Neutrino: their origin and their role in matter-antimatter asymmetry

Arnab Dasgupta

PITT-PACC, Department of Physics and Astronomy,
University of Pittsburgh

March 6, 2024

Outline

- Evidence of mass of neutrinos
  - ↳ ν oscillation
    - ↳ CP? Mass Hierarchy? Nature?
- Mass Models
  - ↳ Majorana mass models
  - ↳ Dirac mass models
- Explanation of Matter Asymmetry
  - ↳ Lepton number violation via Majorana mass
  - ↳ Dirac Leptogenesis
- Correlation & it's constraints from Flavor Physics

Evidence of ν-mass

Discovery of ν-oscillation:

- The flavor eigenstate of ν's are admixtures of mass eigenstates

$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i$$

$$U_{\alpha i} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric angle}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor angle}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar angle}} \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{only if the particle} \\ \text{is Majorana}}}$$

$U_{\alpha i} \Rightarrow$ Pontecorvo-Maki-Nakagawa-Sataka (PMNS) matrix

Evidence of ν-mass

Discovery of ν-oscillation :

- The flavor eigenstate of ν's are admixtures of mass eigenstates

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$+ 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2 \qquad \frac{\Delta m^2 L}{4E} \simeq 1.27 \frac{\Delta m^2}{eV^2} \frac{L}{km} \frac{GeV}{E}$$

Evidence of ν-mass

Global Fit to neutrino Oscillation data

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21} [10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert [10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert [10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

Evidence of ν-mass

Global Fit to neutrino Oscillation data

Mass Hierarchy ? = [

parameter	best fit $\pm$ 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\|\Delta m^2_{31}\|[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\|[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

CP ? {

m_1 ? (NO)

m_3 ? (IO)

Evidence of ν-mass

Nature of ν, Majorana? Dirac?

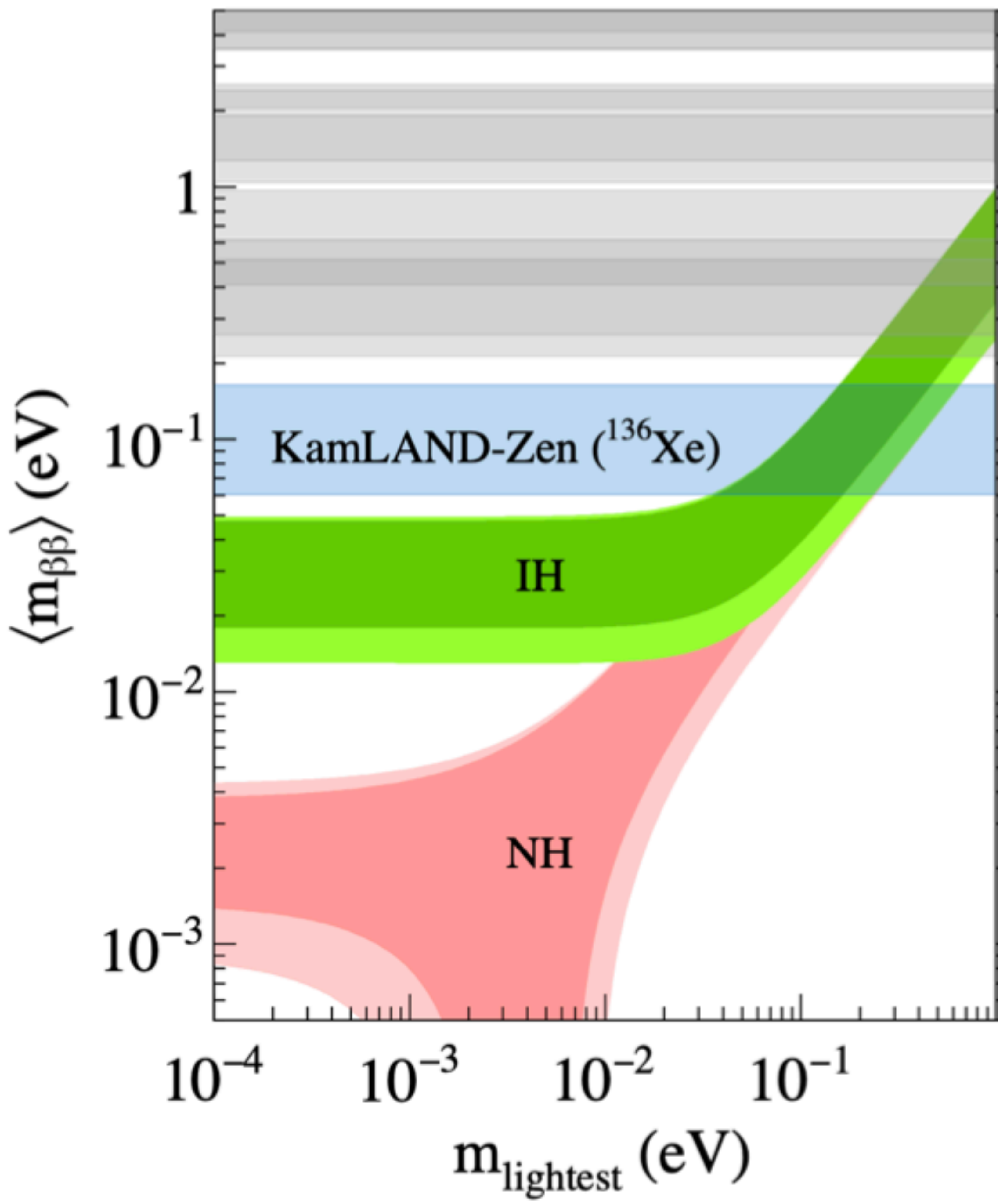
• $0\nu\beta\beta$ Decay Experiment

[arXiv:2108.09364]

If νs are majorana the effective mass is given as

$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3$$

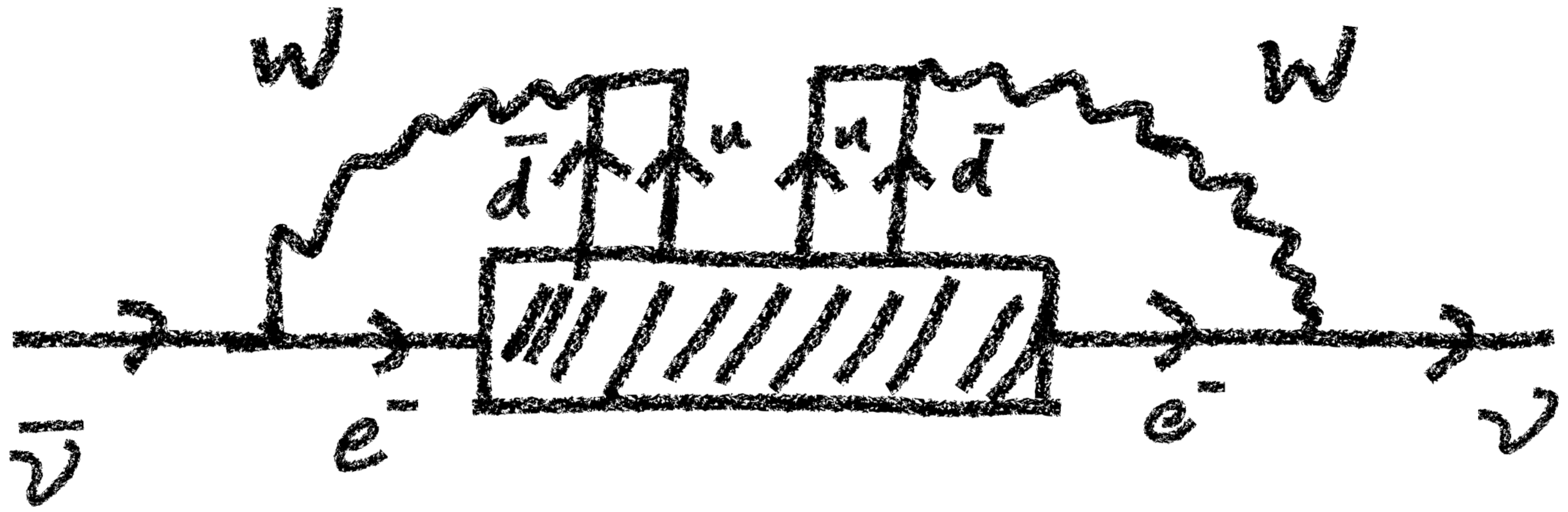


Evidence of ν-mass

Nature of ν, Majorana? Dirac?

If $0\nu\beta\beta$ is discovered ⇒ Lepton number is violated

⇒ νs are Majorana!!



Schechter Valle theorem [PRD 25 (1982) 2951]

Mass Models

- Majorana Neutrinos

Mass Models

- **Majorana Neutrinos**
  - Type I, III

Mass Models

- Majorana Neutrinos
  - Type I, III
  - Type II

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw

Mass Models

- Majorana Neutrinos
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

$\Rightarrow$ Many admixtures

Mass Models

- Majorana Neutrinos
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

⟹ Many admixtures

- Dirac Neutrinos

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

⇒ Many admixtures

- **Dirac Neutrinos**
  - Type-I

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

⟹ Many admixtures

- **Dirac Neutrinos**
  - Type-I
  - Inverse See-Saw

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

⟹ Many admixtures

- **Dirac Neutrinos**
  - Type-I
  - Inverse See-Saw
  - Radiative neutrino mass model

Mass Models

- **Majorana Neutrinos**
  - Type I, III
  - Type II
  - Inverse See-Saw
  - Radiative neutrino mass model

⟹ Many admixtures

- **Dirac Neutrinos**
  - Type-I
  - Inverse See-Saw
  - Radiative neutrino mass model

& Tree → $y_D \bar{L} H \nu_R$

Mass Models (Majorana Scenario)

- **Type I, III :**

	$SU(3)_c \times SU(2)_L \times U(1)_Y$
N_R	$(1\ ,\ 1\ ,\ 0)$

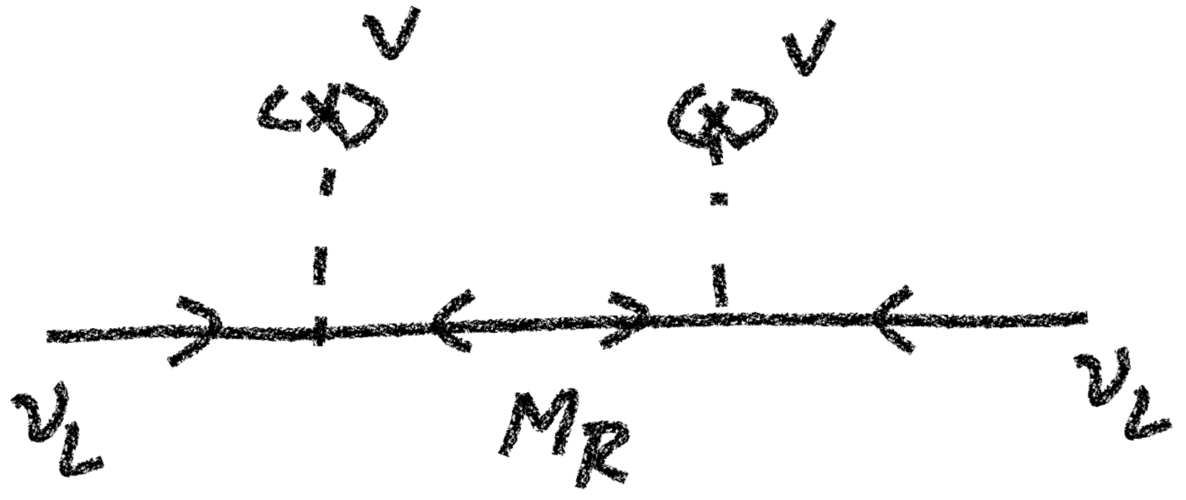
- Type I : $\mathcal{L} \supset y_\nu \bar{L} H N_R + M_R \overline{N_R^c} N_R + h.c$

Breaking B-L: New scale and new symmetry beyond SM.

- Type III : $\mathcal{L} \supset y_\nu \bar{L} \Psi H + M_R \, Tr[\overline{\Psi^c} \Psi] + h.c$

	$SU(3)_c \times SU(2)_L \times U(1)_Y$
Ψ	$(1\ ,\ 3\ ,\ 0)$

$$\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & \Sigma^0/\sqrt{2} \end{pmatrix} \qquad m_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \simeq -y_\nu^2 \frac{v^2}{M_R}$$



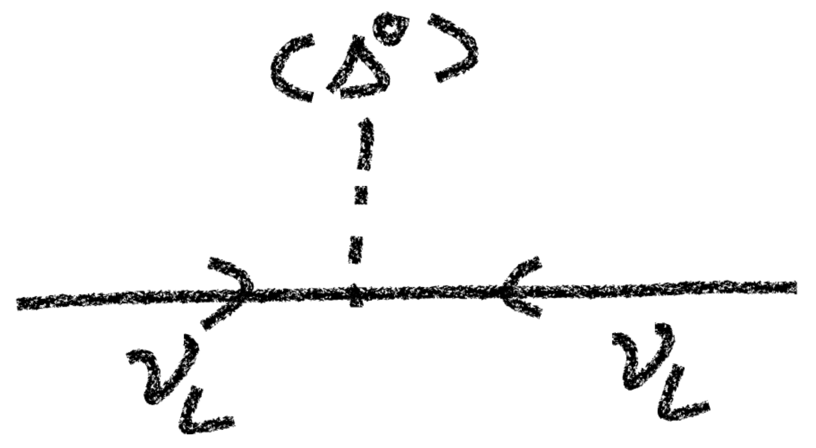
Mass Models (Majorana Scenario)

• Type II :

$$\mathcal{L} \supset y_\nu \overline{L^c}\, i\sigma_2 \Delta L + h.c$$

	$SU(3)_c \times SU(2)_L \times U(1)_Y$
Δ	$(1\ ,\ 3\ ,\ 1)$

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$



$$m_\nu = y_{\nu_{\alpha\beta}} \langle \Delta^0 \rangle$$

Mass Models (Majorana Scenario)

- **Inverse See-Saw:**

	$SU(3)_c \times SU(2)_L \times U(1)_Y$
S_R	$(1, 1, 0)$
N_R	$(1, 1, 0)$

$$\mathcal{L} \supset y_D \bar{L} H N_R + y_\nu \phi \overline{S_R^c} N_R + \mu \overline{S_R^c} S_R$$

$$m_\nu = \begin{pmatrix} 0 & y_D v & 0 \\ y_D v & 0 & y_\nu v_\phi \\ 0 & y_\nu v_\phi & \mu \end{pmatrix} \simeq - y_D^T y_\nu^{-1} \mu y_\nu^{-1} y_D \left(\frac{v_\phi}{v}\right)^2$$

Mass Models (Majorana Scenario)

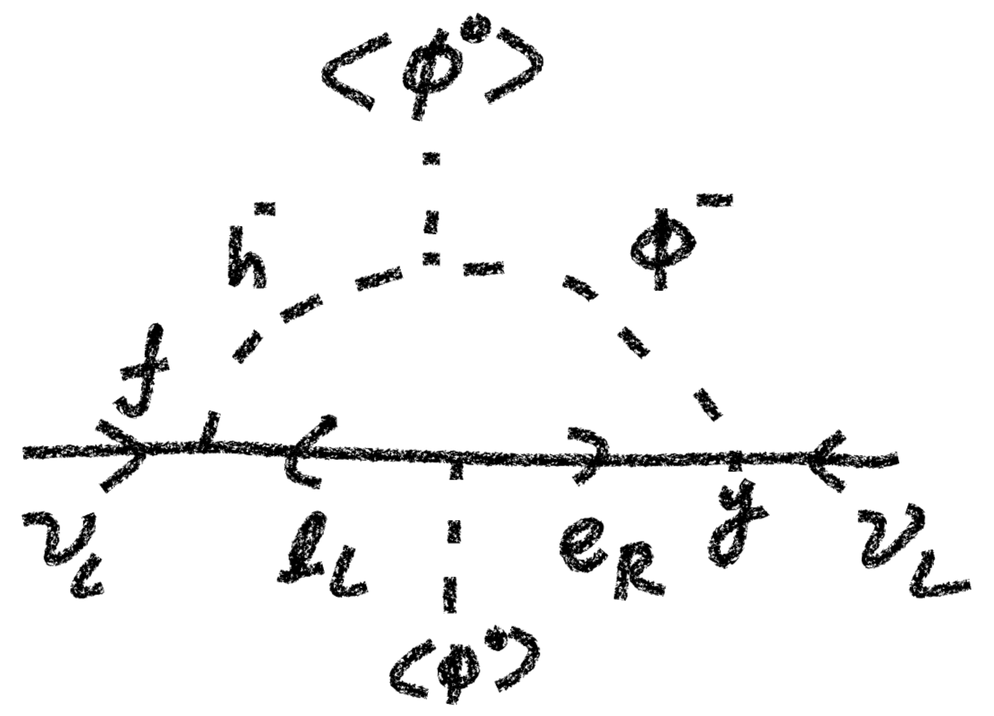
- **Radiative Neutrino Mass Model** (1-Loop only)

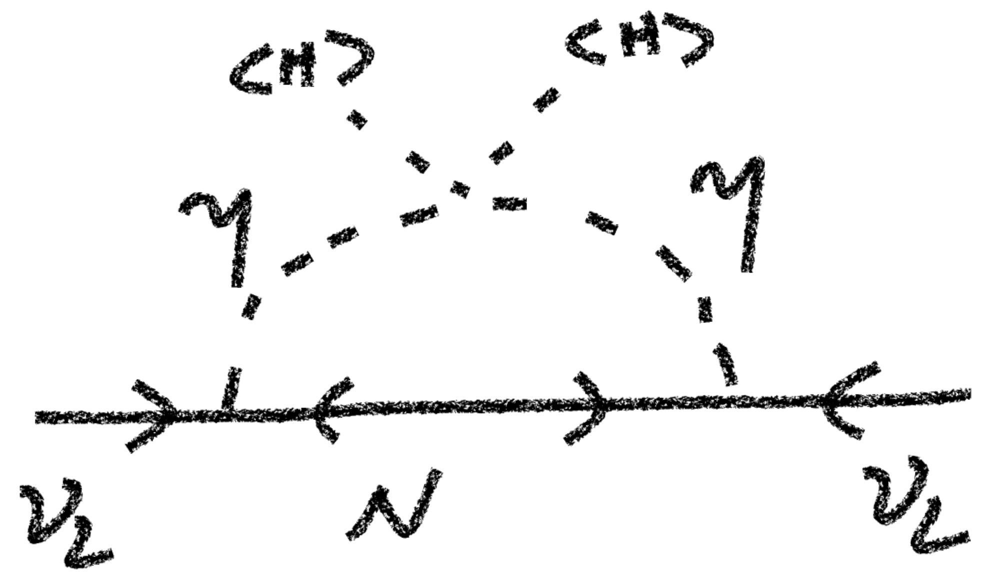
  - Zee-Babu model

    $$\mathcal{L} \supset y_D \bar{L} H e_R + f \bar{\tilde{L}} L h^+ + h.c$$

  - Scotogenic model

    $$\mathcal{L} \supset y_D \bar{L} \eta N_R + M \bar{N_R^c} N_R + h.c$$



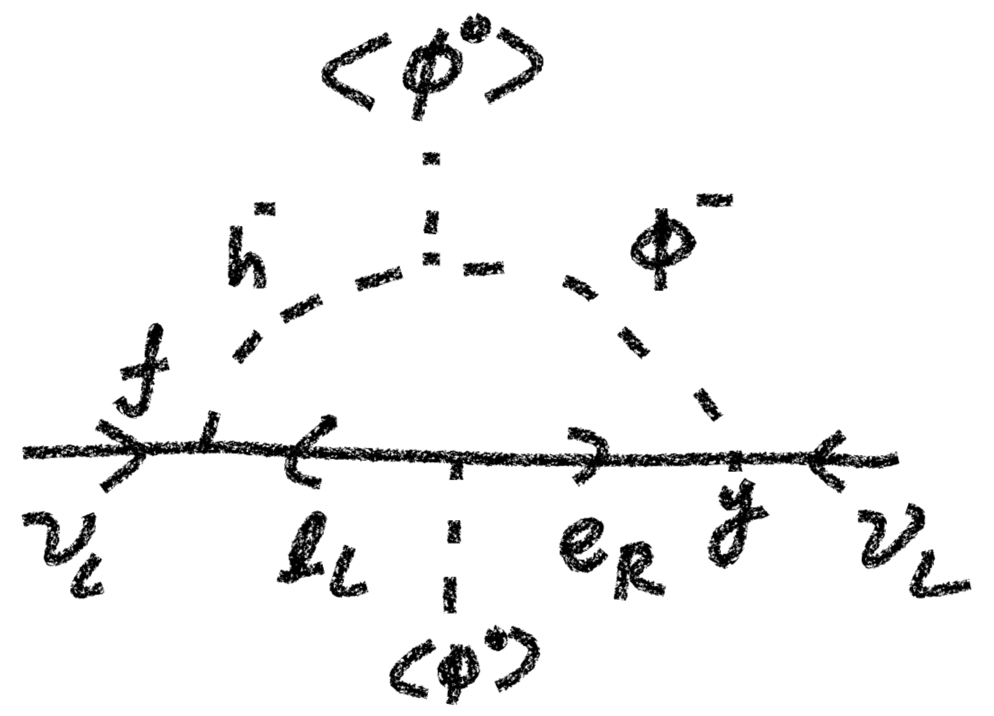


Mass Models (Majorana Scenario)

Radiative Neutrino Mass Model (1-Loop only)

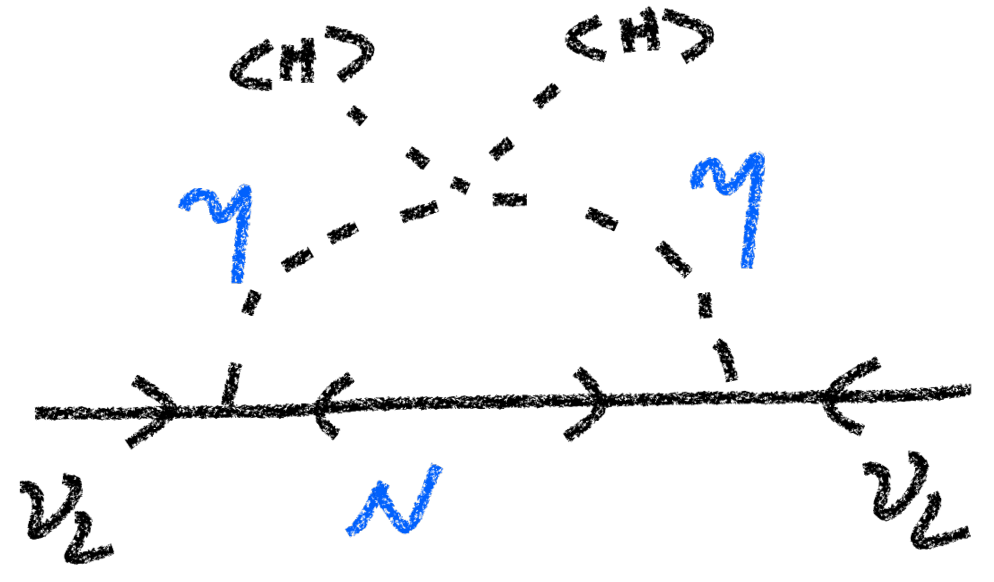
- Zee-Babu model

$$\mathcal{L} \supset y_D \bar{L} H e_R + f \bar{\tilde{L}} L h^+ + h.c$$



- Scotogenic model

$$\mathcal{L} \supset y_D \bar{L} \eta N_R + M \bar{N_R^c} N_R + h.c$$



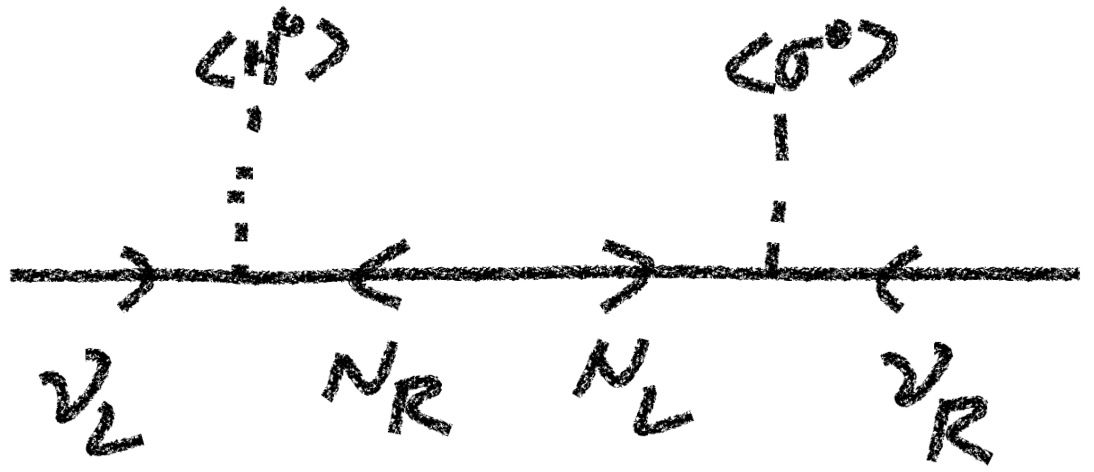
⇒ Dark Matter

Mass Models (Dirac Scenario)

• Type I :

$$\mathcal{L} \supset y_D \bar{L} H N_R + y_\phi \bar{N}_L \nu_R \sigma + M_D \bar{N}_L N_R$$

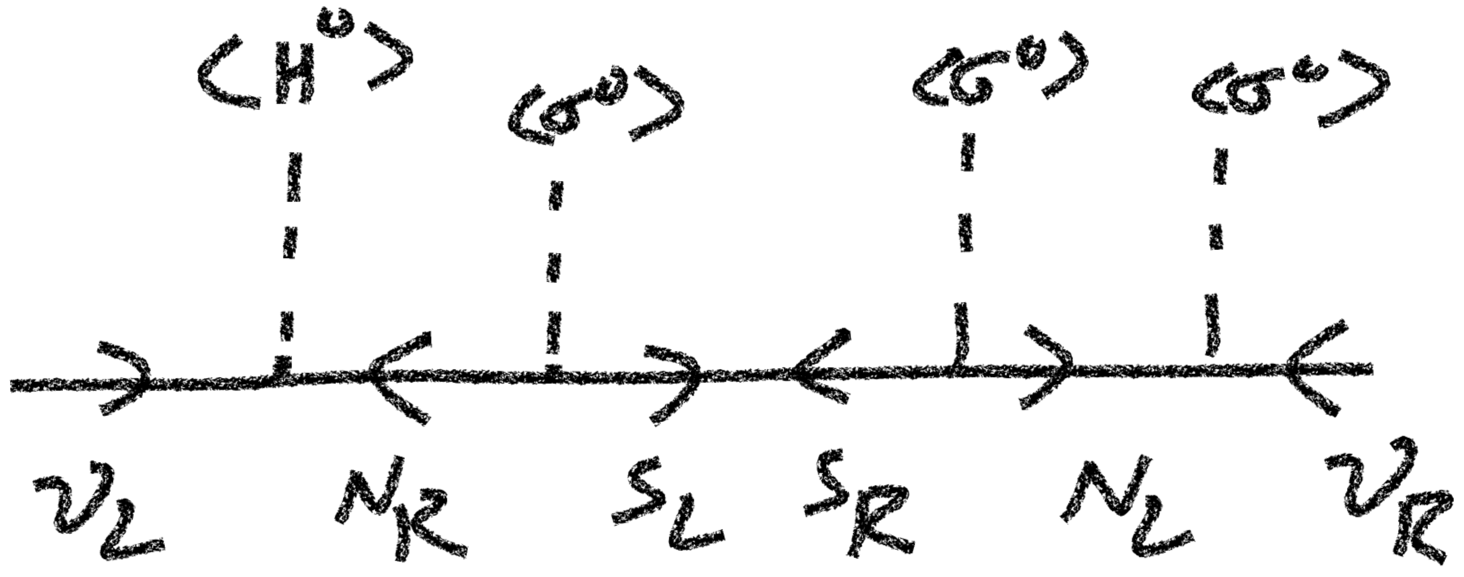
$$m_\nu = \begin{pmatrix} 0 & y_D v_H \\ y_D v_H & M_D \end{pmatrix}$$



• Inverse See-Saw :

$$\mathcal{L} \supset y_D \bar{L} H N_R + y_s \bar{N}_L \nu_R \sigma + y_s \bar{N} S \sigma + \mu_D \bar{S} S + h.c$$

$$m_\nu = \begin{pmatrix} 0 & y_D v_H & 0 \\ y_D v_H & 0 & y_s v_\sigma \\ 0 & y_s v_\sigma & \mu_D \end{pmatrix}$$

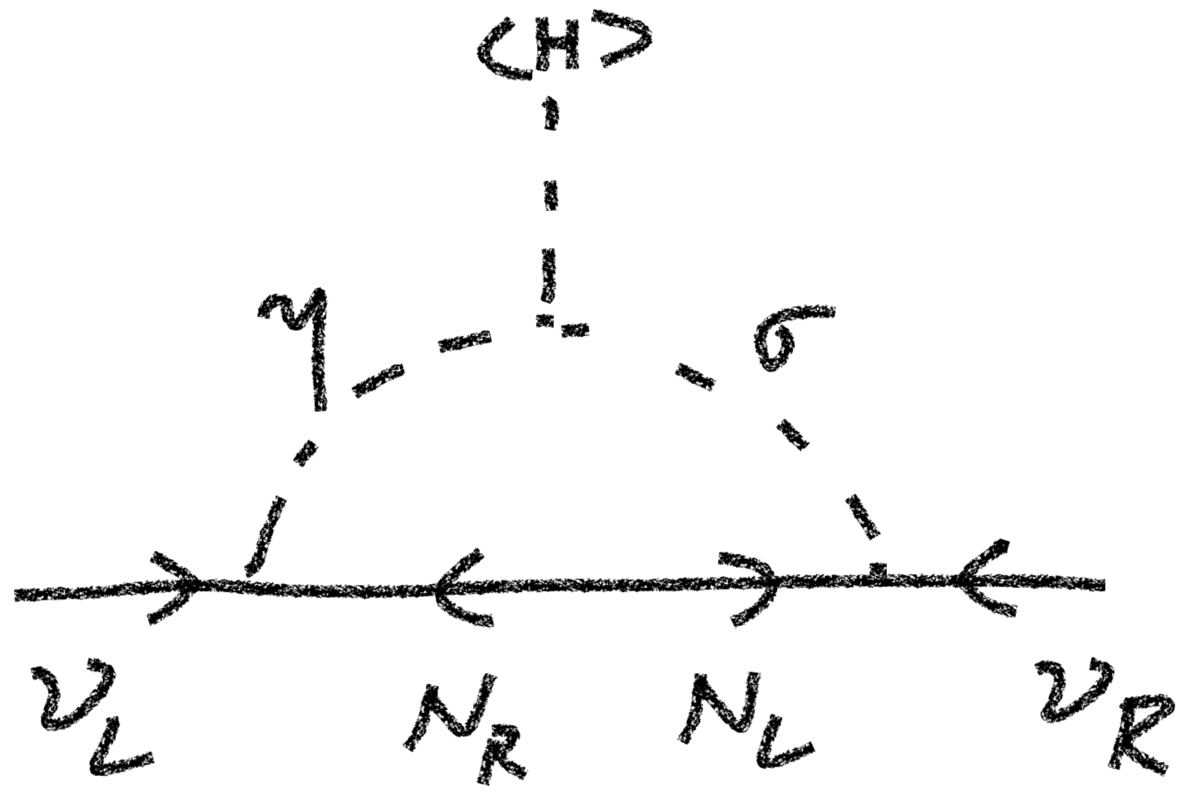


Mass Models (Dirac Scenario)

Radiative Mass Model:

$$\mathcal{L} \supset y_D \bar{L} \eta N_R + M \bar{N}_L N_R + y \sigma \bar{N}_L \nu_R + h.c$$

$$V \supset \mu_{\eta\sigma} \eta^\dagger H \sigma + h.c$$

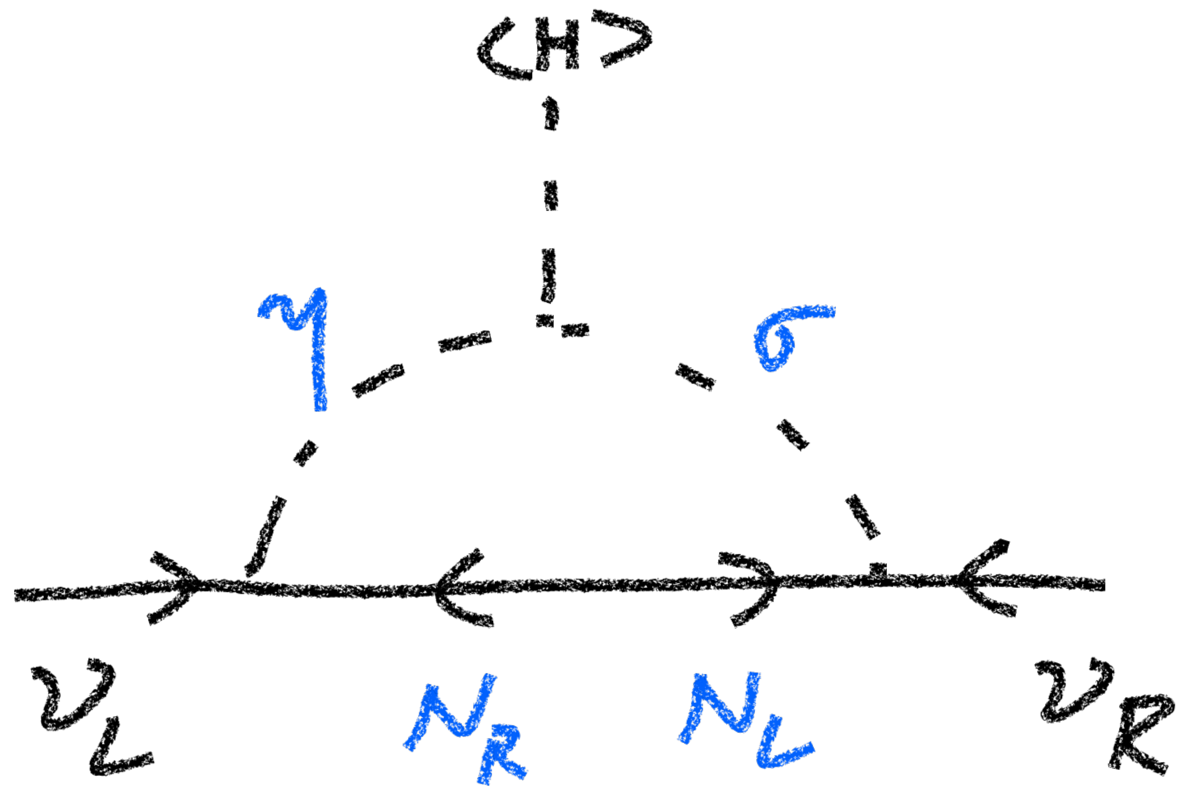


Mass Models (Dirac Scenario)

Radiative Mass Model:

$$\mathcal{L} \supset y_D \bar{L} \eta N_R + M \bar{N}_L N_R + y \sigma \bar{N}_L \nu_R + h.c$$

$$V \supset \mu_{\eta\sigma} \eta^\dagger H \sigma + h.c$$



⇒ Dark Matter

Matter Asymmetry

- The Standard Model does not explain the present asymmetry

  1. The CP violation coming from Jarlskog invarient is of the order 10^{-20}.
  2. The experimental lower bound on the Higgs mass implies the transition is not strongly first order.

Matter Asymmetry

- The observed BAU is often quoted in terms of baryon to photon ratio

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10} \Rightarrow Y_B^0 = \eta_B / 7.04 \Rightarrow \Omega_B h^2 = \frac{s_0}{\rho_{crit}} Y_B^0 \sim 2.26\%$$

- The prediction for this ratio from Big-Bang Nucleosynthesis (BBN) agrees well with the observed value from Cosmic Microwave Background Radiation (CMBR) measurements.

Sakharov's Conditions

- The three basic ingredients necessary to generate a net baryon asymmetry from an initially baryons symmetric Universe (1967)

1. Baryon Number (B) violation $X \to Y + B$
2. C and CP violation
   $$\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$
3. Departure from thermal Equilibrium

Recipe for Asymmetry

- Now, in order to get a non-zero CP violation we ~~start~~ need at-least two distinct amplitude for a particular process.

- In order to understand the above claim we start with the amplitude of a B-violating process $(X \to b)$

$$i\mathcal{M} = (c_1 A_1 + c_2 A_2)\, f$$

Similarly, for anti-particle

$$i\bar{\mathcal{M}} = (c_1^* A_1 + c_2^* A_2)\, f^*$$

$\Longrightarrow$ spinor wave function

Recipe for Asymmetry

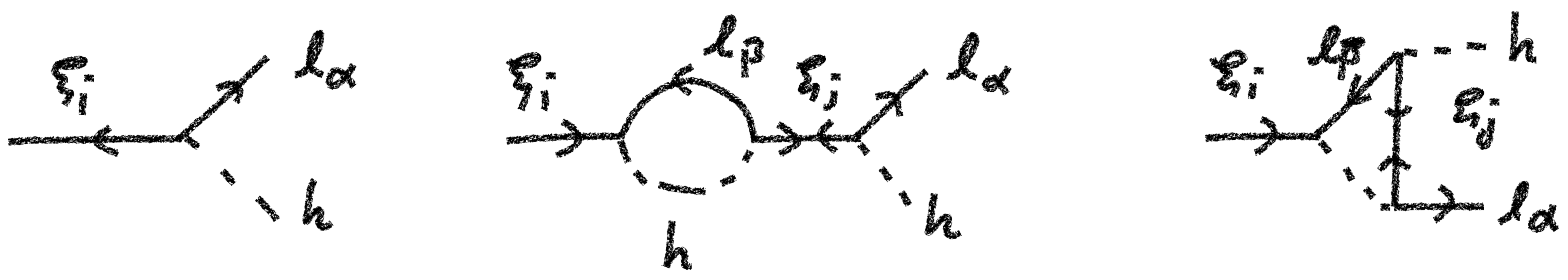
- The difference between the two processes comes out to be

$$\delta = 4\,\underbrace{\mathrm{Im}[\mathcal{C}_1^* \mathcal{C}_2]}_{\text{Purely from coupling}}\,\underbrace{\mathrm{Im}[\mathcal{A}_1^* \mathcal{A}_2]}_{\text{Purely from Amplitudes}}\,|f|^2$$

Leptogenesis from ν-Mass model (Majorana case)

Lagrangian

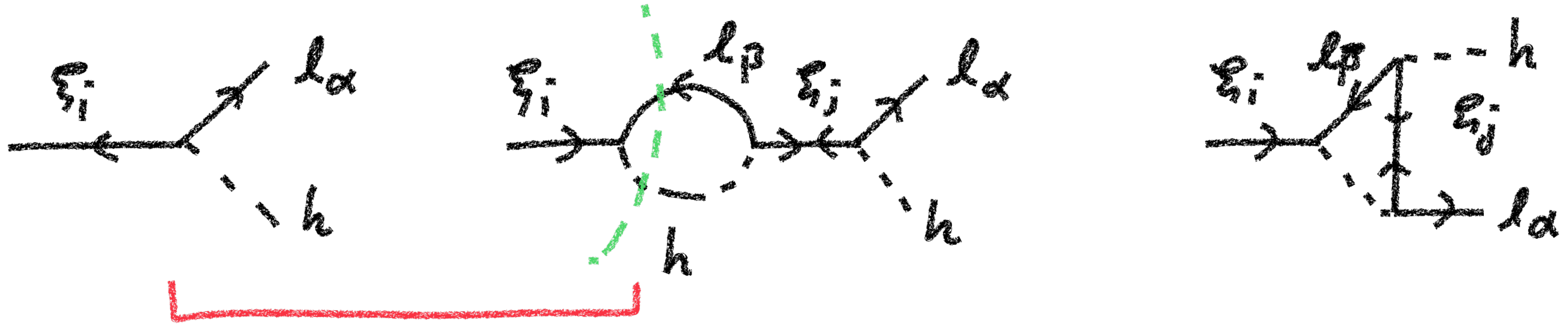
$$\mathcal{L} \supset y_{\alpha i}\, l_\alpha h\, \xi_i + M_{ij}\, \xi_i \xi_j + h.c$$



Leptogenesis from ν-Mass model I (Majorana case)

- **Lagrangian**

$$\mathcal{L} \supset y_{\alpha i}\, l_\alpha h\, \xi_i + M_{ij}\, \xi_i \xi_j + h.c$$

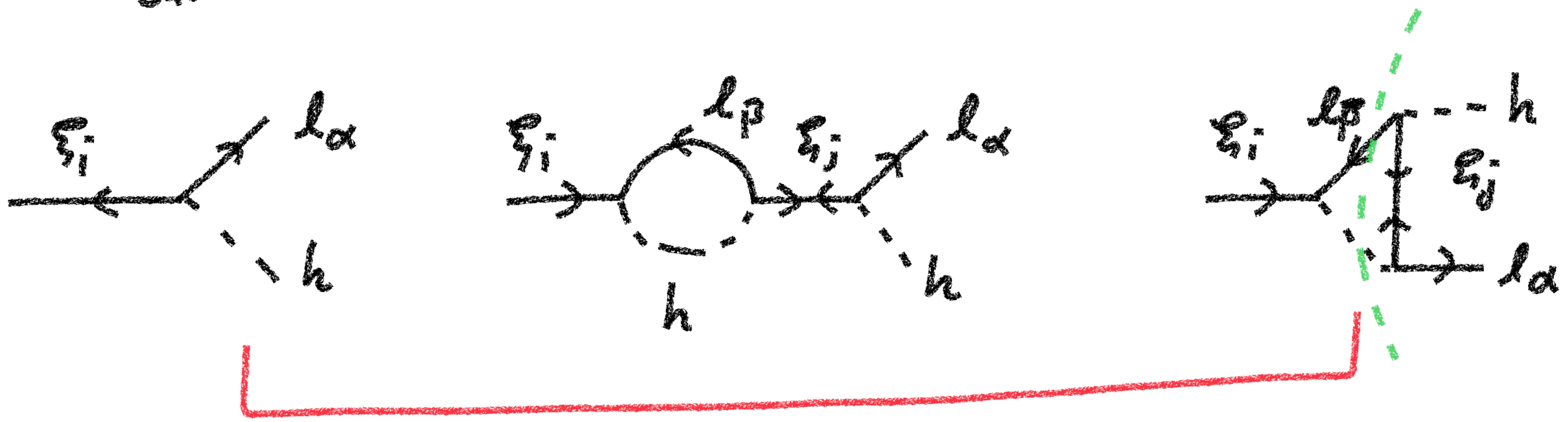


(Liu & Segre '93)

Leptogenesis from ν-Mass model I (Majorana Case)

- **Lagrangian**

$$\mathcal{L} \supset y_{\alpha i}\, \ell_\alpha h\, \xi_i + M_{ij}\, \xi_i \xi_j + h.c$$

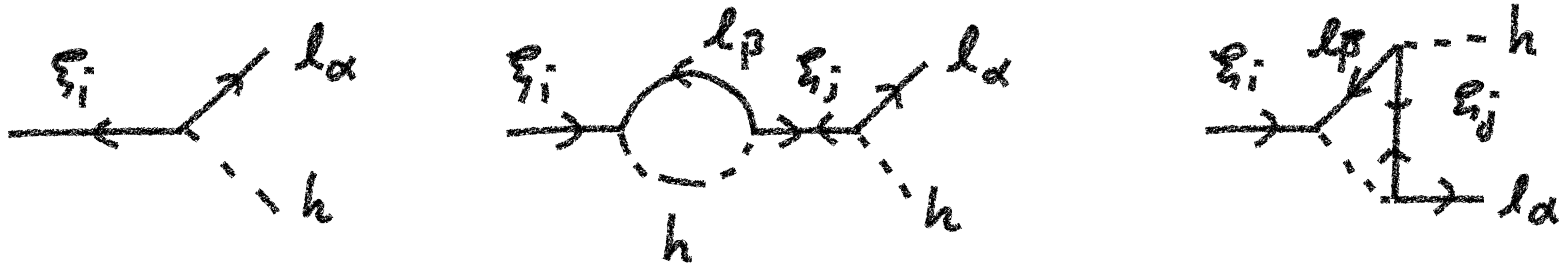


(Fukugida & Yanagida '86)

Leptogenesis from ν-Mass model (Majorana Case)

Lagrangian

$$\mathcal{L} \supset y_{\alpha i}\, \ell_\alpha h\, \xi_i + M_{ij}\, \xi_i \xi_j + h.c$$



$$y_{\alpha i} = \frac{1}{v}\left(U D_{\sqrt{M_\nu}} R^\dagger D_{\sqrt{\Lambda}}\right)_{\alpha i}, \qquad R R^T = \mathbb{1}$$

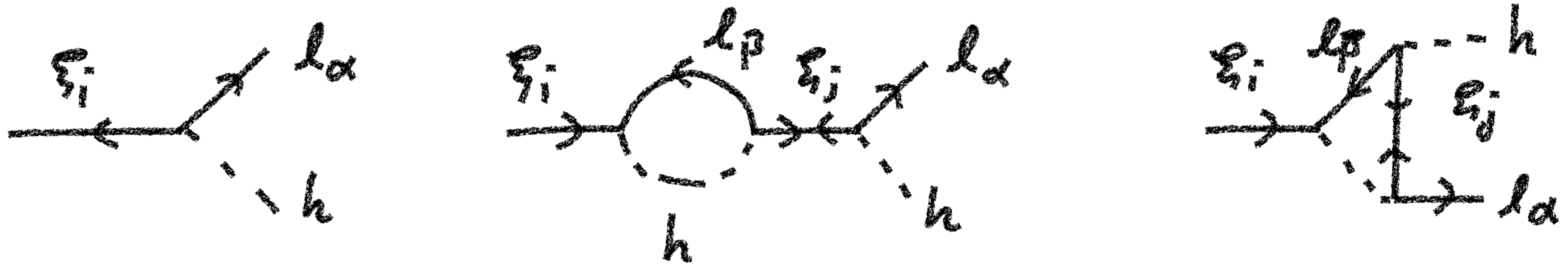
$$\underbrace{\mathcal{M}_\nu}_{\nu\text{-mass}} = y^* \Lambda^{-1} y^\dagger$$

$$D_{\sqrt{M_\nu}} = \begin{pmatrix} \sqrt{M_{\nu_1}} & 0 & 0 \\ 0 & \sqrt{M_{\nu_2}} & 0 \\ 0 & 0 & \sqrt{M_{\nu_3}} \end{pmatrix} ; \quad D_{\sqrt{\Lambda}} = \begin{pmatrix} \sqrt{\Lambda_1} & 0 & 0 \\ 0 & \sqrt{\Lambda_2} & 0 \\ 0 & 0 & \sqrt{\Lambda_3} \end{pmatrix}$$

Leptogenesis from ν-Mass model (Majorana case)

Lagrangian

$$\mathcal{L} \supset y_{\alpha i}\, \ell_\alpha h\, \xi_i + M_{ij}\, \xi_i \xi_j + h.c$$



$$y_{\alpha i} = \frac{1}{v}\left(U D_{\sqrt{M_\nu}} R^\dagger D_{\sqrt{\Lambda}}\right)_{\alpha i},$$

$\hookrightarrow RR^T = \mathbb{1}$

$$\underbrace{\mathcal{M}_\nu}_{\nu\text{-mass}} = y^* \Lambda^{-1} y^\dagger$$

$$D_{\sqrt{M_\nu}} = \begin{pmatrix} \sqrt{m_{\nu_1}} & 0 & 0 \\ 0 & \sqrt{m_{\nu_2}} & 0 \\ 0 & 0 & \sqrt{m_{\nu_3}} \end{pmatrix} ; \quad D_{\sqrt{\Lambda}} = \begin{pmatrix} \sqrt{\Lambda_1} & 0 & 0 \\ 0 & \sqrt{\Lambda_2} & 0 \\ 0 & 0 & \sqrt{\Lambda_3} \end{pmatrix}$$

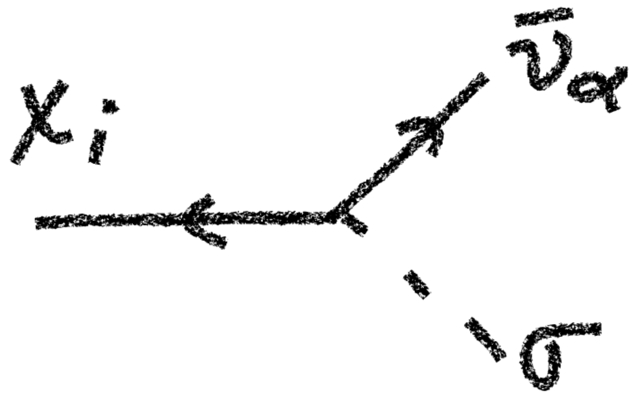
Casas-Ibarra Parameterization

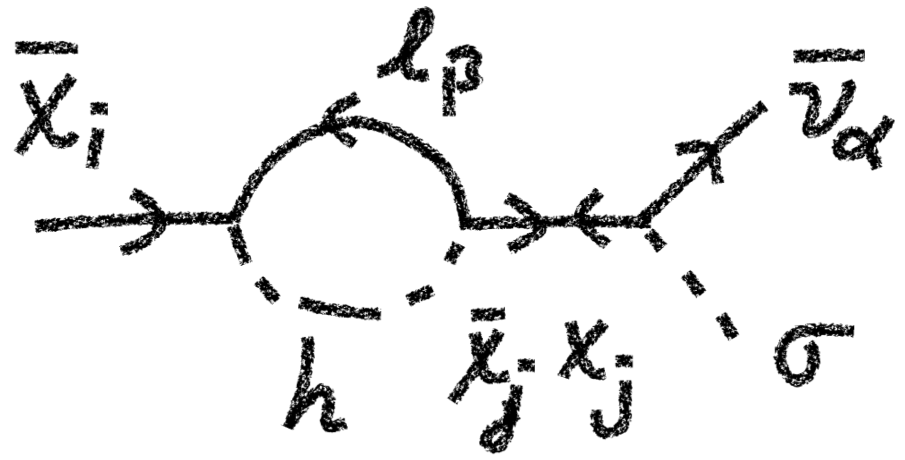
Leptogenesis from ν-Mass model (Dirac case)

- **Lagrangian**

$$\mathcal{L} \supset y_{\alpha i}\, l_\alpha h \bar{\chi}_i + m_{ij}\bar{\chi}_i \chi_j + \tilde{y}_{i\alpha}\, \chi_i \sigma \bar{\nu}_\alpha + h.c$$

(Cerdeño, Dedes & Underwood '06)





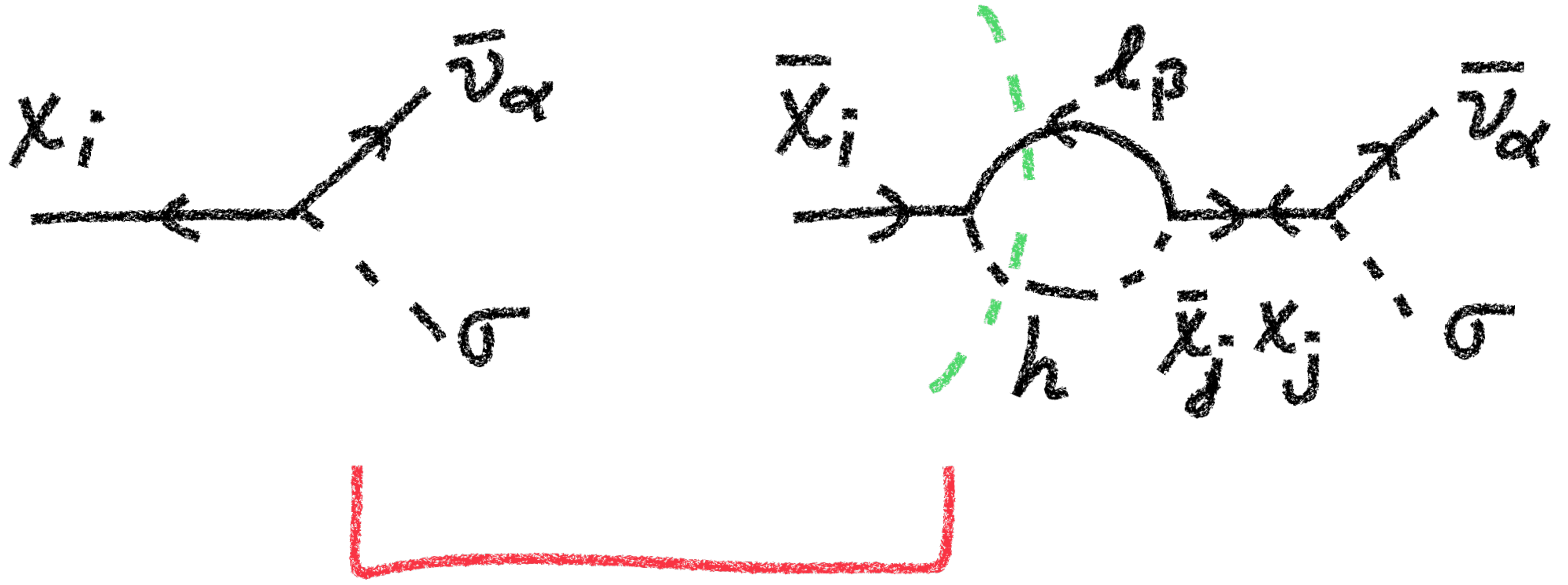
$$y_{\alpha i} = \frac{1}{v}\left(A D_{\sqrt{m_\nu}} W D_{\sqrt{M}}\right)_{\alpha i} \ ; \quad \tilde{y}_{i\alpha} = \frac{1}{v_\sigma}\left(D_{\sqrt{M}} X^\dagger D_{\sqrt{m_\nu}} B^\dagger\right)_{i\alpha} \Rightarrow W X^\dagger = 1$$

$$m_{\nu_{\alpha\beta}} = v v_\sigma \left(y M^{-1} \tilde{y}\right)_{\alpha\beta}$$

Leptogenesis from ν-Mass model (Dirac case)

- **Lagrangian**

$$\mathcal{L} \supset y_{\alpha i}\, \ell_\alpha h \bar{\chi}_i + m_{ij} \bar{\chi}_i \chi_j + \tilde{y}_{i\alpha}\, \chi_i \sigma \bar{\nu}_\alpha + h.c$$



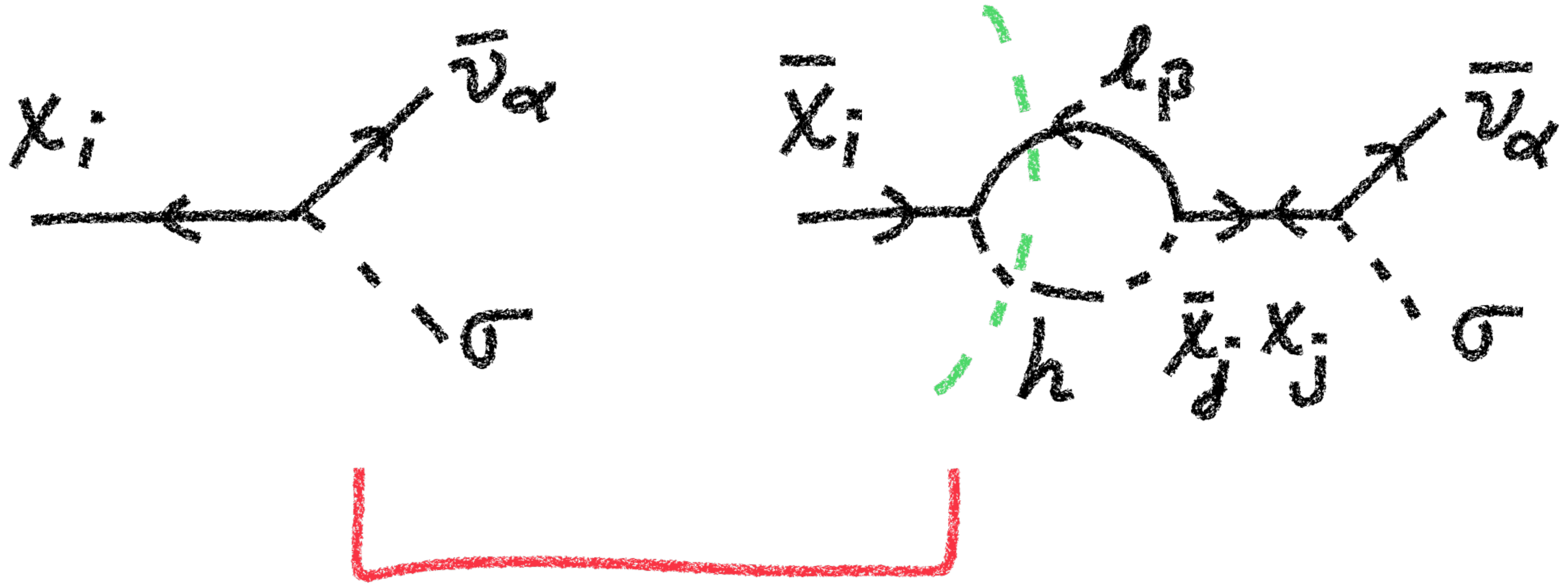
⇒ Dirac Leptogenesis

$$\left.\begin{aligned} Y_B &= \frac{28}{79}\left(Y_B - Y_{L_{SM}}\right) \\ Y_B - Y_{L_{SM}} - Y_{L_{\nu_R}} &= 0 \end{aligned}\right] \Rightarrow Y_B = -\frac{28}{79} Y_{L_{\nu_R}}$$

Leptogenesis from ν-Mass model (Dirac case)

Lagrangian

$$\mathcal{L} \supset y_{\alpha i}\, l_\alpha h \bar{\chi}_i + m_{ij}\,\bar{\chi}_i \chi_j + \tilde{y}_{i\alpha}\,\chi_i \sigma \bar{\nu}_\alpha + h.c$$



⇒ Dirac Leptogenesis

$$Y_B = \frac{28}{79}\left(Y_B - Y_{L_{SM}}\right)$$

$$Y_B - Y_{L_{SM}} - Y_{L_{\nu_R}} = 0$$

$$\Rightarrow Y_B = -\frac{28}{79}\, Y_{L_{\nu_R}}$$

Avoid left-right equilibration

$$LH \leftrightarrow \sigma \nu_R \ ; \quad \Gamma_{L\leftrightarrow R} \sim \frac{|y|^2 |\tilde{y}|^2 T^5}{m_1} \ ; \quad H(T) = \sqrt{\frac{8\pi^3 g_*}{90}}\,\frac{T^2}{M_{Pl}}$$

$$\left.\frac{\Gamma_{L\leftrightarrow R}}{H}\right|_{T=M_1} < 1 \ \Rightarrow\ \frac{|y|^2 |\tilde{y}|^2}{m_1} \lesssim \frac{1}{M_{Pl}}\sqrt{\frac{8\pi^3 g_*}{90}}$$

Correlation & bounds from Flavor Physics

ν-mass & mixing $\longleftrightarrow$ Baryon Asymmetry

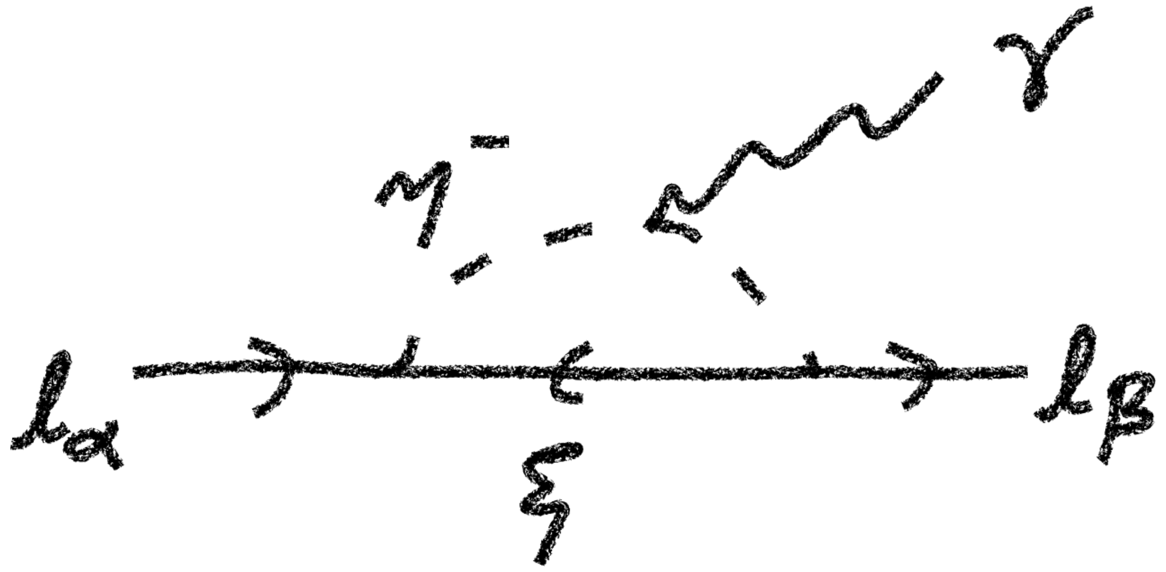
$$y = \frac{1}{v}\left(U\, D_{\sqrt{M_\nu}}\, R^\dagger\, D_{\sqrt{\Lambda}}\right)$$ (Majorana case)

$$y = \frac{1}{v}\left(A\, D_{\sqrt{\hat{m}_\nu}}\, W\, D_{\sqrt{\hat{M}}}\right)$$ (Dirac case)

$$\tilde{y} = \frac{1}{v_\sigma}\left(D_{\sqrt{\hat{M}}}\, X^\dagger\, D_{\sqrt{\hat{m}_\nu}}\, B^\dagger\right)$$

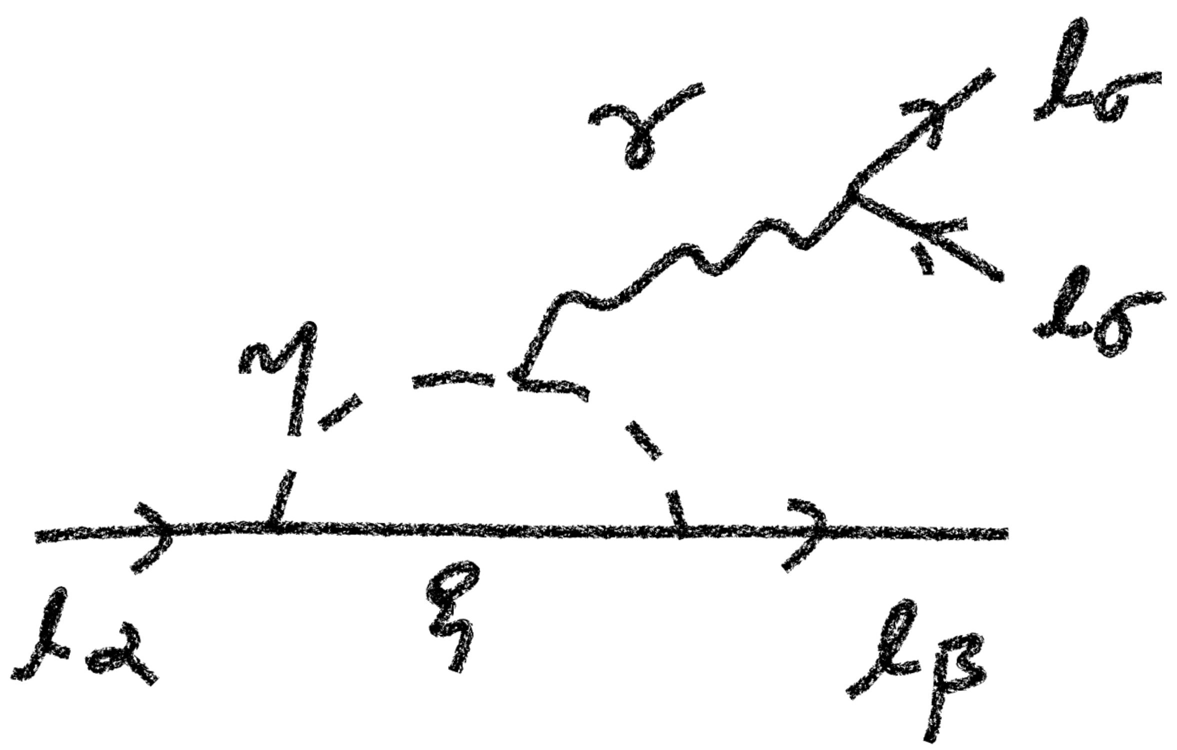
Correlation & bounds from Flavor Physics

- $\ell_\alpha \to \ell_\beta \gamma$



(Scotogenic & it's varient)

- $\ell_\alpha \to \ell_\beta \ell_\sigma \ell_\sigma$

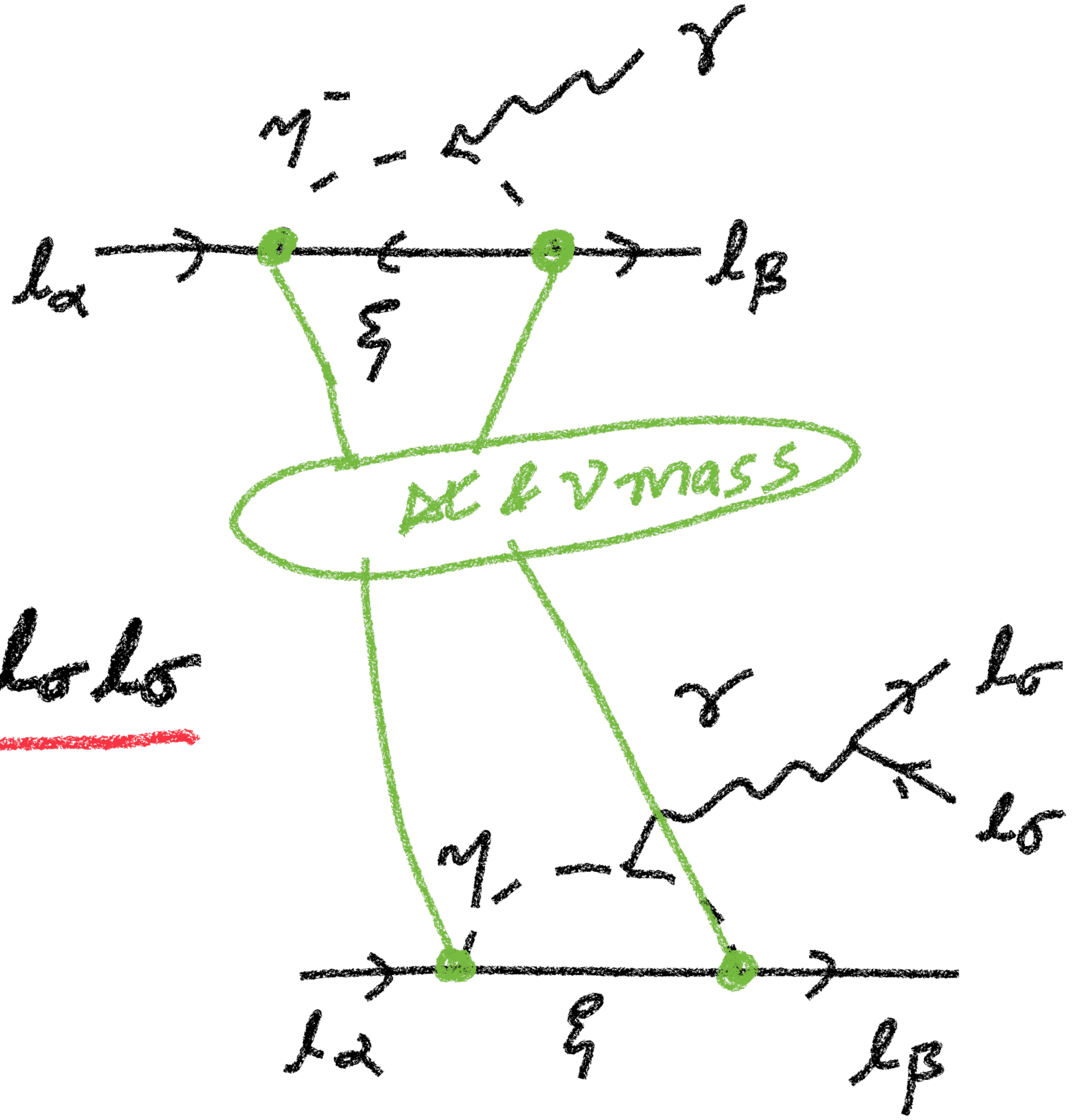


Correlation & bounds from Flavor Physics

- $l_\alpha \to l_\beta \gamma$

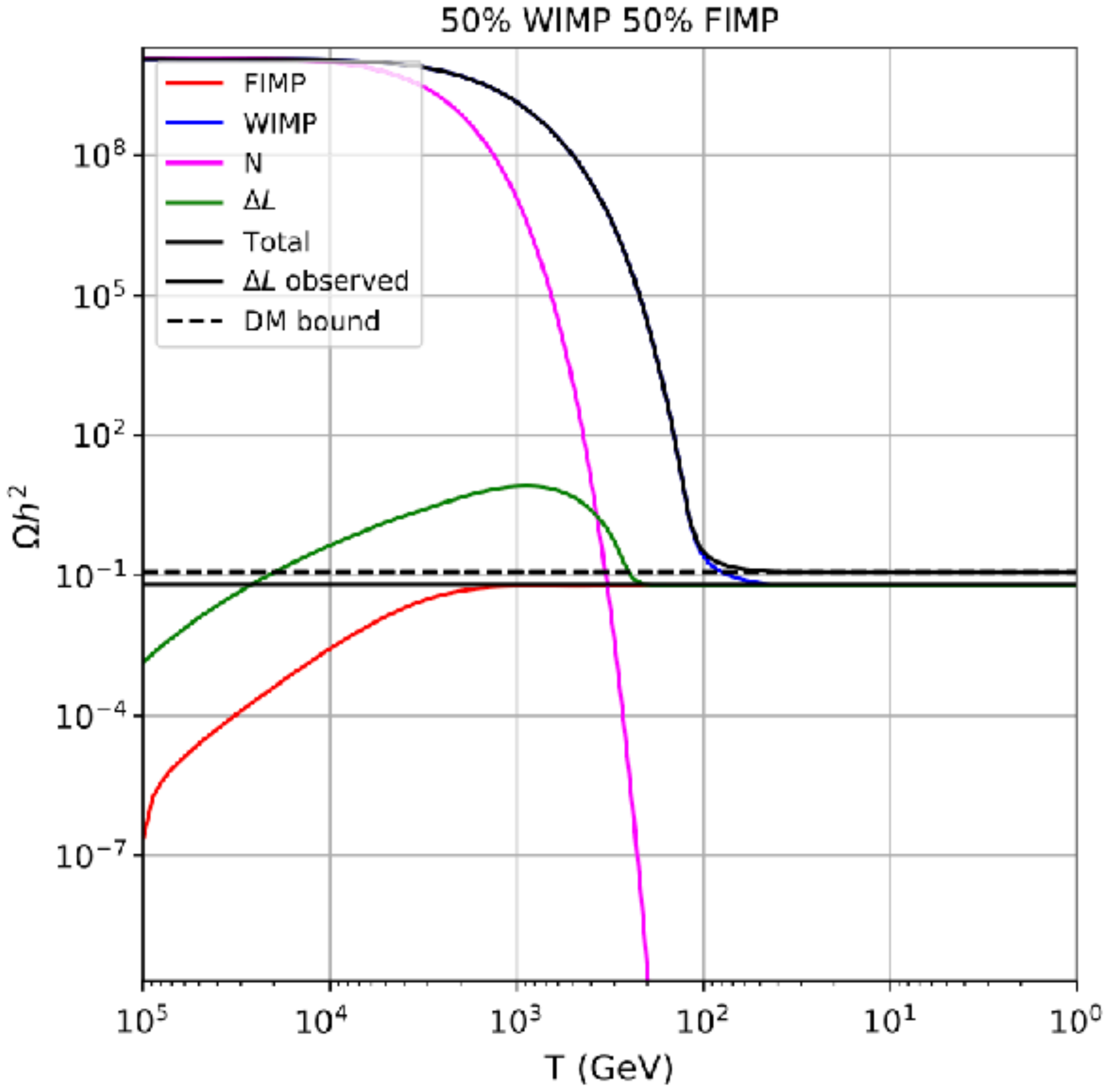
(Scotogenic & it's varient)

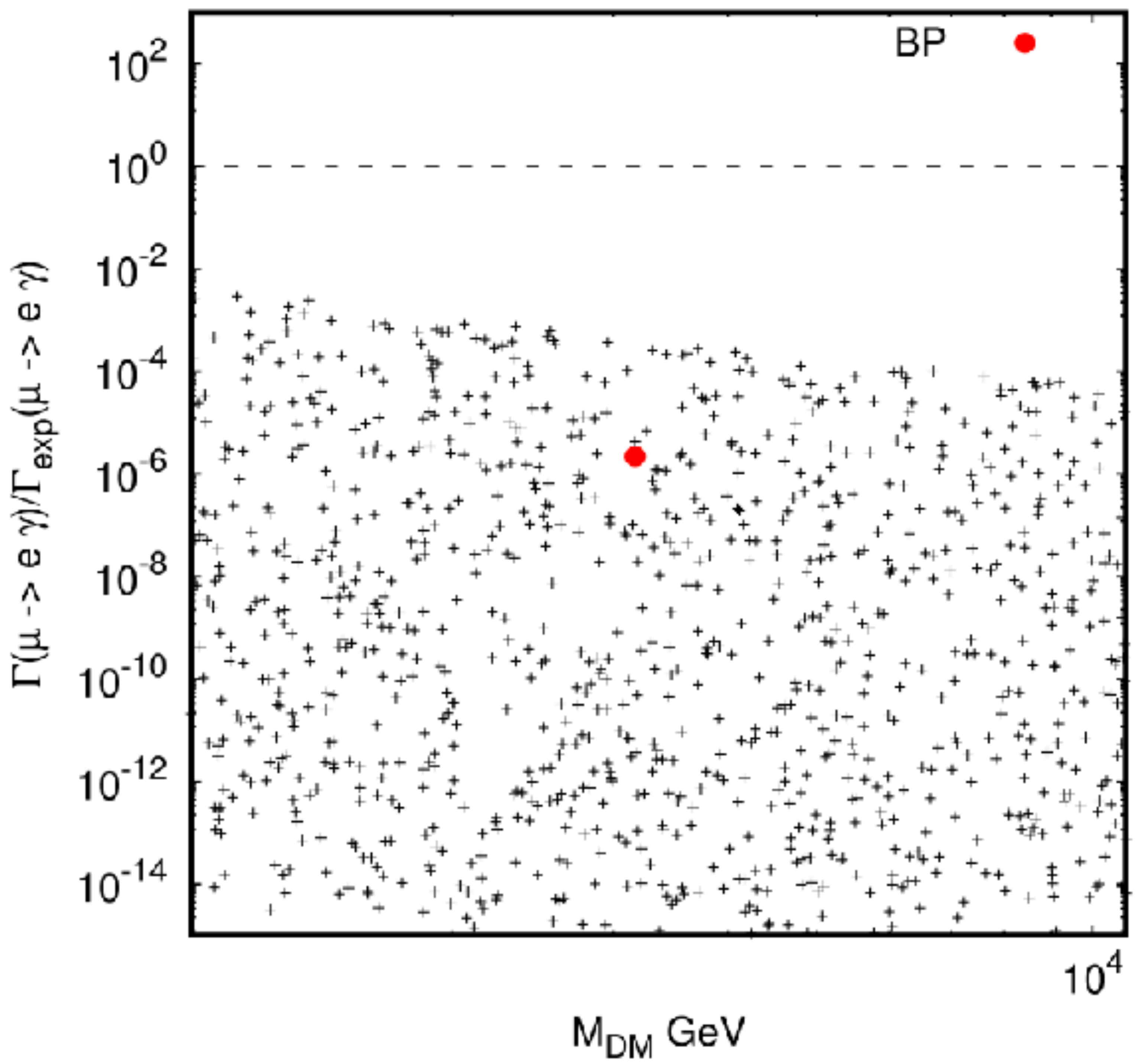
An example

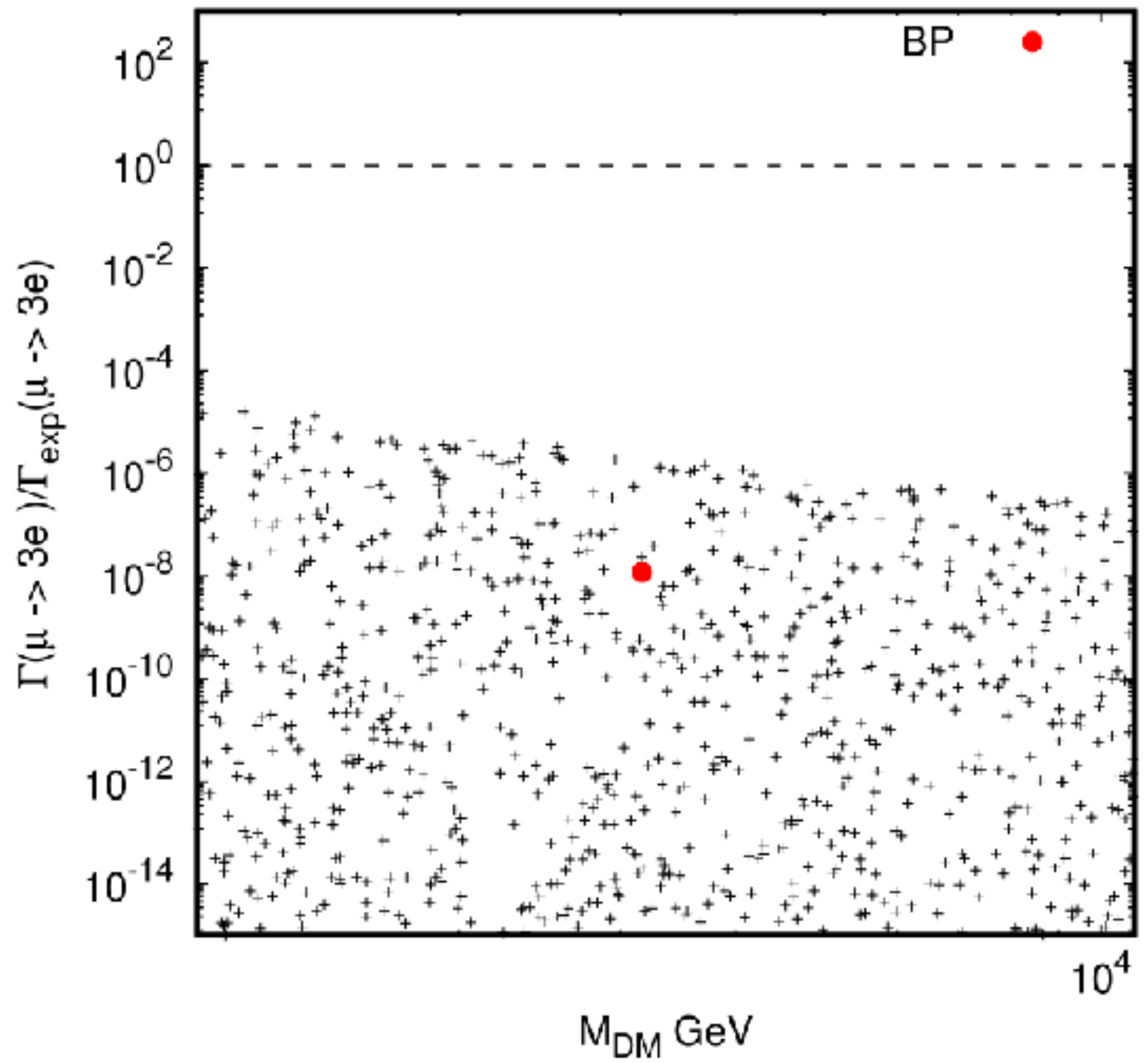


- $l_\alpha \to l_\beta l_\sigma l_\sigma$

Correlation & bounds from Flavor Physics







[arXiv: 1903.10516 D. Borah, A. Dasgupta, S.K. Kang]

Thank you!!