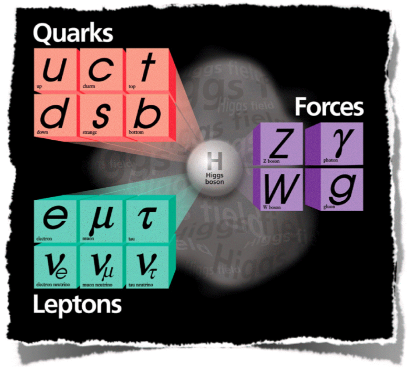
Beyond the Standard Model (or not) after the Higgs

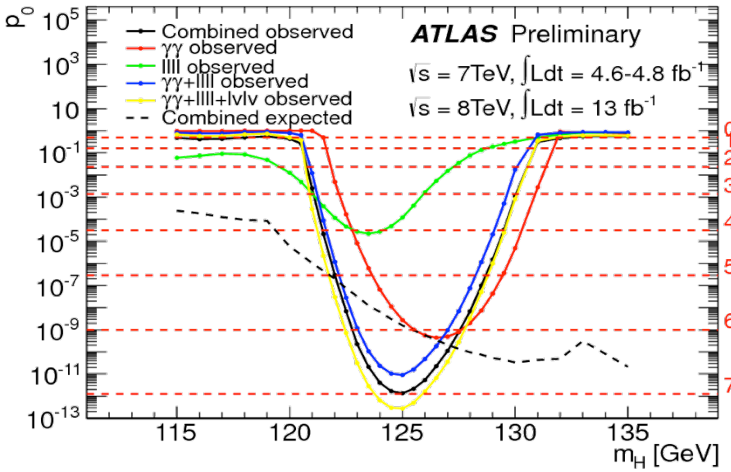
G. Ross,
NBIA-Oxford colloquium,
April2015

LHC 8

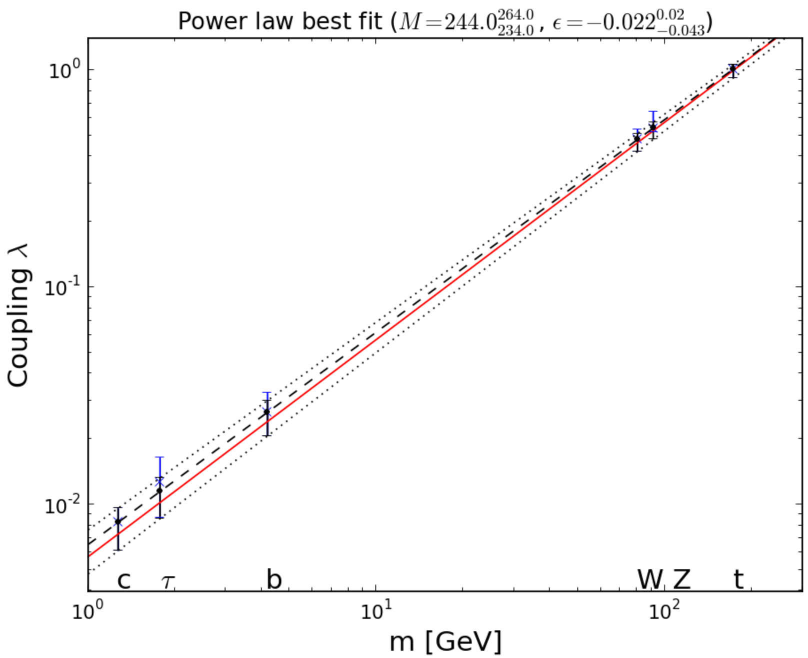
Higgs discovery!

…completes the Standard Model





$m_H = 125.09 \pm 0.24$ (0.21 stat. ± 0.11 syst.) GeV

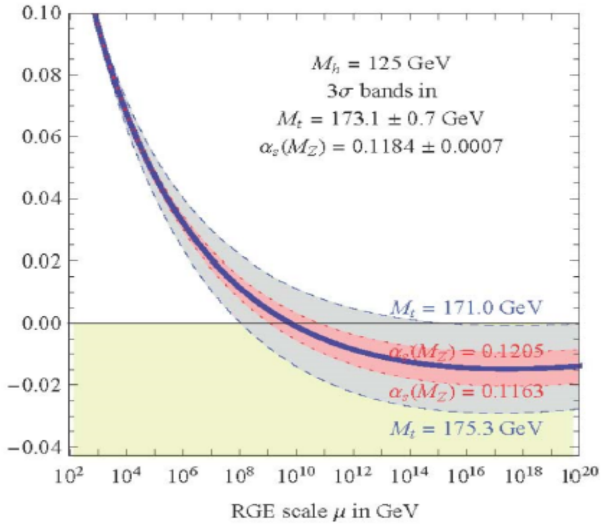


- Strong exclusion of a spin-1 resonance
- 0^- excluded at > 3σ level
- Graviton-like resonances excluded at >3σ

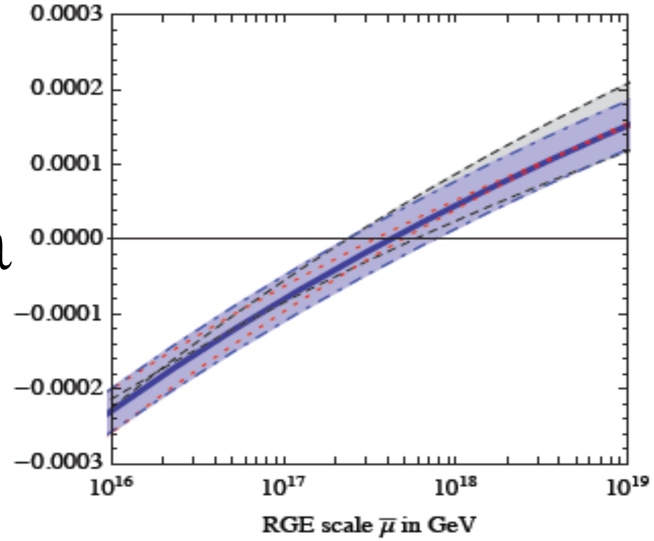
LHC 8

Higgs discovery!

λ



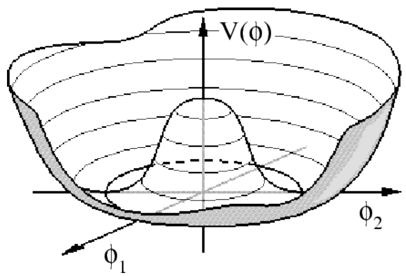
β_λ



DeGrassi et al,...

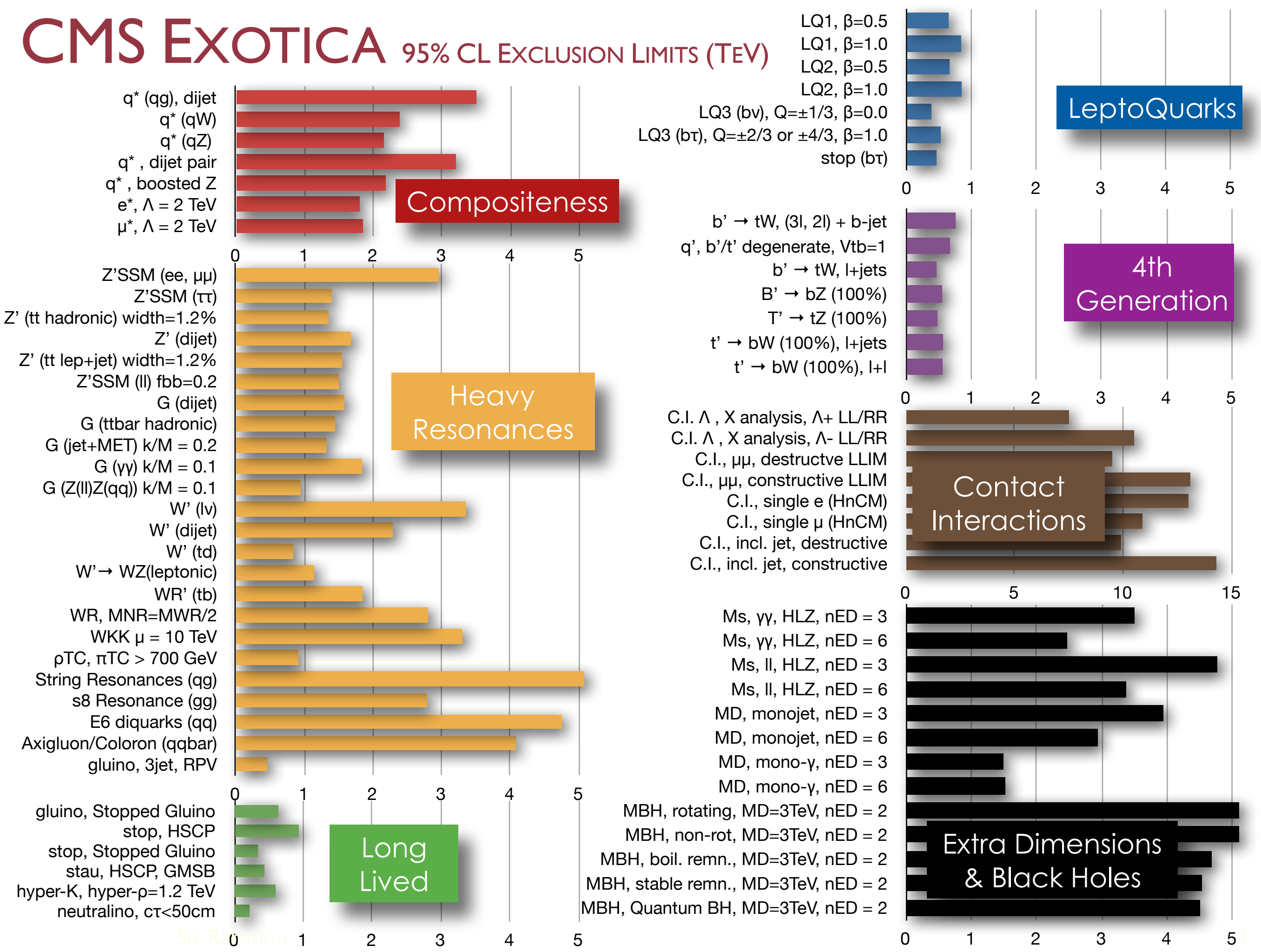
$$V(H) = -m^2 |\phi|^2 + \lambda |\phi|^4$$

$$m^2 \simeq (89GeV^2), \lambda \simeq 0.13$$

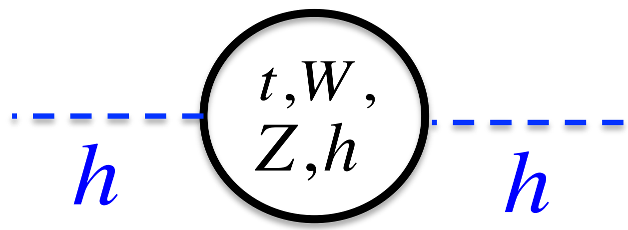


LHC 8

No evidence (yet) for BSM



The Hierarchy problem



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

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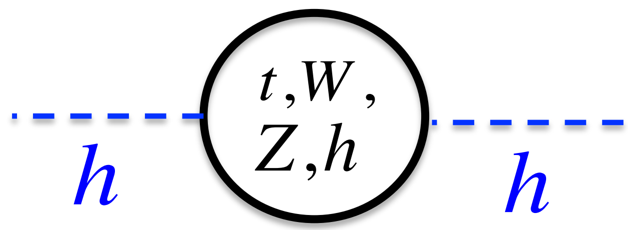

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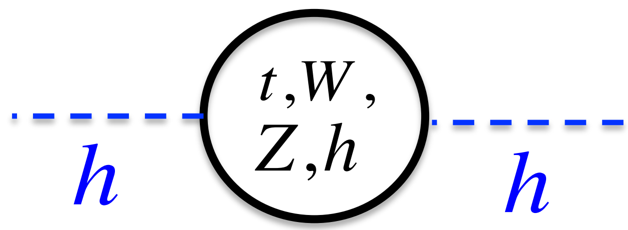
Light Higgs $\Longrightarrow$ Symmetry protection

The Hierarchy problem



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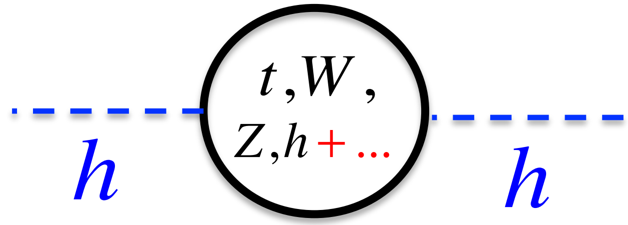
- Composite models – Higgs as Pseudo-Goldstone boson
- Supersymmetric models – Higgs as chiral superpartner
- Scale invariant models - $m_0^2 + \delta m^2 = 0$

The Hierarchy problem

Fine Tuning measure:

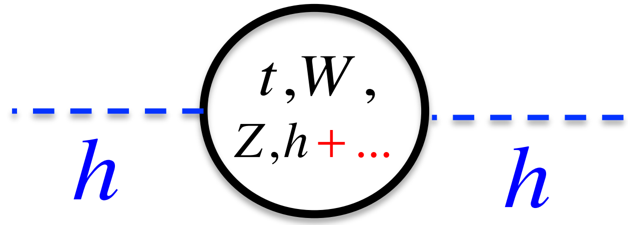
$$\Delta(\gamma_i) = \left| \frac{\gamma_i}{M_Z} \frac{\partial M_Z}{\partial \gamma_i} \right|,$$

$$\Delta_{\mathrm{m}} = Max_{\gamma_i} \Delta(\gamma_i), \quad \Delta_q = \left(\sum \Delta_{\gamma_i}^2 \right)^{1/2}$$



$$M_Z^2 = \sum_i a_i \gamma_i^2$$

The Hierarchy problem



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Fine tuning from a likelihood fit:

"Nuisance" variable

$$L(\text{data} \mid \gamma_i) \propto \int d\text{v}\, \delta(m_Z - m_Z^0)\, \delta\left(\text{v-}\left(-\frac{m^2}{\lambda}\right)^{1/2} \right) L(\text{data} \mid \gamma_i; \text{v})$$

$$= \frac{1}{\Delta_q} \delta\left(n_q (\ln \gamma_i - \ln \gamma_i^S)\right) L(\text{data} \mid \gamma_i; \text{v}_0)$$

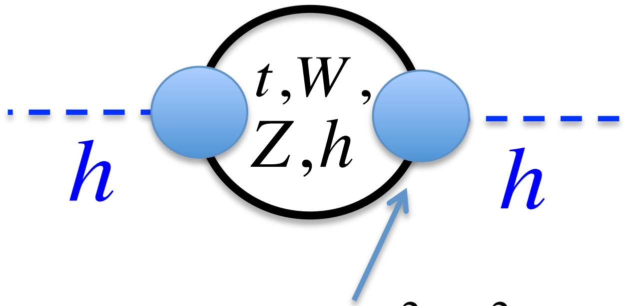
→ Fine tuning not optional!

Probabilistic interpretation:

$$\chi_{new}^2 = \chi_{old}^2 + 2 \ln \Delta_q$$

$$\Delta_q \ll 100$$

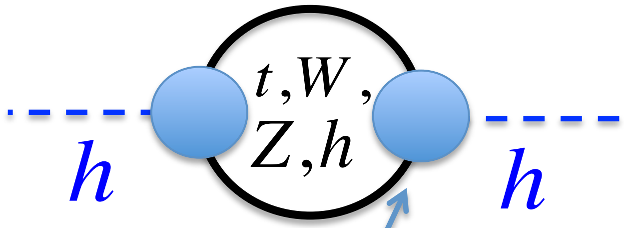
- Composite models – Higgs as Pseudo-Goldstone boson



Form factor $e^{-q^2/\Lambda^2_{composite}}$

$m_h \ll \Lambda_{composite}$?

Composite models – Higgs as Pseudo-Goldstone boson



Form factor $e^{-q^2/\Lambda^2_{composite}}$

$m_h \ll \Lambda_{composite}$?

$H^\dagger H = \sum_1 h_i^2$

$SO(4) \xrightarrow[\langle h_4 \rangle = v]{} SO(3)$

e.g. $SO(5)/SO(3) : W, Z, h$

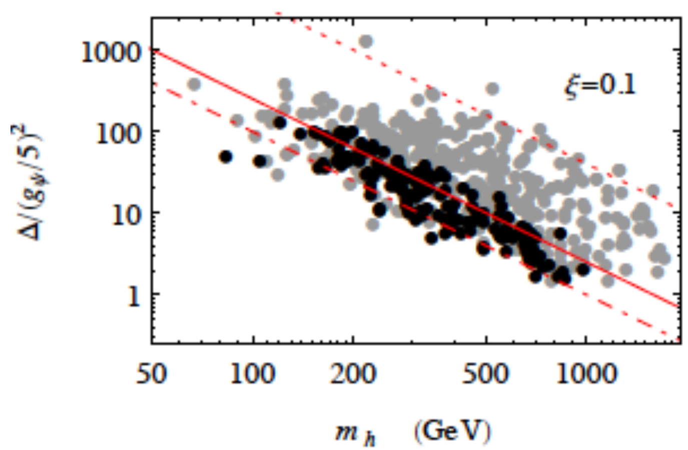
The hierarchy problem and light top quark partners

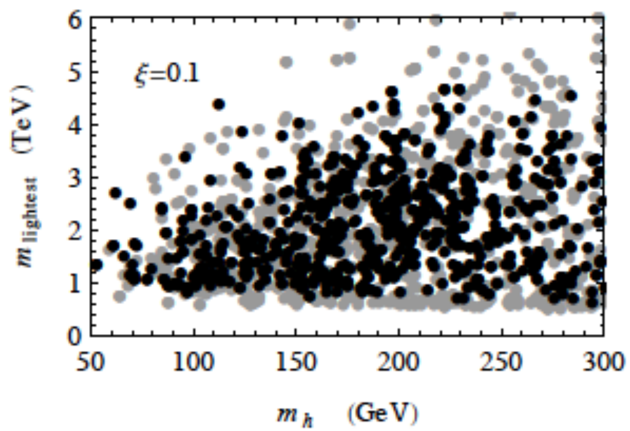
light vectorlike top quark < 1TeV

$$\delta m_h^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \quad \Rightarrow \quad \Delta \geq \frac{\delta m_h^2}{m_h^2} = \left(\frac{\Lambda}{400\,\text{GeV}}\right)^2 \left(\frac{125\,\text{GeV}}{m_h}\right)^2$$

but $m_\rho > 2.5 TeV$ (S-parameter) $\left(\Delta S \sim \frac{m_W^2}{m_\rho^2}\right)$

Hence low cut-off for low Δ must be due to top-quark form factor





Panico et al 1201.7114

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$\Longrightarrow$ Technifermion top quark resonance ~1TeV

Fine tuning   Sensitive to top resonance representations…minimum

$\Delta \sim \xi^{-1} \geq 10$ for $SO(4)$ 9-plet top quark

Top techni-resonance phenomenology

$QCD\ pair\ production: \quad \sigma_{m_t=500GeV} = 570\,fb, \quad \sigma_{m_t=1TeV} = 1.3\,fb \quad (8TeV\ CM)$

$9 \sim 3_{5/3} \oplus 3_{2/3} \oplus 3_{-1/3} \quad (SU(2)_L \times U(1)_Y) \quad \supset 2 \times Q_{5/3} + Q_{8/3}$

↘ $3W^+ + b + \ldots$

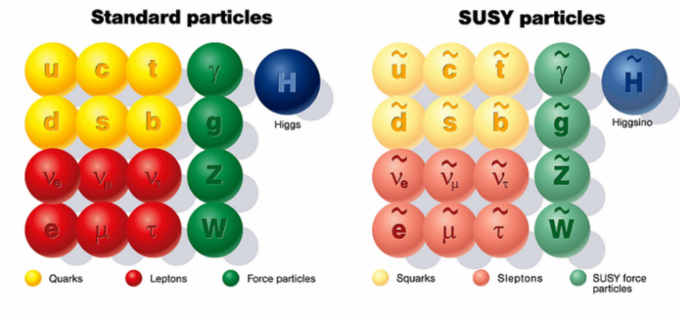
$BR\left(Q_{5/3(8/3)} \to l^+ l^+ ..\right) = 5(6)\%, \quad BR\left(Q_{5/3(8/3)} \to lll..\right) = 3(6.5)\%$

LHC_{8}: $m_t > 770GeV\ (95\%)$

Panico et al 1201.7114
Pappadopulo et al 1303.3062

Supersymmetric models – Higgs as chiral superpartner

e.g. MSSM:



$$\begin{pmatrix} \widetilde{H}_u \\ H_u \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d \\ H_d \end{pmatrix} \qquad \mu \widetilde{H}_u \widetilde{H}_d, \quad \widetilde{H}_u \to e^{i\alpha} \widetilde{H}_u \Rightarrow \mu = 0$$

Supersymmetric models - Higgs as chiral superpartner

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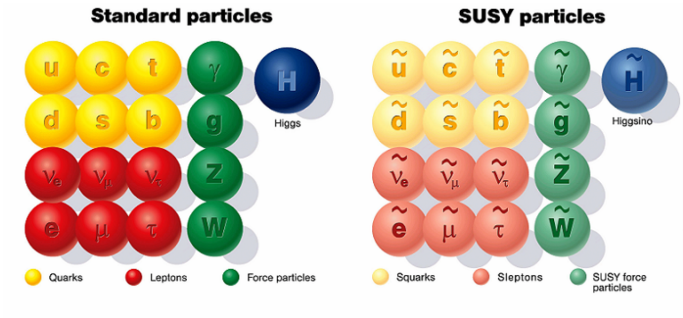


$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots \simeq 126\,GeV$$

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right)$$

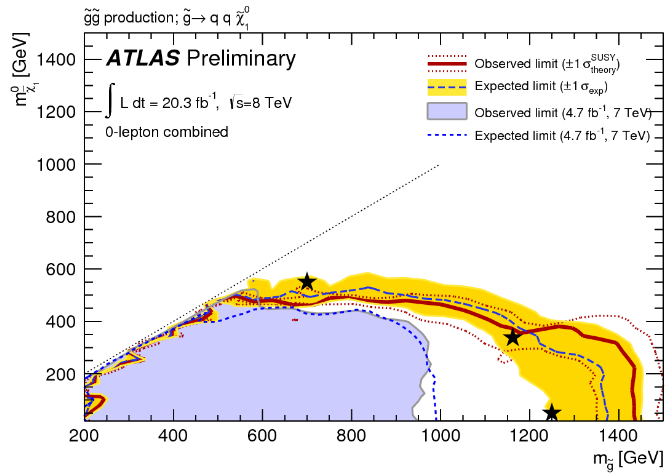
LHC Higgs discovery:

$$\Delta_{\min}^{MSSM} > 350\,, \quad m_h = 125.6 \pm 3GeV$$

...but generalisations still viable

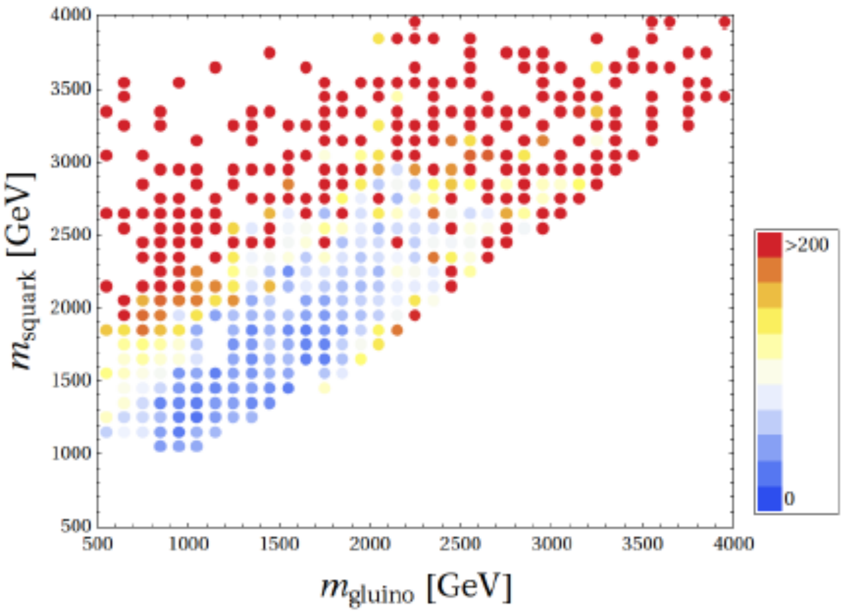
e.g. NMSSM with non-universal gugino masses:

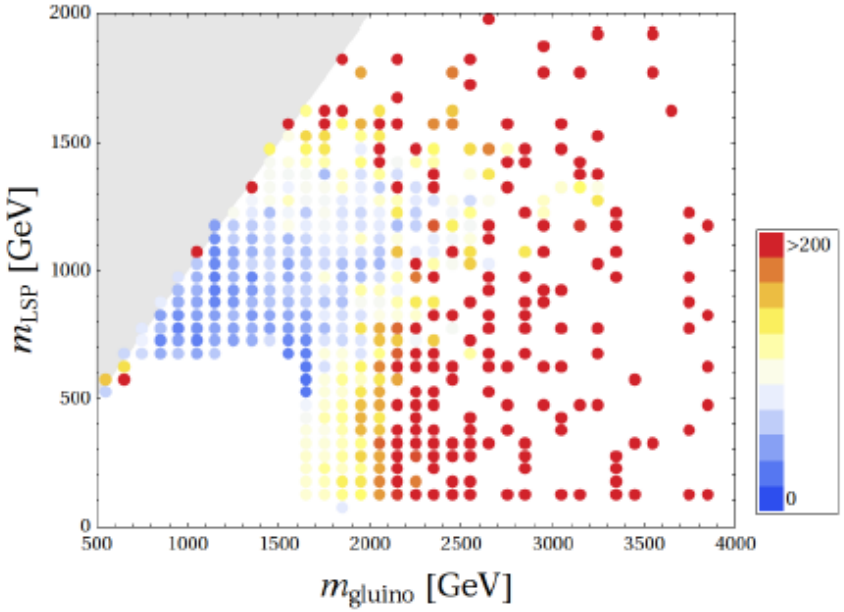
Masses v/s fine tuning



m_{squark}

m_{LSP}





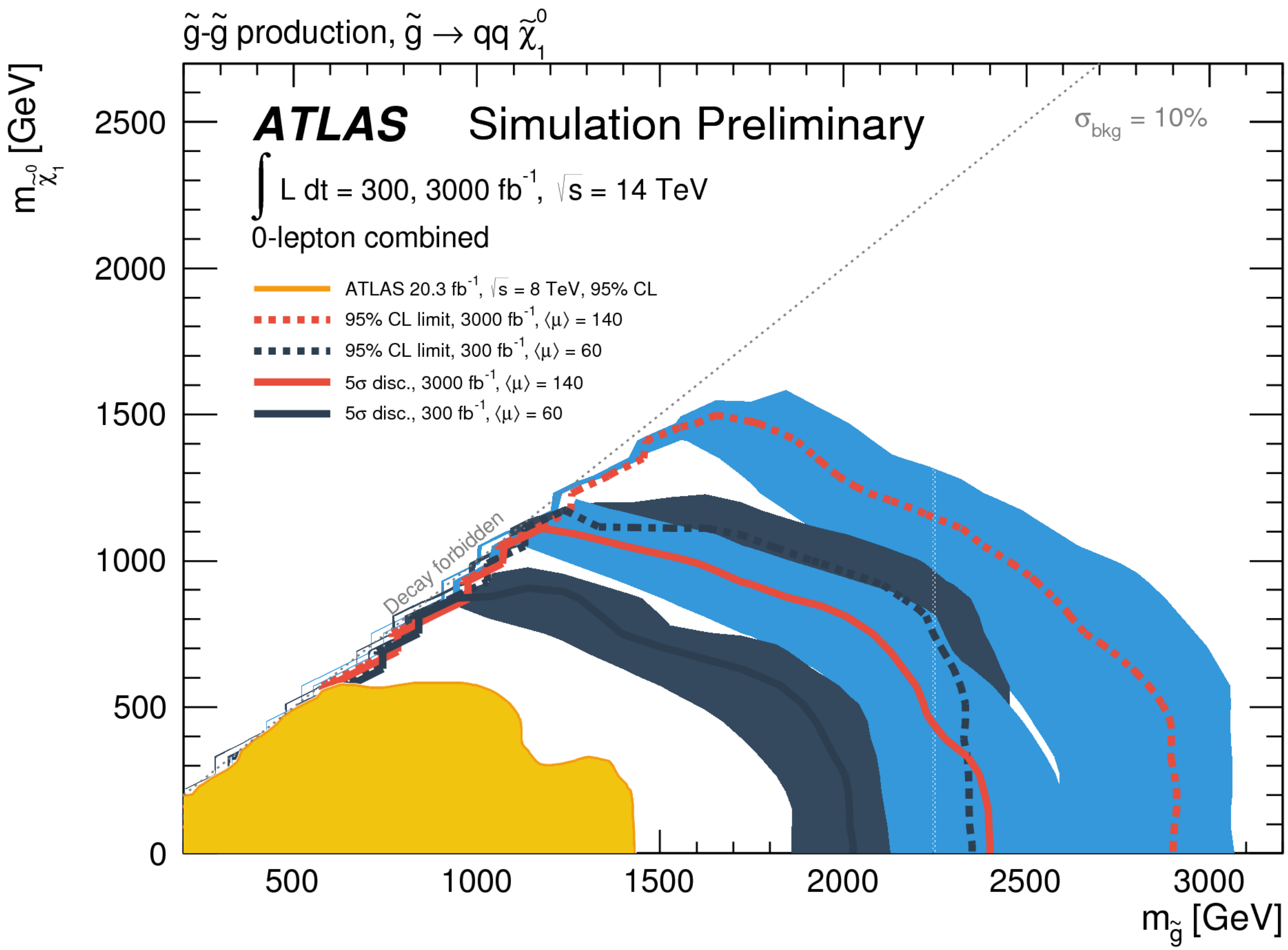
> 200

0

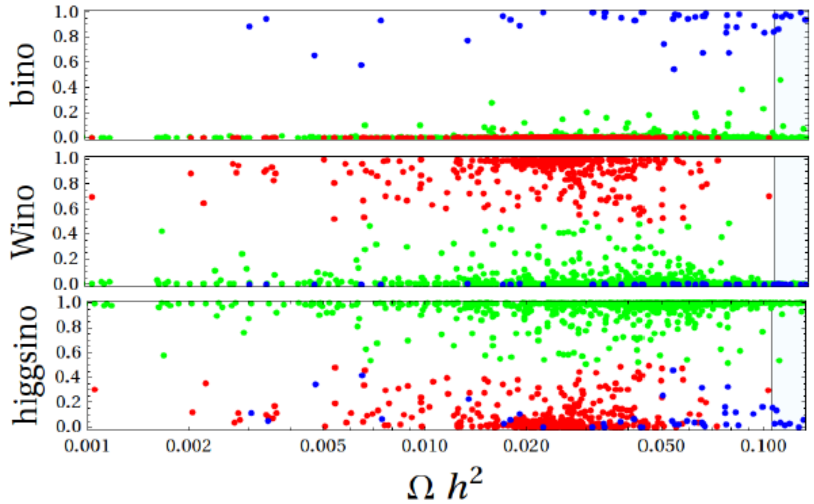
Δ

M_{gluino}

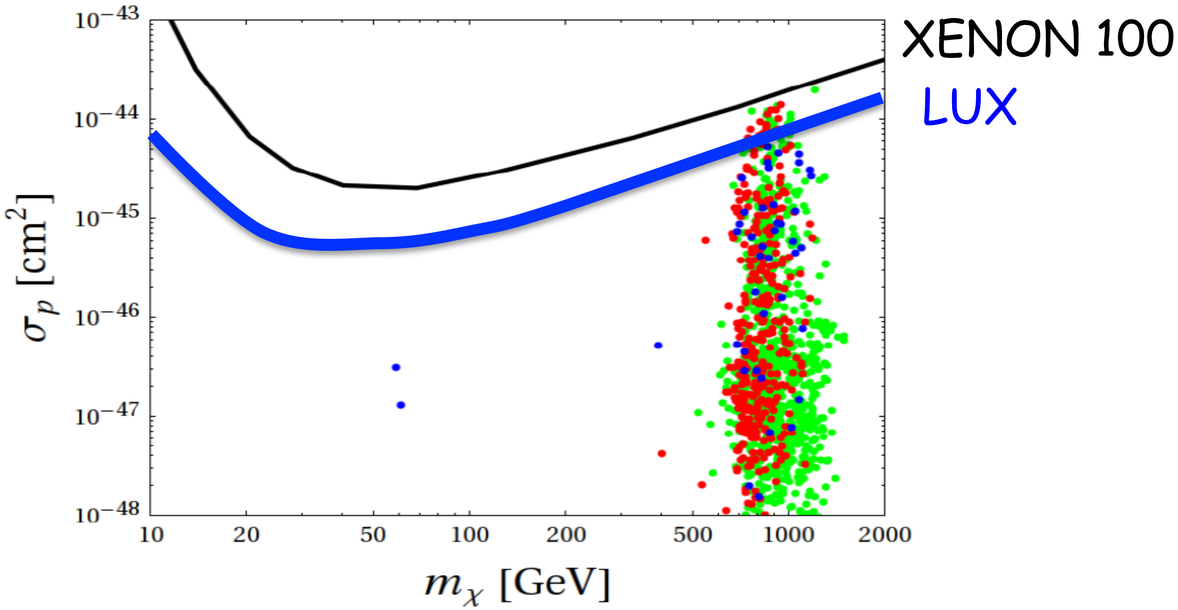
Heavy LSP reach



Dark matter



LSP composition



Direct DM searches

- Scale invariant models:

(SM in absence of Higgs mass is scale invariant)

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Field theory: δm^2 not measureable

...only $m^2 = m_0^2 + \delta m^2$ "physical"

Only $m^2 = 0$ special

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

...no hierarchy problem for SM? (Landau pole?)

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...no hierarchy problem for SM?

... origin of EW breaking?

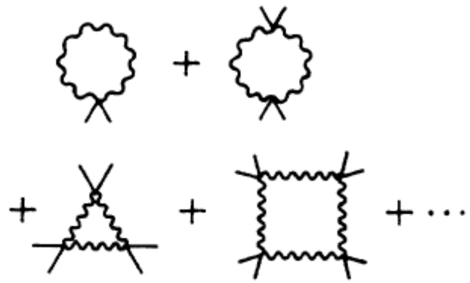
... stress tensor trace anomaly

Coleman-Weinberg - dynamical symmetry breaking :

e.g. scalar electrodynamics

$$V = \left\{ \frac{\lambda}{4!}\phi^4 + \frac{3e^4}{64\pi^2}\phi^4 \ln\frac{\phi^2}{M^2} \right\}$$

$$= \frac{3e^4}{64\pi^2}\phi^4 \left(\ln\frac{\phi^2}{\langle\phi\rangle^2} - \frac{1}{2} \right)$$



$$m_\phi^2 = \frac{3e_\phi^2}{8\pi^2}\langle\phi\rangle^2 \ll m_W^2$$

"real" hierarchy problem

..... many models with new Higgs interactions + no heavy states

No heavy thresholds? (real hierarchy problem)

- Neutrino masses?
- Strong CP problem?
- Baryogenesis?
- Gravity/Inflation?

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- Neutrino masses?
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Neutrino masses:

Add singlet neutrinos ν_{Ra}

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

$$e.g. \quad h_A^2 = 5.10^{-14}, h_B^2 = 5.10^{-15}, M_a = 20 GeV$$

$$m_A \simeq 0.1 eV, \quad m_B \simeq 0.01 eV$$

Ultra-weak:

Natural due to chiral symmetry

- Strong CP problem: $$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \leq 10^{-10} ??$$

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$$S = \left(|S| + f_a\right) e^{i\frac{a}{f_a}}, \qquad 10^{10} GeV \leq f_a \leq 10^{12} GeV$$

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DFSZ axion: 2 Higgs doublets $H_{1,2}$, complex singlet, S

$$V\left(H_1, H_2\right) = \frac{\lambda_1}{2}\left|H_u\right|^4 + \frac{\lambda_2}{2}\left|H_d\right|^4 + \lambda_3\left|H_u\right|^2\left|H_d\right|^2 + \lambda_4\left|H_u^\dagger H_d\right|^2$$
$$+ \zeta_1 |S|^2 \left|H_u\right|^2 + \zeta_2 |S|^2 \left|H_d\right|^2 + \zeta_3 S^2 H_u H_d + h.c.$$

Ultra weak sector: $\zeta_{1,2,3} \leq 10^{-20}\left(\frac{10^{12}\, GeV}{f_a}\right)^2$

Ultra weak sector:

ζ_i multiplicatively renormalised

(Underlying shift symmetry $S \rightarrow S + \delta$)

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Origin of large vev?

Start with $m = m_0 + \delta m = 0$ (Classical scale invariance)

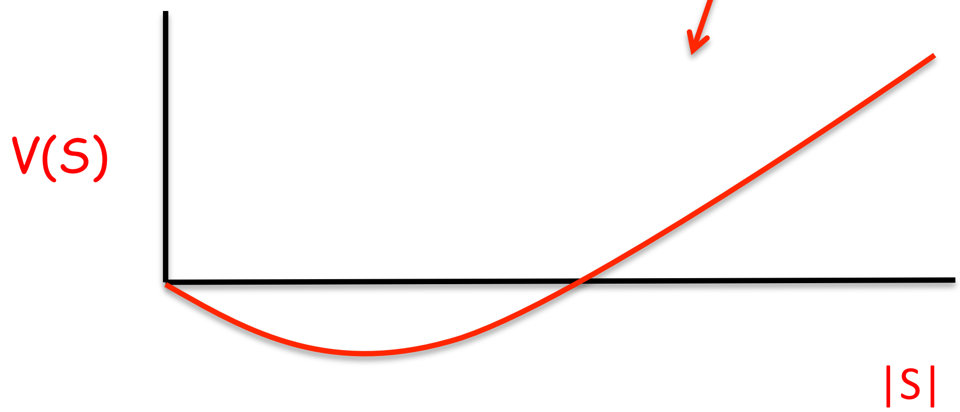
Dimensional transmutation (Coleman Weinberg)

Coleman Weinberg in DFSZ model

$\zeta_2 S^2 |H_d|^2$

$$V_{DFSZ}(H_1,H_2,S) \simeq \frac{\lambda_1}{2}\left(|H_u|^2 + \frac{\zeta_1}{\lambda_1}|S|^2\right)^2 + \frac{1}{64\pi^2}\left(\zeta_2 |S|^2\right)^2\left(-\frac{1}{2} + \ln\frac{|S|^2}{f_a^2}\right)$$

$$+\frac{\lambda_2}{2}|H_d|^4 + \zeta_3 S^2 H_u H_d + h.c.$$



$\langle H_u^2 \rangle = -\frac{\zeta_1}{\lambda_1}\langle S^2 \rangle$ triggers EW breaking

Phenomenology

- Requires two Higgs doublets (type II couplings), light pseudo-dilaton

$$m^2_{H^0_2} = m^2_{H^\pm} = m^2_X = R^2 m^2_h \qquad m_{|S|} \simeq 0.9\left(\frac{10^{12}\,GeV}{f_a}\right) R^2 eV$$

h ≈ SM Higgs

…stable vacuum possible

- **Direct (axion-like) searches** for pseudo-dilaton?

- **Cosmology**

…. potential Polonyi problem:

Coughlan et al

$$V(S_I) \sim +\frac{1}{64\pi^2}\left(\zeta_2 |S_I|^2\right)^2\left(-\frac{1}{2}+\ln\frac{|S_I|^2}{f_a^2}\right)$$

(stored energy after inflation)

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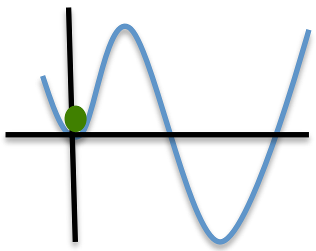
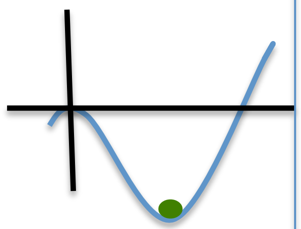
$$m^2_{s,thermal} \simeq \frac{\varsigma_2}{6}T^2$$

$$\rho_S \propto T^4$$

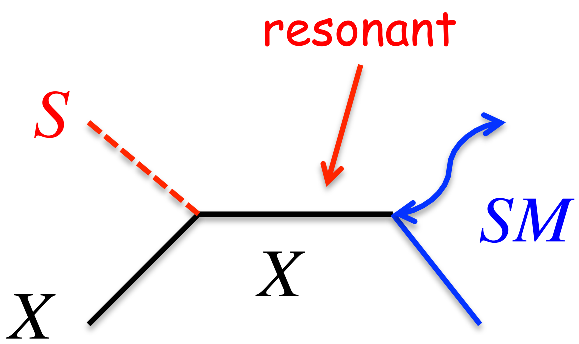


$$T \sim \Lambda_{QCD},\ m_{s,thermal} = 0$$

$$\rho_s \propto T^3$$



$$S + X \rightleftarrows SM$$



$$\rho_s \to 0, \quad \Omega_a ?$$

- Baryogenesis - via neutrino oscillation

Akhmedov, Rubakov, Smirnov

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

- ν_{Ra} produced via Yukawa interactions $\quad L_A = L_B = L_C = 0$
- ν_{Ra} oscillate $\quad \not{CP}, \quad L_{A,B,C} \neq 0, \quad L_A + L_B + L_C = 0$
- $\nu_{R\,A,B}$ in thermal equilibrium by t_{EW} when sphalerons inoperative
- $\Delta_{L\,AB} = L_A + L_B \xrightarrow[Sphalerons]{} \Delta B = \Delta_{L\,AB} / 2$ ✔

ARS demonstrate mechanism viable over range of parameters -

but ν_R not dark matter – need axion as dark matter

Gravity/Inflation

Scale invariance — Spontaneous symmetry breaking $\Longrightarrow M_P$

Hierarchy problem? — $\delta m_h^2 \sim \frac{1}{(2\pi)^4} G_N \Lambda^4 \rightarrow 0$ (Scale invariance)

Inflation — Chaotic - $L \supset \lambda(s) s^4, \xi_S s^2 R$

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Jordan frame

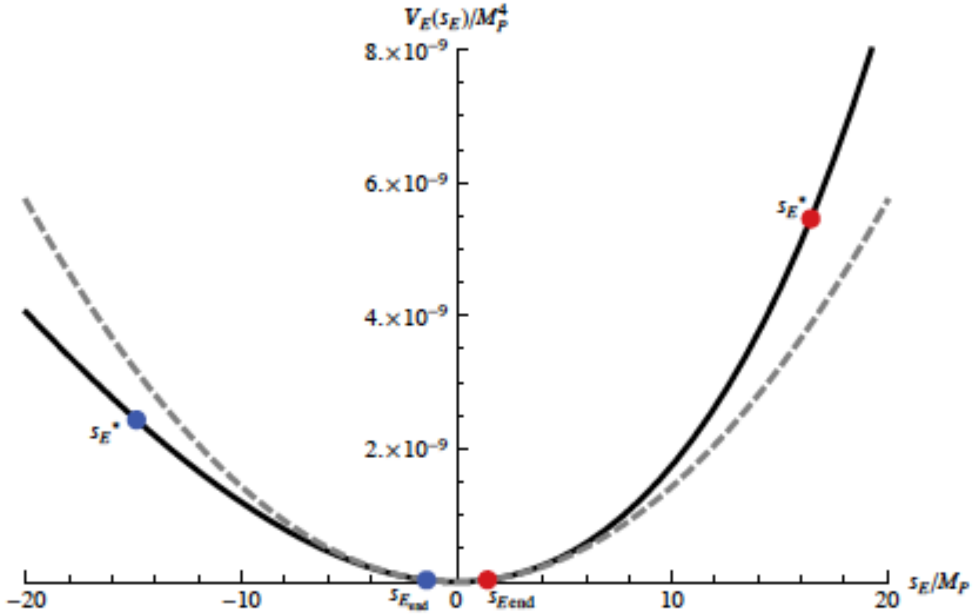
$$\sqrt{-g^J} L^J = -\frac{\xi_S}{2} s^2 R + \frac{(\partial s)^2}{2} + \lambda(s) s^4$$

$$g^E_{\mu\nu} = \Omega(s)^2 g_{\mu\nu}, \quad \Omega(s)^2 = \frac{\xi_s s^2}{M_P^2} = \frac{s^2}{\mathrm{v}_s^2}$$

Einstein frame

$$\sqrt{-g^E} L^E = -\frac{1}{2} M_P^2 R + \frac{(\partial s_E)^2}{2} + \lambda(s_E) M_P^4$$

A simple model



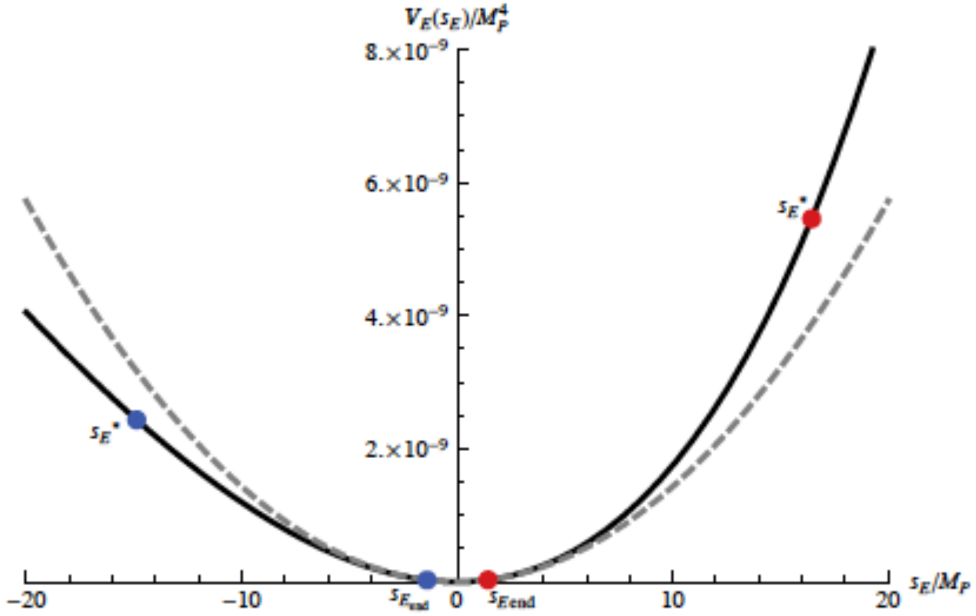
$$\sqrt{-g^J}\mathscr{L}^J = \sqrt{-g^J}\left[\mathscr{L}_{\rm SM} - \frac{\xi_S}{2}s^2 R + \frac{(\partial s)^2}{2} + \frac{(\partial\sigma)^2}{2} + \frac{i}{2}\bar{\psi}^c \not{D}\psi + \mathscr{L}_Y - V\right]$$

$$\mathscr{L}_Y = \frac{1}{2}y_S s\bar{\psi}^c\psi + \frac{1}{2}y_\sigma \sigma\bar{\psi}^c\psi,$$

$$V = \frac{1}{4}\lambda_S s^4 + \frac{1}{4}\lambda_{S\sigma}s^2\sigma^2 + \frac{1}{4}\lambda_\sigma\sigma^4,$$

Kannike et al 1502.01334

A simple model



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Kannike et al 1502.01334

But underlying theory *not* scale invariant??

Summary

- Field theory corrections to Higgs mass inevitable

- If don't appeal to anthropics to keep Higgs light

    ➔ New symmetry

Summary

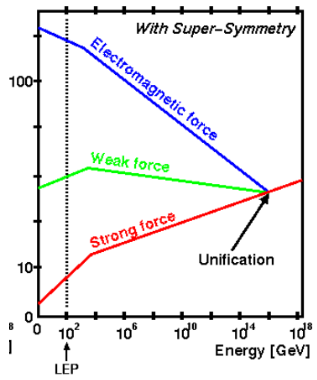
- Field theory corrections to Higgs mass inevitable

- If don't appeal to anthropics need symmetry to keep Higgs light

- Supersymmetry: Non-minimal implementations still viable (Δ~20)

New states should be visible at LHC 13/14

Unification hints



Summary

- Field theory corrections to Higgs mass inevitable
- If don't appeal to anthropics need symmetry to keep Higgs light
- Supersymmetry: Non-minimal implementations still viable ($\Delta \sim 20$)
- Composite: Pseudo Goldstone Higgs ($\Delta \sim 20$)

  Composite states (top partners) should be visible at LHC 13/14

Summary

- Field theory corrections to Higgs mass inevitable
- If don't appeal to anthropics need symmetry to keep Higgs light
- Supersymmetry: Non-minimal implementations still viable (Δ~20)
- Composite: Pseudo Goldstone Higgs (Δ~20)
- Scale invariance:

Still need new light states accessible to LHC 13/14 to generate EW breaking etc.

(i) No unification

But… (ii) In Wilsonian sense quadratically divergent terms seem physical

(iii) Inclusion of gravity problematic

The hierarchy problem and light top quark partners

For partial composite models: $\mathcal{L}_{\rm mix} = \lambda_L f\, q_L \mathcal{O}_L^q + \lambda_R f\, t_R \mathcal{O}_R^t + \text{h.c.}$

$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi}$$

coupling between fermionic resonances $1 < g_\psi \sim \frac{m_\psi}{f} < 4\pi$

$\varepsilon_{L,R} = \frac{\lambda_{L,R}}{g_\psi}$ give degree of compositeness

$$\epsilon^2 \mathcal{F}_1^{(1)} = c_1 \epsilon^2 s_h^2$$

$$\begin{aligned} V(h) &= V^{(1\,\text{loop})}(h/f) + V^{(2\,\text{loop})}(h/f) + \dots \\ &= f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \dots\right) \\ &\quad + f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^4 \left(\epsilon^2 \mathcal{F}_1^{(2)}(h/f) + \dots\right) + \dots , \end{aligned}$$

Simplest case: $O^q, O^t \sim 5_{SO(5)}$ $\quad \propto \varepsilon^2 \sin(h/f)^2 \quad \sim \varepsilon^4 \sin(h/f)^4$

Fine tuning $\Delta \sim \left(\varepsilon^2 \xi\right)^{-1}$ $\quad \left(\xi = \left(\frac{v}{f}\right)^2\right)$