Beyond the Standard Model as of 2015

R. Barbieri
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I. The SM as of 2015

II. Problems of (questions for) the SM

III. New (revisited) ideas to address these problems

IV. What if the hierarchy problem were a dead end?

I. The SM Lagrangian
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} \not{D} \psi \qquad (\sim 1975\text{-}2000)$$

$$+ |D_\mu h|^2 - V(h) \qquad (\sim 1990\text{-}\ 2012)$$

$$+ \psi_i \lambda_{ij} \psi_j h + h.c. \qquad (\sim 2000\text{-}\ \text{now})$$

In () the approximate dates of their experimental shining
(at different levels)

The synthetic nature of PP exhibited

An alternative definition of the SM

1. Gauge group $\mathcal{G} = SU(3) \times SU(2) \times U(1)$

2. Particle content (rep.s of $\mathcal{G}$) - See below

3. All $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ except for $\theta F_{\mu\nu} \tilde{F}^{\mu\nu}$

(In spite of $F_{\mu\nu} \tilde{F}^{\mu\nu} = \partial_\mu J_\mu$, neutron EDM $\approx 10^{-16} \theta \; e \cdot cm$)

Particle content

				$i =$
$u(1968)$	$d(1968)$	$e(1897)$	$\nu_e(1956)$	$\leftarrow 1$
$c(1974)$	$s(1968)$	$\mu(1937)$	$\nu_\mu(1962)$	$\leftarrow 2$
$t(1994)$	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$	$\leftarrow 3$

$J = 1/2$

$G^a(1978)$	$A(1905)$	$W^\pm(1983)$	$Z(1983)$

$J = 1$

$J = 0$

$h(2012)$

Representation content and accidental symmetries

$$\Psi = Q(3,2)_{1/6} \;\; u(\bar{3},1)_{-2/3} \;\; d(\bar{3},1)_{1/3} \;\; L(1,2)_{-1/2} \;\; e(1,1)_1$$

Ψ = next-to-simplest rep of $\mathcal{G}$:

chiral anomaly-free, vector-like under $SU(3) \times U(1)_{em}$

$$[\Xi = (3,2)_0 \;\; (\bar{3},1)_{1/2} \;\; (\bar{3},1)_{-1/2}]$$

(the key to the non-observation of any new particle so far?)

(Un important hint for "algebraic" Unification?)

From $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$

$$\Rightarrow B, \;\; L_e, L_\mu, L_\tau$$

and $U(3)^3 \equiv U(2)_Q \times U(3)_u \times U(3)_d$ only broken by Y_u, Y_d

II. Problems of (questions for) the SM

1. Unaccounted phenomena

neutrino masses
Dark matter
Baryon asymmetry

2. Why $\theta \lesssim 10^{-10}$?

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

unaccounted phenomena (?)
vacuum stability
Landau poles
Gravity

4. Lack of calculability

the hierarchy problem
the flavour paradox

vacuum stability

$$V(\varphi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

$$\frac{d\lambda}{d\log Q} = \frac{3}{2\pi^2}\left[\lambda^2 + \frac{1}{2}\lambda y_t^2 - \frac{1}{4}y_t^4 + \cdots\right]$$

$$m_W = gv/\sqrt{2}$$
$$m_H = 2\sqrt{\lambda}v$$
$$m_t = y_t v$$

With current values of $m_H,\ m_t,\ \alpha_S, \ldots$

$$\lambda(\approx 10^{11}\ GeV) < 0$$

⇒ A second minimum of V at $\phi \gtrsim 10^{11}\ GeV$
to which v should tunnel in a very long time (>> t_{Univ})

- Is there a real meta-stability at $\phi < M_{Pl}$?
- Any experimental implication?
- Connection to inflation?
- Is it a problem?

Landau poles

$$\frac{dg_1^2}{dt} = \frac{41}{40} g_1^4 \quad \Rightarrow \text{ a Landau pole at } \Lambda_1$$

- the problem not cured by including other couplings
- can it be cured by gravity? Yes, since $\Lambda_1 > M_{Pl}$, if gravity important at $E \lesssim M_{Pl}$
- what if gravity softened enough, so that it becomes irrelevant? (How is hard to tell, but...)
- need $SU(3) \times SU(2) \times U(1)$ fully immersed in a non-abelian group

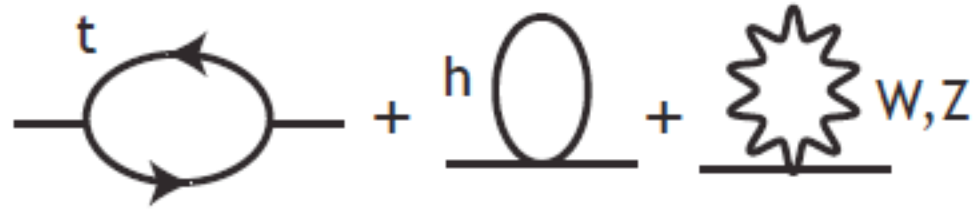
$$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

$$SU(3)_c \times SU(3)_L \times SU(3)_R$$

which requires heavier scales than v

The hierarchy problem, once again

Can we compute the Higgs mass/vev in terms of some fundamental dynamics?



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 + \dots$$

$$\Lambda_t \lesssim 0.4\sqrt{\Delta}\ TeV \qquad \Lambda_g \lesssim 1.1\sqrt{\Delta}\ TeV \qquad \Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$$

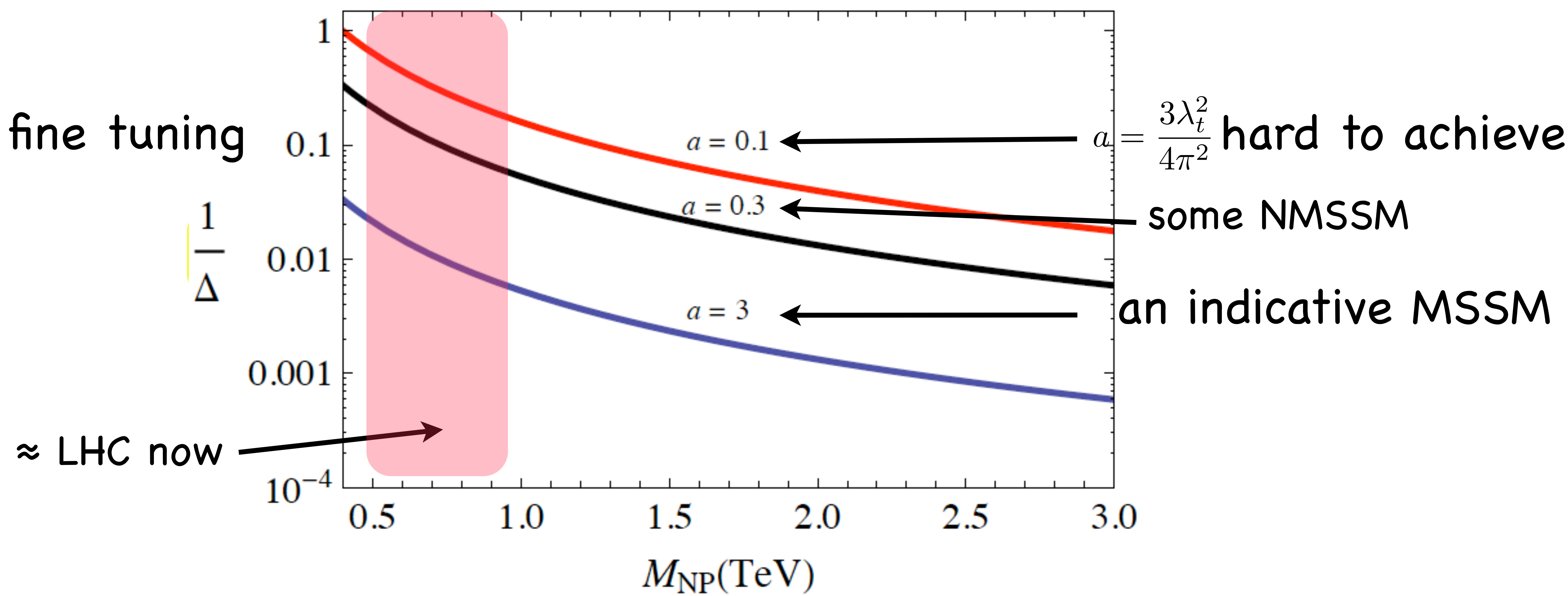
⇒ Look for a top "partner" (coloured, S=0 or 1/2) with a mass not far from 1 TeV

(we have become more prudent!)

How dramatic is the "little hierarchy problem"?

$$\Delta \equiv \frac{\delta m_h^2}{m_h^2} \approx a \frac{M_{NP}^2}{m_h^2}$$

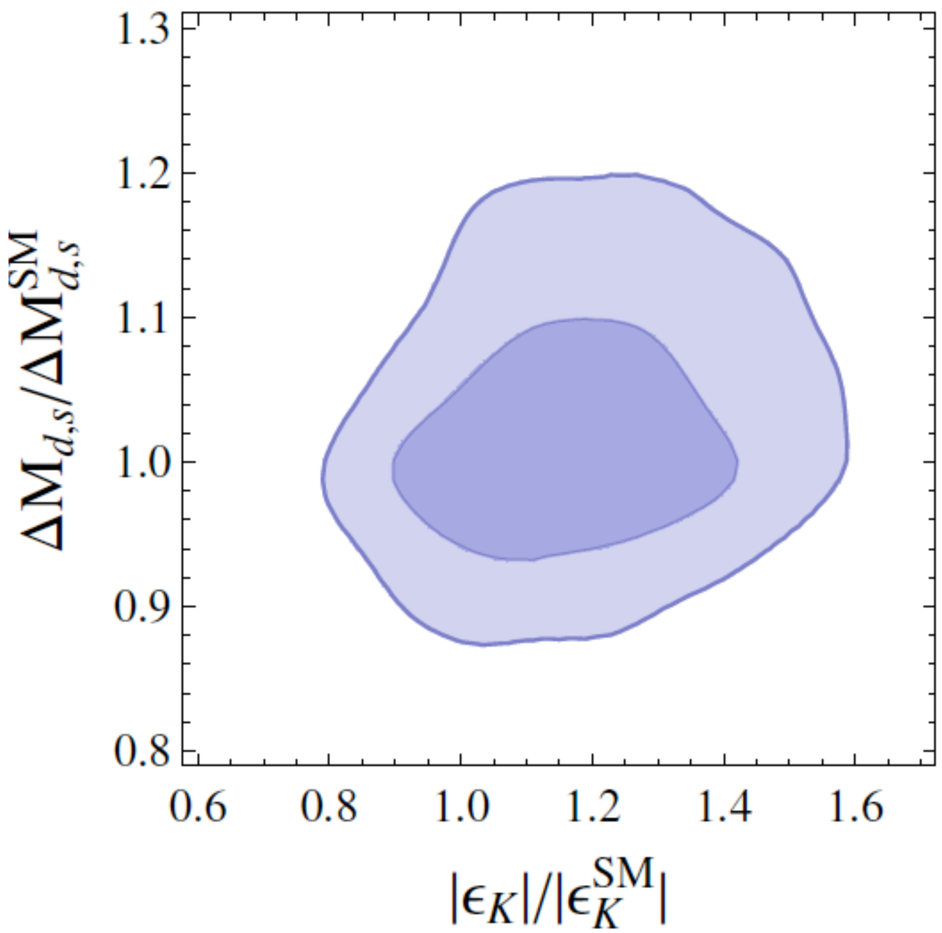
model dependent

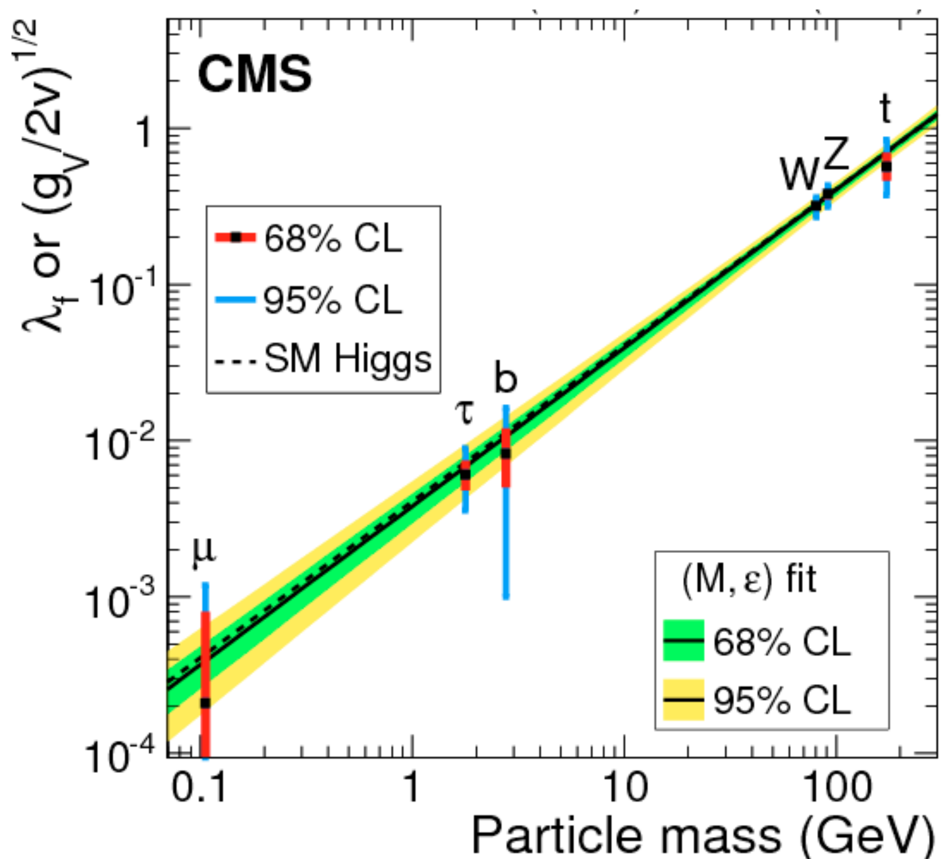


- Things do not work the way they were originally thought
- Not a serious problem at a fundamental level LHC-13 TeV

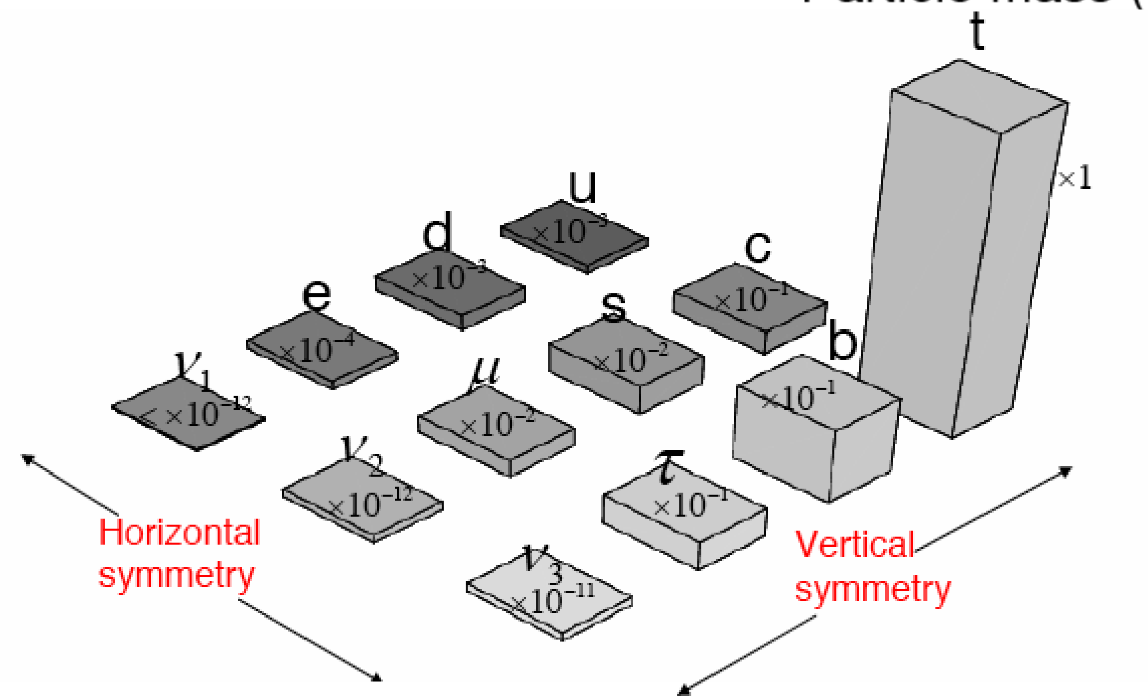
The flavour paradox

Yukawa couplings: a piece of physical reality





as opposed to:



?!?!?

III. New (revisited) ideas to address these problems/questions

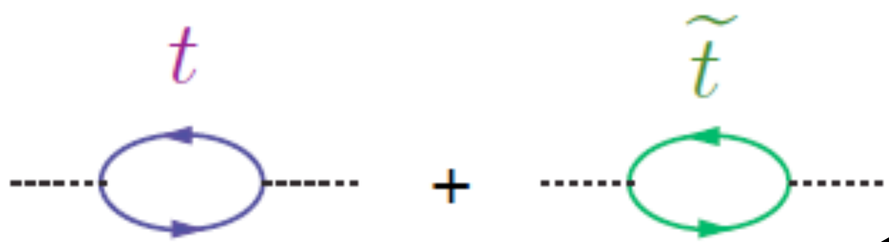
- Neutral top "partners" (fermionic or even bosonic)
- Mirror Dark Matter
- Self-criticality of the Higgs vev
- Axion (light scalar) detection
- Putative anomalies in B-decays

Neutral top "partners" (twin Higgs)

1. "Mirror" the Higgs system ($H, \ \tilde{H}$) with a Z_2 symmetry

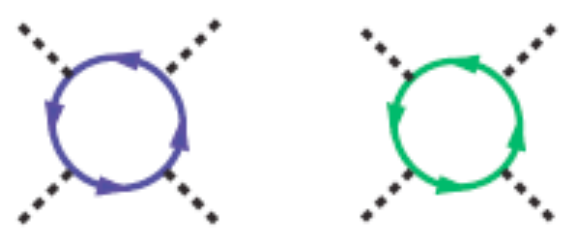
$$V(\mathcal{H}) = -m_{\mathcal{H}}^2(|H|^2 + |\widetilde{H}|^2) + \lambda_*(|H|^2 + |\widetilde{H}|^2)^2 + \frac{\lambda_h}{2}\left(|H|^4 + |\widetilde{H}|^4\right) + \ldots$$

2. "Mirror" the Higgs-top interaction $\mathcal{L}_Y = y_t Q H t + y_t \tilde{Q}\tilde{H}\tilde{t}$



$$\delta m_{\mathcal{H}}^2 \gtrsim \frac{3y_t^2}{4\pi^2}\Lambda_*^2$$

$$V(\mathcal{H}) = -m_{\mathcal{H}}^2(|H|^2 + |\widetilde{H}|^2) + \lambda_*(|H|^2 + |\widetilde{H}|^2)^2 + \frac{\lambda_h}{2}\left(|H|^4 + |\widetilde{H}|^4\right) + \ldots$$



$$\sim \frac{3y_t^4}{32\pi^2}\log \Lambda_*/m_t$$

Vacuum dynamics

$$V(\mathcal{H}) = -m_{\mathcal{H}}^2(|H|^2 + |\widetilde{H}|^2) + \lambda_*(|H|^2 + |\widetilde{H}|^2)^2 + \frac{\lambda_h}{2}\left(|H|^4 + |\widetilde{H}|^4\right) + \ldots$$

$\lambda_h = 0$

- $SO(8) \to SO(7)$ $\qquad \langle \widetilde{H} \rangle^2 = \frac{m_{\mathcal{H}}^2}{2\lambda_*} \equiv f^2$
- 7 NG-bosons = 6 eaten + (SM Higgs)

$\lambda_h \neq 0$

- $\delta m_h^2 = \lambda_h(\delta f^2) = \frac{\lambda_h}{\lambda_*} \times \frac{3y_t^2}{4\pi^2} \times \Lambda_*^2$

$$\Lambda_* \lesssim \sqrt{\frac{\lambda_*}{16\pi^2}} 5\sqrt{\Delta}\ TeV$$

($1/\Delta$ = fine tuning)

Spectrum structure (partial) $\lambda_* \to g_*^2$

$\Lambda_* = g_* f$ — coloured/charged particles

$SO(8) \to SO(7)$ at f

$m_{\tilde{t}} = y_{\tilde{t}} f$ — top "partner"

SM fully neutral

$m_t = y_t v$ — top

m_h — $m_h \sim \sqrt{\frac{3y_t^2}{8\pi^2} \log(\Lambda_*/m_t)}\; y_t v$

fine tuning $\frac{1}{\Delta} \approx \frac{v^2}{f^2}$ $\qquad \Lambda_* \lesssim 0.4 \frac{g_*}{y_t} \sqrt{1/\log \Lambda_*/m_t} \sqrt{\Delta}\; TeV$

Composite Twin Higgs

top $\quad y_L \bar{Q}_L T_R + y_R \bar{t}_R T_L + \tilde{y}_L \bar{\tilde{Q}}_L \tilde{T}_R + \tilde{y}_R \bar{\tilde{t}}_L \tilde{T}_L$

$$y_t \sim \frac{y_L y_R}{g_*}$$

$\mathbb{Z}_2 \rightarrow \quad y_L = \tilde{y}_L \quad y_R = \tilde{y}_R \quad \rightarrow \quad y_t = \tilde{y}_t$

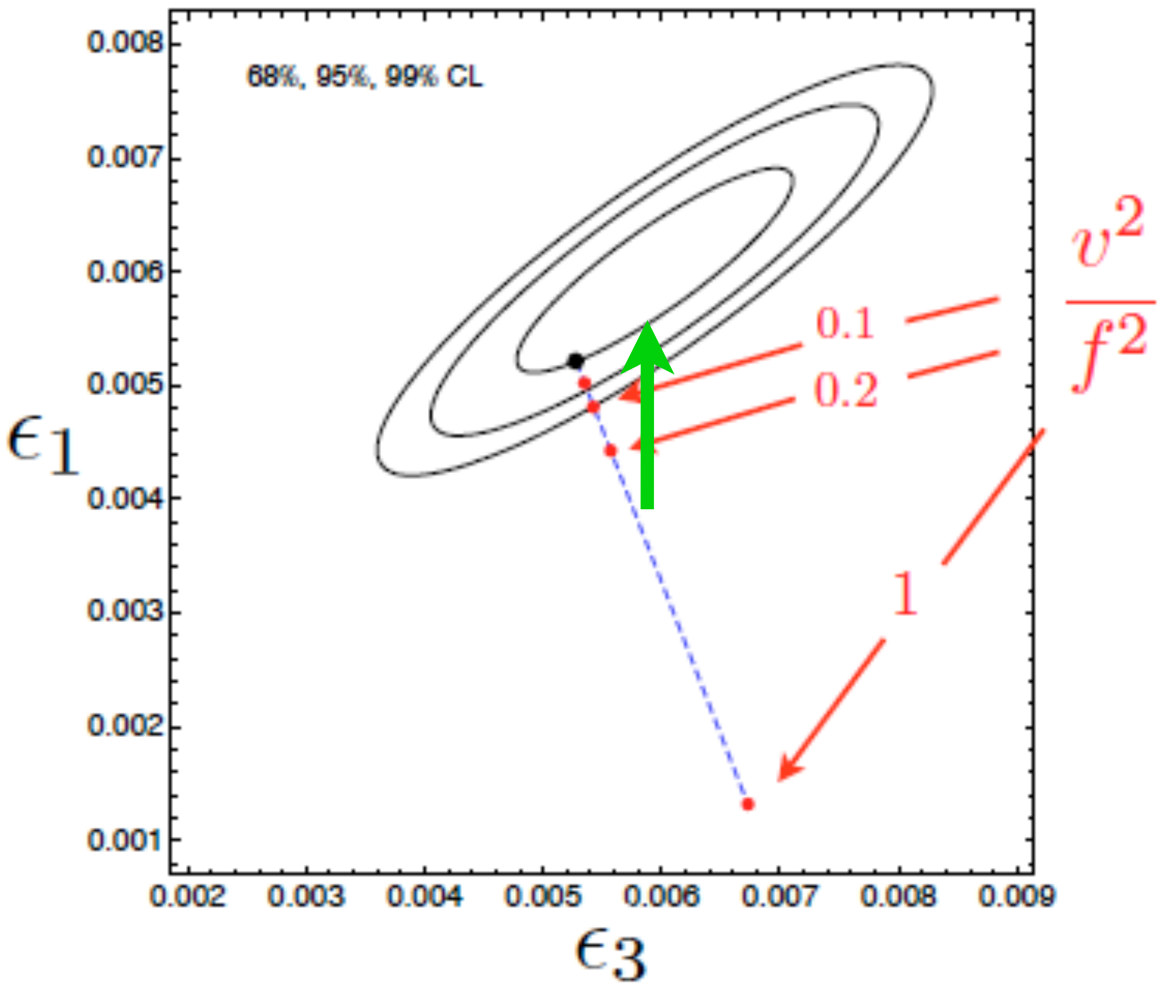
$SU(3)$ need $g_3 \approx \tilde{g}_3$ to preserve $y_{L,R} = \tilde{y}_{L,R}$
and 3 mirror quarks with quite free Yukawas

$SU(2)$ need $g_2 \approx \tilde{g}_2$ to protect $O(g_2^2)$ corr.s to m_h^2

$U(1)_Y$ $\quad \Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$ no real need to gauge $\tilde{Y}$
$\Rightarrow$ no $\tilde{\gamma}$, small Z_2 breaking needed

Phenomenological issues

1. EWPT unaltered in IR logs



$$\Delta\epsilon_3 = O(1)\frac{m_W^2}{\Lambda_*^2} + \frac{g^2}{96\pi^2}\frac{v^2}{f^2}\ln\left(\Lambda_*/m_h\right)$$

$$\Delta\epsilon_1 = O(1)\frac{1}{16\pi^2}\frac{y_L^4 v^2}{\Lambda_*^2} - \frac{3g^2\tan^2\theta_W}{32\pi^2}\frac{v^2}{f^2}\ln\left(\Lambda_*/m_h\right)$$

2. Cosmology and mirror Dark Matter

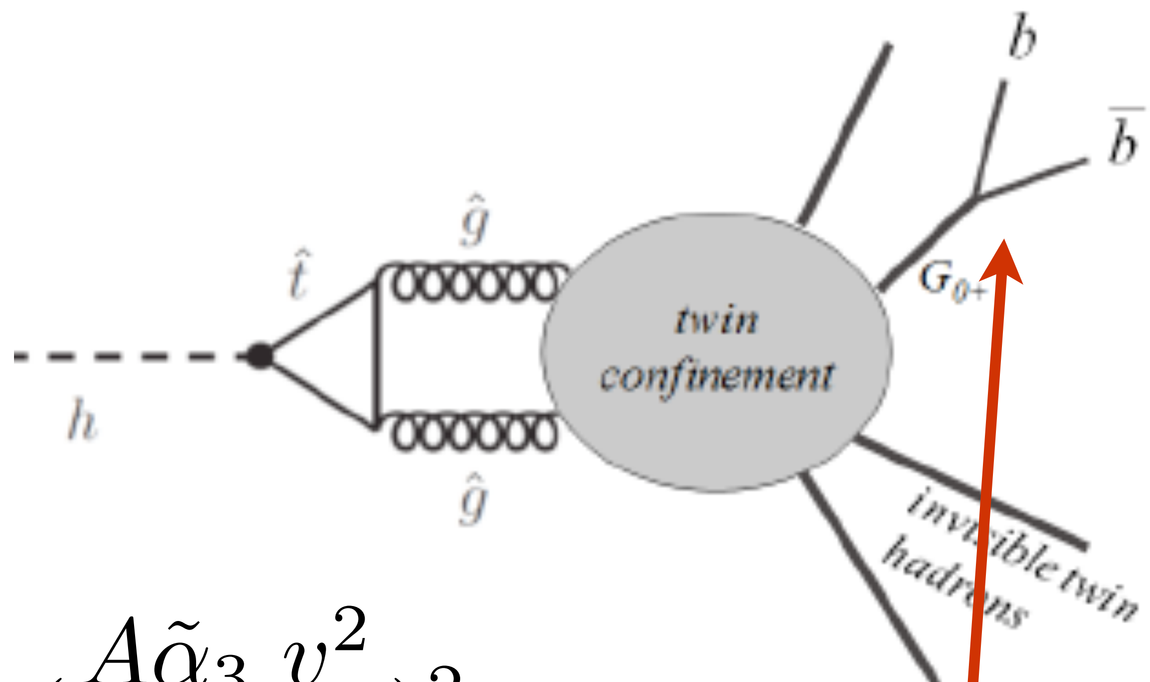
- $\tilde{L},\ \tilde{B},\ \tilde{Q}$ as mirror global symmetries
- Take only mirror third generation as relevant with free Yukawas except $\tilde{y}_t = y_t$ $\quad m_{\tilde{\tau},\tilde{b}} = y_{\tilde{\tau},\tilde{b}} f$

2 x 2 broad options

$\tilde{\eta}_{DM} = 0$	$m_{\tilde{\nu}} \approx 0$
E.g.: DM = $\tilde{\tau}$ with $\Omega_{\tilde{\tau}} = \Omega_{DM}$ for $m_{\tilde{\tau}} = 60 \div 120\ GeV$ and $f/v = 3 \div 5$	need to watch DR $\Lambda_{QCD} < T_M < \tilde{\Lambda}_{QCD}$ $\Delta N_{eff} = 0.075 \div 0.5$
$\tilde{\eta}_{DM} \neq 0$	$m_{\tilde{\nu}} > 10 \div 20\ GeV$
E.g.: DM = $\tilde{\Delta} = (\tilde{b}\tilde{b}\tilde{b})$ with $m_{\tilde{b}} < \tilde{\Lambda} = O(0.5 \div 20) GeV$ $\frac{\Omega_{\tilde{\Delta}}}{\Omega_{baryon}} = \frac{m_{\tilde{\Delta}} \eta_{\tilde{B}}}{m_N \eta_B}$	by introducing $\tilde{\nu}_R$

3. LHC signatures of light mirror glueballs

important parameters: $\tilde{\Lambda}_{QCD},\ m_{\tilde{b}},\ f$



$$\frac{\Gamma(h \to \tilde{g}\tilde{g}}{\Gamma(h \to gg} = (\frac{A\tilde{\alpha}_3}{\alpha_3}\frac{v^2}{f^2})^2$$

$$BR(h \to \tilde{g}\tilde{g}) = 3\%(\frac{3}{f/v})^4$$

$$A = 1 \div 6$$

$\tilde{G}_{0+} \longrightarrow$ SM via Higgs mixing

$$c\tau(\tilde{G}_{0+}) \approx 3m(\frac{8\ GeV}{m(\tilde{G}_{0+})})^7(\frac{f/v}{3})^4$$

A self-critical Higgs vev

1. A Goldstone boson ϕ of a U(1) broken at a scale f

2. A U(1)-breaking coupling of ϕ to H
   (that keeps $\phi \to \phi + 2n\pi f$)

3. A breaking of $\phi \to \phi + 2n\pi f$ controlled by a small mass parameter m entering the Higgs mass term

$$V = -f^2|S|^2 + |S|^4 + \rho(H)\frac{S + S^+}{f} + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$S = se^{-i\phi/f}$

Λ = UV cutoff

V is a natural potential

Minimizing $V(H,\phi)$

$$V = \rho(H)\cos\phi/f + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$$\rho(H) = \cancel{\rho_0} + \rho_1\frac{H}{v_F} + \rho_2(\frac{H}{v_F})^2 + \ldots \qquad v_F^4 > \rho_{1,2}$$

(non trivial)

$$\frac{\partial V}{\partial h} = 0 \ \Rightarrow h^2 \approx \frac{\Lambda^2 - m\phi}{\lambda} > 0$$

$$\frac{\partial V}{\partial \phi} = 0 \ \Rightarrow h \approx v_F\frac{\Lambda^2 m f}{\rho_1}$$

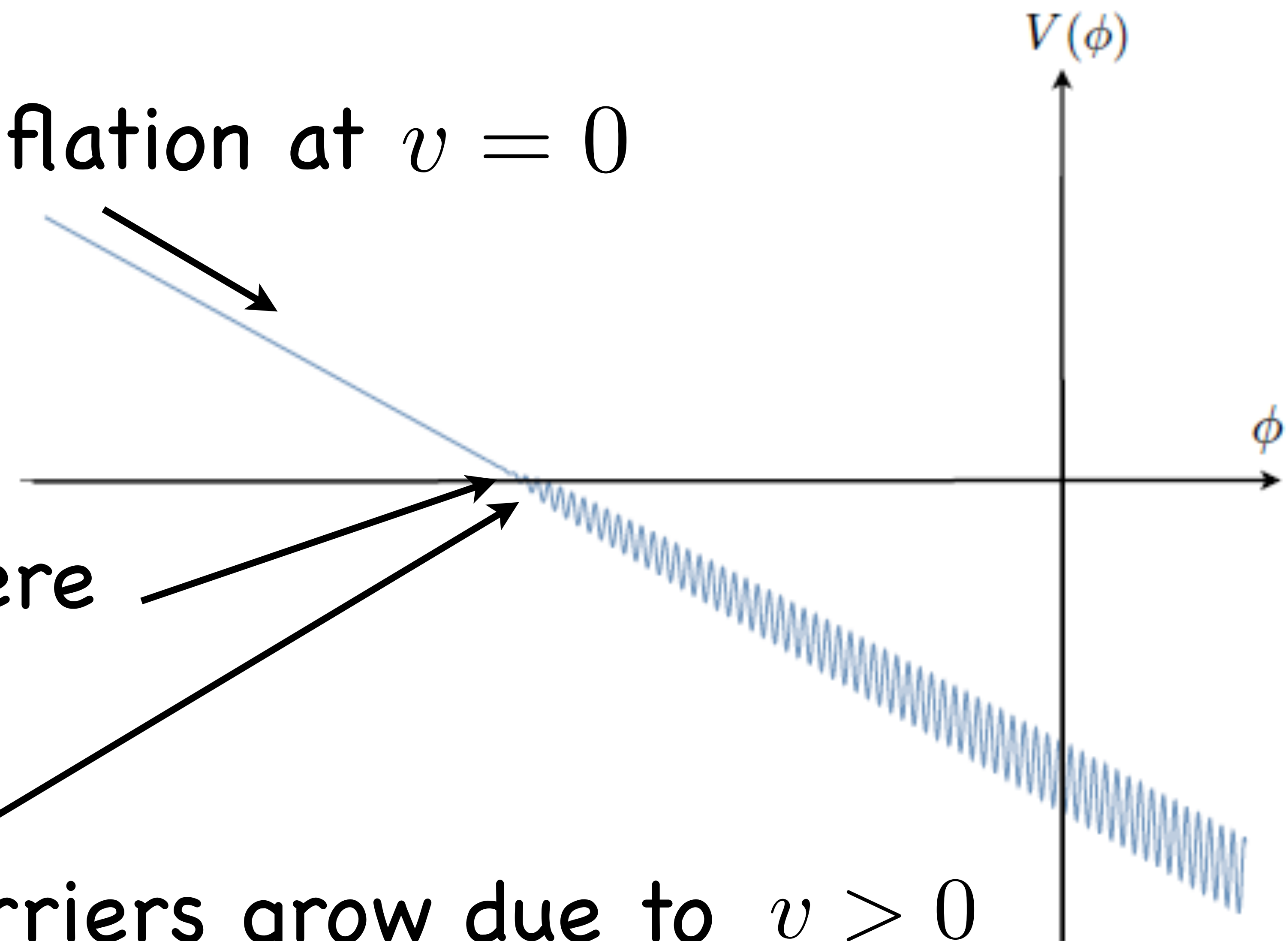
$h = v_F$ natural = moving Λ, m, f, ρ_1 by O(1)
h changes by O(1)

$$m = \frac{\rho_1}{\Lambda^2 f} \lesssim \frac{v_F^4}{\Lambda^2 f} \qquad \phi \approx \frac{\Lambda^2}{m} \gtrsim \frac{\Lambda^4 f}{v_F^4}$$

historical evolution of ϕ (and of v)

(under suitable conditions: e.g. a very very long inflation period)

ϕ slow-rolls during inflation at $v = 0$



until it hits value where m_h^2 crosses zero

rolling stops when barriers grow due to $v > 0$

experimental consequences:??

Where we stand

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III. New (revisited) ideas to address these problems

IV. What if the hierarchy problem were a dead end?