Naturalness after LHC Run I

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Talk at Brookhaven Forum 2013

Pre-LHC theory expectations based on:
1) Dark Matter as a thermal relic
2) Naturalness of the Higgs mass

Mobilitas
ESF programm

Euroopa Liit
Euroopa Sotsiaalfond

Eesti tuleviku heaks

1) Thermal Dark Matter

Predicts $M_{\rm DM} \sim g_{\rm DM}\sqrt{T_{\rm now}\cdot M_{\rm Pl}} \lesssim 10\,\text{TeV}$

Precise results for Minimal DM: **one** electroweak multiplet containing a neutral DM with **only gauge** interactions.

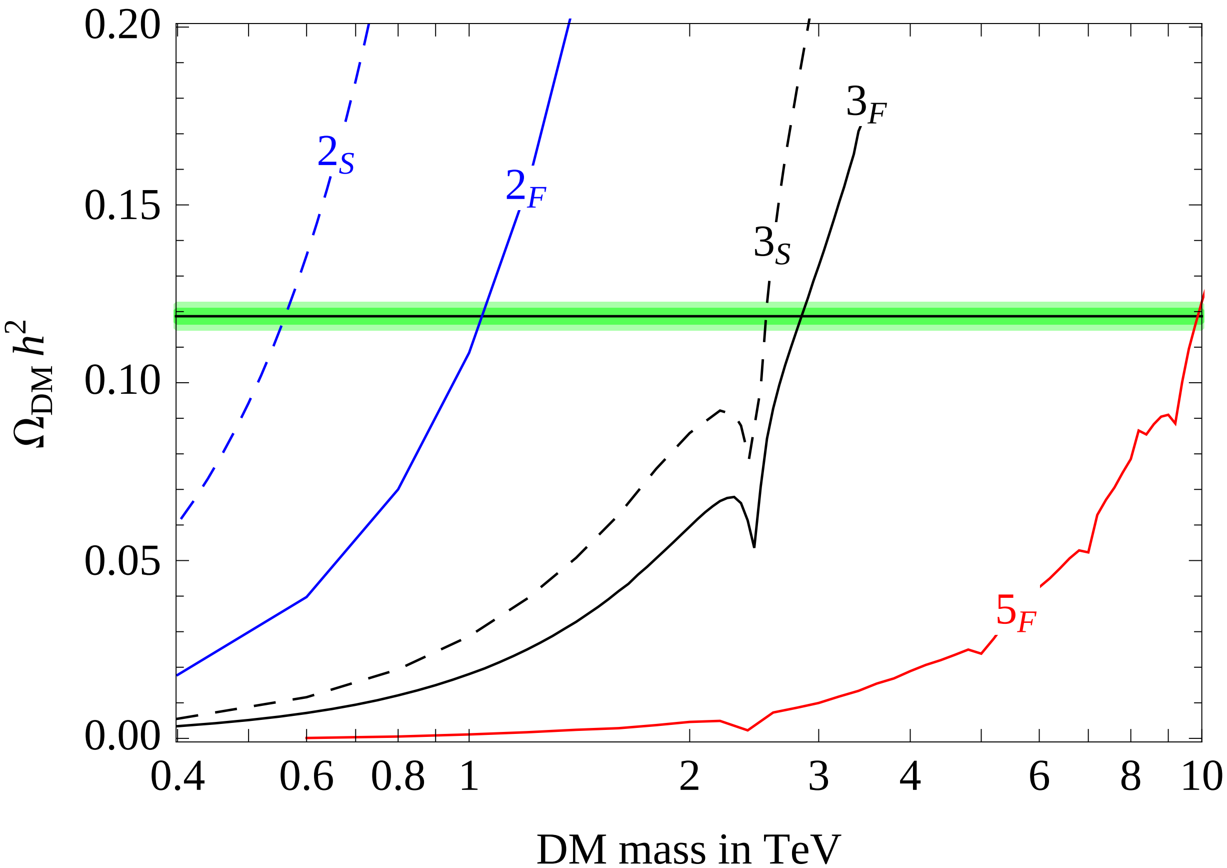
$2_F = F$ermion doublet

$3_S = S$calar doublet, etc.

Finding DM at LHC can be hard

- Multi-TeV mass
- difficult signature.

$M_{3_F} > 100\,\text{GeV}$ from ATLAS!!!



DM (aka 'neutralino') was believed to be a byproduct of the naturalness issue, leading to easy signals: QCD $\tilde g, \tilde q$ production followed by long decay chains. Many works proposed how to best reconstruct the masses. Signal not seen.

2) Naturalness of the Higgs mass

The main goal of LHC is understanding why the weak scale is small.

Maybe LHC will tell which CMSSM parameters are right.
Maybe LHC will tell which SUSY model is right.
Maybe LHC will tell which solution to the hierarchy problem is right.
Maybe LHC will tell that the hierarchy problem is not a good guideline.

	Plausibility	Fertility	Fashion
Super-symmetry	10%	1%	100%
Large extra dimensions	1%	10%	100%
Warped extra dimensions	1%	10%	1000%
Technicolor	2%	1%	1%
Higgsless	1%	10%	10%
Gauge/Higgs unification	0.1%	10%	10%
Little Higgses	1%	10%	10%
LH + T-parity or SUSY	10%	10%	10%
Ant**opic	100%	?	?
Dark Matter	100%	10%	100%

(hep-ph/9811386 — hep-ph/0007265)

Before LHC

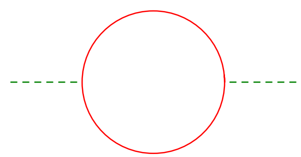
Two observations started to put naturalness in trouble

1) The **top is heavy**, now $M_t \approx 173\,\text{GeV}$

2) The **higgs is light**, now $M_h \approx 126\,\text{GeV}$

In the SM, cut-offing top loop at $E < \Lambda_{\text{cut}-\text{off}}$

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



$$\approx \frac{12\lambda_{\text{top}}^2}{(4\pi)^2}\Lambda_{\text{cut}-\text{off}}^2$$

Imposing a naturally small Higgs mass $\delta M_h^2 \lesssim M_h^2 \times \Delta$ up to a fine-tuning Δ,

$$\Lambda_{\text{cut}-\text{off}} \lesssim 400\,\text{GeV} \times \sqrt{\Delta}$$

400 GeV, not many TeV

The little hierarchy problem

Natural models where the Higgs becomes an extended object (technicolor, extra dimensions...) generically lead to form factors, described in QFT by higher dimensional operators $\mathscr{O}$ such as $|H^\dagger D_\mu H|^2$ or $\frac{1}{2}(\bar{L}\gamma_\mu L)^2$:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \mathscr{O}/\Lambda^2$$

Even restricting to $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$, B, L, B_i, L_i, CP symmetric operators:

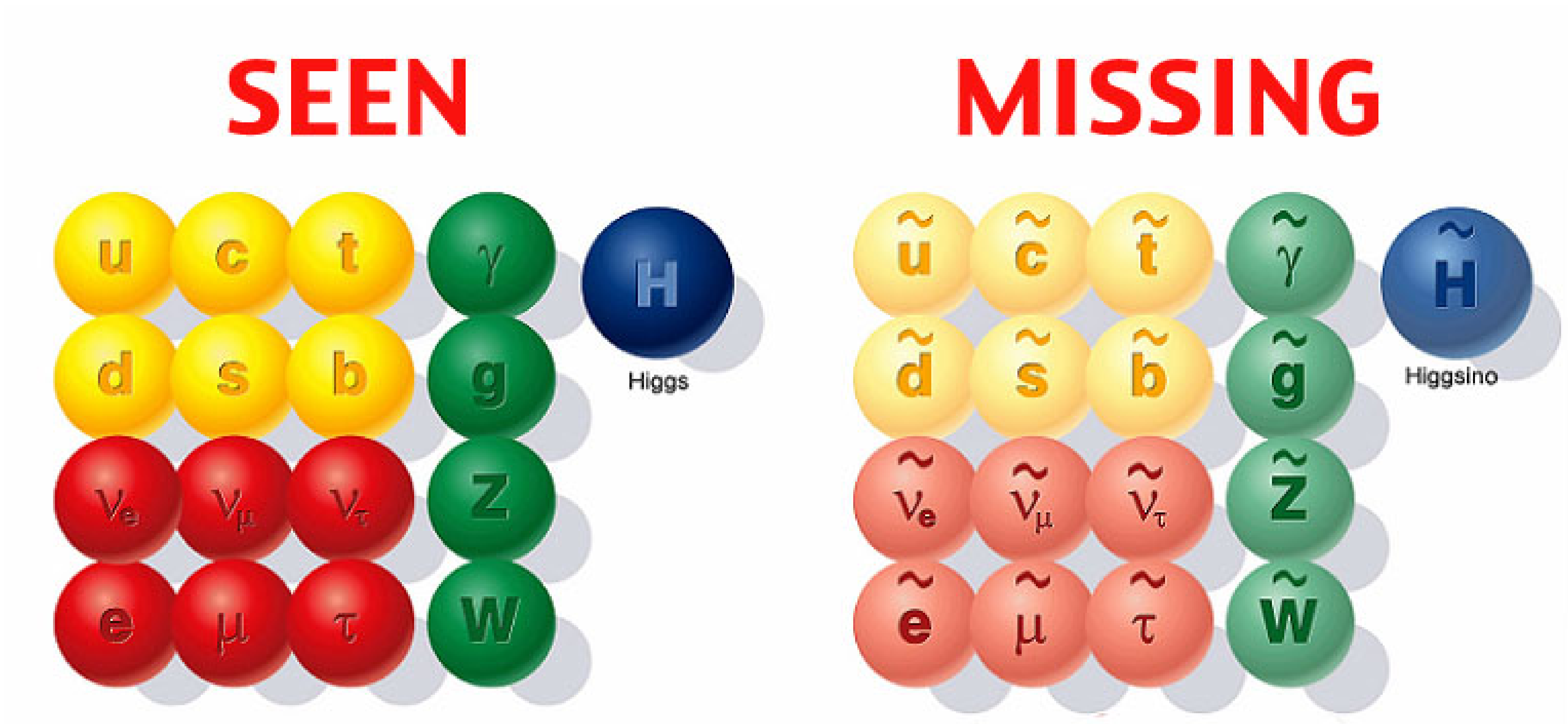
precision data agree with the SM and demand $\Lambda \gtrsim 5 - 10$ TeV

so models where $\Lambda_{\rm cut-off} \sim \Lambda$ are badly fine-tuned, $\delta m_h^2 \sim 500 m_h^2$

Attempts to improve the situation lead to special models: partial compositness. Not clear to me if such models really exist as strong gauge dynamics.

Already before LHC, the natural solution to the naturalness problem was...

Supersymmetry



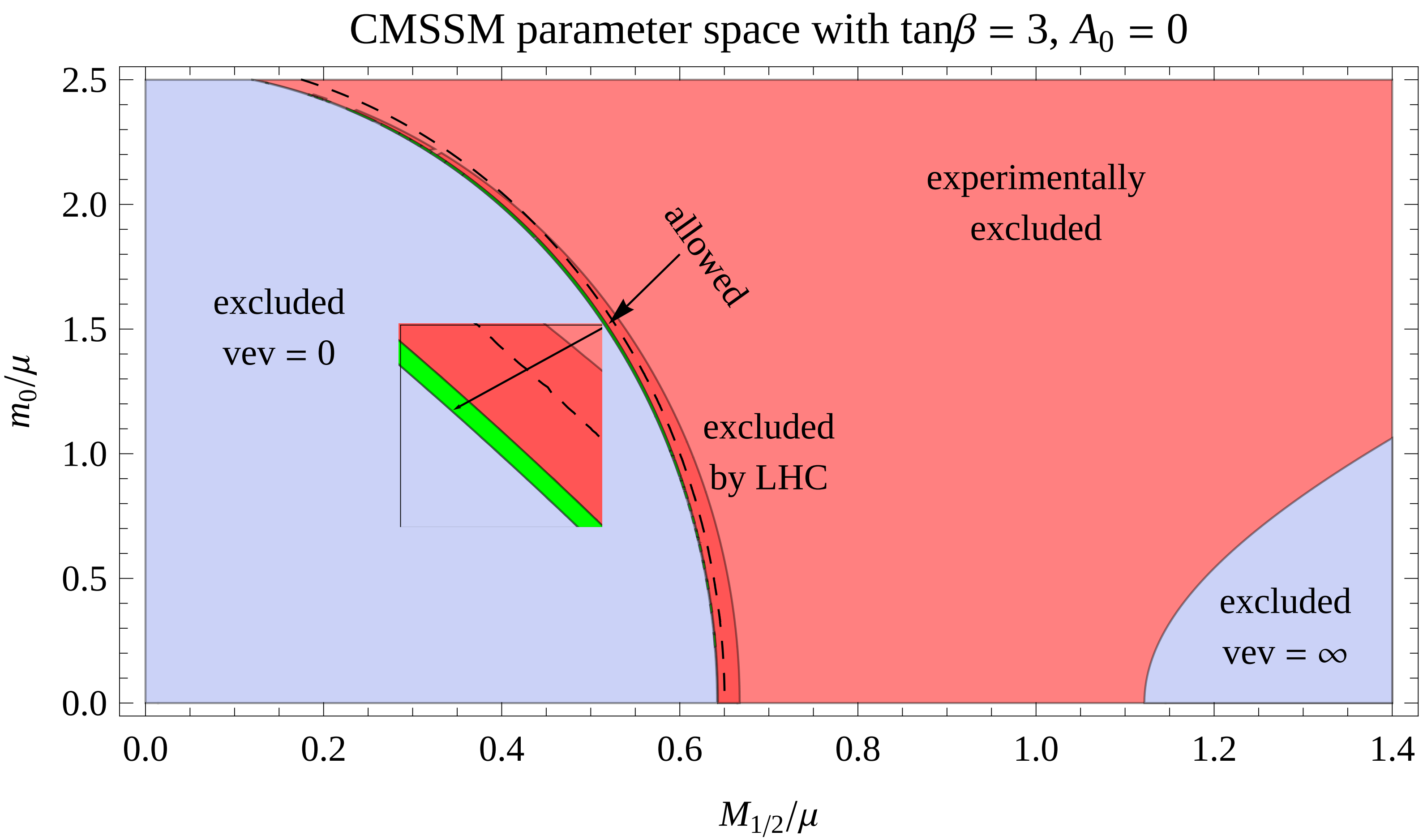
and the missing super-partner problem

The CMSSM

The SUSY scale should have been the scale of EWSB breaking

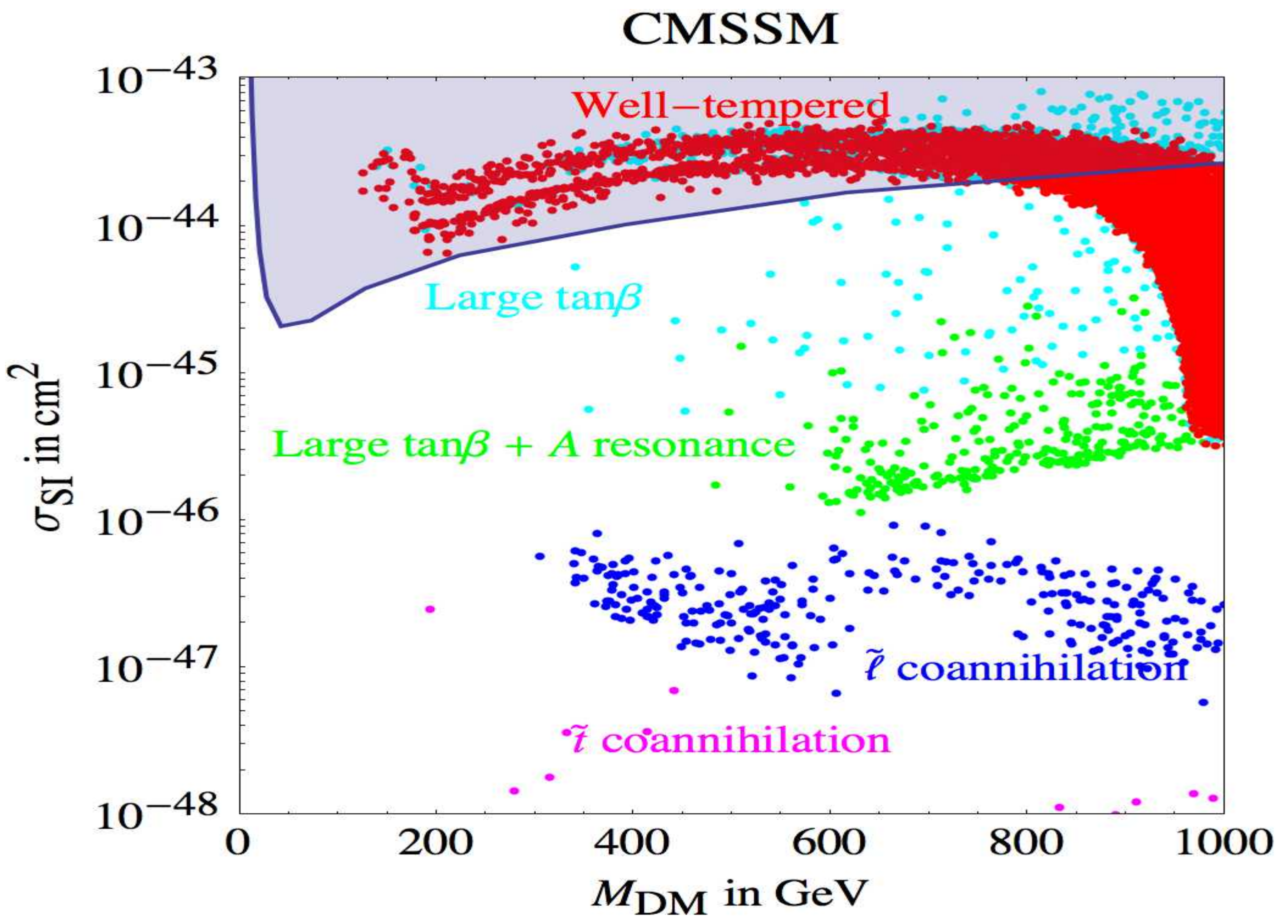
$$M_Z^2 \approx 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2 = (91\,\text{GeV})^2 \times (\frac{M_3}{110\,\text{GeV}})^2 + \cdots$$

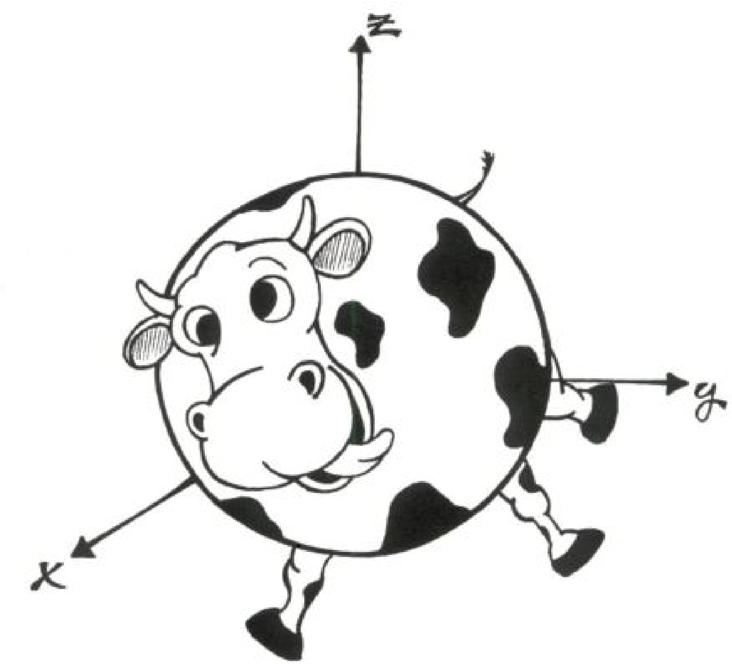
Use adimensional ratios as parameters and fix the SUSY scale from M_Z: LEP and later LHC excluded all the parameter space away from the critical line $v = 0$



Dark Matter in the CMSSM

$\Omega_{\rm DM}$ suggested neutralino annihilations via sleptons up to a few crazy regions.





The 'bulk' region got excluded leaving the tail, the nose: **only special mechanisms can give $\Omega_{\rm DM}$**: $\tilde{\ell}$ co-annihilations, H, A resonance, h, H, A at large $\tan\beta$, $\tilde{t}$ co-annihilations, well-tempered $\tilde{B}/\tilde{H}$ (excluded by Xenon for $\mu > 0$), h resonance (excluded by LHC, $M_3 > 3m_h$). Like dissecting the spherical cow.

Stop co-annihilations

A neutralino and a stop can give the correct thermal $\Omega_{\rm DM}$ via co-annihilations, which needs

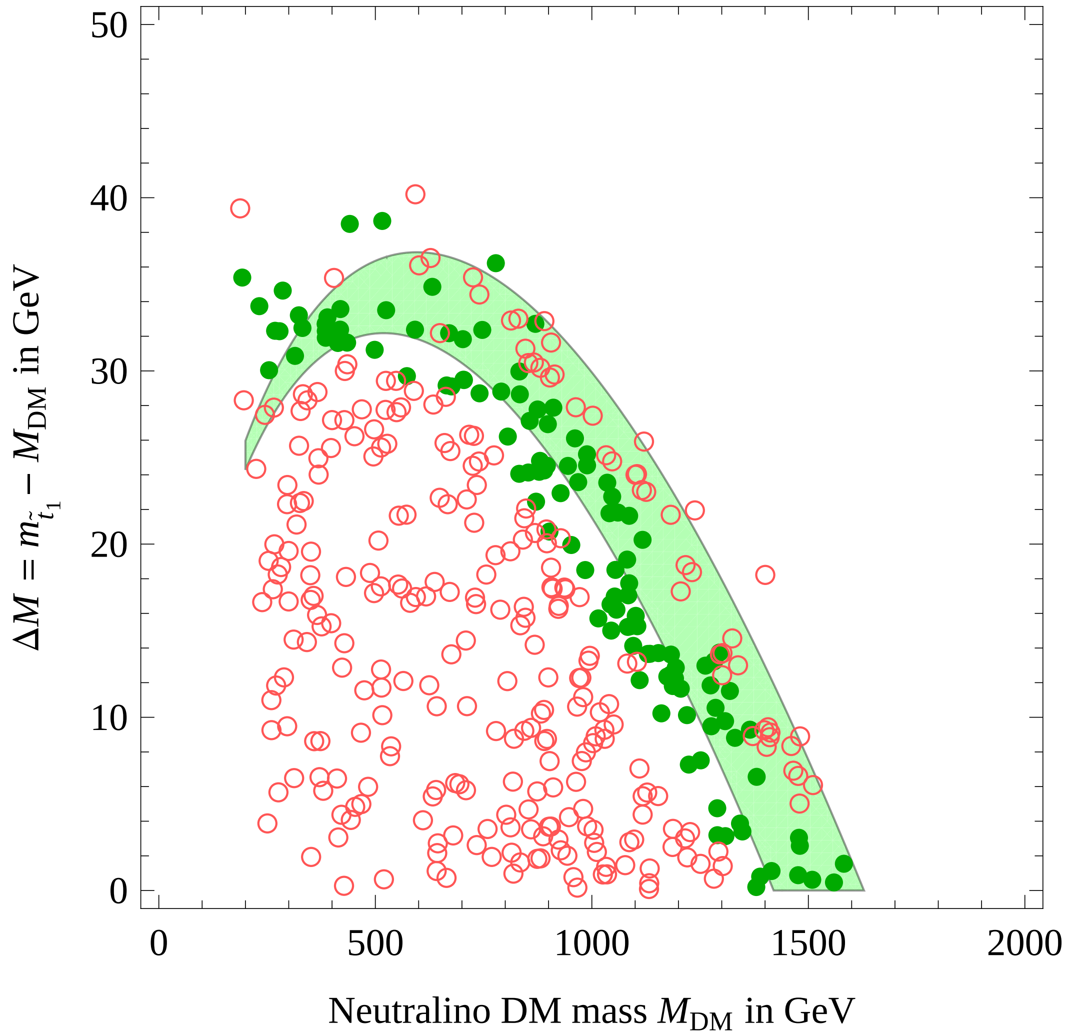
$$\sigma v = \overbrace{\frac{3}{8} e^{-2\Delta M/T}}^{\text{co−annihilation}} \times \overbrace{\frac{7\, g_3^4}{216\pi\, m_{\tilde{t}_1}^2}}^{\sigma(\tilde{t}\tilde{t}^* \to gg)v}$$

$$\approx 2.3 \times 10^{-26}\, \frac{\text{cm}^3}{\text{s}}$$

i.e.

$$\Delta M = m_{\tilde{t}} - M_{\rm DM} \approx 30\,\text{GeV}$$

for $m_{\tilde{t}} < 1.5\,\text{TeV}$.



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

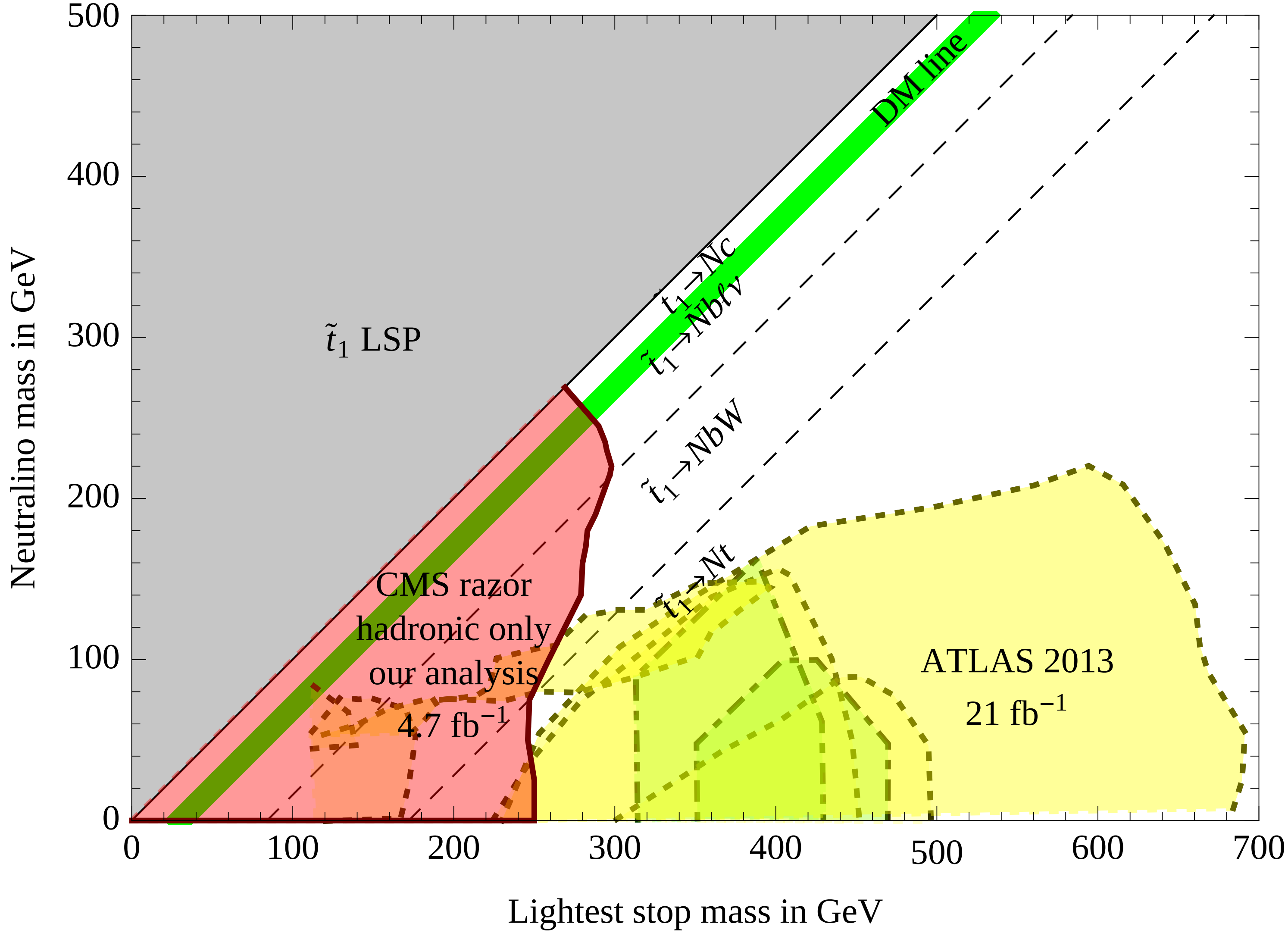
All of them have similar problems: the unit of measure is the kilo-fine-tuning.

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



New fully model independent bound (theorist analyses of 7 TeV data) enters the main region where $\tilde{t}$ decays are ≈invisible, relying on **jet initial state radiation**. Good sensitivity at LHC thanks to big $\sigma(pp \to \tilde{t} + \tilde{t}^* + \text{jets})$ from QCD.

Natural SUSY: “not very satisfactory”

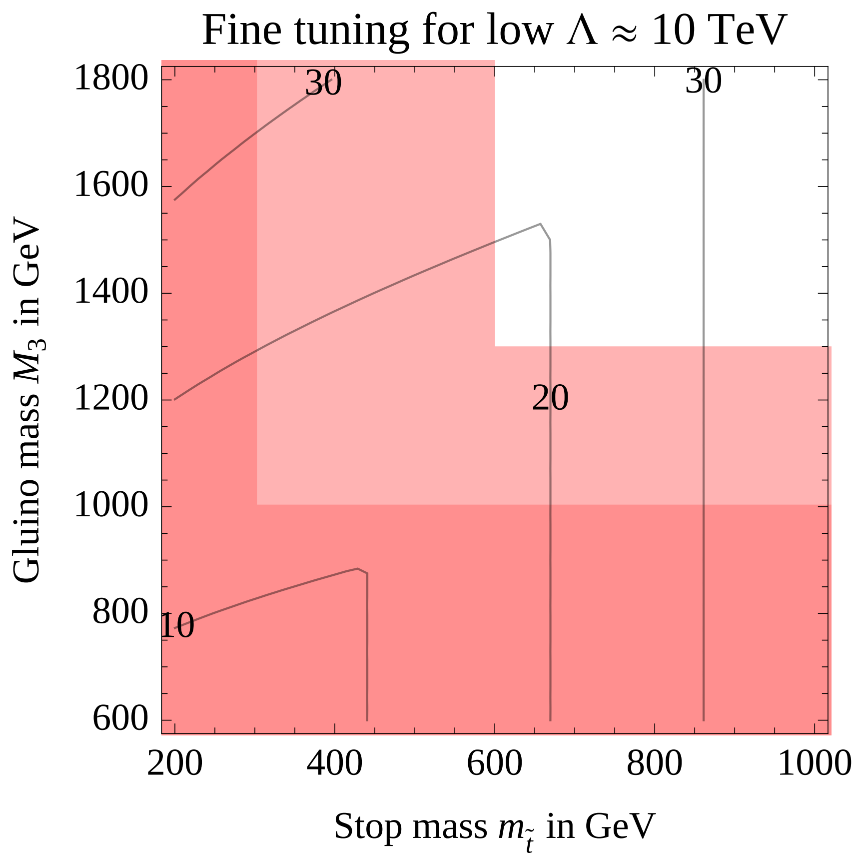
Even including quantum corrections only below a relatively low cut-off Λ,

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

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.

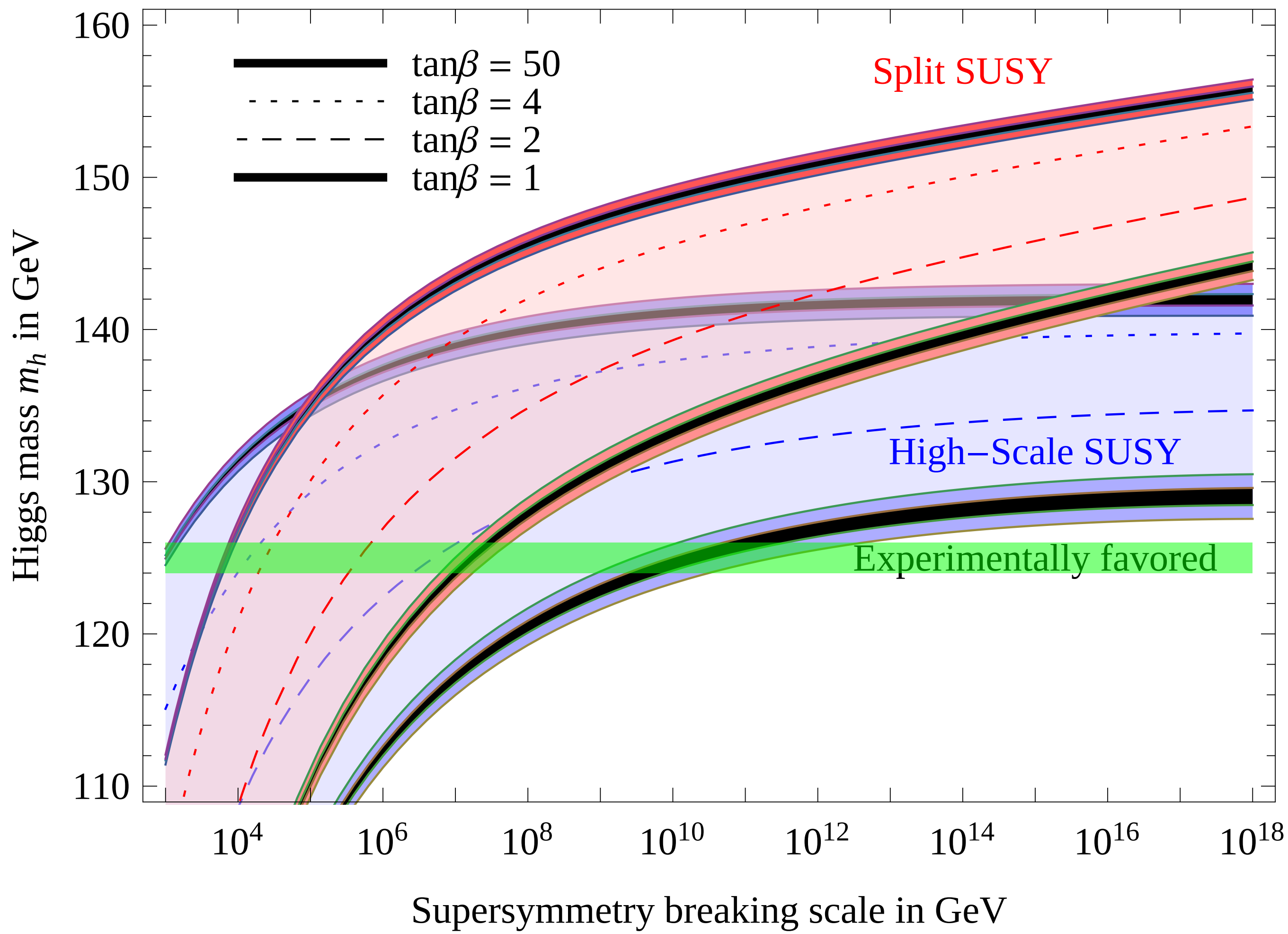
Compressed sparticle spectra to reduce signals, but μ should naturally be light because of $M_Z^2 = -2\mu^2 + \cdots$. And having all sparticles light is bad.

"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).

Getting the SUSY scale from M_h

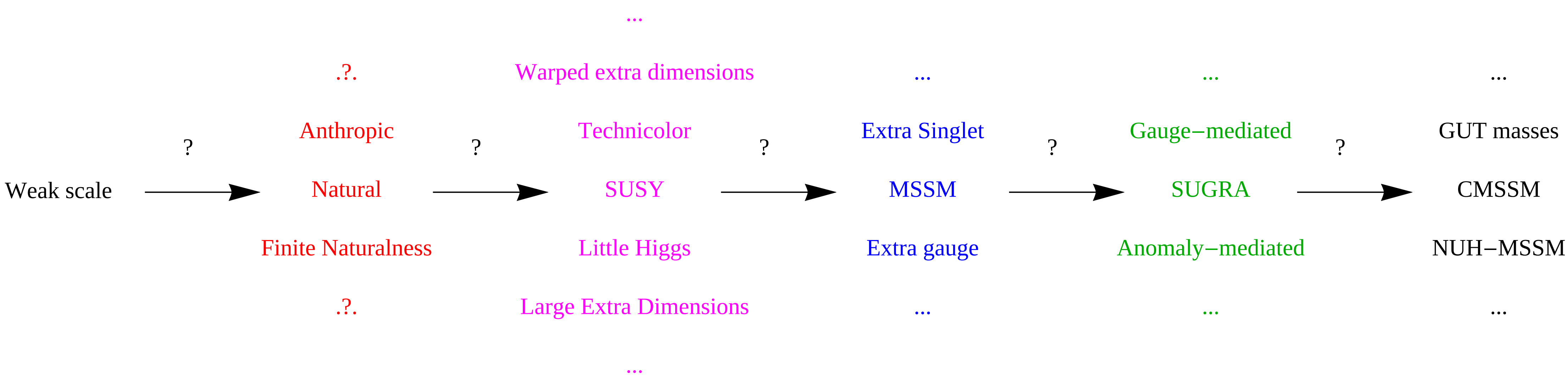
SUSY might exist above the weak scale for reasons unrelated to naturalness. The MSSM predicts $0 < \lambda < (g_2^2 + g_Y^2)/8$, so $M_h \sim \sqrt{\lambda} v$ offers a new handle to guess where SUSY could be. 125 GeV means λ just below 0 at high scale.

Predicted range for the Higgs mass



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

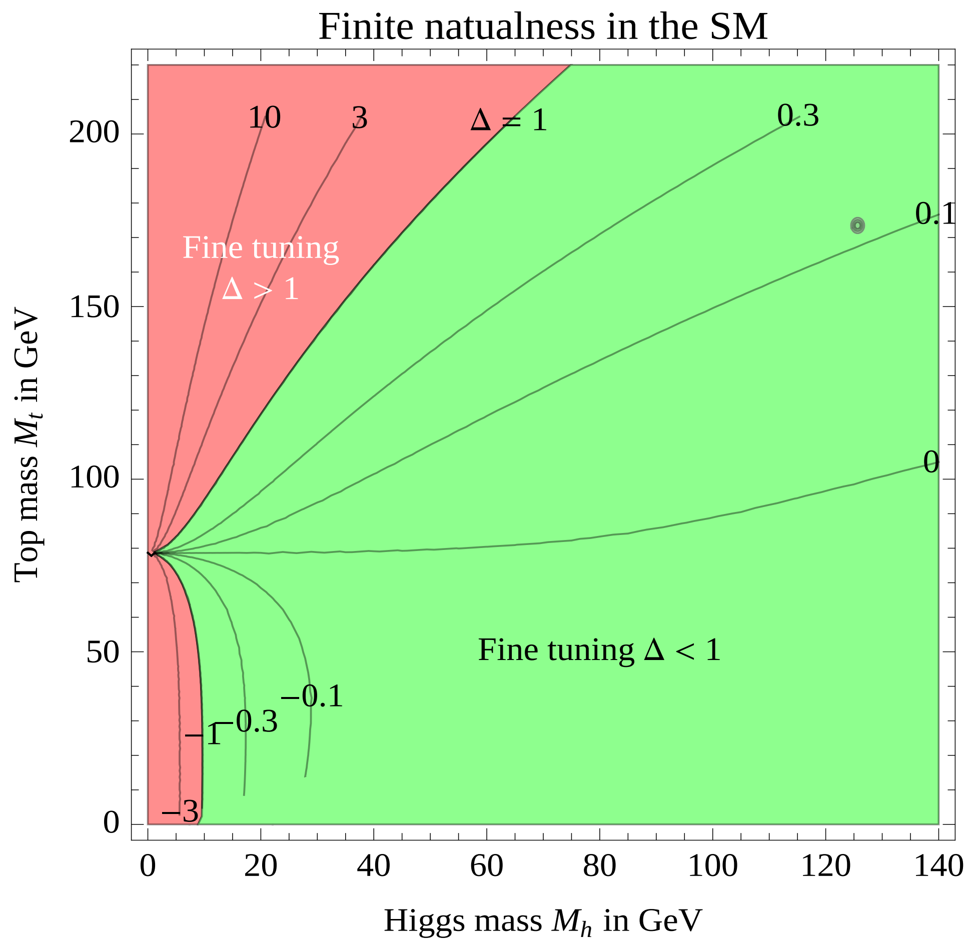
The **bad possibility** is that the Higgs is light due to ant**pic reasons. Then, one expects that H is the only light scalar, so weak-scale DM would be a fermion e.g. Split SUSY, MDM; special fermionic models can fit the $g-2$ anomaly.

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. Deep QFT does not help, because the answer is chosen by the unknown physical cut-off. Maybe it behaves like dimensional regularization. The Planck scale could arise from the spontaneous breaking of a dilatation-like symmetry. The weak scale could arise dynamically as the scale where the quartic coupling of some extra singlet scalar runs negative.

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

The SM satisfies Finite Naturalness

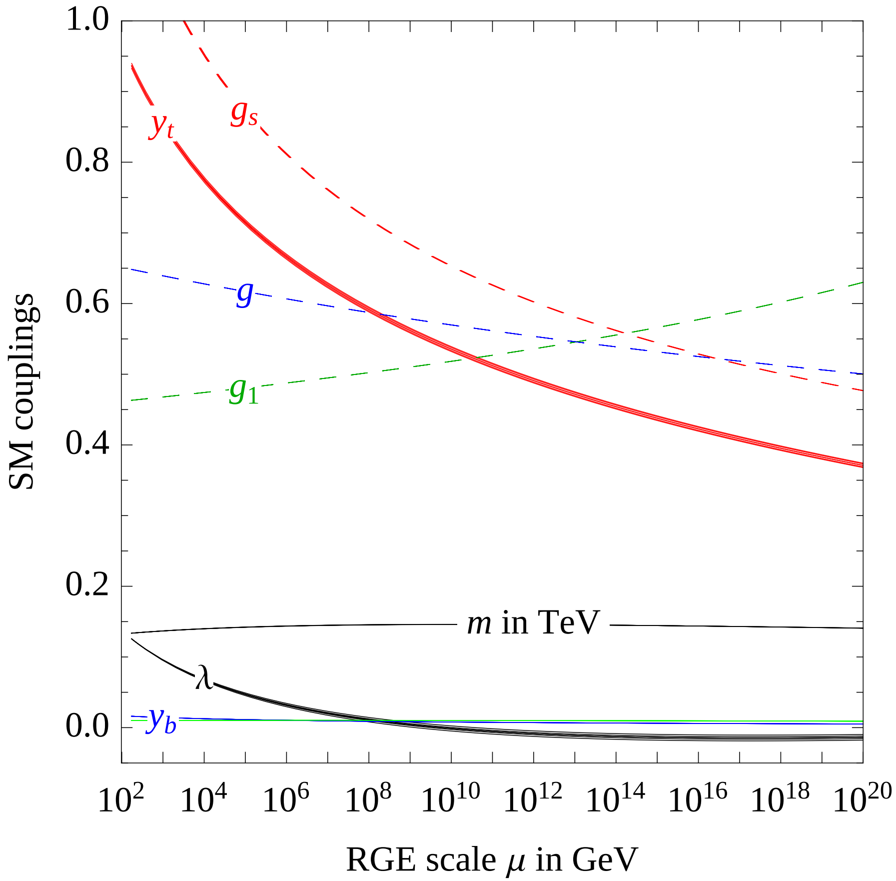
Quantum corrections to the dimensionful parameter $m^2 \simeq M_h^2$ in the SM Lagrangian $\frac{1}{2}m^2|H|^2 - \lambda|H|^4$ are small for the measured values of the parameters

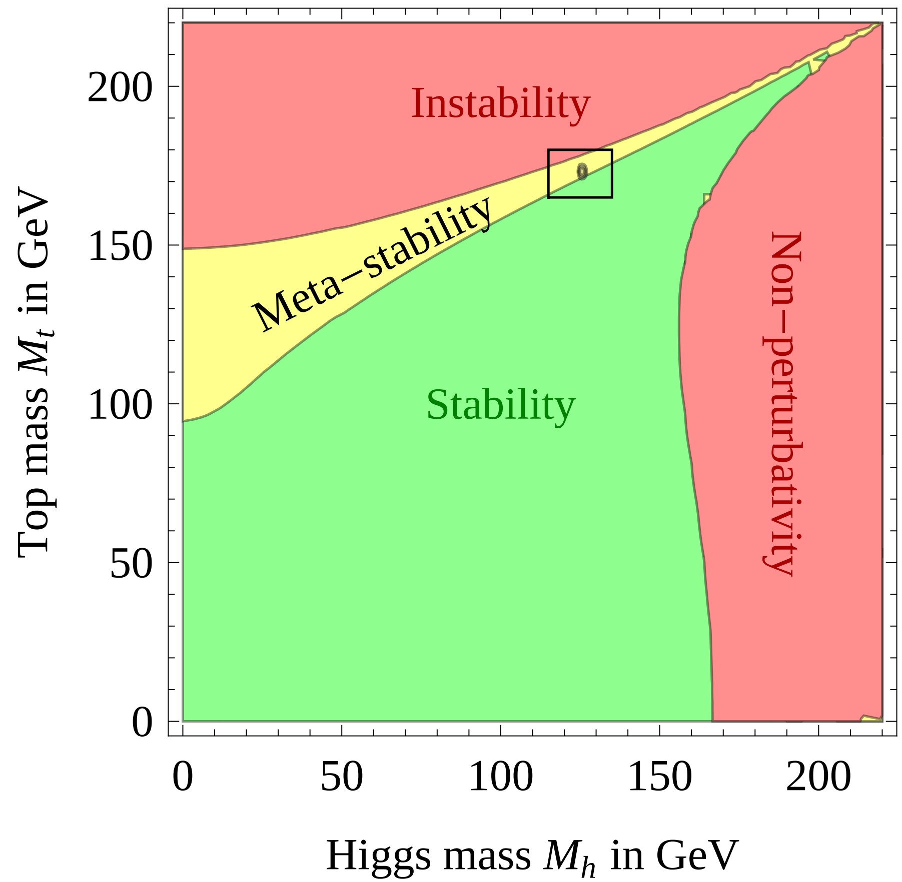


From arXiv:1303.7244

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

Trusting the SM up to the Planck scale





For the measured masses both λ and its β-function ~vanish around $M_{\rm Pl}$

126 GeV comes from $V \sim 0h^2 + 0h^4$: maybe an accident, maybe a big message

Finite Naturalness and new physics

FN would be ruined by new heavy particles coupled to the SM (such as GUT). New physics demanded by data (such as DM, neutrino masses, maybe axions...) satisfies finite naturalness if it is not much above the weak scale: signals!

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 KSVZ models employ heavy quarks with mass M

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

Infation does not need big scales and anyhow flatness implies small couplings.

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

DM with EW gauge interactions

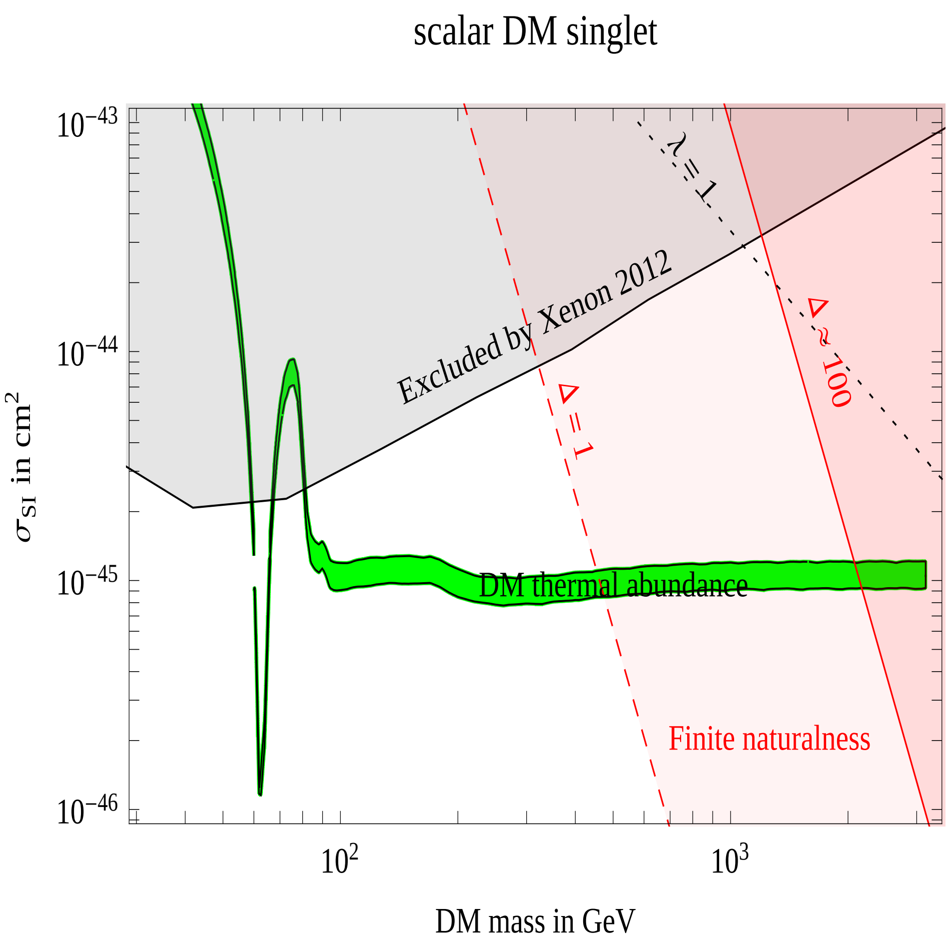
Consider a Minimal Dark Matter n-plet. 2-loop quantum corrections to M_h^2:

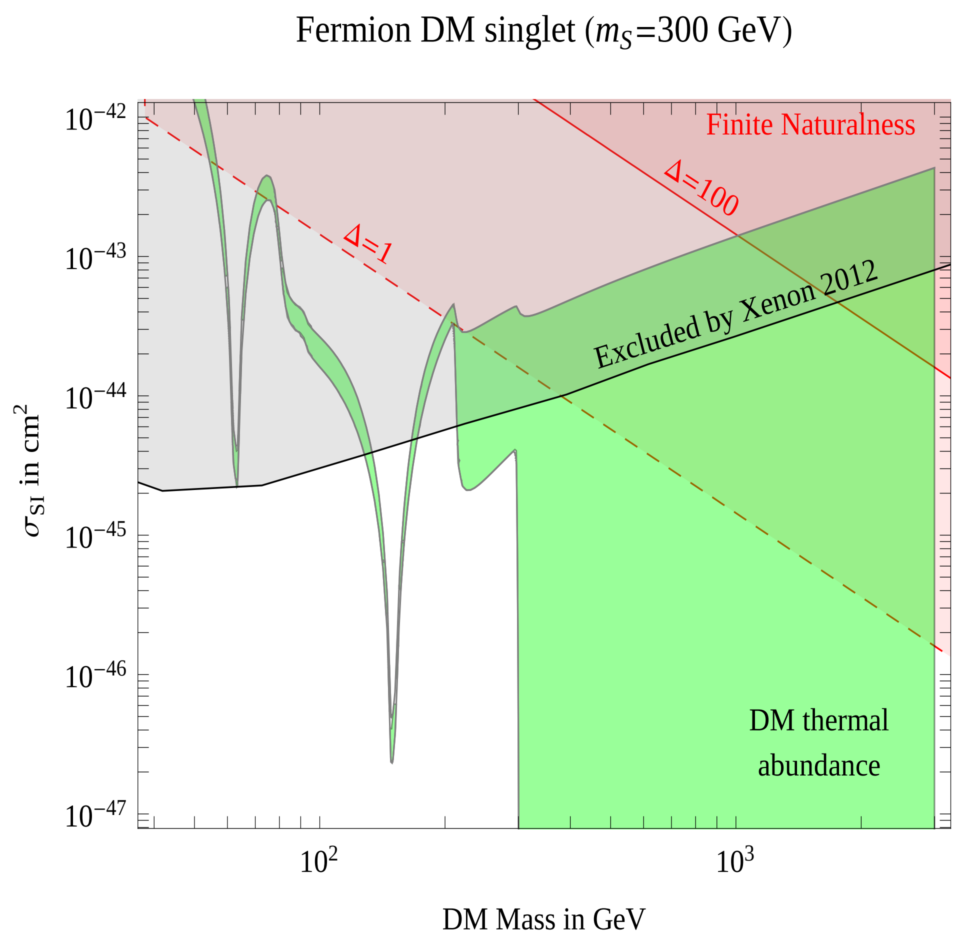
$$\delta m^2 = \frac{cnM^2}{(4\pi)^4}\left(\frac{n^2-1}{4}g_2^4 + Y^2 g_Y^4\right) \times \begin{cases} 6\ln\frac{M^2}{\Lambda^2} - 1 & \text{for a fermion} \\ \frac{3}{2}\ln^2\frac{M^2}{\Lambda\mu^2} + 2\ln\frac{M^2}{\Lambda^2} + \frac{7}{2} & \text{for a scalar} \end{cases}$$

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





Observable DM satisfies Finite Naturalness if lighter than ≈ 1 TeV

Conclusions (pessimistic* version)

LHC went a factor of 4 above Tevatron (from 2 to 8 TeV). Only an extra factor $\lesssim 2$ will be explored. SM higgs and nothing else seen. This was previously called "nightmare scenario". The best signals for DM did not appear: an invisible Higgs width, long decay chains.

- **The naturalness principle is in trouble**

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

- Why DM should be at the weak scale, if nothing new happens there?

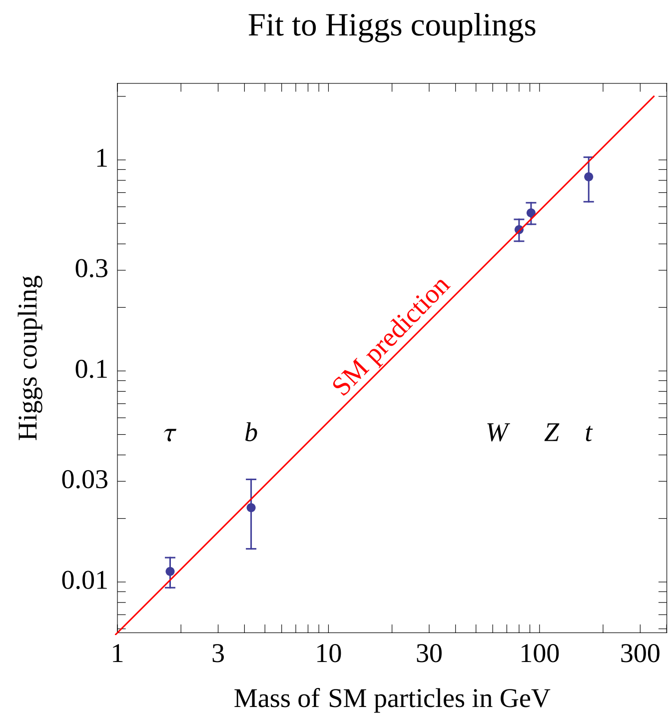
Another historical moment in theory/experiment relations?

theory$_1$		experiment		theory$_2$
Dragged æther	$\rightarrow$	Michelson Morley	$\rightarrow$	Relativity
Natural SUSY	$\rightarrow$	Large Hadron Collider	$\rightarrow$	Ant**pic??

Marx told that "history repeats itself, first as tragedy, second as farce"

Conclusions (optimistic version)

LHC explored 6 TeV above Tevatron (from 2 to 8) and 6 more TeV up to 14 will be soon explored. 2012 will be remembered as the year of Higgs discovery!



Status of weak scale models: excellent! The triumph of the SM! Which principle behind? A deep meaning in $\lambda = \beta(\lambda) = 0$ around M_{Pl}? LHC run II will test naturalness, explore DM as weak multiplets. ADMX can earlier test axion DM