Title: Standard Model Lecture

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Collection: Standard Model 2023/24

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Resulting contribution to $\Pi_{hh}(p^2)$: $\Delta m_h^2 \propto \frac{3}{16\pi^2}\left(m_h^2 + m_Z^2 + 2m_W^2\right.$

shifts higgs mass Δm_h^2

<u>Before</u> exp indication $m_h = 125\ GeV$

Usually with hard cut off $\int^{\Lambda} \frac{d^4k}{(2\pi)^4}$ so ($

$\left(m_h^2 + m_Z^2 + 2m_W^2 - 4m_\psi^2\right)$ 'Veltman condition'

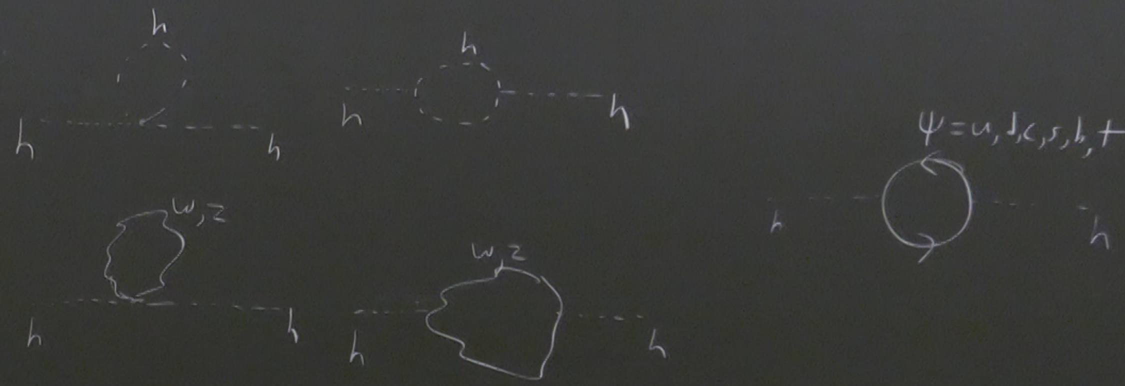
$\psi = u, d, c, s, b, t$

on $m_h = 125\,\mathrm{GeV}$ speculation $m_h = 314\,\mathrm{GeV}$ could lead to $\delta m_h^2 = 0$

cut off $\int^\Lambda \frac{d^4k}{(2\pi)^4}$ so $\left(\delta m_h^2\right)^\Lambda = \frac{\Lambda^2}{v^2}\frac{3}{16\pi^2}\left(m_h^2 + m_Z^2 + 2m_W^2 - 4m_\psi^2\right)$

Quadratic divergences & Hierarchy Problem of m_H

In the S.M. the following diagrams exist



Resulting contribution to $\Pi_{hh}(p^2)$: $\delta m_h^2 \propto \frac{3}{16\pi^2}\left(m_h^2 + m_Z^2 + 2m_W^2 - 4m_\psi^2\right)$

Define $\Delta B = \frac{1}{3}\left(N_Q + N_{u^+} + N_{d^+}\right) - \frac{1}{3}\left(N_{Q^+} + N_u + N_d\right)$

$$\Delta L = N_L + N_{e^+} + N_{\nu^+} - \left(N_{L^+} + N_e + N_\nu\right)$$

For an operator of mass dimension d:

$$\frac{(\Delta B - \Delta L)}{2} \in \mathbb{Z} \begin{cases} \text{even} \Leftrightarrow d \text{ even} \\ \text{odd} \Leftrightarrow d \text{ odd} \end{cases}$$

Weinberg

$\Delta B - \Delta L =$

odd mass

$N_u + N_d)$

Weinberg op $|\Delta L| = 1 \rightarrow d$ odd

$N_\nu)$

$\Delta B - \Delta L = 0 \rightarrow$ even mass dim ops

$d = 6,\ d = 8, \ldots$

$\mathbb{Z}$ $\begin{cases} \text{even} \leftrightarrow d \text{ even} \\ \text{odd} \leftrightarrow d \text{ odd} \end{cases}$

odd mass dimension ops ΔB or ΔL is non zero

Last operator forms to consider up to $d=4$

$$\mathcal{L}_{SM} - \frac{1}{4} B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{4} W_I^{\mu\nu}\tilde{W}^I_{\mu\nu} - \frac{1}{4} G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A$$

In dim reg - subtract $\frac{1}{\varepsilon}$ pole still the finite δm_h^2 after $\frac{1}{\varepsilon}$ subtracti

Regulator independent conclusion associated with physical mass shift. (

Note $\delta m_h^2 \propto \frac{3}{16\pi^2} \Big(\underbrace{m_h^2 + m_Z^2 + 2m_W^2}_{\text{bosons}} \underbrace{-4m_t^2}_{\text{fermions}} \Big)$ $\mathrm{Tr}[\bar{\psi}\psi\bar{\psi}$

subtraction

shift. (Λ proxy for sim.o m)

$[\bar{\psi}\psi\bar{\psi}\psi]$ gives $\underline{-1}$ fermi statistics

If UV physics had $m_{Boson} = m_{fermion}$

and same # degrees of freedom and

same couplings $\rightarrow$ such contributions

<u>cancel</u> $\rightarrow$ SUSY

Lepton & Baryon number violation in Ops

(1604,05726)

$\mathcal{L}_{SM} + \frac{C_{mn}}{\Lambda}(\bar{\ell}^c_m \tilde{H}^*)(\tilde{H}^+ \ell$

Global Lepton

$q \to e^{i\alpha_B} q$

$L \to e^{i\alpha_L} L$

Baryon number preserved at tree level

$D=2$

$D=4$

violates lepton n

$\underline{D=5}$

$$\mathcal{L}_{SM} + \left[\frac{C_{mn}}{\Lambda}(\bar{\ell}^c_m \tilde{H}^*)(\tilde{H}^+ \ell_n) + h.c.\right] + \frac{\mathcal{L}^6}{\Lambda^2} + \frac{\mathcal{L}^7}{\Lambda^3} + \cdots$$

D=2

number D=4

d at

level

violates lepton number

D=5

D=6

Can violate

Baryon of

lepton number

Lepton & Baryon number violation in Ops

(1604.05726) '2016'

$\mathcal{L}_{SM} + \frac{C_{mn}}{\Lambda} (\bar{\ell}^c_m \tilde{H}^*$

Global Lepton $\qquad$ $D=2$

$q \to e^{i\alpha_B} q$ $\qquad$ Baryon number $D=4$

$L \to e^{i\alpha_L} L$ $\qquad$ preserved at tree level

↑ violates lep

$D=5$

Define $\Delta B = \frac{1}{3}\left(N_Q + N_{u^+} + N_{d^+}\right) - \frac{1}{3}\left(N_{Q^+} + N_u + N_d\right)$

$$\Delta L = N_L + N_{e^+} + N_{\nu^+} - \left(N_{L^+} + N_e + N_\nu\right)$$

For an operator of mass dimension d:

$$\frac{(\Delta B - \Delta L)}{2} \in \mathbb{Z} \begin{cases} \text{even} \Leftrightarrow d \text{ even} \\ \text{odd} \Leftrightarrow d \text{ odd} \end{cases}$$

hypercharge conservation

+ Lorentz invariance

$\frac{1}{3}\left(N_{Q^+} + N_u + N_d \right)$

$_{L^+} + N_e + N_\nu \big)$

$\frac{\ldots \Delta L)}{2} \in \mathbb{Z}$ $\begin{cases} \text{even} \leftrightarrow d \text{ even} \\ \text{odd} \leftrightarrow d \text{ odd} \end{cases}$

hypercharge conservation

+ Lorentz invariance

Weinberg op $|\Delta L| = 2 \to d$ odd

$\Delta B - \Delta L = 0 \Rightarrow$ even mass dim ops

$d=6, d=8, \ldots$

odd mass dimension ops ΔB or ΔL is non zero

Last operator forms to consider up to $d=4$

$$\mathcal{L}_{SM} - \frac{1}{4} B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{4} W^{\mu\nu}_{I}\tilde{W}^{I}_{\mu\nu} - \frac{1}{4} G^{A}_{\mu\nu}\tilde{G}^{\mu\nu}_{A}$$

...erator forms to consider up to $d=4$

$$\mathcal{L}_{SM} - \frac{1}{4} B_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} W_I^{\mu\nu} \tilde{W}^I_{\mu\nu} - \frac{1}{4} G^A_{\mu\nu} \tilde{G}_A^{\mu\nu}$$

$$\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$$

...st operator forms to consider up to $d=4$

$$\mathcal{L}_{SM} \supset \underbrace{-\frac{1}{4} B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{4} W_I^{\mu\nu}\tilde{W}^I_{\mu\nu} - \frac{1}{4} G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A}_{\text{CP violating}}$$

$\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta} F$...

$F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\,E$...

E, B CP

CP

s to consider up to $d=4$

$$\underbrace{B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{4} W_I^{\mu\nu}\tilde{W}^I_{\mu\nu} - \frac{1}{4} G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A}_{\text{CP violating}}$$

$$\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$$

$$F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\vec{E}\cdot\vec{B}$$

E, B CP $E \to E$

CP $B \to -B$

$$F_{\mu\nu}\tilde{F}^{\mu\nu} = \partial_\mu\left[2\,\varepsilon^{\mu\nu\alpha\beta} A_\nu \partial_\alpha A_\beta \right]$$

$\tilde{F}$: dual field strength

$\varepsilon^{\mu\nu\alpha\beta} A_\nu \partial_\alpha A_\beta \equiv K^\mu$

"surface term" $\int d^4x$

$B_{\mu\nu}\tilde{B}^{\mu\nu}$ abelian

related total momentum conservation

$W_{\mu\nu}^I \tilde{W}_{\mu\nu}^I \qquad G_{\mu\nu}^A \tilde{G}_{\mu\nu}^A$

Global symmetries

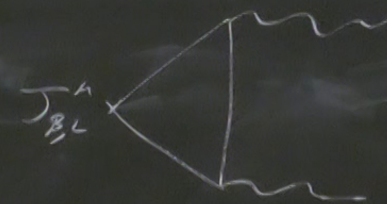
$q \to e^{i\alpha_B} q \qquad J_B^\mu = \frac{1}{3}\left(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d + \cdots\right)$

$\ell \to e^{i\alpha_L} L \qquad J_L^\mu = \bar{e}\gamma^\mu e + \bar{\nu}_e \gamma^\mu \nu_e + \cdots$

$\partial_\mu J_B^\mu = 0$

$\partial_\mu J_L^\mu = 0$

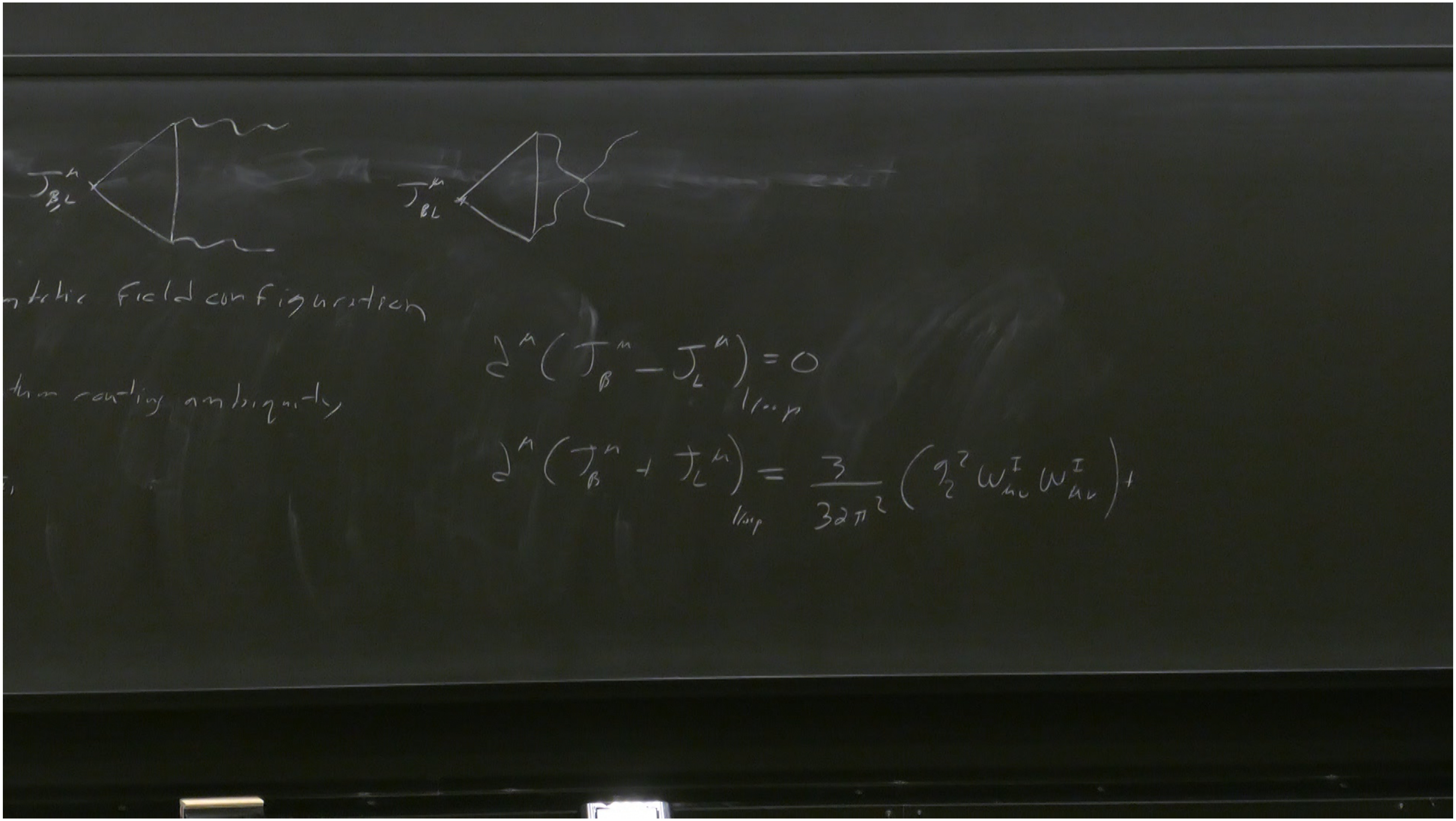
Anomaly diagrams



sensitivity to asymptotic field configuration

$\Rightarrow$ momentum routing ambiguity

$\int \frac{d^4k}{(2\pi)^4}$


J^{μ}_{BL}
J^{μ}_{BL}
field configuration
counting ambiguity
$\partial^{\mu}(J_B^{\mu} - J_L^{\mu})_{1\,loop} = 0$
$\partial^{\mu}(J_B^{\mu} + J_L^{\mu})_{1\,loop} = \frac{3}{32\pi^2}\left(g_2^2 W^I_{\mu\nu} W^I_{\mu\nu}\right) +$

exist

Baryon # Violation   proton decay   at low temperatures

t'hooft Quantum tunneling $\rightarrow e^{-8\pi^2/g_2^2} \sim 10^{-160}$

'instanton'

very consistent with $\tau_{proton} > 10^{33}$ years

$= 0$

loop

$= \frac{3}{32\pi^2}\left(g_2^2 W^I_{\mu\nu}\tilde{W}^I_{\mu\nu}\right) +$