Naturalness after LHC8

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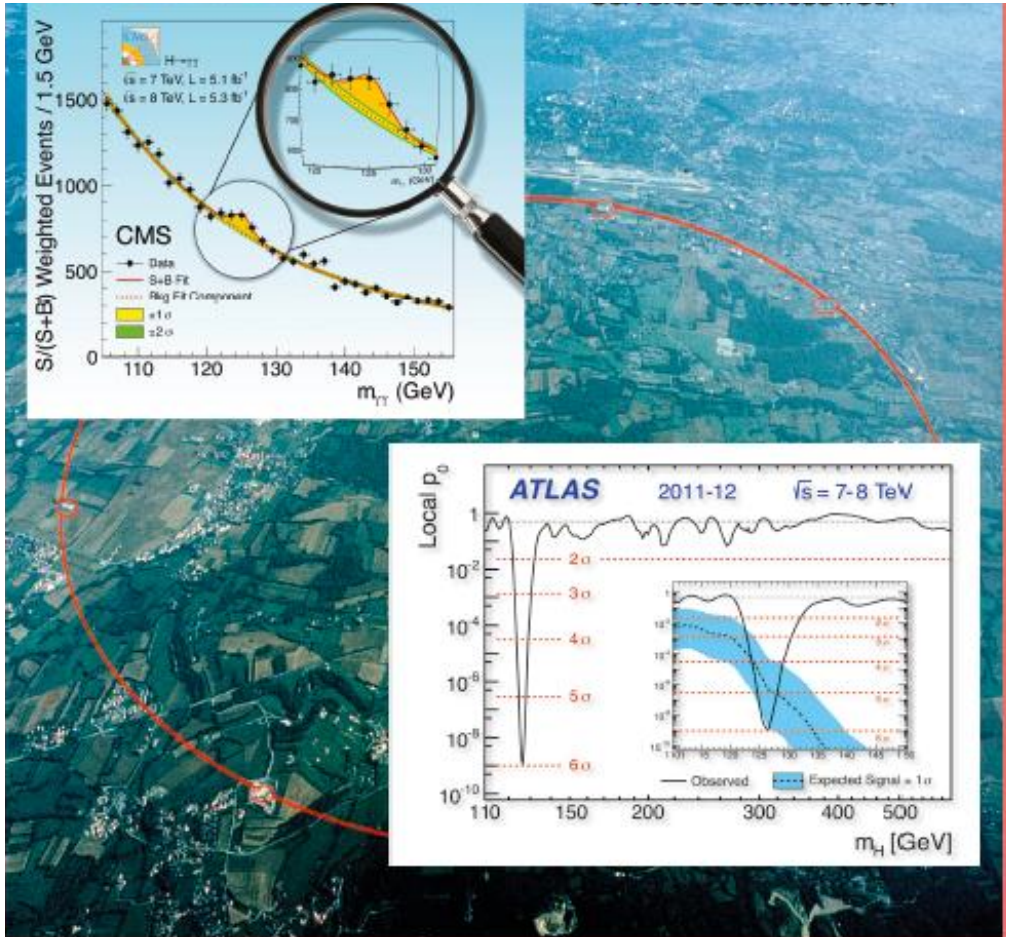
Main goal of LHC: clarify mechanism of ~~EW~~



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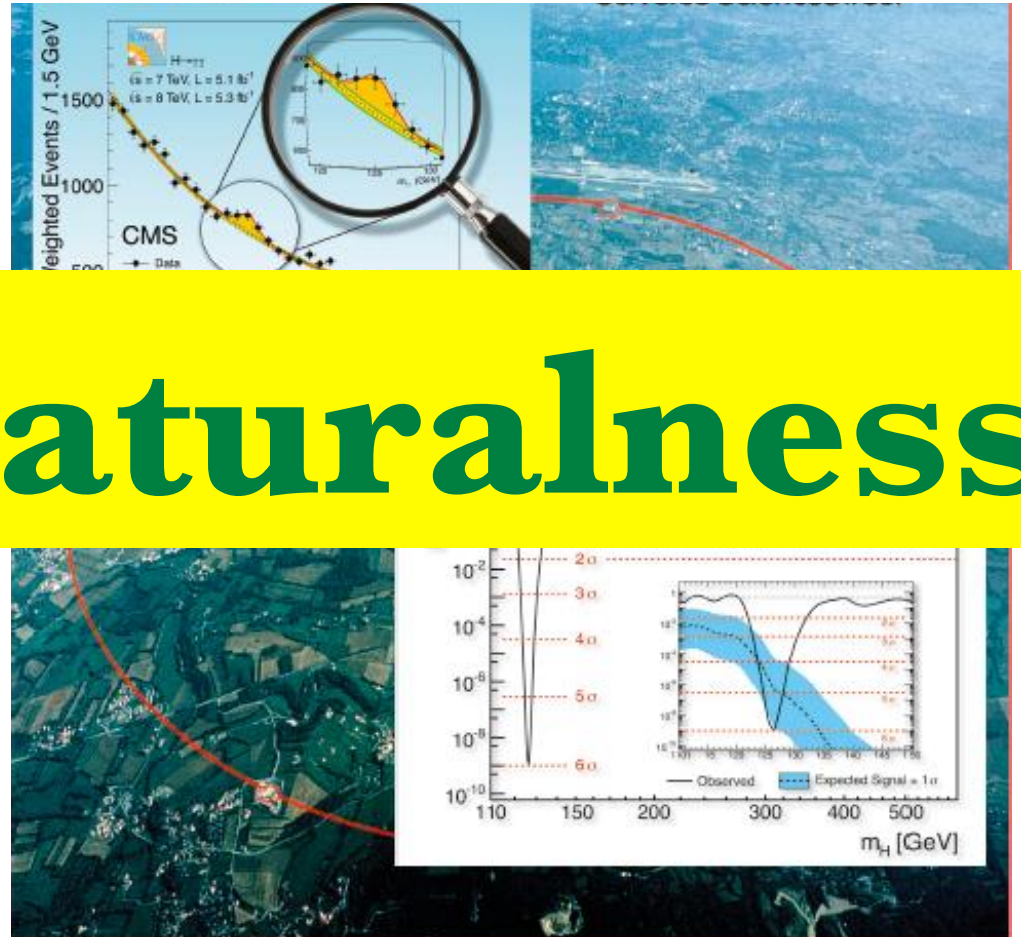

Naturalness ?

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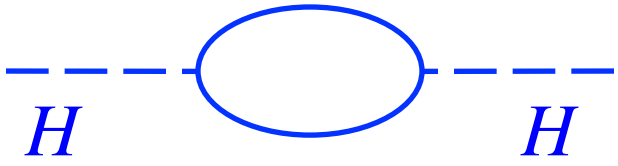
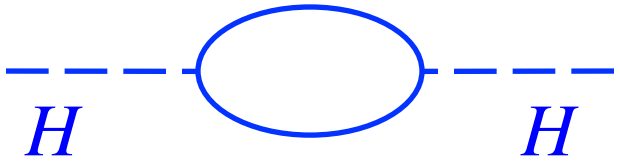


UV sensitivity of m_h in SM as an effective theory

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

Naturalness ?



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Where is new physics?

Naturalness under attack!

Is the effective-field theory approach misleading ?

Is the effective-field theory approach misleading ?

GUT

$$V = m_H^2 |H|^2 + \lambda |H|^4 + M^2 |\Phi|^2 + \lambda_\Phi |H|^2 |\Phi|^2$$

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

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High-scale SUSY

$$V = m_H^2 |H|^2 + \lambda |H|^4 + V_{SUSY}$$

$$\delta m_H^2 \approx \frac{3y_t^2}{16\pi^2} \tilde{m}_t^2 \ln \frac{\tilde{m}_t^2}{\Lambda^2}$$

Lessons

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- Conformal symmetry does not help

- The problem is insensitive to the regularization procedure

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- Lack of conspiracy between phenomena at different scales

- Scale separation is not a necessity,

but it has been a cornerstone for progress in physics

Naturalness at work:
1. classical electron self-energy

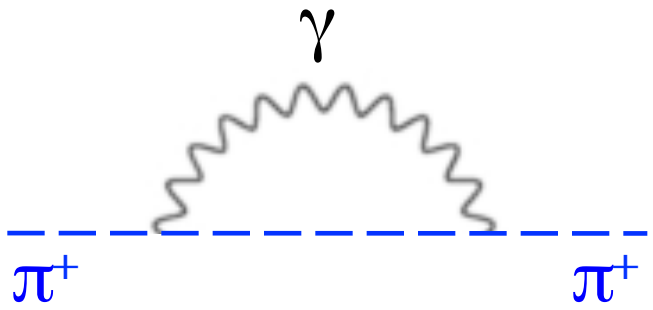
electrostatic energy : $E \approx \frac{\alpha}{r} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha} \approx 70$ MeV

magnetic energy : $E \approx \frac{\mu^2}{r^3}, \mu = \frac{e\hbar}{2m_e c} < m_e c^2 \Rightarrow \Lambda < \frac{m_e}{\alpha^{1/3}} \approx 3$ MeV

(spinning sphere)

New physics (positron) at $m_e < \Lambda$

Naturalness at work:
2. QED contribution to pion mass difference

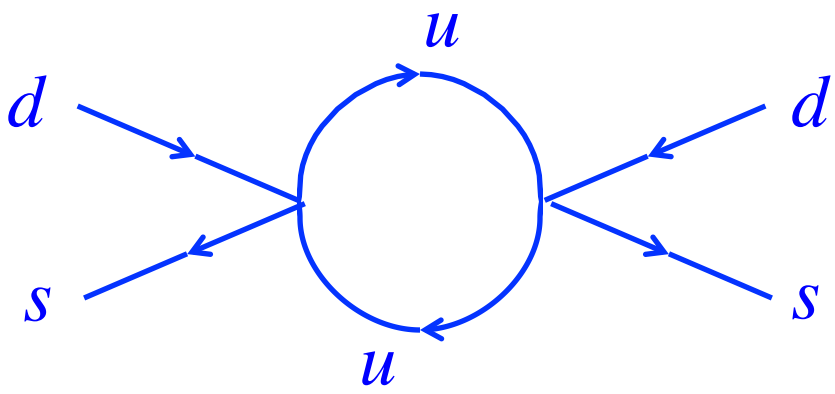


$$\frac{3\alpha}{4\pi}\Lambda^2 < M^2_{\pi^+} - M^2_{\pi^0} \;\Rightarrow\; \Lambda < 850 \text{ MeV}$$

New physics (hadrons) at $M_\rho < \Lambda$ ($M_\rho = 770$ MeV)

Naturalness at work:

3. Neutral kaon mass difference



Effective theory at M_K:

$$\frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2 < \frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} \Rightarrow \Lambda < 2 \text{ GeV}$$

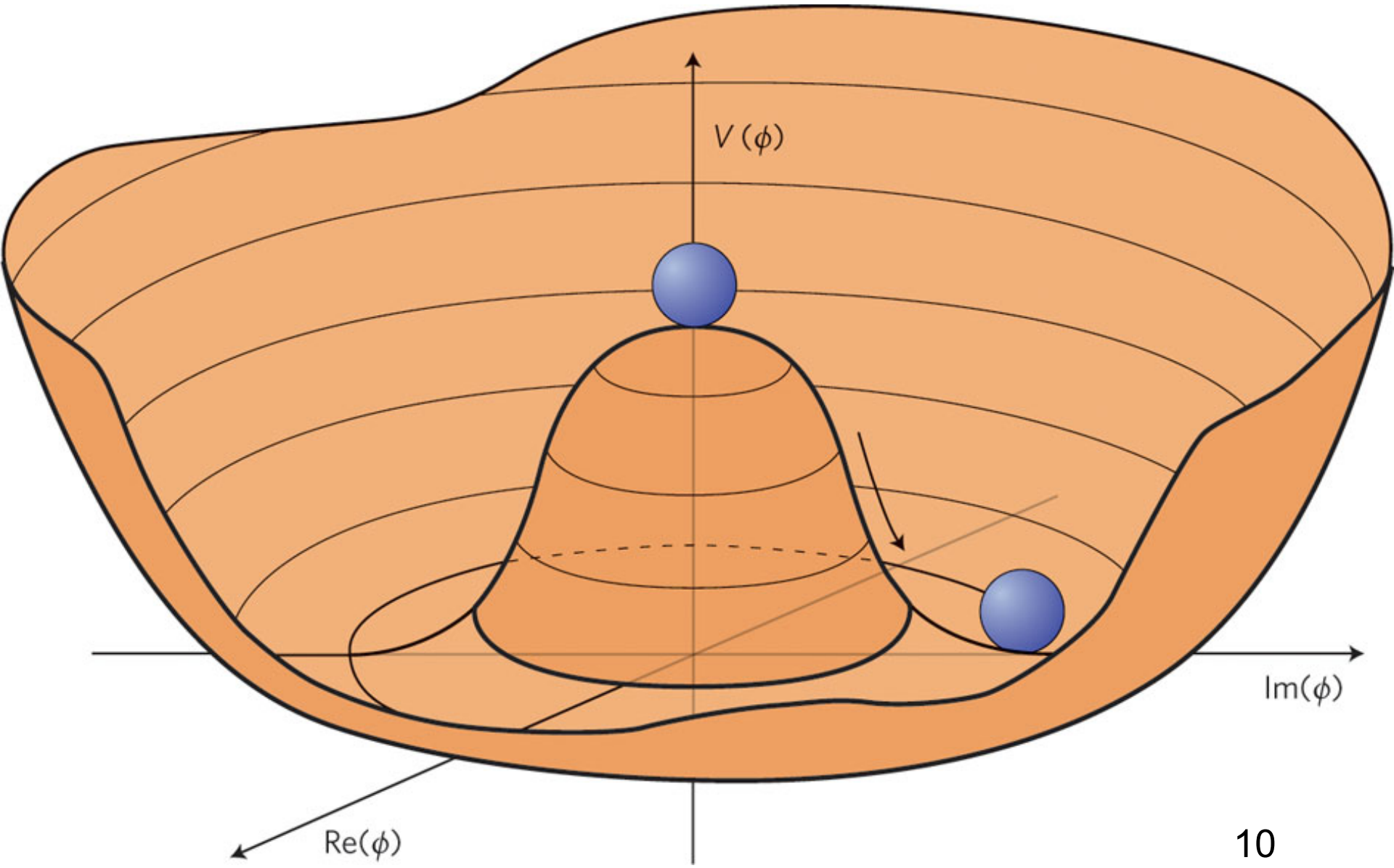
New physics (charm) at $m_c < \Lambda$ ($m_c = 1.2$ GeV)

Dark energy: a counterexample ?

$$\Lambda_{CC} = 2.4 \times 10^{-3} \text{ eV}$$

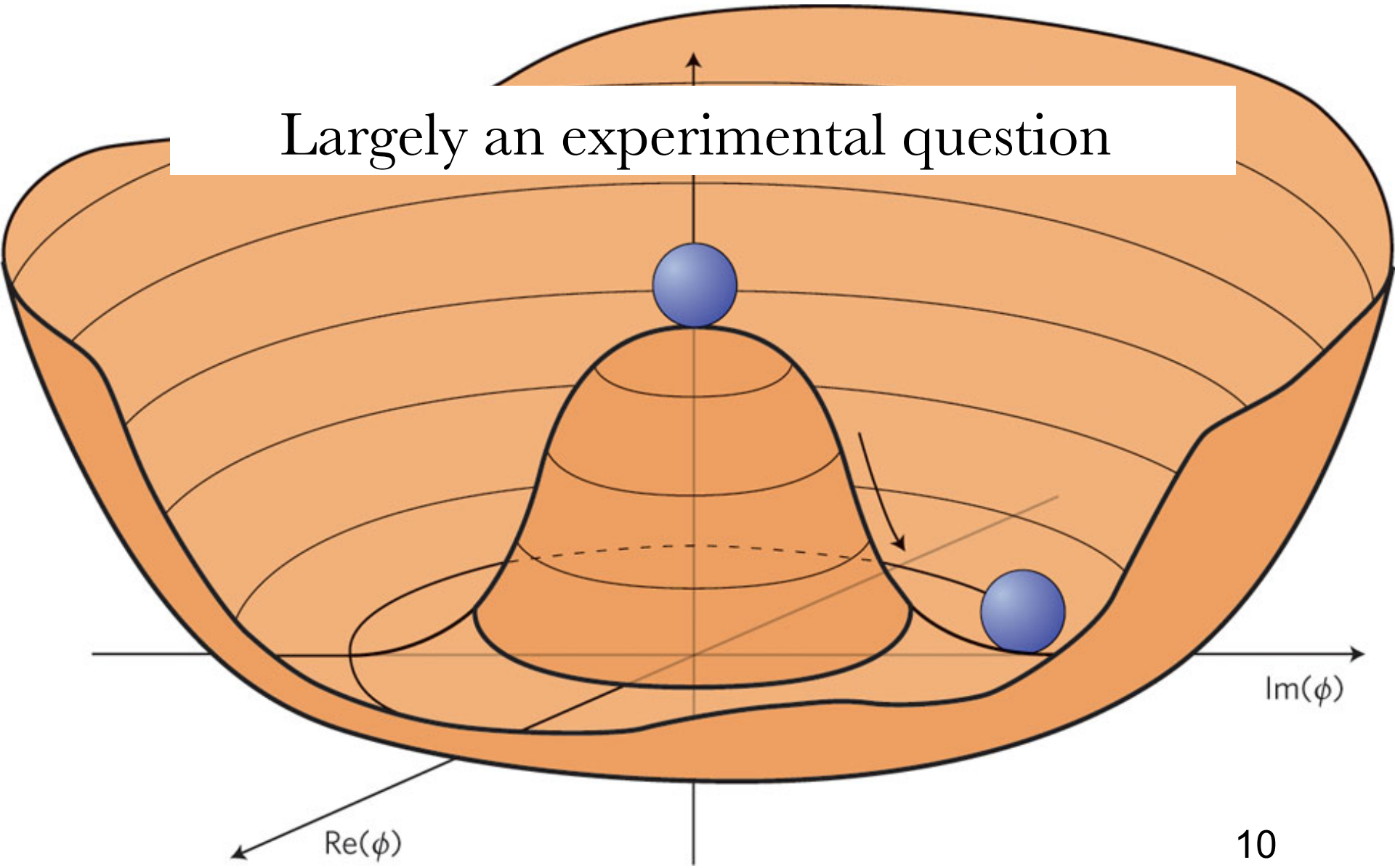
Where is new physics ?

Is the Higgs natural ?



Is the Higgs natural ?

Largely an experimental question



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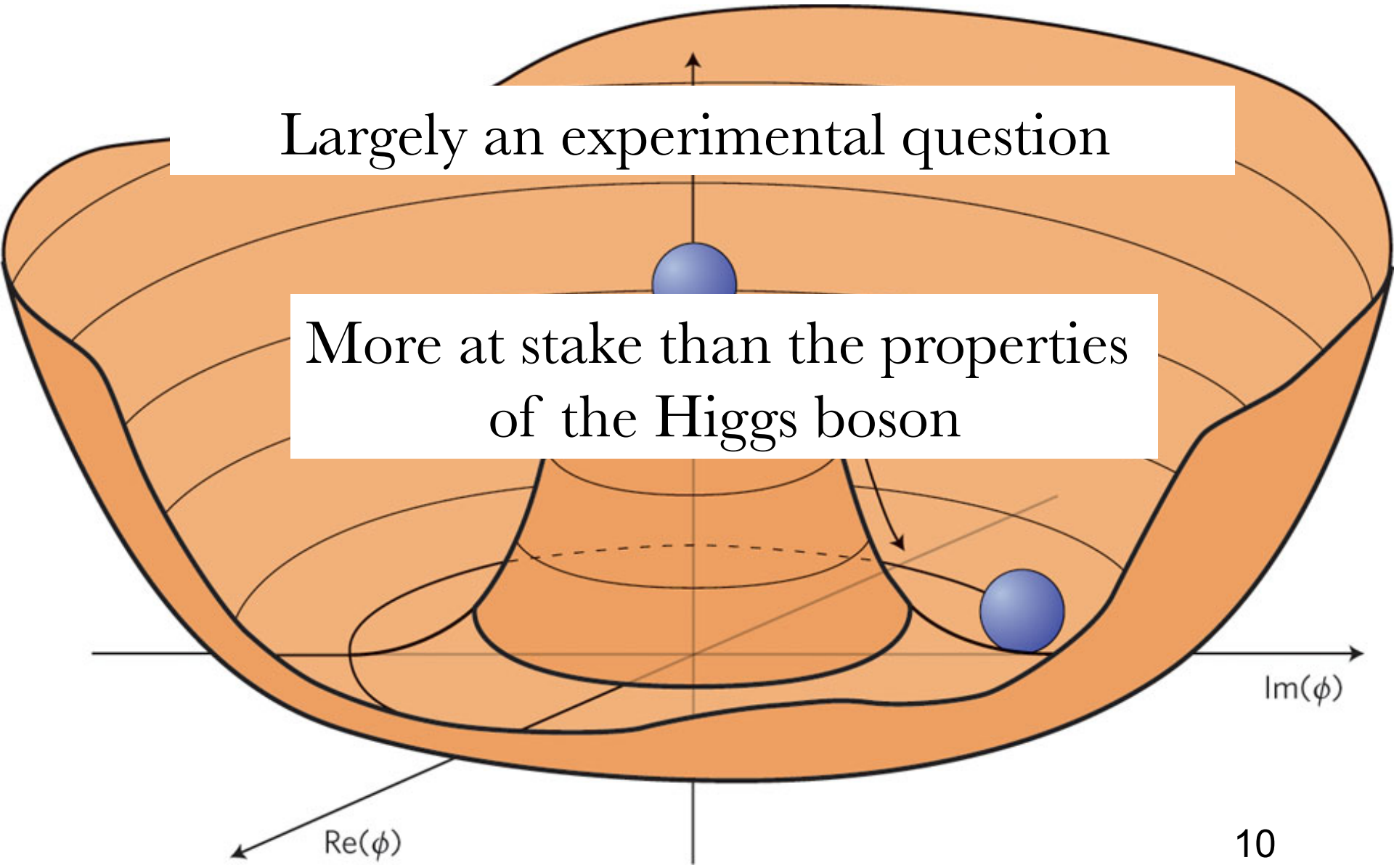

Is the Higgs natural ?

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More at stake than the properties of the Higgs boson

Unnaturalness !

Why unnaturalness?

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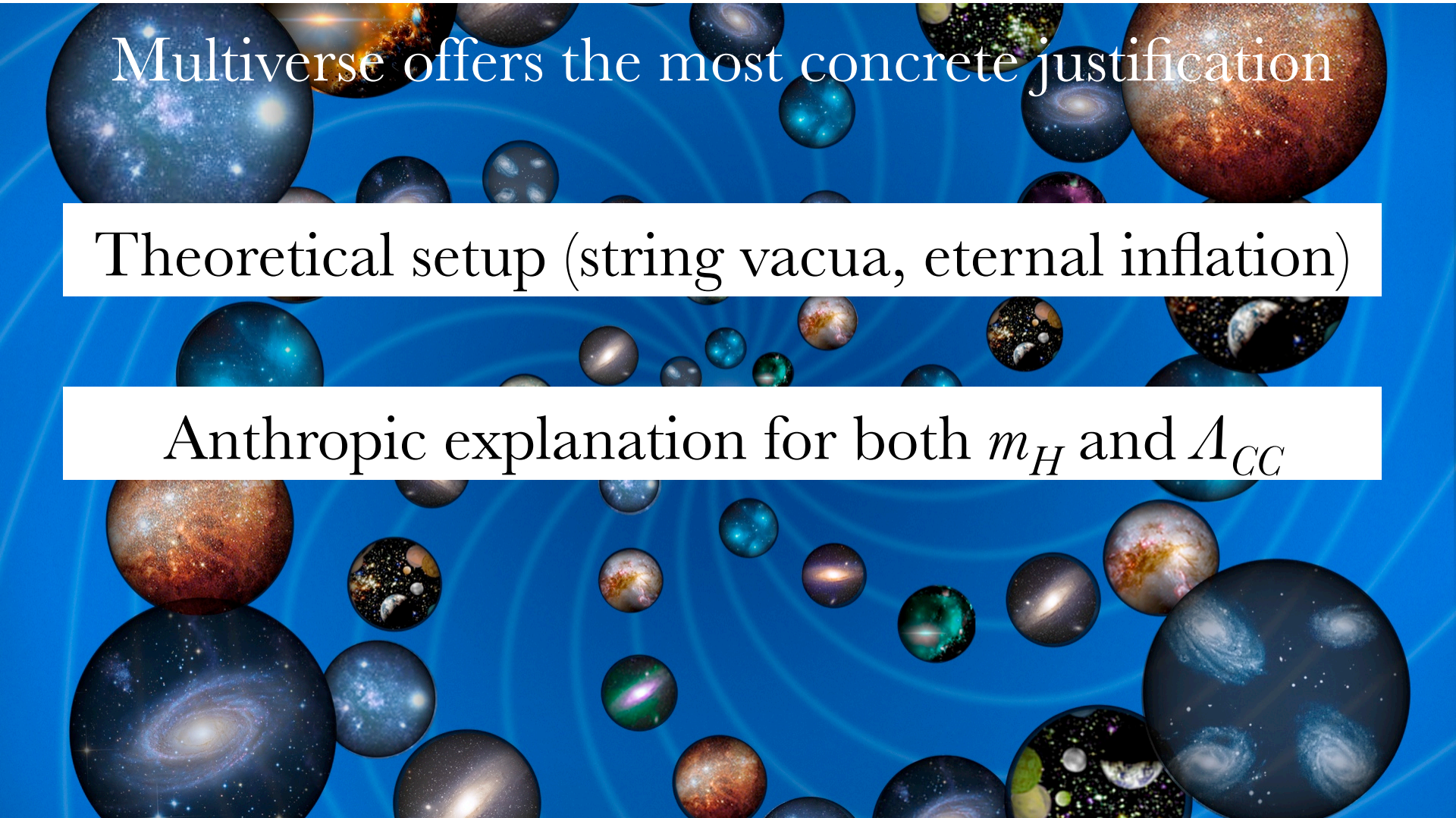


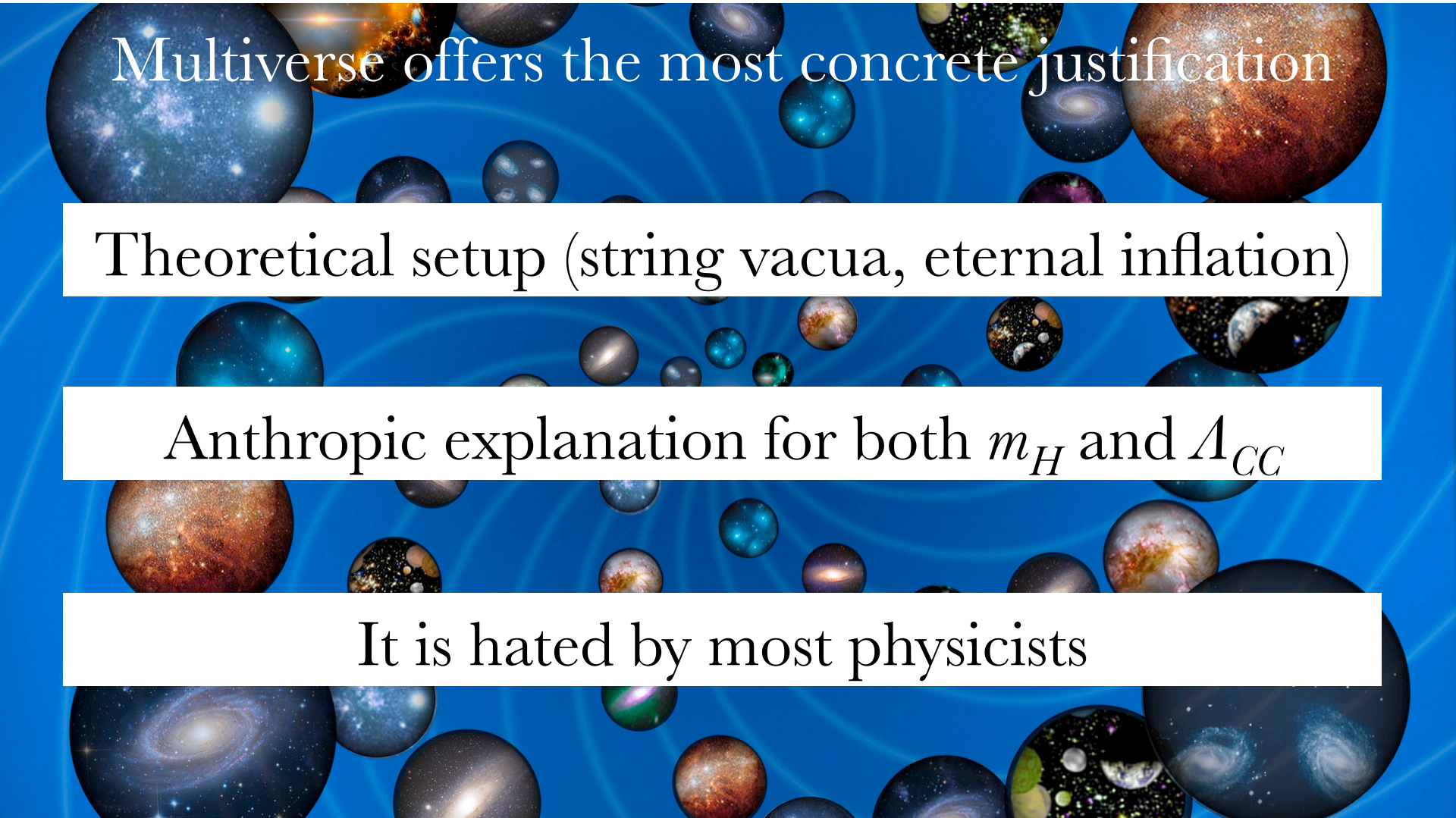
Multiverse offers the most concrete justification

Theoretical setup (string vacua, eternal inflation)

Anthropic explanation for both m_H and Λ_{CC}

Unnaturalness !

Why unnaturalness?



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Theoretical setup (string vacua, eternal inflation)

Anthropic explanation for both m_H and Λ_{CC}

It is hated by most physicists

How can we test it experimentally?

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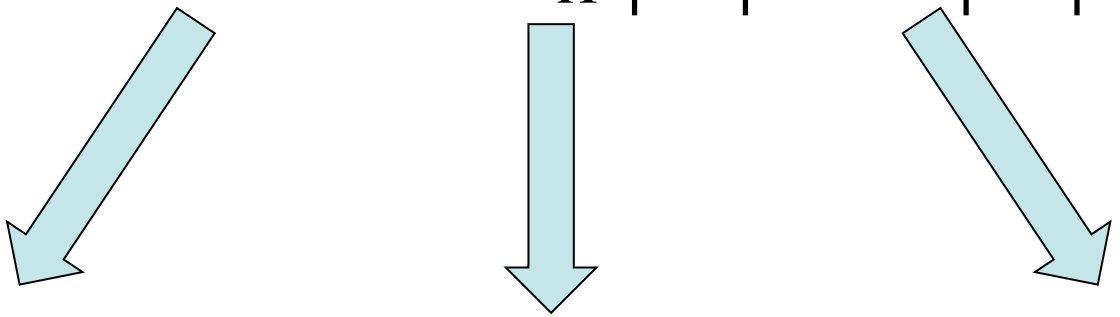
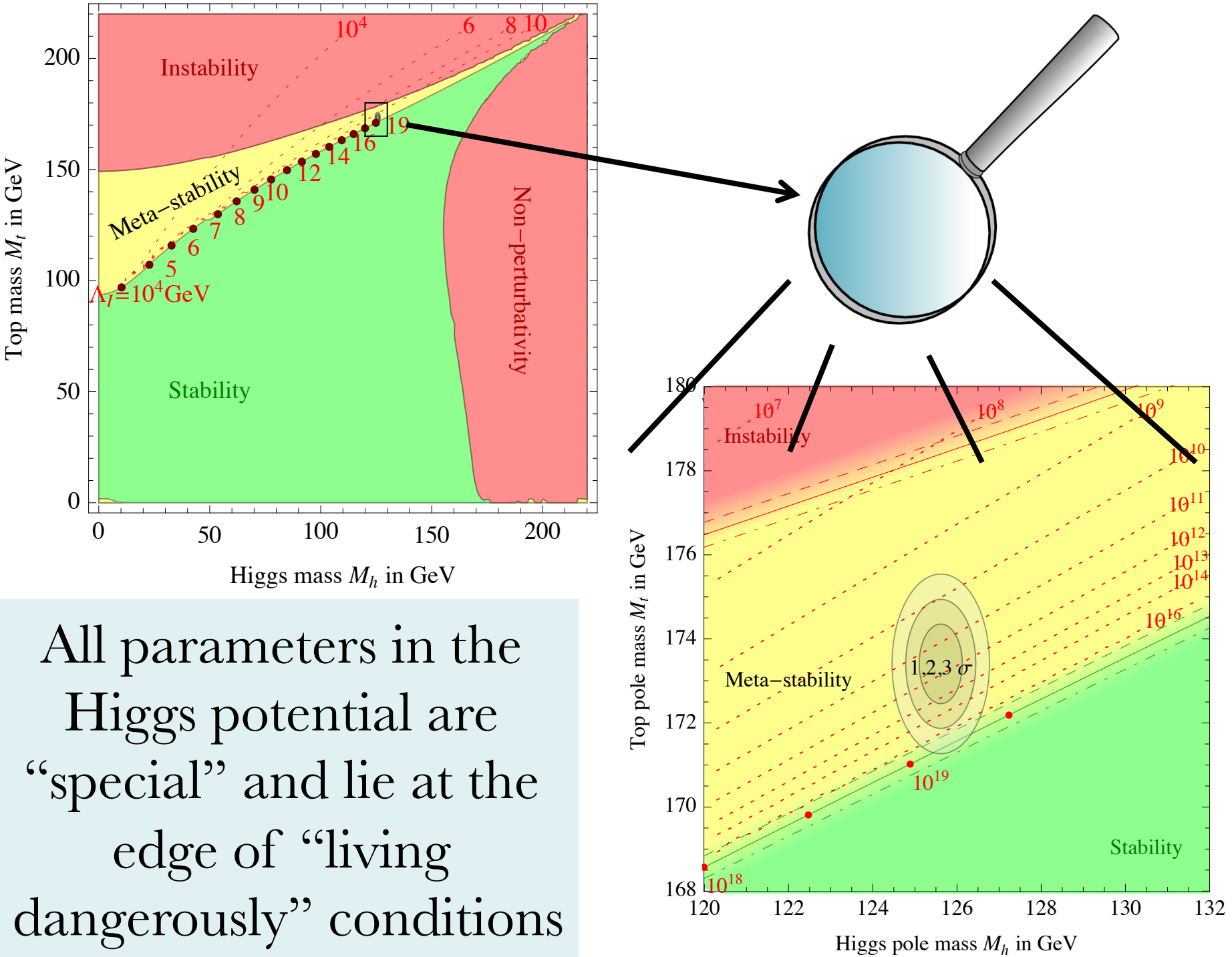
$$V = \text{const} + m_H^2 |H|^2 + \lambda |H|^4$$



Cosmological constant

Higgs naturalness

Higgs criticality



All parameters in the Higgs potential are "special" and lie at the edge of "living dangerously" conditions

Unnaturalness does not mean that there is nothing to discover

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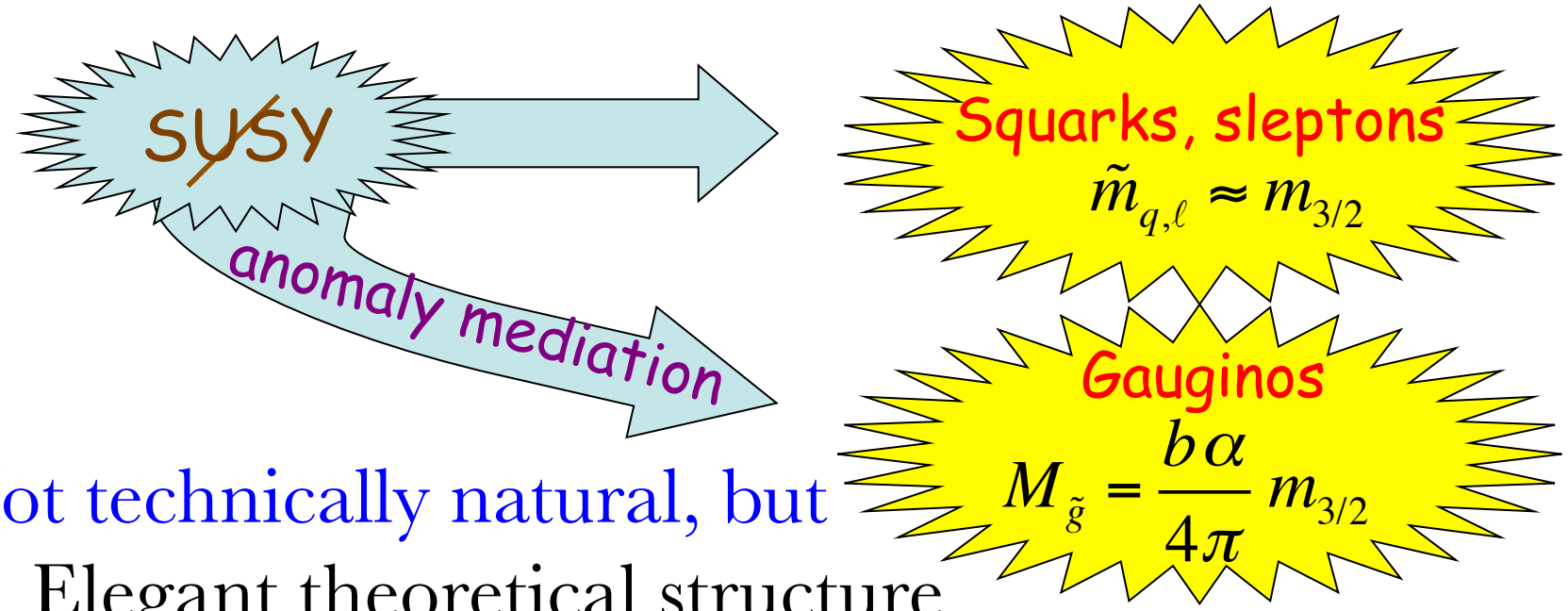
Other open questions in particle physics

- Origin of flavour symmetry breaking
- Dark matter
- Strong CP problem
- Baryogenesis
- Inflation
- Unification of forces
- Dark energy
- Charge quantization

The solution of some of these problem may lie at the TeV scale

An interesting example:

Anomaly mediation + Split Susy



Not technically natural, but

- Elegant theoretical structure
- Gauge unification
- Dark matter
- Well compatible with $m_h = 126$ GeV
- OK with flavour
- Chance of discovery at LHC14

UV naturalness

Particle threshold (mass M) $\Rightarrow$ $m_H^2 = \dfrac{\alpha}{4\pi} M^2$ $\Rightarrow$ naturalness problem

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Does gravity introduce a naturalness problem?

Is G_N just a coupling or is it a dynamical threshold?

Could gravity cure itself in the UV?

Not been proven, but the opposite hasn't been proven either…

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"Silence will save me from being wrong, but it will also deprive me of the possibility of being right."
Igor Stravinsky

Quadratic divergences are fully linked to UV

If $m_H^2 \approx 0$ at Λ and no intermediate-mass thresholds $\Rightarrow$

$$\frac{d\, m_H^2}{d \ln \mu} = \frac{3 m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3}{4} g_2^2 - \frac{3}{20} g_1^2\right)$$ multiplicative renormalization

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UV naturalness

- Accept UV miracle
- Forbid dangerous massive threshold

St. Thomas Aquinas in *Summa contra gentiles*

Miracle of 3rd degree:
God does something that nature can do, but without intervention of a natural agent.

Miracle of 2nd degree:
God does something that nature can do, but without natural temporal order.

Miracle of 1st degree:
God does something that nature can never do.

Summa contra naturalitatem

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

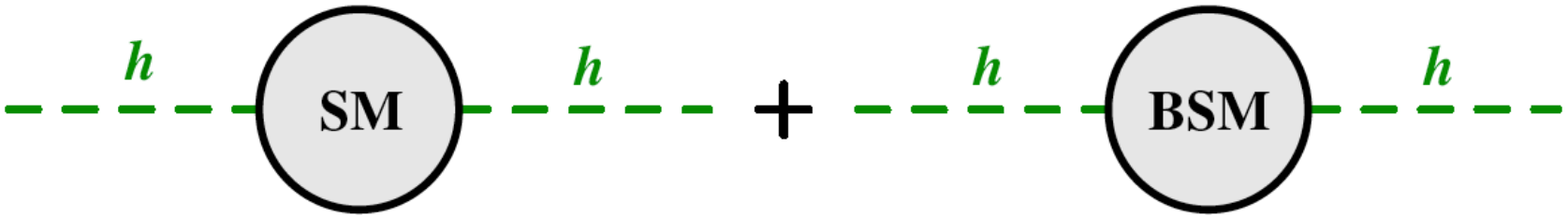
Miracle of 2nd degree:
Gravity cures itself and the SM in the UV, leaving no quadratic divergences.

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

- Accept UV miracle (2^{nd} or 3^{rd} degree)
- Forbid dangerous massive threshold

- Extreme possibility: SM + light ν_R account for DM, inflation, baryogenesis Shaposhnikov et al.
- Room for new physics at the EW scale, with some exceptions for particle weakly coupled to the Higgs ($M_R < 10^7$ GeV) Farina et al.
- No explanation for the cosmological constant

IR naturalness



New physics shuts off Higgs sensitivity to quantum corrections above TeV

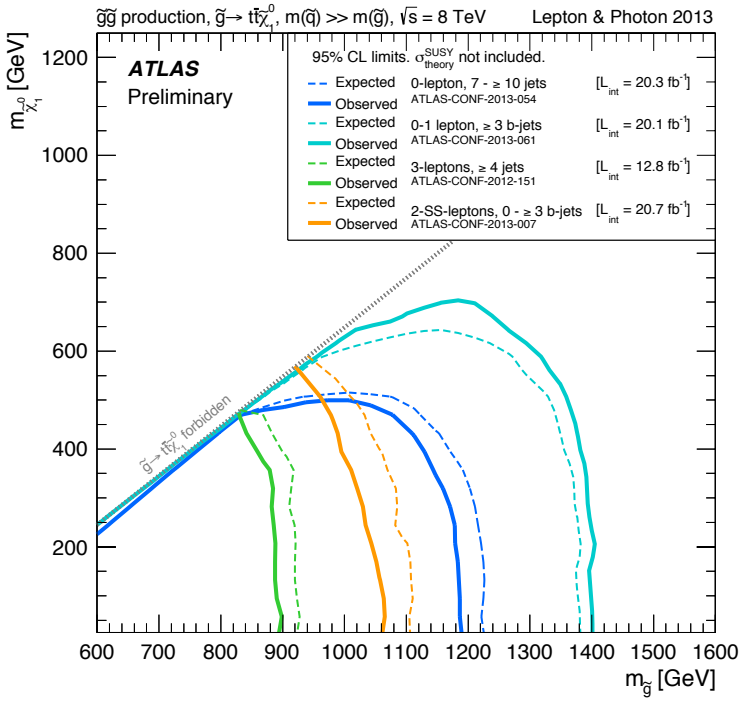
- Supersymmetry
- Technicolor
- Extra dimensions
- Composite Higgs

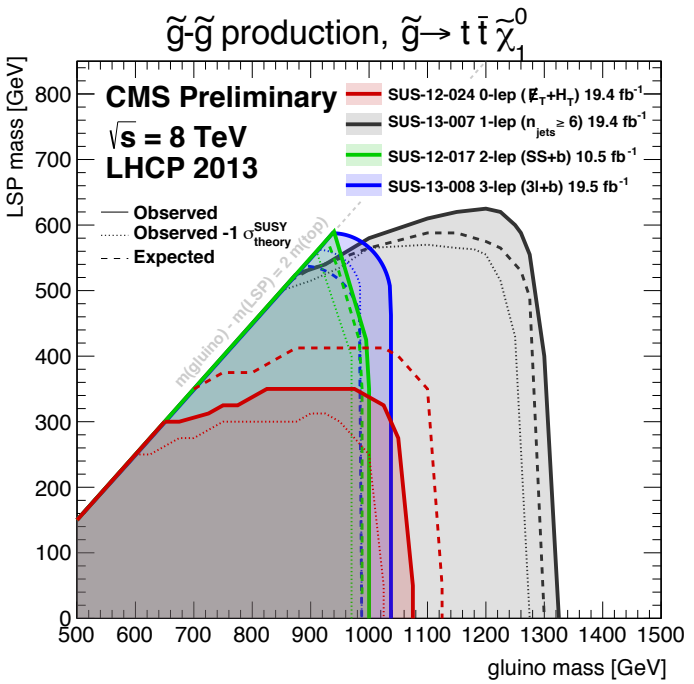
IR naturalness is under siege

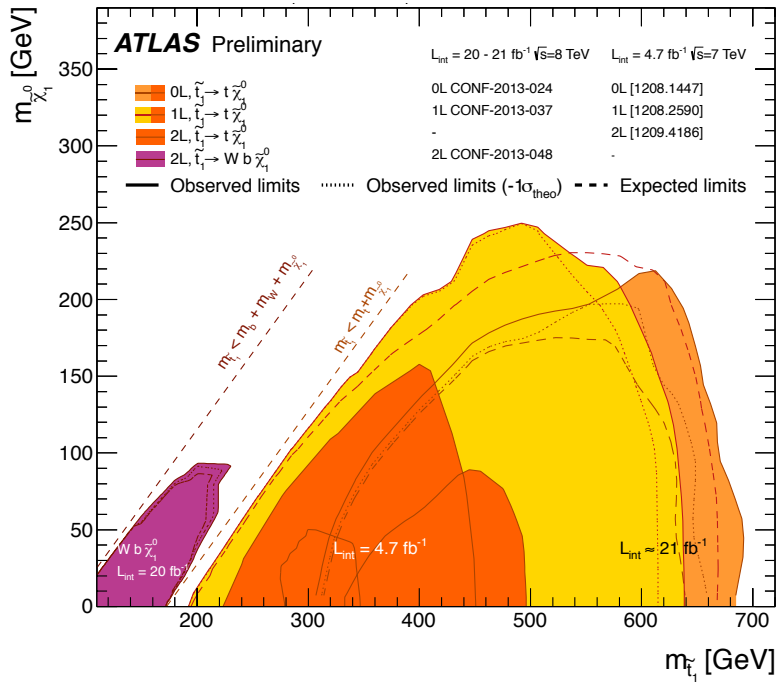
1. LHC direct bounds
2. Higgs mass
3. Higgs couplings
4. EW precision data
5. Flavour constraints
6. Rare processes

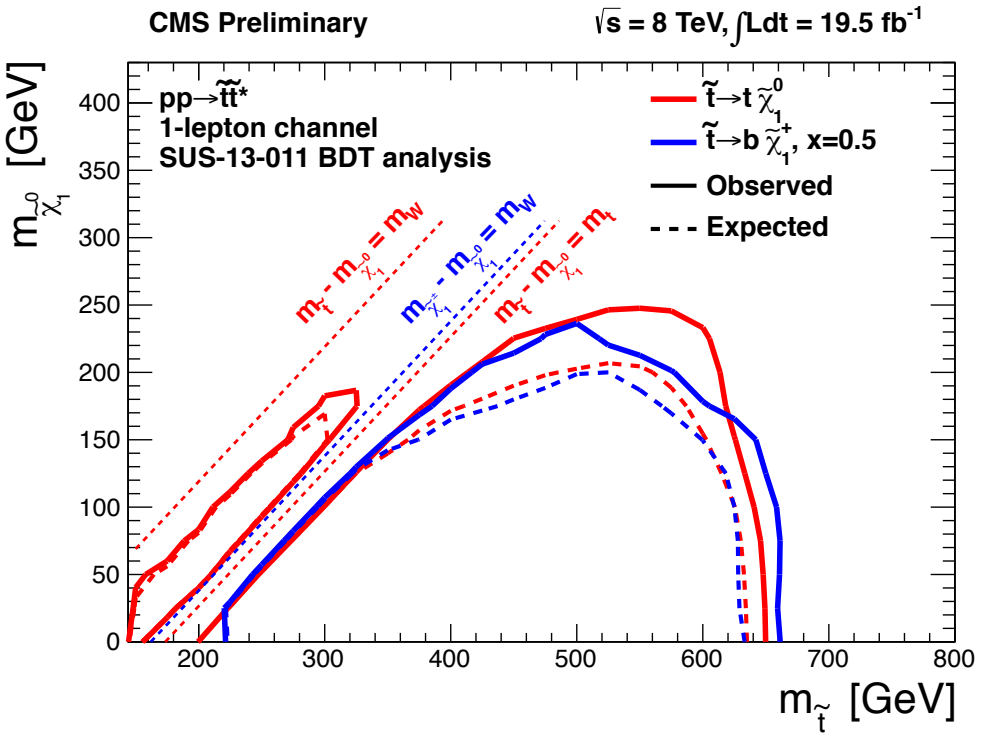
LHC direct bounds


STOP

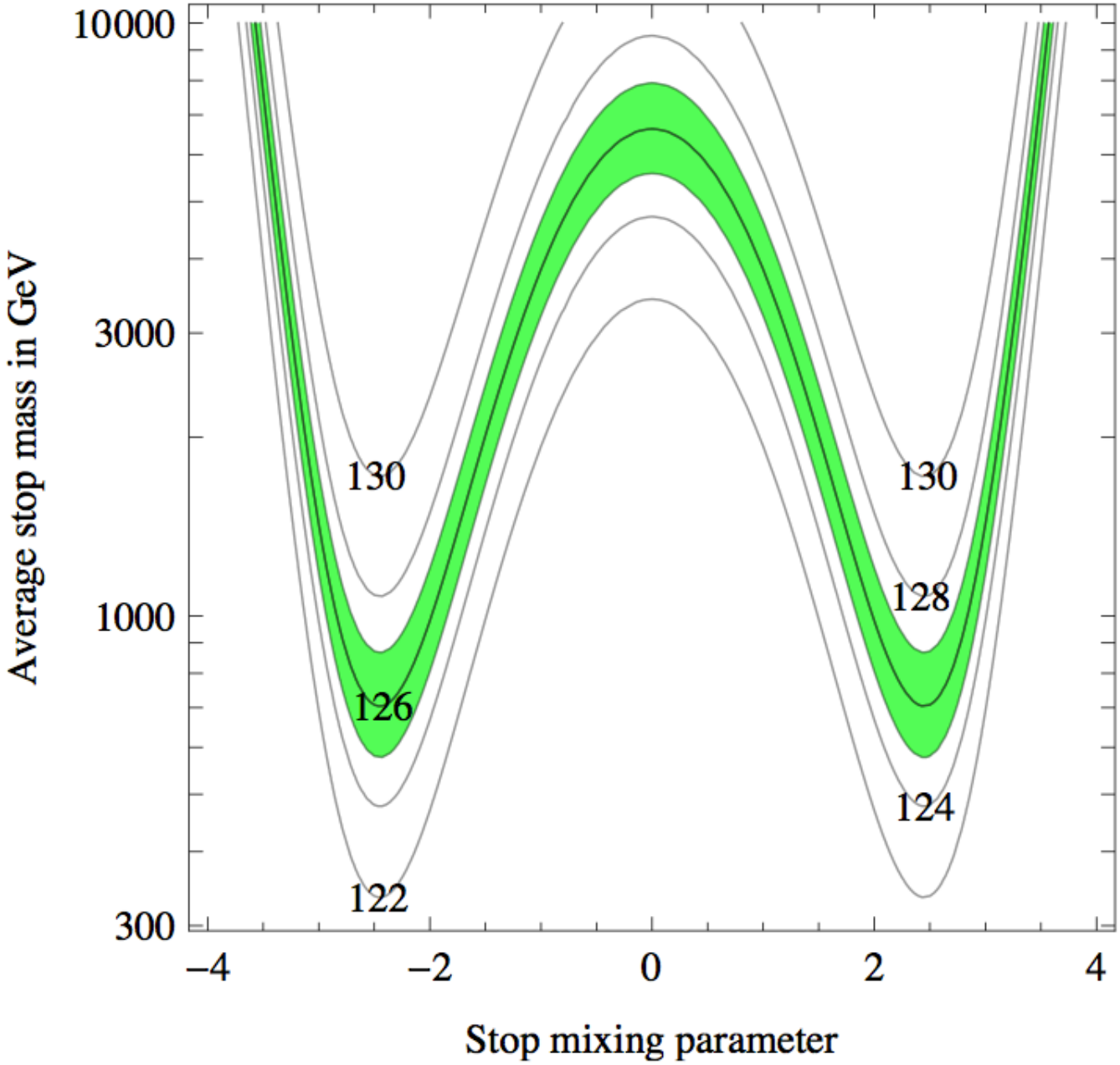

g̃g̃ production, g̃→ tt̄χ̃₁⁰, m(q̃) >> m(g̃), √s = 8 TeV
Lepton & Photon 2013
ATLAS
Preliminary
95% CL limits. σ SUSY theory not included.
Expected 0-lepton, 7 - ≥ 10 jets [L int = 20.3 fb⁻¹]
Observed ATLAS-CONF-2013-054
Expected 0-1 lepton, ≥ 3 b-jets [L int = 20.1 fb⁻¹]
Observed ATLAS-CONF-2013-061
Expected 3-leptons, ≥ 4 jets [L int = 12.8 fb⁻¹]
Observed ATLAS-CONF-2012-151
Expected 2-SS-leptons, 0 - ≥ 3 b-jets [L int = 20.7 fb⁻¹]
Observed ATLAS-CONF-2013-007
g̃→ tt̄χ̃₁⁰ forbidden
m χ̃₁⁰ [GeV]
m g̃ [GeV]


g̃-g̃ production, g̃→ t t̄ χ̃₁⁰
CMS Preliminary
√s = 8 TeV
LHCP 2013
SUS-12-024 0-lep (E T miss+H T) 19.4 fb⁻¹
SUS-13-007 1-lep (n jets ≥ 6) 19.4 fb⁻¹
SUS-12-017 2-lep (SS+b) 10.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
Observed
Observed -1 σ SUSY theory
Expected
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]


ATLAS Preliminary
L int = 20 - 21 fb⁻¹ √s=8 TeV
L int = 4.7 fb⁻¹ √s=7 TeV
0L, t̃₁→ t χ̃₁⁰ 0L CONF-2013-024 0L [1208.1447]
1L, t̃₁→ t χ̃₁⁰ 1L CONF-2013-037 1L [1208.2590]
2L, t̃₁→ t χ̃₁⁰ - 2L [1209.4186]
2L, t̃₁→ W b χ̃₁⁰ 2L CONF-2013-048 -
Observed limits
Observed limits (-1σ theo)
Expected limits
m t̃₁ < m b + m W + m χ̃₁⁰
m t̃₁ < m t + m χ̃₁⁰
W b χ̃₁⁰
L int = 20 fb⁻¹
L int = 4.7 fb⁻¹
L int ≈ 21 fb⁻¹
m χ̃₁⁰ [GeV]
m t̃₁ [GeV]


CMS Preliminary
√s = 8 TeV, ∫Ldt = 19.5 fb⁻¹
pp→t̃t̃*
1-lepton channel
SUS-13-011 BDT analysis
t̃→t χ̃₁⁰
t̃→b χ̃₁⁺, x=0.5
Observed
Expected
m t̃ - m χ̃₁⁰ = m W
m t̃ - m χ̃₁⁰ = m t
m χ̃₁⁰ [GeV]
m t̃ [GeV]

Higgs mass


10000
3000
1000
300
Average stop mass in GeV
130
130
128
126
124
122
−4
−2
0
2
4
Stop mixing parameter

Are the LHC bounds problematic for naturalness?

$$\frac{\delta M_h^2}{M_h^2} = \frac{3\lambda_t^2 \tilde{m}_t^2}{2\pi^2 M_h^2} \ln\frac{\Lambda}{\tilde{m}_t} \approx 140 \left(\frac{\tilde{m}_t}{700\ \text{GeV}}\right)^2 \left(\frac{\ln \Lambda/\tilde{m}_t}{30}\right)$$

10^2 is much smaller than 10^{34}, but it is larger than 1

Can naturalness be saved?

- Small log: low mediation scale
  supersoft & Dirac gauginos
- Hide susy: compressed spectra
  R-parity violation
  new decay chains
- New contributions to Higgs quartic: NMSSM
  new gauge groups or vector-like ferm.

There are still regions of moderate fine-tuning…

… but often the reduction in the EW-scale tuning comes at the price of an increase of the tuning in theory space

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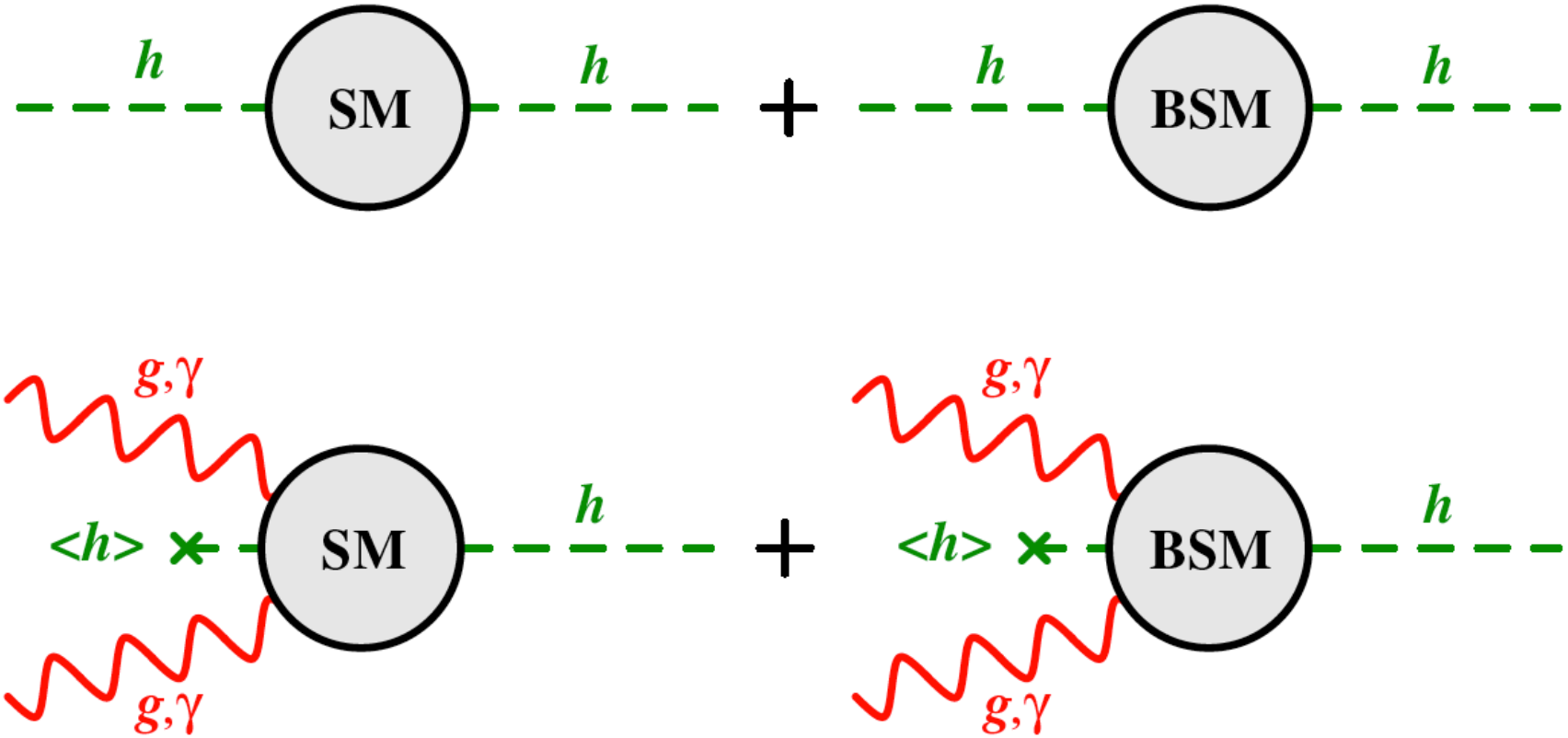
… but often the reduction in the EW-scale tuning comes at the price of an increase of the tuning in theory space

Situation is similar for the composite Higgs

➘ see talk by R. Contino

Higgs couplings

The more natural the Higgs is,
the more its properties deviate from SM.



$$\frac{\sigma\left(gg\to h\right)}{\sigma\left(gg\to h\right)_{\rm SM}}=\left(1+\Delta_t\right)^2 \qquad \frac{\Gamma\left(h\to\gamma\gamma\right)}{\Gamma\left(h\to\gamma\gamma\right)_{\rm SM}}=\left(1-0.3\Delta_t\right)^2$$

$$\Delta_t\approx\frac{m_t^2}{4}\left(\frac{1}{\tilde{m}_{t_1}^2}+\frac{1}{\tilde{m}_{t_1}^2}-\frac{A_t^2}{\tilde{m}_t^4}\right)\approx\left(\frac{700\ \text{GeV}}{\tilde{m}_t}\right)^2\ 3\%$$

$$\frac{\delta\left[\sigma\left(gg\to h\right)\Gamma\left(h\to\gamma\gamma\right)\right]}{\sigma\left(gg\to h\right)_{\rm SM}\Gamma\left(h\to\gamma\gamma\right)_{\rm SM}}=\begin{cases}50\% \ \ (\text{for } \tilde{m}_t=200\ \text{GeV})\\ 4\% \ \ (\text{for } \tilde{m}_t=700\ \text{GeV})\end{cases}$$

Conclusions

- Naturalness is deeply rooted in EFT approach to physical phenomena
- Testing naturalness of the Higgs has far-reaching consequences for particle physics

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Unnaturalness

- Multiverse has the virtue of addressing both Higgs and CC problems
- New physics is possible (but not guaranteed)
- Offers best option for susy models after LHC8

Conclusions

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- Testing naturalness in Higgs has far-reaching consequences for particle physics

UV Naturalness

- Relies on unproven quantum-gravity miracles
- New physics is possible (with highly-constrained mass scales)

Conclusions

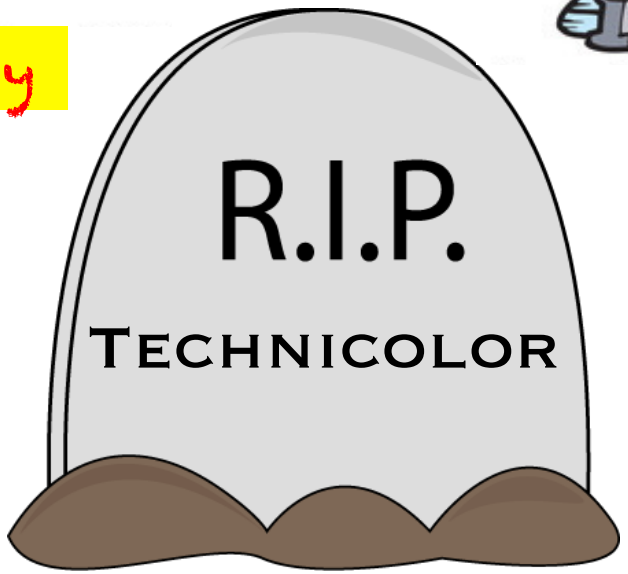
- Naturalness is deeply rooted in EFT approach to physical phenomena
- Testing naturalness in Higgs has far-reaching consequences for particle physics

IR Naturalness

- Most welcome outcome
- New physics is guaranteed
- Heavy casualties after LHC8 …

Supersymmetry

Composite Higgs



Extra dimensions