Implication of nonstandard interaction on microscopic black hole events from ultra high energy neutrinos

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Plan of the Talk

- Hierarchy problem
- Microscopic black hole
- Non standard interaction
- Events generated by ultra high energy neutrinos
- Results
- Conclusion

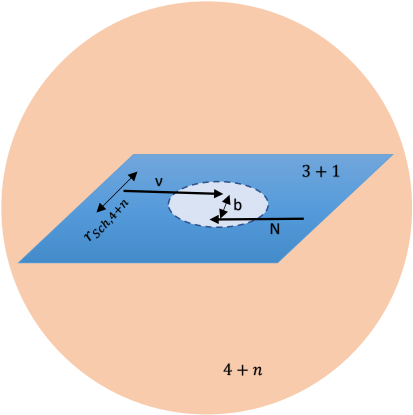
Hierarchy problem and extra dimensions

- Gravity is the weakest among all the fundamental forces ($G_N/G_F \sim 10^{-33}$)
- QFT expects Higgs mass to be much larger than its value observed experimentally
- Gravity is unified with the fundamental gauge forces of standard model (SM) at Planck scale
- Hierarchy problem is the huge disparity existing between electroweak ($E_{EW} \sim 100$ GeV) and Planck scale ($E_{Pl} \sim 10^{19}$ GeV)
- One possible solution is to consider Planck scale at $\sim$ TeV
- The universe is required to have large extra spatial dimensions (LED) $d = 4 + n \implies$ beyond standard model (BSM) physics comes into play
  (Arkani-Hamed et al, Phys. Lett. B 429, 263–272 (1998))

Microscopic black hole

- $E_{Pl,4}^2 \sim R^n E_{Pl,4+n}^2$, R is the length scale of LEDs ($n \geq 2$)
- The SM fields are confined in only $(3+1)$ dimension of a d-dimensional hyperspace, while gravity can propagate in bulk
- If two ultra high energy (UHE) particles collide with a center of mass energy $E_{CM} >> E_{Pl,4+n}$, a microscopic black hole (MBH) is formed semi classically (Emparan et al, Phys. Rev. D 65, 064023 (2002))
- Cross section of MBH formation, $\sigma_{MBH} = \pi r_{Sch,4+n}^2$, $r_{Sch,4+n} = \frac{1}{M_{Pl,4+n}} \left(\frac{M_{MBH}}{M_{Pl,4+n}}\right)^{1/1+n} \left[\frac{2^n \pi^{(n-3)/2}\Gamma(n+3/2)}{2+n}\right]^{1/1+n}$, $r_{Sch,4+n} << R$
- The MBHs decay very fast $\sim \mathcal{O}(10^{-27}$ sec) into SM particles

MBH from UHE neutrinos



UHE neutrinos ($E_\nu \gtrsim 10^{18}$ eV) undergo neutrino nucleon deep inelastic scattering (DIS) in Earth's atmosphere and may produce MBH as an intermediate resonance state ($\nu N \to$ BH, $b \lesssim r_{Sch,4+n}$)

MBH production cross section

- Cross section of MBH production,

  $\sigma^{MBH}(\nu N \to MBH) =$
  $\sum_{i=partons} \int_a^1 dx\ f_i(x) \times \pi r^2_{Sch,4+n}$

  where $a = (M_{Pl,4+n}\ \text{TeV})^2/2m_N E_\nu$,

  $f_i =$ Parton distribution function (PDF)

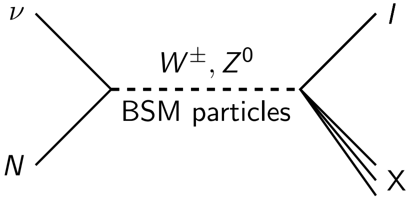
- σ^{MBH} is free of any short distance physics

Non standard interaction (NSI)

- New physics is introduced in terms of NSI in the neutrino sector in model independent way
- CC-NSI is only important at the source and detector. NC-NSI affects neutrino propagation in matter.
- In terms of lepton number conserving dimension-6 four fermion operator,
  $\mathcal{L}_{NC-NSI} \in 2\sqrt{2}G_F \sum_{X=L,R} \epsilon_{\alpha\beta}^{f,X}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_X f)$
- **NSI allows flavour changing neutral current (FCNC) process ($\nu_\alpha \to \nu_\beta,\ \alpha \neq \beta$), which are strongly suppressed in SM**. Flavour conserving NC processes ($\nu_\alpha \to \nu_\alpha$) are allowed in both SM and NSI.

Events generated by UHE neutrino

(1)$\nu N \rightarrow lX(l =$ charged or neutral lepton, X=shower) :



No of events generated, $N_{\nu_i} =$

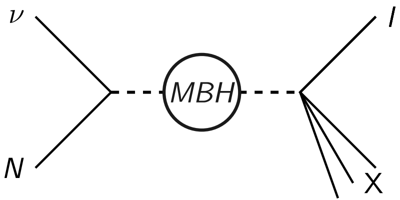
$$2\pi AT \int dcos\theta \int dE_{\nu_i} \frac{d\phi_{\nu_i}}{dE_{\nu_i}} P_{surv,i} \sum_{j=CC,NC} \int_{y_i^{min,j}}^{y_i^{max,j}} \frac{1}{\sigma^j(E_{\nu_i})} \frac{d\sigma^j(E_{\nu_i})}{dy} P^j_{int,i},$$

$$P^j_{int,CC(NC)} = 1 - exp(-N_A L \sigma^{CC(NC)}(E_{\nu_i}))$$

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

(Alvarez-Muniz et al. Phys.Rev.D65:124015,2002)

$(2) \nu N \rightarrow \text{MBH} \rightarrow lX$:



No of events generated, $N_{\nu_i}^{MBH} =$

$$2\pi AT \int dcos\theta \int dE_{\nu_i} \frac{d\phi_{\nu_i}}{dE_{\nu_i}} P_{surv,i}^{MBH} \int_0^1 \frac{1}{\sigma^{MBH}(E_{\nu_i})} \frac{d\sigma^{MBH}(E_{\nu_i})}{dy} P_{int,i},$$

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

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

(Alvarez-Muniz et al. Phys.Rev.D65:124015,2002)

UHE ν flux

- The highest energy neutrinos ($\sim$ EeV) are 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)
- The upper limit of such neutrino flux is restricted by Waxman-Bahcall flux, $E_\nu^2 d\phi_\nu/dE_\nu < 2 \times 10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ (E. Waxman, J.N. Bahcall, Phys. Rev. D 59, 023002 (1999))
- Due to ν oscillation, $\phi_e : \phi_\mu : \phi_\tau = 1 : 1 : 1$, for a distant source
(Athar et al, Mod. Phys. Lett. A 21, 1049–1066 (2006))

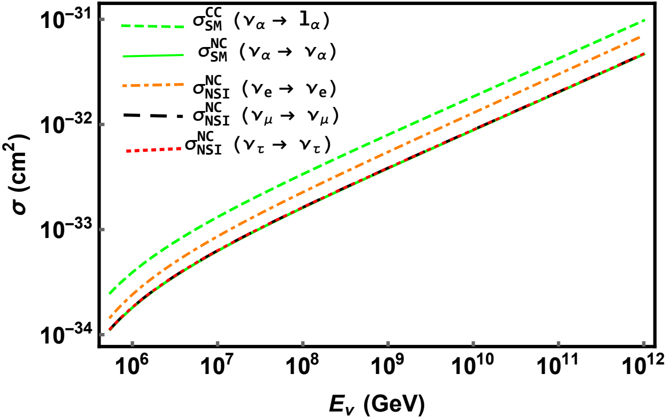


Figure: Variation of scattering cross sections (σ) in CC and NC processes, for flavour diagonal processes allowed in both SM and NSI

Results

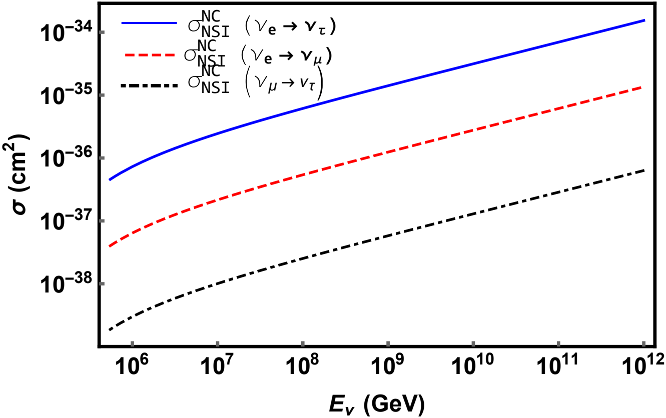


Figure: Variation of scattering cross sections (σ) for FCNC processes allowed by NSI

Results

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: Number of shower events created in the process $\nu N \rightarrow l X$ for both SM and NSI in context of IceCube detector ($A = 1$ km^2) over a period of $T = 1$ year. N_e, N_μ and N_τ are the number of events created individually by ν_e, ν_μ and ν_τ, respectively. $N_{tot} = N_e + N_\mu + N_\tau$.

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Results

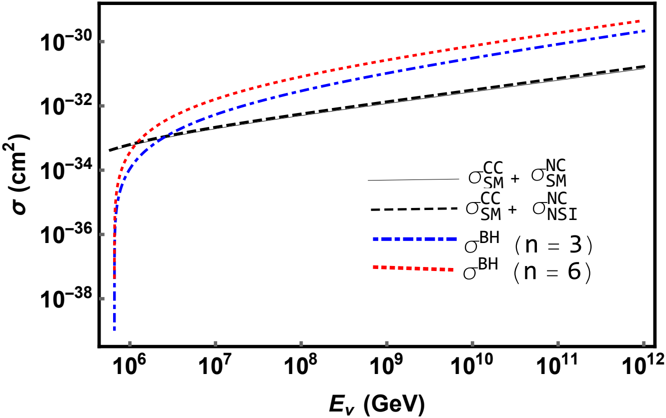

Figure: Variation of total cross section and the cross section of black hole formation

Results

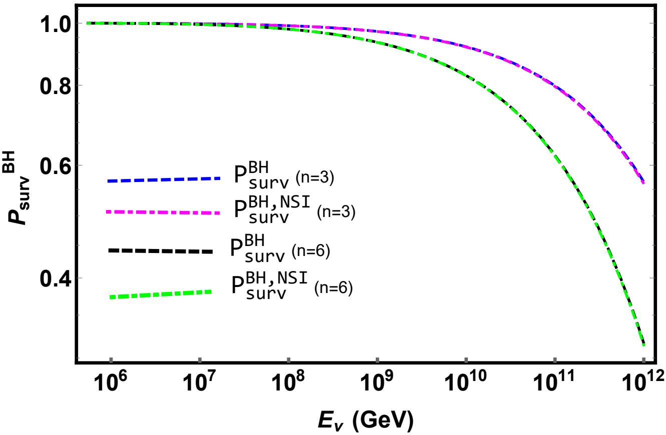

Figure: Variation of BH survival probability P_{surv}^{BH} for the cases $n = 3$ and $n = 6$

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Conclusions

- The effect of NSI is analyzed on the number of events generated by UHE neutrinos in two kinds of interactions, $\nu N \rightarrow lX$ and $\nu N \rightarrow MBH \rightarrow lX$
- The shower events generated from these two processes are differentiated from their topological structures
- NSI can only provide marginal increase in the number of shower events produced in the absence of MBH production
- The number of events produced through MBH production remains nearly unaltered
- A large enhancement in the number of shower events over the SM prediction can provide unambiguous signatures of TeV scale gravity in the form of MBH production

Thank you!

Backup slides

Bounds on LEDs

- $n = 1$ is ruled out as for $E_{Pl,4+n} \sim 1$ TeV, $R \sim 10^{13}$ cm $\implies$ gravity is modified over astronomical distances.
- For $n = 2$, $R \sim 1$ mm $\implies$ the lowest length scale over which gravity has been measured. The lower limit on $E_{Pl,4+n} \gtrsim 30$ TeV which is unreachable by the current accelerator experiments.
- For $n = 3$, $E_{Pl,4+n} \sim 2$ TeV
- For $n \geq 4$, the constraints come from cosmic ray and collider experiments which shows $E_{Pl,4+n} \gtrsim 1 - 2$ TeV.

νN scattering cross section

$\mathcal{L}_{eff}^{(4)} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} C_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} C_i^{(6)} \mathcal{O}_i^{(6)} + \ldots.$

$\mathcal{O}_{1,f}^{(6)} = (\bar{\nu_\alpha} \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu f),\ \mathcal{O}_{2,f}^{(6)} = (\bar{\nu_\alpha} \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu \gamma^5 f)$

$C_{i,f}^{(6)} = C_{i,f}^{(6)}|_{SM} + C_{i,f}^{(6)}|_{NSI}\ (i = 1, 2)$

For the NC transition $\nu_\alpha \to \nu_\beta$, the SM contributions are given by (Altmannshofer et al, JHEP 09, 083 (2019))

$$C_{1,u}^{(6)}|_{SM} = -C_{2,u}^{(6)}|_{SM} + \frac{4\sqrt{2}}{3} G_F s_w^2 \delta_{\alpha\beta},$$

$$C_{1,d}^{(6)}|_{SM} = -C_{2,d}^{(6)}|_{SM} - \frac{2\sqrt{2}}{3} G_F s_w^2 \delta_{\alpha\beta} = C_{1,s}^{(6)}|_{SM},$$

$$C_{2,u}^{(6)}|_{SM} = \frac{G_F}{\sqrt{2}} \delta_{\alpha\beta},\ C_{2,(d,s)}^{(6)}|_{SM} = -C_{2,u}^{(6)}|_{SM}, \quad (1)$$

while the NSI contribution is expressed as,

$$C_{1(2),f}^{(6)}|_{NSI} = \frac{G_F}{\sqrt{2}} \epsilon_{\alpha\beta}^{f,V(A)}. \quad (2)$$

$s_w = \sin\theta_w$, where $\theta_w \sim 28.13^o$ is the Weinberg angle

νN scattering cross section

$$\frac{d^2\sigma^{CC}}{dxdy} = \frac{G_F^2 m_N E_\nu x}{\pi}[f_u(x) + f_d(x) + 2f_s(x) + (1-y)^2(\bar{f}_u(x) + \bar{f}_d(x))]$$

$$\frac{d^2\sigma^{NC}}{dxdy} = \frac{m_N E_\nu x}{\pi}[(C_{L,u}^2 + C_{L,d}^2)\sum_{i=u,d}(f_i(x) + \bar{f}_i(x)(1-y)^2) +$$

$$(C_{R,u}^2 + C_{R,d}^2)\sum_{i=u,d}(f_i(x)(1-y)^2 + \bar{f}_i(x))$$

$$+2\{C_{L,s}^2(s(x) + \bar{s}(x)(1-y)^2) + C_{R,s}^2(s(x)(1-y)^2 + \bar{s}(x))\}]$$

$x, y \rightarrow$ Bjorken varriables, $0 \leq x, y \leq 1$

νN scattering cross section

- At $x \to 0$, the PDFs are divergent and there is no experimental constraint. Hence in this region, consideration of different behaviour of PDFs result in different scattering cross sections
  (Gandhi et al, Phys. Rev. D 58, 093009 (1998))
- UHE neutrinos (10^{10} eV) can probe upto $x \sim 10^{-4}$ at $M_{Pl,4+n} \sim 1$ TeV
- PDFs are extracted from CTEQ6 dataset for momentum transfer $Q^2 = 10^4\ \mathrm{GeV}^2$