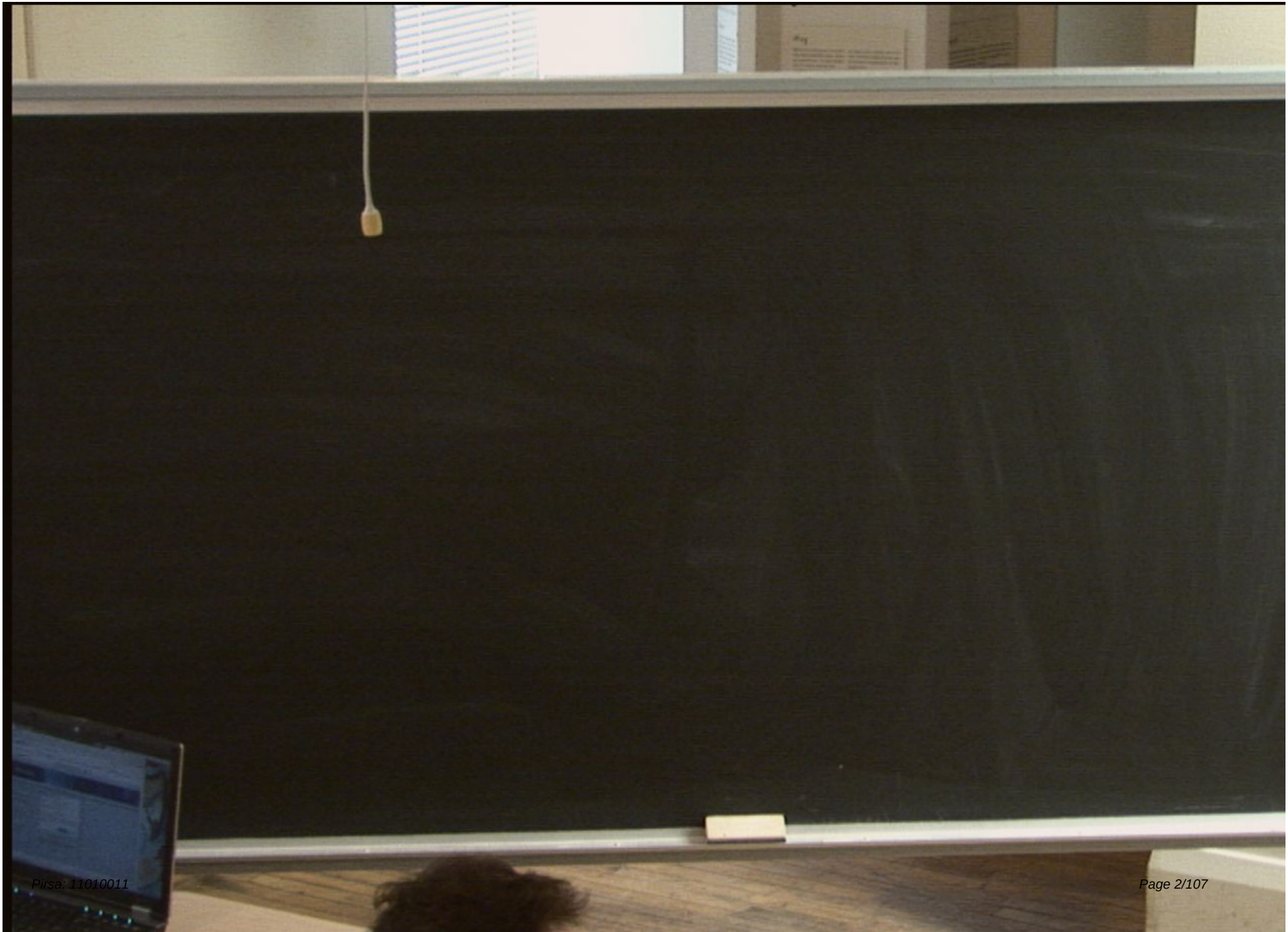
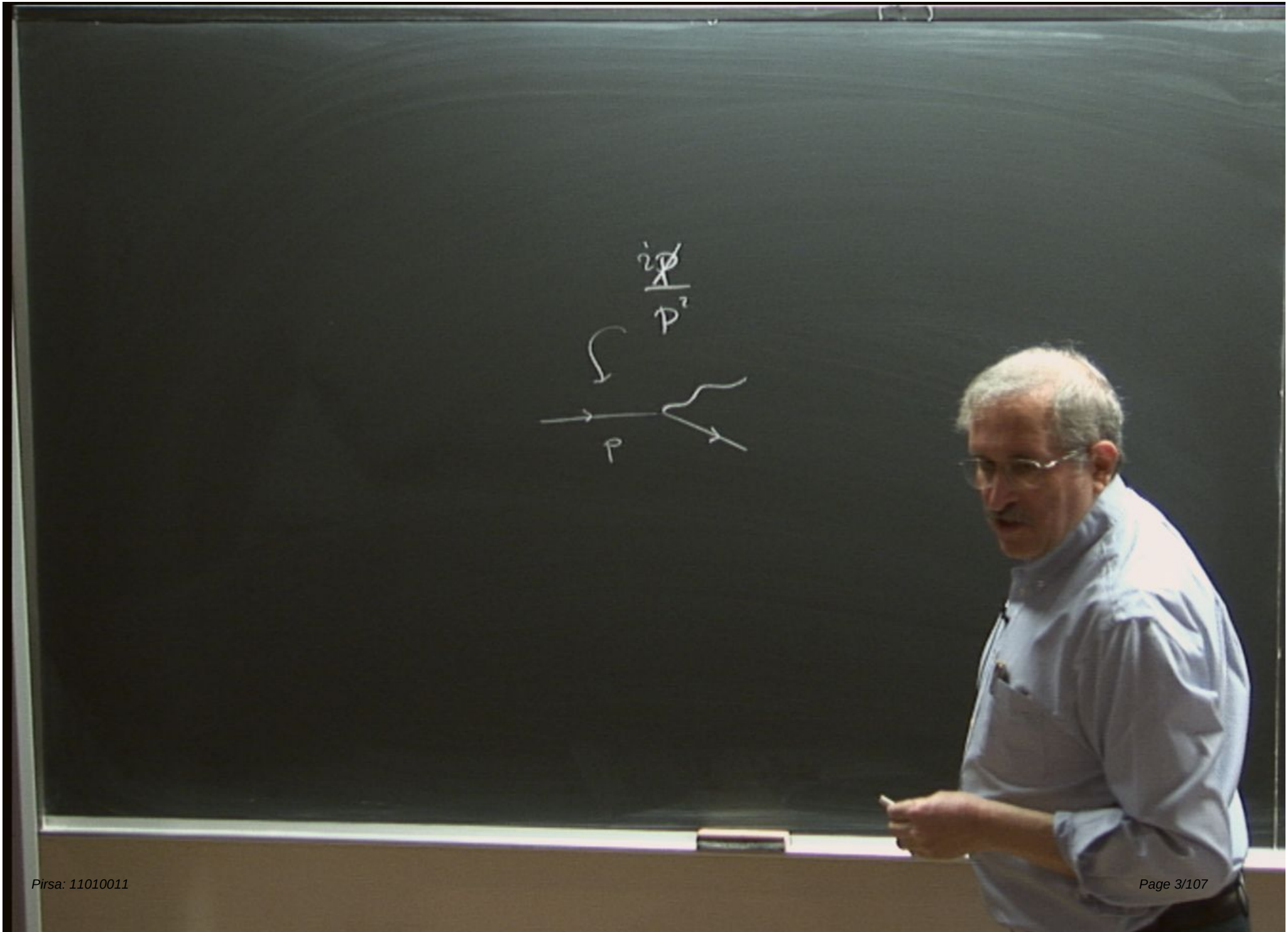
Title: Standard Model - Lecture 10

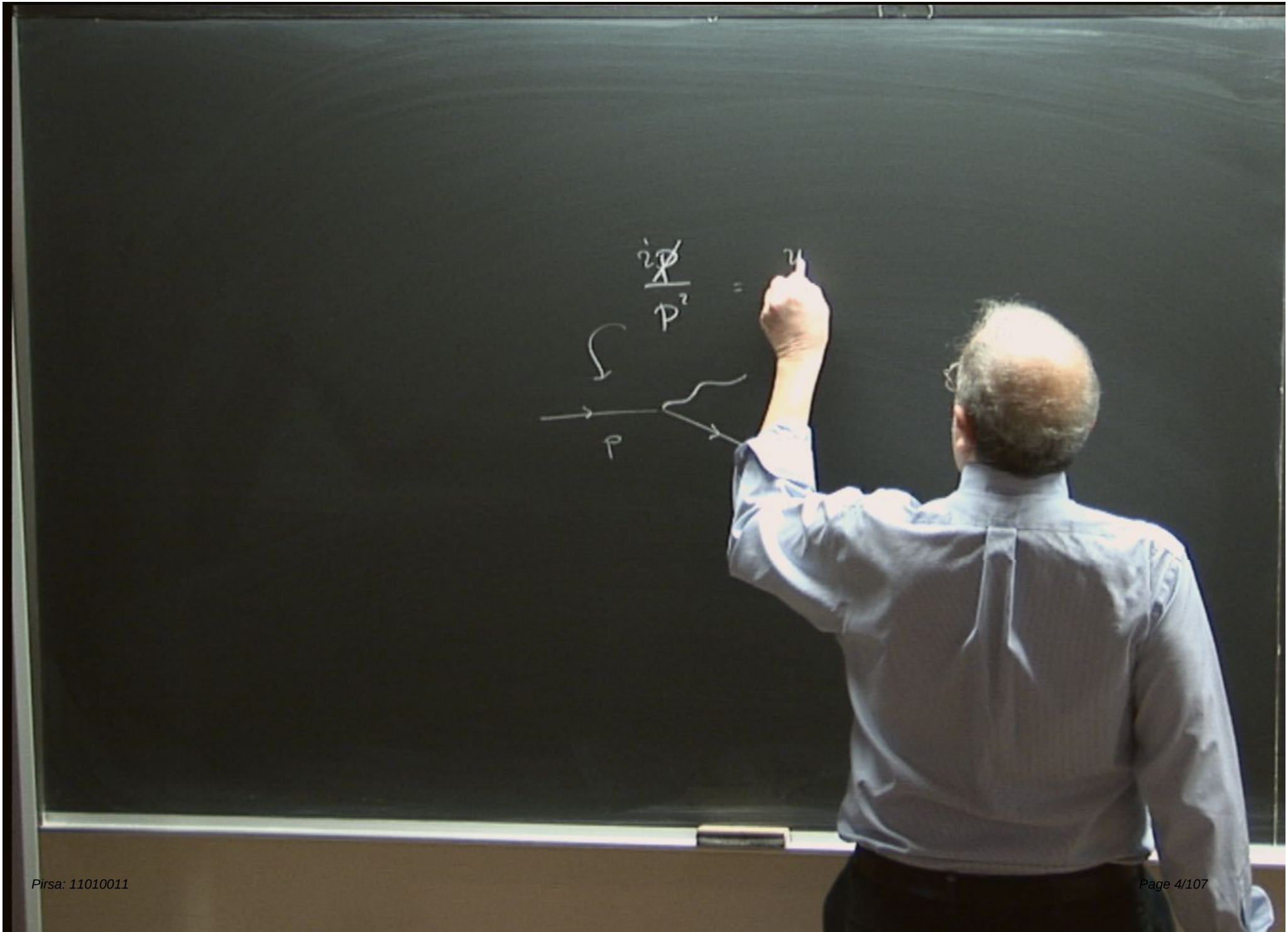
Date: Jan 14, 2011 09:00 AM

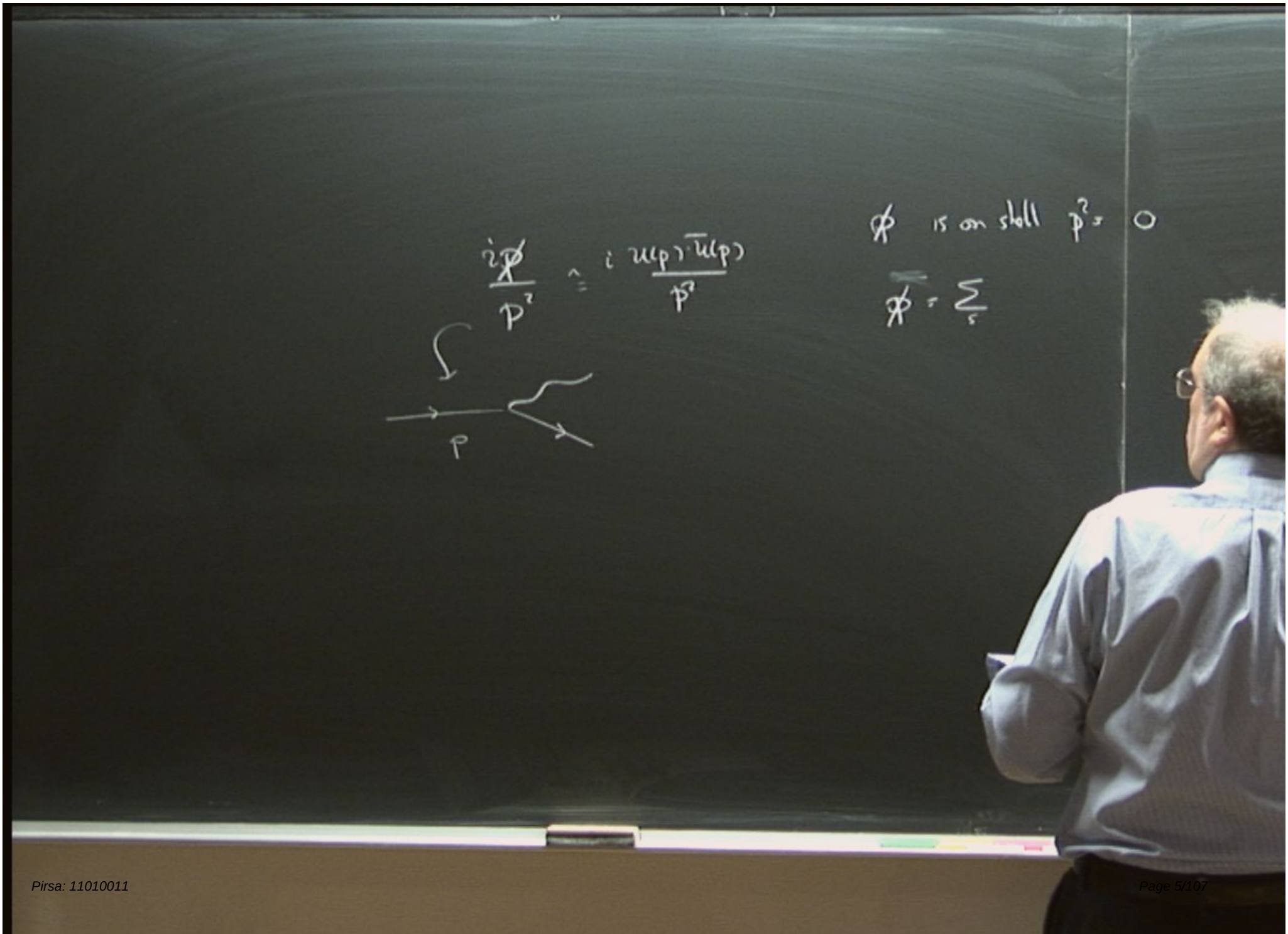
URL: http://pirsa.org/11010011

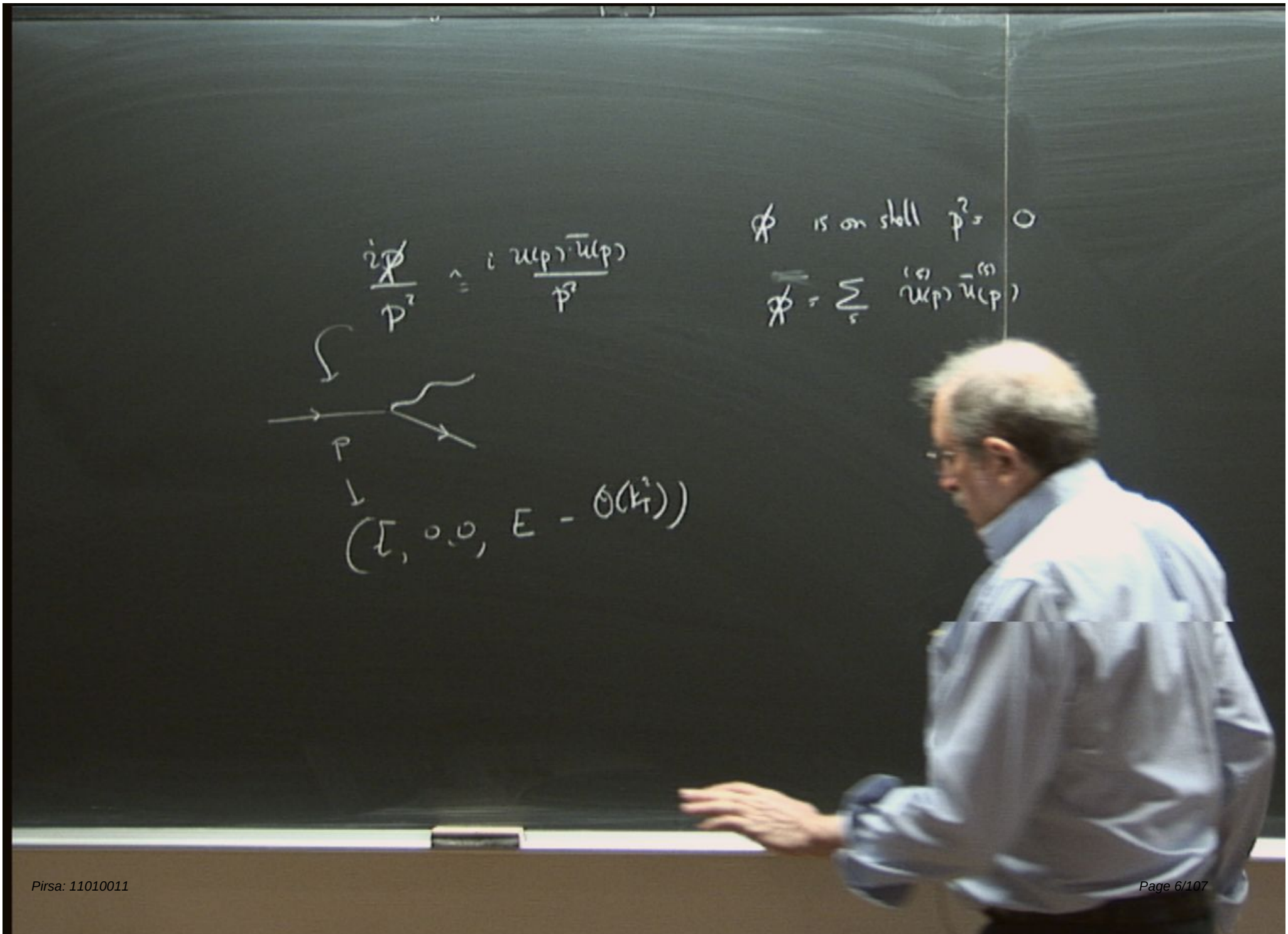
Abstract:

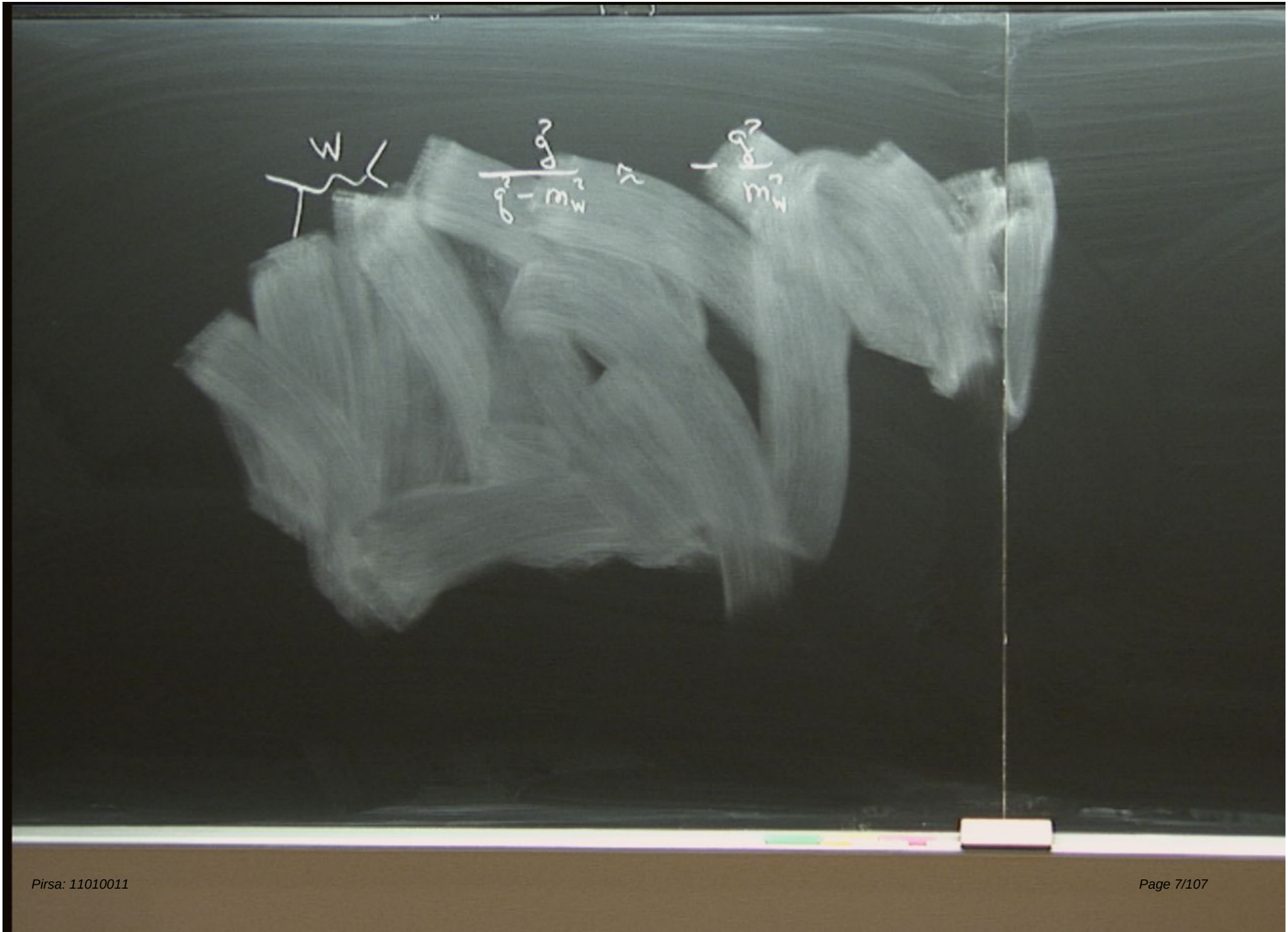


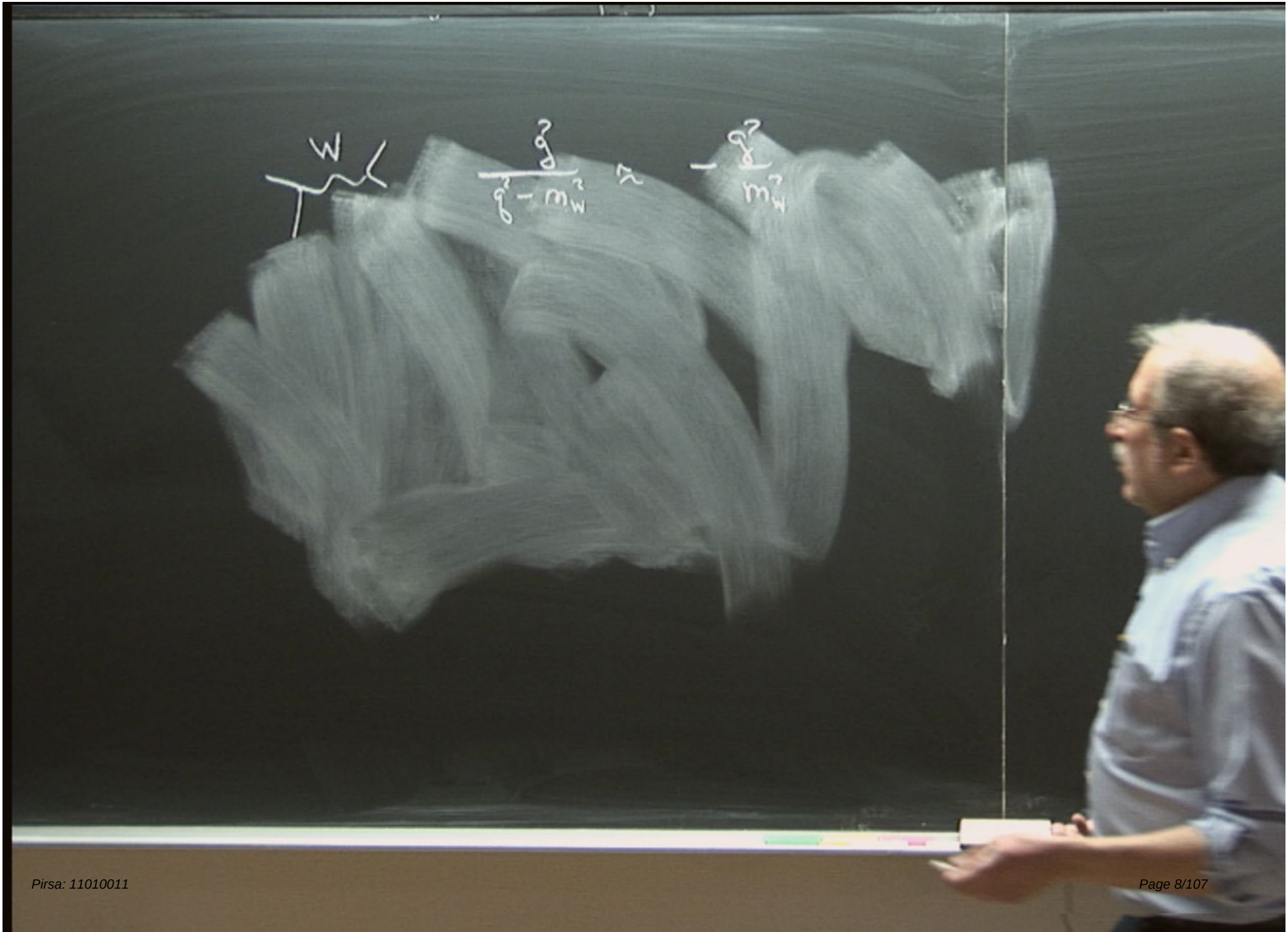

$\frac{i}{p^2}$
p

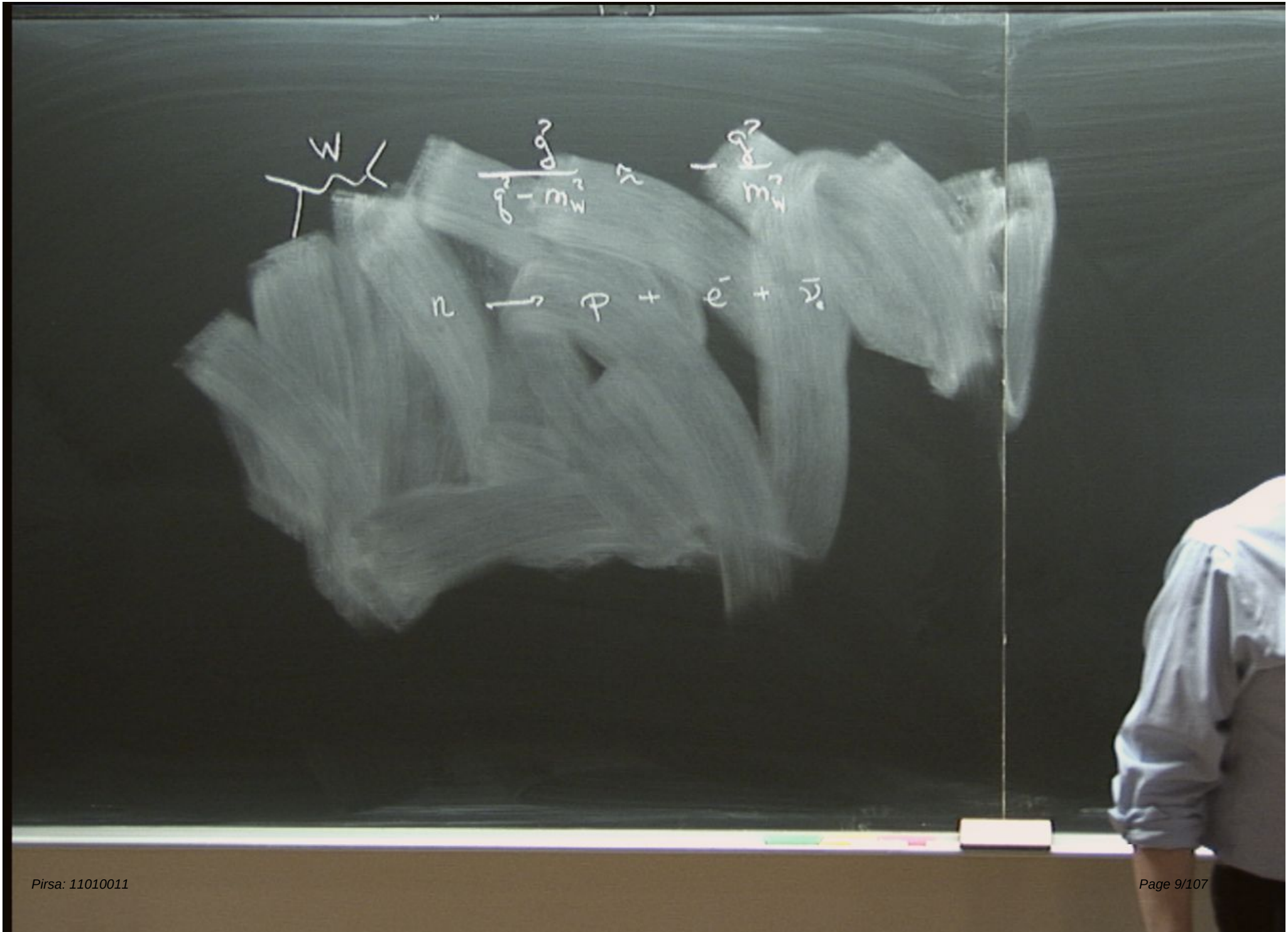

p

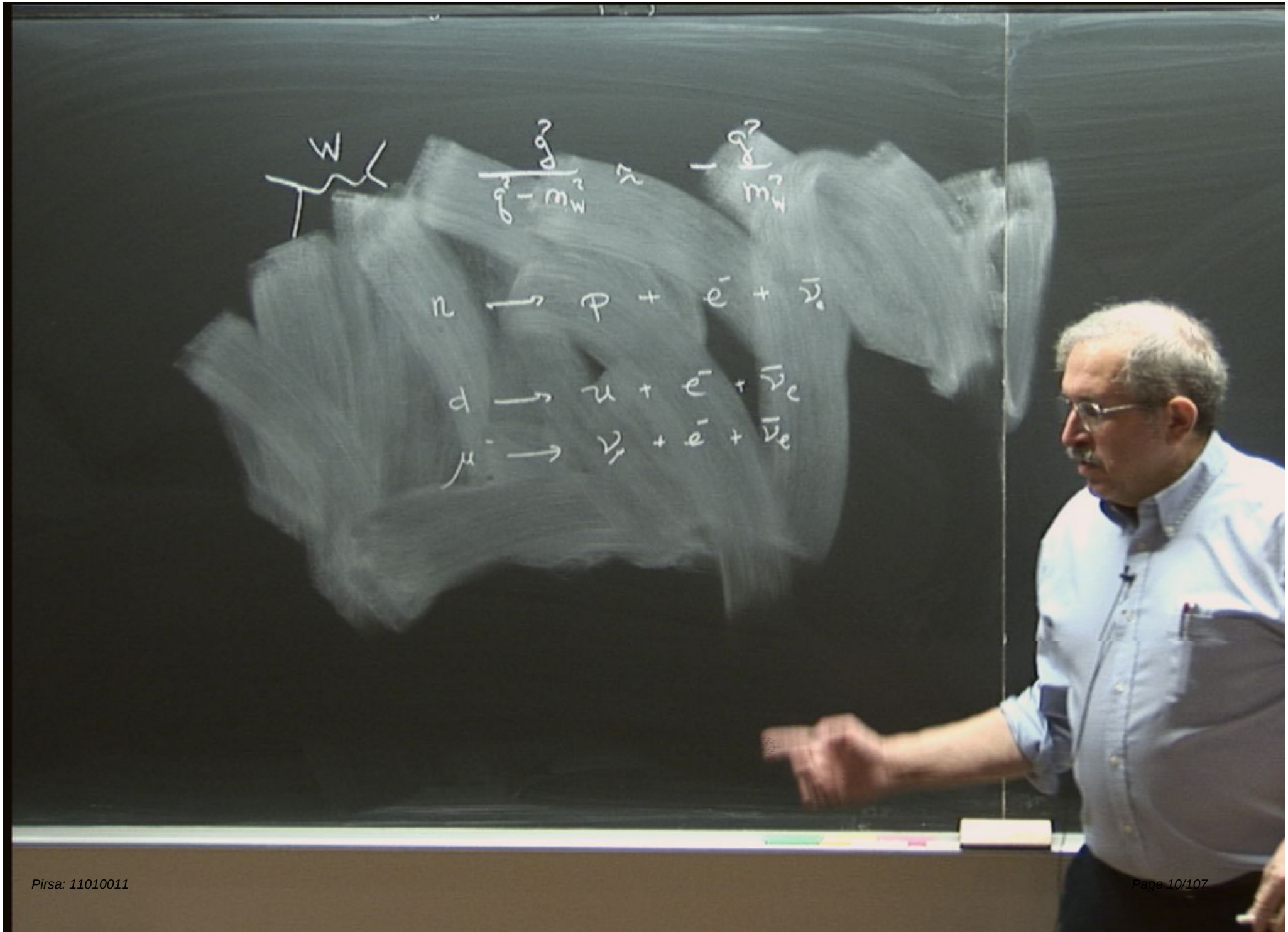

$\frac{i\not{p}}{p^2} \hat{=} i\frac{u(p)\cdot\bar{u}(p)}{p^2}$
$\not{p}$ is on shell $p^2 = 0$
$\not{p} = \sum_s$
p


$\frac{i\not{p}}{p^2} \hat{=} i\frac{u(p)\bar{u}(p)}{p^2}$
$\not{p}$ is on shell $p^2 = 0$
$\not{p} = \sum_s u^{(s)}(p)\bar{u}^{(s)}(p)$
p
$(E, 0, 0, E - O(k_T^2))$

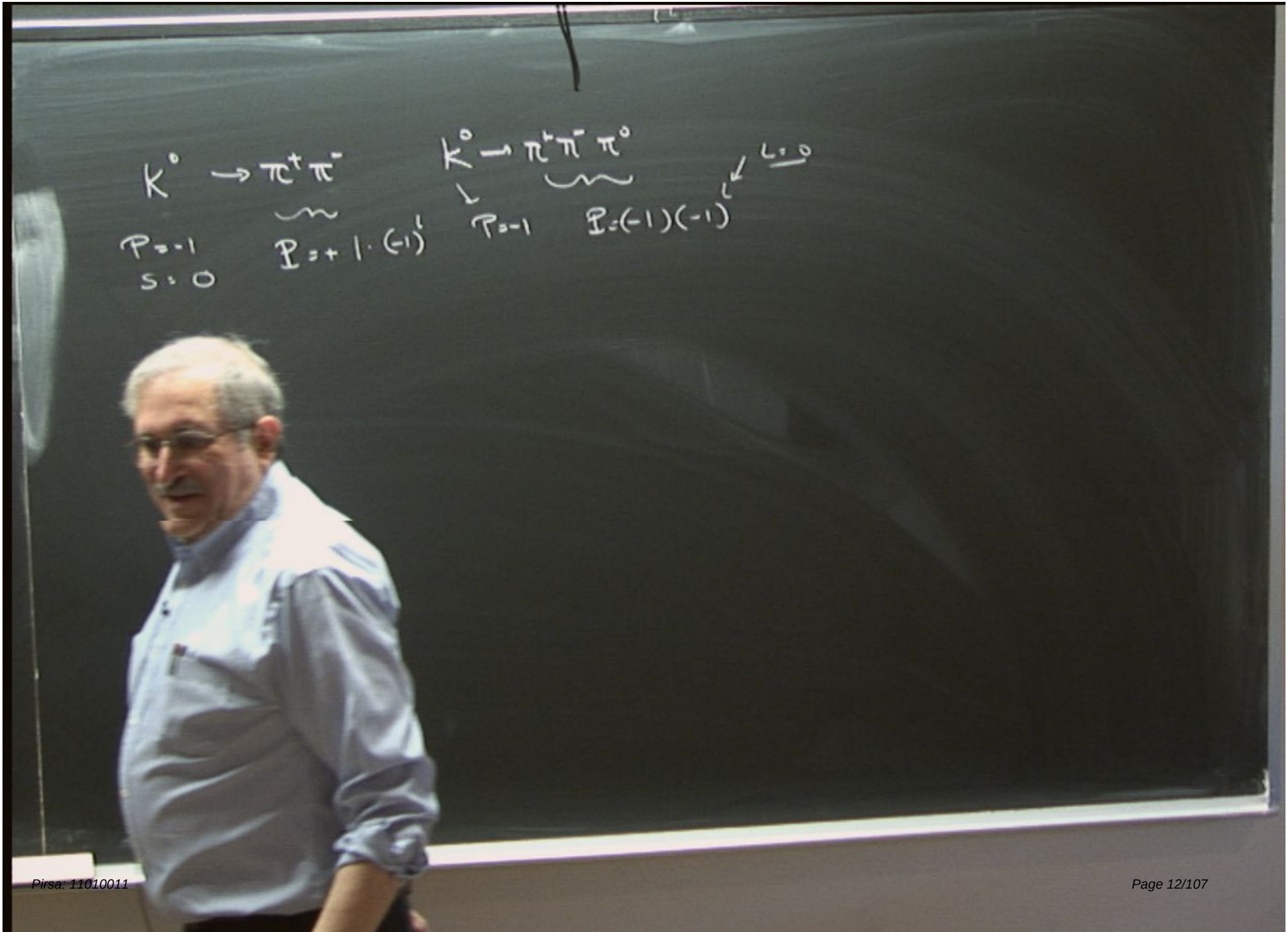

W
$\frac{g^2}{q^2 - m_W^2} \approx -\frac{g^2}{m_W^2}$

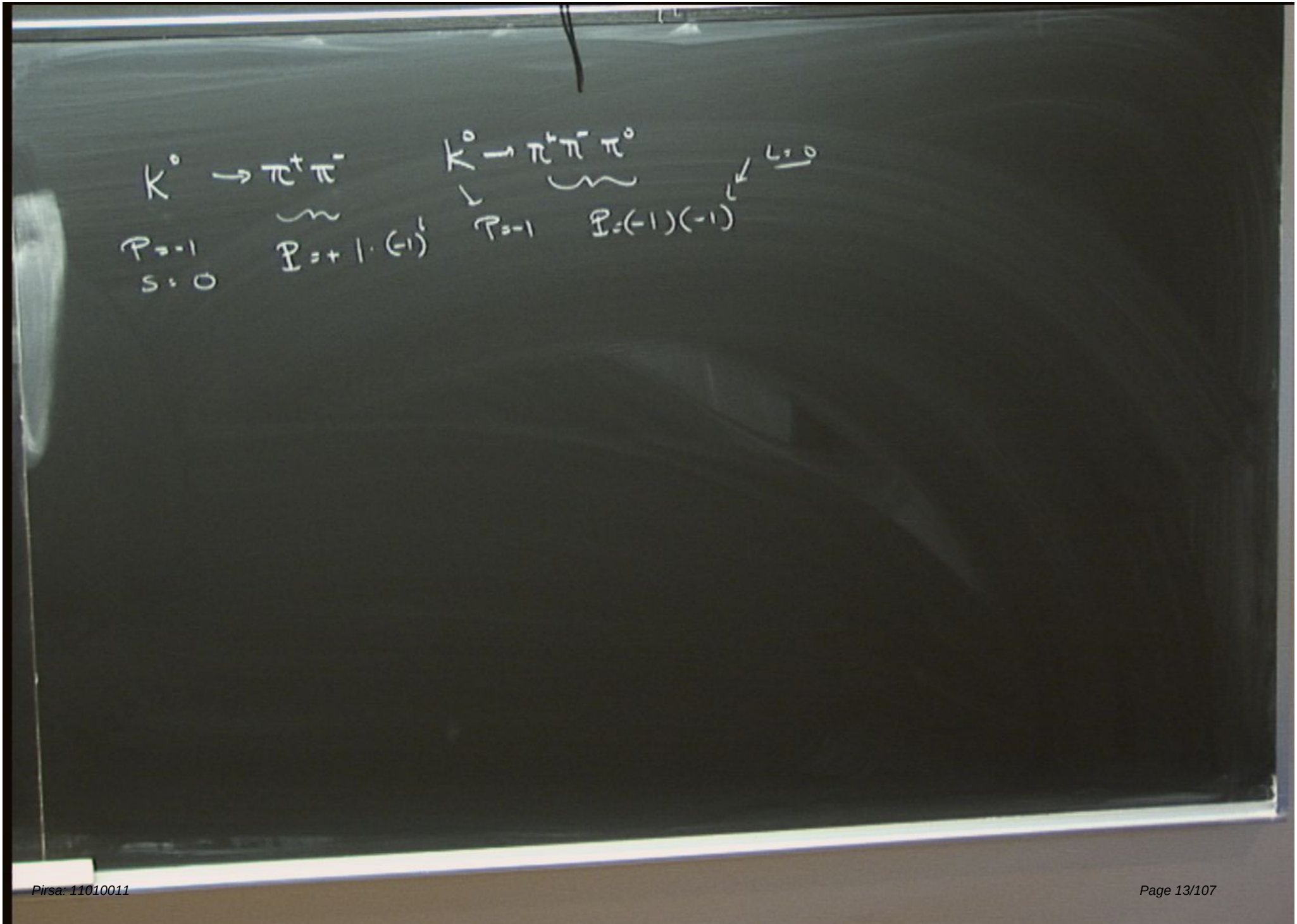

W
$\frac{g^2}{q^2 - m_W^2}$
$\approx$
$-\frac{g^2}{m_W^2}$


W
$\frac{g^2}{q^2 - m_W^2} \approx -\frac{g^2}{m_W^2}$
$n \longrightarrow p + e^- + \bar{\nu}_e$


W
$\frac{g^2}{q^2 - m_W^2} \simeq -\frac{g^2}{m_W^2}$
$n \longrightarrow p + e^- + \bar{\nu}_e$
$d \longrightarrow u + e^- + \bar{\nu}_e$
$\mu^- \longrightarrow \nu_\mu + e^- + \bar{\nu}_e$

$K^0 \to \pi^+\pi^-$ $K^0 \to \pi^+\pi^-\pi^0$


$K^0 \to \pi^+\pi^-$
$P=-1$
$S=0$
$P=+1\cdot(-1)^l$
$K^0 \to \pi^+\pi^-\pi^0$
$P=-1$
$P=(-1)(-1)^l$
$l=0$


$K^0 \to \pi^+\pi^-$
$P = -1$
$S = 0$
$P = +1 \cdot (-1)^1$
$K^0 \to \pi^+\pi^-\pi^0$
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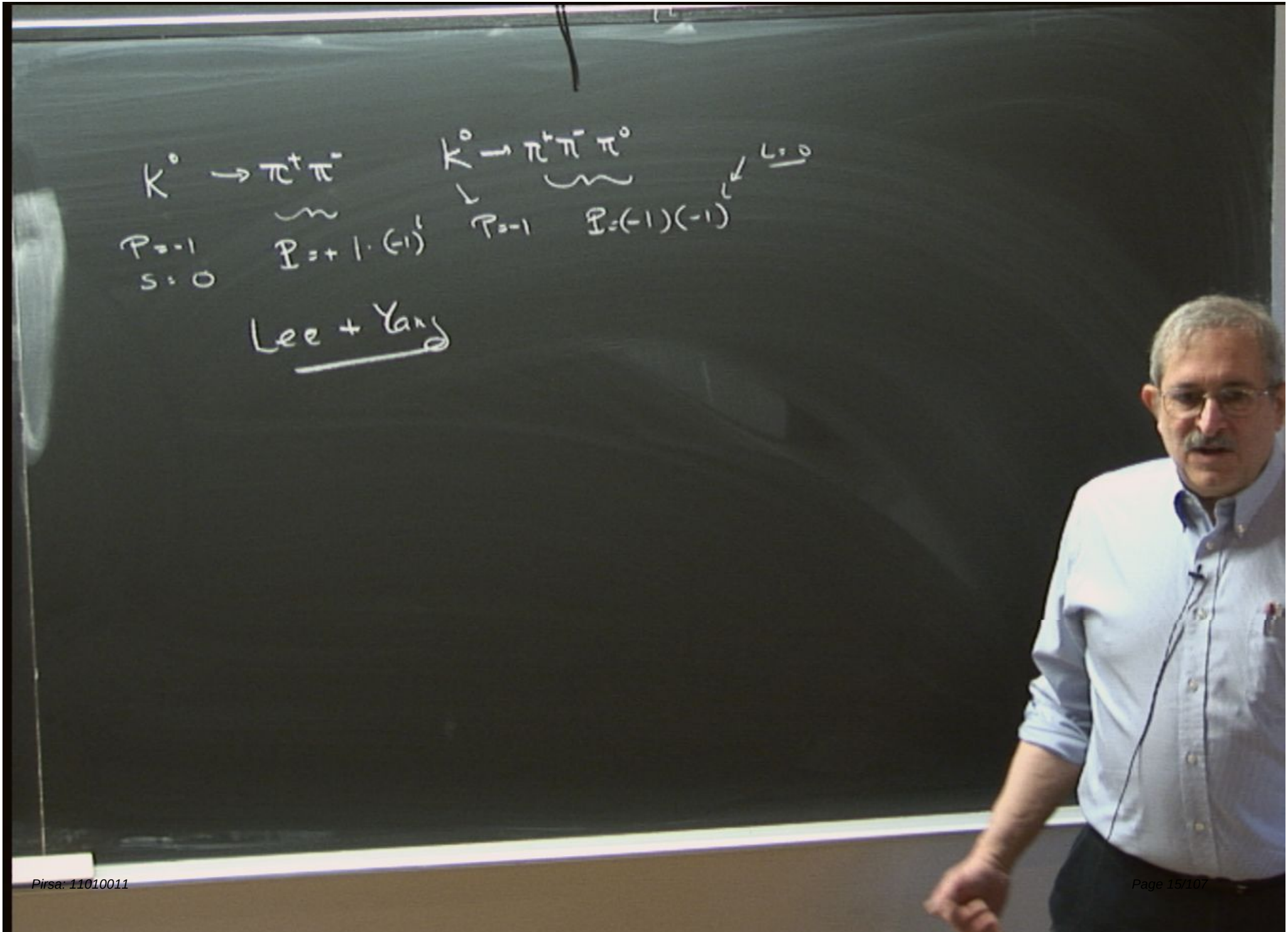
$P = (-1)(-1)^1$
$L = 0$

$K^0 \to \pi^+\pi^-$ $\quad$ $K^0 \to \pi^+\pi^-\pi^0$ $\quad$ $L=0$

$P=-1$ $\quad$ $P=+1\cdot(-1)^1$ $\quad$ $P=-1$ $\quad$ $P=(-1)(-1)^1$

$S=0$

Lee + Yang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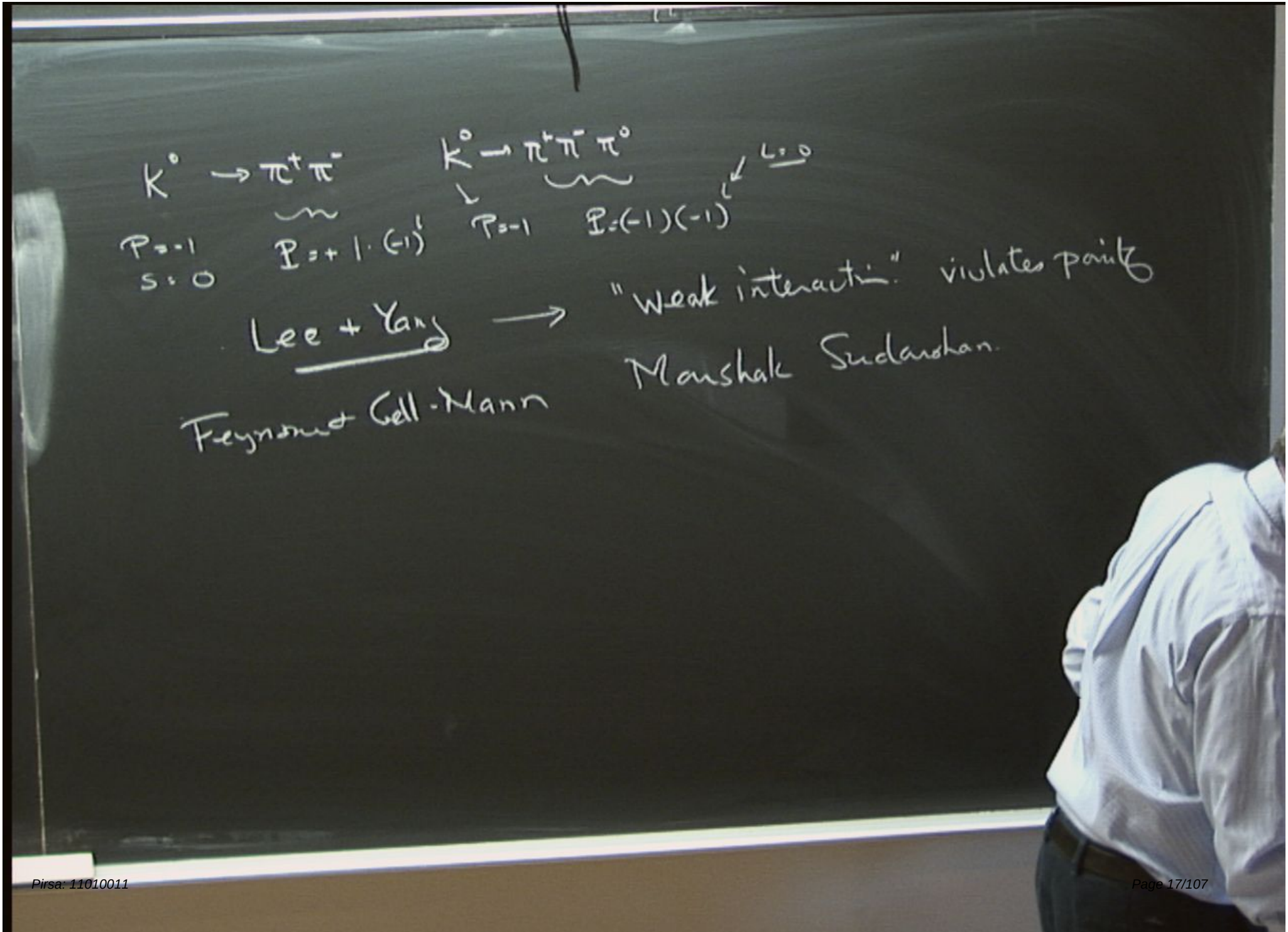
Lee + Yang

$K^0 \to \pi^+\pi^-$ $\quad$ $K^0 \to \pi^+\pi^-\pi^0$ $\quad$ $L=0$

$P=-1$ $\quad$ $P=+1\cdot(-1)^l$ $\quad$ $P=-1$ $\quad$ $P=(-1)(-1)^l$

$S=0$

Lee + Yang $\longrightarrow$ "weak interaction" violates parity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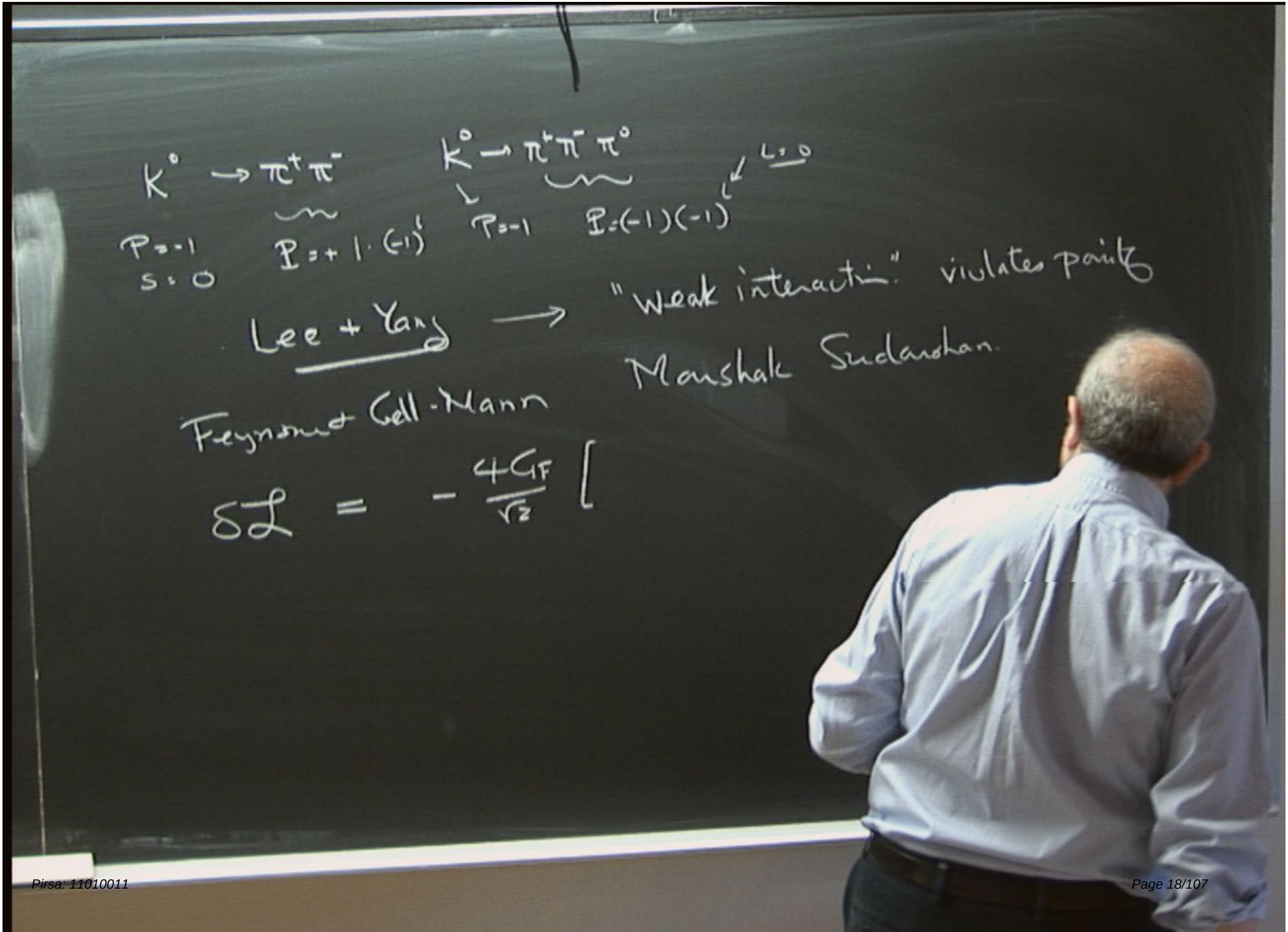
Lee + Yang
"weak interaction" violates parity
Feynman Gell-Mann
Marshak Sudarshan.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Marshak Sudarshan
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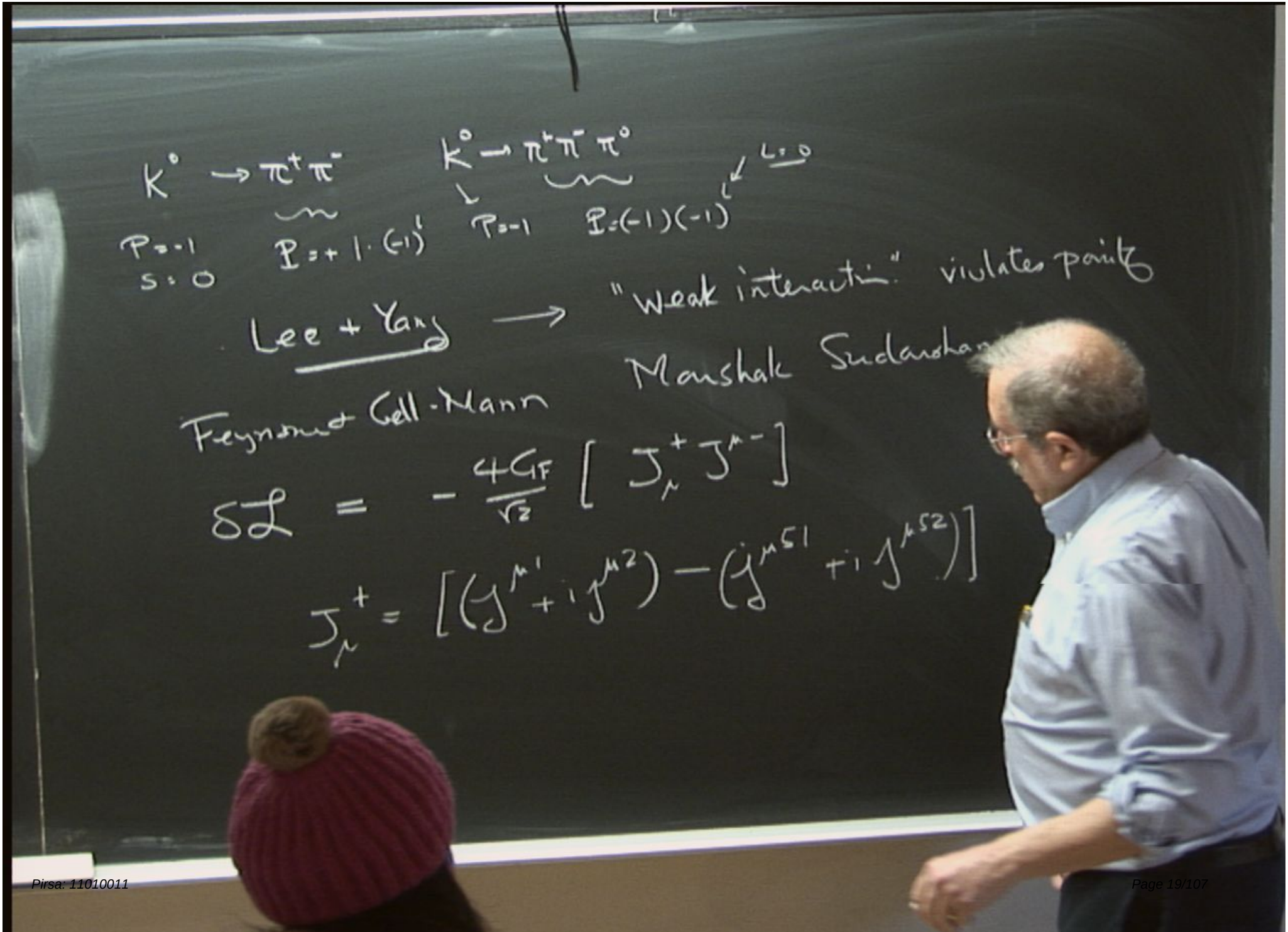
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}[$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Lee + Yang
"Weak interaction" violates parity
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$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}[J_\mu^+ J^{\mu-}]$
$J_\mu^+ = [(j^{\mu 1} + i j^{\mu 2}) - (j^{\mu 51} + i j^{\mu 52})]$

$K^0 \to \pi^+\pi^-$ $\quad$ $K^0 \to \pi^+\pi^-\pi^0$ $\quad$ $L=0$

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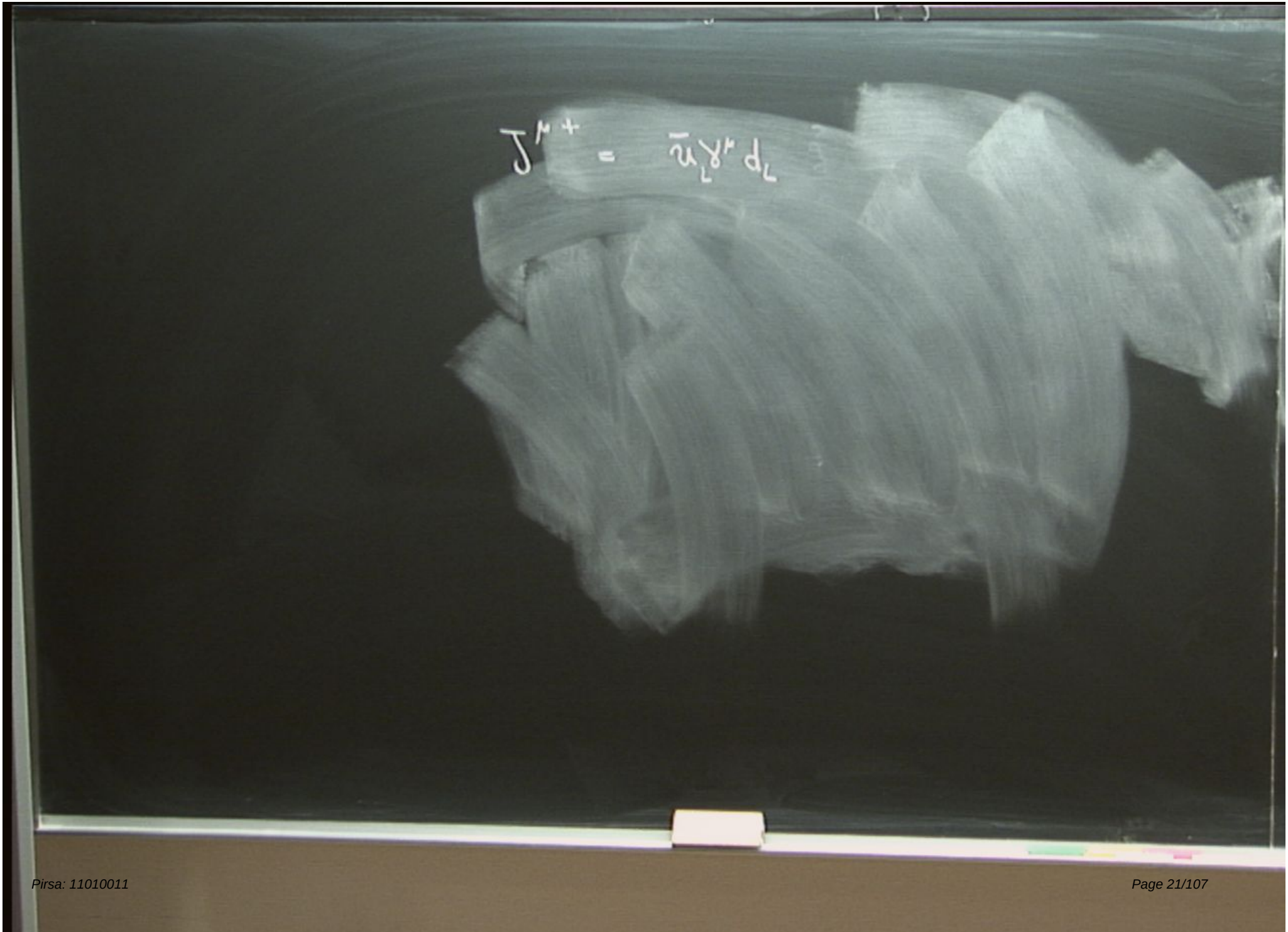
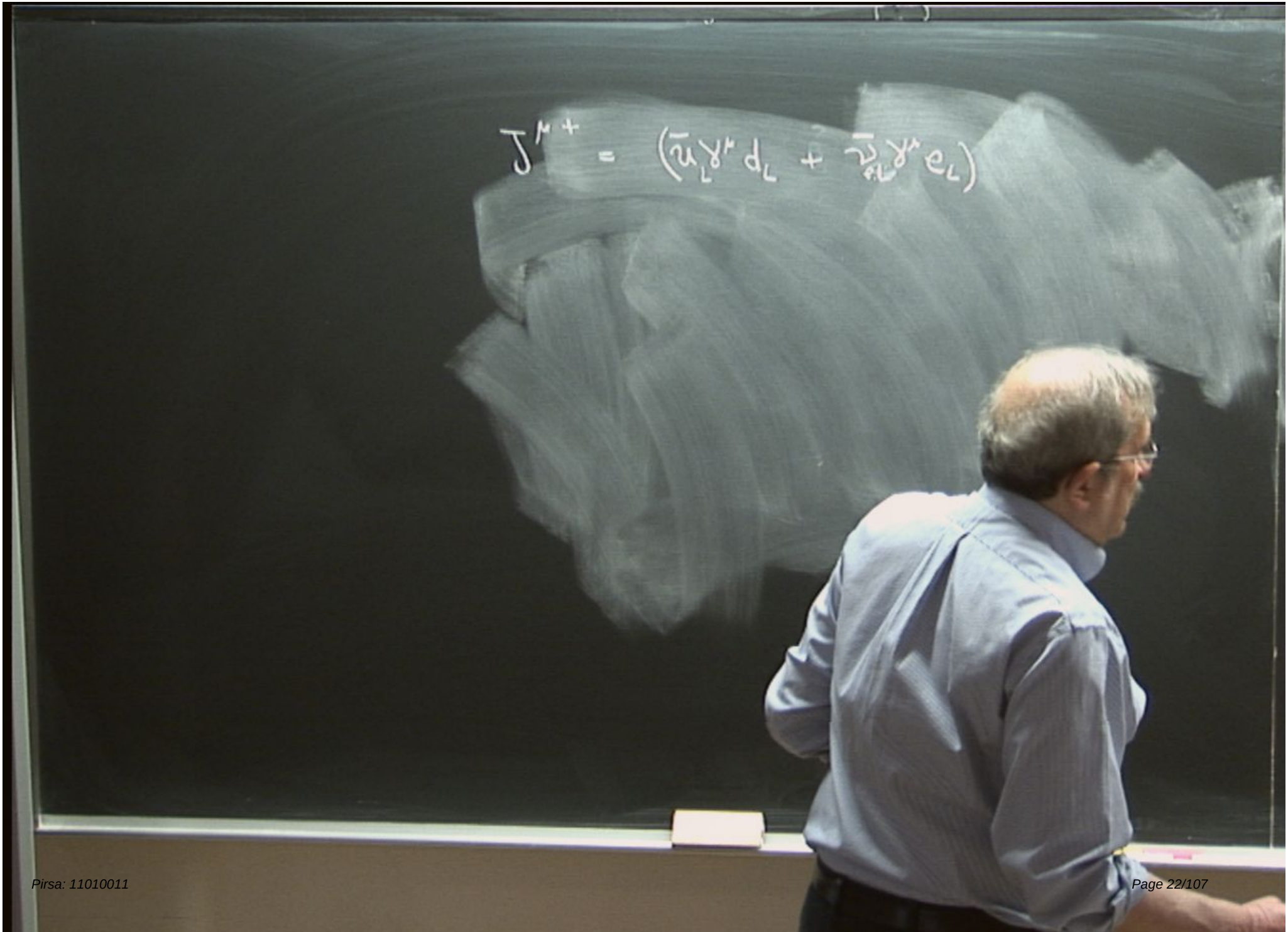
Feynman Gell-Mann $\quad$ Marshak Sudarshan

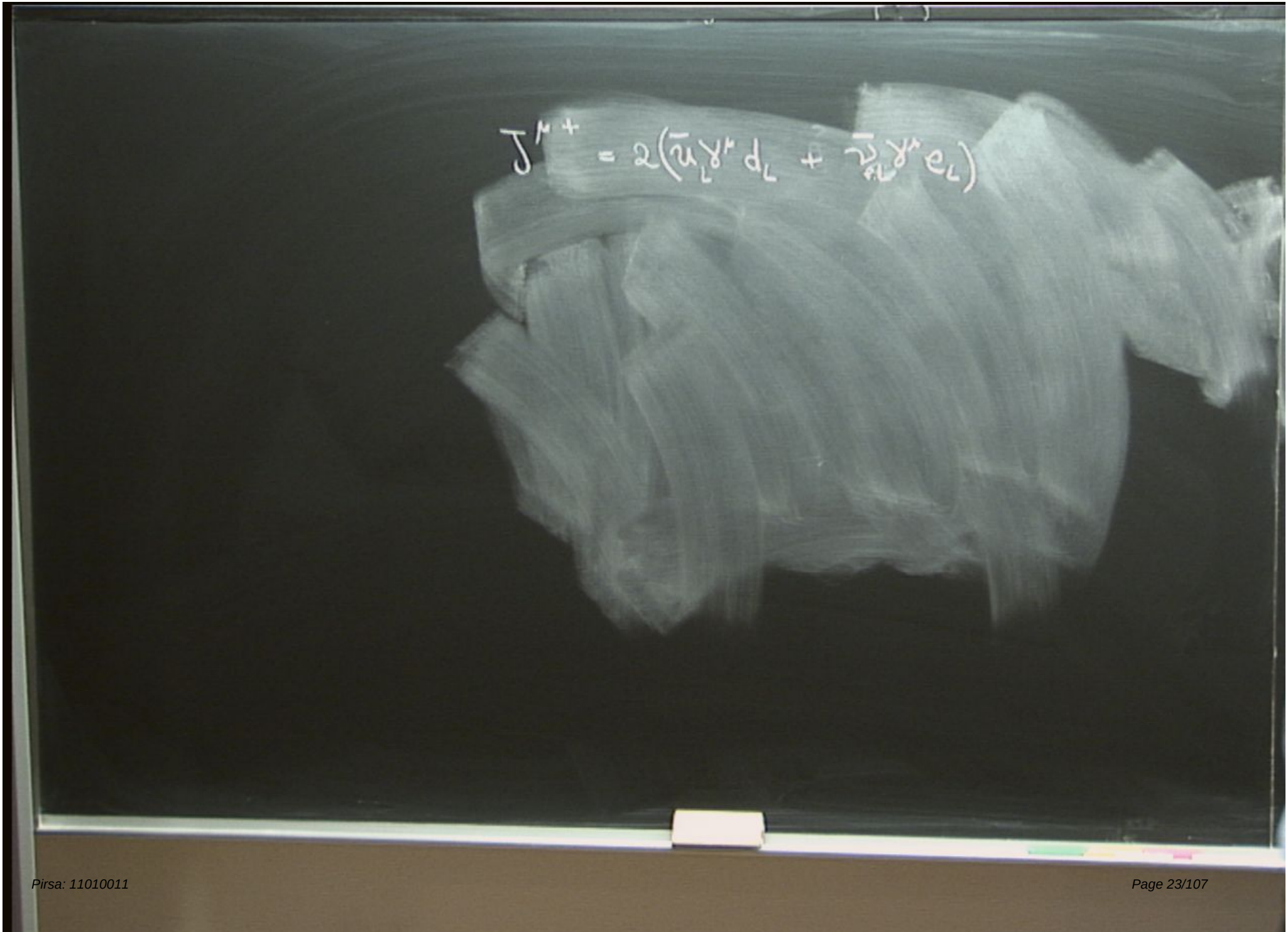
$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[J_\mu^+ J^{\mu-}\right]$$

$$J_\mu^+ = \left[(j^{\mu 1} + i j^{\mu 2}) - (j^{\mu 51} + i j^{\mu 52})\right]$$

$V - A$


$J^{\mu +} = \bar{u} \gamma^{\mu} d$


$J^{\mu +} = (\bar{\nu}_L \gamma^\mu e_L + \bar{u}_L \gamma^\mu d_L)$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

$K^0 \to \pi^+\pi^-$ $\quad$ $K^0 \to \pi^+\pi^-\pi^0$ $\quad$ $L=0$

$P=-1$ $\quad$ $P=+1\cdot(-1)^1$ $\quad$ $P=-1$ $\quad$ $P=(-1)(-1)^1$

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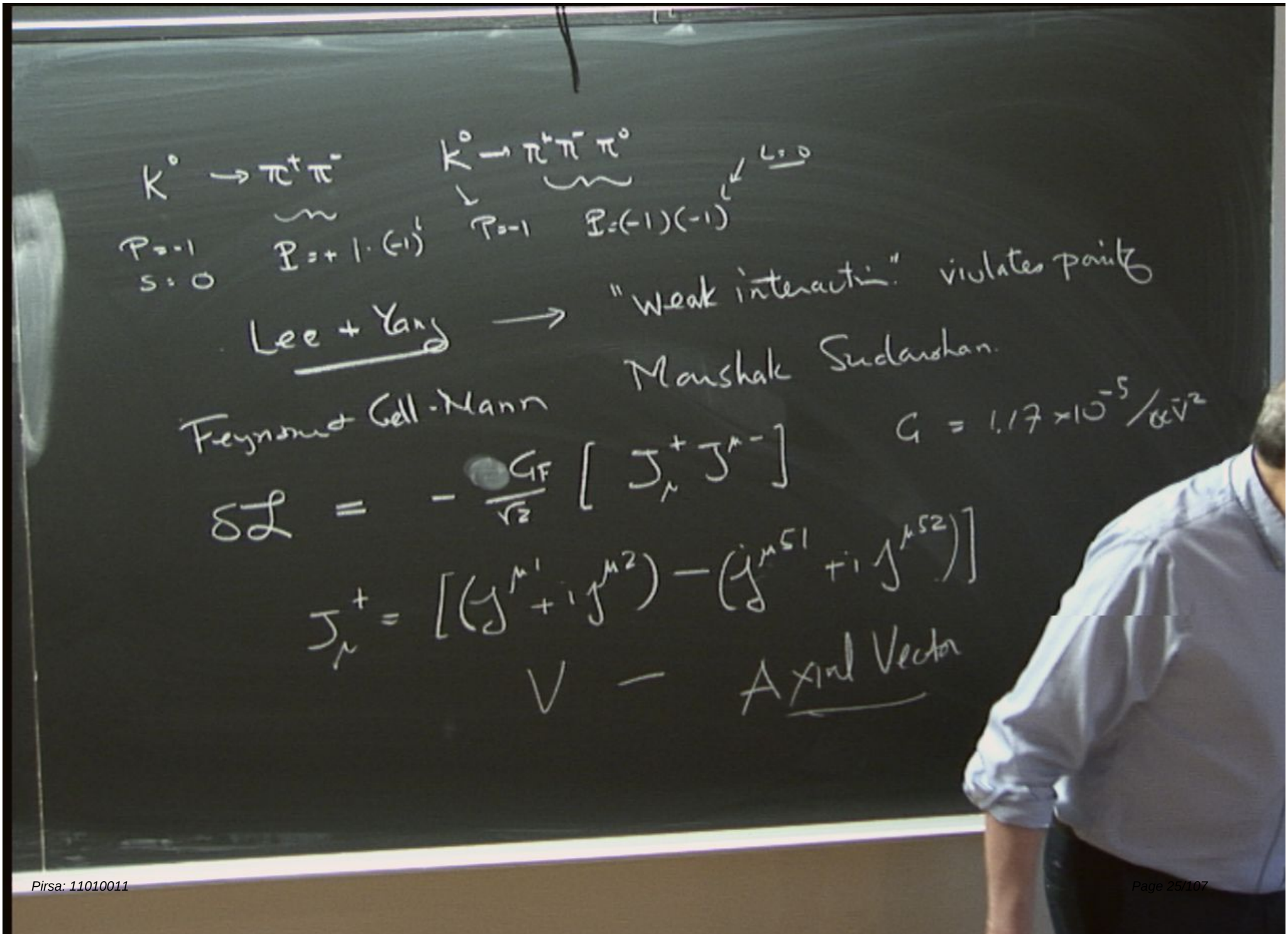
Lee + Yang $\longrightarrow$ "Weak interaction" violates parity

Feynman Gell-Mann $\quad$ Marshak Sudarshan.

$$\delta\mathcal{L} = -\frac{G_F}{\sqrt{2}}\left[J_\mu^+ J^{\mu-}\right]$$

$$J_\mu^+ = \left[(j^{\mu 1} + i j^{\mu 2}) - (j^{\mu 51} + i j^{\mu 52})\right]$$

$V - A$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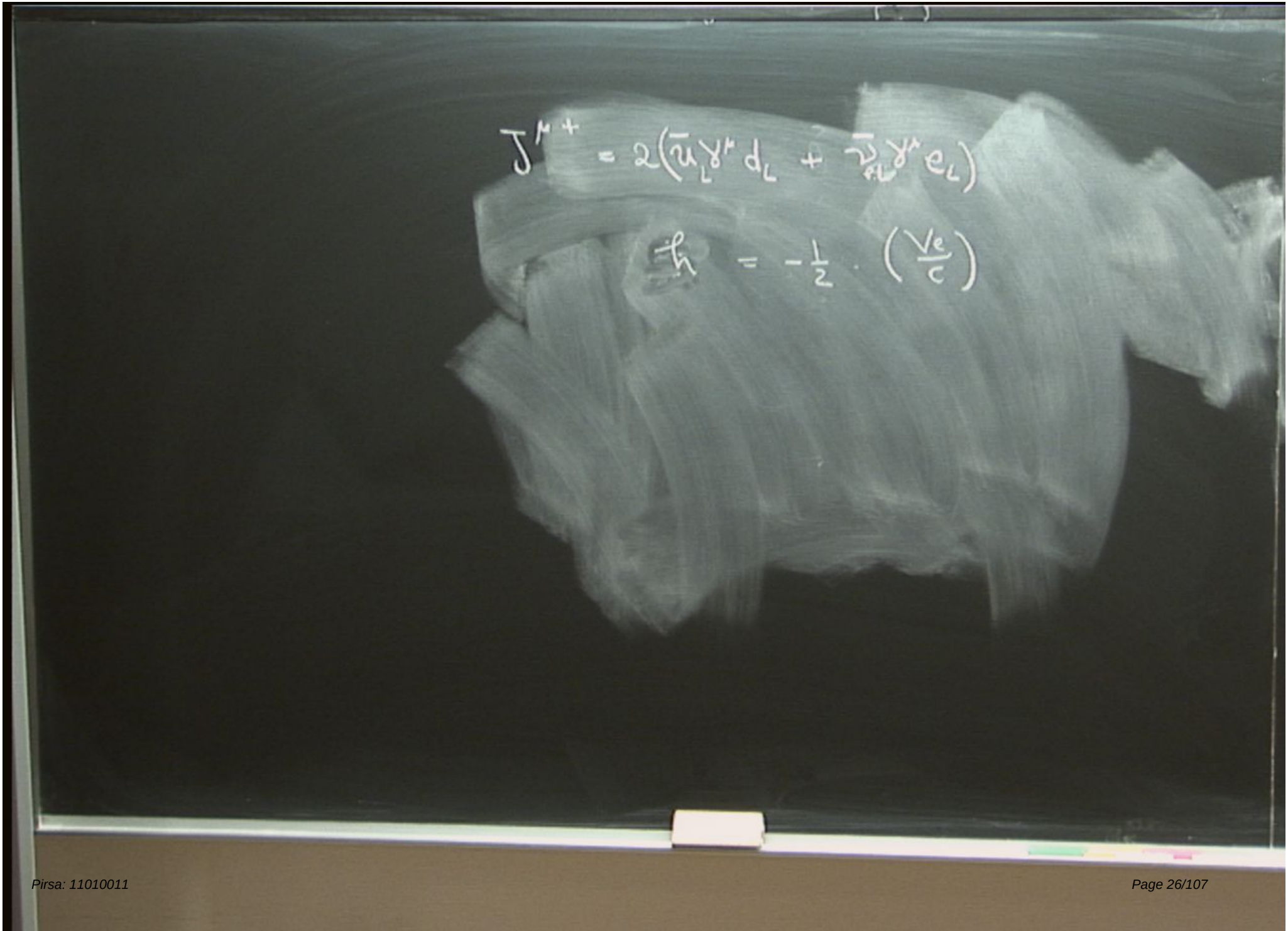
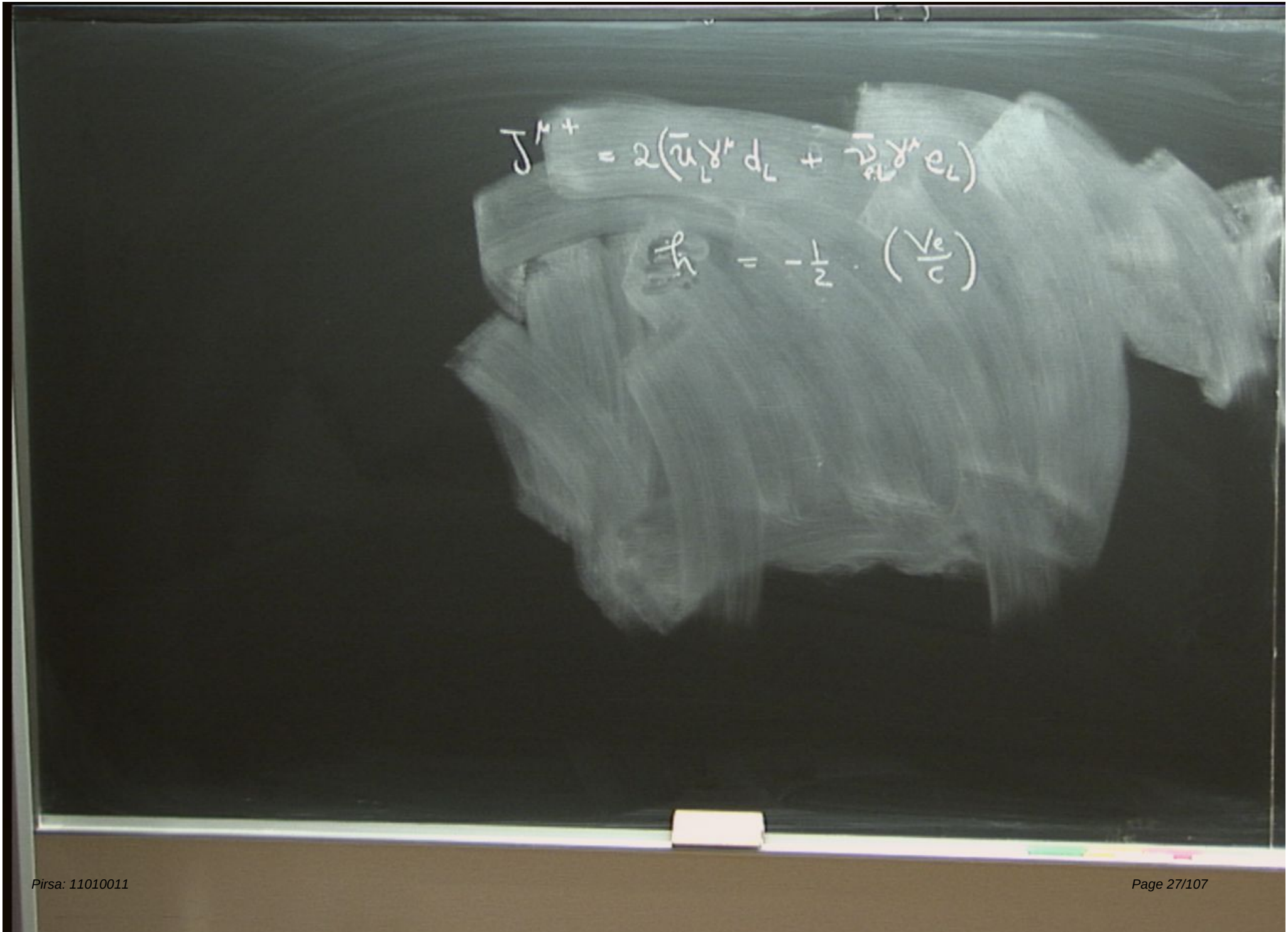
Lee + Yang
"Weak interaction" violates parity
Feynman Gell-Mann
Marshak Sudarshan
$G = 1.17\times10^{-5}/\text{GeV}^2$
$\delta\mathcal{L} = -\frac{G_F}{\sqrt{2}}[J_\mu^+ J^{\mu-}]$
$J_\mu^+ = [(j^{\mu1}+ij^{\mu2})-(j^{\mu51}+ij^{\mu52})]$
V — A and Vector


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$-h = -\frac{1}{2} \cdot \left(\frac{V_e}{c}\right)$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$-\mathcal{L}_{int} = -\frac{1}{2} \cdot \left(\frac{V_e}{c}\right)$

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

$h = -\frac{1}{2} \cdot \left(\frac{v_e}{c}\right)$

K^0

$P = -1$

$S = 0$

Fe

δ

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

$h = -\frac{1}{2} \cdot \left(\frac{v_e}{c}\right)$

K^0

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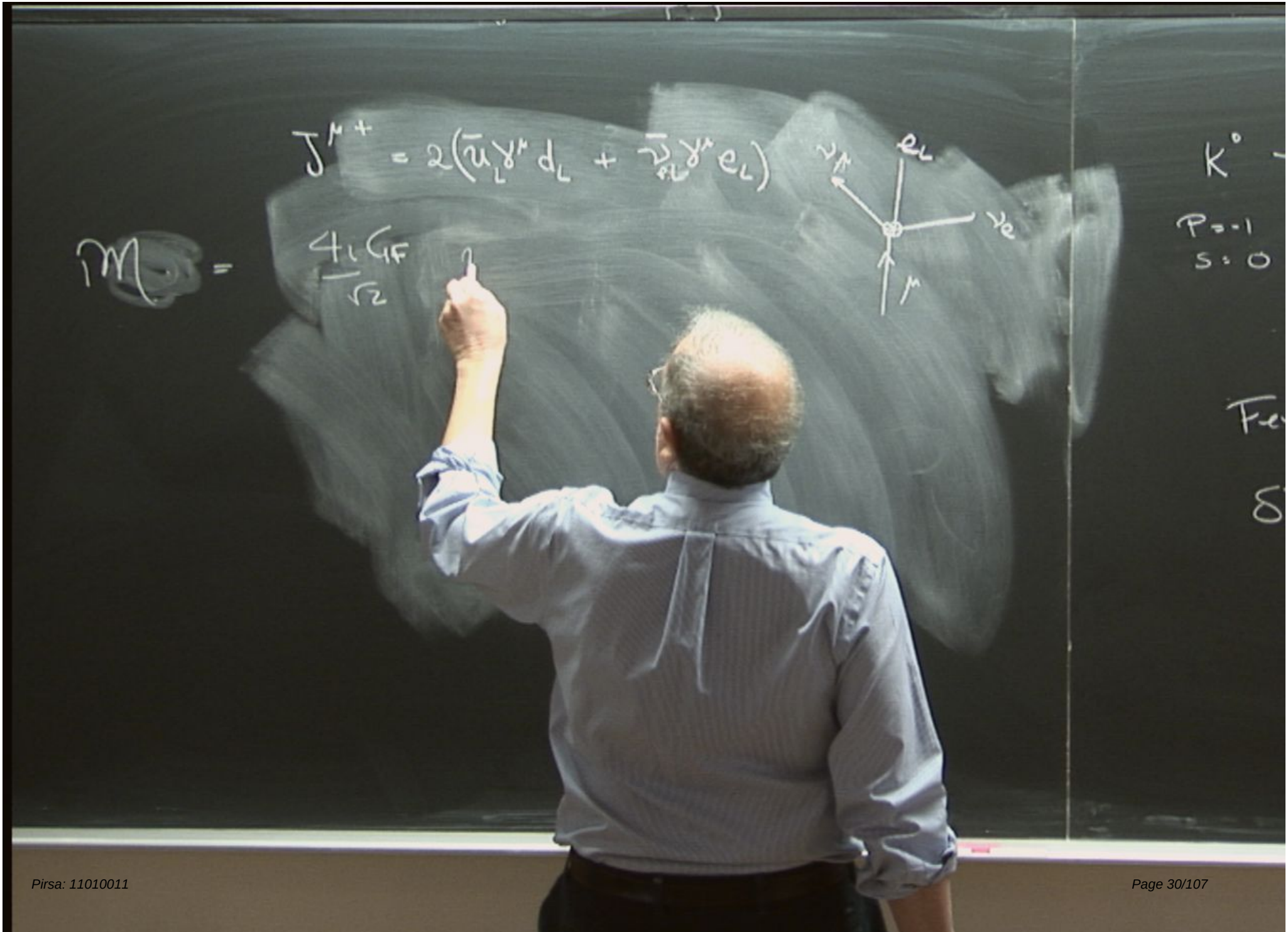
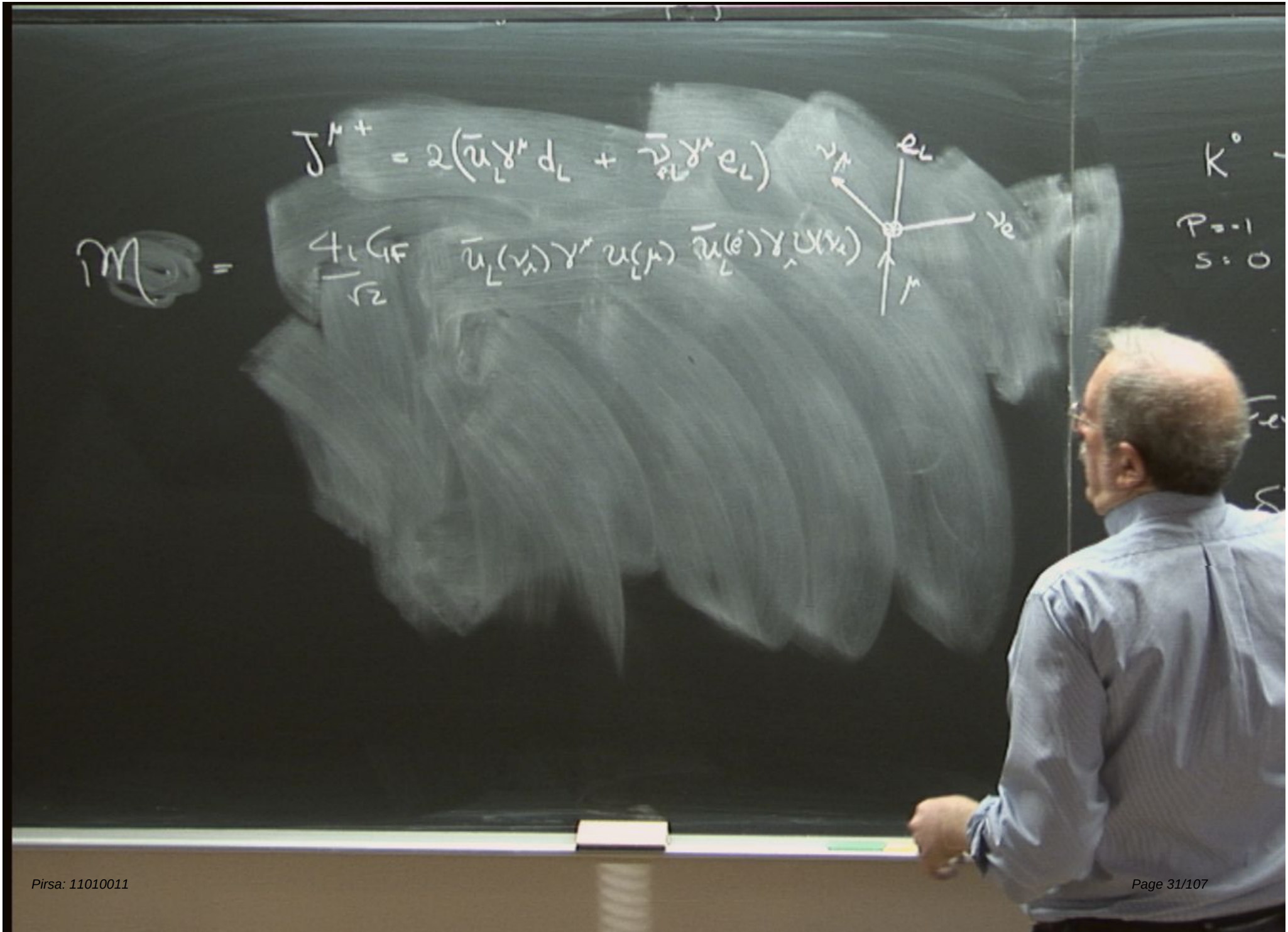
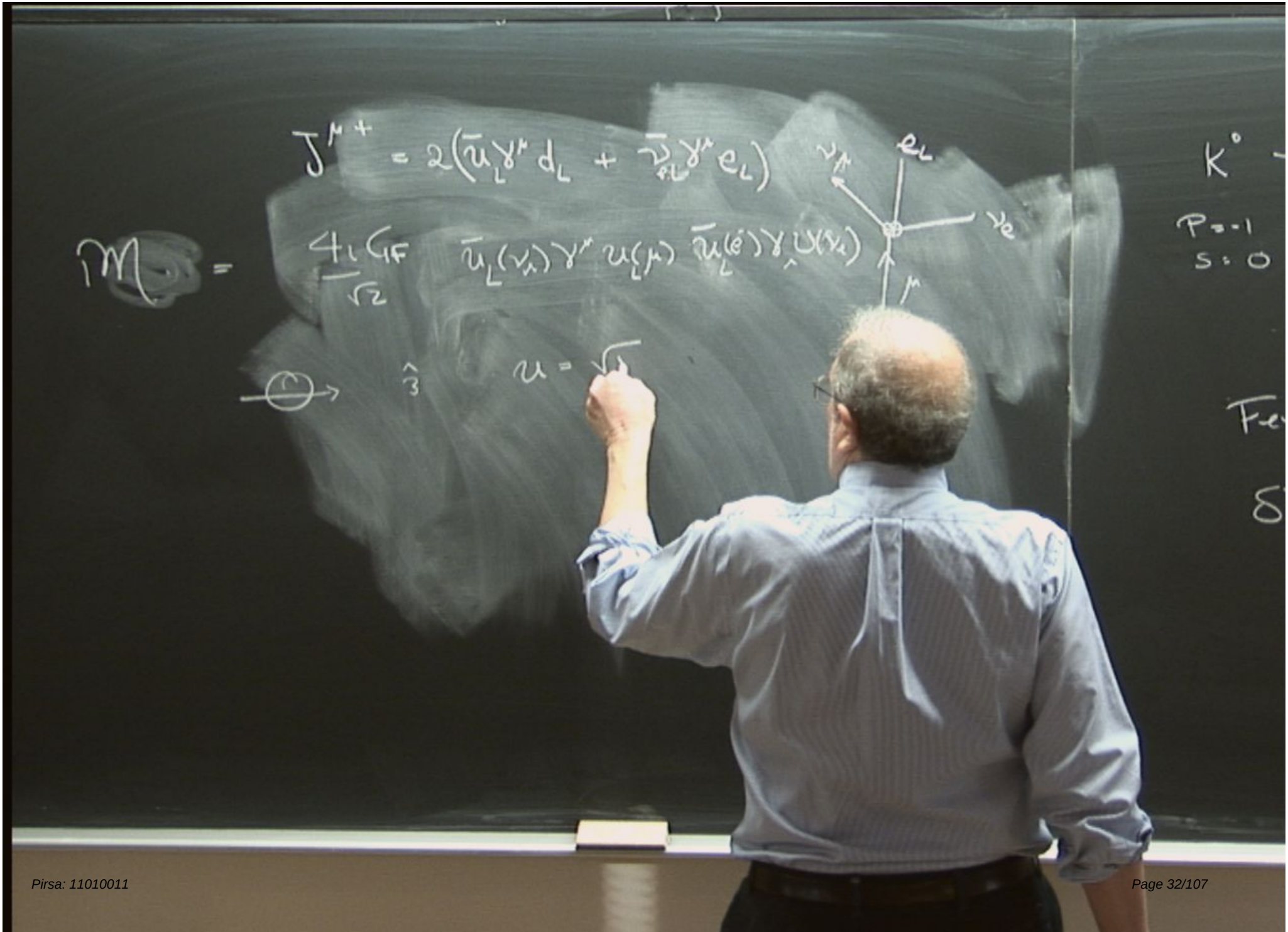
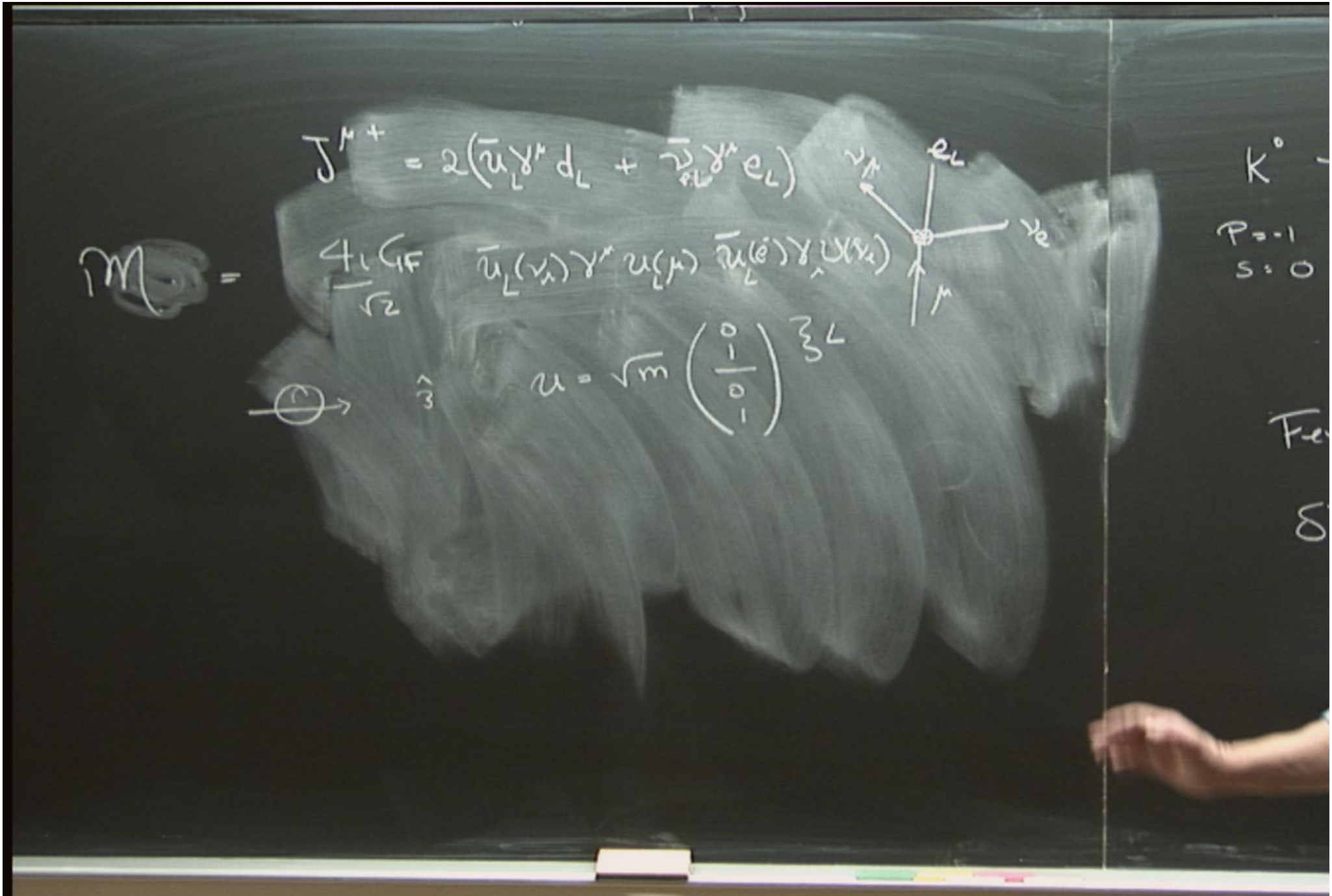
Fe

δ

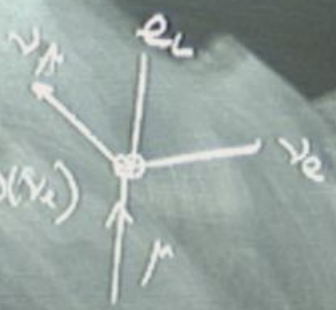

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$\mathcal{M} = \frac{4 i G_F}{\sqrt{2}}$
ν_μ
e_L
ν_e
μ
K^0
$P = -1$
$S = 0$


$J^{\mu +} = 2(\bar{\nu}_e \gamma^\mu \frac{1}{2}(1-\gamma^5) e + \bar{p} \gamma^\mu \frac{1}{2}(1-\gamma^5) n)$
$\mathcal{M} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma^\mu \frac{1}{2}(1-\gamma^5) \mu][\bar{p} \gamma_\mu \frac{1}{2}(1-\gamma^5) n]$
ν_μ
e
ν_e
μ
K^0
$P = -1$
$S = 0$


$J^{\mu +} = 2(\bar{\nu}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)e + \bar{\nu}\gamma^{\mu}\frac{1}{2}(1-\gamma^5)\mu)$
ν_μ
e
ν_e
μ
K^0
$P=-1$
$S=0$


$J^{\mu +} = 2(\bar{\nu}\gamma^\mu d_L + \bar{u}\gamma^\mu e_L)$
ν_μ
e_L
ν_e
μ
K^0
$P=-1$
$S=0$
$\hat{z}$
$u = \sqrt{m}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}\xi$

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$



$$\mathcal{M} = \frac{4 i G_F}{\sqrt{2}} \; \bar{u}_L(\nu_\mu) \gamma^\mu u_L(\mu) \; \bar{u}_L(e^-) \gamma_\mu u(\nu_e)$$

$$\hat{3} \qquad u = \sqrt{m} \begin{pmatrix} 0 \\ 1 \\ \hline 0 \\ 1 \end{pmatrix} \xi^L$$

K^0 –

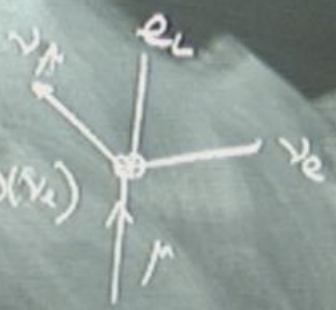
$P = -1$

$S = 0$

Fe

δ

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$



$$\mathcal{M} = \frac{4iG_F}{\sqrt{2}} \; \bar{u}_L(\nu_\mu)\gamma^\mu u_L(\mu) \; \bar{u}_L(e)\gamma_\mu u(\nu_e)$$

$\hat{3}$

$$u = \sqrt{m}\begin{pmatrix} 0 \\ 1 \\ \hline 0 \\ 1 \end{pmatrix} \xi^L$$

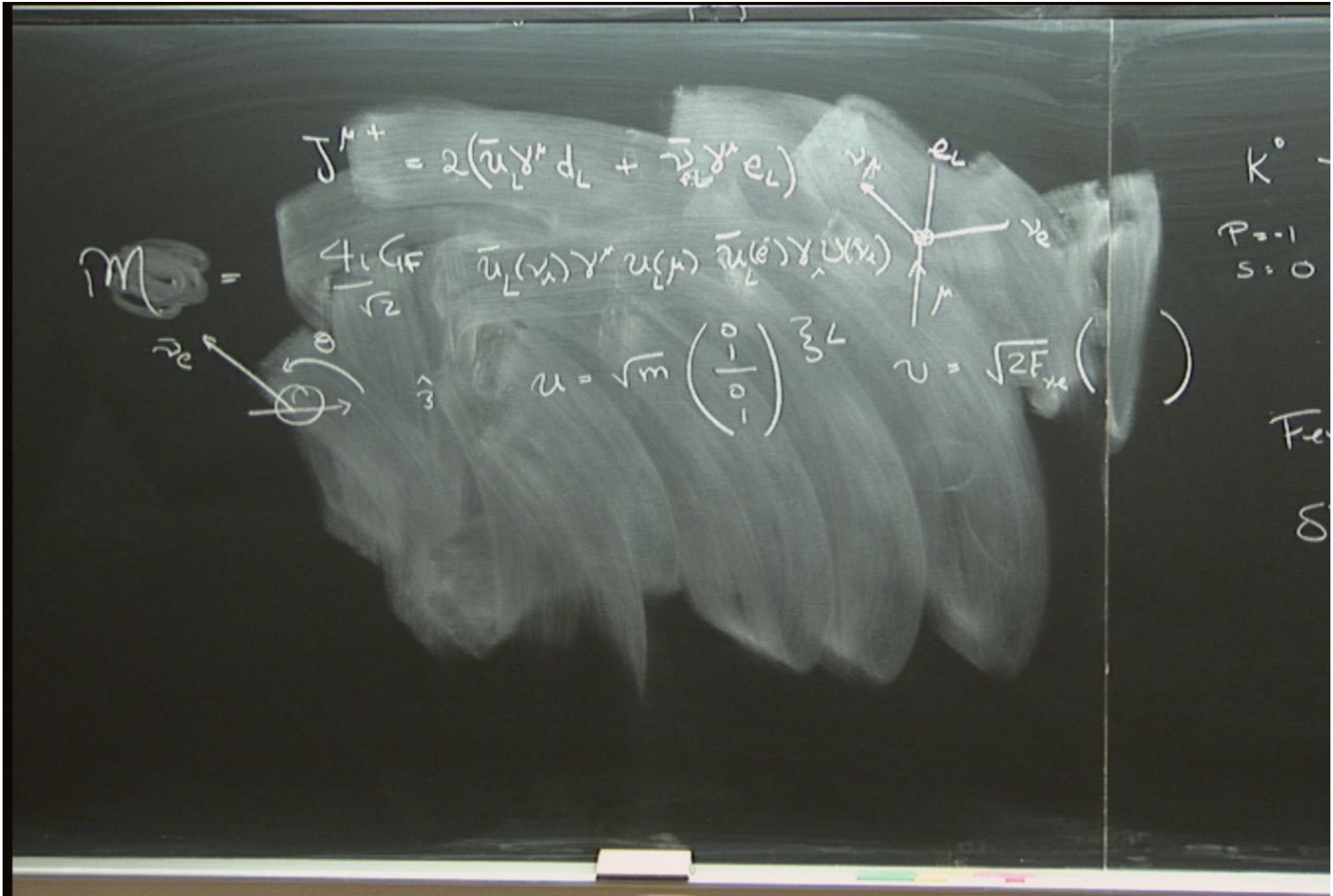
K^0 –

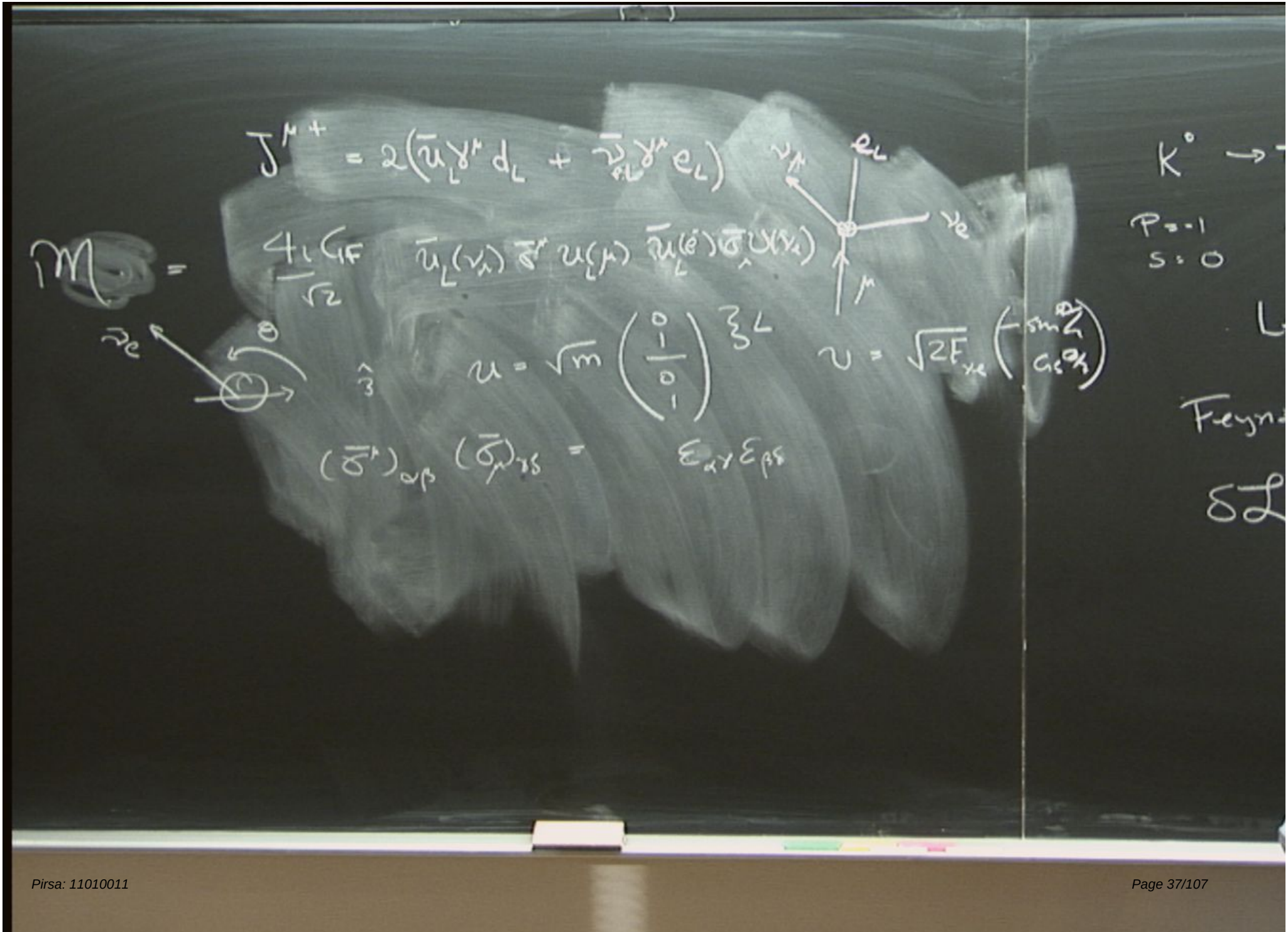
$P = -1$

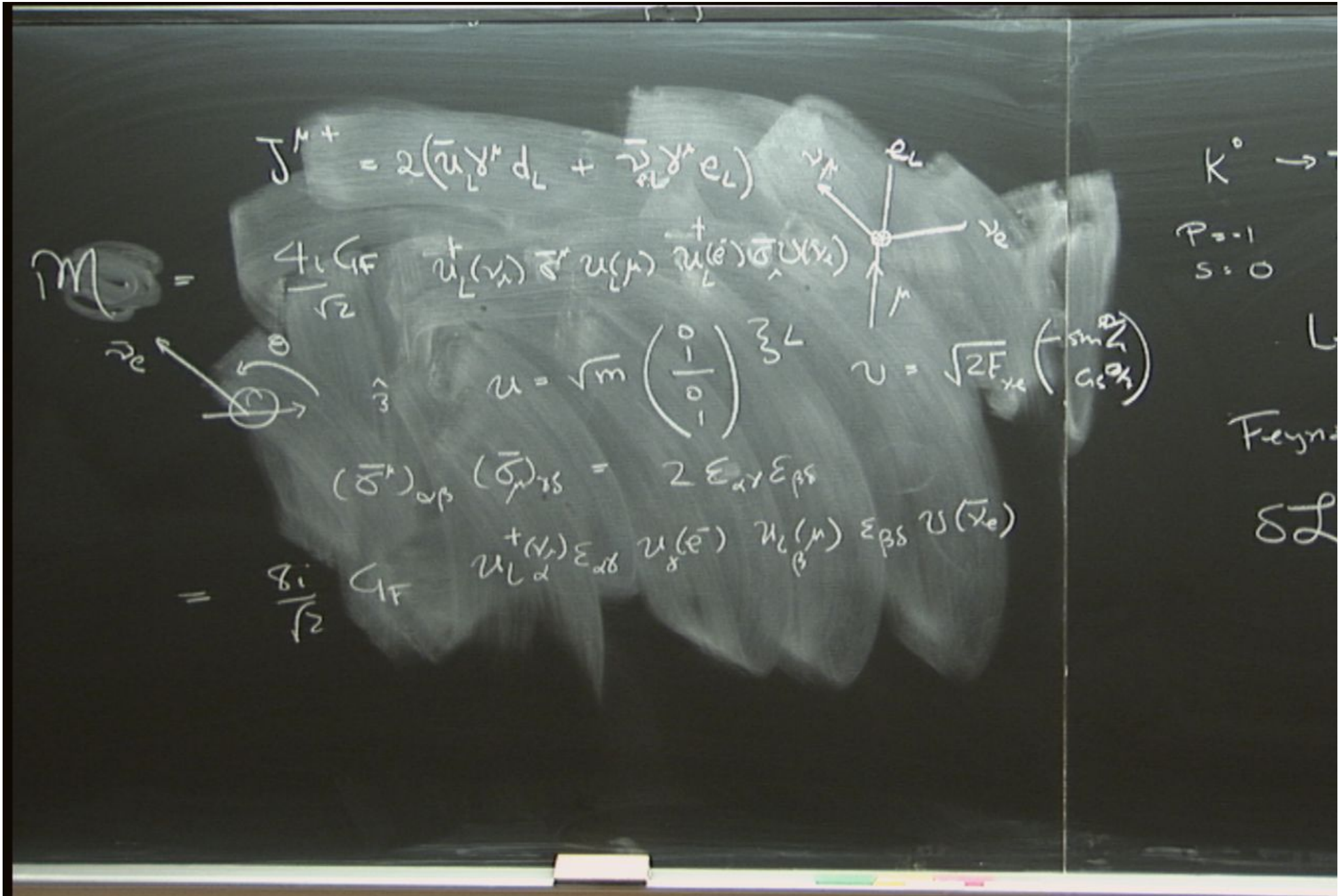
$S = 0$

Fe

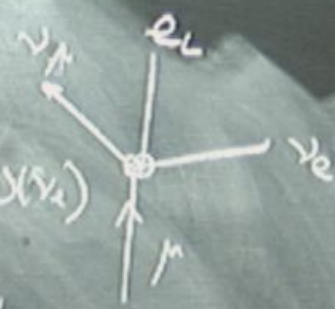
δ


$J^{\mu +} = 2(\bar{\nu}\gamma^\mu d_L + \bar{u}\gamma^\mu e_L)$
$\frac{G_F}{\sqrt{2}}$
$\hat{z}$
θ
ν_e
e_L
ν_μ
μ
K^0
$P=-1$
$S=0$


$J^{\mu +} = 2(\bar{\nu}_e \gamma^\mu \frac{1}{2}(1-\gamma^5) e_L + \bar{\nu}_\mu \gamma^\mu \frac{1}{2}(1-\gamma^5) \mu_L)$
ν_μ
e_L
ν_e
μ
$K^\circ \rightarrow$
$P = -1$
$S = 0$
ν_e
θ
$\hat{z}$
$u = \sqrt{m} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \xi_L$
$v = \sqrt{2E_{\nu e}} \begin{pmatrix} -\sin\frac{\theta}{2} \\ \cos\frac{\theta}{2} \end{pmatrix}$
Feyn
$\delta\Omega$


$J^{\mu +} = 2(\bar{u}\gamma^\mu d_L + \bar{\nu}_e \gamma^\mu e_L)$
$K^\circ \to$
$P = -1$
$S = 0$
$i\mathcal{M} =$
$\frac{4i}{\sqrt{2}} G_F$
θ
$\hat{z}$
$u = \sqrt{m}\begin{pmatrix} \xi \\ \xi \end{pmatrix}$
$v = \sqrt{2E_\pi}\begin{pmatrix} -\sin\frac{\theta_K}{2}\chi \\ \cos\frac{\theta_K}{2}\chi \end{pmatrix}$
$(\bar{\sigma}^\mu)_{\alpha\beta}\,(\bar{\sigma}_\mu)^{\delta\kappa} = 2\varepsilon_{\alpha\gamma}\varepsilon^{\delta\kappa}$
$= \frac{2i}{\sqrt{2}} G_F$
Feyn
$\delta\mathcal{L}$

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$



$$\mathcal{M} = \frac{4i G_F}{\sqrt{2}} u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu)\, u_L^\dagger(e^-)\, \bar{\sigma}_\mu\, v(\bar{\nu}_e)$$

$\hat{3}$

$$u = \sqrt{m}\begin{pmatrix} 0 \\ 1 \\ \hline 0 \\ 1 \end{pmatrix} \xi^L \qquad v = \sqrt{2E_{\nu_e}}\begin{pmatrix} -\sin\theta/2 \\ \cos\theta/2 \end{pmatrix}$$

$$(\bar{\sigma}^\mu)_{\alpha\beta}\,(\bar{\sigma}_\mu)_{\gamma\delta} = 2\,\varepsilon_{\alpha\gamma}\,\varepsilon_{\beta\delta}$$

$$= \frac{8i}{\sqrt{2}} G_F\, u_{L\alpha}^\dagger(\nu_\mu)\, \varepsilon_{\alpha\gamma}\, u_\gamma(e^-)\, \underbrace{u_{L\beta}(\mu)\, \varepsilon_{\beta\delta}\, v(\bar{\nu}_e)}$$

$K^0 \to$

$P = -1$

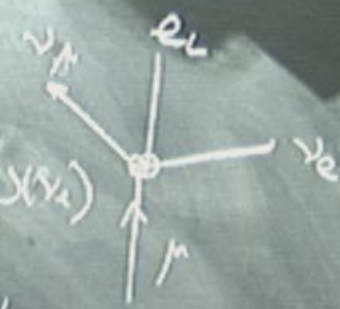
$S = 0$

L

Feyn

$\delta\mathcal{L}$

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$



$$\mathcal{M} = \frac{4i G_F}{\sqrt{2}} u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu)\, u_L^\dagger(e^-)\, \bar{\sigma}_\mu\, v(\bar{\nu}_e)$$

$\hat{z}$

$$u = \sqrt{m}\begin{pmatrix} 0 \\ 1 \\ \hline 0 \\ 1 \end{pmatrix} \xi^L \qquad v = \sqrt{2E_{\nu_e}}\begin{pmatrix} -\sin\theta/2 \\ \cos\theta/2 \end{pmatrix}$$

$$(\bar{\sigma}^\mu)_{\alpha\beta}\,(\bar{\sigma}_\mu)_{\gamma\delta} = 2\,\varepsilon_{\alpha\gamma}\varepsilon_{\beta\delta}$$

$$= \frac{8i}{\sqrt{2}} G_F\, u_{L\alpha}^\dagger(\nu_\mu)\, \varepsilon_{\alpha\gamma}\, u_\gamma(e^-)\, \underbrace{u_{L\beta}(\mu)\, \varepsilon_{\beta\delta}\, v(\bar{\nu}_e)}_{\sqrt{2E_{\bar{\nu}}\, m}\ \sin\theta/2}$$

$K^0 \to$

$P = -1$

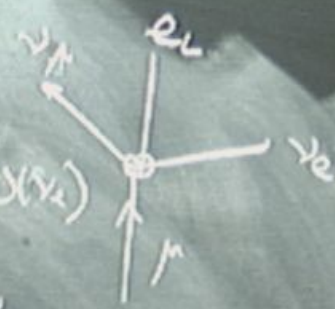
$S = 0$

L

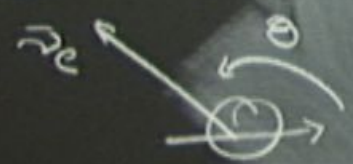
Feyn

$\delta\mathcal{L}$

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$



$$\mathcal{M} = \frac{4i G_F}{\sqrt{2}} u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu)\, u_L^\dagger(e^-)\, \bar{\sigma}_\mu\, v(\bar{\nu}_e)$$



$\hat{3}$

$$u = \sqrt{m}\begin{pmatrix} 0 \\ 1 \\ \hline 0 \\ 1 \end{pmatrix} \xi^L \qquad v = \sqrt{2E_{\nu_e}}\begin{pmatrix} -\sin\theta/2 \\ \cos\theta/2 \end{pmatrix}$$

$$(\bar{\sigma}^\mu)_{\alpha\beta}\,(\bar{\sigma}_\mu)_{\gamma\delta} = 2\,\varepsilon_{\alpha\gamma}\varepsilon_{\beta\delta}$$

$$= \frac{8i}{\sqrt{2}} G_F\, u_{L\alpha}^\dagger(\nu_\mu)\, \varepsilon_{\alpha\gamma}\, u_\gamma(e^-)\, \underbrace{u_{L\beta}(\mu)\, \varepsilon_{\beta\delta}\, v(\bar{\nu}_e)}_{\sqrt{2E_\nu - m}\ \sin\theta/2}$$

$K^0 \to$

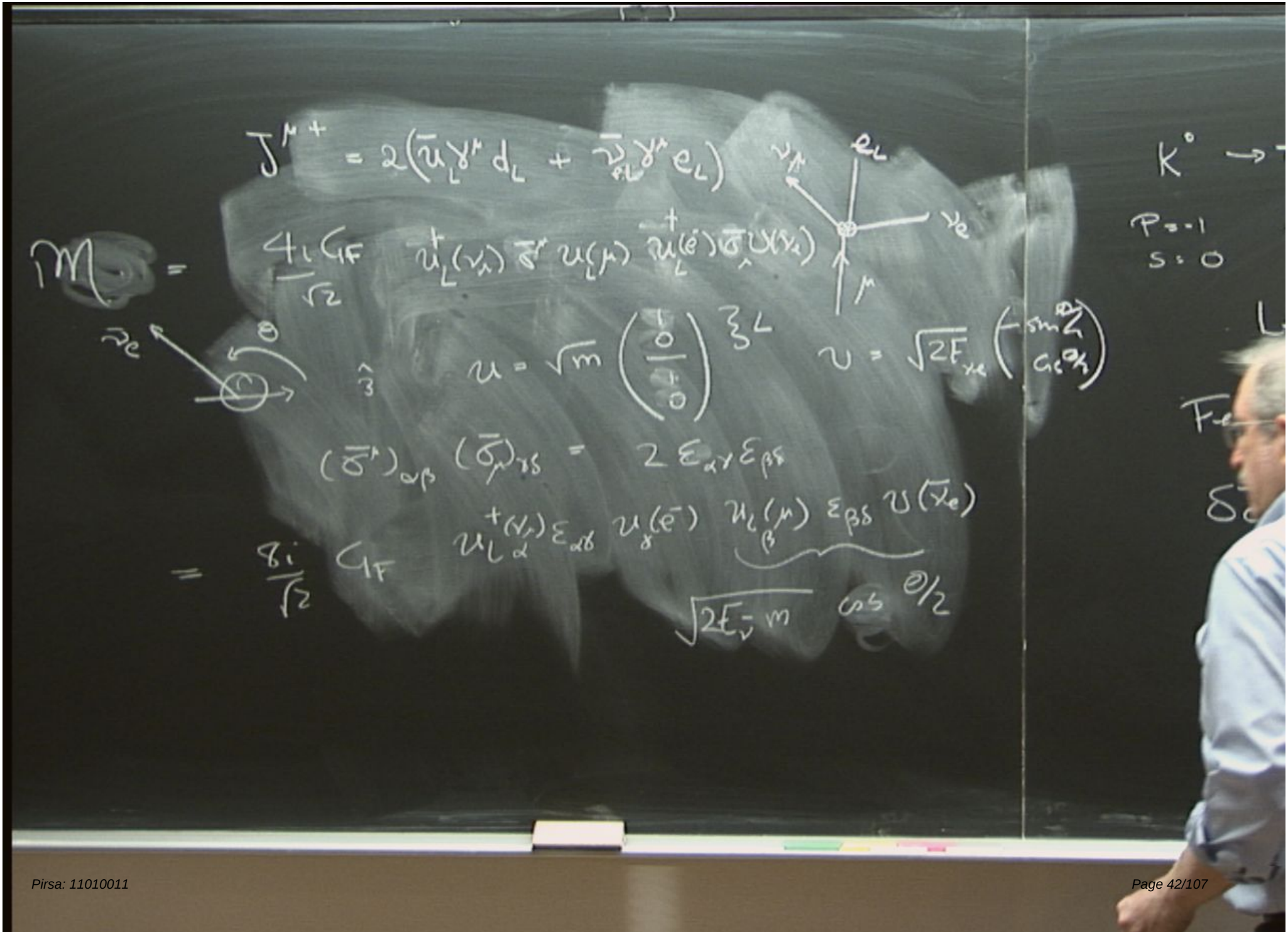
$P = -1$

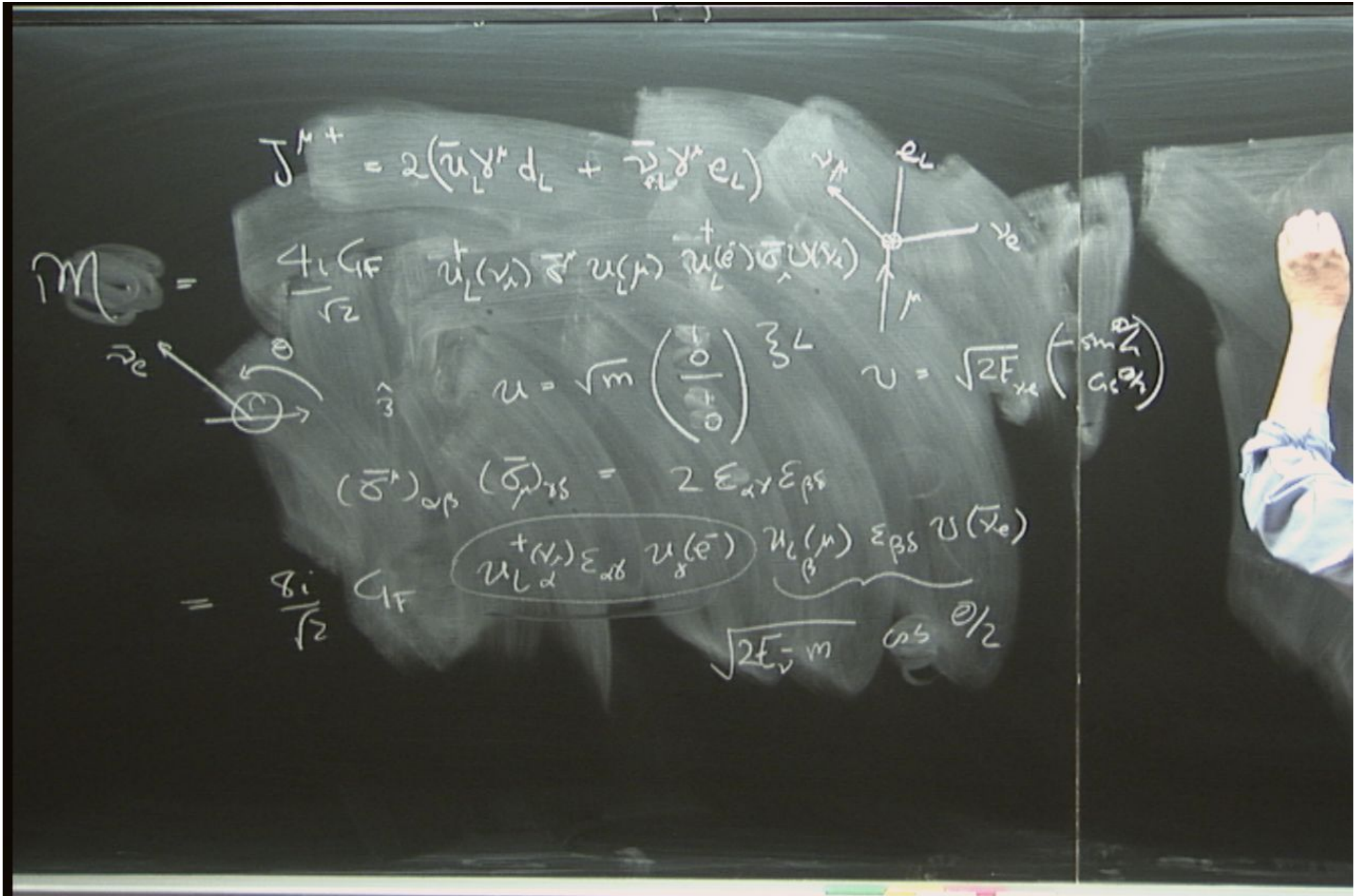
$S = 0$

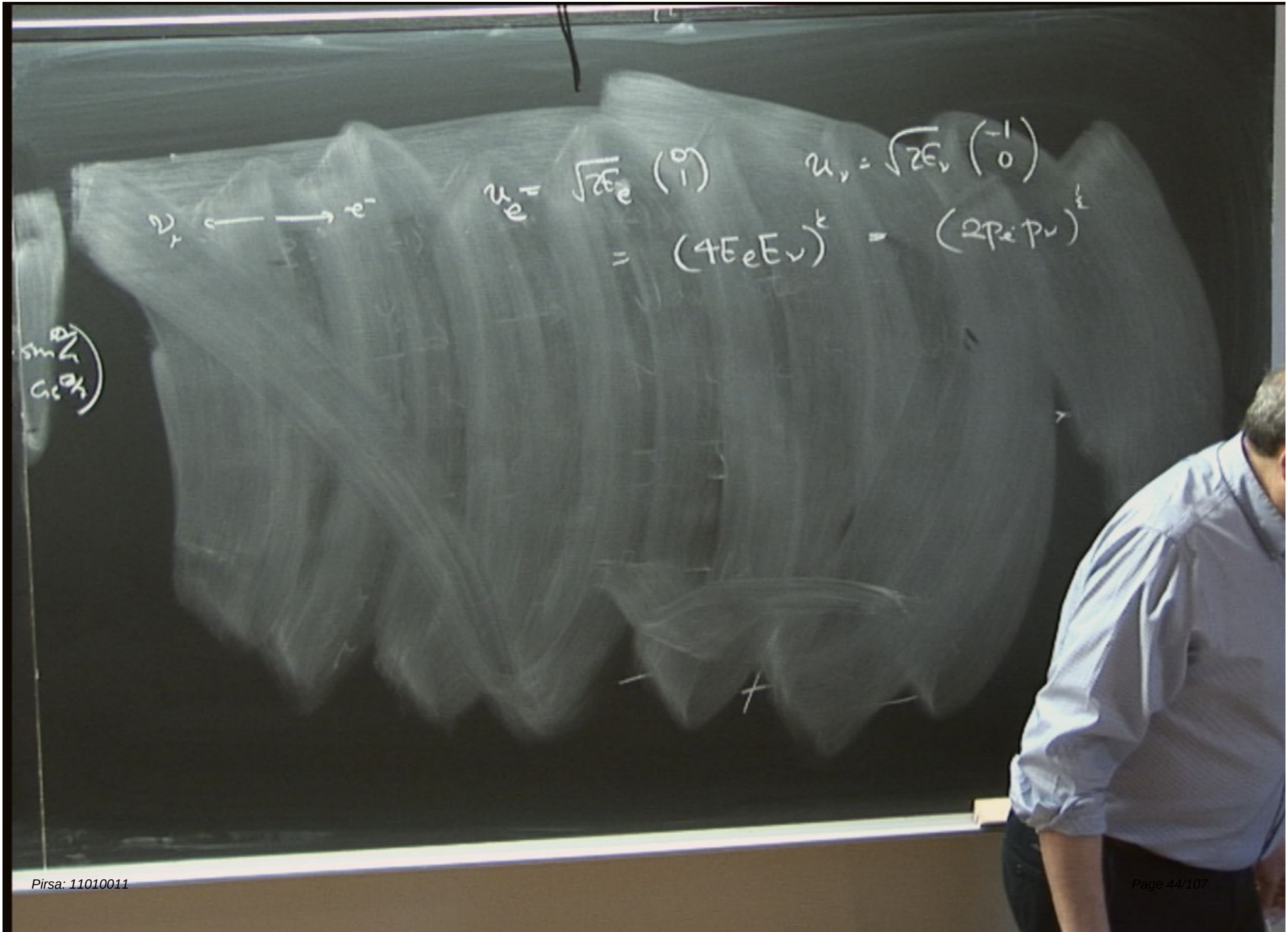
L

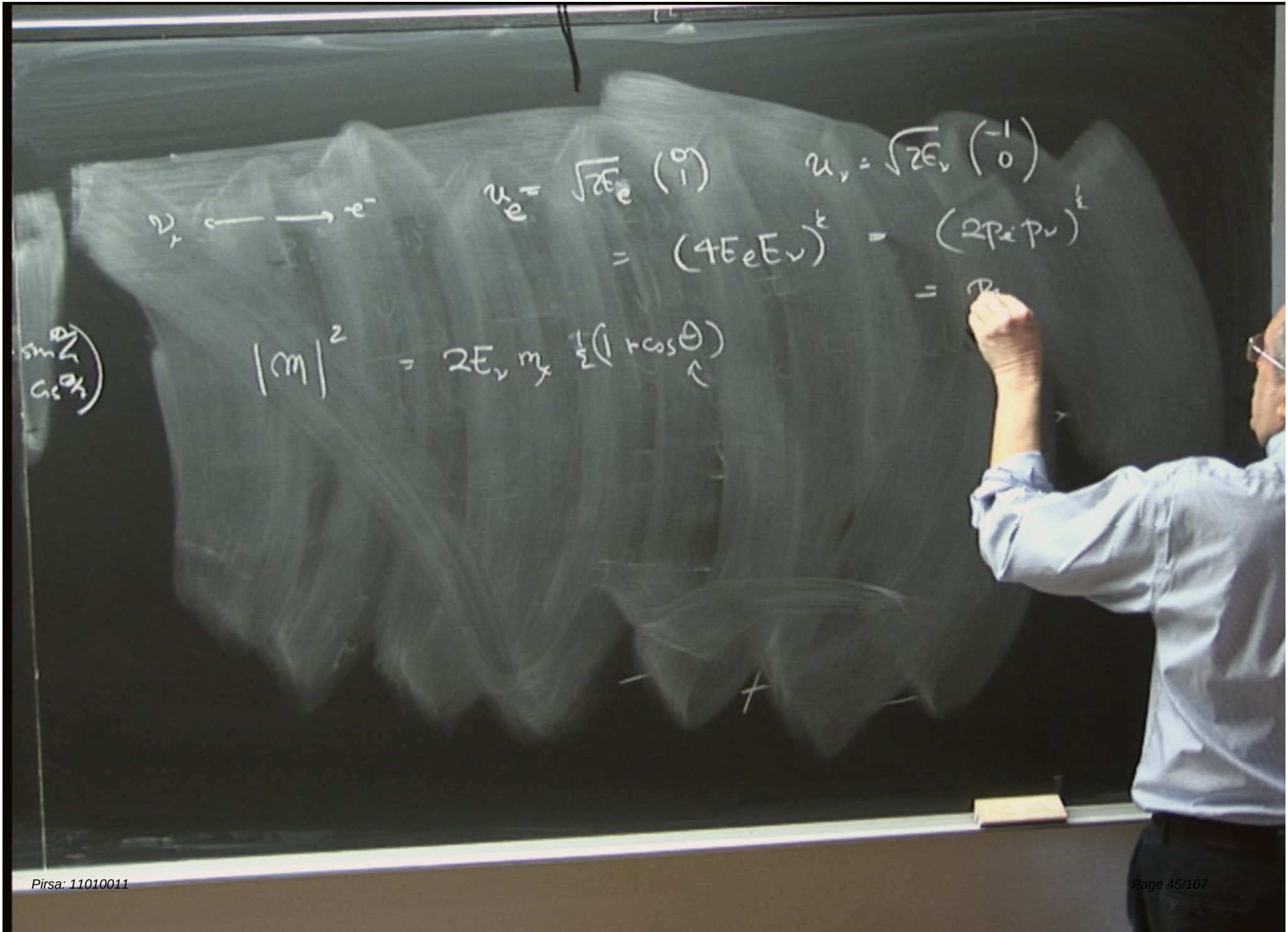
Feyn

$\delta\mathcal{L}$


$J^{\mu +} = 2(\bar{\nu}_e \gamma^\mu e_L + \bar{\nu}_\mu \gamma^\mu \mu_L)$
$i\mathcal{M} = \frac{4i}{\sqrt{2}} G_F \; u_L^\dagger(\nu_\mu) \bar{\sigma}^\mu u_L(\mu) \; u_L^\dagger(e) \hat{\sigma}_\mu v(\bar{\nu}_e)$
$\hat{z}$
$u = \sqrt{m} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 1 \end{pmatrix} \xi_L$
$v = \sqrt{2E_{\nu_e}} \begin{pmatrix} -\sin\frac{\theta}{2} \\ \cos\frac{\theta}{2} \end{pmatrix}$
$(\bar{\sigma}^\mu)_{\alpha\beta} \; (\hat{\sigma}_\mu)_{\gamma\delta} = 2\varepsilon_{\alpha\gamma}\varepsilon_{\beta\delta}$
$= \frac{2i}{\sqrt{2}} G_F \; u_{L\alpha}^\dagger(\nu_\mu) \varepsilon_{\alpha\beta} \; u_\gamma(e^-) \; u_{L\beta}(\mu) \varepsilon_{\beta\delta} v(\bar{\nu}_e)$
$\sqrt{2E_\nu m} \cos\theta/2$
$K^\circ \to$
$P = -1$
$S = 0$




$\nu_x \longleftrightarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^2 = (2p_e \cdot p_\nu)^2$


$\nu_x \longleftrightarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
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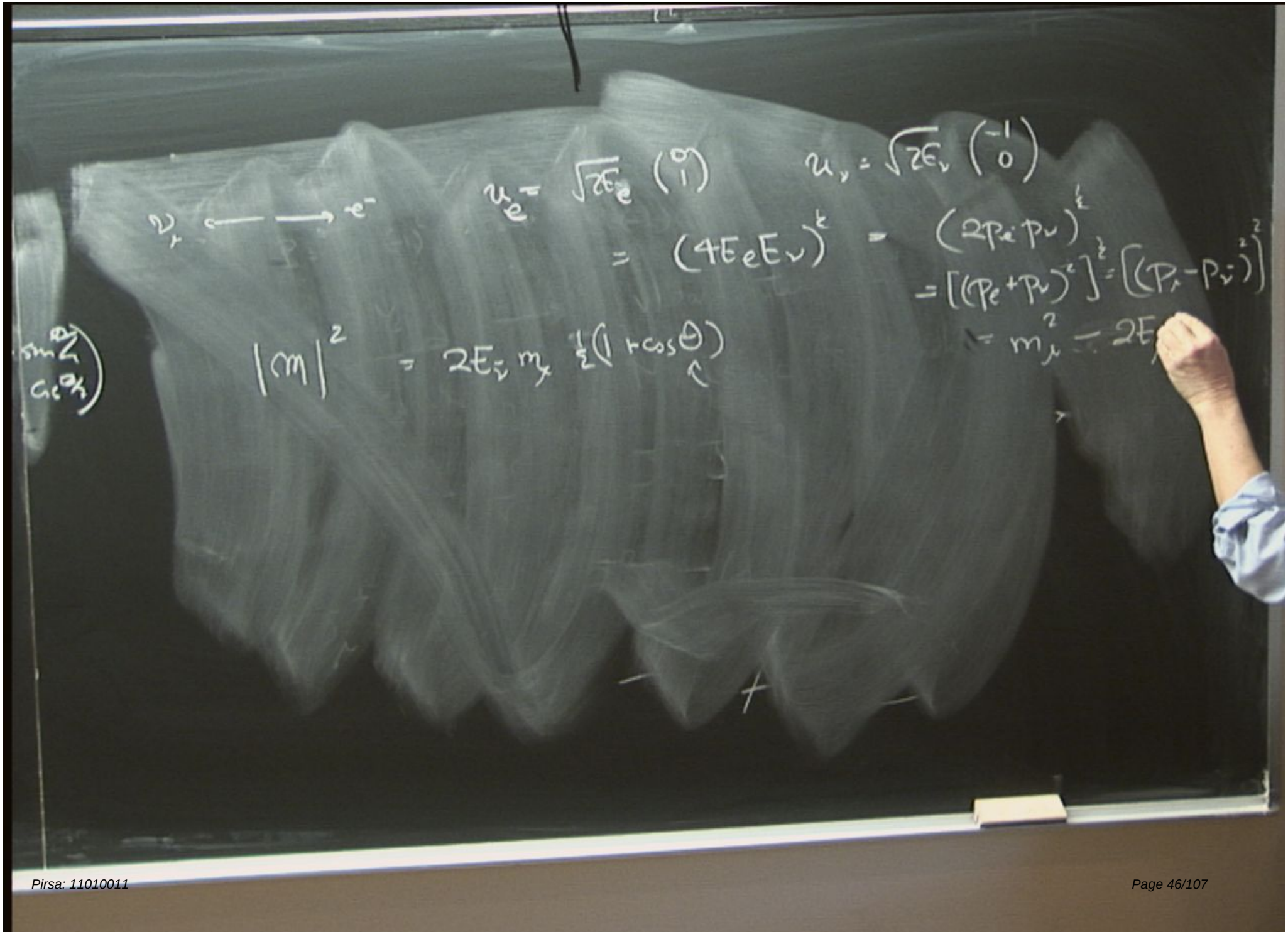
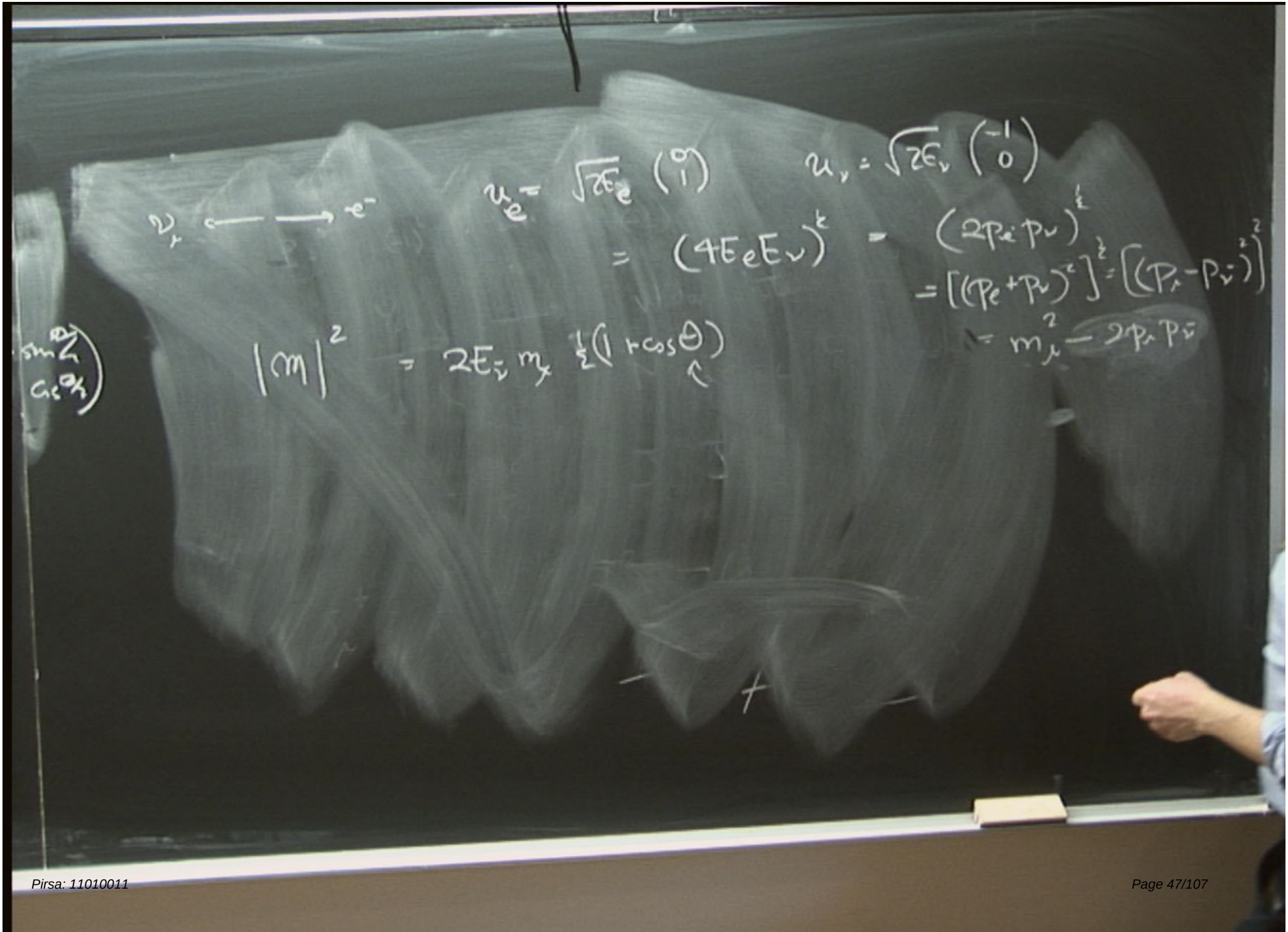
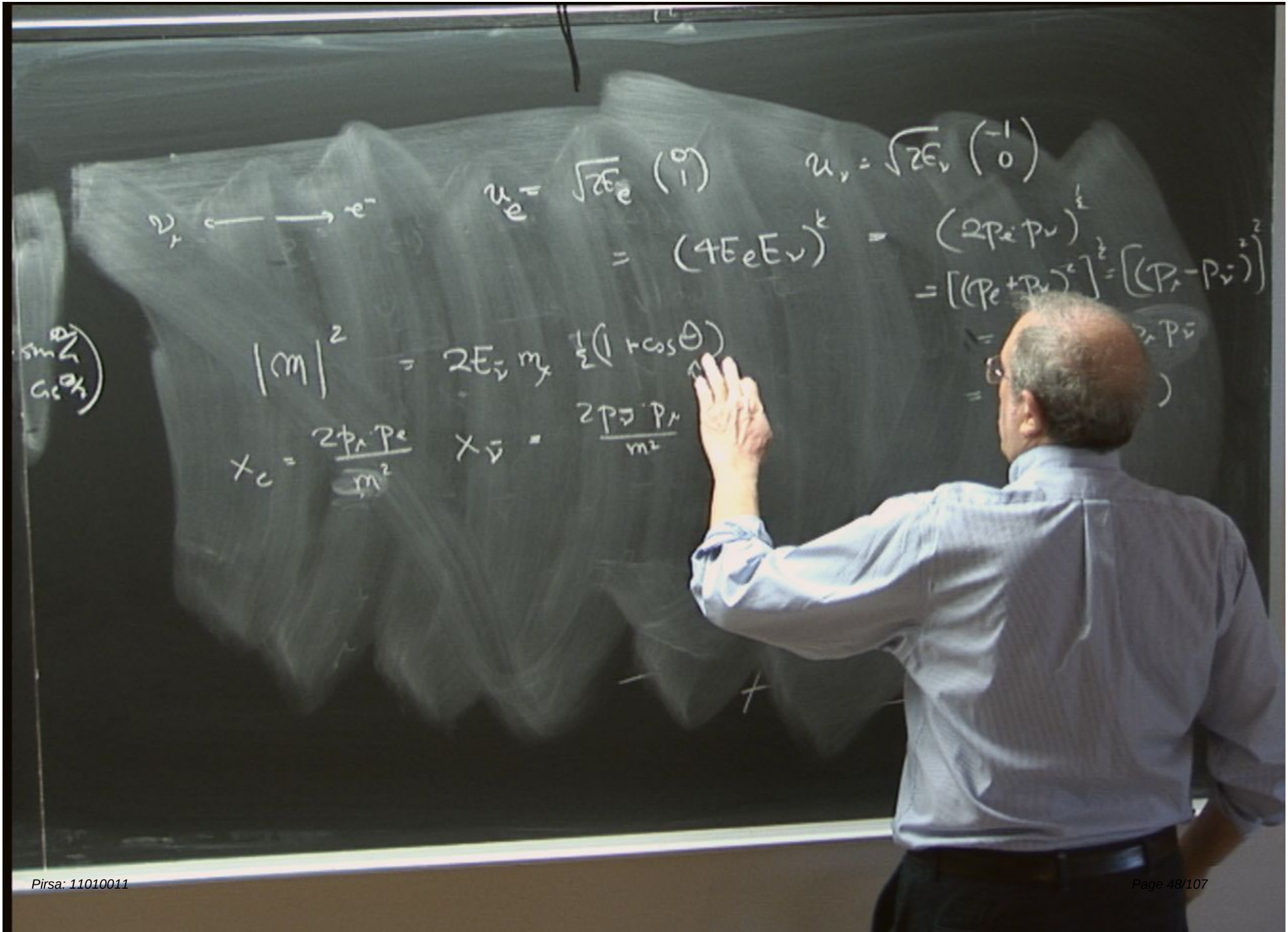
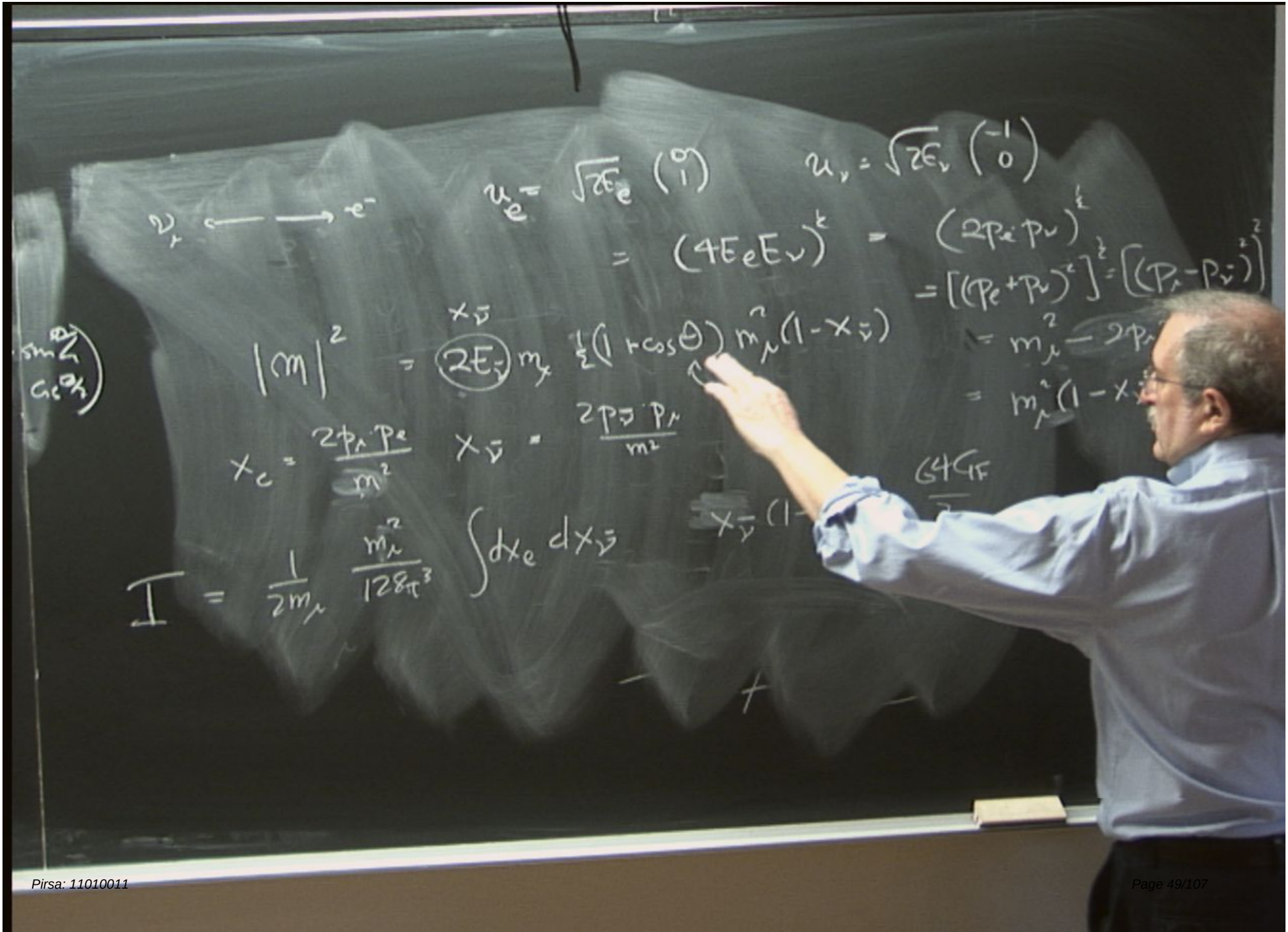
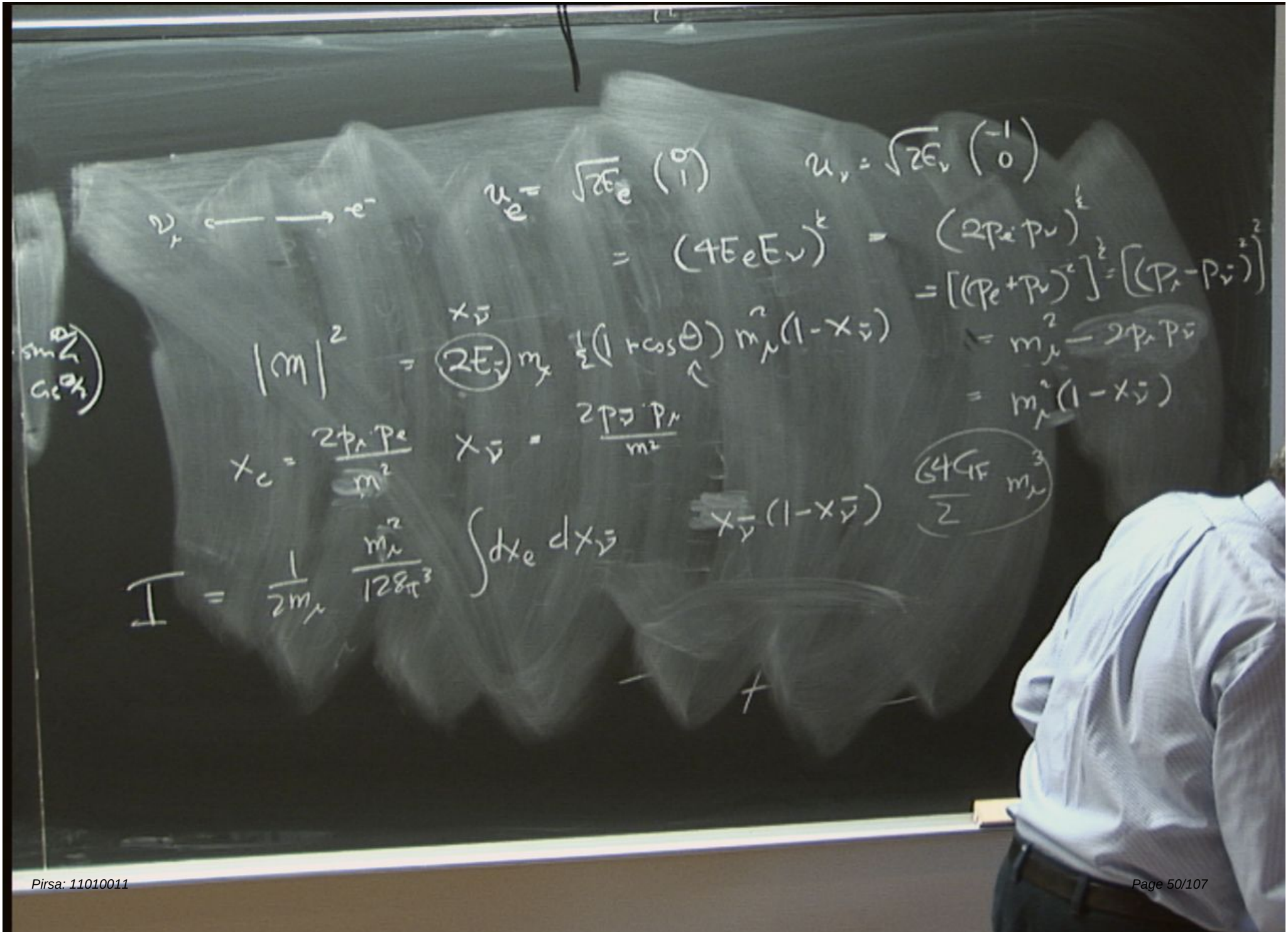
$= (4E_eE_\nu)^2 = (2p_e \cdot p_\nu)^2$
$|m|^2 = 2E_\nu m_x^2 (1 + \cos\theta)$

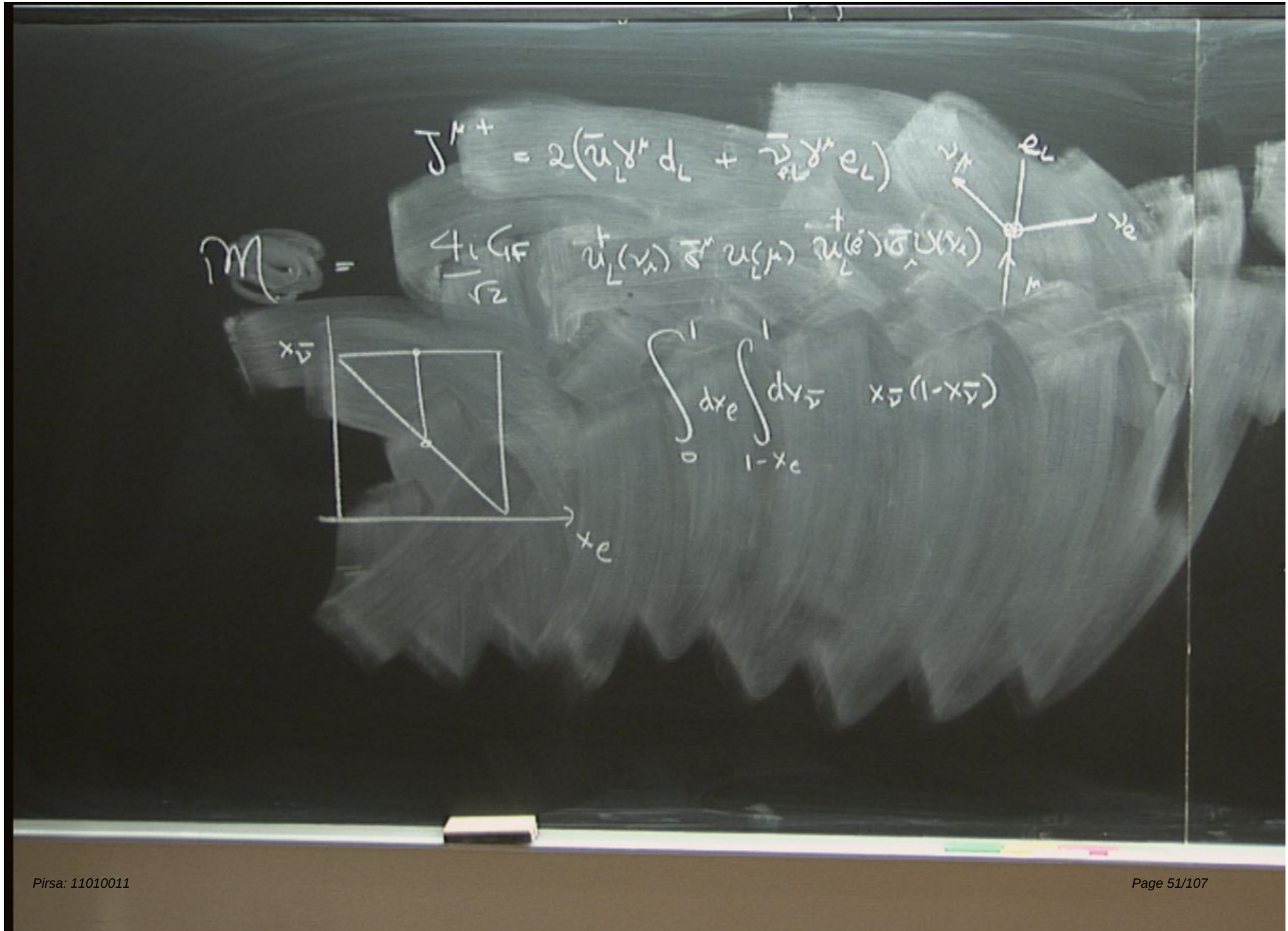

$\nu_x \longleftarrow\longrightarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^2 = (2P_e\cdot P_\nu)^2$
$= [(P_e+P_\nu)^2]^2 = [(P_x-P_\nu)^2]^2$
$= m_\mu^2 - 2E$
$|m|^2 = 2E_\nu m_x \frac{1}{2}(1+\cos\theta)$


$\nu_\mu \longleftarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^2 = (2p_e\cdot p_\nu)^2$
$= [(p_e+p_\nu)^2]^2 = [(p_\mu - p_\nu)^2]^2$
$= m_\mu^2 - 2p_\mu p_\nu$
$|m|^2 = 2E_\nu m_\mu \frac{1}{2}(1+\cos\theta)$

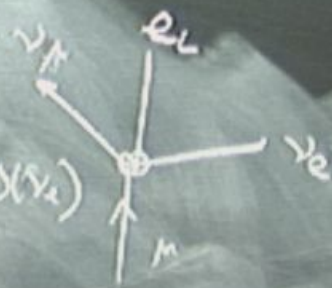

$\nu_x \longleftarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^{\frac{1}{2}} = (2P_e\cdot P_\nu)^{\frac{1}{2}}$
$= [(P_e+P_\nu)^2]^{\frac{1}{2}} = [(P_x-P_{\bar\nu})^2]^{\frac{1}{2}}$
$|m|^2 = 2E_{\bar\nu}m_x\,\frac{1}{2}(1+\cos\theta)$
$x_e = \frac{2P_x\cdot P_e}{m^2}$
$x_{\bar\nu} = \frac{2P_{\bar\nu}\cdot P_x}{m^2}$


$\nu_\mu \longleftrightarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^2 = (2p_e\cdot p_\nu)^2$
$= [(p_e+p_\nu)^2]^2 = [(p_\mu - p_\nu)^2]^2$
$|m|^2 = (2E_\nu)\, m_\mu^2 \tfrac{1}{2}(1+\cos\theta)\, m_\mu^2 (1-x_\nu)$
$= m_\mu^2 - 2p_\mu$
$= m_\mu^2(1-x$
$x_e = \frac{2p_\mu\cdot p_e}{m^2}$
$x_\nu = \frac{2p_\nu\cdot p_\mu}{m^2}$
$\frac{G^4 G_F}{}$
$I = \frac{1}{2m_\mu}\frac{m_\mu^2}{128\pi^3}\int dx_e\, dx_\nu$
$x_\nu(1-$

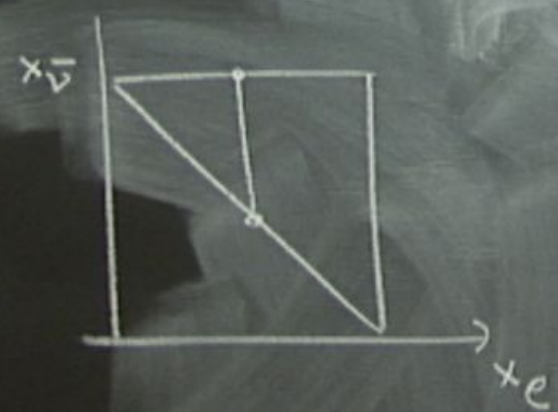

$\nu_\mu \longleftrightarrow e^-$
$u_e = \sqrt{2E_e}\begin{pmatrix}0\\1\end{pmatrix}$
$u_\nu = \sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$= (4E_eE_\nu)^{\frac{1}{2}} = (2p_e\cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e+p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar\nu})^2]^2$
$= m_\mu^2 - 2p_\mu p_{\bar\nu}$
$= m_\mu^2(1-x_{\bar\nu})$
$|m|^2 = 2E_{\bar\nu}\, m_\mu\, \frac{1}{2}(1+\cos\theta)\, m_\mu^2(1-x_{\bar\nu})$
$x_{\bar\nu}$
$x_e = \frac{2p_\mu\cdot p_e}{m^2}$
$x_{\bar\nu} = \frac{2p_{\bar\nu}\cdot p_\mu}{m^2}$
$\frac{64G_F}{2} m_\mu^3$
$x_{\bar\nu}(1-x_{\bar\nu})$
$I = \frac{1}{2m_\mu}\frac{m_\mu^2}{128\pi^3}\int dx_e\, dx_{\bar\nu}$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$i\mathcal{M} = \frac{4 i G_F}{\sqrt{2}} \bar{u}_L(\nu_\mu) \gamma^\mu u(\mu) \bar{u}_L(e) \gamma_\mu (1-\gamma_5) u(\nu_e)$
$\int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}} \; x_{\bar{\nu}}(1-x_{\bar{\nu}})$
$x_{\bar{\nu}}$
x_e
ν_μ
e_L
ν_e
W

$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$

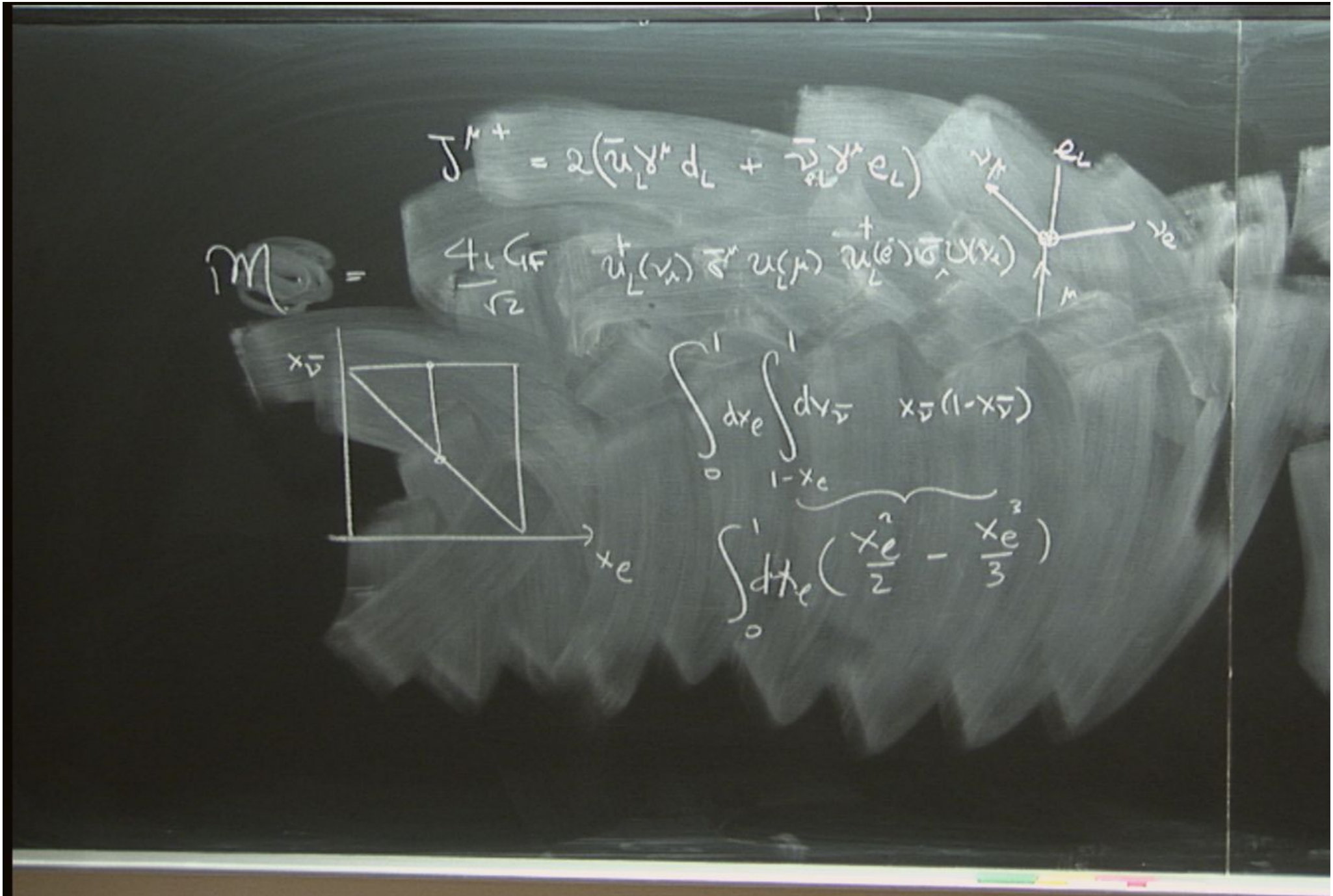


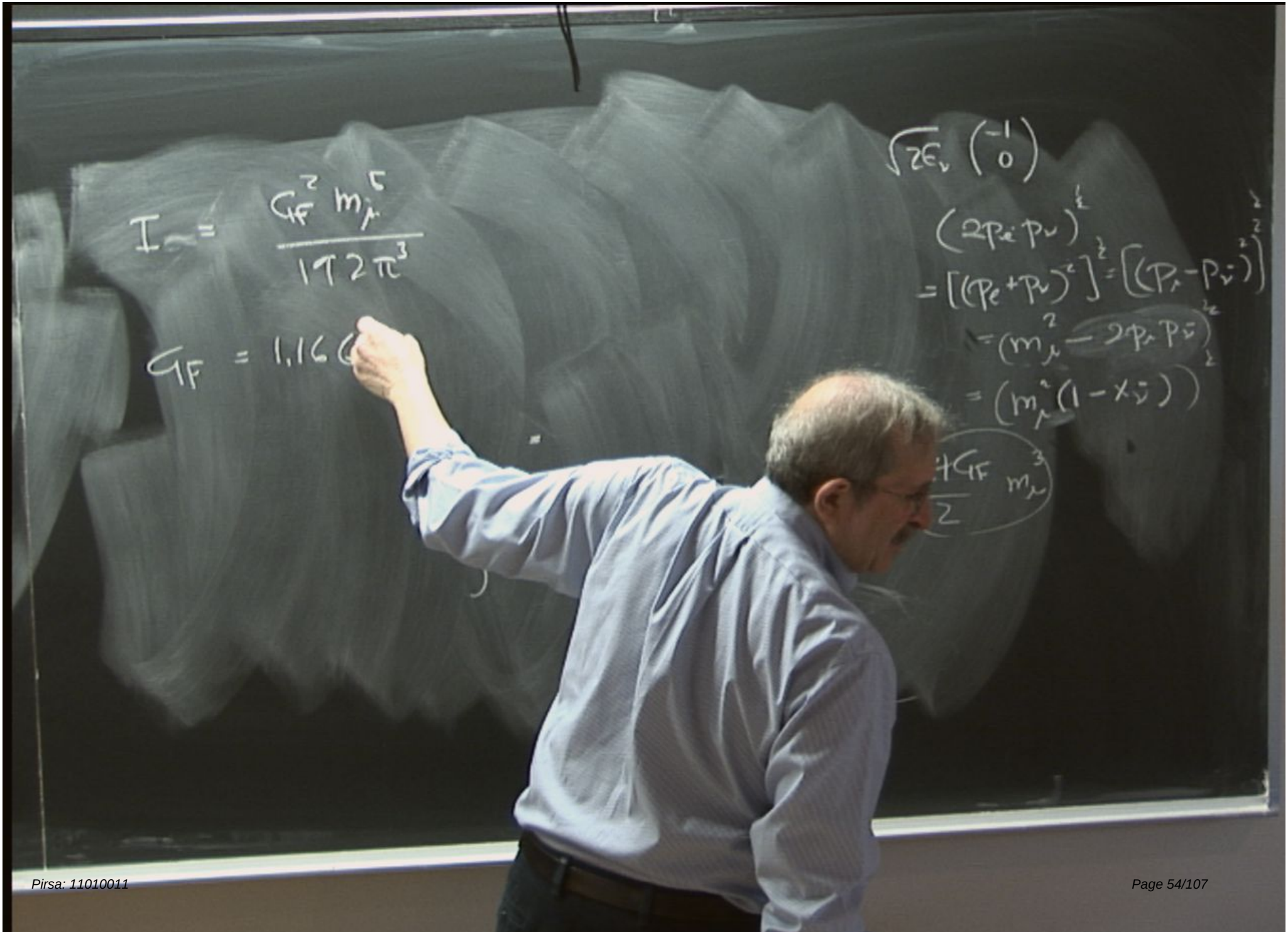
$$i\mathcal{M} = \frac{4iG_F}{\sqrt{2}} \; u_L^\dagger(\nu_\mu)\, \bar{\sigma}^\mu\, u_L(\mu)\; u_L^\dagger(e)\, \bar{\sigma}_\mu\, u(\nu_e)$$

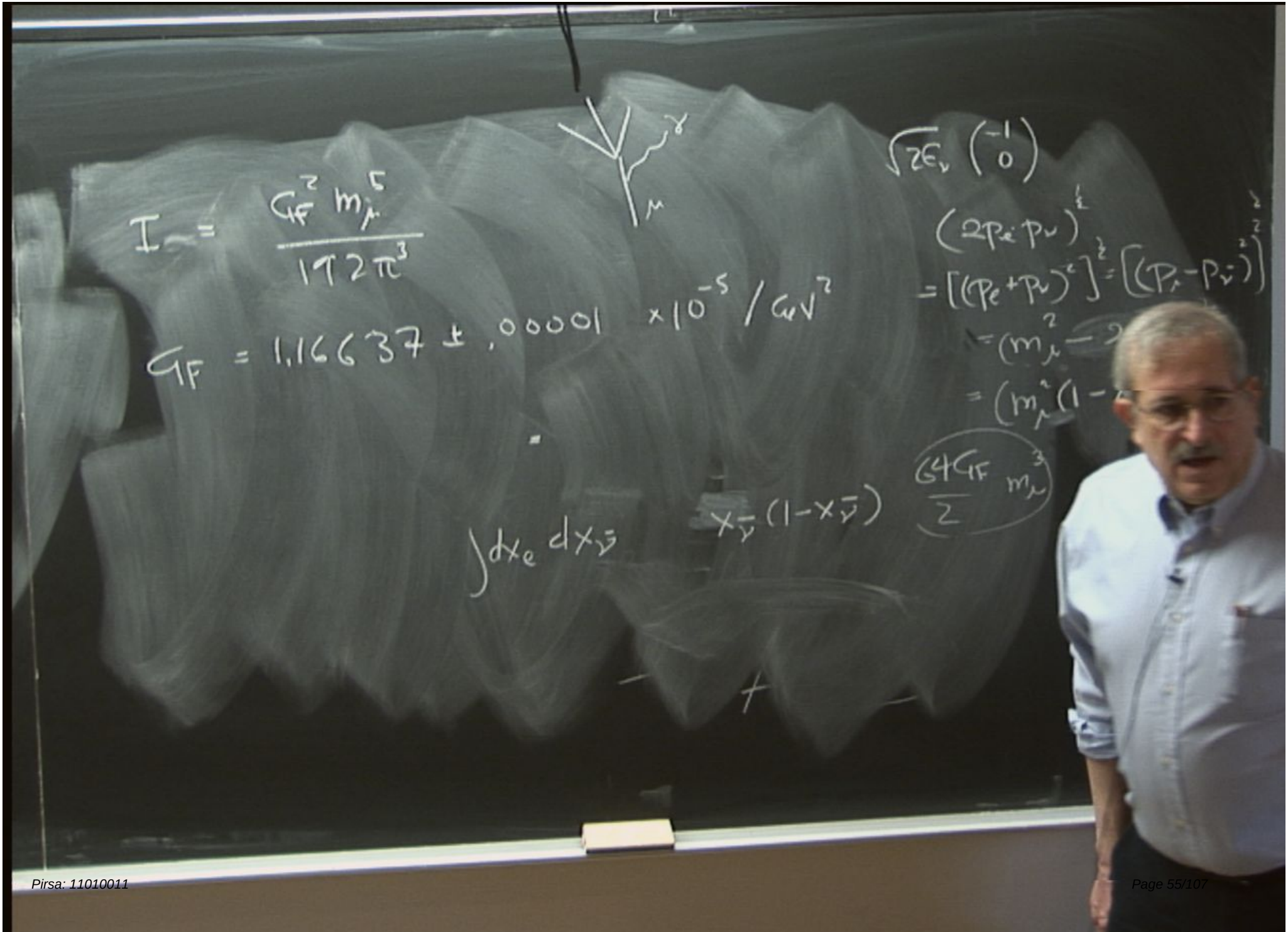


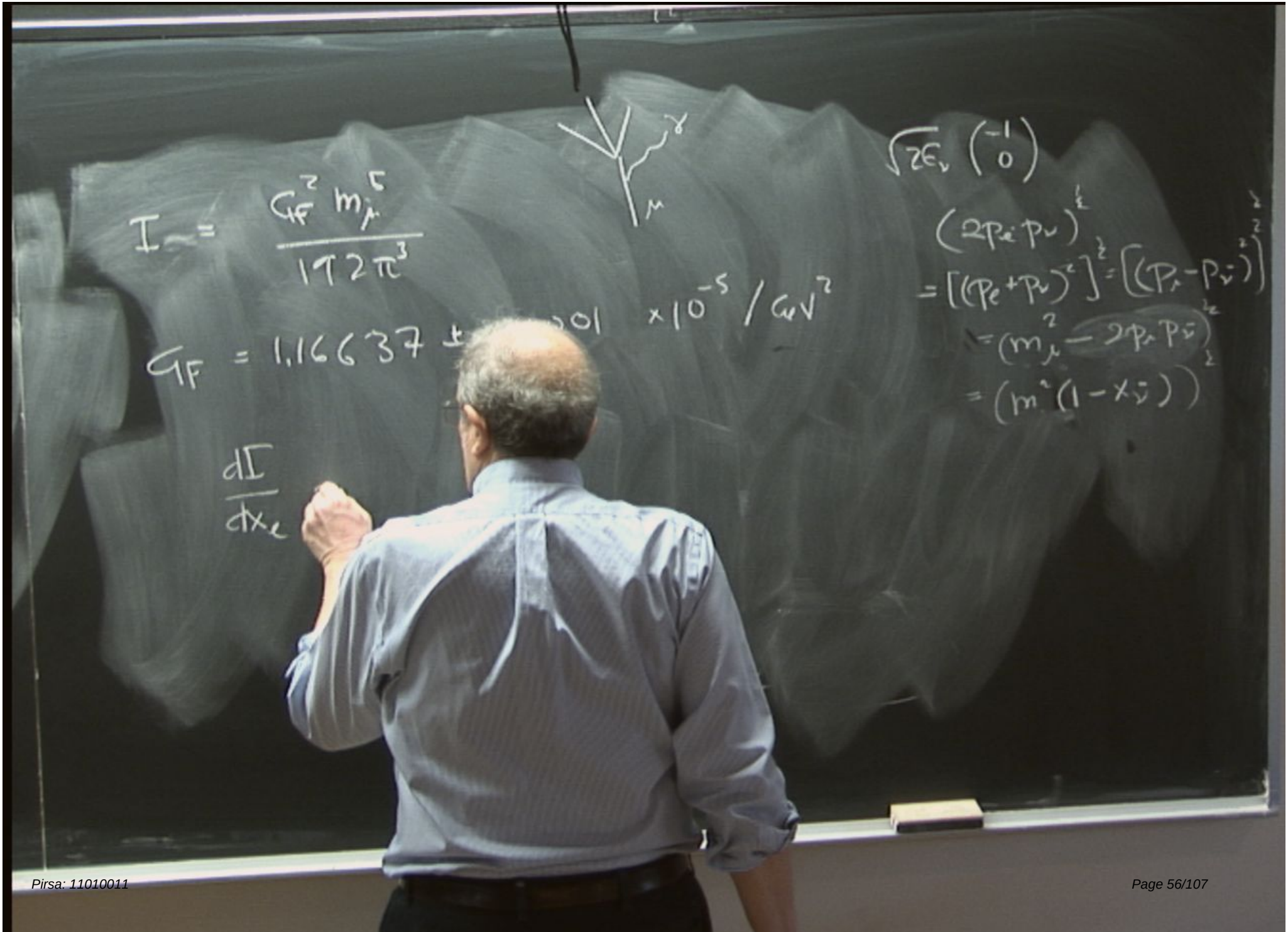
$$\int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}} \; x_{\bar{\nu}}(1-x_{\bar{\nu}})$$

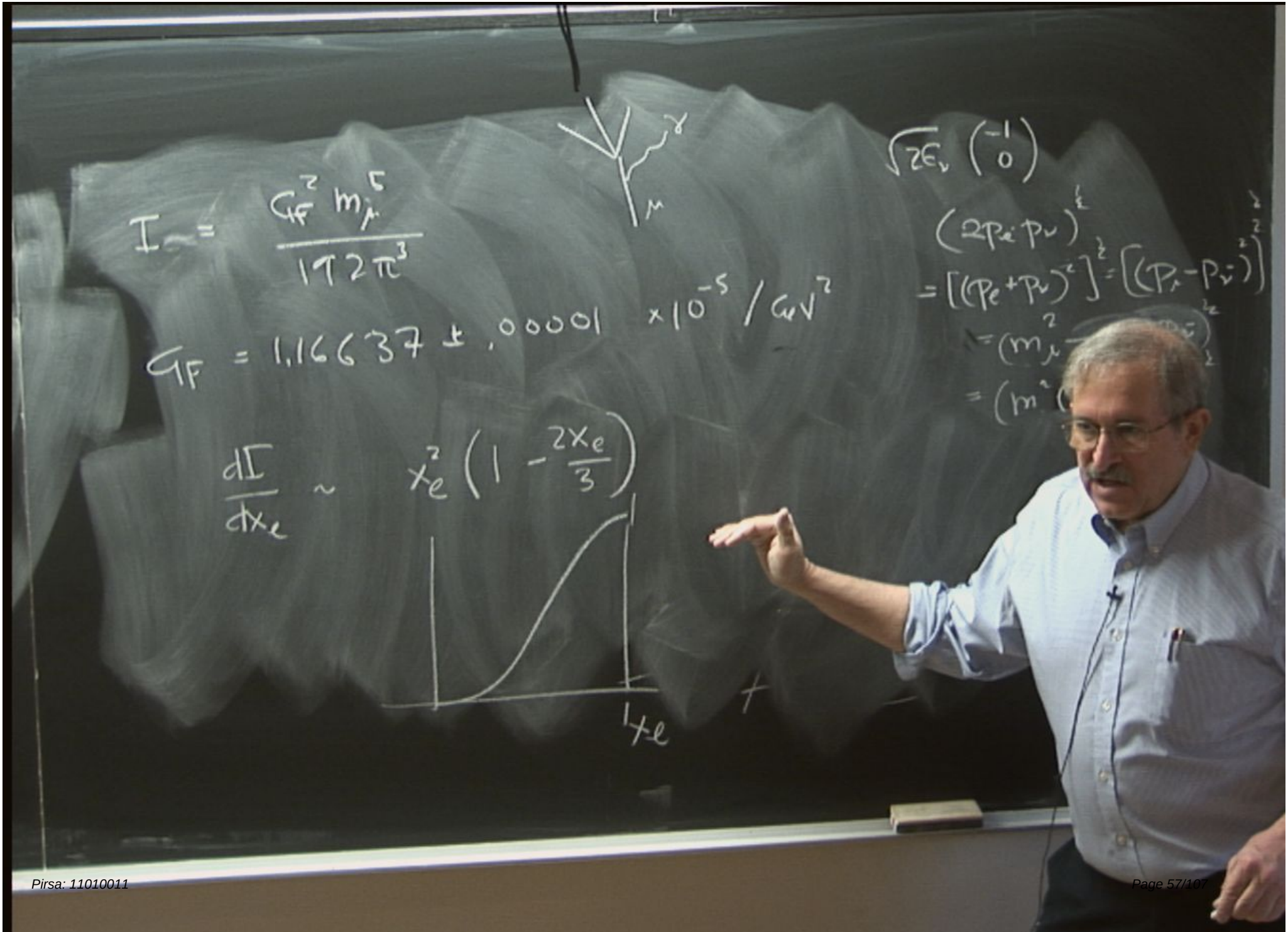
$$\left(\frac{x_e^2}{2} - \frac{x_e^3}{3}\right)$$


$J^{\mu} = 2(\bar{u}\gamma^{\mu}d_L + \bar{\nu}_e\gamma^{\mu}e_L)$
$i\mathcal{M} = \frac{4_1 G_F}{\sqrt{2}}$
$\int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}}$
$x_{\bar{\nu}}(1-x_{\bar{\nu}})$
$\int_0^1 dx_e \left(\frac{x_e^2}{2} - \frac{x_e^3}{3}\right)$
$x_{\bar{\nu}}$
x_e
ν_μ
e_L
ν_e
W


$I \sim = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16$
$\sqrt{2\epsilon_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e \cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e + p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_\nu)^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2p_\mu \cdot p_\nu)^{\frac{1}{2}}$
$= (m_\mu^2(1 - x_\nu))$
$\frac{G_F}{2} m_\mu^3$


$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16637 \pm .00001 \times 10^{-5}\ \mathrm{GeV}^{-2}$
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e \cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e + p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar{\nu}})^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2$
$= (m_\mu^2 (1 -$
$\int dx_e\, dx_{\bar{\nu}}\ x_{\bar{\nu}}(1 - x_{\bar{\nu}})$
$\frac{G_4 G_F}{2} m_\mu^3$
μ
γ

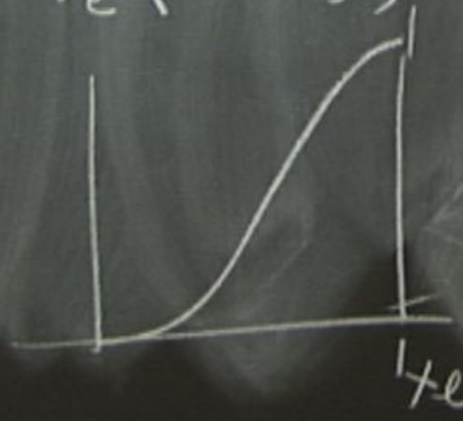

$I = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16637 \pm$ 001 $\times 10^{-5}$ / GeV^2
$\frac{d\Gamma}{dx_e}$
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e \cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e+p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar\nu})^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2p_\mu p_{\bar\nu})^{\frac{1}{2}}$
$= (m^2(1-x_{\bar\nu}))^{\frac{1}{2}}$


$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16637 \pm .00001 \times 10^{-5}\ /\ GeV^2$
$\frac{d\Gamma}{dx_e} \sim x_e^2\left(1 - \frac{2x_e}{3}\right)$
x_e
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2P_e \cdot P_\nu)$
$= [(P_e + P_\nu)^2] = [(P_\mu - P_{\bar\nu})^2]$
$= (m_\mu^2$
$= (m^2$
γ
μ

$$\Gamma \sim \frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$G_F = 1.16637 \pm .00001 \times 10^{-5}\ \text{GeV}^{-2}$$

$$\frac{d\Gamma}{dx_e} \sim x_e^2\left(1 - \frac{2x_e}{3}\right)$$

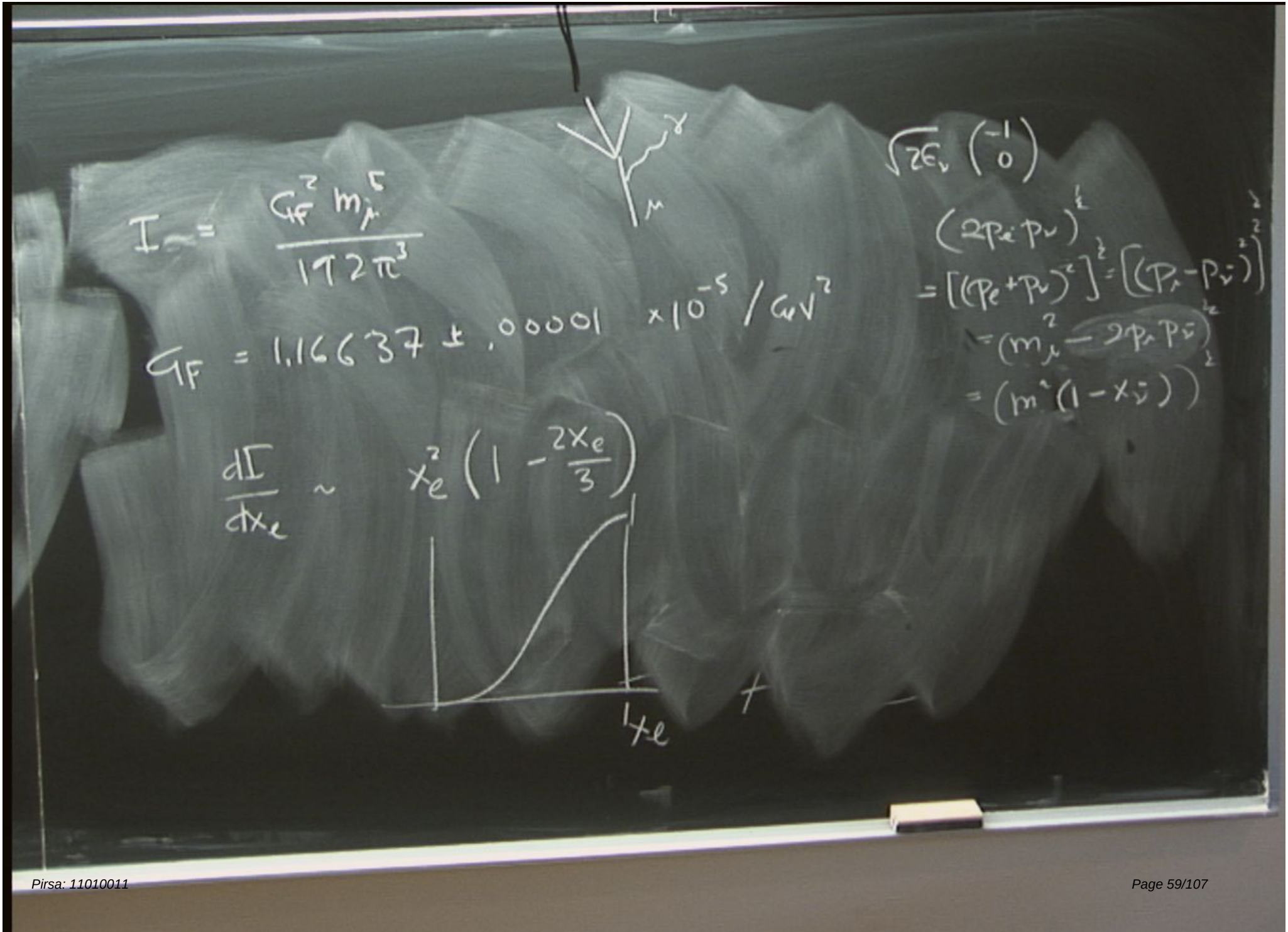


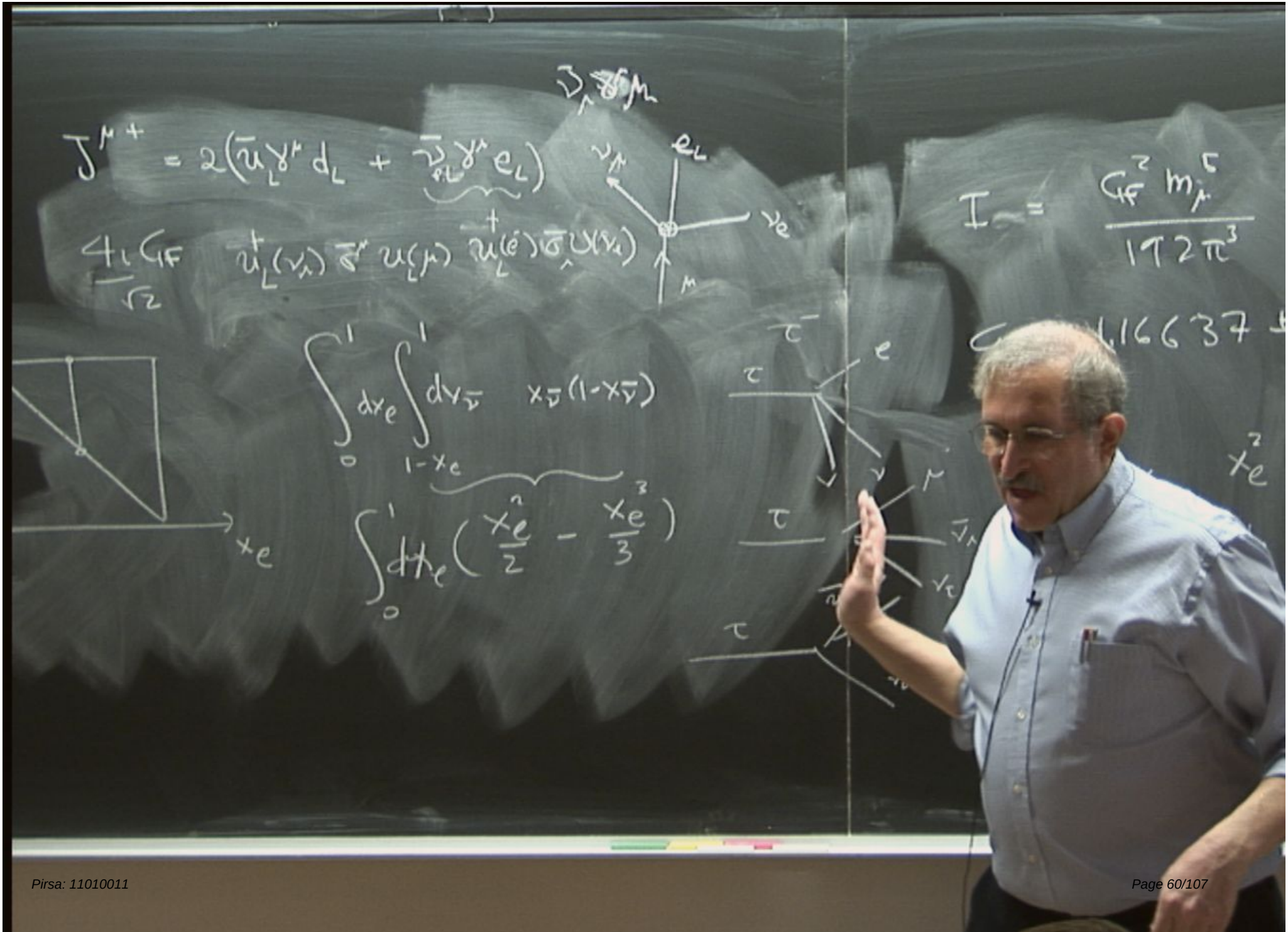
$$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$$

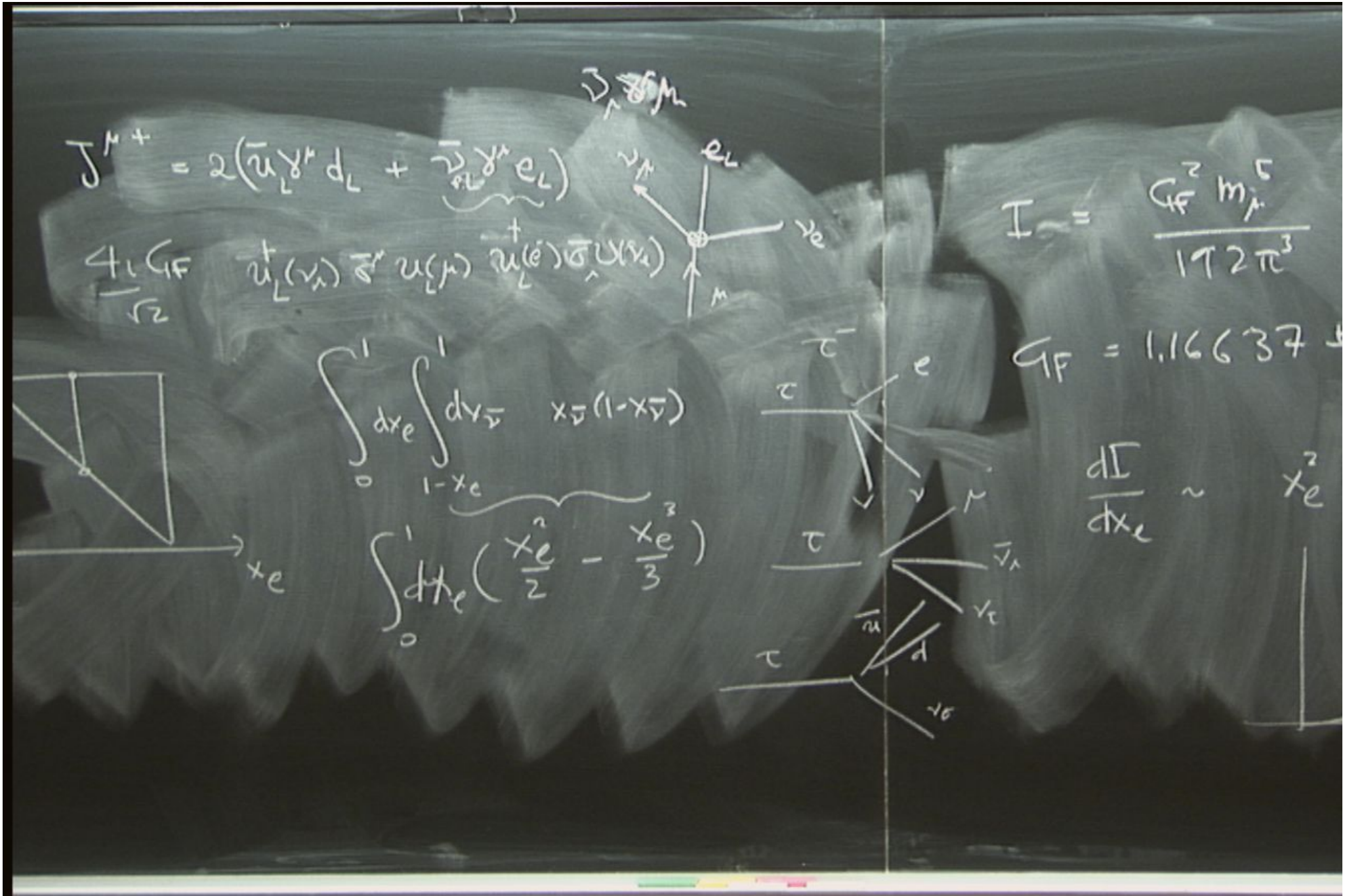
$$(2p_e \cdot p_\nu)^{\frac{1}{2}} = [(p_e + p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar{\nu}})^2]^{\frac{1}{2}}$$

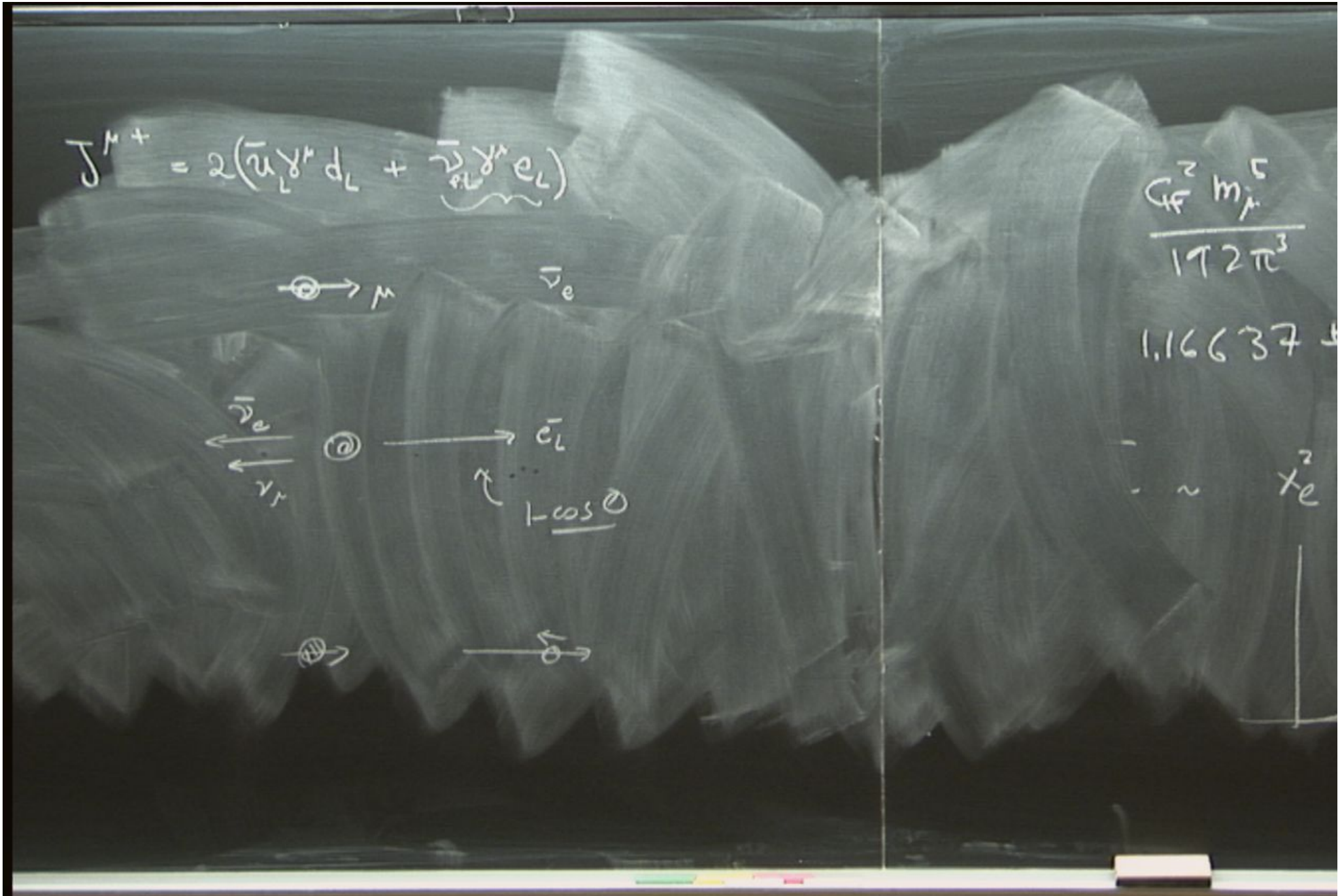
$$= (m_\mu^2 - 2p_\mu \cdot p_{\bar{\nu}})^{\frac{1}{2}}$$

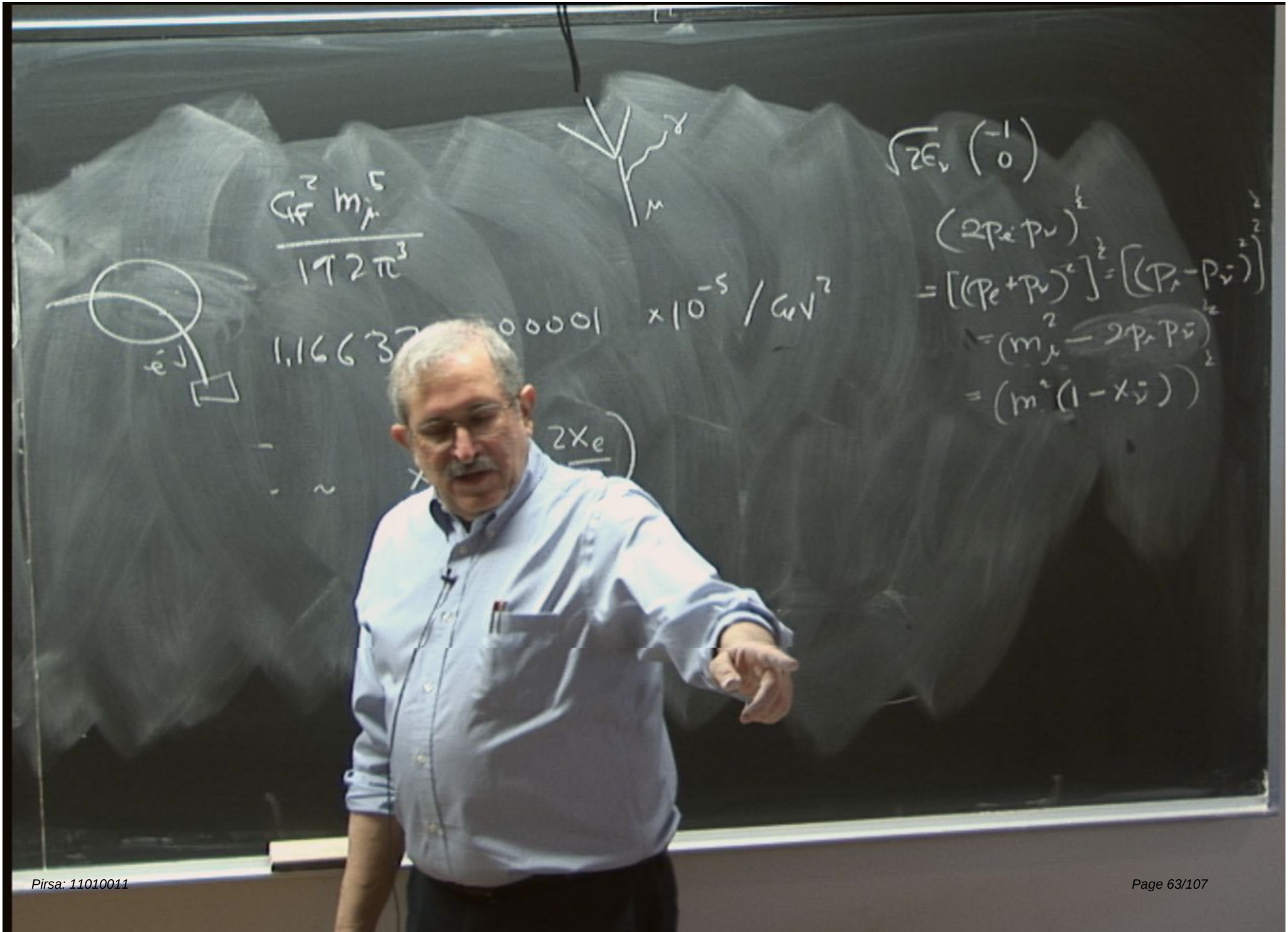
$$= (m^2(1 - x_{\bar{\nu}}))$$

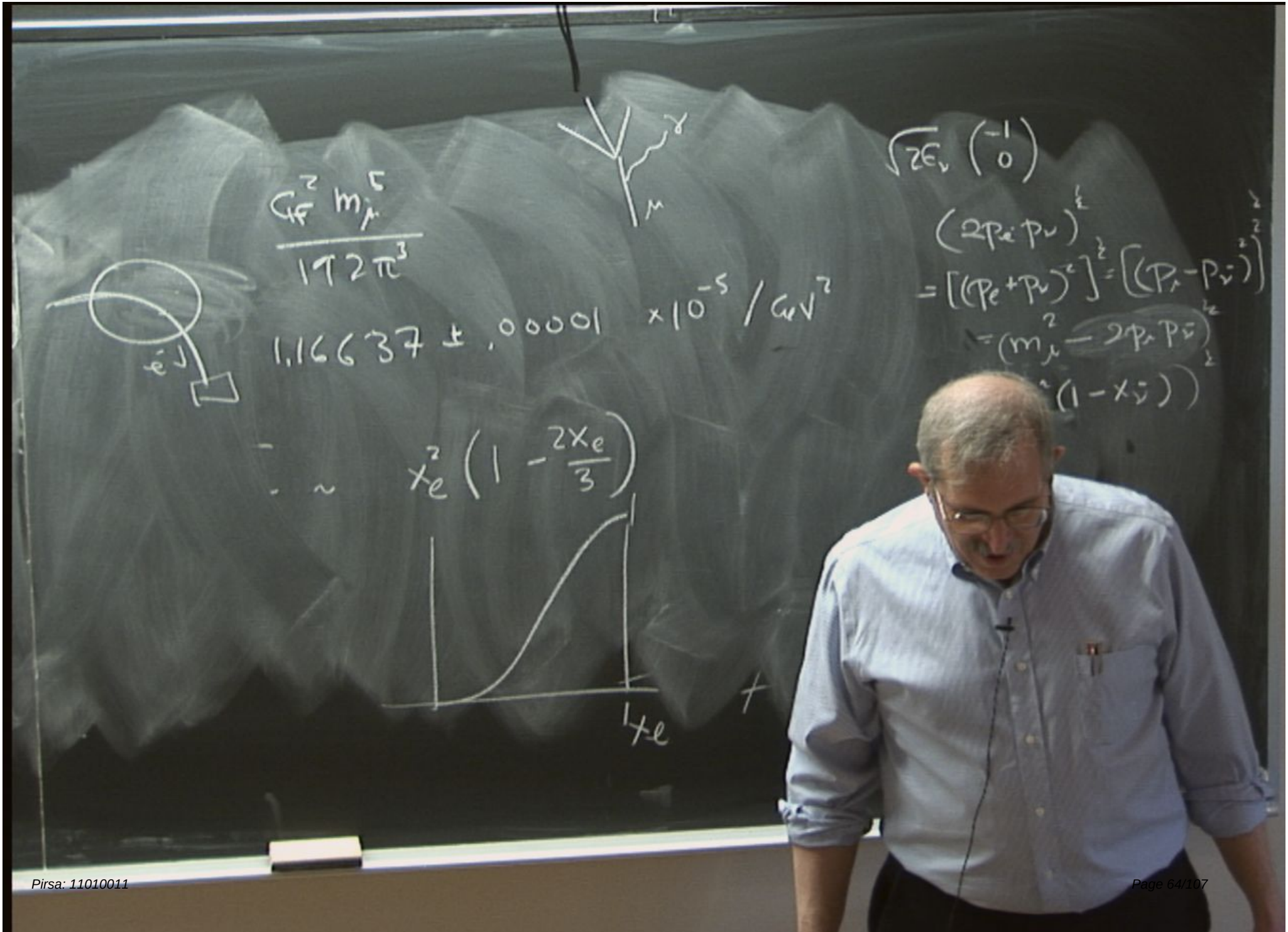

$\Gamma \sim \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16637 \pm .00001 \times 10^{-5}\ /\ GeV^2$
$\frac{d\Gamma}{dx_e} \sim x_e^2\left(1 - \frac{2x_e}{3}\right)$
$1 x_e$
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e \cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e + p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar{\nu}})^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2p_\mu \cdot p_{\bar{\nu}})^{\frac{1}{2}}$
$= (m_\mu(1 - x_{\bar{\nu}}))$

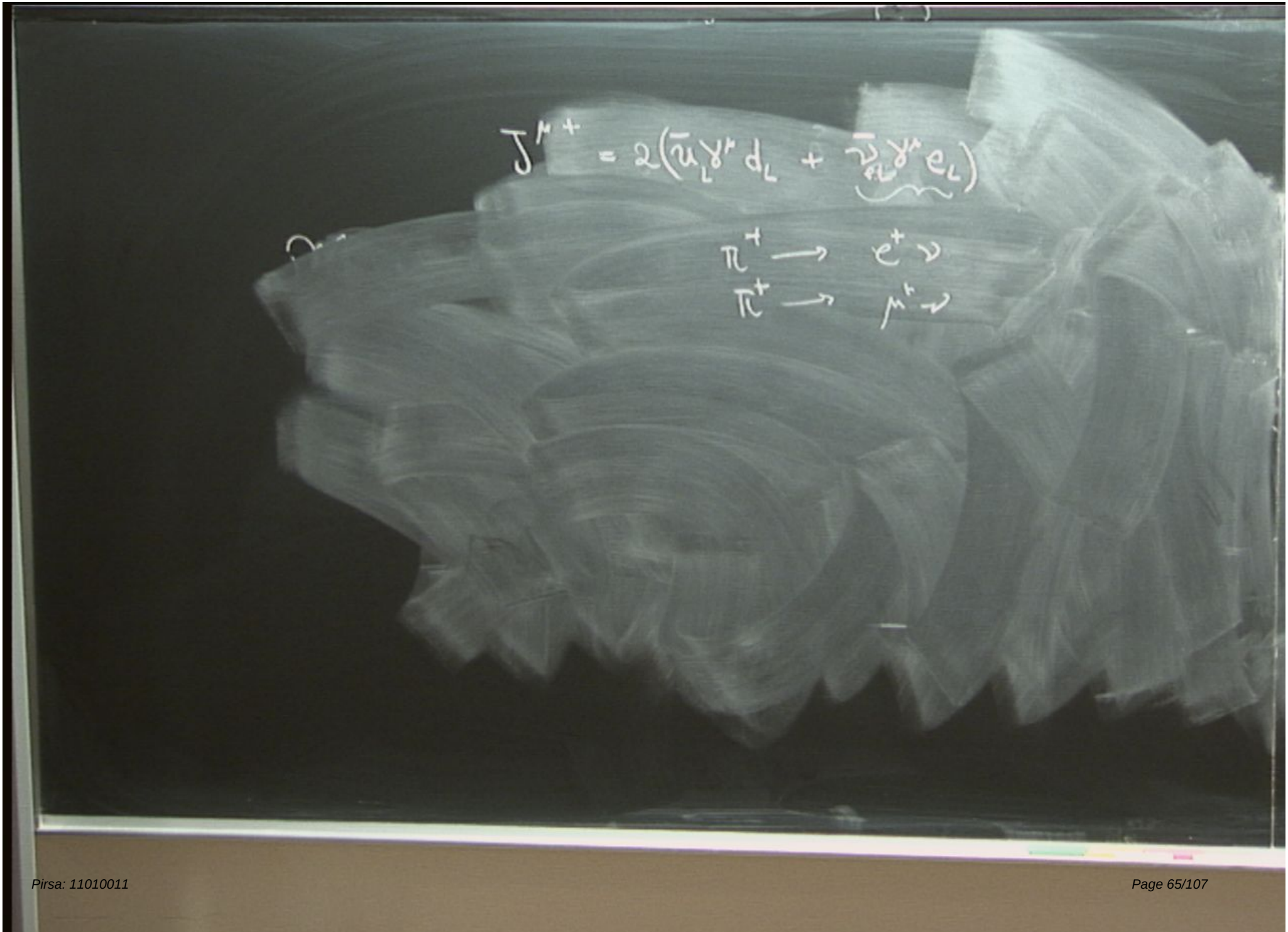

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{e_L} \gamma^\mu e_L)$
$\frac{4}{\sqrt{2}} G_F \; \bar{u}_L(\nu_\lambda) \bar{\sigma}^\mu u_L(\mu) \; \bar{u}_L(e) \bar{\sigma}_\mu v(\nu_\lambda)$
ν_μ
e_L
ν_e
W
$I = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$\int_0^1 dx_e \int_{1-x_e}^1 dy_{\bar{\nu}} \; x_{\bar{\nu}}(1-x_{\bar{\nu}})$
$\int_0^1 dx_e \left(\frac{x_e^2}{2} - \frac{x_e^3}{3} \right)$
x_e
τ^-
e
τ
μ
ν_τ
ν_e
x_e^2

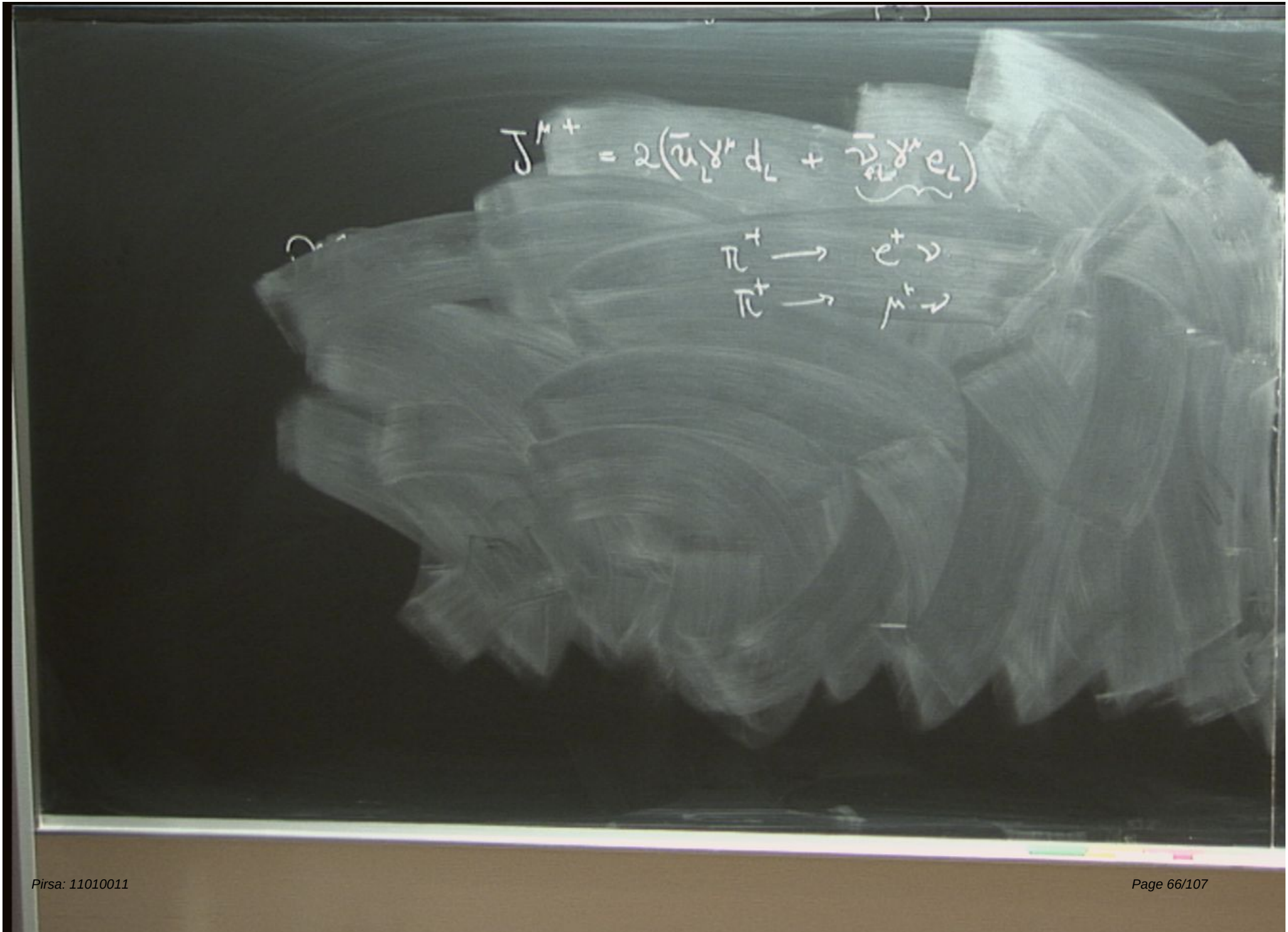

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$\frac{4}{\sqrt{2}} G_F \; \bar{u}_L(\nu_\lambda) \bar{\sigma}^\mu u_L(\mu) \; \bar{u}_L(e) \bar{\sigma}_\mu u(\nu_\lambda)$
ν_μ
e_L
ν_e
W
$I_- = \frac{G_F^2 m_\mu^5}{192\pi^3}$
$G_F = 1.16637$
$\int_0^1 dx_e \int_{1-x_e}^1 dx_{\bar{\nu}} \; x_{\bar{\nu}}(1-x_{\bar{\nu}})$
$\int_0^1 dx_e \left(\frac{x_e^2}{2} - \frac{x_e^3}{3} \right)$
x_e
τ^-
e
τ
ν
ν
μ
τ
$\bar{\nu}_\lambda$
ν_τ
$\bar{u}$
d
τ
ν_τ
$\frac{d\Gamma}{dx_e} \sim x_e^2$

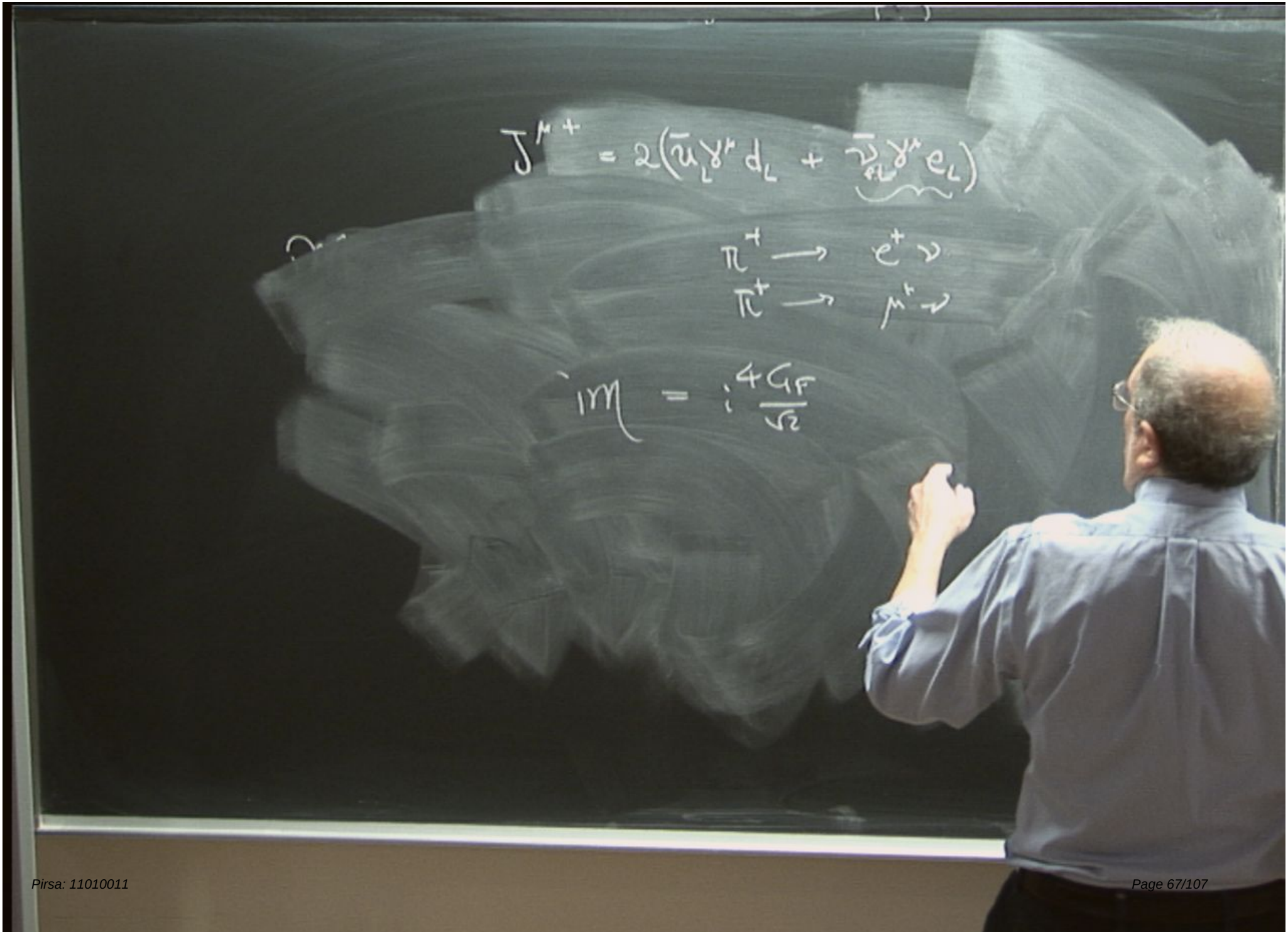

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
μ
$\bar{\nu}_e$
$\bar{\nu}_e$
ν_μ
e_L
$1-\cos\theta$
$\frac{G_F^2 m_\mu^5}{192\pi^3}$
1.16637
$\sim$
x_e^2

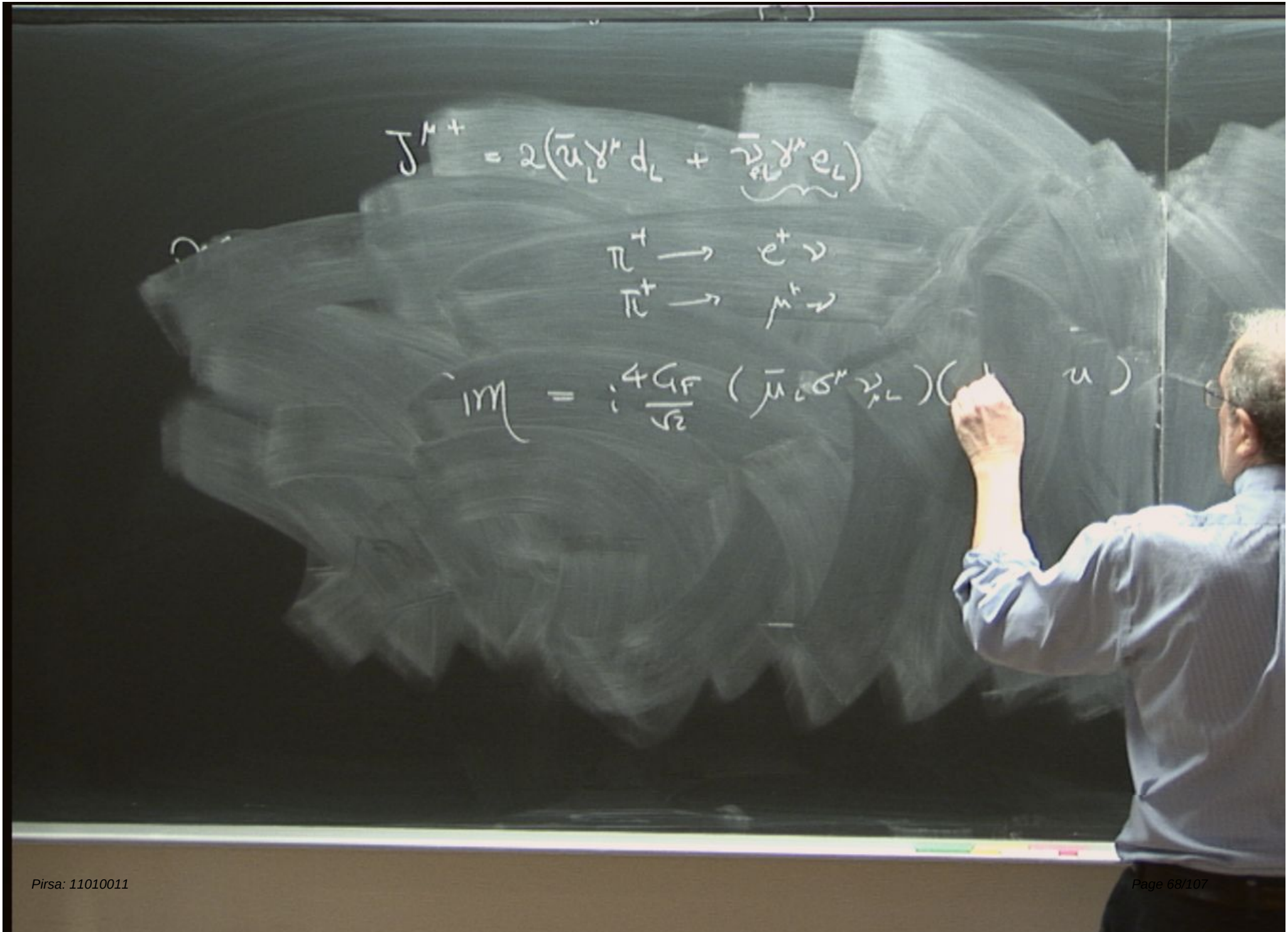

$\frac{G_F^2 m_\mu^5}{192\pi^3}$
$\times 10^{-5} / GeV^2$
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e \cdot p_\nu)^{\frac{1}{2}}$
$= [(p_e+p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar\nu})^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2p_\mu p_{\bar\nu})^{\frac{1}{2}}$
$= (m^2(1-x_{\bar\nu}))^{\frac{1}{2}}$
$2x_e$

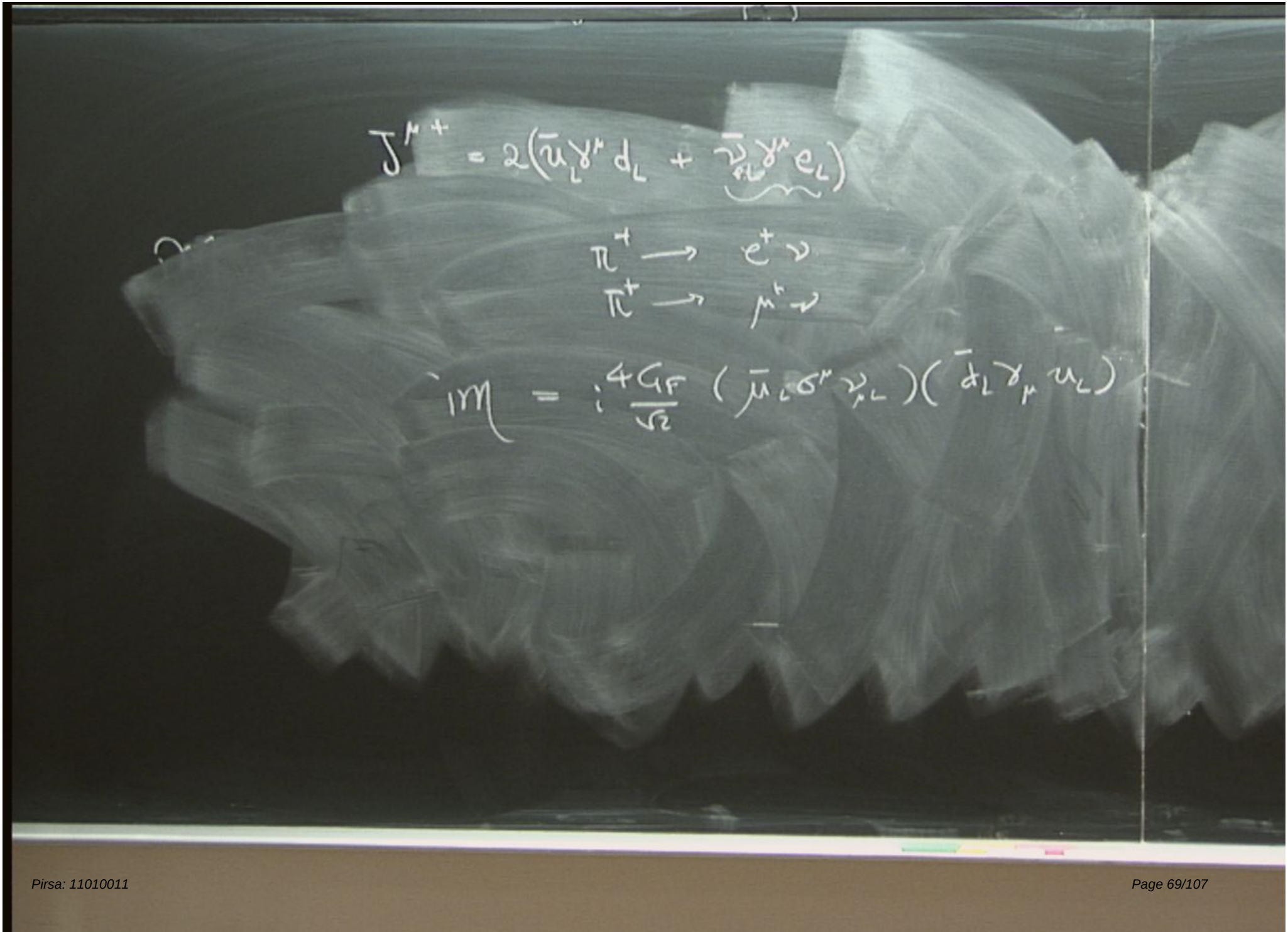

$\frac{G_F^2 m_\mu^5}{192\pi^3}$
$1.16637 \pm .00001 \times 10^{-5}/\mathrm{GeV}^2$
$\sim x_e^2\left(1-\frac{2x_e}{3}\right)$
x_e
$\sqrt{2E_\nu}\begin{pmatrix}-1\\0\end{pmatrix}$
$(2p_e\cdot p_\nu)^{\frac{1}{2}} = [(p_e+p_\nu)^2]^{\frac{1}{2}} = [(p_\mu - p_{\bar{\nu}})^2]^{\frac{1}{2}}$
$= (m_\mu^2 - 2p_\mu p_{\bar{\nu}})^{\frac{1}{2}}$
$(1-x_{\bar{\nu}}))$

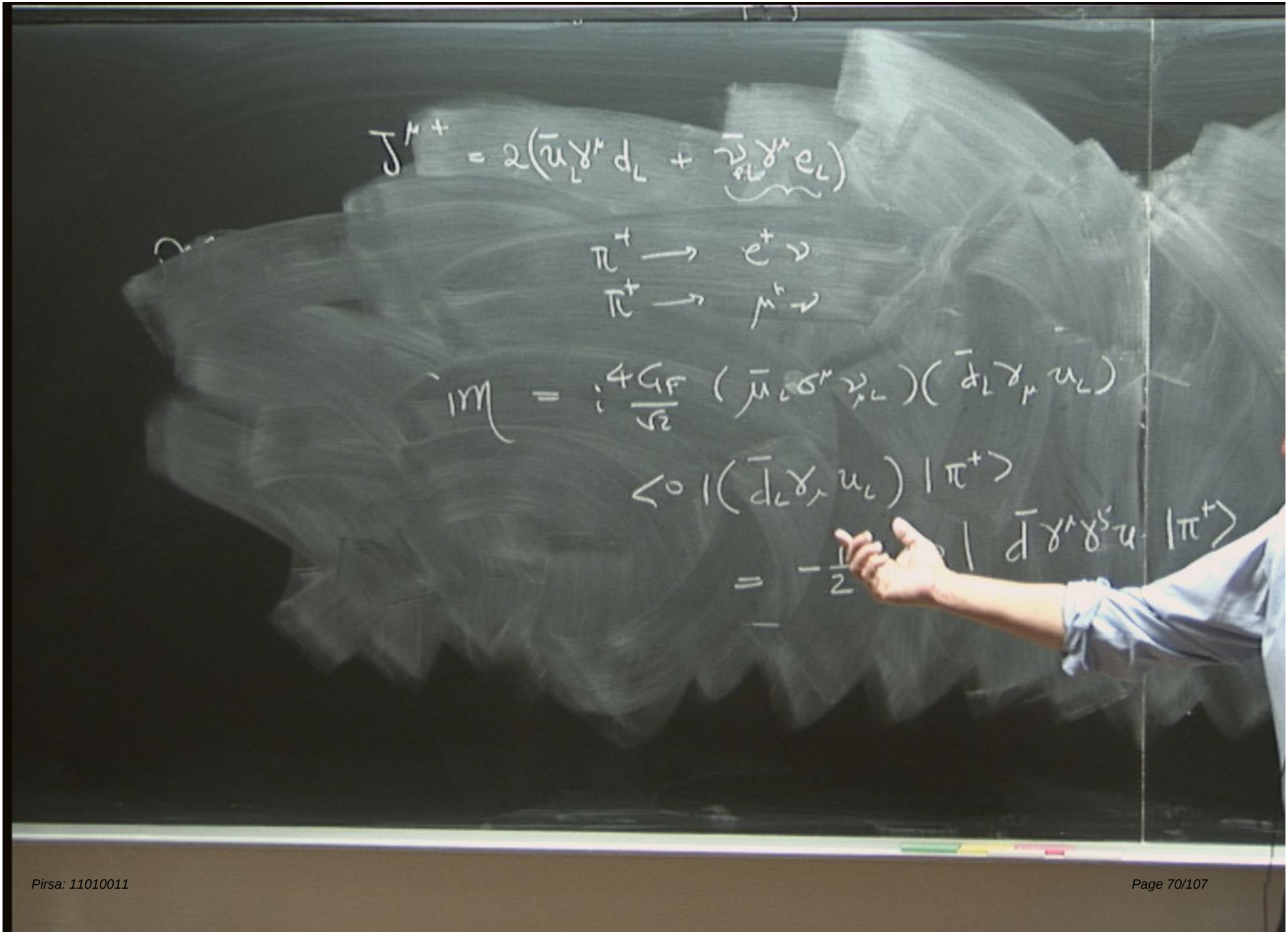

$J^{\mu +} = 2(\bar{u}\gamma^\mu \frac{1}{2}(1-\gamma^5) d + \bar{\nu}_e \gamma^\mu \frac{1}{2}(1-\gamma^5) e)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_L \gamma^\mu e_L)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$
$iM = i \frac{4 G_F}{\sqrt{2}}$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$
$i\mathcal{M} = i\frac{4G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\quad u)$


$J^{\mu +} = 2(\bar{\nu}_L \gamma^\mu e_L + \bar{\nu}_\mu \gamma^\mu \mu_L)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$
$iM = \frac{4G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_L)(\bar{\nu}_L \gamma_\mu u_L)$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$
$i\mathcal{M} = i\frac{4G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$
$\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$
$= -\frac{1}{2} \langle | \bar{d} \gamma^\mu \gamma^5 u | \pi^+ \rangle$

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

$\pi^+ \longrightarrow e^+ \nu$

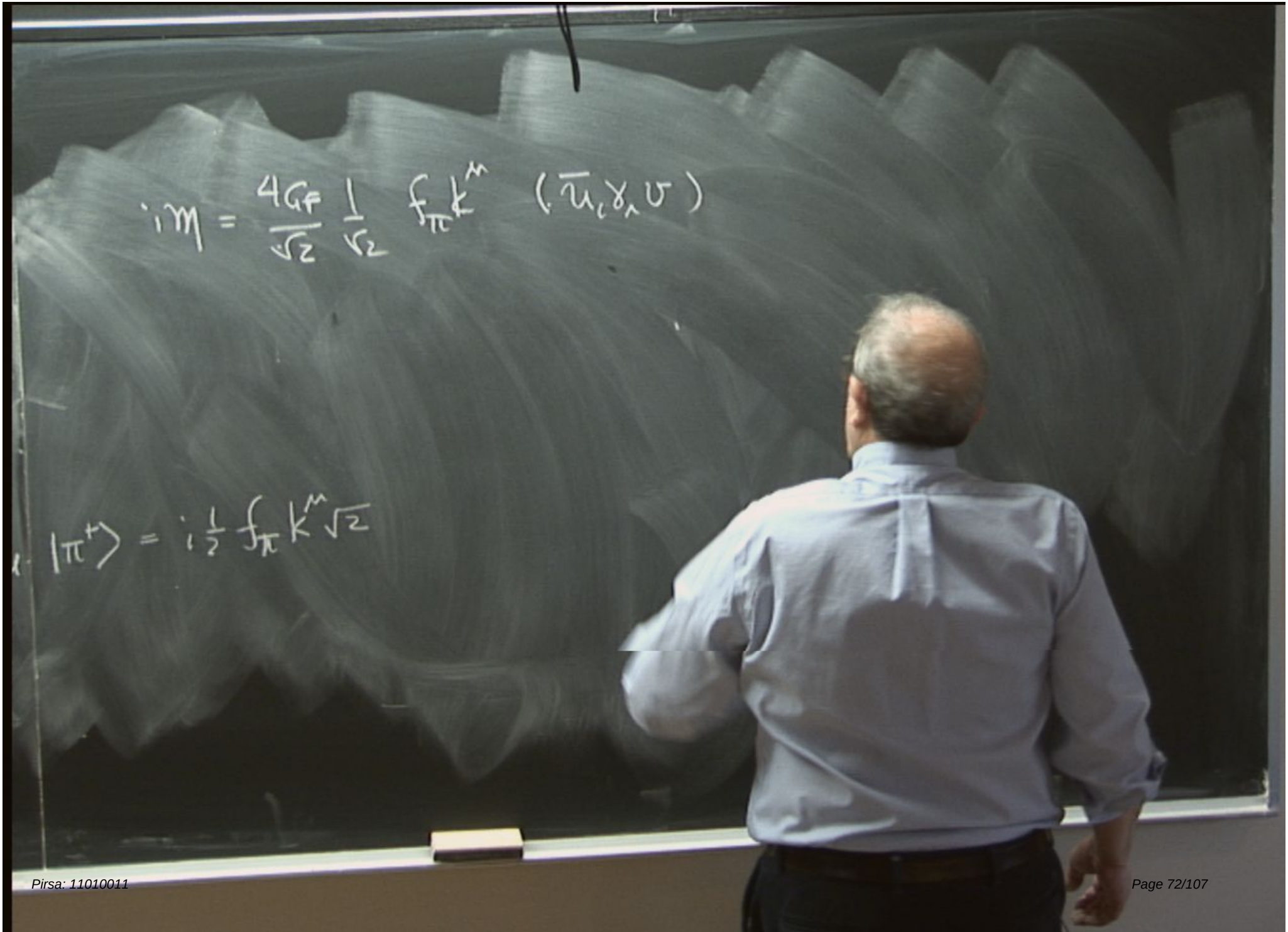
$\pi^+ \longrightarrow \mu^+ \nu$

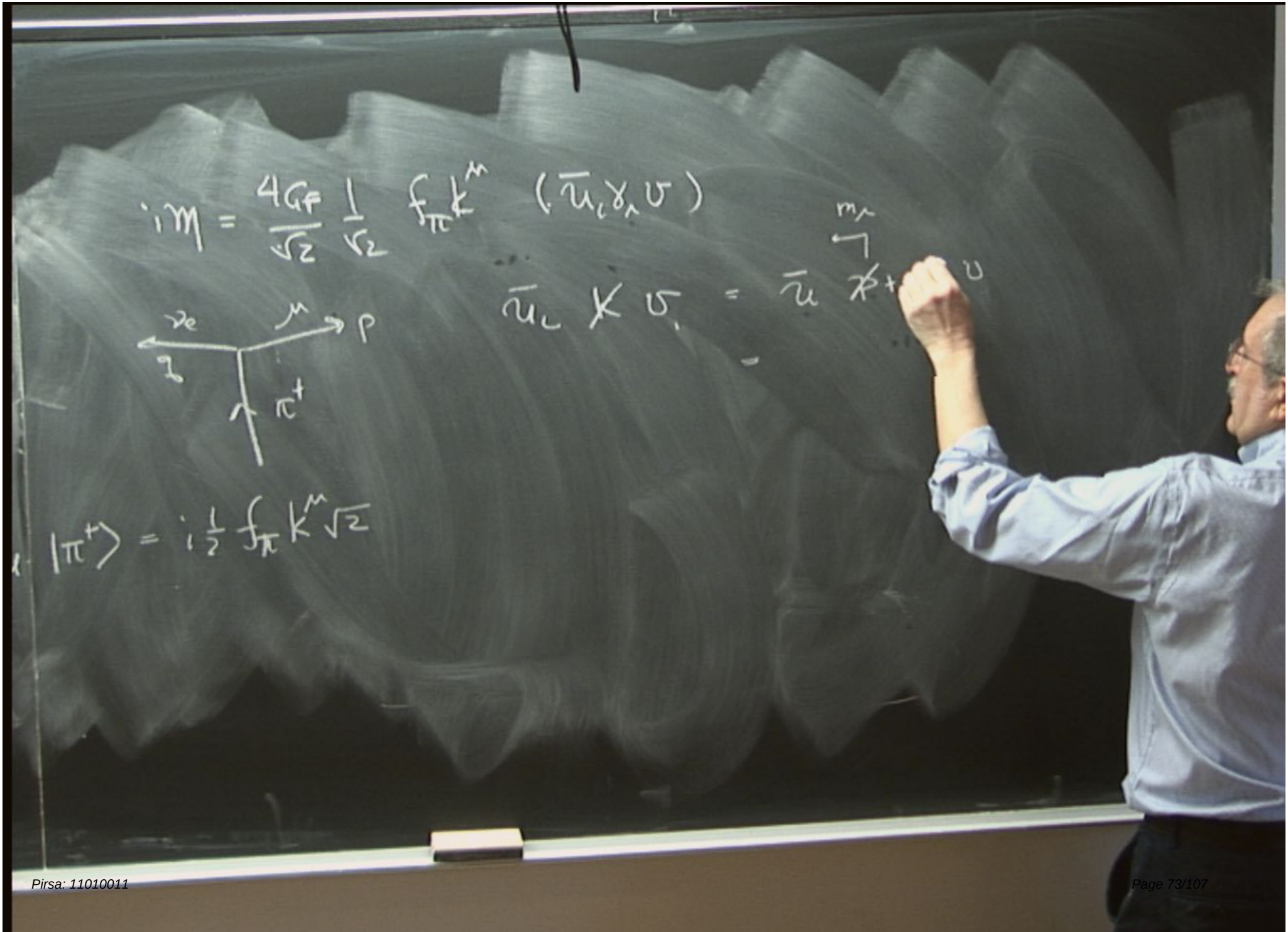
$iM = i \frac{4 G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$

$\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$

$= -\frac{1}{2} \langle 0 | \bar{d} \gamma^\mu \gamma^5 u | \pi^+ \rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$

$P_L = \frac{1 - \gamma^5}{2}$


$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu \; (\bar{u}_i \gamma_\lambda v)$
$|\pi^+\rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$

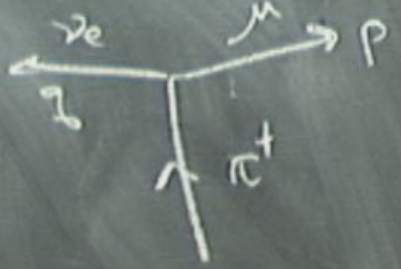

$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu (\bar{u}_\nu \gamma_\mu v)$
$\bar{u}_\nu \not{K} v_\mu = \bar{u}$
m_μ
ν_e
μ
p
π^+
$\langle 0 | \pi^+ \rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$

$$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu \, (\bar{u}_\nu \gamma_\mu v)$$

$m_\mu \quad 0$

$\bar{u}_L \not{K} v_L = \bar{u} \not{k} + \not{k}_0 \, v$

$= m_\mu \, \bar{u}_L v_L$



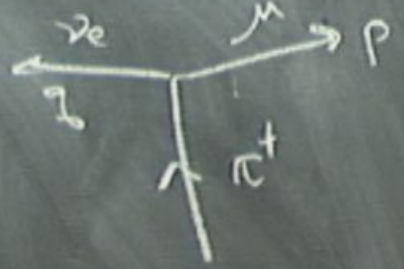
$|\pi^+\rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$

$$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu (\bar{u}_\nu \gamma_\mu v)$$

$m_\mu \leftarrow \quad \rightarrow 0$

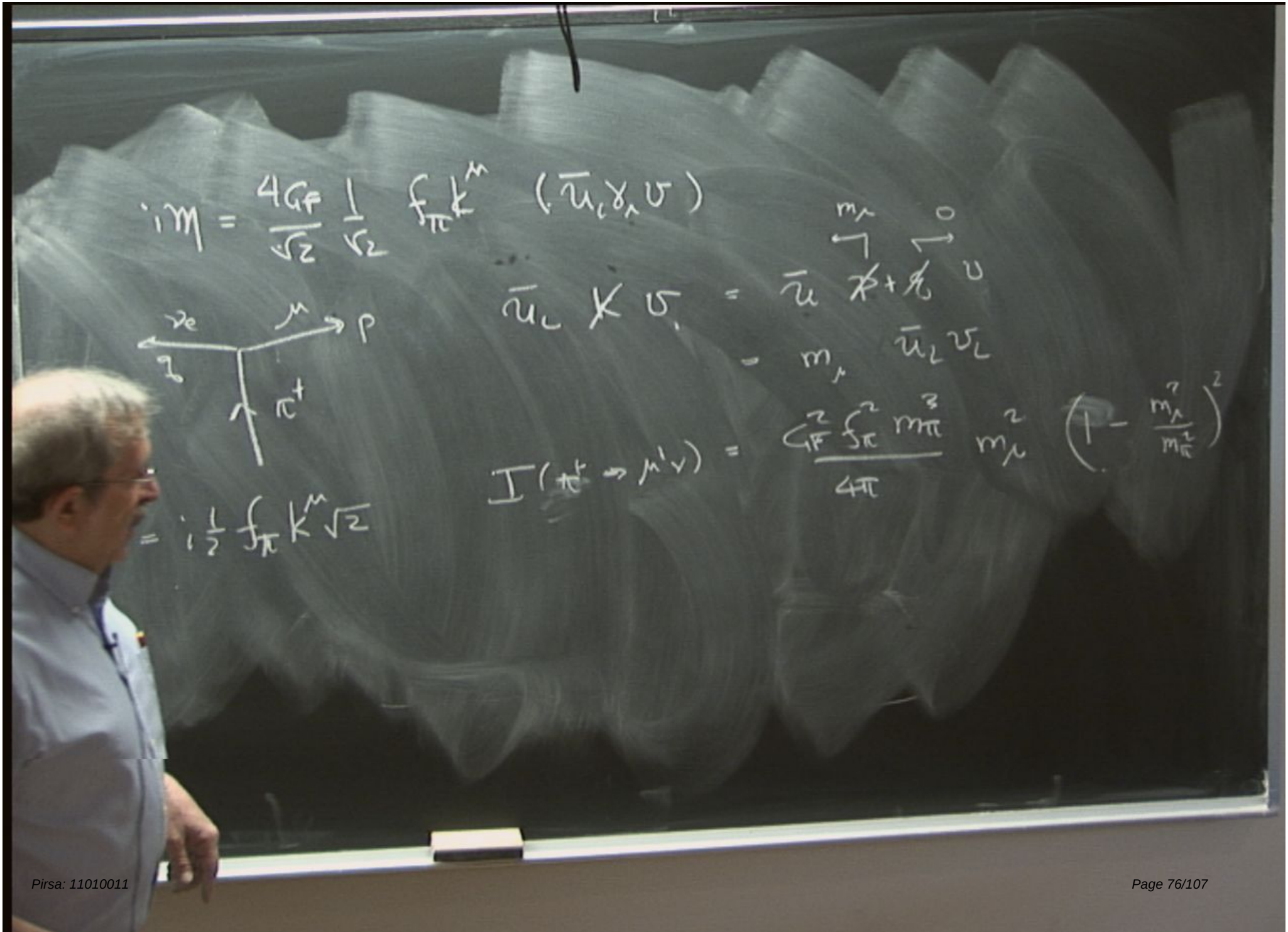
$$\bar{u}_\nu \not{K} v_\mu = \bar{u} \not{k} + \not{k}_0 \, v$$

$$- m_\mu \bar{u}_\nu v_\nu$$



$$\Gamma(\pi^+ \to \mu^+ \nu) = \frac{G_F^2 f_\pi^2 m_\pi}{4\pi} m_\mu^2$$

$$|\pi^+\rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$$

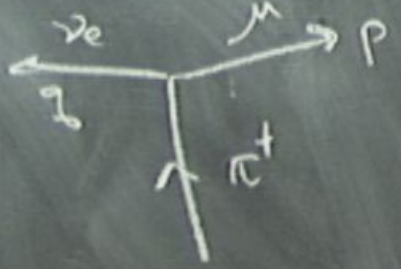

$iM = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu (\bar{u}_\nu \gamma_\mu v)$
$\bar{u}_L \not{K} v_L = \bar{u} \not{K} + \not{K}_0 v$
$- m_\mu \bar{u}_L v_L$
m_μ
0
ν_e
μ
p
n
π^+
$= i \frac{1}{2} f_\pi k^\mu \sqrt{2}$
$\Gamma(\pi^+ \to \mu^+ \nu) = \frac{G_F^2 f_\pi^2 m_\pi}{4\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$

$$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu \, (\bar{u}_\nu \gamma_\mu v)$$

$m_\mu \leftarrow \quad \rightarrow 0$

$$\bar{u}_L \not{K} v_L = \bar{u} \not{k} + \not{k}_0 \, v$$

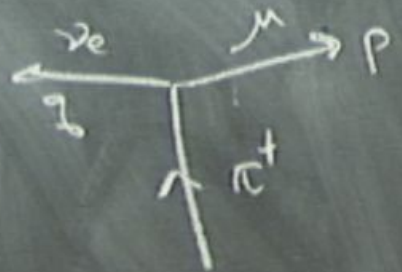
$$= m_\mu \, \bar{u}_L v_L$$



$$\Gamma(\pi^+ \to \mu^+ \nu) = \frac{G_F^2 f_\pi^2 m_\pi^3}{4\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$$

$$|\pi^+\rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$$

$$i\mathcal{M} = \frac{4G_F}{\sqrt{2}}\frac{1}{\sqrt{2}} f_\pi k^\mu \left(\bar{u}_L \gamma_\mu v\right)$$



$$\bar{u}_L \not{k}\, v = \bar{u}\, \overset{m_\mu}{\not{p}} + \overset{0}{\not{q}}\, v$$

$$= m_\mu\, \bar{u}_L v_L$$

$$\Gamma(\pi^+ \to \mu^+ \nu) = \frac{G_F^2 f_\pi^2 m_\pi^3}{4\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$$

$$|\pi^+\rangle = i\frac{1}{2} f_\pi k^\mu \sqrt{2}$$

$$\left(\frac{\Gamma \to e^+}{\Gamma \to \mu^+}\right) \sim \left(\frac{m_e}{m_\mu}\right)^2 \left(\;\right) \sim 1.28\times10^{-4}$$

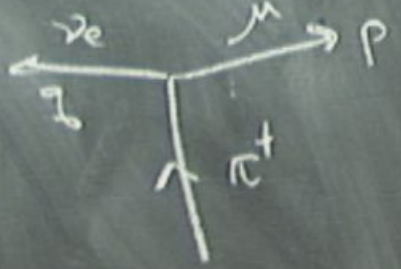
(expt 1.23×10^{-4})

$$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\sqrt{2}} f_\pi k^\mu \; (\bar{u}_\nu \gamma_\mu v)$$

$m_\mu \leftarrow \quad \rightarrow 0$

$$\bar{u}_L \not{K} v_L = \bar{u} \not{k} + \not{k}_0 \; v$$

$$= m_\mu \; \bar{u}_L v_L$$



$$\Gamma(\pi^+ \to \mu^+ \nu) = \frac{G_F^2 f_\pi^2 m_\pi^3}{4\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$$

$$|\pi^+\rangle = i \frac{1}{2} f_\pi k^\mu \sqrt{2}$$

$$\left(\frac{\Gamma \to e}{\Gamma \to \mu}\right) \sim \left(\frac{m_e}{m_\mu}\right)^2 (\;) \sim 1.28 \times 10^{-4}$$

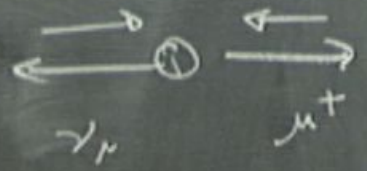
(expt 1.23×10^{-4})

$$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$$

π^+

$\pi^+ \longrightarrow e^+ \nu$

$\pi^+ \longrightarrow \mu^+ \nu$



$$\frac{4G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$$

$$\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$$

$$= -\frac{1}{2} \langle 0 | \bar{d} \gamma^\mu \gamma^5 u$$

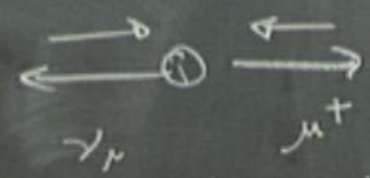
$$P_L = \frac{1-\gamma^5}{2}$$

$$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \underbrace{\bar{\nu}_{eL} \gamma^\mu e_L})$$

π^+

$\pi^+ \longrightarrow e^+ \nu$

$\pi^+ \longrightarrow \mu^+ \nu$



$$i \frac{4 G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$$

helicity-violating $\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$

$$= -\frac{1}{2} \langle 0 | \bar{d} \gamma^\mu \gamma^5 u$$

$$\left(\frac{m_\mu}{E_\mu}\right)$$

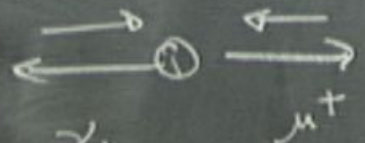
$$P_L = \frac{1-\gamma^5}{2}$$

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

π^+

$\pi^+ \longrightarrow e^+ \nu$

$\pi^+ \longrightarrow \mu^+ \nu$



$\frac{4 G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$

helicity suppression

$\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$

$= -\frac{1}{2} \langle 0 | \bar{d} \gamma^\mu \gamma^5 u$

$\left(\frac{m_\mu}{E_\nu}\right)$

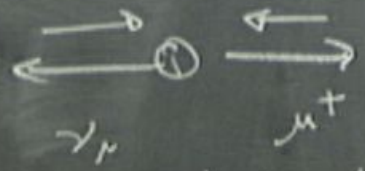
$P_L = \frac{1 - \gamma^5}{2}$

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$

π^+

$\pi^+ \longrightarrow e^+ \nu$

$\pi^+ \longrightarrow \mu^+ \nu$



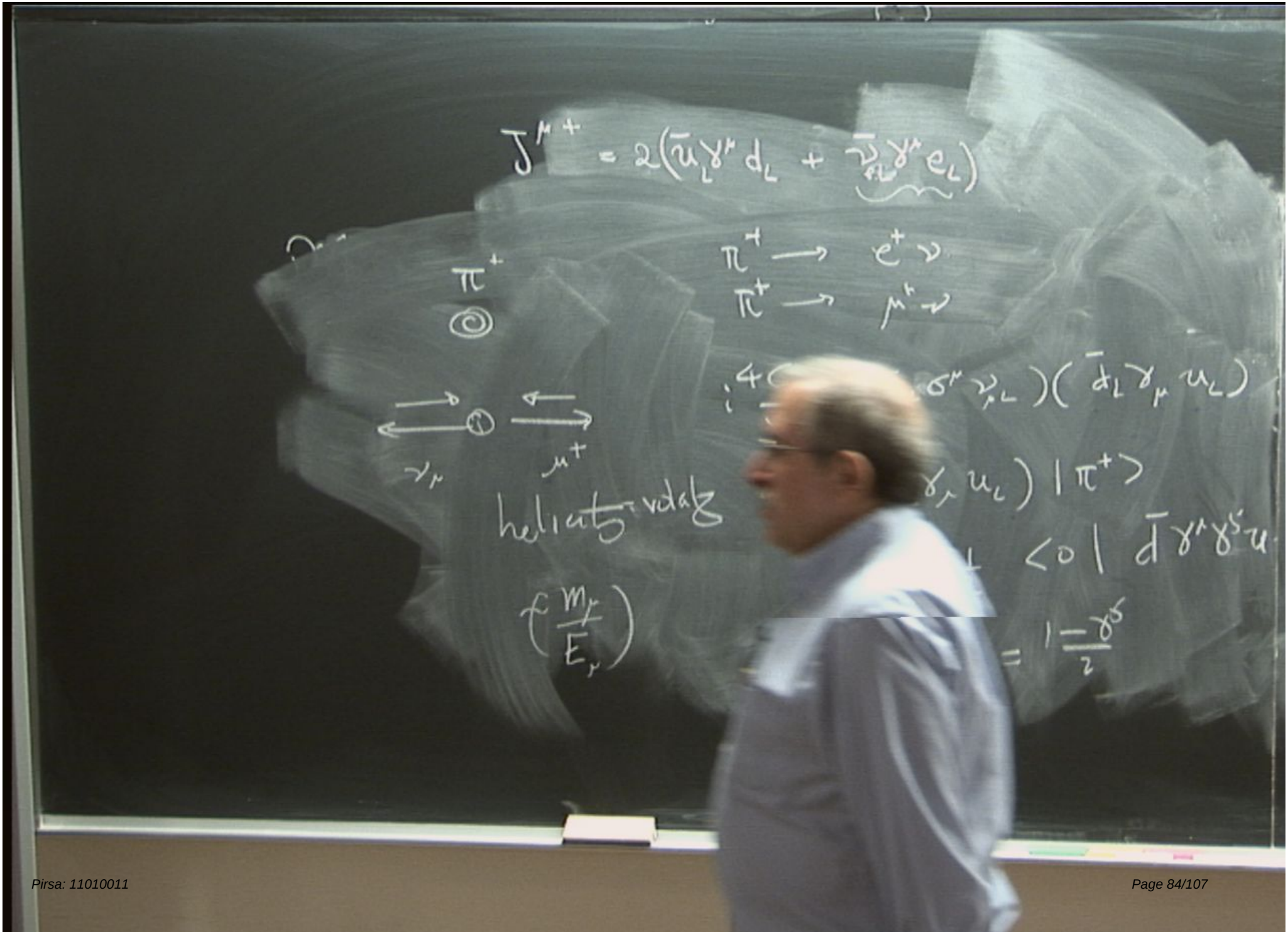
$\frac{4 G_F}{\sqrt{2}} (\bar{\mu}_L \sigma^\mu \nu_{\mu L})(\bar{d}_L \gamma_\mu u_L)$

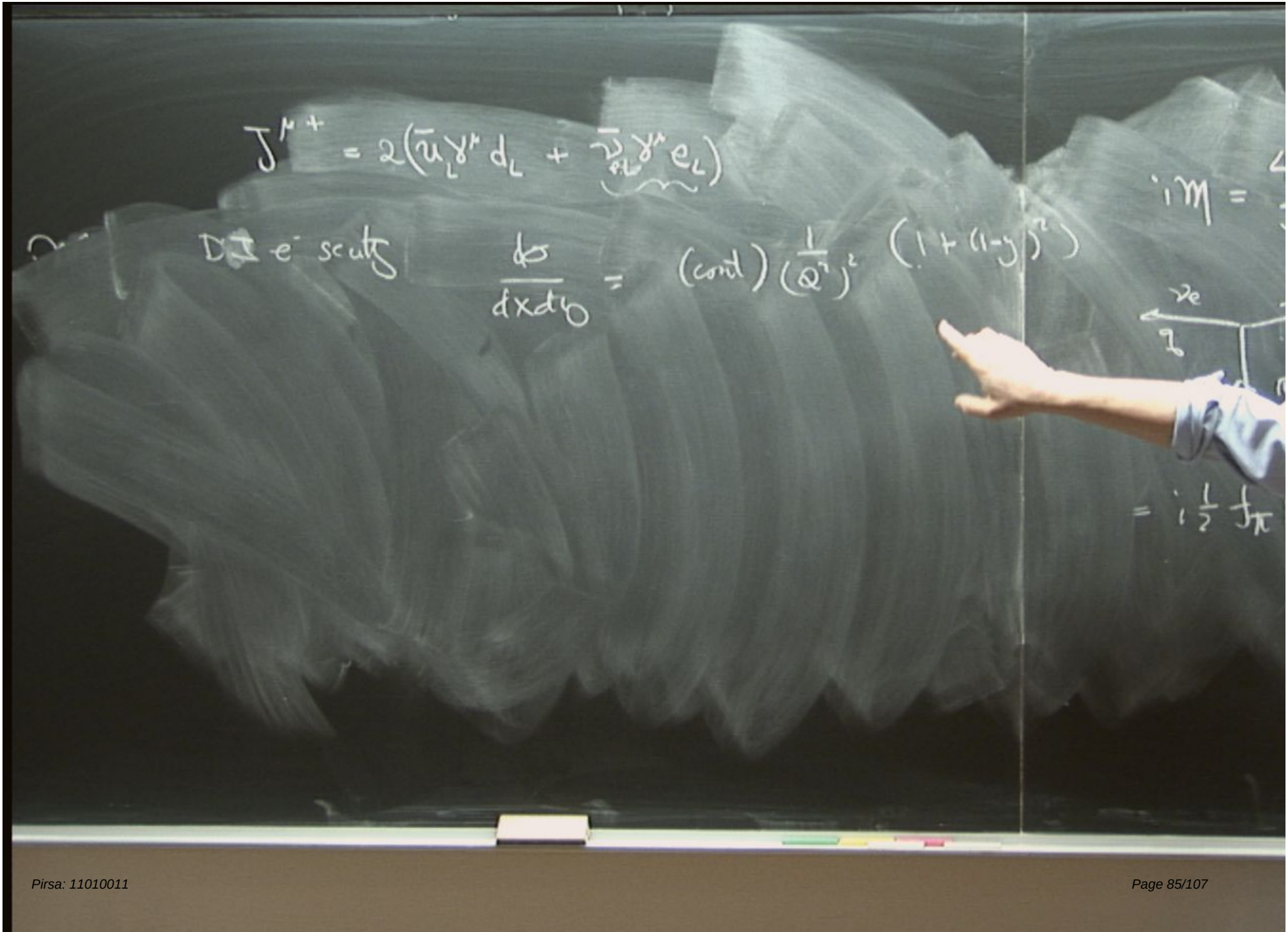
helicity $\langle 0 | (\bar{d}_L \gamma_\mu u_L) | \pi^+ \rangle$

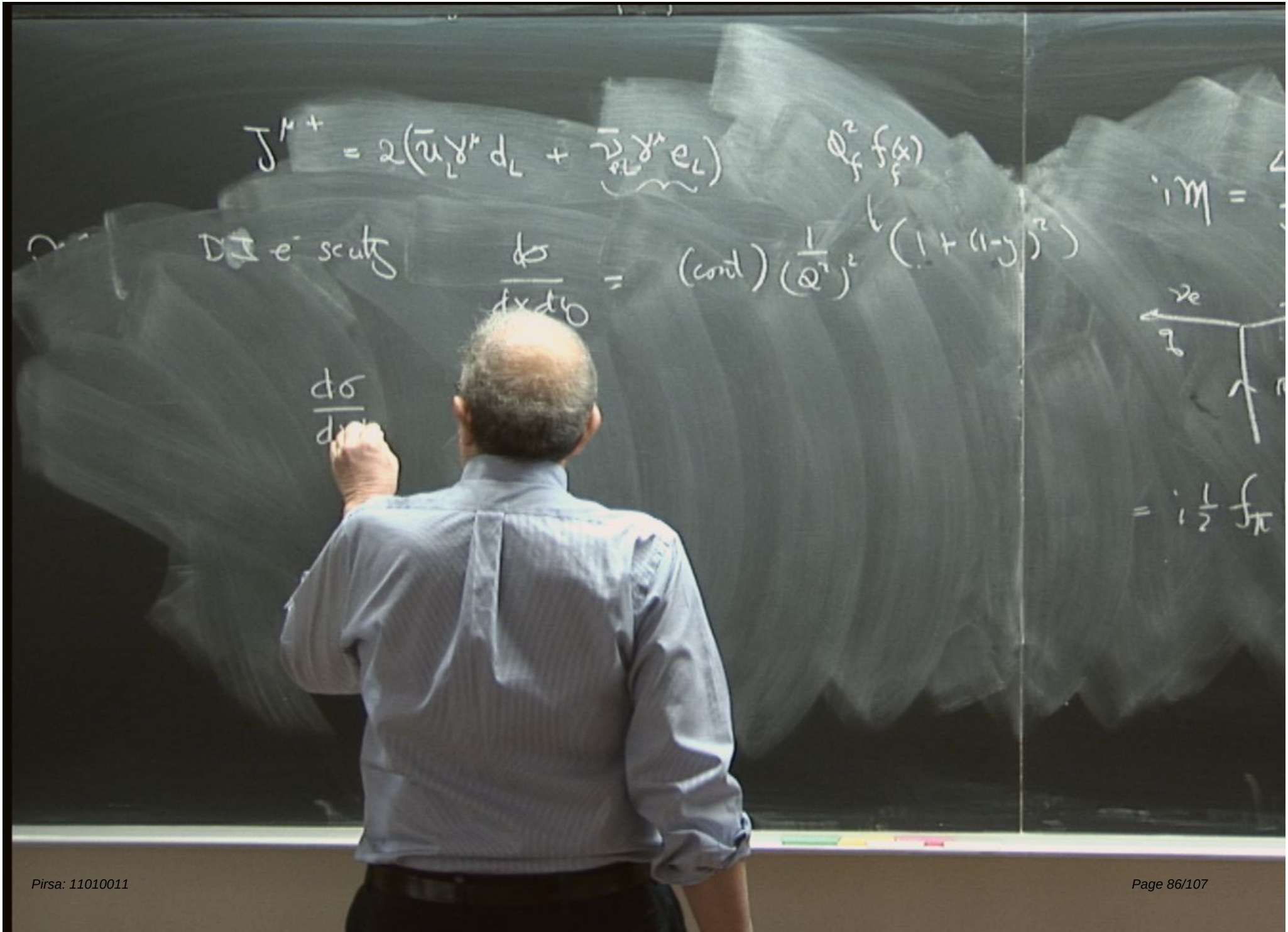
$= -\frac{1}{2} \langle 0 | \bar{d} \gamma^\mu \gamma^5 u$

$f\left(\frac{m_\mu}{E_\mu}\right)$

$P_L = \frac{1 - \gamma^5}{2}$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
π^+
$\pi^+ \longrightarrow e^+ \nu$
$\pi^+ \longrightarrow \mu^+ \nu$
ν_μ
μ^+
helicity
$\left(\frac{m_\mu}{E_\mu}\right)$
$\gamma_\mu u_L) |\pi^+>$
$<0| \bar{d} \gamma^\mu \gamma^5 u$
$= \frac{1-\gamma^5}{2}$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
D.I. e⁻ scatt
$\frac{d\sigma}{dx\,dy} = (\text{const})\left(\frac{1}{Q^2}\right)^2 \left(1 + (1-y)^2\right)$
ν_e
$= i\frac{1}{2} f_\pi$

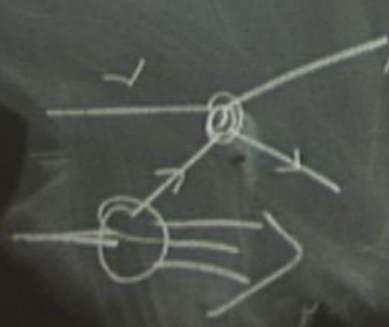

$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$Q_f^2 f_f(x)$
DIS e^- scatt
$\frac{d\sigma}{dx\,dQ^2} = (\text{const}) \left(\frac{1}{Q^2}\right)^2 \left(1 + (1-y)^2\right)$
$\frac{d\sigma}{d}$
ν_e
$= i \frac{1}{2} f_\pi$

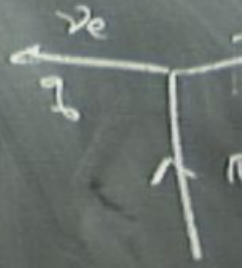
$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{e,L} \gamma^\mu e_L)$ $\quad Q_f^2 f_f(x)$

$i\mathcal{M} =$

D.I. e^- scatt $\quad \frac{d\sigma}{dx\,dy} = (\text{const})\left(\frac{1}{Q^2}\right)^2 \left(1 + (1-y)^2\right)$

$\frac{d\sigma}{dx\,dy}(\nu p \to \mu^- X)$



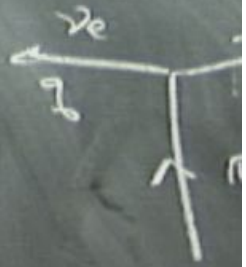


$= i\frac{1}{2} f_\pi$

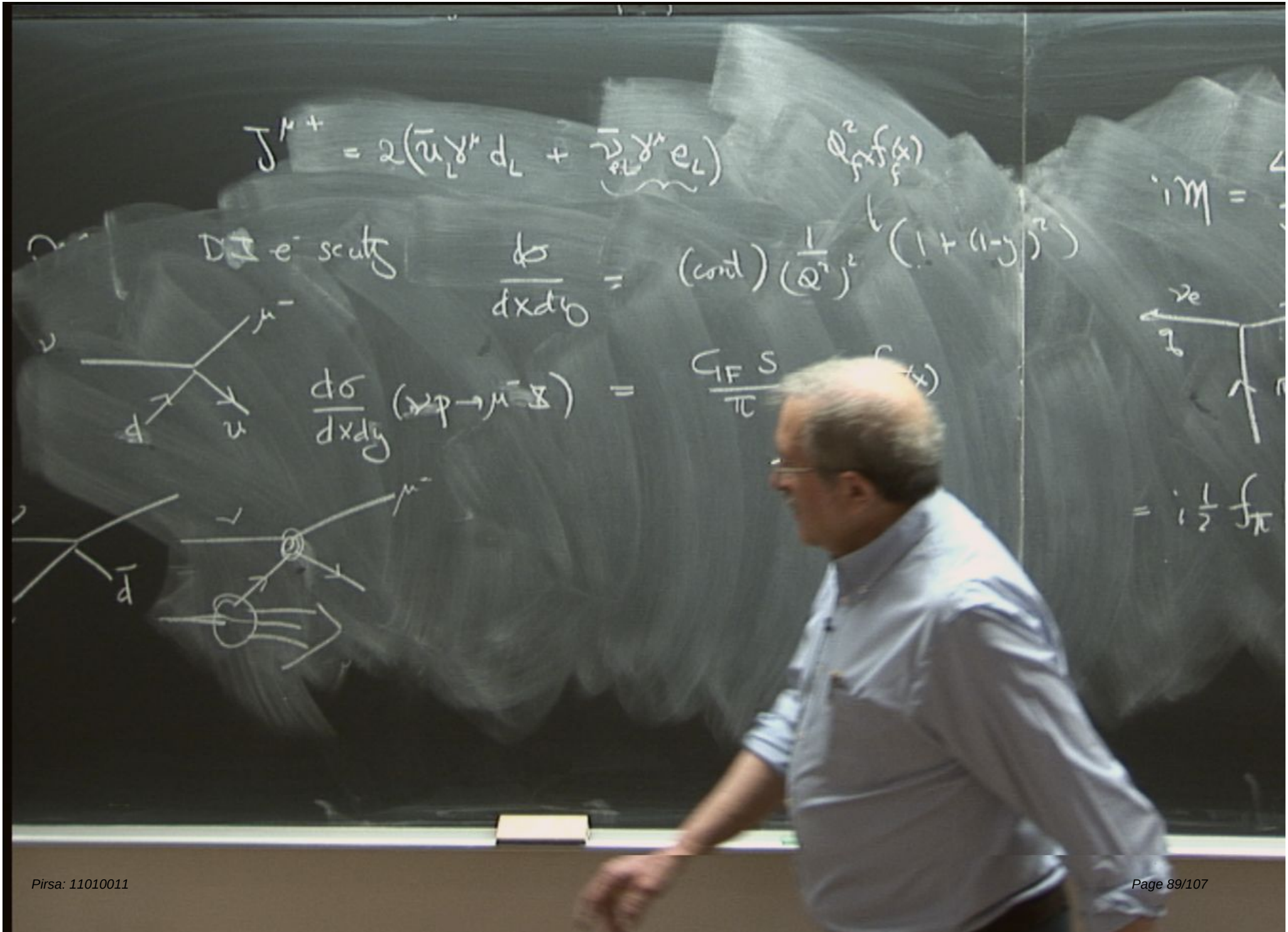
$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$ $Q_f^2 f_f(x)$

D.I. e^- scatt $\frac{d\sigma}{dx dy} = (\text{const}) \left(\frac{1}{Q^2}\right)^2 \left(1 + (1-y)^2\right)$

$\frac{d\sigma}{dx dy}(\nu p \to \mu^- X) = \frac{G_F^2 S}{\pi}$



$= i \frac{1}{2} f_\pi$


$J^{\mu +} = 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$Q^2 f_i(x) f_j(x)$
$\frac{d\sigma}{dx dy} = (\text{const}) \left(\frac{1}{Q^2}\right)^2 (1 + (1-y)^2)$
$\frac{d\sigma}{dx dy}(\nu p \to \mu^- X) = \frac{G_F^2 s}{\pi}$
ν_e
μ^-
ν
d
$\bar{d}$

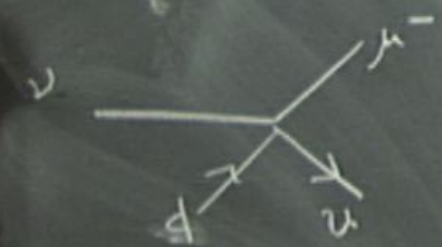
$$J^{\mu +} = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L\right)$$

$Q_f^2 x f_f(x)$

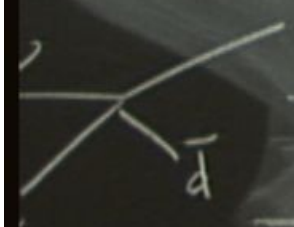
$i\mathcal{M} =$

DIS e^- scatt

$$\frac{d\sigma}{dx\,dy} = (\text{const}) \frac{1}{(Q^2)^2} \left(1 + (1-y)^2\right)$$



$$\frac{d\sigma}{dx\,dy}(\nu p \to \mu^- X) = \frac{G_F s}{\pi}\left[x f_d(x) + x f_{\bar{u}}(x)(1-y)^2\right]$$



$= 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$ $\quad Q_f^2 f_f(x)$

$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \; f_\pi k^\mu$ (

scaling $\quad \frac{d\sigma}{dx\,dy} = (\text{const}) \left(\frac{1}{Q^2}\right)^2 \; \frac{1}{2}\left(1 + (1-y)^2\right)$

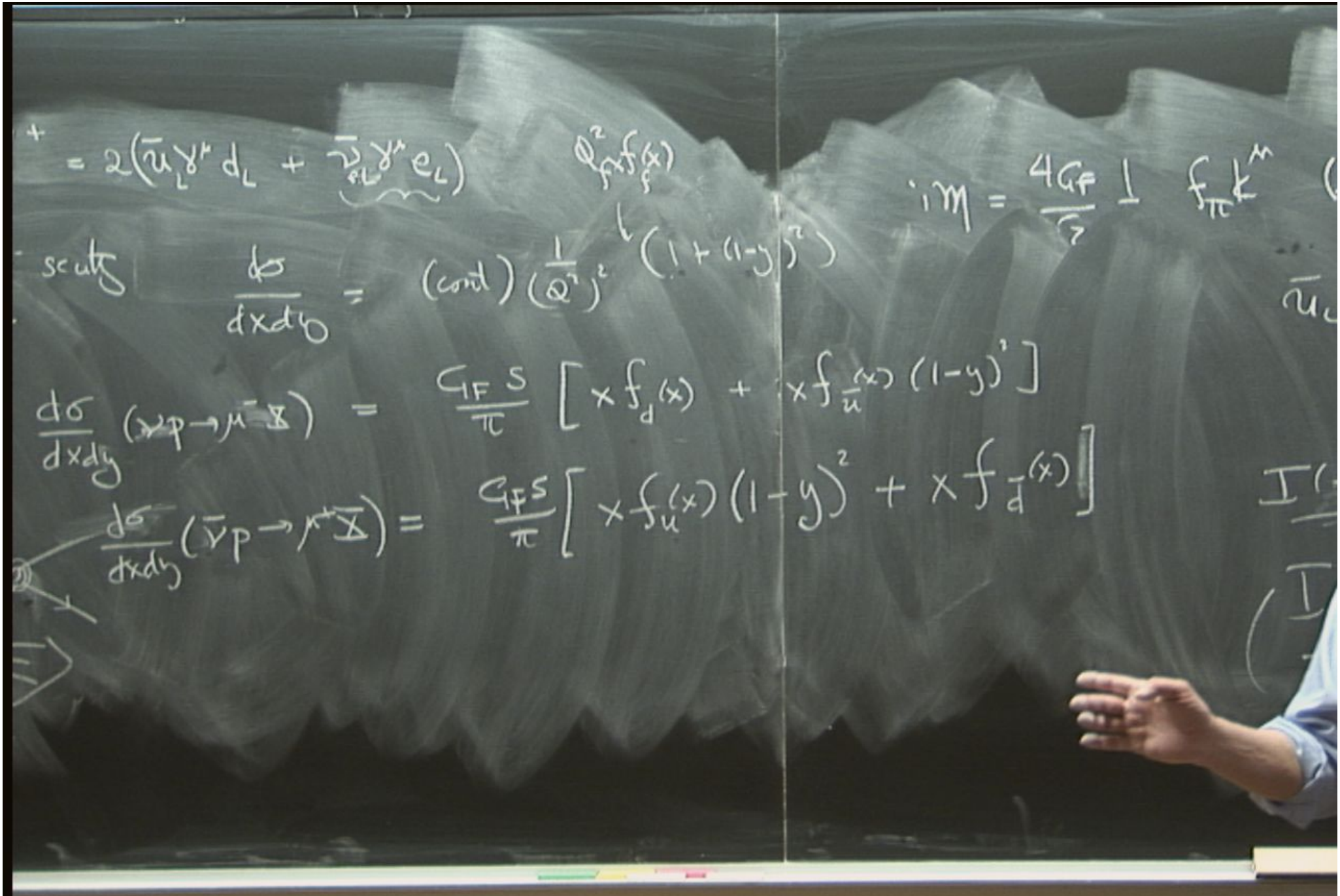
$\bar{u}_L$

$$\frac{d\sigma}{dx\,dy}(\nu p \to \mu^- X) = \frac{G_F^2 s}{\pi}\left[x f_d(x) + x f_{\bar{u}}(x)\,(1-y)^2\right]$$

$$\frac{d\sigma}{dx\,dy}(\bar{\nu} p \to \mu^+ X) = \frac{G_F^2 s}{\pi}\left[x f_u(x)\,(1-y)^2 + x f_{\bar{d}}(x)\right]$$

$I($

$\left(\frac{I}{\pi}\right.$

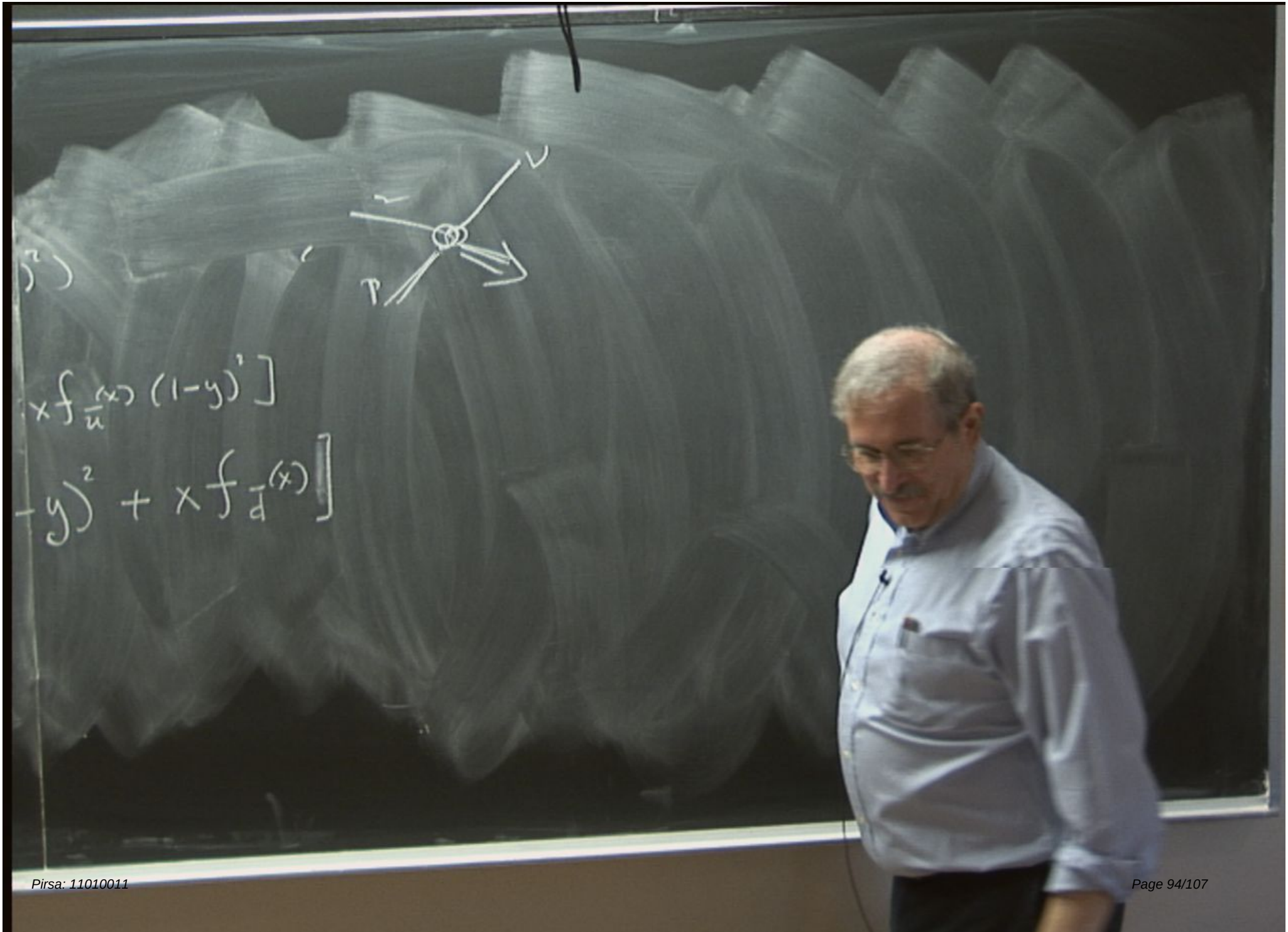

$= 2(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{eL} \gamma^\mu e_L)$
$Q_f^2 x f_f(x)$
$(1 + (1-y)^2)$
$i\mathcal{M} = \frac{4G_F}{\sqrt{2}} \frac{1}{\ } f_\pi k^\mu$
scuts
$\frac{d\sigma}{dx\,dy} = (\text{const}) \frac{1}{(Q^2)^2}$
$\frac{d\sigma}{dx\,dy}(\nu p \to \mu^- X) = \frac{G_F s}{\pi}\left[x f_d(x) + x f_{\bar{u}}(x)(1-y)^2\right]$
$\frac{d\sigma}{dx\,dy}(\bar{\nu} p \to \mu^+ X) = \frac{G_F s}{\pi}\left[x f_u(x)(1-y)^2 + x f_{\bar{d}}(x)\right]$

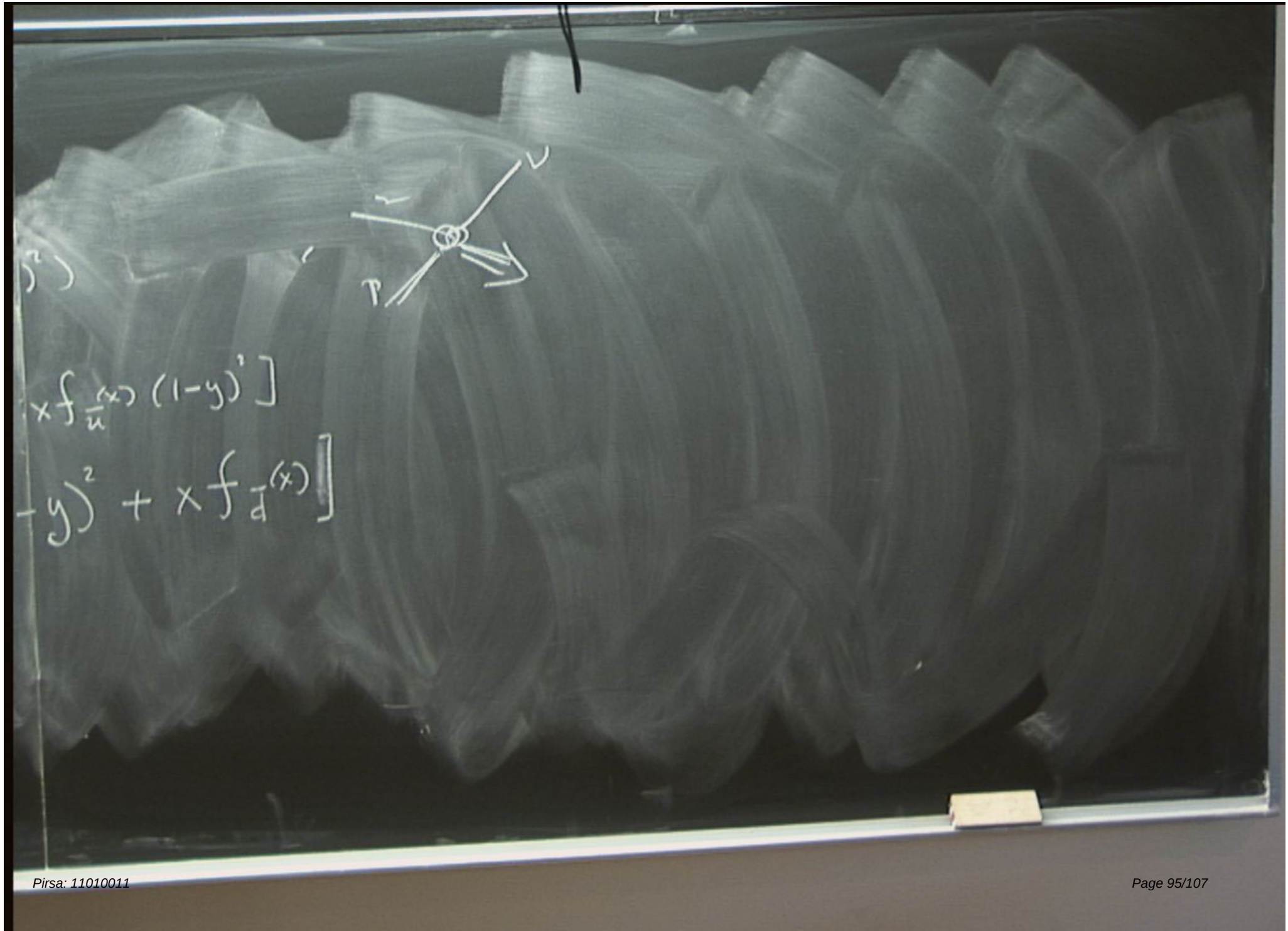
$$+ = 2\left(\bar{u}_L \gamma^\mu d_L + \bar{\nu}_{e_L} \gamma^\mu e_L\right) \qquad Q_f^2 x f_f(x)$$

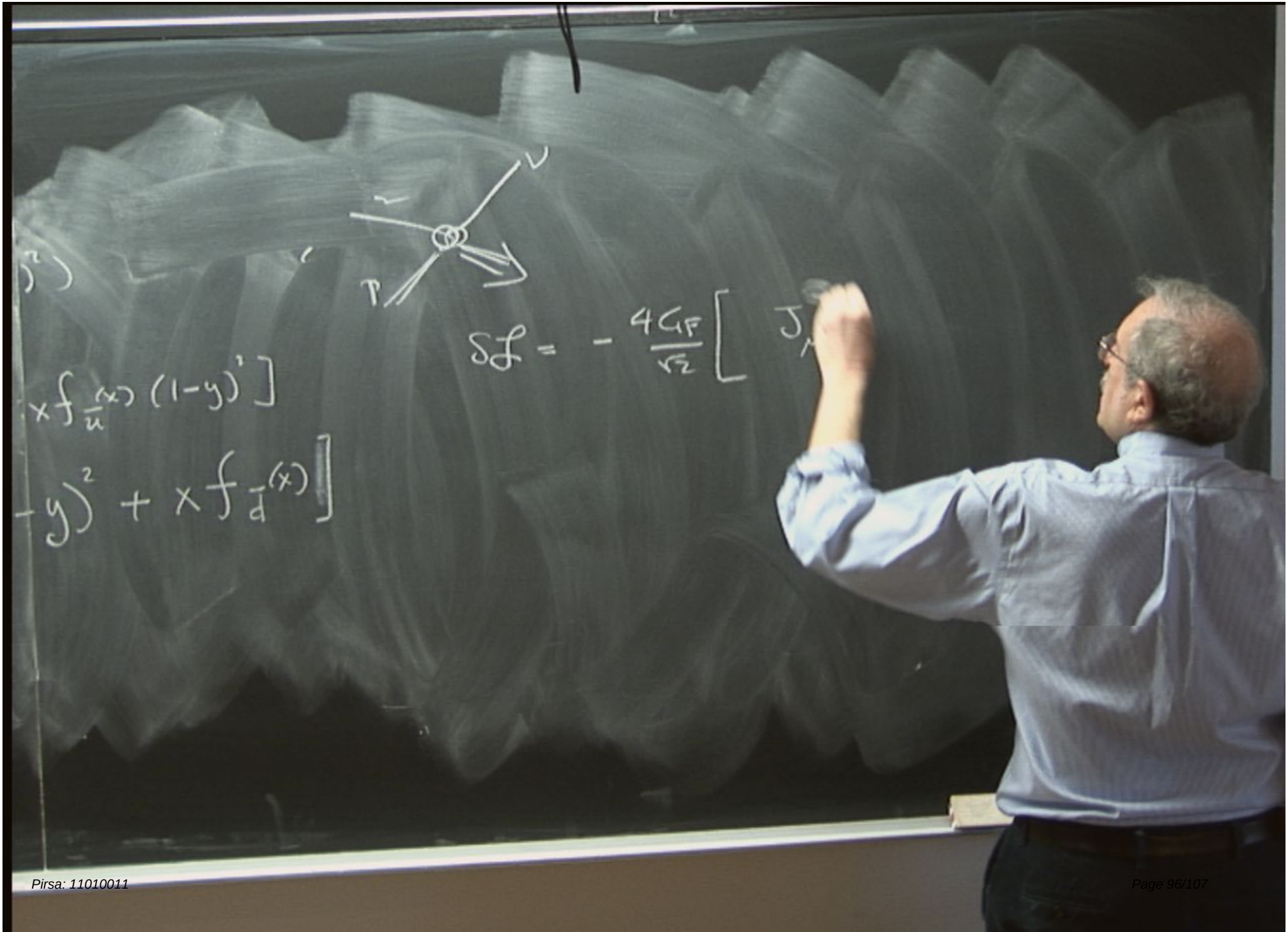
scatg $\quad \frac{d\sigma}{dx\,dy} = (\text{const}) \left(\frac{1}{Q^2}\right)^2 \left(1 + (1-y)^2\right)$

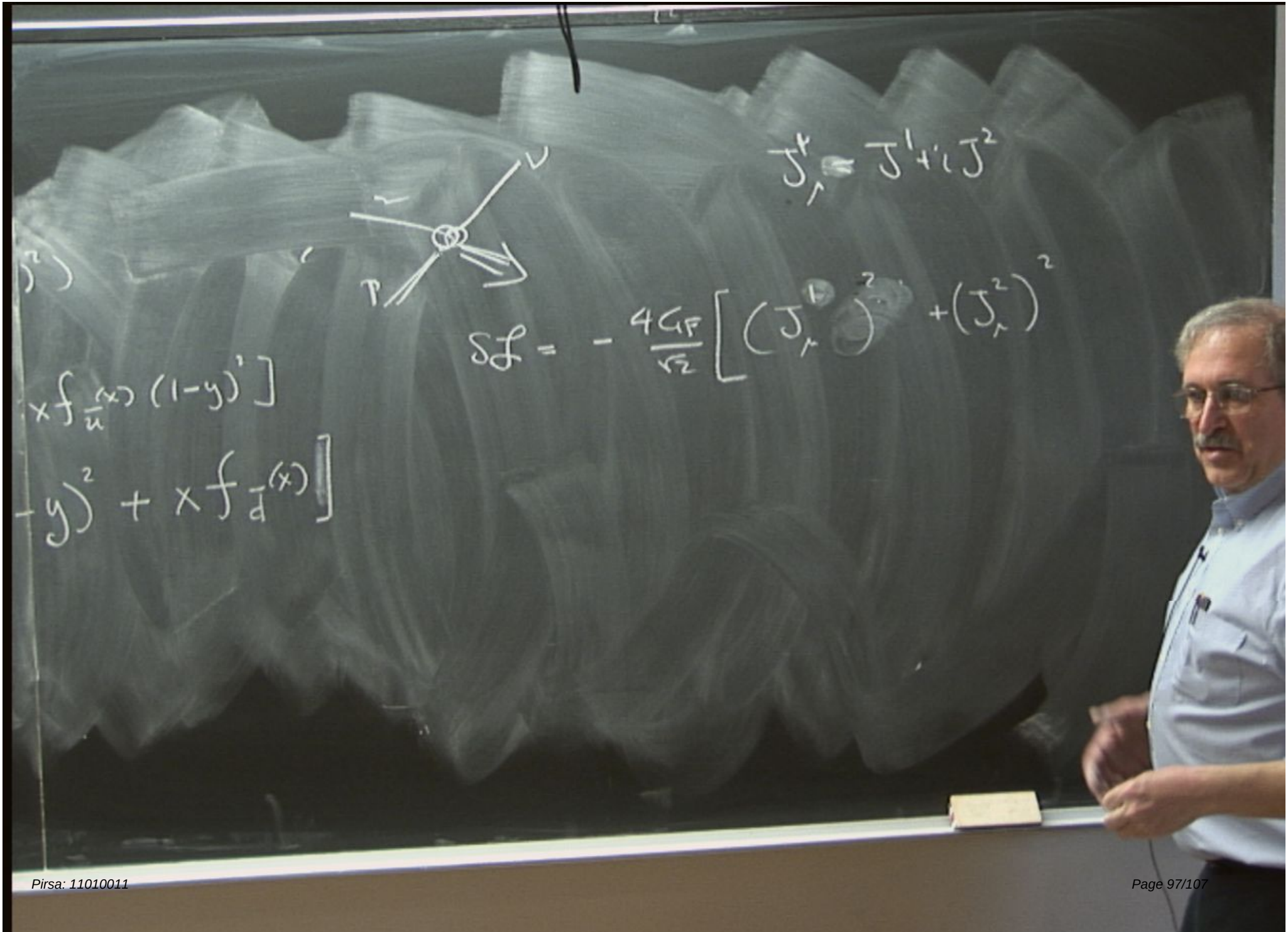
$$\frac{d\sigma}{dx\,dy}(\nu p \to \mu^- X) = \frac{G_F^2 s}{\pi}\left[x f_d(x) + x f_{\bar{u}}(x)\,(1-y)^2\right]$$

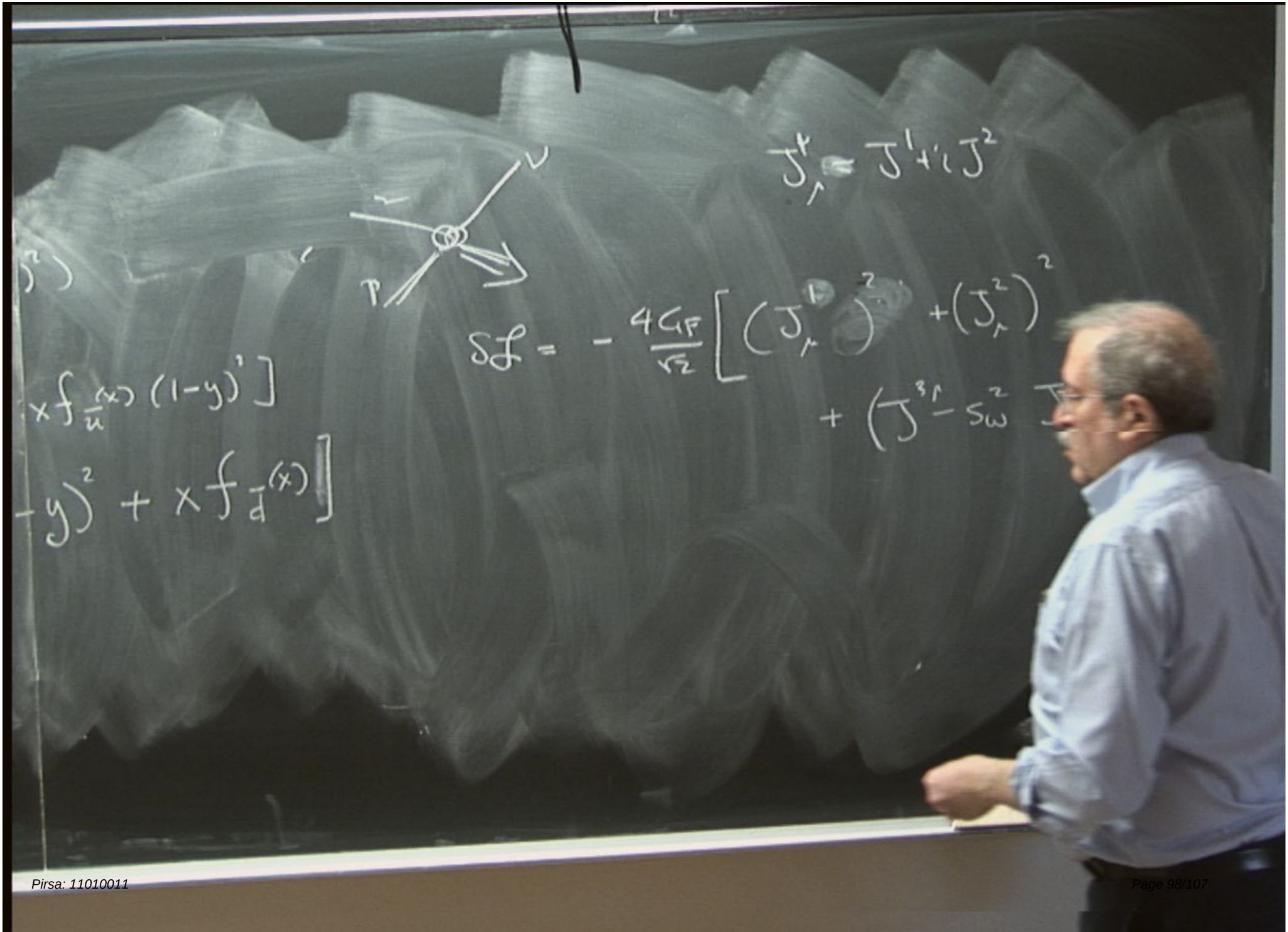
$$\frac{d\sigma}{dx\,dy}(\bar{\nu} p \to \mu^+ X) = \frac{G_F^2 s}{\pi}\left[x f_u(x)\,(1-y)^2 + x f_{\bar{d}}(x)\right]$$

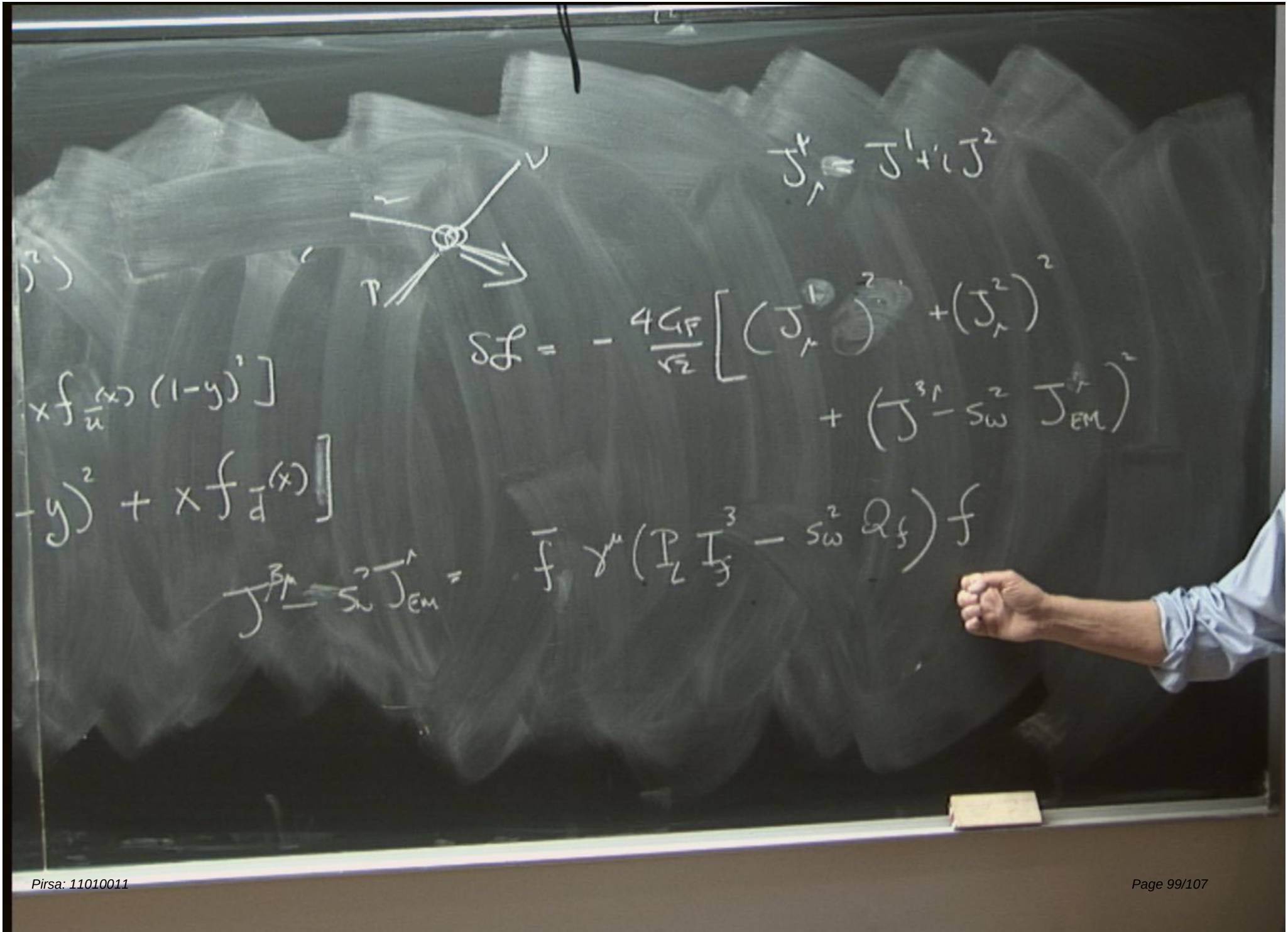

ν
p
$x f_{\bar{u}}(x) (1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$

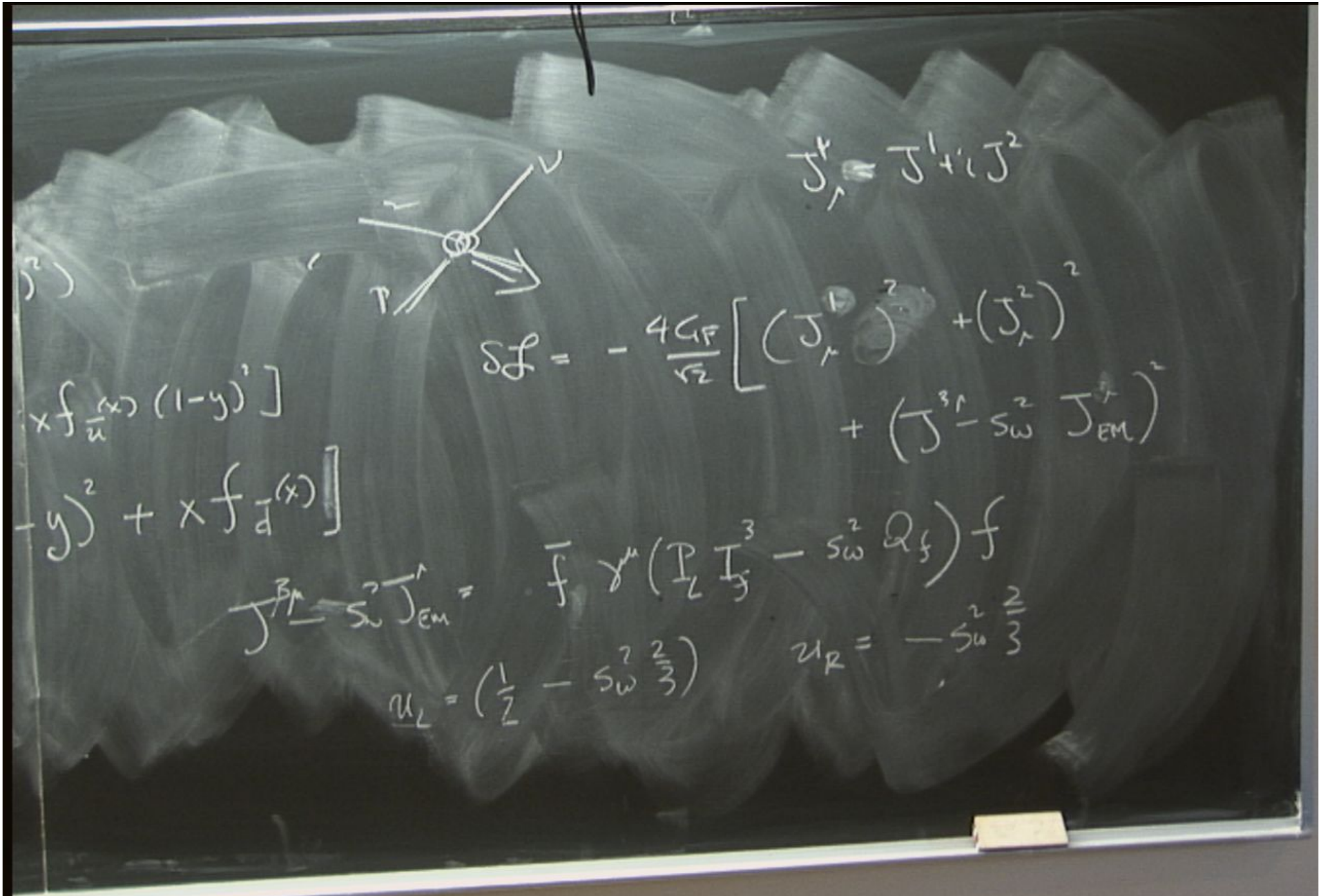

ν
p
$x f_{\bar{u}}(x)\,(1-y)^2\,]$
$-y)^2 + x f_{\bar{d}}(x)\,]$


ν
τ
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[J_\lambda \right.$
$\times f_{\bar{u}}^{(x)} (1-y)^1 \Big]$
$-y)^2 + x f_{\bar{d}}^{(x)} \Big]$

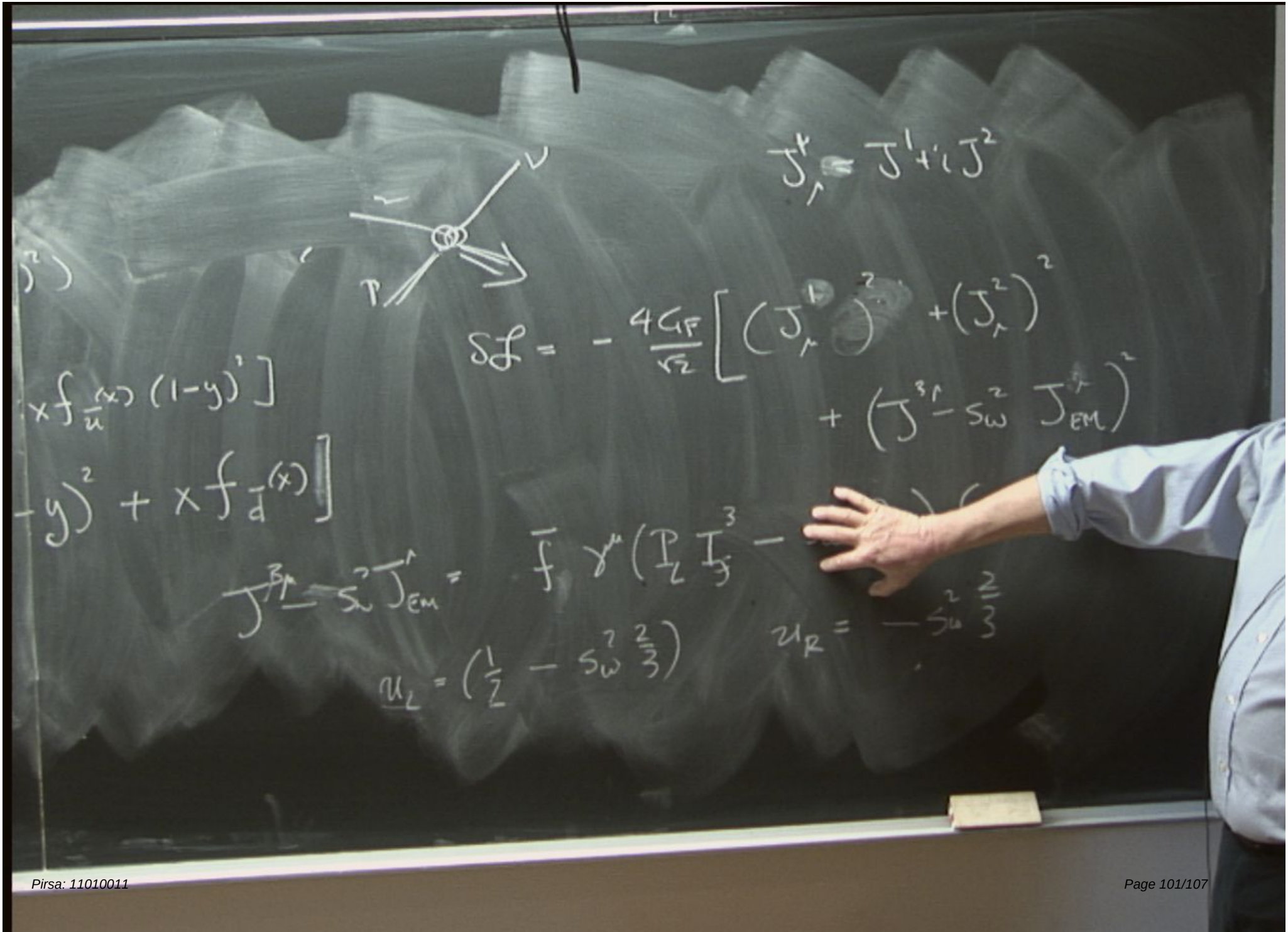

$J^\mu_\mu = J^1 + i J^2$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 \right.$
$x f_{\bar{u}}(x)(1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$

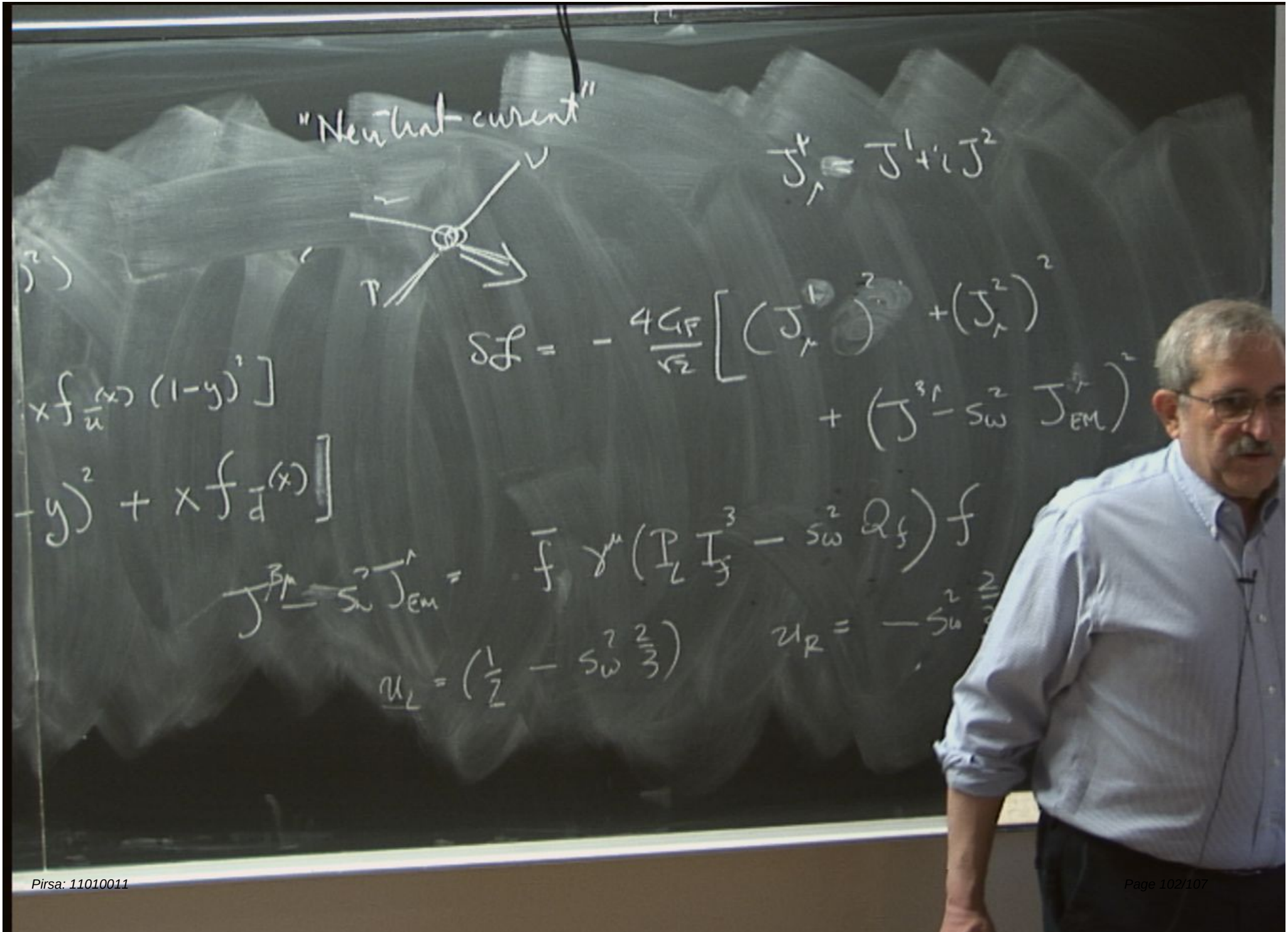

$J^\mu_\mu = J^1 + i J^2$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 \right.$
$+ (J^{3\mu} - s_w^2$
$x f_{\bar{u}}(x) (1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$


$J^\mu = J^1 + iJ^2$
$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 + (J^3 - s_\omega^2 J^1_{EM})^2 \right.$
$\left. + (J^{3\mu} - s_\omega^2 J^\mu_{EM})^2 \right]$
$\bar{f}\gamma^\mu (I_L^3 I_f^3 - s_\omega^2 Q_f) f$
$x f_{\bar{u}}(x)(1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$



$J^\mu_\mu = J^1 + i J^2$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 + (J^{3\mu} - s_w^2 J^\mu_{EM})^2 \right]$
$x f_{\bar{u}}(x)(1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$
$J^{3\mu} - s_w^2 J^\mu_{EM} = \bar{f}\gamma^\mu (P_L I^3_f - s_w^2 Q_f) f$
$u_L = (\frac{1}{2} - s_w^2 \frac{2}{3})$
$u_R = -s_w^2 \frac{2}{3}$


$J^\mu = J^1 + iJ^2$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 \right.$
$+ (J^3_\mu - s_w^2 J^\mu_{EM})^2$
$J^{3\mu} - s_w^2 J^\mu_{EM} = \bar{f}\gamma^\mu (I_L^3 -$
$u_L = (\frac{1}{2} - s_w^2 \frac{2}{3})$
$u_R = -s_w^2 \frac{2}{3}$


"Neutral-current"
ν
T
$J^\mu_\lambda = J^1 + iJ^2$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 + (J^3 - s_\omega^2 J^1_{EM})^2\right.$
$J^{3\mu} - s_\omega^2 J^\mu_{EM} = \bar{f}\gamma^\mu(T_L I_3^3 - s_\omega^2 Q_f) f$
$u_L = (\frac{1}{2} - s_\omega^2 \frac{2}{3})$
$x f_{\bar{u}}(x)(1-y)^2]$
$-y)^2 + x f_{\bar{d}}(x)]$

$\nu_p \to \nu_n$ "Neutral-current"

$q \sim \begin{pmatrix} u \\ d \end{pmatrix}$ $\quad J^\mu = J^1 + iJ^2$

$(\bar{q}_L \gamma^\mu \frac{\tau^i}{2} q_L)$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 + (J^3_\mu - s_\omega^2 J^\mu_{EM}) \right]$$

$$s_\omega^2 \overline{J}^\mu_{EM} = \bar{f}\gamma^\mu (I_L^3 - s_\omega^2 Q_f) f$$

$u_L = \left(\frac{1}{2} - s_\omega^2 \frac{2}{3}\right)$ $\quad u_R = -s_\omega^2 \frac{2}{3}$

$\nu_p \rightarrow \nu_n$ "Neutral current"

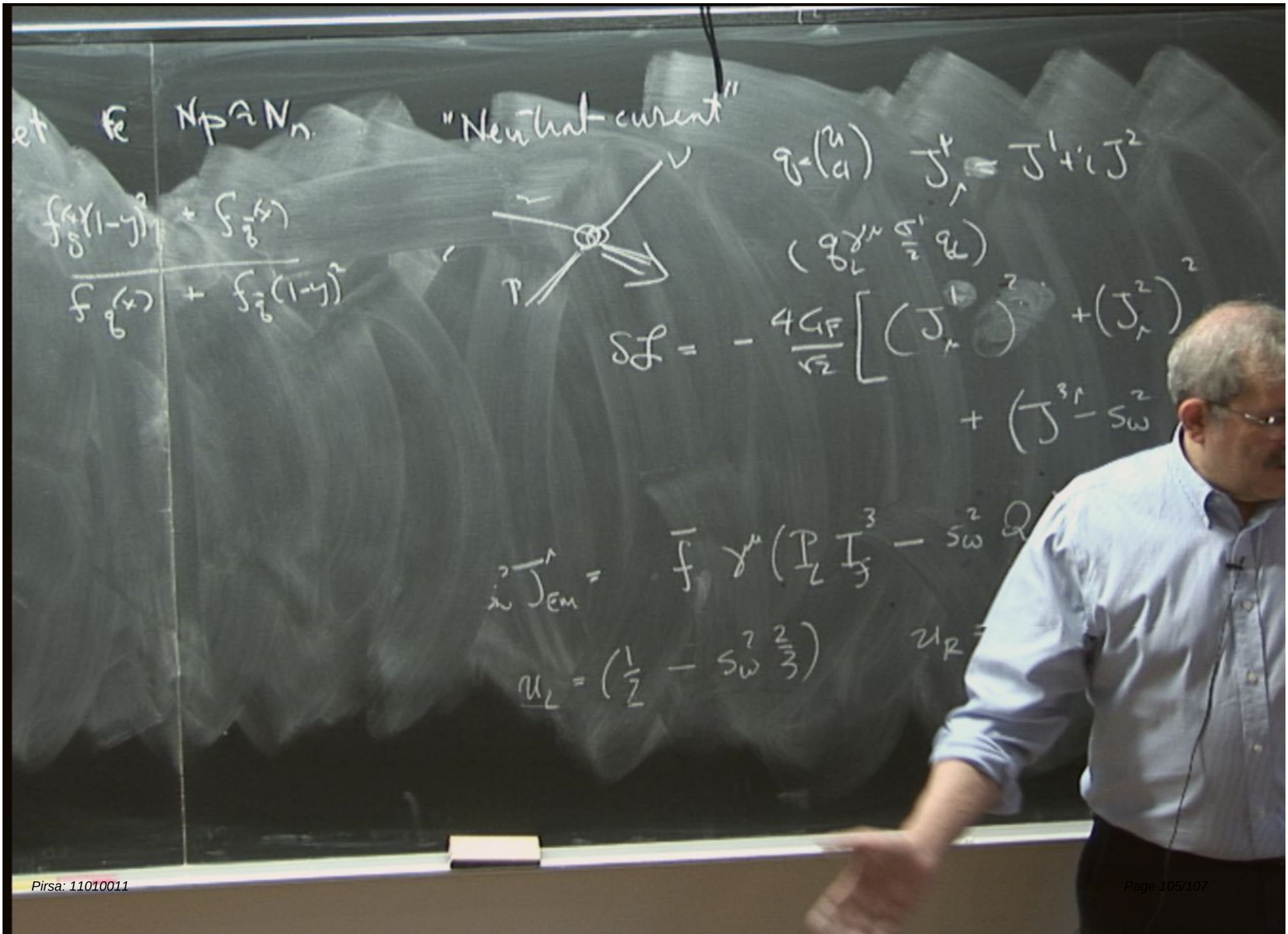
$q = \begin{pmatrix} u \\ d \end{pmatrix}$ $\quad J^\mu = J^1 + iJ^2$

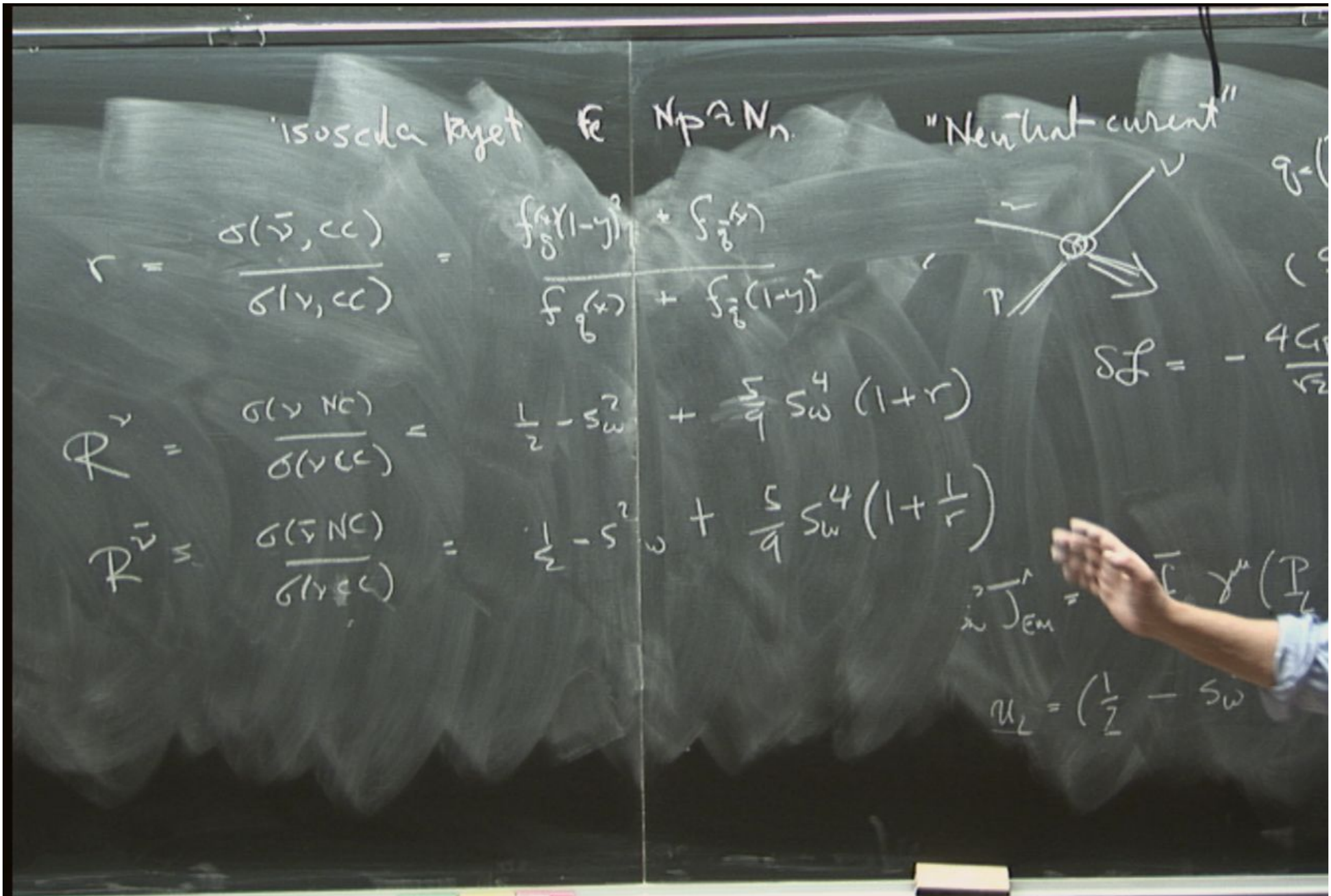
$(\bar{q}_L \gamma^\mu \frac{\sigma^i}{2} q_L)$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2 + (J^3_\mu - s_w^2 J^\mu_{EM})^2\right]$$

$$J^\mu_{EM} = \bar{f}\gamma^\mu(I^3_L I^3_f - s_w^2 Q_f) f$$

$$u_L = \left(\frac{1}{2} - s_w^2 \frac{2}{3}\right) \qquad u_R = -s_w^2 \frac{2}{3}$$


"Neutral-current"
$q = \binom{u}{d}$ $J^\mu_\mu = J^1 + iJ^2$
$(q_L \gamma^\mu \frac{\sigma^1}{2} q_L)$
$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}\left[(J^1_\mu)^2 + (J^2_\mu)^2\right.$
$+ (J^{3\mu} - s_w^2$
$J^\mu_{EM} = \bar{f}\gamma^\mu(P_L I^3_f - s_w^2 Q$
$u_L = (\frac{1}{2} - s_w^2 \frac{2}{3})$
$u_R =$


isoscalar kyet fe Np ≈ Nn
"Neutral current"
r = σ(ν̄, cc) / σ(ν, cc) = (f_q(x)(1-y)² + f_q̄(x)) / (f_q(x) + f_q̄(1-y)²)
R^ν = σ(ν NC) / σ(ν cc) = 1/2 - s_w² + 5/9 s_w⁴ (1+r)
R^ν̄ = σ(ν̄ NC) / σ(ν cc) = 1/2 - s_w² + 5/9 s_w⁴ (1+1/r)
δL = - 4G
u_L = (1/2 - s_w

'isoscalar target' $N_p \cong N_n$ "Neutral-current"

$$r = \frac{\sigma(\bar{\nu}, CC)}{\sigma(\nu, CC)} = \frac{f_q^{(x)}(1-y)^2 + f_{\bar{q}}^{(x)}}{f_q^{(x)} + f_{\bar{q}}(1-y)^2}$$

$$\delta\mathcal{L} = -\frac{4G_F}{\sqrt{2}}$$

$$R^{\nu} = \frac{\sigma(\nu\ NC)}{\sigma(\nu\ CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 (1+r)$$

$$R^{\bar{\nu}} = \frac{\sigma(\bar{\nu}\ NC)}{\sigma(\bar{\nu}\ CC)} = \frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4 \left(1+\frac{1}{r}\right)$$

$$J_{EM}^{\mu} = \bar{f}\gamma^{\mu}(I_L$$

$$u_L = \left(\frac{1}{2} - s_w^2 \frac{2}{3}\right)$$