Lecture II:

Neutrino Masses - Beyond the Standard Model

Many Experimental Evidences

Neutrinos Change Flavor in Nature

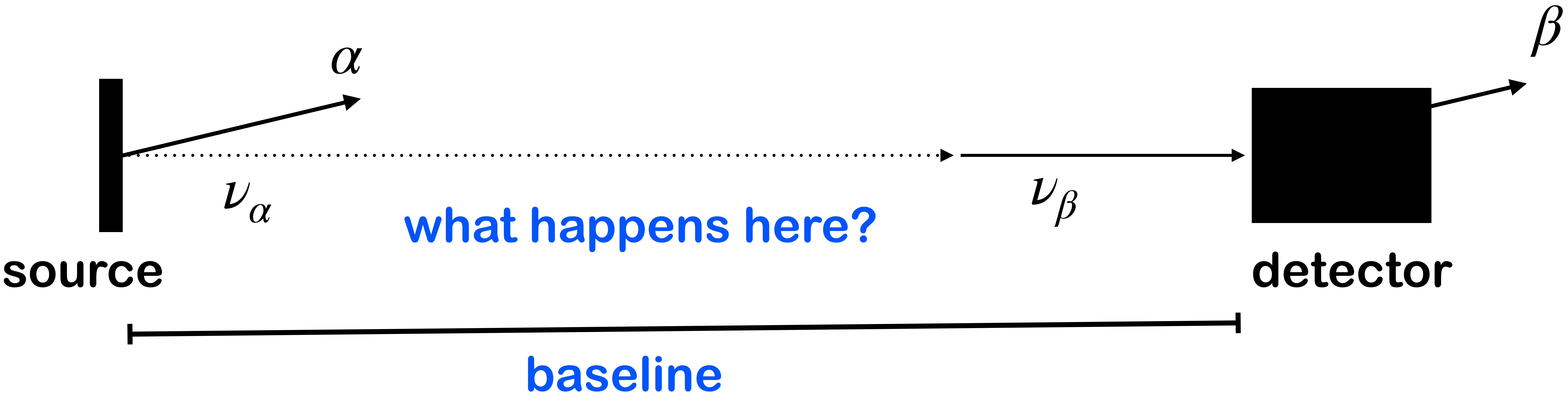
- Solar ν_e transitioning to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- Atmospheric ν_μ & $\bar{\nu}_\mu$ disappearing mostly to ν_τ (SK, IceCube/DeepCore)
- Accelerator ν_μ & $\bar{\nu}_\mu$ disappearing (K2K, T2K, MINOS, NOνA)
- Accelerator $\nu_\mu/\bar{\nu}_\mu$ reappearing as $\nu_e/\bar{\nu}_e$ (T2K, MINOS, NOνA)
- Reactor $\bar{\nu}_e$ disappearing (KamLAND, DC, Daya Bay, RENO)

This is Evidence of Neutrino Mass

Neutrino Change Flavor in Nature

[Lecture II]

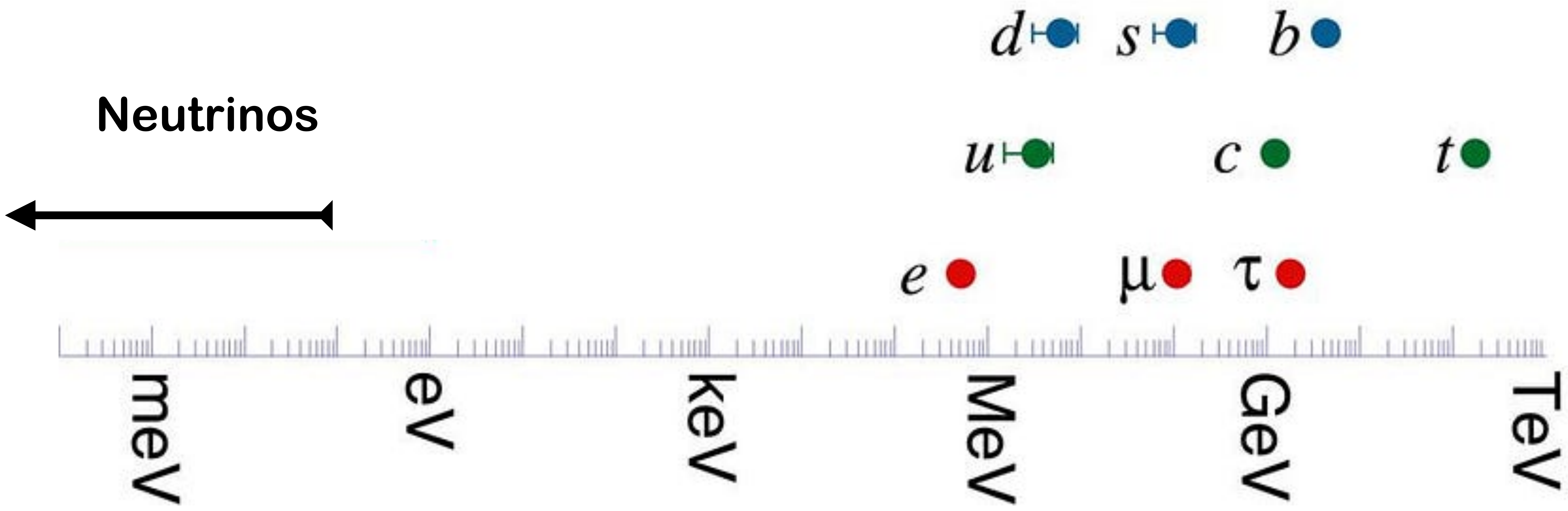
L_α is violated



We need go Beyond the SM

What About Neutrino Mass ?

The fermion mass spectrum



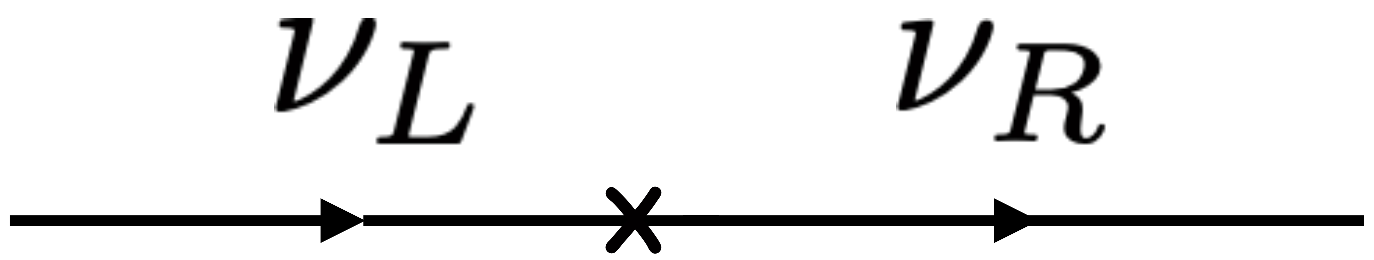
@ least 12 orders of magnitude below the top mass

How to Implement Neutrino Masses

Beyond SM Physics I : add new right chirality fields

Dirac Mass (as SM fermions)

$$-\mathcal{L}^{D}_{\text{mass}} = m_D\, \bar{\nu}\nu = m_D\left(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R\right)$$



$$\nu = (P_L + P_R)\nu = \nu_L + \nu_R$$

$$|\Delta L| = 0$$

can use Higgs mechanisms to generate this term after EWSB

$$(m_D)_{\alpha\beta}\, \bar{\nu}_\alpha \nu_\beta = y_{\alpha\beta} \frac{v}{\sqrt{2}} \bar{\nu}_\alpha \nu_\beta$$

complex 3x3 matrix

neutrino masses would have the same origin of other SM fermions

neutrino $\neq$ antineutrino

neutrino mainly h=-1 (negative helicity)

antineutrino mainly h=+1 (positive helicity)

ν_R is a sterile neutrino

How to Implement Neutrino Masses

Beyond SM Physics II : Neutrinos as Majorana Fermions

Neutrinos are (the only) neutral fermions in the SM

They can admit a gauge invariant mass term that does not need the Higgs if

Neutrino = Antineutrino

How to Implement Neutrino Masses

Beyond SM Physics II : Neutrinos as Majorana Fermions

Neutrinos are (the only) neutral fermions in the SM

They can admit a gauge invariant mass term that does not need the Higgs if

Neutrino = Antineutrino

i.e. if they are Majorana fermions

$$\nu^c = \nu$$ (up to a phase)

cannot have any type of charge

E. Majorana

How to Implement Neutrino Masses

Beyond SM Physics II : Neutrinos as Majorana Fermions

$$\nu^c(x) = \sum_{s,\vec{p}} \left[b_s(\vec{p})\, u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p})\, v_s(\vec{p}) e^{ipx} \right]$$

$$= \sum_{s,\vec{p}} \left[a_s(\vec{p})\, u_s(\vec{p}) e^{-ipx} + b_s^\dagger(\vec{p})\, v_s(\vec{p}) e^{ipx} \right] = \nu(x)$$

$$\Rightarrow \quad b_s(\vec{p}) = a_s(\vec{p})$$

$$\nu(x)_M = \sum_{s,\vec{p}} \left[a_s(\vec{p})\, u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p})\, v_s(\vec{p}) e^{ipx} \right]$$

A Majorana field can only create and destroy the same particle

Only 2 independent dof : ν_L and $(\nu_L)^c$ **or** ν_R and $(\nu_R)^c$

How to Implement Neutrino Masses

Beyond SM Physics II : Neutrinos as Majorana Fermions

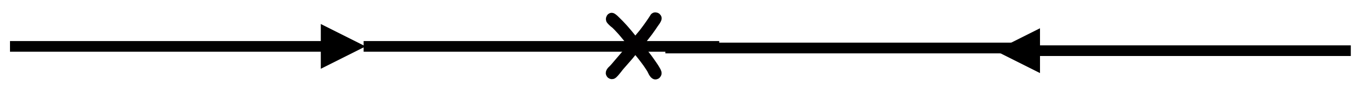
Right Majorana Mass

(this transforms like a left chirality state)

lead to processes that

$$|\Delta L| = 2$$

$$\nu_R \qquad (\nu_R)^c \equiv C\bar{\nu}_R^T$$



this is allowed by SM symmetry group

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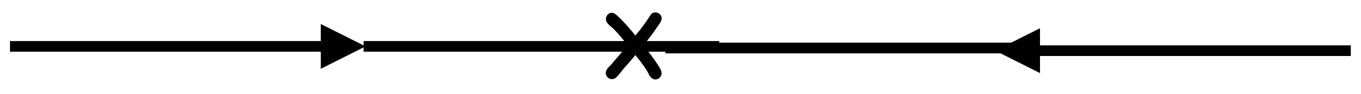

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new mass scale(s)?

$$-\mathcal{L}^M_{\text{mass}} = \frac{m_R}{2}\bar{\nu}_M \nu_M = \frac{m_R}{2}\left(\bar{\nu}_R\,(\nu_R)^c + \overline{(\nu_R)^c}\,\nu_R\right)$$

$$\nu_M = \nu_R + (\nu_R)^c = \nu^c$$ Majorana condition

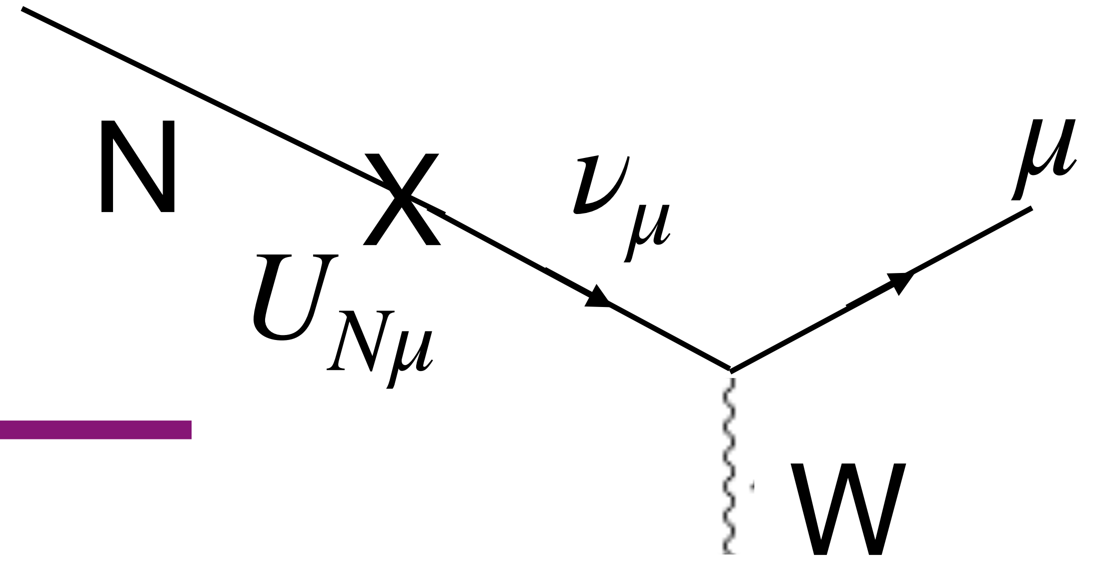
right chirality states have no SM charges $I_{3L} = Y = 0$ (sterile)

they do not couple to W and Z

How to Implement Neutrino Masses

Beyond SM Physics II : Neutrinos as Majorana Fermions

- The number of sterile states is unrestricted
- The mass scale(s) m_R have no restrictions
- In general will lead to active-sterile mixing after diagonalization
- Sterile states can interact with Z and W through mixing — can be searched for in Experiments



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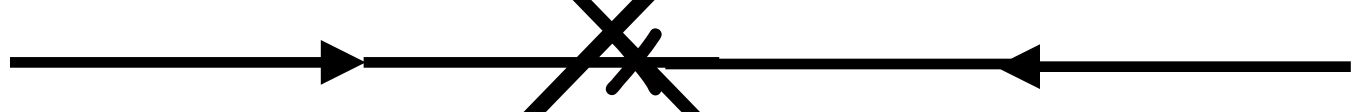


this is allowed by SM symmetry group

In this case neutrinos are Dirac particles and
the mixing in the neutrino sector is like for quarks (CKM-matrix)

3 mixing angle + 1 phase (δ)

to have Dirac neutrinos you have to avoid this term
i.e. impose by hand L conservation

How to Implement Neutrino Masses

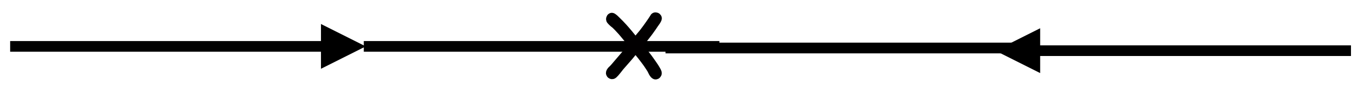
Beyond SM Physics II : Neutrinos as Majorana Fermions

But we do not need to add more fermion fields …

Left Majorana Mass

ν_L $(\nu_L)^c \equiv C\,\bar{\nu}_L^T$

(this transforms like a right chirality state)



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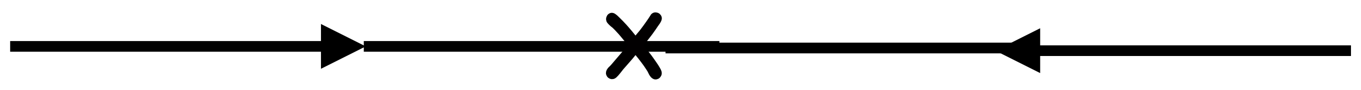

lead to processes that

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$$-\mathcal{L}^M_{\rm mass} = \frac{m_M}{2}\bar{\nu}^M\nu^M = \frac{m_M}{2}\left(\bar{\nu}_L(\nu_L)^c + \overline{(\nu_L)^c}\nu_L\right)$$

complex 3x3 symmetric matrix

neutrino = antineutrino

neutrino has both h=-1 (negative) and h=+1 (positive) helicities

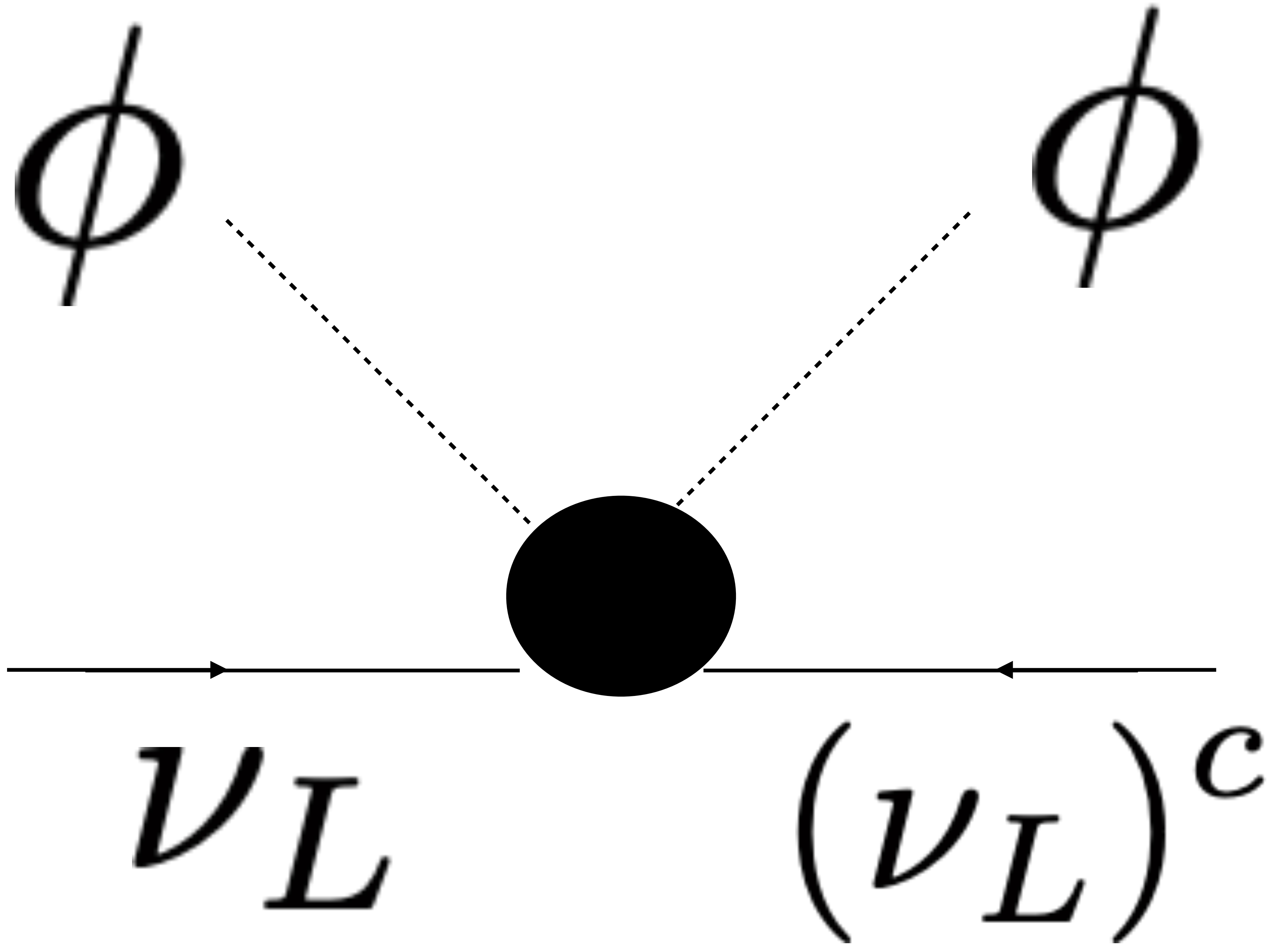
need to add other (scalar) fields to make it gauge invariant

A Rational for the Smallness of Neutrino Masses

The Weinberg Operator and the Seesaw Mechanism

The most general method which allows to describe effects of BSM physics (EFT)

Lowest dimension (D=5) local operator that can be build from SM fields



lead to processes that

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[S. Weinberg, (1979)]

A Rational for the Smallness of Neutrino Masses

The Weinberg Operator and the Seesaw Mechanism

Lowest dimension (D=5) local operator that can be build from SM fields

$$-\mathcal{L}_{\rm eff}^{\rm Weinberg} = -\frac{1}{\Lambda}(\bar{L}_\alpha\,\tilde{\phi})\,c_{\alpha\beta}\,(\tilde{\phi}^T\,L_\beta^c) + \text{h.c.}$$

scale of new physics

$$\tilde{\phi} = i\sigma_2\phi^*$$

$$L_\alpha = (\nu_\alpha \quad \ell_\alpha)^T \qquad \ell_\alpha = e, \mu, \tau$$

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scale of new physics

after EWSB

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\frac{v^2}{\Lambda}\bar{\nu}_{\alpha L}\,c_{\alpha\beta}\,(\nu_{\beta L})^c + \text{h.c.}$$

$$= m_i\,\bar{\nu}_i\,\nu_i$$

$$m_i = \frac{v^2}{2\Lambda}y_i$$

$$\tilde{\phi} = i\sigma_2\phi^*$$

$$L_\alpha = (\nu_\alpha \quad \ell_\alpha)^T \qquad \ell_\alpha = e, \mu, \tau$$

A Rational for the Smallness of Neutrino Masses

The Weinberg Operator and the Seesaw Mechanism

Seesaw Mechanism

[P. Minkowski (1977); M. Gell-Mann, P. Ramond and R. Slansky (1979); T. Yanagida (1979); S.L. Glashow (1979); R.N. Mohapatra and G. Senjanovic (1980)]

$$\Lambda \gg v$$

$$m_i = \frac{v^2}{2\Lambda} y_i \sim \frac{m_D^2}{\Lambda}$$

$$\Lambda \sim 10^{15}\ \mathrm{GeV} \quad \mathrm{y_i} \sim 1$$

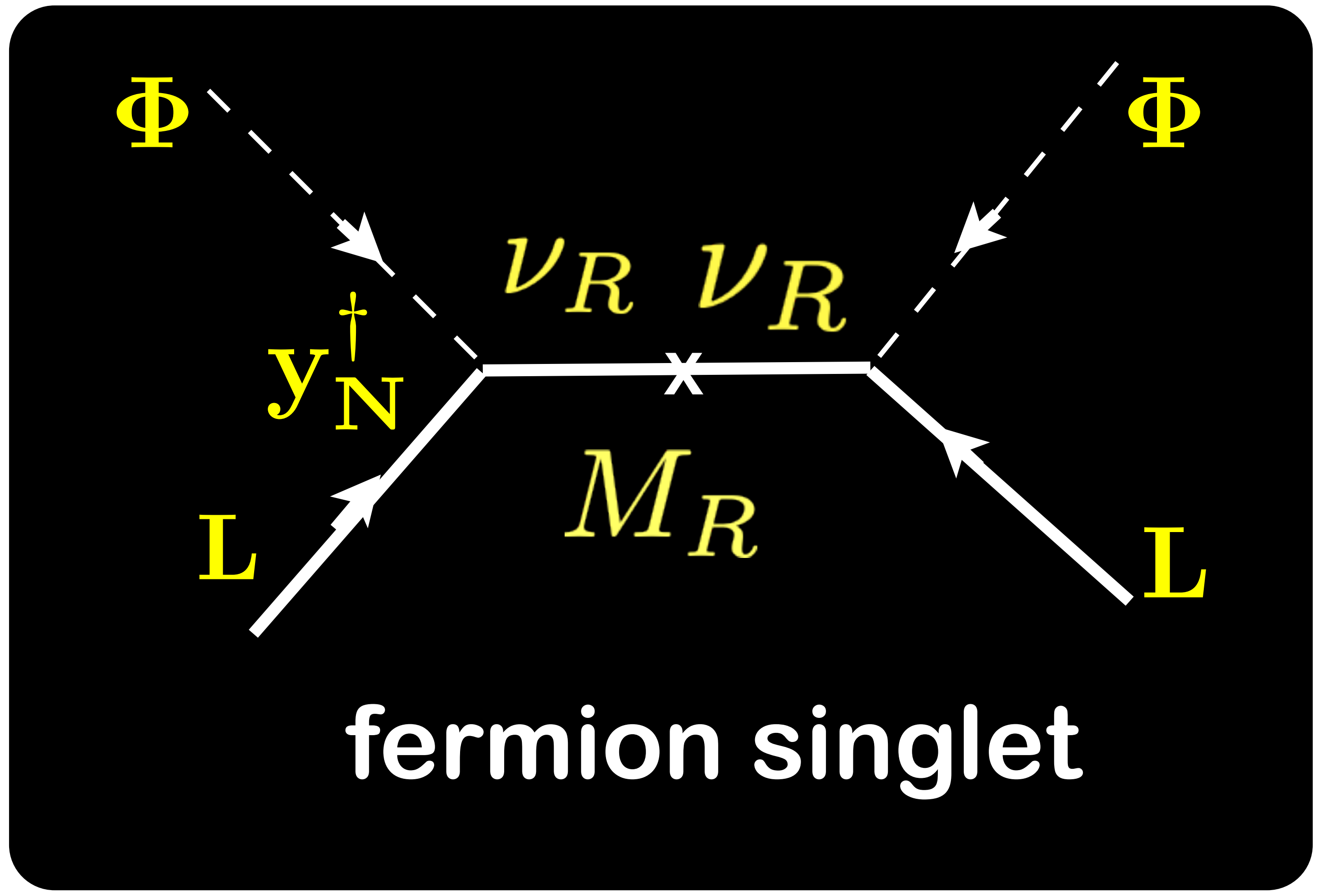
seems to be a natural explanation for the smallness of neutrino masses

Neutrino Mass Models

Only 3 tree-level realizations of the Weinberg Operator

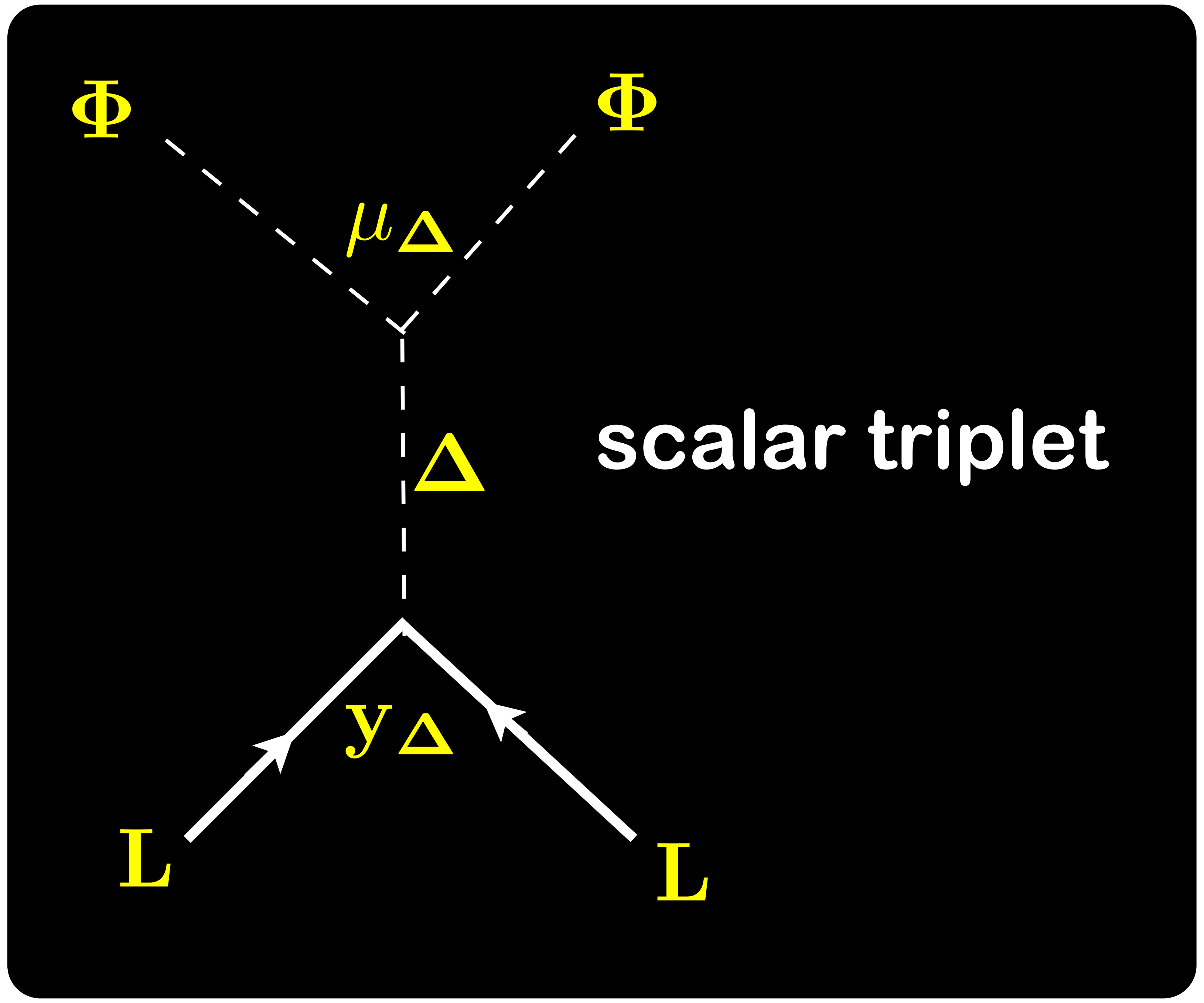
Many Loop-Level Realizations

Seesaw Type I



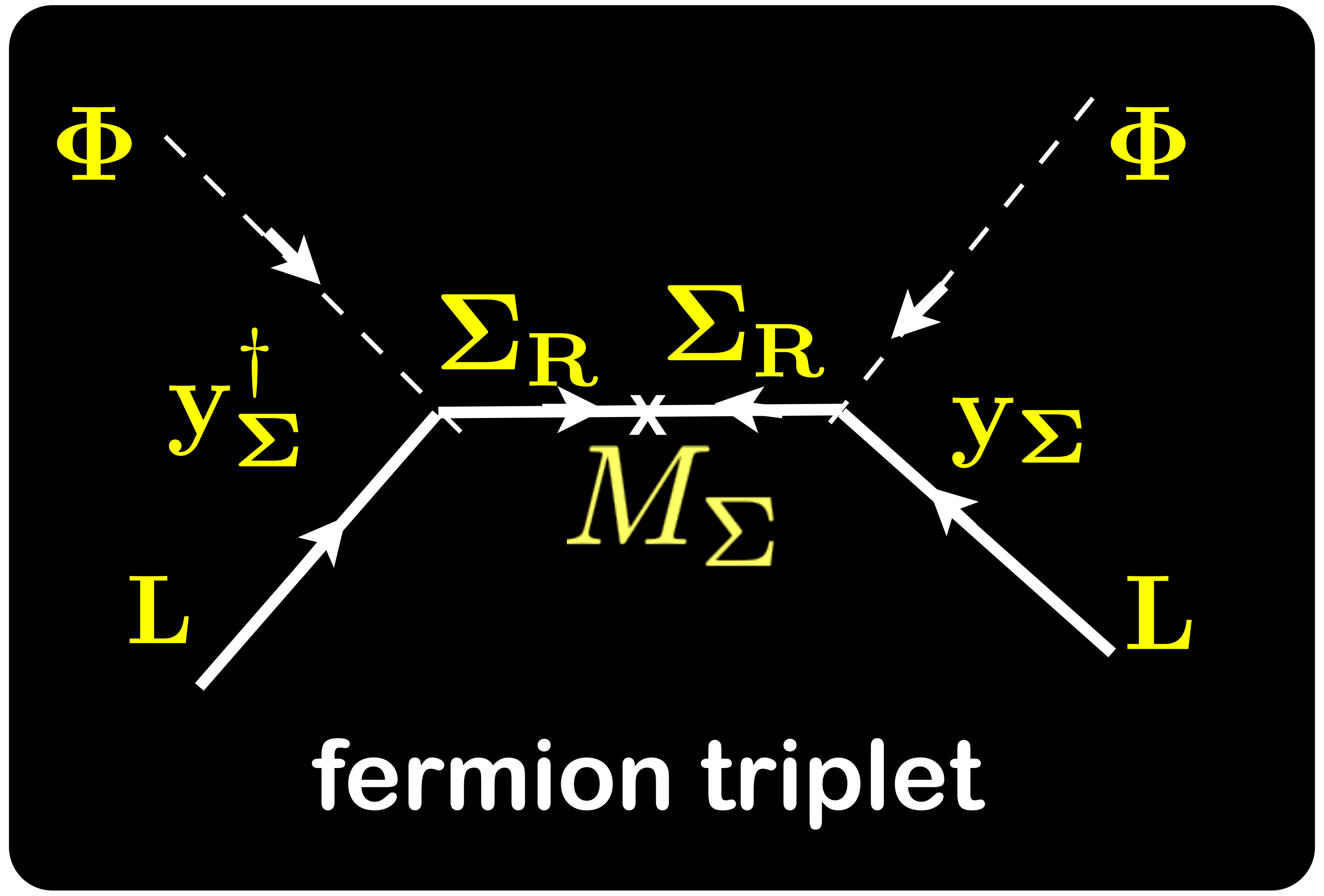
$$m_\nu \sim \frac{y_N^2 v^2}{M_R}$$

Seesaw Type II



$$m_\nu \sim y_\Delta \frac{\mu_\Delta v^2}{M_\Delta^2}$$

Seesaw Type III



$$m_\nu \sim y_\Sigma^2 \frac{v^2}{M_\Sigma}$$

Masses & Mixings

For the Majorana case

$$-\mathcal{L}^{M}_{\text{mass}} = \frac{1}{2}\sum_{\alpha\beta} \bar{\nu}_{L\alpha}(m_M)_{\alpha\beta}(\nu_{L\beta})^c + \text{h.c.}$$

can be diagonalized by an orthogonal transformation

$$U\,\hat{m}\,U^T = m_M \qquad \hat{m} = \text{diag}(\text{m}_1, \text{m}_2, \text{m}_3) \qquad UU^\dagger = I$$

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Majorana neutrinos

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Majorana neutrinos

$$\nu_{L\alpha} = \sum_i^3 U_{\alpha i}\,\nu_{iL}$$

3x3 mixing matrix

CC-interaction

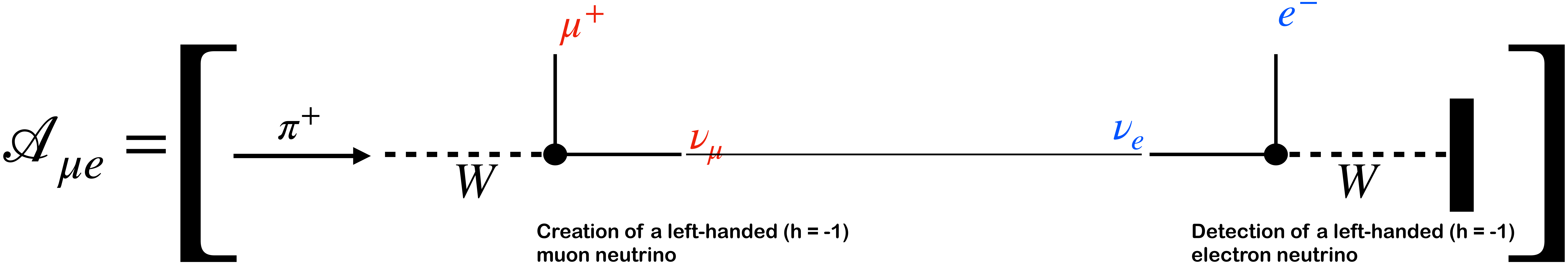
$$J^\mu_W \propto \bar{\ell}_{\alpha L}\gamma^\mu \nu_{L\alpha} = \sum_{i=1}^{3} \bar{\ell}_{\alpha L}\gamma^\mu U_{\alpha i}\nu_{iL}$$

in the mass basis

[show that the mixing matrix has 3 phases]

Neutrino Flavor Oscillations

How they are induced by mass and mixing



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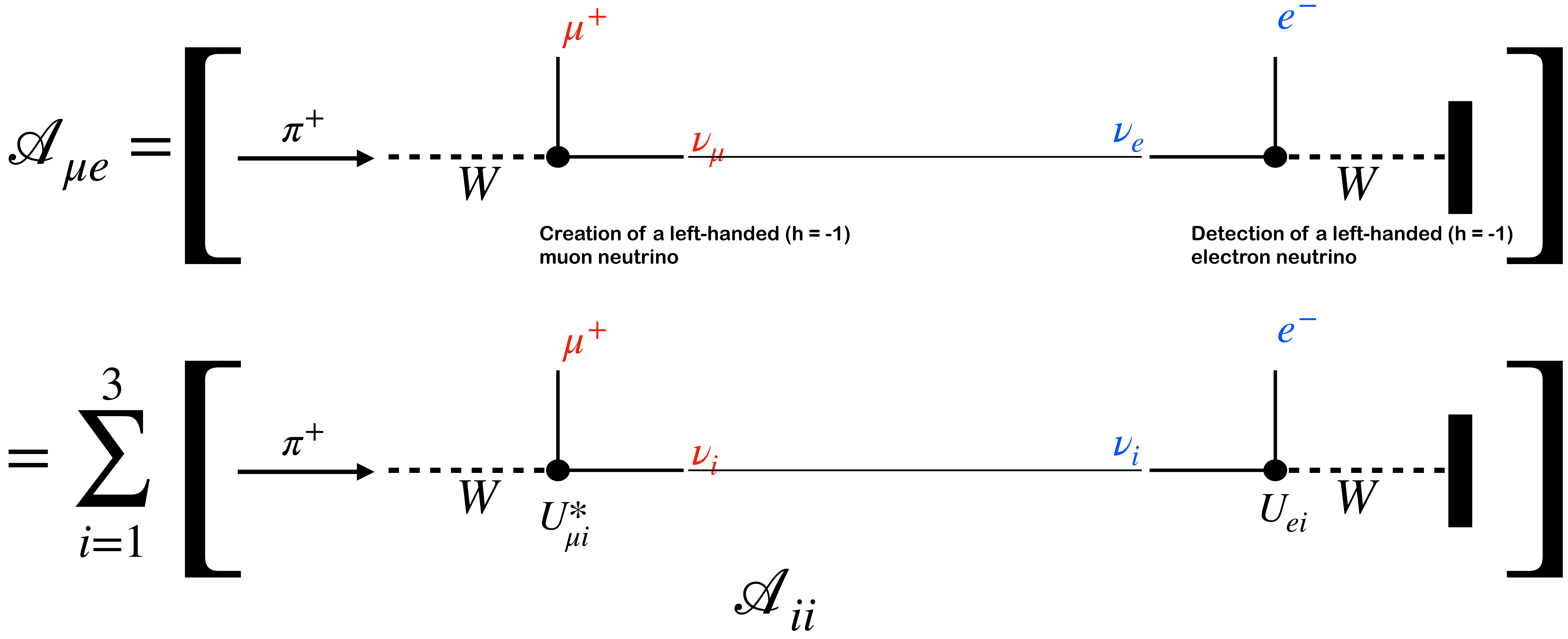

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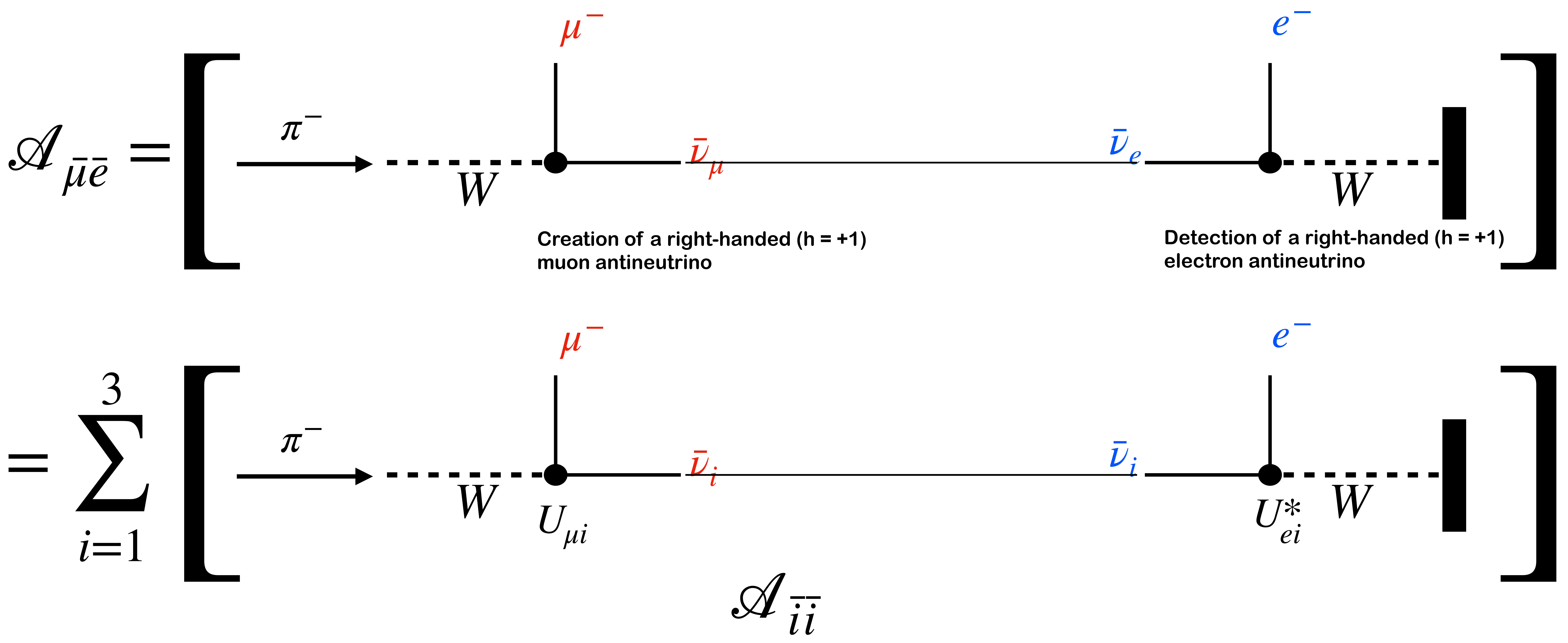

Question

Does it matter if they are Dirac or Majorana ?

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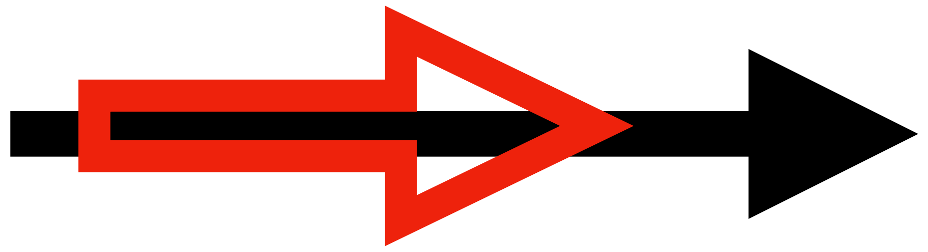
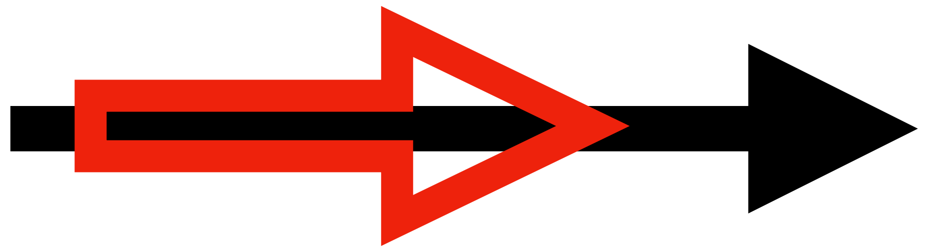
DIRAC

$$\nu$$  left-handed (h=-1) $$+ \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right)$$  right-handed (h=+1)

$$\bar{\nu}$$  right-handed (h=+1) $$+ \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right)$$  left-handed (h=-1)

neutrinos and antineutrinos are different particles (4 states)

can use lepton number to distinguish them

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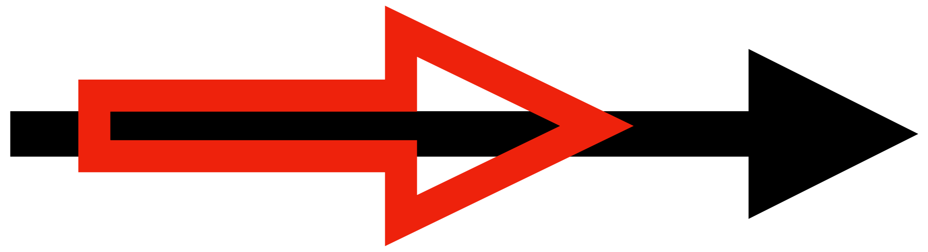
MAJORANA

ν

left-handed

(h=-1)

$+ \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right)$



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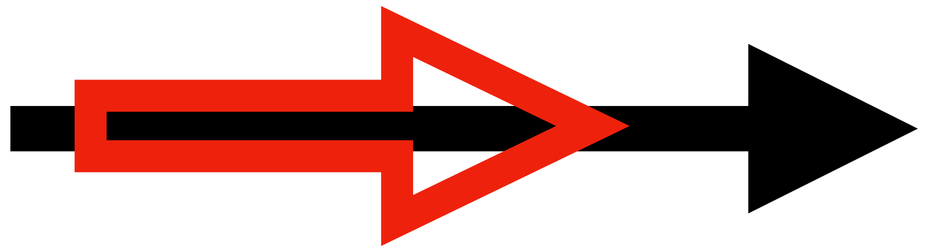
(h=+1)

$\bar{\nu}$



right-handed

(h=+1)

$+ \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right)$

left-handed

(h=-1)

neutrinos = antineutrinos of opposite helicity (two states)

cannot have (any) charge

Question

Does it matter if they are Dirac or Majorana ?

MAJORANA

$$\nu \quad \text{left-handed (h=-1)} \quad + \quad \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right) \quad \text{right-handed (h=+1)}$$

ARE THE SAME STATE

$$\bar{\nu} \quad \text{right-handed (h=+1)} \quad + \quad \mathcal{O}\left(\frac{m_\nu}{E_\nu}\right) \quad \text{left-handed (h=-1)}$$

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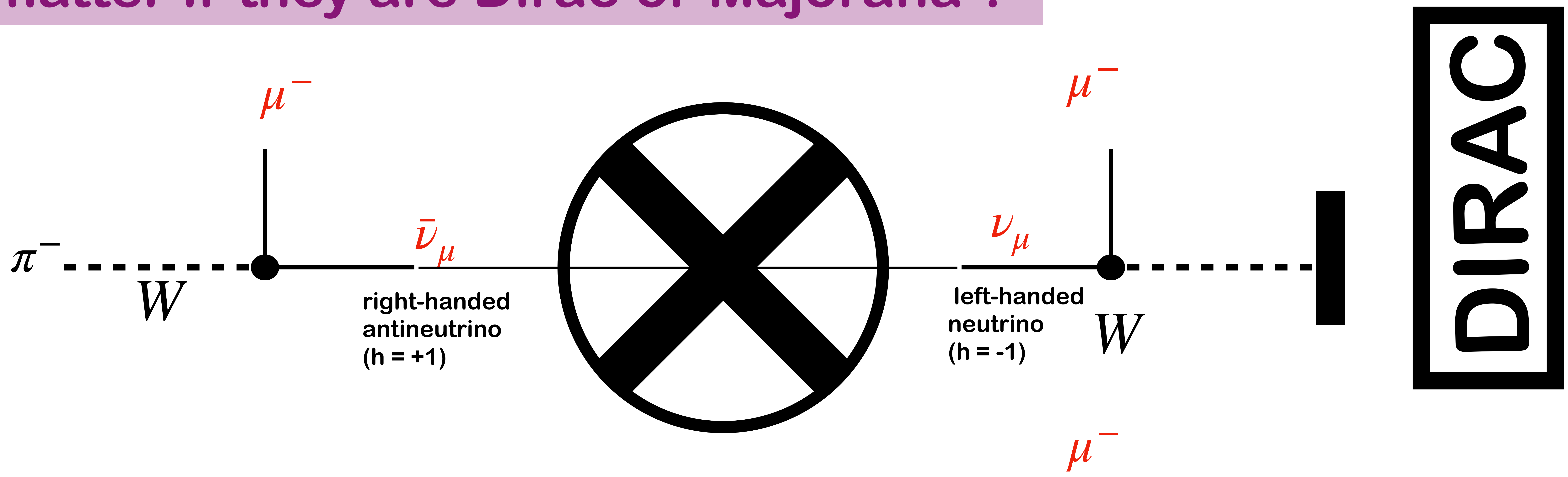

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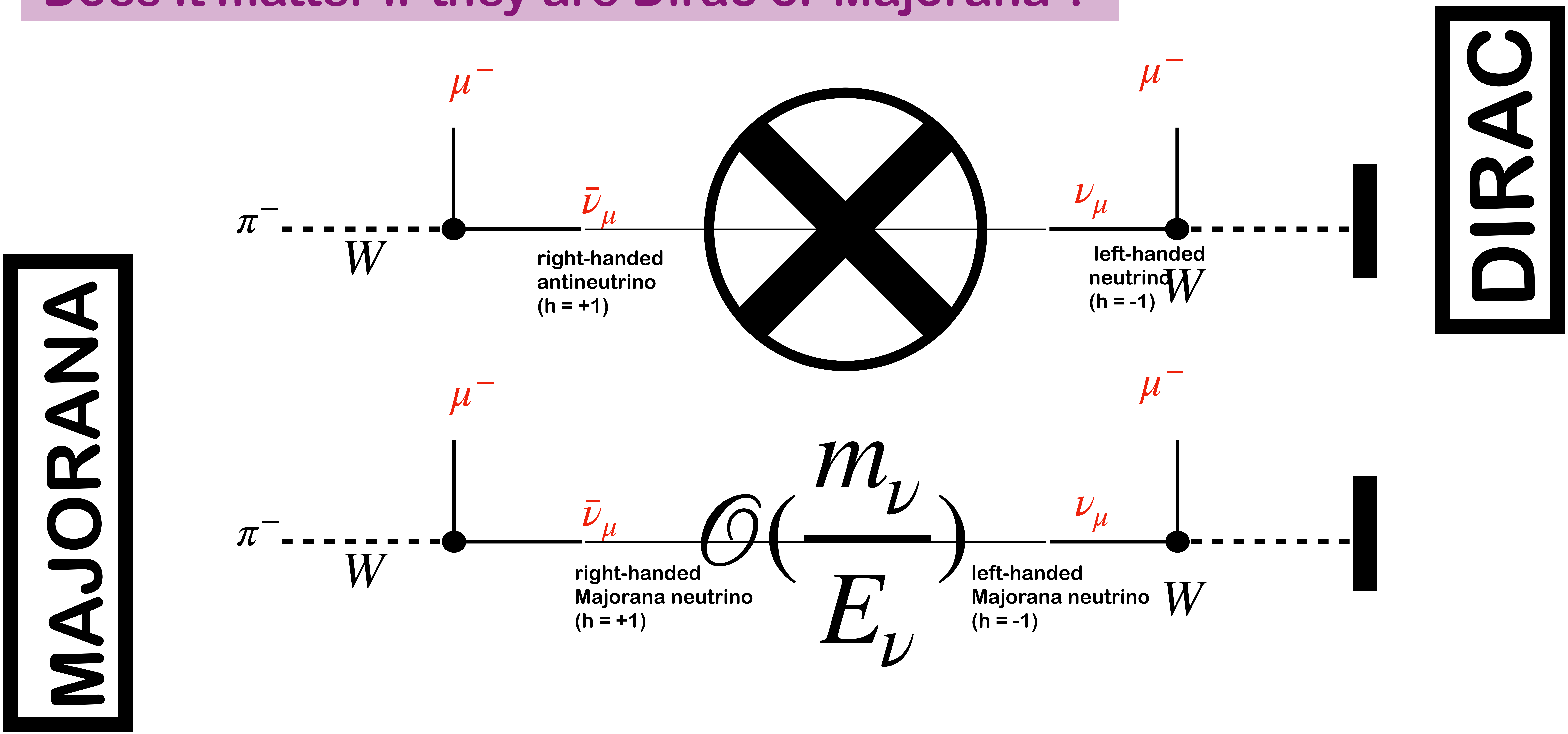

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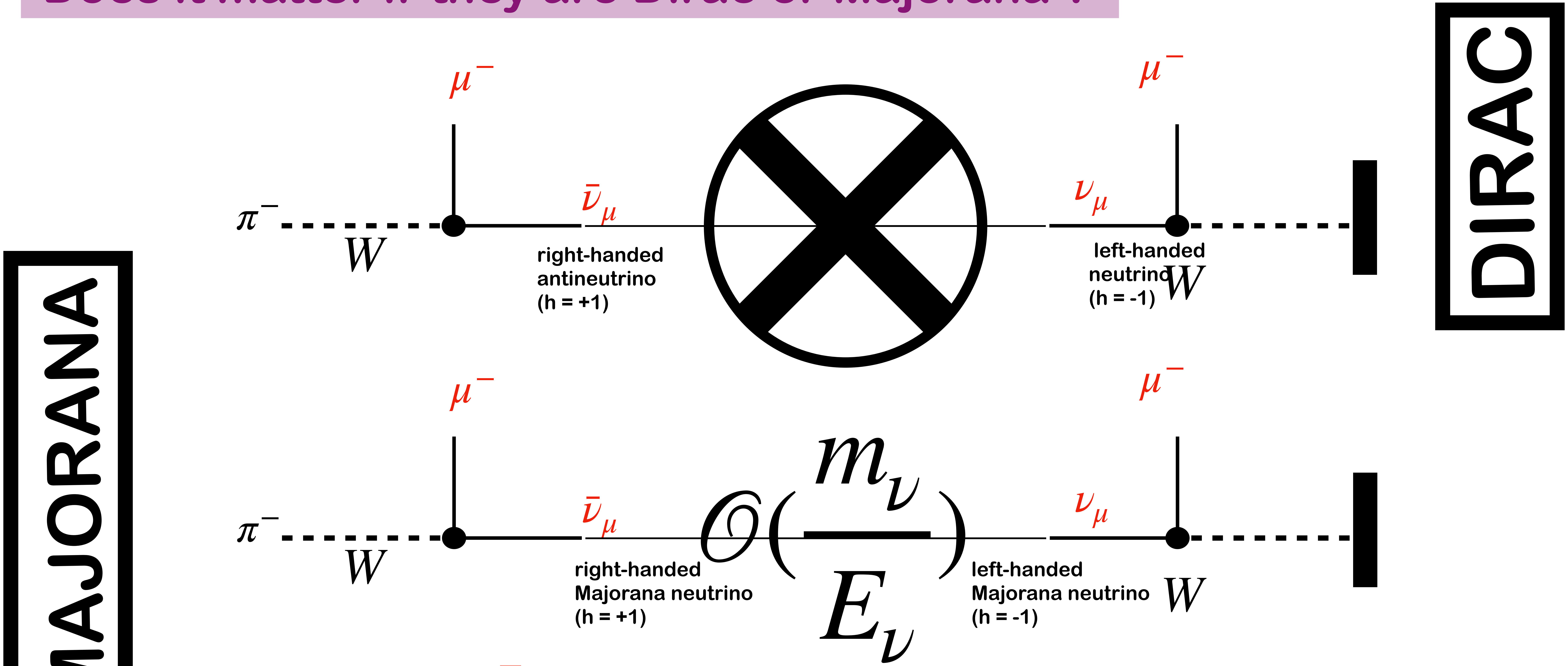

because $m_\nu \ll E_\nu$ in normal conditions there is no RH $\leftrightarrow$ LH flip

SUMMARY OF LECTURES I & II

What have we learned?

- Neutrinos come in 3 $\neq$ flavors ν_e, ν_μ, ν_τ
- Neutrinos are left-handed (h=-1) : if massless chirality $\equiv$ helicity
- CC & NC only couple to left-chiral neutrino fields (flavor diagonal)
- In the SM neutrinos are massless (no ν_R) - Dirac = Majorana
- SM has accidental global symmetry $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$

$$\to m_\nu = 0$$

- Experiments have observer L_α is violated (neutrino change flavor)
- Need flavor mixing i.e. need to implement $m_\nu \neq 0$ (BSM Physics)

Dirac neutrino $\nu \neq \nu^c$ (L is conserve)

Majorana neutrino $\nu = \nu^c$ (L is broken)

- Weinberg Operator ⟶ Majorana Mass Seesaw Mechanism
- Neutrino masses ⟶ Flavor Mixing ⟶ Neutrino Oscillations

LECTURE III