Discussion

1) very basic introduction to the hierarchy problem
2) some ‘controversial’ statements

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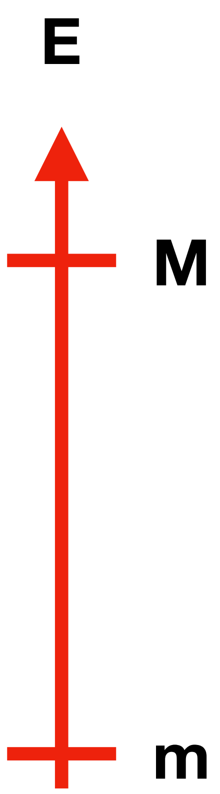
Hierarchy problem



- No hierarchy problem without hierarchy
- M (high scale) >> m(low scale)
- *Relevant* operator *unprotected* by symmetry will be sensitive to high scale.

Quantum effects

$$m\,\bar{\psi}\psi$$

Relevant operator in SM, UV insensitive
b/c protected by (chiral) symmetry

$$m^2\,\phi^*\phi \qquad \sqrt{-g}\,\Lambda_{cc}^4$$

relevant UV sensitive operators in SM

$$\delta m_{QM} \approx m\frac{g^2}{16\pi^2}\log\frac{\Lambda}{m}$$

No problem!

QM effects ~ m (low scale)

$$\delta m^2_{QM} \approx \frac{g^2}{16\pi^2}\Lambda^2$$

Problem!

QM effects ~ Highest scale

Quantum effects 2

$$m_h^2(\mu)\,\phi^*\phi$$

Leading log effects in “pure SM” (no other physics above m_h):

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar{\mu}} = \frac{3m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\right)$$

No hierarchy problem: corrections are ~ m_h^2 !

“No hierarchy problem without hierarchy”

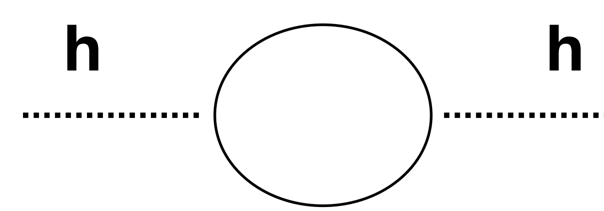
Quantum effects 3

$$m_h^2(\mu)\,\phi^*\phi \qquad\qquad y\,\phi\,\bar{\psi}\psi + M\,\bar{\psi}\psi$$

Add heavy Dirac fermion of mass ***M >> m_h*** *with coupling y*

$$\delta m_h^2 = \mathrm{Re}\,\Pi_{hh}|_{p^2=m_h^2} = \frac{y^2}{2(4\pi)^2}\,\mathrm{Re}\left[\Delta_\epsilon + (m_h^2 - 4M^2)B_0(m_h; M, M) - 2A_0(M)\right]$$

$$= \frac{y^2}{2(4\pi)^2}\Big(\Delta_\epsilon + (6M^2 - m_h^2)\log\frac{m_h^2}{\bar{\mu}^2} + f(m_h, M)\Big),$$



$$\beta_{m_h^2} = \frac{d\,m_h^2(\bar{\mu})}{d\log\bar{\mu}} = \frac{y^2}{(4\pi)^2}(m_h^2 - 6M^2) + \cdots$$

Quantum effects 3

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$$m_h^2(m_h) \approx m_h^2(M) - \mathcal{O}(1)\,M^2\,\log\frac{M}{m_h}$$

Need to tune $m_h^2(M)$ vs. $\mathcal{O}(1)$ to get $m_h^2(m_h) \ll M^2$

Solutions

- Protect $m_h^2\,\phi^*\phi$ by some symmetry
  - Susy: chiral symmetry. Super-multiplet (higgs,higgsino). Exact susy guarantees equal mass of fermion and higgs boson (also at quantum level).
  - Composite Higgs: shift symmetry $\phi \to \phi + \alpha$
- Make dynamical and select $(\Lambda^2 - \varphi)\,\phi^*\phi$ vacuum (relaxion)

Fine-tuning “measure”

- We want to quantify the severity of this cancellation. Factors of O(1) are irrelevant. Logs are not.

$$\log \frac{\mathrm{GUT}}{\mathrm{TeV}} \approx 30$$

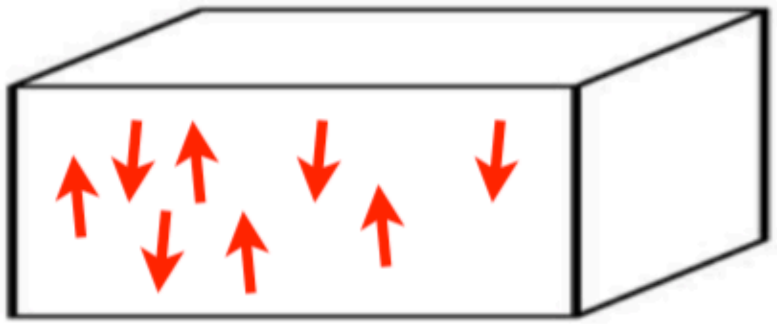
- Which measure?

- “I know it, when I see it” *

- We have experimentally performed this tuning many times…

* *Supreme court Justice Potter Stewart describing his threshold test for obscenity (1964)*

For generic T ferromagnet is not a critical point:



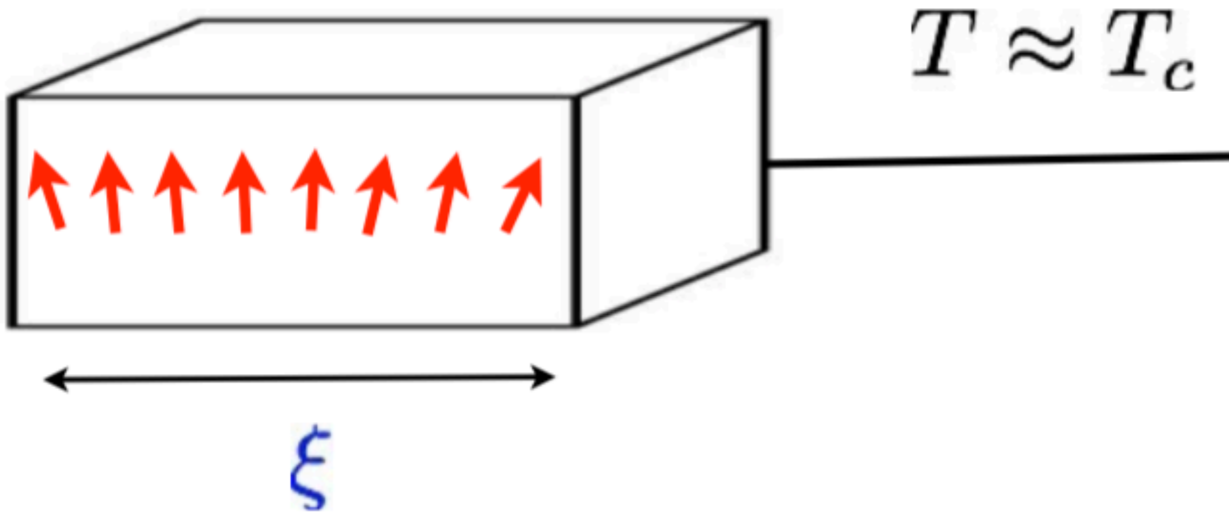
Landau,Ginzburg

$\Lambda^{-1} \longleftrightarrow a$ - atomic spacing

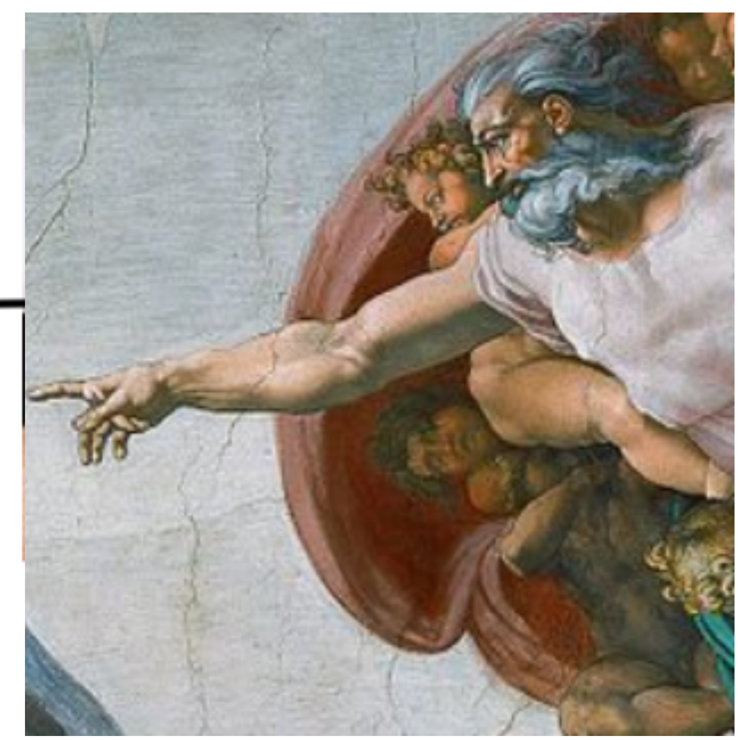
$m^{-1} \longleftrightarrow \xi$ - correlation length

$\Lambda \gg m \quad \Longleftrightarrow \quad \xi \gg a$ - critical point

T→ T_c requires to finetune the temperature:



$T \approx T_c$



Correlation length >> atomic spacing

Inspired by S. Rychkov

Barbieri Giudice

For the tuning calculation, we will use the Barbieri-Giudice measure [2], reformulated in terms of $m_h^2 \approx (125\text{ GeV})^2$ instead of m_Z^2 [5], in order to better take into account the radiative corrections to the Higgs quartic:

$$\Delta_{M^2} = \left| \frac{\partial \log m_h^2}{\partial \log M^2} \right| \tag{1.1}$$

where M^2 is a UV mass-squared parameter (e.g. μ^2, M_3^2, or $m_{Q_3}^2$). When multiple sources of tuning are present, we take the maximum tuning as our measure, $\Delta = \max_{\{M_i^2\}} \Delta_{M_i^2}$.

Example from recent paper http://arxiv.org/abs/arXiv:1611.05873

Example:

$$m_h^2(m_h) \approx m_h^2(M) - \frac{6y^2}{16\pi^2} M^2 \log \frac{M}{m_h}$$

$$\Delta_{BG} = \frac{\partial \log m_h^2}{\partial \log M^2} = \frac{M^2}{m^2} \frac{\partial m_h^2}{\partial M^2}$$

Here:

$$\Delta_{BG} \approx \frac{M^2}{m_h^2} \frac{6y^2}{16\pi^2} \ln \frac{M}{m_h}$$

This makes sense. Roughly: $\ln_{10} \Delta_{BG}$ corresponds to # digits which need to cancel in UV parameters vs. quantum.

Natural EWSB in Susy

Fine-tuning of (Higgs mass)^2 *MSSM,NMSSM,GNMSSM ...*

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

Higgsinos

Barbieri/Guidice,

1loop $$\delta m^2_H|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{U_3} + m^2_{Q_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

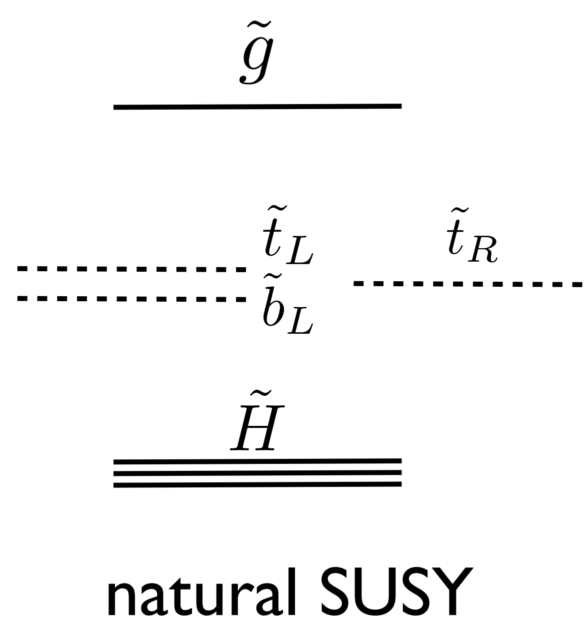
stops, sbottom$_L$

2loop $$\delta m^2_H|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

gluino

Minimally natural susy

sparticle masses	δm_H^2 <<		vs	Current Limits (13 TeV, 36 fb^{-1})
$\approx 1000\,\mathrm{GeV}$	2loop			**2020 GeV**
$\approx 500\,\mathrm{GeV}$	1loop			**1050 GeV**
$\approx 250\,\mathrm{GeV}$	tree			**145 GeV**



O(1) departure from natural expectation!

(Non?)Alternatives

- Howie's measure. “EW fine-tuning” (no logs, cancellations?)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$$\Sigma_u^u(\tilde{t}_{1,2}) = \frac{3}{16\pi^2} F(m_{\tilde{t}_{1,2}}^2) \times \left[f_t^2 - g_Z^2 \mp \frac{f_t^2 A_t^2 - 8g_Z^2(\frac{1}{4} - \frac{2}{3}x_W)\Delta_t}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2} \right]$$

- Focus points (Hyung Do Kim will show what's wrong with them)

EW Fine-tuning

2% change in UV parameter

-> 100 % change in EWfine-tuning measure

Case A			Case B		
$m_{H_u}^2(M_{\rm GUT})$	μ	$\Delta_{\rm EW}$	$m_{H_u}^2(M_{\rm GUT})$	μ	$\Delta_{\rm EW}$
1.03×10^7	150	9.04	2.73×10^7	150	15.4
1.02×10^7	250	18.8	2.72×10^7	250	24.1
1.00×10^7	400	42.4	2.70×10^7	400	49.5

Table 1: An illustration of the insensitivity of the EWFT fine-tuning measure $\Delta_{\rm EW}$ to $m_{H_u}^2(M_{\rm GUT})$. For case **A** the NUHM2 parameters are $m_0 = 2.5$ TeV, $m_{1/2} = 400$ GeV, $\tan\beta = 10$, $m_A = 1$ TeV, while for case **B** we have, $m_0 = 4$ TeV, $m_{1/2} = 1$ TeV, $\tan\beta = 15$, $m_A = 2$ TeV. For both cases, we take $A_0 = -1.6m_0$. The numbers in the Table are in GeV units.

https://arxiv.org/pdf/1212.2655v1.pdf , **Baer et. al**

Fine-tuned fine-tuning measure?

- Hyung Do's slide

Focus point RG equation

uses the following equation

$$m^2(Q) = e^{-c y_t^2 d \log \frac{\Lambda^2}{Q^2}} m^2(\Lambda)$$

thus it is sensitive to y_t and cutoff $\frac{\Lambda}{Q}$ (GUT / EW)

vs $\tan\beta$