

# Probing the origin of neutrino mass

## Lecture I : BASICS

Fermilab

14/8/2023



• Standard Model (SM) :

gauge theory of weak int.



-||- of ew int.



the theory of origin  
of mass

particle p : -  $g p h \bar{p} \bar{p}$



$$m_p = \delta_P(\phi) = v$$

111

VEV

$$\phi = v + h$$

↓

$$\Gamma(h \rightarrow p\bar{p}) \propto m_p^2$$

origin of mass =

= Higgs mechanism

(SSB of gauge sym)

Spontaneous symmetry

Breeding

$$W, Z, t, b, \tau$$

- $\mathcal{SM} \Rightarrow m_\nu = 0$



$m_\nu = a$  (the?) does

to Beyond SM (BSM)

$$SU = S \otimes B$$

of gauge group.

$$\bullet \quad G_H = SU(2)_L \times U(1)_Y^{g'}$$

$$[T_a, \gamma] = 0$$

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - ig T_a A_\mu^a$$

$$-ig' \frac{1}{2} B_\mu$$

• matter (fermions)

$$q_L = \begin{pmatrix} u \\ \sigma \end{pmatrix}_L \quad u_R, \sigma_R$$

$$l_L = \begin{pmatrix} v \\ e \end{pmatrix}_L \quad e_R$$



$$Ta = \frac{\sigma a}{n} \quad Ta = 0$$

$$\psi_L \equiv L \varphi \equiv \frac{1+\delta_5}{2} \varphi = \begin{pmatrix} u_L \\ 0 \end{pmatrix}$$

$$\psi_R \equiv R \varphi = \frac{1-\delta_5}{2} \varphi = \begin{pmatrix} 0 \\ u_R \end{pmatrix}$$

$$\delta_5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$



$$\phi \text{ (Higgs)} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\phi \rightarrow U \phi$$

$$U = e^{iT_a \theta_a}, \quad T_a = \frac{\Omega_a}{2}$$

$$Q_{eu} = T_3 + \frac{Y}{2}$$

$$J$$

$$Y = 2 [Q_{eu} - T_3]$$

$$Y(\varrho_e) = 1, \quad Y(\ell_2) = -1$$

$$Y(\phi) = +1$$

$$\begin{array}{ccc} \downarrow & & \\ \mu_{L,R} & \xrightarrow{\quad} & e^{i\vec{\sigma}/2} \left( \vec{\theta} \pm i\vec{x} \right) \\ & & \downarrow \\ \text{ROT} & & \text{BOOSES} \\ \downarrow & & \downarrow \end{array}$$

$$v_3 = \text{tanh } x_3$$

A diagram illustrating a coupled oscillator system. Two variables,  $u_L$  and  $u_R$ , are shown within a rectangular boundary. They are connected by a horizontal double-headed arrow labeled  $P$ . A curved arrow originates from the bottom right corner of the rectangle and points to a second rectangular box below it. This second box contains a state vector with three components:  $u_L^+$ ,  $u_R^+$ , and  $\psi_{x0}$ .

# masses

$$\int \mu_D u_L + u_R = \mu_D \bar{\psi}_L \psi_R$$

$$\cancel{u_L^+ u_L} \rightarrow u_L^+ e^{-\hat{\sigma} \vec{\tau}^a} \cancel{u_L}$$

$$m_D (u_L^+ u_R + h.c.) = m_D \bar{\psi}_D \gamma_D$$

$$\psi_D = \psi_L + \psi_R = \begin{pmatrix} u_L \\ u_R \end{pmatrix}$$



$$\mathcal{L}_0 = i \bar{\psi}_D \gamma^\mu \partial_\mu \psi_D - m_D \bar{\psi}_D \psi_D$$



$$\psi : \frac{i}{\not{p} - m}$$

$$\boxed{U+V=1}$$



$$(ii) \bar{\xi}_L \gamma_\mu \phi \quad d_R v \rightarrow \bar{\xi}_L U^+ U \phi \phi_R \checkmark$$

$\pi$

$$(\xi_L \rightarrow U \xi_L, \phi \rightarrow U \phi)$$

$$\phi_{\text{un}} = \begin{pmatrix} 0 \\ \vartheta + h \end{pmatrix}$$

$$(iii) \bar{\xi}_L \gamma_\mu \tilde{\phi} \quad u_R v$$

$$\overbrace{\phi \rightarrow U \phi, \quad \tilde{\phi} \rightarrow U \tilde{\phi}}$$

$$\tilde{\phi} \equiv i \sigma_2 \phi^* \quad ?$$

$$\rightarrow i\sigma_2 U^* \phi^* = U i\sigma_2 \phi_V^*$$

$$(irr) \quad \bar{l}_L \phi e_R \gamma_e$$

$$\Downarrow \qquad \qquad M_W = \frac{g}{2} v$$

$$u_f = g_f v$$

$$\Rightarrow y_f \bar{f} f h \quad (\text{Higgs})$$



$$y_f = \frac{g}{2} \frac{u_f}{M_W}$$

y

$$\Gamma(h \rightarrow f\bar{f}) = \frac{1}{8\pi} \left( \frac{e}{2} \frac{m_f}{m_h} \right)^2 m_h$$

- $\psi \rightarrow \psi^c = c \bar{\psi}^\top = c \gamma_0 \psi^*$

$$C = i \gamma^2 \gamma^0$$

$$\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

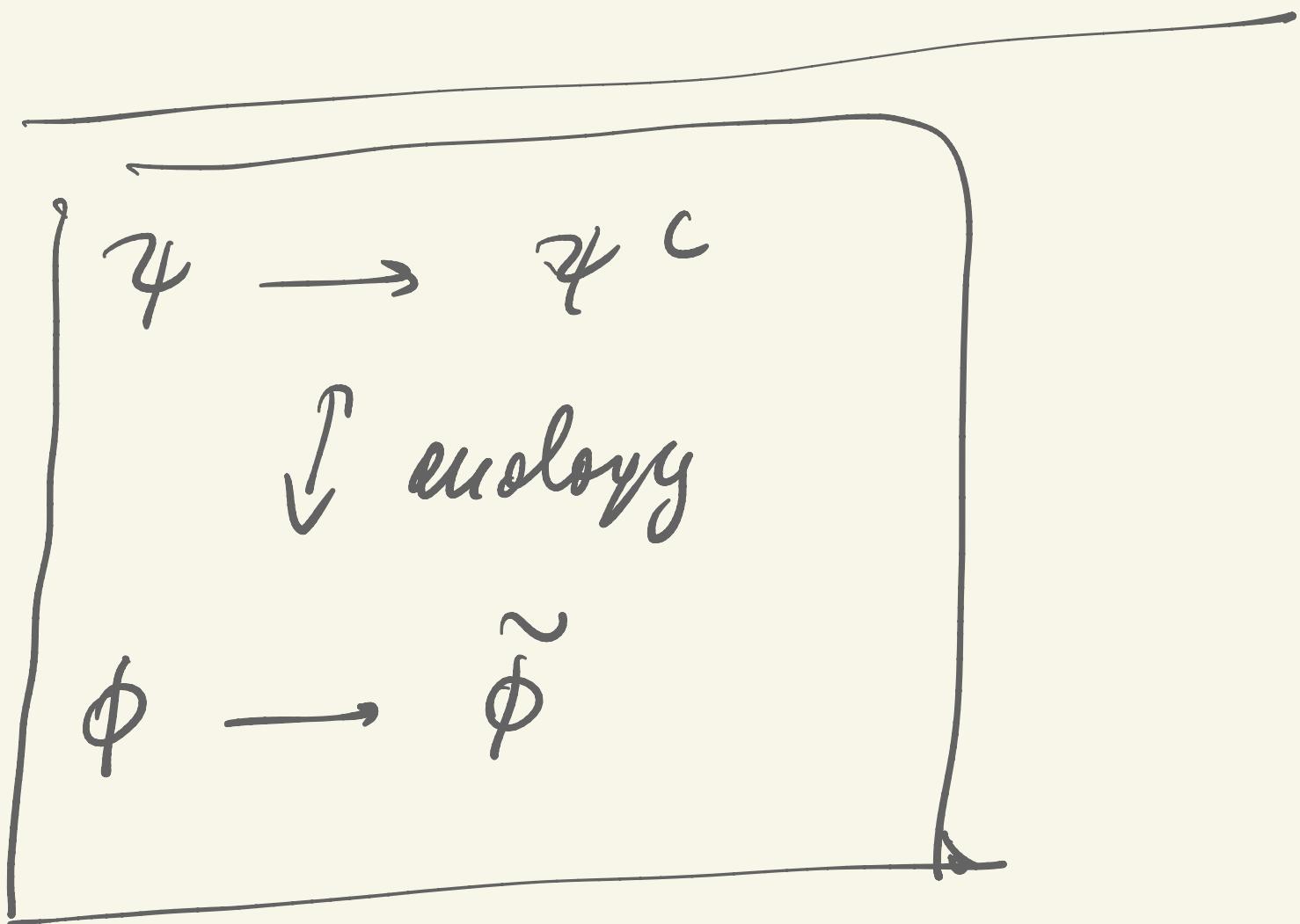
$$\psi^c = i \gamma^2 \psi^*$$

$$\psi_L = \begin{pmatrix} u_L \\ 0 \end{pmatrix} \Rightarrow \psi^c = \begin{pmatrix} 0 & i\sigma_2 \\ -i\sigma_2 & 0 \end{pmatrix} \begin{pmatrix} \bar{u}_L \\ 0 \end{pmatrix}$$

J

$$\gamma^c = (\gamma^c)_R = \begin{pmatrix} 0 \\ -i\sigma_2 u_L^* \end{pmatrix}$$

$$C: u_L \rightarrow -i\sigma_2 u_R^* \quad (LR)$$



$$\tilde{\phi} \rightarrow \cup \hat{\phi}$$

$$\Rightarrow \phi_1^+ \hat{\phi}_2^- = iuv.$$



$$(\phi_1^+ i\sigma_2 \phi^*)^* = iw.$$



$$\phi_1^T i\sigma_2 \phi_2^- = iuv.$$

$$\phi = \begin{pmatrix} i\sigma_2 \\ \phi_2^- \end{pmatrix} \Rightarrow$$

$$\phi_1^T i\sigma_2 \phi_2^- = |T\downarrow - \downarrow\uparrow\rangle,$$



Højgaard 1937

$$\underline{u}_L \underline{u}_L^T i \sigma_2 u_2 = iw.$$

C

not close zw.

$$\underline{u}_L^T i \sigma_2 \underline{u}_L \equiv \underline{\psi}_L^T c \underline{\chi}_L$$

//

$$c = i \gamma^0 \gamma^0$$

$$\boxed{\underline{\psi}_L^T c \underline{\psi}_L} \quad \boxed{\phi_0} \quad l_L = \begin{pmatrix} v \\ e \end{pmatrix}_L$$

C  $\rightarrow$   $\phi_0 = v + l$

L-werts zw.

$$T_3: \frac{1}{2} + \frac{1}{2} \left| -\frac{1}{2} \right| = \frac{1}{2} \neq 0$$

~~P maximal (WI)~~



Higgs (Weinberg)

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Imagine:  $P = \text{good}$

$$\varrho_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \xrightarrow{P} \begin{pmatrix} u \\ d \end{pmatrix} = \varrho_R$$

$$G_{SH} = \underset{L+R}{SU(2)} \times U(1)$$

$$\left. \begin{array}{c} \bar{\epsilon}_L \quad M \quad \epsilon_R \\ \downarrow \qquad \qquad \qquad \downarrow \end{array} \right\} \begin{array}{l} \epsilon_L \rightarrow U \epsilon_L \\ \epsilon_R \rightarrow U \epsilon_R \end{array}$$

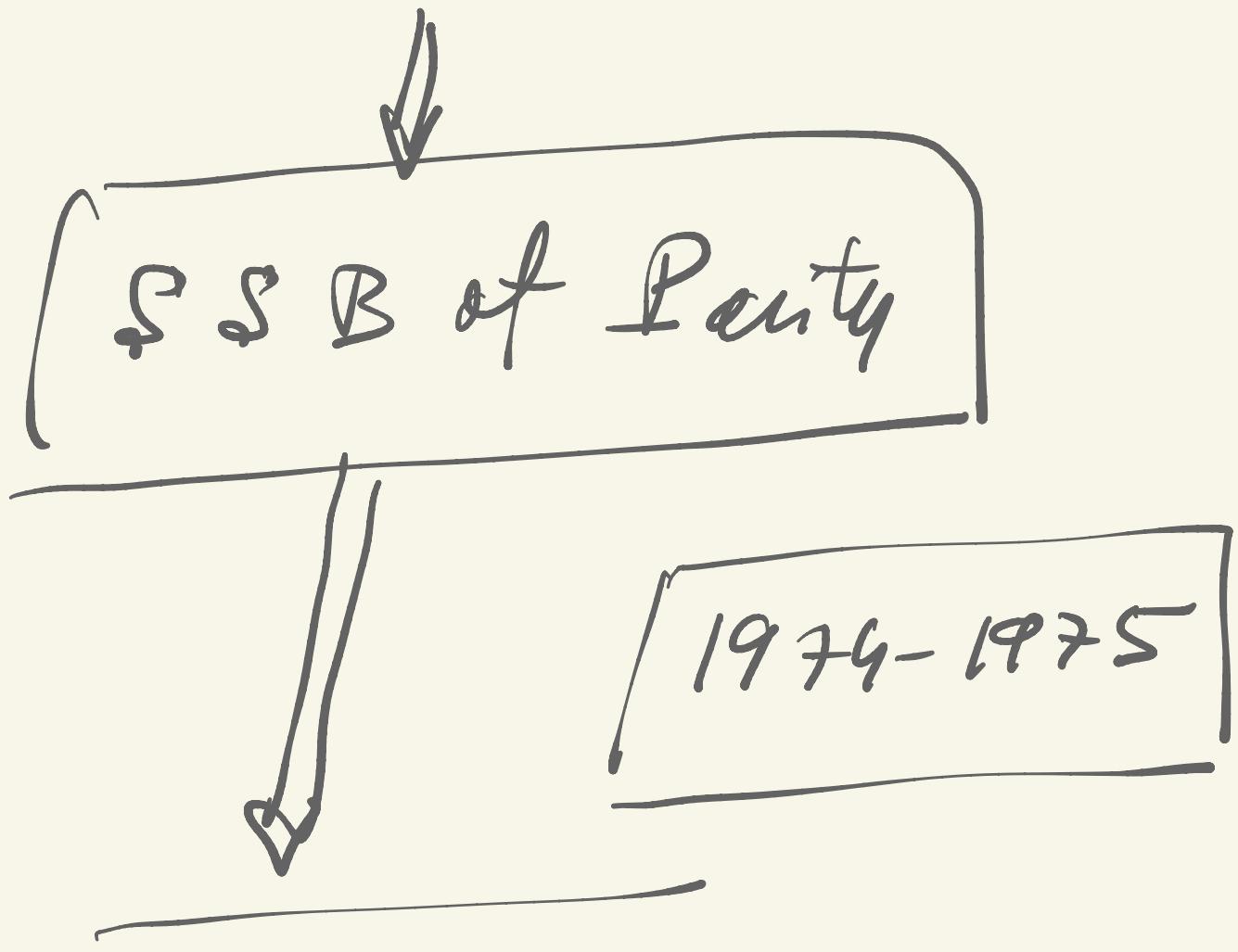
$$\boxed{m_u = m_d} \quad \begin{array}{l} \bar{\epsilon}_L M \epsilon_R \rightarrow \\ \bar{\epsilon}_L U^+ M U \epsilon_R \end{array}$$

$$\left( \begin{array}{c} \nu \\ e \end{array} \right)_L \leftrightarrow \left( \begin{array}{c} \nu \\ e \end{array} \right)_R = \bar{\epsilon}_L M \epsilon_R \quad \checkmark$$

$$\boxed{m_\nu \neq 0}$$

$$\cancel{\rho} = m_{\max} \quad \leftarrow \quad \begin{array}{l} m_\rho \neq 0 \\ m_e \neq 0 \end{array}$$

$P = \text{good} \leftrightarrow W_\nu \neq 0$



$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)$

Pati, Salam

Mohapatra, G.S.



$$Q_L = \begin{pmatrix} u \\ 0 \end{pmatrix}_L \xrightarrow{P} \begin{pmatrix} u \\ 0 \end{pmatrix}_R = Q_R$$

$$l_L = \begin{pmatrix} v \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} v \\ e \end{pmatrix}_R = l_R$$



$$\boxed{u_v \neq 0}$$



LRSM  $\Rightarrow$  self-contained  
predictive theory &  
was  
left-right symmetric Model

Q.  $6_{LR} \xrightarrow{\underline{M_R}} 6_{SM} \xrightarrow{\underline{U_W}} V_{(1)} \text{ eu}$



$$\left\{ \begin{array}{l} M_{W_R}, M_{Z_R} \gg M_W \end{array} \right.$$

$\rightarrow$  decay  $\Rightarrow$  only  $e_L$  !

but  $e_R$  via  $e_R \nu_R$  int

however, no  $\nu_R$  ever

$\mu \rightarrow p + e + (\bar{\nu} + \text{Pauli})$

(1930)

$\downarrow$

$\bar{\nu} + p \rightarrow \mu + e^+$  (Cowen  
Reines)

$\cap$

water

1956

Wu et al

produce W boson

$$M_W = 80 \text{ GeV}$$

$$m_e = 0.5 \text{ MeV}$$

$$W^- \rightarrow e + \bar{\nu} \quad m_\nu = 0$$

1

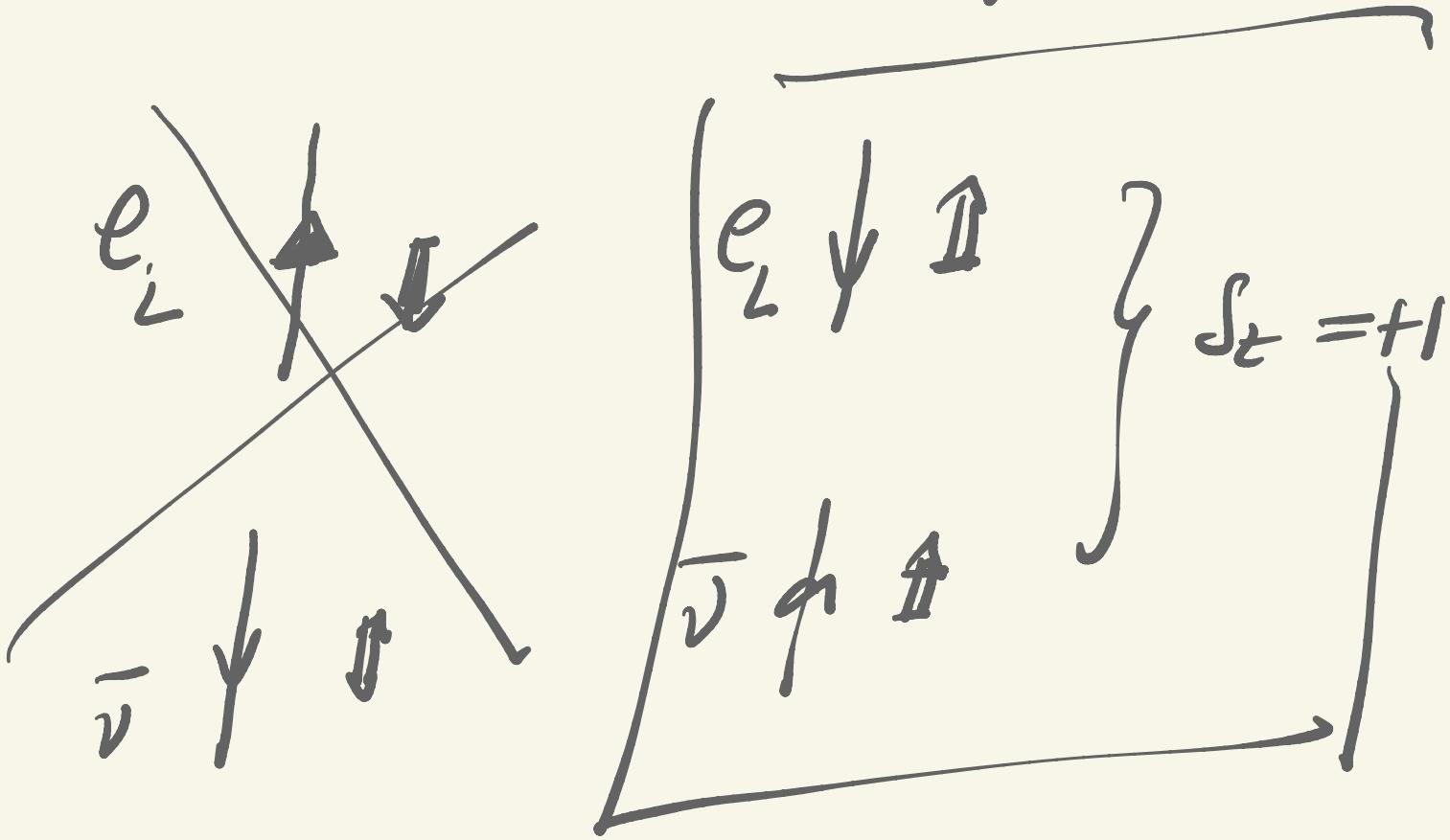
assume:  $m_e = m_\nu = 0$

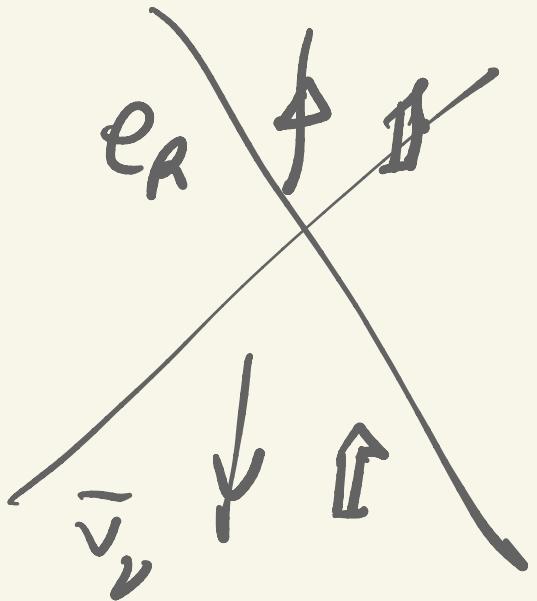
$$S_L = +1$$

↓

$$h e_L = -\frac{1}{2} \quad h \in \overleftrightarrow{s} \cdot \overleftrightarrow{p}$$

$$h(\bar{\nu})_R = +\frac{1}{2}$$





$e_L, v_L$  have  
wedge cut.