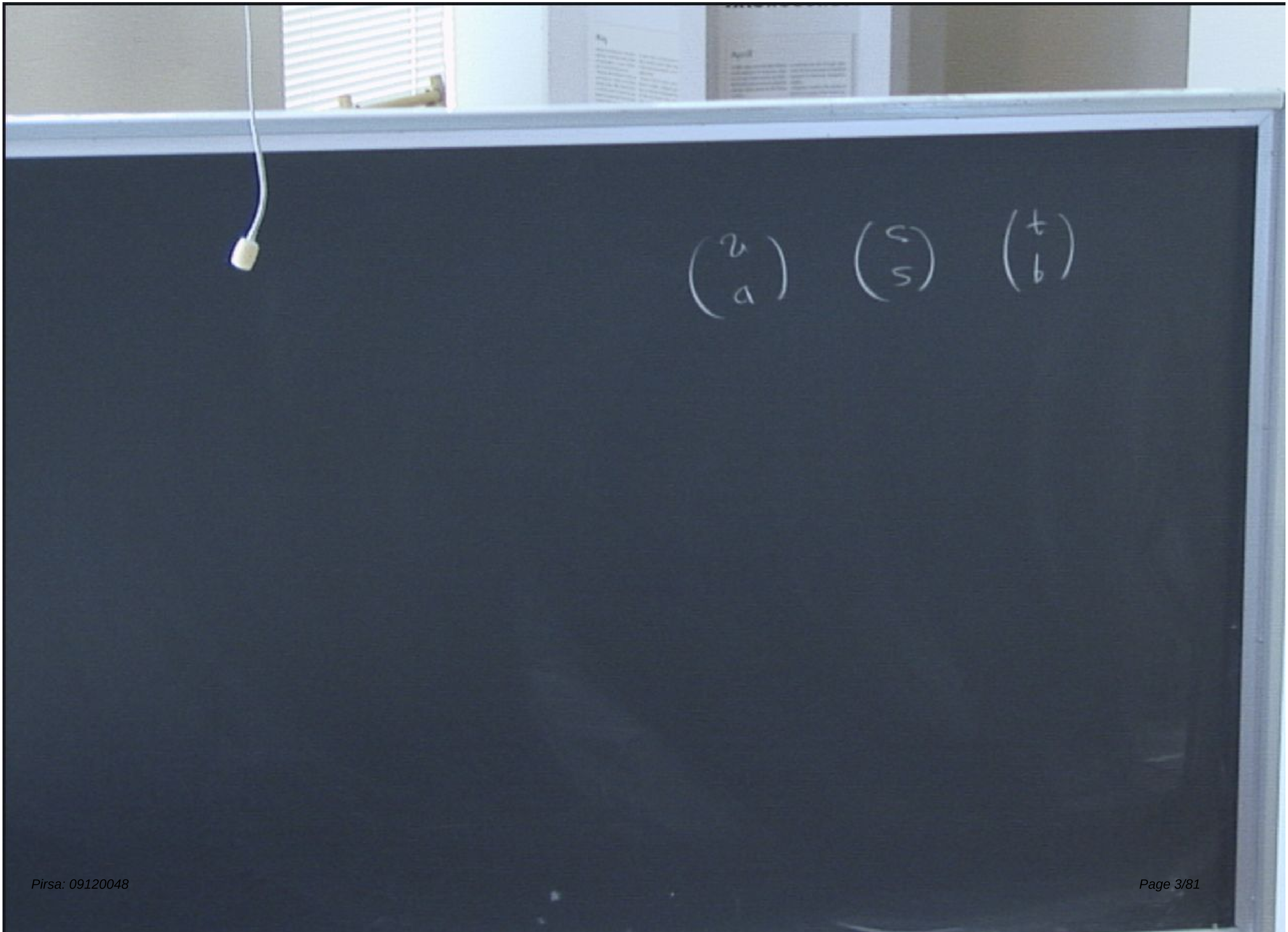
Title: Standard Model - Review (PHYS 622) - Lecture 14

Date: Dec 17, 2009 09:00 AM

URL: http://pirsa.org/09120048

Abstract:

perimeter scholars
international



$$\begin{pmatrix} u \\ a \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$K \rightarrow \mu\nu \quad K^- \rightarrow \pi^0 \mu^- \nu \quad \Lambda^0 \rightarrow p\pi^-$

$s \rightarrow u \mu^- \nu \quad s \rightarrow u \bar{u} d$

$K \to \mu\nu$ $K^- \to \pi^0 \mu^- \nu$ $\Lambda^0 \to p\pi^-$

$s \to u \mu^- \nu$ $s \to u \bar{u} d$

$s \to d \mu^+ \mu^-$ $K^0 \to \mu^+ \mu^-$

$K \to \mu\nu \qquad K^- \to \pi^0 \mu^- \nu \qquad \Lambda^0 \to p\pi^-$

$s \to u \mu^- \nu \qquad s \to u \bar{u} d$

$s \to d \mu^+ \mu^- \qquad K^0 \to \mu^+ \mu^-$

$BR(K_L^0 \to \pi e \nu) = 41\% \qquad BR(K_L \to \pi \mu \nu) = 27\%$

$BR(K_L^0 \to \mu^+ \mu^-) = 7 \times 10^{-9}$

$\mu\nu$ $K^- \to \pi^0 \mu^- \bar{\nu}$ $\Lambda^0 \to p \pi^-$

$s \to u \mu^- \bar{\nu}$ $s \to u \bar{u} d$

$\cancel{s \to d \mu^+ \mu^-}$ $K^0 \to \mu^+ \mu^-$

$BR(K_L^0 \to \pi e \nu) = 41\%$ $BR(K_L \to \pi \mu \nu) = 27\%$

$BR(K_L^0 \to \mu^+ \mu^-) = 7 \times 10^{-9}$

$\mu\nu$ $\quad K^- \to \pi^0 \mu^- \nu$ $\quad \Lambda^0 \to p\pi^-$ $\quad \Lambda \to p e^- \bar{\nu}_e$

$s \to u \mu^- \nu$ $\quad s \to u \bar{u} d$

$\cancel{s \to d \mu^+ \mu^-}$ $\quad K^0 \to \mu^+ \mu^-$

$BR(K_L^0 \to \pi e \nu) = 41\%$ $\quad BR(K_L \to \pi \mu \nu) = 27\%$

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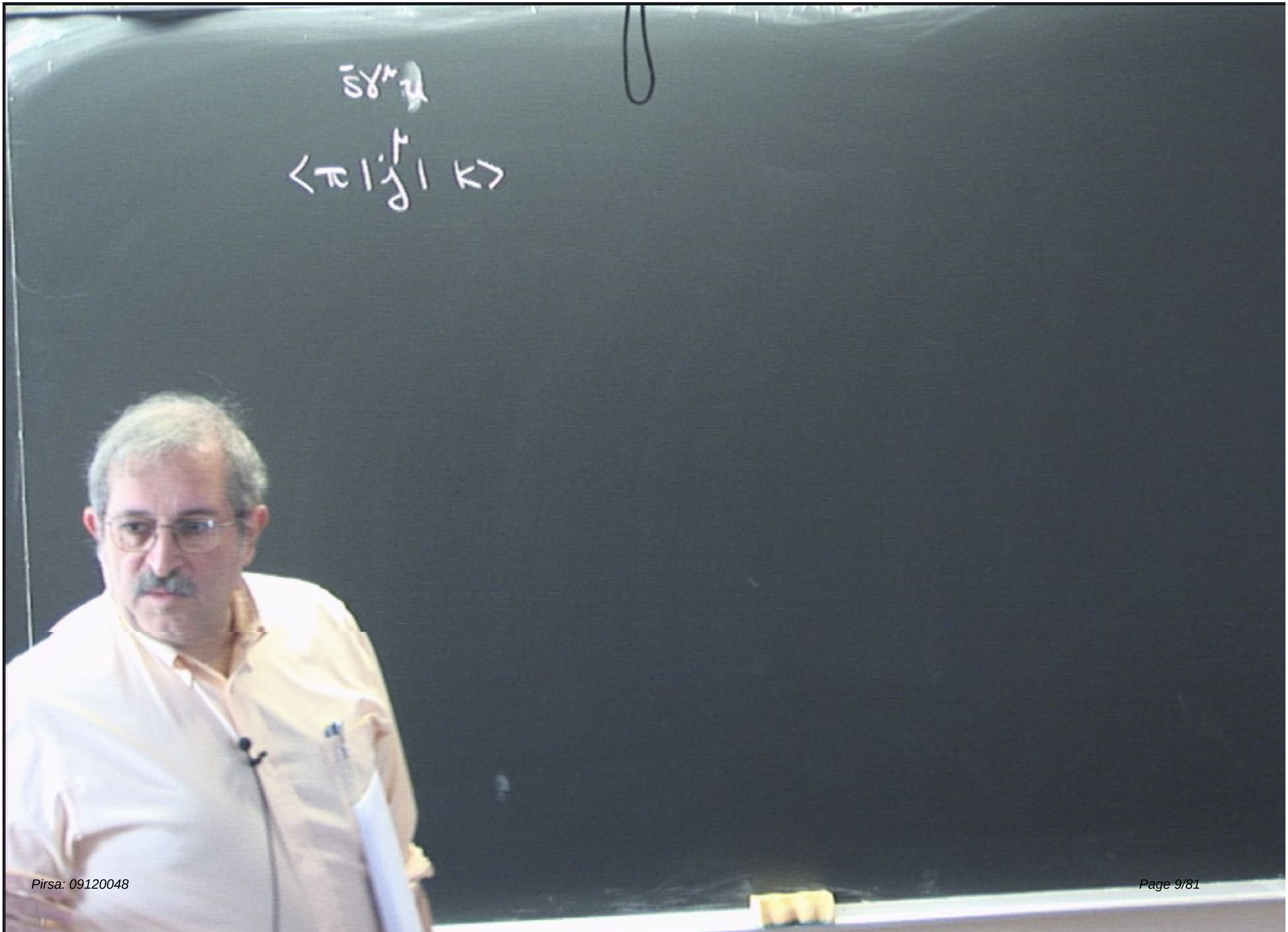


$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle$

$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ where $f_+(q^2=0) = 1$

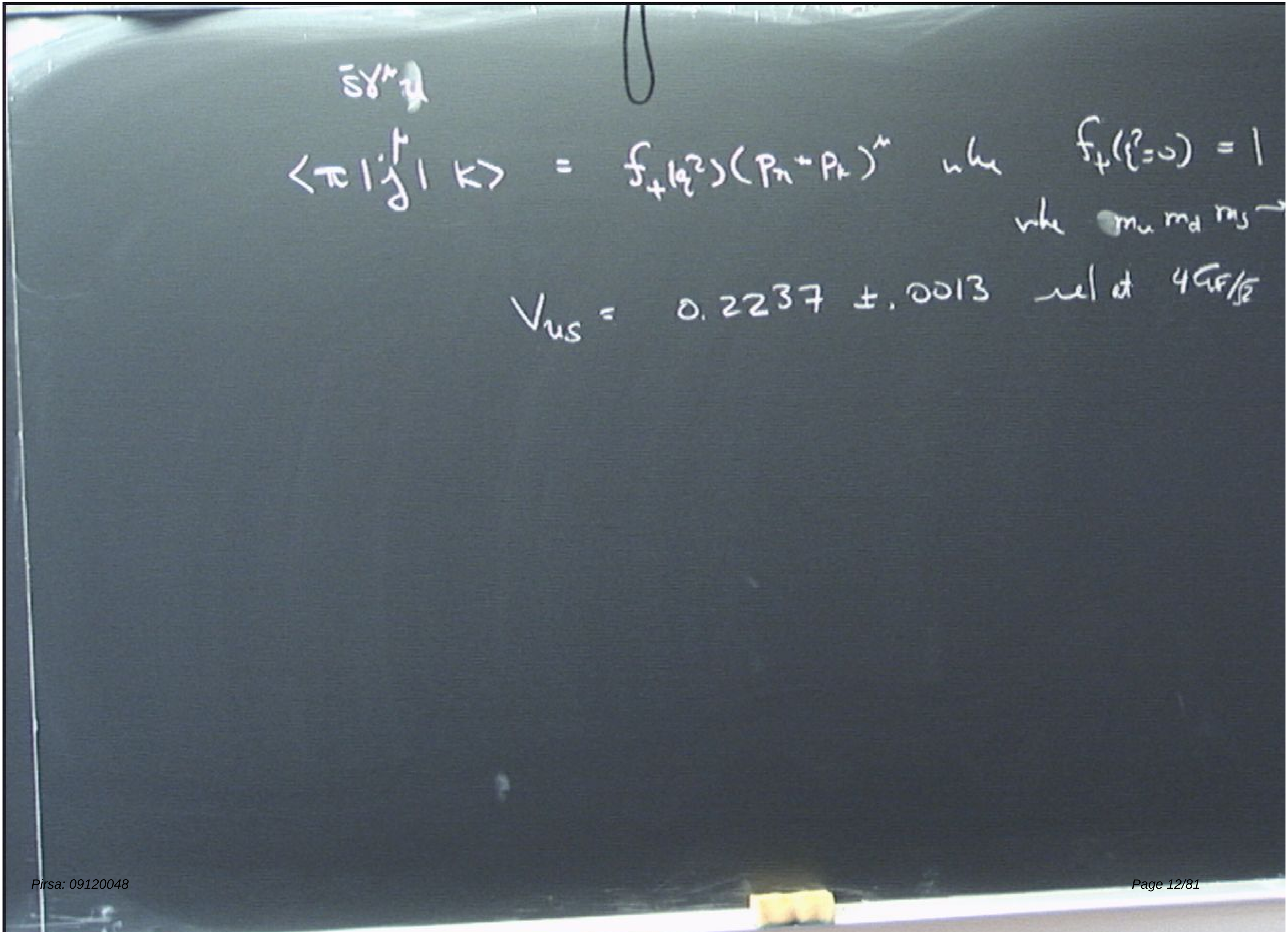
when $m_u \; m_d \; m_s \rightarrow$

$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ whe $f_+(q^2=0) = 1$

whe m_u m_d $m_s \rightarrow$

$V_{us} = 0.2237 \pm .0013$ rel at $4G_F/\sqrt{2}$

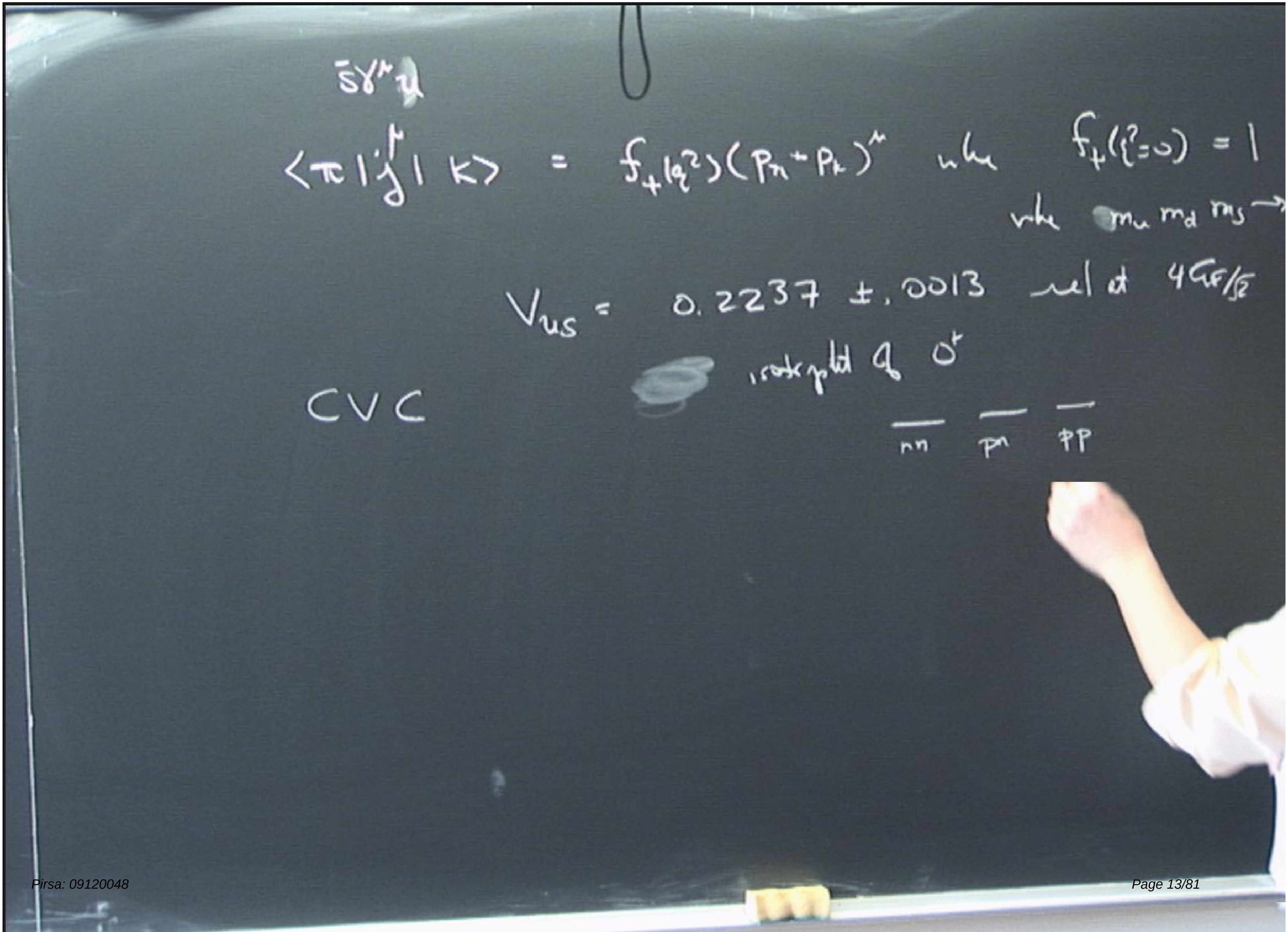


$\bar{s}\gamma^\mu u$

$$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$$ where $f_+(q^2=0) = 1$

when $m_u\ m_d\ m_s \to$

$$V_{us} = 0.2237 \pm .0013$$ rel at $4G_F/\sqrt{2}$



$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ whe $f_+(q^2=0) = 1$

whe $m_u \; m_d \; m_s \to$

$V_{us} = 0.2237 \pm .0013$ rel at $4G_F/\sqrt{2}$

CVC

isotriplet of 0^+

$\overline{}$ $\overline{}$ $\overline{}$

nn pn pp

$\bar{s}\gamma^\mu u$

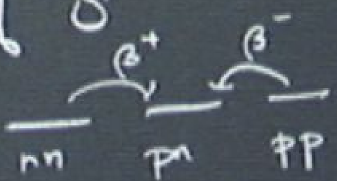
$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ where $f_+(q^2=0) = 1$

when $m_u\ m_d\ m_s \to$

$V_{us} = 0.2237 \pm .0013$ rel at $4G_F/\sqrt{2}$

CVC

isotriplet of 0^+



$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ whe $f_+(q^2=0) = 1$

whe $m_u\ m_d\ m_s \to 0$

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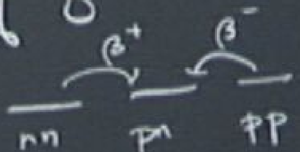
CVC

isotriplet of 0^+



$\bar{d}\gamma^\mu u$

$\langle I^3=0 | j^\mu | I^3=+1 \rangle = (2p^\mu)\, F_1(q^2=0)$

CVC: $F_1(q^2=0) = 1$

$\bar{s}\gamma^\mu u$

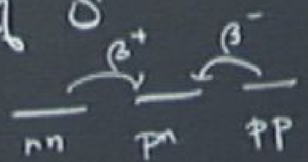
$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ when $f_+(q^2=0) = 1$

when $m_u\ m_d\ m_s \to 0$

$V_{us} = 0.2237 \pm .0013$ rel at $4G_F/\sqrt{2}$

CVC

isotriplet of 0^+



$\bar{d}\gamma^\mu u$

$\langle I^3=0 | j^\mu | I^3=+1 \rangle = (2p^\mu)\, F_1(q^2=0)$ CVC: $F_1(q^2=0) = 1$

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

$\bar{s}\gamma^\mu u$

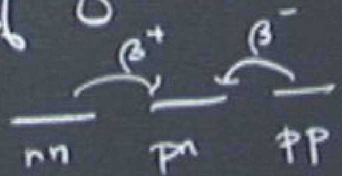
$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ where $f_+(q^2=0) = 1$

when $m_u \; m_d \; m_s \to$

$\sin\Theta_c = V_{us} = 0.2237 \pm .0013$ rel at $4G_F/\sqrt{2}$

CVC

isotriplet of 0^+



$\bar{d}\gamma^\mu u$

1963

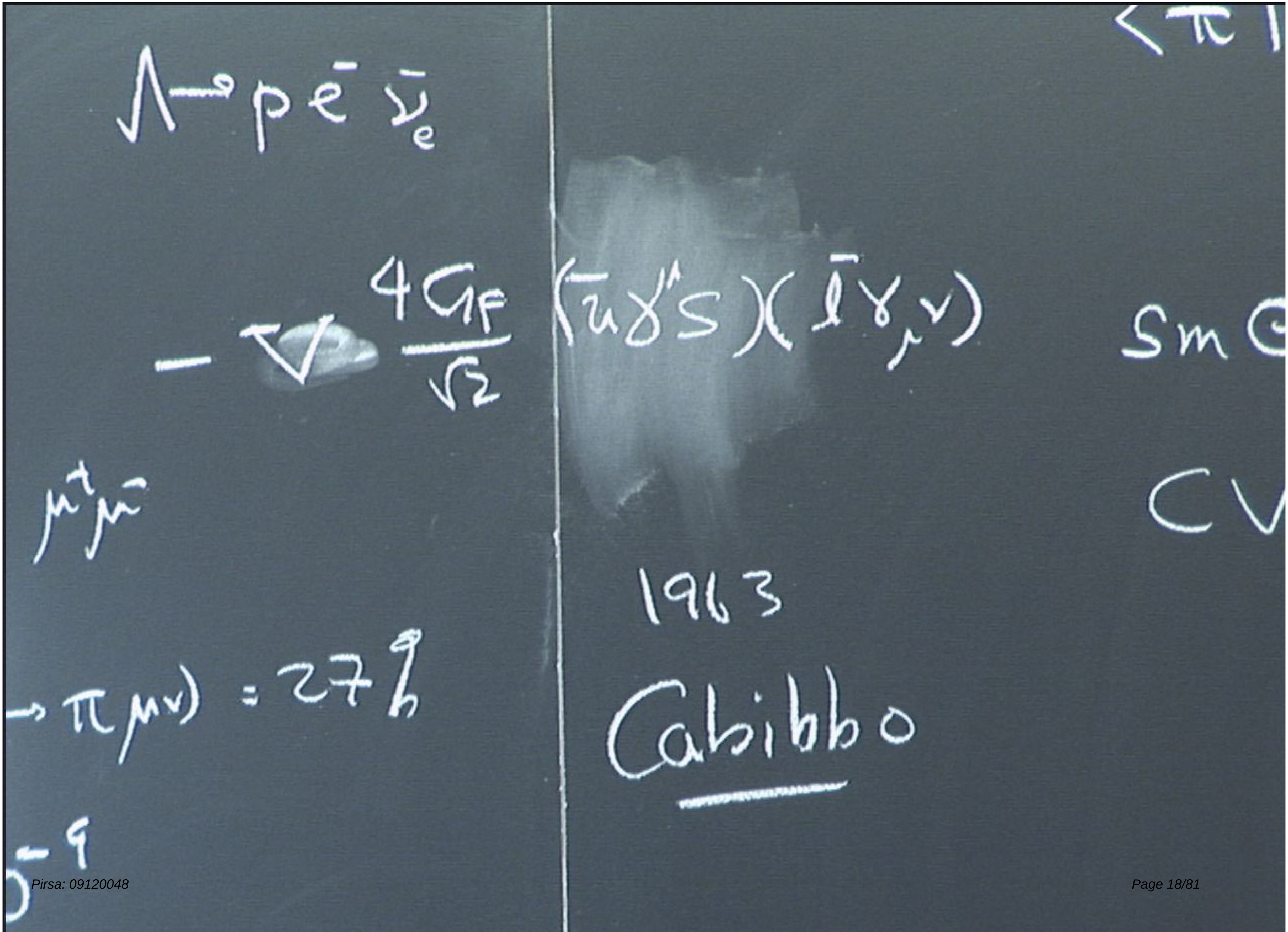
Cabibbo

$\langle I^3=0 | j^\mu | I^3=+1 \rangle = (2p^\mu)\, F_1(q^2=0)$

CVC: F_1

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

$\sin^2\Theta_c + \cos^2\Theta_c =$



$\Lambda \to p e^- \bar{\nu}_e$

$- V \frac{4G_F}{\sqrt{2}} (\bar{u}\gamma^\mu s)(\bar{l}\gamma_\mu \nu)$

$\langle \pi |$

$\sin\Theta$

CV

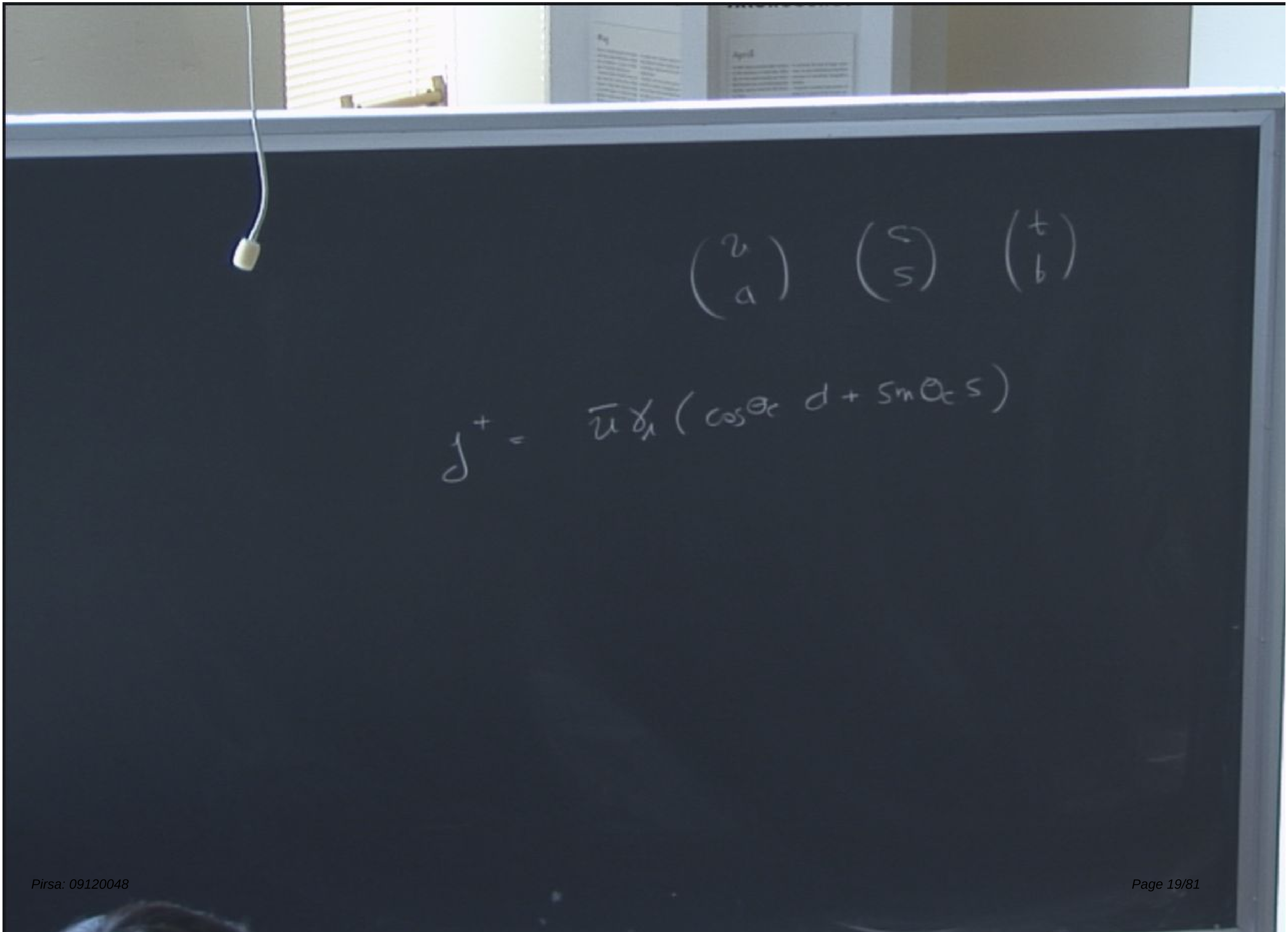
$\mu^+\mu^-$

1963

$\to \pi(\mu\nu) = 27\overset{9}{h}$

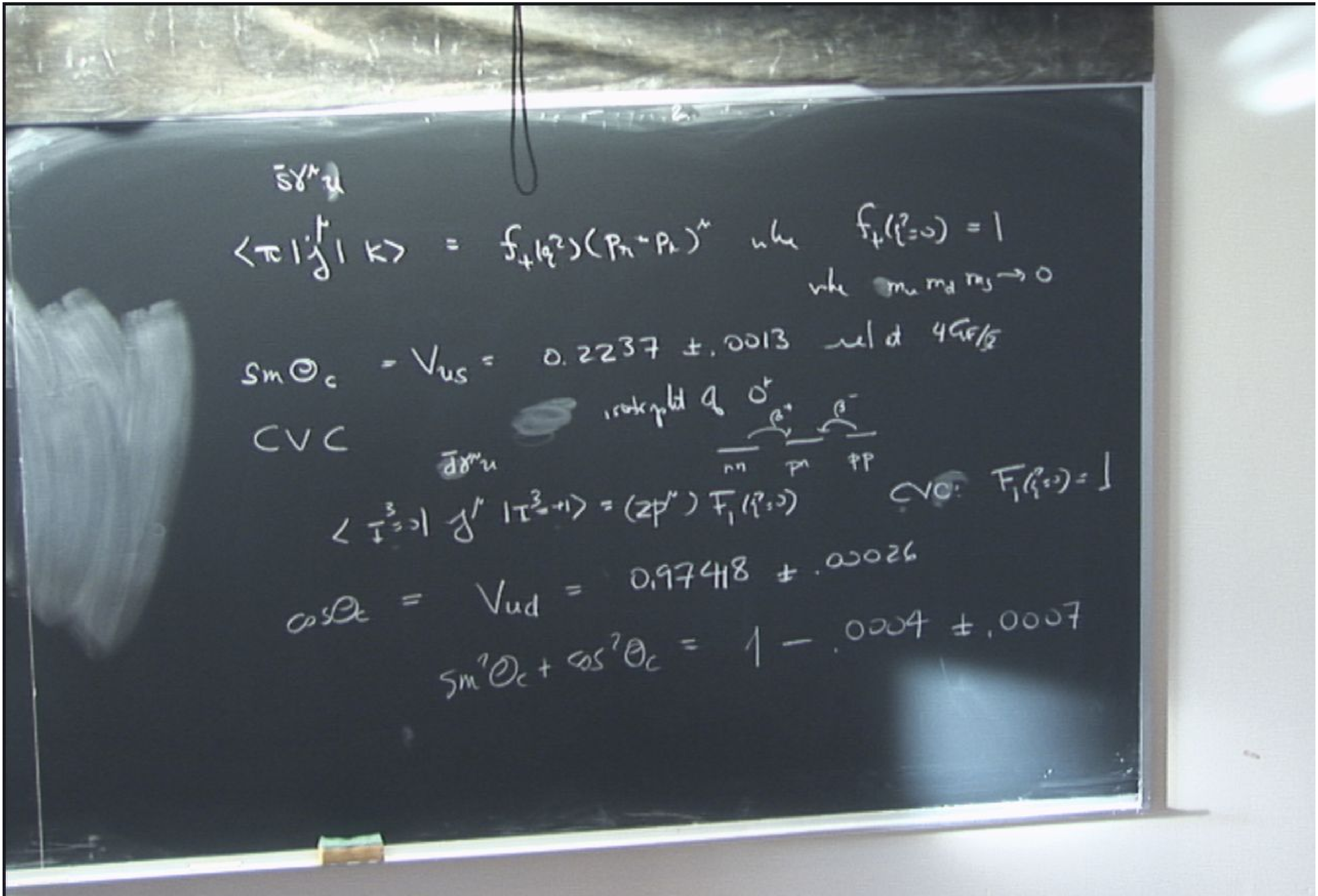
Cabibbo

-9



$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$J^+ = \bar{u}\gamma_\lambda(\cos\theta_c\, d + \sin\theta_c\, s)$$



$\bar{s}\gamma^\mu u$

$\langle \pi | j^\mu | K \rangle = f_+(q^2)(p_\pi + p_K)^\mu$ where $f_+(q^2=0) = 1$

when $m_u\ m_d\ m_s \to 0$

$\sin\Theta_c = V_{us} = 0.2237 \pm .0013$ rel of $4G_F/\sqrt{2}$

CVC

isotriplet of 0^+

β^+ β^-

nn pn pp

$\bar{d}\gamma^\mu u$

$\langle I^3=0 | j^\mu | I^3=+1 \rangle = (2p^\mu)\, F_1(q^2=0)$

CVC: $F_1(q^2=0) = 1$

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

$\sin^2\Theta_c + \cos^2\Theta_c = 1 - .0004 \pm .0007$

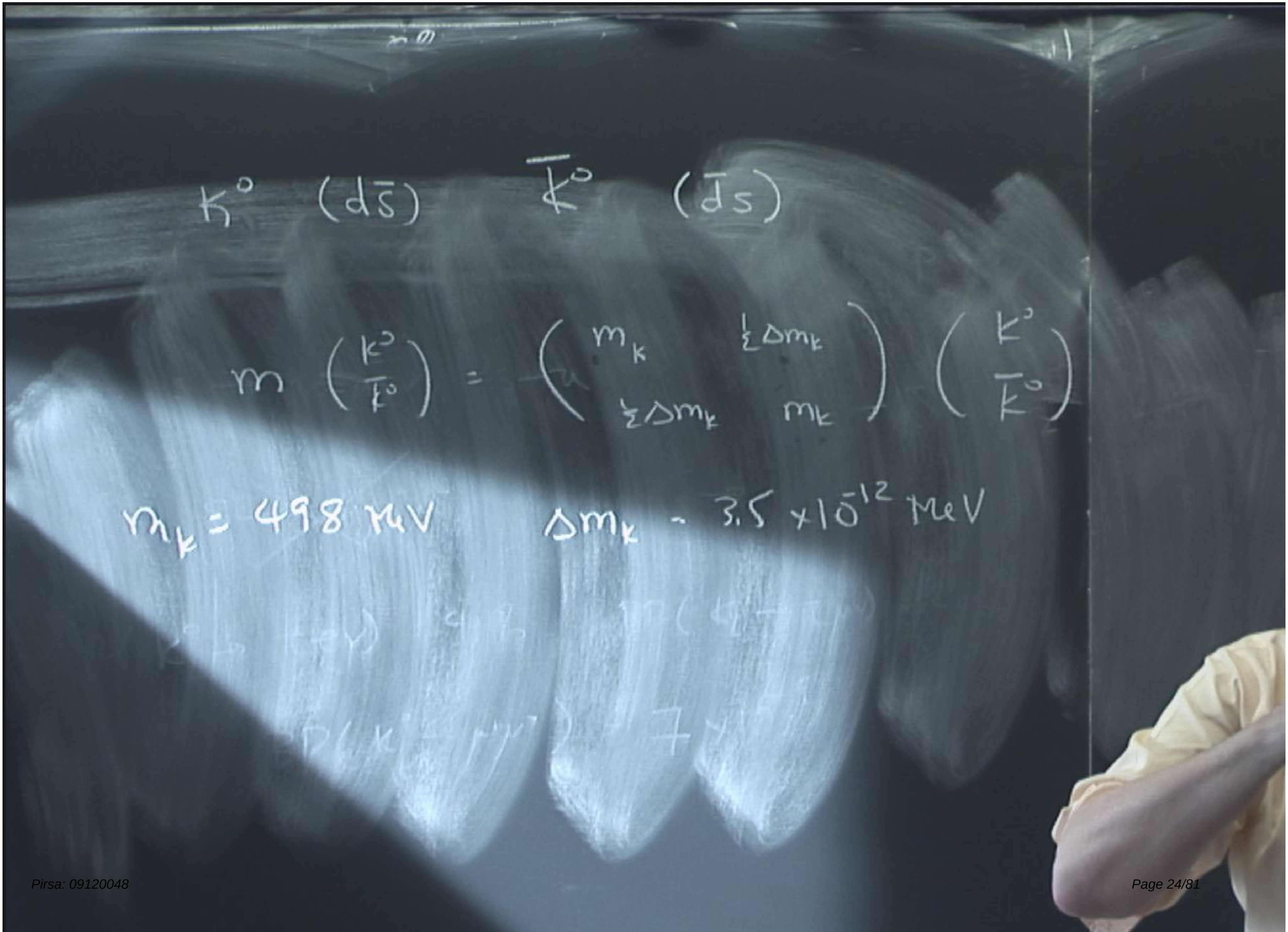
K^0 $(d\bar{s})$ $\bar{K}^0$ $(\bar{d}s)$

$K^0 \quad (ds) \qquad K \quad (ds)$

$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix}$$

$$K^0 \quad (d\bar{s}) \qquad \bar{K}^0 \quad (\bar{d}s)$$

$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix} \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$



$K^0 \quad (d\bar{s}) \qquad \bar{K}^0 \quad (\bar{d}s)$

$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix} \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$

$m_K = 498$ MeV $\qquad \Delta m_K = 3.5 \times 10^{-12}$ MeV

$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix} \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$

$m_K = 498$ MeV $\quad \Delta m_K - 3.5 \times 10^{-12}$ MeV

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

$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix} \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$

$m_K = 498$ MeV $\quad \Delta m_K = 3.5 \times 10^{-12}$ MeV

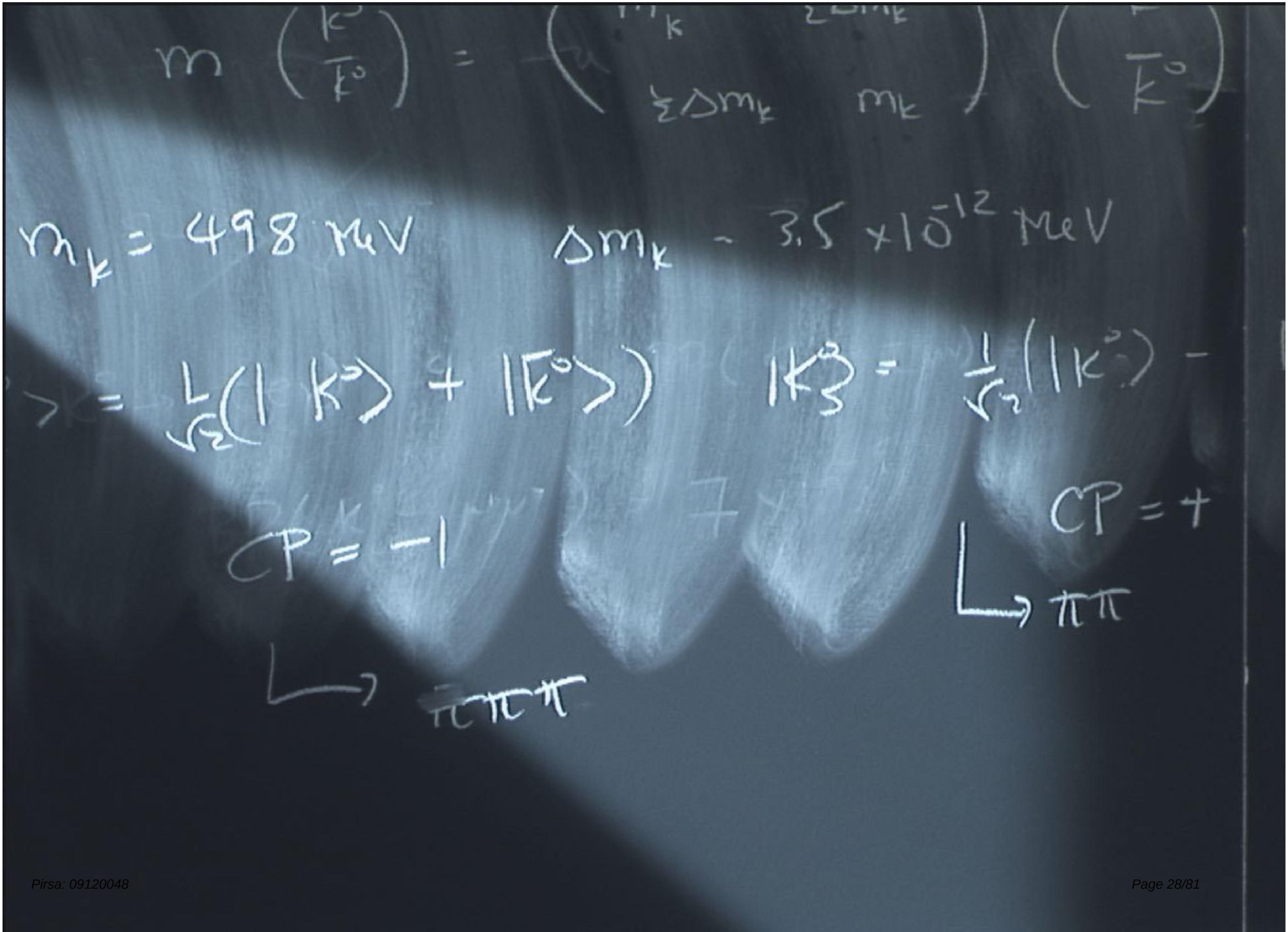
$|K^0_l\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad |K^0_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$

$CP = -1 \qquad CP = +$

$$K^0, \bar{K}^0 \rightarrow \pi\pi \qquad \pi\pi\pi$$

$$CP = + \qquad CP = -$$

$|\bar{K}^0\rangle)$



$$m \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = \begin{pmatrix} m_K & \frac{1}{2}\Delta m_K \\ \frac{1}{2}\Delta m_K & m_K \end{pmatrix} \begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$

$m_K = 498$ MeV $\quad \Delta m_K \sim 3.5 \times 10^{-12}$ MeV

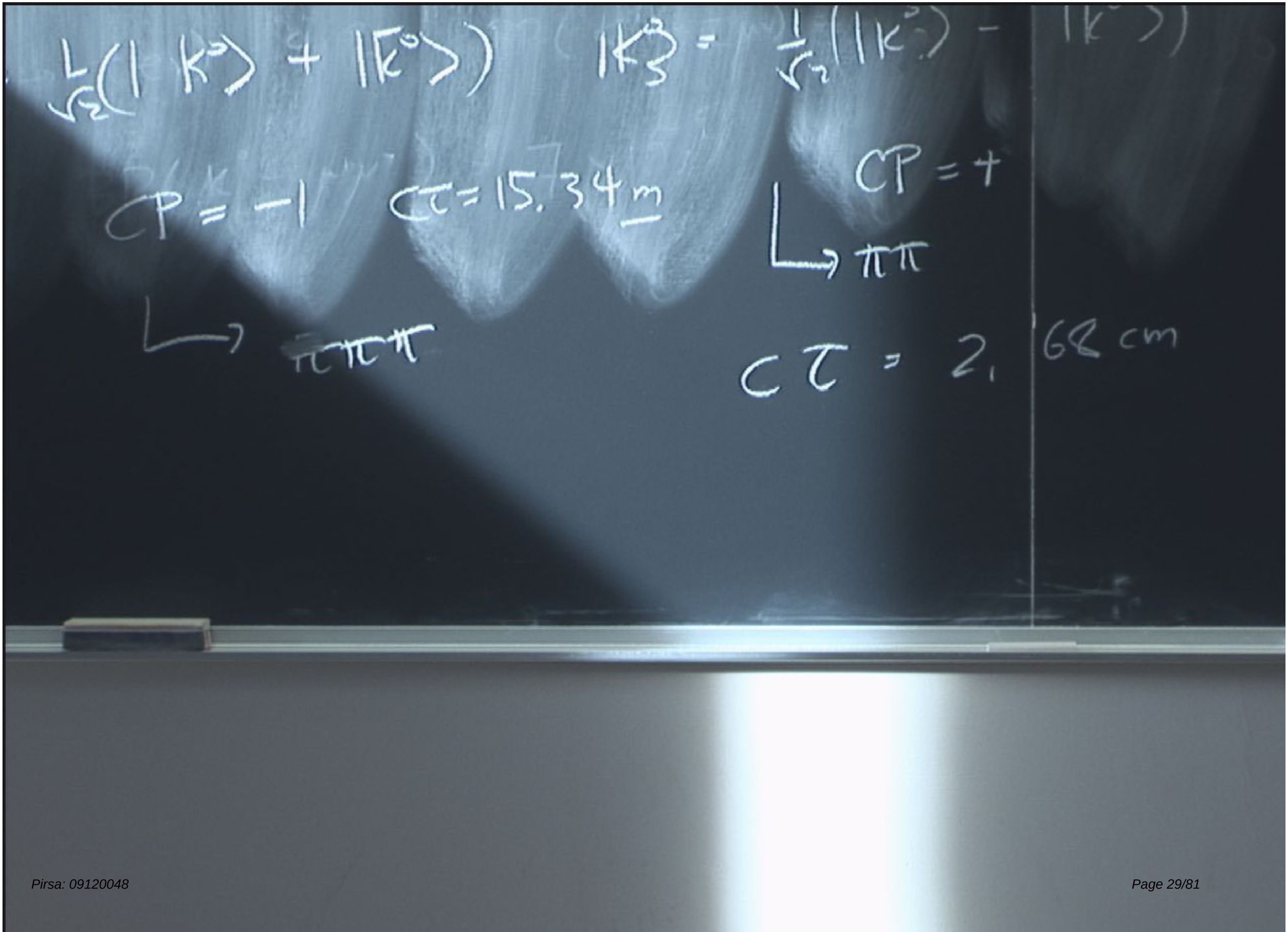
$\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad |K_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle -$

$CP = -1$

$\hookrightarrow \pi\pi\pi$

$CP = +$

$\hookrightarrow \pi\pi$



$\frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$ $|K^0_S\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$

$CP = -1$ $c\tau = 15.34\,\underline{m}$

$\hookrightarrow \pi\pi\pi$

$CP = +$

$\hookrightarrow \pi\pi$

$c\tau = 2.68\text{ cm}$

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

$CP = + \qquad CP = -$

$|\bar{K}^0\rangle)$

68 cm

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

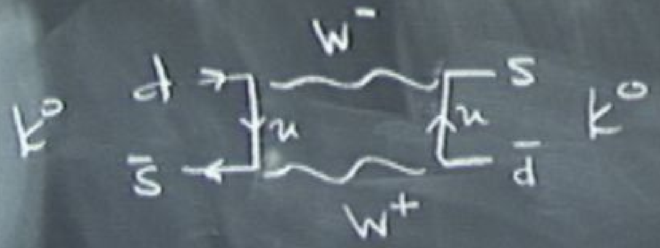
$CP = + \qquad CP = -$

$|\bar{K}^0\rangle)$

68 cm

$K^0, \bar{K}^0 \to \pi\pi \quad \pi\pi\pi$

$CP = + \quad CP = -$

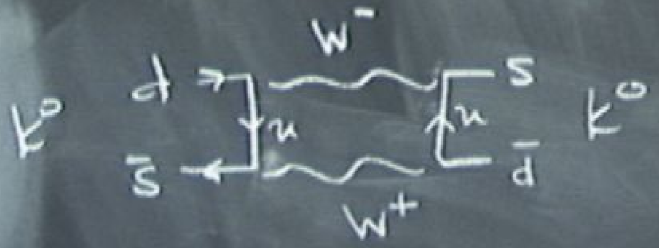


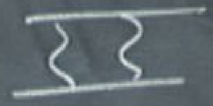
$|\bar{K}^0\rangle)$

62 cm

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

$CP = + \qquad CP = -$



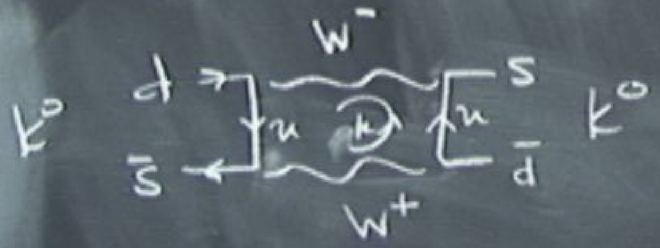


$|\bar{K}^0\rangle)$

68 cm

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

$CP = + \qquad CP = -$



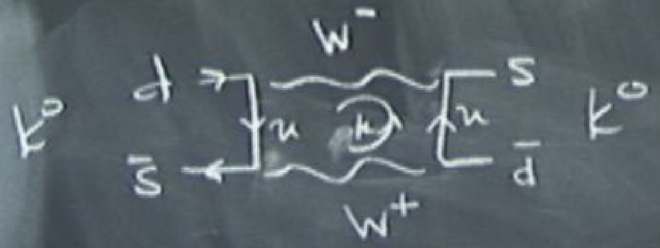
$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{(k^2-m_W^2)^2} \frac{K}{k^2}\frac{K}{k^2} \quad g^4 \sim \quad \alpha_w G_F \; V_{ud}^{?} \,|\, V_{us}^{?}$$

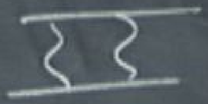
$|\bar{K}^0\rangle)$

62 cm

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

$CP = + \qquad CP = -$





$g^4 \sim \quad \alpha_W G_F \quad V_{ud}^2 \mid V_{us}^2 \; f_\pi^2$

$|\bar{K}^0\rangle) \quad \frac{\Delta m_K}{m_K} = f_\pi^2 \int \frac{d^4k}{(2\pi)^4} \; \frac{1}{(k - m_W^2)^2} \frac{K}{k^2} \frac{K}{k^2}$

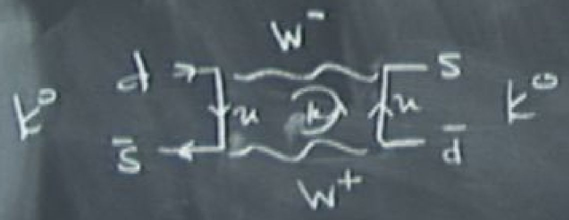
62 cm

$K^0, \bar{K}^0 \to \pi\pi \qquad \pi\pi\pi$

$CP = + \qquad CP = -$

K^0

$\bar{K}^0$)



V

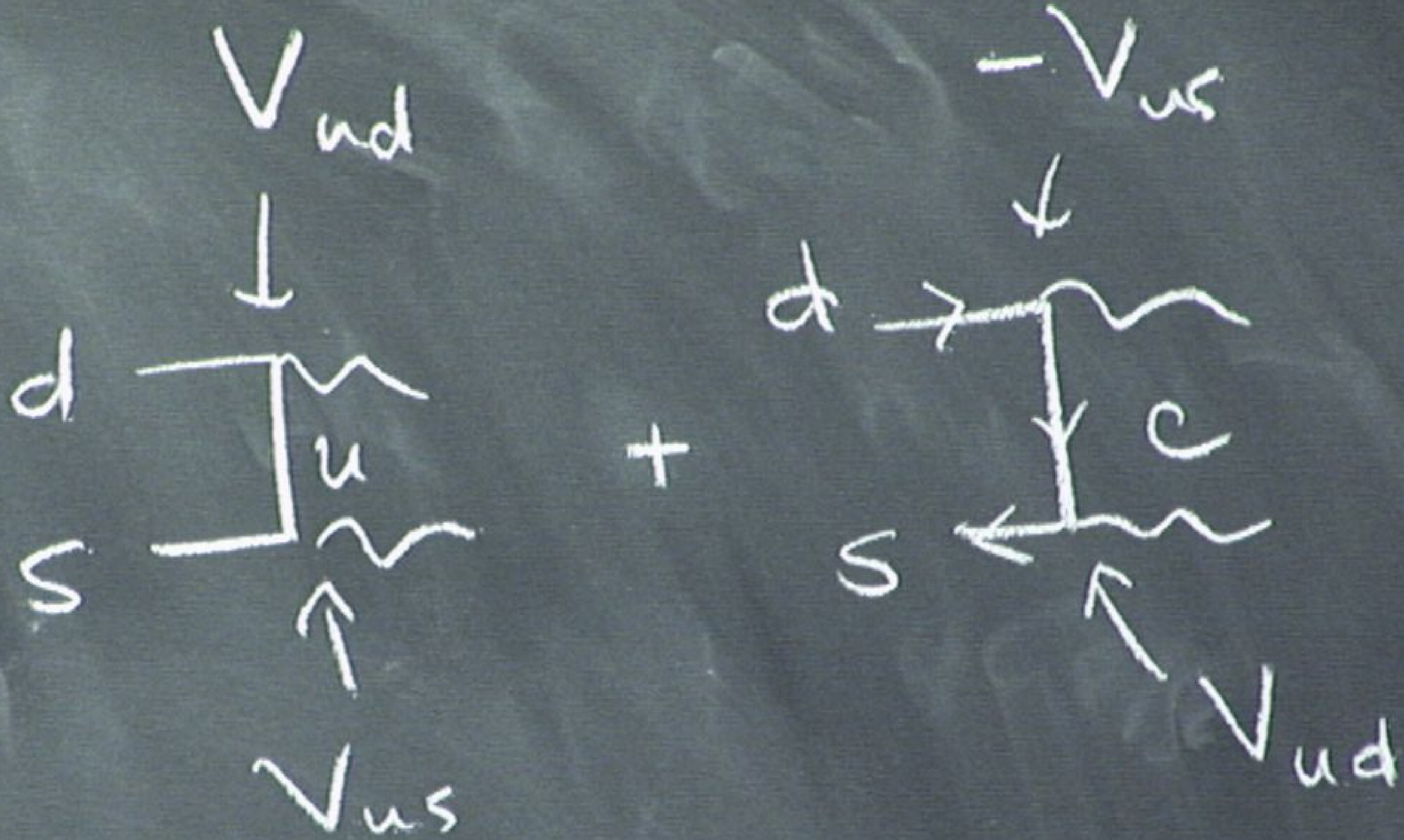
$K^0\rangle) - \quad |\bar{K}^0\rangle)$

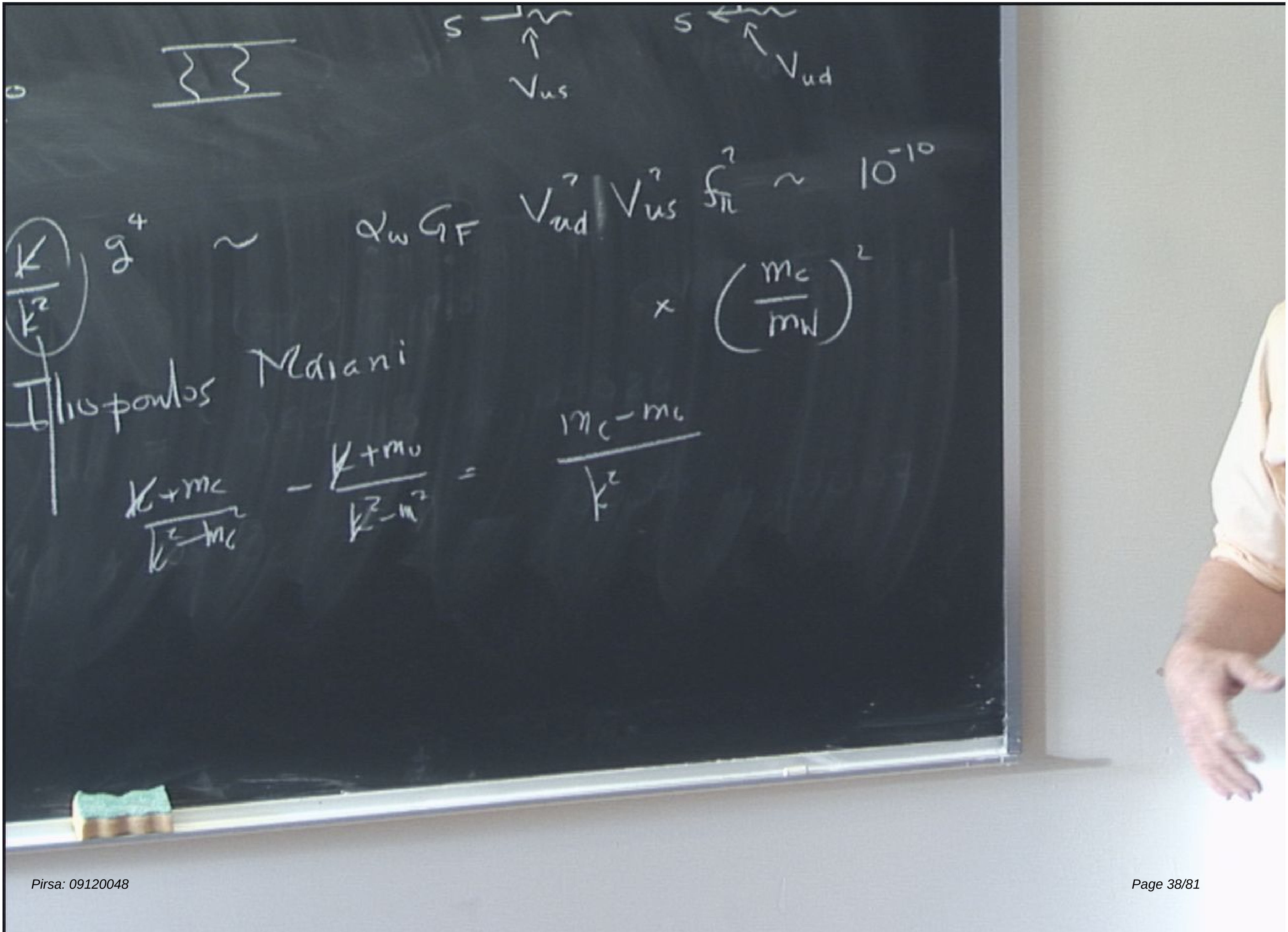
$$\frac{\Delta m_K}{m_K} = f_\pi^2 \int \frac{d^4k}{(2\pi)^4} \; \frac{1}{(k^2-m_W^2)^2} \frac{k}{k^2} \frac{k}{k^2} \quad g^4 \quad \sim \quad \alpha_w G_F \; V_{ud}^2 \,|\, V_{us}^2 \; f_\pi^2 \; \sim \; 10^{-10}$$

P = +

ππ

= 2. 62 cm


V_{ud}
d
u
s
V_{us}
+
$-V_{us}$
d
c
s
V_{ud}

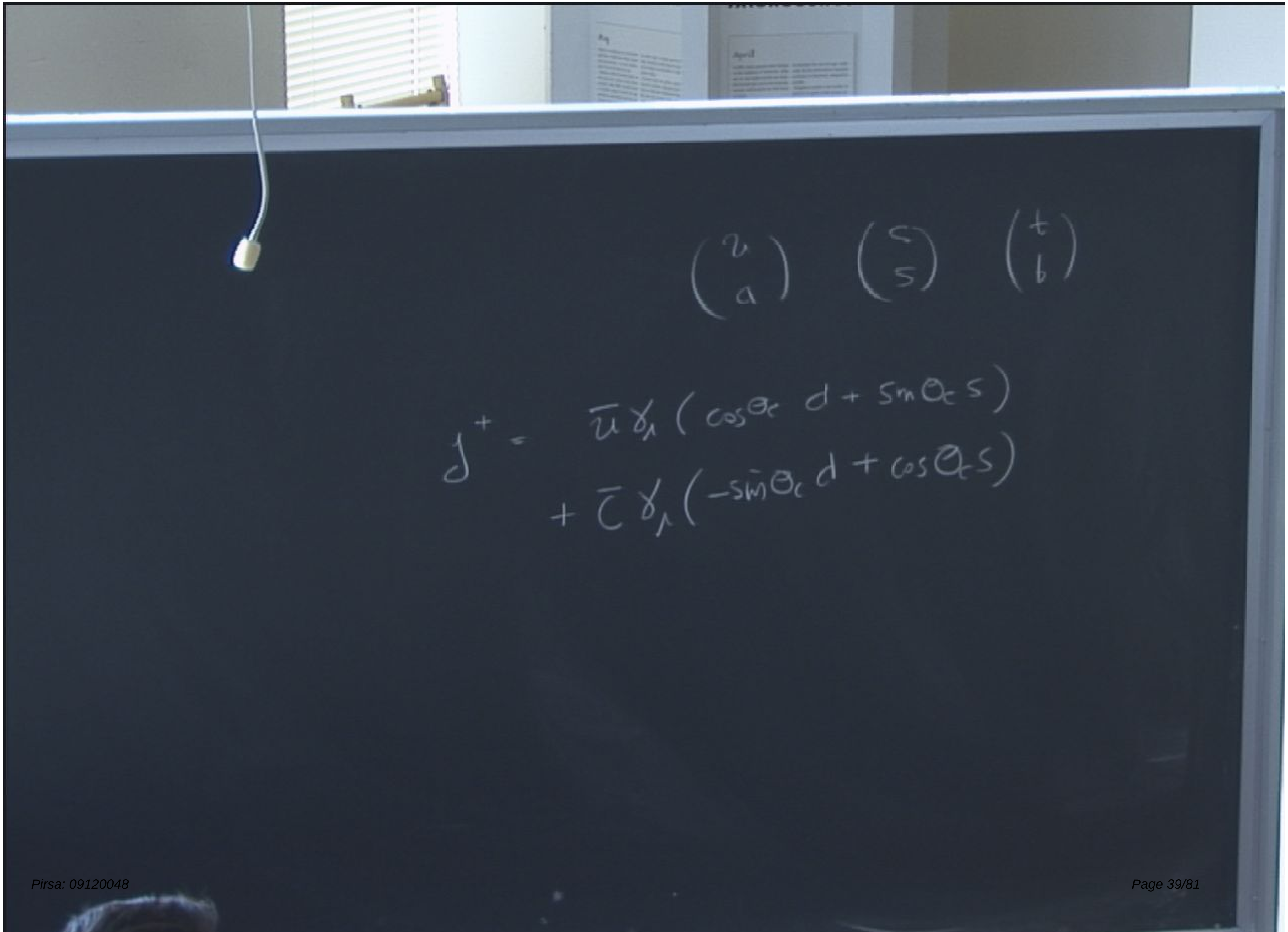


$$\boxed{\frac{k}{k^2}}\ g^4 \sim \alpha_w G_F V_{ud}^2 V_{us}^2 f_\pi^2 \sim 10^{-10}$$

$$\times \left(\frac{m_c}{m_W}\right)^2$$

Iliopoulos Maiani

$$\frac{k+m_c}{k^2-m_c^2} - \frac{k+m_u}{k^2-m^2} = \frac{m_c-m_u}{k^2}$$



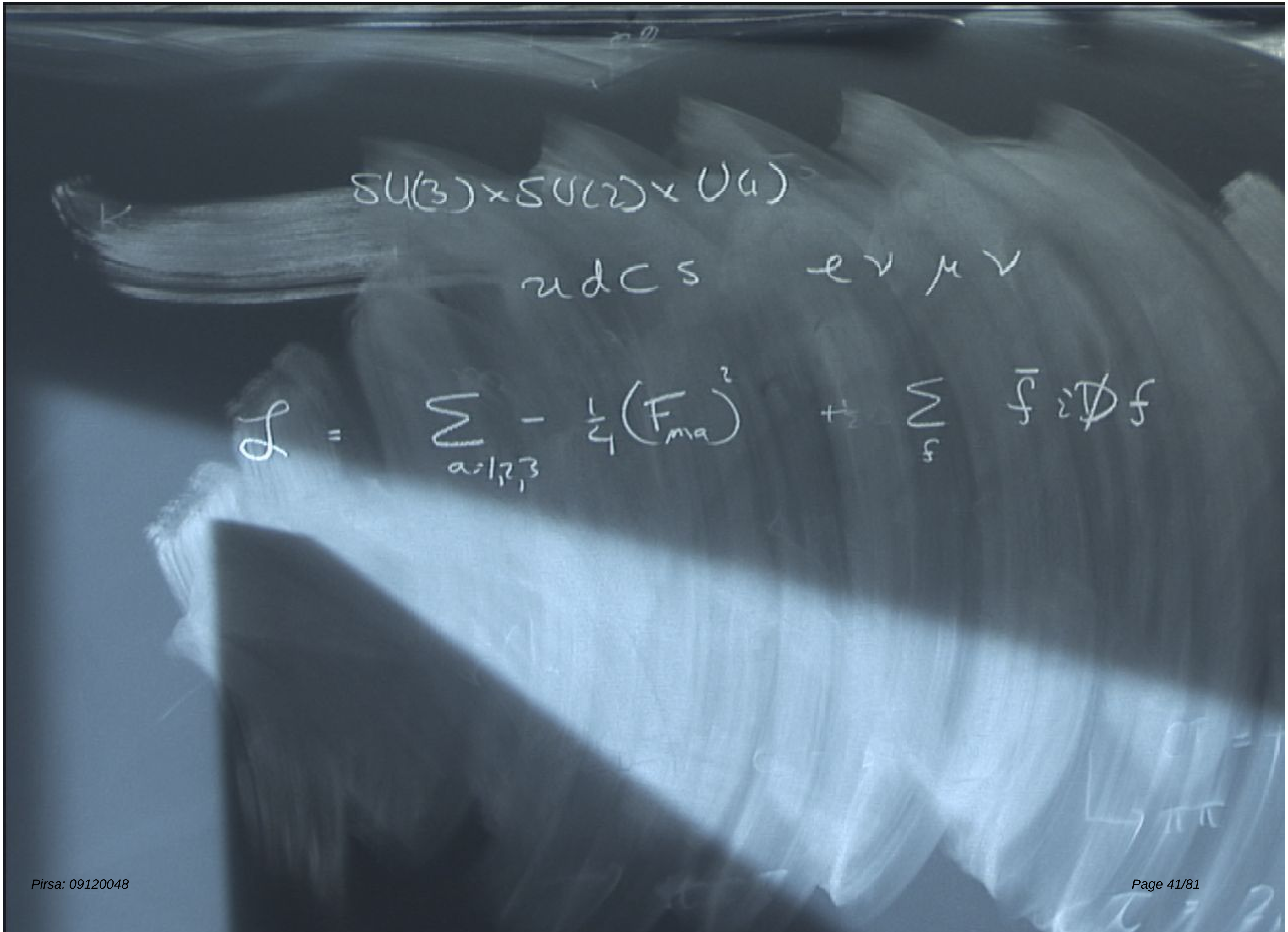
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$J^{+} = \bar{u}\gamma_{\lambda}\left(\cos\theta_c\, d + \sin\theta_c\, s\right) + \bar{c}\gamma_{\lambda}\left(-\sin\theta_c\, d + \cos\theta_c\, s\right)$$

$SU(3) \times SU(2) \times U(1)$

u d c s   e ν μ ν

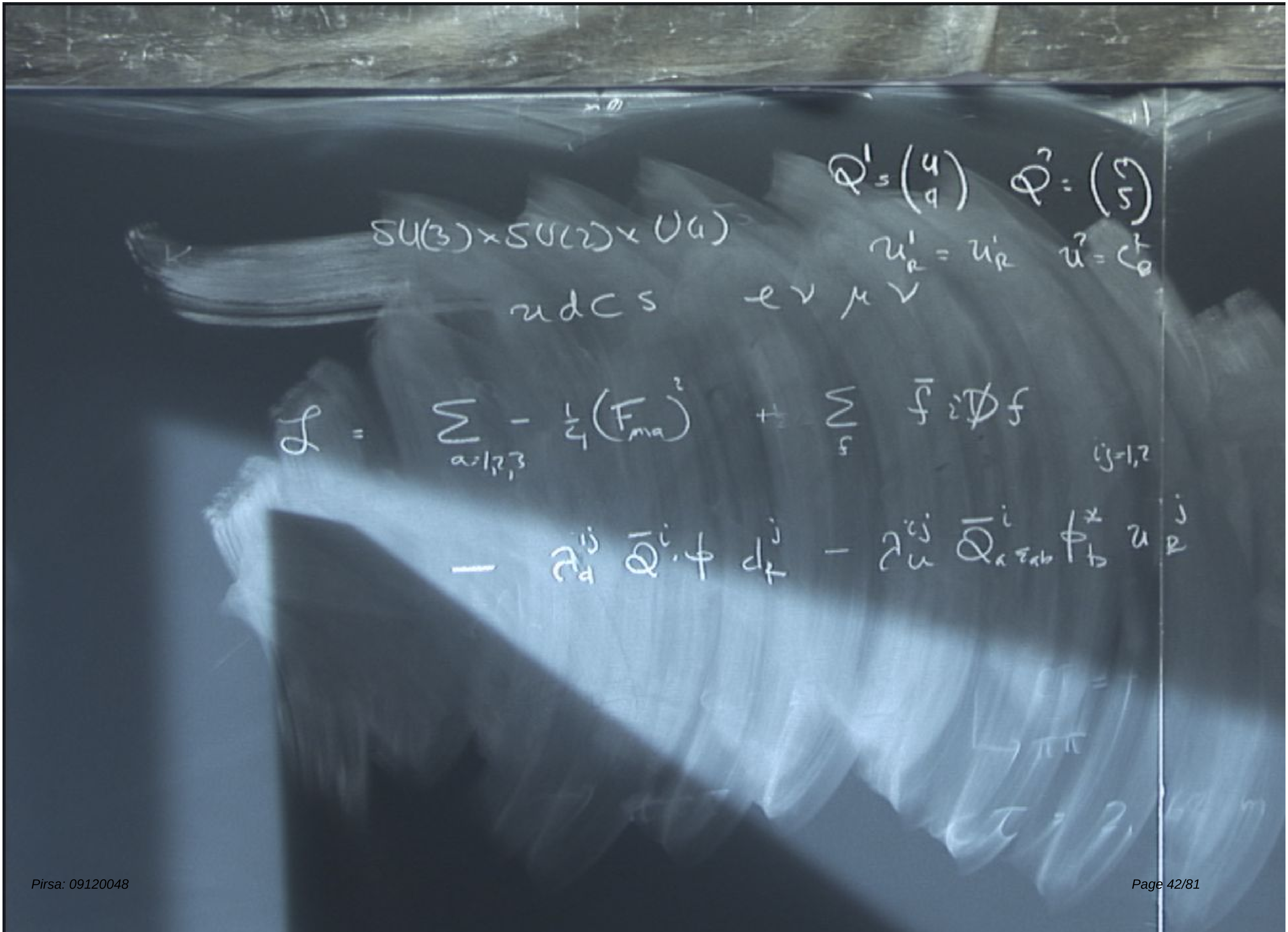
$$\mathcal{L} = \sum_{a=1,2,3} - \frac{1}{4}\left(F_{\mu a}\right)^2$$



$SU(3) \times SU(2) \times U(1)$

$u\ d\ c\ s \quad e\ \nu\ \mu\ \nu$

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}\left(F_{ma}\right)^2 + \sum_{f} \bar{f}\, i \not{D} f$$



$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix}$ $Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$SU(3) \times SU(2) \times U(1)$

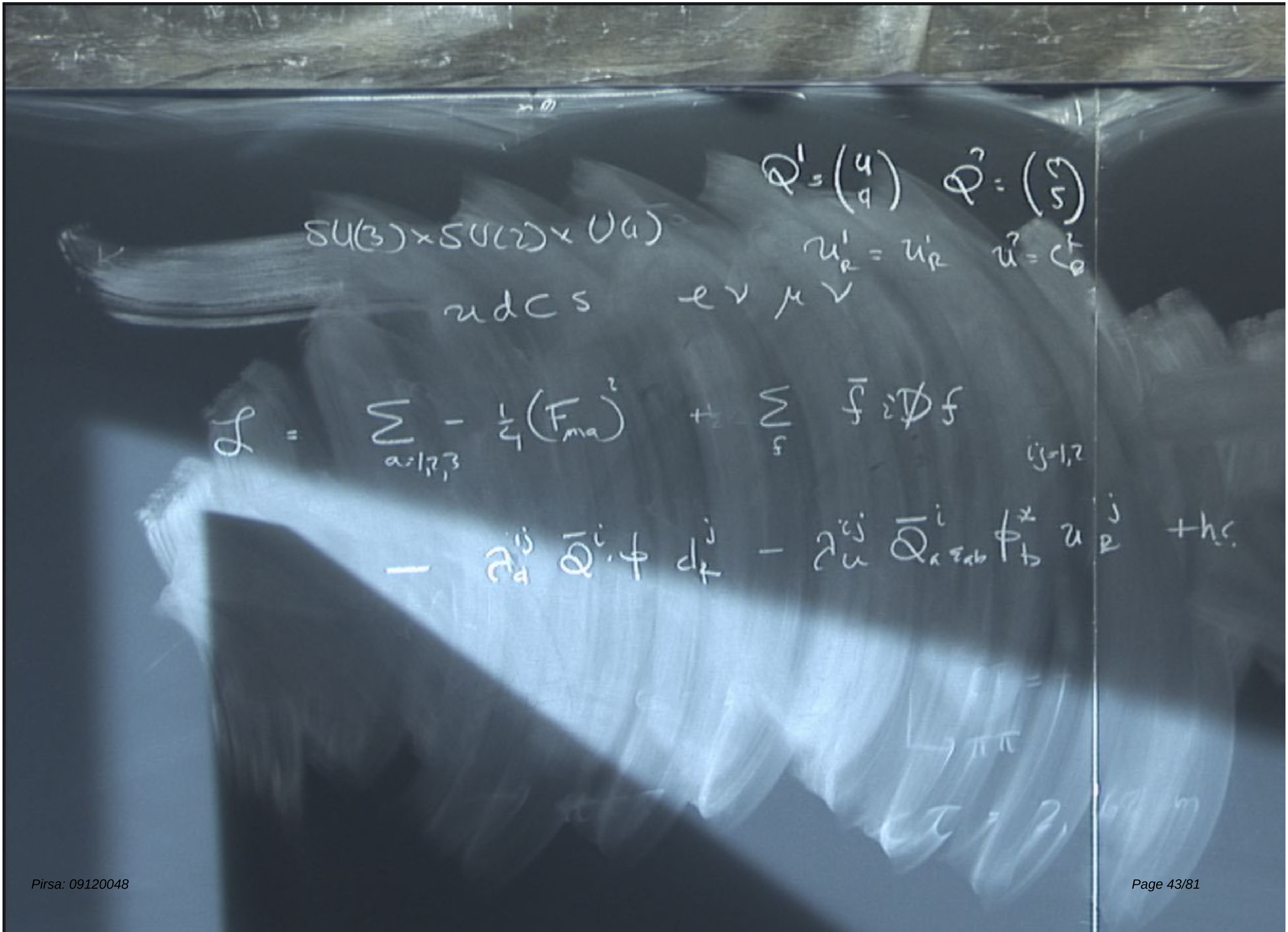
$u^1_R = u_R$ $u^2 = c_R$

u d c s   e ν μ ν

$$\mathcal{L} = \sum_{a=1,2,3} - \frac{1}{4}(F_{\mu a})^2 + \sum_f \bar{f}\, i \not{D} f$$

$ij = 1,2$

$$- \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j - \lambda_u^{ij}\, \bar{Q}^i_a \epsilon_{ab} \phi^*_b u_R^j$$



$SU(3)\times SU(2)\times U(1)$

$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix}$ $Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$u^1_R = u_R$ $u^2 = c_R$

$u\, d\, c\, s$ $e\, \nu$ $\mu\, \nu$

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}(F_{ma})^2 + \sum_f \bar{f}\, i \not{D} f$$

$i,j=1,2$

$$- \lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j - \lambda_u^{ij}\, \bar{Q}^i_a \varepsilon_{ab} \phi^*_b u_R^j + h.c.$$

$$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix} \quad Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$$

$SU(3) \times SU(2) \times U(1)$

$$u^1_R = u_R \quad u^2 = c_R$$

$u\ d\ c\ s \quad e\ \nu \quad \mu\ \nu$

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}\left(F_{\mu a}\right)^2 + \sum_f \bar{f}\, i \not{D} f$$

$i,j=1,2$

$$- \lambda_d^{ij}\, \bar{Q}^i \phi\, d_R^j - \lambda_u^{ij}\, \bar{Q}^i_a \varepsilon_{ab} \phi^*_b\, u_R^j + h.c.$$

$$- \lambda_\ell^{ij}\, L^i \phi\, e_R^j$$

$$\frac{1}{4}\left(F_{\mu a}\right) \quad + \sum_{f} f\, i \not{D}\, f$$

$ij = 1,2$

$$\lambda_d^{ij}\, \bar{Q}^i \cdot \phi\, d_R^j - \lambda_u^{ij}\, \bar{Q}^i_a\, \varepsilon_{ab}\, \phi^*_b\, u_R^j \quad + h.c.$$

$$- \lambda_\ell^{ij}\, L^i \cdot \phi\, e_R^j$$

$$+ |D_\mu \phi|^2 - V(\phi) \quad + \quad (\theta\text{-term})$$

$\frac{1}{4}(F_{ma}) + \sum_{f} f \, i \not{D} \, f$

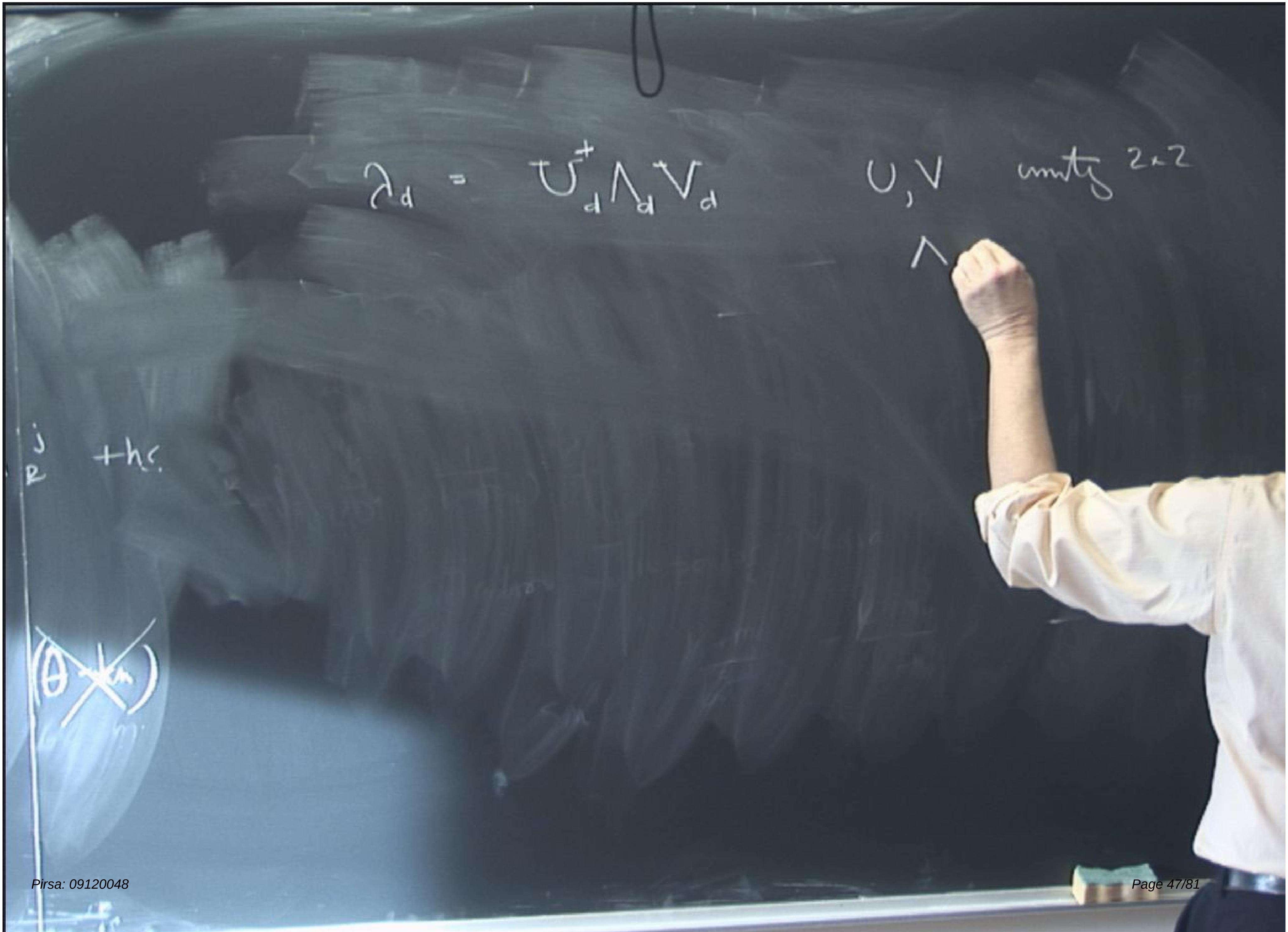
$i,j=1,2$

$\lambda_d^{ij} \bar{Q}^i \cdot \phi \, d_R^j - \lambda_u^{ij} \bar{Q}^i_a \epsilon_{ab} \phi^*_b u_R^j + h.c.$

$- \lambda_\ell^{ij} \bar{L}^i \cdot \phi \, e_R^j$

$+ |D_\mu \phi|^2 - V(\phi) +$

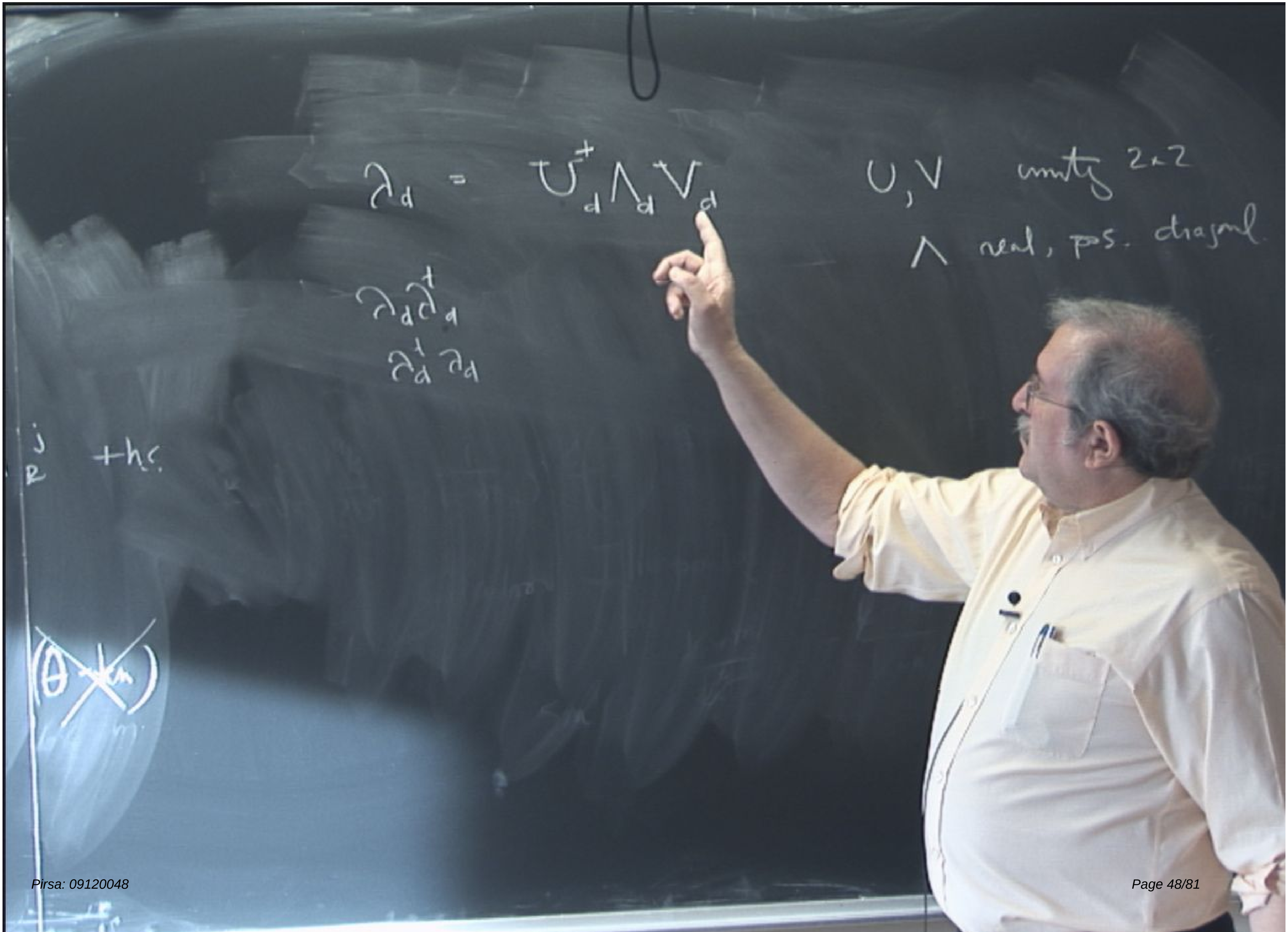
$\xcancel{(\theta \text{ term})}$



$$\lambda_d = U_d^{\dagger} \Lambda_d V_d \qquad U, V \text{ unity } 2\times 2$$

Λ

$^{j}_{k}$ + h.c.



$\lambda_d = U_d^\dagger \Lambda_d V_d$ U, V unitary 2×2

Λ real, pos. diagonal

$\lambda_d \lambda_d^\dagger$

$\lambda_d^\dagger \lambda_d$

^j_R + h.c.

$\cancel{(\theta \ldots m)}$

$\lambda_d = U_d^\dagger \Lambda_d V_d$ U, V unitary 2×2

Λ real, pos. diagonal

$d_R' = V_d d_R$

${}_R^j$ + h.c.

~~(θ [illegible])~~

$\lambda_d = U_d^\dagger \Lambda_d V_d$ U, V unity 2×2

Λ real, pos. diagnl

$d_R' = V_d \, d_R$

$\bar{d}_R \, i\not\partial \, d_R = \bar{d}_R' \, V \, i\not\partial \, V^\dagger d_R' = \bar{d}_R \, i\not\partial$

${}_R^j$ + h.c.

$\cancel{(\theta - m)}$

$\lambda_d = U_d^{\dagger} \Lambda_d V_d$ U, V unitary 2×2

Λ real, pos. diagonal

$d'_R = V_d \, d_R$

$\bar{d}_R \, i\not{\partial} \, d_R = \bar{d}'_R V \, i\not{\partial} \, V^{\dagger} d'_R = \bar{d}_R \, i\not{\partial} \, d_R$

$Q_d \, \bar{d}_R \gamma^{\mu} d_R = \bar{d}'_R V \gamma^{\mu} V^{\dagger} d'_R = \bar{d}_R \gamma^{\mu} d_R$

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

U, V unitary 2×2

Λ real, pos. diagonal

$$d_R' = V_d d_R$$

$$\bar d_R i \not\partial d_R = \bar d_R' V i \not\partial V^\dagger d_R' = \bar d_R i \not\partial d_R$$

$$= \bar d_R' V \gamma^\mu V^\dagger d_R' = \bar d_R \gamma^\mu d_R$$

$$Q_d \bar d_R \gamma^\mu d_R =$$

$$\bar u_L \gamma^\mu d_L = \bar u_L' U_u \gamma^\mu U_d^\dagger d_L'$$

$$\lambda_d = U_d^\dagger \Lambda_d V_d \qquad U, V \text{ unitary } 2\times 2$$

Λ real, pos. diagonal

$$d'_R = V_d \, d_R$$

$$\bar{d}_R \, i\not{\partial} \, d_R = \bar{d}'_R V \, i\not{\partial} \, V^\dagger d'_R = \bar{d}_R \, i\not{\partial} \, d_R$$

$$Q_d \, \bar{d}_R \gamma^\mu d_R = \bar{d}'_R V \gamma^\mu V^\dagger d'_R = \bar{d}_R \gamma^\mu$$

$$\bar{u}_L \gamma^\mu d_L = \bar{u}'_L U_u \gamma^\mu U_d^\dagger d'_L$$

$$= \bar{u}'_L \gamma^\mu V_{CKM} \, d'_L$$

$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix}$ $Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$SU(3) \times SU(2) \times U(1)$ $u_R^1 = u_R$ $u^2 = c_R$

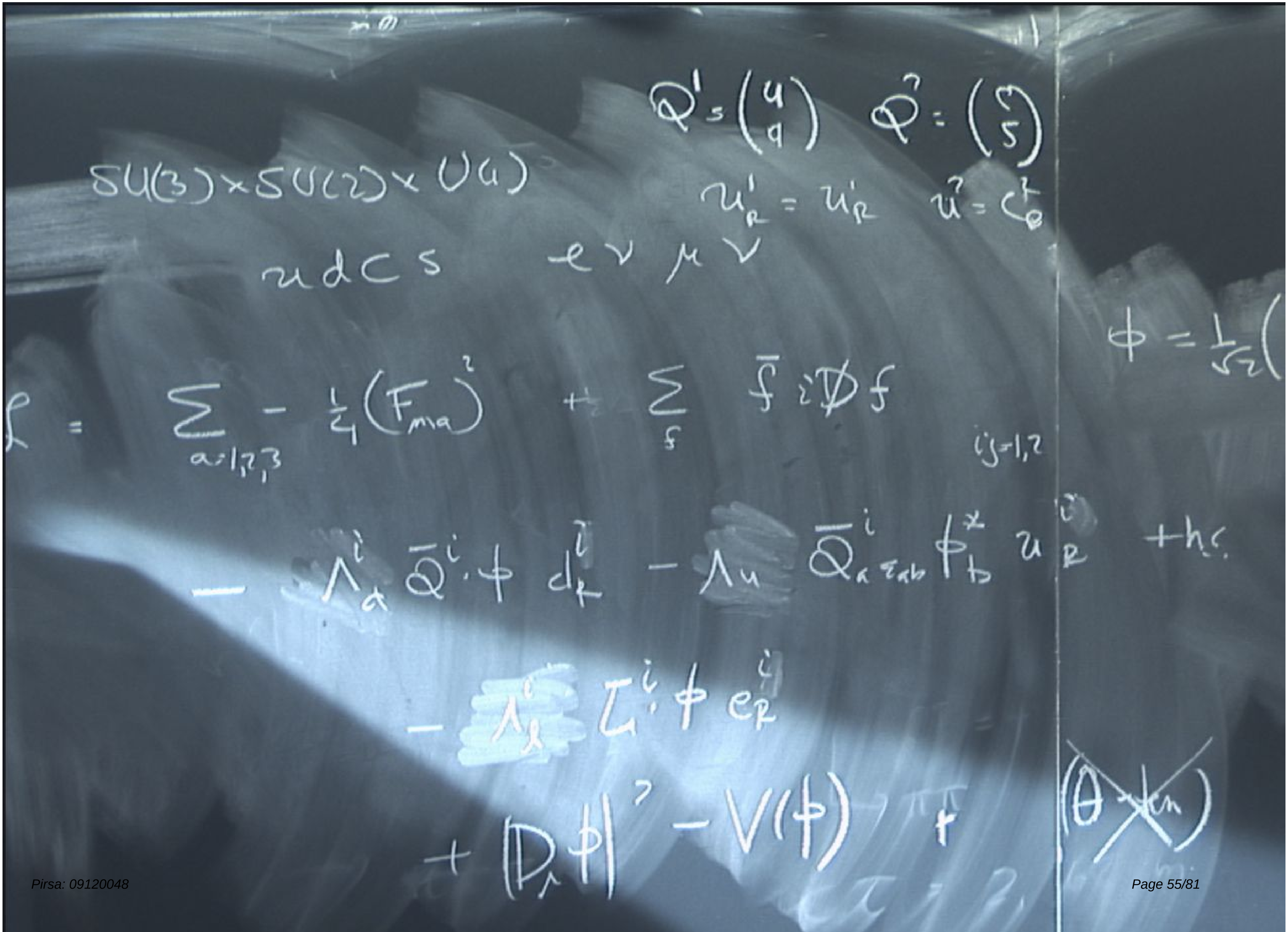
$u\, d\, c\, s$ $e\, \nu\, \mu\, \nu$

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}\left(F_{\mu a}\right)^2 + \sum_f \bar{f}\, i \not{D} f \qquad i,j=1,2$$

$$- \Lambda_d^{ij} \bar{Q}^i \cdot \phi\, d_R^j - \Lambda_u \bar{Q}^i_a \varepsilon_{ab} \phi^*_b u_R^j + h.c.$$

$$- \Lambda_\ell^{ij} \bar{L}^i \cdot \phi\, e_R^j$$

$$+ |D_\mu \phi|^2 - V(\phi) + \cancel{(\theta\text{-term})}$$



$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix}$ $Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$SU(3) \times SU(2) \times U(1)$

$u^1_R = u_R$ $u^2 = c_R$

$u\ d\ c\ s$ $e\ \nu\ \mu\ \nu$

$\phi = \frac{1}{\sqrt{2}}($

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}\left(F_{mn\,a}\right)^2 + \sum_f \bar{f}\, i \not{D} f \qquad i,j=1,2$$

$$- \Lambda_d^i \bar{Q}^i \cdot \phi\, d_R^i - \Lambda_u \bar{Q}^i_a \epsilon_{ab} \phi^*_b u_R^i + h.c.$$

$$- \Lambda_\ell^i \bar{L}^i \cdot \phi\, e_R^i$$

$$+ |D_\mu \phi|^2 - V(\phi) \qquad \cancel{(\theta + F_m)}$$

$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix} \quad Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$SU(3) \times SU(2) \times U(1)$

$u_R^1 = u_R^1 \quad u^2 = c_R^2$

$u\ d\ c\ s \quad e\ \nu\ \mu\ \nu$

λ

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

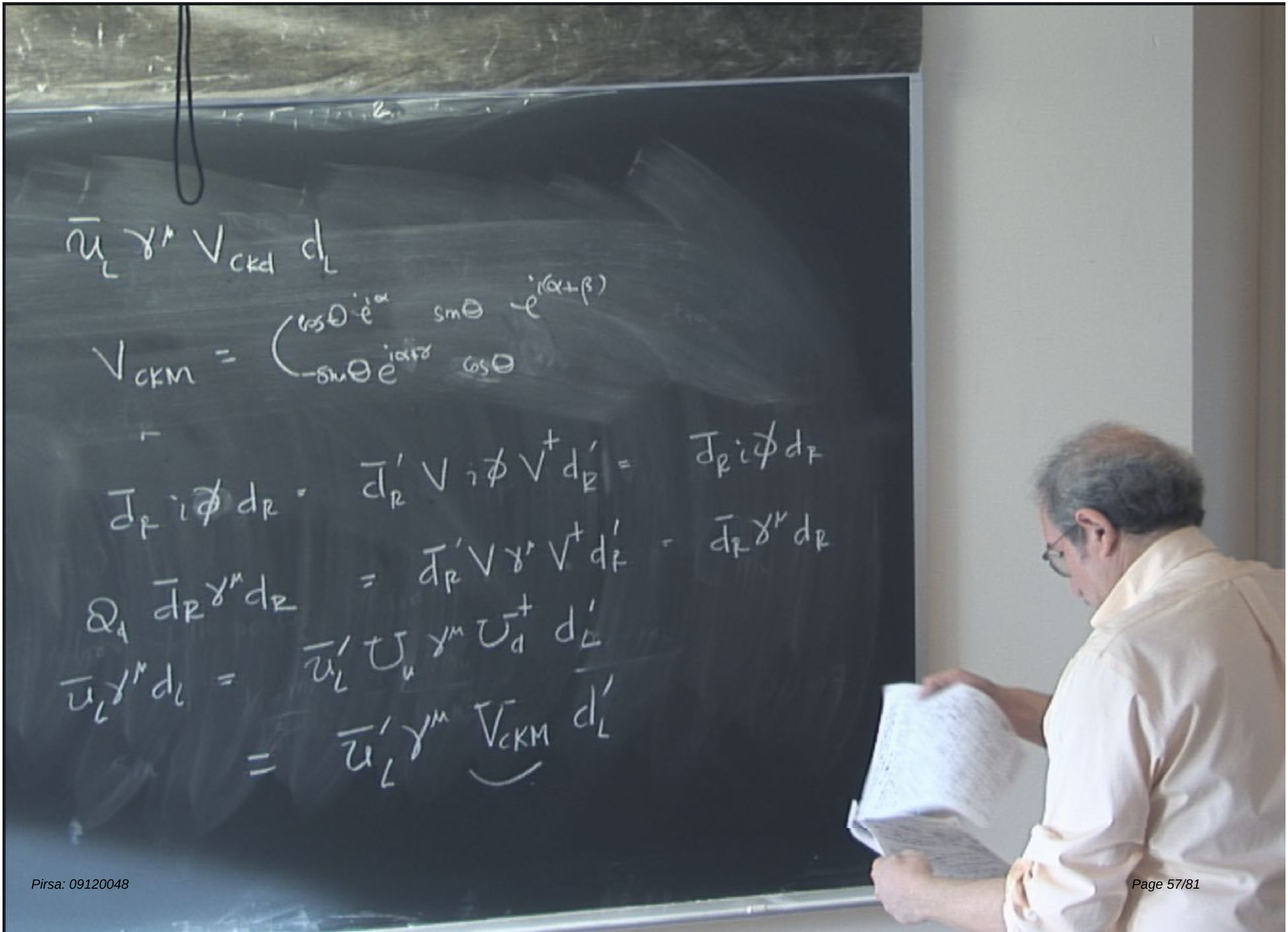
d_R'

$$\mathcal{L} = \sum_{a=1,2,3} -\frac{1}{4}(F_{\mu a})^2 + \sum_f \bar{f}\, i \not{D} f \qquad i,j = 1,2$$

$$- \frac{\Lambda_d^i}{\sqrt{2}} \bar{d}_L (v+h) d_R^i - \frac{\Lambda_u}{\sqrt{2}} u\, (v+h)\, u_R^i + h.c.$$

$$- \frac{\Lambda_e}{\sqrt{2}} \bar{L}^i (v+h) e_R^i$$

$$+ |D_\mu \phi|^2 - V(\phi) + \cancel{(\theta\ \ldots)}$$



$$\bar{u}_L \gamma^\mu V_{CKM}\, d_L$$

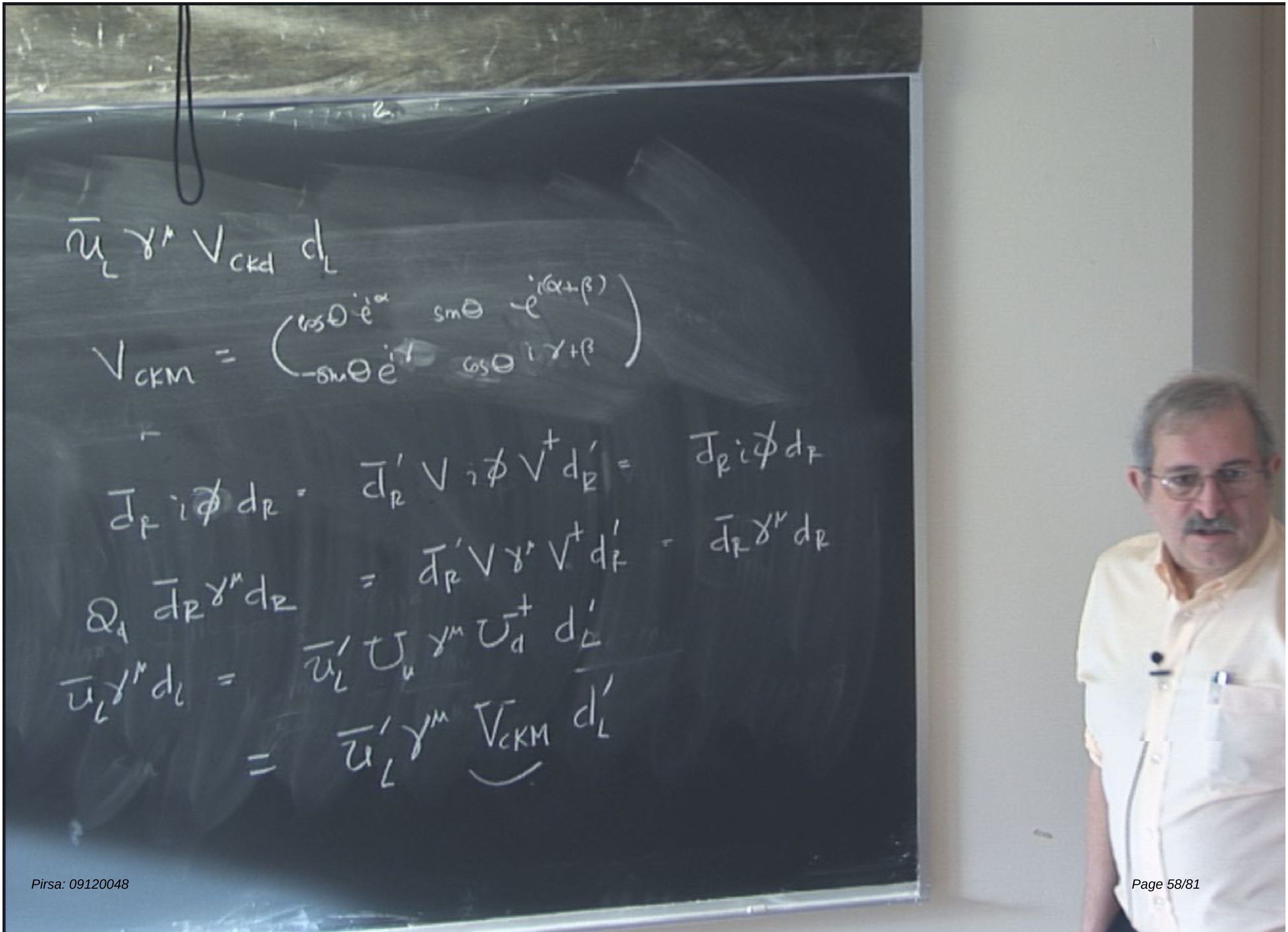
$$V_{CKM} = \left(\begin{matrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i(\alpha+\beta)} \\ -\sin\theta\, e^{i\alpha+\gamma} & \cos\theta \end{matrix} \right.$$

$$\bar{d}_R\, i\not\partial\, d_R = \bar{d}_R'\, V\, i\not\partial\, V^+ d_R' = \bar{d}_R\, i\not\partial\, d_R$$

$$Q_d\, \bar{d}_R \gamma^\mu d_R = \bar{d}_R'\, V \gamma^\mu V^+ d_R' = \bar{d}_R \gamma^\mu d_R$$

$$\bar{u}_L \gamma^\mu d_L = \bar{u}_L'\, U_u \gamma^\mu U_d^+ d_L'$$

$$= \bar{u}_L' \gamma^\mu \underbrace{V_{CKM}}\, d_L'$$



$$\bar{u}_L \gamma^\mu V_{CKd}\, d_L$$

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

$$\bar{d}_R i\not\partial d_R = \bar{d}'_R V i\not\partial V^\dagger d'_R = \bar{d}_R i\not\partial d_R$$

$$= \bar{d}'_R V \gamma^\mu V^\dagger d'_R = \bar{d}_R \gamma^\mu d_R$$

$$Q_d\, \bar{d}_R \gamma^\mu d_R$$

$$\bar{u}_L \gamma^\mu d_L = \bar{u}'_L U_u \gamma^\mu U_d^\dagger d'_L$$

$$= \bar{u}'_L \gamma^\mu \underbrace{V_{CKM}}_{} d'_L$$

$e^{i\alpha} u = u'$ $\quad e^{i\gamma} c = c'$

$$\bar{u}_L \gamma^\mu V_{Ckd}\, d_L$$

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

$$V_{CKM} = \begin{array}{c} (u\ c\ ) \\ \begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i(\alpha+\beta)} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\ i\,\gamma+\beta \end{pmatrix} \end{array} \begin{pmatrix} d \\ s \end{pmatrix}$$

$+ h.c.$

$$\bar{d}_R\, i\not\partial\, d_R = \bar{d}_R'\, V\, i\not\partial\, V^\dagger d_R' = \bar{d}_R\, i\not\partial$$

$$Q_d\, \bar{d}_R \gamma^\mu d_R = \bar{d}_R' V \gamma^\mu V^\dagger d_R' = \bar{d}_R$$

$$\bar{u}_L \gamma^\mu d_L = \bar{u}_L' U_u \gamma^\mu U_d^\dagger d_L'$$

$$= \bar{u}_L' \gamma^\mu \underbrace{V_{CKM}}\, d_L'$$

$\cancel{(\theta_{km})}$

$e^{i\alpha} u = u'$ $\quad e^{i\gamma} c = c'$

$e^{i\beta} s = s'$

$$\bar{u}_L \gamma^\mu V_{CKd}\, d_L$$

$$V_{CKM} = \begin{array}{c} (u\ c\ ) \\ \end{array} \begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i(\alpha+\beta)} \\ -\sin\theta\, e^{i} & \cos\theta\ i\gamma+\beta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}$$

$$\bar{d}_R\, i\not\partial\, d_R = \bar{d}_R'\, V\, i\not\partial\, V^\dagger d_R' = \bar{d}_R\, i\not\partial\, d_R$$

$$= \bar{d}_R' V \gamma^\mu V^\dagger d_R' = \bar{d}_R \gamma^\mu d_R$$

$$Q_d\ \bar{d}_R \gamma^\mu d_R$$

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

$$V_{CKM} = \begin{pmatrix} \cos\theta\, e & \\ -\sin\theta\, e^{i\delta} & \end{pmatrix}$$

$i,j = 1,2$

$h)\ u_R^i \quad + h.c.$

$$g\ \bar{u}\gamma^\mu d + h.c.$$

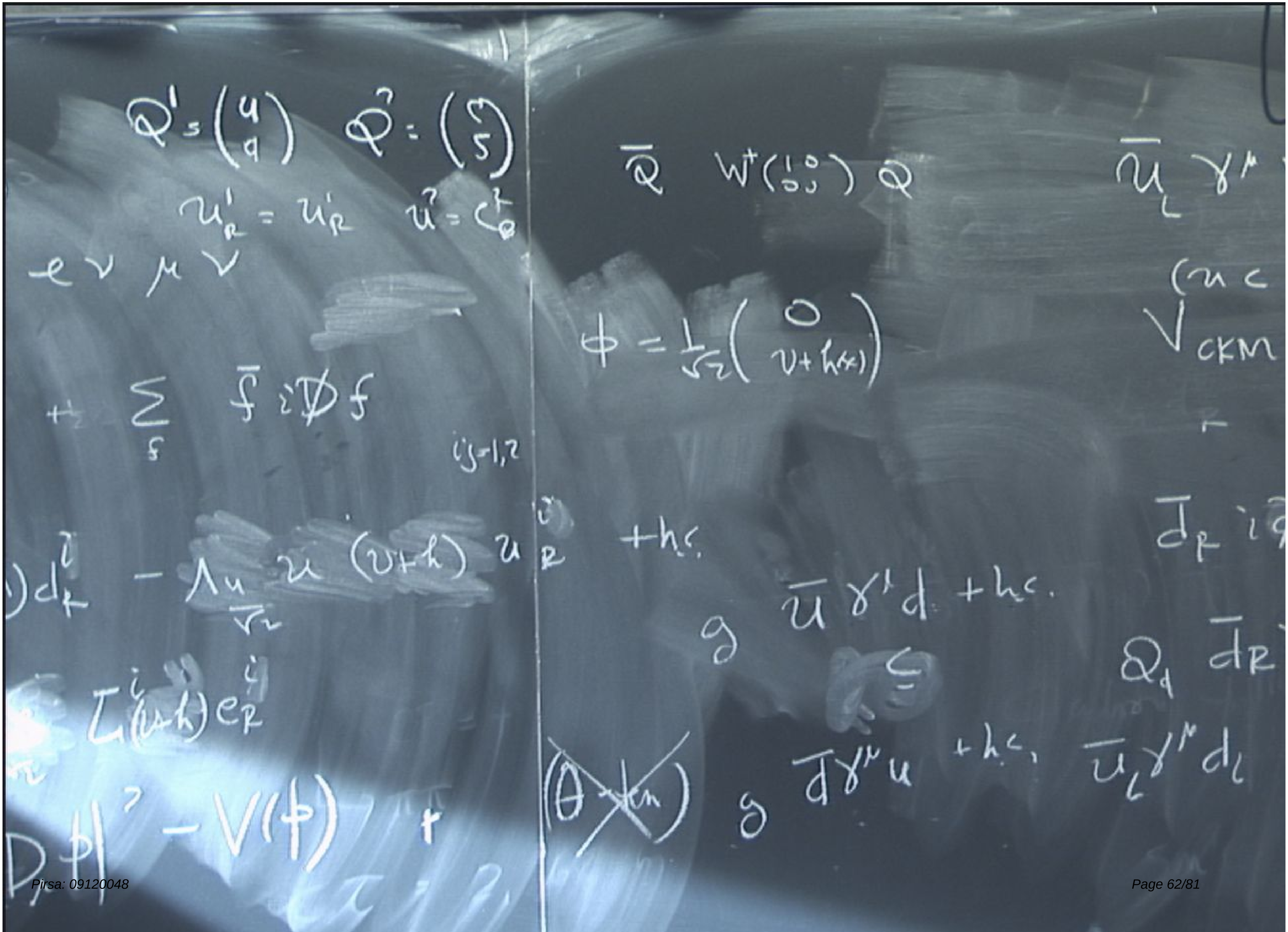
$$\bar{d}_R\, i\not\partial\, d_R = \bar{d}_R'\, V$$

$$Q_d\ \bar{d}_R\gamma^\mu d_R = \bar{d}_R$$

$$g\ \bar{d}\gamma^\mu u + h.c. \qquad \bar{u}_L\gamma^\mu d_L = \bar{u}_L'\, U_u\, \gamma^\mu$$

$$\cancel{(\theta\ \ tm)}$$

$$= \bar{u}_L'\gamma^\mu$$



$Q^1 = \begin{pmatrix} u \\ d \end{pmatrix} \quad Q^2 = \begin{pmatrix} c \\ s \end{pmatrix}$

$u^1_R = u^1_R \quad u^2 = c^2_R$

$e\ \nu\ \mu\ \nu$

$+ \sum_f \bar{f}\, i \not{D} f$

$ij = 1,2$

$) d^i_R \quad - \frac{\Lambda_u}{\sqrt{2}}\, u\, (v+h)\, u^i_R \quad + h.c.$

$L^i (v+h) e^i_R$

$D_\mu \phi|^2 - V(\phi) +$

$\bar{Q} \quad W^+ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} Q$

$\bar{u}_L \gamma^\mu$

$(u\ c$

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

V_{CKM}

$\bar{d}_R\ i$

$g\ \bar{u} \gamma^\mu d + h.c.$

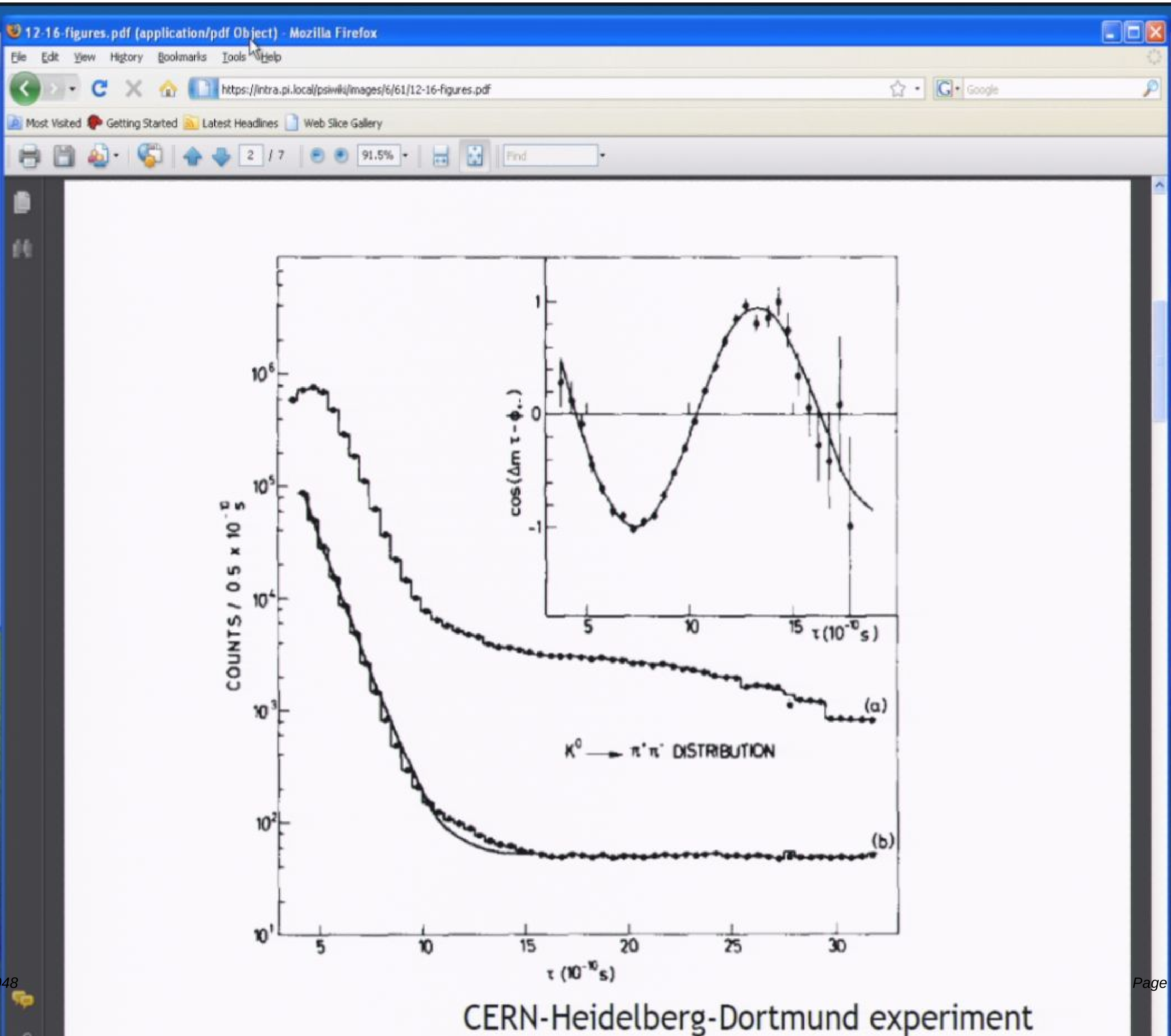
$Q_1\ \bar{d}_R$

$\cancel{(\theta \quad m)}$

$g\ \bar{d} \gamma^\mu u + h.c. \quad \bar{u}_L \gamma^\mu d_L$

$$\begin{tikzcd}
 & K^0_S \arrow[r] & \pi\pi \\
K^0 \bar{K}^0 \arrow[ur] \arrow[dr] & & \\
 & K^0_L &
\end{tikzcd}$$

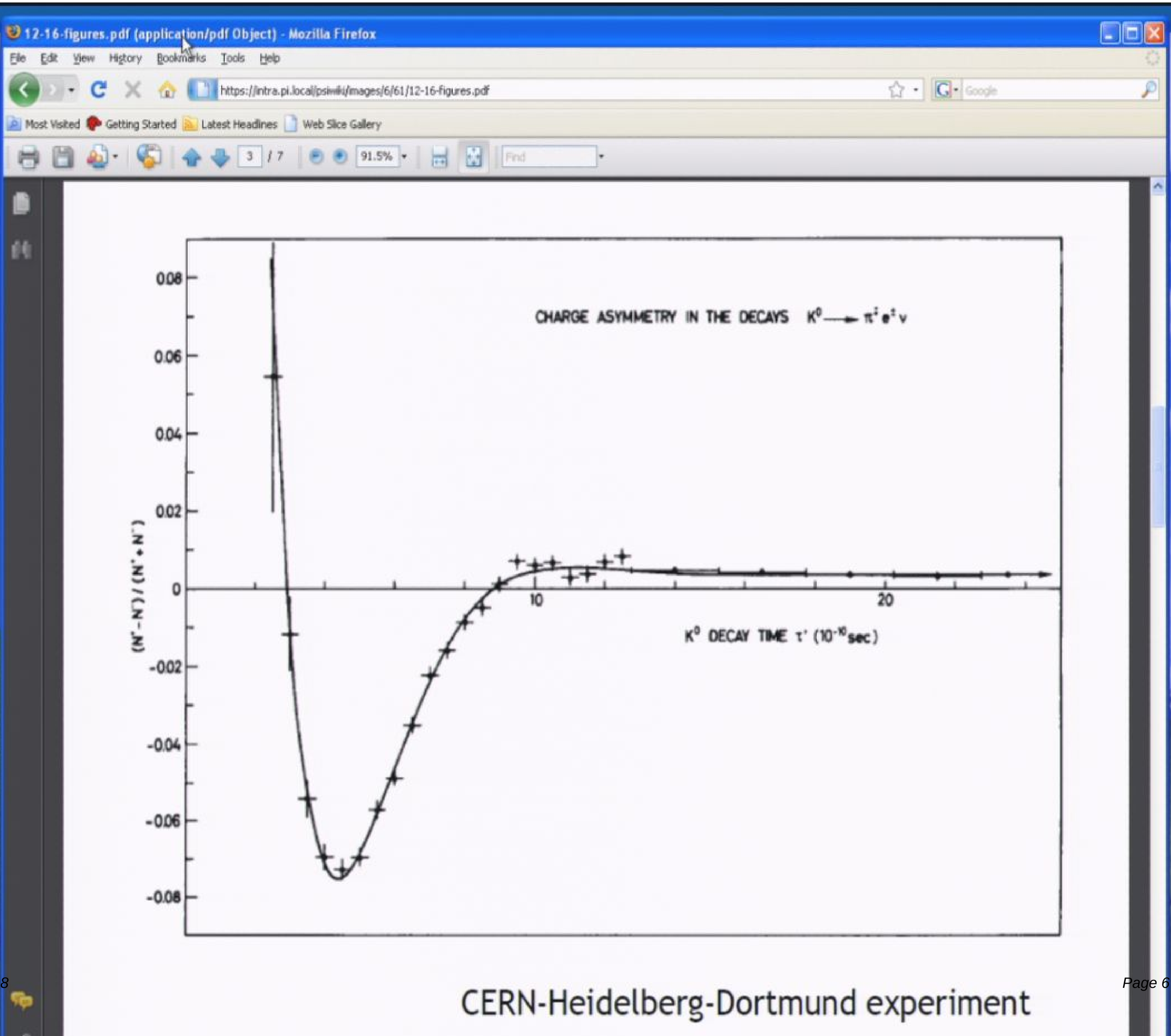
$$K^0 \ \bar{K}^0 \ \begin{cases} \to K^0_S \longrightarrow \pi\pi & 1964 \\ \to K^0_L \longrightarrow \pi\pi\pi \ , \quad \pi\pi & \end{cases}$$



CERN-Heidelberg-Dortmund experiment

$$\begin{tikzcd} & K^0_S \arrow[r] & \pi\pi & & 1964 \\ K^0\ \bar{K}^0 \arrow[ur] \arrow[dr] & & & & \\ & K^0_L \arrow[r] & \pi\pi\pi\ , & \pi\pi & \end{tikzcd}$$

$BR(K^0_L \to \pi\pi) = 3\times10^{-3}$



CERN-Heidelberg-Dortmund experiment

$_{L} \quad V_{CKd} \quad _{L}$

$$V_{CKM} = \begin{array}{c} (u \quad c\,) \\ \left(\begin{array}{c} \cos\theta\, e^{i\alpha} \\ -\sin\theta\, e^{i} \end{array} \right. \end{array}$$

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

$\bar{K}^0 \to e^- \pi^+ \bar{\nu}$

3×10^{-3}

$$\delta = \left(\frac{e^+ - e^-}{e^+ + e^-} \right)$$

$\bar{d}_R\, i\not{\partial}\, d_R = \bar{d}_R'$

$Q_d \quad \bar{d}_R \gamma^\mu d_R$

$\bar{u}_L \gamma^\mu d_L = \bar{u}_L'$

$= \bar{u}_L' \gamma$

$L \quad V_{CKd} \quad L$

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

$\bar{K}^0 \to e^- \pi^+ \bar{\nu}$

3×10^{-3}

$$\delta = \left(\frac{e^+ - e^-}{e^+ + e^-} \right)$$

$$\delta = 3 \times 10^{-3}$$

$(u \; c \;)$

$$V_{CKM} = \Big(\begin{matrix} \cos\theta \, e^{i\alpha} \\ -\sin\theta \, e^{i\gamma} \end{matrix}$$

R

$$\bar{d}_R \, i \not{\partial} \, d_R = \bar{d}'_R$$

$$Q_d \, \bar{d}_R \gamma^\mu d_R =$$

$$\bar{u}_L \gamma^\mu d_L = \bar{u}'_L U_u$$

L

$e^{i\alpha} u = u'$ $e^{i\gamma} c = c'$

$e^{i\beta} s = s'$

$\bar{u}_L \gamma^\mu V_{CKd}\, d_L$

$$\begin{array}{cc} & (u \quad c\ ) \\ V_{CKM} = & \begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i(\alpha+\beta)} \\ -\sin\theta\, e^{i\gamma} & \cos\theta \;\; i\,\gamma+\beta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \end{array}$$

$e^+ \pi^- \nu$

$e^- \pi^+ \bar{\nu}$

$\frac{\bar{e}}{-e}\Big)$

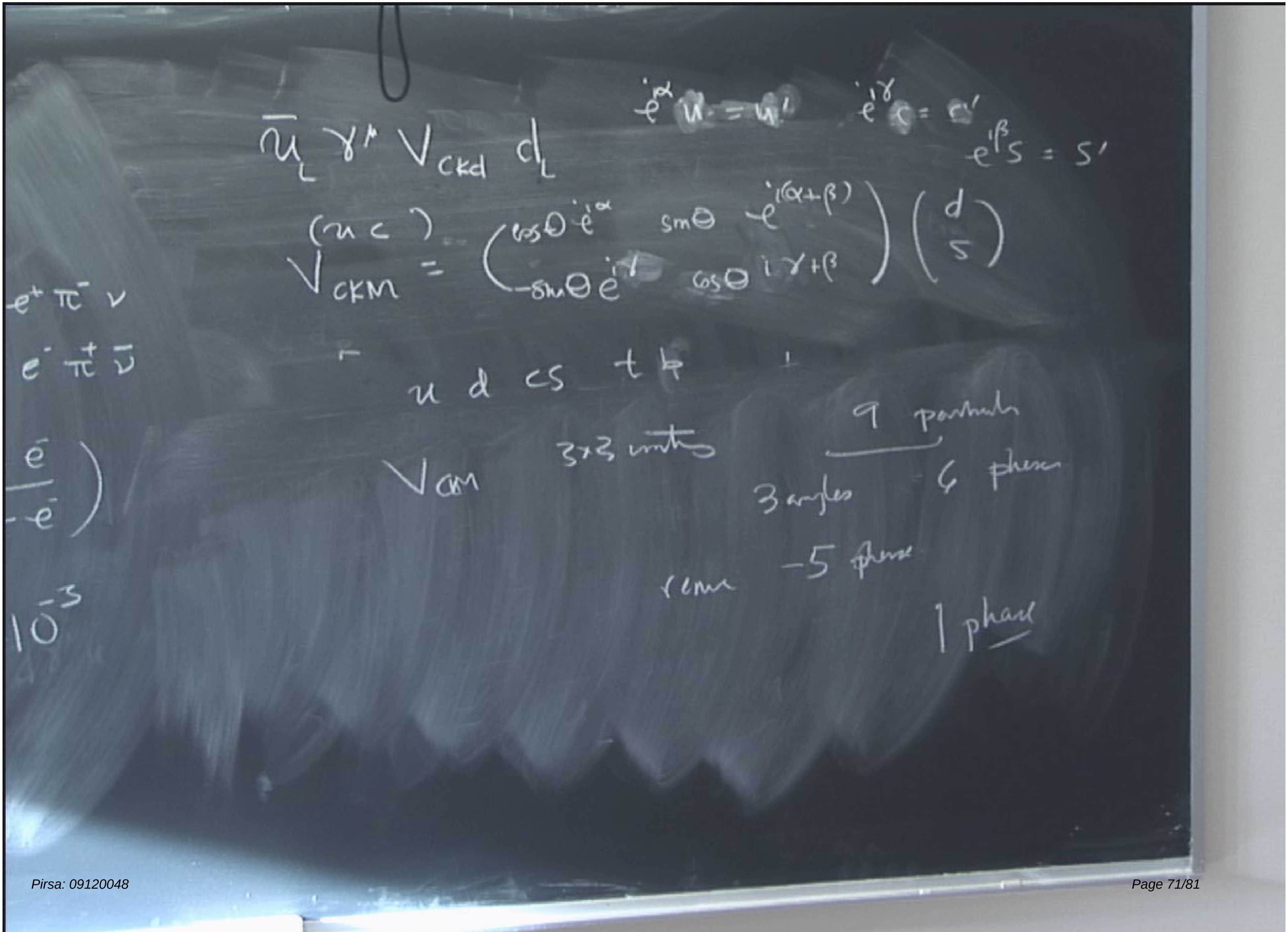
10^{-3}

u d cs t d

V_{CKM} 3×3 unitary

$$\underbrace{9 \text{ parameters}}_{3 \text{ angles} \quad 6 \text{ phases}}$$

remove 5 phases



$e^{i\alpha} u = u'$ $e^{i\gamma} c = c'$

$e^{i\beta} s = s'$

$\bar{u}_L \gamma^\mu V_{CKd}\, d_L$

$(u\ c\ )$

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

$e^+ \pi^- \nu$

$e^- \pi^+ \bar{\nu}$

$\frac{e^-}{-e^-})$

10^{-3}

$u\ d\ c\ s\ t\ b$

V_{CKM} 3×3 unitary

$\underline{9}$ parameters

3 angles 6 phases

remove −5 phase

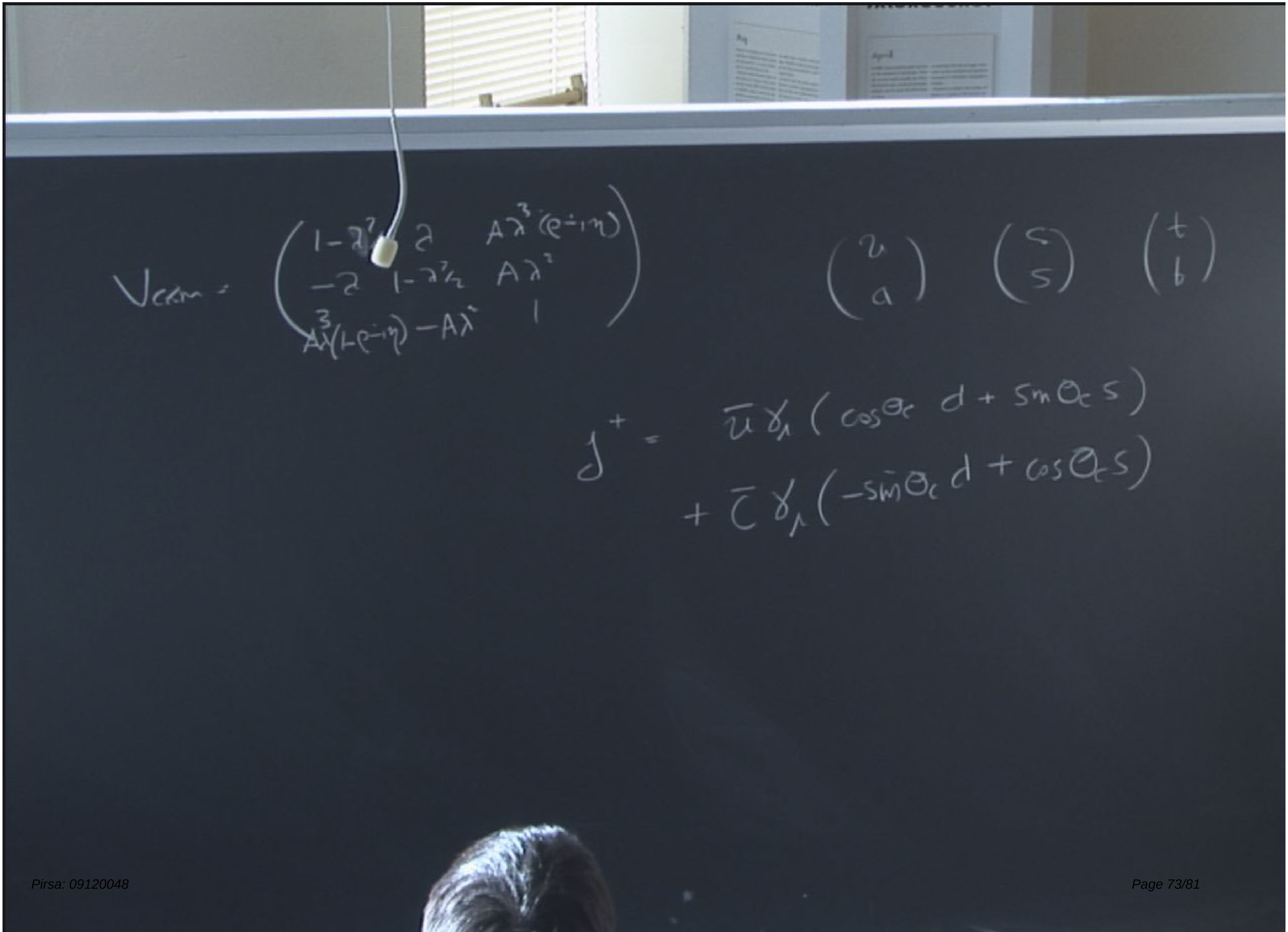
1 $\underline{\text{phase}}$

$B \to D \ell \nu$ $\quad b \to c$

$V_{cb} = 4, \times 10^{-2}$

$B \to \rho \ell \nu \quad \pi \ell \nu$ $\quad b \to u$

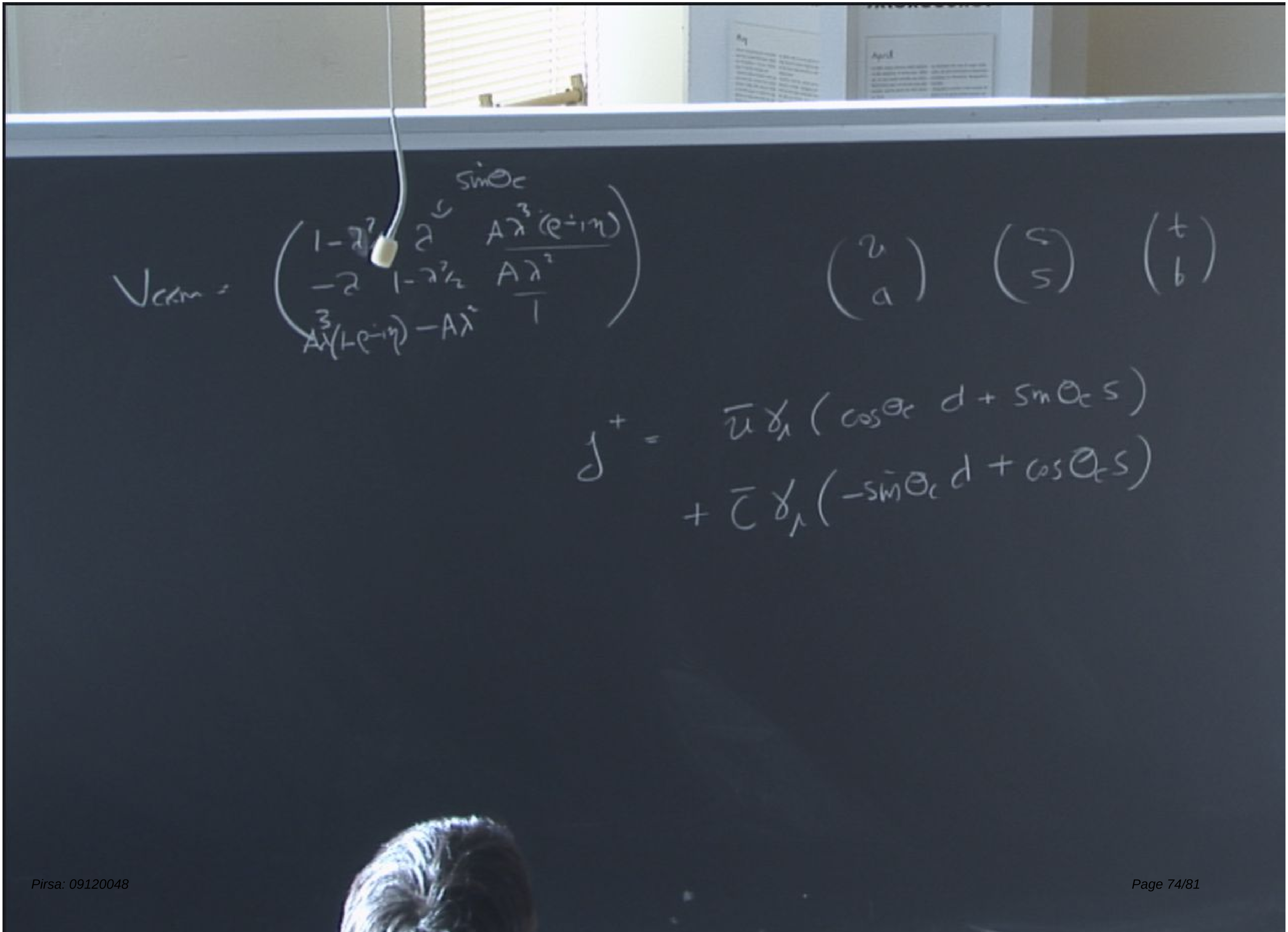
$V_{ub} - 4 \times 10^{-3}$



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

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{aligned} J^+ = {} & \bar{u}\gamma_\lambda(\cos\theta_c\, d + \sin\theta_c\, s) \\ & + \bar{c}\gamma_\lambda(-\sin\theta_c\, d + \cos\theta_c\, s) \end{aligned}$$



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

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

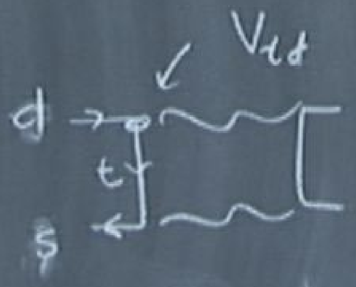
$$J^+ = \bar{u}\gamma_\lambda(\cos\theta_c\, d + \sin\theta_c\, s) + \bar{c}\gamma_\lambda(-\sin\theta_c\, d + \cos\theta_c\, s)$$

$B \to D \ell \nu$ $b \to c$

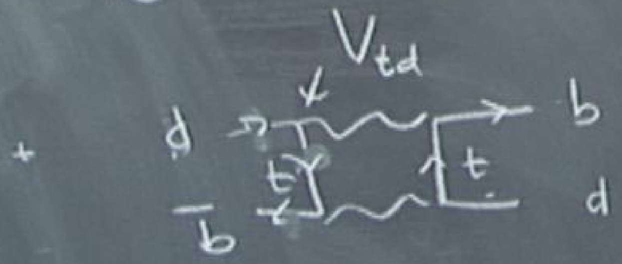
$V_{cb} = 4, \times 10^{-2}$

$B \to \rho \ell \nu \quad \pi \ell \nu$ $b \to u$

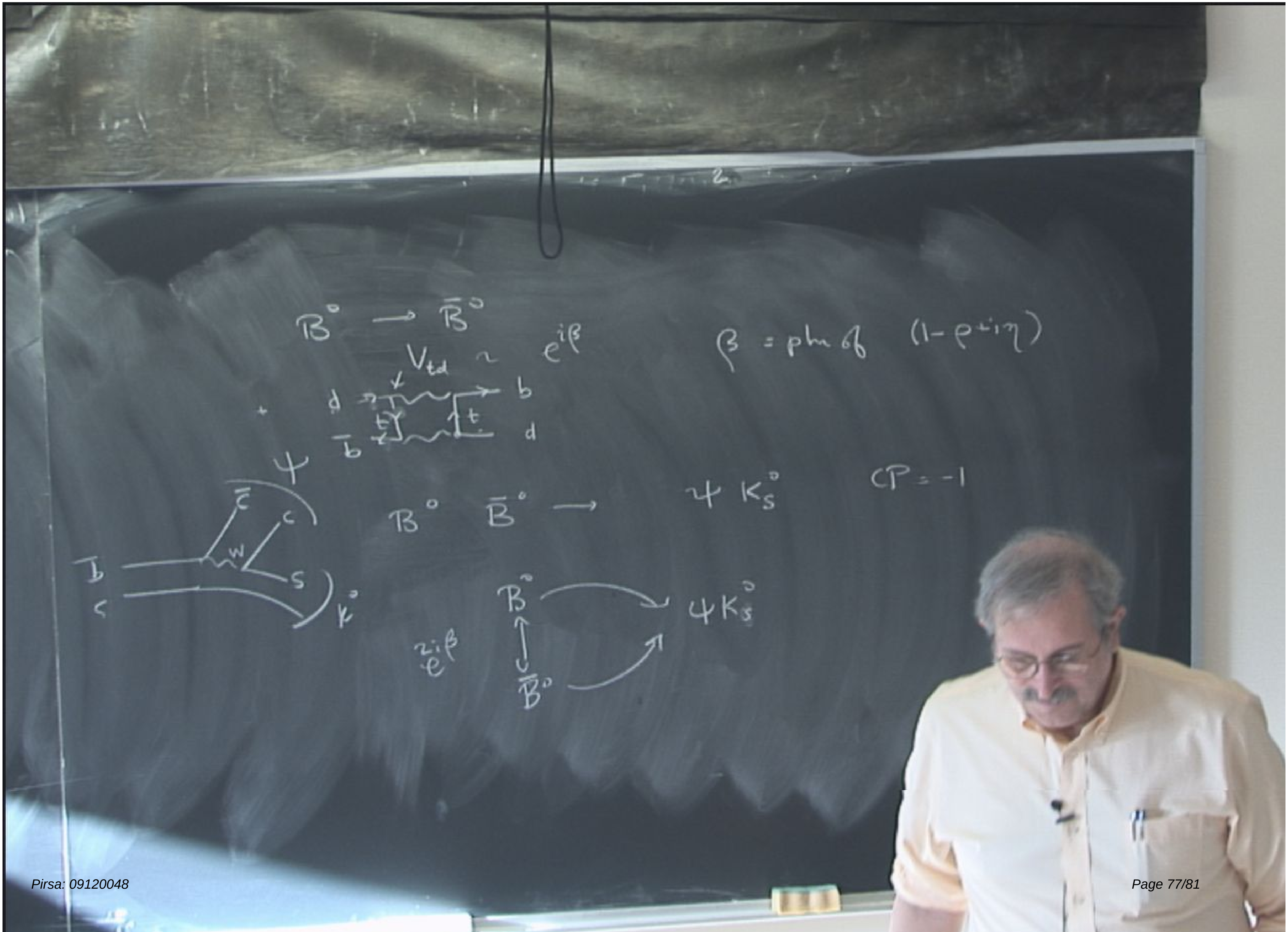
$V_{ub} - 4 \times 10^{-3}$



$$B^0 \longrightarrow \bar{B}^0$$

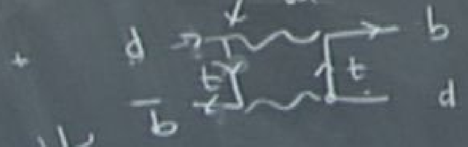


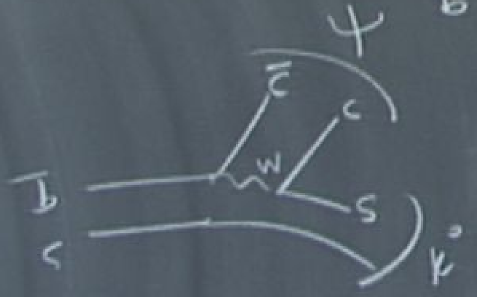
$$B^0 \quad \bar{B}^0 \longrightarrow \quad \psi K_S^0$$


B° → B̄°
V_td ~ e^iβ
β = phase of (1-ρ-iη)
d
b
t
t
b̄
d
ψ
c̄
c
W
b̄
s
s
K°
B° B̄° → ψ K_S°
CP = -1
B°
ψ K_S°
e^2iβ
B̄°

$B^0 \longrightarrow \bar{B}^0$

$V_{td} \sim e^{i\beta}$ $\qquad \beta = \text{phase of } (1-\rho-i\eta)$





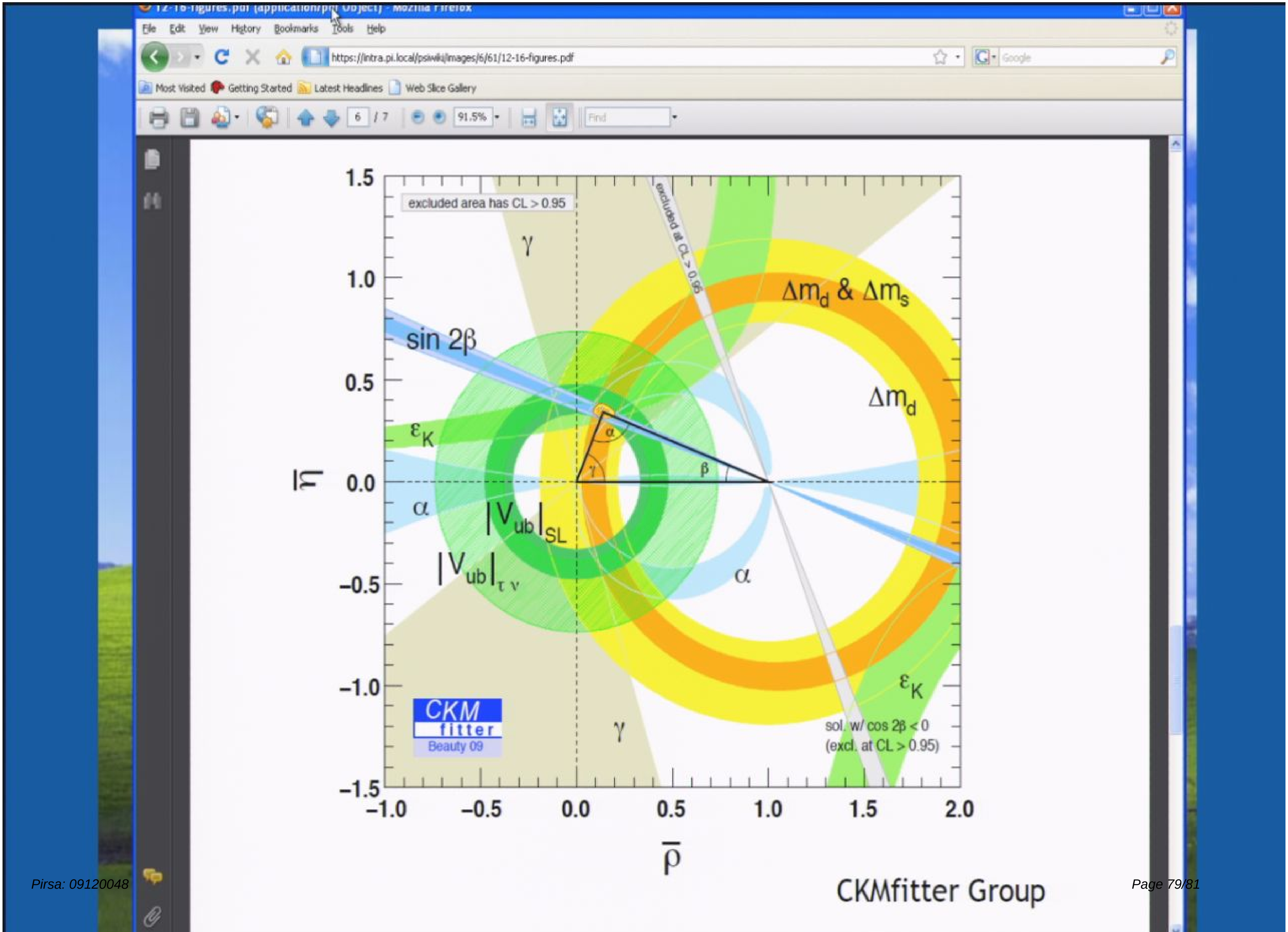
$B^0 \quad \bar{B}^0 \longrightarrow \quad \psi K_S^0 \qquad CP = -1$

$$\begin{tikzcd}
B^0 \arrow[r, bend left] \arrow[d, leftrightarrow, "e^{2i\beta}"'] & \psi K_s^0 \\
\bar{B}^0 \arrow[ur, bend right] &
\end{tikzcd}$$

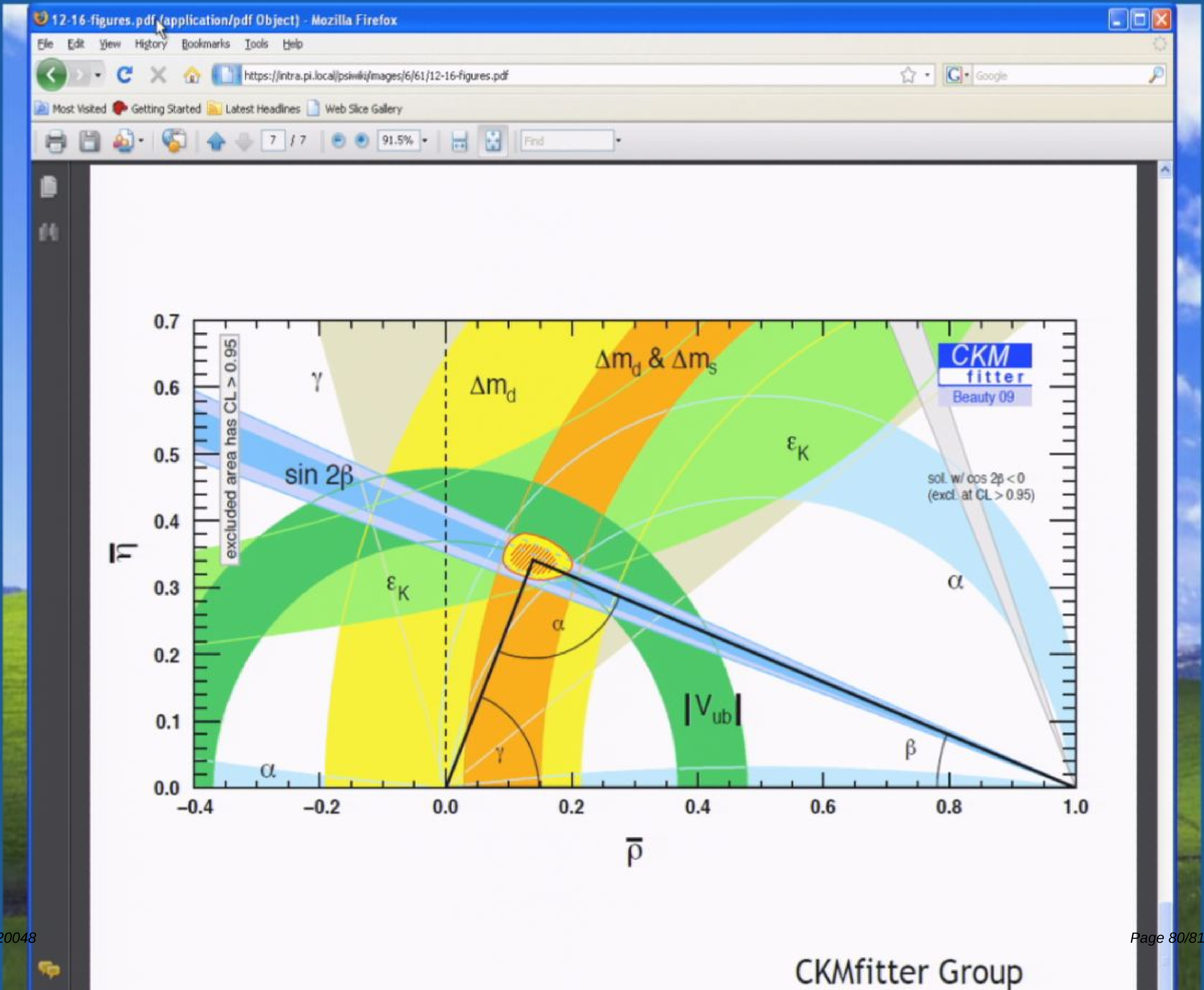
$\sin 2\beta = 0.686 \pm .023$

ee

DK



CKMfitter Group



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perimeter scholars

international