Title: Standard Model Lecture

Speakers: Michael Trott

Collection: Standard Model 2023/24

Date: February 06, 2024 - 9:00 AM

URL: https://pirsa.org/24020023

Recall: In SM we neglect

$$B_{\mu\nu}\tilde{B}^{\mu\nu} + W^I_{\mu\nu}\tilde{W}_I^{\mu\nu}$$

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

$\partial_\mu J^\mu_B$

$\partial_\mu J^\mu_L$

$J^\mu_B = \bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d + \cdots$

trivial asymptotic field configurations

non-abelian but B-L transformations allows neglect

What about $\cancel{G^A_{\mu\nu}\tilde{G}_A^{\mu\nu}}$

Axial anomaly

vector $\bar{\Psi}\gamma_\mu\Psi$

axial $\bar{\Psi}\gamma_\mu\gamma_5\Psi$

recall massless

Define $q = \begin{pmatrix} u \\ s \\ d \end{pmatrix}$

nt about $\underline{G^A_{\mu\nu}\tilde{G}_A^{\mu\nu}}$ and QCD?

l anomaly

recall massless quark limit of QCD χ_{PT}

$\bar{\Psi}\gamma_\mu\Psi$

$\bar{\Psi}\gamma_\mu\gamma_5\Psi$

Define $q = \begin{pmatrix} u \\ s \\ d \end{pmatrix}$, $\mathcal{L}_{QCD} \to \frac{f^2}{8} Tr(\partial_\mu \Sigma^\dagger \partial_\mu \Sigma) + V' Tr[m_q^\dagger \Sigma + m_q \Sigma^\dagger]$

$\Sigma \sim \langle q \bar{q} \rangle$ condensate

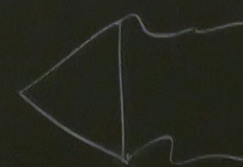
$$\mathcal{L}_{QCD} = \bar{q}\, i\not{\partial}\, q \rightarrow q'^{\dagger} e^{i\theta\gamma_5\gamma_0}\, i\not{\partial}\, e^{-i\theta\gamma_5} q'$$

$$\rightarrow \bar{q}'\, i\not{\partial}\, q + q'^{\dagger}\, i\theta\, \gamma_5\gamma_0\, i\not{\partial}\, q' + \bar{q}'\, i\not{\partial} \ldots$$

$$q' \rightarrow e^{-i\theta\gamma_5} q$$

axial symmetry → preserved at tree level $m_q \rightarrow 0$

$$[\gamma_5, \gamma_m] = 0$$

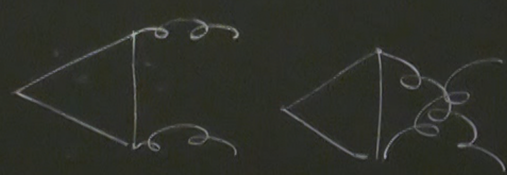


anomaly diagrams

check if loops also

$U(1)_{axial}$ symmetry

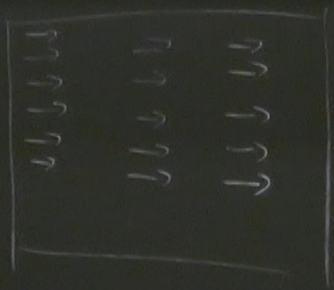
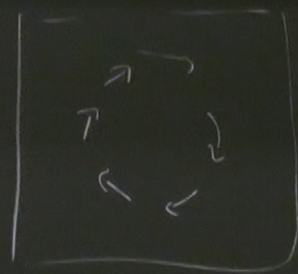
Define $T^{ab}_{\mu\alpha\beta}(k,q) = i\int d^4x\, d^4y\, e^{ik\cdot x} e^{iq\cdot y} \langle 0 | T\, J_{5\mu}(x)\, J^a_\alpha(y)\, J^b_\beta(z) | 0 \rangle$



$\int \frac{d^4k}{(2\pi)^4} \frac{\not k}{k^2} \frac{\not k}{k^2} \frac{\not k}{k^2}$

$\partial^\alpha J_\alpha \overset{?}{=} 0$ vector $\partial^\alpha J_\mu = q^\alpha T^{ab}_{\mu\alpha\beta}(k$

axial $\partial^\mu J_{5\mu} \Rightarrow k^\mu T^{ab}_{\mu\alpha\beta}(k,$

$$n = \frac{c\, g_s^2}{24\pi^2} \int d^3x \; Tr\left[\vec{A}_a(x)\, \vec{A}_b(x)\, \vec{A}_c(x) \right] \varepsilon^{abc}$$

$$\frac{g^2}{32\pi^2} \int d^4x \; G^A_{\mu\nu} \tilde{G}^{\mu\nu}_A = \frac{g^2}{32\pi^2} \int d^4x \; \partial_\mu K^\mu$$

$$K^\mu = \varepsilon^{\mu\nu\lambda\sigma} \left[A^a_\nu G^a_{\lambda\sigma} + \frac{1}{3} g_s f_{abc} A^a_\mu A^b_\lambda A^c_\sigma \right]$$

$$n = \frac{i g_s^2}{24\pi^2}\int d^3x\, \mathrm{Tr}\left[\vec{A}_a(x)\,\vec{A}_b(x)\,\vec{A}_c(x)\right]\varepsilon^{abc}$$

$$\frac{g^2}{32\pi^2}\int d^4x\, G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A = \frac{g^2}{32\pi^2}\int d^4x\, \partial_\mu K^\mu = \frac{g_s^2}{32\pi^2}\int d^3x\, K^0\Big|_{t=-\infty}^{t=\infty}$$

$$K^\mu = \varepsilon^{\mu\nu\lambda\sigma}\left[A^a_\nu G^a_{\lambda\sigma} + \frac{1}{3} g_s f_{abc} A^a_\nu A^b_\lambda A^c_\sigma\right]$$

$$= \frac{g_s^2}{32\pi^2}\int d^3x\, \varepsilon^{abc}\,\mathrm{Tr}\left[\vec{A}_a(x)\,\vec{A}_b(x)\,\vec{A}_c(x)\right]$$

$x)]\,\varepsilon^{abc}$

winding number

$$\partial_\mu K^\mu \quad = \frac{g_2^2}{32\pi^2}\int d^3x \; K^0 \Big|_{t=-\infty}^{t=\infty}$$

$$= \frac{g_2^2}{32\pi^2}\int d^3x \; \varepsilon^{abc}\, Tr\left[\vec{A}_a(x)\,\vec{A}_b(x)\,\vec{A}_c(x)\right]$$

Gauge invariant vacuum

$$|\theta\rangle = \sum_n e^{-in\theta}|n\rangle$$

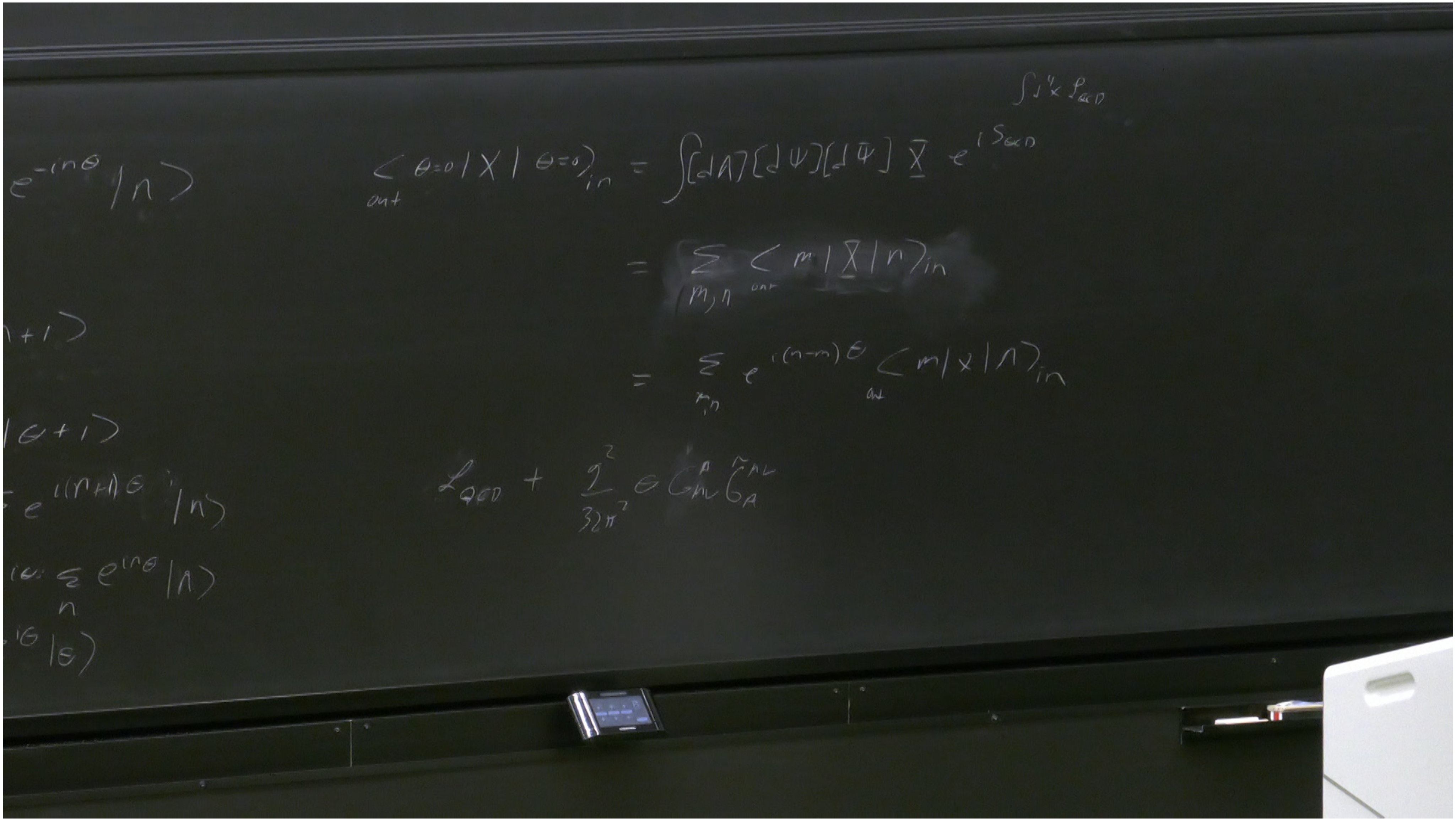
$$U|n\rangle = |n+1\rangle$$

$$U|\theta\rangle = |\theta+1\rangle$$

$$= \sum_n e^{in(\theta+1)}|n\rangle$$

$$= e^{i\theta}\sum_n e^{in\theta}|n\rangle$$

$$= e^{i\theta}|\theta\rangle$$


$\int d^4x\, \mathcal{L}_{QCD}$
${}_{out}\langle \theta=0 | X | \theta=0\rangle_{in} = \int [dA][d\Psi][d\bar{\Psi}]\, X\, e^{iS_{QCD}}$
$= \sum_{m,n} {}_{out}\langle m | X | n\rangle_{in}$
$= \sum_{m,n} e^{i(n-m)\theta}\, {}_{out}\langle m | X | n\rangle_{in}$
$\mathcal{L}_{QCD} + \frac{g^2}{32\pi^2}\theta G^A_{\mu\nu}\tilde{G}^{\mu\nu}_A$
$e^{-in\theta}|n\rangle$
$n+1\rangle$
$|\theta+1\rangle$
$e^{i(n+1)\theta}|n\rangle$
$\sum_n e^{in\theta}|n\rangle$
$e^{i\theta}|\theta\rangle$

$$\mathcal{L} \to \bar{\Psi}_L i\not{\partial} \Psi_L + \bar{\Psi} i\not{\partial} \Psi_R - \left[H^\dagger \bar{d}_R Y_d Q_L + \tilde{H}^\dagger \bar{u}_R Y_u Q_L + h.c. \right]$$

CP violation $\to V_{CKM}$

θ

$$e^{i\alpha_L} U(\psi, L)$$

$$\psi_L' \to U(\psi, L)\, \psi_L \qquad P_{L/R} = \frac{1}{2}(1 \pm \gamma_5)$$

$$\psi_R' \to U(\psi, R)\, \psi_R \qquad M_{sm} \to U^\dagger(L)\, M_{ass}\, U(R)$$

$$e^{i\alpha_R} U(\psi, R) \qquad \arg\det M_{ass} = 0 = \arg\det\left(U_L^\dagger \det m\, U_R \right)$$

$$= 2N_F(\alpha_R - \alpha_L) + \arg\det M$$

$$\mathcal{L}_{SM} + \frac{g_s^2\theta}{32\pi^2} G^{a}_{\mu\nu}\tilde{G}^{a}_{\mu\nu} \to \bar{\Psi}_L i\not{\partial}\Psi_L + \bar{\Psi} i\not{\partial}\Psi_R - \left[H^\dagger \bar{d}_R Y_d Q_L + \tilde{H}^\dagger \bar{u}_R Y_u Q_L + h.c.\right]$$

CP violation $\to V_{CKM}$

θ

$e^{i\alpha_L} U(\Psi,L)$

$\Psi_L' \to U(\Psi,L)\Psi_L$

$P_{L/R} = \frac{1}{2}(1 \pm \gamma_5)$

$d_e = \bar{\theta} \times 10^{-15}$ e-cm

$d_e \leq 3 \times 10^{-26}$ e-cm

$\Psi_R' \to U(\Psi,R)\Psi_R$

$M_{SM} \to U^\dagger(L)\, M_{SM}\, U(R)$

$e^{i\alpha_R} U(\Psi,R)$

$\arg\det M_{SM} = 0 = \arg\det\left(U_L^\dagger \det M\, U_R\right)$

$= 2N_F(\alpha_R - \alpha_L) + \arg\det M$