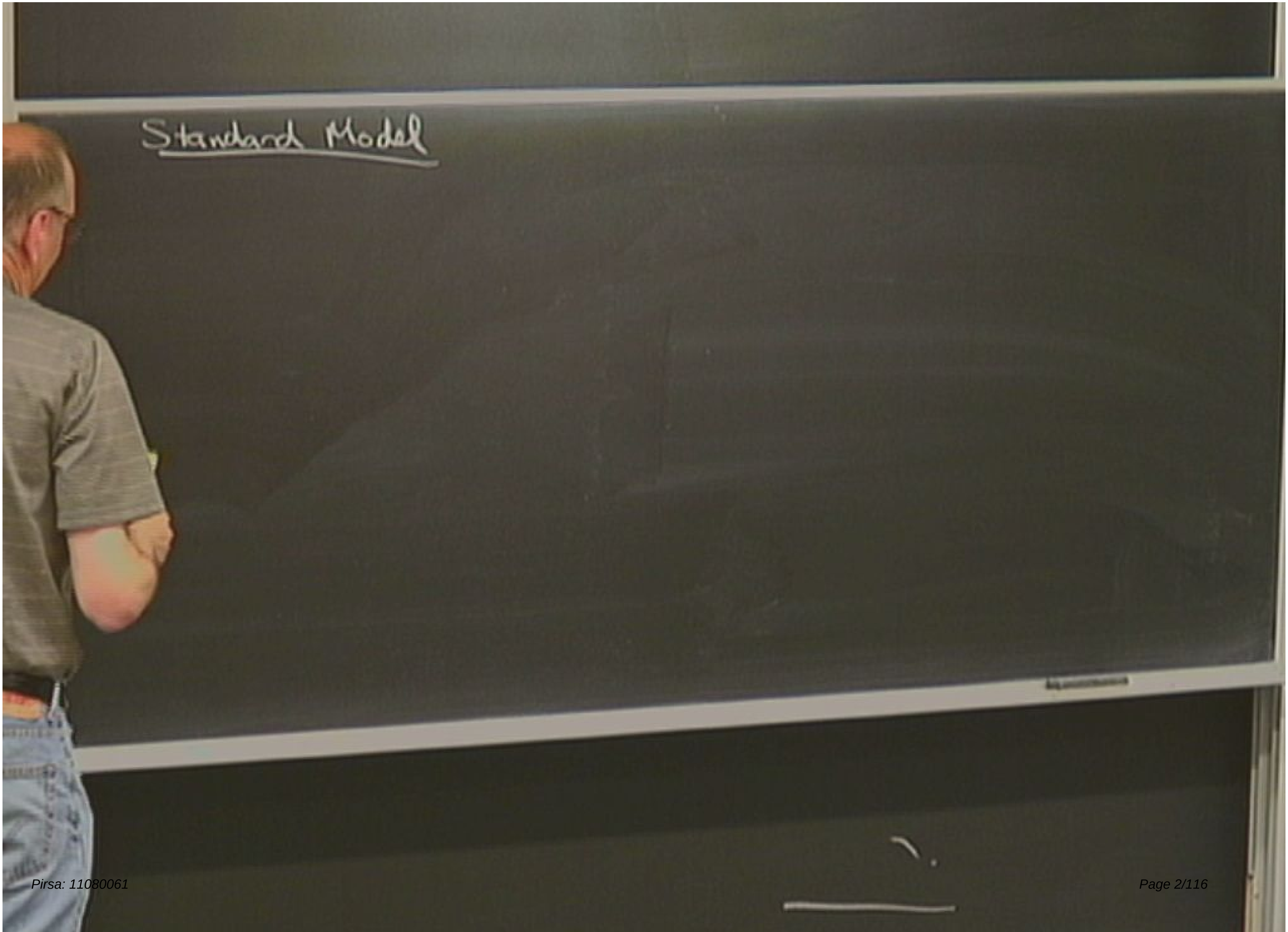
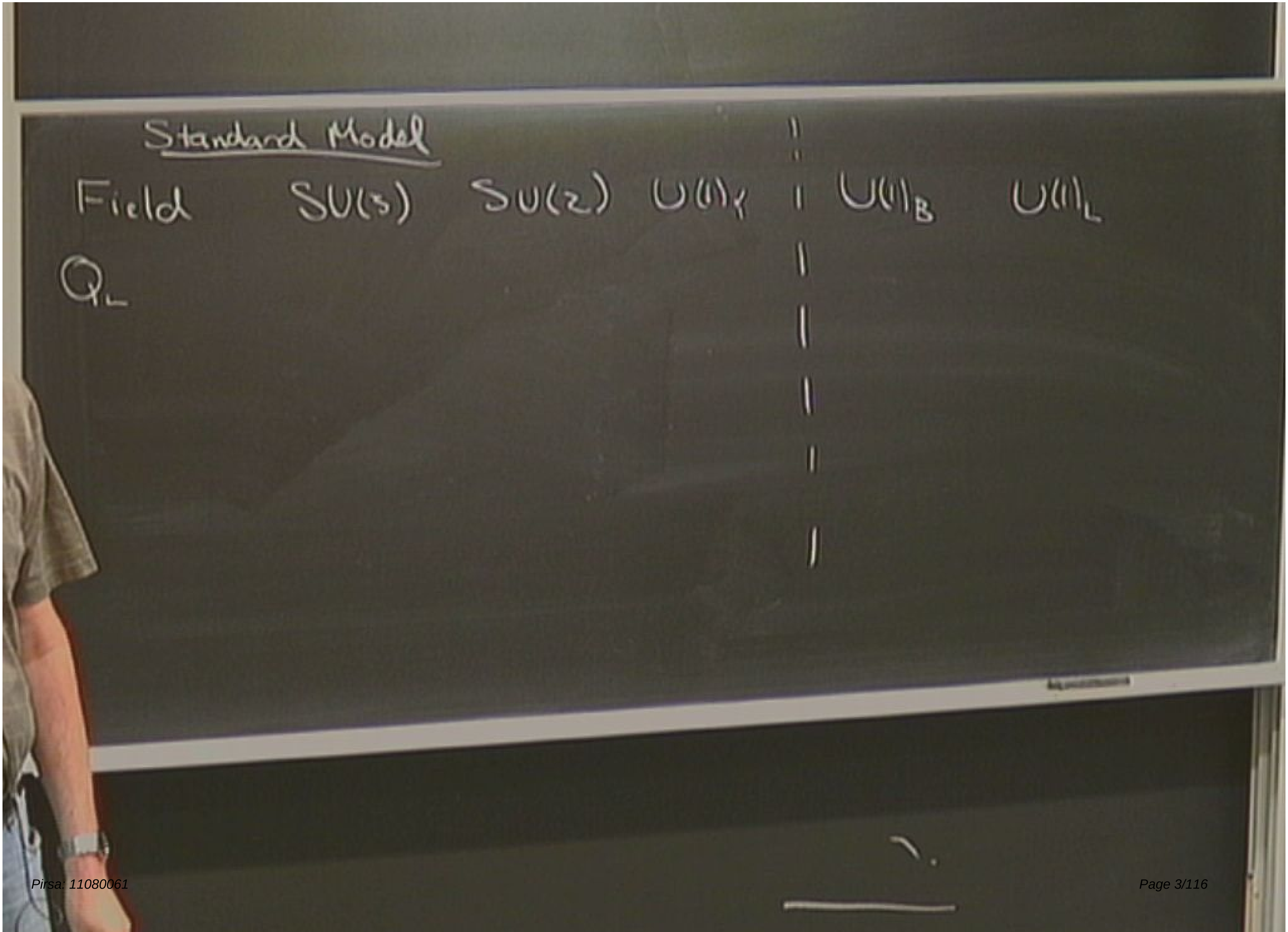
Title: Baryon Number and Lepton Number as Gauge Symmetries

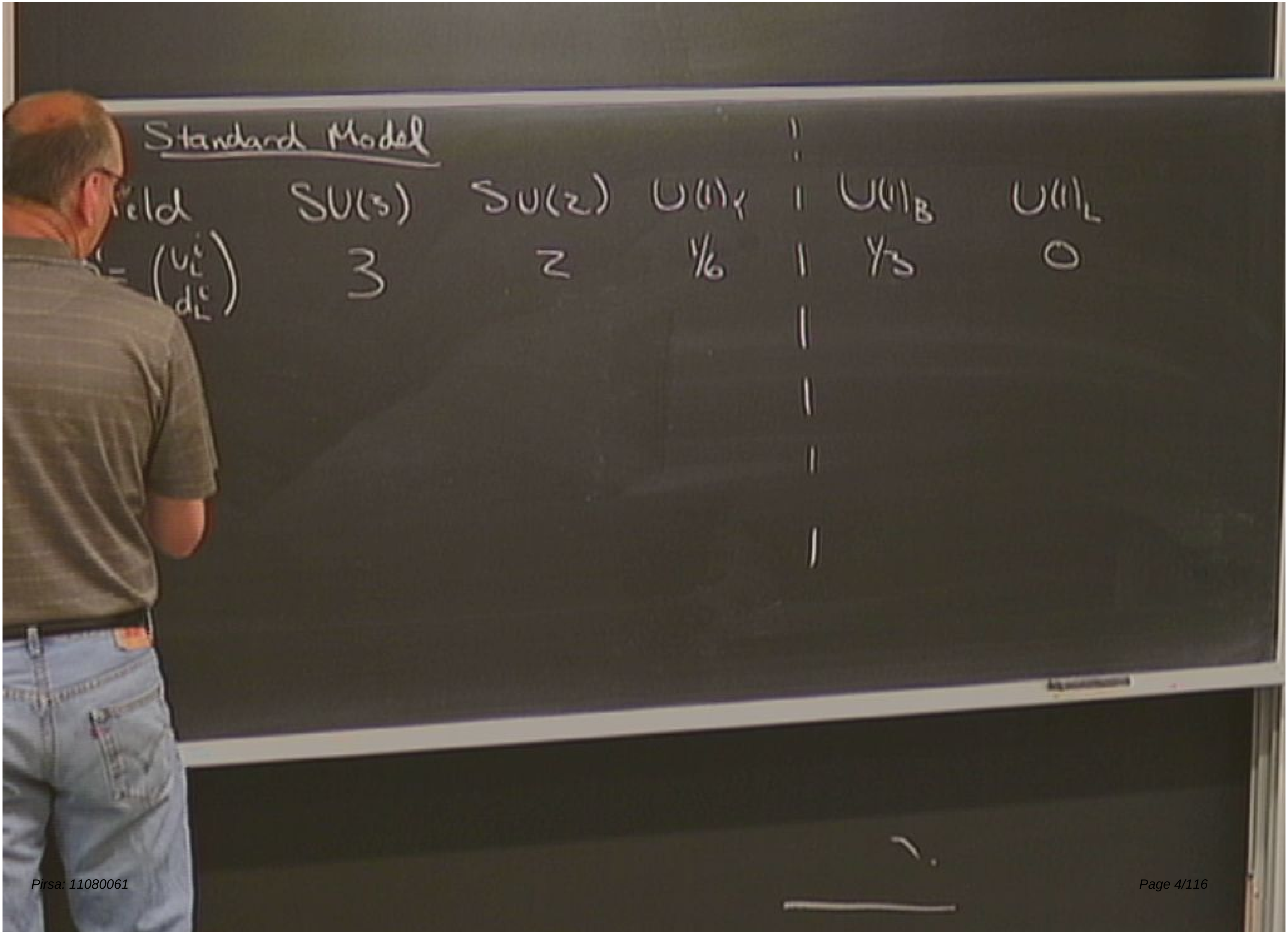
Date: Aug 16, 2011 12:30 PM

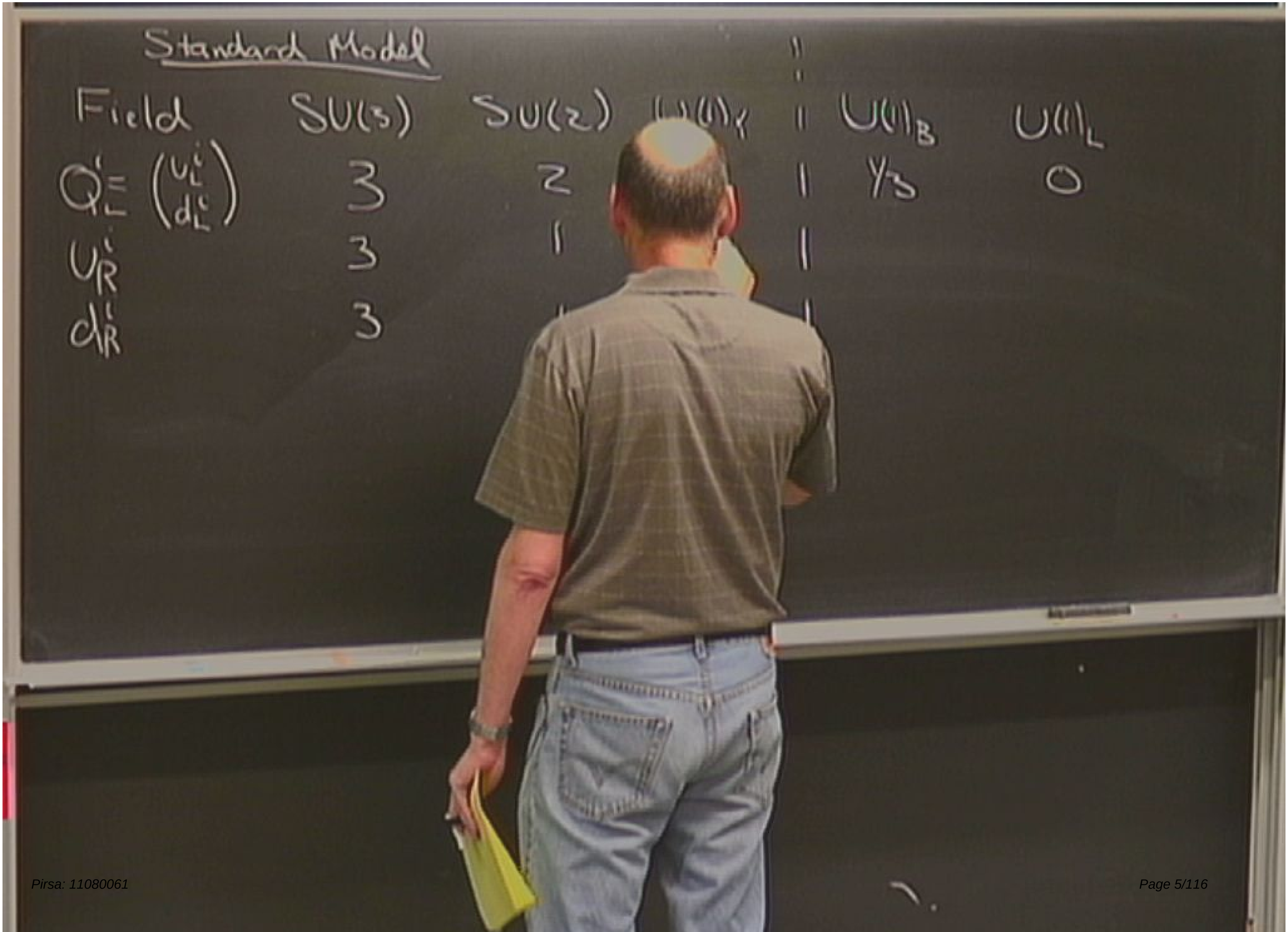
URL: http://pirsa.org/11080061

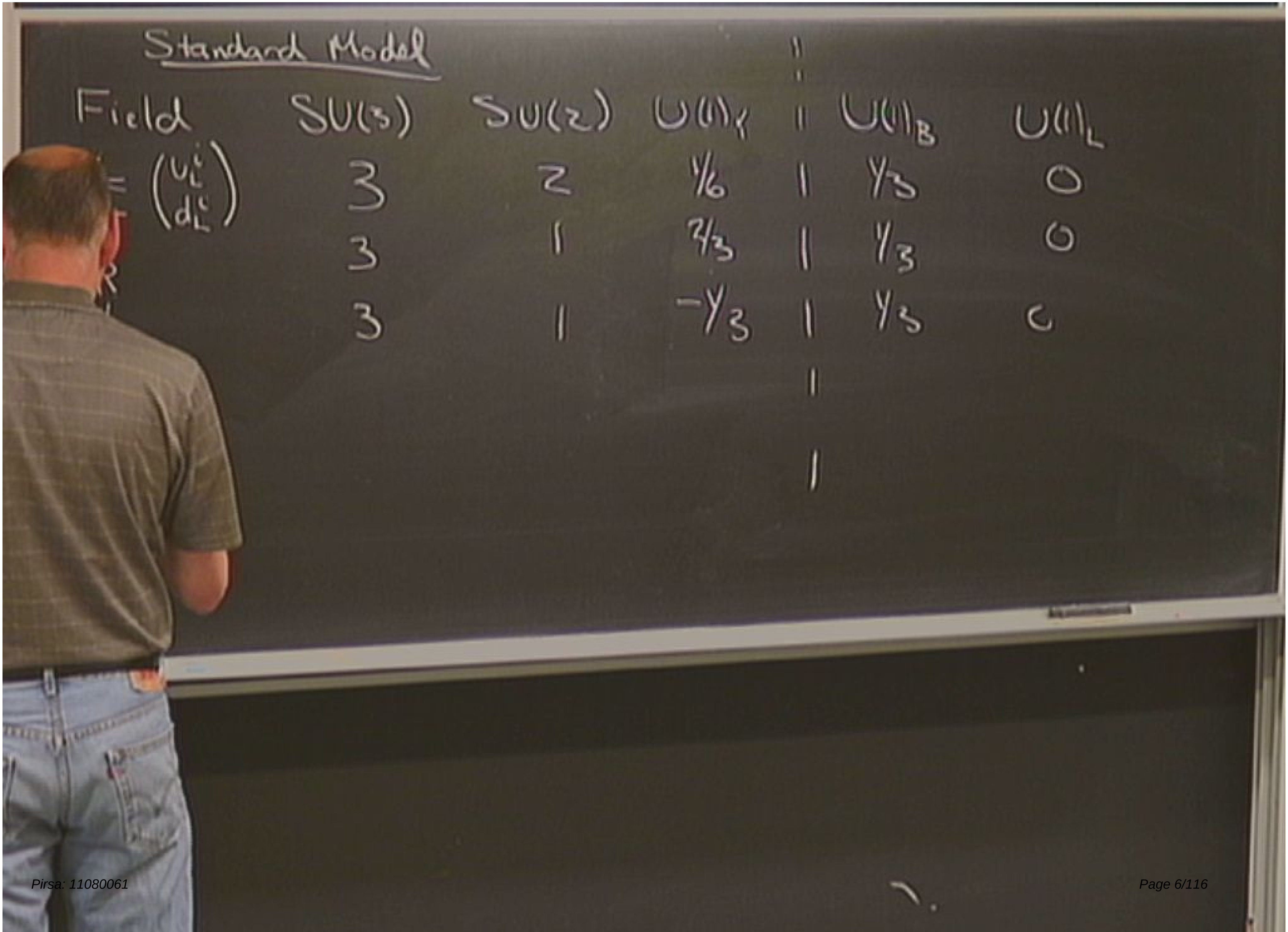
Abstract: The observed conservation of Baryon and Lepton number may arise because they are gauge symmetries. Models are discussed where Baryon and lepton number are the charges for a spontaneously broken U(1) gauge symmetries. The best of these models is: (1) free of Landau poles that are near the weak scale, (2) has no flavor changing neutral currents at tree level and (3) contains a dark matter candidate.

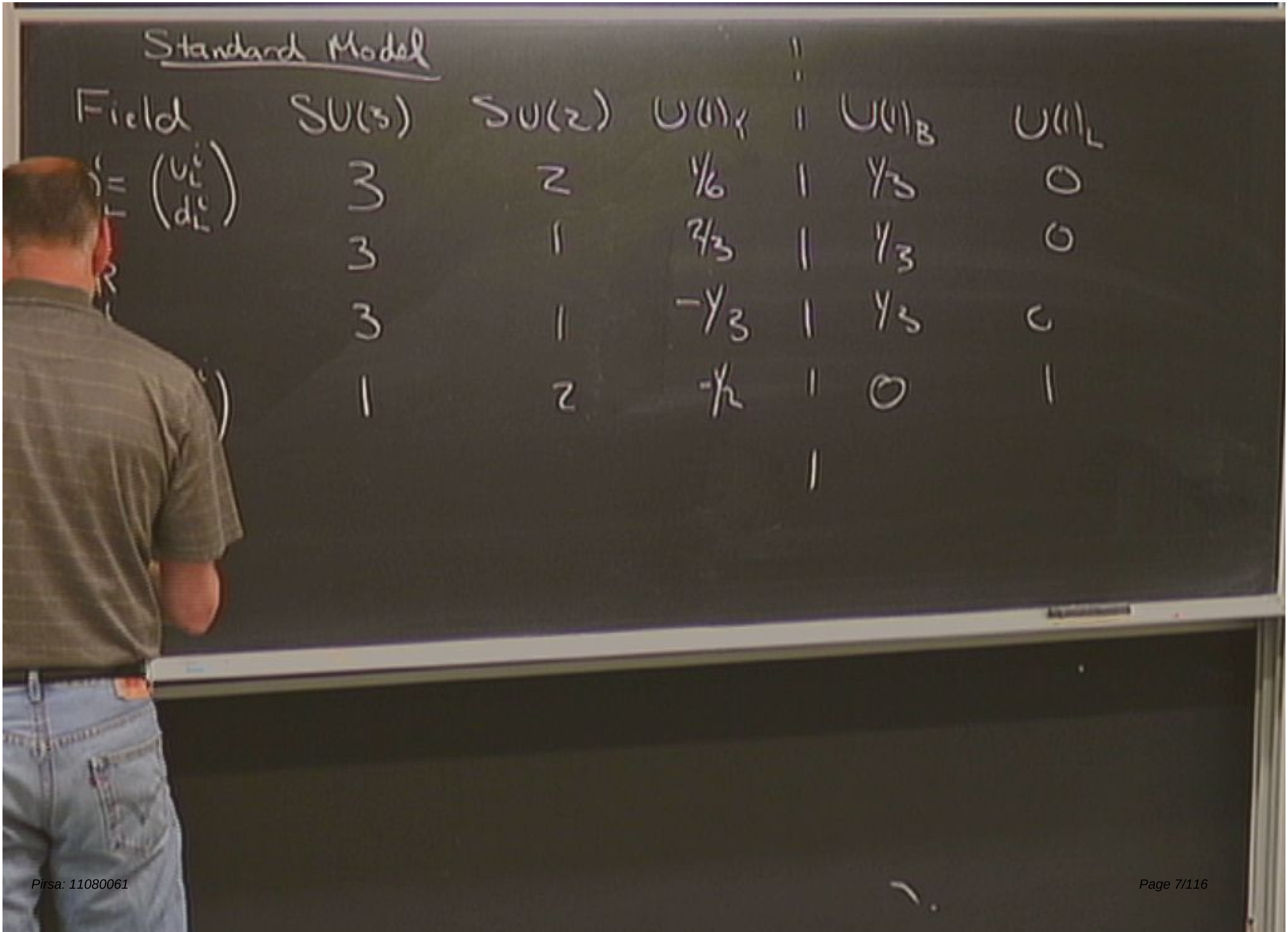

Standard Model

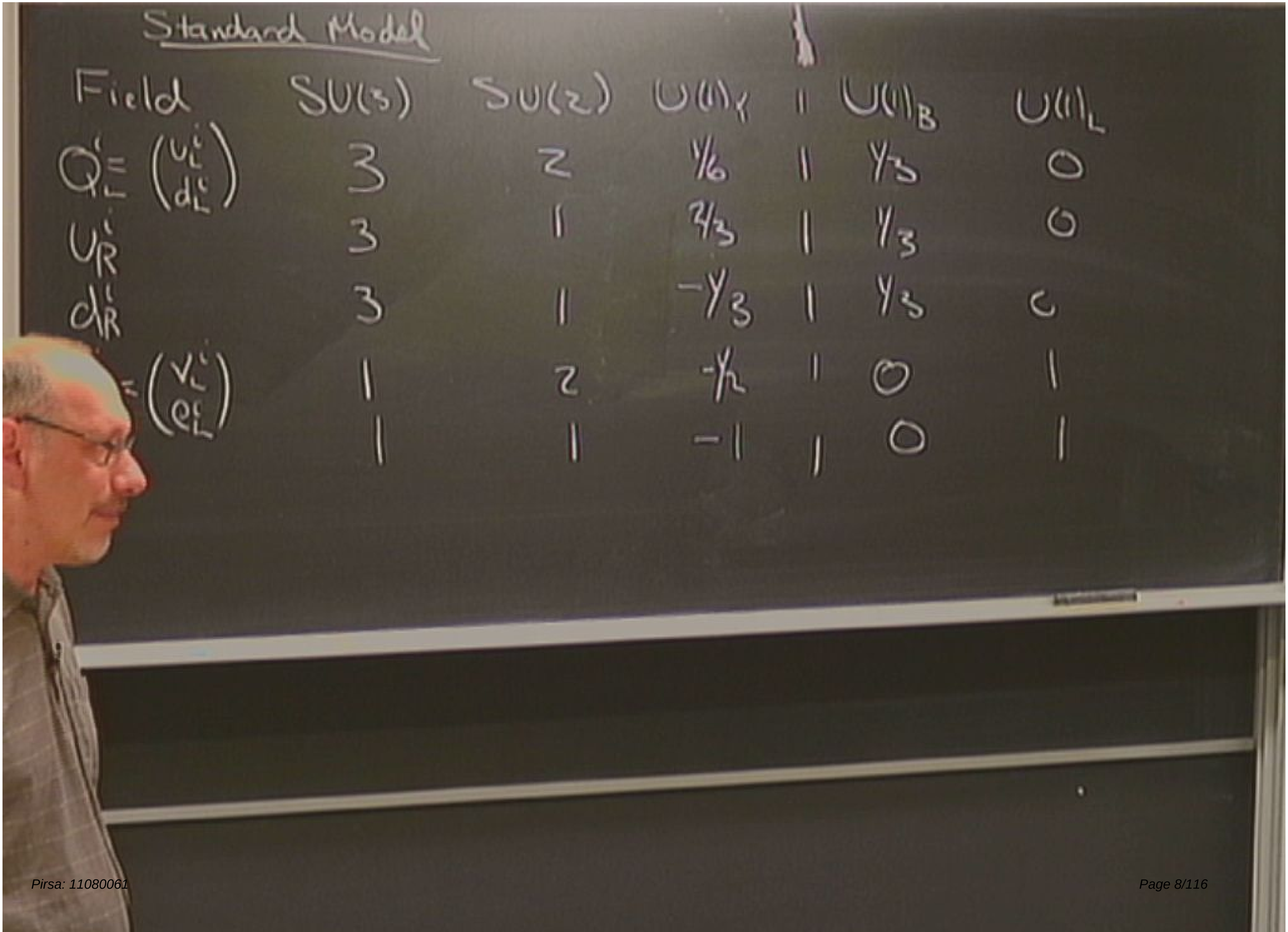

Standard Model
Field SU(3) SU(2) $U(1)_Y$ $U(1)_B$ $U(1)_L$
Q_L

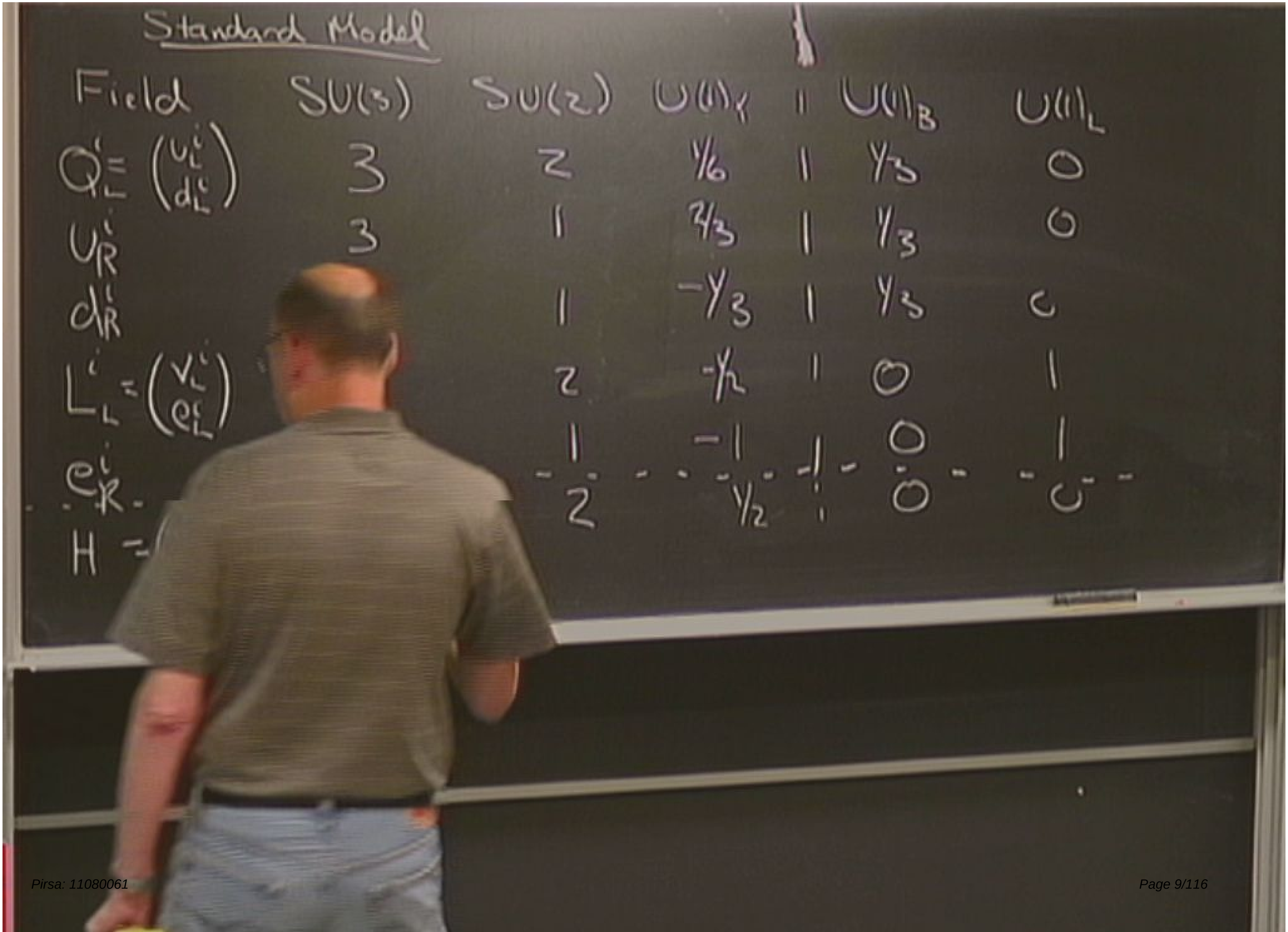

Standard Model
ield SU(3) SU(2) U(1)Y U(1)B U(1)L
3 2 1/6 1/3 0


Standard Model
Field SU(3) SU(2) U(1)Y U(1)B U(1)L
Qi L = (ui L di L) 3 2 1/3 0
ui R 3 1
di R 3 1


Standard Model
Field SU(3) SU(2) U(1)_Y U(1)_B U(1)_L
= (u_L^i d_L^i) 3 2 1/6 1/3 0
3 1 2/3 1/3 0
3 1 −1/3 1/3 0

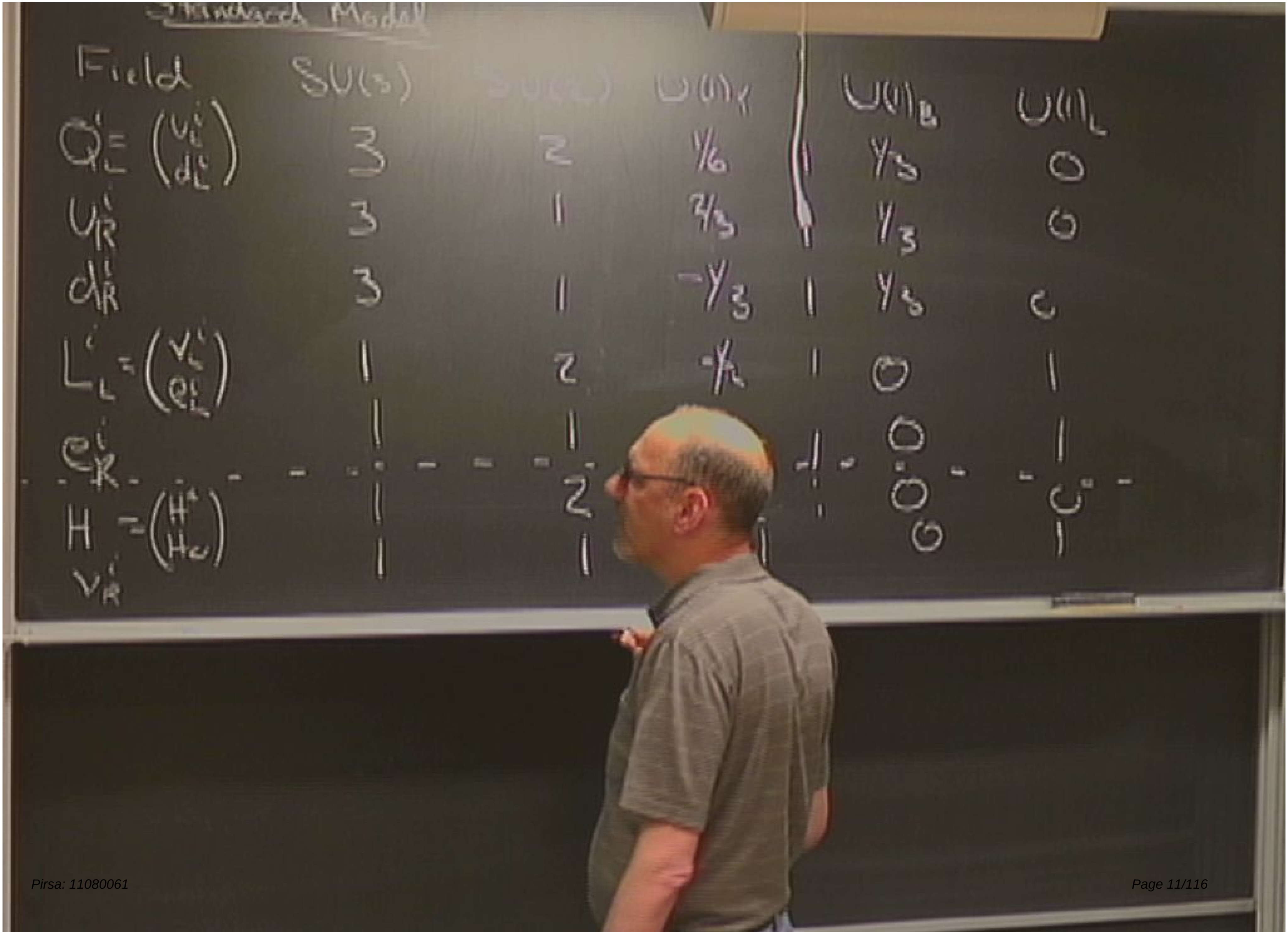

Standard Model
Field SU(3) SU(2) U(1)Y U(1)B U(1)L
3 2 1/6 1/3 0
3 1 2/3 1/3 0
3 1 -1/3 1/3 0
1 2 -1/2 0 1

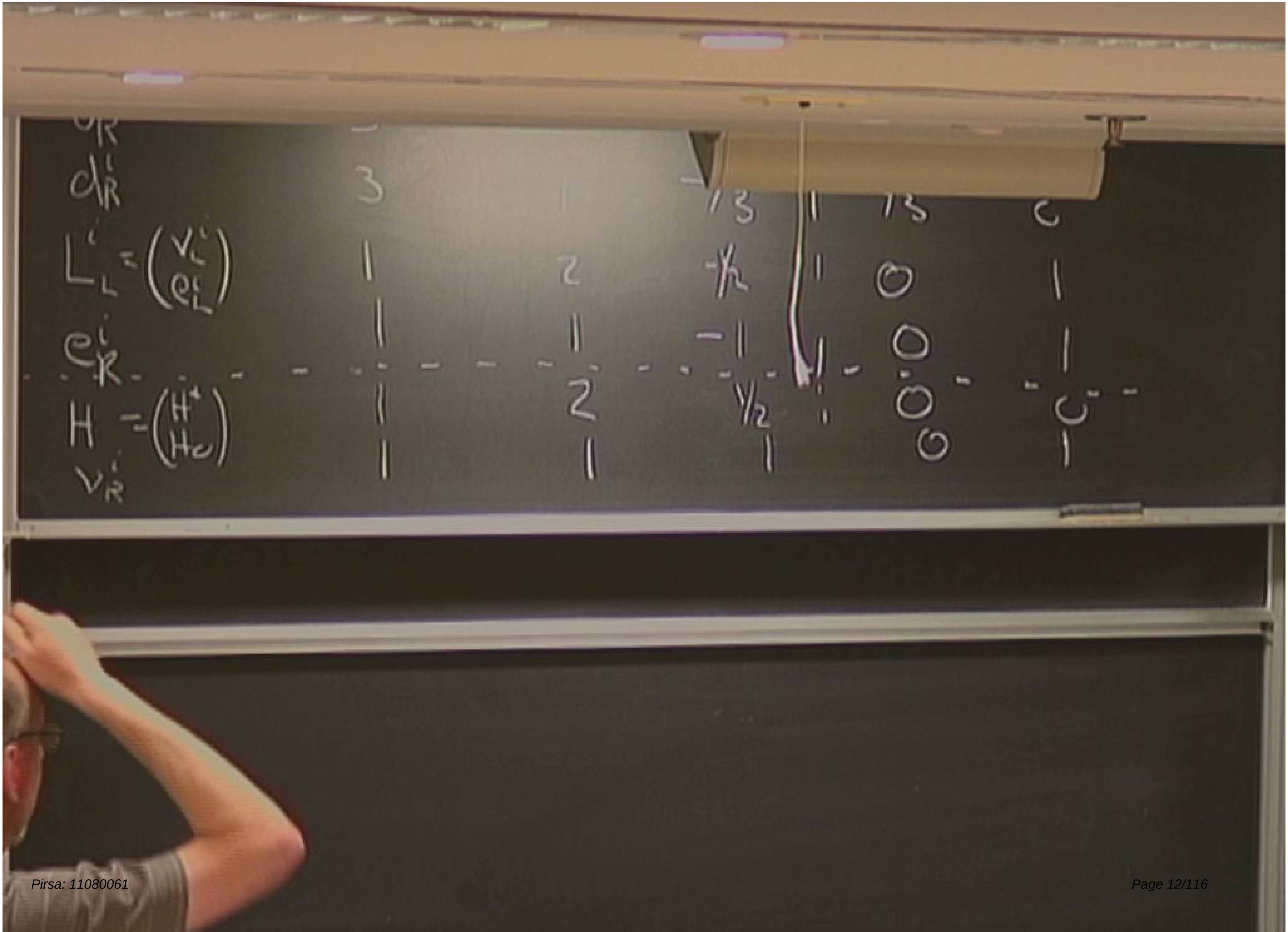

Standard Model
Field SU(3) SU(2) U(1)_Y U(1)_B U(1)_L
Q_L^i = (u_L^i, d_L^i) 3 2 1/6 1/3 0
U_R^i 3 1 2/3 1/3 0
d_R^i 3 1 -1/3 1/3 0
= (ν_L^i, e_L^i) 1 2 -1/2 0 1
1 1 -1 0 1


Standard Model
Field SU(3) SU(2) U(1)_Y U(1)_B U(1)_L
Q_L^i = (u_L^i d_L^i) 3 2 1/6 1/3 0
u_R^i 3 1 2/3 1/3 0
d_R^i 1 -1/3 1/3 0
L_L^i = (ν_L^i e_L^i) 2 -1/2 0 1
e_R^i 1 -1 0 1
H = 2 1/2 0 0

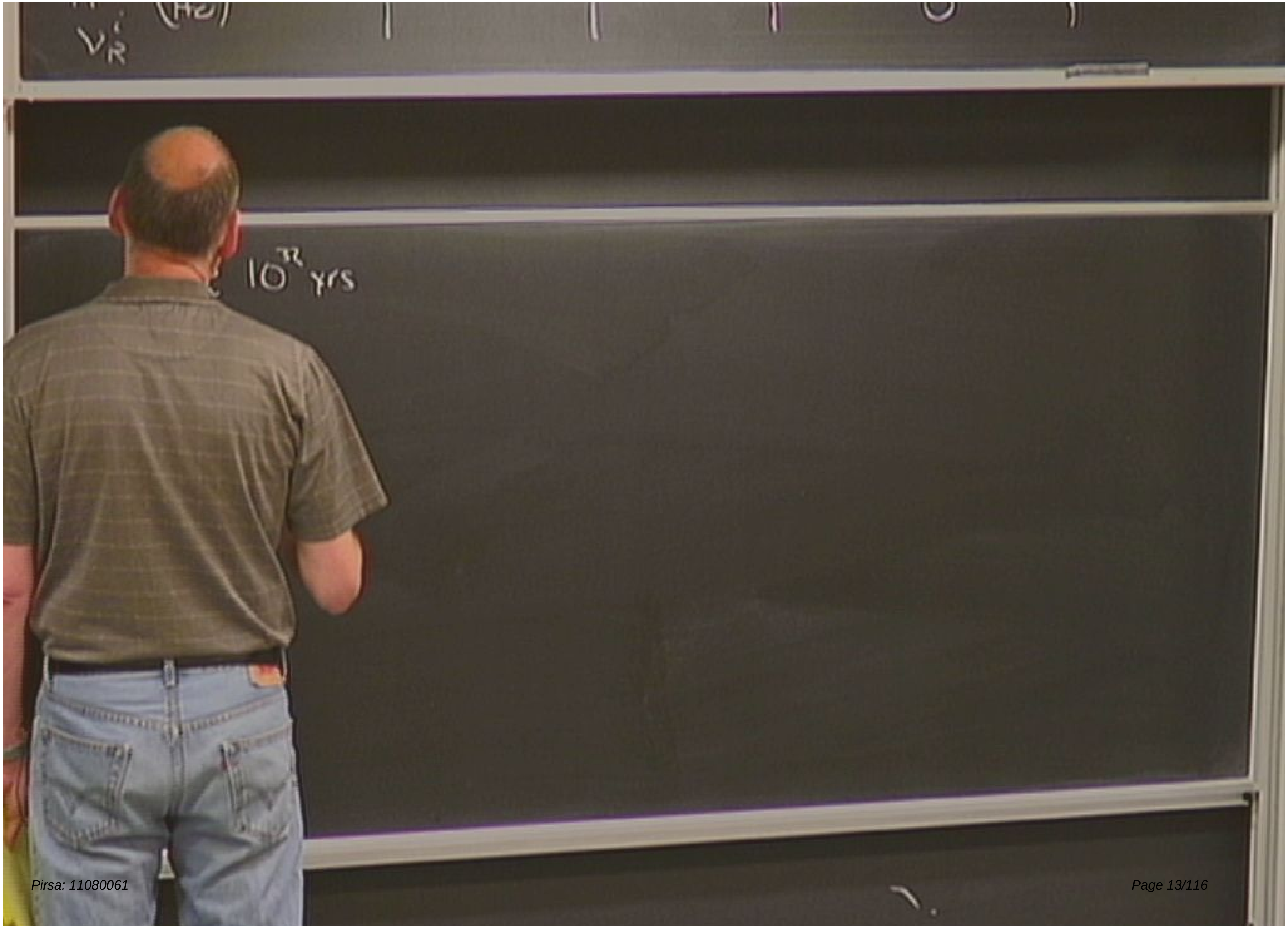
Standard Model

Field	SU(3)	SU(2)	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6	1/3	0
u_R^i	3	1	2/3	1/3	0
d_R^i	3	1	−1/3	1/3	0
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	1	2	−1/2	0	1
e_R^i	1	1	−1	0	1
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1	2	1/2	0	0


Standard Model
Field SU(3) SU(2) U(1)Y U(1)B U(1)L
Q_L^i = (u_L^i, d_L^i) 3 2 1/6 1/3 0
u_R^i 3 1 2/3 1/3 0
d_R^i 3 1 -1/3 1/3 0
L_L^i = (ν_L^i, e_L^i) 1 2 -1/2 0 1
e_R^i 1 1 0 1
H = (H^+, H^0) 1 2 0 0
ν_R^i 1 1 0 1

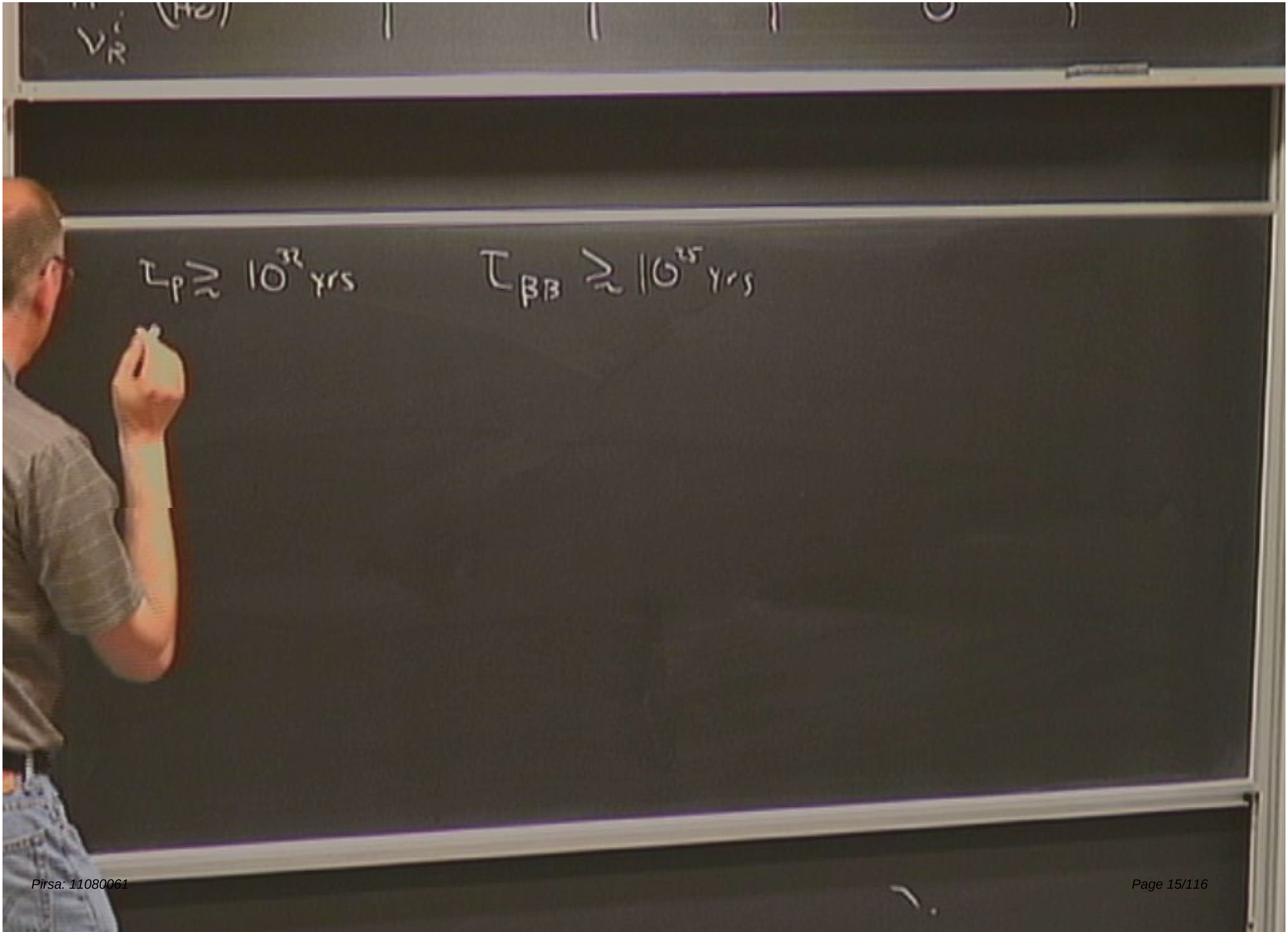


d_R^i 3 1 -1/3 1 1/3 0
L_L^i = (ν_L^i e_L^i) 1 2 -1/2 1 0 1
e_R^i 1 1 -1 1 0 1
H = (H^+ H_0) 1 2 1/2 0 0
1 1 1 0 1
ν_R^i



ν_R^i

$\tau_p \gtrsim 10^{32}$ yrs


$\tau_p \gtrsim 10^{32}$ yrs
$\tau_{\beta\beta} \gtrsim 10^{25}$ yrs

ν_R^i (H_2)

$\tau_p \gtrsim 10^{32}$ yrs $\tau_{\beta\beta} \gtrsim 10^{25}$ yrs

ν_R^i (H2)

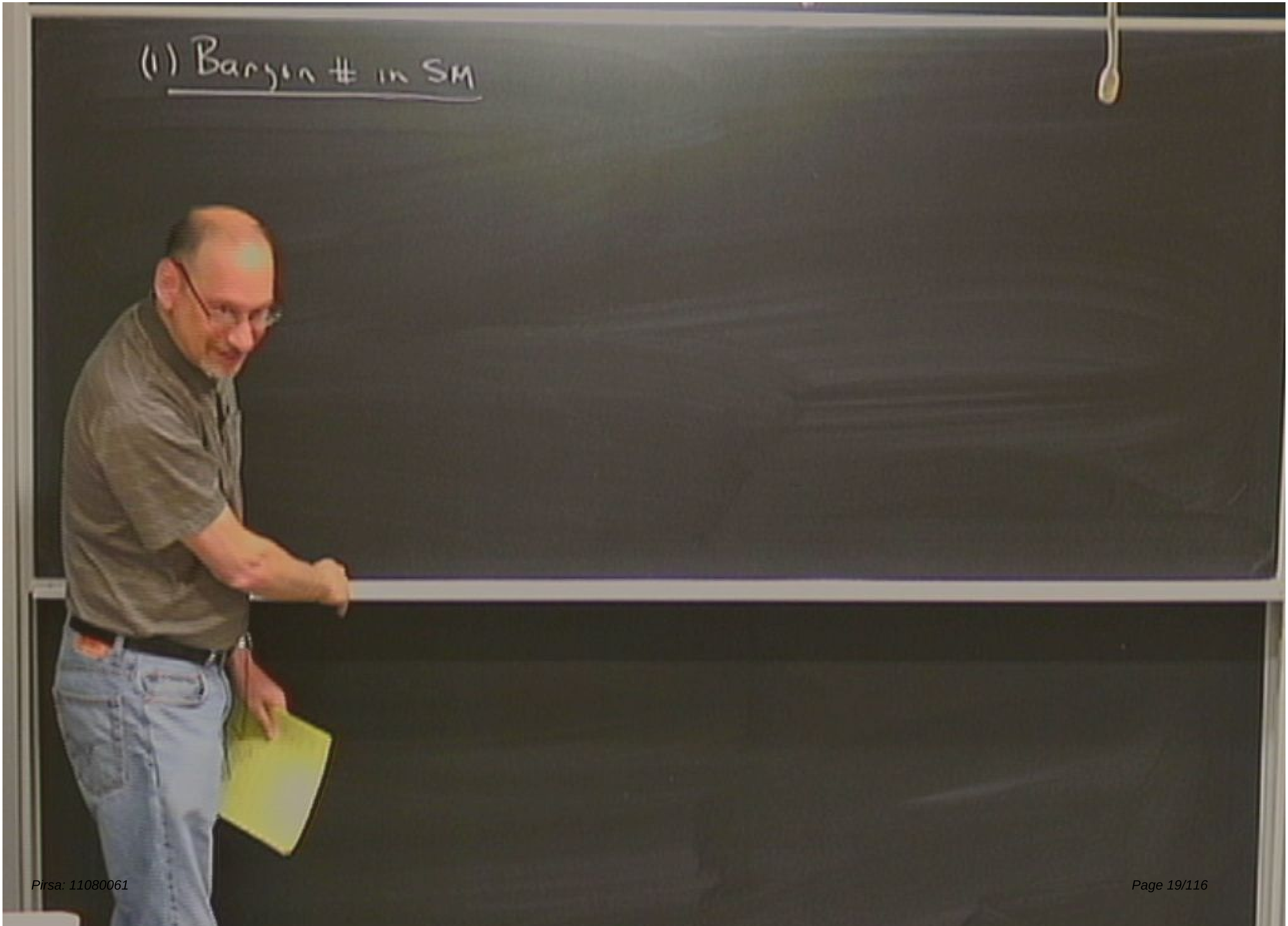
$\tau_p \gtrsim 10^{32}$ yrs $\qquad \tau_{\beta\beta} \gtrsim 10^{25}$ yrs

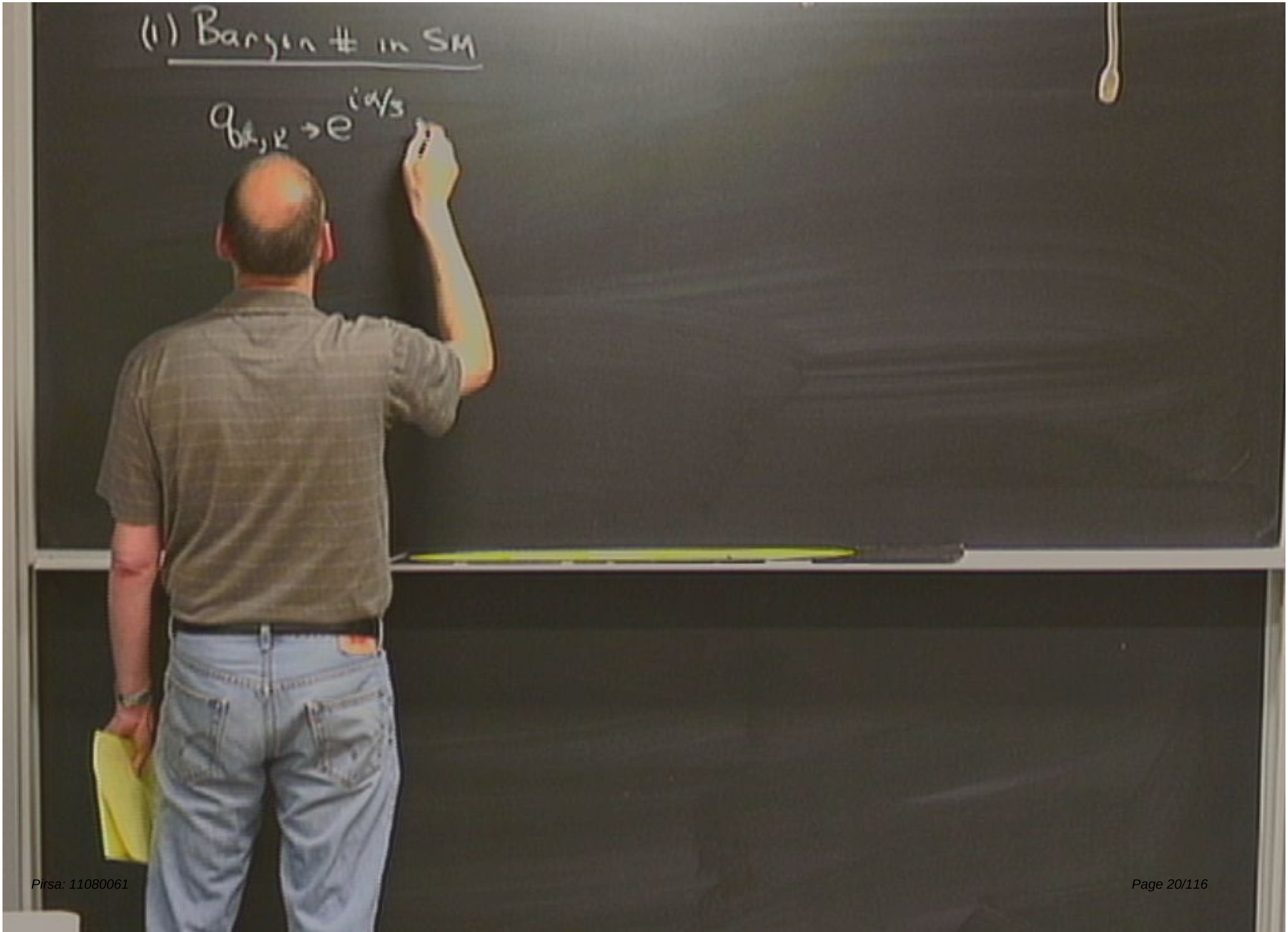
$\Delta m^2_{21} = 8 \times 10^{-5}\ \text{eV}^2 \; , \; \Delta m^2_{32} = 3 \times 10^{-3}\ \text{eV}^2$

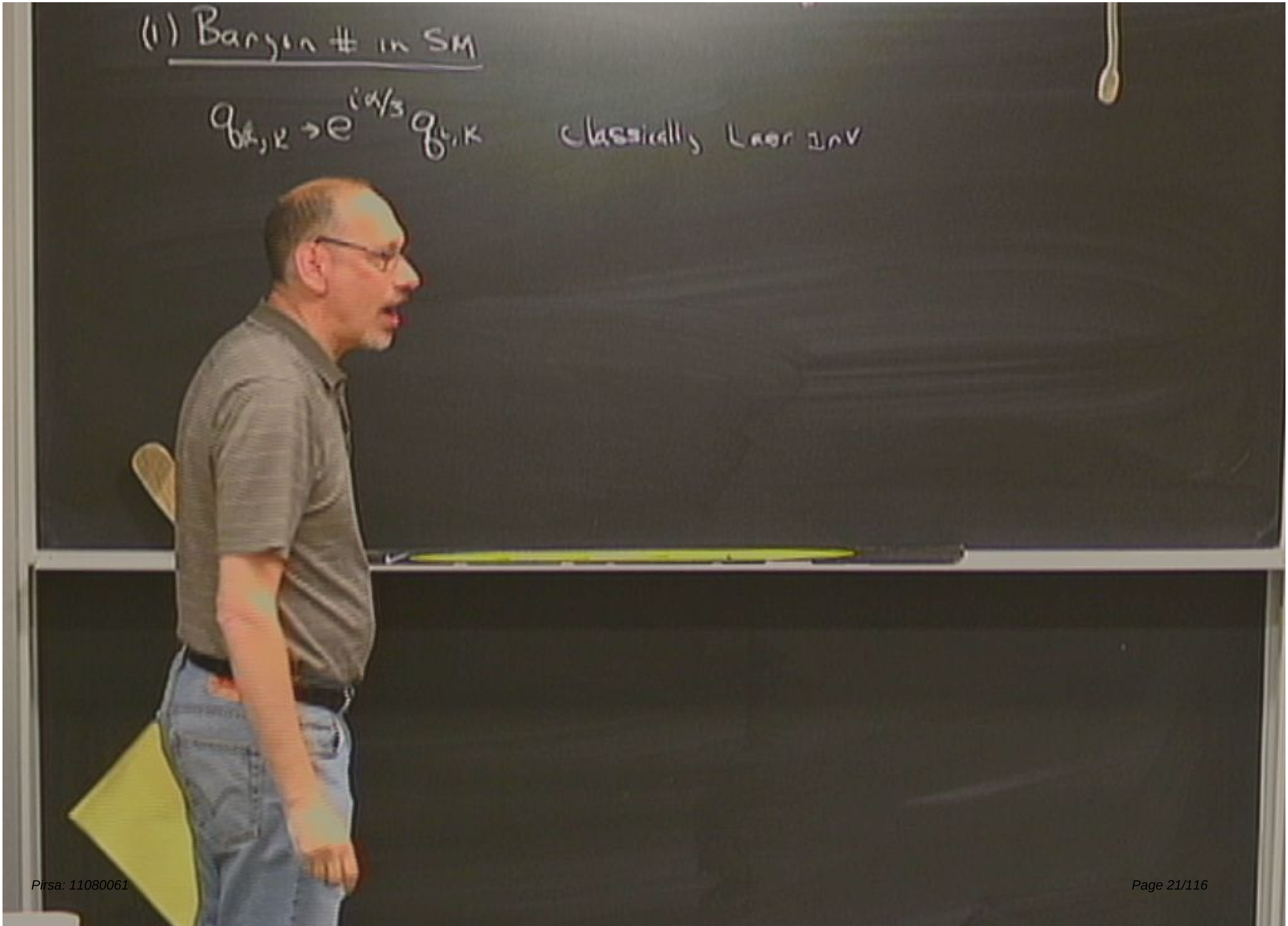
ν_R^i (H_2)

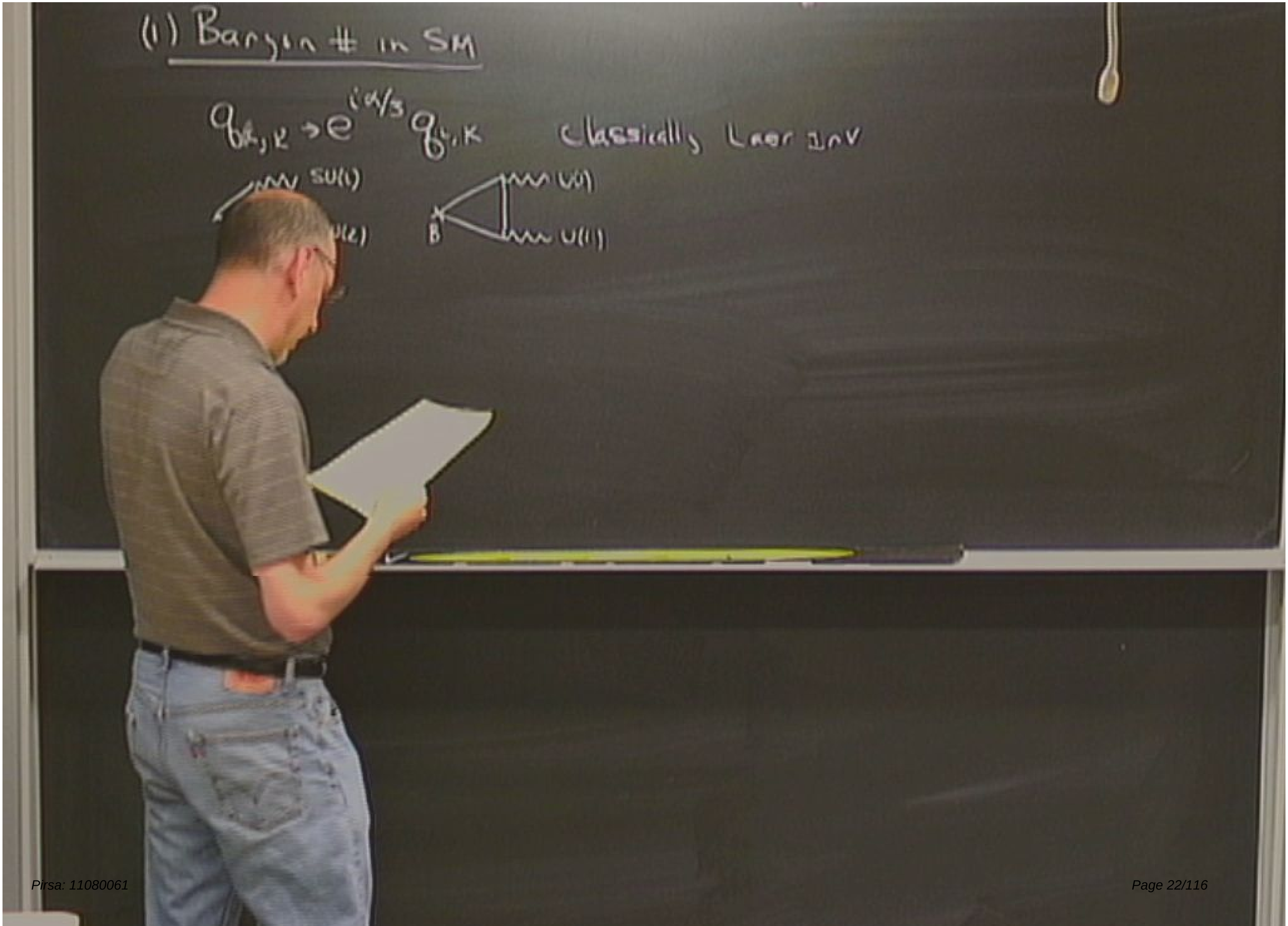
$\tau_p \gtrsim 10^{32}$ yrs $\tau_{\beta\beta} \gtrsim 10^{25}$ yrs

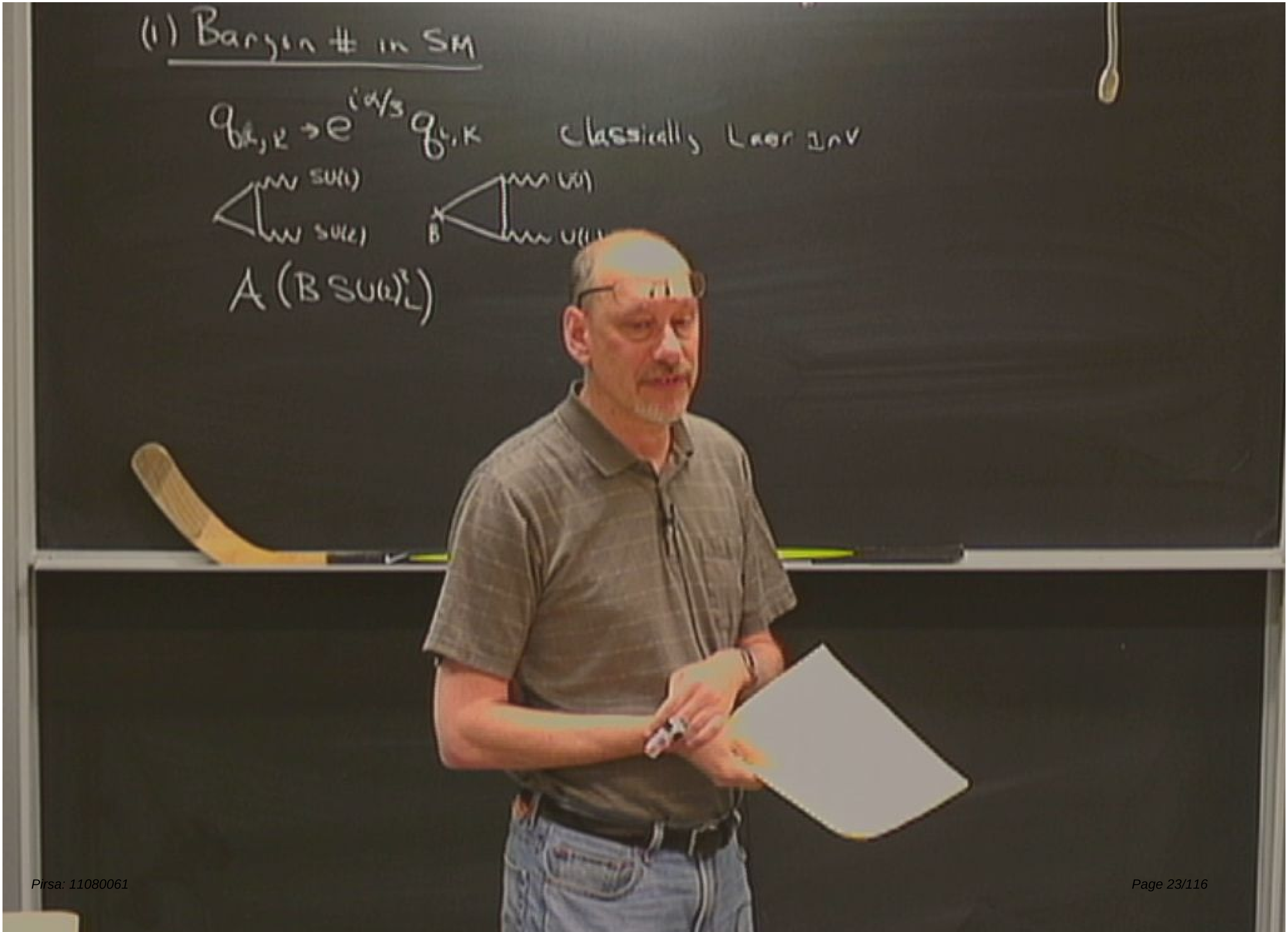
$\Delta m_{21}^2 = 8 \times 10^{-5}\ eV^2$, $\Delta M_{32}^2 = 3 \times 10^{-3}\ eV^2$


(1) Baryon # in SM


(1) Baryon # in SM

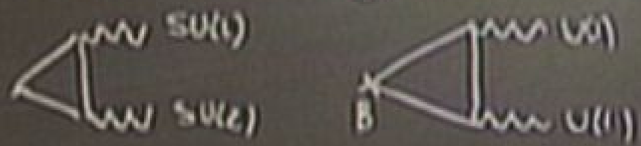

(1) Baryon # in SM
classically Lagr Inv


(1) Baryon # in SM
classically Lagr inv
SU(3)
U(1)
B
U(1)

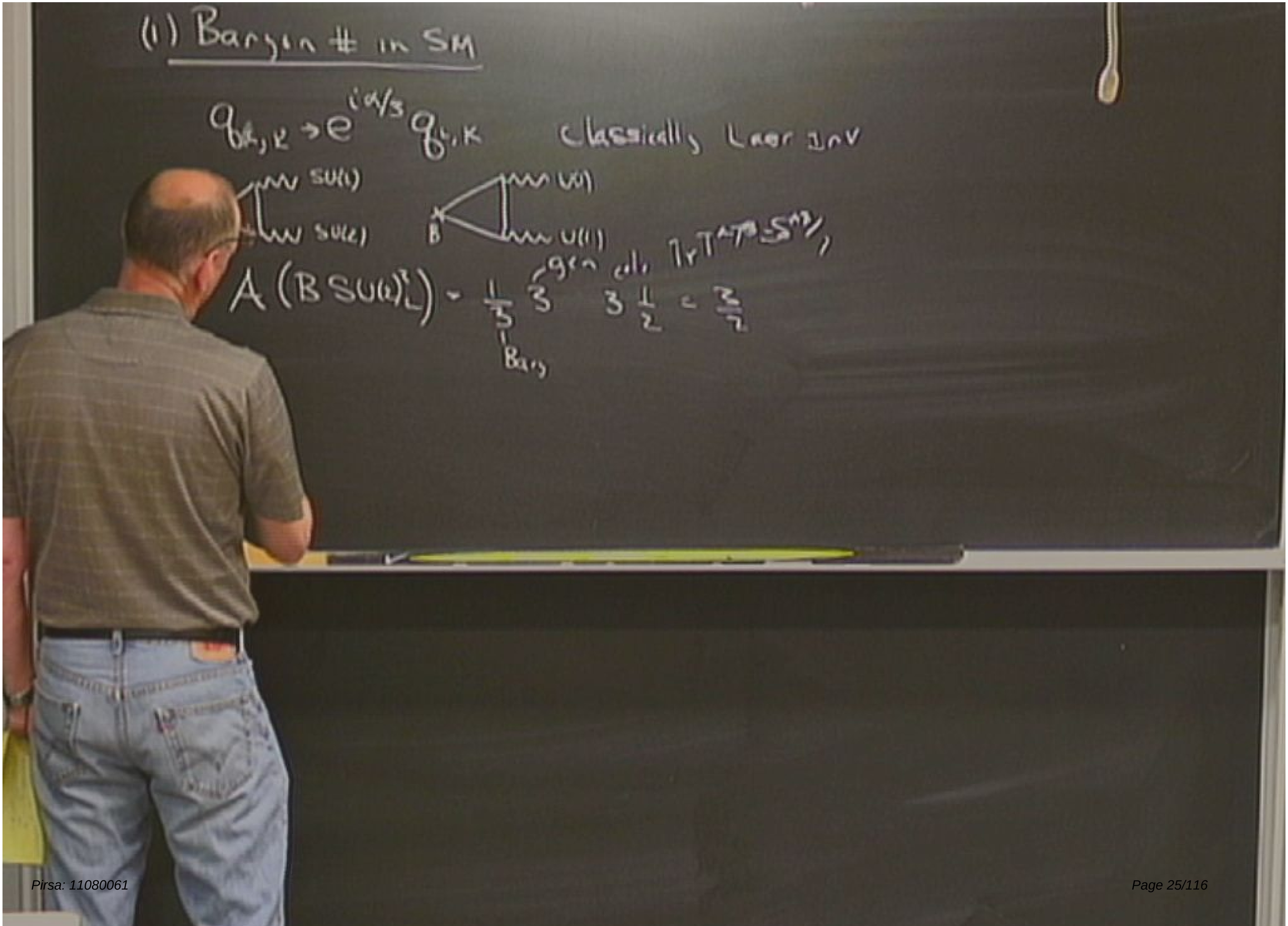

(1) Baryon # in SM
classically Lagr inv
SU(2)
U(1)
B
A (B SU(2)$_L^2$)

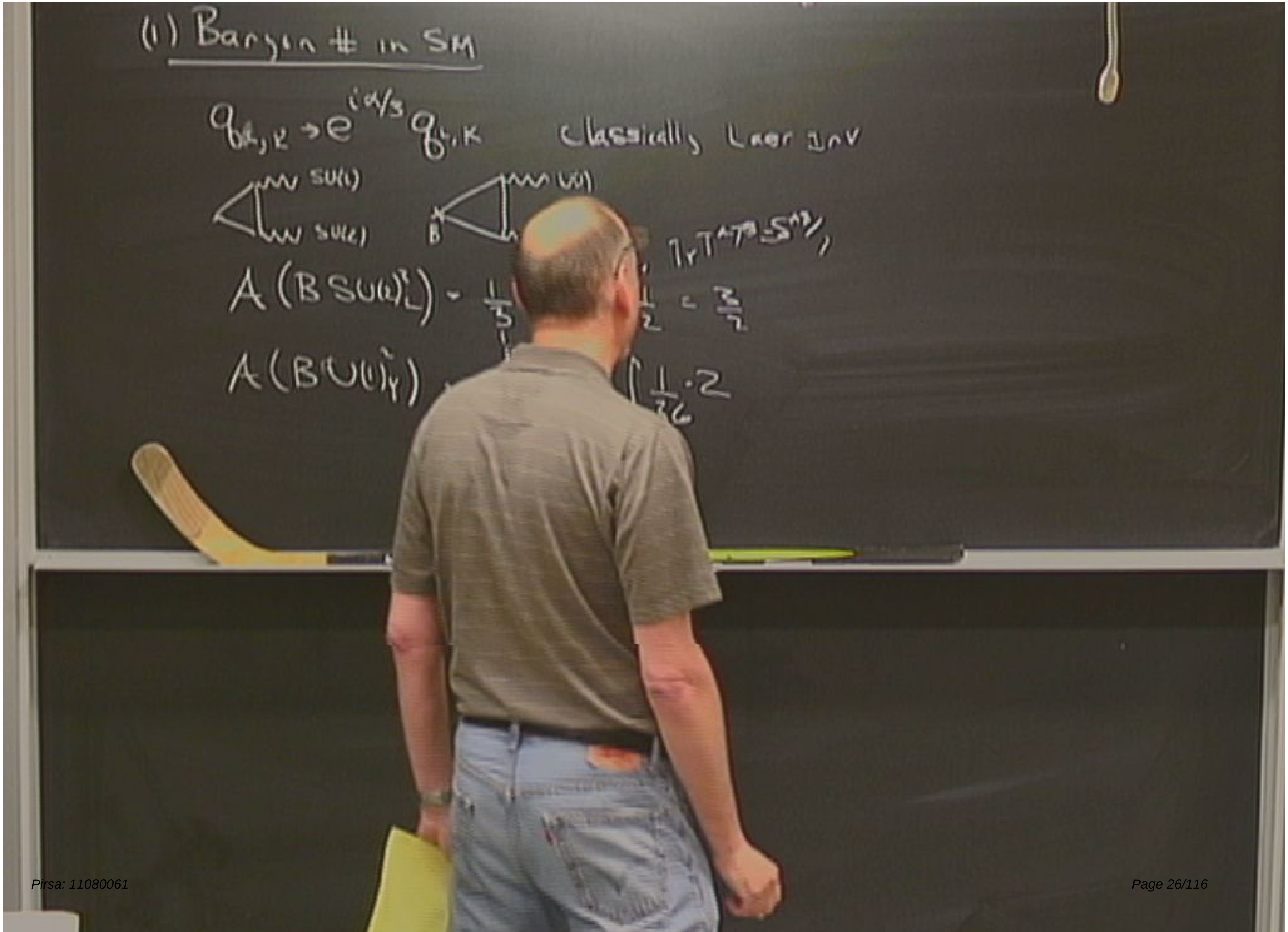
(1) Baryon # in SM

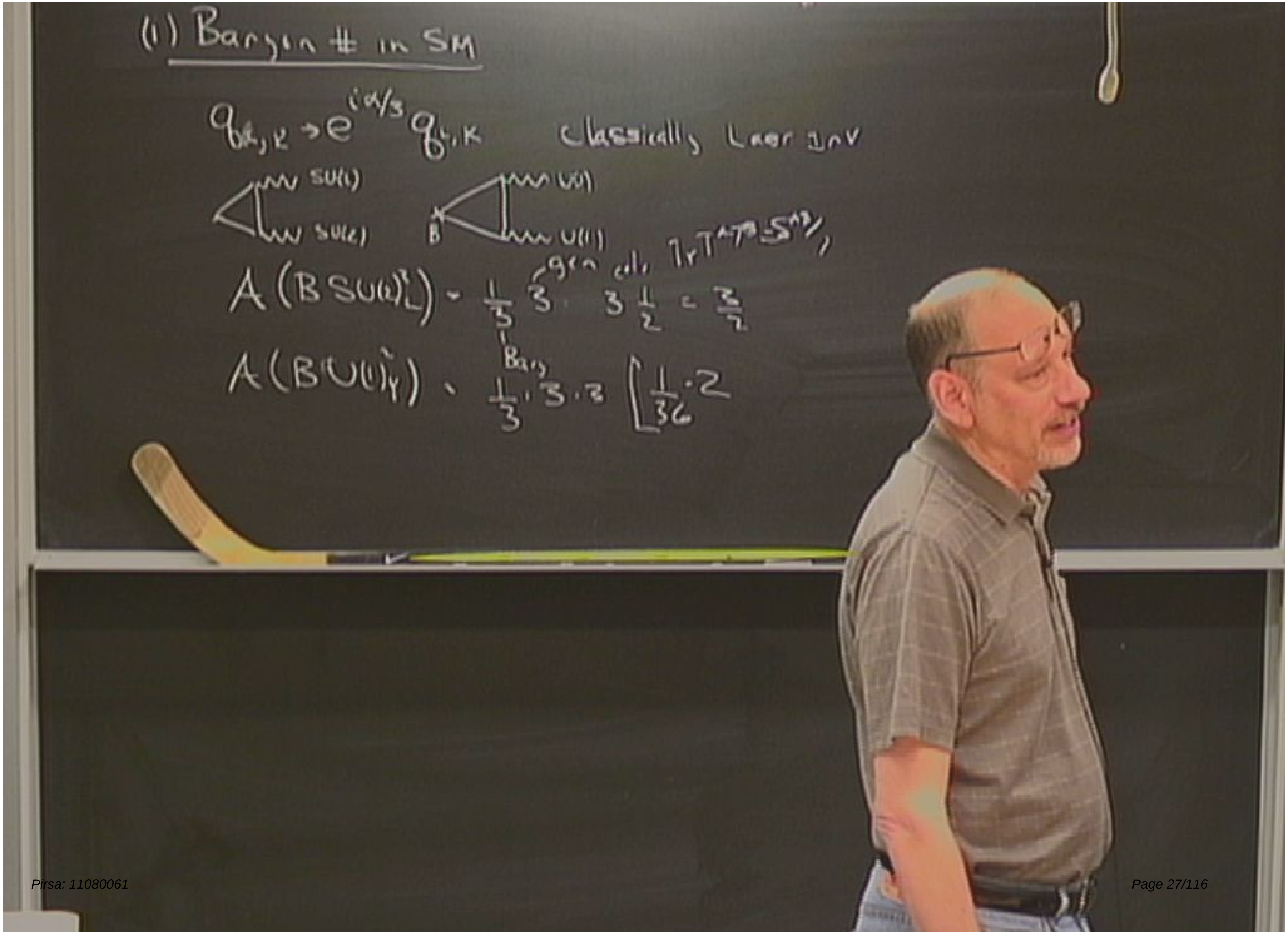
$q_{B,L/R} \to e^{i\alpha/3} q_{L,R}$ classically Lagr inv

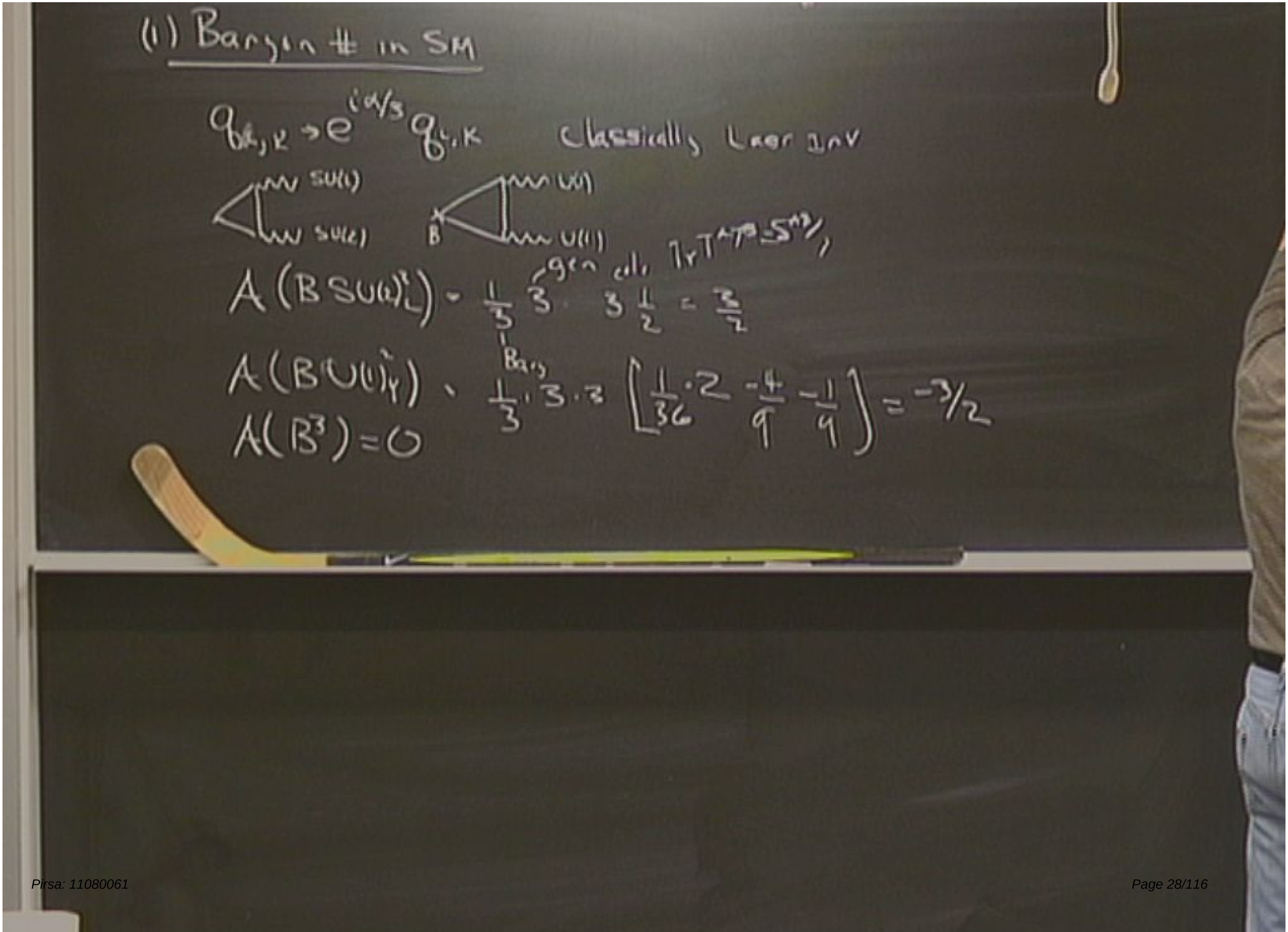


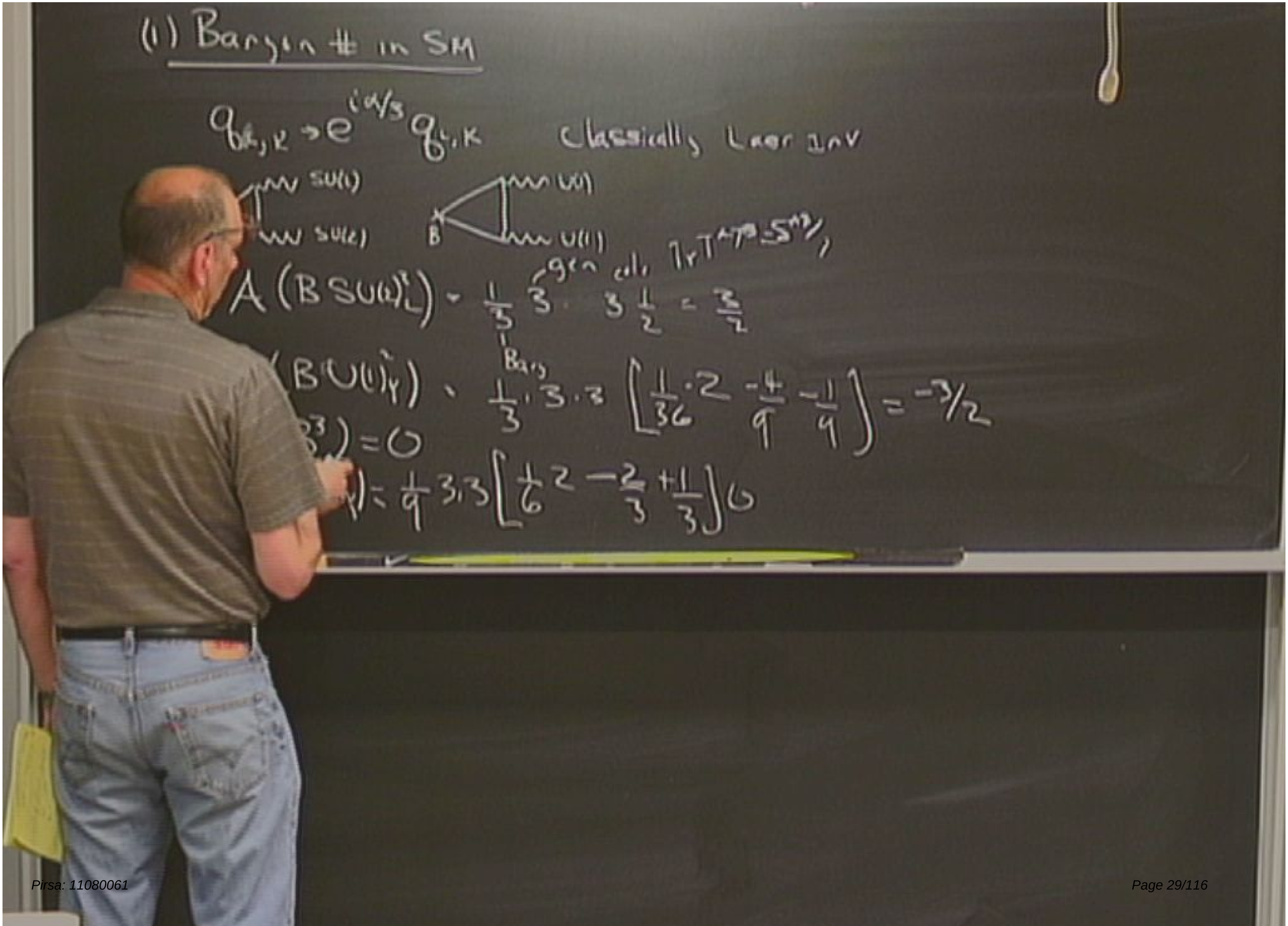
$A(B\, SU(2)_L^2) \sim \frac{1}{3}\, 3$


(1) Baryon # in SM
classically Lagr Inv
SU(2)
SU(2)
U(1)
U(1)
B
gen
Tr T^A T^B = δ^AB/2
A (B SU(2)^2_L) =
Bary


(1) Baryon # in SM
classically Lagr inv
SU(2)
U(1)
B


(1) Baryon # in SM
classically Lagr inv
SU(2)
SU(2)
U(1)
U(1)
B
gen col
Baryon


(1) Baryon # in SM
q_{L,R} → e^{iα/3} q_{L,R} classically Lagr inv
SU(2)
SU(2)
U(1)
U(1)
B
gen col Tr T^A T^B = δ^{AB}/2
A(B SU(2)^2_L) = 1/3 · 3 · 3 · 1/2 = 3/2
Bary
A(B U(1)^2_Y) = 1/3 · 3 · 3 [1/36 · 2 − 4/9 − 1/9] = −3/2
A(B^3) = 0


(1) Baryon # in SM
Classically Lagr Inv
SU(2)
SU(2)
U(1)
U(1)
B
gen
Baryon
= -3/2
= 0

(1) Baryon # in SM

$q_{b\ell,R} \to e^{i\alpha/3} q_{b\ell,R}$ Classically Lagr Inv

gen, color, $\mathrm{Tr}\, T^a T^b = \delta^{ab}/2$

$A(B\, SU(2)_L^2) = \frac{1}{3} \cdot 3 \cdot 3 \frac{1}{2} = \frac{3}{2}$

(Bary)

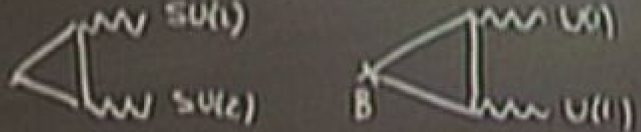
$A(B\, U(1)_Y^2) = \frac{1}{3} \cdot 3 \cdot 3 \left[\frac{1}{36} \cdot 2 - \frac{4}{9} - \frac{1}{4}\right] = -3/2$

$A(B^3) = 0$

$A(B^2 U(1)_Y) = \frac{1}{9}\, 3 \cdot 3 \left[\frac{1}{6}\, 2 - \frac{2}{3} + \frac{1}{3}\right] 0$

(1) Baryon # in SM

$q_{b\ell,R} \to e^{i\alpha/3} q_{b\ell,R}$ classically Lagr inv



gen colr $\mathrm{Tr}\, T^a T^b = \delta^{ab}/2$

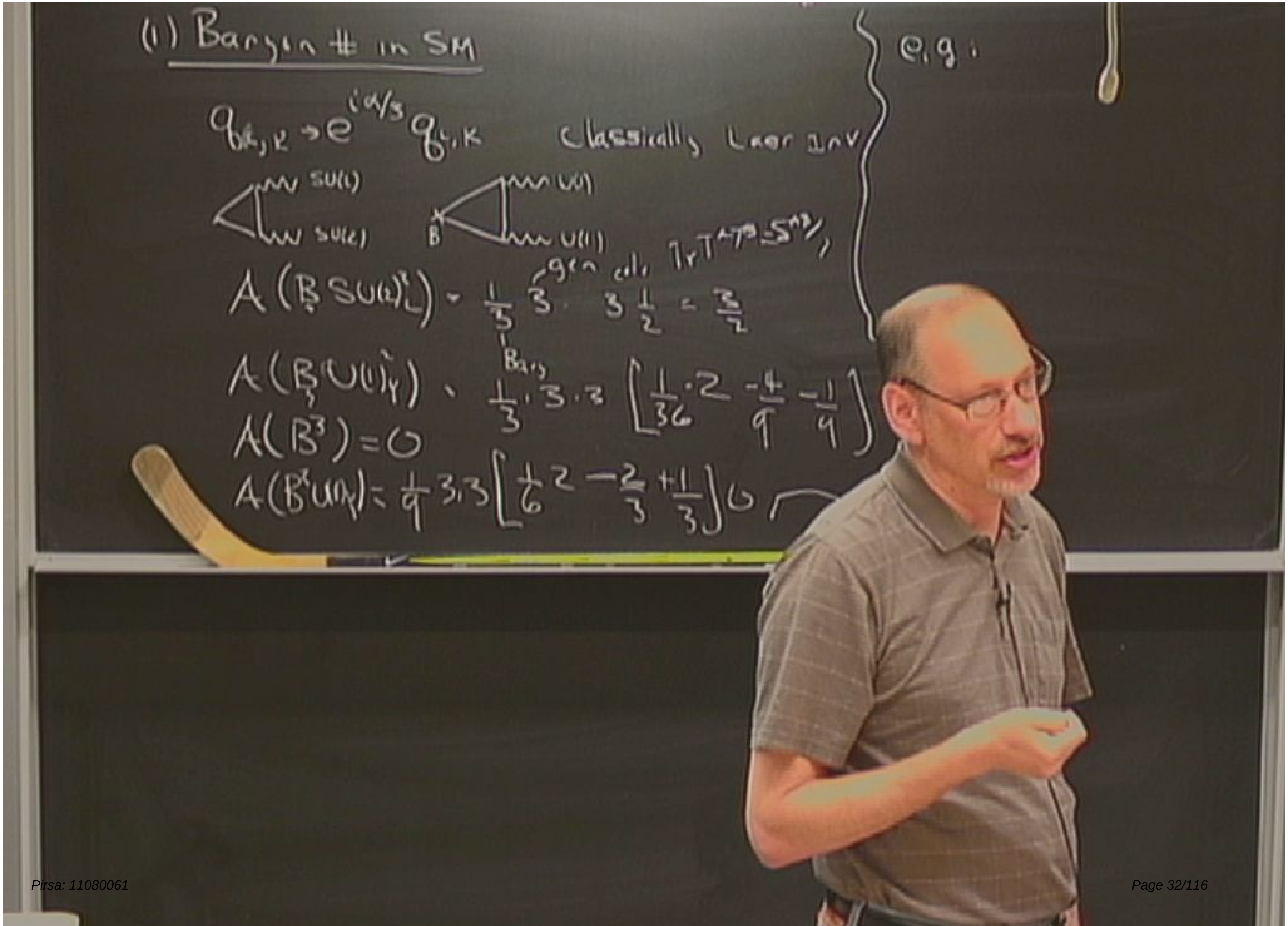
$A(B\, SU(2)_L^2) = \frac{1}{3} \cdot 3 \cdot 3 \frac{1}{2} = \frac{3}{2}$

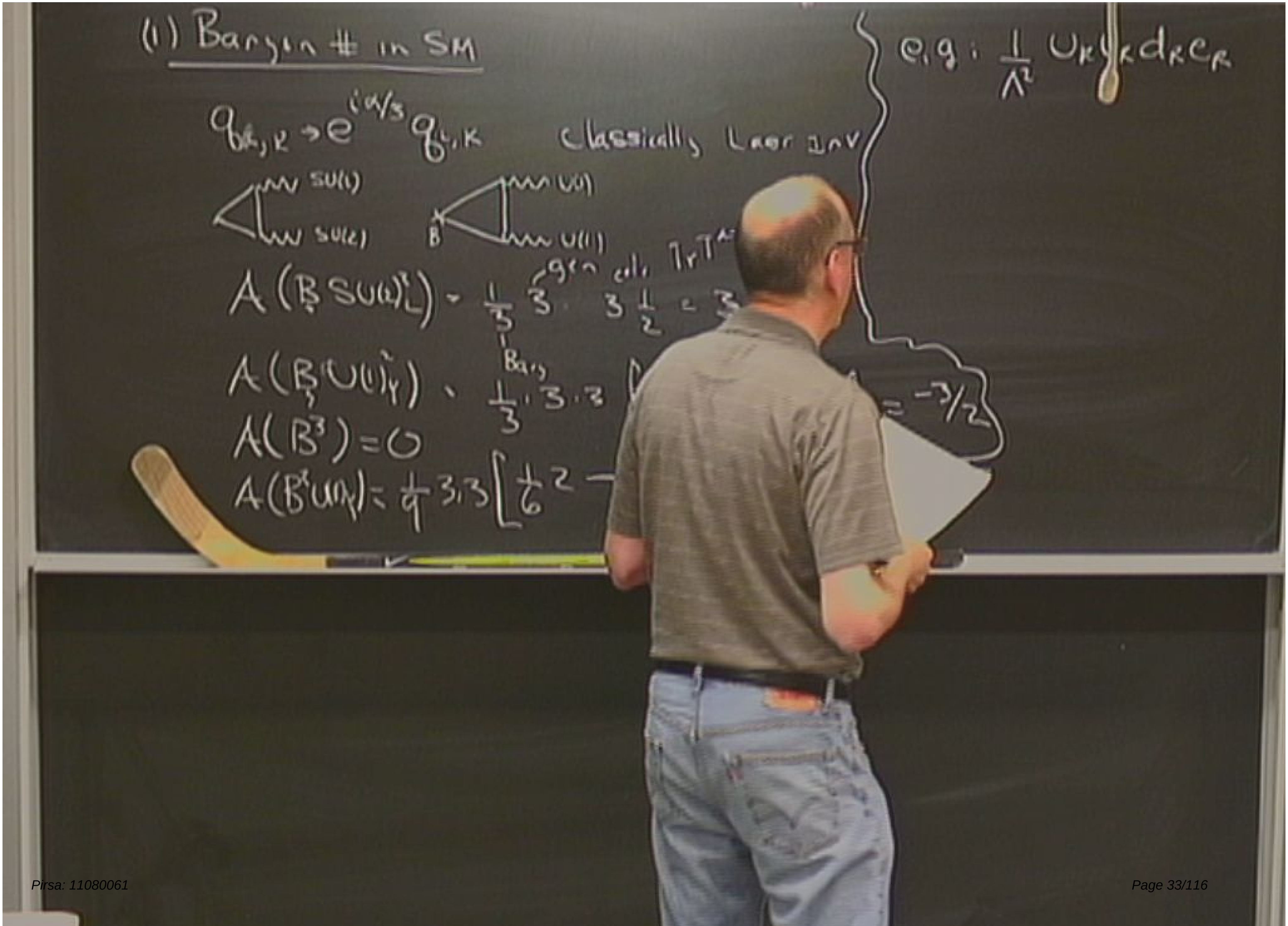
Bary

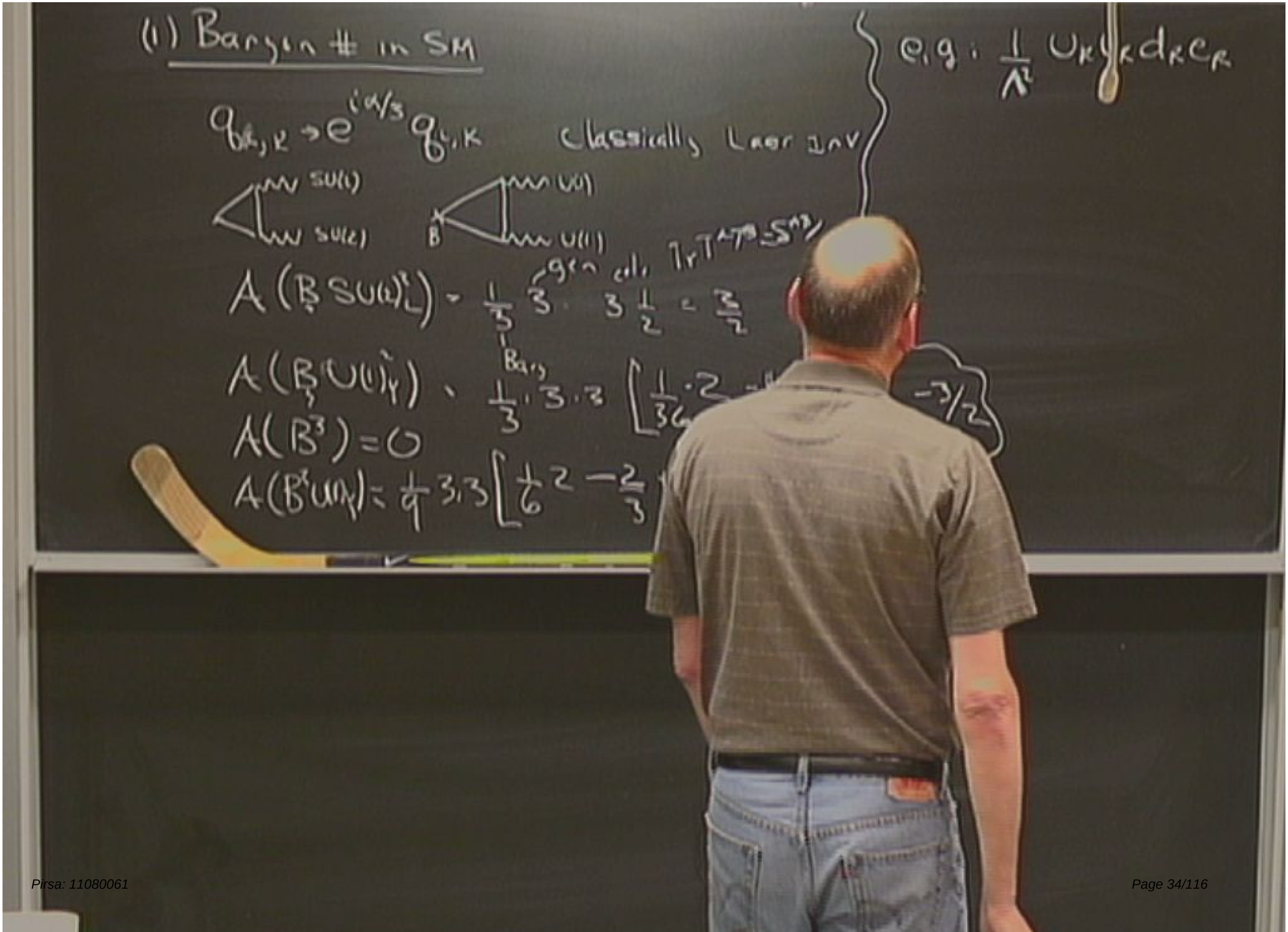
$A(B\, U(1)_Y^2) = \frac{1}{3} \cdot 3 \cdot 3 \left[\frac{1}{36} \cdot 2 - \frac{4}{9} - \frac{1}{4} \right] = -3/2$

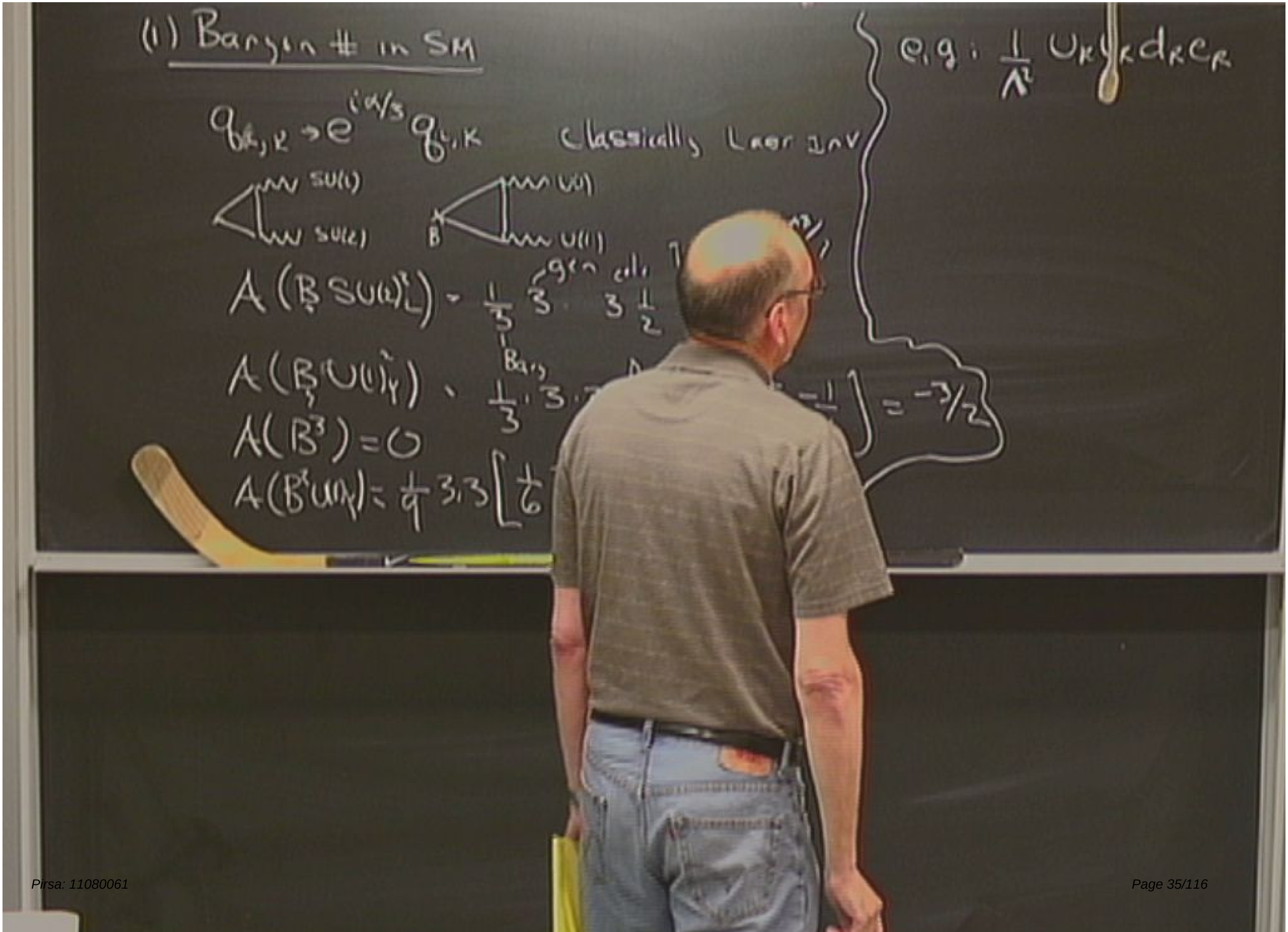
$A(B^3) = 0$

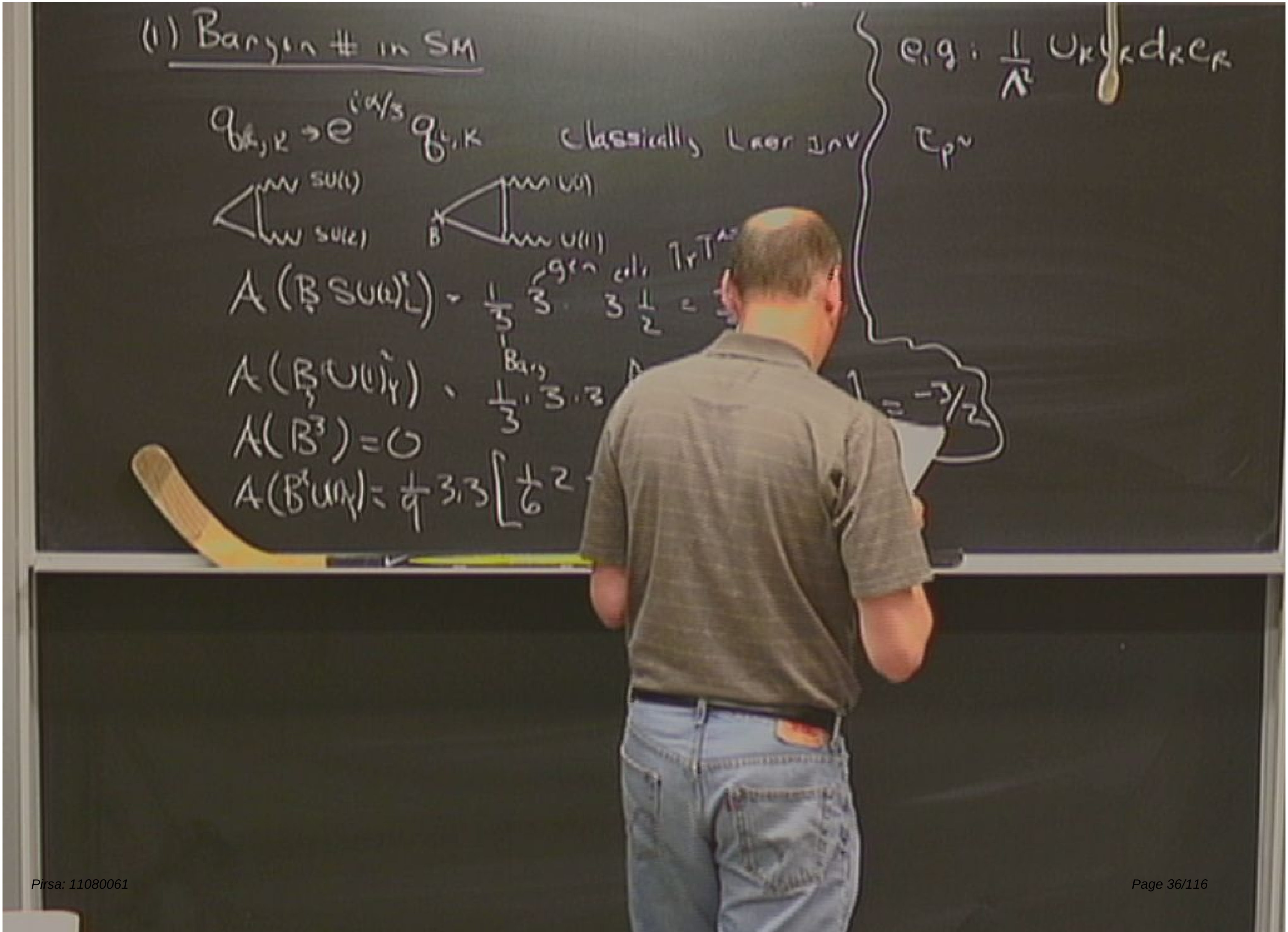
$A(B^2 U(1)_Y) = \frac{1}{9} 3 \cdot 3 \left[\frac{1}{6} 2 - \frac{2}{3} + \frac{1}{3} \right] 0$

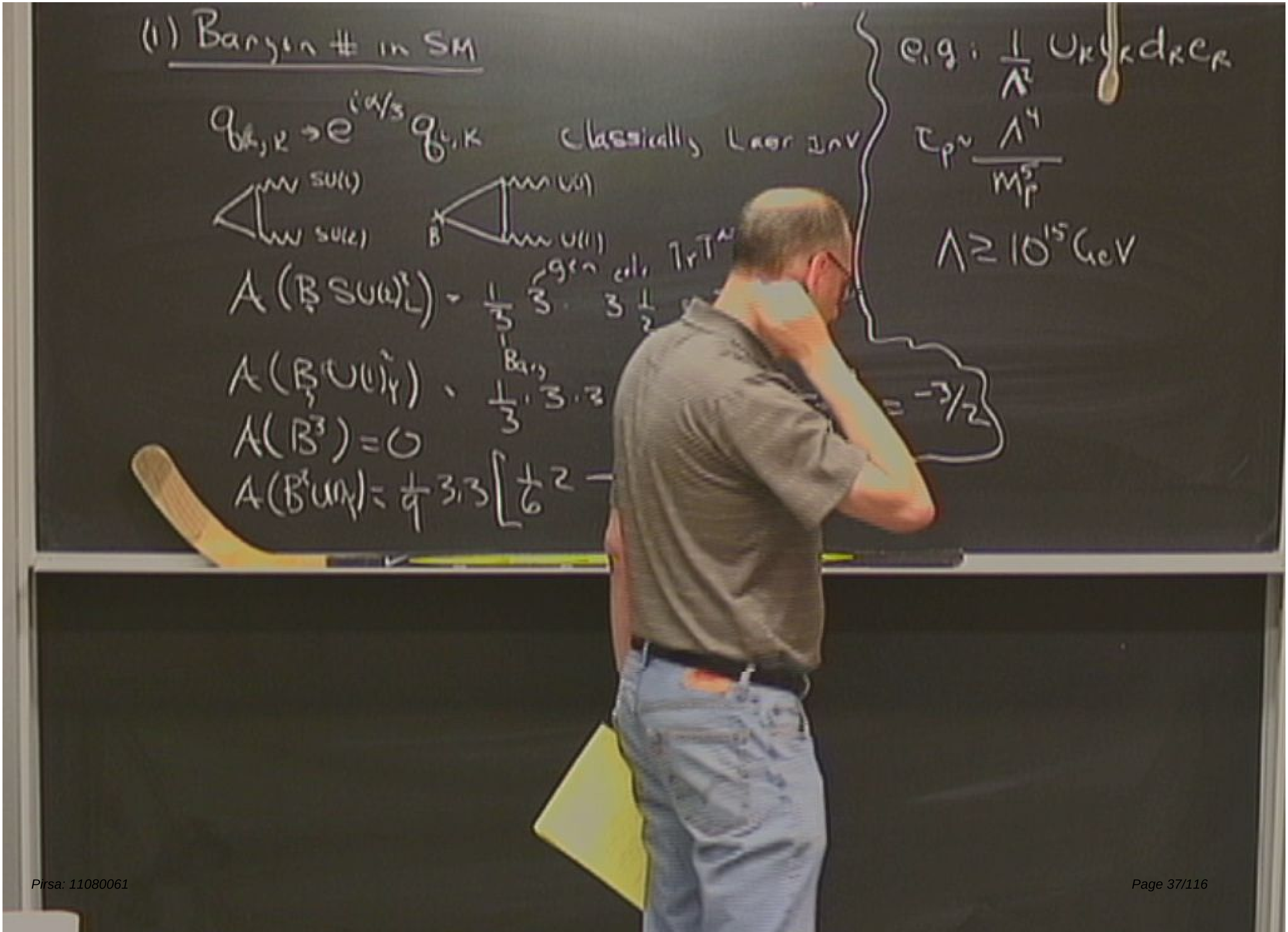

(1) Baryon # in SM
classically Lagr inv
e.g.:
A(B³) = 0

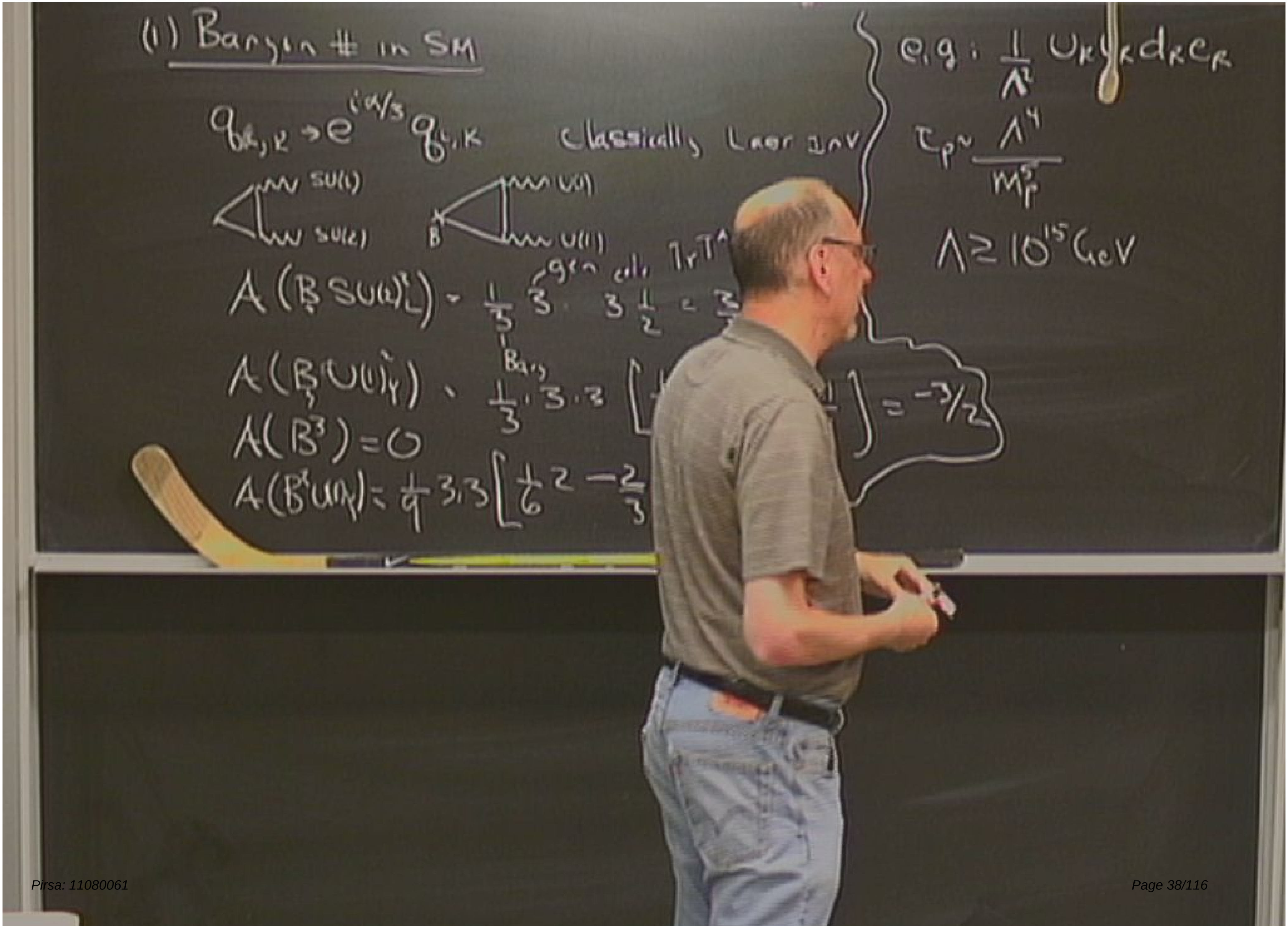

(1) Baryon # in SM
Classically Lagr inv
SU(2)
SU(2)
U(1)
U(1)
B
e.g.: 1/Λ²
A(B³) = 0
-3/2
Bary
gen

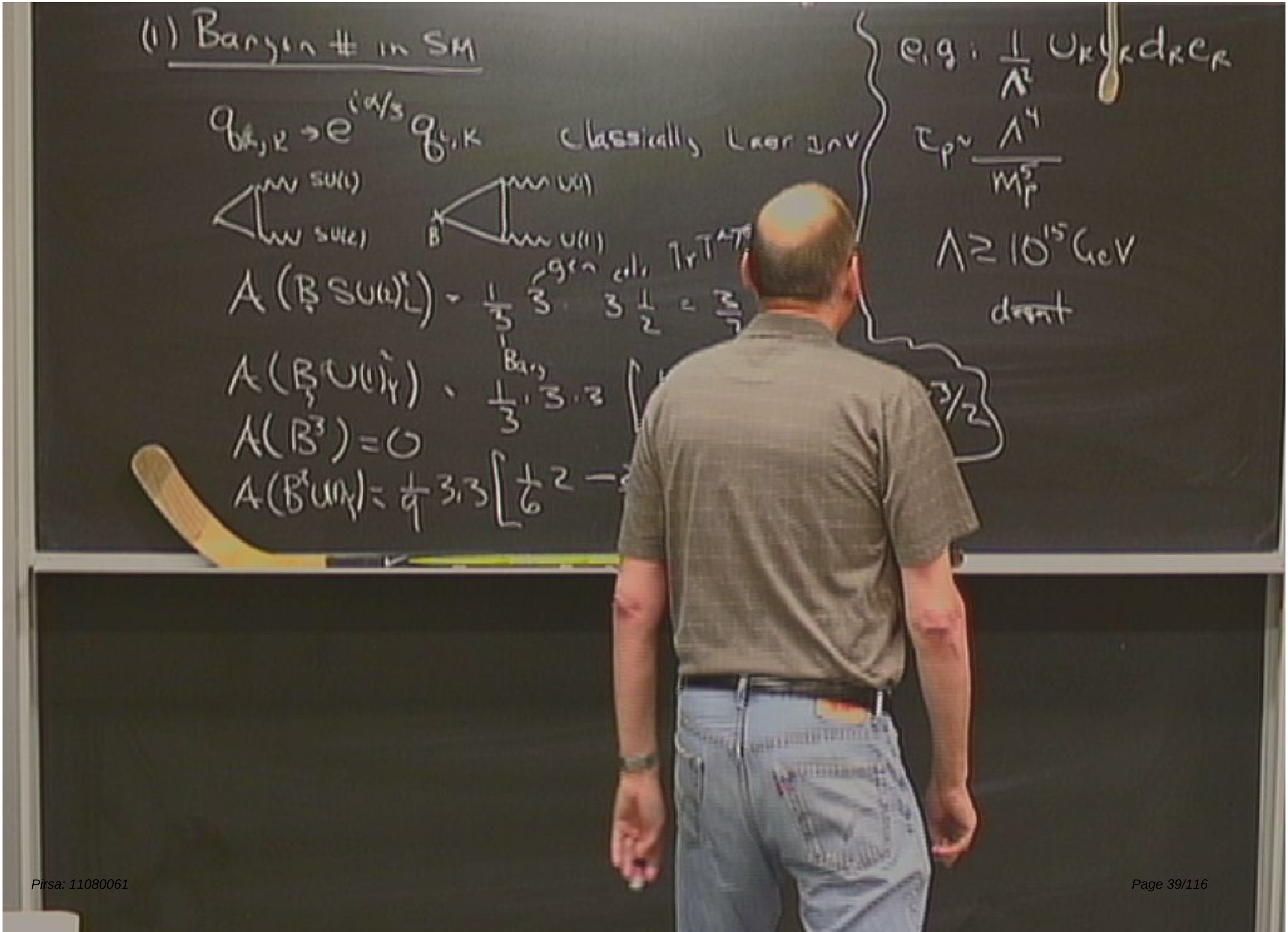

(1) Baryon # in SM
Classically Lagr INV
SU(2)
SU(2)
U(1)
U(1)
B
gen
col
Bary
e.g.: 1/Λ²
A(B³) = 0
-3/2


(1) Baryon # in SM
Classically Lagr Inv
SU(2)
U(1)
B
gen
Bary
A(B³) = 0
= -3/2

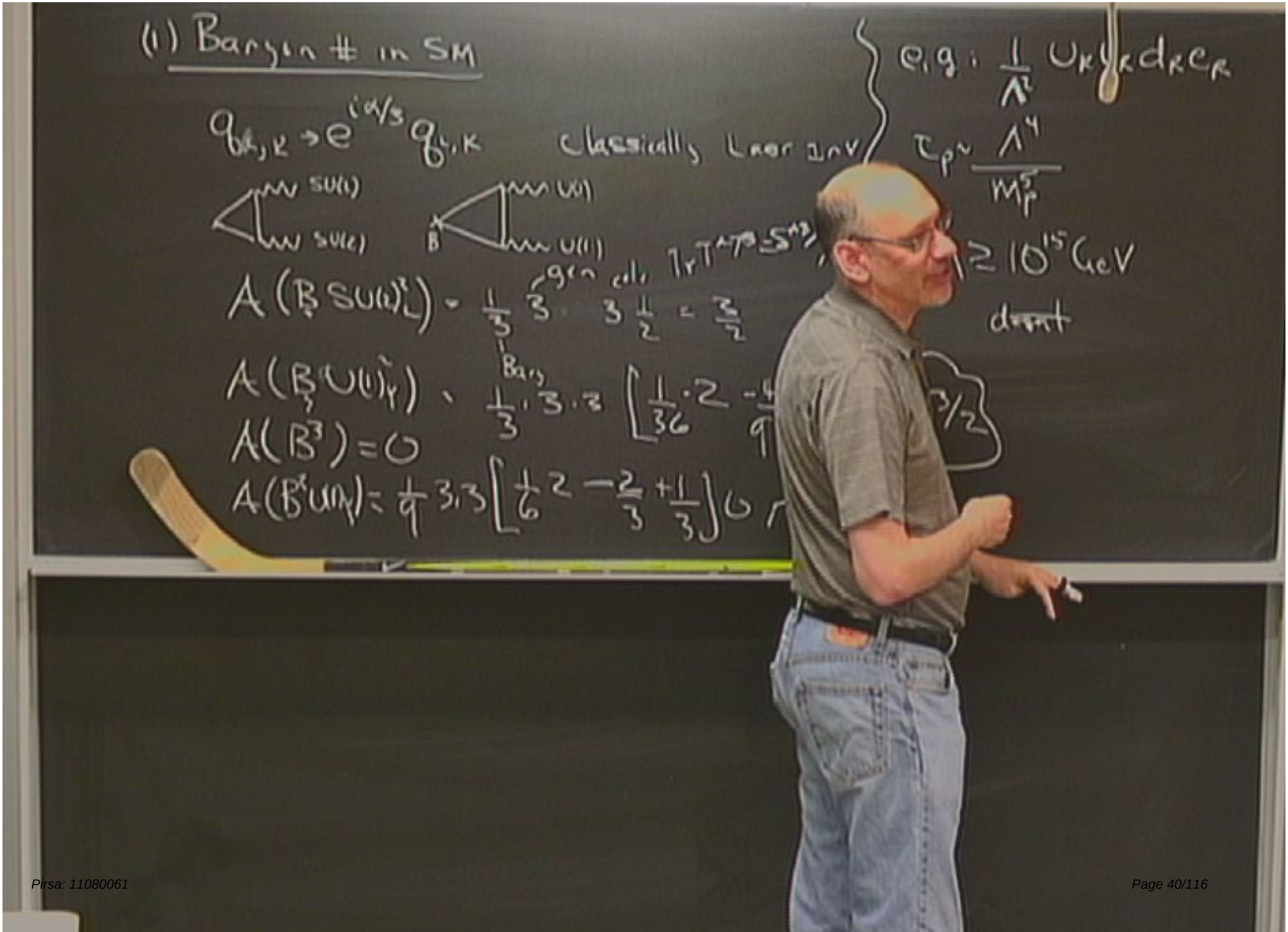

(1) Baryon # in SM
classically Lagr inv
e.g. : $\frac{1}{\Lambda^2} u_R u_R d_R e_R$
$A(B^3) = 0$

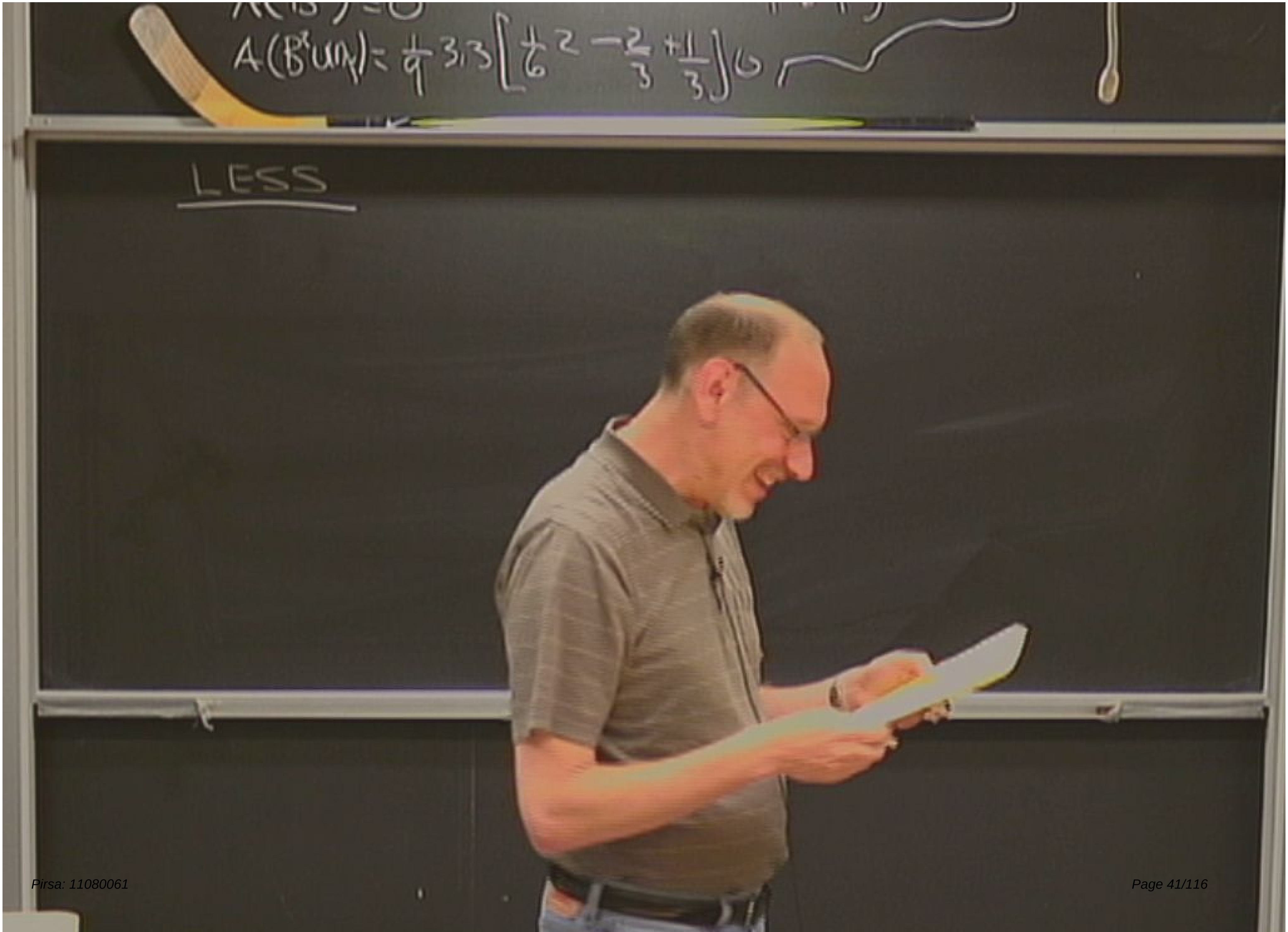

(1) Baryon # in SM
Classically Lagr Inv
e.g.
SU(2)
U(1)
A(B³)=0
Λ ≥ 10^15 GeV

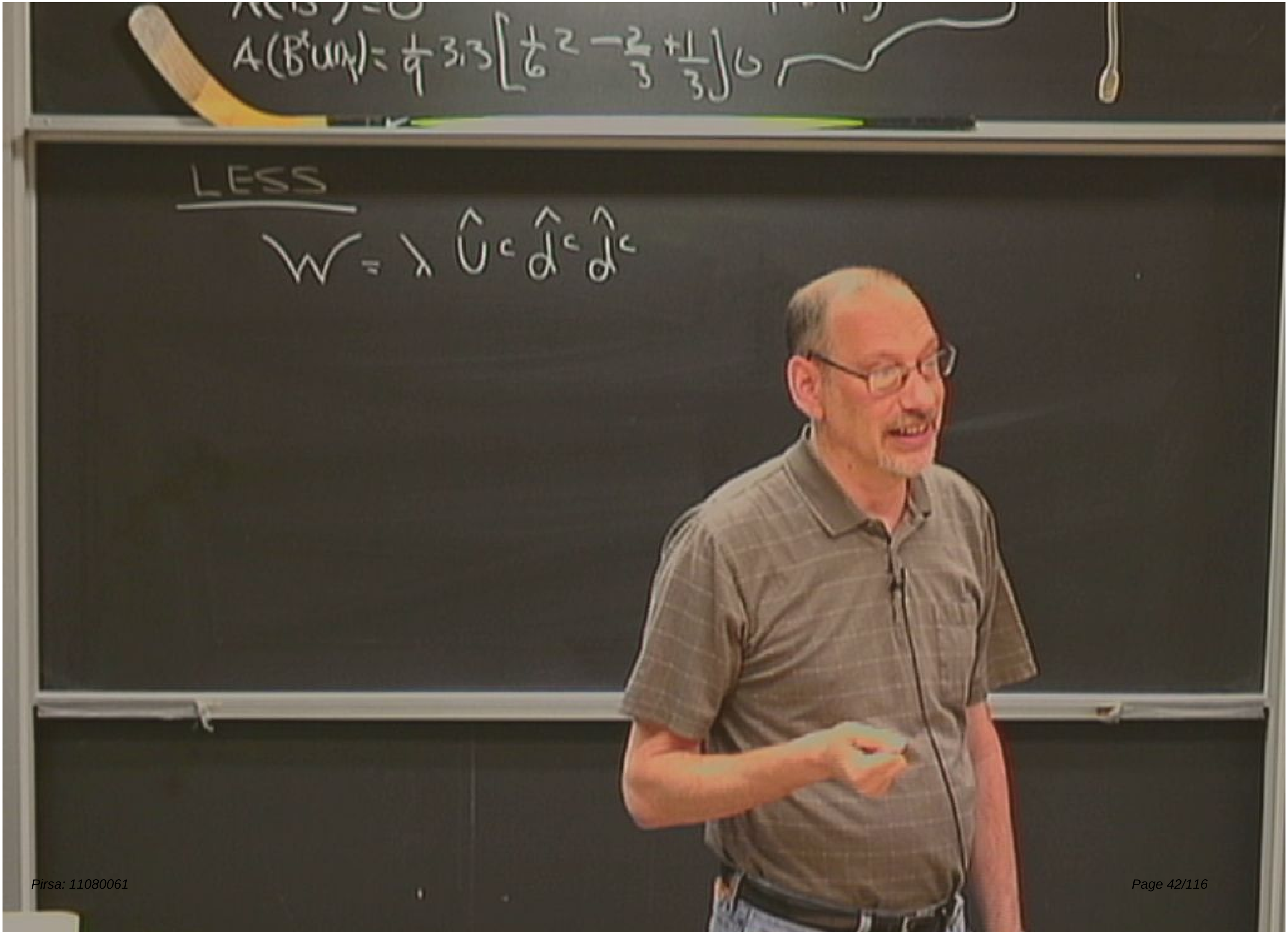

(1) Baryon # in SM
Classically Lagr inv
SU(2)
U(1)
B
gen
A(B^3) = 0
e.g.
Λ ≥ 10^15 GeV
= −3/2

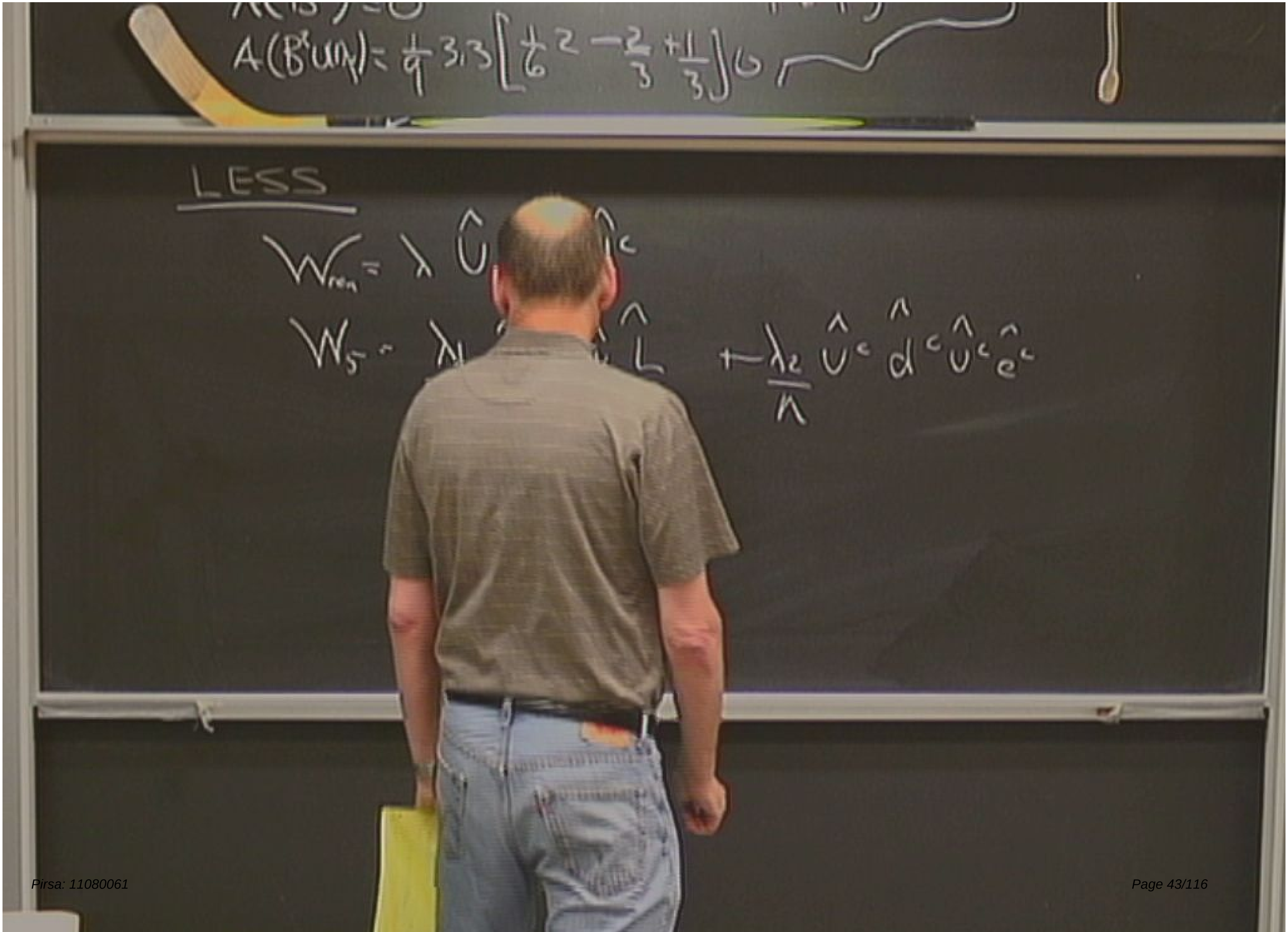


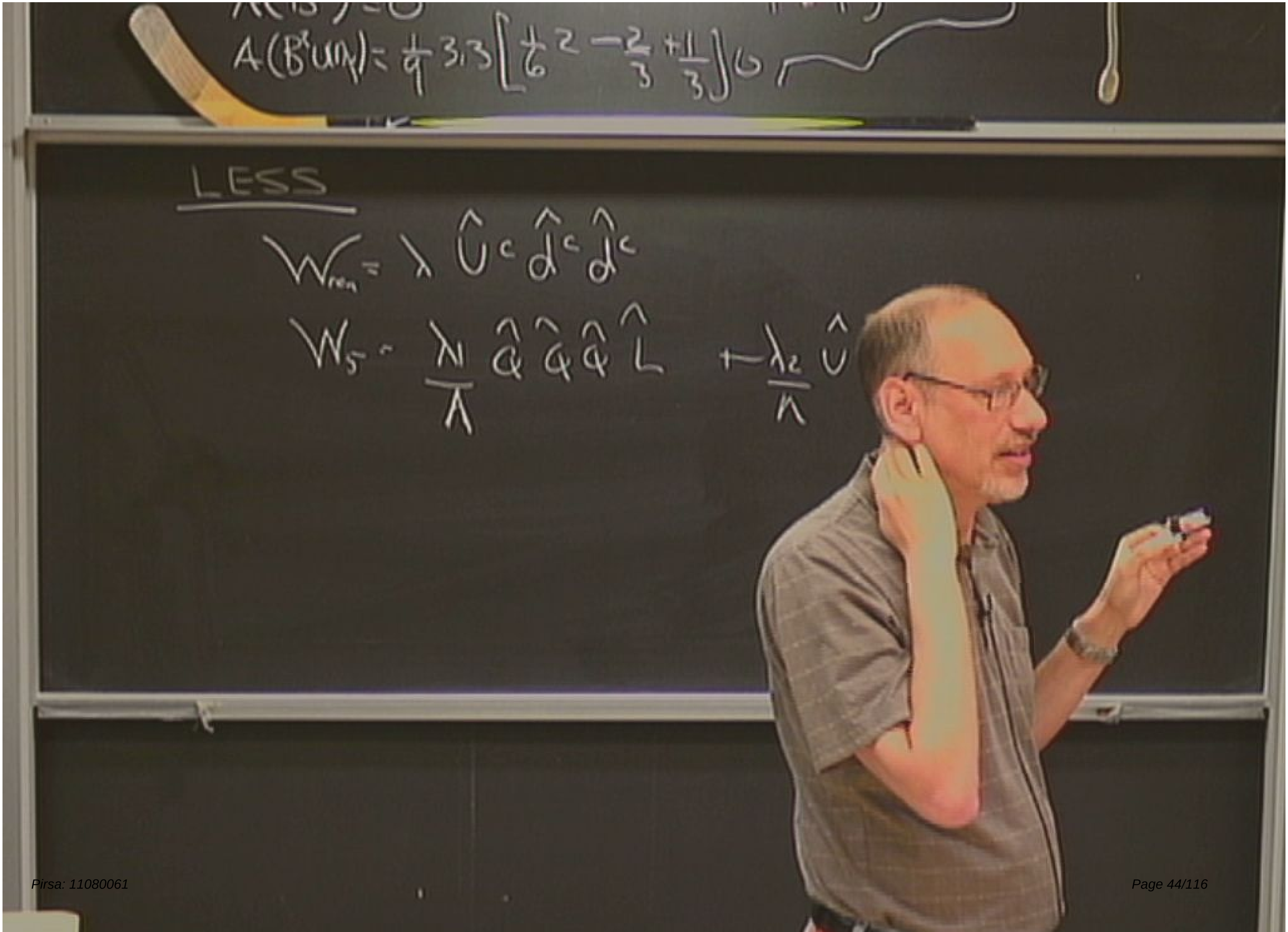
(1) Baryon # in SM
Classically Lagr Inv
e.g.:
Λ ≥ 10^15 GeV
A(B^3) = 0

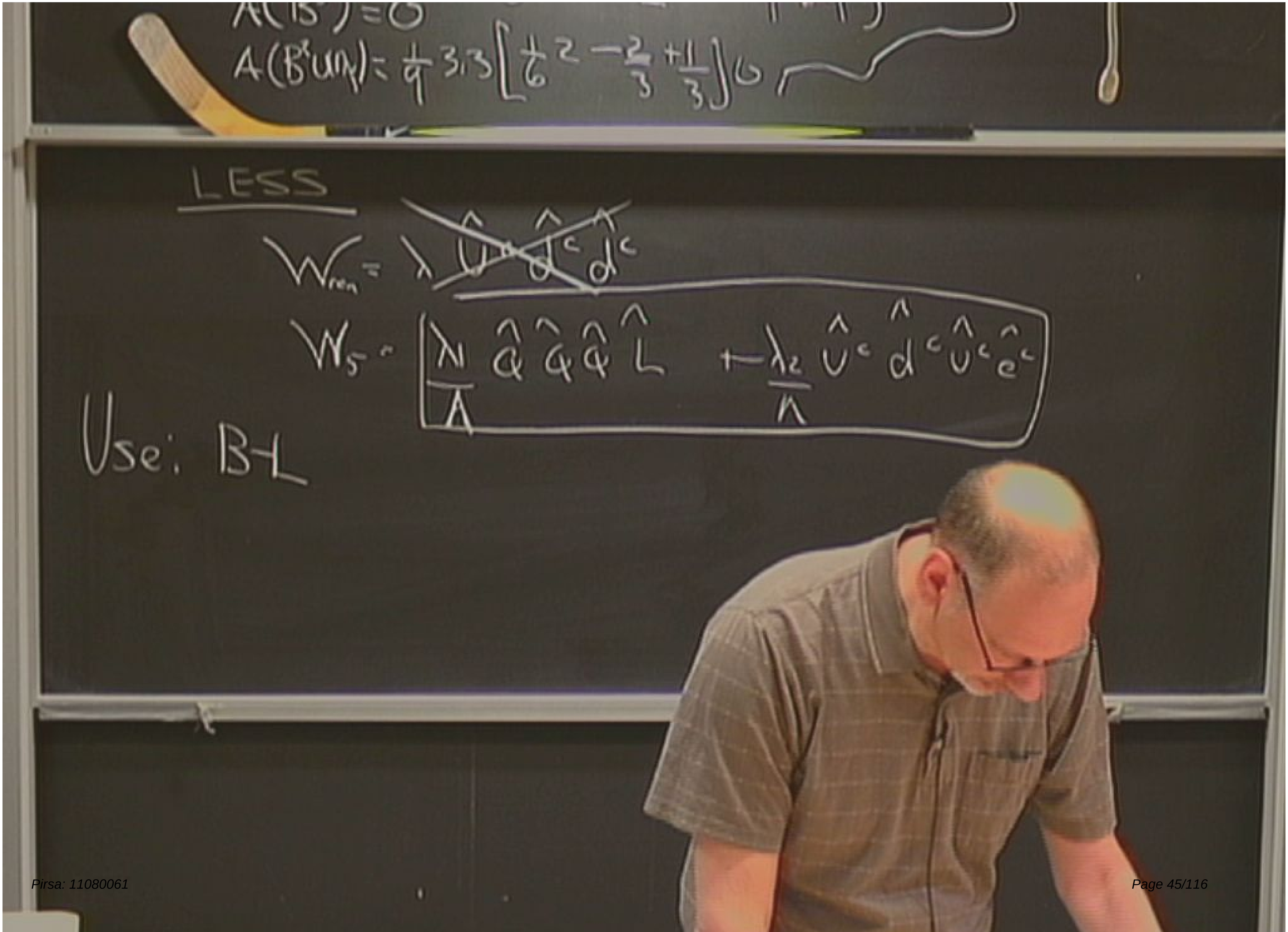

(1) Baryon # in SM
classically Lagr inv
SU(3)
SU(2)
U(1)
U(1)
B
gen
Bary
A(B³) = 0
e.g.: 1/Λ²
≥ 10¹⁵ GeV
3/2


A(B³uη)= 1/9 3,3 [1/6 2 −2/3 +1/3] 6
LESS


LESS
W = λ Û^c d̂^c d̂^c


LESS


LESS
W_ren = λ Û^c d̂^c d̂^c
W_5 = λ1/Λ Q̂ Q̂ Q̂ L̂ + λ2/Λ Û


LESS
Use: B-L

$$A(B^2 U(N)) = \frac{1}{9} 3,3 \left[\frac{1}{6} 2 - \frac{2}{3} + \frac{1}{3} \right] 6$$

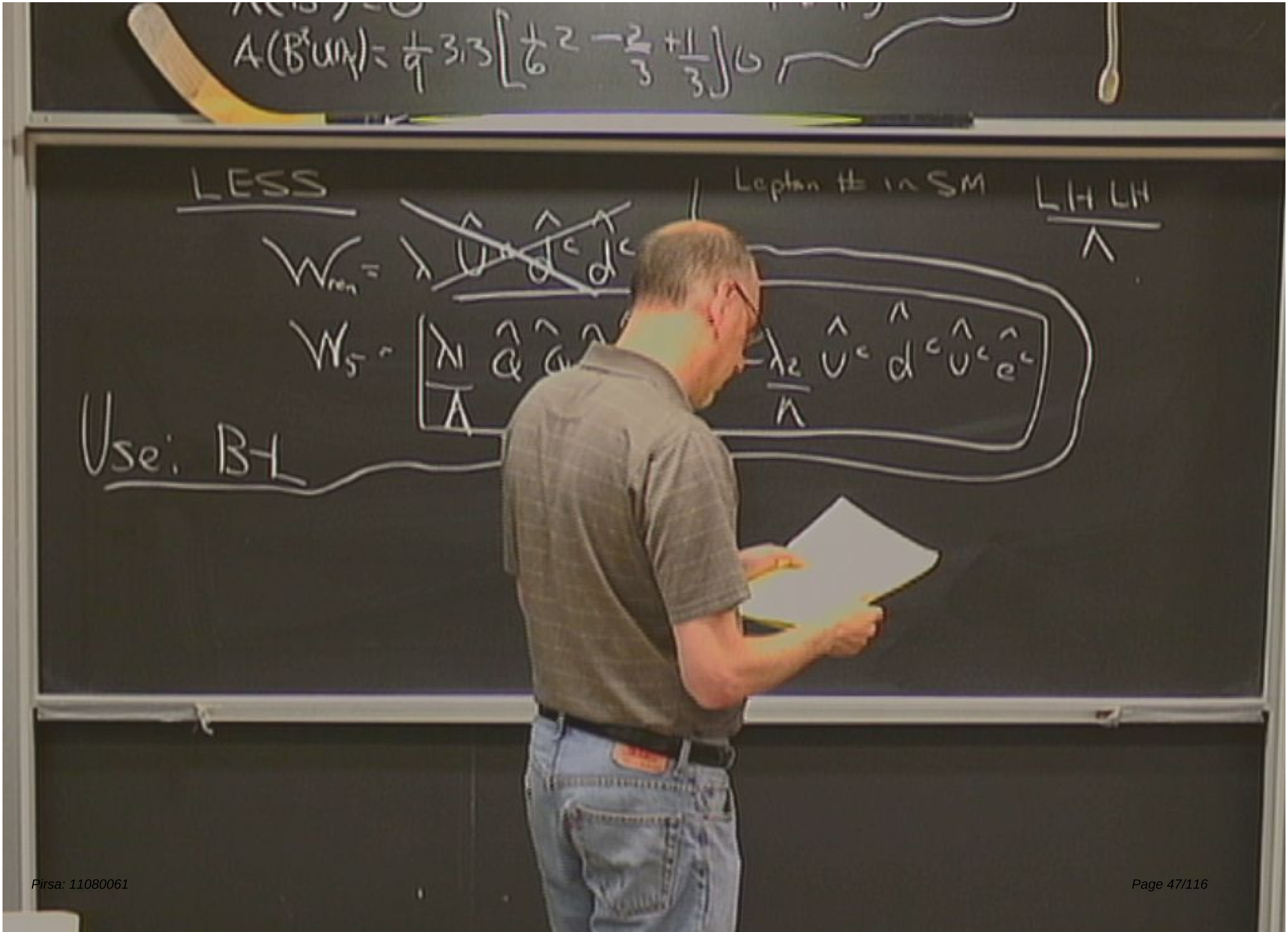
LESS

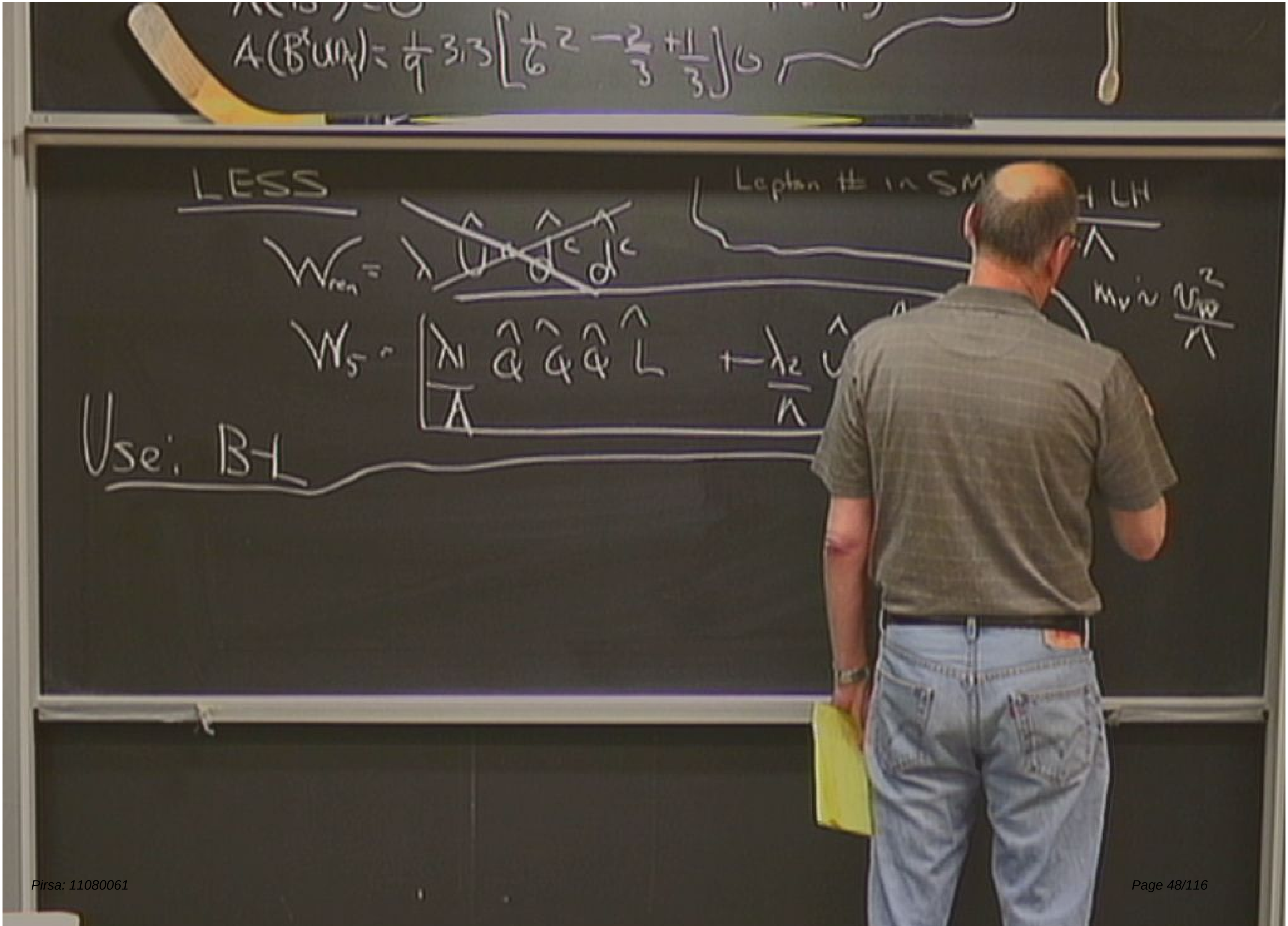
Lepton # in SM

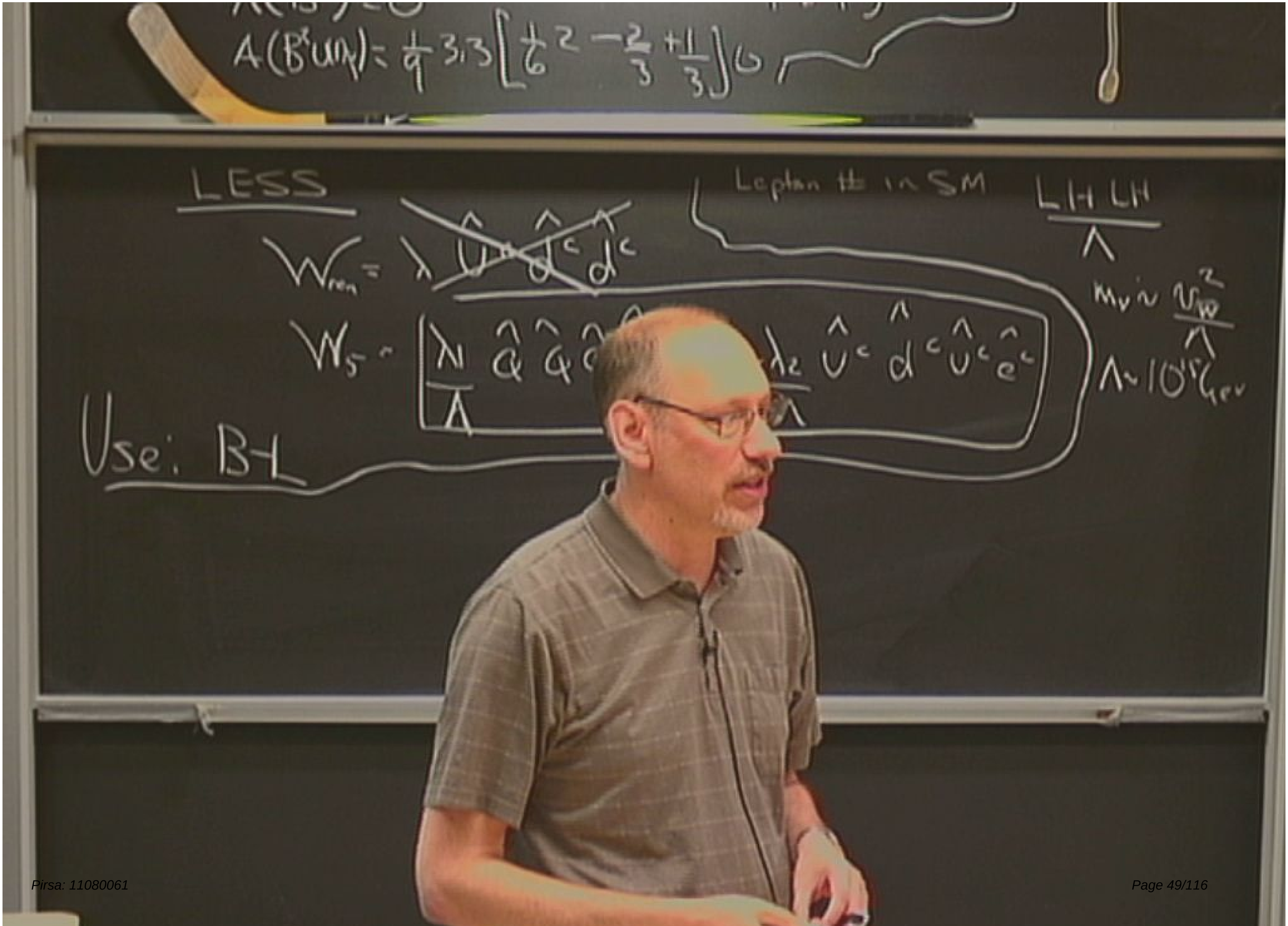
$$W_{ren} = \lambda \hat{U}^c \hat{d}^c \hat{d}^c$$

$$W_5 = \frac{\lambda_1}{\Lambda} \hat{Q}\hat{Q}\hat{Q}\hat{L} + \frac{\lambda_2}{\Lambda} \hat{U}^c \hat{d}^c \hat{U}^c \hat{e}^c$$

Use: B-L


LESS
Lepton # in SM
Use: B-L


LESS
W5 =
Use: B-L
Lepton # in SM


LESS
Lepton # in SM
LH LH
Use: B-L

$A(B^2 U N_f) = \frac{1}{9} 3 \cdot 3 \left[\frac{1}{6} 2 - \frac{2}{3} + \frac{1}{3} \right] G$

LESS

Lepton # in SM

$\frac{LH\,LH}{\Lambda}$

$W_{ren} = \lambda \hat{U}^c \hat{d}^c \hat{d}^c$

$m_\nu \sim \frac{v_{EW}^2}{\Lambda}$

$W_5 = \frac{\lambda_1}{\Lambda} \hat{Q}\hat{Q}\hat{Q}\hat{L} + \frac{\lambda_2}{\Lambda} \hat{U}^c \hat{d}^c \hat{U}^c \hat{e}^c$

$\Lambda \sim 10^{14}$ GeV

Use: B-L

$A(B^2 U(1)_Y) = \frac{1}{9} 3 \cdot 3 \left[\frac{1}{6} 2 - \frac{2}{3} + \frac{1}{3} \right] G$

LESS

$W_{ren} = \lambda \hat{U} \hat{d}^c \hat{d}^c$

$W_5 = \frac{\lambda_1}{\Lambda} \hat{Q}\hat{Q}\hat{Q}\hat{L} + \frac{\lambda_2}{\Lambda} \hat{U}^c \hat{d}^c \hat{U}^c \hat{e}^c$

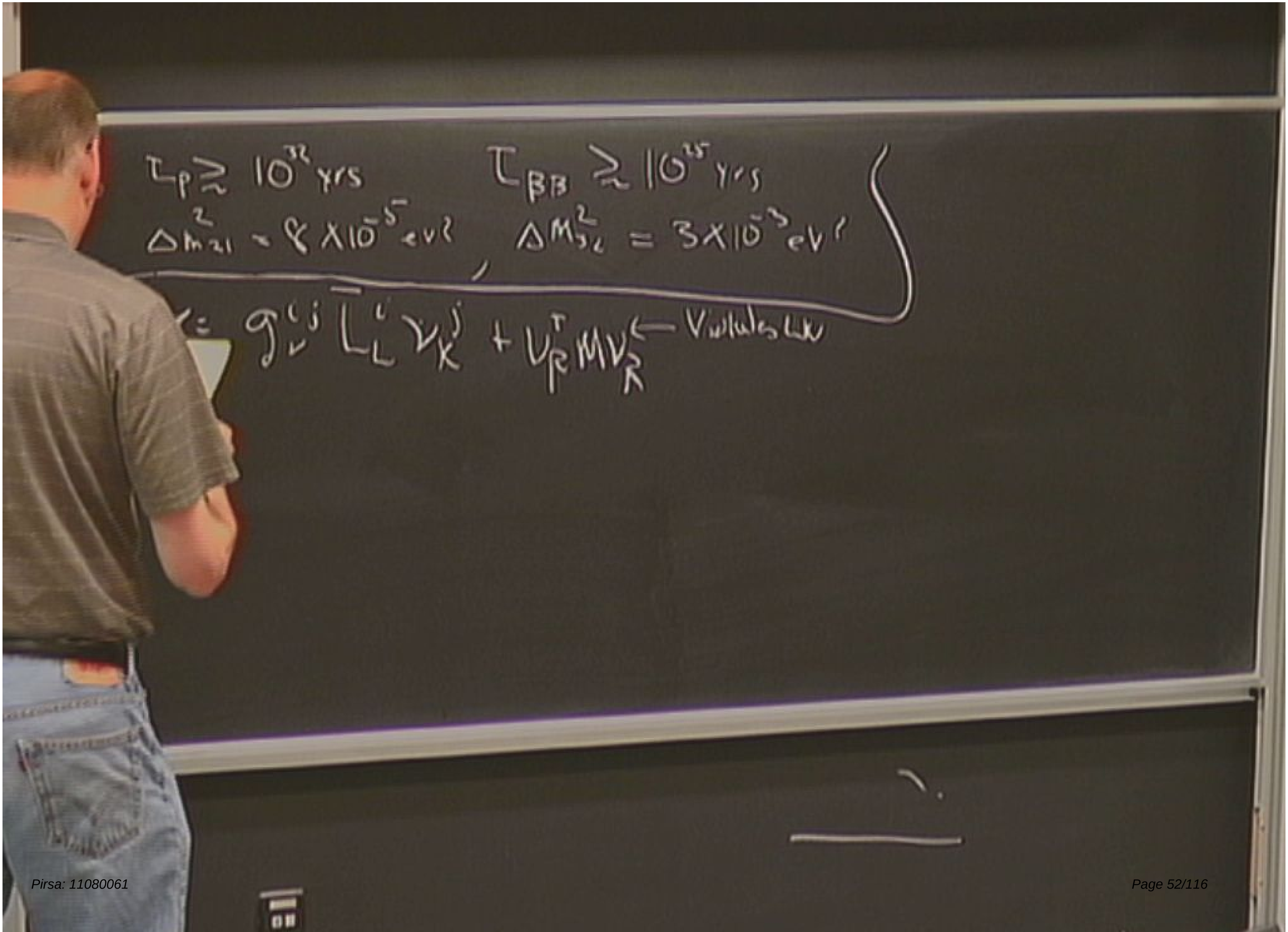
Use: B-L

Lepton # in SM

$\frac{LH\,LH}{\Lambda}$

$m_\nu \sim \frac{v_W^2}{\Lambda}$

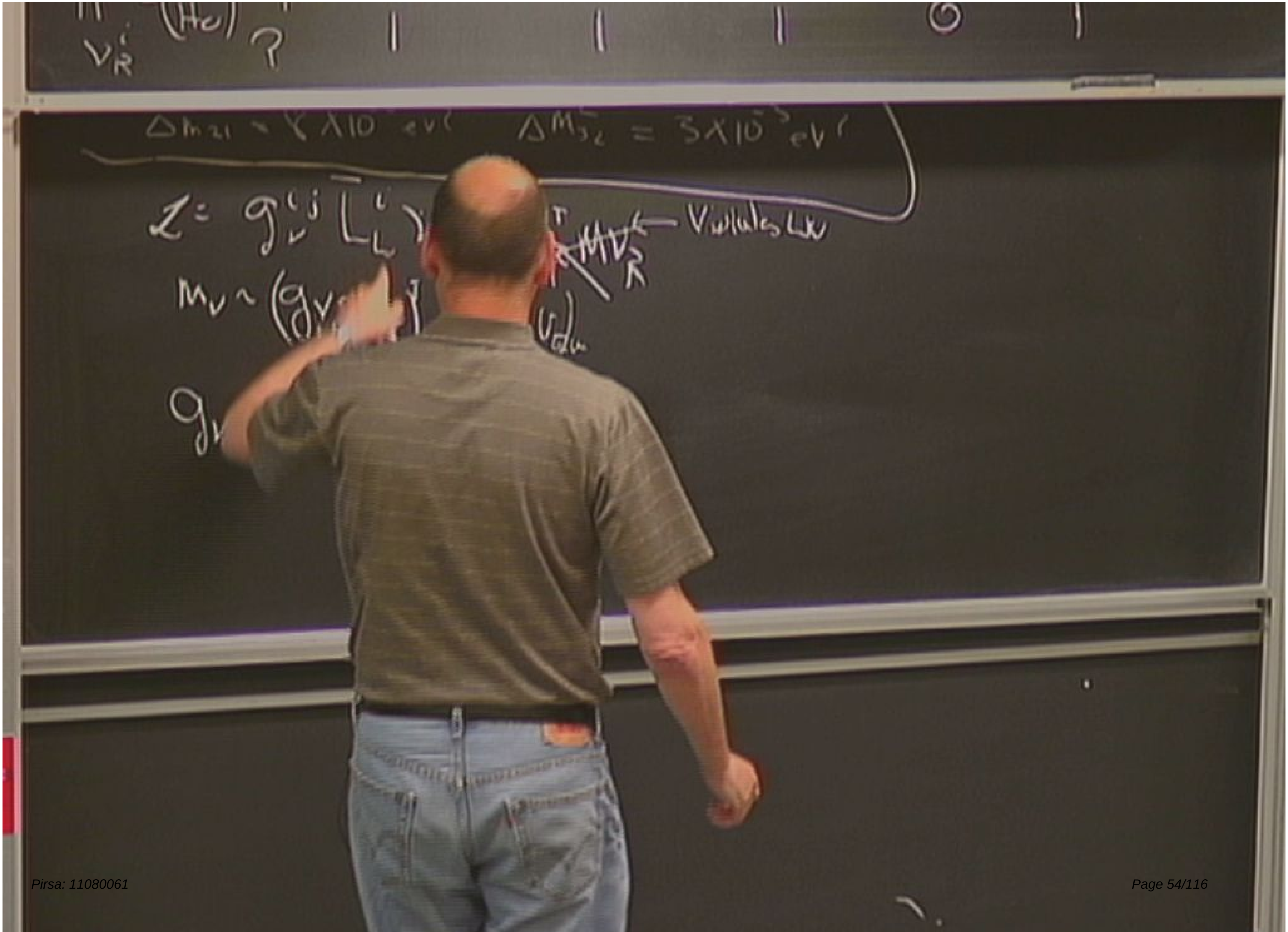
$\Lambda \sim 10^{14}$ GeV

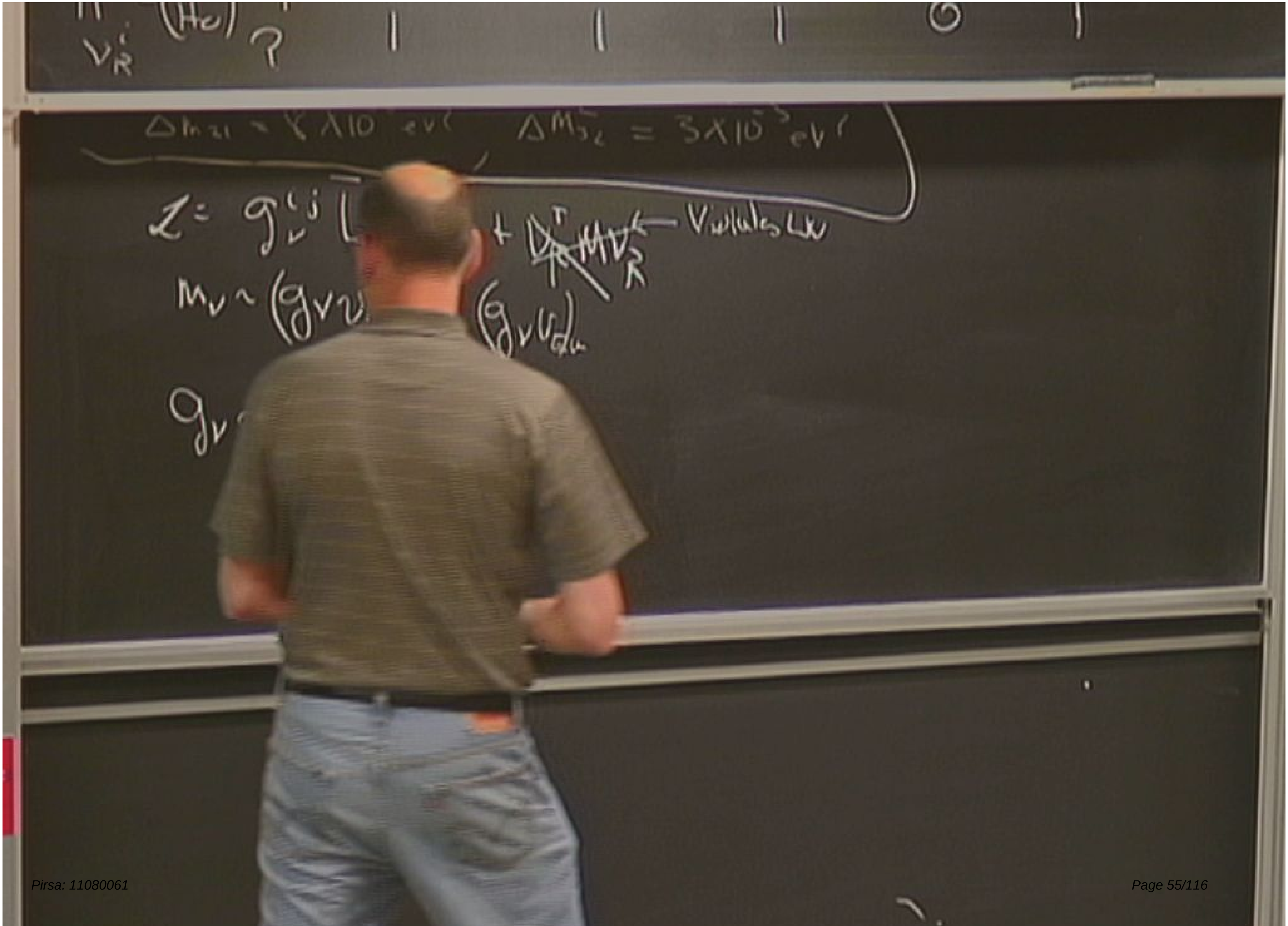

τp ≳ 10^32 yrs
τββ ≳ 10^25 yrs
Δm²21 ≈ 8 × 10^-5 eV²
ΔM²32 = 3 × 10^-3 eV²

$$\mathcal{L} = g_\nu^{ij} \bar{L}_L^i \nu_R^j + \nu_R^T M \nu_R \quad \text{violates LN}$$

$$m_\nu \sim (g_\nu v_{EW})^2 \frac{1}{M} (g_\nu v_{EW})$$

$$g_\nu \sim 10^{-14}$$





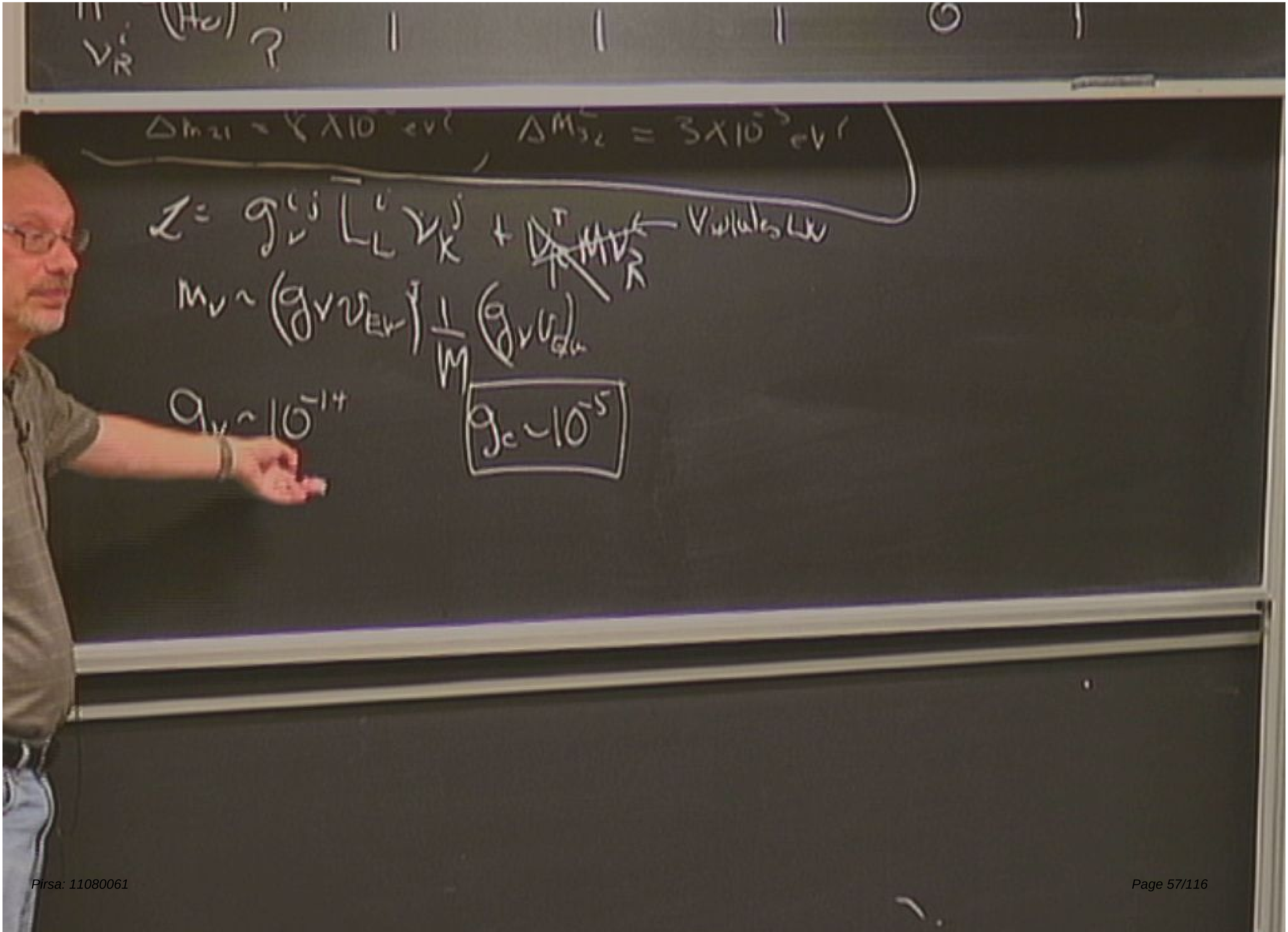
ν_R^i ?

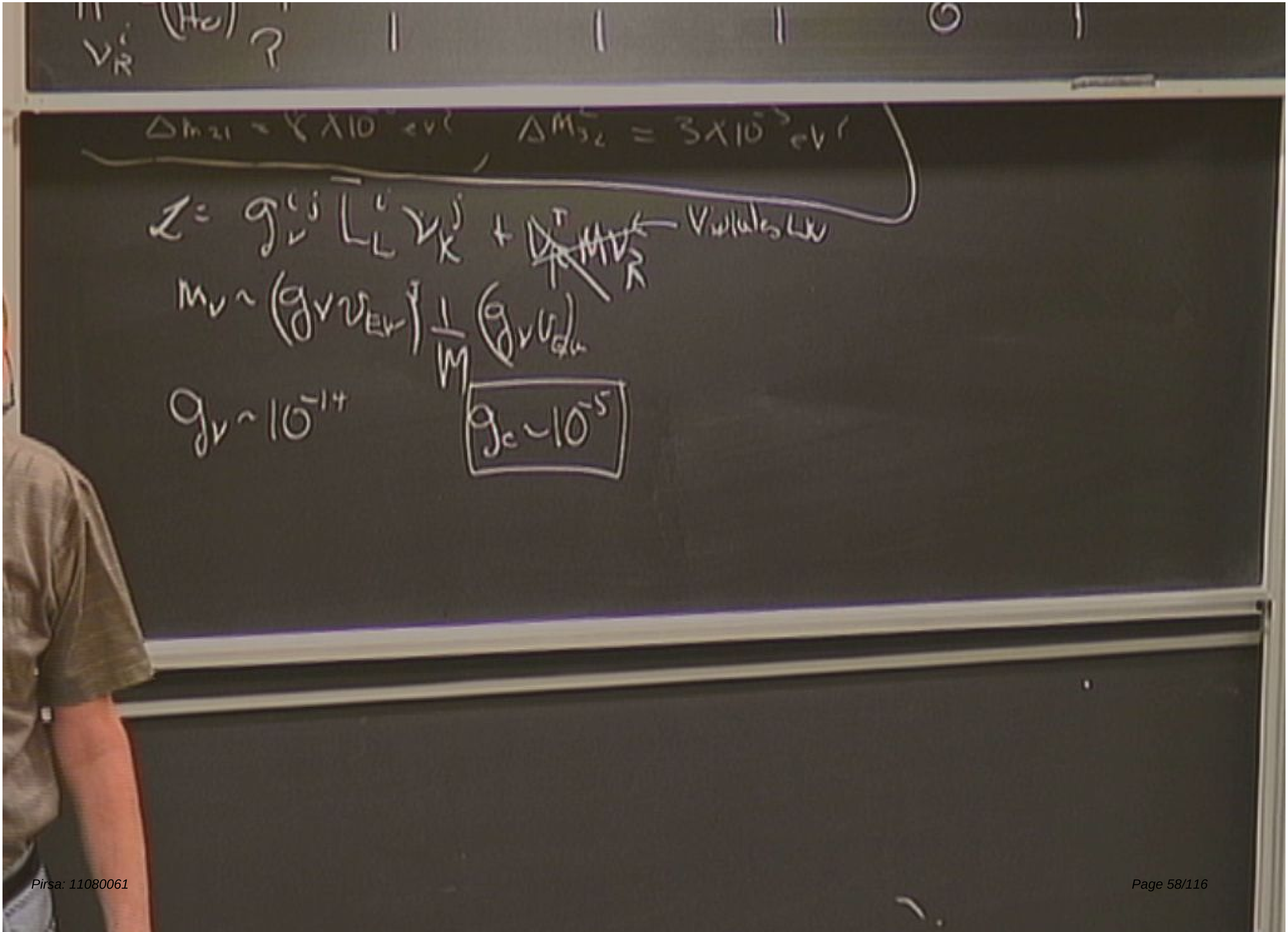
$\Delta m_{21}^2 = 8\times10^{-5}\,eV^2$ $\Delta m_{32}^2 = 3\times10^{-3}\,eV^2$

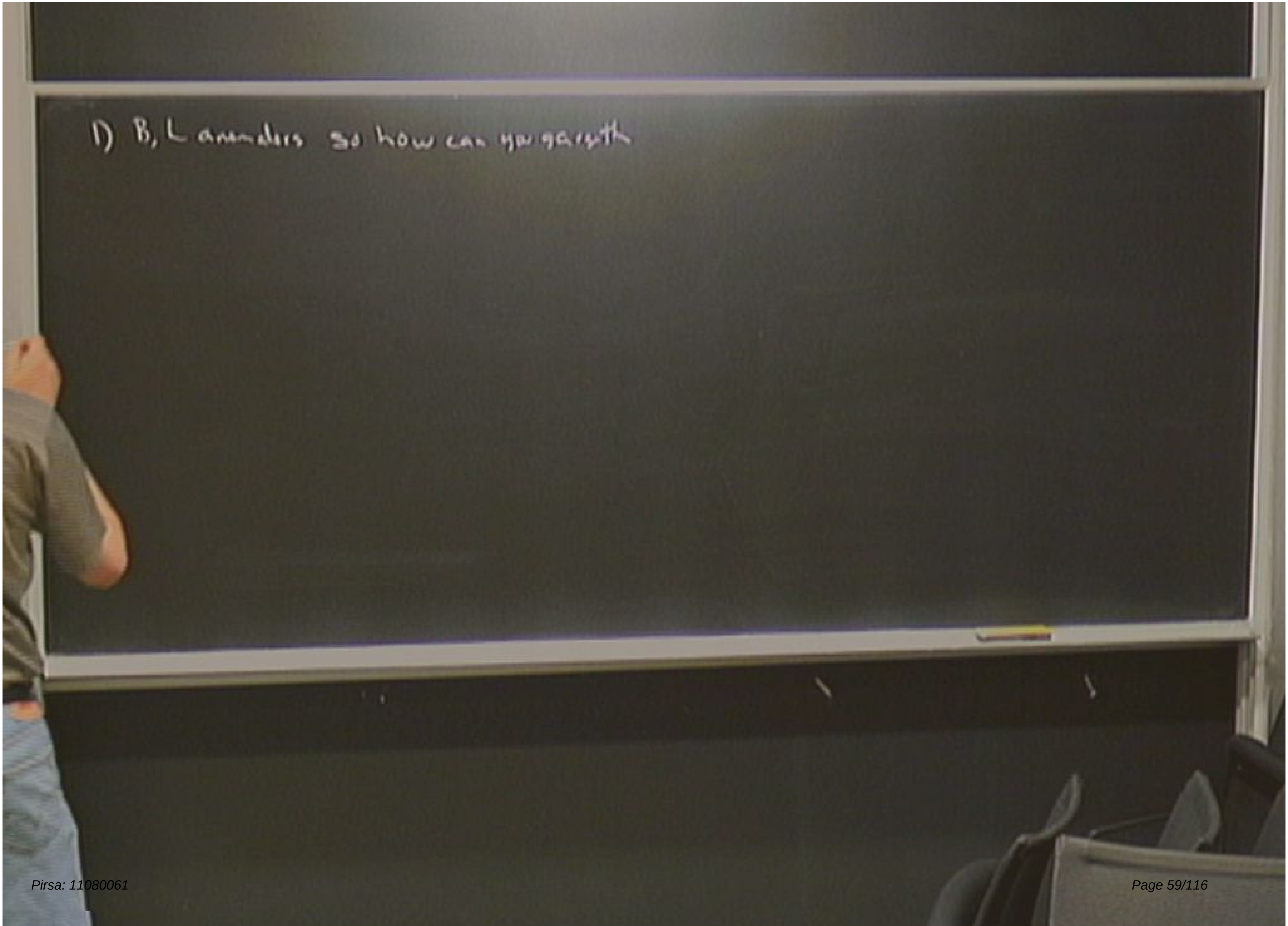
$\mathcal{L} = g_\nu^{ij}\,\bar{L}_L^i\,\nu_R^j + \nu_R^T M \nu_R$ ← violates L#

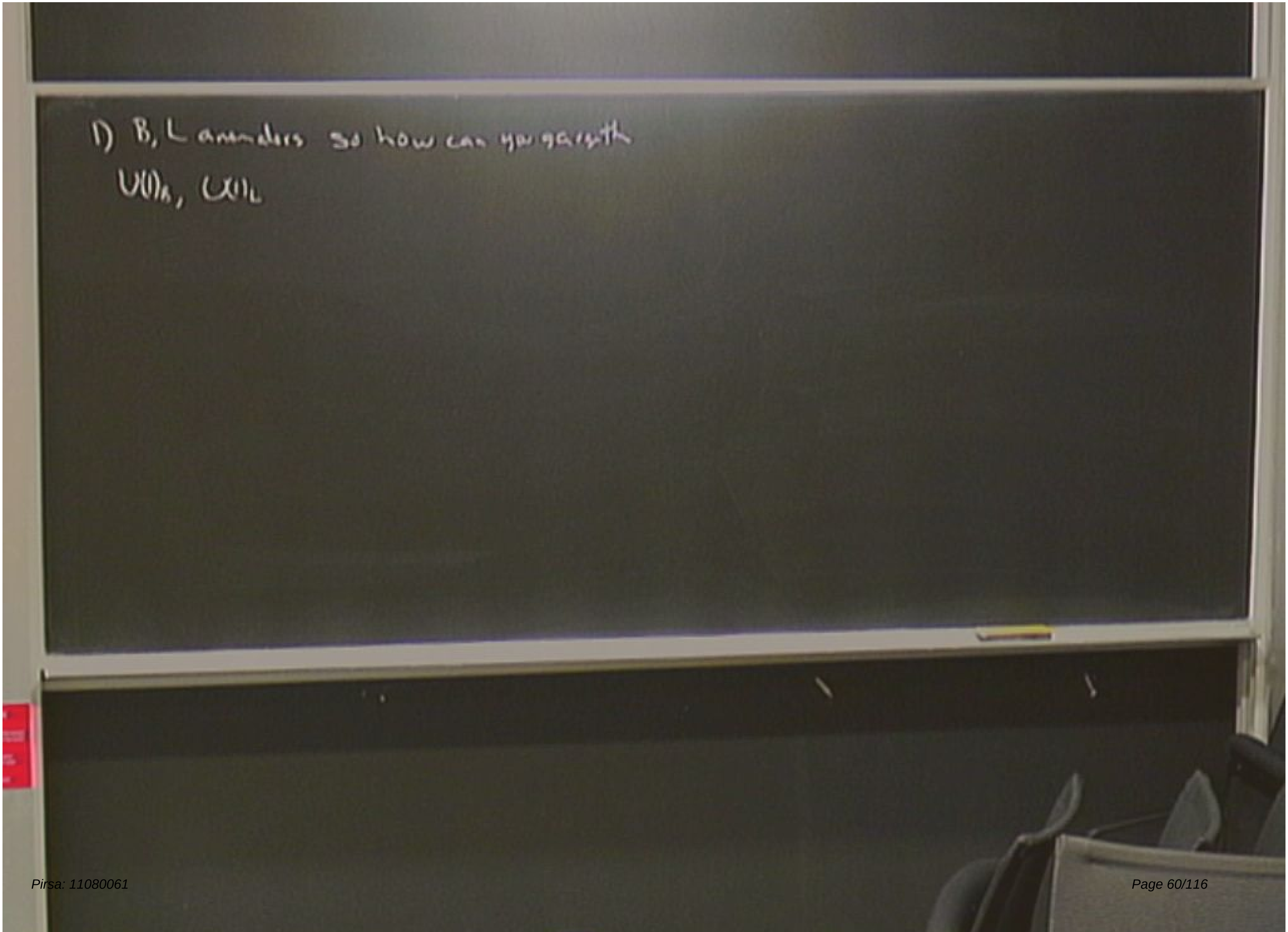
$m_\nu \sim (g_\nu v_{EW})\,\frac{1}{M}\,(g_\nu v_{EW})$

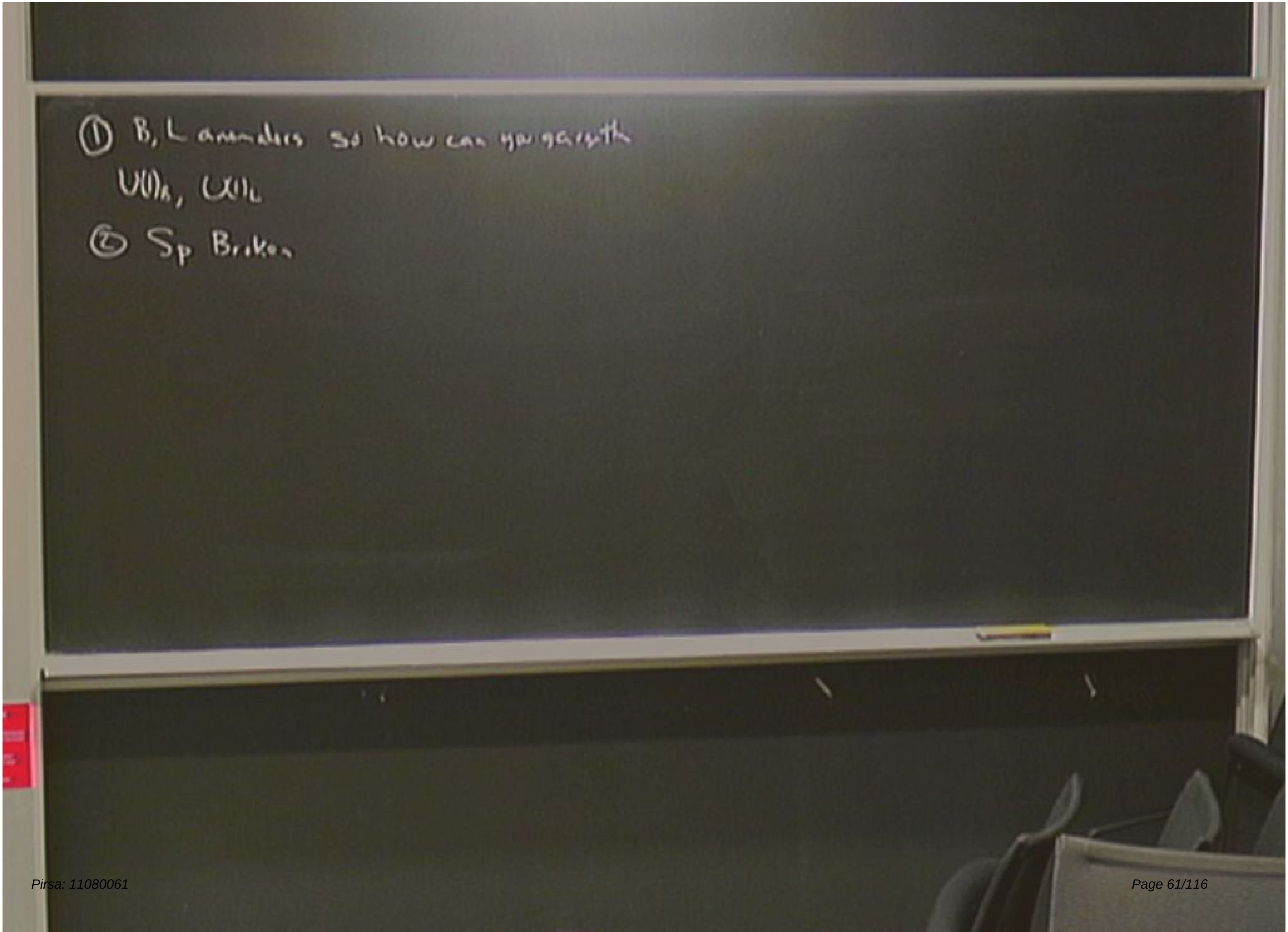
$g_\nu \sim 10^{-14}$

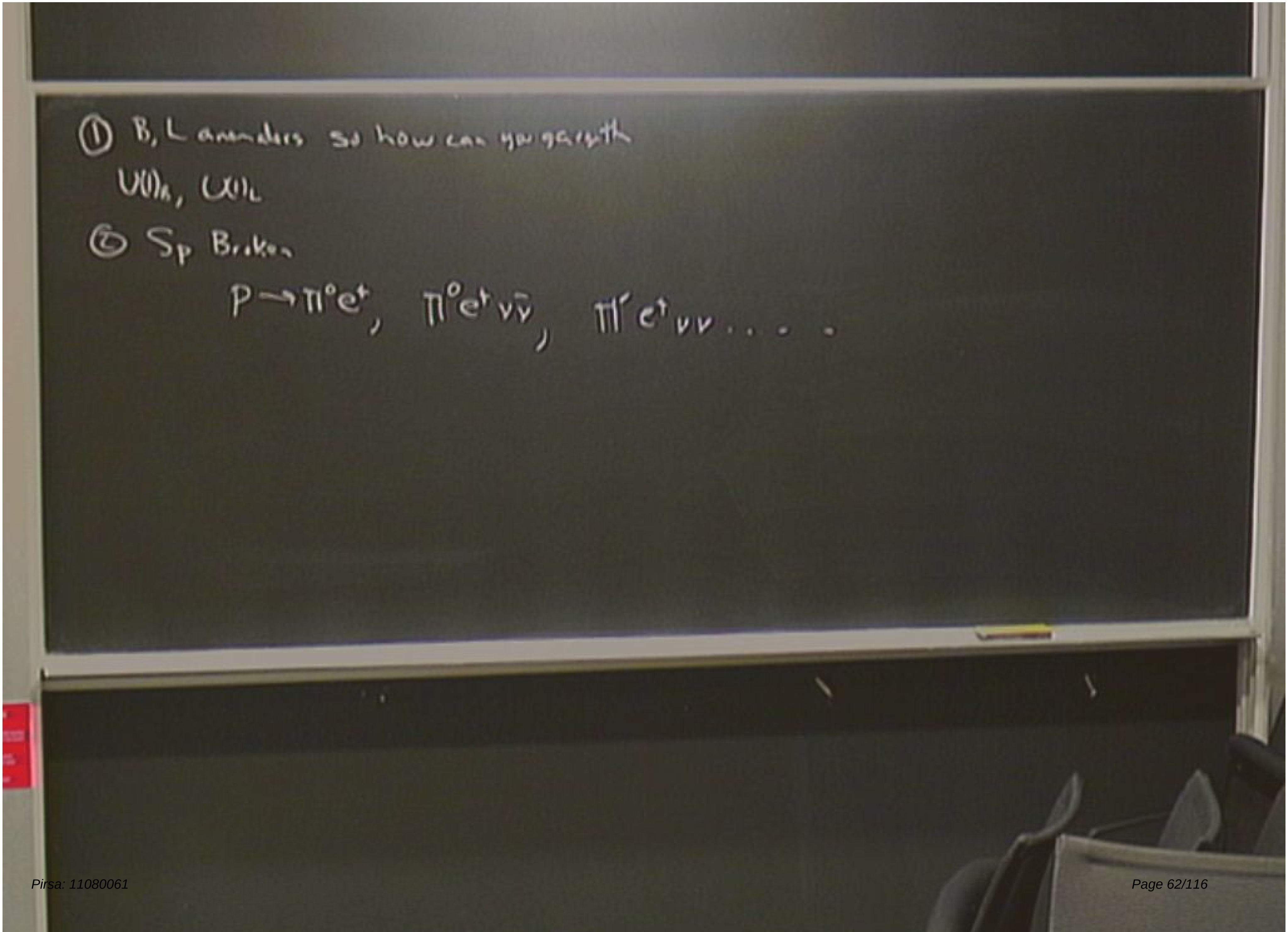

ΔM²₃₂ = 3×10⁻³ eV²
L = g_ν^ij L̄_L^i ν_R^j + ν_R^T M ν_R
violates LN
m_ν ~ (g_ν v_EW)² 1/M
g_ν ~ 10⁻¹⁴
g_e ~ 10⁻⁵

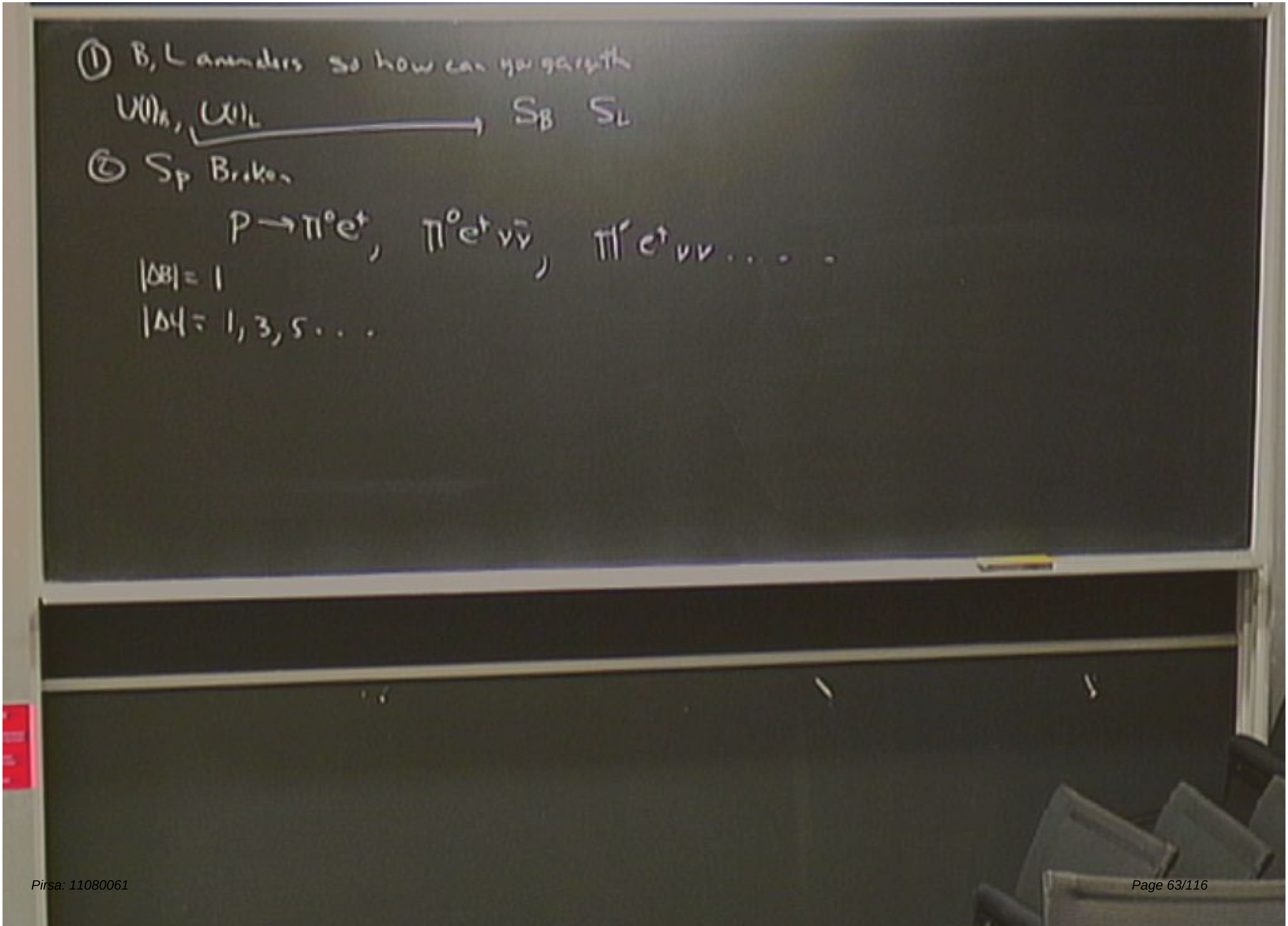

ν_R^i ?
$\Delta m_{21}^2 \approx 8\times10^{-5}\,eV^2$ $\Delta m_{32}^2 = 3\times10^{-3}\,eV^2$
$\mathcal{L} = g_\nu^{ij}\,\bar{L}_L^i\,\nu_R^j + \nu_R^T M \nu_R$ ← violates LN
$m_\nu \sim (g_\nu v_{EW})\,\frac{1}{M}\,(g_\nu v_{EW})$
$g_\nu \sim 10^{-14}$
$g_e \sim 10^{-5}$


1) B, L anomalies so how can you get this


1) B, L anomalies so how can you gauge th
$U(1)_B$, $U(1)_L$


(1) B, L anomalies so how can you
U(1)B, U(1)L
(2) Sp Broken


① B, L anomalies so how can you
U(1)_B, U(1)_L
② Sp Broken
p → π⁰e⁺, π⁰e⁺νν̄, π⁺e⁺νν . . . .


① B, L anomalies so how can you
U(1)_B, U(1)_L → S_B S_L
② S_P Broken
P → π⁰e⁺, π⁰e⁺νν̄, π e⁺νν . . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .

① B, L accidentals so how can you get them

$U(1)_B, U(1)_L \longrightarrow S_B \quad S_L$

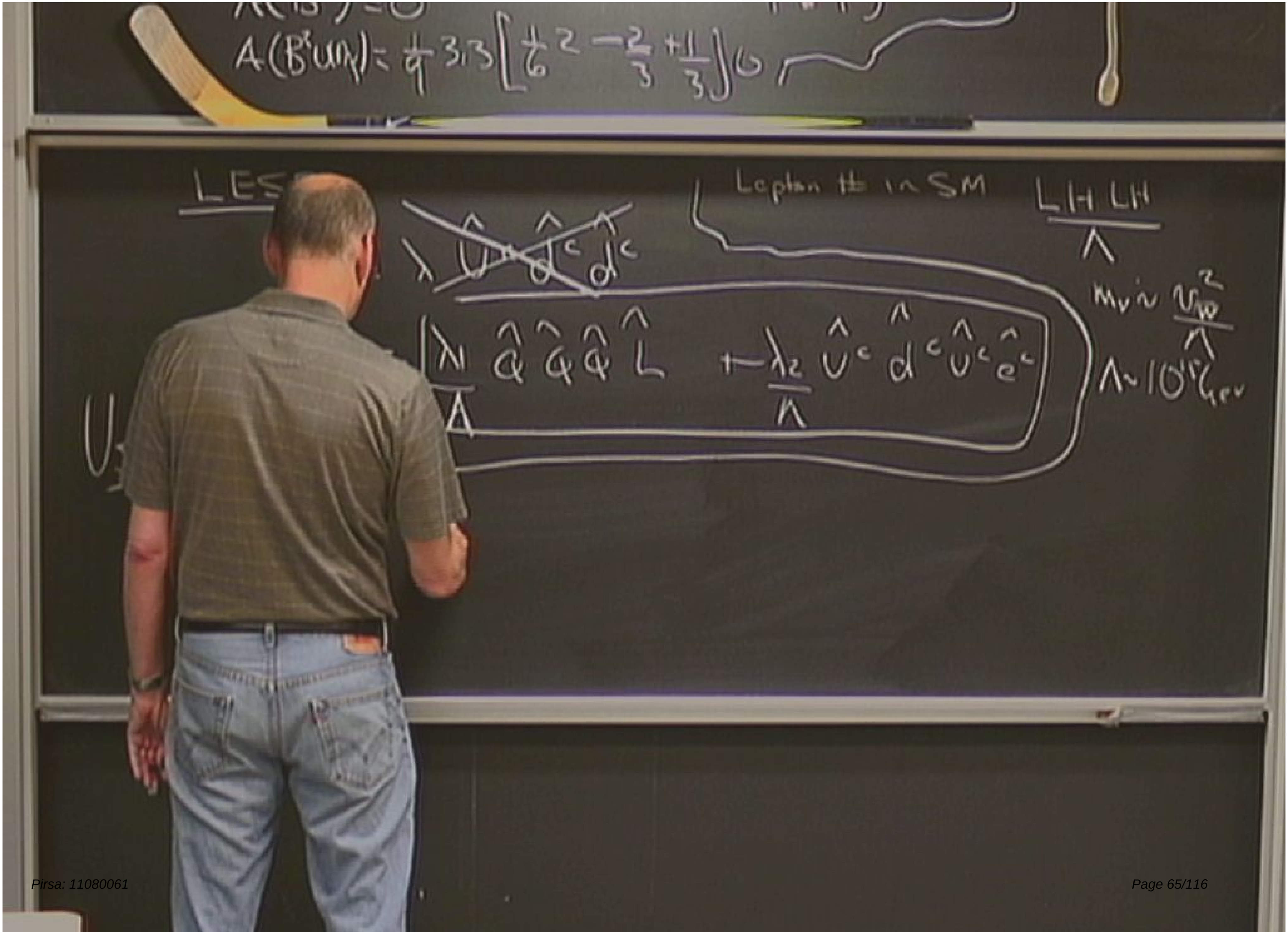
② S_p Broken

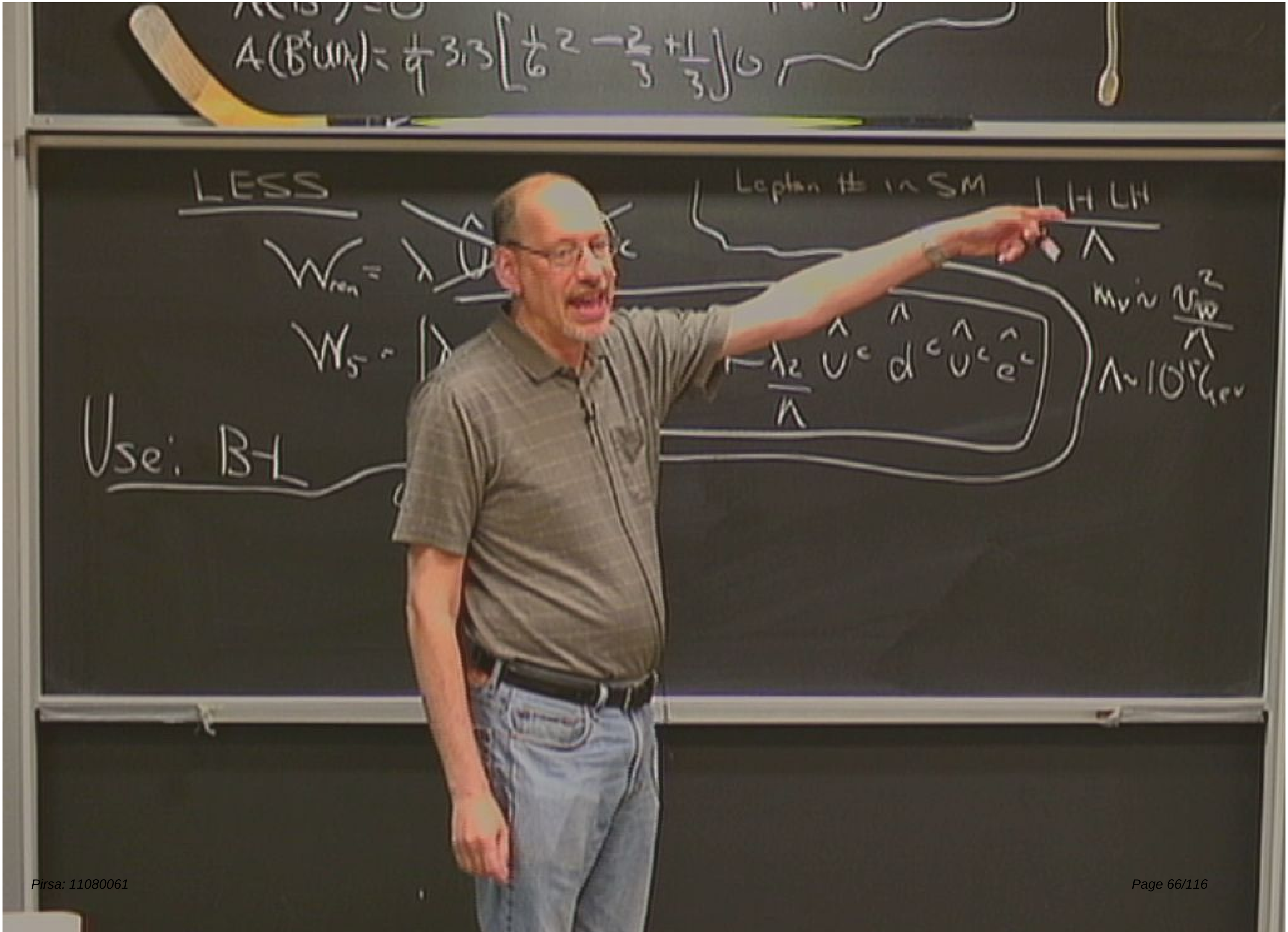
$$p \to \pi^0 e^+, \quad \pi^0 e^+ \nu\bar{\nu}, \quad \pi^+ e^+ \nu\nu \ldots$$

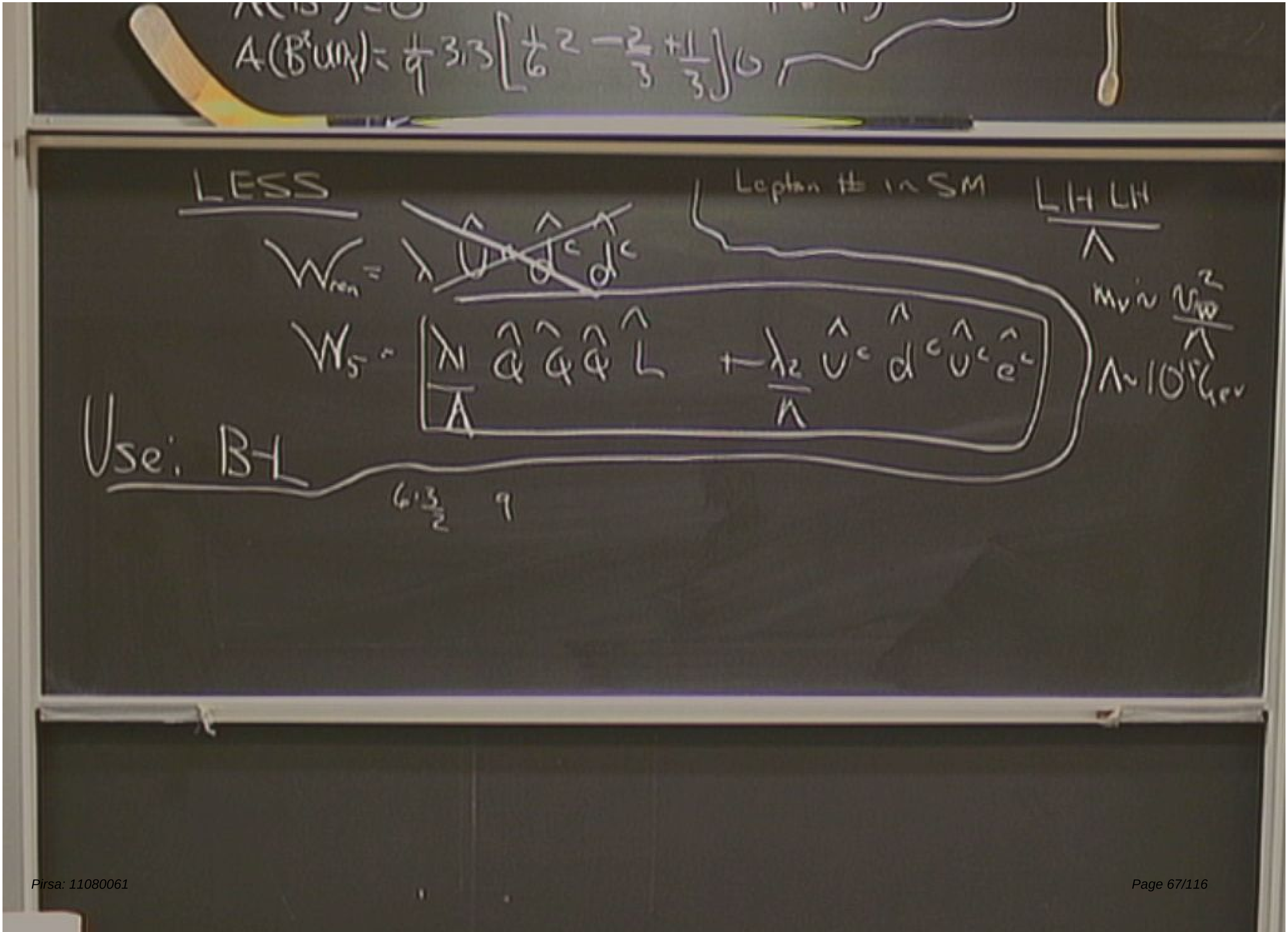
$|\Delta B| = 1$

$|\Delta 4| = 1, 3, 5 \ldots$

③


Lepton # in SM
LH LH


LESS
Lepton # in SM
Use: B-L


A(B²ur) = 1/9 3,3 [1/6 2 − 2/3 + 1/3] 6
LESS
Lepton # in SM
LH LH / Λ
W_ren = λ Û d̂^c d̂^c
W_5 = λ1/Λ Q̂ Q̂ Q̂ L̂ + λ2/Λ Û^c d̂^c Û^c ê^c
m_ν ~ v²/Λ
Λ ~ 10^14 GeV
Use: B-L

① B, L anomalies so how can you get with

$U(1)_B$, $U(1)_L$ ⟶ S_B S_L

② S_p Broken

$$P \to \pi^0 e^+, \quad \pi^0 e^+ \nu\bar{\nu}, \quad \pi^- e^+ \nu\nu \ldots$$

$|\Delta B| = 1$

$|\Delta L| = 1, 3, 5 \ldots$

③ Cosmology

① B, L anomalies so how can you gauge th

$U(1)_B,\ U(1)_L \longrightarrow S_B\ \ S_L$

② S_P Broken

$$P \to \pi^0 e^+,\quad \pi^0 e^+ \nu\bar{\nu},\quad \pi^- e^+ \nu\nu \ldots$$

$|\Delta B| = 1$

$|\Delta L| = 1, 3, 5 \ldots$

③ Cosmology

① B, L anomalies so how can you gauge th

$U(1)_B, \; U(1)_L \longrightarrow S_B \quad S_L$

② S_p Broken

$$p \to \pi^0 e^+, \quad \pi^0 e^+ \nu \bar{\nu}, \quad \pi e^+ \nu \nu \dots$$

$|\Delta B| = 1$

$|\Delta L| = 1, 3, 5 \dots$

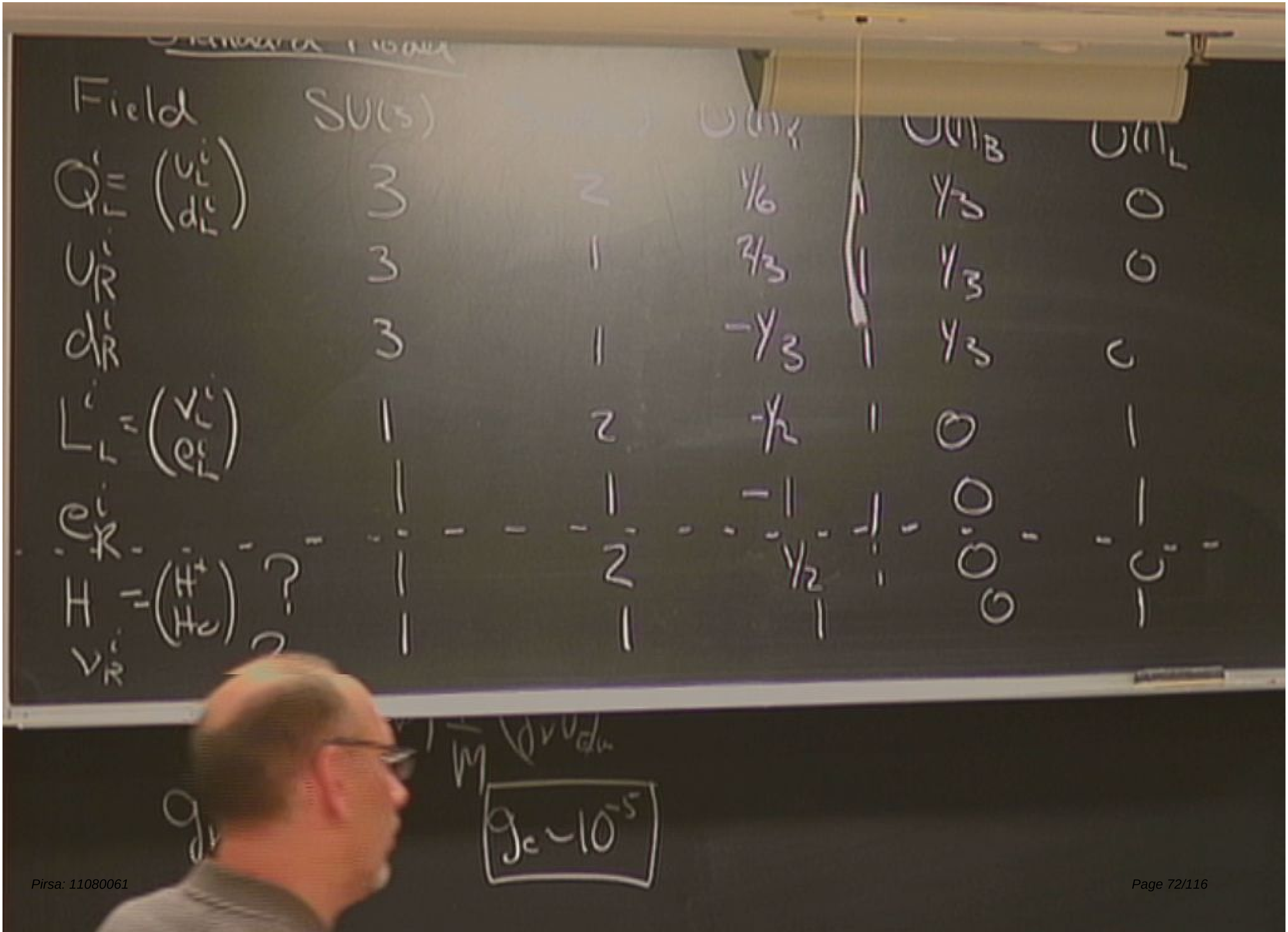
③ Cosmology

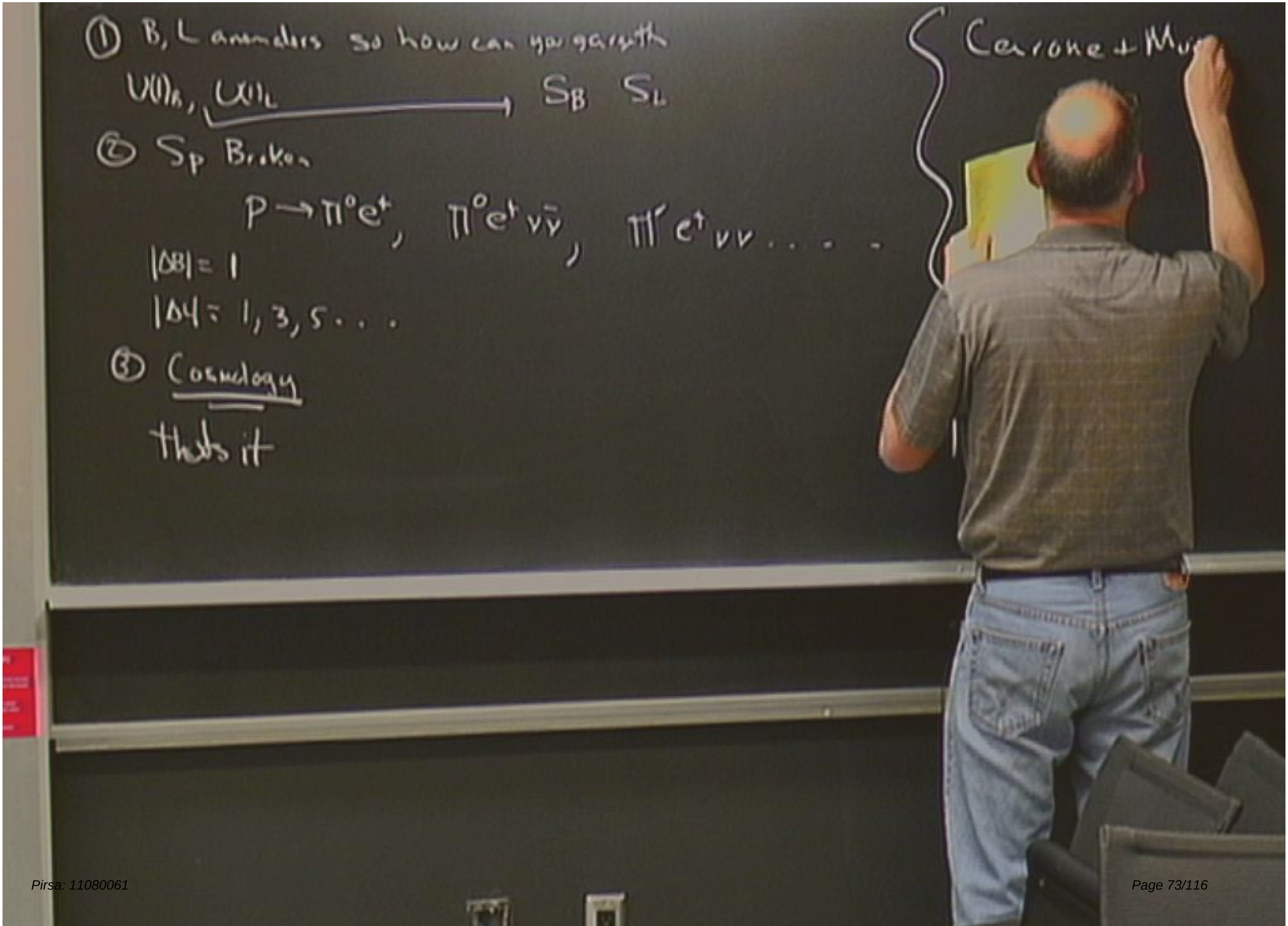
thats it

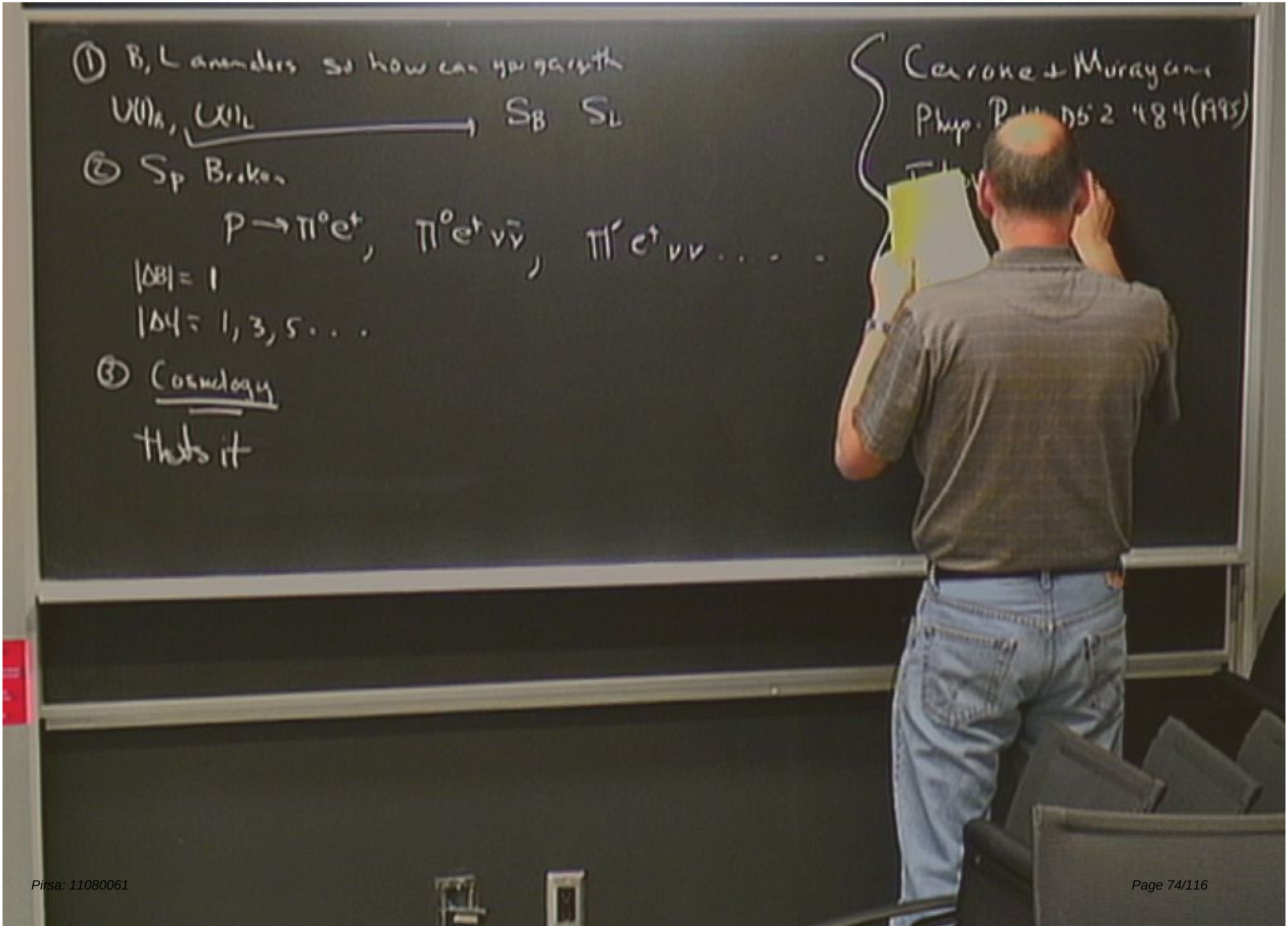
Field	SU(3)		$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6	1/3	0
u_R^i	3	1	2/3	1/3	0
d_R^i	3	1	-1/3	1/3	0
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	1	2	-1/2	0	1
e_R^i	1	1	-1	0	1
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$?	1	2	1/2	0	0
ν_R^i ?	1	1	1	0	1

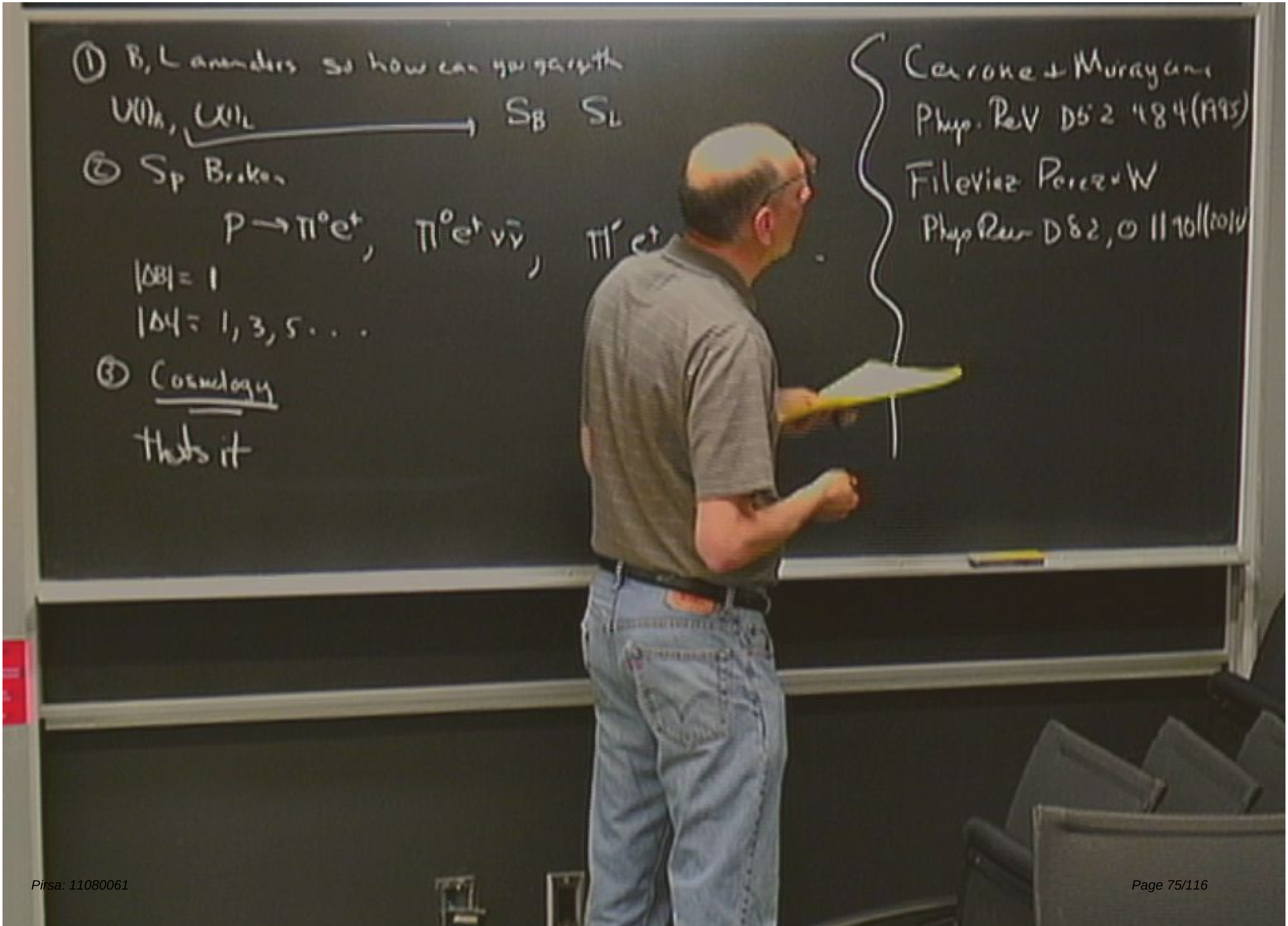
$g_\nu \sim 10^{-14}$

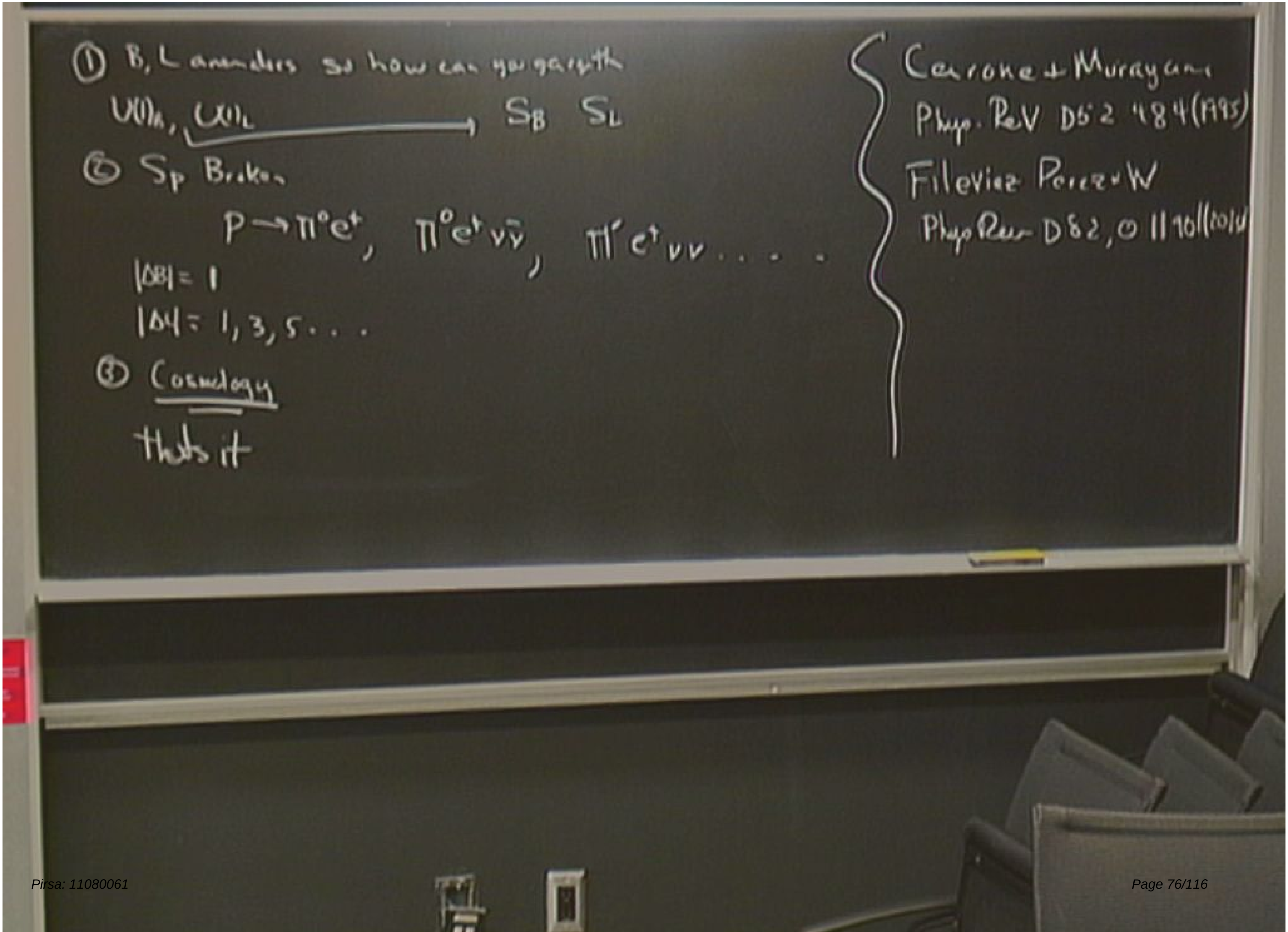
$\boxed{g_e \sim 10^{-5}}$

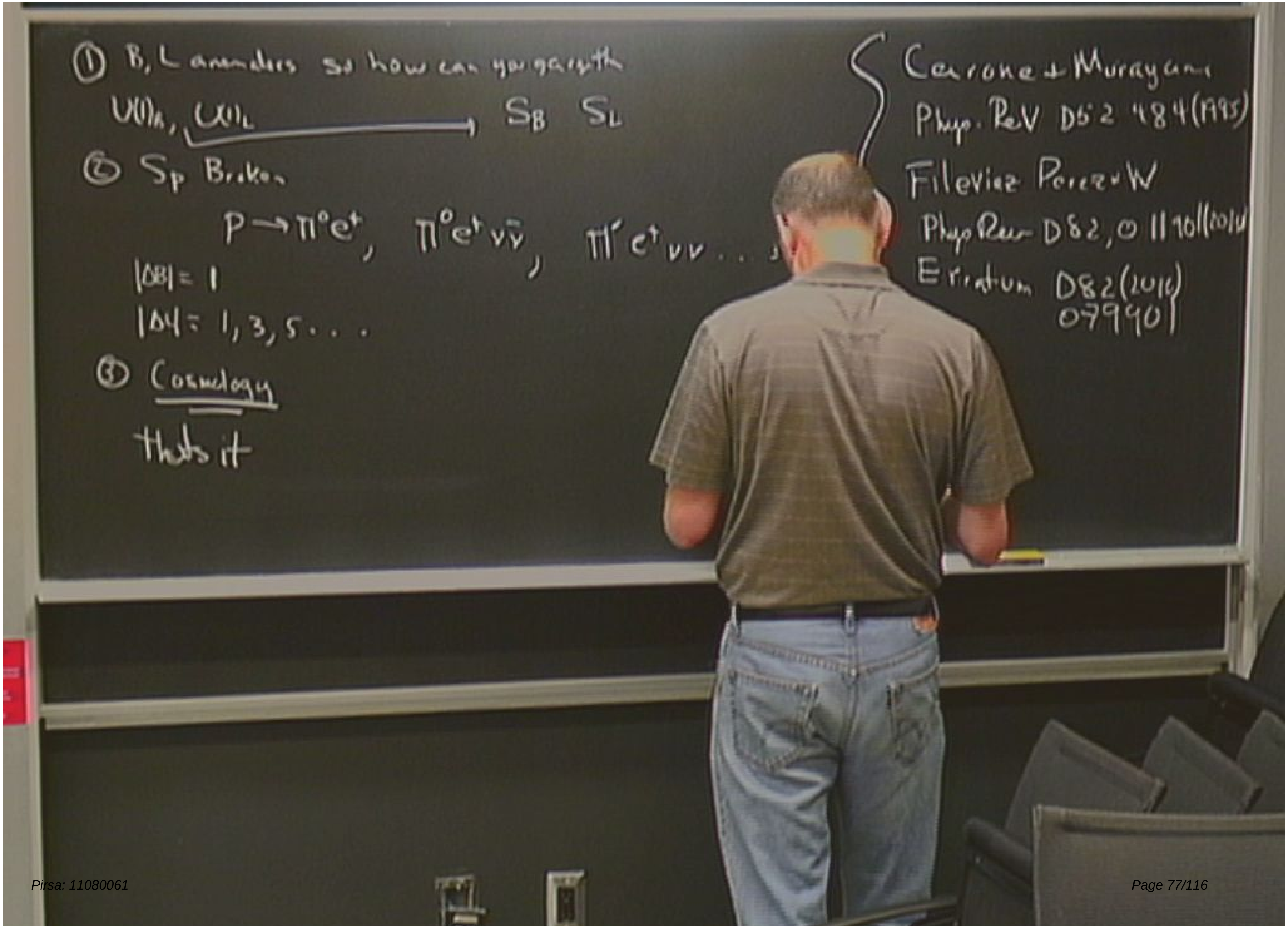

Field
SU(3)
U(1)B
U(1)L
Q^i_L = (u^i_L d^i_L) 3 2 1/6 1/3 0
u^i_R 3 1 2/3 1/3 0
d^i_R 3 1 −1/3 1/3 0
L^i_L = (ν^i_L e^i_L) 1 2 −1/2 0 1
e^i_R 1 1 −1 0 1
H = (H^+ H^0) ? 1 2 1/2 0 0
ν^i_R ? 1 1 1 0 1
g_c ~ 10^-5


① B, L anomalies
U(1)B, U(1)L → SB SL
② Sp Broken
P → π⁰e⁺, π⁰e⁺νν̄, π⁺e⁺νν . . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
that's it

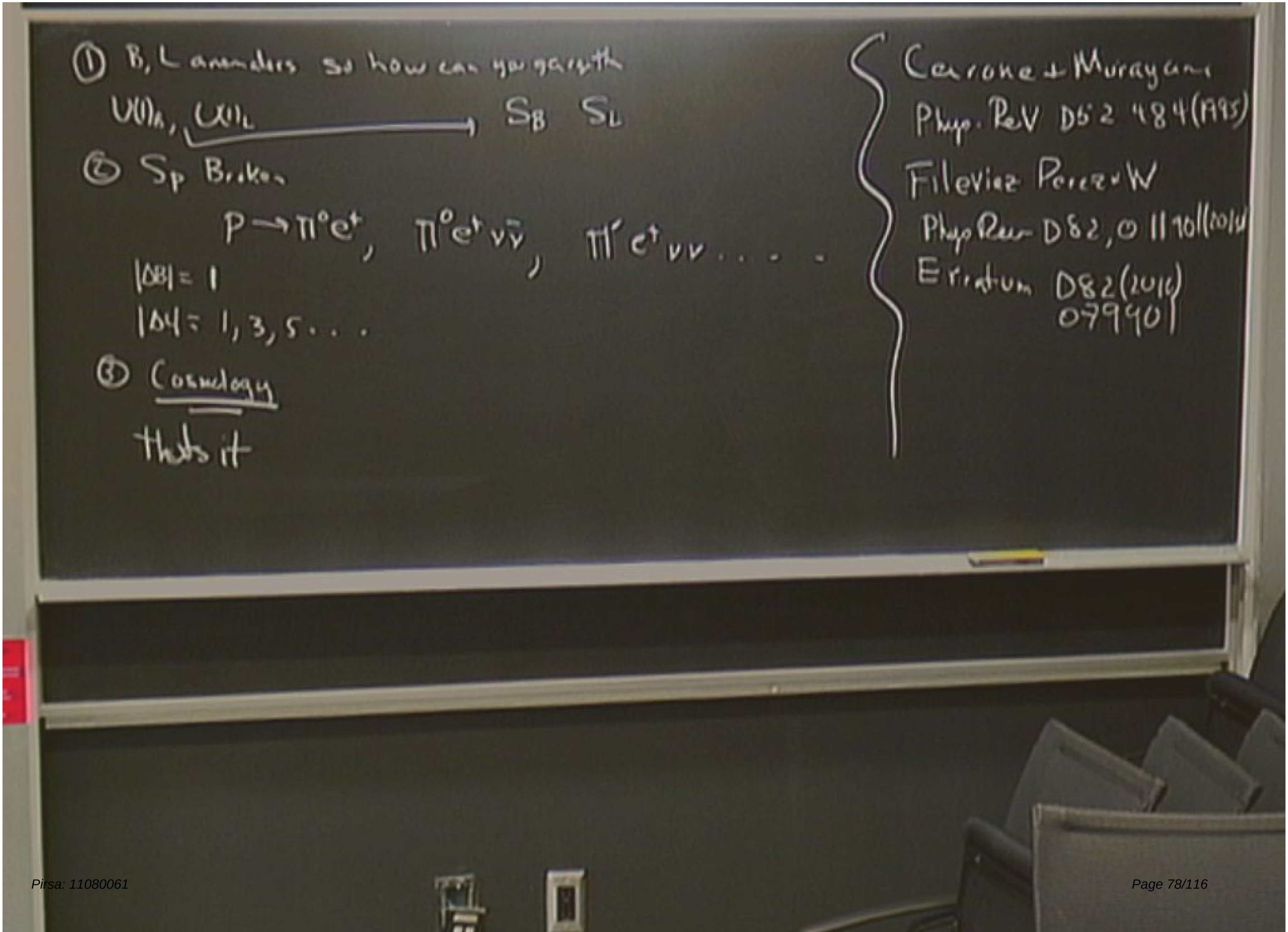

① B, L anomalies so how can you gauge them
U(1)B, U(1)L
SB SL
② Sp Broken
P → π0e+, π0e+νν̄, π+e+νν . . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
that's it
Carone & Murayama
Phys. Rev. D52 484 (1995)

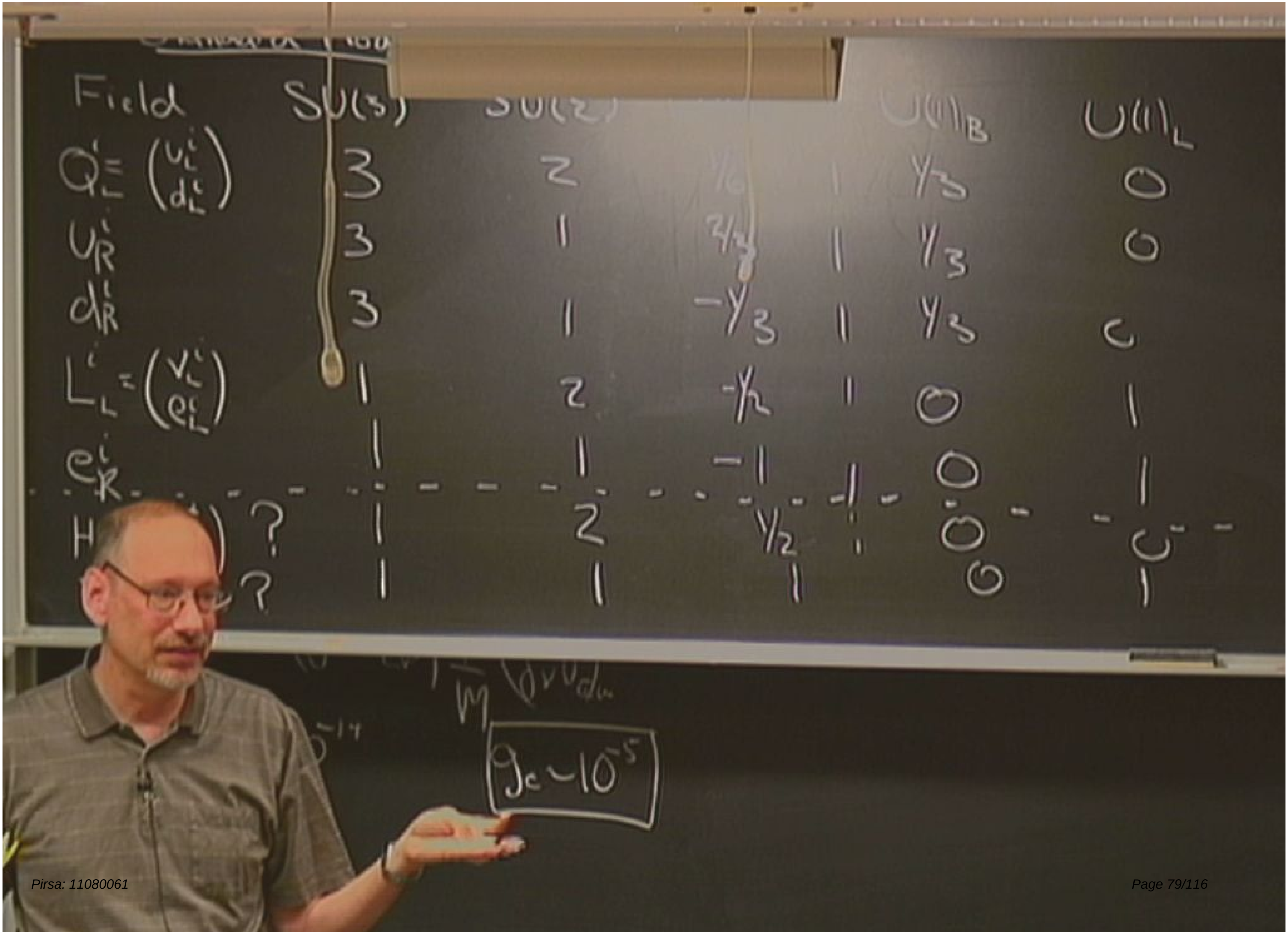

① B, L anomalies so how can you get th
U(1)B, U(1)L → SB SL
② Sp Broken
P → π0e+, π0e+νν̄, π+e+
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
thats it
Cerrone & Murayama
Phys. Rev D52 484 (1995)
Fileviez Perez & W
Phys Rev D82, 011901 (2010)

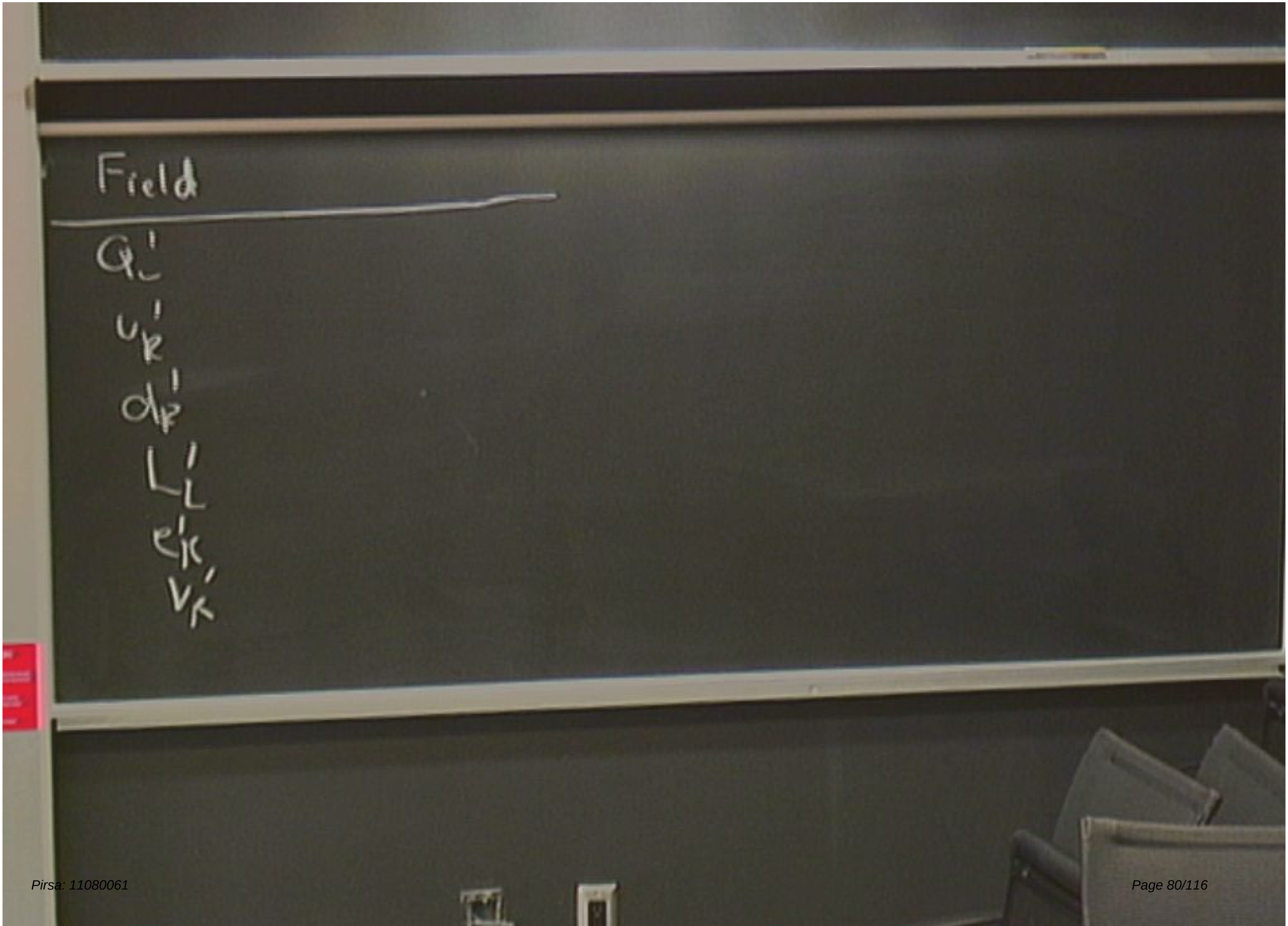

① B, L anomalous so how can you gauge them
U(1)B, U(1)L → SB SL
② Sp Broken
P → π°e⁺, π°e⁺νν̄, π⁺e⁺νν . . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
that's it
Carone + Murayama
Phys. Rev D52 484 (1995)
Fileviez Perez + W
Phys Rev D82, 011901 (2010)

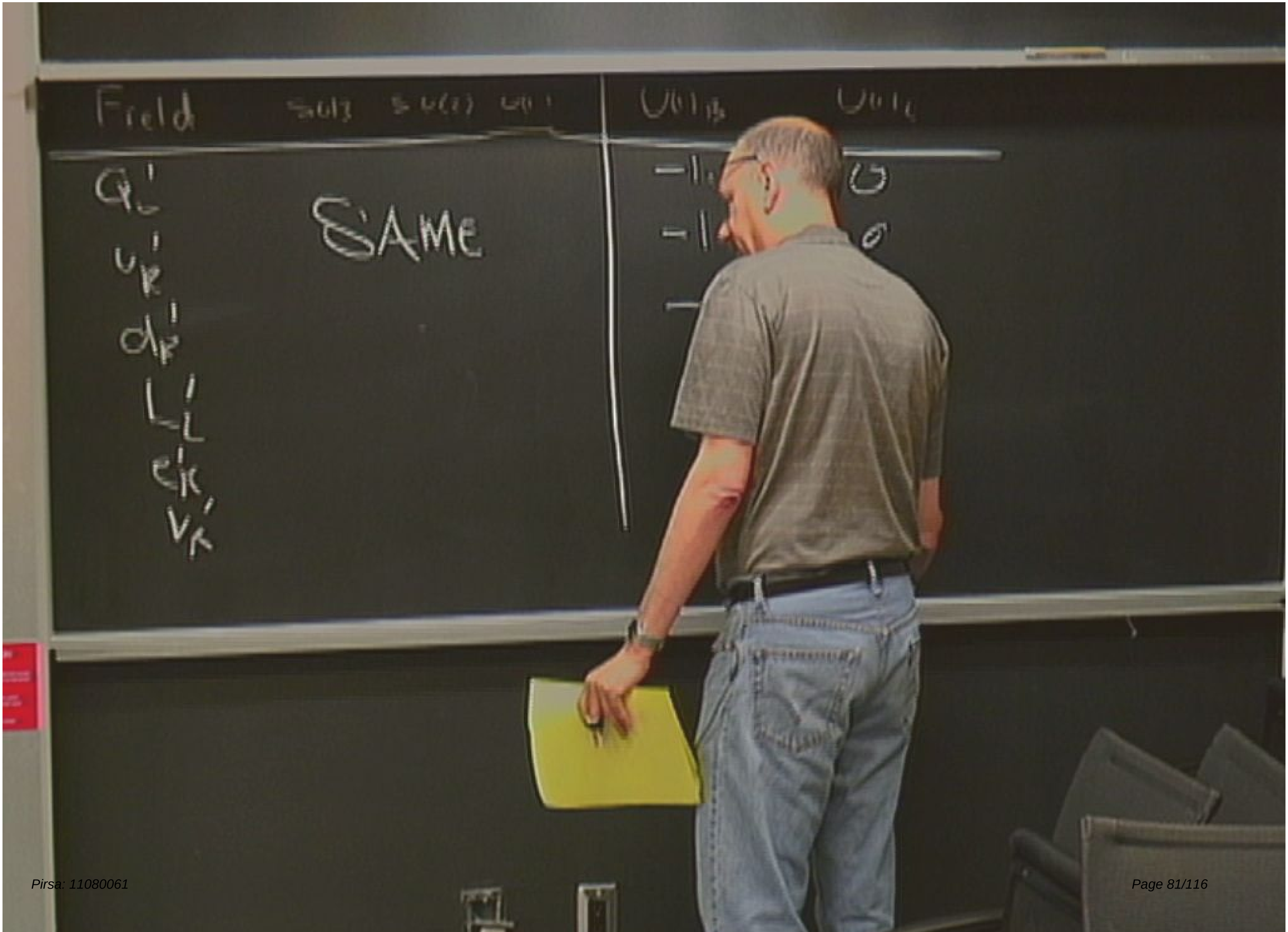


① B, L anomalies
U(1)B, U(1)L
SB SL
② Sp Broken
P → π0e+, π0e+νν̄, π+e+νν . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
thats it
Phys. Rev D52 484 (1995)
Fileviez Perez & W
Phys Rev D82, 011901 (2010)
Erratum D82 (2010) 079901


① B, L anomalies so how can you get rid
U(1)B, U(1)L → SB SL
② Sp Broken
P → π°e+, π°e+νν̄, π+e+νν . . . .
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
thats it
Carone + Murayama
Phys. Rev D52 484 (1995)
Fileviez Perez + W
Phys Rev D82, 011901 (2010)
Erratum D82 (2010) 079901


Field
SU(3)
SU(2)
U(1)B
U(1)L
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$ 3 2 1/3 0
u_R^i 3 1 2/3 1/3 0
d_R^i 3 1 −1/3 1/3 0
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$ 1 2 −1/2 0 1
e_R^i 1 1 −1 0 1
H ? 1 2 1/2 0 0
? 1 1 1 0 1
$g_e \sim 10^{-5}$


Field
Q'_L
u'_R
d'_R
L'_L
e'_R
ν'_R


Field
SAME

d_R' | 0 | −3

L_L' | 0 | −3

e_R', ν_R' | 0 | −3

① B, L anomalies so how can you gauge them

$U(1)_B$, $U(1)_L$ ⟶ S_B S_L

② S_p Broken

$p \to \pi^0 e^+$, $\pi^0 e^+ \nu \bar{\nu}$, $\pi^+ e^+ \nu \nu$ . . . .

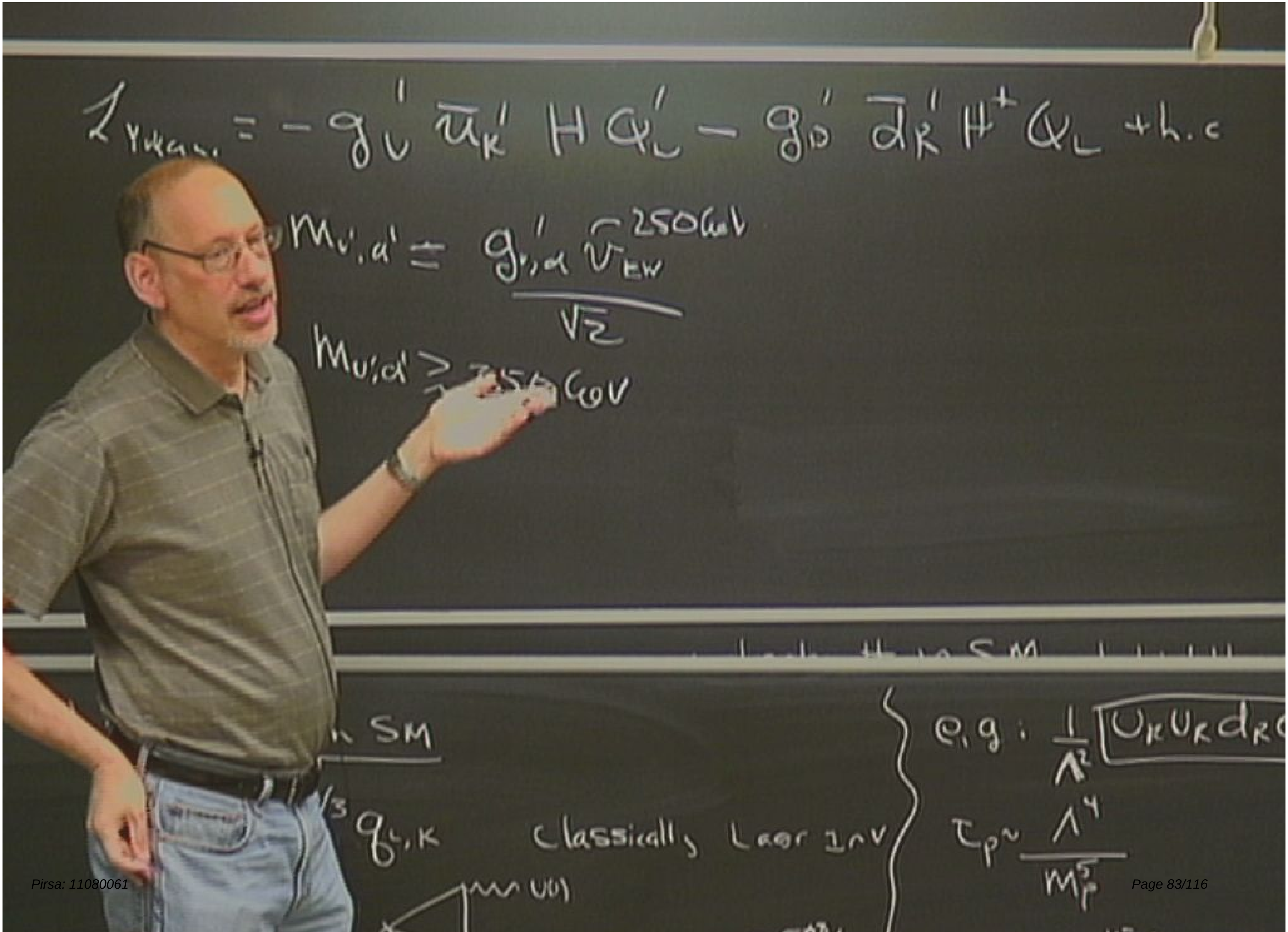
$|\Delta B| = 1$

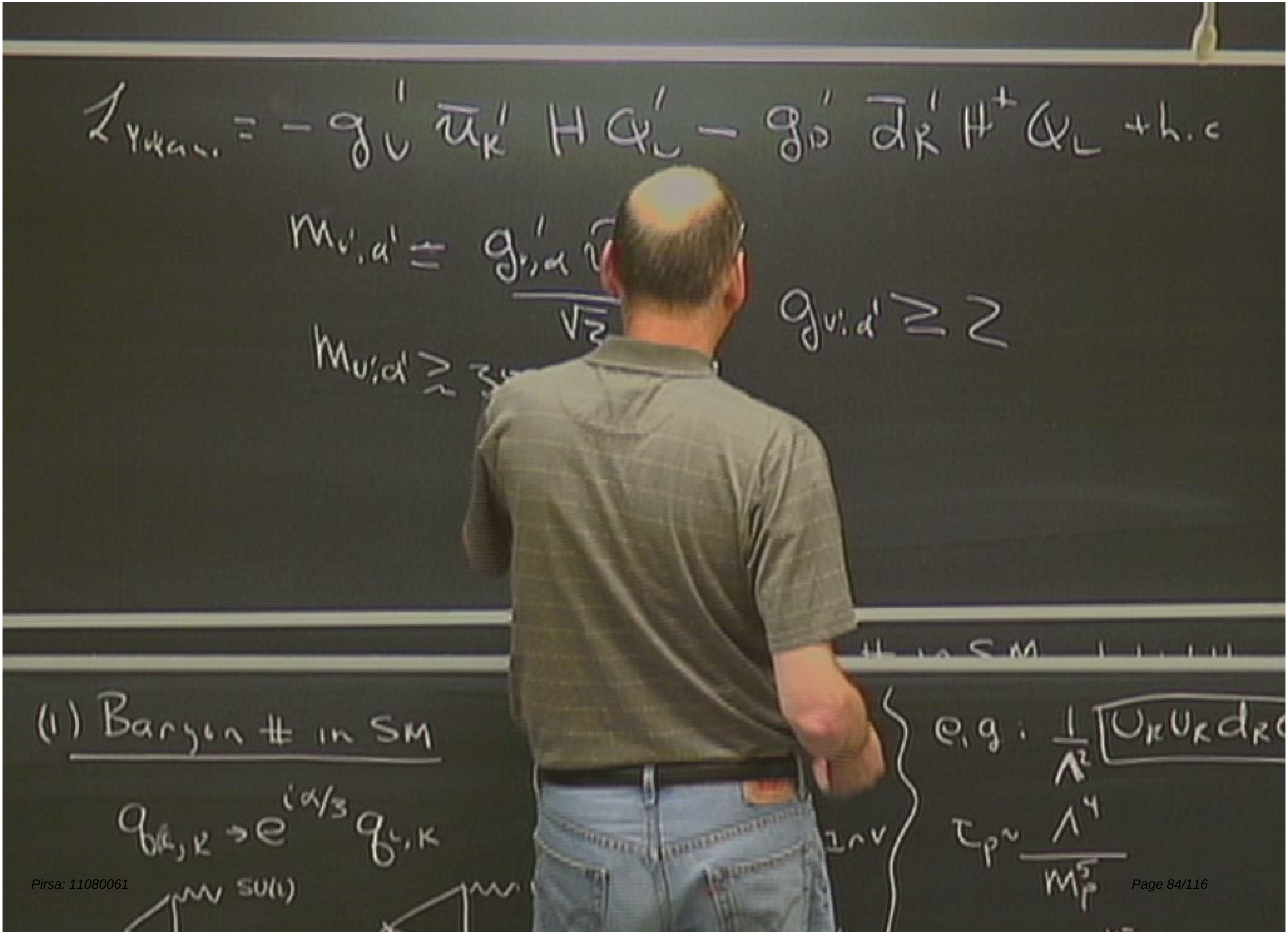
$|\Delta L| = 1, 3, 5 \ldots$

③ Cosmology

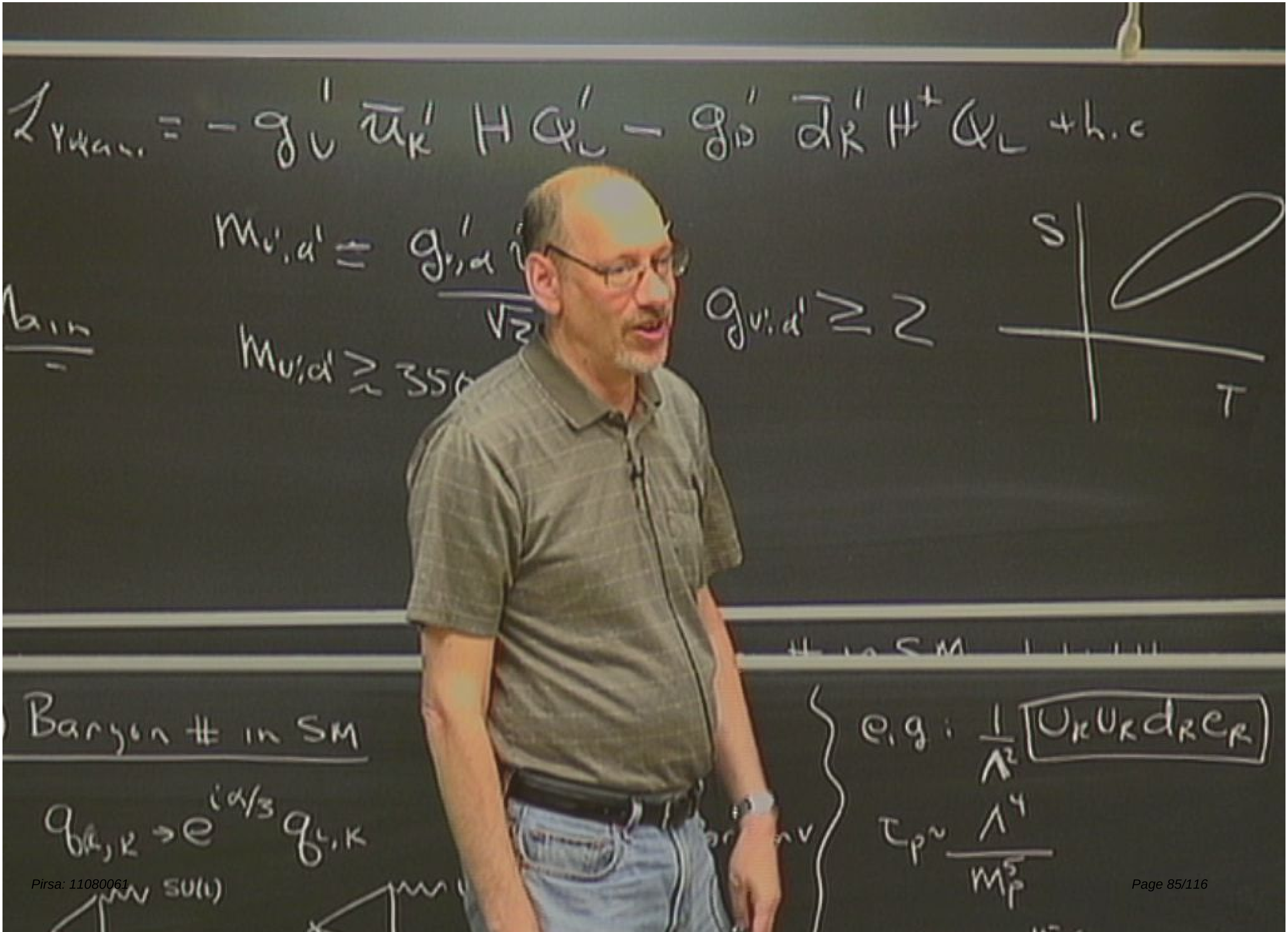
Carone + Murayama
Phys. Rev D52 484 (199[illegible]

Fileviez Perez + W
Phys Rev D82, 011901 (20[illegible]
Erratum D82 (2010) 079901

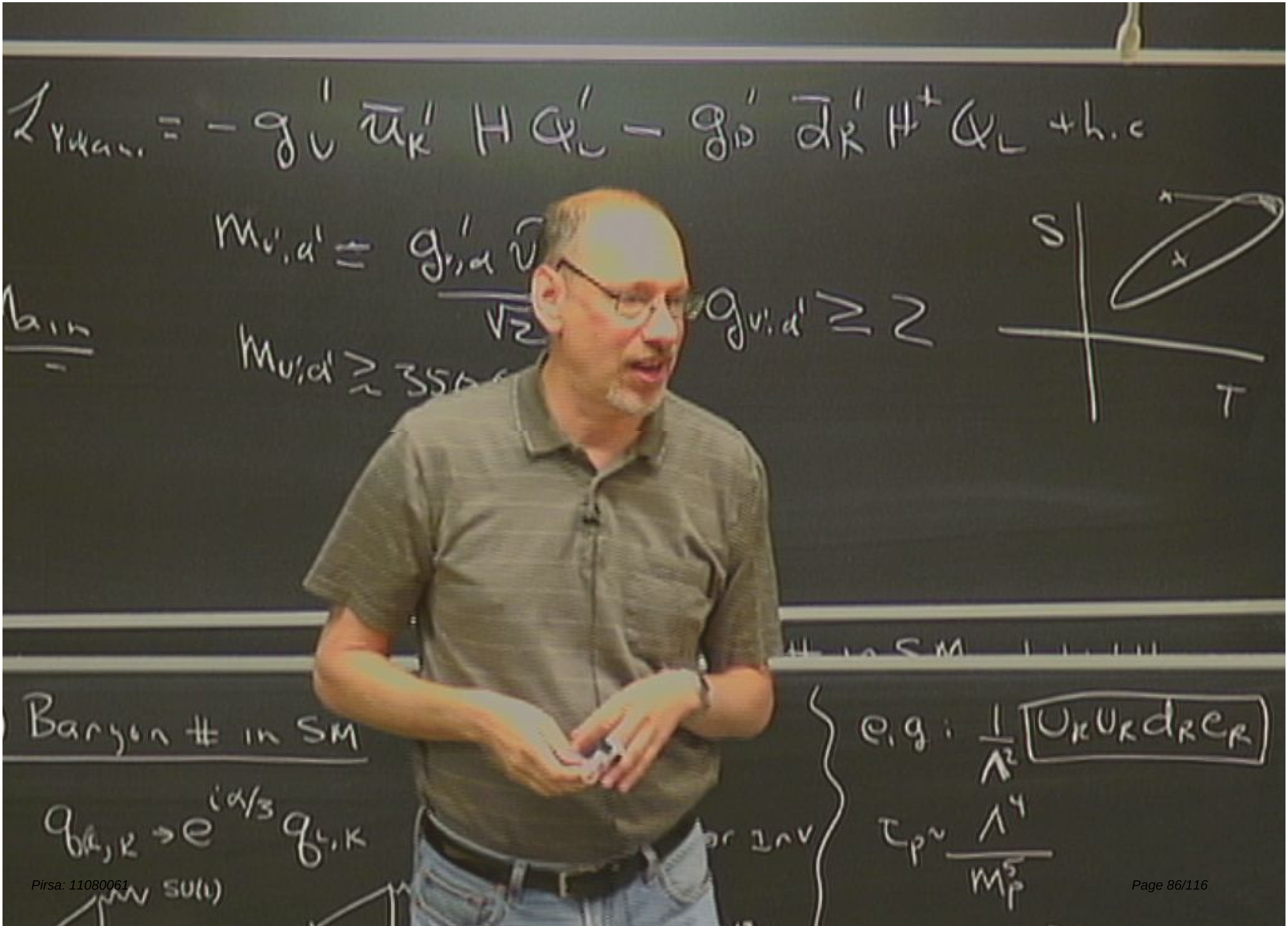

L_Yukawa = − g_U' ū_R' H Q_L' − g_D' d̄_R' H^+ Q_L + h.c
m_u',d' ≐ g_u,d v_EW / √2 ~250 GeV
m_u',d' ≳ 250 GeV
SM
classically Lepr Inv
e.g: 1/Λ² U_R U_R d_R
τ_p ~ Λ⁴ / m_p⁵
U(1)

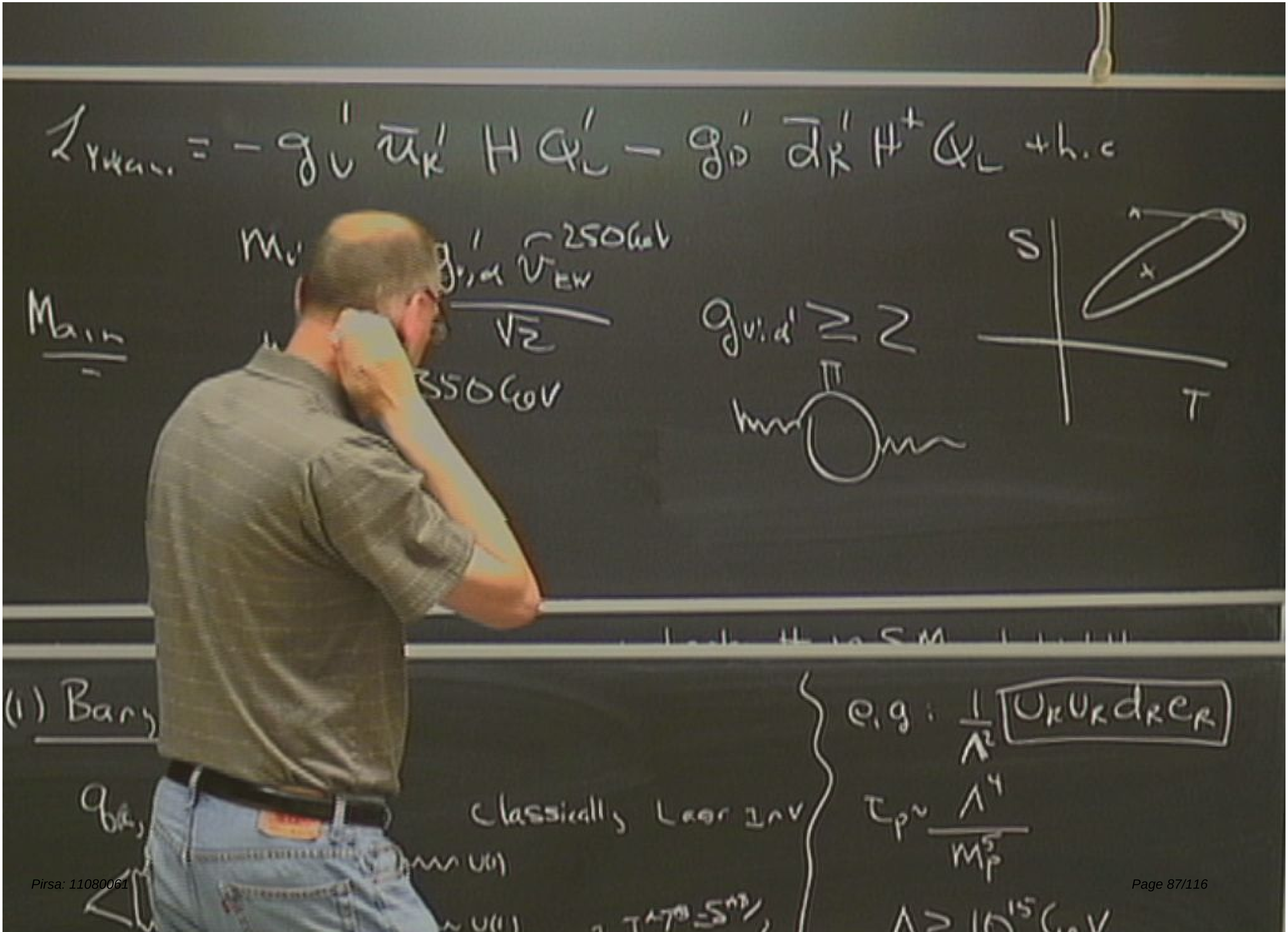


(1) Baryon # in SM
e.g.



L_Yukawa = − g_U' ū_R' H Q_L' − g_D' d̄_R' H^+ Q_L + h.c
m_u',d' = g_u',d' ... / √2
g_u',d' ≥ 2
m_u',d' ≳ 350
S
T
Baryon # in SM
q_R,L → e^(iα/3) q_L,R
SU(1)
e.g.: 1/Λ² u_R u_R d_R e_R
τ_p ~ Λ⁴ / m_p⁵


$\mathcal{L}_{Yukawa} = -g_U' \bar{u}_R' H Q_L' - g_D' \bar{d}_R' H^+ Q_L + h.c$
$m_{u',d'} = g_{u',d'} \frac{v}{\sqrt{2}}$
$g_{u',d'} \geq 2$
$m_{u',d'} \gtrsim 350$
S
T
Baryon # in SM
e.g: $\frac{1}{\Lambda^2}$ $u_R u_R d_R e_R$
$\tau_p \sim \frac{\Lambda^4}{m_p^5}$
SU(1)


L_Yukawa = − g_U' ū_R' H Q_L' − g_D' d̄_R' H^+ Q_L + h.c
Main
250 GeV
v_EW
√2
350 GeV
g_U,d' ≥ 2
S
T
(1) Bary
e.g.: 1/Λ² U_R U_R d_R e_R
τ_p ~ Λ⁴/m_p⁵

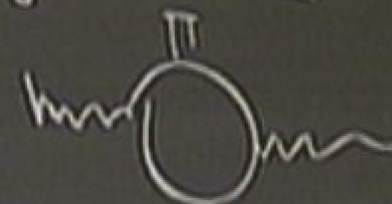
$$\mathcal{L}_{Yukawa} = -g_U' \, \bar{u}_R' \, H \, Q_L' - g_D' \, \bar{d}_R' \, H^+ \, Q_L + h.c.$$

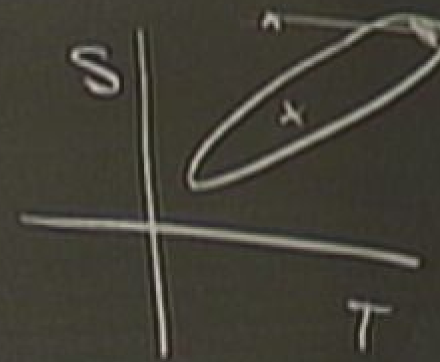
$$m_{u',d'} = \frac{g_{u,d}' \, v_{EW}}{\sqrt{2}} \qquad (v_{EW} \sim 250\,\text{GeV})$$

Main

$$m_{u',d'} \gtrsim 350\,\text{GeV}$$

$$g_{u',d'} \gtrsim 2$$





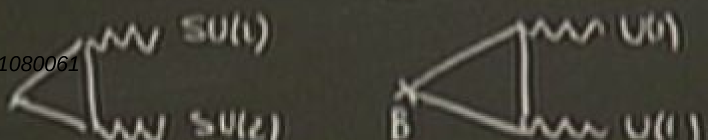
(1) Baryon # in SM

$$q_{R,L} \to e^{i\alpha/3} q_{L,R} \qquad \text{Classically Lagr Inv}$$

e.g.: $\frac{1}{\Lambda^2}$ $\boxed{u_R u_R d_R e_R}$

$$\tau_p \sim \frac{\Lambda^4}{m_p^5}$$

$$\Lambda \gtrsim 10^{15}\,\text{GeV}$$



d_R'

L_L' | 0 | −3

e_R' | 0 | −3

ν_R' | 0 | −3

Or Mirror

① B, L anomalous so how can you gauge them

$U(1)_B$, $U(1)_L$ ⟶ S_B S_L

② S_p Broken

$p \to \pi^0 e^+$, $\pi^0 e^+ \nu\bar{\nu}$, $\pi^+ e^+ \nu\nu$ . . . .

$|\Delta B| = 1$

$|\Delta L| = 1, 3, 5 \ldots$

③ Cosmology

thats it

Cerrone + Murayama
Phys. Rev D52 484 (1995)

Fileviez Perez + W
Phys Rev D82, 011901 (2010)
Erratum D82 (2010) 079901

d_R' | | 0 | −3
L_L' | | 0 | −3
e_R' | | 0 | −3
ν_R'

Or Mirror

① B, L anomalies so how can you gauge them

$U(1)_B$, $U(1)_L$ → S_B S_L

② Sp Broken

$p \to \pi^0 e^+$, $\pi^0 e^+ \nu \bar{\nu}$, $\pi^+ e^+ \nu \nu$ . . . .

$|\Delta B| = 1$

$|\Delta L| = 1, 3, 5 \ldots$

③ Cosmology

that's it

Carone + Murayama
Phys. Rev D52 484 (1995)

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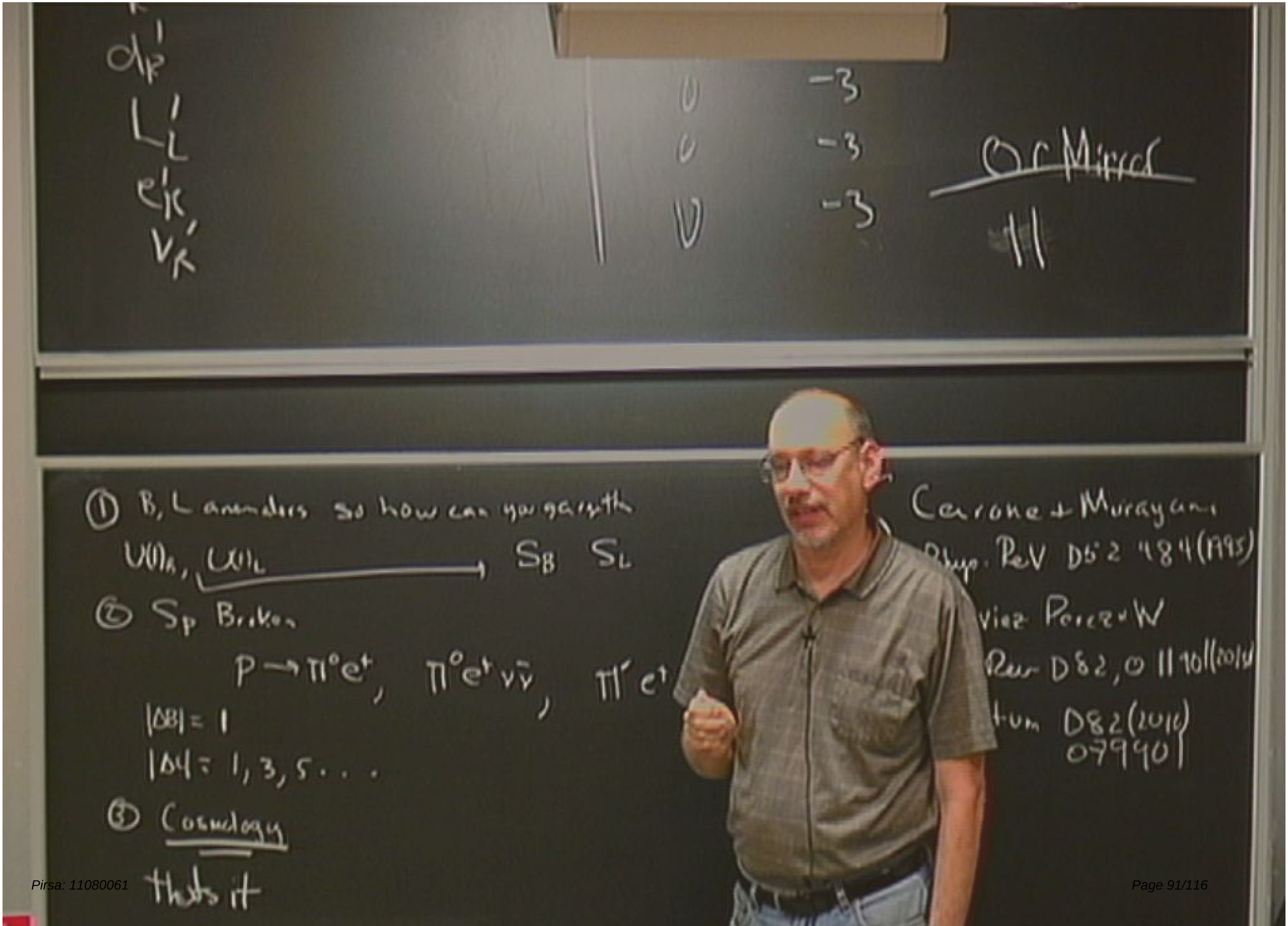
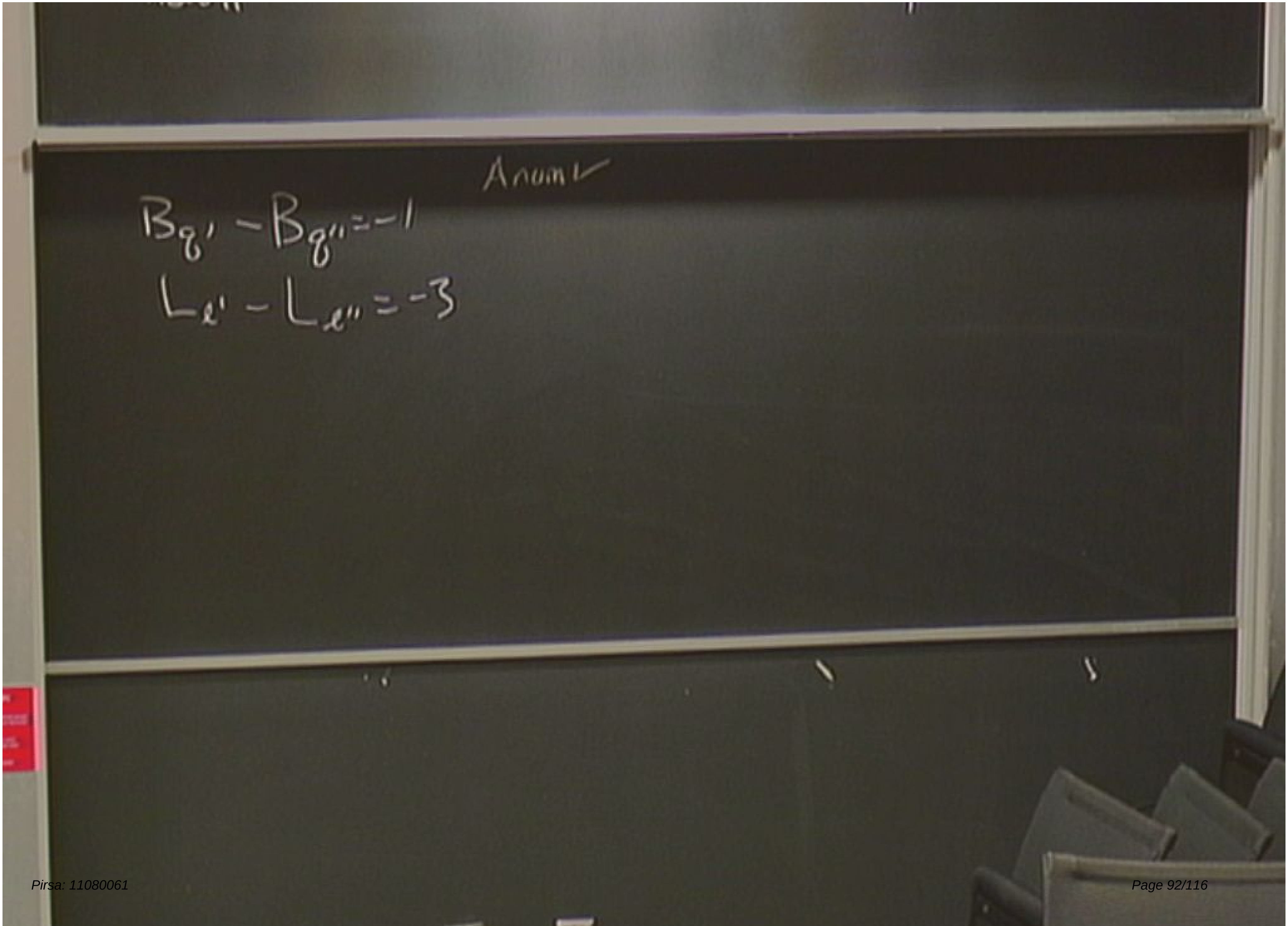
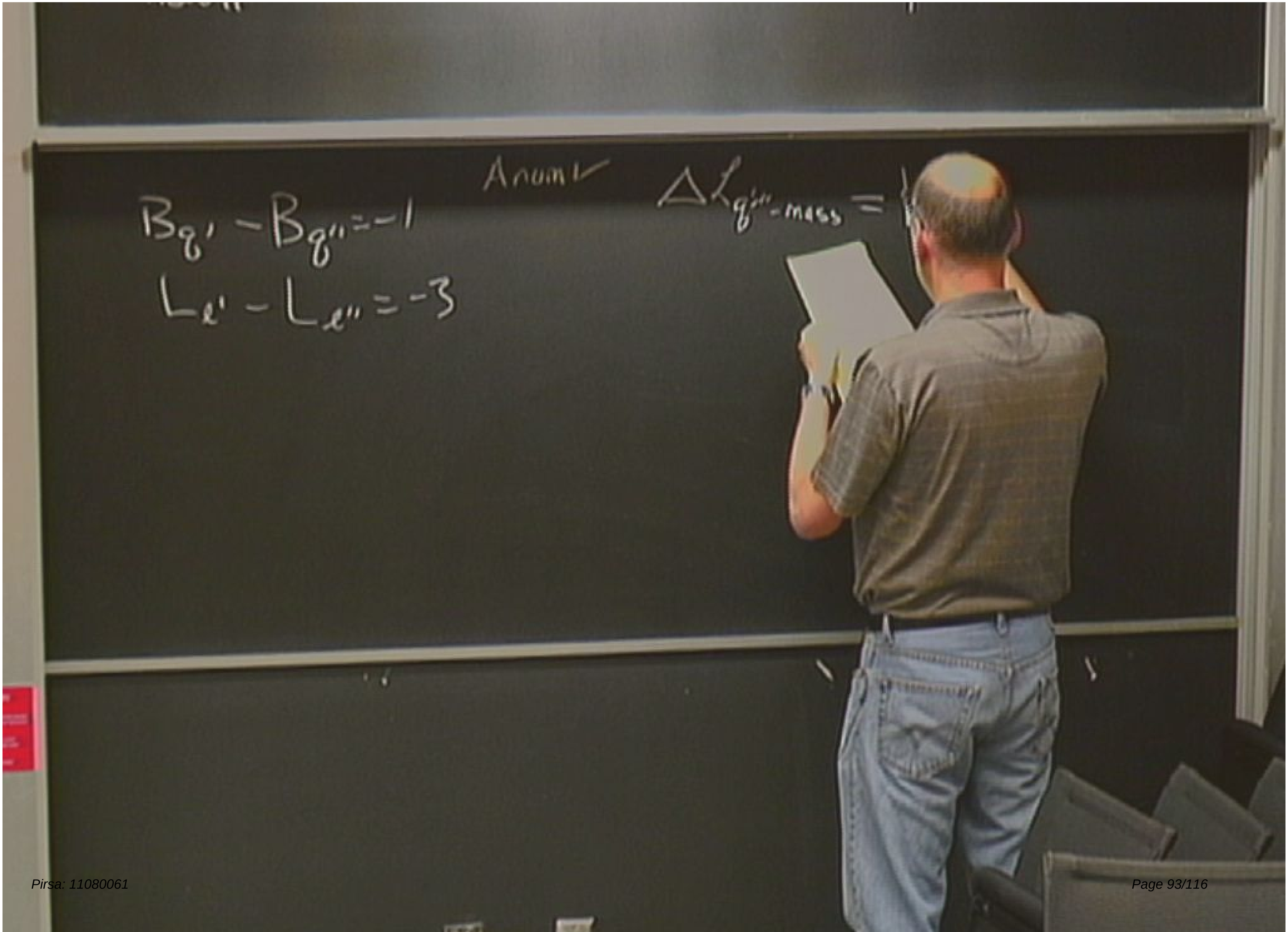
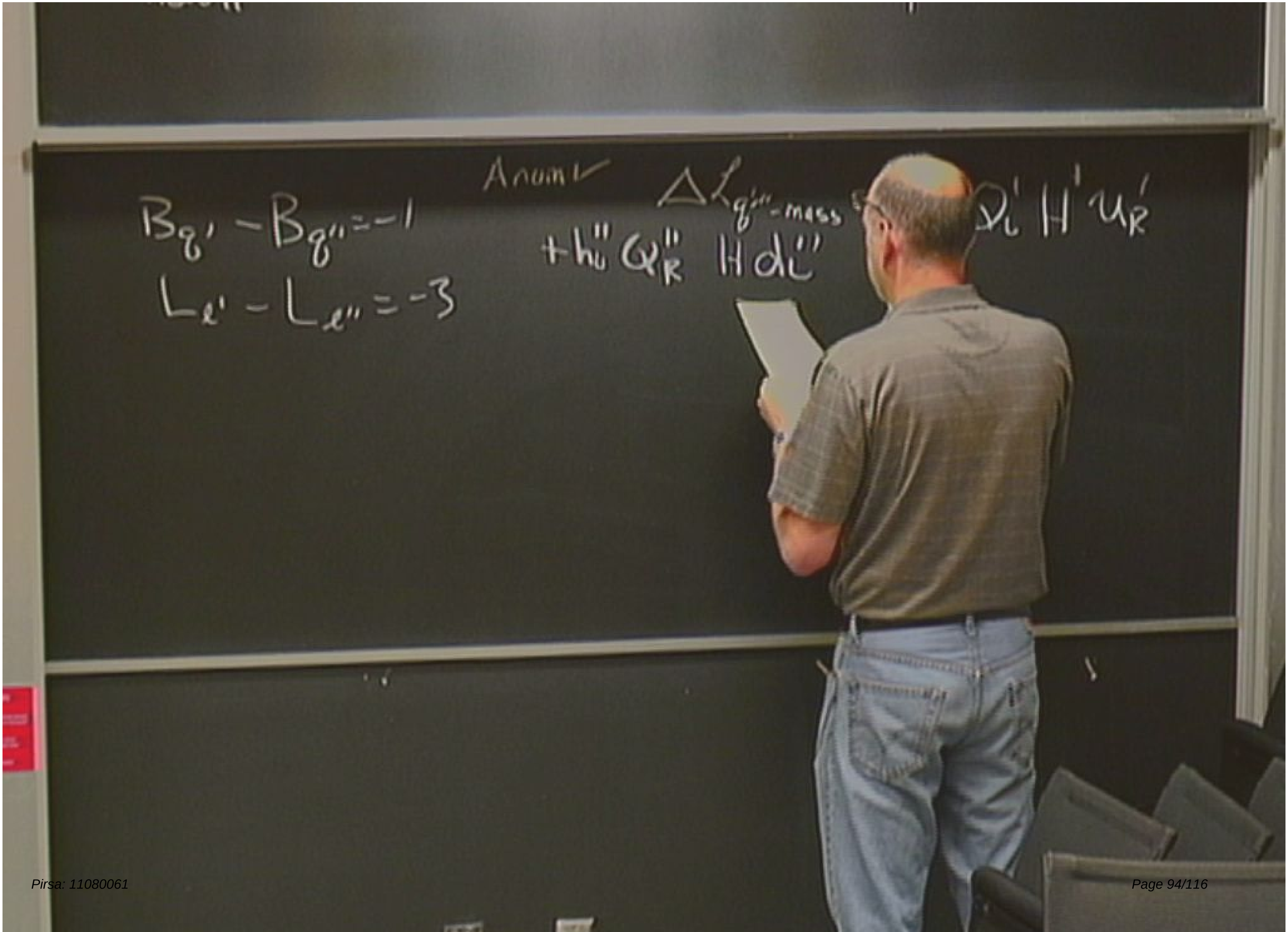
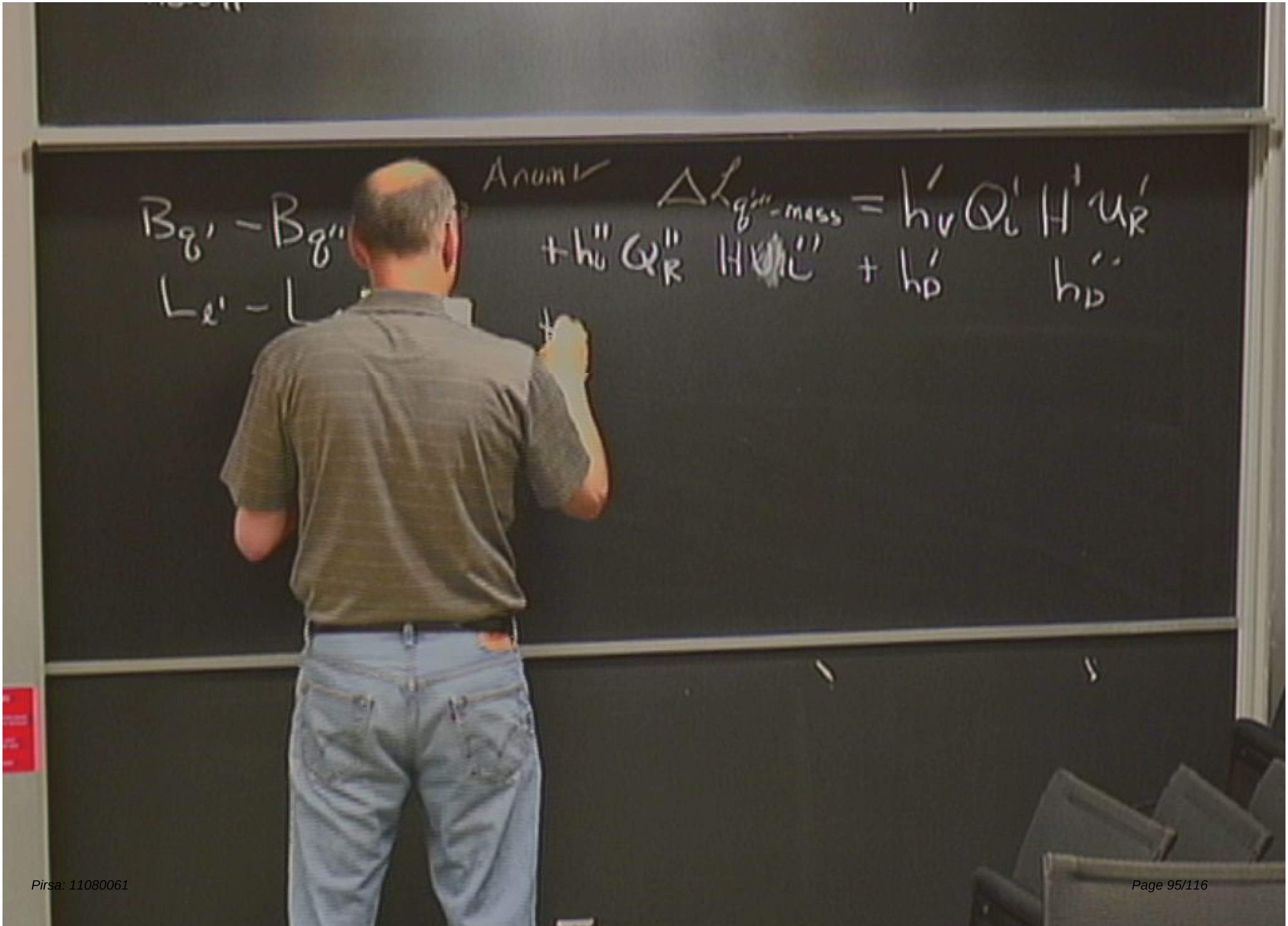
Phys Rev D82, 011901 (2010)
Erratum D82 (2010) 079901

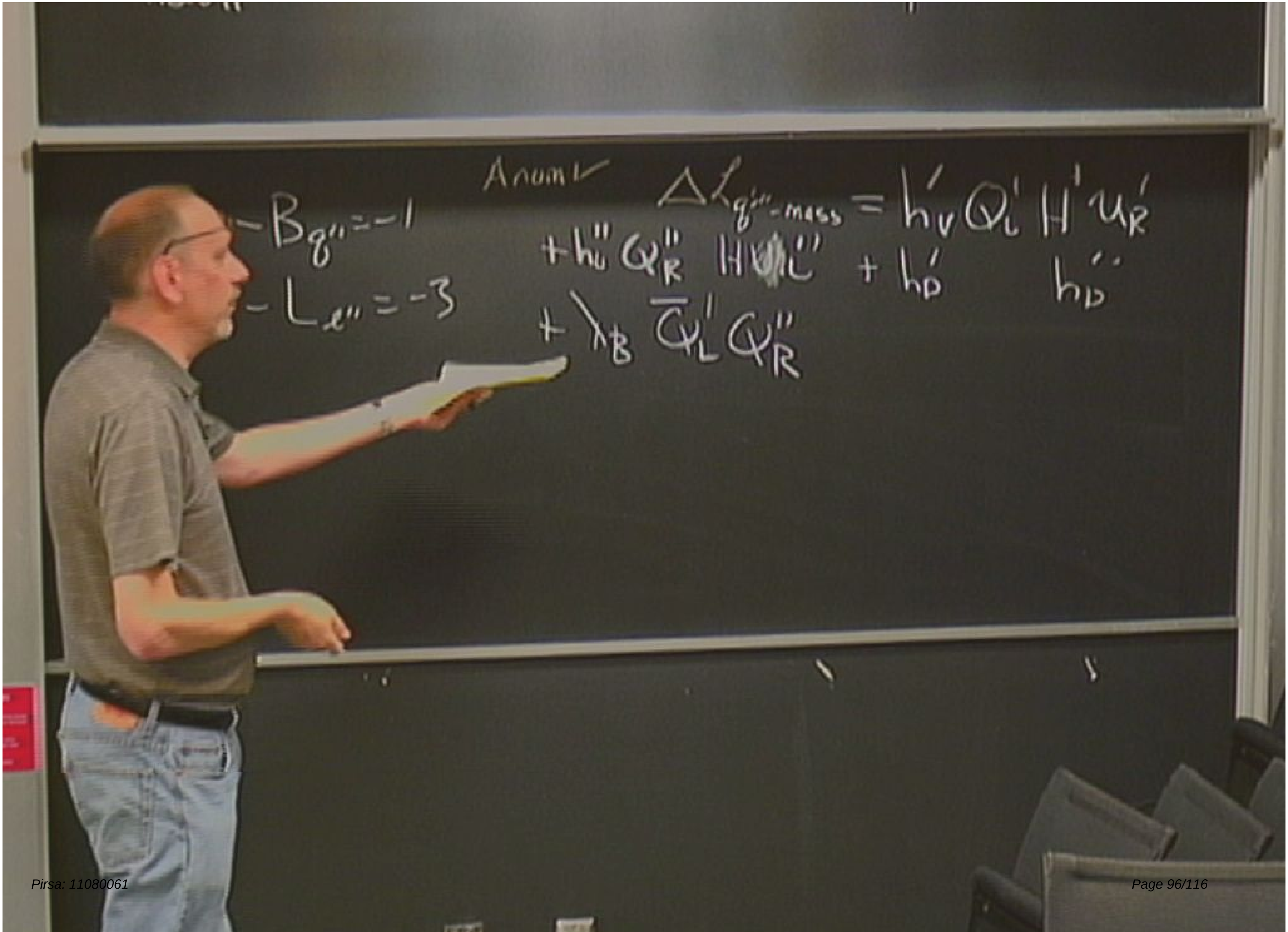

Or Mirror
① B, L anomalies so how can you get the
U(1)B, U(1)L → SB SL
② Sp Broken
p → π°e⁺, π°e⁺νν̄, π⁺e⁺
|ΔB| = 1
|ΔL| = 1, 3, 5 . . .
③ Cosmology
thats it
Carone + Murayama
Phys. Rev D52 484 (1995)
Perez + W
D82, 011901 (2010)
D82 (2010) 079901

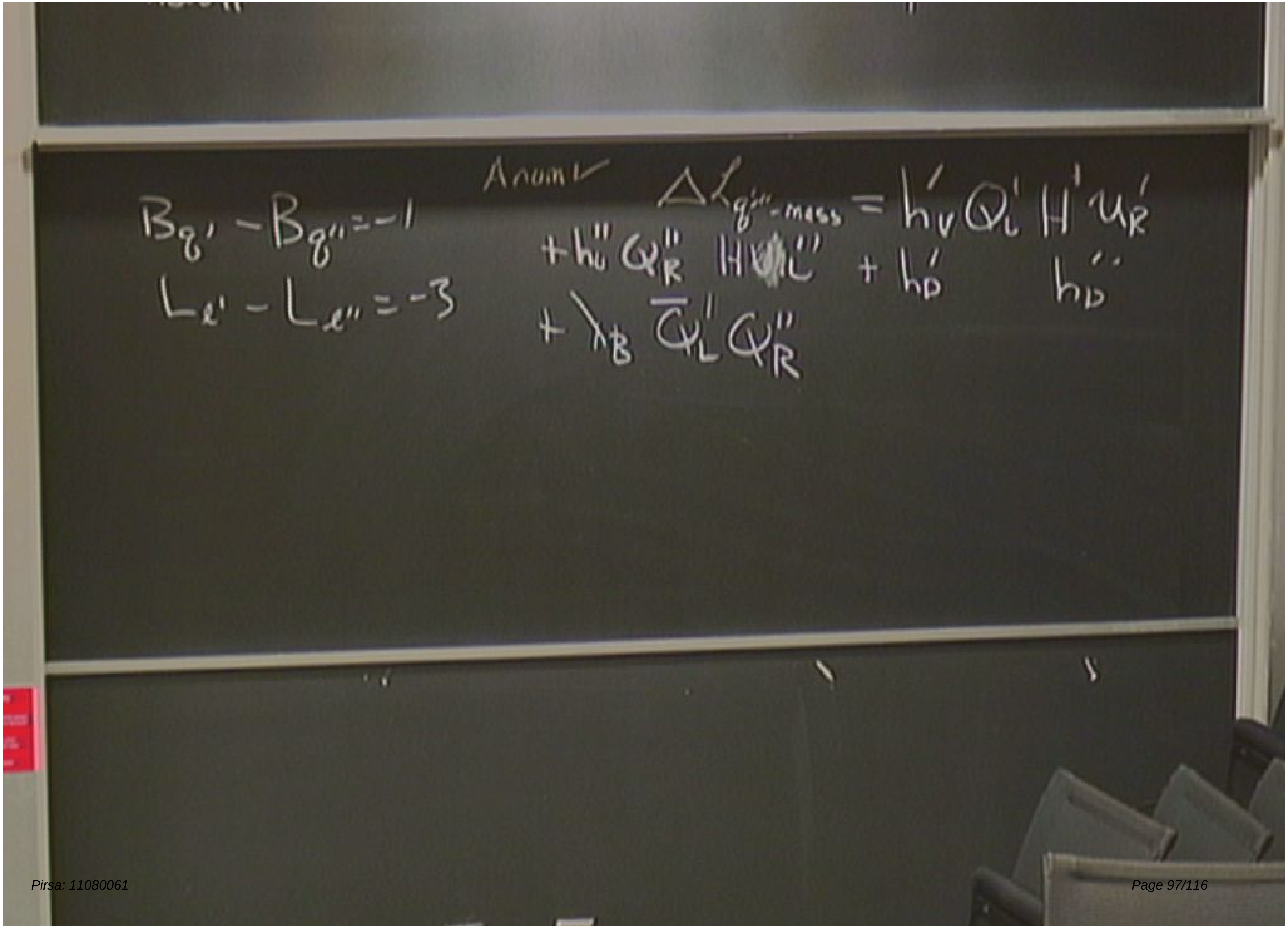

Anom ✓
Bq' − Bq'' = −1
Lℓ' − Lℓ'' = −3

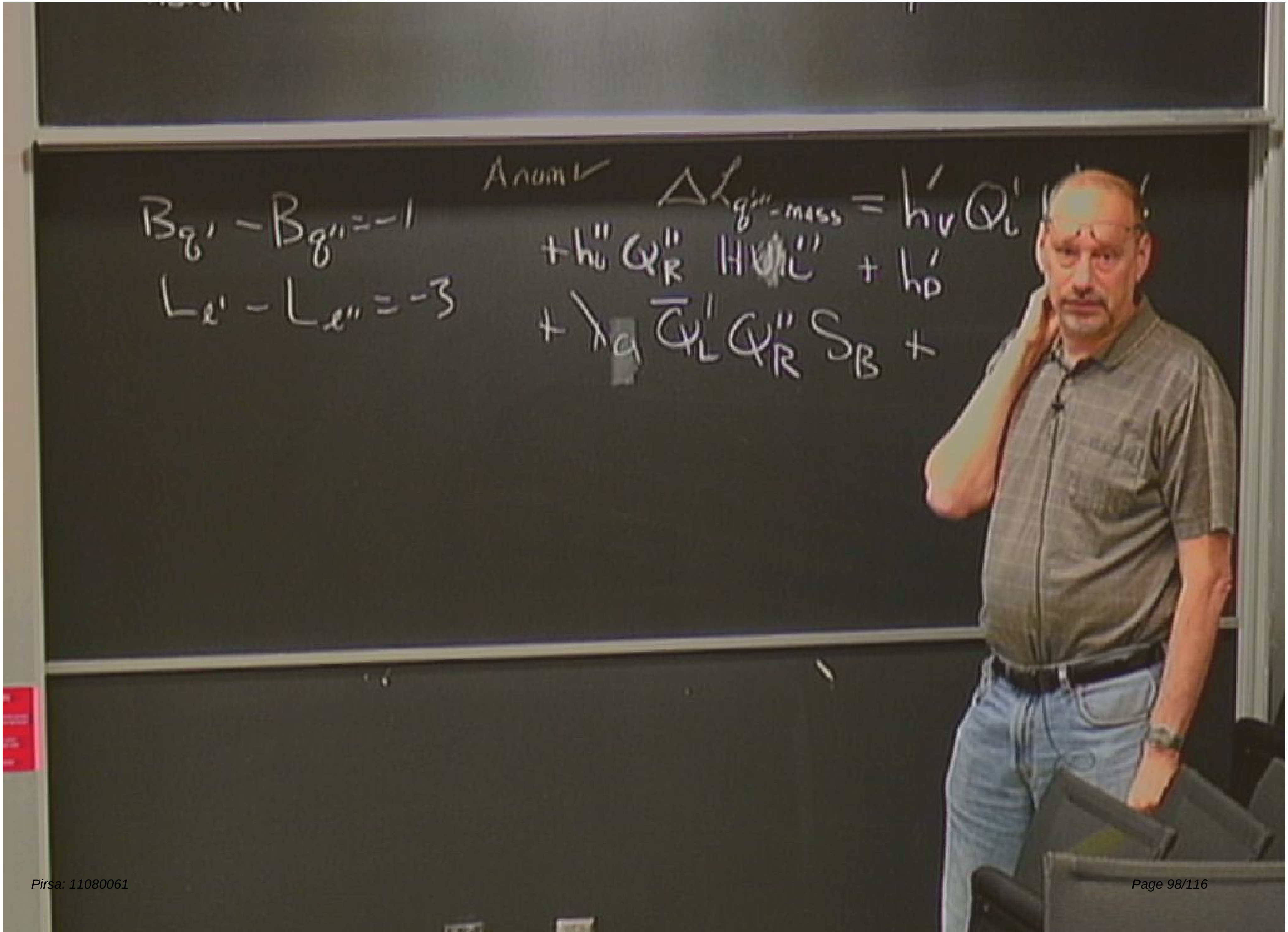

Anom ✓
$\Delta \mathcal{L}_{q'q''\text{-mass}} =$
$B_{q'} - B_{q''} = -1$
$L_{\ell'} - L_{\ell''} = -3$


Anom ✓
B_q' − B_q'' = −1
L_ℓ' − L_ℓ'' = −3
ΔL_q''-mass
Q_L' H' u_R'
+ h_u'' Q_R'' H d_L''


Anom ✓
B_q' − B_q''
L_l' − L
ΔL_q''-mass = h'_u Q'_L H' u'_R
+ h''_u Q''_R H ... L'' + h'_D h''_D


Anom ✓
-B_q'' = -1
-L_ℓ'' = -3
ΔL_q''-mass = h'_U Q'_L H' u'_R
+ h''_U Q''_R H L'' + h'_D h''_D
+ λ_B Q̄'_L Q''_R


Anom ✓
$B_{q'} - B_{q''} = -1$
$L_{\ell'} - L_{\ell''} = -3$
$\Delta \mathcal{L}_{q'q''\text{-mass}} = h'_U Q'_L H' u'_R$
$+ h''_U Q''_R H Q''_L + h'_D \quad h''_D$
$+ \lambda_B \bar{Q}'_L Q''_R$


Anom ✓
B_q' - B_q'' = -1
L_l' - L_l'' = -3
ΔL_q'''-mass = h'_U Q'_L
+ h''_U Q''_R + h'_D
+ λ_Q Q̄'_L Q''_R S_B +

Anom ✓

$B_{q'} - B_{q''} = -1$

$L_{\ell'} - L_{\ell''} = -3$

$$\Delta \mathcal{L}_{q'''\text{-mass}} = h'_U Q'_L H' u'_R + h''_U Q''_R H Q''_L + h'_D \quad h''_D + \lambda_Q \bar{Q}'_L Q''_R S_B +$$

Anom ✓

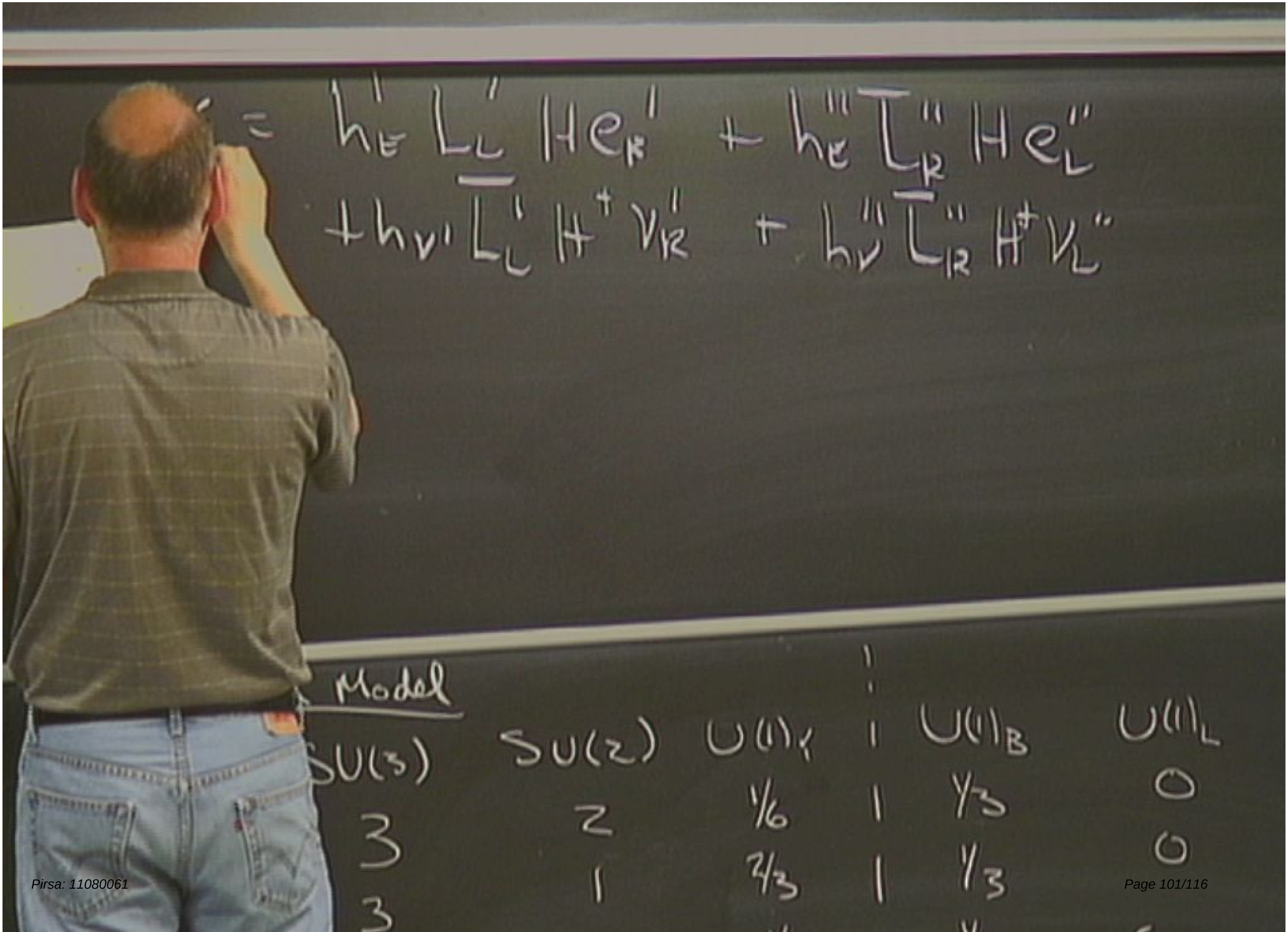
$B_{q'} - B_{q''} = -1$

$L_{\ell'} - L_{\ell''} = -3$

$$\Delta \mathcal{L}_{q'q''\text{-mass}} = h'_U Q'_L H' u'_R + h''_U Q''_R H u''_L + h'_D \quad h''_D$$

$$+ \lambda_Q \bar{Q}'_L Q''_R S_B + \lambda_U , \lambda_D$$

$$\langle S_B \rangle = v_B$$


= h_E' L_L' H e_R' + h_e'' L_R'' H e_L''
+ h_ν' L_L' H† ν_R' + h_ν'' L_R'' H† ν_L''
Model
SU(3) SU(2) U(1)_Y | U(1)_B U(1)_L
3 2 1/6 | 1/3 0
3 1 2/3 | 1/3 0
3

$$\Delta \mathcal{L}_{\substack{l', l'' \\ mass}} = h_E' \bar{L}_L' H e_R' + h_E'' \bar{L}_R'' H e_L'' + h_{\nu'} \bar{L}_L' H^\dagger \nu_R' + h_\nu'' \bar{L}_R'' H^\dagger \nu_L''$$

$$\Delta \mathcal{L}_{e.n} = g_E \bar{L}_L H e_R + g_\nu \bar{L}_L H^\dagger \nu_R + \lambda_{\nu_R} \nu_R \nu_R S_L$$

Standard Model

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6	1/3	0
u^i	3	1	2/3	1/3	0

$$\Delta \mathcal{L}_{\ell',\ell''\ \text{mass}} = h_E' \bar{L}_L' H e_R' + h_E'' \bar{L}_R'' H e_L''$$

$$+ h_{\nu'} \bar{L}_L' H^\dagger \nu_R' + h_\nu'' \bar{L}_R'' H^\dagger \nu_L''$$

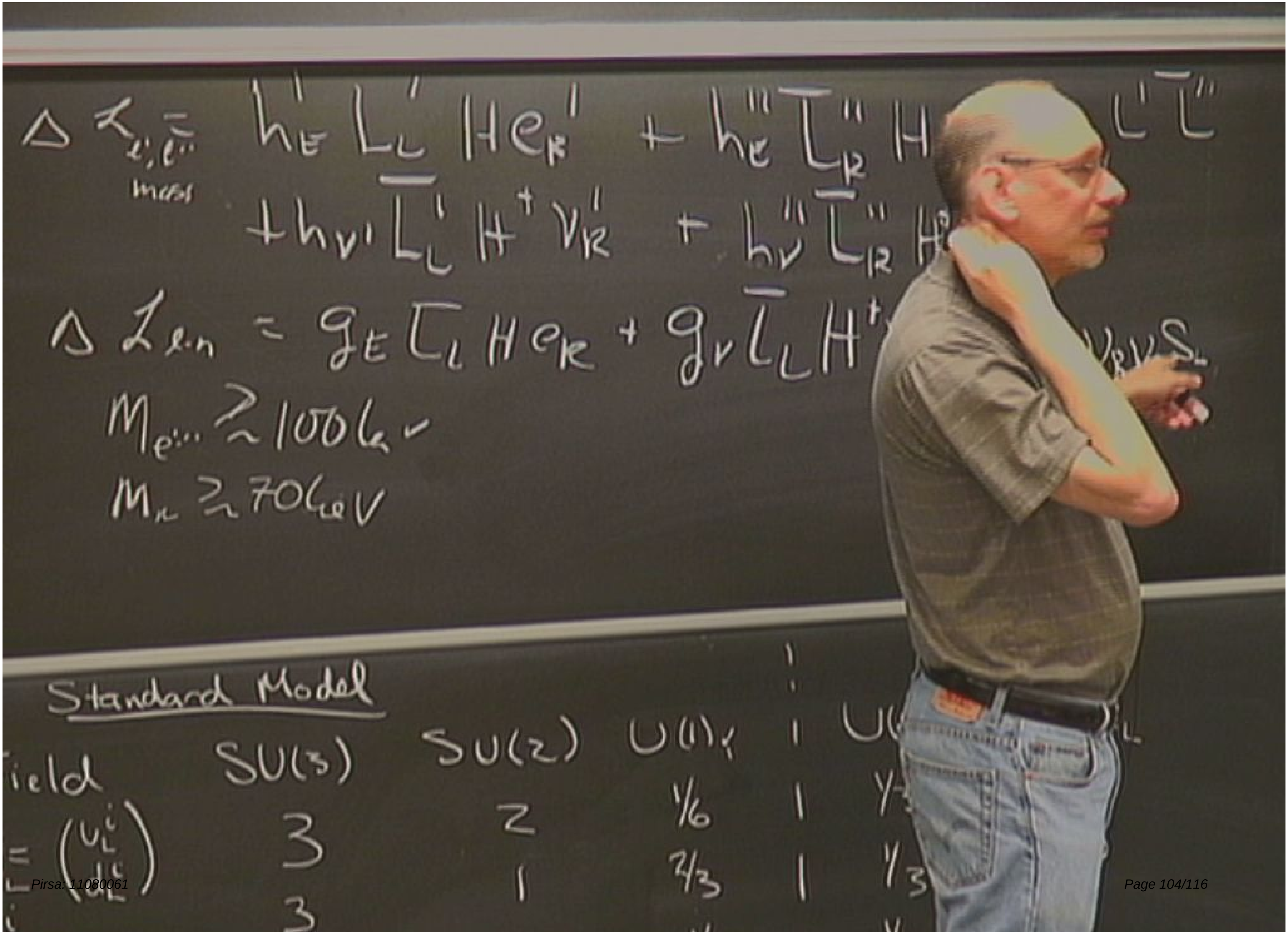
$$\Delta \mathcal{L}_{\ell.n} = g_E \bar{L}_L H e_R + g_\nu \bar{L}_L H^\dagger \nu_R + \lambda_{\nu_R} \nu_R \nu_R S_L$$

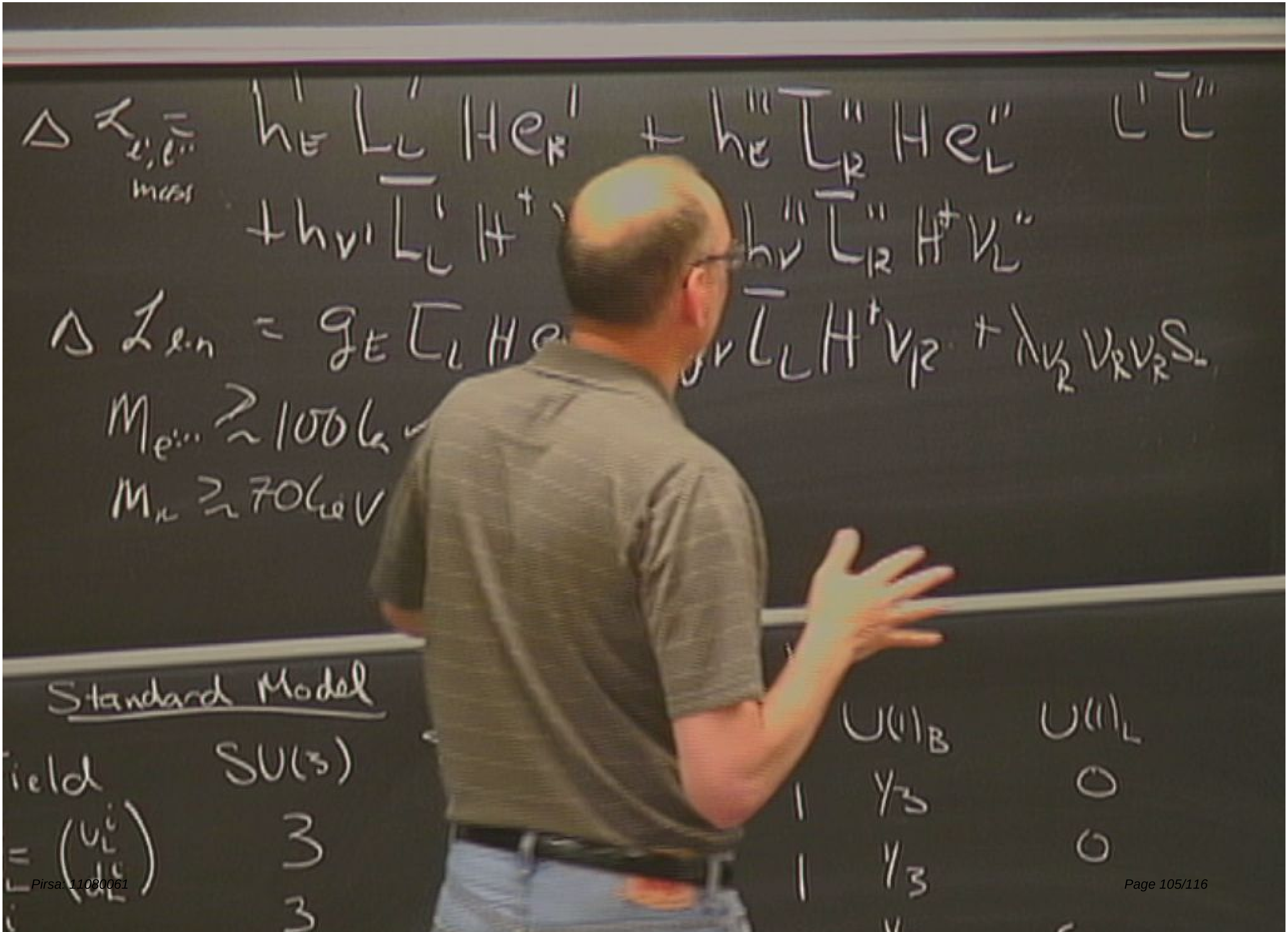
$M_{e'''} \gtrsim 100\,\text{GeV}$ ✓

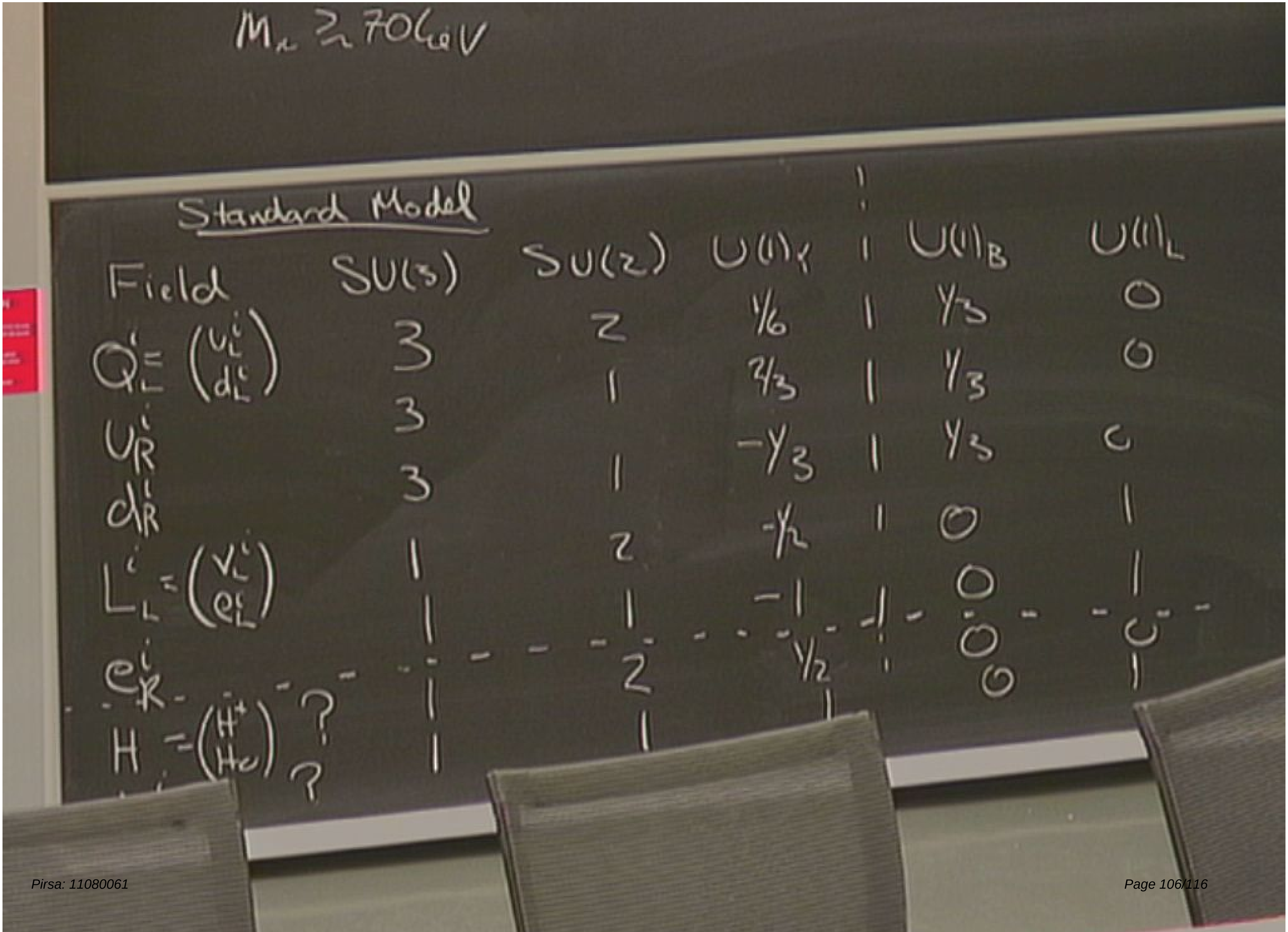
$M_\nu \gtrsim 70\,\text{GeV}$

Standard Model

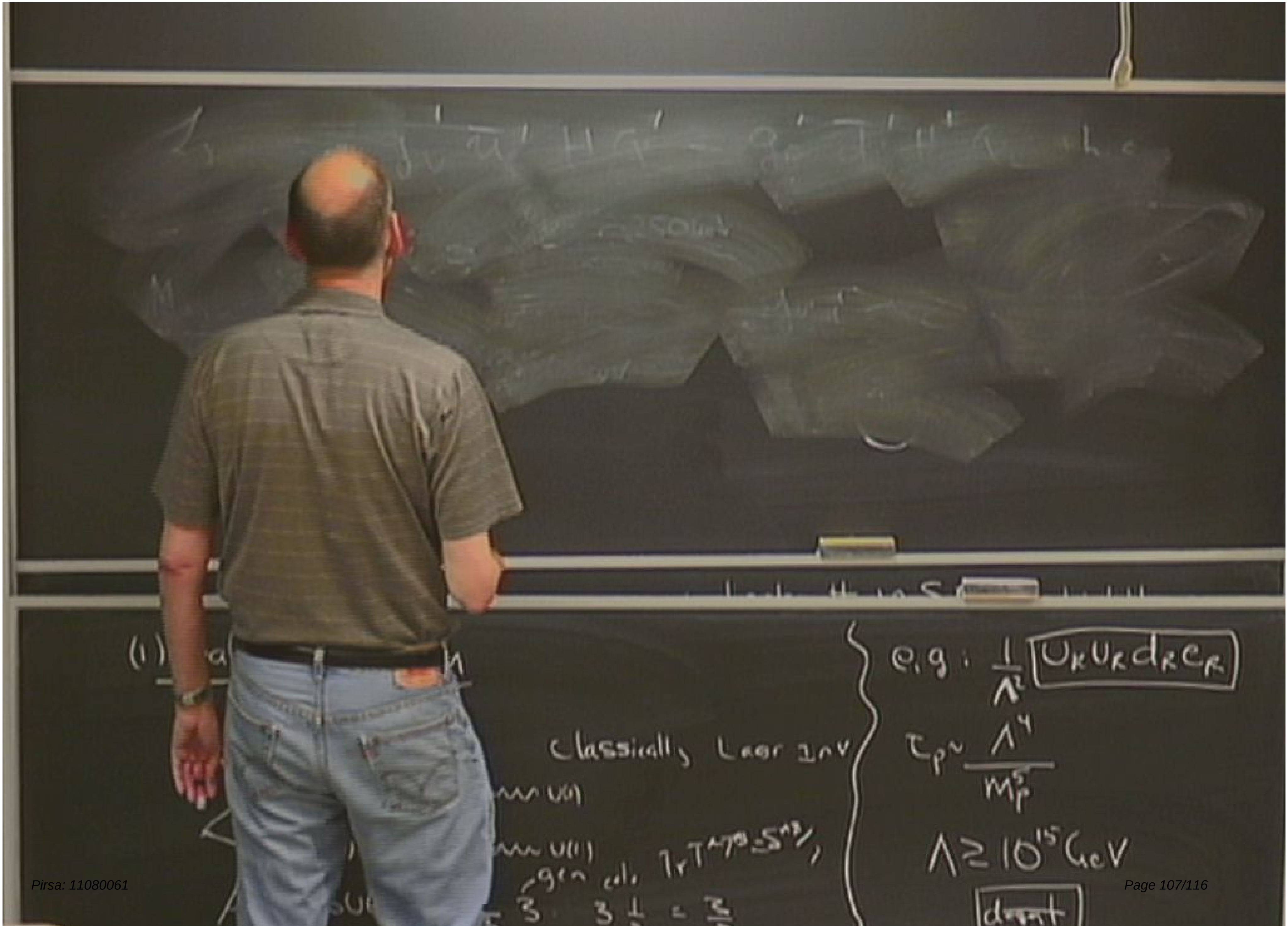
Field	SU(3)	SU(2)	$U(1)_Y$	$U(1)_B$	$U(1)_L$
$Q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6	1/3	0
u^i	3	1	2/3	1/3	0

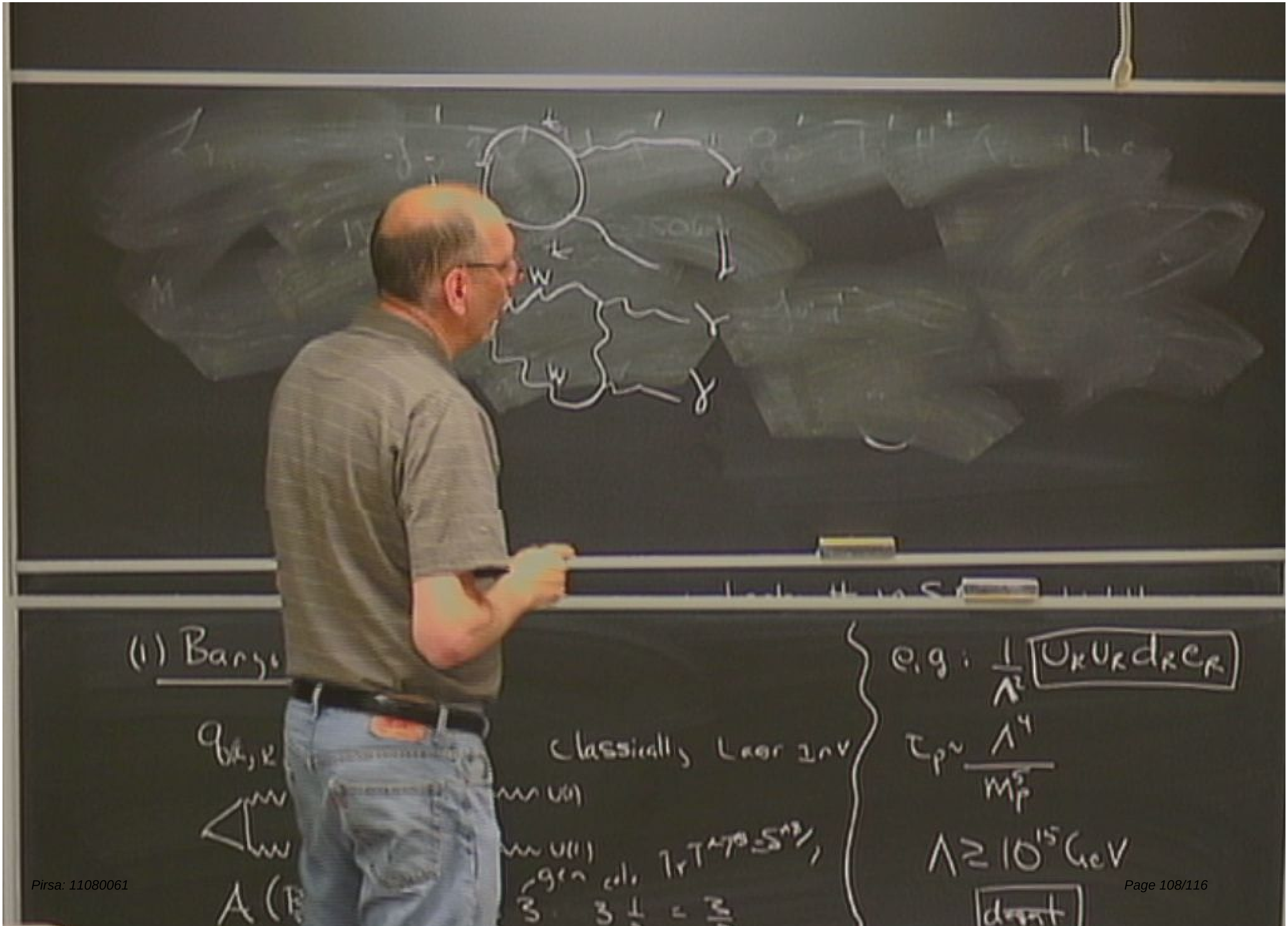

Standard Model
SU(3)
SU(2)
ield


Standard Model
Field
SU(3)
U(1)B
U(1)L
M ≳ 70 GeV

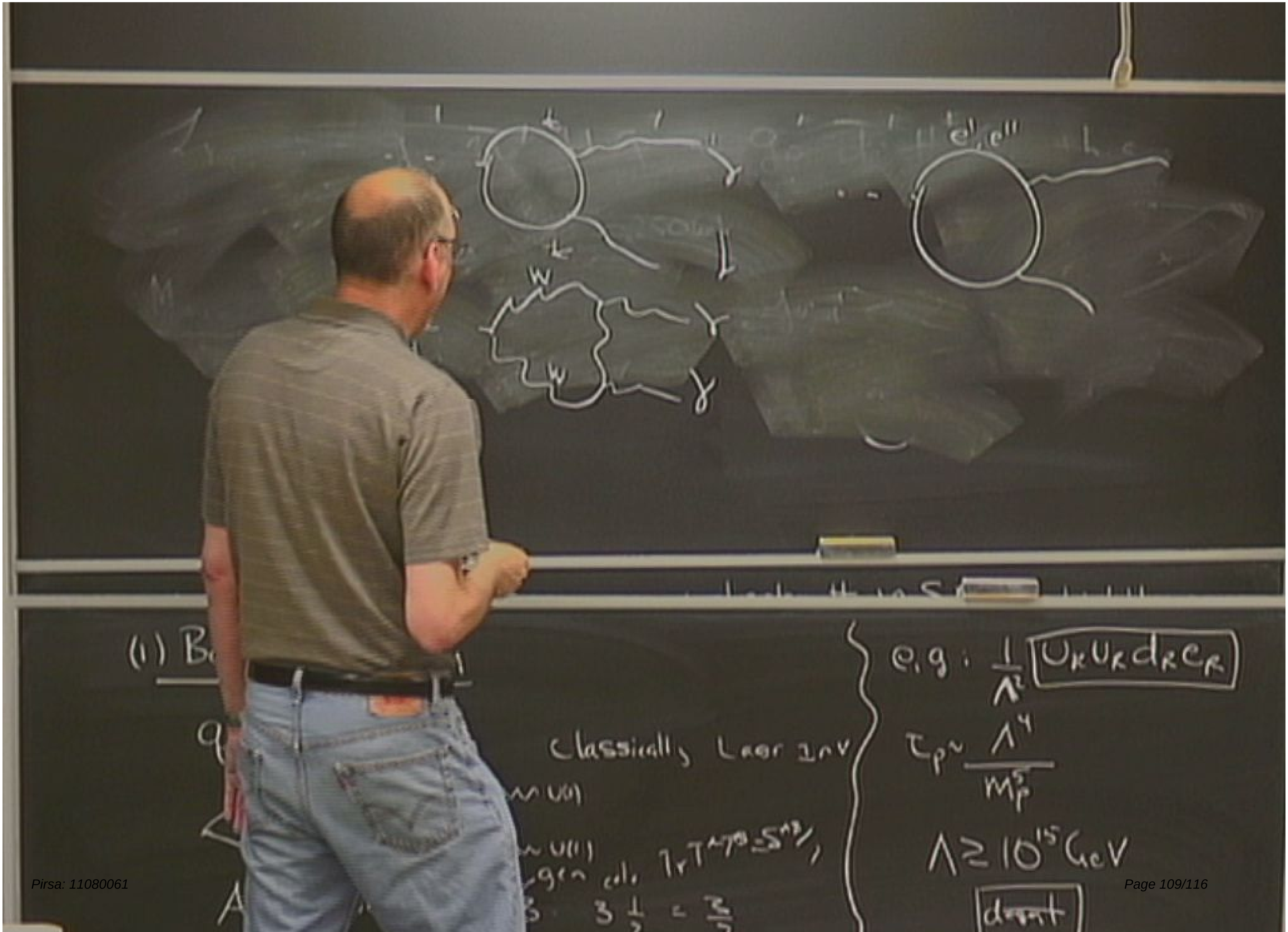


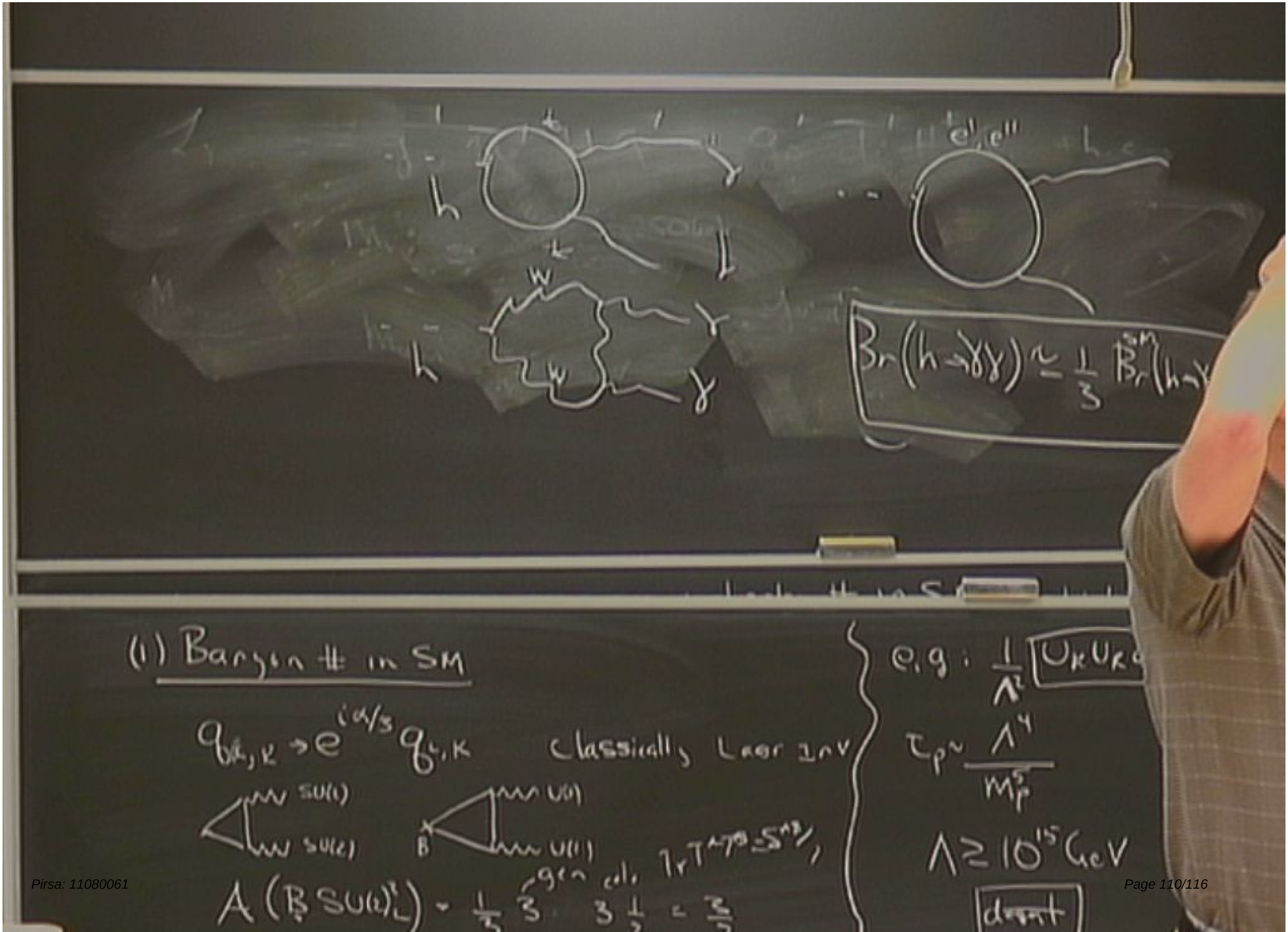
$M_x \gtrsim 70\,GeV$
Standard Model
Field | SU(3) | SU(2) | U(1)$_Y$ | U(1)$_B$ | U(1)$_L$
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$ | 3 | 2 | 1/6 | 1/3 | 0
u_R^i | 3 | 1 | 2/3 | 1/3 | 0
d_R^i | 3 | 1 | -1/3 | 1/3 | 0
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$ | 1 | 2 | -1/2 | 0 | 1
e_R^i | 1 | 1 | -1 | 0 | 1
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ | 1 | 2 | 1/2 | 0 | 0
?
?


e.g.
Λ ≥ 10^15 GeV

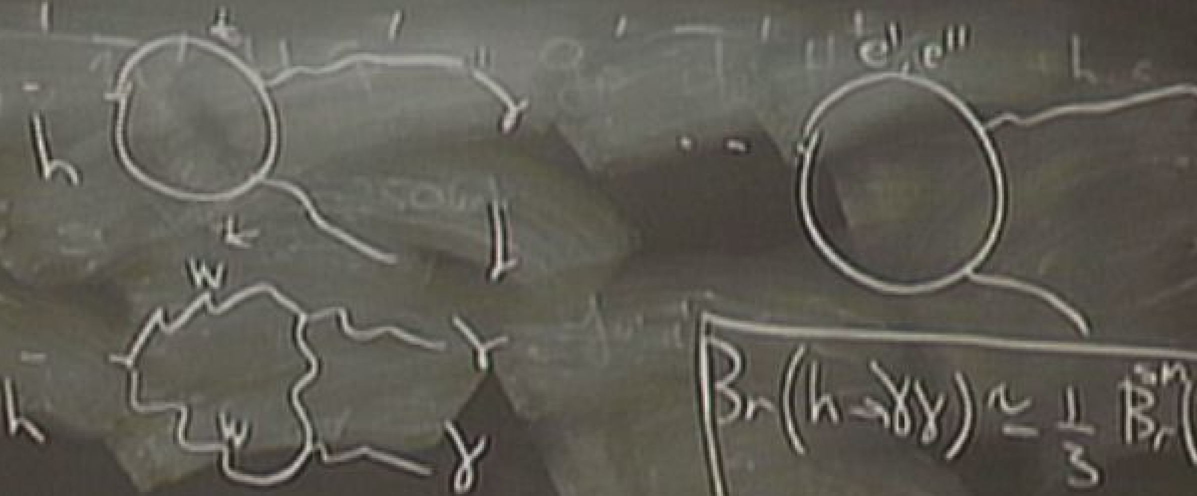


(1) Bary
Classically
e.g. : 1/Λ² $U_R U_R d_R e_R$
$\tau_p \sim \Lambda^4 / m_p^5$
$\Lambda \geq 10^{15}$ GeV


W
W
e.g. 1/Λ² u_R u_R d_R e_R
Classically Lepr Inv
Λ ≥ 10^15 GeV



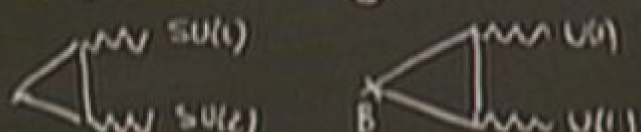
h
W
γ
(1) Baryon # in SM
classically Lagr inv
SU(2)
U(1)
e.g.
Λ ≥ 10^15 GeV



$$Br(h\to\gamma\gamma) \simeq \frac{1}{3} Br^{SM}(h\to\gamma\gamma)$$

(1) Baryon # in SM

$q_{L,R} \to e^{i\alpha/3} q_{L,R}$ Classically Lagr Inv



$Tr\, T^a T^b = \delta^{ab}/2$

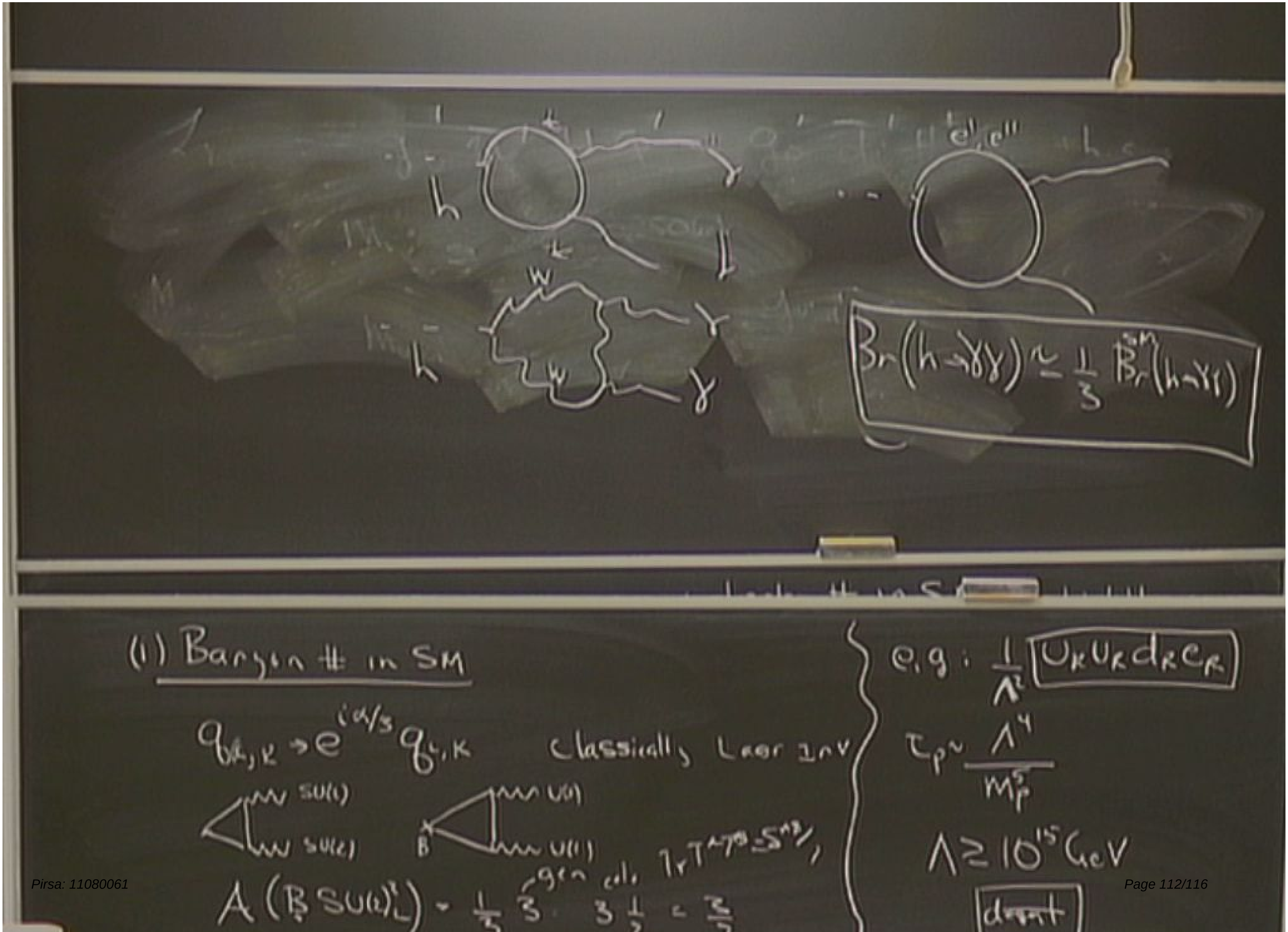
$A(B\, SU(2)_L^2) \sim \frac{1}{3} \cdot 3 \cdot 3 \cdot \frac{1}{2} = \frac{3}{2}$ (gen, col)

e.g. $\frac{1}{\Lambda^2} u_R u_R d_R e_R$

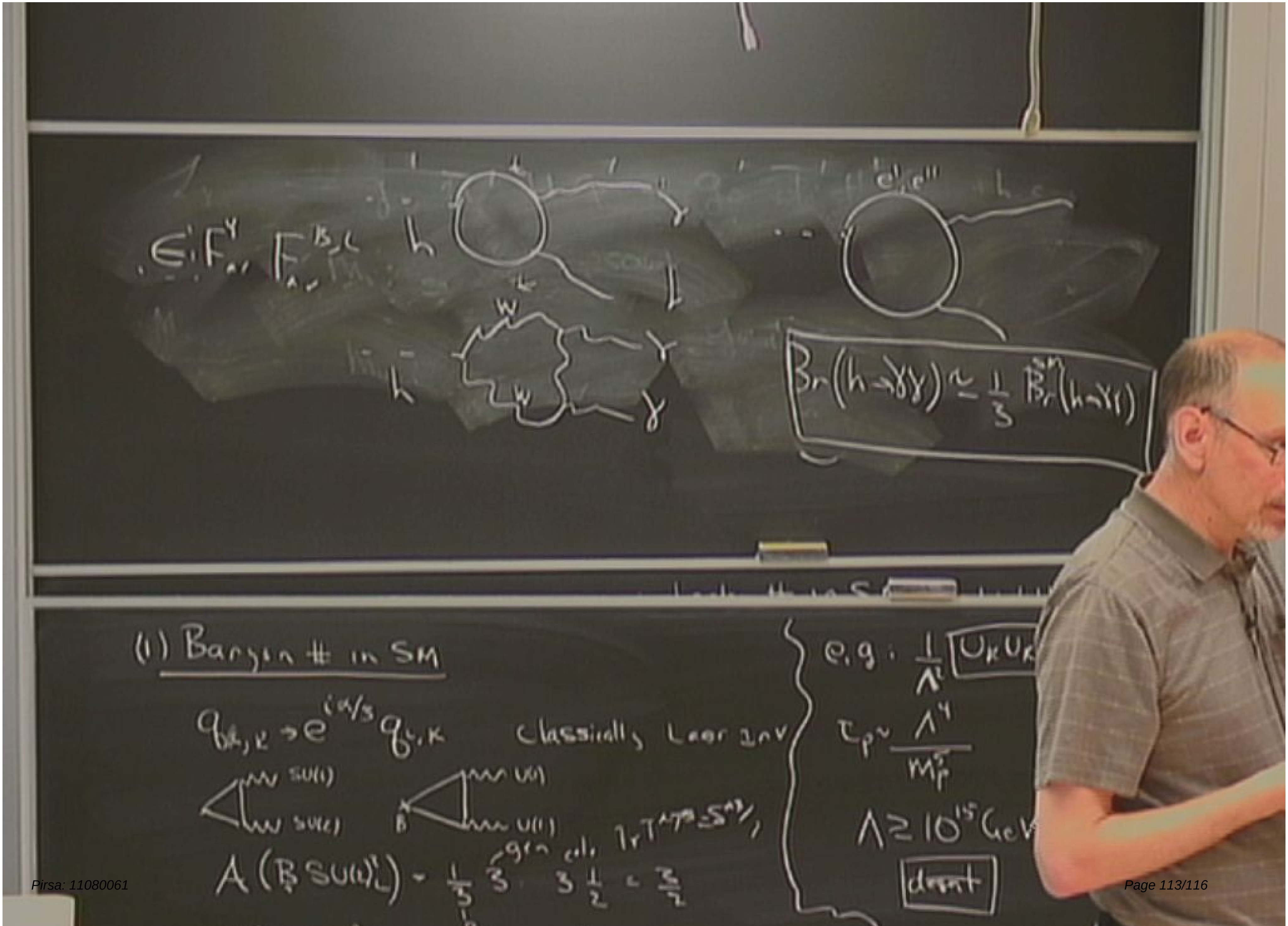
$\tau_p \sim \frac{\Lambda^4}{m_p^5}$

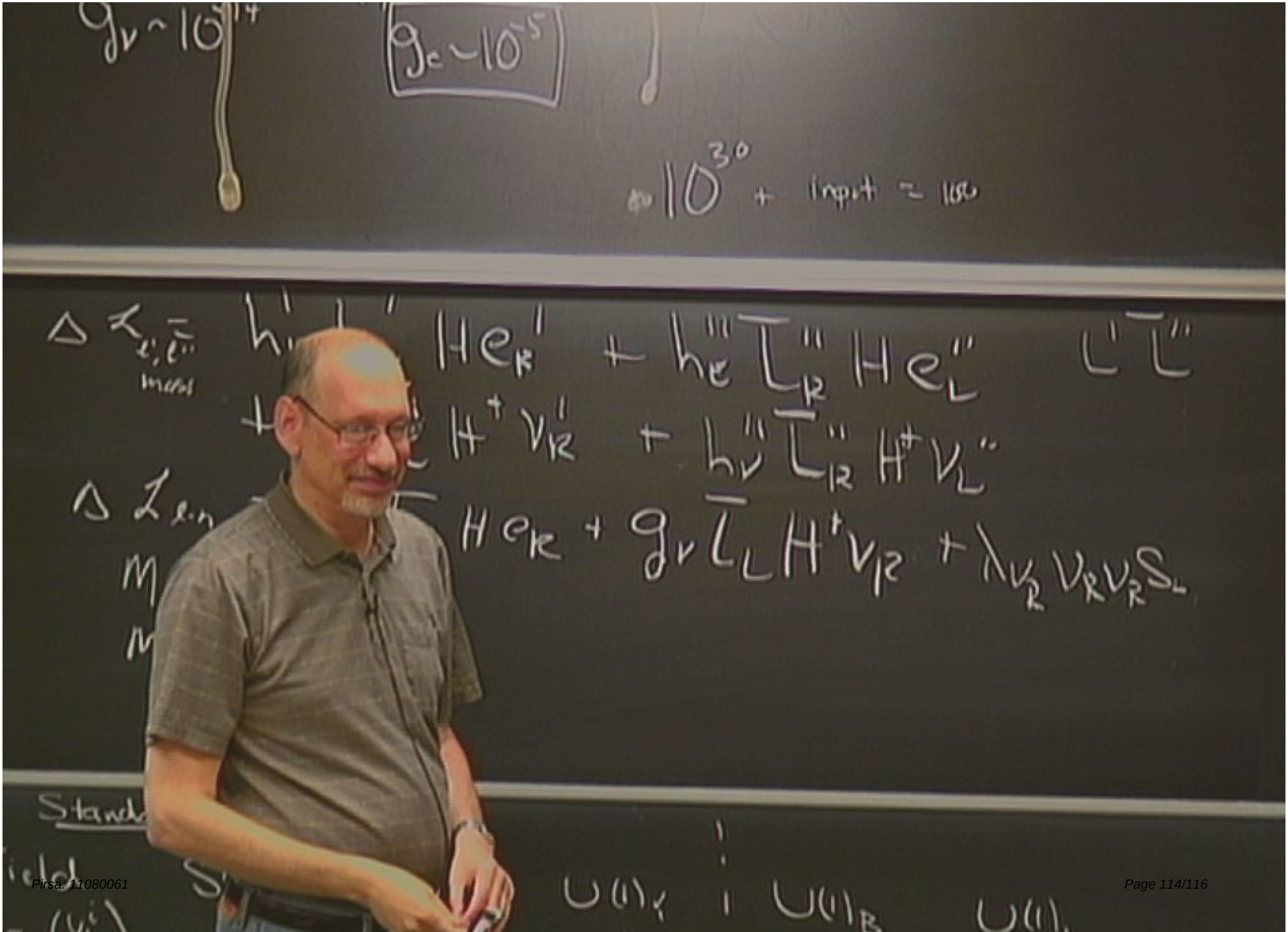
$\Lambda \geq 10^{15}$ GeV

~~dont~~



h
t
W
h
W
γ
γ
$Br(h \to \gamma\gamma) \simeq \frac{1}{3} Br^{SM}(h \to \gamma\gamma)$
(1) Baryon # in SM
$q_{L,R} \to e^{i\alpha/3} q_{L,R}$ classically Lagr inv
SU(2)
SU(2)
B
U(1)
U(1)
e.g. $\frac{1}{\Lambda^2} u_R u_R d_R e_R$
$\tau_p \sim \frac{\Lambda^4}{m_p^5}$
$\Lambda \geq 10^{15}$ GeV


(1) Baryon # in SM
Classically Lagr Inv
SU(3)
SU(2)
U(1)
e.g.



$g_\nu \sim 10^{-14}$
$g_e \sim 10^{-5}$
10^{30} + input = 10
mass
+ $h_\nu'' \bar{L}_R'' H^+ \nu_L''$
$H e_R + g_\nu \bar{L}_L H^+ \nu_R + \lambda_{\nu_R} \nu_R \nu_R S_L$
U(1) U(1)$_B$ U(1)

$g_\nu \sim 10^{-14}$

$g_e \sim 10^{-5}$

10^{30} + input = 10^{30}

$$\Delta \mathcal{L}_{\ell', \ell''\ \text{mass}} = h_{e'} \bar{L}'_L H e'_R + h_{e''} \bar{L}''_R H e''_L \qquad L' \bar{L}''$$

$$+ h_{\nu'} \bar{L}'_L H^{+} \nu'_R + h_{\nu''} \bar{L}''_R H^{+} \nu''_L$$

$$\Delta \mathcal{L}_{e.n} = g_E \bar{L}_L H e_R + g_\nu \bar{L}_L H^{+} \nu_R + \lambda_{\nu_R} \nu_R \nu_R S_L$$

$M_{e'''} \gtrsim 100\,\text{GeV}$

$M_\nu \gtrsim 70\,\text{GeV}$

Standard Model

Field SU(3) SU(2) $U(1)_Y$: $U(1)_B$ $U(1)_L$

Anom ✓

$$B_{q'} - B_{q''} = -1$$

$$L_{\ell'} - L_{\ell''} = -3$$

$$\Delta \mathcal{L}_{q'''\text{-mass}} = h_V' Q_L' H' u_R' + h_u'' Q_R'' H u_L'' + h_D' \quad h_D''$$

$$+ \lambda_Q \bar{Q}_L' Q_R'' S_B + \lambda_U , \lambda_D$$

$$\langle S_B \rangle = v_B$$