A New Mechanism for Matter Anti-Matter Asymmetry

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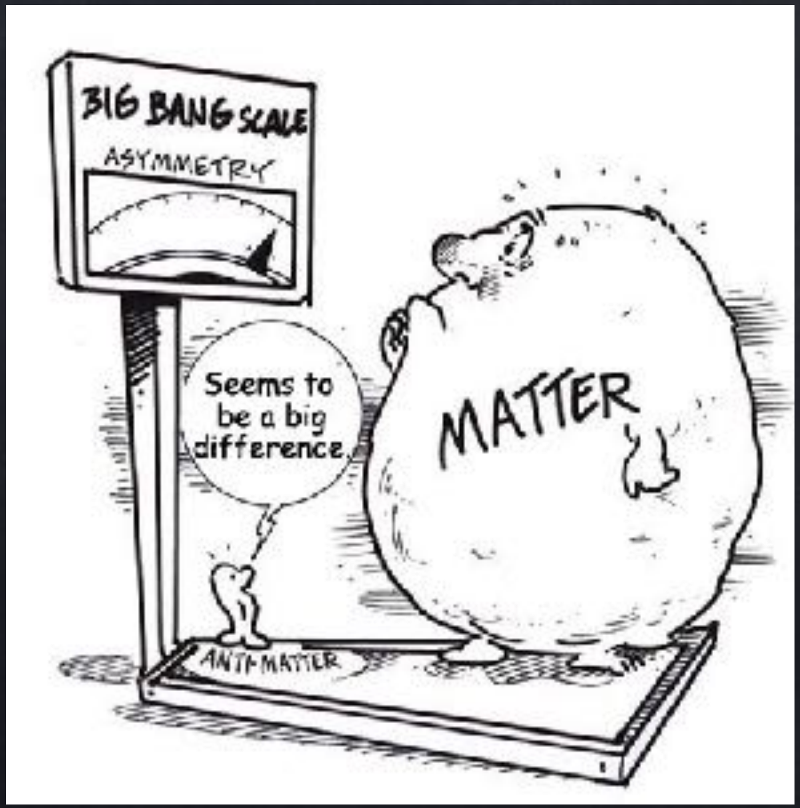
Outline

- Introduction
- Recipe for attaining Asymmetry
- Subtlety in CP violation from Amplitude
- Model
- Results
- Conclusion

One of the Problems in the SM

SM cannot explain the observed baryon asymmetry



Baryon Asymmetry of the Universe

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

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10}$$

- The prediction for this ratio from Big Bang Nucleosynthesis (BBN) agrees well with the observed value from Cosmic Microwave Background Radiation (CMBR) measurements (Planck, arXiv: 1502.01589).

Kinds of Mechanism in generating Asymmetry

- Baryogenesis from Decay/Scattering
- Baryogenesis from Electroweak Phase Transitions
- Spontaneous Baryogenesis
- .... (Affleck-Dine,Gravitational Baryogenesis, etc.)

Sakharov's Conditions

Three basic ingredients necessary to generate a net baryon asymmetry from an initially baryons symmetric Universe (Sakharov 1967):

- Baryon Number (B) violation $X \to Y + B$
- C and CP violation.

$$\Gamma(X \to Y + B) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

$$\Gamma(X \to q_L + q_L) + \Gamma(X \to q_R + q_R) \neq \Gamma(\overline{q}_L + \overline{q}_L) + \Gamma(\overline{q}_R + \overline{q}_R)$$

- Departure from thermal equilibrium.

Issues in Baryogenesis from Decays/Scattering

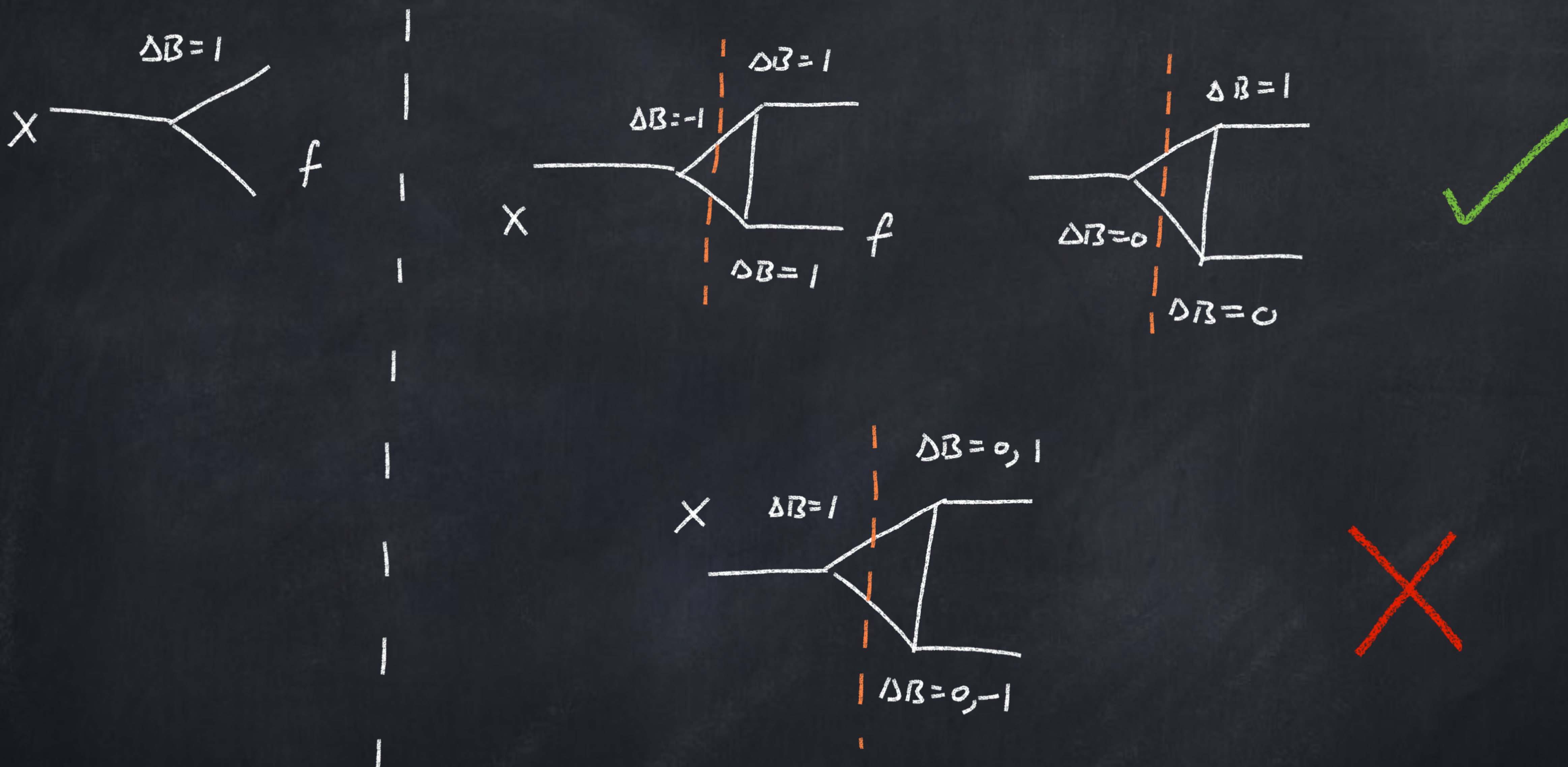
- Additional to the Sakharov's Conditions one needs to take care of two more important issues.

  1. In order to get asymmetry one needs to be sure to have atleast 2 $\not{B}$* coupling in the loop* diagram.

  2. The 2 $\not{B}$ violating coupling should be to the right of the "cut" of the loop.

* this is necessary if the decaying (scattering) particle(s) does not have any other channel. If it does have a channel without the $\not{B}$ coupling then one needs only 1 coupling in the loop.

Which Diagrams this Applies?



- One may note that all the diagrams are a result of Nanopolous-Weinberg theorem.

Realization of low scale Leptogenesis

- In order to realise leptogenesis/Baryogenesis at TeV scale the major constraint comes from the out-of-equilibrium condition

$$\Gamma < H(T=M_K) = \sqrt{\frac{4\pi^3 g_*}{45}}\,\frac{T^2}{M_{Pl}}\Bigg|_{T=M_K}$$

- Now, this condition naturally poses a constraint on the coupling to be very tiny.

$\Rightarrow$ This is due to two reasons $\left\{ \begin{array}{l} \text{This condition is mediated by Planck Scale} \\ \\ \text{In this condition the decay width is} \\ \text{linear mass scale in contrast to Hubble} \\ \text{rate which is quadratic.} \end{array} \right.$

- Natural solution to this is to consider asymmetry from a 3 body decay or 2-2 scattering process.

  ⇒ This is due to the fact that the rates are naturally phase space suppressed as compared to 2-body decay.

  ⇒ Additionally the process has more couplings.

- But the asymmetry remains to be quadratic.

CP violation from the Amplitude

- 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 $(X \to b)$

$$iM = (\mathcal{C}_1 \mathcal{A}_1 + \mathcal{C}_2 \mathcal{A}_2) f$$

Similarly, for anti-particle

$$i\bar{M} = (\mathcal{C}_1^* \mathcal{A}_1 + \mathcal{C}_2^* \mathcal{A}_2) f^*$$

$\rightarrow$ spinor wave function

- The difference between the two processes comes out to be

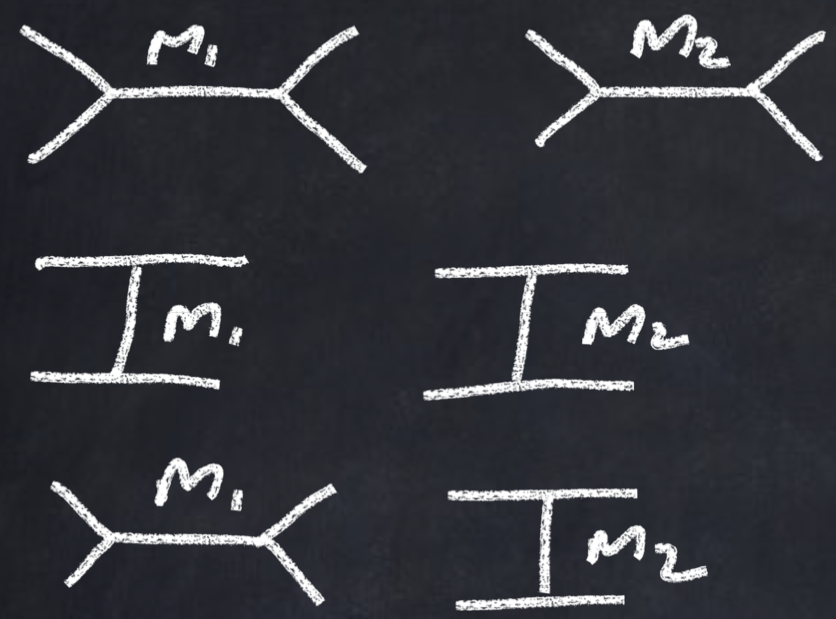
$$\delta = 4\,\underbrace{\mathrm{Im}[c_1^* c_2]}_{\text{Purely from coupling}}\;\underbrace{\mathrm{Im}[A_1^* A_2]}_{\text{Purely from Amplitudes}}\,|f|^2$$

- Now, originally the imaginary part comprises of 1-loop

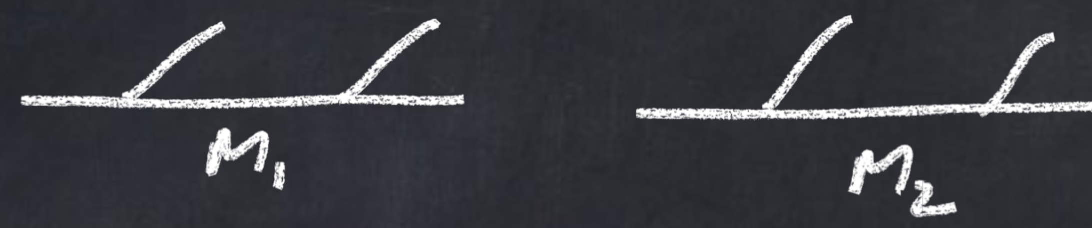
  $\Rightarrow$ Which was due to the fact it was a 2-body decay

- But if we consider a 2-2 process or a 3-body decay the imaginary part comes from the imaginary part of the amplitude.

For $2 \to 2$ processes



For $1 \to 3$ processes



$$\delta = 4\,\mathrm{Im}\left[c_1^* c_2\right]\left[\frac{(s_1 - M_1^2)M_2\Gamma_2 - (s_2 - M_2^2)M_1\Gamma_1}{\left((s_1 - M_1^2)^2 + M_1^2\Gamma_1^2\right)\left((s_2 - M_2^2)^2 + M_2^2\Gamma_2^2\right)}\right] \times |f|^2$$

Depends on the spin structure of the incoming and outgoing particle

Model

- We consider SM extended with

1) Triplet-Scalar] → Responsible for giving mass to ν's through type-II mechanism

2) 3-copies of $\mathbb{Z}_2$ odd Majorana Fermion (N's)

3) A $\mathbb{Z}_2$ odd scalar doublet

] → Responsible for giving mass to ν's radiatively.

$$\mathcal{L}_Y \subset Y^N_{i\alpha}\, \tilde{\eta}^\dagger L_\alpha N_i + Y^\Delta_{\alpha\beta}\, \overline{L^c_\alpha}\, \Delta L_\beta$$

Main ingredient in the asymmetry

$$V \supset \mu_{\eta\Delta}\, \eta^\dagger \Delta^\dagger \tilde{\eta} + m_H^2\, H^\dagger H + \lambda_\Delta \mathrm{Tr}[\Delta^\dagger \Delta]^2 + \lambda_H (H^\dagger H)^2 + \lambda'_\Delta \mathrm{Tr}[\Delta^\dagger \Delta \Delta^\dagger \Delta]$$

$$+ m_\Delta^2 \mathrm{Tr}[\Delta^\dagger \Delta] + \mu_{H\Delta}\, \tilde{H}^\dagger \Delta H + m_\eta^2\, \eta^\dagger \eta + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda_{H\eta} |H^\dagger \eta|^2 + \lambda'_{H\eta} (H^\dagger H)(\eta^\dagger \eta)$$

$$+ \lambda_{H\Delta} (H^\dagger H) \mathrm{Tr}[\Delta^\dagger \Delta] + \lambda_{\Delta\eta} \mathrm{Tr}[\Delta^\dagger \Delta]\, \eta^\dagger \eta + M_{N_{ij}} N_i^c N_j + \lambda''_{H\eta}\left((H^\dagger \eta)^2 + h.c\right)$$

$$+ \lambda'_{H\Delta} \mathrm{Tr}[H^\dagger \Delta \Delta^\dagger H] + \lambda'_{\eta\Delta} \mathrm{Tr}[\eta^\dagger \Delta \Delta^\dagger \eta]$$

$$M_h = \begin{pmatrix} \lambda_H v^2 & -\sqrt{2}\, \mu_{H\Delta} v \\ -\sqrt{2}\, \mu_{H\Delta} v & \dfrac{\mu_{H\Delta} v^2}{\sqrt{2}\, v_\Delta} \end{pmatrix} ;$$

$$M^2_{\Delta_I} = \frac{\mu_{H\Delta}}{\sqrt{2}\, v_\Delta} (v^2 + 4 v_\Delta^2)$$

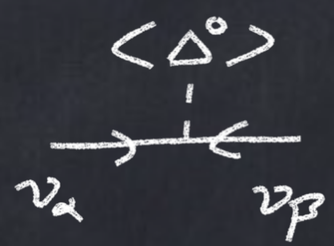
$$M^2_{\Delta^\pm} = M^2_{\Delta^{\pm\pm}} = \left(\frac{\mu_{H\Delta}}{\sqrt{2}\, v_\Delta} + \frac{1}{4} \lambda'_{H\Delta}\right)(v^2 + 2 v_\Delta^2)$$

$$M^2_{\eta_{R,I}} = \frac{1}{2}\left(2 m_\eta^2 + (\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}) v^2\right) + v_\Delta \left(\lambda_{\eta\Delta} v_\Delta \mp 2\sqrt{2}\, \mu_{\eta\Delta}\right)$$

$$M^2_{\eta^\pm} = \frac{1}{2}\left(2 m_\eta^2 + \lambda_{H\eta} v^2 + v_\Delta^2 (\lambda_{\eta\Delta} + \lambda'_{\eta\Delta})\right)$$

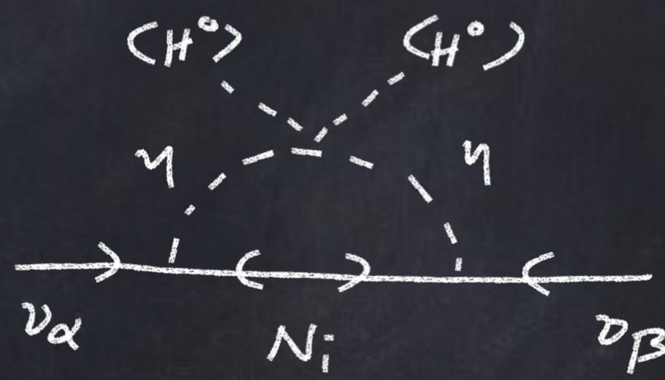
Neutrino Mass

- Type-II Mechanism



$$M_{\alpha\beta} = f_{II}\, Y^{\Delta}_{\alpha\beta} \langle \Delta^0 \rangle$$

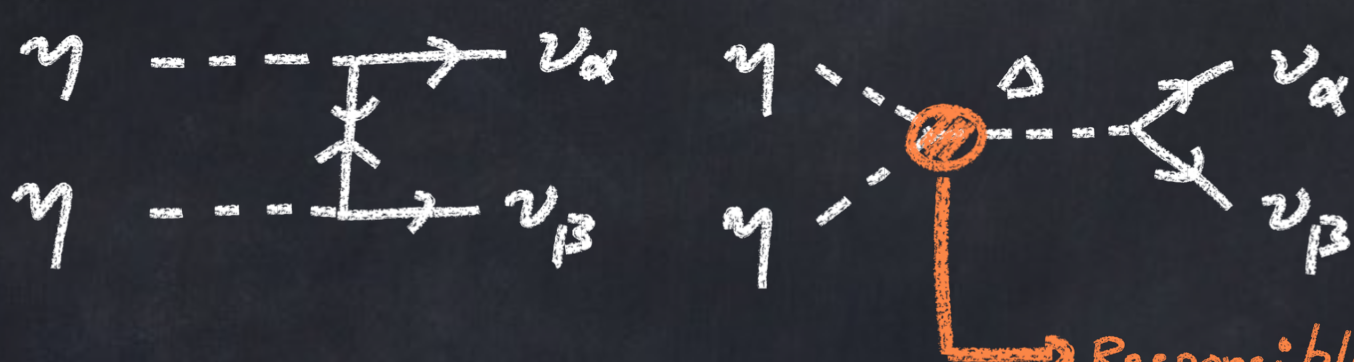
- Radiative Mass Generation



$$M_{\alpha\beta} = \frac{f_I}{16\pi^2} \sum_i Y^N_{i\alpha} Y^N_{i\beta} M_{N_i} \left[\frac{x^i_R}{x_R - 1} \ln x^i_R - \frac{x^i_I}{x^i_I - 1} \ln x^i_I \right] \quad ; \quad x^i_j = \frac{M^2_{N_i}}{M^2_{\eta_j}}$$

Generation of Asymmetry

- In our scenario the following diagrams violate $\Delta L = 2$



Responcible for asymmetry from Coupling

- And the resultant asymmetry is given as

$$\delta = 4\,\mathrm{Im}\left[M_{\eta D}\, Y^N_{i\alpha} Y^N_{i\beta} Y^{\Delta *}_{\alpha\beta}\right] \frac{M_{N_i}\, s\, M_\Delta \Gamma_\Delta}{\left((s-M_\Delta^2)^2 + M_\Delta^2 \Gamma_\Delta^2\right)} \left[\frac{1}{t-M_{N_i}^2} + \frac{1}{u-M_{N_i}^2}\right]$$

- Assuming the following parameterization

$$Y^N_{i\alpha} = f_I^{-1/2}\left(\sqrt{\Lambda}^{-1} R \sqrt{M_\nu^{diag}}\, U^\dagger_{PMNS}\right)_{i\alpha} \; ; \; Y^\Delta_{\alpha\beta} = \frac{f_{II}^{-1}}{\langle \Delta^0 \rangle}\left(U^*_{PMNS} M_\nu^{diag} U^\dagger\right)_{\alpha\beta}$$

- This parameterization simplifies the asymmetry as

fixed by the neutrino mass matrix

$$\delta = f_{I} f_{II}\, 4\, \mathrm{Im}\left[\mu_{\Delta\eta}\right] \left(\frac{M^{diag}}{\langle \Delta^0 \rangle}\right)^2 (\Lambda)^{-1} \frac{M_{N_i}\, s\, M_\Delta \Gamma_\Delta}{\left[(s - M_\Delta^2) + M_\Delta^2 \Gamma_\Delta^2\right]} \left[\frac{1}{t - M_{N_i}^2} + \frac{1}{u - M_{N_i}^2}\right]$$

- Now, the rate for the above assymetry is given

$$\gamma^\delta = \frac{T}{256\pi^5} \int_{s_{in}}^{\infty} \int_{-1}^{1} ds\, d\cos\theta\, \frac{P_{in} P_{out}}{\sqrt{s}}\, \delta\, K_1(\sqrt{s}/T)$$

$$P_{in} = \frac{1}{2} \sqrt{\frac{\lambda(s, M_\eta^2, M_\eta^2)}{s}}$$

$$P_{out} = \frac{1}{2} \sqrt{s}$$

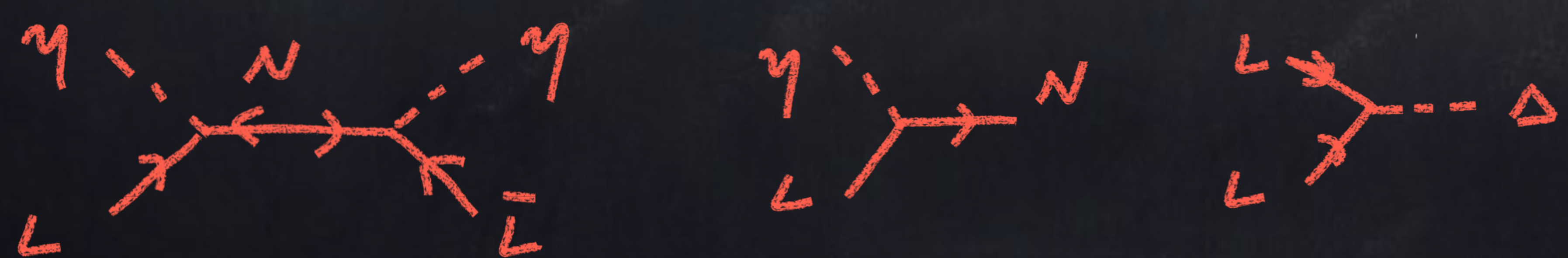
Boltzmann Equation

- We solve the following boltzmann Equation

$$\frac{\partial Y_\eta}{\partial z} = \frac{-1}{z s H}\left[\left(\frac{Y_\eta^2}{(Y_\eta^{eq})^2} - 1\right)\gamma^{eq}_{scatt}(\eta\eta \to SM\,SM)\right]$$

$$\frac{\partial Y_{\Delta L}}{\partial z} = \frac{1}{z s H}\Bigg[\left(\frac{Y_\eta^2}{(Y_\eta^{eq})^2} - 1\right)\gamma^{\delta} - 2\frac{Y_{\Delta L}}{Y_\ell^{eq}}\Big[\gamma^{eq}_{scatt}(\eta\eta \to LL)$$

$$+\,\gamma^{eq}_{scatt}(\eta L \to \eta \bar{L}) + \gamma_D(N \to L\eta) + \gamma_D(\Delta \to LL)\Big]\Bigg]$$



Suppressed as the mass are taken heavy

- The most general solution of the lepton asymmetry is given as

$$Y_{\Delta L}(x) = \int_0^x dx' \frac{s\langle\sigma v\rangle_\delta}{x' H(x')} \left(Y_\eta^2 - Y_\eta^{eq^2}\right) \exp\left[-\int_{x'}^{x} \frac{\gamma_{wo}}{y\, s\, H(y)} dy\right]$$

$$= \int_0^x \epsilon\, dx' \frac{dY_\eta}{dx'} \left[\exp\left[-\int_{x'}^{x} \frac{\gamma_{wo}}{y\, H(y)\, s} dy\right]\right]$$

$$Y_{\Delta L}(\infty) \simeq \frac{\epsilon}{2}\left[Y_\eta(x_{washout}) - Y_\eta(\infty)\right] \qquad \frac{\gamma_{wo}}{s\, x_{washout} H(x_{washout})} = 1$$

$$\gamma_{wo} = \left[\gamma^{eq}_{scatt}(\eta\eta \to LL) + \gamma^{eq}_{scatt}(\eta L \to \bar{L}\eta^{+}) + \gamma_D(N \to \eta L) + \gamma_D(\Delta \to LL)\right]$$

$$\langle\sigma v\rangle_\delta(\eta\eta \to LL) = \frac{1}{(n_\eta^{eq}(T))^2}\gamma_\delta(\eta\eta \to LL)$$

$$\langle\sigma v\rangle_{ann} = \frac{1}{(n_\eta^{eq}(T))^2}\gamma(\eta\eta \to SM\,SM) \qquad \epsilon := \frac{\langle\sigma v\rangle_\delta(\eta\eta \to LL)}{\langle\sigma v\rangle_{ann}(\eta\eta \to SM\,SM)}$$

- This is only feasible if the wash-out process freezes out before the freeze-out of the DM annihilation

- This is feasible if the following relation is satisfied

$$\frac{\Gamma_{washout}}{\Gamma_{WIMP}} \simeq \frac{\langle \sigma v \rangle_{washout} \prod_i Y_i^{eq}}{4 \langle \sigma v \rangle_{ann} \, Y_\eta^{eq} \, Y_\gamma^{eq}} < 1$$

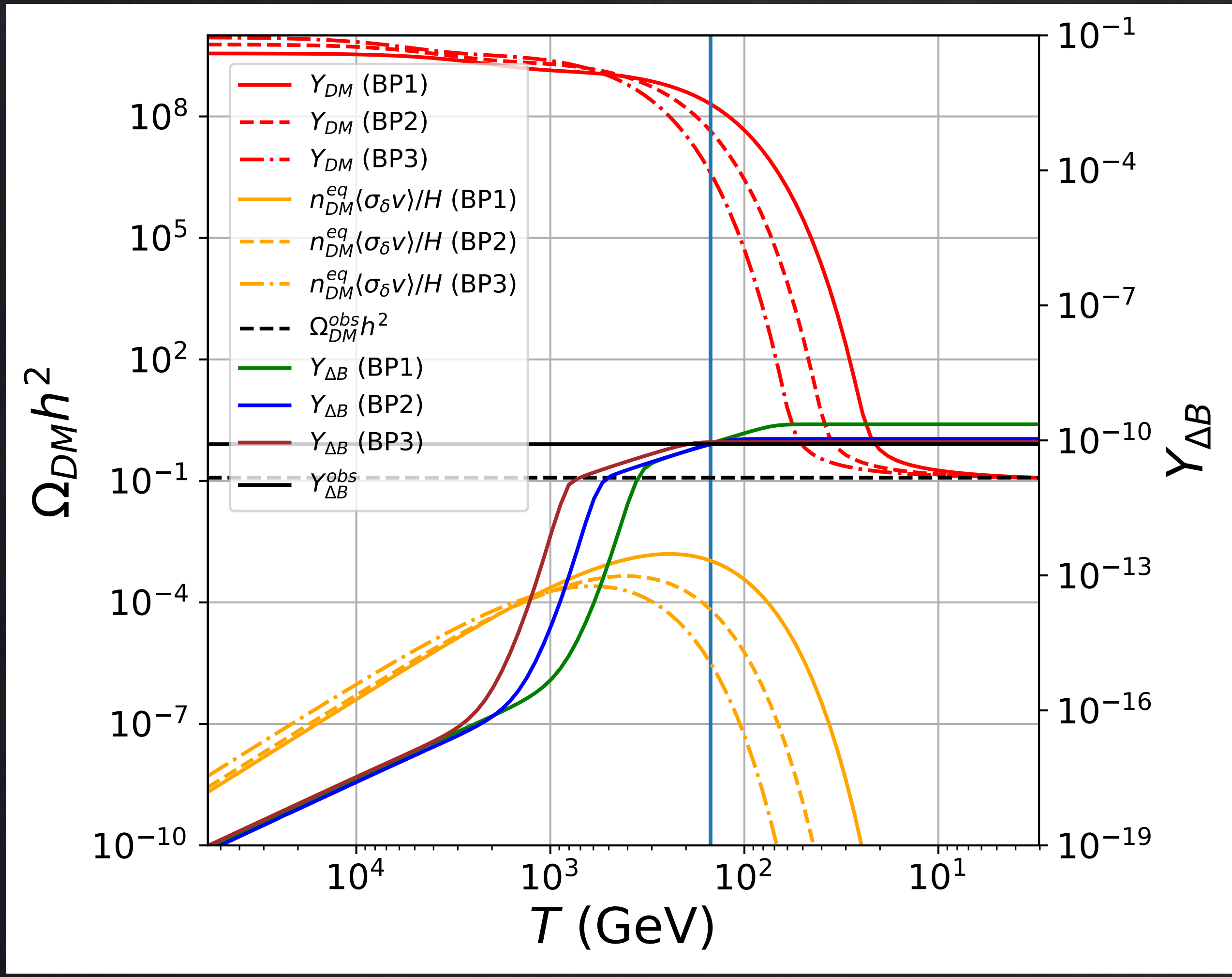
- Now, the above relation is possible for 2 kinds of scenario

  ⇒ One of the final state of the lepton violating process should be heavier than Dark Matter candidate i.e $\dfrac{\prod_i Y_i^{eq}(x)}{Y_\eta^{eq} \, Y_\gamma^{eq}} < 1$

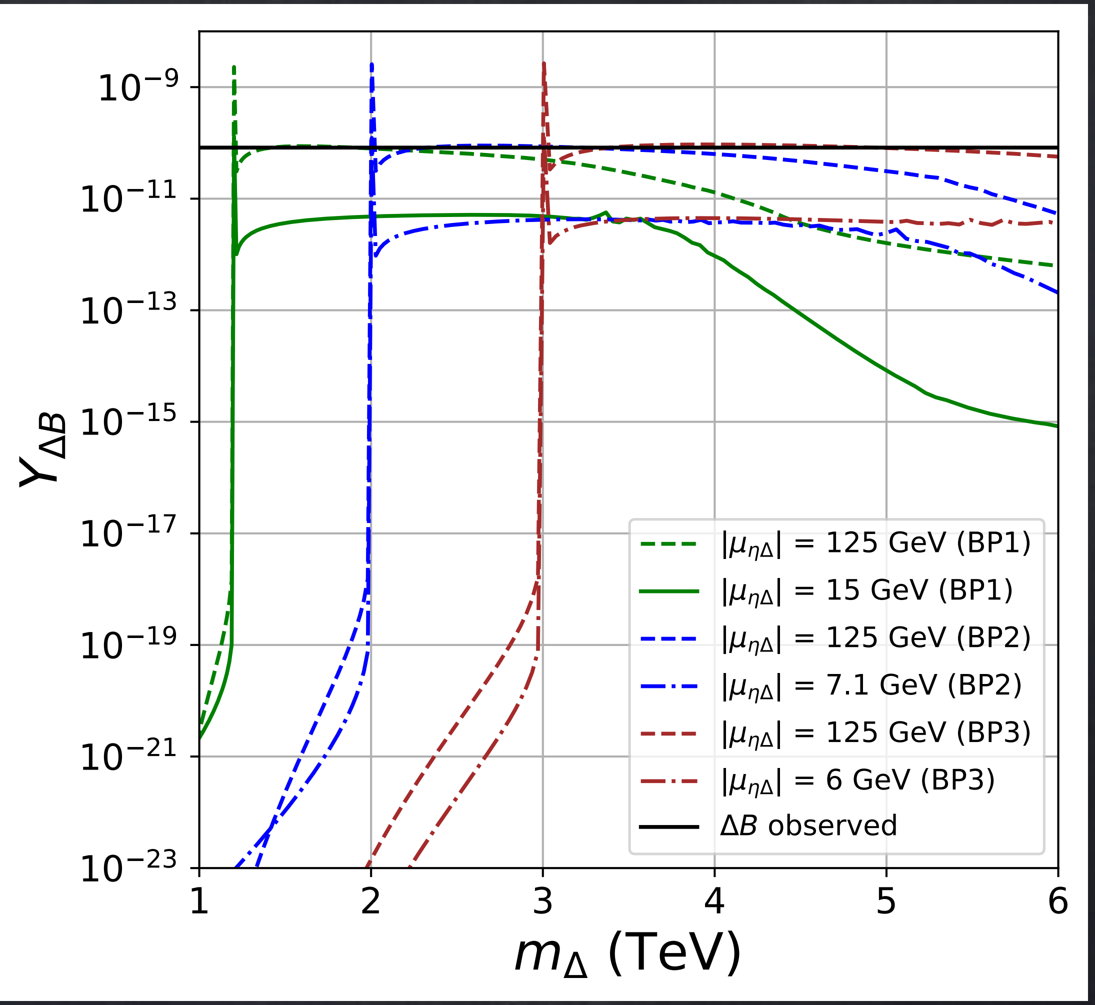
  ⇒ The lepton-number violating process is smaller than the DM annihilation process.

- In our scenario the second possibility arises as the major channel for DM annihilation is $\eta^+\eta^- \to W^+W^-$ which is far stronger than lepton violating process $\eta\eta \to L_\alpha L_\beta$.

Result



Y_{DM} (BP1)
Y_{DM} (BP2)
Y_{DM} (BP3)
$n_{DM}^{eq}\langle\sigma_\delta v\rangle/H$ (BP1)
$n_{DM}^{eq}\langle\sigma_\delta v\rangle/H$ (BP2)
$n_{DM}^{eq}\langle\sigma_\delta v\rangle/H$ (BP3)
$\Omega_{DM}^{obs}h^2$
$Y_{\Delta B}$ (BP1)
$Y_{\Delta B}$ (BP2)
$Y_{\Delta B}$ (BP3)
$Y_{\Delta B}^{obs}$
$\Omega_{DM}h^2$
$Y_{\Delta B}$
T (GeV)



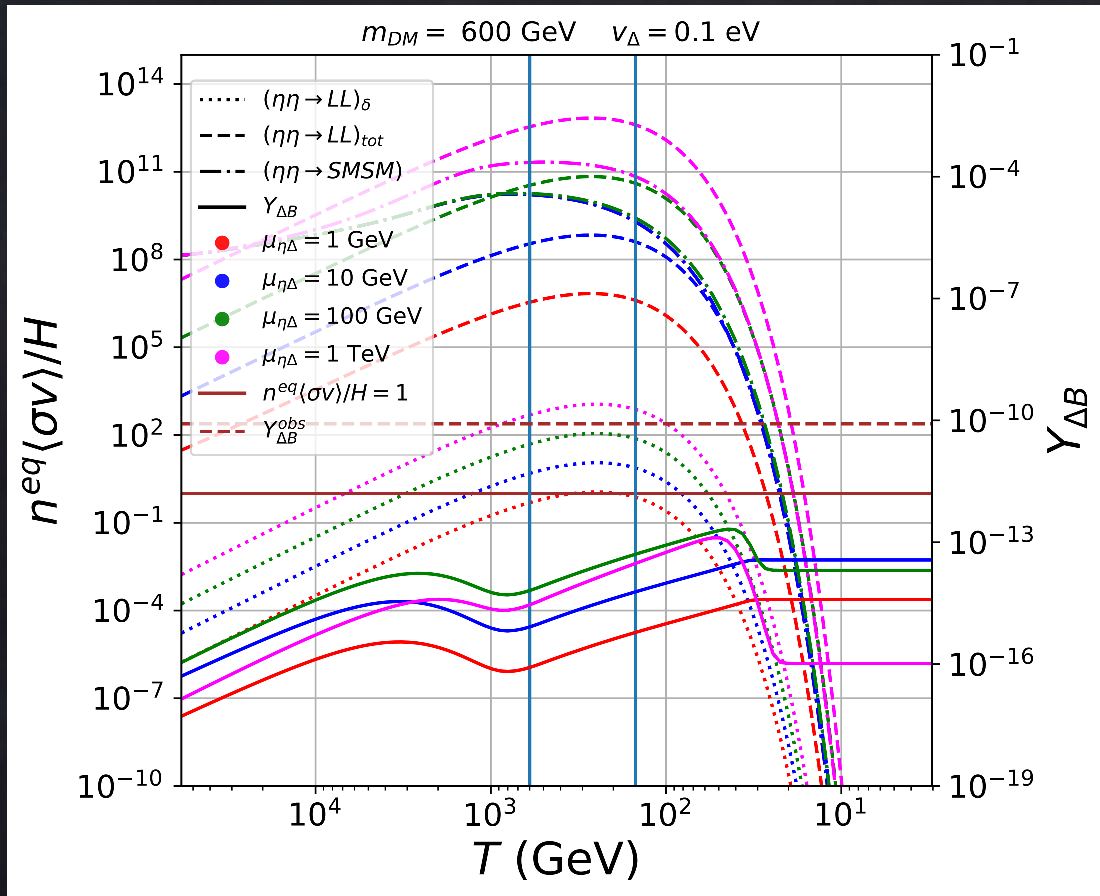
$|\mu_{\eta\Delta}|$ = 125 GeV (BP1)
$|\mu_{\eta\Delta}|$ = 15 GeV (BP1)
$|\mu_{\eta\Delta}|$ = 125 GeV (BP2)
$|\mu_{\eta\Delta}|$ = 7.1 GeV (BP2)
$|\mu_{\eta\Delta}|$ = 125 GeV (BP3)
$|\mu_{\eta\Delta}|$ = 6 GeV (BP3)
ΔB observed
$Y_{\Delta B}$
m_Δ (TeV)

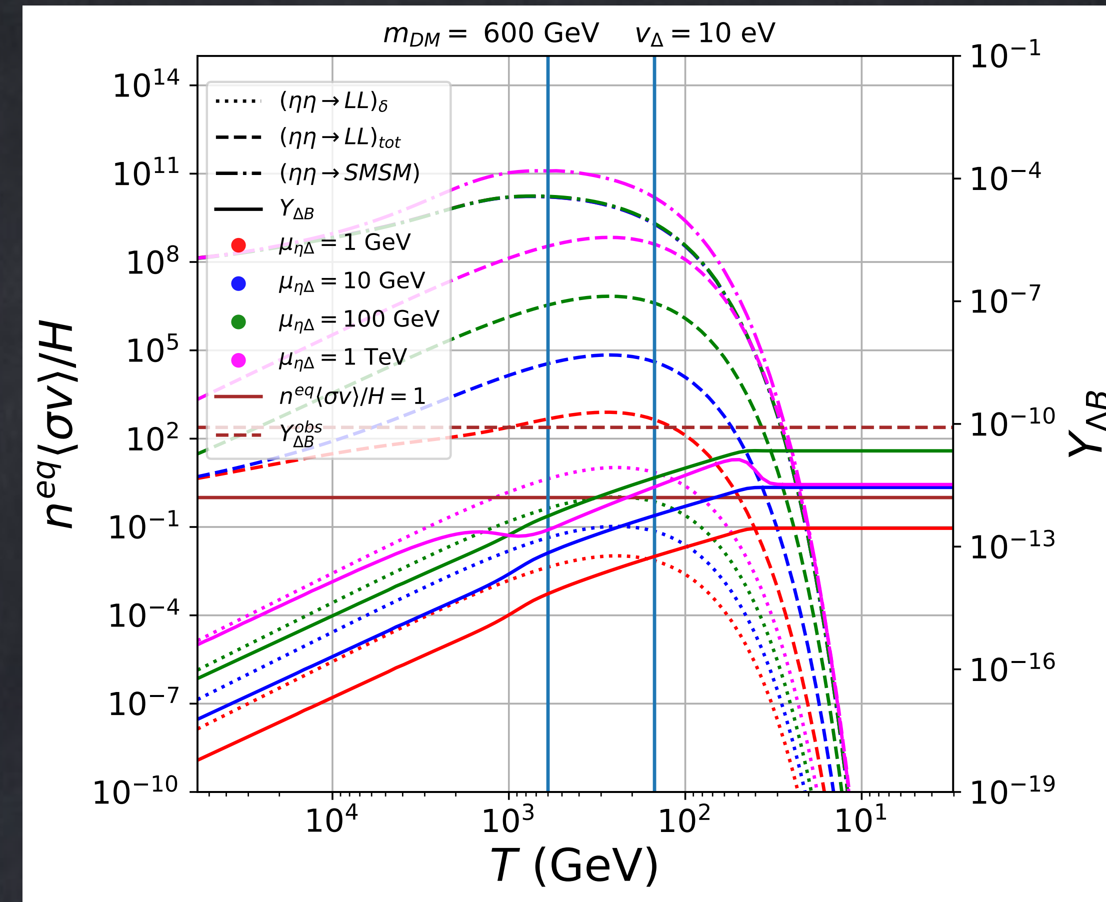
Benchmark Points

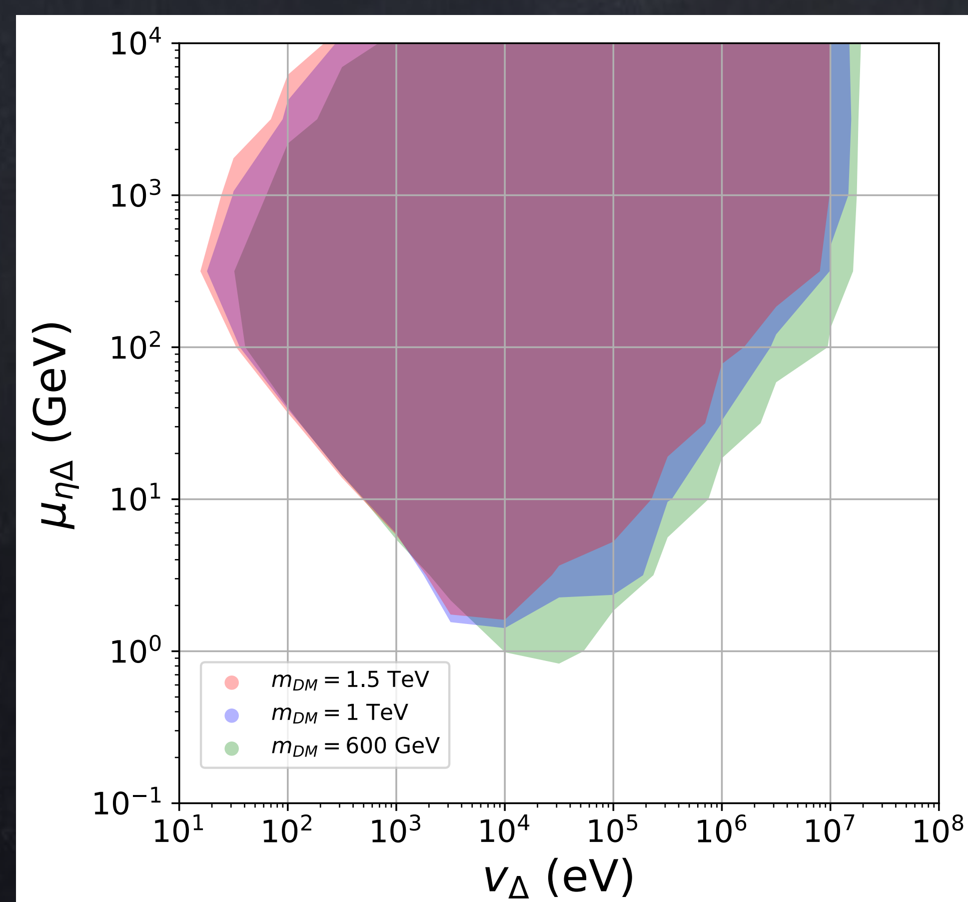
	BP 1	BP 2	BP 3
v_Δ	1 keV	1 keV	1 keV
μ_η	600 GeV	1 TeV	1.5 TeV
$\mu_{H\Delta}$	33.6 keV	93.5 keV	210 keV
$\mu_{\eta\Delta}$	$15\,i$ GeV	$7.1\,i$ GeV	$6\,i$ GeV
M_{N_1}	6 TeV	10 TeV	15 TeV
M_{N_2}	6.6 TeV	11 TeV	16.5 TeV
M_{N_3}	7.2 TeV	12 TeV	18 TeV
M_{η^0}	600 GeV	1 TeV	1.5 TeV
ΔM_{η^0}	506 keV	300 keV	200 keV
M_Δ	1.2 TeV	2 TeV	3 TeV
$\lambda_{H\eta} = -\lambda'_{H\eta}$	0.24	0.59	0.93

$\lambda_H = 0.253$

$\lambda''_{H\eta} = 10^{-5}$


$m_{DM} =$ 600 GeV $v_\Delta = 0.1$ eV
$(\eta\eta \to LL)_\delta$
$(\eta\eta \to LL)_{tot}$
$(\eta\eta \to SMSM)$
$Y_{\Delta B}$
$\mu_{\eta\Delta} = 1$ GeV
$\mu_{\eta\Delta} = 10$ GeV
$\mu_{\eta\Delta} = 100$ GeV
$\mu_{\eta\Delta} = 1$ TeV
$n^{eq}\langle\sigma v\rangle/H = 1$
$Y_{\Delta B}^{obs}$
$n^{eq}\langle\sigma v\rangle/H$
$Y_{\Delta B}$
T (GeV)


$m_{DM} =$ 600 GeV $v_\Delta = 10$ eV
$(\eta\eta \to LL)_\delta$
$(\eta\eta \to LL)_{tot}$
$(\eta\eta \to SMSM)$
$Y_{\Delta B}$
$\mu_{\eta\Delta} = 1$ GeV
$\mu_{\eta\Delta} = 10$ GeV
$\mu_{\eta\Delta} = 100$ GeV
$\mu_{\eta\Delta} = 1$ TeV
$n^{eq}\langle\sigma v\rangle/H = 1$
$Y_{\Delta B}^{obs}$
$n^{eq}\langle\sigma v\rangle/H$
$Y_{\Delta B}$
T (GeV)


$m_{DM} = 1.5$ TeV
$m_{DM} = 1$ TeV
$m_{DM} = 600$ GeV
$\mu_{\eta\Delta}$ (GeV)
v_Δ (eV)

Conclusion

- In this work we have shown a new mechanism of realising asymmetry without* loops.

- There are plethora of models in which can be explored in such mechanism.

- The main interesting feature of this mechanism is that the leptonic asymmetry is related to the decay width of the unstable particle.

- The models are readily testable in the next-generation collider or LFV experiments.

Thank You