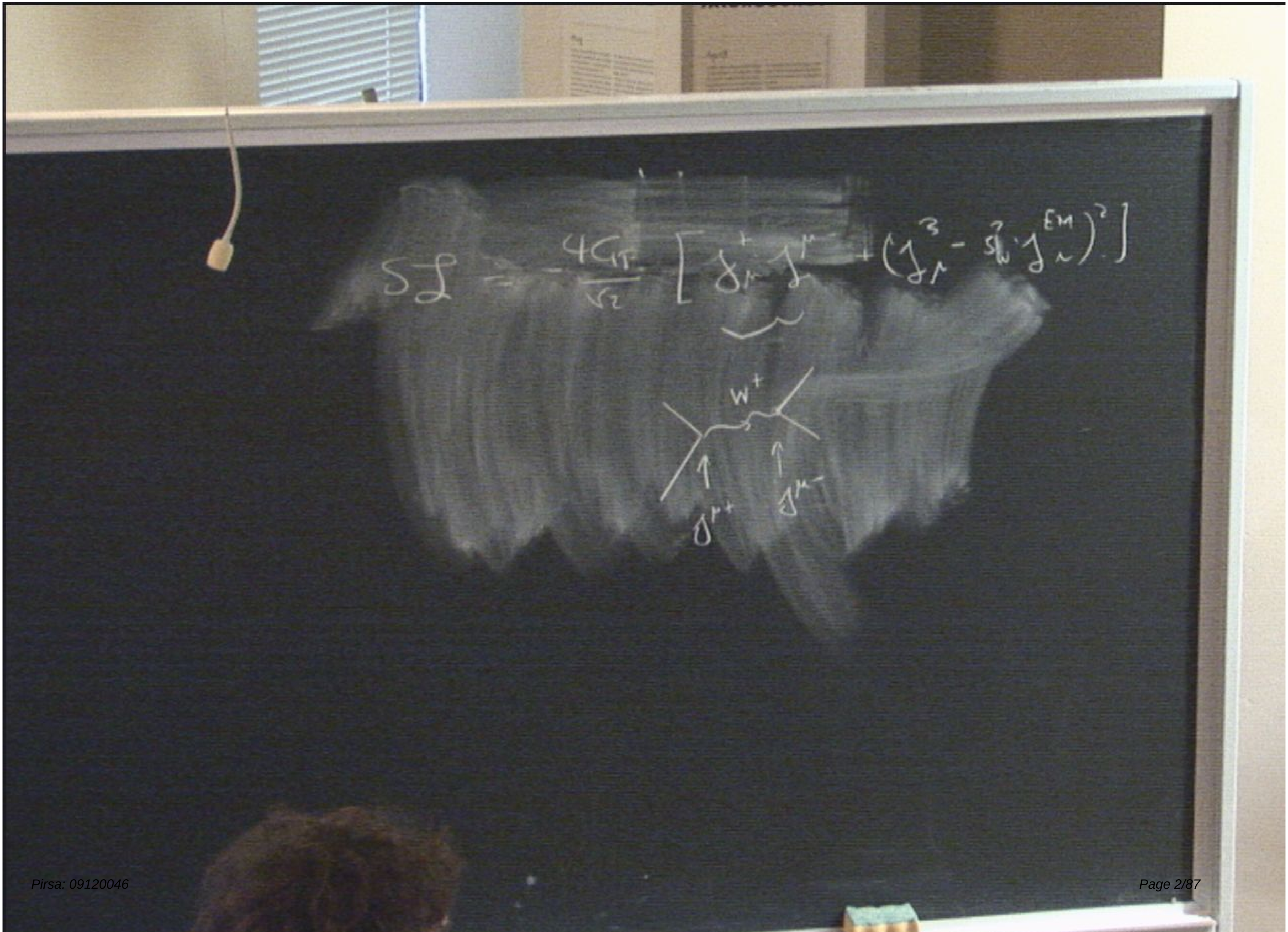
Title: Standard Model - Review (PHYS 622) - Lecture 12

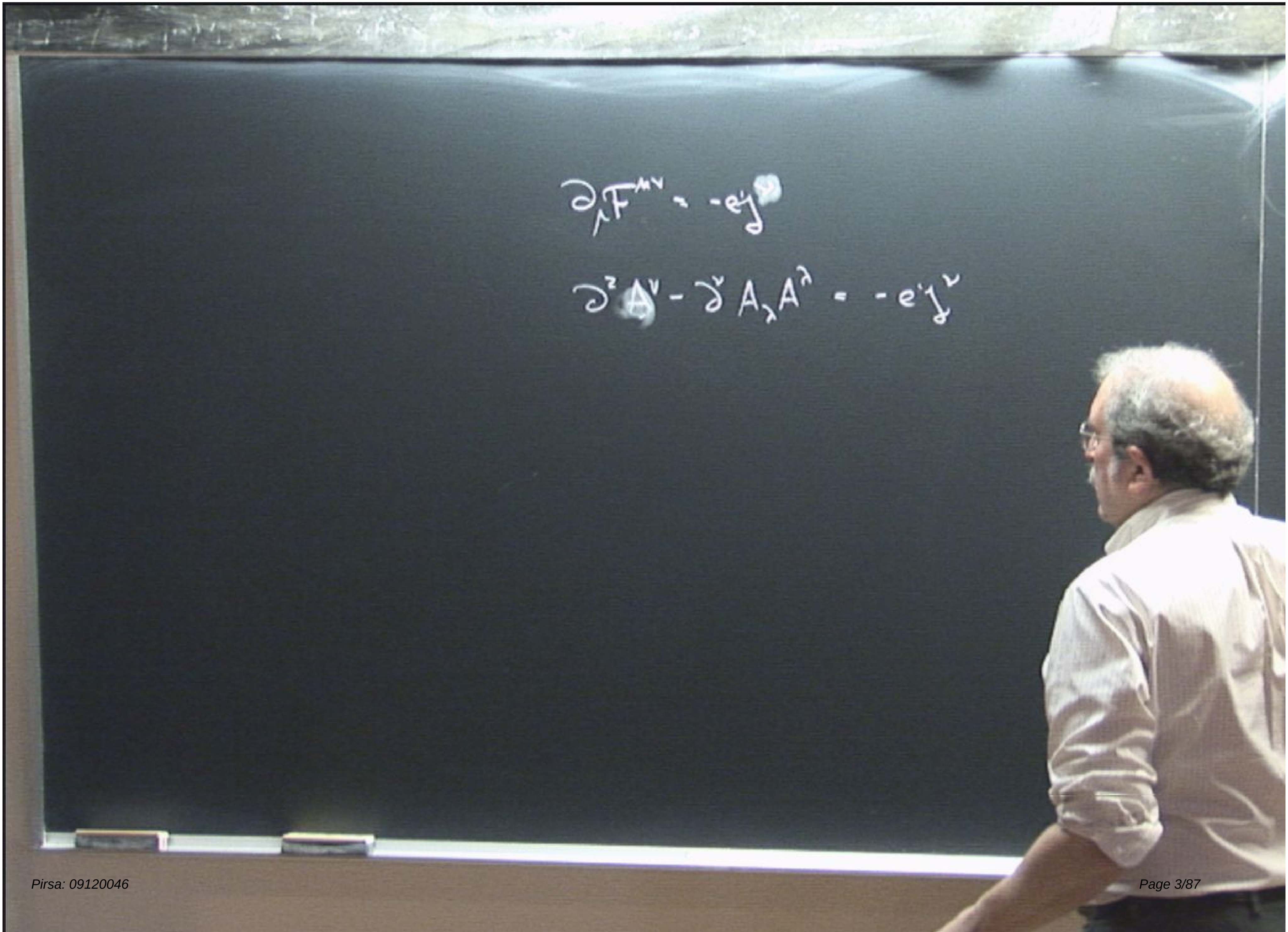
Date: Dec 15, 2009 09:00 AM

URL: http://pirsa.org/09120046

Abstract:



$$\delta \mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J_\mu^+ J^{\mu-}} + (J_\mu^3 - s_w^2 J_\mu^{EM})^2\right]$$



$$\partial_\lambda F^{\mu\nu} = -e' j^{\nu}$$

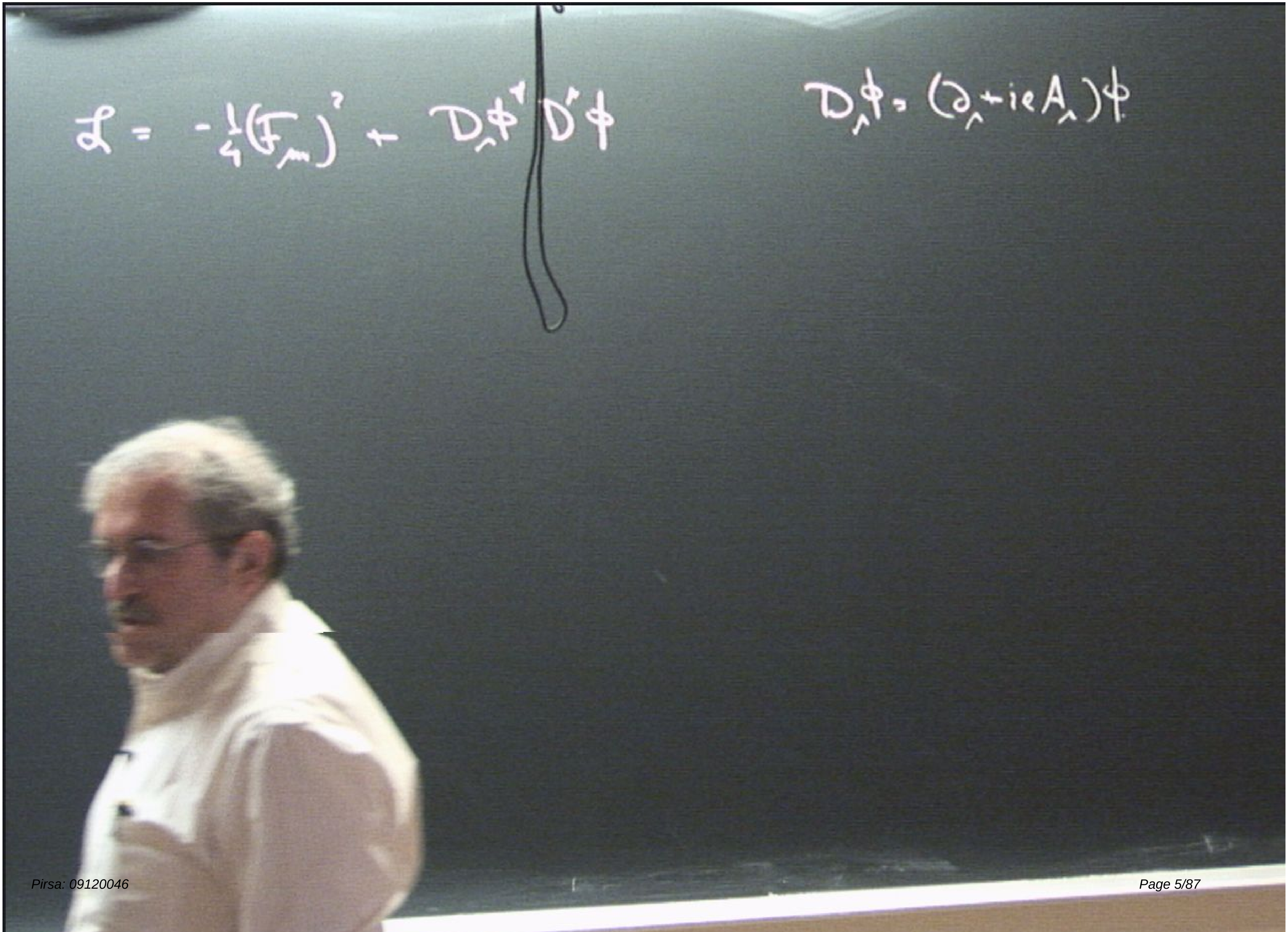
$$\partial^2 A^\nu - \partial^\nu A_\lambda A^\lambda = -e' j^\nu$$

$$\partial_\lambda F^{\mu\nu} = -e' j^{\nu}$$

$$\partial^2 A^\nu - \partial^\nu \partial_\lambda A^\lambda = -e' j^\nu$$

$$\partial_\lambda A^\lambda = 0$$

$$\partial^2 A^\nu = -e' j^\nu$$



$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + D_\mu\phi^* D^\mu\phi$$

$$D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

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$$J^\mu = \frac{1}{e}\frac{\delta\mathcal{L}}{\delta A_\mu} = i(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi)$$

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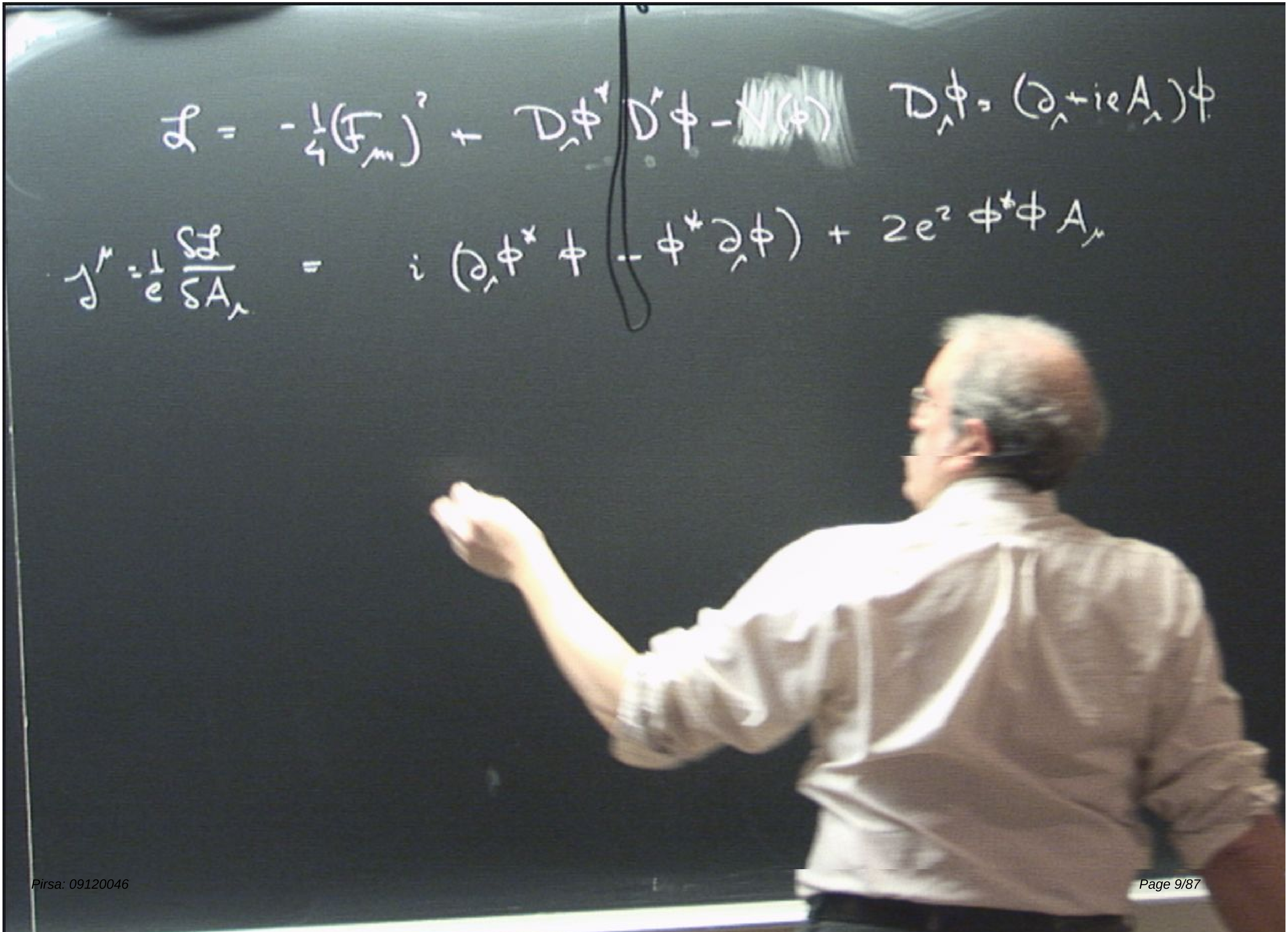
$$J^\mu = \frac{1}{e}\frac{\delta\mathcal{L}}{\delta A_\mu} = i(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + D_\mu\phi^* D^\mu\phi - m^2\phi^*\phi \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$J^\mu = \frac{1}{e}\frac{\delta\mathcal{L}}{\delta A_\mu} = i(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$



$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + D_\mu\phi^* D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$J^\mu = \frac{1}{e}\frac{\delta\mathcal{L}}{\delta A_\mu} = i(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$

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$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + D_\mu\phi^* D^\mu\phi - \text{[illegible]}(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

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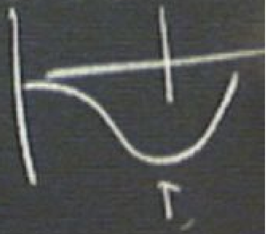
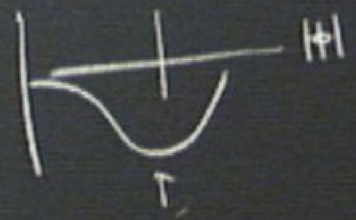


$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + D_\mu\phi^* D^\mu\phi - \text{[illegible]} \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$J^\mu = \frac{1}{e}\frac{\delta\mathcal{L}}{\delta A_\mu} = i(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$

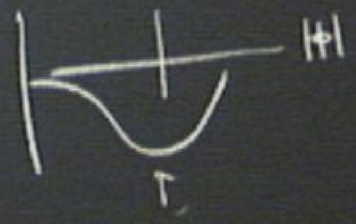
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^\dagger D^\mu\phi -$$ [illegible]

$$D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

ej^μ [illegible] $\frac{\delta\mathcal{L}}{\delta A_\mu}$ $= ie(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$



$eA_\mu j^\mu$

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

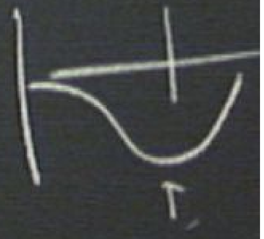
at min $\phi = \frac{v}{\sqrt{2}}$ $\qquad \frac{v}{\sqrt{2}}e^{i\alpha}$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^* D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$e j^\mu = \frac{\delta\mathcal{L}}{\delta A_\mu}\Big|_{\text{rhs}} = ie(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$

$$eA_\mu j^\mu$$

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



$$\frac{v}{\sqrt{2}}e^{i\alpha}$$

at min $\phi = \frac{v}{\sqrt{2}}$

$$\partial_\lambda F^{\mu\nu} = -e j^{\nu}$$

$$\partial^2 A^\nu - \partial^\nu \partial_\lambda A^\lambda = -e j^\nu$$

$$j^\nu =$$

$$\partial_\lambda F^{\mu\nu} = -ej$$

$$\partial^2 A^\nu - \partial^\nu \partial_\lambda A^\lambda = -ej^\nu$$

$$\partial_\lambda A^\lambda = 0$$

$$ej^\nu = e^2 v^2 A_\nu$$

$$\partial^2 A^\nu = - e^2 v^2 A_\nu$$

$$(\partial^2 + e^2 v^2) A_\nu = 0$$

ej

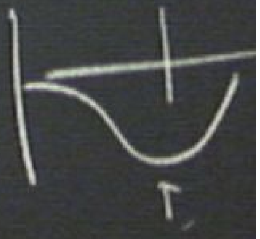
e

$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^* D^\mu\phi - V(\phi)$ $\quad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$

$eJ^\mu = \frac{\delta\mathcal{L}}{\delta A_\mu}\Big|_{2ms} = ie(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$

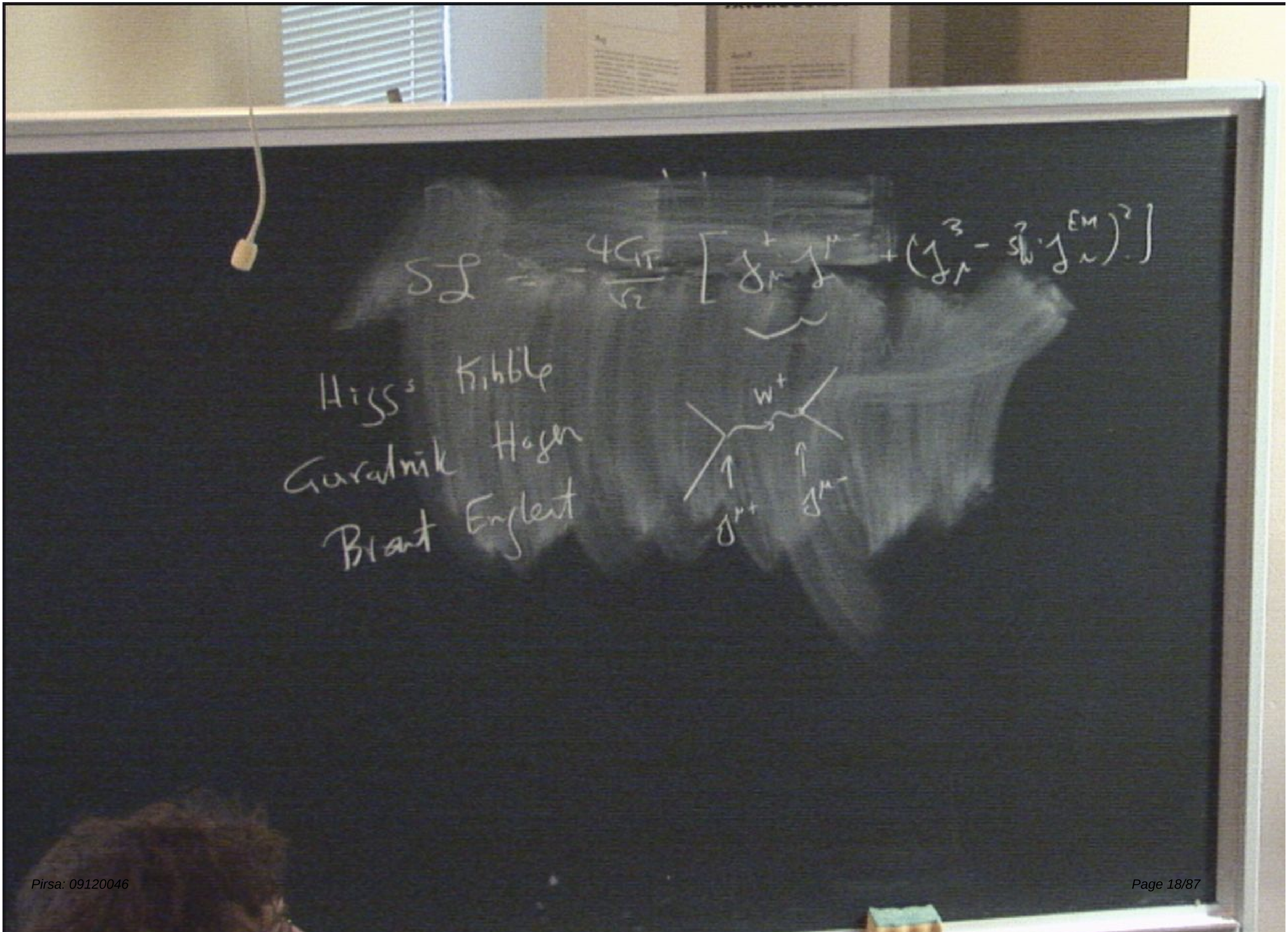
$eA_\mu J^\mu$

$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$



$\frac{v}{\sqrt{2}}e^{i\alpha}$

at min $\underline{\phi = \frac{v}{\sqrt{2}}}$



$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J_\mu^+ J^{\mu -}} + (J_\mu^3 - s_W^2 \cdot J_\mu^{EM})^2\right]$$

Higgs Kibble

Guralnik Hagen

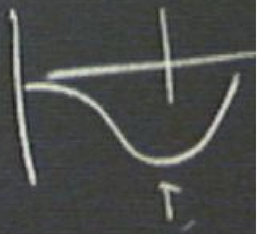
Brout Englert

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^* D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$e j^\mu = \frac{\delta\mathcal{L}}{\delta A_\mu}\Big|_{\text{RHS}} = ie(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi) + 2e^2\phi^*\phi A_\mu$$

$e A_\mu j^\mu$

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

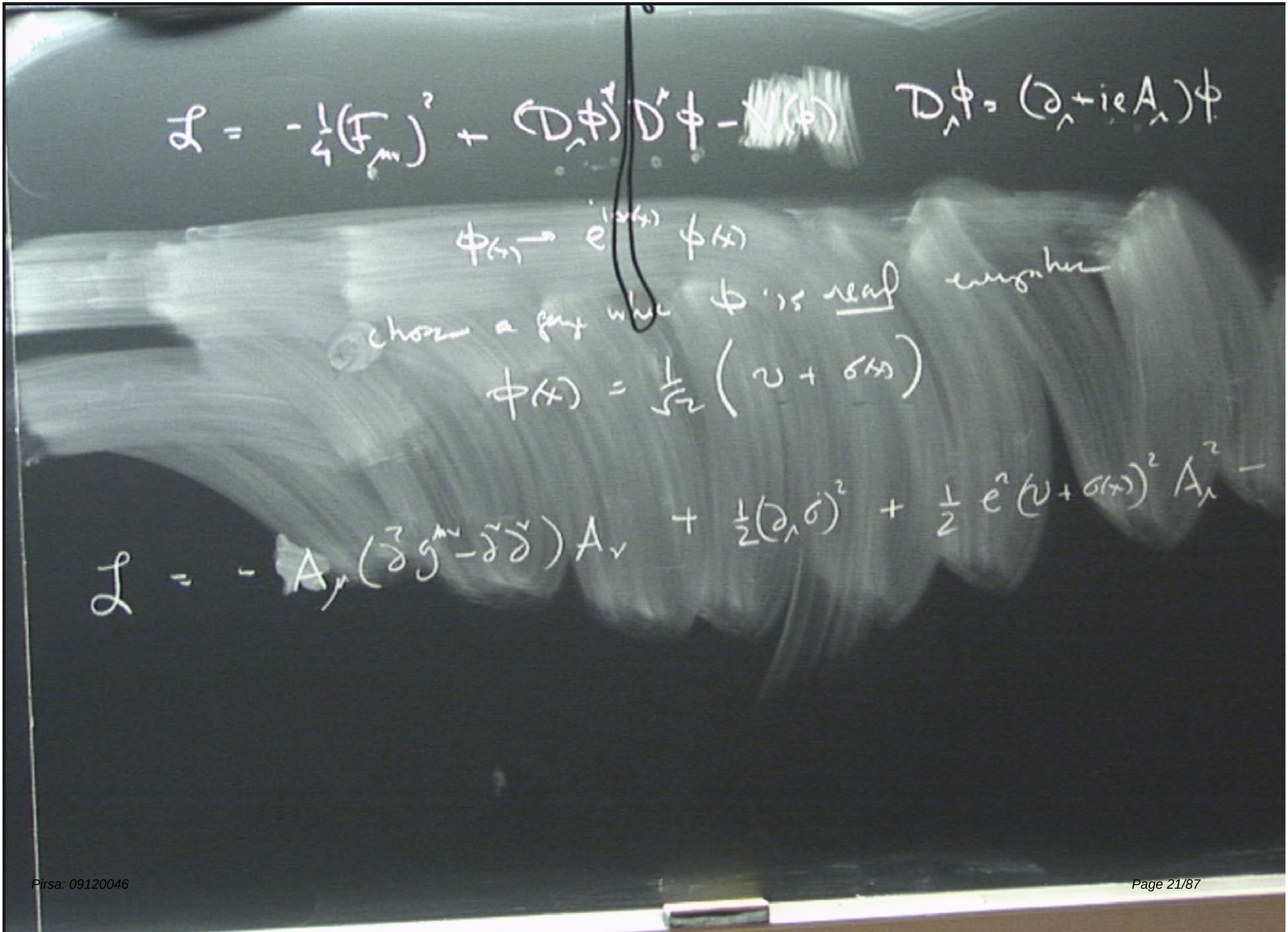


$\frac{v}{\sqrt{2}}e^{i\alpha}$

at min $\underline{\phi = \frac{v}{\sqrt{2}}}$

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$\phi(x) \rightarrow e^{i\alpha(x)}\,\phi(x)$$



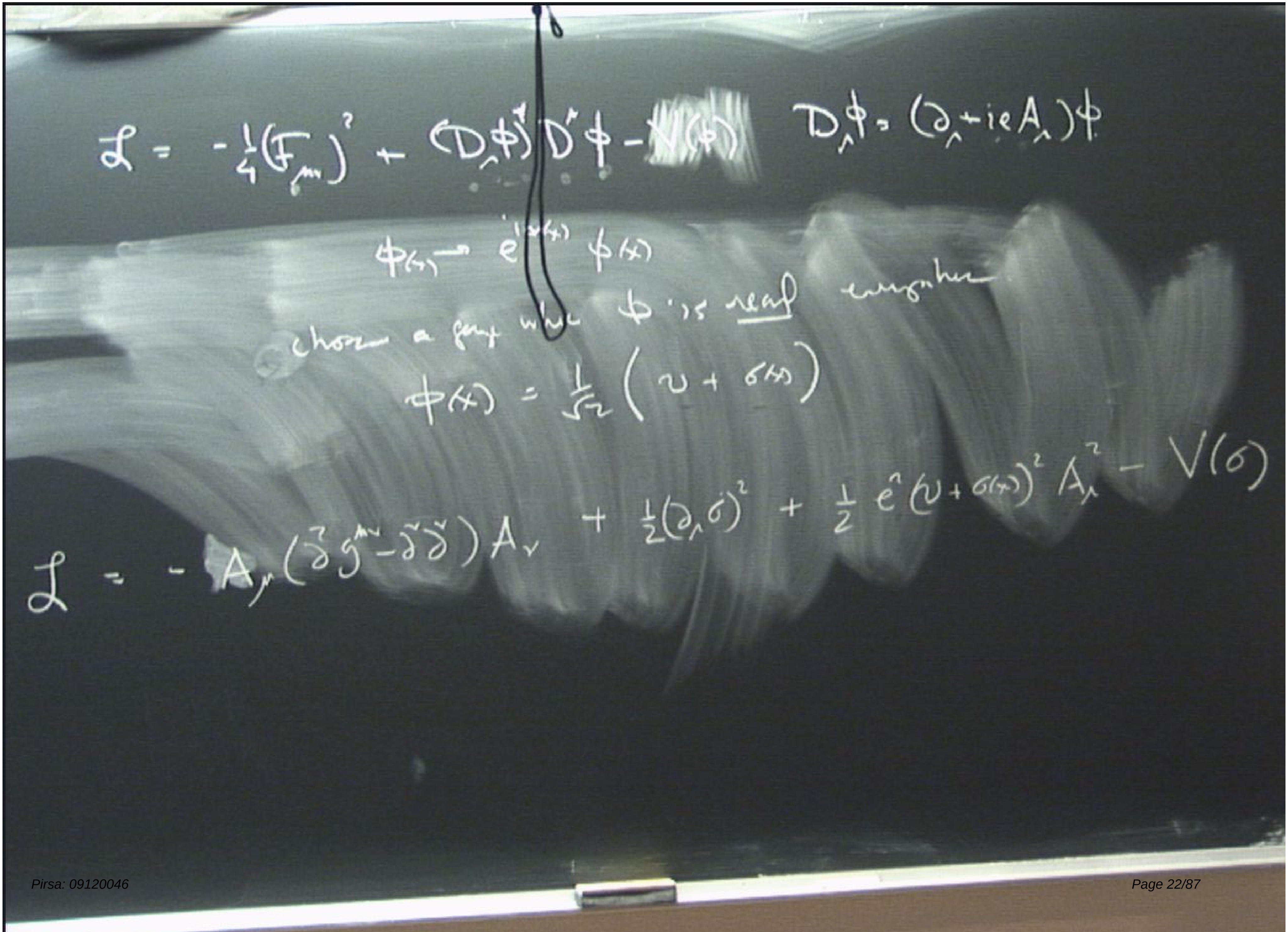
$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

$$\phi(x) \to e^{i\alpha(x)}\phi(x)$$

choose a gauge where ϕ is real everywhere

$$\phi(x) = \frac{1}{\sqrt{2}}\left(v + \sigma(x)\right)$$

$$\mathcal{L} = -A_\mu(\partial^2 g^{\mu\nu} - \partial^\nu\partial^\mu)A_\nu + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}e^2(v+\sigma(x))^2 A_\mu^2 -$$



$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) \qquad D_\mu\phi = (\partial_\mu + ieA_\mu)\phi$$

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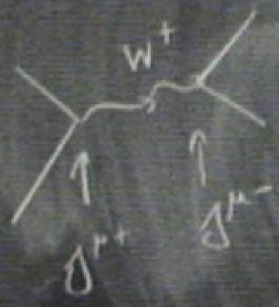
$$\delta\mathcal{L} \to -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J^+_\mu J^{\mu-}} + (J^3_\mu - s^2_W J^{EM}_\mu)^2\right]$$

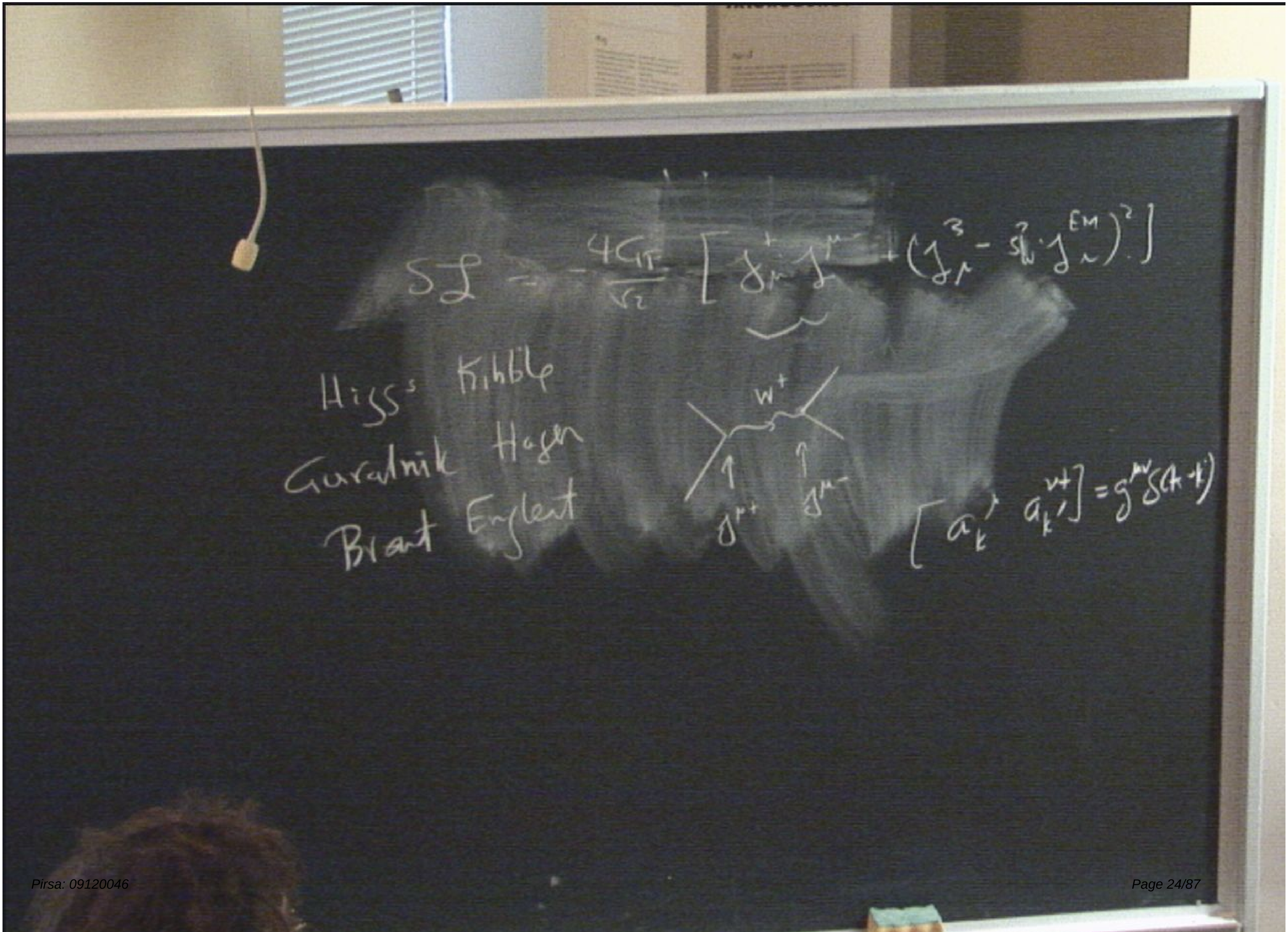
Higgs Kibble

Guralnik Hagen

Brout Englert



$$[a^\mu_k \; a^{\nu+}_k] = g^{\mu\nu}$$



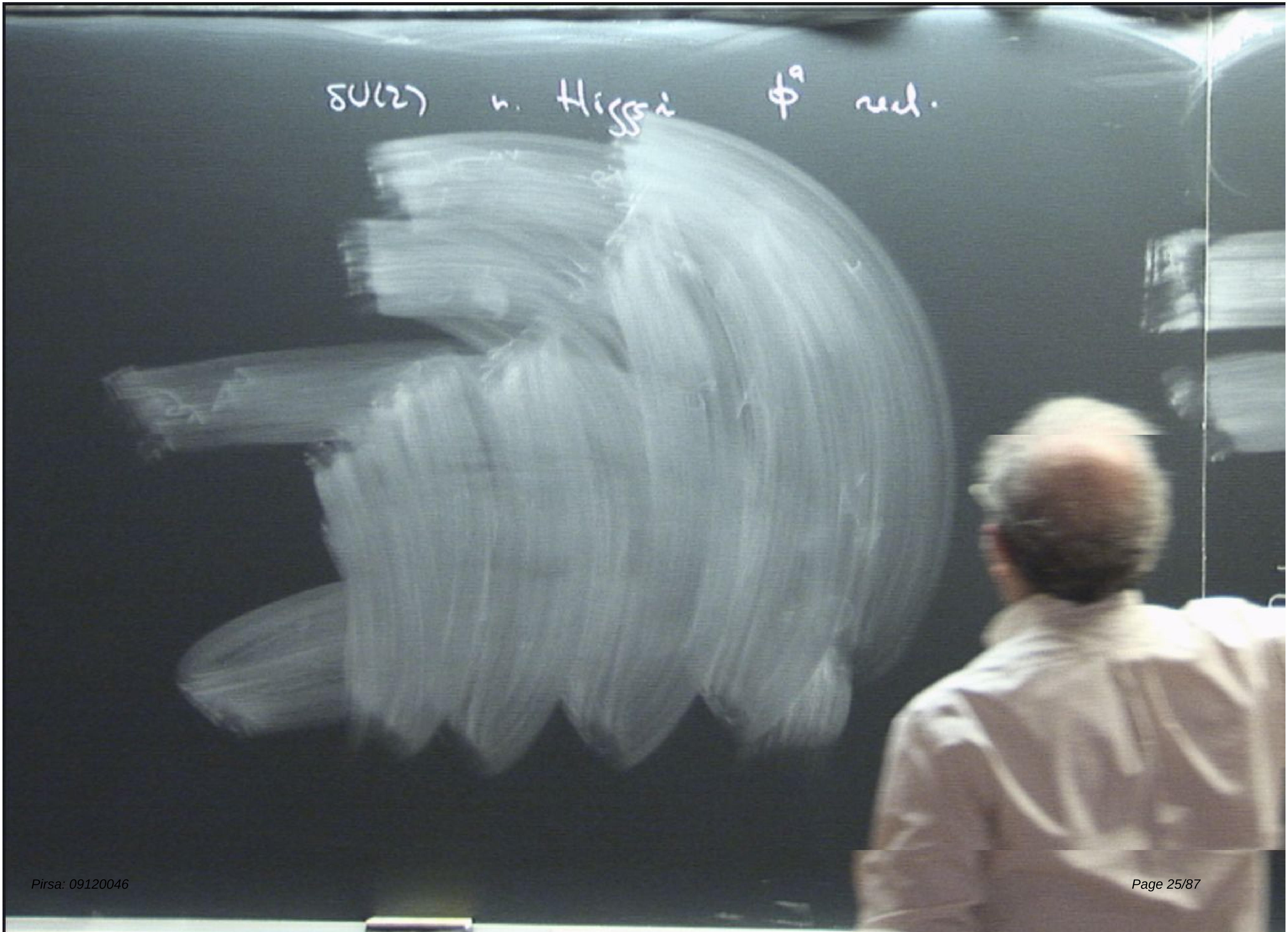
$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J^+_\mu J^{\mu-}}_{} + \left(J^3_\mu - s_W^2 \cdot J^{EM}_\mu\right)^2\right]$$

Higgs Kibble

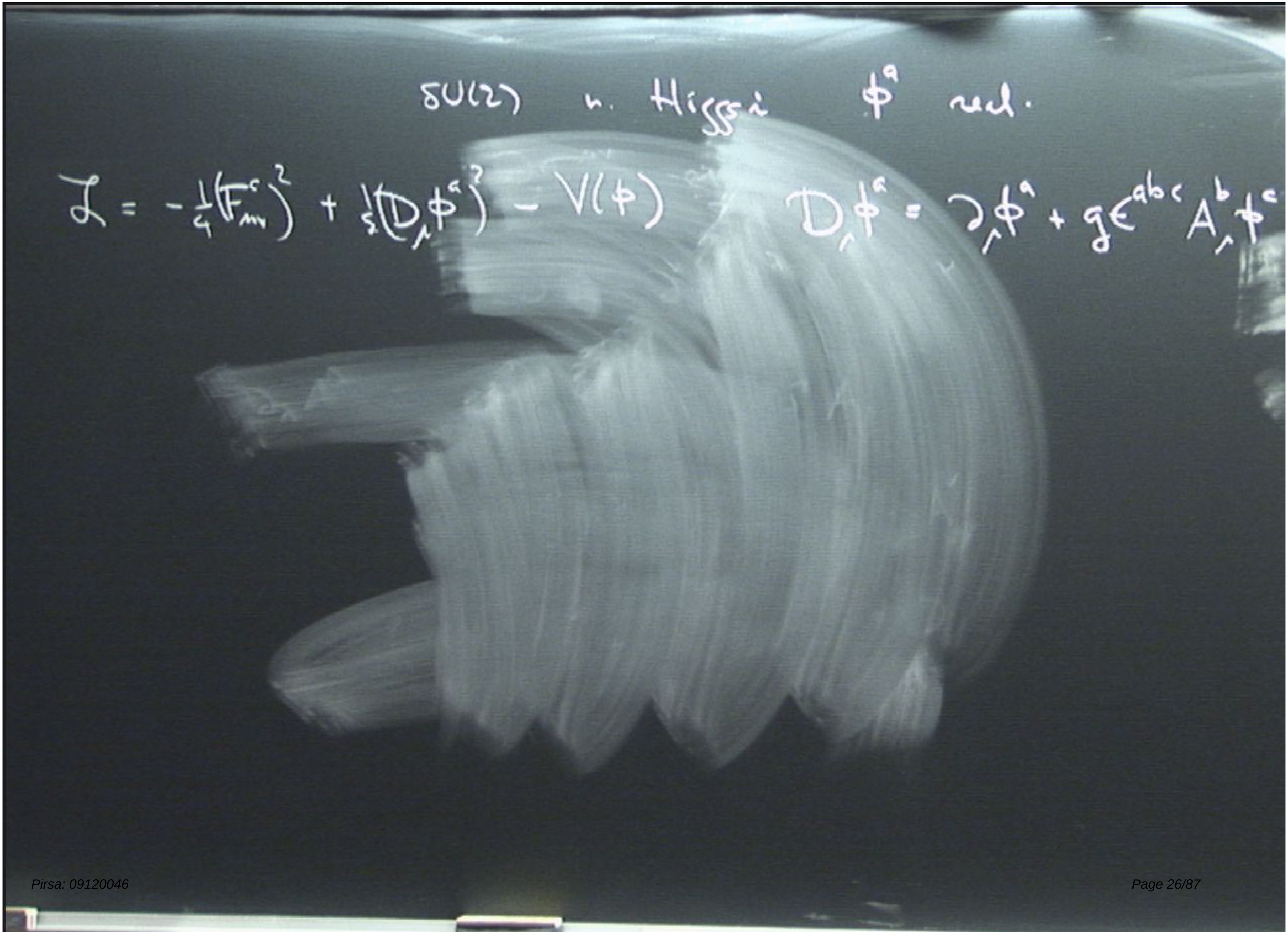
Guralnik Hagen

Brout Englert

$$\left[a_k^\mu, a_{k'}^{\nu\dagger}\right] = g^{\mu\nu}\delta(k-k')$$



SU(2) w. Higgs ϕ^a real.



SU(2) w. Higgs in ϕ^a real.

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \frac{1}{2}(D_\mu\phi^a)^2 - V(\phi) \qquad D_\mu\phi^a = \partial_\mu\phi^a + g\epsilon^{abc}A^b_\mu\phi^c$$

SU(2) w. Higgs in ϕ^a real.

$$\mathcal{L} = -\frac{1}{4}(F^c_{\mu\nu})^2 + \frac{1}{2}(D_\mu \phi^a)^2 - V(\phi) \qquad D_\mu \phi^a = \partial_\mu \phi^a + g\epsilon^{abc} A^b_\mu \phi^c$$

SU(2) w. Higgs in ϕ^a adj.

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \frac{1}{2}(D_\mu \phi^a)^2 - V(\phi) \qquad D_\mu \phi^a = \partial_\mu \phi^a + g\epsilon^{abc} A^b_\mu \phi^c$$

m g $\quad \langle \phi^a \rangle = v\, \delta^{a3}$

SU(2) w. Higgs in ϕ^a real.

$$\mathcal{L} = -\frac{1}{4}(F^c_{\mu\nu})^2 + \frac{1}{2}(D_\mu\phi^a)^2 - V(\phi) \qquad D_\mu\phi^a = \partial_\mu\phi^a + g\epsilon^{abc}A^b_\mu\phi^c$$

m q $\langle\phi^a\rangle = v\,\delta^{a3}$

$$\frac{1}{2}(D_\mu\phi)^2 = \frac{1}{2}\left(g\epsilon^{abc}A^b_\mu\delta^{c3}v\right)^2$$

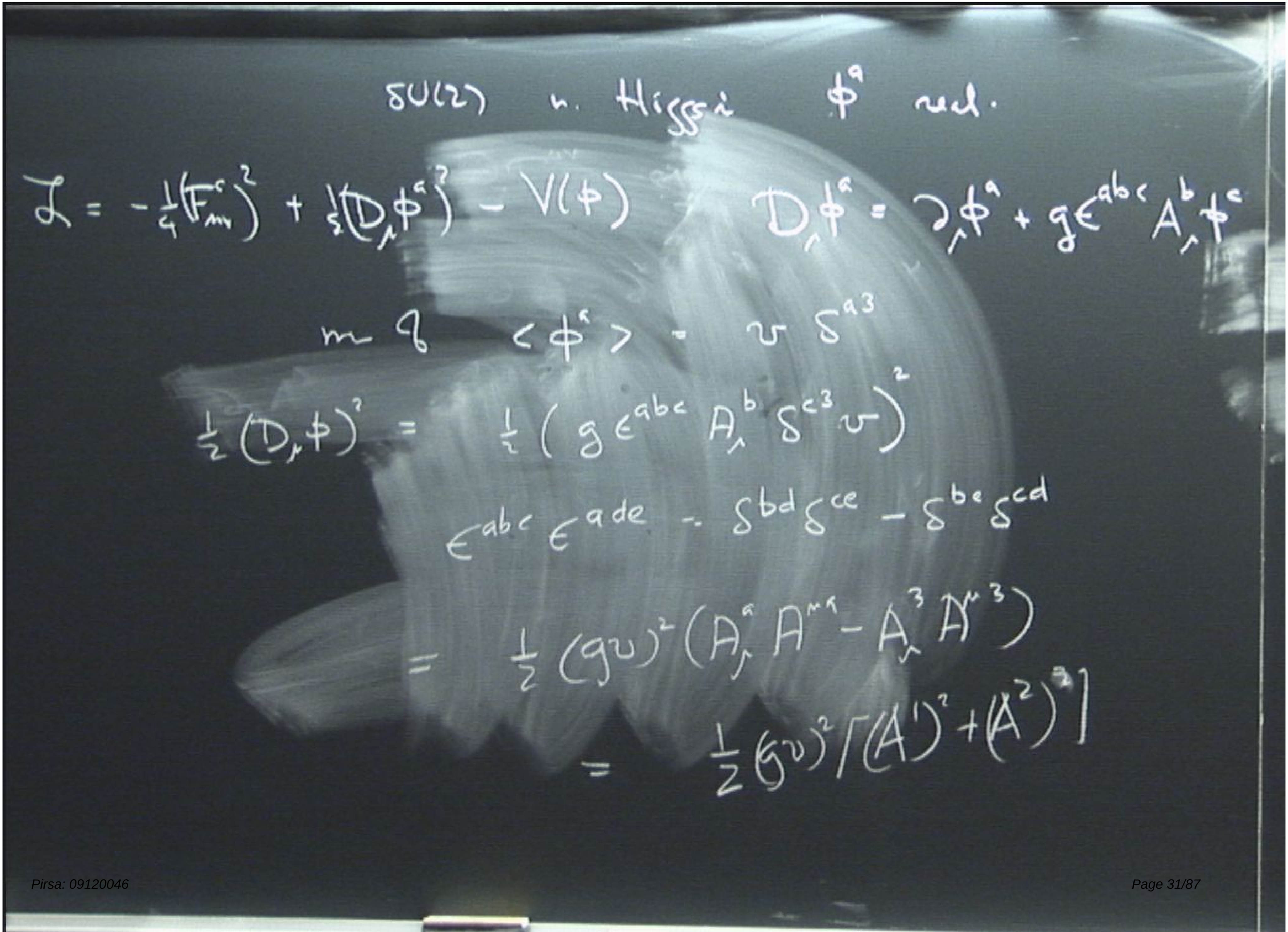
SU(2) w. Higgs in ϕ^a rep.

$$\mathcal{L} = -\frac{1}{4}(F^c_{\mu\nu})^2 + \frac{1}{2}(D_\mu\phi^a)^2 - V(\phi) \qquad D_\mu\phi^a = \partial_\mu\phi^a + g\epsilon^{abc}A^b_\mu\phi^c$$

m g $\quad \langle\phi^a\rangle = v\,\delta^{a3}$

$$\frac{1}{2}(D_\mu\phi)^2 = \frac{1}{2}\left(g\epsilon^{abc}A^b_\mu\delta^{c3}v\right)^2$$

$$\epsilon^{abc}\epsilon^{ade} = \delta^{bd}\delta^{ce} - \delta^{be}\delta^{cd}$$



SU(2) w. Higgs in ϕ^a ad.

$$\mathcal{L} = -\frac{1}{4}(F^a_{\mu\nu})^2 + \frac{1}{2}(D_\mu\phi^a)^2 - V(\phi) \qquad D_\mu\phi^a = \partial_\mu\phi^a + g\epsilon^{abc}A^b_\mu\phi^c$$

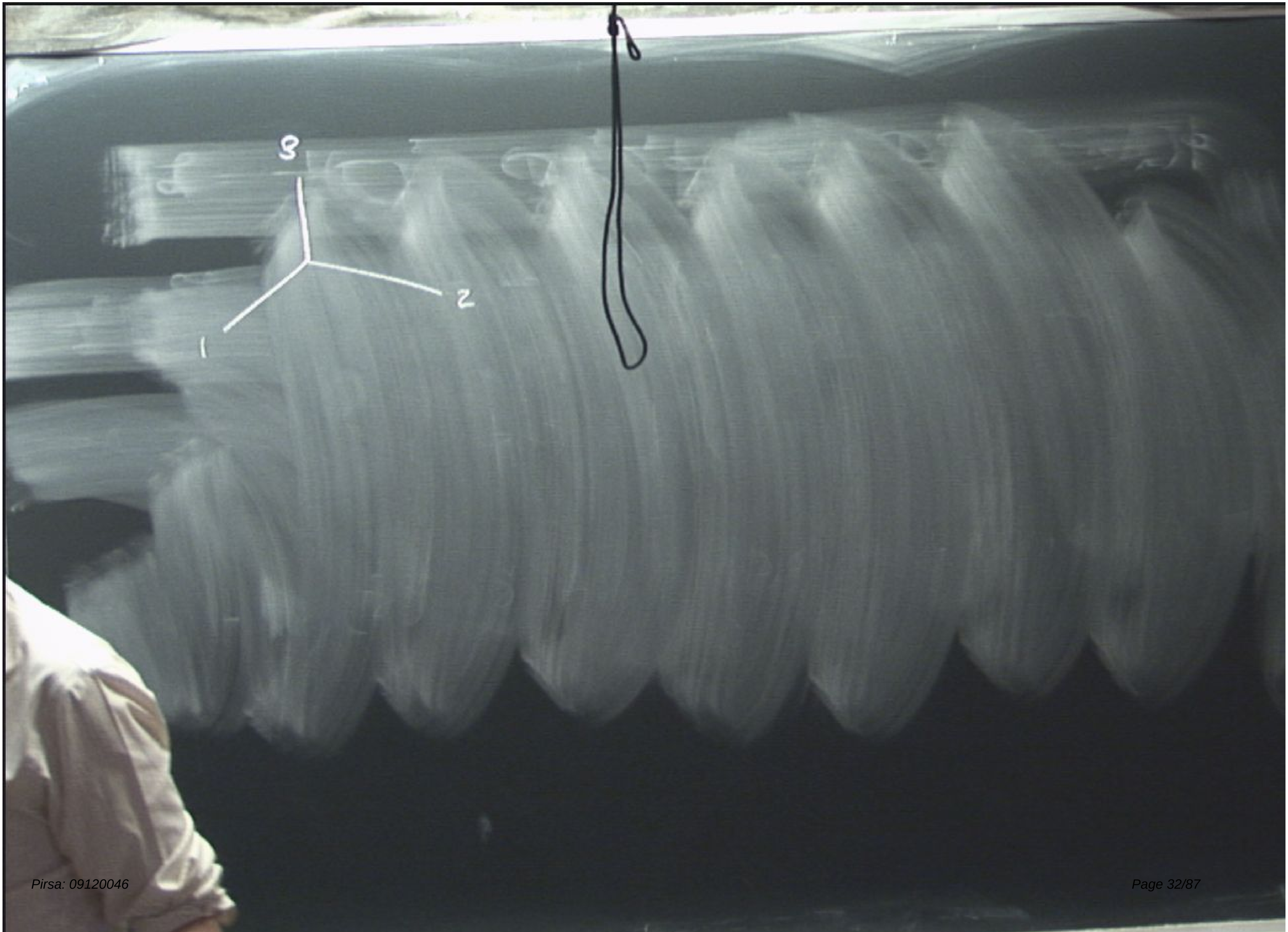
$$m \sim g \qquad \langle\phi^a\rangle = v\,\delta^{a3}$$

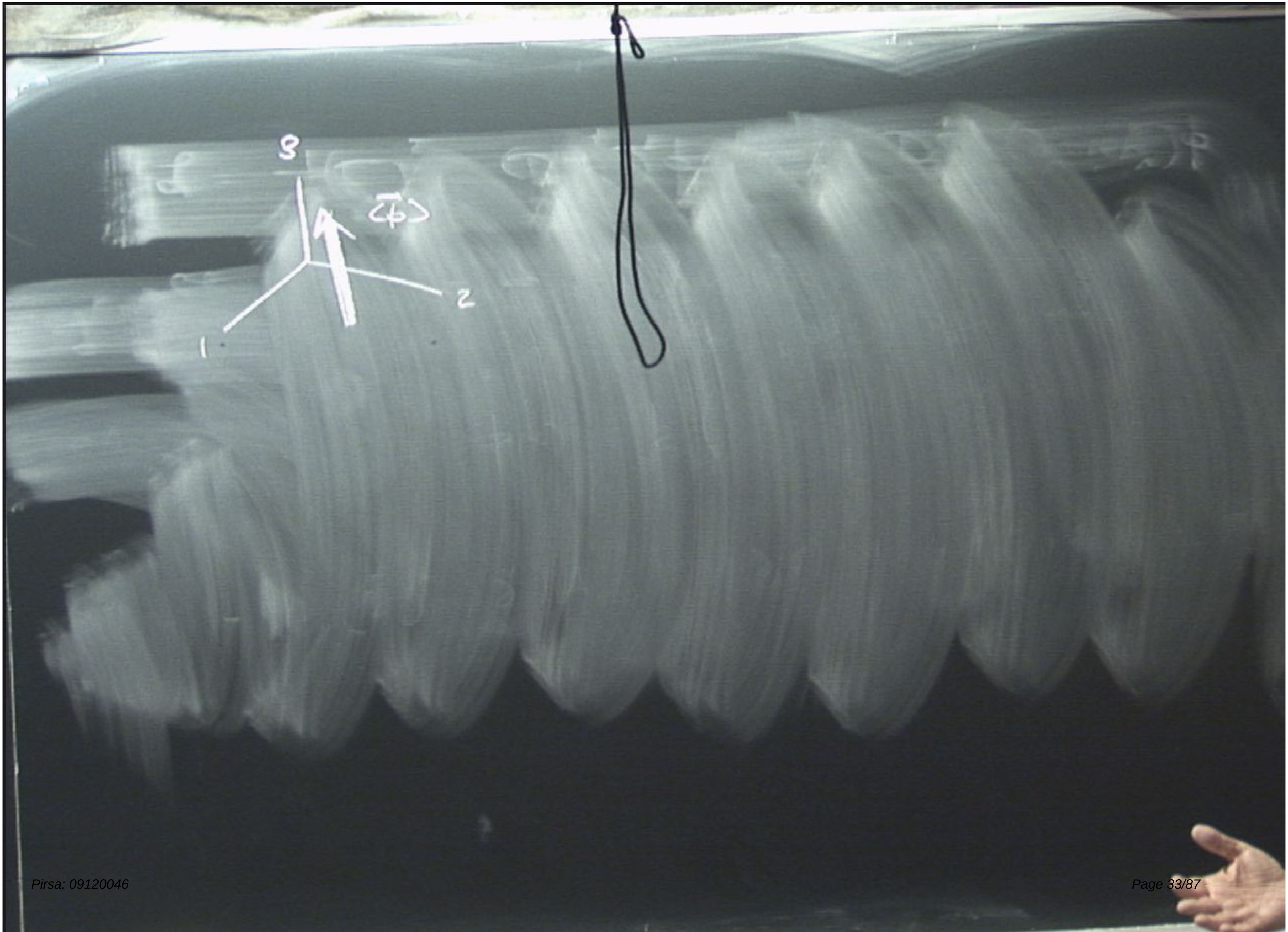
$$\frac{1}{2}(D_\mu\phi)^2 = \frac{1}{2}\left(g\epsilon^{abc}A^b_\mu\delta^{c3}v\right)^2$$

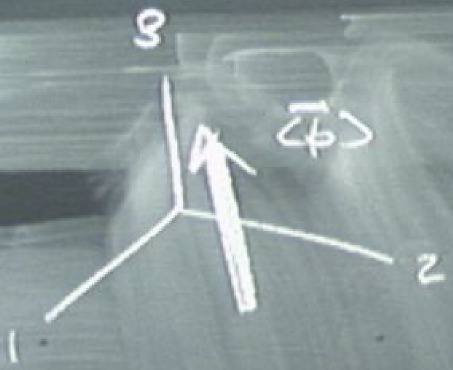
$$\epsilon^{abc}\epsilon^{ade} = \delta^{bd}\delta^{ce} - \delta^{be}\delta^{cd}$$

$$= \frac{1}{2}(gv)^2\left(A^a_\mu A^{\mu a} - A^3_\mu A^{\mu 3}\right)$$

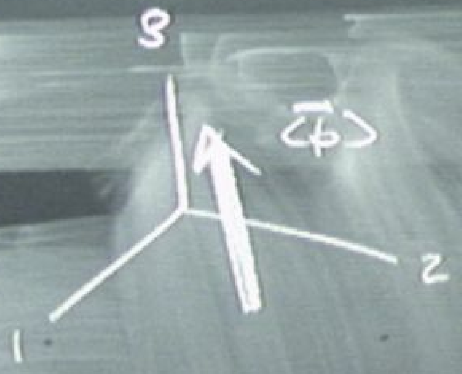
$$= \frac{1}{2}(gv)^2\left[(A^1)^2 + (A^2)^2\right]$$


3
2
1

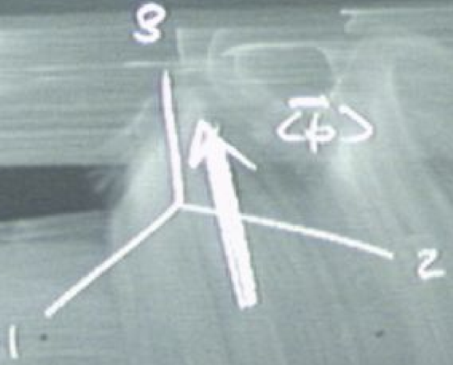

3
$\langle\vec{\phi}\rangle$
2
1



$$W^{\pm} = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right)$$

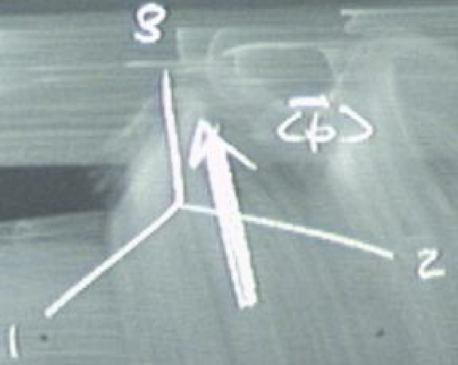


$$W^{\pm} = \frac{1}{\sqrt{2}}(A^1 \mp i A^2)$$



$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right)$$

$$\mathcal{A} = A^3$$

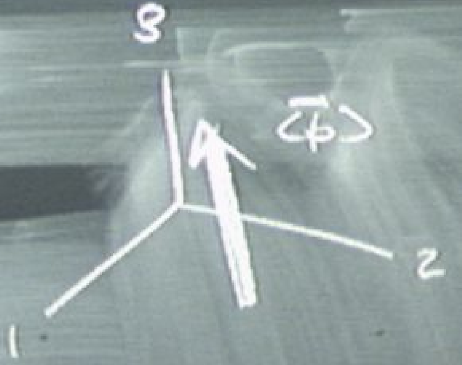


$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}\left(A^{1} \mp iA^{2}\right)$$

$$\mathcal{A} = A^{3}$$

SU(2) × U(1)

Glashow Weinberg Salam



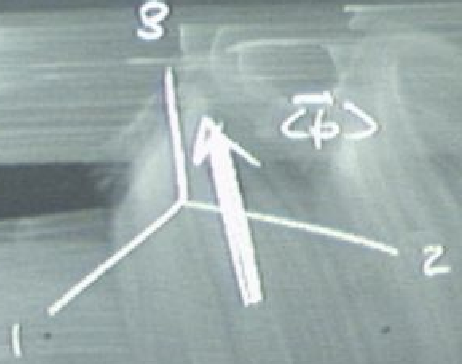
$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right)$$

$$A = A^3$$

SU(2) × U(1)

Glashow Weinberg Salam

ϕ_α 2 of SU(2)



$$W_\mu^{\pm} = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right)$$

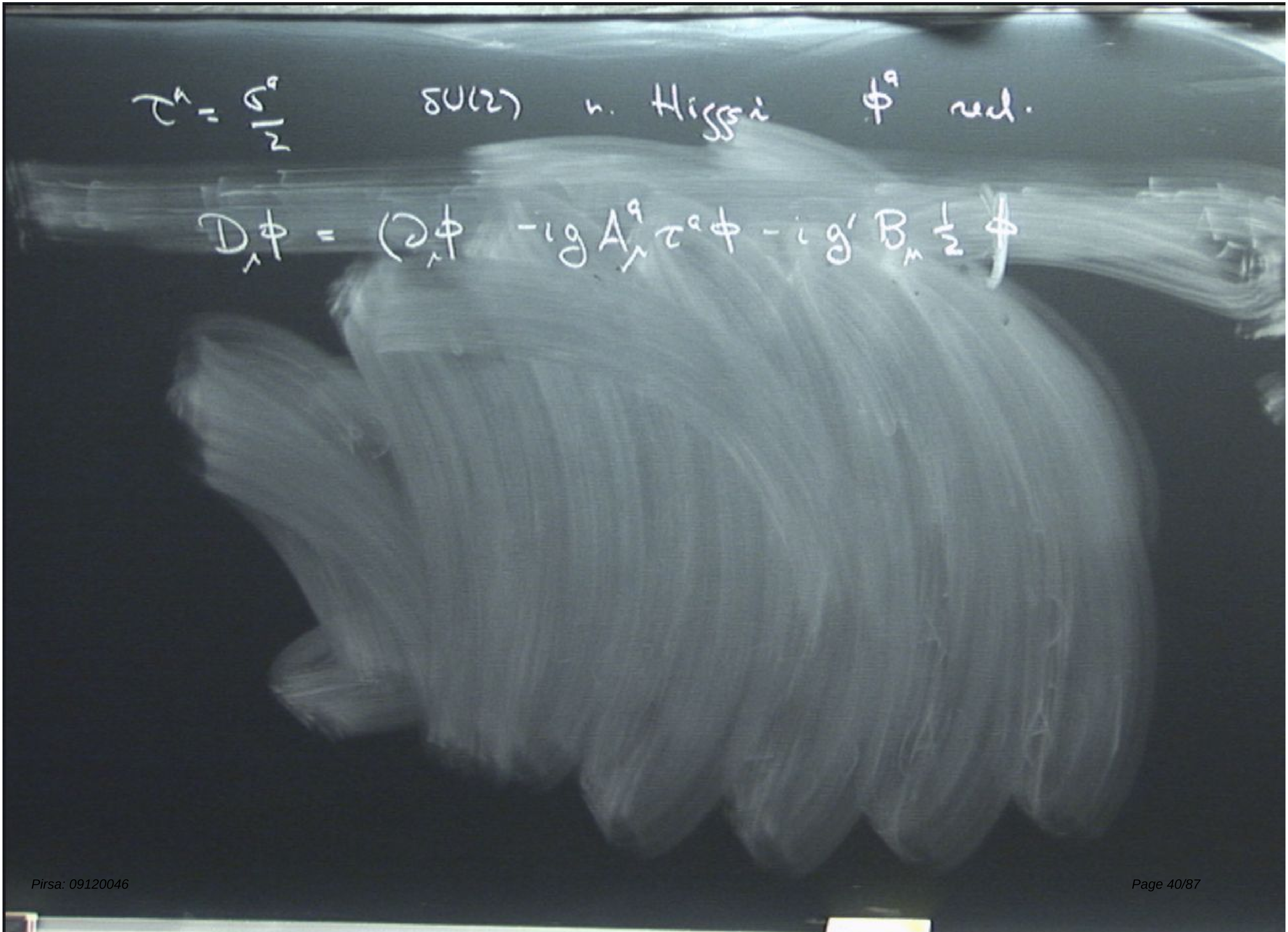
$$\mathcal{A} = A^3$$

$SU(2) \times U(1)$

Glashow Weinberg Salam

ϕ_α 2 of $SU(2)$ $+\frac{1}{2}$ under $U(1)$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgsi ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

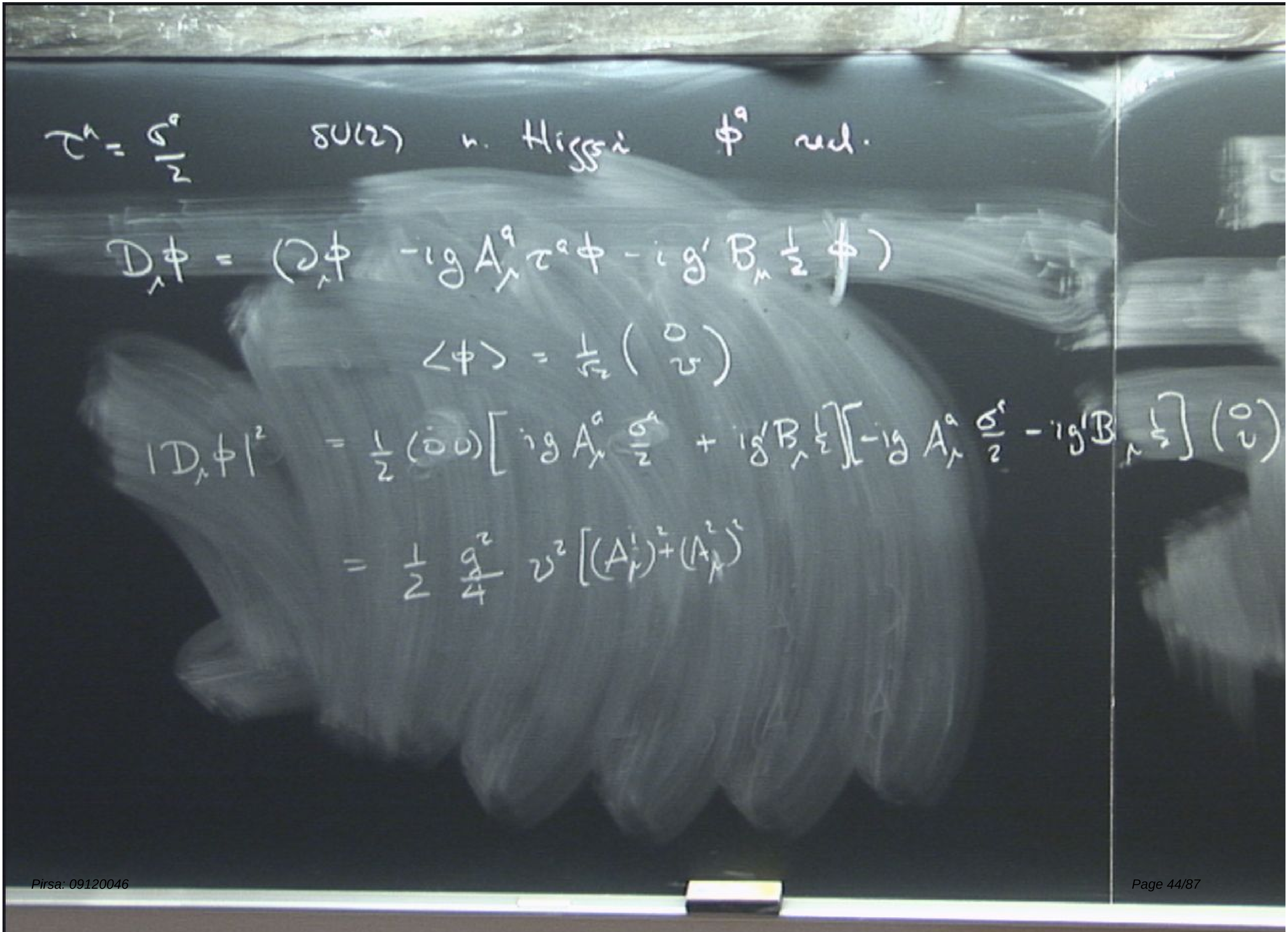
$$|D_\mu \phi|^2$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - ig A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$|D_\mu \phi|^2 = \frac{1}{2} (0\ v) \left[ig A_\mu^a \frac{\sigma^a}{2} + ig' B_\mu \frac{1}{2} \right] \left[-ig A_\mu^a \frac{\sigma^a}{2} - ig' B_\mu \frac{1}{2} \right] \begin{pmatrix} 0 \\ v \end{pmatrix}$$



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu\phi = (\partial_\mu\phi - igA^a_\mu\tau^a\phi - ig'B_\mu\tfrac{1}{2}\phi)$$

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v\end{pmatrix}$$

$$|D_\mu\phi|^2 = \frac{1}{2}(0\ v)\left[igA^a_\mu\frac{\sigma^a}{2} + ig'B_\mu\frac{1}{2}\right]\left[-igA^a_\mu\frac{\sigma^a}{2} - ig'B_\mu\frac{1}{2}\right]\begin{pmatrix}0\\v\end{pmatrix}$$

$$= \frac{1}{2}\frac{g^2}{4}v^2\left[(A^1_\mu)^2+(A^2_\mu)^2\right.$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - ig A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$|D_\mu \phi|^2 = \frac{1}{2} (0 \; v) \left[ig A^a_\mu \frac{\sigma^a}{2} + ig' B_\mu \tfrac{1}{2} \right] \left[-ig A^a_\mu \frac{\sigma^a}{2} - ig' B_\mu \tfrac{1}{2} \right] \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$= \frac{1}{2} \frac{1}{4} v^2 \left[(gA^1_\mu)^2 + (gA^2_\mu)^2 + (-gA^3_\mu + g' B_\mu)^2 \right]$$

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}\left(A^{1} \mp i A^{2}\right)$$

$$Z^{0}_{\mu} = \frac{g A_{\mu} - g' B_{\mu}}{\sqrt{g^{2}+g'^{2}}}$$

$$B_{\mu} \frac{1}{2}\Big] \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$W_\mu^{\pm} = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right)$$

$$Z_\mu^0 = \frac{g A_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}}$$

$$B_\mu \frac{1}{2}\Big] \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$A_\mu = \frac{g' A_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}}$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right) \qquad m_W^2 = \left(\frac{gv}{2}\right)^2$$

$$Z_\mu^0 = \frac{g A_\mu^3 - g' B_\mu}{\sqrt{g^2+g'^2}} \qquad m_Z^2 = \frac{v^2}{2}\left(g^2+g'^2\right)$$

$$A_\mu = \frac{g' A_\mu^3 + g B_\mu}{\sqrt{g^2+g'^2}}$$

$$W_\mu^{\mp} = \frac{1}{\sqrt{2}}\left(A^1 \mp iA^2\right) \qquad m_W^2 = \left(\frac{gv}{2}\right)^2$$

$$Z_\mu^0 = \frac{gA_\mu^3 - g'B_\mu}{\sqrt{g^2+g'^2}} \qquad m_Z^2 = \frac{v^2}{2}\left(g^2+g'^2\right)$$

$$A_\mu = \frac{g'A_\mu^3 + gB_\mu}{\sqrt{g^2+g'^2}} \qquad m_A = 0$$

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}\left(A^{1} \mp i A^{2}\right) \qquad m_W^{2} = \left(\frac{gv}{2}\right)^{2}$$

$$Z^{0}_{\mu} = \frac{g A^{3}_{\mu} - g' B_{\mu}}{\sqrt{g^{2}+g'^{2}}} \qquad m_Z^{2} = \frac{v^{2}}{2}\left(g^{2}+g'^{2}\right)$$

$$A_{\mu} = \frac{g' A^{3}_{\mu} + g B_{\mu}}{\sqrt{g^{2}+g'^{2}}} \qquad m_A = 0$$

$$\phi \longrightarrow e^{i\alpha\sigma^{3}/2}\, e^{+i\alpha/2}\, \phi = e^{i\alpha\begin{pmatrix}1&0\\0&0\end{pmatrix}}$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A^1 \mp i A^2\right) \qquad m_W^2 = \left(\frac{gv}{2}\right)^2$$

$$Z_\mu^0 = \frac{g A_\mu^3 - g' B_\mu}{\sqrt{g^2+g'^2}} \qquad m_Z^2 = \frac{v^2}{2}\left(g^2+g'^2\right)$$

$$A_\mu = \frac{g' A_\mu^3 + g B_\mu}{\sqrt{g^2+g'^2}} \qquad m_A = 0$$

$$\phi \longrightarrow e^{i\alpha\sigma^3/2}\, e^{+i\alpha/2}\,\phi = e^{i\alpha\begin{pmatrix}1&0\\0&0\end{pmatrix}}\,\phi$$

$$\text{s}\,\Theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

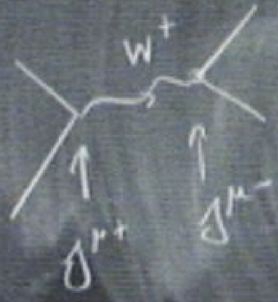
$$\sin\Theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J^+_\mu J^{\mu-}} + (J^3_\mu - s_W^2 J^{EM}_\mu)^2\right]$$

Higgs Kibble

Guralnik Hagen

Brout Englert



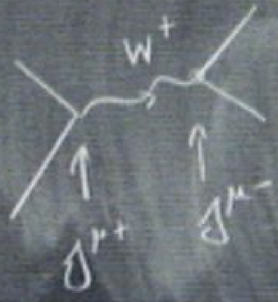
$$[a_k^\mu, a_{k'}^{\nu+}] = -g^{\mu\nu}\delta(k-k')$$

$$s\,\Theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

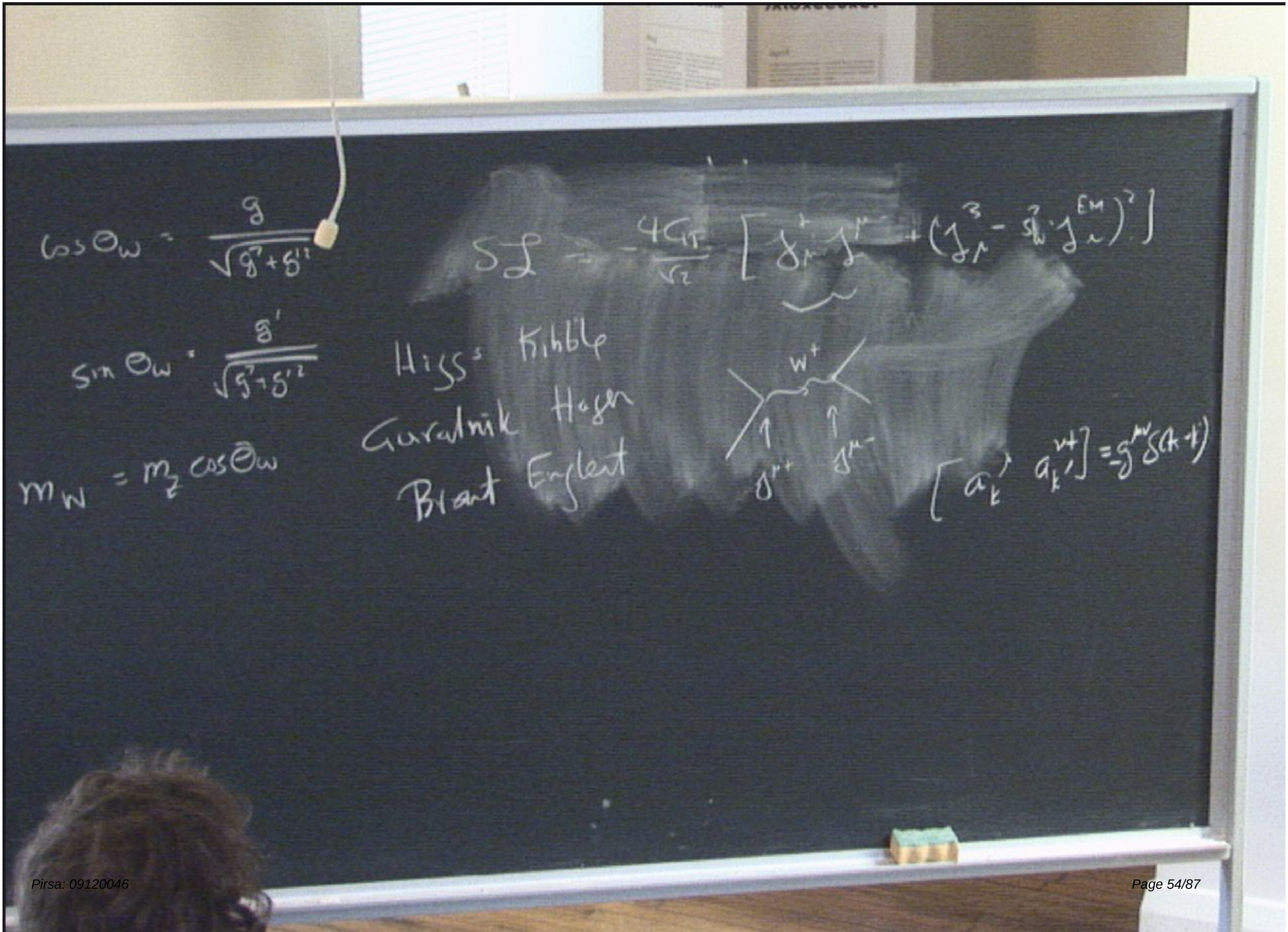
$$\sin\Theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J_\mu^+ J^{\mu-}} + (J_\mu^3 - s_W^2 \cdot J_\mu^{EM})^2\right]$$

Higgs Kibble
Guralnik Hagen
Brout Englert



$$[a_k^\mu, a_{k'}^{\nu+}] = -g^{\mu\nu}\delta(k-k')$$



$$\cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

$$\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$$

$$m_W = m_Z \cos\theta_W$$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[\underbrace{J^+_\mu J^{\mu-}} + (J^3_\mu - s^2_W J^{EM}_\mu)^2\right]$$

Higgs Kibble

Guralnik Hagen

Brout Englert

$$[a^\mu_k, a^{\nu\dagger}_{k'}] = -g^{\mu\nu}\delta(k-k')$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = \partial_\mu \psi - i g A^a_\mu t^a$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) w. Higgs i ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu \psi - i g A^a_\mu \underset{\substack{\uparrow \\ \text{"weak isospin"}}}{t^a} - i g' B_\mu Y) \psi$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu - i g A^a_\mu \underset{\substack{\uparrow \\ \text{"weak isospin"}}}{t^a} - i g' B_\mu \underset{\substack{\uparrow \\ \text{"hypercharge"}}}{Y}) \psi$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) w. Higgs in ϕ^a real.

$$D_\mu\phi = (\partial_\mu\phi - igA_\mu^a\tau^a\phi - ig'B_\mu\tfrac{1}{2}\phi)$$

$$D_\mu\psi = (\partial_\mu - igA_\mu^a \underset{\substack{\uparrow\\ \text{"weak isospin"}}}{t^a} - ig'B_\mu \underset{\substack{\uparrow\\ \text{"hypercharge"}}}{Y})\psi$$

$$\begin{pmatrix}u\\d\end{pmatrix}_L \quad \begin{pmatrix}\nu\\e^-\end{pmatrix}_L \quad u_R \quad d_R \quad e^-_R$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) w. Higgs in ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - ig A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu \quad - ig A^3_\mu \underset{\overset{\uparrow}{\text{"weak isospin"}}}{t^3} - i g' B_\mu \underset{\overset{\uparrow}{\text{"hypercharge"}}}{Y}) \psi$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \qquad u_R \quad d_R \quad e^-_R$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu - i g A_\mu^3 \underset{\substack{\uparrow \\ \text{"weak isospin"}}}{\frac{\sigma^3}{2}} - i g' B_\mu \underset{\substack{\uparrow \\ \text{"hypercharge"}}}{Y}) \psi$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \quad u_R \quad d_R \quad e^-_R$$

u $I^3 = +\frac{1}{2}$ d $I^3 = -\frac{1}{2}$

$\tau^a = \frac{\sigma^a}{2}$ SU(2)   w. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu - i g A_\mu^3 \underset{\substack{\uparrow \\ \text{"weak isospin"}}}{\frac{\sigma^3}{2}} - i g' B_\mu \underset{\substack{\uparrow \\ \text{"hypercharge"}}}{Y}) \psi$$

$\begin{pmatrix} u \\ d \end{pmatrix}_L$ $\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$ u_R d_R e^-_R

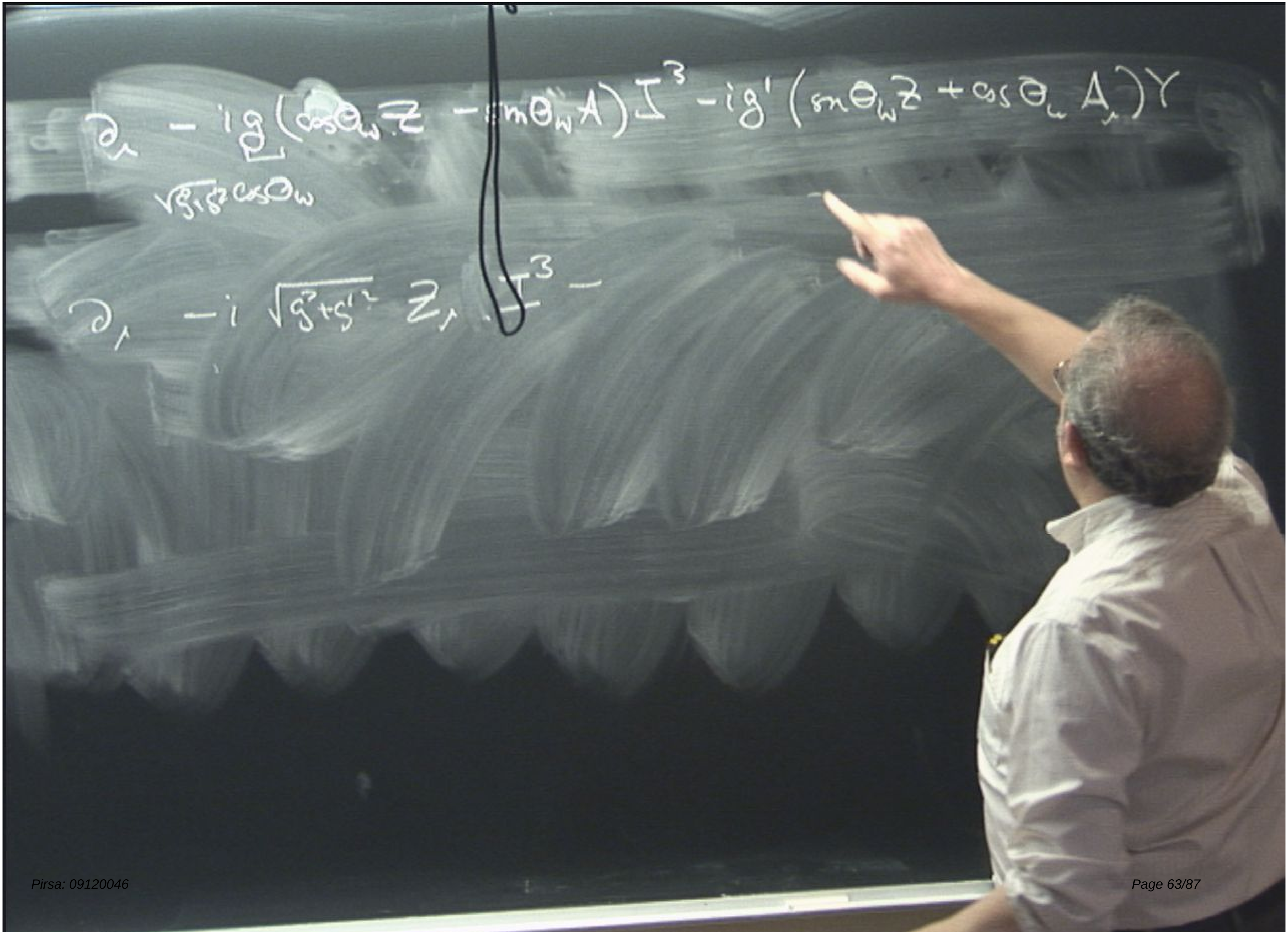
u_L $I^3 = +\frac{1}{2}$ d_L $I^3 = -\frac{1}{2}$

u_R $I^3 = 0$ d_R $I^3 = 0$

$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_W}(\cos\theta_W Z - \sin\theta_W A) I^3 - ig'(\sin\theta_W Z + \cos\theta_W A_\mu) Y$$

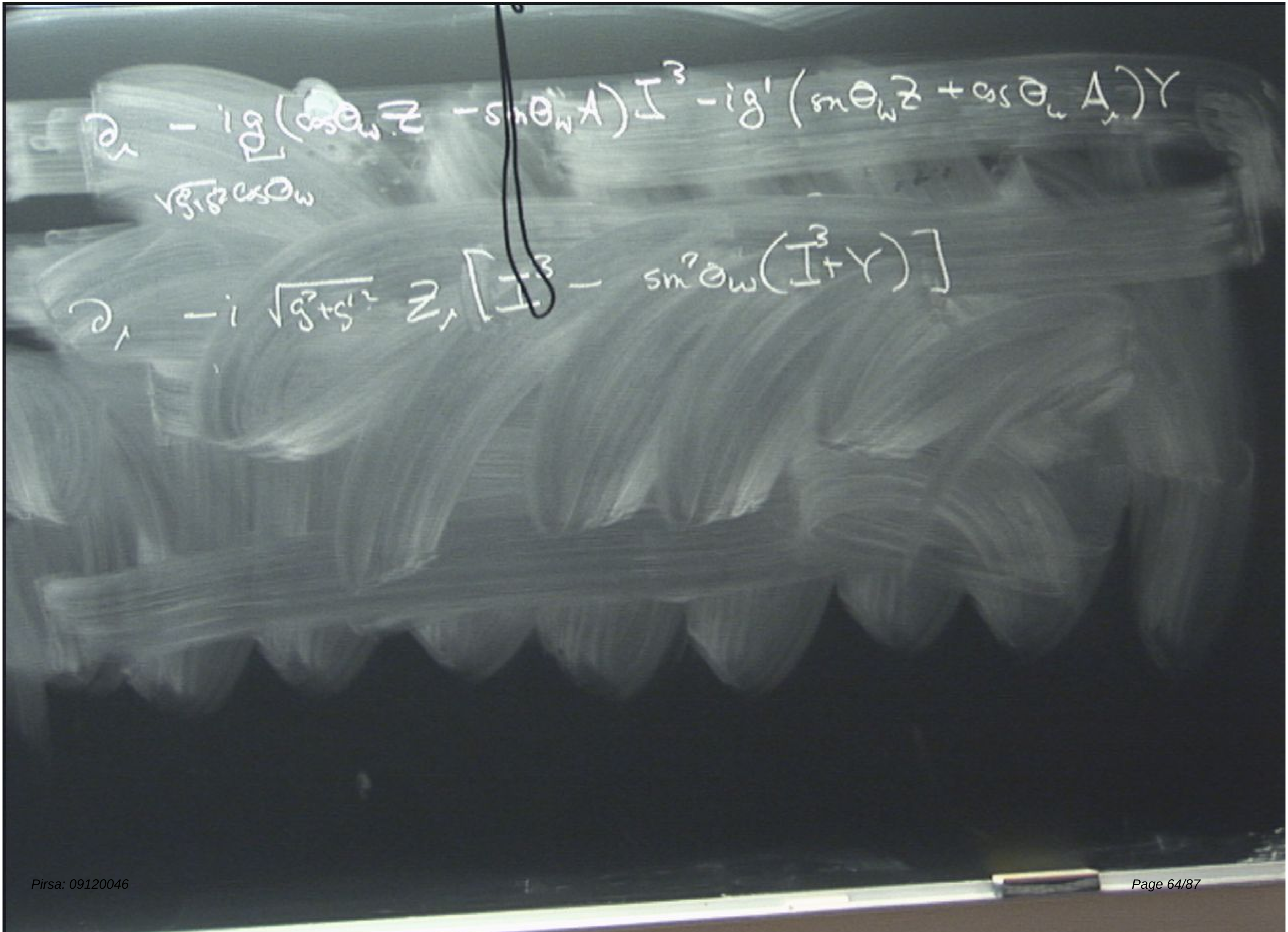
$$Z^0_\mu = \frac{g A^3_\mu - g' B_\mu}{\sqrt{g^2+g'^2}} \qquad m_Z^2 = \frac{v^2}{4}(g^2+g'^2)$$

$$A_\mu = \frac{g' A^3_\mu + g B_\mu}{\sqrt{g^2+g'^2}} \qquad m_A = 0$$



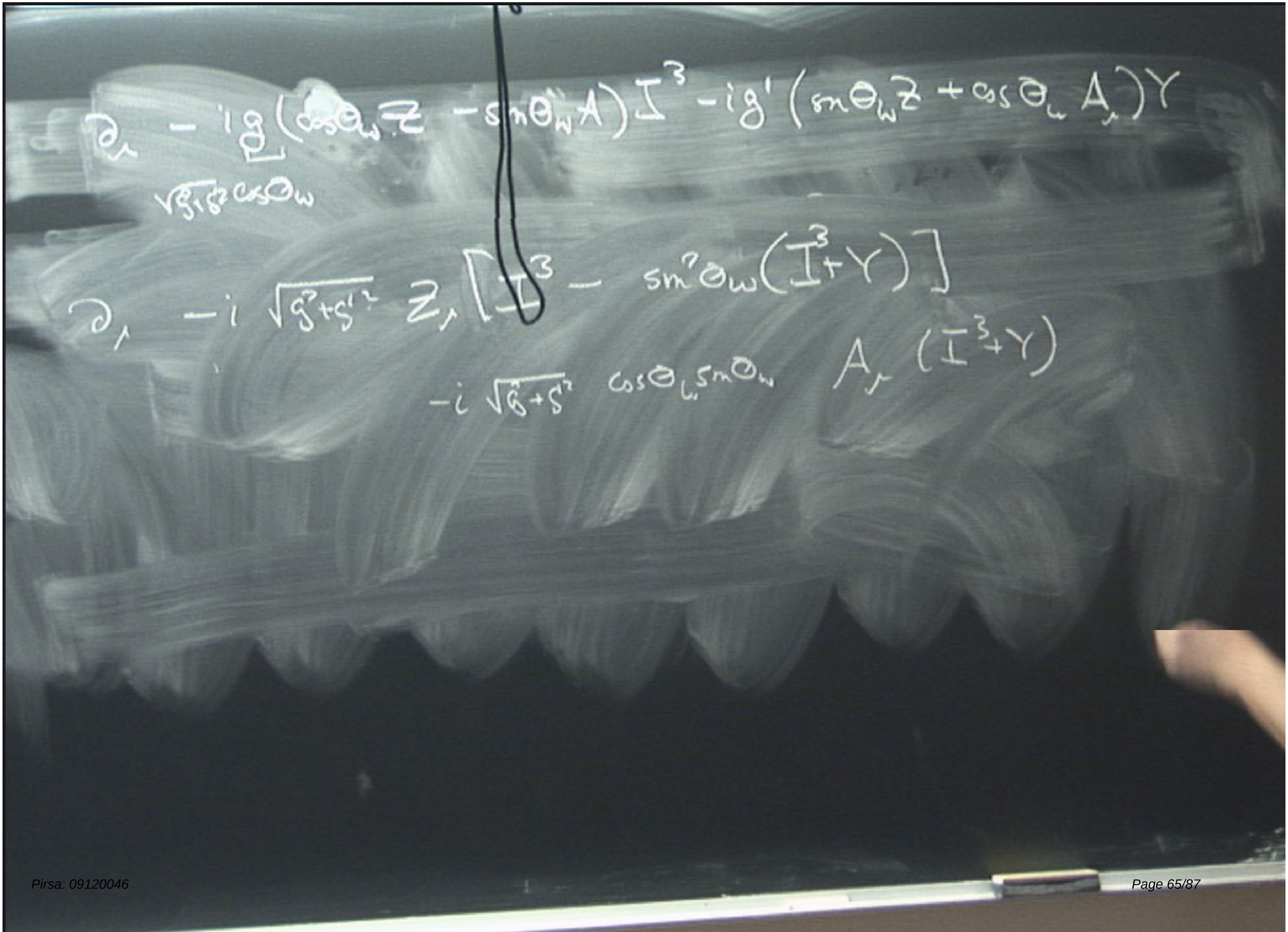
$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_W}(\cos\theta_W Z - \sin\theta_W A) I^3 - ig'(\sin\theta_W Z + \cos\theta_W A_\mu) Y$$

$$\partial_\mu - i\sqrt{g^2+g'^2}\, Z_\mu I^3 -$$



$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_W}(\cos\theta_W Z - \sin\theta_W A)I^3 - ig'(\sin\theta_W Z + \cos\theta_W A_\mu)Y$$

$$\partial_\mu - i\sqrt{g^2+g'^2}\, Z_\mu \left[I^3 - \sin^2\theta_W (I^3+Y)\right]$$



$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_W}(\cos\theta_W Z - \sin\theta_W A) I^3 - ig'(\sin\theta_W Z + \cos\theta_W A_\mu) Y$$

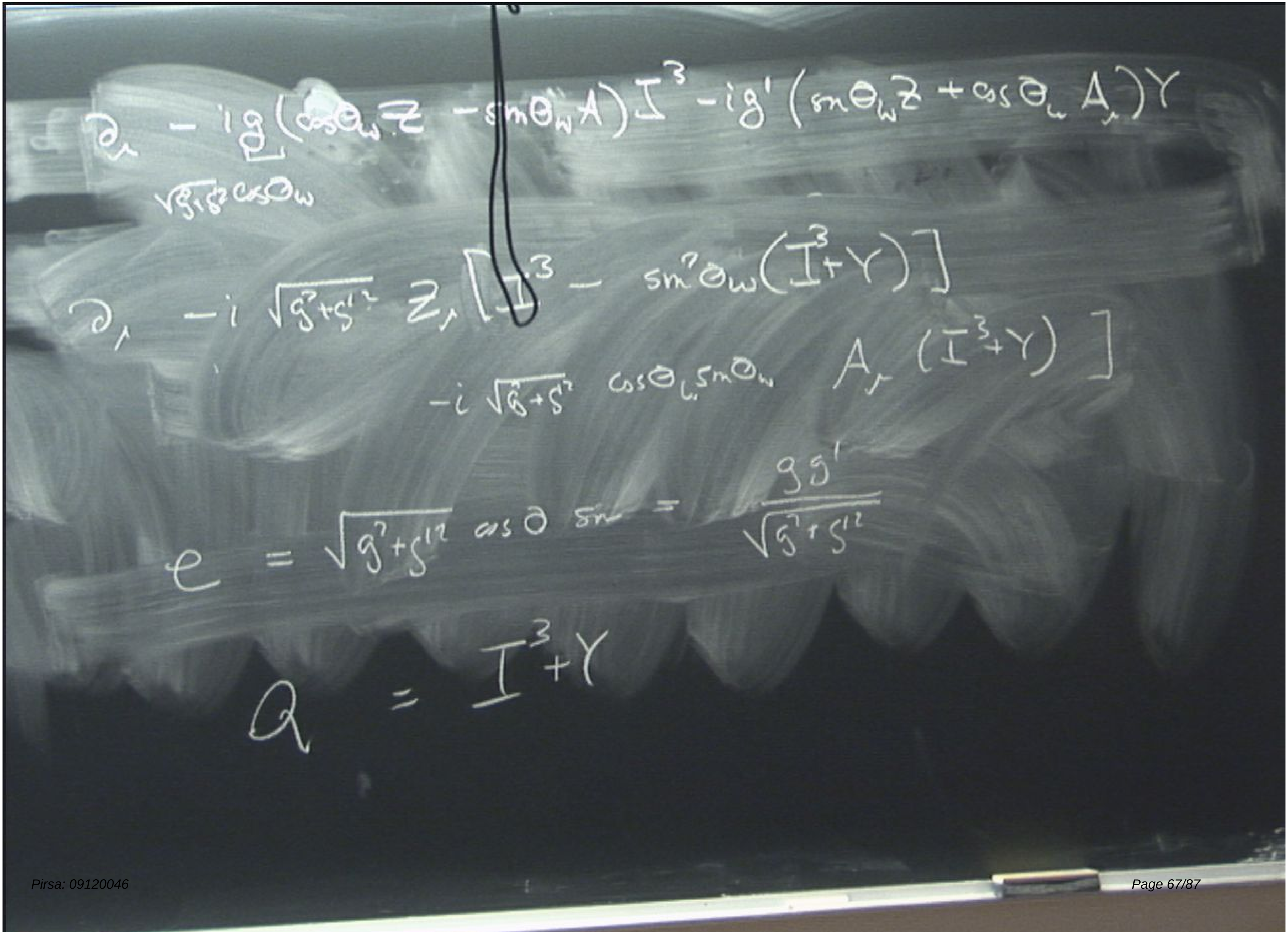
$$\partial_\mu - i\sqrt{g^2+g'^2}\, Z_\mu \left[I^3 - \sin^2\theta_W (I^3+Y) \right]$$

$$-i\sqrt{g^2+g'^2}\cos\theta_W \sin\theta_W \quad A_\mu \, (I^3+Y)$$

$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_w}(\cos\theta_w Z - \sin\theta_w A)I^3 - ig'(\sin\theta_w Z + \cos\theta_w A_\mu)Y$$

$$\partial_\mu \; - i\sqrt{g^2+g'^2}\; Z_\mu \left[I^3 - \sin^2\theta_w (I^3+Y) \right]$$

$$-i\sqrt{g^2+g^2}\;\cos\theta_w \sin\theta_w \;\; A_\mu \; (I^3+Y) \;]$$



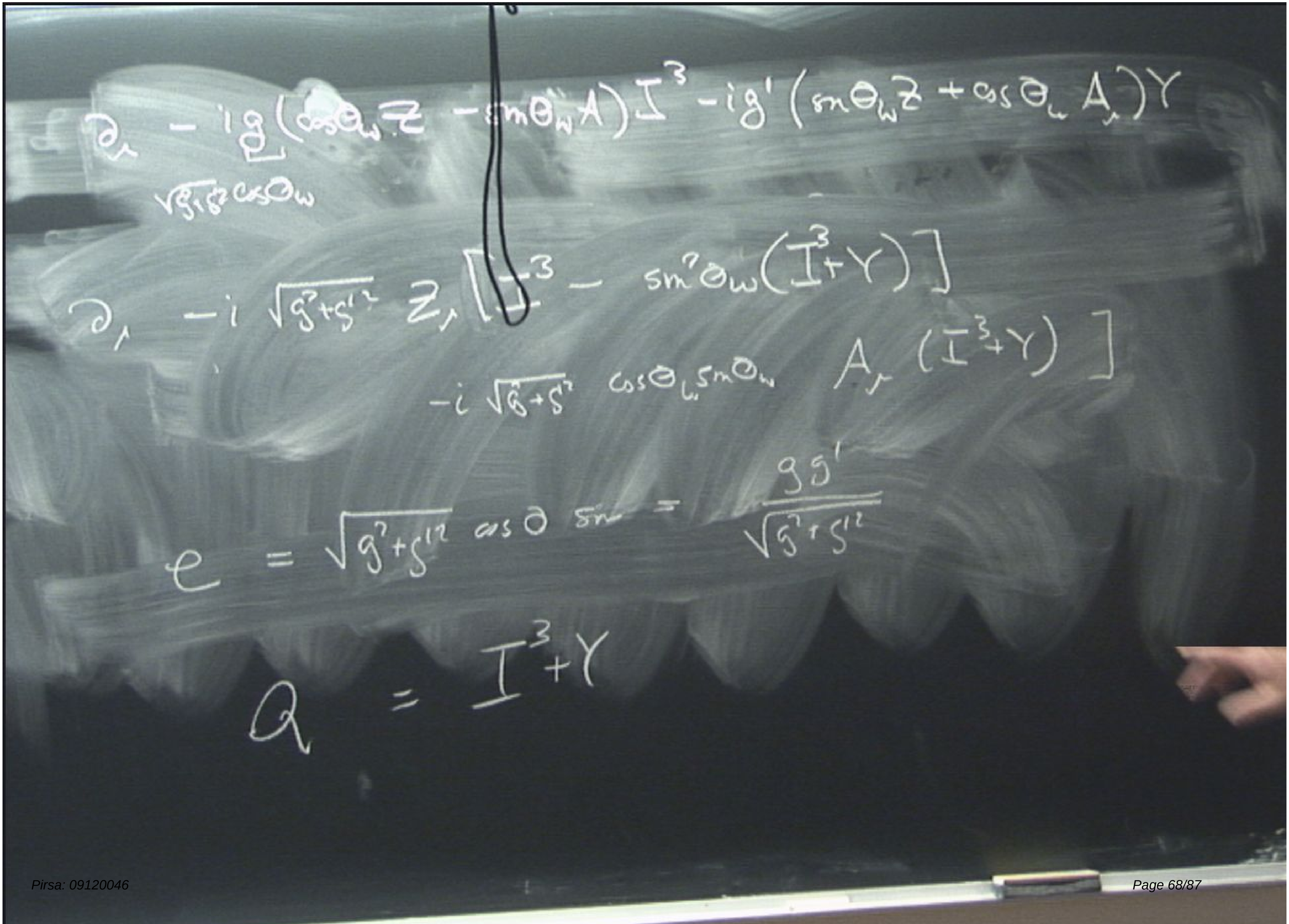
$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_W}(\cos\theta_W Z - \sin\theta_W A) I^3 - ig'(\sin\theta_W Z + \cos\theta_W A_\mu) Y$$

$$\partial_\mu - i\sqrt{g^2+g'^2}\, Z_\mu \left[I^3 - \sin^2\theta_W (I^3+Y) \right]$$

$$-i\sqrt{g^2+g'^2}\, \cos\theta_W \sin\theta_W \quad A_\mu \, (I^3+Y) \quad]$$

$$e = \sqrt{g^2+g'^2}\cos\theta \sin = \frac{gg'}{\sqrt{g^2+g'^2}}$$

$$Q = I^3+Y$$



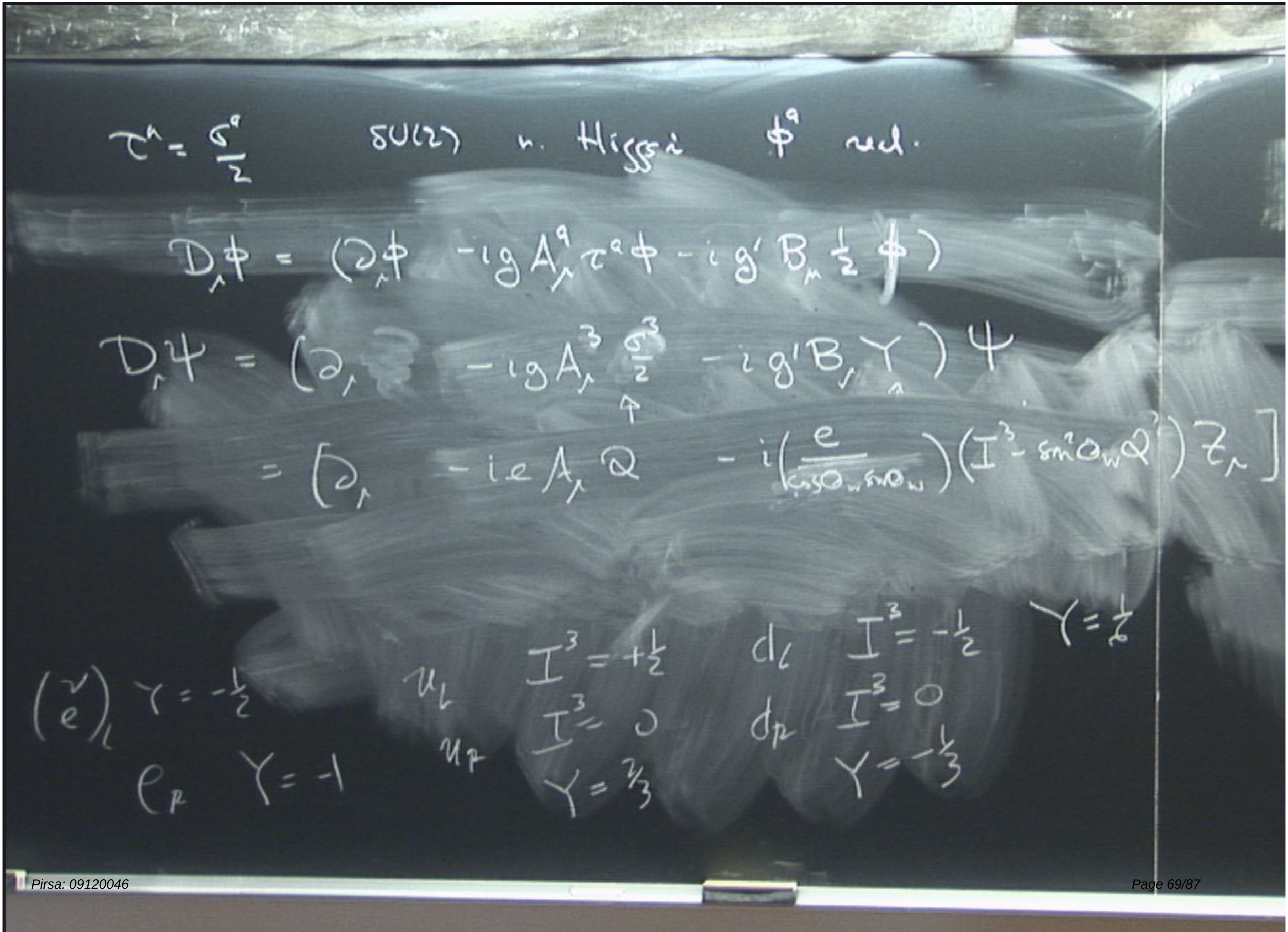
$$\partial_\mu - i\underbrace{g}_{\sqrt{g^2+g'^2}\cos\theta_w}(\cos\theta_w Z - \sin\theta_w A) I^3 - i g'(\sin\theta_w Z + \cos\theta_w A_\mu) Y$$

$$\partial_\mu - i\sqrt{g^2+g'^2}\, Z_\mu \left[I^3 - \sin^2\theta_w (I^3+Y) \right]$$

$$-i\sqrt{g^2+g'^2}\cos\theta_w \sin\theta_w \quad A_\mu \; (I^3+Y) \;]$$

$$e = \sqrt{g^2+g'^2}\cos\theta\,\sin = \frac{gg'}{\sqrt{g^2+g'^2}}$$

$$Q = I^3+Y$$



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - i g A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu - i g A^3_\mu \underset{\uparrow}{\frac{\sigma^3}{2}} - i g' B_\mu \underset{\wedge}{Y}) \psi$$

$$= [\partial_\mu - i e A_\mu Q - i\left(\frac{e}{\cos\theta_W \sin\theta_W}\right)(I^3 - \sin^2\theta_W Q) Z_\mu]$$

$Y = \frac{1}{6}$

$\binom{\nu}{e}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

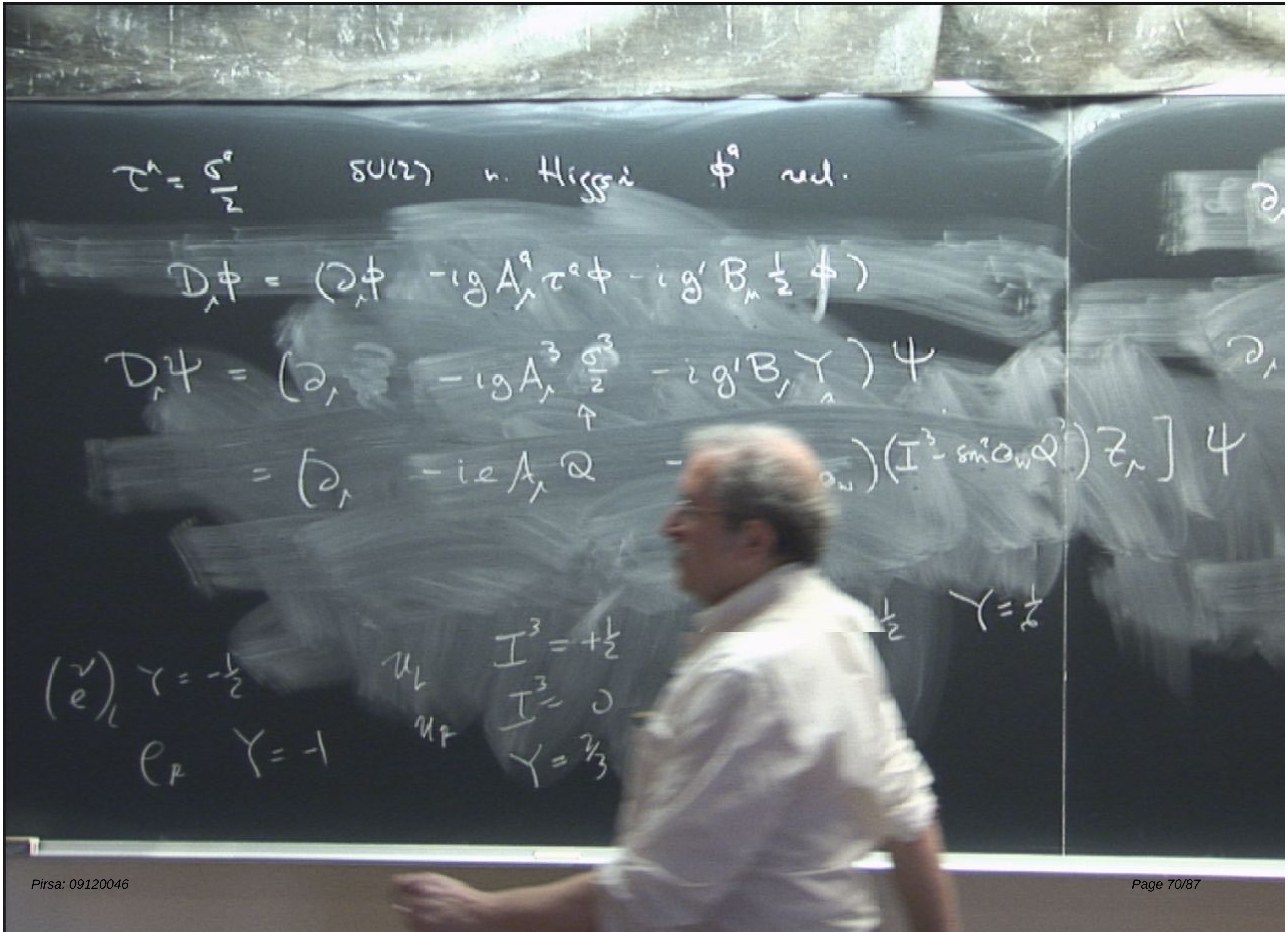
u_R $I^3 = 0$

$Y = \frac{2}{3}$

d_L $I^3 = -\frac{1}{2}$

d_R $I^3 = 0$

$Y = -\frac{1}{3}$



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$D_\mu \phi = (\partial_\mu \phi - i g A_\mu^a \tau^a \phi - i g' B_\mu \frac{1}{2} \phi)$

$D_\mu \Psi = (\partial_\mu - i g A_\mu^3 \frac{\sigma^3}{2} - i g' B_\mu Y) \Psi$

$= [\partial_\mu - i e A_\mu Q - \ldots \theta_W)(I^3 - \sin^2\theta_W Q) Z_\mu] \Psi$

∂_μ

∂_μ

$\frac{1}{2}$ $Y = \frac{1}{6}$

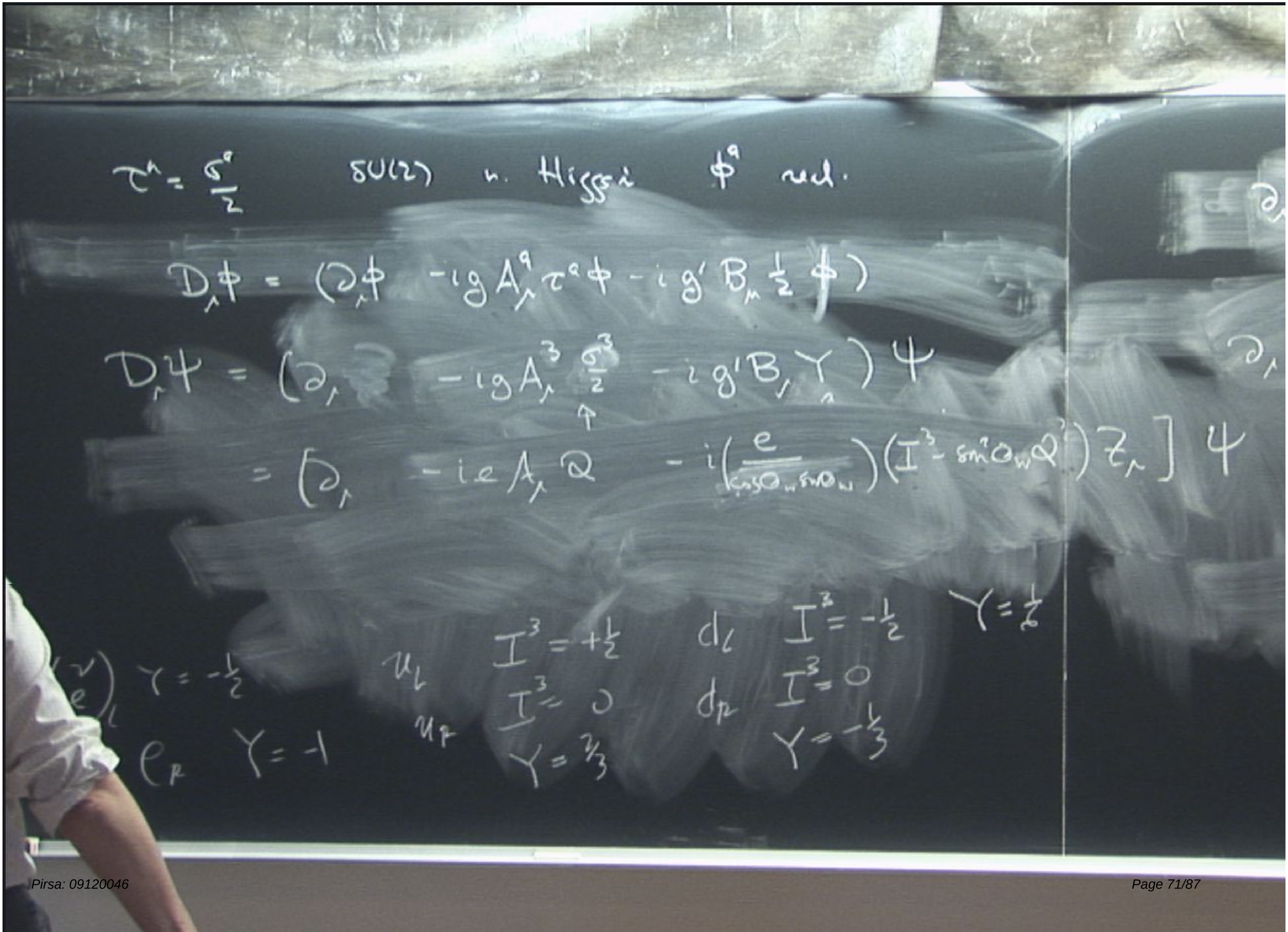
$\binom{\nu}{e}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

u_R $I^3 = 0$

$Y = \frac{2}{3}$



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi \; - i g A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu \; - i g A^3_\mu \underset{\uparrow}{\frac{\sigma^3}{2}} - i g' B_\mu Y_\mu) \psi$$

$$= [\partial_\mu \; - i e A_\mu Q \; - i \left(\frac{e}{\cos\theta_W \sin\theta_W}\right)(I^3 - \sin^2\theta_W Q) Z_\mu] \psi$$

$Y = \frac{1}{6}$

$\binom{\nu}{e}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

u_R $I^3 = 0$

$Y = \frac{2}{3}$

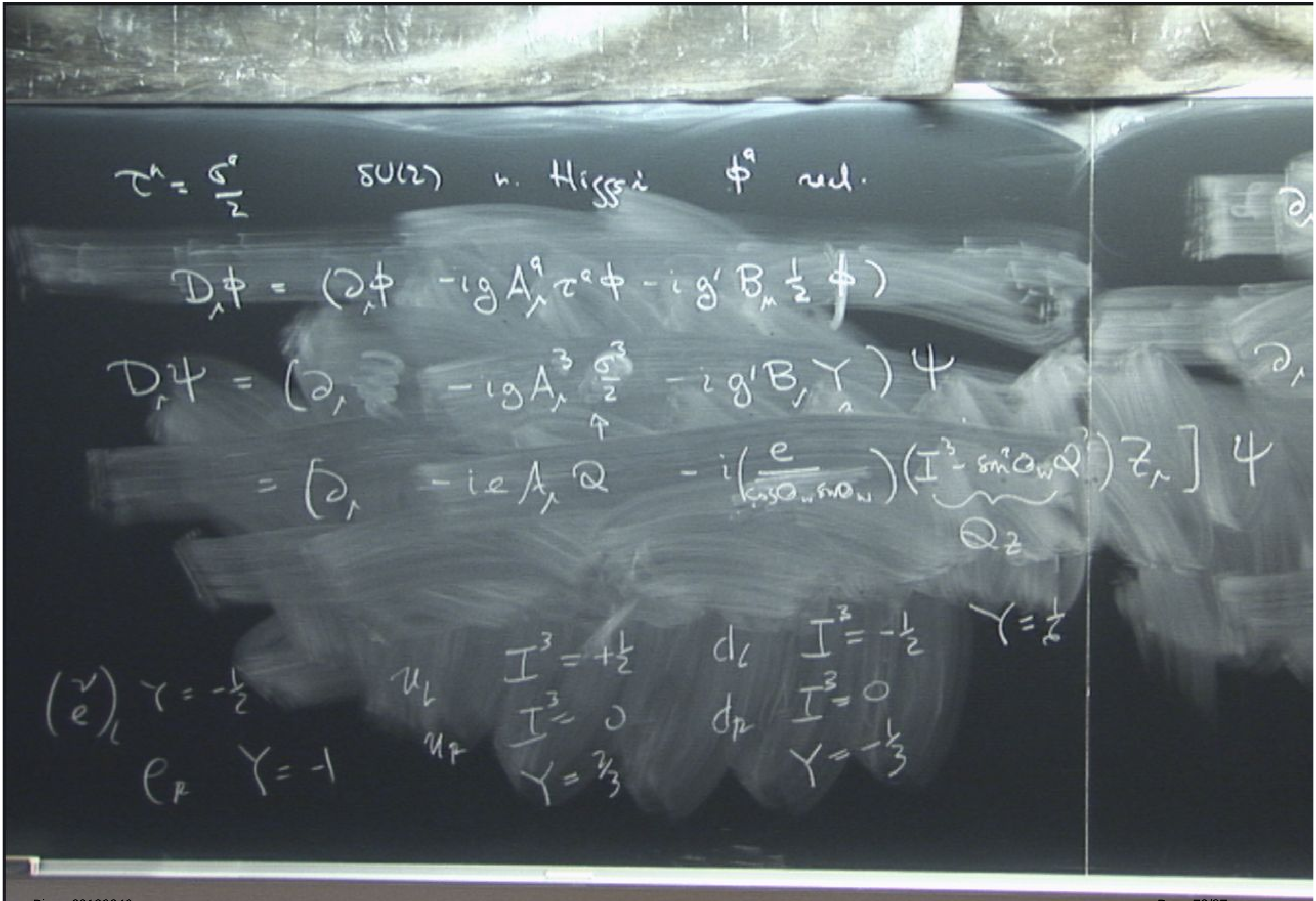
d_L $I^3 = -\frac{1}{2}$

d_R $I^3 = 0$

$Y = -\frac{1}{3}$

$d \; \partial$

∂_μ



$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs ϕ^a real.

$$D_\mu \phi = (\partial_\mu \phi - ig A^a_\mu \tau^a \phi - i g' B_\mu \tfrac{1}{2} \phi)$$

$$D_\mu \psi = (\partial_\mu - ig A^3_\mu \underset{\uparrow}{\frac{\sigma^3}{2}} - i g' B_\mu Y) \psi$$

$$= [\partial_\mu - ie A_\mu Q - i\left(\frac{e}{\cos\theta_W \sin\theta_W}\right)(\underbrace{I^3 - \sin^2\theta_W Q}_{Q_Z}) Z_\mu] \psi$$

∂_μ

$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

u_R $I^3 = 0$ $Y = \frac{2}{3}$

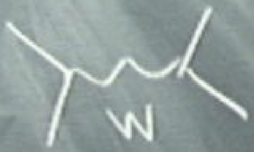
d_L $I^3 = -\frac{1}{2}$ $Y = \frac{1}{6}$

d_R $I^3 = 0$ $Y = -\frac{1}{3}$

$$\partial_\mu - i\frac{g}{\sqrt{2}}\left[W_\mu^+ j_\mu^+ + W_\mu^- j_\mu^-\right]$$

$) Z_\mu]$ 4

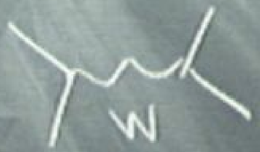
$$\left(\partial_\mu - i\frac{g}{\sqrt{2}}\left[W^+_\mu \overset{\sigma^+}{\begin{pmatrix}1&0\\0&0\end{pmatrix}} + W^-_\mu\,\sigma^-\right]\right)\begin{pmatrix}\nu\\e\end{pmatrix}$$



$$\left(\frac{ig}{\sqrt{2}}\right)^2 \frac{-i}{(q^2-m_W^2)}\, J^+_\mu\, J^{-\mu}$$

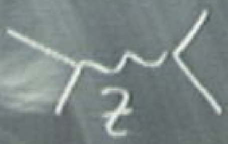
$$) Z_\mu]\, \psi$$

$$\left(\partial_\mu - i\frac{g}{\sqrt{2}}\left[W^+_\mu \overset{\sigma^+}{\begin{pmatrix}1&0\\0&0\end{pmatrix}} + W^-_\mu\,\sigma^-\right]\right)\begin{pmatrix}\nu\\e\end{pmatrix}$$



$$\left(\frac{ig}{\sqrt{2}}\right)^2 \frac{-i}{(q^2-m_W^2)}\; J^+_\mu\, J^{-\mu}$$

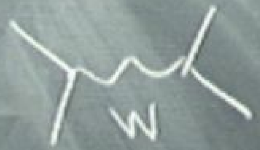
] 4



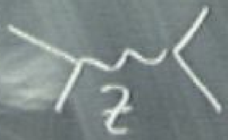
$$\frac{1}{2}\left(\frac{ig}{\cos\theta_W}\right)^2 \frac{-i}{q^2-m_Z^2}\left(J^3_\mu - \sin^2\theta_W\, J^{EM}\right)^2$$

$$\left(\partial_\mu - i\frac{g}{\sqrt2}\left[W^+_\mu \overset{\sigma^+}{\begin{pmatrix}1&0\\0&0\end{pmatrix}} + W^-_\mu\,\sigma^-\right]\right)\begin{pmatrix}\nu\\ d\end{pmatrix}$$

$$)\,Z_\mu]\,\psi$$



$$\left(\frac{ig}{\sqrt2}\right)^2 \frac{-i}{(q^2-m_W^2)}\; J^+_\mu\, J^{-\mu}$$

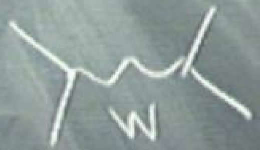


$$\frac12\left(\frac{ig}{\cos\theta_W}\right)^2 \frac{-i}{q^2-m_Z^2}\;(J^3_\mu - \sin^2\theta_W$$

$$q^2 \to 0$$

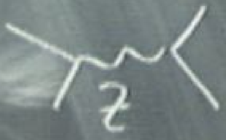
$$\frac{g^2}{2m_W^2} = \frac{4G_F}{\sqrt2}$$

$$\left(\partial_\mu - i\frac{g}{\sqrt{2}}\left[W^+_\mu \overset{\sigma^+}{\begin{pmatrix}1&0\\0&0\end{pmatrix}} + W^-_\mu\,\sigma^-\right]\right)\begin{pmatrix}\nu\\e\end{pmatrix}$$



$$\left(\frac{ig}{\sqrt{2}}\right)^2 \frac{-i}{(q^2-m_W^2)}\, J^+_\mu\, J^{-\mu}$$

$$)Z_\mu]\,\psi$$



$$\frac{1}{2}\left(\frac{ig}{\cos\theta_W}\right)^2 \frac{-i}{q^2-m_Z^2}\,(J^3_\mu - \sin^2\theta_W$$

$$q^2 \to 0$$

$$\frac{e^2}{2m_W^2\sin^2\theta_W} = \frac{g^2}{2m_W^2} = \frac{4G_F}{\sqrt{2}}$$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$e^2 = 4\pi\alpha$

$\begin{pmatrix}\nu\\ e\end{pmatrix}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

u_R $I^3 = 0$

$Y = 2/3$

d_L $I^3 = -\frac{1}{2}$

d_R $I^3 = 0$

$Y = -1/3$

$\tau^a = \frac{\sigma^a}{2}$ SU(2) n. Higgs i ϕ^a real.

$$e^2 = 4\pi\alpha = 1/129$$

$$\sin^2\theta_W = 0.23$$

$$m_W = \left[\frac{4\pi\alpha}{4\sqrt{2}\,G_F \sin^2\theta_W}\right]^{\frac{1}{2}} =$$

$$m_Z = \left[\frac{4\pi\alpha}{\sqrt{2}\,G_F \sin 2\theta_W}\right]^{\frac{1}{2}} -$$

$\binom{\nu}{e}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

u_L $I^3 = +\frac{1}{2}$

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$Y = \frac{2}{3}$

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$$e^2 = 4\pi\alpha = 1/129$$

$$\sin^2\theta_W = 0.23$$

$$m_W = \left[\frac{4\pi\alpha}{4\sqrt{2}\,G_F \sin^2\theta_W}\right]^{\frac{1}{2}} = 80.1 \text{ GeV}$$

$$m_Z = \left[\frac{4\pi\alpha}{\sqrt{2}\,G_F \sin 2\theta_W}\right]^{\frac{1}{2}} = 91.3 \text{ GeV.}$$

$\binom{\nu}{e}_L$ $Y = -\frac{1}{2}$

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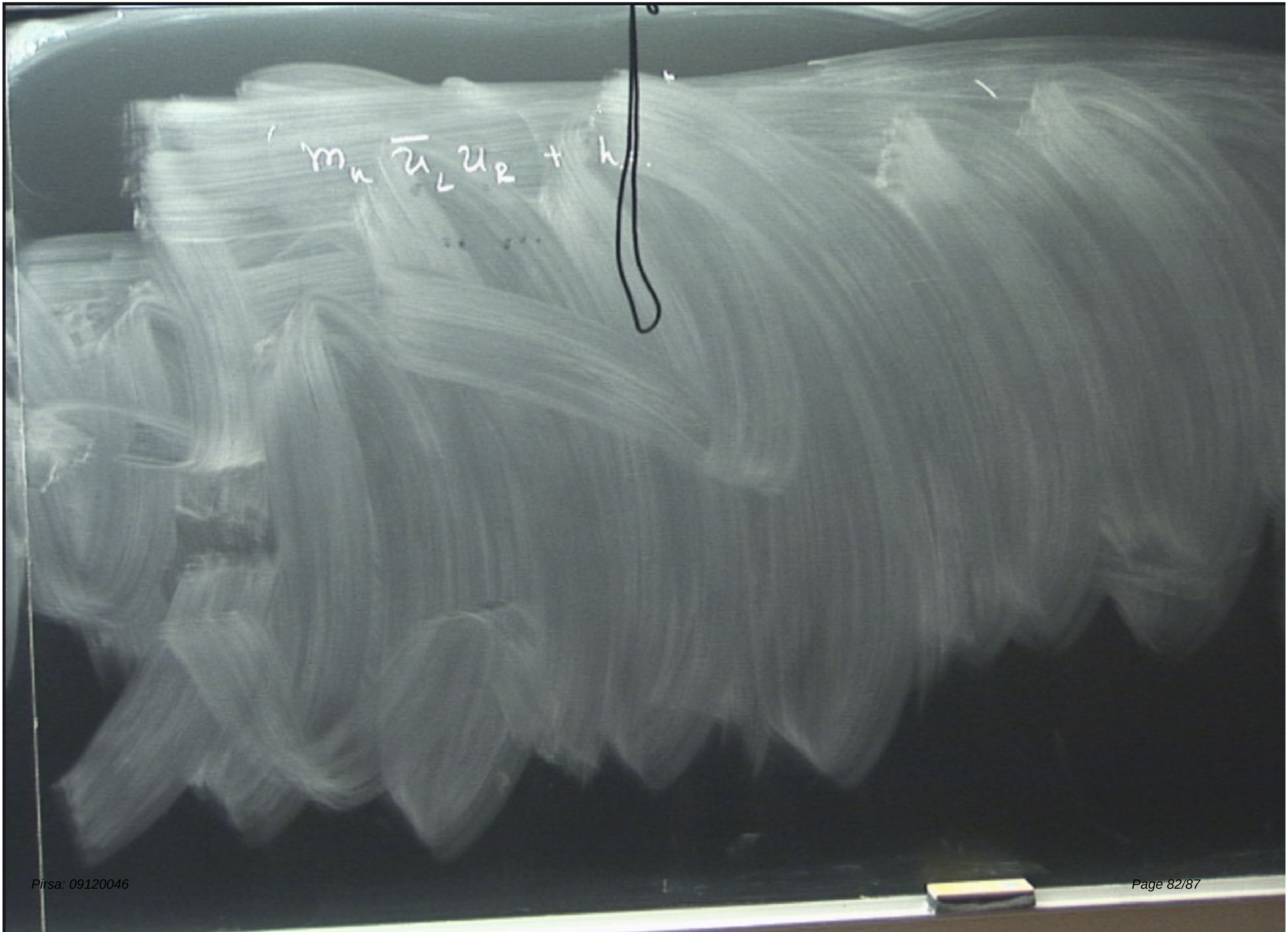
d_R $I^3 = 0$

$Y = -\frac{1}{3}$

$$m_u \bar{u}_L u_R + h. .$$



$m_u \bar{u}_L u_R + h.c.$

$m_u \bar{u}_L u_R + h.$ $L = \binom{\nu}{e}_L$

$\delta\mathcal{L} = - \lambda_e \bar{L}_1 \cdot \phi$

$m_u \bar{u}_L u_R + h.$ $\quad L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$

$\delta\mathcal{L} = -\lambda_e \bar{L} \cdot \phi \, e_R + h.c.$

$+\frac{1}{2} \quad \frac{1}{2} \quad -1 \quad = 0$

$m_u \bar{u}_L u_R + h.c.$

$L = \binom{\nu}{e}_L$

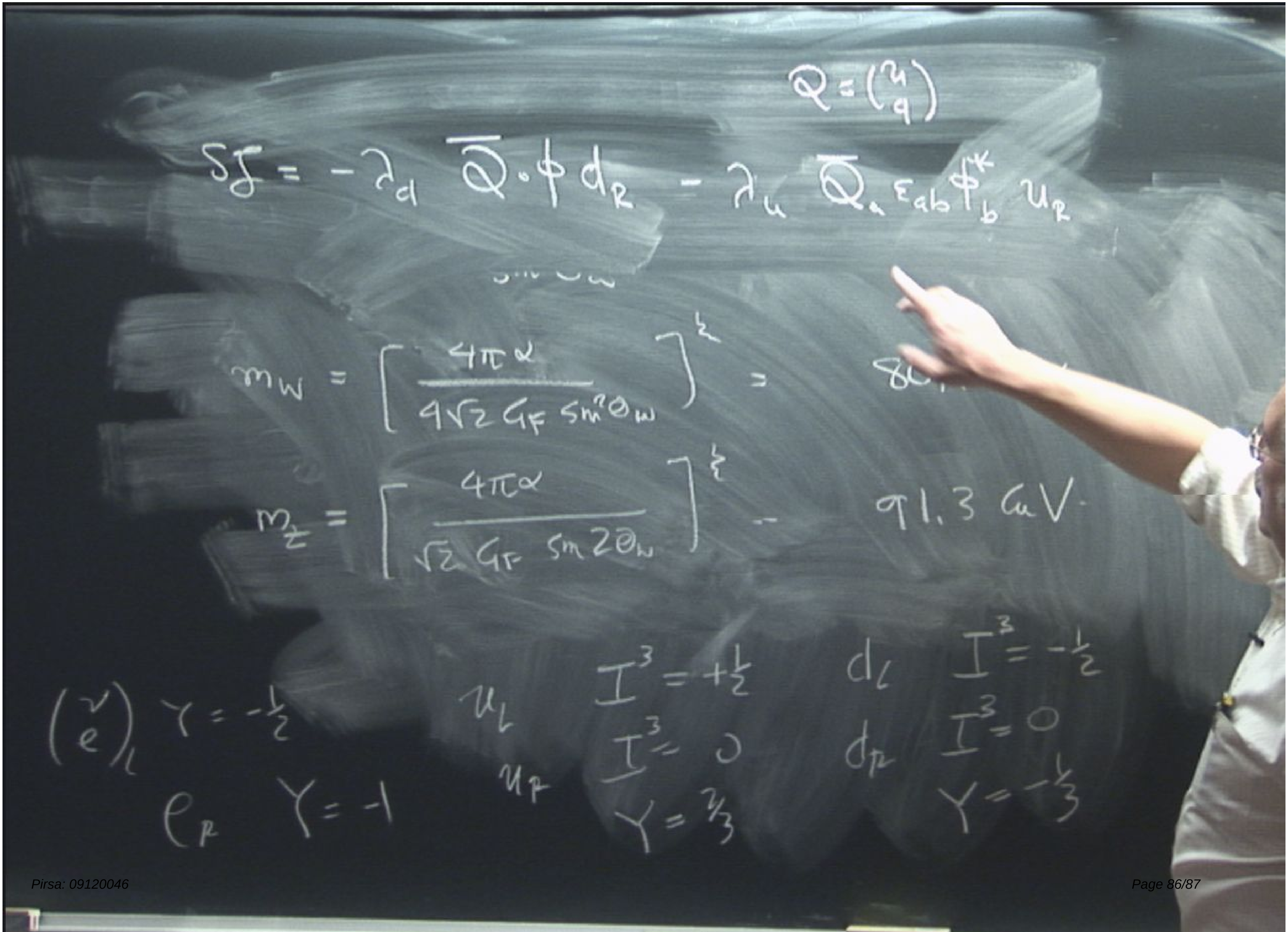
$m_e = \frac{\lambda_e v}{\sqrt{2}}$

$$\delta \mathcal{L} = - \lambda_e \bar{L} \cdot \phi \, e_R + h.c.$$

$$+\tfrac{1}{2} \quad \tfrac{1}{2} \quad -1 = 0$$

$$\phi = \frac{1}{\sqrt{2}} \binom{0}{v}$$

$$= - \frac{\lambda_e v}{\sqrt{2}} \bar{e}_L e_R + h.c.$$



$Q = \binom{u}{d}$

$\delta\mathcal{L} = -\lambda_d\, \bar{Q}\cdot\phi\, d_R - \lambda_u\, \bar{Q}_a\, \varepsilon_{ab}\, \phi^*_b\, u_R$

$m_W = \left[\frac{4\pi\alpha}{4\sqrt{2}\, G_F \sin^2\theta_W}\right]^{\frac{1}{2}} = 80.$

$m_Z = \left[\frac{4\pi\alpha}{\sqrt{2}\, G_F \sin 2\theta_W}\right]^{\frac{1}{2}} = 91.3$ GeV.

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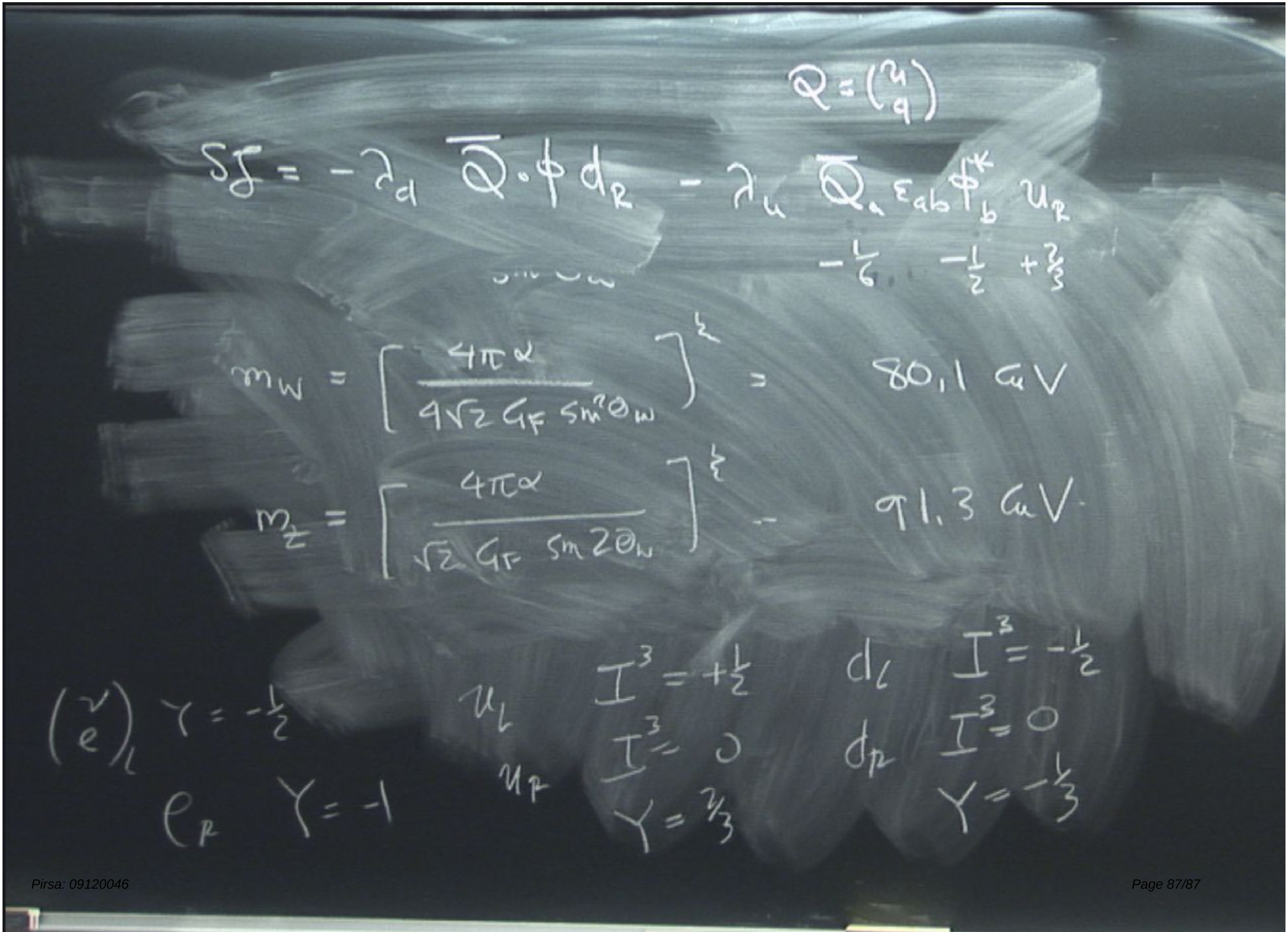

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\delta\mathcal{L} = -\lambda_d \, \overline{Q} \cdot \phi \, d_R - \lambda_u \, \overline{Q}_a \varepsilon_{ab} \phi^*_b \, u_R$$

$$-\tfrac{1}{6} \quad -\tfrac{1}{2} \quad +\tfrac{2}{3}$$

$$m_W = \left[\frac{4\pi\alpha}{4\sqrt{2}\, G_F \sin^2\theta_W} \right]^{\frac{1}{2}} = 80.1 \text{ GeV}$$

$$m_Z = \left[\frac{4\pi\alpha}{\sqrt{2}\, G_F \sin 2\theta_W} \right]^{\frac{1}{2}} = 91.3 \text{ GeV}$$

$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $Y = -\frac{1}{2}$

e_R $Y = -1$

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u_R $I^3 = 0$

$Y = \frac{2}{3}$

d_L $I^3 = -\frac{1}{2}$

d_R $I^3 = 0$

$Y = -\frac{1}{3}$