Title: PSI 2015/2016 Standard Model - Lecture 4

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Abstract:

Nonatelian Higgs model

example $SU(2)$ gauge theory $\quad \Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$ $\quad \phi_{1,2}$ = complex fields

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) - \frac{1}{2} \mathrm{Tr}\left(F_{\mu\nu} F^{\mu\nu}\right)$$

$$D_\mu \Phi = \left(\partial_\mu + i g T^a A^a_\mu\right) \Phi \quad , \quad T^a = \frac{\sigma^a}{2}$$

Nonabelian Higgs model

example: $SU(2)$ gauge theory $\quad \Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) - \frac{1}{2} \mathrm{Tr}(F_\mu$$

$$D_\mu \Phi = (\partial_\mu + i g T^a A^a_\mu) \Phi \quad , \quad T$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g \varepsilon^{abc} A^b_\mu A^c_\nu$$

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \qquad \phi_{1,2} = \text{complex fields}$$

$$-\frac{1}{2} \mathrm{Tr}\left(F_{\mu\nu} F^{\mu\nu}\right)$$

$$\Phi \quad , \quad T^a = \frac{\sigma^a}{2}$$

$$\varepsilon^{abc} A^b_\mu A^c_\nu \quad , \quad V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

tential is at $\Phi^\dagger\Phi = \frac{v^2}{2}$, $v = \sqrt{\frac{\mu^2}{\lambda}}$ $(\mu^2 > 0)$

y gauge where only the real component of ϕ_2 is n

$$\Phi(x) = \exp\left(i T^a \xi^a(x)/v\right) \begin{pmatrix} 0 \\ \frac{v + h(x)}{\sqrt{2}} \end{pmatrix}$$

$$v = \sqrt{\frac{\mu^2}{\lambda}} \qquad (\mu^2 > 0)$$

real component of ϕ_2 is non zero.

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

, four real fields $\xi^{1,2,3}$ and h.

potential is at $\Phi^\dagger\Phi = \frac{v^2}{2}$, $v = \sqrt{\frac{\mu^2}{\lambda}}$ $(\mu^2 > 0$

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y gauge where only the real component of ϕ_2 is n

$$\Phi(x) = \exp\left(i T^a \xi^a(x)/v\right) \begin{pmatrix} 0 \\ \frac{v + h(x)}{\sqrt{2}} \end{pmatrix},$$

way $\xi^{1,2,3}$ by a gauge transformation:

$$\Phi(x) \longrightarrow \Phi'(x) = \exp\left(-iT^a\xi^a/v\right)\Phi = \begin{pmatrix} 0 \\ \frac{v + h(x)}{\sqrt{2}} \end{pmatrix}$$

Covariant derivative term:

$$(D_\mu \Phi)^\dagger (D^\mu \Phi) = \frac{1}{2}(0, v+h)\left(\overleftarrow{\partial_\mu} - igT^a A_\mu^a\right)\left(\overrightarrow{\partial_\mu} + igT^a A_\mu^a\right)$$

$$= \frac{1}{2}(\partial_\mu h)^2 + \frac{g^2}{8}(0, v+h)\begin{pmatrix} A_\mu^3 & A_\mu^1 - iA_\mu^2 \\ A_\mu^1 + iA_\mu^2 & -A_\mu^3 \end{pmatrix}^2 \begin{pmatrix}$$

$$= \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}\left(\frac{gv}{2}\right)^2\left[(A_\mu^1)^2 + (A_\mu^2)^2 + (A_\mu^3)^2\right]\left(1 + \frac{h}{v}\right)^2$$

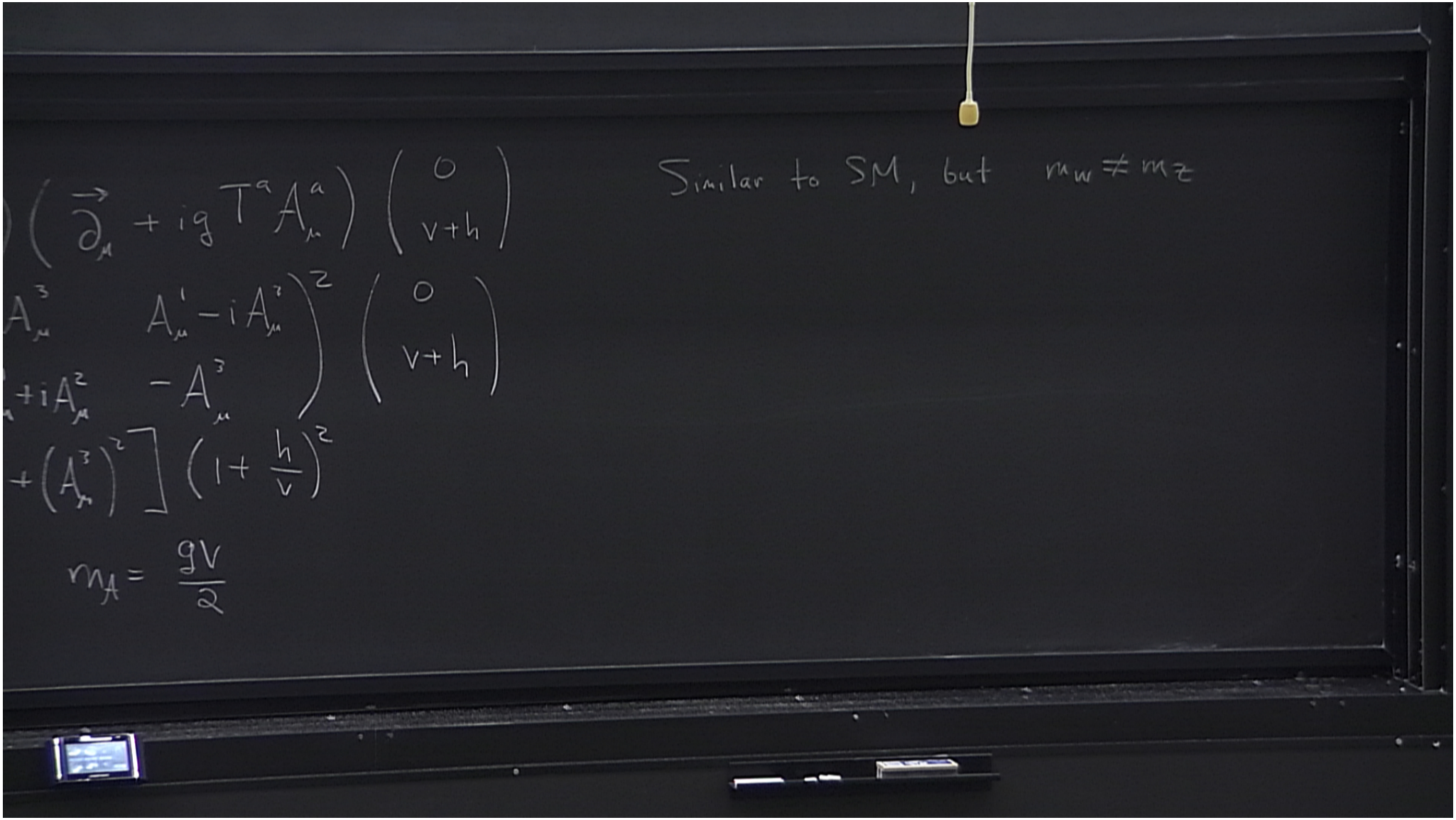
Covariant derivative term:

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All three vector bosons $A_\mu^{1,2,3}$ get the same mass $m_A = \frac{gv}{2}$


$\left(\vec{\partial}_\mu + ig T^a A^a_\mu\right)\begin{pmatrix}0\\ v+h\end{pmatrix}$
Similar to SM, but $m_W \neq m_Z$
$A^3_\mu \qquad A^1_\mu - iA^2_\mu$
$+iA^2_\mu \qquad -A^3_\mu$
$+\left(A^3_\mu\right)^2\Big]\left(1+\frac{h}{v}\right)^2$
$m_A = \frac{gv}{2}$

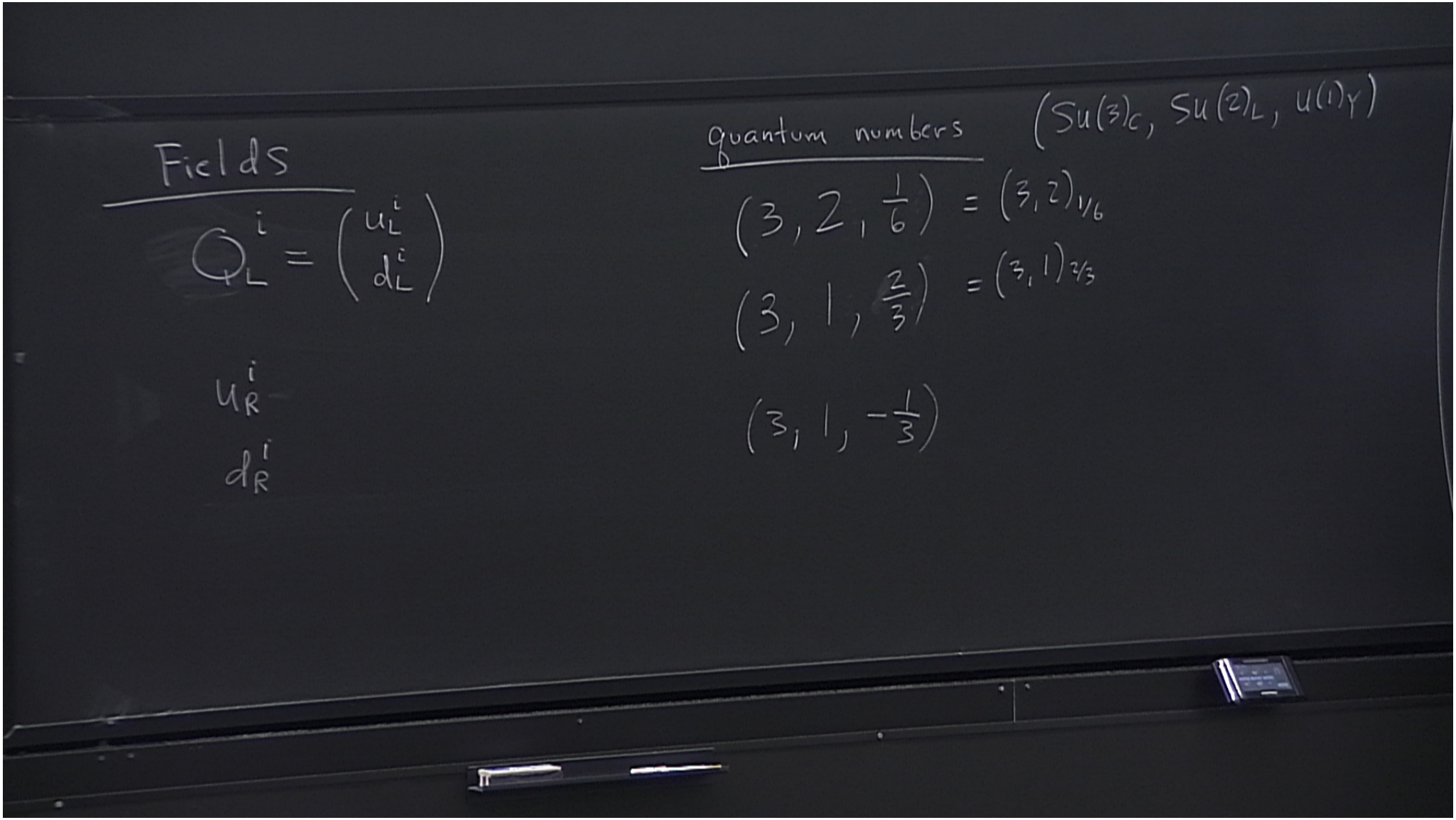
SM Lagrangian

Need to know gauge group, the d.o.f. (field), quantum numbers of field.

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

(C = color)
QCD

$SU(2)_L \times U(1)_Y$: Electroweak gauge group
L = left
Y = hypercharge


Fields
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$
u_R^i
d_R^i
quantum numbers $(SU(3)_C, SU(2)_L, U(1)_Y)$
$(3, 2, \frac{1}{6}) = (3,2)_{1/6}$
$(3, 1, \frac{2}{3}) = (3,1)_{2/3}$
$(3, 1, -\frac{1}{3})$

Fields

$$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$$

u_R^i

d_R^i

$$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

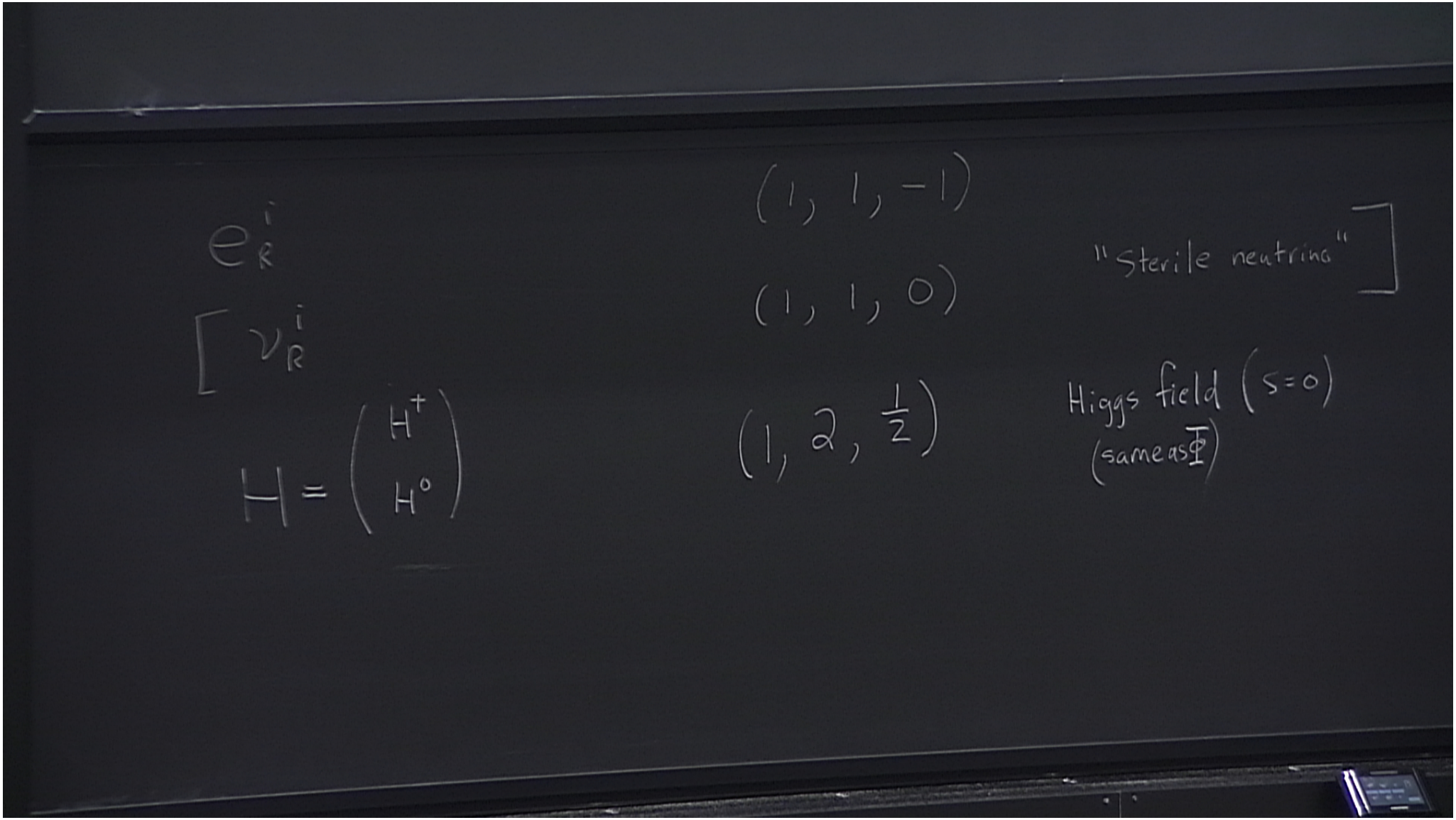
quantum numbers $(SU(3)_C, SU(2)_L, U(1)_Y)$

$(3, 2, \frac{1}{6}) = (3, 2)_{1/6}$

$(3, 1, \frac{2}{3}) = (3, 1)_{2/3}$

$(3, 1, -\frac{1}{3})$

$(1, 2, -\frac{1}{2})$


e_R^i
$(1, 1, -1)$
$[\nu_R^i$
$(1, 1, 0)$
"Sterile neutrino"]
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$
$(1, 2, \frac{1}{2})$
Higgs field (s=0)
(same as Φ)

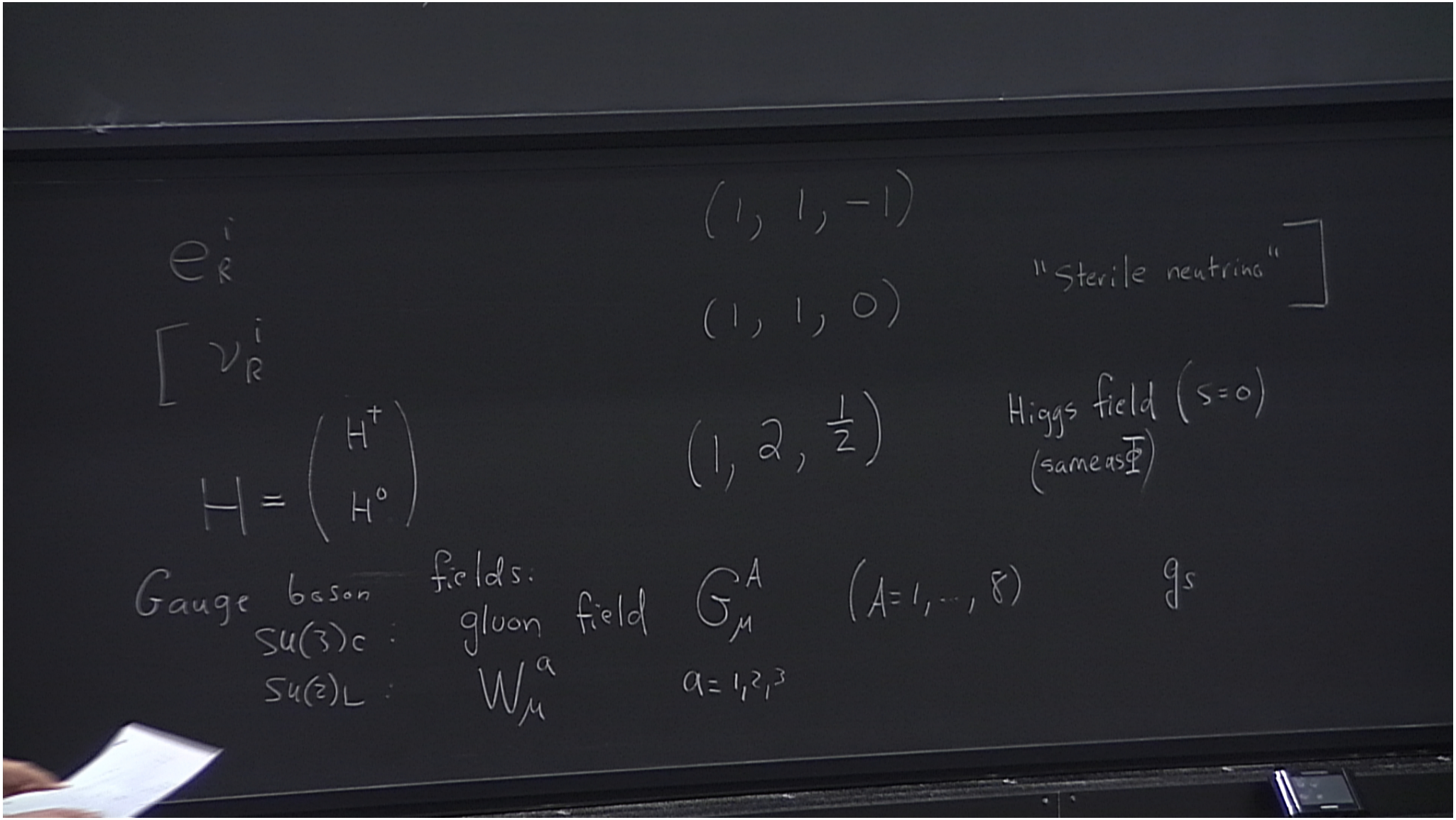
$)_L, U(1)_Y)$

i labels generation

$$Q_L^1 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad Q_L^2 = \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \quad Q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$L_L^1 = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \quad L_L^2 = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \quad L_L^3 = \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

$$e_R^1 = e_R, \quad e_R^2 = \mu_R, \quad e_R^3 = \tau_R$$


e_R^i
$(1, 1, -1)$
"Sterile neutrino"
$[\nu_R^i$
$(1, 1, 0)]$
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$
$(1, 2, \frac{1}{2})$
Higgs field $(s=0)$
(same as Φ)
Gauge boson fields:
$SU(3)_C$: gluon field G_μ^A $(A = 1, \cdots, 8)$ g_s
$SU(2)_L$: W_μ^a $a = 1, 2, 3$

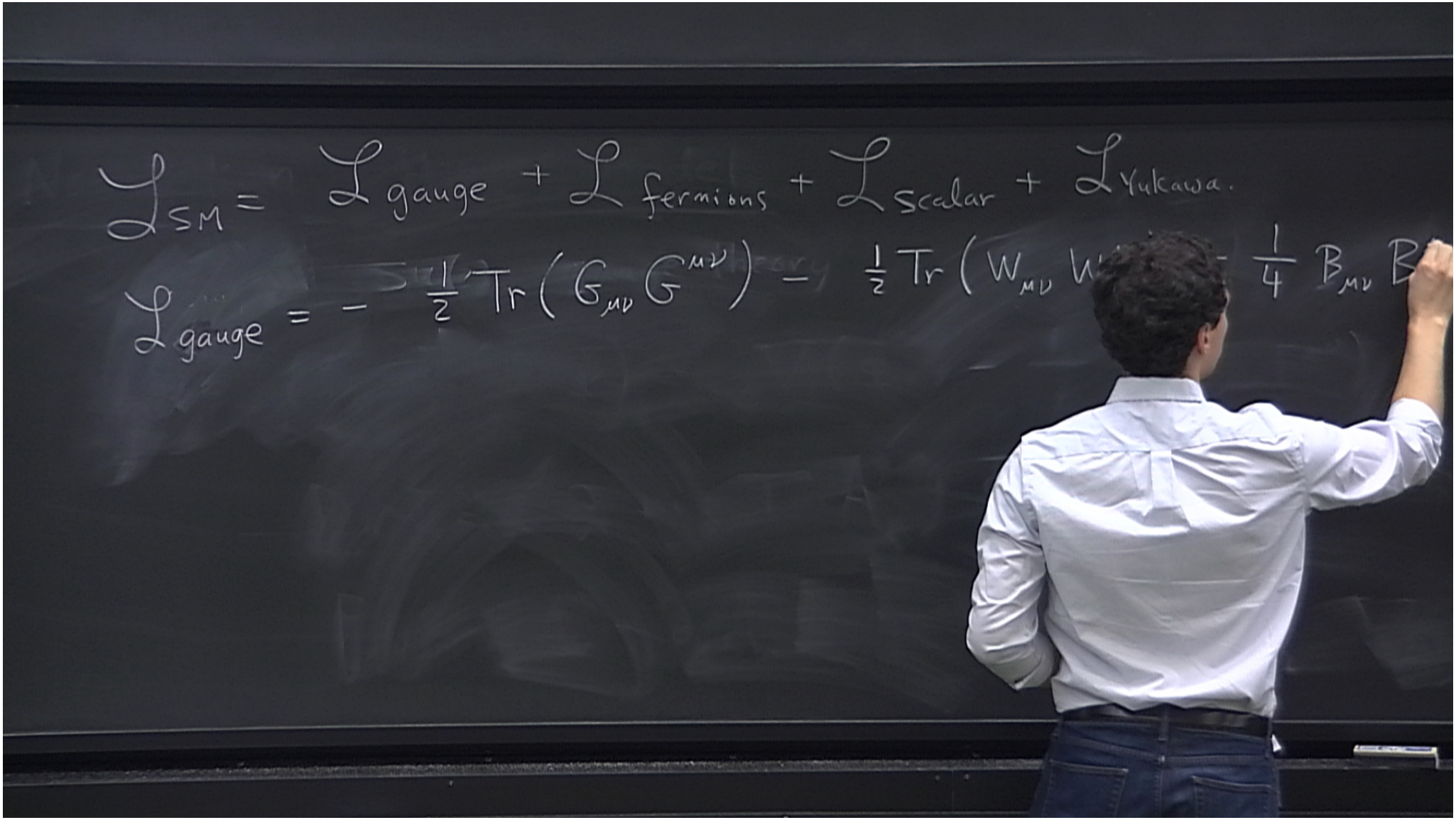
e_R^i $(1, 1, -1)$

$[\nu_R^i$ $(1, 1, 0)$ "Sterile neutrino" $]$

$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ $(1, 2, \frac{1}{2})$ Higgs field $(s=0)$ (same as Φ)

Gauge boson fields:

$SU(3)_C$:	gluon field G_μ^A	$(A = 1, \dots, 8)$	g_s
$SU(2)_L$:	W_μ^a	$a = 1, 2, 3$	g
$U(1)_Y$:	B_μ		g'


$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{scalar} + \mathcal{L}_{Yukawa}$.
$\mathcal{L}_{gauge} = -\frac{1}{2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) - \frac{1}{2}\mathrm{Tr}(W_{\mu\nu}$
$\frac{1}{4}B_{\mu\nu}$

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{scalar} + \mathcal{L}_{Yukawa}.$$

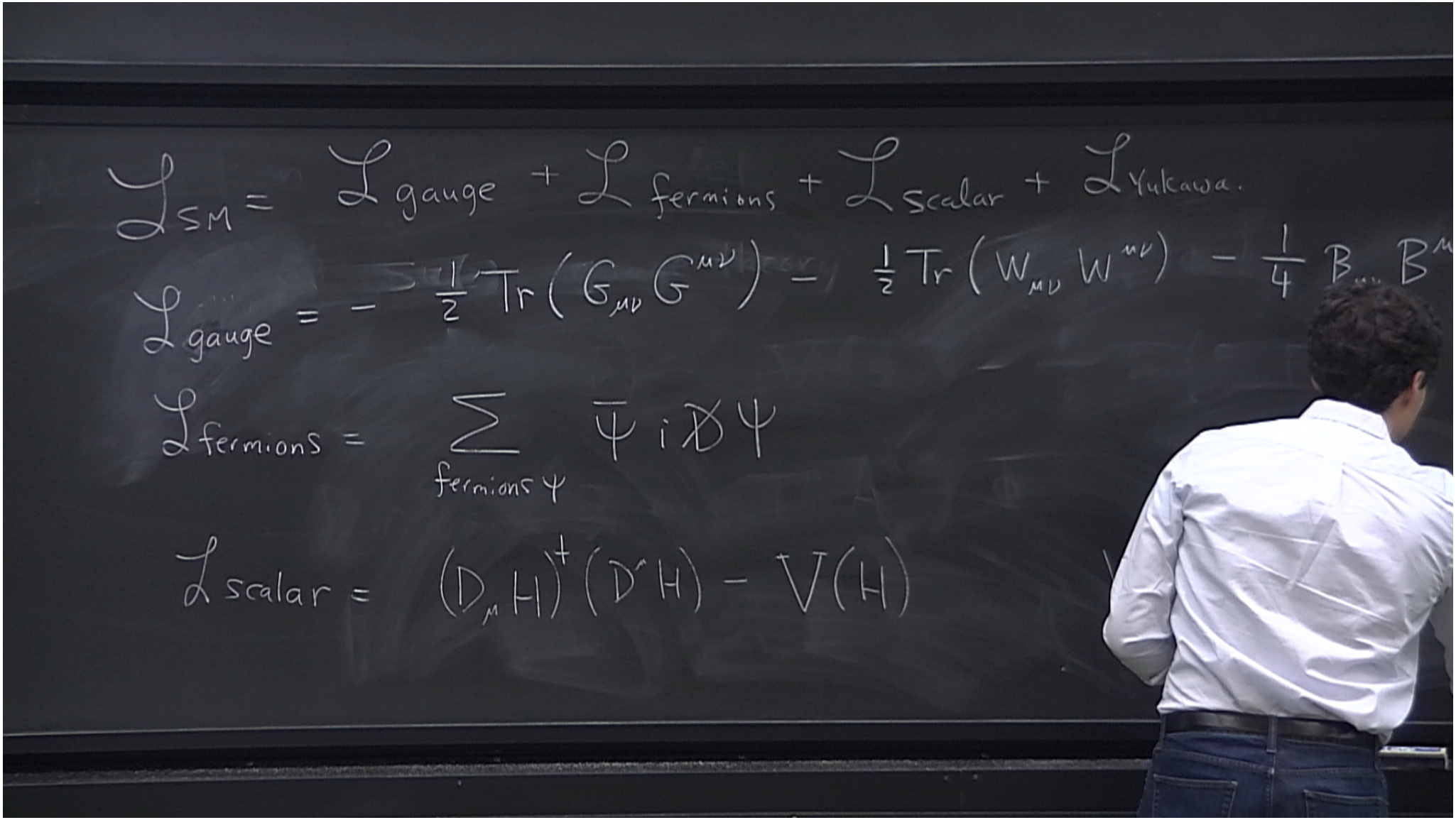
$$\mathcal{L}_{gauge} = -\frac{1}{2}\mathrm{Tr}\left(G_{\mu\nu}G^{\mu\nu}\right) - \frac{1}{2}\mathrm{Tr}\left(W_{\mu\nu}W^{\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

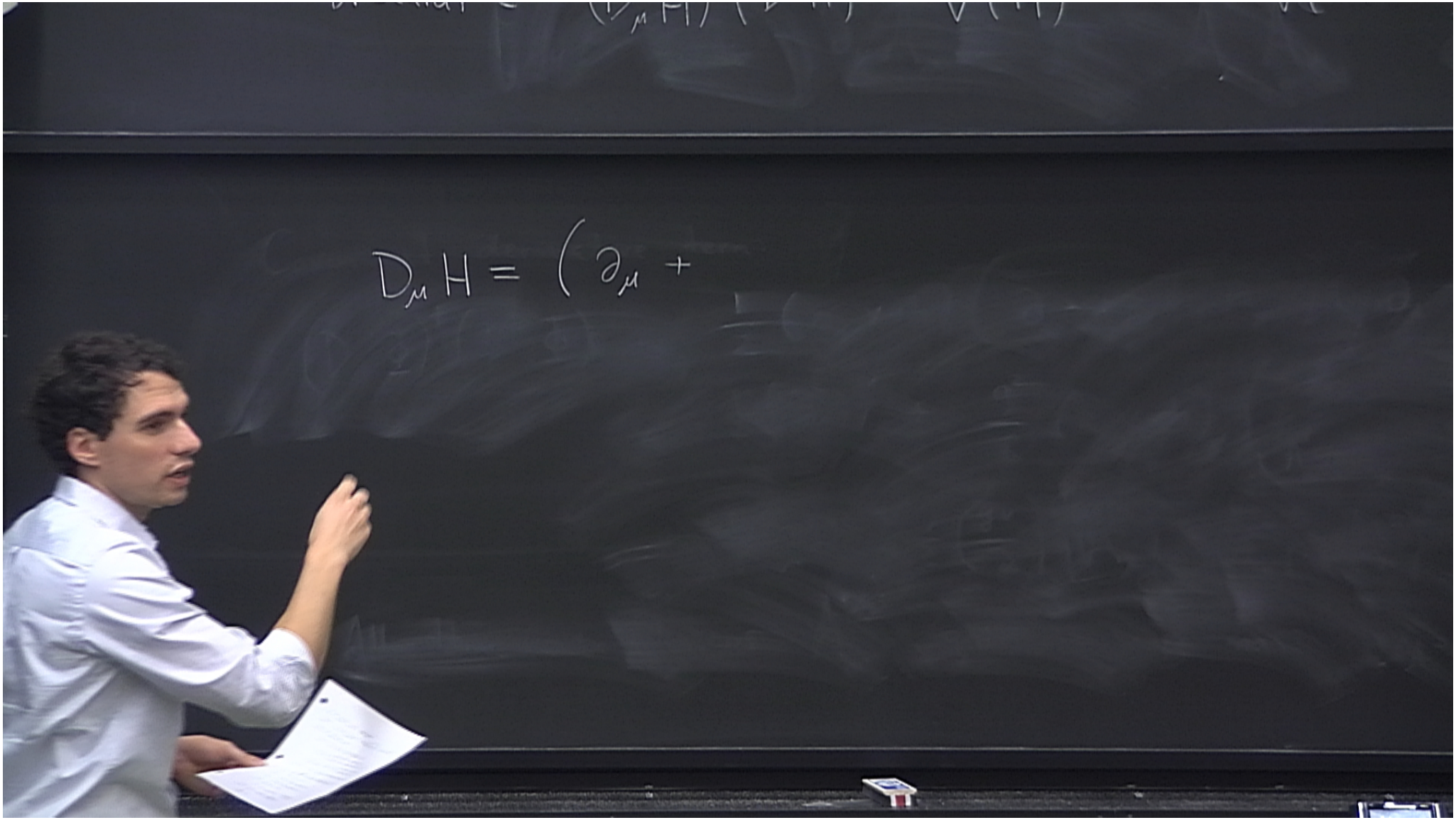
$$\mathcal{L}_{fermions} = \sum_{\text{fermions } \psi} \bar{\psi} i \not{D} \psi$$

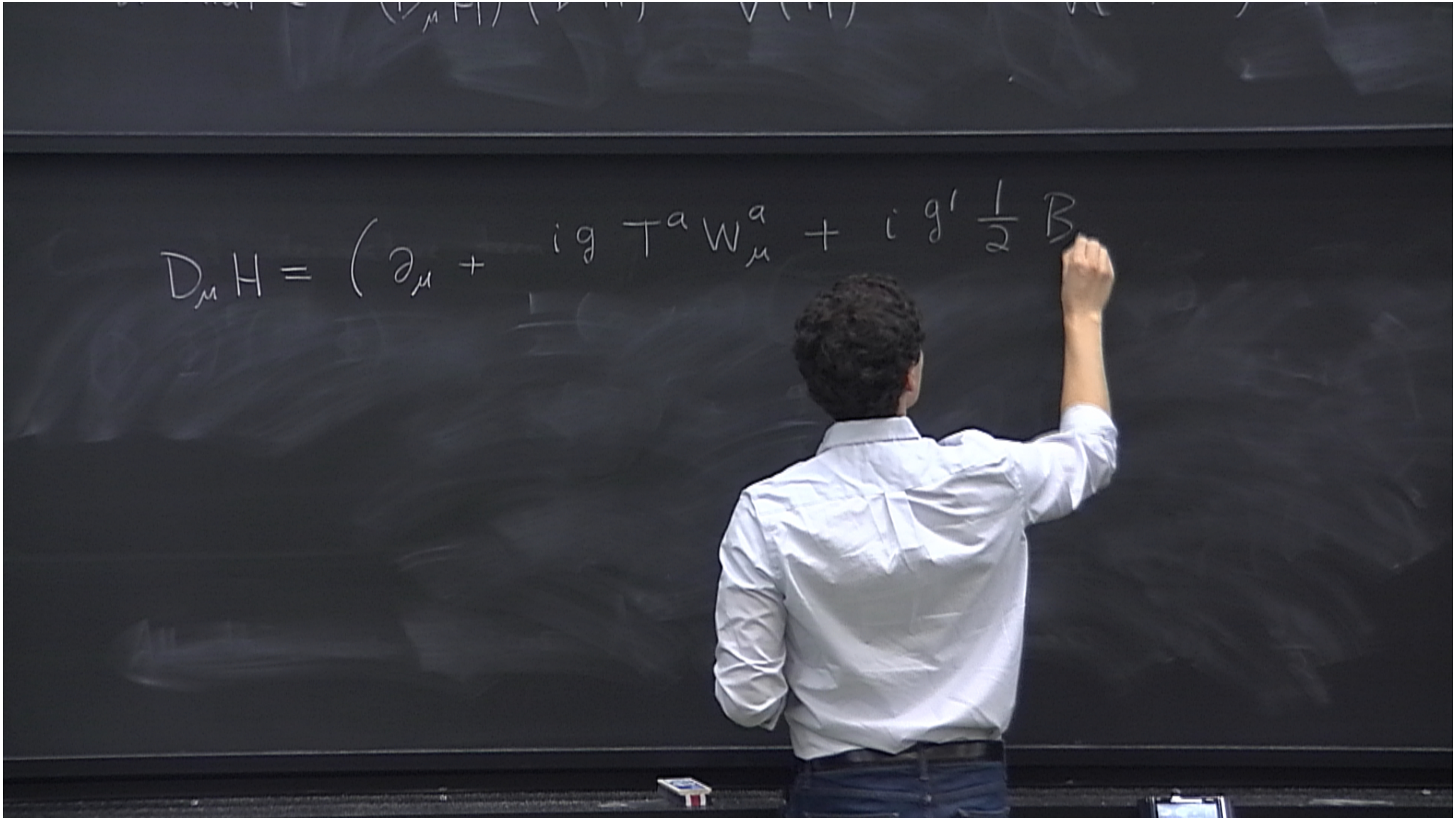
$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{scalar} + \mathcal{L}_{Yukawa}.$$

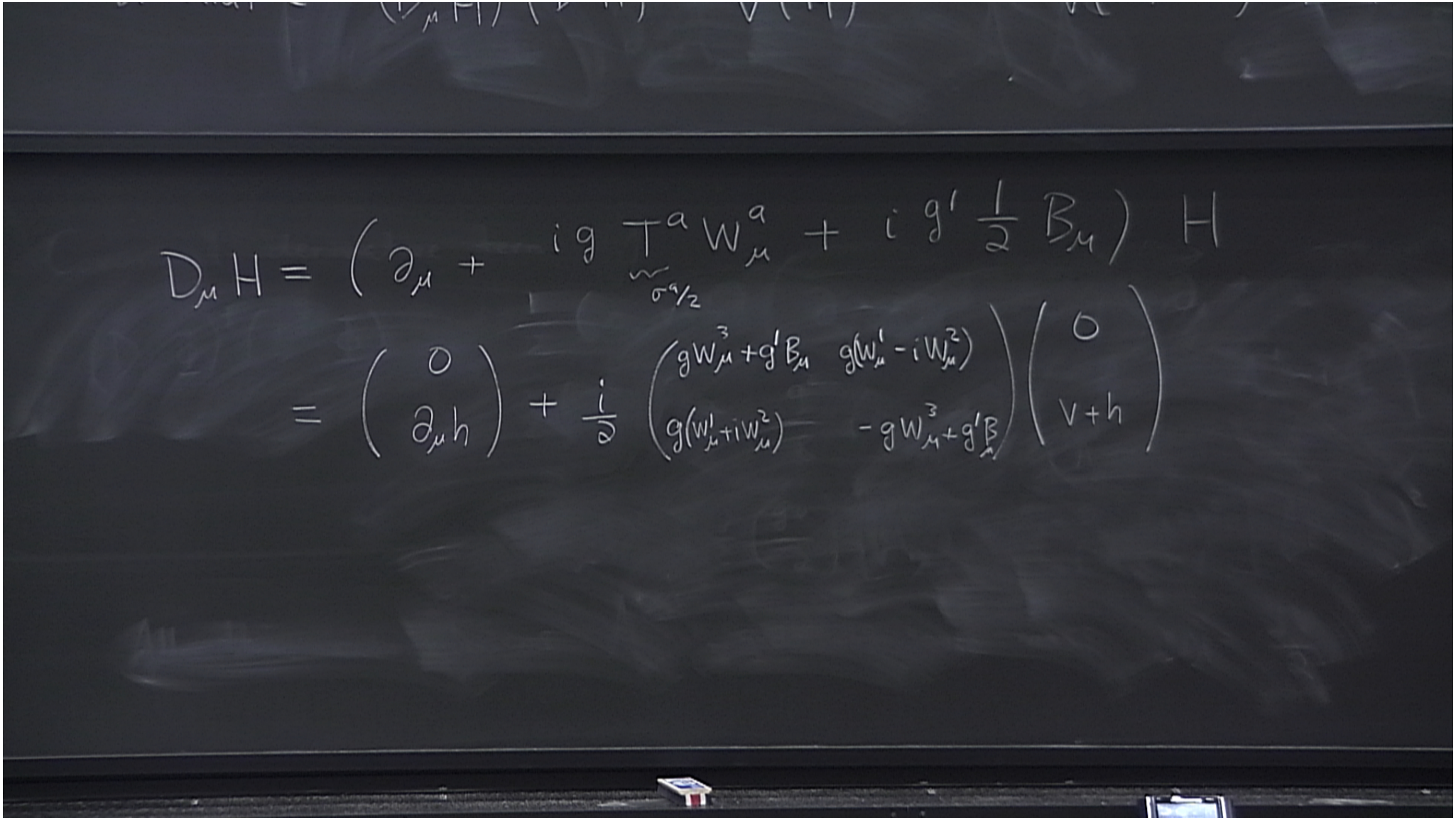
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$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{fermions} + \mathcal{L}_{scalar} + \mathcal{L}_{Yukawa}$.
$\mathcal{L}_{gauge} = -\frac{1}{2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) - \frac{1}{2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{4}B_{\mu\nu}B^{\mu}$
$\mathcal{L}_{fermions} = \sum_{fermions\ \psi} \bar{\psi} i \not{D} \psi$
$\mathcal{L}_{scalar} = (D_\mu H)^\dagger (D^\mu H) - V(H)$

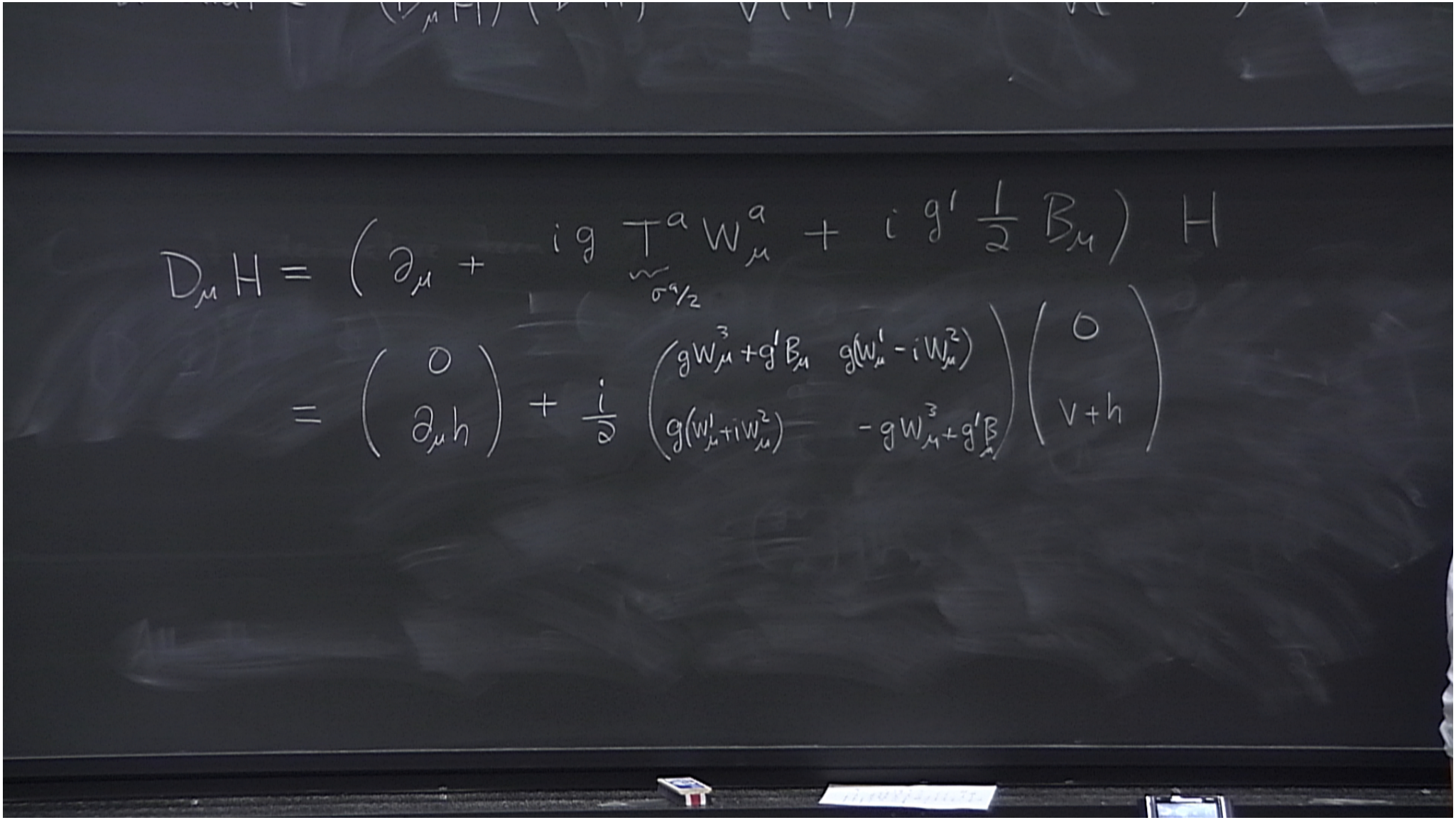

$D_\mu H = (\partial_\mu +$

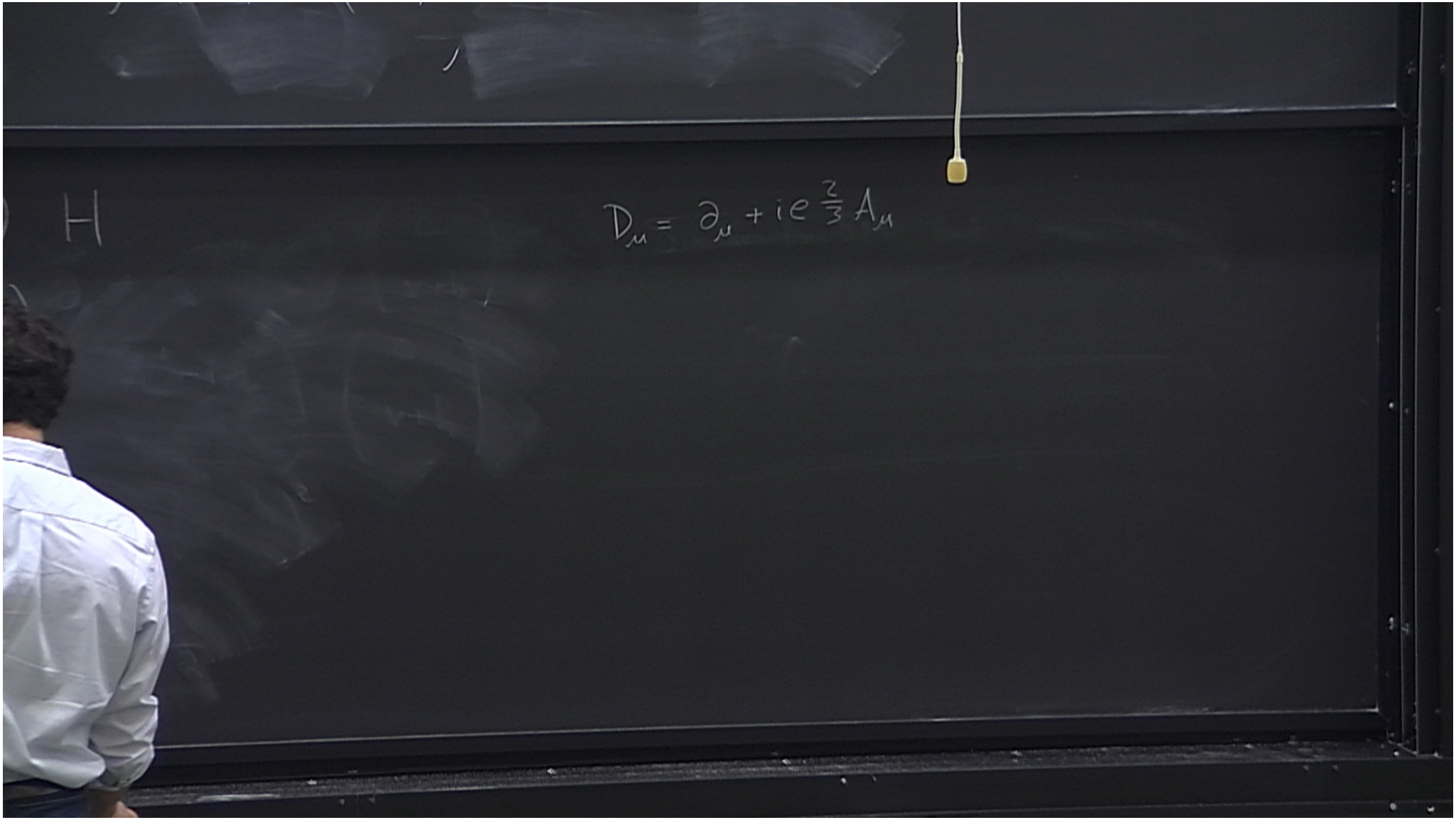

$D_\mu H = \left(\partial_\mu + i g T^a W_\mu^a + i g' \frac{1}{2} B_\mu\right)$

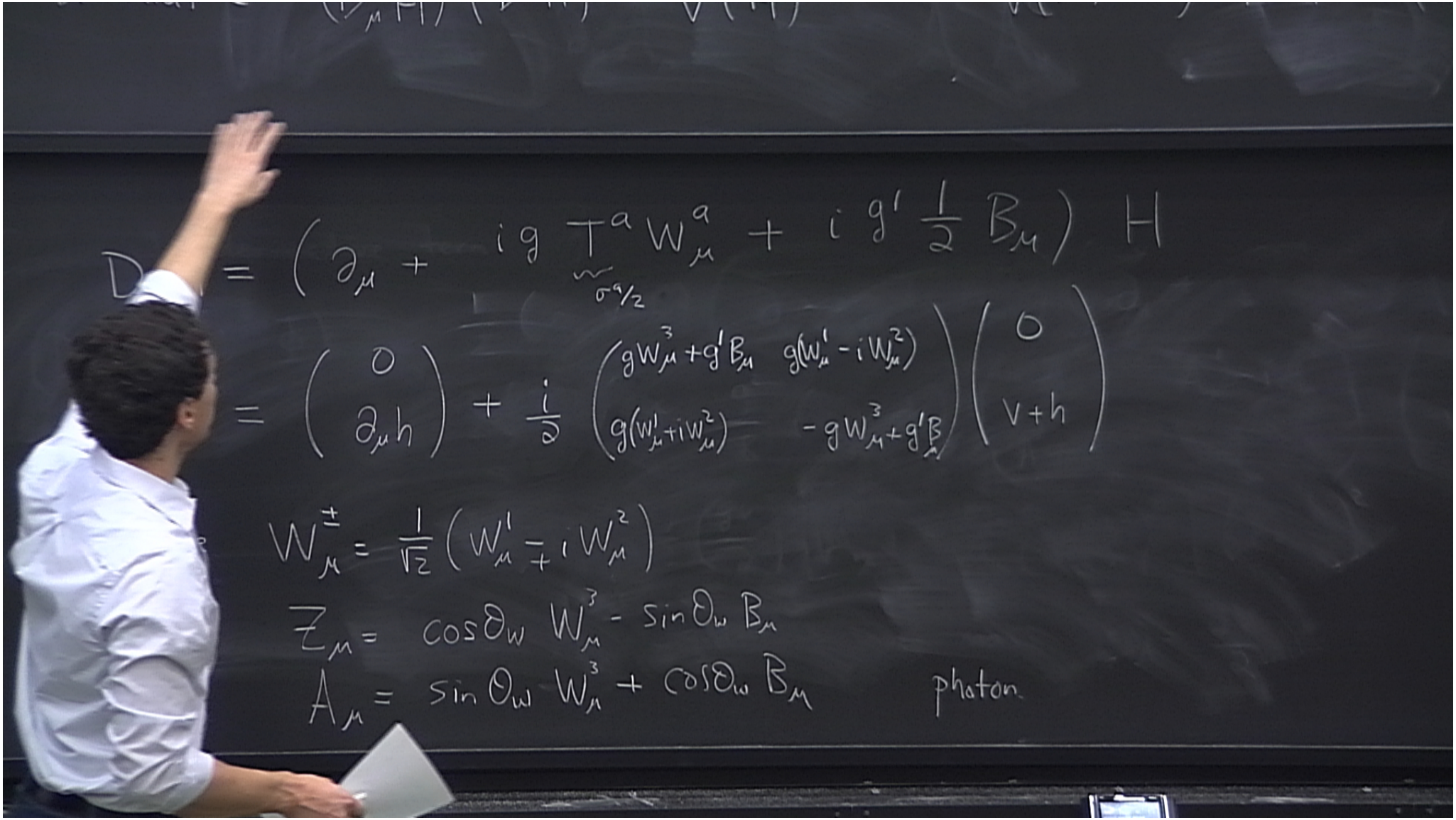

$D_\mu H = \left(\partial_\mu + i g \underbrace{T^a}_{\sigma^a/2} W^a_\mu + i g' \frac{1}{2} B_\mu\right) H$
$= \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} + \frac{i}{2} \begin{pmatrix} g W^3_\mu + g' B_\mu & g(W^1_\mu - i W^2_\mu) \\ g(W^1_\mu + i W^2_\mu) & -g W^3_\mu + g' B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$

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H
$D_\mu = \partial_\mu + ie\frac{2}{3}A_\mu$


$D_\mu = \left(\partial_\mu + i g \underbrace{T^a}_{\sigma^a/2} W_\mu^a + i g' \frac{1}{2} B_\mu\right) H$
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$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2)$
$Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$
$A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$
photon

$$D_\mu H = \left(\partial_\mu + i g \underbrace{T^a}_{\sigma^a/2} W_\mu^a + i g' \frac{1}{2} B_\mu\right) H$$

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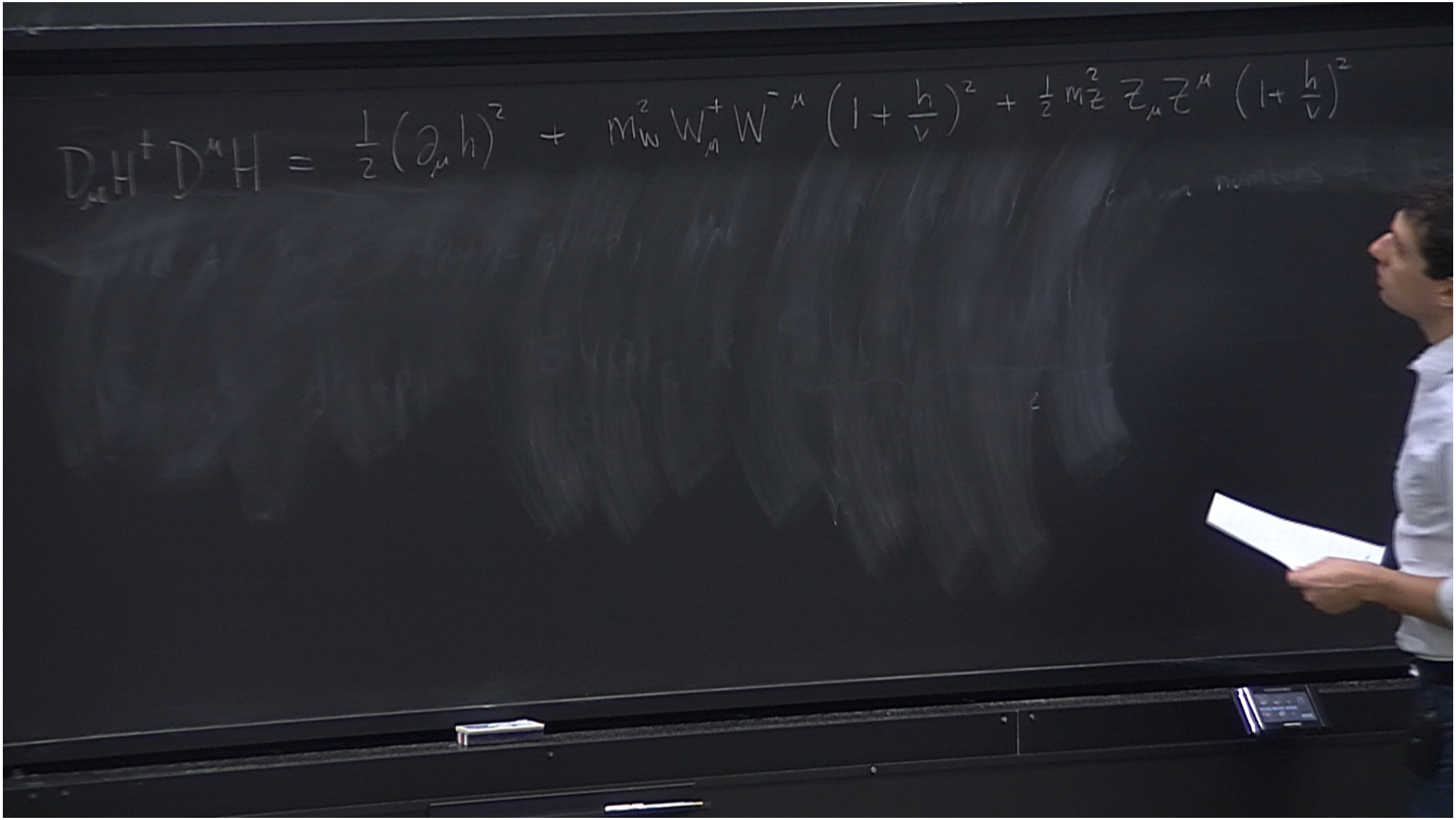
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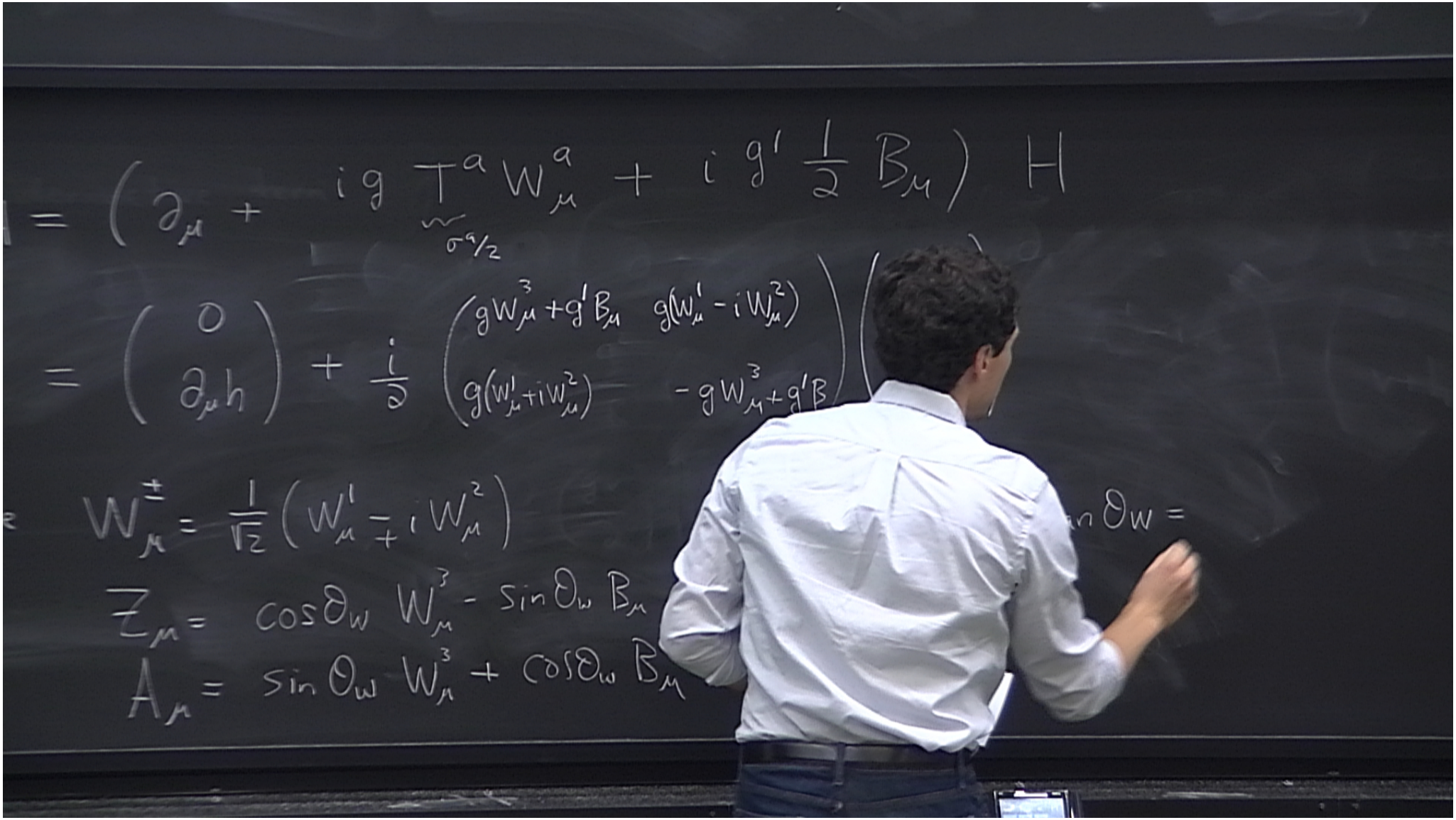
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$Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$

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$D_\mu H^\dagger D^\mu H = \frac{1}{2}(\partial_\mu h)^2 + m_W^2 W_\mu^+ W^{-\mu}\left(1+\frac{h}{v}\right)^2 + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1+\frac{h}{v}\right)^2$


$= \left(\partial_\mu + ig \underbrace{T^a}_{\sigma^a/2} W^a_\mu + ig' \frac{1}{2} B_\mu\right) H$
$= \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} + \frac{i}{2} \begin{pmatrix} gW^3_\mu + g'B_\mu & g(W^1_\mu - iW^2_\mu) \\ g(W^1_\mu + iW^2_\mu) & -gW^3_\mu + g'B \end{pmatrix} \begin{pmatrix}$
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$\sin\theta_W =$

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$$A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu \quad \text{photon}$$

$$\tan\theta_W = \frac{g'}{g}$$

θ_W = weak mixi

$$D_\mu H = \left(\partial_\mu + i g \underbrace{T^a}_{\sigma^a/2} W_\mu^a + i g' \frac{1}{2} B_\mu\right) H$$

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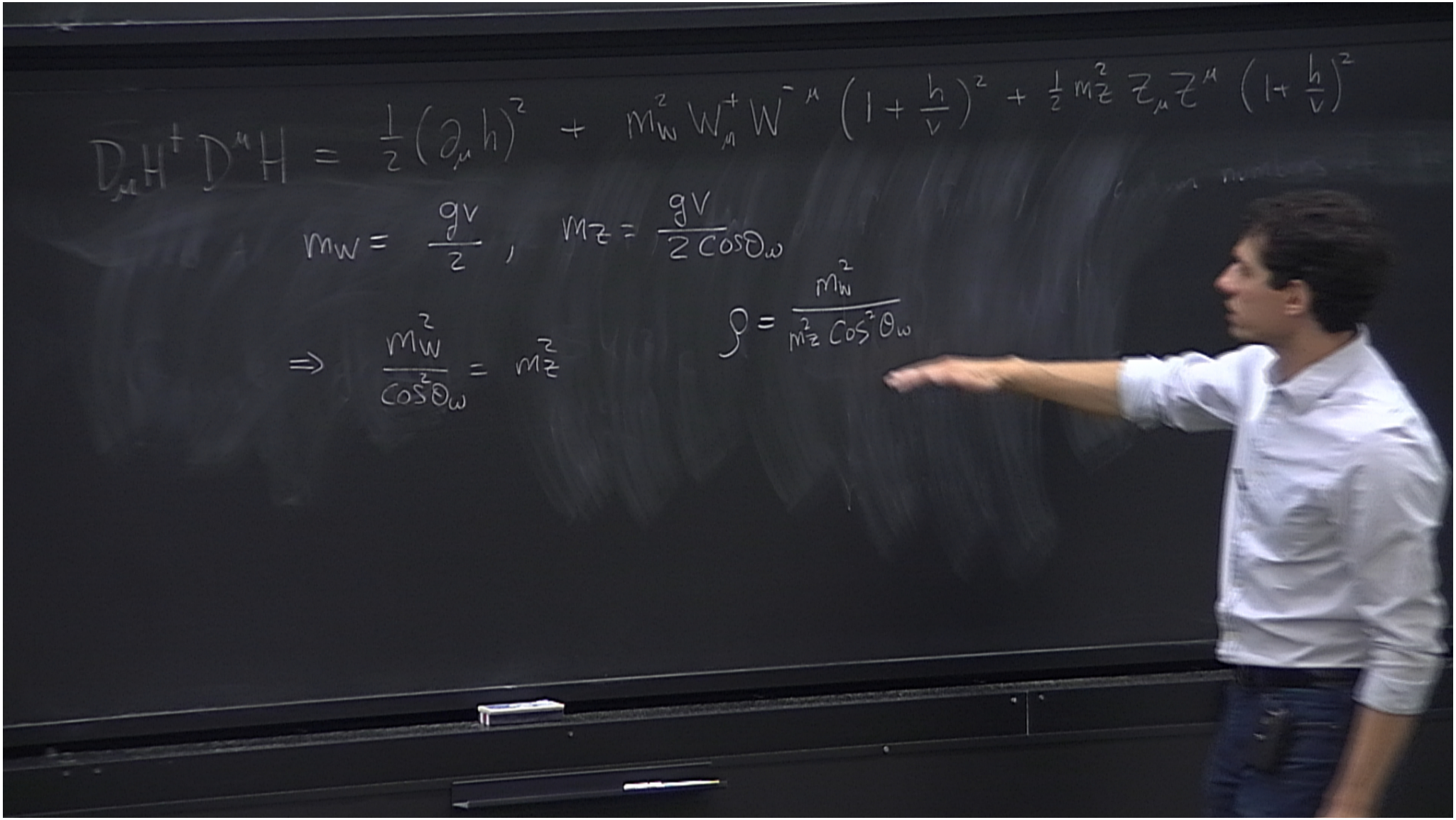
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$$A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu \quad \text{photon}$$

$\tan\theta_W = \frac{g'}{g}$

θ_W = weak mixi


$D_\mu H^\dagger D^\mu H = \frac{1}{2}(\partial_\mu h)^2 + m_W^2 W_\mu^+ W^{-\mu}\left(1+\frac{h}{v}\right)^2 + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1+\frac{h}{v}\right)^2$
$m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2\cos\theta_W}$
$\Rightarrow \frac{m_W^2}{\cos^2\theta_W} = m_Z^2$
$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$

$$D_\mu H^\dagger D^\mu H = \frac{1}{2}(\partial_\mu h)^2 + m_W^2 W_\mu^+ W^{-\mu}\left(1+\frac{h}{v}\right)^2 + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1+\frac{h}{v}\right)^2$$

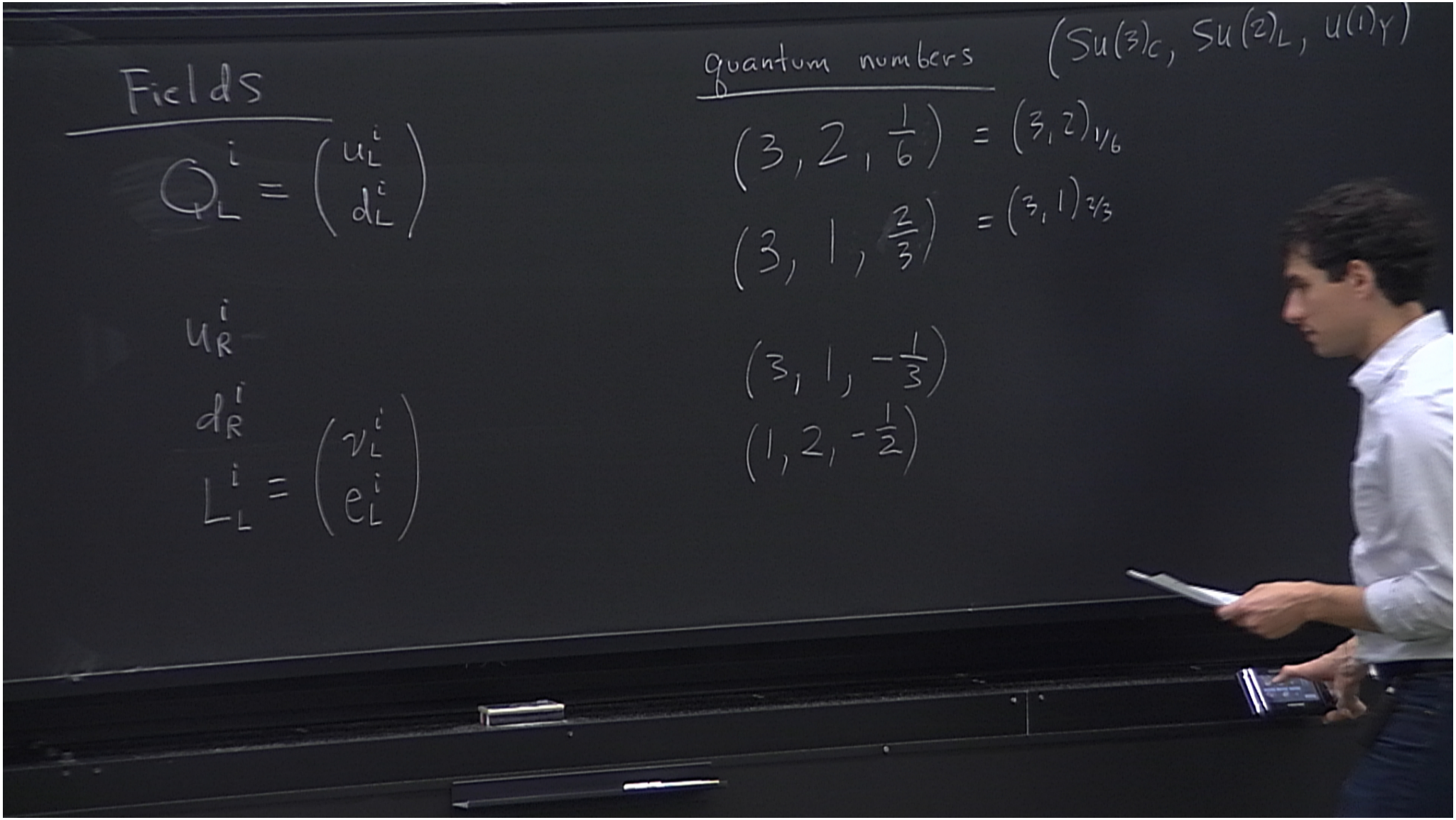
$$m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2\cos\theta_W}$$

$$\Rightarrow \frac{m_W^2}{\cos^2\theta_W} = m_Z^2 \qquad \rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

$$D_\mu H^\dagger D^\mu H = \frac{1}{2}(\partial_\mu h)^2 + m_W^2 W_\mu^+ W^{-\mu}\left(1+\frac{h}{v}\right)^2 + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1+\frac{h}{v}\right)^2$$

$$m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2\cos\theta_W}$$

$$\Rightarrow \frac{m_W^2}{\cos^2\theta_W} = m_Z^2 \qquad \rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$


Fields
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$
u_R^i
d_R^i
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$
quantum numbers
$(SU(3)_C, SU(2)_L, U(1)_Y)$
$(3, 2, \frac{1}{6}) = (3, 2)_{1/6}$
$(3, 1, \frac{2}{3}) = (3, 1)_{2/3}$
$(3, 1, -\frac{1}{3})$
$(1, 2, -\frac{1}{2})$

Fermion terms

$$\mathcal{L}_{\text{fermion}} = \sum_{\Psi} \bar{\Psi}\, i \not{D} \Psi$$

$$= \bar{Q}_L^i\, i \left(\not{\partial} + \frac{ig}{2} \sigma^a \not{W}^a + ig' \frac{1}{6} \not{B} + i \frac{g_s}{2} \lambda^A \not{G}^A \right) Q_L^i$$

$$+ \bar{u}_R^i\, i \left(\not{\partial} + i g' \frac{2}{3} \not{B} + \frac{i g_s}{2} \lambda^A \not{G}^A \right) u_R^i$$

$$+ \bar{d}_R^i\, i \left(\not{\partial} + i g' \left(-\frac{1}{3}\right) \not{B} + \frac{i g_s}{2} \lambda^A \not{G}^A \right) d_R^i$$

Fermion terms

$$\mathcal{L}_{\text{fermion}} = \sum_{\Psi} \bar{\Psi}\, i \not{D} \Psi$$

$$= \bar{Q}_L^i\, i \left(\not{\partial} + \frac{ig}{2} \sigma^a \not{W}^a + ig' \frac{1}{6} \not{B} + i \frac{g_s}{2} \lambda^A \not{G}^A \right) Q_L^i$$

$$+ \bar{u}_R^i\, i \left(\not{\partial} + i g' \frac{2}{3} \not{B} + \frac{i g_s}{2} \lambda^A \not{G}^A \right) u_R^i$$

$$+ \bar{d}_R^i\, i \left(\not{\partial} + i g' \left(-\frac{1}{3}\right) \not{B} + \frac{i g_s}{2} \lambda^A \not{G}^A \right) d_R^i$$

$$+ \bar{L}_L^i \, i\left(\not{\partial} + i\frac{g}{2}\sigma^a \not{W}^a + ig'\left(-\tfrac{1}{2}\right)\not{B}\right) L_L^i$$

$$+ \bar{e}_R^i \, i\left(\not{\partial} + ig'(-1)\not{B}\right) e_R^i$$