Ultra-High Energy Neutrinos and the Glashow Resonance

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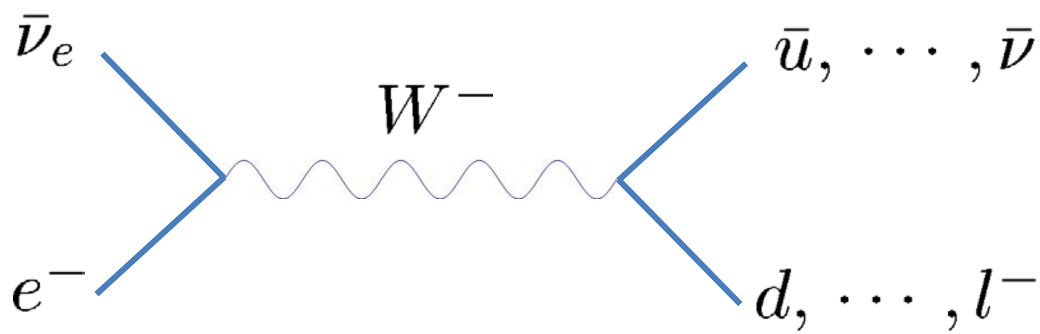
29/09/2011 @ DESY THEORY WORKSHOP

We focus on

The Glashow Resonance

$\bar{\nu}_e e \to \text{anything}$



$$E_\nu = 6.3 \text{ PeV}$$

1) The signals of the resonace at the UHE neutrino detector; shower, pure muon, contained lollipop

2) The event specrum and the flavor ratio at the resonant energy

Plan of talk

1) Introduction
Cosmic rays and high energy neutrinos,
IceCube detector, shower, muon track

2) Glashow Resonance —event number study
shower, pure muon, contained lollipop

3) Glashow Resonance and New Physics

Cosmic rays and neutrinos

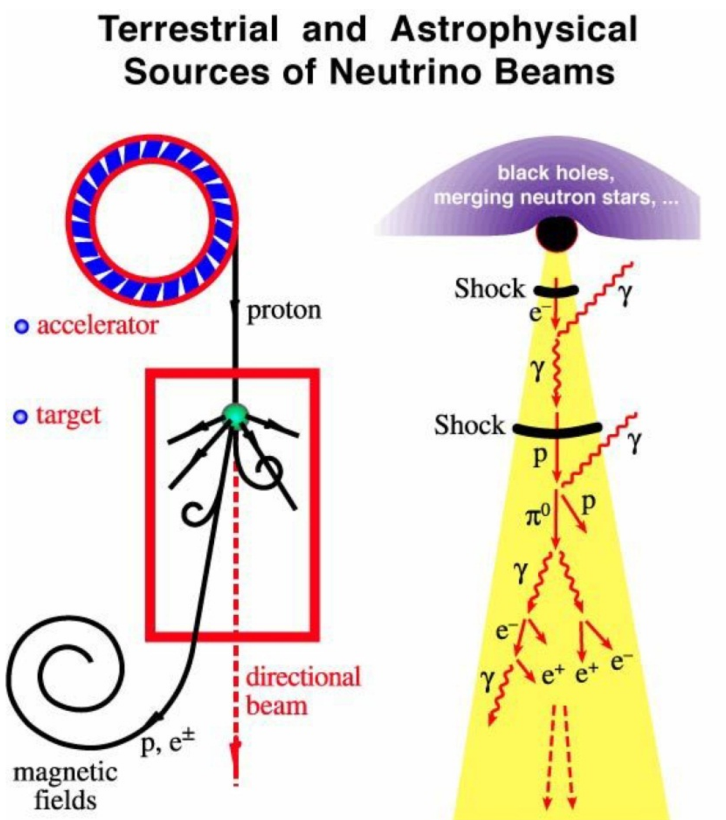
$$p\,\gamma \to \Delta^+ \to \begin{cases} \pi^0\, p \\ \pi^+\, n \end{cases}$$

$$p\,p \to \pi^\pm + X$$

The followings come out

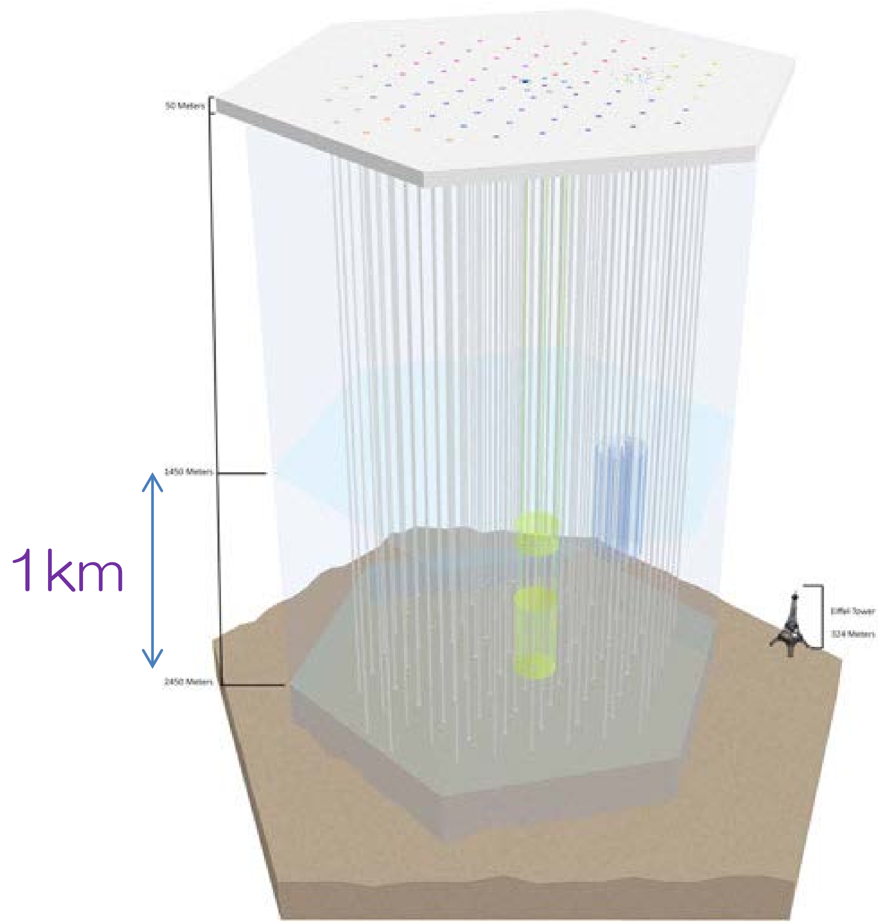
CR(protons) ← Neutron decay
Gamma ← π^0
Neutrinos ← π^+

The others are trapped by the magnetic fields around the source



F. Halzen, 2007

Neutrino detection — e.g. IceCube



http://icecube.wisc.edu

Cherenkov lights from showers and muon tracks

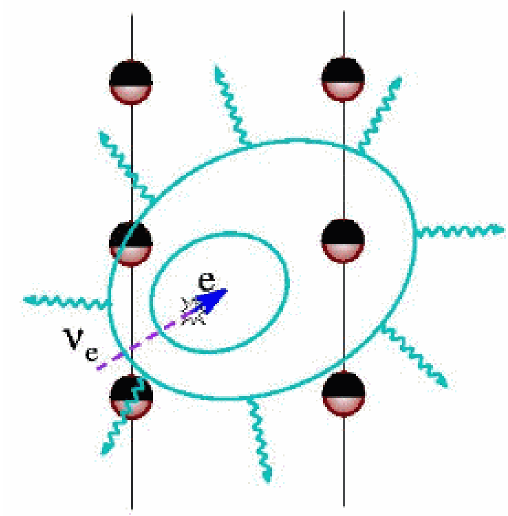
The construction was completed on Dec. 2010 with 86 strings

$V = 1\ km^3$

Recent papers (IC-40) :
Diffuse flux of all flavor [arXiv:1103.4250]
Diffuse flux of ν_μ [arXiv:1104.5187]

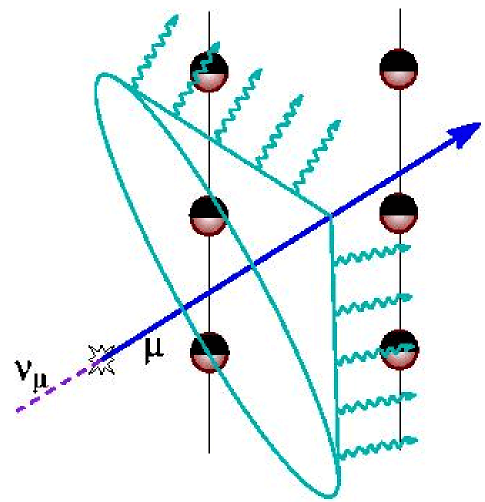
Shower and muon track events

Shower



$$\nu_e N + \bar{\nu}_e N \ (\mathrm{CC})$$
$$\nu_\tau N + \bar{\nu}_\tau N \ (\mathrm{CC}) \text{ with } E_\tau < 1\,\mathrm{PeV}$$
$$\nu_\alpha N + \bar{\nu}_\alpha N \ (\mathrm{NC})$$

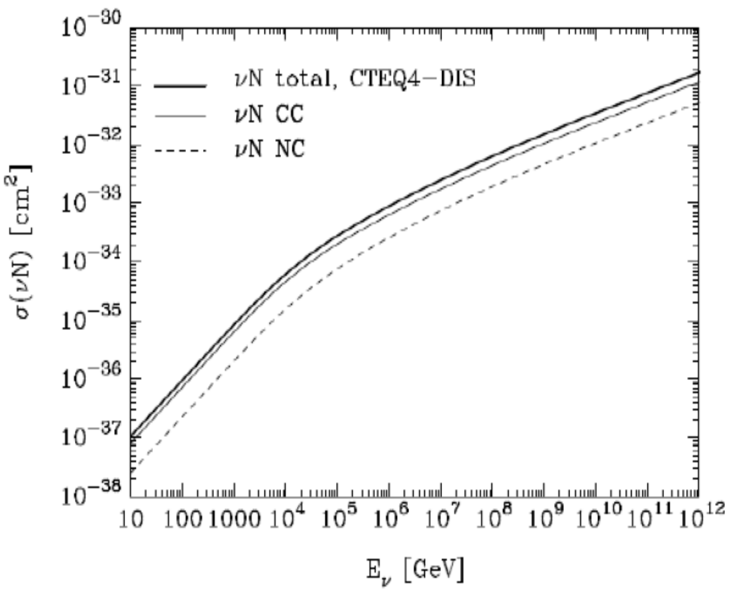
Muon track



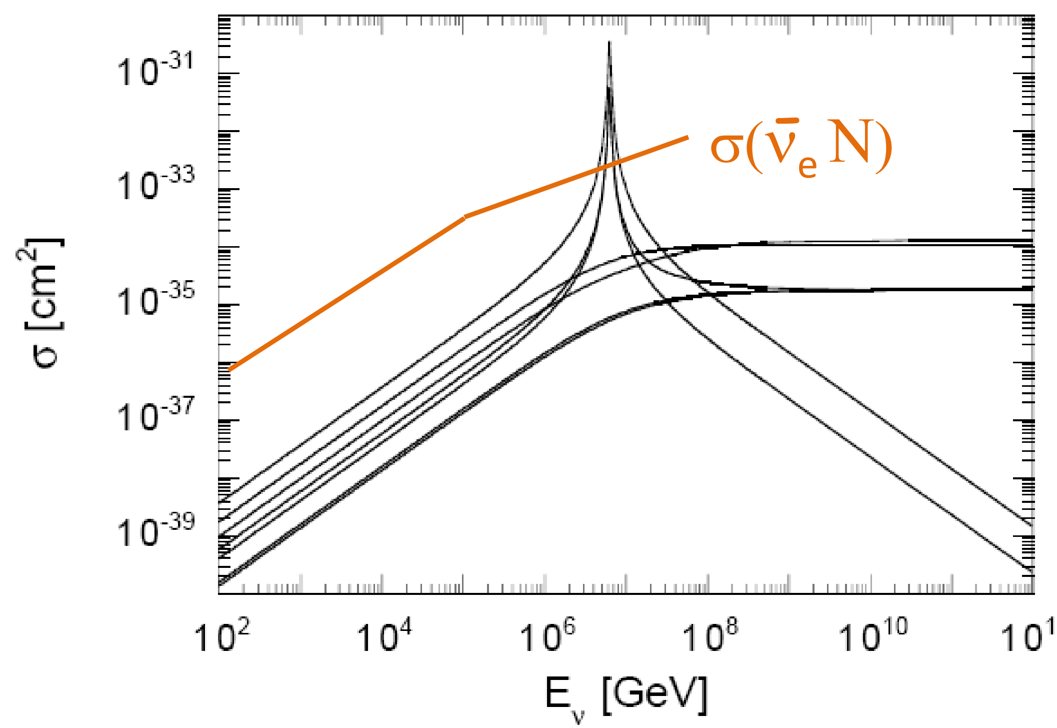
$$\nu_\mu N + \bar{\nu}_\mu N \ (\mathrm{CC})$$

Cross sections

Gandhi, Quigg, Reno, Sarcevic, 1995

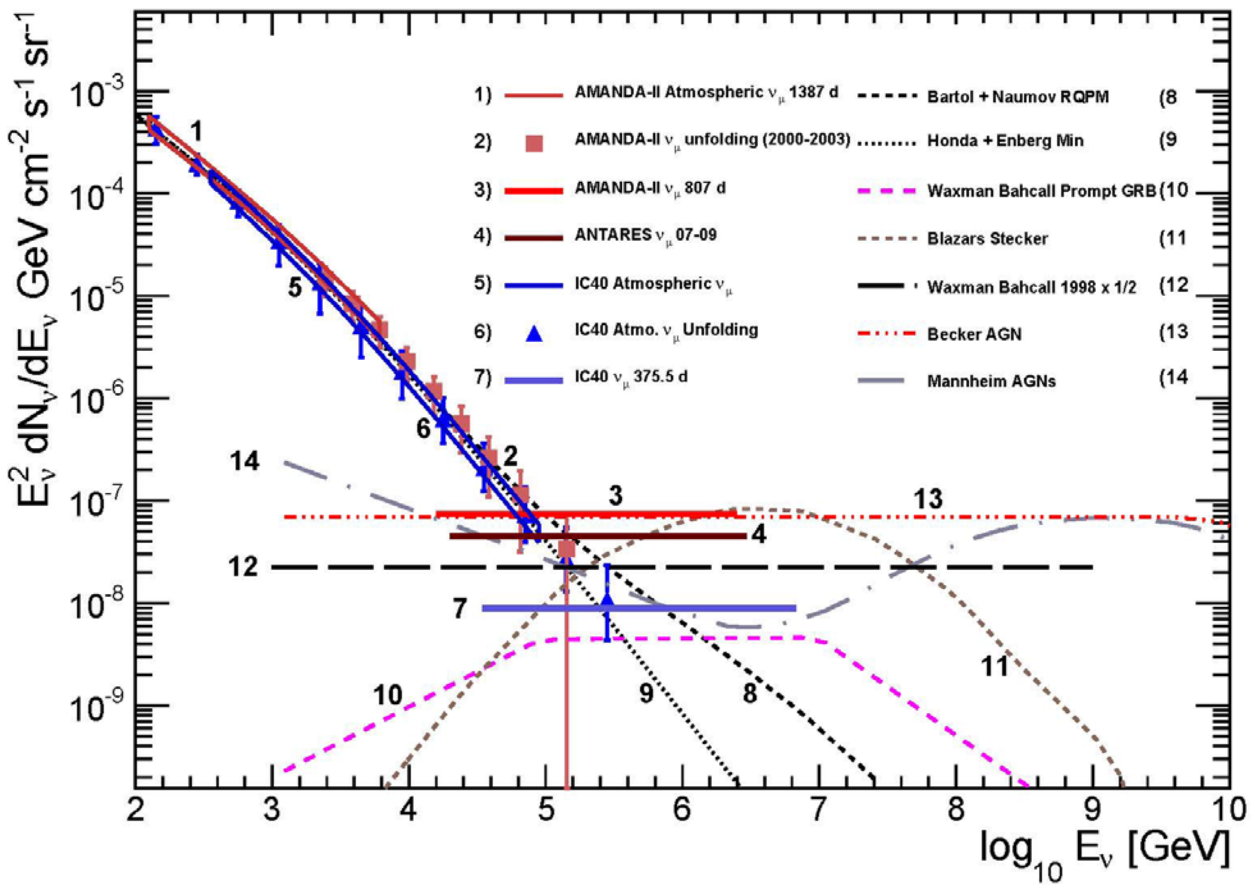


ν N is dominant in most cases, but …



$$\frac{\bar{\nu}_e e \to \text{anything}}{\nu_\mu N \to \mu + \text{anything}} \approx 360$$

Current limits of the neutrino fluxes



IceCube Collaboratiion, arXiv:1104.5187

pp or pγ?

Anchordoqui, Goldberg, Halzen, Weiler, 2005

Neutrino/Anti-neutrino ratio is important
to observe the Glashow resonance

$$E_\nu^2 \Phi_{\nu+\bar{\nu}} = 6 \times 10^{-8} \epsilon_\pi \quad (\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}),$$

$$\epsilon_\pi = \begin{cases} 0.6 & \text{for } pp \\ 0.25 & \text{for } p\gamma \end{cases}$$

pp

3.2 events/yr at IceCube ⇔ 0.6 background/yr
⇒ 3 years 9.6/~2 : well above 99% CL (6.69)

pγ

0.8 events/yr
⇒ The resonance cannot be separated from background

Neutrino fluxes

Let us parameterize the flux as

$$\Phi_{\rm source} = x\Phi^{pp}_{\rm source} + (1-x)\Phi^{p\gamma}_{\rm source}$$

$$\Phi^{pp}_{\rm source} \propto \underbrace{\begin{pmatrix}1\\2\\0\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}1\\2\\0\end{pmatrix}}_{\bar{\nu}} \qquad \Phi^{p\gamma}_{\rm source} \propto \underbrace{\begin{pmatrix}1\\1\\0\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}0\\1\\0\end{pmatrix}}_{\bar{\nu}}$$

These ratios are changed by the neutrino oscillation

$$L^{\rm ocs} = \frac{4\pi E}{\Delta m^2}$$

$$L^{\rm ocs} \simeq 10^{n+8}\ ({\rm cm})$$ with $$E = 10^n\ ({\rm GeV})$$

E	$L^{\rm osc}$
1 (MeV)	10^5 (cm)
1 (GeV)	10^8 (cm)
⋮	⋮
1 (EeV)	$10^{17} \sim 0.1$(pc)

$\Rightarrow$ incoherent oscillation

$$\Phi_\alpha^{\rm earth} = |U_{\alpha i}|^2 |U_{\beta i}|^2 \Phi_\beta^{\rm source}$$

Athar, Jezabek, Yasuda 2000

For the tri-bimaximal mixing, for example,

$$\Phi_{\nu_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.78}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

$$\Phi_{\nu_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.61}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\nu_\tau},$$

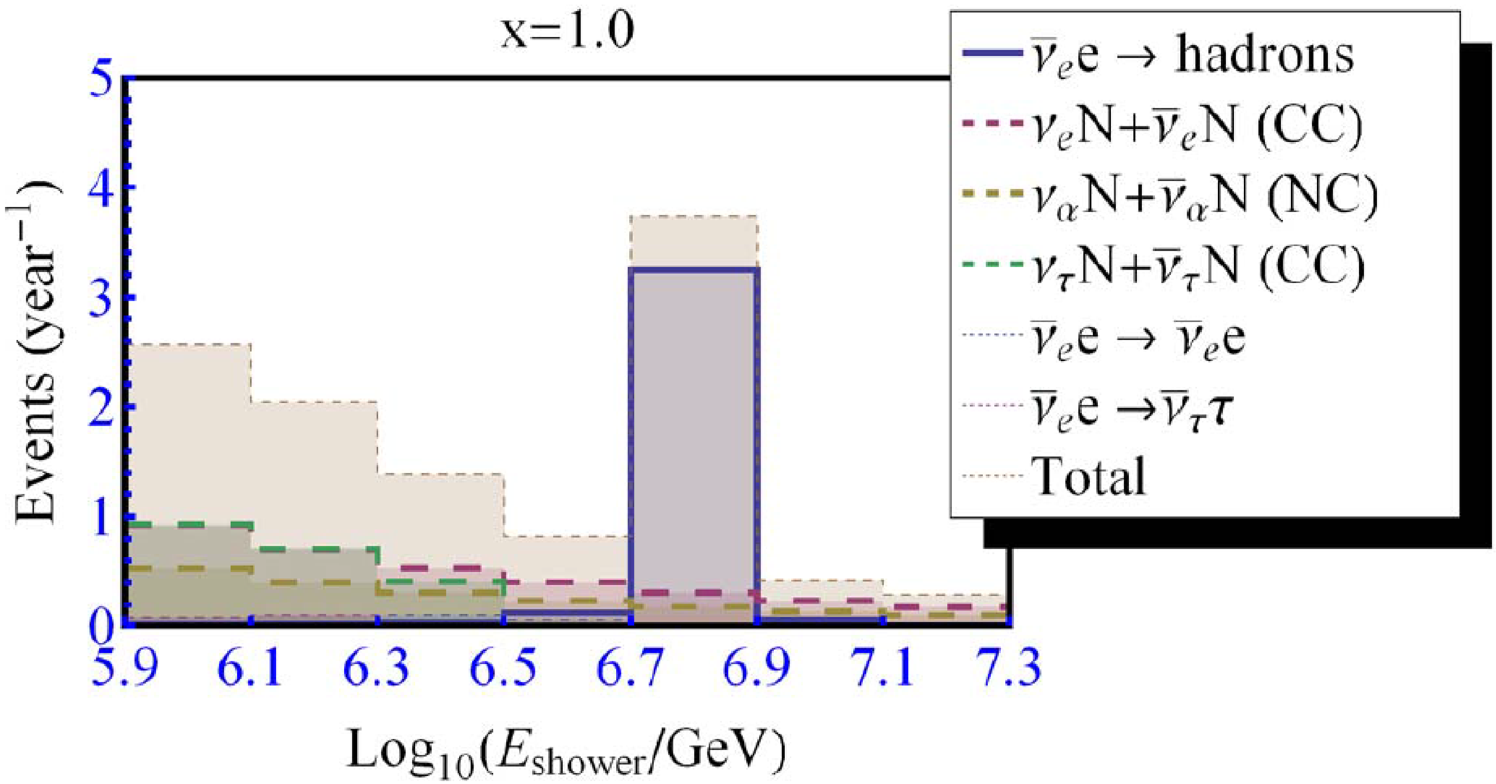
$$\Phi_{\bar\nu_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.22}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

$$\Phi_{\bar\nu_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.39}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\bar\nu_\tau}.$$

Shower events

$V_{\rm eff} = 2\,{\rm km}, \quad \Delta\Omega = 2\pi$

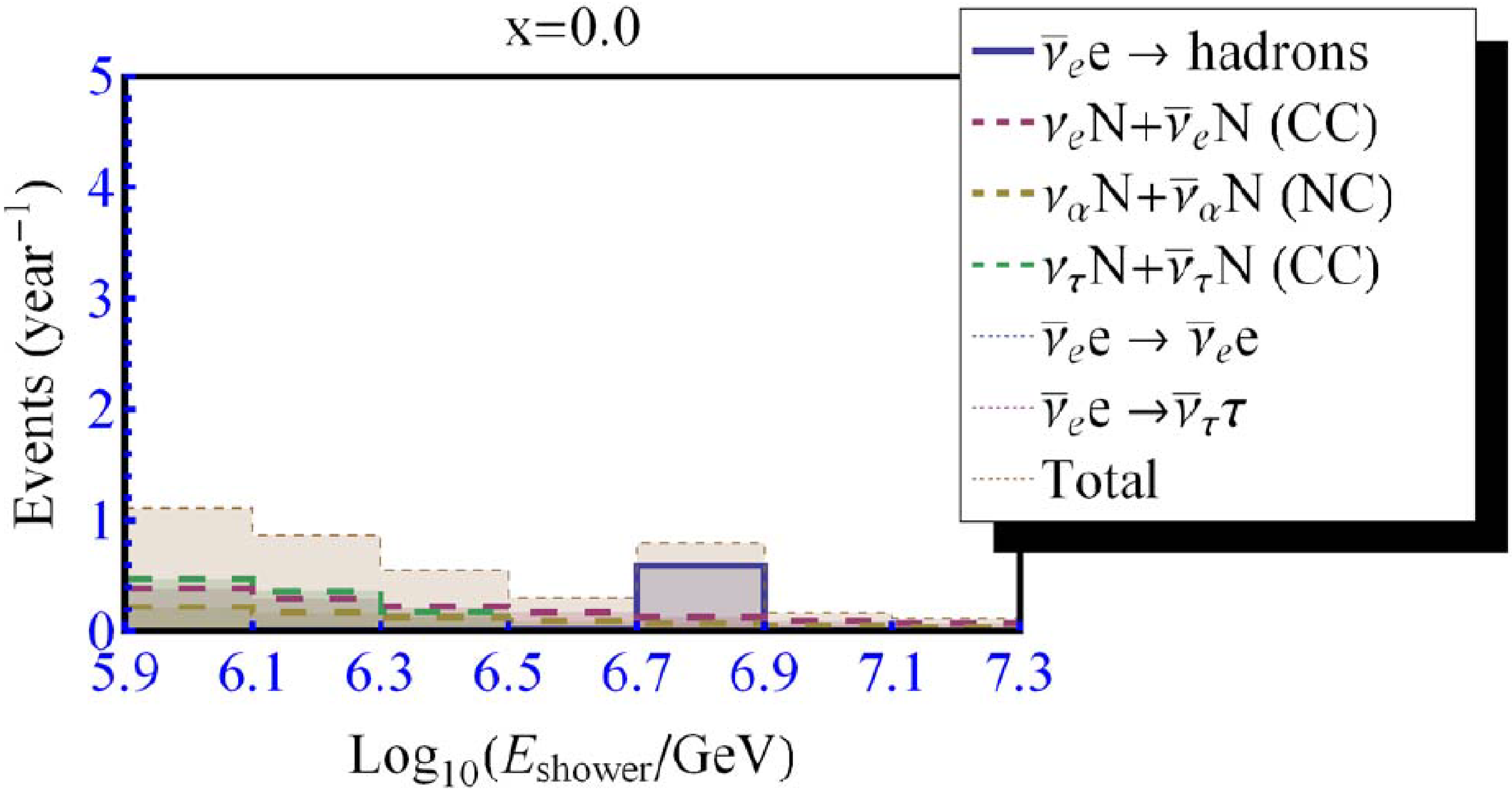
For pp



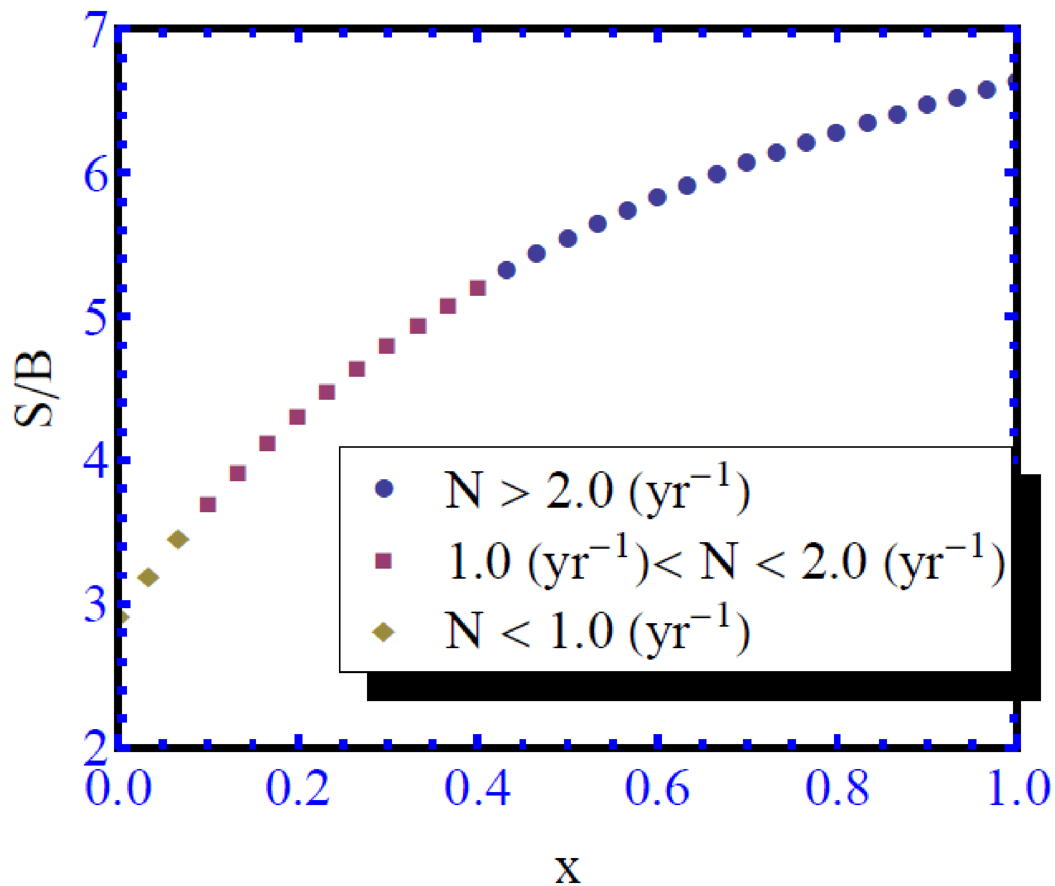
Shower events

$V_{\rm eff} = 2\,{\rm km}, \quad \Delta\Omega = 2\pi$

For pγ

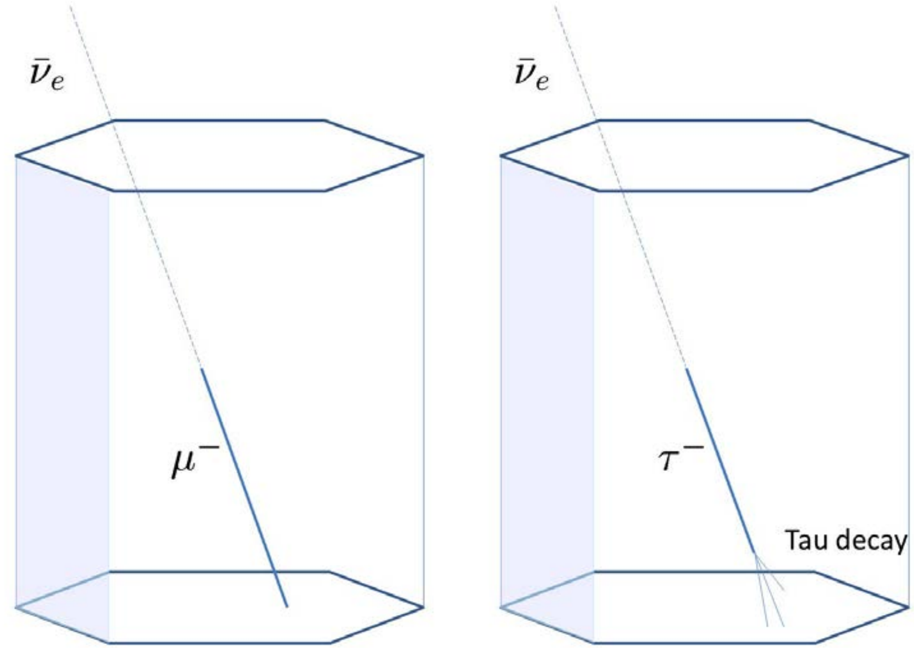


Resonant/off-resonant ratio



Pure lepton tracks

$$\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$$
$$\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$$



Without shower at the
Interaction vertex

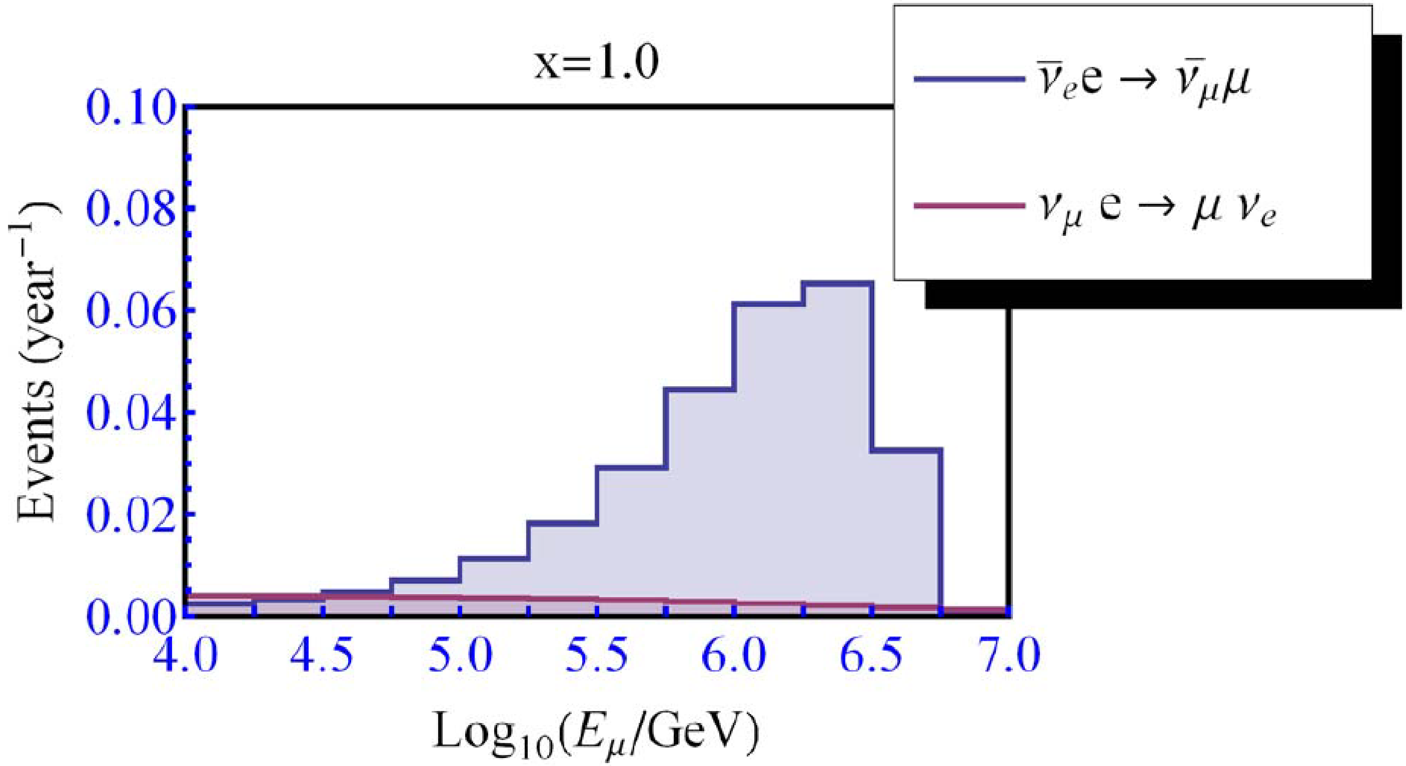
$$\nu_\mu N \rightarrow \mu X$$
$$\nu_\tau N \rightarrow \tau X$$

Neutrino-Nucleon scattering produce large showers at the interaction vertex

$$\langle y \rangle \approx 0.26 \text{ at PeV regime, where } y = (E_\nu - E_{\mu,\tau})/E_\nu$$

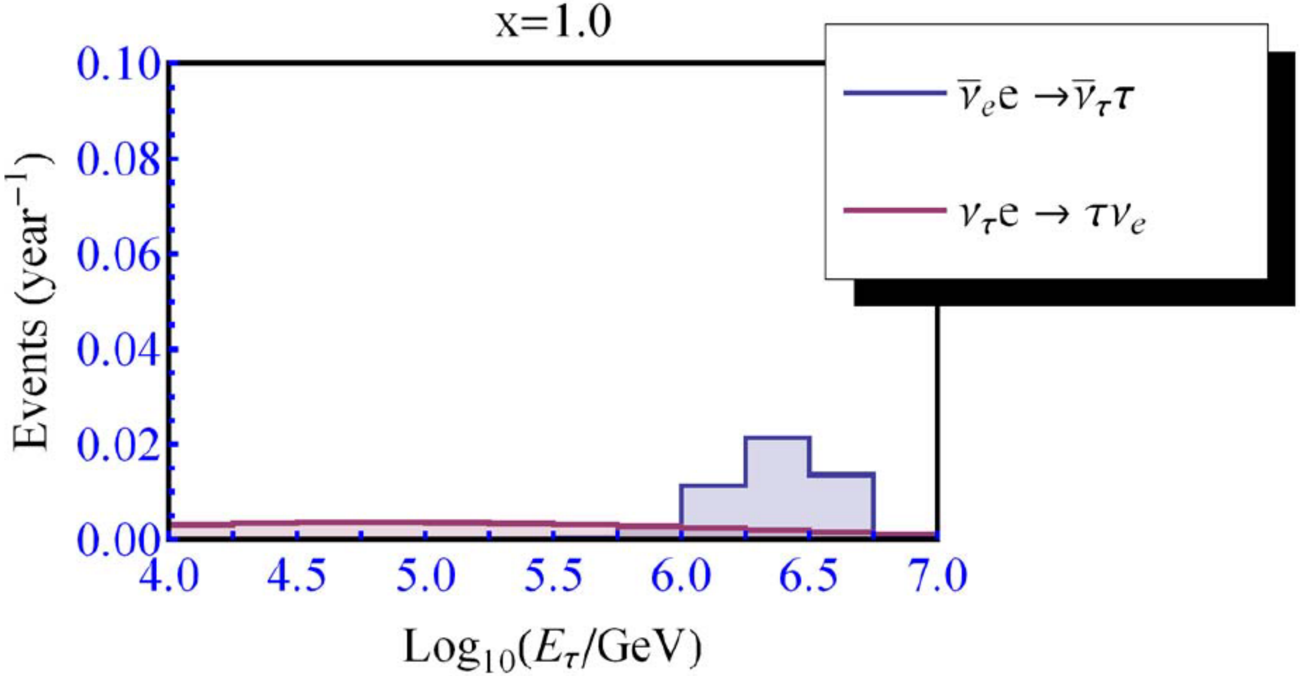
Pure muons

$V = 1\,\mathrm{km}, \quad \Delta\Omega = 2\pi$



Almost all background free at 5.0 < Log(E/GeV) < 6.75

Pure taus (contained lollipop)



Background free at 6.0 < Log(E/GeV) < 6.75,
(though the number of event is small)

Shower + mu + tau

After all, the resonant signals are the following three;

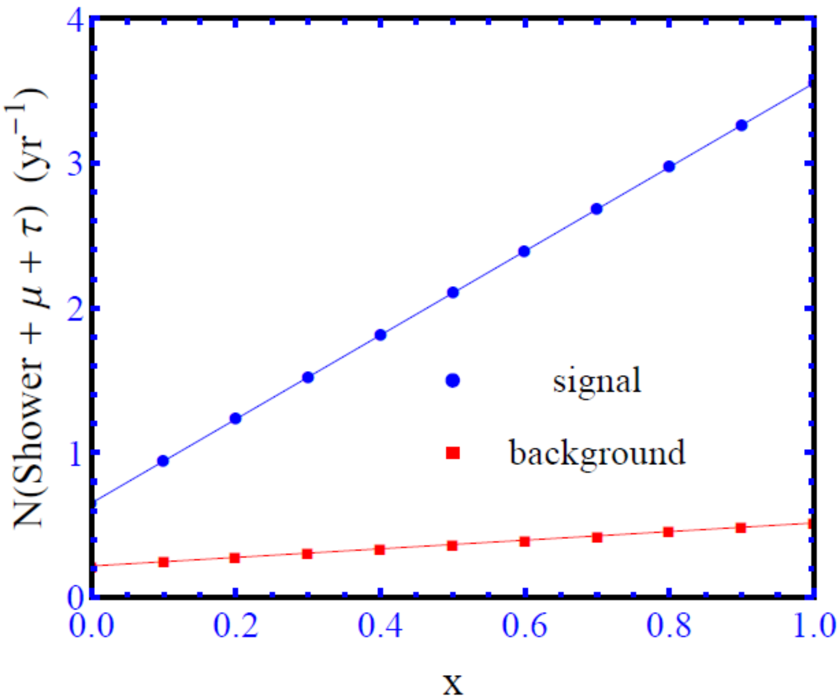
- Showers (by $\bar{\nu}_e e \to$ hadrons) with $6.7 < \log(E_{\rm shower}/{\rm GeV}) < 6.9$
- Pure muons with $5.0 < \log(E_\mu/{\rm GeV}) < 6.75$
- Contained lollipops with $6.0 < \log(E_\tau/{\rm GeV}) < 6.75$

Contents of the signal (event/yr)

x	N(shower)	$N(\bar{\nu}_e e \to \bar{\nu}_\mu \mu)$	$N(\bar{\nu}_e e \to \bar{\nu}_\tau \tau)$	total
0.0	0.60	0.0481	0.0085	0.65
0.5	1.9	0.15	0.027	2.1
1.0	3.2	0.26	0.046	3.6

Contents of the background (event/yr)

x	$B(\text{shower})$	$B(\nu_\mu e \to \mu \nu_e)$	$B(\nu_\tau e \to \tau \nu_e)$	total	signal
0.0	0.20	0.0096	0.0031	0.21	0.65
0.5	0.35	0.014	0.0046	0.37	2.1
1.0	0.49	0.019	0.0061	0.51	3.6



To reach 99%CL

x=1 about 2 years
x=0.5 about 3 years
x=0 more than 10 years

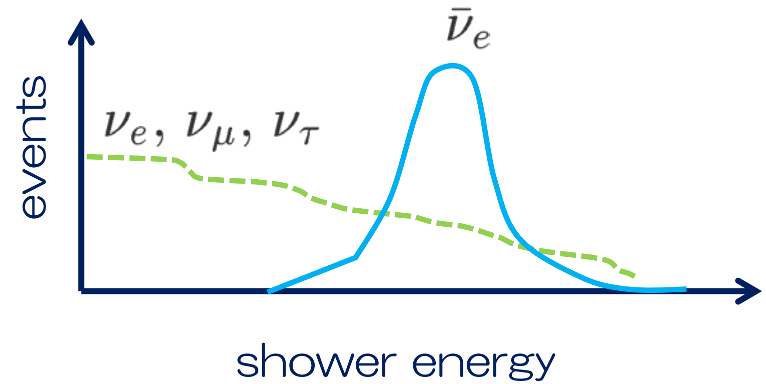
c.f.

b	99% C.L.
1.0	5.79
1.5	6.27
2.0	6.69

Feldman, Cousins, 2001

The GR and new physics

Resonant： anti-electron neutrino
Non res.： all neutrinos



If the flavor ratio deviates from the standardratio 1:1:1,
it may be possible to see the anomalous ratio with the GR.

Example：Decay of active neutrino
NH（ν_1 stable） ⇒ 4:1:1
IH（ν_3 stable） ⇒ 0:1:1

Beacom, Bell, Hooper, Pakvasa, Weiler, 2002

ν_2, ν_3 unstable

$\nu_{3,2} \to \nu_1 X$ (with $m_1 \ll m_2, m_3$)

Electron neutrino

$$E^2 F_{\nu_e}(\text{earth}) = 6 \times 10^{-8} |U_{e1}|^2 \left[x\, C_{pp}^{\nu_e} \frac{0.6}{6} + (1-x) C_{p\gamma}^{\nu_e} \frac{0.25}{3} \right],$$

$$C_{pp}^{\nu_e} = |U_{e1}|^2 + 2|U_{\mu1}|^2 + \frac{1}{2} B_{2\to1} (|U_{e2}|^2 + 2|U_{\mu2}|^2) + \frac{1}{2} B_{3\to1} (|U_{e3}|^2 + 2|U_{\mu3}|^2),$$

$$C_{p\gamma}^{\nu_e} = |U_{e1}|^2 + |U_{\mu1}|^2 + \frac{1}{2} B_{2\to1} (|U_{e2}|^2 + |U_{\mu2}|^2) + \frac{1}{2} B_{3\to1} (|U_{e3}|^2 + |U_{\mu3}|^2),$$

Anti-electron neutrino

$$E^2 F_{\bar{\nu}_e}(\text{earth}) = 6 \times 10^{-8} |U_{e1}|^2 \left[x\, C_{pp}^{\bar{\nu}_e} \frac{0.6}{6} + (1-x) C_{p\gamma}^{\bar{\nu}_e} \frac{0.25}{3} \right],$$

$$C_{pp}^{\bar{\nu}_e} = C_{pp}^{\nu_e},$$

$$C_{p\gamma}^{\bar{\nu}_e} = |U_{\mu1}|^2 + \frac{1}{2} B_{2\to1} |U_{\mu2}|^2 + \frac{1}{2} B_{3\to1} |U_{\mu3}|^2$$

μ & τ

$$F_{\nu_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

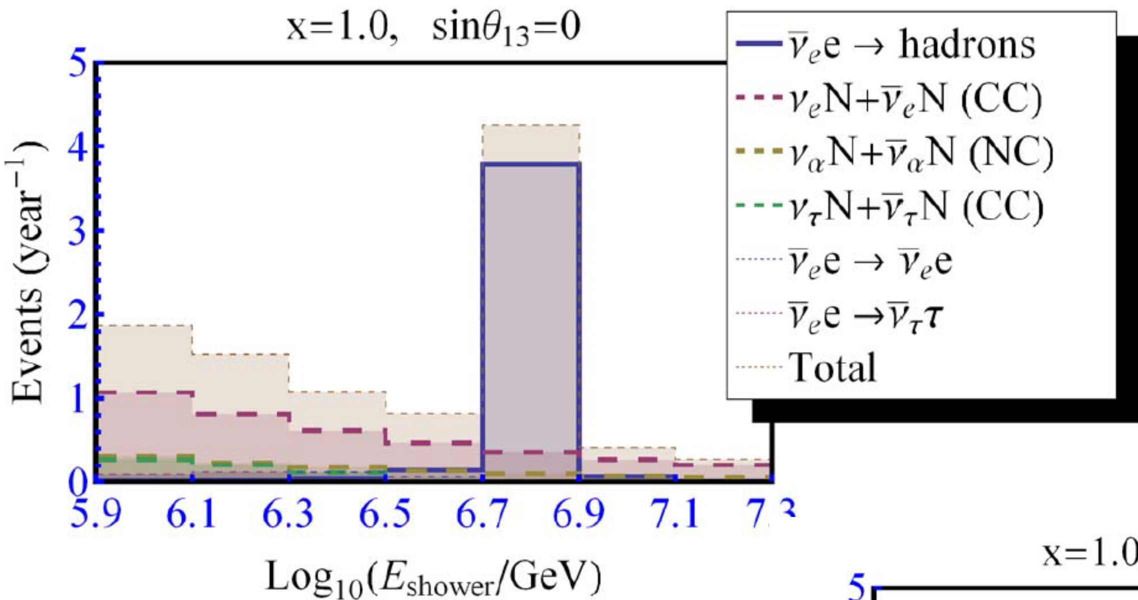
$$F_{\bar{\nu}_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}),$$

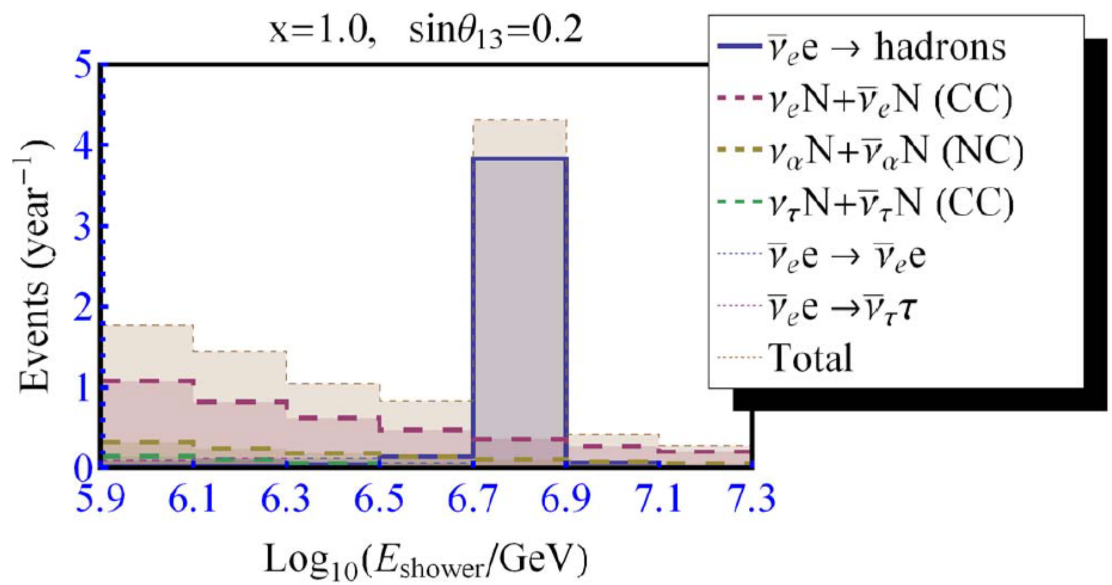
$$F_{\nu_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

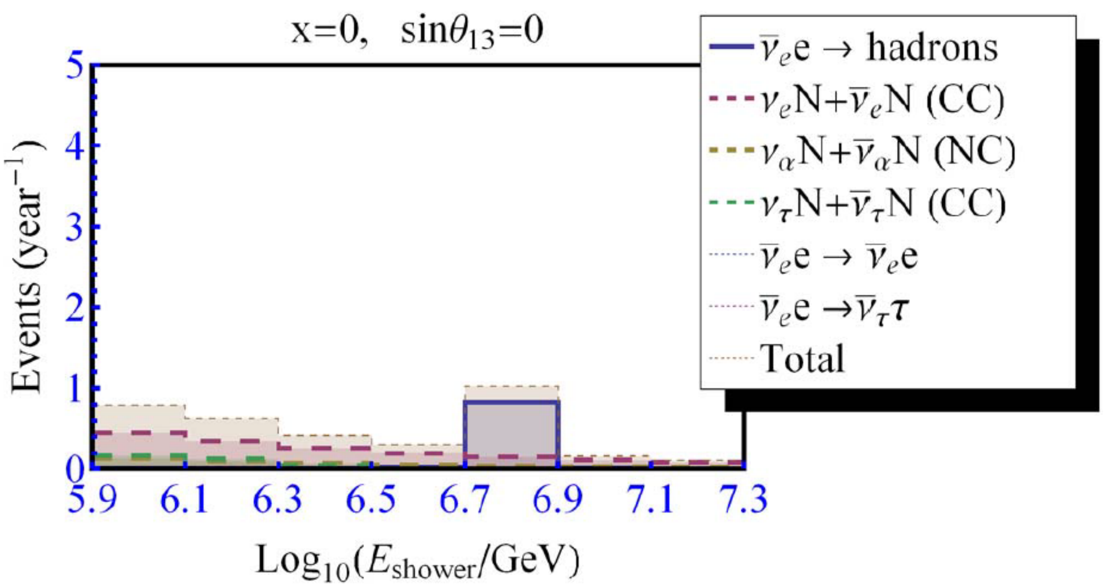
$$F_{\bar{\nu}_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}).$$

- Flavor ratios are independent from branching and pp/pγ ratio
- Daughter lifts the fluxes flavor-blindly
- $\delta \rightarrow \delta + \pi$, $\mu \Leftrightarrow \tau$

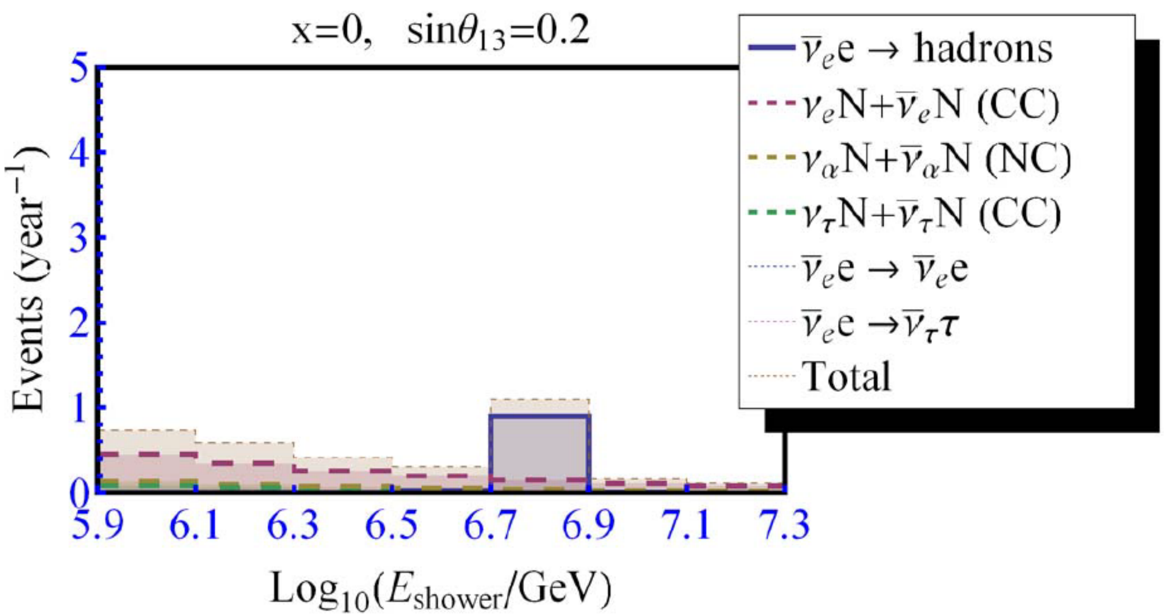
Shower events with decay





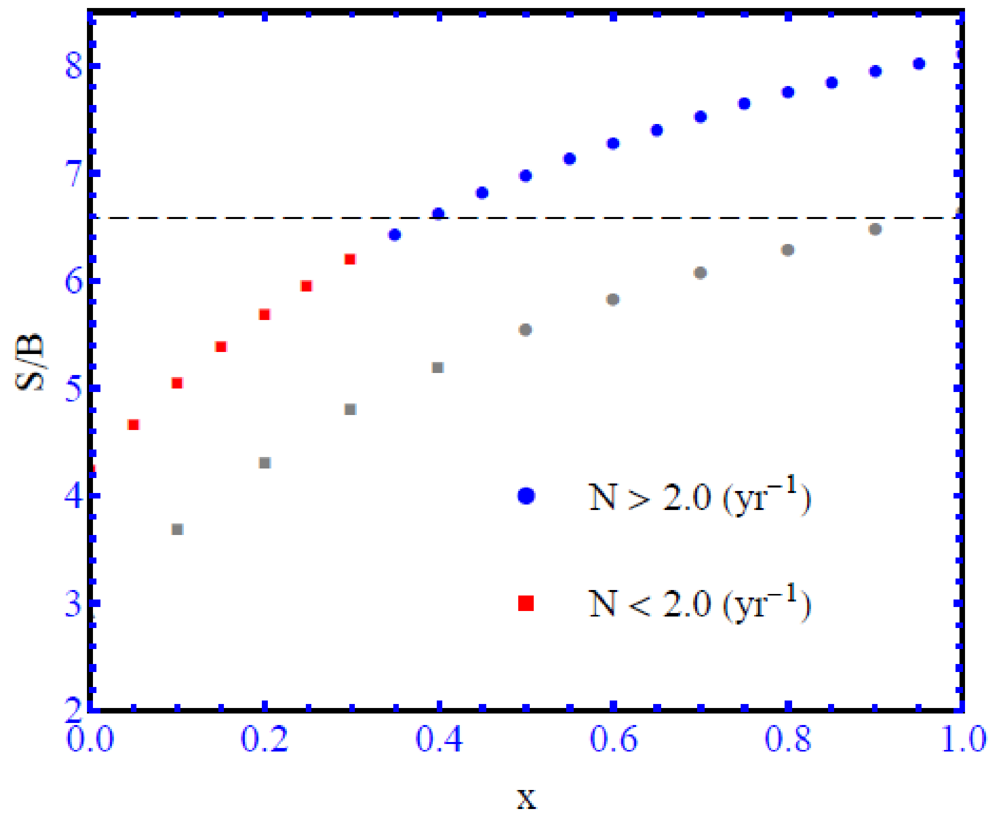


x=0, sinθ13=0
$\bar{\nu}_e$e → hadrons
ν_eN+$\bar{\nu}_e$N (CC)
ν_αN+$\bar{\nu}_\alpha$N (NC)
ν_τN+$\bar{\nu}_\tau$N (CC)
$\bar{\nu}_e$e → $\bar{\nu}_e$e
$\bar{\nu}_e$e → $\bar{\nu}_\tau\tau$
Total
Events (year^{-1})
0
1
2
3
4
5
5.9
6.1
6.3
6.5
6.7
6.9
7.1
7.3
Log$_{10}$($E_{\rm shower}$/GeV)



x=0, sinθ13=0.2
$\bar{\nu}_e$e → hadrons
ν_eN+$\bar{\nu}_e$N (CC)
ν_αN+$\bar{\nu}_\alpha$N (NC)
ν_τN+$\bar{\nu}_\tau$N (CC)
$\bar{\nu}_e$e → $\bar{\nu}_e$e
$\bar{\nu}_e$e → $\bar{\nu}_\tau\tau$
Total
Events (year^{-1})
0
1
2
3
4
5
5.9
6.1
6.3
6.5
6.7
6.9
7.1
7.3
Log$_{10}$($E_{\rm shower}$/GeV)

Comparison with the standard case



Decay can be seen if x is large

Summary

We have discussed the Glashow resonance in UHE neutrinos in detail

- Shower + mu + tau ⇒ enhancement of the signal
- Sensitivitly for new physics
  (An independent test placefrom shower/muon ratio)

On the other decay patterns

NH and only ν_3 unstable ⇒ Flavor ratio depends on the branching ratio, not extreme as 4:1:1

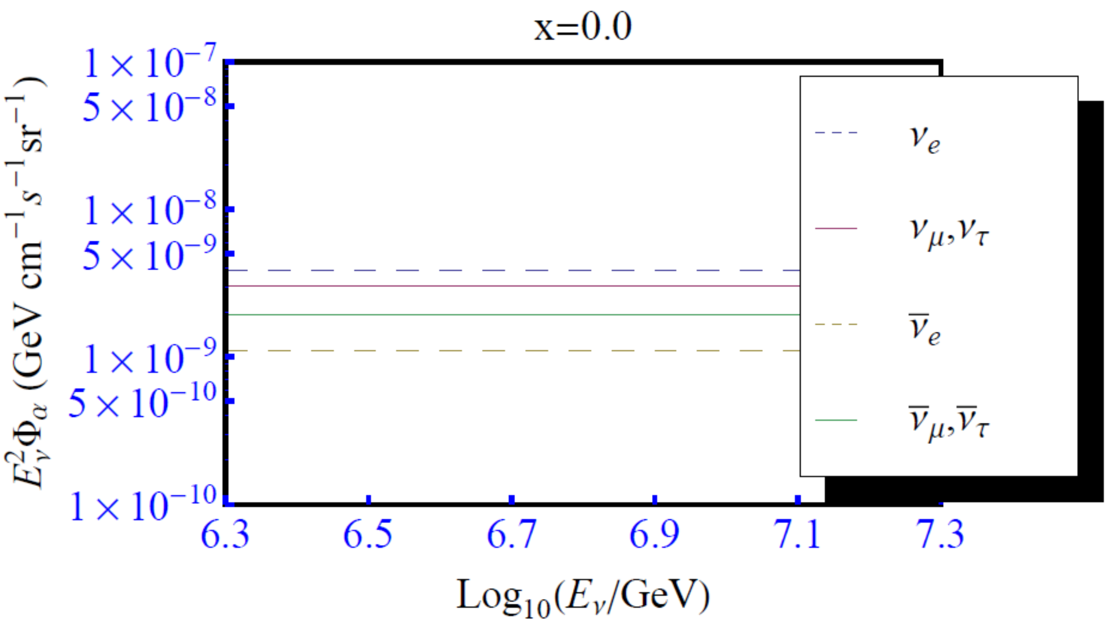
IH ⇒ almost excluded from SN1987A observation

SN $$\frac{\tau}{m} = \frac{L}{cE}$$

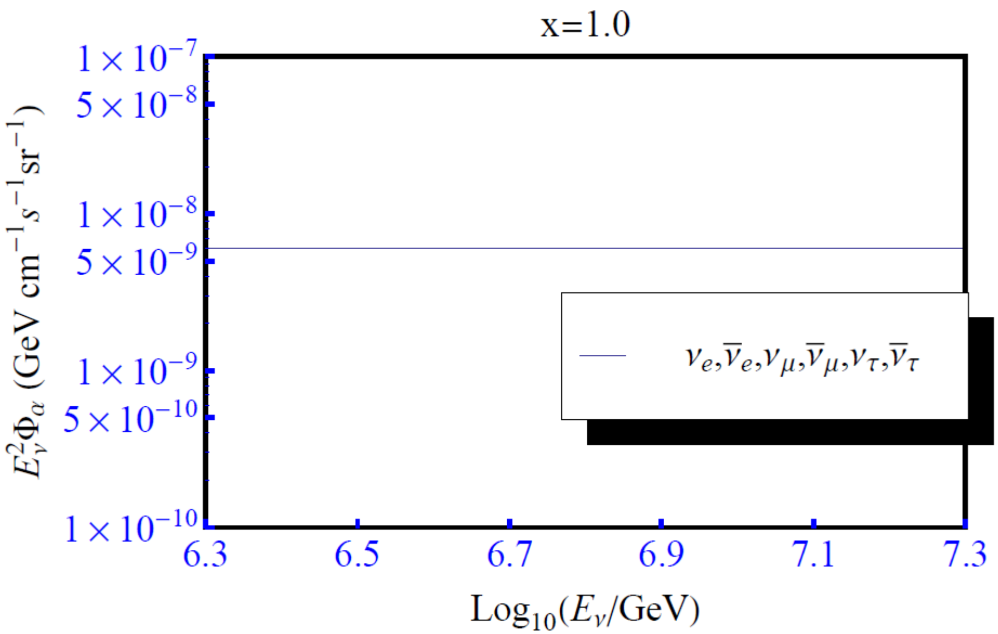
L = 10 kpc, E = 10 MeV
⇒ $\tau/m > 10^5$ s/eV

Xgal $$E = \frac{L}{c}\frac{m}{\tau}$$

L = 100 Mpc
⇒ E < 100 GeV で decay



Anti-electron neutrino component is small for pγ



Democratic for pp

In any case, mu = tau

Neutrino decay

$W^{\mu}\overline{\nu}_i\gamma_\mu l_\beta$ （π、μ decay）produces neutrinos

$$\Rightarrow \qquad F^{\beta}_{\nu_i} = |U_{\beta i}|^2 A E^{-2},$$

Suppose ν_2, ν_3 decay and disapper

$$\Rightarrow \qquad F^{\beta}_{\nu_1} = |U_{\beta 1}|^2 A E^{-2}, \text{ and } F^{\beta}_{\nu_2} = F^{\beta}_{\nu_3} = 0$$

This ν_1 is to be detected by the chaged current

$$F^{\beta}_{\nu_\alpha} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 A E^{-2}$$

Effective
``flavor eigenstate flux"

$$\Rightarrow \qquad F_{\nu_e}/F_{\nu_\mu} = |U_{e1}|^2/|U_{\mu 1}|^2 \simeq 4.$$