Do We Need Physics Beyond the Standard Model ?

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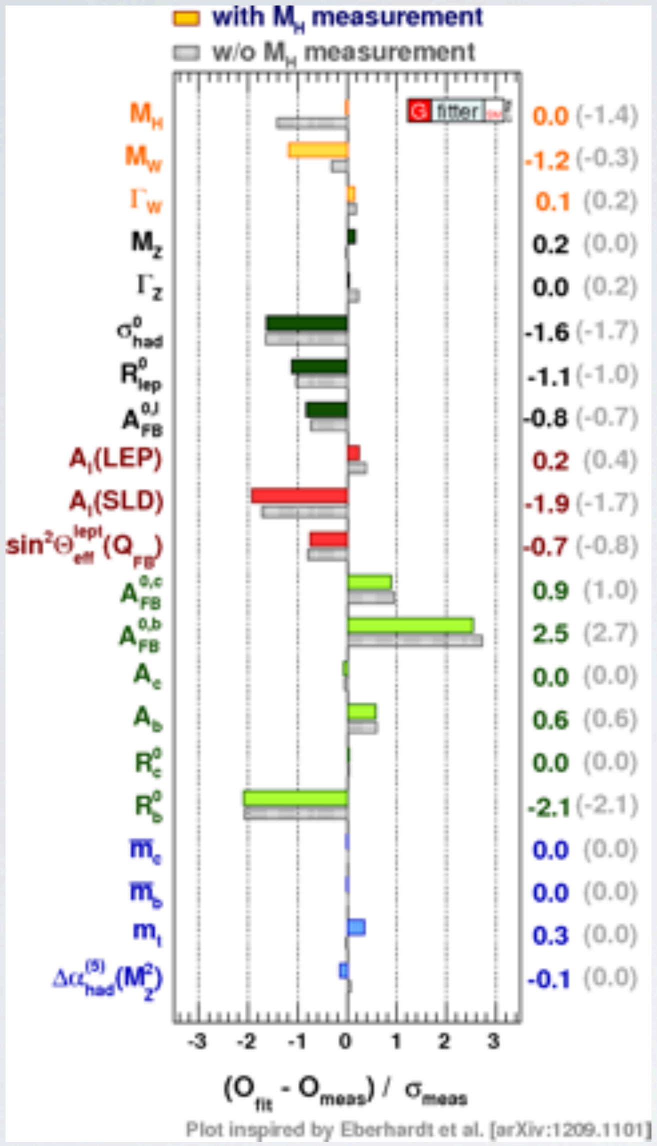
Outline

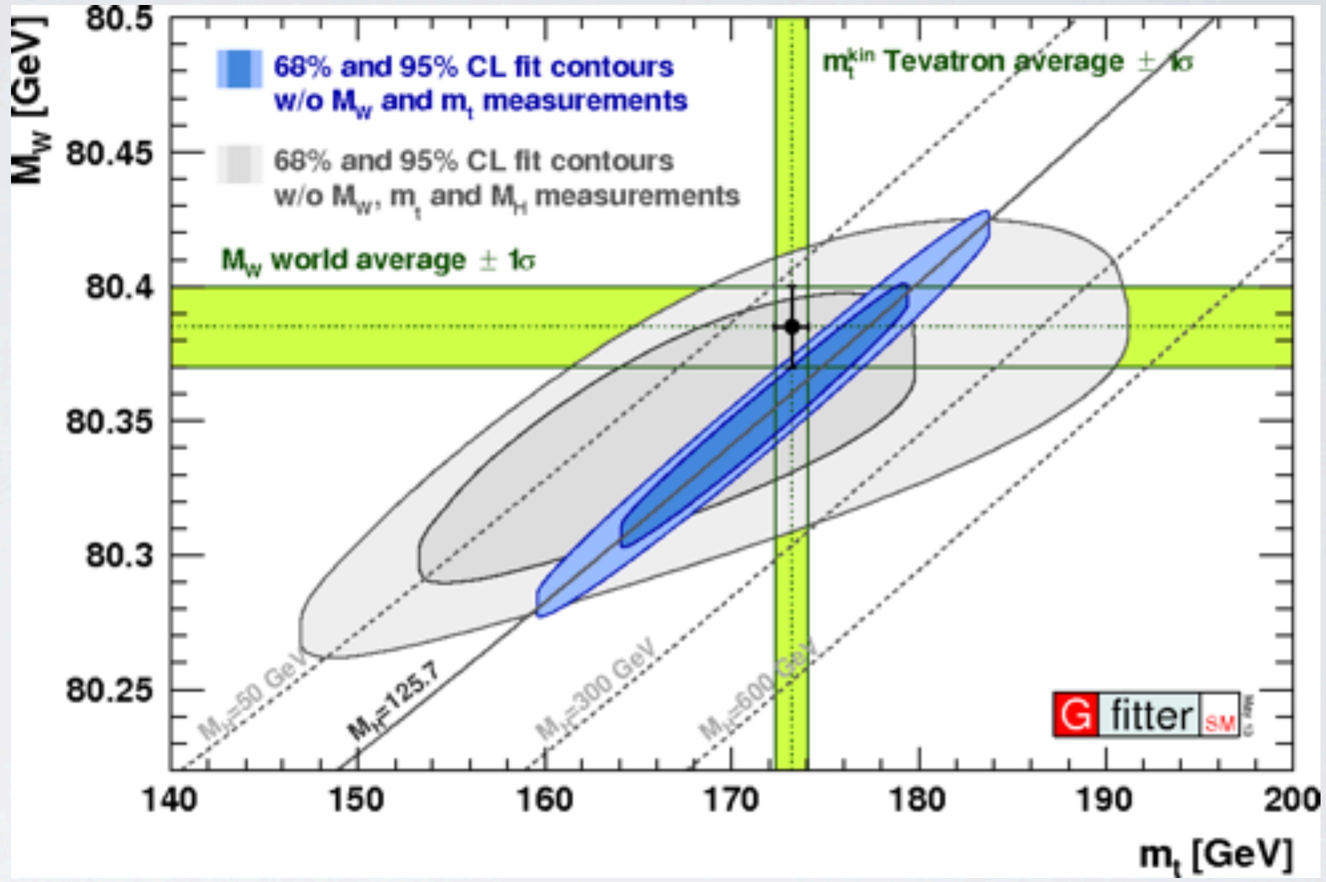
- Naturalness ? What Naturalness ?

- A Comment on the Multiverse

- Our (fine-tuned) natural theories

The Standard Model is Fine





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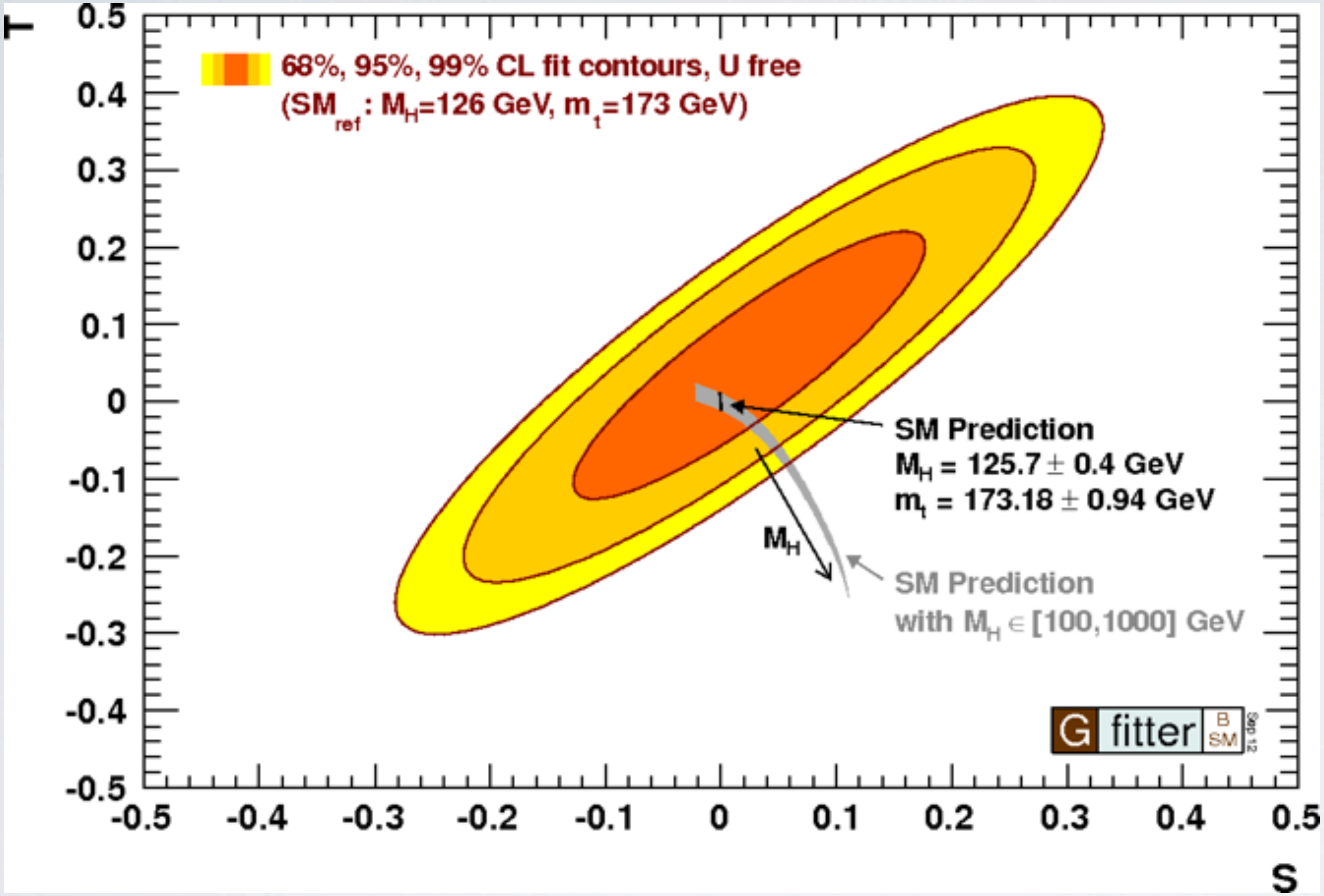

$$U = 0.03 \pm 0.10$$

The Standard Model is not All

- *Quantum Gravity* requires something new at $\simeq M_{\mathrm{Planck}}$

- *Neutrino masses* require new physics,
  but scale could be very high

- *Dark Matter* seems to need new particle(s)
  most likely below the multi-TeV scale

- *Baryogenesis, Strong CP problem, ...*

No guarantee that we will see anything

Are we going so see New Physics at the LHC ?

Our guidance has always been *naturalness:*

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger \, D^\mu \Phi + V(\Phi^\dagger \Phi)$$

with

$$V(\Phi^\dagger\Phi) = -m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \; + \sum_{n=1}^{\infty} \frac{c_n}{\Lambda^{2n}} (\Phi^\dagger \Phi)^{n+2}$$

SM corresponds to first 2 terms

$$m_h = \sqrt{2\lambda} v$$

Naturalness

Quantum Field Theory tells us that

$$m_h \simeq \Lambda$$

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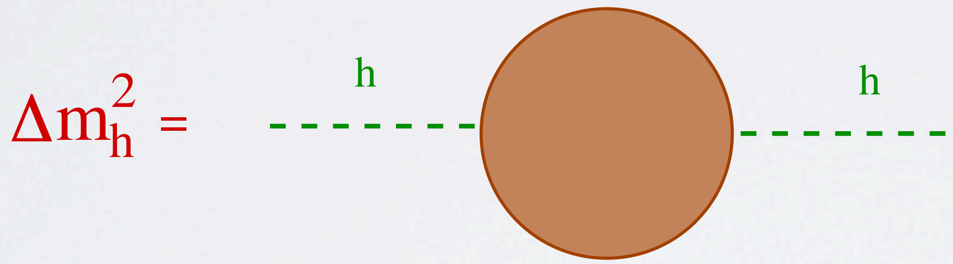
One way of seeing this:



$$\Delta m_h^2 \simeq \frac{c}{16\pi^2}\Lambda^2$$ quadratically divergent

c determined by SM states: $t, W^\pm, Z^0, h$

Naturalness

Quadratic sensitivity of m_h to the UV cutoff

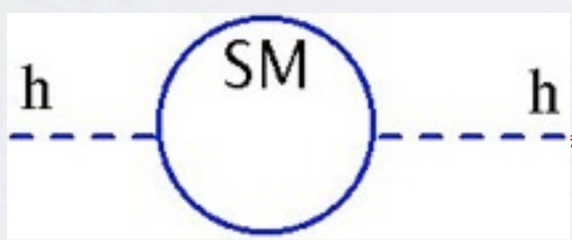
Naturalness

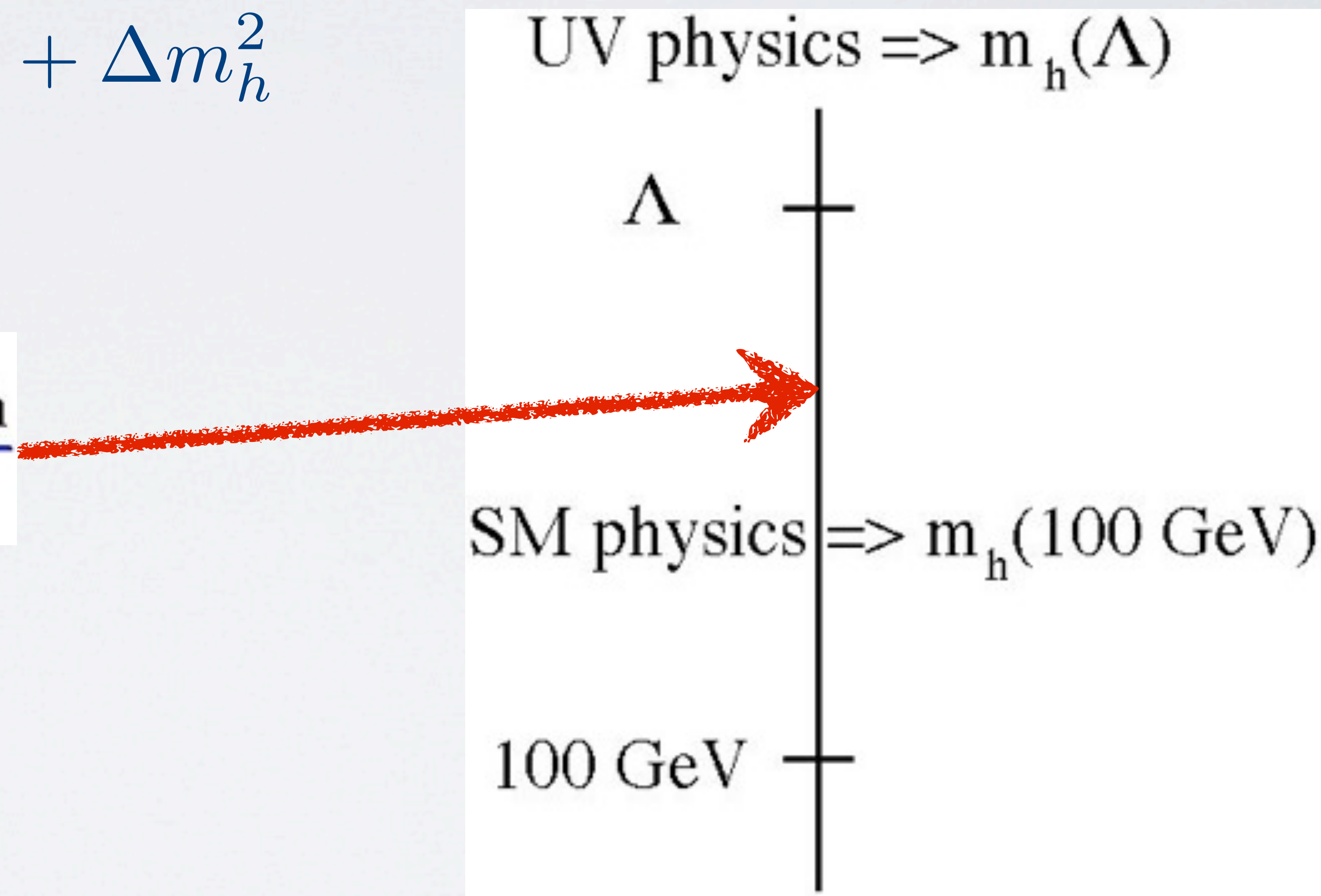
Quadratic sensitivity of m_h to the UV cutoff

- Generic in Quantum Field Theory

  It does not depend on there being new heavy particles

$$m_h^2(100\ \mathrm{GeV}) = m_h^2(\Lambda) + \Delta m_h^2$$





Naturalness

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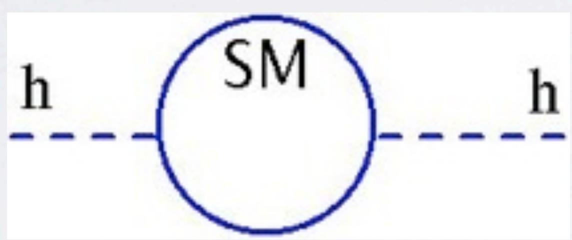

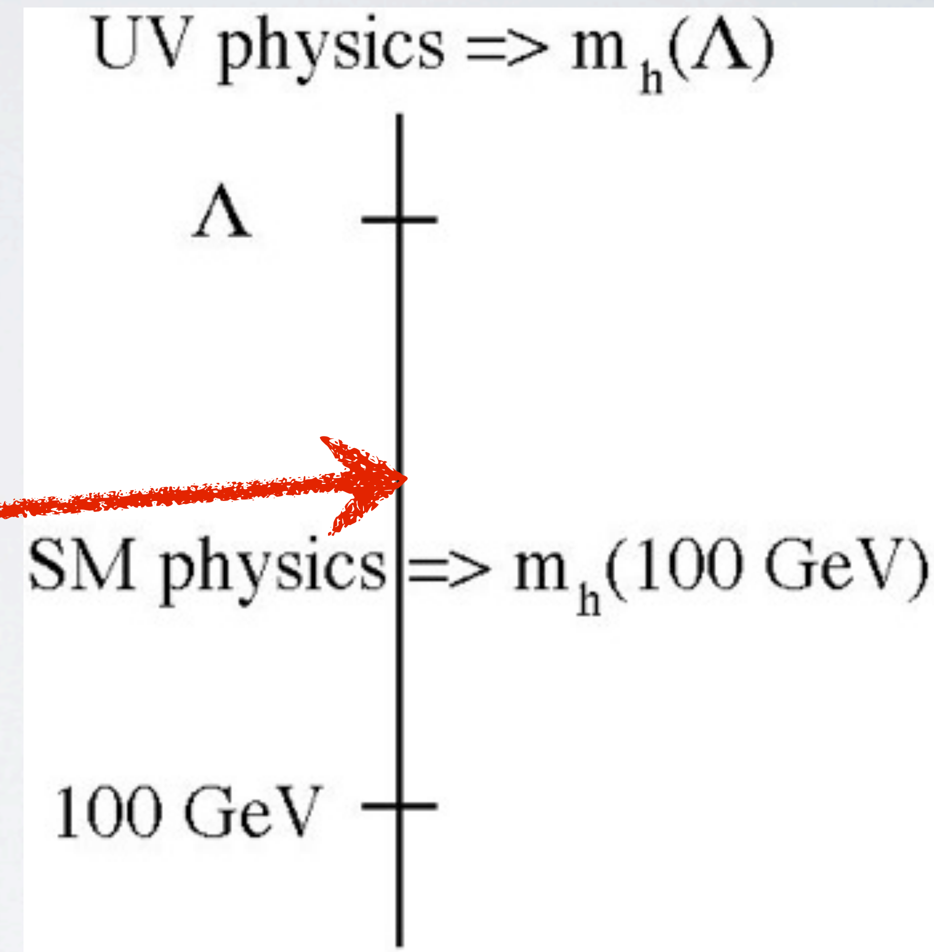

All momentum shells above $100\ \text{GeV}$ contribute to quadratic sensitivity of the UV boundary condition !

Naturalness

Renormalization Group flow viewpoint

Critical surface in RG flow $\Rightarrow$ light Higgs

If we can be close enough to it then we are OK.

But *how close* to the CS we need to be ?

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But *how close* to the CS we need to be ?

Answer: to within 1 part in $\dfrac{v^2}{\Lambda^2}$!

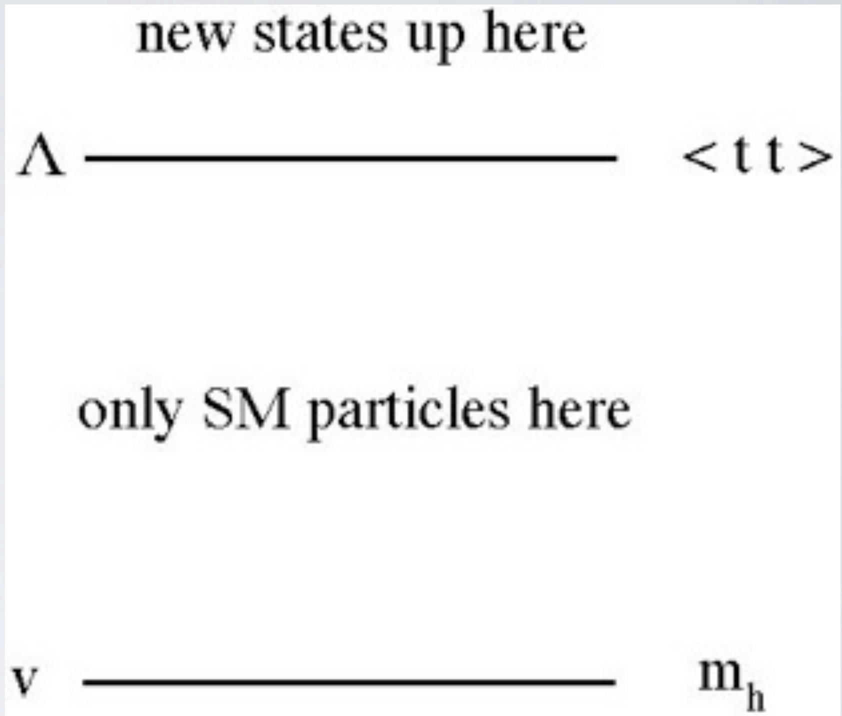
This fine-tuning is there even in the absence of heavy particles

between v and Λ

Naturalness

Example model: top condensation

At Λ new interaction $\Rightarrow \langle \bar{t}t \rangle$



this triggers EWSB and forms Higgs

to get $\begin{cases} m_t \simeq 172 \text{ GeV} \\ m_h \simeq O(100) \text{ GeV} \end{cases}$

we need $\Lambda \simeq (10^{15} - 10^{16}) \text{ GeV}$

- No new states up to Λ
- No quadratic divergences at UV cutoff (Higgs is composite)

Naturalness

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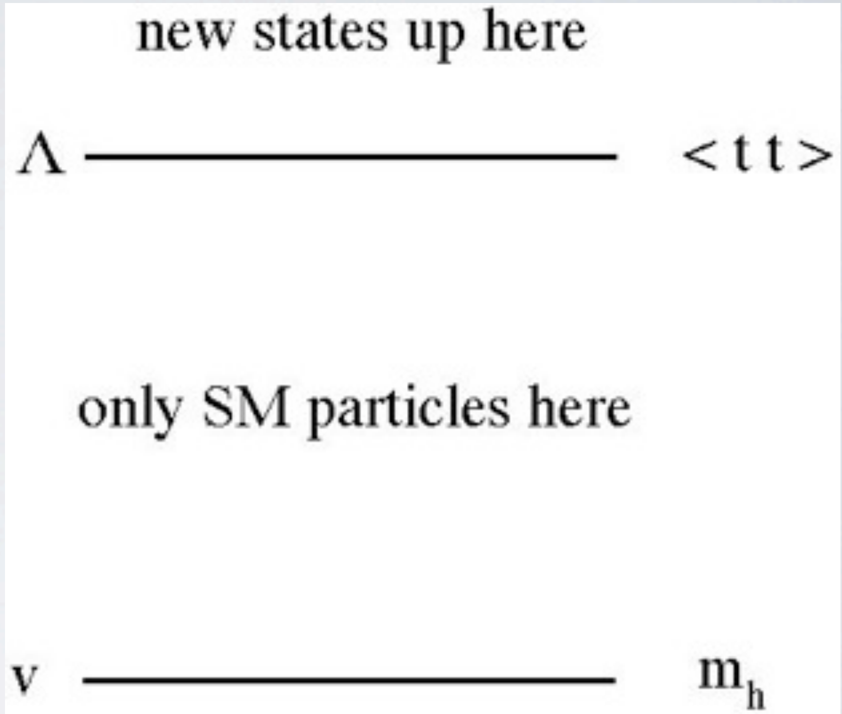

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- No new states up to Λ
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But we need the coupling of new interaction at Λ

tuned to within $\dfrac{v^2}{\Lambda^2}$ of its critical value!

Naturalness and Scale Invariance

- Classical Scale Invariance of the SM

  If quantum breaking of SI is soft $\Rightarrow m_h$ light

- Assume SM transitions to a CFT at scale Λ

  Then SI at the UV protects m_h

  As long as no new particles above the TeV scale

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Naturalness and Scale Invariance

- All SM couplings must transition to CFT behavior

(Tavares, Schmaltz, Skiba 1308.0025)

- Constraining to gravity and $U(1)_Y$
- Also true for asymptotically free couplings
- Problem traced to change in anomalous dimensions at transition scale Λ

$$\delta m_h^2 \simeq O(1)\Lambda^2$$

even in the absence of new particles below Λ

Naturalness

Summary

- Quantum Field Theory still tells us that the SM Higgs is fine tuned to 1 part in $\frac{v^2}{\Lambda^2}$
- This *does not depend* on whether or not there are heavy particles above the weak scale
- The choices are

Insist on *naturalness*, live with some fine-tuning

Do not care about *naturalness*

Something is wrong with QFT

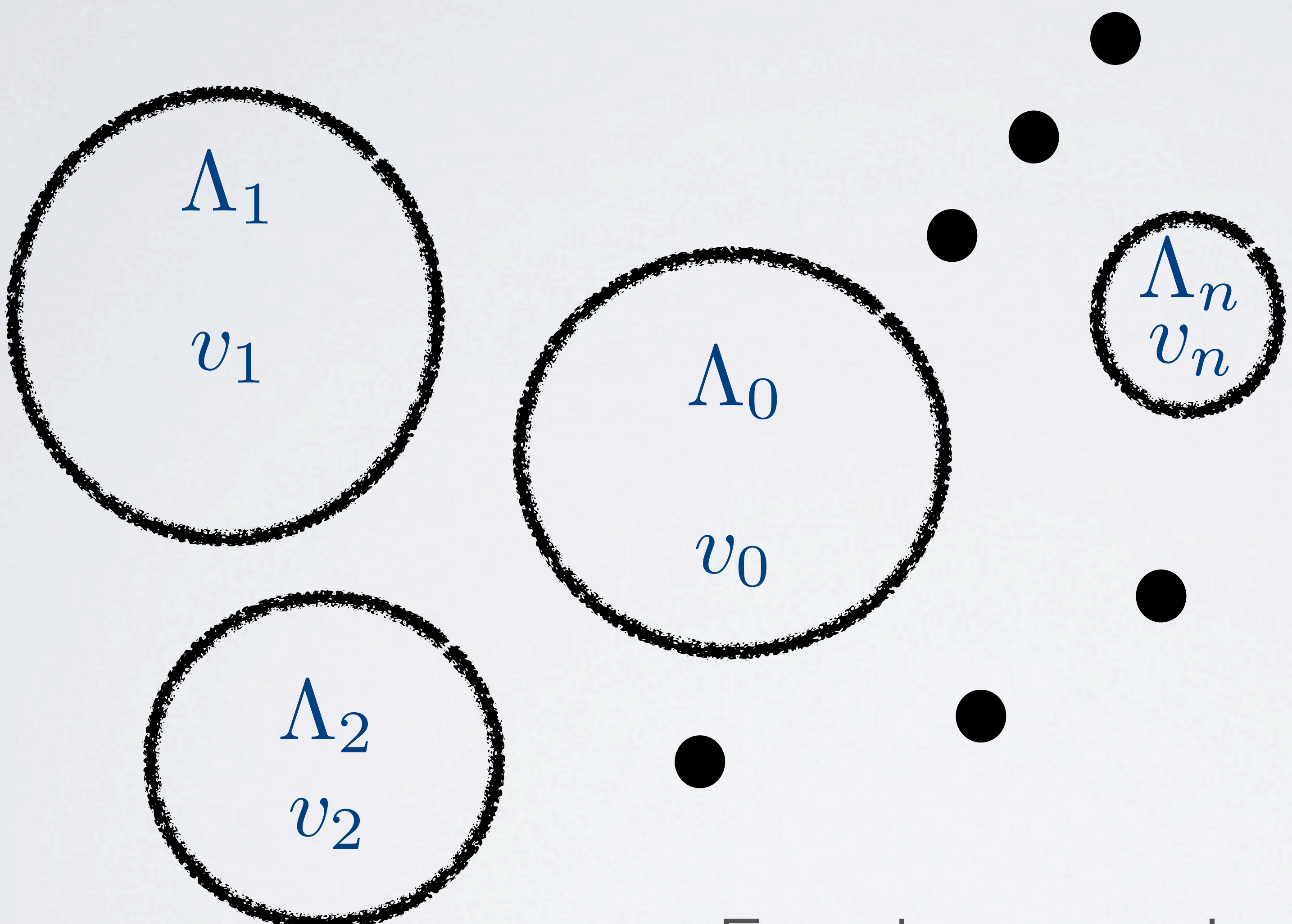
Do not Care about Naturalness

The Multiverse

The Multiverse

Some fundamental parameters environmentally determined

- "Quantum Cosmology" → multiple domains (e.g. multiverse)



Fundamental parameters
can vary from one domain to the next

Environmental Selection

Parameters up against a catastrophic boundary :
<u>cosmological constant</u>

No large scale structure

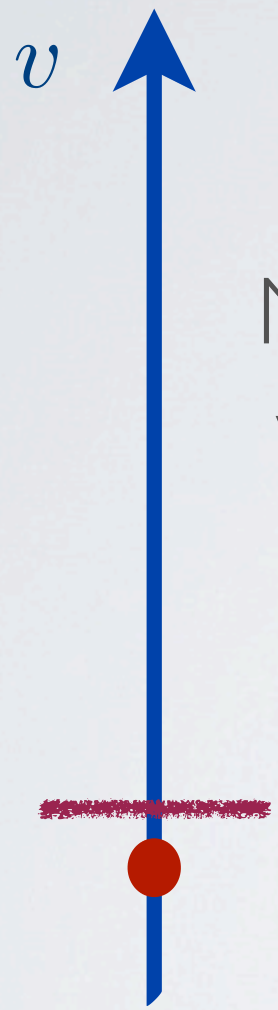
S. Weinberg '87

Probability of Λ_{CC} large is higher

$\Rightarrow$ pushed against boundary

Environmental Selection

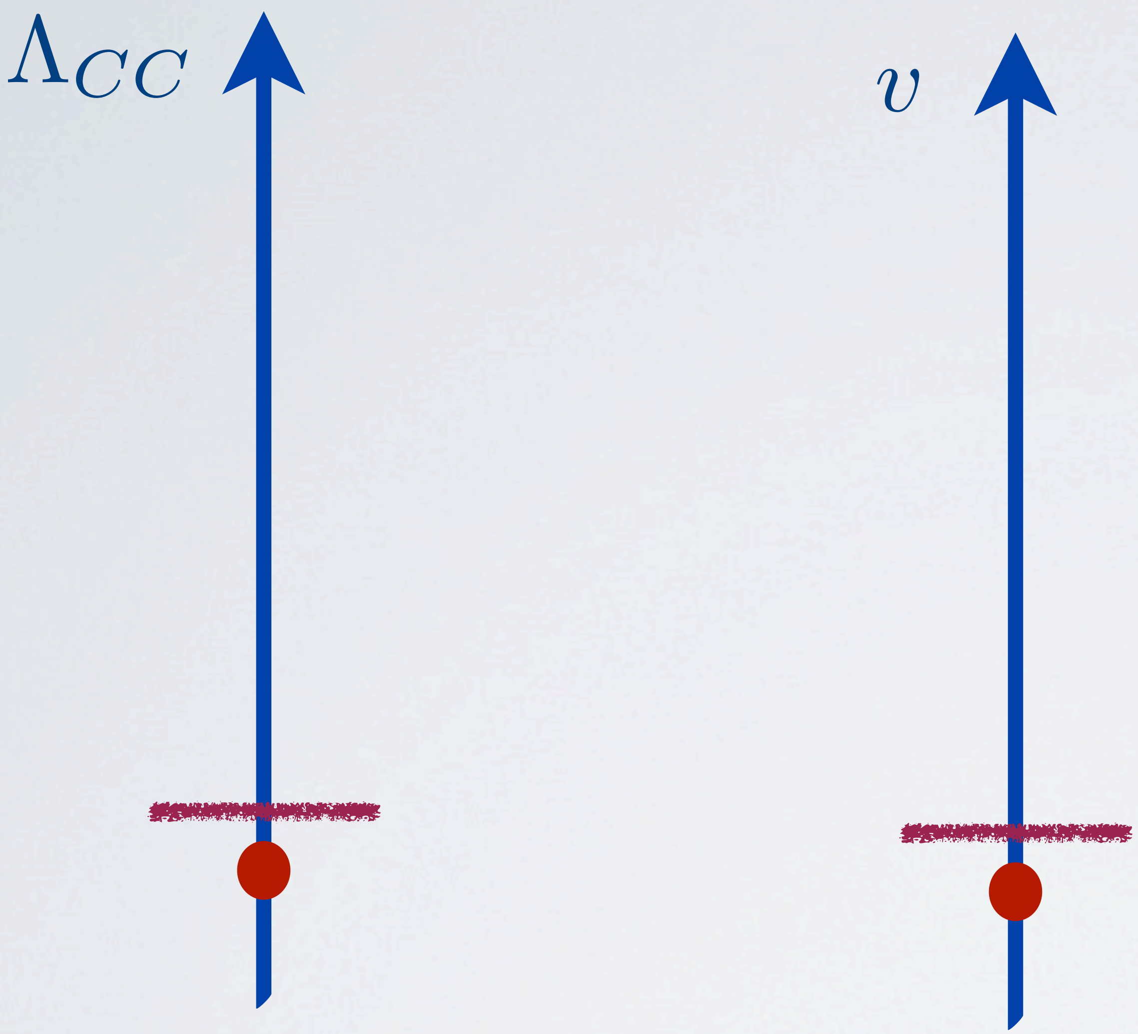
Parameters up against a catastrophic boundary:
<u>weak scale</u>



No complex nuclei

V. Agrawal, S. Barr, J. Donoghue, D. Seckel '98

Environmental Selection

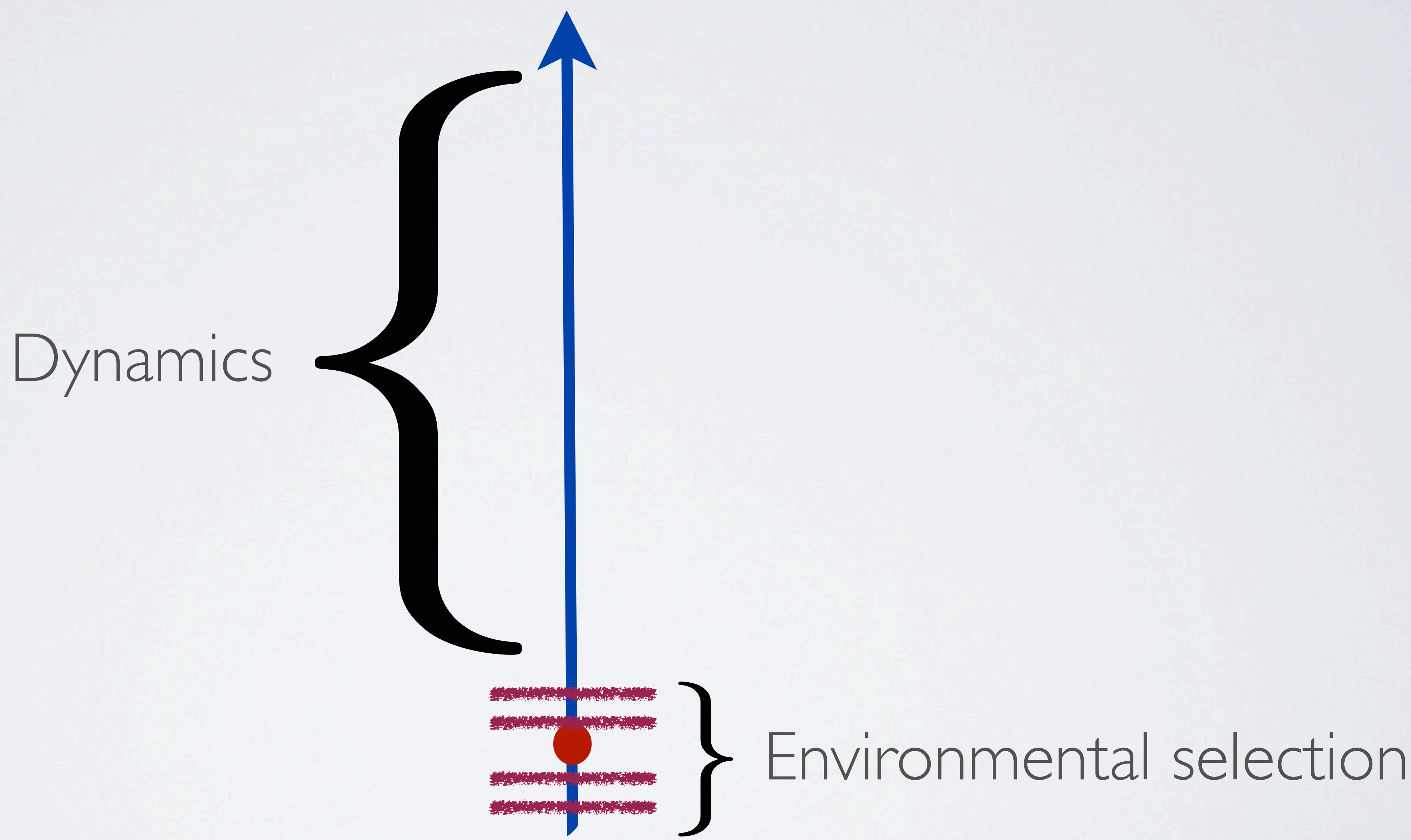


+ .....

These could be coincidences. Or maybe not !

The Little Multiverse

- Dynamics determines large gap
- Environmental selection determines exact value



Back to Naturalness

Our natural candidate theories for TeV scale new physics

Explain a light Higgs by

- Supersymmetry

  SUSY just above the weak scale protects m_h

  Super-partners not too far above the TeV scale

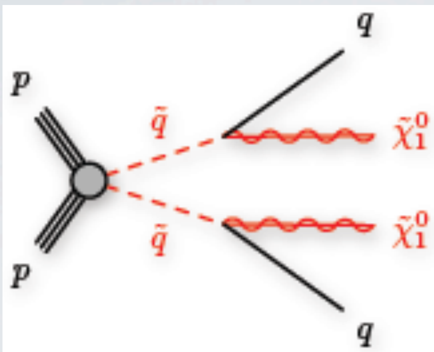
- pNGB Higgs

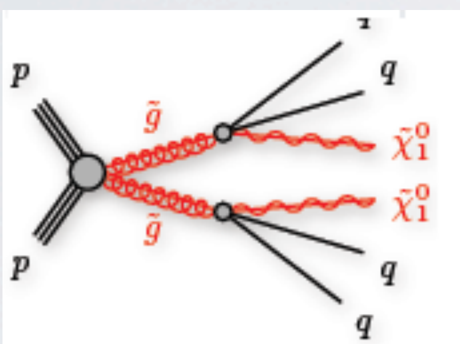
  Spontaneously broken global symmetry protects m_h

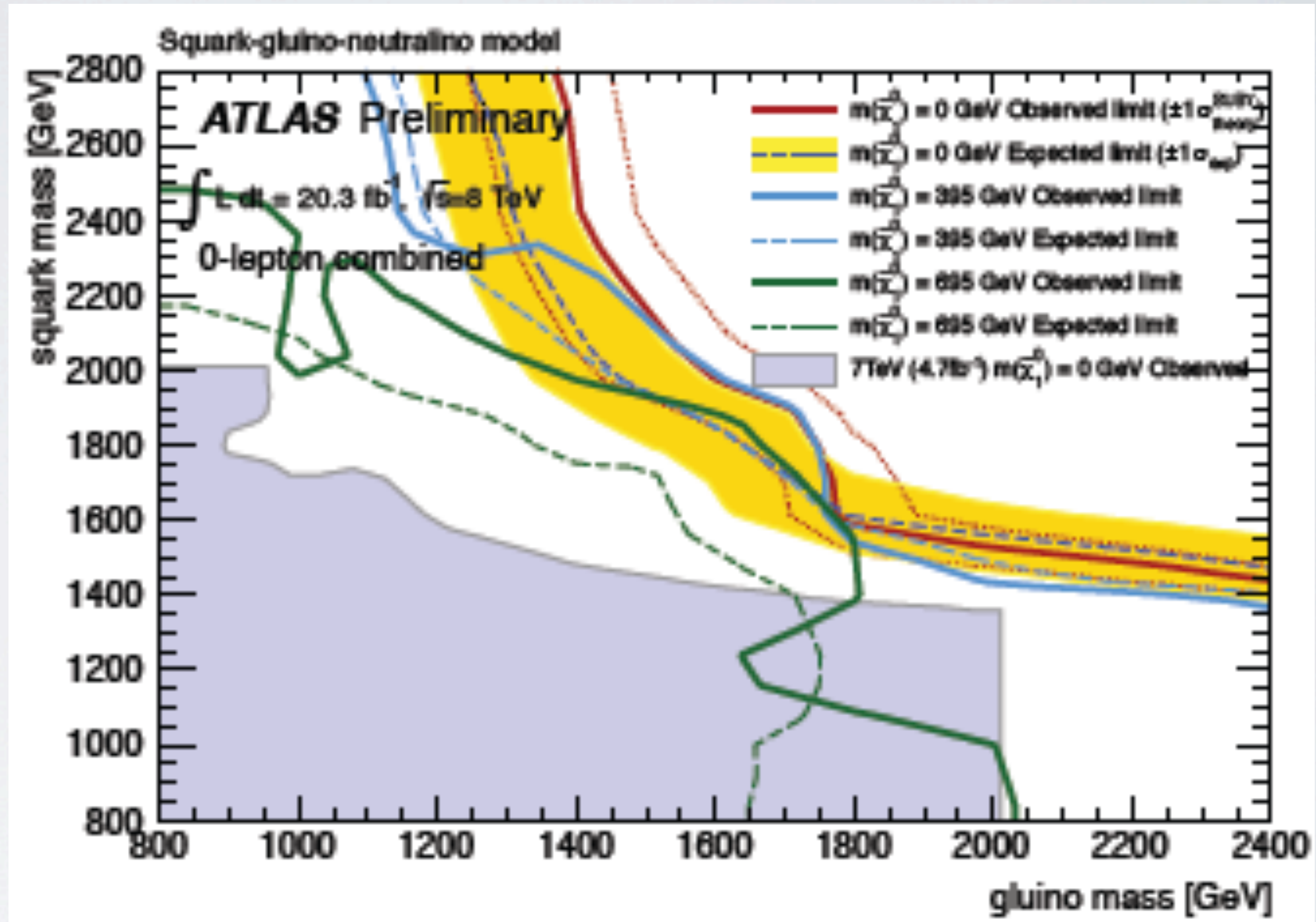
  Vector and fermion resonances not too far above the TeV scale

Supersymmetry

SUSY searches beginning to eat natural space in MSSM







Generic searches already constraining

Why we haven't seen Supersymmetry

- *Compressed Spectrum*

  Not enough $E_T^{\text{miss.}}$

- *R-parity Violation*

  LSP not stable. Different decay modes. Not enough $E_T^{\text{miss.}}$

- *Natural SUSY*

  Light *higgsinos, 3rd. gen. squarks*

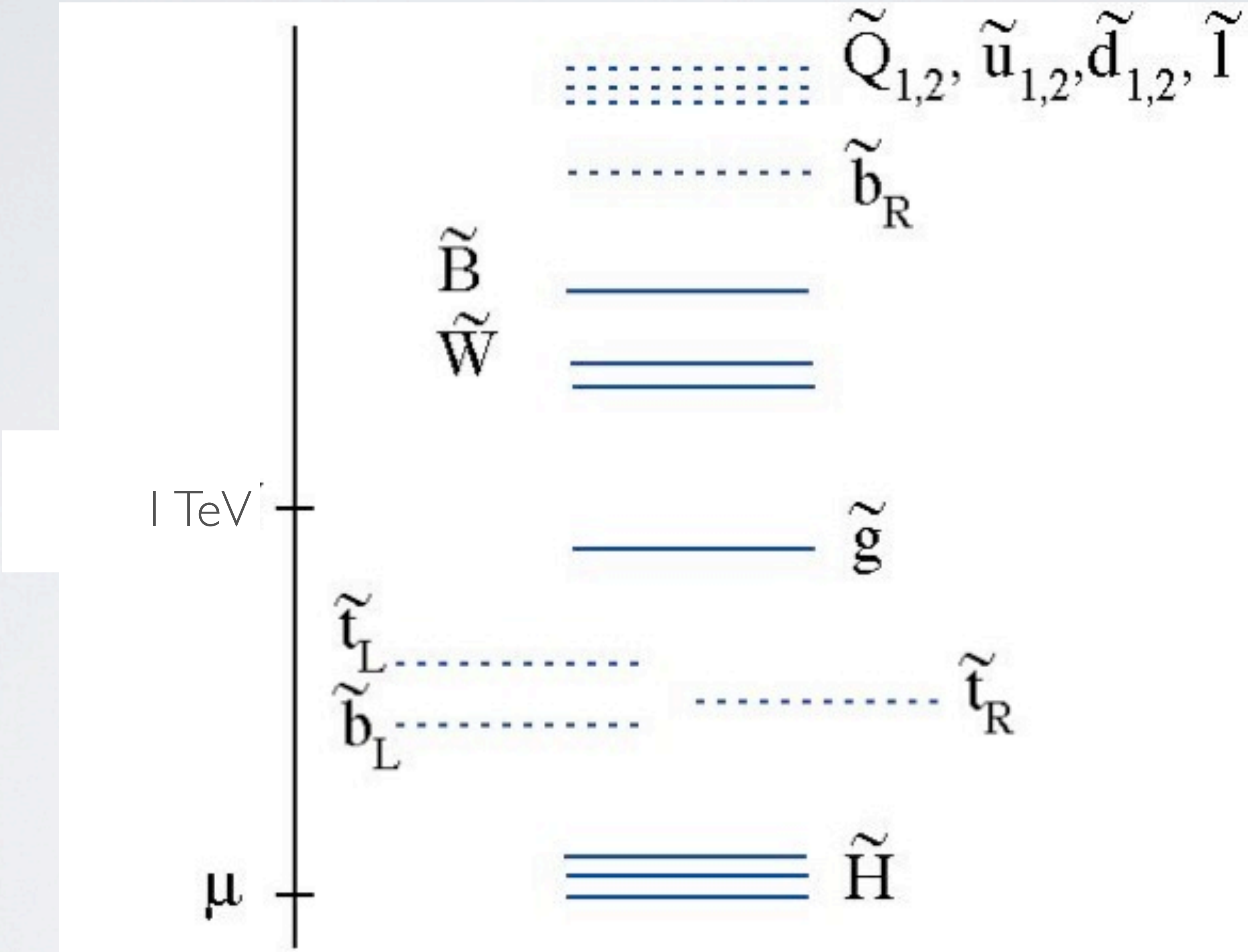
  Everybody else heavy

- Dirac gauginos (gluinos): heavy but natural gluinos

- ......

Natural SUSY

Naturalness only requires Higgsinos, stops and gluinos to be "light"



Natural SUSY

Some specific models:

- *The Least Supersymmetric SM* A. Delgado, M. Quirós '12

  Gauge mediation gives large $\tilde{m}$ for first 2 generations

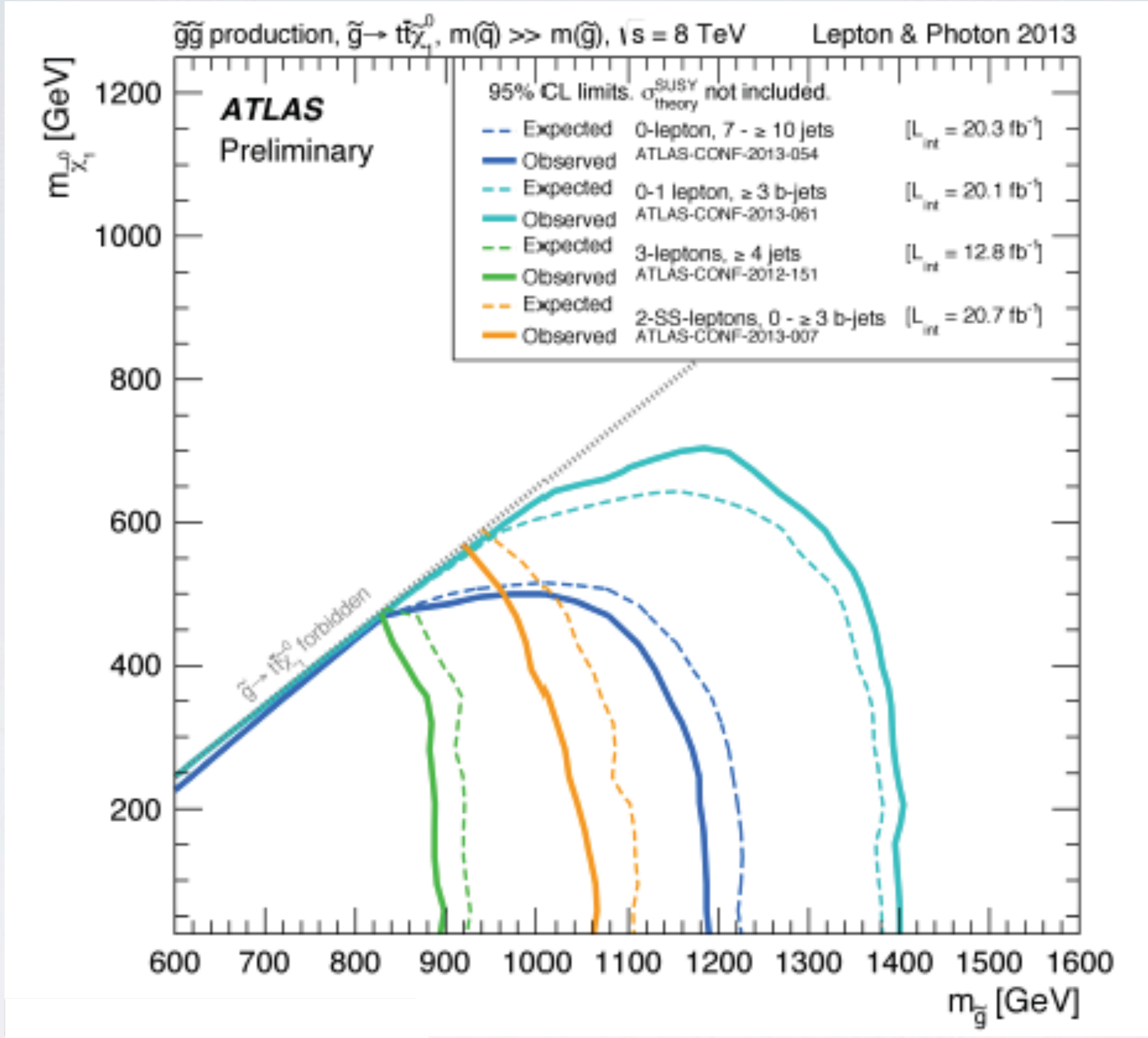
  Gravity mediation gives Higgsinos, gauginos and $\tilde{m}_3 \sim O(1)\mathrm{TeV}$

- *Light Stops from Seiberg Duality* C. Csaki, L. Randall, J. Terning '12

  Light part of the natural SUSY spectrum is composite

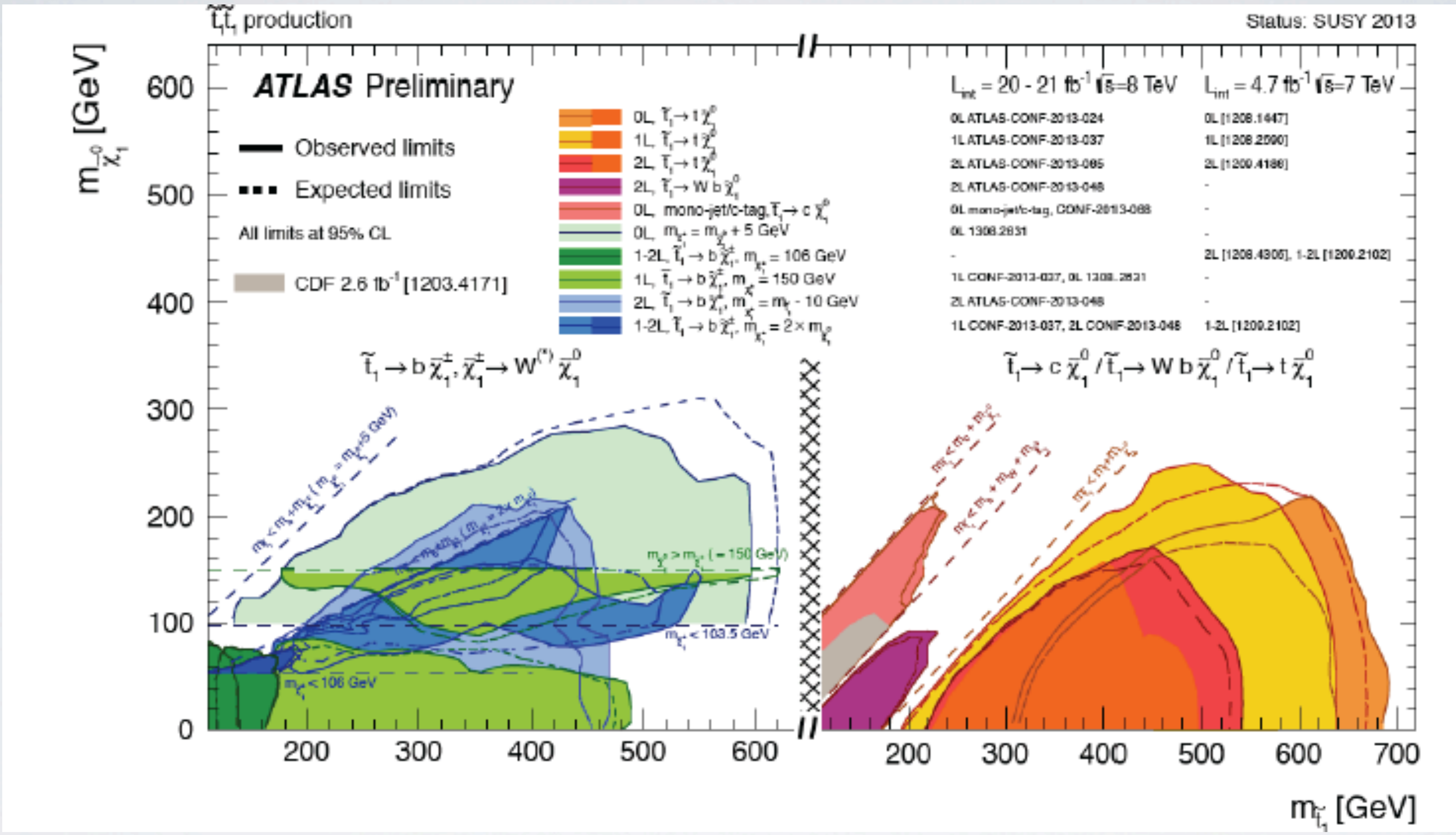
  SUSY breaking mostly felt by elementary states

Natural SUSY



Natural SUSY

Direct stop production



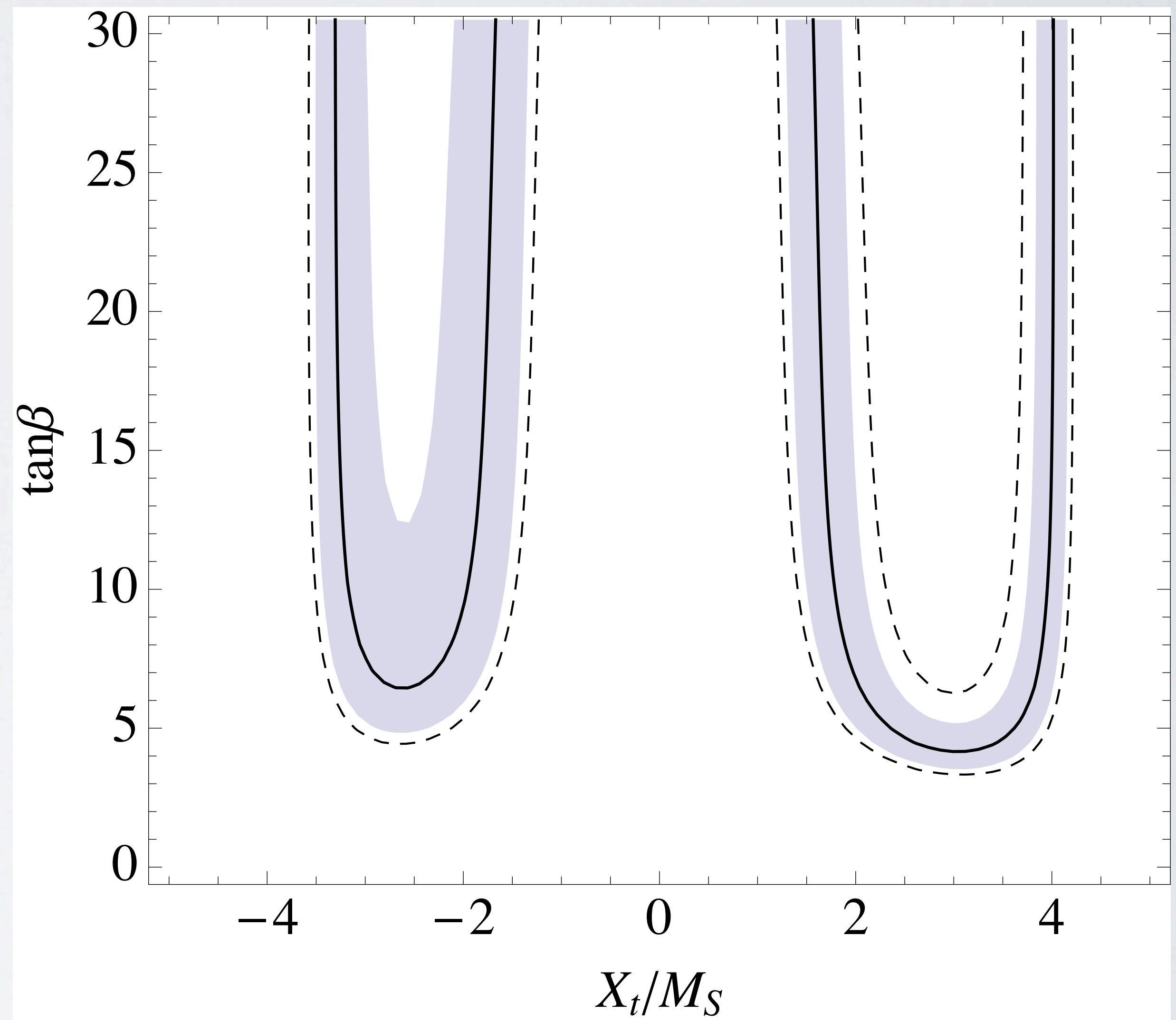
SUSY and the Higgs

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

For $m_h = 125 \text{ GeV}$

$\Rightarrow \tan\beta > 3.5$

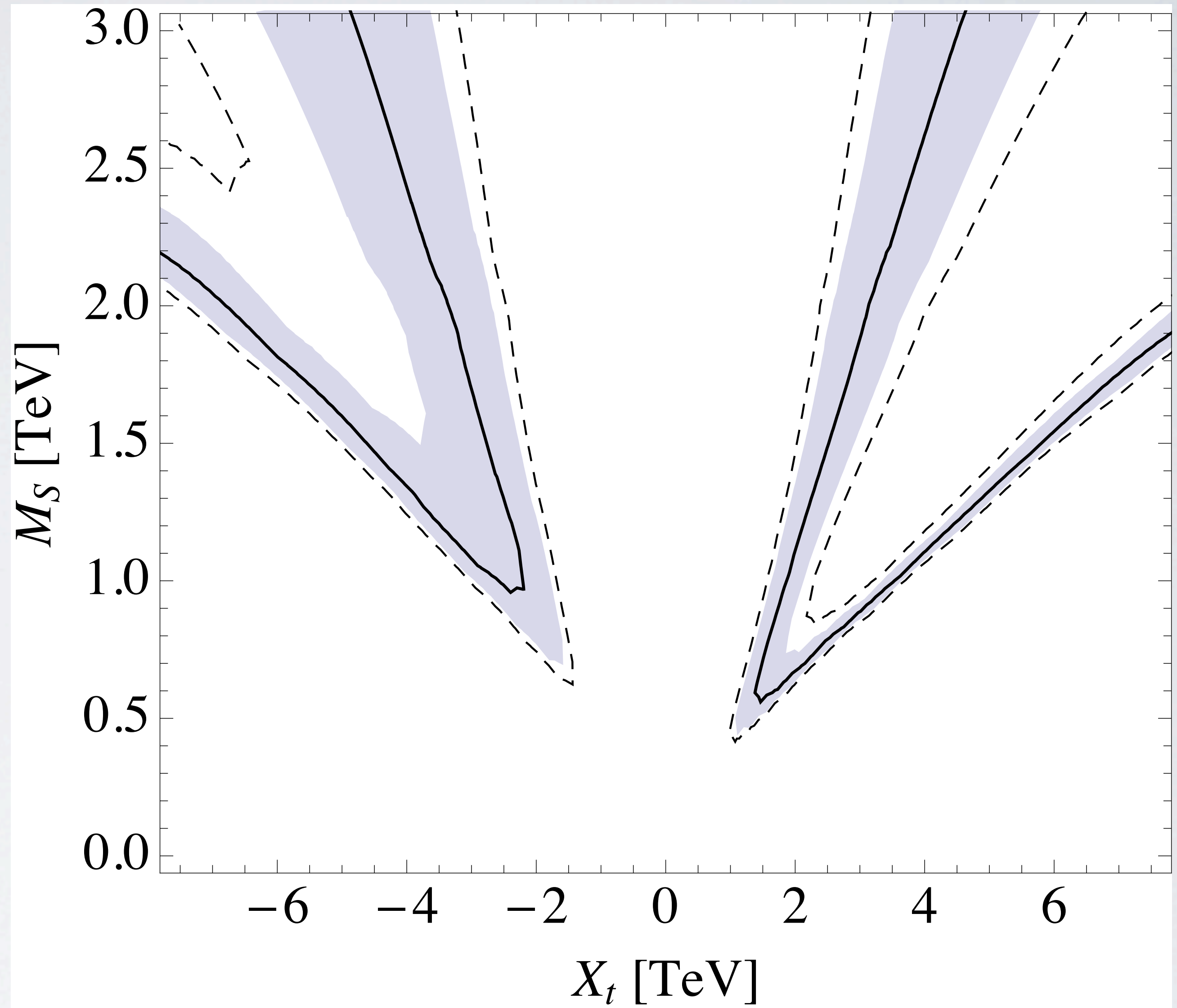
Draper, Meade, Reece, Shih '12



SUSY and the Higgs

For fixed $\tan\beta = 30$

$$\Rightarrow \begin{cases} |X_t| > 1 \text{ TeV} \\ M_S > 500 \text{ GeV} \end{cases}$$



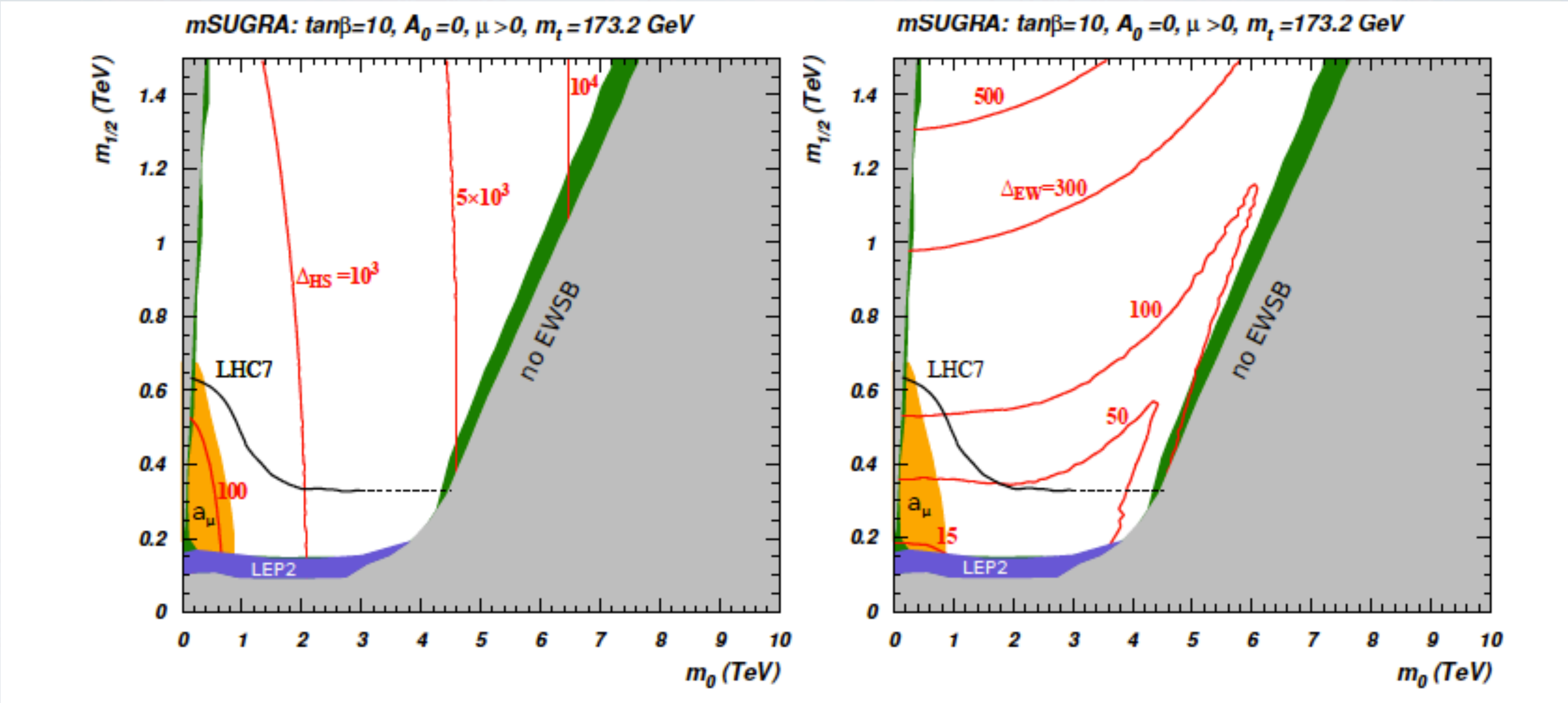
$\Rightarrow$ Trouble for GMSB:

pressure on M_{mess} to be large

SUSY and Fine Tuning

E.g. For mSUGRA

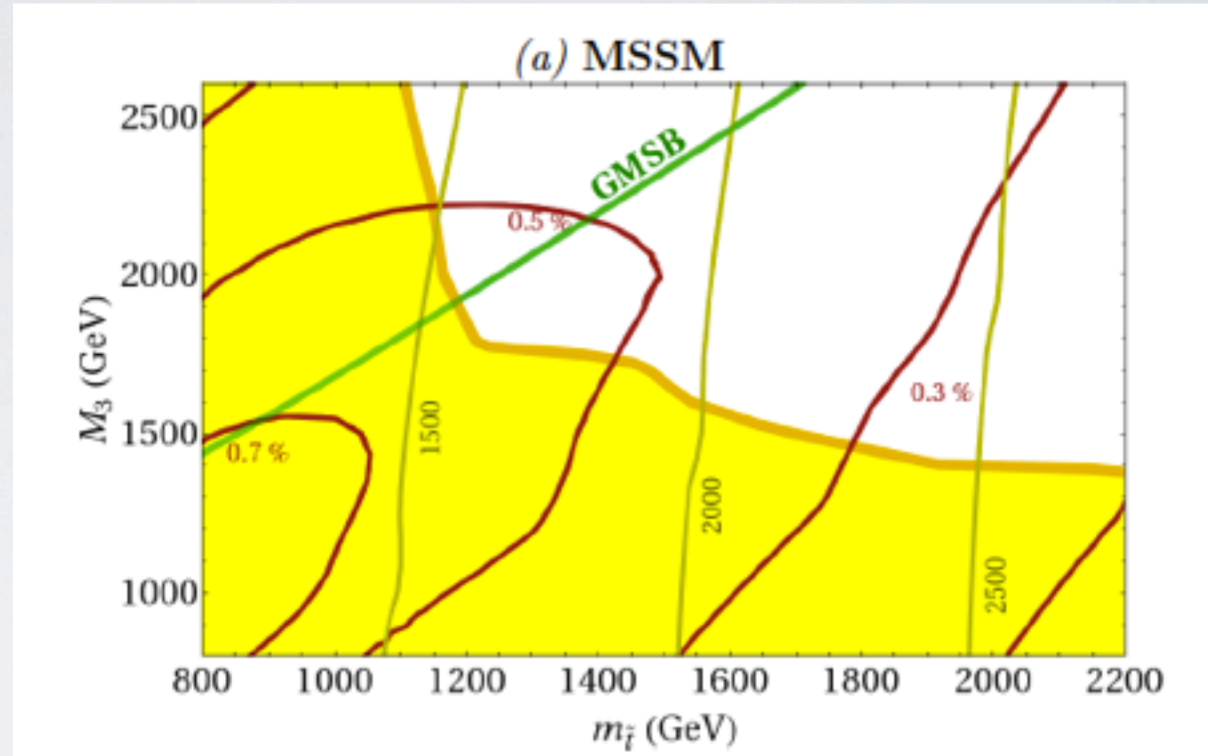
H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, X. Tata 1210.3019



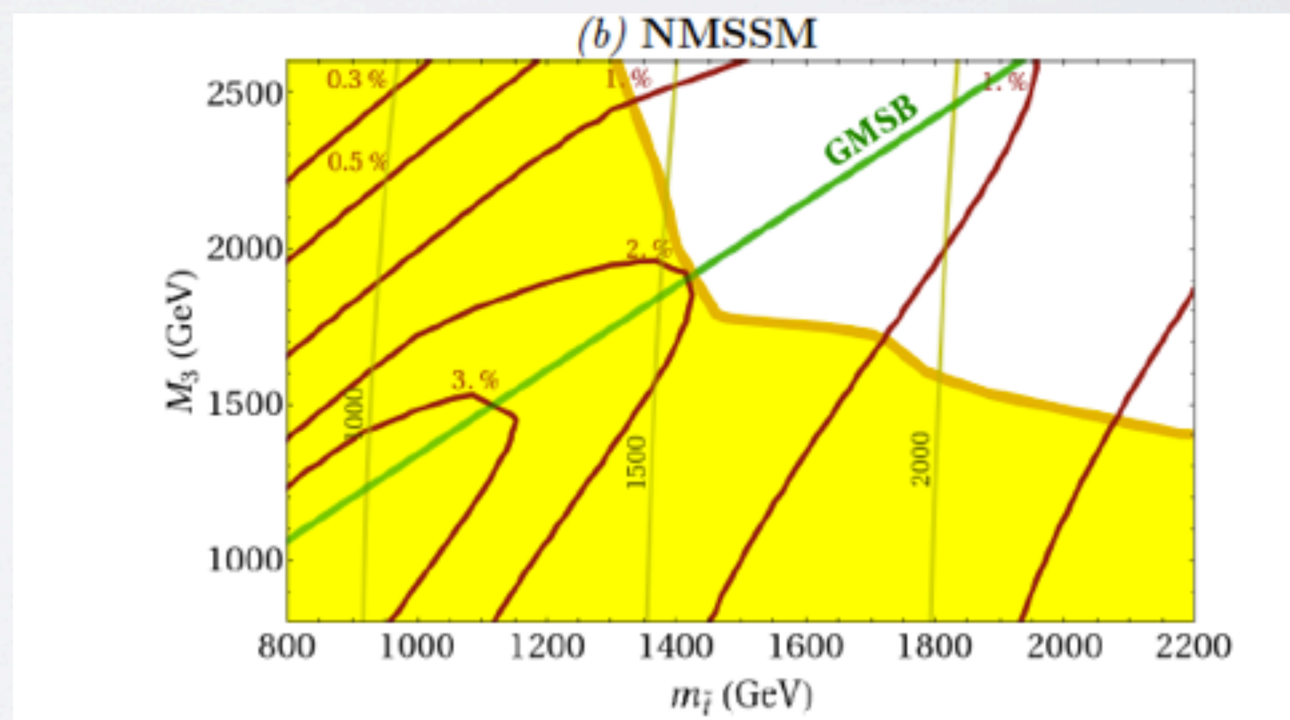
SUSY and Fine Tuning

In the MSSM tuning dominated by m_h

A. Arvanitaki, M. Baryakhtar, X. Huang, K. Tilburg, G. Villadoro, 1309.3568

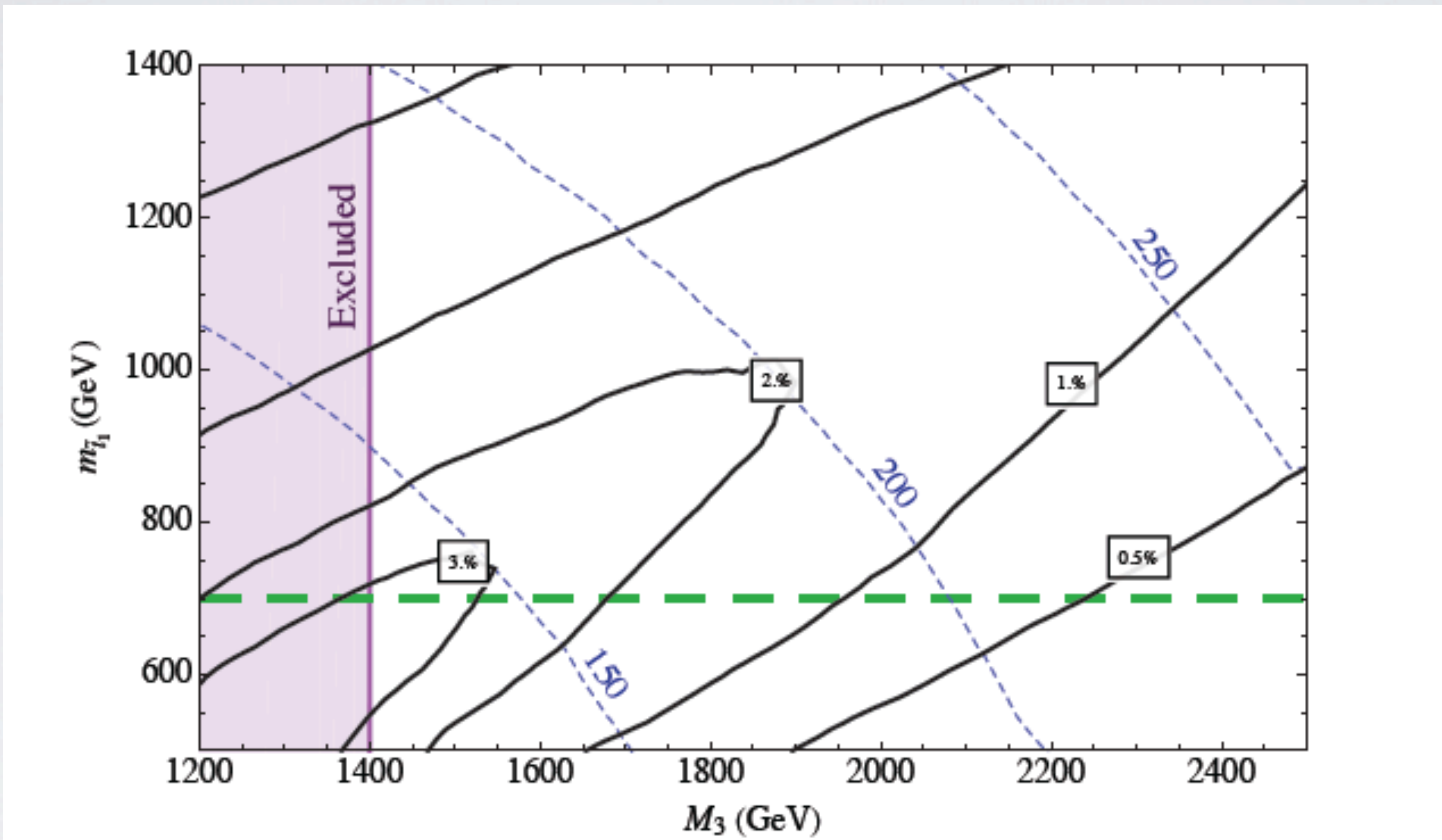


If model fixes m_h (e.g. NMSSM) tuning dominated by LHC bounds



Natural SUSY and Fine Tuning

Split families, with U(1)'



Strong Dynamics: the Higgs as a pNGB

In the analogy with QCD

- Technicolor:

$$\left.\begin{aligned} h &\simeq \sigma \\ m_h &\simeq \Lambda \end{aligned}\right\}$$

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- Higgs is a pNGB: H. Georgi and D. B. Kaplan '80

$$\left.\begin{aligned} h &\sim \pi \\ m_h &\ll \Lambda \end{aligned}\right\}$$ remnant from spontaneous breaking of global symmetry

Global symmetry protects $m_h \;\Rightarrow V(h) = 0$

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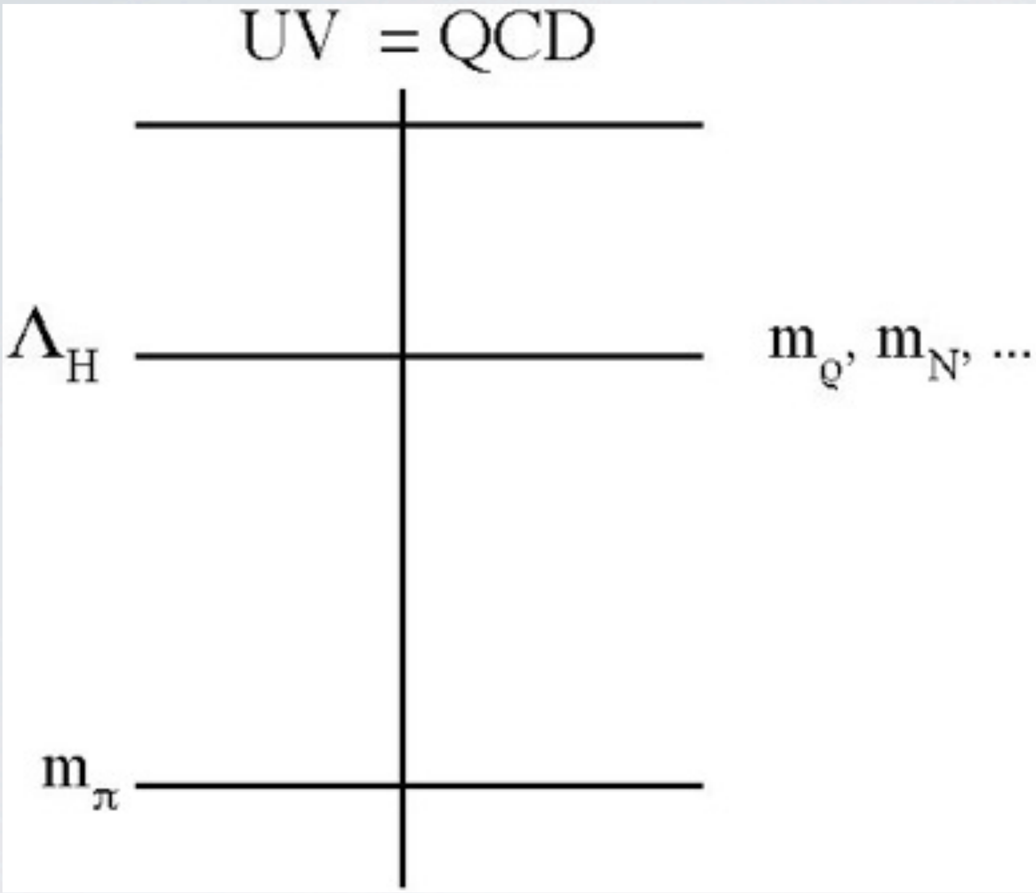
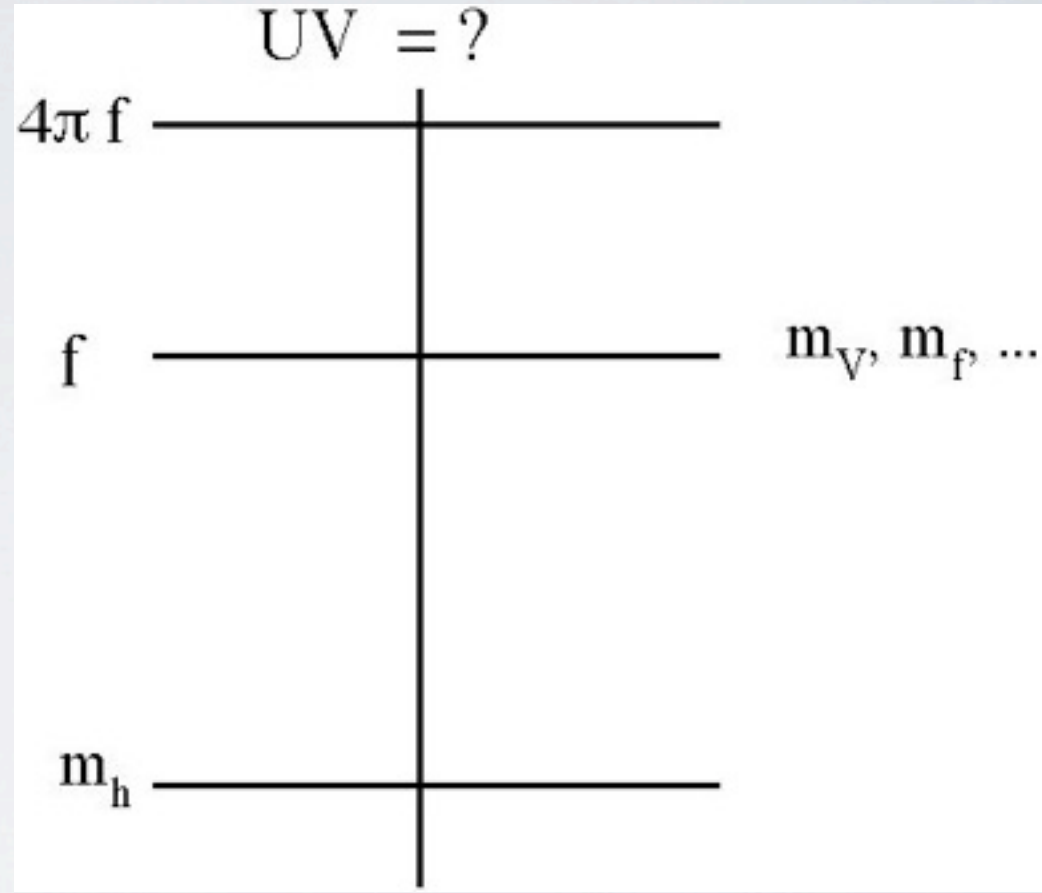
Global symmetry protects $m_h \;\Rightarrow V(h) = 0$

Explicit breaking: from gauge/Yukawa interactions $\Rightarrow m_h \neq 0$

The Higgs as a pNGB



QCD



Electroweak

The Higgs as a pNGB

To extract h from NGB:

Need to get from adjoint of G to fundamental of $SU(2)$

$\Rightarrow$ $G >$ SM gauge group

E.g. $SU(3) \to SU(2) \times U(1) \Rightarrow$ 4 NGBs for a complex doublet

Gauging $SU(2) \times U(1)$ $\longrightarrow$ $m_h \neq 0$

Just as in QCD: $U(1)_{\rm EM} \Rightarrow (m_{\pi^\pm} - m_{\pi^0})$

The Higgs as a pNGB

- In general, realistic models need custodial protection

E.g. $SO(5) \to SO(4)$ K. Agashe, R. Contino, A. Pomarol '05

- New vector and fermion resonances at f
  coupled with $g_* < 4\pi$ (partners)

Depending on models
bounds still allow natural values of f

- Many models: e.g. 2HDM E. Bertuzzo's talk in WG1.

The Higgs as a pNGB

- Higgs: tends to be heavy

  E.g. for partially composite tops

$$m_h^2 \simeq \frac{3}{4\pi^2}\, g_*^3\, y_t\, v^2$$ requires small g_*

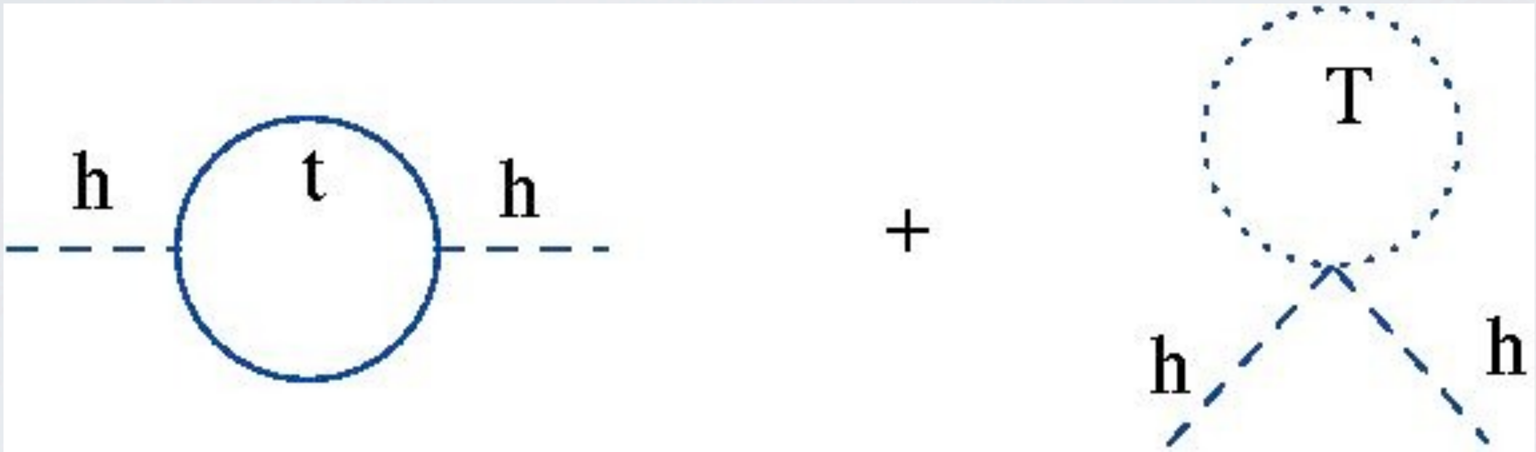
- pNGB theories from coarse RS deconstruction

  GB, N. Fonseca, L. de Lima 2012

  Have small g_* since resonances are weakly coupled

Colorless Partners

Canceling top quadratic divergences does not require top partners transforming under $SU(3)_c$



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OK if $\left\{ \begin{array}{l} y_t^2 \\ N_c \text{ copies of } T \end{array} \right.$

→ Avoid direct and indirect (e.g. Higgs) bounds

Colorless Partners

Examples

- Twin Higgs Z. Chacko, H. Goh, R. Harnik '05

  Mirror SM sector, connects only through Higgs

- Folded SUSY GB, Z. Chacko, H. Goh, R. Harnik '06

Orbifold SUSY theories with enlarged gauge symmetries

E.g. $SU(3) \times SU(3) \rightarrow SU(3)_c \times SU(3)_F$

Choose 5D orbifold at 10 TeV: ZM squarks carry F-color

Protections only at one loop, but enough for Little Hierarchy

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- Other models: Quirky Little Higgs (H.Cai, H. Cheng, J. Terning '09),
  Dark Top (D. Poland, J. Thaler '08)

Colorless Partners

- Hard to produce at LHC (8 and 13)
- Modified Higgs couplings: GB, Z. Chacko, R. Harnik, L. de Lima, in progress

Either through loops only (F-SUSY), or also at tree level (all others)

More precision here maybe competitive
with direct production

Conclusions

- The SM is fine-tuned in QFT. This is still a problem.
- A Little Multiverse: a bit of environmental selection might be present, even if dynamics determines the main features
- SUSY is still viable. It might well be there, a bit tuned.
- pNGB Higgs: Tuning goes up with bounds on resonances
- Colorless partners: must explore.
  Could be last refuge of naturalness