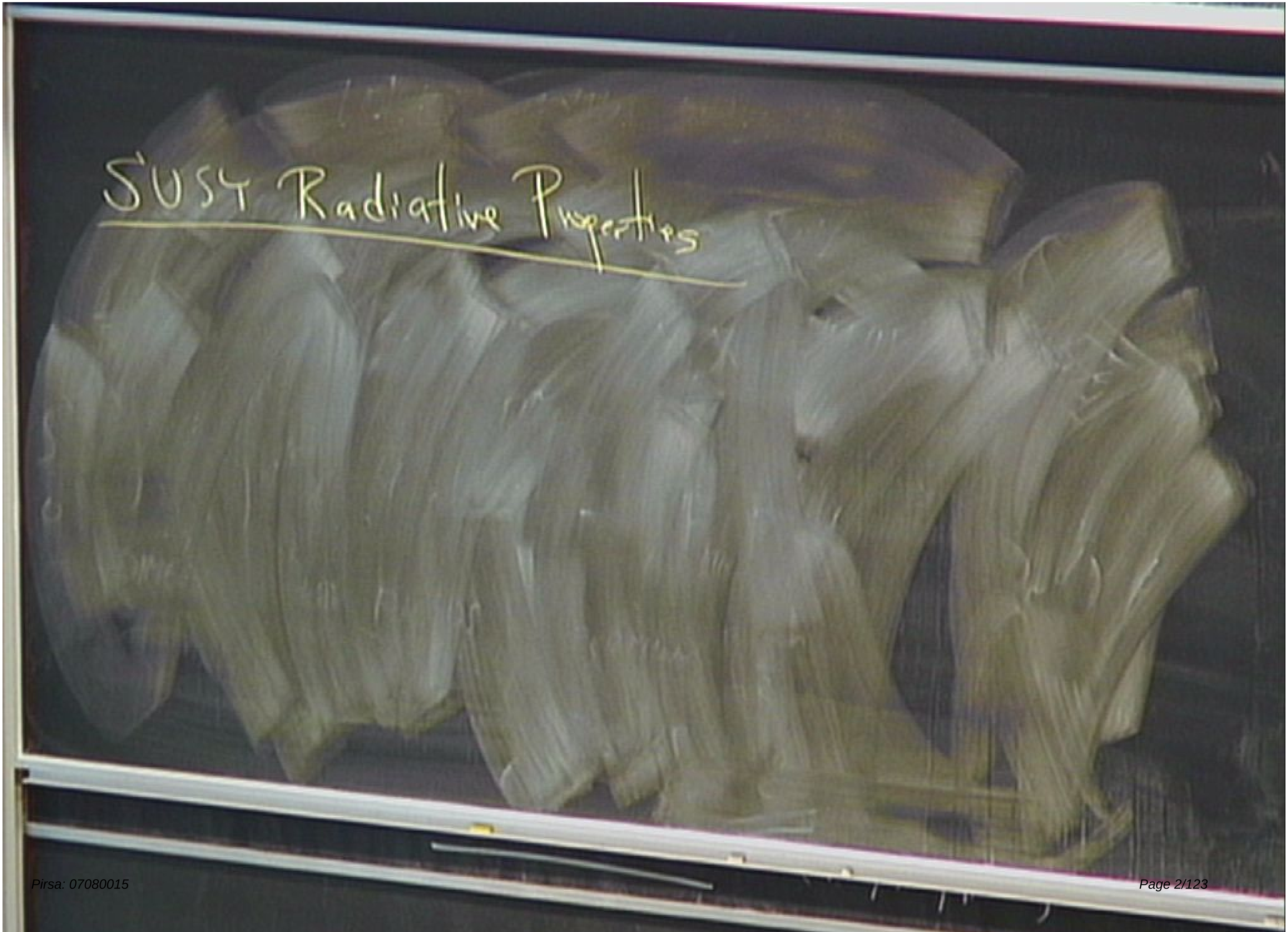
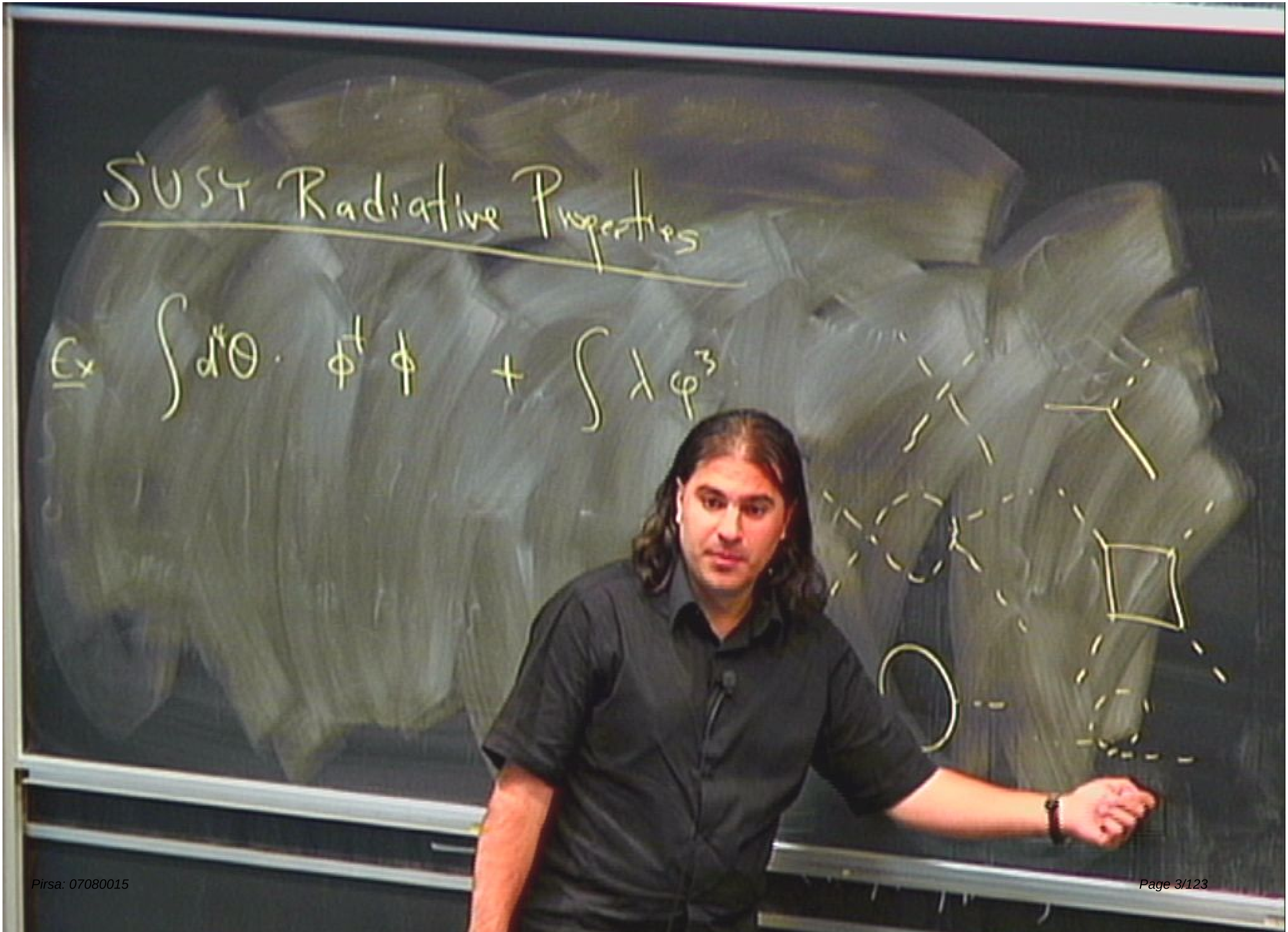
Title: Introduction to Low Energy Supersymmetry

Date: Aug 10, 2007 11:00 AM

URL: http://pirsa.org/07080015

Abstract:


SUSY Radiative Properties


SUSY Radiative Properties
Ex $\int d^4\theta \cdot \phi^\dagger \phi + \int \lambda \varphi^3$

SUSY Radiative Properties

Ex $\int d^4\theta \cdot \phi^\dagger \phi + \int \lambda \varphi^3$


$\lambda + a\lambda^2 \log \Lambda^2$

$$\lambda \quad + \frac{a\lambda^2}{16\pi^2} \log \Lambda^2$$

SUSY Radiative Properties

Ex $\int d^4\theta \; \phi^\dagger \phi \quad + \int \lambda \phi^3$

$$\int d^4\theta \; \phi^\dagger \phi + \int \lambda \phi^3 + \frac{a\lambda^2}{16\pi^2} \log\Lambda \; \phi^3$$

$$\times \frac{\lambda^\dagger \lambda}{16\pi^2} \log\Lambda$$

SUSY Radiative Properties

Ex $\int d^4\theta \cdot \phi^\dagger \phi + \int \lambda \varphi^3$

$$\int d^4\theta \, \phi^\dagger \phi \left(1 + \frac{a \lambda^\dagger \lambda}{16\pi^2} \log \Lambda^2\right) + \int \lambda \, \cancel{\phi^3 + \frac{a\lambda^2}{16\pi^2} \log} \Lambda \, \phi^3$$

$$\times \frac{\lambda^\dagger \lambda}{16\pi^2} \log \Lambda$$

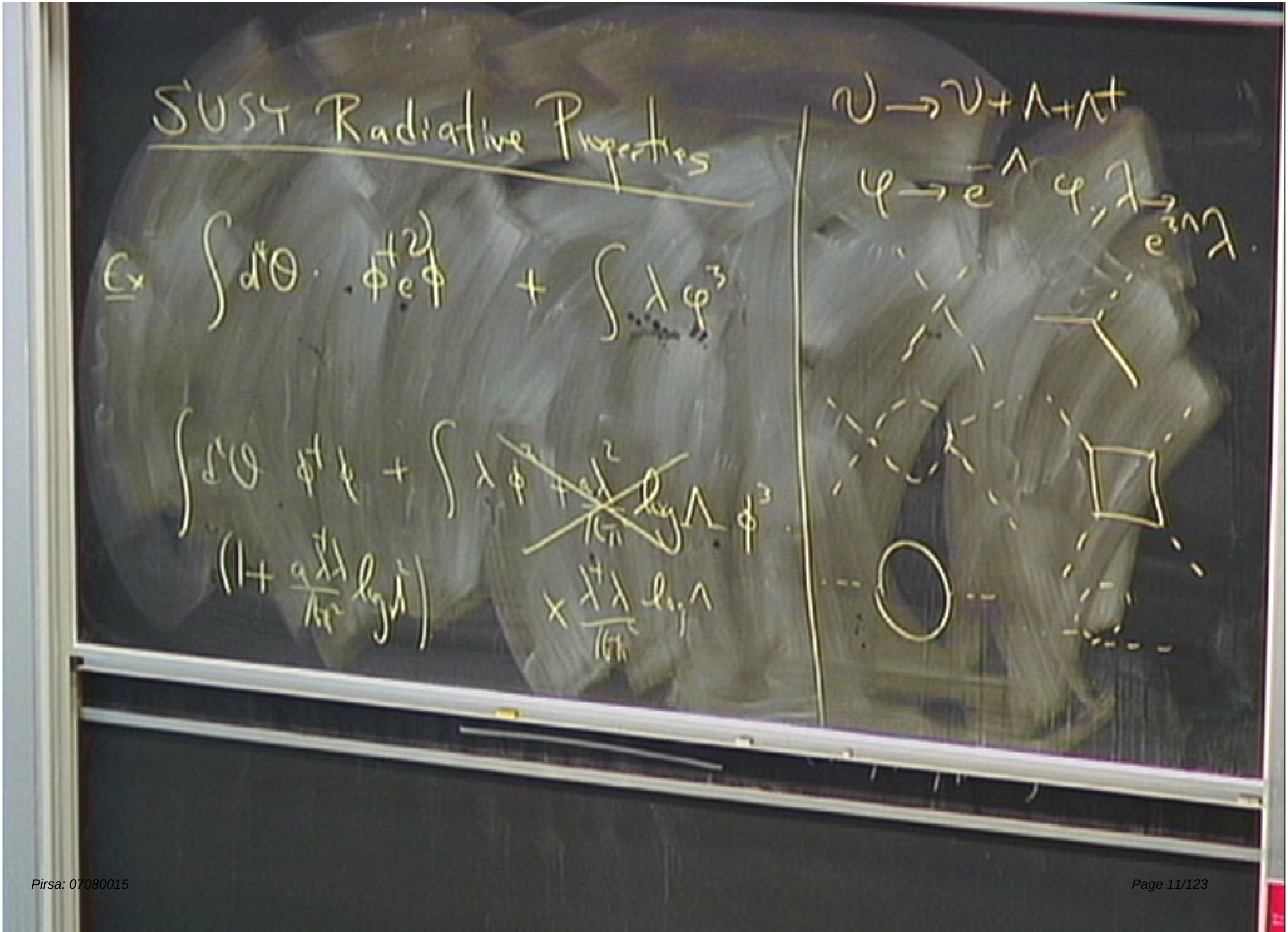
SUSY Radiative Properties

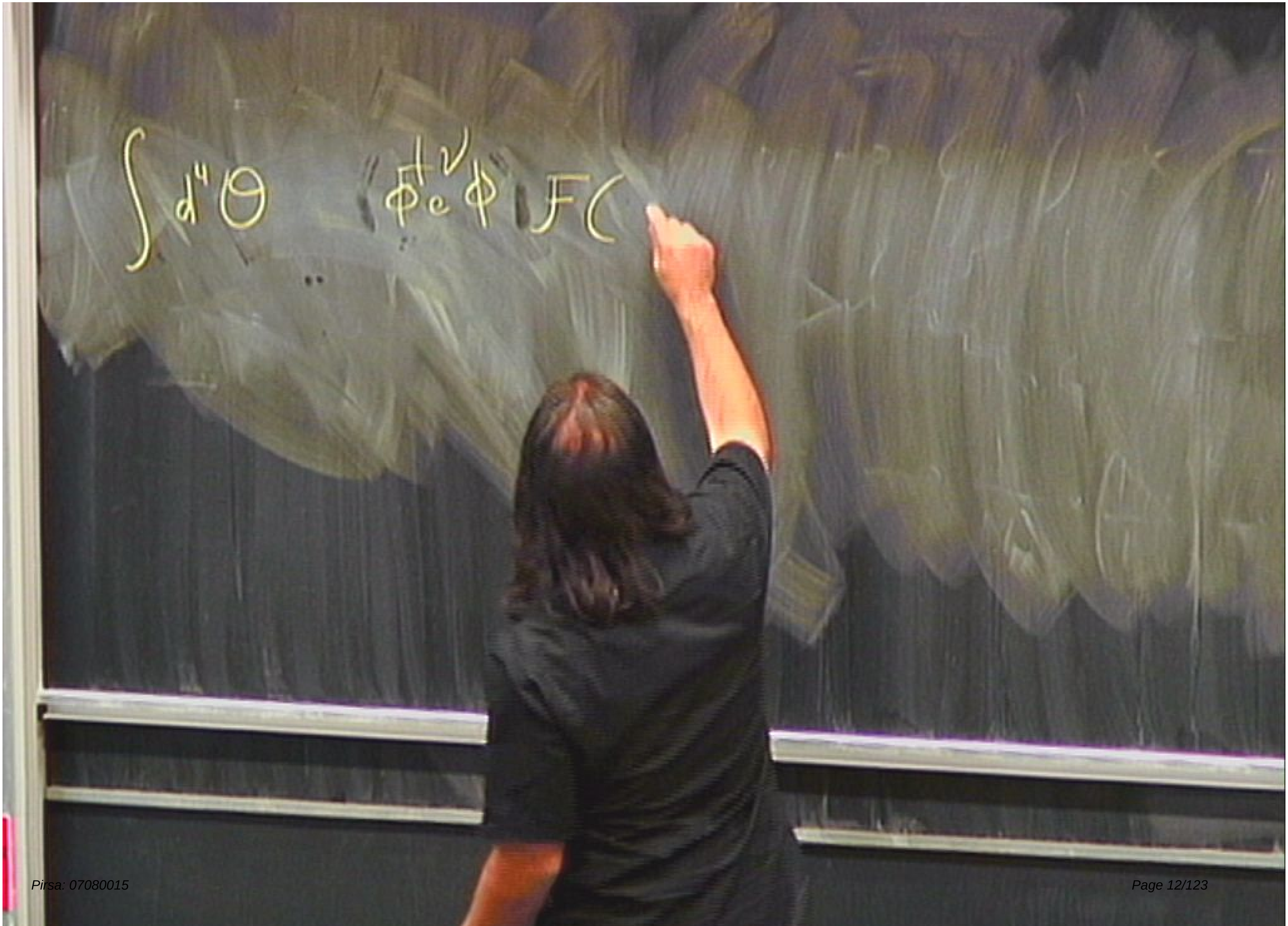
Ex $\int d^4\theta \cdot \phi^\dagger \phi \; + \int \lambda \phi^3$

$\int d^4\theta \; \phi^\dagger \phi \; + \int \lambda \phi^3 \cancel{+ \frac{a\lambda^2}{16\pi^2} \log\Lambda} \; \phi^3$

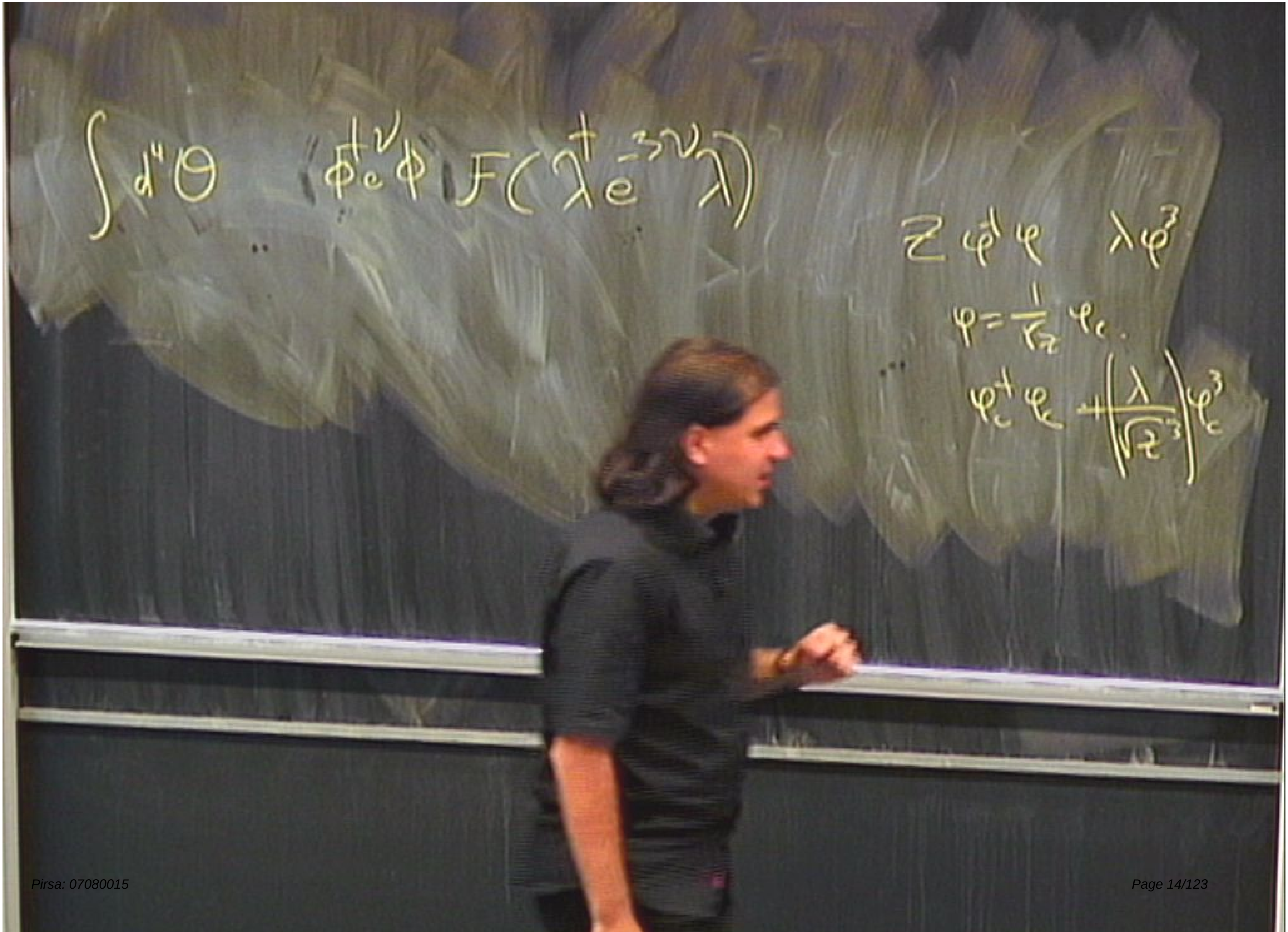
$\left(1 + \frac{a\lambda^\dagger\lambda}{16\pi^2} \log\Lambda^2\right)$ $\qquad \times \frac{\lambda^\dagger\lambda}{16\pi^2} \log\Lambda$

$$\int d^4\theta \quad \Phi^\dagger \Phi \, F($$


SUSY Radiative Properties
Ex $\int d^4\theta \, \phi^\dagger e^{2V} \phi + \int \lambda \varphi^3$
$\int d^4\theta \, \phi^\dagger \phi \left(1 + \frac{a \lambda^\dagger \lambda}{16\pi^2} \log \Lambda^2\right) + \int \lambda \phi^3 \times \frac{\lambda^\dagger \lambda}{16\pi^2} \log \Lambda$
$V \to V + \Lambda + \Lambda^\dagger$
$\varphi \to e^{-\Lambda} \varphi, \; \lambda \to e^{3\Lambda} \lambda$


$\int d^4\theta \; (\Phi^\dagger e^V \Phi)\, F($

$$\int d^4\theta \quad (\phi^\dagger e^V \phi) \, F(\lambda^\dagger e^{-3V} \lambda)$$


$\int d^4\theta \;\; \phi_c^\dagger e^V \phi \; F(\lambda^\dagger e^{-3V} \lambda)$
$Z \varphi^\dagger \varphi \quad \lambda \varphi^3$
$\varphi = \frac{1}{\sqrt{Z}} \varphi_c$
$\varphi_c^\dagger \varphi_c + \left(\frac{\lambda}{\sqrt{Z^3}}\right) \varphi_c^3$

$\Lambda,$

$$\mu \int d^4\theta \quad \phi_0^\dagger e^{V_{\mu}} \phi \, F(\lambda^\dagger e^{-3V} \lambda)$$

$$Z \varphi^\dagger \varphi \qquad \lambda \varphi^3$$

$$\phi^\dagger e^{V(\mu)} \phi$$

$$\varphi = \frac{1}{\sqrt{Z}} \varphi_c .$$

$$\varphi_c^\dagger \varphi_c + \left(\frac{\lambda}{\sqrt{Z^3}}\right) \varphi_c^3$$

$$\mu \frac{\partial}{\partial \mu} V(\mu)$$

$\Lambda,$

$$\mu \int d^4\theta \quad \phi^\dagger e^{V_\mu} \phi \; F(\lambda^\dagger e^{-3V} \lambda)$$

$$Z\,\varphi^\dagger \varphi \qquad \lambda \varphi^3$$

$$\phi^\dagger e^{V(\mu)} \phi$$

$$\varphi = \frac{1}{\sqrt{Z}} \varphi_c .$$

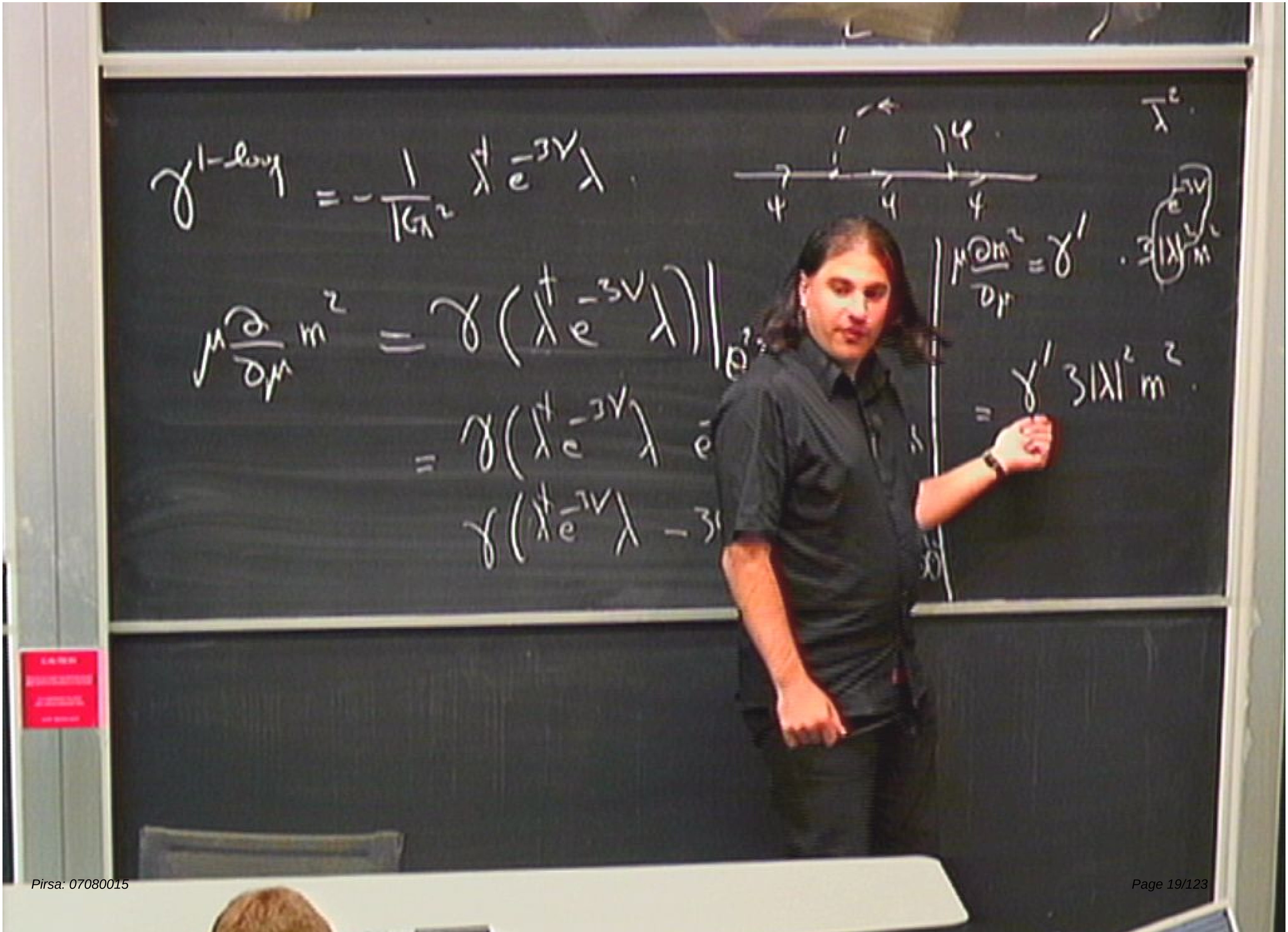
$$\varphi_c^\dagger \varphi_c + \left(\frac{\lambda}{\sqrt{Z^3}}\right) \varphi_c^3$$

$$\left.\begin{array}{l} \mu \frac{\partial}{\partial \mu} V(\mu) = \gamma\left(\lambda^\dagger e^{-3V} \lambda\right) \\ \left[\, \mu \frac{\partial}{\partial \mu} \log Z = \gamma\left(\lambda^2_{phys}\right) \right. \end{array}\right\} \gamma : \text{anom. dimension}$$

$$\gamma^{1-loop} = -\frac{1}{16\pi^2}\, \lambda^{\dagger} e^{-3V} \lambda \, .$$

$$\gamma^{1\text{-loop}} = -\frac{1}{16\pi^2}\lambda^{\dagger} e^{-3V}\lambda$$

$$\mu\frac{\partial}{\partial\mu} m^2 =$$



$\gamma^{1\text{-loop}} = -\frac{1}{16\pi^2} \lambda^\dagger e^{-3V} \lambda$
$\mu \frac{\partial}{\partial \mu} m^2 = \gamma(\lambda^\dagger e^{-3V} \lambda)|$
$= \gamma(\lambda^\dagger e^{-3V} \lambda$
$\gamma(\lambda^\dagger e^{-3V} \lambda - 3$
$\mu \frac{\partial m^2}{\partial \mu} = \gamma'$
$= \gamma' \, 3|\lambda|^2 m^2$

$$\gamma^{1\text{-loop}} = -\frac{1}{16\pi^2}\,\bar{\lambda}\,e^{-3V}\lambda$$

$\bar{\lambda}^2$

$$\mu\frac{\partial}{\partial\mu} m^2 = \gamma\left(\bar{\lambda}\,e^{-3V}\lambda\right)\Big|_{\theta^2\bar{\theta}^2}$$

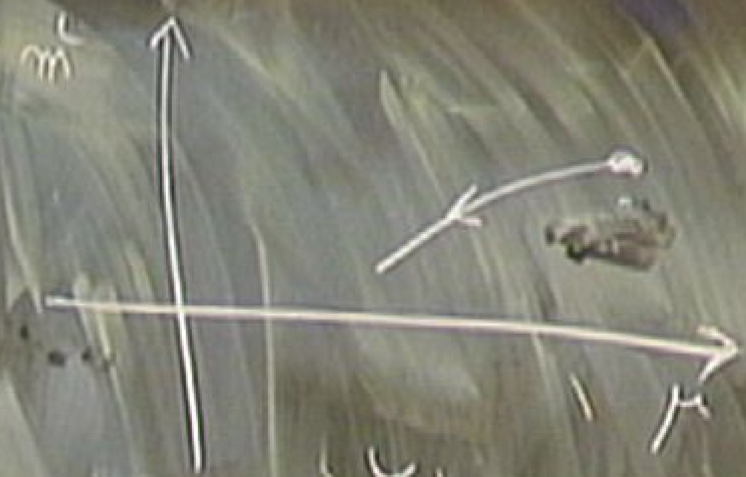
$$= \gamma\left(\bar{\lambda}\,e^{-3V}\lambda\; e^{-3\theta^2\bar{\theta}^2 m^2}\right)\Big|_{\theta^2\bar{\theta}^2}$$

$$\gamma\left(\bar{\lambda}\,e^{-3V}\lambda - 3\theta^2\bar{\theta}^2 m^2\,\bar{\lambda}\,e^{-V}\lambda\right)\Big|_{\theta^2\bar{\theta}^2}$$

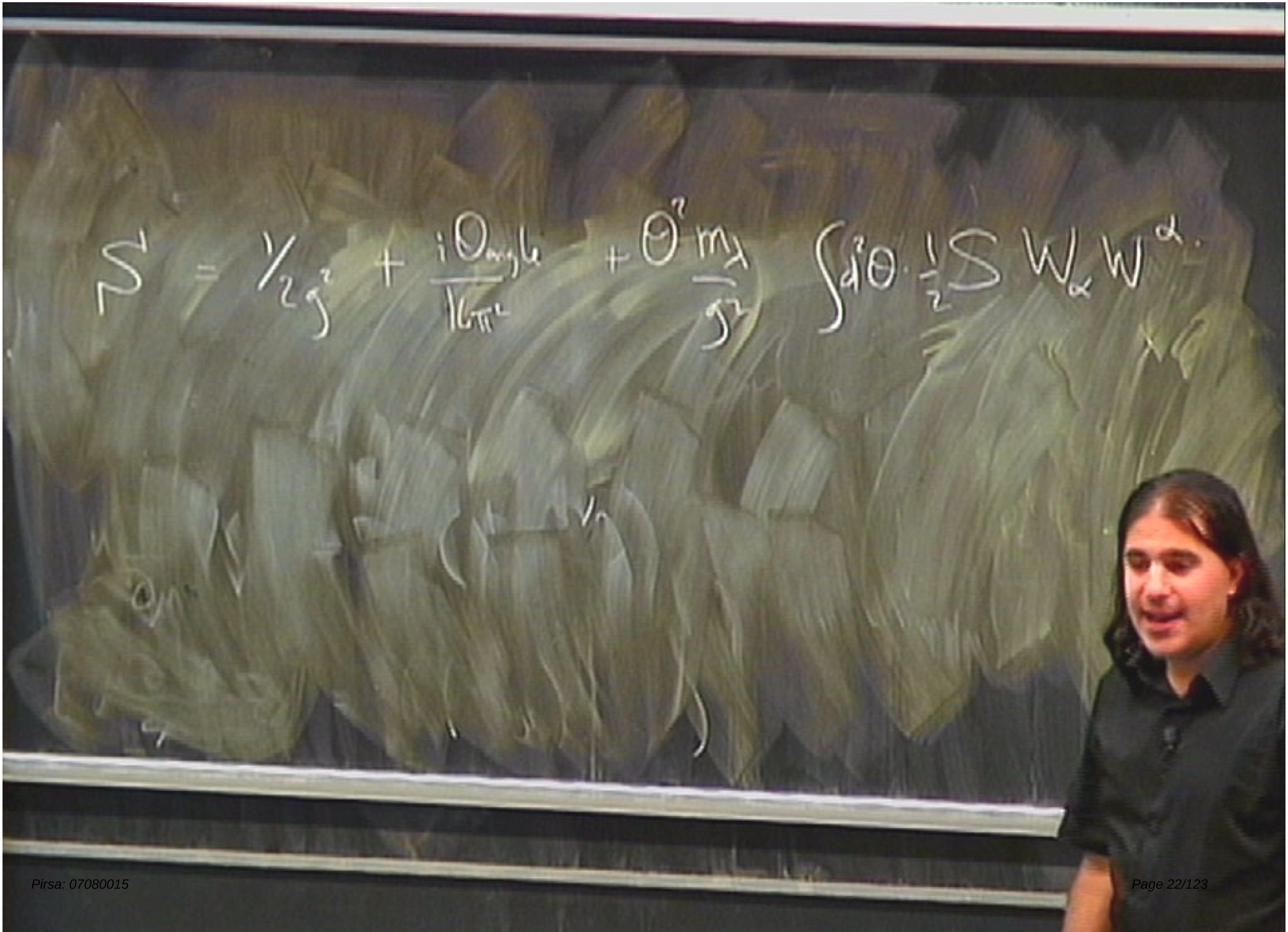
$$\mu\frac{\partial m^2}{\partial\mu} = \gamma' \cdot 3|\lambda|^2 m^2$$

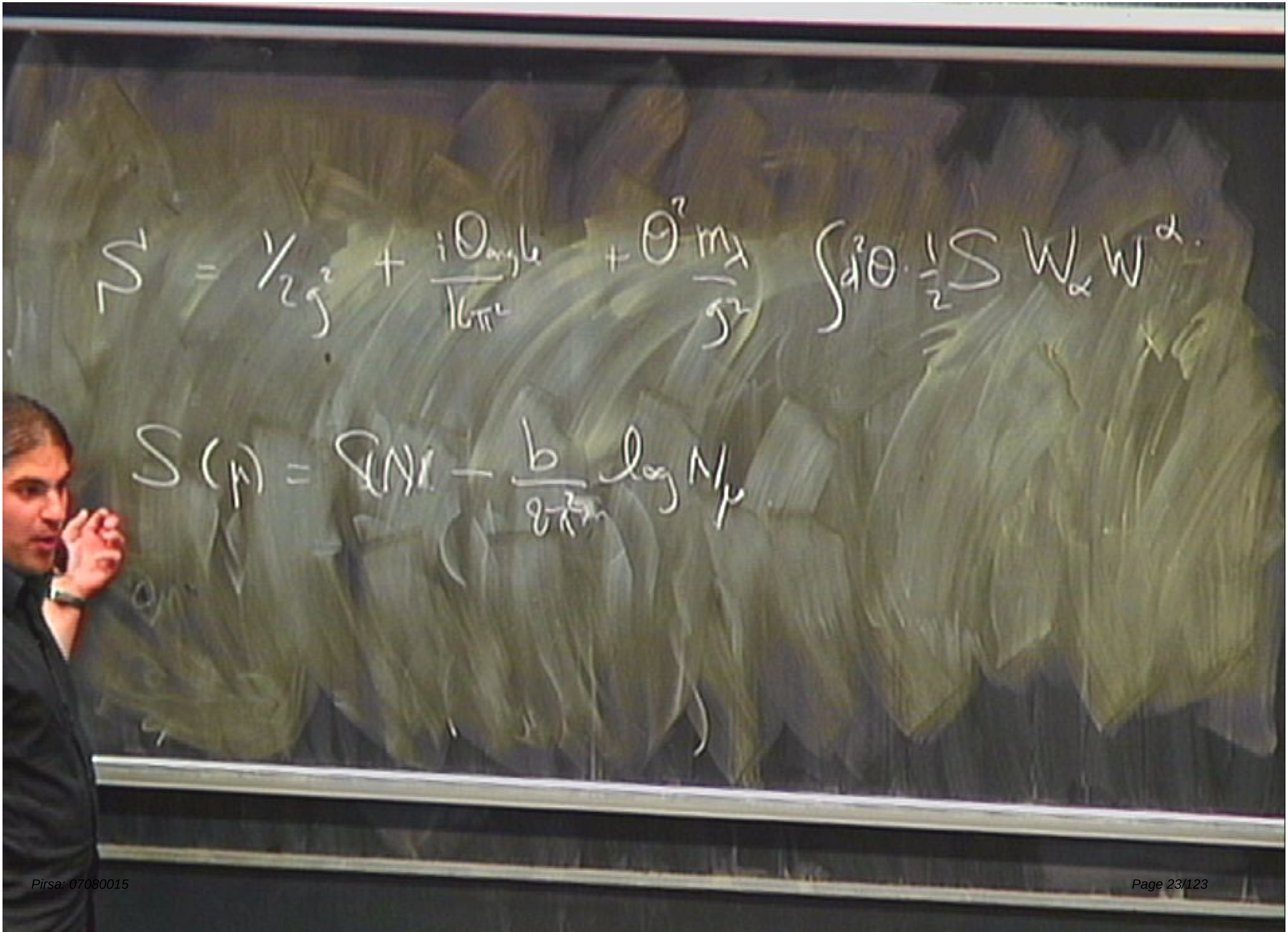
$$= \gamma'\, 3|\lambda|^2 m^2$$

$$\mu \frac{\partial m^2}{\partial \mu} = \frac{3}{16\pi^2} |\lambda| \, m^2$$



This decreases soft masses.


$S = \frac{1}{2g^2} + \frac{i\theta_{angle}}{16\pi^2} + \theta^2 \frac{m_\lambda}{g^2} \int d^2\theta \cdot \frac{1}{2} S\, W_\alpha W^\alpha$


S = 1/2g^2 + iθ_angle/16π^2 + θ^2 m_λ/g^2   ∫d^2θ · 1/2 S W_α W^α
S(μ) = S(M) − b/8π^2 log M/μ

$$S = \frac{1}{2g^2} + \frac{i\theta_{angle}}{16\pi^2} + \theta^2 \frac{m_\lambda}{g^2} \qquad \int d^2\theta \cdot \frac{1}{2} S\, W_\alpha W^\alpha$$

$$S(\mu) = S(\Lambda) - \frac{b}{8\pi^2} \log \Lambda/\mu$$

$$\boxed{\left(\frac{m_\lambda}{g^2}\right)(\mu) = \left(\frac{m_\lambda}{g^2}\right)(\Lambda)}$$

Φ_r

$$\gamma^{1\text{-loop}} = \frac{1}{8\pi^2}\, 2C_r\, g^2$$

Φ_r

$$\gamma^{1\text{-loop}} = \frac{+1}{8\pi^2}\, 2C_r\, g^2$$

$$\mu \frac{\partial}{\partial\mu} V_r = \frac{1}{8\pi^2}\,\frac{2C_r}{S+S^\dagger}$$

$$S = 1/g^2 + i\,\Theta_{\text{angle}} + \ldots$$

$$S^\dagger = 1/g^2 - i\,\Theta_{\text{angle}} + \ldots$$

$$S = \left(\frac{1}{2g^2} + \frac{i\theta_{angle}}{16\pi^2} + \theta^2 \frac{m_\lambda}{g^2}\right) \int d^2\theta \cdot \frac{1}{2} S\, W_\alpha W^\alpha$$

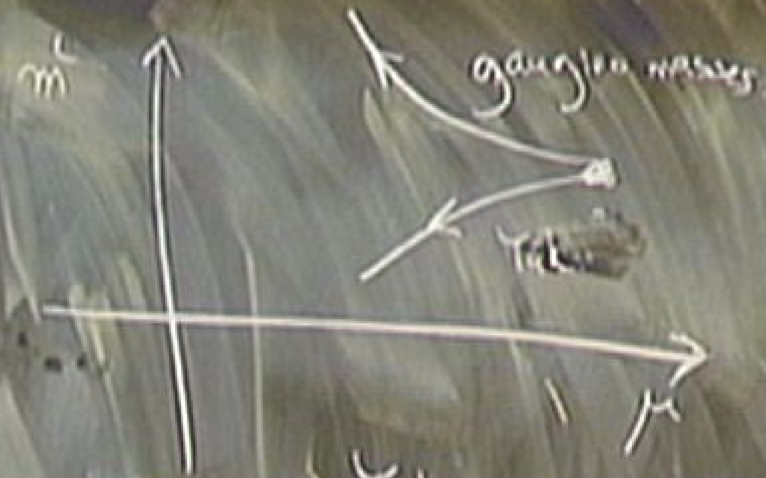
$$S(\mu) = S(\Lambda) - \frac{b}{8\pi^2} \log \Lambda/\mu$$

$$\boxed{\left(\frac{m_\lambda}{g^2}\right)(\mu) = \left(\frac{m_\lambda}{g^2}\right)(\Lambda)}$$

$$\mu \frac{\partial}{\partial \mu} m_r^2 = \frac{2C_r}{16\pi^2} \left. \frac{1}{\frac{1}{g^2} + \theta^2 \frac{m}{g^2} + \bar{\theta}^2 \frac{m^*}{g^2}} \right|_{\theta^2 \bar{\theta}^2}$$

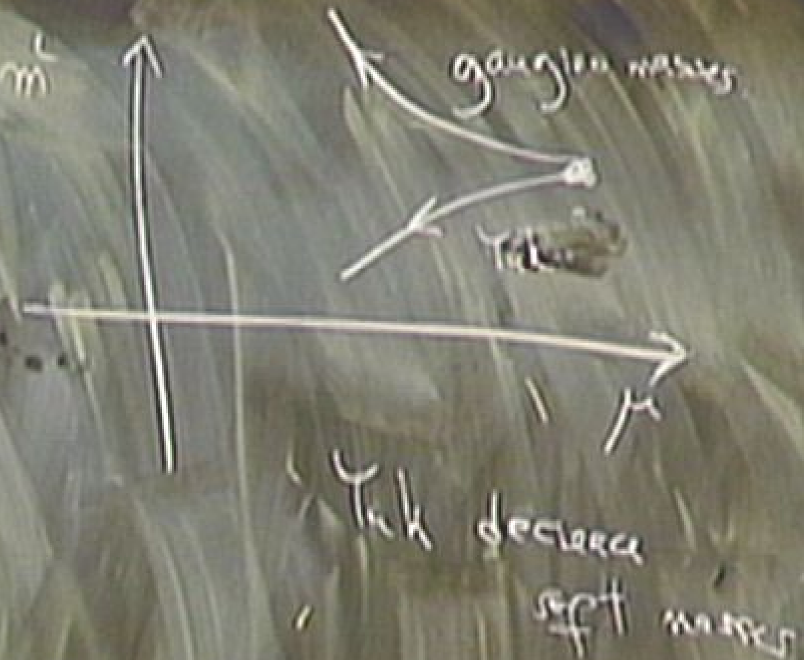
$$= -\frac{C_r}{16\pi^2}\, 4 g^2 m_\lambda^2$$

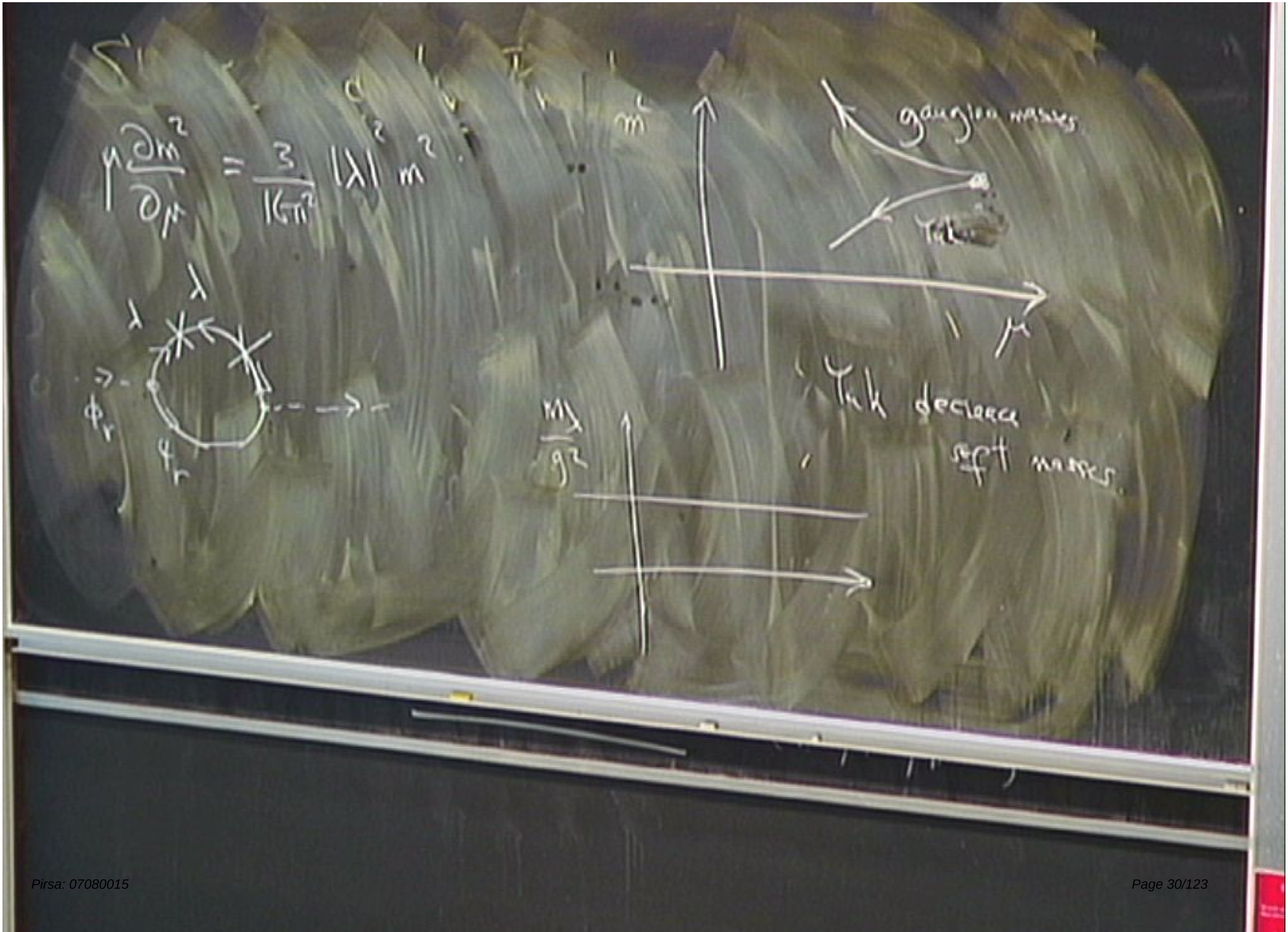
$$\mu \frac{\partial m^2}{\partial \mu} = \frac{3}{16\pi^2} |\lambda|^2 m^2$$



Yuk decrease
soft masses.

$$\mu \frac{\partial m^2}{\partial \mu} = \frac{3}{16\pi^2} |\lambda| m^2$$



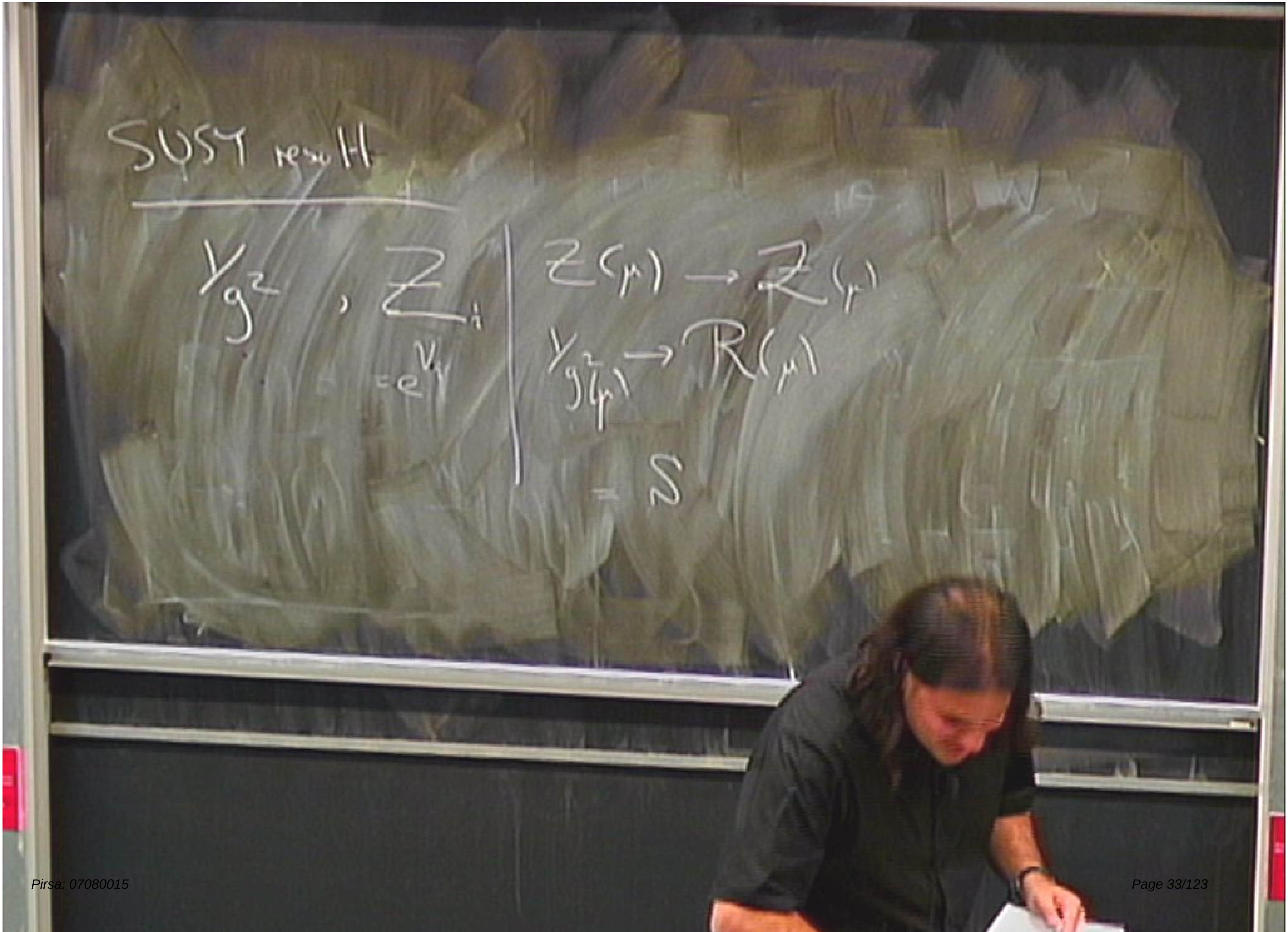


$\mu \frac{\partial m^2}{\partial \mu} = \frac{3}{16\pi^2} |\lambda| m^2$
gaugino masses
soft masses


SUSY result

SUSY result

$1/g^2$, Z


SUSY result
Y_{g^2} , Z_i = e^{V_i}
Z(μ) → Z(μ)
Y_{g^2(μ)} → R(μ)
= S

SUSY result

Y_{g^2} , Z_i
$= e^{V_i}$

$Z(\mu) \to \mathcal{Z}(\mu)$

$Y_{g^2(\mu)} \to R(\mu)$

$= S + S^\dagger + \frac{T_G}{8\pi^2} \log(S + S^\dagger)$

$- \sum_r \frac{T_r \log Z_r}{8\pi^2}.$

SUSY result

$\frac{1}{g^2}$, $Z_i = e^{V_i}$

$Z(\mu) \to \mathcal{Z}(\mu)$

$\frac{1}{g^2(\mu)} \to R(\mu)$

$S'(\mu) = S(\Lambda) - \frac{b}{8\pi^2} \log(\Lambda/\mu)$

$= S + S^\dagger + \frac{T_G}{8\pi^2} \log(S + S^\dagger)$

$- \sum_r \frac{T_r \log Z_r}{8\pi^2}.$

SUSY result

$$1/g^2, \quad Z_i = e^{V_i}$$

$$Z(\mu) \to \mathcal{Z}(\mu)$$

$$1/g^2(\mu) \to R(\mu)$$

$$S(\mu) = S(\Lambda) - \frac{b}{8\pi^2}\log(\Lambda/\mu)$$

$$= S + S^\dagger + \frac{T_G}{8\pi^2}\log(S+S^\dagger) - \sum_r \frac{T_r \log \mathcal{Z}_r}{8\pi^2}.$$

SUSY result

$1/g^2\,,\; Z_i = e^{V_i}$

$Z(\mu) \to \mathcal{Z}(\mu)$

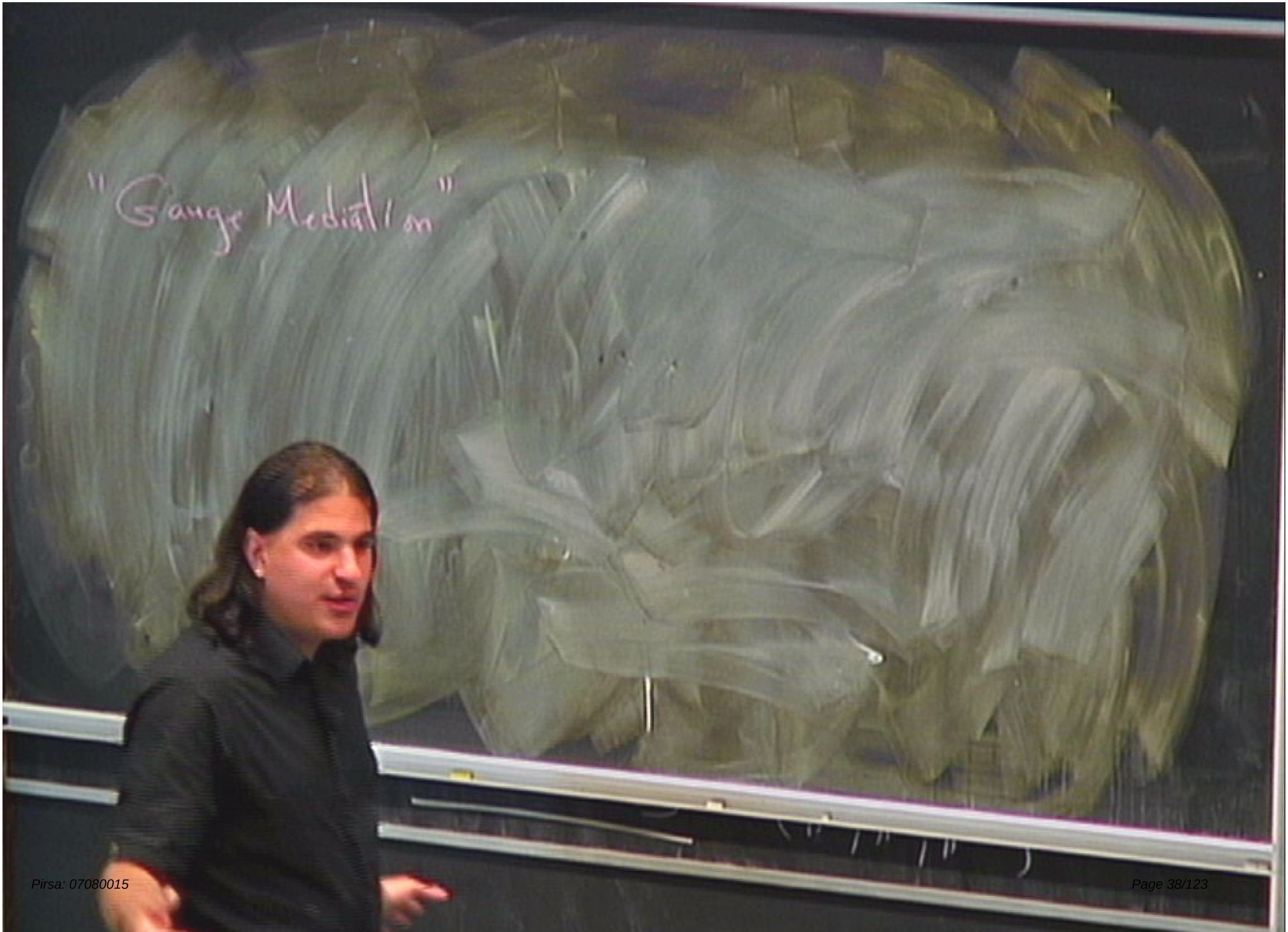
$1/g^2(\mu) \to R(\mu)$

$\boxed{\mathrm{tr}\, T^a_r T^b_r = T_r \delta^{ab}}$

$S(\mu) = S(\Lambda) - \frac{b}{8\pi^2}\log(\Lambda/\mu)$

$= S + S^\dagger + \frac{T_G}{8\pi^2}\log(S + S^\dagger)$

$- \sum_r \frac{T_r \log \mathcal{Z}_r}{8\pi^2}.$

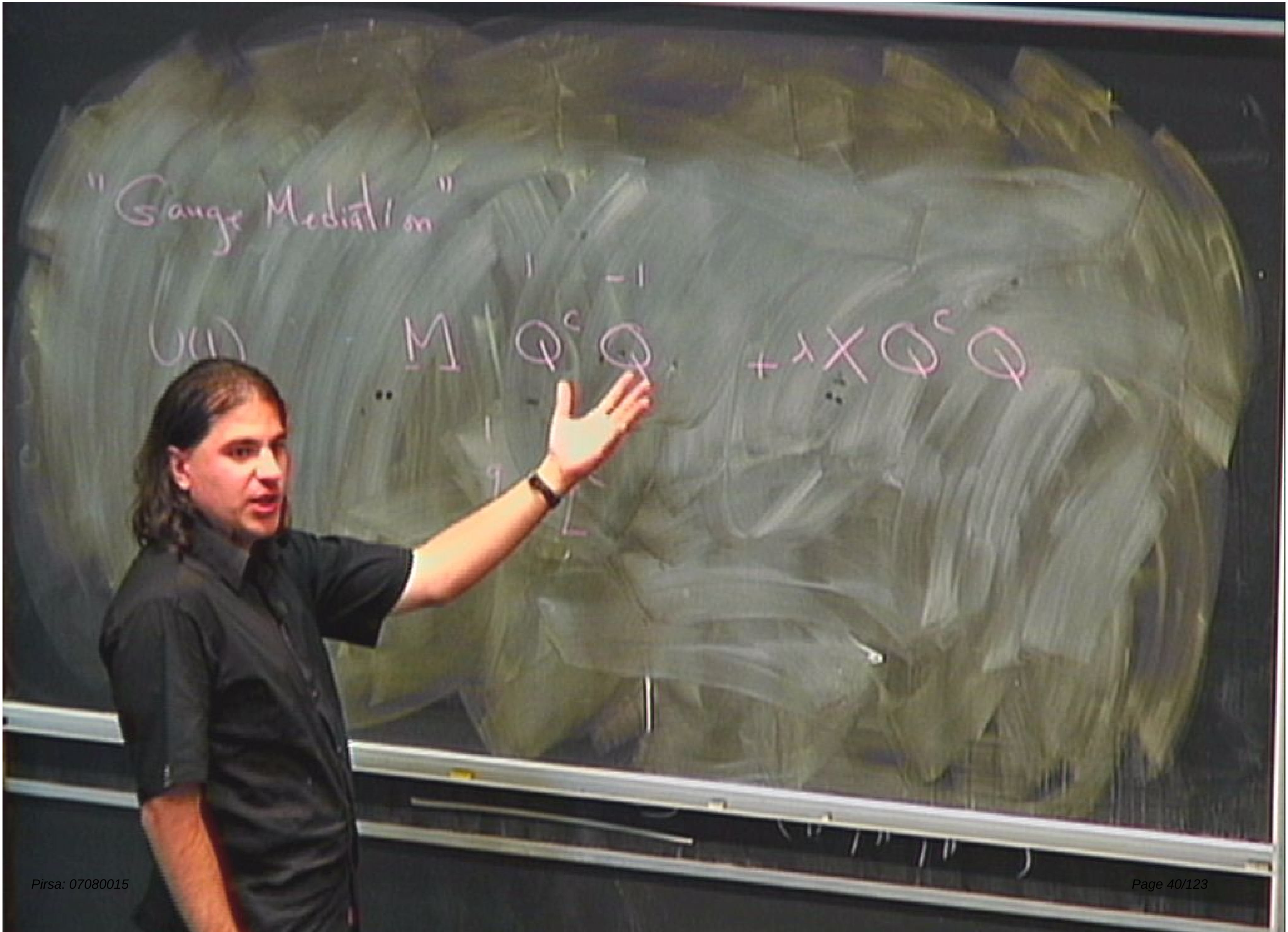

"Gauge Mediation"

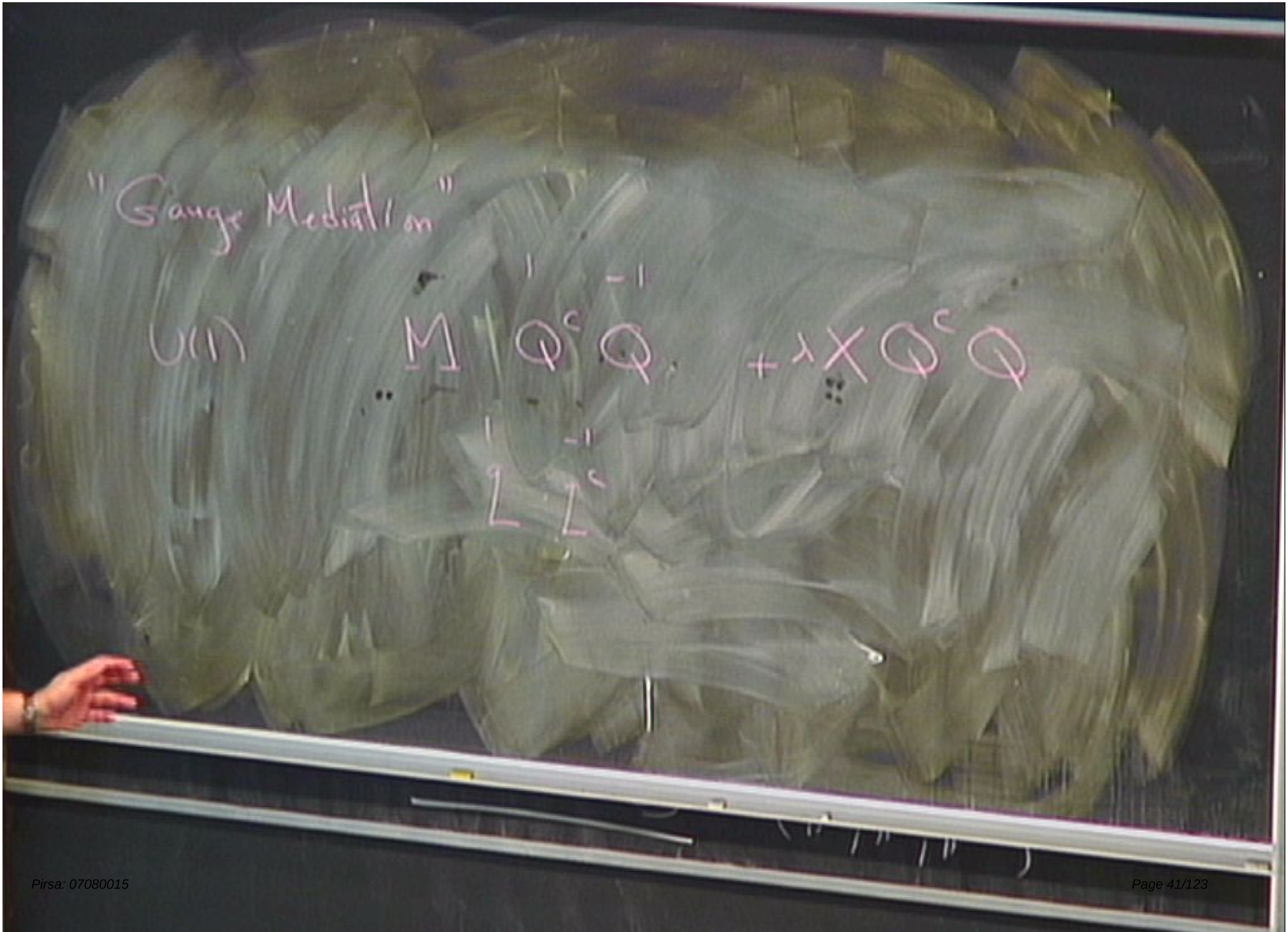
"Gauge Mediation"

$U(1)$

$$\underline{M} \mid \overset{1}{Q^c} \overset{-1}{Q}$$

$$\overset{1}{L} \overset{-1}{L^c}$$


"Gauge Mediation"
U(1)
1 -1
M Q^c Q + λXQ^cQ


"Gauge Mediation"
U(1)
1 -1
M Q^c Q + λ X Q^c Q
1 -1
L L^c

"Gauge Mediation"

$U(1)$

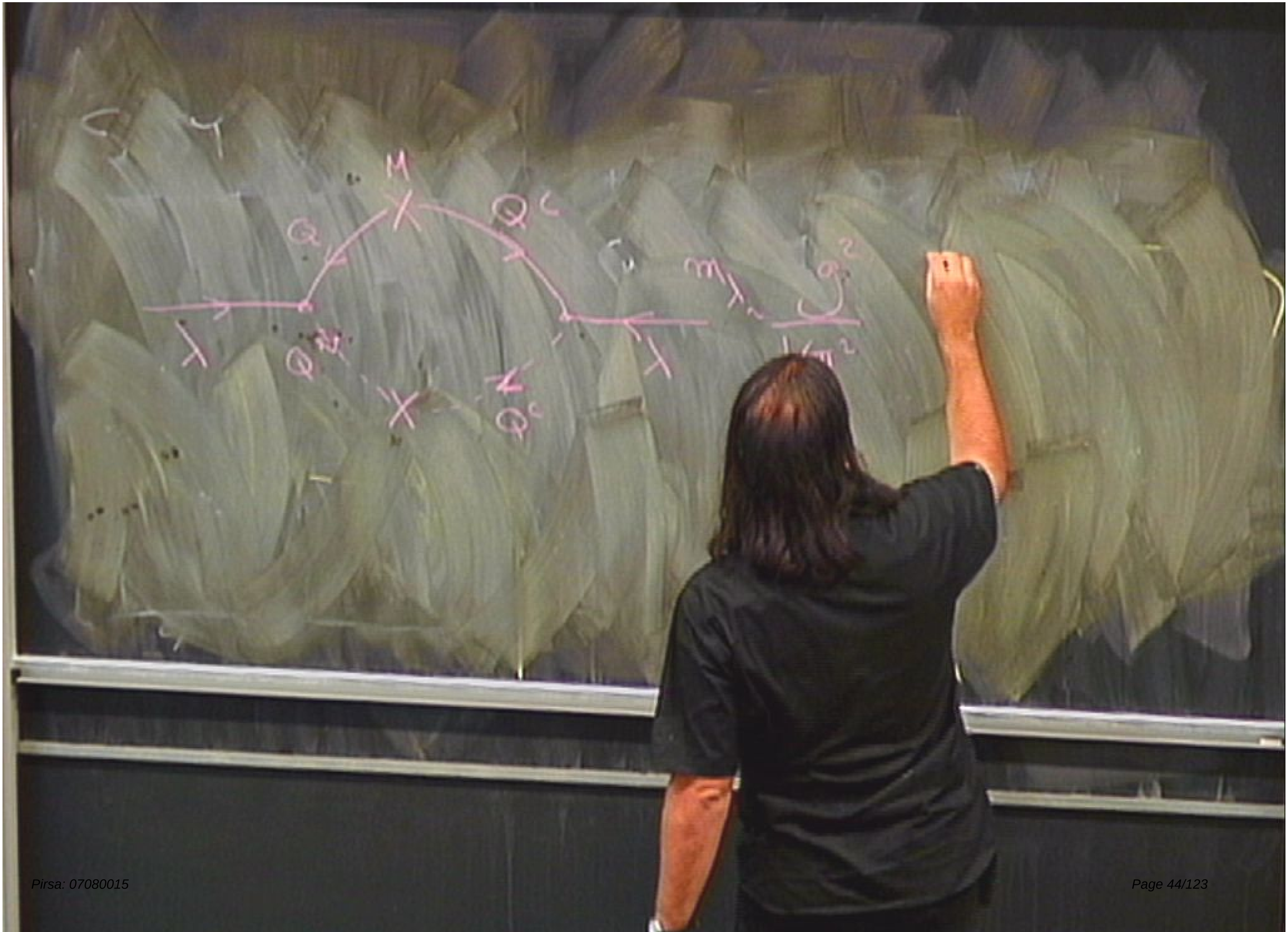
$$\overset{1}{Q}\;\overset{-1}{Q^c}$$

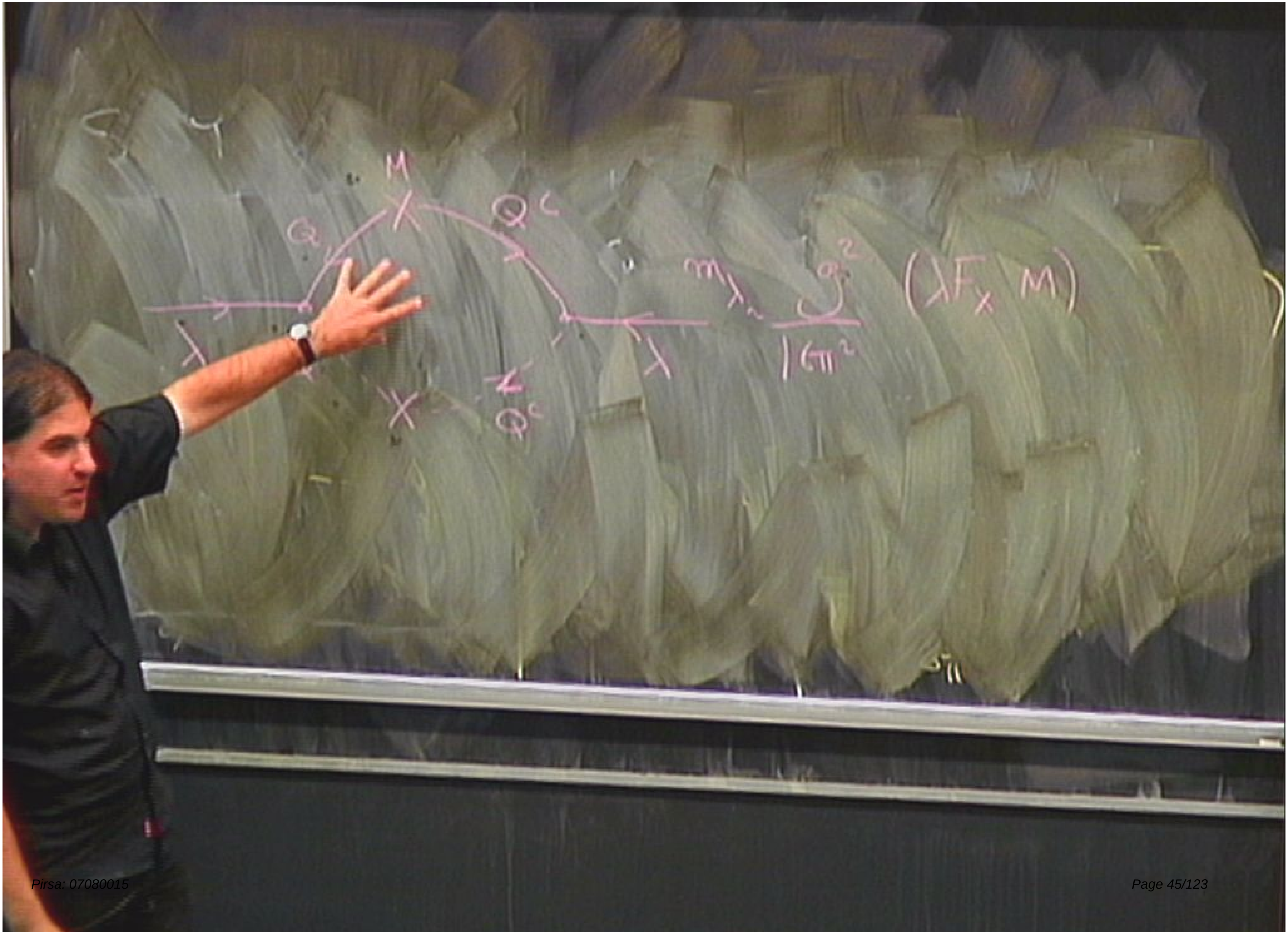
$$M\, Q^c Q + \lambda X Q^c Q$$

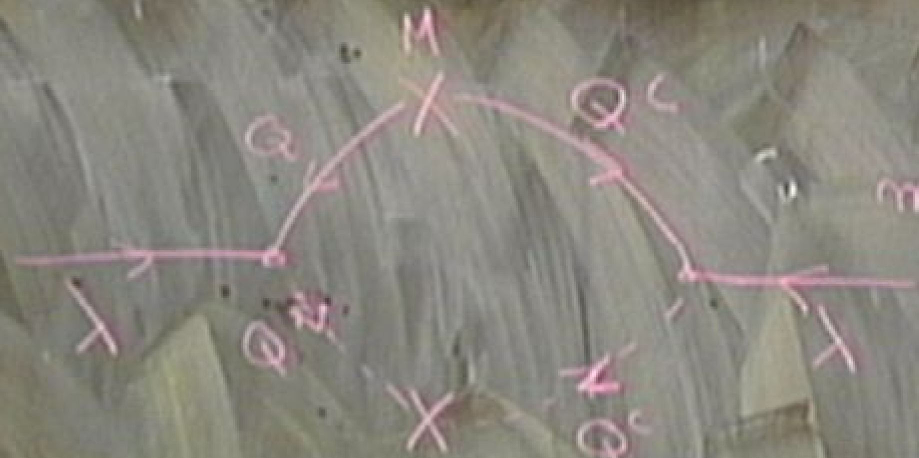
$$Q \rightarrow X \leftarrow Q^c$$

(λF_X)

$$\overset{1}{L}\;\overset{-1}{L^c}$$

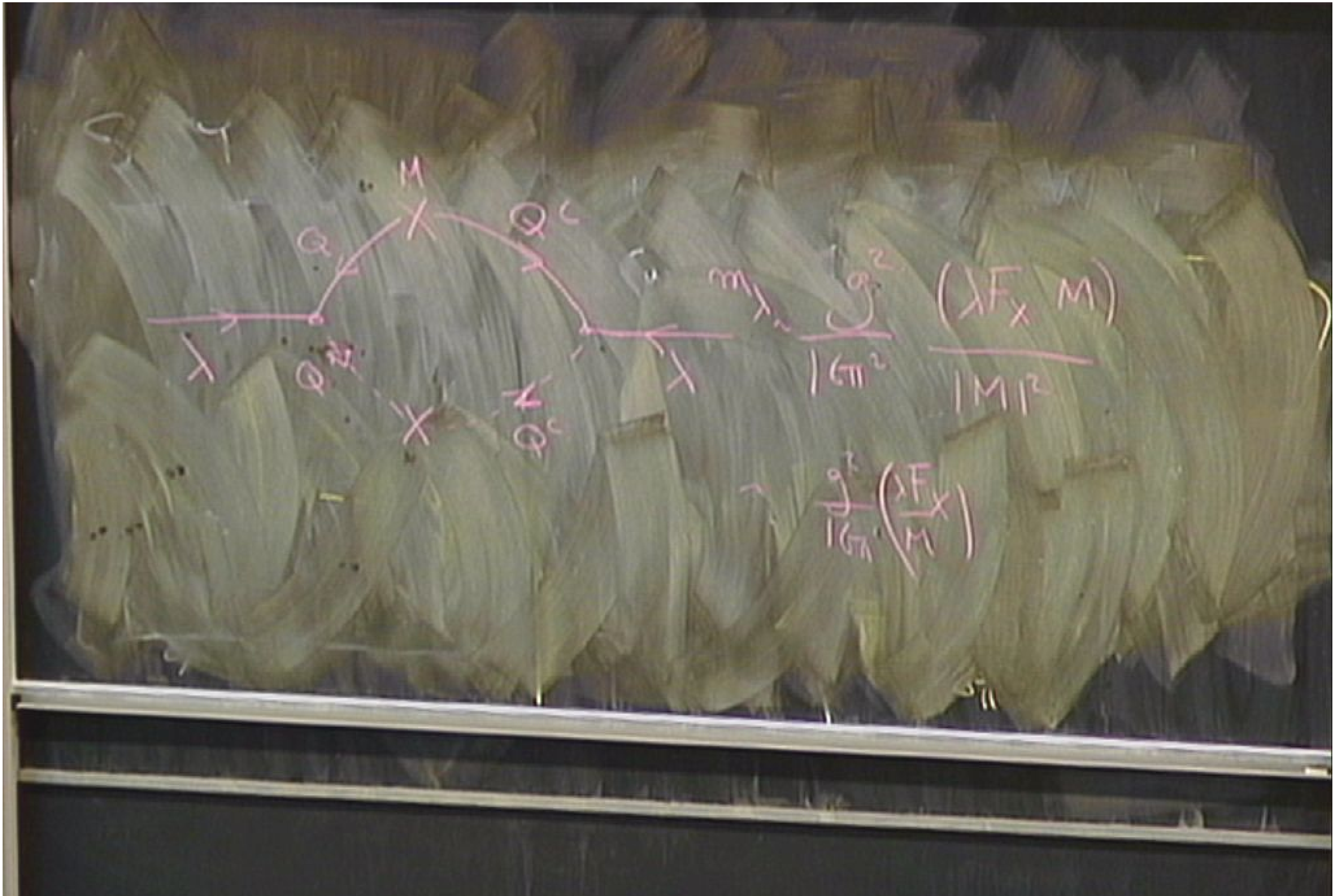


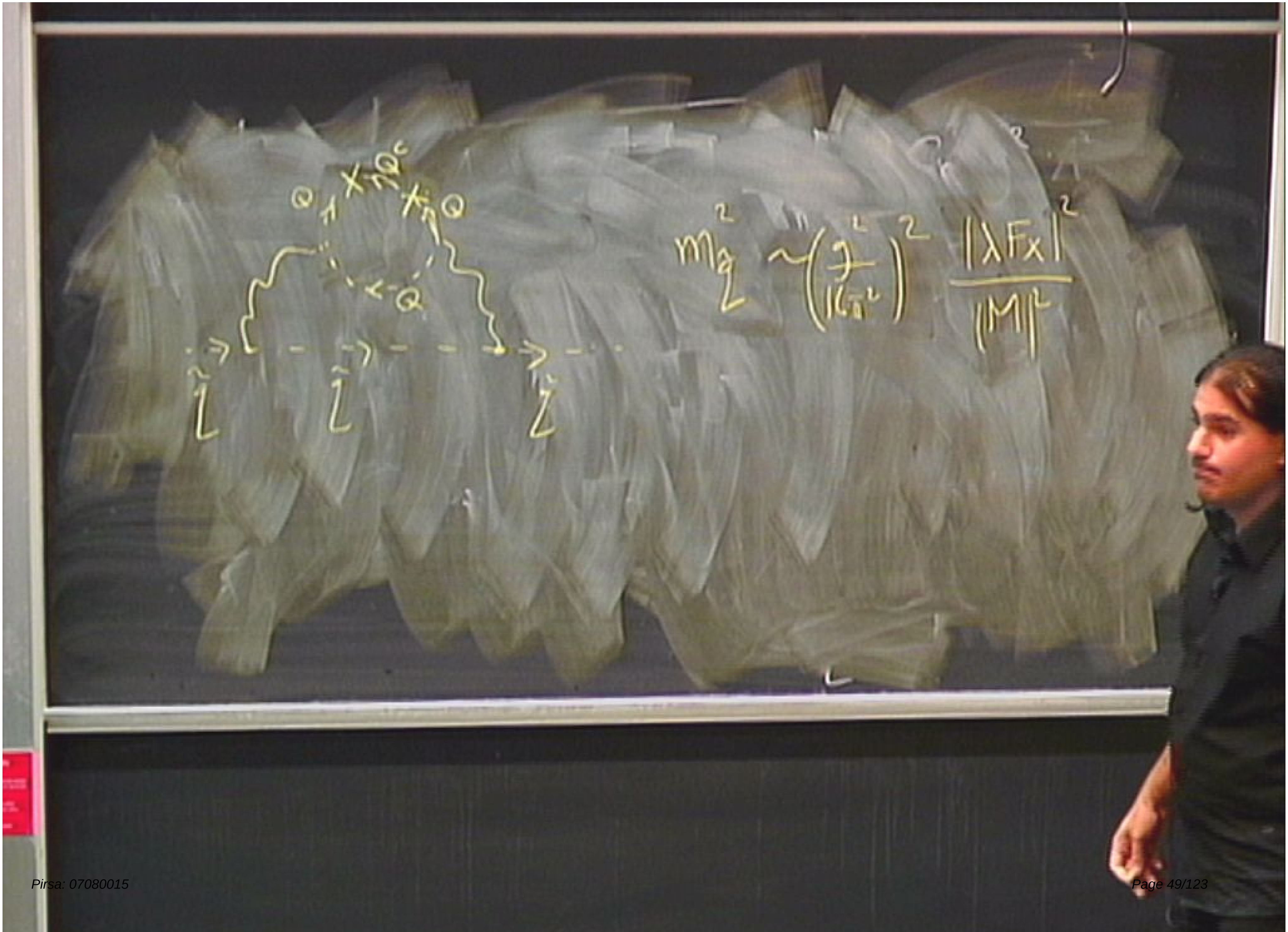

M
Q
Q^c
m_λ ~ g^2/16π^2 (λF_X M)

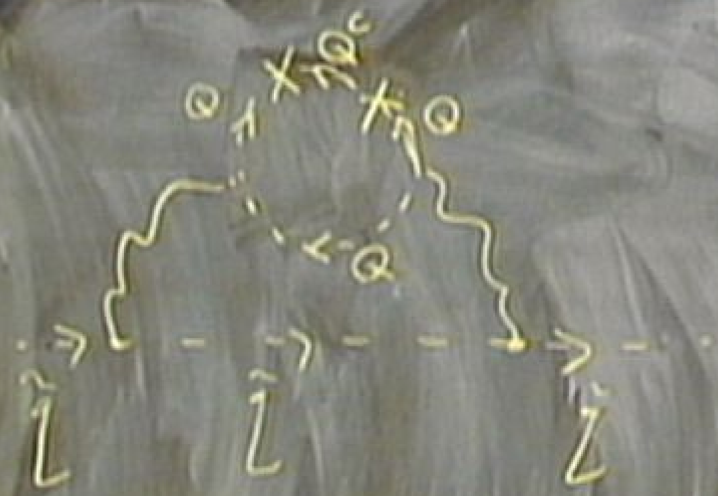


$$m_\lambda \sim \frac{g^2}{16\pi^2}\frac{(\lambda F_X M)}{|M|^2}$$

$$\sim \frac{g^2}{16\pi^2}\left(\frac{\lambda F_X}{M}\right)$$


M
Q
Q^c
λ
λ
$m_\lambda \sim \frac{g^2}{16\pi^2} \frac{(\lambda F_X M)}{|M|^2}$
$\sim \frac{g^2}{16\pi^2}\left(\frac{\lambda F_X}{M}\right)$


Q
Q^c
Q
Q
$\tilde{\ell}$
$\tilde{\ell}$
$\tilde{\ell}$
$m_{\tilde{\ell}}^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 \frac{|\lambda F_X|^2}{|M|^2}$



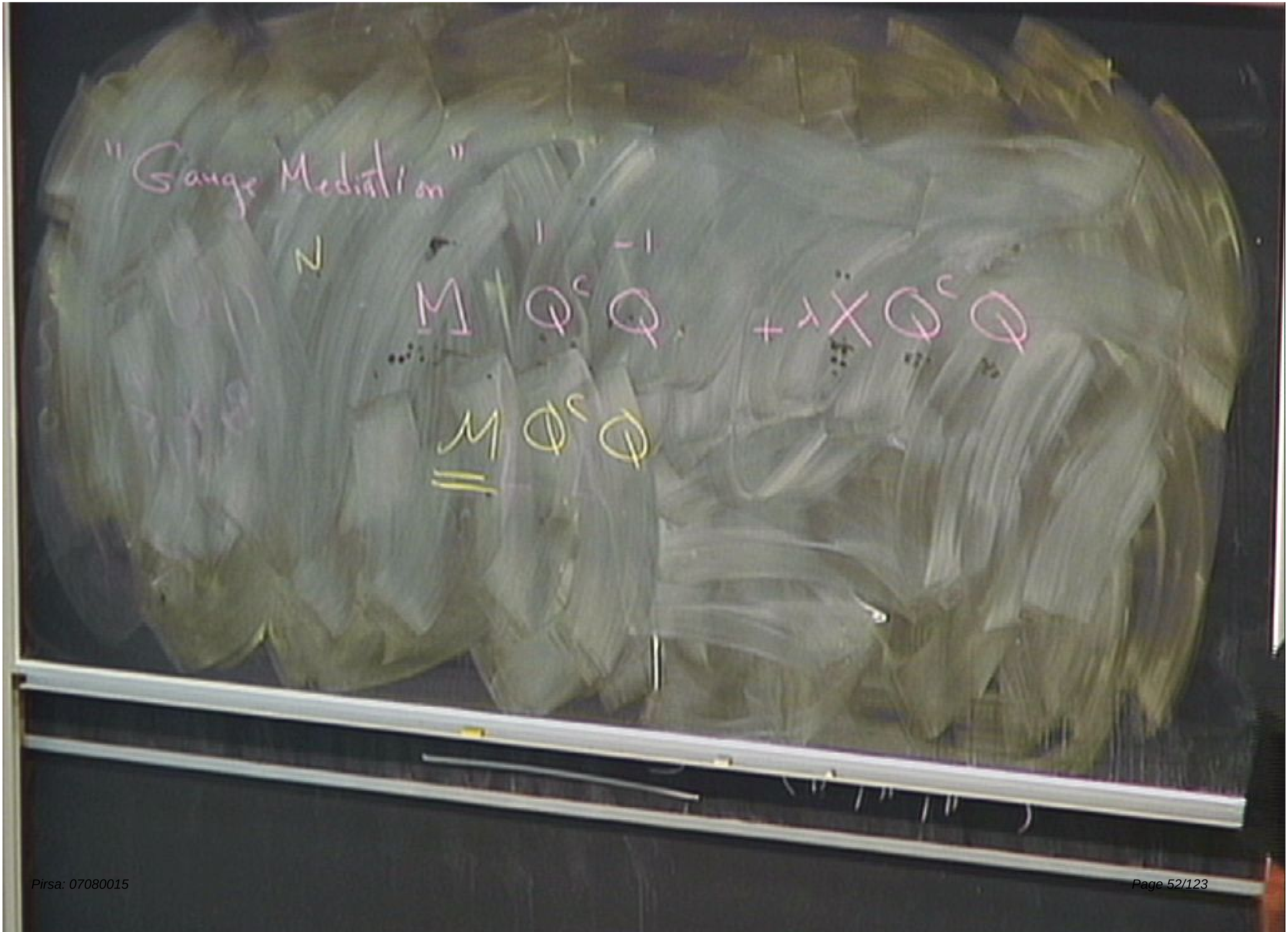
$$m_{\tilde q}^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 \frac{|\lambda F_X|^2}{|M|^2}$$

m_λ, $m_{\tilde q}$ about same

"Gauge Mediation"

$$M \, \overset{1}{Q^c} \, \overset{-1}{Q} + \lambda X Q^c Q$$

$$\underline{\underline{M}} \, \Phi^c \Phi$$


"Gauge Mediation"
N
1 -1
M Q^c Q + λ X Q^c Q
M Φ^c Φ


(N+1)
M

Λ

M ——— $(N+1)$ Q^i, L ; $L^c Q^c$

μ ——— 1 L, L^c

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} - \frac{b_{HE}}{8\pi^2}\log \Lambda/M - \frac{b_{LE}}{8\pi^2}\log M/\mu$$

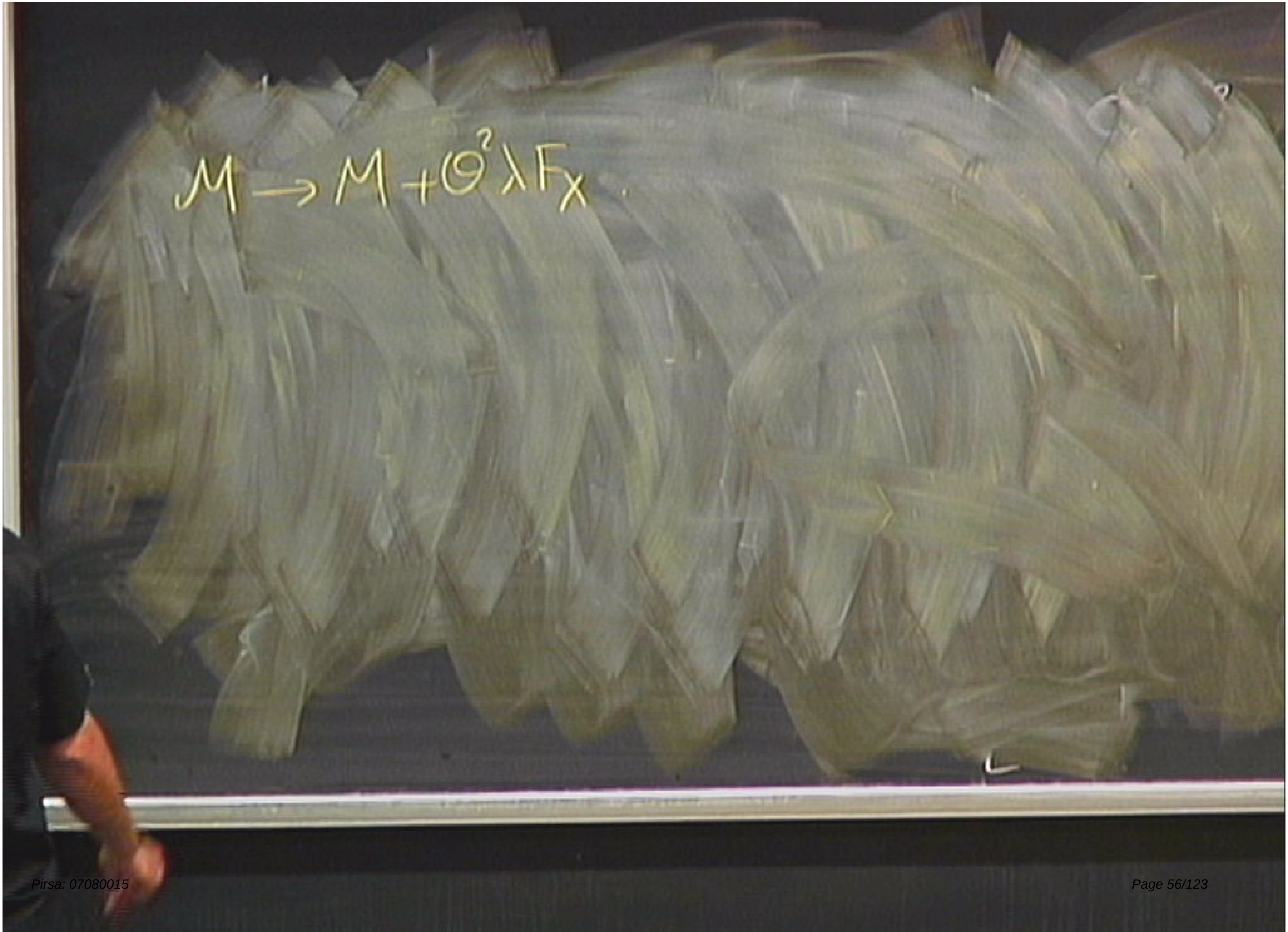
Λ

$(N+1) \quad Q^i, Z \quad , \quad Z^c Q^c$

M

$\mu \qquad 1 \qquad Z, Z^c$

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} - \frac{b_{HE}}{8\pi^2} \log \Lambda/M - \frac{b_{LE}}{8\pi^2} \log M/\mu$$


$\mathcal{M} \to M + \theta^2 \lambda F_X$

$$\mathcal{M} \to M + \Theta^2 \lambda F_X$$

$$\log \Lambda/_M \to \log \Lambda/_{\mathcal{M}} = \log \frac{\Lambda}{M}\left(1+\Theta^2 \frac{\lambda F_X}{M}\right)$$

$$= \log \Lambda/_M - \log\left(1+\Theta^2 \frac{\lambda F_X}{M}\right)$$

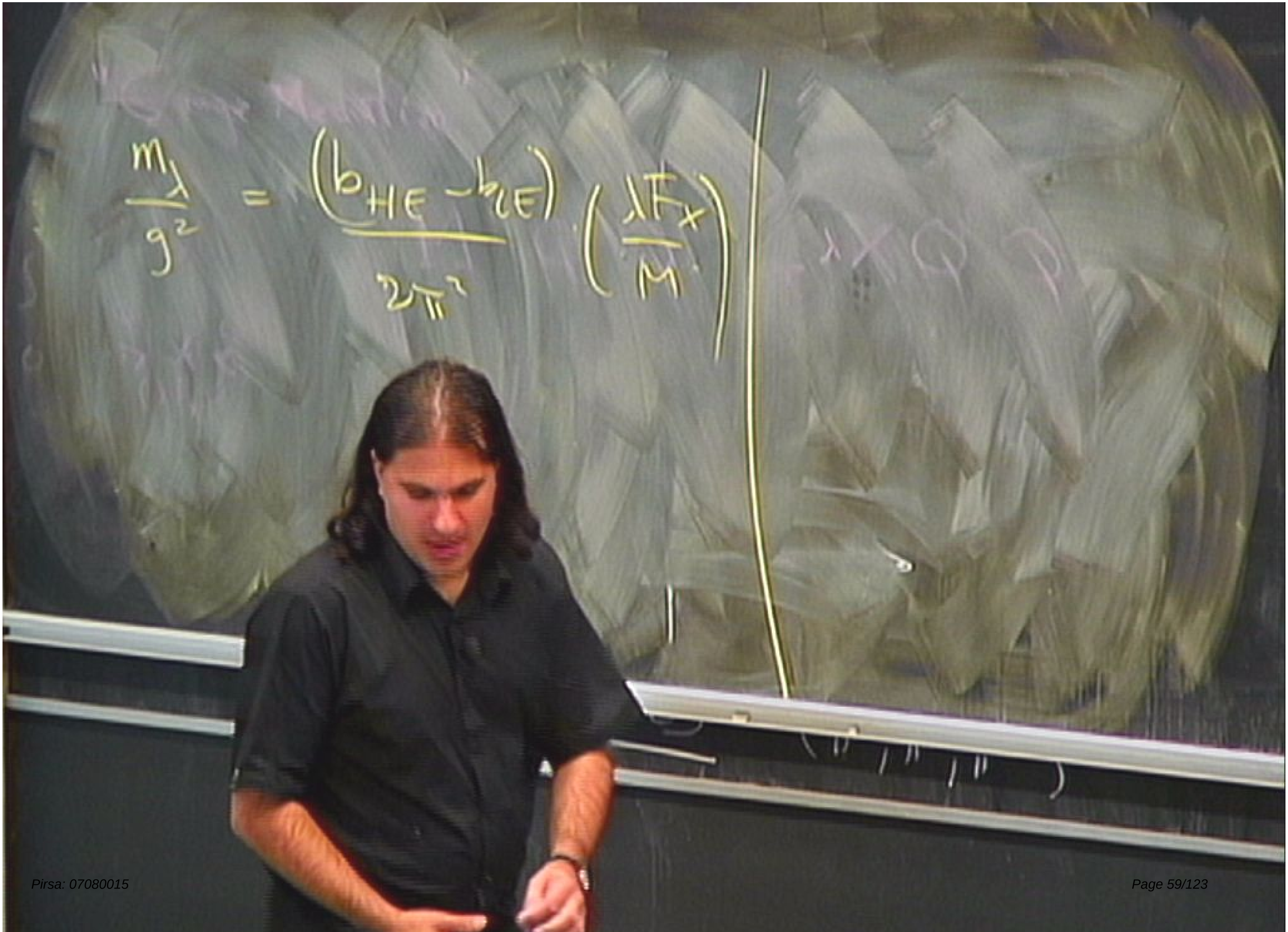
$$= \quad '' \quad - \Theta^2 \frac{\lambda F_X}{M}$$

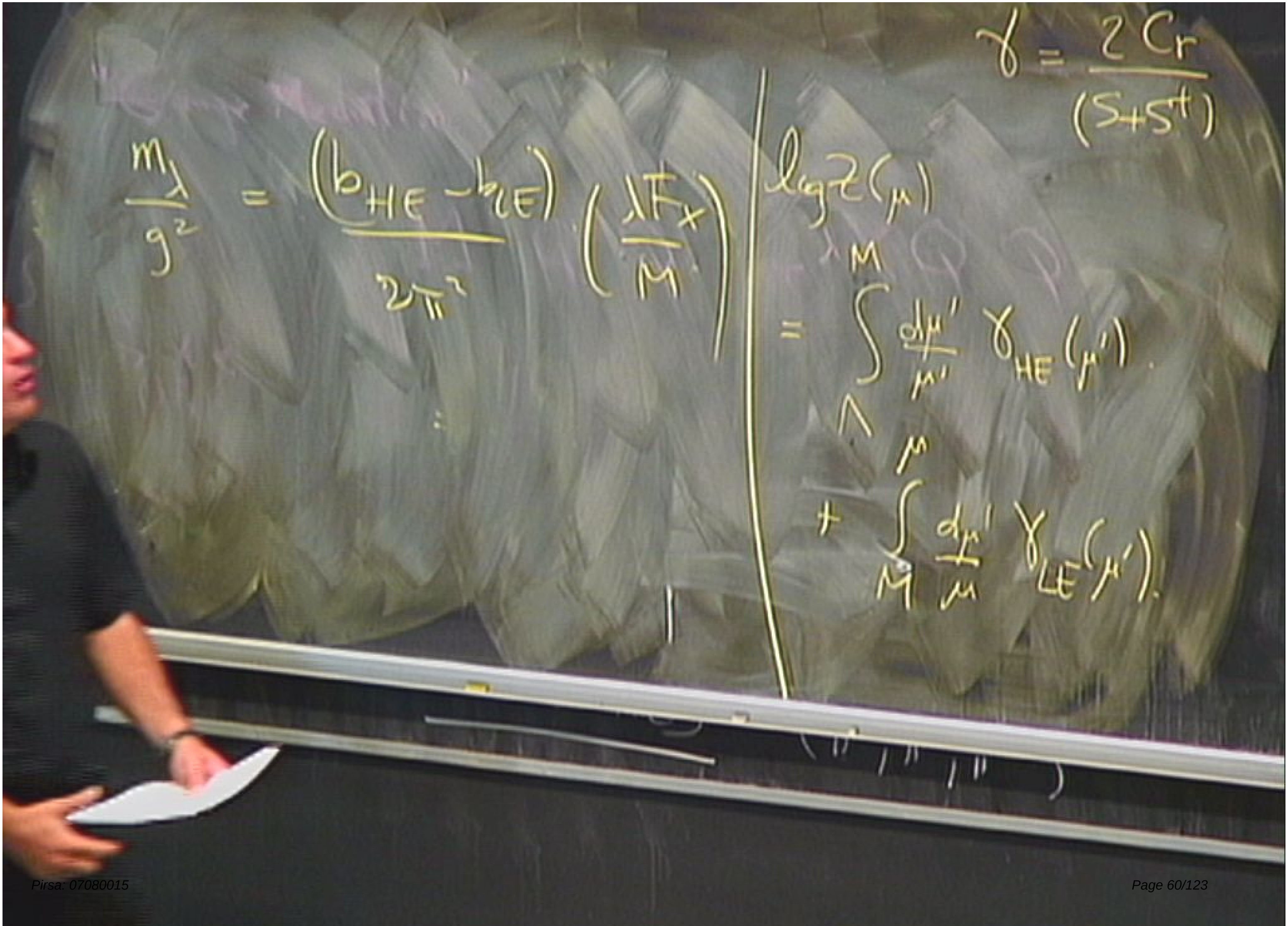
$$\mathcal{M} \to M + \theta^2 \lambda F_X$$

$$\log \Lambda/M \to \log \Lambda/\mathcal{M} = \log \frac{\Lambda}{M\left(1+\theta^2 \frac{\lambda F_X}{M}\right)}$$

$$= \log \Lambda/M - \log\left(1+\theta^2 \frac{\lambda F_X}{M}\right)$$

$$\log M/\mu \to \log \frac{M}{\mu} + \theta^2 \frac{\lambda F_X}{M} = \quad '' \quad - \theta^2 \frac{\lambda F_X}{M}$$

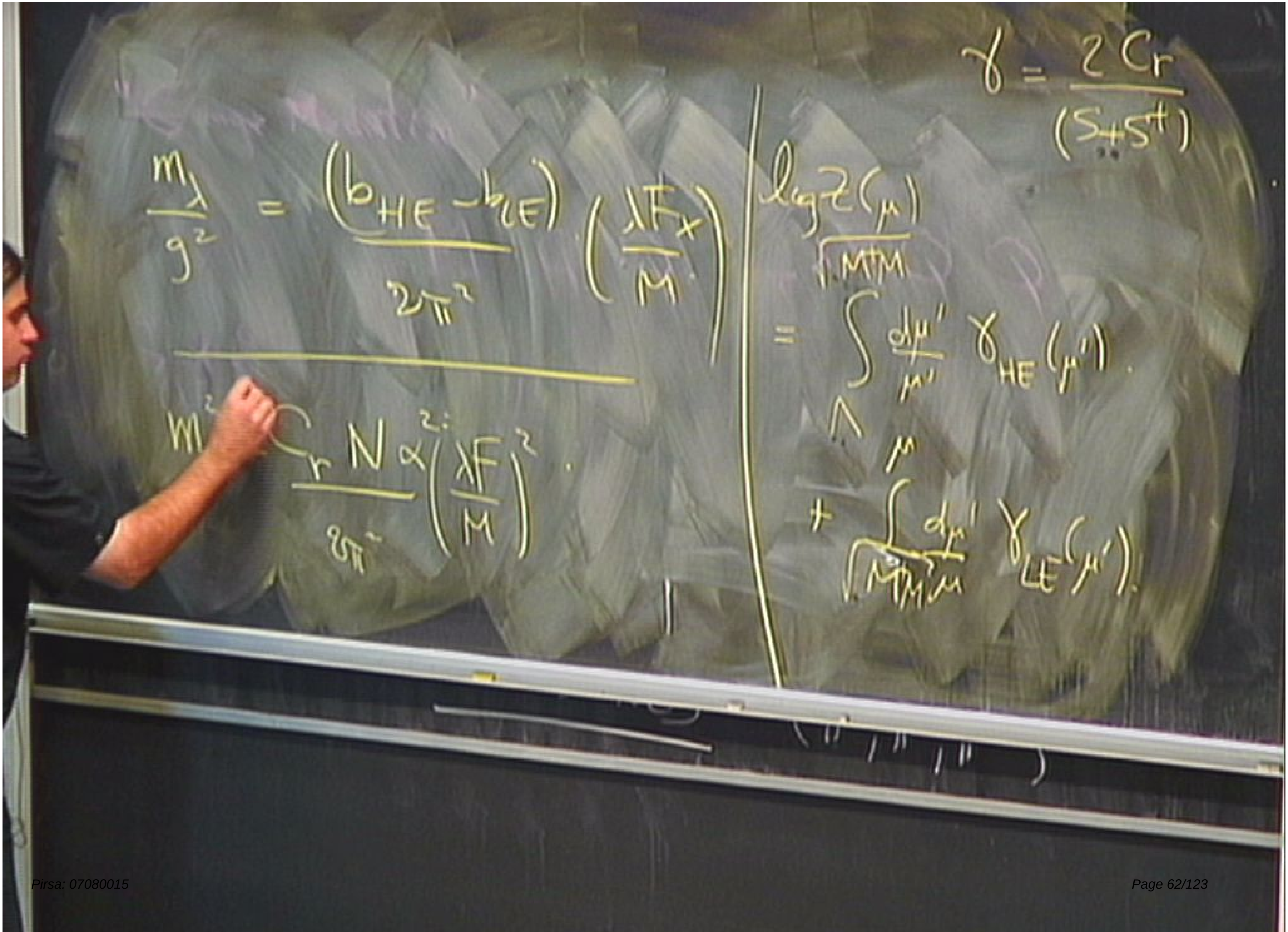

$\frac{m_\lambda}{g^2} = \frac{(b_{HE} - b_{LE})}{2\pi^2} \left(\frac{\lambda F_X}{M}\right)$

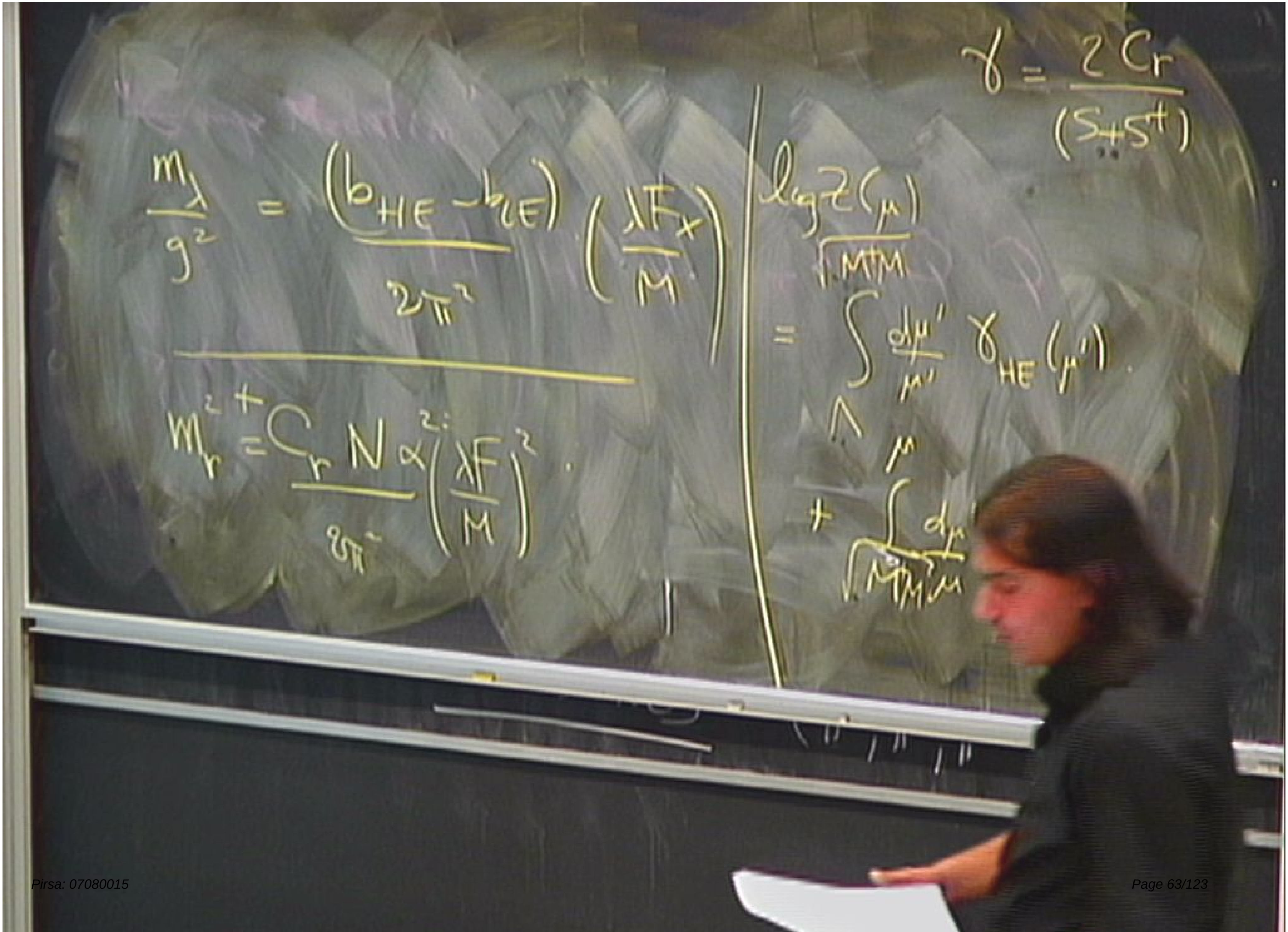

$\gamma = \frac{2 C_r}{(S+S^\dagger)}$
$\frac{m_\lambda}{g^2} = \frac{(b_{HE} - b_{LE})}{2\pi^2} \left(\frac{\lambda F_x}{M}\right)$
$\log Z(\mu) = \int_\Lambda^M \frac{d\mu'}{\mu'} \gamma_{HE}(\mu') + \int_M^\mu \frac{d\mu'}{\mu'} \gamma_{LE}(\mu')$

$$\gamma = \frac{2C_r}{(S + S^\dagger)}$$

$$\frac{m_\lambda}{g^2} = \frac{(b_{HE} - b_{LE})}{2\pi^2}\left(\frac{\lambda F_x}{M}\right)$$

$$\log Z(\mu) = \int_{\Lambda}^{\sqrt{M^\dagger M}} \frac{d\mu'}{\mu'}\, \gamma_{HE}(\mu') + \int_{\sqrt{M^\dagger M}}^{\mu} \frac{d\mu'}{\mu'}\, \gamma_{LE}(\mu').$$


$\gamma = \frac{2C_r}{(S+S^\dagger)}$
$\frac{m_\lambda}{g^2} = \frac{(b_{HE}-b_{LE})}{2\pi^2}\left(\frac{\lambda F_X}{M}\right)$
$m^2 \; \frac{C_r N \alpha^2}{8\pi^2}\left(\frac{\lambda F}{M}\right)^2$
$\log Z(\mu) / \sqrt{M^\dagger M}$
$= \int_\Lambda^\mu \frac{d\mu'}{\mu'} \gamma_{HE}(\mu')$
$+ \int_{\sqrt{M^\dagger M}}^{\mu} \frac{d\mu'}{\mu'} \gamma_{LE}(\mu')$


γ = 2 C_r / (S + S†)
m_λ / g² = (b_HE − b_LE) / 2π² (λF_X / M)
m_r² = C_r N α² / 8π² (λF / M)²
log Z(μ) / √(M†M)
= ∫ dμ'/μ' γ_HE(μ')
Λ μ
+ ∫ dμ'

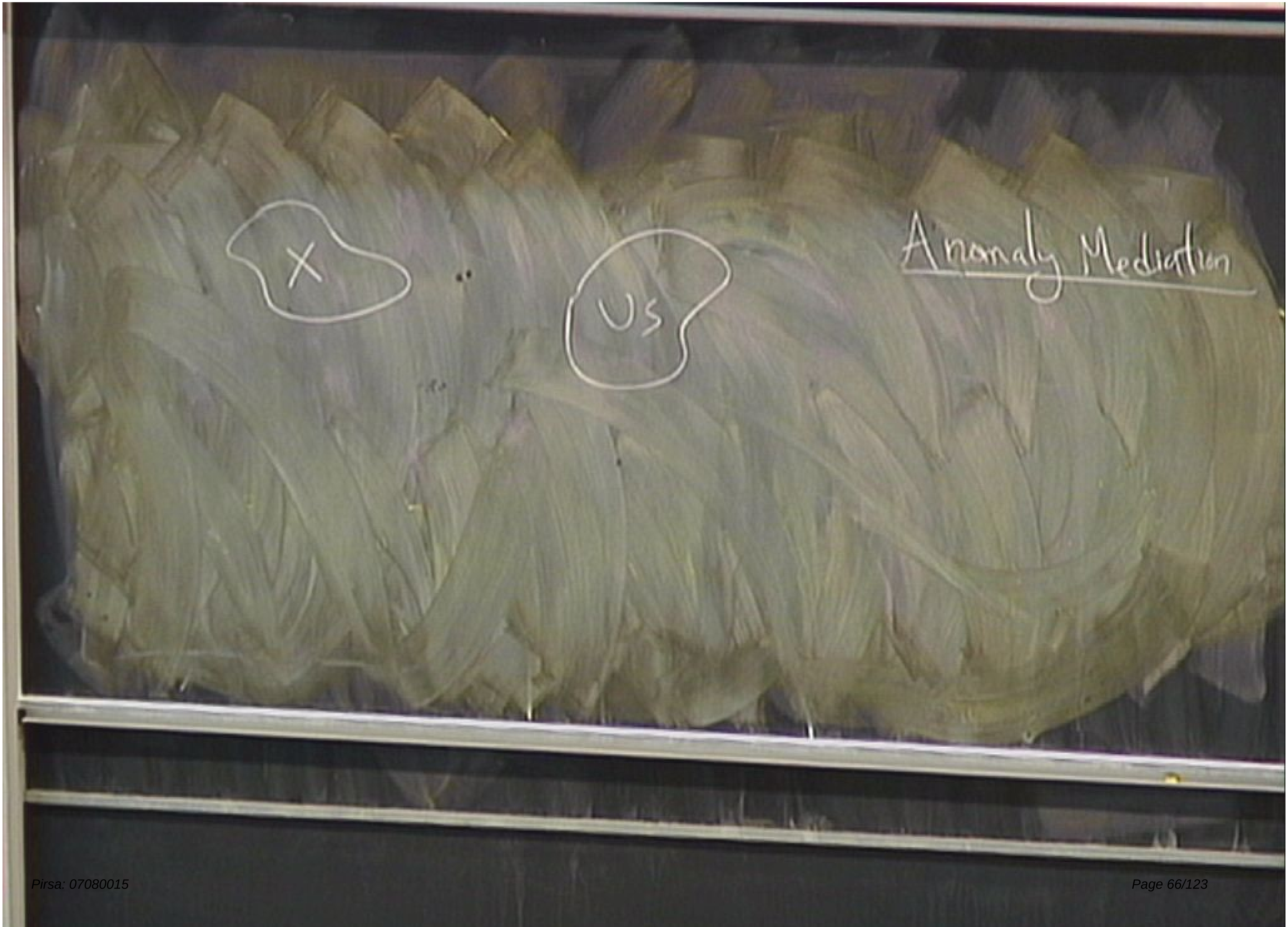
$$\gamma = \frac{2C_r}{(S+S^\dagger)}$$

$$\frac{m_\lambda}{g^2} = \frac{(b_{HE} - b_{LE})}{2\pi^2}\left(\frac{\lambda F_X}{M}\right)$$

$$m_r^2 = \frac{C_r N \alpha^2}{8\pi^2}\left(\frac{\lambda F}{M}\right)^2, \quad \alpha = \left(\frac{g^2}{4\pi}\right)$$

$$\frac{\log Z(\mu)}{\sqrt{M^\dagger M}} = \int_\Lambda^\mu \frac{d\mu'}{\mu'}\,\gamma_{HE}(\mu') + \int^{\sqrt{M^\dagger M}/\mu} \frac{d\mu'}{\mu'}\,\gamma_{LE}(\mu').$$


X
Us



Anomaly Mediation
X
Us

X

Us

Anomaly Mediation

$$M$$

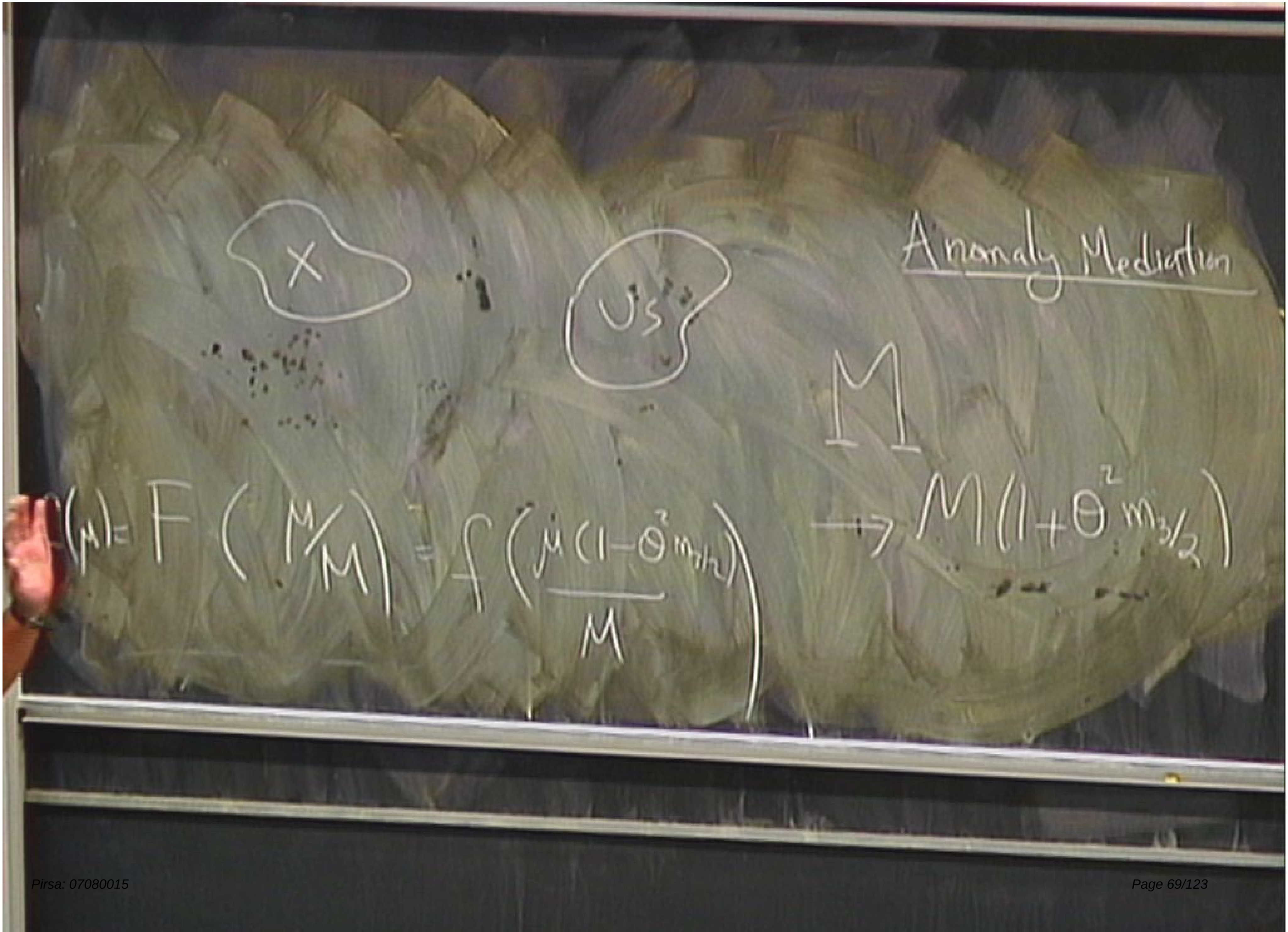
$$\rightarrow M(1+\theta^2 m_{3/2})$$

Anomaly Mediation

X U_5

$F\left(\mu/M\right)$

$$M \to M(1+\theta^2 m_{3/2})$$


Anomaly Mediation
X
U_s
M
$(\mu) = F\left(\mu/M\right) = f\left(\frac{\mu(1-\theta^2 m_{3/2})}{M}\right)$
$\to M(1+\theta^2 m_{3/2})$

Anomaly Mediation

X $\qquad$ U_S

M

$$f(\mu) = F\left(\mu/M\right) = f\left(\frac{\mu(1-\theta^2 m_{3/2})}{M}\right) \rightarrow M(1+\theta^2 m_{3/2})$$

Anomaly Mediation

X

U_S

M

$$f(\mu) = F\left(\mu/M\right) = f\left(\frac{\mu(1-\theta^2 m_{3/2})}{M}\right) \longrightarrow M\left(\underline{1+\theta^2 m_{3/2}}\right)$$

$$\log Z(\mu) \xrightarrow{F_x} \log Z\left(\sqrt{\mu^\dagger \mu}\right)$$

$$= \log Z(\mu) - \frac{\gamma(\mu)}{2} m_{3/2} \theta^2 + h.c.$$

$$+ \frac{\dot{\gamma}(\mu)}{4} m_{3/2}^2 \theta^2 \bar{\theta}^2$$

$$\log Z(\mu) \to \log Z\left(\sqrt{\mu^\dagger \mu}\right)$$

$$= \log Z(\mu) - \frac{\dot\gamma(\mu)}{2} m_{3/2}\,\theta^2 + h.c. + \frac{\ddot\gamma(\mu)}{4} m_{3/2}^2\,\theta^2\bar\theta^2$$

$$m^2(\mu) = -\frac{\ddot\gamma(\mu)}{4} m_{3/2}^2$$

F_X

$$\log Z(\mu) \to \log Z\left(\sqrt{\mu^\dagger \mu}\right)$$

$$= \log Z(\mu) - \frac{\gamma(\mu)}{2} m_{3/2}\,\theta^2 + h.c.$$

$$+ \frac{\dot\gamma(\mu)}{4} m_{3/2}^2\,\theta^2\bar\theta^2$$

$$m^2(\mu) = -\frac{\dot\gamma(\mu)}{4} m_{3/2}^2$$

$$A(\mu) = -\frac{\gamma_i}{2} m_{3/2}$$

$$m_\lambda = -\frac{\beta(g^2)}{2g^2} m_{3/2}$$

Fx

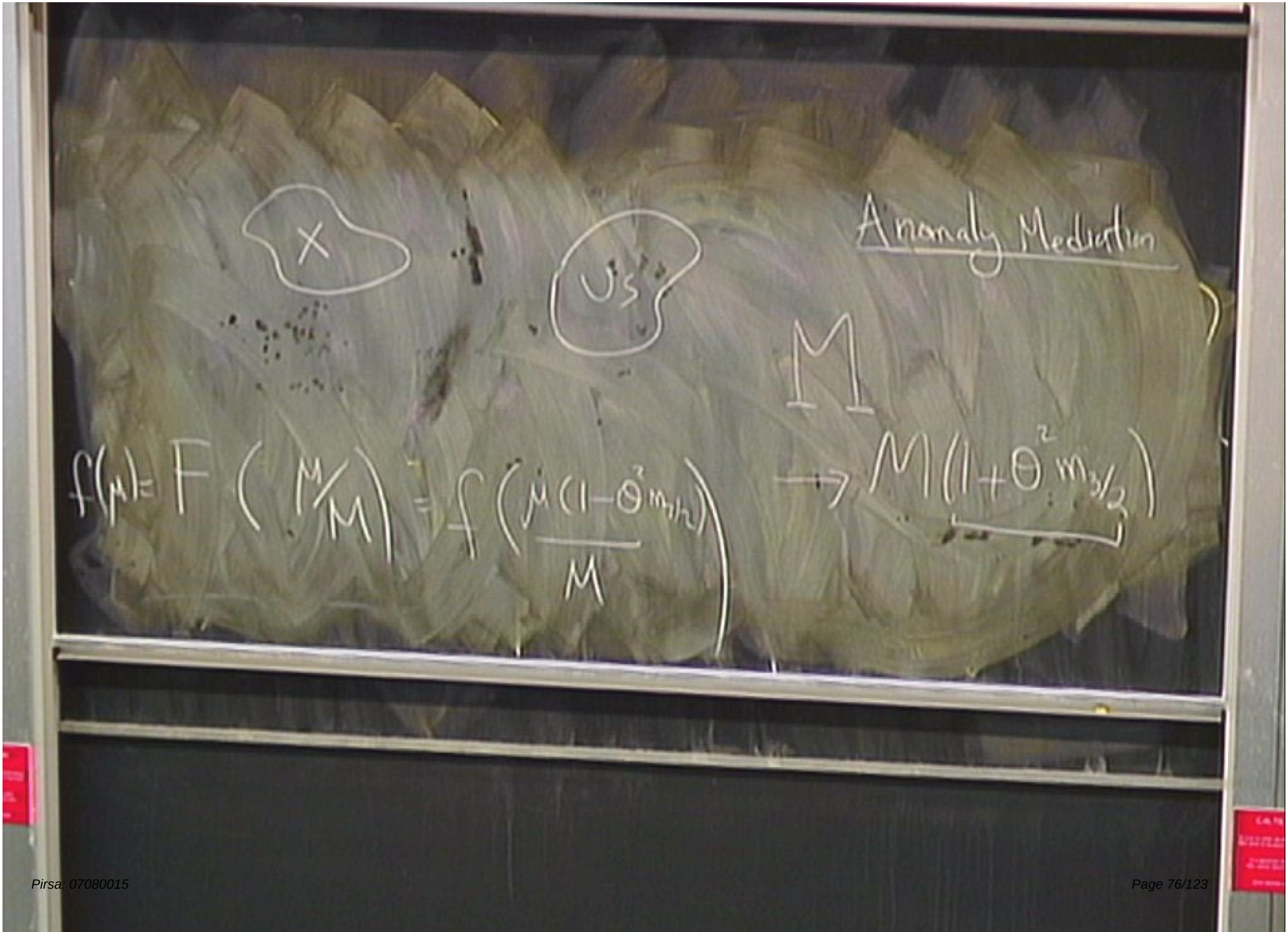
$$\log Z(\mu) \to \log Z\left(\sqrt{\bar{\mu}\mu}\right)$$

$$= \log Z(\mu) - \frac{\gamma(\mu)}{2} m_{3/2}\theta^2 + h.c. - \frac{\dot{\gamma}(\mu)}{4} m_{3/2}^2 \theta^2 \bar{\theta}^2$$

$$m^2(\mu) = -\frac{\dot{\gamma}(\mu)}{4} m_{3/2}^2$$

$$A(\mu) = -\frac{\gamma_i}{2} m_{3/2}$$

$$m_\lambda = -\frac{\beta(g^2)}{2g^2} m_{3/2}$$


Anomaly Mediation
X
Us
M
$f(\mu) = F\left(\mu/M\right) = f\left(\frac{\mu(1-\theta^2 m_{3/2})}{M}\right)$
$\to M(1+\theta^2 m_{3/2})$


$\frac{X^{-1} X}{M^2}$
$Q^{-1} Q$


MSSM

MSSM

$V_{3,2,1}$ $SU(3)\times SU(2)\times U(1)$

chiral

$$\left\{\begin{array}{l} Q \\ U^c \\ D^c \\ L \\ E^c \end{array}\right.$$

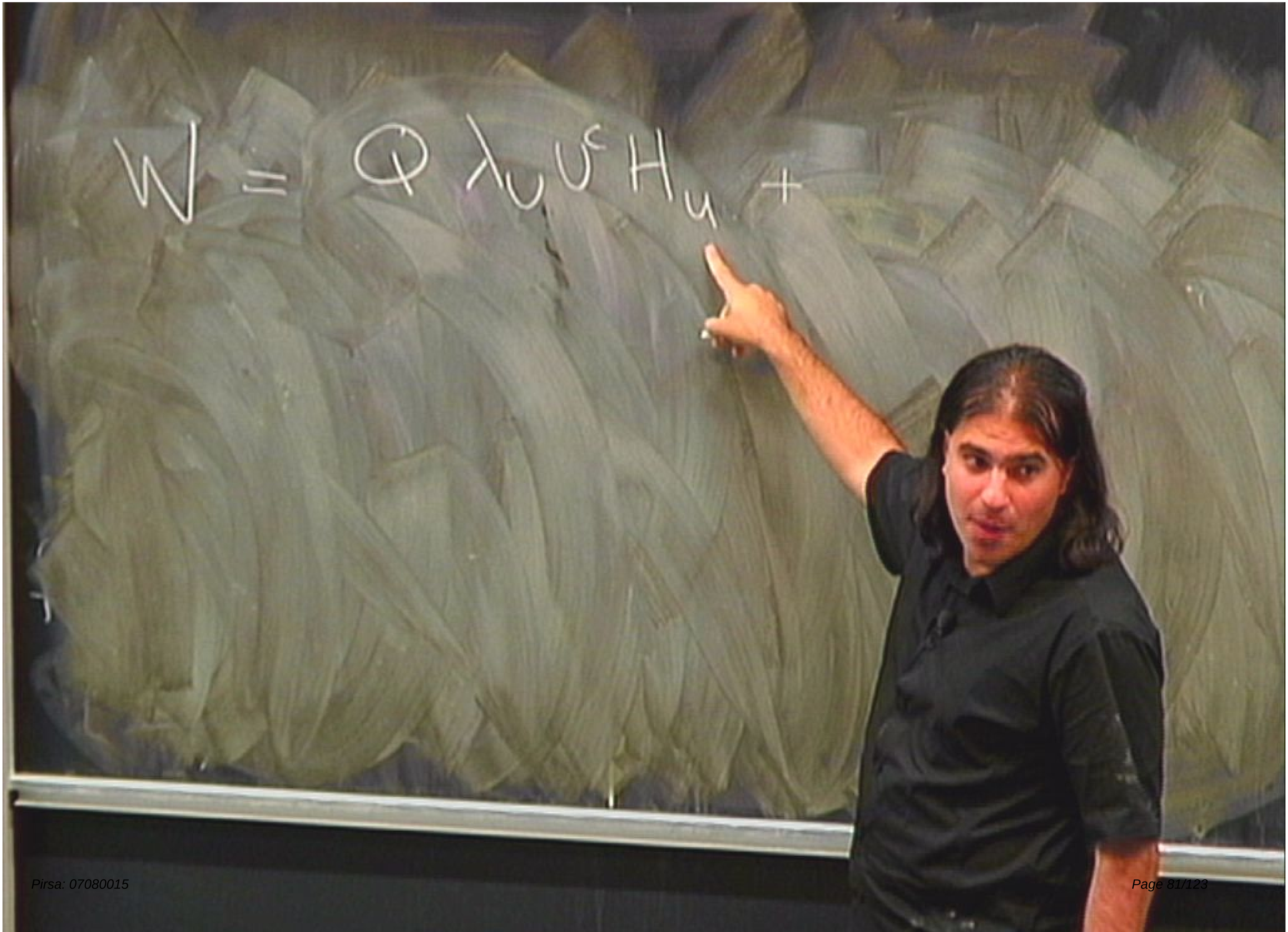
H

MSSM

$V_{3,2,1}$ $SU(3)\times SU(2)\times U(1)$

chiral superfields $\left\{ \begin{array}{l} Q \\ U^c \\ D^c \\ L \\ E^c \end{array} \right.$

$(2,+1/2)$ H_u $(2,-1/2)$ H_d


$W = Q \lambda_u u^c H_u +$

$$W = Q\lambda_U U^c H_u + Q\lambda_D D^c H_D$$
$$+ L\lambda_E E^c H_D$$

MSSM

$V_{3,2,1}$ $SU(3) \times SU(2) \times U(1)$

chiral superfields $\left\{ Q, U^c, D^c, L, E^c \right.$

$(2, +1/2)$ H_u $(2, -1/2)$ H_d

	3	2	1
Q	3	2	$1/6$
U^c	$\bar{3}$	1	$-2/3$
D^c	$\bar{3}$	1	$+1/3$
E^c	1	1	$+1$
L	1	2	$-1/2$
H_u	1	2	$+1/2$
H_d	1	2	$-1/2$

$$W = Q\lambda_u U^c H_u + Q\lambda_D D^c H_D + L\lambda_E E^c H_D$$

$$QLD^c \qquad LLE^c$$

$$W = Q \lambda_U U^c H_U + Q \lambda_D D^c H_D + L \lambda_E E^c H_D$$

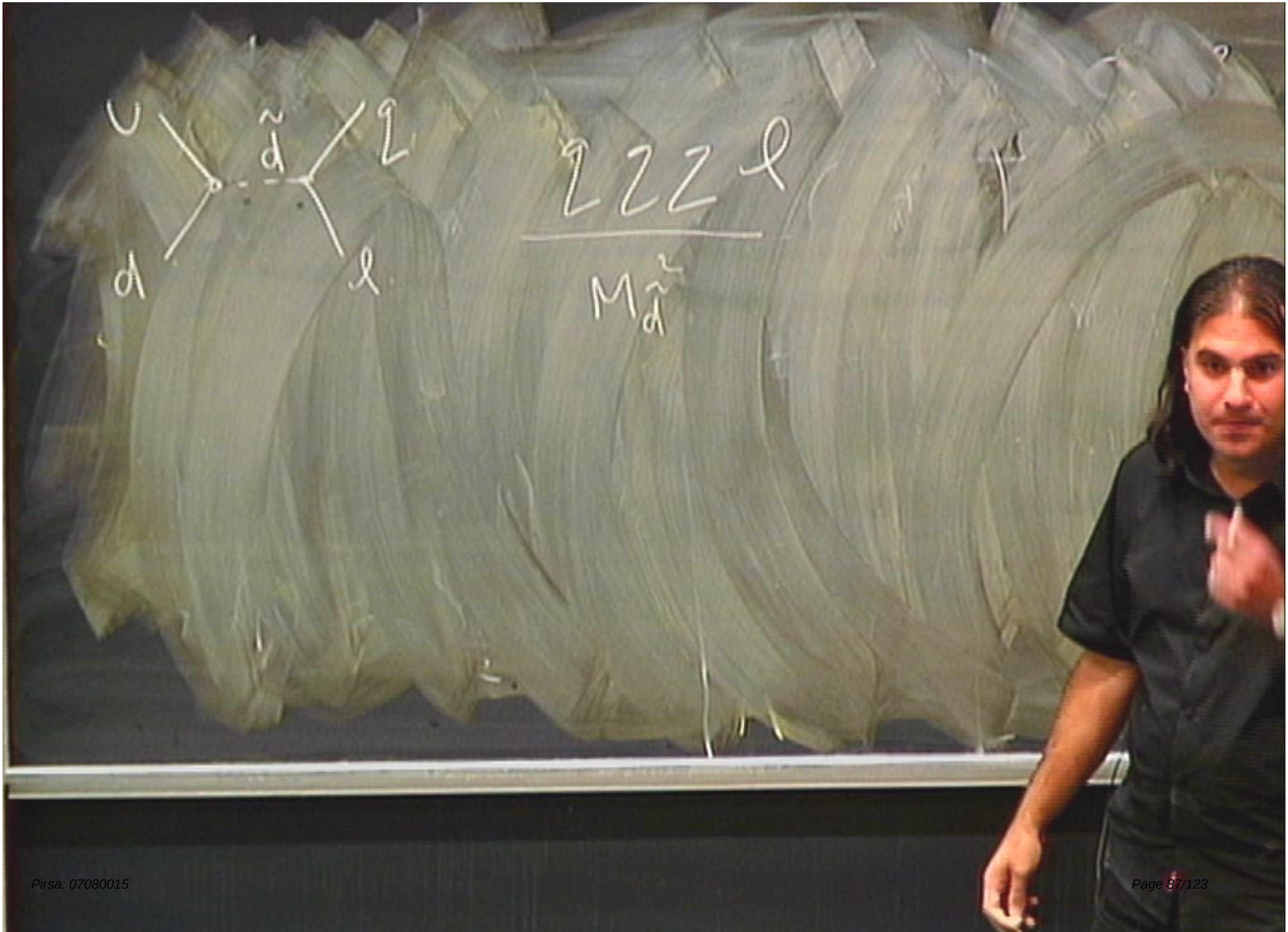
$$U^c D^c D^c \qquad Q L D^c \qquad L L E^c$$

$$W = Q \lambda_U U^c H_U + Q \lambda_D D^c H_D + L \lambda_E E^c H_D$$

$$\epsilon^{\alpha\beta\gamma}$$

$$U^c_\alpha D^c_\beta D^c_\gamma \qquad Q L D^c \qquad L L E^c$$

$$\not{B} \qquad \not{L}$$


u
d̃
q
d
ℓ
qqqℓ
M

$$(\lambda\lambda)\,\frac{\hat{Q}QQ\ell}{M_{\tilde{d}}^{2}}$$

$$W = Q\lambda_U U^c H_u + Q\lambda_D D^c H_D + L\lambda_E E^c H_D$$

$\epsilon^{\alpha\beta\gamma}\, U^c_\alpha D^c_\beta D^c_\gamma$ $\quad$ $\cancel{Q L D^c}$ $\quad$ LLE^c

$\not{B}$ $\quad$ $\not{L}$

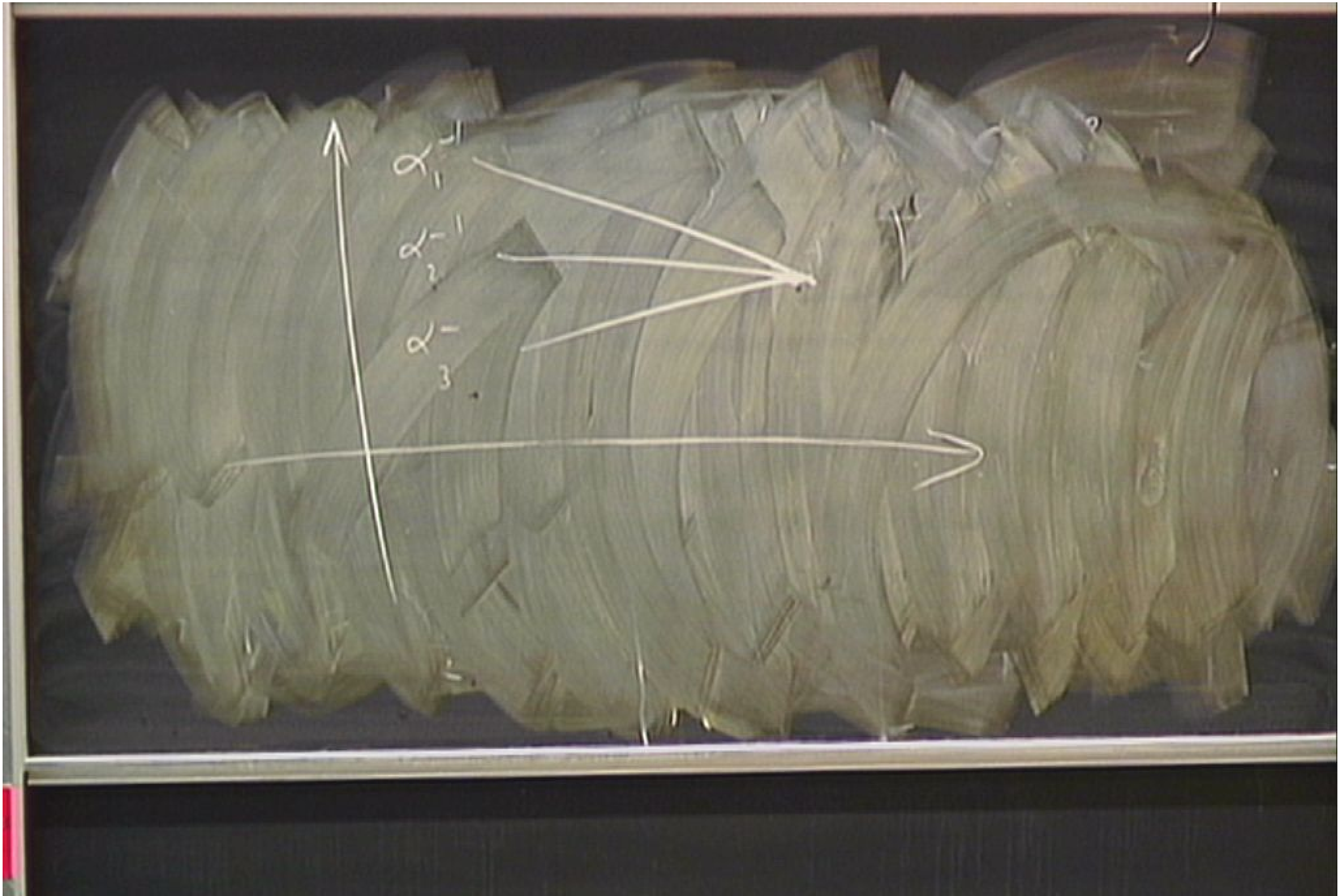
$\mathbb{Z}_2$: Matter Parity

$QUDLE^c \to -(\ \ )$

$H_u, H_d \to +(\ \ )$

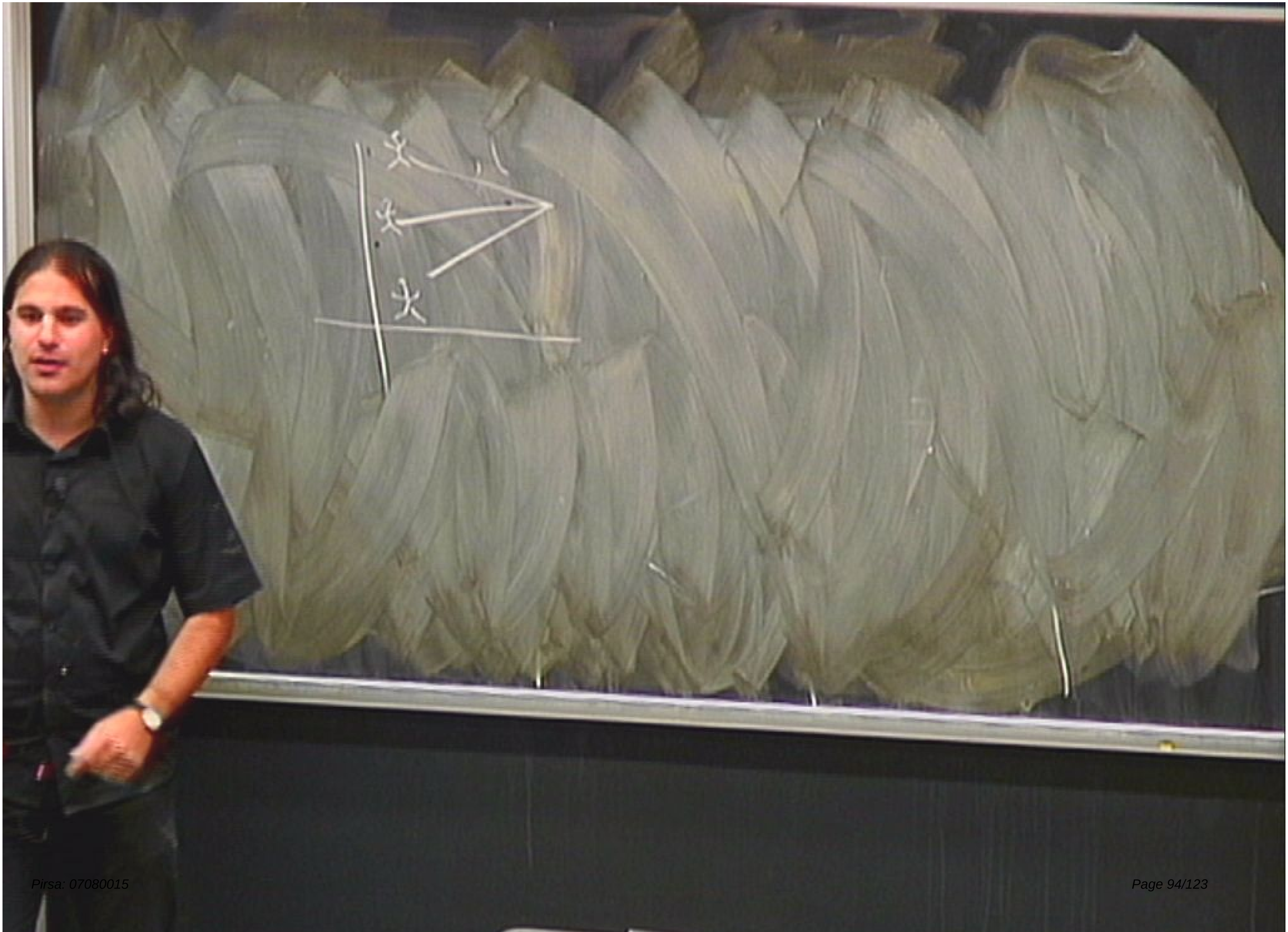
LSP is stable

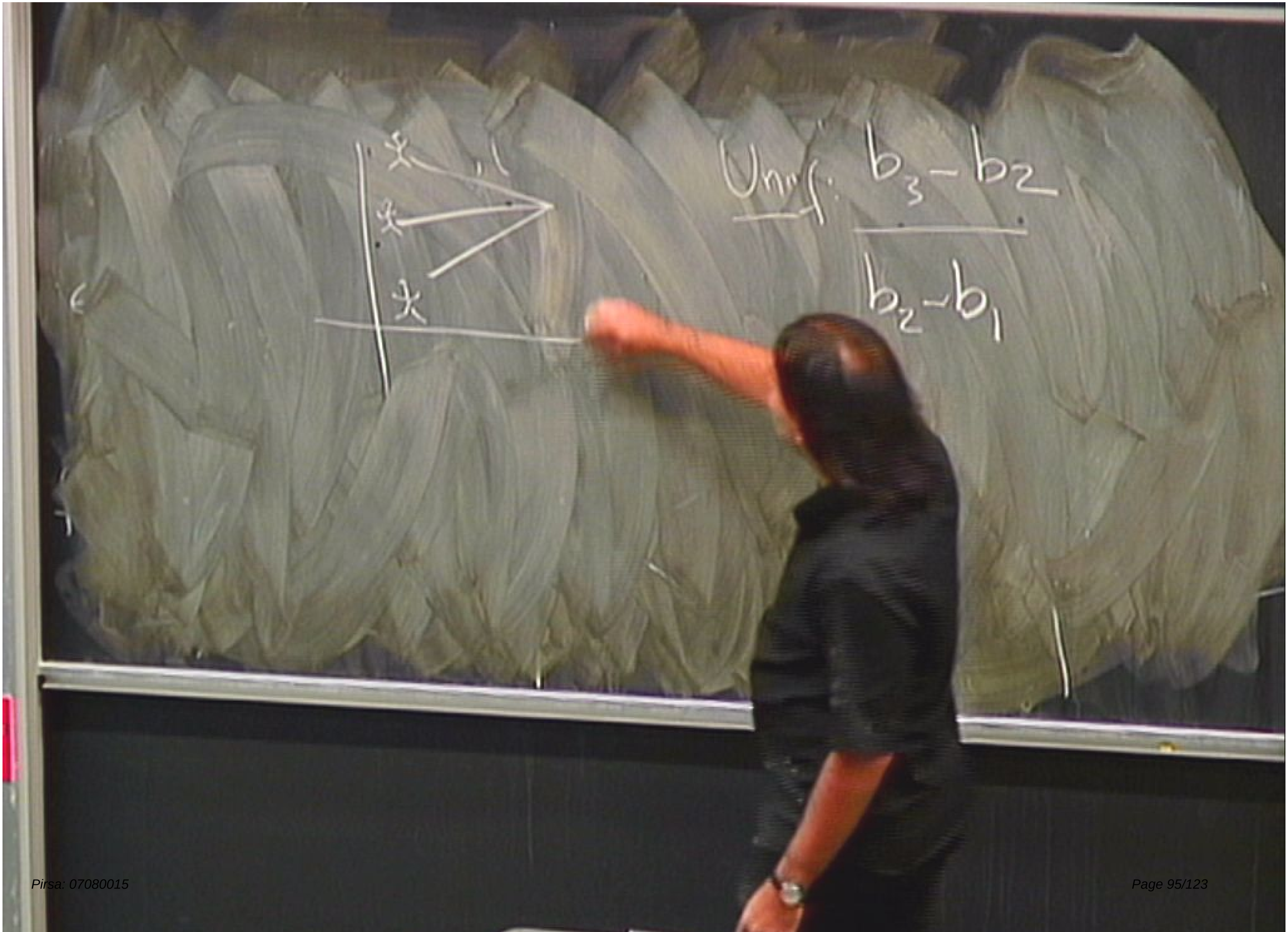
α_1^{-1}
α_2^{-1}
α_3^{-1}

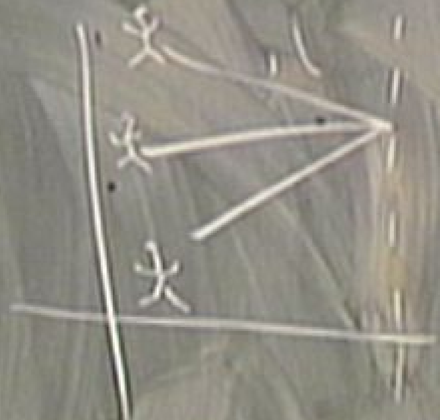

α_1^{-1}
α_2^{-1}
α_3^{-1}


α_1^{-1}
α_2^{-1}
α_3^{-1}
$\sin^2\theta$

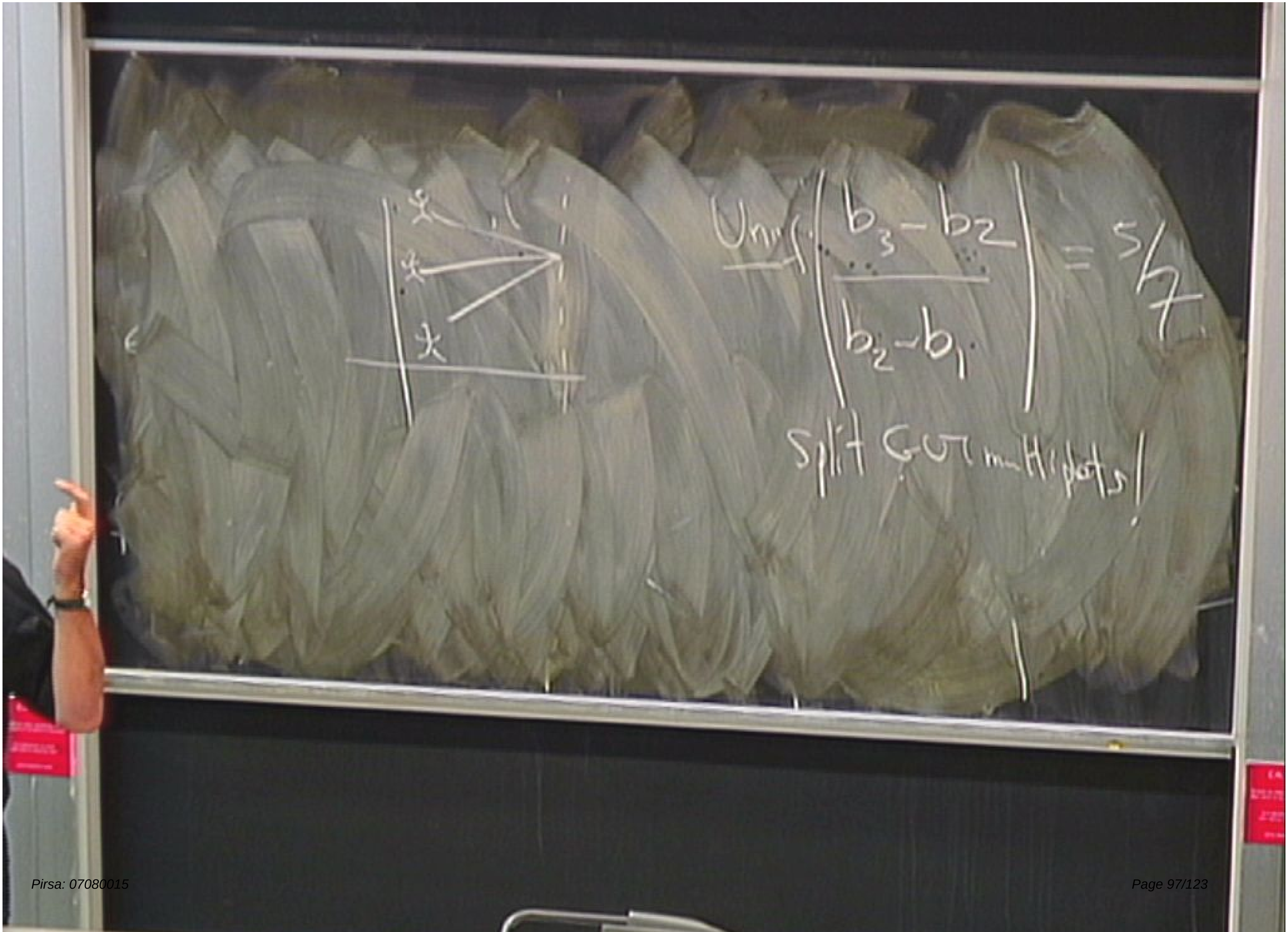

α_1^{-1}
α_2^{-1}
α_3^{-1}
$\sin^2\theta$
α_3

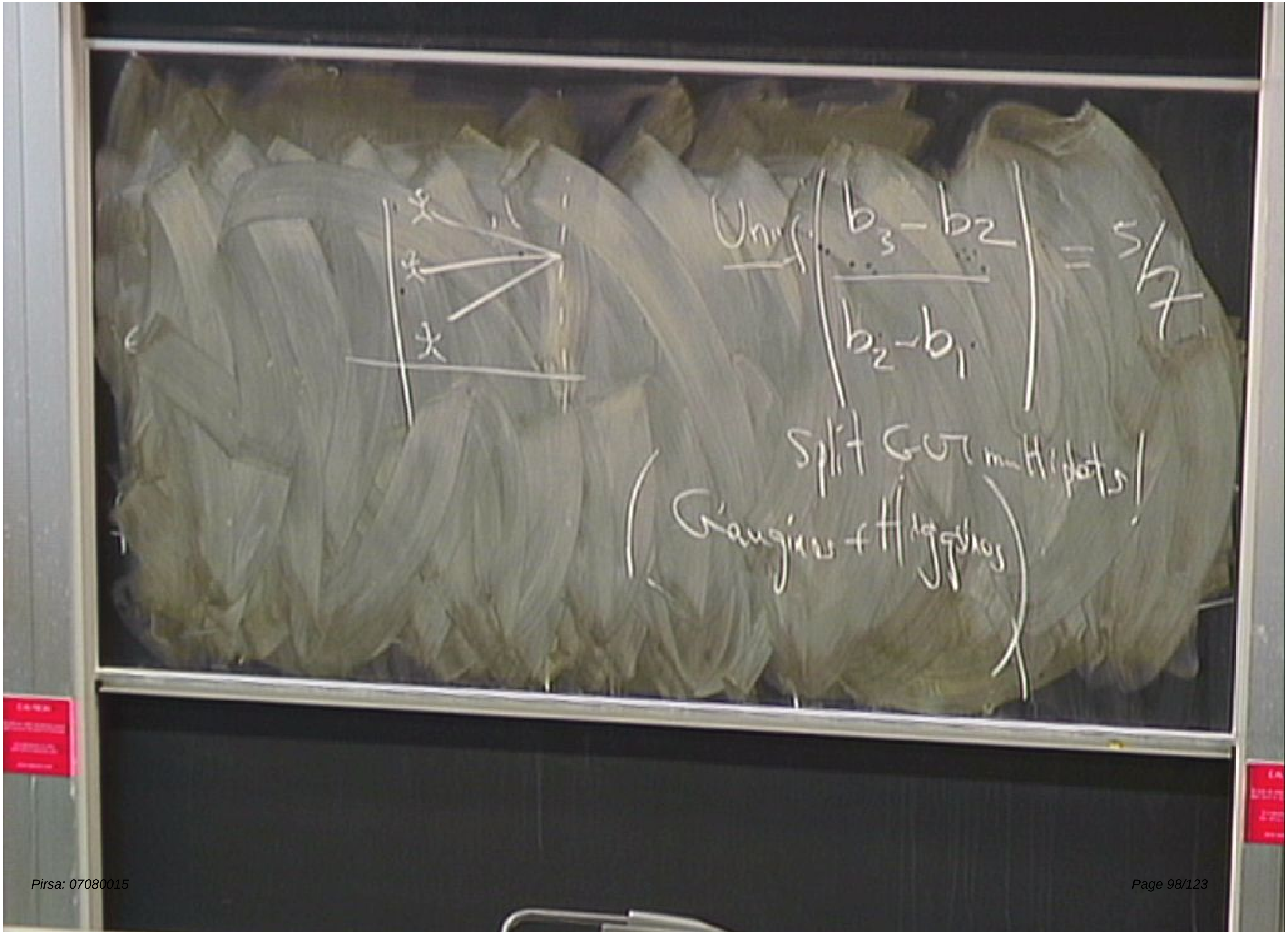


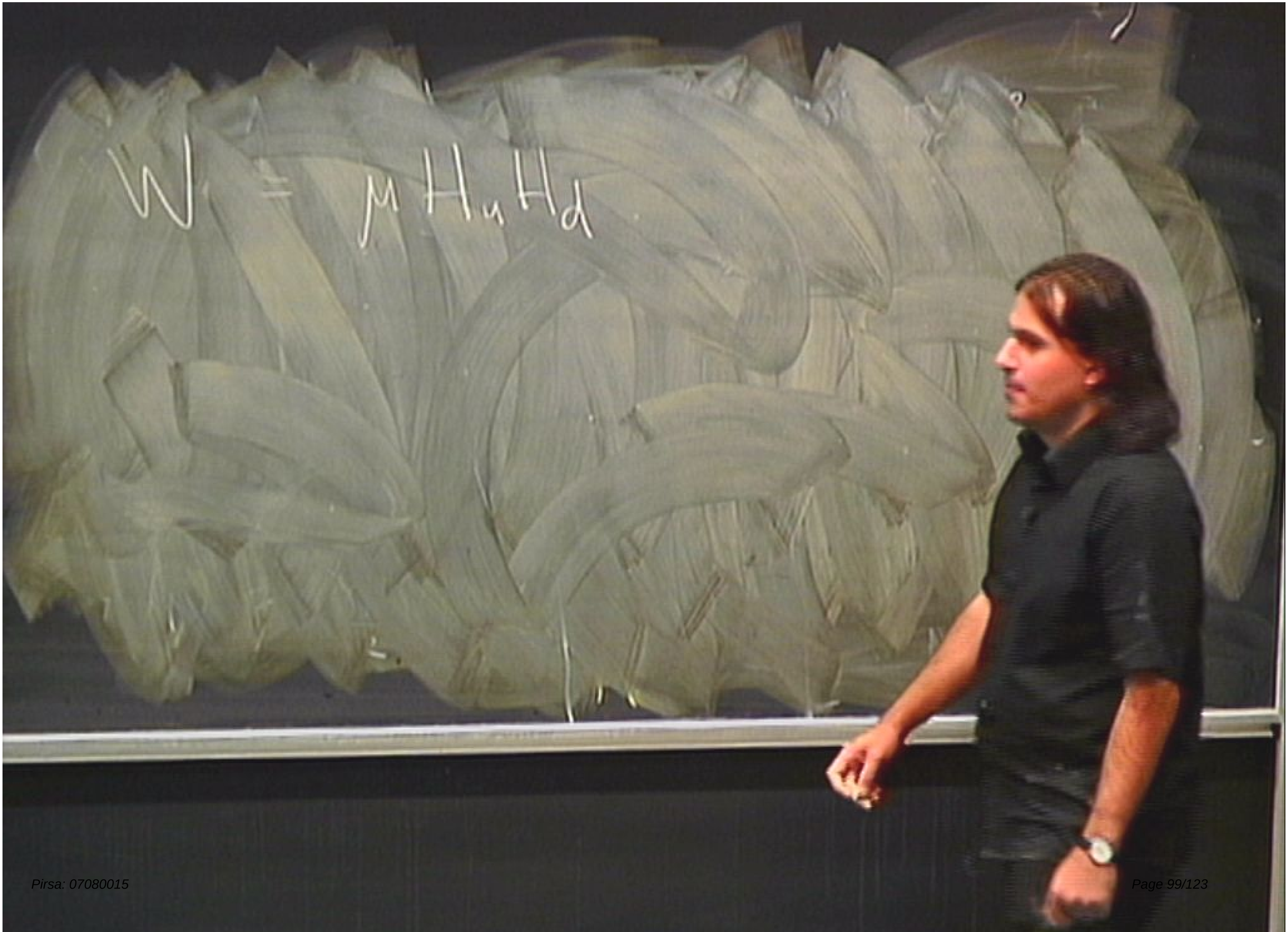

Unif: $\frac{b_3 - b_2}{b_2 - b_1}$

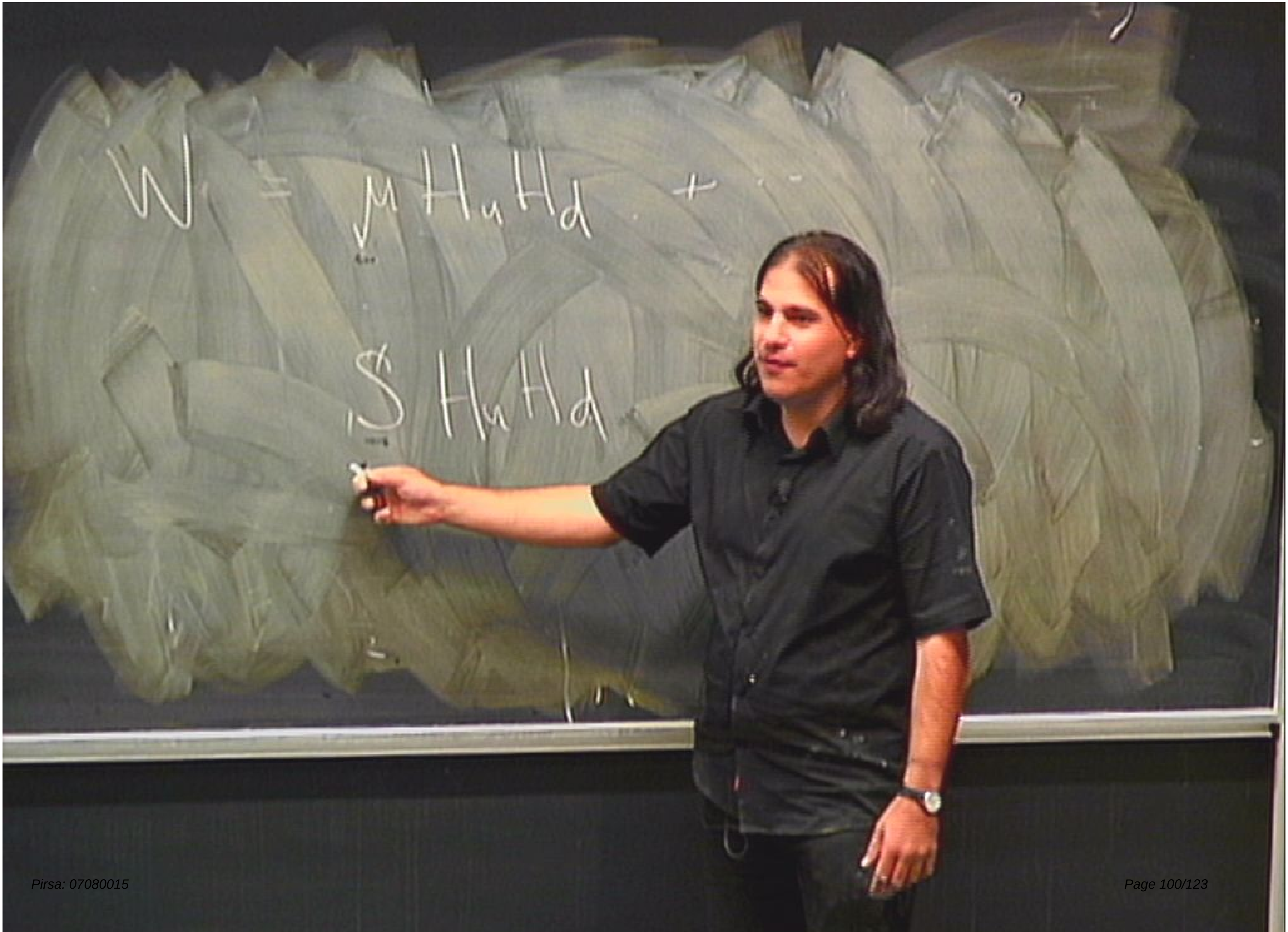


$$\mathrm{Unif}\left(\frac{b_3-b_2}{b_2-b_1}\right) = 5/7$$


Unif.
|b3 - b2 / b2 - b1| = 5/7
Split GUT multiplets!

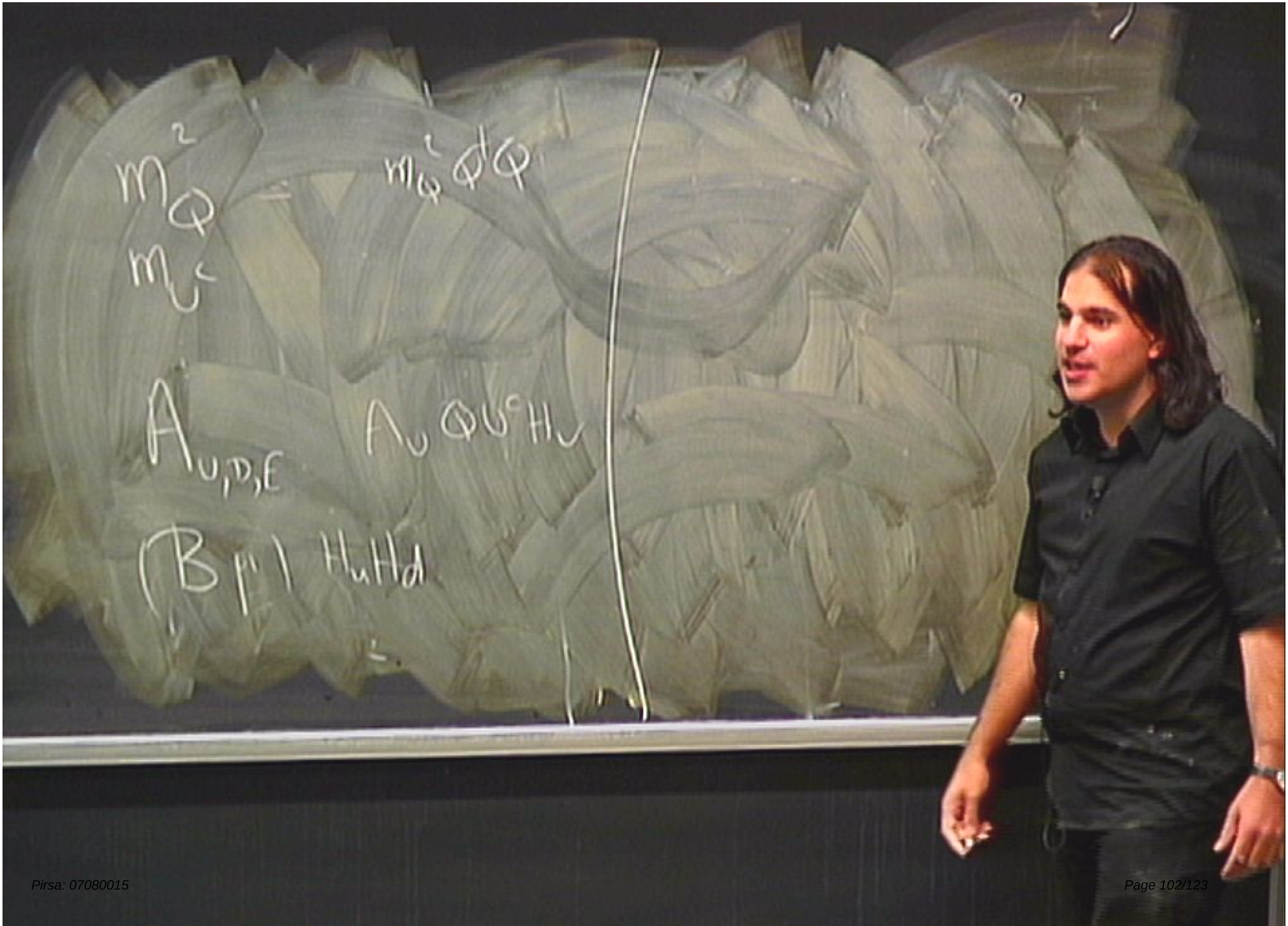

Unif. $\left|\frac{b_3-b_2}{b_2-b_1}\right| = 5/7$
split GUT multiplets!
(Gauginos + Higgsinos)


$W = \mu H_u H_d$


$W = \mu H_u H_d + \ldots$
$S H_u H_d$

$$W = \mu H_u H_d + \dots$$

$$S H_u H_d$$


m_Q^2 $m_Q^2 Q^\dagger Q$
m_{U^c}
$A_{U,D,E}$ $A_U Q U^c H_u$
$(B\mu)$ $H_u H_d$

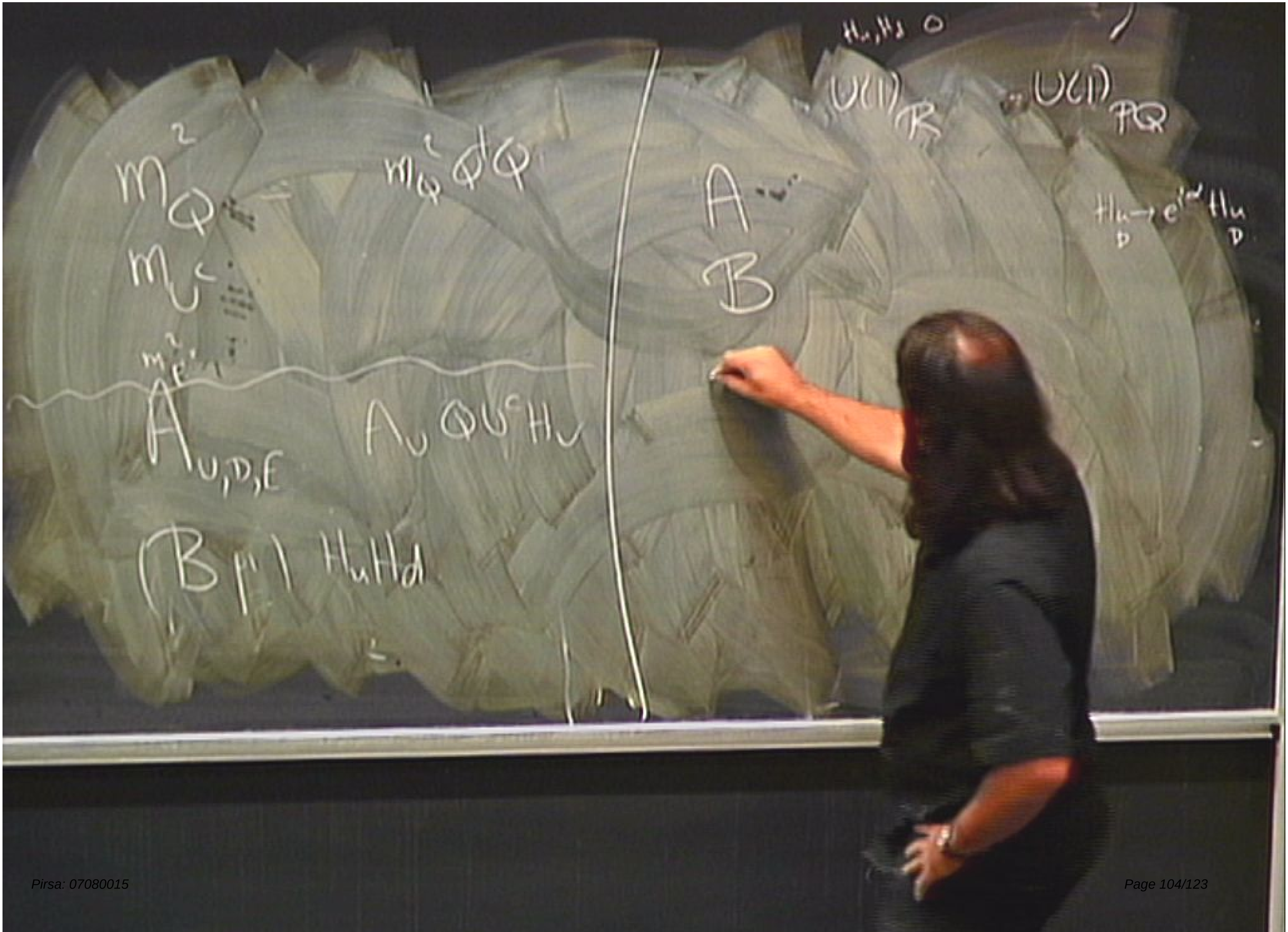
m_Q^2 $\quad m_Q^2 Q^\dagger Q$

m_{U^c}

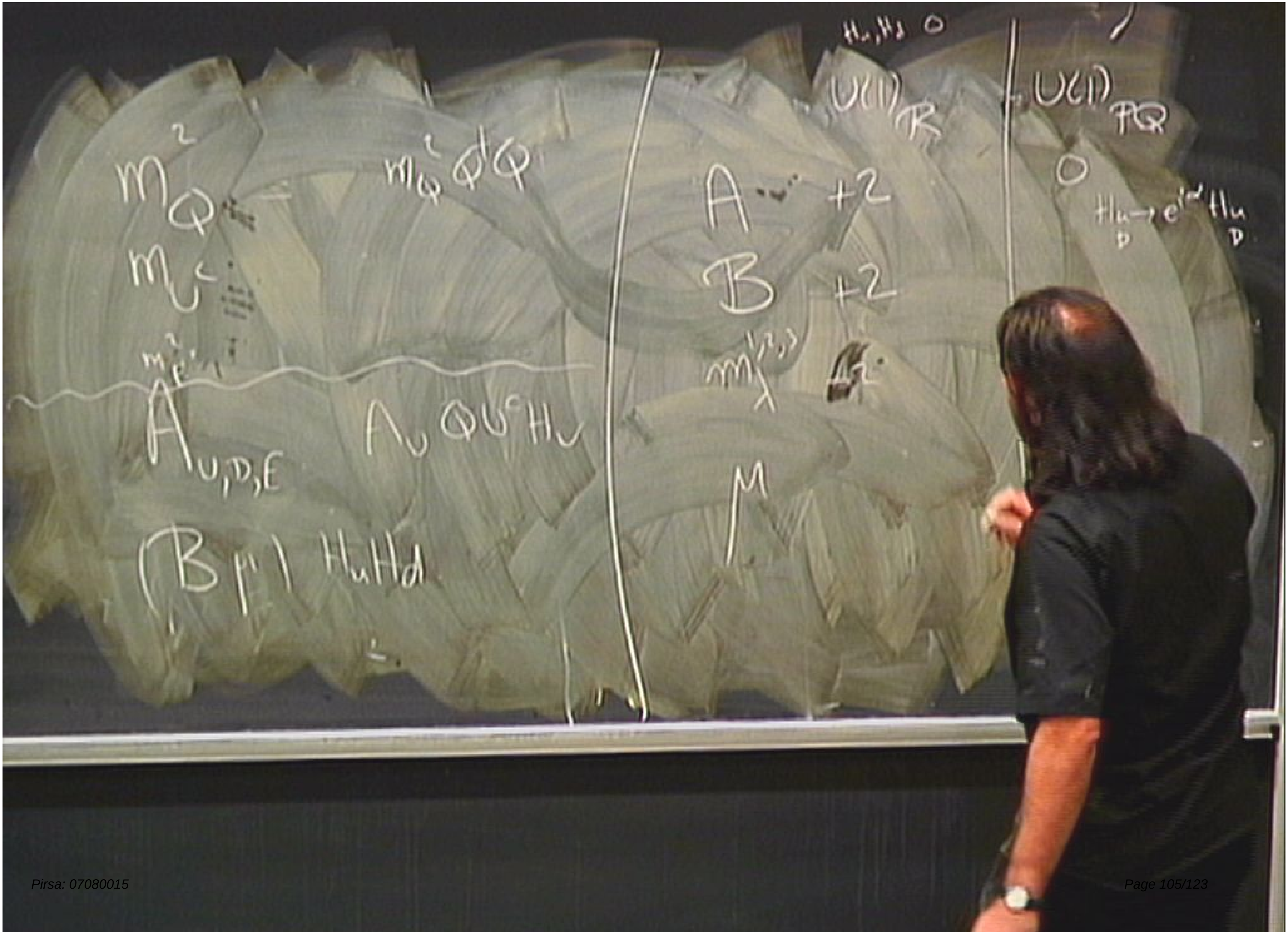
$m^2_{E^c}$

$A_{U,D,E}$ $\quad A_U Q U^c H_u$

$(B\mu)$ $\quad H_u H_d$



m_Q^2
$m_Q^2 Q^\dagger Q$
m_{U^c}
$A_{U,D,E}$
$A_U Q U^c H_u$
$B\mu$ $H_u H_d$
A
B
$U(1)_R$
$U(1)_{PQ}$
$H_{u,D} \to e^{i\alpha} H_{u,D}$


H_u, H_d 0
$U(1)_R$
$U(1)_{PQ}$
m_Q^2
$m_Q^2 Q^\dagger Q$
A +2
0
$H_{u,D} \to e^{i\alpha} H_{u,D}$
m_{U^c}
B +2
$m^2_{E^c}$
$m_\lambda^{1,2,3}$
$A_{U,D,E}$
$A_U Q U^c H_u$
M
$(B\mu)\, H_u H_d$

H_u, H_d 0

$\mu + H_u + H_d$

m_Q^2 $\quad m_Q^2 Q^\dagger Q$

m_{U^c}

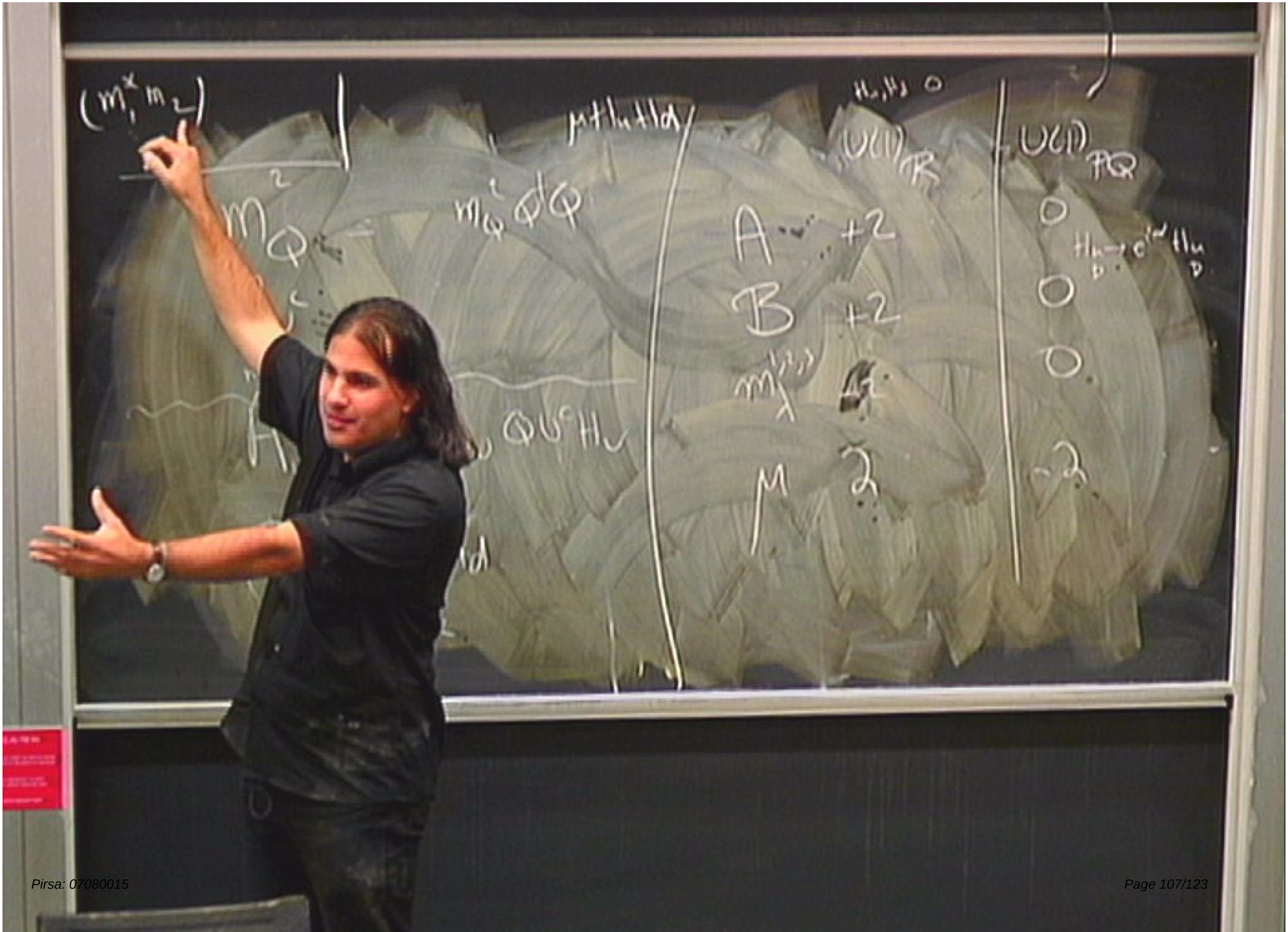
$m_{E^c}^2$

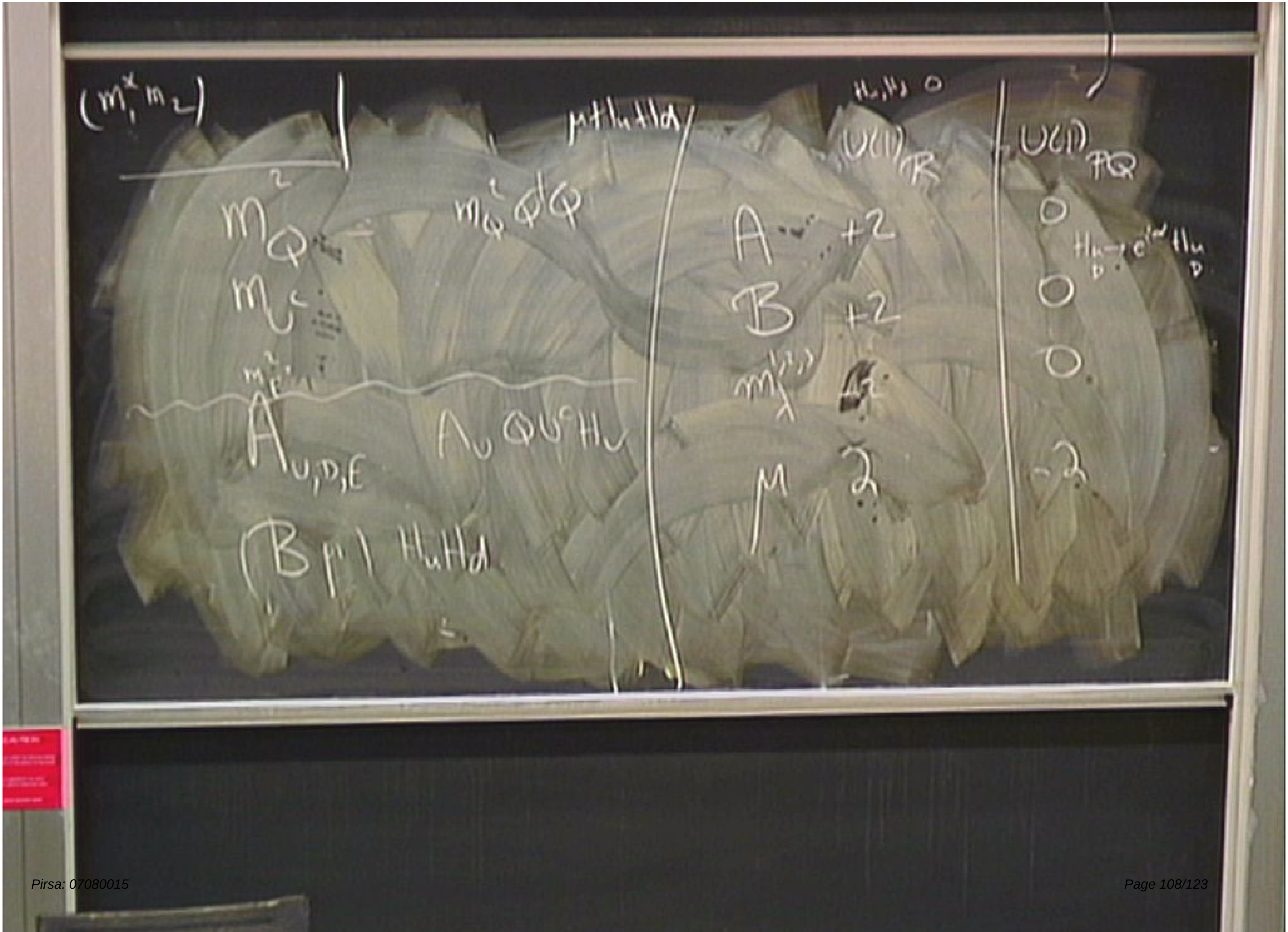
$A_{U,D,E}$ $\quad A_U Q U^c H_u$

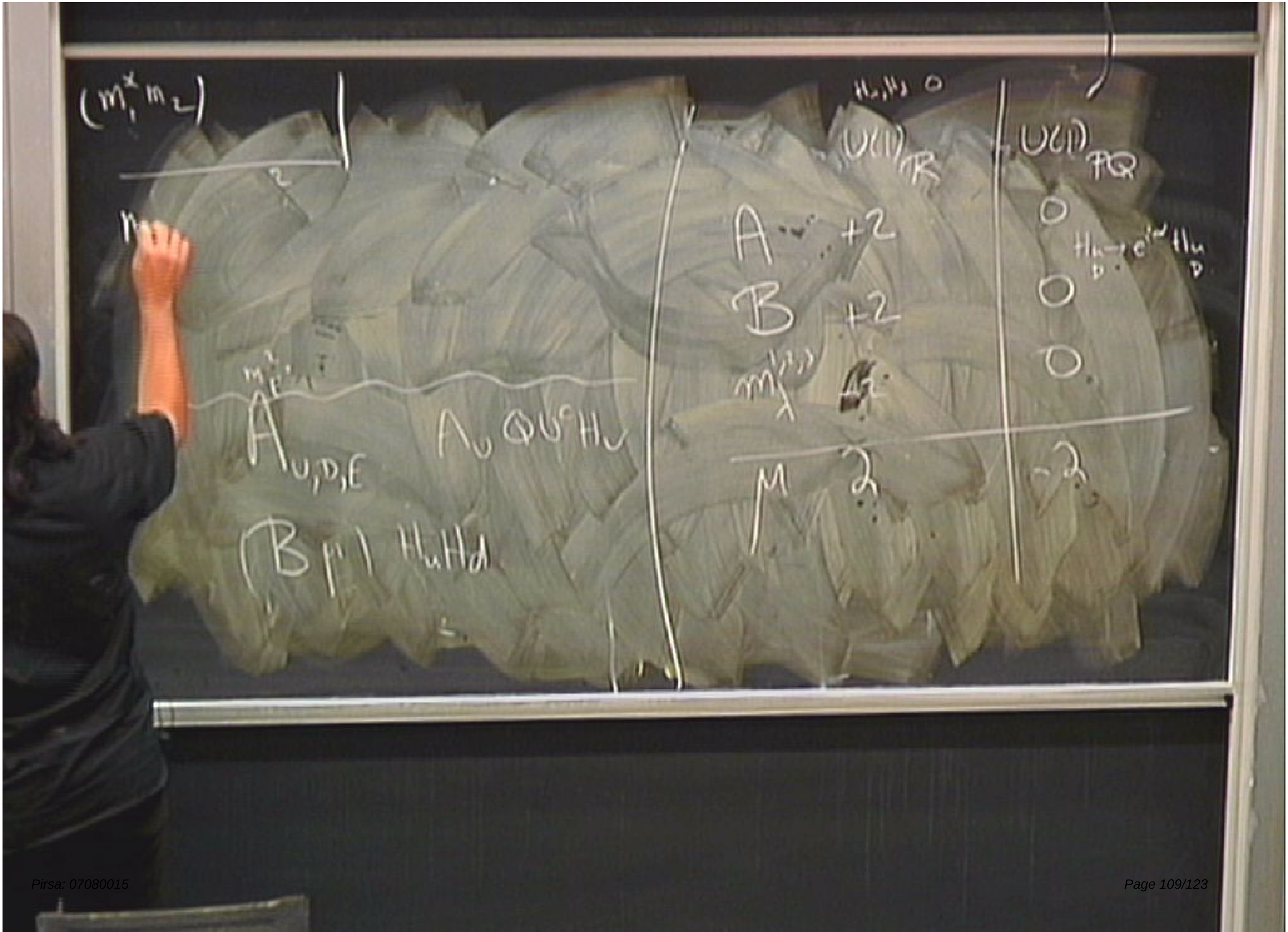
$(B\mu)$ $\quad H_u H_d$

	$U(1)_R$	$U(1)_{PQ}$
A	$+2$	0
B	$+2$	0
$m_\lambda^{1,2,3}$	[illegible]	0
μ	2	-2

$H_{u,D} \to e^{i\alpha} H_{u,D}$


U(1)_R
U(1)_PQ
A +2 0
B +2 0
M 2 -2


$(m_1^x m_2)$
m_Q^2
m_{U^c}
$m_{E^c}^2$
$A_{U,D,E}$
$B\mu$ $H_u H_d$
$m_Q^2 Q^\dagger Q$
$A_U Q U^c H_U$
$\mu + H_u + H_d$
$H_u H_d$ 0
$U(1)_R$
$U(1)_{PQ}$
A +2 0
$H_{u,D} \to e^{i\alpha} H_{u,D}$
B +2 0
$m_\lambda^{(1,2,3)}$ 0
M 2 -2


(m1 m2)
Hu,Hd 0
U(1)R
U(1)PQ
A +2 0
B +2 0
0
M 2 -2
AU,D,E
AU QUc Hu
Bμ HuHd

$(m_1^* m_2)$

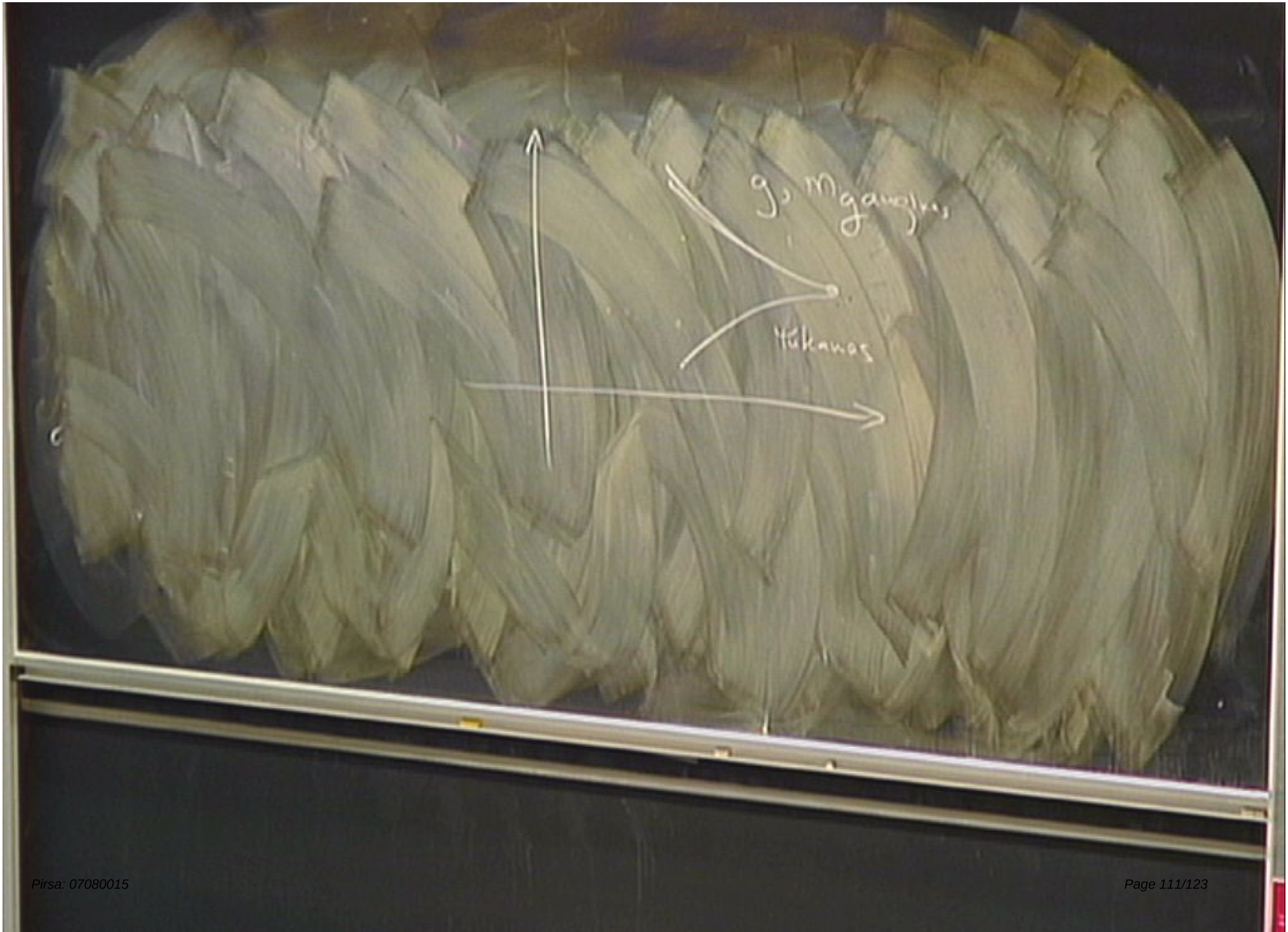
$$\boxed{(m^* B)^2 (m^* A)}$$

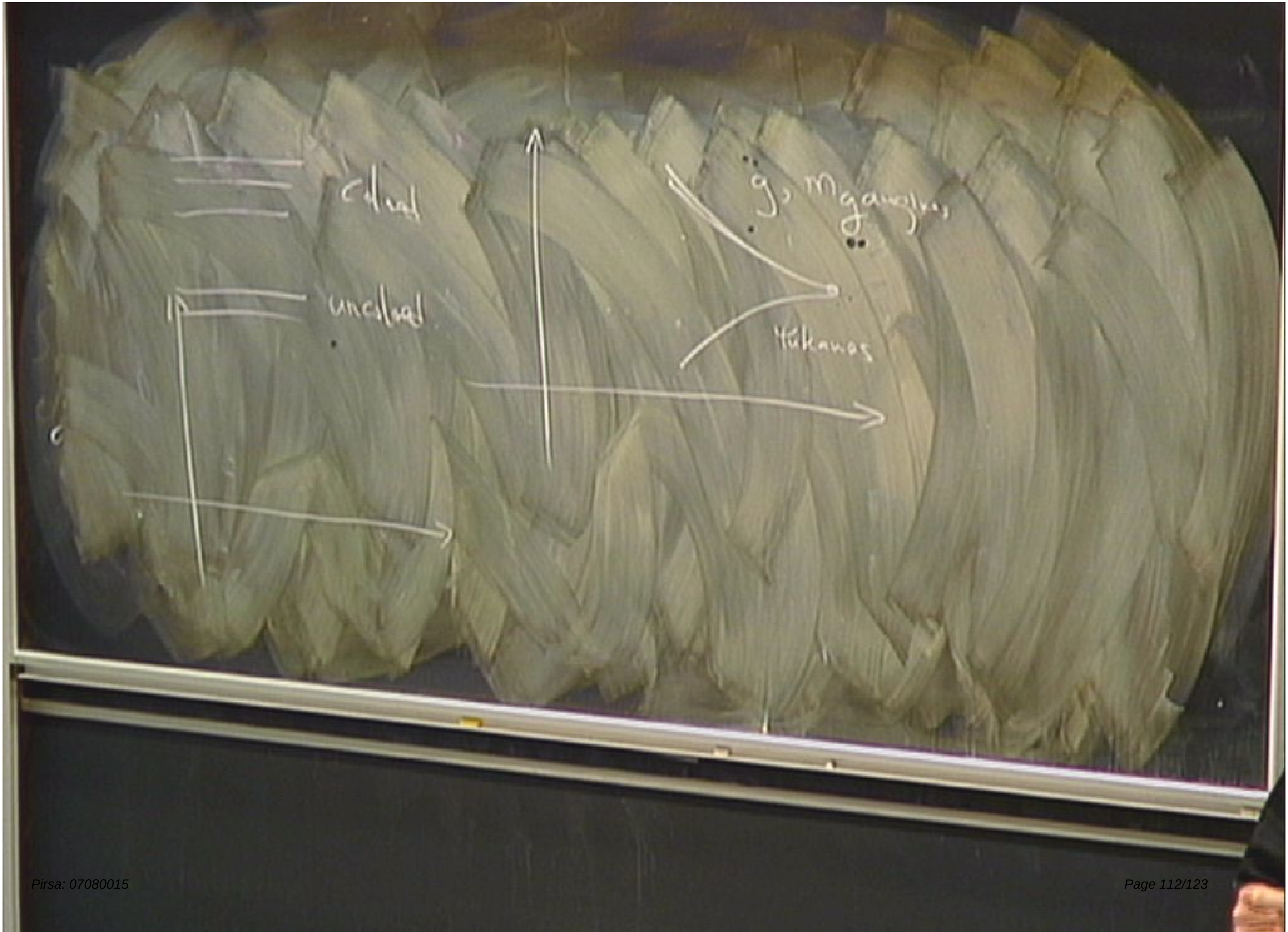
$A_{U,D,E}$ $\quad A_U Q U^c H_U$

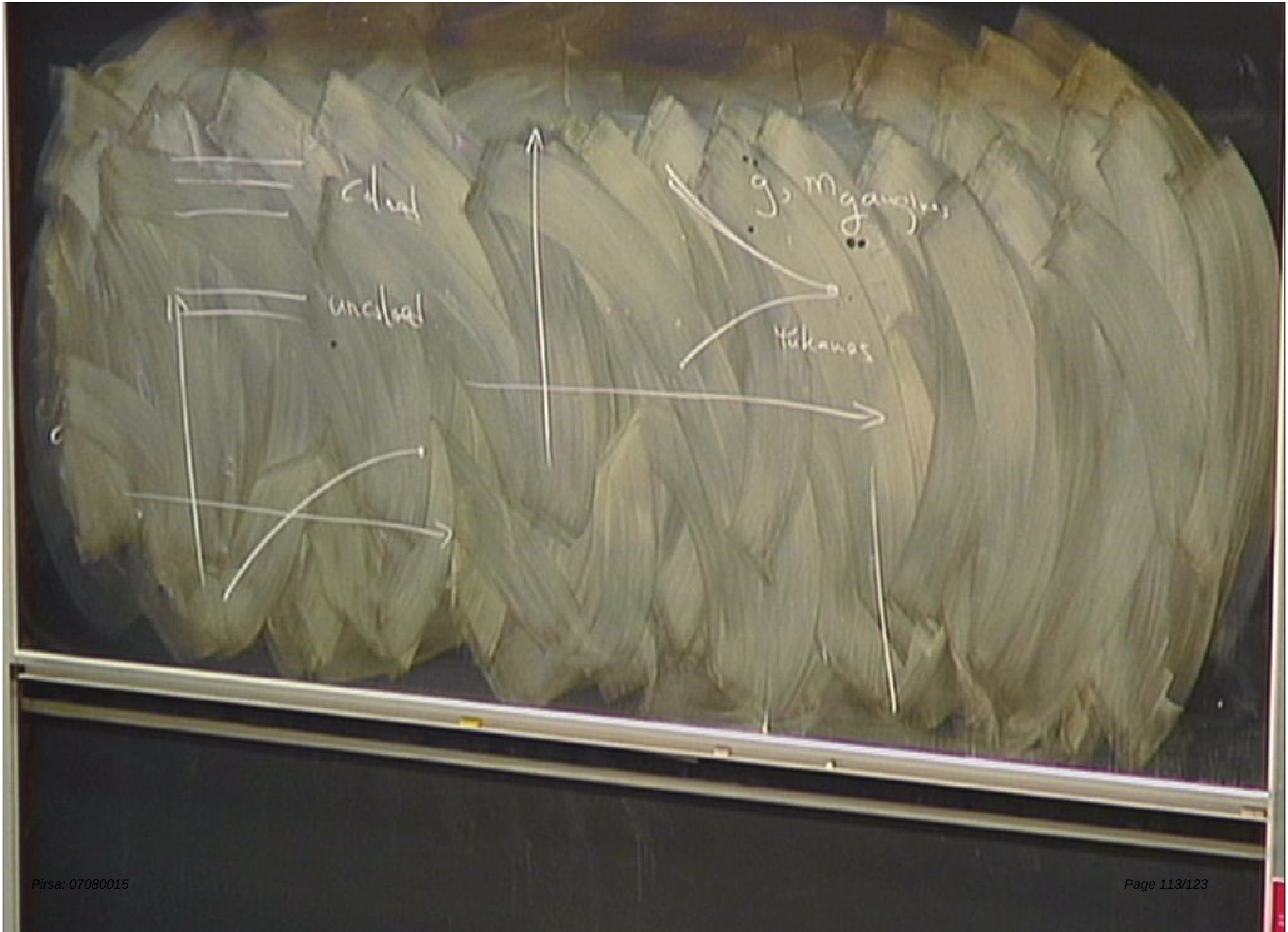
$(B\mu)\; H_u H_d$

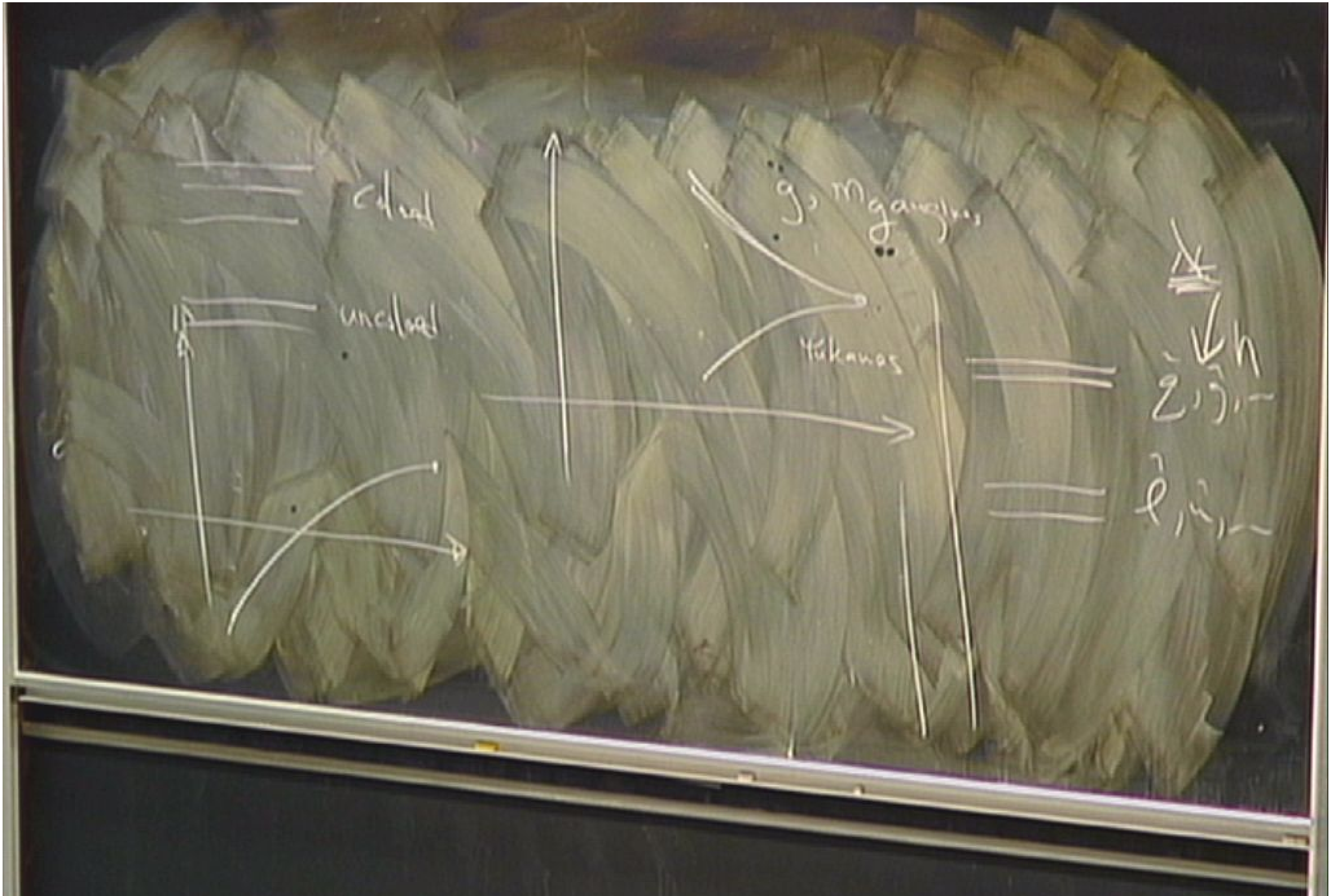
	$U(1)_R$	$U(1)_{PQ}$
H_u, H_d	0	
A	$+2$	0
B	$+2$	0
$m_\lambda^{(1,2)}$	[illegible]	0
M	2	-2

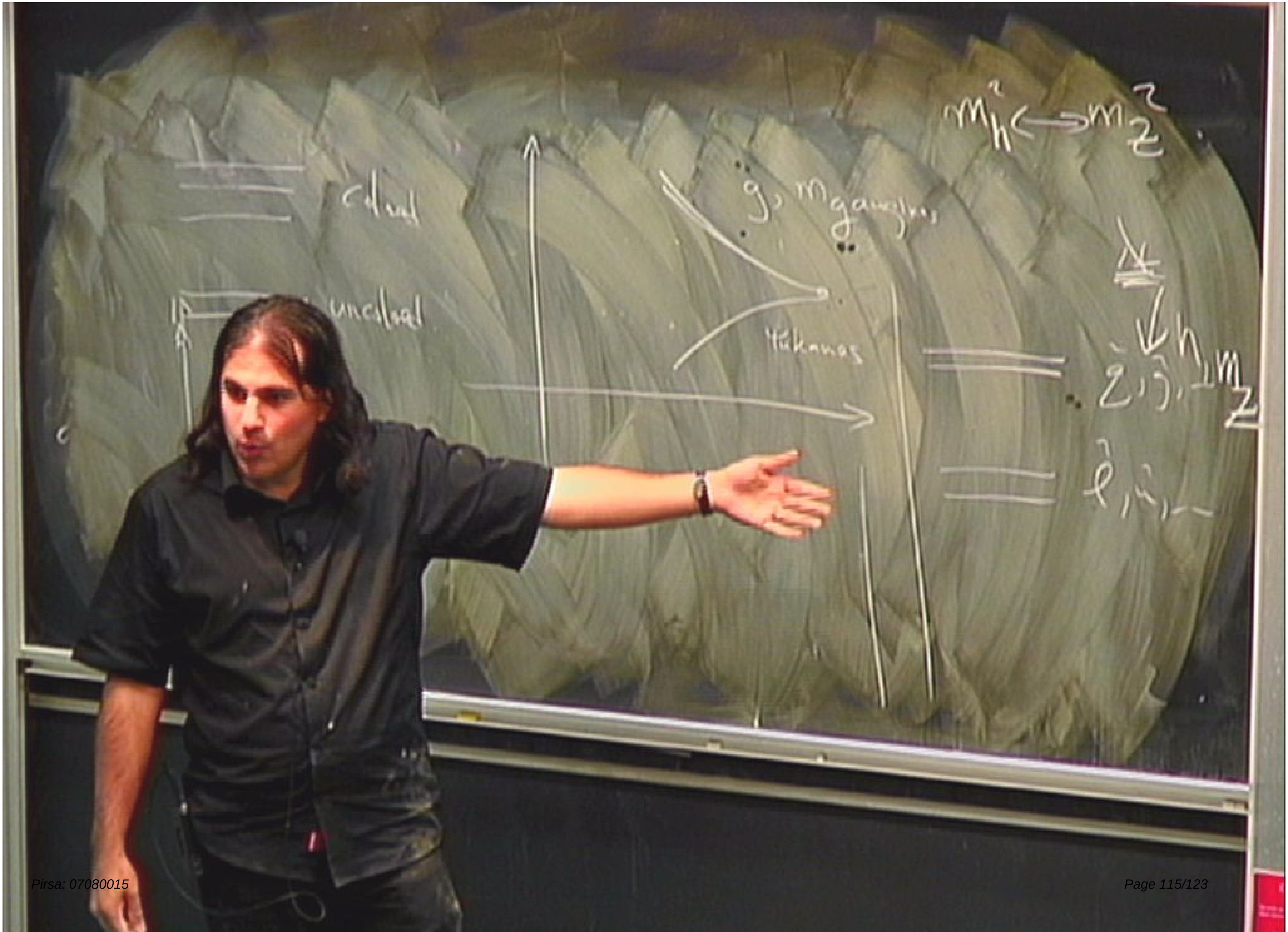
$H_{u,D} \to e^{i\alpha} H_{u,D}$


g, Mgaugino,
Yukawas

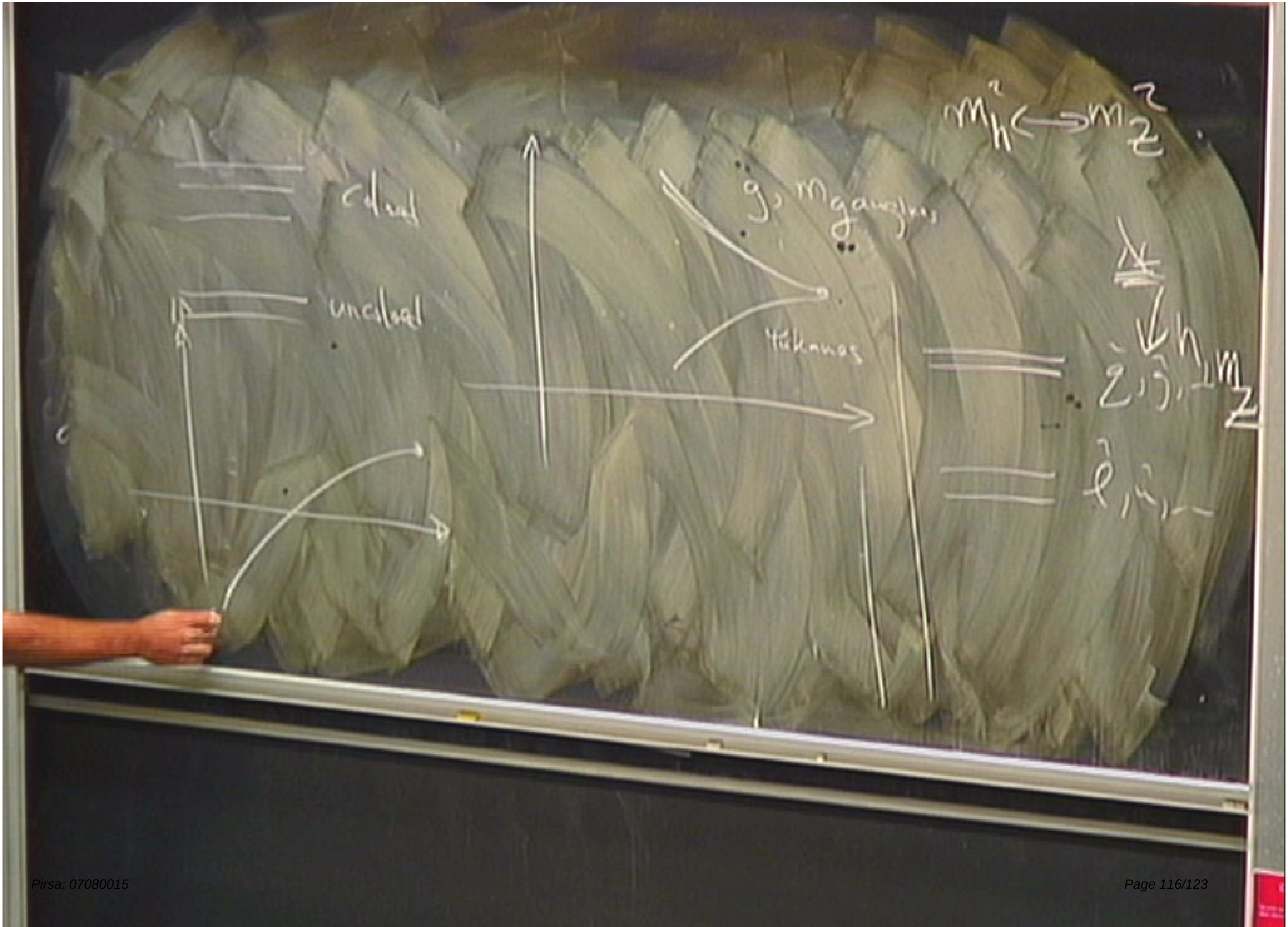

g, Mgaugino,
Yukawas

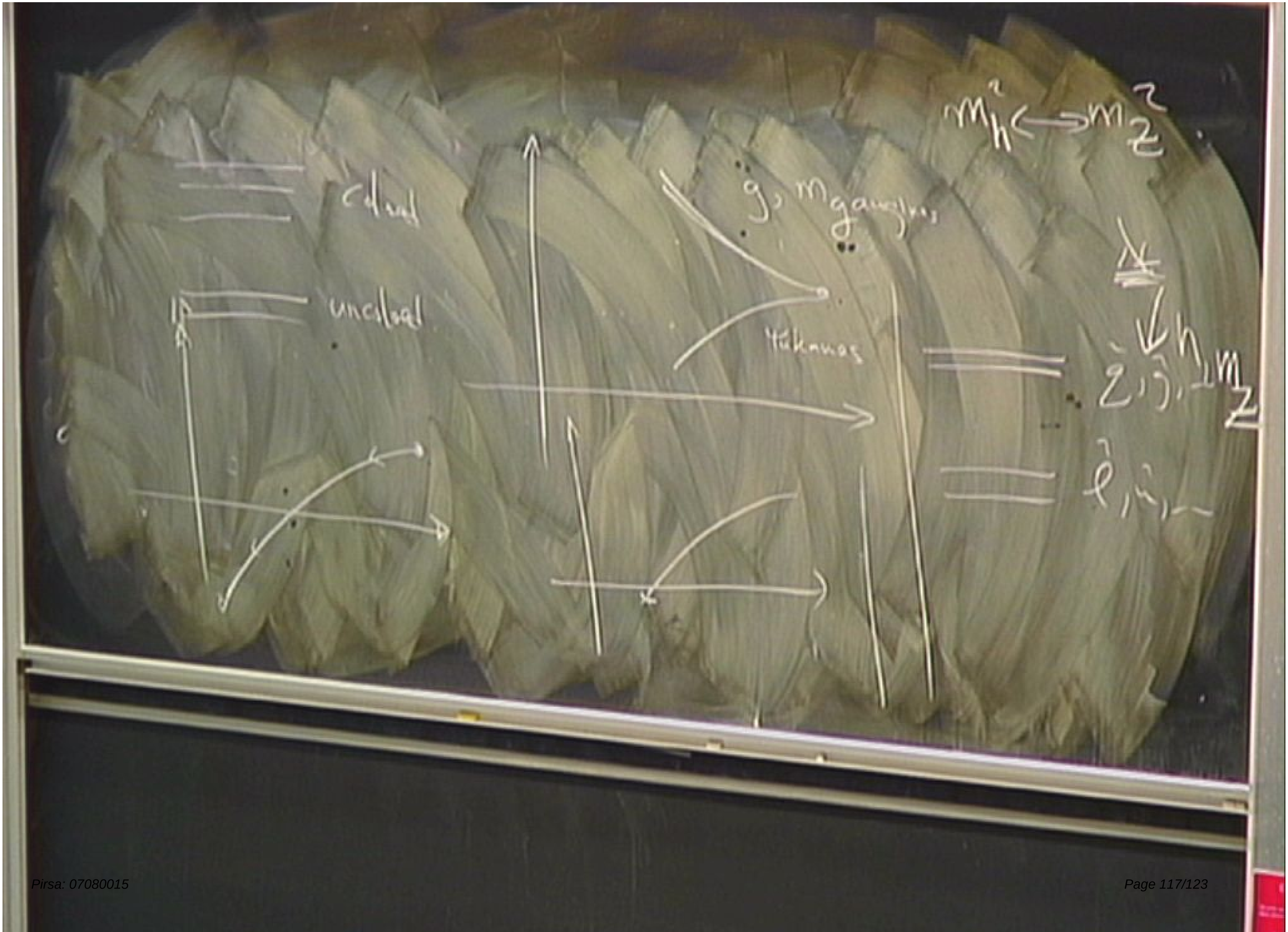

colored
uncolored
g, M gaugino,
Yukawas

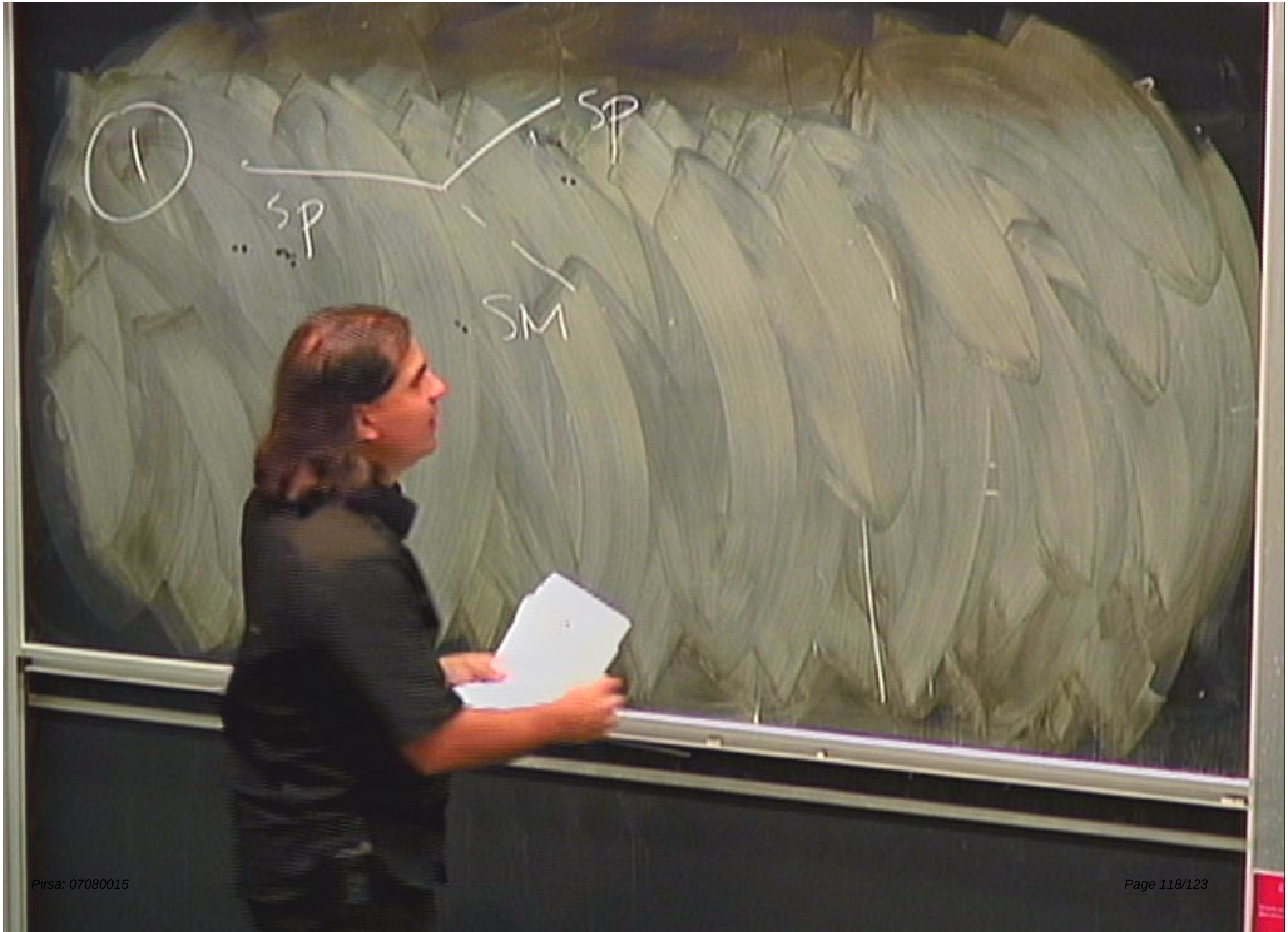

colored
uncolored
Yukawas
h

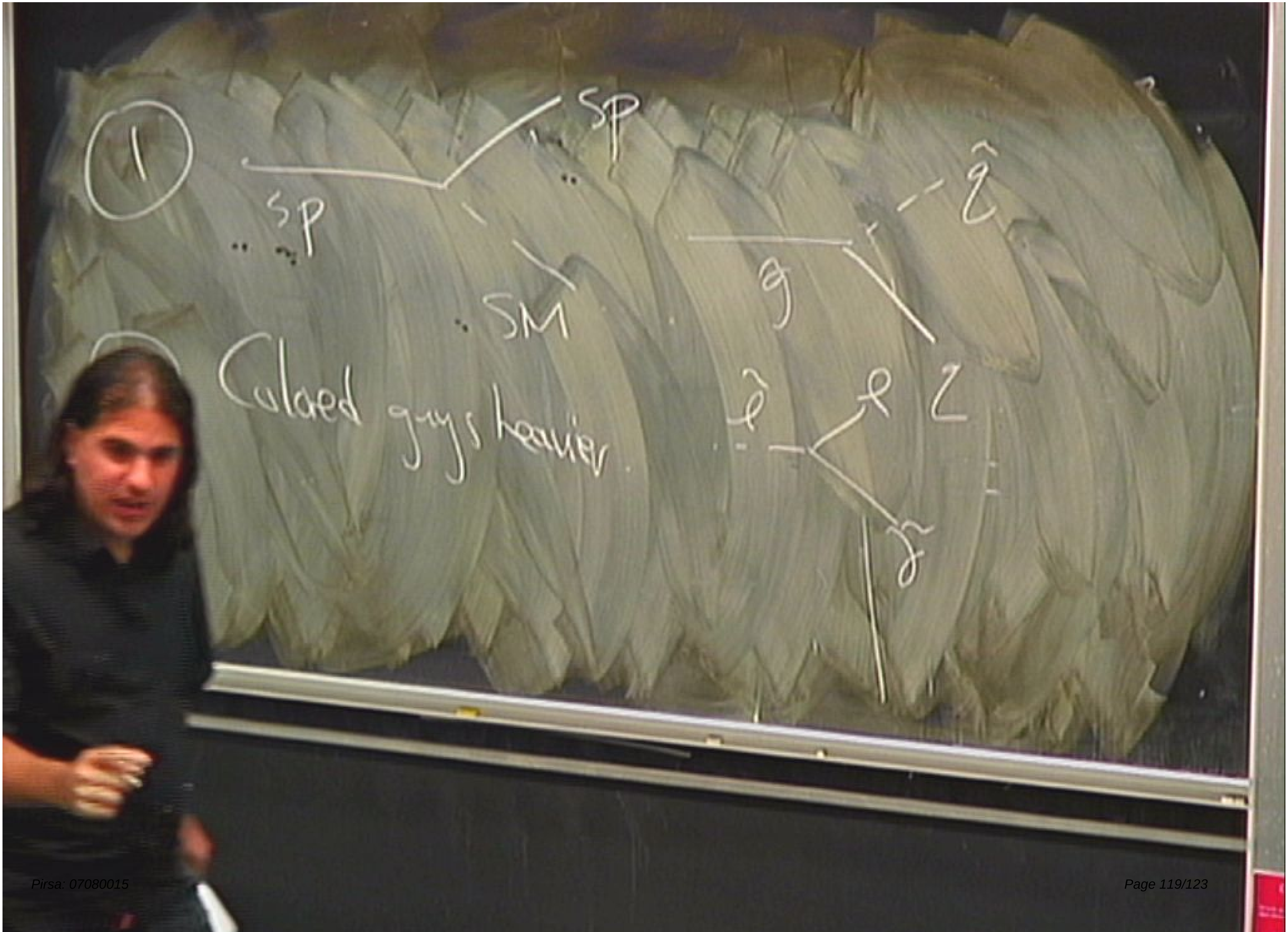


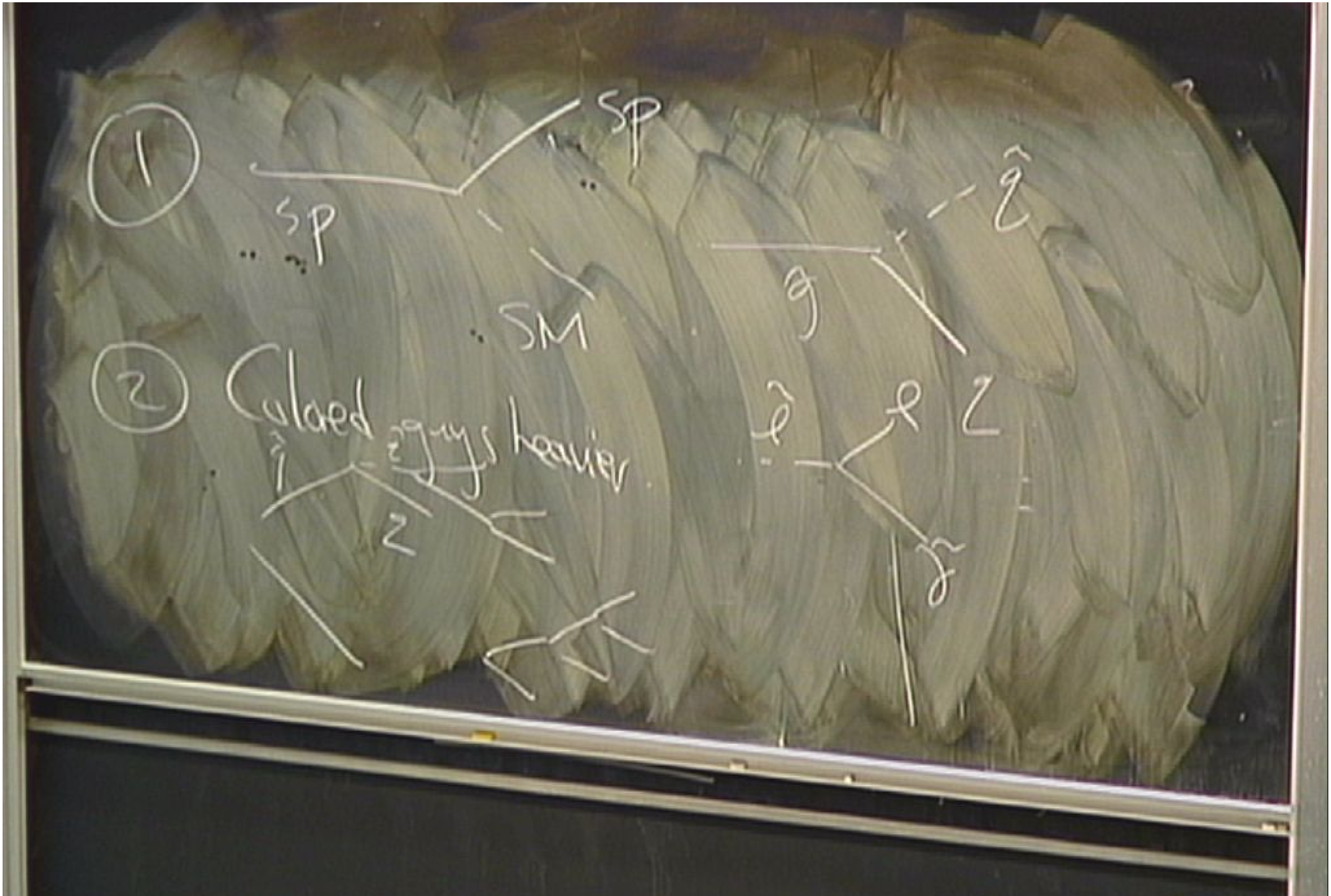
$m_h^2 \longleftrightarrow m_Z^2$
g, m gaugino
Yukawas
uncolored
colored
h, m_Z

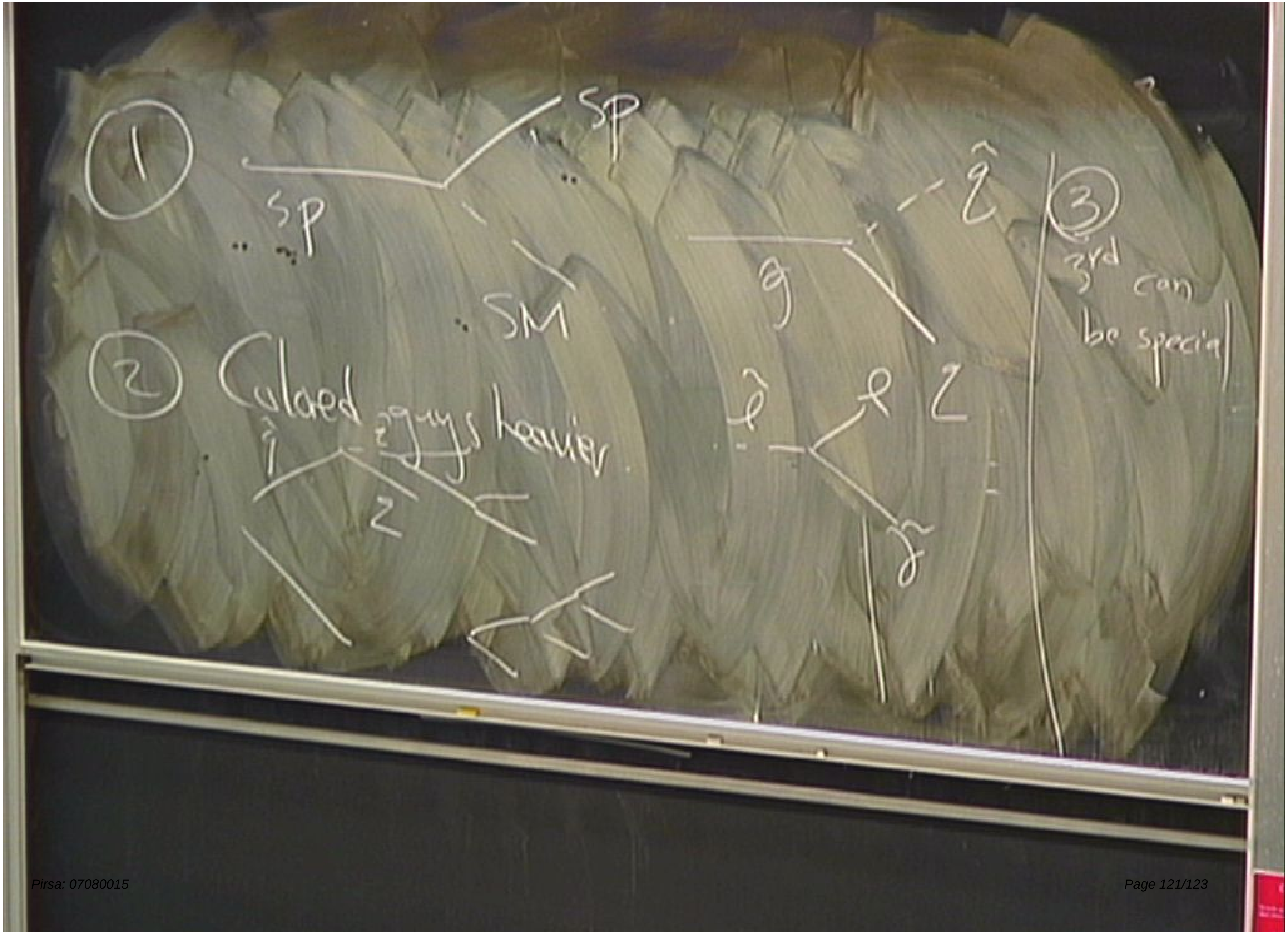

colored
uncolored
$\tilde{g}$, m_{gaugino}
Yukawas
$m_h^2 \longleftrightarrow m_Z^2$
$\tilde{Z}, \tilde{\gamma}, \ldots m_Z$
$\tilde{\ell}, \tilde{\nu}, \ldots$


colored
uncolored
$m_h^2 \longleftrightarrow m_Z^2$
$\tilde{g}$, m_{gaugino}
Yukawas
$\tilde{z}, \tilde{\gamma}, m_Z$
$\tilde{e}, \tilde{\mu}, \ldots$

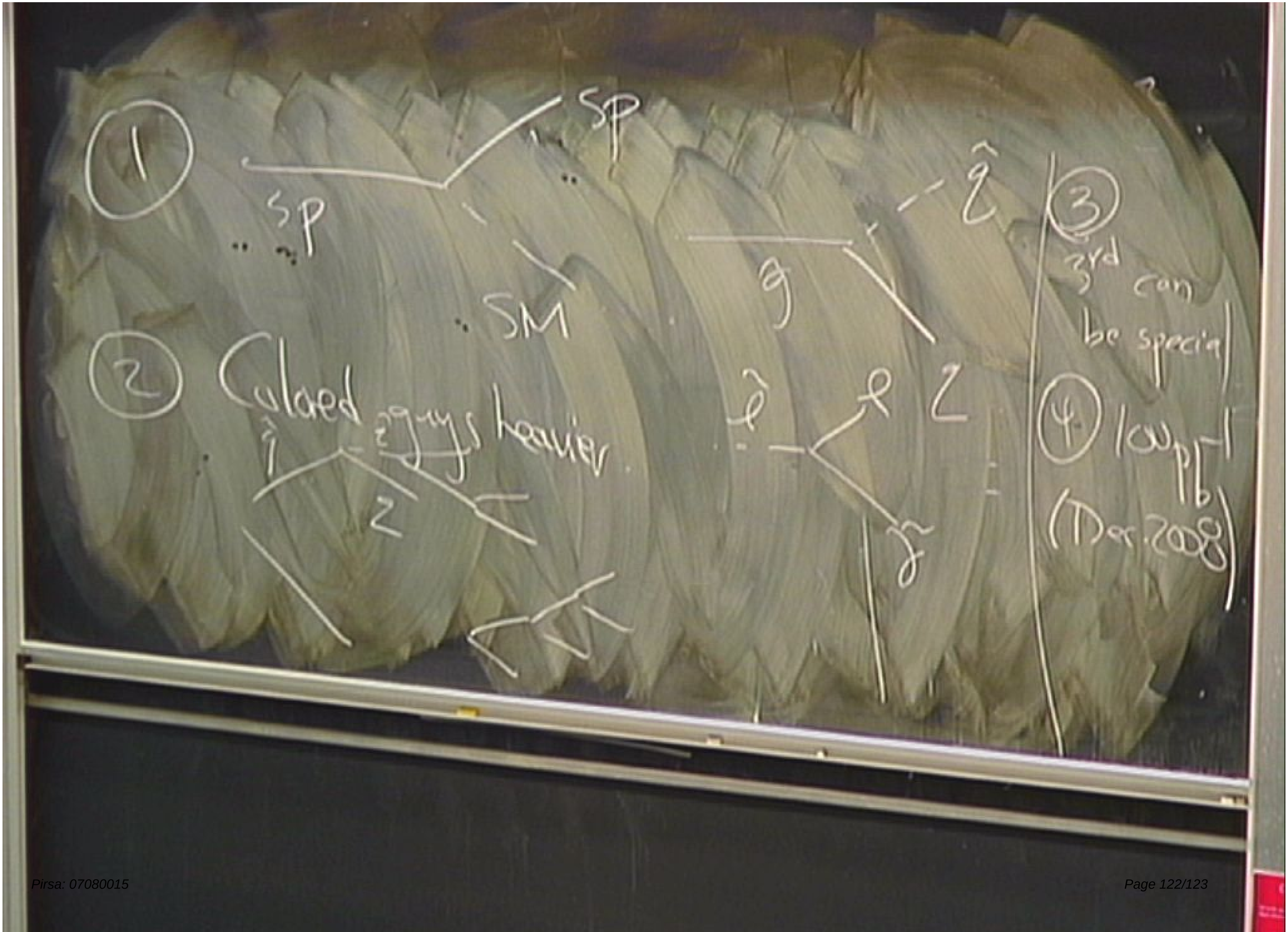

1
SP
SP
SM

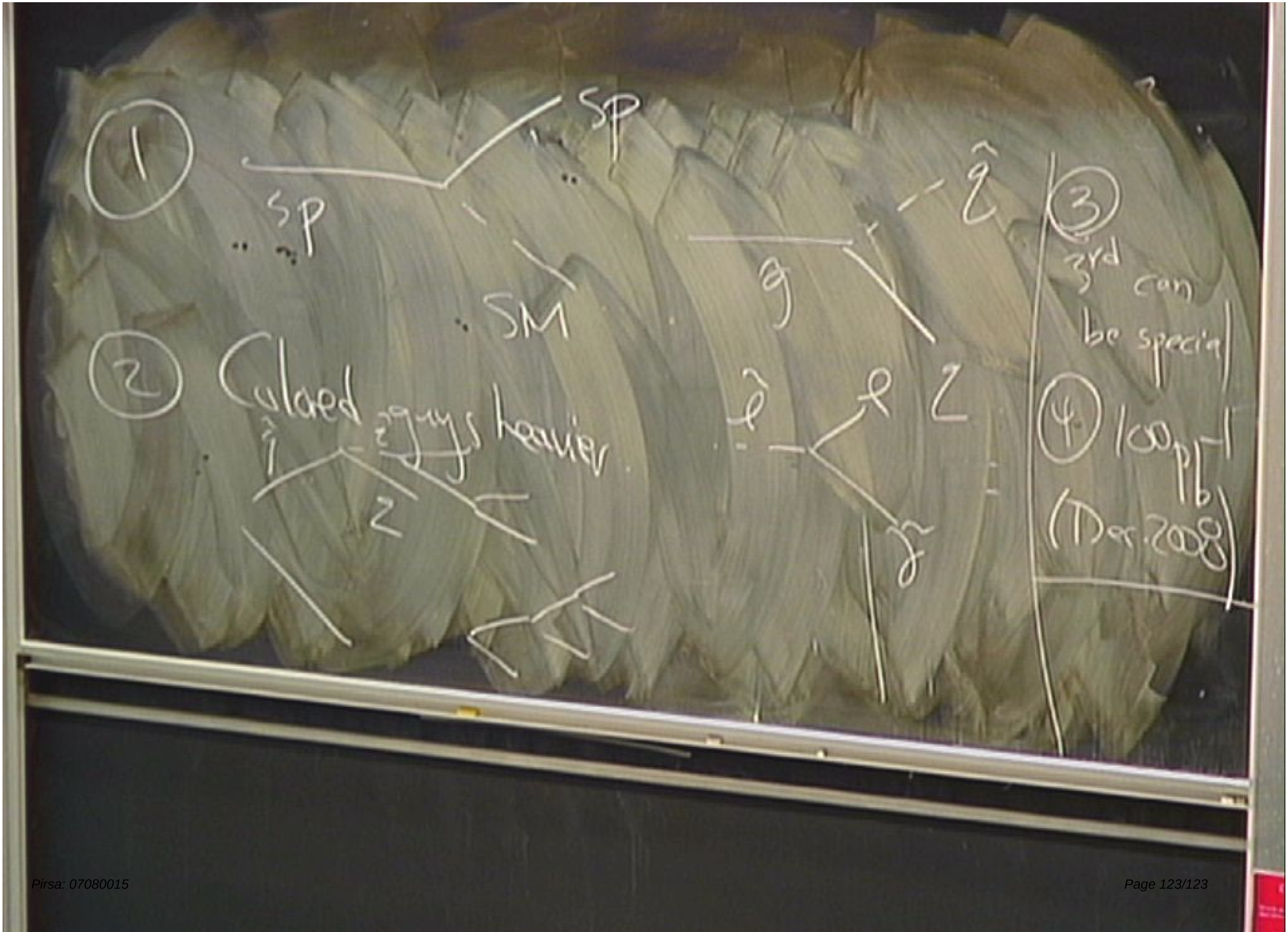

1
SP
SP
SM
Colored guys heavier
$\hat{q}$
q
$\tilde{e}$
e
Z
$\tilde{\gamma}$


SP
SP
SM
Colored guys heavier
Z



1
SP
SP
SM
2
Colored guys heavier
3
3rd can be special


1
SP
SP
SM
2 Colored guys heavier
Z
3 3rd can be special
4 100 pb-1 (Dec. 2008)


1
SP
SP
SM
2 Colored guys heavier
3 3rd can be special
4 100 pb-1 (Dec. 2008)