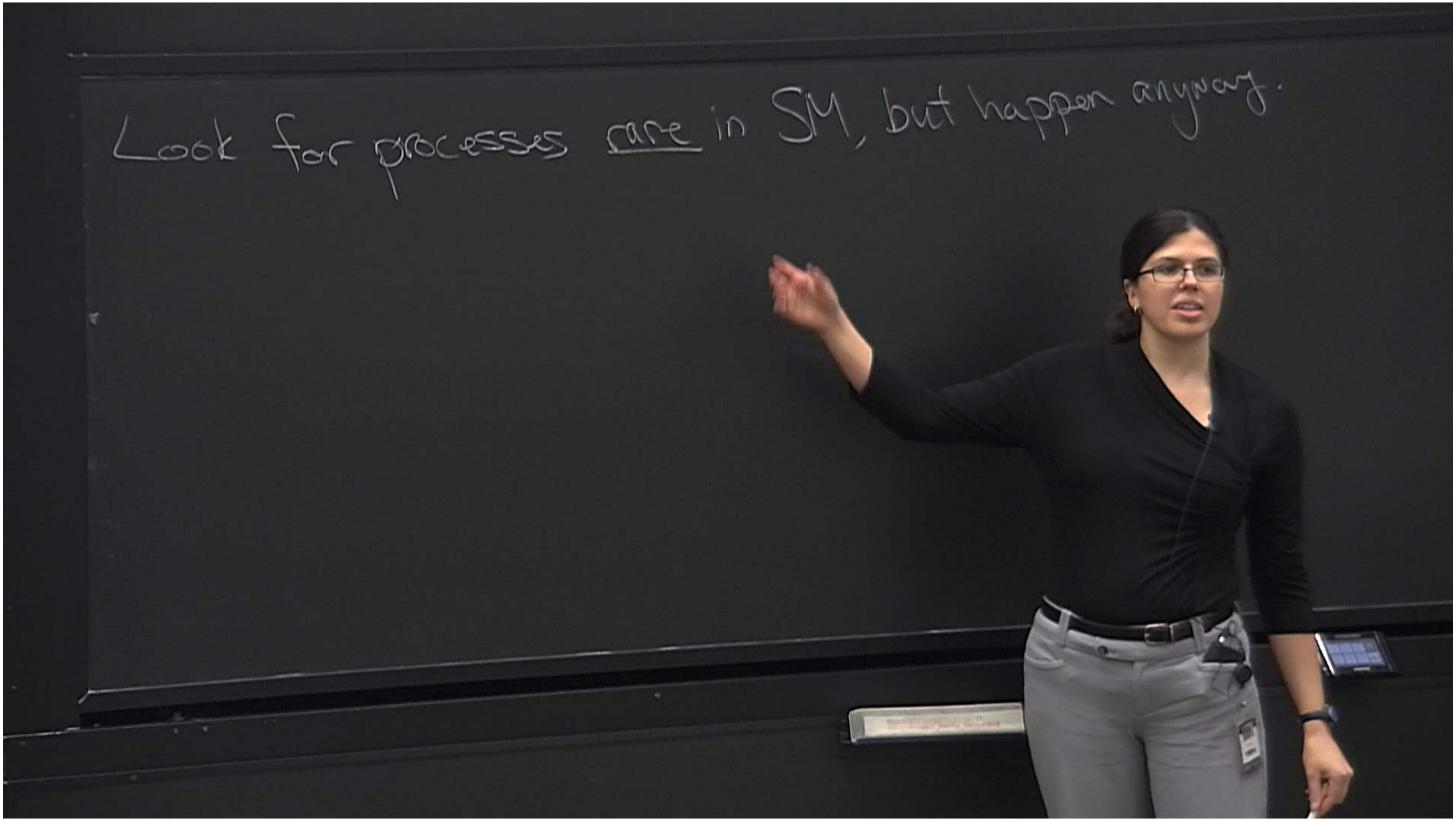
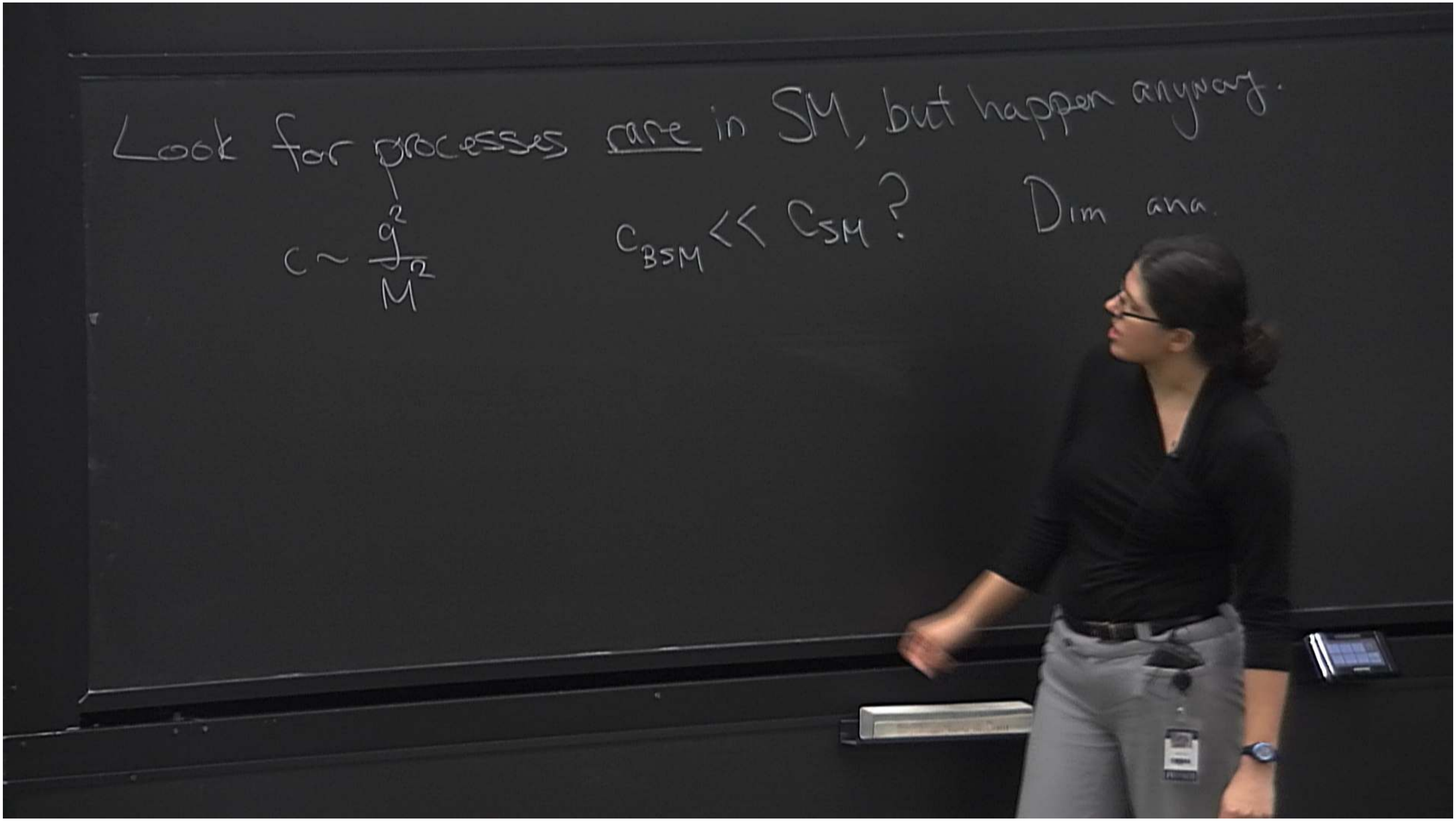
Title: 12/13 PSI - Beyond the Standard Model Lecture 10

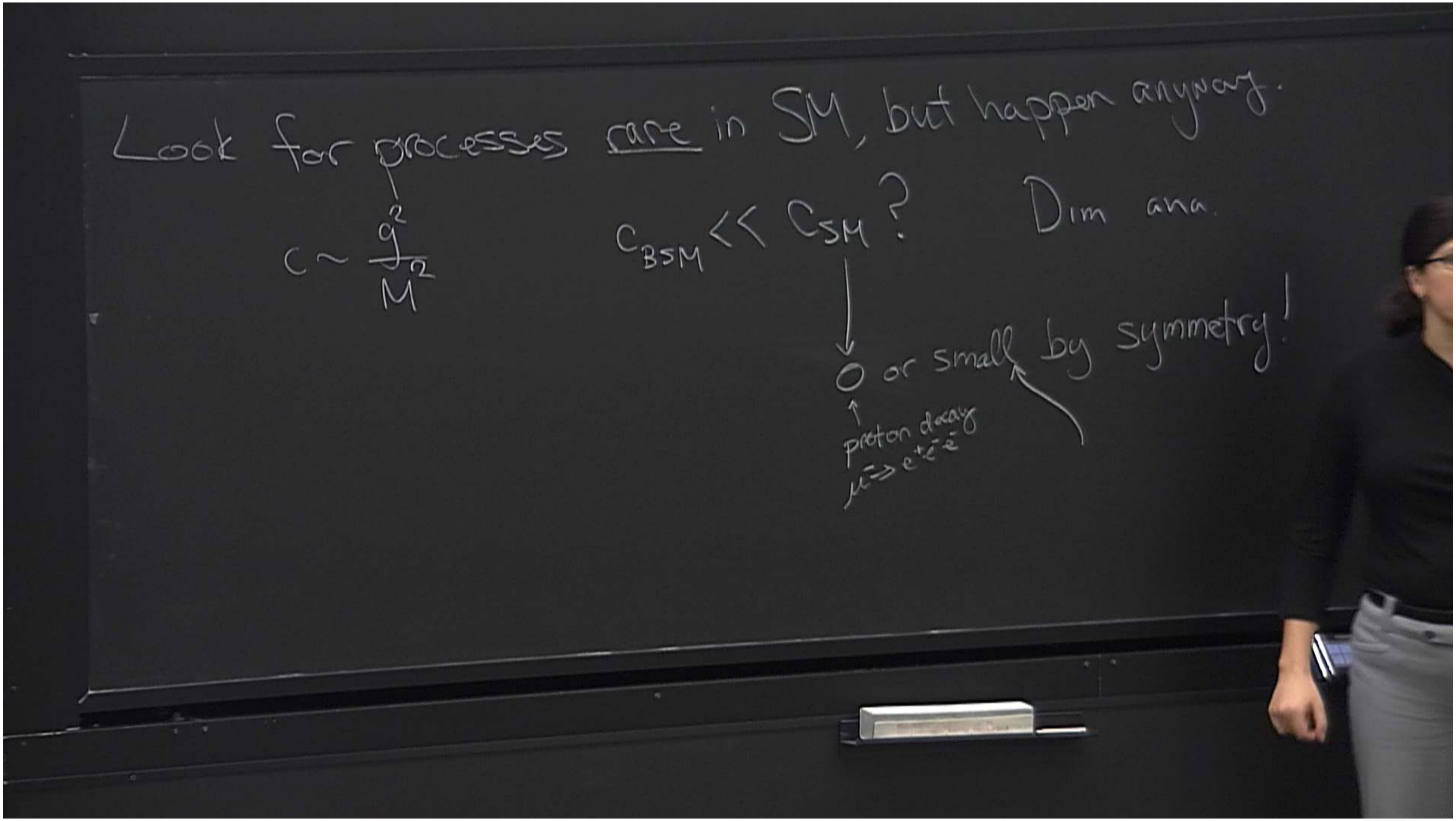
Date: Mar 04, 2013 09:00 AM

URL: http://pirsa.org/13030033

Abstract:


Look for processes rare in SM, but happen anyway.


Look for processes rare in SM, but happen anyway.
c ~ g^2/M^2
c_BSM << c_SM ?
Dim ana.


Look for processes rare in SM, but happen anyway.
$c \sim \frac{g^2}{M^2}$
$c_{BSM} << c_{SM}$?
Dim ana.
0 or small by symmetry!
proton decay
$\mu^- \Rightarrow e^+ e^- e^-$

Look for processes rare in SM, but happen anyway.

$$c \sim \frac{g^2}{M^2}$$

$c_{BSM} \ll c_{SM}$?   Dim ana

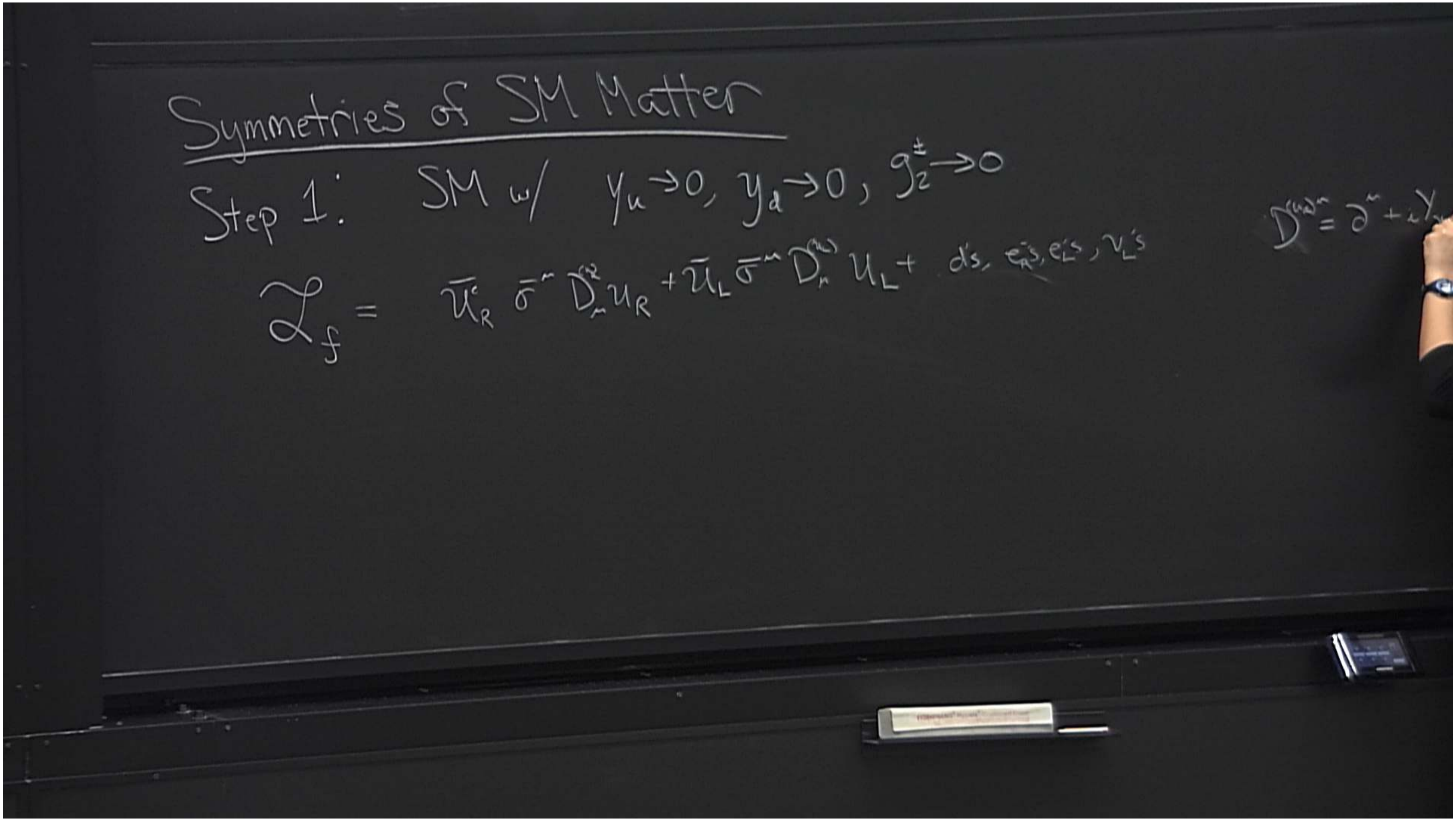
0 or small by symmetry!

proton decay

$\mu^- \to e^+ e^- e^-$

$K^0 \bar{K}^0$ mixing $\to$ $c_{SM} \sim \frac{1}{(10^3\,\mathrm{TeV})^2}$


0 or small by symmetry!
proton decay
μ⁻ → e⁺e⁻e⁻
K°K̄° mixing → C_SM ~ 1/(10³ TeV)² << g₂²/(100 GeV)²


Symmetries of SM Matter
Step 1: SM w/ $y_u \to 0$, $y_d \to 0$, $g_2^{\pm} \to 0$
$\mathcal{L}_f = \bar{u}_R^c \bar{\sigma}^\mu D_\mu^{(R)} u_R + \bar{u}_L \bar{\sigma}^\mu D_\mu^{(u)} u_L +$ d's, e_R's, e_L's, ν_L's
$D^{(u)\mu} = \partial^\mu + i Y$

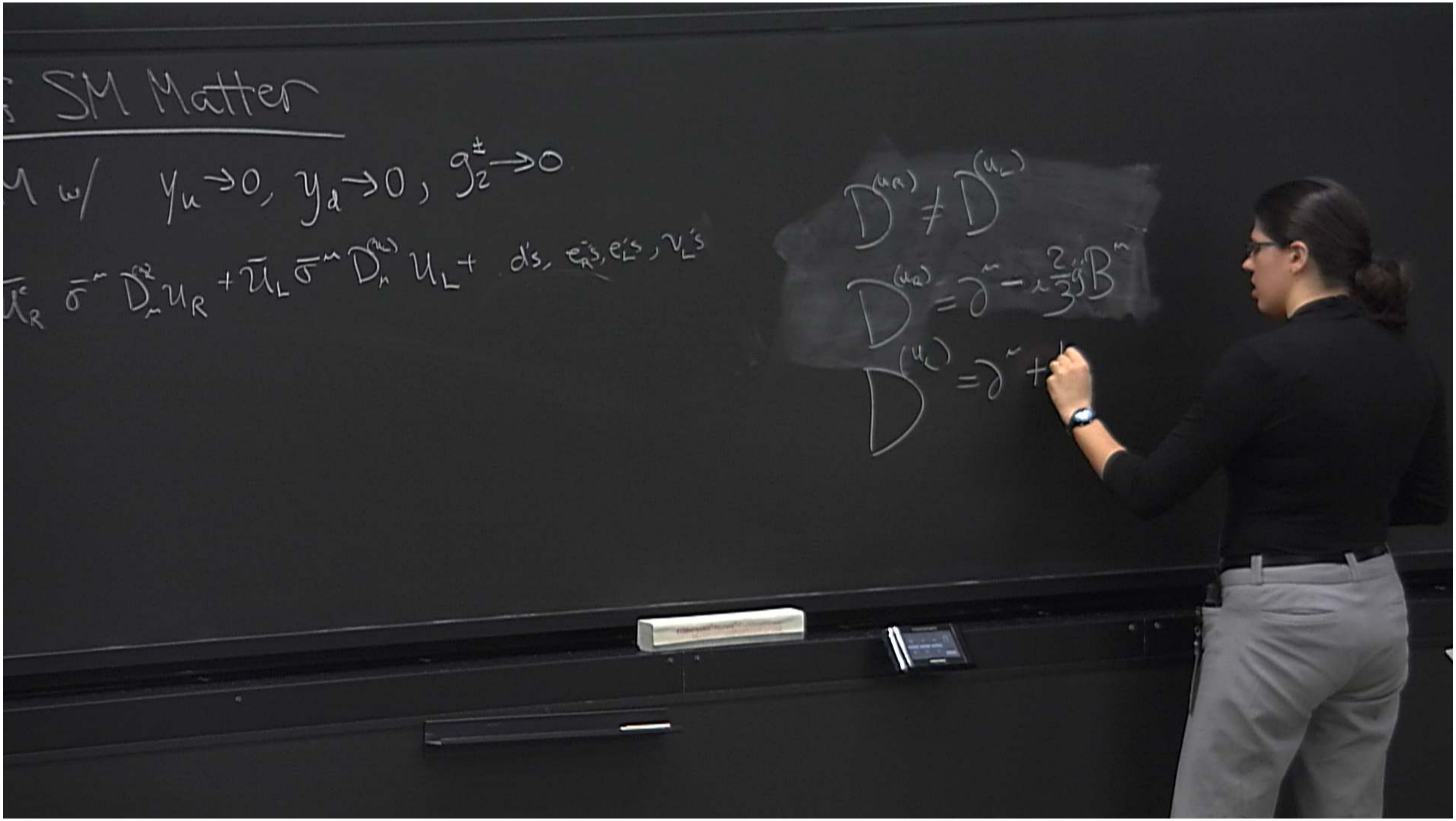
SM Matter

M w/ $y_u \to 0$, $y_d \to 0$, $g_2^{\pm} \to 0$

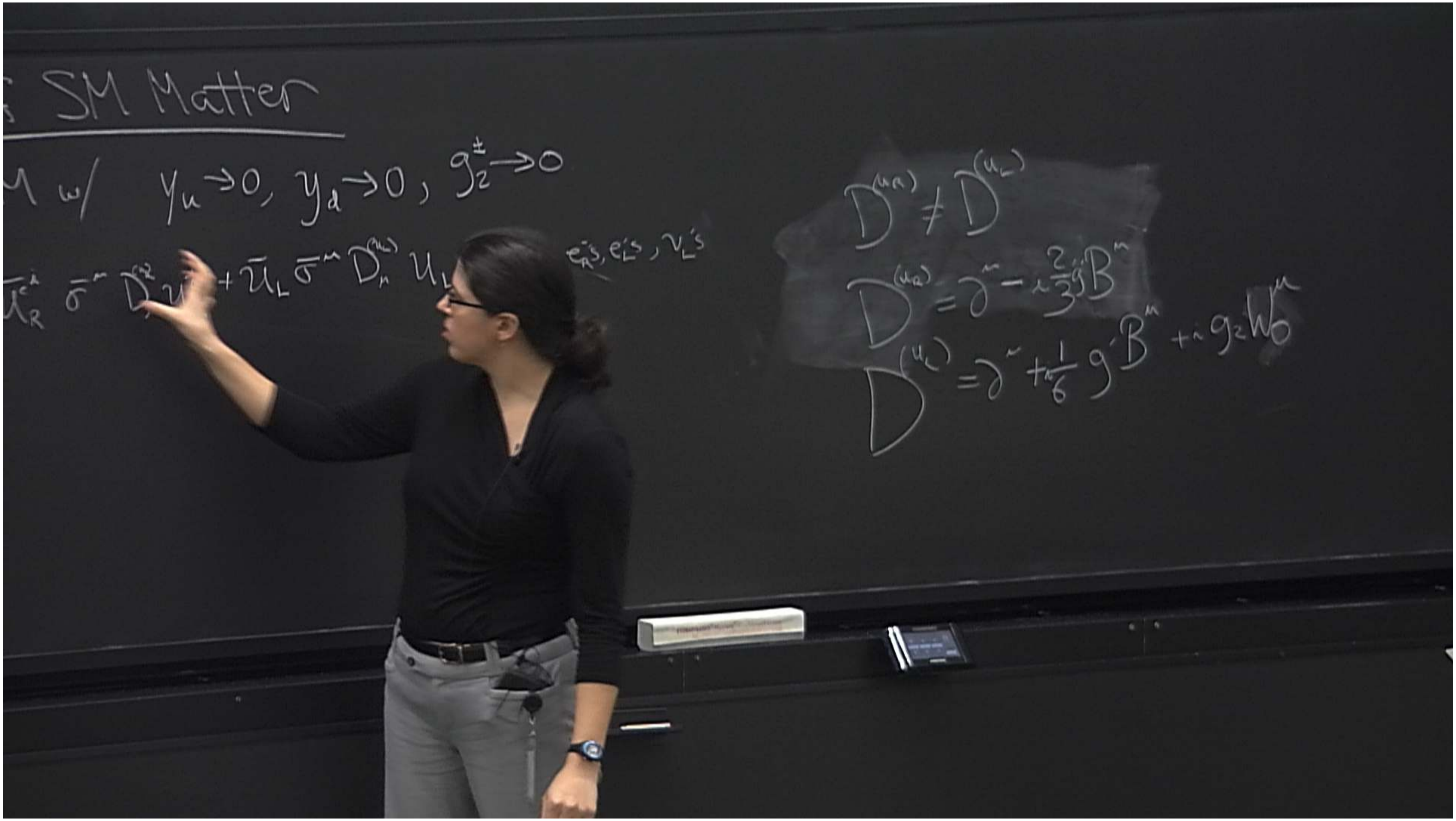
$\bar{u}^c_R \bar{\sigma}^\mu D^{(u_R)}_\mu u_R + \bar{u}_L \bar{\sigma}^\mu D^{(u_L)}_\mu u_L +$ d's, e_R^-'s, e_L^-'s, ν_L's

$D^{(u_R)\mu} = \partial^\mu + i Y_{u_R} g B^\mu$

$D^{(u_L)} = \partial^\mu + i Y_{u_L} g B^\mu + i g_2 Z^\mu$



SM Matter
M w/ y_u → 0, y_d → 0, g_2^± → 0
ū_R σ̄^μ D_μ^(uR) u_R + ū_L σ̄^μ D_μ^(uL) u_L + d's, e_R's, e_L's, ν_L's
D^(uR) ≠ D^(uL)
D^(uR) = ∂^μ − i 2/3 g' B^μ
D^(uL) = ∂^μ +


SM Matter
w/ $y_u \to 0$, $y_d \to 0$, $g_2^{\pm} \to 0$
$e_R^- s, e_L^- s, \nu_L^- s$
$D^{(u_R)} \neq D^{(u_L)}$
$D^{(u_R)} = \partial^\mu - i\frac{2}{3}g' B^\mu$
$D^{(u_L)} = \partial^\mu + i\frac{1}{6}g' B^\mu + i g_2 W_0^\mu$

Symmetries of SM Matter

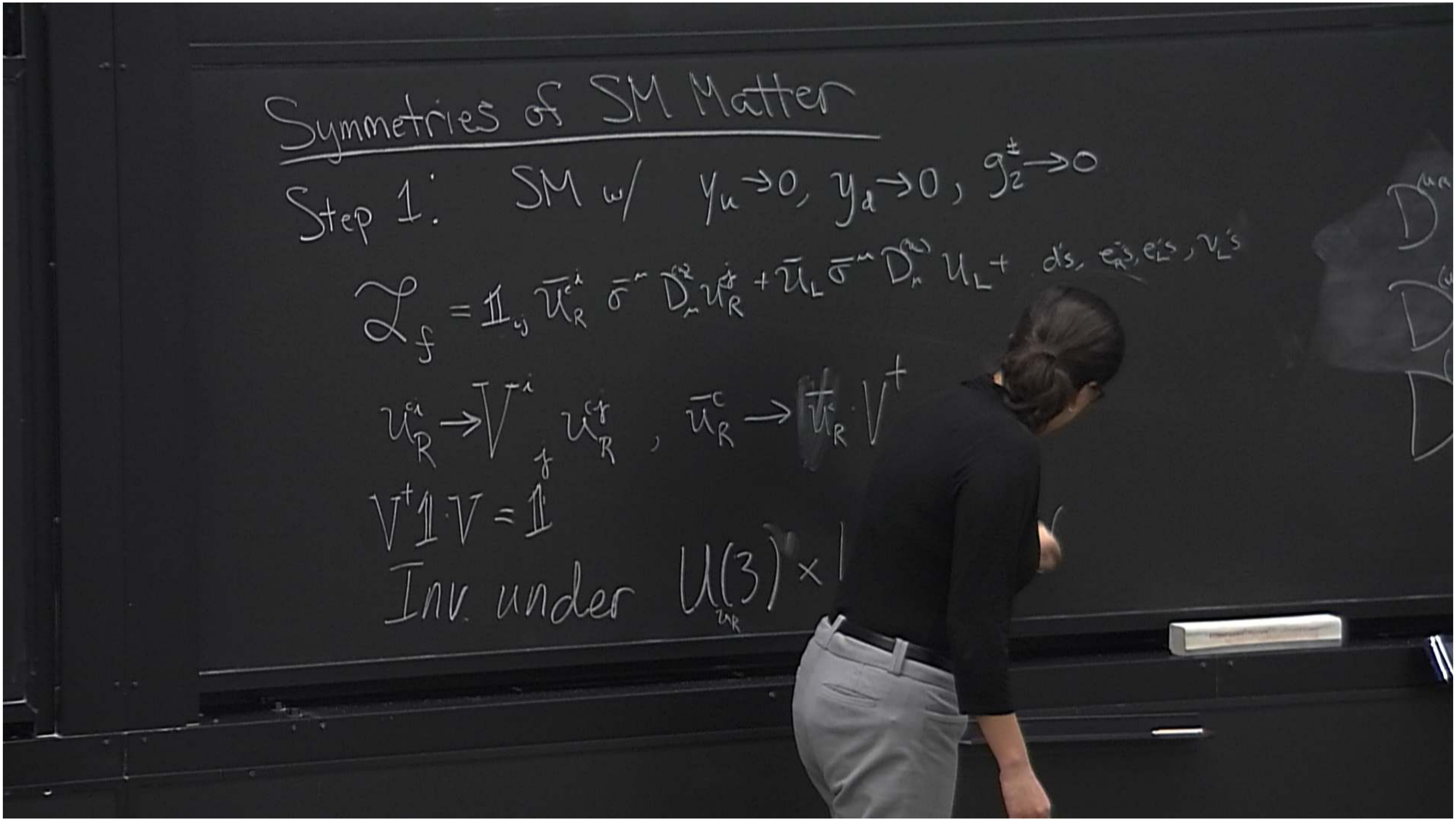
Step 1: SM w/ $y_u \to 0$, $y_d \to 0$, $g_2^{\pm} \to 0$

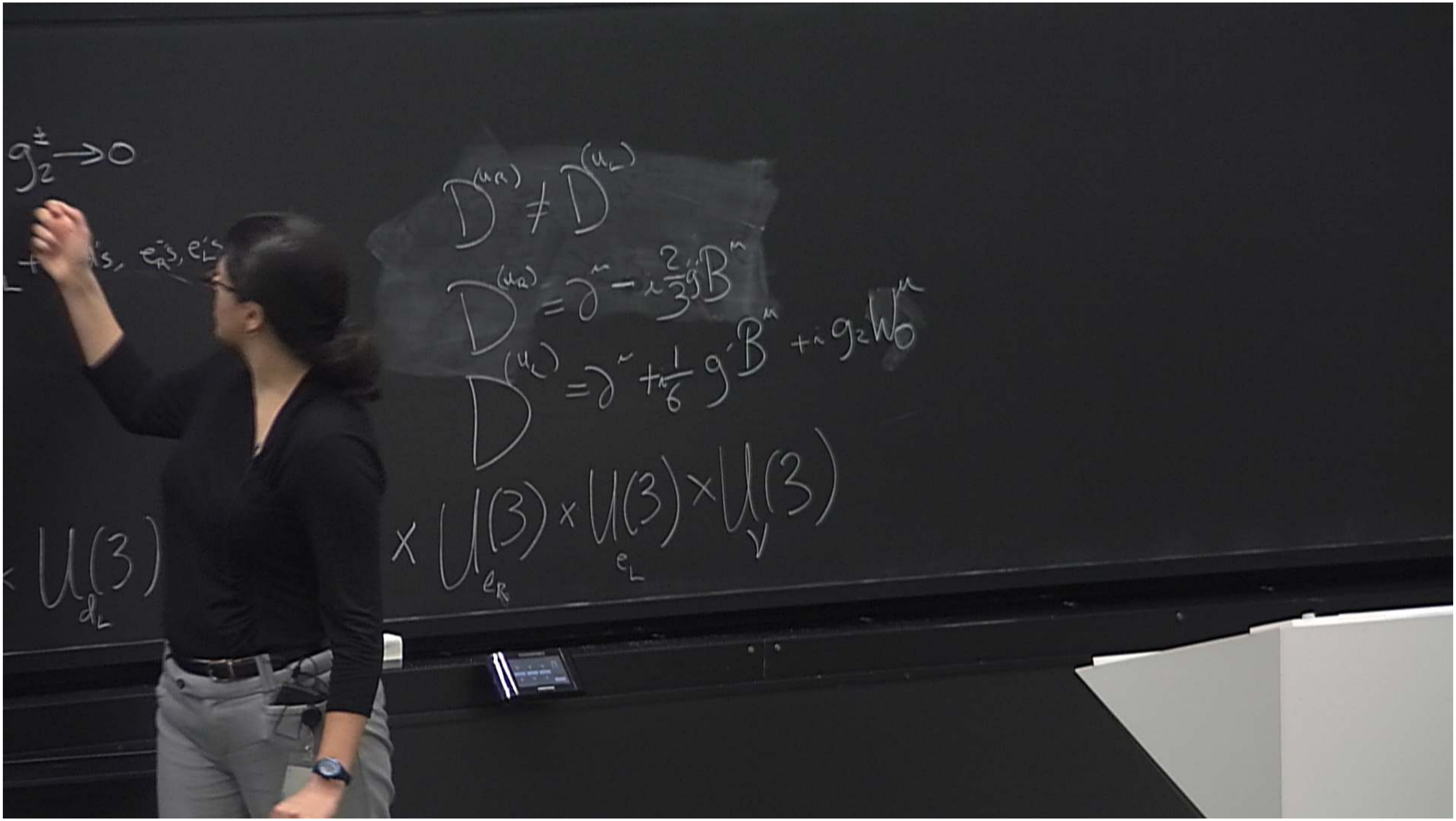
$$\mathcal{L}_f = \mathbb{1}_{ij}\, \bar{u}_R^{ci} \bar{\sigma}^\mu D_\mu^{(R)} u_R^{j} + \bar{u}_L \bar{\sigma}^\mu D_\mu^{(u_L)} u_L + \; d\text{'s},\ e_R\text{'s},\ e_L\text{'s},\ \nu_L\text{'s}$$

$$u_R^{ci} \to V^{i}{}_{j}\, u^{cj} \qquad \bar{u}_R^{c} V^{\dagger}$$

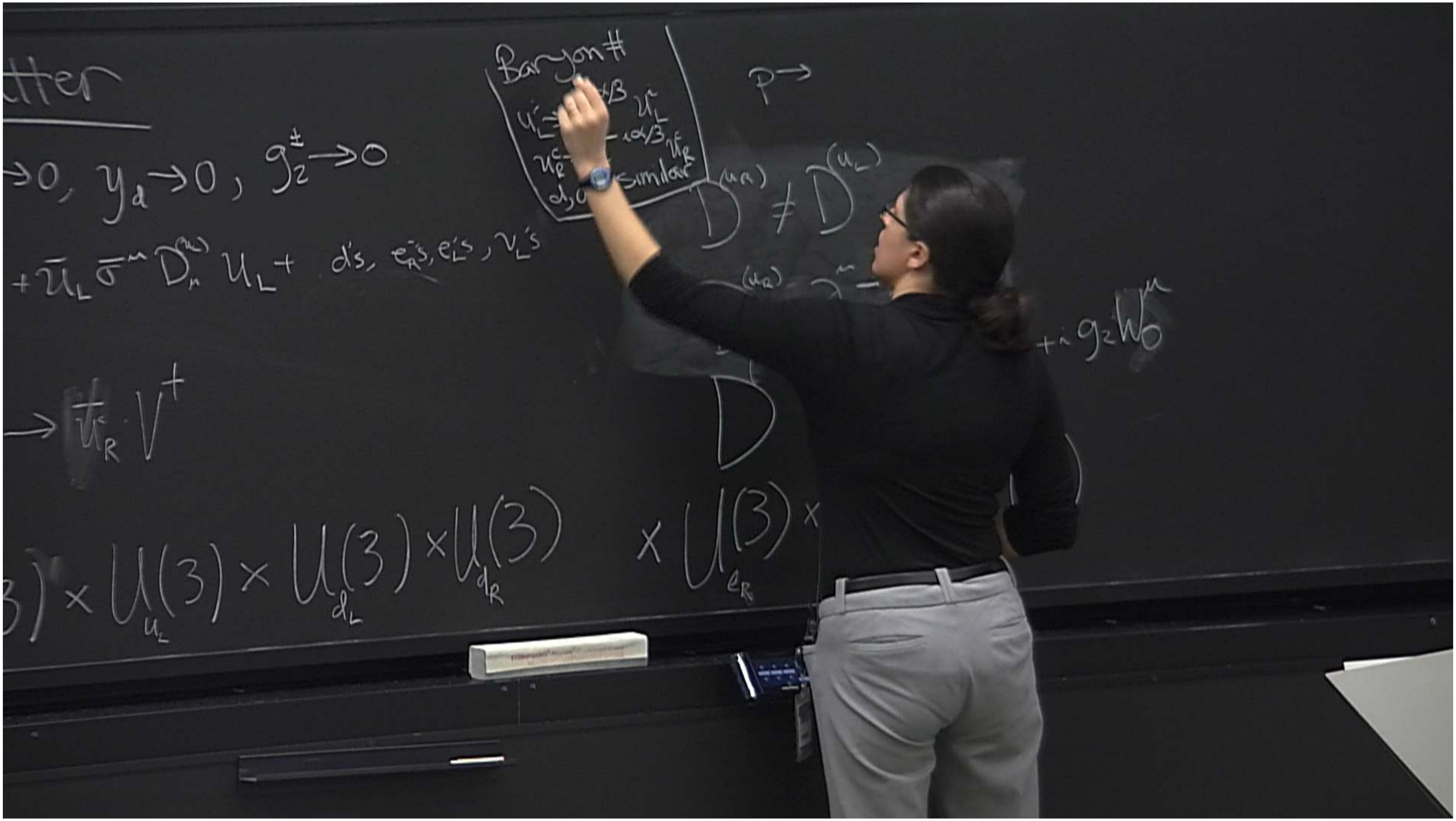
$$V^{\dagger} \mathbb{1} V = \mathbb{1}$$

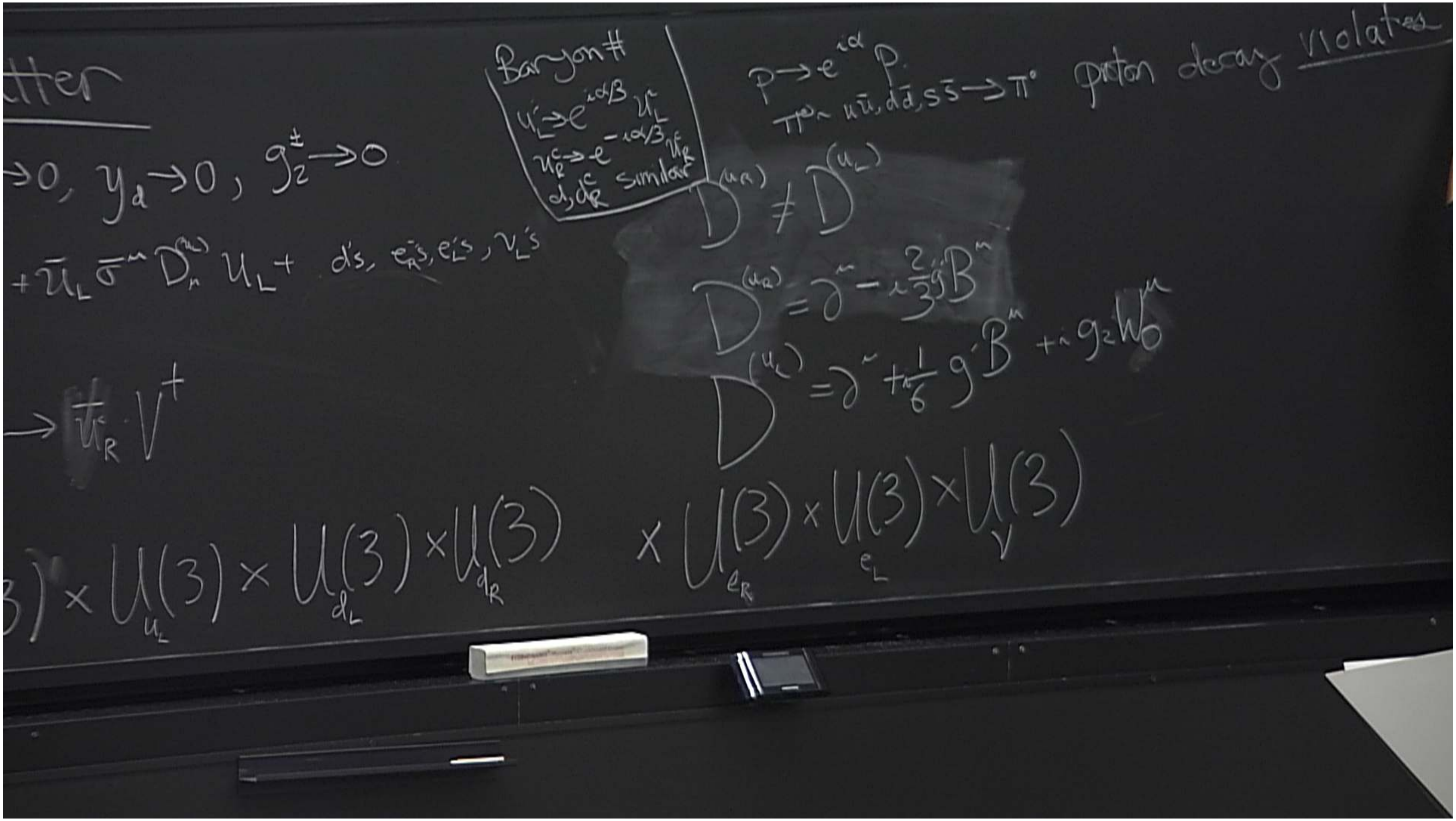
Inv. un

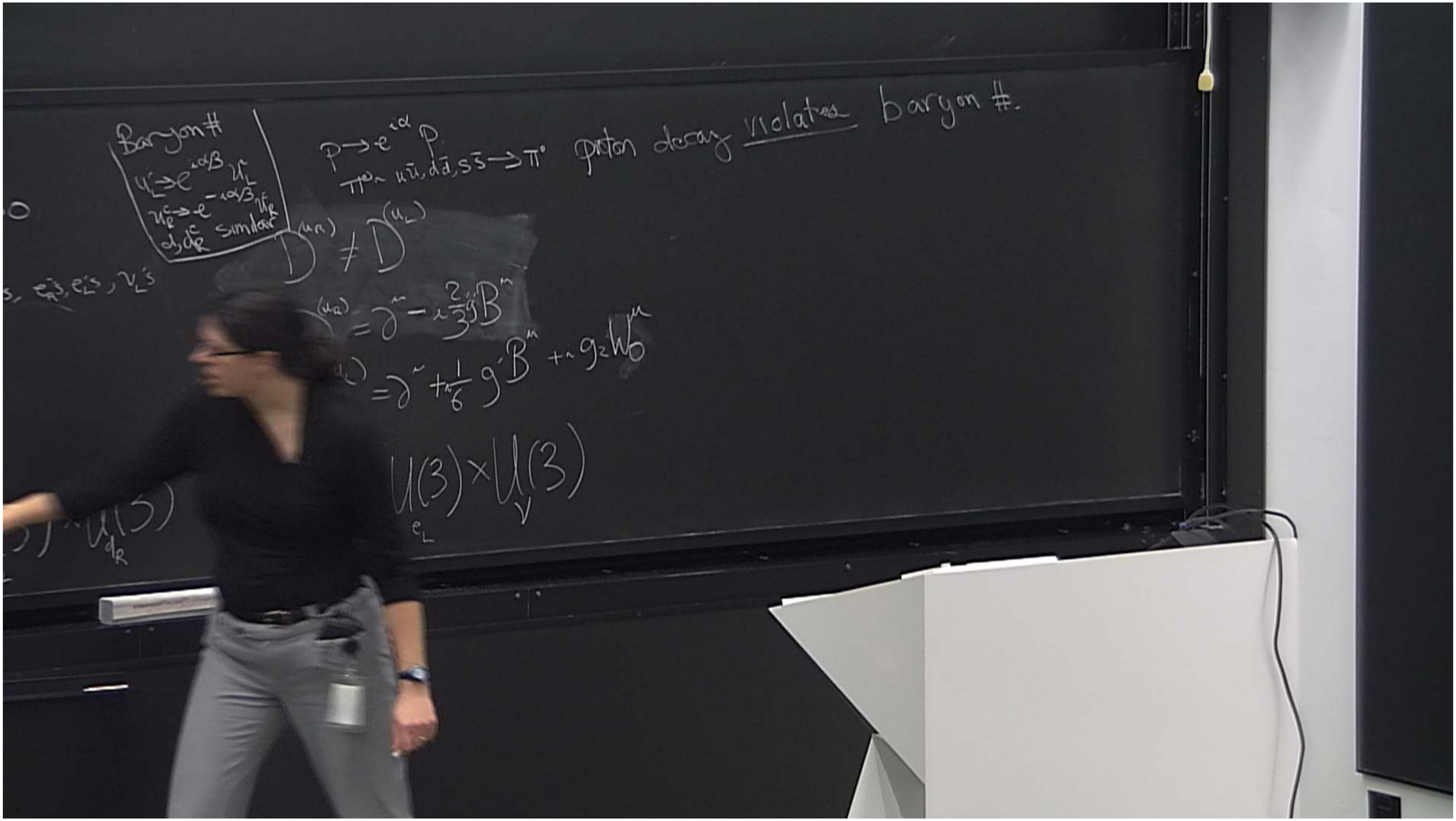

Symmetries of SM Matter
Step 1: SM w/ $y_u \to 0$, $y_d \to 0$, $g_2^{\pm} \to 0$
$\mathcal{L}_f = \mathbb{1}_{ij}\, \bar{u}_R^{c\,i}\, \bar{\sigma}^\mu D_\mu^{(R)} u_R^{c\,j} + \bar{u}_L \bar{\sigma}^\mu D_\mu^{(L)} u_L +$ d's, e_R's, e_L's, ν_L's
$u_R^{c\,i} \to V^{i}{}_{j}\, u_R^{c\,j}$, $\bar{u}_R^c \to \bar{u}_R^c V^\dagger$
$V^\dagger \mathbb{1} V = \mathbb{1}$
Inv. under $U(3)_{u_R} \times$

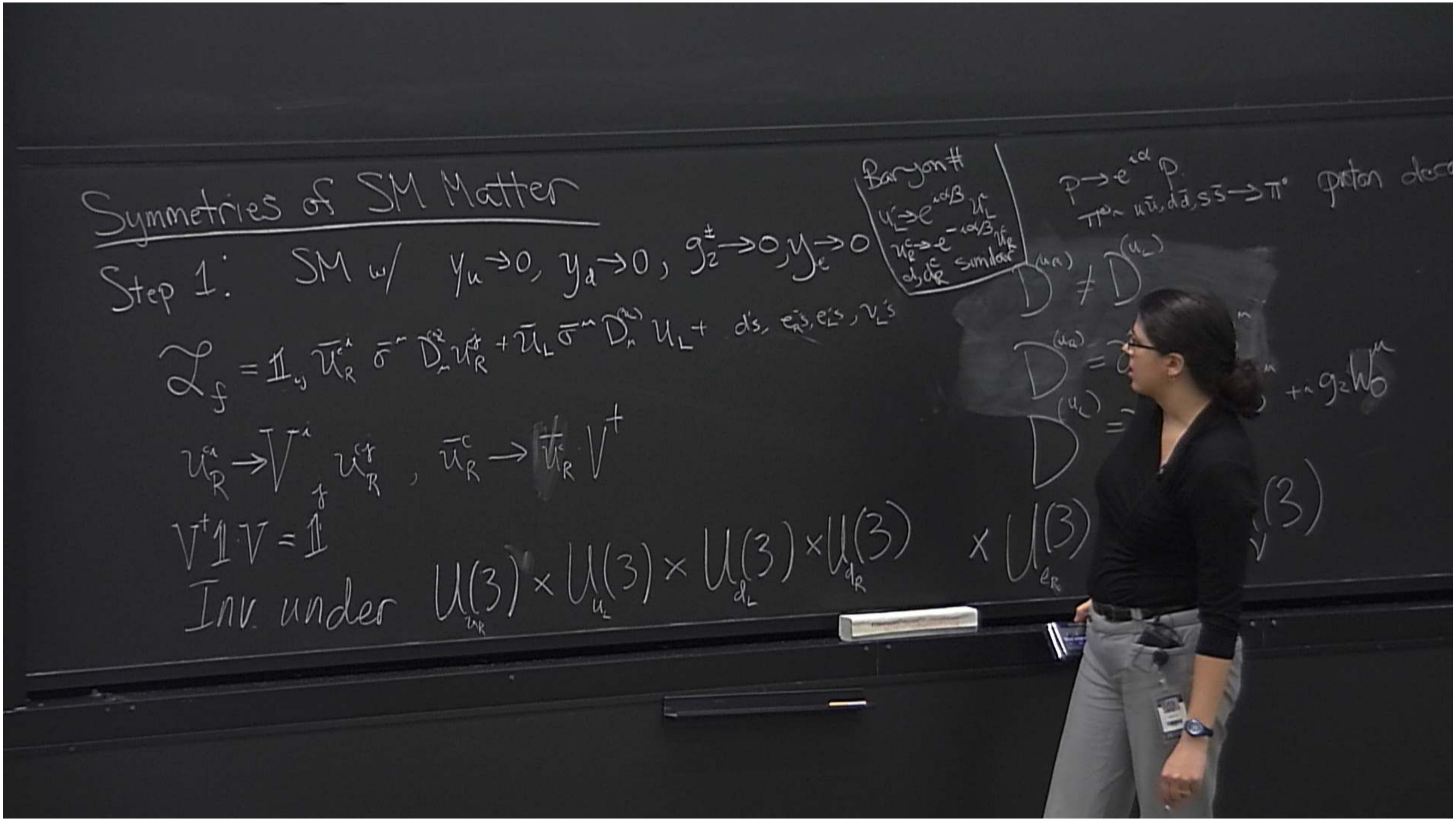


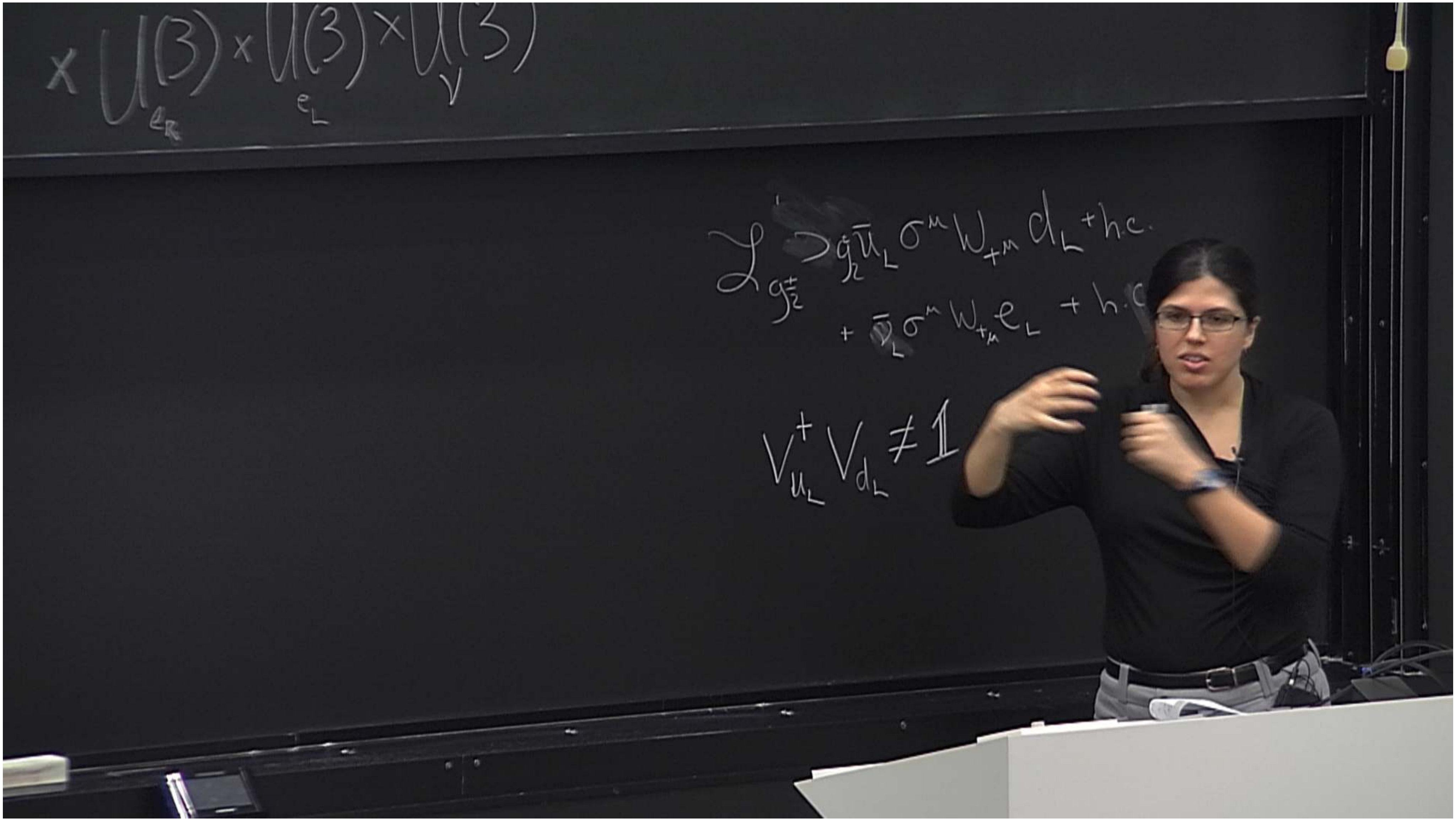
$g_2^{\pm} \to 0$
$D^{(u_R)} \neq D^{(u_L)}$
$D^{(u_R)} = \partial^\mu - i\frac{2}{3} g' B^\mu$
$D^{(u_L)} = \partial^\mu + i\frac{1}{6} g' B^\mu + i g_2 W_0^\mu$
$\times U_{d_L}(3)$
$\times U_{e_R}(3) \times U_{e_L}(3) \times U_{\nu}(3)$

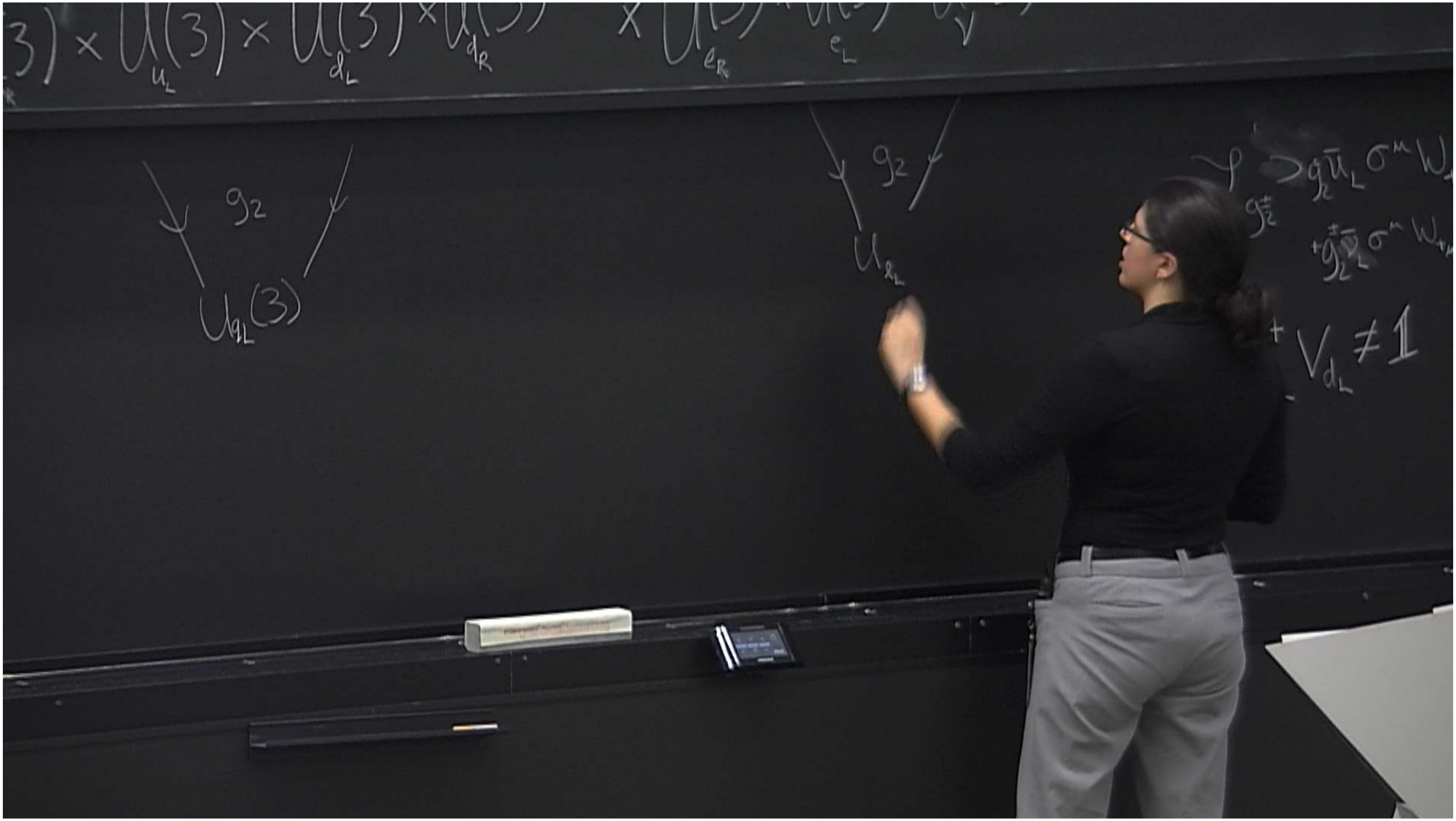

tter
Baryon #
similar
p →


tter
Baryon #
$u_L^c \to e^{i\alpha/3} u_L^c$
$u_R^c \to e^{-i\alpha/3} u_R^c$
d, d_R^c similar
$p \to e^{i\alpha} p$
$\pi^0 \sim u\bar{u}, d\bar{d}, s\bar{s} \to \pi^0$
proton decay violates
$\to 0,\ y_d \to 0,\ g_2^{\pm} \to 0$
$+\bar{u}_L \bar{\sigma}^\mu D_\mu^{(u_L)} u_L +$ d's, e_R^-'s, e_L^-'s, ν_L's
$D^{(u_R)} \neq D^{(u_L)}$
$D^{(u_R)} = \partial^\mu - i\frac{2}{3} g' B^\mu$
$D^{(u_L)} = \partial^\mu + i\frac{1}{6} g' B^\mu + i g_2 W_0^\mu$
$\to \bar{u}_R^c V^\dagger$
$3) \times U_{u_L}(3) \times U_{d_L}(3) \times U_{d_R}(3) \times U_{e_R}(3) \times U_{e_L}(3) \times U_{\nu}(3)$

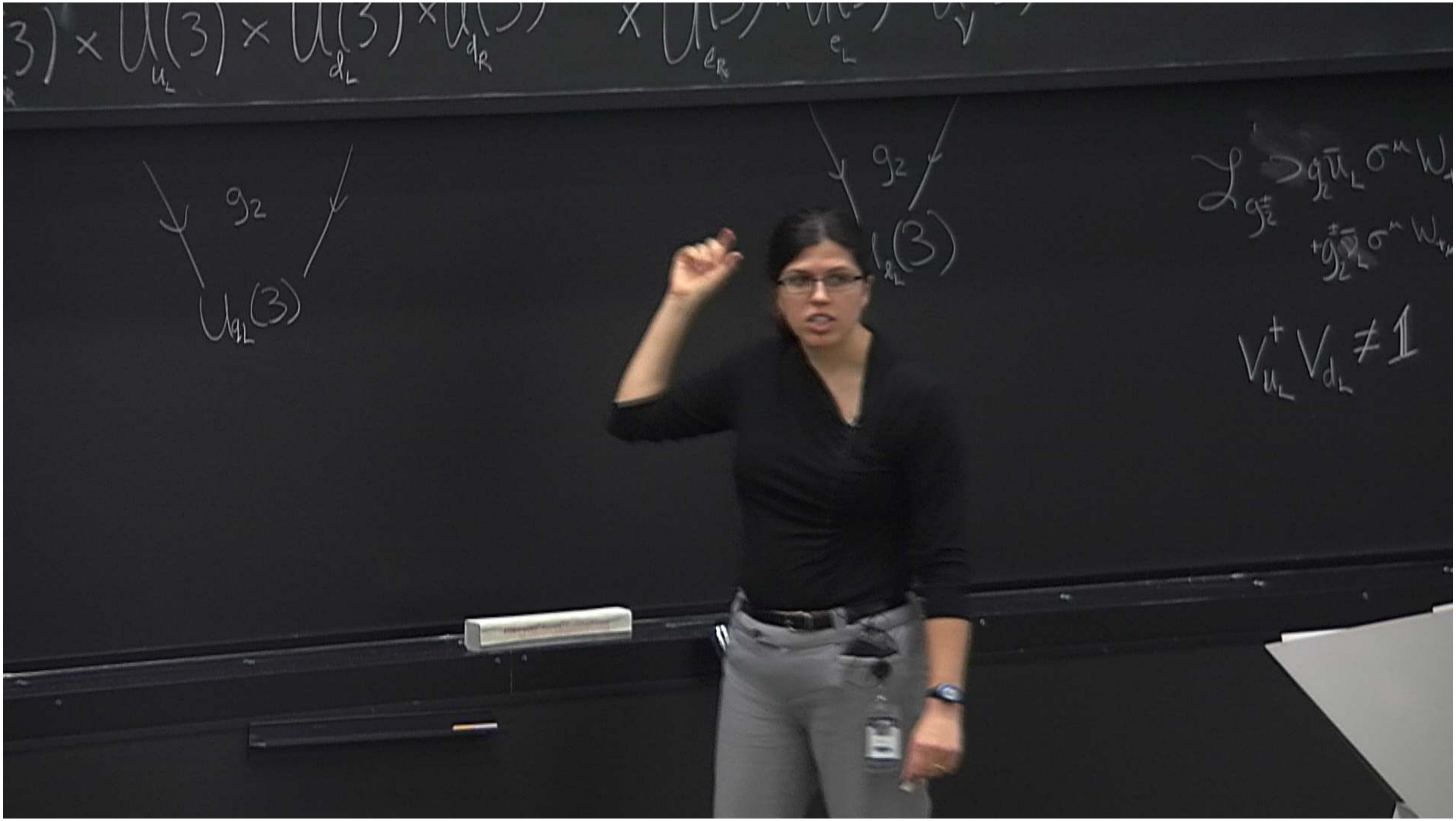

Baryon #
similar
proton decay violates baryon #.


Symmetries of SM Matter
Step 1: SM w/ $y_u \to 0,\ y_d \to 0,\ g_2^\pm \to 0,\ y_e \to 0$
$\mathcal{L}_f = \mathbb{1}_{ij}\, \bar{u}_R^{ci}\, \bar\sigma^\mu D_\mu^{(u_R)} u_R^{cj} + \bar{u}_L \bar\sigma^\mu D_\mu^{(u_L)} u_L +$ d's, e_R's, e_L's, ν_L's
$u_R^{ci} \to V^i{}_j\, u_R^{cj}$, $\bar{u}_R^c \to \bar{u}_R^c V^\dagger$
$V^\dagger \mathbb{1} V = \mathbb{1}$
Inv. under $U(3)_{u_R} \times U(3)_{u_L} \times U(3)_{d_L} \times U(3)_{d_R} \times U(3)_{e_R}$
Baryon #
$u_L^c \to e^{i\alpha B} u_L^c$
$u_R^c \to e^{-i\alpha B} u_R^c$
d, d_R^c similar
$p \to e^{i\alpha} p$
$\pi^0 \sim u\bar{u}, d\bar{d}, s\bar{s} \to \pi^0$ proton dec
$D^{(u_R)} \neq D^{(u_L)}$

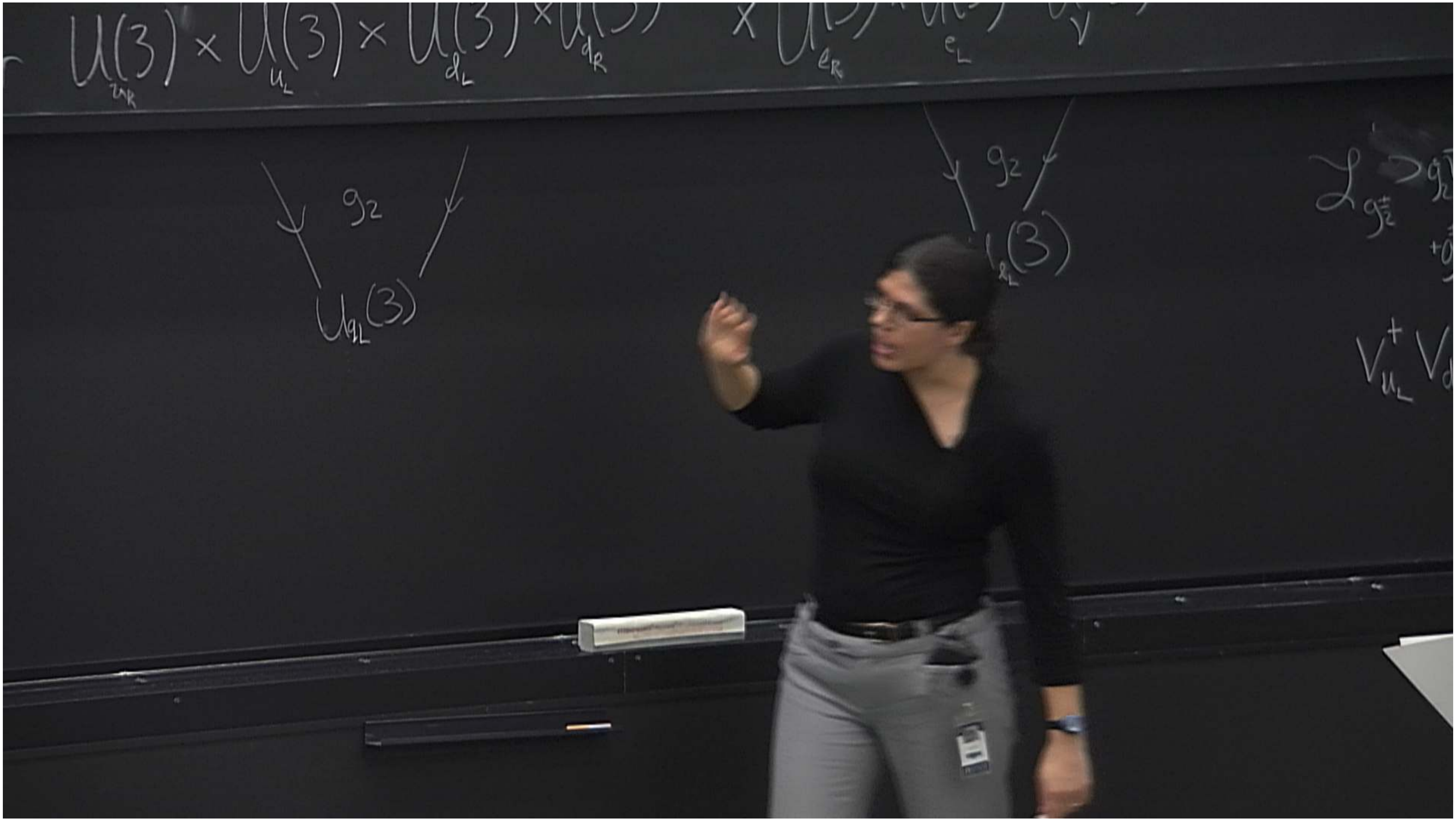

$\times U(3)_{e_R} \times U(3)_{e_L} \times U(3)_{\nu}$
$\mathcal{L}_{g_2^\pm} \supset g_2 \bar{u}_L \sigma^\mu W_{+\mu} d_L + h.c.$
$+ \bar{\nu}_L \sigma^\mu W_{+\mu} e_L + h.c.$
$V_{u_L}^\dagger V_{d_L} \neq \mathbb{1}$

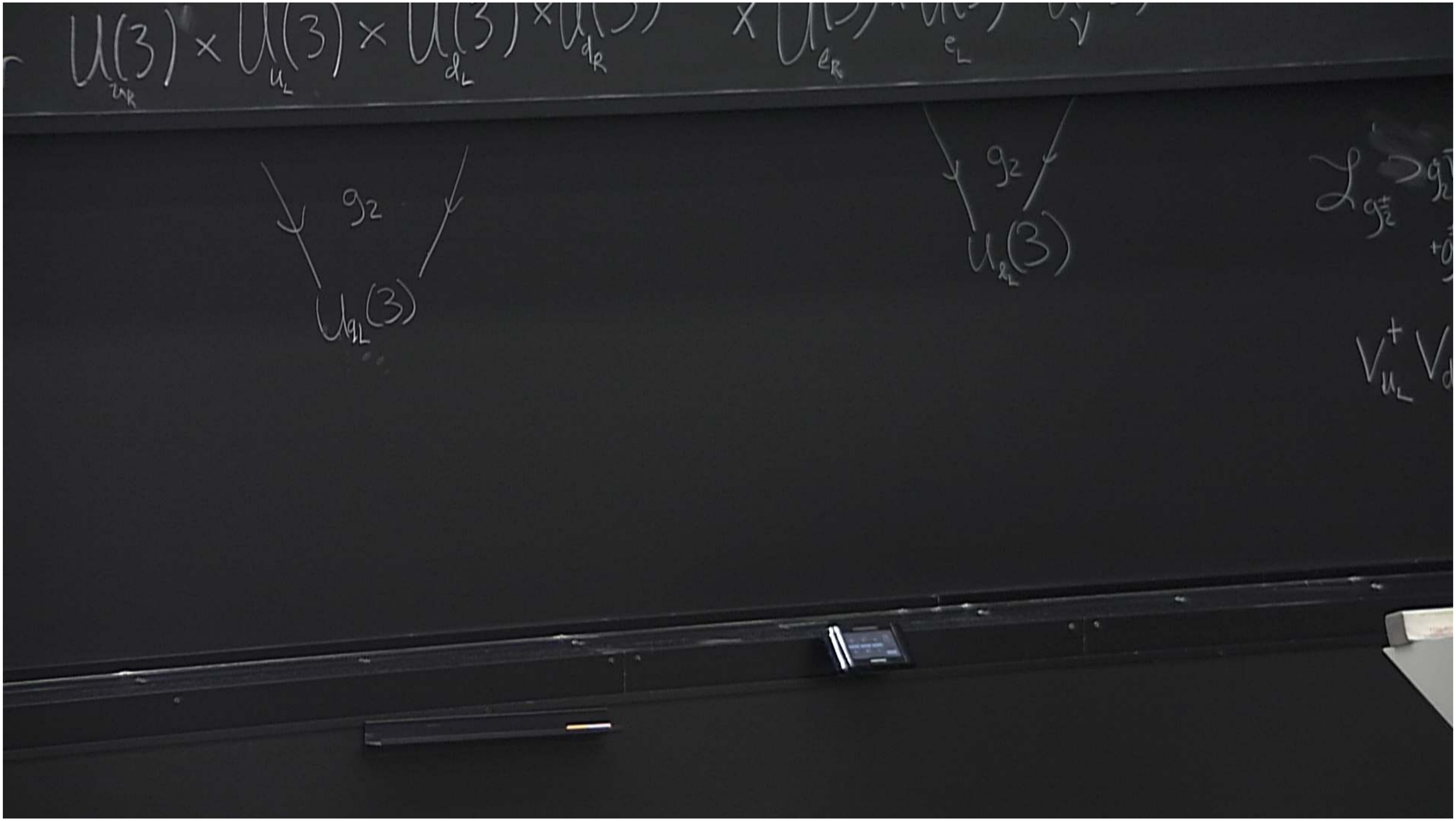


$\times\, U_{u_L}(3) \times U_{d_L}(3) \times U_{d_R}(3)$
g_2
$U_{q_L}(3)$
g_2
U_{e_L}
$V_{d_L} \neq \mathbb{1}$



g_2
$U_{q_L}(3)$
g_2
$U_{\ell_L}(3)$
$V_{u_L}^{+} V_{d_L} \neq \mathbb{1}$

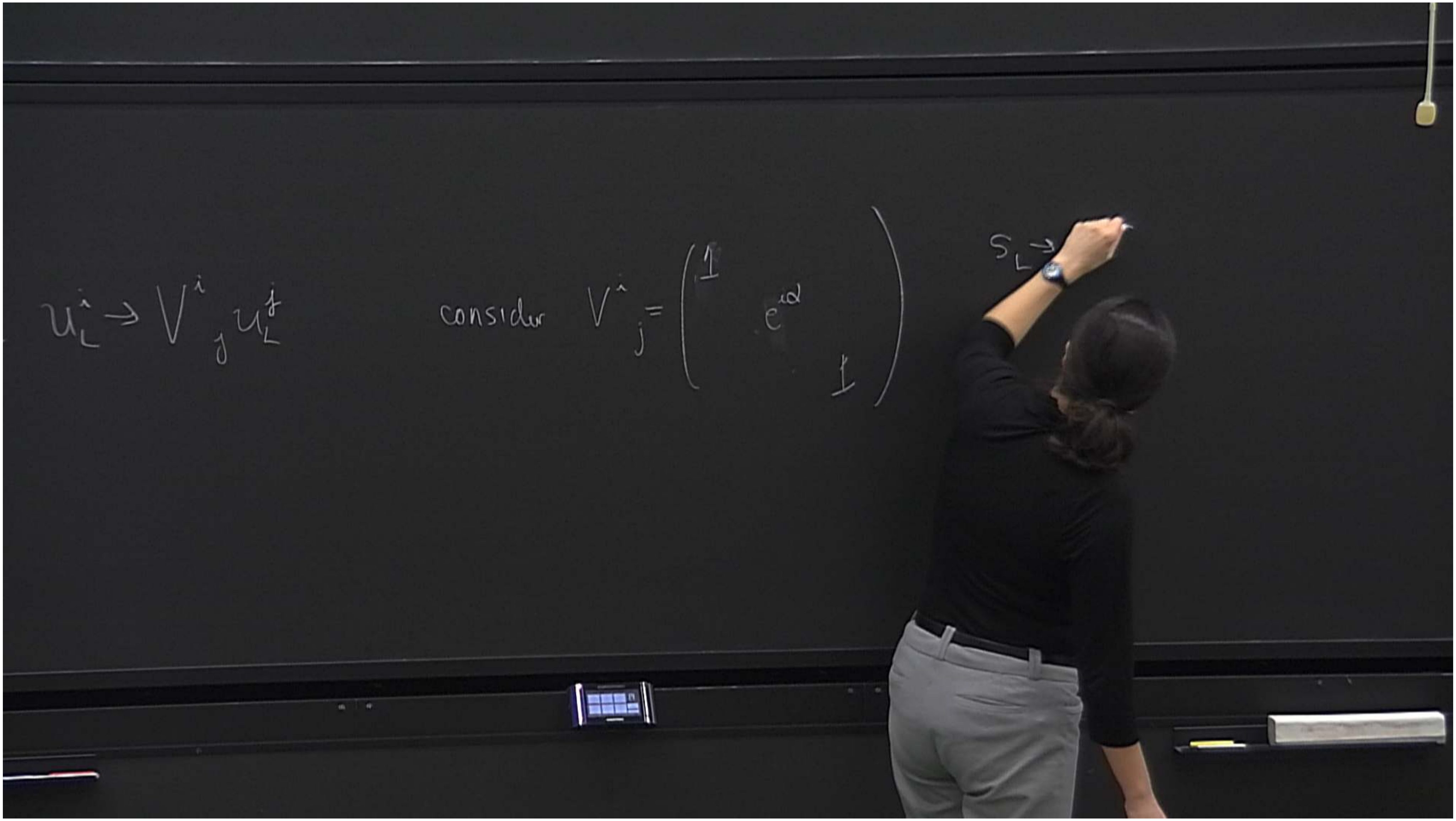

g2
g2
U_{q_L}(3)


$U_{u_R}(3) \times U_{u_L}(3) \times U_{d_L}(3) \times U_{d_R}$
$\times U_{e_R}$
g_2
$U_{q_L}(3)$
g_2
$U_{\ell_L}(3)$
$V^+_{u_L} V_d$

$$(\bar{s}_L \sigma^\mu d_L)^2$$

$U(3)_{q_L} \Longrightarrow \quad d_L^i \to V^i{}_j\, d_L^j\,, \quad u_L^i \to V^i{}_j\, u_L^j$

consider $V^i{}_j =$


$u_L^i \to V^i{}_j u_L^j$
consider $V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$
$s_L \to$

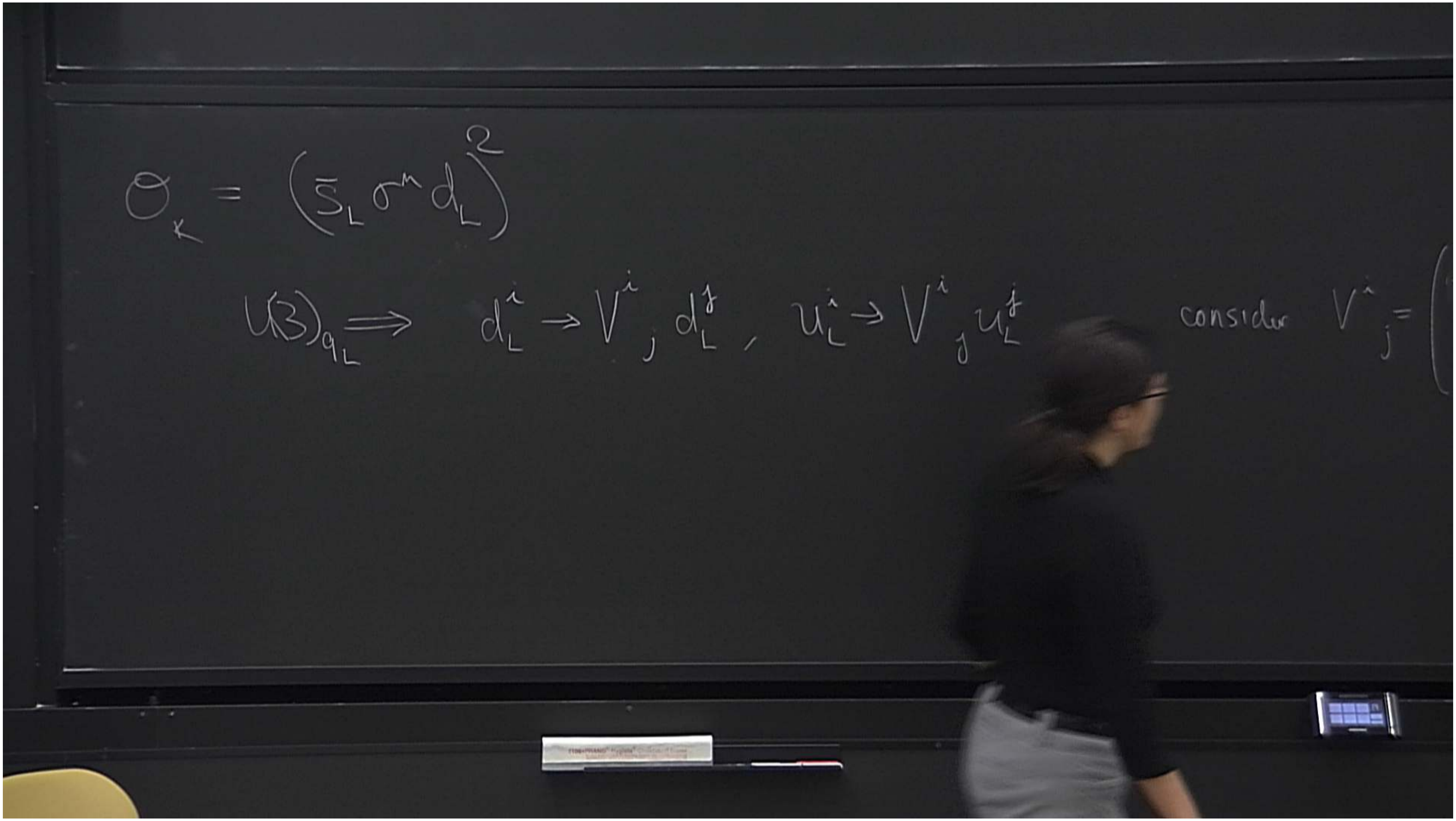
$u_L^i \to V^i{}_j \, u_L^j$

consider $V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$

$s_L \to e^{i\alpha} s_L$

$\bar{s}_L \to e^{-i\alpha} s_L$

$d_L \to d_L$

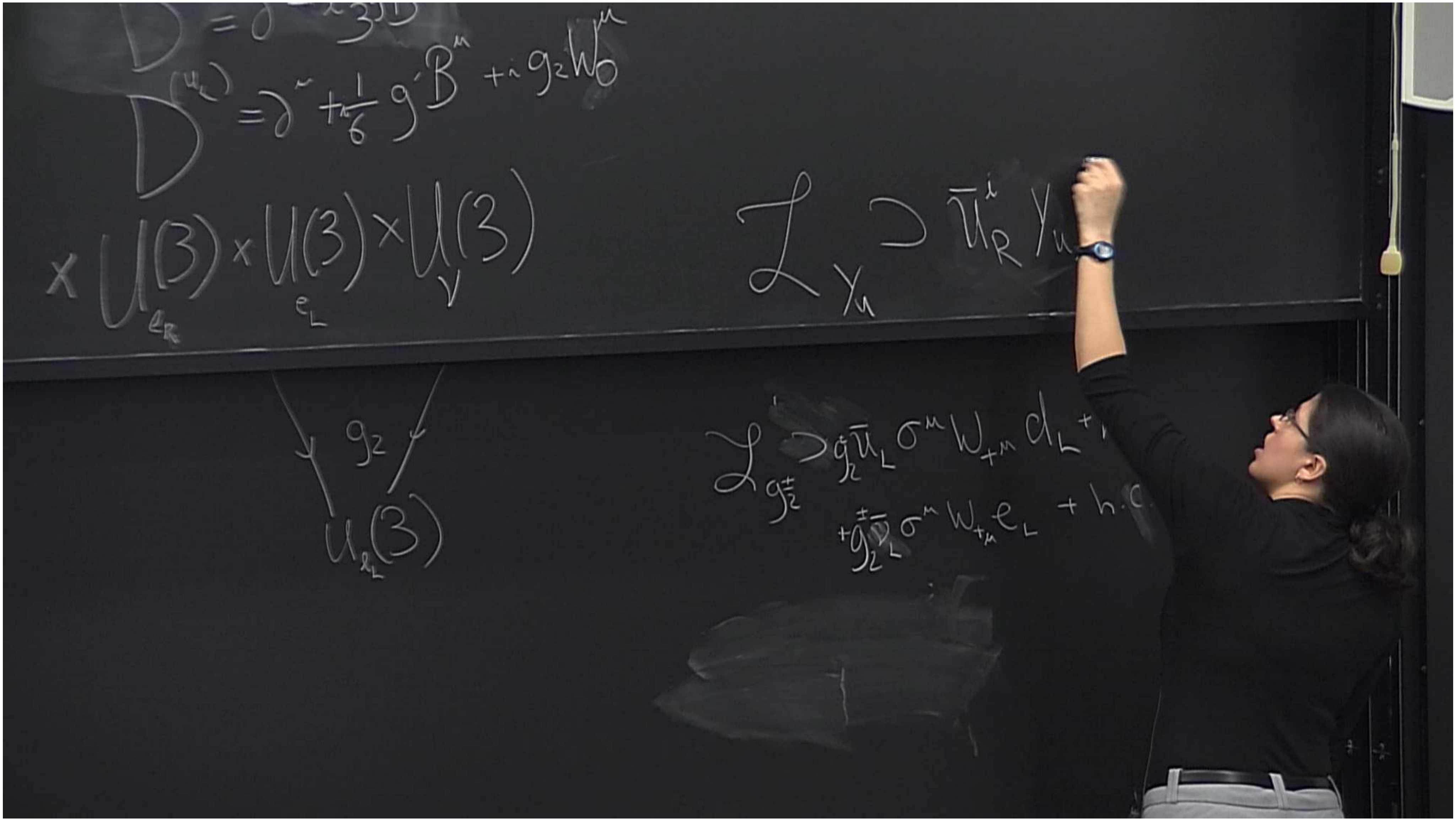


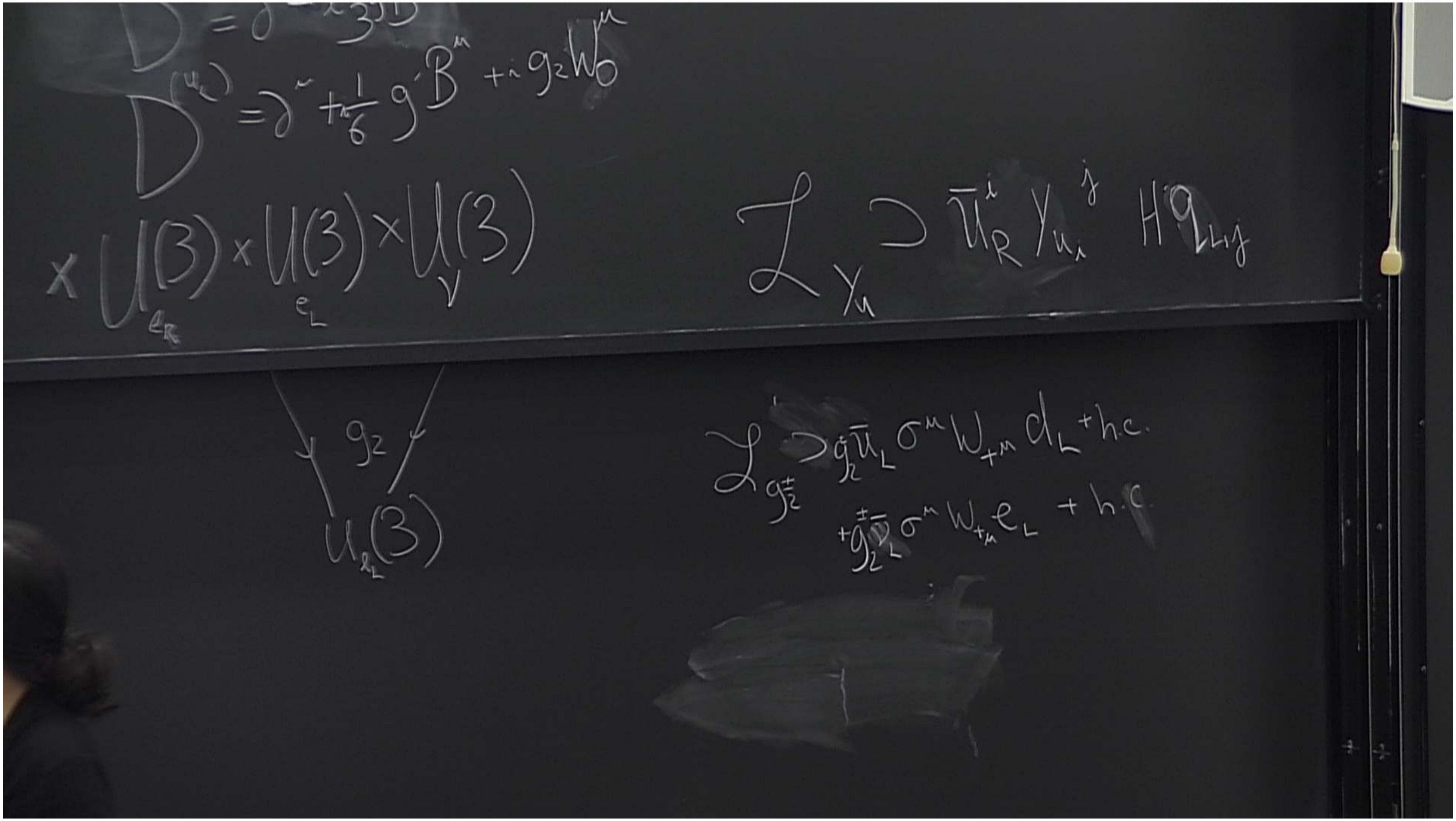
$O_K = (\bar{s}_L \sigma^\mu d_L)^2$
$U(3)_{q_L} \Longrightarrow \quad d_L^i \to V^i{}_j\, d_L^j\,, \quad u_L^i \to V^i{}_j\, u_L^j$
consider $V^i{}_j = ($

sider $V^{\wedge}{}_{j} = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$

$$s_L \to e^{i\alpha} s_L$$
$$\bar{s}_L \to e^{-i\alpha} \bar{s}_L$$
$$d_L \to d_L$$

$$\mathcal{O}_K \to e^{-2i\alpha} \mathcal{O}_K$$


× U(3) × U(3) × U(3)
g2
U(3)



$D^{(u_L)} = \partial^\mu + i\frac{1}{6} g' B^\mu + i g_2 W_0^\mu$
$\times U_{e_R}(3) \times U_{e_L}(3) \times U_\nu(3)$
$\mathcal{L}_{Y_u} \supset \bar{u}_R^i Y_{u_i}^{\ j} H q_{Lj}$
g_2
$U_{\ell_L}(3)$
$\mathcal{L}_{g_2^\pm} \supset g_2^\pm \bar{u}_L \sigma^\mu W_{+\mu} d_L + h.c.$
$+ g_2^\pm \bar{\nu}_L \sigma^\mu W_{+\mu} e_L + h.c.$

$$D^{\mu} = \partial^{\mu} - i g_3 \ldots$$

$$D^{(u_L)} = \partial^{\mu} + i\frac{1}{6} g' B^{\mu} + i g_2 W^{\mu}$$

$$3) \times U_{e_R}(3) \times U_{e_L}(3) \times U_{\nu}(3)$$

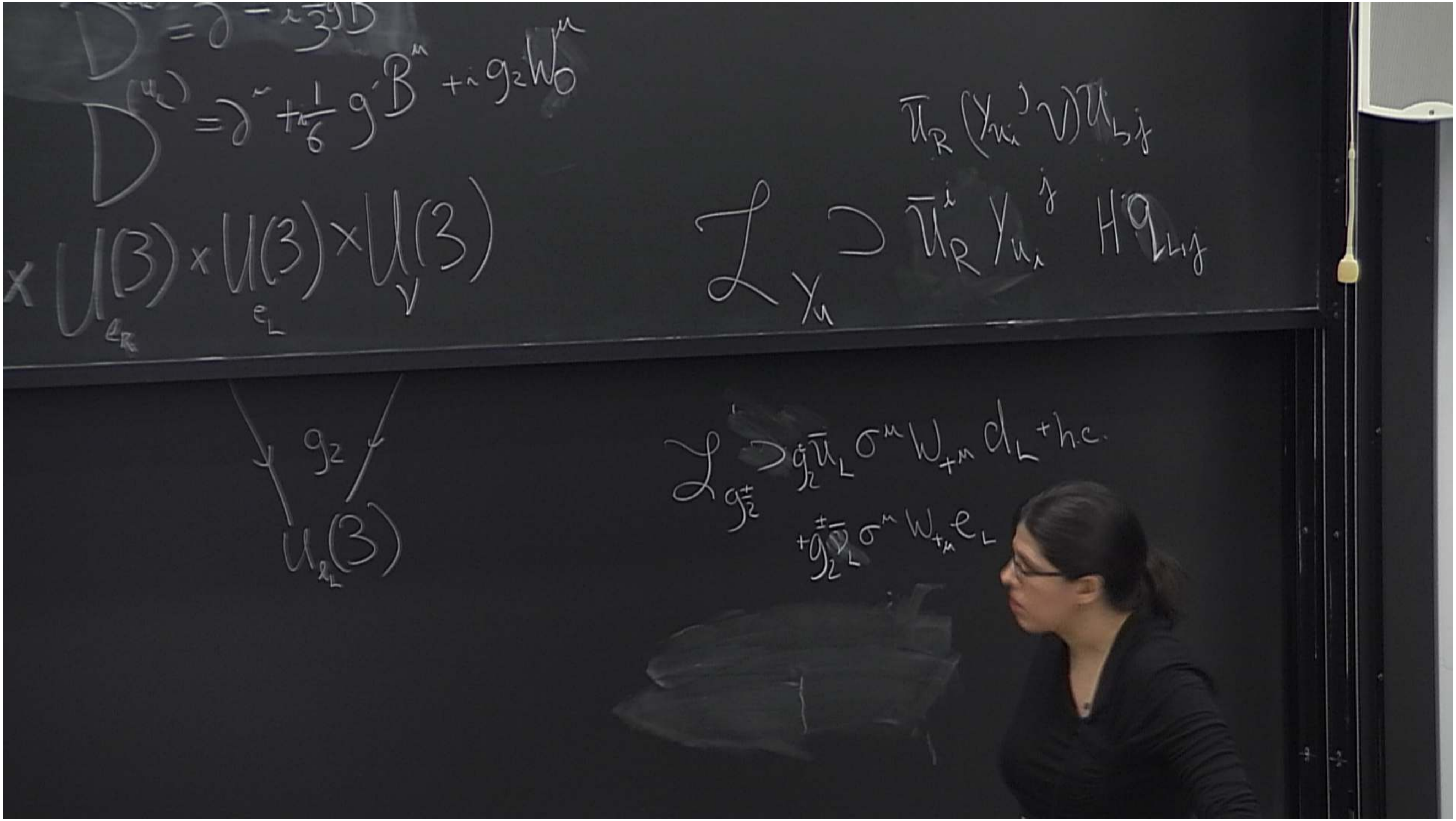
$$\bar{u}_R \left(Y_{u_i}{}^{j} V\right) u_{L j}$$

$$\mathcal{L}_{Y_u} \supset \bar{u}_R^{i} Y_{u_i}{}^{j} H q_{L j}$$

g_2

$U_{e_L}(3)$

$$\mathcal{L}_{g_2^{\pm}} \supset g_2 \bar{u}_L \sigma^{\mu} W_{+\mu} d_L + h.c.$$
$$+ g_2^{\pm} \bar{\nu}_L \sigma^{\mu} W_{+\mu} e_L + h.c.$$


$D^{(u_L)} = \partial^\mu + i\frac{1}{6} g' B^\mu + i g_2 W^\mu$
$\times U(3)_{e_R} \times U(3)_{e_L} \times U(3)_\nu$
$\bar{u}_R (Y_{u_i}{}^j v) u_{L j}$
$\mathcal{L}_{Y_u} \supset \bar{u}_R^i Y_{u_i}{}^j H q_{L j}$
g_2
$U(3)_{e_L}$
$\mathcal{L}_{g_2^\pm} \supset g_2 \bar{u}_L \sigma^\mu W_{+\mu} d_L + h.c.$
$+ g_2 \bar{\nu}_L \sigma^\mu W_{+\mu} e_L$

$$D^{\mu} = \partial^{\mu} - i\frac{1}{3} g' B^{\mu}$$

$$D^{(u_L)} = \partial^{\mu} + i\frac{1}{6} g' B^{\mu} + i g_2 W^{\mu}$$

$$\times U_{e_R}(3) \times U_{e_L}(3) \times U_{\nu}(3)$$

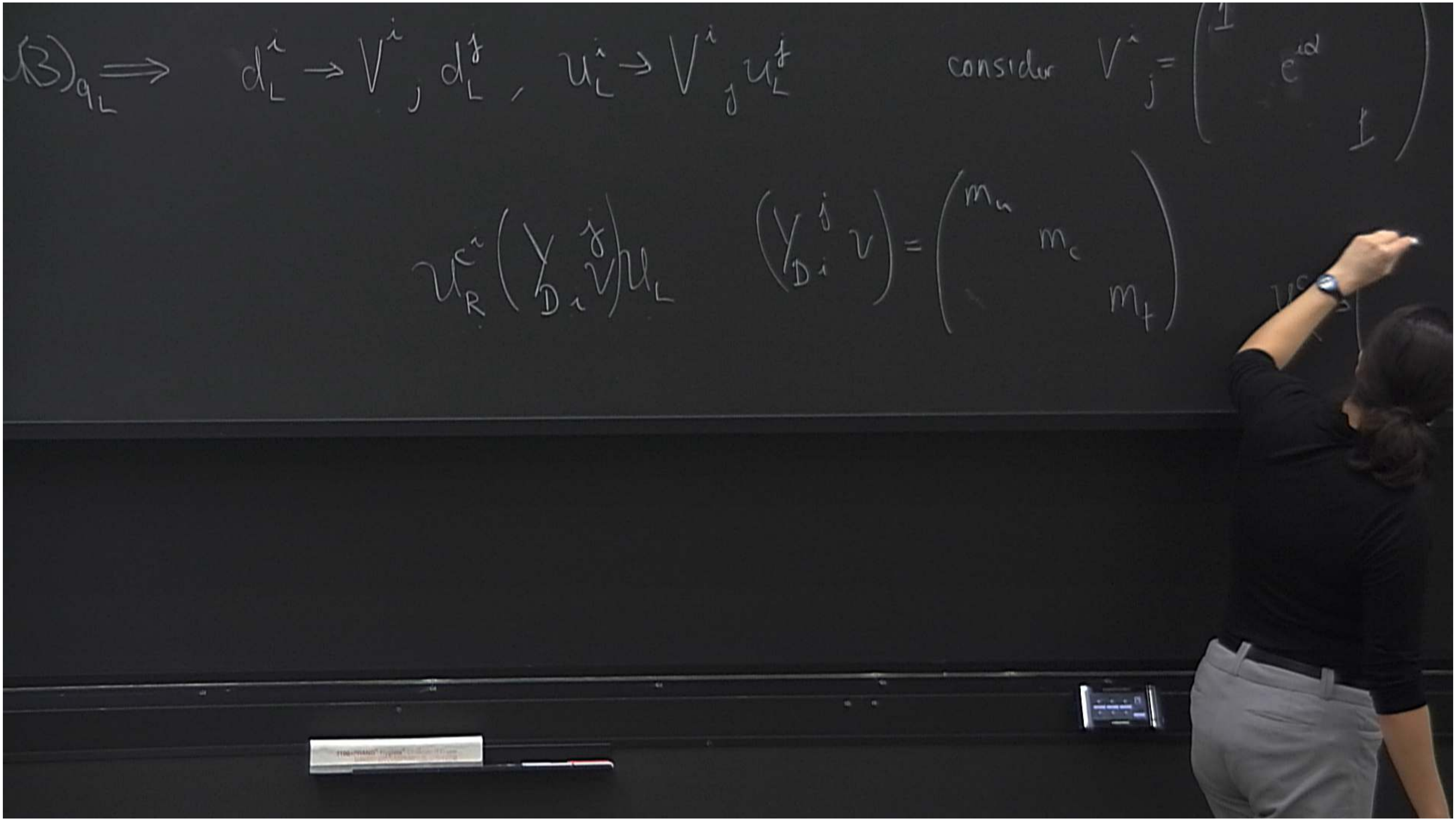
$$\bar{u}_R^{c} (Y_{u_i}^{\ j} v) u_{L j}$$

$$\mathcal{L}_{Y_u} \supset \bar{u}_R^{ic} Y_{u_i}^{\ j} H q_{L j}$$

g_2

$U_{e_L}(3)$

$$\mathcal{L}_{g_2^{\pm}} \supset g_2 \bar{u}_L \sigma^{\mu} W_{+\mu} d_L + h.c.$$
$$+ g_2^{\pm} \bar{\nu}_L \sigma^{\mu} W_{+\mu} e_L + h.c.$$


$U(3)_{q_L} \Longrightarrow d_L^i \to V^i{}_j d_L^j , \; u_L^i \to V^i{}_j u_L^j$
consider $V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$
$u_R^{c\,i} (Y_D{}_i^j v) u_L$
$(Y_D{}_i^j v) = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$

$\left(\bar{u}_L \sigma^\mu d_L\right)^2$

$\Longrightarrow \quad d_L^i \to V^i{}_j d_L^j, \quad u_L^i \to V^i{}_j u_L^j$ consider $V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$

$s_L \to e^{i\alpha} s_L$

$\bar{s}_L \to e^{-i\alpha} \bar{s}_L$

$d_L \to d_L$

$O_K \to e^{2i\alpha} O_K$

$u_R^{c\,i} \left(Y_D{}_i{}^j V\right) u_L \qquad \left(Y_D{}_i{}^j V\right) = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$

$u_R^c \to \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}, \quad u_L \to (\ )^\dagger$

$u_L^i \to V^i{}_j u_L^j$ consider $V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$

$s_L \to e^{i\alpha} s_L$

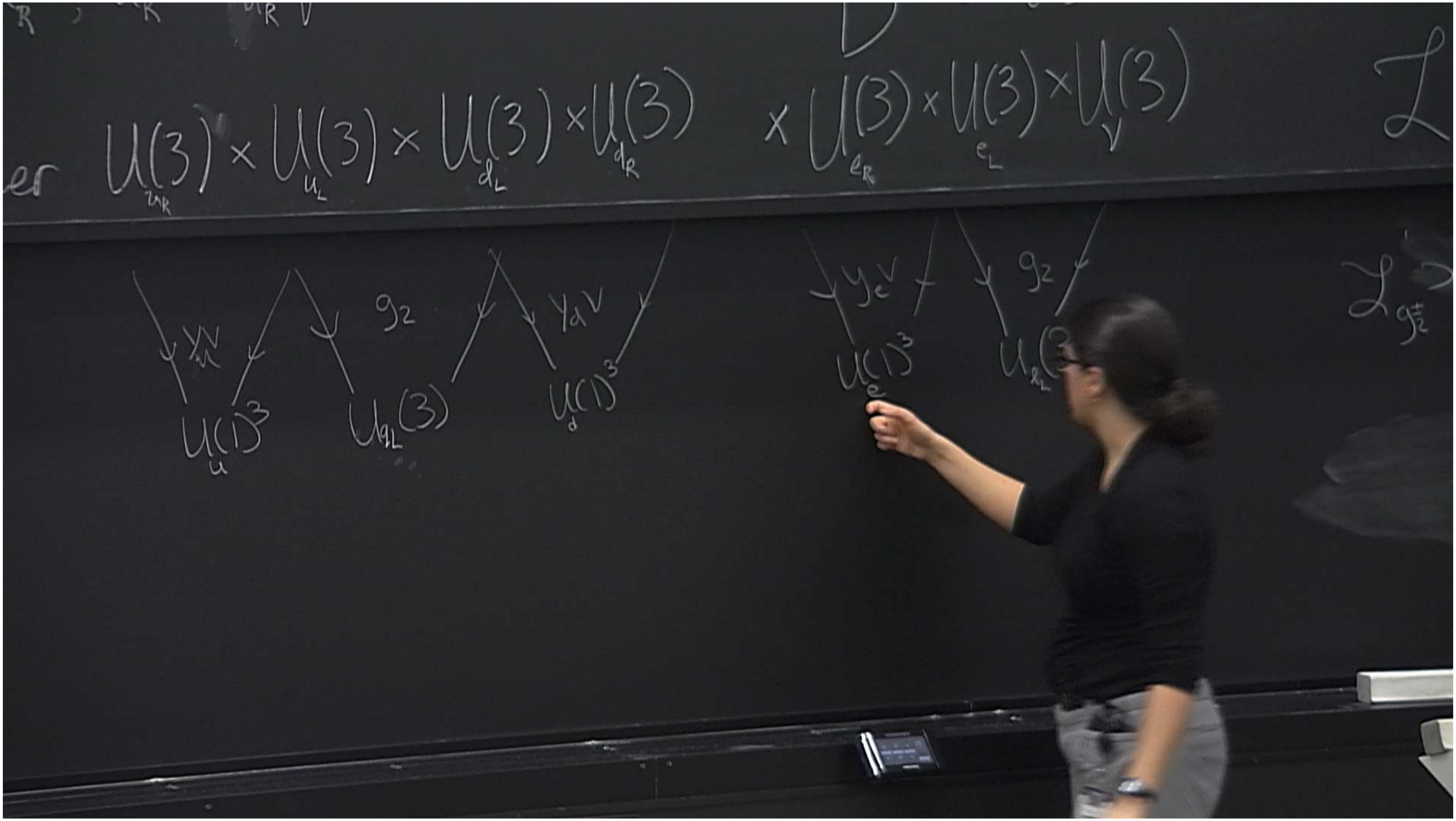
$\bar{s}_L \to e^{-i\alpha} s_L$

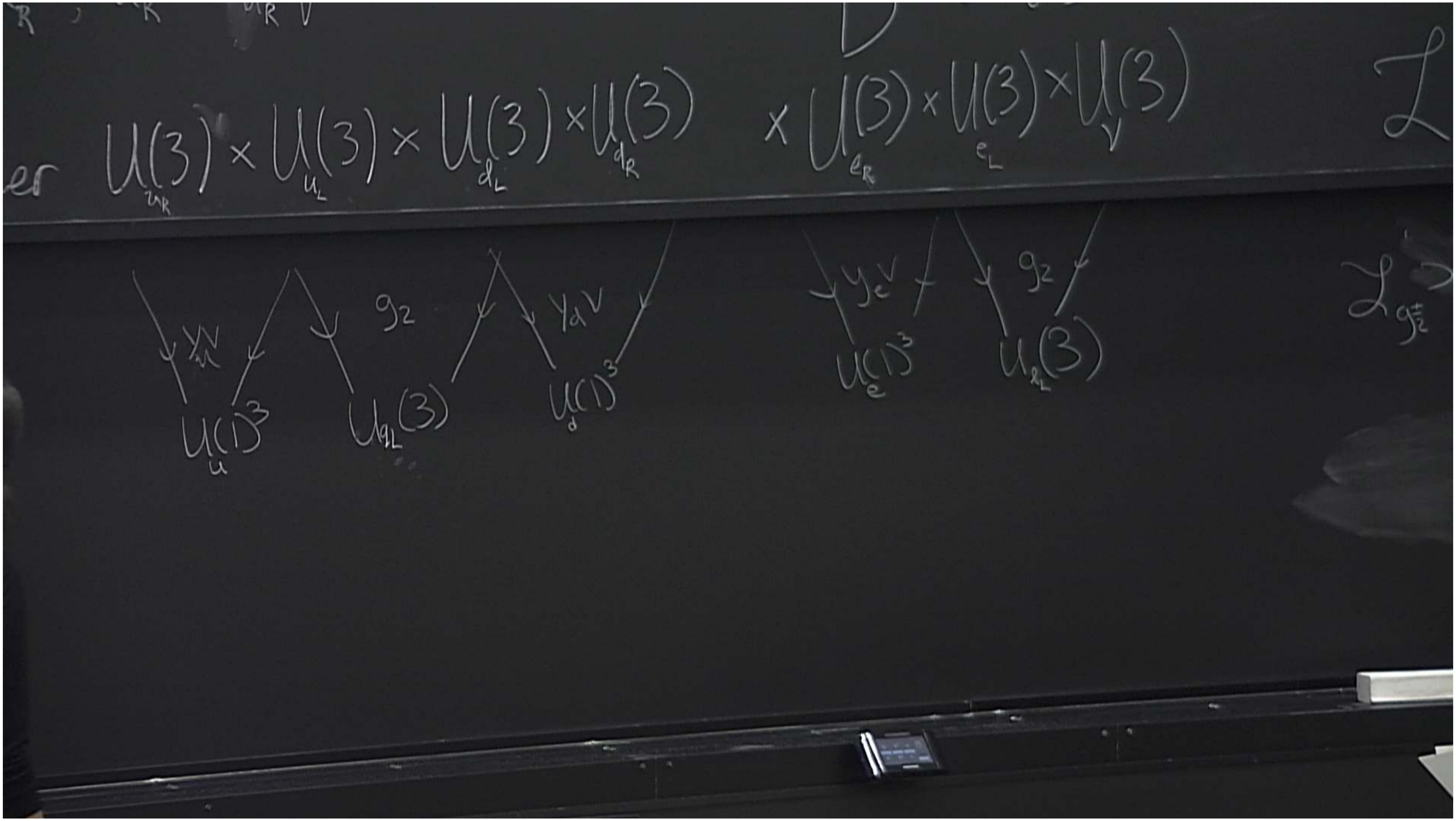
$d_L \to d_L$

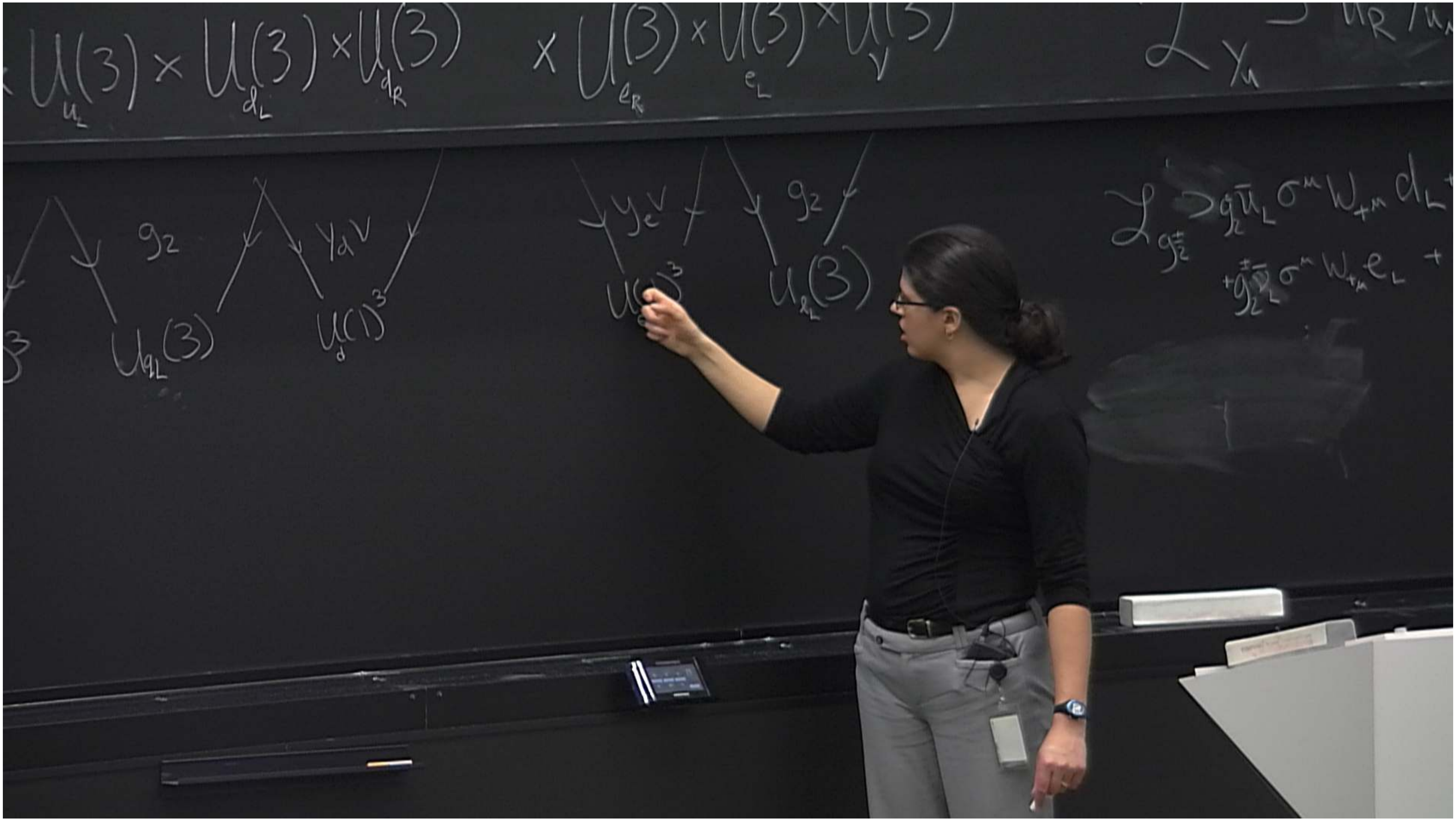
$\theta_K \to e^{2i\alpha}$

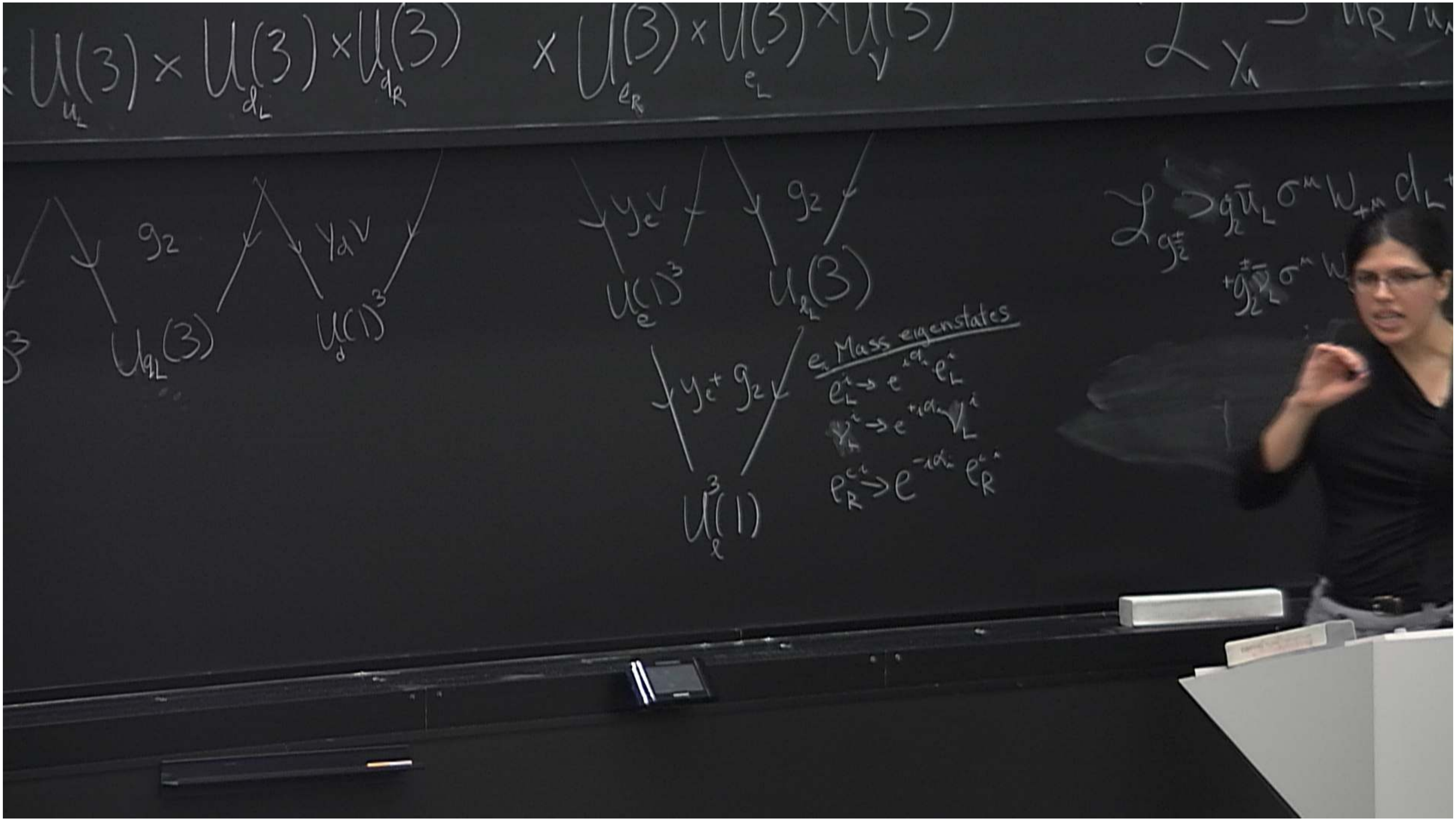
$\left(Y_D{}^j{}_i\, v\right) = \begin{pmatrix} \cancel{m_u} & & \\ & \cancel{m_c} & \\ & & m_t \end{pmatrix}$ $u_R^c \to \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$, $u_L \to (\ \ )^\dagger$

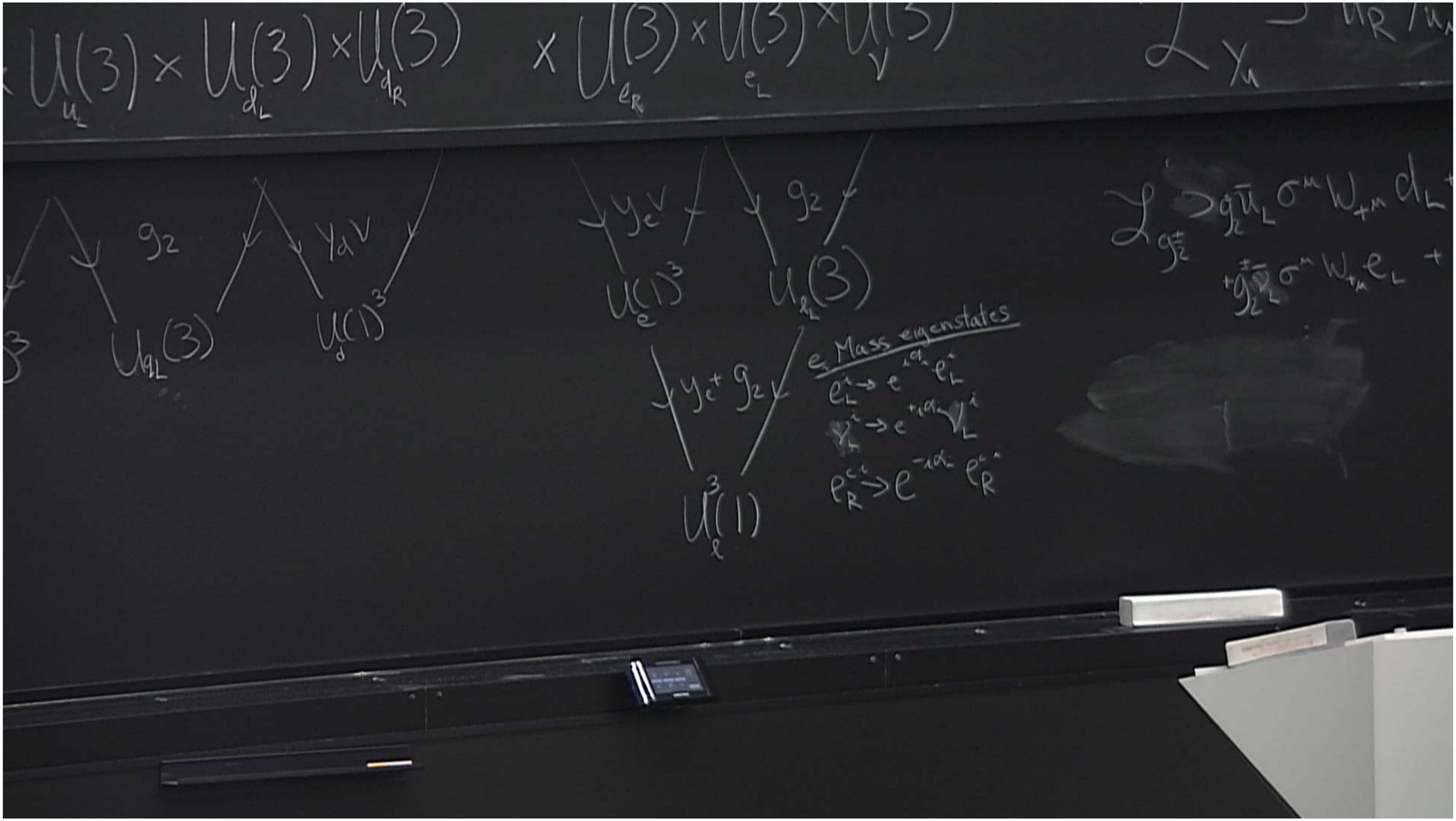
neglected m_u, m_c: $U_t(1) \times U_{u,c}(2)$

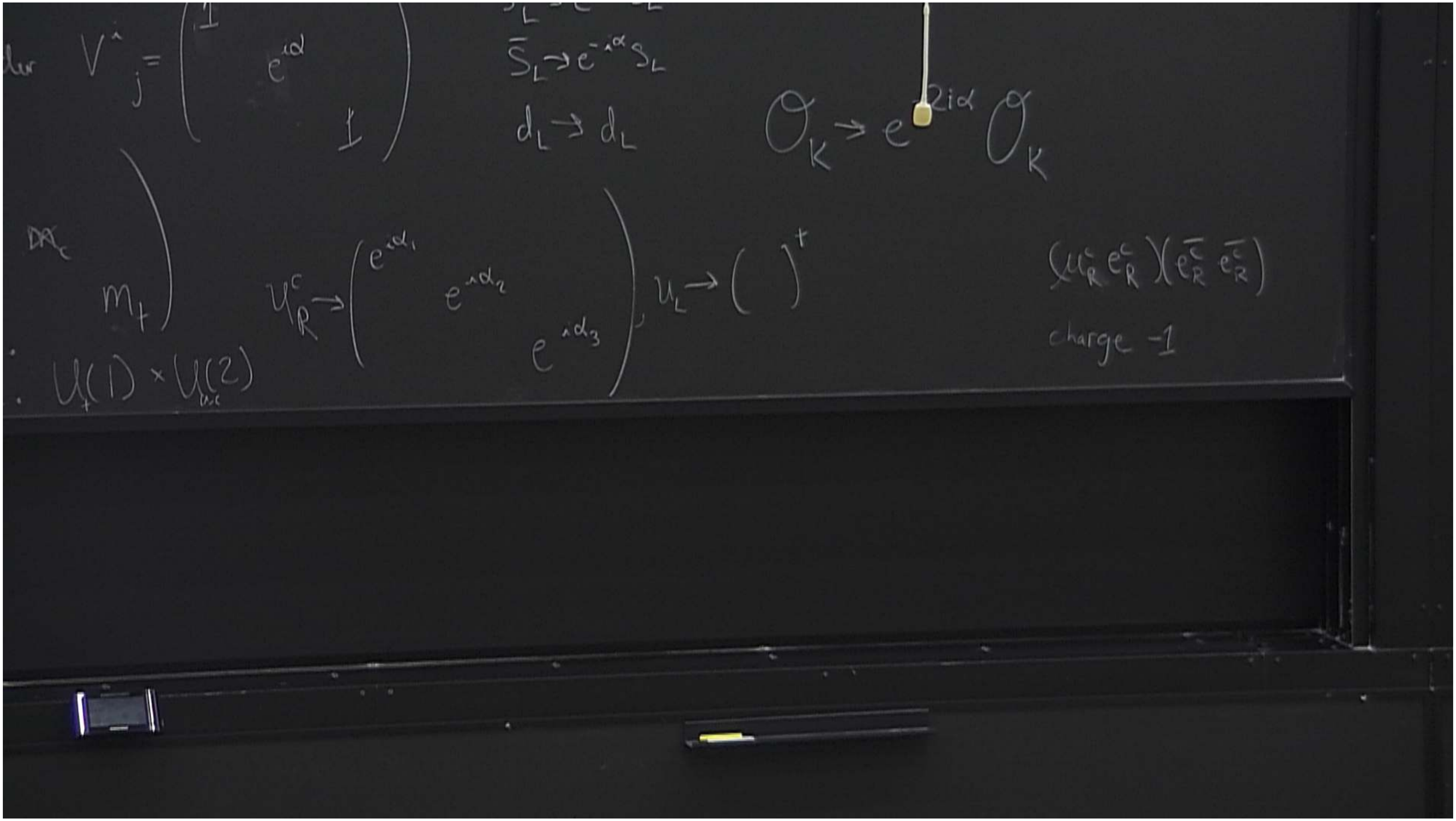



er $U(3)_{u_R} \times U(3)_{u_L} \times U(3)_{d_L} \times U(3)_{d_R} \times U(3)_{e_R} \times U(3)_{e_L} \times U(3)_{\nu}$
$\mathcal{L}$
$y_u v$
g_2
$y_d v$
$U(1)^3_u$
$U_{q_L}(3)$
$U(1)^3_d$
$y_e v$
g_2
$U(1)^3_e$
$U_{\ell_L}(3)$

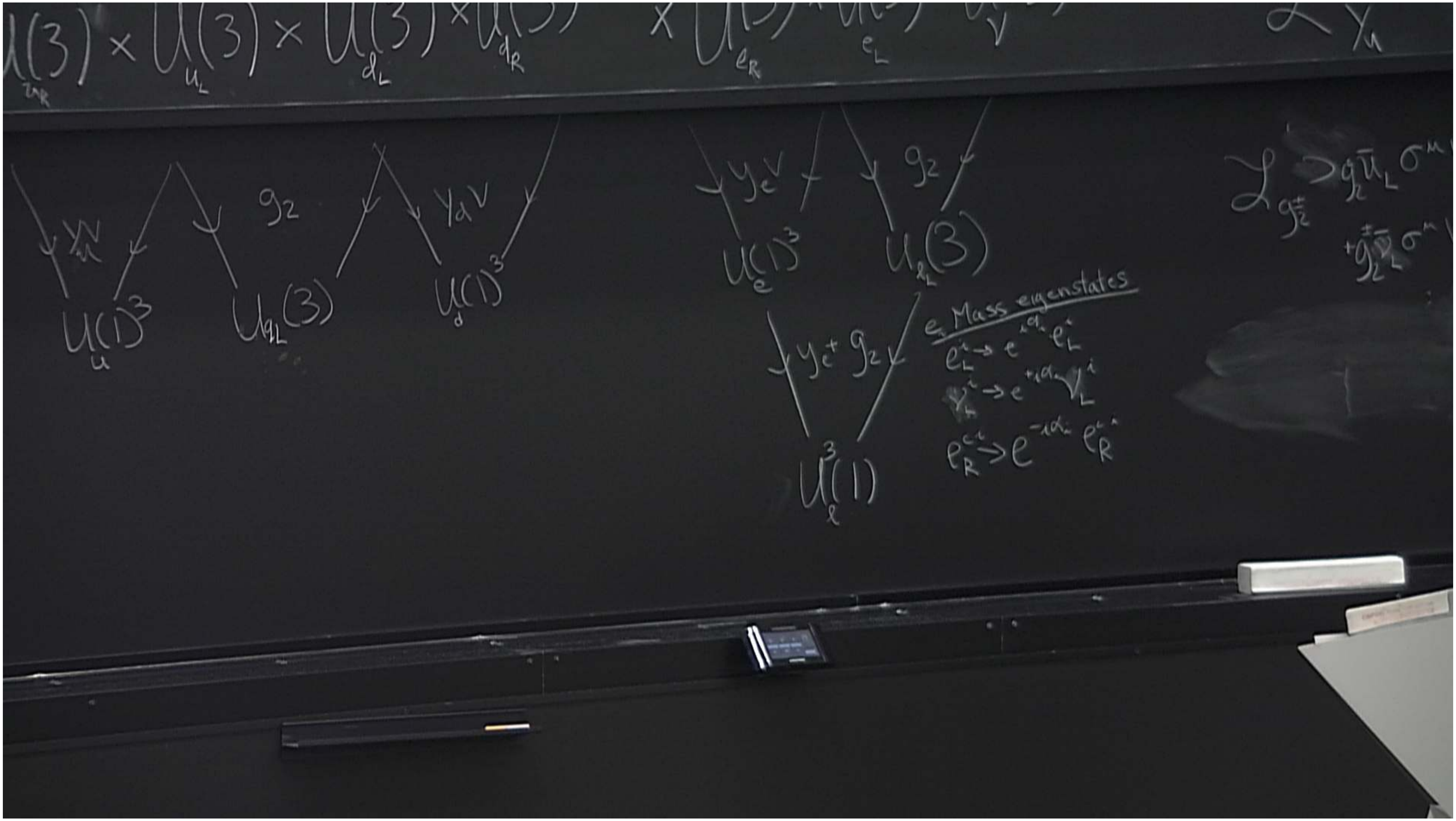


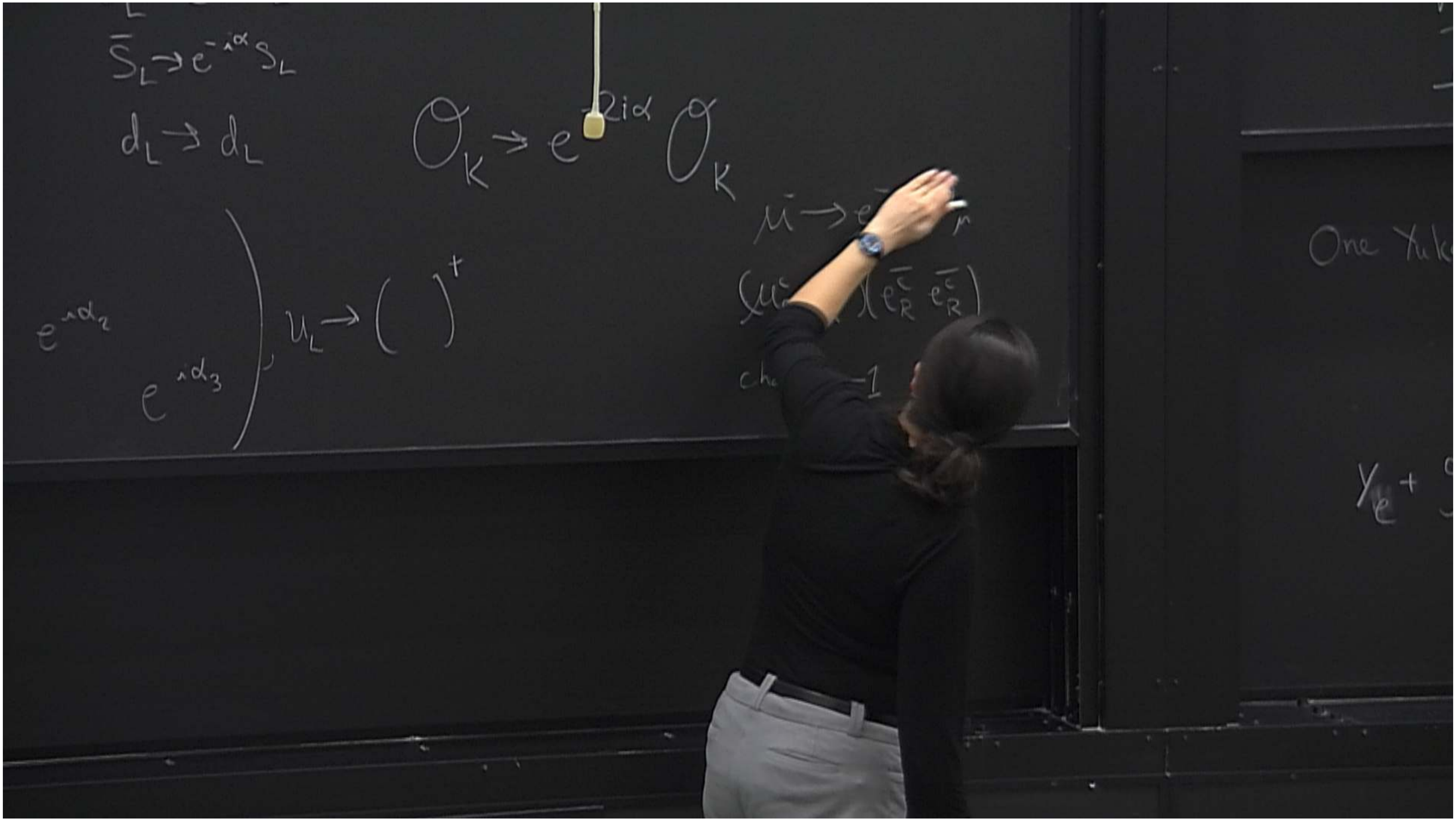

Mass eigenstates

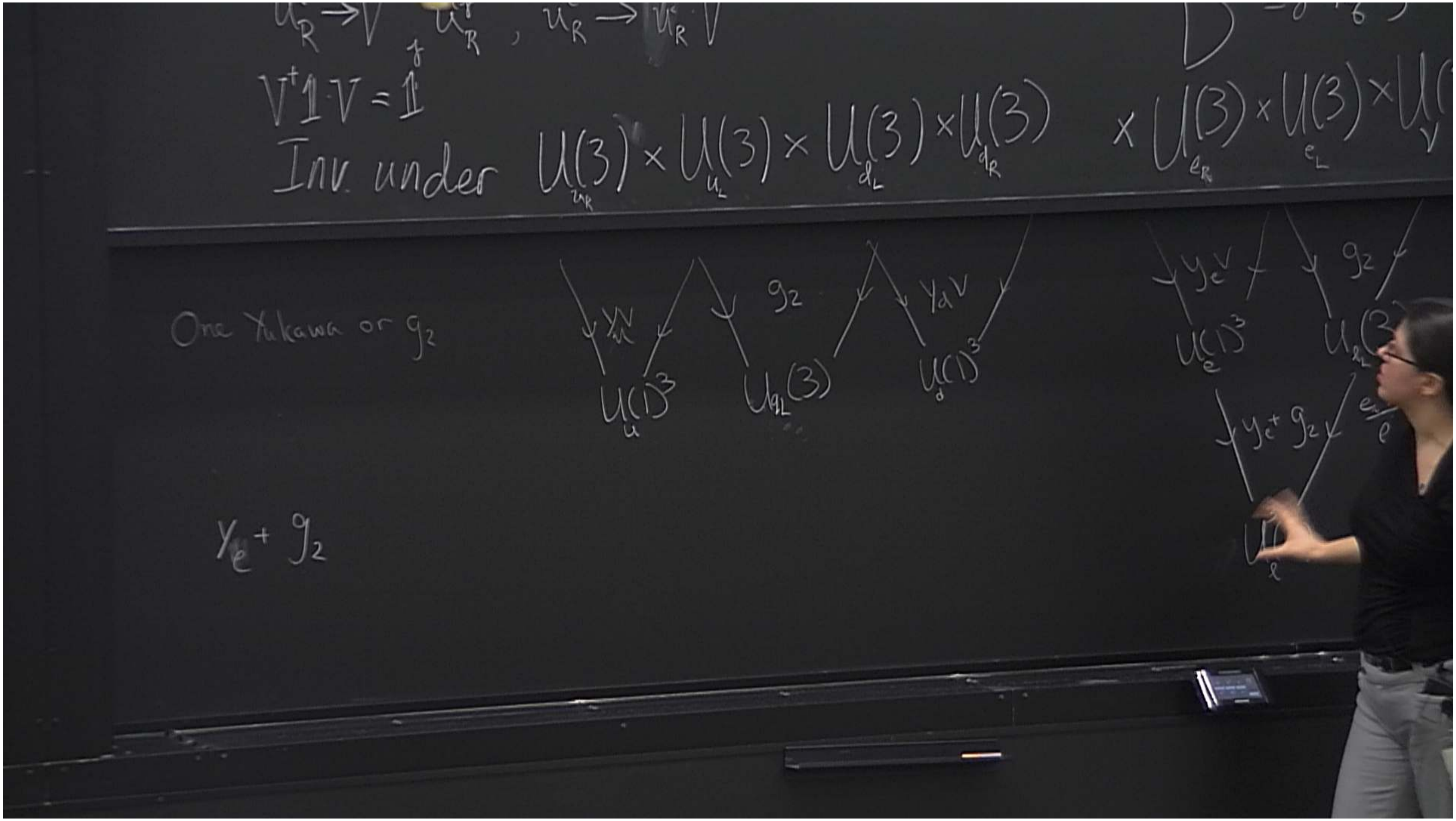

$U_{u_L}(3) \times U_{d_L}(3) \times U_{d_R}(3) \times U_{e_R}(3) \times U_{e_L}(3) \times U_{\nu}(3)$
$\mathcal{L}_{Y_u} \supset \bar{u}_R Y_u$
g_2
$y_d v$
$U_{q_L}(3)$
$U_d(1)^3$
$y_e v$
g_2
$U_e(1)^3$
$U_{\ell_L}(3)$
$y_e + g_2$
$U_\ell^3(1)$
e Mass eigenstates
$e_L^i \to e^{i\alpha_i} e_L^i$
$\nu_L^i \to e^{i\alpha_i} \nu_L^i$
$e_R^{c\,i} \to e^{-i\alpha_i} e_R^{c\,i}$
$\mathcal{L}_{g_2} \supset g_2 \bar{u}_L \sigma^\mu W_{+\mu} d_L$
$+ g_2 \bar{\nu}_L \sigma^\mu W_{+\mu} e_L +$



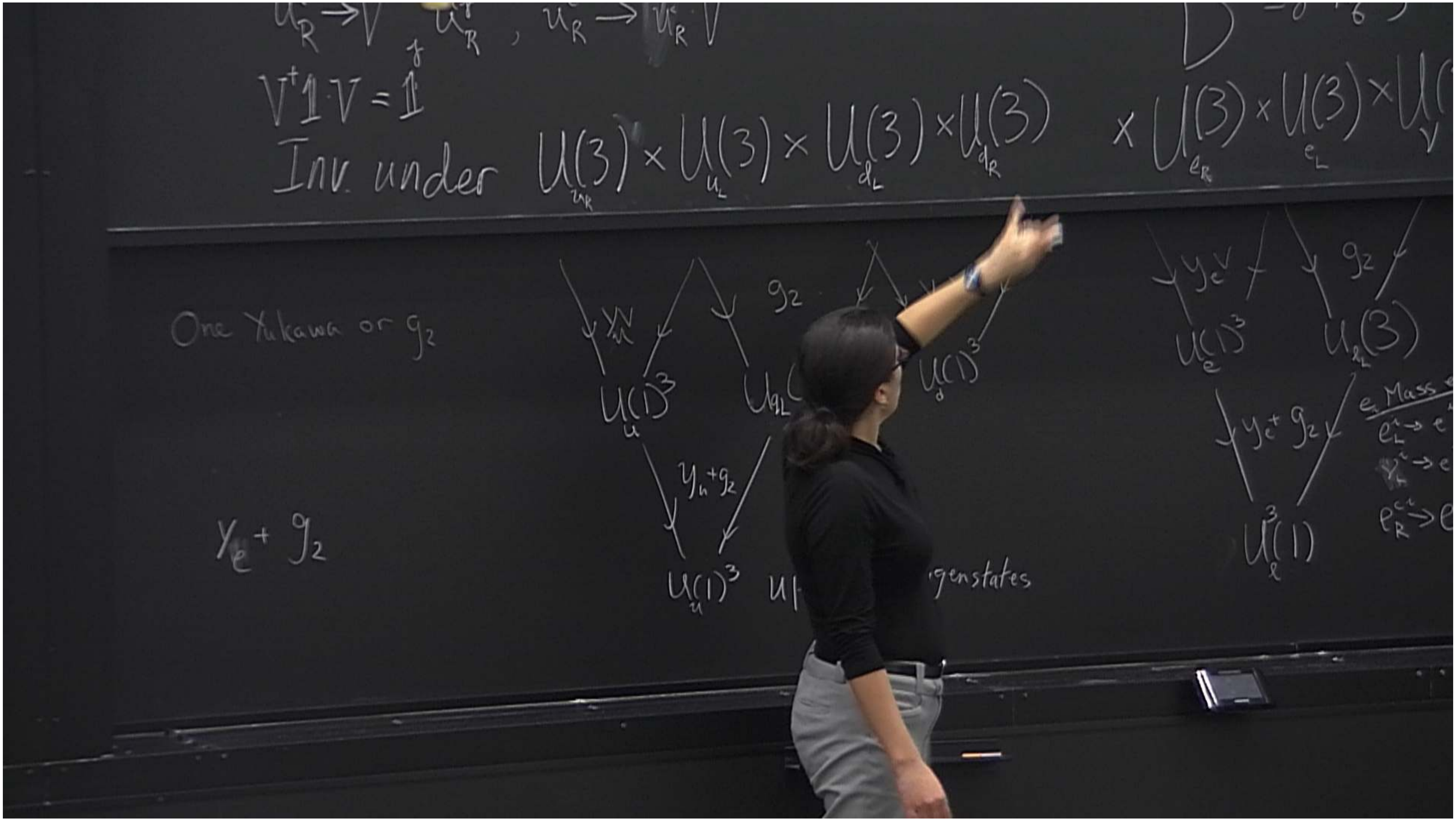
$V^i{}_j = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & 1 \end{pmatrix}$
$\bar{S}_L \to e^{-i\alpha} s_L$
$d_L \to d_L$
$O_K \to e^{2i\alpha} O_K$
m_t
$u^c_R \to \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$, $u_L \to (\ )^\dagger$
$(u^c_R e^c_R)(\bar{e}^c_R \bar{e}^c_R)$
charge -1
$U_t(1) \times U_{u,c}(2)$


Mass eigenstates

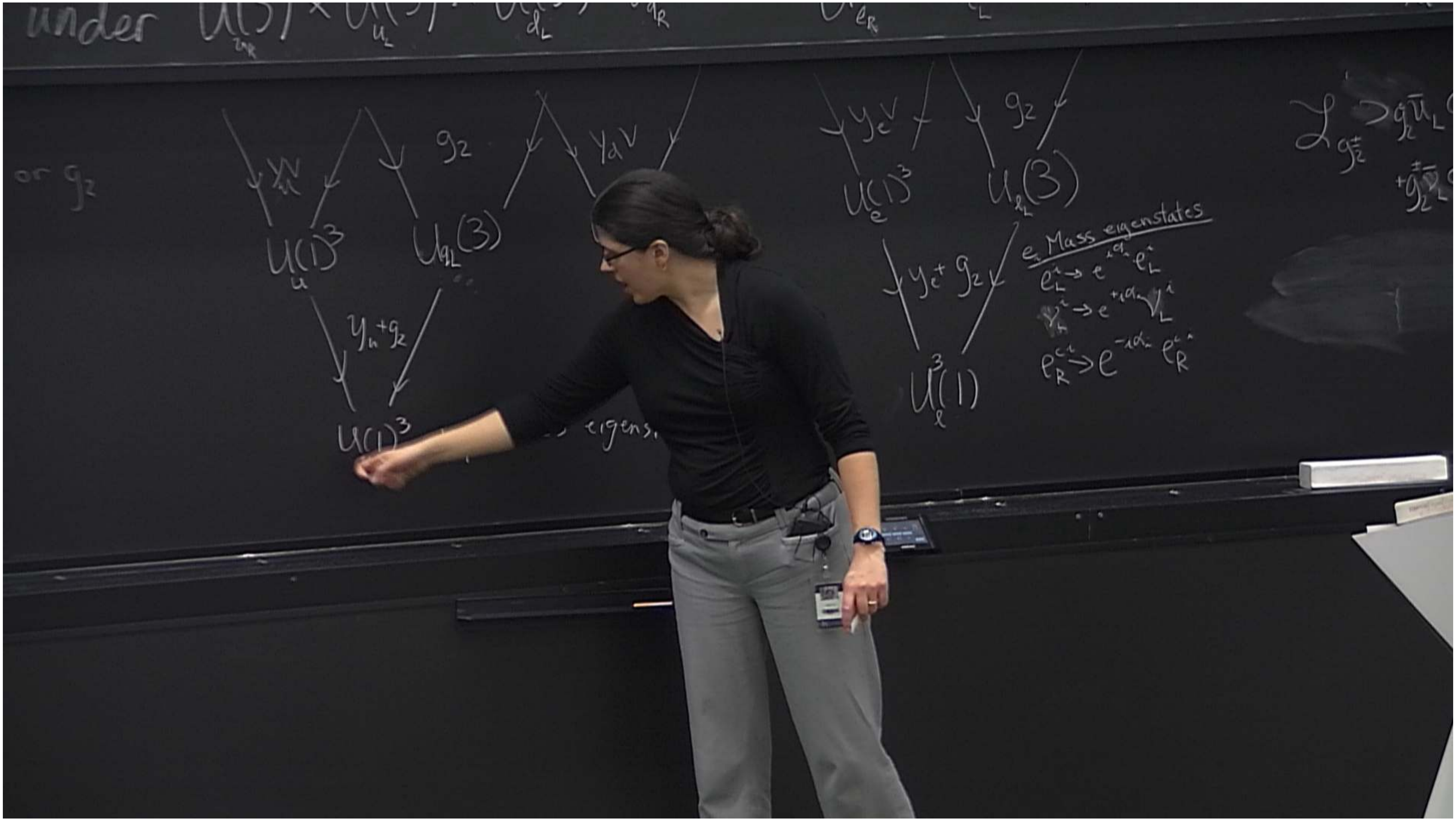

d_L → d_L
One Yuk

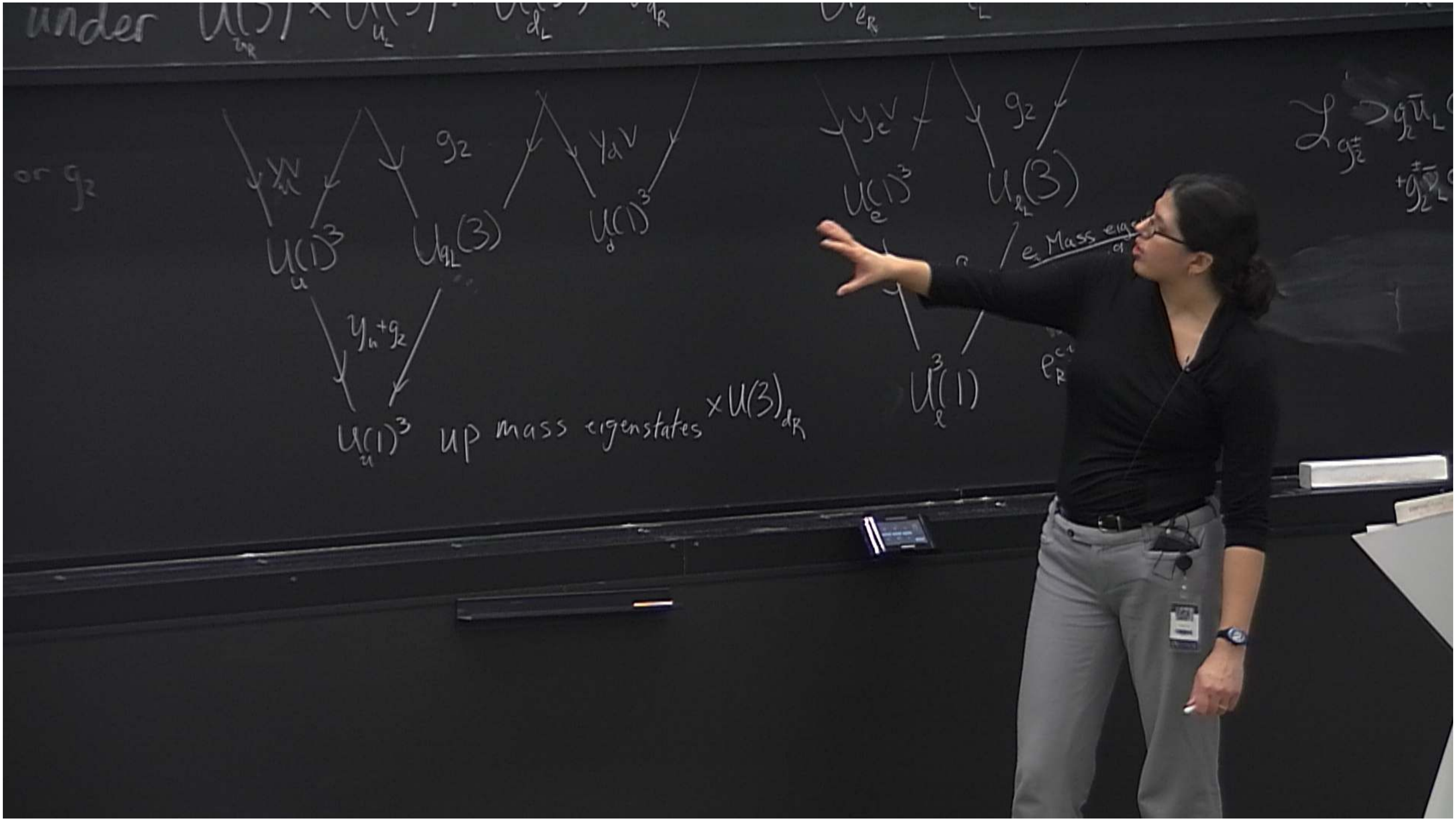


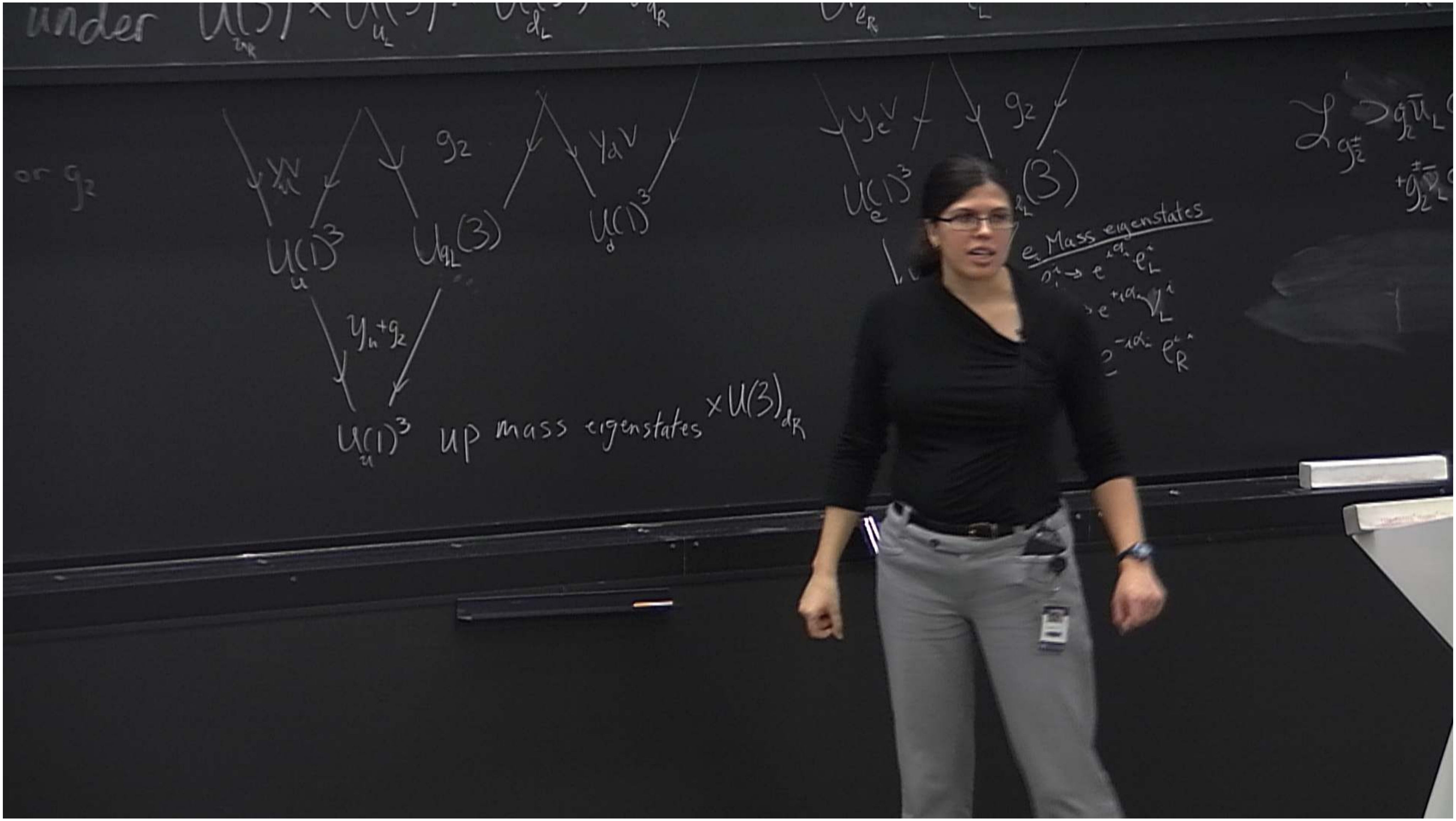
V†1V = 1
Inv. under U(3) × U(3) × U(3) × U(3) × U(3) × U(3) × U
One Yukawa or g2
g2
U(1)3
U(3)
ye + g2



V†1V = 1
Inv. under U(3) × U(3) × U(3) × U(3) × U(3) × U(3) × U(
One Yukawa or g2
g2
U(1)³
Yu + g2
U(1)³
genstates
Ye + g2
U(3)
U(1)³
Ye + g2
U(1)
e Mass


under
or g_2
g_2
$y_d v$
$y_u + g_2$
$y_e v$
$y_e + g_2$
Mass eigenstates
eigens


under
or g2
y2
U(1)3
Uq_L(3)
g2
yd v
ye v
Ue(1)3
Uℓ(3)
yu+g2
U(1)3 up mass eigenstates × U(3)dR


under
or g_2
$y_u v$
g_2
$y_d v$
$U(1)^3_u$
$U_{q_L}(3)$
$U(1)^3_d$
$y_u + g_2$
$U(1)^3_u$ up mass eigenstates $\times U(3)_{d_R}$
$y_e v$
g_2
Mass eigenstates