Title: Standard Model Lecture

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Collection: Standard Model 2023/24

Date: January 30, 2024 - 9:00 AM

URL: https://pirsa.org/24010047

However what are Quantum numbers of $\nu_R$ ?

| $SU(2)$ | $U(1)_Y$ |
| --- | --- |
| 1 | 0 ! |

Singlet under all gauge groups in SM.

$\therefore$ its own antiparticle $\Rightarrow$ majorana field

mass term $\nu_R \nu_R$ allowed

Neutrino's have mass!

$$\mathcal{L}_{SM} \Rightarrow m_{\nu_1} = m_{\nu_2} = m_{\nu_3} = 0$$

$$Exp \Rightarrow \Delta m^2_{12} = 7.37 \times 10^{-5}\, eV^2$$

$$\Delta m^2_{13/32} = 2.5 \times 10^{-3}\, eV^2$$

$$|\nu\rangle \rightarrow |\nu)$$

Schr... 

So how to make $\Delta m^2_{\nu_{12}} \neq 0$ , $\Delta m^2_{\nu_{13}} \neq 0$

'Dirac Masses' – Add to SM $\rightarrow \mathcal{L}_{SM} - [\tilde{H}^{\dagger} \bar{\nu}_R Y_\nu \ell_L + h.c]$

Higgs gets vev $\Rightarrow -\frac{v}{\sqrt{2}} \bar{\nu}_R^{i} Y_L^{ij} \nu_L^{j} + h.c.$

Rotate to mass eigenstates $\nu_L \rightarrow U(\nu, L)\, \nu_L'$ $\quad M_\nu = \frac{v}{\sqrt{2}} Y_L$

$\nu_R \rightarrow U(\nu, R)\, \nu_R'$ (not diagonal to start)

## Majorana masses vs dirac masses

When fermion charged under $U(1)_Y$

$H \, \bar{\Psi}_L \Psi_R$ dirac masses

$\Sigma(x)$ $SU(2)_L \times SU(2)_R$

$= \exp(i \sigma \cdot \pi_a / v)$

Recall Lorentz group $\rightarrow$ rotations $J_i$

boosts $K_i$

$$[J_i, J_j] = i \varepsilon_{ijk} J_k$$

Hermitian generators $\Rightarrow$

$$[K_i, K_j] = -i \varepsilon_{ijk} J_k$$

$$[J_i, K_j] = i \varepsilon_{ijk} K_k$$

Denote a $(1/2, 0)$ Weyl spinor $\chi$ : $\chi \to e^{-i/2\,\sigma\cdot\theta}\chi$ under rotatio

$\chi \to e^{-1/2\,\sigma\cdot\eta}\chi$ under boos

$(\tanh \eta = \beta$

rapidity

$$\mathcal{L} = \frac{1}{2} m \left(\chi^T \varepsilon \chi + h.c.\right)$$ is allow

$$\varepsilon = i\sigma_2$$

$^{\sigma\cdot\theta}\chi$ under rotations

$^{\sigma\cdot n}\chi$ under boosts

$(\tanh n = \beta)$

rapidity

$\chi + h.c.)$ <u>is allowed</u>

$= i\sigma_2$

Explicitly $\chi^T \varepsilon \chi \to \chi^T M^T \varepsilon M \chi$ where $M = e^{i/2\,\sigma\cdot\theta}$ or $e^{-1/2\,\sigma\cdot n}$

In components $(M^T)_{\alpha\beta}\, \varepsilon_{\beta\gamma}\, M_{\gamma\delta} = \varepsilon_{\beta\gamma}\, M_{\beta\alpha}\, M_{\gamma\delta}$

$= \varepsilon_{\alpha\delta} \det M$

$= \varepsilon_{\alpha\delta}$

<u>Majorana mass term allowed</u>

mass term $\bar{\nu}_R \nu_R$ allowed

Choice: $m <<< y v$ Dirac mass

$m >>> y v \to$ Seesaw model

$p^2/m^2 << 1$

Expect $\underset{(m_\nu = 0)}{\mathcal{L}_{SM}} + \frac{\mathcal{L}^5}{M} + \frac{\mathcal{L}^6}{M^2} + \frac{\mathcal{L}^7}{M^3} + \dots$

$\mathcal{L}^5 = \frac{C_{mn}}{\Lambda}$

$$\mathcal{L}^5 = \frac{C_{mn}}{\Lambda}\left[ (\overline{\ell^c_m}\tilde{H}^*)(\tilde{H}^\dagger \ell^n) + h.c \right] \quad \underline{\text{allowed}}$$

$$\tfrac{3}{2} \quad 1 \quad 1 \quad \tfrac{3}{2}$$

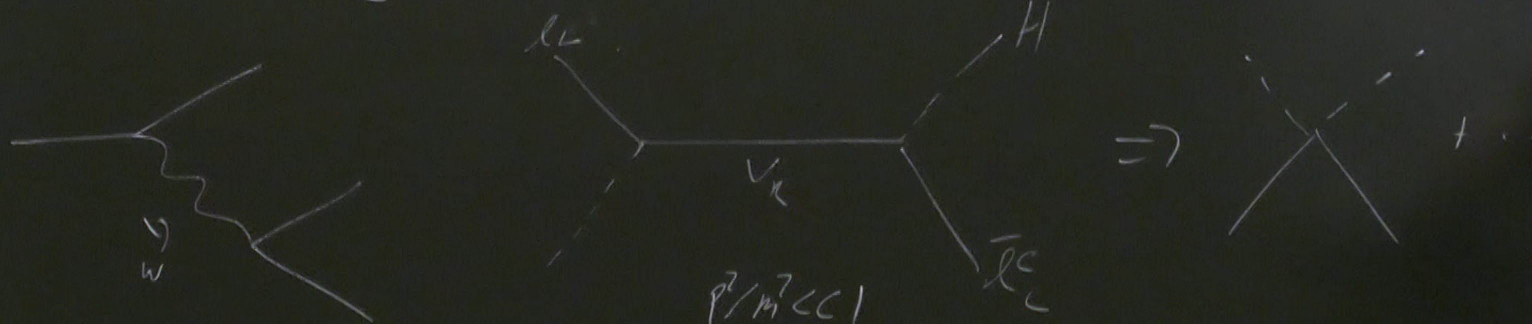
$$\langle H \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \Rightarrow -\frac{m_{\nu,k}}{2} \overline{\nu_L^{c,k}} \nu_L^k + h.c$$

By assumption $\Lambda \gg v$

$$m_{\nu,k} = -\frac{v^2}{2\Lambda} U^T(\nu,L)\, C_{mn}\, U(\nu,L)$$

Seesaw Model:  $\psi^c = C\bar{\psi}^T$, $C = -i\gamma_2\gamma_0$

$$\mathcal{L}_{SM} + \frac{1}{2}\bar{\nu}_R^p(i\not\partial - m_p)\nu_R^p - \bar{\ell}_L^\beta \tilde{H}(Y_\nu^\dagger)_{\beta p}\nu_R^p + h.c.$$



## Baryon number violation

$$\text{Baryon number} \equiv \frac{1}{3}\left(n_q - n_{\bar{q}}\right)$$

Global Symmetry

$$\psi_q \to e^{i\alpha_q}\psi_q$$

$$\psi_{\bar{q}} \to e^{-i\alpha_q}\psi_{\bar{q}}$$

Preserved lightest Ba

(proton

$\mathcal{L}_{Sm}$ classically preserve

violation

number $\equiv \frac{1}{3}(n_q - n_{\bar q})$

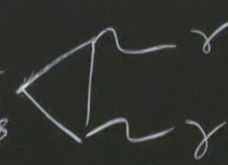
$\to e^{i\alpha_q}\psi_q$

$\to e^{-i\alpha_q}\psi_{\bar q}$

Preserved lightest Baryon stable
(proton)

Motivat

$\mathcal{L}_{SM}$ classically preserves global sym for $B$

anomalies $\to$ $J_B$ 


$J^\mu_B = (\bar u \gamma_\mu u + \bar d \gamma_\mu d + \ldots \text{quarks})$

KEK Japan

Motivation to $p \to \gamma \gamma \pi$

$\tau_{proton} = 8.2 \times 10^{33}$ years

$$\partial_\mu J^\mu_B \neq 0$$

for $B$

$$= \frac{g^2}{16\pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu}$$

$$\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$$

Baryon number violating ops

charge conjugation

Dim 6 $\quad Q^{duql}_{prst} = \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{ij} \left(d_p^{\alpha T} C\, u_r^{\beta}\right)\left(q_s^{i\gamma T} C\, \ell_t^{j}\right)$

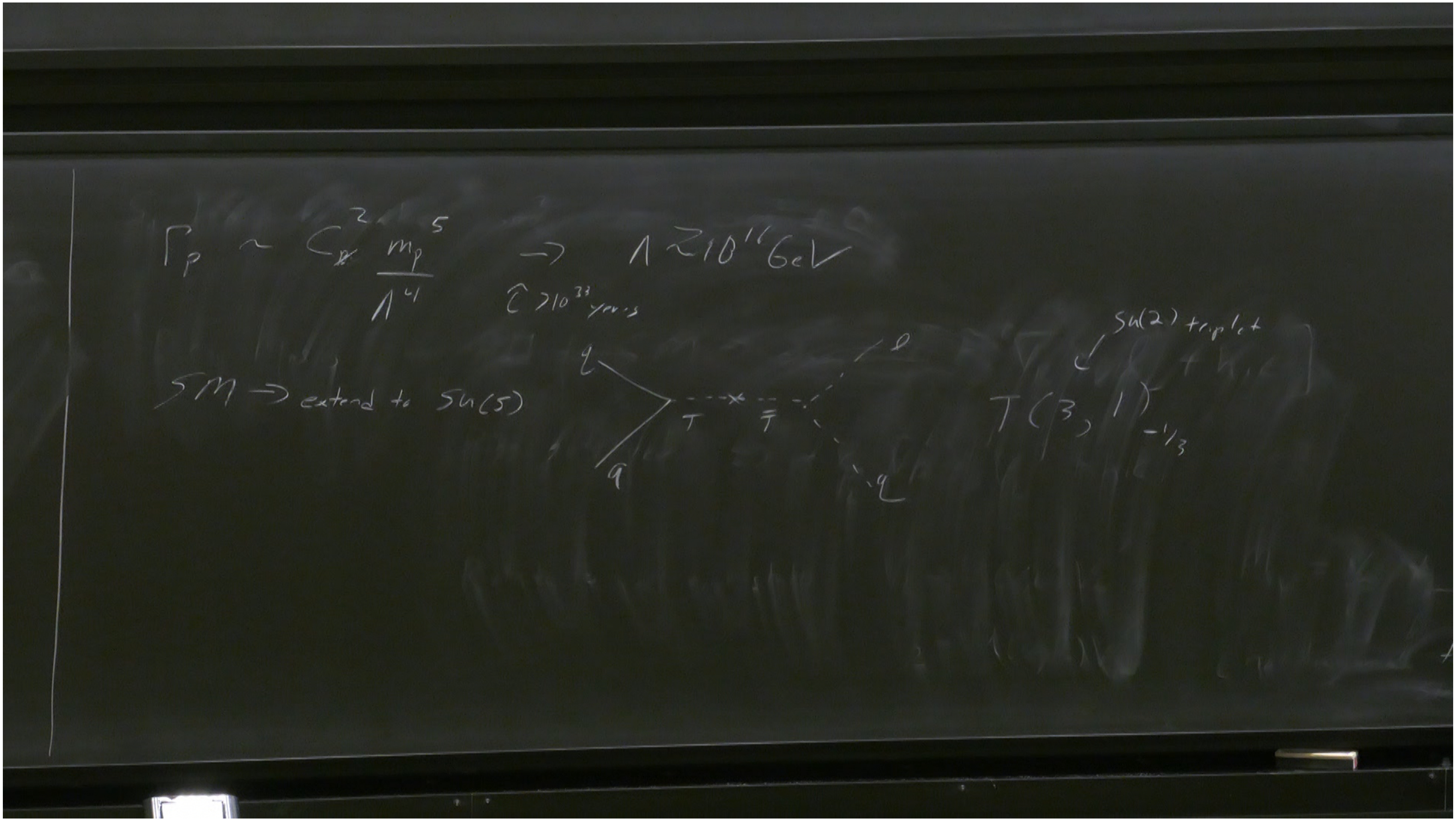
flavor $\qquad$ SU(3) $\qquad$ SU(2)

flavor prst

$Q^{qque}$

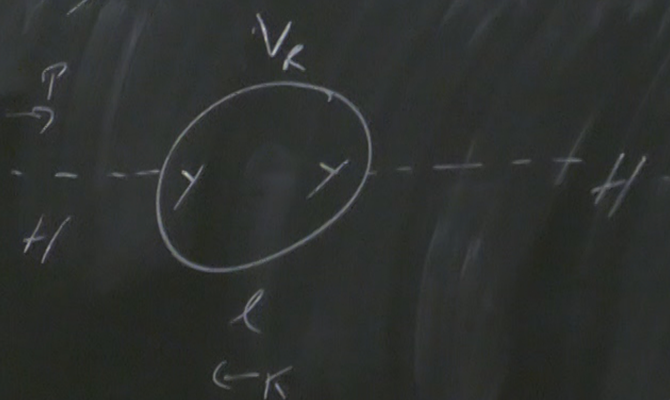
$Q^{qqql}$

$Q^{duue}$


$\Gamma_p \sim C_x^2 \frac{m_p^5}{\Lambda^4} \rightarrow \Lambda \gtrsim 10^{11}\,\mathrm{GeV}$
$\tau > 10^{33}$ years
SM → extend to SU(5)
q
q
T
$\bar{T}$
ℓ
q
SU(2) triplet
$T(3,1)_{-1/3}$

h.c.

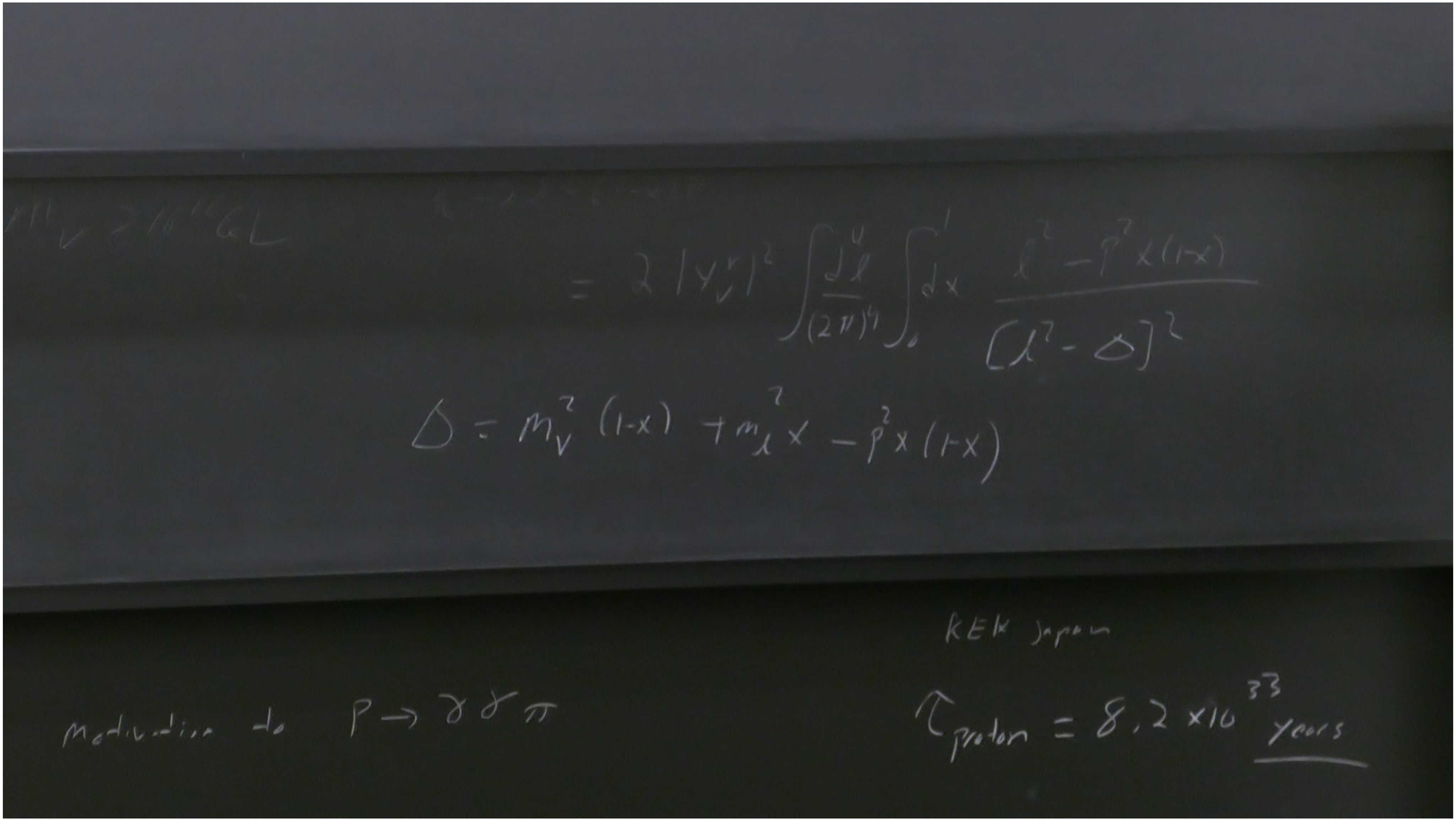
~~Necessarily~~ $\to k+p$




$$\Pi_{H^+H}(p) = \frac{1}{2}\,|Y_\nu^r|^2 \int \frac{d^4k}{(2\pi)}$$

$+ \ldots$ neutrino mass $m_\nu > 10^{14}\,\mathrm{GeV}$

Baryon number conservation


$= 2\,|Y_\nu^N|^2 \int \frac{d^4\ell}{(2\pi)^4} \int_0^1 dx \, \frac{\ell^2 - p^2 x(1-x)}{[\ell^2 - \Delta]^2}$
$\Delta = m_V^2 (1-x) + m_\ell^2 x - p^2 x(1-x)$
KEK Japan
Motivation to $p \to \gamma\gamma\pi$
$\tau_{proton} = 8.2 \times 10^{33}$ years

$$= -\frac{|Y_\nu|^2}{16\pi^2 \varepsilon}\left(2m_\ell^2 + 2m_\nu^2 - p^2\right)$$

$$- \frac{|Y_\nu|^2}{48\pi^2}\left(3m_\ell^2 + 3m_\nu^2 - p^2\right)$$

$(DH)^\dagger(DH)$

$+$ log terms

Shifted higgs

$\mathcal{L}_V =$

$\Rightarrow -$

Shifted higgs mass

Modi

$(2m_\lambda^2 + 2m_\nu^2 - p^2)$

$$\mathcal{L}_V = \frac{\lambda}{4}\left(H^\dagger H - v^2/2\right)^2$$

$(3m_\lambda^2 + 3m_\nu^2 - p^2)$

$(DH)^\dagger (DH)$

$$\Rightarrow -\frac{\lambda}{4} v^2 H^\dagger H - \frac{|y^\nu|^2 m_p^2}{8\pi^2} H^\dagger H$$

$$H^\dagger H\left[-\frac{\lambda}{4}v^2 - \frac{|y_\nu|^2 m_p^2}{8\pi^2}\right]$$