Neutrino Physics Course

Lecture XV

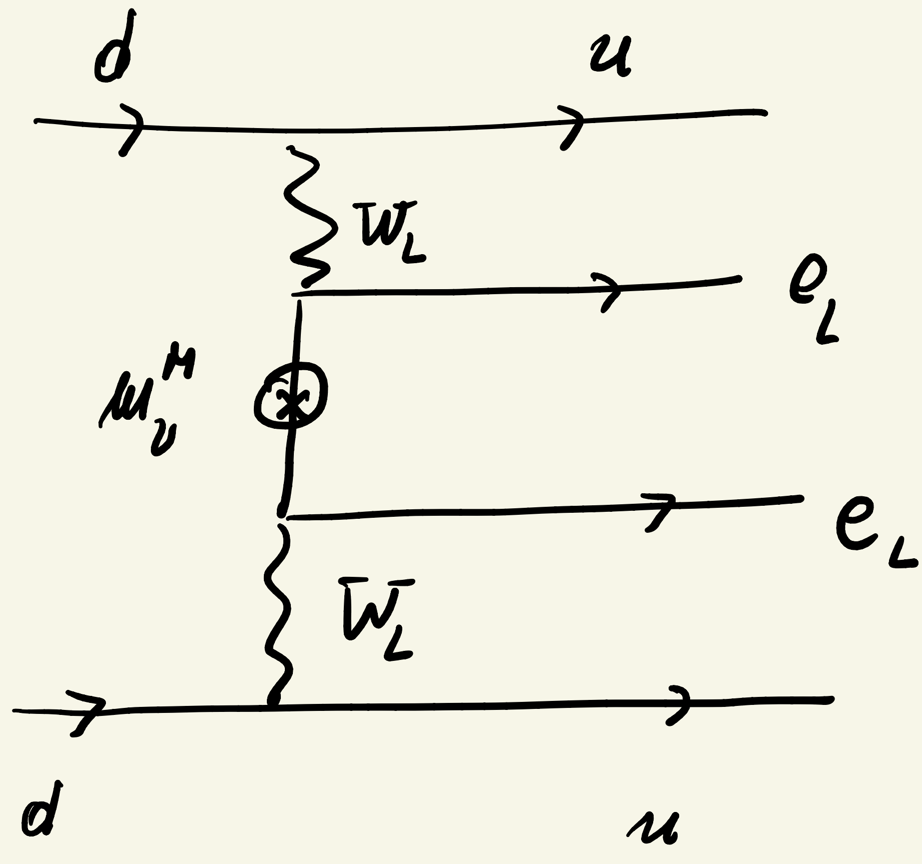
17/6/2023

LMU

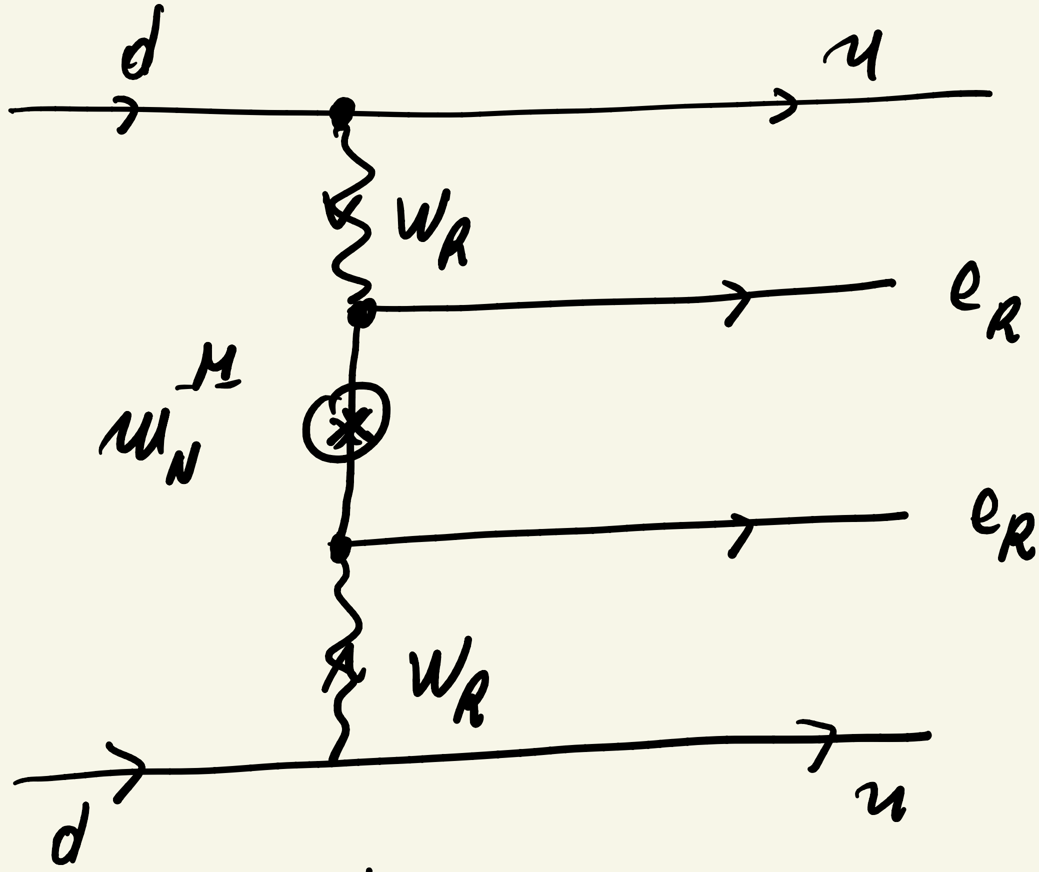
Summer 2023

LNV @ colliders: KS process

- **low E** : ($0\nu 2\beta$)

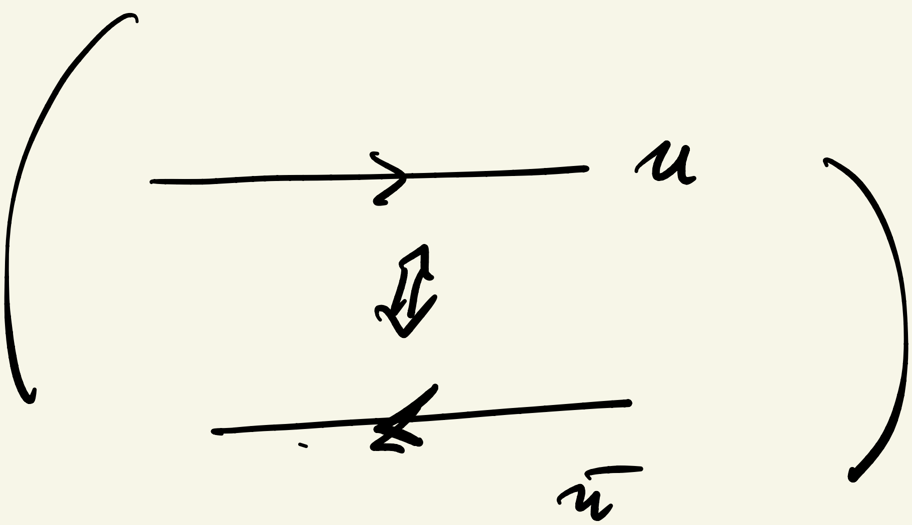


$L \longrightarrow R$



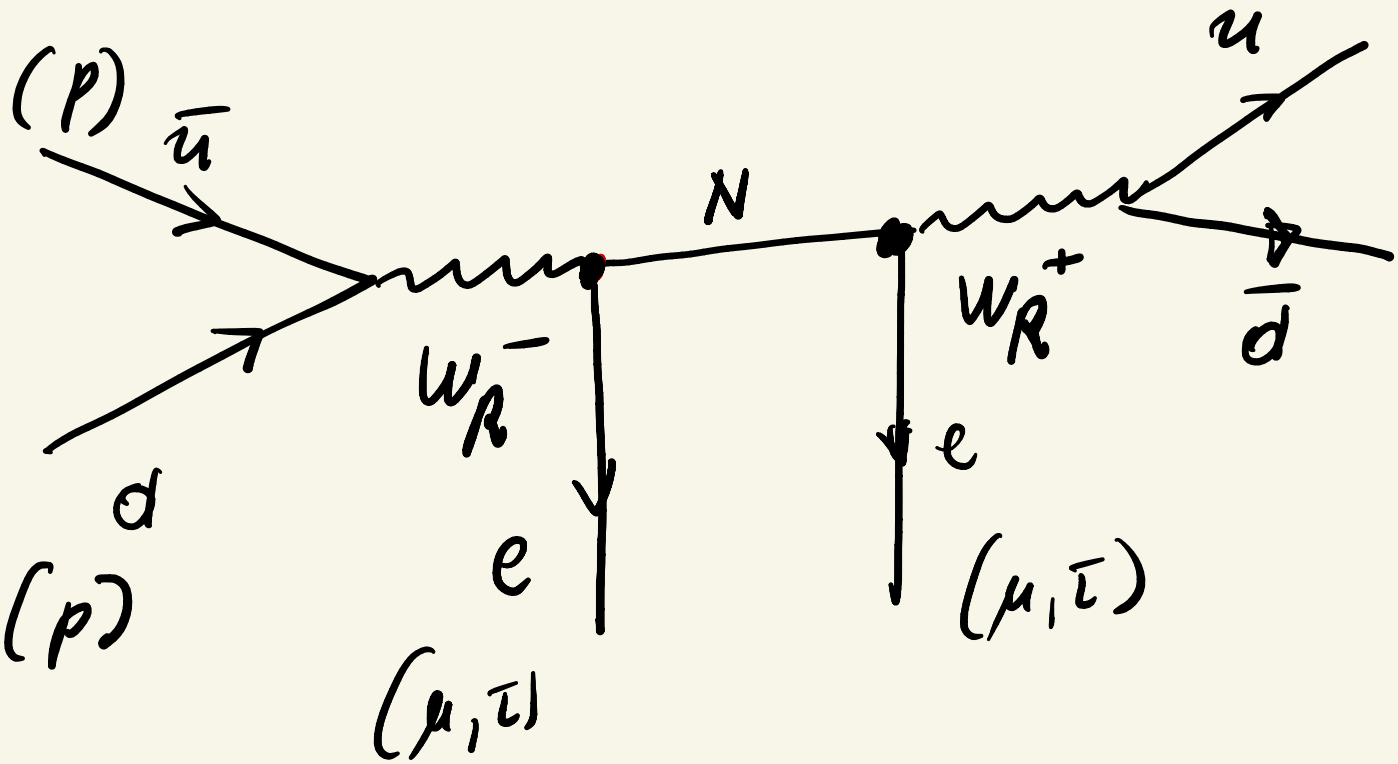
high E

rotation in a plane



Keung, G.S. '83

• <u>high E</u> : US LNV



$$p + p \longrightarrow e + e + 2q$$

$(\Lambda_{QCD} \simeq \text{GeV})$

↑

strong int.

initially $t \sim E^{-1}$

finally $t \sim \Lambda_{QCD}^{-1}$

$q + \bar{q}' \longrightarrow$ hadrons

(pions, ...)

$\Downarrow$ (jets)

$$\boxed{p + p \longrightarrow e + e + 2j}$$

$\downarrow$ physics!

a) $W_R^- \longrightarrow \underbrace{e + e + j_1 + j_2}$

(at rest)

measure E, p

$\Downarrow$

M_{W_R}!

b) $W_R^- \longrightarrow e_1 + N$ → measure E_e, p_e

$N \longrightarrow \underbrace{e_2 + j + j}_{\text{measure } E, p}$

$\Downarrow$

$$\boxed{m_N\ !}$$

CMS, ATLAS

$$\boxed{M_{W_R} \gtrsim 4\ \mathrm{TeV}}$$

$(M_{W_R} \gtrsim 5\,\mathrm{TeV},\ m_N \simeq 100\text{-}500\,\mathrm{GeV})$

$\Downarrow$ $\boxed{\text{predict}}$

$(0\nu 2\beta)_R$

$\boxed{\text{deep connection} : \text{KS} \leftrightarrow 0\nu 2\beta}$

$\downarrow$

$\boxed{(0\nu 2\beta)_R \Rightarrow \text{KS @ LHC?} \quad \text{new collider!}}$

$\Downarrow \qquad \Uparrow$

$$\boxed{M_{W_R} \gtrsim 10 - 15 \text{ TeV}}$$

- $N \to \nu$ in KS process

$$N \to e + j + j$$

ν = missing E

no KS process

$\Downarrow$

$0\nu 2\beta$ = Holy Grail of ν physics

$\updownarrow$

LNV

NEMO, CUORE, MAJORANA, EXO, $\boxed{\text{GERDA}}$, - - - -

experiments

$$m_\nu^{M} \leq 0.3\,\mathrm{eV} \quad (*)$$

KATRIN (β decay) : $m_\nu \leq \mathrm{eV}$

(*) $A_\nu(0\nu 2\beta) \propto G_F^2 \frac{m_\nu^4}{p^2}$

$T_{0\nu 2\beta} \gtrsim 10^{26}$ yr

$\Rightarrow A(0\nu 2\beta) \leq 10^{-18}$ GeV^{-5}

theory

$\Downarrow$

$m_\nu^4 \leq$ - - -

· $\boxed{LNV + \overline{LFV}}$

$\downarrow$

Lepton Flavour Violation

$$p + p \to \begin{pmatrix} e + e \\ e + \mu \\ e + \tau \\ \mu + \tau \\ \mu + \mu \\ \vdots \end{pmatrix} + 2j$$

$\boxed{\text{LFV @ E} \sim \text{TeV}}$

$$\Updownarrow$$

- low E LFV

$$\boxed{\mu \to e + \gamma}$$

$$\tau \to \mu + \gamma, \quad e + \gamma$$

$$\boxed{\mu \to e + e + \bar{e}} \quad (\mu \to 3e)$$

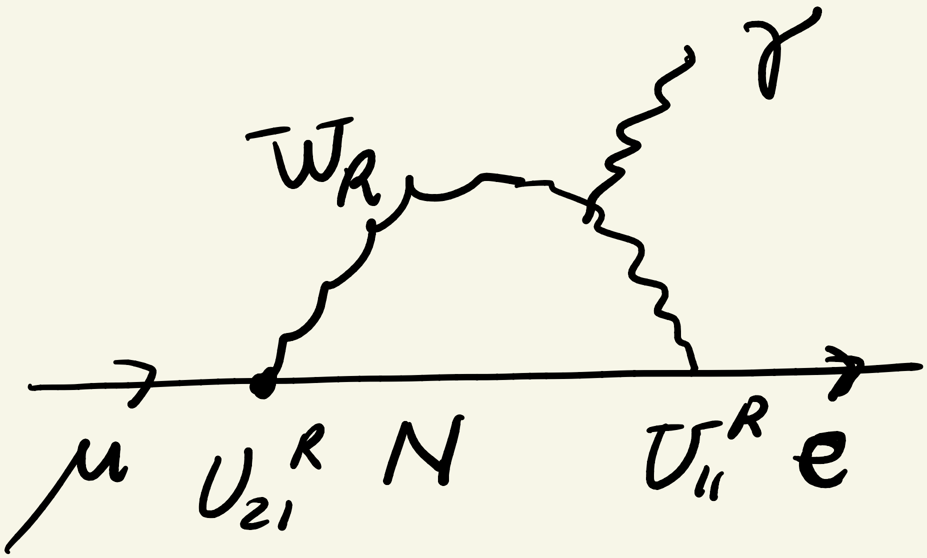
$\tau \to e + e + \bar{e}, \; \mu + \mu + \bar{e}$

$$\boxed{\begin{aligned} Br(\mu \to e\gamma) &\leq 10^{-12} \\ Br(\mu \to 3e) &\leq 10^{-12} \end{aligned}}$$

$$\boxed{Br(\text{decay}) = \frac{\Gamma(\text{decay})}{\Gamma_{total}}}$$

$$\Gamma_{total} \simeq \Gamma_{dominant} = \underbrace{\Gamma(\mu \to e + \nu + \bar{\nu})}_{\text{tree level}}$$

- $\mu \longrightarrow e\gamma$



(depends on $\underbrace{m_N,\ M_{W_R}}_{\text{LHC}}$)

$\boxed{\text{Tello, PhD 2012}}$

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_L \longleftrightarrow \begin{pmatrix}\nu\\ e\end{pmatrix}_R$$

$$
\begin{tikzcd}
(\nu_1, \nu_2, \nu_3)_L \arrow[r, leftrightarrow] \arrow[d, leftrightarrow] & (N_1, N_2, N_3)_L \arrow[d, leftrightarrow] \\
(\nu_e, \nu_\mu, \nu_\tau)_L \arrow[r, leftrightarrow] & (N_e, N_\mu, N_\tau)_L
\end{tikzcd}
$$

$$\nu_1 = U^L_{1e}\, \nu_e + U^L_{1\mu}\, \nu_\mu + U^L_{1\tau}\, \nu_\tau$$

$$\equiv U^L_{11}\, \nu_e + U^L_{12}\, \nu_\mu + U^L_{13}\, \nu_\tau$$

$$\nu_2 = U^L_{21}\, \nu_e + U^L_{22}\, \nu_\mu + U^L_{23}\, \nu_\tau$$

$$\updownarrow$$

$$N_1 = U^R_{11}\, N_e + - - - \;\; -$$

- $\nu - N$ mixing Θ

$$N \to e + W^+$$

- direct W_R couplings

$$N \to e + q + q' \quad (e + 2j)$$

$$\boxed{\text{Higgs sector of LRSM: SSB}}$$

$$\begin{array}{ccccc} G_{LR} & \xrightarrow[\langle \Delta_R \rangle]{} & G_{SM} & \xrightarrow[\langle \Phi \rangle]{} & U(1)_{em} \\ & \shortparallel & & \shortparallel & \\ & M_R & & M_W \ (M_L) & \end{array}$$

$\cdot \quad \Delta_R \longrightarrow U_R \, \Delta_R \, U_R^{\dagger}$

$$(B-L)\,\Delta_R = 2\,\Delta_R$$

<u>Invariants!</u>

(i) $\mathrm{Tr}\, \Delta_R^{\dagger} \Delta_R \longrightarrow \mathrm{Tr}\, U_R \Delta_R^{\dagger} \overbrace{U_R^{\dagger} U_R}^{1} \Delta_R U_R^{\dagger}$

$= \mathrm{Tr}\, U_R \Delta_R^{\dagger} \Delta_R U_R^{\dagger} = \mathrm{Tr}\, U_R^{\dagger} U_R \Delta_R^{\dagger} \Delta_R$

$= \mathrm{Tr}\, \Delta_R^{\dagger} \Delta_R$

(ii) $\left(\mathrm{Tr}\, \Delta_R^{\dagger} \Delta_R\right)^2$

(iii) $\mathrm{Tr}\, \Delta_R^{\dagger} \Delta_R \Delta_R^{\dagger} \Delta_R$ (Prove)

Q. $\mathrm{Tr}\,\Delta_R^2 \overset{?}{=} \mathrm{inv.}$

$$\mathrm{Tr}\,\Delta_R^2 \to \mathrm{Tr}\, U_R \Delta_R \overbrace{U_R^\dagger U_R}^{1} \Delta_R U_R^\dagger$$

$$= \mathrm{Tr}\, U_R^\dagger U_R \,\Delta_R \Delta_R = \mathrm{Tr}\,\Delta_R^2$$

A. NO, since $(B-L)\Delta_R^2 \neq 0$

Q. $\mathrm{Tr}\,\Delta_R^2\, \mathrm{Tr}(\Delta_R^\dagger)^2 = \mathrm{inv.}$

<u>but.</u>

$$\boxed{\begin{aligned}\mathrm{Tr}\,\Delta_R^\dagger \Delta_R \Delta_R^\dagger \Delta_R &= a\left(\mathrm{Tr}\,\Delta_R^\dagger \Delta_R\right)^2 \\ &\quad + b\,\mathrm{Tr}\,\Delta_R^2\, \mathrm{Tr}(\Delta_R^\dagger)^2\end{aligned}}$$

$\nexists$

only 2 $d=4$ inv.

$\Downarrow$

$(\Delta_R \equiv \Delta)$

$$V_\Delta = -\frac{\mu_\Delta^2}{2} \mathrm{Tr}\, \Delta^+ \Delta \; +$$

$$\frac{\lambda}{4}(\mathrm{Tr}\, \Delta^+ \Delta)^2 + \frac{\lambda'}{2} \mathrm{Tr}\, \Delta^2\, \mathrm{Tr}(\Delta^+)^2$$

$$\Delta = \begin{pmatrix} \Delta^+ & \Delta^{++} \\ \Delta^0 & -\Delta^+ \end{pmatrix}$$

assume

$$\langle \Delta \rangle = \begin{pmatrix} 0 & 0 \\ v & 0 \end{pmatrix} \qquad (v \equiv v_R)$$

$$\mathrm{Tr}\langle\Delta\rangle^2 = 0$$

$$\Downarrow$$

$$\langle V\rangle = -\frac{\mu^2}{2}v^2 + \frac{\lambda}{4}v^4$$

$$\Rightarrow \frac{\partial\langle V\rangle}{\partial v} = 0 \Rightarrow v^2 = \mu^2/\lambda$$

$$\Updownarrow$$

$$\langle\Delta\rangle = \begin{pmatrix} 0 & 0 \\ v & 0 \end{pmatrix}$$ is extremum

- Is $\langle\Delta\rangle$ a minimum?

$$\Updownarrow$$

$$\Delta = \begin{pmatrix} G^+ & \delta^{++} \\ v + H + iG^0 & -G^+ \end{pmatrix} \quad \begin{matrix} (H \equiv H_R) \\ (H \equiv h_R) \end{matrix}$$

$$(G^+, G^-, G^0) = ?$$

$$\parallel\!\!\!\mid$$

$$\boxed{(G_R^+, G_R^-, G_R^0) = \text{would be NG bosons} = \text{eaten by } W_R^+, W_R^-, Z_R}$$

$$\Updownarrow$$

$$\boxed{m_{G^+} = m_{G^-} = m_{G^0} = 0}$$

• $m_H^2 = ?$, $m_{++}^2 = ?$

check

$(m_{\delta^{++}} \equiv m_{++})$

$\boxed{m_H^2 = 2\lambda v^2}$ $\boxed{(\lambda > 0)}$

• Hint: $\Delta = \begin{pmatrix} 0 & 0 \\ v+H & 0 \end{pmatrix}$

when computing m_H

$\mathrm{Tr}\,\Delta^2 = 0 \Rightarrow$ only λ enters

$\mathrm{Tr}\,\Delta^\dagger \Delta = (v+H)^2$

$$(\mathrm{Tr}\,\Delta^{+}\Delta)^{2} = v^{4} + 6v^{2}H^{2} + \cdots$$

$\Downarrow$ complete it!

$$\boxed{m_{H}^{2} = 2\lambda v^{2}}$$

$$\boxed{\cdot\ m_{++}^{2} \propto \lambda' v^{2}}$$

<u>Proof:</u>

(i) take $\lambda' = 0$

$\Downarrow$

$$V = -\frac{\mu^{2}}{2}\,\mathrm{Tr}\,\Delta^{+}\Delta + \frac{\lambda}{4}(\mathrm{Tr}\,\Delta^{+}\Delta)^{2}$$

$\uparrow$

symmetry of V?

$$\Delta = \begin{pmatrix} R_1 + i I_1 & R_2 + i I_2 \\ R_3 + i I_3 & -(R_1 + i I_1) \end{pmatrix}$$

$$\Downarrow$$

$$\boxed{\begin{aligned} \mathrm{Tr}\, \Delta^\dagger \Delta = \; & R_1^2 + I_1^2 + R_2^2 + I_2^2 + \\ & + R_3^2 + I_3^2 \end{aligned}}$$

symmetry of $\mathrm{Tr}\, \Delta^\dagger \Delta = ?$

$$V = f\left(R_1^2 + I_1^2 + \cdots\right)$$

$$\boxed{\text{SO(6) symmety}}$$

$$\Delta \rightarrow \begin{pmatrix} R_1 \\ I_1 \\ \vdots \\ R_3 \\ I_3 \end{pmatrix} \rightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_6 \end{pmatrix}$$

$$V = f(\underbrace{\phi_1^2 + \cdots \phi_6^2}_{SO(6)})$$

$$\langle \Delta \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \hline v \end{pmatrix} \begin{array}{l} \left.\begin{matrix} \\ \\ \\ \\ \\ \end{matrix}\right\} SO(5) \\ \\ \end{array}$$

$$\boxed{SO(6) \xrightarrow[\langle \Delta \rangle]{} SO(5)}$$

$$\frac{6 \cdot 5}{2} \text{ gen} \qquad\qquad \frac{5 \cdot 4}{2} \text{ gen}$$

\# of broken gen =

$$= \frac{6 \cdot 5}{2} - \frac{5 \cdot 4}{2} = 5$$

$\Updownarrow$

$\boxed{\text{5 NG bosons}}$

$\downarrow$

$\boxed{G^+,\ G^-,\ G^0,\ \delta^{++},\ \delta^{--}}$

$\Longrightarrow\quad m_{++} = 0 \text{ when } \lambda' = 0$

$\Downarrow$

$\boxed{m_{++}^2 \propto \lambda' v^2}\quad (\lambda' > 0)$