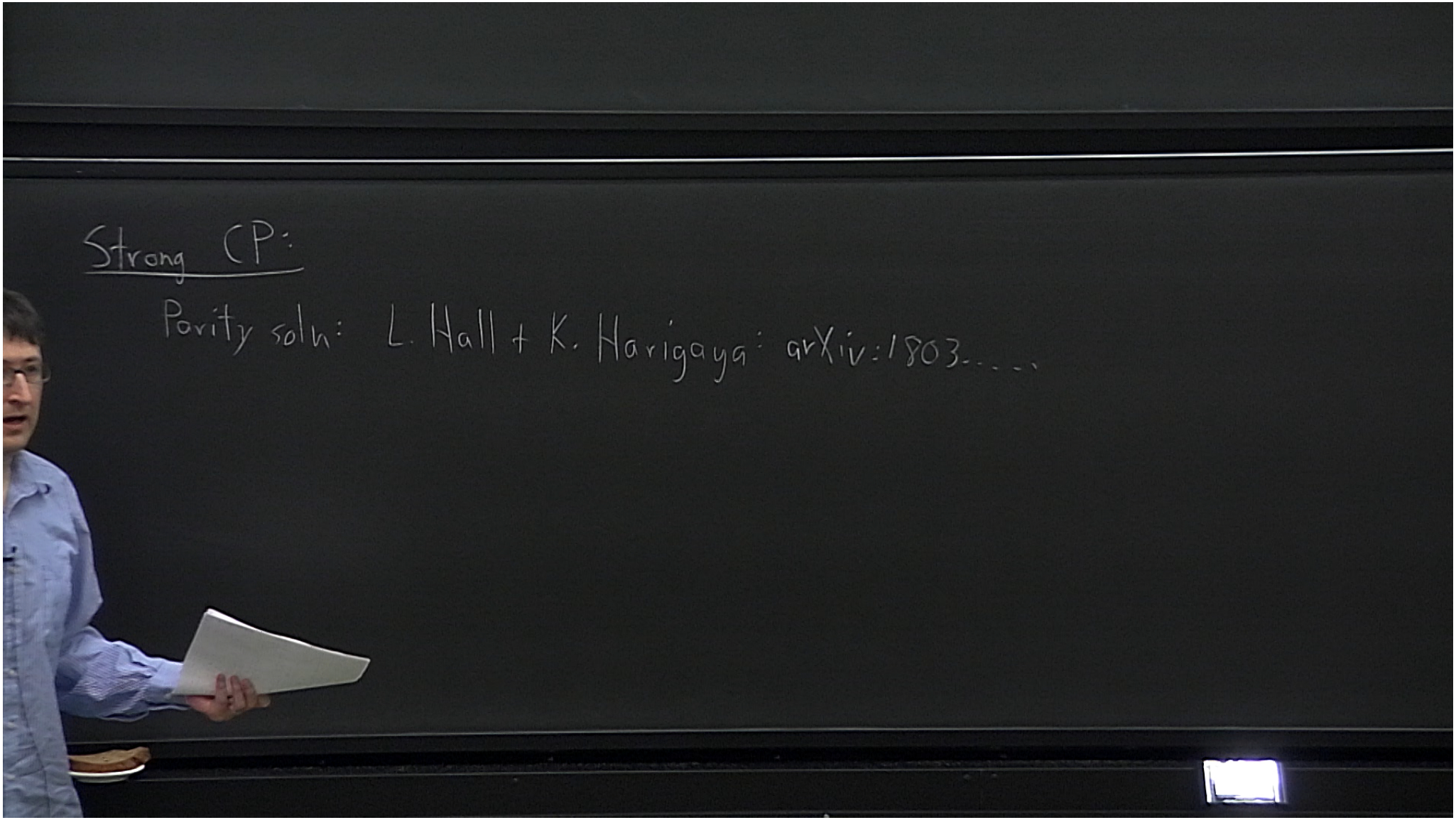
Title: PSI 2018/2019 - Beyond Standard Model - Lecture 13

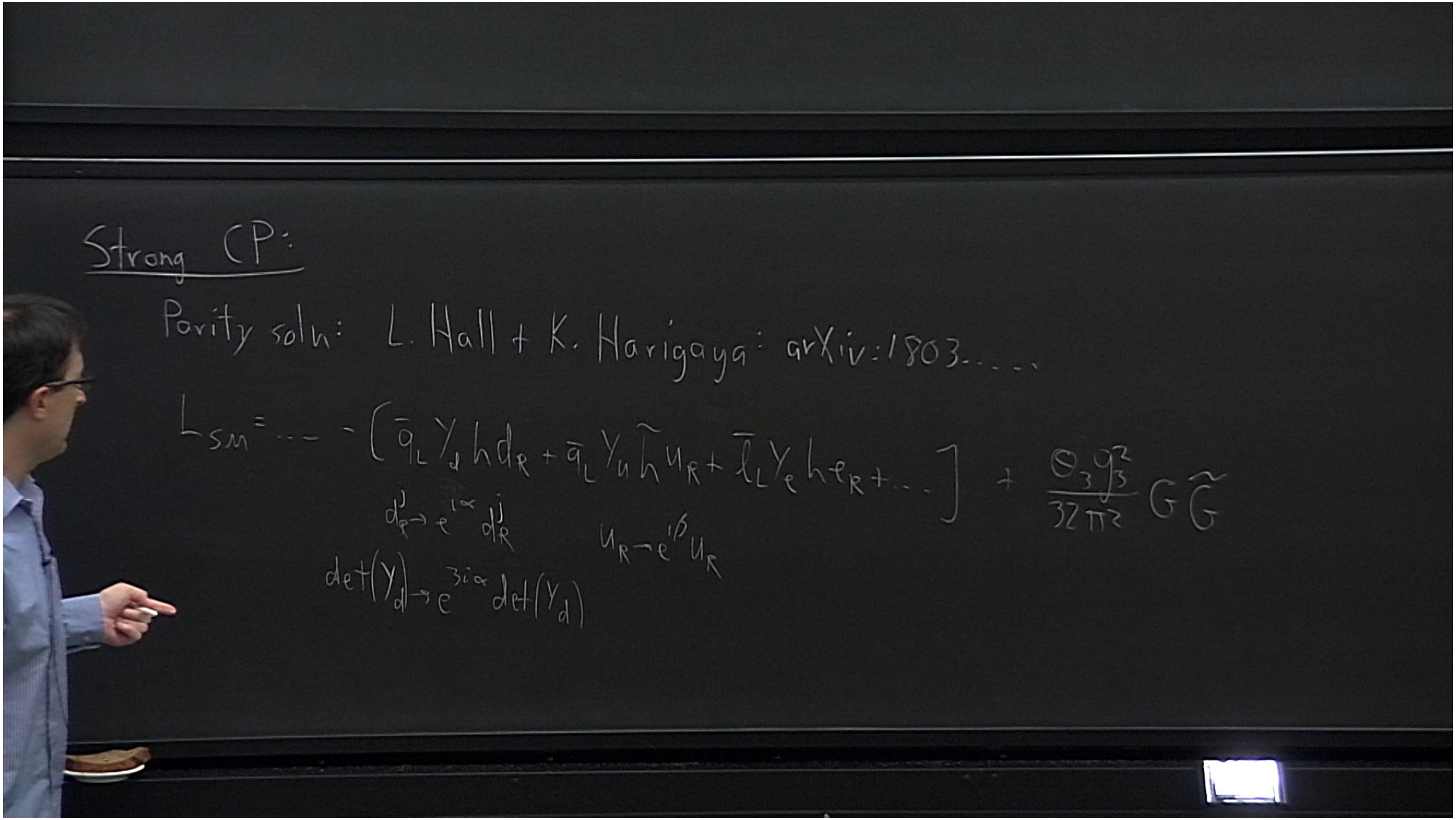
Speakers: Latham Boyle

Collection: PSI 2018/2019 - Beyond Standard Model (Boyle)

Date: April 11, 2019 - 11:30 AM

URL: http://pirsa.org/19040029


Strong CP:
Parity soln: L. Hall + K. Harigaya: arXiv:1803.....


Strong CP:
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$\mathcal{L}_{SM} = \ldots - \left[\bar{q}_L Y_d h d_R + \bar{q}_L Y_u \tilde{h} u_R + \bar{l}_L Y_e h e_R + \ldots\right] + \frac{\Theta_3 g_3^2}{32\pi^2} G\tilde{G}$
$d_R^j \to e^{i\alpha} d_R^j \qquad u_R \to e^{i\beta} u_R$
$\det(Y_d) \to e^{3i\alpha} \det(Y_d)$

Strong CP:

Parity soln: L. Hall + K. Harigaya: arXiv:1803....

$$\mathcal{L}_{SM} = \ldots - \left(\bar{q}_L Y_d h d_R + \bar{q}_L Y_u \tilde{h} u_R + \bar{l}_L Y_e h e_R + \ldots \right] + \frac{\Theta_3 g_3^2}{32\pi^2} G\tilde{G}$$

$d_R^j \to e^{i\alpha} d_R^j \qquad u_R \to e^{i\beta} u_R$

$\det(Y_d) \to e^{3i\alpha} \det(Y_d) \qquad \det(Y_u) \to e^{3i\beta} \det(Y_u)$

Strong CP:

$\bar{\theta} =$

Parity soln: L. Hall + K. Harigaya: arXiv:1803....

$$\mathcal{L}_{SM} = \cdots - \left(\bar{q}_L Y_d h d_R + \bar{q}_L Y_u \tilde{h} u_R + \bar{l}_L Y_e h e_R + \cdots \right) + \frac{\theta_3 g_3^2}{32\pi^2} G\tilde{G}$$

$d_R^j \to e^{i\alpha} d_R^j \qquad u_R \to e^{i\beta} u_R$

$\det(Y_d) \to e^{3i\alpha} \det(Y_d) \qquad \det(Y_u) \to e^{3i\beta} \det(Y_u)$

$\theta_3 \to \theta_3 + 3\alpha + 3\beta$

$\lambda = W_{ij}$

$\bar{\theta} = \theta_3 - \arg[\det(Y_u Y_d)]$

	SU(3)	$SU(2)_L$	$SU(2)_R$	U(1)
q_L	3	2	1	1/6
q_R	3	1	2	1/6
l_L	1	2	1	-1/2
l_R	1	1	2	-1/2
h_1	1	2	1	1/2
h_2	1	1	2	1/2

$\psi_L(t,\vec{x}) \longleftrightarrow \psi_R(t,-\vec{x})$

$\frac{\theta_3 g_3^2}{32\pi^2} G\tilde{G}$

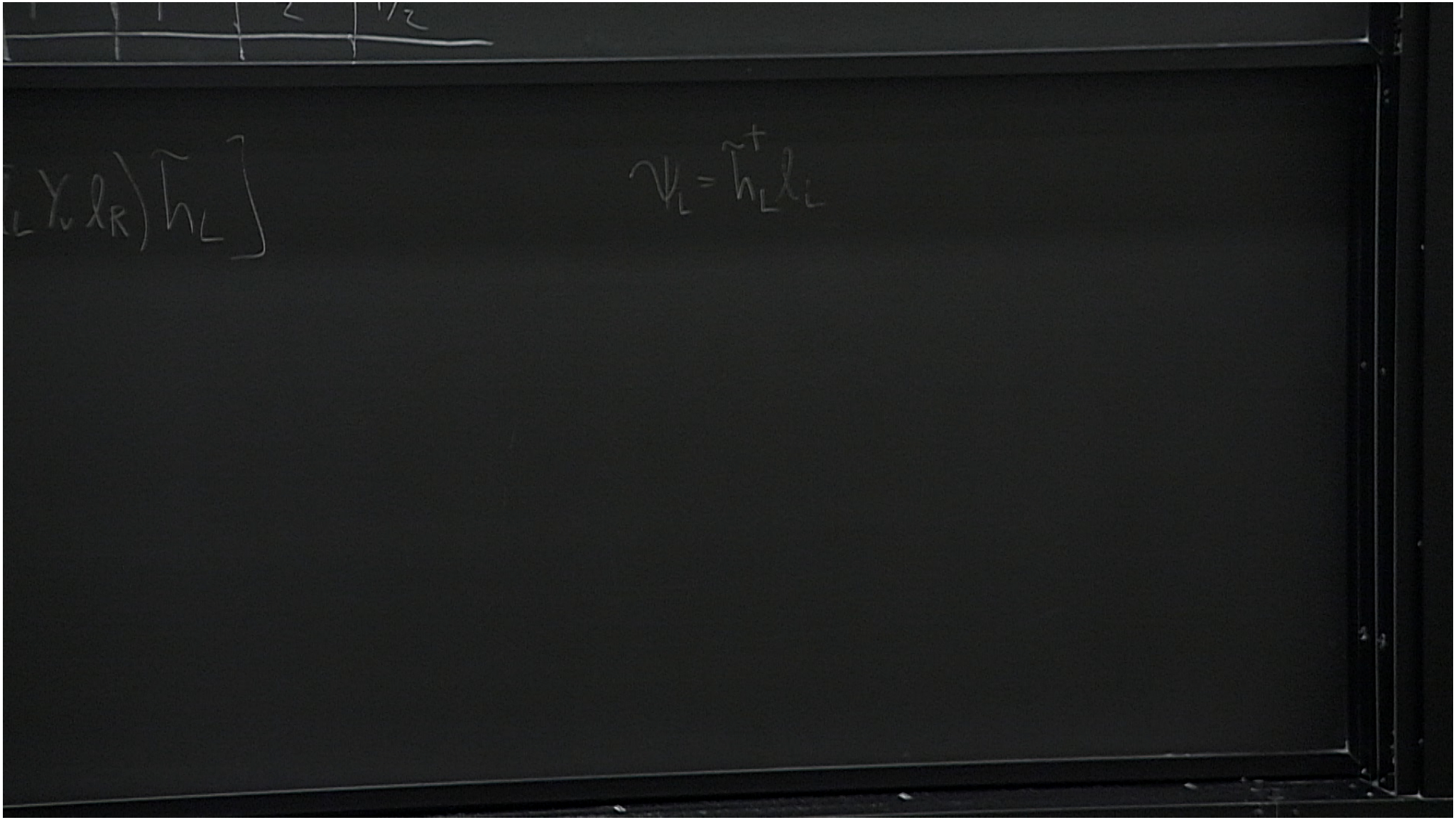
$\to \theta_3 + 3\alpha + 3\beta$

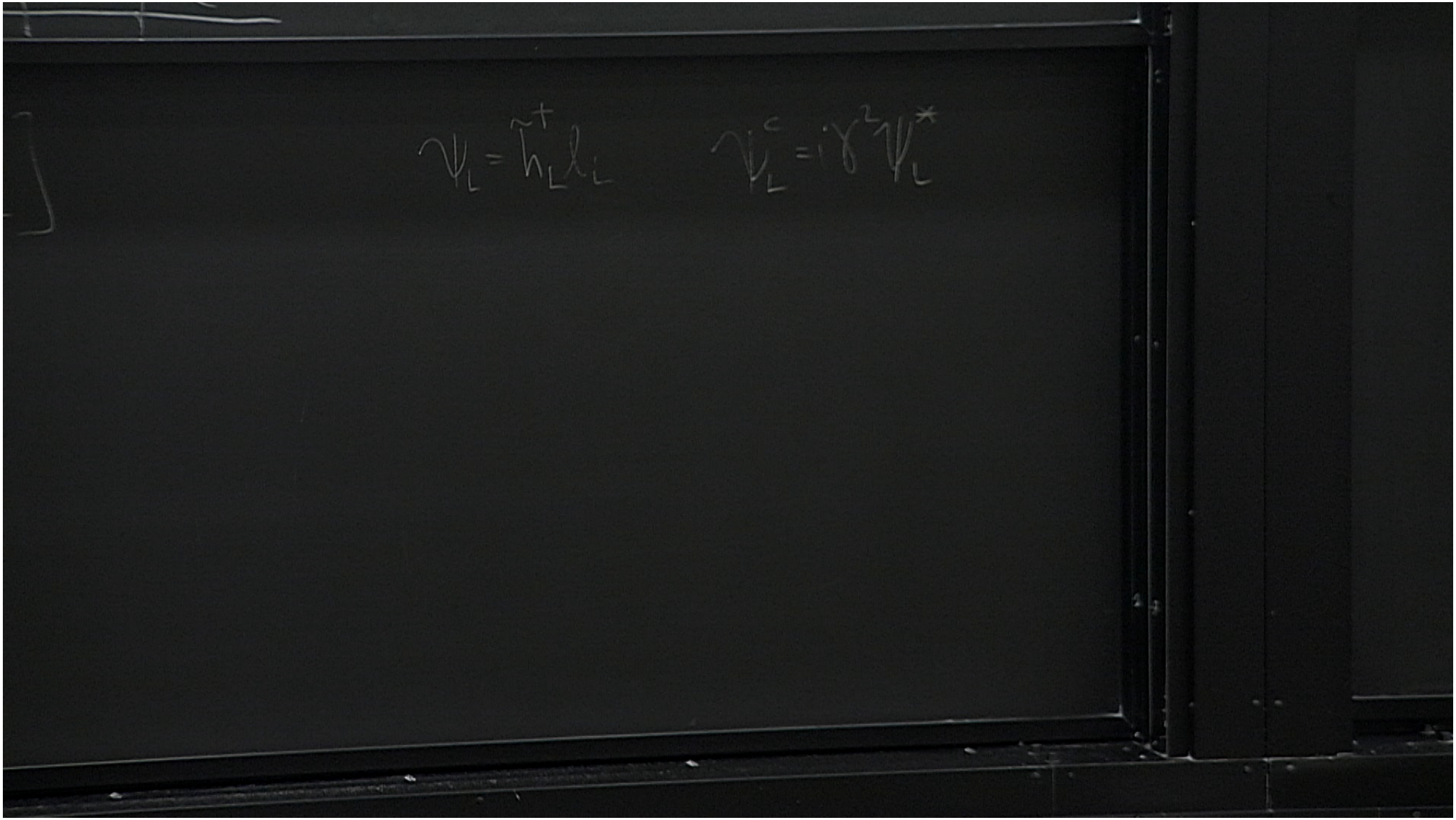
$d_R^j \to e^{i\alpha} d_R^j$ $\quad u_R \to e^{i\beta} u_R$ $\quad \frac{g_3^2}{32\pi^2} G\tilde{G}$

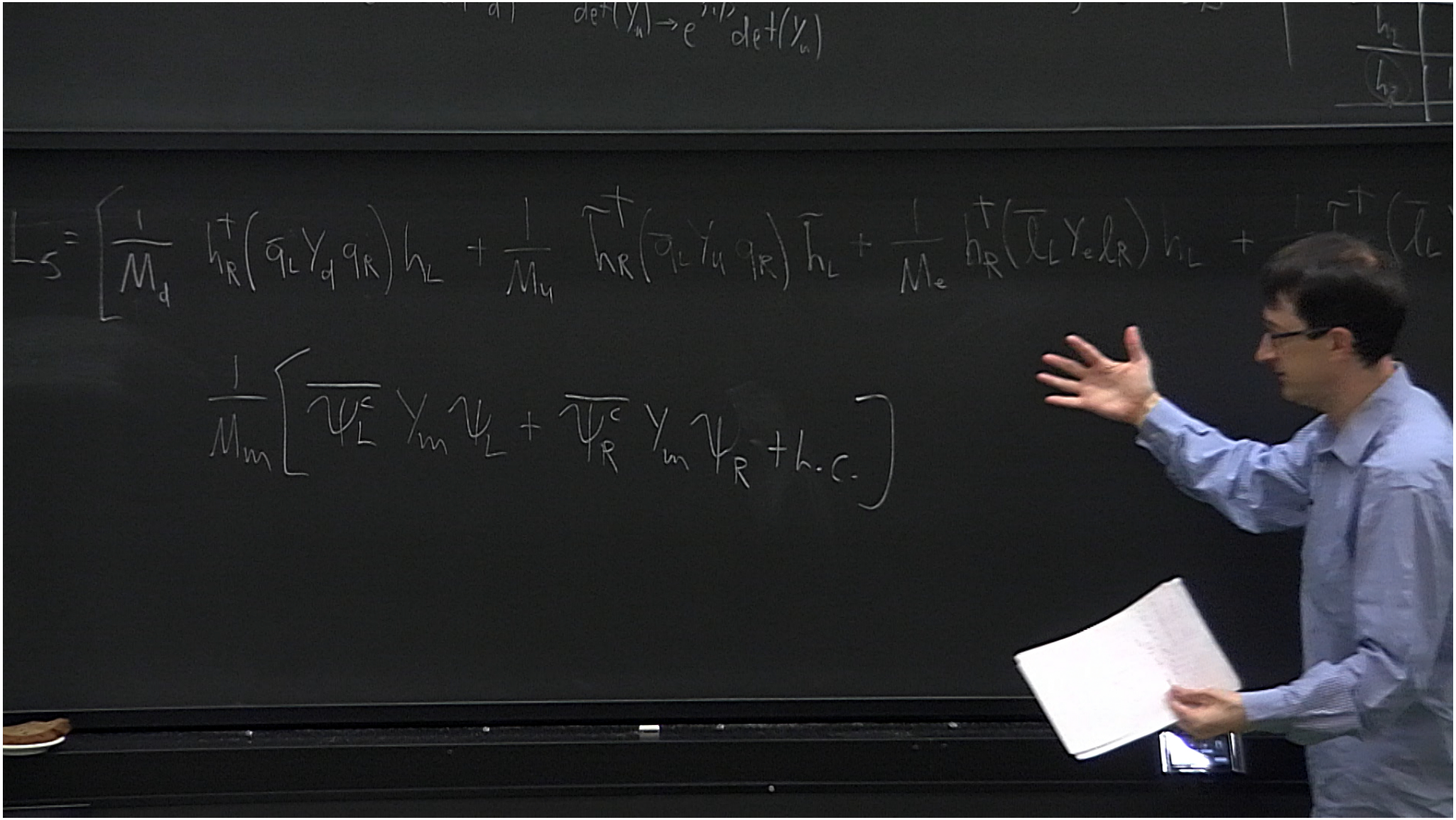
$\det(Y_d) \to e^{3i\alpha} \det(Y_d)$ $\quad \det(Y_u) \to e^{3i\beta} \det(Y_u)$ $\quad \theta_3 \to \theta_3 + 3\alpha + 3\beta$

q_L	1	2	1
l_L	1	2	1
l_R	1	1	2
h_1	1	2	1
h_2	1	1	2

$$\mathcal{L}_5 = \left[\frac{1}{M_d} h_R^\dagger (\bar{q}_L Y_d q_R) h_L + \frac{1}{M_u} \tilde{h}_R^\dagger (\bar{q}_L Y_u q_R) \tilde{h}_L + \frac{1}{M_e} h_R^\dagger (\bar{l}_L Y_e l_R) h_L + \frac{1}{M_\nu} \tilde{h}_R^\dagger (\bar{l}_L Y_\nu l_R) \tilde{h}_L \right]$$


$\nu_L = \tilde{h}_L^\dagger l_L$


$\psi_L = \tilde{h}_L^{\dagger} l_L$
$\psi_L^c = i\gamma^2 \psi_L^*$


$\det(Y_u) \to e^{i\theta} \det(Y_u)$
$\mathcal{L}_S = \left[\frac{1}{M_d} h_R^\dagger (\bar{q}_L Y_d q_R) h_L + \frac{1}{M_u} \tilde{h}_R^\dagger (\bar{q}_L Y_u q_R) \tilde{h}_L + \frac{1}{M_e} h_R^\dagger (\bar{\ell}_L Y_e \ell_R) h_L + \right.$
$\left. \frac{1}{M_m} \left[\overline{\psi_L^c} Y_m \psi_L + \overline{\psi_R^c} Y_m \psi_R + h.c. \right] \right]$

h_1	1	2	1	1/2
h_2	1	1	2	1/2

$$h_R^\dagger(\bar{l}_L Y_e l_R) h_L + \frac{1}{M_\nu} \tilde{h}_R^\dagger (\bar{l}_L Y_\nu l_R) \tilde{h}_L + h.c.]$$

$$\psi_L = \tilde{h}_L^\dagger l_L \qquad \psi_L^c = i\gamma^2 \psi_L^*$$

$$h \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad Q = T_3 + Y$$

$$h_R \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R + H_R \end{pmatrix}$$

$$SU(3) \times SU(2)_L \times SU(2)_R + U(1)_{B-L}$$

h_2	1	2	1	1/2
h_3	1	1	2	1/2

$$h_R^\dagger(\bar{l}_L Y_e l_R) h_L + \frac{1}{M_\nu} \tilde{h}_R^\dagger (\bar{l}_L Y_\nu l_R) \tilde{h}_L + h.c.]$$

$$\psi_L = \tilde{h}_L^\dagger l_L \qquad \psi_L^c = i\gamma^2 \psi_L^*$$

$$h \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad Q = T_3 + Y$$

$$h_R \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R + H_R \end{pmatrix}$$

$$SU(3) \times SU(2)_L \times \underbrace{SU(2)_R \times U(1)_{B-L}}_{U(1)_Y}$$

h_1	1	2	1	1/2
h_2	1	1	2	1/2

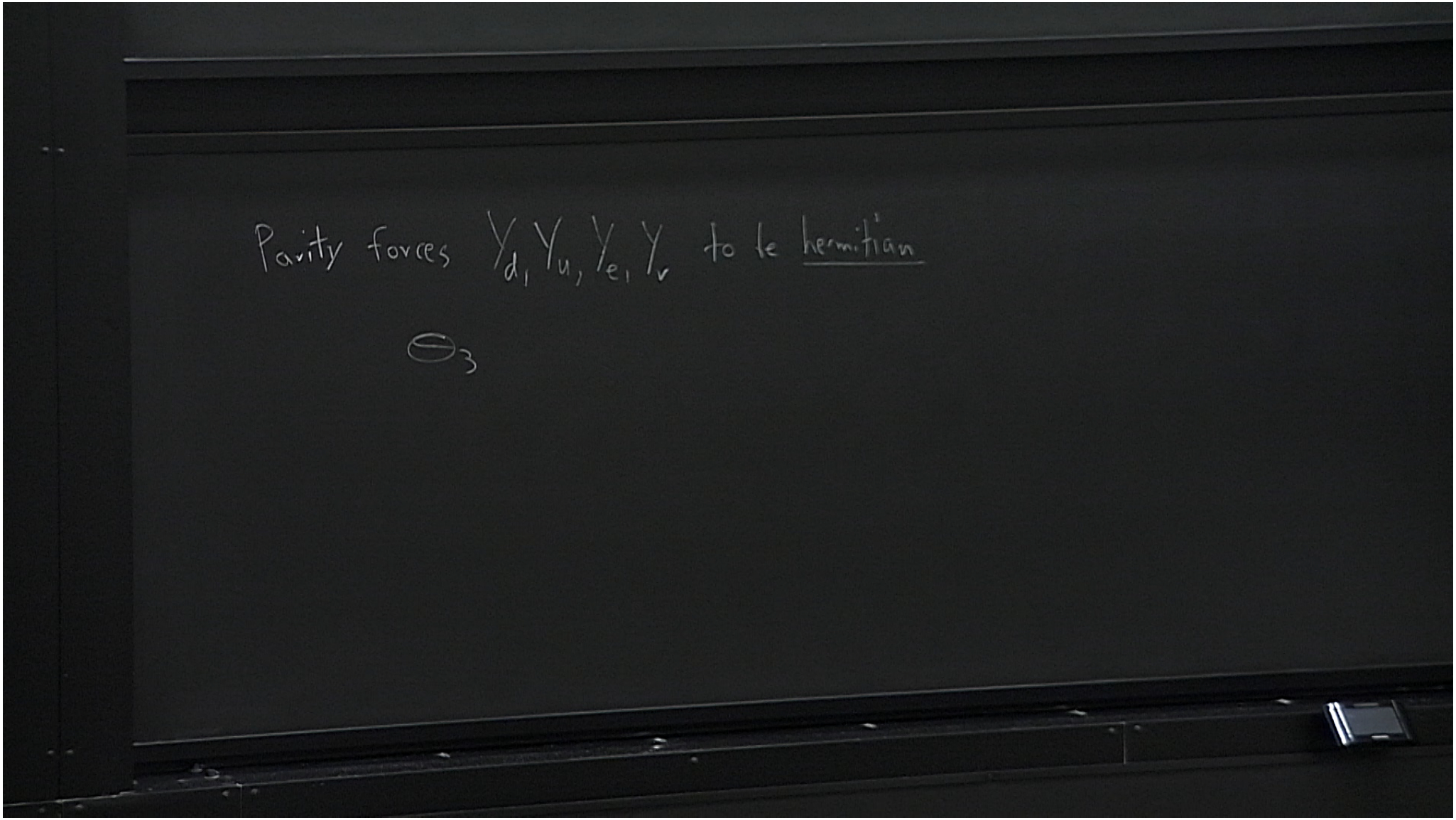
$$\tilde{h}_R^\dagger(\bar{l}_L Y_e l_R) h_L + \frac{1}{M_\nu}\tilde{h}_R^\dagger(\bar{l}_L Y_\nu l_R)\tilde{h}_L + \text{h.c.}\Big] \qquad \psi_L = \tilde{h}_L^\dagger l_L \qquad \psi_L^c = i\gamma^2\psi_L^*$$

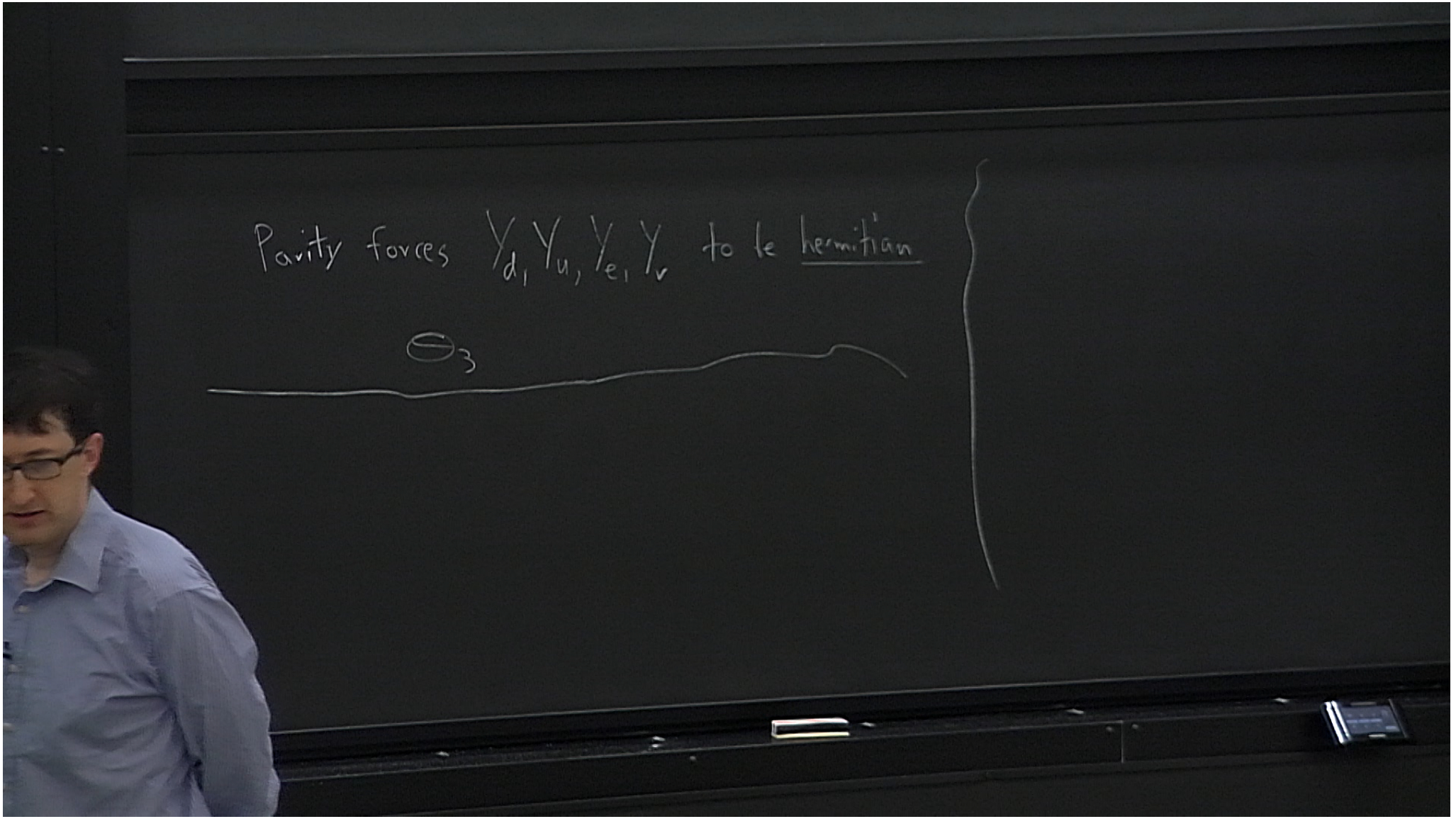
$$h \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \qquad Q = T_3 + Y$$

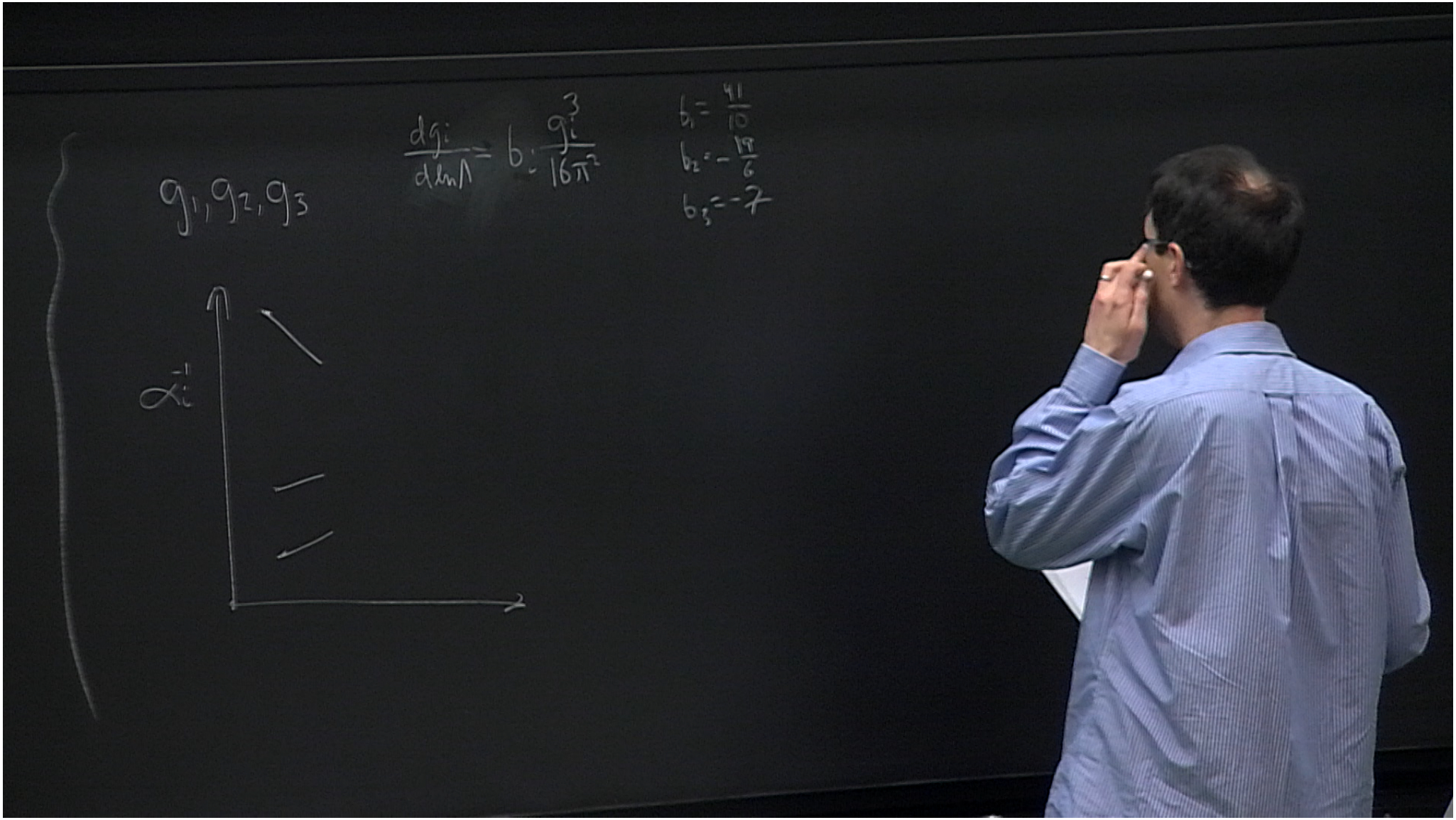
$$h_R \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_R + H_R \end{pmatrix}$$

$$SU(3)\times SU(2)_L \times \underbrace{SU(2)_R \times U(1)_{B-L}}_{U(1)_Y}$$

recover Yukawa/mass terms of vSM


Parity forces Y_d, Y_u, Y_e, Y_ν to be hermitian
Θ_3


Parity forces Y_d, Y_u, Y_e, Y_ν to be hermitian
Θ_3


g_1, g_2, g_3
$\frac{dg_i}{d\ln\Lambda} = b_i \frac{g_i^3}{16\pi^2}$
$b_1 = \frac{41}{10}$
$b_2 = -\frac{19}{6}$
$b_3 = -7$
α_i^{-1}

g_1, g_2, g_3

$\frac{dg_i}{d\ln\Lambda} = b_i \frac{g_i^3}{16\pi^2}$

g_1 $b_1 = \frac{41}{10}$

g_2 $b_2 = -\frac{19}{6}$

g_3 $b_3 = -7$

g_{B-L} $b_{B-L} = +9/2$

g_2: $b_2 = -\frac{19}{6}$

g_3: $b_3 = -7$

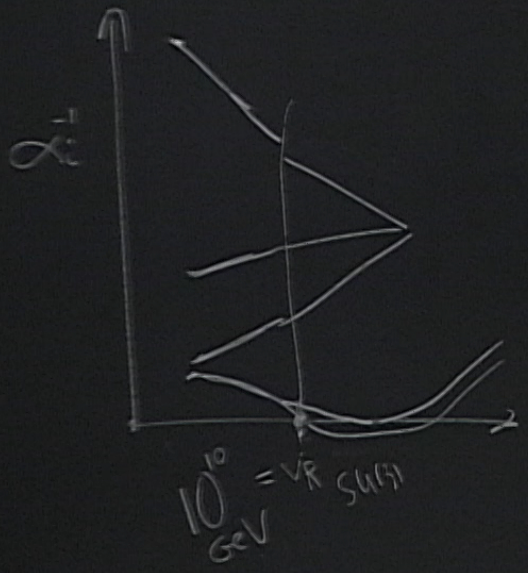
$$\frac{1}{g_1^2} = \frac{2}{5}\frac{1}{g_{B-L}^2} + \frac{3}{5}\frac{1}{g_2^2}$$

$h_R \to v_R$

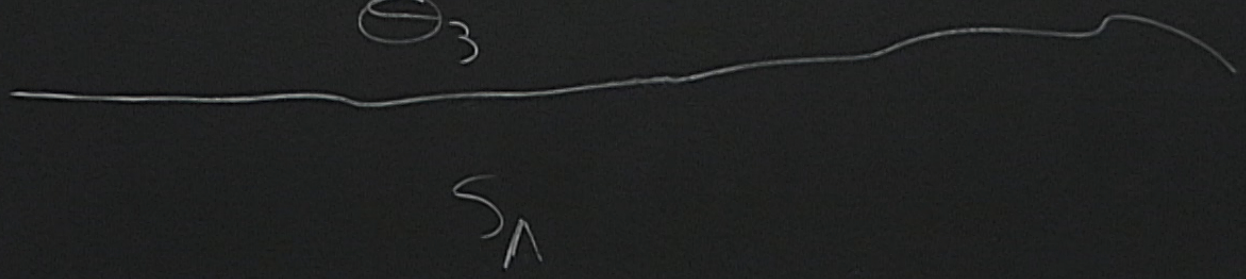
$$V(h_L, h_R) = -m^2\left(h_L^\dagger h_L + h_R^\dagger h_R\right) + \frac{\lambda}{2}\left(h_L^\dagger h_L + h_R^\dagger h_R\right)^2 + \lambda'\left(h_L^\dagger h_L\right)\left(h_R^\dagger h_R\right)$$

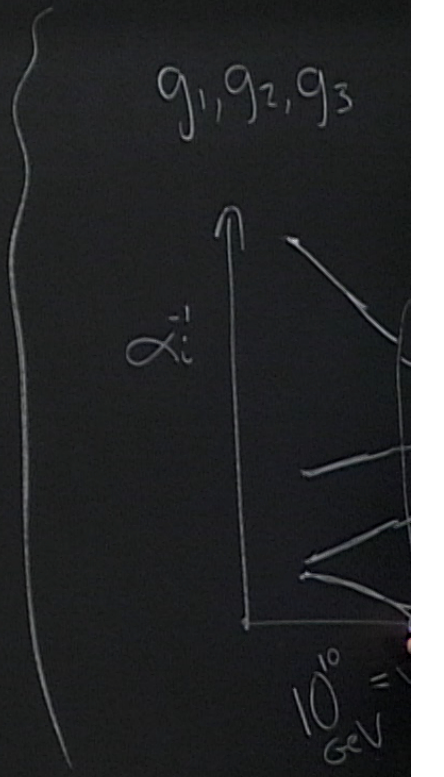
$$\langle h_R^2 \rangle = m^2/\lambda$$

$$V_{eff}(h_L) = \underbrace{\lambda \langle h_R \rangle^2}\left(h_L^\dagger h_L\right) - \underbrace{\lambda'\left(1 + \frac{\lambda'}{2\lambda}\right)}_{\lambda_{SM}}\left(h_L^\dagger h_L\right)^2$$



Parity forces Y_d, Y_u, Y_e, Y_ν to be hermitian





g_1, g_2, g_3

$\frac{dg_i}{d\ln\Lambda} = b_i \frac{g_i^3}{16\pi^2}$

g_1 $b_1 = \frac{41}{10}$

g_2 $b_2 = -\frac{19}{6}$

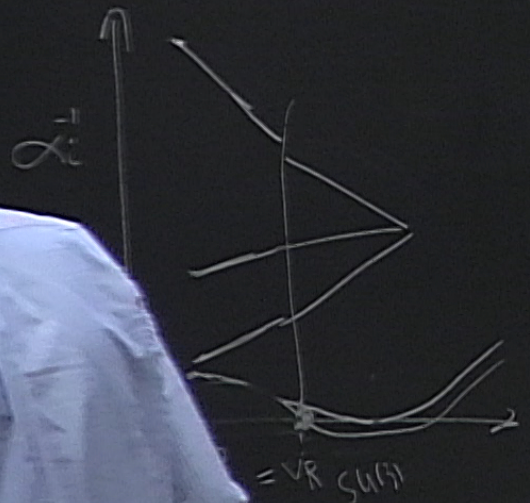
g_3 $b_3 = -7$

g_{B-L}: $b_{B-L} = +9/2$

g_2: $b_2 = -\frac{19}{6}$

g_3: $b_3 = -7$

$$\frac{1}{g_1^2} = \frac{2}{5}\frac{1}{g_{B-L}^2} + \frac{3}{5}\frac{1}{g_2^2}$$



$h_R \to v_R$

$$V(h_L, h_R) = -m^2\left(h_L^\dagger h_L + h_R^\dagger h_R\right) + \frac{\lambda}{2}\left(h_L^\dagger h_L + h_R^\dagger h_R\right)^2 + \lambda'\left(h_L^\dagger h_L\right)\left(h_R^\dagger h_R\right)$$

$$\langle h_R^2 \rangle = m^2/\lambda$$

$$V_{eff}(h_L) = \lambda' \langle h_R \rangle^2 \left(h_L^\dagger h_L\right) - \lambda'\left(1 + \frac{\lambda'}{2\lambda}\right)\left(h_L^\dagger h_L\right)^2$$

λ_{SM}

Parity forces Y_d, Y_u, Y_e, Y_ν to be hermitian

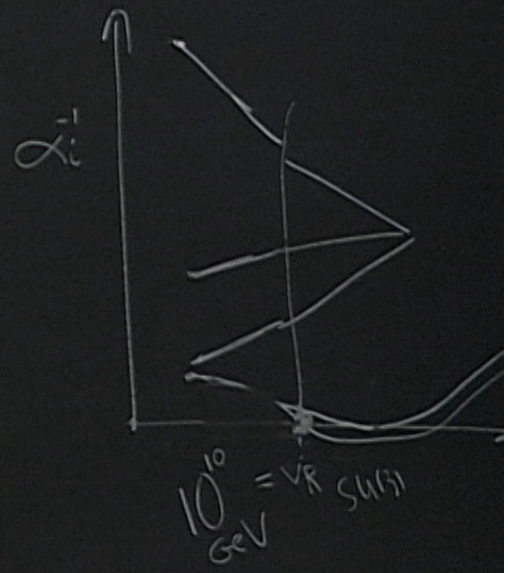
Θ_3

S_Λ

$V_{eff}[\ h^\dagger h\ ,\ i(h^\dagger h)^2\ ,\ \ldots]$

g_1, g_2, g_3

$\frac{dg_i}{d\ln\Lambda} =$



Parity forces Y_d, Y_u, Y_e, Y_ν to be hermitian

Θ_3

S_Λ

$V_{eff}[\ h^\dagger h\ ,\ (h^\dagger h)^2\ ,\ \ldots]$

g_1, g_2, g_3

$\frac{dg_i}{d\ln\Lambda} =$

