

NSI effect on the microscopic black hole events from UHE neutrino

This chapter is based on the work done in the ref. [275]. It has been discussed in Chapter 2 that the UHE neutrino undergoes CC and NC interactions by the DIS process after bombarding with the nuclei in the Earth's atmosphere. The secondary particles generated in these processes propagate further inside the medium and give rise to electromagnetic radiation in the radio or optical wavelength region. The currently ongoing neutrino telescopes are built to look for these signals that can provide more insights into the nature of neutrino-matter interaction at extreme energy scales, as well as the information of their sources and their production mechanism in extreme environments. The UHE neutrinos have immense potential to look for the signature of the BSM physics. The production of microscopic black holes (BH) is one such BSM phenomenon, as these black holes are generated in the presence of large extra dimensions, while the theory of SM is constructed by assuming only four dimensions of the Universe.

In the LED scenario the formation of the microscopic BH depends on the center of mass energy of the system. This has been studied extensively in many literatures in the context of the current high energy collider experiments [215, 216, 224, 276–281]. Since the extent of these collider experiments is constrained by the CM energy available for the high energy particle scattering, the cosmic ray particles, including UHE neutrino provide an excellent alternative because of their far greater energy reach as compared to the particle colliders. Several works have been done over the years focusing on the production of the air shower from the microscopic BH generated by UHE particle collisions in the Earth's atmosphere [221, 225, 282–285]. The UHE neutrinos are more favourable over cosmic ray particles. Also, the neutrino telescopes, such as the IceCube observatory at the South Pole have immense potential to distinguish between the events generated from the microscopic BH and the ordinary SM weak interactions in matter.

The neutrino interaction in matter is affected in the presence of NSI which alters the neutrino-nucleon DIS cross section. While the NSI encompasses short distance physics, the production of the microscopic BH at trans-Planckian energies requires semi-classical description. The NSI is introduced through the additional effective operators suppressed by the new physics energy scale (Λ), as shown in Eqn. (2.1) in Chapter 2. The effect of NSI is implanted in the Wilson coefficients corresponding to the different operators in the effective Lagrangian. In this analysis, the effect of the dimension-6 NC NSI operator is taken into consideration, since it is relevant for the neutrino propagation. This chapter is arranged as follows. In Section 5.1 the mathematical formulation of the neutrino nucleon scattering cross section is given for both the electroweak CC and NC processes and the microscopic BH production. The description of the different types of events generated from these interactions is discussed in Section 5.2 and finally, an estimation of the number of events detectable at the neutrino telescope is presented in Section 5.3 both in the presence of NSI and SM interactions.

5.1 Cross section of neutrino nucleon interaction

Previously in Eqn. (2.5), the dimension-6 operators are mentioned that give rise to NC NSI. The corresponding Lagrangian is given by

$$\mathcal{L}_{NC-NSI} = \frac{G_F}{\sqrt{2}} \sum_{f,\alpha,\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\epsilon_{\alpha\beta}^{fV} \bar{f} \gamma^\mu f + \epsilon_{\alpha\beta}^{fA} \bar{f} \gamma^\mu \gamma_5 f). \quad (5.1)$$

The summation index f corresponds to the quark flavours and the indices α and β denote the active neutrino flavours. The coefficients $\epsilon_{\alpha\beta}^{fV}$ and $\epsilon_{\alpha\beta}^{fA}$ represent the vector and axial vector NSI couplings. The flavour diagonal ($\alpha = \beta$) NC interactions can occur in both SM and NSI, while the FCNC interactions are highly suppressed in SM. The Wilson coefficients for the processes include the contributions from both SM and NSI, $C_{i,f}^{(6)} = C_{i,f}^{(6)}|_{SM} + C_{i,f}^{(6)}|_{NSI}$ ($i = 1, 2$), which are given by the following expressions

$$\begin{aligned} C_{1,u}^{(6)}|_{SM} &= -\frac{G_F}{\sqrt{2}} \left(1 - \frac{8}{3} G_F s_w^2\right) \delta_{\alpha\beta}, C_{2,u}^{(6)}|_{SM} = \frac{G_F}{\sqrt{2}} \delta_{\alpha\beta} \\ C_{1,d}^{(6)}|_{SM} &= \frac{G_F}{\sqrt{2}} \left(1 - \frac{4}{3} s_W^2\right) \delta_{\alpha\beta}, C_{2,d}^{(6)}|_{SM} = -\frac{G_F}{\sqrt{2}} \delta_{\alpha\beta} \\ C_{1,d}^{(6)}|_{SM} &= C_{1,s}^{(6)}|_{SM}, C_{2,d}^{(6)}|_{SM} = C_{2,s}^{(6)}|_{SM} \\ C_{1(2),f}^{(6)}|_{NSI} &= \frac{G_F}{\sqrt{2}} \epsilon_{\alpha\beta}^{f,V(A)} \quad (f = u, d, s) \end{aligned} \quad (5.2)$$

Here s_w denotes $\sin \theta_w$, $\theta_w \approx 28.13^\circ$ is Weinberg angle. The coefficients $\epsilon_{\alpha\beta}^{fV(A)}$ denote the vector (axial vector) NSI parameters for NC interaction for the neutrino scattering with the fermion f . In this work, the analysis of the ref. [286] is followed to determine νN scattering cross section for large neutrino energy (E_ν) and momentum exchange (Q). The expression for differential scattering cross section for CC ($\nu_\alpha N \rightarrow l_\alpha^- X$) and NC ($\nu_\alpha N \rightarrow \nu_\beta X$) processes is given as [286]

$$\begin{aligned} \frac{d^2 \sigma^{CC}}{dx dy} &= \frac{G_F^2 m_N E_\nu}{\pi} [xu(x) + xd(x) + 2s(x) + (1-y)^2 \{\bar{u}(x) + \bar{d}(x)\}] \\ \frac{d^2 \sigma^{NC}}{dx dy} &= \frac{m_N E_\nu}{\pi} [(C_{L,u}^2 + (C_{L,d}^2) \sum_{f=u,d} \{xf(x) + x\bar{f}(x)(1-y)^2\} \\ &\quad + (C_{R,u}^2 + C_{R,d}^2) \sum_{f=u,d} \{xf(x)(1-y)^2 + x\bar{f}(x)\} \\ &\quad + 2\{C_{L,s}^2(xs(x) + \bar{s}(x)(1-y)^2) + C_{R,s}^2(xs(x)(1-y)^2 + \bar{s}(x))\}]. \end{aligned} \quad (5.3)$$

Here, $C_{L(R),f} = C_{1,f} \mp C_{2,f}$.

- Microscopic BH production: The neutrino nucleon DIS interaction can generate microscopic BHs with the production cross section given as follows [225, 282]

$$\sigma(\nu N \rightarrow BH) = \sum_i \int_a^1 dx f_i(x) \times \pi r_S^2 = \sigma^{BH}, \quad (5.4)$$

where i represents the parton index, $a = (M_{min}^{BH})^2 / 2m_N E_\nu$. M_{min}^{BH} is the minimum mass of the BH which is considered to be equal to the modified Planck scale, given by $M_{Pl,4+n}$. The microscopic BHs produced in such parton collisions are far smaller than the length of the LEDs and hence they can be described as the $(4+n)$ -dimensional solution of the Einstein action, given by Eqn. (2.13). The number of extra dimensions (n) and the modified Planck scale ($E_{Pl,4+n}$) are constrained by many cosmological and astrophysical phenomena [287]. The

case with only one extra dimension is ruled out as for $E_{Pl,4+n} \sim 1$ TeV, $R \sim 10^{13}$ cm which implies that gravity is modified over astronomical distances. For $n = 2$, $R \sim 1$ mm which is the lowest length scale over which gravity has been measured. In case of $n = 2$, the lower limit on $M_{Pl,4+n}$ was found to be exceeding 30 TeV [287–289] which is unreachable by the current accelerator experiments. For $n = 3$, $M_{Pl,4+n} \sim 2$ TeV [288]. For $n \geq 4$, the constraints come from cosmic ray and collider experiments [290] which shows $M_{Pl,4+n} \sim 1 - 2$ TeV. The analysis on the bound of the size of the LEDs has been performed in several works in the neutrino oscillation scenario considering the mixing between the three active neutrino flavours and three sterile neutrinos in the context of several neutrino oscillation experiments [291–294].

5.2 Types of events generated



Figure 5.1: Feynman diagrams representing the neutrino-nucleon scattering. Left panel: the event generation in the absence of BH $\nu N \rightarrow lX$, which is mediated by $W^\pm$ or Z^0 depending on CC or NC interaction in the SM framework, which is mediated by any BSM particle in presence of NSI; Right panel: In case of BH production $\nu N \rightarrow BH \rightarrow lX$. Here l and X are the charged or neutral lepton and the shower counterpart respectively

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In the neutrino telescopes, the events are generated by the following two scattering channels,

1. $\nu N \rightarrow lX$
2. $\nu N \rightarrow BH \rightarrow lX$

Here X and l denote the hadrons and leptons respectively $l = (\nu_l \ l^-)^T$. The Feynman diagrams for the shower production corresponding to the SM interactions and the BH production are shown in Fig. 5.1. Depending on the event topology observed in the detector, three different kinds of events are observed: (a) Shower like events which are produced by both CC and NC interactions of neutrinos, and the energy is accumulated in a nearly spherical structure, (b) track like events which are produced by muons from CC interaction and (c) double bang events generated by tau leptons coming from CC interaction of the neutrinos which appear as two distinct shower events [295, 296]. Since in this work, the NSI effect is investigated on the number of events, only the shower like events are studied which can be induced by the NC interactions as well as from the CC interaction.

(1) If the BH formation is absent, the number of shower events generated via the process $\nu N \rightarrow lX$ is given by $N_{sh} = N_{\nu_e} + N_{\nu_\mu} + N_{\nu_\tau}$. Here N_{ν_i} ($i = e, \mu, \tau$) presents the number of shower

events generated by the neutrino of particular flavour i , which is given by the following expression

$$N_{\nu_i} = 2\pi AT \int \cos \theta_z \int dE_{\nu_i} \frac{d\phi_{\nu_i}}{dE_{\nu_i}} P_{surv}^i \left(\int_{y_{i,CC}^{min}}^{y_{i,CC}^{max}} dy \frac{1}{\sigma^{CC}(E_{\nu_i})} \frac{d\sigma^{CC}(E_{\nu_i})}{dy} P_{int,i}^{CC} \right. \\ \left. + \int_{y_{i,NC}^{min}}^{y_{i,NC}^{max}} dy \frac{1}{\sigma^{NC}(E_{\nu_i})} \frac{d\sigma^{NC}(E_{\nu_i})}{dy} P_{int,i}^{NC} \right). \quad (5.5)$$

Here $y_{CC}^{min} = 0$, $y_{CC}^{max} = 1$, $y_{NC}^{min} = E_{sh}^{thr}$ and $y_{NC}^{max} = 1$. The threshold energy for the detection of the shower in the neutrino telescope is denoted by E_{sh}^{thr} , A and T represent the area of the detector and the time interval over which the detection process is continued, respectively. P_{int} represents the probability that the neutrino interacts to induce shower events inside the detector of length scale L , given by

$$P_{int,i}^{CC,NC} = 1 - \exp(-N_A L \sigma^{CC,NC}(E_{\nu_i})), \quad (5.6)$$

P_{surv} is the probability that the neutrino (of flavour i) survives to reach the detector, which is expressed as

$$P_{surv}^i = \exp[-X(\theta)N_A(\sigma^{CC}(E_{\nu_i}) + \sigma^{NC}(E_{\nu_i}))]. \quad (5.7)$$

Here θ is the zenith angle and $X(\theta)$ is the column density of the medium through which the neutrino passes to reach the detector. N_A represents Avogadro's number.

(2) The number of shower events produced from the BH decay by the interaction channel $\nu N \rightarrow BH \rightarrow lX$ is given by $N^{BH} = N_{\nu_e}^{BH} + N_{\nu_\mu}^{BH} + N_{\nu_\tau}^{BH}$, with $N_{\nu_i}^{BH}$ being the number of events induced by the specific flavour ($i = e, \mu, \tau$) of the incoming neutrino. The expression of N^{BH} is given by

$$N_{\nu_i}^{BH} = 2\pi AT \int \cos \theta \int dE_{\nu_i} \frac{d\phi_{\nu_i}}{dE_{\nu_i}}(E_{\nu_i}) P_{surv}^{BH,i} \int_{y_l}^{y_u} dy \frac{1}{\sigma^{BH}(E_{\nu_i})} \frac{d\sigma^{BH}(E_{\nu_i})}{dy} P_{int}^i, \quad (5.8)$$

where σ_{BH} denotes the cross section of BH production, mentioned in Eqn. (5.4). The probability that the neutrino interacts inside the detector to create a microscopic BH is denoted by P_{int}^i which is expressed as follows

$$P_{int}^i = 1 - \exp[-N_A L \sigma^{BH}(E_{\nu_i})]. \quad (5.9)$$

In Eqn. (5.8), $P_{surv}^{BH,i}$ is the probability of survival of the neutrino to reach the detector, given by

$$P_{surv}^{BH,i} = \exp[-X(\theta)N_A(\sigma^{CC}(E_{\nu_i}) + \sigma^{NC}(E_{\nu_i}) + \sigma^{BH}(E_{\nu_i}))]. \quad (5.10)$$

In Eqn. (5.5) & (5.8), $d\phi_{\nu_i}/dE_{\nu_i}$ is the incoming neutrino flux. The highest energy neutrinos ($\sim \text{EeV}$) are predicted to be generated in the GZK process ($p\gamma \rightarrow n\pi^+, \pi^+ \rightarrow \mu^+\nu_\mu, \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$; $pp \rightarrow \pi^+ \rightarrow \mu^+\nu_\mu$) in gamma ray burst (GRB) and active galactic nucleus (AGN) [297, 298]. The upper limit of such neutrino flux is restricted by Waxman-Bahcall flux (WB), $E_\nu^2 d\phi_\nu/dE_\nu < 2 \times 10^{-8} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ [297]. The flux is similar for all three flavours of neutrinos, ν_e, ν_μ, ν_τ in the neutrino oscillation framework for a distant source [299]. In this work the dependence of the column density X on the zenith angle is neglected. As the description of microscopic BH production is not affected by any short distance physics, the shower events produced by the decay of BH are only affected by NSI through the NC cross section σ^{NC} , which alters the survival probability term $P_{surv}^{BH,i}$.

5.3 NSI effects on the number of event

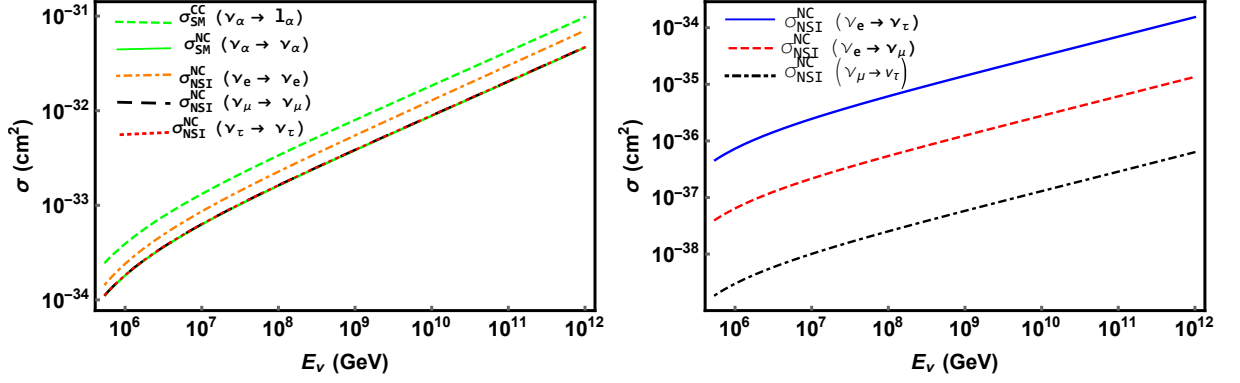


Figure 5.2: The figures depict the scattering cross sections (σ) in CC and NC processes. Top panel: For CC and NC flavour conserving processes (NC includes both SM and NSI); bottom panel: For flavour off-diagonal processes for the NC interactions allowed by NSI only.

In the following, the analysis of the effect of NSI on the microscopic BH events is discussed in the context of IceCube neutrino detector which is $\sim \text{km}^3$ array embedded in the Antarctic ice [182, 184, 300]. The possibility of detection of such BH events along with the ordinary shower events induced by the SM weak interaction is substantially greater in such a large scale neutrino telescope because of its high sensitivity and accuracy of detection technique. The essential component to calculate the number of shower events is the νN scattering cross section. In this analysis, considering the lowest limit as $x = 10^{-4}$, the PDFs are extracted from CTEQ6 dataset for the momentum transfer $Q^2 = 10^4 \text{ GeV}^2$ [301]. The cross sections are not susceptible to the choice of Q^2 at UHE regions [225, 302]. The scattering cross sections for the CC and NC processes considering flavour diagonal and off-diagonal processes are illustrated in Fig. 5.2. In the limit $x \rightarrow 0$, the PDFs are divergent. In this region since there is no experimental constraint, consideration of different behaviour of PDFs results in different scattering cross sections [303] which is discussed in detail in Chapter 3. However, UHE neutrinos with energies around $\sim 10^{10} \text{ eV}$ probe upto the range $x \sim 10^{-4}$ for $M_{Pl,4+n} \sim 1 \text{ TeV}$.

The NSI parameters used in this analysis are obtained from the global analysis of the neutrino oscillation and COHERENT data considering CP conserving variables [304]. In COHERENT experiment the axial vector NSI couplings are neglected [305], hence in our analysis, we consider them to be zero. Also, the contribution of the strange quark is considered to be zero [305, 306]. The ranges of NSI parameters considered in this analysis are given in Table 5.1.

Bounds on $\epsilon_{\alpha\beta}^{u(d),V}$			
$\epsilon_{ee}^{u,V}$	[0.043, 0.384]	$\epsilon_{ee}^{d,V}$	[0.036, 0.354]
$\epsilon_{e\mu}^{u,V}$	[-0.055, 0.027]	$\epsilon_{e\mu}^{d,V}$	[-0.052, 0.024]
$\epsilon_{e\tau}^{u,V}$	[-0.14, 0.09]	$\epsilon_{e\tau}^{d,V}$	[-0.106, 0.082]
$\epsilon_{\mu\mu}^{u,V}$	[-0.05, 0.062]	$\epsilon_{\mu\mu}^{d,V}$	[-0.046, 0.057]
$\epsilon_{\mu\tau}^{u,V}$	[-0.006, 0.006]	$\epsilon_{\mu\tau}^{d,V}$	[-0.005, 0.005]
$\epsilon_{\tau\tau}^{u,V}$	[-0.05, 0.065]	$\epsilon_{\tau\tau}^{d,V}$	[-0.046, 0.059]

Table 5.1: Range of the NSI parameters obtained from COHERENT experiment within 2σ interval. The contribution of $\epsilon_{\alpha\beta}^{s,V}$ and $\epsilon_{\alpha\beta}^{f,A}$ for all the three quarks ($f \in u, d, s$) are considered to be zero.

For the CC process, the contribution to the cross section involves only the SM interaction as plotted in Fig. 5.2. In the SM, only the flavour diagonal NC processes are allowed, given by $\nu_\alpha N \rightarrow \nu_\alpha X$. The three processes corresponding to $\alpha = e, \mu, \tau$ results in equal cross sections. This is due to the fact that the SM Wilson coefficients do not depend on the incoming neutrino flavour,

as seen from Eqn. (5.2). This is shown by $\sigma_{SM}^{NC}(\nu_\alpha \rightarrow \nu_\alpha)$ in the plot, $\sigma_{SM}^{NC}(\nu_e \rightarrow \nu_e) = \sigma_{SM}^{NC}(\nu_e \mu \rightarrow \nu_\mu) = \sigma_{SM}^{NC}(\nu_\tau \rightarrow \nu_\tau)$. However, in case of NSI, the cross sections corresponding to these three channels are not identical because of the different values of $\epsilon_{\alpha\beta}$ for different FCNC channels giving rise to different Wilson coefficients, which is also understood from the left panel of Fig. 5.2.

For $\alpha \neq \beta$, the non-zero value of the NSI parameters implies the existence of FCNC which allows the additional interaction channels apart from the ones allowed by the SM *e.g.* $\nu_e \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$. The scattering cross sections of these processes are represented in the right panel of Fig. 5.2. It is clearly evident from the plot that the cross sections for the FCNC processes are much smaller as compared to that for the flavour conserving processes. For example, at $E_\nu \sim 10^{10}$ GeV, the maximum value of cross section for flavour conserving NSI is around $\sim 10^{-32}$ cm², while the maximum value of cross section in case of FCNC processes does not exceed even 10^{-35} cm². Therefore, the FCNC processes allowed by NSI are expected to not produce significant contributions to the total number of events.

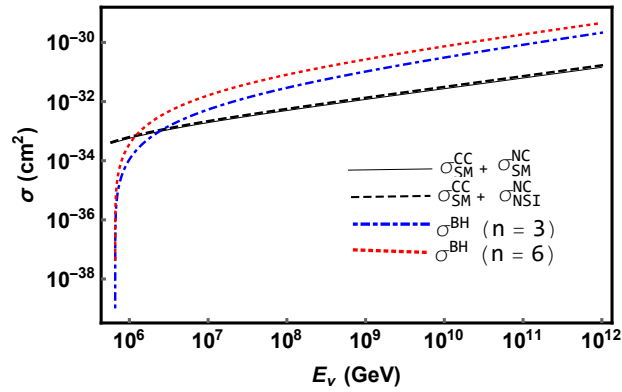


Figure 5.3: The variation of the total cross section (*i.e.* the sum of CC and NC interactions, NC includes both the cases of SM and NSI) and the cross section of black hole formation are presented.

The cross section corresponding to the BH formation (σ^{BH}) is depicted in Fig. 5.3 considering the number of LEDs to be $n = 3$ and 6 . The value of the modified Planck scale is set at $M_{Pl,4+n} = 1$ TeV. The total cross sections of the νN scattering interaction for both CC and NC interactions corresponding to SM ($\sigma_{SM}^{CC} + \sigma_{SM}^{NC}$) and NSI ($\sigma_{SM}^{NSI} + \sigma_{NSI}^{NC}$) are also illustrated in the figure for a comparative analysis. It can be seen that the total cross section in the presence of NSI is enhanced marginally as compared to the SM scenario. It is also observed that at UHE regime ($E_\nu \gtrsim 10^8$ GeV), the cross section of the microscopic BH production $\sigma(\nu N \rightarrow BH \rightarrow lX)$ is greater by at least two orders of magnitude as compared to $\sigma(\nu N \rightarrow lX)$.

SM				NSI			
N_e	N_μ	N_τ	N_{tot}	N_e	N_μ	N_τ	N_{tot}
1.68	1.68	1.68	5.04	1.85	1.64	1.65	5.15

Table 5.2: Number of shower events generated via the channel $\nu N \rightarrow lX$ ($l = e, \mu, \tau$) in case of SM and NSI. Here N_e , N_μ , N_τ represent the respective number of events produced separately by the different neutrino flavours ν_e , ν_μ and ν_τ .

The number of shower events produced by the scattering process $\nu N \rightarrow lX$ is determined using the Eqn. (5.5). The comparative results are presented in Table 5.2 for SM and NSI in the context of IceCube experiment, considering the area of detection to be about $A \sim 1$ km² and the period of detection is taken as $T = 1$ year. As mentioned earlier, the zenith angle is considered to be independent of the column density X which provides a factor of two from the integral over the angle. From Table 5.2 it is evident that the deviation in the number of shower events is inconsequential in the presence of NSI.

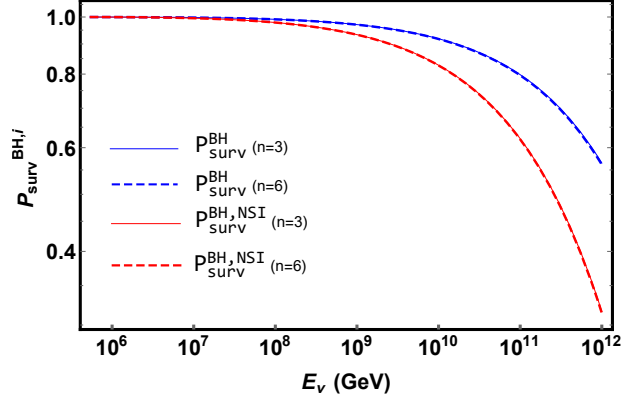


Figure 5.4: The figure illustrates the variation of the survival probability of BH, $P_{surv}^{BH,i}$, with energy E_{ν_i} of a particular neutrino flavour ν_i considering the number of LEDs, $n = 3$ and 6 .

The new physics affects the number of events produced from BH decay through the quantity $P_{surv}^{BH,i}$ through the NC scattering cross section $\sigma^{NC}(E_{\nu_i})$ given by Eqn. (5.8). This implies that the effect of NSI observed in the number of microscopic BH events is reflected in the term $P_{surv}^{BH,i}$. In Fig. 5.4, the variation of $P_{surv}^{BH,i}$ is shown with the neutrino energy. It is evident from the plot that the presence of NSI cannot provide any significant alteration from its SM prediction throughout the entire energy range, which further implies that the NSI effect on the number of shower events generated from microscopic BH will also be insignificant. The results do not alter significantly if different sets of NSI parameters are used instead of those obtained from the COHERENT experiment. Thus, the number of events produced through BH production would remain nearly unaltered in the presence of NSI and a large enhancement in the number of observed shower events over its SM prediction indicates the unequivocal signatures of the TeV scale gravity in the form of microscopic BH production.