Naturalness after the first run of the LHC

UC Davis
October 18, 2013

Marco Farina
Cornell University

Gott ist tot

“*Have you not heard of that madman who lit a lantern in the bright morning hours, ran to the market place, and cried incessantly: "I seek God! I seek God! [...] I will tell you. We have killed him -- you and I. All of us are his murderers."* “

- Nietzsche

If Naturalness = God, have we already lost faith?

Is the Higgs the God particle or more God corpse?

SM

Standard Model as an effective field theory

Λ_{UV}

- extremely successful (proton stability, flavour, GUT, neutrino masses)
  i.e. very large cutoff

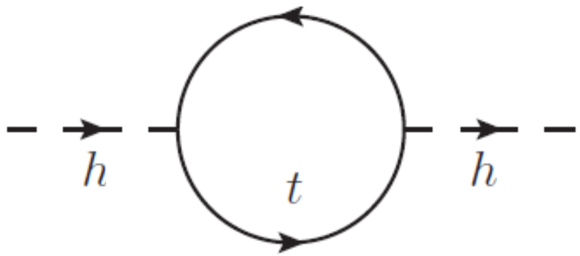
- Higgs mass is additively renormalized, sensitive to high scale

Λ_{IR}

Naturalness in trouble?

Naturalness is now in trouble, two measurements:

- top is heavy $M_t \approx 173$ GeV
- Higgs is light $M_h \approx 126$ GeV



$$\frac{\delta m_h^2}{m_h^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(\frac{4m_t^2}{m_h^2} - \frac{2m_W^2}{m_h^2} - \frac{m_Z^2}{m_h^2} - 1\right)\Lambda^2 = \left(\frac{\Lambda}{500\ \text{GeV}}\right)^2$$

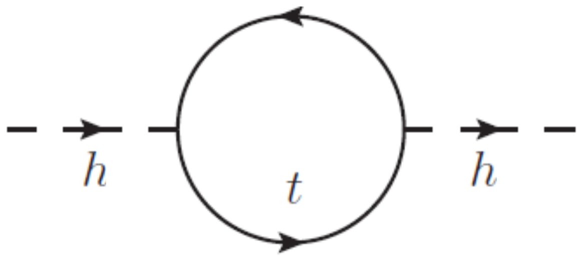
$$\delta m_H^2 \approx \frac{\lambda_\Phi}{16\pi^2} M^2 \ln\frac{M^2}{\Lambda^2}.$$

Naturalness in trouble?

Naturalness is now in trouble, ~~two~~ three measurements:

- top is heavy $M_t \approx 173\,\text{GeV}$
- Higgs is light $M_h \approx 126\,\text{GeV}$
- Higgs couplings are SM like

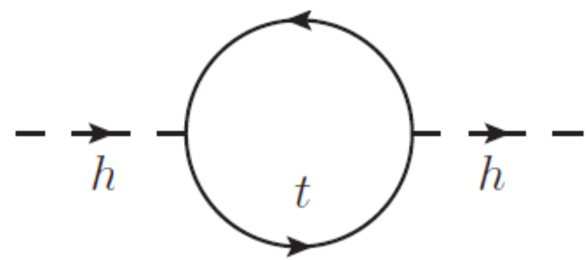
  E.g.: Composite Higgs, coupling and tuning scaling with v/f



Naturalness in trouble?

Naturalness is now in trouble, ~~two~~ three measurements:

- top is heavy $M_t \approx 173\,\text{GeV}$
- Higgs is light $M_h \approx 126\,\text{GeV}$
- Higgs couplings are SM like



Partners in loops

Extended scalar sector (λ-SUSY)

Top partners?

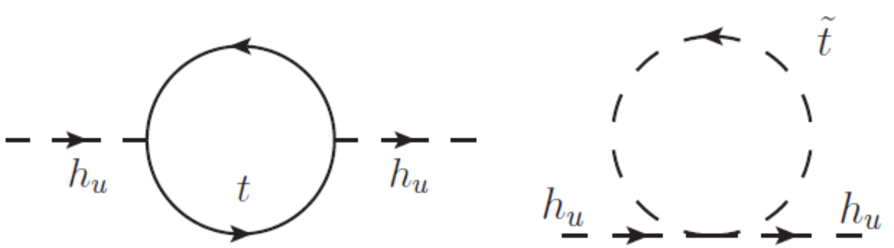
The biggest issue is in the third generation.

Model independent 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?

The biggest issue is in the third generation.
Model independent 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 ⇨ $6y_t^2 = \sum_i g_i(-1)^{F_i} c_i$

- Consequences recently explored: -DM and colliders

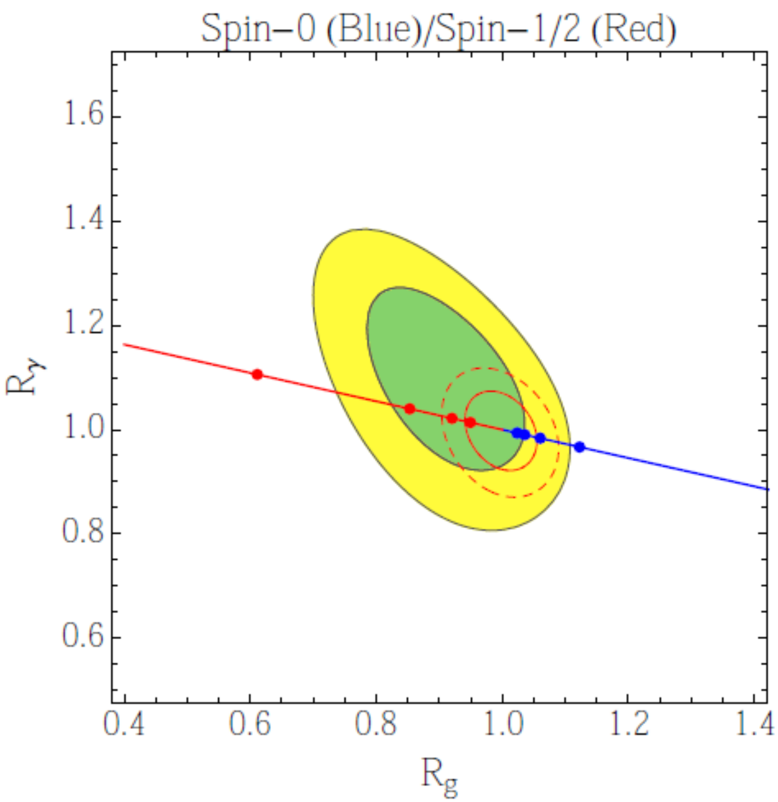
  El Hendri, Hook 1305.6608

  - gauge singlet partner

  Craig, Englert, McCullough 1305.5251

Top partners?

Low-Energy Theorems relate to Higgs couplings:



Green/Yellow: 7+8 TeV LHC at 68% and 95% CL
Dashed Red: 14 TeV projection at 68% and 95% CL
(dots for 350, 500, 650, and 800 GeV)

14 TeV data from Peskin 1207.2516

$$\mathcal{L}_{h\gamma\gamma} = \frac{2\alpha}{9\pi v} C_\gamma h F_{\mu\nu} F^{\mu\nu} \qquad \mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} C_g h G_{\mu\nu} G^{\mu\nu}$$

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

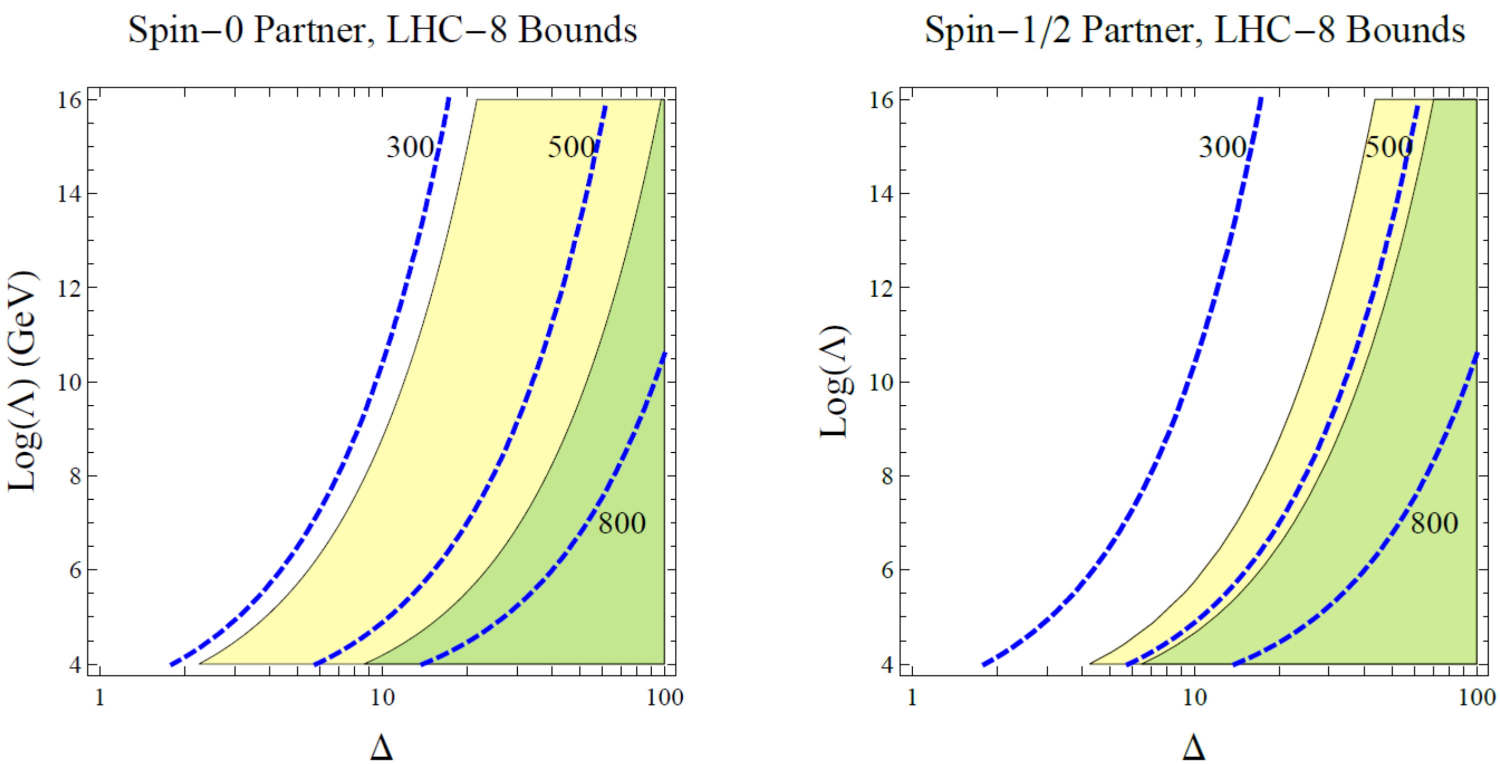
$$C_g \approx 1 + 2 \sum_f \frac{C(r_f) c_f v^2}{m_{0,f}^2 + c_f v^2} + \frac{1}{2} \sum_f s \frac{C(r_s) c_s v^2}{m_{0,s}^2 + c_s v^2}$$

- Slope is set by rep
- Position on the line depends on (mass of the particle, etc.)

F, Perelstein, Rey-Le Lorier 1305.6068

Top partners

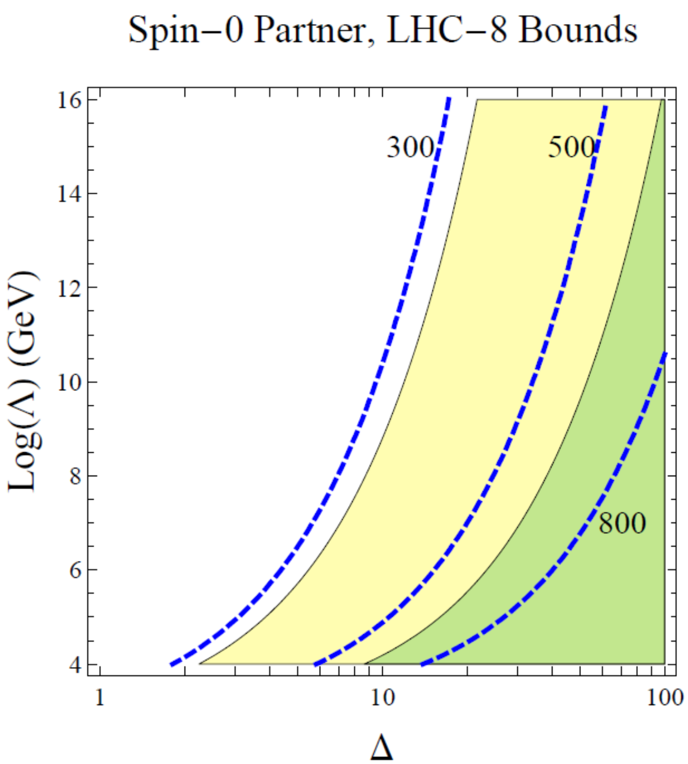
Only log divergencies are left, still sensitive to cut-off (but very model dependent)

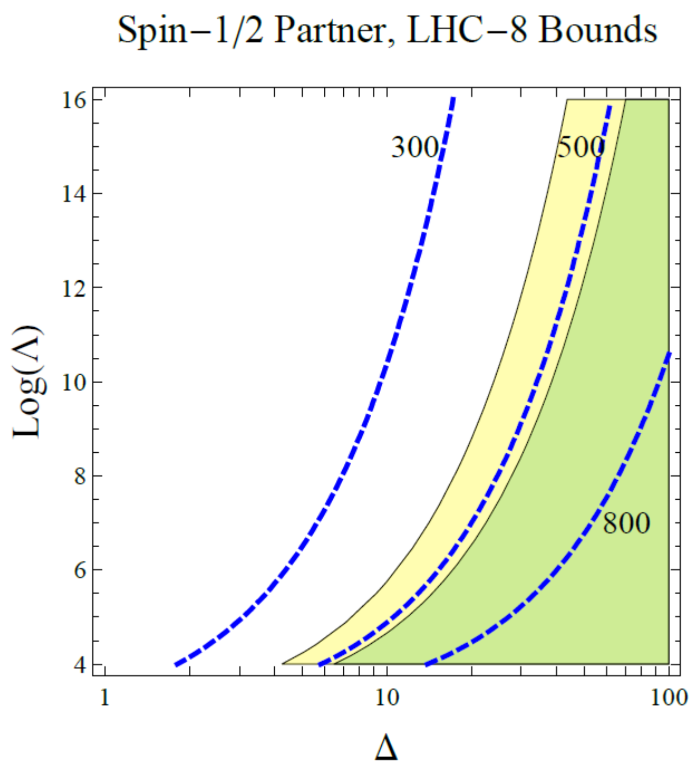


$$\Delta = \frac{\delta\mu^2}{\mu^2} \approx 0.78 \left(\sum_i g_i (-1)^{F_i} c_i \left(\frac{m_{0,i}}{1\ \text{TeV}}\right)^2 \log\frac{\Lambda^2}{m_{0,i}^2} - 6 y_t^2 \left(\frac{m_t}{1\ \text{TeV}}\right)^2 \log\frac{\Lambda^2}{m_t^2} \right)$$

Top partners

Only log divergencies are left, still sensitive to cut-off (but very model dependent)





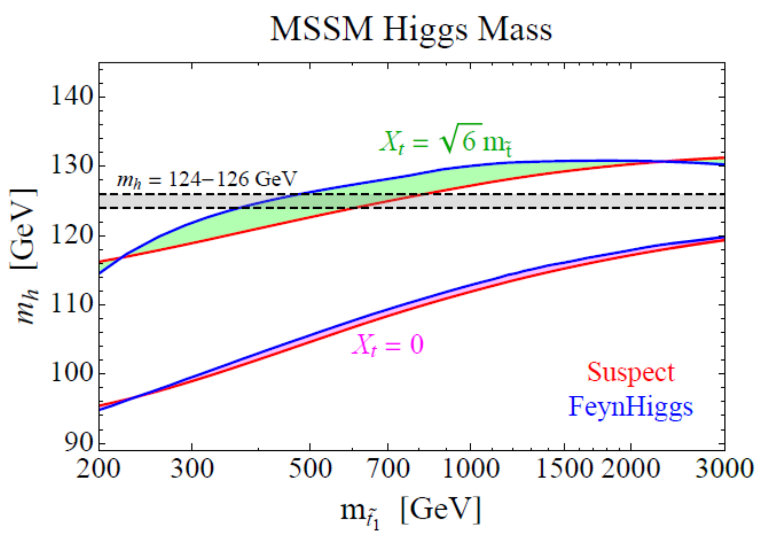
1% acc. gluon coupling gives ~20x FT
(e.g. @ ILC)

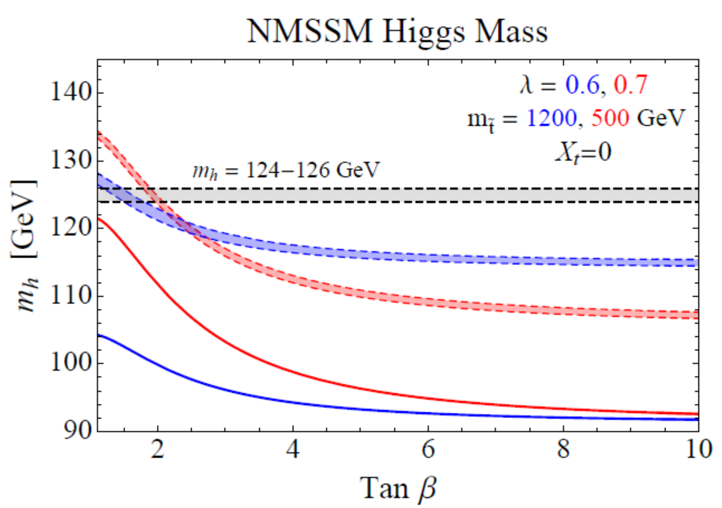
What the mass is telling us

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

Different ways to get 125 GeV:

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





Hall, Pinner, Ruderman 1112.2703

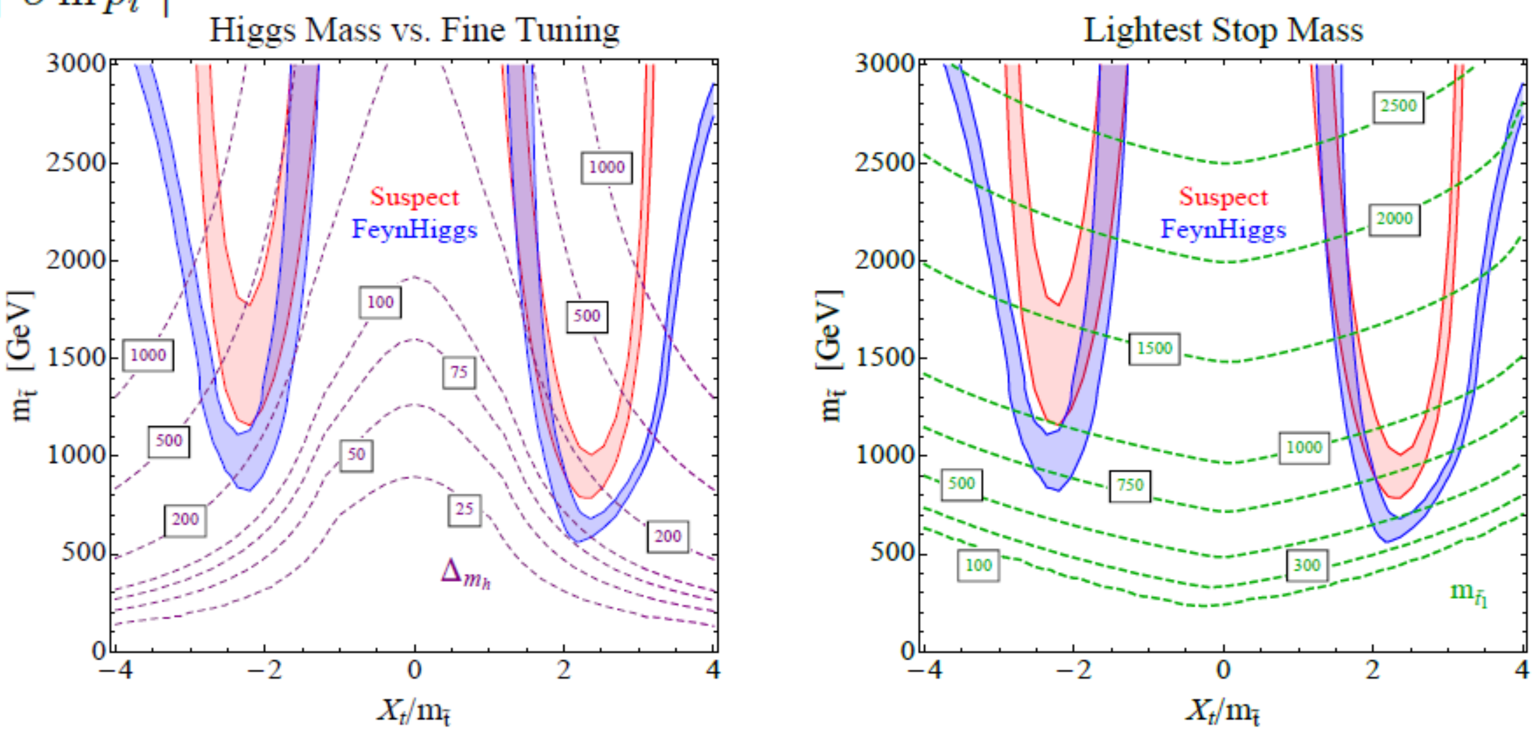
Stops and Naturalness

If too large ⇨ tuned parameters to get correct EWSB scale →

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

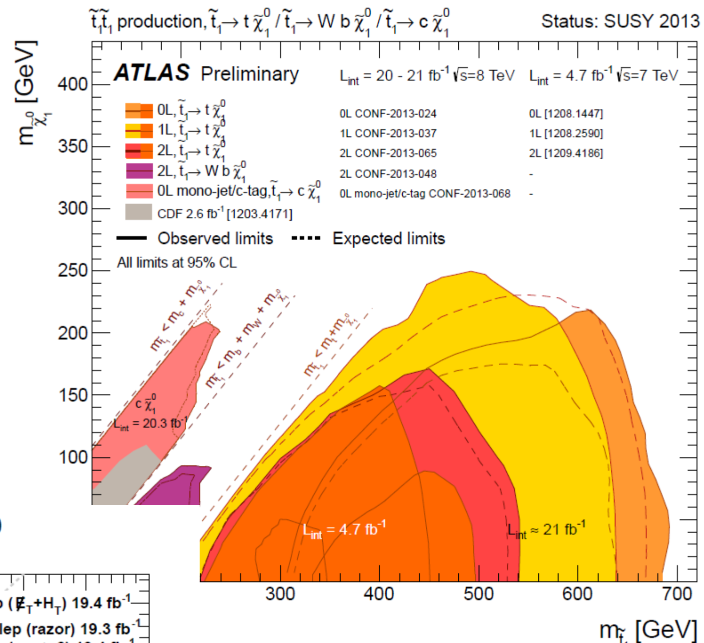
$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

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

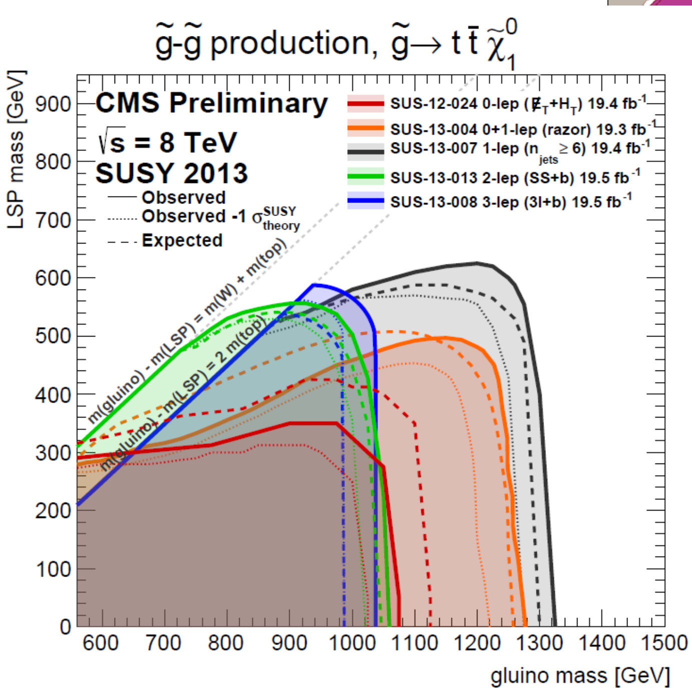


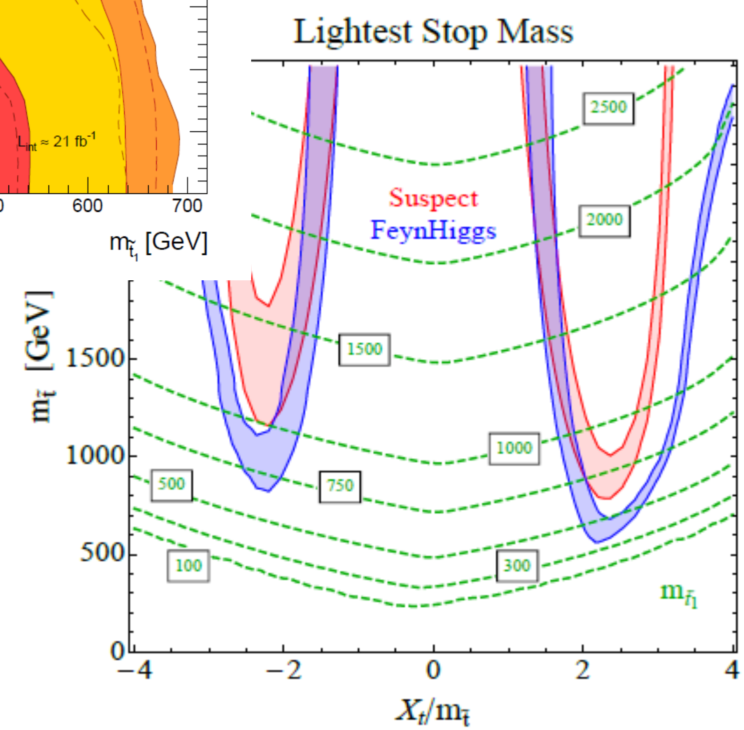
Hall, Pinner, Ruderman
1112.2703

Stops and Naturalness



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





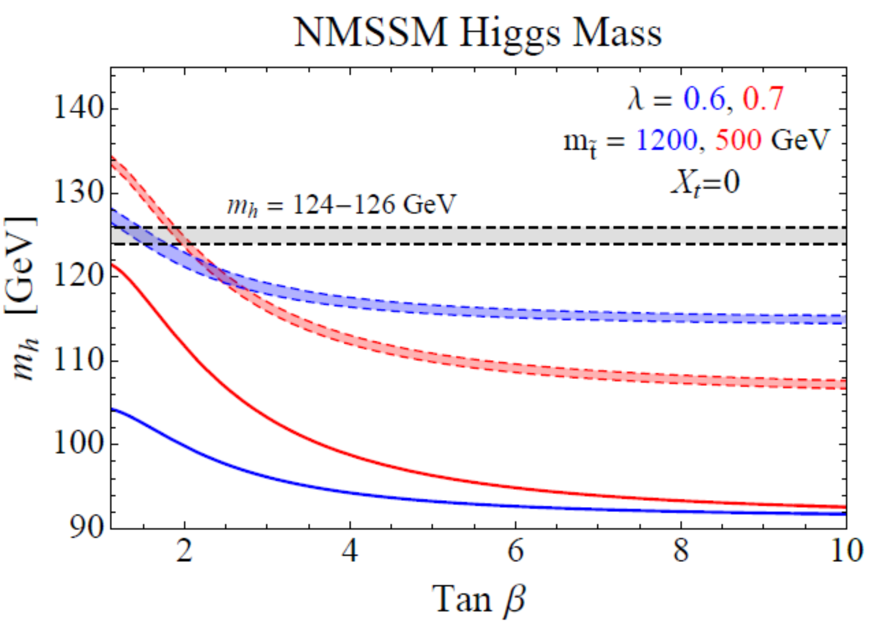
Hall, Pinner, Ruderman 1112.2703

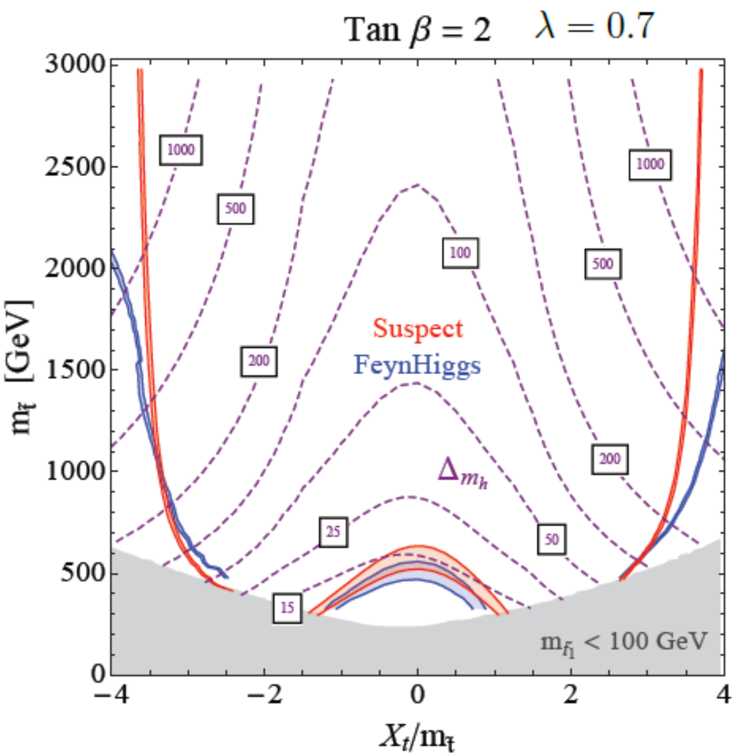
Is the NMSSM the solution?

Add a singlet

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

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





Hall, Pinner, Ruderman
1112.2703

Enlarge λ

So far:

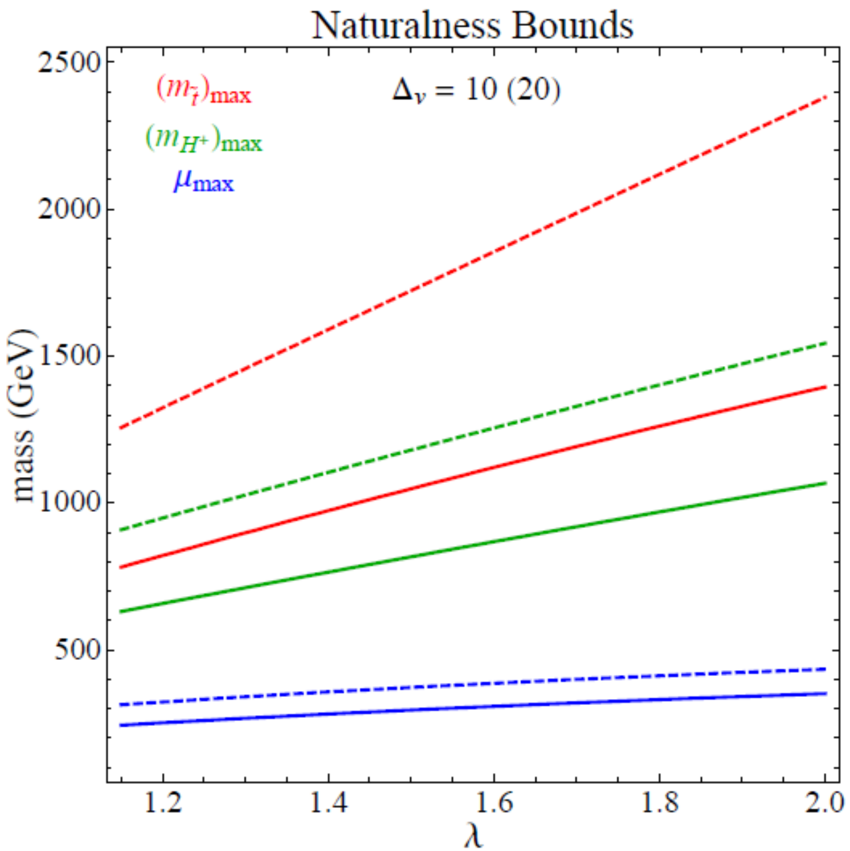
- MSSM: stop tuning ~1%
- NMSSM: ~5%

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

$$m_Z^2 \sim \frac{g^2}{\lambda^2} m_{H_u}^2$$



Hall, Pinner, Ruderman 1112.2703

Enlarge your λ

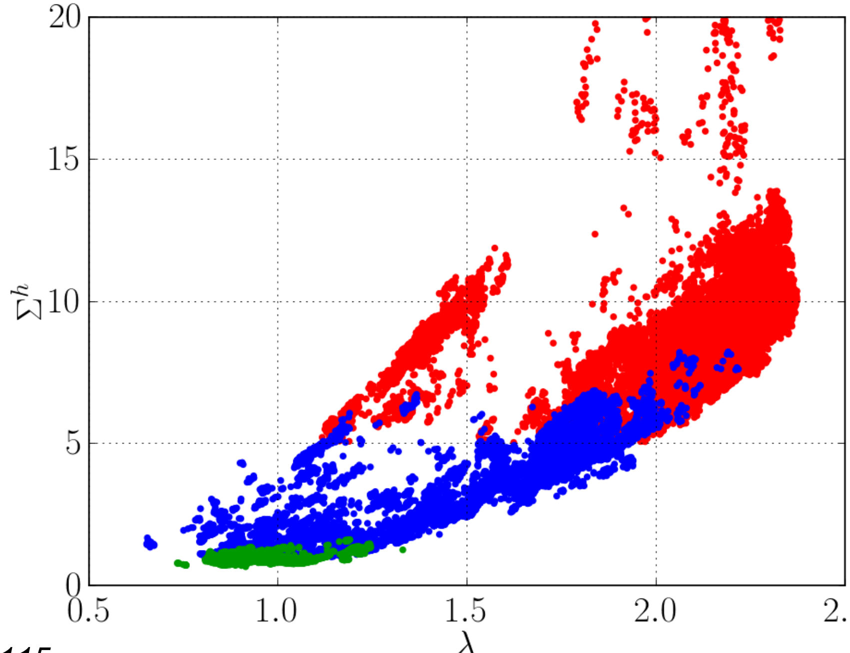
λ-SUSY:

- 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 (pull-down)

⇩

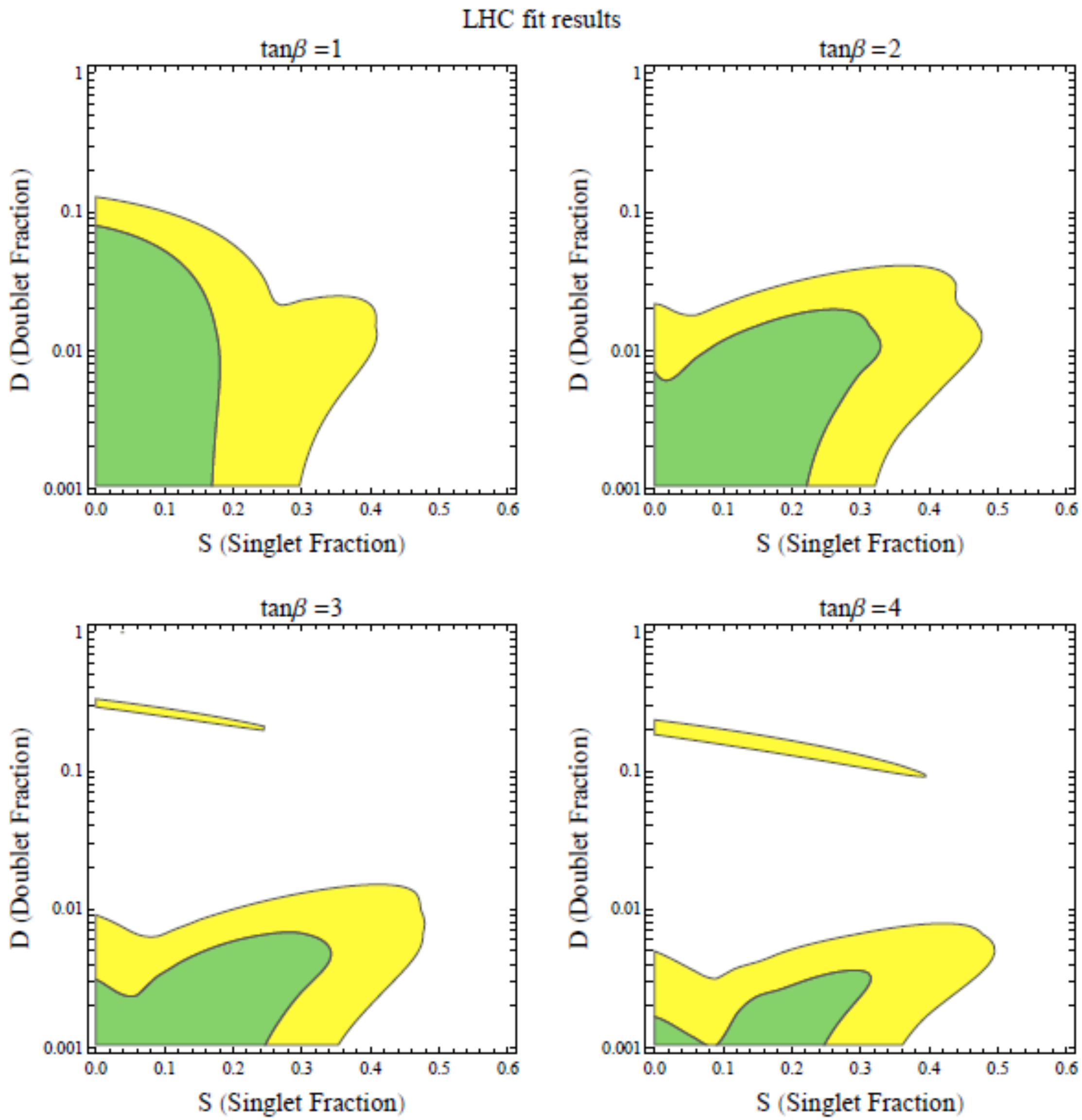
Fine Tuning!

Agashe, Cui, Franceschini 1209.2115



Gherghetta et al. 1212.5243

Missing Ingredient



F, Perelstein, Shakya 1310.0459

- Mixing with H is ~few %

- Decoupling limit

- Large singlet fraction still allowed (reduction to h-s)

$$h^0_{126} = \alpha_h h^0_v + \alpha_H H^0_v + \alpha_s h^0_s$$

$$S = |\alpha_s|^2 \qquad D = |\alpha_H|^2$$

Setup

- Our setup: scale invariant NMSSM

$$W = \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \kappa \hat{S}^3$$

$$V_{\rm soft} = m_u^2|H_u|^2 + m_d^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u \cdot H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{ h.c.}\right)$$

- Few parameters $p_i = \{\lambda, \kappa, m_u^2, m_d^2, m_S^2, A_\lambda, A_\kappa\}$

  usual trading plus exchanging Ak to have 126 GeV

$$\{\lambda, \kappa, \tan\beta, s, A_\lambda\}$$

- (Analytical approach for tb=1 with Aλ - singlet fraction trade)

$$\phi = \arctan \frac{\lambda^2 v^2 - m_h^2}{2\lambda v\left((\lambda - \kappa)s - \frac{1}{2}A_\lambda\right)}$$

Fine tuning

- tb=1 enforce H decoupling

- Analytical approach possible (After fixing Higgs mass and singlet fraction only two free parameters left)

$$\{\lambda, \kappa, \tan\beta, s, A_\lambda\}$$

- Expected FT ~15% for λ=2

$$m_h^2 \approx \mathcal{M}_{11}^2 - \frac{\mathcal{M}_{13}^4}{\mathcal{M}_{33}^2} .$$

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

Fine tuning

- tb=1 ⟶ H decoupling
- Analytical approach
-

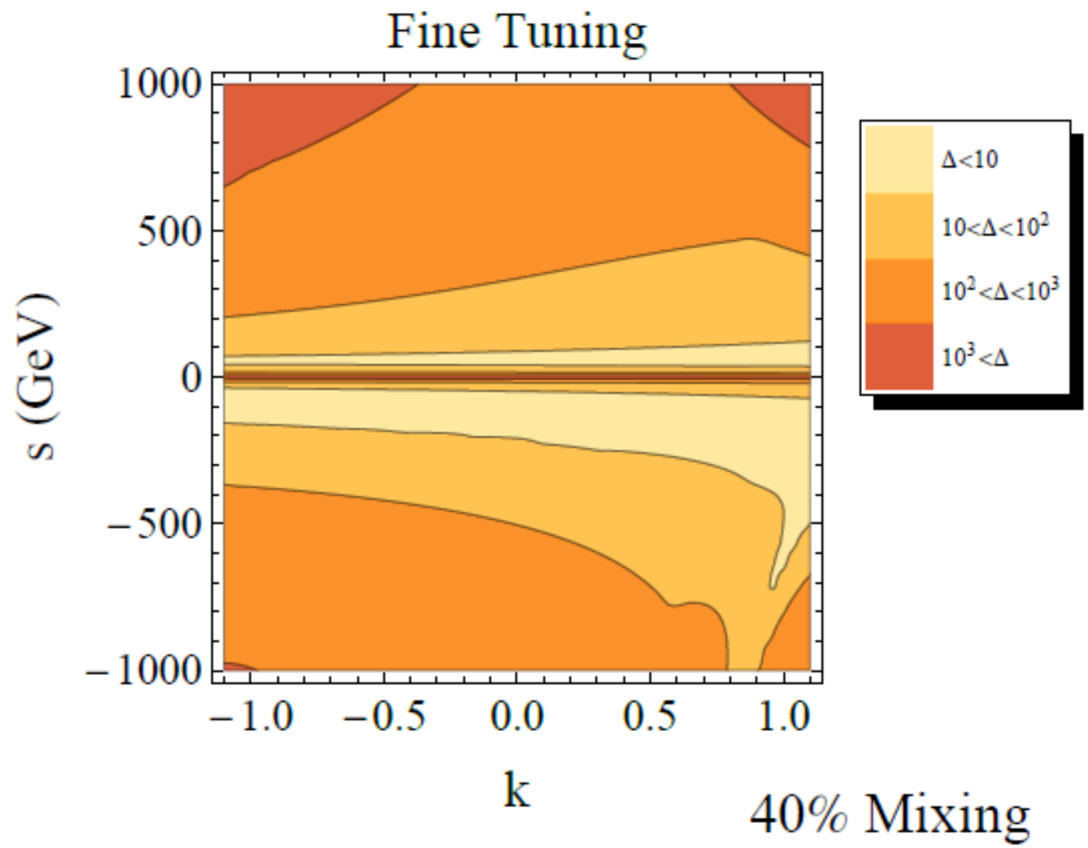
$$\{\lambda, \kappa, \tan\beta, s, A_\lambda\}$$

- Expected FT

$$m_h^2 \approx \mathcal{M}_{11}^2 - \frac{\mathcal{M}_{13}^4}{\mathcal{M}_{33}^2}.$$

~15% for λ=2

- Minimum FT for s~v and small A-terms



Fine tuning

- tb=1 ⟶ H decoupling
- Analytical approach
-

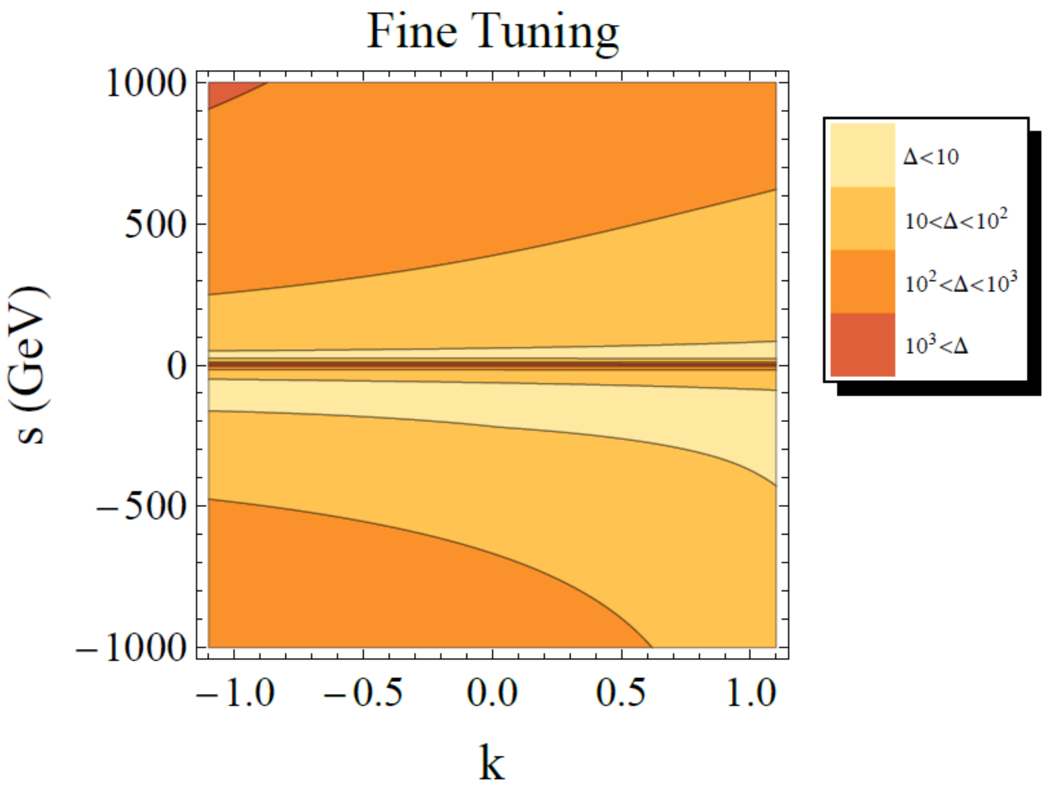
$$\{\lambda, \kappa, \tan\beta, s, A_\lambda\}$$

- Expected FT

$$m_h^2 \approx \mathcal{M}_{11}^2 - \frac{\mathcal{M}_{13}^4}{\mathcal{M}_{33}^2}\,.$$

~15% for λ=2

- Minimum FT for s~v and small A-terms



15% Mixing

Constraints

Various constraints to be imposed on parameter space

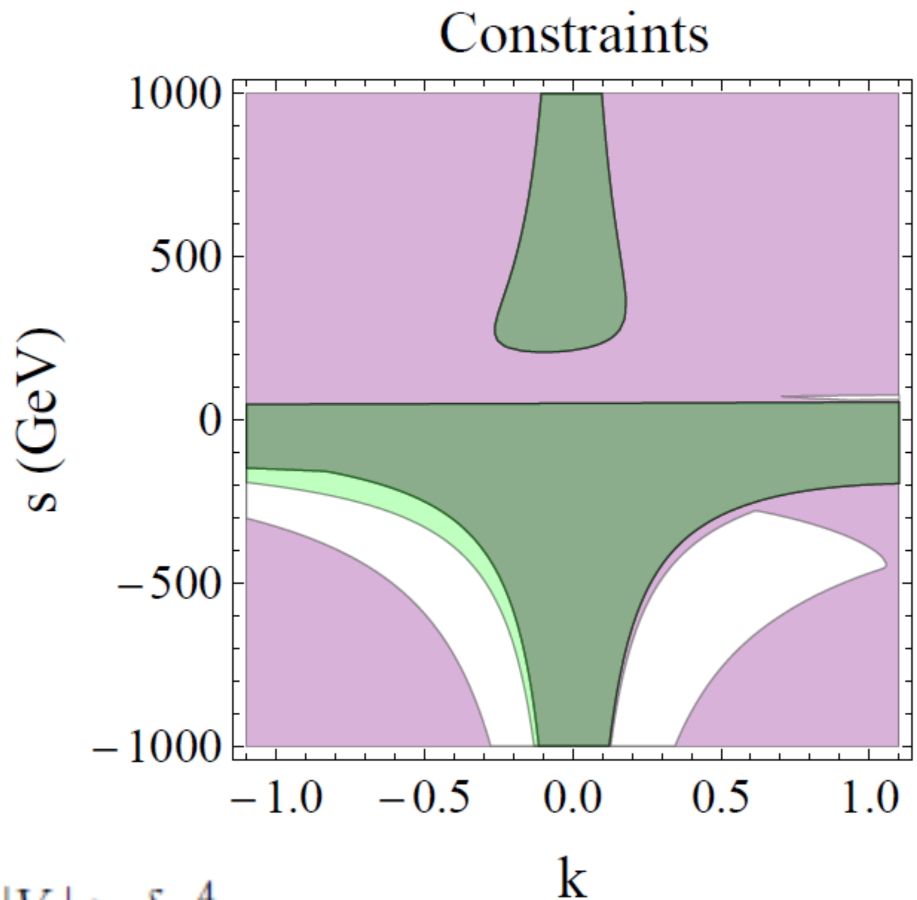
- Spectrum (Green):
  No-tachyonic particles, Collider searches (chargino, Z invisible width)

$$\kappa^2 s^2 + \left(1 - \frac{1}{2S}\right)\lambda^2(v^2 - m_h^2) \gtrsim 0$$

- Unrealistic Minima (purple)

$$V_r - V_{u,min} > \delta\,(|V_r| + |V_{u,min}|) \qquad |V_r| > \delta\, v^4$$

$$\delta = 0.2$$



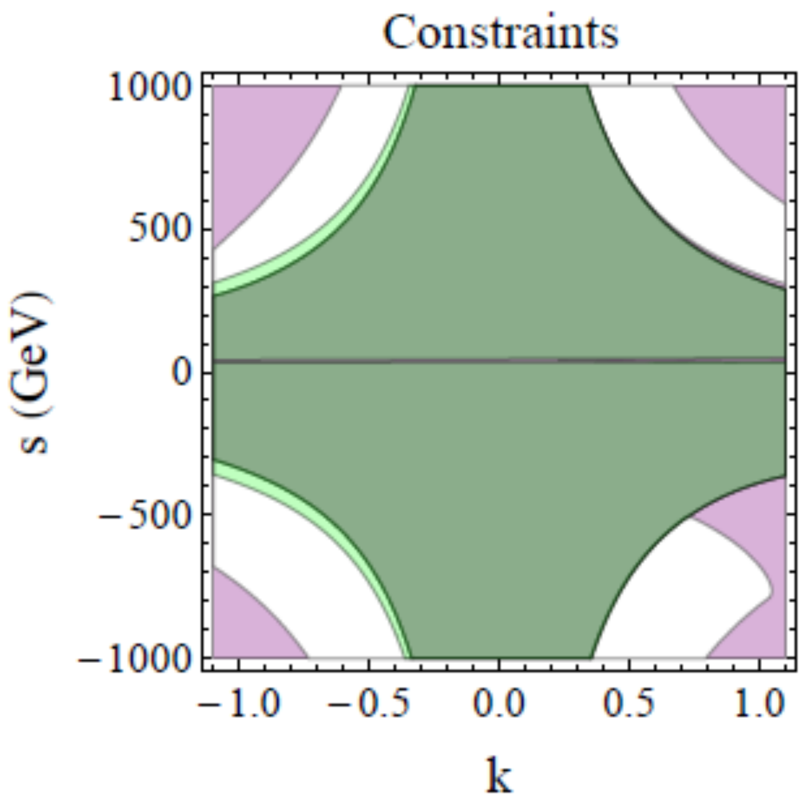
40% Mixing

Constraints

Various constraints to be imposed on parameter space

- Spectrum (Green):
  No-tachyonic particles,
  Collider searches
  (chargino, Z invisible
  width)

$$\kappa^2 s^2 + \left(1 - \frac{1}{2S}\right) \lambda^2 (v^2 - m_h^2) \gtrsim 0$$



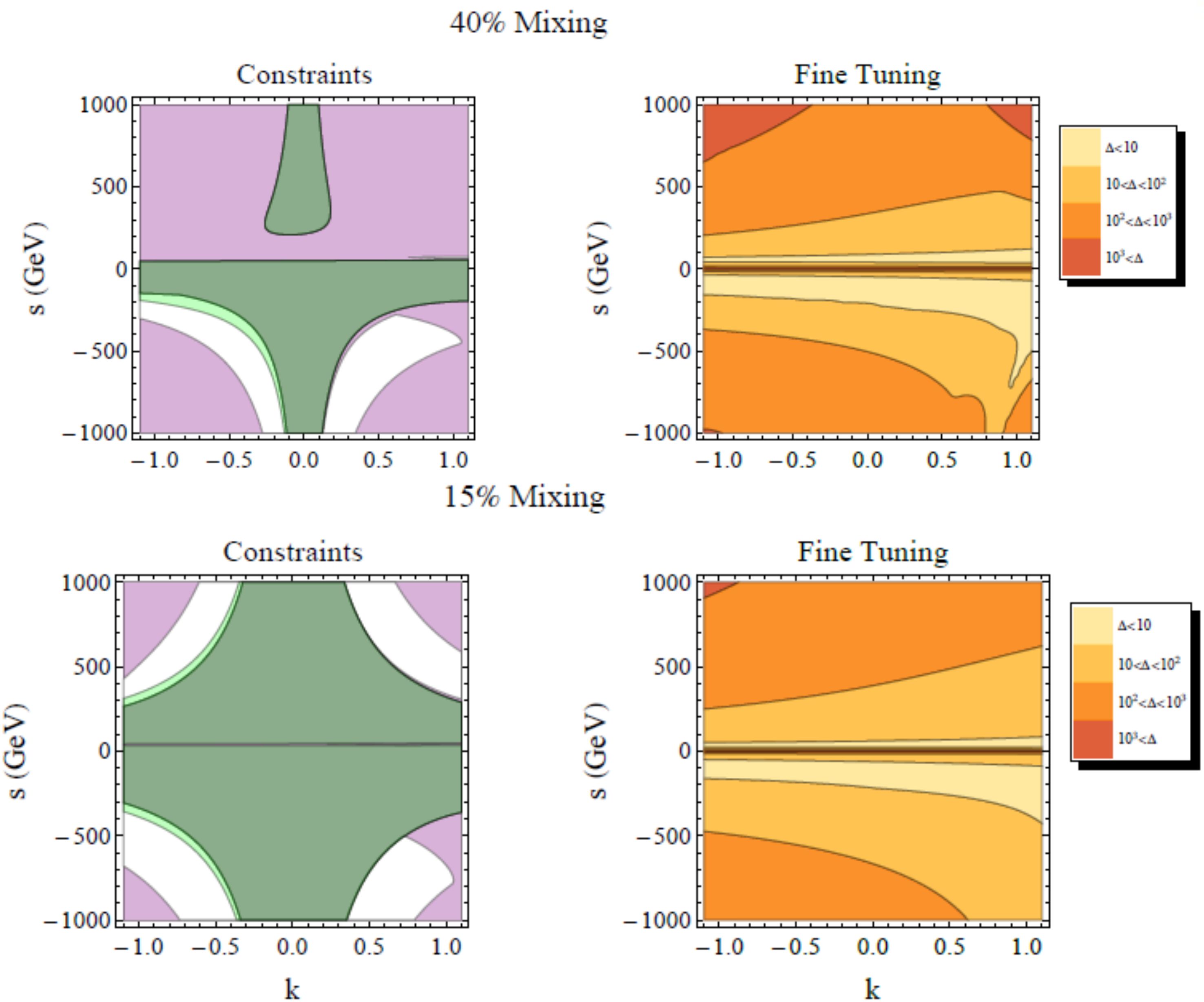
- Unrealistic Minima (purple)

$$V_r - V_{u,min} > \delta \left(|V_r| + |V_{u,min}|\right) \qquad |V_r| > \delta\, v^4$$

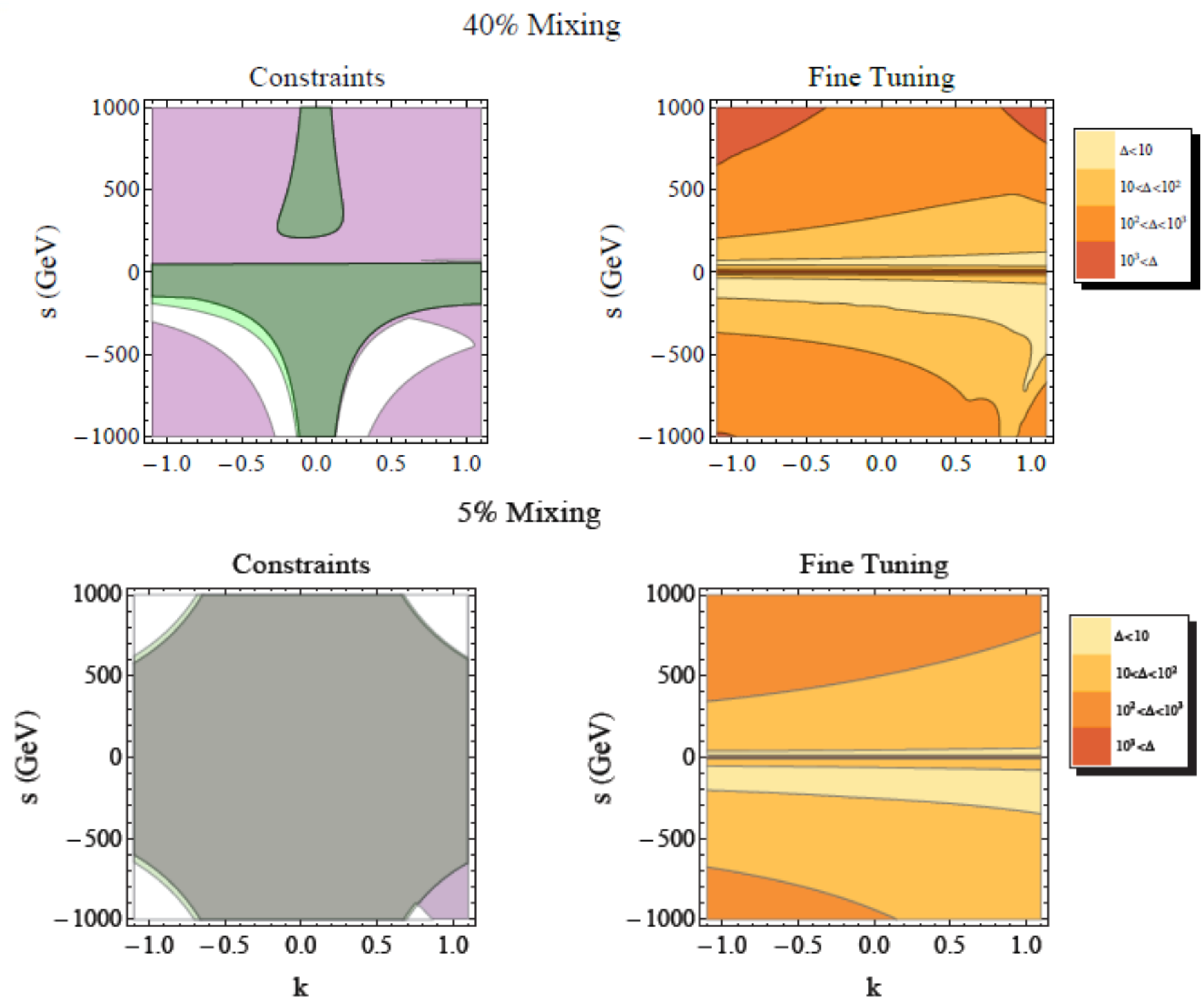
$$\delta = 0.2$$

40% Mixing

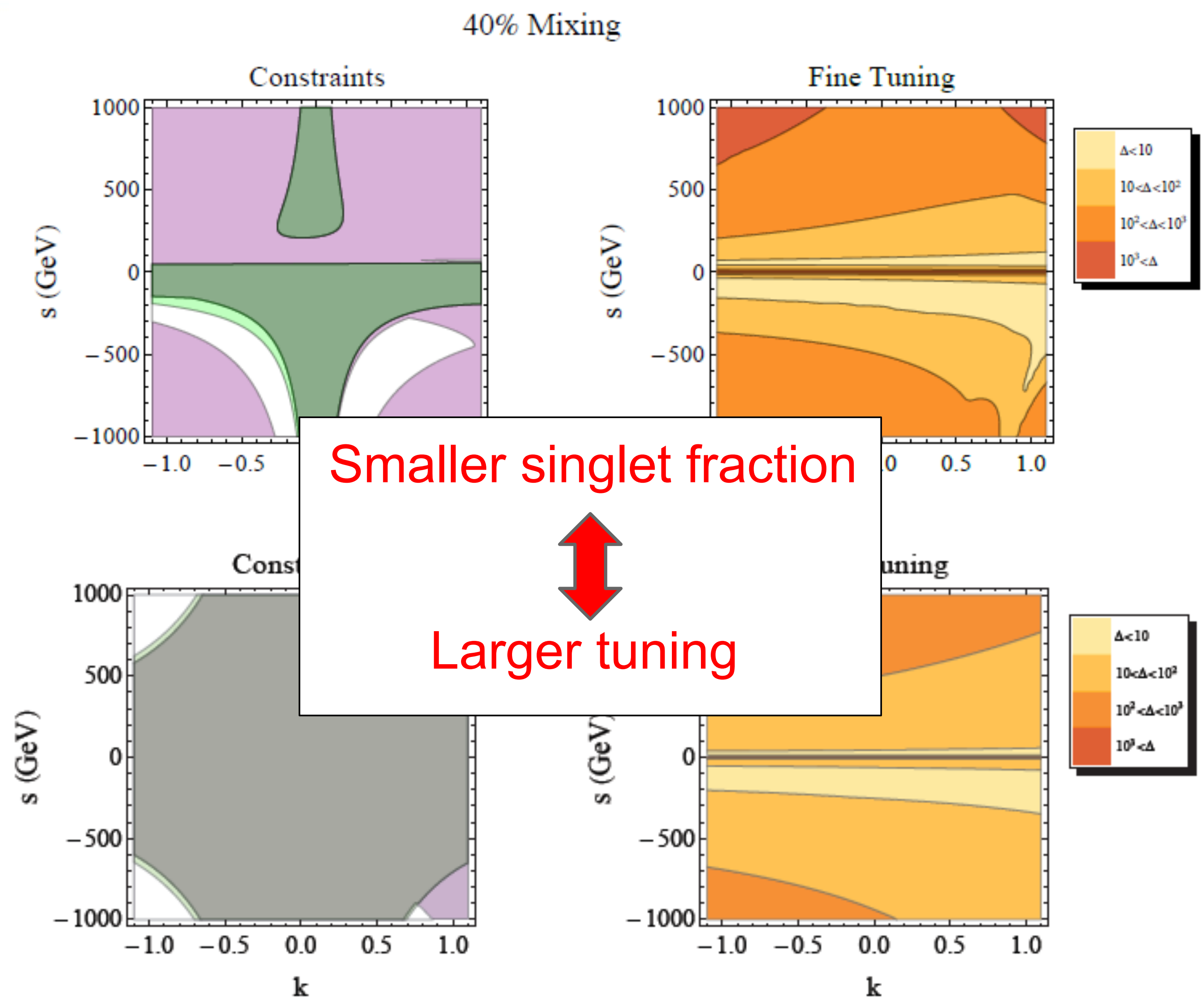
FT vs Constraints



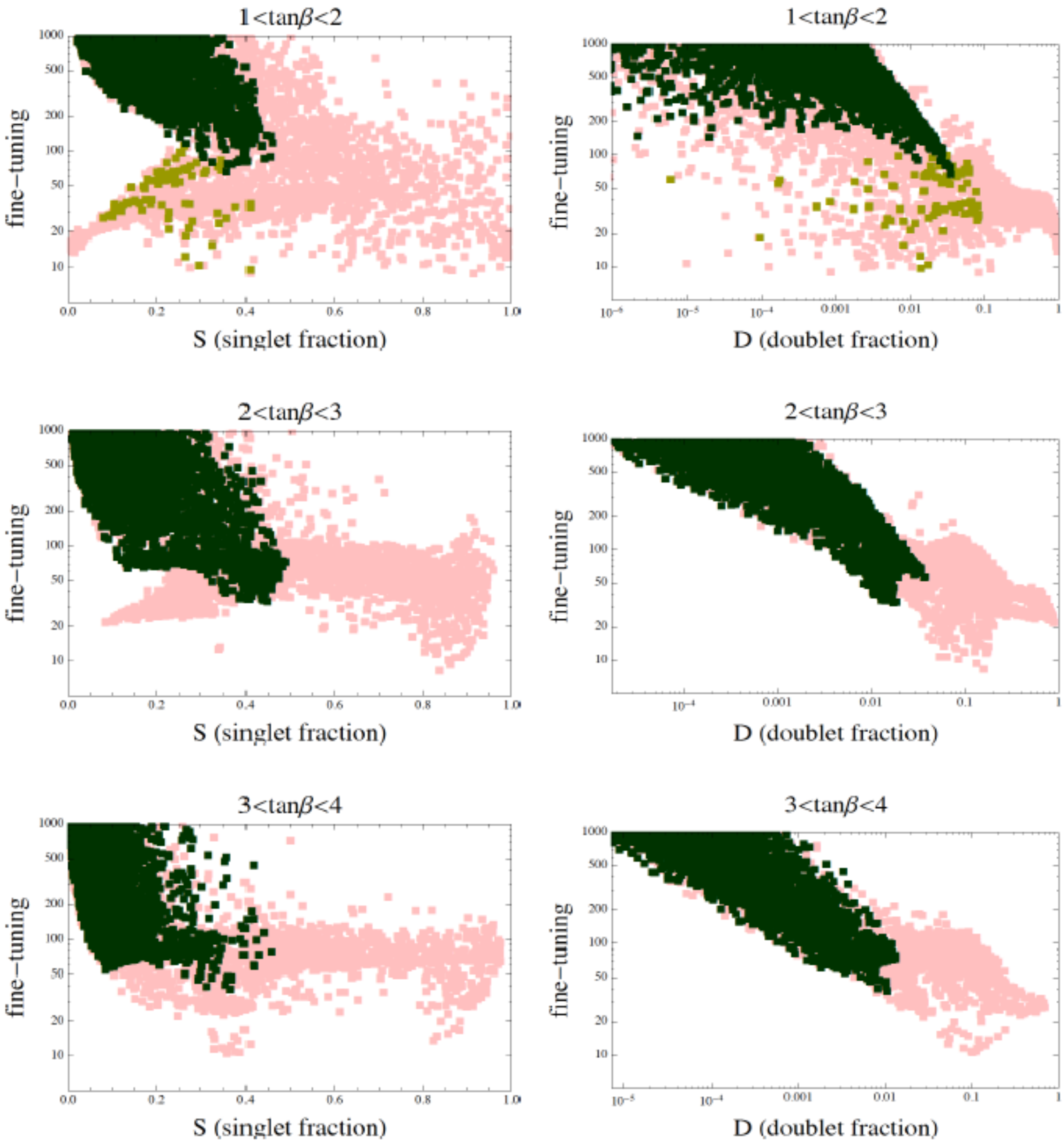
FT vs Constraints



FT vs Constraints

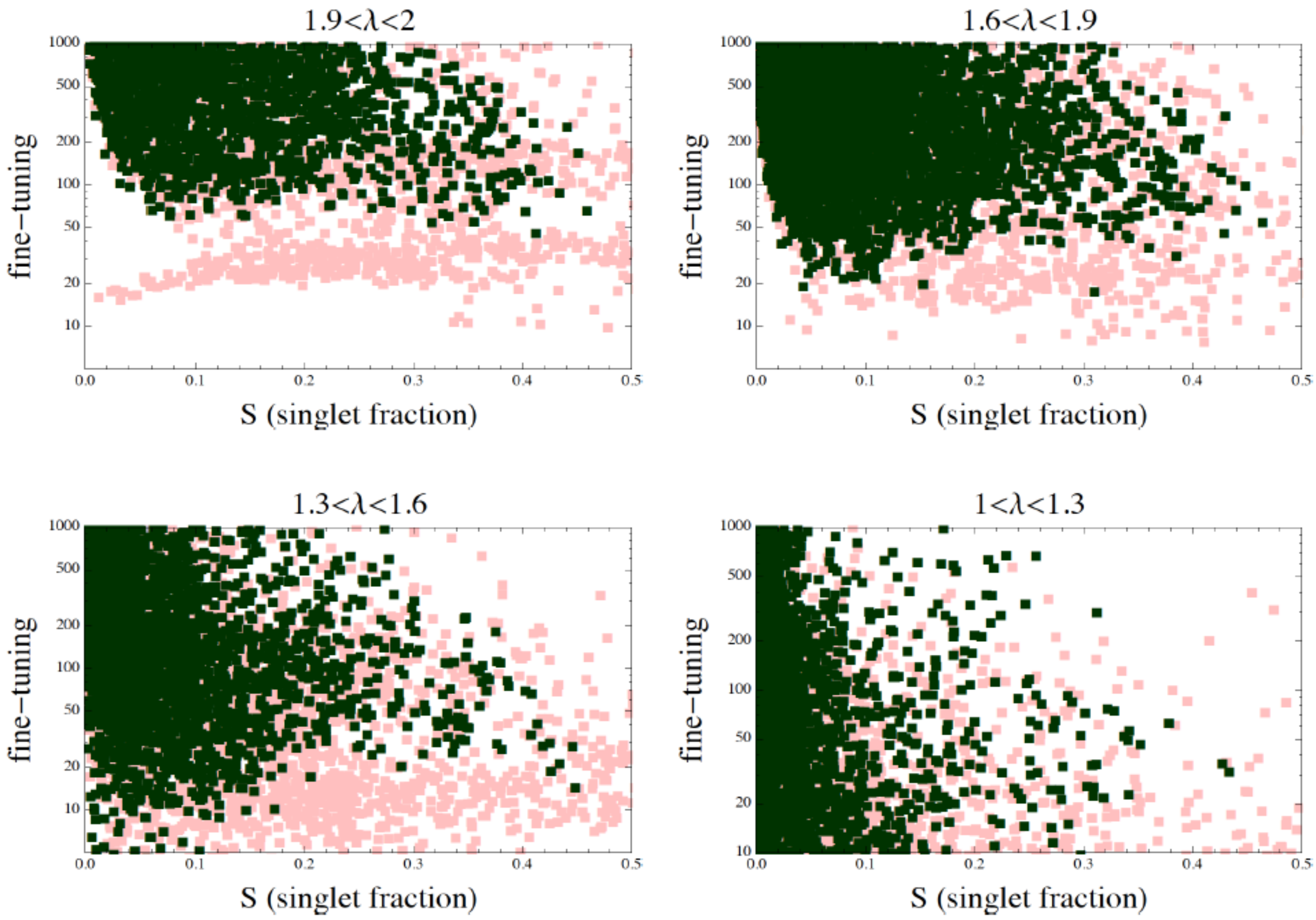


Some scatter plot



- Going beyond tb=1 with scan over parameter space
- FT vs s-fraction trend confirmed
- Less tuned points excluded by LHC data (pink points)

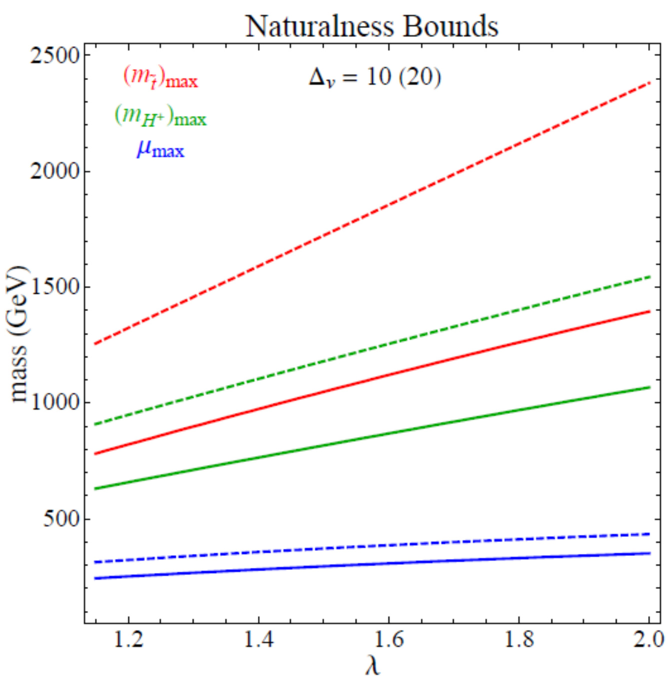
Decreasing λ

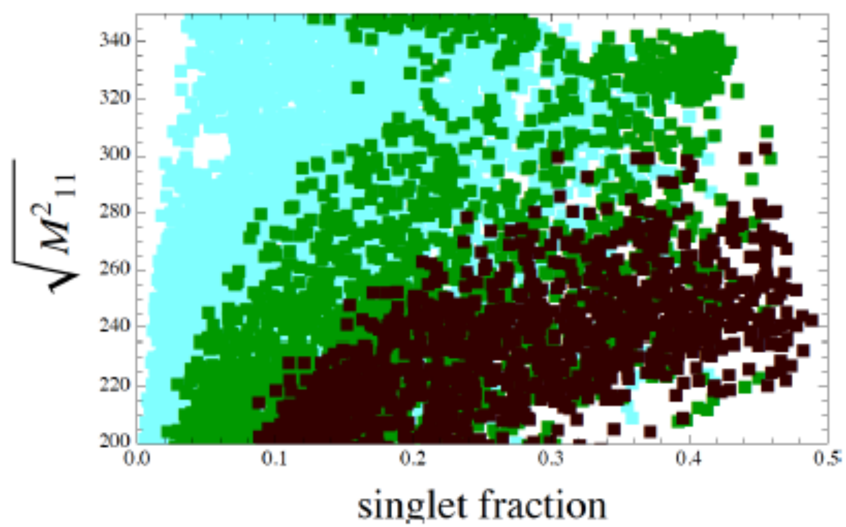


Back to stops

- Which is the best value for λ?
- Interplay between Higgs measurements and direct searches (not only in the stop sector… light scalars)

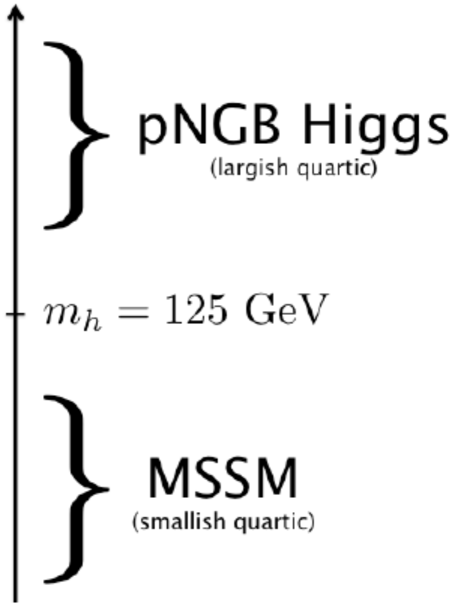
Barbieri et al. 1304.3670





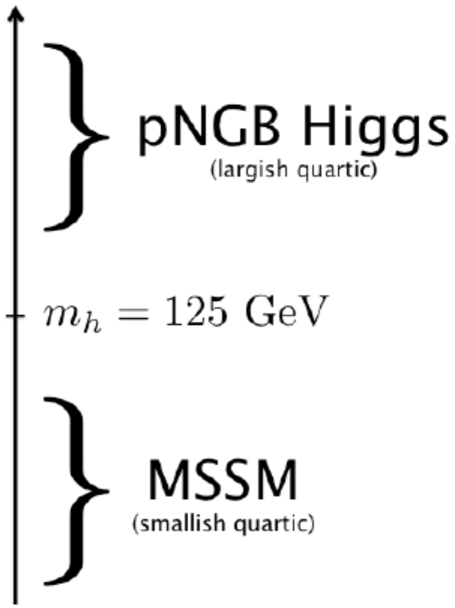
$$\lambda^2 v^2 \sin^2 2\beta + m_Z^2 \cos^2 2\beta$$

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



- **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% ?

What if there is only the SM?

Is nature natural?

Two (?) roads in front of us:

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

Is nature natural?

Any threshold coupled to the Higgs contributes to its mass

$$\delta m_H^2 \approx \frac{\alpha}{4\pi} M^2$$

Is gravity different? Does it introduce a new scale?

Maybe not, one example in 2D.

Dubovsky, Gorbenko, Mirbabayi 1305.6939

And in 4D?

Is nature natural?

Summa contra naturalitatem

from Giudice talk @ EPS

Giudice 1307.7879

Miracle of 3rd degree:
Gravity cures itself in UV and does not affect m_H (hypercharge asymptotic freedom? Landau poles?)

Miracle of 2nd degree:
Gravity cures itself and the SM in the UV, leaving no quadratic divergences.

Miracle of 1st degree:
Gravity cures UV and IR contributions to m_H.

19

Many have been focusing on 2nd degree miracle

(Bardeen, Meissner/Nicolai, Foot, Shaposhnikov, Lykken…)

A third (ugly) option

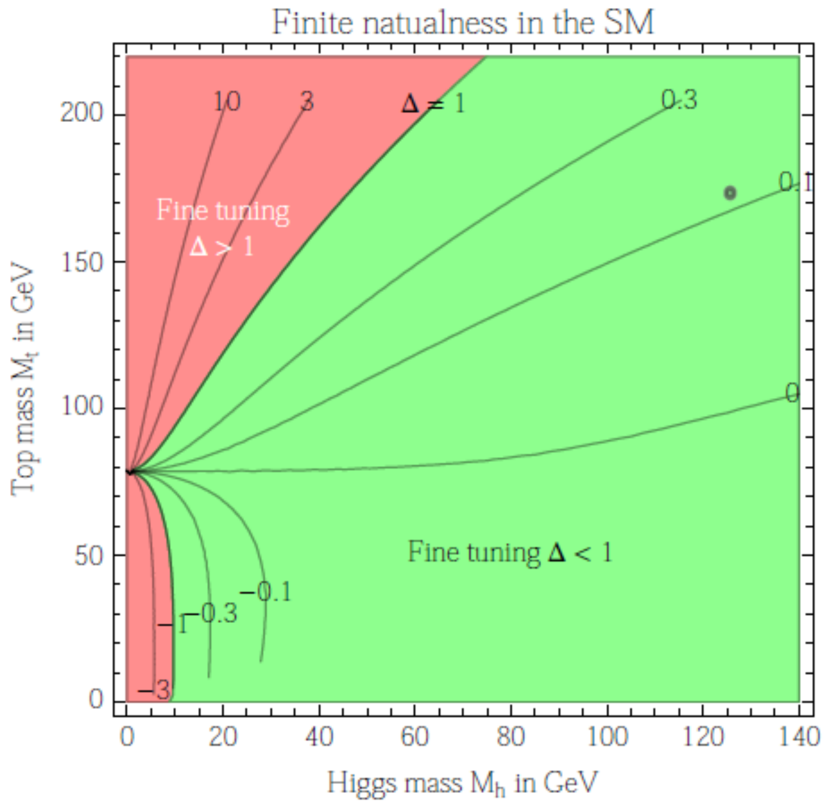
There is a third (ugly) path:

F, Pappadopulo, Strumia 1303.7244

- **Finite Naturalness**: the SM is valid up to arbitrary scale (i.e. up to Planck scale). Assume 2nd/3rd degree miracle
- However new physics is expected (dark matter, neutrino masses, strong CP problem/axions, etc...)
- Recipe: compute effective poten $\delta m_h^2 \lesssim M_h^2 \times \Delta$ ing quadratic divergences and ask the usual

The SM satisfies Finite Naturalness

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



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

Minimal Dark Matter

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Finite naturalness bound in TeV	σ_{SI} in $10^{-46}\ \text{cm}^2$
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(2.3 \pm 0.3)\ 10^{-2}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(2.5 \pm 0.8)\ 10^{-2}$
3	0	0	HH^*	$2.0 \to 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.60 ± 0.04
3	0	1/2	LH	$2.4 \to 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.60 ± 0.04
3	1	0	HH, LL	$1.6 \to ?$	540	$0.22 \times \sqrt{\Delta}$	0.06 ± 0.02
3	1	1/2	LH	$1.9 \to ?$	526	$1.0 \times \sqrt{\Delta}$	0.06 ± 0.02
4	1/2	0	HHH^*	$2.4 \to ?$	353	$0.14 \times \sqrt{\Delta}$	1.7 ± 0.1
4	1/2	1/2	(LHH^*)	$2.4 \to ?$	347	$0.6 \times \sqrt{\Delta}$	1.7 ± 0.1
4	3/2	0	HHH	$2.9 \to ?$	729	$0.14 \times \sqrt{\Delta}$	0.08 ± 0.04
4	3/2	1/2	(LHH)	$2.6 \to ?$	712	$0.6 \times \sqrt{\Delta}$	0.08 ± 0.04
5	0	0	(HHH^*H^*)	$5.0 \to 9.4$	166	$0.10 \times \sqrt{\Delta}$	5.4 ± 0.4
5	0	1/2	stable	$4.4 \to 10$	166	$0.4 \times \sqrt{\Delta}$	5.4 ± 0.4
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	22 ± 2

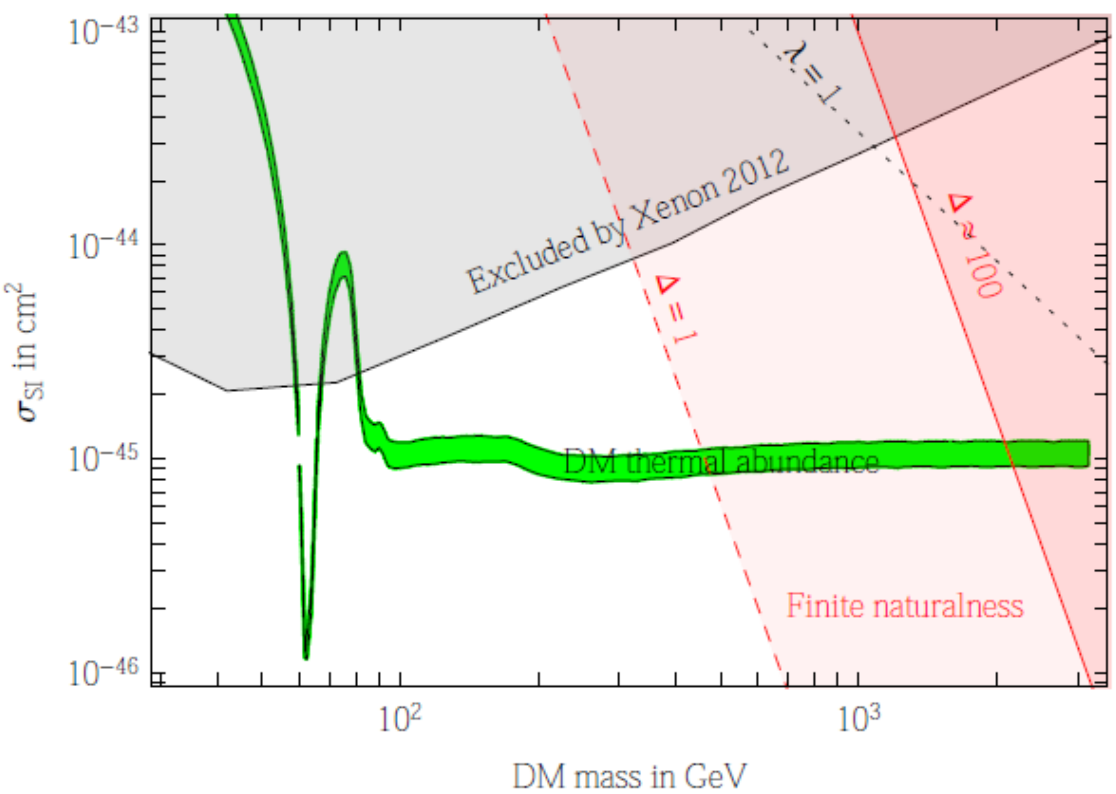
2-loops EW contribution

XENON100 limit > 10^-45

Singlet Dark Matter

Another possibility: DM without electroweak interactions.

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

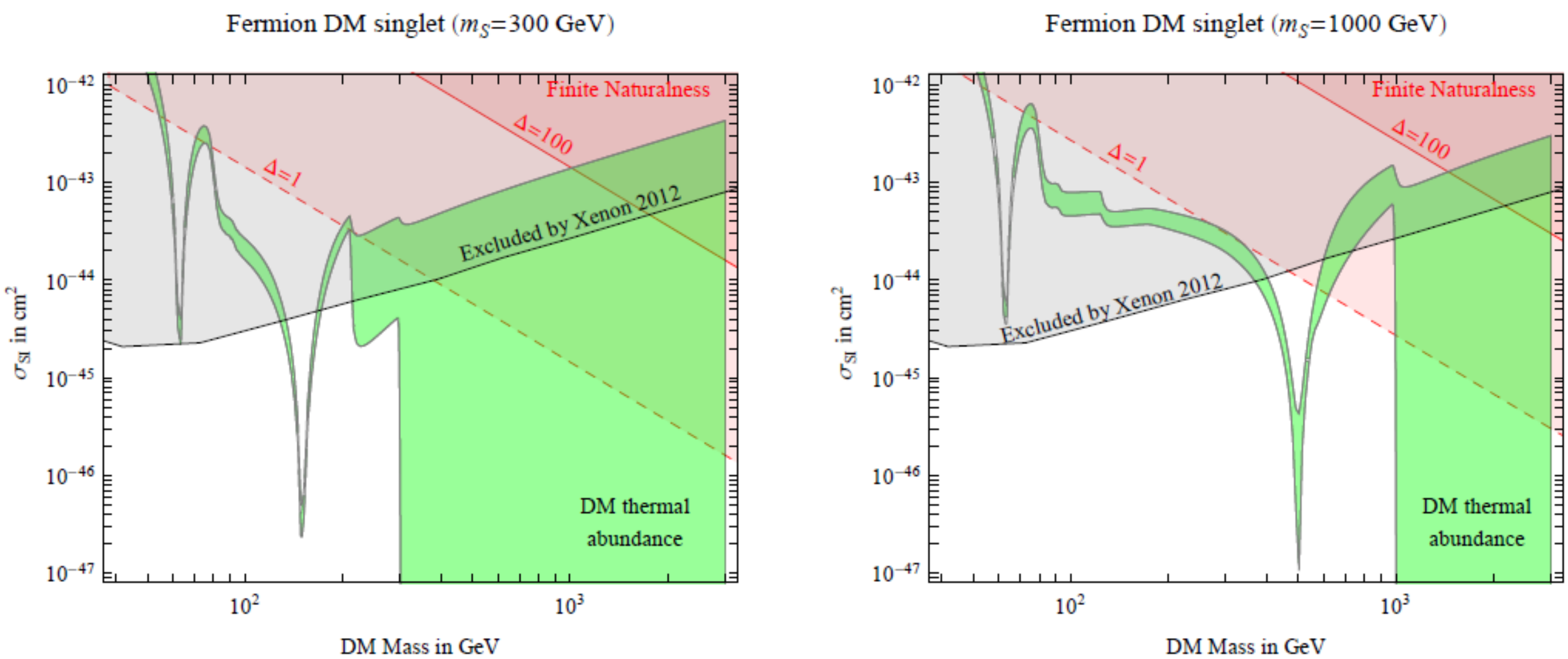


Singlet Dark Matter

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**:

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

- **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.).
  Do we have to rethink concepts taken for granted?

Conclusions II

Not very paradoxically the more natural the Higgs is the less it looks like a (SM) Higgs

- **Generic top partners**: direct connection of loop induced couplings and divergences cancellation (current FT ~10% - important at future colliders)

- **NMSSM**: large lambda can hurt, singlet mixing less helpful than expected (FT ~few %)

Conclusions

- **New states at TeV scale** (for any kind of Naturalness)
- **Higgs couplings deviations**

Conclusions

- **New states at TeV scale** (for any kind of Naturalness)

- **Higgs couplings deviations**

(Nothing is found. If the Higgs is God corpse just a long and detailed autopsy awaits…)