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Summer School on Particle Physics in the LHC Era

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Beyond the Standard Model

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Behind and Beyond the Standard Model

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1. A critical view on the Standard Model
   - Obvious limitations of the Standard Model
   - Effective Quantum Field Theories: couplings, mass scales and accidental symmetries
   - The Standard Model as an effective theory (baryon & lepton number, flavor, precision EW tests)
   - Naturally light particles & generation of mass hierarchies in field theory
   - Strong CP problem and the axion

2. Supersymmetry

3. Grand Unification

4. Overview

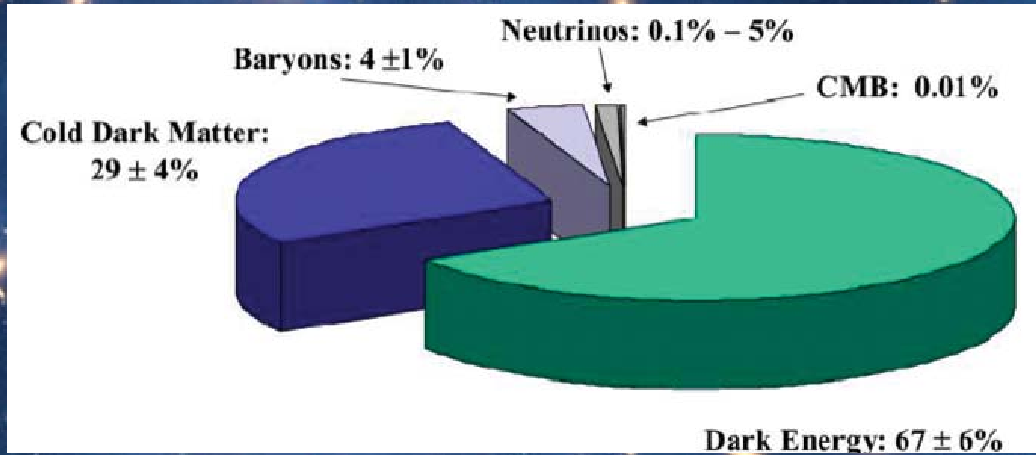
Standard Model: defined by gauge symmetry & multiplet content

gauge group $\quad SU(3) \times SU(2) \times U(1)_Y \times \text{gravity}$

bosons
$$\begin{cases} G_\mu^A \quad W_\mu^I \quad B_\mu \quad g_{\mu\nu} \\ H^\alpha \end{cases}$$

fermions $\quad q_L, \quad u_R, \quad d_R, \quad \ell_L, \quad e_R$

$$\begin{aligned} \mathcal{L} = \; & -\frac{1}{4g_3^2}G_{\mu\nu}^2 - \frac{1}{4g_2^2}W_{\mu\nu}^2 - \frac{1}{4g_Y^2}B_{\mu\nu}^2 + |D_\mu H|^2 + V(H) \\ & \bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{\ell}_L \not{D} \ell_L + \bar{e}_R \not{D} e_R \\ & + Y_u^{ij} \bar{q}_L^i H^\dagger u_R + Y_d^{ij} \bar{q}_L^i H d_R^j + Y_e^{ij} \bar{\ell}_L^i H e_R + \frac{\lambda^{ij}}{M}(H\ell^i)(H\ell^j) + \cdots \\ & + \sqrt{g} M_P^2 \left(R(g) - \lambda + \cdots \right) \end{aligned}$$

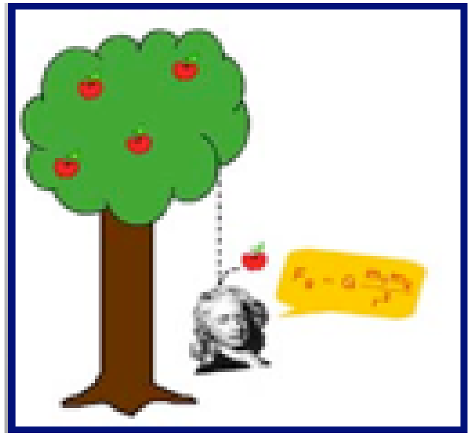


Dark Matter is not made of any known particle

What could it be ?

- ✦ WIMPS ~ 1 TeV
- ✦ sterile neutrini ~ 10 keV
- ✦ axions $\sim 10^{-2}$ meV
- ✦ Wimp-zillas $\gg 1$ TeV

Gravity

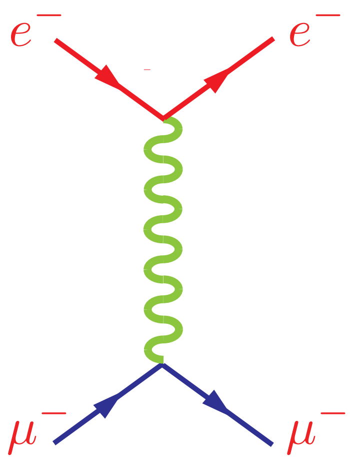


General Relativity at the quantum level only makes sense as an ***Effective*** Quantum Field Theory

There is an absolute upper bound on the energy scale at which General Relativity makes sense

Gravity couples to all other particles ⇒ absolute upper bound on energy scale up to which the SM can be valid

$\mathcal{A}_{\text{gravity}} =$



$= \frac{s}{M_P^2}\frac{1}{t}$

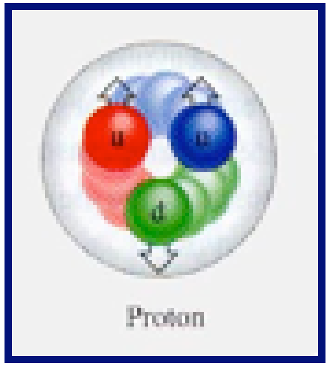
quantum effects untractable at $E \sim M_P \simeq 10^{19}$ GeV

M_P is huge and thus gravity is not necessarily
of urgent concern for the LHC

But previous argument only sets an upper bound
on relevant gravity scale. In the scenario of large extra dimensions
gravity becomes indeed strong at around a TeV

The fate of gravity is of crucial importance to develop
a theory of the very early universe

The other 3 forces...



Gauge Group → $G = SU(3) \times SU(2) \times U(1)_Y$

matter fermions →

$$\left\{ \begin{array}{lcl} q_L &=& (3\ ,\ 2\ ,\ 1/3) \\ u_R &=& (3\ ,\ 1\ ,\ 4/3) \\ d_R &=& (3\ ,\ 1\ ,\ -2/3) \\ l_L &=& (1\ ,\ 2\ ,\ -1) \\ e_R &=& (1\ ,\ 1\ ,\ -2) \end{array} \right.$$

- why this apparently bizarre spectrum ?
- why is hypercharge quantized ?

non-abelian group
Ex: SU(2) →

$$[T_3, T_\pm] = \pm T_\pm$$
$$[T_+, T_-] = 2T_3$$

⇒ $T_3|\psi\rangle = \frac{n}{2}|\psi\rangle$ (integer ↓ n)

abelian group: no quantization condition

Can one build new theory with non-abelian hypercharge ?

Strength of forces at E ≈ M_z

SU(3)	⟶	$g_3^2 \simeq 1.5$
SU(2)	⟶	$g_W^2 \simeq 0.42$
$U(1)_Y$	⟶	$g_Y^2 \simeq 0.13$

- they differ, but n o t w i l d l y

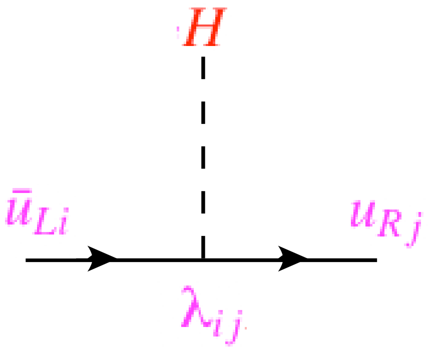
- strength of gravity at E ≈ M_z

$$G_N M_Z^2 \equiv \frac{M_Z^2}{M_P^2} \sim 10^{-34}$$

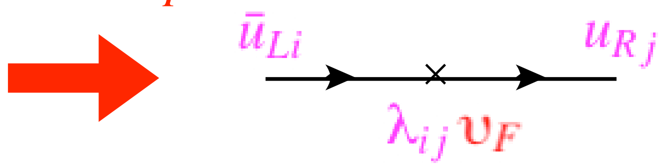
Matter

Yukawa couplings ⟷ Fermion masses

Ex: up quarks



$H \rightarrow \upsilon_F$



- mass eigenvalues: $m_i = \lambda_i \langle H \rangle \equiv \lambda_i \upsilon_F = \lambda_i \times (174\text{GeV})$

- fermion masses are inputs ... but the observed spectrum begs for an explanation

family \ type	ups	downs	leptons
3rd	$m_t = 175$	$m_b = 4.2$	$m_\tau = 1.7$
2nd	$m_c = 1.2$	$m_s = 0.1$	$m_\mu = 0.1$
1st	$m_u = 3 \times 10^{-3}$	$m_d = 5 \times 10^{-3}$	$m_e = 5 \times 10^{-4}$

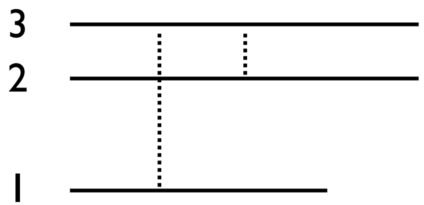
masses in GeV

ratios ⇒

$$ups: \quad \frac{m_c}{m_t} \sim \frac{1}{200} \qquad \frac{m_u}{m_c} \sim \frac{1}{400}$$

$$downs: \quad \frac{m_s}{m_b} \sim \frac{1}{40} \qquad \frac{m_d}{m_s} \sim \frac{1}{20}$$

- analogy with the spectrum of hydrogen lines before Bohr



Balmer fomula: $$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) R$$

n,m= integers

Rydberg const.

explained by Bohr

$$E_n = -\frac{2\pi^2 e^4 m_e}{h^2 n^2}$$

▲ what is the analogue of Bohr atom in the case of fermion masses ?

Neutrino masses

$$\Delta m^2_{atm} \simeq 2 \times 10^{-3}\,\mathrm{eV}^2 \qquad \Delta m^2_{sol} \simeq 0.8 \times 10^{-4}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{atm} = 0.9 - 1.0 \qquad \tan^2\theta_{sol} = 0.3 - 0.6$$

we were hoping to get illuminated on the structure of quarks and charged lepton spectrum, but we weren't

overall neutrino mass scale points to existence of new dynamics at a scale around 10^{14} GeV

the smallness of neutrino masses can be viewed as yet another success of SM

Is this simple picture correct? Are neutrini Majorana particles?

The fifth force

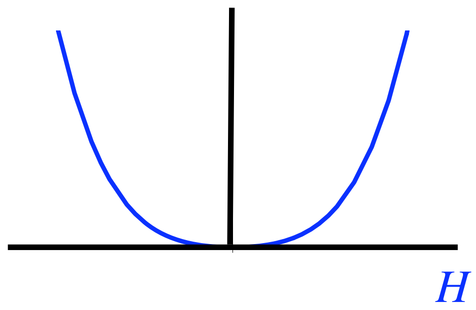
or

how weak interactions became weak

Fermi scale ⟷ Higgs field H vacuum expectation value

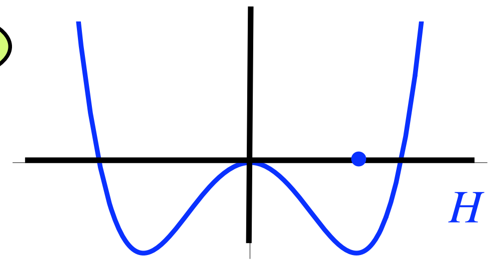
Higgs potential: $$V(H) \quad = \quad m^2 H^2 + \lambda H^4$$

$m^2 > 0$



$< H >= 0$

$m^2 < 0$



$$< H > \equiv \upsilon_F = \frac{|m^2|}{2\lambda}$$

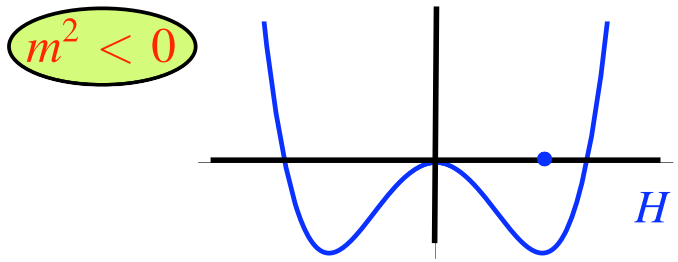
Fermi scale ⟷ Higgs field H vacuum expectation value

Higgs potential: $$V(H) = m^2 H^2 + \lambda H^4$$

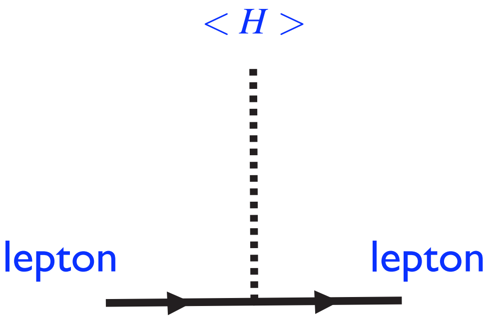
$m^2 < 0$ in our world:

$$< H > = \upsilon_F$$

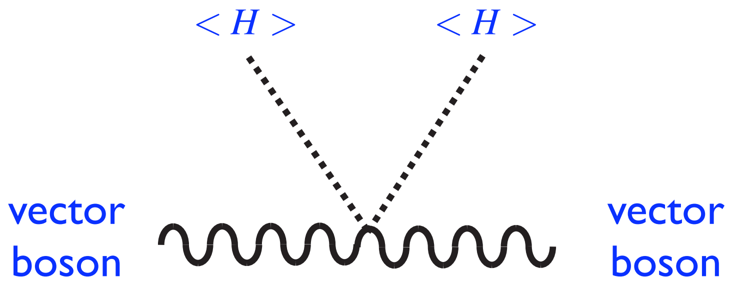
gives rise to all other masses



$$< H > \equiv \upsilon_F = \frac{|m^2|}{2\lambda}$$



$$m_\ell = \lambda_\ell < H >$$



$$m_W^2 = g^2 < H >^2$$

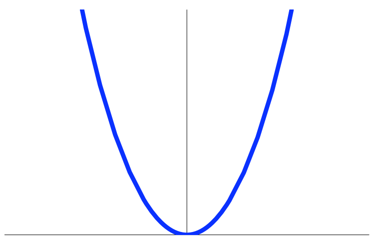
$$V(H) = m^2 H^2 + \lambda H^4$$

perturbativity $\lambda \lesssim 16\pi^2$ ⇒ $< H > = \sqrt{\frac{-m^2}{2\lambda}} \gtrsim O(\frac{|m|}{4\pi})$

- m^2 picks up all sorts of additive quantum corrections

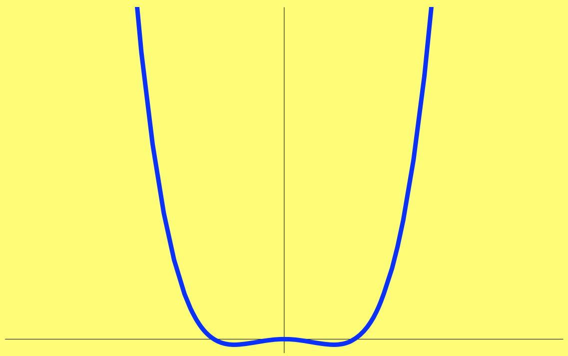
if SM valid up to Planck scale then it is natural to expect $|m^2| \sim O(M_{\text{Planck}}^2)$

either



$< H > = 0$

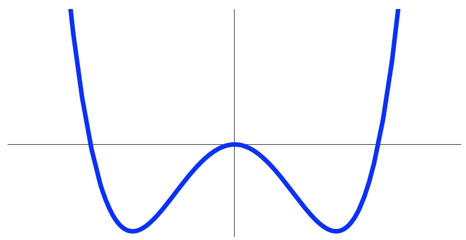
but we need



$< H > = \varepsilon M_{\text{Planck}}$

$\varepsilon \sim 10^{-17}$

or

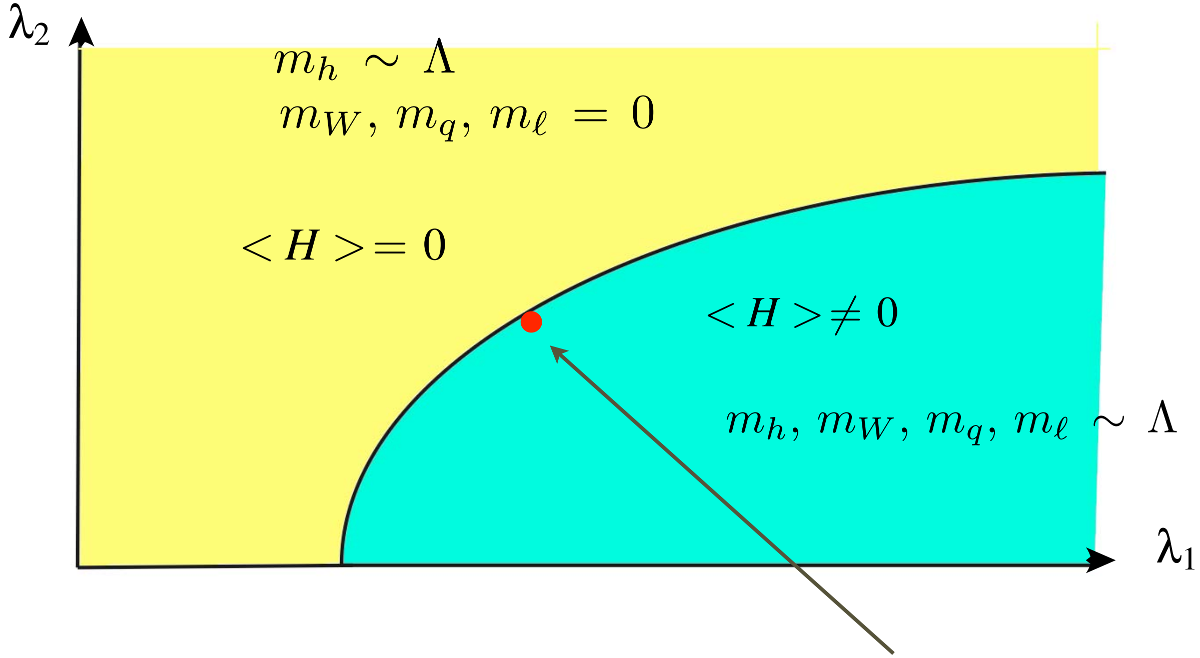


$< H > = O(M_{\text{Planck}})$

Graphical picture of hierarchy puzzle

$$\mathcal{L}_{fund} = \mathcal{L}(g_1, g_2, \Lambda, \ldots; H, W^I_\mu, q, \ell, \ldots)$$

phase diagram



SM lives extremely close to the critical line is

One way to phrase the hierarchy problem is more simply

Why $v_F \ll M_{Planck}$?

$$(G_F \gg G_N)$$

- In order to better appreciate this question, we must understand why $m_{proton} \ll M_{Planck}$ is not considered to be a problem

- As we shall see, the problem is in a sense deeper than stated above: bringing Planck scale down to TeV is not fully satisfactory

Not enough to generically ask ***why***

In order to infere ***where**** do we expect new physics to show up

We need to better understand ***what*** is the Standard Model

* *at what energy scale*

Effective field theory approach to particle physics

working at tree level first

Physical scales & couplings

Ex: most general Lagrangian for scalar field

$$\mathcal{L} = \partial_\mu\phi\partial^\mu\phi - m^2\phi^2 + \lambda_4\phi^4 + \frac{\lambda_6}{\Lambda^2}\phi^6 + \frac{\lambda_8}{\Lambda^4}\phi^8 + \cdots$$
$$+ \frac{\eta_4}{\Lambda^2}\phi^2\partial_\mu\phi\partial^\mu\phi + \frac{\eta_6}{\Lambda^4}\phi^4\partial_\mu\phi\partial^\mu\phi \cdots$$

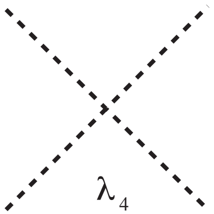
dimensions ➡

$$\begin{cases} [\mathcal{L}] = \dfrac{Energy}{(Length)^3} = E^4 \\ [\partial_\mu] = \dfrac{1}{Length} = E \end{cases}$$

$$[\phi] = E$$

$\lambda_i,\ \eta_i\ =$ dimensionless (assume $O(1)$)

$$\mathcal{A}(2 \to 2) =$$



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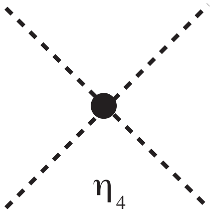
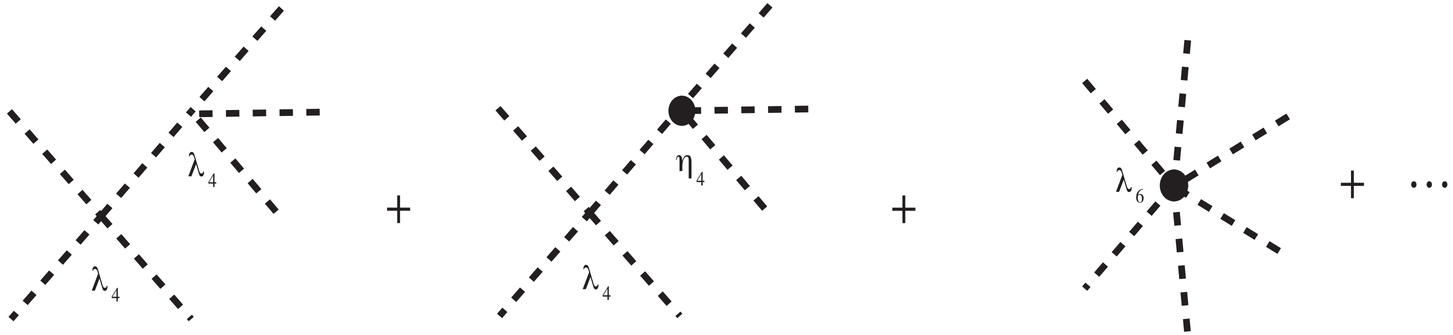


$$= \lambda_4 + \eta_4\frac{E^2}{\Lambda^2} \xrightarrow{E\to 0} \lambda_4$$

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi - m^2 \phi^2 + \lambda_4 \phi^4 + \frac{\lambda_6}{\Lambda^2}\phi^6 + \frac{\lambda_8}{\Lambda^4}\phi^8 + \cdots$$
$$+ \frac{\eta_4}{\Lambda^2}\phi^2 \partial_\mu \phi \partial^\mu \phi + \frac{\eta_6}{\Lambda^4}\phi^4 \partial_\mu \phi \partial^\mu \phi \cdots$$

$\mathcal{A}(2 \to 4) =$ 

$$\frac{1}{E^2}\left\{ \quad \lambda_4^2 \quad + \quad \lambda_4 \eta_4 \frac{E^2}{\Lambda^2} \quad + \quad \lambda_6 \frac{E^2}{\Lambda^2} \right.$$

$E \ll \Lambda$ only a finite number of terms in the lagrangian are important

the infinite set of couplings with negative mass dimensions is *irrelevant* coupling g with dimension $[g] = d$

$$\bar{g} \equiv gE^{-d}$$

dimensionless quantity controlling strength of interaction

weak coupling $\longleftrightarrow$ $\bar{g} \ll 1$

★ d > 0 : relevant at small E

- *Ex: can treat mass as perturbation at E>> m* $\left(\bar{m}^2 = \frac{m^2}{E^2}\right)$

★ d = 0 : relevant at all energies (marginal)

- *gauge and Yukawa couplings*

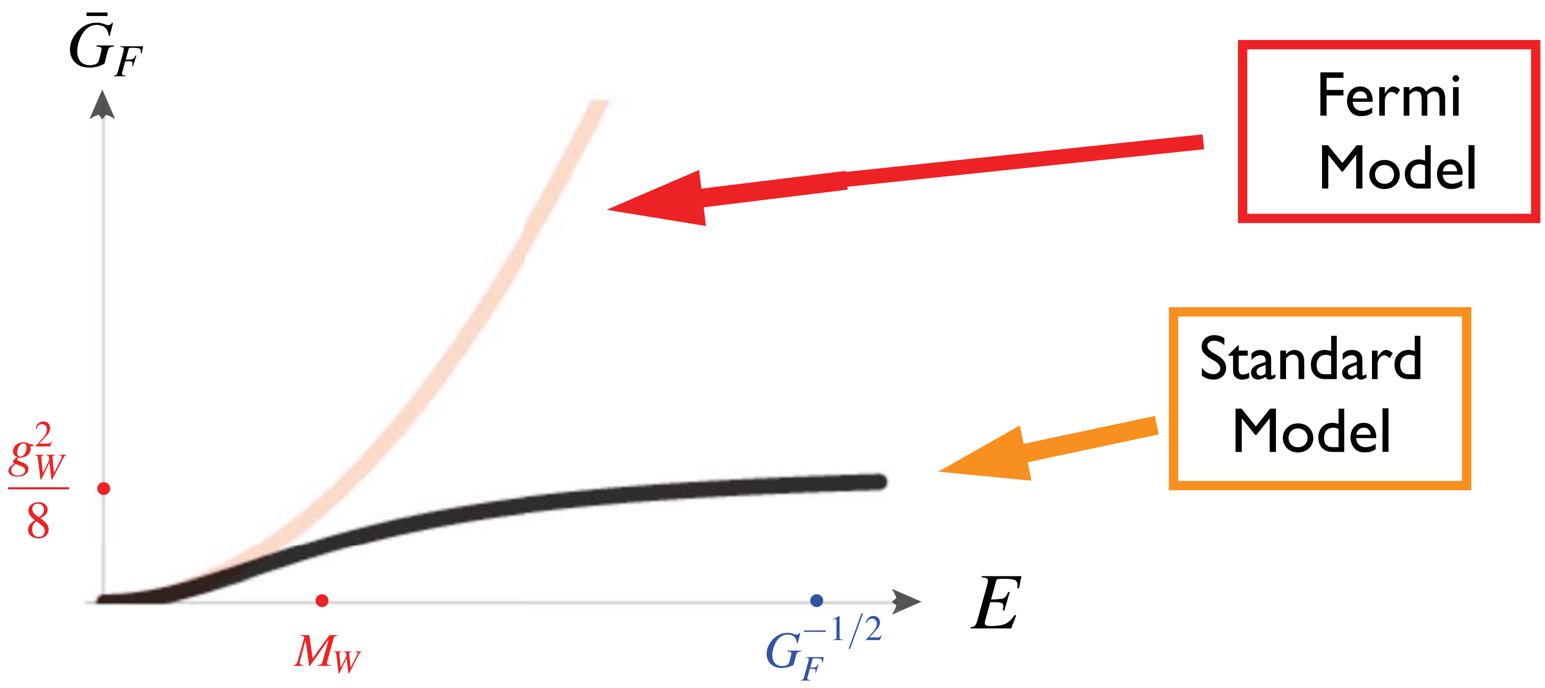
★ d < 0 : irrelevant al small E

- *perturbative expansion breaks down at high enough E*

Ex. : Fermi Lagrangian

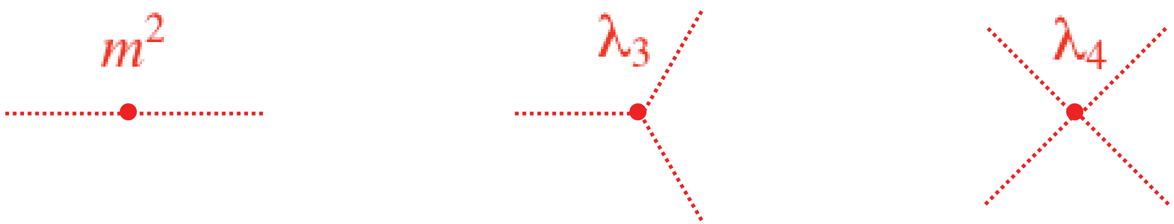
$$L_{Fermi} = G_F\left(\bar{p}\gamma_\mu n\right)\left(\bar{e}\gamma^\mu \nu\right)$$

$$\bar{G}_F \equiv G_F E^2$$



Imagine all couplings with $d_i < 0$ scale like inverse powers of a single scale Λ

dynamics at $E \ll \Lambda$ ⟷ couplings with $d_i \geq 0$



- $(m^2, \lambda_3, \lambda_4)$ fully describe an elementary (pointlike) particle
- $(\lambda_5, \lambda_6, \ldots)$ correspond to inner structure
- to probe structure, $E \approx \Lambda$ is needed ➡ wavelength $\approx \dfrac{1}{\Lambda}$

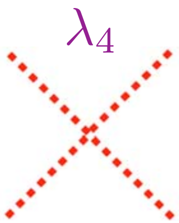
Now at the quantum level......

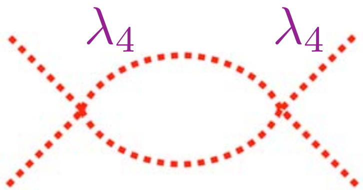
(a more physical picture of renormalizability)

Problem: internal momentum of loops is not fixed by external momentum

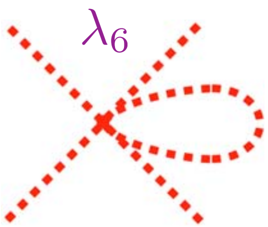
→ contributions enhanced by powers of cut-off

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{1}{4!}\lambda_4\phi^4 - \frac{1}{6!}\frac{\lambda_6}{\Lambda^2}\phi^6 - \frac{\lambda_8}{\Lambda^4}\phi^8 + \cdots$$

$\mathcal{A}(2 \to 2) =$ 

+ 

→ $$\lambda_4\left(1 + \frac{\lambda_4}{32\pi^2}\ln(-\frac{s}{\Lambda^2}) + \ldots\right)$$

+ 

→ $$\frac{1}{\Lambda^2}\frac{\lambda_6}{32\pi^2}\int_0^{\sim\Lambda^2}\frac{p^2dp^2}{p^2+m^2} \to \frac{\lambda_6}{32\pi^2}$$

does not vanish when $\Lambda \to \infty$

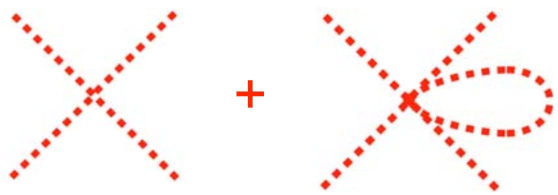
tree level $\frac{\lambda_6 E^2_{external}}{\Lambda^2}$ → small

loop level $\frac{\lambda_6 E^2_{virtual}}{\Lambda^2}$ → in principle $E_{virtual} \sim \Lambda$

not small

❖ Apparently operators of arbitrarily high dimension matter!

❖ But notice that UV enhanced contribution is ***local***



$$\lambda'_4 \equiv \lambda_4 + \frac{\lambda_6}{32\pi^2}$$

UV enhanced contribution is just a renormalization of quartic term

Result generalizes to all orders

Power divergent effects can be reabsorbed by renormalization of coefficient of lower dimension operators

must exist a scheme where these effects are absent ab initio

Dimensional Regularization

$$\mathcal{L}_{eff} = \mathcal{L}(g,\lambda)^{d\leq 4} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \dots$$

at $E \ll \Lambda$, neglecting effects $(\frac{E}{\Lambda})^{\#}$, $\mathcal{L}_{eff}$ is equivalent to

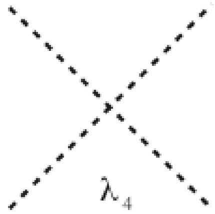
$$\mathcal{L}'_{eff} = \mathcal{L}(g',\lambda')^{d\leq 4} + 0$$

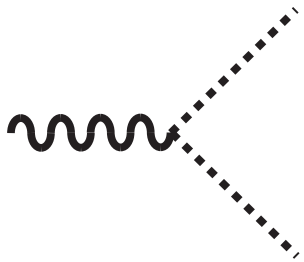
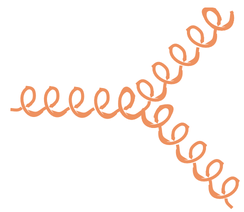
virtual effects of $\mathcal{L}^{d=5}, \mathcal{L}^{d=6}, \dots$ accounted just by *renormalization*

$$g,\ \lambda \longrightarrow g',\ \lambda'$$

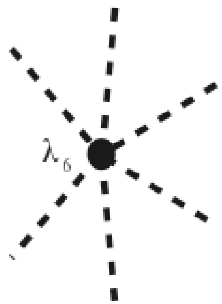
$E \ll \Lambda$ physics is described by *renormalizable* Lagrangian $\mathcal{L}^{d\leq 4}$

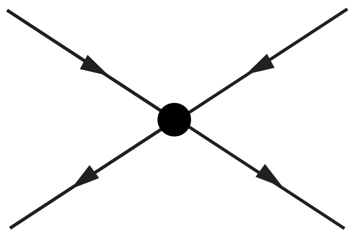
the ‘renormalizable’ terms (dimension 4 or less)
fully describe elementary (pointlike) particles



‘non-renormalizable’ terms (dimension 5 or more)
describe inner structure of particles



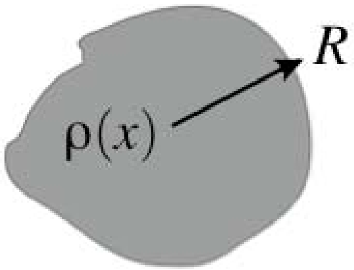


$$E \sim \Lambda$$

needed to directly probe structure

wawelengths $\sim \dfrac{1}{\Lambda}$

▲ Analogy with multipole expansion in electrodynamics



$\rho(x)$ = charge density

$\Phi(x)$ = electric potential

$$E_{\text{int}} = \int \Phi(x)\,\rho(x)\,d^3x \quad = \quad \Phi(0)\int \rho(x) + \partial_i\Phi(0)\int x^i\rho(x) + \frac{1}{2}\partial_i\partial_j\Phi(0)\int x^i x^j\rho(x) + \ldots$$

$$= \quad \Phi(0)\,Q_0 \quad + \quad \partial_i\Phi(0)\,Q_1^i \quad + \quad \tfrac{1}{2}\partial_i\partial_j\Phi(0)\,Q_2^{ij} \quad + \ldots$$

$$\sim Q \qquad\qquad \sim QR \qquad\qquad \sim QR^2$$

At wavelengths > R light emission is dominated by dipole term

Accidental symmetries

$$E \ll \Lambda$$

dynamics determined by a ***few*** `renormalizable' couplings

⬇

extra (accidental) symmetries

Example: parity in QED is respected by `renormalizable' interactions

$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\gamma^\mu D_\mu\psi + \bar{\psi}(m_1 + i\gamma_5 m_2)\psi + \frac{a}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$(m_1 + i\gamma_5 m_2) \quad \rightarrow \quad m = \sqrt{m_1^2 + m_2^2}$ by chiral rotation $\psi \quad \longrightarrow \quad e^{i\beta\gamma_5}\psi$

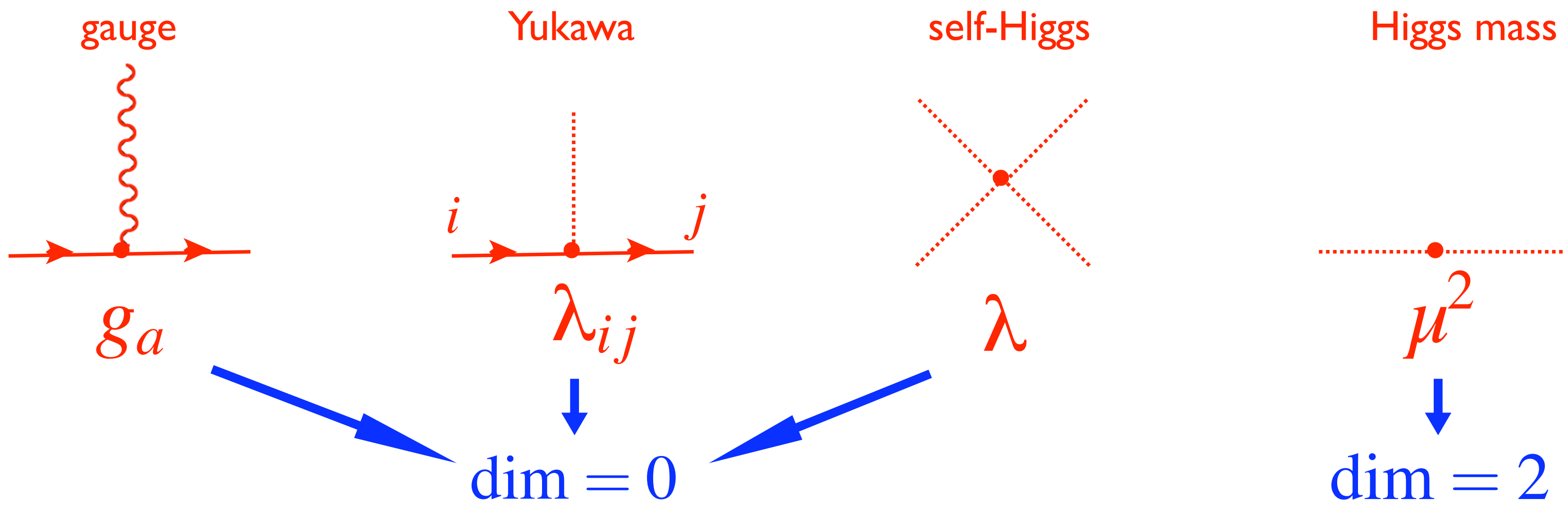
$F_{\mu\nu}\tilde{F}^{\mu\nu}$ = total derivative

dim 6 operator violates parity

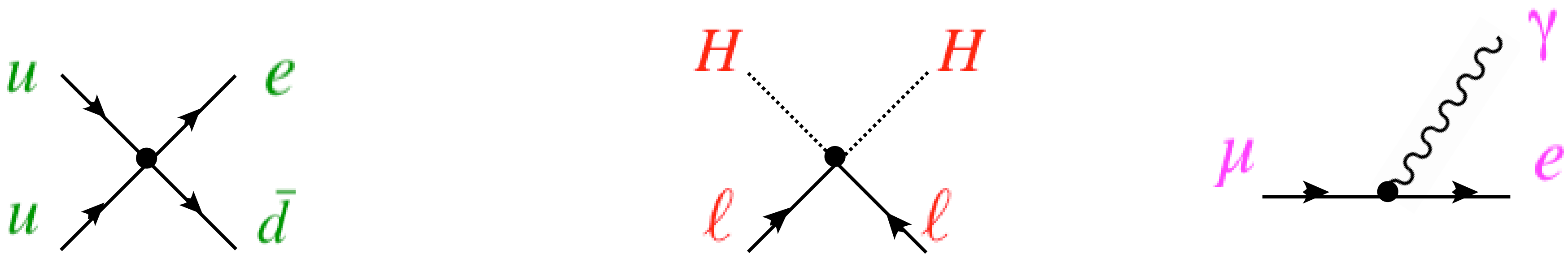
$$O_{\not{P}} = \frac{1}{\Lambda^2}(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma_\mu\gamma_5\psi)$$

generated in SM by Z-exchange $\frac{1}{\Lambda^2} \sim G_F = \frac{1}{v^2}$

Standard Model interactions



★ By allowing dim < 0 we would also have:



$$\frac{1}{\Lambda_{\not{B}}^2}\left(u_\alpha C\gamma_\mu u_\beta\right)\left(eC\gamma^\mu d_\delta\right)\varepsilon^{\alpha\beta\gamma}$$

Baryon number violation

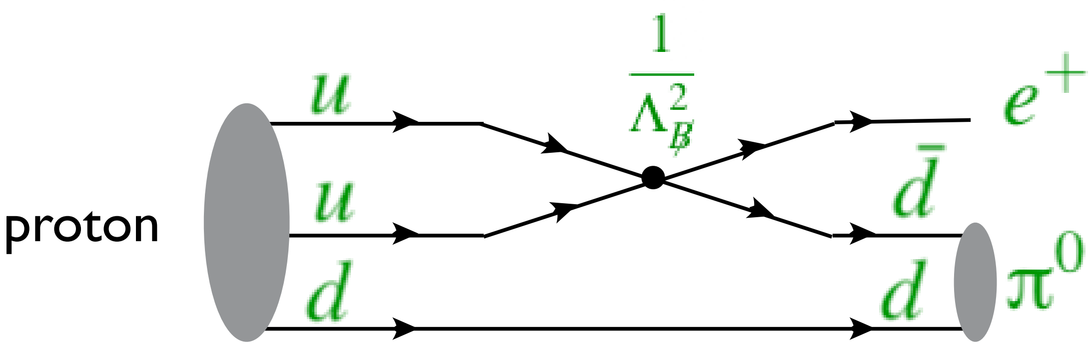
$$\frac{1}{\Lambda_{\not{L}}}\left(\ell^a C\,\ell^b\right) H_a H_b$$

Lepton number violation

$$\frac{m_\mu}{\Lambda_{\not{F}}^2}\left(\bar{e}\gamma_\mu\gamma_\nu\,\mu\right) F^{\mu\nu}$$

Flavor violation

1) B+L violation: proton decay



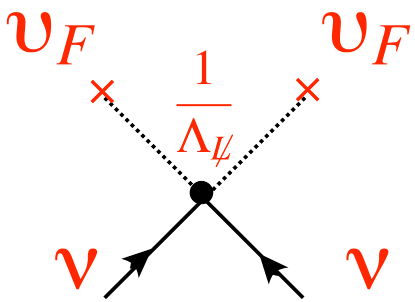
$$p \to e^+ \pi^0$$

Superkamiokande: $\tau_p > 8.2 \times 10^{33}$ years

$$\Lambda_{\not B} \geq 10^{15}\,\mathrm{G}eV$$

2) L violation: neutrino masses

$H \to \upsilon_F$



$$m_\nu \sim \frac{\upsilon_F^2}{\Lambda_{\not L}}$$

observed neutrino oscillations: $m_\nu \sim 0.1\mathrm{e}V$ $\Lambda_{\not L} \sim 10^{14}\,\mathrm{G}eV$

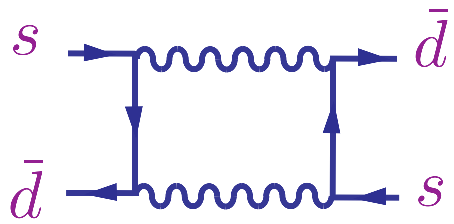
3) Flavor violation

$$\mathcal{L} = \bar{q}_L \hat{Y}_d H^\dagger d_R + \bar{q}_L V_{CKM} \hat{Y}_u H u_R + \bar{\ell} \hat{Y}_\ell H^\dagger e_R$$

$$\hat{Y}_d = \begin{pmatrix} \lambda_d & & \\ & \lambda_s & \\ & & \lambda_b \end{pmatrix} \qquad \hat{Y}_u = \begin{pmatrix} \lambda_u & & \\ & \lambda_c & \\ & & \lambda_t \end{pmatrix} \qquad \hat{Y}_\ell = \begin{pmatrix} \lambda_e & & \\ & \lambda_\mu & \\ & & \lambda_\tau \end{pmatrix}$$

- absence of ν_R ⇒ $L_e,\ L_\mu,\ L_\tau$ are conserved
- very special quark Flavor violation all due to V_{CKM} ⇒ Glashow-Iliopoulos-Maiani (GIM) suppression mechanism

$K - \bar{K}$ mixing



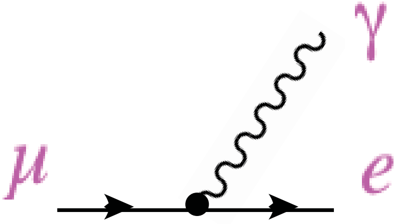
$$\sim \frac{G_F \alpha_W}{4\pi} (\sin\theta_C \cos\theta_C)^2 \left(\frac{m_c}{M_W}\right)^2 \left[\bar{d}_L \gamma^\mu s_L\right]^2$$

non-renormalizable contribution $\frac{1}{\Lambda_{\not{F}}^2}\left[\bar{d}_L \gamma^\mu s_L\right]^2$

$$\left.\frac{\Delta m_K}{m_K}\right|_{\exp} \longrightarrow \Lambda_{\not{F}} > 10^6 \mathrm{GeV}$$

lepton flavor violation

$$\frac{m_\mu}{\Lambda_{\not F}^2} \left(\bar e\, \gamma_\mu \gamma_\nu\, \mu\right) F^{\mu\nu}$$



$\mathrm{Br}(\mu \to e\gamma) < 10^{-11}$ → $\Lambda_{\not F} > 10^6\,\mathrm{GeV}$

- We are tempted to conclude that the scale of "compositeness" Λ in the S.M. is extremely high

... but can we ?

The hierarchy problem

$$\mathcal{L}_{SM} = \mathcal{L}^{d=2} + \mathcal{L}(g,\lambda)^{d=4} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \ldots$$

$$\Downarrow$$

$$\mu^2 H^\dagger H$$

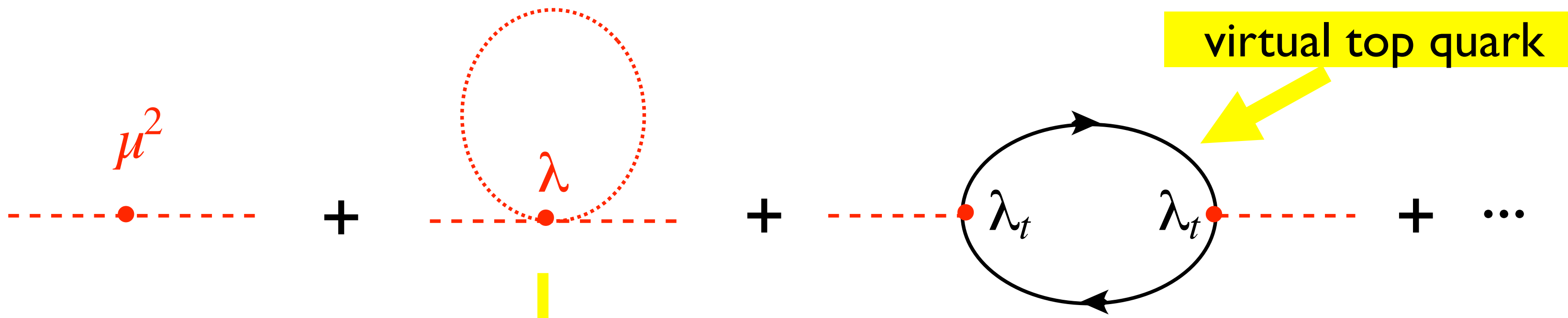
▲ is it *reasonable* to expect $|\mu^2| \ll \Lambda^2$?

one way to try and answer is to assume a hierarchy exists at tree level:

$$|\mu^2_{\rm tree}| \ll \Lambda^2$$

and estimate quantum effects to see if they mantain this hierarchy

$\mu^2_{\text{eff}} =$



$$\sim \; + \frac{3\lambda}{(2\pi)^4} \int \frac{d^4p}{p^2} \; - \frac{6\lambda_t^2}{(2\pi)^4} \int \frac{d^4p}{p^2}$$

$$+ \frac{3\lambda}{16\pi^2} \Lambda^2 \; - \frac{3\lambda_t^2}{8\pi^2} \Lambda^2$$

cut-off integral at p ~ Λ

μ^2_{eff} does not like to stay small when $\Lambda \to \infty$!!

quantum correction to the vacuum energy: top quark contribution

$$\Delta E = -\frac{1}{2}\sum_{i,k}\omega(k) = -\frac{12}{2}\int\sqrt{k^2+m_t^2}\,\frac{d^3k}{(2\pi)^3} =$$

$$= -6\int\left\{k+\frac{m_t^2}{2k}+\cdots\right\}\frac{d^3k}{(2\pi)^3}$$

$$m_t^2 = \lambda_t^2 H^\dagger H$$

$$= \quad -\frac{3}{2\pi^2}\int k^2 dk^2 \qquad -H^\dagger H\times\left(\frac{3}{4\pi^2}\lambda_t^2\int dk^2\right)$$

Λ^4 contribution
to vacuum energy !!

$\Delta\mu^2$

$$\mu_{eff}^2 = \mu^2 + c\Lambda^2$$

large Λ ➡ μ^2 must be tuned to make μ_{eff}^2 small

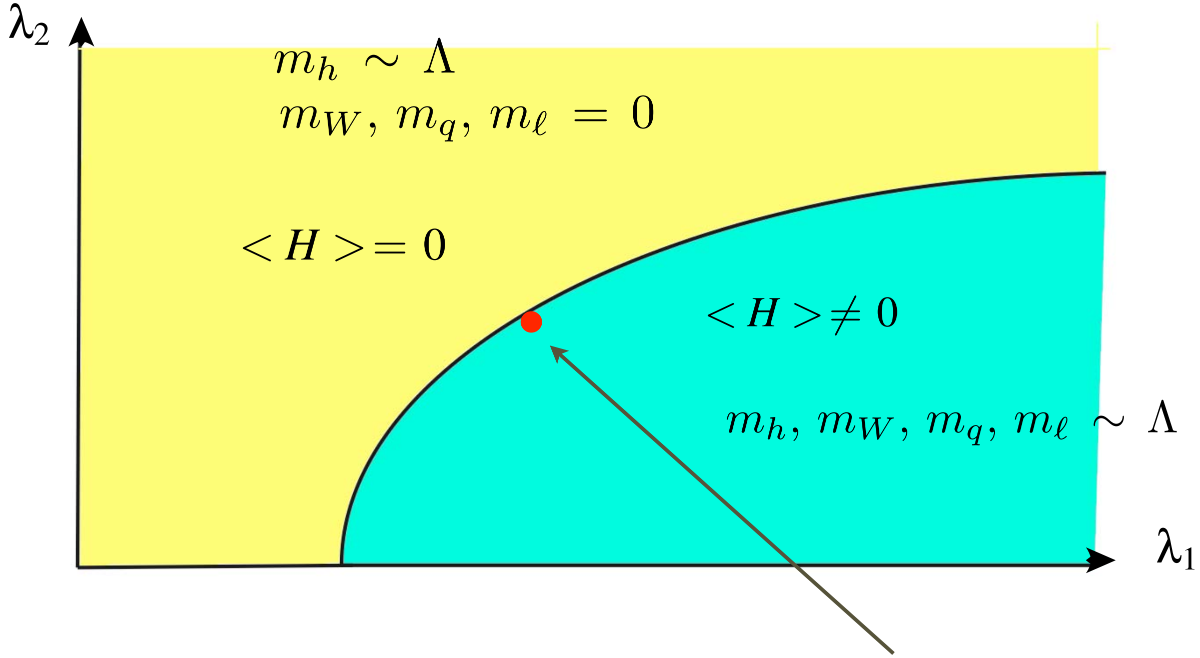
fine-tuning: $$\frac{\mu^2 + c\Lambda^2}{\Lambda^2} \sim \frac{\upsilon_F^2}{\Lambda^2} \stackrel{\Lambda=10^{15}\mathrm{GeV}}{=} 10^{-30}$$

This is the hierarchy problem

Graphical picture of hierarchy puzzle

$$\mathcal{L}_{fund} = \mathcal{L}(g_1, g_2, \Lambda, \ldots; H, W^I_\mu, q, \ell, \ldots)$$

phase diagram



SM lives extremely close to the critical line is

$p \to e^+ \pi^0$
$\mu \to e\gamma$

$\Rightarrow \quad \sim \quad \dfrac{1}{\Lambda^n} \qquad n > 0$

effective
Higgs mass

$\Rightarrow \quad \sim \quad \mu^2 \quad + \quad c\,\Lambda^2$

▲ 2 possibilities

I. $\Lambda \gg \upsilon_F$

- B, L & Flavor conservation naturally follow
- separation of mass scales mysterious

II. S.M. is replaced by more fundamental theory at $E \gtrsim \upsilon_F$

In New Theory

- no Λ^2 corrections to μ^2
- must preserve as much as possible B, L, Flavor...

The possibility of having $\Lambda \sim \upsilon_F$

makes LHC very exciting