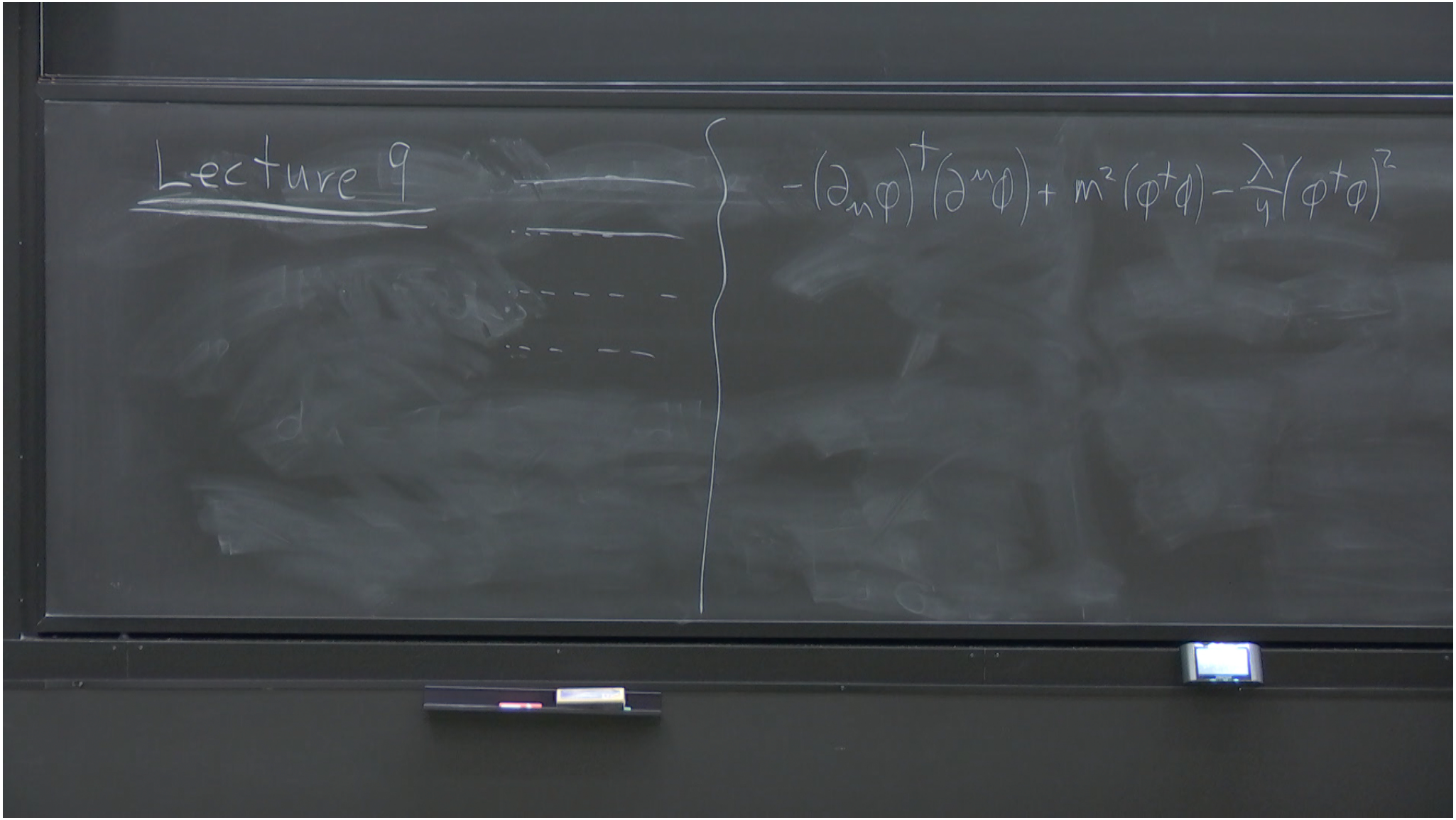
Title: PSI 2019/2020 - Standard Model and Beyond - Part 1 - Lecture 9

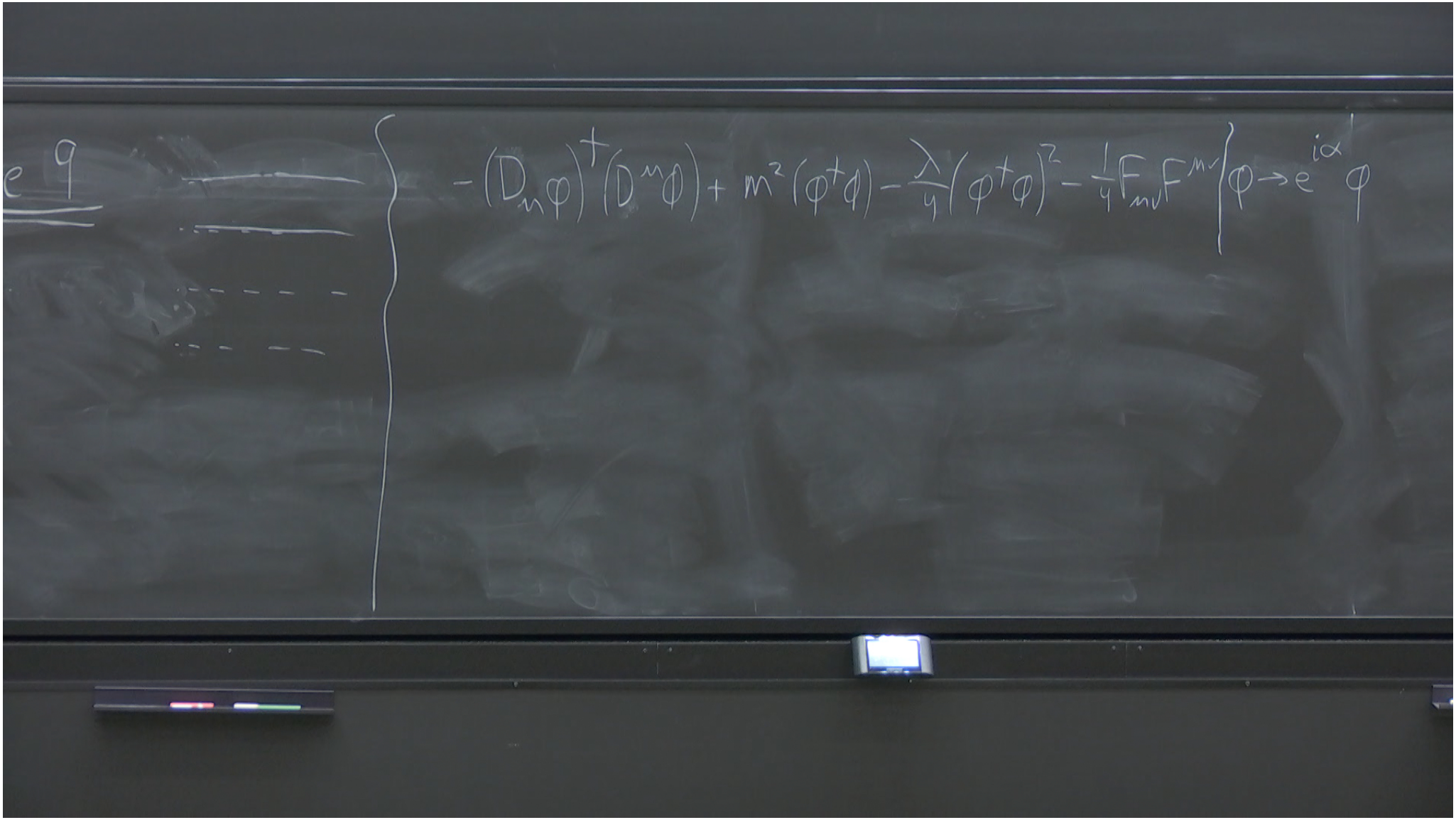
Speakers: Latham Boyle

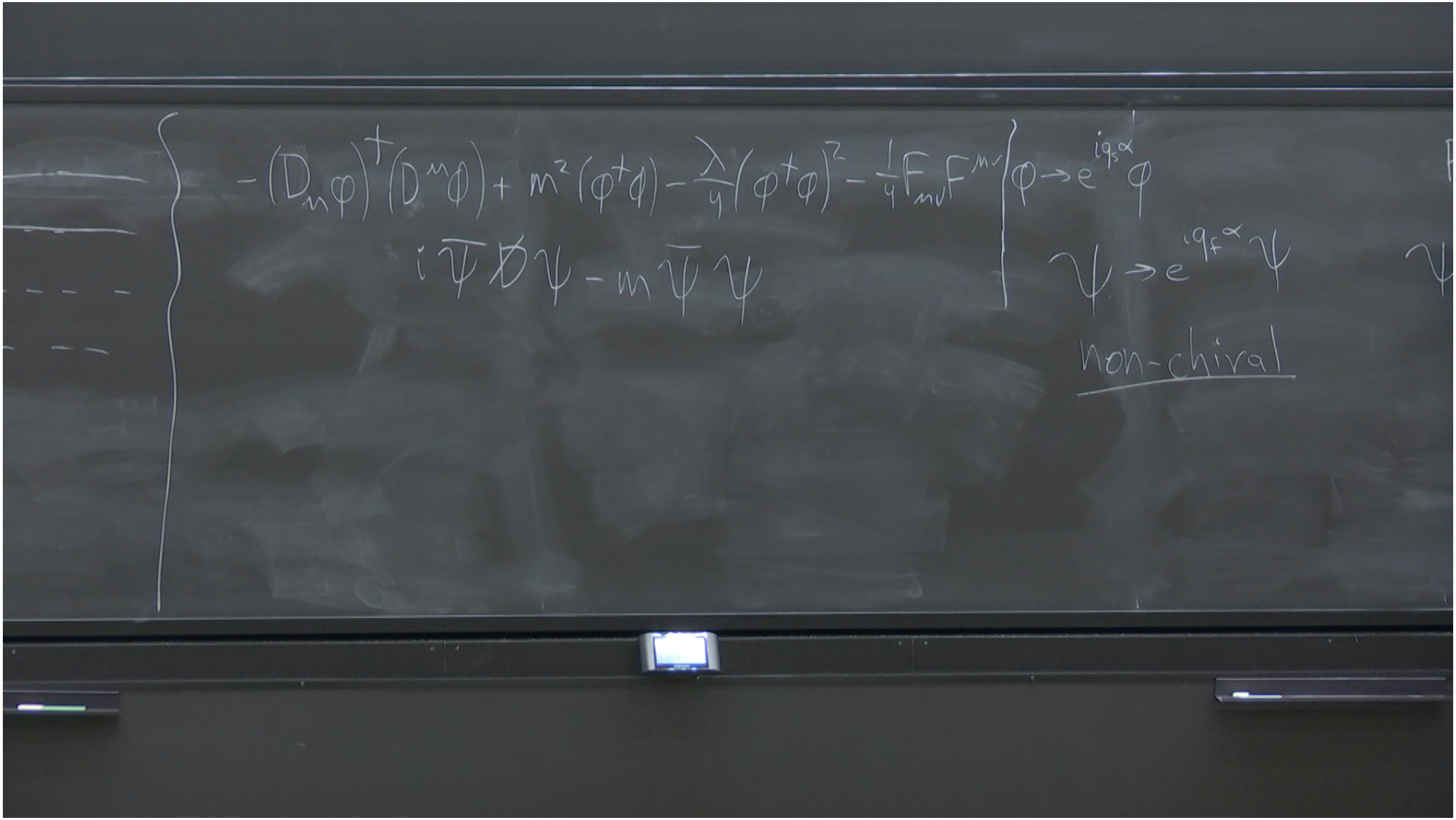
Collection: PSI 2019/2020 - Standard Model and Beyond - Part 1

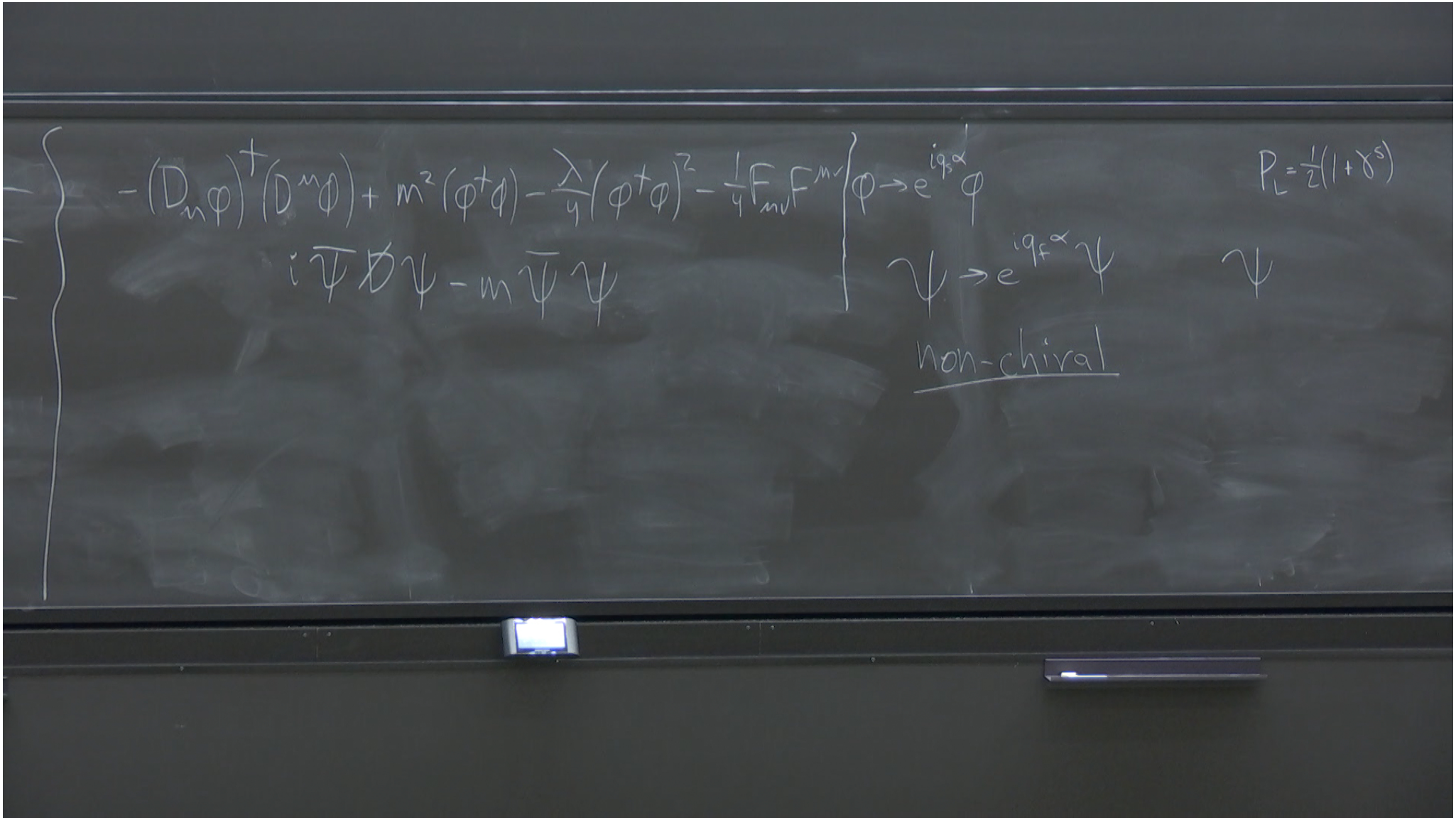
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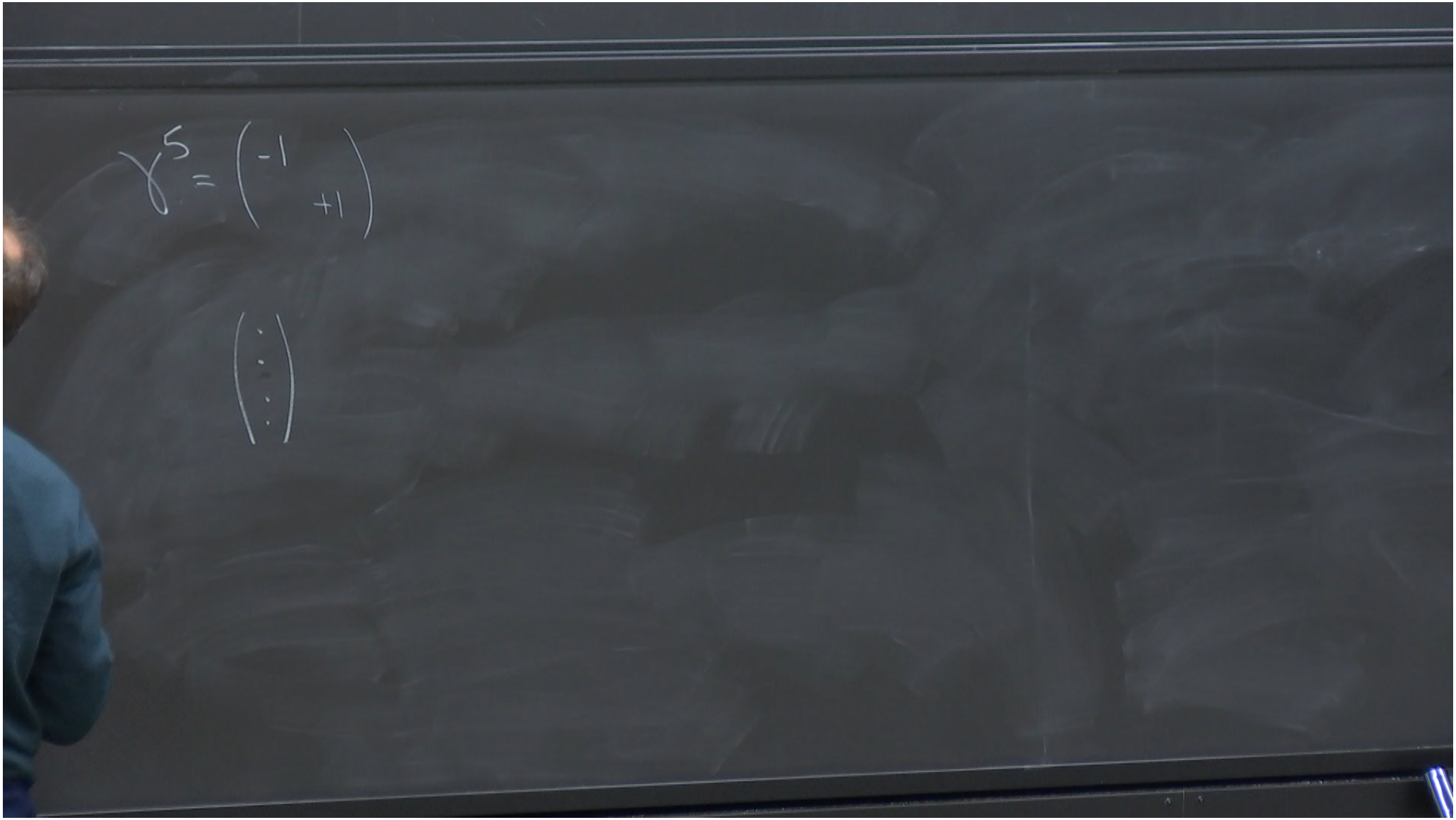
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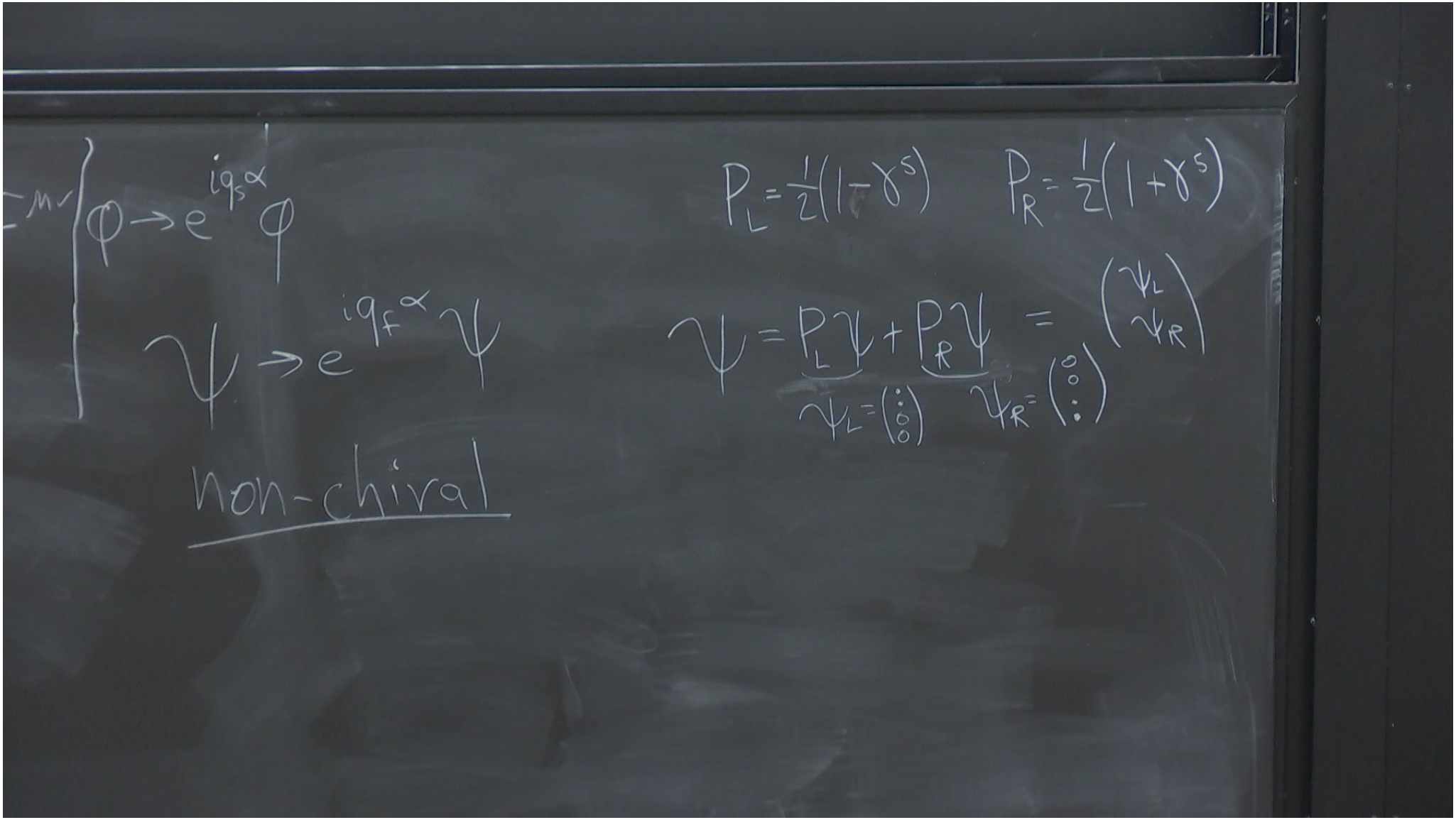

Lecture 9
$-(\partial_\mu\phi)^\dagger(\partial^\mu\phi) + m^2(\phi^\dagger\phi) - \frac{\lambda}{4}(\phi^\dagger\phi)^2$


e q
$-(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$\varphi \to e^{i\alpha}\varphi$


$-(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$
$\varphi \to e^{iq_s\alpha}\varphi$
$\psi \to e^{iq_f\alpha}\psi$
non-chiral


$-(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$
$\varphi \to e^{iq_s\alpha}\varphi$
$\psi \to e^{iq_f\alpha}\psi$
non-chiral
$P_L = \frac{1}{2}(1+\gamma^5)$
$\psi$

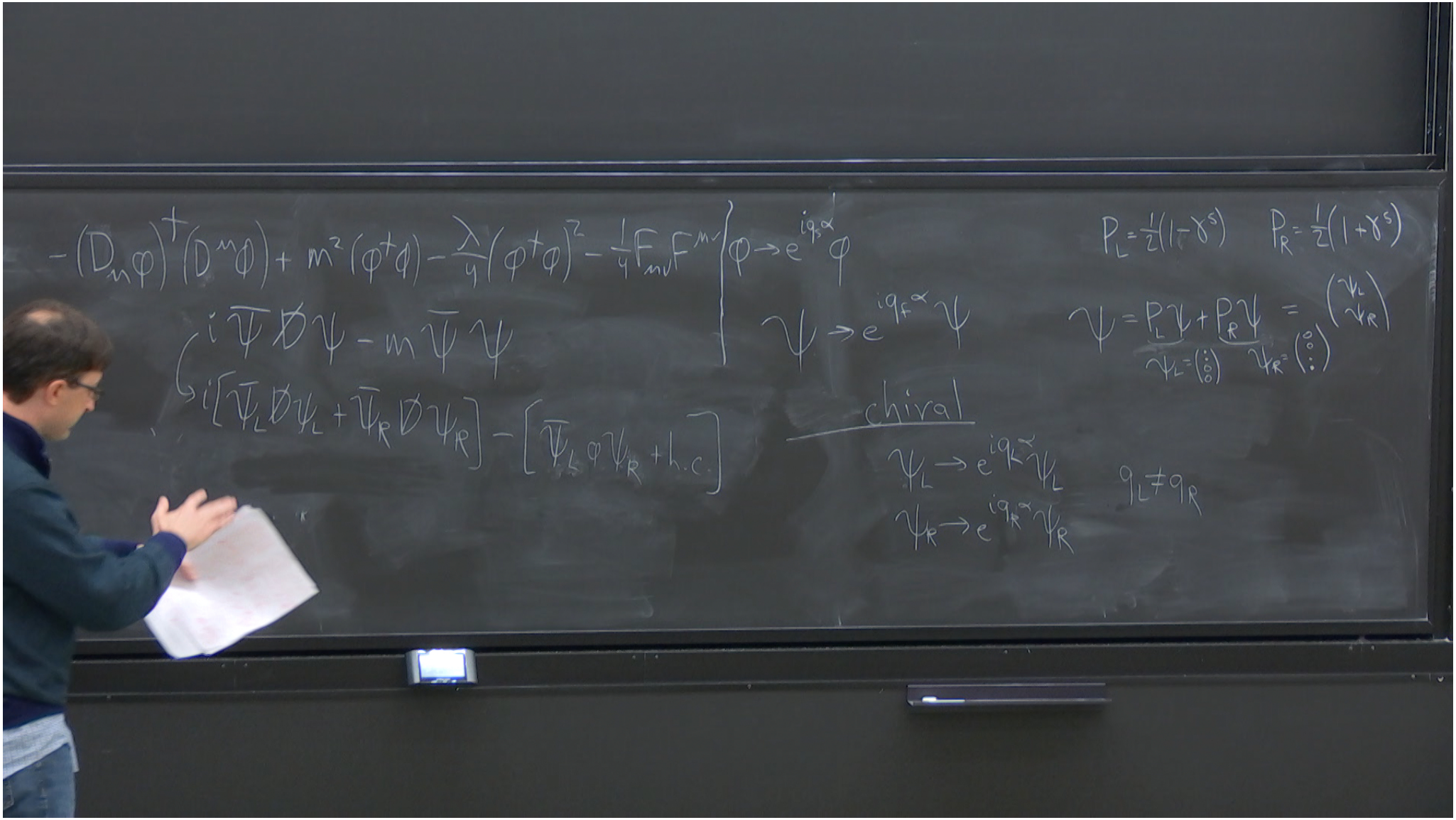

$\gamma^5 = \begin{pmatrix} -1 & \\ & +1 \end{pmatrix}$
$\begin{pmatrix} \cdot \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}$

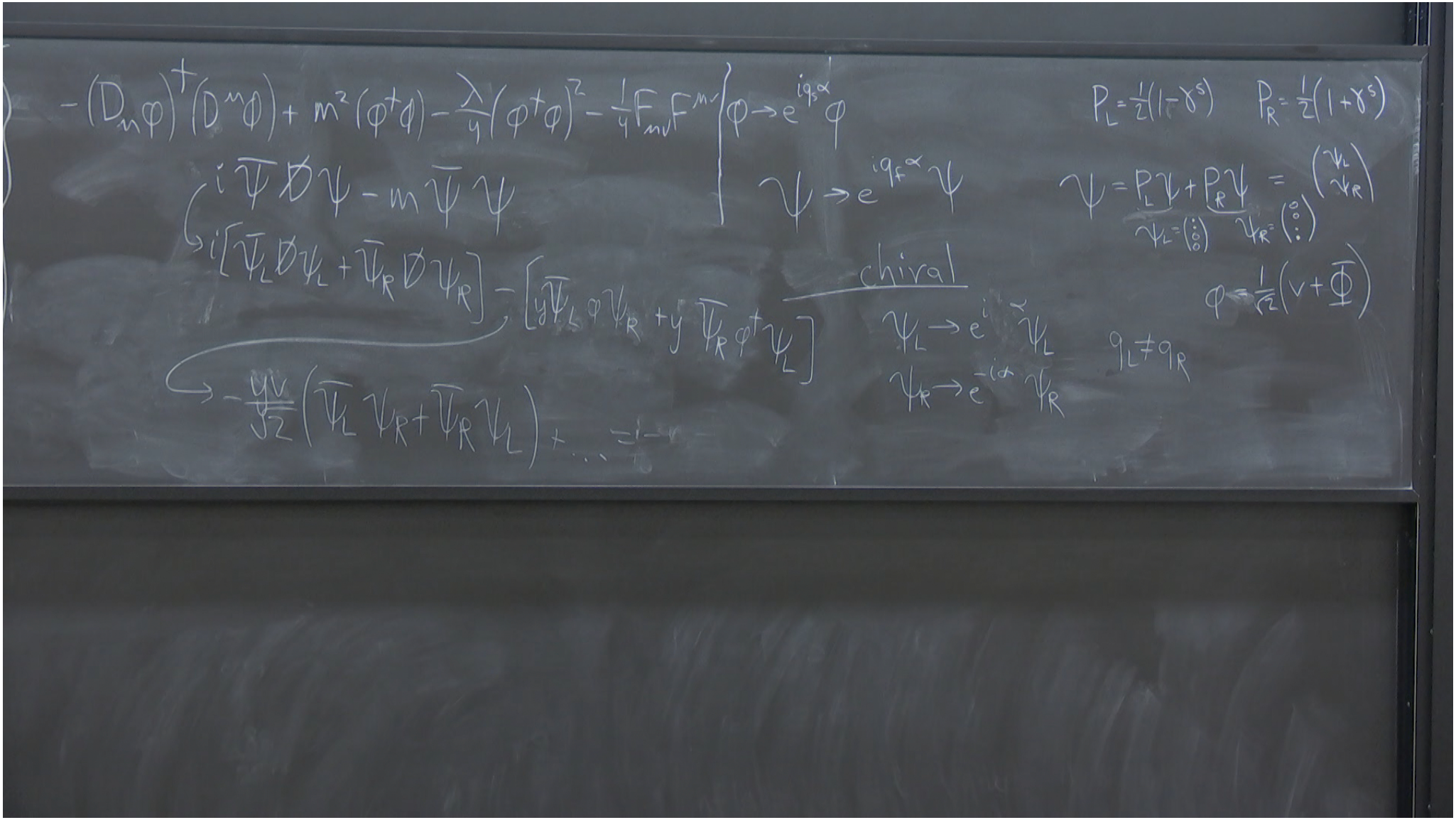

$\mathcal{L}_M$
$\varphi \to e^{iq_s\alpha}\varphi$
$\psi \to e^{iq_f\alpha}\psi$
non-chiral
$P_L = \frac{1}{2}(1-\gamma^5)$
$P_R = \frac{1}{2}(1+\gamma^5)$
$\psi = P_L\psi + P_R\psi = \begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix}$
$\psi_L = \begin{pmatrix}\vdots \\ 0 \\ 0\end{pmatrix}$
$\psi_R = \begin{pmatrix}0 \\ 0 \\ \vdots\end{pmatrix}$

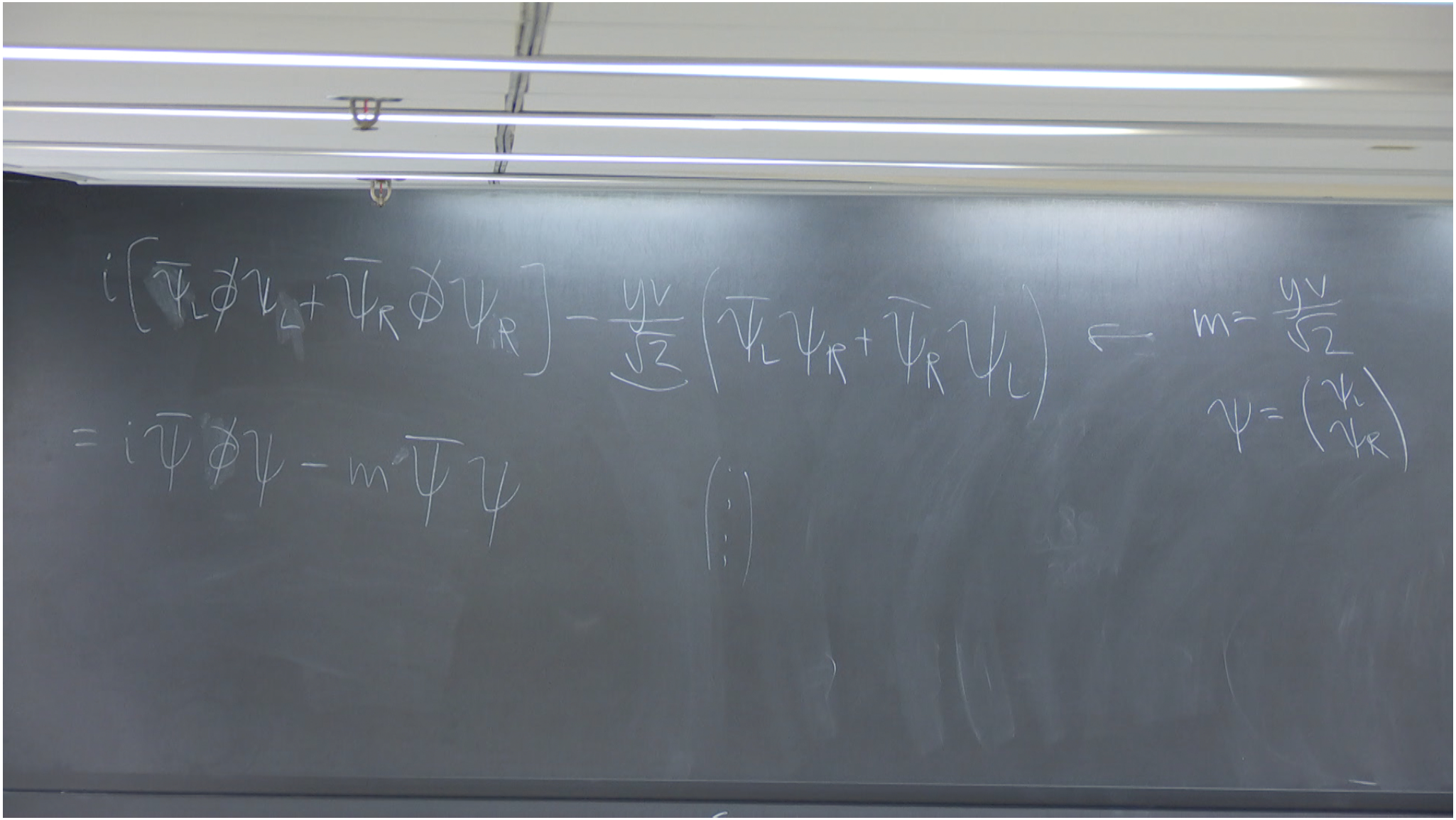
$$\left\{ -(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \right| \varphi \to e^{i q_s \alpha}\varphi$$

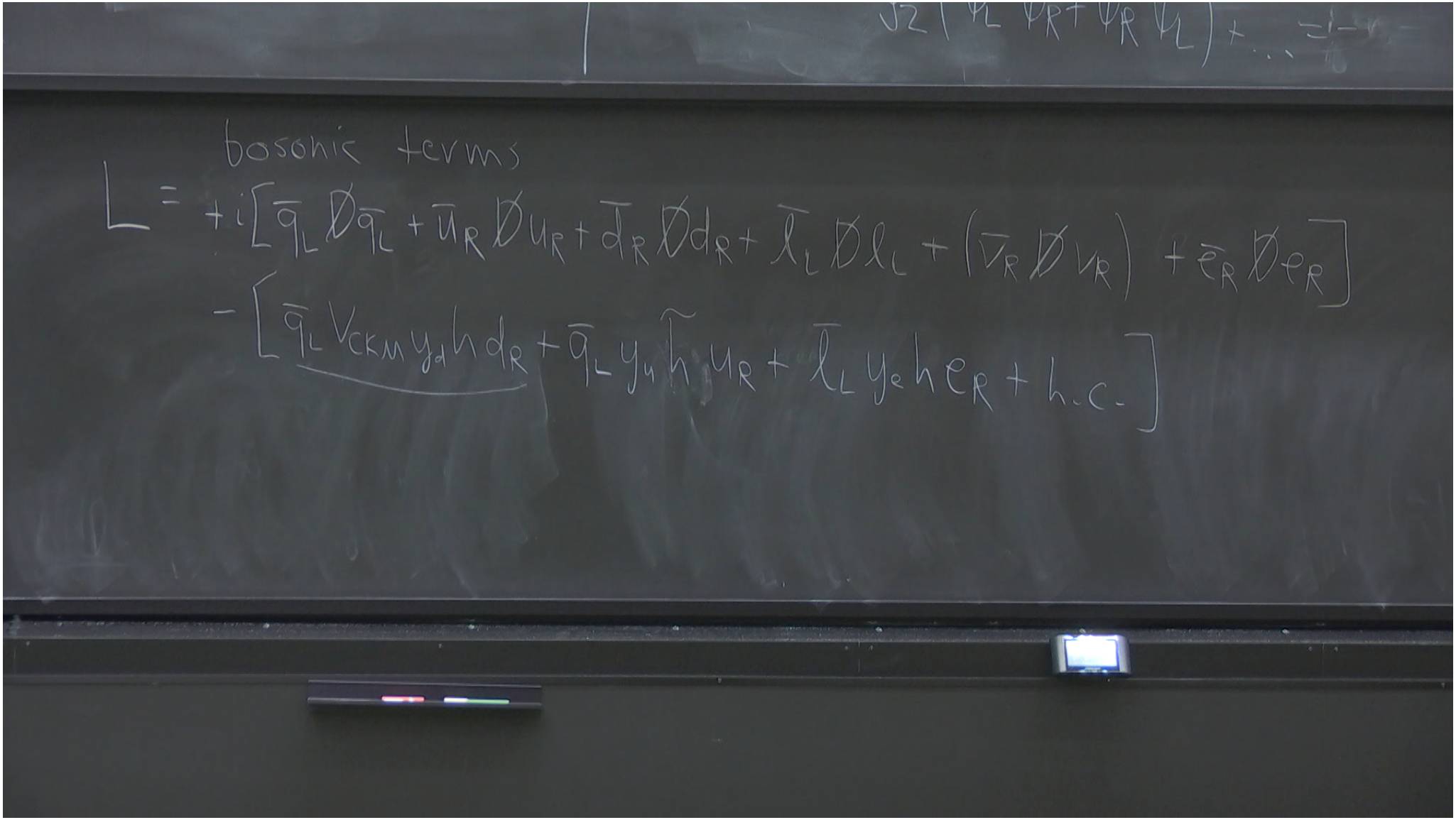
$$i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi \qquad \psi \to e^{i q_f \alpha}\psi$$

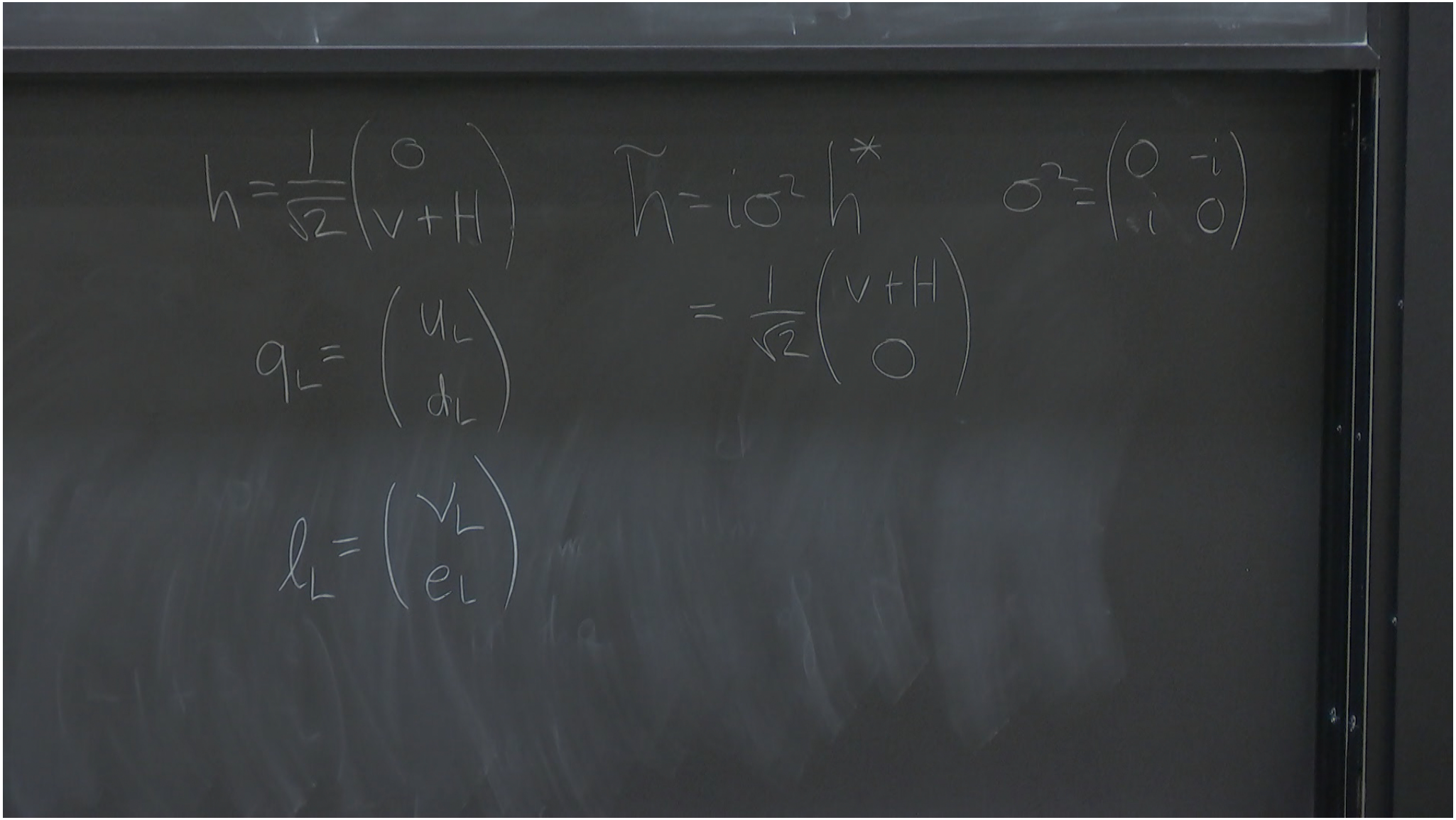
$$\hookrightarrow i\left[\bar{\psi}_L \not{D}\psi_L + \bar{\psi}_R \not{D}\psi_R\right] - m\left[\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R\right] \quad \underline{\text{non-chiral}}$$


$-(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$\varphi \to e^{iq_s\alpha}\varphi$
$\psi \to e^{iq_f\alpha}\psi$
$i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$
$i[\bar{\psi}_L\not{D}\psi_L + \bar{\psi}_R\not{D}\psi_R] - [\bar{\psi}_L\varphi\psi_R + h.c.]$
chiral
$\psi_L \to e^{iq_L\alpha}\psi_L$
$\psi_R \to e^{iq_R\alpha}\psi_R$
$q_L \neq q_R$
$P_L = \frac{1}{2}(1-\gamma^5)$
$P_R = \frac{1}{2}(1+\gamma^5)$
$\psi = \underbrace{P_L\psi}_{\psi_L=\begin{pmatrix}\psi_L\\0\end{pmatrix}} + \underbrace{P_R\psi}_{\psi_R=\begin{pmatrix}0\\\psi_R\end{pmatrix}} = \begin{pmatrix}\psi_L\\\psi_R\end{pmatrix}$


$-(D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{4}(\varphi^\dagger\varphi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$\varphi \to e^{iq_s\alpha}\varphi$
$\psi \to e^{iq_f\alpha}\psi$
$i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$
$i[\bar{\psi}_L\not{D}\psi_L + \bar{\psi}_R\not{D}\psi_R] - [y\bar{\psi}_L\varphi\psi_R + y\bar{\psi}_R\varphi^\dagger\psi_L]$
$-\frac{yv}{\sqrt{2}}(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) + \dots$
$P_L = \frac{1}{2}(1-\gamma^5)$ $P_R = \frac{1}{2}(1+\gamma^5)$
$\psi = P_L\psi + P_R\psi = \begin{pmatrix}\psi_L\\ \psi_R\end{pmatrix}$
$\psi_L = \begin{pmatrix}\cdot\\ \cdot\\ \cdot\end{pmatrix}$ $\psi_R = \begin{pmatrix}\cdot\\ \cdot\\ \cdot\end{pmatrix}$
$\varphi = \frac{1}{\sqrt{2}}(v+\Phi)$
chiral
$\psi_L \to e^{i\alpha}\psi_L$
$\psi_R \to e^{-i\alpha}\psi_R$
$q_L \neq q_R$


$i\left[\bar{\psi}_L \not{\partial} \psi_L + \bar{\psi}_R \not{\partial} \psi_R\right] - \frac{yv}{\sqrt{2}}\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$
$m = \frac{yv}{\sqrt{2}}$
$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$
$= i\bar{\psi} \not{\partial} \psi - m\bar{\psi}\psi$


bosonic terms
$\mathcal{L} = +i[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + (\bar{\nu}_R \not{D} \nu_R) + \bar{e}_R \not{D} e_R]$
$- [\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \tilde{h} u_R + \bar{l}_L y_e h e_R + h.c.]$


$h = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$
$\tilde{h} = i\sigma^2 h^*$
$= \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix}$
$\sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

bosonic terms

$$\mathcal{L} = +i\left[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + \left(\bar{\nu}_R \not{D} \nu_R\right) + \bar{e}_R \not{D} e_R\right]$$

$$- \left[\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \tilde{h} u_R + \bar{l}_L y_e h e_R + h.c.\right]$$

$$= i\left[\bar{u}_L \not{\partial} u_L + \bar{d}_L \not{\partial} d_L + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R + \bar{\nu}_L \not{\partial} \nu_L + \bar{e}_L \not{\partial} e_L + \bar{e}_R \not{\partial} e_R\right]$$

$$\frac{v}{\sqrt{2}}\left(\bar{d}_L V_{CKM} y_d d_R + \bar{u}_L y_u u_R + \bar{e}_L y_e e_R + h.c.\right)$$

bosonic terms

$$\mathcal{L} = +i\left[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + (\bar{\nu}_R \not{D} \nu_R) + \bar{e}_R \not{D} e_R\right]$$

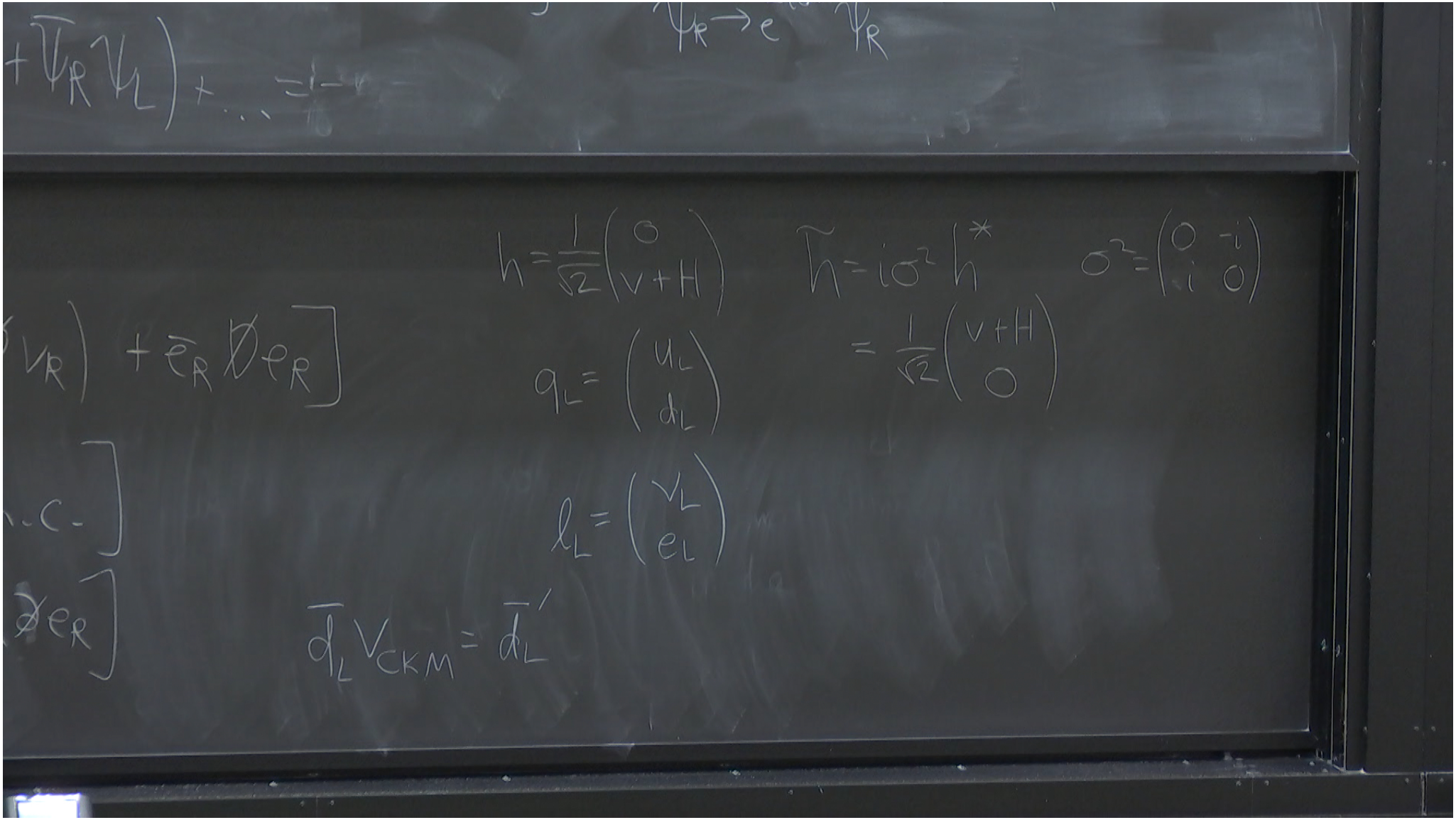
$$- \left[\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \tilde{h} u_R + \bar{l}_L y_e h e_R + \text{h.c.}\right]$$

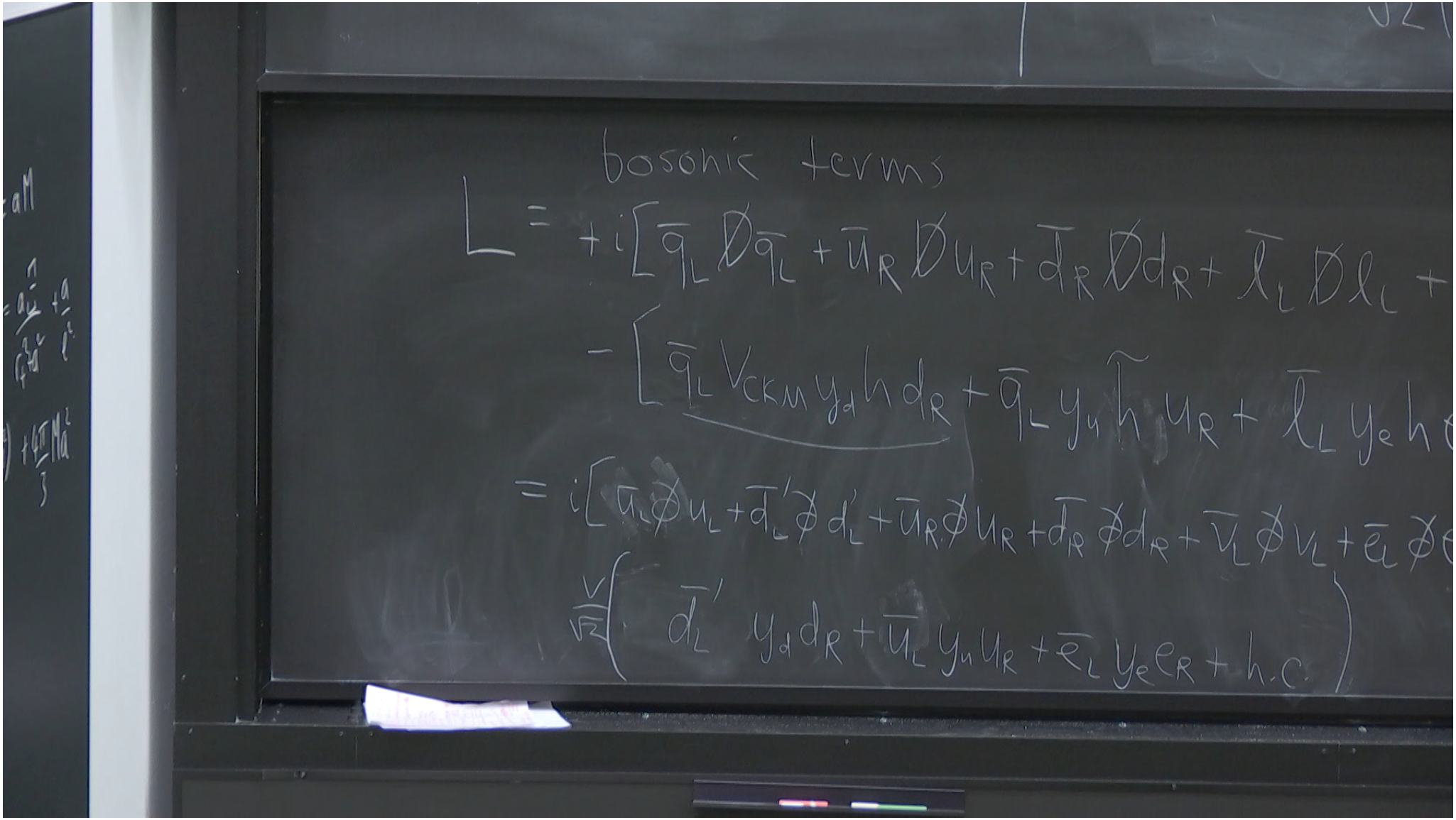
$$= i\left[\bar{u}_L \not{\partial} u_L + \bar{d}_L \not{\partial} d_L + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R + \bar{\nu}_L \not{\partial} \nu_L + \bar{e}_L \not{\partial} e_L + \bar{e}_R \not{\partial} e_R\right]$$

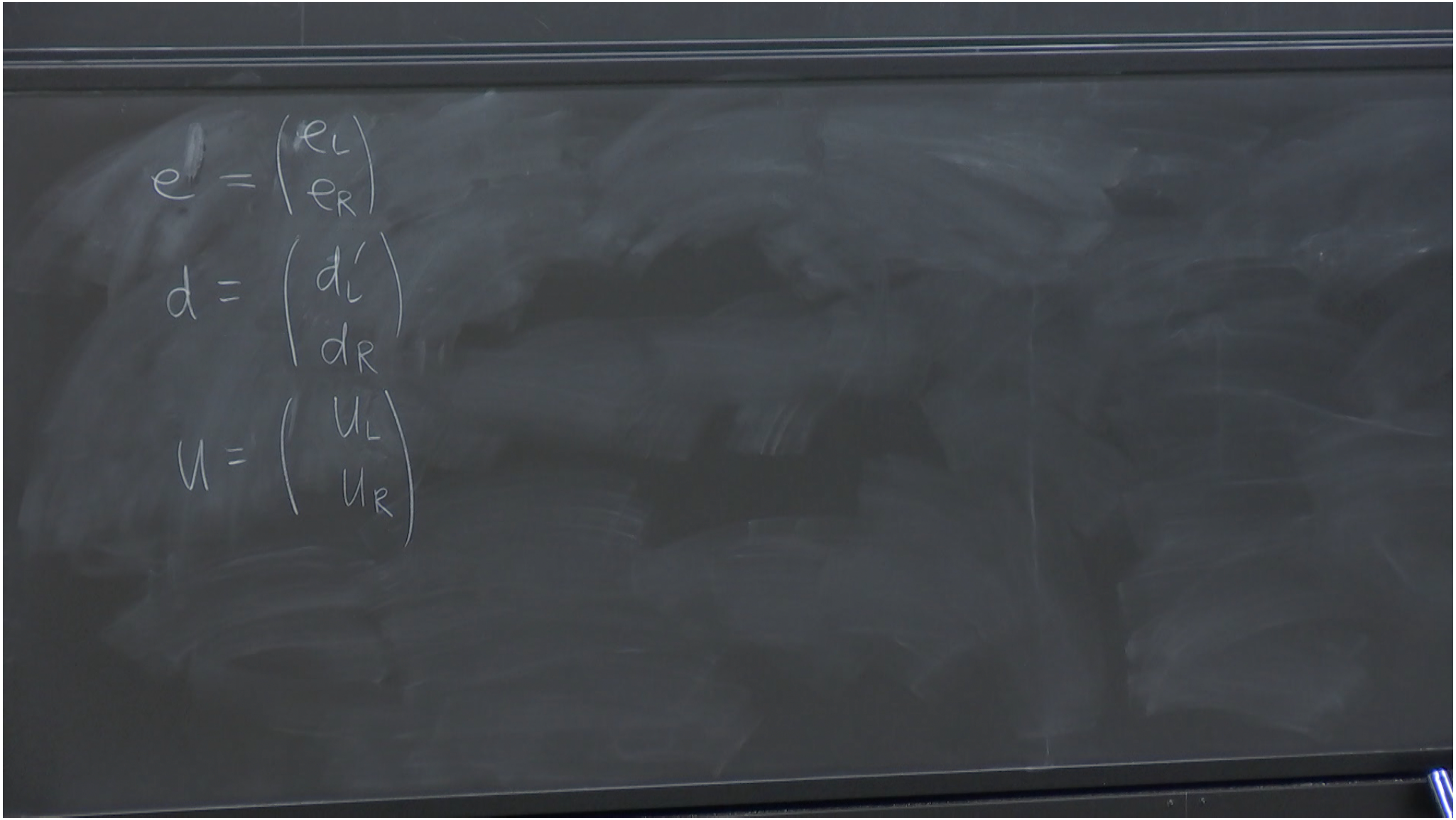
$$\frac{v}{\sqrt{2}}\left(\bar{d}_L V_{CKM} y_d d_R + \bar{u}_L y_u u_R + \bar{e}_L y_e e_R + \text{h.c.}\right)$$

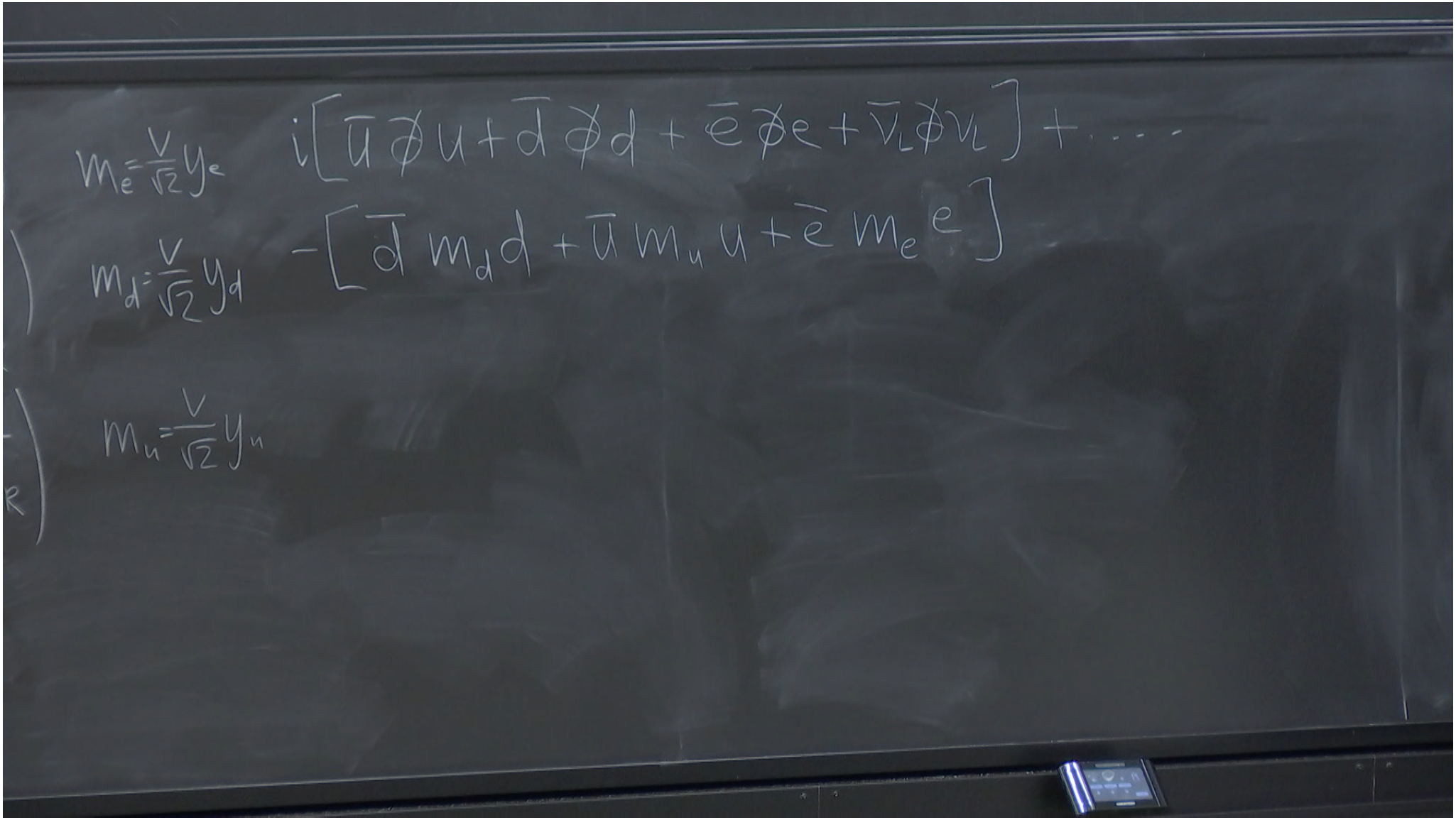
$$e = e_L + e_R = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

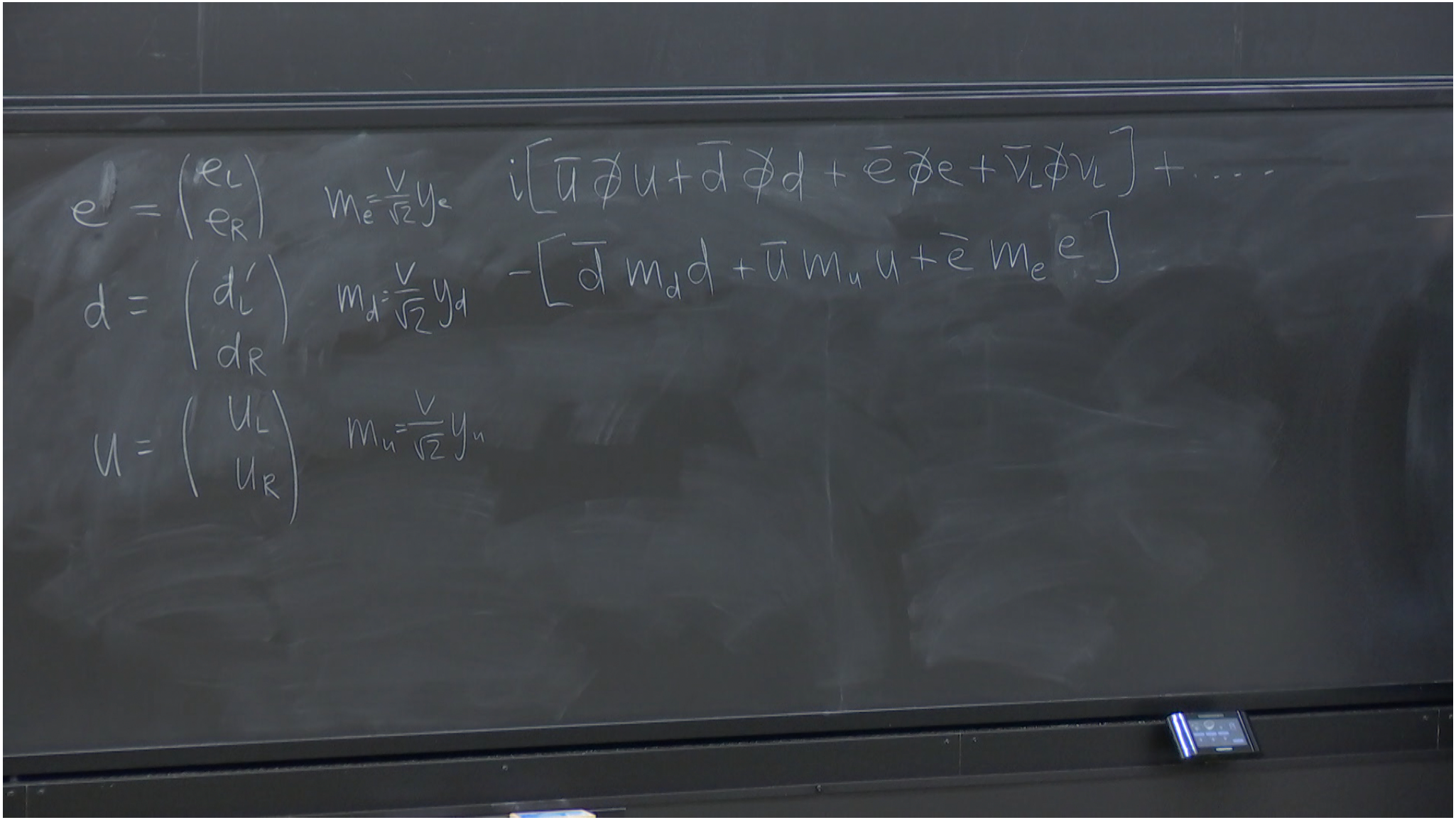
$$-\underbrace{\frac{v}{\sqrt{2}} y_e}_{m_e} \bar{e} e$$

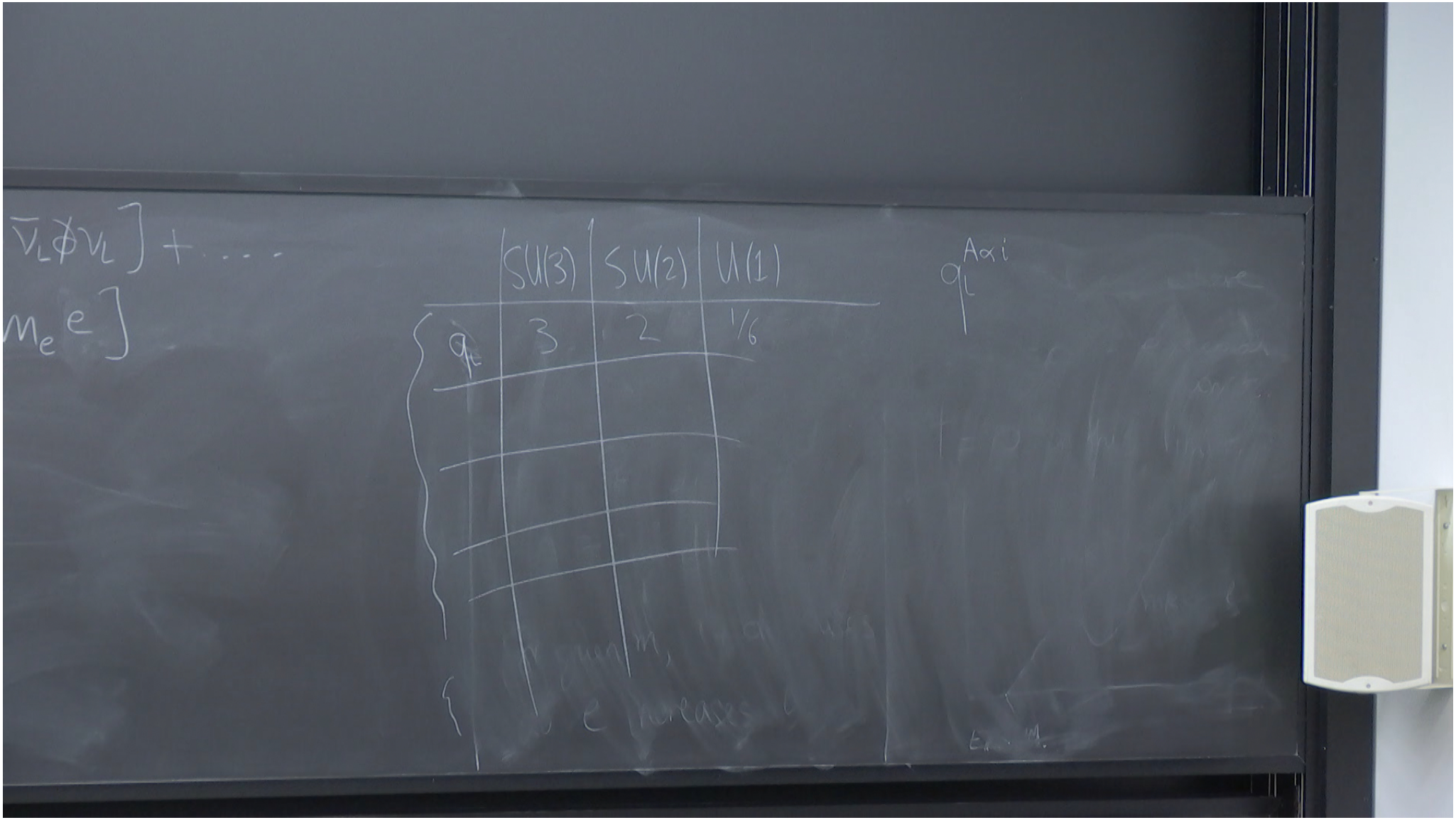

$+\bar{\psi}_R \psi_L) + \ldots$
$\psi_R \to e \quad \psi_R$
$h = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$
$\tilde{h} = i\sigma^2 h^*$
$\sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
$= \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix}$
$\psi_R) + \bar{e}_R \not{D} e_R]$
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
$\bar{d}_L V_{CKM} = \bar{d}'_L$

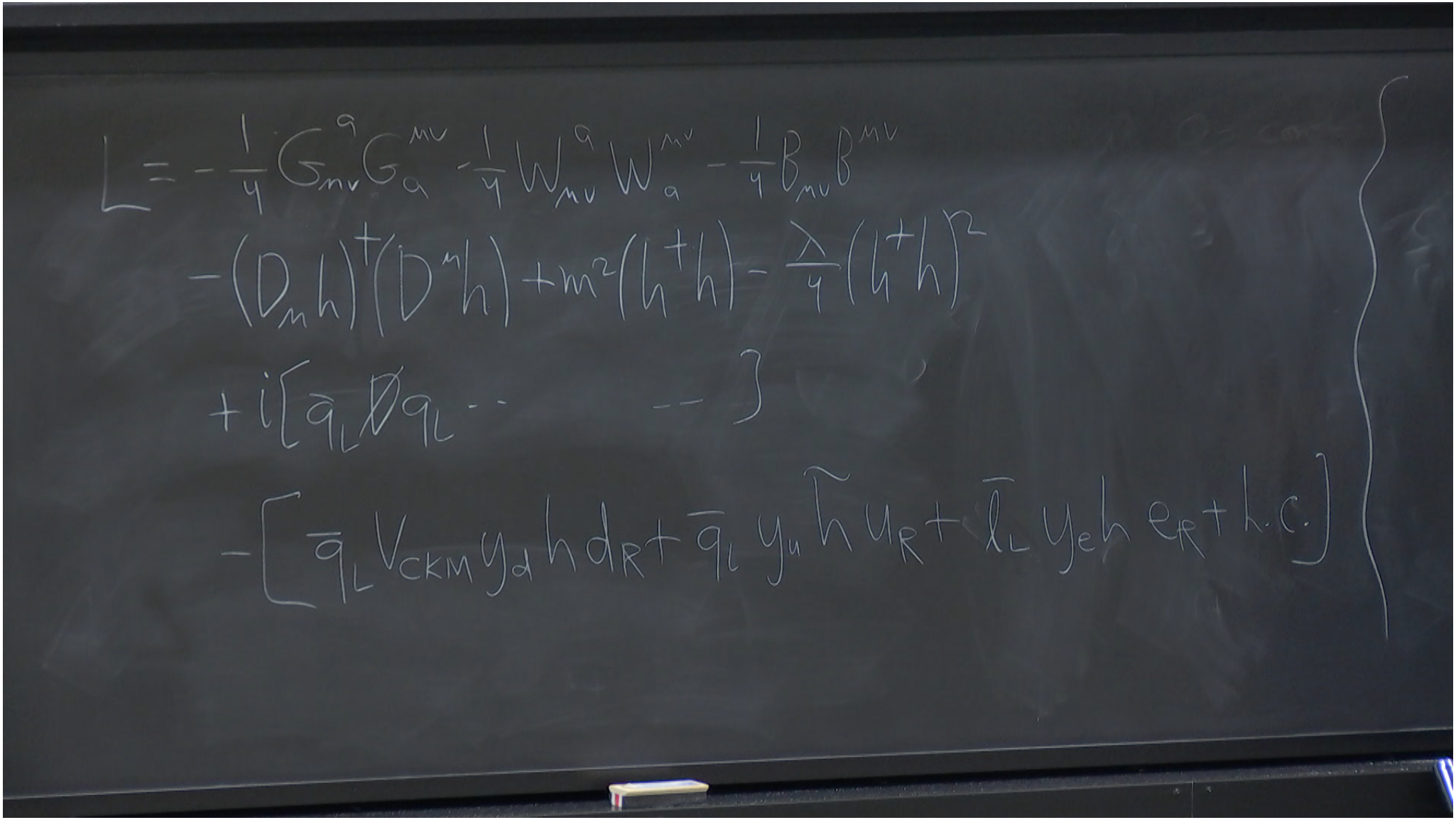

bosonic terms
$\mathcal{L} = +i[\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L +$
$- [\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \tilde{h} u_R + \bar{l}_L y_e h$
$= i[\bar{u}_L \not{\partial} u_L + \bar{d}'_L \not{\partial} d'_L + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R + \bar{\nu}_L \not{\partial} \nu_L + \bar{e}_L \not{\partial}$
$\frac{v}{\sqrt{2}}( \bar{d}'_L y_d d_R + \bar{u}_L y_u u_R + \bar{e}_L y_e e_R + h.c.)$

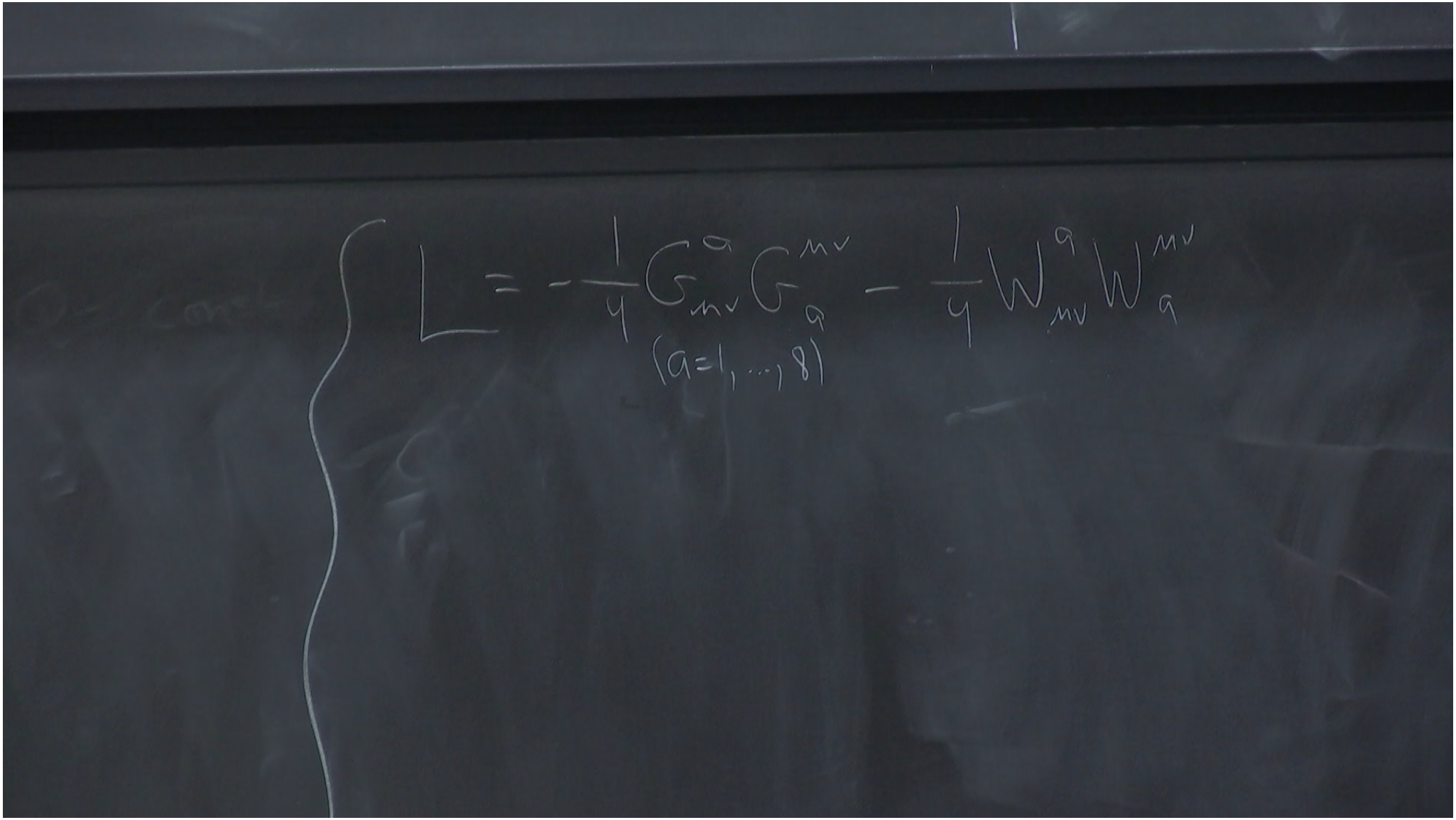

$e = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$
$d = \begin{pmatrix} d'_L \\ d_R \end{pmatrix}$
$u = \begin{pmatrix} u_L \\ u_R \end{pmatrix}$

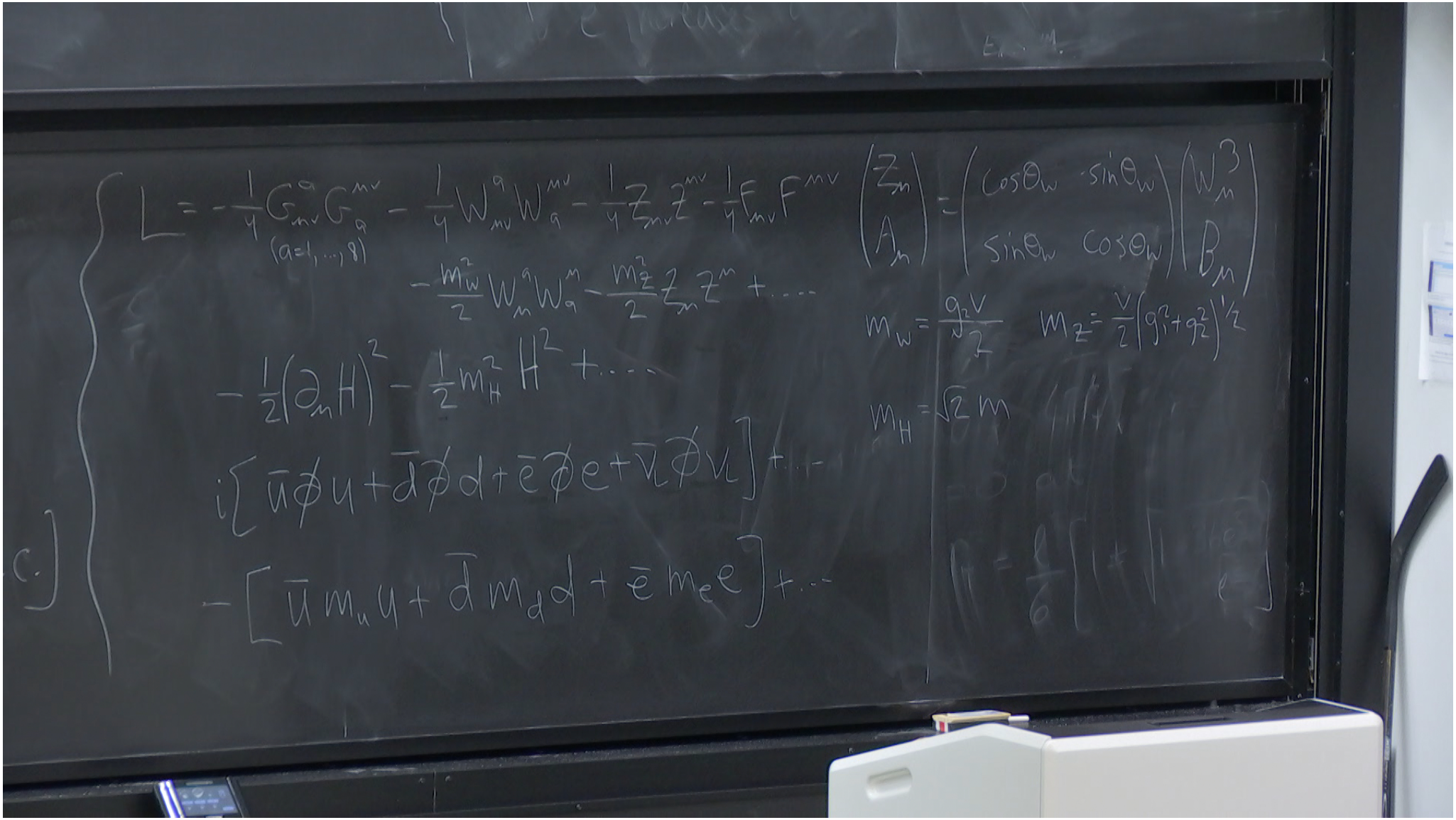

$m_e = \frac{v}{\sqrt{2}} y_e$
$i[\bar{u} \not{\partial} u + \bar{d} \not{\partial} d + \bar{e} \not{\partial} e + \bar{\nu}_L \not{\partial} \nu_L] + \dots$
$m_d = \frac{v}{\sqrt{2}} y_d$
$-[\bar{d} m_d d + \bar{u} m_u u + \bar{e} m_e e]$
$m_u = \frac{v}{\sqrt{2}} y_u$

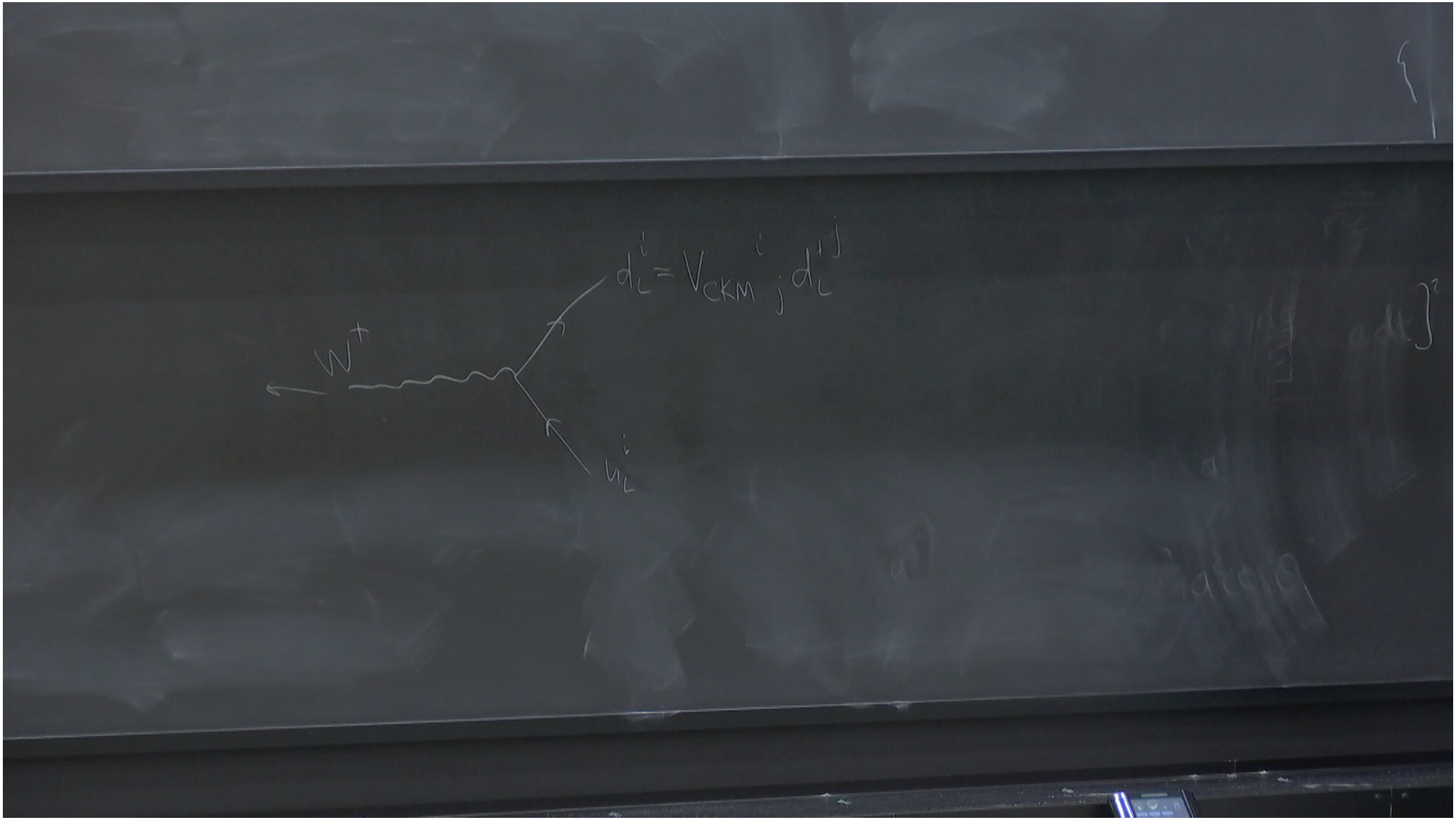

$e = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$ $m_e = \frac{v}{\sqrt{2}} y_e$
$d = \begin{pmatrix} d'_L \\ d_R \end{pmatrix}$ $m_d = \frac{v}{\sqrt{2}} y_d$
$u = \begin{pmatrix} u_L \\ u_R \end{pmatrix}$ $m_u = \frac{v}{\sqrt{2}} y_u$
$i[\bar{u}\partial\!\!\!/ u + \bar{d}\partial\!\!\!/ d + \bar{e}\partial\!\!\!/ e + \bar{\nu}_L \partial\!\!\!/ \nu_L] + \dots$
$-[\bar{d} m_d d + \bar{u} m_u u + \bar{e} m_e e]$


$\bar{\nu}_L \phi \nu_L ] + \cdots$
$m_e e ]$
SU(3) SU(2) U(1)
$q_L$ 3 2 1/6
$q_L^{Axi}$


$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$
$-(D_\mu h)^\dagger (D^\mu h) + m^2 (h^\dagger h) - \frac{\lambda}{4} (h^\dagger h)^2$
$+ i[\bar{q}_L \not{D} q_L \cdots \quad \cdots]$
$-[\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \tilde{h} u_R + \bar{l}_L y_e h e_R + h.c.]$


$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a - \frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a$
$(a = 1, \ldots, 8)$


$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a - \frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$(a = 1, \dots, 8)$
$- \frac{m_W^2}{2} W^a_\mu W^\mu_a - \frac{m_Z^2}{2} Z_\mu Z^\mu + \dots$
$- \frac{1}{2} (\partial_\mu H)^2 - \frac{1}{2} m_H^2 H^2 + \dots$
$i[\bar{u} \not\partial u + \bar{d} \not\partial d + \bar{e} \not\partial e + \bar{\nu}_L \not\partial \nu_L] + \dots$
$- [\bar{u} m_u u + \bar{d} m_d d + \bar{e} m_e e] + \dots$
$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$
$m_W = \frac{g_2 v}{2}$ $m_Z = \frac{v}{2} (g_1^2 + g_2^2)^{1/2}$
$m_H = \sqrt{2}\, m$


$d_L^i = V_{CKM}{}^i{}_j\, d_L'^j$
$W^+$
$u_L^i$