QCD lecture 6b

November 15

Axial anomaly

In massless QCD there are two conserved currents

$$\bar{u}(p')\gamma^{\mu}u(p) \qquad \bar{u}(p')\gamma^{\mu}\gamma_5 u(p)$$

We will show that when loop corrections are included only one current remains conserved. We now from gauge invariancde that the vector current must be conserved, so it is the axial-vector current that is not conserved.
This phenomenon is called axial anomaly.

Conserved currents

$$\begin{aligned} q_\mu j^\mu(q) &= q_\mu \overline{u}(p')\gamma^\mu u(p) \\ &= \overline{u}(p')(\not{p}' - \not{p})u(p) \\ &= 0 \end{aligned}$$

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 \qquad \{\gamma^\mu, \gamma_5\} = 0$$

$$\begin{aligned} q_\mu j^\mu(q) &= q_\mu \overline{u}(p')\gamma^\mu\gamma_5 u(p) \\ &= \overline{u}(p')(\not{p}' - \not{p})\gamma_5 u(p) \\ &= \overline{u}(p')(\not{p}'\gamma_5 + \gamma_5\not{p})u(p) \\ &= 2m\,\overline{u}(p')\gamma_5 u(p) \end{aligned}$$

Chiral symmetry

$$\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$$

$$\{\gamma^\mu, \gamma_5\} = 0$$

Dirac equation in chrial representation for gamma matrices

$$\gamma^0 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \; \gamma^i = \begin{bmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{bmatrix}, \; \gamma_5 = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$

splits into two equations

$$(i\partial_t - i\boldsymbol{\sigma}\cdot\boldsymbol{\nabla})\,\psi_L - m\psi_R = 0, \qquad (i\partial_t + i\boldsymbol{\sigma}\cdot\boldsymbol{\nabla})\,\psi_R - m\psi_L = 0,$$

where $\psi = \begin{bmatrix} \psi_L \\ \psi_R \end{bmatrix}$. Note that for massless fermions these eqs. are *independent*.

Projection operators: $P_L = \frac{1}{2}(1-\gamma_5), \; P_R = \frac{1}{2}(1+\gamma_5)$ project solutions of

given chirality (eigen value of γ_5)

$$\psi_- = \begin{bmatrix} \psi_L \\ 0 \end{bmatrix}, \quad \psi_+ = \begin{bmatrix} 0 \\ \psi_R \end{bmatrix}$$

Axial anomaly

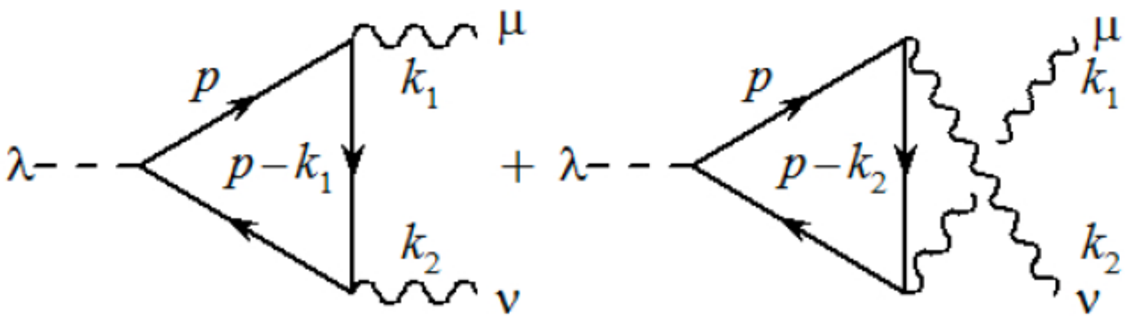
pseudoscalar density

Gauge invariance of QED (and QCD): $q_\mu j^\mu(q) = q_\mu \overline{u}(p')\gamma^\mu u(p) = 0$

divergence of axial-vector current: $q_\mu j_5^\mu(q) = q_\mu \overline{u}(p')\gamma^\mu \gamma_5 u(p) = 2m\overline{u}(p')\gamma_5 u(p)$

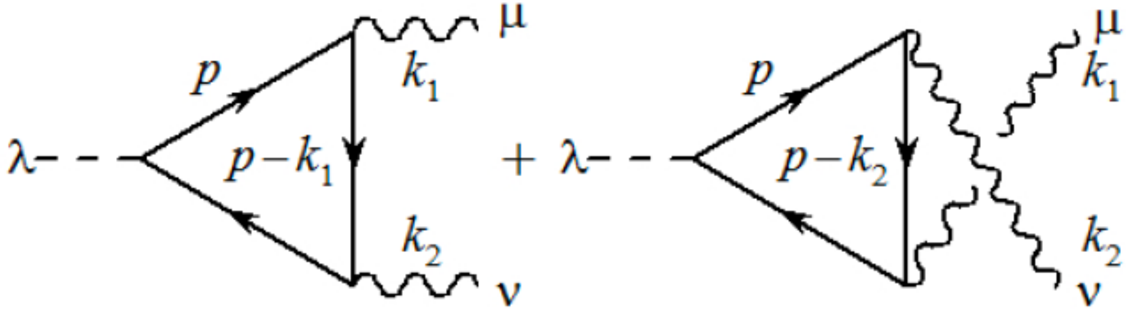
Axial current is conserved for massless fermions: chiral symmetry

It is not possible to maintain both symmetries when loop corrections are included. This is called: AXIAL ANOMALY



photons are bosons and they are not distinguishable hence amplitude has to be symmetrized

Naïve current conservation



$$q = k_1 + k_2$$

Skipping coupling constants (charges) the amplitude reads:

$$\begin{aligned} T_{\mu\nu\lambda} \;=\; & -i\int \frac{d^4p}{(2\pi)^4}\,\mathrm{Tr}\left[\frac{i}{\not p - m}\gamma_\lambda\gamma_5\frac{i}{(\not p - \not q) - m}\gamma_\nu\frac{i}{(\not p - \not k_1) - m}\gamma_\mu\right] \\ & -i\int \frac{d^4p}{(2\pi)^4}\,\mathrm{Tr}\left[\frac{i}{\not p - m}\gamma_\lambda\gamma_5\frac{i}{(\not p - \not q) - m}\gamma_\mu\frac{i}{(\not p - \not k_2) - m}\gamma_\nu\right] \end{aligned}$$

Naively we expect:

$$k_1^\mu T_{\mu\nu\lambda} = k_2^\nu T_{\mu\nu\lambda} = 0 \qquad q^\lambda T_{\mu\nu\lambda} = 2mT_{\mu\nu}$$

Naïve current conservation

Vector current, first diagram:

$$k_1^\mu T_{\mu\nu\lambda} \sim \mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{(\not{p}-\not{k}_1)-m}\not{k}_1 \frac{i}{\not{p}-m}\right]$$

use trick:

$$\not{k}_1 = (\not{p}-m) - ((\not{p}-\not{k}_1)-m)$$

we get:

$$= i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{(\not{p}-\not{k}_1)-m}\right] - i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{\not{p}-m}\right]$$

Naïve current conservation

Vector current, first diagram:

$$k_1^\mu T_{\mu\nu\lambda} \sim \mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{(\not{p}-\not{k}_1)-m}\not{k}_1 \frac{i}{\not{p}-m}\right]$$

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$$= \ i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{(\not{p}-\not{k}_1)-m}\right] - i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{\not{p}-m}\right]$$

same trick with the second diagram gives

$$= \ i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu \frac{i}{\not{p}-m}\right] - i\,\mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not{p}-\not{k}_2)-m}\gamma_\nu \frac{i}{\not{p}-m}\right]$$

Naïve current conservation

$$k_1^\mu T_{\mu\nu\lambda} \sim \int \frac{d^4p}{(2\pi)^4}$$

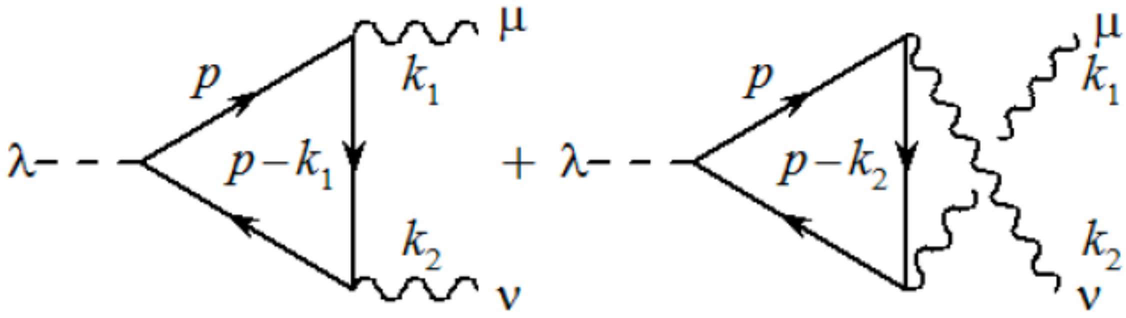
$$\left\{ \mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not p - \not q) - m}\gamma_\nu \frac{i}{(\not p - \not k_1) - m}\right] - \mathrm{Tr}\left[\gamma_\lambda\gamma_5 \frac{i}{(\not p - \not k_2) - m}\gamma_\nu \frac{i}{\not p - m}\right]\right\}$$

change variable in the first integral $p \to p + k_1$

$$q = k_1 + k_2$$

It seems we get zero

Naïve current conservation



$$q = k_1 + k_2$$

Skipping coupling constants (charges) the amplitude reads:

$$\begin{aligned} T_{\mu\nu\lambda} \quad = \quad & -i \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr} \left[\frac{i}{\not{p} - m} \gamma_\lambda \gamma_5 \frac{i}{(\not{p} - \not{q}) - m} \gamma_\nu \frac{i}{(\not{p} - \not{k}_1) - m} \gamma_\mu \right] \\ & -i \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr} \left[\frac{i}{\not{p} - m} \gamma_\lambda \gamma_5 \frac{i}{(\not{p} - \not{q}) - m} \gamma_\mu \frac{i}{(\not{p} - \not{k}_2) - m} \gamma_\nu \right] \end{aligned}$$

Naively we expect:

$$q^\lambda T_{\mu\nu\lambda} = 2mT_{\mu\nu}$$

Axial current

To calculate $q^\lambda T_{\mu\nu\lambda}$

we use the following trick:

$$\begin{aligned} \not{q}\gamma_5 &= -\gamma_5 \not{q} \\ &= \gamma_5 \left[(\not{p} - \not{q}) - m\right] - \gamma_5 \left[\not{p} - m\right] \\ &= \gamma_5 \left[(\not{p} - \not{q}) - m\right] + \left[\not{p} - m\right] \gamma_5 + 2m\gamma_5 \end{aligned}$$

and for the first diagram we obtain

$$\begin{aligned} q^\lambda \left[\frac{i}{\not{p} - m} \gamma_\lambda \gamma_5 \frac{i}{(\not{p} - \not{q}) - m} \right] &= 2m \frac{i}{\not{p} - m} \gamma_5 \frac{i}{(\not{p} - \not{q}) - m} \\ &\quad + i \frac{i}{\not{p} - m} \gamma_5 + i \gamma_5 \frac{i}{(\not{p} - \not{q}) - m} \end{aligned}$$

Axial current

Sum from the two diagrams $$q^\lambda T_{\mu\nu\lambda} = 2m T_{\mu\nu} + \Delta^{(1)}_{\mu\nu} + \Delta^{(2)}_{\mu\nu}$$

$$\begin{aligned} &\Delta^{(1)}_{\mu\nu} + \Delta^{(2)}_{\mu\nu} \\ = &\int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\frac{i}{\not p - m}\gamma_5\gamma_\nu \frac{i}{(\not p - \not k_1) - m}\gamma_\mu + \gamma_5 \frac{i}{(\not p - \not q) - m}\gamma_\nu \frac{i}{(\not p - \not k_1) - m}\gamma_\mu\right] \\ + &\int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left[\frac{i}{\not p - m}\gamma_5\gamma_\mu \frac{i}{(\not p - \not k_2) - m}\gamma_\nu + \gamma_5 \frac{i}{(\not p - \not q) - m}\gamma_\mu \frac{i}{(\not p - \not k_2) - m}\gamma_\nu\right] \end{aligned}$$

Axial current

$$\Delta^{(1)}_{\mu\nu} = \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\frac{i}{\not{p}-m}\gamma_5\gamma_\nu \frac{i}{(\not{p}-\not{k}_1)-m}\gamma_\mu - \frac{i}{(\not{p}-\not{k}_2)-m}\gamma_5\gamma_\nu \frac{i}{(\not{p}-\not{q})-m}\gamma_\mu\right]$$

$$\Delta^{(2)}_{\mu\nu} = \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\frac{i}{\not{p}-m}\gamma_5\gamma_\mu \frac{i}{(\not{p}-\not{k}_2)-m}\gamma_\nu - \frac{i}{(\not{p}-\not{k}_1)-m}\gamma_5\gamma_\mu \frac{i}{(\not{p}-\not{q})-m}\gamma_\nu\right]$$

The question is: are $\Delta^{(1,2)}_{\mu\nu}$ equal zero?

Changing variables $\quad p \to p + k_2$

seems to nullify $\Delta^{(1,2)}_{\mu\nu}$. $\quad p \to p + k_1$

However, $\quad \Delta^{(1,2)}_{\mu\nu} \sim \int^{\infty} dp\, p^3 \frac{1}{p^2} \sim \int^{\infty} dp\, p \quad$ are UV divergent

Due to the minus sign the divergence is only linear

The same applies to vector current conservation.

Mathematical diggression

Consider the integral that is naively zero:

$$\int_{-\infty}^{\infty} dx\,[f(x+a) - f(x)]$$

However, if

$$f(\pm\infty) \neq 0.$$

we can calculate this integral by Taylor expansion:

$$\int_{-\infty}^{\infty} dx\,[f(x+a) - f(x)] = a\,[f(\infty) - f(-\infty)] + \frac{a^2}{2}\,[f'(\infty) - f'(-\infty)] + \ldots$$

it may happen that $\neq 0$