m_{\tilde{g}} \lesssim 2 m_{\tilde{t}}$$





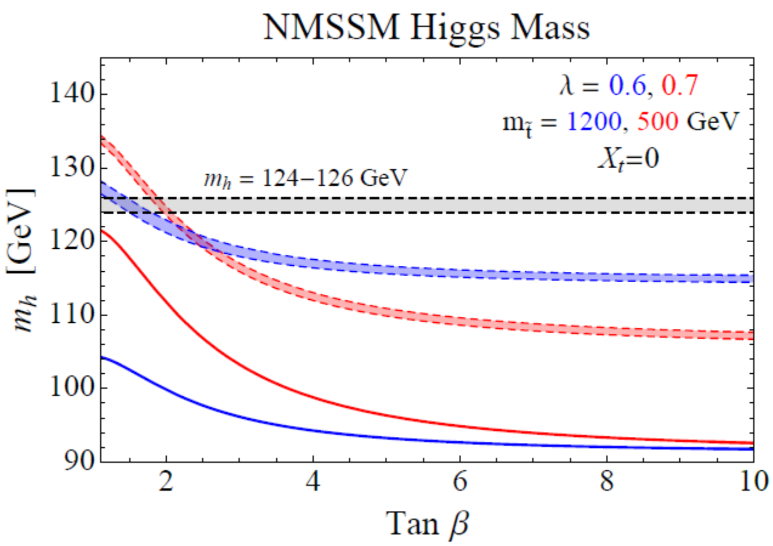
Hall, Pinner, Ruderman
1112.2703

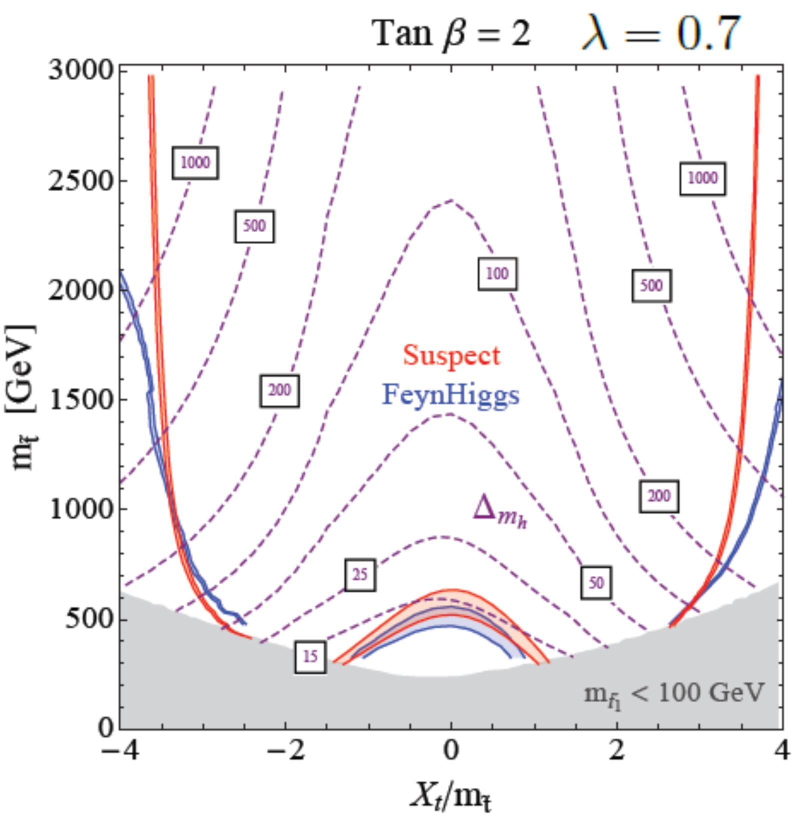
Is the NMSSM the solution?

Add a singlet

$$W_{NMSSM} = \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

$$(m_h{}^2)_{\rm tree} \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$





Hall, Pinner, Ruderman
1112.2703

Enlarge your λ

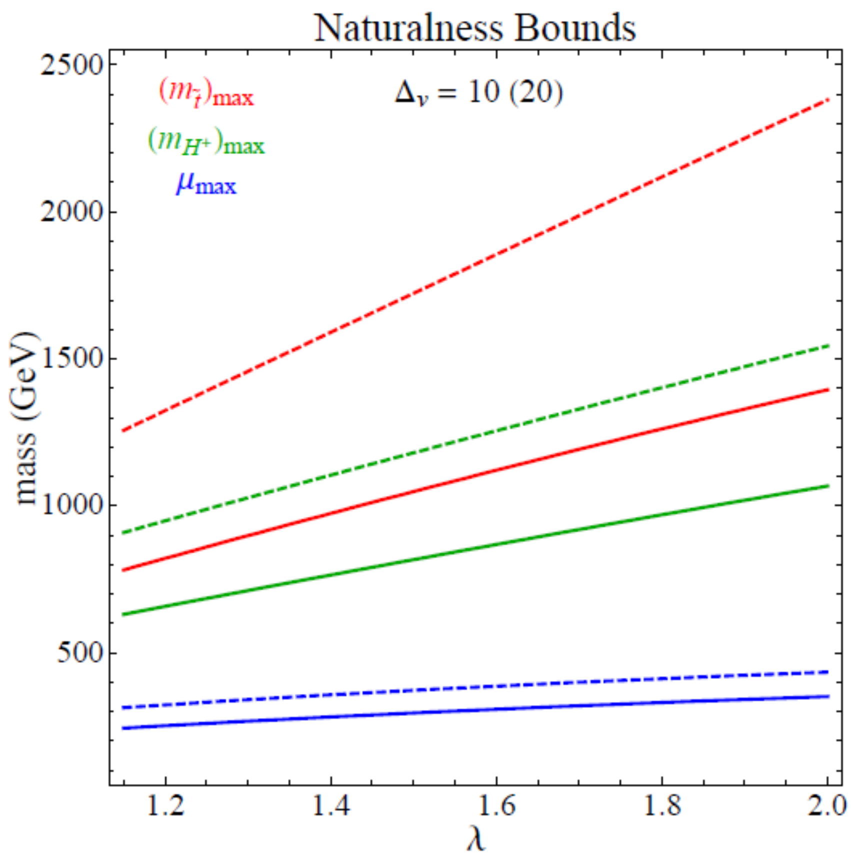
So far:

- MSSM: stop tuning ~1%
- NMSSM: ~5%

Why don't we push it further?

λ-SUSY:

- perturivity lost before ~10 TeV if λ>2
- Higgs mass naturally ~λv up to 350 GeV



Hall, Pinner, Ruderman
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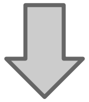
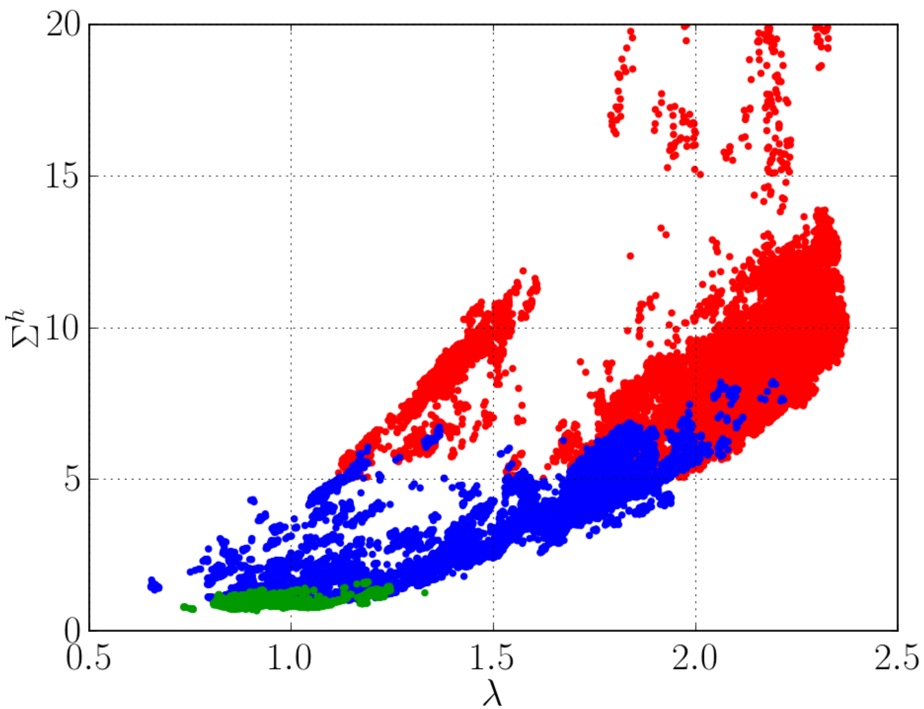
Enlarge your λ

λ-SUSY:

- perturivity lost before ~10 TeV if λ>2
- Higgs mass naturally ~λv up to 350 GeV
- observed Higgs mass obtained by mixing with the singlet

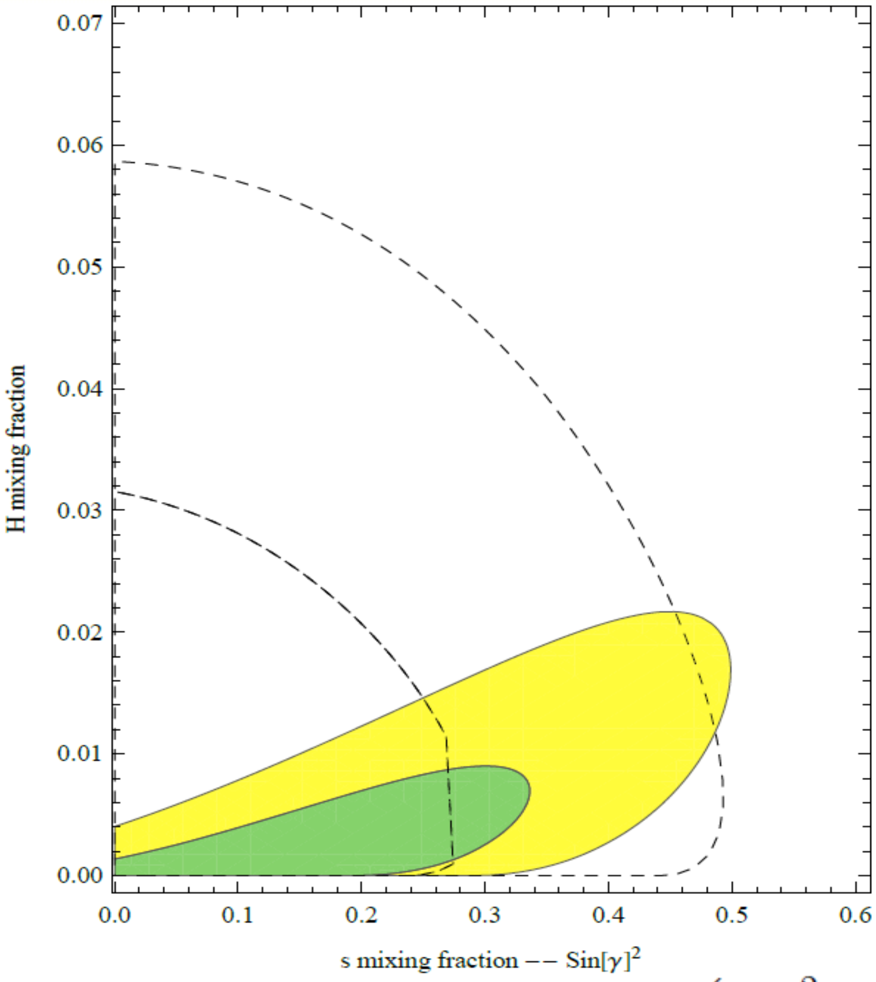


Fine Tuning!



Gherghetta et al. 1212.5243

Missing Ingredient

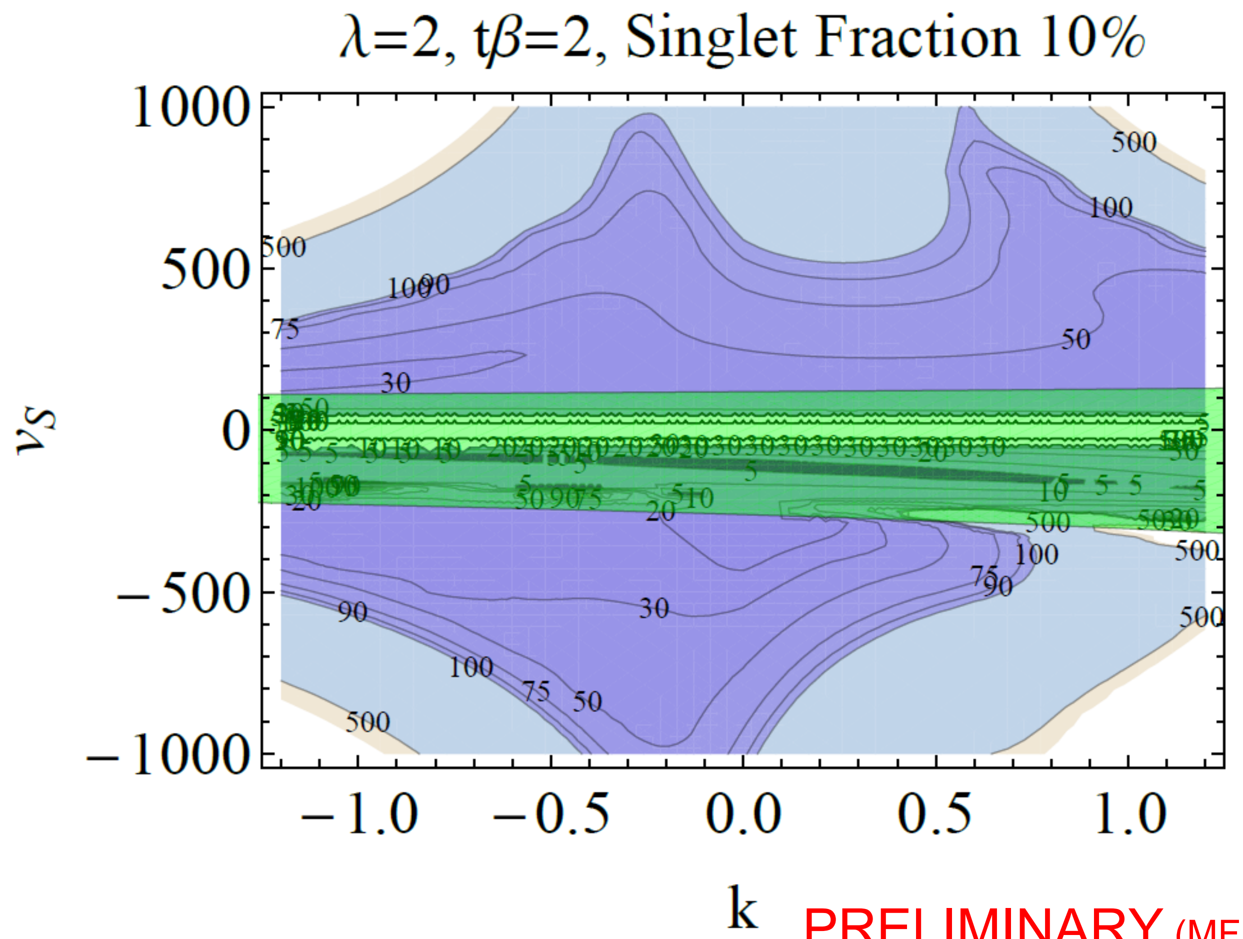


- Mixing with H is ~few %
- Can describe the problem with just (h,s)

$$\begin{pmatrix} \mathcal{M}^2_{11} & \mathcal{M}^2_{13} \\ \mathcal{M}^2_{31} & \mathcal{M}^2_{33} \end{pmatrix} = \begin{pmatrix} \lambda^2 v^2 & 2\lambda^2 sv - (2\lambda\kappa sv + \lambda A_\lambda v) \\ \cdot & 4\kappa^2 s^2 + A_\kappa \kappa s + \frac{v^2}{2s} A_\lambda \lambda \end{pmatrix}$$

Fine tuning

- After fixing Higgs mass and singlet fraction only two free parameters left

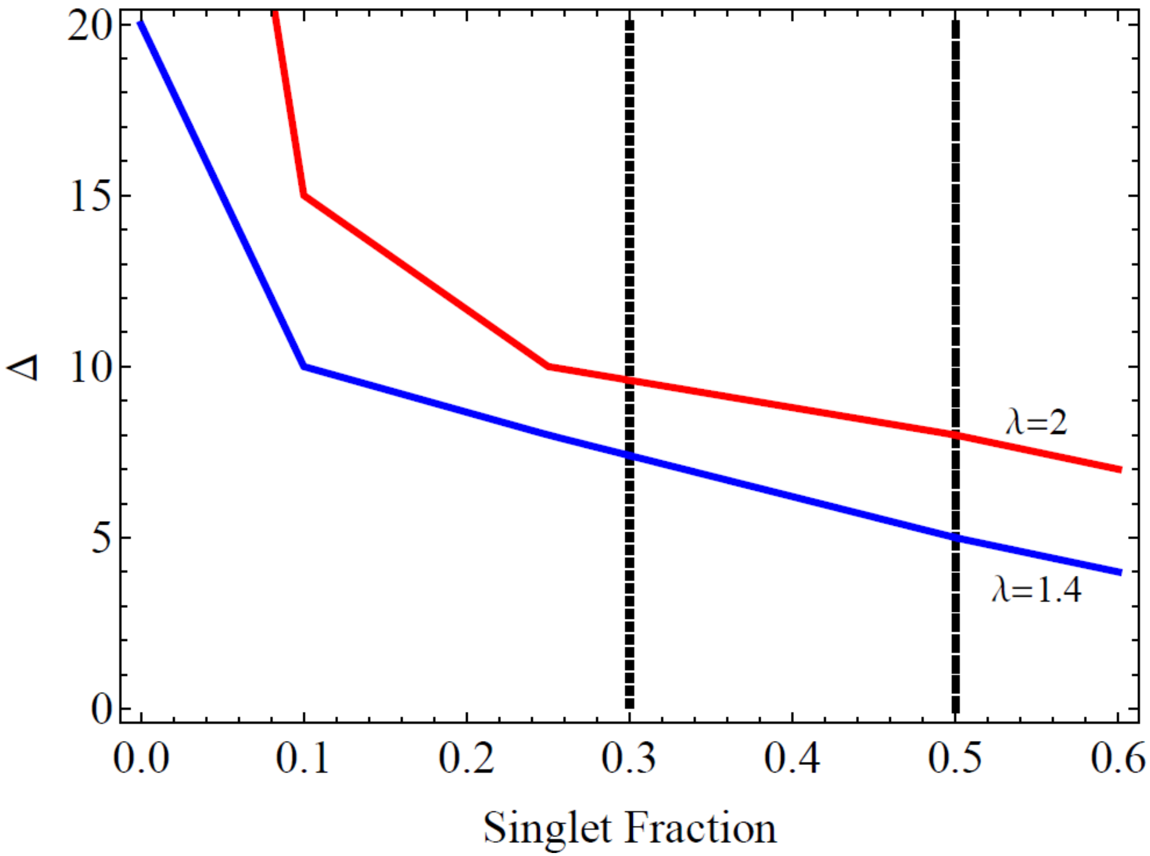


PRELIMINARY (MF, M. Perelstein, B. Shakya)

FT vs Singlet Fraction

- Singlet fraction is a crucial parameter
- Mixing necessary for lowering mass

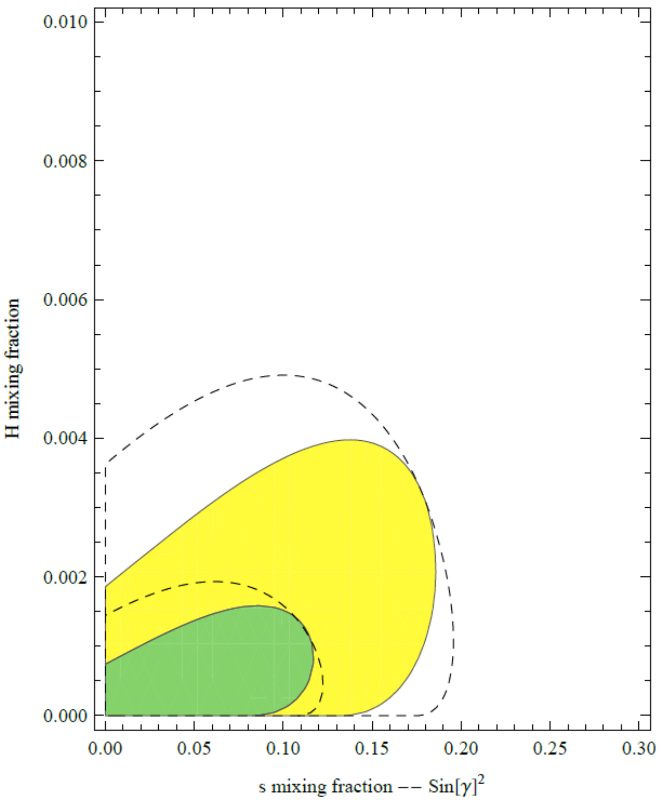
Large Mixing constrained by data

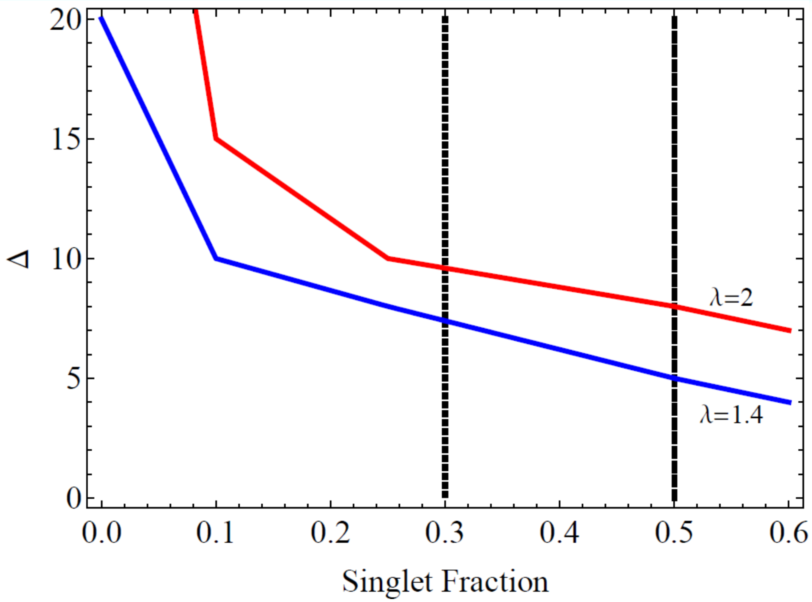


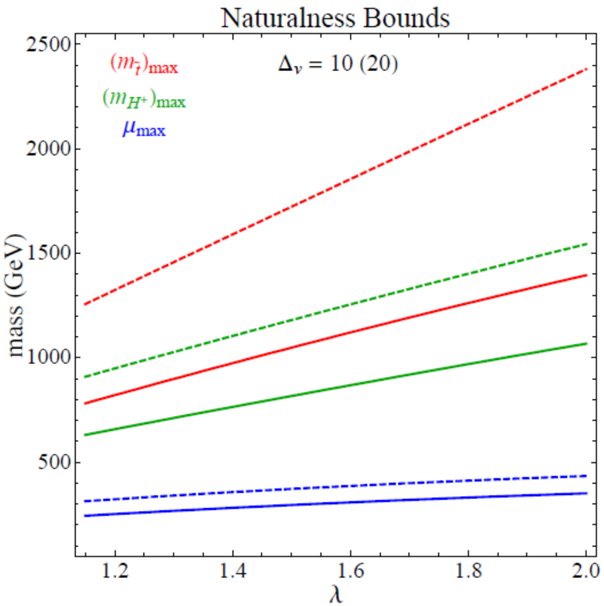
PRELIMINARY ((MF, M. Perelstein, B. Shakya)

Future?

LHC at 14 TeV with 300 fb^{-1}

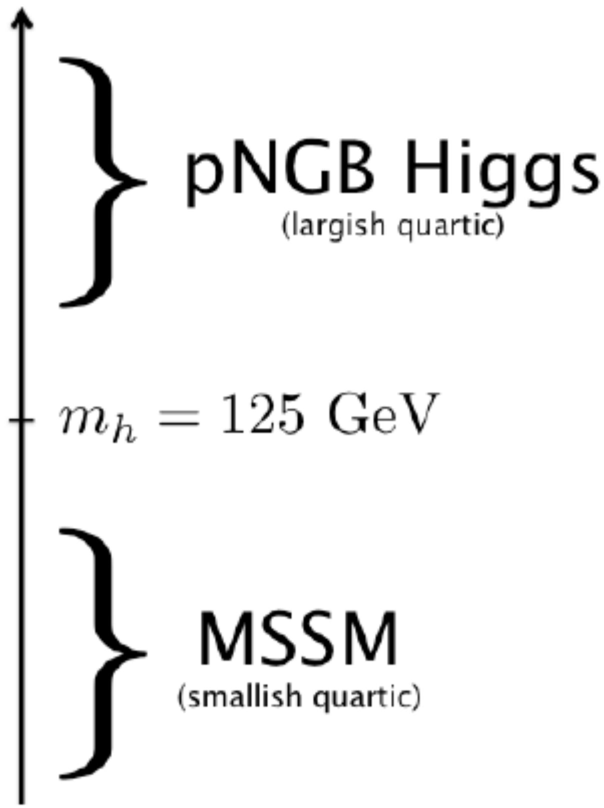






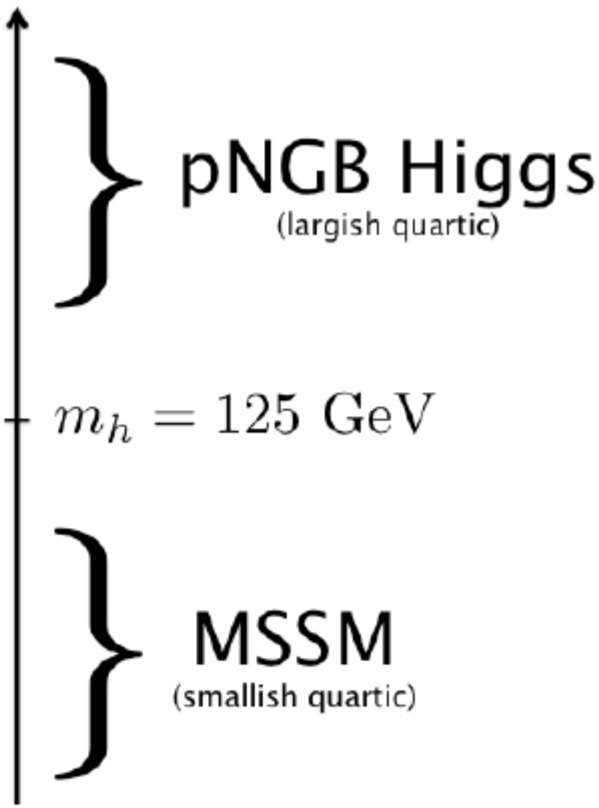
Data from Peskin 1207.2516

Beyond SM vs Naturalness



- **MSSM**: tuning at ~1% or worse
- **NMSSM & λ-SUSY**: ~5-10%
- **pNGB Higgs**: no sign of strong sector, mh too light. FT ~few %
  (FT~v/f and f~few TeV)
- **Top Partners:** ~15% ?

Beyond SM vs Naturalness



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- **Top Partners:** ~15% ?

What if there is only the SM?

Is nature natural?

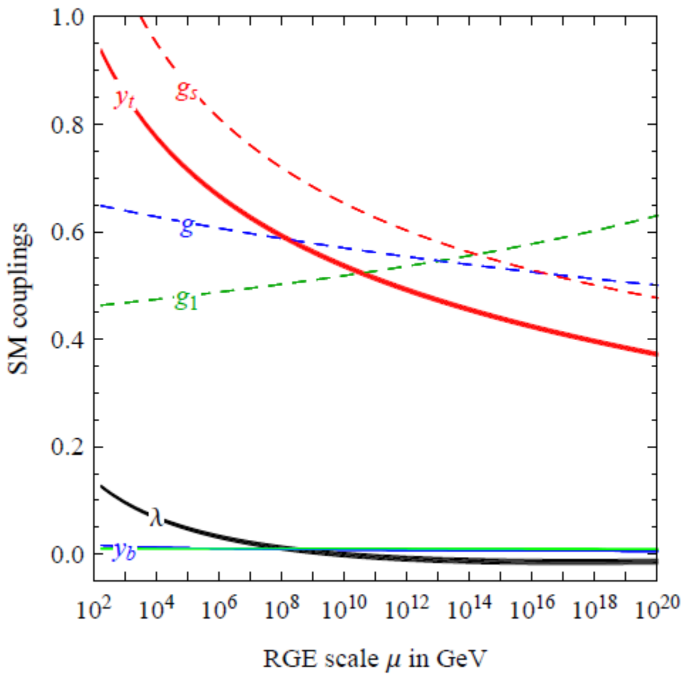
from Strumia talk @ Brookhaven

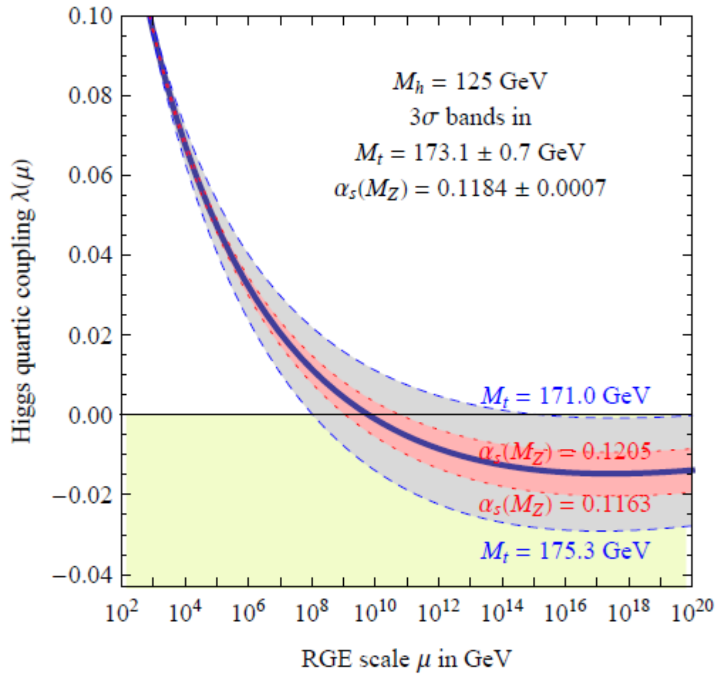
Two (?) roads in front of us:

- **Naturalness**: in trouble.
- **Fine Tuning**: Higgs mass light due to antropic principles.

SM: stability?

- Experimentally now we know $\lambda \approx 0.13, \; y_t \approx 1$
- All SM parameters are measured and beta functions determined



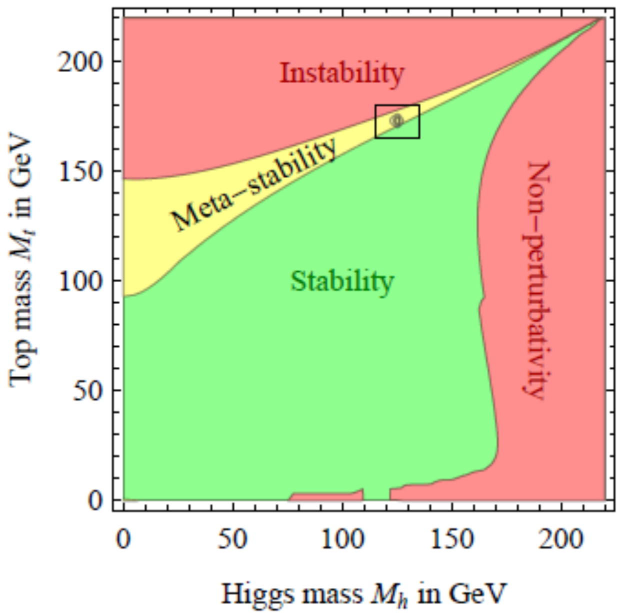


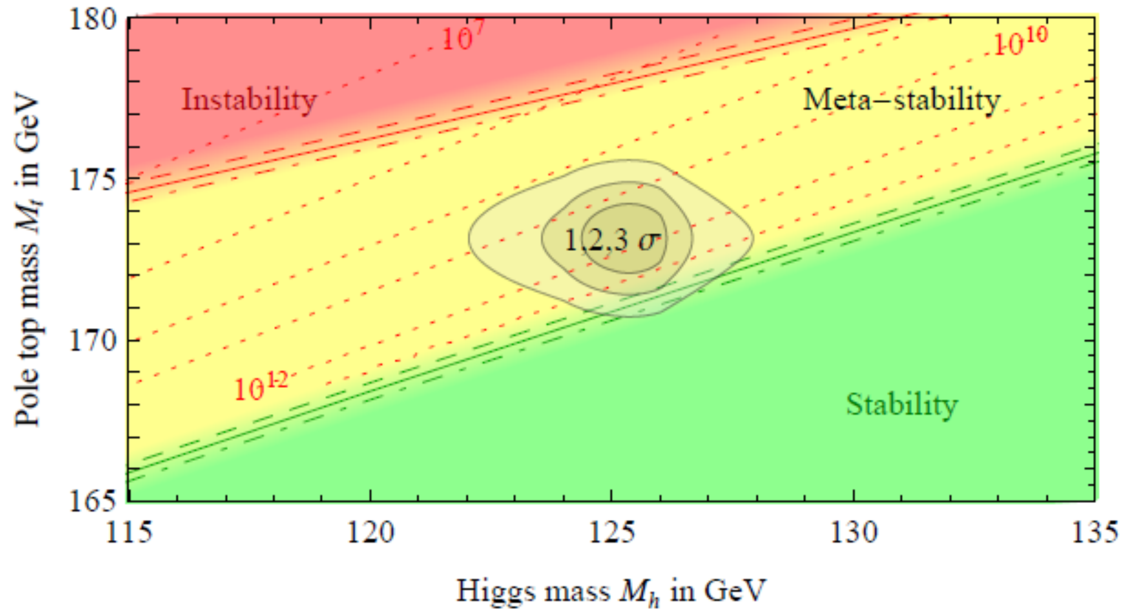
Degrassi et al. 1205.6497

SM: stability

- Second minimum when λ<0

$$V = \lambda(|H|^2 - v^2)^2 \approx \frac{\lambda}{4} h^4$$



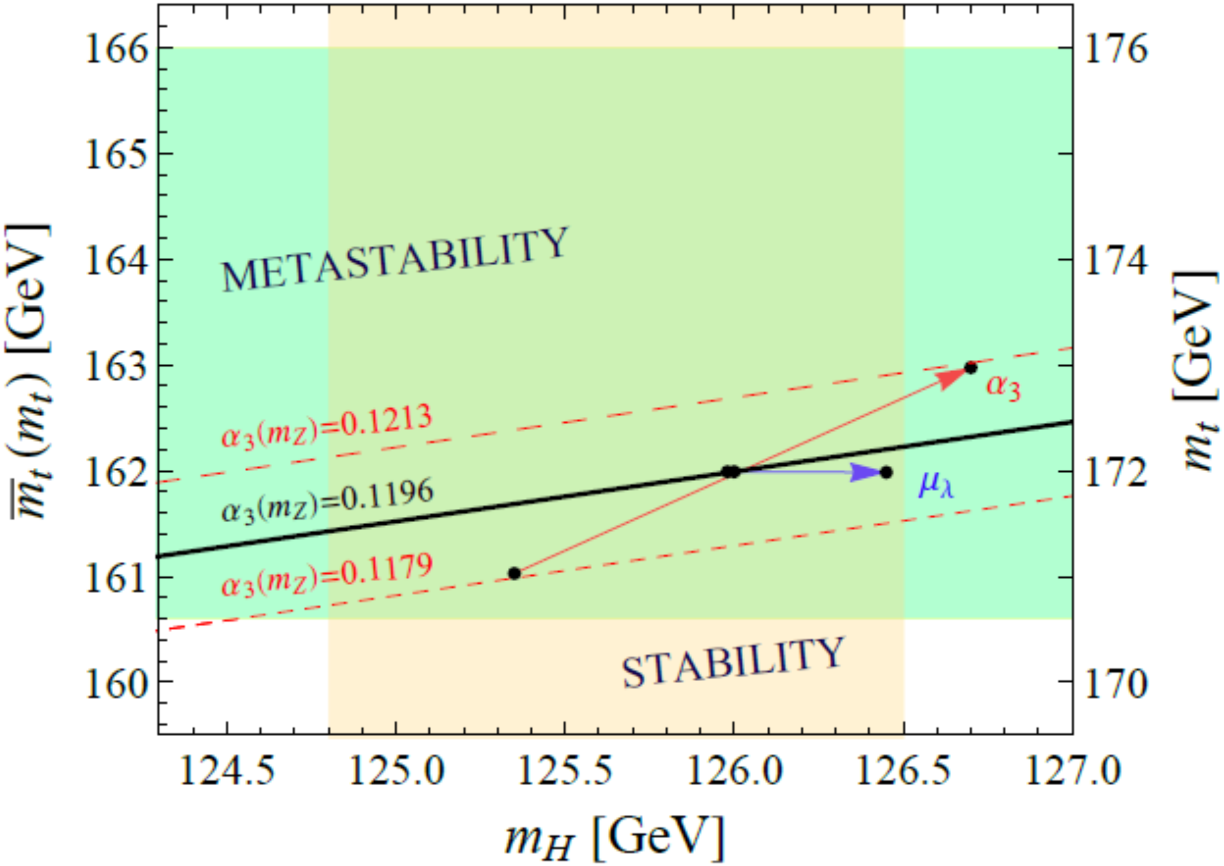


Degrassi et al. 1205.6497

- Is it a coincidence? A (big) message hiding behind it?

Top uncertainties

- Top uncertainties are fully considered?
  More precise measurements are needed



Masina 1209.0393

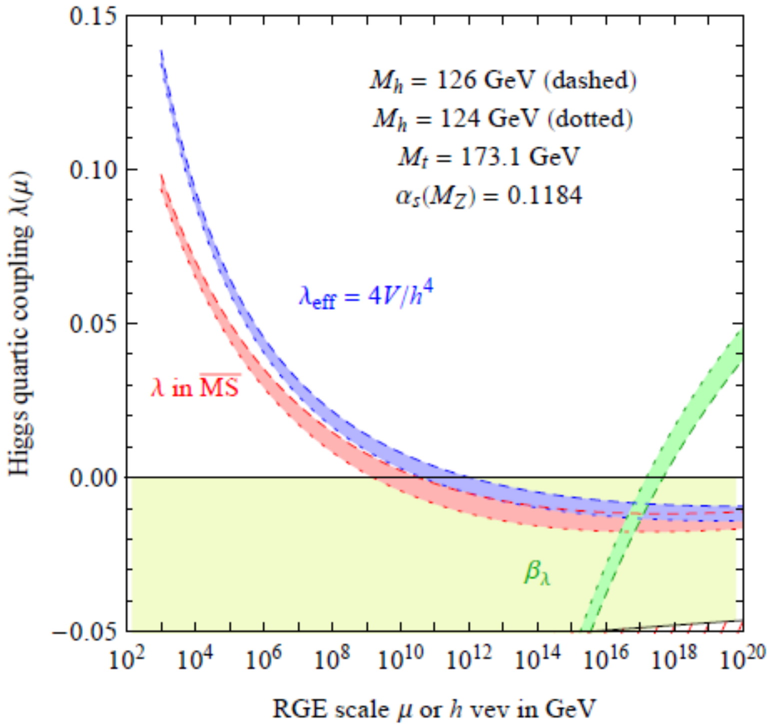
Special boundary conditions?

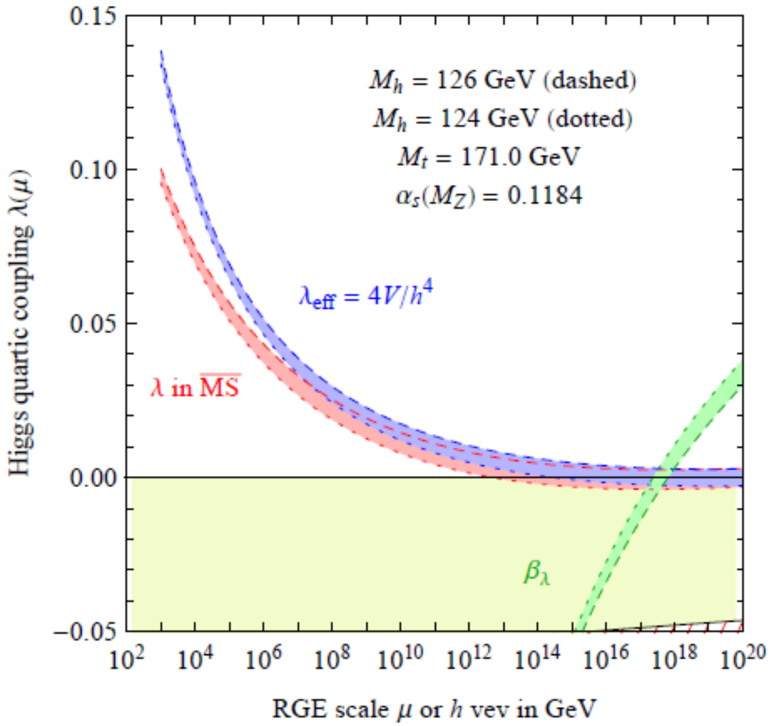
- Are those all hints of special boundary conditions?

$$\lambda(k_{tr}) \approx 0\ ,\ \beta_\lambda(k_{tr}) \approx 0$$

Shaposhnikov, Wetterich 0912.0208

- Sign of some UV-completion before the Planck scale?

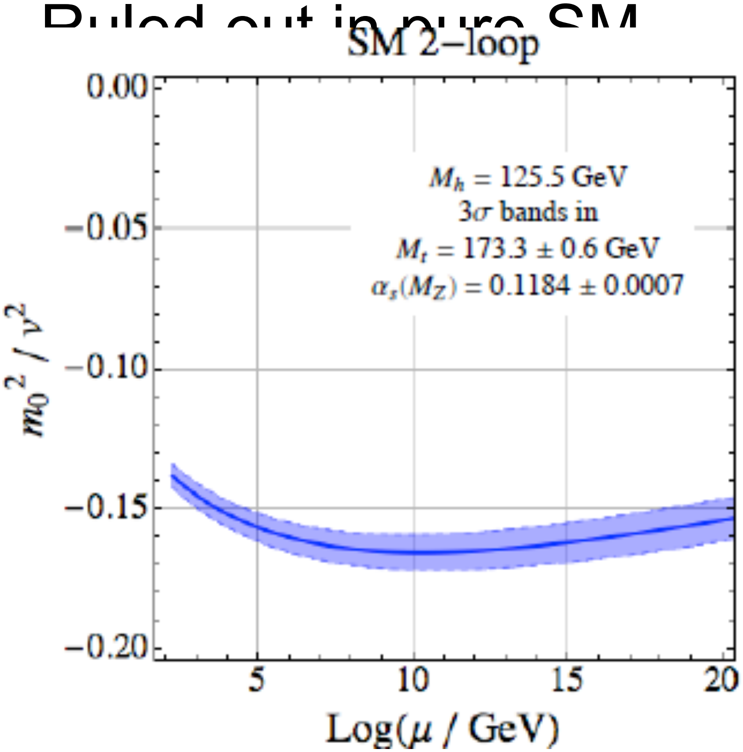




Degrassi et al. 1205.6497

Special boundary conditions?

- Other boundary conditions are possible?
- EWSB could be generated radiatively. Coleman-Weinberg
- Ruled out in pure SM



Lykken @ MITP Workshop, Mainz

Scale invariance

- **Scale invariance**: obvious candidate to forbid quadratic divergence

⇕

- Dimensional Regularization is the natural choice

Bardeen Fermilab-Conf-95-391

- The Higgs quadratic term is the only one breaking the symmetry. Some non-SUSY extention could enforce the special boundary conditions.
"Classically conformal" *Meissner, Nicolai hep-th/0612165*

- Even more vanishing? Also λ=0
Shift symmetry restored. *Hebecker, Knochel, Weigand, 1204.2551*

More examples

Why should the true cutoff behave like dimensional regularization?

- Conformal invariance at high scales.
  For example adding a singlet scalar.

  Lykken @ MITP Workshop, Mainz
  Englert et al. 1301.4224
  Heikinheimo et al. 1304.7006

- Infinite tower of states at Planck scale

  Dienes hep-ph/0104274

- New physics leading to a Veltman throat

  Bezrukov et al. 1205.2893

Is nature natural?

from Strumia talk @ Brookhaven

Or maybe there is a third option...

A third (ugly) option

There is a third (ugly) path:

MF, D. Pappadopulo, A. Strumia 1303.7244

- **Finite Naturalness**: the SM is valid up to arbitrary scale (i.e. up to Planck scale). We are agnostic about gravity, quadratic divergences are not physical and thus have to ignored.

- However new physics is expected (dark matter, neutrino masses, strong CP problem/axions, etc...)

- Recipe: compute effective potential discarding quadratic divergences and ask the usual $\delta m_h^2 \lesssim M_h^2 \times \Delta$

A third (ugly) option

MF, D. Pappadopulo, A. Strumia 1303.7244

There is a third (ugly) path:

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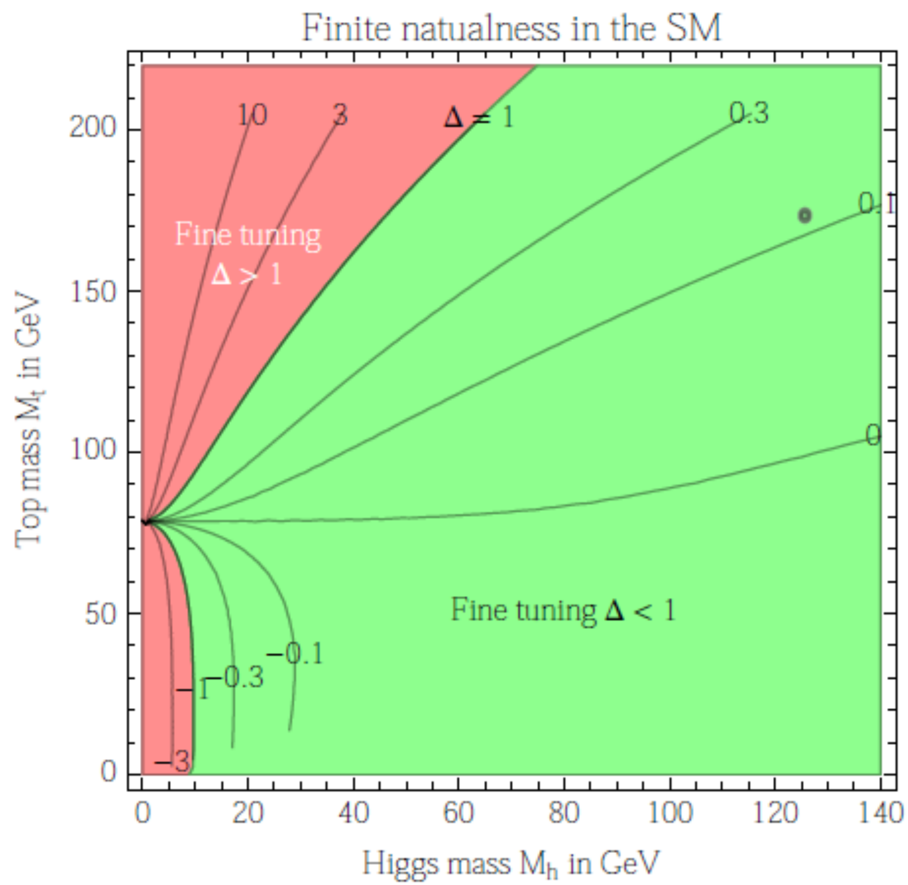
DISCLAIMER: I don't want to advocate, but to explore its consequences and tests

The SM satisfies Finite Naturalness

Is the SM "finite natural"?
Logarithmic sensitivity is still present.



P.s. GUTs usually don't satisfy Finite Naturalness

Neutrinos

Three different see-saw models (M used in general as the mass of the new heavy particles):

- Type-I: heavy N right handed neutrinos
- Type-II: a scalar triplet T, with Y=1
- Type-III: heavy triplets replace the heavy singlets of type-I

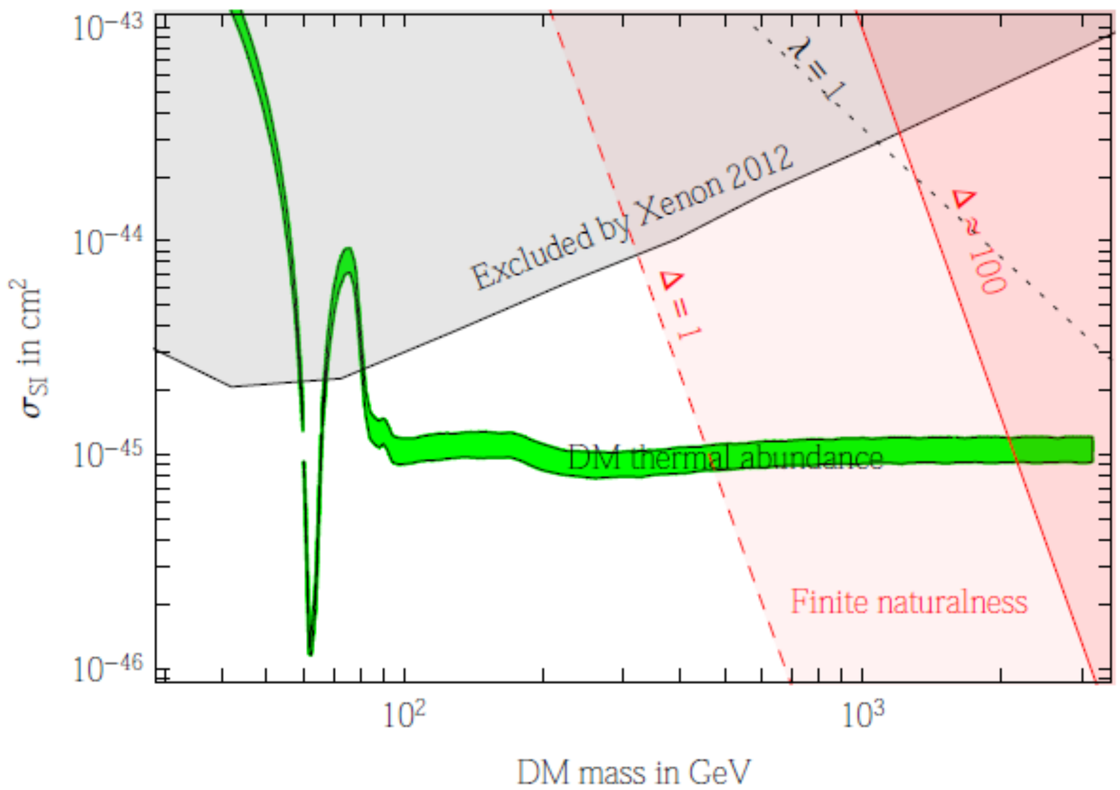
$$M \lesssim \begin{cases} 0.7\,10^7\,\mathrm{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\mathrm{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\mathrm{GeV} \times \sqrt{\Delta} & \text{type III see-saw model,} \end{cases}$$

- Only Type-I could be compatible with Leptogenesis

Singlet Dark Matter

Another possibility: DM without electroweak interactions.

- Scalar: $\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} - \frac{m_S^2}{2} S^2 - \lambda_{HS} S^2 |H|^2 - \frac{\lambda_S}{4} S^4$

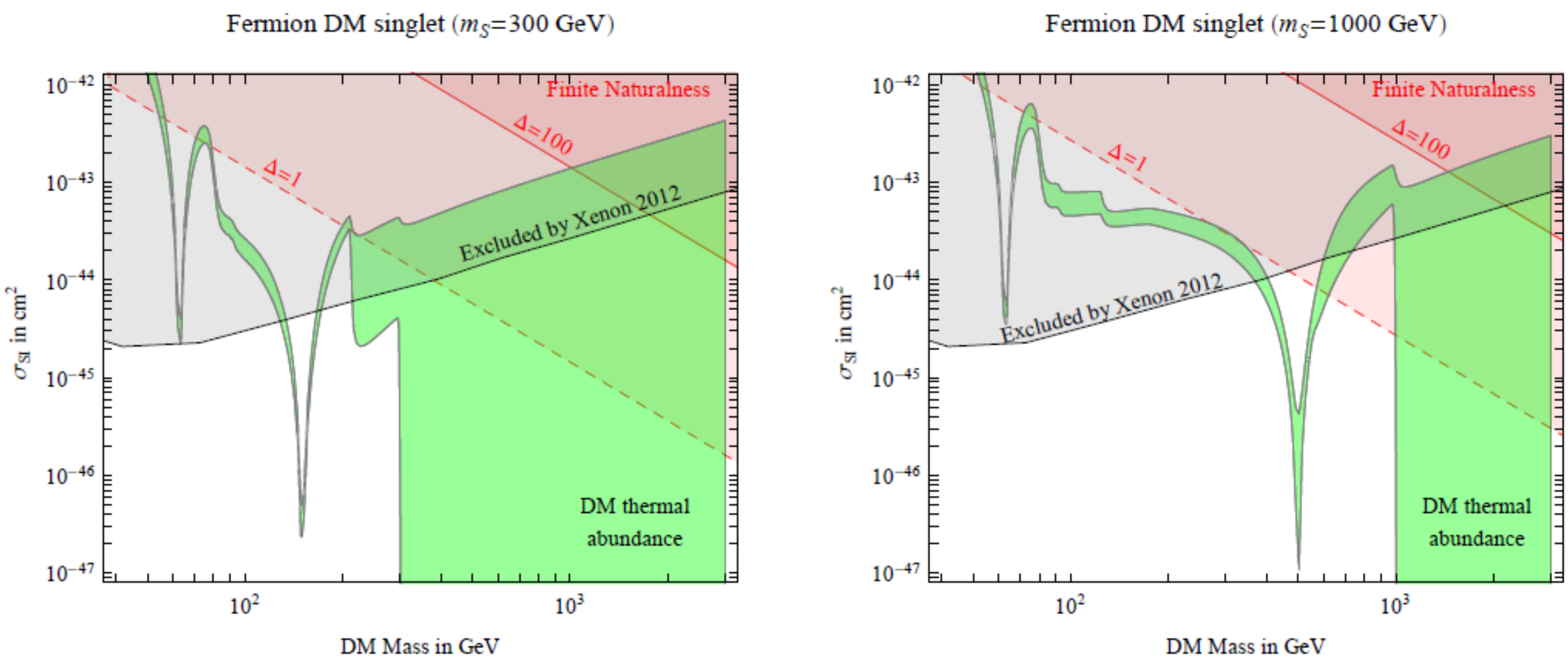


Singlet Dark Matter

Another possibility: DM without electroweak interactions.

- Fermion:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} + \bar{\psi} i \partial\!\!\!/ \psi - \frac{m_S^2}{2} S^2 - \frac{\lambda_S}{4} S^4 - \lambda_{HS} S^2 |H|^2 + \frac{y}{2} S \psi\psi + \frac{M_\psi}{2} \psi\psi + \text{h.c.}$$



Finite Naturalness bounds

In general finite naturalness requires new particles around the TeV scale:

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

- **Dark Matter**: scalars/fermions M ~1 Tev with/without EW interactions

- **Axions** (KSVZ model): $$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\ \text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\ \text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\ \text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

- Other models do not have FN bounds

Conclusions I

- **Pessimistic (antropic)**: simplest/most popular models tuned to % level.
  Nature is fine tuned, give up!

- **Optimistic**:Nature is Natural!
  Soon we will observe new particles and deviations from SM in Higgs data.

- **Finite Naturalness:** new states could be within reach of LHC and other experiments (dark matter direct detection, etc.).
  We have to rethink concepts taken for granted.

Conclusions II

History repeating?

- **SUSY and MSSM**: CMSSM, PMSSM, BMSSM, NMSSM, RMSSM and so on...

Conclusions II

History repeating?

- **SUSY and MSSM**: CMSSM, PMSSM, BMSSM, NMSSM, RMSSM and so on...

- **Naturalness**: Absolute Naturalness, Technical Naturalness, Finite Naturalness, $!&@!# Naturalness...

We hope not.