Possible constraints on New Physics from matter effects on neutrino oscillations

Prepared by Minako Honda (Ochanomizu Univ.)

Presented by Tatsu Takeuchi (Virginia Tech)

with

Naotoshi Okamura (YITP)

Alexey Pronin (Virginia Tech)

Yee Kao (Virginia Tech)

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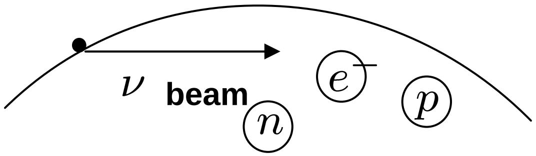
第19回「宇宙ニュートリノ」研究会

2006.7.6 @ ICRR

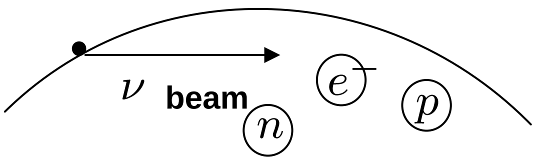
Can interactions between neutrinos and matter due to New Physics have any effect on neutrino oscillations?



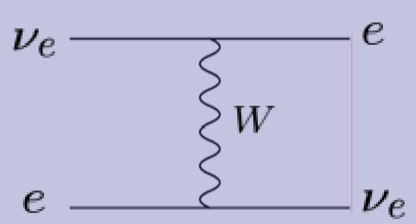
Can such effects be measured experimentally and be used to constrain New Physics?

0. Introduction

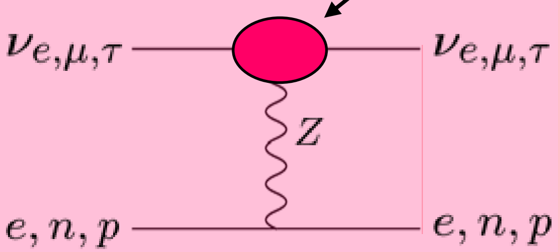
Matter effect



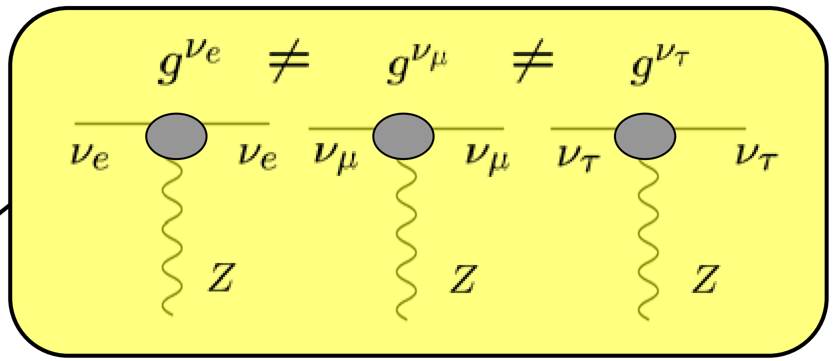
(a) charged current interaction



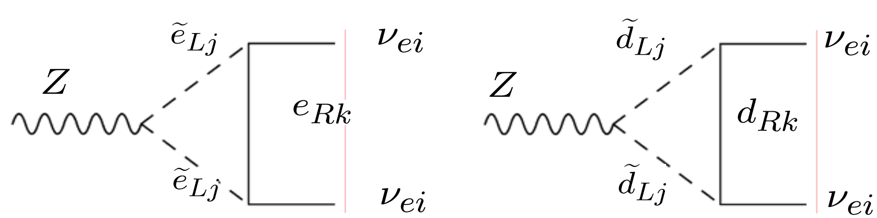
(b) neutral current interaction



In a number of models beyond the SM, the universality of the $Z\nu_\ell\nu_\ell(\ell = e, \mu, \tau)$ couplings can be violated through radiative corrections.

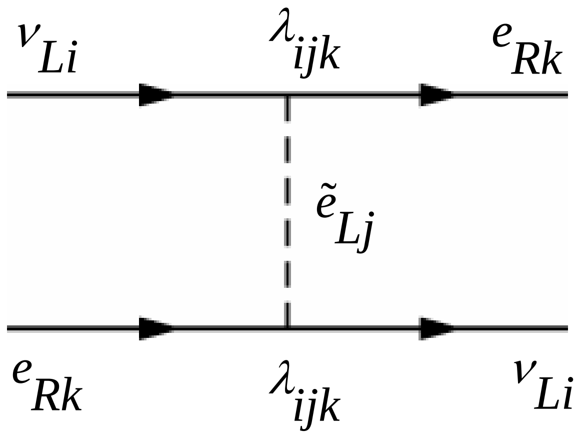


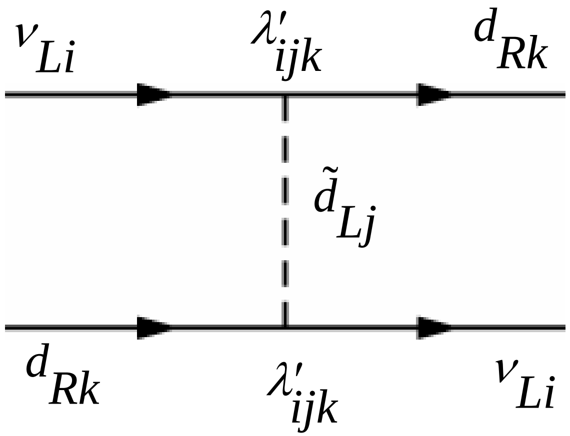
ex) MSSM with $\not{R}$ processes



etc…

➡ ***lead to the violation of universality***



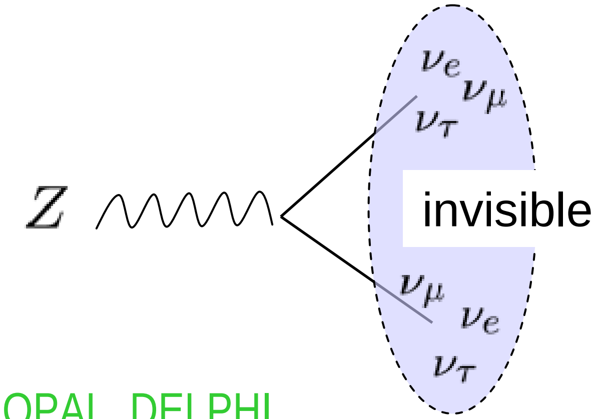


New Physics that can contribute to neutrino oscillations:

- R-parity violating couplings
- Gauged B-αL_e-βL_μ-γL_τ $(\alpha+\beta+\gamma=3)$
- Z' in Topcolor assisted Technicolor
- Leptoquarks that couple different generations
- etc.

The experimental constraints on universality violation in NC

from LEP



Z DECAY MODES	Fraction (Γ_i/Γ)
$e^+ e^-$	(3.363 $\pm$0.004) %
$\mu^+ \mu^-$	(3.366 $\pm$0.007) %
$\tau^+ \tau^-$	(3.370 $\pm$0.008) %
invisible	(20.00 $\pm$0.06) %
hadrons	(69.91 $\pm$0.06) %

LEP/ OPAL, DELPHI, L3, ALEPH, SLD

➡ ***NO CONSTRAINT***

No information is available on the individual decay widths into each flavor

The experimental constraints on universality violation in NC

from CHARM, CHARM II

@ CERN ('80s)

Z couplings to neutrinos

g^{ν_e}	0.528 ± 0.085
g^{ν_μ}	0.502 ± 0.017
g^{ν_e}/g^{ν_μ}	$1.05^{+0.15}_{-0.18}$

→ 0.9-1.2

PLB180,303(1986), PLB320,203(1994)

cf) Z couplings to charged leptons

g_V^e	-0.0382 ± 0.0005
g_V^μ	-0.0367 ± 0.0023
g_V^τ	-0.0366 ± 0.0010
g_A^e	-0.5011 ± 0.0004
g_A^μ	-0.5012 ± 0.0005
g_A^τ	-0.5020 ± 0.0006

LEP/ OPAL, DELPHI, L3, ALEPH, SLD

(LEP invisible width $\Rightarrow (g^{\nu_e})^2 + (g^{\nu_\mu})^2 + (g^{\nu_\tau})^2 \approx$ SM)

- ***The theoretical possibility of universality violation in many models***
- ***The weakness of the current experimental bounds***

CHARM, CHARM II

g^{ν_e}	0.528 ± 0.085
g^{ν_μ}	0.502 ± 0.017
g^{ν_e}/g^{ν_μ}	$1.05^{+0.15}_{-0.18}$

PLB180,303(1986), PLB320,203(1994)

It would be interesting to analyze the effect of such a violation on neutrino oscillations.

Plan of Talk

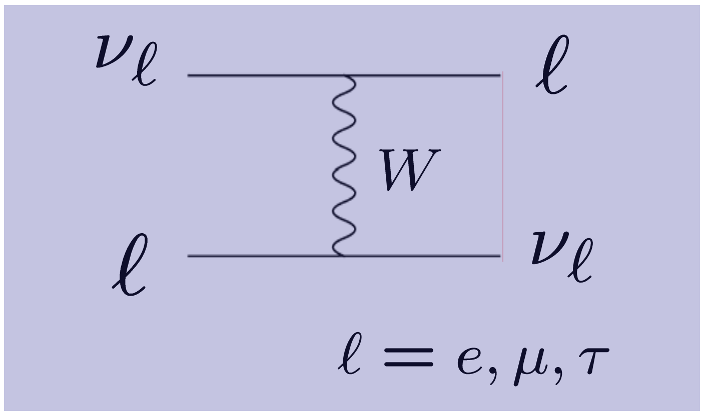
- Introduction
- Matter effect
  - effective potentials for neutrinos in matter
    - **W and Z exchange**
  - effective hamiltonian

    in the presence of neutral current (NC) universality violation
- Numerical results
- A hypothetical experiment

  Fermilab NuMI beam
  $\Rightarrow$ Hyper-Kamiokande detector (1Mt)
- Constraints on New Physics
- Summary

1-1. The effective potentials due to W & Z exchange

charged current interaction

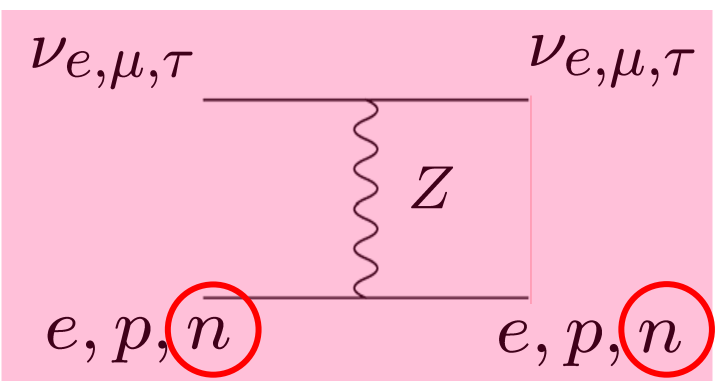


$V_{CC} = \sqrt{2} G_F N_\ell$ (N_ℓ : number density)

$N_\mu = N_\tau = 0$ in ordinary matter

$$V_{CC} = \begin{cases} \sqrt{2} G_F N_e & \text{(for } \nu_e\text{)} \\ 0 & \text{(for } \nu_\mu, \nu_\tau\text{)} \end{cases}$$

neutral current interaction



(N_n : neutron number density)

$$V_{NC} = -\frac{1}{2}\left(\sqrt{2} G_F N_n\right)$$

$N_n \approx N_p = N_e$

$$\approx -\frac{1}{2} V_{CC} \quad \text{(for } \nu_e, \nu_\mu, \nu_\tau\text{)}$$

1-2. The effective Hamiltonian in the presence of NC universality violation

U : MNS matrix

CC NC

$$H^2_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \delta m^2_{21} & 0 \\ 0 & 0 & \delta m^2_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} b_e & 0 & 0 \\ 0 & b_\mu & 0 \\ 0 & 0 & b_\tau \end{bmatrix}$$

$$= U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \delta m^2_{21} & 0 \\ 0 & 0 & \delta m^2_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} a & 0 & 0 \\ 0 & b\xi & 0 \\ 0 & 0 & -b\xi \end{bmatrix}$$

$$= \tilde{U} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \tilde{U}^\dagger$$

derived from universality violation in Neutral Current interaction

central value of CHARM $\xi = 0.025$

ξ : measure of universality violation in NC

$\tilde{U}$: **effective mixing matrix**

$\lambda_1, \lambda_2, \lambda_3$: **effective mass-squares**

$$a \equiv 2EV_{CC} = 2\sqrt{2}G_F N_e E = 7.56 \times 10^{-5} (\text{eV})^2 \left(\frac{n_e}{\text{g/cm}^3}\right)\left(\frac{E}{\text{g/GeV}}\right)$$

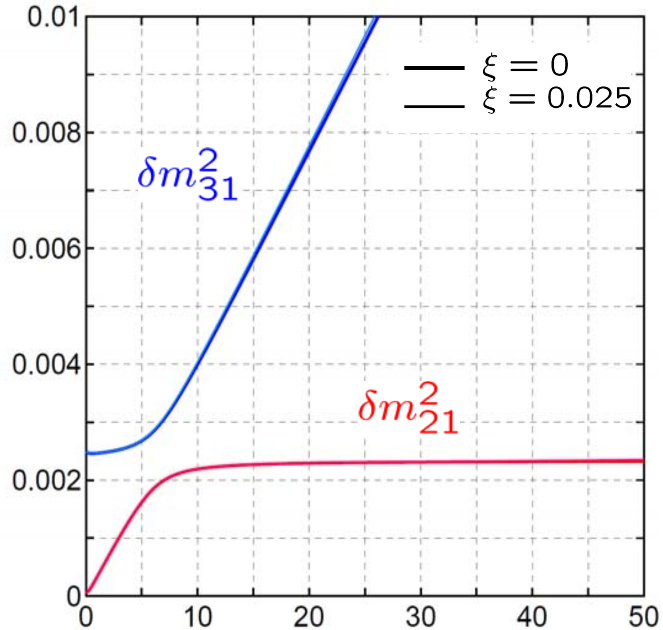
$$b \equiv 2EV_{NC} = -\sqrt{2}G_F N_n E \approx -\frac{1}{2}a$$

3. Numerical Results

The energy dependence of the effective mass squared differences

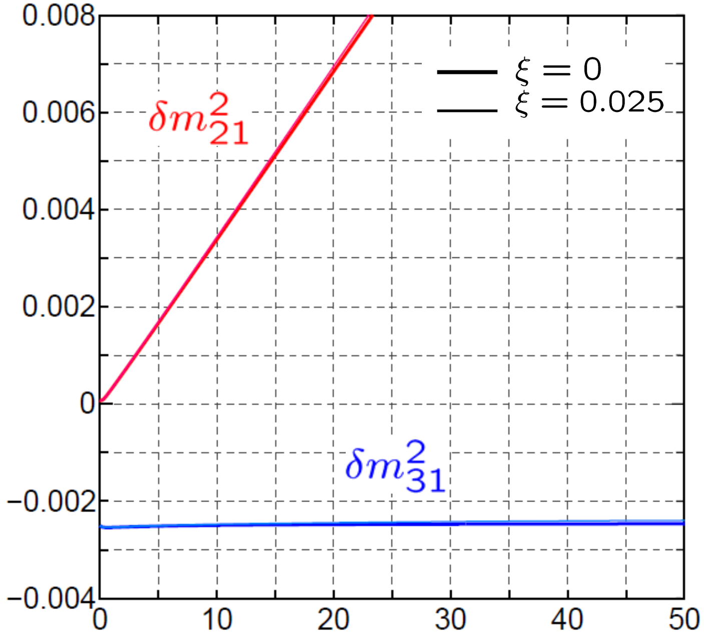
matter density $=$ 4.6 g/cm^3	$\sin^2(2\theta_{\rm atm}) = 1.0$	$\delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2
CP phase $\delta = 0$	$\tan^2(\theta_{\rm sun}) = 0.40$	$\delta m^2_{21} = 8.0 \times 10^{-5}$ eV^2
	$\sin^2(2\theta_{\rm rct}) = 0.16$	

normal hierarchy



neutrino beam energy [GeV]

inverted hierarchy

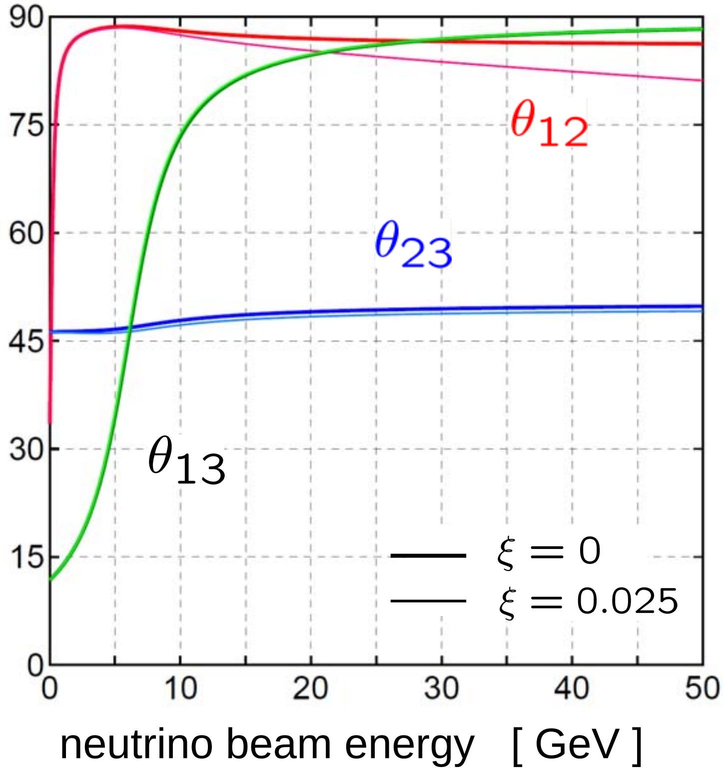


neutrino beam energy [GeV]

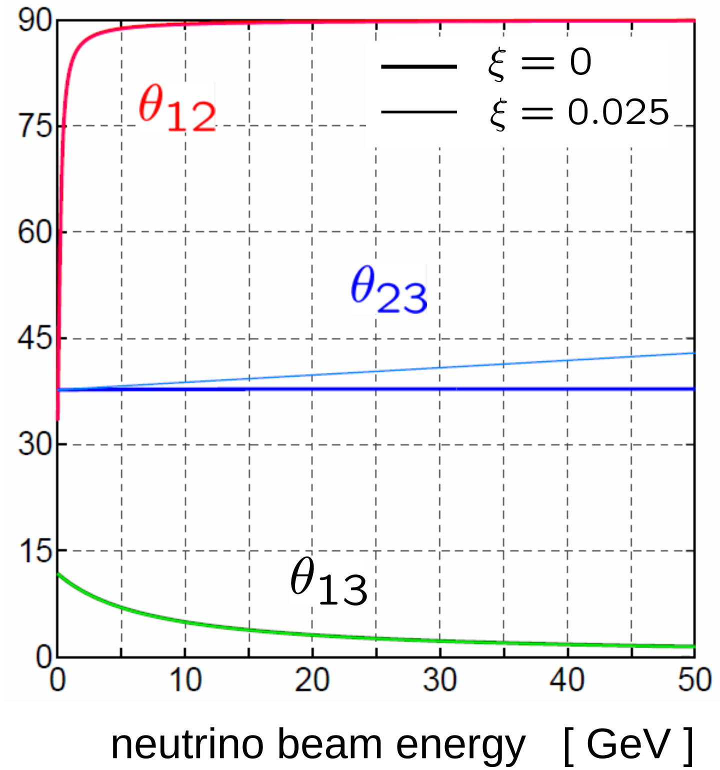
The energy dependence of the effective mixing angles

matter density $= 4.6\ \mathrm{g/cm^3}$	$\sin^2(2\theta_{\mathrm{atm}}) = 1.0$	$\delta m^2_{31} = 2.5 \times 10^{-3}\ \mathrm{eV^2}$
CP phase $\delta = 0$	$\tan^2(\theta_{\mathrm{sun}}) = 0.40$	$\delta m^2_{21} = 8.0 \times 10^{-5}\ \mathrm{eV^2}$
	$\sin^2(2\theta_{\mathrm{rct}}) = 0.16$	

normal hierarchy



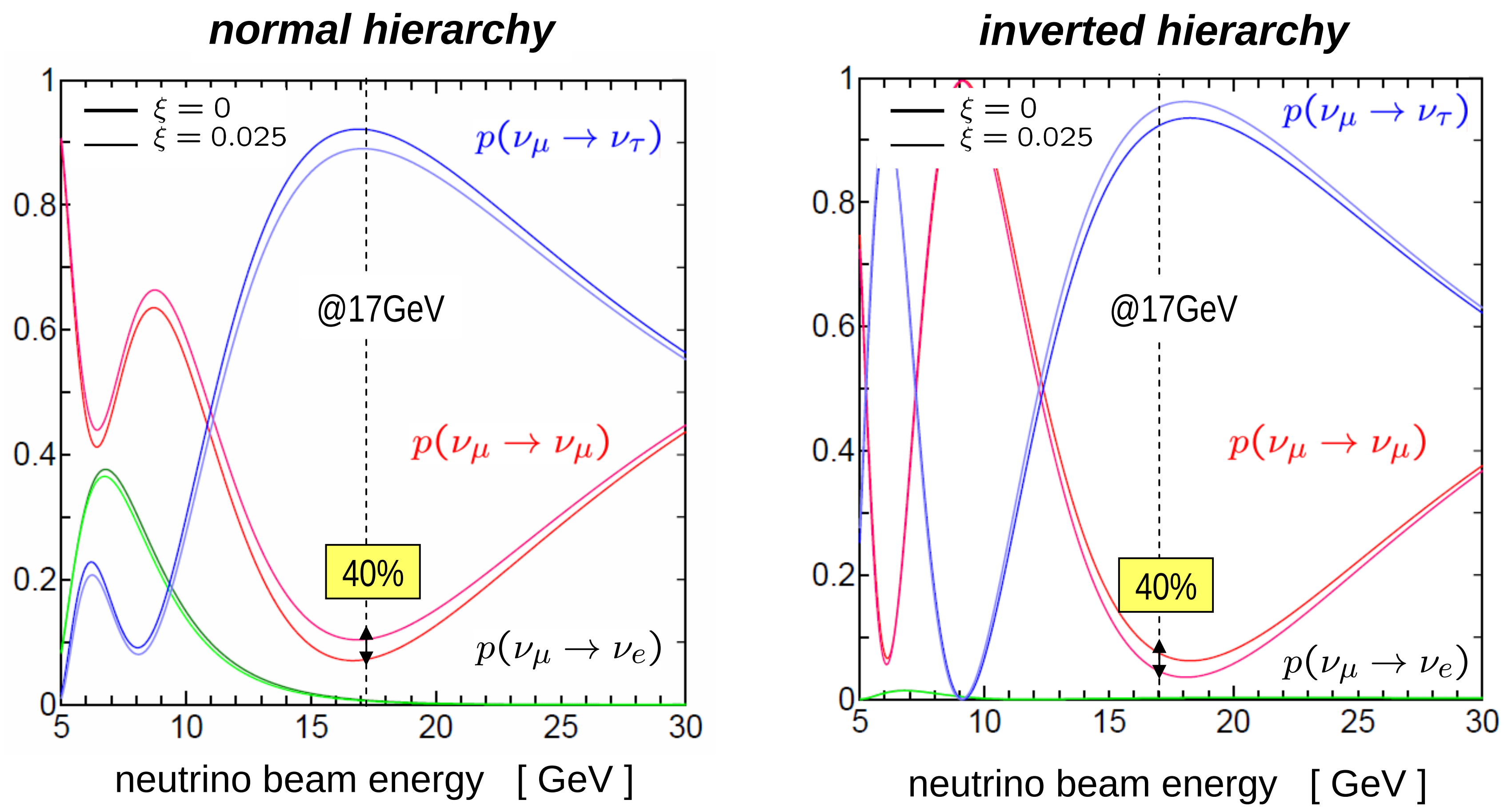
inverted hierarchy



The oscillation probabilities (L=9,120km)

$\sin(2\theta_{atm}) = \sin\theta_{23}\cos\theta_{13} \approx \sin\theta_{23}$

matter density	=	4.6 g/cm^3	$\sin^2(2\theta_{atm})$	=	0.92	δm^2_{31}	=	2.5×10^{-3} eV^2
CP phase δ	=	0	$\tan^2(\theta_{sun})$	=	0.40	δm^2_{21}	=	8.0×10^{-5} eV^2
			$\sin^2(2\theta_{rct})$	=	0.16			

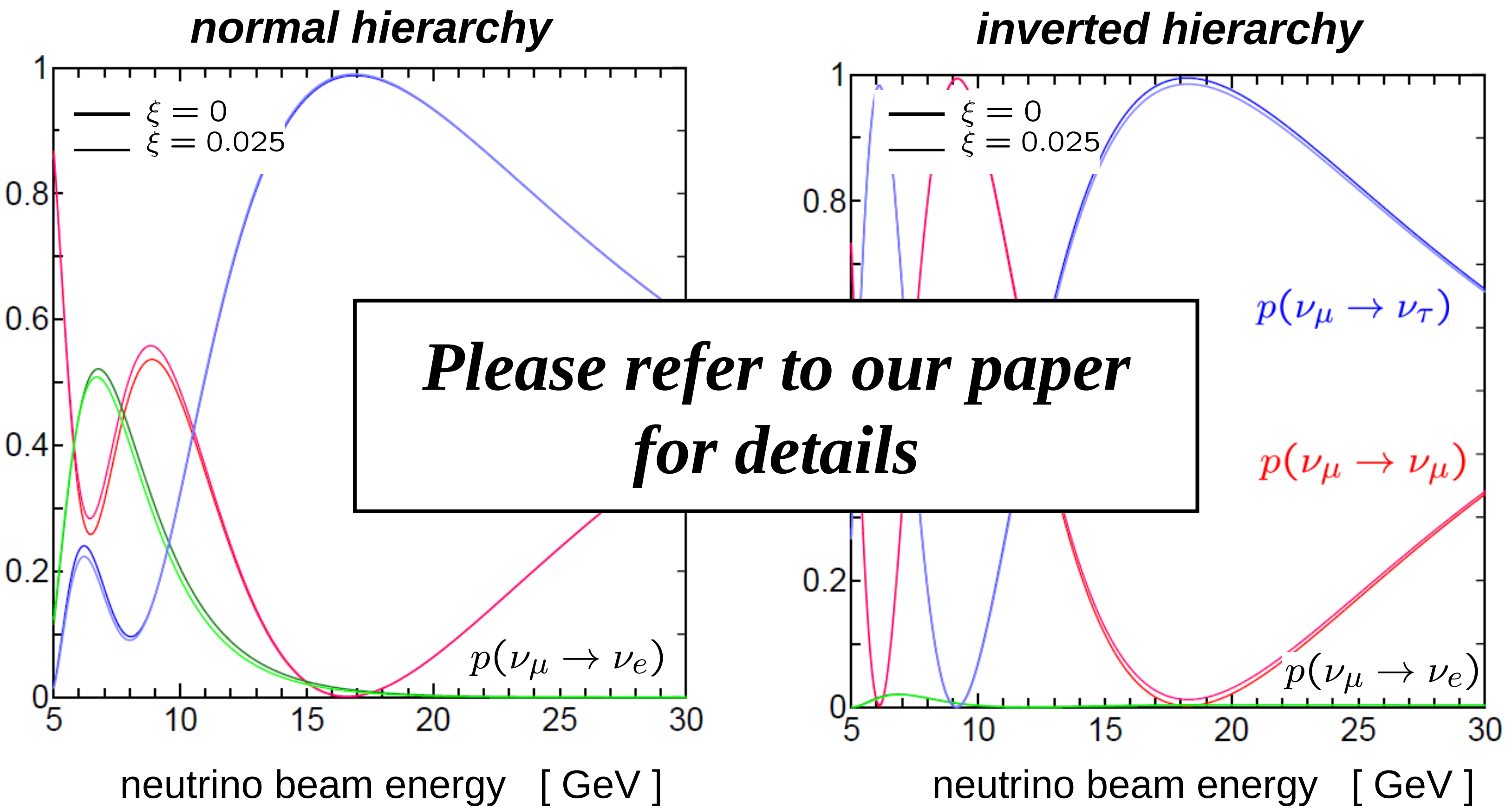


In the case $\sin^2(2\theta_{atm}) = 1$ *the oscillation probabilities (L=9,120km)*

$$\text{matter density} = 4.6\ \text{g/cm}^3 \qquad \sin^2(2\theta_{atm}) = 1 \qquad \delta m^2_{31} = 2.5 \times 10^{-3}\ \text{eV}^2$$

$$\text{CP phase } \delta = 0 \qquad \tan^2(\theta_{sun}) = 0.40 \qquad \delta m^2_{21} = 8.0 \times 10^{-5}\ \text{eV}^2$$

$$\sin^2(2\theta_{rct}) = 0.16$$



Please refer to our paper for details

The oscillation probabilities (L=9,120km)

$\sin(2\theta_{\mathrm{atm}}) = \sin\theta_{23}\cos\theta_{13} \approx \sin\theta_{23}$

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$$\text{CP phase } \delta = 0$$

$$\sin^2(2\theta_{\mathrm{atm}}) = 0.92$$

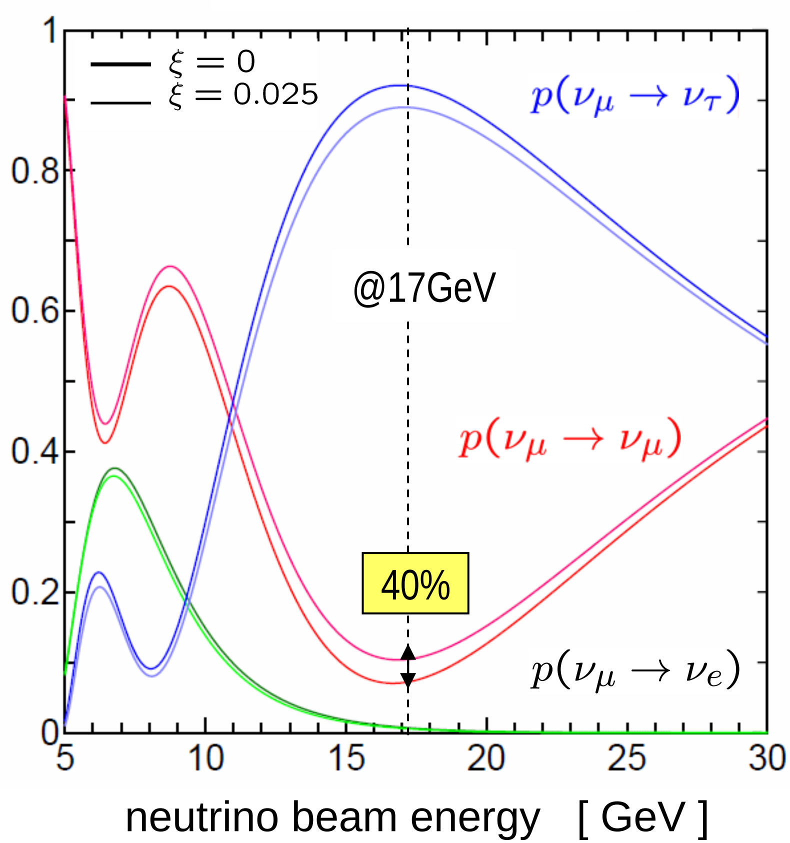
$$\tan^2(\theta_{\mathrm{sun}}) = 0.40$$

$$\sin^2(2\theta_{\mathrm{rct}}) = 0.16$$

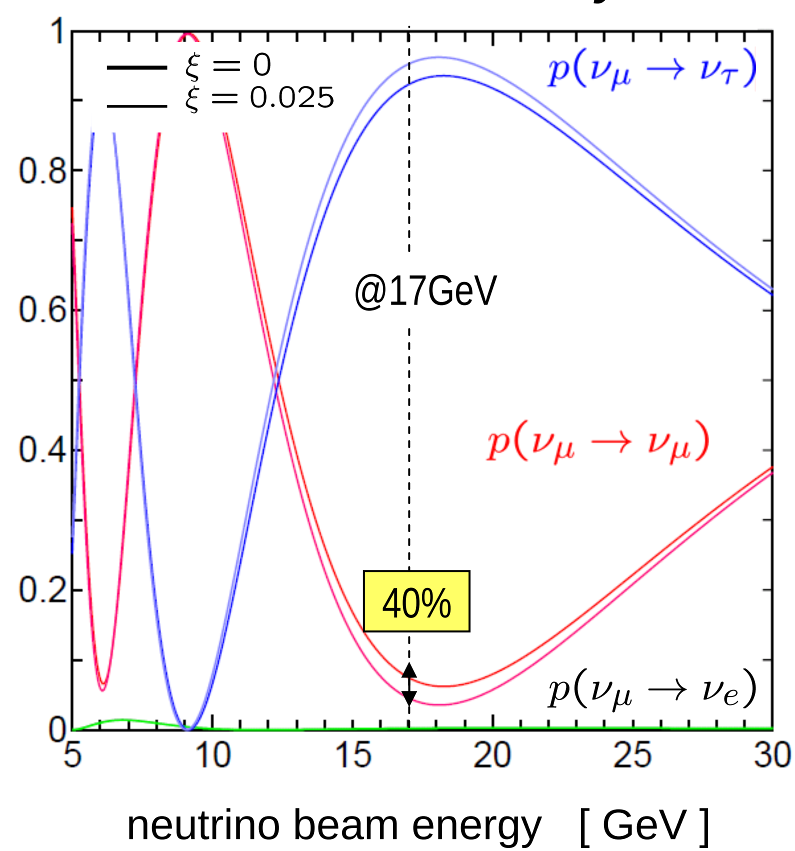
$$\delta m^2_{31} = 2.5\times10^{-3}\ \mathrm{eV^2}$$

$$\delta m^2_{21} = 8.0\times10^{-5}\ \mathrm{eV^2}$$

normal hierarchy



inverted hierarchy



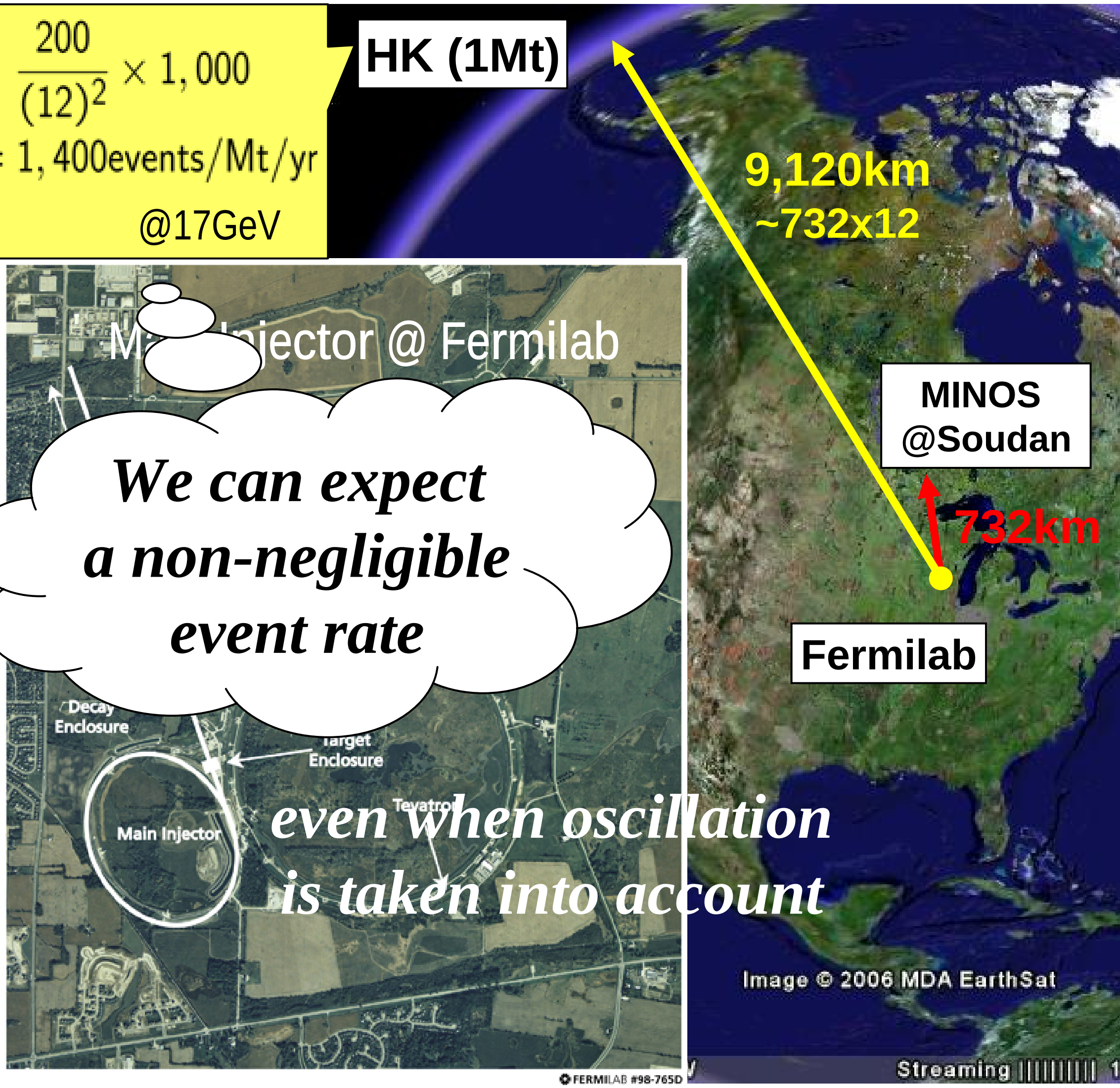
Can these shifts
be measured experimentally ??

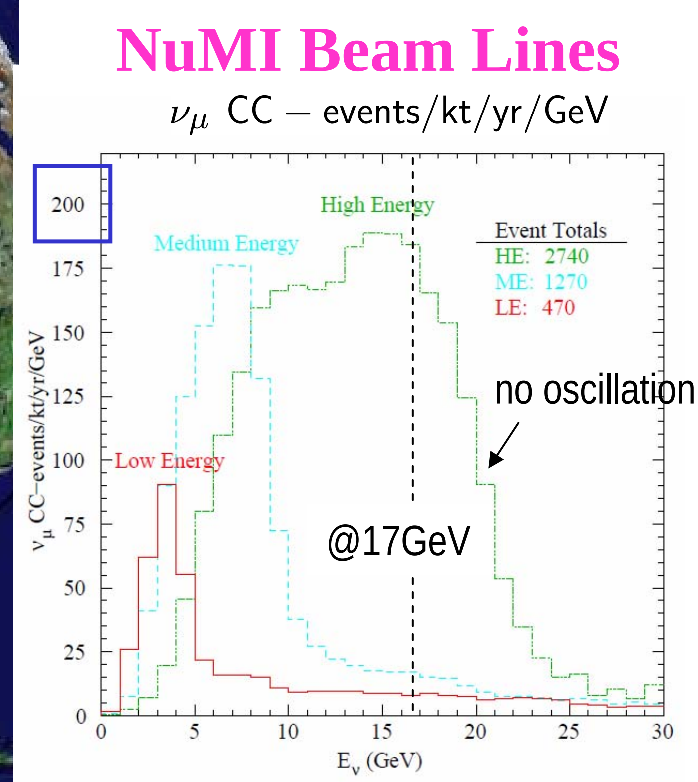
Fermilab (NuMI) $\xrightarrow{\nu_\mu}$ *Hyper-Kamiokande*

[L~9,120 km] *(1Megaton detector)*

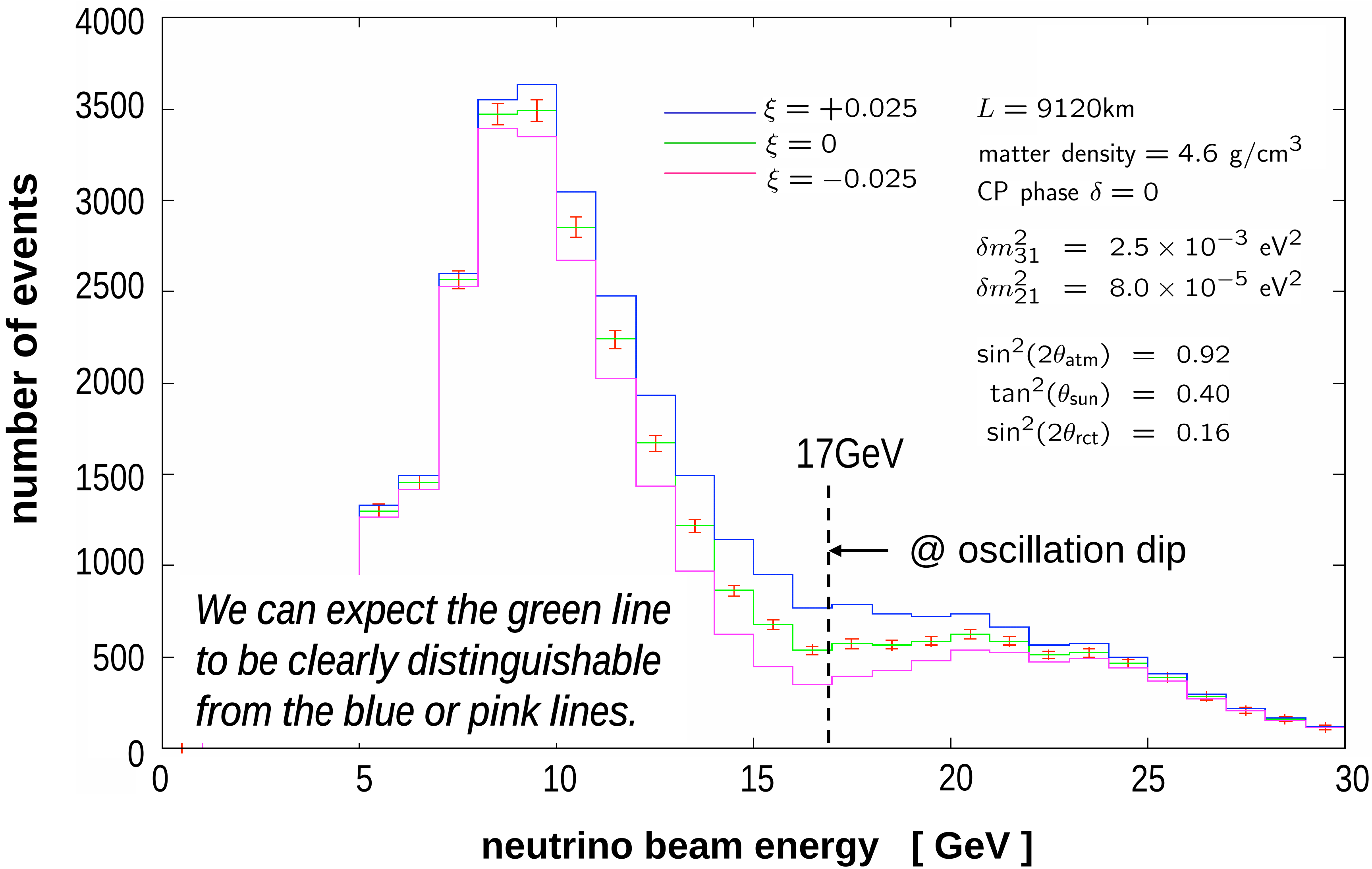
$$\frac{200}{(12)^2} \times 1,000 = 1,400 \text{events/Mt/yr}$$

@17GeV

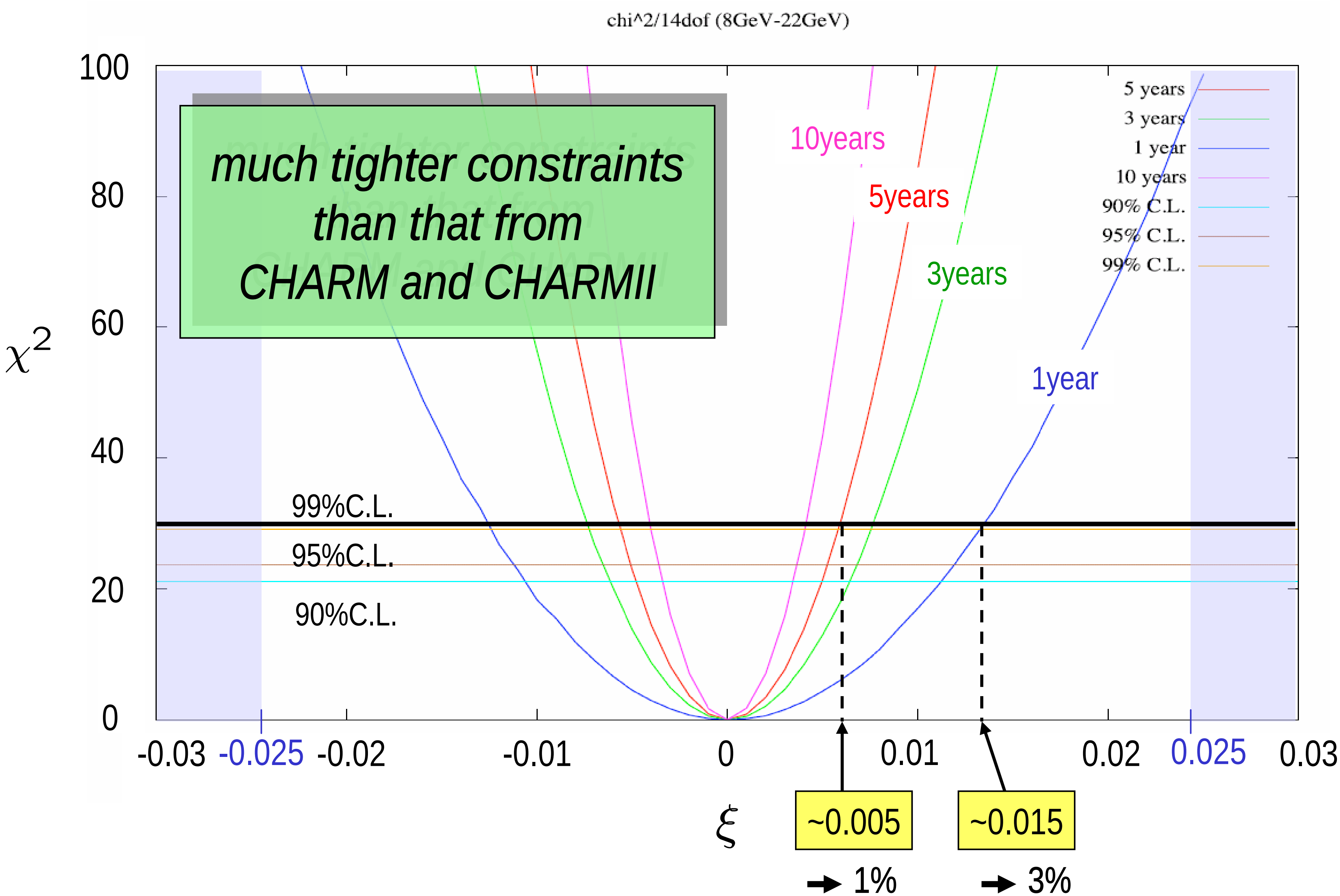




The expected number of $\nu_\mu \to \nu_\mu$ events @ HK
after 5years of data taking



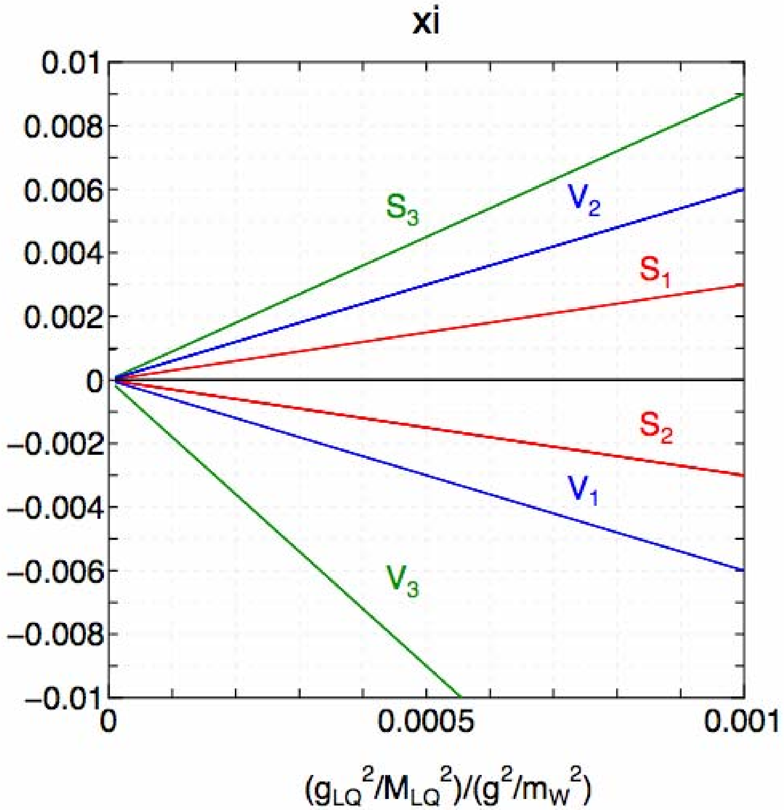
The constrains on universality violation ξ

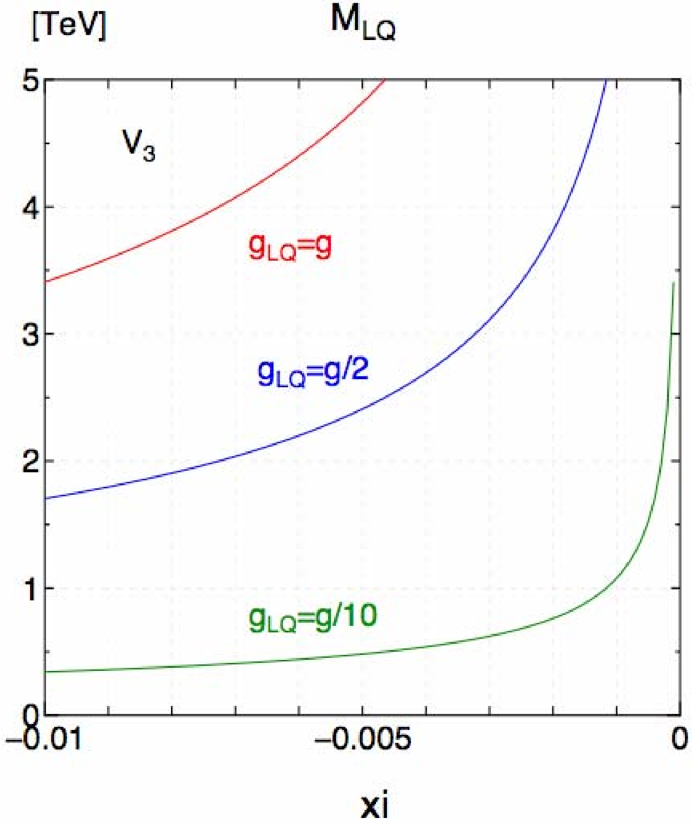


Constraints on New Physics

Leptoquarks that couple 1st and 2nd generations

S : scalar, V : vector, subscript : dim of SU(2) rep.





Summary

We investigated the matter effect on neutrino oscillation from universality violation in neutral current interactions.

The violation effects	normal	inverted
mixing angle	θ_{12}	θ_{23}
oscillation probability (L=9,120 km, 17GeV)	$\sin^2(2\theta_{23}) = 0.92$: ☺ ☺ ☺ ☺	$\sin^2(2\theta_{23}) = 0.92$: ☺ ☺ ☺ ☺
	$\sin^2(2\theta_{23}) = 1$ (best fit): ×	$\sin^2(2\theta_{23}) = 1$ (best fit): ×

➢**This result is highly sensitive to the value of** $\sin^2(2\theta_{23})$.

Fermilab ⇒ Hyper-Kamiokande

➢**If** $\sin^2(2\theta_{23})$ **is NOT too close to 1,**

we may be able to either observe this effect, or impose a much tighter constraint on universality violation than that from CHARM and CHARMII.