Title: Graduate Course on Standard Model & Quantum Field Theory - 5A

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URL: http://pirsa.org/06110027

Abstract: Graduate Course on Standard Model & Quantum Field Theory

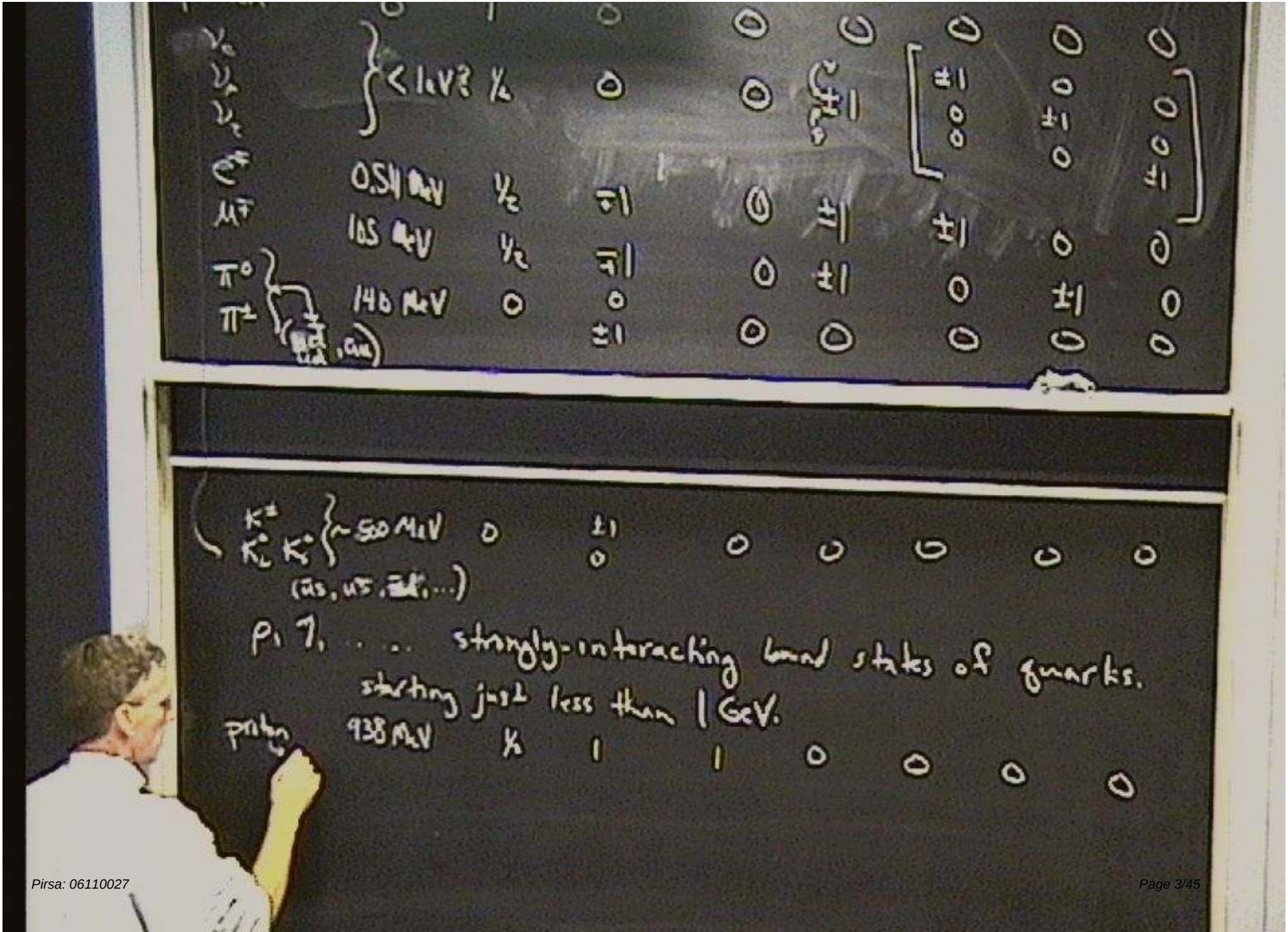
particle	Mass	J	B	L	L_e	L_μ	L_τ
graviton	0	2	0	0	0	0	0
photon	0	1	0	0	0	0	0
ν_e	< 1 keV?	$\frac{1}{2}$	0	0	$+1$	0	0
ν_μ				$+1$	0	$+1$	0
ν_τ					0	0	$+1$
$e^\mp$	0.511 MeV	$\frac{1}{2}$	∓ 1	0	± 1	0	0
$\mu^\mp$	105 MeV	$\frac{1}{2}$	∓ 1	0	± 1	0	0
π^0	140 MeV	0	0	0	0	± 1	0
$\pi^\pm$			± 1	0	0	0	0
$K^\pm$	~ 500 MeV	0	± 1	0	0	0	0
K_L^0 K_S^0			0				

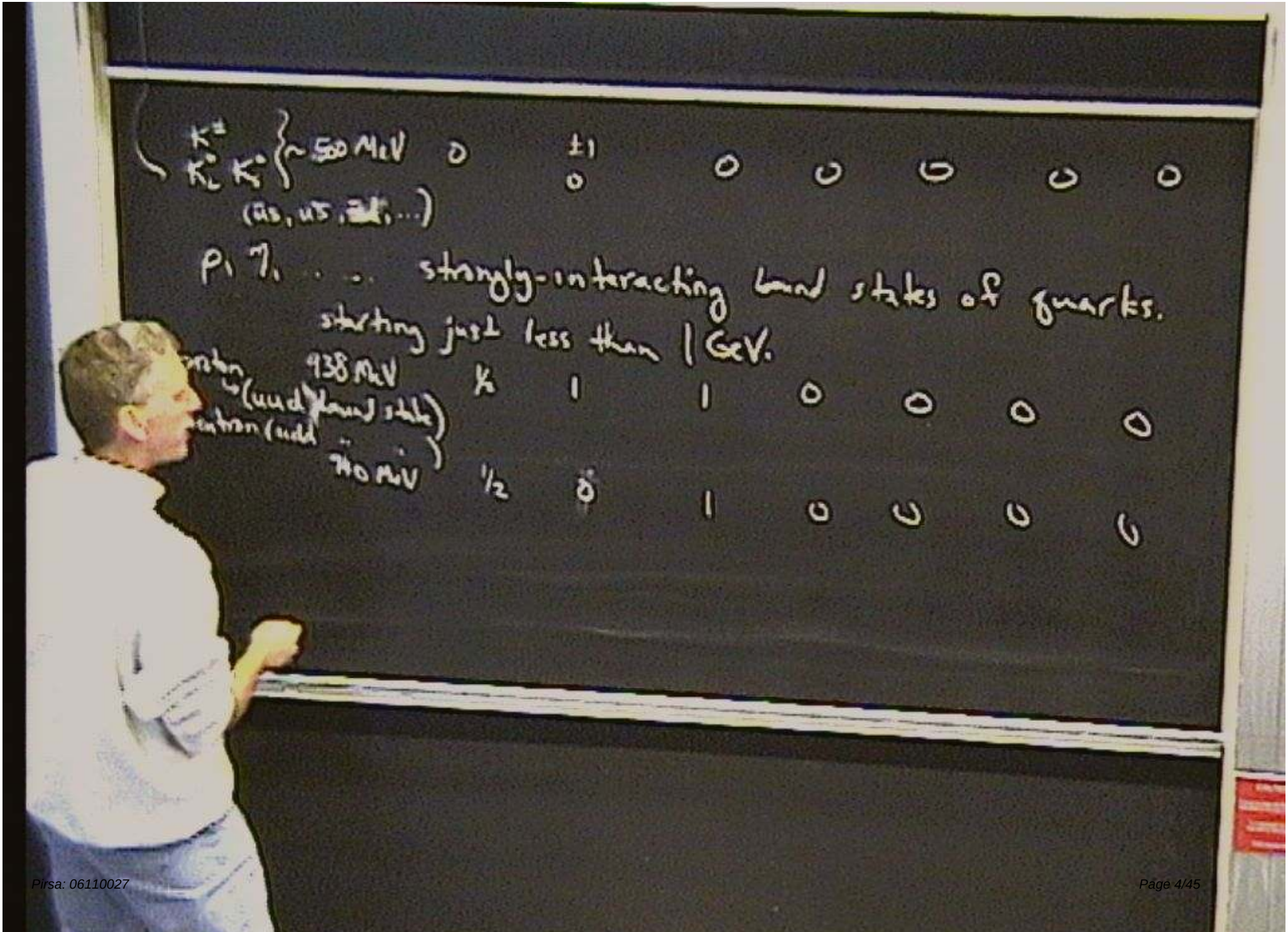
$(\bar{u}s, u\bar{s}, \bar{d}s, \ldots)$

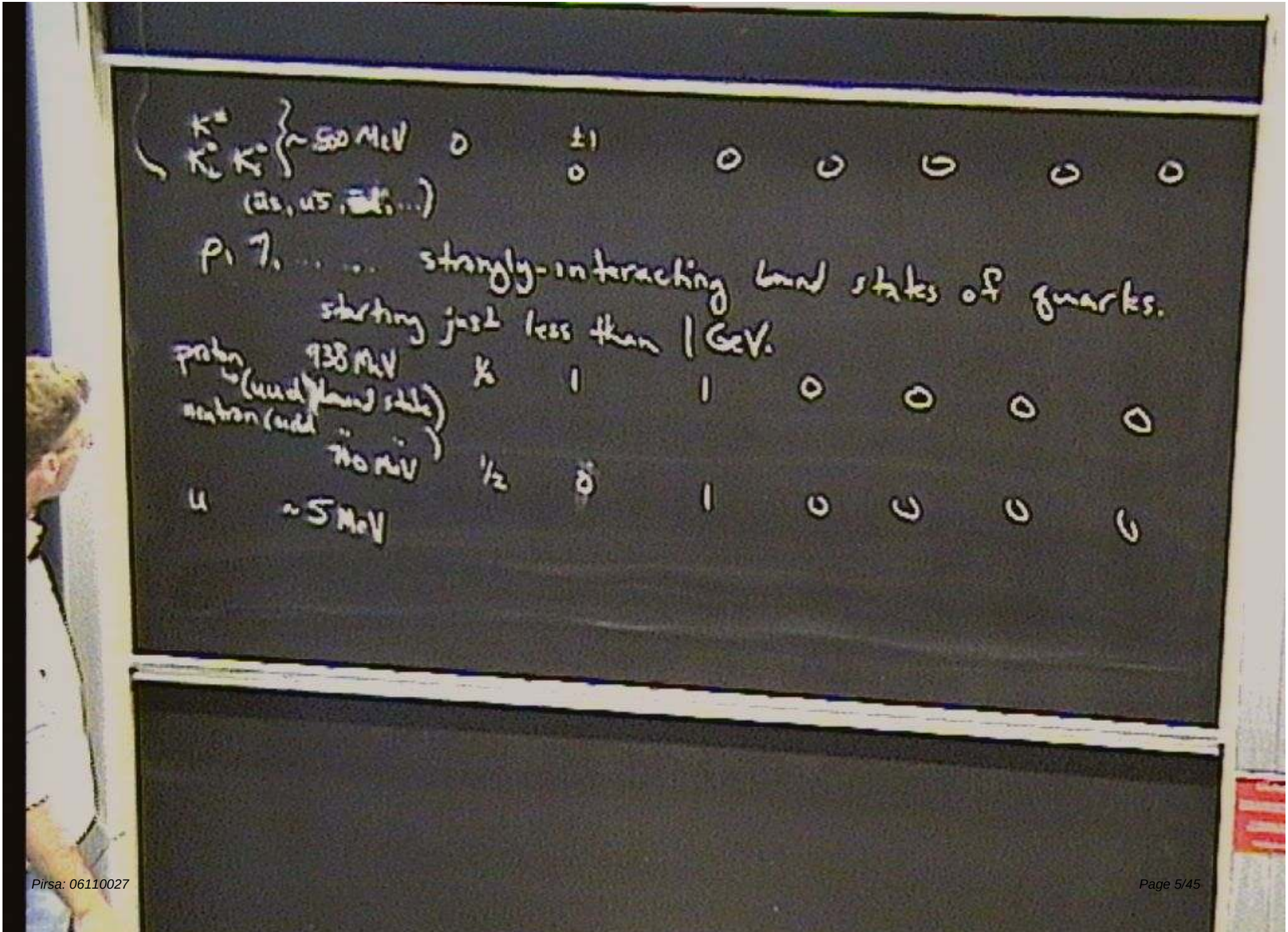
$p, n, \ldots$ strongly-interacting bound states of quarks.

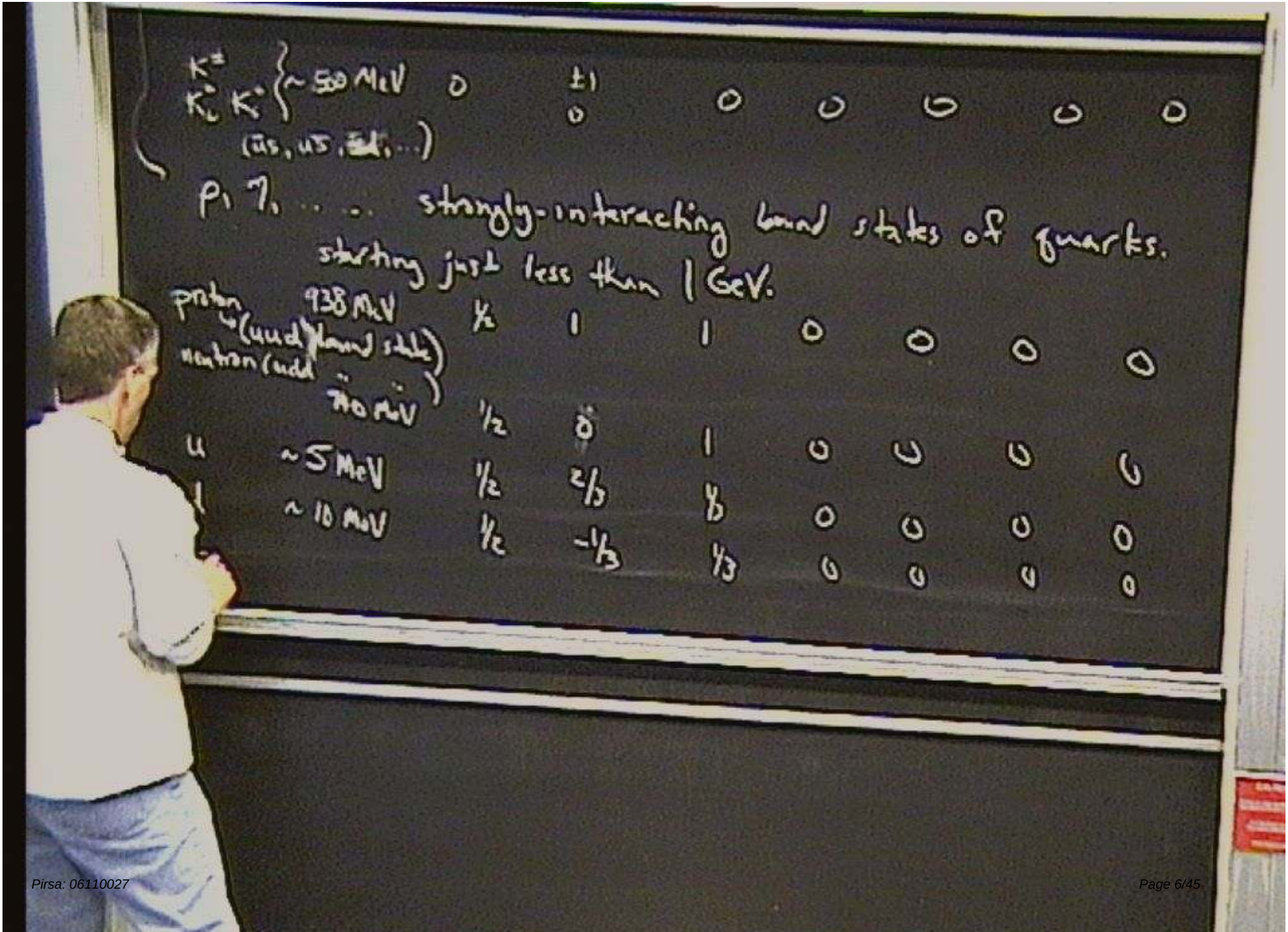
starting just less than 1 GeV.

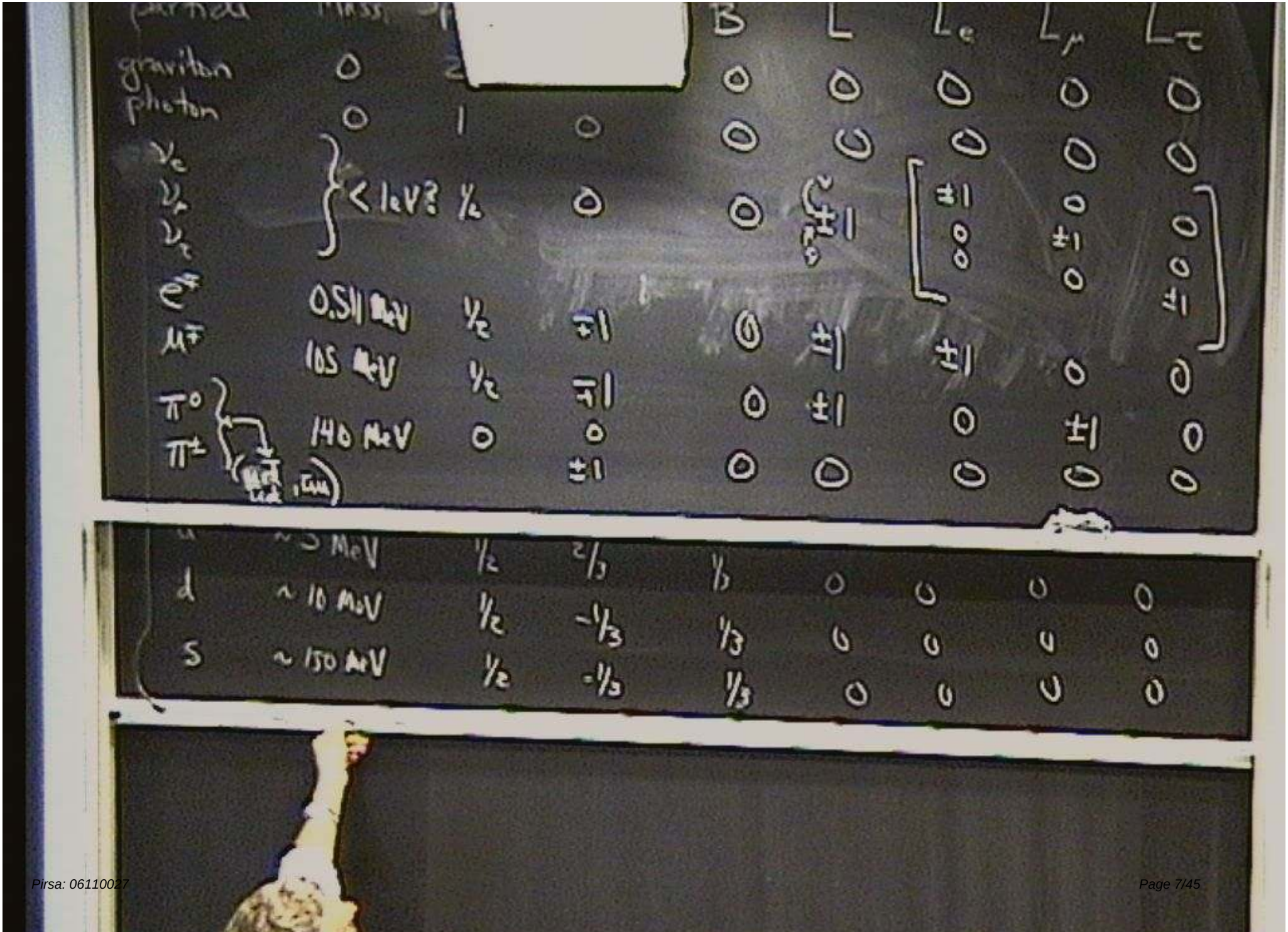
proton 938 MeV

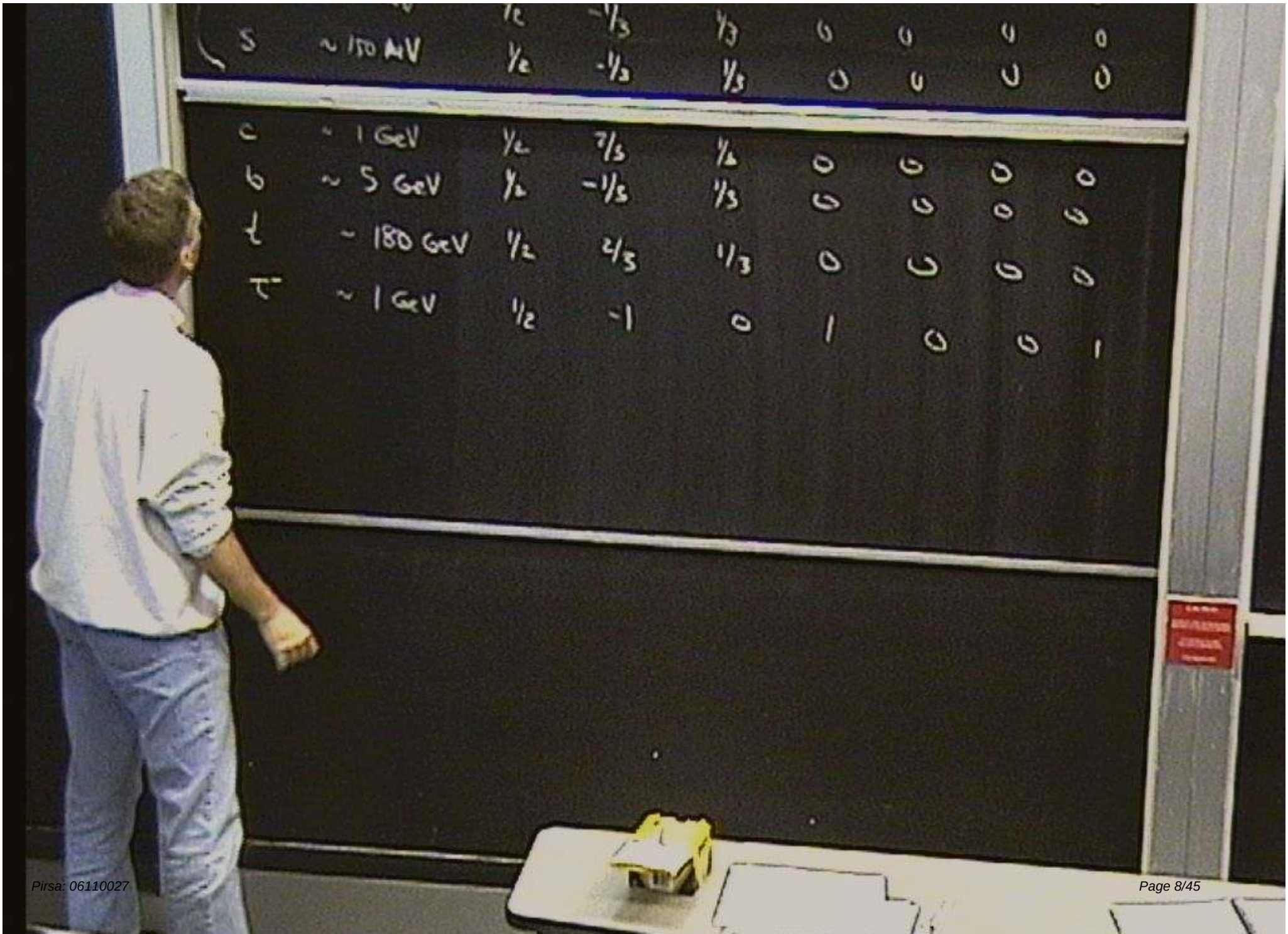

ν_e ν_μ ν_τ
< 1 keV?
$e^\mp$
0.511 MeV
$\mu^\mp$
105 MeV
π^0 $\pi^\pm$
140 MeV
$K^\pm$ K_L^0 K_S^0
~ 500 MeV
proton
938 MeV
p, n, ... strongly-interacting bound states of quarks.
starting just less than 1 GeV.

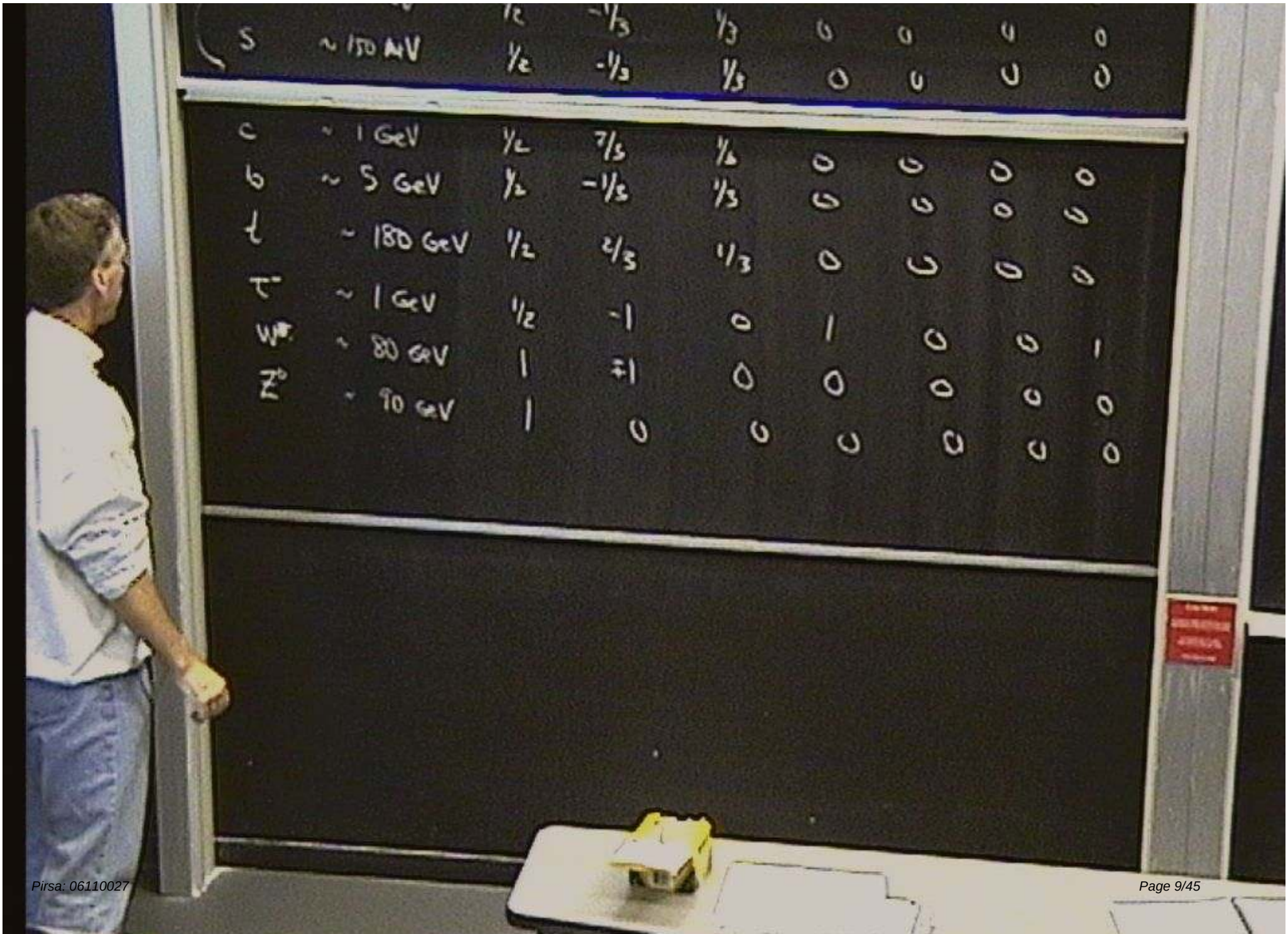

K^+
K_L^0 K_S^0 ~500 MeV 0 ±1 0 0 0 0 0 0
(as, us, ...)
ρ, η, ... strongly-interacting bound states of quarks.
starting just less than 1 GeV.
938 MeV ½ 1 1 0 0 0 0
(uud bound state)
(udd
770 MeV ½ 0 1 0 0 0 0

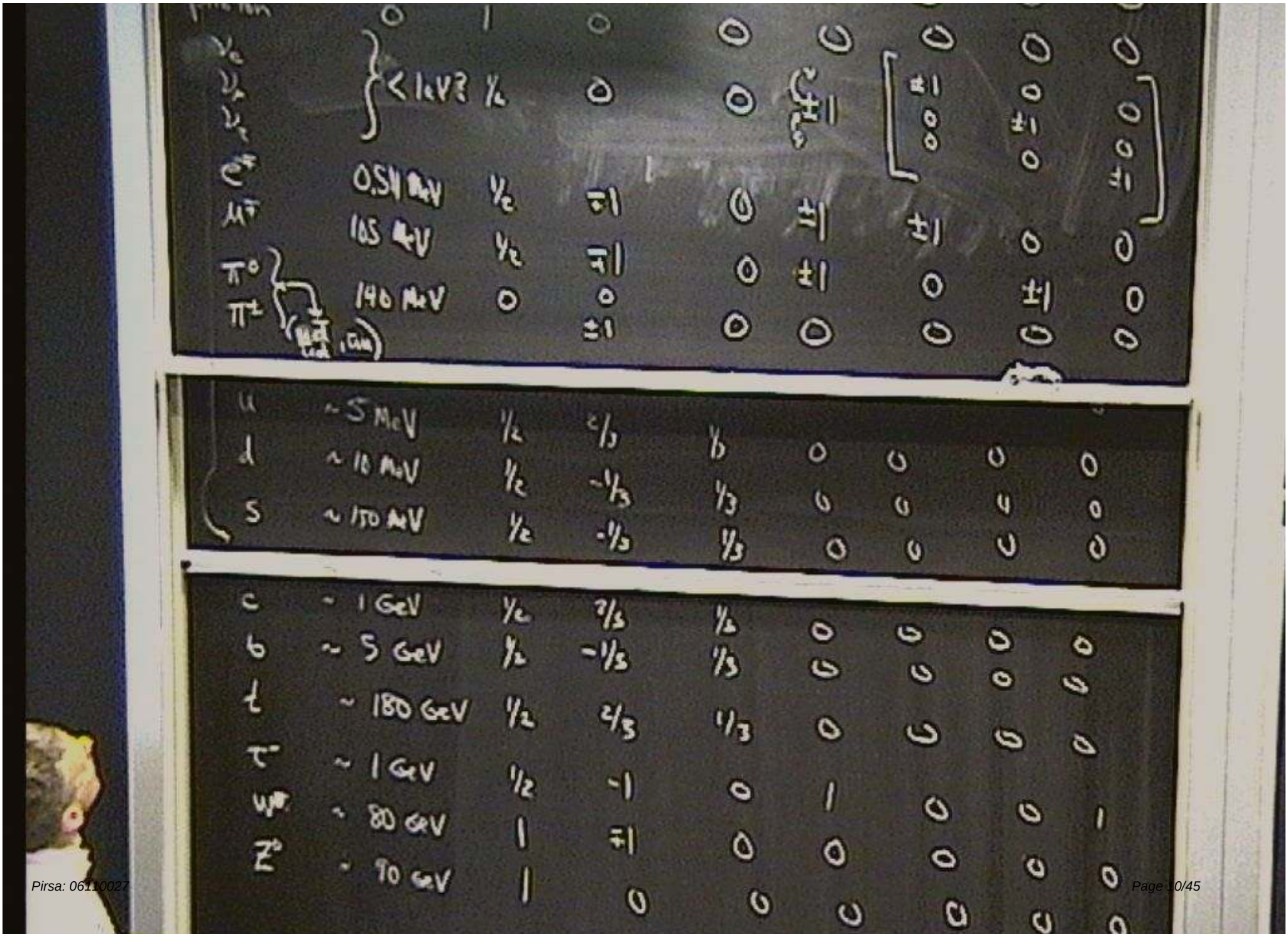

K^*
K_L^0 K^0 ~500 MeV 0 ±1
0 0 0 0 0 0
$(\bar{d}s, u\bar{s}, \ldots)$
$p, \pi, \ldots$ strongly-interacting bound states of quarks.
starting just less than 1 GeV.
proton 938 MeV ½ 1 1 0 0 0 0
$\rightarrow (uud$ bound state$)$
neutron $(udd$
940 MeV
u ~5 MeV ½ ½ 1 0 0 0 0

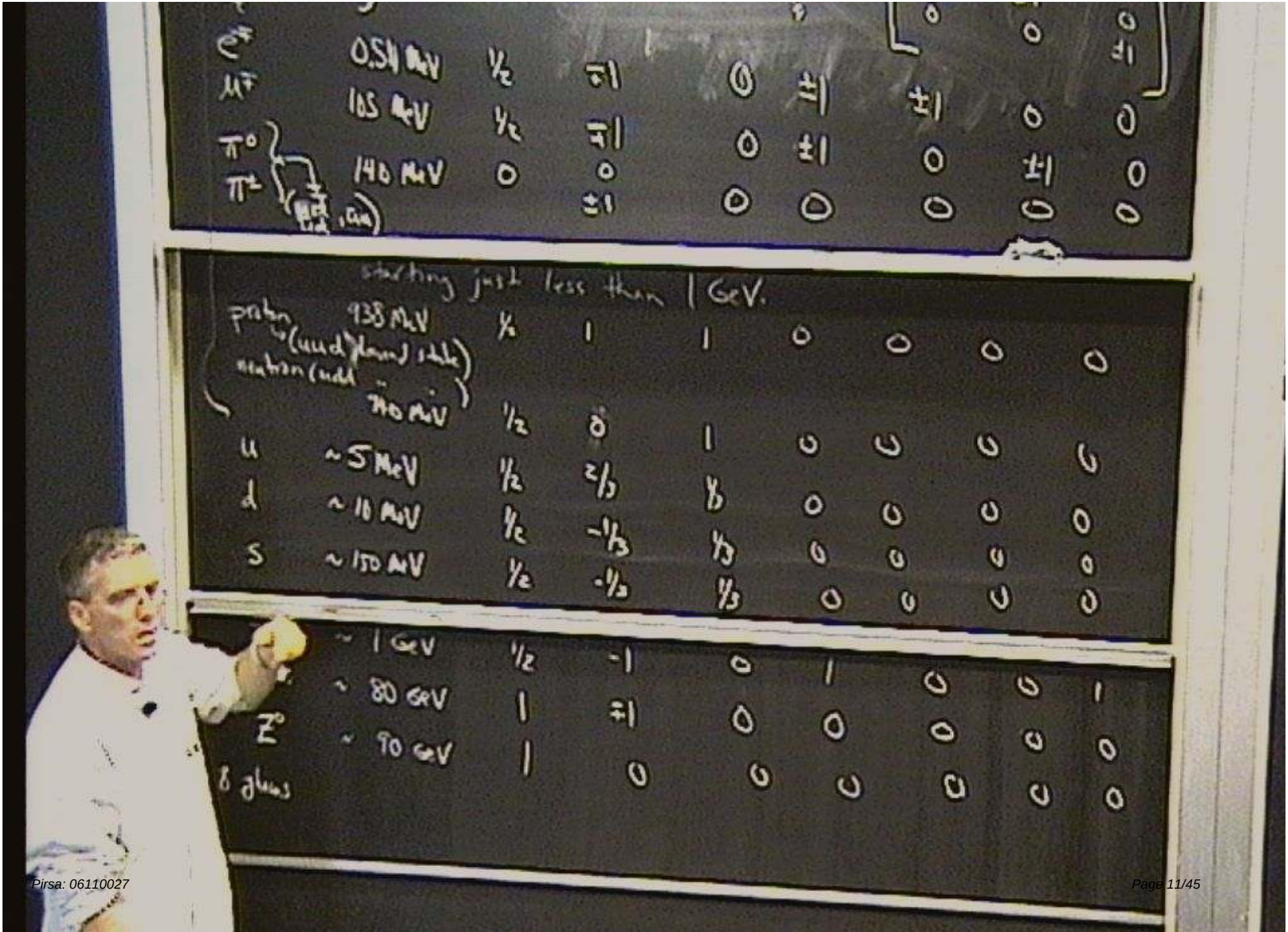

K^+
K^0 K^- $\bar{K}^0$ ~500 MeV 0 ±1
0
$(\bar{u}s, u\bar{s}, d\bar{s}, \ldots)$
$\rho, \eta, \ldots$ strongly-interacting bound states of quarks.
starting just less than 1 GeV.
proton 938 MeV ½ 1 1 0 0 0 0
(uud) bound state
neutron (udd) ~940 MeV ½ 0 1 0 0 0 0
u ~5 MeV ½ ⅔ ⅔ 0 0 0 0
d ~10 MeV ½ −⅓ ⅓ 0 0 0 0

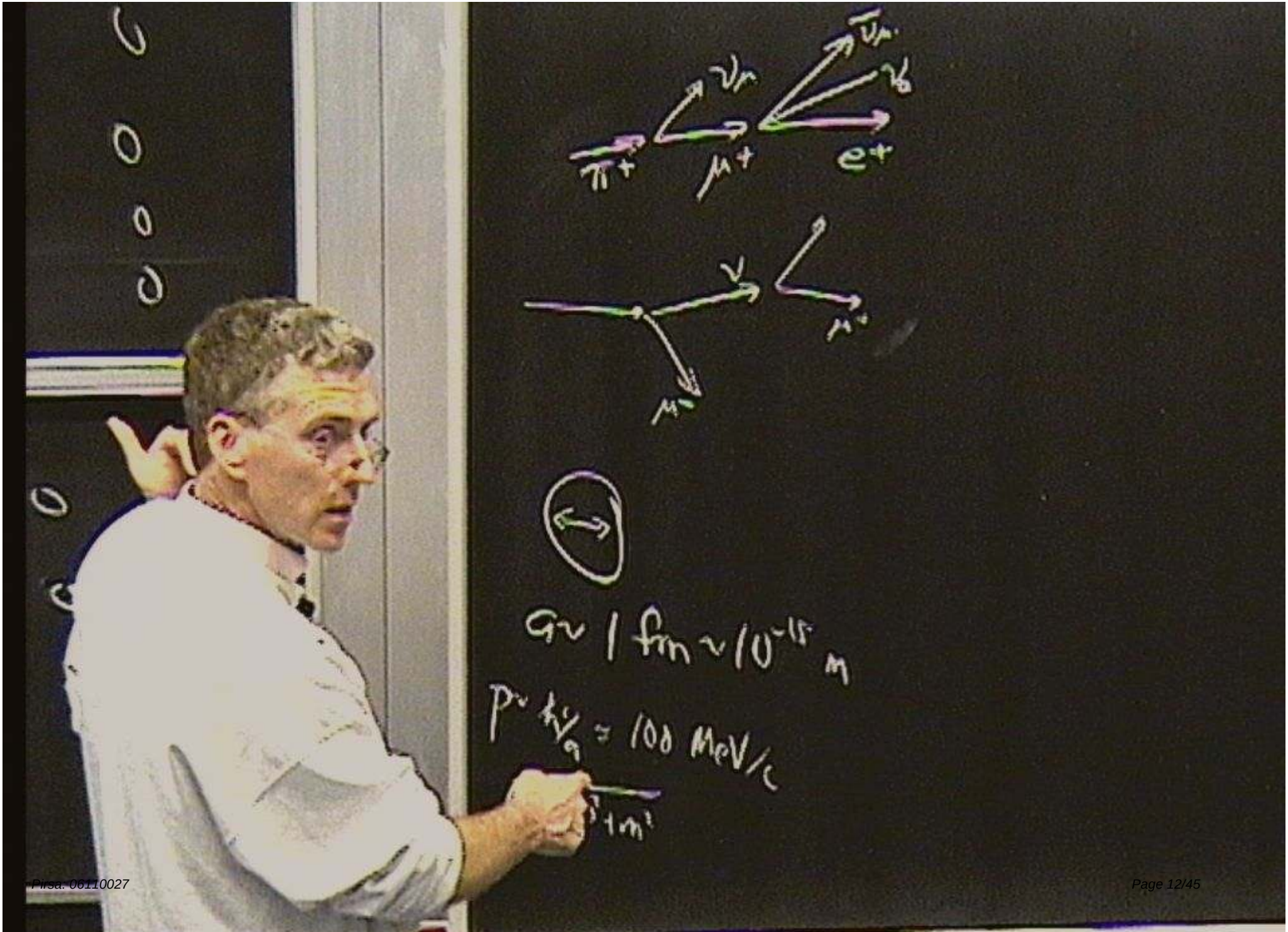

B L L_e L_μ L_τ
graviton 0 2 0 0 0 0 0 0
photon 0 1 0 0 0 0 0 0
ν_e
ν_μ
ν_τ
< 1 eV? ½ 0 0 ~0 0 0 ±1 0 0
$e^\mp$ 0.511 MeV ½ ±1 0 ±1 ±1 0 0
$\mu^\mp$ 105 MeV ½ ±1 0 ±1 0 ±1 0
π^0 140 MeV 0 0 0 0 0 0 0
$\pi^\pm$ ±1 0 0 0 0 ±1 0
d ~ 10 MeV ½ -⅓ ⅓ 0 0 0 0
s ~ 150 MeV ½ -⅓ ⅓ 0 0 0 0

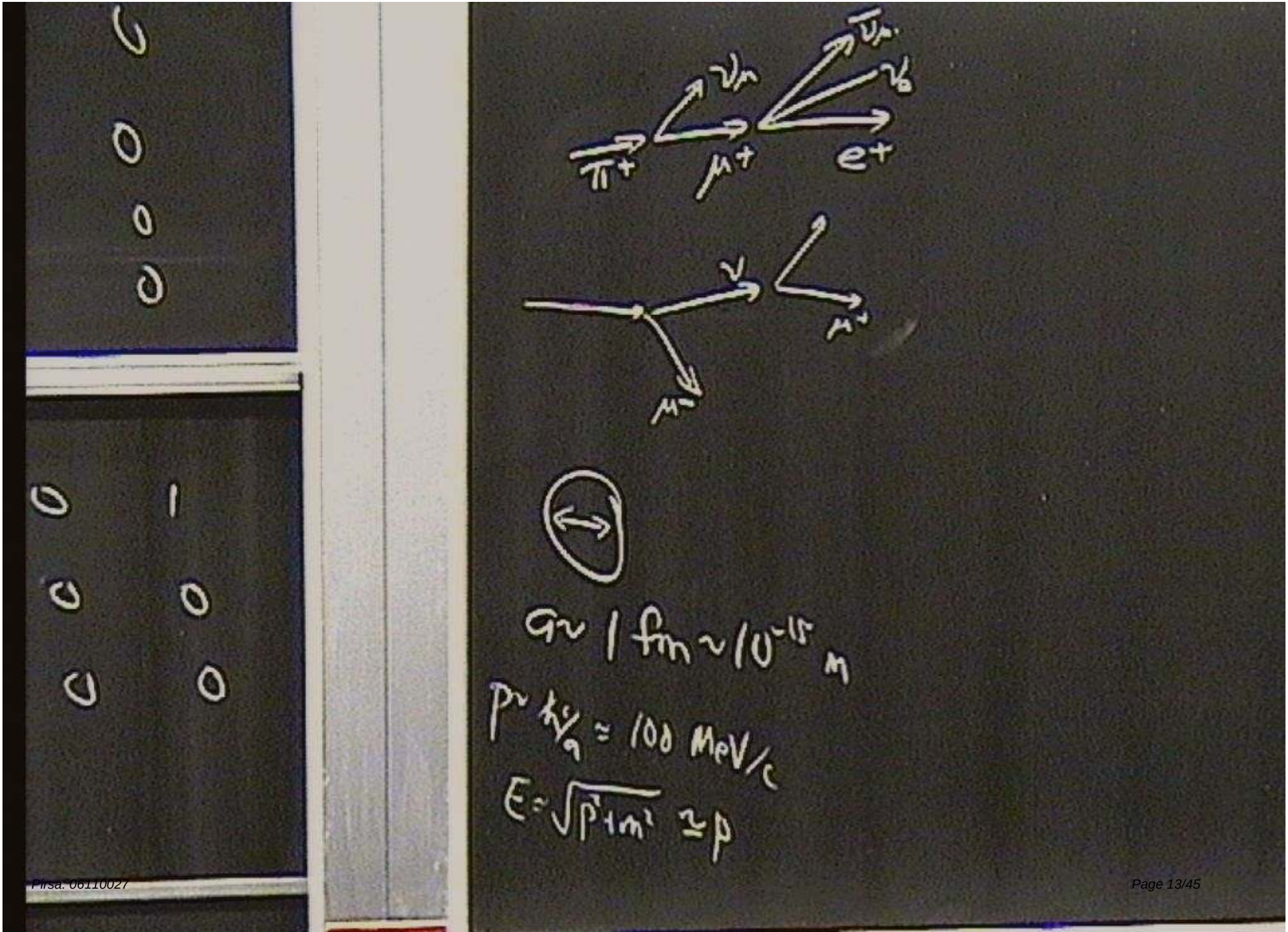

s ~ 150 MeV 1/2 -1/3 1/3 0 0 0 0
1/2 -1/3 1/3 0 0 0 0
c ~ 1 GeV 1/2 2/3 1/2 0 0 0 0
b ~ 5 GeV 1/2 -1/3 1/3 0 0 0 0
t ~ 180 GeV 1/2 2/3 1/3 0 0 0 0
τ⁻ ~ 1 GeV 1/2 -1 0 1 0 0 1

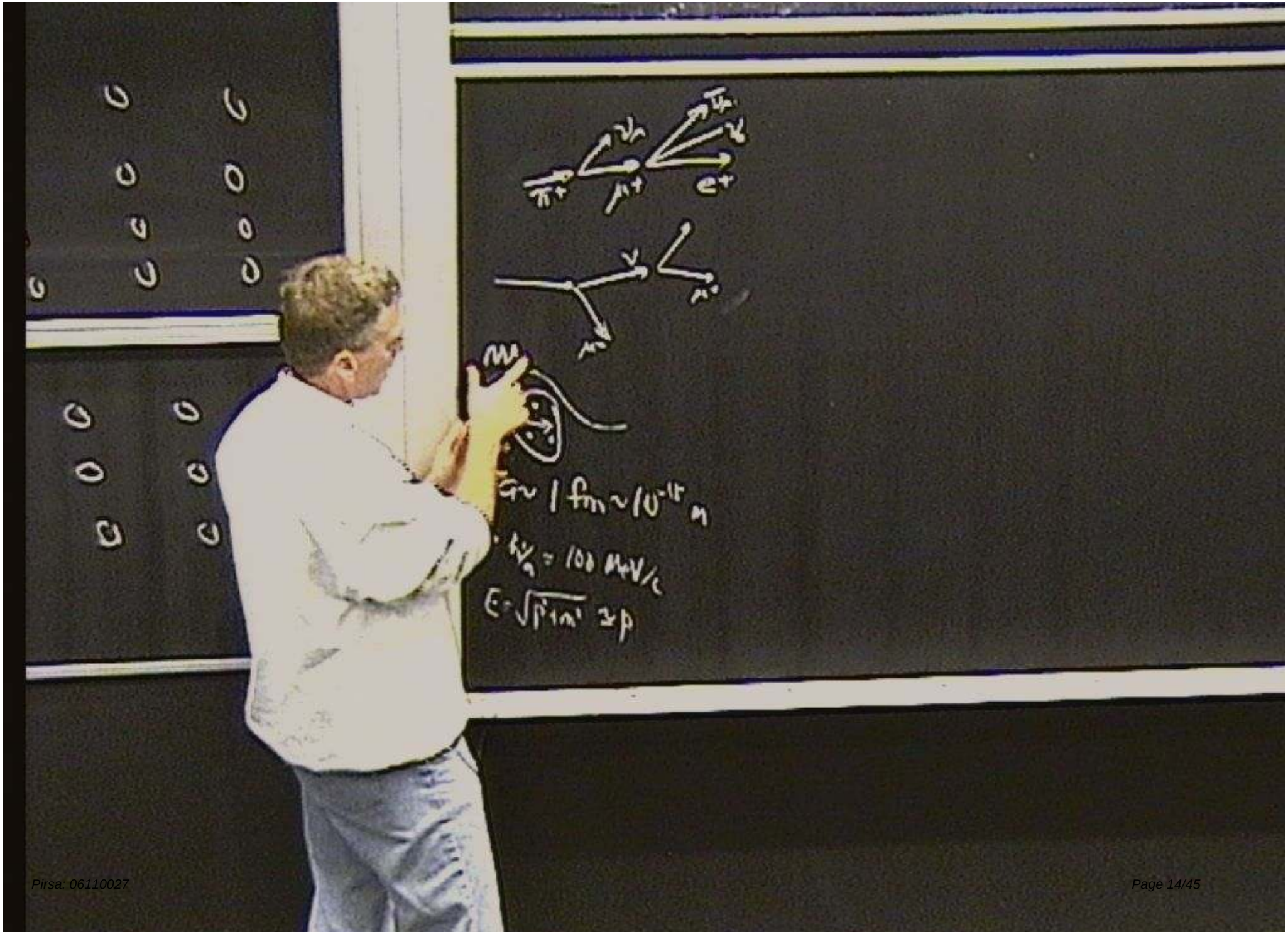

s ~ 150 MeV 1/2 -1/3 1/3 0 0 0 0
1/2 -1/3 1/3 0 0 0 0
c ~ 1 GeV 1/2 2/3 1/3 0 0 0 0
b ~ 5 GeV 1/2 -1/3 1/3 0 0 0 0
t ~ 180 GeV 1/2 2/3 1/3 0 0 0 0
τ⁻ ~ 1 GeV 1/2 -1 0 1 0 0 1
W± ~ 80 GeV 1 ±1 0 0 0 0 0
Z⁰ ~ 90 GeV 1 0 0 0 0 0 0

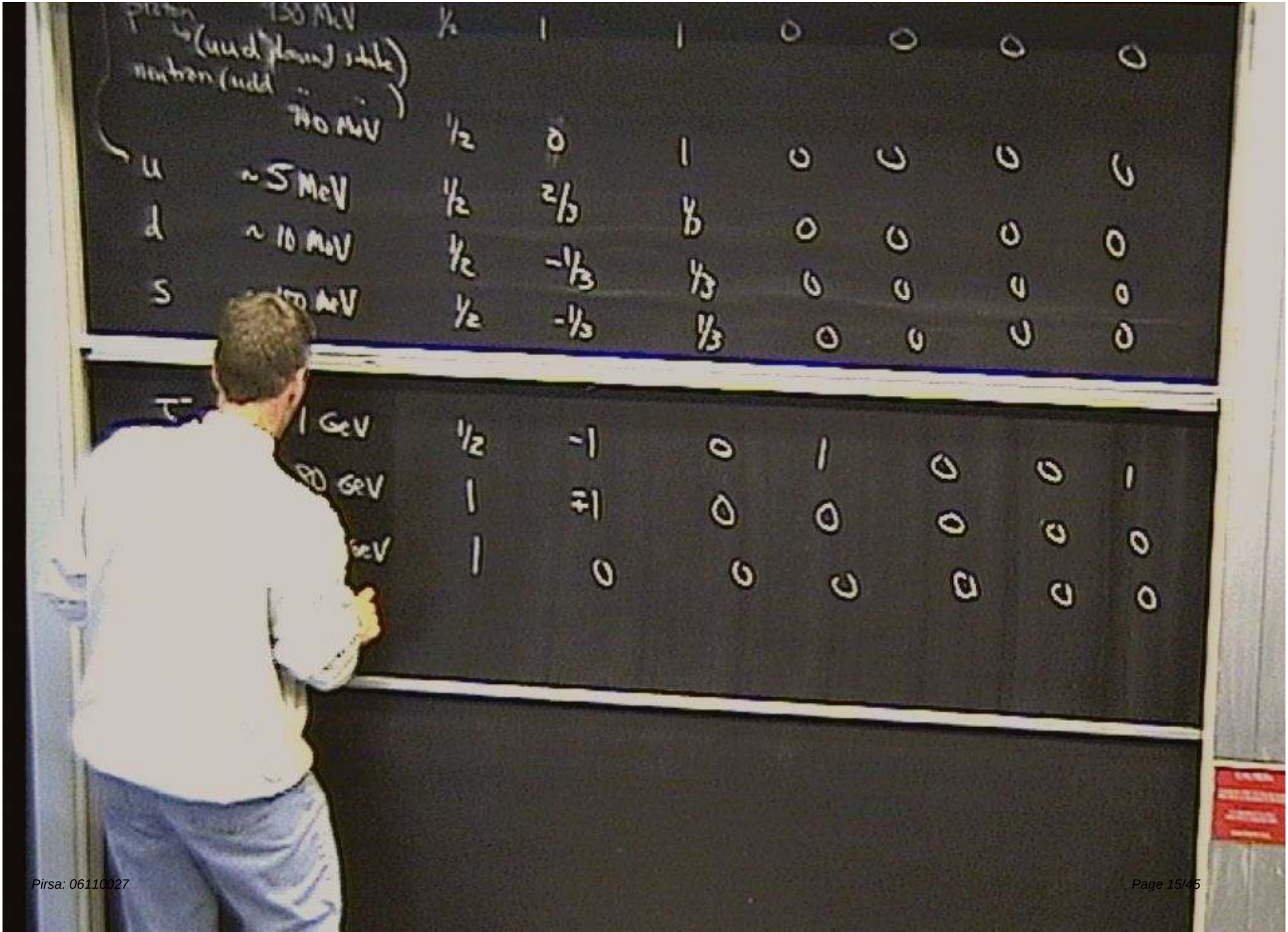

ν_e
ν_μ
ν_τ
< 1 eV?
e^-
0.511 MeV
μ^-
105 MeV
π^0
$\pi^\pm$
140 MeV
u
~ 5 MeV
d
~ 10 MeV
s
~ 150 MeV
c
~ 1 GeV
b
~ 5 GeV
t
~ 180 GeV
τ^-
~ 1 GeV
$W^\pm$
~ 80 GeV
Z^0
~ 90 GeV

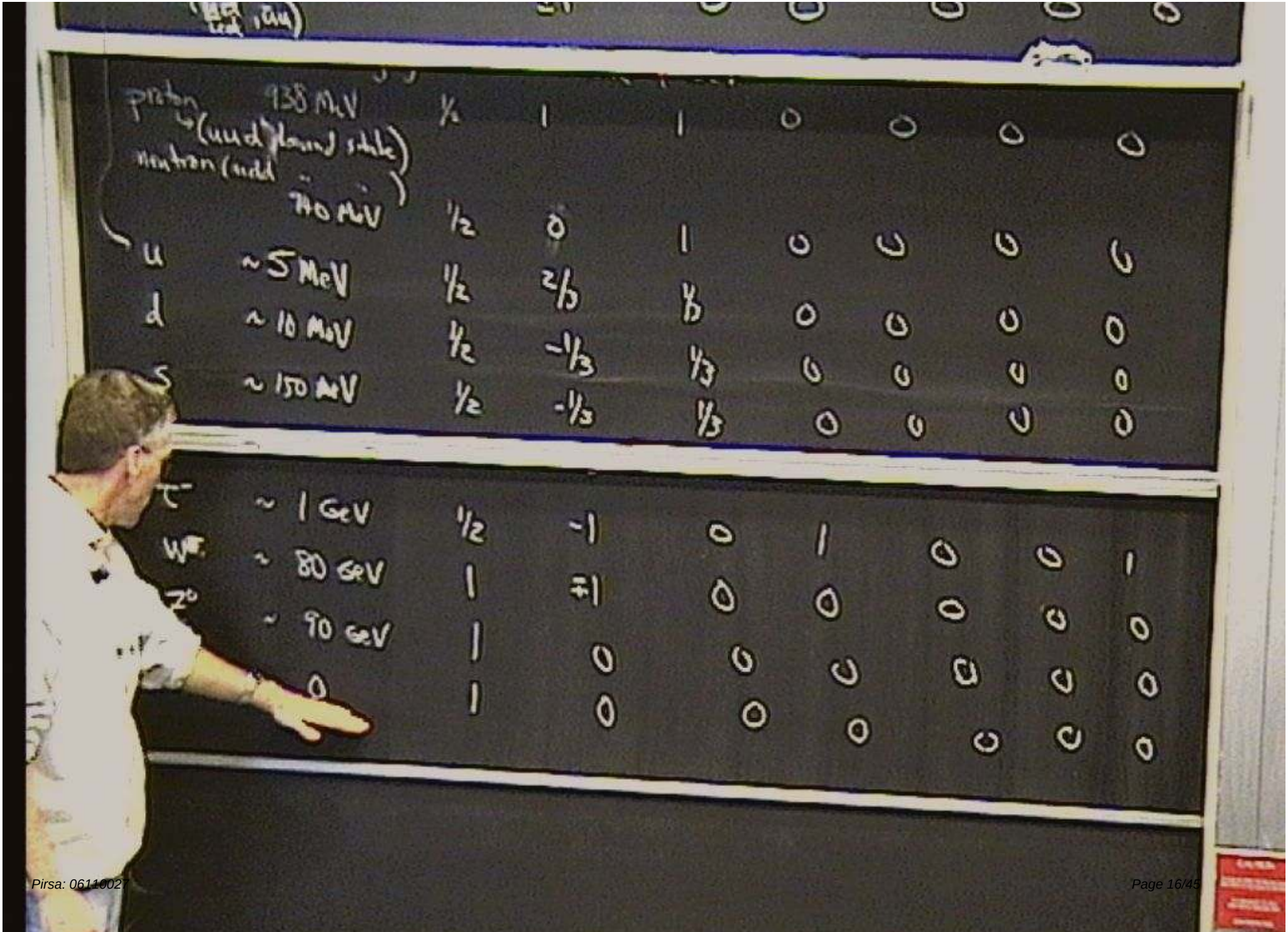

0.511 MeV
105 MeV
140 MeV
starting just less than 1 GeV.
938 MeV
940 MeV
~5 MeV
~10 MeV
~150 MeV
~1 GeV
~80 GeV
~90 GeV
8 gluons

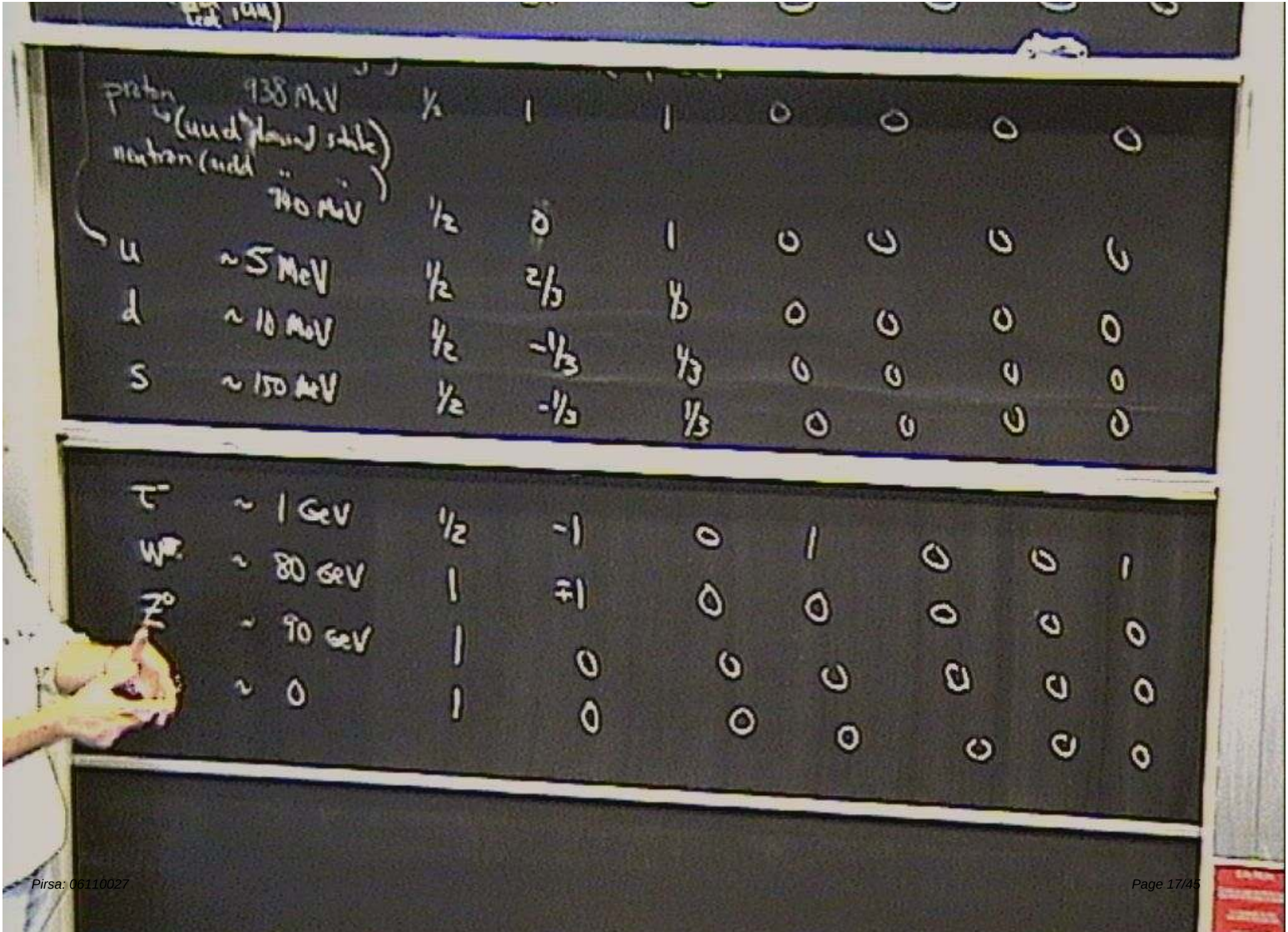

π^+
μ^+
e^+
ν_μ
$\bar{\nu}_\mu$
γ
ν
μ^-
e^-
~ 1 fm $\sim 10^{-15}$ m
$p^\nu \hbar/a \approx 100$ MeV/c
mc^2

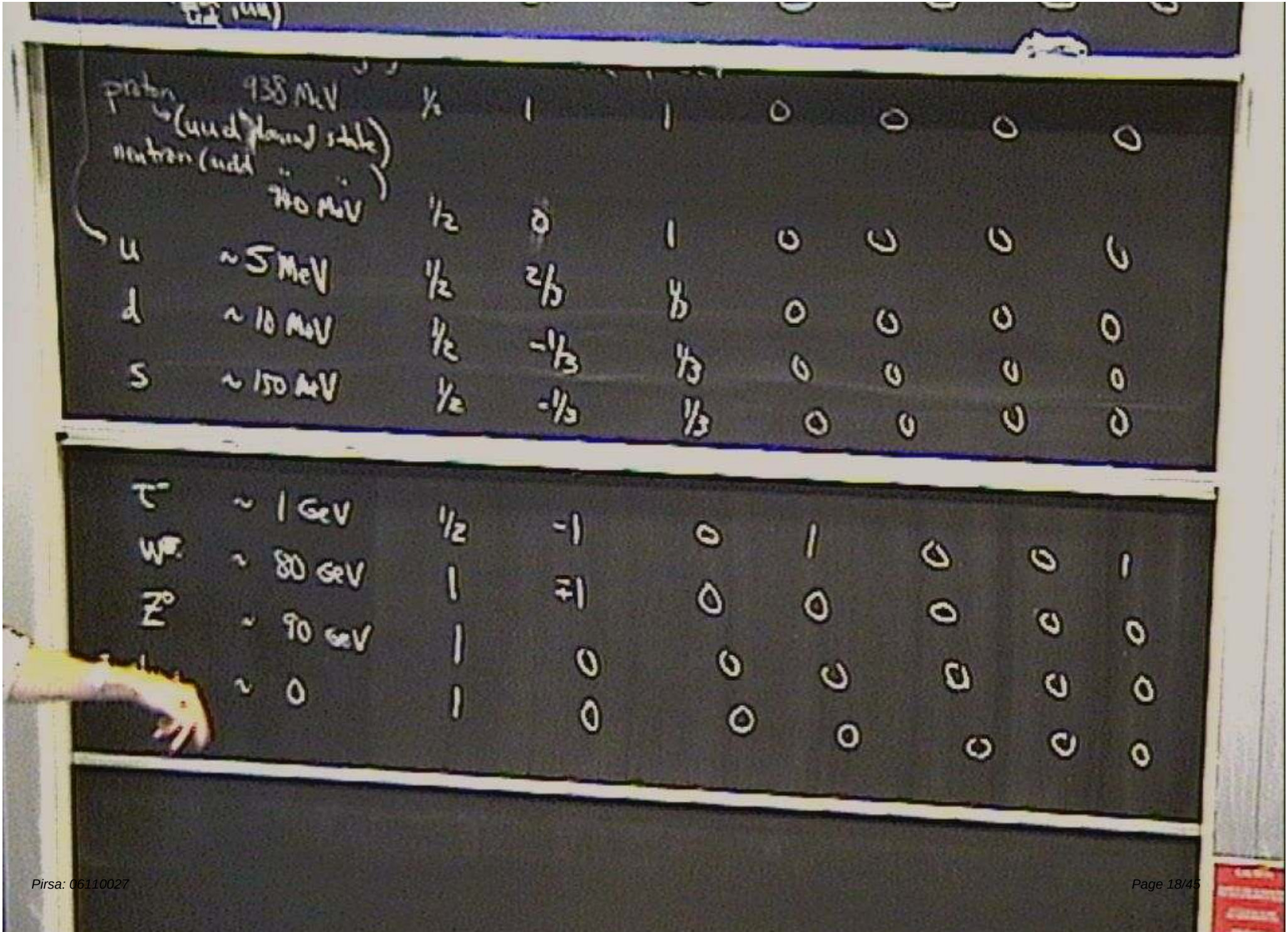

π^+
μ^+
e^+
ν_μ
$\bar{\nu}_\mu$
ν_e
ν
μ^+
μ^-
$q \sim 1\,fm \sim 10^{-15}\,m$
$p \sim \hbar/q \approx 100\,MeV/c$
$E \simeq \sqrt{p^2 + m^2} \simeq p$

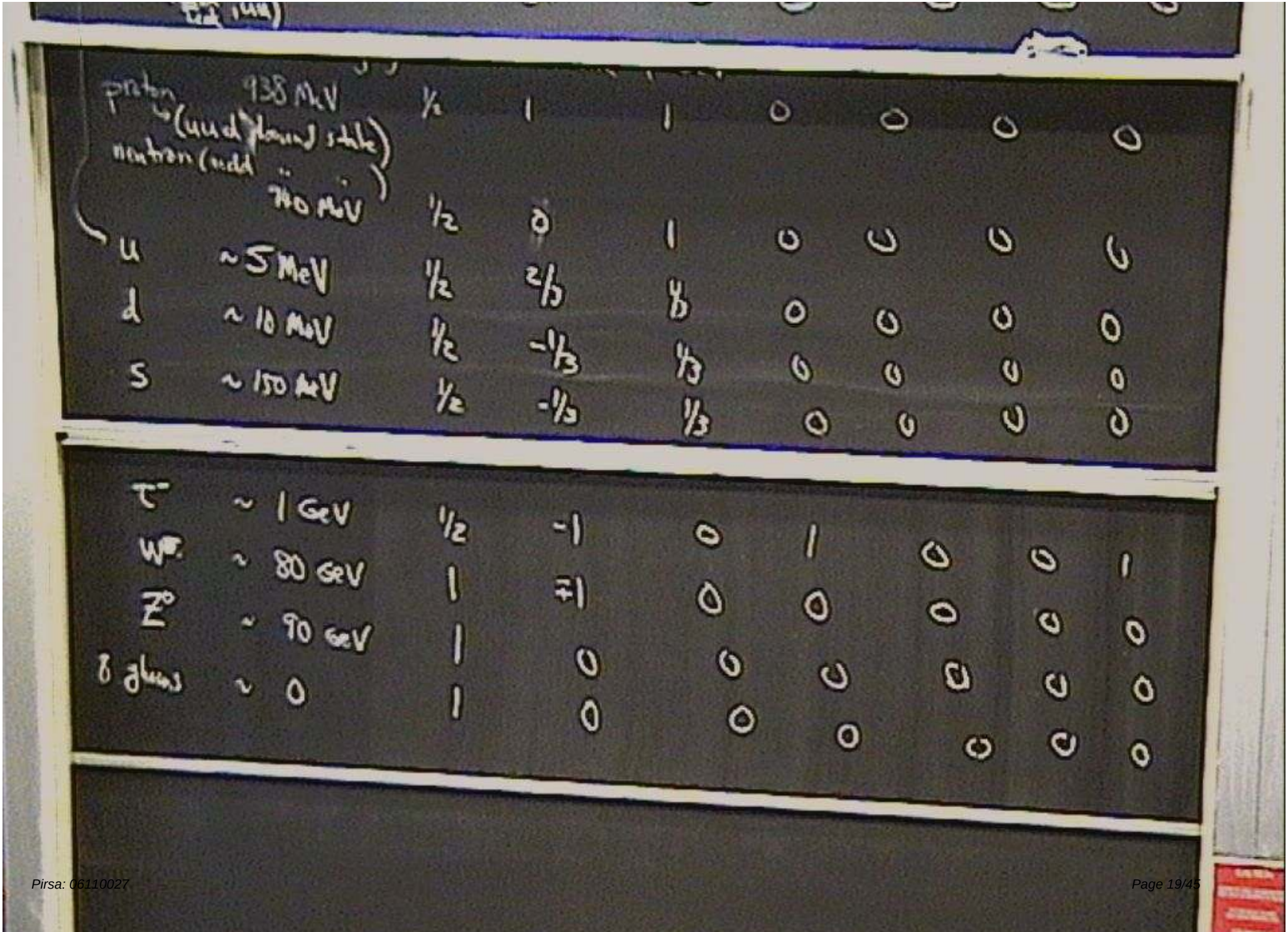

π^+
μ^+
e^+
ν_μ
ν_e
$\bar{\nu}_\mu$
ν
μ^+
μ^-
$\sim 1\ fm \sim 10^{-13}\ m$
$E = \sqrt{p^2 c^2 + m^2 c^4} \approx pc$

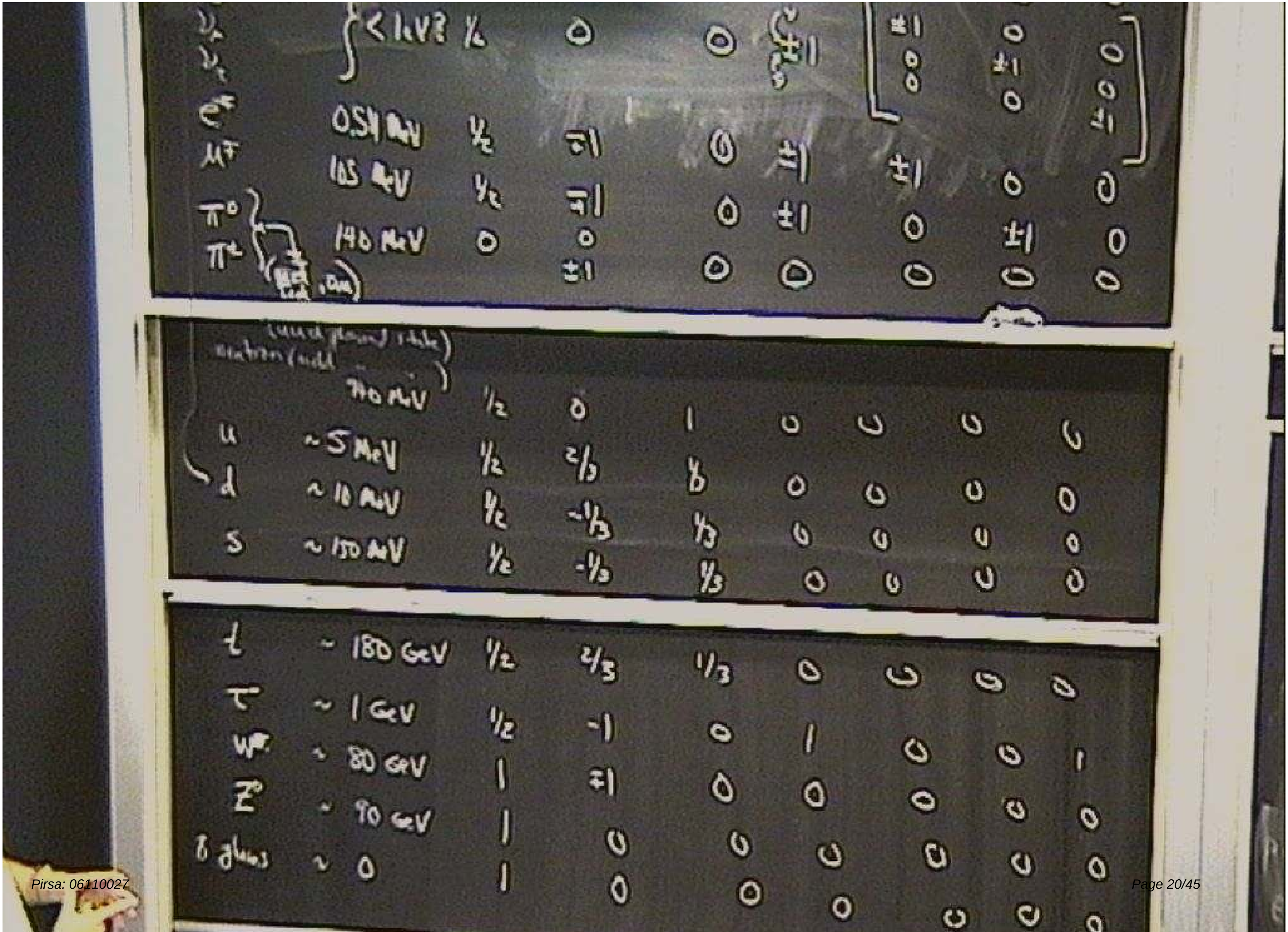

(uud bound stable)
neutron (udd
940 MeV
u ~5 MeV
d ~10 MeV
1 GeV
80 GeV


proton 938 MeV
(uud bound stable)
neutron (udd ... 940 MeV)
u ~5 MeV
d ~10 MeV
s ~150 MeV
τ⁻ ~1 GeV
W± ~80 GeV
Z⁰ ~90 GeV

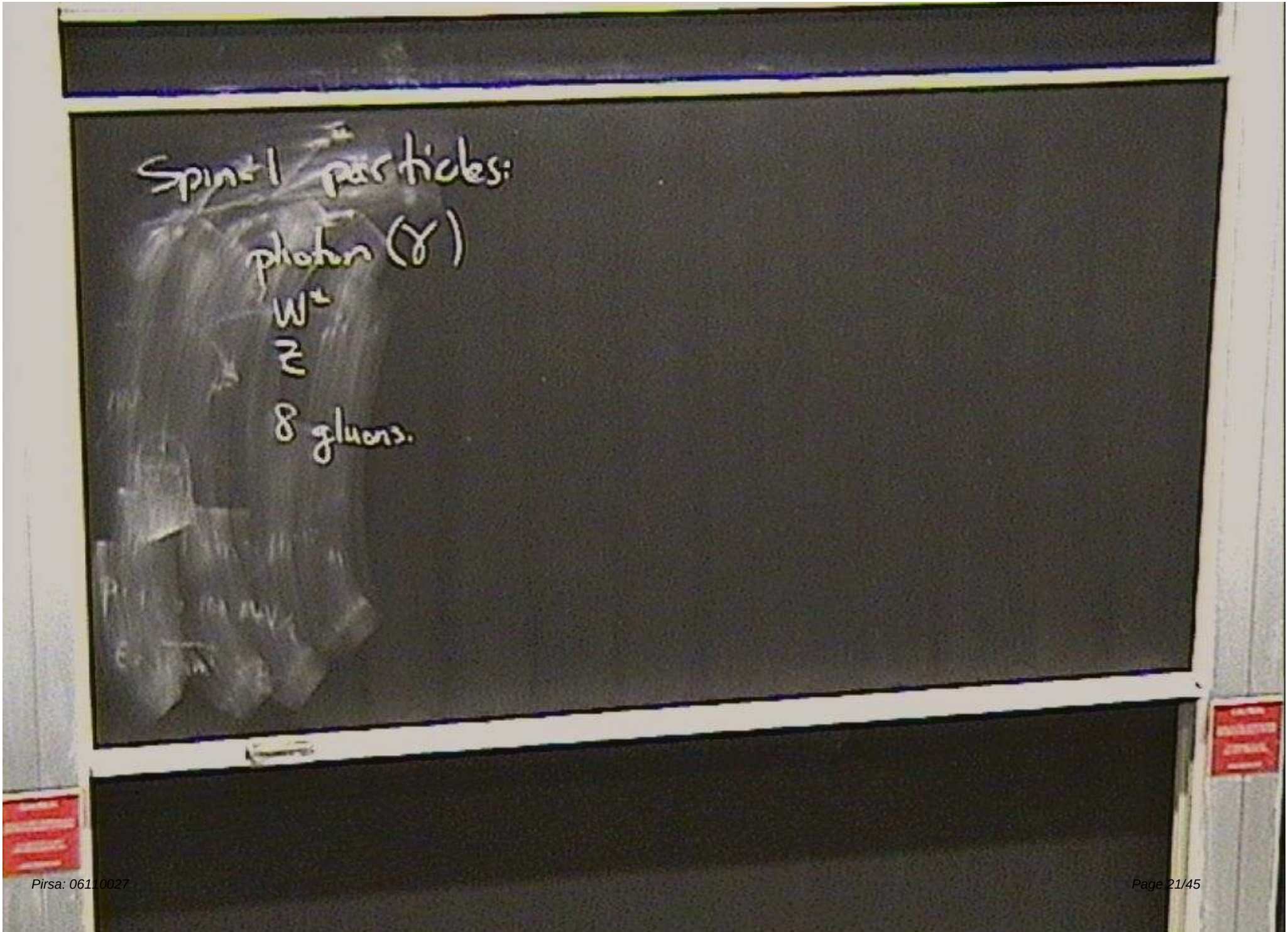

proton 938 MeV
(uud stable)
neutron (udd 940 MeV)
u ~5 MeV
d ~10 MeV
s ~150 MeV
τ⁻ ~1 GeV
W± ~80 GeV
Z⁰ ~90 GeV
~0

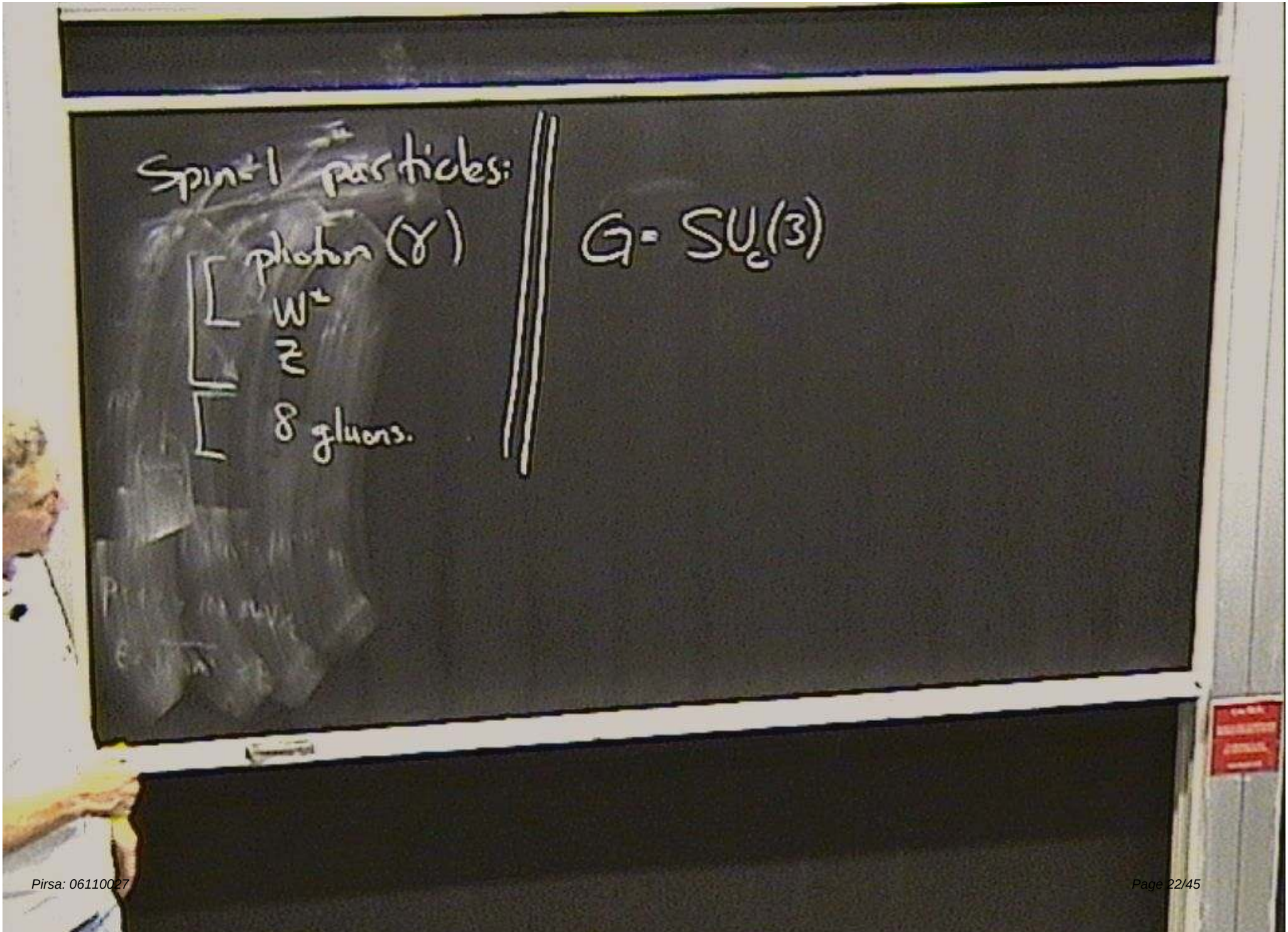

proton 938 MeV
(uud)
neutron (udd)
940 MeV
u ~5 MeV
d ~10 MeV
s ~150 MeV
τ⁻ ~1 GeV
W± ~80 GeV
Z⁰ ~90 GeV
~0

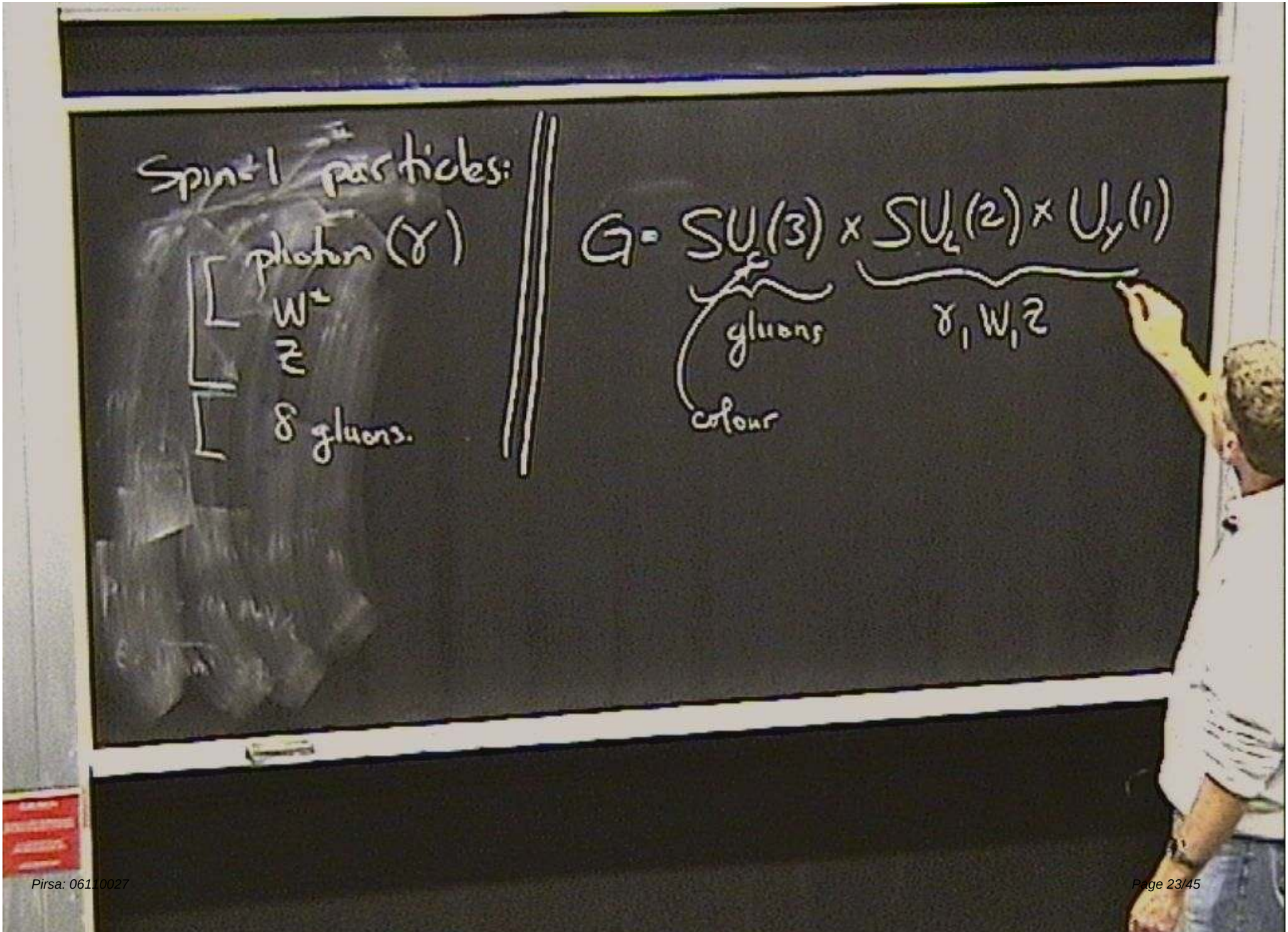

proton 938 MeV
(uud)
neutron (udd)
940 MeV
u ~5 MeV
d ~10 MeV
s ~150 MeV
τ⁻ ~1 GeV
W± ~80 GeV
Z⁰ ~90 GeV
8 gluons ~0

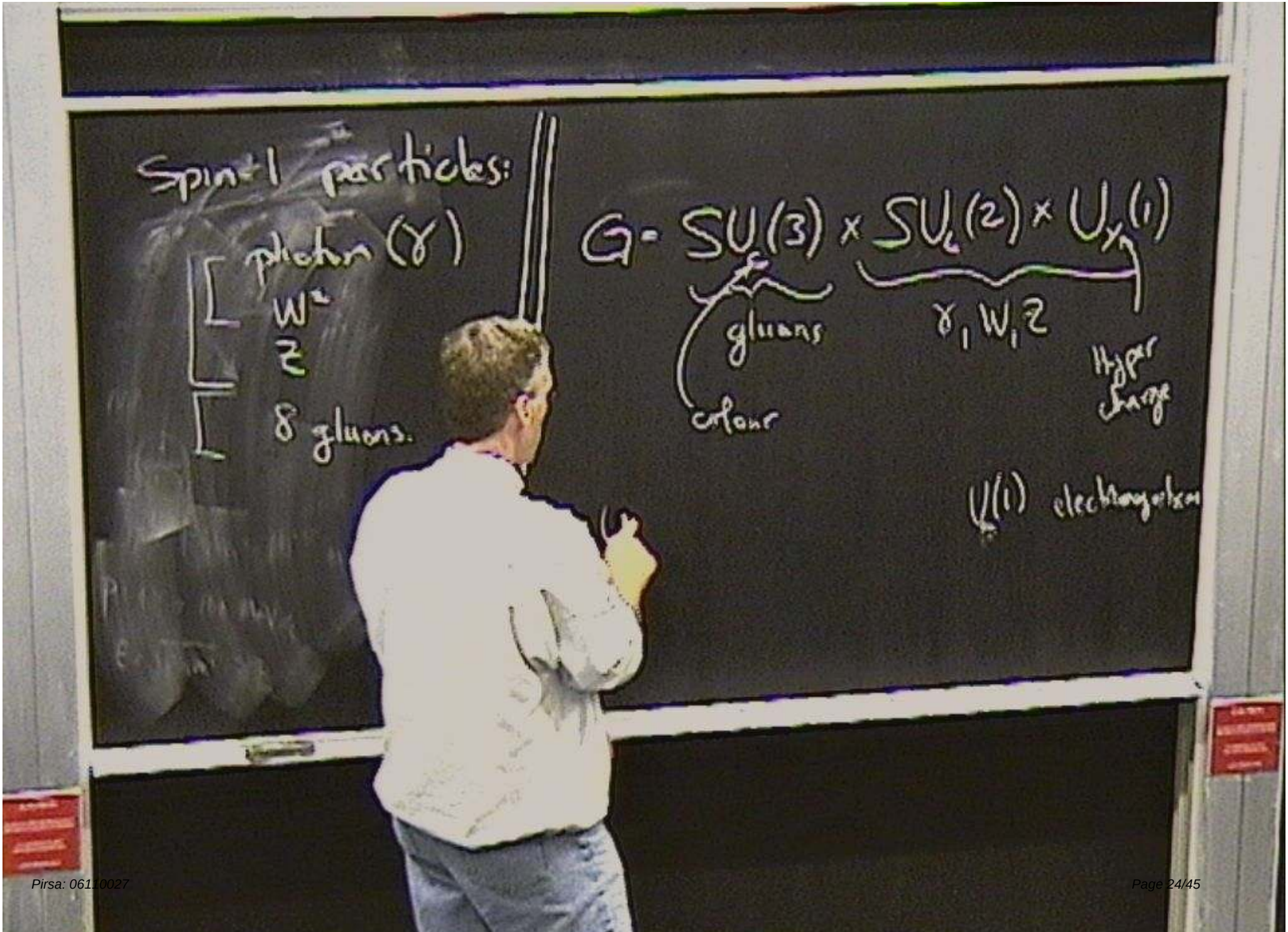


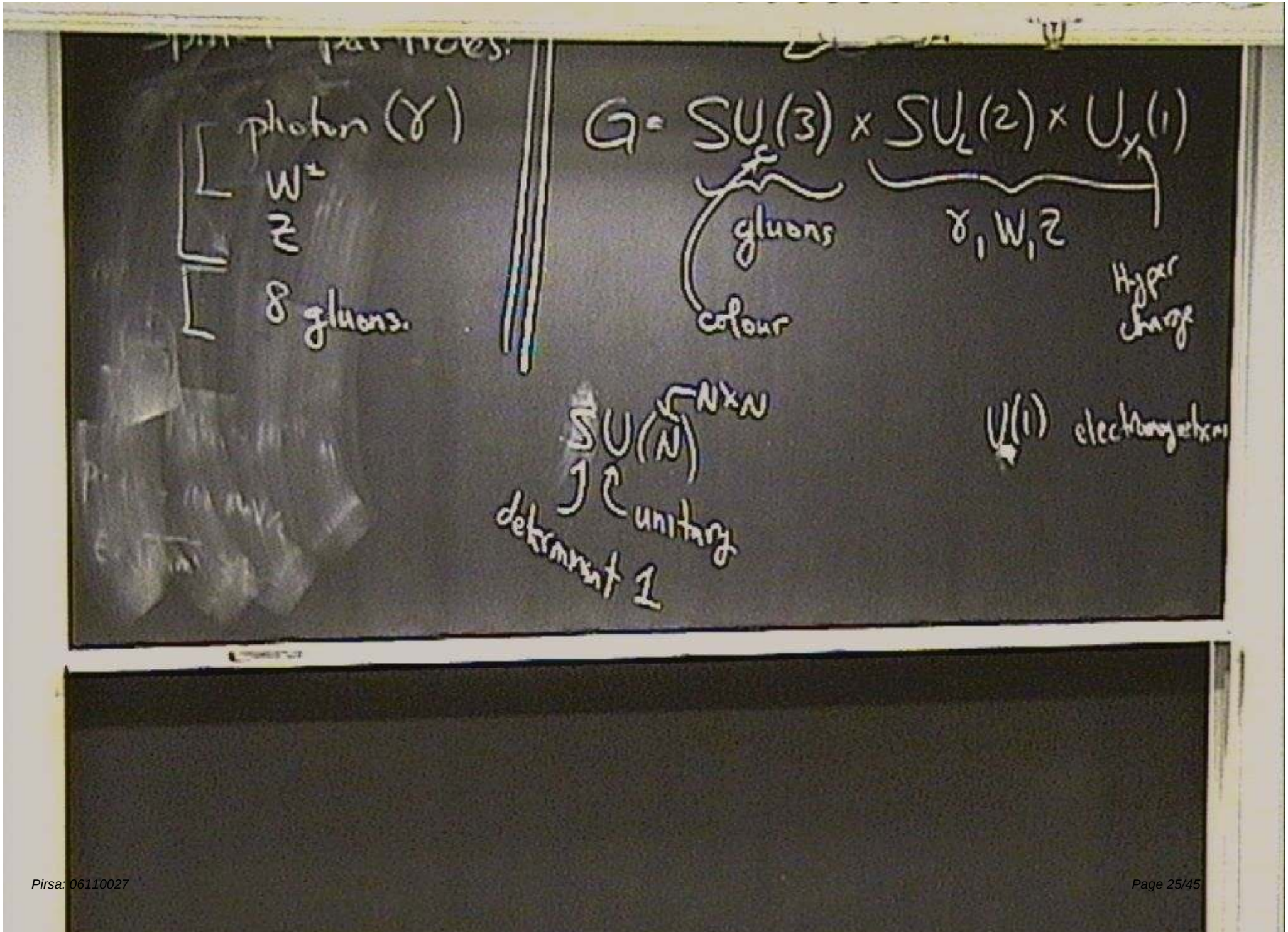
< 1 eV? ½ 0 0 ±1 ±1 0 0
0.511 MeV ½ ∓1 0 ±1
105 MeV ½ ∓1 0 ±1 ±1 0 0
140 MeV 0 0 0 ±1 0 ±1 0
±1 0 0 0 0 0
940 MeV ½ 0 1 0 0 0 0
u ~5 MeV ½ 2/3 ⅓ 0 0 0 0
d ~10 MeV ½ -⅓ ⅓ 0 0 0 0
s ~150 MeV ½ -⅓ ⅓ 0 0 0 0
t ~180 GeV ½ 2/3 ⅓ 0 0 0 0
τ ~1 GeV ½ -1 0 1 0 0 1
~80 GeV 1 ±1 0 0 0 0 0
Z° ~90 GeV 1 0 0 0 0 0 0
8 gluons ~0 1 0 0 0 0 0 0

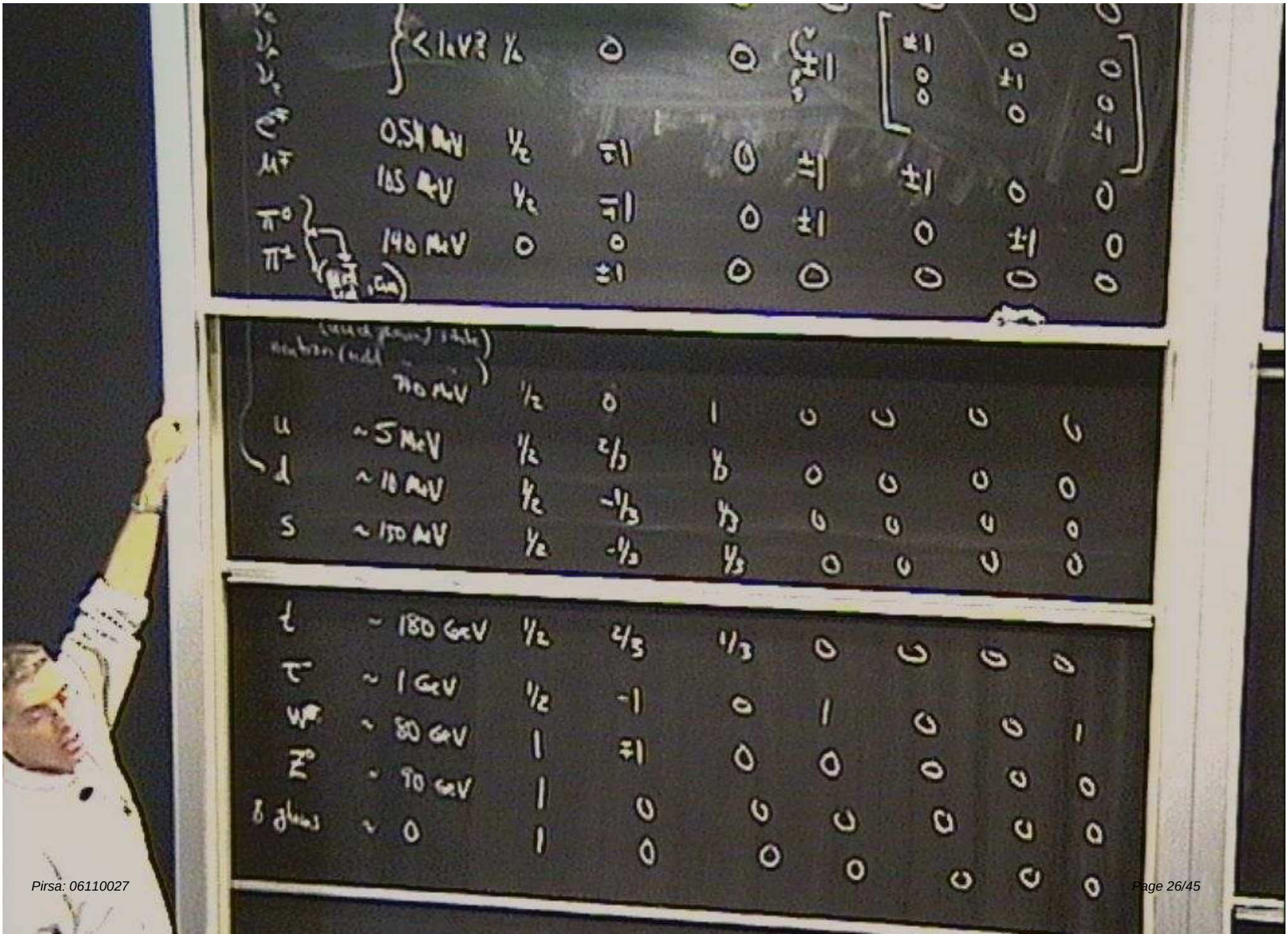

Spin-1 particles:
photon (γ)
W±
Z
8 gluons.

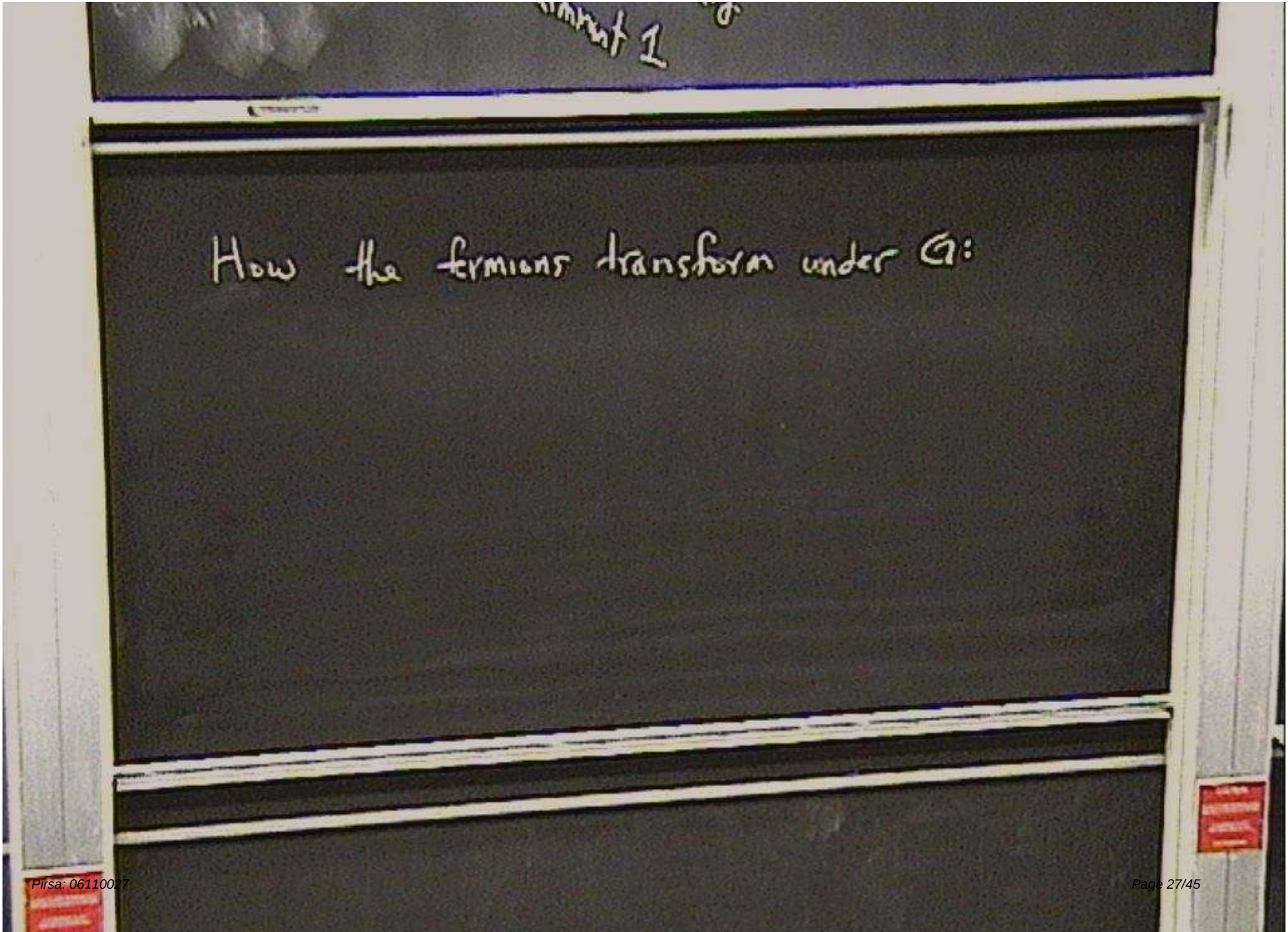

Spin=1 particles:
photon (γ)
W±
Z
8 gluons.
G = SU_c(3)


Spin-1 particles:
photon (γ)
W±
Z
8 gluons.
G = SU_c(3) × SU_L(2) × U_Y(1)
gluons
colour
γ, W, Z


Spin=1 particles:
photon (γ)
W±
Z
8 gluons.
G = SU(3) × SU_L(2) × U_Y(1)
gluons
colour
γ, W, Z
Hyper charge
U(1) electromagnetism


photon (γ)
W±
Z
8 gluons.
G = SU_c(3) × SU_L(2) × U_Y(1)
gluons
colour
γ, W, Z
Hyper charge
SU(N)
N×N
unitary
determinant 1
U(1) electromagnetism


< 1 eV?
0.5 MeV
105 MeV
140 MeV
~ 5 MeV
~ 180 GeV
~ 1 GeV
~ 80 GeV
~ 90 GeV
~ 0


How the fermions transform under G:

How the fermions transform under G:

$(r_3, r_2)_y$ ← hypercharge.

r_2 ← dimension of SU(2)

r_3 ← dimension of SU(3)

How the fermions transform under G:

$(r_3, r_2)_Y$ ← hypercharge.

r_2 ← dimension of $SU(2)$

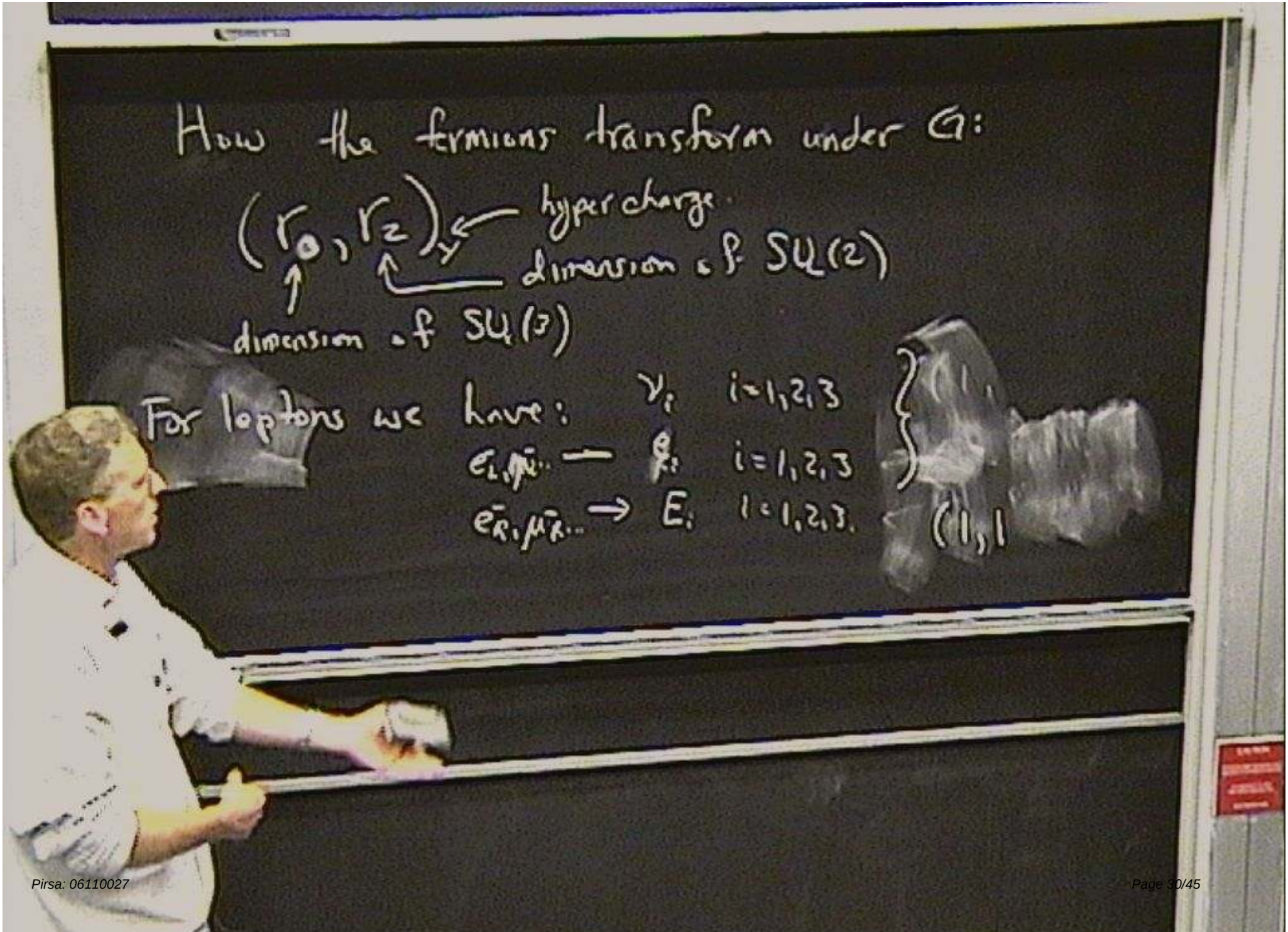
r_3 ↑ dimension of $SU(3)$

For leptons we have:

ν_i $i=1,2,3$

e_i $i=1,2,3$ ← LH: e_L^-, μ_L^-, τ_L^-

E_i $i=1,2,3$ ← RH: e_R^-, μ_R^-, τ_R^-


How the fermions transform under G:
$(r_3, r_2)_y$
hypercharge
dimension of SU(2)
dimension of SU(3)
For leptons we have:
ν_i $i=1,2,3$
$e_{L,i}, \bar{\nu}_i \rightarrow$ ℓ_i $i=1,2,3$
$e_{R,i}, \bar{\mu}_{R,i} \rightarrow$ E_i $i=1,2,3$
$(1,1$

How the fermions transform under G:

$(r_3, r_2)_y$ ← hypercharge

r_2 ← dimension of SU(2)

r_3 ↑ dimension of SU(3)

For leptons we have:

ν_i $i=1,2,3$ } $(1,1)_0$

$e_i, \mu_i \ldots$ — E_i $i=1,2,3$ }

$e_{Ri}, \mu_{Ri} \ldots \rightarrow E_i$ $i=1,2,3$ $(1,1)_{+1}$

How the fermions transform under G:

$(r_3, r_2)_y$ ← hypercharge.

r_2 ← dimension of $SU_L(2)$

r_3 ← dimension of $SU_c(3)$

For leptons we have:

ν_i $\quad i = 1,2,3$

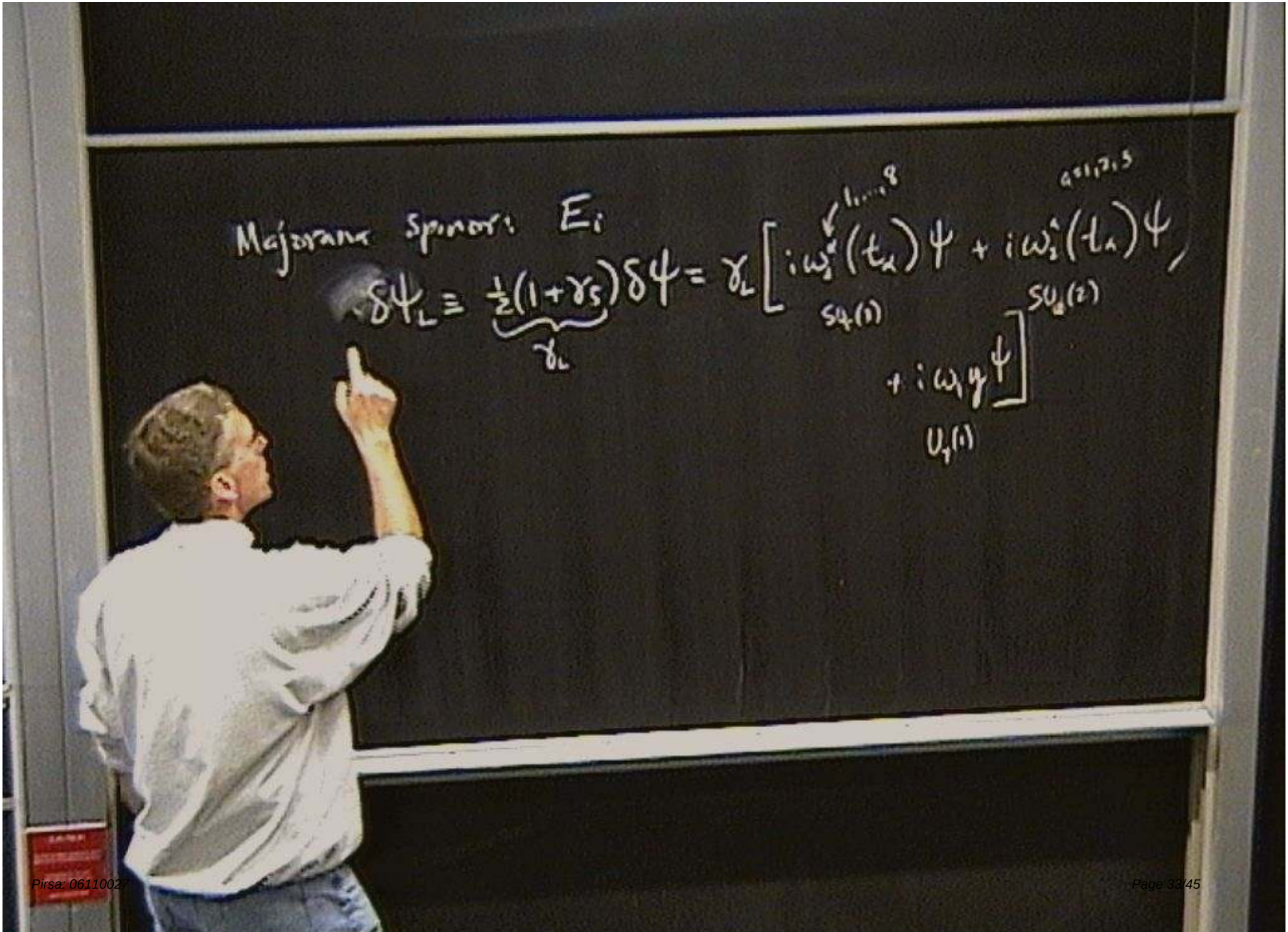
$e_i, \mu_i \ldots \longrightarrow e_i \quad i = 1,2,3$

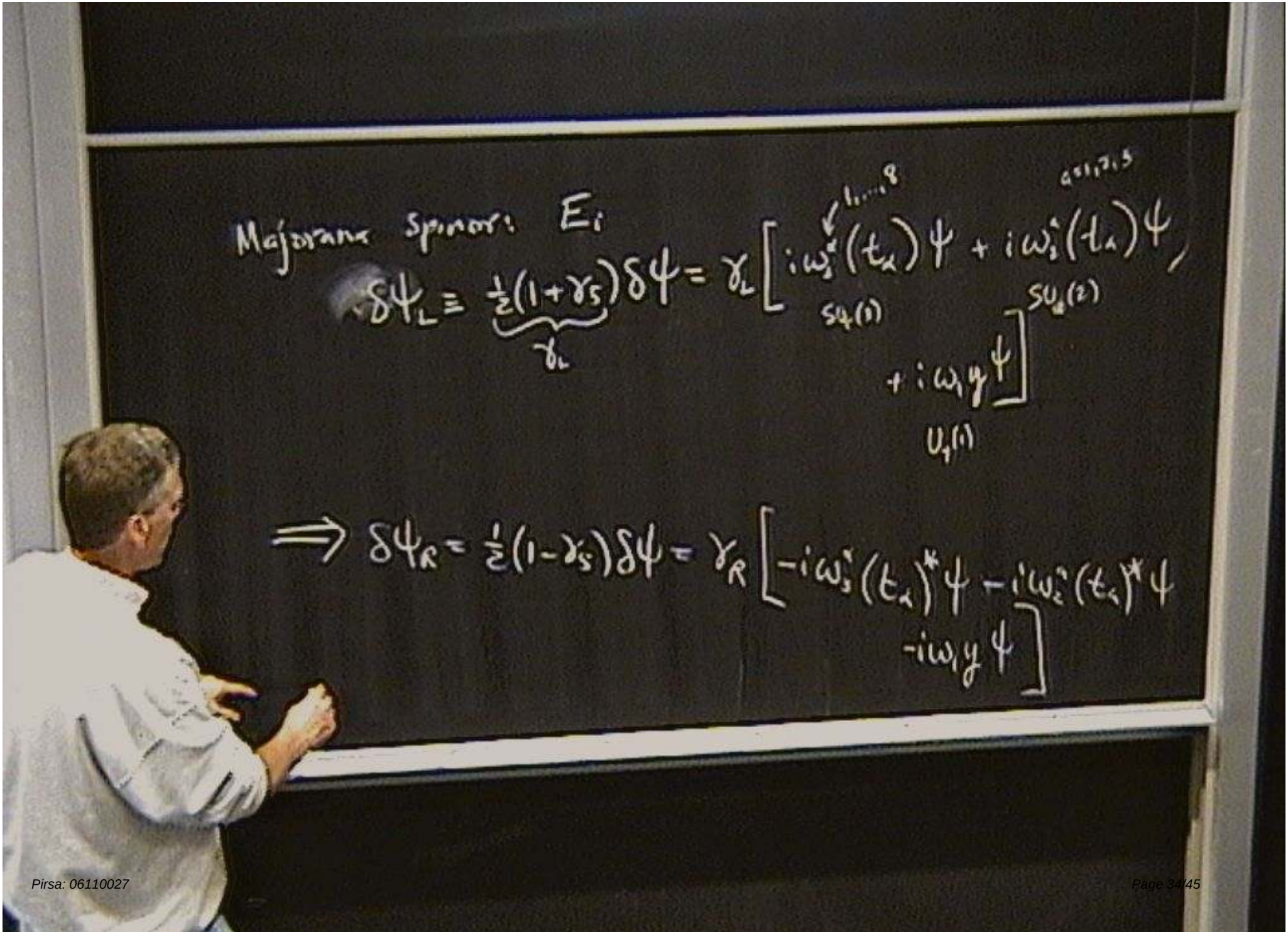
$\bar{e}_i, \bar{\mu}_i \ldots \longrightarrow E_i \quad i = 1,2,3.$

"family"

$\left.\begin{matrix} \\ \\ \end{matrix}\right\} (1,2)_{-1/2}$

$(1,1)_{+1}$


Majorana Spinors: E_i
$\delta\psi_L \equiv \underbrace{\frac{1}{2}(1+\gamma_5)}_{\gamma_L}\delta\psi = \gamma_L\Big[i\omega_1^a(t_a)\psi + i\omega_2^{\hat{a}}(t_{\hat{a}})\psi + i\omega_3 y\psi \Big]$
$a=1,\dots,8$
$\hat{a}=1,2,3$
$SU_3(1)$
$SU_2(2)$
$U_1(1)$


Majorana spinors: E_i
$\delta\psi_L \equiv \underbrace{\frac{1}{2}(1+\gamma_5)}_{\gamma_L}\delta\psi = \gamma_L\Big[i\omega_3^a(t_a)\psi + i\omega_2^a(t_a)\psi + i\omega_1 y\psi\Big]$
$a=1,\dots,8$
$SU_3(3)$
$SU_2(2)$
$U_1(1)$
$\Rightarrow \delta\psi_R = \frac{1}{2}(1-\gamma_5)\delta\psi = \gamma_R\Big[-i\omega_3^a(t_a)^*\psi - i\omega_2^a(t_a)^*\psi - i\omega_1 y\psi\Big]$

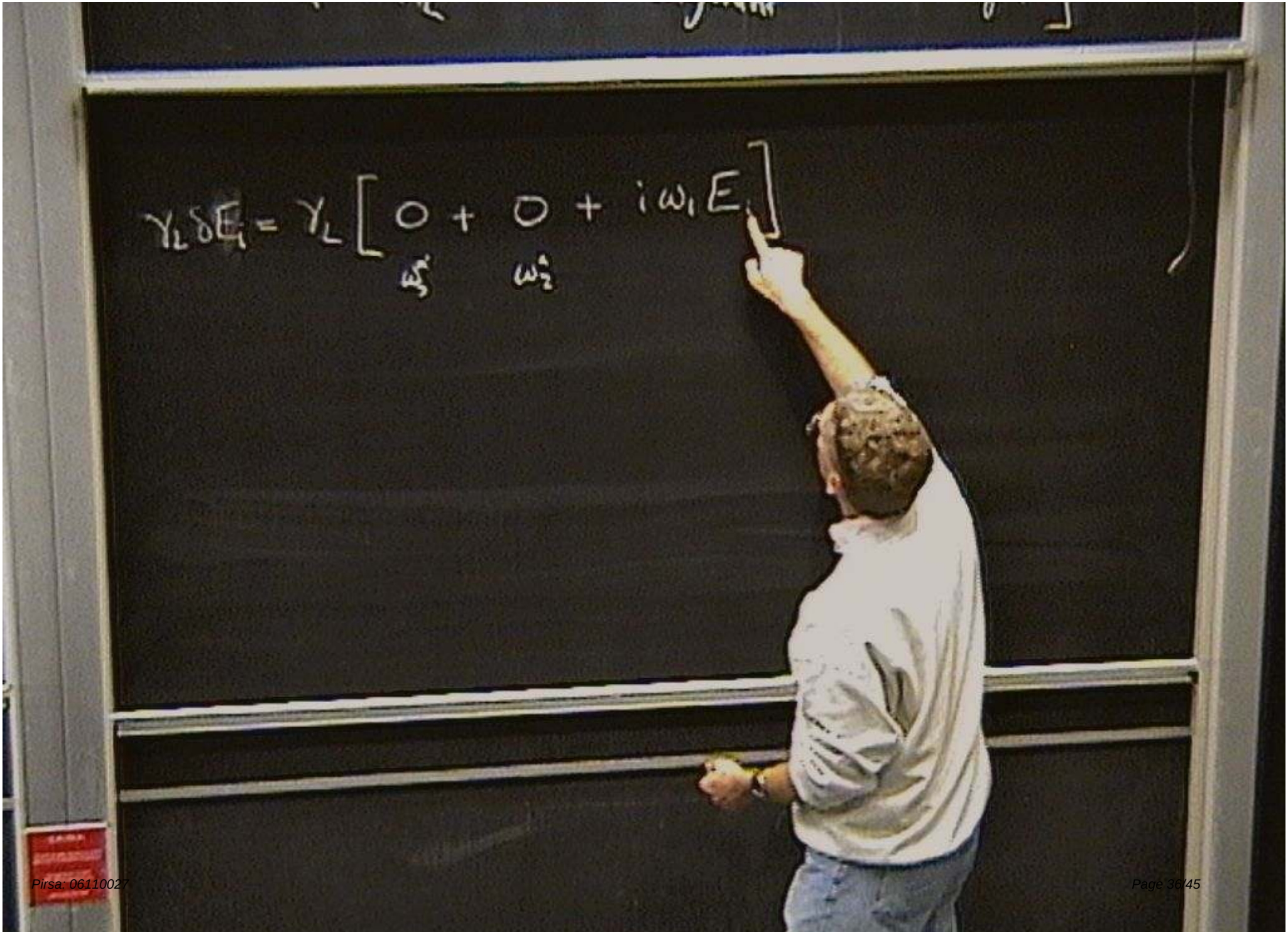
Majorana spinors: E_i

$$\delta\psi_L \equiv \underbrace{\tfrac{1}{2}(1+\gamma_5)}_{\gamma_L}\delta\psi = \gamma_L\Big[\underbrace{i\omega_3^a(t_a)}_{SU_4(1)}\psi + \underbrace{i\omega_2^a(t_a)}_{SU_2(2)}\psi + i\omega_1 y\psi\Big]$$

$a=1,\dots,8$; $a=1,2,3$; $U_1(1)$

$$\Longrightarrow \delta\psi_R = \tfrac{1}{2}(1-\gamma_5)\delta\psi = \gamma_R\Big[-i\omega_3^a(t_a)^*\psi - i\omega_2^a(t_a)^*\psi - i\omega_1 y\psi\Big]$$

$\begin{pmatrix} L \\ R \end{pmatrix}$ $\quad \psi_R = M\psi_L^*$ if ψ is majorana


$\gamma_L \delta E_1 = \gamma_L [0 + 0 + i\omega_1 E_1]$
ω_1 ω_2

How the fermions transform under G:

$(r_3, r_2)_Y$ ← hypercharge

r_3: dimension of $SU_c(3)$

r_2: dimension of $SU_L(2)$

For leptons we have: ν_i $i=1,2,3$

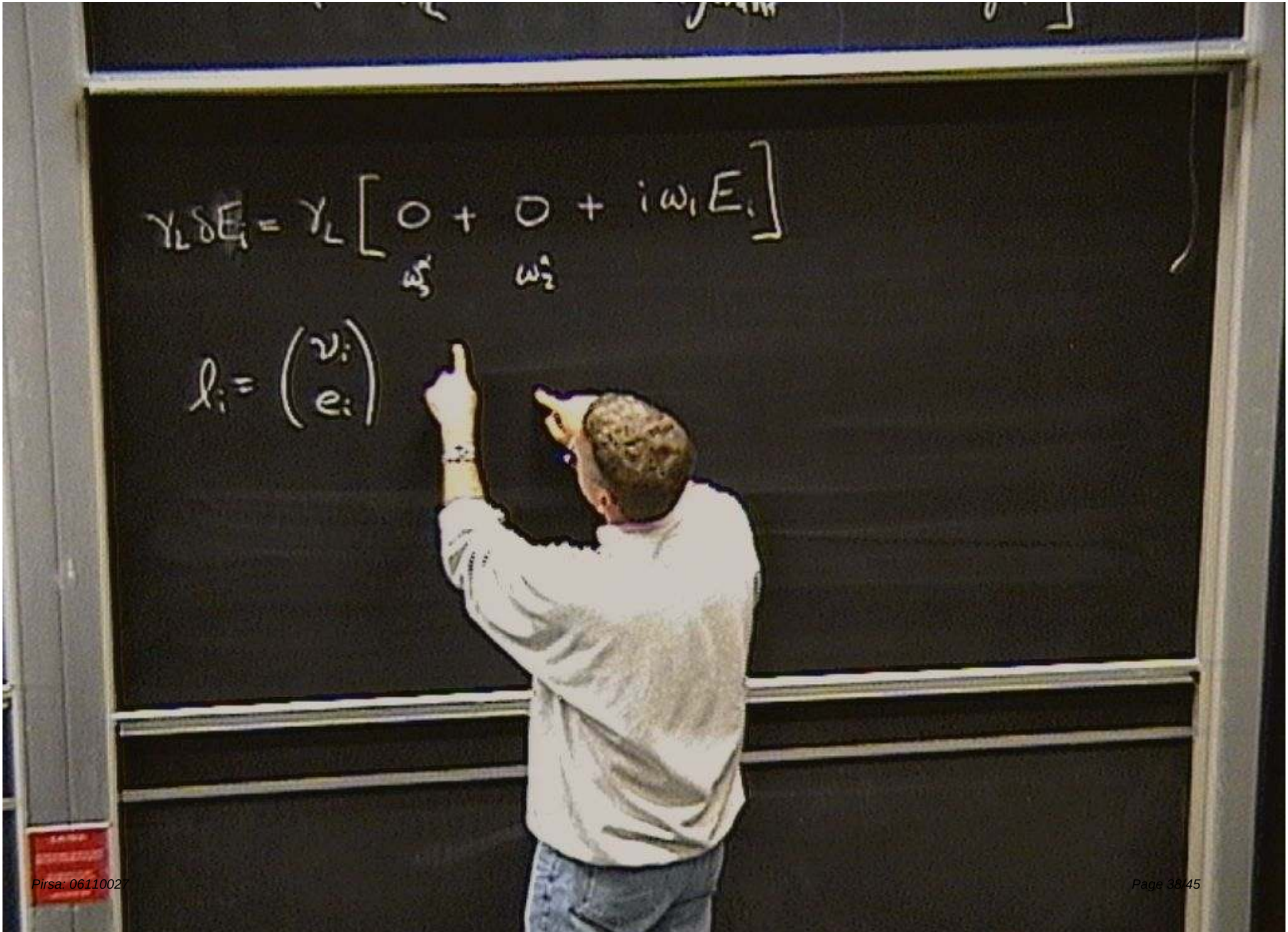
$e, \mu, \ldots \rightarrow E_i$ $i=1,2,3$

$e^c, \mu^c, \ldots \rightarrow E_i^c$ $i=1,2,3$

"family"

$\left.\begin{matrix} \\ \\ \end{matrix}\right\} (1,2)_{-1/2}$

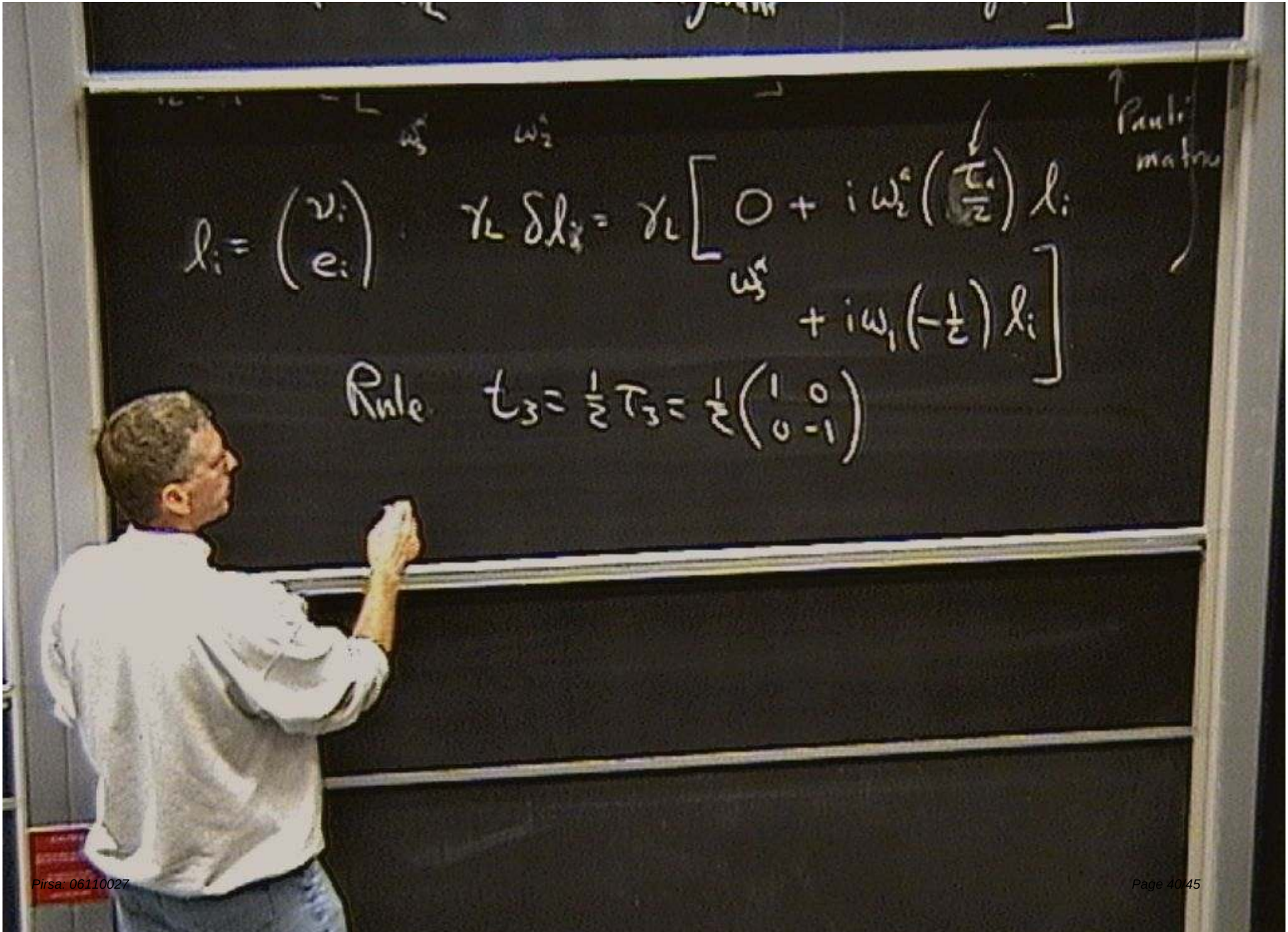
$(1,1)_{+1}$


$\gamma_L \delta E_i = \gamma_L [0 + 0 + i\omega_i E_i]$
ω_i ω_i^*
$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$

$$\gamma_L \delta E_i = \gamma_L \Big[\underset{\omega_3^2}{0} + \underset{\omega_2^2}{0} + i\omega_1 E_i \Big]$$

$t_a = \frac{1}{2}\tau_a$ ← Pauli matrices

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix} \qquad \gamma_L \delta l_i = \gamma_L \Big[\underset{\omega_3^2}{0} + i\omega_2^2 \left(\frac{\tau_2}{2}\right) l_i + i\omega_1 \left(-\frac{1}{2}\right) l_i \Big]$$


$\omega_3^i \quad \omega_2^i$
Pauli matrices
$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$
$\gamma_L \delta l_i = \gamma_L \left[0 + i\omega_2^i \left(\frac{\tau_i}{2}\right) l_i \right.$
ω_3^i
$\left. + i\omega_1 \left(-\frac{1}{2}\right) l_i \right]$
Rule $t_3 = \frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

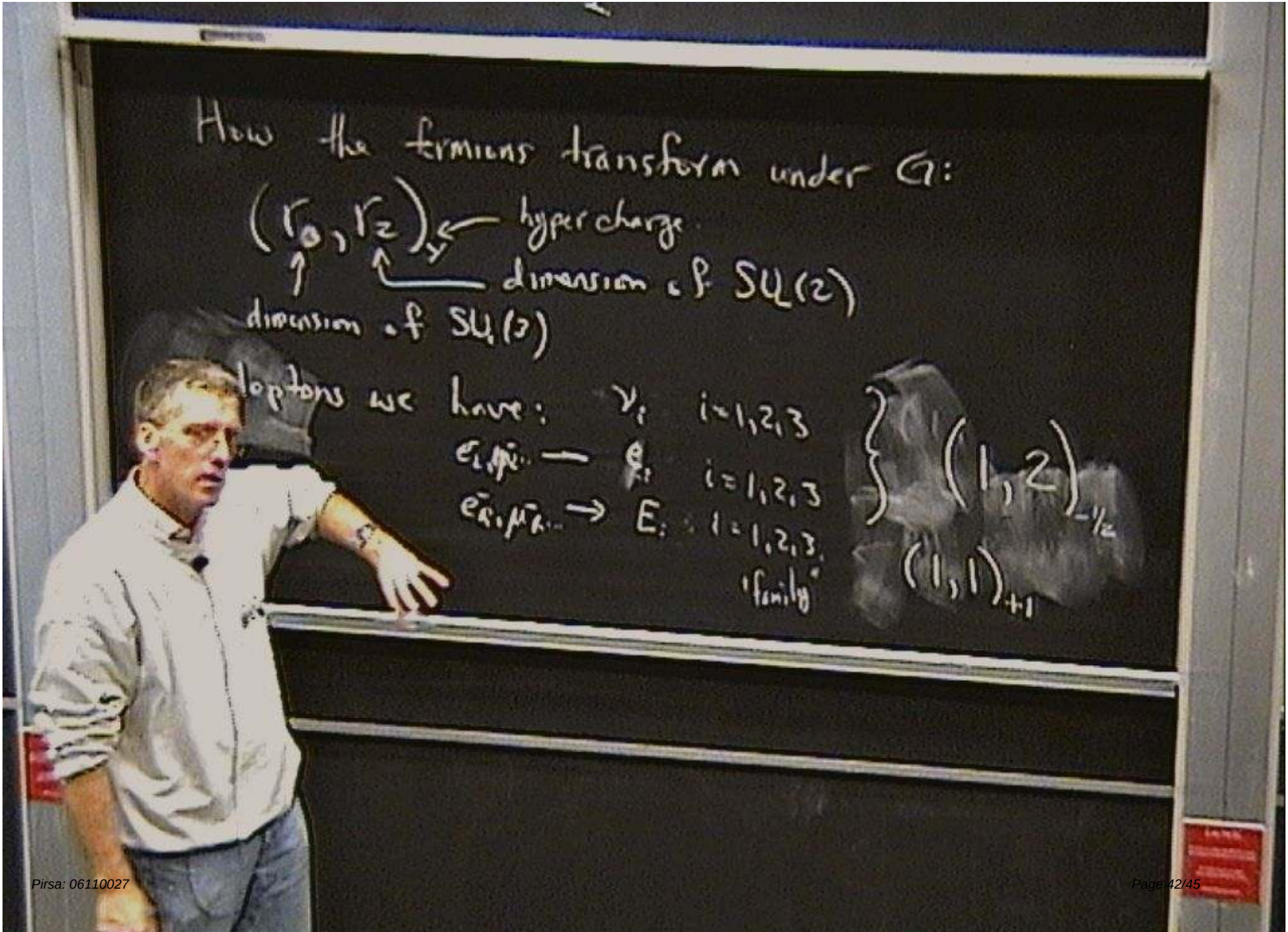
$$\gamma_L \delta E_i = \gamma_L \Big[\underset{\omega_3^a}{0} + \underset{\omega_2^a}{0} + i\omega_1 E_i \Big]$$

$t_a = \frac{1}{2}\tau_a$ ← Pauli matrices

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix} \qquad \gamma_L \delta l_i = \gamma_L \Big[\underset{\omega_3^a}{0} + i\omega_2^a \left(\tfrac{\tau_a}{2}\right) l_i + i\omega_1 \left(-\tfrac{1}{2}\right) l_i \Big]$$

Rule $t_3 = \frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Rule $Q = t_3 + Y$ for the particle destroyed by the LH field.


How the fermions transform under G:
$(r_3, r_2)_Y$ ← hyper charge
dimension of SU(2)
dimension of SU(3)
leptons we have: ν_i $i=1,2,3$
e_i $i=1,2,3$
E_i $i=1,2,3$
'family'
$(1,2)_{-1/2}$
$(1,1)_{+1}$

$$\gamma_L \delta E_i = \gamma_L \Big[\underbrace{0}_{\omega_3^i} + \underbrace{0}_{\omega_2^i} + i\omega_1 E_i \Big]$$

$t_A = \frac{1}{2}\tau_A$ ← Pauli matrix

$$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix} \qquad \gamma_L \delta l_i = \gamma_L \Big[\underbrace{0}_{\omega_3^i} + i\omega_2^i \left(\tfrac{\tau_2}{2}\right) l_i + i\omega_1 \left(-\tfrac{1}{2}\right) l_i \Big]$$

Rule $t_3 = \frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Rule $Q = t_3 + Y$ for the particle destroyed by the LH field.

$$\gamma_L \delta E_i = \gamma_L \Big[\underbrace{0}_{\omega_3^i} + \underbrace{0}_{\omega_2^i} + i\omega_1 E_i \Big] \qquad t_A = \tfrac{1}{2}\tau_A$$

↑ Pauli matrix

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix} \qquad \gamma_L \delta l_i = \gamma_L \Big[\underbrace{0}_{\omega_3^i} + i\omega_2^i \Big(\frac{\tau_i}{2}\Big) l_i + i\omega_1 \Big(-\tfrac{1}{2}\Big) l_i \Big]$$

Rule $t_3 = \frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Rule $Q = t_3 + Y$ for the particle destroyed by the LH field.

How the fermions transform under G:

$(r_3, r_2)_Y$ ← hypercharge

r_3: dimension of $SU_c(3)$

r_2: dimension of $SU_L(2)$

For leptons we have: ν_i $i=1,2,3$

$e_{L,\mu_L,\ldots} \longrightarrow e_i$ $i=1,2,3$

$e_{R,\mu_R,\ldots} \longrightarrow E_i$ $i=1,2,3$ "family"

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

$\left.\begin{matrix} (1,2)_{-1/2} \\ (1,1)_{+1} \end{matrix}\right\}$