A crisis in physics? LHC results so far do not confirm the dominant theoretical paradigm about the origin of the weak scale

Is Nature Natural?

— A modified naturalness principle and its experimental tests —

1) What was found
2) What was not found
3) What does it mean?

Alessandro Strumia, Pisa University, INFN and NICPB

Talk at WIN 2013, September 19, 2013

Mobilitas
ESF programm
Euroopa Liit
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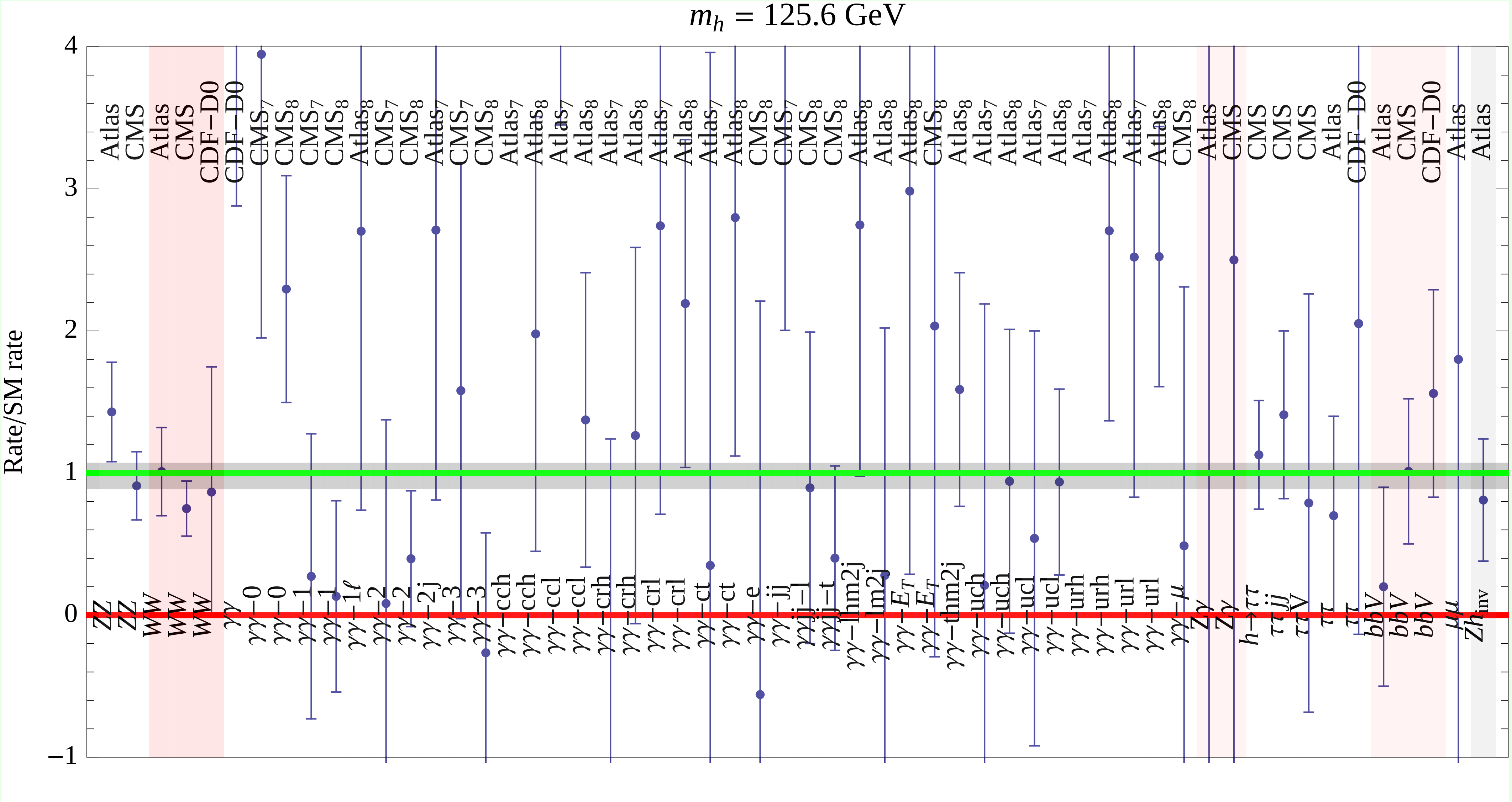
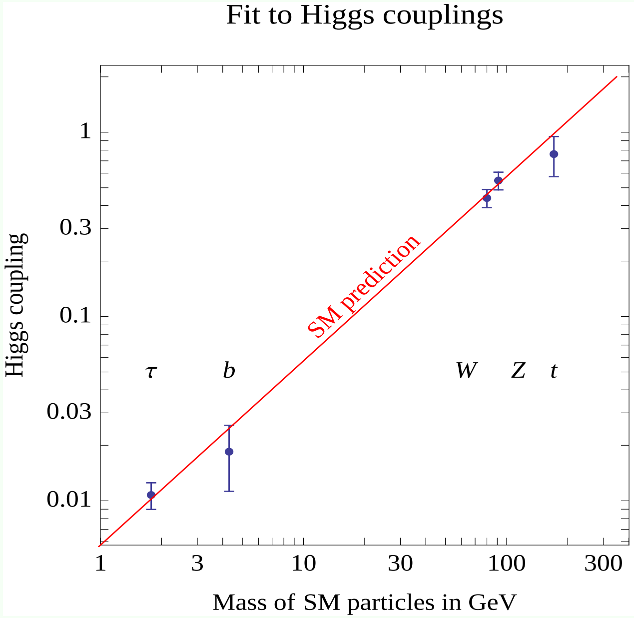
1) What was found

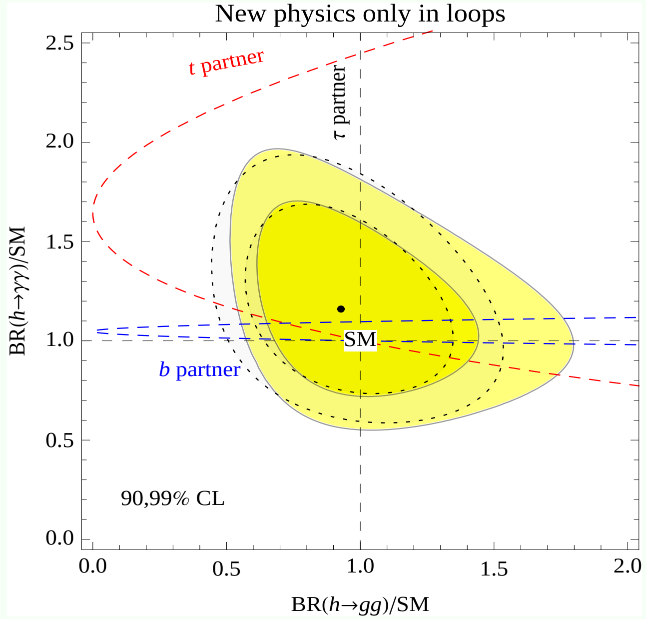
But should not have been found

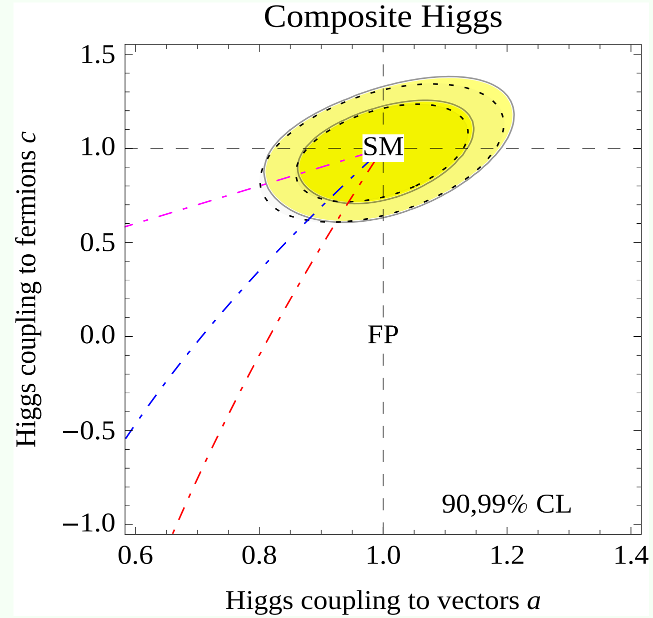
Only the Higgs

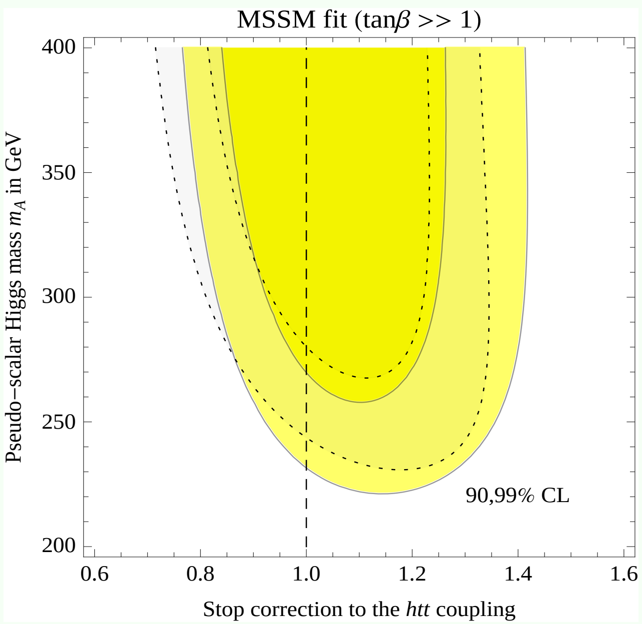


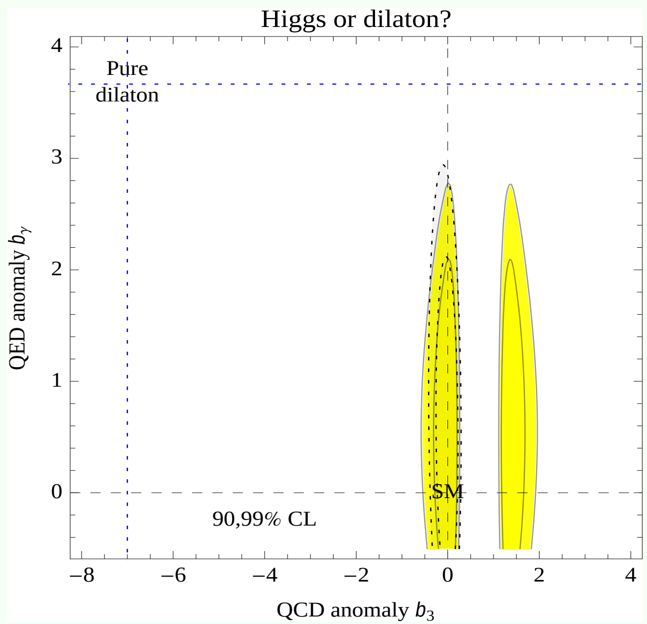
The SM Higgs

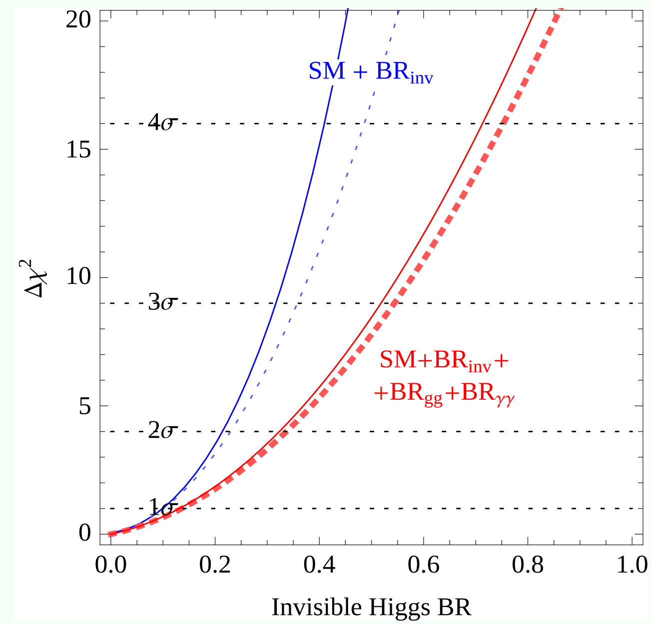

Fit to Higgs couplings
Higgs coupling
Mass of SM particles in GeV
SM prediction
τ
b
W
Z
t
1
0.3
0.1
0.03
0.01
1
3
10
30
100
300


New physics only in loops
BR(h→γγ)/SM
BR(h→gg)/SM
t partner
τ partner
b partner
SM
90,99% CL
0.0
0.5
1.0
1.5
2.0
2.5


Composite Higgs
Higgs coupling to fermions c
Higgs coupling to vectors a
SM
FP
90,99% CL
1.5
1.0
0.5
0.0
−0.5
−1.0
0.6
0.8
1.0
1.2
1.4


MSSM fit (tanβ >> 1)
Pseudo-scalar Higgs mass m_A in GeV
Stop correction to the htt coupling
90,99% CL
400
350
300
250
200
0.6
0.8
1.0
1.2
1.4
1.6

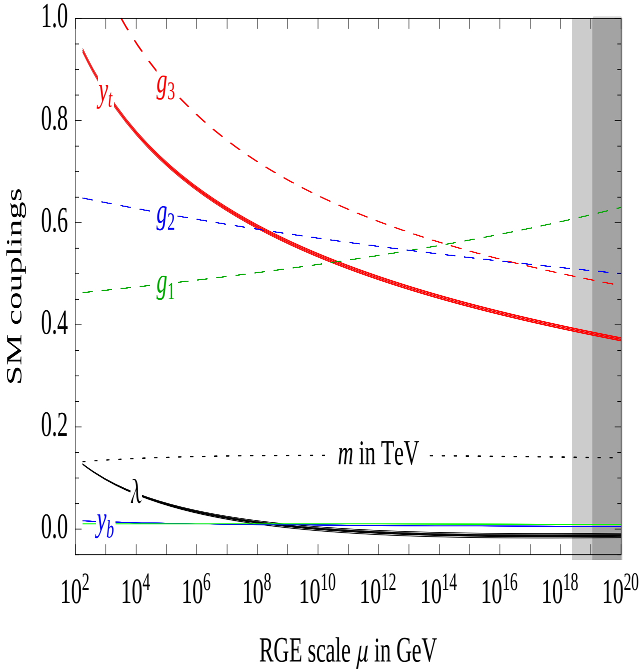

Higgs or dilaton?
QED anomaly b_γ
QCD anomaly b_3
Pure
dilaton
SM
90,99% CL
4
3
2
1
0
−8
−6
−4
−2
0
2
4

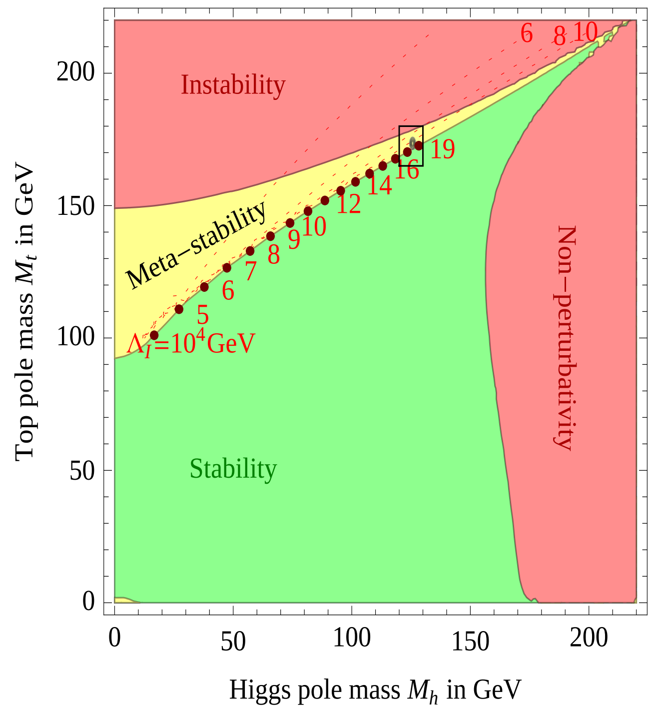

Δχ²
Invisible Higgs BR
SM + BR_inv
SM+BR_inv+
+BR_gg+BR_γγ
4σ
3σ
2σ
1σ
20
15
10
5
0
0.0
0.2
0.4
0.6
0.8
1.0

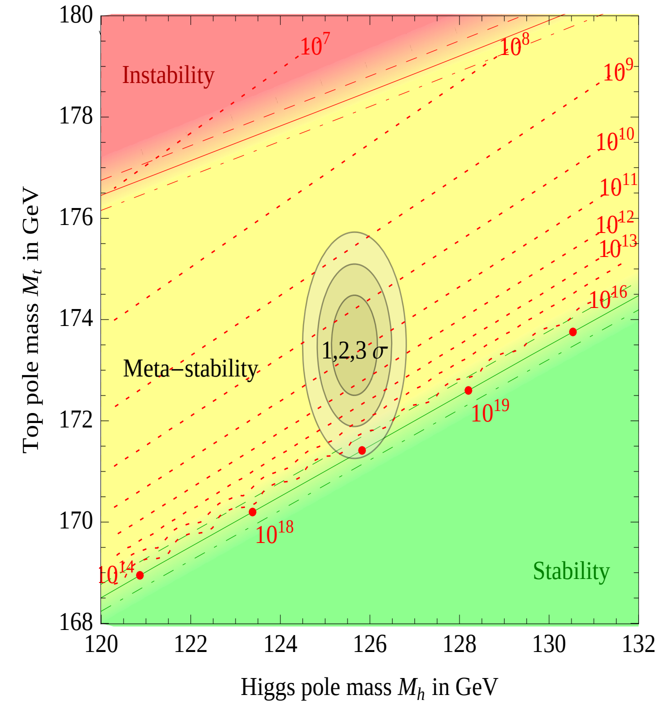
And nothing else

Maybe up to the Planck scale

For the measured M_h, M_t the SM can go up to $M_{\rm Pl}$ and is close to meta-stability





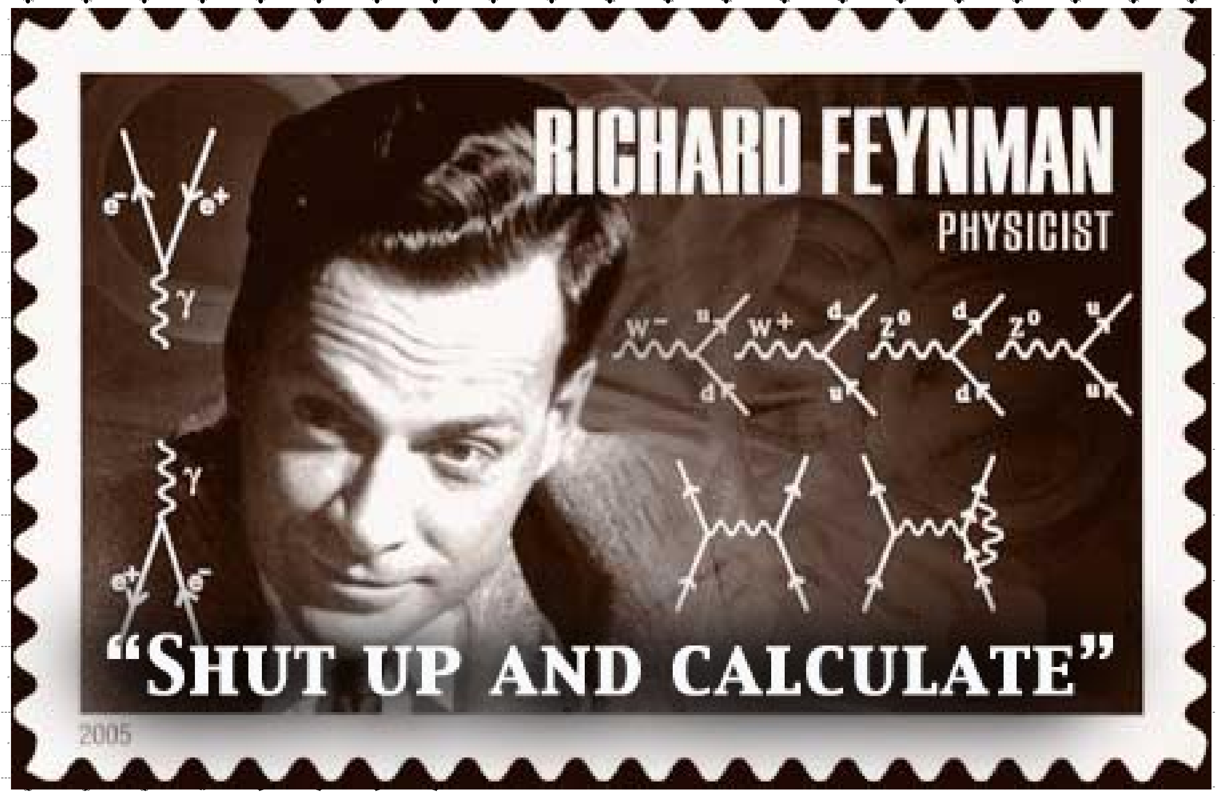


Parameters extracted with 2 loop accuracy and extrapolated with 3 loop RGE

$$\lambda(\bar\mu = M_t) = 0.1271 + 0.0021\left(\frac{M_h}{\rm GeV} - 125.66\right) - 0.00004\left(\frac{M_t}{\rm GeV} - 173.35\right) \pm 0.0003_{\rm th}$$

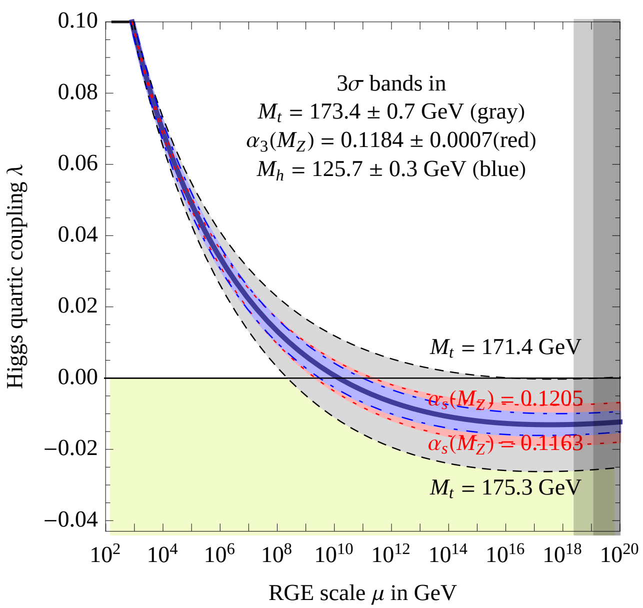
$$y_t(\bar\mu = M_t) = 0.9370 + 0.0055\left(\frac{M_t}{\rm GeV} - 173.35\right) - 0.0004\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.0005_{\rm th}$$

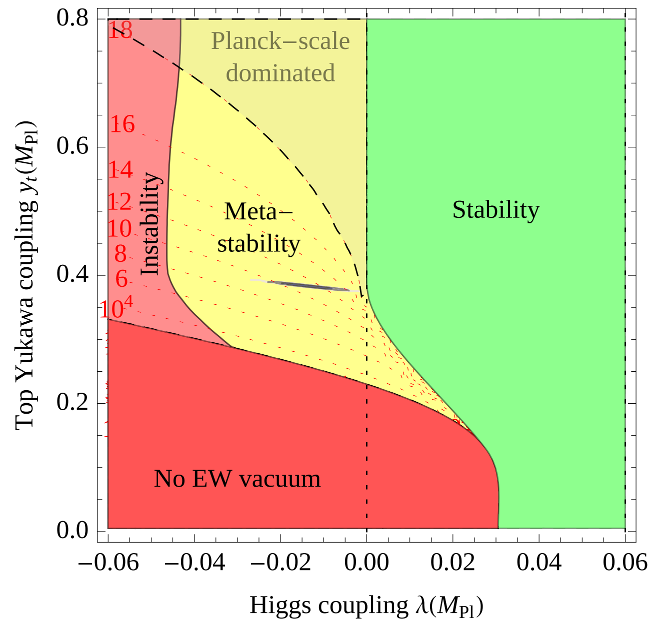
A tribute to Pier Paolo Giardino

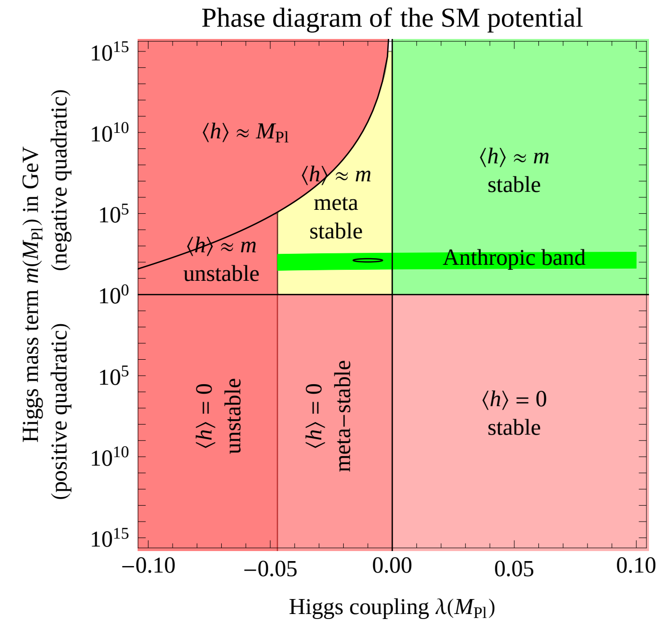


The SM close to criticality?

$M_h = (129.6 \pm 1.5)$ GeV **comes from** $V \approx 0h^2 + 0h^4$ **at** $M_{\rm Pl}$







For the measured masses even the β-function of λ ~vanishes around $M_{\rm Pl}$

An accident or a big message?

- Easy to explain $\lambda \approx 0$. Pseudo-Goldstone? SUSY with $\tan\beta = 1$?
- Difficult to explain $\beta(\lambda) \approx g^4 - y_t^4 \approx 0$. Criticality? Extrapolation to infinity?

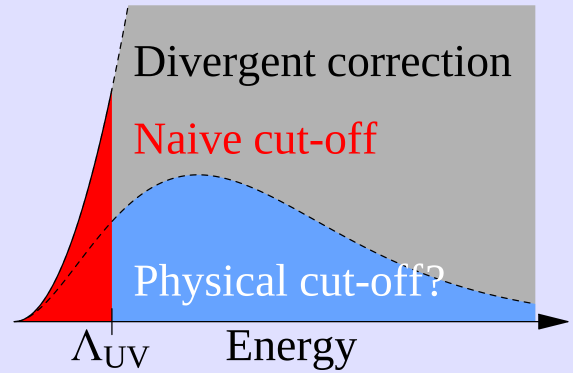
2) What was not found

But it should have been found

A solution to the hierarchy problem

In quantum "Everything not forbidden is mandatory" (Hassan i Sabbah).
No symmetry forbids a large quantum correction to $m^2_{\rm Higgs} \sim 10^{-32} M^2_{\rm Pl}$.
New physics must cut-off the loop integral before it gets unnaturally big.

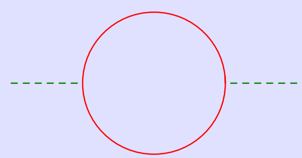
$$\delta m^2_{\rm Higgs} \sim \int^\Lambda \frac{d^4k}{k^2} =$$



The naturalness principle: light scalars do not exist unless they come together with new physics that protects their lightness, such as SUSY, technicolor…

The top loop gives a quadratically divergent correction to M_h, cut-offing at M:

$$\delta m_h^2 \approx \delta m_h^2(\text{top}) =$$



$$\approx \frac{12\lambda^2_{\rm top}}{(4\pi)^2} M^2 \times \begin{cases} 1 \\ \ln M^2_{\rm Pl}/M^2 \end{cases}$$

Imposing naturalness $\delta m_h^2 \lesssim m_h^2 \times \Delta$ up to a fine-tuning Δ,

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 400\ \text{GeV} \\ 50\ \text{GeV} \end{cases}$$ **Not many TeV!**

Past performance

$\surd$ Those Higgs-like scalars present in field theories of condensed matter are not unnaturally lighter than their ultimate cut-off: the atomic lattice.

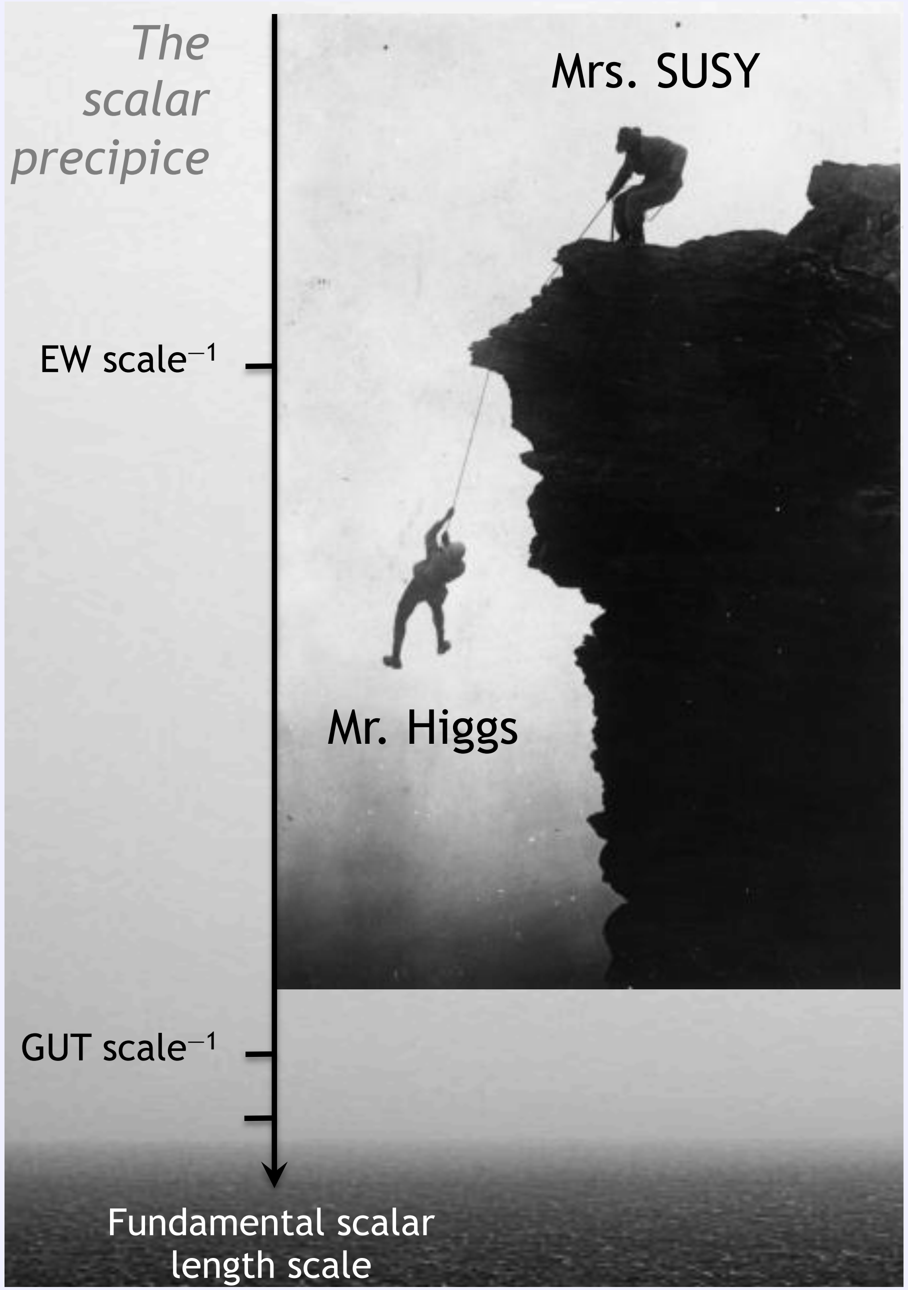
$\surd$ The electron mass receives divergent electromagnetic corrections
Naturalness holds thanks to new physics: chiral symmetry of $e^{\pm}$ fermions.

$\surd$ $m^2_{\pi^\pm} - m^2_{\pi^0}$ receives power divergent electromagnetic corrections.
Naturalness holds thanks to new physics: π are QCD composite of fermions.

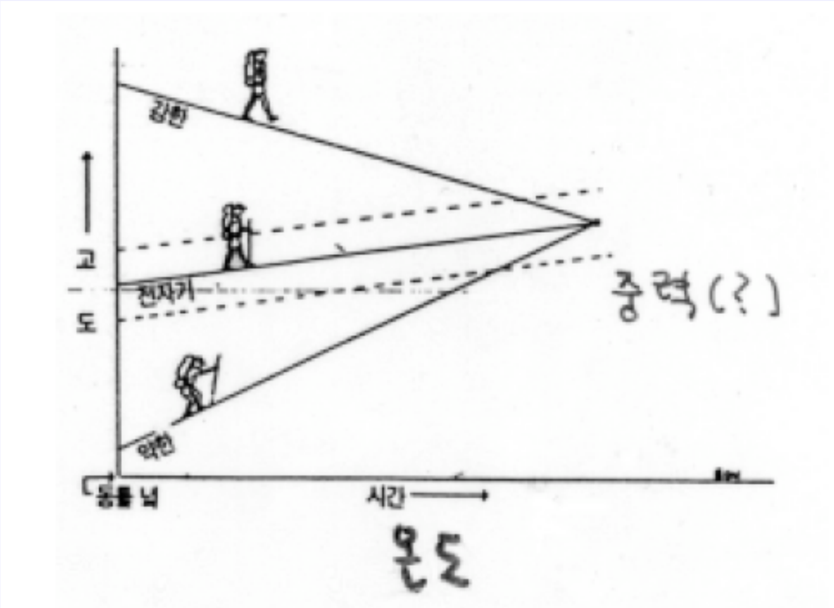
$\surd$ K mixing receives power divergent corrections.
Naturalness holds thanks to new physics: the charm.

? *The Higgs mass receives power divergent corrections.*
Naturalness wants new physics to again appear at the right energy.

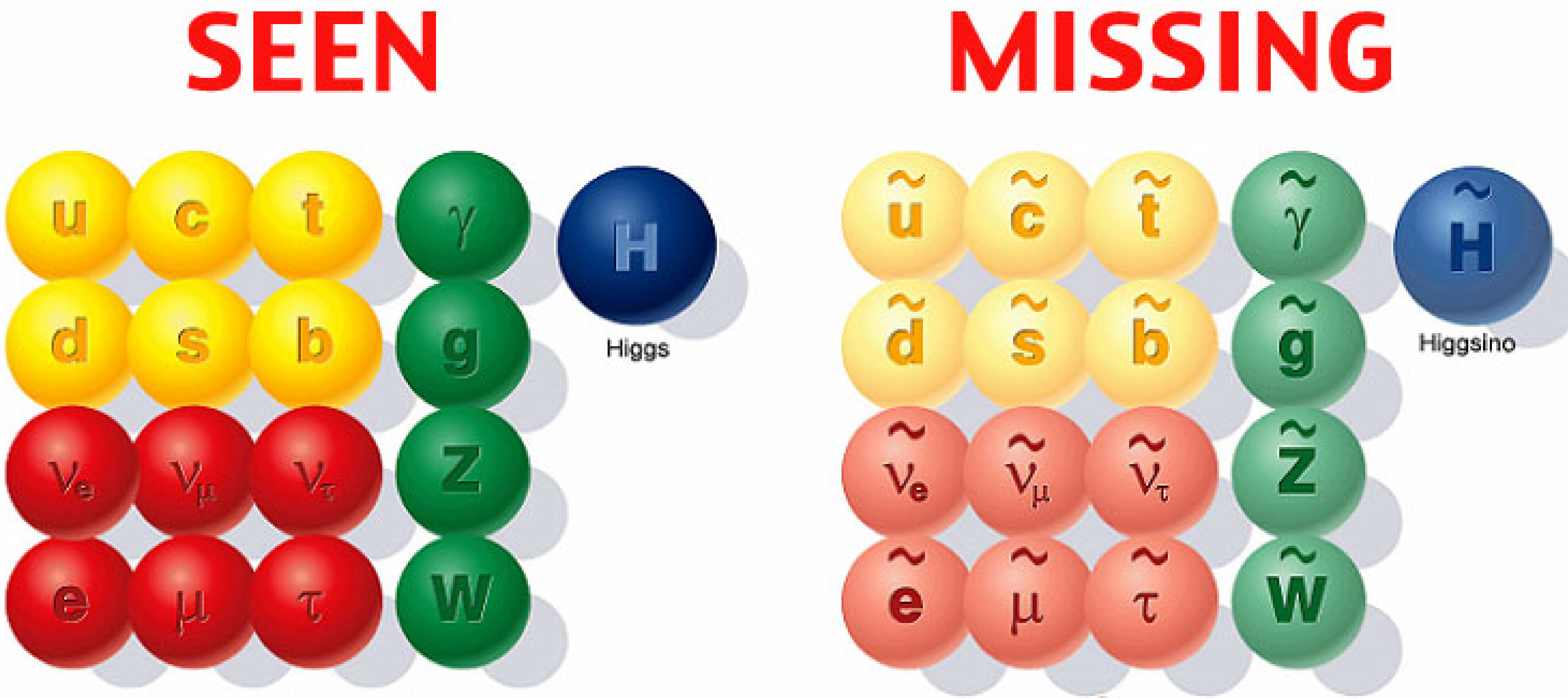
The solution to the hierarchy problem



- ⋆ SUSY stabilizes Higgs: the weak scale is the scale of SUSY breaking.
- ⋆ SUSY extends Lorentz.
- ⋆ SUSY unifies fermions with bosons.
- ⋆ SUSY unifies gauge couplings.



- ⋆ SUSY gives DM aka ‘neutralino’.
- ⋆ SUSY is predicted by super-strings.
- ⋆ Worry: too many sparticles at LHC?



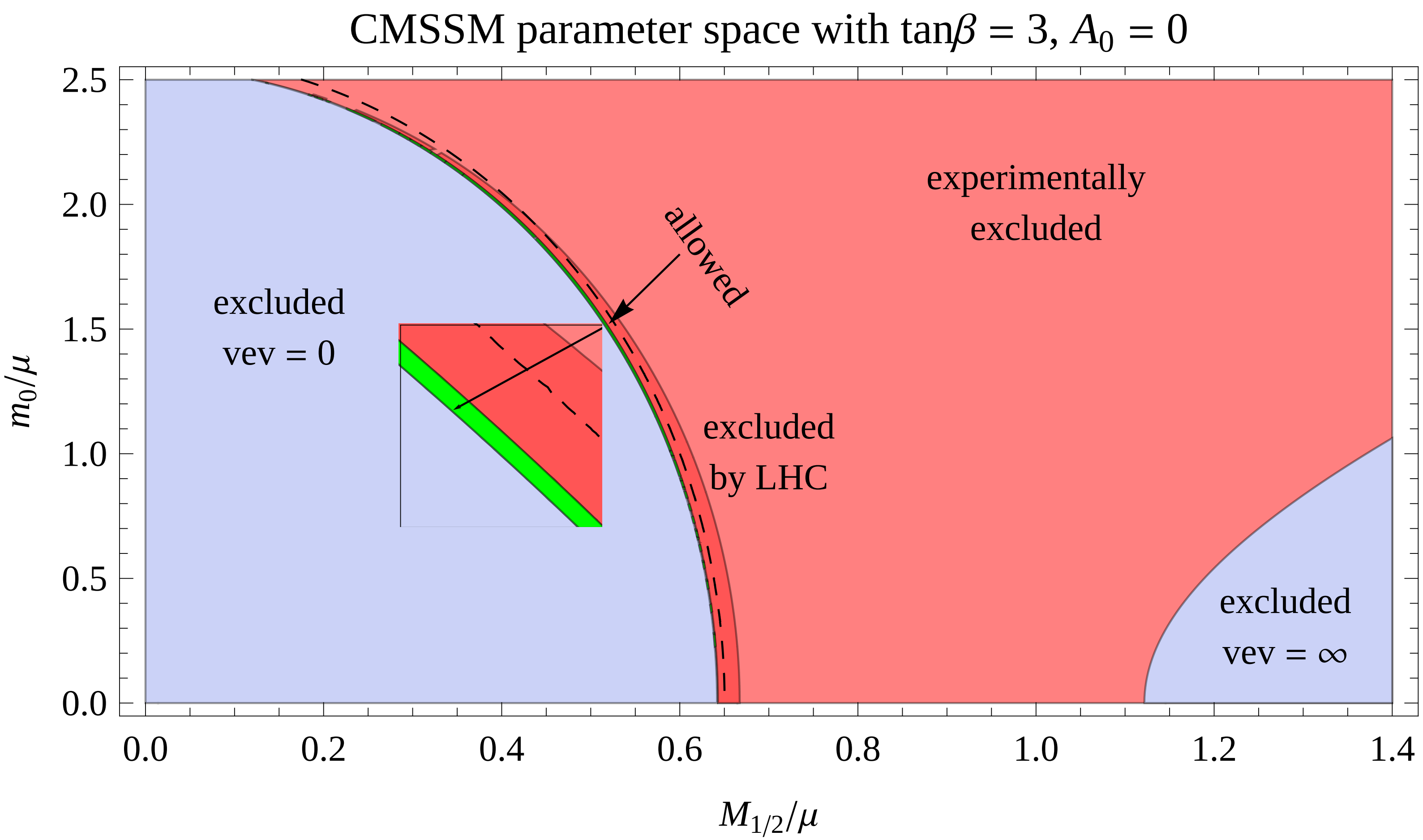
After LHC run I the missing super-partner problem can no longer be ignored

The CMSSM

The SUSY scale should have been the scale of EWSB breaking

$$M_Z^2 \approx 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2 = (91\,\text{GeV})^2 \times (\frac{M_3}{110\,\text{GeV}})^2 + \cdots$$

Use adimensional ratios as parameters and fix the SUSY scale from M_Z: LEP and later LHC excluded all the parameter space away from the critical line $v = 0$



Beyond the CMSSM

Many models, even at the level of one-letter extensions of the MSSM

AMSSM, BMSSM, CMSSM, DMSSM, EMSSM, FMSSM, GMSSM, HMSSM, IMSSM, KMSSM, MMSSM, NMSSM, OMSSM, PMSSM, QMSSM, RMSSM, SMSSM, TMSSM, UMSSM, VMSSM, XMSSM, YMSSM, ZMSSM

All of them have similar problems: the unit of measure is the kilo-fine-tuning.

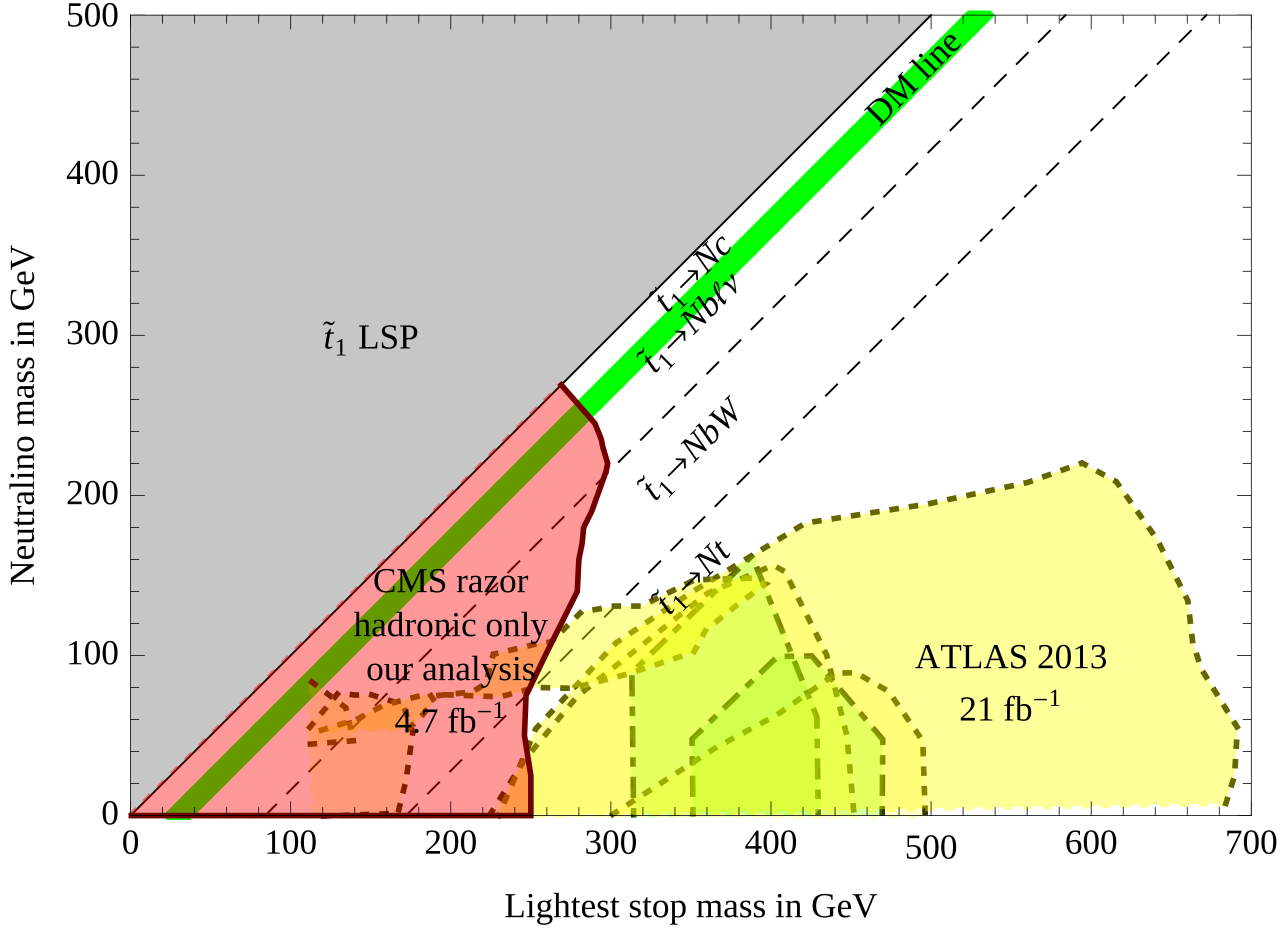
A possibility often considered after LHC is 'natural SUSY': abandon models and maximise naturalness keeping only the sparticles more relevant for it: $\tilde{t}, \tilde{b}_L, \tilde{g}$:

$$\delta M_Z^2 \propto y_t^2 m_{\tilde{t}}^2 \qquad \delta m_{\tilde{t}}^2 \propto g_3^2 M_3^2$$

So searches for gluinos and stops are particularly important.

Stop bounds

Gren band: correct DM abundance thanks to neutralino/stop coannihilations.



Small stop/neutralino mass difference: 30 GeV. Stop decays are $\approx$ invisible. Bound from theorist re-analyses of 7 TeV data relying on **jet initial state radiation**. Big and fully model independent QCD cross section $pp \to \tilde{t}\,\tilde{t}^* +$jets.

Natural SUSY: "not very satisfactory"

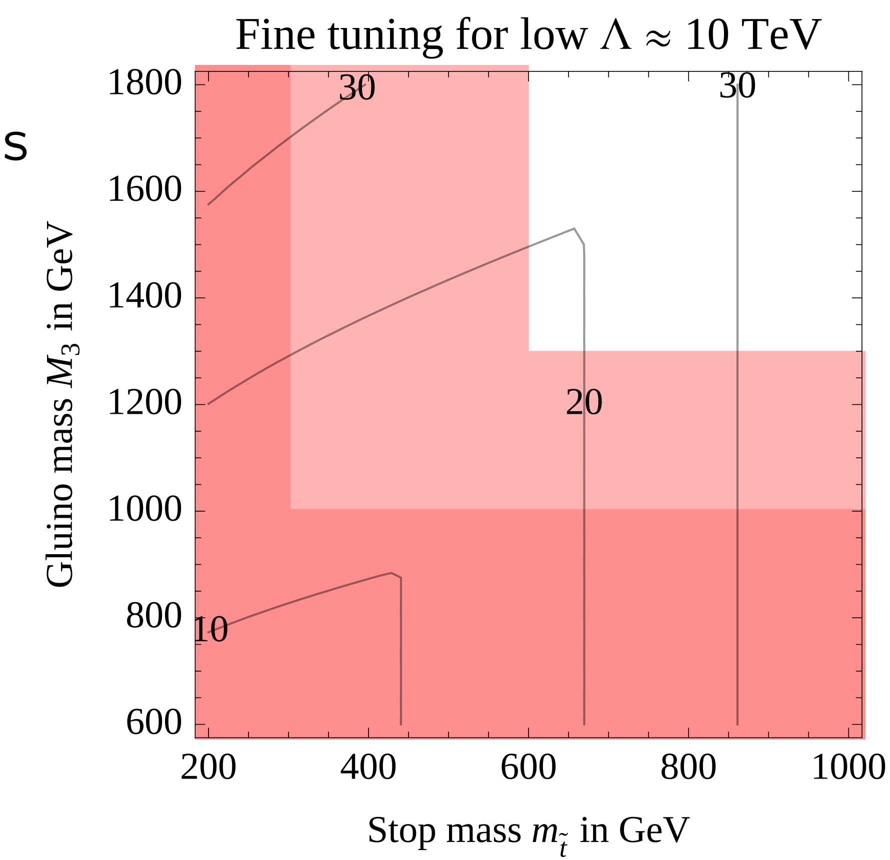
Even including quantum corrections only below a relatively low cut-off Λ,

$$\delta M_Z^2 \approx \frac{24 y_t^2}{(4\pi)^2} m_{\tilde t}^2 \left(1 + \frac{X_t^2}{3}\right) \ln \frac{\Lambda}{m_{\tilde t}}$$

for $\tan\beta \gg 1$, and

$$\delta m_{\tilde t}^2 \approx \frac{32 g_3^2}{3(4\pi)^2} M_3^2 \ln \frac{\Lambda}{M_3},$$

the fine-tuning now is $\Delta \sim 10 - 20$.



Reducing $\tan\beta$ does not help, worse FT to get a heavy enough Higgs:

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde t}^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] \qquad X_t = \frac{A_t + \mu\cot\beta}{m_{\tilde t}}$$

Jumping the shark

Break R-parity to try to weaken the experimental bound $M_3 \gtrsim 1.1\,\text{TeV}$:

- Leptonic RPV give leptonic gluino decays making bounds on M_3 stronger.
- Hadronic RPV is crazy and does not allow to go at $M_3 < 700\,\text{GeV}$.

Dirac gauginos reduce $\ln \Lambda/M_3 \to \mathcal{O}(1)$ but increase the exp bound on M_3.

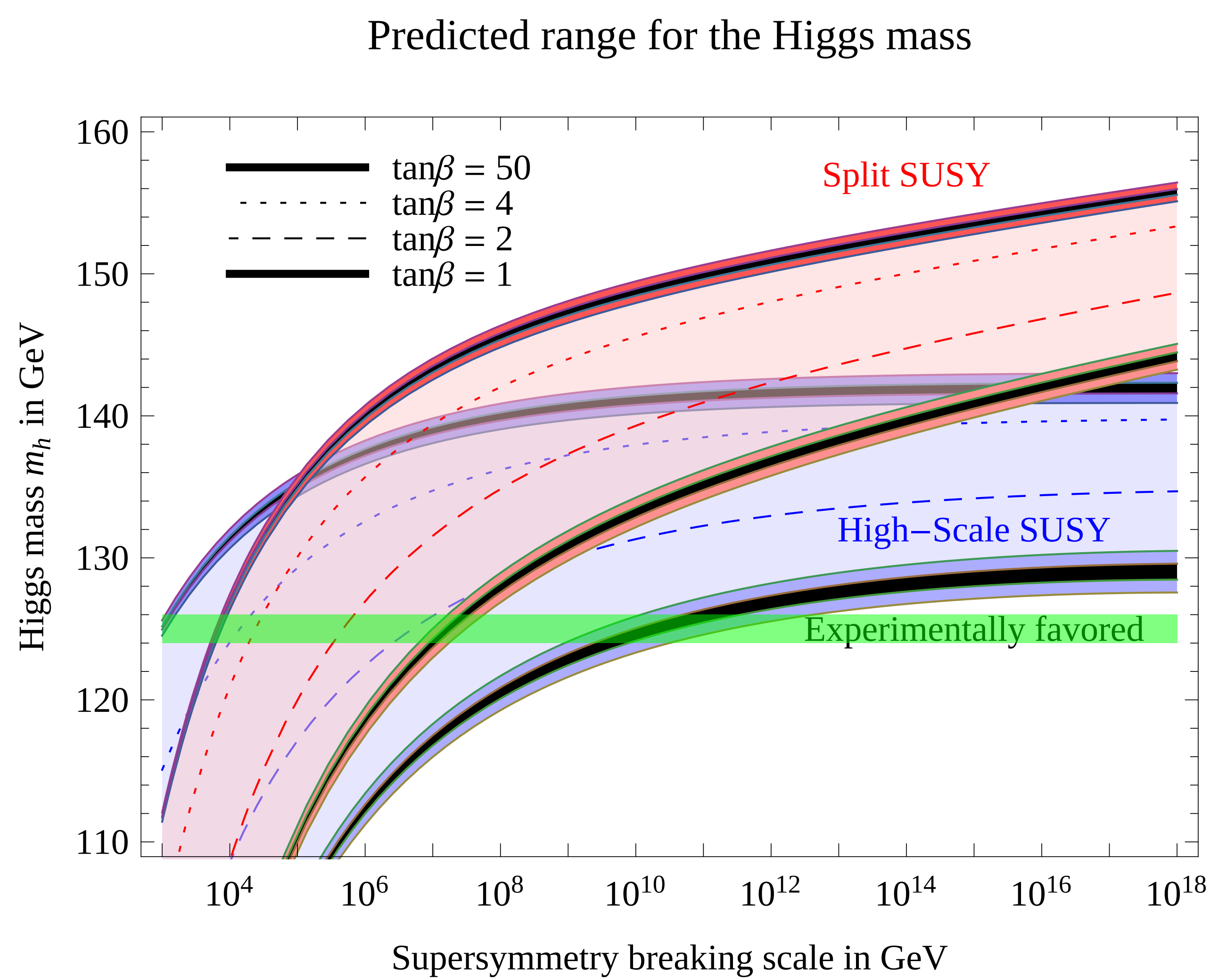
Compressed sparticle spectra to reduce signals, but μ should naturally be light because of $M_Z^2 = -2\mu^2 + \cdots$. And having all sparticles light is bad.

"We must be careful to rashly reject a new idea. Yet I dare say that this assumption ... is not very satisfactory" (Lorentz about the Stokes-Planck proposal that the aether can be compressed by gravity in the vicinity of earth).

Fine-tuning started and we do not know where it will stop: TeV? PeV? EeV?

Getting the SUSY scale from M_h

SUSY might exist above the weak scale for reasons unrelated to naturalness. The MSSM predicts $0 < \lambda < (g_2^2 + g_Y^2)/8$, so $M_h \sim \sqrt{\lambda} v$ offers a new handle to guess where SUSY could be. 125 GeV means λ just below 0 at high scale.

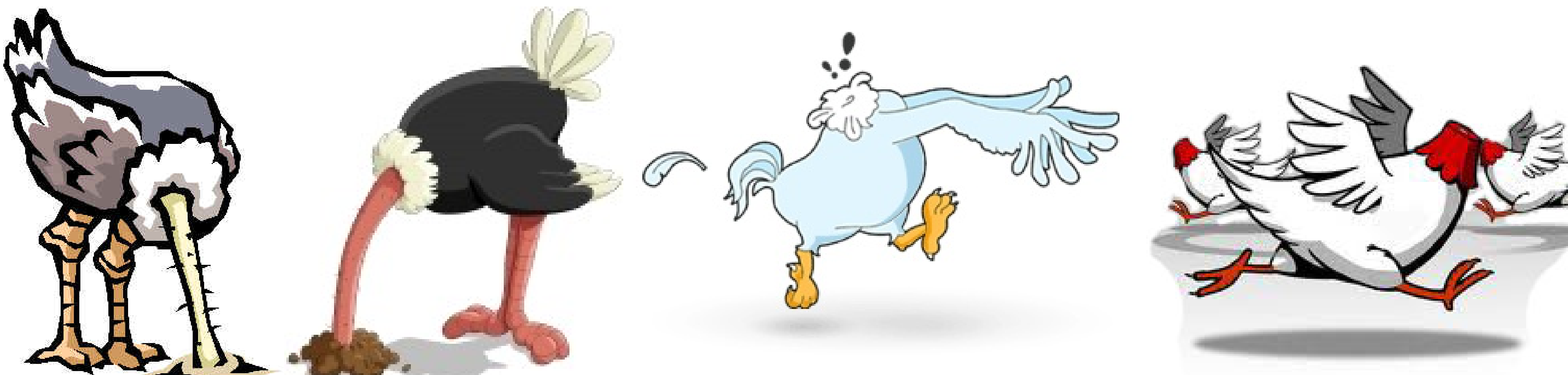


Like ambiguos oracles: Ibis redibis non morieris in bello

3) What does it mean?

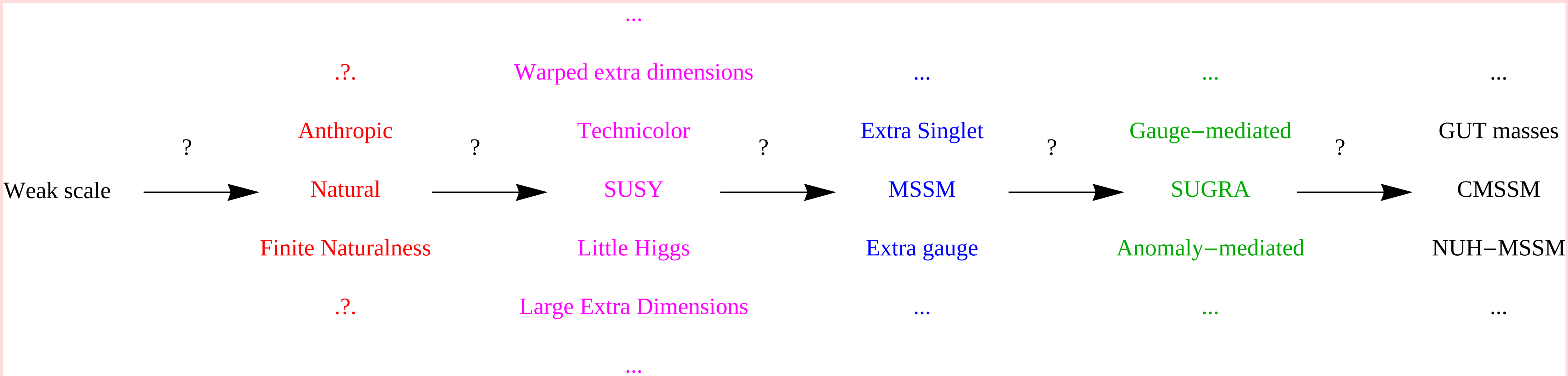
SCALAR FOUND, NO SUSY

The triumph of the SM. Naturalness in trouble. Vacuum will decay?



The Great Leap Backward

Theorists proposed a beautiful plausible detailed scenario beyond the SM



LHC brings us to reconsider the most interesting and basic question

Is Nature Natural?

Data do not support the **naturalness principle**. Waiting for the 14 TeV run, the present situation is often presented as a dichotomy, even as a monochtomy

From talks of Arvinataki, Dimopoulos, and Villadoro with the wall

There is at least one more possibility...

The good, the bad, the ugly

The **good possibility** of naturalness is in trouble.

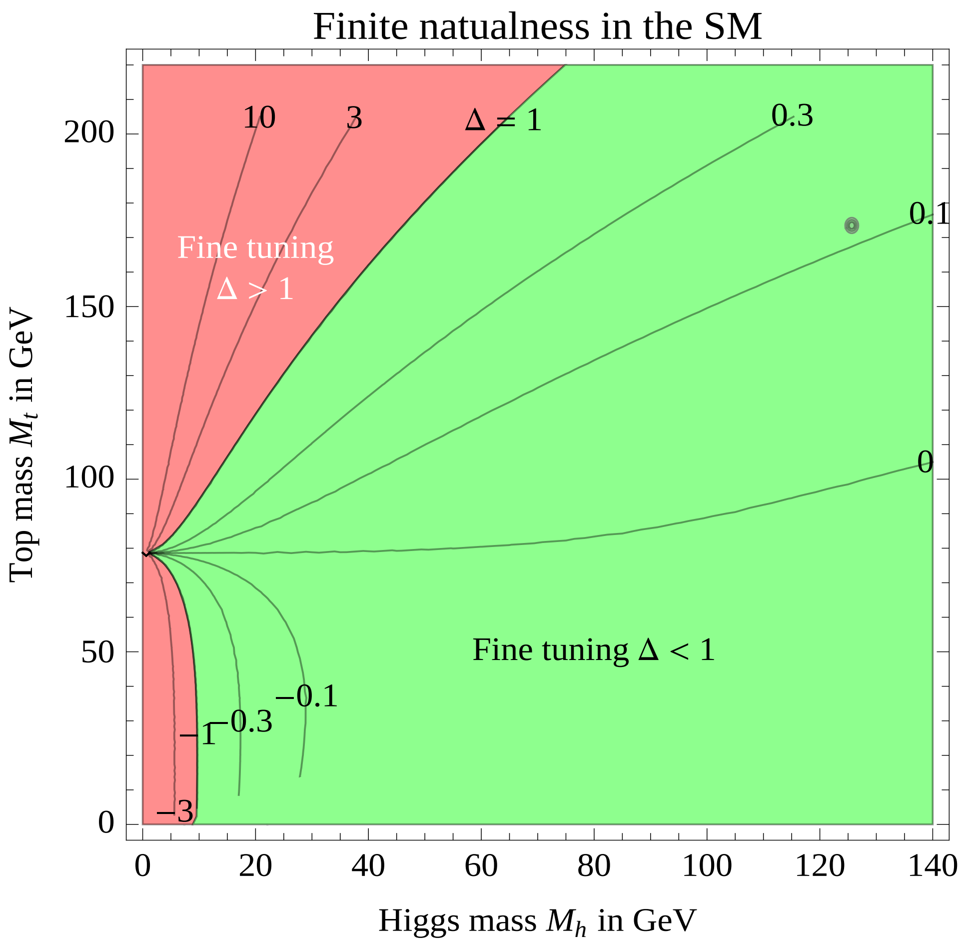
The **bad possibility** is that the Higgs is light because of ant**pic selection. (A bigger vev makes atoms impossible; a bigger Λ makes galaxies impossible). Then, one expects that H is the only light scalar. So DM — if at the weak-scale (but why?) — would be a fermion: Split SUSY, Minimal Dark Matter. Axions/Higgs unification, special fermionic models can fit the $g-2$ anomaly...

The ugly possibility is that a modified Finite Naturalness applies, where quadratic divergences are ignored. They are unphysical, so nobody knows if they vanish or not. Scale invariance does not help, because the answer is chosen by the unknown physical cut-off. Surely it is not a Lorentz-breaking lattice. Maybe it behaves like dimensional regularization.

I don't want to advocate, but to explore its consequences and tests.
Finite naturalness is here considered only as a pure
mathematical hypothesis without any pretence of truth

The SM satisfies Finite Naturalness

Quantum corrections to the dimensionful parameter $m^2 \simeq M_h^2$ in the SM Lagrangian $\frac{1}{2}m^2|H|^2 - \lambda|H|^4$ are small for the measured values of the parameters



From arXiv:1303.7244

$$M_h = 125.6\,\text{GeV} \;\Rightarrow\; m(\bar\mu = M_t) = 132.7\,\text{GeV} \;\Rightarrow\; m(\bar\mu = M_{\text{Pl}}) = 140.9\,\text{GeV}$$

Finite Naturalness and new physics

FN would be ruined by new heavy particles coupled to the SM (such as GUT).

FN holds if the top really is the top — if the weak scale is the highest scale.

New physics is demanded by data: DM, neutrino masses, maybe axions...

FN still holds if such new physics lies not much above the weak scale.

Is this possible? If yes what are the signals?

Finite Naturalness and new physics

Neutrino mass models add extra particles with mass M

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

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

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

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.

DM with EW gauge interactions

Consider a Minimal Dark Matter n-plet. 2-loop quantum corrections to M_h^2:

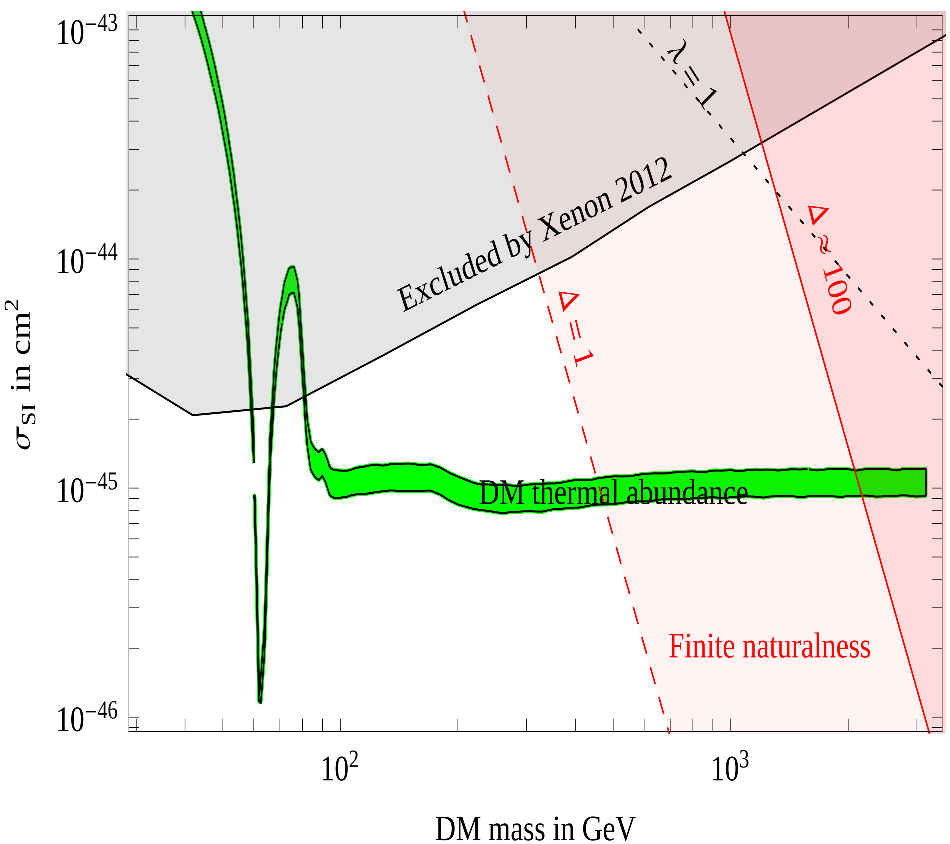
$$\delta m^2 = \frac{cnM^2}{(4\pi)^4}\left(\frac{n^2-1}{4}g_2^4 + Y^2 g_Y^4\right) \times \begin{cases} 6\ln\frac{M^2}{\Lambda^2} - 1 & \text{for a fermion} \\ \frac{3}{2}\ln^2\frac{M^2}{\Lambda\mu^2} + 2\ln\frac{M^2}{\Lambda^2} + \frac{7}{2} & \text{for a scalar} \end{cases}$$

Quantum numbers $\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{\mathrm{DM}^\pm} - m_{\mathrm{DM}}$ in MeV	Finite naturalness bound in TeV, $\Lambda \sim M_{\mathrm{Pl}}$	σ_{SI} in $10^{-46}\,\mathrm{cm}^2$
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

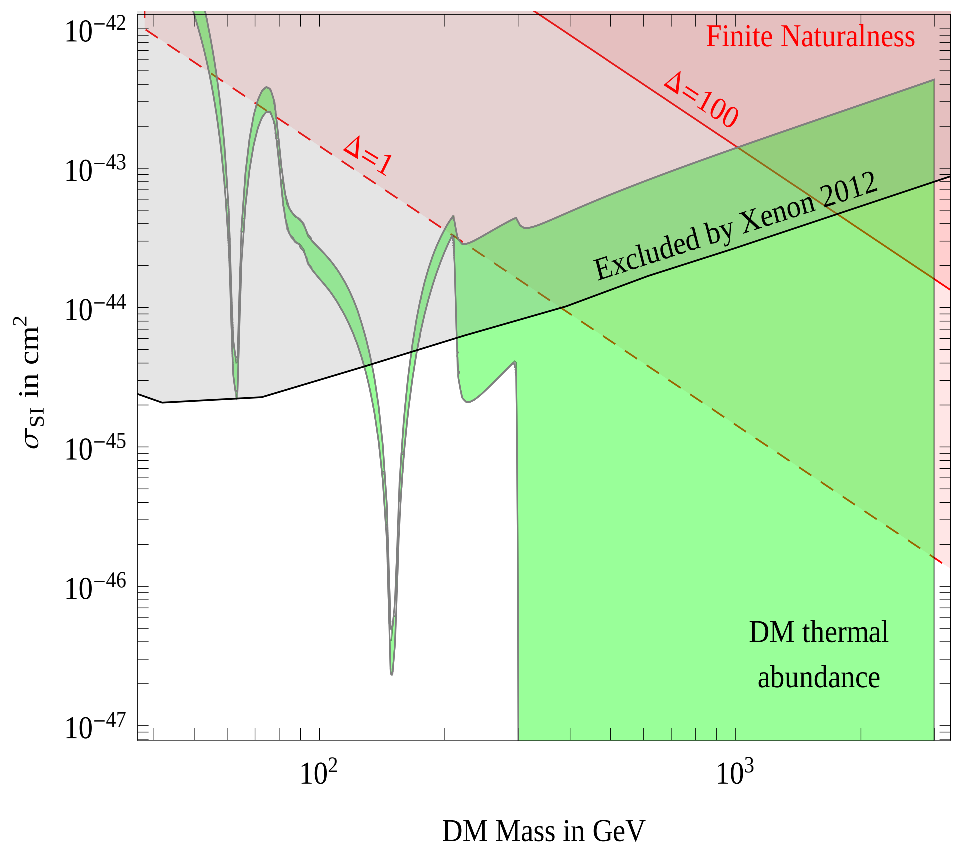
DM without EW gauge interactions

DM coupling to the Higgs determines Ω_{DM}, σ_{SI} and Finite Naturalness δm^2

scalar DM singlet



Fermion DM singlet (m_S=300 GeV)



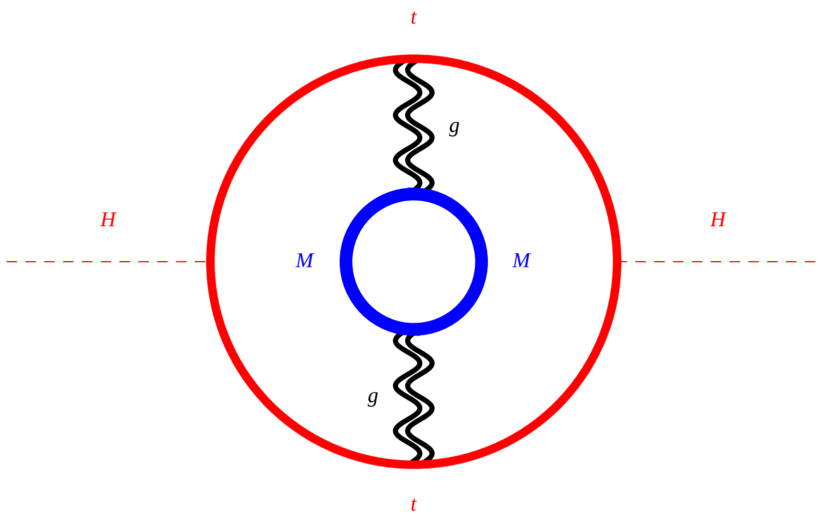
Observable DM satisfies Finite Naturalness if lighter than $\approx 1\,\text{TeV}$

What is the weak scale?

In the context of FN

1. Could be the only scale of particle physics. Just so.

2. Could be the shadow of a new particle with mass $M \sim 10^{14}$ GeV coupled only gravitationally to the SM. At 3 loops it gives $\pm$ the Higgs mass.



Other scalars (DM?) would similarly be at the weak scale.

3. Could be generated dynamically from nothing, like the QCD scale...

Dynamical generation of the weak scale

Goals:

1) **Dynamically generate** the weak scale and weak scale DM
2) **Preserve** the successful automatic features of the SM: B, L...
3) **Get DM stability** as one extra automatic feature.

Model: $G_{\mathsf{SM}} \otimes \mathsf{SU}(2)_X$ with one extra scalar S, doublet under $\mathsf{SU}(2)_X$ and

$$V = \lambda_H |H|^4 - \lambda_{HS} |HS|^2 + \lambda_S |S|^4.$$

Dynamical generation of the weak scale

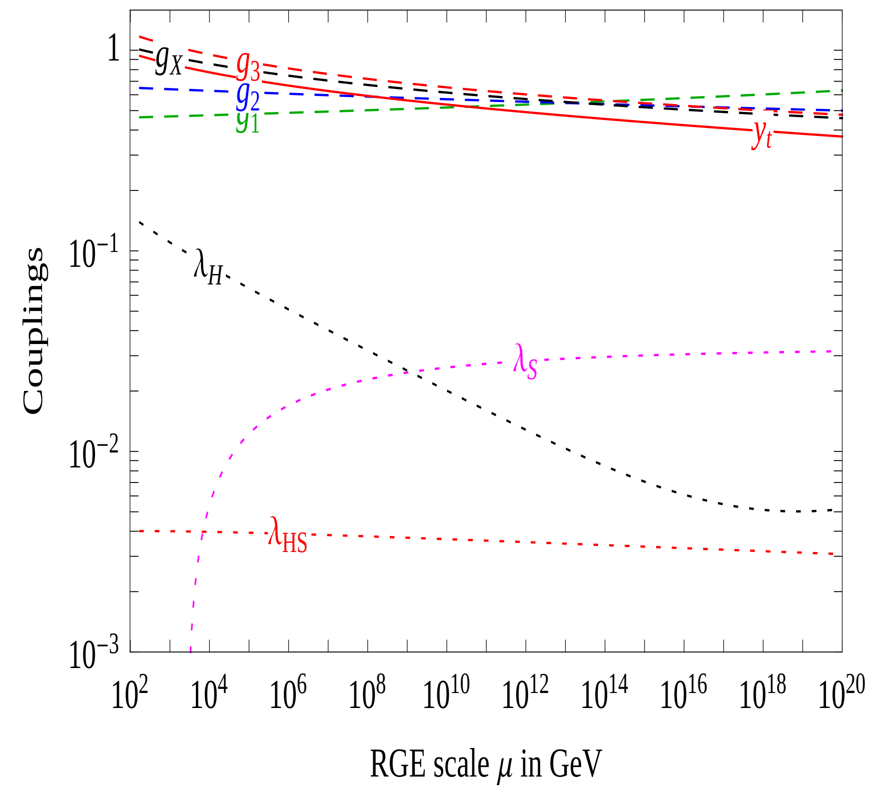
1) λ_S runs negative at low energy:

$$\lambda_S \simeq \beta_{\lambda_S} \ln \frac{s}{s_*} \qquad \text{with} \qquad \beta_{\lambda_S} \simeq \frac{9 g_X^4}{8(4\pi)^2}$$

$$S(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ w + s(x) \end{pmatrix} \qquad w \simeq s_* e^{-1/4}$$

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \qquad v \simeq w \sqrt{\frac{\lambda_{HS}}{2\lambda_H}}$$

2) No new Yukawas.



3) SU(2)$_X$ vectors get mass $M_X = \frac{1}{2} g_X w$ and are automatically stable [Hambye].

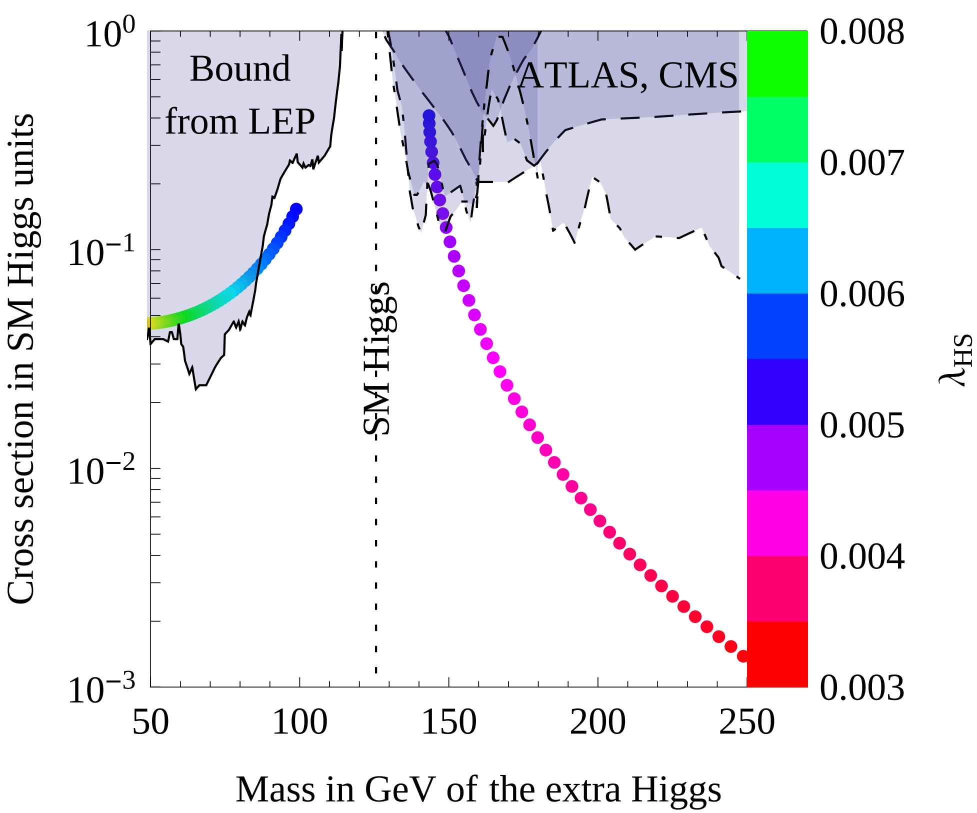
4) Bonus: threshold effect stabilises $\lambda_H = \lambda + \lambda_{HS}^2/\beta_{\lambda_S}$.

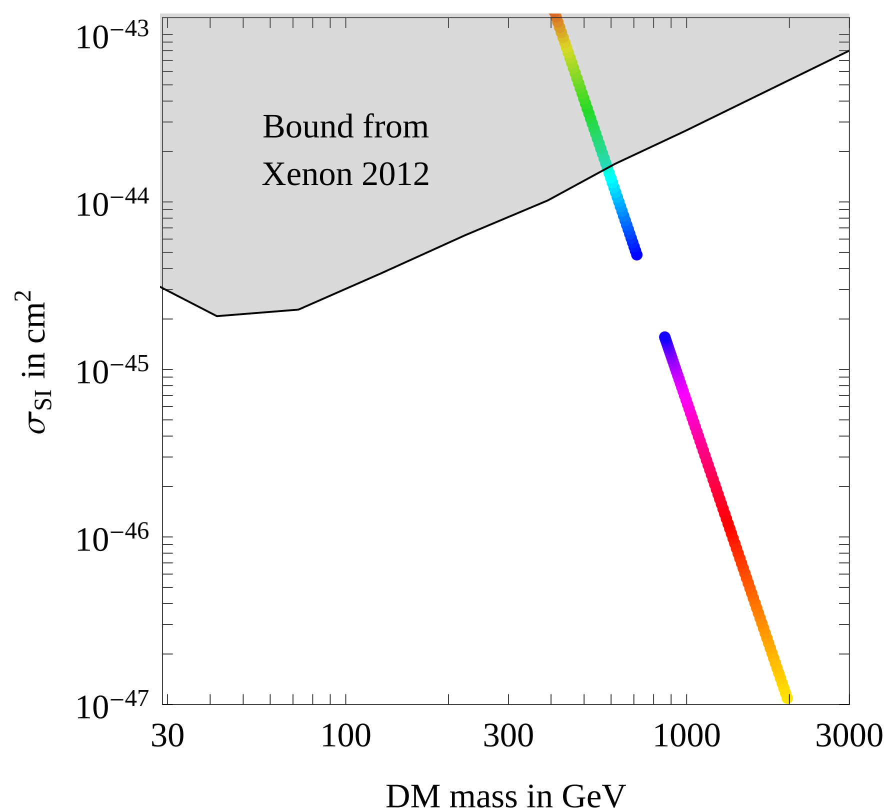
Experimental implications

1) New scalar s: like another h with suppressed couplings; $s \to hh$ if $M_s > 2M_h$.
2) Dark Matter coupled to s, h. Assuming that DM is a thermal relict

$$\sigma v_{\rm ann} + \frac{1}{2}\sigma v_{\rm semi-ann} = \frac{11 g_X^2}{1728\pi w^2} + \frac{g_X^2}{64\pi w^2} \approx 2.3 \times 10^{26}\,\frac{\rm cm^3}{\rm s}$$

fixes $g_X = w/1.9\,\text{TeV}$, so all is predicted in terms of one parameter λ_{HS}:





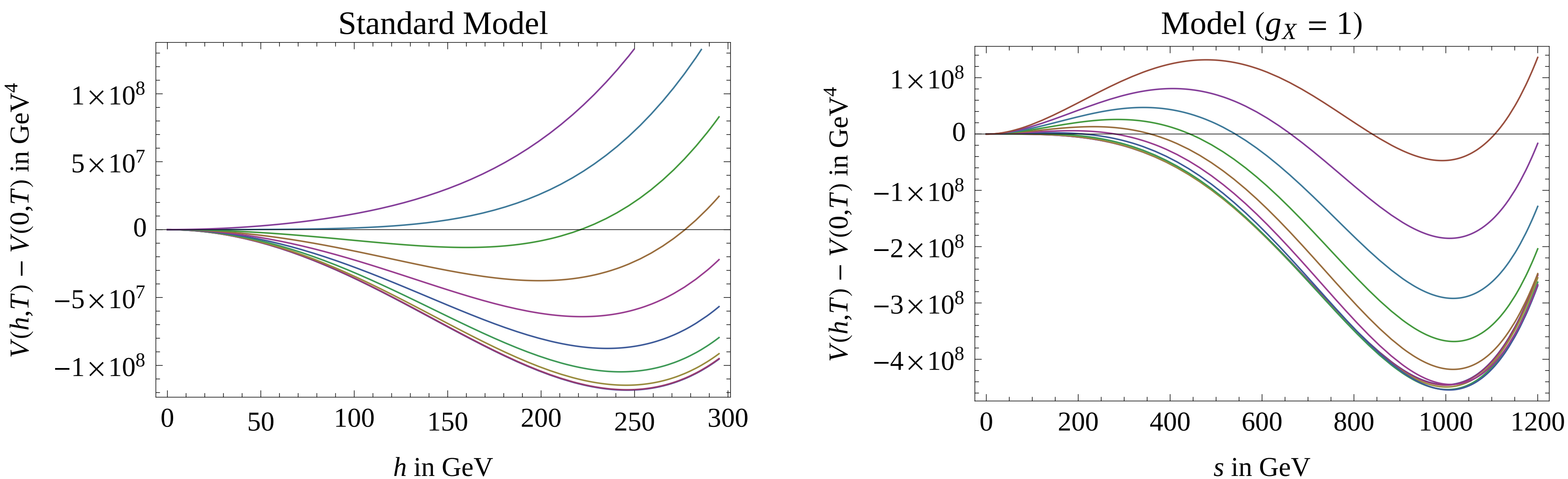
(Insignificant hint in ZZ and $\gamma\gamma$ data around 143 GeV)

Dark/EW phase transition

(At large temperature $h, s = 0$. During the big bang vev appear at $T \sim v, w$. The EW SM phase transition is second order: h smoothly goes from 0 to v).

The model predicts a first order phase transition for s

The universe remains trapped at $s = 0$ until the potential energy ΔV is violently released via thermal tunnelling: $\Gamma \sim T^4 e^{-S/T}$ with $S \propto g_X^4$.



- For the critical value $g_X \approx 1.2$ one has $\Delta V \approx \rho$ such that

$$f_{\text{peak}} \approx 0.3\,\text{mHz} \qquad \Omega_{\text{peak}} h^2 \approx 2\ 10^{-11} \qquad \text{detectable at LISA}$$

- For $g_X > 1.2$ gravitational waves become weaker.
- For $g_X < 1.2$ the universe gets trapped in a (too long?) inflationary phase.

Finite naturalness and gravity

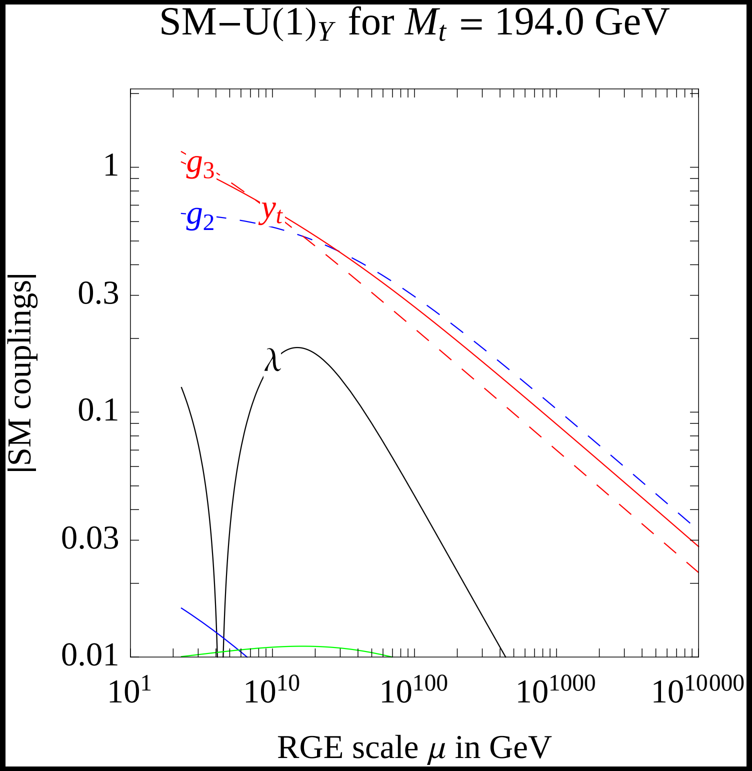
But non-perturbative quantum gravity gives $\delta M_h^2 \sim M_{\rm Pl}^2$!?

Nobody knows: maybe $1/M_{\rm Pl}$ is just a small coupling and there are no new particles around $M_{\rm Pl}$, as in a 2-dim model by Dubovsky et al. Then, maybe the SM RGE hold above $M_{\rm Pl}$. So Landau poles for g_Y and λ become a problem. To modify the SM into a theory that holds up to infinity energy one needs:

1. **A special value for** y_t, predicted in terms of gauge couplings:

$$M_t \approx 194\,\text{GeV} \qquad \text{for } g_Y \sim 0$$

   λ must become negative at large energy.



2. **Hypercharge made non-abelian**. All models (Pati-Salam, trinification) include $SU(2)_R$ and so two Higgs coupled to u and d: $K_0/\bar{K}_0$ mixing and $K \to \mu e$ demand that this can only happen at unnaturally large E.

FN needs that quantum gravity cures itself and the SM UV problems.

Conclusions

Naturalness?

1) **Stick to it** like mussels. Naturalness should be fresh, spontaneous. Present bounds are so strong that it can only be imposed with kicks in ...

2) **Abandon it**. Go ant**pic. Multiverse is the only 'rationale' we have for Λ.

3) **Modify it**. Naturalness is satisfied by the SM **if** quadratic divergences vanish. M_h at the meta/stability border: a deep meaning in $\lambda(M_{\rm Pl}) \sim \beta(\lambda(M_{\rm Pl})) \sim 0$?

	Higgs mass	Cosmological constant
Naturalness	Wrong?	Wrong
Finite naturalness	Viable	Wrong
Ant**pic multiverse	Not even wrong	Not even wrong

Exploring higher energies is the only way to clarify.
Unnaturalness would have bigger significance than the discovery of SUSY.