Title: Course 15 A

Date: Mar 21, 2007 11:00 AM

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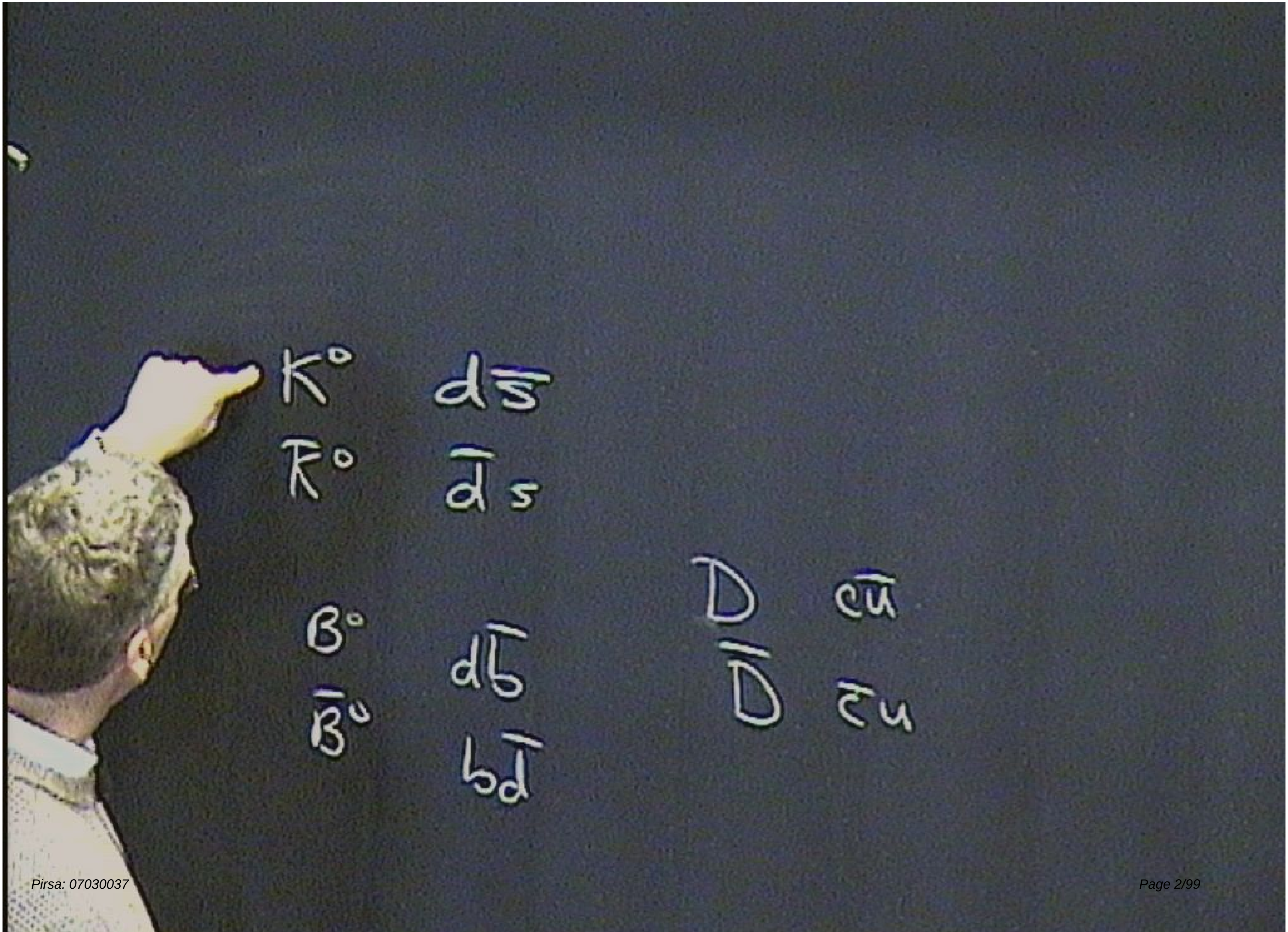
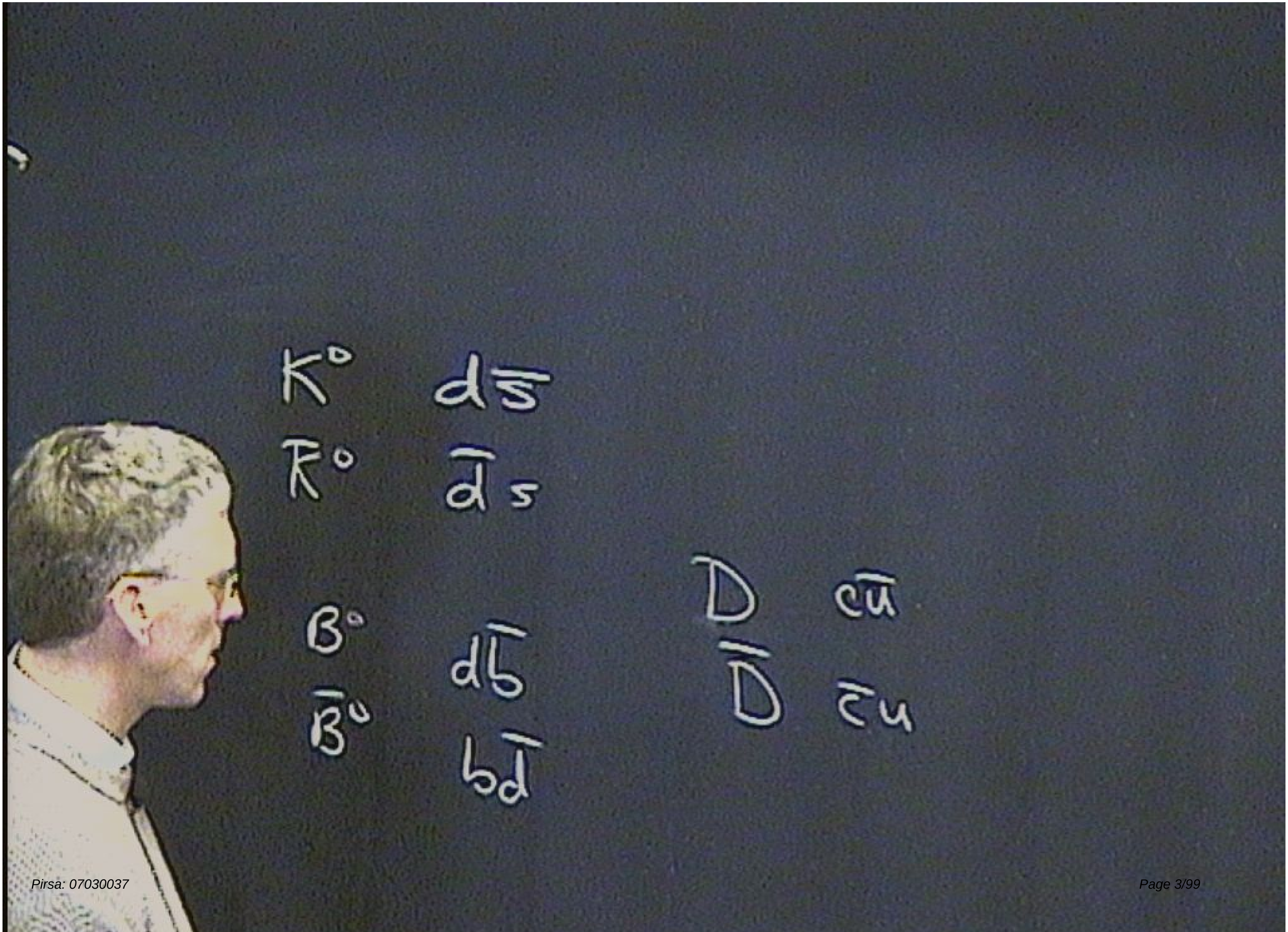
Abstract: Graduate Course on Standard Model & Quantum Field Theory


K^0 $d\bar{s}$
$\bar{K}^0$ $\bar{d}s$
B^0 $d\bar{b}$
$\bar{B}^0$ $b\bar{d}$
D $c\bar{u}$
$\bar{D}$ $\bar{c}u$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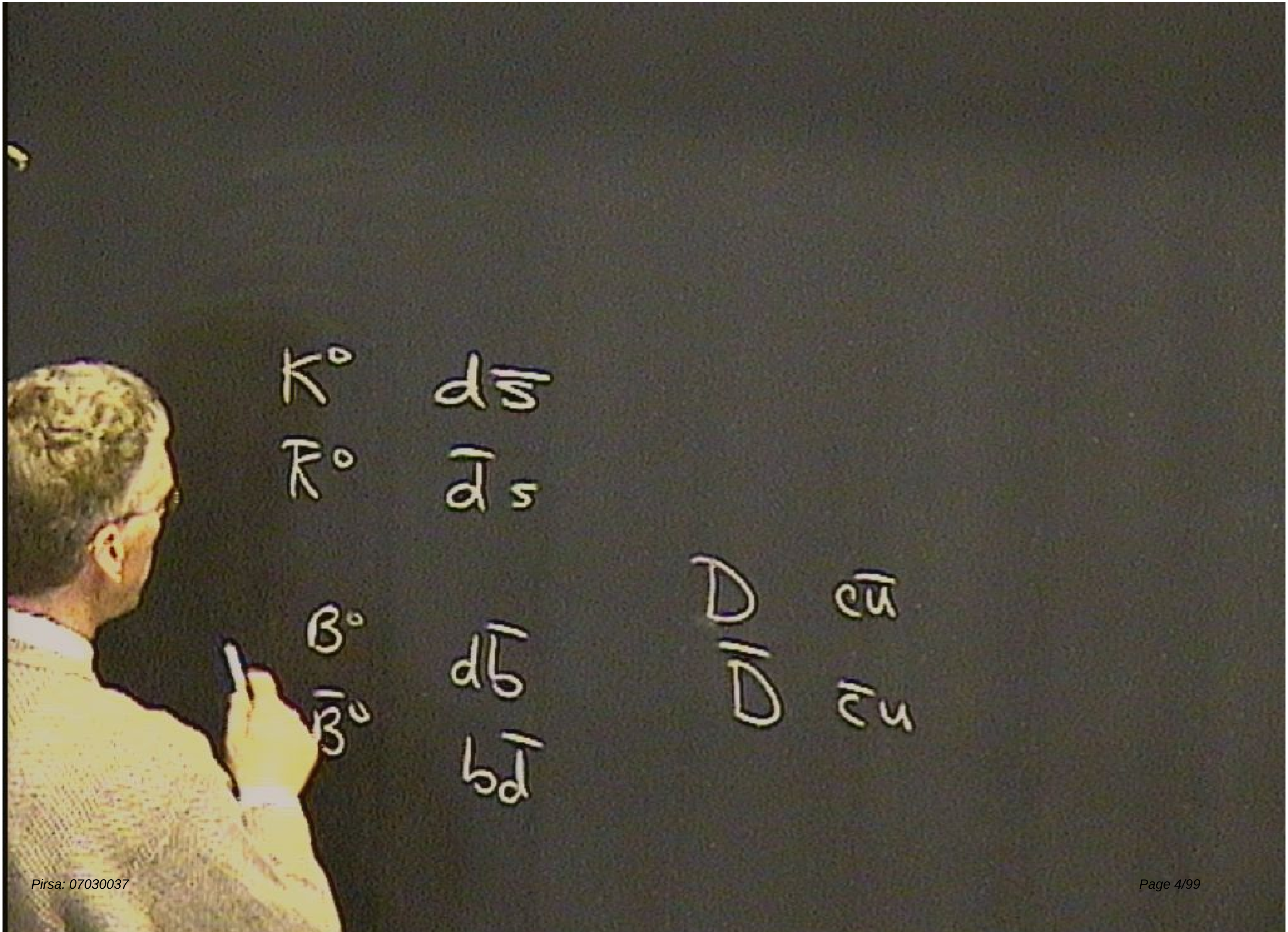
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$K^0 \quad d\bar{s}$

$\bar{K}^0 \quad \bar{d}s$

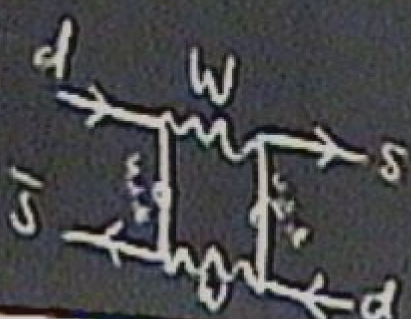
$B^0 \quad d\bar{b}$

$\bar{B}^0 \quad b\bar{d}$

$D \quad c\bar{u}$

$\bar{D} \quad \bar{c}u$

$K \to \bar{K}$



$\propto m_t^2$

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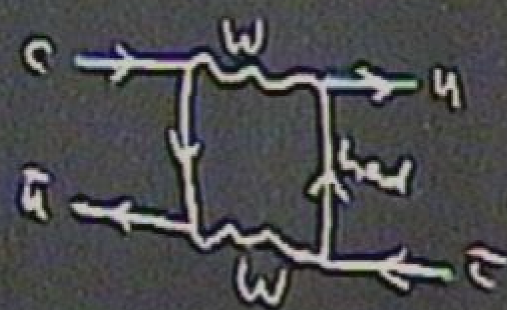
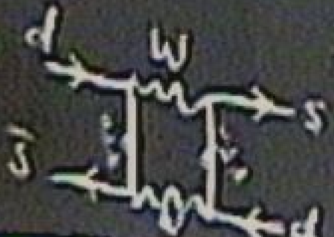
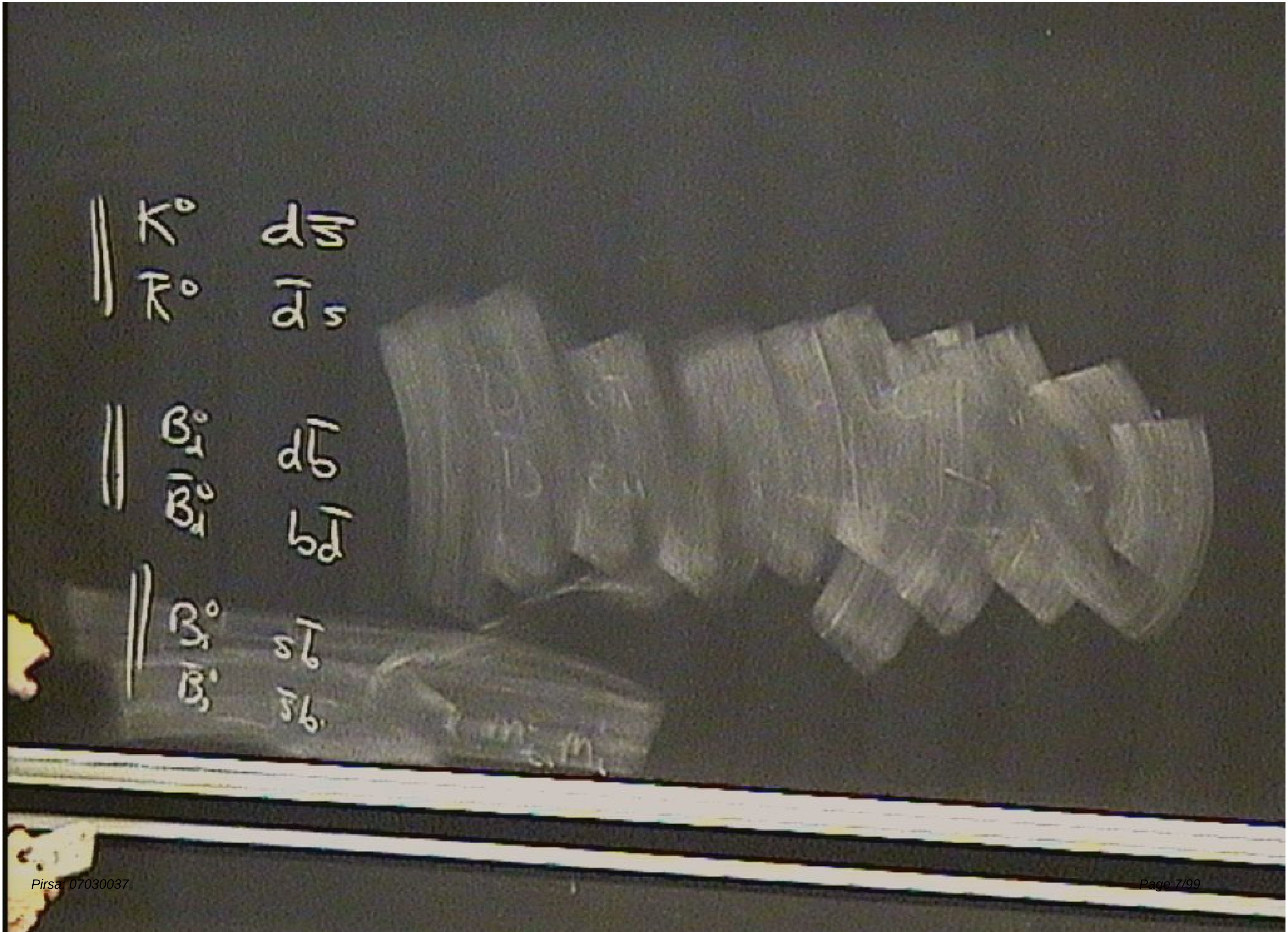


$\simeq m_b^2$

$K \to \bar{K}$



$\propto m_t^2, m_c^2$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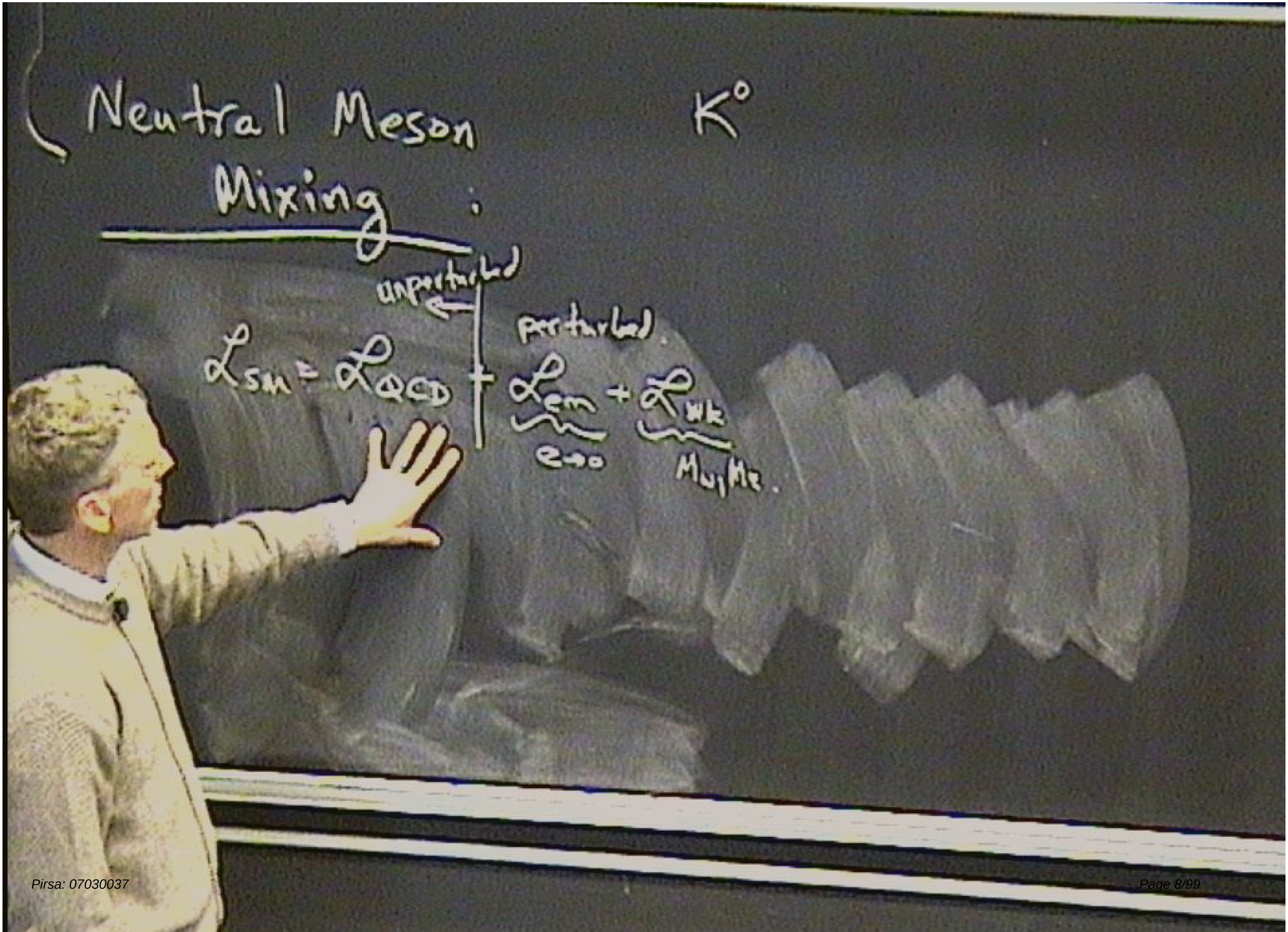
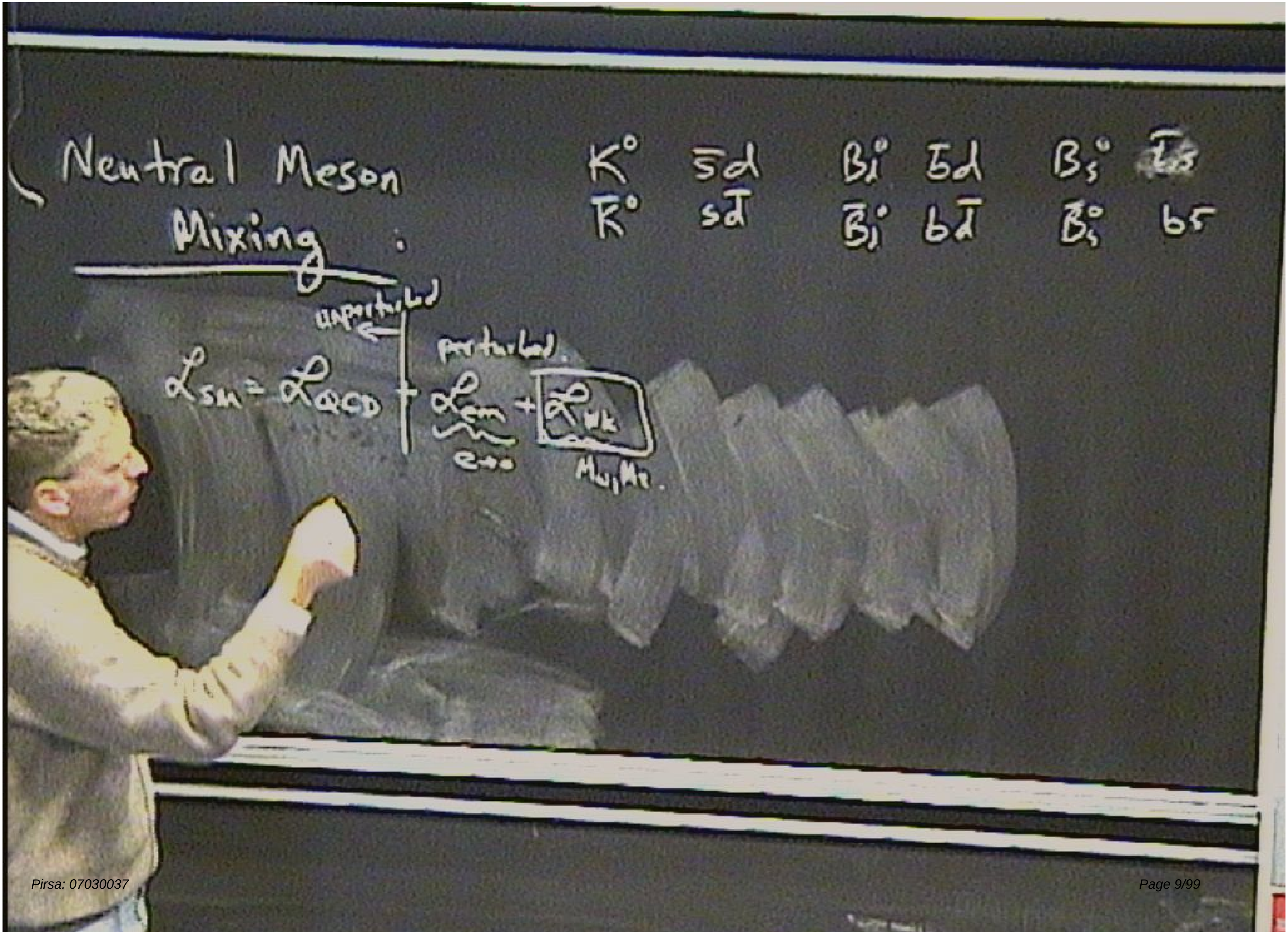
$\bar{K}^0$ $\bar{d}s$
B_d^0 $d\bar{b}$
$\bar{B}_d^0$ $b\bar{d}$
B_s^0 $s\bar{b}$
$\bar{B}_s^0$ $\bar{s}b$


Neutral Meson Mixing :
K°
unperturbed
perturbed
L_SM = L_QCD + L_em + L_wk
e→0
M_W, M_Z.


Neutral Meson Mixing :
K° s̄d
K̄° sd̄
B°d b̄d
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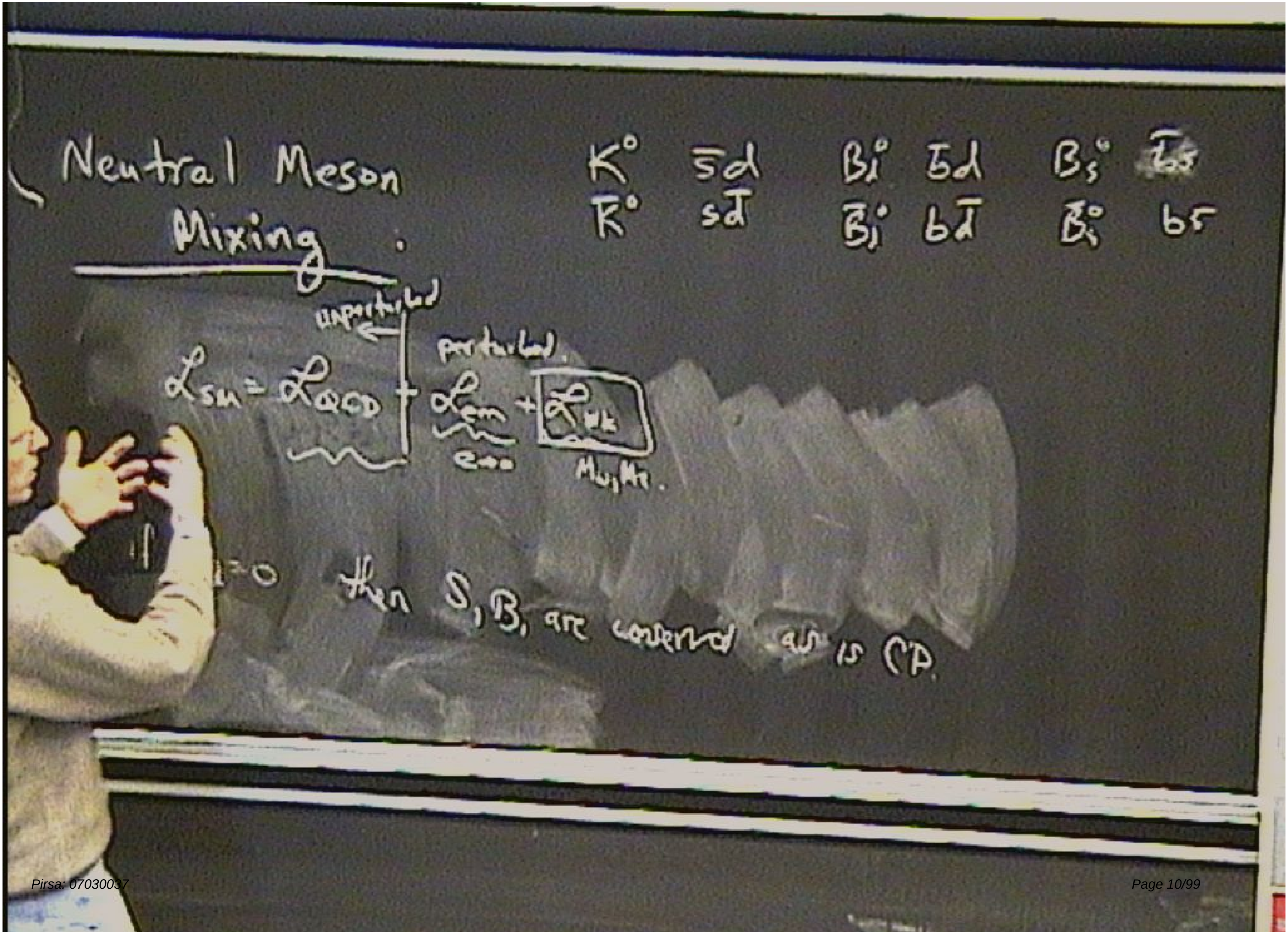
Neutral Meson Mixing :
K° s̄d B°d b̄d B°s b̄s
K̄° sd̄ B̄°d bd̄ B̄°s bs̄
unperturbed
perturbed.
LSM = LQCD + Lem + Lwk
e→0
MW, MZ.
then S, B, are conserved as is CP.

Neutral M[illegible]

Mixing

$\bar{B}_d^0$ $b\bar{d}$ $\bar{B}_s^0$ $b\bar{s}$

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}_{QCD}}_{\text{unperturbed}} + \underbrace{\mathcal{L}_{em}}_{e\to 0} + \boxed{\mathcal{L}_{wk}}_{M_W, M_Z}$$

perturbed

if $\mathcal{L}_{wk} = 0$ then S, B, are conserved as is CP

but when $\mathcal{L}_{wk} \neq 0$ it allows the K, B to decay, and it allows mixing

between fla[illegible]

But when $\Delta m \neq 0$ it allows the $\nu_i \beta$ to decay, <u>and</u> it allows <u>mixing</u>

between flavour + propagation eigenstates.

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To describe the mixing: use an effective field theory describing weakly interacting mesons:

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ϕ : complex scalar field.

$(\bar{a}_p \neq a_p)$

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* ϕ : complex scalar field.

α_p

if $\alpha_{uk} \neq 0$ $K \to \bar{K}$ is possible, But when $\alpha_{wk} \neq 0$ it allows the K, B to decay, and it allows mixing

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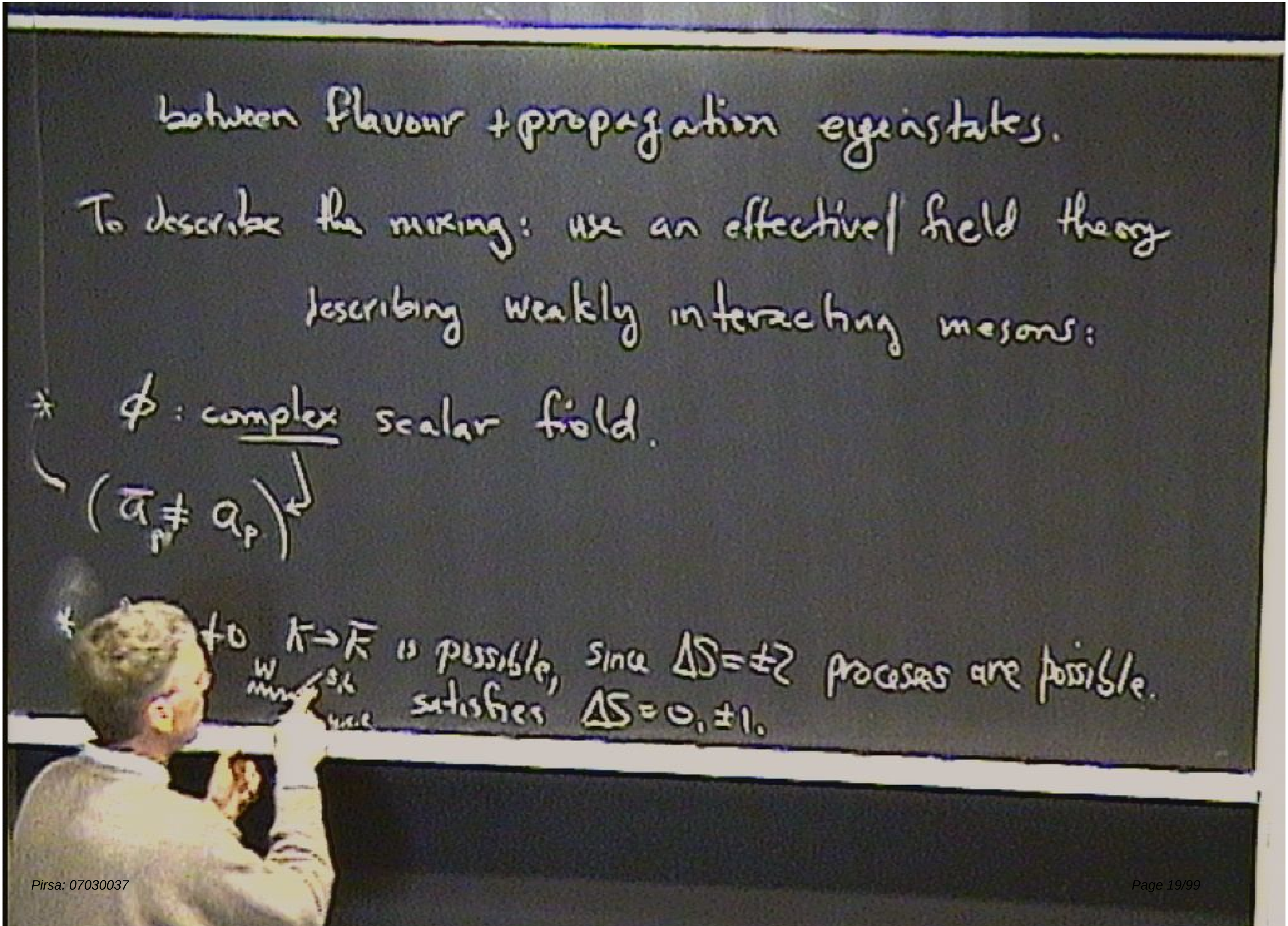
if $\alpha_{wk} \neq 0$ $K \to \bar{K}$ is possible, since $\Delta S = \pm 2$ processes are possible.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To describe the mixing: use an effective field theory
describing weakly interacting mesons:
* φ : complex scalar field.
(ā_p ≠ a_p)
* ≠0 K → K̄ is possible, since ΔS = ±2 processes are possible.
W s.i. w.i. satisfies ΔS = 0, ±1.

between flavour + propagation eigenstates.

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  $W \langle^{s,d}_{u,c}$ satisfies $\Delta S = 0, \pm 1$.

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But W satisfies $\Delta S = 0, \pm 1$. $\Rightarrow$ work to 2nd order in $\mathcal{L}_{int}$.

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$$m \to m - i\Gamma/2$$

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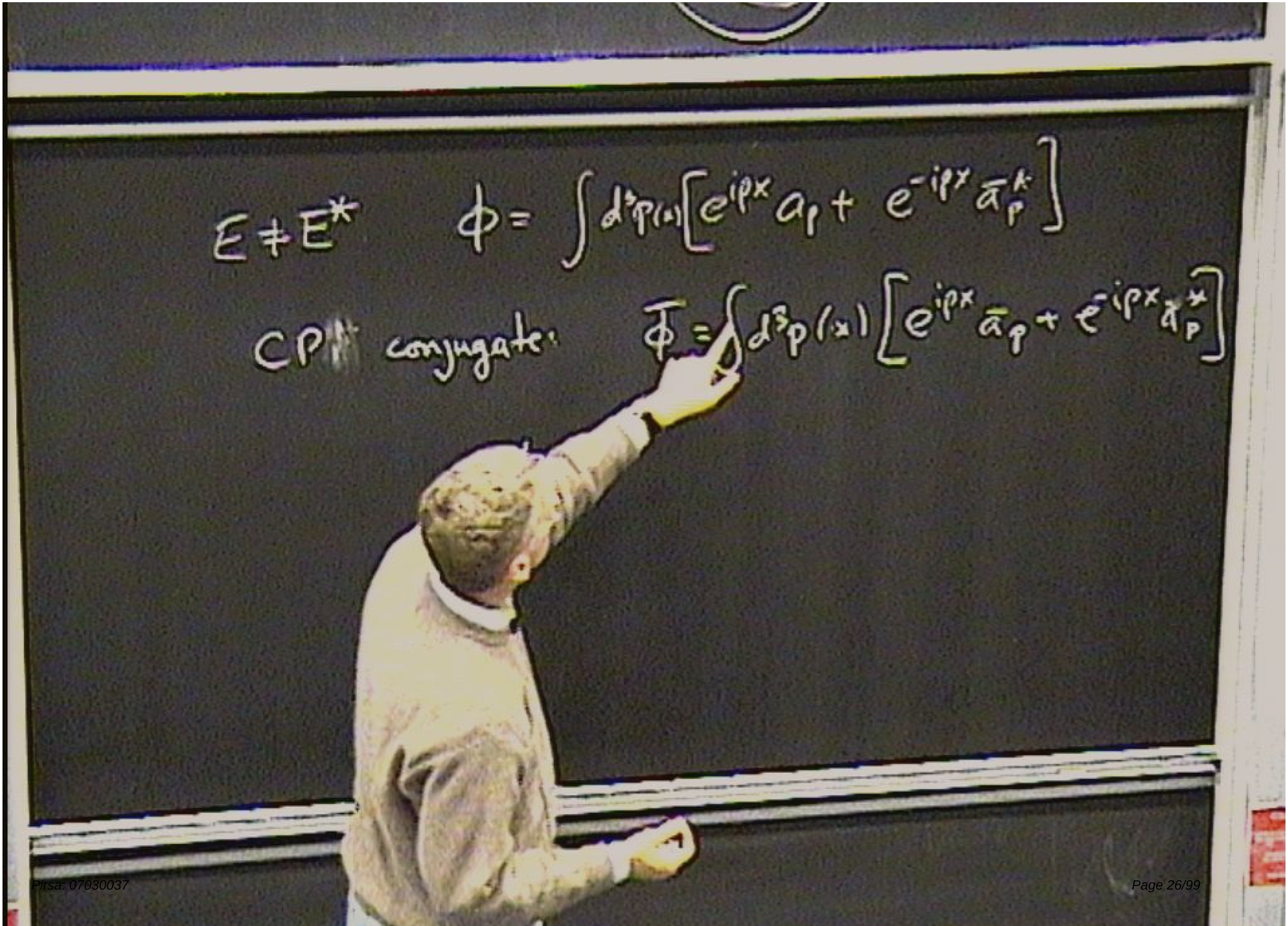
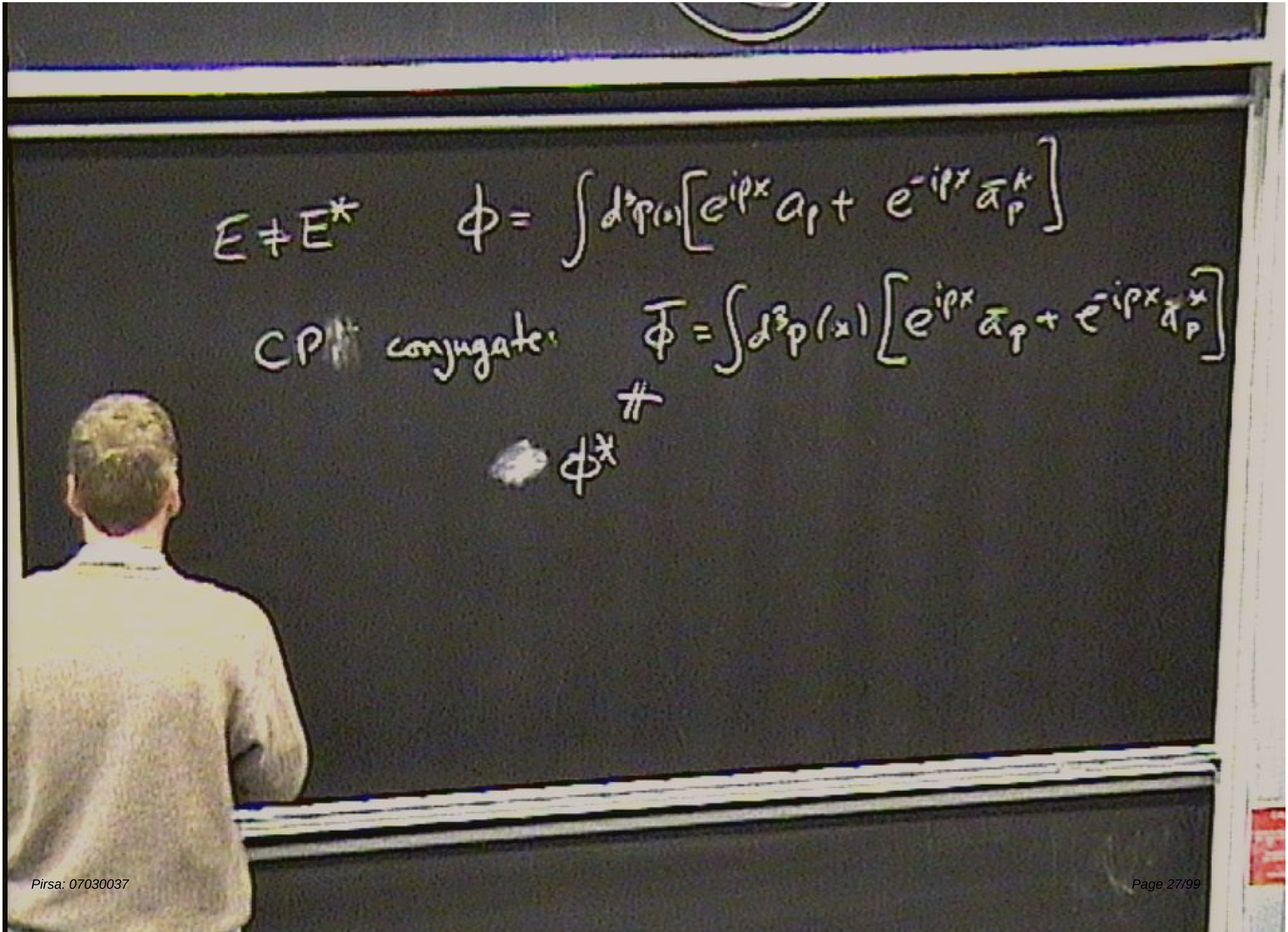
⇒ Must track the loss of probability due to decays.

$$m \to m - i\Gamma/2$$

$$E(p) = \sqrt{p^2+m^2} \to \sqrt{p^2+m^2} - \frac{i\Gamma m}{2\sqrt{p^2+m^2}} \qquad -\frac{i\Gamma(p)}{2}$$


E ≠ E*
ϕ = ∫d³p (x) [e^{ipx} a_p + e^{-ipx} ā_p^*]
CP conjugate:
ϕ̄ = ∫d³p (x) [e^{ipx} ā_p + e^{-ipx} a_p^*]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#
φ*

$E \neq E^*$ $\quad \phi = \int d^3p\,(x)\left[e^{ipx} a_p + e^{-ipx} \bar{a}_p^*\right]$

CP conjugate: $\quad \bar{\Phi} = \int d^3p\,(x)\left[e^{ipx} \bar{a}_p + e^{-ipx} a_p^*\right]$

$\neq$

ϕ^*

The general quadratic lagrangian describing the propagation of ϕ particles:

$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \bar{\Phi} - A \phi \bar{\Phi} - \tfrac{1}{2}\left(B \phi^2 + C \bar{\phi}^2\right)$$

Special cases: ① Charge conservation: $\phi \to e^{i\alpha}\phi$ is symmetry

$\bar{\phi} \to e^{-i\alpha}\bar{\phi}$

$\longrightarrow B = C = 0.$

②

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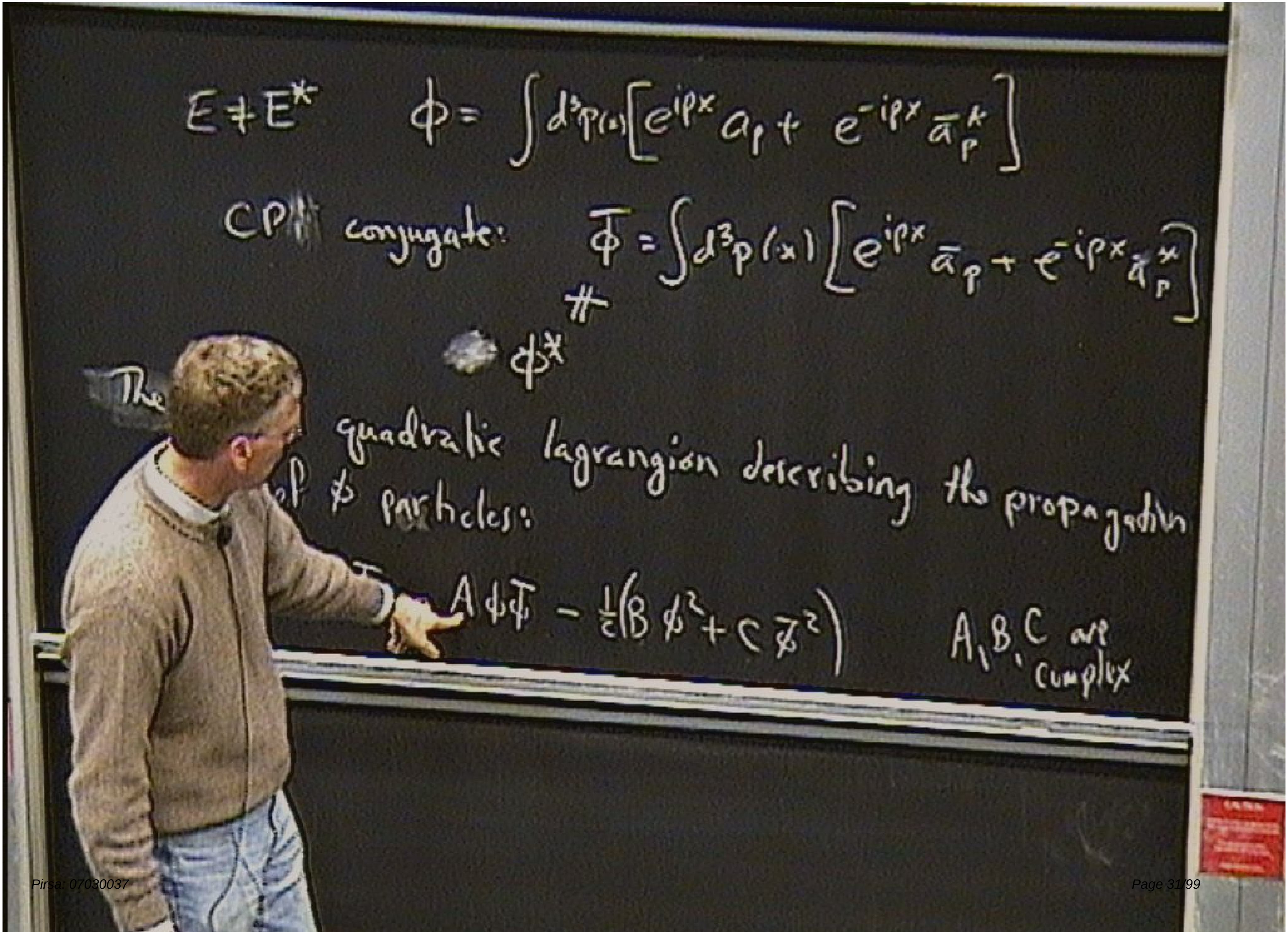
② CP conservation: Sym: $\phi \leftrightarrow \bar{\Phi}$: $B = C$

③ Unitary evolution: $\bar{\Phi} = \phi^*$ $\mathcal{L} = \mathcal{L}^*$: $A = A^*$, $B = C^*$.


$E \neq E^*$ $\phi = \int d^3p\,(\alpha)\left[e^{ipx} a_p + e^{-ipx} \bar{a}_p^*\right]$
CP conjugate: $\bar{\Phi} = \int d^3p\,(\alpha)\left[e^{ipx} \bar{a}_p + e^{-ipx} a_p^*\right]$
$\neq \phi^*$
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$A\,\phi\bar{\Phi} - \frac{1}{2}(B\,\phi^2 + C\,\bar{\phi}^2)$
A, B, C are complex

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Special cases: (1) Charge [illegible] ϕ is symmetry;

$\bar{\Phi} \to e^{-i\alpha} \bar{\Phi}$

$\longrightarrow B = C = 0$.

(2) CP conservation: Sym: $\phi \leftrightarrow \bar{\Phi}$: $B = C$

(3) Unitary evolution: $\bar{\Phi} = \phi^*$ $\mathcal{L} = \mathcal{L}^*$: $A = A^*$
$B = C^*$.

All 3 are true for $\mathcal{L}_{int} = 0$, i.e. $B = C = 0$, $A = m_b^2 = A^*$

$E \neq E^*$ $\quad \phi = \int d^3p\,(\ast)\left[e^{ipx} a_p + e^{-ipx} \bar{a}_p^*\right]$

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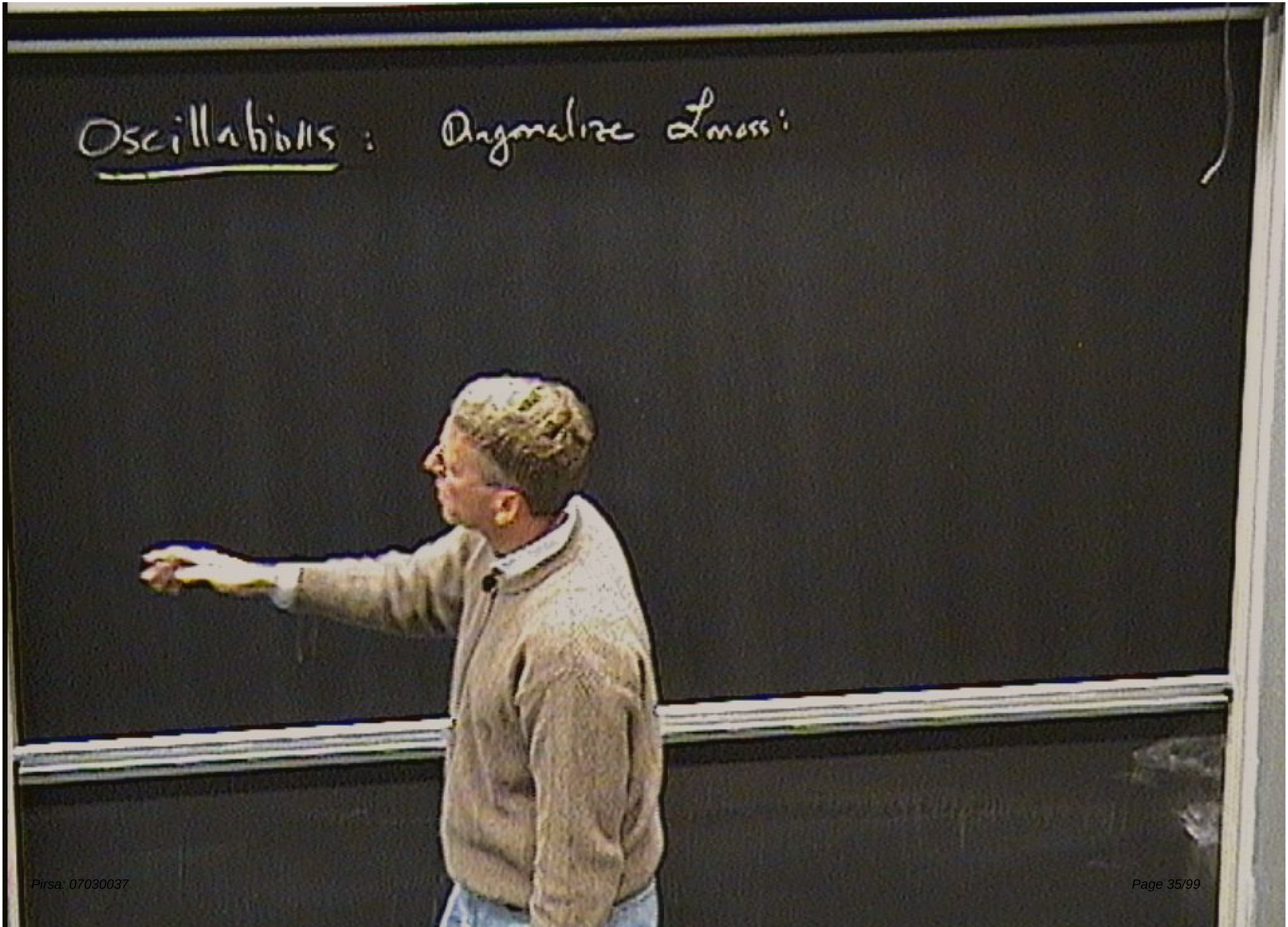
Oscillations : Diagonalize ℒmass :

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the propagation eigenstates become:

$$\psi_+ = \frac{\psi + \bar{\Psi}}{\sqrt{2}} \qquad \psi_- = \frac{i}{\sqrt{2}}\left(\psi - \bar{\Psi}\right)$$

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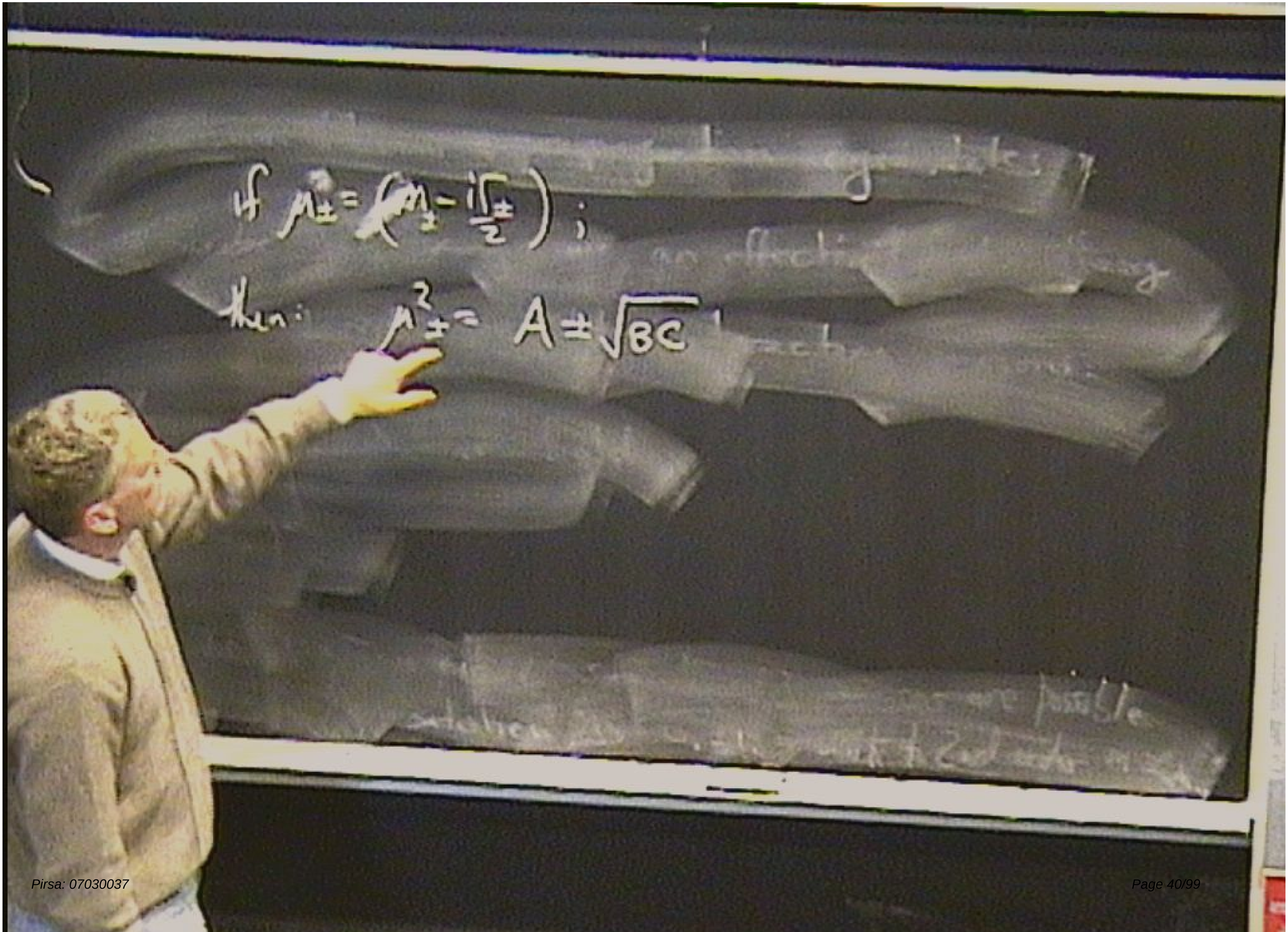
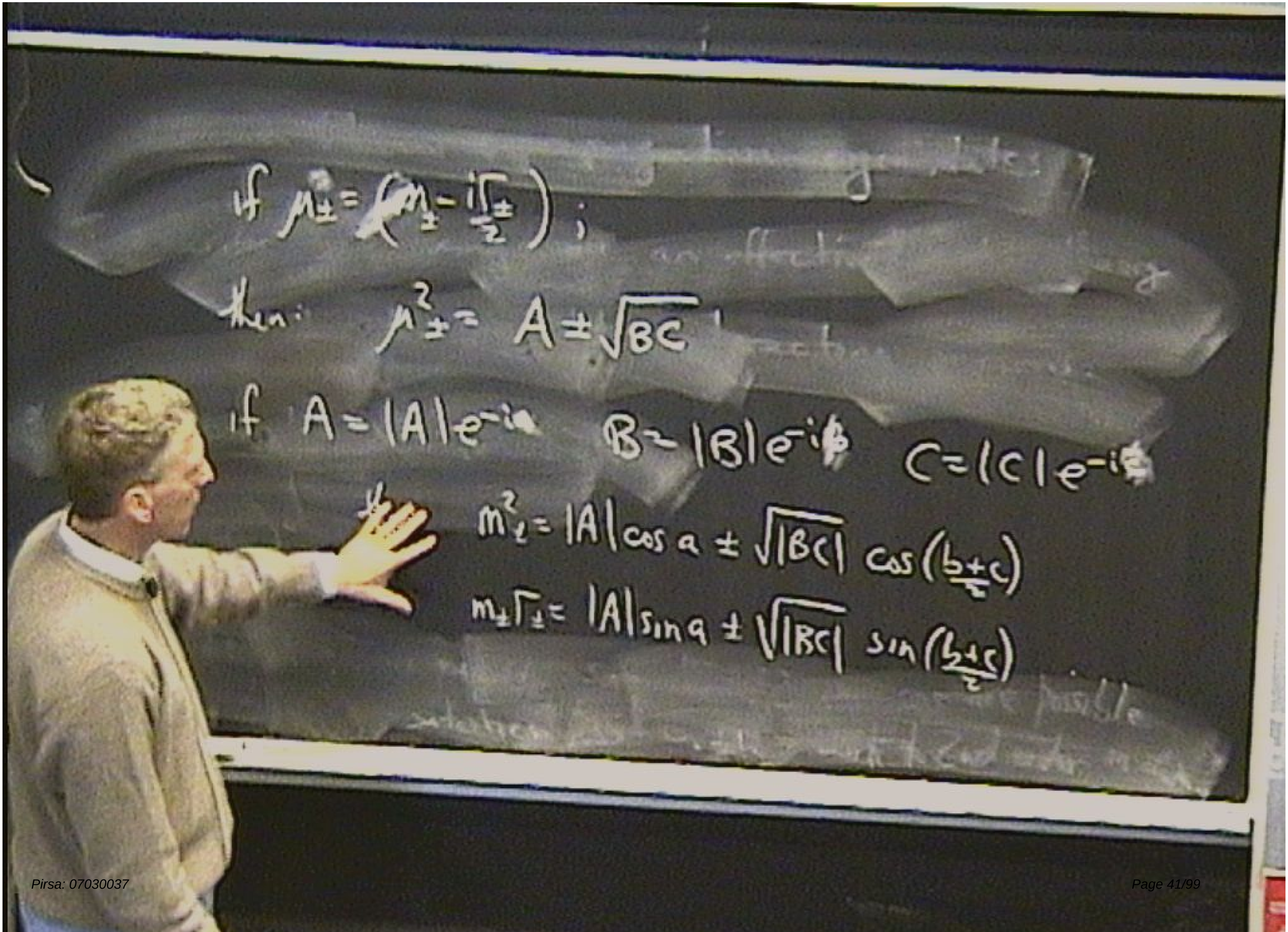
if $|\psi_\pm\rangle$ is the state destroyed by $a_p^\pm$ where $\psi_\pm = \int d^3p\,(\ldots)\left[e^{ipx} a_p^\pm + \ldots\right]$

then $|\psi_\pm(t)\rangle = e^{-iE_\pm(p)t}\,|\psi_\pm(t)\rangle$ $\quad E_\pm = \sqrt{p^2 + m_\pm^2} - \frac{i\Gamma_\pm m_\pm}{\sqrt{p^2+m_\pm^2}} + O(\Gamma^2)$


if μ± = (m± − iΓ±/2) ;
then: μ±² = A ± √BC


if $\mu_\pm = (m_\pm - \frac{i\Gamma_\pm}{2})$;
then: $\mu_\pm^2 = A \pm \sqrt{BC}$
if $A = |A|e^{-ia}$ $B = |B|e^{-ib}$ $C = |C|e^{-ic}$
$m_\pm^2 = |A|\cos a \pm \sqrt{|BC|}\cos(\frac{b+c}{2})$
$m_\pm\Gamma_\pm = |A|\sin a \pm \sqrt{|BC|}\sin(\frac{b+c}{2})$

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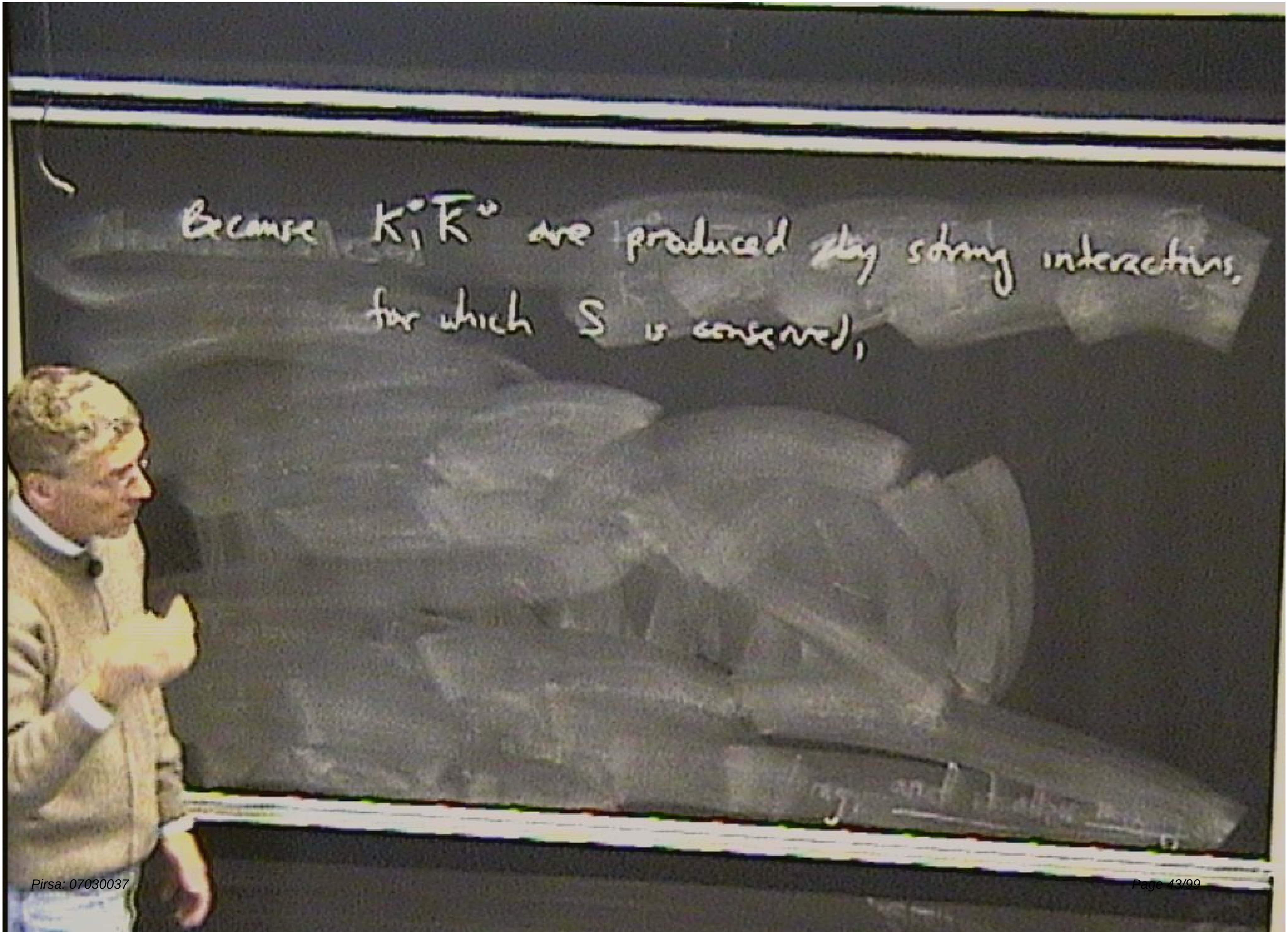
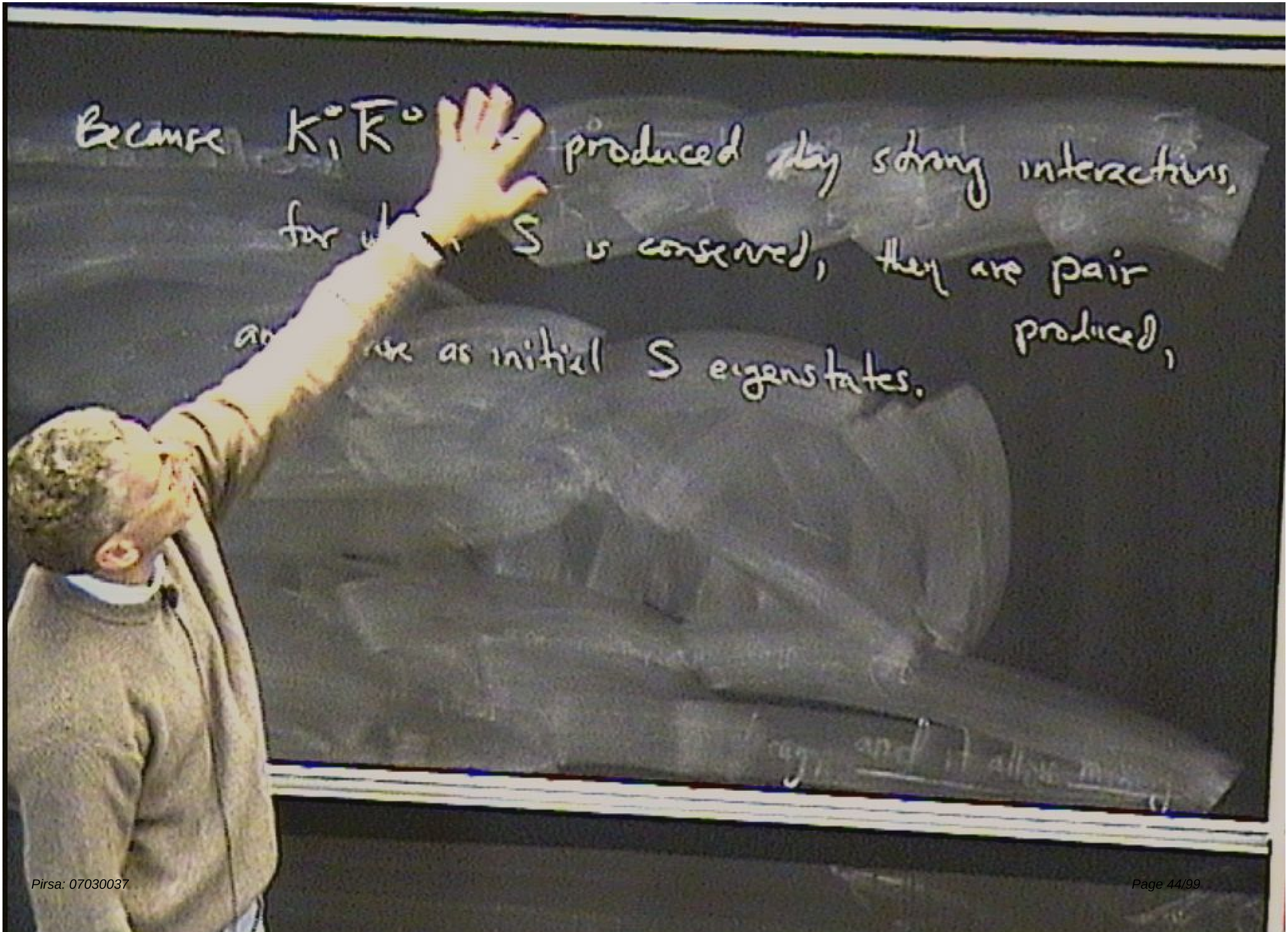
then $m_\pm^2 = |A| \cos a \pm \sqrt{|BC|} \cos\left(\frac{b+c}{2}\right)$

$m_\pm \Gamma_\pm = |A| \sin a \pm \sqrt{|BC|} \sin\left(\frac{b+c}{2}\right)$


Because K°, K̄° are produced by strong interactions,
for which S is conserved,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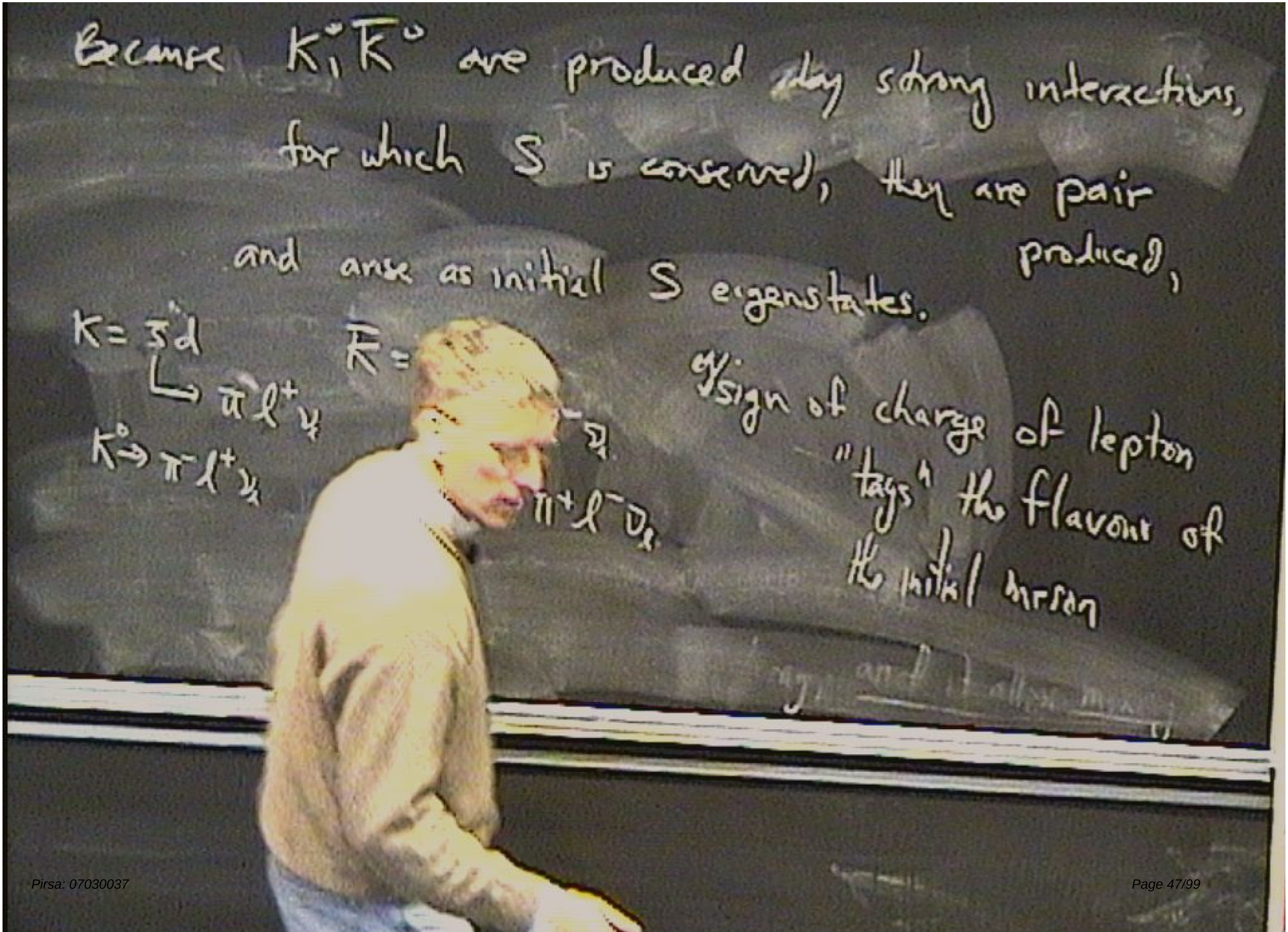
$K = \bar{s}d$

$\hookrightarrow \pi l^+$

$\bar{K} = s\bar{d}$

$\hookrightarrow u l^- \bar{\nu}$


Because K, K̄° are produced by strong interactions,
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K = s̄d
→ π l⁺ ν
K° → π⁻ l⁺ ν
K̄ =
π⁺ l⁻ ν̄
sign of charge of lepton
"tags" the flavour of
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Because $K, \bar{K}^0$ are produced by strong interactions, for which S is conserved, they are pair produced, and arise as initial S eigenstates.

$K = \bar{s}d$

$\hookrightarrow \bar{u}\, l^+ \nu_l$

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

$\bar{K} = s\bar{d}$

$\hookrightarrow u\, l^- \bar{\nu}_l$

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

∴ sign of charge of lepton "tags" the flavour of the initial meson

Can ask experimentally $|\langle\phi(t)|\phi(0)\rangle|^2 = P_t(\phi\to\phi)$

or $|\langle\bar{\Phi}(t)|\phi(0)\rangle|^2 = P_t(\phi\to\bar{\Phi})$

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Notation conventions.

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Notation conventions.

$$|\psi_+\rangle = \frac{p|\phi\rangle + q|\bar{\phi}\rangle}{\sqrt{|p|^2+|q|^2}} \qquad |\psi_-\rangle = \frac{i\left(p|\bar{\phi}\rangle - q|\phi\rangle\right)}{\sqrt{|p|^2+|q|^2}}$$

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Notation conventions

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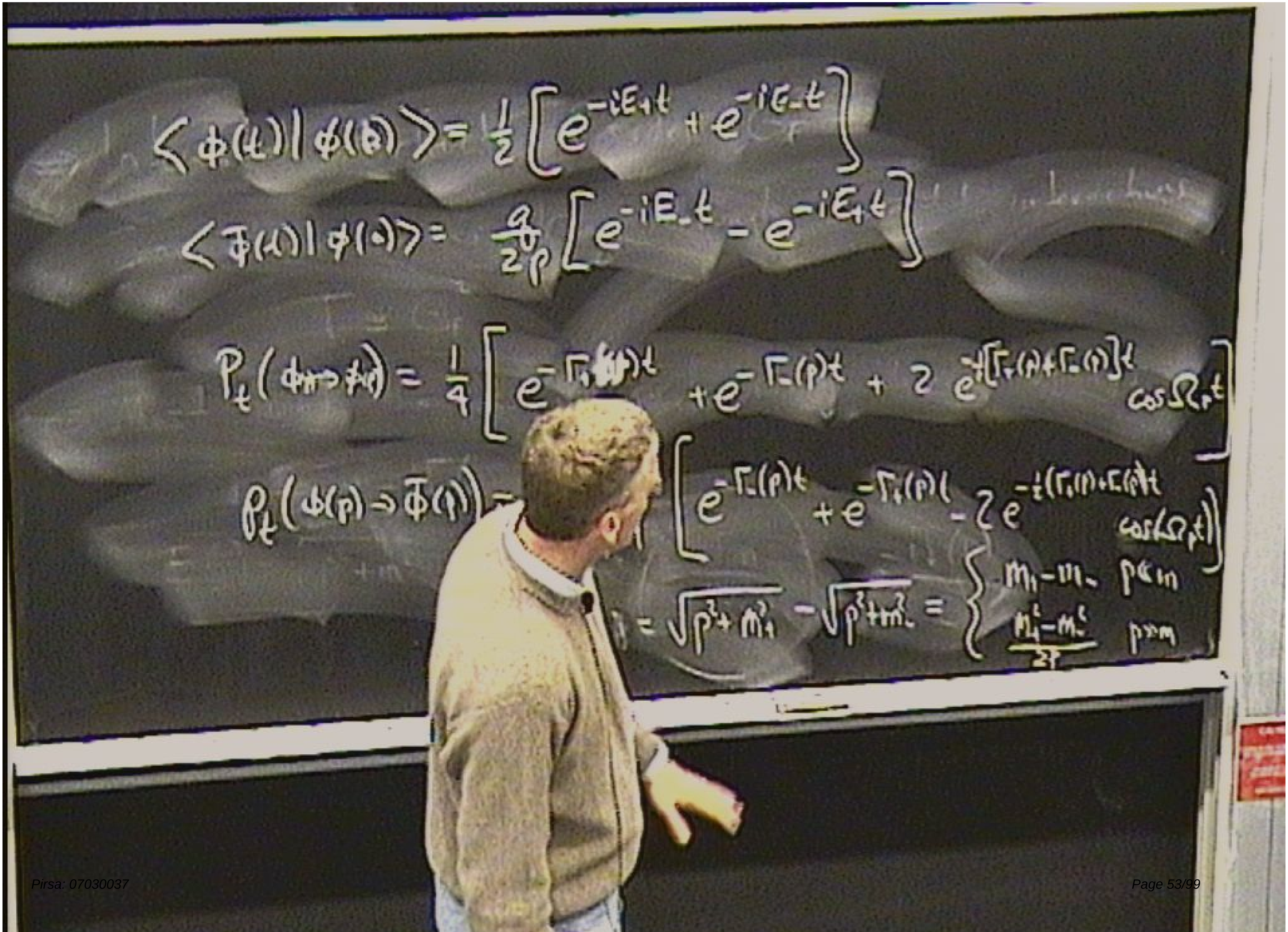
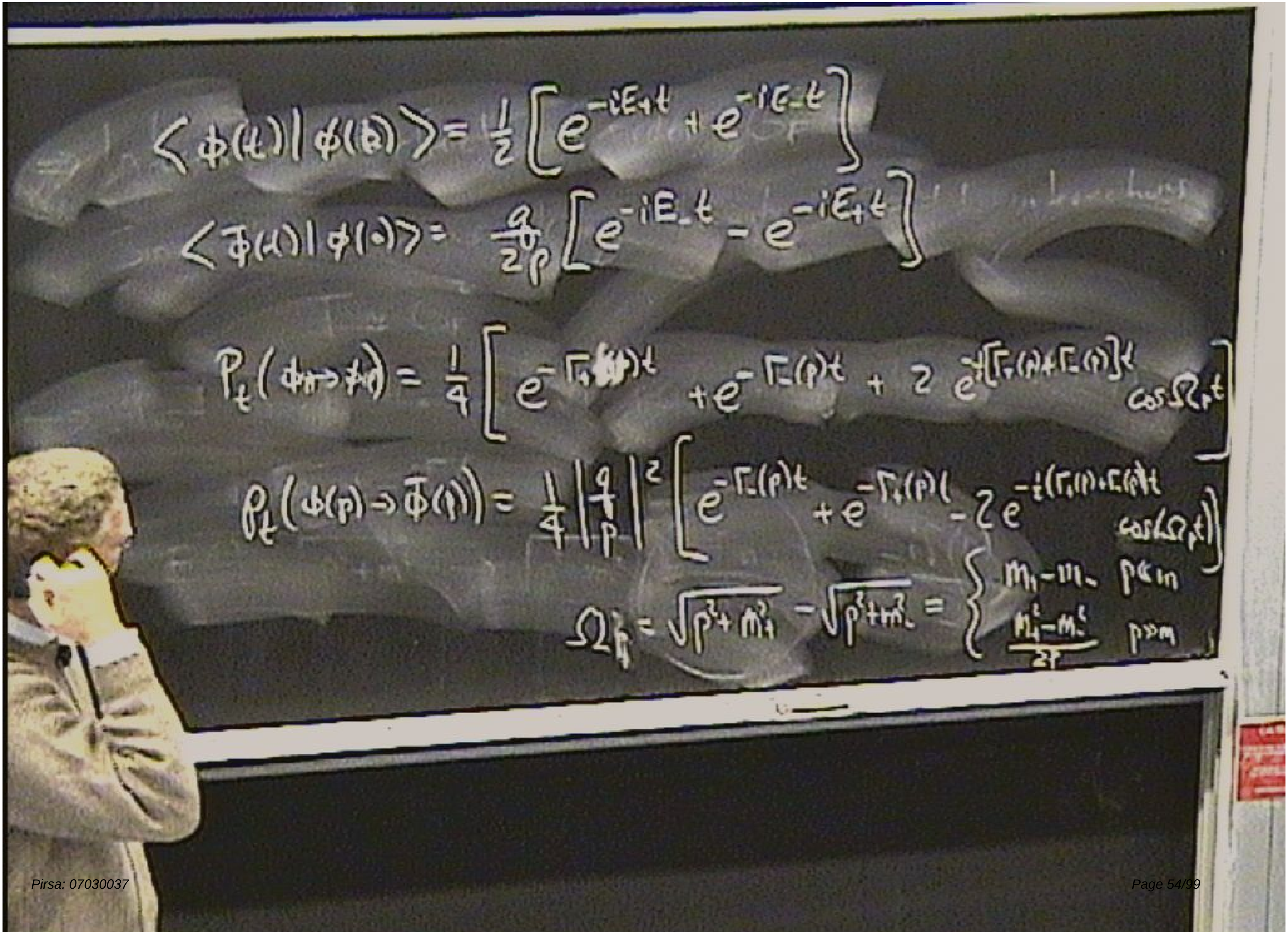
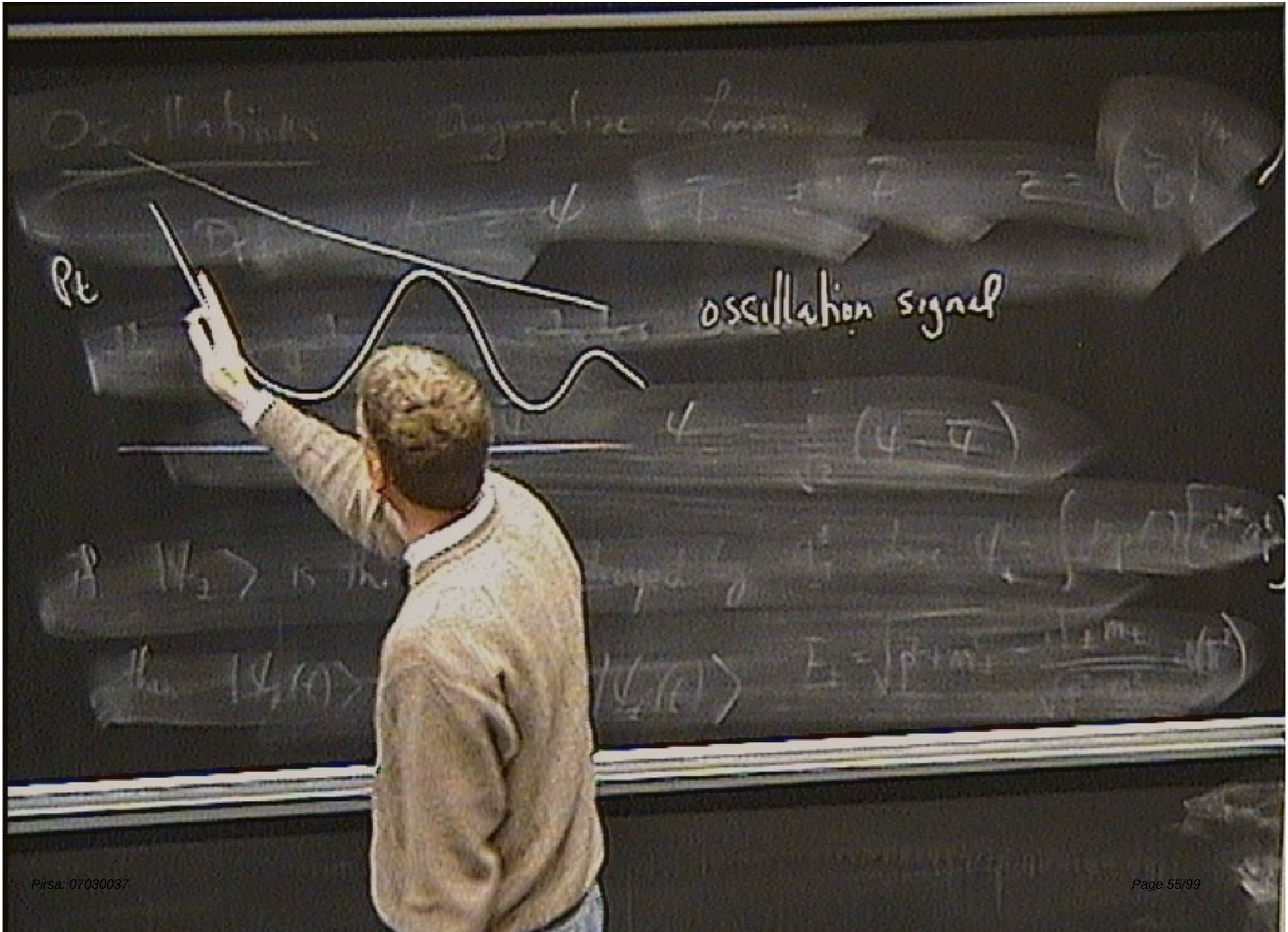
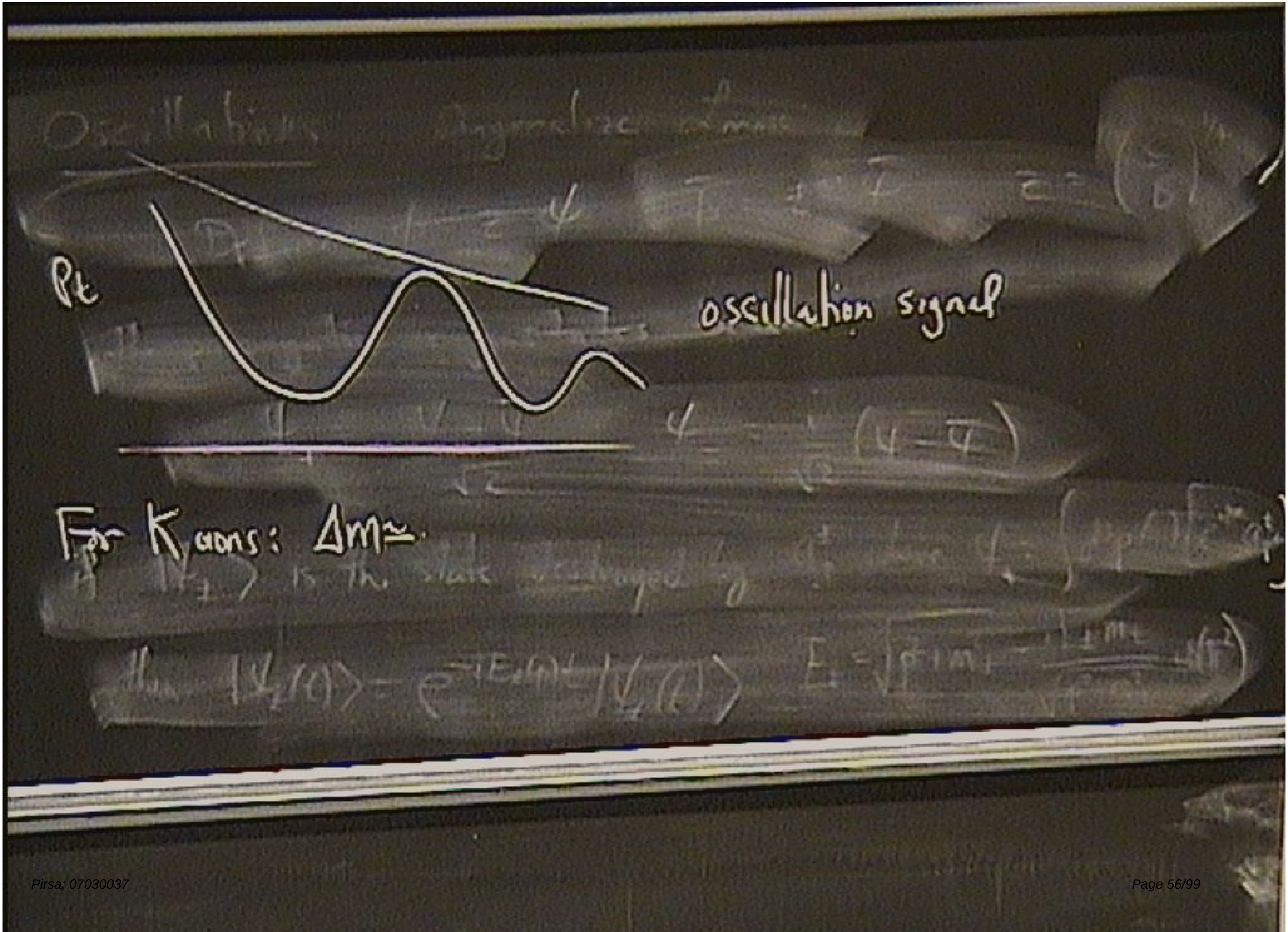
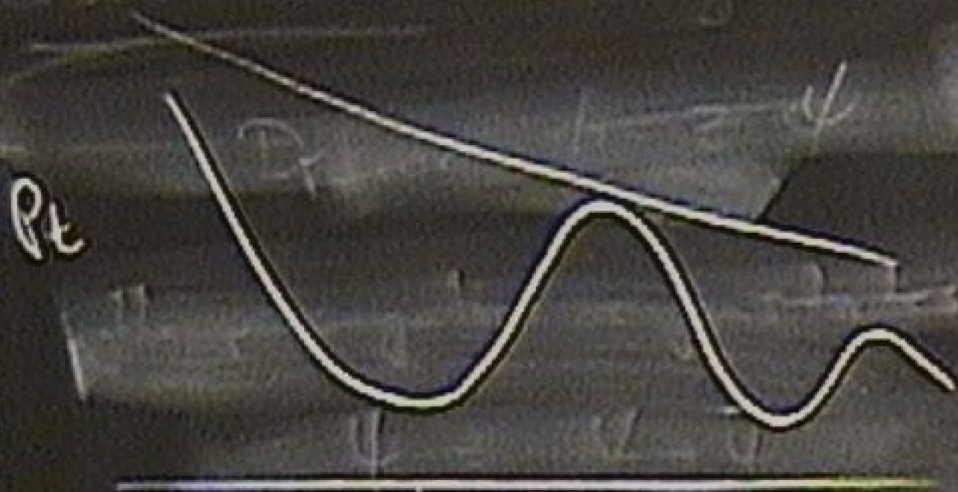
$$\Longrightarrow p/q = z^2 = \left(\frac{C}{B}\right)^{1/2}$$


$\langle \phi(t) | \phi(0) \rangle = \frac{1}{2}\left[e^{-iE_+ t} + e^{-iE_- t}\right]$
$\langle \bar{\Phi}(t) | \phi(0) \rangle = \frac{q}{2p}\left[e^{-iE_- t} - e^{-iE_+ t}\right]$
$P_t(\phi(p) \to \phi(p)) = \frac{1}{4}\left[e^{-\Gamma_+(p)t} + e^{-\Gamma_-(p)t} + 2\, e^{-\frac{1}{2}[\Gamma_+(p)+\Gamma_-(p)]t} \cos\Omega_p t\right]$
$P_t(\phi(p) \to \bar{\Phi}(p))$
$\left[e^{-\Gamma_-(p)t} + e^{-\Gamma_+(p)t} - 2\, e^{-\frac{1}{2}(\Gamma_+(p)+\Gamma_-(p))t} \cos(\Omega_p t)\right]$
$= \sqrt{p^2+m_+^2} - \sqrt{p^2+m_-^2} = \begin{cases} m_+ - m_- & p \ll m \\ \frac{m_+^2 - m_-^2}{2p} & p \gg m \end{cases}$


⟨φ(t)|φ(0)⟩ = 1/2 [e^{-iE+t} + e^{-iE-t}]
⟨φ̄(t)|φ(0)⟩ = q/2p [e^{-iE-t} - e^{-iE+t}]
P_t(φ(p)→φ(p)) = 1/4 [e^{-Γ+(p)t} + e^{-Γ-(p)t} + 2 e^{-½[Γ+(p)+Γ-(p)]t} cos Ω_p t]
P_t(φ(p)→φ̄(p)) = 1/4 |q/p|² [e^{-Γ-(p)t} + e^{-Γ+(p)t} - 2 e^{-½(Γ+(p)+Γ-(p))t} cos(Ω_p t)]
Ω_p = √(p²+m+²) - √(p²+m-²) = { m+ - m-   p≪m
(m+² - m-²)/2p   p≫m }


Pt
oscillation signal

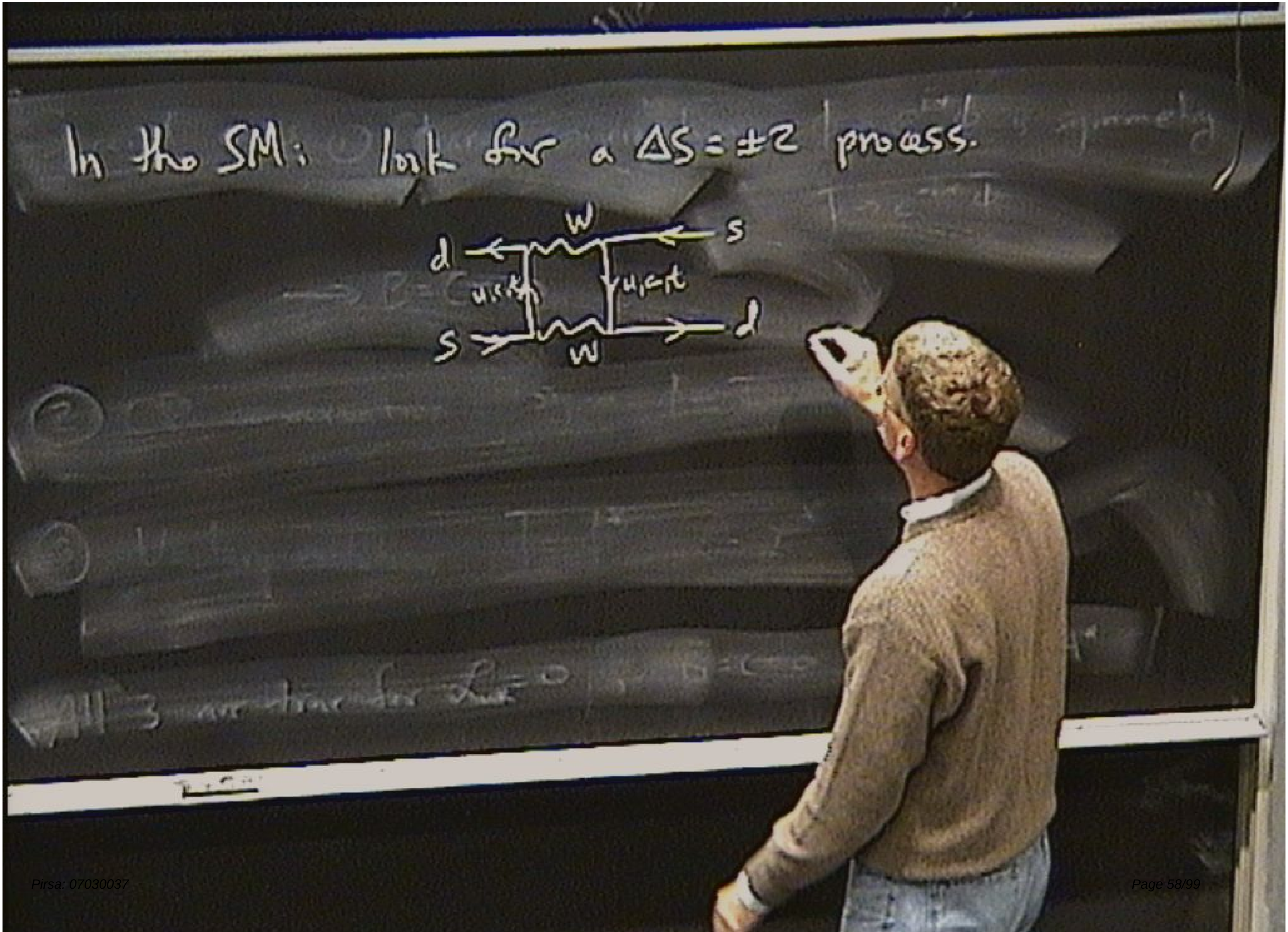

Pt
oscillation signal
For Kaons: Δm ≃

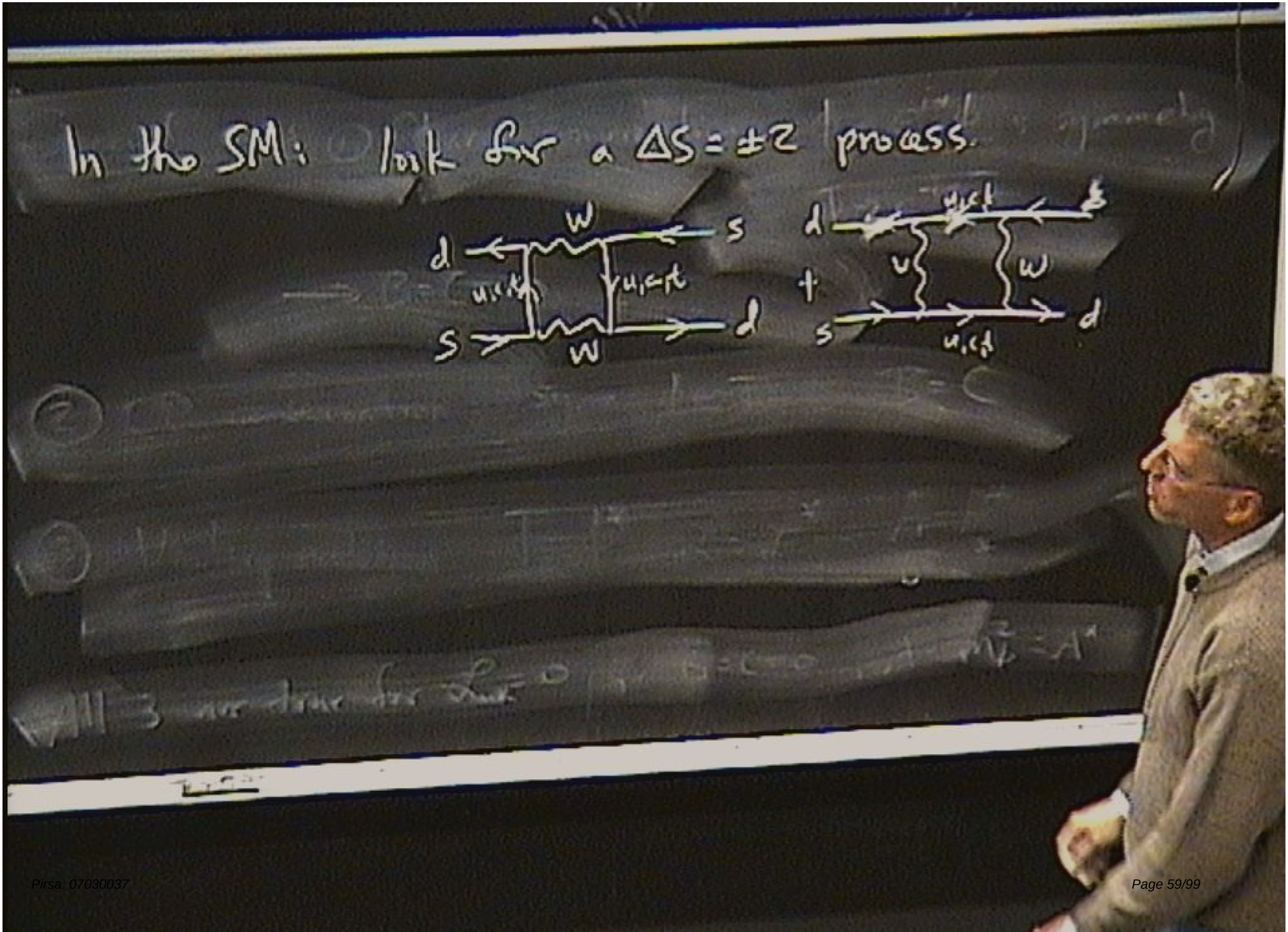


oscillation signal

For Kaons: $\Delta m \simeq (3.483 \pm 0.006) \times 10^{-15}$ GeV ←

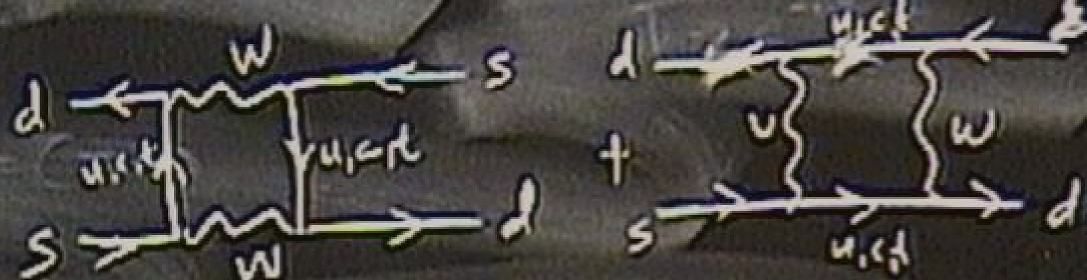
very accurate


In the SM: look for a ΔS = ±2 process.
W
s
d
u,c,t
u,c,t
s
d
W

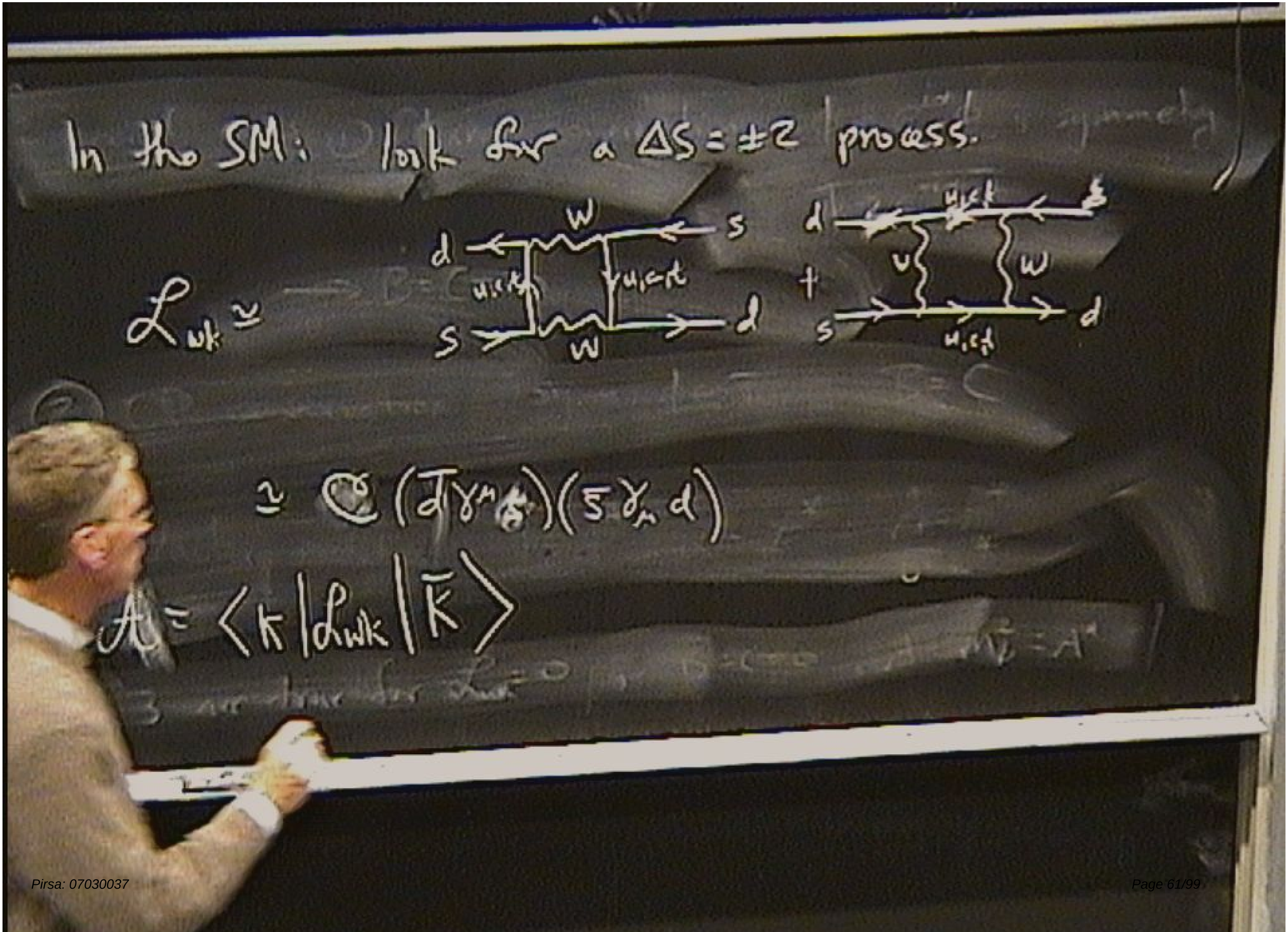

In the SM: look for a ΔS = ±2 process.
W
s
d
u,c,t
u,c,t
S
W
d
+
u,c,t
W
s

In the SM: look for a $\Delta S = \pm 2$ process.

$\mathcal{L}_{wk} \simeq$



$$\simeq K \, (\bar{d}\gamma^{\mu} s)(\bar{s}\gamma_{\mu} d)$$


In the SM: look for a ΔS = ±2 process.
W
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+
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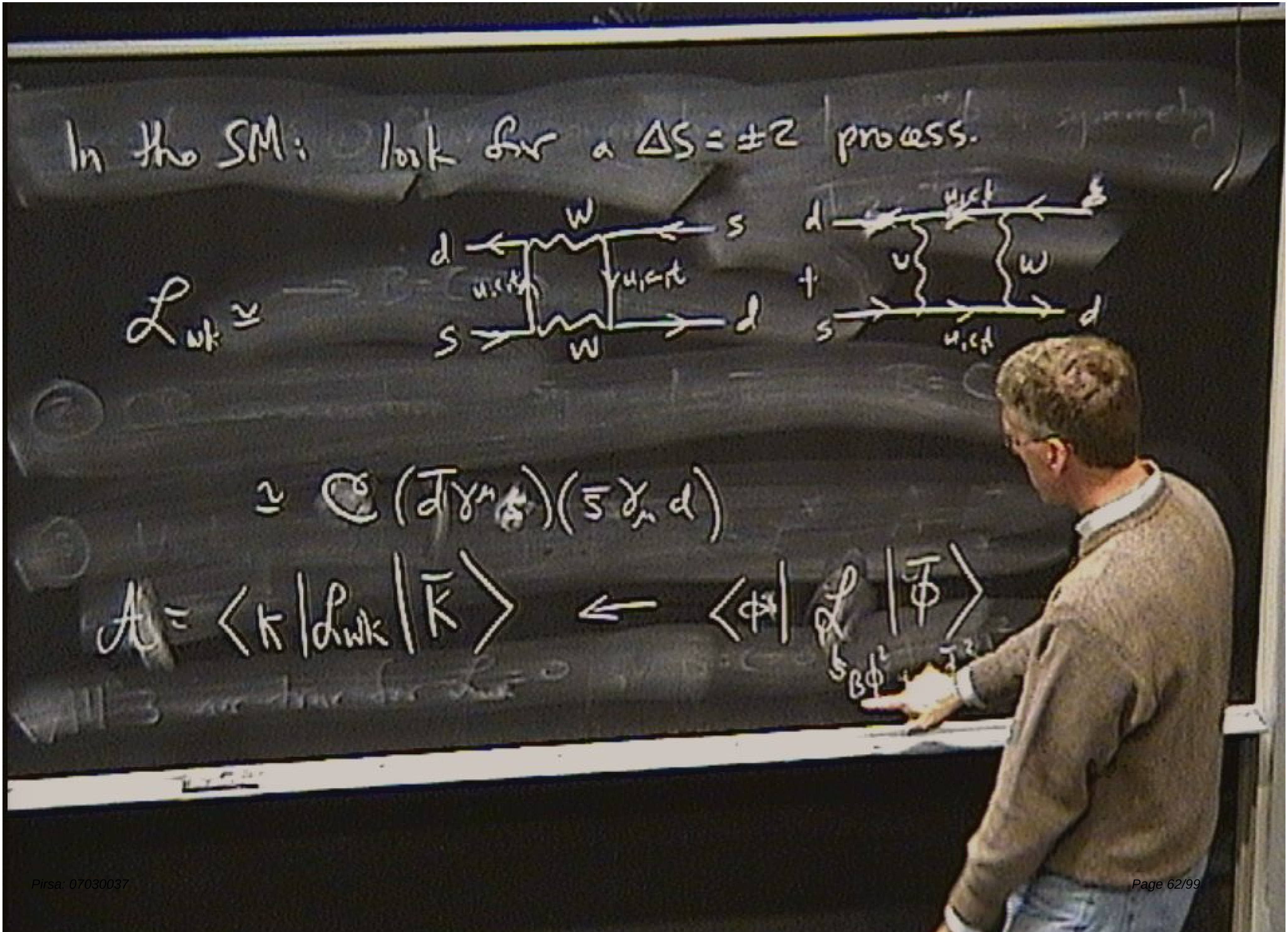
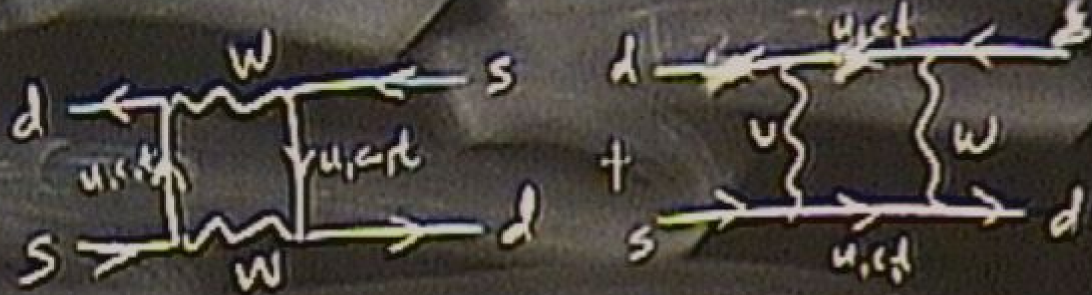
u,c,t
s
W
W
d
s
u,c,t
d
L_wk ≃
≃ C (d̄ γ^μ s)(s̄ γ_μ d)
A = ⟨K| L_wk |K̄⟩


In the SM: look for a ΔS = ±2 process.
W
d
s
u,c,t
d
S
W
+
w
W
L_wk ≃
≃ C (d̄ γ^μ s)(s̄ γ_μ d)
A = ⟨K | L_wk | K̄⟩ ← ⟨Φ | L | Φ̄⟩

In the SM: look for a $\Delta S = \pm 2$ process.

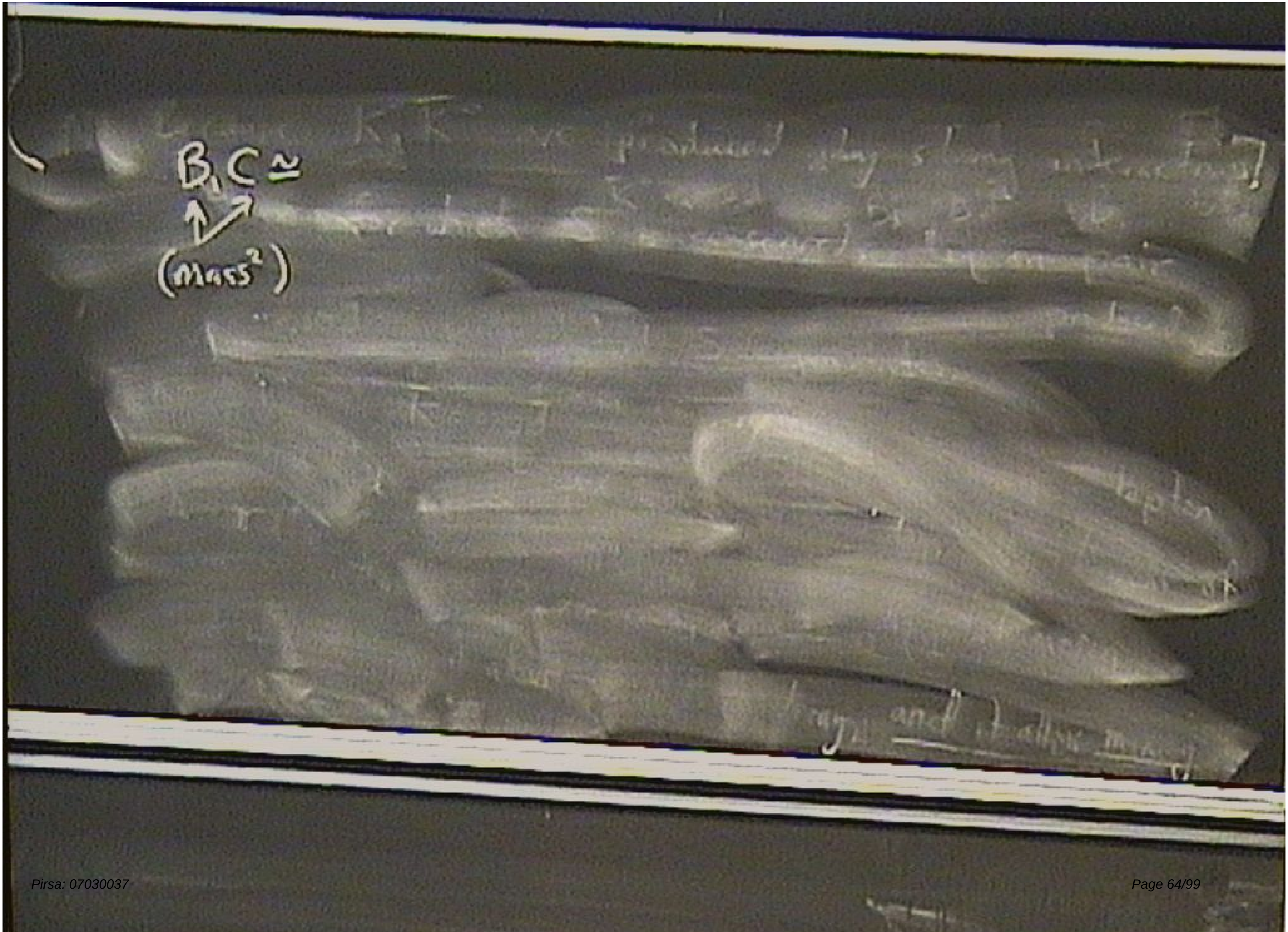
$\mathcal{L}_{wk} \simeq$

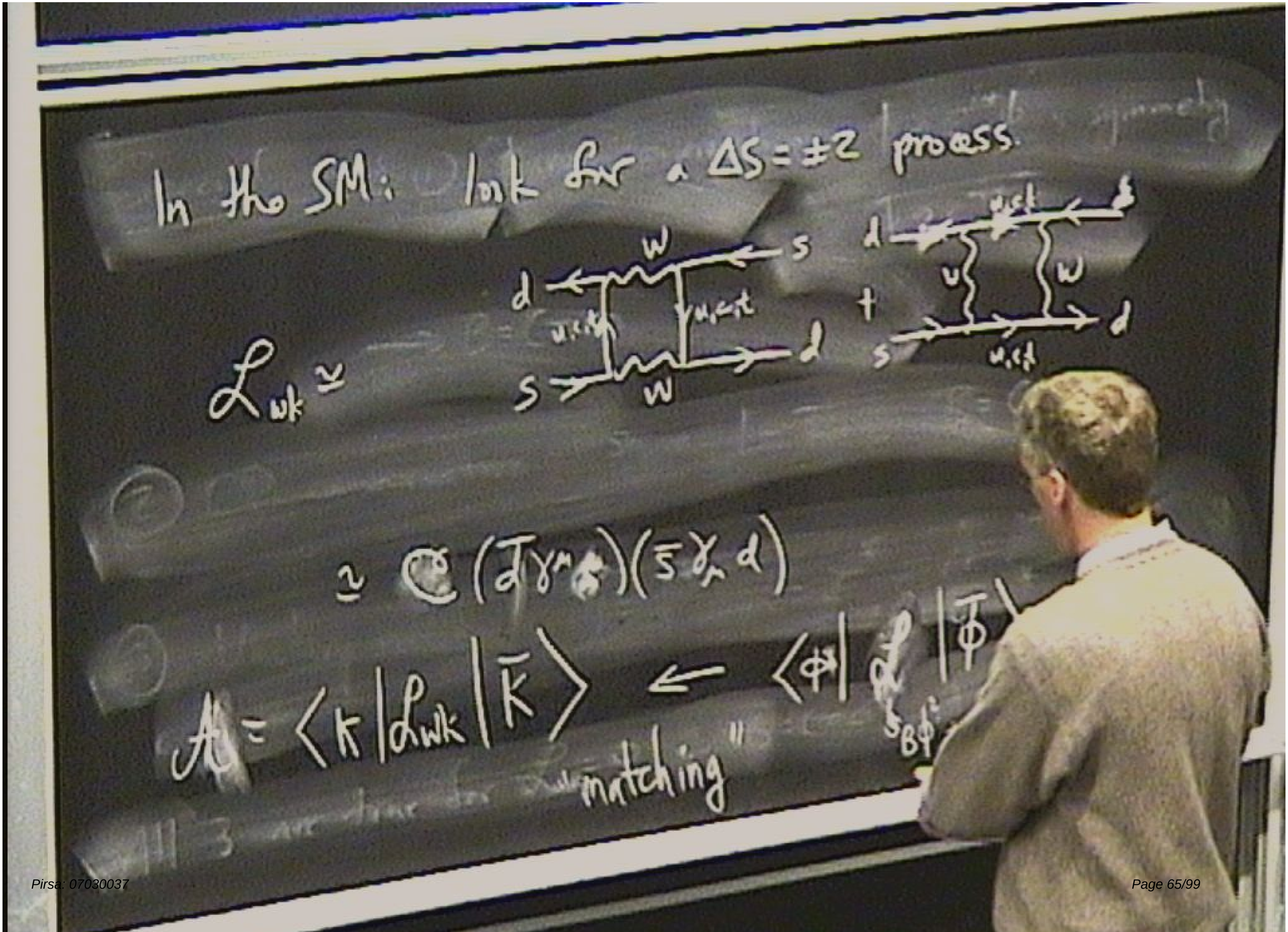


$$\simeq C(\bar{d}\gamma^\mu s)(\bar{s}\gamma_\mu d)$$

$$A = \langle K | \mathcal{L}_{wk} | \bar{K} \rangle \leftarrow \langle \phi | \mathcal{L} | \bar{\phi} \rangle$$

$$\mathcal{L} \ni B\phi^2 + C\bar{\phi}^2$$


B, C ≈
(mass²)


In the SM: look for a ΔS = ±2 process.
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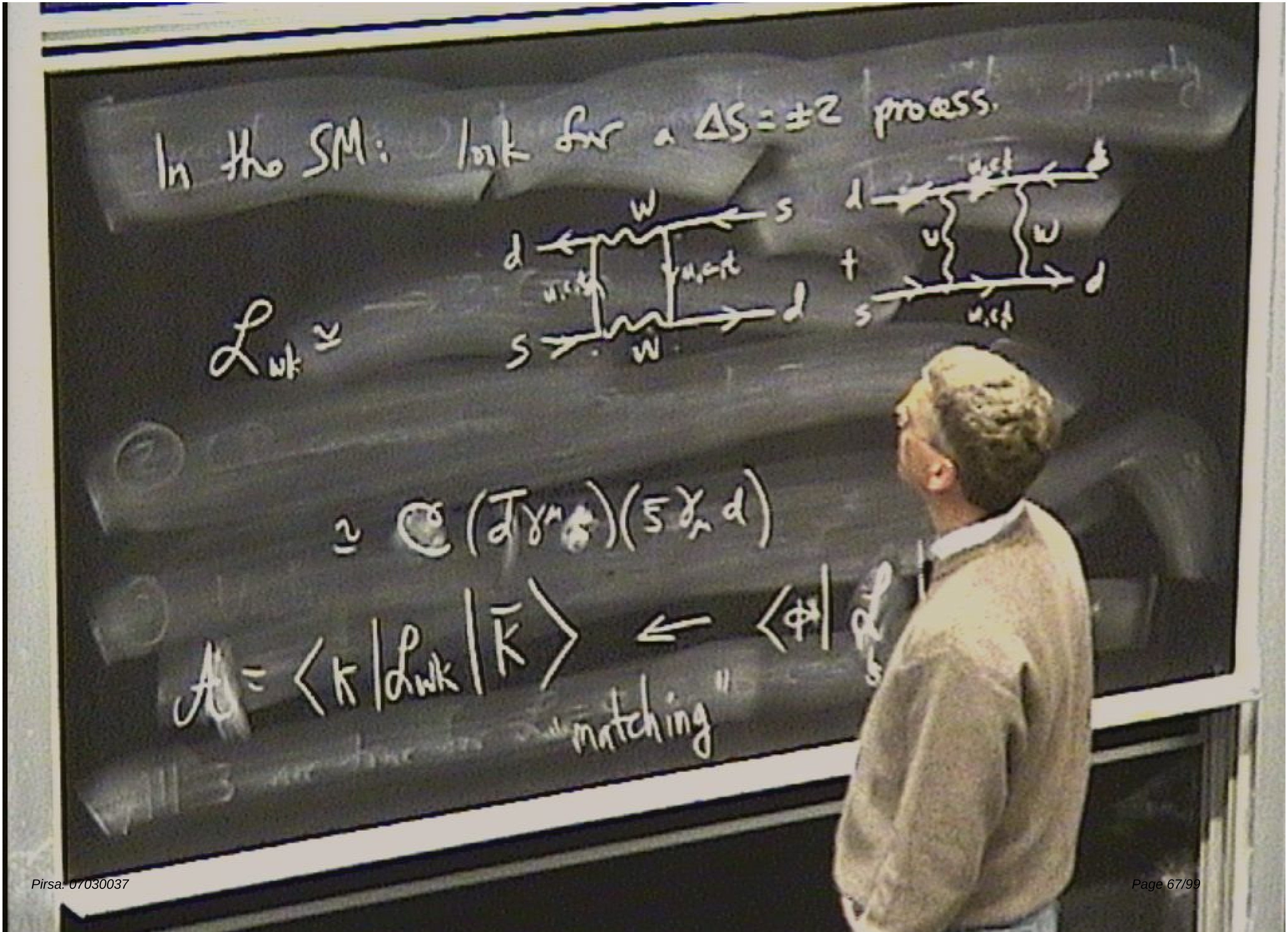
u,c,t
d
s
W
+
d
W
W
d
s
u,c,t
u,c,t
L_wk ≃
≃ C (d̄ γ^μ s)(s̄ γ_μ d)
A = ⟨K | L_wk | K̄⟩ ← ⟨Φ| L |Φ̄⟩
"matching"

$$B, C \simeq \frac{g^4}{(16\pi^2)}$$

(Mass^2)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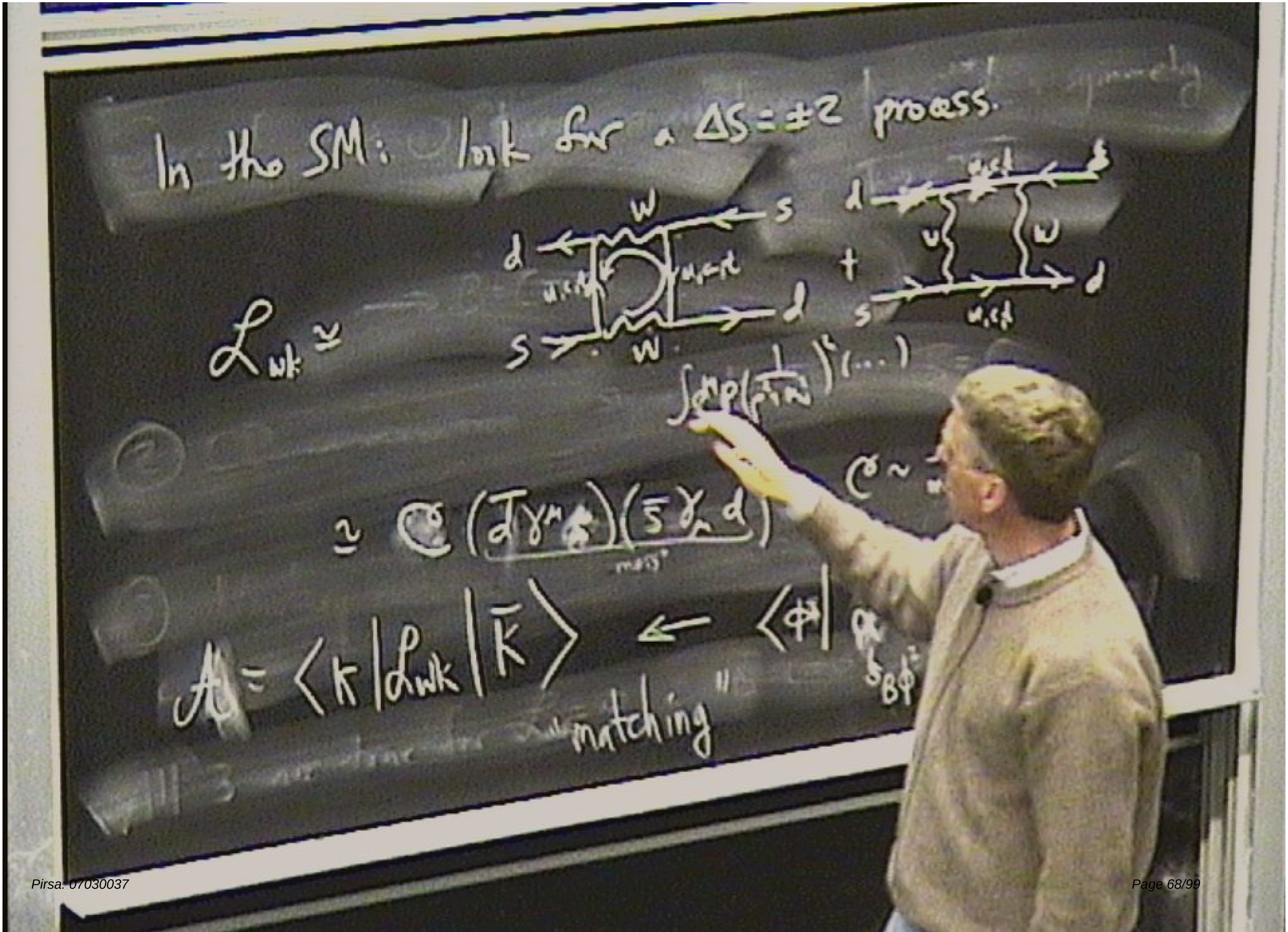
u,c,t
d
s
W
+
d
s
W
W
u,c,t
u,c,t
d
L_wk ≃
≃ C (d̄ γ^μ s)(s̄ γ_μ d)
A = ⟨K | L_wk | K̄⟩ ←
"matching"


In the SM: look for a ΔS = ±2 process.
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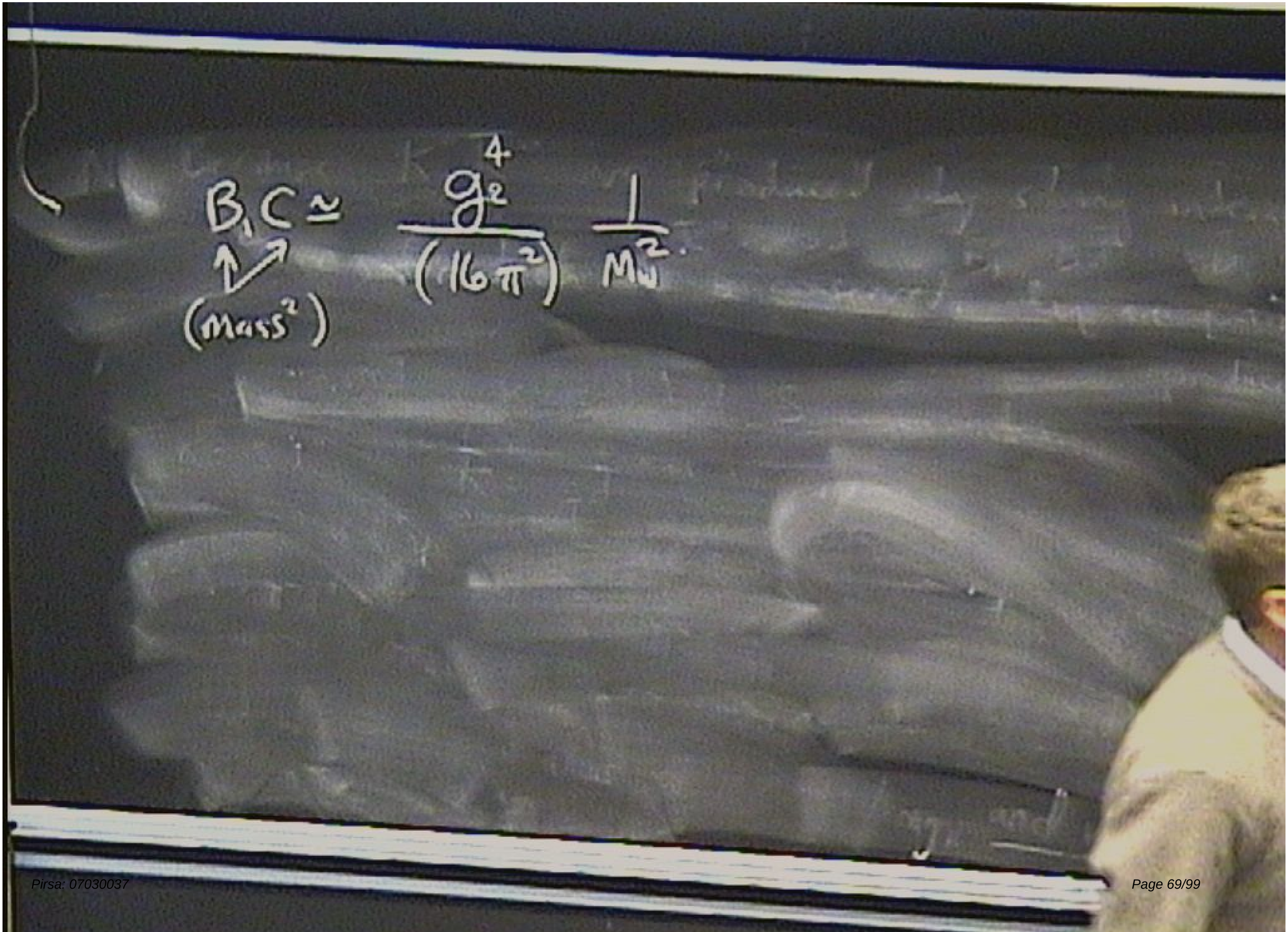
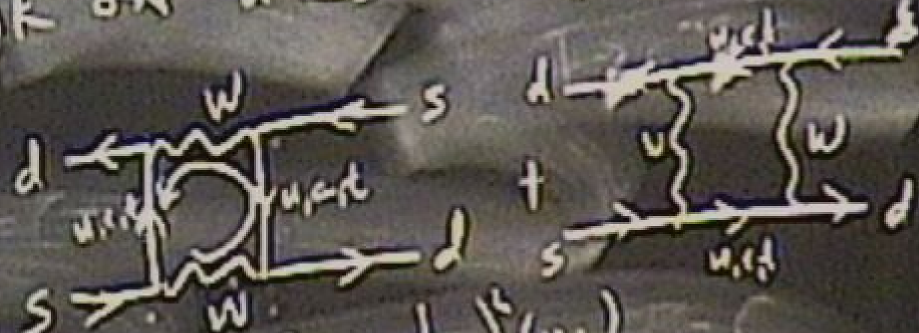

$B, C \simeq \frac{g_2^4}{(16\pi^2)} \frac{1}{M_W^2}$
$(Mass^2)$

In the SM: look for a $\Delta S = \pm 2$ process.

$\mathcal{L}_{wk} \simeq$



$\int d^4p \left(\frac{1}{p^2+M_W^2}\right)^2 (\ldots)$

$\simeq \mathcal{C}\, \underbrace{(\bar d \gamma^\mu s)(\bar s \gamma_\mu d)}_{\text{mass}^6}$ $\qquad \mathcal{C} \sim \frac{g_2^4}{(16\pi)^2}\frac{1}{M_W^2}$

$\mathcal{A} = \langle K | \mathcal{L}_{wk} | \bar K \rangle \leftarrow \langle \phi | \mathcal{L} | \bar\phi \rangle$ $\qquad \mathcal{L} \ni B\phi^2 + C\bar\phi^2$

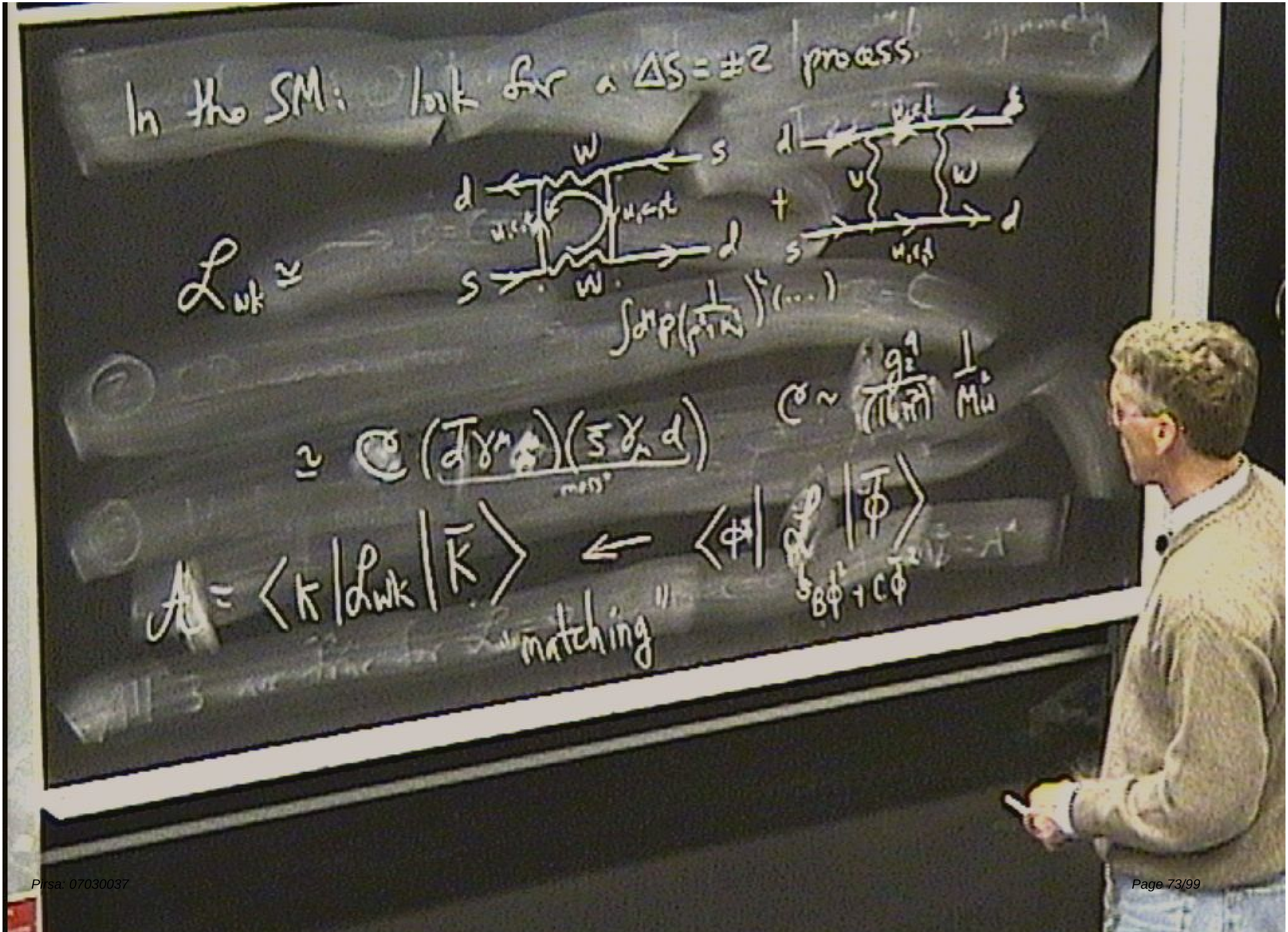
"matching"

$B, C \simeq \mathcal{E}$

(mass^2)

$$B, C \simeq \epsilon M_K^4 \simeq \frac{g_2^4}{(16\pi^2)} \frac{M_K^4}{M_W^2}$$

(mass^2)


In the SM: look for a ΔS = ±2 process.
$\mathcal{L}_{wk} \simeq$
W
W
s
d
d
s
u,c,t
+
$\simeq \mathcal{C}\,(\bar{d}\gamma^\mu s)(\bar{s}\gamma_\mu d)$
$\mathcal{C} \sim \frac{g_2^4}{16\pi^2}\frac{1}{M_W^2}$
$\langle\phi|\,\mathcal{L}\,|\bar{\phi}\rangle$
$B\phi^2 + C\phi^4$
$\mathcal{A} = \langle K|\mathcal{L}_{wk}|\bar{K}\rangle$
"matching"

$$B, C \simeq \epsilon\, m_K^4 \simeq \frac{g_2^4}{(16\pi^2)} \frac{m_K^4}{M_W^2} \simeq \Delta m^2$$

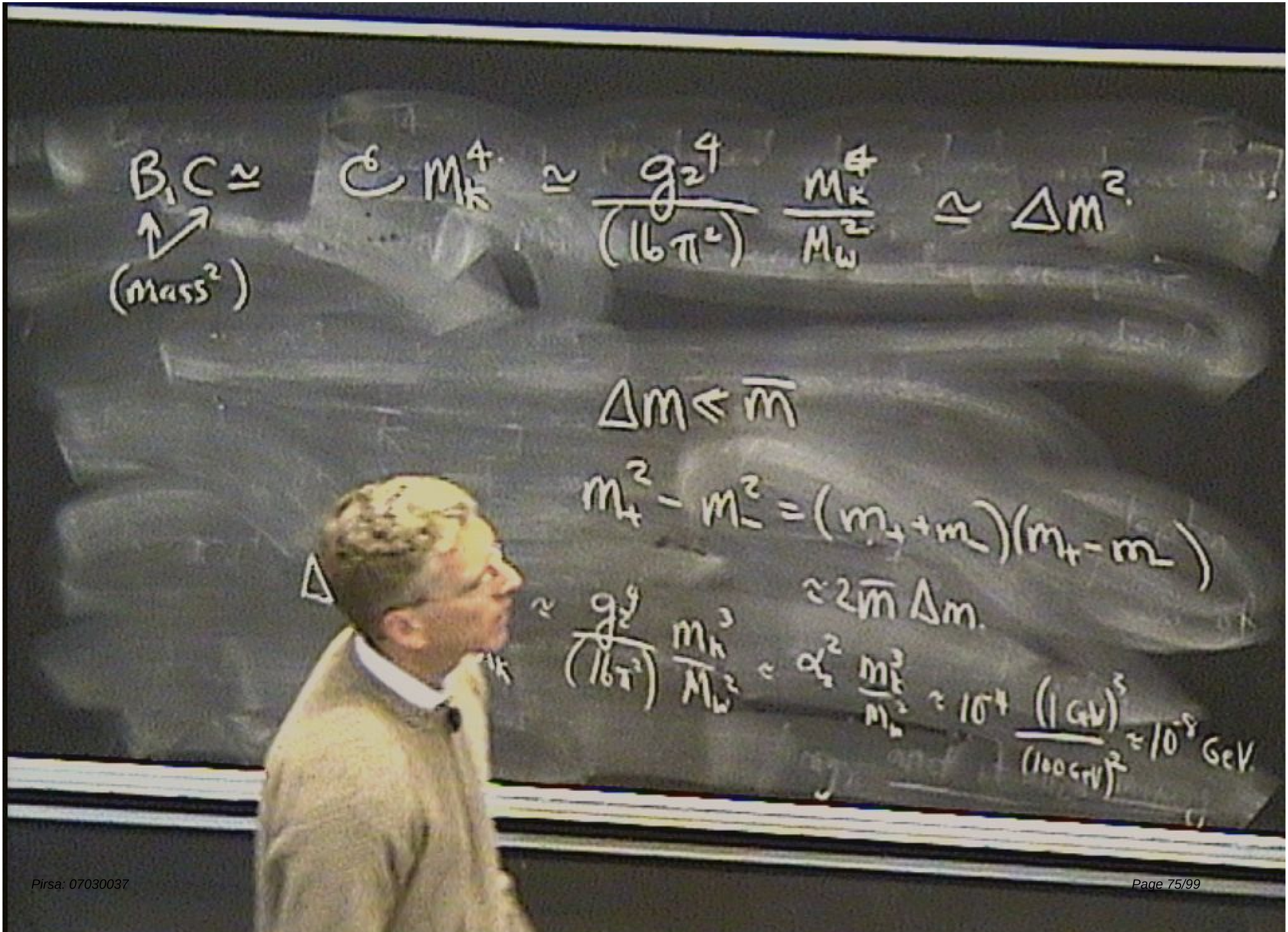
(B, C: (mass^2))

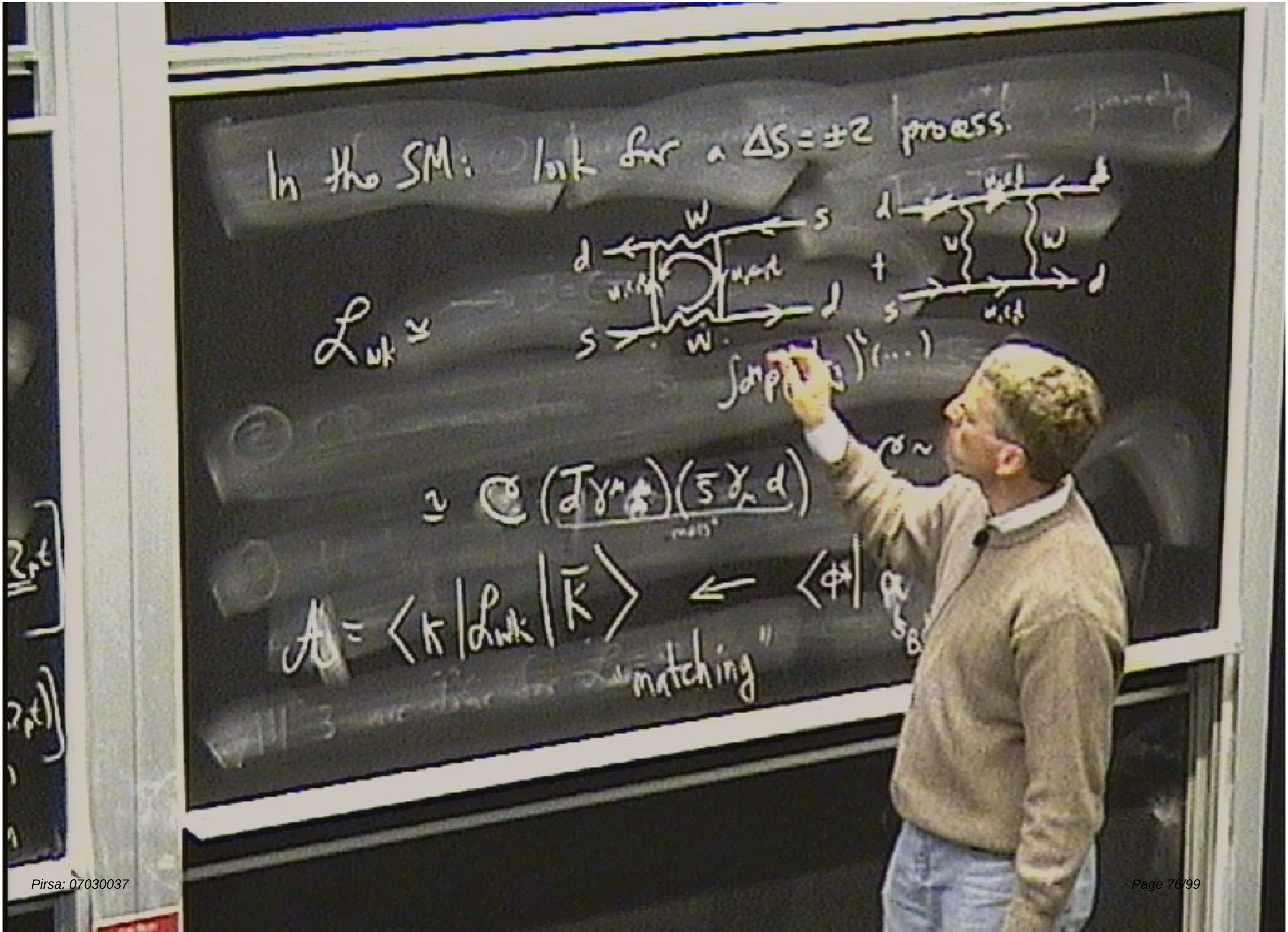
$$\Delta m \ll \bar{m}$$

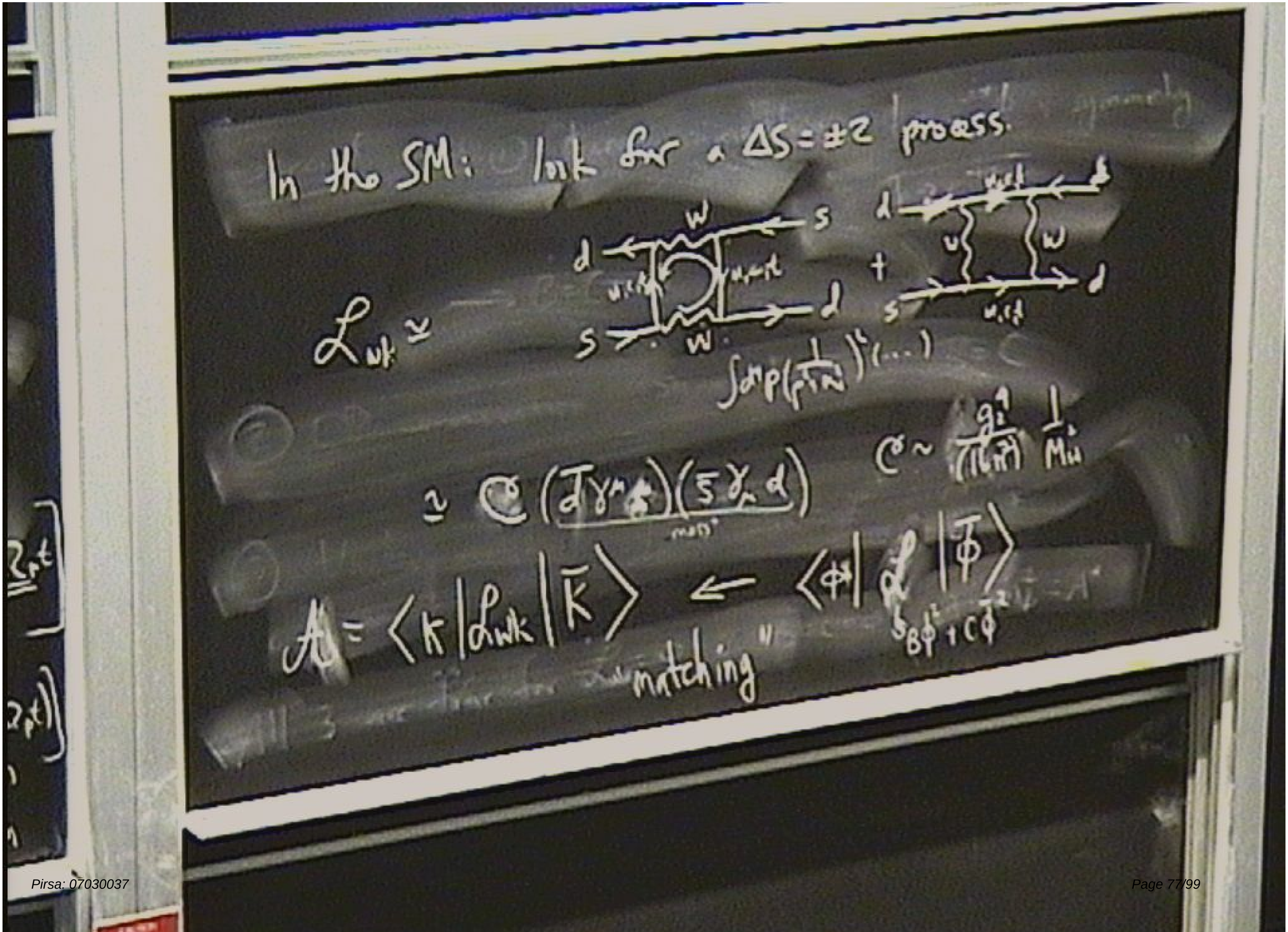
$$m_+^2 - m_-^2 = (m_+ + m_-)(m_+ - m_-)$$

$$\simeq 2\bar{m}\,\Delta m$$

$$\simeq \frac{g_2^4}{(16\pi^2)} \frac{m_K^3}{M_W^2} \approx \alpha$$


B, C ≃ ε m_k^4 ≃ g_2^4/(16π²) m_k^4/M_W^2 ≃ Δm²
(mass²)
Δm ≪ m̄
m_+^2 − m_-^2 = (m_+ + m_-)(m_+ − m_-)
≃ 2m̄ Δm
≃ g_2^4/(16π²) m_k^3/M_W^2 ≃ α_2^2 m_k^3/M_W^2 ≃ 10^-4 (1 GeV)^3/(100 GeV)^2 ≃ 10^-8 GeV.


In the SM: look for a ΔS = ±2 process.
matching


In the SM: look for a ΔS = ±2 process
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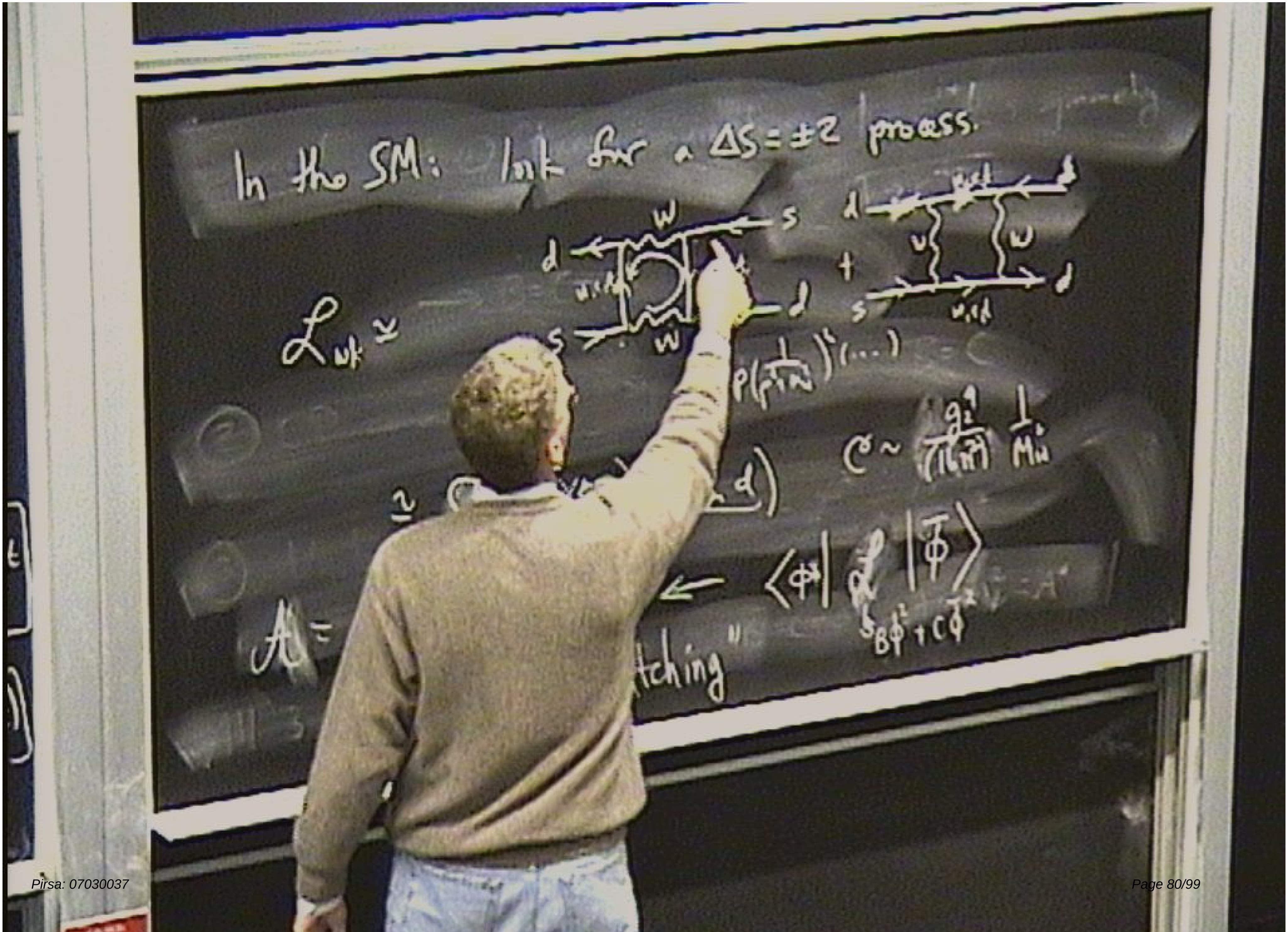
L_wk ≈
matching

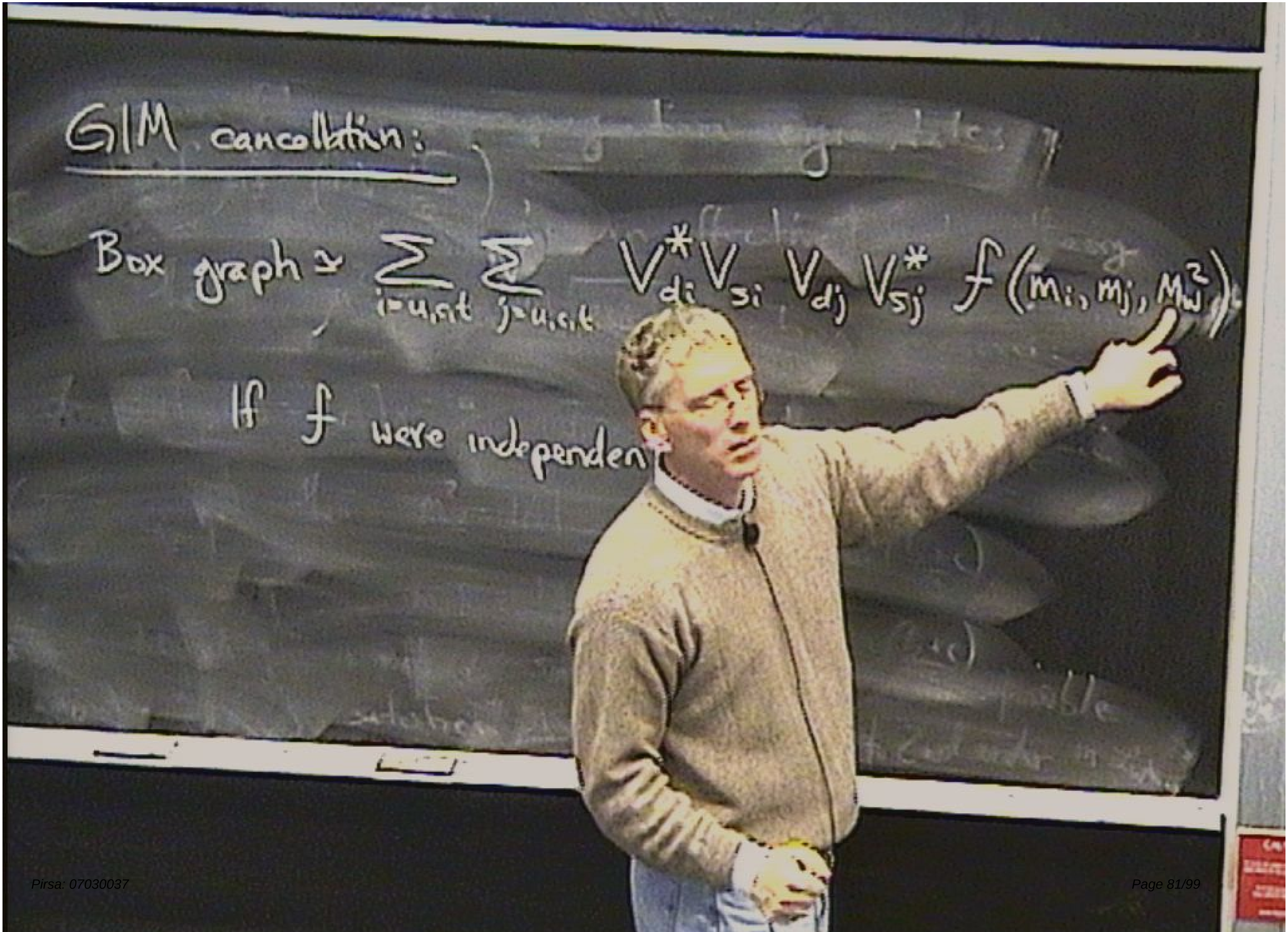
GIM cancellation:

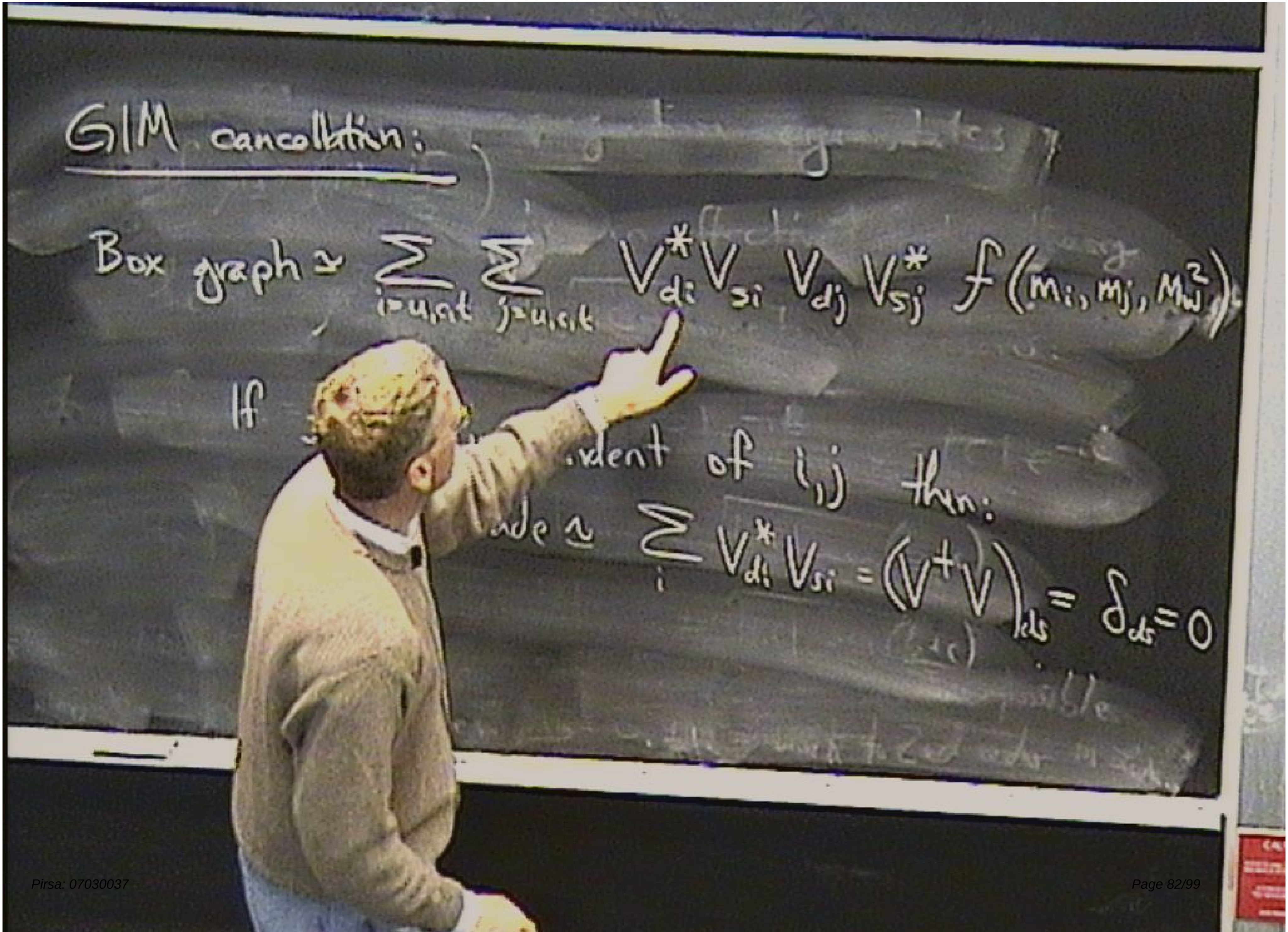
Box graph $\propto \sum_{i=u,c,t} \sum_{j=u,c,t} V^*_{di}$

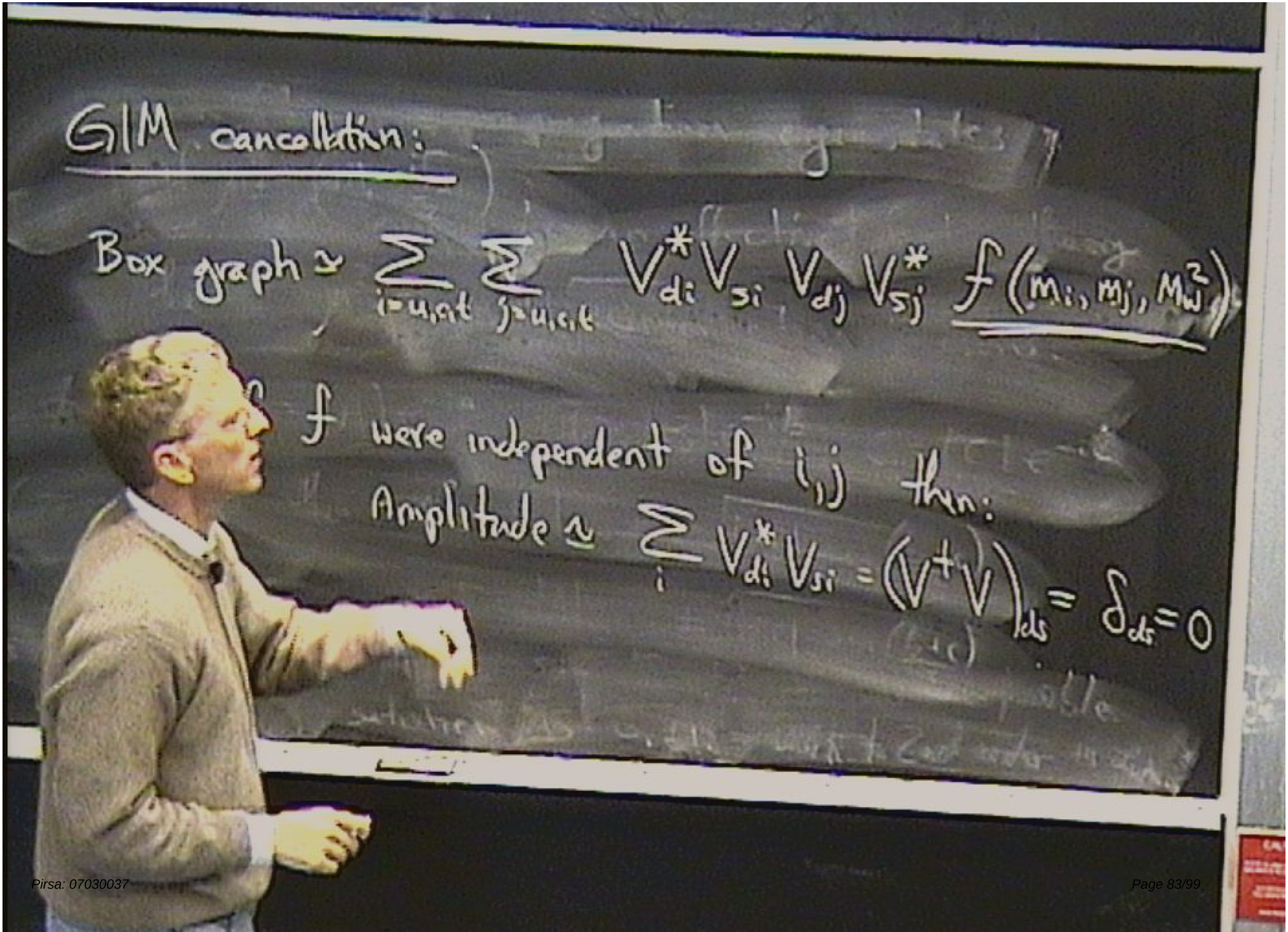
GIM cancellation:

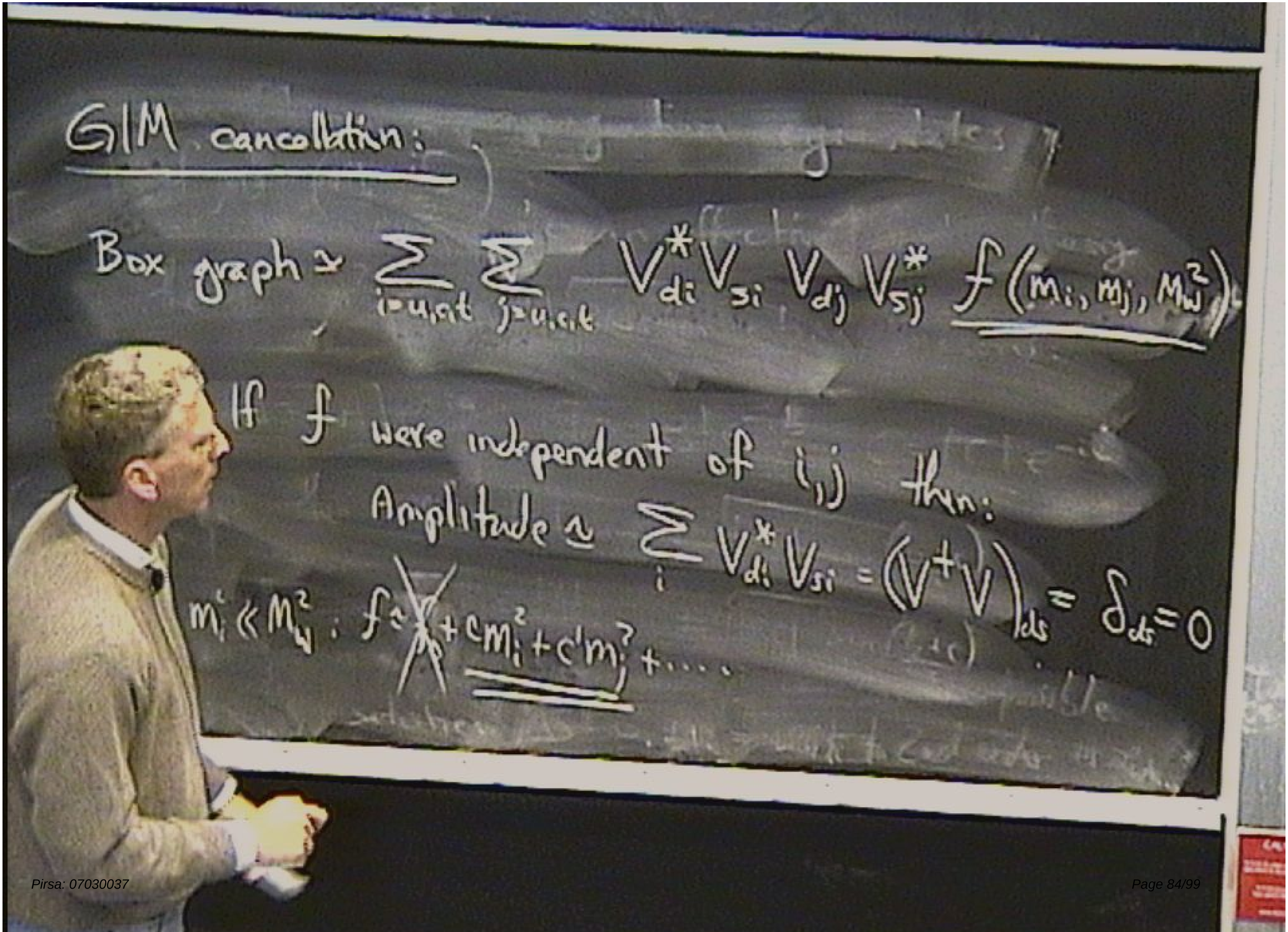
Box graph $\sim \sum_{i=u,c,t} \sum_{j=u,c,t} V^*_{di} V_{si} V_{dj} V^*_{sj}$

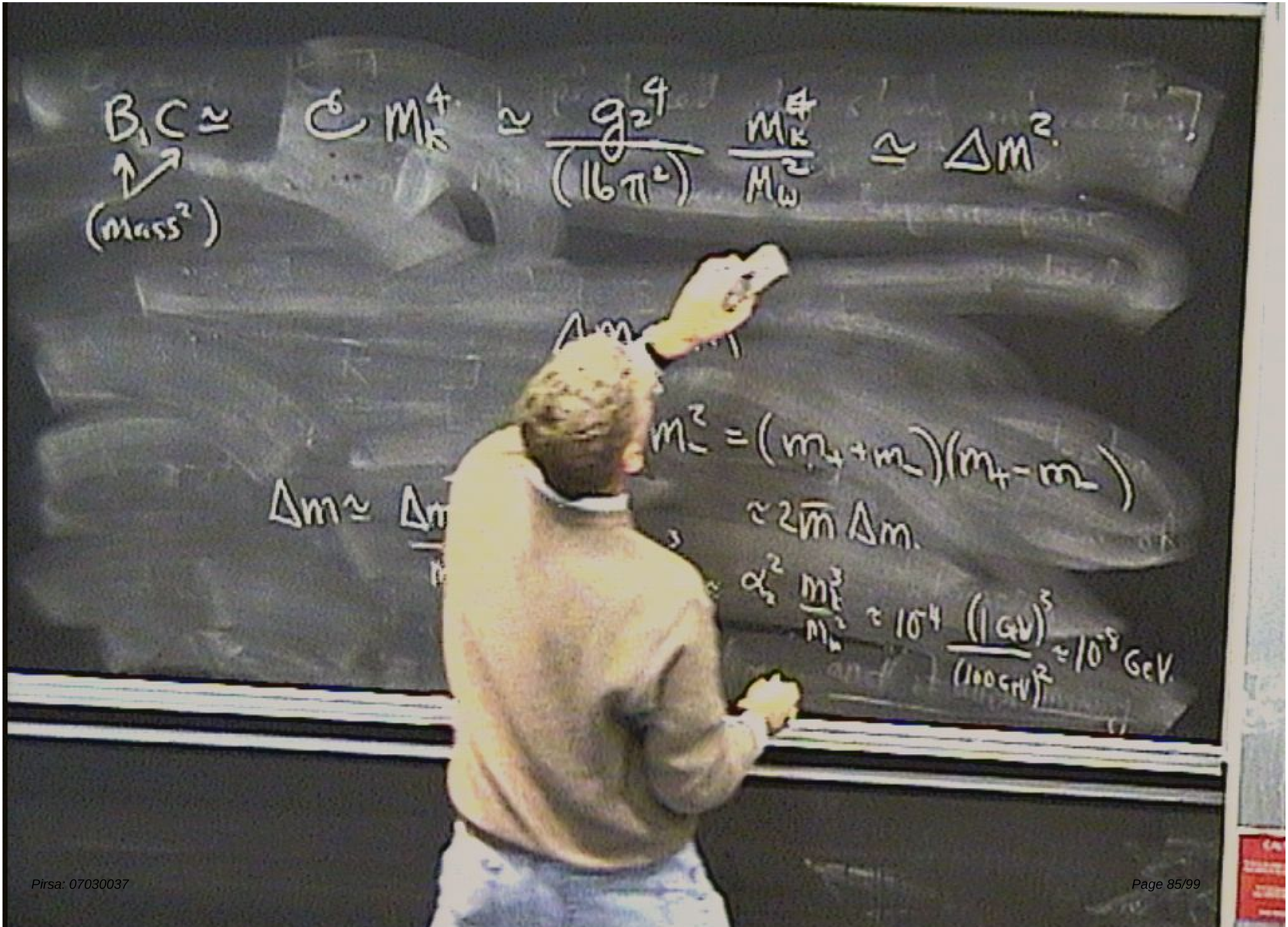

In the SM: look for a ΔS = ±2 process.

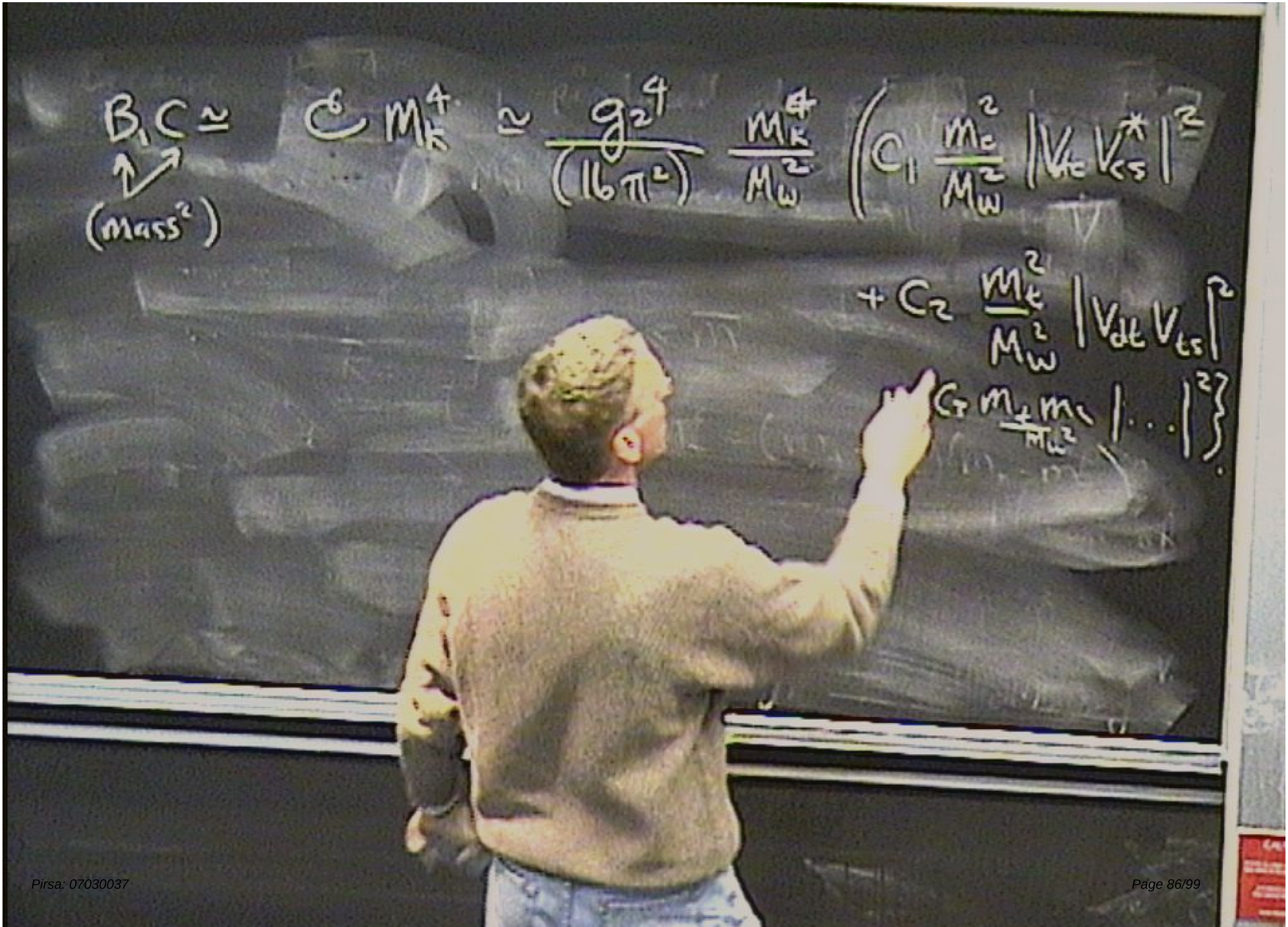

GIM cancellation:
Box graph ∝ $\sum_{i=u,c,t} \sum_{j=u,c,t} V_{di}^* V_{si} V_{dj} V_{sj}^* f(m_i, m_j, M_W^2)$
If f were independen

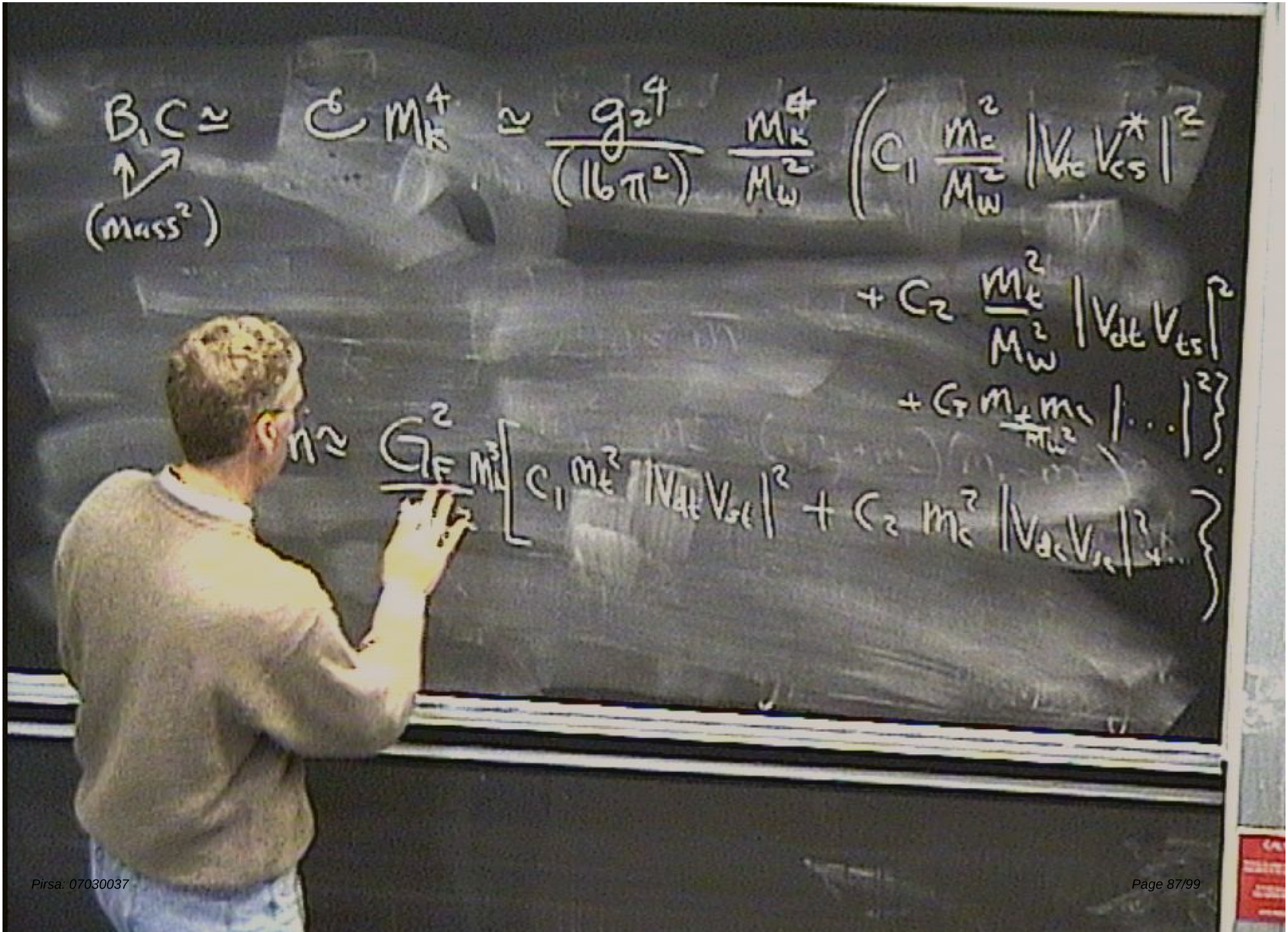

GIM cancellation:
Box graph ~ $\sum_{i=u,c,t} \sum_{j=u,c,t} V^*_{di} V_{si} V_{dj} V^*_{sj} f(m_i, m_j, M_W^2)$
If
endent of i,j then:
ude ~ $\sum_i V^*_{di} V_{si} = (V^\dagger V)_{ds} = \delta_{ds} = 0$


GIM cancellation:
Box graph ~ $\sum_{i=u,c,t} \sum_{j=u,c,t} V_{di}^* V_{si} V_{dj} V_{sj}^* f(m_i, m_j, M_W^2)$
If f were independent of i,j then:
Amplitude ~ $\sum_i V_{di}^* V_{si} = (V^\dagger V)_{ds} = \delta_{ds} = 0$


GIM cancellation:
Box graph $\propto \sum_{i=u,c,t} \sum_{j=u,c,t} V^*_{di} V_{si} V_{dj} V^*_{sj} f(m_i, m_j, M_W^2)$
If f were independent of i,j then:
Amplitude $\simeq \sum_i V^*_{di} V_{si} = (V^\dagger V)_{ds} = \delta_{ds} = 0$
$m_i^2 \ll M_W^2$: $f \simeq c + c m_i^2 + c' m_j^2 + \dots$


B, C ≃ c M_K^4 ≃ g_2^4/(16π^2) M_K^4/M_W^2 ≃ Δm^2
(mass^2)
m_-^2 = (m_+ + m_-)(m_+ - m_-)
≃ 2m̄ Δm
Δm ≃
≃ α_2^2 m_K^3/M_W^2 ≃ 10^-4 (1 GeV)^3/(100 GeV)^2 ≃ 10^-8 GeV

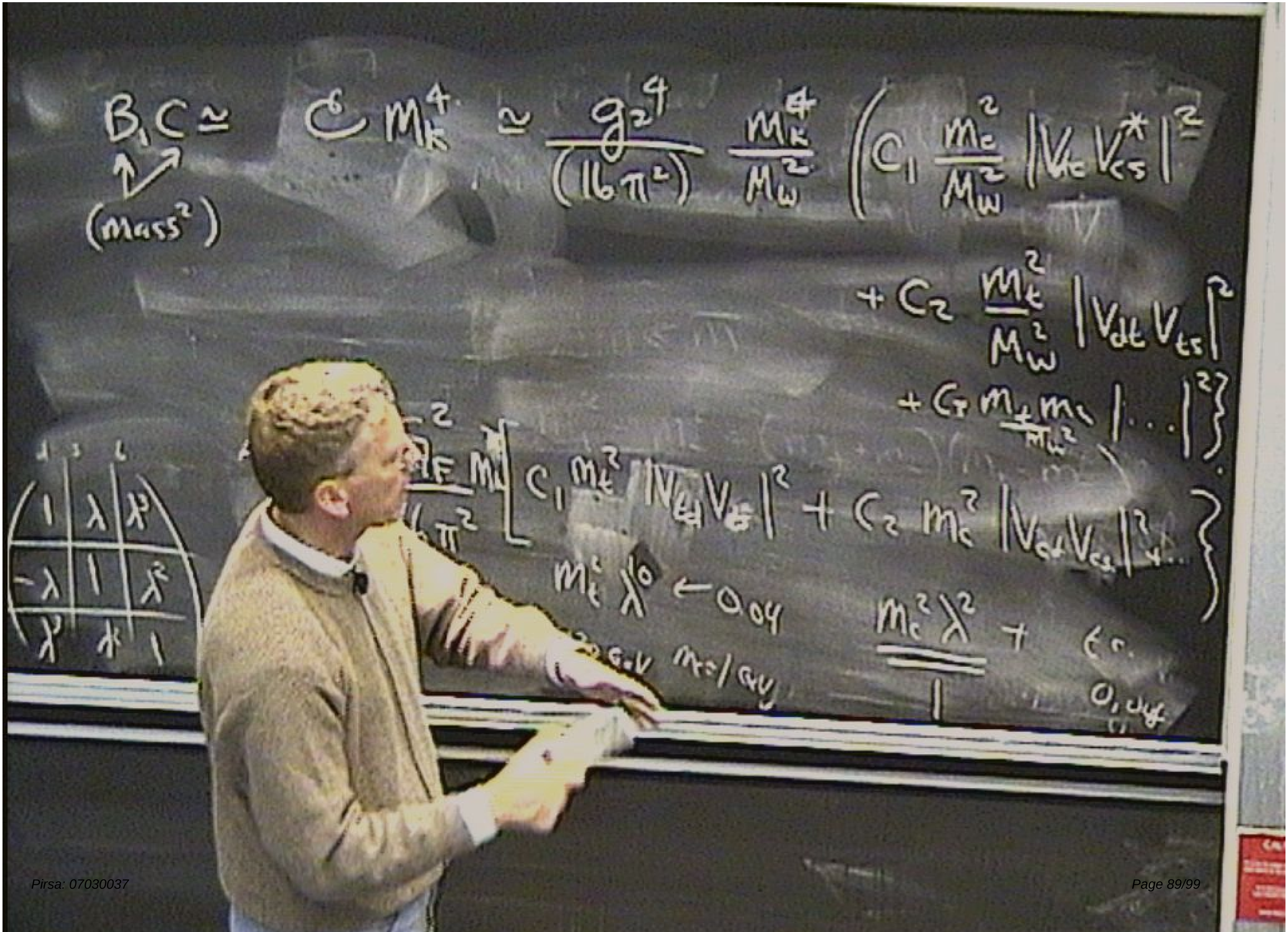

$B, C \simeq c\, M_K^4 \simeq \frac{g_2^4}{(16\pi^2)} \frac{M_K^4}{M_W^2} \Big(C_1 \frac{m_c^2}{M_W^2} |V_{cd} V_{cs}^*|^2$
(mass^2)
$+ C_2 \frac{m_t^2}{M_W^2} |V_{dt} V_{ts}|^2$
$C_3 \frac{m_t m_c}{M_W^2} |\ldots|^2 \Big\}$

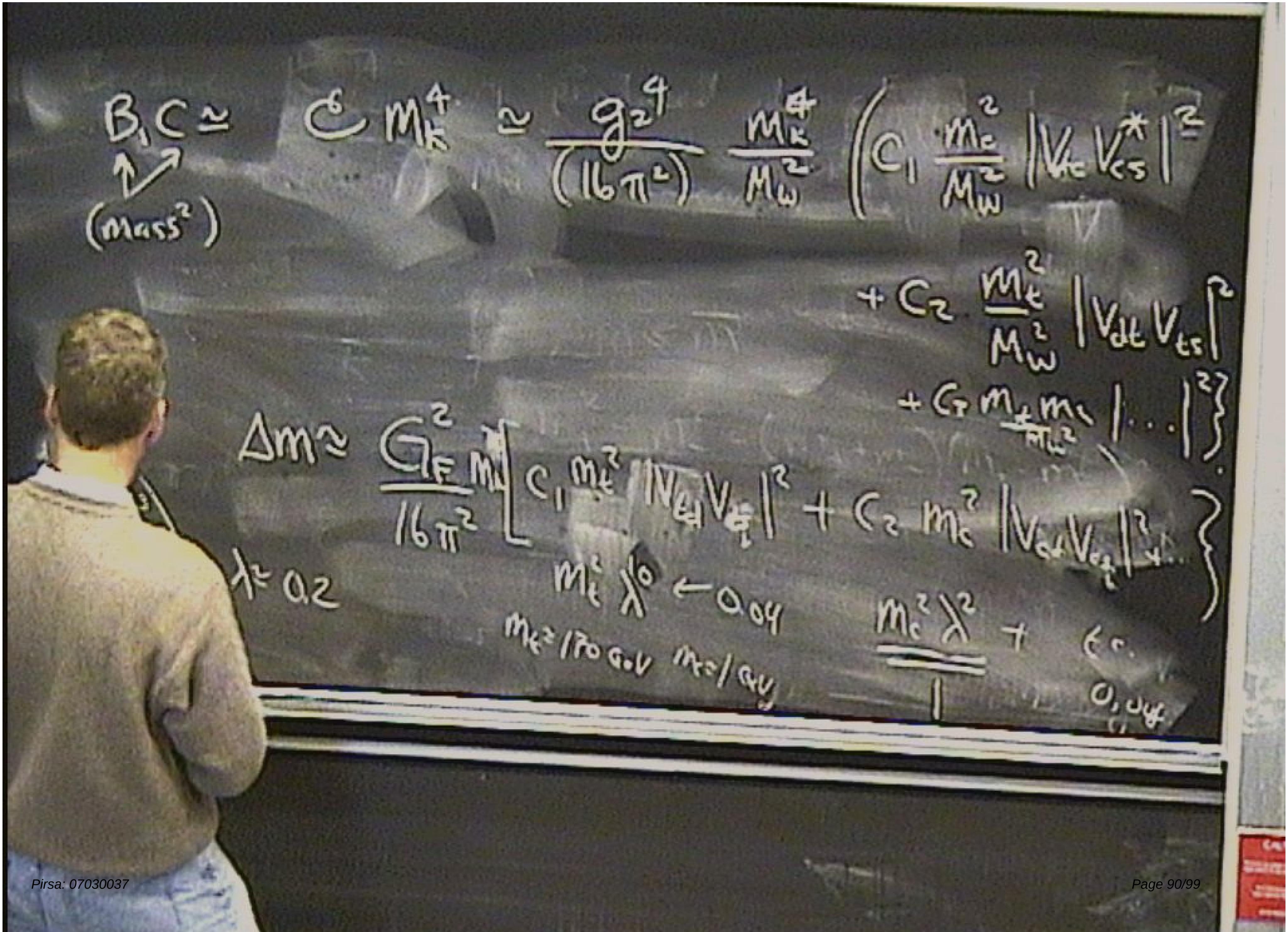

B, C ≃ C M_K^4 ≃ g_2^4 / (16π^2) · M_K^4 / M_W^2 (C_1 m_c^2 / M_W^2 |V_cd V_cs^*|^2
(mass^2)
+ C_2 m_t^2 / M_W^2 |V_dt V_ts|^2
+ C_7 m_t m_c / M_W^2 |...|^2 }
n ≃ G_F^2 m^3 [C_1 m_t^2 |V_dt V_st|^2 + C_2 m_c^2 |V_dc V_sc|^2 + ... }

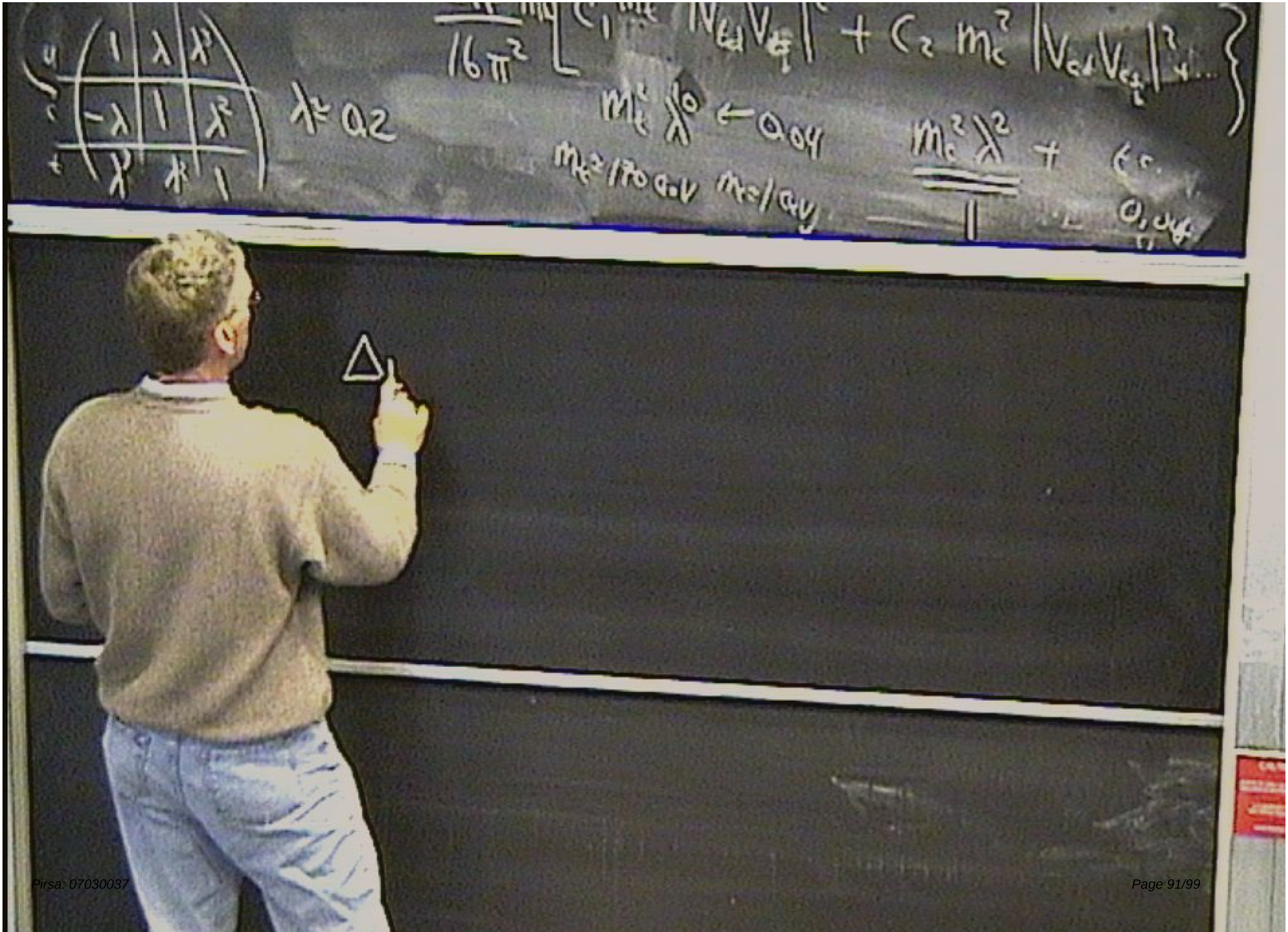
$$B, C \simeq \mathcal{C}\, m_K^4 \simeq \frac{g_2^4}{(16\pi^2)} \frac{m_K^4}{M_W^2} \left(C_1 \frac{m_c^2}{M_W^2} |V_{dc} V_{cs}^*|^2 + C_2 \frac{m_t^2}{M_W^2} |V_{dt} V_{ts}|^2 + C_3 \frac{m_t m_c}{M_W^2} |\ldots|^2 \right\}$$

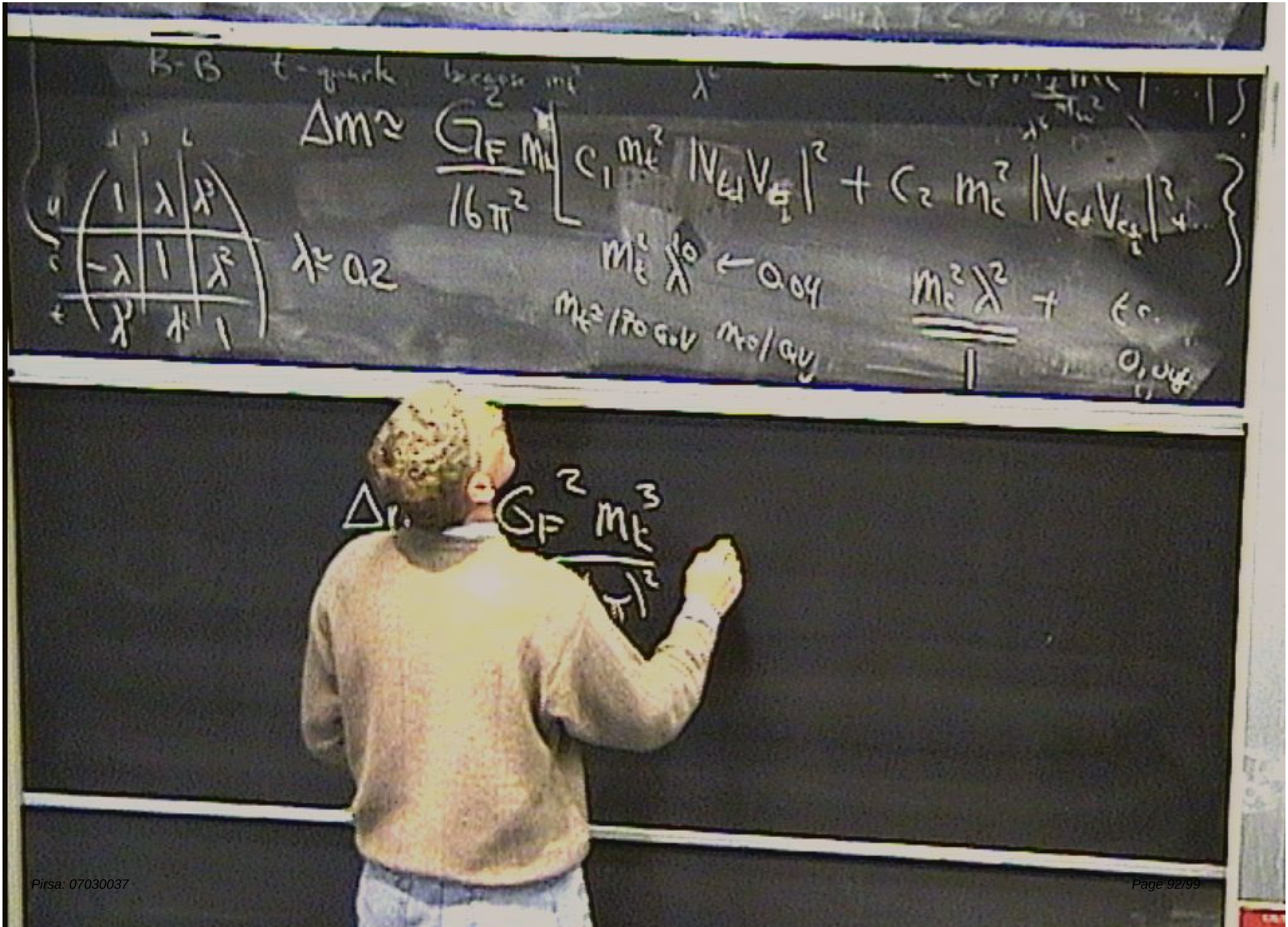
(Mass^2)

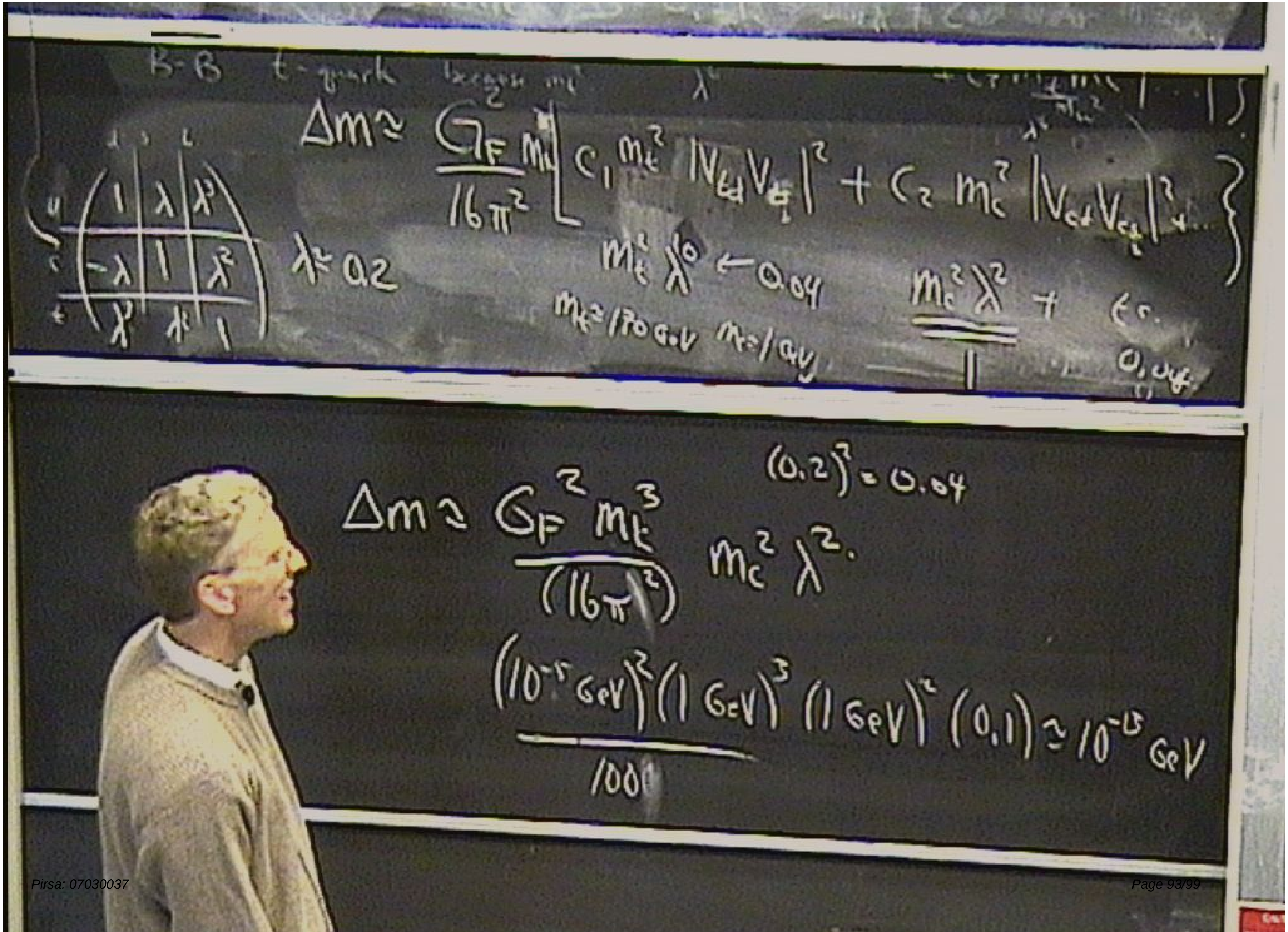
$$\Delta m \simeq \frac{G_F^2 m_K}{16\pi^2} \Big[C_1 m_t^2 |V_{dt} V_{st}|^2 + C_2 m_c^2 |V_{dc} V_{sc}|^2 + \ldots \Big\}$$

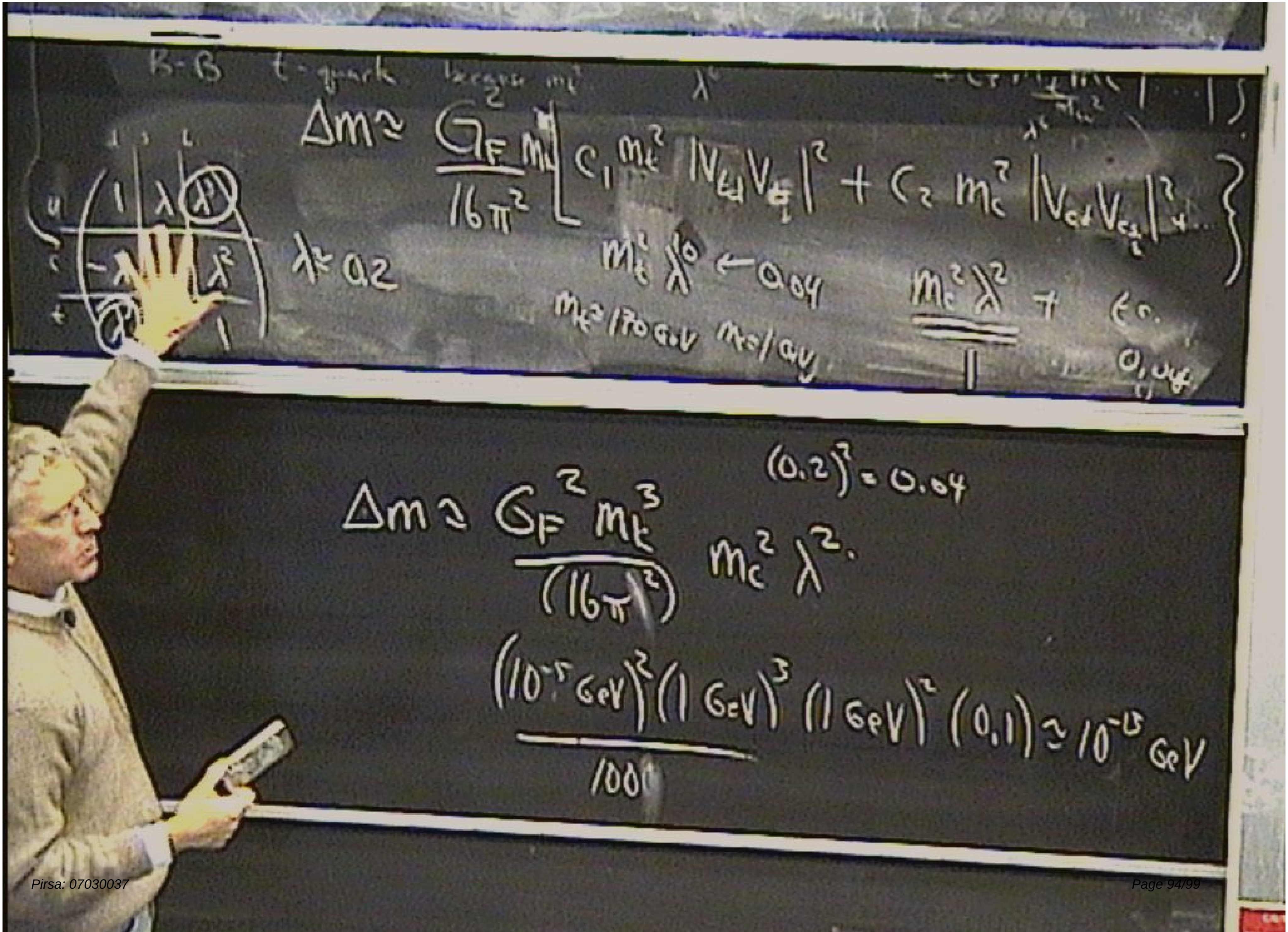

B, C ≃ c Mk^4 ≃ g_2^4 / (16π^2) · Mk^4 / Mw^2 (C1 mc^2/Mw^2 |Vcd Vcs*|^2
(mass^2)
+ C2 mt^2/Mw^2 |Vdt Vts|^2
+ C3 mt mc/Mw^2 |...|^2 }
C1 mt^2 |Vtd Vts|^2 + C2 mc^2 |Vcd Vcs|^2 + ... }
mt^2 λ^10 ← 0.04
mc^2 λ^2
1 λ λ^3
-λ 1 λ^2
λ^3 λ 1

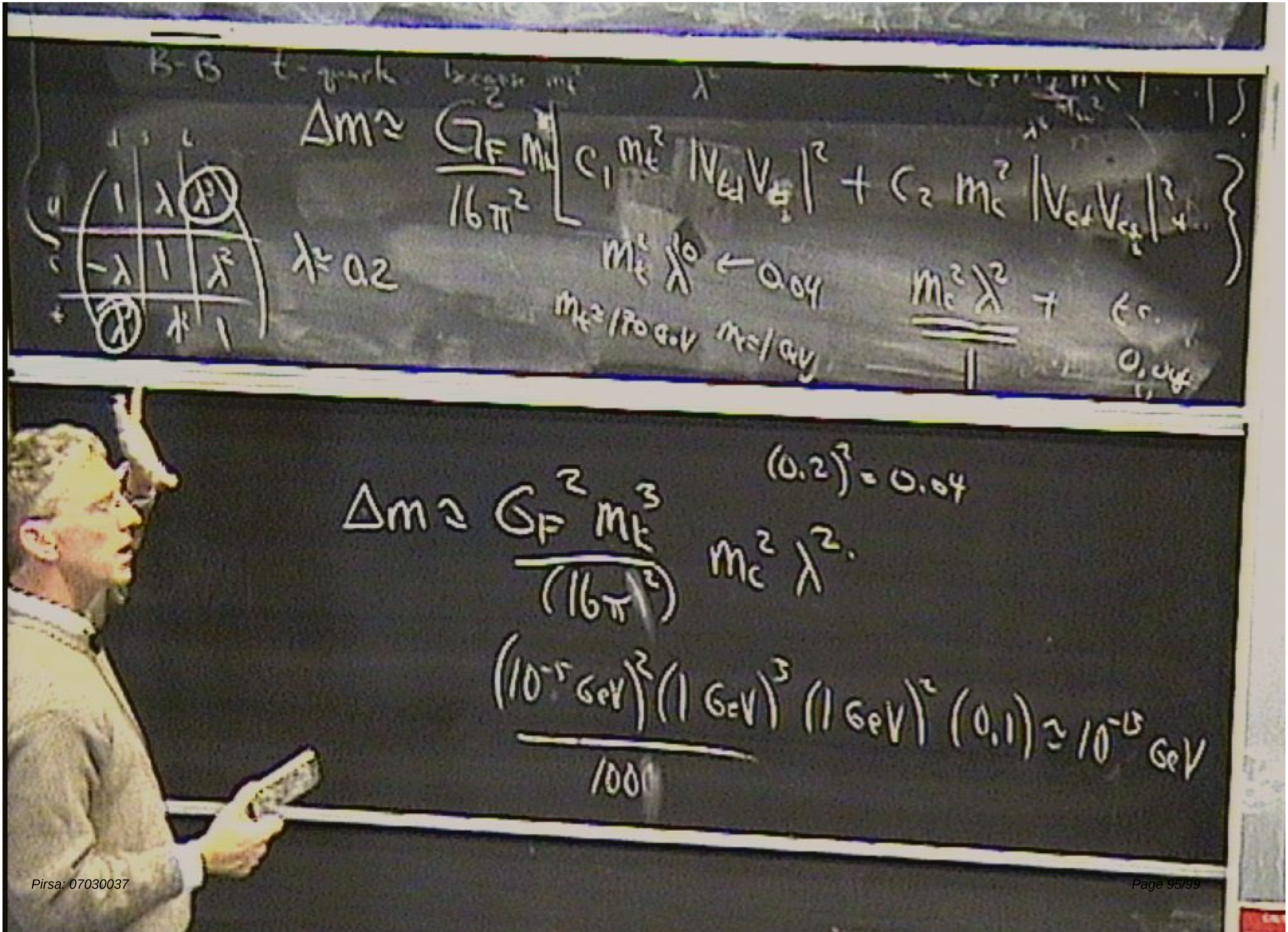

B, C ≃ c m_K^4 ≃ g_2^4 / (16π^2) m_K^4 / M_W^2 (C_1 m_c^2 / M_W^2 |V_tc V_cs^*|^2
(mass^2)
+ C_2 m_t^2 / M_W^2 |V_dt V_ts|^2
+ C_3 m_t m_c / M_W^2 |...|^2 }
Δm ≃ G_F^2 m_K / 16π^2 [C_1 m_t^2 |V_td V_ts|^2 + C_2 m_c^2 |V_cd V_cs|^2 + ... }
λ ≈ 0.2
m_t^2 λ^10 ← 0.04
m_c^2 λ^2 + εc
m_t = 170 GeV m_c = 1 GeV
1
0.04


λ ≈ 0.2
16π²


B-B
t-quark
λ ≈ 0.2
0.04


B-B t-quark
Δm ≃ G_F m_t / 16π² [c₁ m_t² |V_td V_tb|² + c₂ m_c² |V_cd V_cb|² + ...
λ ≈ 0.2
m_t² λ^10 ← 0.04
m_c² λ²
m_t ≈ 170 GeV m_c ≈ 1 GeV
(0.2)² = 0.04
Δm ≃ G_F² m_t³ / (16π²) m_c² λ²
(10⁻⁵ GeV)² (1 GeV)³ (1 GeV)² (0.1) / 1000 ≃ 10⁻¹³ GeV


B-B t-quark
Δm ≃ G_F m_t / 16π² [c₁ m_t² |V_td V_tb|² + c₂ m_c² |V_cd V_cb|² + ...]
λ ≃ 0.2
m_t² λ^10 ← 0.04
m_c² λ²
m_t ≈ 170 GeV   m_c ≈ 1 GeV
(0.2)² = 0.04
Δm ≃ G_F² m_t³ / (16π²) m_c² λ²
(10^-5 GeV)² (1 GeV)³ (1 GeV)² (0.1) / 1000 ≃ 10^-15 GeV


B-B t-quark
$\Delta m \simeq \frac{G_F m}{16\pi^2}\left[c_1 m_t^2 |V_{td} V_{tb}|^2 + c_2 m_c^2 |V_{cd} V_{cb}|^2 + \ldots \right\}$
$\lambda \simeq 0.2$
$m_t^2 \lambda^0 \leftarrow 0.04$
$m_c^2 \lambda^2$
$m_t \simeq 170$ GeV $m_c \simeq 1$ GeV
$(0.2)^2 = 0.04$
$\Delta m \simeq \frac{G_F^2 m_t^3}{(16\pi^2)} m_c^2 \lambda^2.$
$\frac{(10^{-5}\,GeV)^2 (1\,GeV)^3}{1000} (1\,GeV)^2 (0.1) \simeq 10^{-13}$ GeV

$$\langle \phi(t) | \phi(0) \rangle = \frac{1}{2}\left[e^{-iE_+t} + e^{-iE_-t}\right]$$

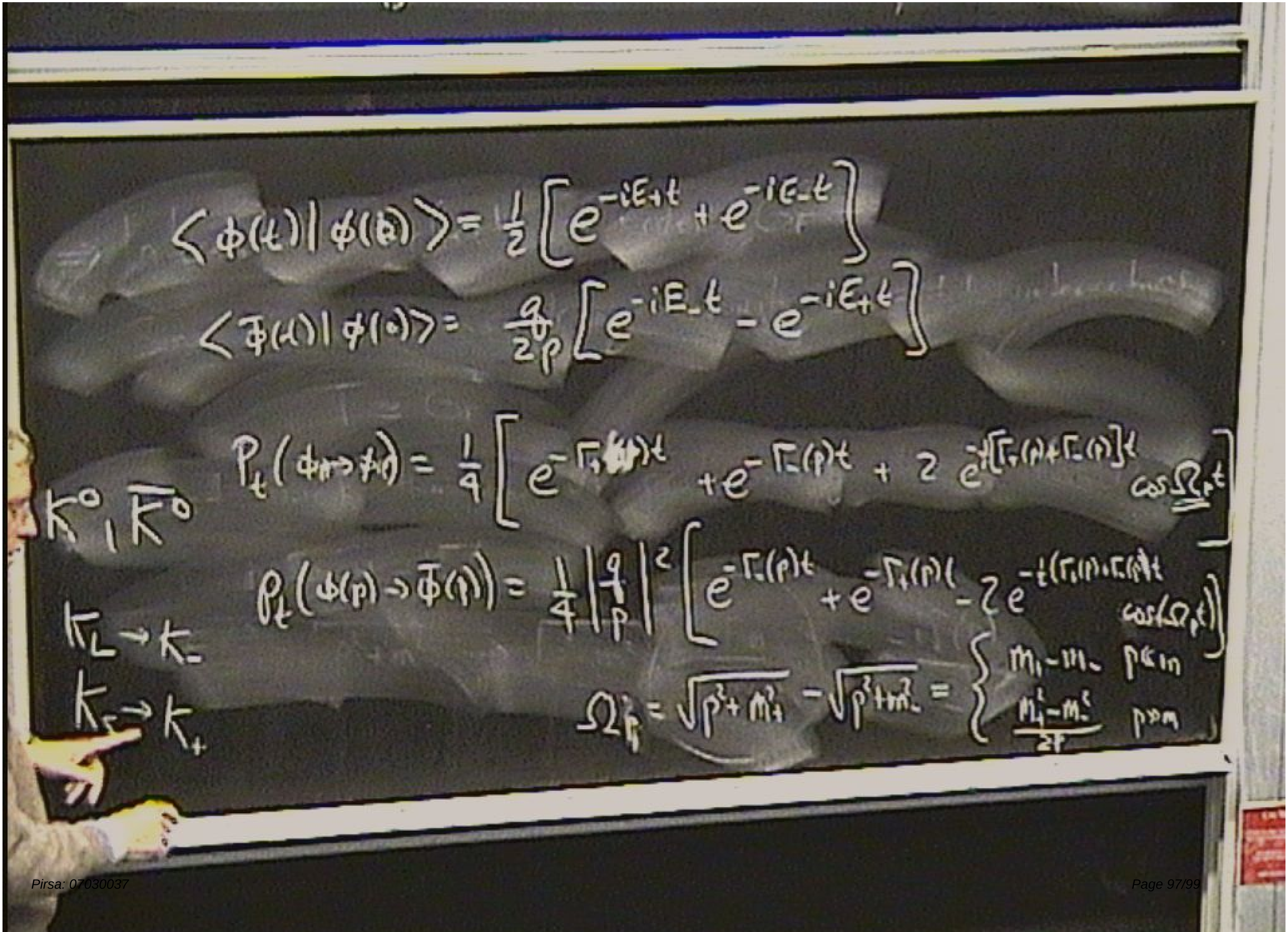
$$\langle \bar{\phi}(t) | \phi(0) \rangle = \frac{q}{2p}\left[e^{-iE_-t} - e^{-iE_+t}\right]$$

$K^0, \bar{K}^0$

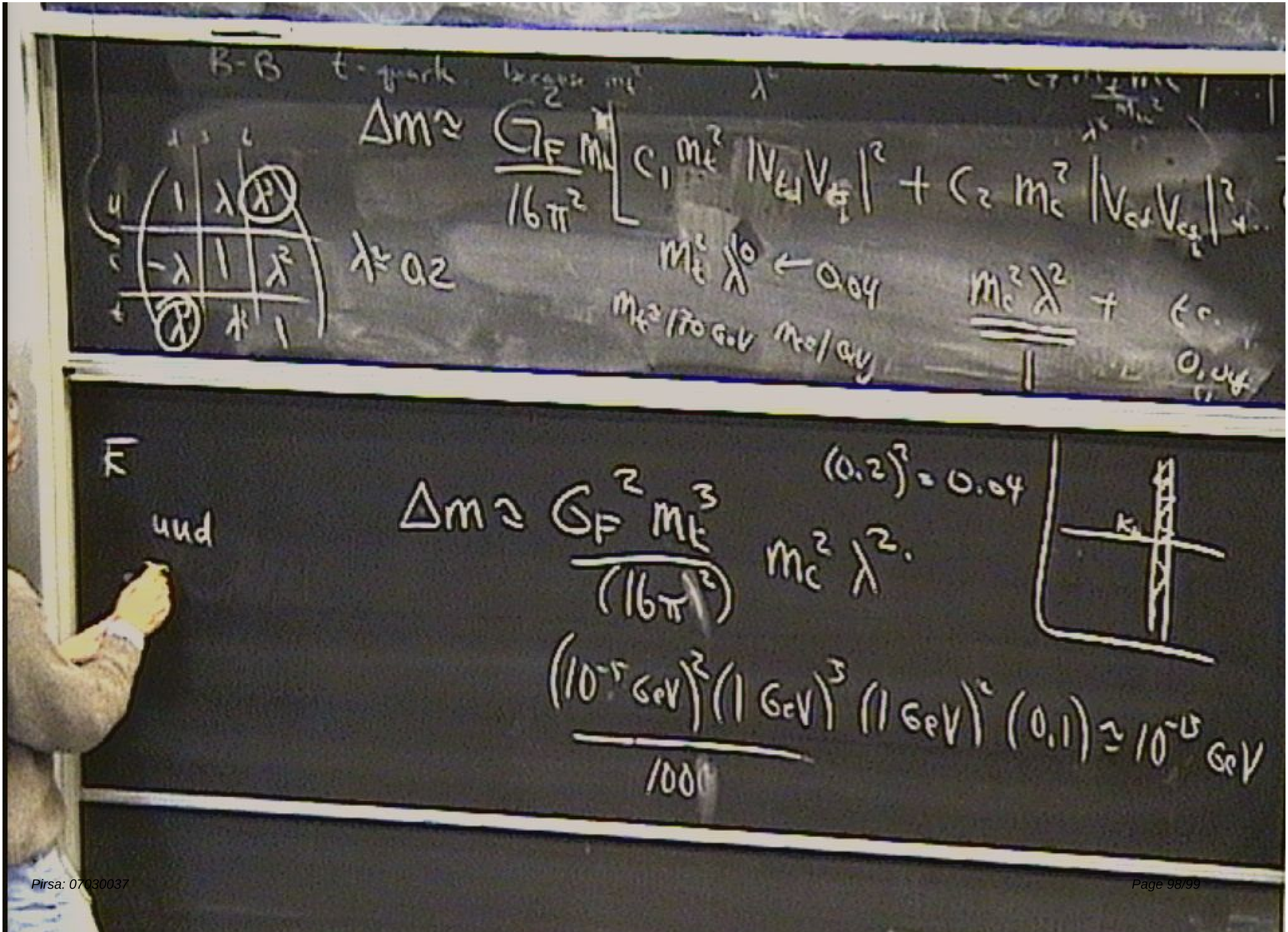
$$P_t(\phi(p)\to\phi(p)) = \frac{1}{4}\left[e^{-\Gamma_+(p)t} + e^{-\Gamma_-(p)t} + 2\, e^{-\frac{1}{2}[\Gamma_+(p)+\Gamma_-(p)]t}\cos\Omega_p t\right]$$

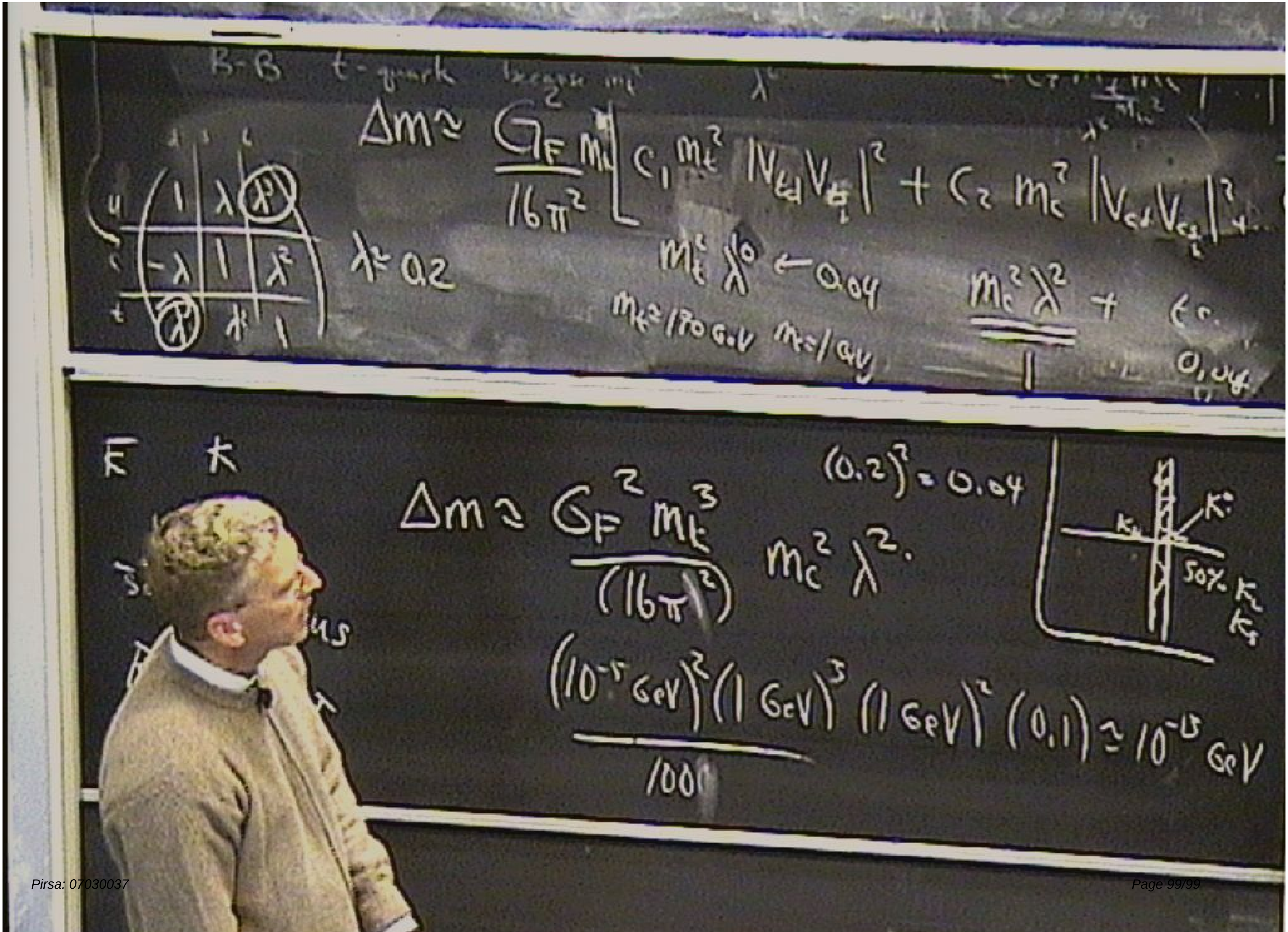
$$P_t(\phi(p)\to\bar{\phi}(p)) = \frac{1}{4}\left|\frac{q}{p}\right|^2\left[e^{-\Gamma_-(p)t} + e^{-\Gamma_+(p)t} - 2\, e^{-\frac{1}{2}(\Gamma_+(p)+\Gamma_-(p))t}\cos(\Omega_p t)\right]$$

$$\Omega_p = \sqrt{p^2+m_+^2} - \sqrt{p^2+m_-^2} = \begin{cases} m_+ - m_- & p \ll m \\ \frac{m_+^2 - m_-^2}{2p} & p \gg m \end{cases}$$



$\langle \phi(t) | \phi(0) \rangle = \frac{1}{2}\left[e^{-iE_+t} + e^{-iE_-t}\right]$
$\langle \bar{\Phi}(t) | \phi(0) \rangle = \frac{q}{2p}\left[e^{-iE_-t} - e^{-iE_+t}\right]$
$K^0, \bar{K}^0$
$P_t(\phi(p) \to \phi(p)) = \frac{1}{4}\left[e^{-\Gamma_+(p)t} + e^{-\Gamma_-(p)t} + 2\, e^{-\frac{1}{2}[\Gamma_+(p)+\Gamma_-(p)]t} \cos\Omega_p t\right]$
$P_t(\phi(p) \to \bar{\Phi}(p)) = \frac{1}{4}\left|\frac{q}{p}\right|^2\left[e^{-\Gamma_-(p)t} + e^{-\Gamma_+(p)t} - 2\, e^{-\frac{1}{2}(\Gamma_+(p)+\Gamma_-(p))t} \cos(\Omega_p t)\right]$
$K_L \to K_-$
$K_S \to K_+$
$\Omega_p = \sqrt{p^2+m_+^2} - \sqrt{p^2+m_-^2} = \begin{cases} m_+ - m_- & p \ll m \\ \frac{m_+^2 - m_-^2}{2p} & p \gg m \end{cases}$


B-B t-quark
Δm ≈ G_F² m_t / 16π² [c₁ m_t² |V_td V_tb|² + c₂ m_c² |V_cd V_cb|² …
λ ≈ 0.2
m_t² λ^10 ← 0.04
m_c² λ² + …
m_t ≈ 170 GeV m_c ≈ 1 GeV
K
uud
Δm ≈ G_F² m_t³ / (16π²) m_c² λ².
(0.2)² = 0.04
((10⁻⁵ GeV)² (1 GeV)³ (1 GeV)² (0.1) / 1000) ≈ 10⁻¹⁵ GeV



B-B   t-quark
Δm ≃ G_F² m_B / 16π² [c₁ m_t² |V_td V_tb|² + c₂ m_c² |V_cd V_cb|² + ...
λ ≃ 0.2
m_t² λ⁰ ← 0.04
m_c² λ² + ...
m_t ≃ 170 GeV   m_c = 1 GeV
K̄   K
Δm ≃ G_F² m_K³ / (16π²) m_c² λ².
(0.2)² = 0.04
(10⁻⁵ GeV)² (1 GeV)³ (1 GeV)² (0.1) / 1000 ≃ 10⁻¹⁵ GeV
50%