Ultra weak sectors

G. Ross, Planck 2014, Paris, May 2014

LHC 8

No evidence (yet) for BSM

Higgs discovery

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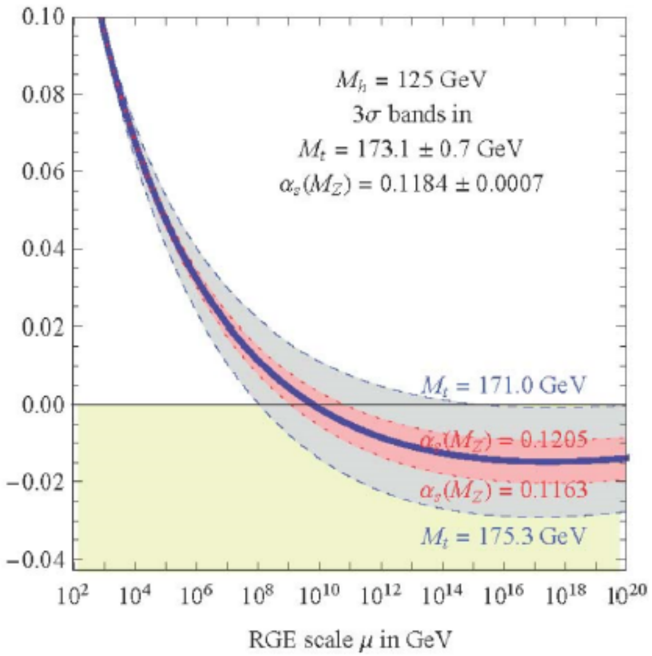
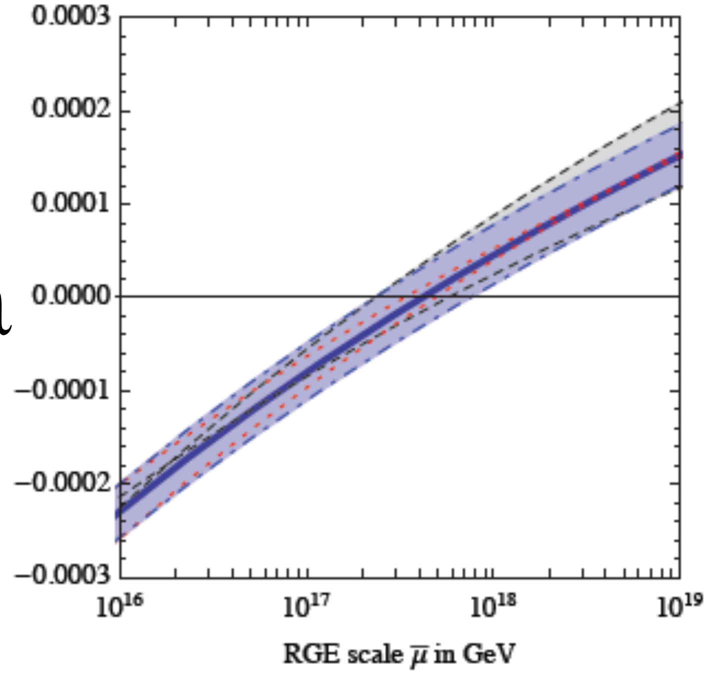
} "Just" the SM (JSM)?

λ



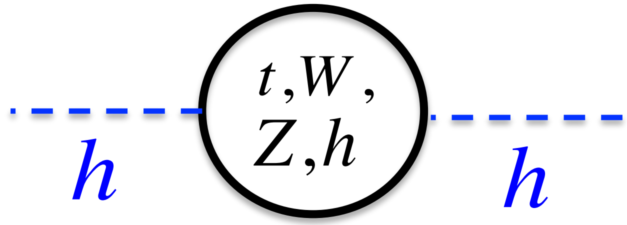
β_λ



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

Espinosa and Strumia talks

JSM - Hierarchy problem?



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

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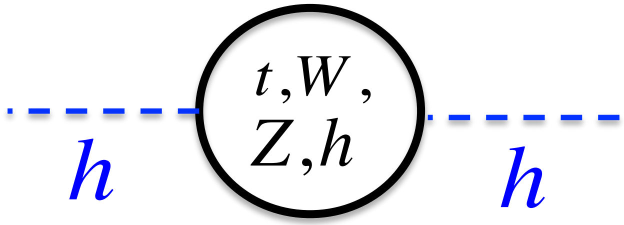

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Field theory: δm^2 not measureable

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

Only $m^2 = 0$ special (scale invariance)

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

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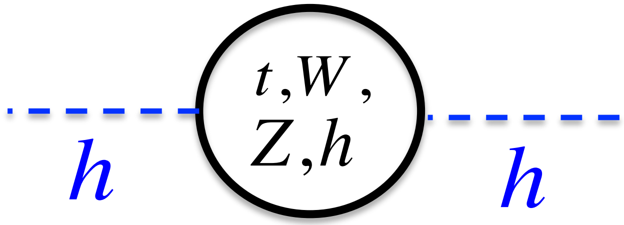

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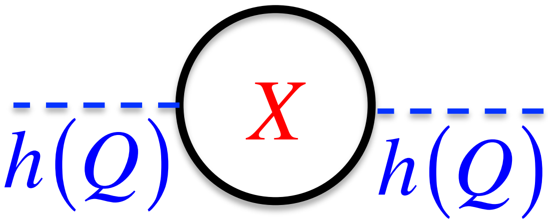
c.f. heavy state corrections, *e.g.* GUTS

$$\delta m_h^2 \propto M_X^2 \ln\left(\frac{Q^2 + M_X^2}{\Lambda^2}\right)$$



- "real hierarchy problem"

GGR, Llewellyn-Smith

$\Longrightarrow$ no heavy thresholds?

No heavy thresholds?

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

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$\zeta \bar{L}_L \nu_R H \quad \Rightarrow$ Ultra weak sector $\zeta \sim 10^{-12}$

Natural due to chiral symmetry .... ζ multiplicatively renormalised

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Low scale baryogenesis possible

– e.g. leptogenesis via ν_R neutrino oscillations + sphalerons

Shaposhnikov et al

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ν_R dark matter?

Shaposhnikov et al

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KSVZ axion: New vectorlike quarks, complex singlet, S

$$L \supset \zeta \psi_L \psi_R S + h.c.$$

$$S = (|S| + f_a) e^{-a/f_a}$$

Ultra weak sector: $\zeta \le 10^{-9} \left(\frac{10^{12} GeV}{f_a} \right)$ $\left(\psi = Q + \overline{Q} \right)$

(To avoid unacceptable Higgs mass contribution)

Farina, Pappadopulo, Strumia

No heavy thresholds?

Strong CP problem: $10^{11}GeV \le f_a \le 10^{12}GeV$

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

$$
\begin{aligned}
V(H_1, H_2) &= \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\
&+ \lambda_4|H_1^\dagger H_2|^2 + \zeta_1|S|^2|H_1|^2 + \zeta_2|S|^2|H_2|^2 \\
&+ \zeta_3 S^2 H_1 H_2 + h.c.
\end{aligned}
$$

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

Ultra weak sector:

ζ_i multiplicatively renormalised

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

Origin of large vev?

Dimensional transmutation (Coleman Weinberg)

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

Coleman Weinberg in DFSZ model

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

$$+\frac{\lambda_2}{2}|H_2|^4+\zeta_3 S^2 H_1 H_2+h.c.$$

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$$+\frac{\lambda_2}{2}|H_2|^4+\zeta_3 S^2 H_1 H_2+h.c. \quad (\zeta_2>\zeta_1>\zeta_3 \text{ assumed})$$

$$\mathrm{v}_S=f_a, \quad \mathrm{v}_{H_1}=\frac{\zeta_1}{\lambda_1}f_a, \quad \mathrm{v}_{H_2}=\frac{\zeta_3}{2\zeta_2}\mathrm{v}_{H_1}$$

$$m_{H_2^0}^2=m_{H^\pm}^2=m_X^2=-\frac{\zeta_2}{2\zeta_1}m_h^2$$

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$$m^2_{H_2^0} = m^2_{H^\pm} = m^2_X = -\frac{\zeta_2}{2\zeta_1} m_h^2$$

$$m^2_{|S|} = -\left(\frac{\zeta_2^2}{32\pi^2\zeta_1}\right)^2 m_h^2 \simeq 0.8\left(\frac{10^{12}\,GeV}{\mathrm{v}_S}\right)^2\left(\frac{m_{H_2}}{m_h}\right)^4 eV^2$$

$|S|$ Pseudo-dilaton

K. Allison, C.Hill, GGR

Phenomenology

Collider signals

Ultra weak couplings … just 2HD model with nearly degenerate heavy Higgs

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Collider signals

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

$$m_{|S|} \sim eV, \qquad \zeta_{1,2,3}^{|S|} \leq 10^{-20}$$

Phenomenology

Collider signals

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Cosmology

If inflation scale below PQ phase transition $\Delta < 10^5 \left(\frac{10^{12}GeV}{f_a}\right)^{1/2}\left(\frac{m_{H_2}}{m_h}\right)GeV$

…. no cosmological constraints

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If inflation scale above PQ phase transition

…. potential Polonyi problem:

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

(stored energy after inflation)

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

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S rolls when $9H_r^2 = m_S^2 \simeq \frac{\zeta_2^2 S_I^{\,2}}{8\pi^2}\left(1+\frac{3}{2}\ln\frac{S_I^{\,2}}{f_a^2}\right), \quad T = T_r$

$$\rho_S \propto T^{6n/(n+2)}, \quad V(S) \propto S^n, \quad n = 4 \text{ radiation}, \quad \text{n=2 matter}$$

$$\rho_S(T_{NR}) = V(S_I)\left(\frac{T_r}{T_{nr}}\right)^4\left(\frac{T_{nr}}{T_{NR}}\right)^3$$

(if dilaton stable)

$$\Omega_s \simeq 885R\left(\frac{s_I}{10^{14}GeV}\right)^{3/2}$$

$$R = \frac{m_{H_2}}{m_h}$$

Stable dilaton case:

$$\Omega_s \simeq 885 R \left(\frac{s_i}{10^{14} GeV} \right)^{3/2}$$

s_i ?

During inflation |S| performs a random walk of step size $H_I / 2\pi$

$e.g.$ If $H_I = 10^{14} GeV$ (BICEP2), $S_I \sim H_I \sqrt{N} / 2\pi \sim 10^{14} GeV$

For dilatonic dark matter $\Omega_s = 0.23, \quad s_i = 4 \times 10^{11} R^{-2/3} GeV$

Unstable dilaton case:

$$\tau_{s\to aa} \simeq 1.45\times 10^{27}\left(\frac{f_a}{10^{12}\,GeV}\right)^5 \frac{1}{R^6}\,\mathrm{sec}$$

$$\left(\frac{f_a}{10^{12}\,GeV}\right)^5 \frac{1}{R^6} < 10^{-10}$$ dilaton decays

$$\Omega_a^{hot} \sim \frac{49}{R^2}\left(\frac{f_a}{10^{10}\,GeV}\right)^{5/2}\left(\frac{s_i}{10^{14}\,GeV}\right)^{3/2}$$

For $\Omega_a^{hot} < 10^{-5}$ (CMB bound) $s_i < 10^{10} R^{4/3}\left(\frac{10^{10}\,GeV}{f_a}\right)^{5/3} GeV$

Unstable dilaton case:

may be

For $f_a = 2\times 10^9\,GeV$ dilaton $\rightarrow h$ ^ briefly in thermal equilibrium

$$S_m \simeq S + \left(\frac{v_1}{f_a}\right) h$$

$W^{\pm}, Z, h, t$

$$\Gamma_S \sim n.\sigma.v = T^3 \frac{1}{16\pi^2}\left(\frac{v_1}{f_a}\right)^2 \frac{\lambda^2}{T^2} > H = 10^{-18}\left(\frac{T_{TE}}{GeV}\right)^2$$

$$T_{TE} < 200\,GeV \quad \Rightarrow \quad T_{TE} > M_{W,Z,h,t}$$ ✔

Dilaton energy $\rightarrow SM\ states$ ✔

(Consistent with BICEP 2 inflation scale - but needs more careful study)

Summary

- "JSM" requires ultra-weak sectors – chiral and shift symmetries

- DFSZ axion + dimensional trasmutation $\Longrightarrow f_a$

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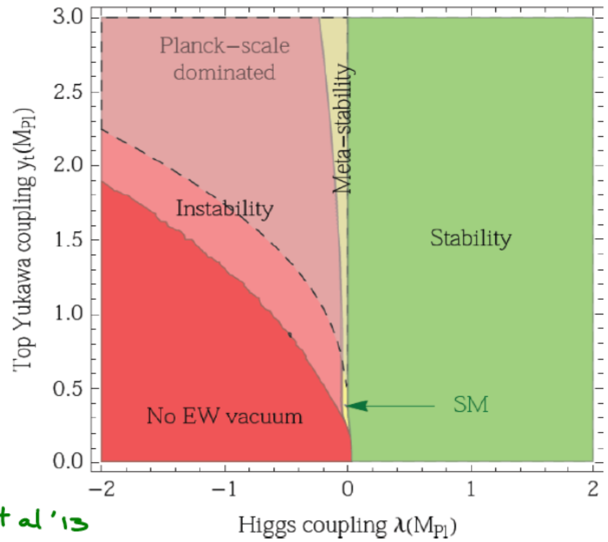
$$m^2_{H_2^0} = m^2_{H^\pm} = m^2_X = R^2 m^2_h \qquad m_{|S|} \simeq 0.9\left(\frac{10^{12}\,GeV}{f_a}\right) R^2 eV$$

$H = h_{SM}(1+O(1/R^2))$

...stable vacuum but loses simplicity of SM

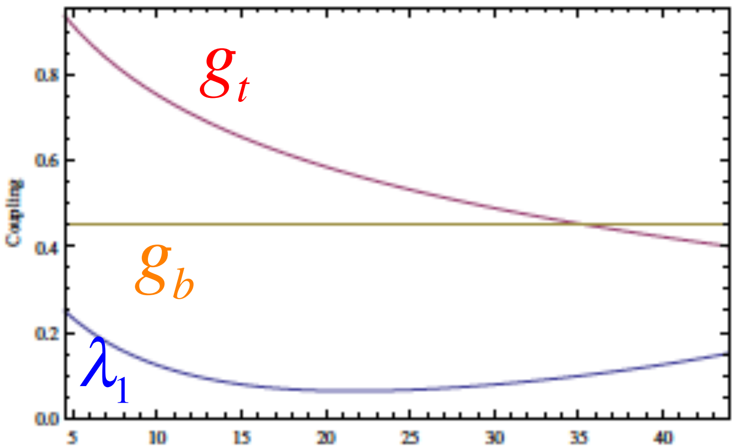
Energy dependence of couplings

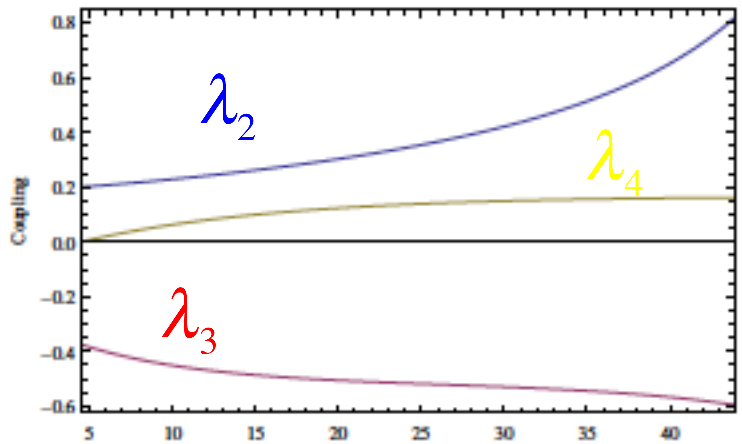
SM:



Buttazzo et al '13

DFSZ:





$\ln(E/GeV)$ $\ln(E/GeV)$

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h ≈ SM Higgs

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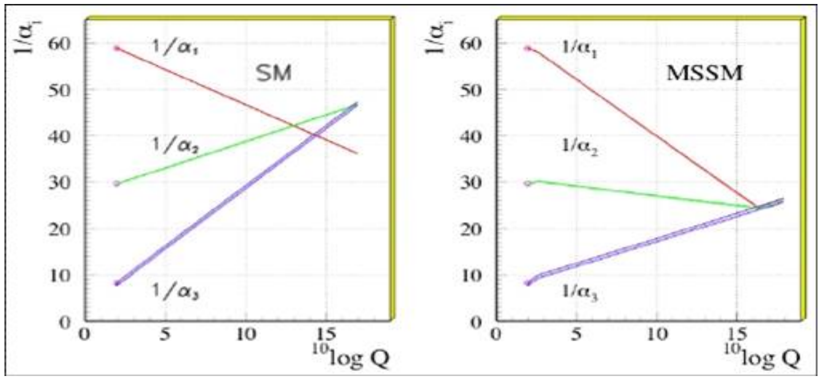
- GUTS $\Longrightarrow$ SUSY GUTS



✔

  "Real" hierarchy problem

  ...SUSY DFSZ scale invariant generalisation straightforward:

A SUSY version

- $$W = W_{MSSM} + \zeta \hat{S} \widehat{H}_1 \widehat{H}_2$$

$$V_{soft}(H_{1,2}, S) = m_S^2 \, | S |^2 + m_1^2 \, | H_1 |^2 + m_2^2 \, | H_2 |^2 + T_{cl} S H_1 H_2$$

c.f.Dreiner, Staub, Ubaldi

Rajagopal, Turner, Wilczek

- Radiative breaking $m_S \ll m_{H_{1,2}}$

$$m_S^2(|S|^2)|S|^2 \propto \zeta^2 m_{1,2}^2 |S|^2 \ln\left(|S|^2 / \mathrm{v}_S^2\right)$$

$$m_H^2(|H|^2)|H|^2 + \frac{1}{8}(g^2 + g'^2)|H|^4 \sim \frac{3y_t^2}{8\pi^2} m_{\tilde{t}}^2 |H|^2 \ln\left(\frac{|H|^2}{\Lambda^2}\right) + g^2 |H|^4$$

Dilaton properties essentially unchanged

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