Investigating Dark Matter signatures at FCC-ee

by

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Introduction

- Direct evidence that the SM is not a complete theory of particle physics:
- The lack of a candidate for Dark Matter (DM).
- These instances of (NPBSM) are exemplified by the Scotogenic Model.
- From this point, more prominent windows into New Physics Beyond the SM (NPBSM) when the Large Hadron Collider (LHC) at CERN has been

Commenced:

Higgs discovery and **collider anomalies**

The Higgs physics has witnessed a continuous expansion

Motivation of our Study

The process $e^+e^- \rightarrow H^+H^-$ can be used to search possible collider signatures taking into account :

- observations like dark matter relic density measurement that has been updated in the recent years.

Having updated constraints:

- Allows us to give correct predictions of the cross section of the process $e^+e^- \rightarrow H^+H^-$ in the next run of FCC-ee at CERN,
- The produced H^+H^- pair can decay to many final states with different combinations of particles including dark matter candidates under scotogenic model.
- One common effect for all such decay modes is the size of the cross section of $e^+e^- \rightarrow H^+H^-$.

Scotogenic Model

- considered one of the simplest and viable solutions that accommodates essential elements for NPBSM.

- In this model neutrinos acquire mass through radiative processes involving one-loop interactions with nonstandard particles.

- New particles :
  - consist of both fermions in addition to scalars,
  - lightest one serving as DM candidate.

- three singlet Majorana fermions, denoted as $N_{1,2,3}$.

- an additional scalar doublet referred to as η among the inert scalar doublets.

- Furthermore, a Z_2 symmetry, for which, the new added fields will be odd in contrast with particles in SM will remain even.

- the Lagrangian describing the scalar sector of the Scotogenic model can be written as:

$$\mathcal{L} = (\mathcal{D}^{\mu}\Phi)^{\dagger}\mathcal{D}_{\mu}\Phi + (\mathcal{D}^{\mu}\eta)^{\dagger}\mathcal{D}_{\mu}\eta - \mathcal{V}$$

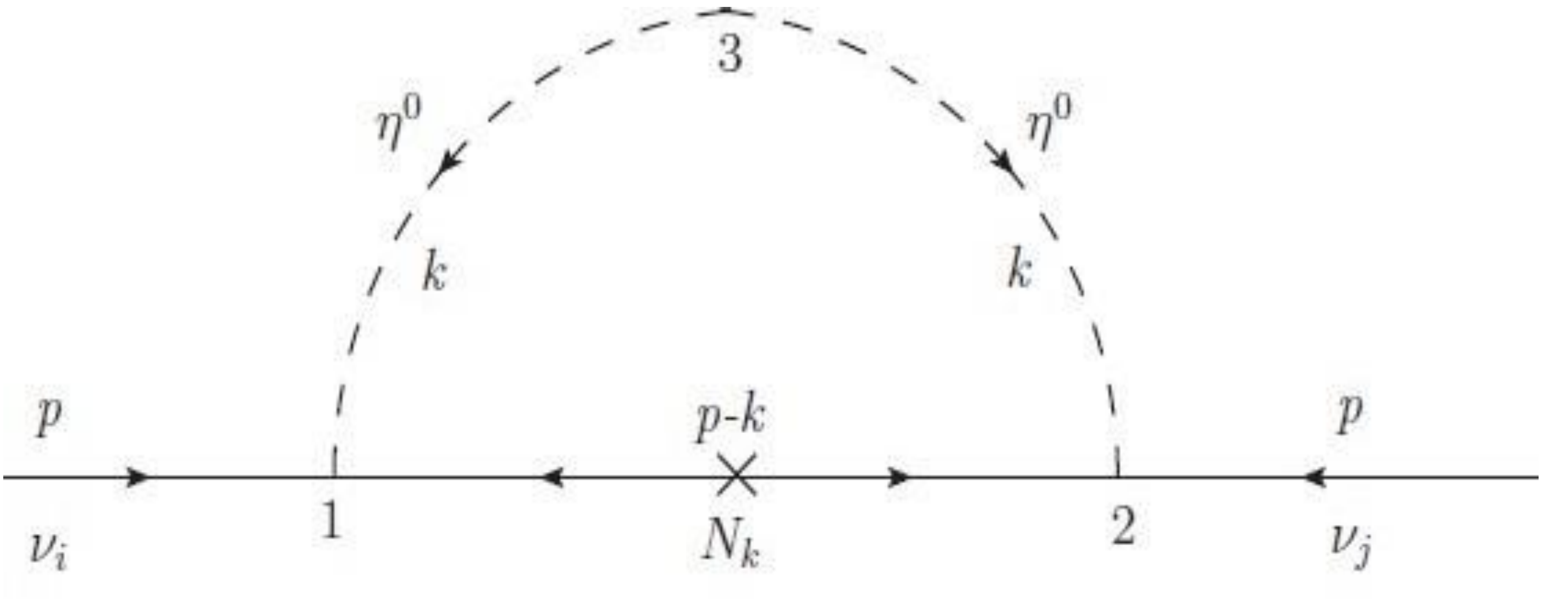
- the Lagrangian for the new singlet Majorana fermions of the Scotogenic model can be written as:

$$\mathcal{L}_N = -\frac{1}{2} M_k \overline{N_k^{c}} P_R N_k + Y_{rk} \bar{\ell}_r H^- P_R N_k + \text{H.c.}$$

to masses of N_k. the c for N_k is the charge conjugation of the field.

Generation of Neutrino Mass in Scotogenic Model

- neutrinos exist in three flavor states denoted as ν_α, where α = e,μ,τ.
- The masses of these neutrinos can be generated at the one-loop level with internal S, P, and N_k through Figure.



- The mass eigenvalues m_j are expressed as follows:

$$\mathrm{diag}(m_1, m_2, m_3) = \mathcal{U}^\dagger \mathcal{M}_\nu \mathcal{U}^*$$

- depending on the neutrino mass eigenvalues, we get the mass for the neutrinos:

$$m_1 = \frac{\Lambda_1 y_{e1}^2 e^{-i\alpha_1}}{c_{12}^2 c_{13}^2}, \qquad m_2 = \frac{\Lambda_2 y_{e2}^2 e^{-i\alpha_2}}{s_{12}^2 c_{13}^2}, \qquad m_3 = \frac{\Lambda_3 y_3^2}{c_{13}^2 c_{23}^2}.$$

- The experimental results does not give us the exact mass of neutrinos but give us the difference between their masses.

Dark Matter in the Scotogenic Model

- In our study, we adopt the familiar scenario.
  - We take the N_1 as the DM particle.
  - For N_2, we set it as the 2nd lightest particle that degenerate in mass with N_1

- The relic density (Ωˆh²) is introduced in terms of the DM density relative to its critical value, denoted by Ω, and the Hubble parameter, denoted by ˆh, as Ωˆh². Theoretically, it can be estimated from the relation:

$$\Omega\hat{h}^2 = \frac{1.07\times 10^9\, x_f\, \mathrm{GeV}^{-1}}{\sqrt{g_*}\, m_{\mathrm{Pl}}\left[a+3(b-a/4)/x_f\right]}$$

- In our analysis of the resultant constraint, from the measured value for DM relic density, on the parameter space of the model under concern, we consider the case that the DM and the new scalar particles are not degenerate in mass to avoid the contributions of the coannihilation processes of the scalars to the relic density.

Constraints

- In our analysis, sum of the neutrino masses constraint $\Sigma m_i < 0.12$ eV.
- neutrino oscillations ratio based on the 90% CL ranges of the data on

$$32.0 < \frac{|\Delta m_{31}^2|}{\Delta m_{21}^2} < 36.0$$

- The limits from up to date-experimental data on LFV processes are

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

- The flavor-diagonal counterpart of the previous LFV processes leads to a modification of the anomalous magnetic moment $a_{\ell i}$ of the lepton ℓ_i given by:

$$\Delta a_{\ell_i} = \frac{-m_{\ell_i}^2}{16\pi^2 m_H^2} \sum_k |y_{ik}|^2 \mathcal{F}(M_k^2/m_H^2)$$

- For the DM candidate N_1, the interactions with nucleons appear at the one-loop level.
- set the couplings $\lambda_{3,4} = 0.01$ to avoid the strong constraints from direct detection.
- from the discussion about scalar masses we find that:

$$m_0 \simeq m_S \simeq m_P \simeq m_{H^\pm} + \frac{1}{2}\lambda_4 v^2 \simeq m_{H^\pm} + 350\ \text{GeV}.$$

- It should be noted that the strong constraints from the direct detection were not studied before.
- In our study, we first to allocate the mixing angles $\theta_{12,23,13}$ and the Dirac phase δ to their central values got in the fit to the global data on neutrino oscillation.

- In the second step, we apply a scan over the parameter space of the model recognized, the masses of the new scalars m_H, m_0 and the new singlet fermions $N_{1,2,3}$ and the input parameters $Y_{1,2,3}$ appearing in the Yukawa couplings.
- For light dark matter masses M1 < 100 GeV, LFV and direct search at LHC:

Experimentally, constraints can be set on the masses of the new scalars using the data on W and Z widths and the null results of direct searches for new particles at e^+e^- colliders:

$$m_{H^\pm} + m_{\mathcal{S},\mathcal{P}} > m_{W^\pm}, m_{H^\pm} > 70\,\text{GeV}, m_{\mathcal{S}} + m_{\mathcal{P}} > m_Z,$$

Cross Section of $e^+e^- \rightarrow H^+H^-$

- The cross section of our process $e^+e^- \rightarrow H^+H^-$ in the FCC-ee is given by :

$$
\begin{aligned}
\sigma_{e\bar{e}\rightarrow H\bar{H}} = & \frac{\pi\,\alpha^2\beta^3}{3s} + \frac{\alpha}{12}\,\frac{\left(g_L^2+g_Lg_R\right)\beta^3}{s-m_Z^2} + \frac{\left(g_L^4+g_L^2g_R^2\right)\beta^3 s}{96\pi\left(s-m_Z^2\right)^2} + \sum_k \frac{|\dagger_{1k}|^4}{64\pi\,s}\left(w_k \ln\frac{w_k+\beta}{w_k-\beta} - 2\beta\right) \\
& + \left[\frac{\alpha}{16s} + \frac{g_L^2}{64\pi\left(s-m_Z^2\right)}\right]\sum_k |\dagger_{1k}|^2\left[\left(w_k^2-\beta^2\right)\ln\frac{w_k+\beta}{w_k-\beta} - 2\beta\, w_k\right] \\
& + \sum_{j,k>j}\frac{|\dagger_{1j}\mathcal{Y}_{1k}|^2}{64\pi\,s}\left(\frac{w_j^2-\beta^2}{w_j-w_k}\,\ln\frac{w_j+\beta}{w_j-\beta} + \frac{w_k^2-\beta^2}{w_k-w_j}\,\ln\frac{w_k+\beta}{w_k-\beta} - 2\beta\right), \qquad (4.14)
\end{aligned}
$$

Results and Discussion

- We start first by showing the effect of the different constraints on the parameter space of the model.
- The allowed parameter space of the scotogenic model is determined by the regions in the $(M_1, M_2, M_3, m_0, m_H, y_1, y_2, y_3)$ plane satisfying all the strong constraints.
- We consider two scenarios depending on the values of M_1 and M_2.
  - In the first one, we take $M_3 > M_2 > M_1$
  - In the second scenario, $M_2 \simeq M_1$ which is favored:

    to allow simultaneous satisfaction of constraints from dark matter relic density and branching ratio of $\mu \to e\gamma$.

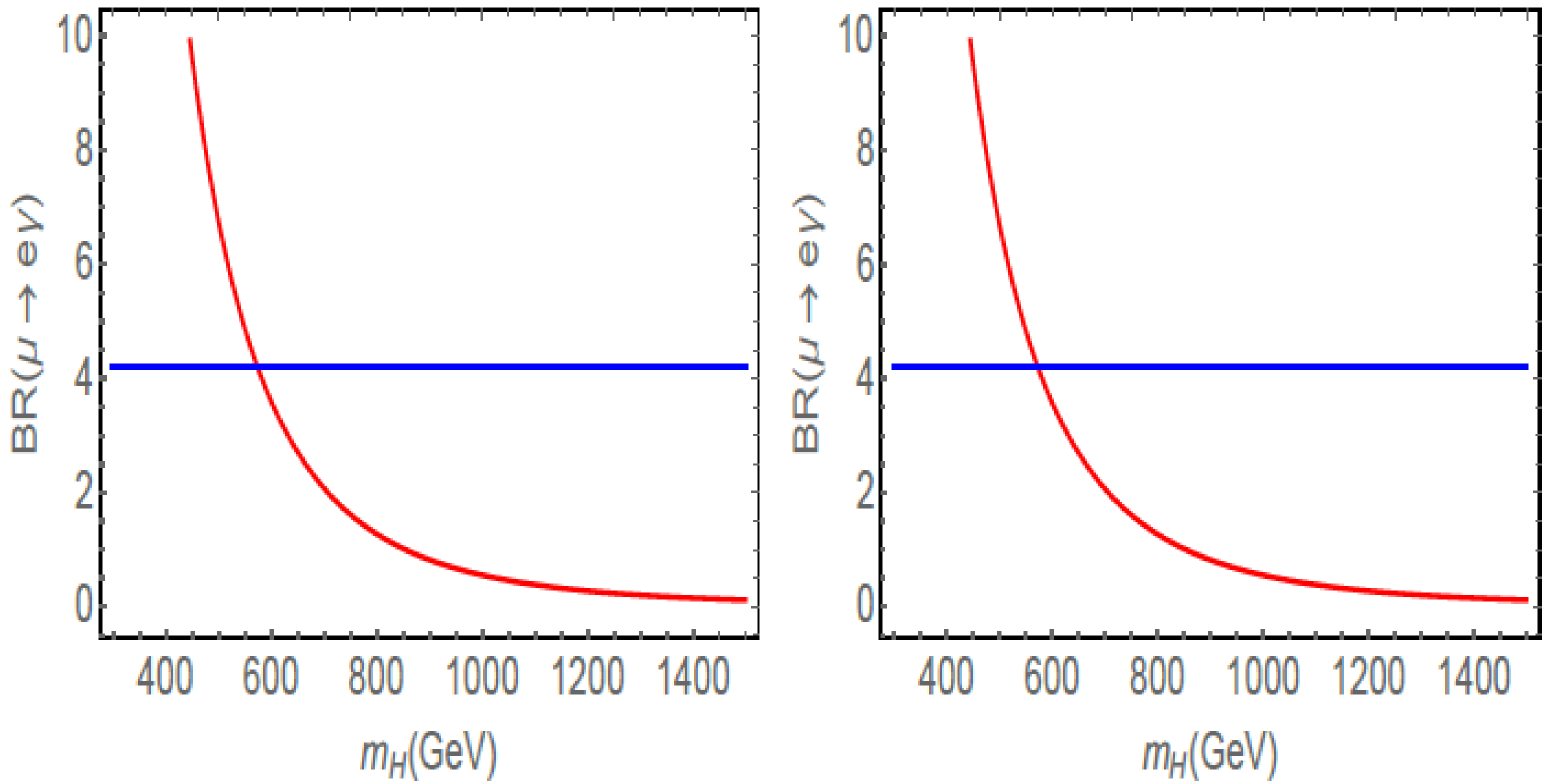


Figure 5.1. Left (Right) plot: $BR(\mu \to e\gamma)$ in units of 10^{-13} in red color as a function of m_H in the first (second) scenario. For the left plot we impose $M_1 = 200$ Gev, $M_2 = M_1 + 100$ GeV, $M_3 = M_1 + 200$ GeV, $y_1 = 0.03, y_2 = 0.01$, $y_3 = 0.02$, and for the right one we set $M_1 = M_2 = 200$ Gev, $M_3 = M_1 + 200$ GeV, $y_1 = 0.03$, $y_2 = 0.01$, $y_3 = 0.02$. The blue line represent the experimental upper bound on $BR(\mu \to e\gamma)$.

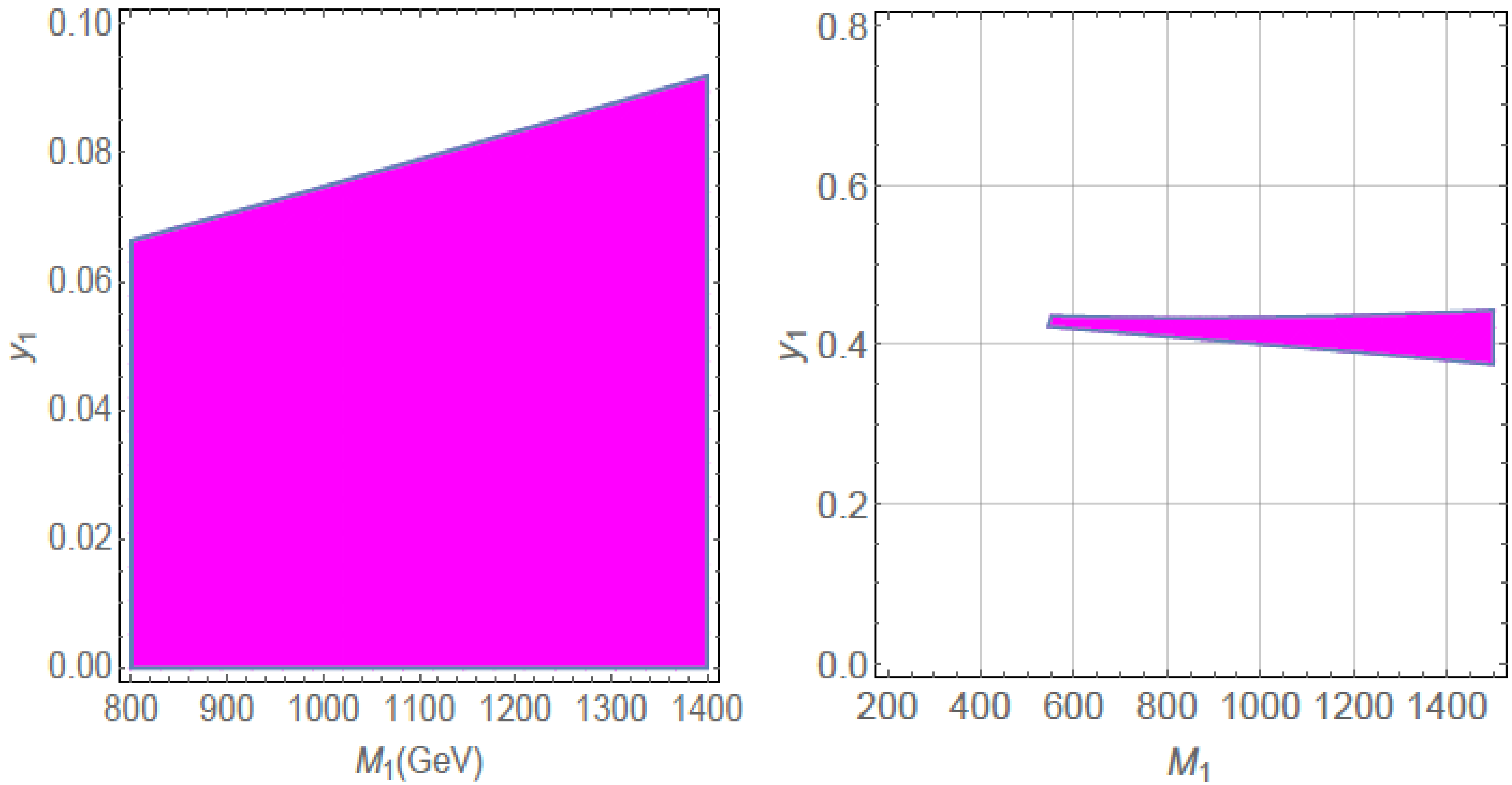


Figure 5.2. Left (Right) plot: regions in magenta color satisfying the constraints $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$. The left plot is obtained after setting $M_2 = M_1 + 100$ GeV, $m_H = M_1 + 400$ GeV, $M_3 = M_1 + 200$ GeV, $y_2 = 0.01$, $Y_3 = 0.02$ where the right one is obtained upon taking $M_2 = M_1$ GeV, $M_3 = M_1 + 1370$ GeV, $y_2 = 0.49$, $y_3 = 0.66$.

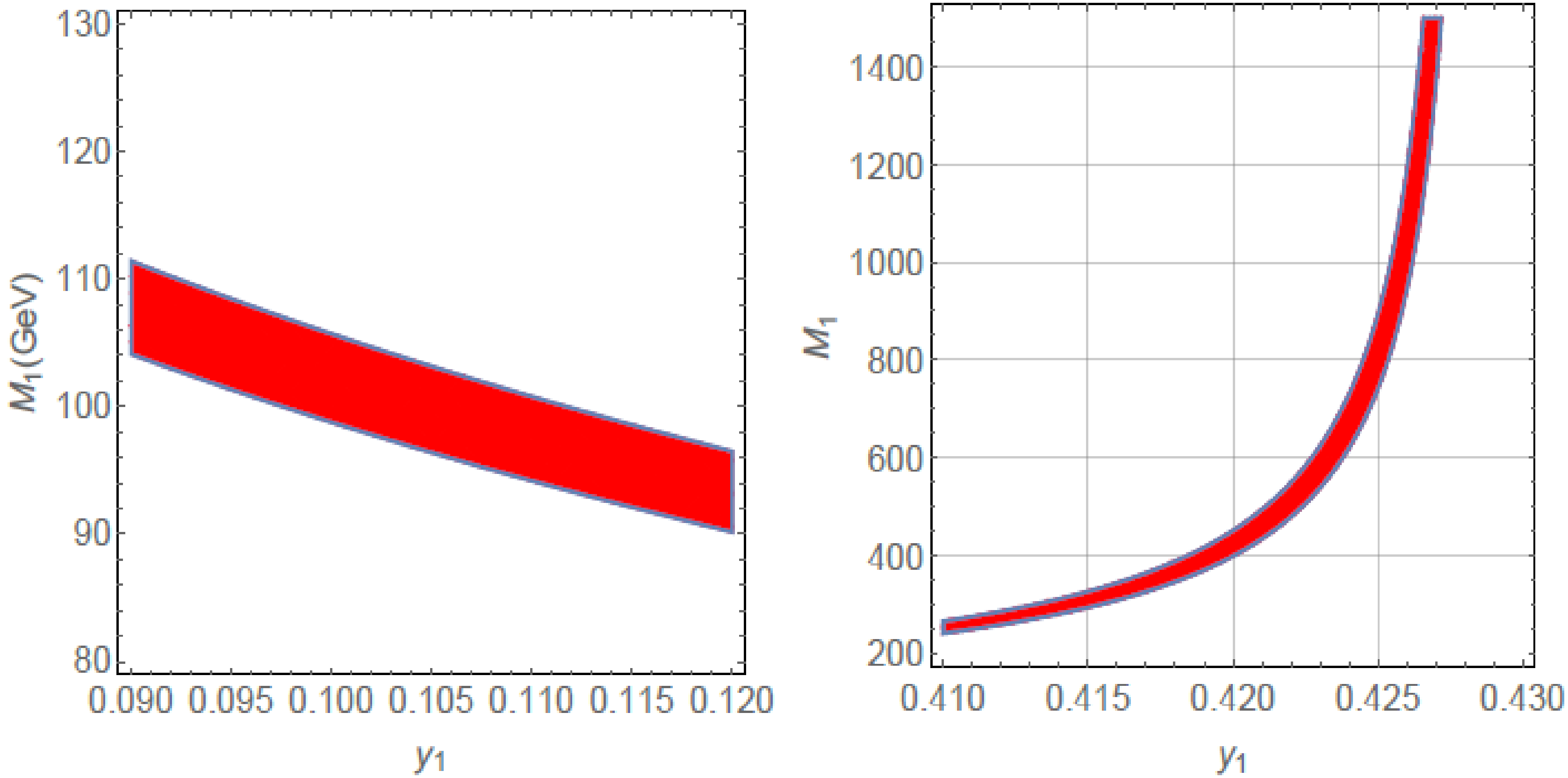


Figure 5.3. left (Right) plots, allowed region in $M_1 - y_1$ plane satisfying the constraint $32 < R_m < 36$ corresponding to first(second) scenario mentioned before. We took $m_0 = M_1 + 500$ GeV, $M_2 = M_1 + 50$ GeV, $M_3 = M_1 + 170$ GeV, $y_2 = 0.2, Y_3 = 0.3$ to obtain the left plot where for the right plot we set $M_2 = M_1$ for $M_3 = M_1 + 380$ GeV, $m_0 = M_1 + 750$, $y_2 = 0.49$, $y_3 = 0.66$.

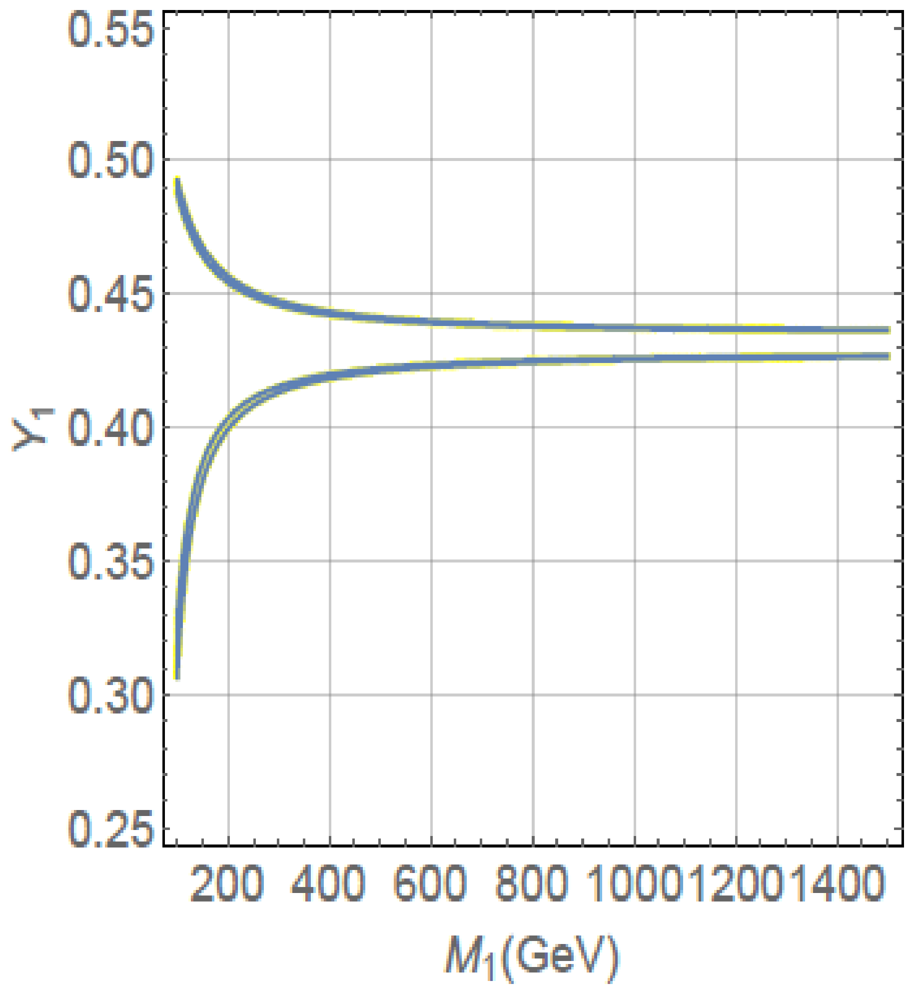


Figure 5.4. Allowed regions in the $M_1 - y_1$ plane after imposing $32 < R_m < 36$ constraints for the choice of the parameters as $M_2 = M_1$, $M_3 = M_1 + 380$ GeV, $m_0 = M_1 + 750$ GeV, $y_2 = 0.49$ and $y_3 = 0.66$.

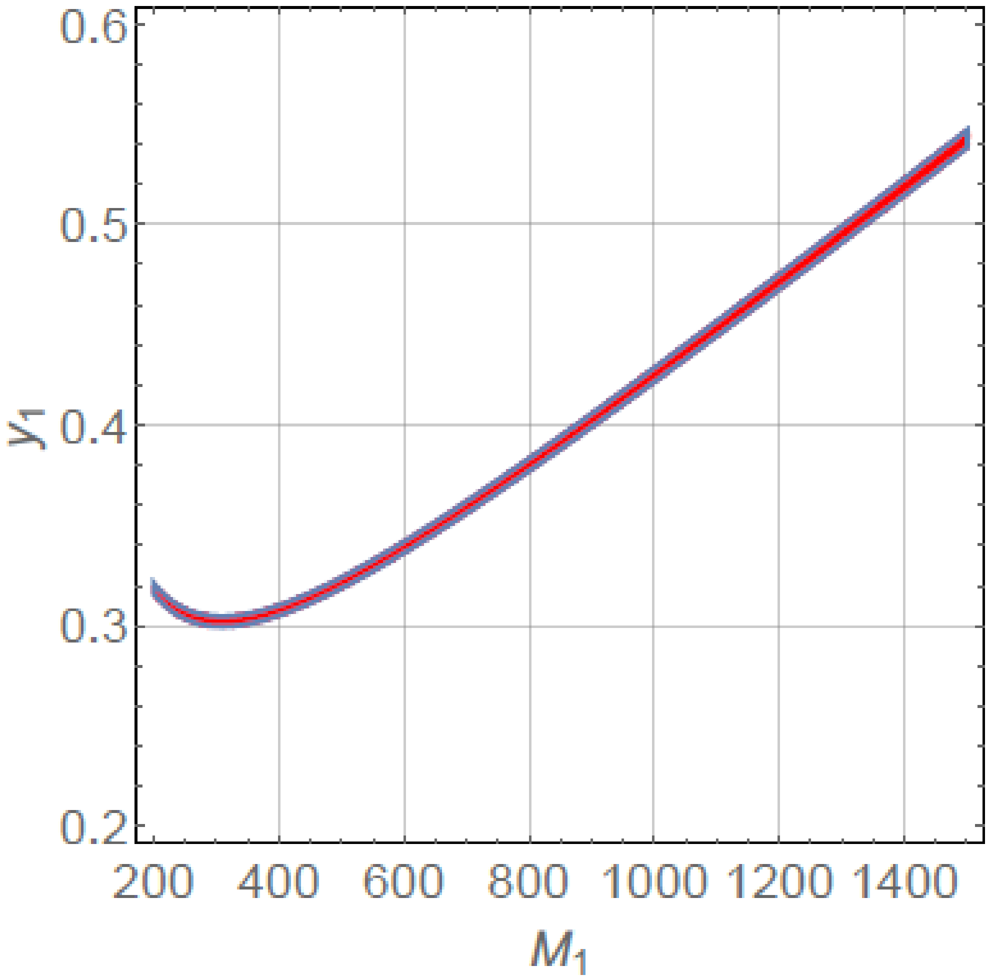


Figure 5.5. Allowed region in $M_1 - y_1$ plane satisfying the $0.118 \leq \Omega\hat{h}^2 \leq 0.122$ for $m_0 = M_1 + 750$ GeV, $m_H = M_1 + 400$ GeV, $g_s = 100$, $y_2 = 0.49$.

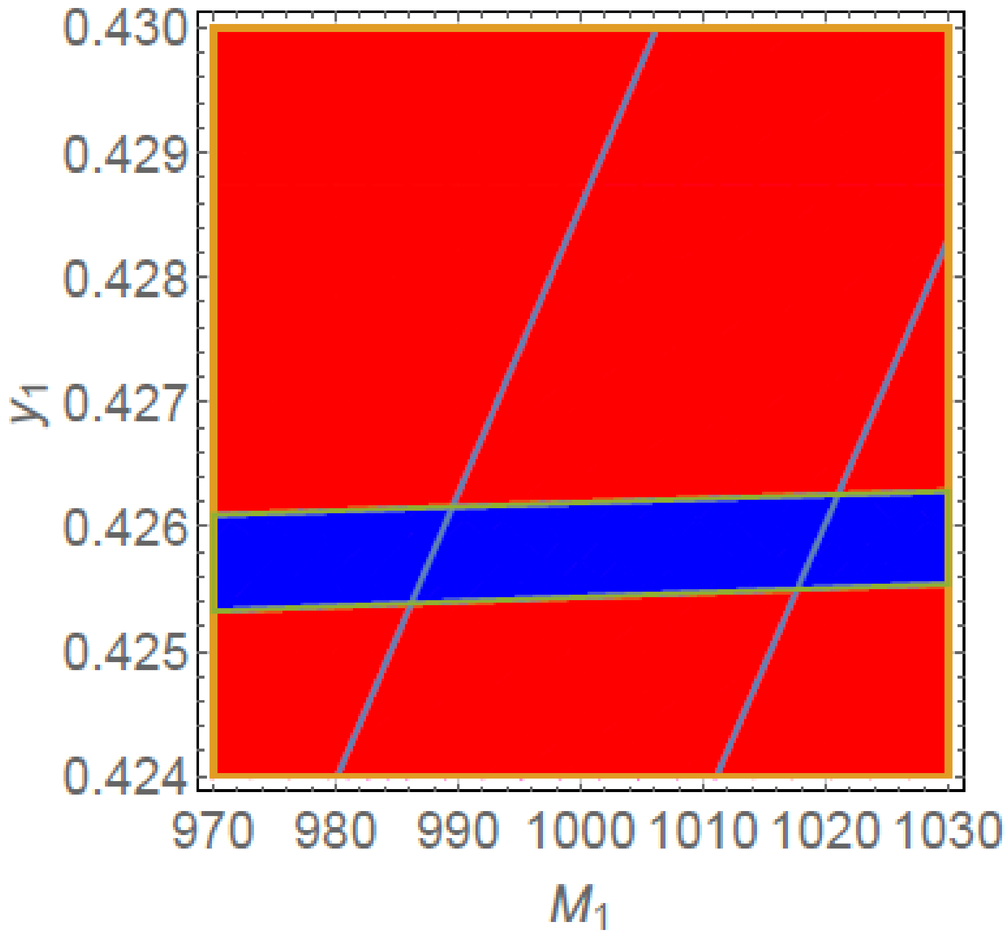


Figure 5.6. Allowed region in $M_1 - y_1$ plane satisfying our constrains $0.118 \leq \Omega\hat{h}^2 \leq 0.122$, $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ and $32 < R_m < 36$. for $m_0 = M_1 + 750$ GeV, $m_H = M_1 + 400$ GeV, $g_s = 100$, $M_3 = M_1 + 380$ GeV, $y_2 = 0.49$, $y_3 = 0.66$.

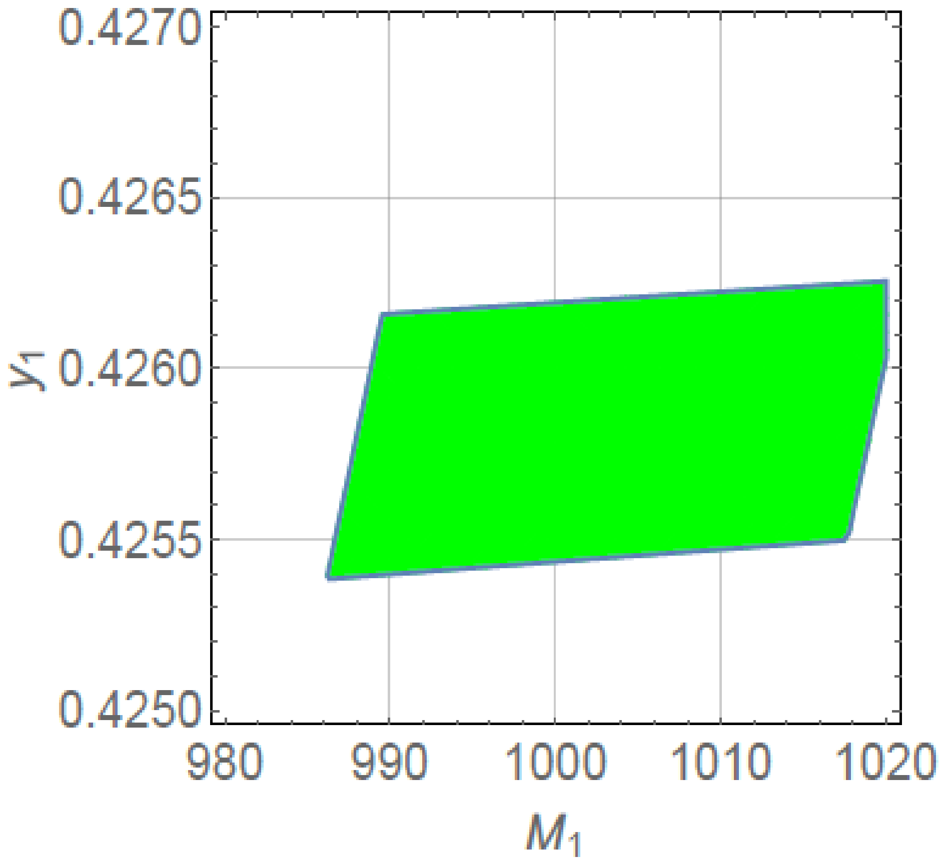


Figure 5.7. Allowed region in $M_1 - y_1$ plane interaction point for $0.118 \leq \Omega\hat{h}^2 \leq 0.122$, $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ and $32 < R_m < 36$, for $m_0 = M_1 + 750$ GeV, $m_H = M_1 + 400$ GeV, $g_s = 100$, $M_3 = M_1 + 380$ GeV, $y_2 = 0.49$, $y_3 = 0.66$.

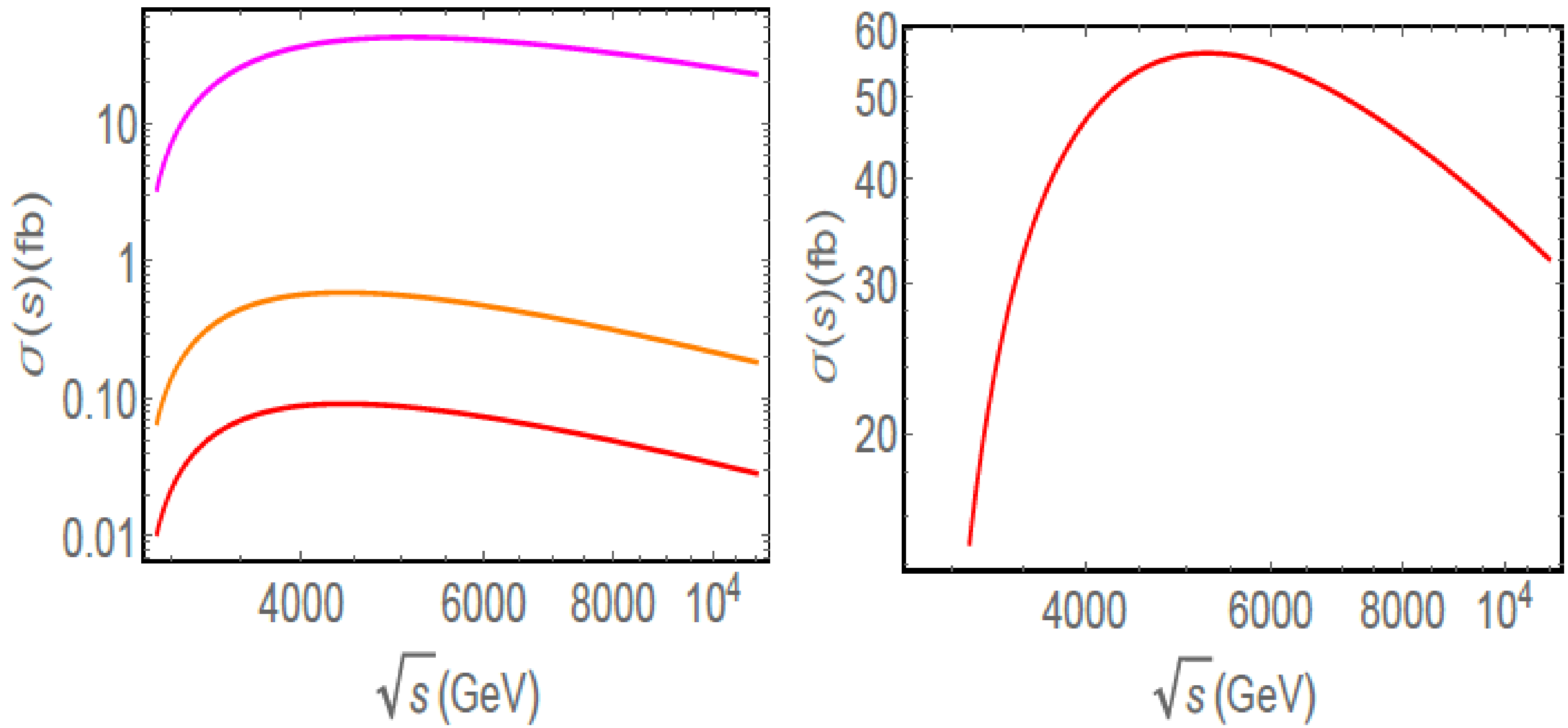


Figure 5.8. Left: photon, Z boson and singlet fermions $N_{1,2,3}$ contributions to the cross section for the process $e^+e^- \to H^+H^-$ in orange, red and magenta colors respectively as a function of $\sigma(s)\ (fb) - \sqrt{s}(GeV)$ for $m_H = M_1 + 400$ GeV, $M_1 = 990$ Gev, $M_2 = M_1 + 0.0000035$ Gev, $M_3 = M_1 + 380$ Gev, $y_1 = 0.4258$, $y_2 = 0.49$, $y_3 = 0.66$, Right: total cross section for the process $e^+e^- \to H^+H^-$ in red color as a function of $\sigma(s)\ (fb) - \sqrt{s}(GeV)$ for $m_H = M_1 + 400$ GeV, $M_1 = 990$ Gev, $M_2 = M_1 + 0.0000035$ Gev, $M_3 = M_1 + 380$ Gev, $y_1 = 0.4258$, $y_2 = 0.49$, $y_3 = 0.66$.

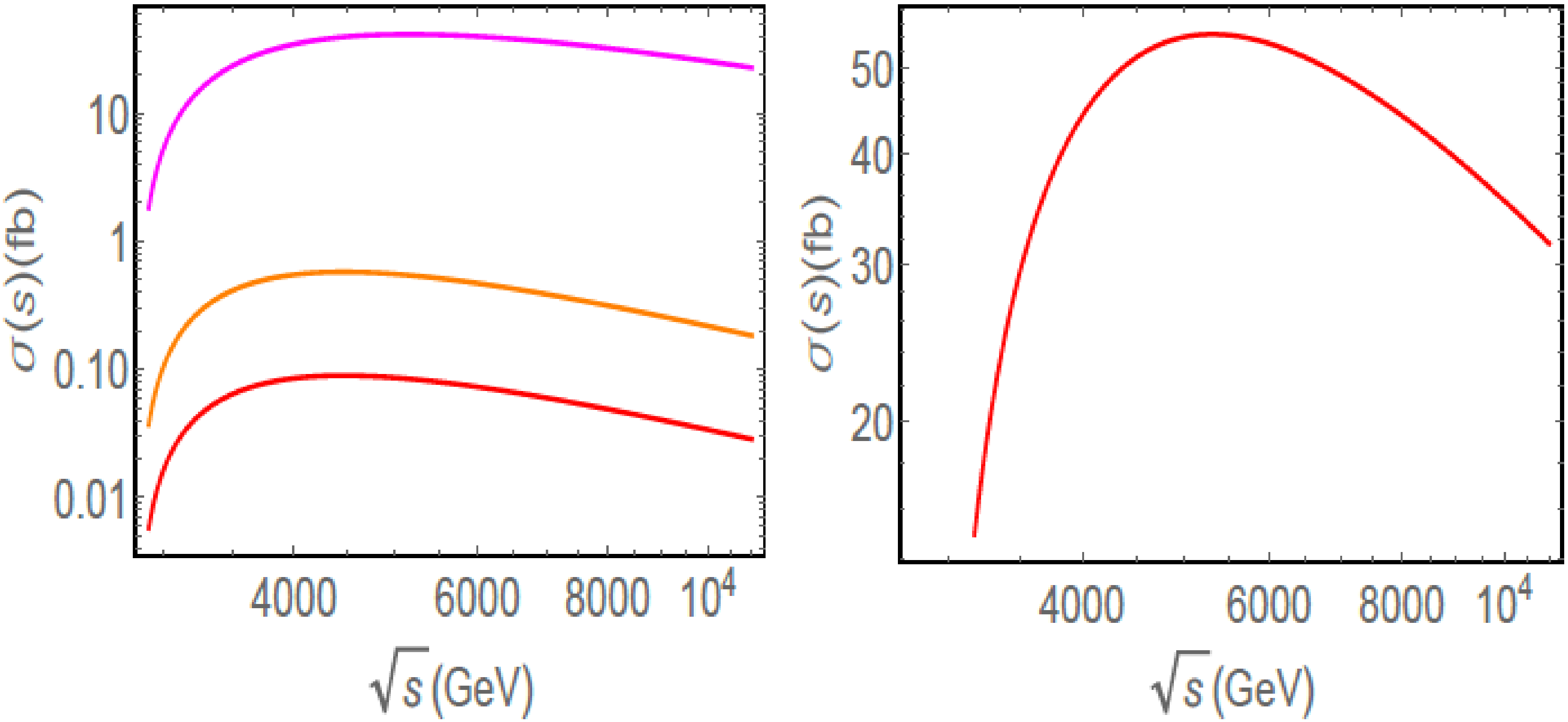


Figure 5.9. Left: photon, Z boson and singlet fermions $N_{1,2,3}$ contributions to the cross section for the process $e^+e^- \to H^+H^-$ in orange, red and magenta colors respectively as a function of $\sigma(s)$ $(fb) - \sqrt{s}(GeV)$ for $m_H = M_1 + 400$ GeV, $M_1 =$ 1010 Gev, $M_2 = M_1 + 0.0000035$ Gev, $M_3 = M_1 + 380$ Gev, $y_1 =$ 0.4258, $y_2 =$ 0.49, $y_3 =$ 0.66, Right: total cross section for the process $e^+e^- \to H^+H^-$ in red color as a function of $\sigma(s)$ $(fb) - \sqrt{s}(GeV)$ for $m_H = M_1 + 400$ GeV, $M_1 =$ 1010 Gev, $M_2 = M_1 + 0.0000035$ Gev, $M_3 = M_1 + 380$ Gev, $y_1 =$ 0.4258, $y_2 =$ 0.49, $y_3 =$ 0.66 .

CONCLUSIONS

- we have studied the process $e^+e^- \to H^+H^-$ in the scotogenic model.
- The different contributions to the amplitude of the process originate from tree-level diagrams mediated by photon, Z boson and from the right-handed fermions $N_{1,2,3}$.
- We have studied the processes with strong constraints on the parameter space relevant to the process $e^+e^- \to H^+H^-$.
- we have estimated the size of the individual contributions of each of photon, Z boson and the right-handed fermions $N_{1,2,3}$ to the cross section of $e^+e^- \to H^+H^-$ after taking into account all stringent constraints on the parameters of the model.

- We have shown that the main contribution to the cross section arise from the new singlet right handed fermions N1,2,3.

- Finally, we have shown the dependency of the cross section on the center of mass energy for set of benchmark points of the parameter space of the model respecting the strong obtained bounds.

- Future e^+e^- colliders will search for the process $e^+e^- \to H^+H^-$ and thus can test our predictions for either verifying these predictions or setting more stringent constraints.

Thank you

for

listening ☺