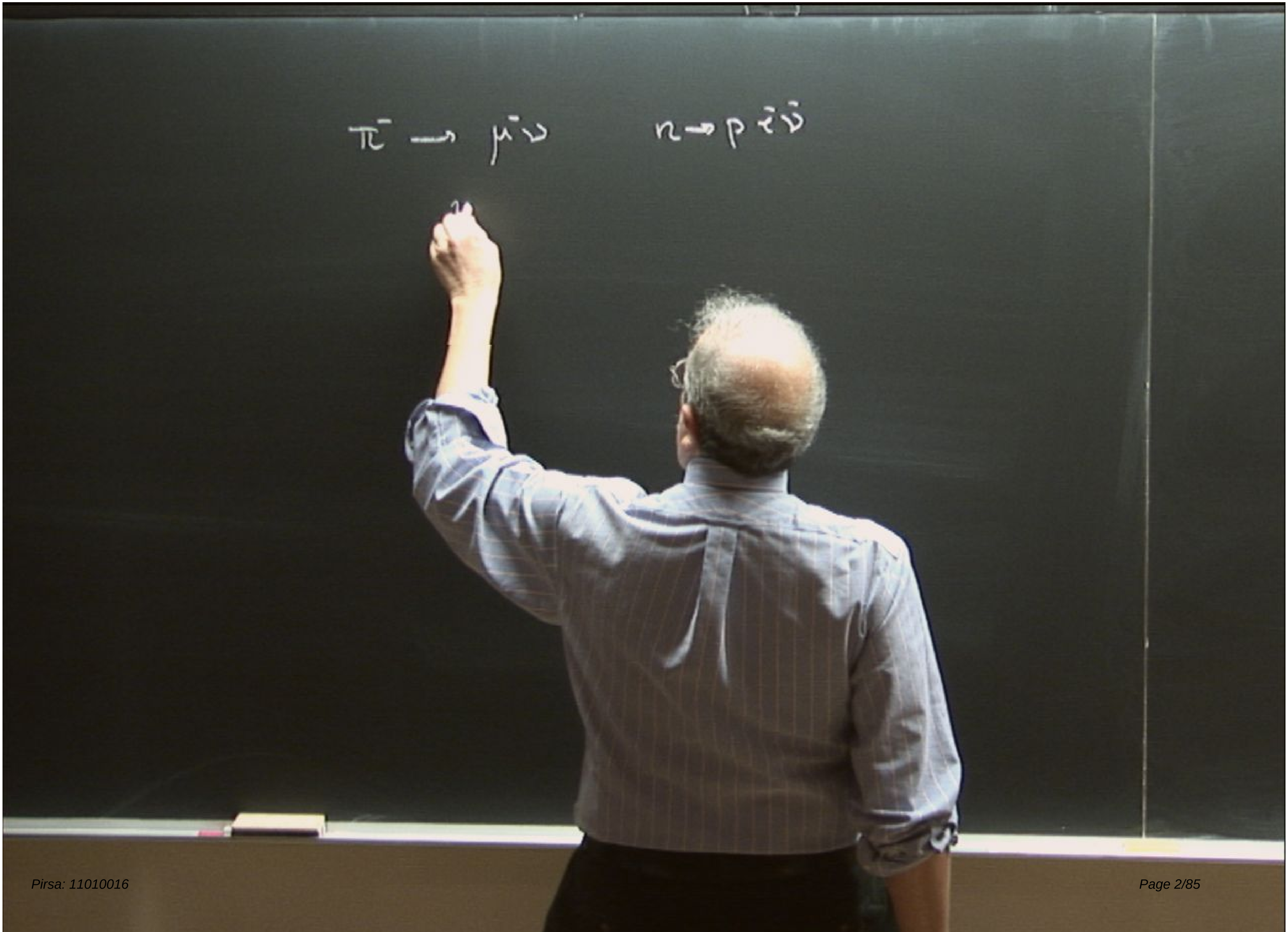
Title: Standard Model - Lecture 13

Date: Jan 19, 2011 09:00 AM

URL: http://pirsa.org/11010016

Abstract:


$\pi^- \to \mu^- \bar{\nu}$
$n \to p e^- \bar{\nu}$

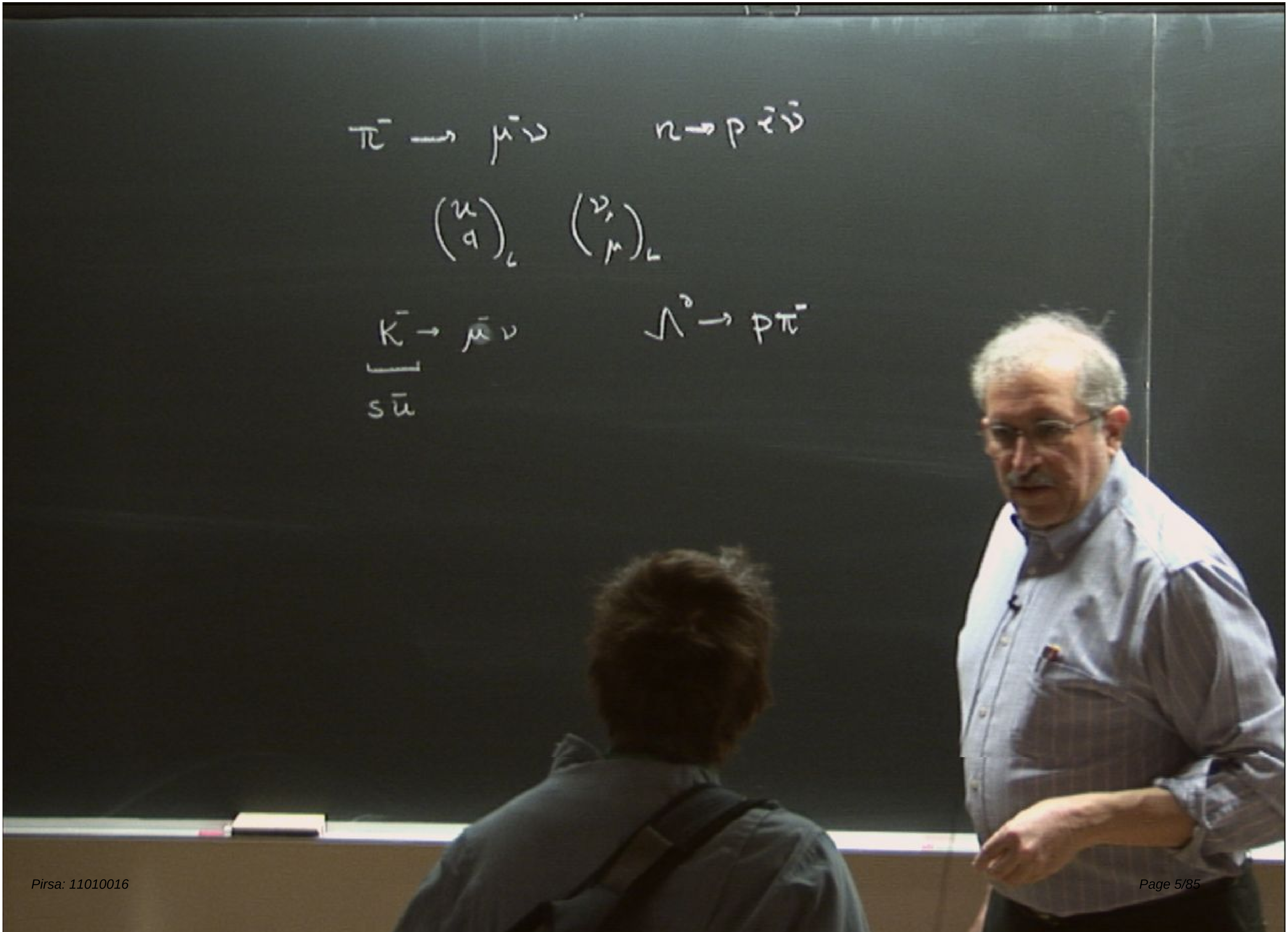
$\pi^- \to \mu^- \nu \qquad n \to p\, e^- \bar{\nu}$

$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$

$$\pi^- \to \mu^- \bar{\nu} \qquad n \to p\, e^- \bar{\nu}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

$$K^- \to \mu^- \bar{\nu}$$


$\pi^- \to \mu^- \bar{\nu}$
$n \to p e^- \bar{\nu}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$
$\underbrace{K^-}_{s\bar{u}} \to \mu^- \bar{\nu}$
$\Lambda^0 \to p \pi^-$

$\pi^- \to \mu^- \bar{\nu}$ $\qquad n \to p\, e^- \bar{\nu}$

$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$

$\underbrace{K^-}_{s\bar{u}} \to \mu^- \nu$ $\qquad \Lambda^0 \to p \pi^-$

$s \to u + W^-$

$s \not\to d + Z^0 \hookrightarrow \mu^+ \mu^-$

$$\pi^- \to \mu^- \nu \qquad n \to p\, e^- \bar{\nu}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

$$\underbrace{K^-}_{s\bar{u}} \to \mu^- \nu \qquad \Lambda^0 \to p\pi^-$$

$$s \to u + W^-$$

$$s \not\to d + Z^0 \hookrightarrow \mu^+\mu^-$$

$$BR(K^0 \to \pi^+ \mu^- \nu) = 27\%$$

$$BR(K^0 \to \mu^+\mu^-) \sim 10^{-8}\ !$$

$\pi^- \longrightarrow \mu^- \nu$ $\qquad n \to p\, e^- \bar{\nu}$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

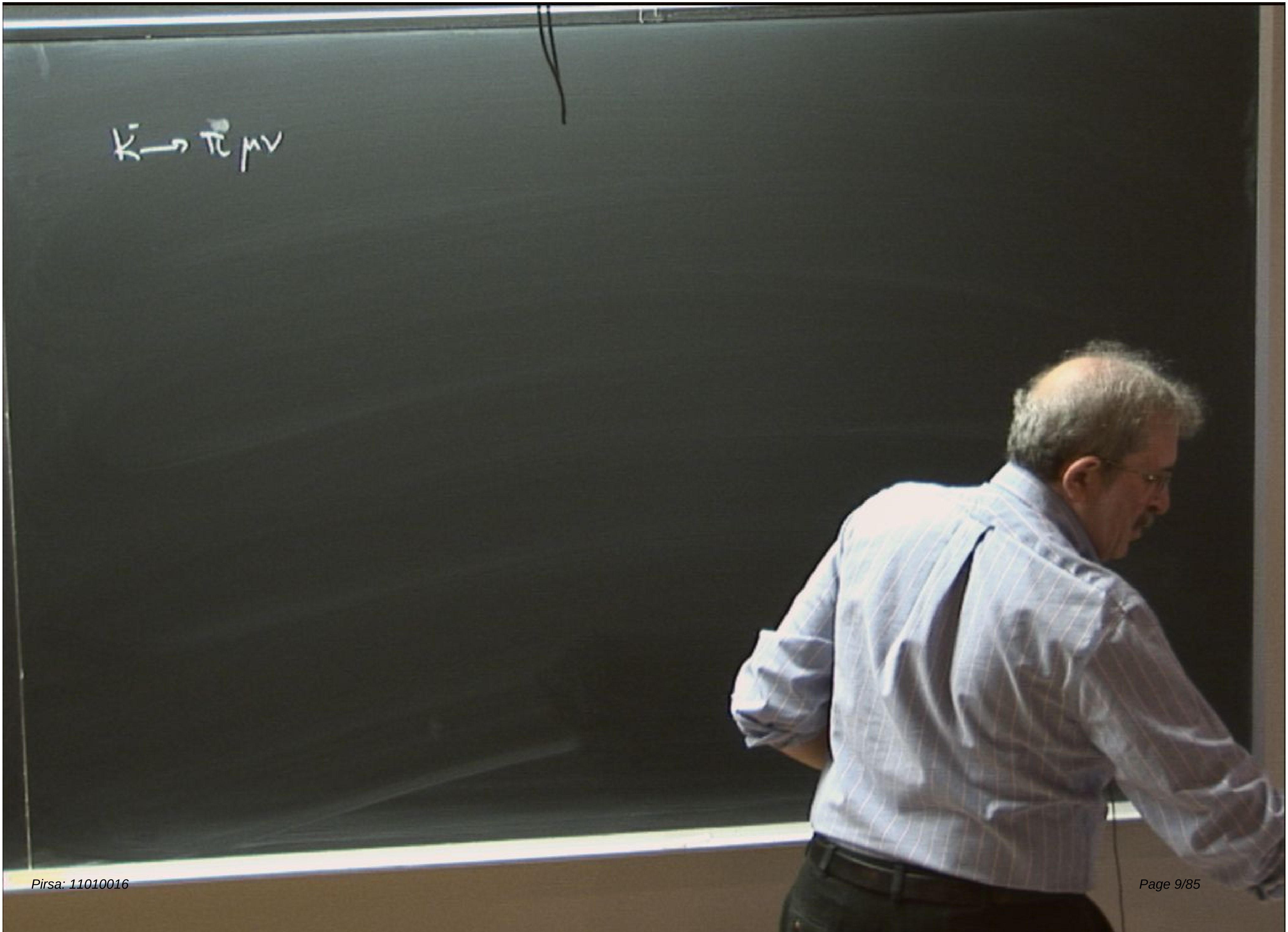
$\underbrace{K^-}_{s\bar{u}} \to \mu^- \nu$ $\qquad \Lambda^0 \to p\pi^-$

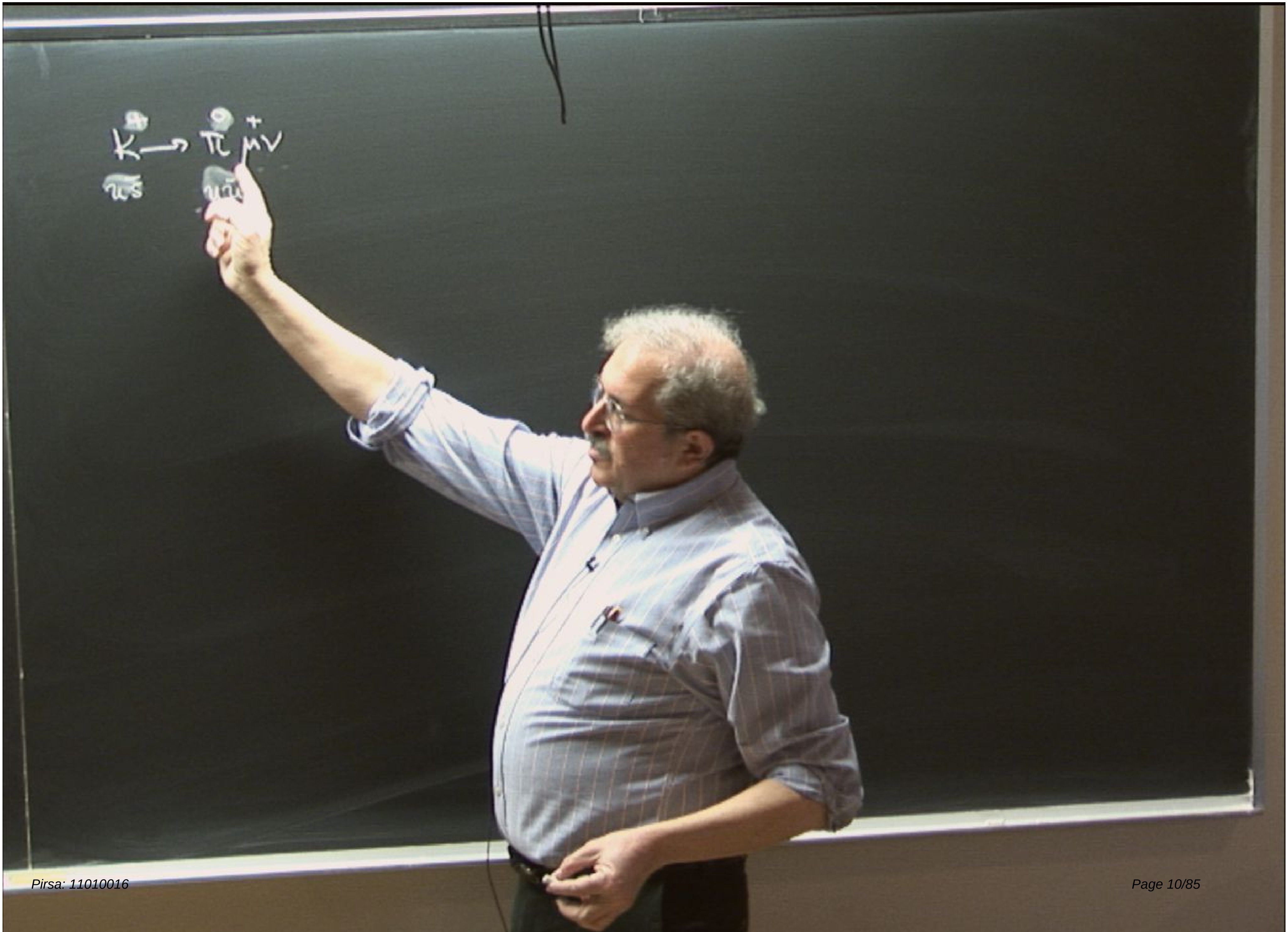
$$s \longrightarrow u + W^-$$

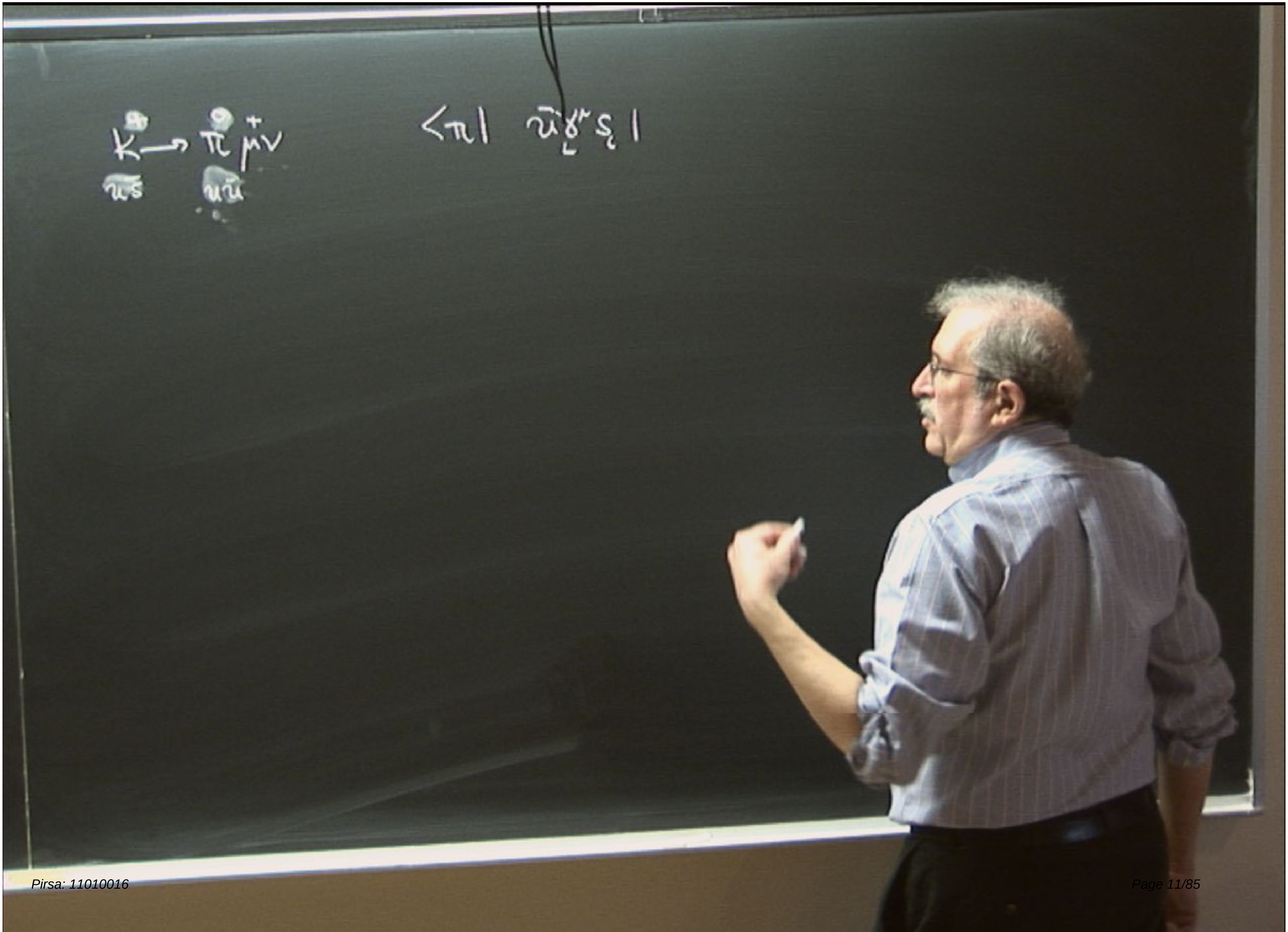
$$s \not\to d + \underset{\hookrightarrow \mu^+\mu^-}{Z^0}$$

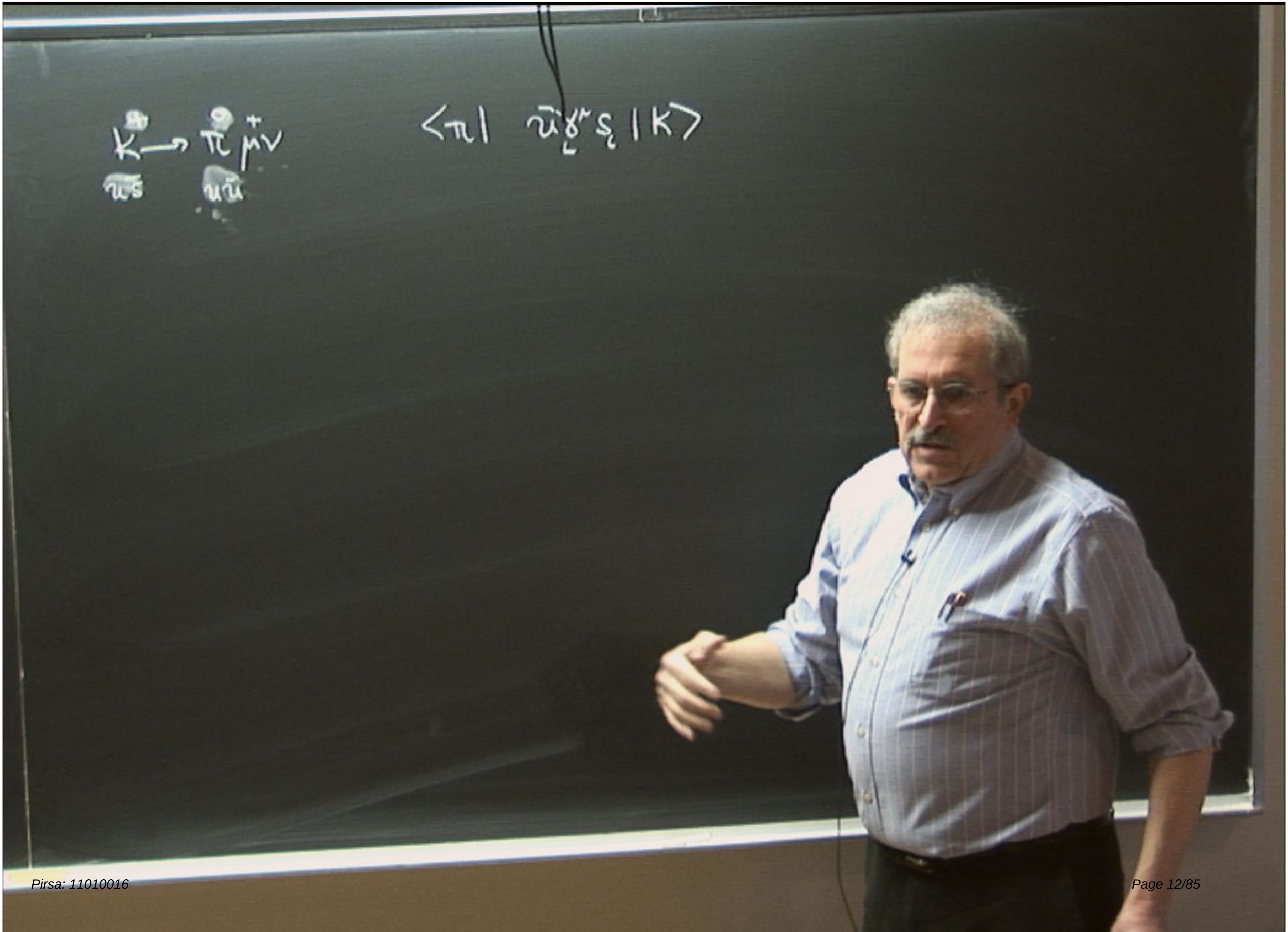
$$BR(K^0 \to \pi^+ \mu^- \nu) = 27\%$$

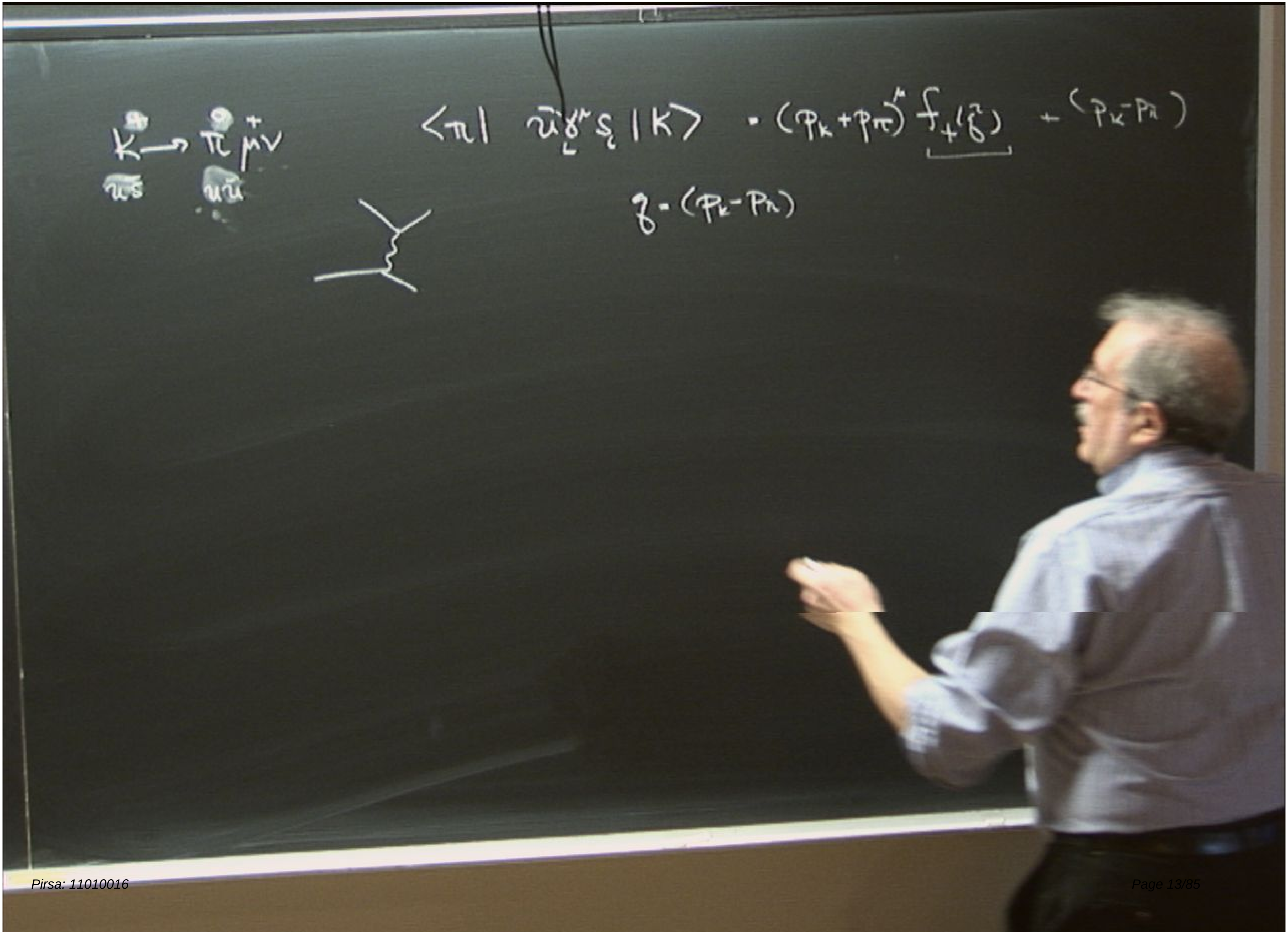
$$BR(K^0 \to \mu^+\mu^-) \sim 10^{-8}\ !$$

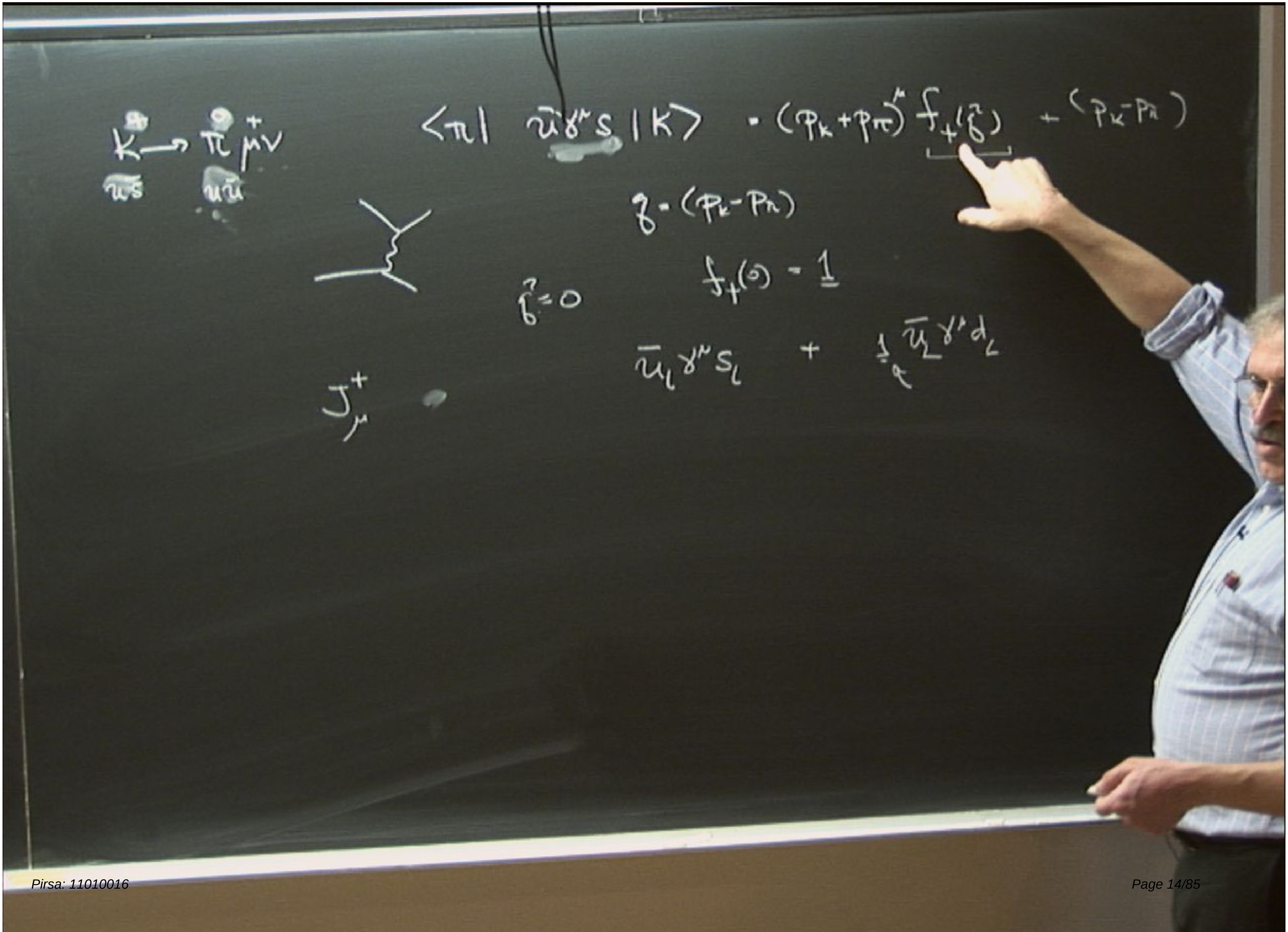

$K^{-} \to \pi \mu \nu$

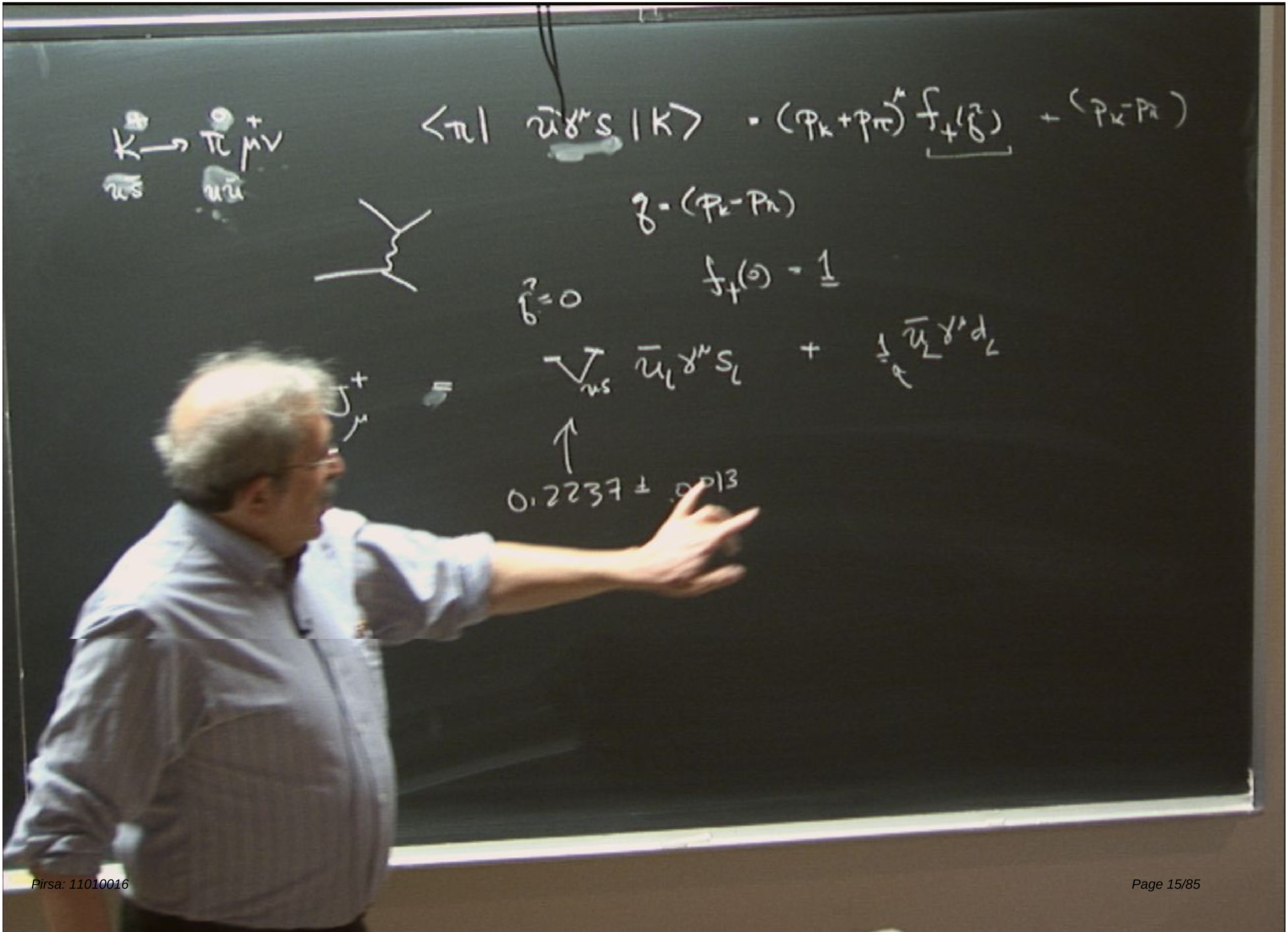

K → π μ⁺ν


K → π μ⁺ ν
us̄ uū
<π| ūγ^μ s_L |


K⁺ → π⁰ μ⁺ ν
u s̄   u ū
<π| ū γ^μ s_L |K>

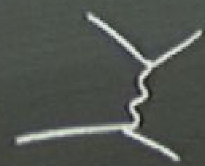

K → π μ⁺ ν
us̄ uū
<π| ūγ^μ s |K> = (p_K + p_π)^μ f_+(q²) + (p_K − p_π)
q = (p_K − p_π)


K⁺ → π⁰ μ⁺ ν
us̄   uū
⟨π| ūγ^μ s |K⟩ = (p_K + p_π)^μ f₊(q²) + (p_K − p_π)
q = (p_K − p_π)
q² = 0   f₊(0) = 1
ū_L γ^μ s_L + ½ ū_L γ^μ d_L
J⁺_μ


K → π μ⁺ ν
ūs   uū
<π| ū γ^μ s |K> = (p_K + p_π)^μ f_+(q²) + (p_K − p_π)
q = (p_K − p_π)
q² = 0
f_+(0) = 1
J_μ^+ = V_us ū_L γ^μ s_L + ū_L γ^μ d_L
0.2237 ± .0013

$K \to \pi \, \mu^+ \nu$

$\bar{u}s \qquad u\bar{u}$



$$\langle \pi | \, \bar{u}\gamma^\mu s \, | K \rangle = (p_K + p_\pi)^\mu \underbrace{f_+(q^2)} + (p_K - p_\pi)$$

$$q = (p_K - p_\pi)$$

$$q^2 = 0 \qquad f_+(0) = \underline{1}$$

$$J^+_\mu = V_{us} \, \bar{u}_L \gamma^\mu s_L + \tfrac{1}{4} \bar{u}_L \gamma^\mu d_L$$

$\uparrow$

$0.2237 \pm .0013$

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

$\bar u s \qquad u \bar u$

$$\langle \pi | \, \bar u \gamma^\mu s \, | K \rangle = (p_K + p_\pi)^\mu \underbrace{f_+(q^2)} + (p_K - p_\pi)$$

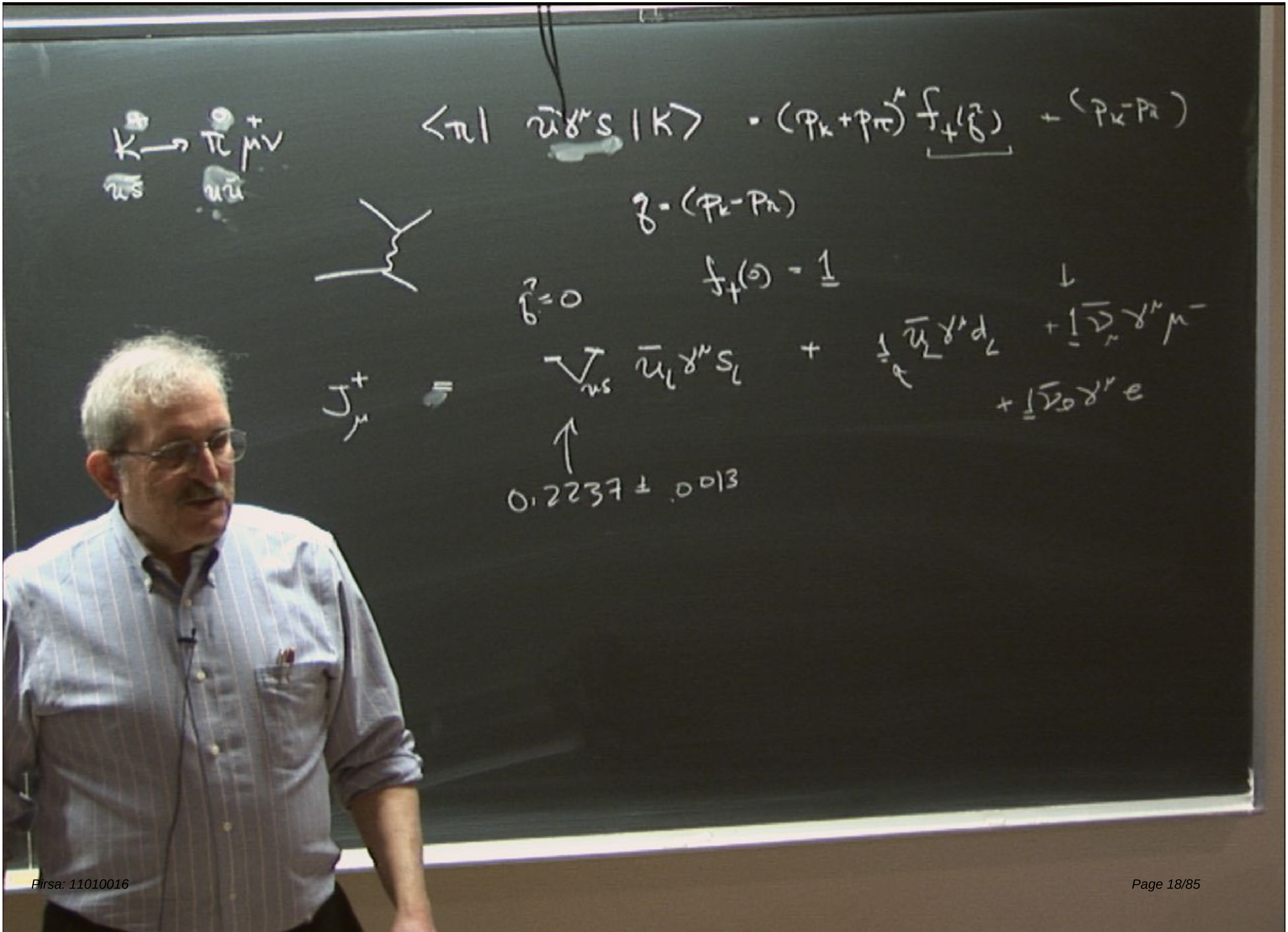
$$q = (p_K - p_\pi)$$

$q^2 = 0 \qquad f_+(0) = \underline{1}$

$$J^+_\mu = V_{us} \, \bar u_L \gamma^\mu s_L + \frac{1}{?} \bar u_L \gamma^\mu d_L + \underline{1} \, \bar \nu_\mu \gamma^\mu \mu^- + \underline{1} \, \bar \nu_e \gamma^\mu e$$

$\uparrow$

$0.2237 \pm .0013$


$K \to \pi \mu^+ \nu$
$\bar{u}s$ $u\bar{u}$
$\langle \pi | \bar{u}\gamma^\mu s | K \rangle = (p_K + p_\pi)^\mu f_+(q^2) + (p_K - p_\pi)$
$q = (p_K - p_\pi)$
$q^2 = 0$
$f_+(0) = 1$
$J^+_\mu = V_{us}\, \bar{u}_L \gamma^\mu s_L + \bar{u}_L \gamma^\mu d_L + \bar{\nu}_\mu \gamma^\mu \mu^-$
$+ \bar{\nu}_e \gamma^\mu e$
$0.2237 \pm .0013$

$K^{+} \rightarrow \pi^{0} \mu^{+} \nu$

$\bar{u}s \qquad u\bar{u}$

$\langle \pi | \, \bar{u} \gamma^\mu s \, | K \rangle = (p_K + p_\pi)^\mu \underbrace{f_+(q^2)} + (p_K - p_\pi)$

$q = (p_K - p_\pi)$

$q^2 = 0 \qquad f_+(0) = \underline{1}$

$J^+_\mu = V_{us} \, \bar{u}_L \gamma^\mu s_L + \underline{1} \, \bar{u}_L \gamma^\mu d_L + \underline{1} \, \bar{\nu}_\mu \gamma^\mu \mu^- + \underline{1} \, \bar{\nu}_e \gamma^\mu e$

$0.2237 \pm .0013$

$A \longrightarrow B + e^- + \bar{\nu}_e$

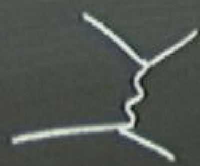
$\langle I^3 = 0 | \, \bar{u} \gamma^\mu d \, | I^3 = +1 \rangle = \sqrt{2} \, P^\mu_A$

$P = +1 \qquad P = +1$

$p \qquad A$

$K \to \pi \, \mu^+ \nu$

$\bar u s \quad u \bar u$



$\langle \pi | \, \bar u \gamma^\mu s \, | K \rangle = (p_K + p_\pi)^\mu \underbrace{f_+(q^2)} + (p_K - p_\pi)$

$q = (p_K - p_\pi)$

$q^2 = 0 \qquad f_+(0) = \underline{1}$

$J^+_\mu = V_{us}\, \bar u_L \gamma^\mu s_L + V_{ud}\, \bar u_L \gamma^\mu d_L + \underline{1}\, \bar\nu_\mu \gamma^\mu \mu^- + \underline{1}\, \bar\nu_e \gamma^\mu e$

$0.2237 \pm .0013$

$A \to B + e^- + \bar\nu_e$

$\langle I^3 = 0 | \, \bar u \gamma^\mu d \, | I^3 = +1 \rangle = \sqrt{2}\, P^\mu$

$P = +1 \qquad P = +1$

$\beta \qquad A$

$V_{ud} = 0.97418 \pm .00026$

Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1$

Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1 - .0004$

$\pm .0007$

$V_{us} = \sin\Theta_c \quad V_{ud} = \cos\Theta_c$

$J_\mu^+ = \bar{\nu}_{e_L}\gamma_\mu e_L + \bar{\nu}_{\mu_L}\gamma_\mu \mu_L + \bar{u}\gamma_\mu(\cos\Theta_c d + \sin\Theta_c s)$

$K^0 \longrightarrow \pi^+\pi^- \longleftarrow \bar{K}^0$

$d\bar{s} \quad d\bar{u} \quad u\bar{d} \quad s\bar{d}$

$K^+ \longrightarrow \pi^0 \mu^+ \nu$

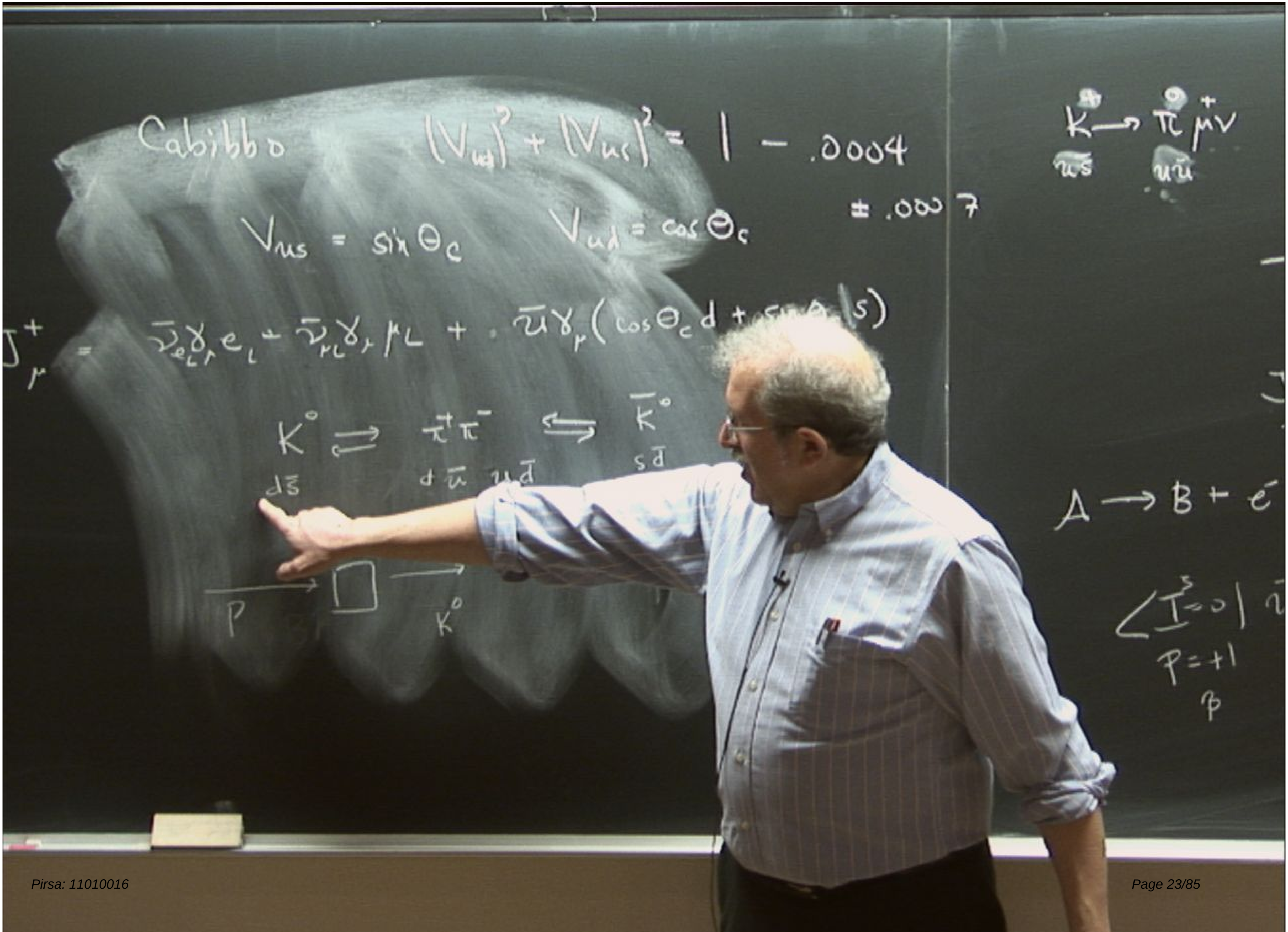
$u\bar{s} \quad u\bar{u}$

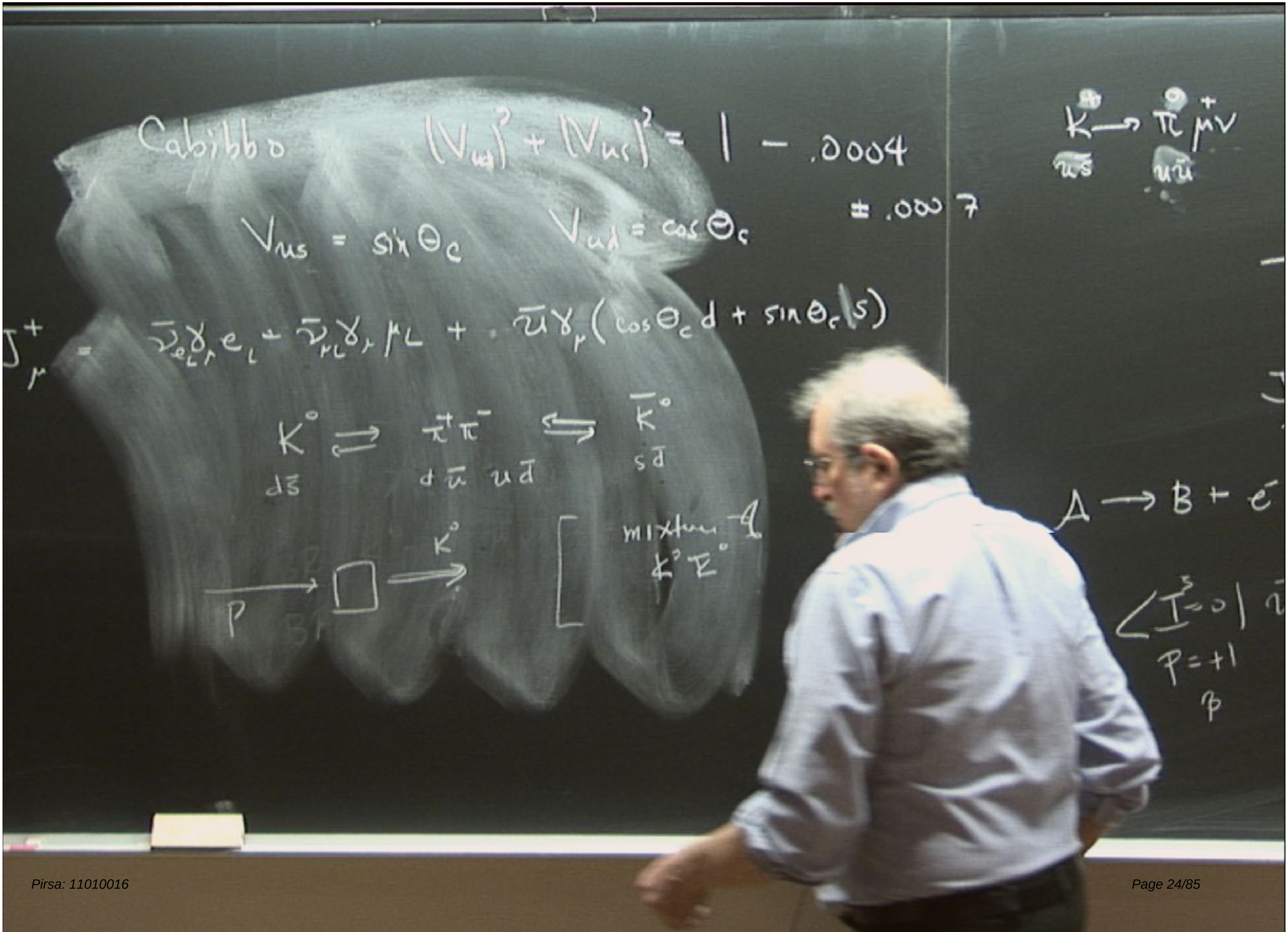
$A \longrightarrow B + e^-$

$\langle I^s = 0 |$

$P = +1$

P


Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1 - .0004$
$\pm .0007$
$V_{us} = \sin\Theta_c \quad V_{ud} = \cos\Theta_c$
$J^+_\mu = \bar{\nu}_{eL}\gamma_\mu e_L + \bar{\nu}_{\mu L}\gamma_\mu \mu_L + \bar{u}\gamma_\mu(\cos\Theta_c d + \sin\Theta_c s)$
$K^0 \rightleftarrows \pi^+\pi^- \leftrightarrows \bar{K}^0$
$d\bar{s} \quad d\bar{u} \quad u\bar{d} \quad s\bar{d}$
$P \quad K^0$
$K^+ \to \pi^0 \mu^+ \nu$
$u\bar{s} \quad u\bar{u}$
$A \to B + e^-$
$P = +1$


Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1 - .0004$
$\pm .0007$
$V_{us} = \sin\Theta_C$ $V_{ud} = \cos\Theta_c$
$J^+_\mu = \bar{\nu}_{eL}\gamma_\mu e_L + \bar{\nu}_{\mu L}\gamma_\mu \mu_L + \bar{u}\gamma_\mu(\cos\Theta_c d + \sin\Theta_c s)$
$K^0 \rightleftarrows \pi^+\pi^- \leftrightarrows \bar{K}^0$
$d\bar{s}$ $d\bar{u}$ $u\bar{d}$ $s\bar{d}$
K^0
p
mixture of $K^0 \bar{K}^0$
$K^+ \to \pi^0 \mu^+ \nu$
$u\bar{s}$ $u\bar{u}$
$A \to B + e^-$
$P = +1$

Cabibbo $\quad |V_{ud}|^2 + |V_{us}|^2 = 1 - .0004$

$\pm .0007$

$V_{us} = \sin\theta_C \qquad V_{ud} = \cos\theta_C$

$J^+_\mu = \bar{\nu}_{eL}\gamma_\mu e_L + \bar{\nu}_{\mu L}\gamma_\mu \mu_L + \bar{u}\gamma_\mu(\cos\theta_C\, d + \sin\theta_C\, s)$

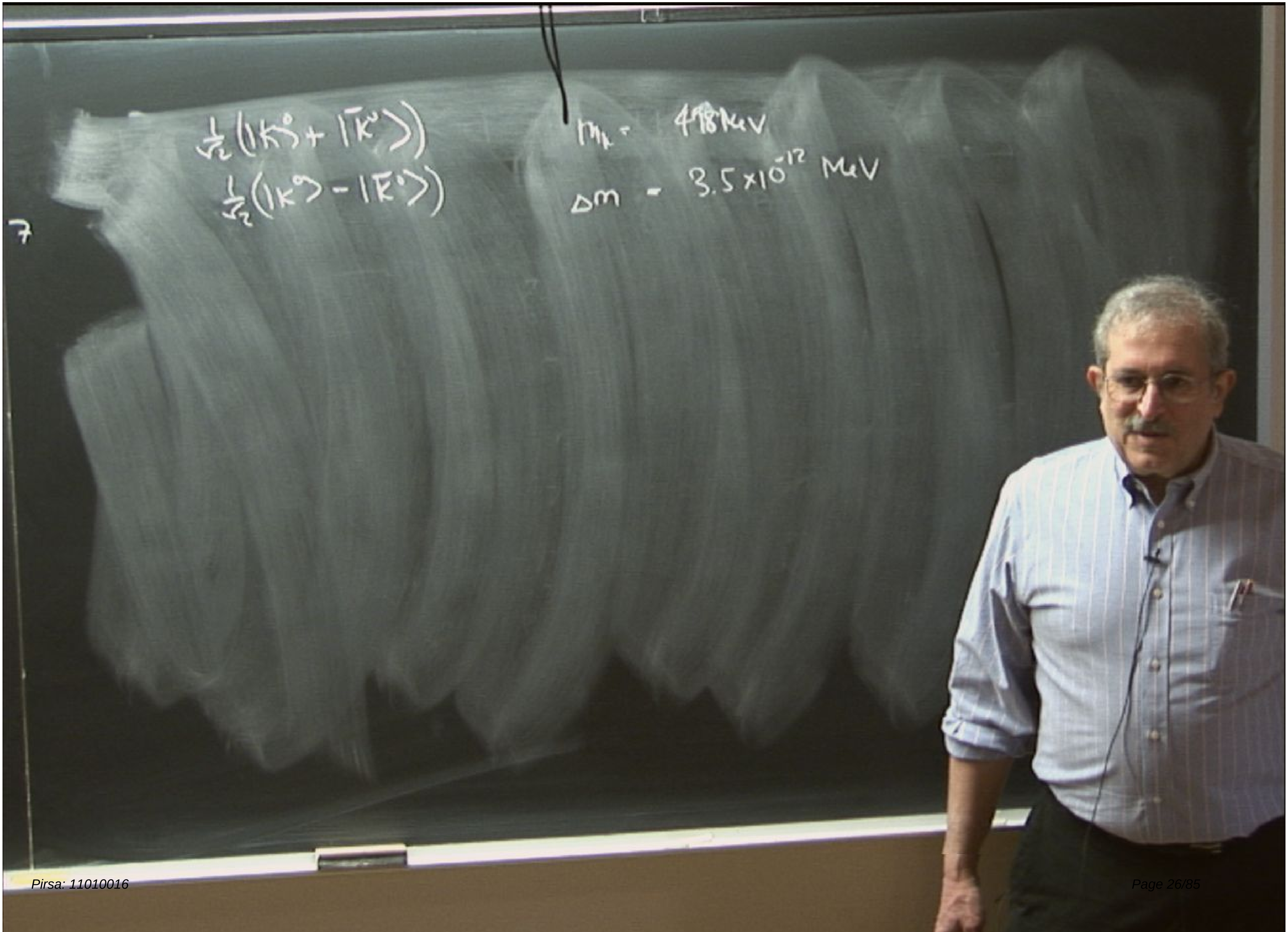
$K^0 \rightleftarrows \pi^+\pi^- \leftrightarrows \bar{K}^0$

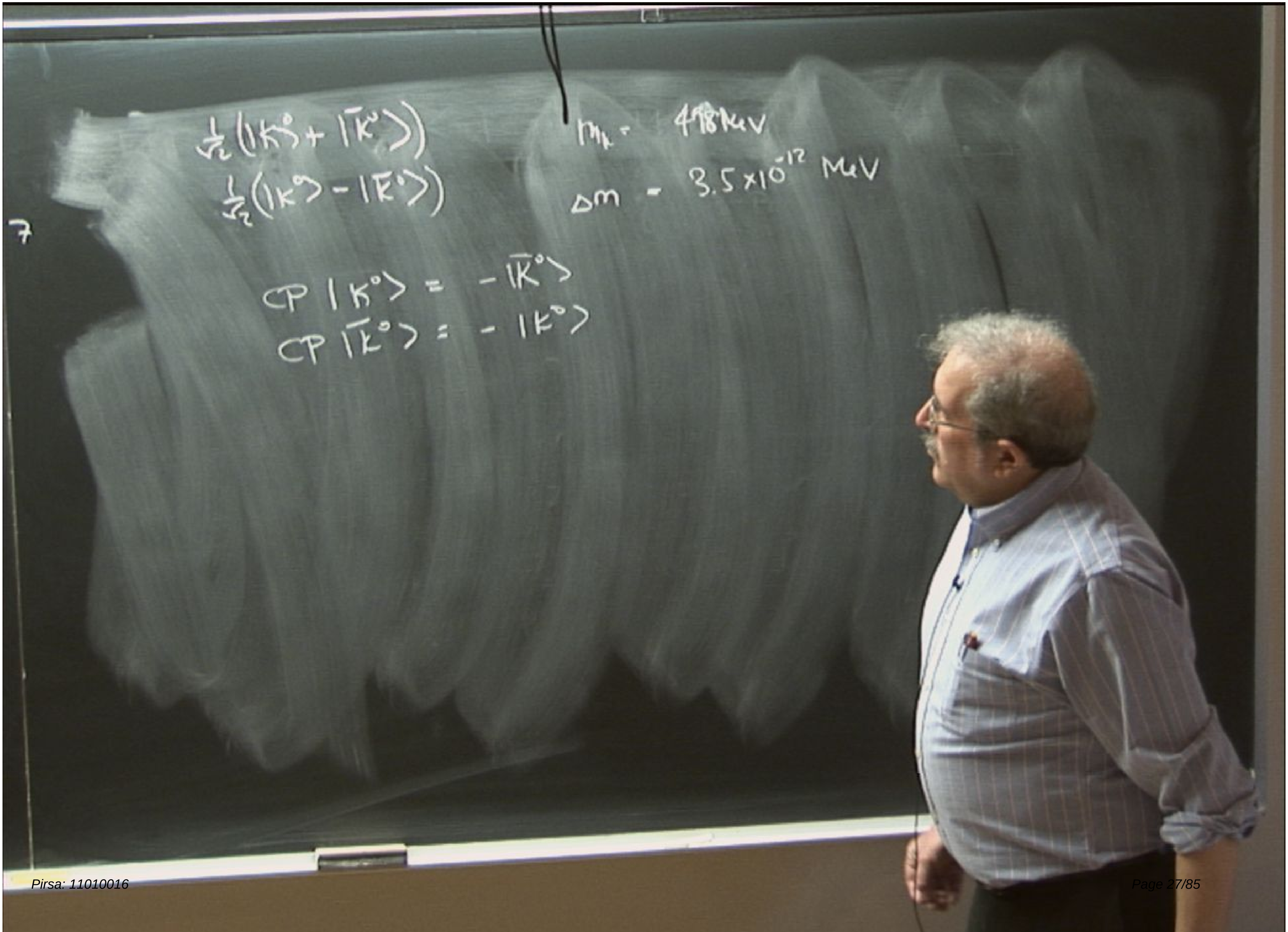
$d\bar{s} \qquad d\bar{u} \quad u\bar{d} \qquad s\bar{d}$

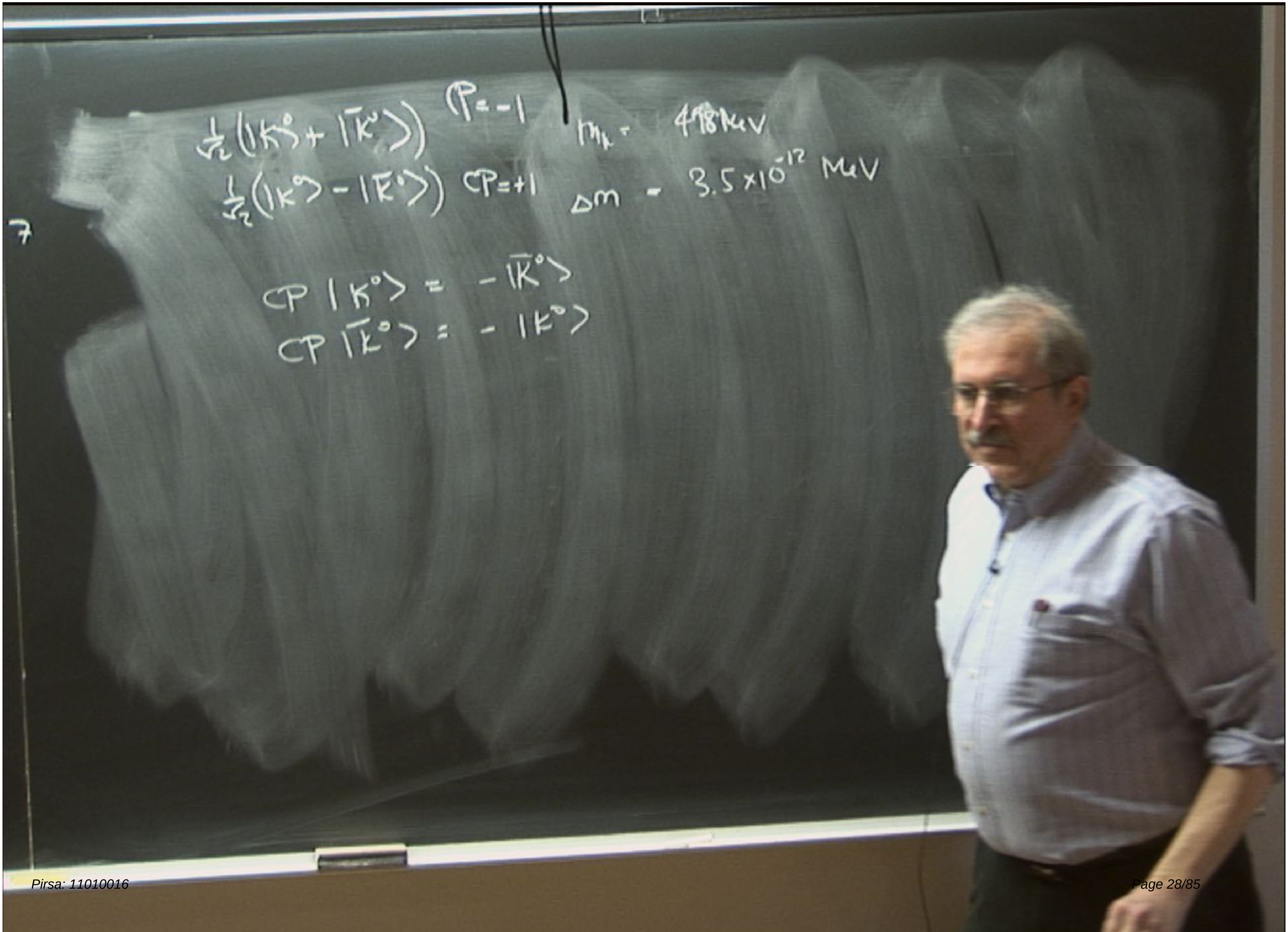
$p \longrightarrow \square \xrightarrow{K^0}$ [mixture of $K^0\,\bar{K}^0$

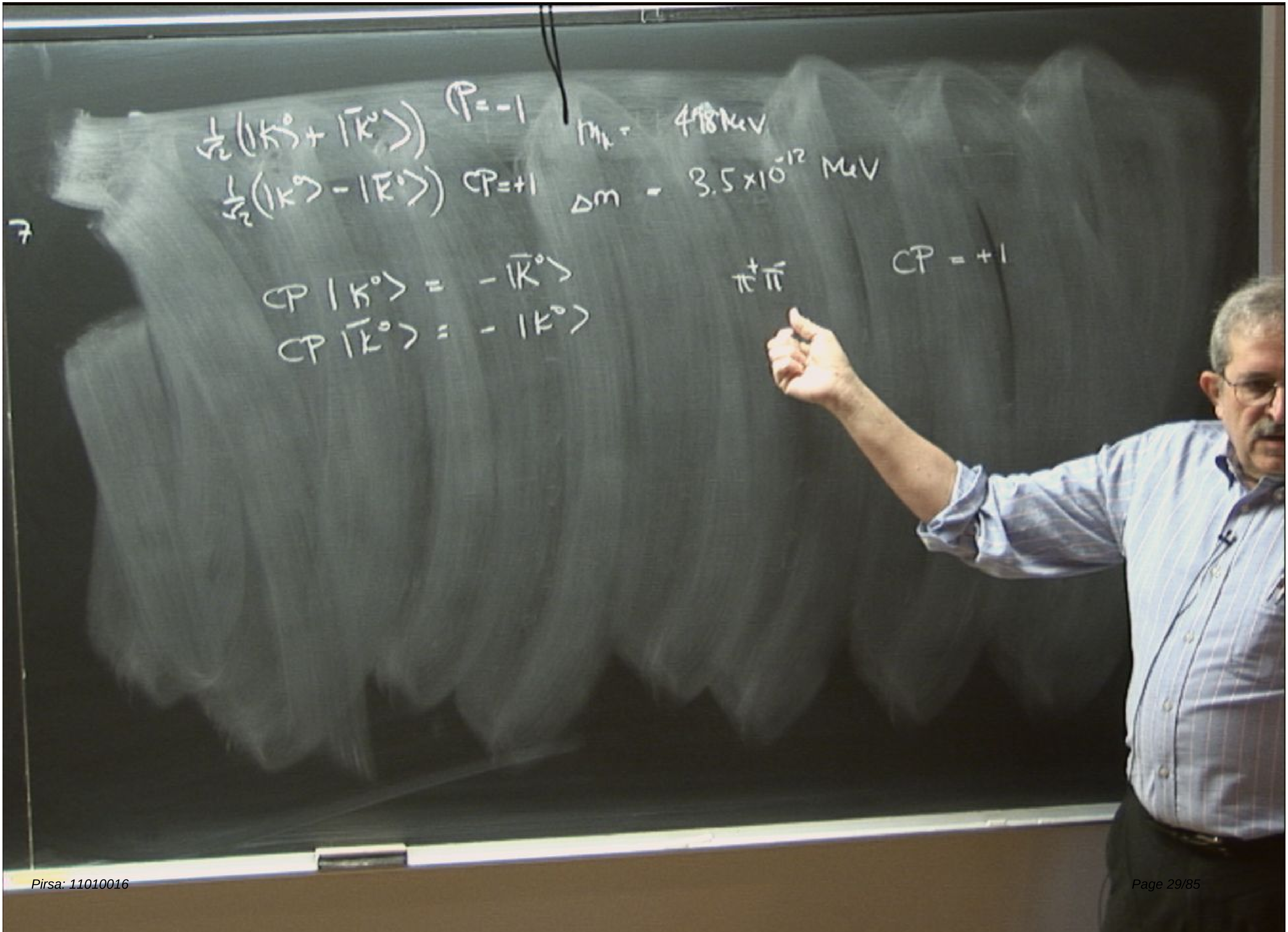
$\frac{1}{\sqrt{2}}(|K^0\rangle +$

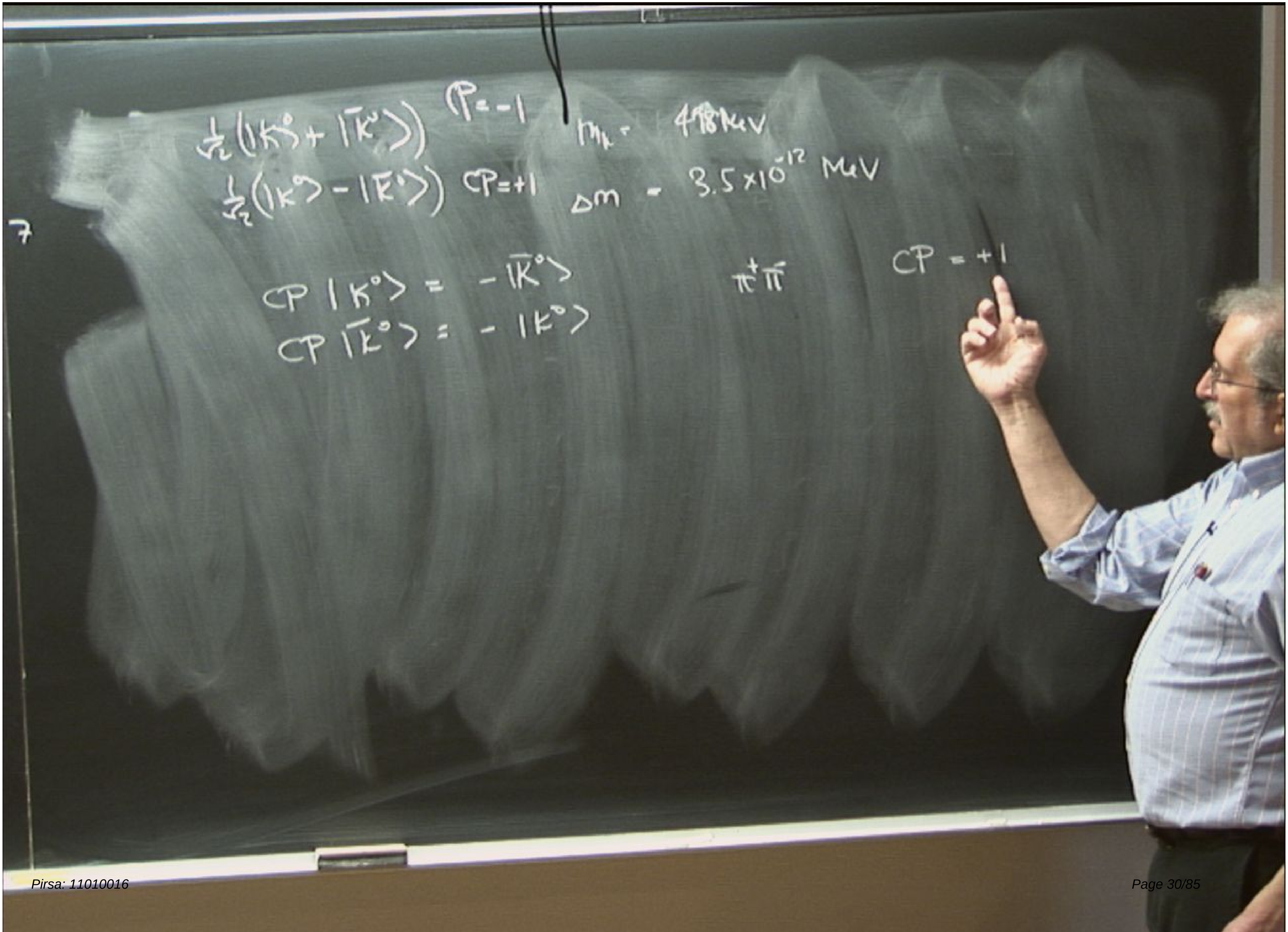
$\frac{1}{\sqrt{2}}(|K^0\rangle$

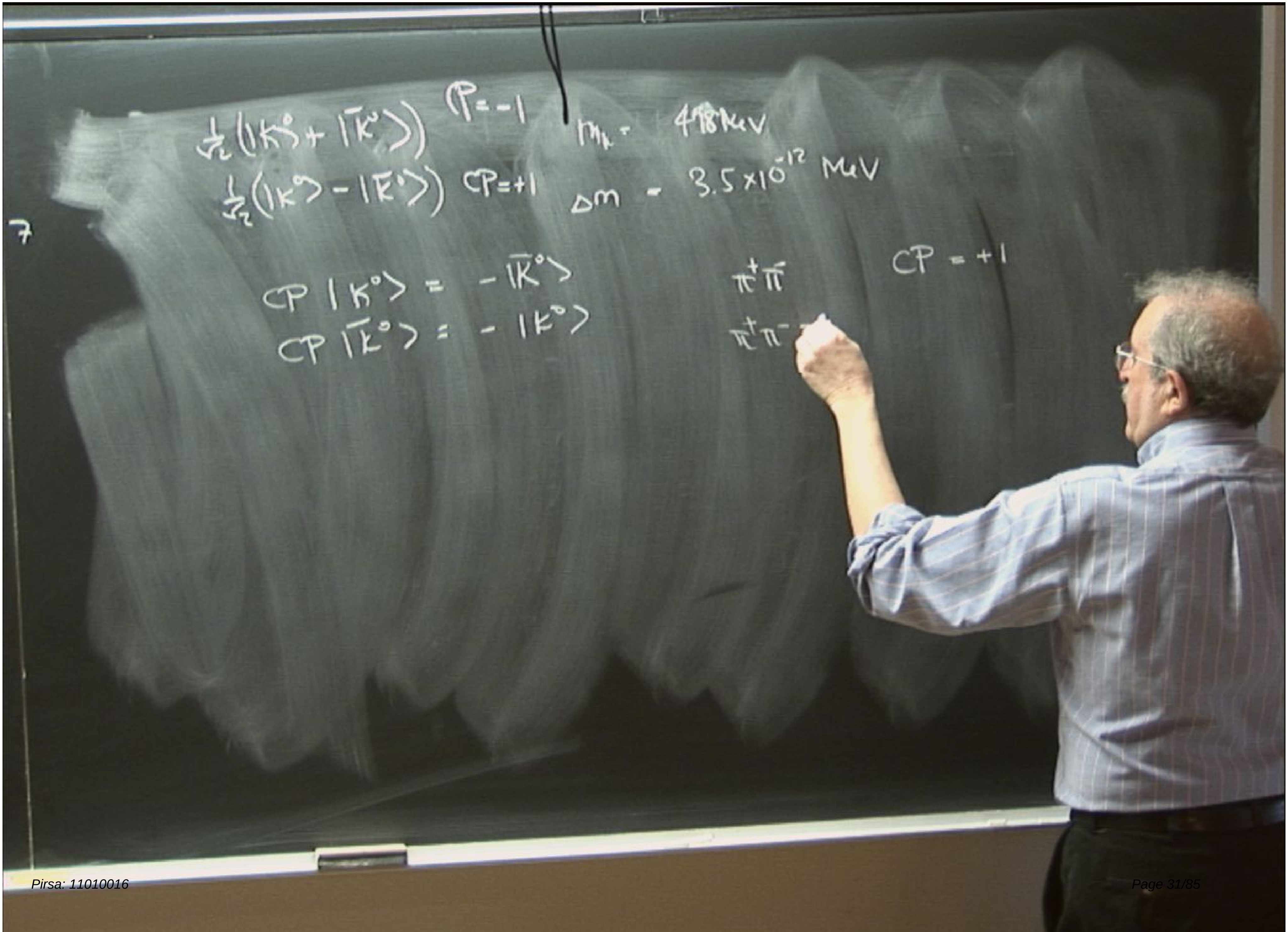

$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$
$\frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$
$m_K = 498$ MeV
$\Delta m = 3.5 \times 10^{-12}$ MeV


$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$
$\frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$
$m_K = 498\,\mathrm{MeV}$
$\Delta m = 3.5\times10^{-12}\,\mathrm{MeV}$
$CP\,|K^0\rangle = -|\bar{K}^0\rangle$
$CP\,|\bar{K}^0\rangle = -|K^0\rangle$

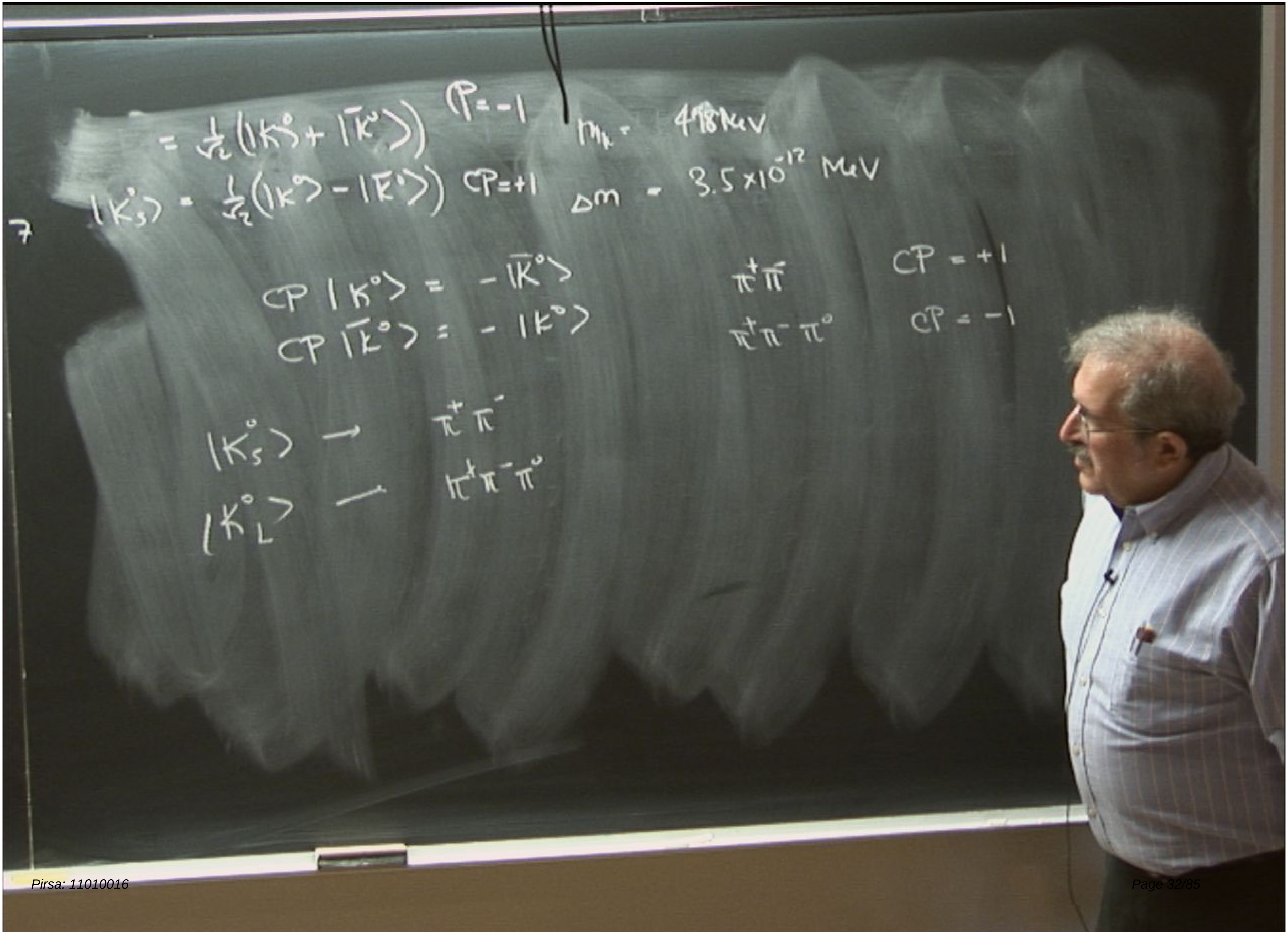

$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ CP = -1
$m_K = 498$ MeV
$\frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ CP = +1
$\Delta m = 3.5 \times 10^{-12}$ MeV
7
$CP\,|K^0\rangle = -|\bar{K}^0\rangle$
$CP\,|\bar{K}^0\rangle = -|K^0\rangle$


$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ $CP = -1$
$m_K = 498$ MeV
$\frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ $CP = +1$
$\Delta m = 3.5 \times 10^{-12}$ MeV
7
$CP\,|K^0\rangle = -|\bar{K}^0\rangle$
$CP\,|\bar{K}^0\rangle = -|K^0\rangle$
$\pi^+\pi^-$
$CP = +1$


1/√2 (|K°> + |K̄°>) CP = -1
m_K = 498 MeV
1/√2 (|K°> - |K̄°>) CP = +1
Δm = 3.5 × 10^-12 MeV
7
CP |K°> = - |K̄°>
CP |K̄°> = - |K°>
π+ π-
CP = +1



$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ CP = -1
m_K = 498 MeV
$\frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ CP = +1
Δm = 3.5×10^{-12} MeV
$CP\,|K^0\rangle = -|\bar{K}^0\rangle$
$CP\,|\bar{K}^0\rangle = -|K^0\rangle$
$\pi^+\pi^-$
CP = +1
$\pi^+\pi^-$



$= \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ $CP = -1$
$m_K = 498\ MeV$
$|K^0_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ $CP = +1$
$\Delta m = 3.5 \times 10^{-12}\ MeV$
7
$CP\,|K^0\rangle = -|\bar{K}^0\rangle$
$CP\,|\bar{K}^0\rangle = -|K^0\rangle$
$\pi^+\pi^-$ $CP = +1$
$\pi^+\pi^-\pi^0$ $CP = -1$
$|K^0_S\rangle \longrightarrow \pi^+\pi^-$
$|K^0_L\rangle \longrightarrow \pi^+\pi^-\pi^0$

$= \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ $CP = -1$ $m_K = 498\ \text{MeV}$

$|K_S^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ $CP = +1$ $\Delta m = 3.5 \times 10^{-12}\ \text{MeV}$

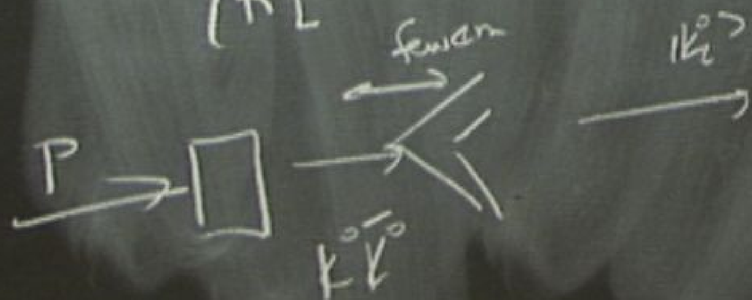
7

$CP\,|K^0\rangle = -|\bar{K}^0\rangle$ $\pi^+\pi^-$ $CP = +1$

$CP\,|\bar{K}^0\rangle = -|K^0\rangle$ $\pi^+\pi^-\pi^0$ $CP = -1$

$|K_S^0\rangle \longrightarrow \pi^+\pi^-$ 10^3 time longer

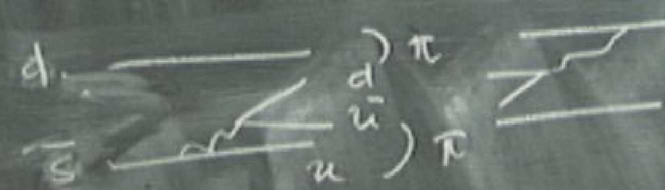
$|K_L^0\rangle \longrightarrow \pi^+\pi^-\pi^0$

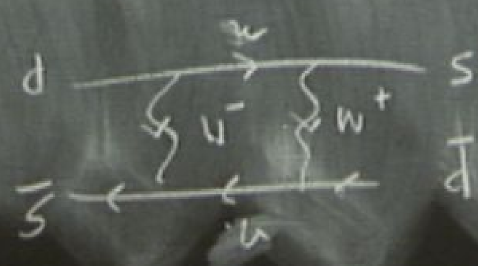


Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1 - .0004 \pm .0007$

$V_{us} = \sin\theta_c \qquad V_{ud} = \cos\theta_c$

$J^+_\mu = \bar{\nu}_{e_L}\gamma_\mu e_L + \bar{\nu}_{\mu_L}\gamma_\mu \mu_L + \bar{u}\gamma_\mu(\cos\theta_c\, d + \sin\theta_c\, s)$





Cabibbo $|V_{ud}|^2 + |V_{us}|^2 = 1 - .0004 \pm .0007$

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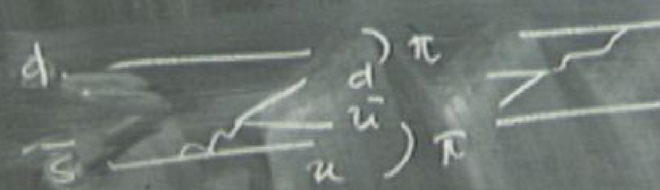
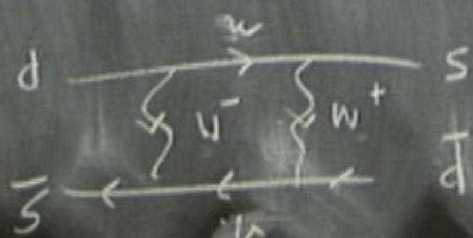


$$\int \frac{d^4k}{(\;)} \frac{1}{(k^2-m^2)} \frac{k}{k^2} \frac{k}{k^2}$$



Cabibbo $\quad |V_{ud}|^2 + |V_{us}|^2 = 1 - .0004$

$\pm .0007$

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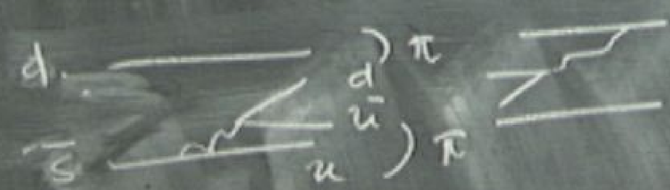
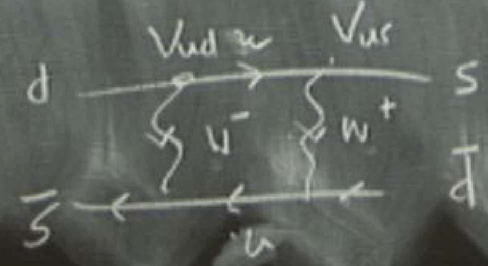
$$J^+_\mu = \bar\nu_{eL}\gamma_\mu e_L + \bar\nu_{\mu L}\gamma_\mu \mu_L + \bar u \gamma_\mu(\cos\theta_c\, d + \sin\theta_c\, s)$$

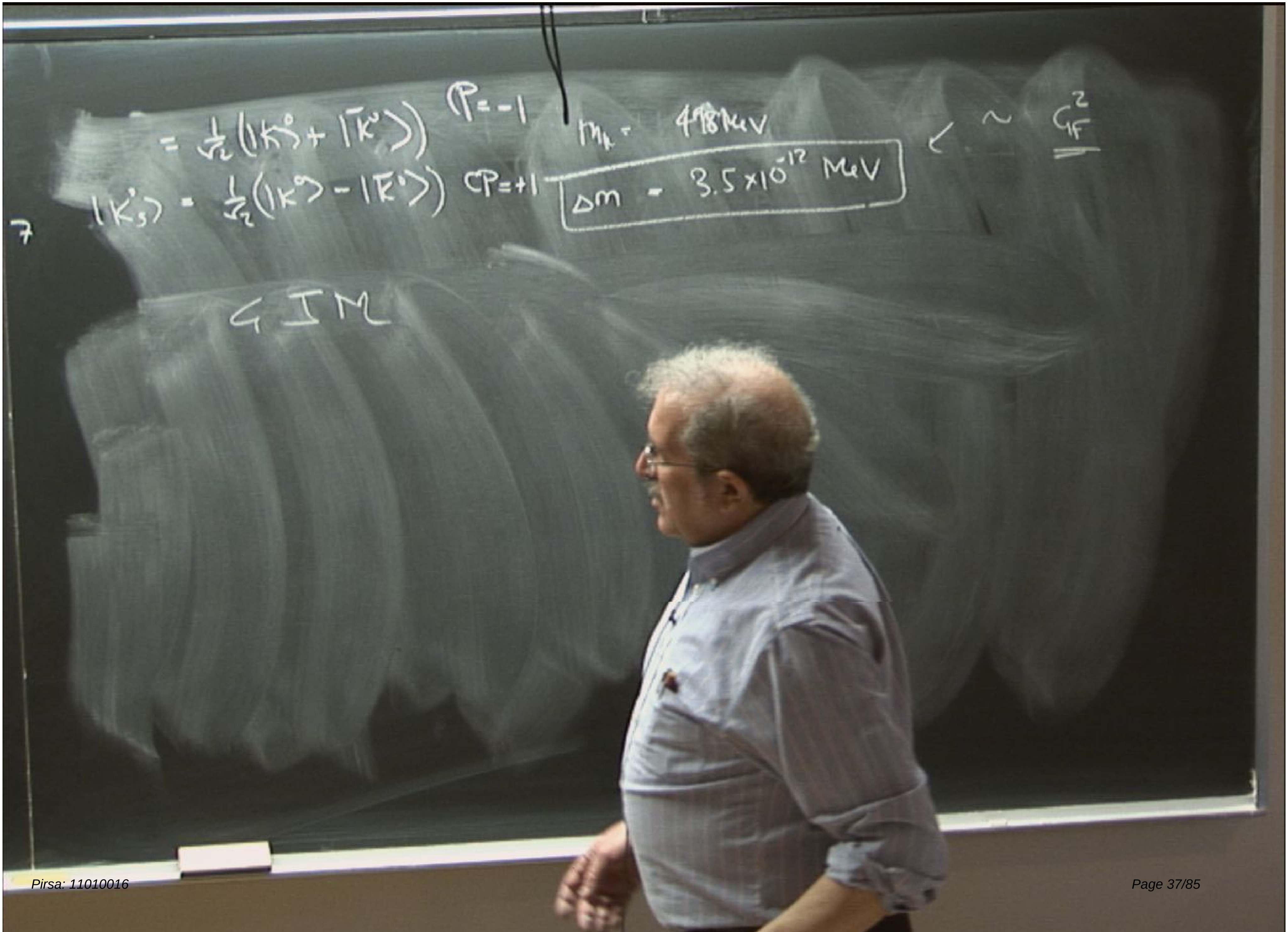


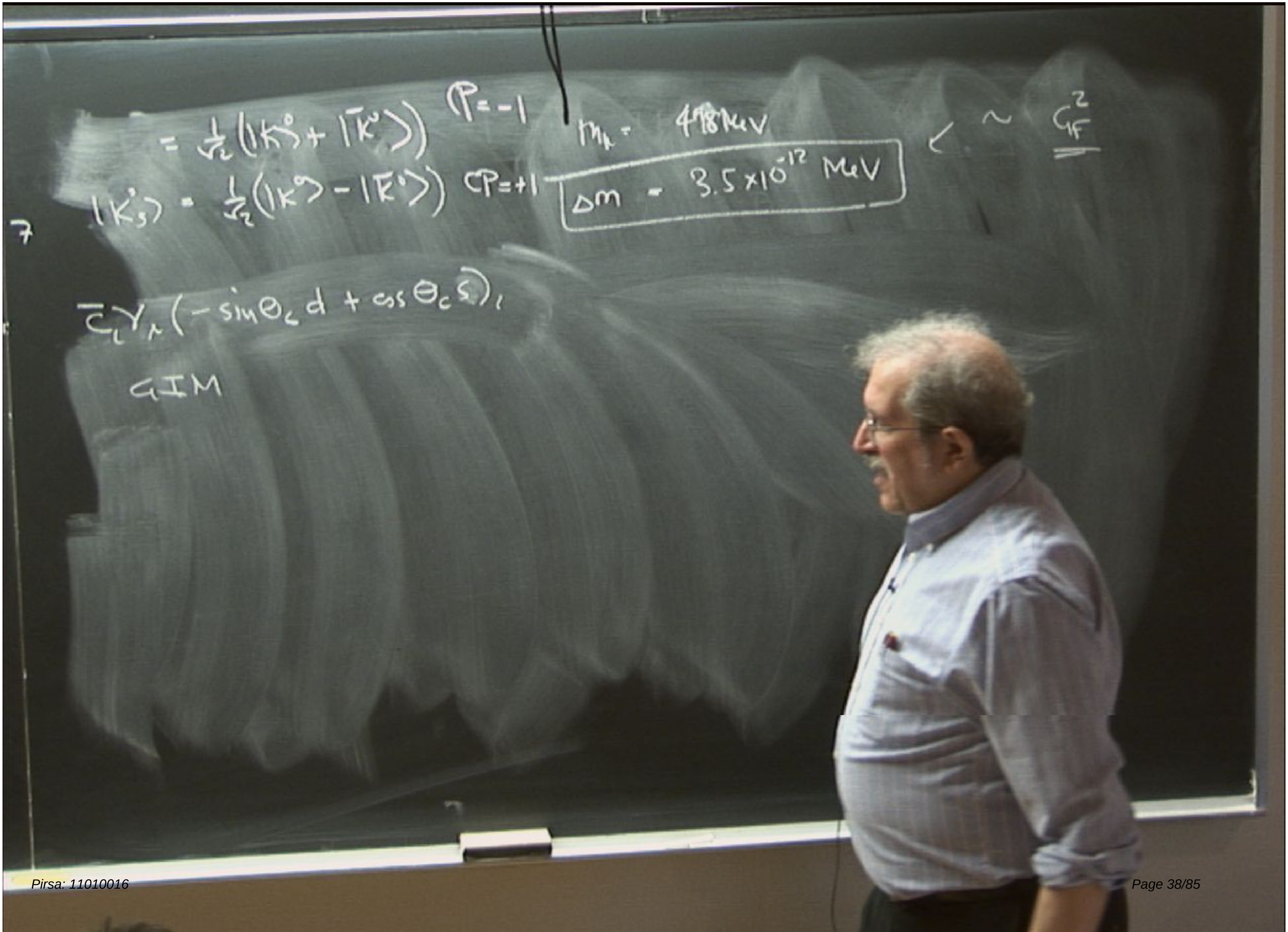


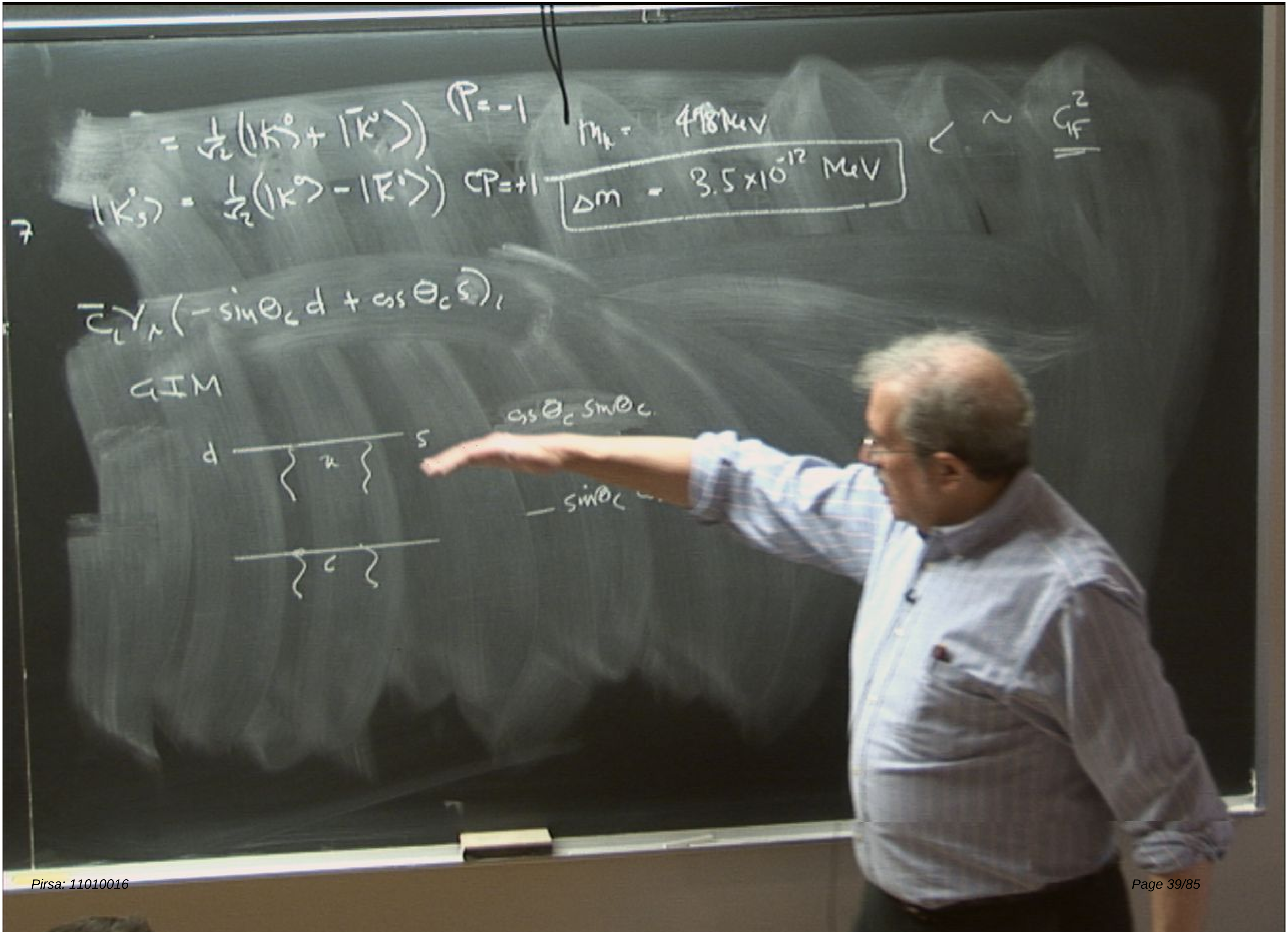
$$\int \frac{d^4k}{(\;)} \frac{1}{(k^2-m_W^2)^2} \frac{\not k}{k^2} \frac{\not k}{k^2}$$

$$g^4 \frac{1}{m_W^2} \quad V_{ud}^2 V_{us}^2$$

$\alpha_W G_F$


= $\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ CP = -1
$|K'_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ CP = +1
m_K = 498 MeV
$\Delta m = 3.5 \times 10^{-12}$ MeV
$\sim G_F^2$
7
GIM


= 1/√2 (|K⁰⟩ + |K̄⁰⟩) CP = -1
|K₂⁰⟩ = 1/√2 (|K⁰⟩ − |K̄⁰⟩) CP = +1
m_K = 498 MeV
Δm = 3.5×10⁻¹² MeV
~ G_F²
c̄_L γ_μ (− sin θ_c d + cos θ_c s)_L
GIM


$= \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ $CP = -1$
$m_K = 498$ MeV
$\sim G_F^2$
$|K_S^0\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$ $CP = +1$
$\boxed{\Delta m = 3.5 \times 10^{-12}\ \text{MeV}}$
$\bar{c}_L \gamma_\mu (-\sin\theta_c d + \cos\theta_c s)_L$
GIM
$\cos\theta_c \sin\theta_c$
d
s
u
$-\sin\theta_c$
c

$$= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \quad CP = -1$$

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \quad CP = +1$$

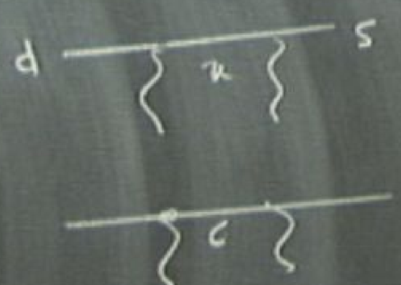
$m_K = 498\ \mathrm{MeV}$

$$\boxed{\Delta m = 3.5 \times 10^{-12}\ \mathrm{MeV}} \quad \sim G_F^2$$

$$\bar{c}_L \gamma_\mu \left(-\sin\theta_c\, d + \cos\theta_c\, s\right)_L$$

$$\alpha_W G_F V_{ud}^2 V_{us}^2 \left(\frac{m_c}{m_W}\right)^2$$

GIM



$\cos\theta_c \sin\theta_c$

$-\sin\theta_c \cos\theta_c$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \qquad e^-_R \qquad \delta\mathcal{L} = m_e \bar{e} e$$

$$I = \tfrac{1}{2} \qquad I = 0 \qquad = m_e \left(\bar{e}_L e_R + \bar{e}_R e_L \right)$$

$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \qquad e^-_R$

$I = \frac{1}{2} \qquad I = 0$

$\delta\mathcal{L} = \cancel{m_e \bar{e} e}$

$\cancel{= m_e (\bar{e}_L e_R + \bar{e}_R e_L)}$

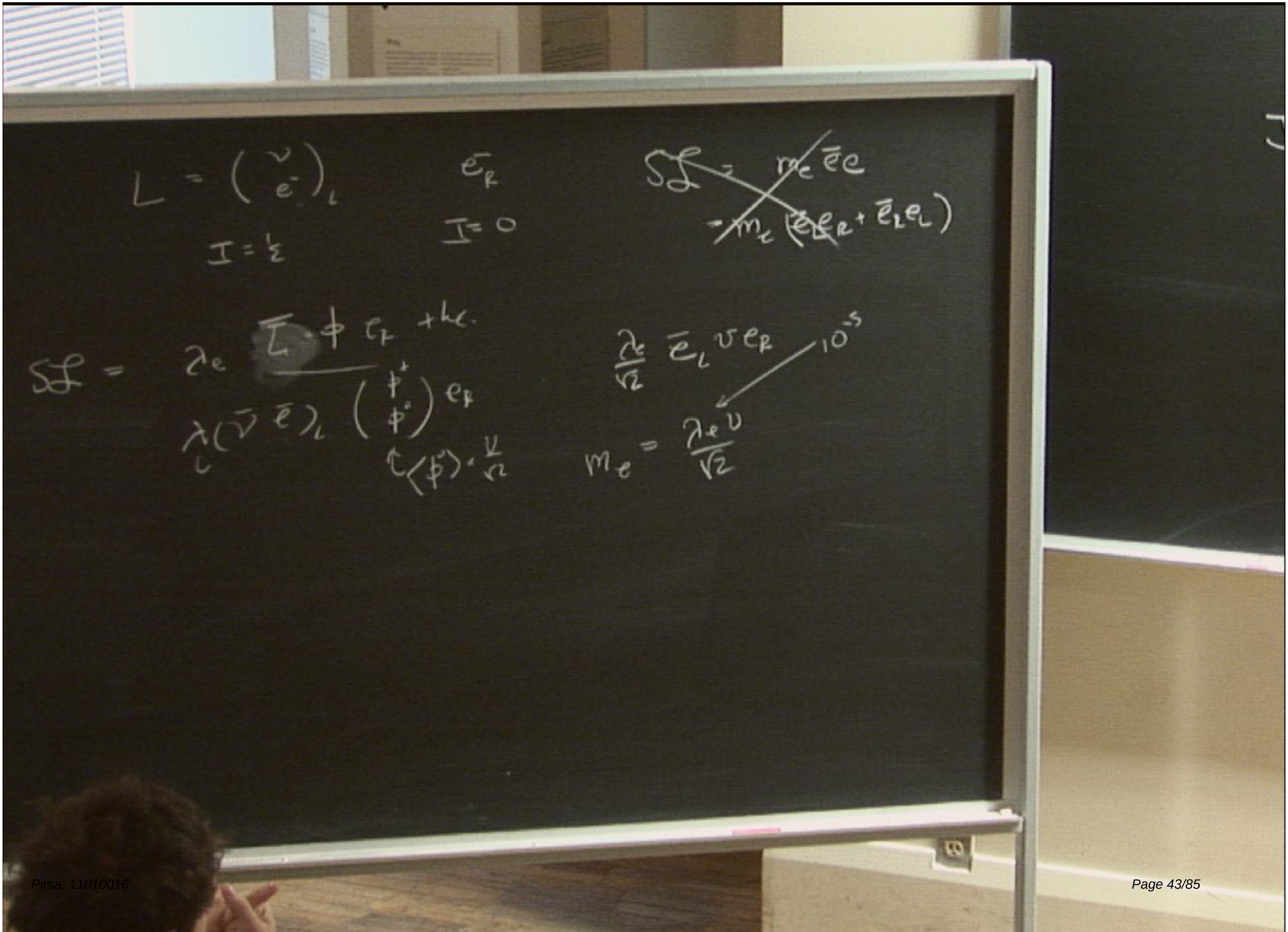
$\delta\mathcal{L} = \lambda_e \bar{L} \phi e_R + h.c.$

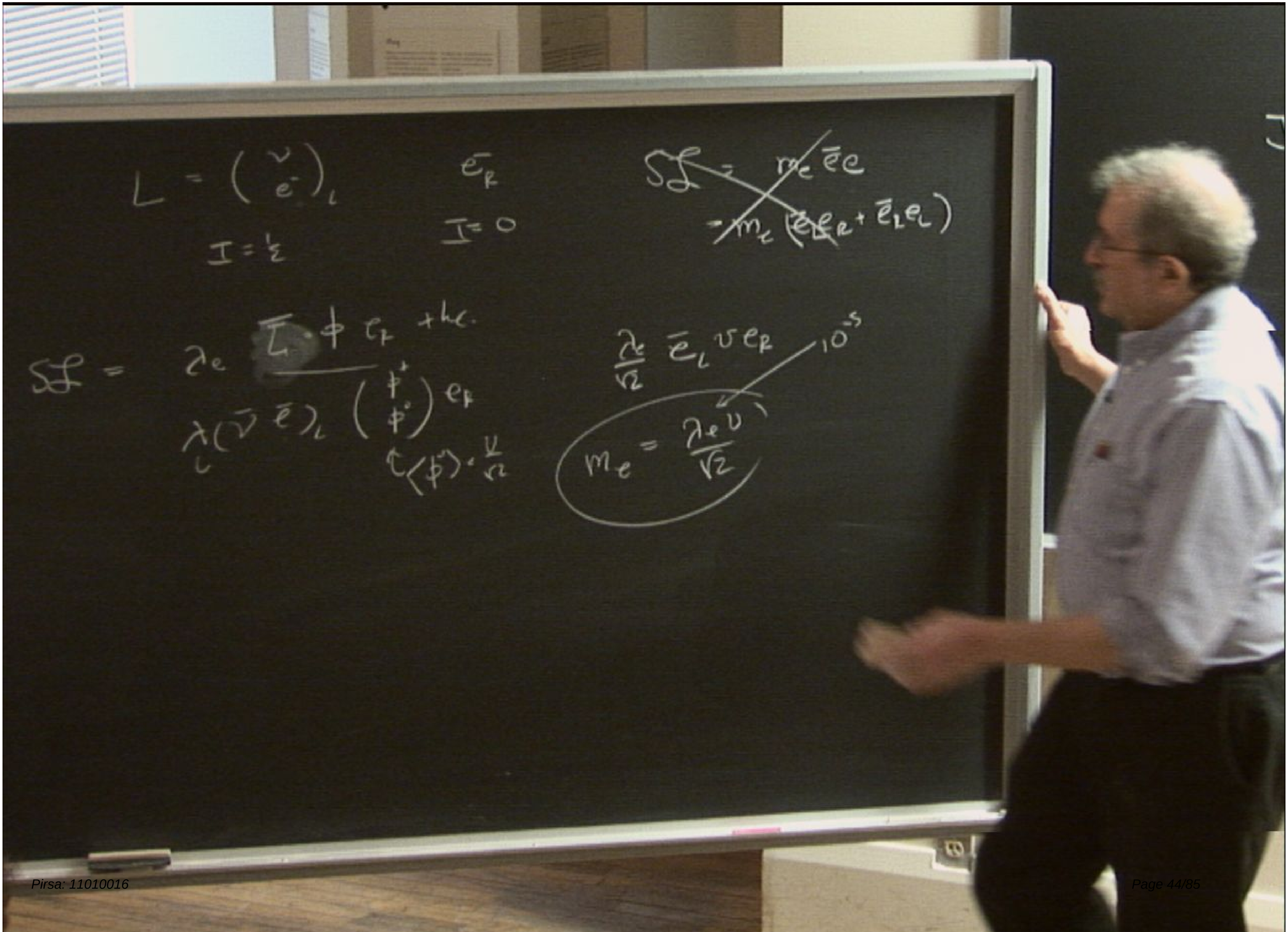
$\lambda_e (\bar{\nu}\ \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R$

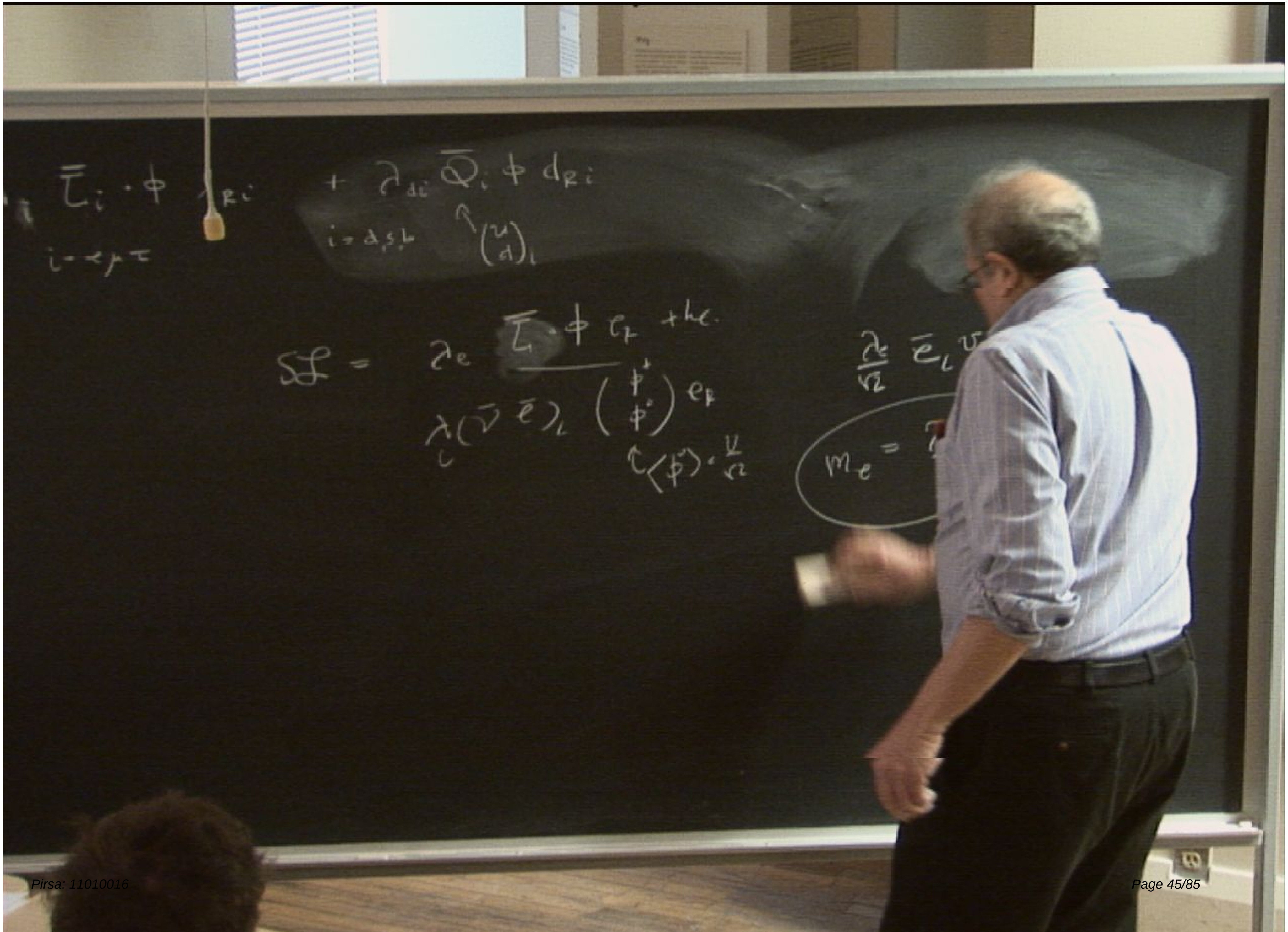
$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}$

$\frac{\lambda_e}{\sqrt{2}} \bar{e}_L v e_R$

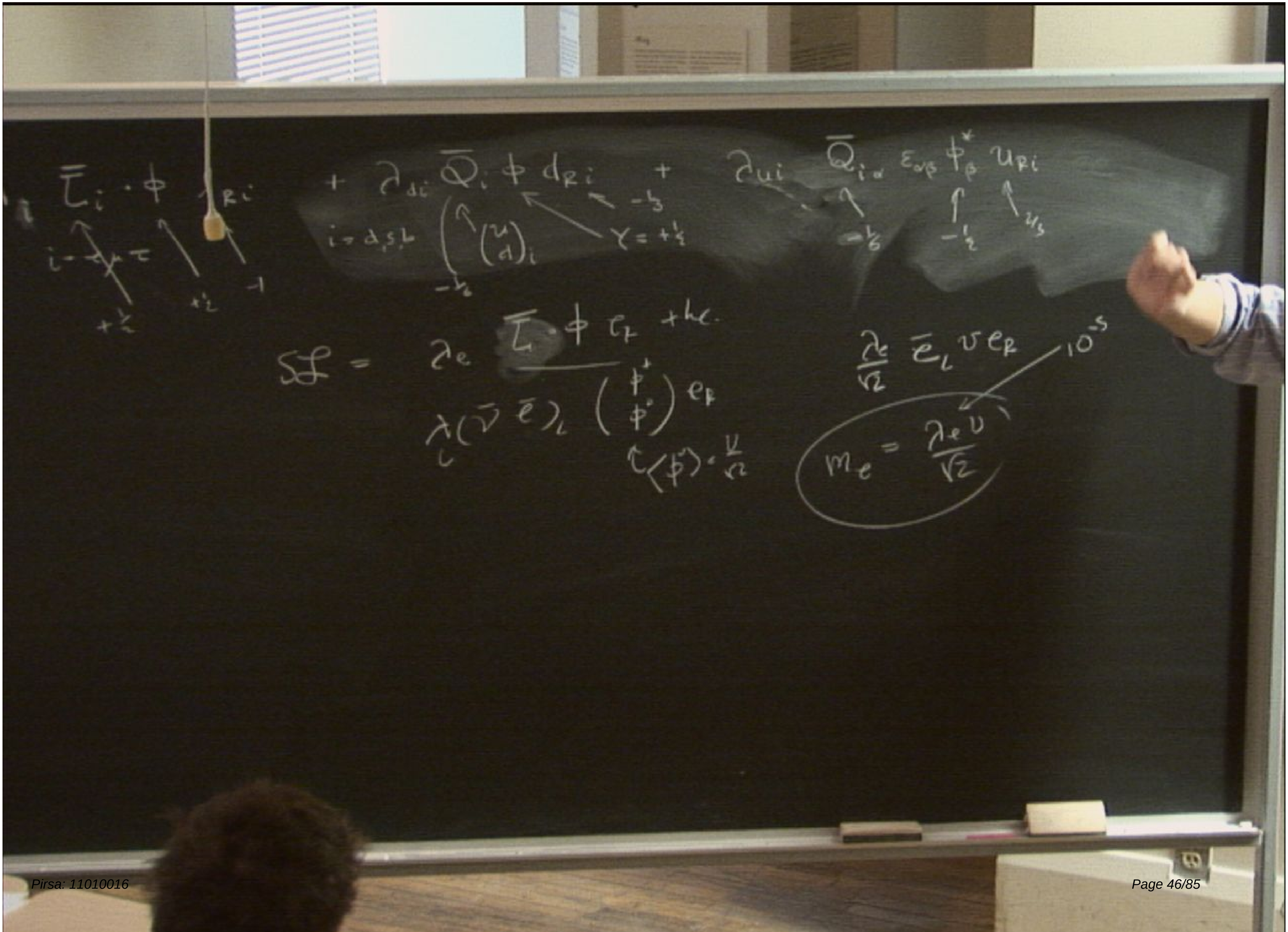
$m_e = \frac{\lambda_e v}{\sqrt{2}}$


$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$
e_R
$I = \frac{1}{2}$
$I = 0$
$\cancel{\delta\mathcal{L} = m_e \bar{e} e = m_e(\bar{e}_L e_R + \bar{e}_R e_L)}$
$\delta\mathcal{L} = \lambda_e \bar{L} \phi e_R + h.c.$
$\lambda_e (\bar{\nu}\ \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R$
$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}$
$\frac{\lambda_e}{\sqrt{2}} \bar{e}_L v e_R$
10^{-5}
$m_e = \frac{\lambda_e v}{\sqrt{2}}$


L = (ν e⁻)_L
e_R
I = 1/2
I = 0
δℒ = m_e ē e
= m_e (ē_R e_R + ē_L e_L)
δℒ = λ_e L̄ φ e_R + h.c.
λ_e (ν̄ ē)_L (φ⁺ φ⁰) e_R
⟨φ⁰⟩ = v/√2
λ_e/√2 ē_L v e_R
10⁻⁵
m_e = λ_e v/√2



i = e, μ, τ
i = d, s, b
+ h.c.
δℒ =
m_e =


$\bar{L}_i \phi\, e_{Ri}$ + $\lambda_{di} \bar{Q}_i \phi\, d_{Ri}$ + $\lambda_{ui} \bar{Q}_{i\alpha} \epsilon_{\alpha\beta} \phi^*_\beta u_{Ri}$
$i = e, \mu, \tau$
$+\frac{1}{2}$ $+\frac{1}{2}$ -1
$i = d, s, b$ $\begin{pmatrix} u \\ d \end{pmatrix}_i$ $-\frac{1}{6}$ $-\frac{1}{3}$ $Y = +\frac{1}{2}$
$-\frac{1}{6}$ $-\frac{1}{2}$ $\frac{2}{3}$
$\delta\mathcal{L} = \lambda_e \bar{L}_L \phi\, e_R$ + h.c.
$\lambda_e (\bar\nu\ \bar e)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R$
$\langle\phi^0\rangle = \frac{v}{\sqrt2}$
$\frac{\lambda_e}{\sqrt2} \bar{e}_L v\, e_R$ 10^{-5}
$m_e = \frac{\lambda_e v}{\sqrt2}$

$$\bar{L}_i \phi\, e_{Ri} + \lambda_{di} \bar{Q}_i \phi\, d_{Ri} + \lambda_{ui} \bar{Q}_{i\alpha} \epsilon_{\alpha\beta} \phi^*_\beta u_{Ri}$$

$i = e, \mu, \tau$ $\quad +\frac{1}{2} \quad +\frac{1}{2} \quad -1$

$i = d, s, b$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_i$ $\quad -\frac{1}{6} \quad Y = +\frac{1}{2} \quad -\frac{1}{3}$

$-\frac{1}{6} \quad -\frac{1}{2} \quad \frac{2}{3}$

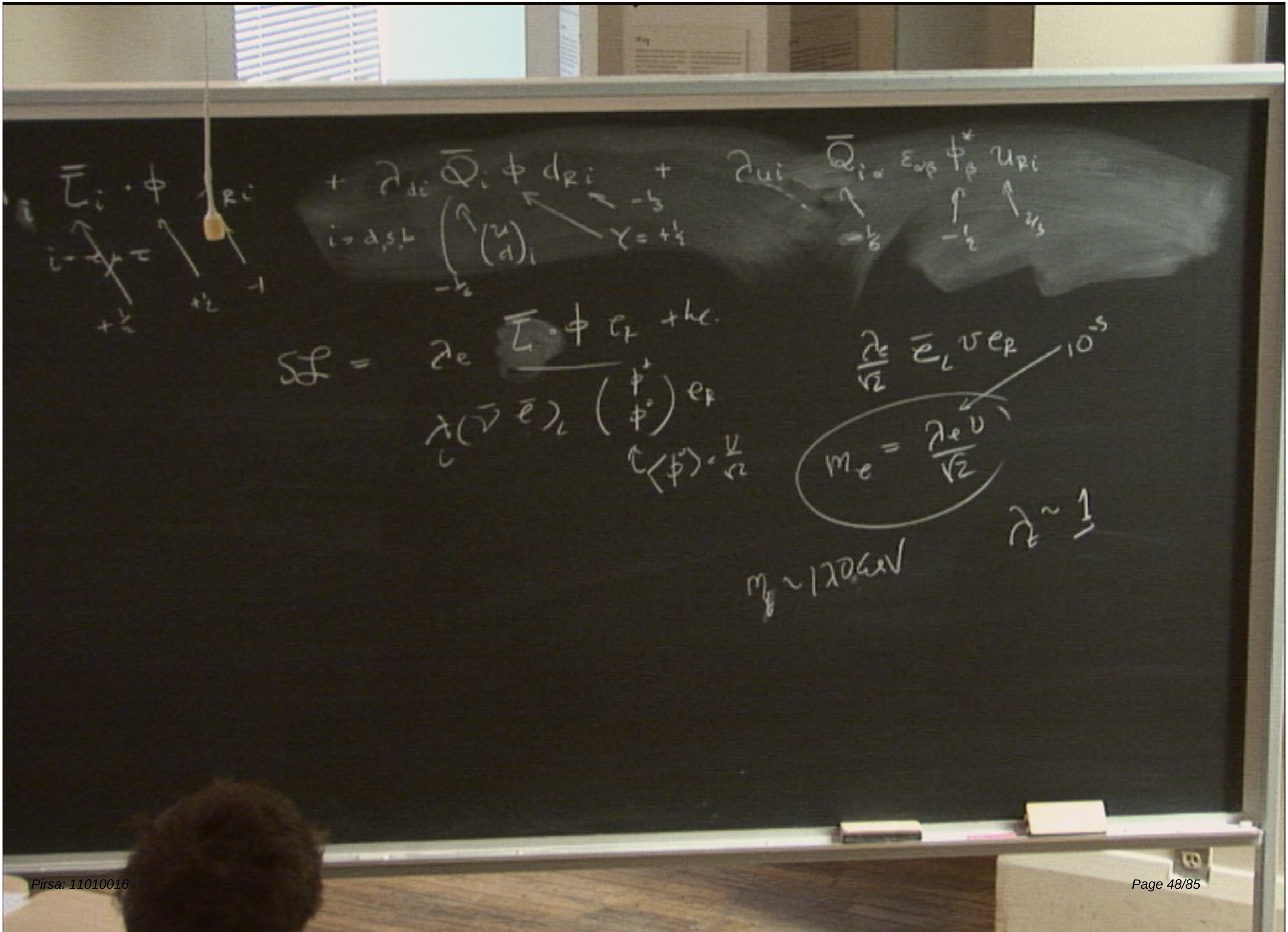
$$\delta\mathcal{L} = \lambda_e \bar{L}_L \phi\, e_R + h.c.$$

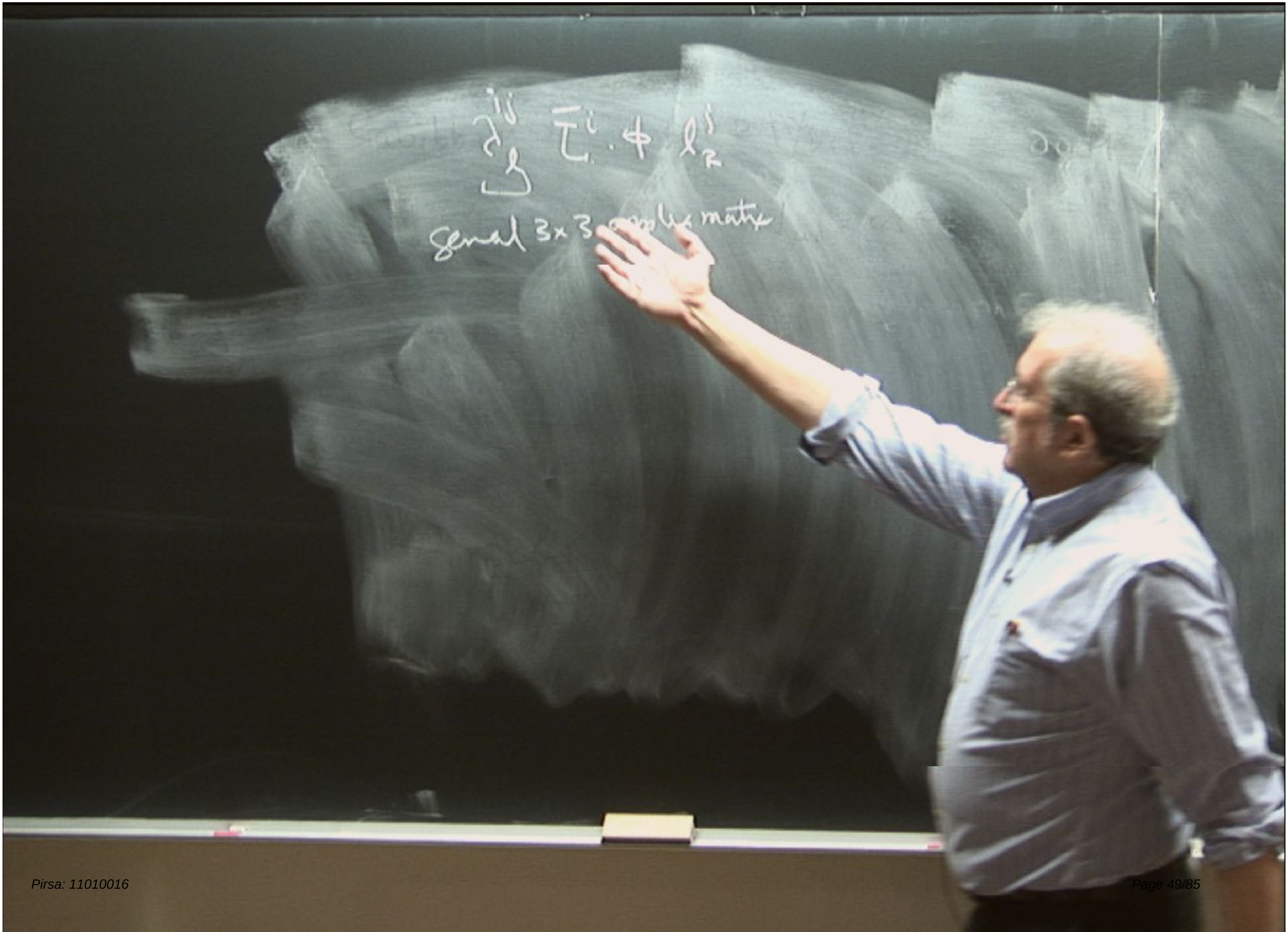
$$\lambda_e (\bar{\nu}\, \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R$$

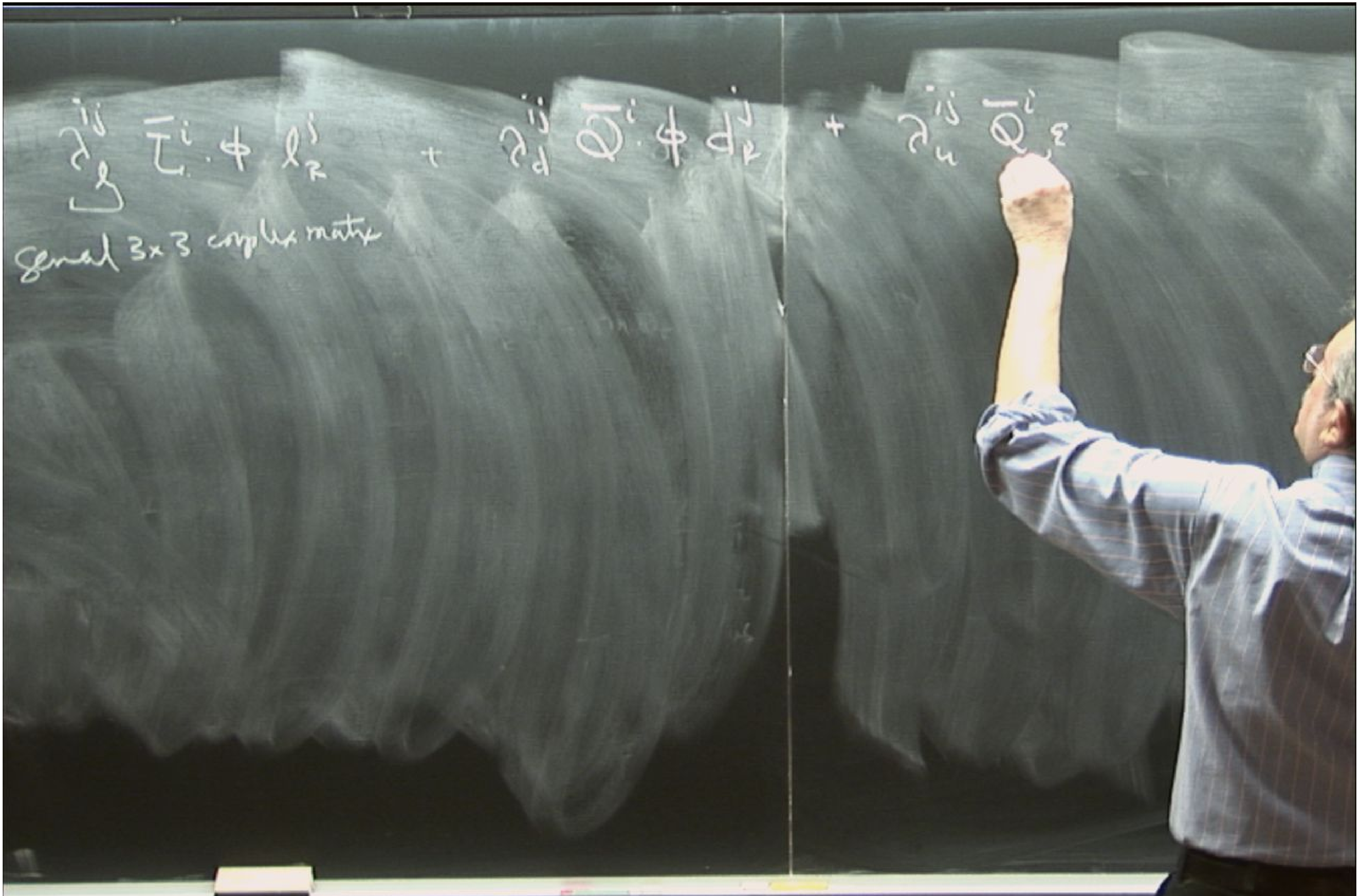
$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}$$

$$\frac{\lambda_e}{\sqrt{2}} \bar{e}_L v e_R \qquad 10^{-5}$$

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

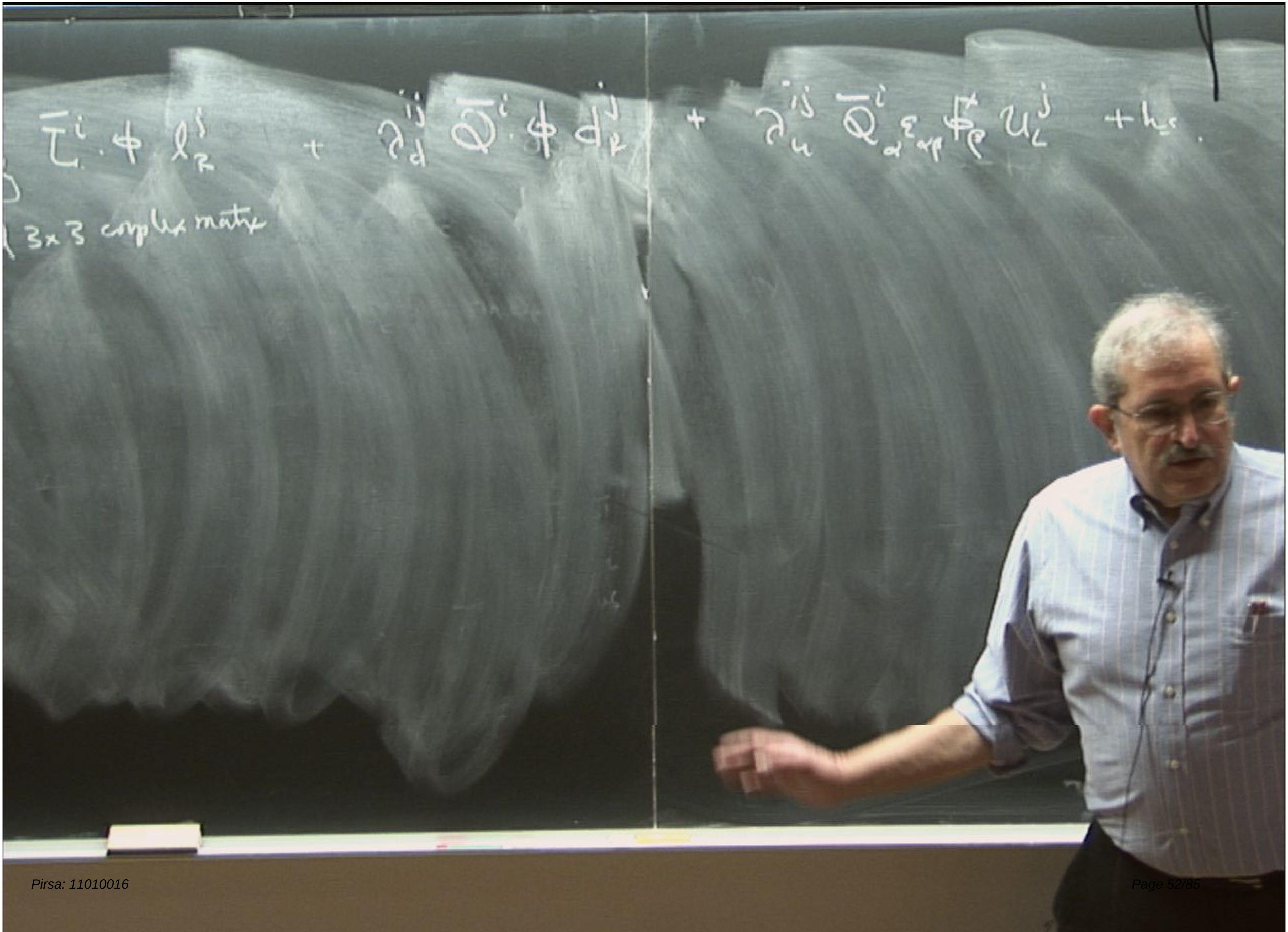

$\bar{L}_i \cdot \phi\, e_{Ri}$
$i = e, \mu, \tau$
$+\tfrac{1}{2}$ $+\tfrac{1}{2}$ -1
$+ \lambda_{di} \bar{Q}_i \phi\, d_{Ri} + \lambda_{ui} \bar{Q}_{i\alpha} \varepsilon_{\alpha\beta} \phi^*_\beta u_{Ri}$
$i = d, s, b$
$\binom{u}{d}_i$
$Y = +\tfrac{1}{3}$
$-\tfrac{1}{3}$ $-\tfrac{1}{6}$ $-\tfrac{1}{6}$ $-\tfrac{1}{2}$ $\tfrac{2}{3}$
$\delta\mathcal{L} = \lambda_e \bar{L}_L \phi\, e_R + h.c.$
$\lambda_e (\bar{\nu}\ \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R$
$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}$
$\frac{\lambda_e}{\sqrt{2}} \bar{e}_L v\, e_R$
10^{-5}
$m_e = \frac{\lambda_e v}{\sqrt{2}}$
$\lambda_t \sim 1$
$m_t \sim 170\,\mathrm{GeV}$

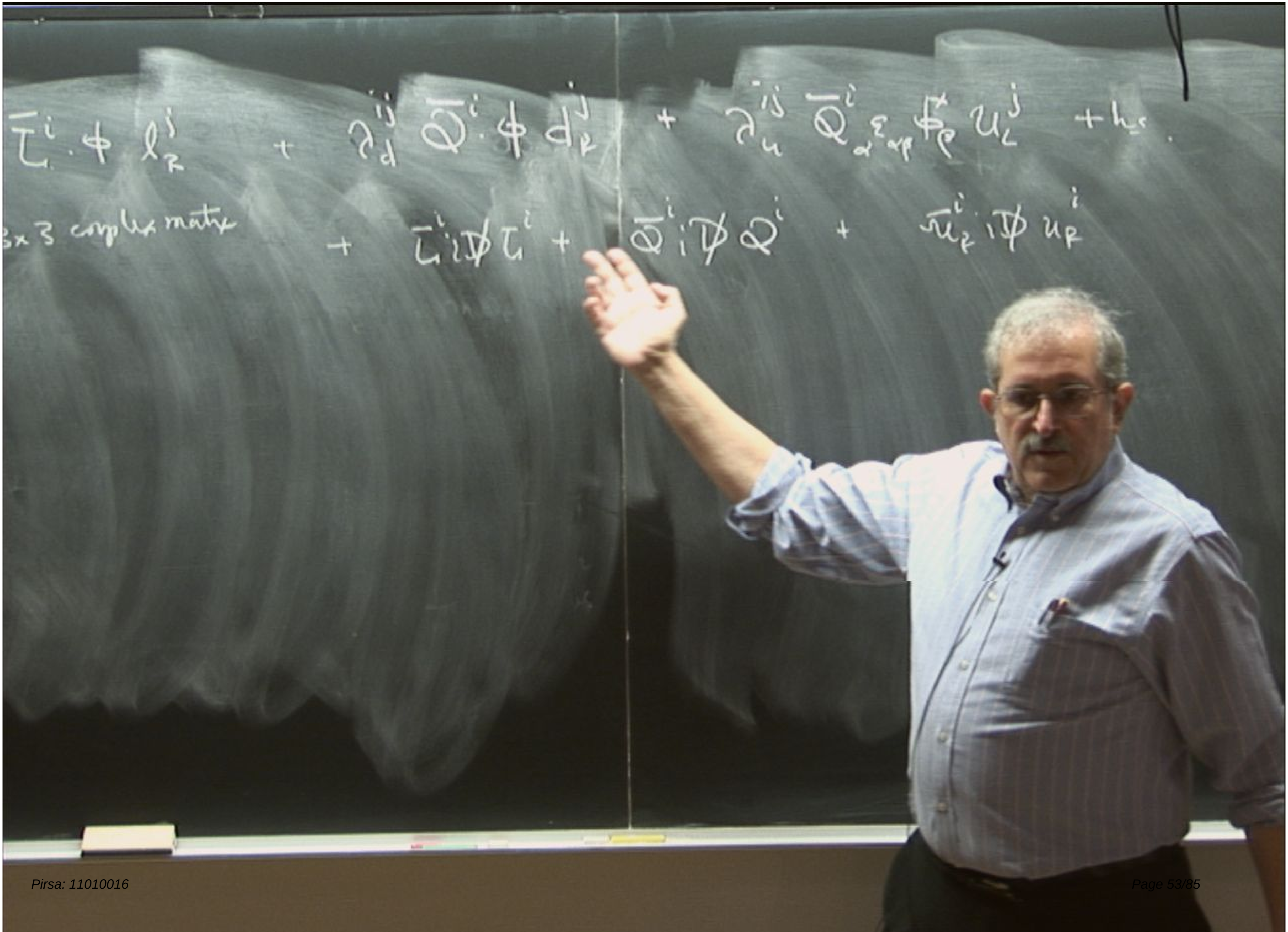

$\lambda_\ell^{ij}\ \bar{L}^i \cdot \Phi\ l_R^j$
general 3x3 complex matrix

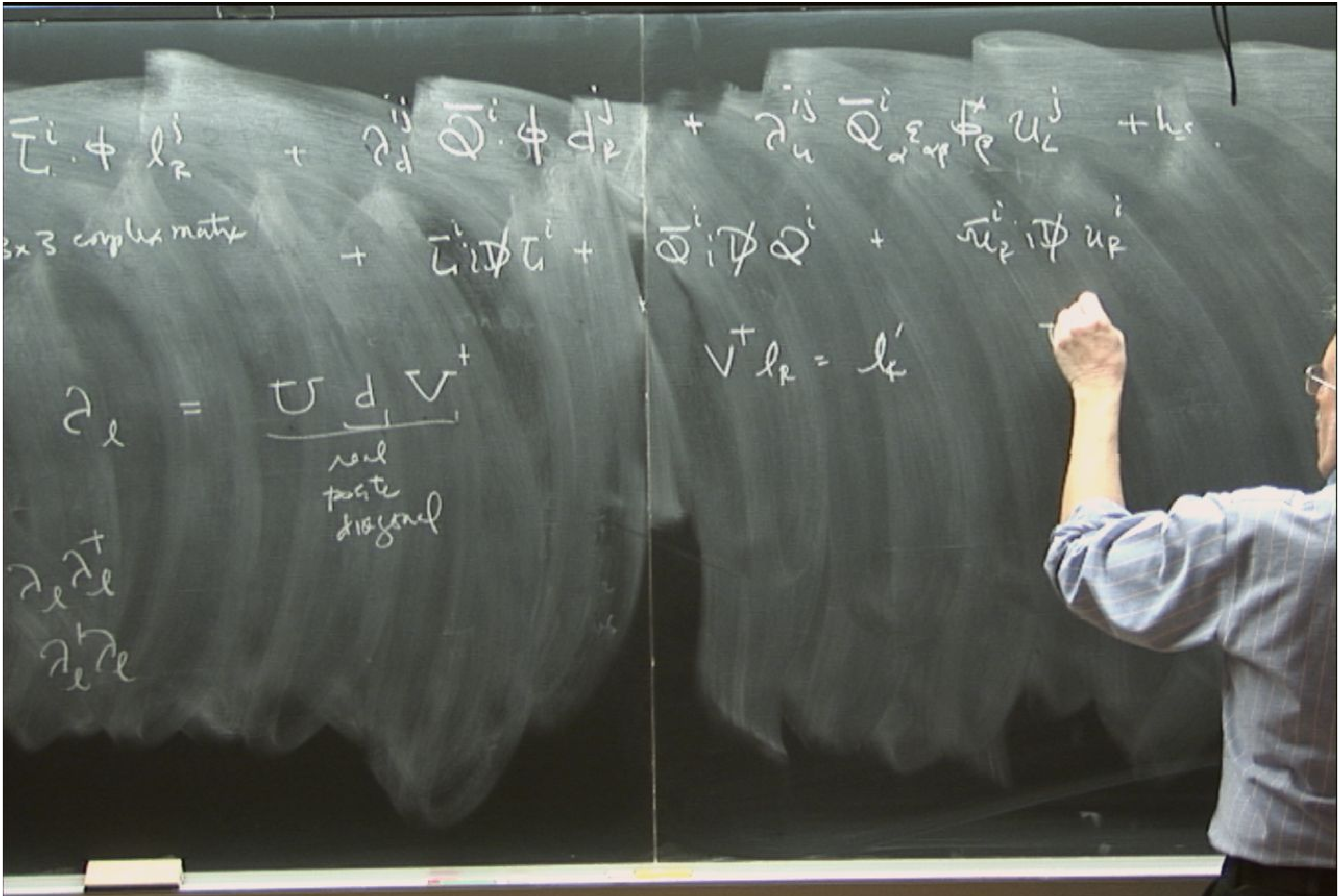

$\lambda_\ell^{ij}\ \bar{L}^i \cdot \phi\ \ell_R^j + \lambda_d^{ij}\ \bar{Q}^i \cdot \phi\ d_R^j + \lambda_u^{ij}\ \bar{Q}^i \epsilon$
general 3x3 complex matrix

$$\lambda_\ell^{ij}\,\bar{L}^i\cdot\Phi\,\ell_R^j + \lambda_d^{ij}\,\bar{Q}^i\cdot\Phi\,d_R^j + \lambda_u^{ij}\,\bar{Q}^i_\alpha\,\varepsilon_{\alpha\beta}\,\Phi^*_\beta\,u_R^j + h.c.$$

general 3×3 complex matrix


$\bar{L}^i \cdot \phi\, l_R^j \;+\; \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j \;+\; \lambda_u^{ij}\, \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \phi^*_\beta u_L^j \;+ h.c.$
3x3 complex matrix


$\bar{L}^i \cdot \phi\, l_R^j + \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j + \lambda_u^{ij}\, \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u_L^j + h.c.$
3x3 complex matrix
$+ \bar{L}^i i\not{D} L^i + \bar{Q}^i i\not{D} Q^i + \bar{u}_R^i i\not{D} u_R^i$



$\bar{L}^i \cdot \phi \, l_R^j + \lambda_d^{ij} \bar{Q}^i \cdot \phi \, d_R^j + \lambda_u^{ij} \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u_L^j + h.c.$
3x3 complex matrix
$+ \bar{L}^i i\not{D} L^i + \bar{Q}^i i\not{D} Q^i + \bar{u}_R^i i\not{D} u_R^i$
$V^\dagger l_R = l_R'$
$\lambda_l = \underbrace{U \, d \, V^\dagger}$
real
positive
diagonal
$\lambda_l \lambda_l^\dagger$
$\lambda_l^\dagger \lambda_l$

$$\bar{L}^i \cdot \phi\, l_R^j \quad + \quad \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j \quad + \quad \lambda_u^{ij}\, \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u_L^j \quad + h.c.$$

3x3 complex matrix

$$+ \quad \bar{L}^i i \not{D} L^i + \bar{Q}^i i \not{D} Q^i \quad + \quad \bar{u}_R^i i \not{D} u_R^i$$

$$V^\dagger l_R = l_R' \qquad U^\dagger L = L'$$

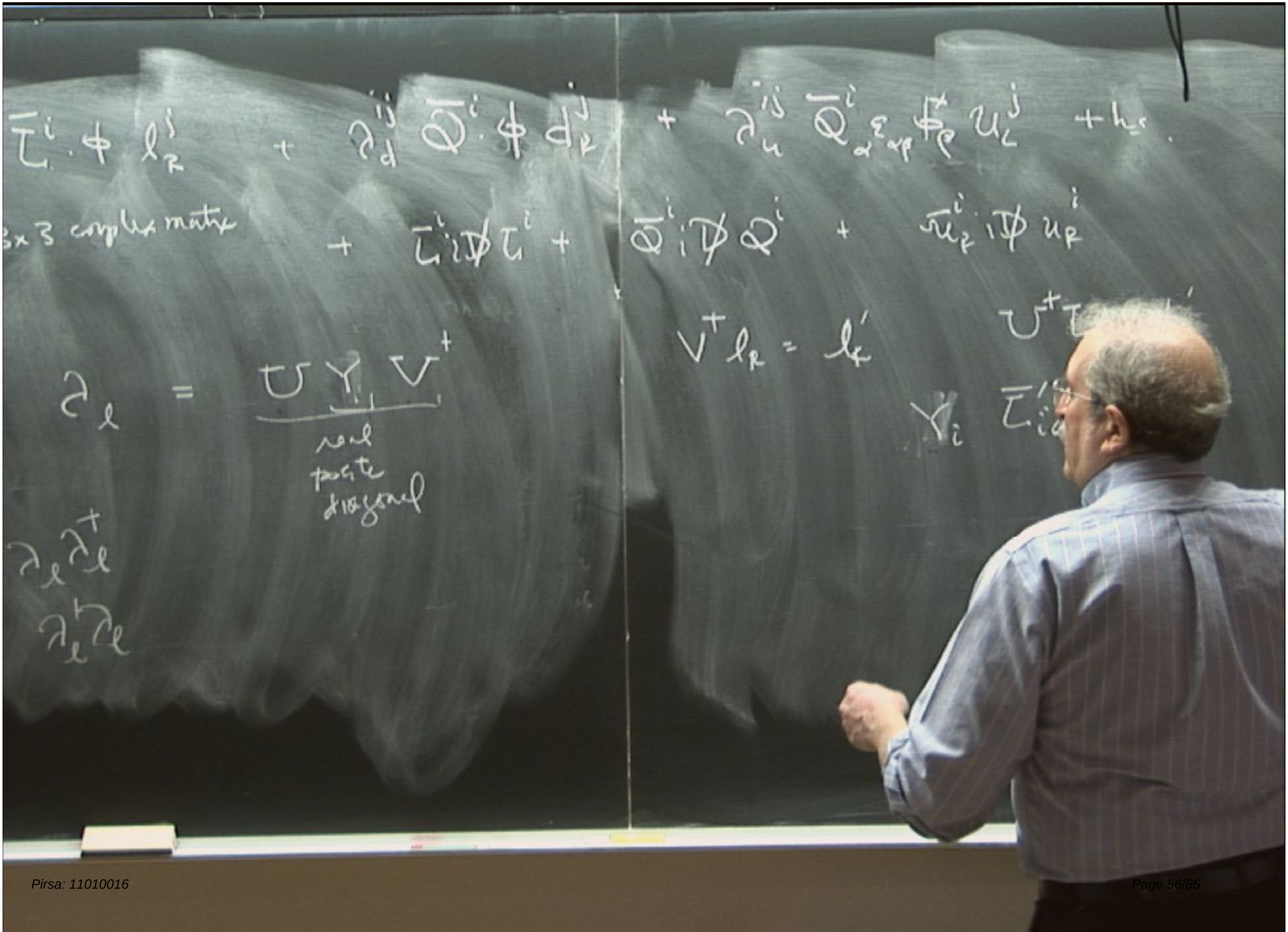
$$\lambda_l = \underbrace{U\, Y_l\, V^\dagger}$$

real
positive
diagonal

$$Y_i \quad \bar{L}'_{iL} \phi\, l'_{iR}$$

$$\lambda_l \lambda_l^\dagger$$

$$\lambda_l^\dagger \lambda_l$$


$\bar{\ell}^i \phi\, \ell_R^j + \lambda_d^{ij} \bar{Q}^i \phi\, d_R^j + \lambda_u^{ij} \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \phi^*_\beta u_L^j + h.c.$
3x3 complex matrix
$+ \bar{\ell}^i i\not{D} \ell^i + \bar{Q}^i i\not{D} Q^i + \bar{u}_R^i i\not{D} u_R^i$
$V^\dagger \ell_R = \ell_R'$
$\lambda_\ell = \underbrace{U Y V^\dagger}$
real
positive
diagonal
$\lambda_\ell \lambda_\ell^\dagger$
$\lambda_\ell^\dagger \lambda_\ell$
Y_i

$\bar{L}^i \cdot \phi\, l_R^j \quad + \quad \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j \quad + \quad \lambda_u^{ij}\, \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \phi^*_\beta u_L^j \quad + h.c.$

3x3 complex matrix

$+ \quad \bar{L}^i i \not{D} L^i + \bar{Q}^i i \not{D} Q^i + \bar{u}_R^i i \not{D} u_R^i$

$V^\dagger l_R = l_R' \qquad U^\dagger L = L'$

$$\lambda_l = \underbrace{U\, Y_i\, V^\dagger}_{\text{real positive diagonal}}$$

$Y_i \quad \bar{L}' \, l_R'$

$\bar{L}' i A^a_\mu \frac{\sigma^a}{2} L'$

$\lambda_l \lambda_l^\dagger$

$\lambda_l^\dagger \lambda_l$

$\bar{L}^i \cdot \phi \, l_R^j \quad + \quad \lambda_d^{ij} \bar{Q}^i \cdot \phi \, d_R^j \quad + \quad \lambda_u^{ij} \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u_L^j \quad + h.c.$

3x3 complex matrix

$+ \quad \bar{L}^i i \not{D} L^i + \bar{Q}^i i \not{D} Q^i + \bar{u}_R^i i \not{D} u_R^i$

$$\lambda_\ell = \underbrace{U Y_\ell V^\dagger}$$

real
positive
diagonal

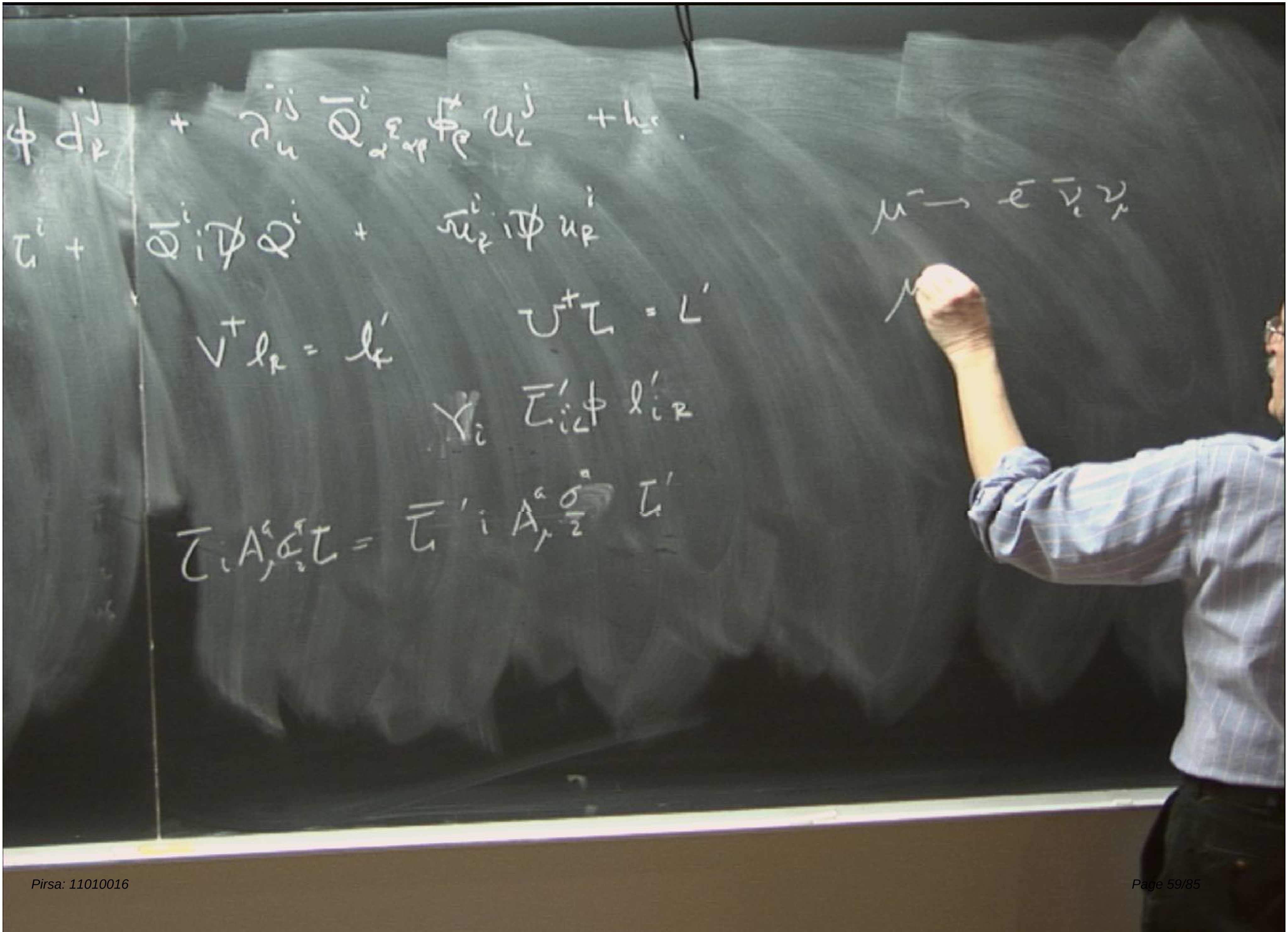
$V^\dagger l_R = l_R'$ $\qquad U^\dagger L = L'$

$Y_i \, \bar{L}'_{iL} \phi \, l'_{iR}$

$\lambda_\ell \lambda_\ell^\dagger$

$\lambda_\ell^\dagger \lambda_\ell$

$\bar{L} \, i A_\mu^a \frac{\sigma^a}{2} L = \bar{L}' \, i A_\mu^a \frac{\sigma^a}{2} L'$


$\mu^- \to e^- \bar{\nu}_e \nu_\mu$
$V^\dagger l_R = l_R'$
$U^\dagger L = L'$
$Y_i \, \bar{L}_{iL}' \phi \, l_{iR}'$
$\bar{L} \, i A_\mu^a \frac{\sigma^a}{2} L = \bar{L}' \, i A_\mu^a \frac{\sigma^a}{2} L'$

$$\phi\, d_R^j + \lambda_u^{ij}\, \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \phi^*_\beta\, u_L^j + h.c.$$

$$L^i + \bar{Q}^i\, i\not{D}\, Q^i + \bar{u}_R^i\, i\not{D}\, u_R^i$$

$$V^\dagger l_R = l_R' \qquad U^\dagger L = L'$$

$$\gamma_i\, \bar{L}'_{iL}\, \phi\, l'_{iR}$$

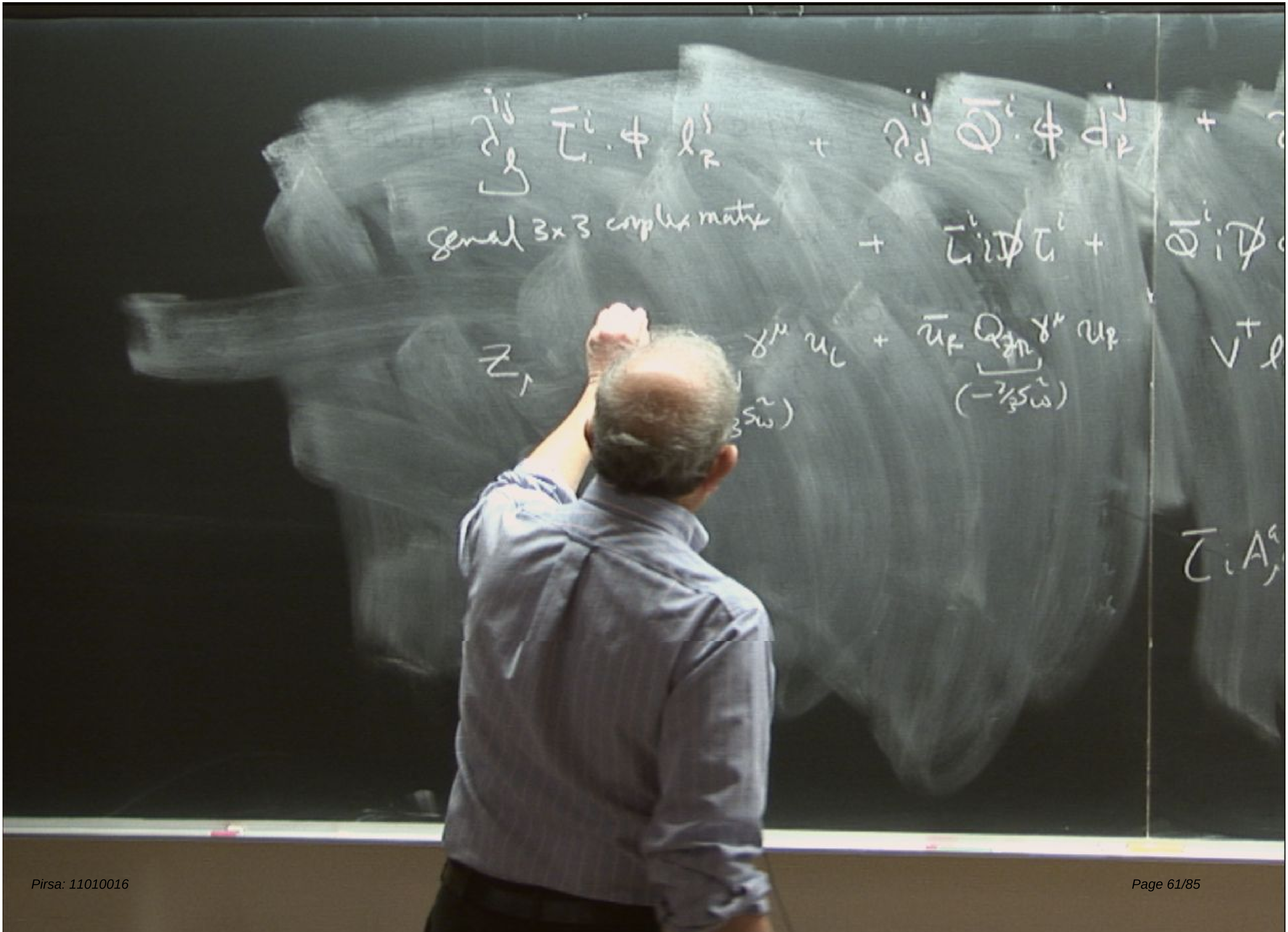
$$\bar{L}\, i A_\mu^a \frac{\sigma^a}{2} L = \bar{L}'\, i A_\mu^a \frac{\sigma^a}{2} L'$$

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$$\mu^- \not\to e^- \gamma$$

$$\lambda_d = U_d \gamma_d V_d^\dagger$$

$$\lambda_u = U_u \gamma_u V_u^\dagger$$


$\lambda_\ell^{ij}\,\bar{L}^i\cdot\phi\,\ell_R^j + \lambda_d^{ij}\,\bar{Q}^i\cdot\phi\,d_R^j +$
3x3 complex matrix
$+\ \bar{L}^i\,i\not{D}\,L^i + \bar{Q}^i\,i\not{D}$
$\gamma^\mu u_L + \bar{u}_R\,Q\,\gamma^\mu u_R$
$(-\tfrac{2}{3}s_w^2)$
$V^+\ell$

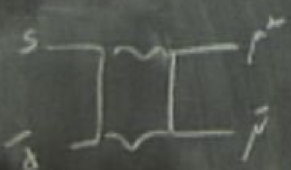
$$\lambda_\ell^{ij}\, \bar{L}^i \cdot \phi\, \ell_R^j + \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j + \lambda_u^{ij}\, \bar{Q}^i_\alpha \epsilon_\alpha$$

λ_ℓ: general 3x3 complex matrix

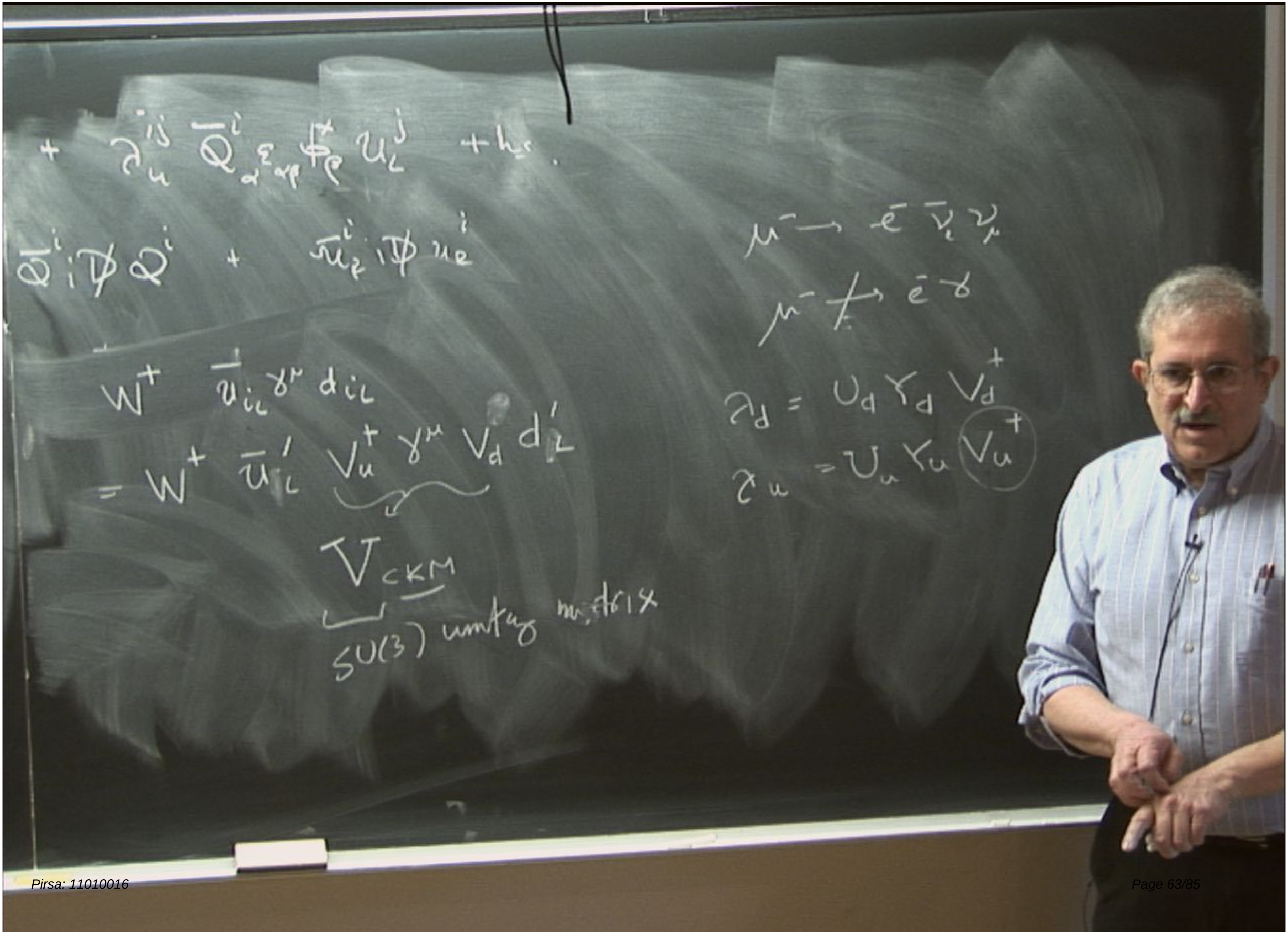
$$+ \bar{L}^i i \not{D} L^i + \bar{Q}^i i \not{D} Q^i +$$

$$Z_\mu \quad \bar{u}'_L \underbrace{Q_{ZL}}_{(\frac{1}{2} - \frac{2}{3} s_w^2)} \gamma^\mu u'_L + \bar{u}_R \underbrace{Q_{ZR}}_{(-\frac{2}{3} s_w^2)} \gamma^\mu u_R$$

$V_u^\dagger V_u = 1$ $\qquad$ $U_u^\dagger U_u = 1$



$$s \not\to d + Z^0$$
$$Z^0 \to \mu^+ \mu^-$$


+ $\lambda_u^{ij} \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u^j_L$ + h.c.
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$
$\mu^- \not\to e^- \gamma$
$W^+ \bar{u}_{iL} \gamma^\mu d_{iL}$
$= W^+ \bar{u}'_L V_u^+ \gamma^\mu V_d d'_L$
$\lambda_d = U_d \gamma_d V_d^+$
$\lambda_u = U_u \gamma_u V_u^+$
V_{CKM}
SU(3) unitary matrix

$+ \lambda_u^{ij} \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \Phi^*_\beta u^j_L + h.c.$

$\bar{Q}^i \, i \not{D} Q^i + \bar{u}^i_R \, i \not{D} u^i_R$

$W^+ \bar{u}_{iL} \gamma^\mu d_{iL}$

$= W^+ \bar{u}'_L \underbrace{V_u^+ \gamma^\mu V_d}_{} d'_L$

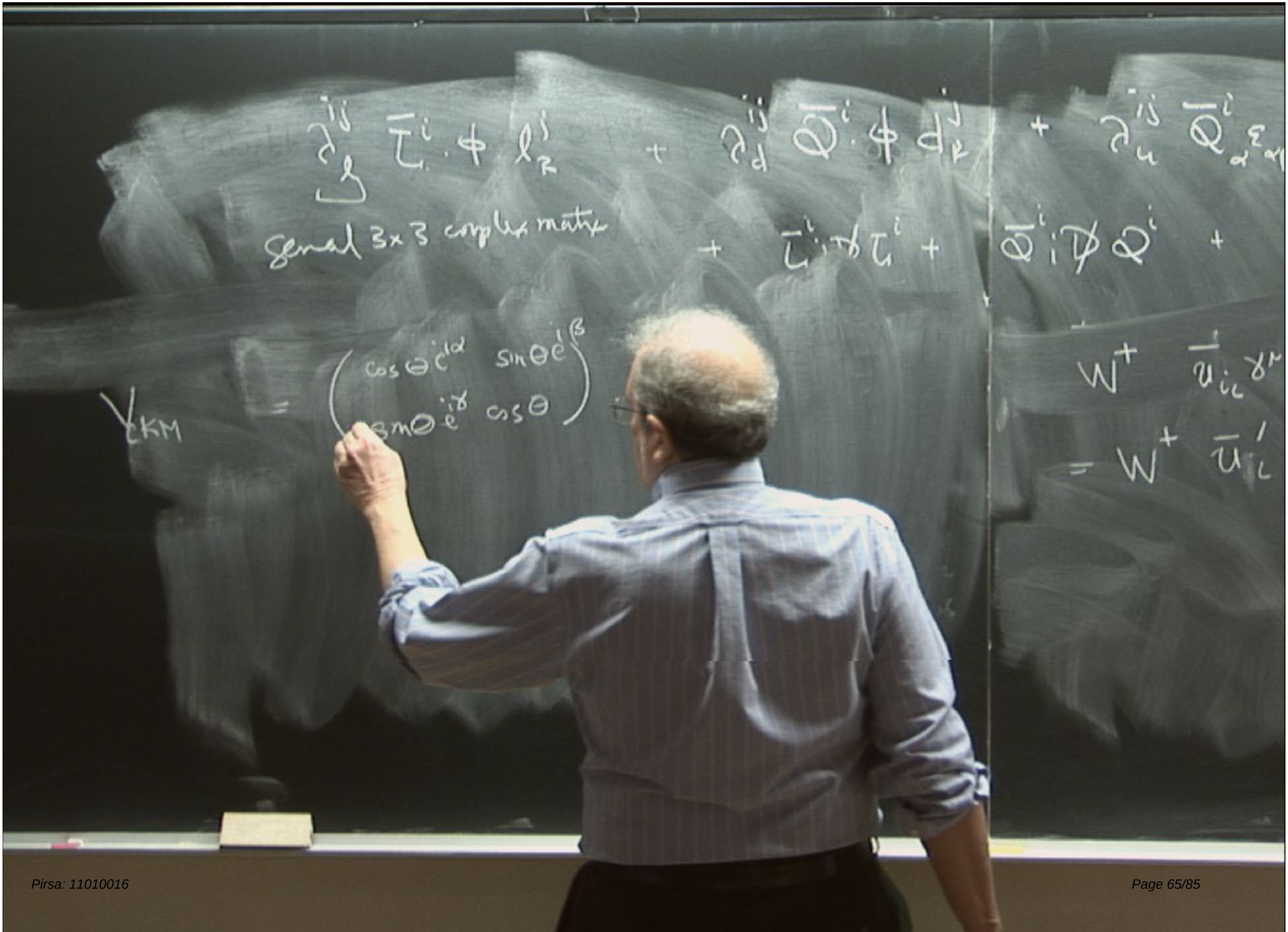
$\underbrace{V}_{\text{SU(3) unitary matrix}}{}_{CKM}$

$\mu^- \to e^- \bar{\nu}_e \nu_\mu$

$\mu^- \not\to e^- \gamma$

$\lambda_d = U_d Y_d V_d^+$

$\lambda_u = U_u Y_u V_u^+$


$\lambda_\ell^{ij} \bar{L}^i \cdot \phi \, l_R^j$ + $\lambda_d^{ij} \bar{Q}^i \cdot \phi \, d_R^j$ + $\lambda_u^{ij} \bar{Q}^i_\alpha \epsilon_{\alpha}$
general 3x3 complex matrix
+ $\bar{L}^i i \not\partial L^i$ + $\bar{Q}^i i \not D Q^i$ +
$V_{CKM} = \begin{pmatrix} \cos\theta e^{i\alpha} & \sin\theta e^{i\beta} \\ \sin\theta e^{i\gamma} & \cos\theta \end{pmatrix}$
$W^+ \bar{u}_{iL} \gamma^\mu$
$= W^+ \bar{u}'_L$

$$\underbrace{\lambda_\ell^{ij}}\ \bar{L}^i\,\phi\,\ell_R^j \;+\; \lambda_d^{ij}\,\bar{Q}^i\,\phi\,d_R^j \;+\; \bar{\lambda}_u^{ij}\,\bar{Q}^i_\alpha\,\varepsilon_{\alpha\beta}$$

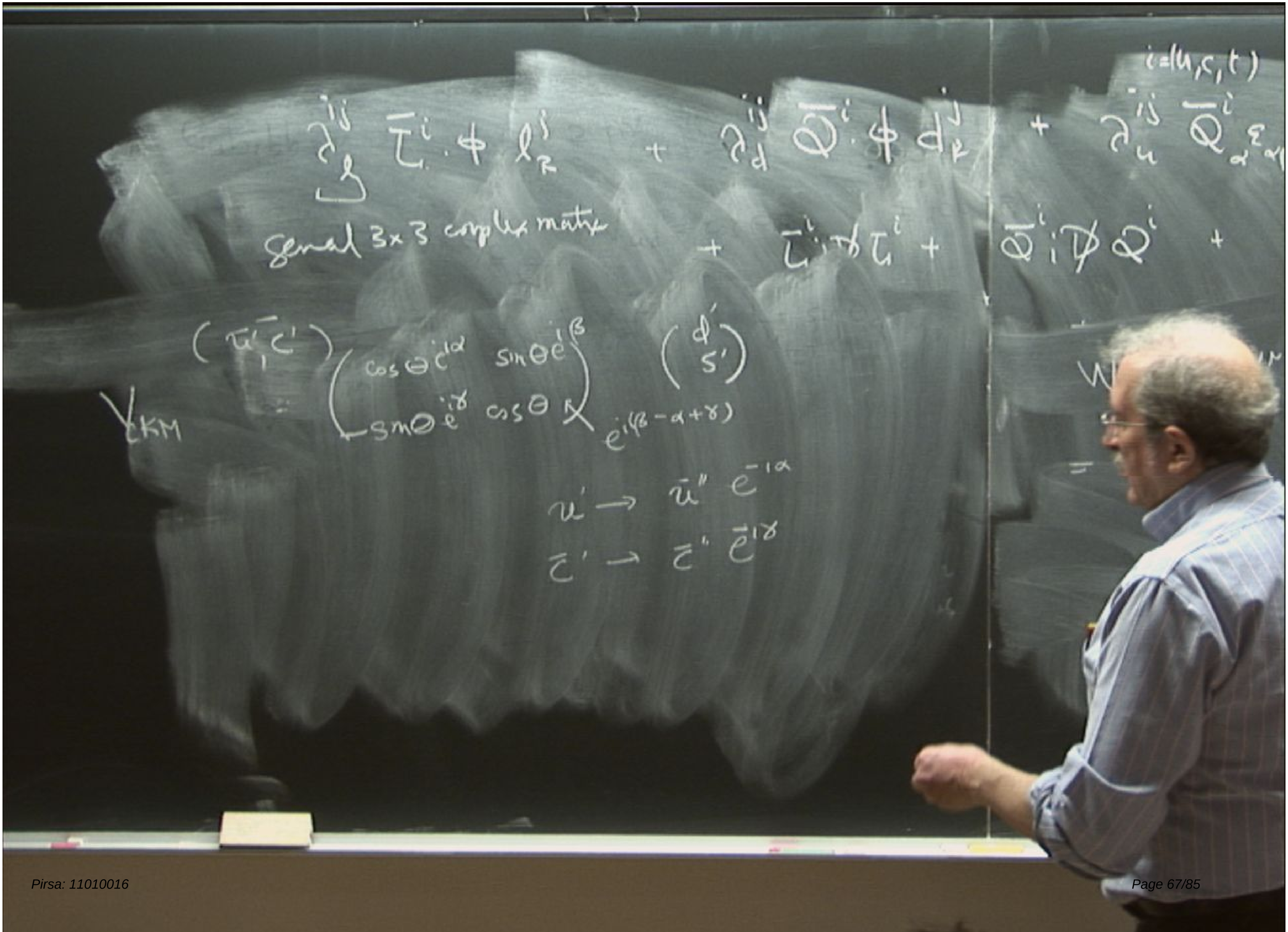
general 3x3 complex matrix

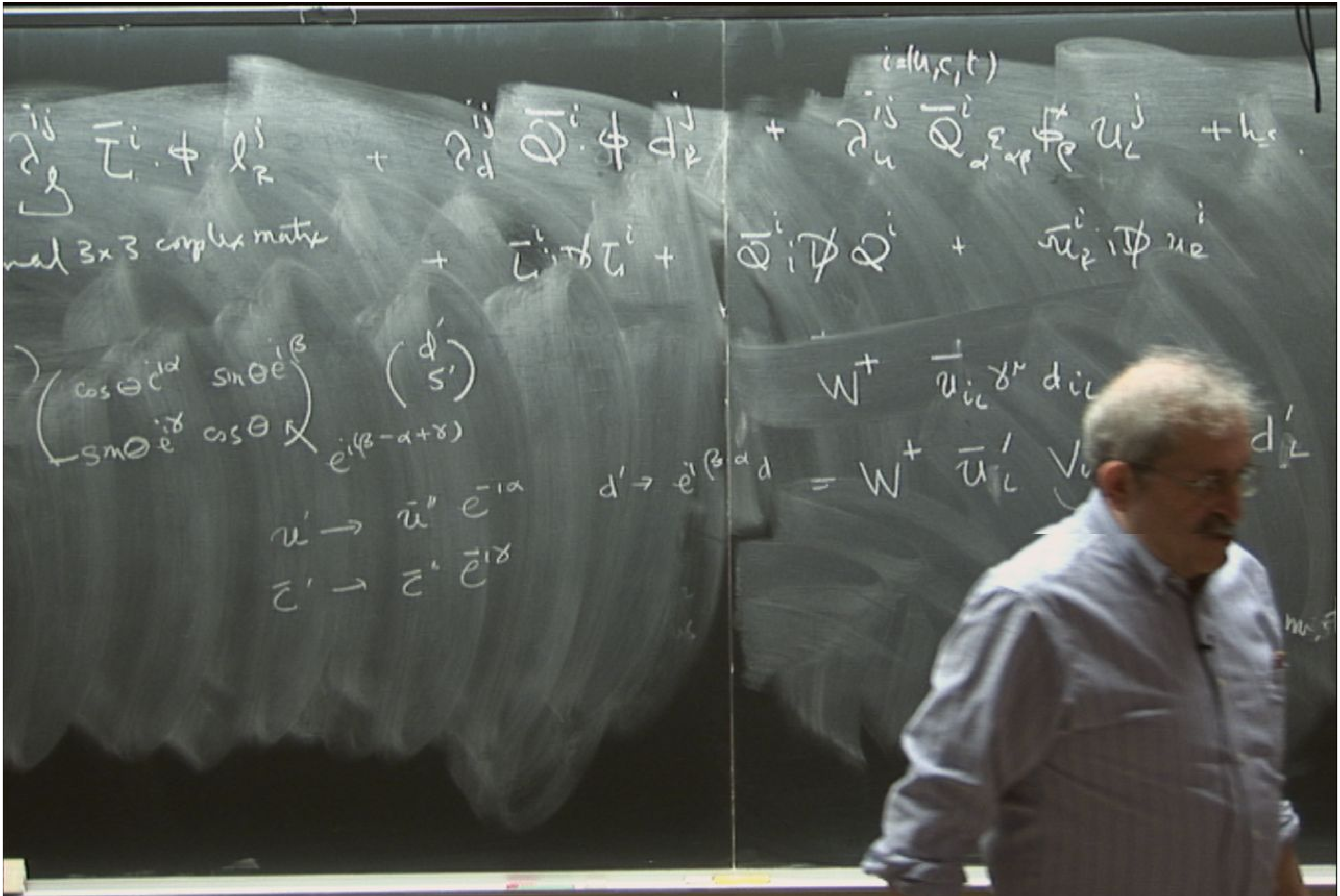
$$+\; \bar{L}^i\, i\not{\partial}\, L^i \;+\; \bar{Q}^i\, i\not{D}\, Q^i \;+$$

$$W^+\,\bar{u}_{iL}\gamma^\mu$$

$$= W^+\,\bar{u}'_L$$

$$Y_{CKM} = \begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i\beta} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\, e^{i(\beta-\alpha+\gamma)} \end{pmatrix}$$


i=(u, c, t)
λ_l^ij L̄^i φ l_R^j + λ_d^ij Q̄^i φ d_R^j + λ_u^ij Q̄^i ε
general 3×3 complex matrix
+ L̄^i i∂̸ L^i + Q̄^i i∂̸ Q^i +
(ū', c̄') (cos θ e^iα sin θ e^iβ / −sin θ e^iγ cos θ) (d' / s')
V_CKM
e^i(β−α+γ)
u' → ū'' e^−iα
c̄' → c̄'' e^−iγ


i = (u, c, t)
+ h.c.
nal 3x3 complex matrix
W⁺

$i = (u, c, t)$

$$\lambda_{\ell}^{ij}\ \bar{L}^i \cdot \phi\ \ell_R^j \;+\; \lambda_d^{ij}\ \bar{Q}^i \cdot \phi\ d_R^j \;+\; \lambda_u^{ij}\ \bar{Q}^i_{\alpha}\, \varepsilon_{\alpha\beta}\, \phi^*_{\beta}\, u_L^j \;+\; h.c.$$

...al 3x3 complex matrix

$$+\ \bar{L}^i\, i\not{\partial}\, L^i \;+\; \bar{Q}^i\, i\not{D}\, Q^i \;+\; \bar{u}_R^i\, i\not{D}\, u_R^i$$

$$\begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i\beta} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\, e^{i(\beta-\alpha+\gamma)} \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

$d' \to e^{i(\beta-\alpha)} d$

$u' \to \bar{u}''\, e^{-i\alpha}$

$c' \to \bar{c}'\, e^{-i\gamma}$

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$W^+\ \bar{u}_{iL}\, \gamma^{\mu}\, d_{iL}$$

$$= W^+\ \bar{u}'_L\ \underbrace{V_u^{+}\, \gamma^{\mu}\, V_d}\ d'_L$$

V_{CKM}

$U(3)$ unitary matri...

$i = (u, c, t)$

$$\lambda_\ell^{ij}\, \bar{L}^i \cdot \phi\, \ell_R^j + \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j + \lambda_u^{ij}\, \bar{Q}^i_\alpha\, \varepsilon_{\alpha\beta}\, \phi^*_\beta\, u_L^j + h.c.$$

...al 3x3 complex matrix

$$+ \bar{L}^i\, i\not\partial\, L^i + \bar{Q}^i\, i\not\partial\, Q^i + \bar{u}_R^i\, i\not\partial\, u_R^i$$

$$\begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i\beta} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\, e^{i(\beta-\alpha+\gamma)} \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

$$d' \to e^{i(\beta-\alpha)} d$$

$$\bar{u}' \to \bar{u}'' e^{-i\alpha}$$

$$\bar{c}' \to \bar{c}' e^{-i\gamma}$$

$$\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$W^+\, \bar{u}_{iL}\, \gamma^\mu\, d_{iL}$$

$$= W^+\, \bar{u}'_L\, V_u^\dagger\, \gamma^\mu\, V_d$$

V

$i = (u, c, t)$

$$\lambda_\ell^{ij}\, \bar{L}^i \phi\, \ell_R^j + \lambda_d^{ij}\, \bar{Q}^i \phi\, d_R^j + \lambda_u^{ij}\, \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \phi^*_\beta u_L^j + h.c.$$

nal 3x3 complex matrix

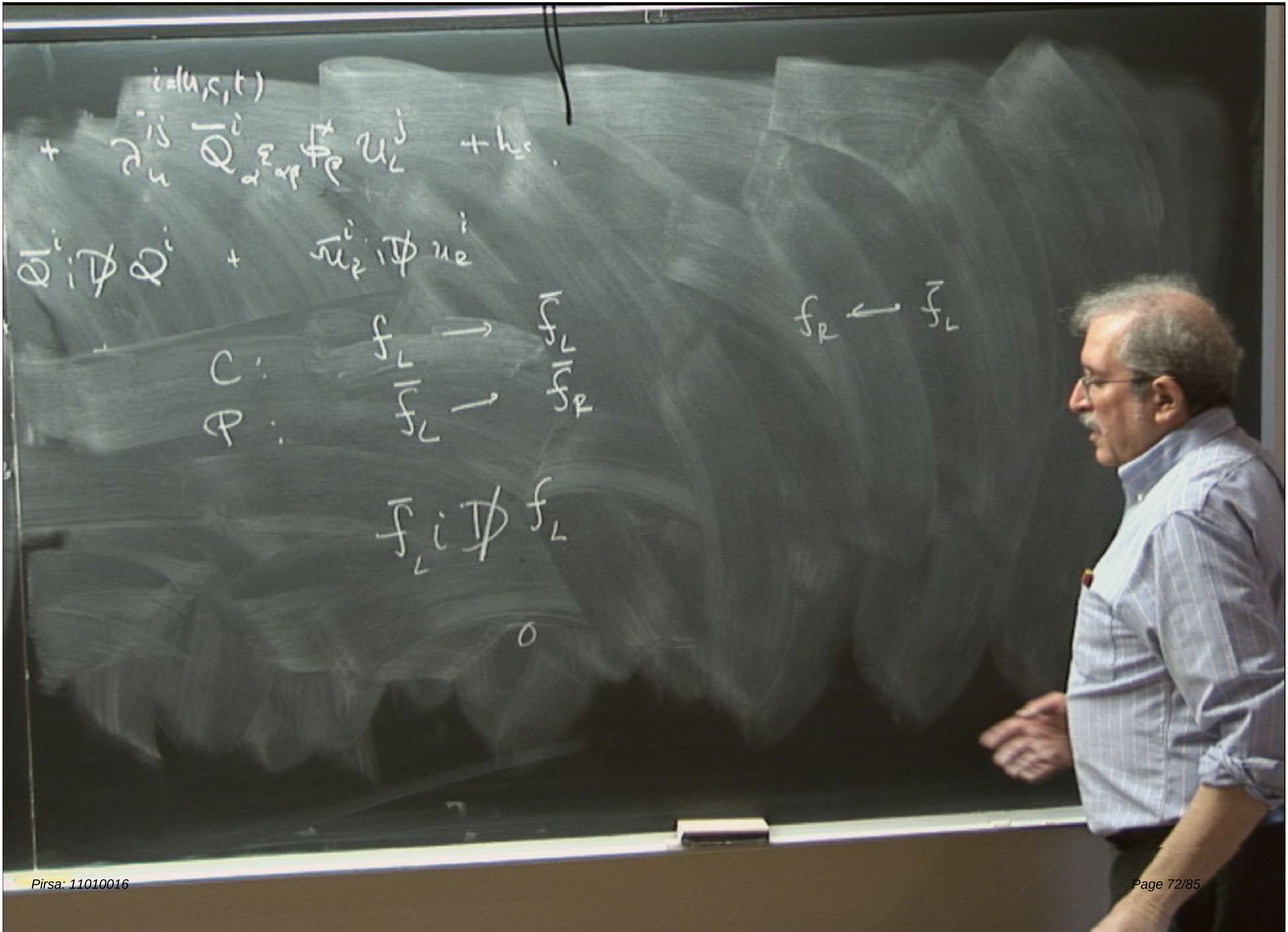
$$+ \bar{L}^i i\not{D} L^i + \bar{Q}^i i\not{D} Q^i + \bar{u}_R^i i\not{D} u_R^i$$

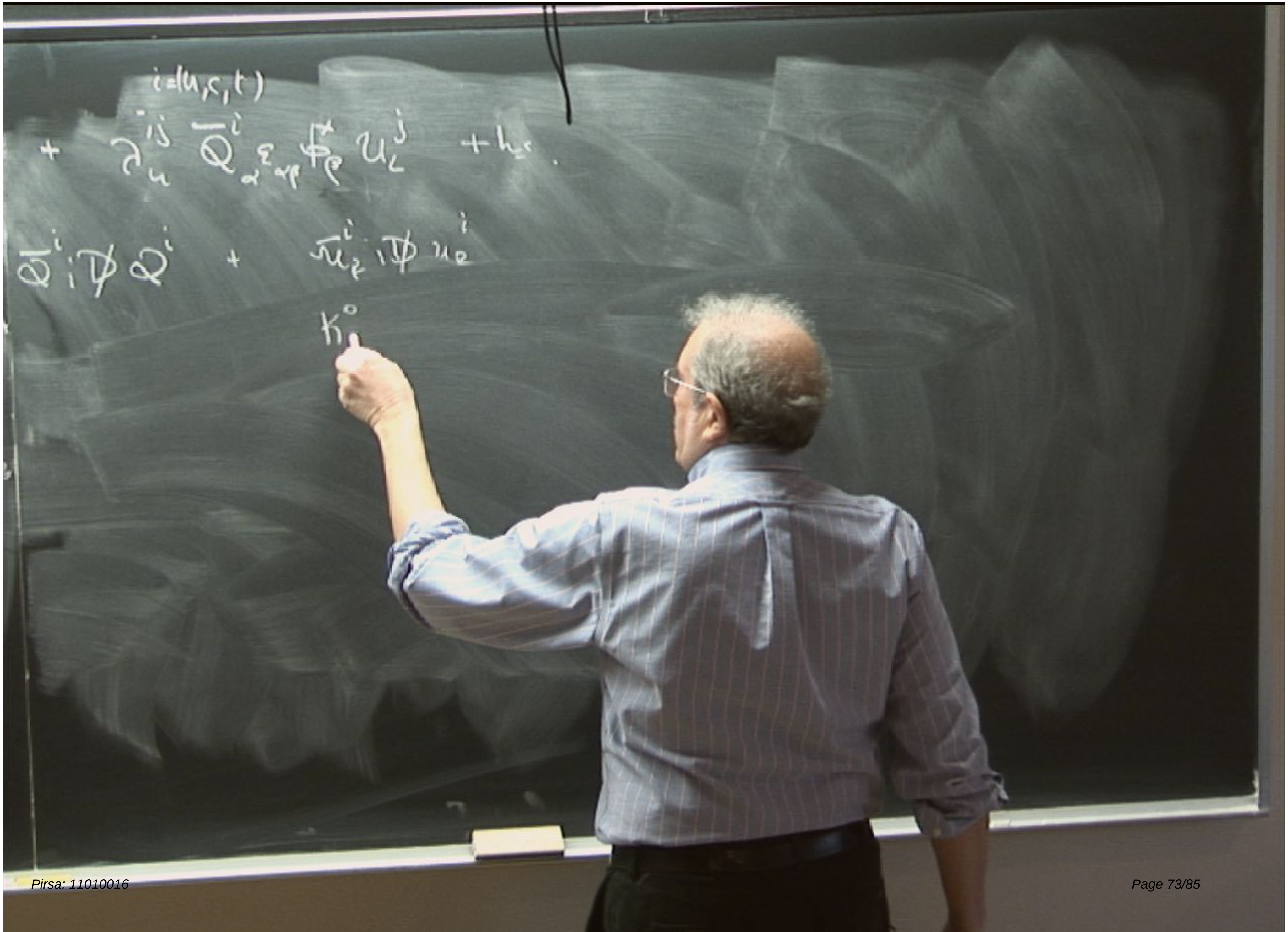
$$\begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i\beta} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\, e^{i(\beta-\alpha+\gamma)} \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

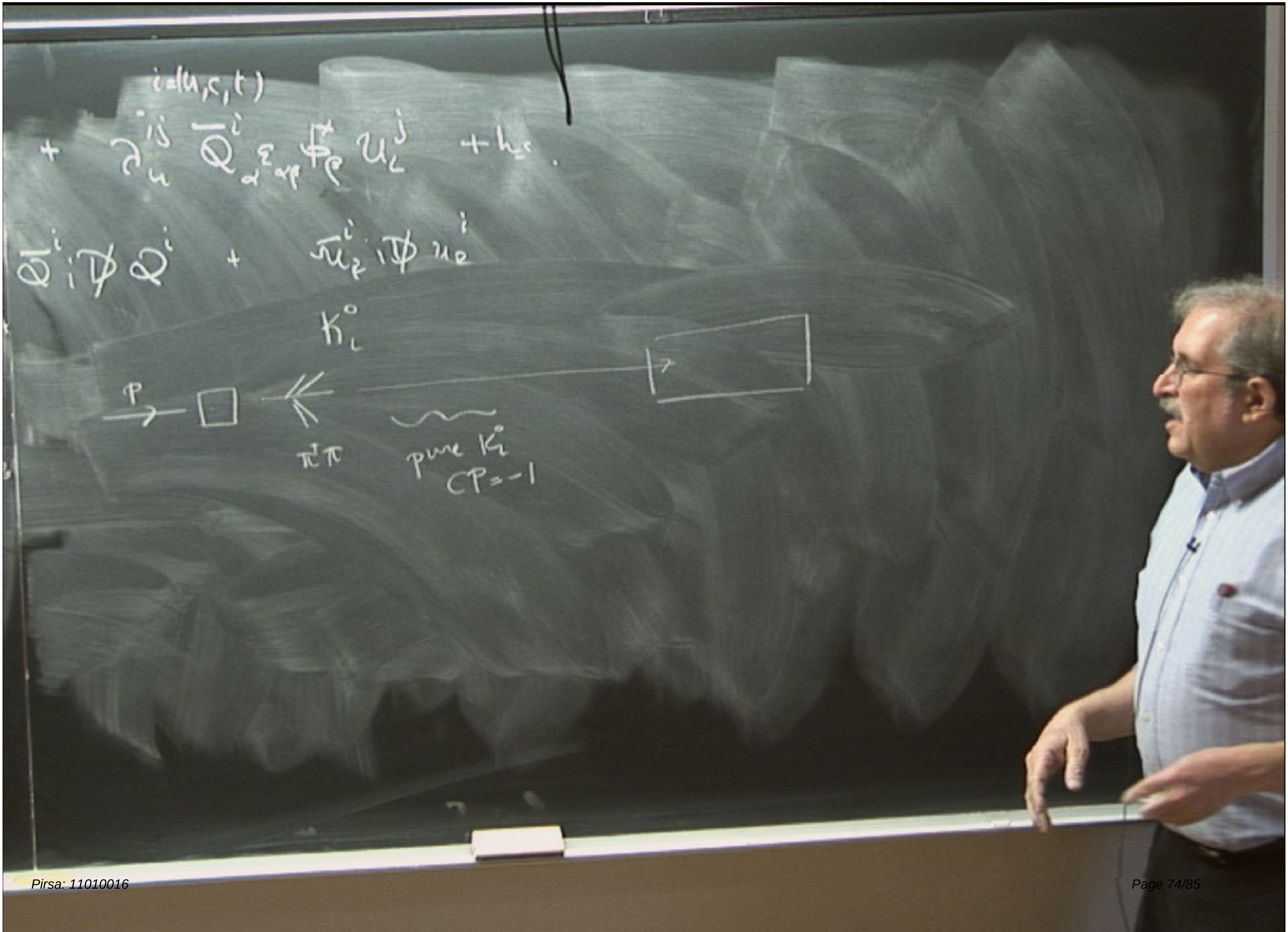
$$u' \to \bar{u}''\, e^{-i\alpha}$$

$$\bar{c}' \to \bar{c}'\, \bar{e}^{i\gamma}$$

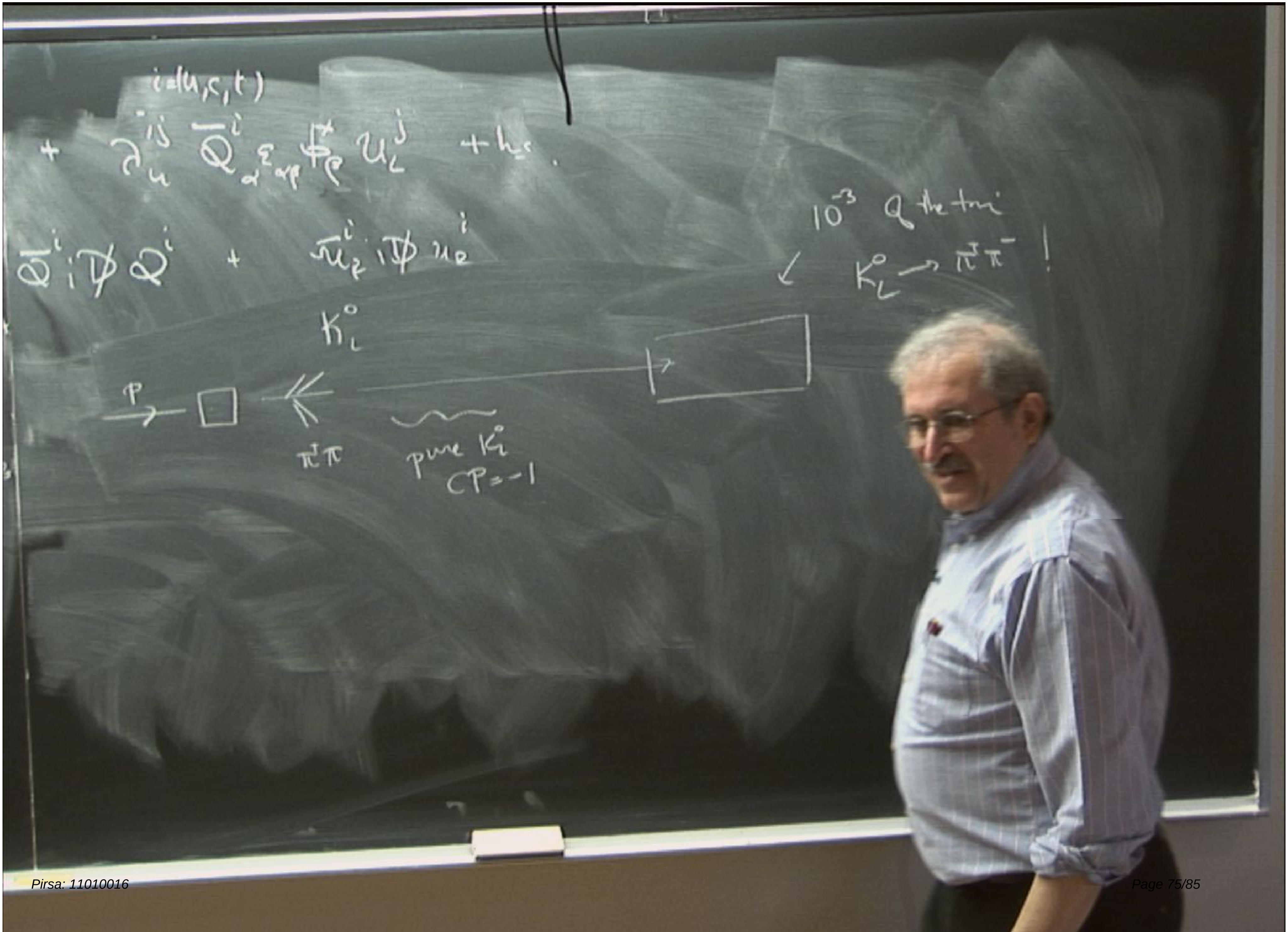
$$\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$


i=(u,c,t)
+ λ_u^ij Q̄^i_α ε_αβ Φ*_β u_L^j + h.c.
Q̄^i iD̸ Q^i + ū_R^i iD̸ u_R^i
C : f_L ⟶ f̄_L
P : f̄_L ⟶ f̄_R
f_R ⟵ f̄_L
f̄_L iD̸ f_L
0

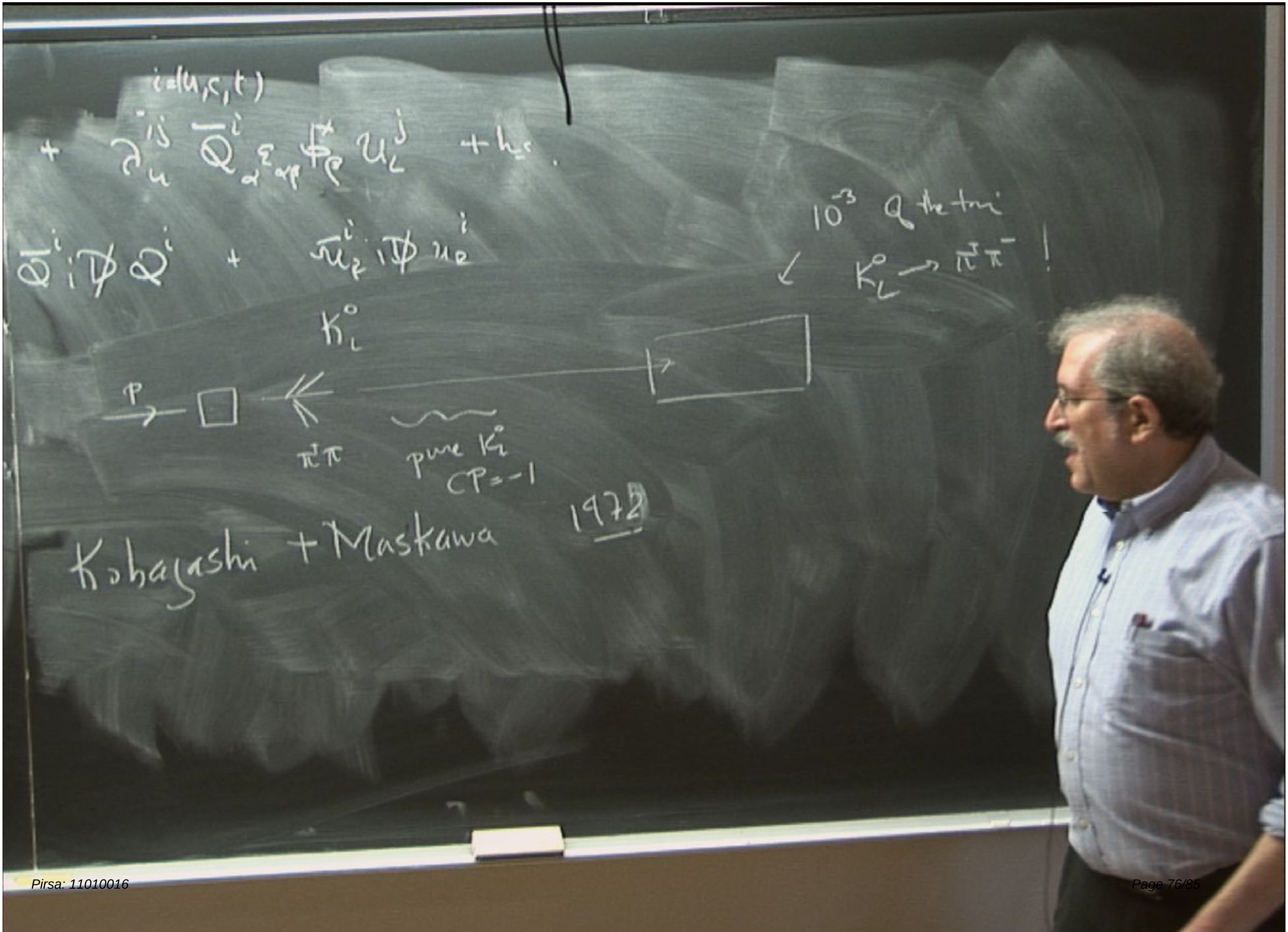

$i=(u,c,t)$
$+\ \lambda_u^{ij}\ \bar{Q}^i_\alpha\, \varepsilon_{\alpha\beta}\, \Phi^*_\beta\, u_L^j\ +\ h.c.$
$\bar{Q}^i\, i\not{D}\, Q^i\ +\ \bar{u}_R^i\, i\not{D}\, u_R^i$
K^0

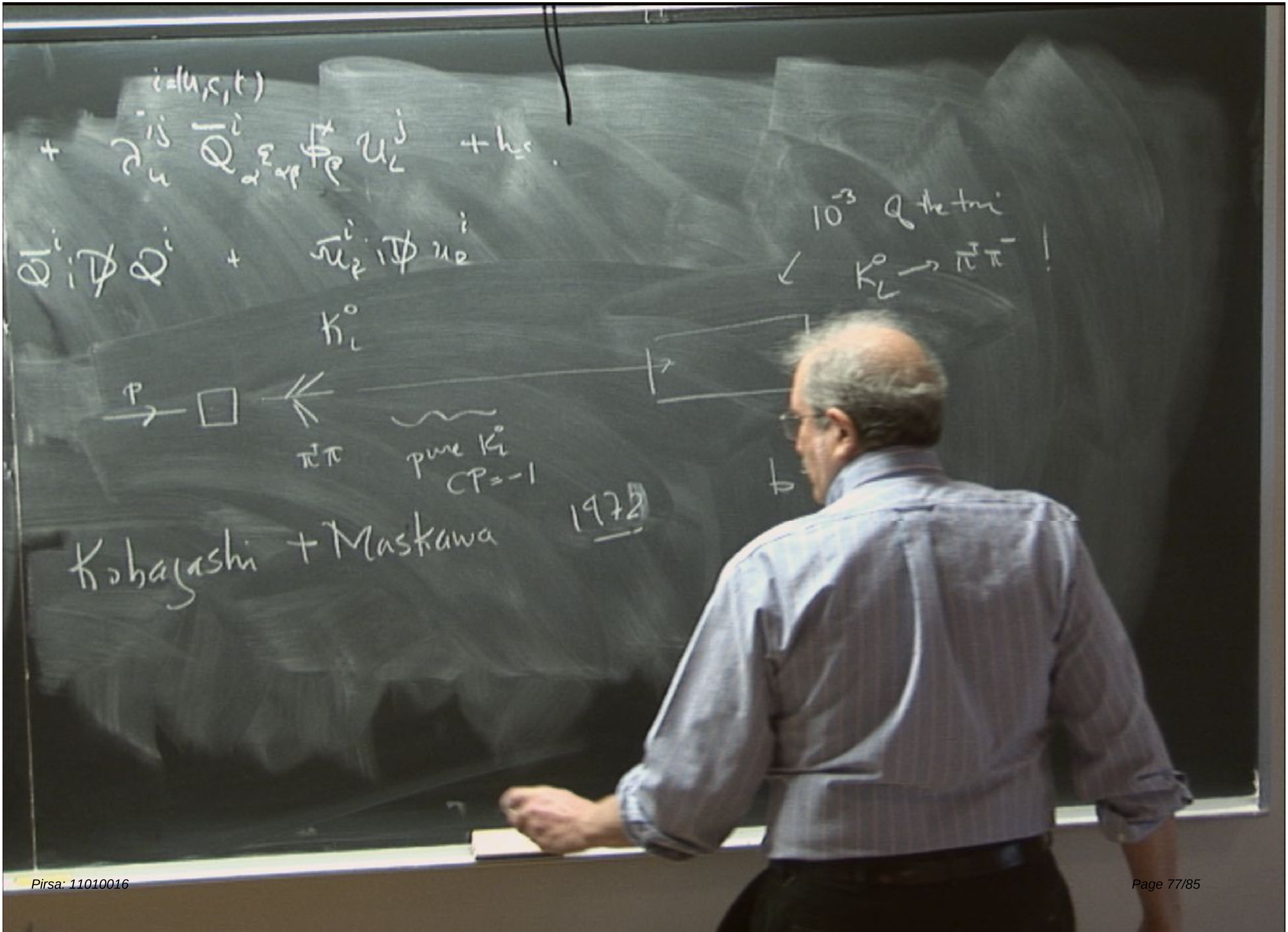


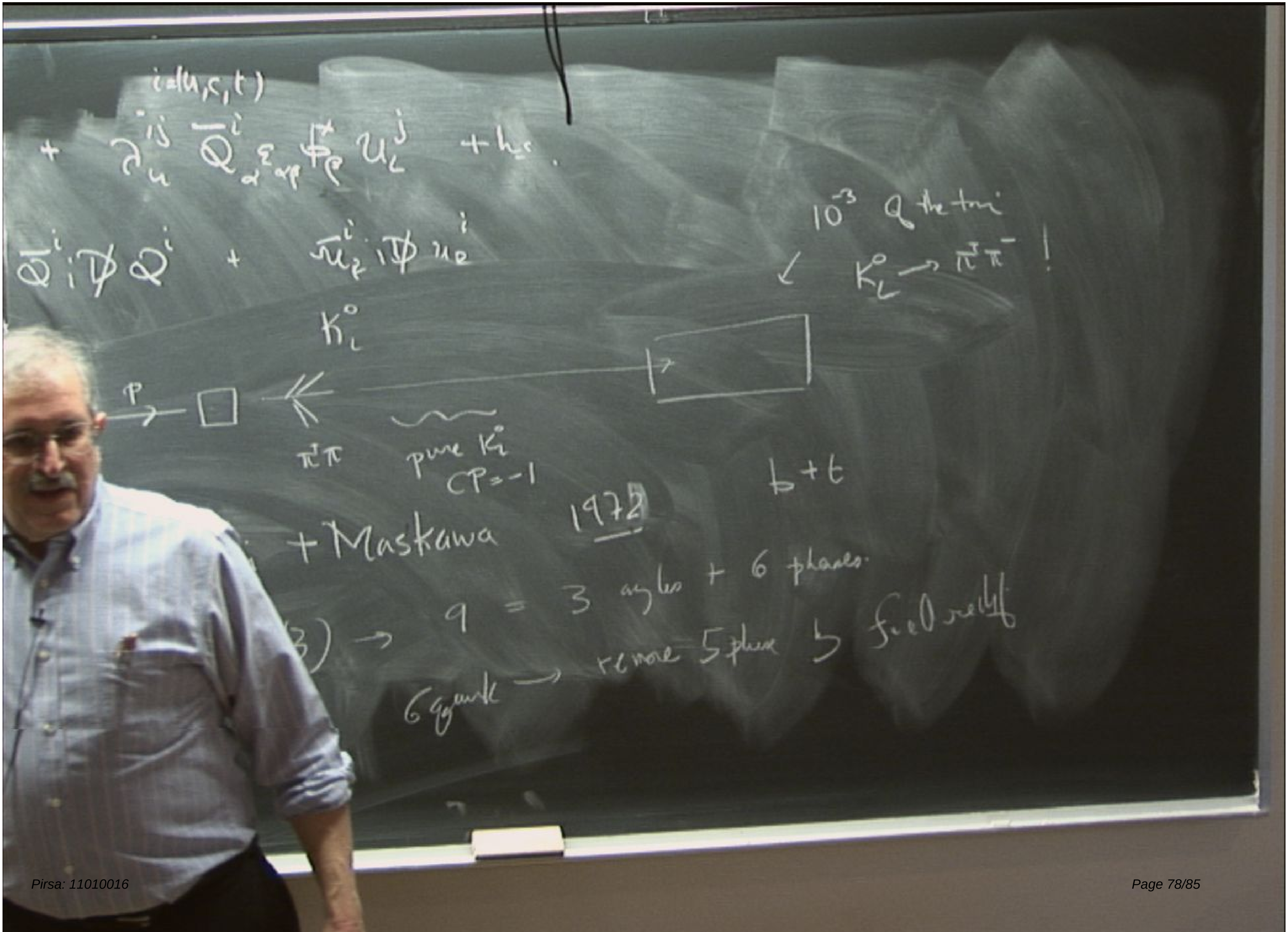
$i=(u,c,t)$
$+ \lambda_u^{ij}\, \bar{Q}^i_\alpha \varepsilon_{\alpha\beta} \Phi^*_\beta u_L^j + h.c.$
$\bar{Q}^i\, i\not{D}\, Q^i + \bar{u}_R^i\, i\not{D}\, u_R^i$
K^0_L
p
$\pi^+\pi^-$
pure K^0_L
$CP=-1$



i=(u,c,t)
+ λ_u^ij Q̄^i_α ε_αβ Φ*_β u_L^j + h.c.
Q̄^i i∂̸ Q^i + ū_R^i i∂̸ u_R^i
10^-3 of the time
K_L^0 → π^+π^- !
K_L^0
p
π^+π^-
pure K_L^0
CP = -1


i=(u,c,t)
+ h.c.
10^-3 of the time
K_L^0 → π+π- !
K_L^0
p
ππ
pure K_2^0
CP=-1
Kobayashi + Maskawa
1972


i=(u,c,t)
+h.c.
10^-3 of the time
K_L^0 → π^+π^- !
K_L^0
p
π^+π^-
pure K_L^0
CP=-1
1972
Kobayashi + Maskawa


i=(u,c,t)
+ h.c.
10^-3 of the time
K°L → π+π- !
K°L
π+π
pure K°L
CP=-1
b+t
+Maskawa
1972
9 = 3 angles + 6 phases
remove 5 phase by field redefs
6 quark →

$i=(u,c,t)$

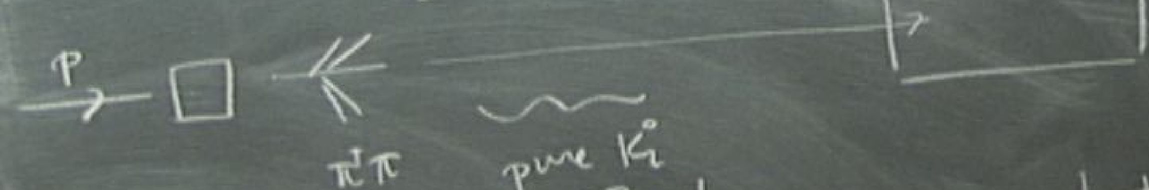
$$+\ \lambda_u^{ij}\ \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \Phi^*_\beta u^j_L \ + h.c.$$

$$\bar{Q}^i i \not{D} Q^i + \bar{u}^i_R i \not{D} u^i_R$$

10^{-3} of the time

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

K^0_L

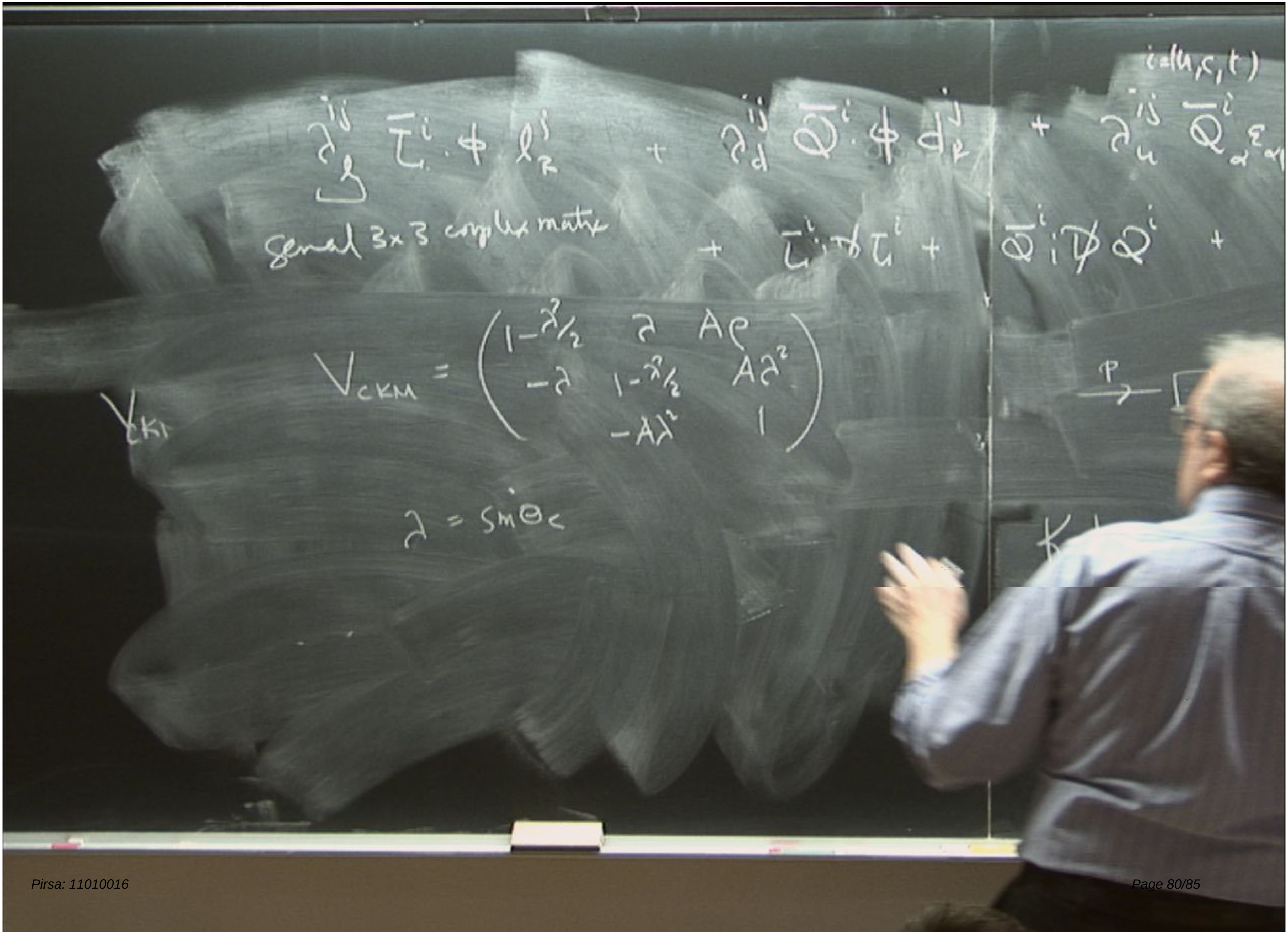


$b+t$

Kobayashi + Maskawa 1972

$U(3) \to 9 = 3$ angles $+\ 6$ phases

6 quarks $\to$ remove 5 phase by field redefs


i=(u,c,t)
$\lambda_\ell^{ij}\,\bar{L}^i\,\phi\,\ell_R^j + \lambda_d^{ij}\,\bar{Q}^i\,\phi\,d_R^j + \lambda_u^{ij}\,\bar{Q}^i_\alpha\,\varepsilon_{\alpha\beta}$
general 3x3 complex matrix
$+\ \bar{L}^i\, i\not{D}\, L^i + \bar{Q}^i\, i\not{D}\, Q^i +$
$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\rho \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ & -A\lambda^2 & 1 \end{pmatrix}$
$\lambda = \sin\theta_c$

$i = (u, c, t)$

$$\underbrace{\lambda_\ell^{ij}}_{\text{general } 3\times 3 \text{ complex matrix}} \bar{L}^i \cdot \phi \, \ell_R^j + \lambda_d^{ij} \bar{Q}^i \cdot \phi \, d_R^j + \lambda_u^{ij} \bar{Q}^i_\alpha \epsilon_{\alpha\beta} \ldots$$

$$+ \bar{L}^i i \not{D} L^i + \bar{Q}^i i \not{D} Q^i +$$

V_{CKM}

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda = \sin\theta_c$

$\xrightarrow{p} \square$

Kobayashi +

$O(3$

$i = (u, c, t)$

$$\lambda_\ell^{ij}\, \bar{L}^i \cdot \phi\, \ell_R^j \;+\; \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j \;+\; \lambda_u^{ij}\, \bar{Q}^i_\alpha \varepsilon_{\alpha\ldots}$$

general 3x3 complex matrix

$$+\; \bar{L}^i\, i\not\partial\, L^i \;+\; \bar{Q}^i\, i\not D\, Q^i \;+$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ & -A\lambda^2 & 1 \end{pmatrix}$$

V_{CKM}

$$\lambda = \sin\theta_c \qquad A\lambda^3(1-e^{-i\eta})$$

$\xrightarrow{p} \square$

Kobaya

$i = (u, c, t)$

$$\lambda_\ell^{ij}\, \bar{L}^i \phi\, \ell_R^j \;+\; \lambda_d^{ij}\, \bar{Q}^i \phi\, d_R^j \;+\; \lambda_u^{ij}\, \bar{Q}^i_\alpha \epsilon_{\alpha\beta}$$

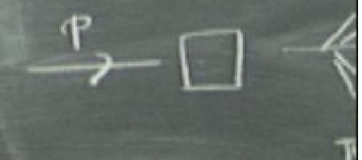
general 3x3 complex matrix

$$+\; \bar{L}^i\, i\not\partial\, L^i \;+\; \bar{Q}^i\, i\not D\, Q^i \;+$$

V_{CKI}

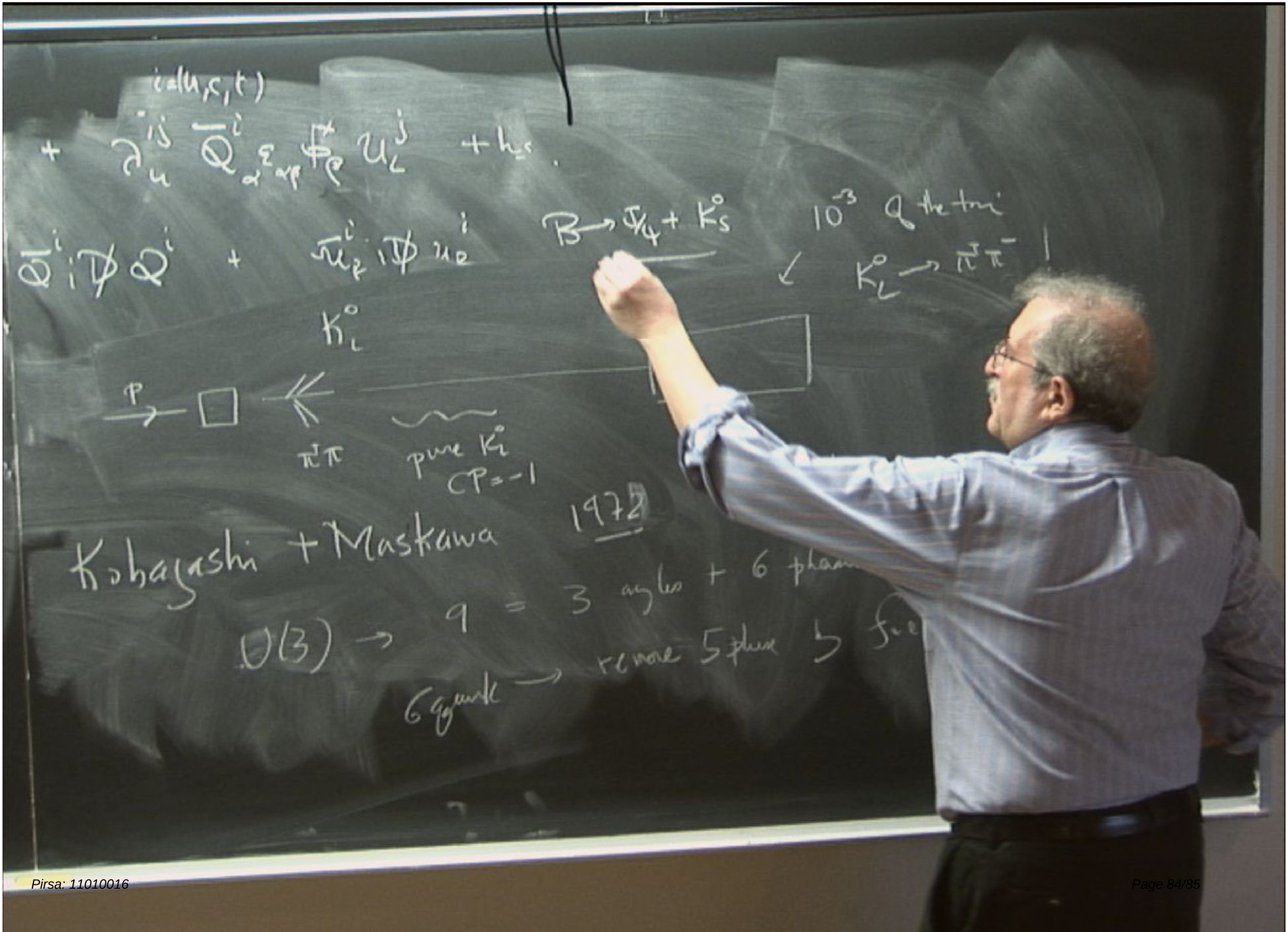
$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ & -A\lambda^2 & 1 \end{pmatrix}$$

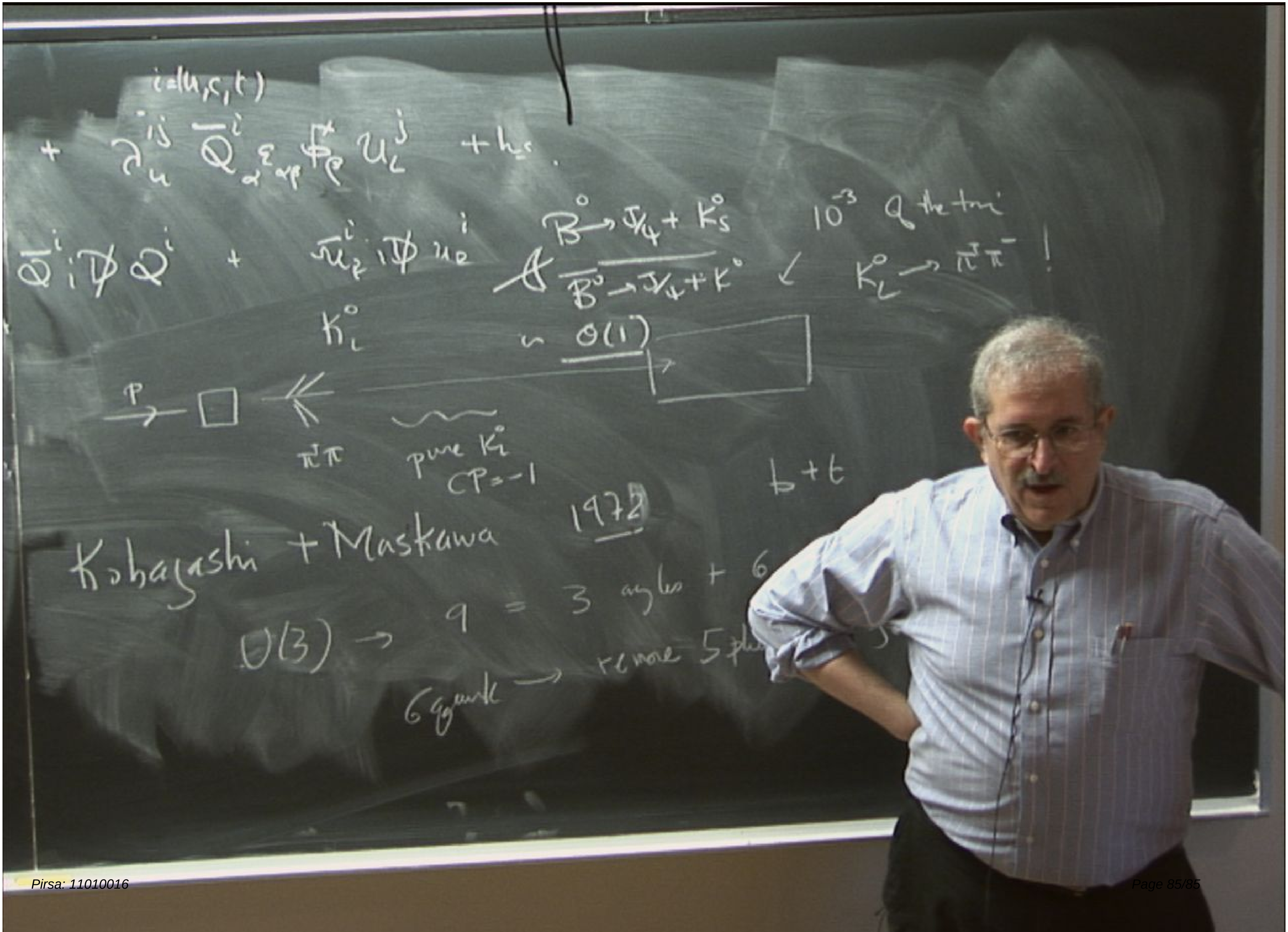
$\lambda = \sin\theta_c$ $\quad A\lambda^3(1-\rho-i\eta)$



Kobayashi +

$O(3$


i=(u,c,t)
+ h.c.
pure K
CP=-1
Kobayashi + Maskawa 1972
9 = 3 angles + 6 phase
remove 5 phase


i = (u, c, t)
+ h.c.
10^-3 of the time
$K_L^0 \to \pi^+\pi^-$!
$B^0 \to J/\psi + K_S^0$
$\sim O(1)$
$\pi\pi$
pure K_L^0
CP = -1
b + t
Kobayashi + Maskawa
1972
O(3) →
9 = 3 angles + 6
remove 5 phases
6 quarks →