Title: Lecture - Standard Model, PHYS 622

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Collection/Series: Standard Model (Elective), PHYS 622, January 6 - February 5, 2025

Subject: Particle Physics

Date: January 20, 2025 - 10:15 AM

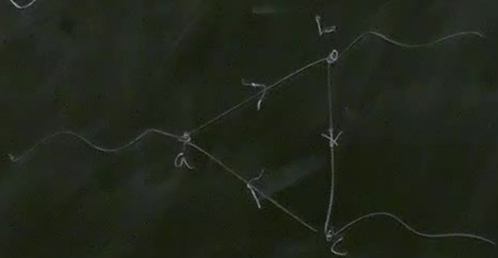
URL: https://pirsa.org/25010019

omalies

$$\partial_\mu j^\mu_a = \frac{A_{abc}}{64\pi^2} \epsilon^{\alpha\beta\gamma\delta} g_b F^b_{\alpha\beta} g_c F^c_{\gamma\delta} = \frac{A_{abc}}{32\pi^2} g_b g_c F^b_{\alpha\beta} \tilde{F}^{c\,\alpha\beta}$$

$$A_{abc} = \mathrm{tr}\left[T_a \{T_b, T_c\}\right]$$

generators of symmetries



$\bar{u}\gamma^\mu d$

$\frac{\ }{ } = g_b g_c F^b_{\alpha\beta} \tilde{F}^{c\alpha\beta}$

$\}]$

, of symmetries

if $\boxed{A_{abc} = 0}$ anomaly free.

A transformation is anomaly-free if it is left-right symm

Ex Prove this.

① $a=3, b=3, c=3$

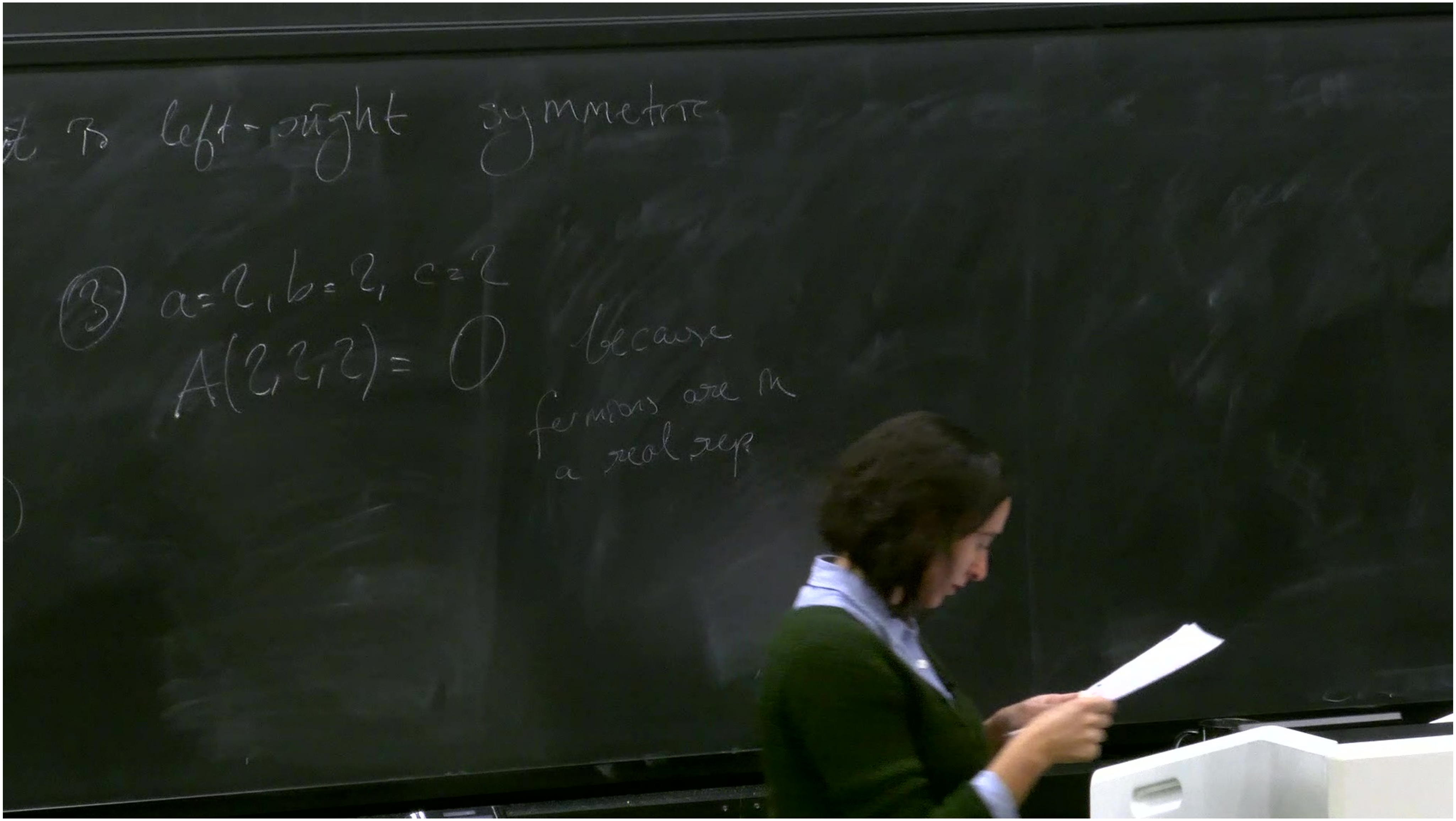
$A(3,3,3)=0$

② $A(3,2,1)=A(3,2,2)=A(3,1,1)=0$

$tr(\lambda_\alpha)=0$

③ $a=2, b=2, c=2$

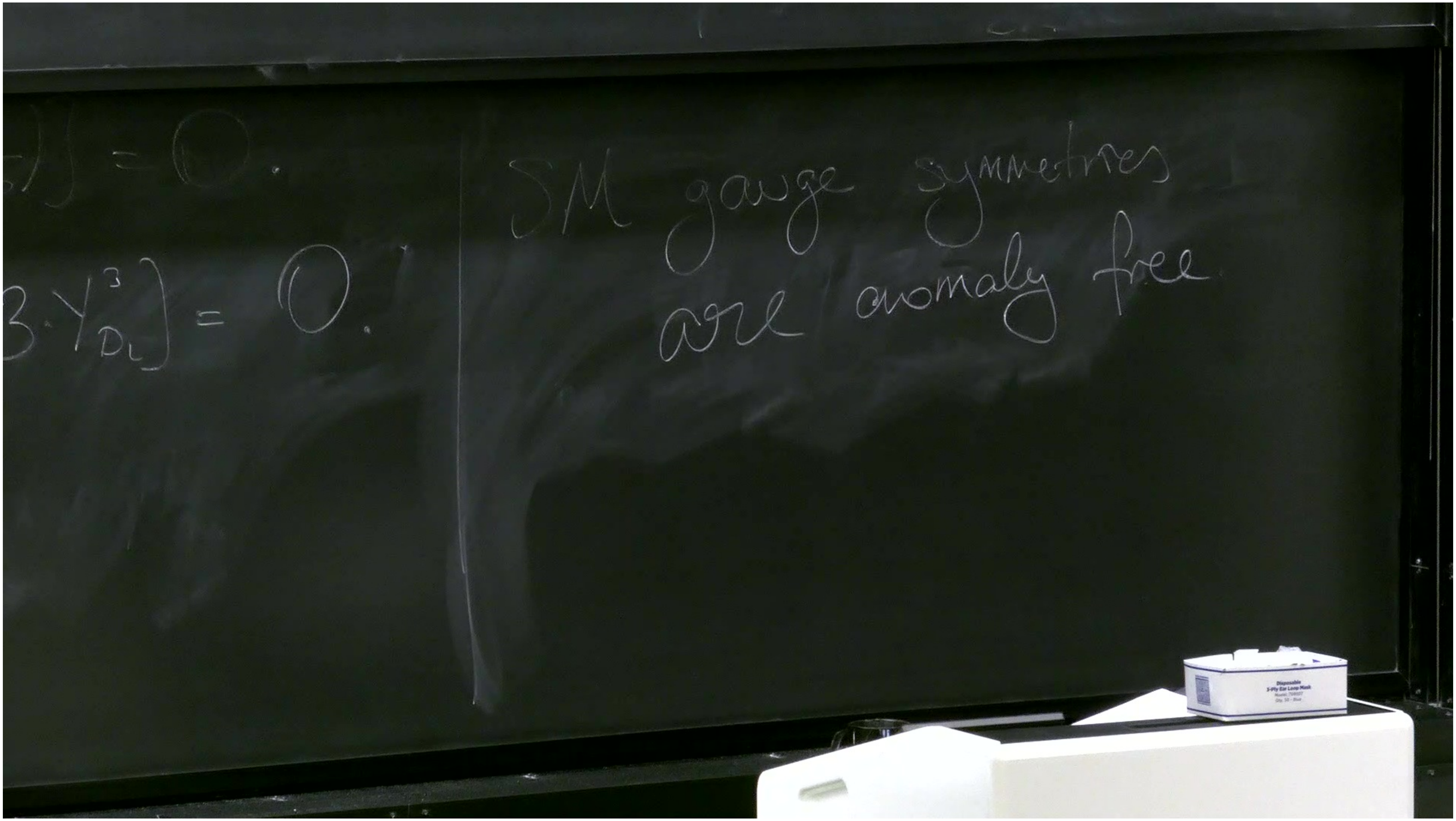
$A(2,2,2)=0$


to left-right symmetric
③ a=2, b=2, c=2
A(2,2,2) = 0 because
fermions are in
a real rep

$$\mathrm{tr}(\lambda_a) = 0$$

(4) $$A(2,2,1) = \sum_{\text{doublets}} Y = \underbrace{3}_{\text{generations}} \left[Y_{L_L} + \underbrace{3}_{\text{color}} Y_{Q_L} \right] = 3\left[\left(-\frac{1}{2}\right) + 3\cdot\left(\frac{1}{6}\right) \right] = 0.$$

(5) $$A(1,1,1) = \sum_{\text{left-handed fermion}} Y^3 = 3\cdot\left[2\, Y_{L_L}^3 + Y_{E_L}^3 + 3\cdot 2\cdot Y_{Q_L}^3 + 3\cdot Y_{U_L}^3 + 3\cdot Y_{D_L}^3 \right] =$$


SM gauge symmetries
are anomaly free

$$\mathcal{L} \supset \bar{q} \not{D} q + y_q h \bar{q} q$$

$$B_q = \frac{1}{3} \qquad B_{\bar{q}} = -\frac{1}{3}$$

$$\partial_\mu j^\mu_B = \frac{3}{64\pi^2} g_2^2$$

(1) $A(2,2,B) = \sum_{\text{doublets}} B = 3 \cdot 3\left(\frac{1}{3}\right) = 3.$

(2) $A(2,2,L_{e,\mu,\tau}) = \sum_{\text{doublets}} L_{e,\mu,\tau} = 1$

$$\partial_\mu j^\mu_B = \frac{3}{64\pi^2} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$\partial_\mu j^\mu_L = \frac{3}{64\pi} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$A(2,2,B-L) = 0$$

$$A(2,2,B+L) \neq 0$$

$$L = L_e + L_\mu + L_\tau$$

$$\partial_\mu j^\mu_B = \frac{3}{64\pi^2} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$\partial_\mu j^\mu_L = \frac{3}{64\pi} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$(2,2,B-L) = 0$$

$$(2,2,B+L) \neq 0$$

$$L = L_e + L_\mu + L_\tau$$

$L_e - L_\mu,\ L_e - L_\tau,\ L_\mu - L_\tau$ B

always anomaly free.

Ex Gauge $U(1)_{L_e - L_\mu}$ and write that Lagrangian.

$$\left[\left(-\frac{1}{2}\right) + 3\cdot\left(\frac{1}{6}\right)\right] = 0.$$

$$Y_{Q_L}^3 + 3\cdot Y_{U_L}^3 + 3\cdot Y_{D_L}^3\Big] = 0.$$

$(g-2)_\mu$: muon g-2.

R_K, R_K^* $\quad \dfrac{K \to e^+ \cdots}{K \to \mu^+ \cdots}$

SM gauge symmetrie

are anomaly f

$$\partial_\mu j^\mu_B = \frac{3}{64\pi^2} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu} \sim e^{-\frac{M_W}{T}}$$

$$\partial_\mu j^\mu_L = \frac{3}{64\pi} g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu}$$

$$A(2,2,B-L) = 0$$

$$A(2,2,B+L) \neq 0$$

$$L = L_e + L_\mu + L_\tau$$

$L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ B

always anomaly free.

Ex Gauge $U(1)_{L_e - L_\mu}$ and write that Lagrangian.

QCD, Chiral Symmetry / Breaking

$$\mathcal{L}_{QCD} = \underbrace{-\frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu}}_{\text{gluon kinetic terms + self interactions}} + \sum_{\text{quarks}} \left(-\bar{q}(\not{\partial} + m_q) q + i \frac{\boxed{g_s}}{2} \underbrace{G^{\alpha}_{\mu}\, \bar{q} \gamma^{\mu} \lambda_{\alpha} q}_{\text{quark-gluon interactions}} \right)$$

Gell-Mann matrices

$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_s(M_Z)} + b_3 \ln\left(\frac{M_Z^2}{\mu^2}\right)$$

$$b_3 = \frac{1}{12\pi}\Big(2.$$

$$\bar{q}\,(i\not{\partial} + m_q)\, q + i\,\frac{\boxed{g_s}}{2}\, \underbrace{G^{\alpha}_{\mu}\; \bar{q}\, \gamma^{\mu} \lambda_{\alpha}\, q}_{\text{quark-gluon interactions}} \Big) ,$$

Gell-Mann matrices

$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_s(M_Z)} + b_3 \ln\left(\frac{M_Z^2}{\mu^2}\right)$$

$$b_3 = \frac{1}{12\pi}\left(2\cdot n_q - 33\right)$$

n_q → # of Dirac fermions that are $SU_c(3)$ triplets and lighter than μ

$$\frac{g_s}{2} \underbrace{G^\alpha_\mu \, \bar{q}\, \gamma^\mu \lambda_\alpha \, q}_{\text{quark-gluon interactions}} \Big)$$

Gell-Mann matrices

$$\alpha_3 = \frac{g_3^2}{4\pi}$$

$$+ \, b_3 \ln\left(\frac{M_Z^2}{\mu^2}\right)$$

$$b_3 = \frac{1}{12\pi}\left(2 \cdot n_q - 33\right)$$

# of Dirac fermions that are $SU_c(3)$ triplets and lighter than μ

$\mu = m_b \simeq 5$ GeV

$n_q = 5$

$b_3 = -0.61$

QCD, Chiral Symmetry Breaking

$$\mathcal{L}_{QCD} = -\frac{1}{4} \underbrace{G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu}}_{\text{gluon kinetic terms + self interactions}} + \sum_{\text{quarks}} \left(-\bar{q} (\not{\partial} + m_q) q + i \boxed{\frac{g_3}{2}} G^{\alpha}_{\mu} \right.$$

quar

m

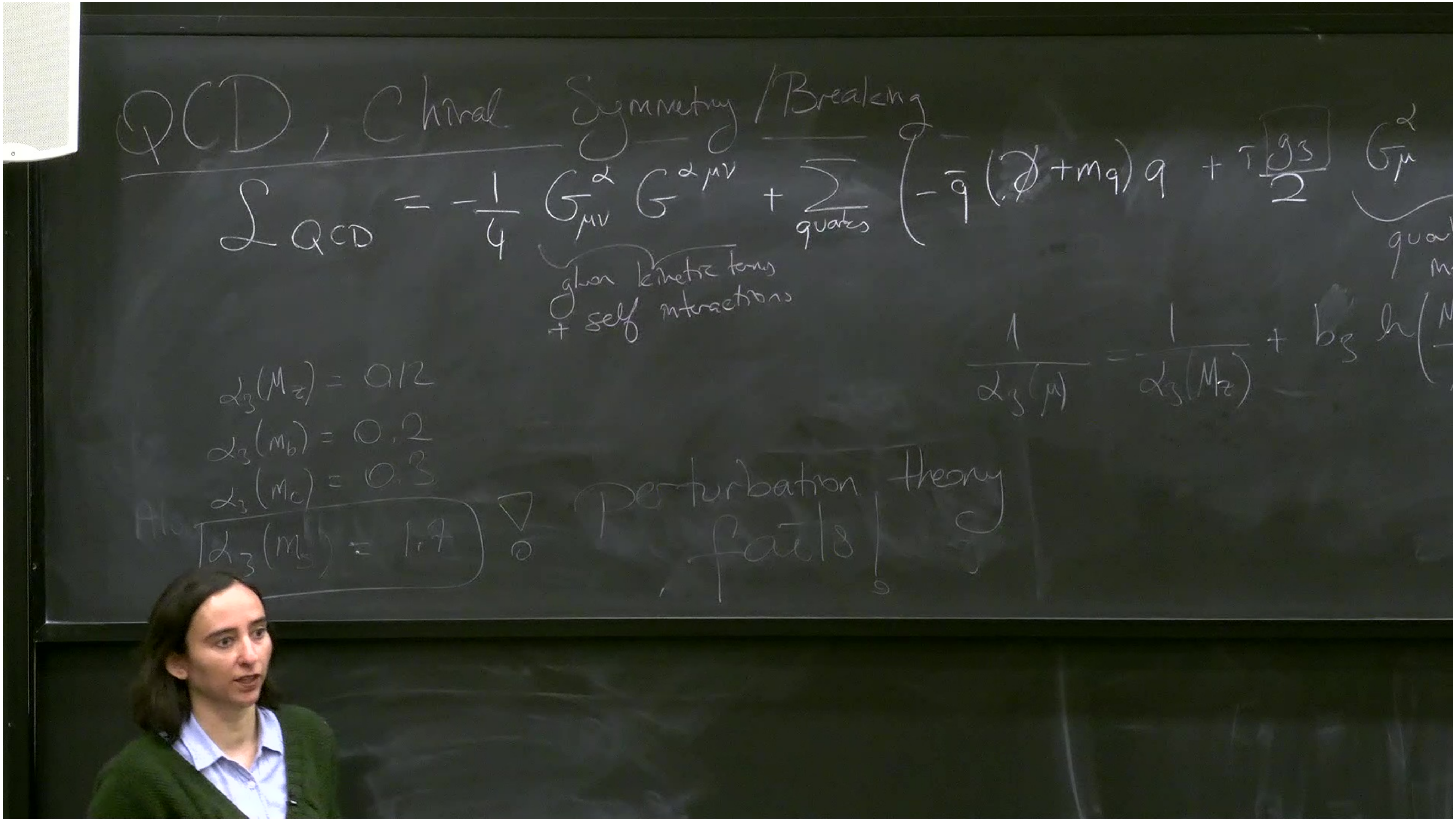
$$\frac{1}{\alpha_3(\mu)} = \frac{1}{\alpha_3(M_Z)} + b_3 \ln\left(\right.$$

$\alpha_3(M_Z) = 0.12$

$\alpha_3(m_b) = 0.2$

$\alpha_3(m_c) = 0.3$

Also $\boxed{\alpha_3(m_s) = 1.7}$!


QCD, Chiral Symmetry / Breaking
$\mathcal{L}_{QCD} = -\frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu} + \sum_{\text{quarks}} \left(-\bar{q}(\not{\partial} + m_q) q + i \frac{g_3}{2} G^{\alpha}_{\mu}\right.$
gluon kinetic terms
+ self interactions
$\frac{1}{\alpha_3(\mu)} = \frac{1}{\alpha_3(M_Z)} + b_3 \ln($
$\alpha_3(M_Z) = 0.12$
$\alpha_3(m_b) = 0.2$
$\alpha_3(m_c) = 0.3$
Also $\alpha_3(m_s) = 1.?$
perturbation theory fails!

$$\frac{1}{\alpha_3(\Lambda_{QCD})} = \frac{1}{\alpha_3(M_Z)} + b_3 \ln\left(\frac{M_Z^2}{\Lambda_{QCD}^2}\right) = 0$$

(definition of Λ_{QCD})

$$\boxed{\Lambda_{QCD} = M_Z \cdot \exp\left(\frac{1}{2 b_3 \alpha_3(M_Z)}\right)}$$

QCD scale

$n_q = 5$: $\Lambda_{QCD} \simeq 80\ \mathrm{MeV}$

$n_q = 3$: $\Lambda_{QCD} = 220\ \mathrm{MeV}$

$n_q = 5$
$b_8 = -0.61$

of Λ_{QCD})

scale

short distance

$$V \sim \frac{\alpha_s}{r}$$

long distances

$$V \sim \underbrace{\sigma}_{\text{string tension}} \cdot r$$: (hypothetical)

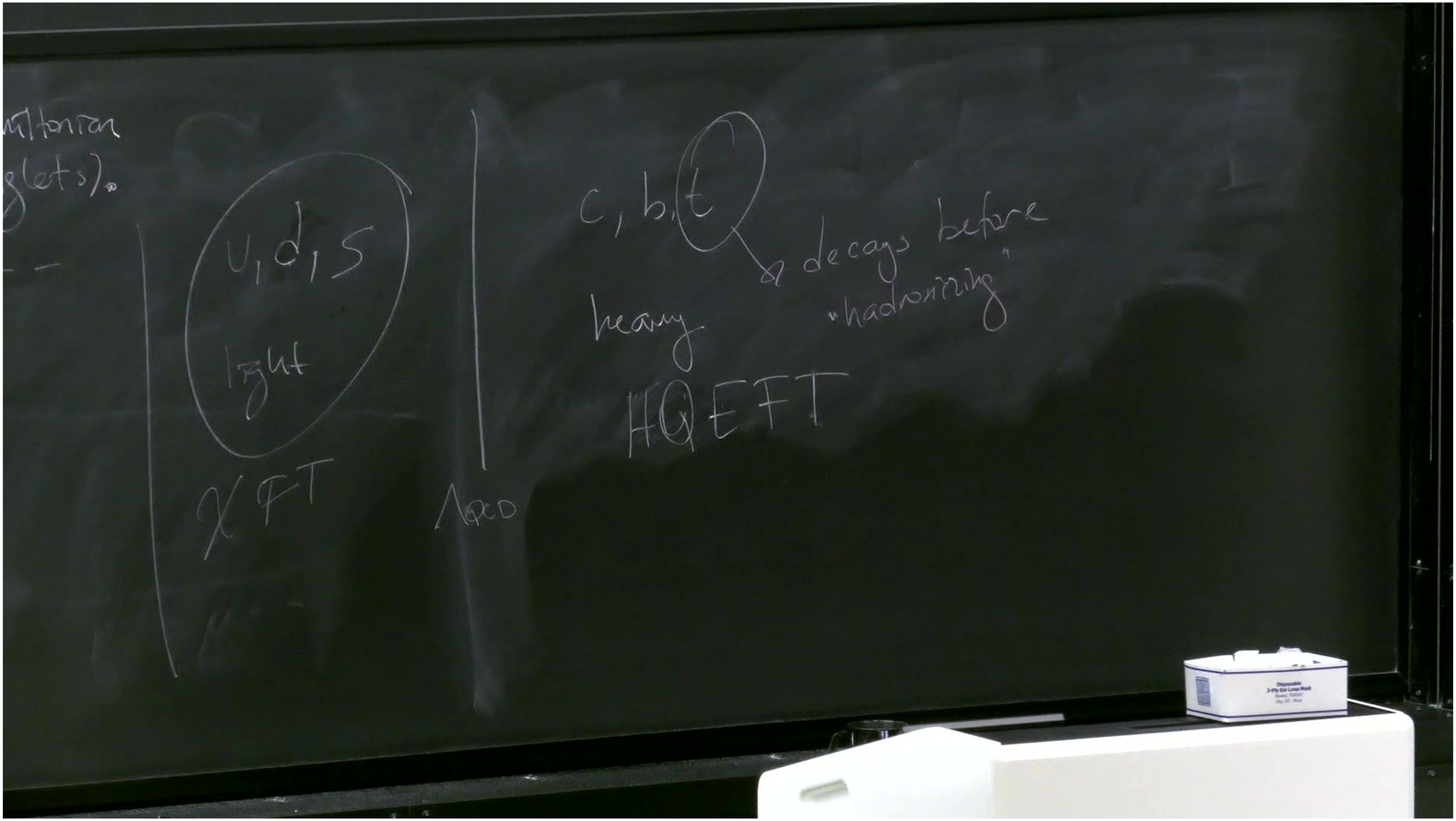
$$r_c \simeq \frac{1}{\Lambda_{QCD}}$$: confinement scale.

Confinement hypothesis: The only energy eigenstates of the QCD Hamiltonian which have finite energy are color neutral (singlets).

$$3 \otimes \bar{3} = \underset{\substack{\uparrow \\ \text{mesons}}}{1} \oplus 8$$

$$3 \otimes 3 \otimes 3 = \underset{\substack{\uparrow \\ \text{baryon}}}{1} \oplus + \cdots$$

$$8 \otimes 8 = \underset{\substack{\downarrow \\ \text{glueball}}}{1} \oplus \cdots$$


u, d, s
light
c, b, t
decays before
"hadronizing"
heavy
HQEFT