Constraints on new physics from long baseline neutrino oscillation experiments

ニュートリノで探る “non-standard” physics

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第20回宇宙ニュートリノ研究会
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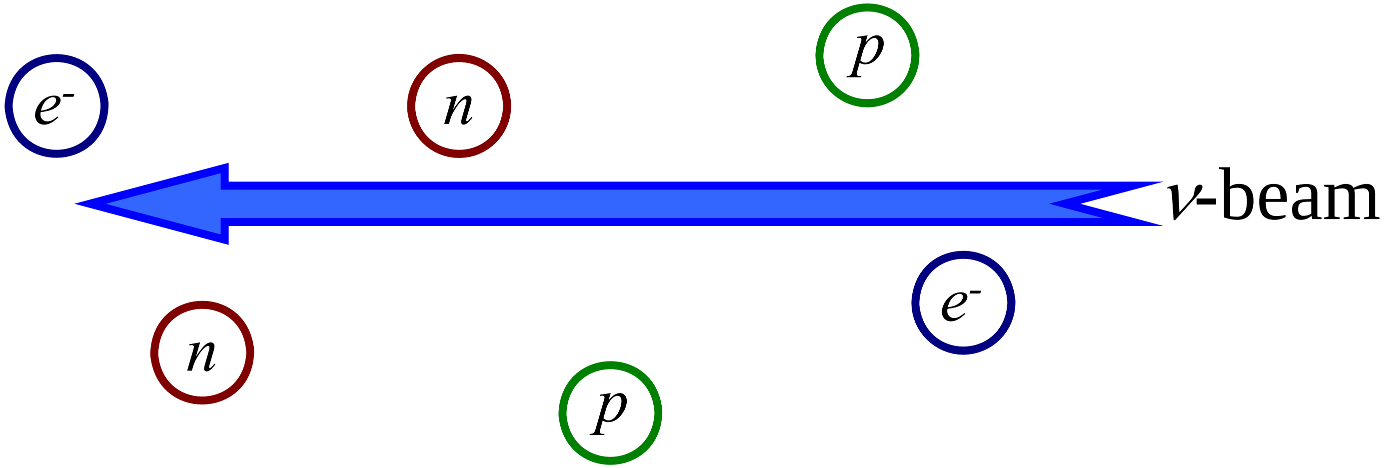
based on
hep-ph/0602115
hep-ph/0603268
hep-ph/0702xxx

Motivation

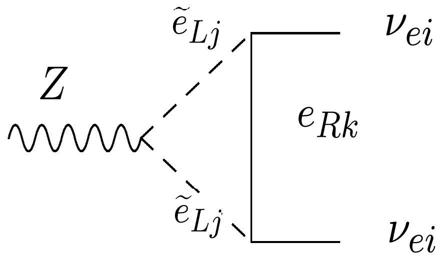
1. Can interactions between neutrinos and matter due to New Physics have any effect on neutrino oscillations ?

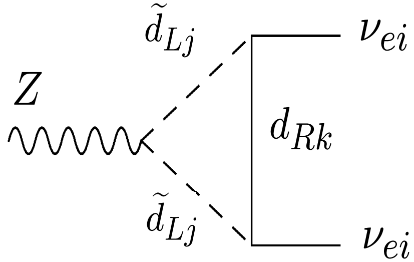


2. Can such effects be measured experimentally and be used to constrain New Physics ?

New Physics effect

- New Physics breaks the NC interaction
  - radiative corrections
    e.g. MSSM with
    R-parity violation





- Direct exchange of the New Particle
  - Gauged B-αL_e-βL_μ-γL_τ
  - *Z'* in topcolor assisted Technicolor
  - Leptoquarks that couple different generations
  - MSSM with R-Parity violating couplings
  - *etc etc*, *Please consider the "fantastic model"*.

Contents

- Motivation
- Can be measured ? (FNAL-to-HK)
- New Physics
  - ***Z'*** gauge boson
  - Leptoquarks
  - ***R***-parity violation, SUSY
  - Extended Higgs Model
  - ……as you wish……
- Summary

The effective Hamiltonian

CC **NP** ***U*:MNS matrix**

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

derived from universality violation in NC and/or New Physics

$$= U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \delta m^2_{21} & 0 \\ 0 & 0 & \delta m^2_{31} \end{bmatrix} U^\dagger \cdot$$

central value of CHARM $\xi = 0.025$

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

ξ : universality violation in NC, New Physics

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

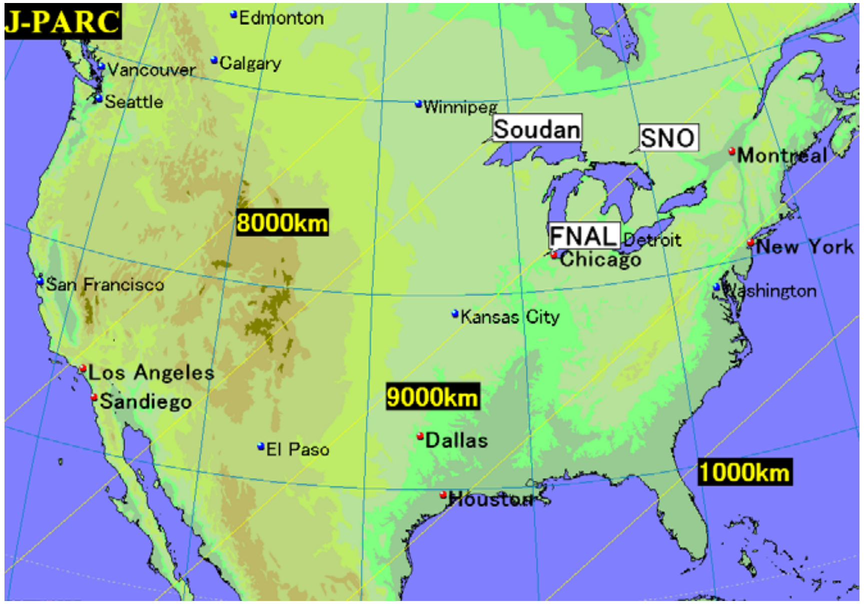
$\lambda_1, \lambda_2, \lambda_3$: **effective mass-squares**

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

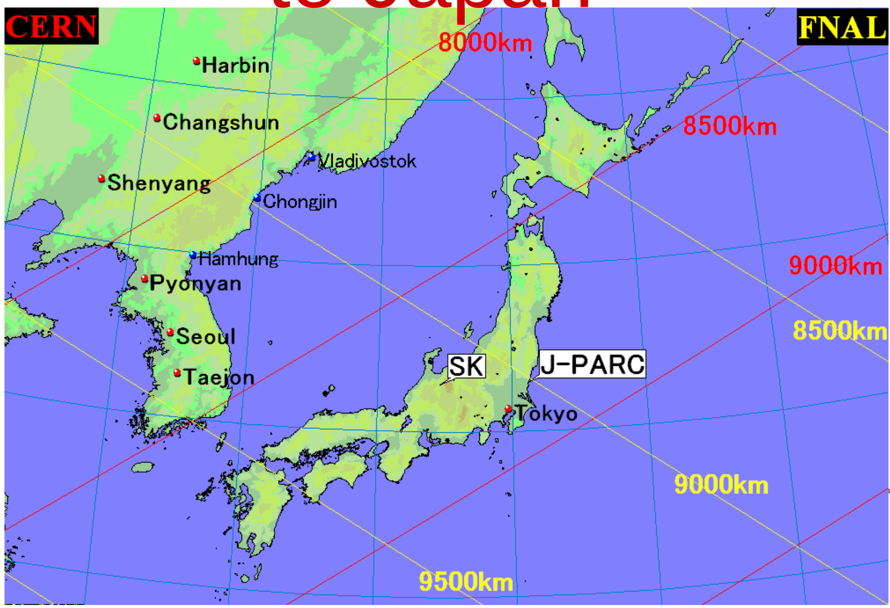
$$b \equiv \underbrace{2EV_{NC} = -\sqrt{2}G_F N_n E}_{\text{loop correction}} \approx -\frac{1}{2}a \qquad (N_e = N_n = N_p)$$

Can be measured ?

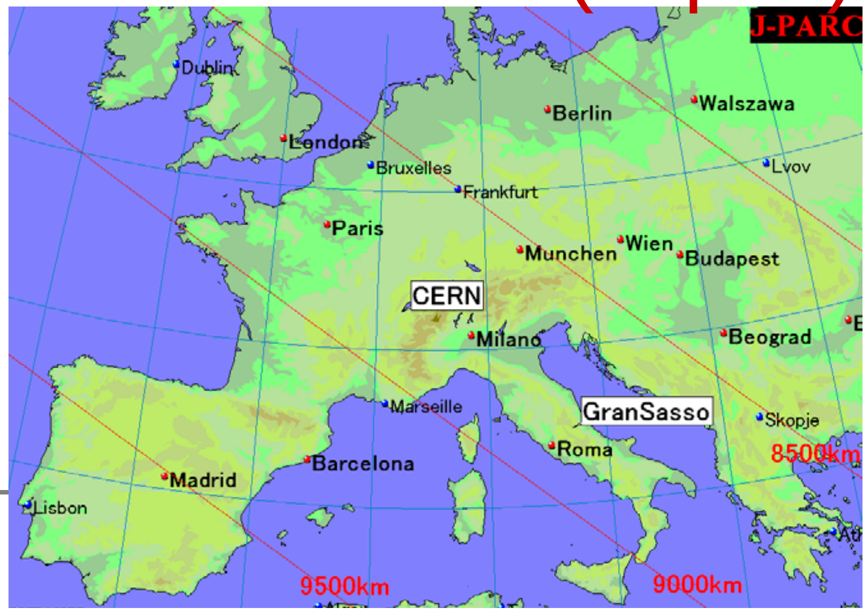
small value(ξ)
large matter effect
⇔high energy
⇔long base-line



to Japan

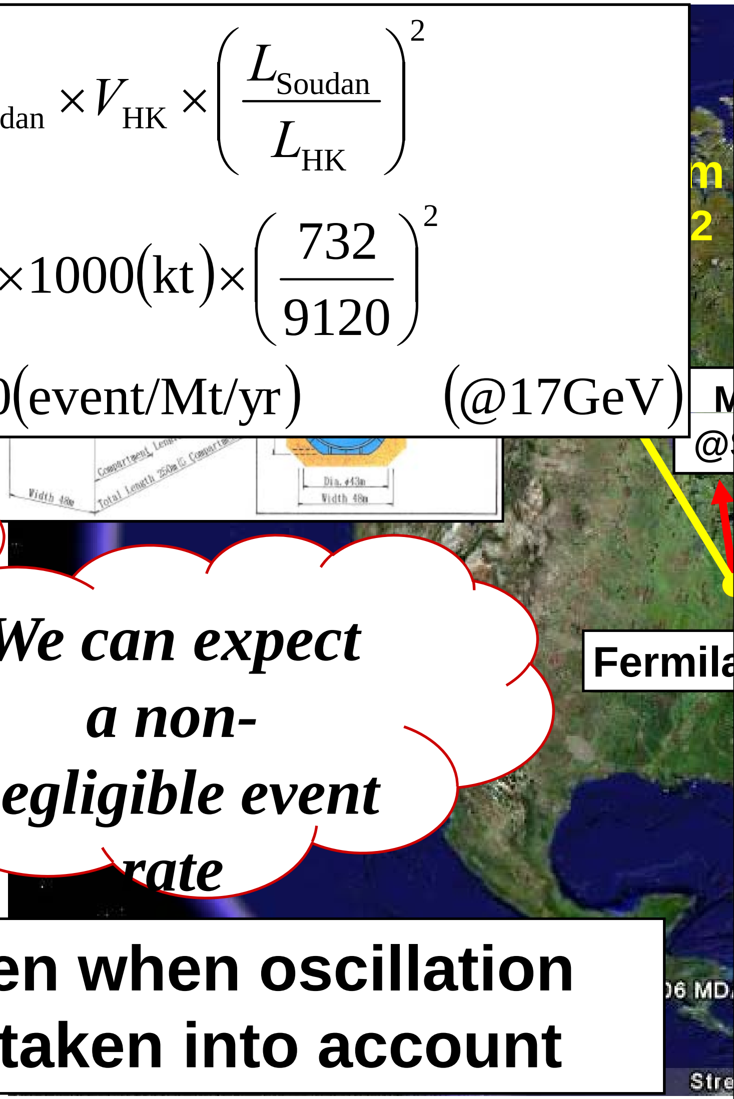


from J-PARC (Japan)



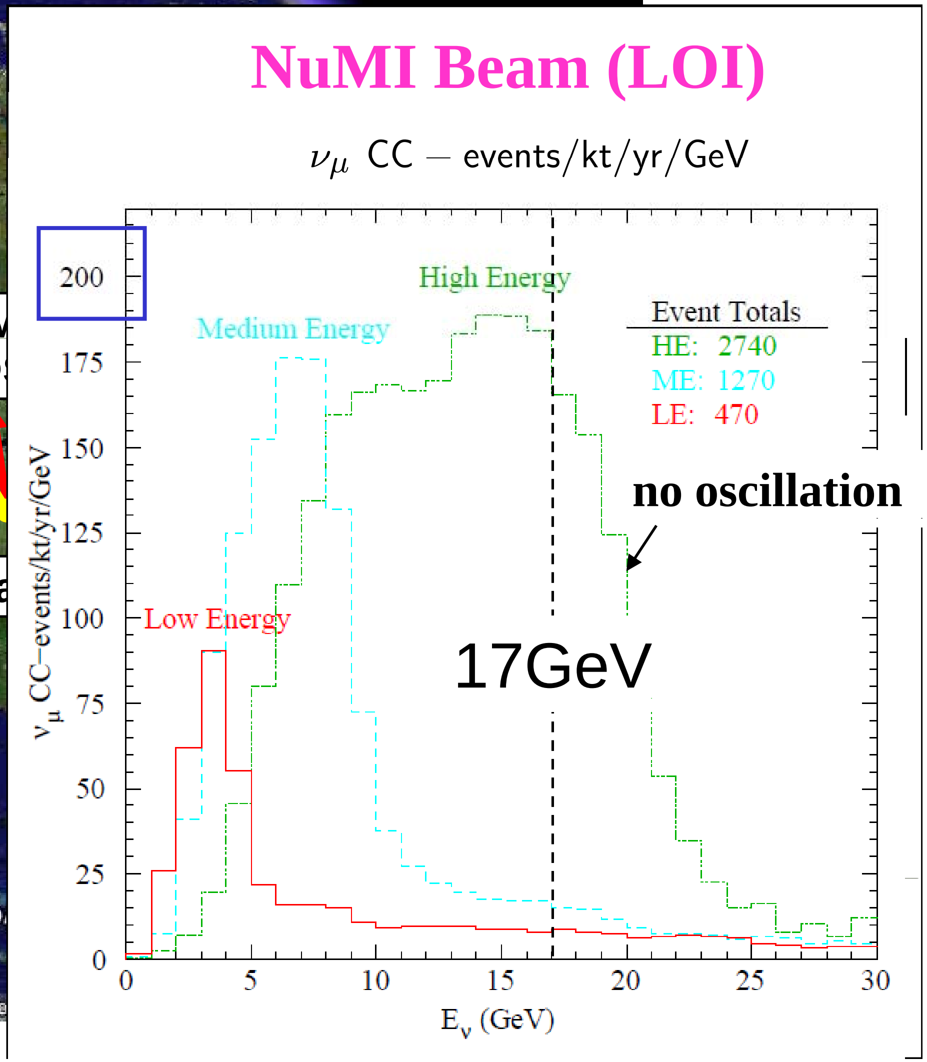
Fermilab $\xrightarrow{\nu_\mu}$ HK[L~9,120 km]

$$
\begin{aligned}
N_{\mathrm{HK}} &= N_{\mathrm{Soudan}} \times V_{\mathrm{HK}} \times \left(\frac{L_{\mathrm{Soudan}}}{L_{\mathrm{HK}}} \right)^2 \\
&\approx 200 \times 1000(\mathrm{kt}) \times \left(\frac{732}{9120} \right)^2 \\
&\approx 1300(\mathrm{event/Mt/yr}) \qquad (@17\mathrm{GeV})
\end{aligned}
$$



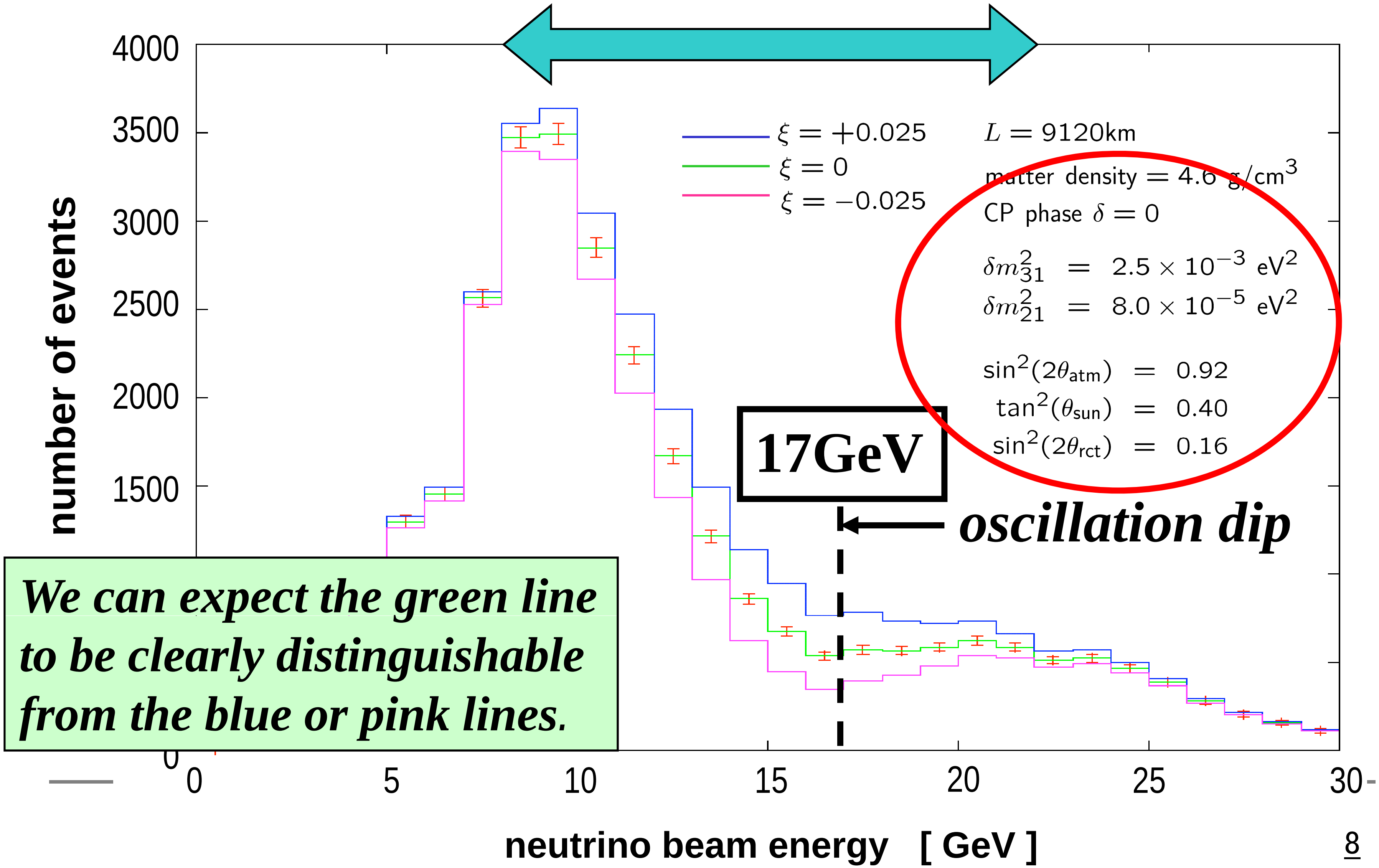
We can expect a non-negligible event rate

even when oscillation is taken into account

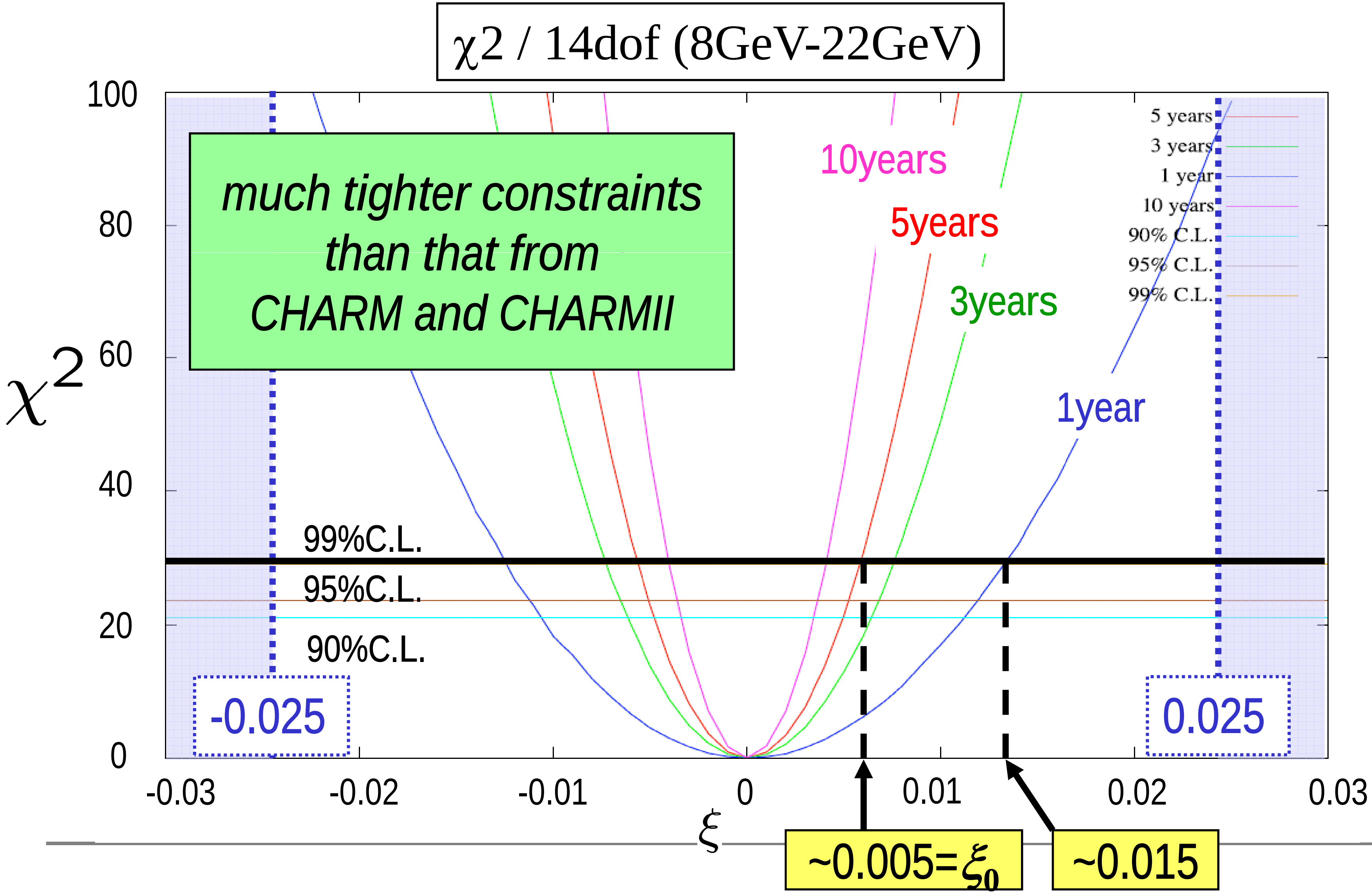


The expected number of $\nu_\mu \rightarrow \nu_\mu$ events@ HK

after 5 years of data taking (1Mton)



The constrains on universality violation ξ



New Physics

FNAL-to-HK

$$\xi > \xi_0 = 0.005$$

$$\downarrow$$

constraints on new physics

Constraints on the New Physics

- ***Z'*** gauge boson
  - gauged B-$(\alpha L_e+\beta L_\mu+\gamma L_\tau)$ with $(\alpha+\beta+\gamma=3)$
  - Topcolor Assisted Technicolor
- Leptoquarks
  - Scalar leptoquark
  - Vector leptoquark
- R-parity violation
- Extended Higgs Model

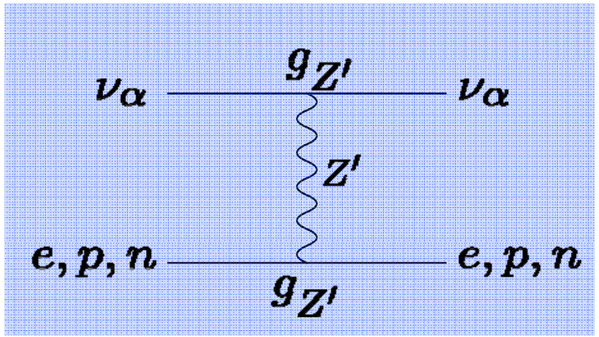
Z' boson

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$$

Z' boson

1. gauged B-($\alpha L_e+\beta L_\mu+\gamma L_\tau$) with ($\alpha+\beta+\gamma = 3$)

$$L_{Z'} = g_{z'}\left[\sum_q \left(\bar{q}\gamma^\mu q\right) - \alpha\left(\bar{l}_e\gamma^\mu l_e\right) - \beta\left(\bar{l}_\mu\gamma^\mu l_\mu\right) - \gamma\left(\bar{l}_\tau\gamma^\mu l_\tau\right)\right] Z'_\mu$$



$$\begin{cases} V_{\nu_e} = \alpha\left[\alpha N_e - \left(N_p + N_n\right)\right]\dfrac{g_{Z'}^2}{M_{Z'}^2} \approx \alpha(\alpha-2)N\dfrac{g_{Z'}^2}{M_{Z'}^2} \\ V_{\nu_\mu} = \beta\left[\alpha N_e - \left(N_p + N_n\right)\right]\dfrac{g_{Z'}^2}{M_{Z'}^2} \approx \beta(\alpha-2)N\dfrac{g_{Z'}^2}{M_{Z'}^2} \\ V_{\nu_\tau} = \gamma\left[\alpha N_e - \left(N_p + N_n\right)\right]\dfrac{g_{Z'}^2}{M_{Z'}^2} \approx \gamma(\alpha-2)N\dfrac{g_{Z'}^2}{M_{Z'}^2} \end{cases}$$

$$\xi_{Z'} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}}$$

$$= -4(\alpha-2)(\alpha+2\beta-3)\frac{(g_{Z'}/M_{Z'})^2}{(g/M_W)^2}$$

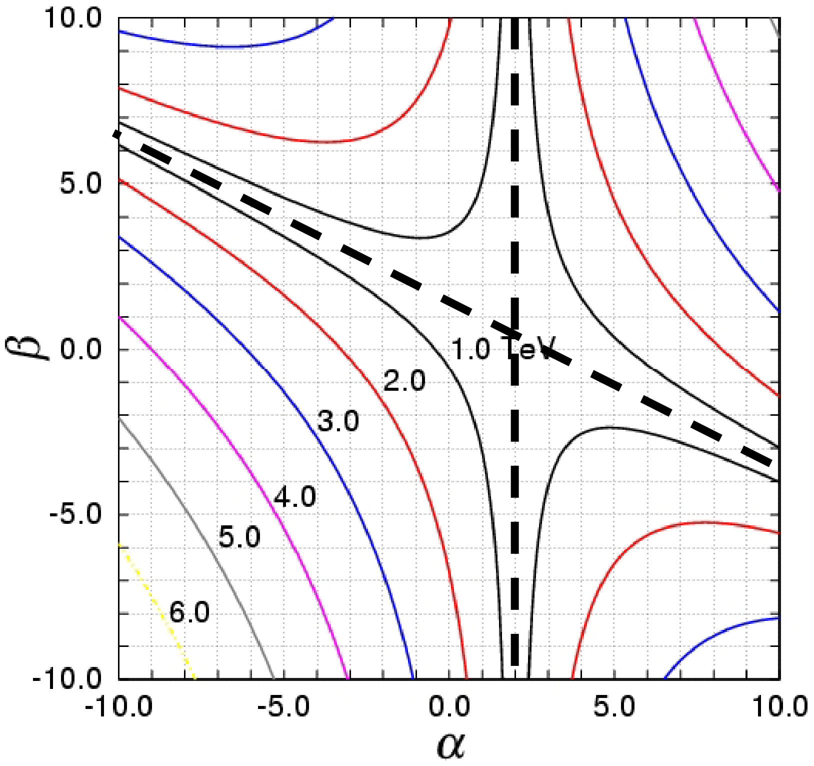
$$\left|\xi_{Z'}\right| \le \xi_0 = 0.005$$

If ξ_0 is larger than 0.005,
the effect on the neutrino oscillation
gives the constraint on the mass of Z'

$$M_{Z'} \ge g_{Z'}\sqrt{\frac{|\alpha-2||\alpha+2\beta-3|}{\sqrt{2}G_F\xi_0}}$$

Constraint on $M_{Z'}$ (gauged)

$|\xi_0|=0.005,\ \alpha+\beta+\gamma=3,\ g_{Z'}=0.10$



$$M_{Z'} \geq g_{Z'}\sqrt{\frac{|\alpha-2||\alpha+2\beta-3|}{\sqrt{2}G_F\xi_0}}$$

Current Limit

Improve the limit

$\alpha=\beta=0\quad(\gamma=3)$

$g_{z'}=0.65:$

$M_{Z'}\geq 860\text{GeV} \Rightarrow 5500\text{GeV}$

$g_{z'}=0.35:$

$M_{Z'}\geq 370\text{GeV} \Rightarrow 3000\text{GeV}$

Not "Improve" the limit

Current Limit

$\beta=\gamma=1.5\quad(\alpha=0)$

$g_{z'}=0.65:$

$M_{Z'}\geq 1100\text{GeV} \Rightarrow$ no limit

$g_{z'}=0.35:$

$M_{Z'}\geq 490\text{GeV} \Rightarrow$ no limit

Z' boson

C.T.Hill, PLB345,483(95)
G.Buchalla,etal, PRD53,5185(96)
W.Loinaz,etal,PRD60,015005(99)

2. Topcolor Assisted Technicolor

$$L = g'\left(\cot\theta \cdot J^{\mu}_{1s} - \tan\theta \cdot J^{\mu}_{1w}\right)Z'_{\mu} + g'\left(J^{\mu}_{1s} + J^{\mu}_{1w}\right)B_{\mu} \qquad \theta << 1$$

$$J^{\mu}_{1s} = \frac{1}{6}\left(\bar{t}_L\gamma^{\mu}t_L + \bar{b}_L\gamma^{\mu}b_L\right) + \frac{2}{3}\bar{t}_R\gamma^{\mu}t_R - \frac{1}{2}\bar{b}_R\gamma^{\mu}b_R - \frac{1}{2}\left(\bar{\tau}_L\gamma^{\mu}\tau_L + \bar{\nu}_{\tau}\gamma^{\mu}\nu_{\tau}\right) - \bar{\tau}_R\gamma^{\mu}\tau_R$$

$$J^{\mu}_{1w} = \left[\text{1st. and 2nd. generation}\right]$$

Current limit
$\boldsymbol{M_{Z'}}$ ~200GeV

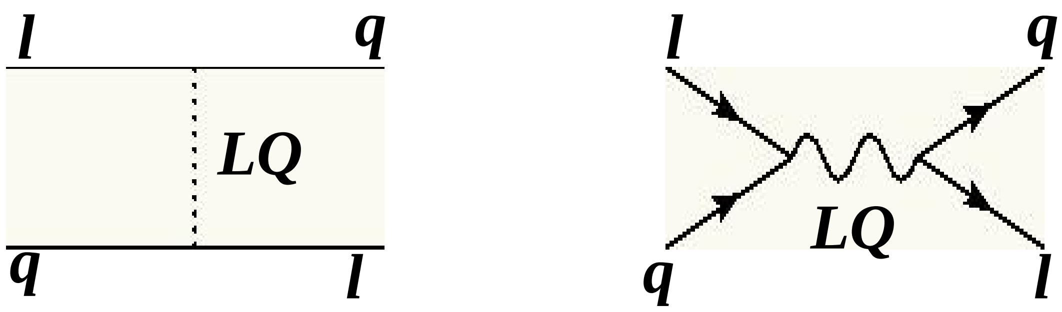
$$V_{\nu_e} \approx 0, \quad V_{\nu_\mu} \approx 0, \quad V_{\nu_\tau} \approx -\frac{N}{8}\frac{g^2_{Z'}}{M^2_{Z'}}$$

$$\xi_{TT} = -\frac{V_{\nu_\tau}}{2V_{NC}} = -\frac{1}{2}\frac{\left(g'/M_{Z'}\right)^2}{\left(g/M_W\right)^2} = -\frac{1}{2}\sin^2\theta_W\frac{M^2_Z}{M^2_{Z'}} \approx -0.1\frac{M^2_Z}{M^2_{Z'}}$$

$$M_{Z'} \geq \sqrt{\frac{0.2311\times(91.19)^2}{2\times 0.005}} \approx 440\text{GeV}\left(\frac{0.005}{\xi_{\rm TT}}\right)^{1/2}$$

If $M_{Z'}$<440 GeV ⇔ The effect can be measured.

Leptoquarks



Leptoquarks

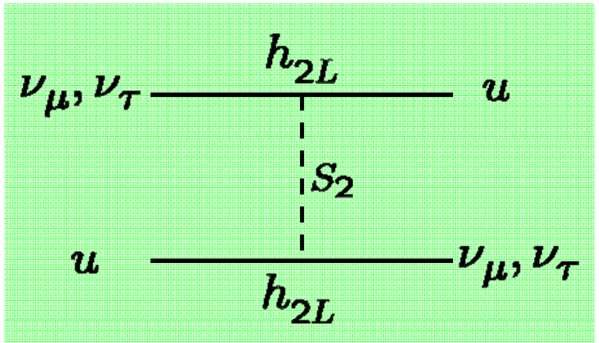
There are many leptoquarks (more than 10)

Fermion number : $F=3B+L$, S : scalar, V : vector, subscript:dim.SU(2)

$$F=2: S_1, \tilde{S}_1, \vec{S}_3, V_{2\mu}, \tilde{V}_{2\mu} \qquad F=0: S_2, \tilde{S}_2, V_{1\mu}, \tilde{V}_{1\mu}, \vec{V}_{3\mu}$$

$$L_{F=2} = \left[g_{1L}\bar{q}_L^C i\tau_2 l_L + g_{1R}\bar{u}_R^C e_R\right]S_1 + \tilde{g}_{1R}\left[\bar{d}_R^C e_R\right]\tilde{S}_1 + g_{3L}\left[\bar{q}_L^C i\tau_2\vec{\tau} l_L\right]\vec{S}_3$$
$$+\left[g_{2L}\bar{d}_R^C\gamma^\mu l_L + g_{2R}\bar{q}_R^C\gamma^\mu e_L\right]V_{2\mu} + \tilde{g}_{2L}\left[\bar{u}_R^C\gamma^\mu l_L\right]\tilde{V}_{2\mu} + h.c.$$

$$L_{F=0} = \left[h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R\right]S_2 + \tilde{h}_{2L}\left[\bar{d}_R l_L\right]\tilde{S}_2$$
$$+\left[h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R\right]V_{1\mu} + \tilde{h}_{1R}\left[\bar{u}_R\gamma^\mu e_R\right]\tilde{V}_{1\mu} + h_{3L}\left[\bar{q}_L\vec{\tau}\gamma^\mu l_L\right]\vec{V}_{3\mu} + h.c.$$

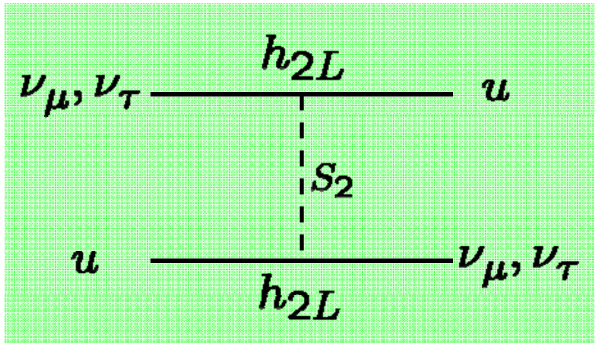


Only S_2 and V_3 cases are shown, today.
(The others are in our paper)
There is no special reason.

Leptoquarks (S_2)

$$L_{F=0} = \left[h_{2L}^{ijk}\overline{u}_{iR}l_{jL} + h_{2R}^{ijk}\overline{q}_{iL}i\tau_2 e_{jR}\right]S_{2k} + \widetilde{h}_{2L}^{ijk}\overline{d}_{iR}l_{jL}\widetilde{S}_{2k} + h.c. \quad (k = 1\cdots L)$$

$$= h_{2L}^{12k}\left(\overline{u}_R \nu_{\mu L}\right)S_{2k}^{-} + h_{2L}^{13k}\left(\overline{u}_R \nu_{\tau L}\right)S_{2k}^{-} + \widetilde{h}_{2L}^{12k}\left(\overline{d}_R \nu_{\mu L}\right)\widetilde{S}_{2k}^{-} + \widetilde{h}_{2L}^{13k}\left(\widetilde{d}_R \nu_{\tau L}\right)\widetilde{S}_{2k}^{-} + h.c.$$



$$V_{\nu_\mu} = \frac{3}{4}N\sum_{k=1}^{L}\frac{\left|h_{2L}^{12k}\right|^2}{M_{S_{2k}^-}^2}, \quad V_{\nu_\tau} = \frac{3}{4}N\sum_{k=1}^{L}\frac{\left|h_{2L}^{13k}\right|^2}{M_{S_{2k}^-}^2}$$

$$\xi_{S_2^-} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}} = -3\sum_{k=1}^{L}\frac{\left|h_{2L}^{12k}/M_{S_{2k}^-}\right|^2 - \left|h_{2L}^{13k}/M_{S_{2k}^-}\right|^2}{\left(g/M_W\right)^2}$$

For $M_{S_2^-} = 100\text{GeV}$ and $L = 1$

Current Limit

$$\left|\left|h_{2L}^{12}\right|^2 - \left|h_{2L}^{13}\right|^2\right| < 1.1\times10^{-3} \qquad \left(h_{2L}^{12}\right)^2 \le 1 \quad (\mu N \to \mu X)$$

$$\left|\left|\widetilde{h}_{2L}^{12}\right|^2 - \left|\widetilde{h}_{2L}^{13}\right|^2\right| < 1.1\times10^{-3} \qquad \left(\widetilde{h}_{2L}^{12}\right)^2 \le 2 \quad (\mu N \to \mu X)$$

Leptoquarks (V_3)

$$L_{F=0} = h_{3L}^{ijk}\left[\bar{q}_{iL}\vec{\tau}\gamma^{\mu}l_L\right]\vec{V}_{3k,\mu} \qquad (k=1\cdots L)$$
$$= h_{3L}^{12k}\left[\left(\bar{u}_L\gamma^{\mu}\nu_{\mu L}\right)V_{3k,\mu}^{0} + \sqrt{2}\left(\bar{d}_L\gamma^{\mu}\nu_{\mu L}\right)V_{3k,\mu}^{-}\right]$$
$$+ h_{3L}^{13k}\left[\left(\bar{u}_L\gamma^{\mu}\nu_{\tau L}\right)V_{3k,\mu}^{0} + \sqrt{2}\left(\bar{d}_L\gamma^{\mu}\nu_{\tau L}\right)V_{3k,\mu}^{-}\right] + h.c.$$

$$V_{\nu_\mu} = 3N\sum_{k=1}^{L}\left|h_{3L}^{12k}\right|^2\left[\frac{1}{2M_{V_{3k}^0}^2} + \frac{1}{M_{V_{3k}^-}^2}\right], \quad V_{\nu_\tau} = 3N\sum_{k=1}^{L}\left|h_{3L}^{13k}\right|^2\left[\frac{1}{2M_{V_{3k}^0}^2} + \frac{1}{M_{V_{3k}^-}^2}\right]$$

$$\xi_{\vec{V}_3} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}} = -\frac{6}{(g/M_W)^2}\sum_{k=1}^{L}\left(\left|h_{3L}^{12k}\right|^2 - \left|h_{3L}^{13k}\right|^2\right)\left[\frac{1}{M_{V_{3k}^0}^2} + \frac{2}{M_{V_{3k}^-}^2}\right]$$

For $M_{S_2^-} = 100\,\text{GeV}$ and $L=1$

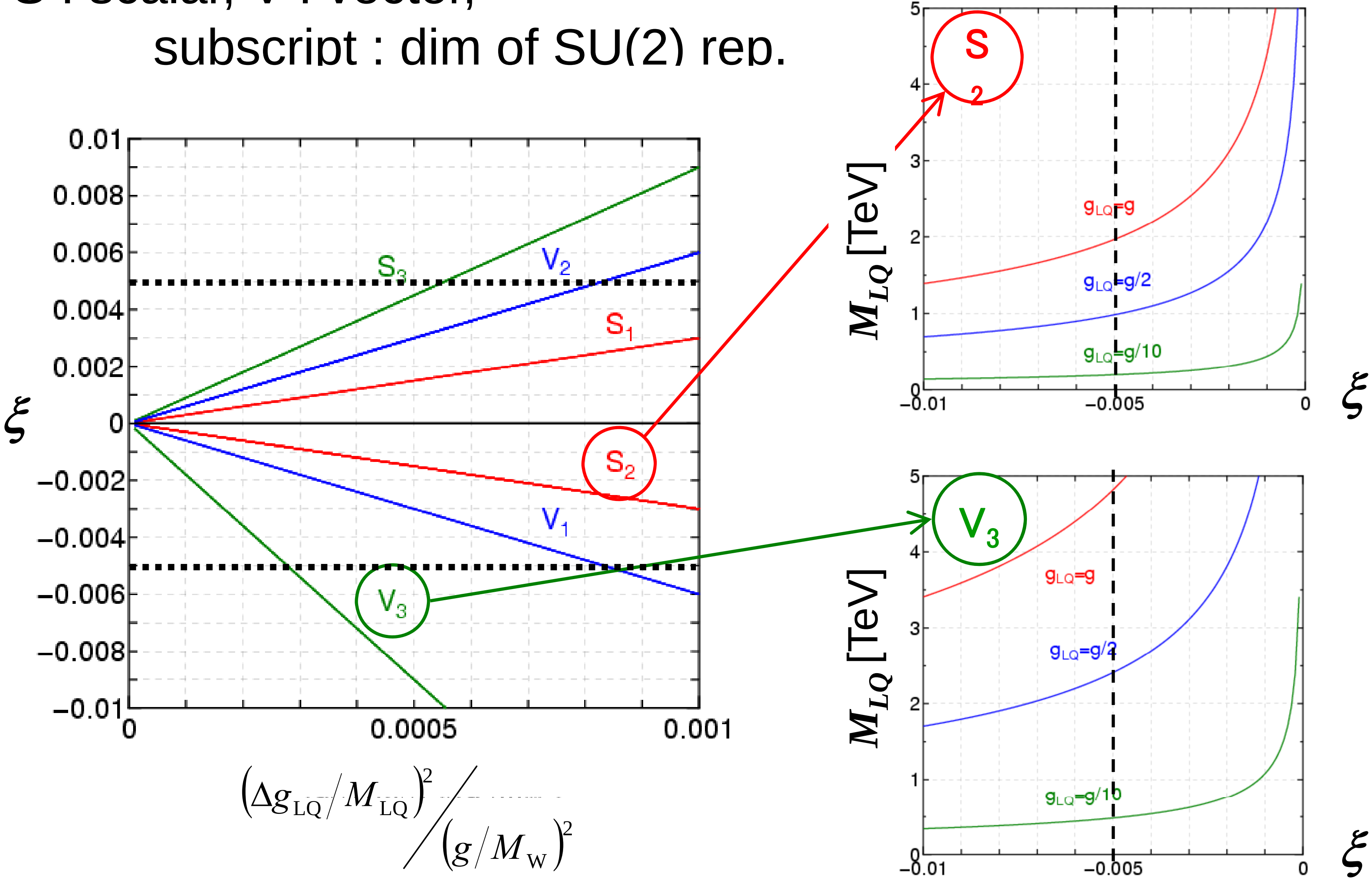
$$\left|\left|h_{3L}^{12}\right|^2 - \left|h_{3L}^{13}\right|^2\right| < 1.8\times10^{-4} \qquad \left(h_{3L}^{12}\right)^2 \le 0.004\,(R_\pi), \quad \left(h_{3L}^{13}\right)^2 \le 0.1\,(D\to\mu\nu)$$

Current Limit

Leptoquarks

S : scalar, V : vector,

subscript : dim of SU(2) rep.



SUSY
R-parity Violation

$$W_{\not{R}} = \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k + \frac{1}{2}\lambda''_{ijk}\hat{U}_i\hat{D}_j\hat{D}_k$$

tightly constrained by lepton univ.

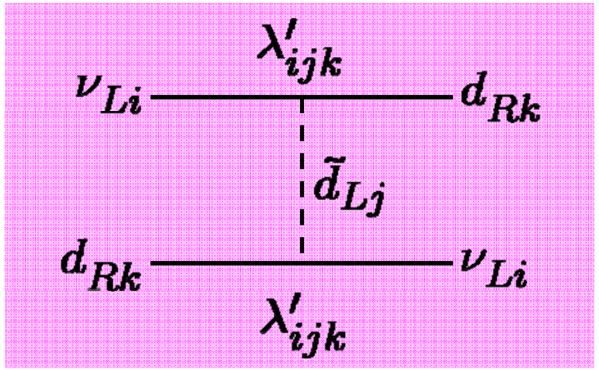
less stringent

irrelevant

SUSY

R-parity violation

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \underline{\lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k} + \frac{1}{2}\lambda''_{ijk}\hat{U}_i\hat{D}_j\hat{D}_k$$



Similar to S_1 and $\tilde{S}_2^-$ type leptoquarks

$$V_{\nu_\mu} = \sum_{j=1}^{3} \frac{3N}{4M_{\tilde{d}_j}^2}\left(\left|\lambda'_{2j1}\right|^2 - \left|\lambda'_{21j}\right|^2\right)$$

$$V_{\nu_\tau} = \sum_{j=1}^{3} \frac{3N}{4M_{\tilde{d}_j}^2}\left(\left|\lambda'_{3j1}\right|^2 - \left|\lambda'_{31j}\right|^2\right)$$

$$\xi_{\tilde{d}} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}} = -3\sum_{j=1}^{3}\frac{\left(\left|\lambda'_{2j1}\right|^2 - \left|\lambda'_{21j}\right|^2\right) - \left(\left|\lambda'_{3j1}\right|^2 - \left|\lambda'_{31j}\right|^2\right)}{\left(g/M_W\right)^2}\frac{1}{M_{\tilde{d}_j}^2} = -\frac{3\sqrt{2}}{8G_F}\frac{\Delta\lambda_{\tilde{d}}^2}{M_{\tilde{d}}^2}$$

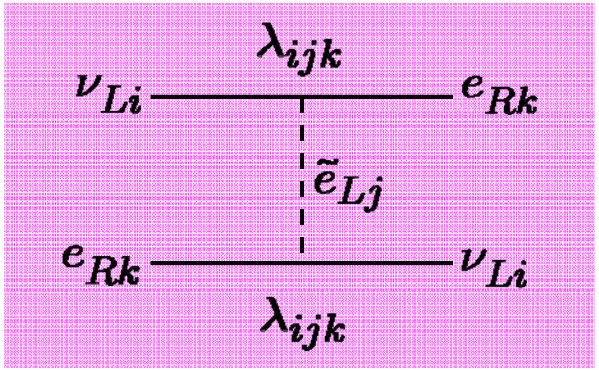
$$M_{\tilde{d}} \geq \sqrt{\left|\Delta\lambda_{\tilde{d}}^2\right|\frac{\sqrt{3}}{2}}\sqrt{\frac{1}{\sqrt{2}G_F\xi_{\tilde{d}}}} \approx 3.0[\mathrm{TeV}]\sqrt{\left|\Delta\lambda_{\tilde{d}}^2\right|}\left(\frac{0.005}{\xi_{\tilde{d}}}\right)^{1/2}$$

Current Limit
M_d>300GeV

SUSY

R-parity violation

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k + \frac{1}{2}\lambda''_{ijk}\hat{U}_i\hat{D}_j\hat{D}_k$$



Similar S_1, S_2^- and $\tilde{S}_2^-$ type leptoquarks

$$V_{\nu_\mu} = \frac{N}{4}\left(\sum_{i=1,3}\frac{|\lambda'_{i21}|^2}{M^2_{\tilde{e}_i}} - \sum_{i=1}^{3}\frac{|\lambda'_{21i}|^2}{M^2_{\tilde{e}_i}}\right)$$

$$V_{\nu_\tau} = \frac{N}{4}\left(\sum_{i=1,2}\frac{|\lambda'_{i31}|^2}{M^2_{\tilde{e}_i}} - \sum_{i=1}^{3}\frac{|\lambda'_{31i}|^2}{M^2_{\tilde{e}_i}}\right)$$

$$\xi_{\tilde{e}} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}} = -\frac{\sum_{i=1,3}|\lambda_{i21}|^2/M^2_{\tilde{e}_i} + \sum_{i=1,2}|\lambda_{i31}|^2/M^2_{\tilde{e}_i} - \sum_{i=1}^{3}\left(|\lambda_{21i}|^2 + |\lambda_{31i}|^2\right)/M^2_{\tilde{e}_i}}{(g/M_W)^2}$$

$$= -\frac{\sqrt{2}}{8G_F}\frac{\Delta\lambda^2_{\tilde{e}}}{M^2_{\tilde{e}}},$$

$$M_{\tilde{e}} \geq 1.7[\mathrm{TeV}]\sqrt{|\Delta\lambda^2_{\tilde{e}}|}\left(\frac{0.005}{\xi_{\tilde{e}}}\right)^{1/2}$$

Current Limit
$\lambda \sim O(10^{-2})$

Extended Higgs

triplet Higgs for neutrino mass

Extended Higgs Models

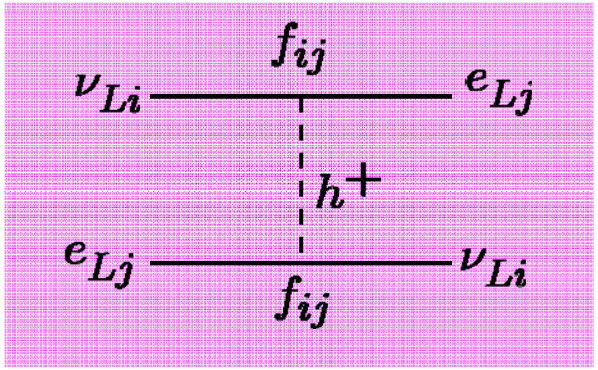
K.S.Babu, PLB203, 132 (88)
A.Zee, PLB93, 389 (80)
E.Accomande etal, hep-ph/0608079, p497

$$L = f_{ij}\left(\bar{l}^{C}_{iL}\, i\tau_2 l_{jL}\right)h^+ + h.c.$$
$$= -2\left(f_{e\mu}\bar{\nu}^{C}_{\mu} e_L + f_{e\tau}\bar{\nu}^{C}_{\tau} e_L\right)h^+ + h.c. + \cdots$$

f_{ij}: Yukawa couplings (anti-symmetric)
h^+: Higgs particle with Y=1

$$V_{\nu_\mu} = -N\frac{|f_{e\mu}|^2}{M^2_{h^+}}, \qquad V_{\nu_\tau} = -N\frac{|f_{e\tau}|^2}{M^2_{h^+}}$$

$$\xi_{h^+} = \frac{V_{\nu_\mu} - V_{\nu_\tau}}{2V_{NC}} = 4\frac{\left(|f_{e\mu}|^2 - |f_{e\tau}|^2\right)/M^2_{h^+}}{(g/M_W)^2} = \frac{4\sqrt{2}}{8G_F}\frac{\Delta\lambda^2_{h^+}}{M^2_{h^+}}$$



$$\left|\frac{|f_{e\mu}|^2 - |f_{e\tau}|^2}{M^2_{h^+}}\right| = \sqrt{2}G_F\xi_0 \approx 8.2\times10^{-8} \Longleftrightarrow 3.4\times10^{-8}\left(\tau^- \to \nu_\tau e^- \bar{\nu}_e\right)$$

Current Limit

Summary

- New Physics effects on neutrino oscillation
- FNAL -to- HK
  - $\xi_0 = (V_{\nu\mu} - V_{\nu\tau})/V_{NC} \sim 0.005$
  - (coupling / mass)^2
- Loop correction to the NC
- Direct interaction
  - ***Z'*** gauge boson
  - Leptoquarks
  - *R*-parity violation
  - Extended Higgs Model

Thank you very much for your attention

topcolor assisted technicolor

topcolor

top quark condensate gives rise to a triplet of NG bosons ⇔ ***W***,***Z***.

***top*-pions**

$$f_\pi^2 = m_t^2 \left(\frac{N_C}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2} \right), \qquad O(\mu) \sim O(m_t)$$

$f_\pi = 174\mathrm{GeV} \Leftrightarrow \Lambda \sim 10^{13-14}\mathrm{GeV}$ ⇔ large hierarchy ⇔ fine tuning of the c.c.

T.A.T.

$$SU(3)_S \times SU(3)_W \times U(1)_S \times U(1)_W \times SU(2)_L \xrightarrow{TechniC} SU(3)_C \times U(1)_Y \times SU(2)_L$$

$$\xrightarrow{TopC} SU(3)_C \times U(1)_{em}$$

$$F_\pi \approx 167\mathrm{GeV},\ TechniC \qquad f_\pi \approx 50\mathrm{GeV},\quad \Lambda_{TopC} \sim \mathrm{TeV}$$

The majority of the ***W*** and ***Z*** masses come from the technifermion condensate.

$\boxed{\begin{matrix} SU(3)_S \\ U(1)_S \end{matrix}} \begin{matrix} \times \\ \times \end{matrix} \boxed{\begin{matrix} SU(3)_W \\ U(1)_W \end{matrix}} \begin{matrix} \to \\ \to \end{matrix}$ $SU(3)_C$. : colorons and gluons

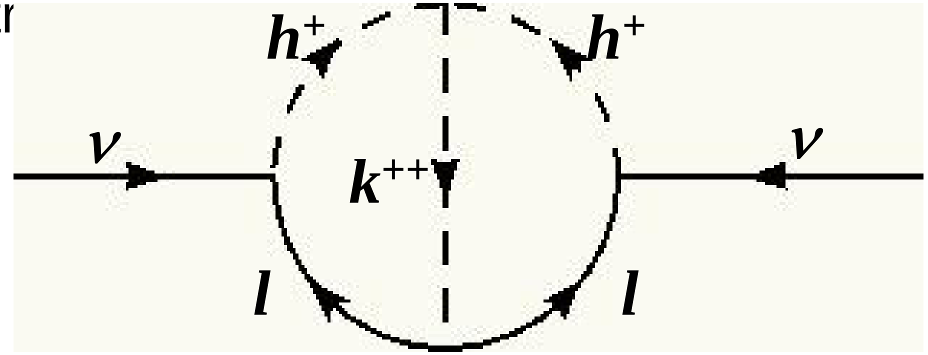
$U(1)_Y$: ***Z'*** and ***B***

3rd. gene. 1st. 2nd. gene.

Extended Higgs Models

$$L = f_{ij}\left(\bar{l}_{iL}^{C} i\tau_2 l_{jL}\right)h^{+} + h_{ij}\left(\bar{l}_{iR}^{C} l_{jR}\right)k^{++} - \mu h^{+}h^{+}k^{--} + h.c.$$

$\boldsymbol{f_{ij}}$: anti-symmetric, $\boldsymbol{h_{ij}}$: symmetri



$\boldsymbol{h^{+}}$: Higgs #*L* = -2
$\boldsymbol{k^{++}}$: Higgs #*L* = -2

$$(M_\nu)_{ij} = 8\mu f_{ia} m_a h^{*}_{ab} m_b f_{bj} \cdot I_{ab}$$

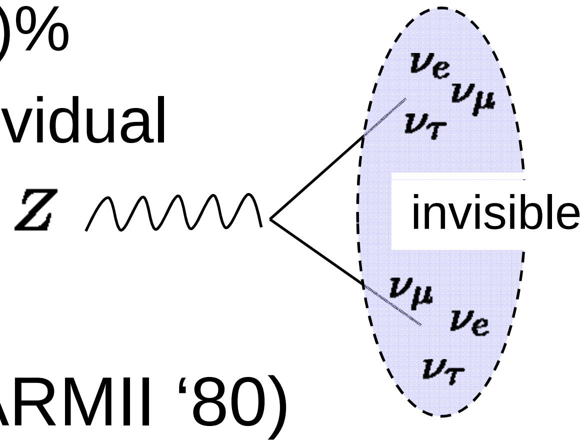
$$I_{ab} \approx \frac{1}{(16\pi^2)^2}\frac{1}{m_h^2}\tilde{I}\left(\frac{m_k^2}{m_h^2}\right)$$

$$\tilde{I}(r) = -\int_0^1 dx \int_0^{1-x} dy \frac{1-y}{x+(r-1)y+y^2}\log\frac{y(1-y)}{x+ry}$$


“ぺんぎんだいあぐらむ”って知ってる？
こんな格好でしょ？

Experimental Constraints (NC)

- Invisible decay width (LEP/SLC)
  - Invisible *Z* decay width, (20.00 ± 0.06)%
  - No information is available on the individual decay widths into each flavor.



- Individual decay width (CHARM/CHARMII '80)
  - *Z* couplings to neutrinos [PLB180,303('86), PLB320 203('94)]

$$\boxed{g^{\nu_e} : 0.528 \pm 0.085 \qquad g^{\nu_e} : 0.502 \pm 0.017}$$

$$g^{\nu_e}/g^{\nu_\mu} = 1.05^{+0.15}_{-0.18} \Rightarrow \boxed{0.9\text{-}1.2}$$

•**The theoretical possibility of universality violation in many models**

•**The weakness of the current experimental bounds**

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) %

CHARM,CHARM II

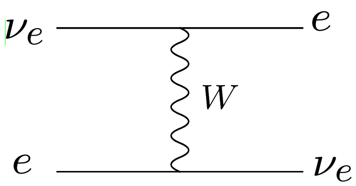
g^{ν_e}	0.528 ± 0.085
g^{ν_μ}	0.502 ± 0.017
g^{ν_e}/g^{ν_μ}	$1.05^{+0.15}_{-0.18}$

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


Yeah!!
Yeah!!

The effective potentials

- **charged current interaction**



$$\mathcal{M}_{CC} = -\frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu(1-\gamma_5)\nu_e][\bar{\nu}_e\gamma_\mu(1-\gamma_5)e]$$

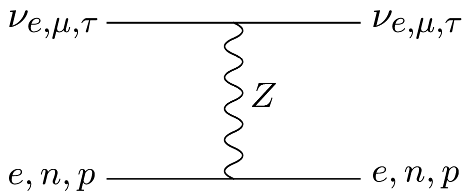
$\Downarrow$ ***Fierz tran.***

$$= +\frac{G_F}{\sqrt{2}}\underbrace{[\bar{e}\gamma^\mu(1-\gamma_5)e]}_{N_e}\underbrace{[\bar{\nu}_e\gamma_\mu(1-\gamma_5)\nu_e]}_{2}$$

$\Rightarrow$ $\boxed{V_{CC} = \sqrt{2}G_F N_e}$

N_e: electron number density in matter

- **neutral current interaction**



$$\mathcal{M}_{NC} = \rho\frac{G_F}{\sqrt{2}}\underbrace{[\bar{\nu}_\alpha\gamma^\mu(1-\gamma_5)\nu_\alpha]}_{2} \qquad (\alpha = e, \mu, \tau)$$

$$\times\left[g_L^f\underbrace{\bar{\psi}_f\gamma_\mu(1-\gamma_5)\psi_f}_{N_f} + g_R^f\underbrace{\bar{\psi}_f\gamma_\mu(1+\gamma_5)\psi_f}_{N_f}\right]$$

$$g_L^f = I_3^f - Q_f\sin^2\theta_W, \quad g_R^f = -Q_f\sin^2\theta_W \qquad (f = e, n, p)$$

$$g_L^f + g_R^f = I_3^f - 2Q_f\sin^2\theta_W$$

$f = e^-$: $(-1/2) - 2(-1)\sin^2\theta_W$

p : $(+1/2) - 2(+1)\sin^2\theta_W$

$\Big\}$ 0

n : $(-1/2) - 2(0)\sin^2\theta_W \sim -\frac{1}{2}$

$\Rightarrow$

$$V_{NC} = \rho\sqrt{2}G_F N_f(g_L^f + g_R^f)$$

$$= \rho\sqrt{2}G_F N_n(-1/2)$$

$$\boxed{\begin{aligned} V_{NC} &\approx (-\sqrt{2}/2)G_F N_n \\ &\approx (-1/2)V_{CC} \end{aligned}}$$

N_n : neutron number density

effective mixing angles (normal)

$$\delta = 0 \text{ case, expanded in powers of } \varepsilon \equiv \sqrt{\frac{\delta m_{21}^2}{\left|\delta m_{31}^2\right|}} = 0.15 \sim 0.24$$

$$\text{in the region of } \frac{a}{\left|\delta m_{31}^2\right|} \sim O\left(\varepsilon^{-1}\right): \left(E(\text{GeV}) \sim O(10)\right), \xi \sim O\left(\varepsilon^2\right)$$

neutrino

$$\tilde{\theta}_{13} = \theta'_{13} \approx \frac{\pi}{2} - \left(\frac{\delta m_{31}^2}{a}\right)\theta_{13}$$

$$\tilde{\theta}_{12} = \frac{\pi}{2} - \frac{c_{13}}{c'_{13}}\left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12} \boxed{-\xi \frac{a}{2\delta m_{31}^2}}$$

$$\tilde{\theta}_{23} = \theta_{23} + \frac{s_\phi}{c'_{13}}\left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12}$$

$$\tilde{\delta} = 0$$

$$\left(\phi = \frac{\pi}{2} - \theta_{13} - \left(\frac{\delta m_{31}^2}{a}\right)\theta_{13}\right)$$

anti - neutrino

$$\tilde{\theta}_{13} = \theta'_{13} \approx \left(\frac{\delta m_{31}^2}{a}\right)\theta_{13}$$

$$\tilde{\theta}_{12} = \left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12}$$

$$\tilde{\theta}_{23} = \theta_{23} \boxed{+\xi \frac{a}{2\delta m_{31}^2}}$$

$$\tilde{\delta} = 0$$

effective mixing angles (inverted)

$$\delta = 0 \text{ case,} \quad \text{expanded in powers of } \varepsilon \equiv \sqrt{\frac{\delta m_{21}^2}{\left|\delta m_{31}^2\right|}} = 0.15 \sim 0.24$$

$$\text{in the region of } \frac{a}{\left|\delta m_{31}^2\right|} \sim O\left(\varepsilon^{-1}\right) : \left(E(\text{GeV}) \sim O(10)\right), \ \xi \sim O\left(\varepsilon^2\right)$$

neutrino

$$\tilde{\theta}_{13} = \theta'_{13} \approx -\left(\frac{\delta m_{31}^2}{a}\right)\theta_{13}$$

$$\tilde{\theta}_{12} = \frac{\pi}{2} - \left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12}$$

$$\tilde{\theta}_{23} = \theta_{23} \boxed{+\xi\frac{a}{2\left|\delta m_{31}^2\right|}}$$

$$\tilde{\delta} = 0$$

anti-neutrino

$$\tilde{\theta}_{13} = \theta'_{13} \approx \frac{\pi}{2} + \left(\frac{\delta m_{31}^2}{a}\right)\theta_{13}$$

$$\tilde{\theta}_{12} = \frac{c_{13}}{c'_{13}}\left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12} \boxed{-\xi\frac{a}{2\left|\delta m_{31}^2\right|}}$$

$$\tilde{\theta}_{23} = \theta_{23} - \frac{s_\phi}{c'_{13}}\left(\frac{\delta m_{21}^2}{2a}\right)\sin 2\theta_{12}$$

$$\tilde{\delta} = 0$$

$$\left(\phi = \frac{\pi}{2} - \theta_{13} - \left(\frac{\left|\delta m_{31}^2\right|}{a}\right)\theta_{13}\right)$$

shift of effective mixing by ξ

	neutrino	***anti-neutrino***
normal hierarchy	$\tilde{\theta}_{12}$ is shifted by $-\frac{a}{2\left\|\delta m_{31}^2\right\|}\xi$	$\tilde{\theta}_{23}$ is shifted by $+\frac{a}{2\left\|\delta m_{31}^2\right\|}\xi$
inverted hierarchy	$\tilde{\theta}_{23}$ is shifted by $+\frac{a}{2\left\|\delta m_{31}^2\right\|}\xi$	$\tilde{\theta}_{12}$ is shifted by $-\frac{a}{2\left\|\delta m_{31}^2\right\|}\xi$

in the region of

$$\frac{a}{\left|\delta m_{31}^2\right|} \approx O\left(\varepsilon^{-1}\right) : \left(E(\mathrm{GeV}) \sim O(10)\right), \quad \xi \approx O\left(\varepsilon^2\right), \quad \left(\varepsilon \equiv \sqrt{\frac{\delta \mathrm{m}_{21}^2}{\left|\delta m_{31}^2\right|}} = 0.15 \sim 0.24\right)$$

Survival Probability

$$\tilde{P}(\nu_\mu \to \nu_\mu) = 1 - 4|\tilde{U}_{\mu 2}|^2\left(1 - |\tilde{U}_{\mu 2}|^2\right)\sin^2\frac{\tilde{\Delta}_{21}}{2} - 4|\tilde{U}_{\mu 3}|^2\left(1 - |\tilde{U}_{\mu 3}|^2\right)\sin^2\frac{\tilde{\Delta}_{31}}{2}$$
$$+ 2|\tilde{U}_{\mu 2}|^2|\tilde{U}_{\mu 3}|^2\left(4\sin^2\frac{\tilde{\Delta}_{21}}{2}\sin^2\frac{\tilde{\Delta}_{31}}{2} + \sin\tilde{\Delta}_{21}\sin\tilde{\Delta}_{31}\right)$$
$$\tilde{U}_{\mu 2} = \tilde{c}_{12}\tilde{c}_{23} - \tilde{s}_{12}\tilde{s}_{13}\tilde{s}_{23}, \qquad \tilde{U}_{\mu 3} = \tilde{c}_{13}\tilde{s}_{23}$$

neutrino (normal hierarchy)

$$\tilde{U}_{\mu 2} \approx \cos(\tilde{\theta}_{12} + \tilde{\theta}_{23}), \qquad \tilde{U}_{\mu 3} \approx 0$$
$$\tilde{P}(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2\left[2\left(\theta_{23} \boxed{- \frac{a}{2|\delta m_{31}^2|}\xi}\right)\right]\sin^2\frac{\tilde{\Delta}_{21}}{2}$$
$$\tilde{\Delta}_{21} \approx \delta m_{31}^2 c_{13}^2 - \delta m_{21}^2 c_{12}^2$$

anti - neutrino (normal hierarchy)

$$\tilde{U}_{\mu 2} \approx \tilde{c}_{23}, \qquad \tilde{U}_{\mu 3} \approx \tilde{s}_{23}$$
$$\tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2\left[2\left(\theta_{23} \boxed{+ \frac{a}{2|\delta m_{31}^2|}\xi}\right)\right]\sin^2\frac{\tilde{\Delta}_{32}}{2}$$
$$\tilde{\Delta}_{32} \approx \delta m_{31}^2 c_{13}^2 - \delta m_{21}^2 c_{12}^2$$

neutrino (inverted hierarchy)

$$\tilde{U}_{\mu 2} \approx 0, \qquad \tilde{U}_{\mu 3} \approx \tilde{s}_{23}$$
$$\tilde{P}(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2\left[2\left(\theta_{23} \boxed{+ \frac{a}{2|\delta m_{31}^2|}\xi}\right)\right]\sin^2\frac{\tilde{\Delta}_{31}}{2}$$
$$\tilde{\Delta}_{31} \approx \delta m_{31}^2 c_{13}^2 - \delta m_{21}^2 c_{12}^2$$

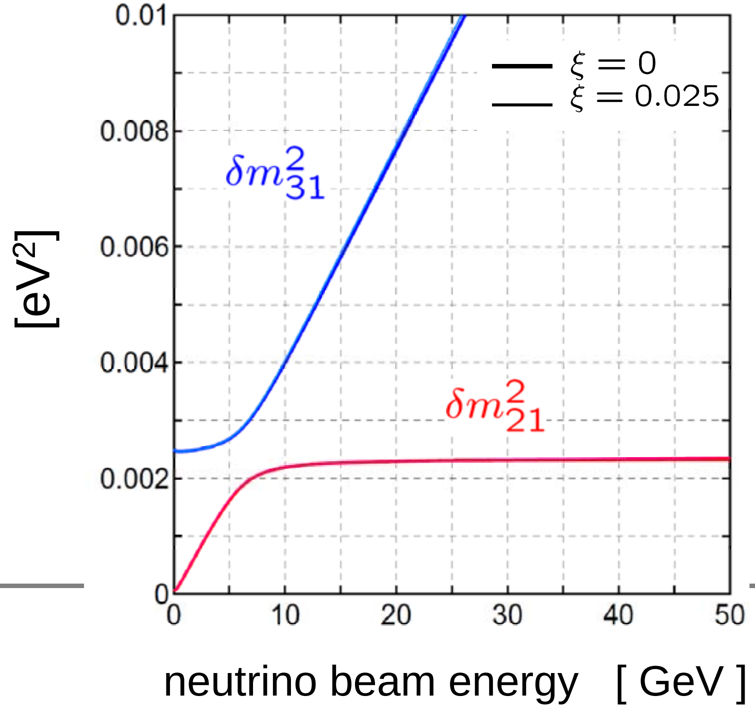
anti - neutrino (inverted hierarchy)

$$\tilde{U}_{\mu 2} \approx \cos(\tilde{\theta}_{12} + \tilde{\theta}_{23}), \qquad \tilde{U}_{\mu 3} \approx 0$$
$$\tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2\left[2\left(\theta_{23} \boxed{- \frac{a}{2|\delta m_{31}^2|}\xi}\right)\right]\sin^2\frac{\tilde{\Delta}_{21}}{2}$$
$$\tilde{\Delta}_{21} \approx -\delta m_{31}^2 c_{13}^2 + \delta m_{21}^2 c_{12}^2$$

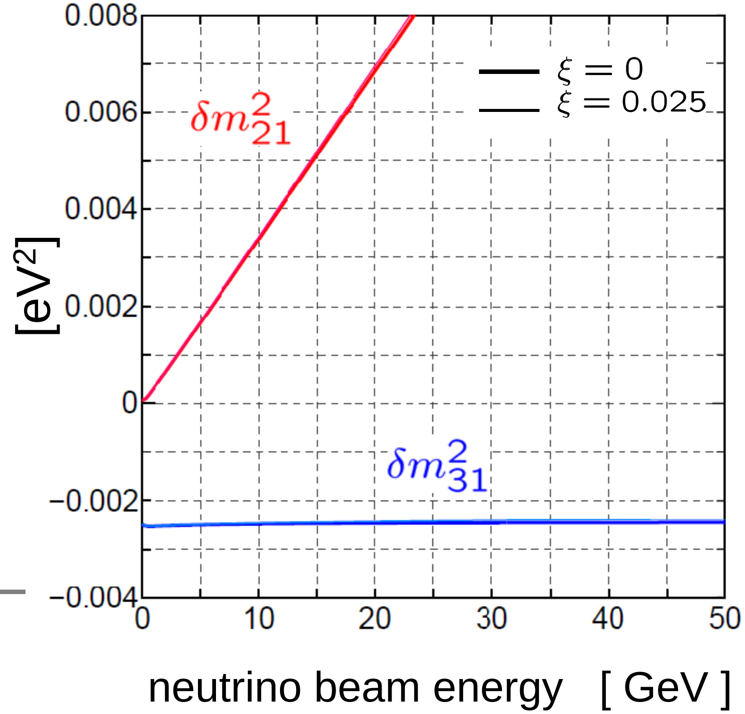
The energy dependence of the effective mass squared differences

matter density	=	4.6 g/cm^3	$\sin^2(2\theta_{atm})$	=	1.0	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			

normal hierarchy



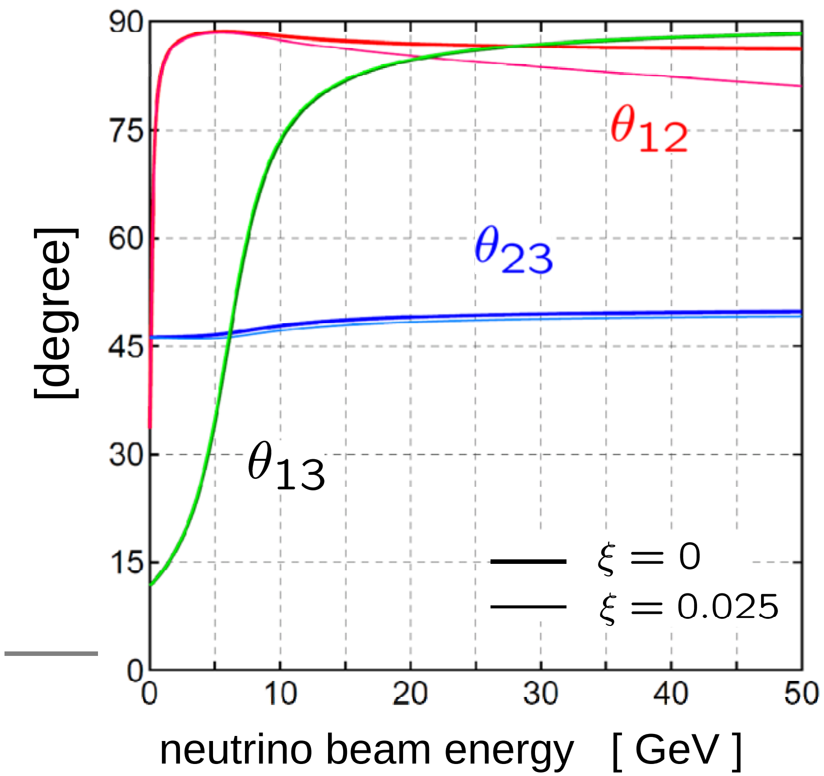
inverted hierarchy



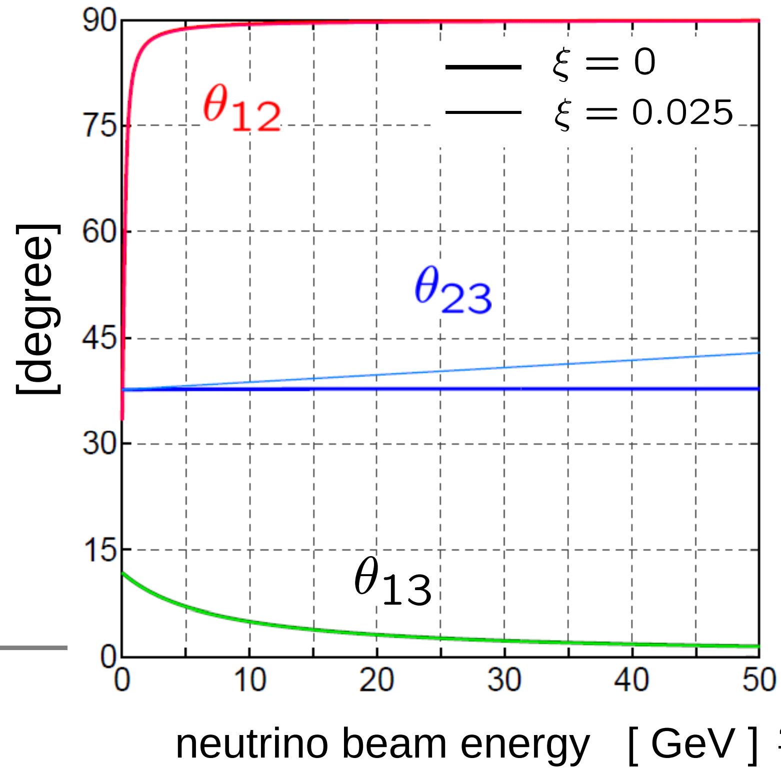
The energy dependence of the effective mixing angles

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

normal hierarchy



inverted hierarchy



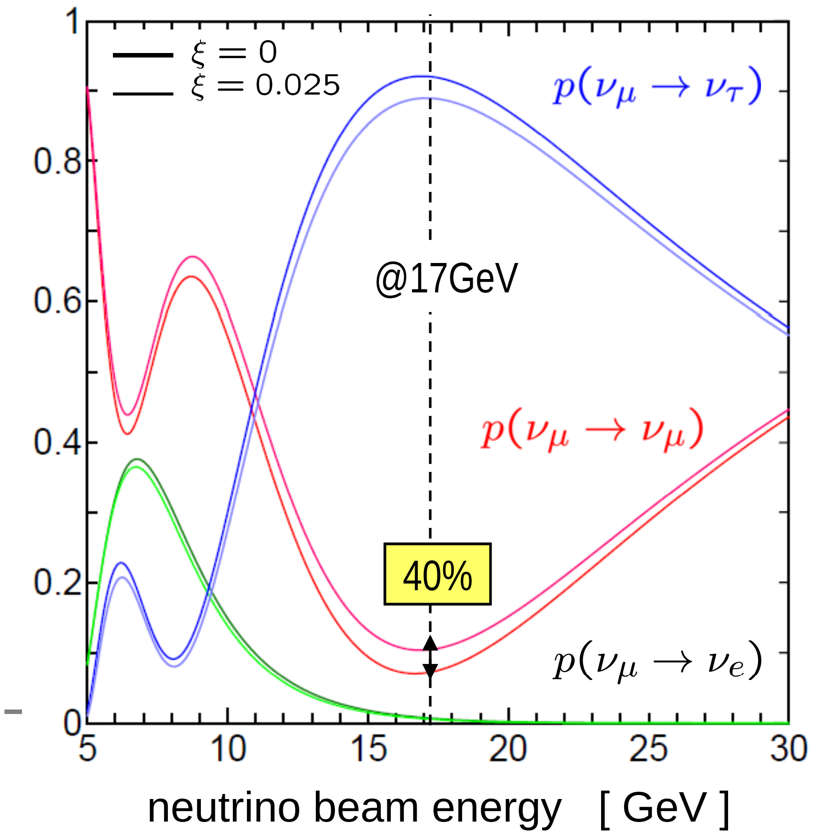
The oscillation probabilities (L=9,120km)

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

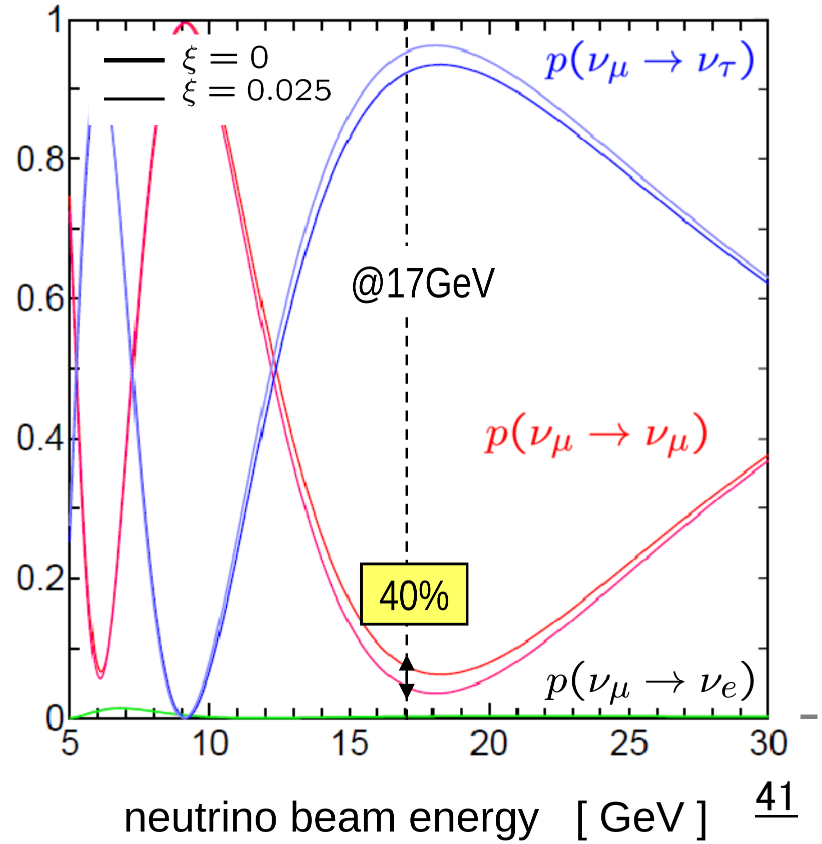
matter density $= 4.6\ g/cm^3$	$\sin^2(2\theta_{atm}) = 0.92$	$\delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$
CP phase $\delta = 0$	$\tan^2(\theta_{sun}) = 0.40$	$\delta m^2_{21} = 8.0 \times 10^{-5}\ eV^2$
	$\sin^2(2\theta_{rct}) = 0.16$	

$\theta_{atm} < \pi/4$

normal hierarchy



inverted hierarchy

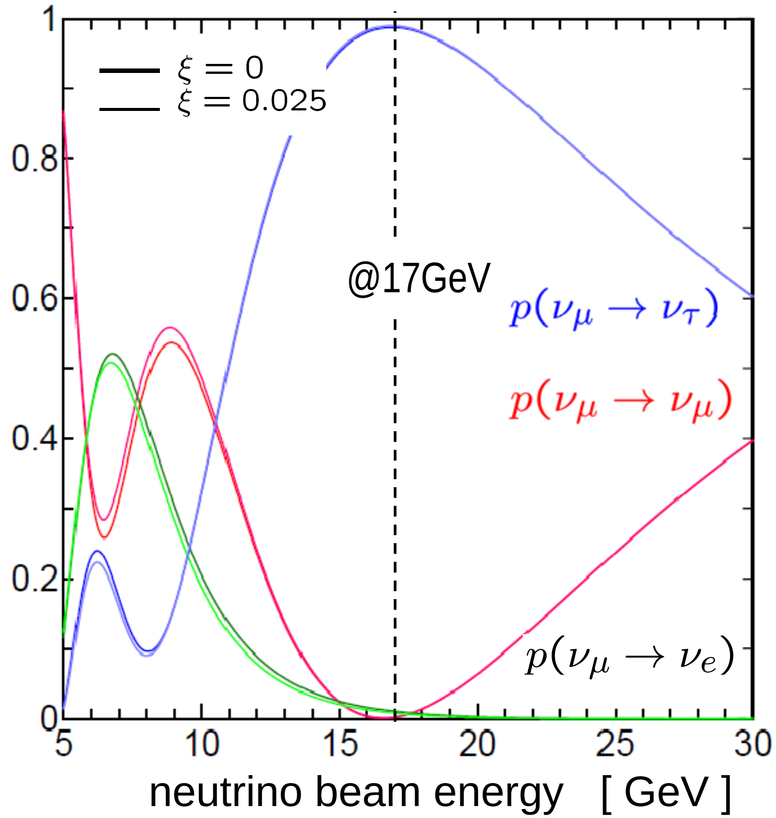


The oscillation probabilities (L=9,120km)

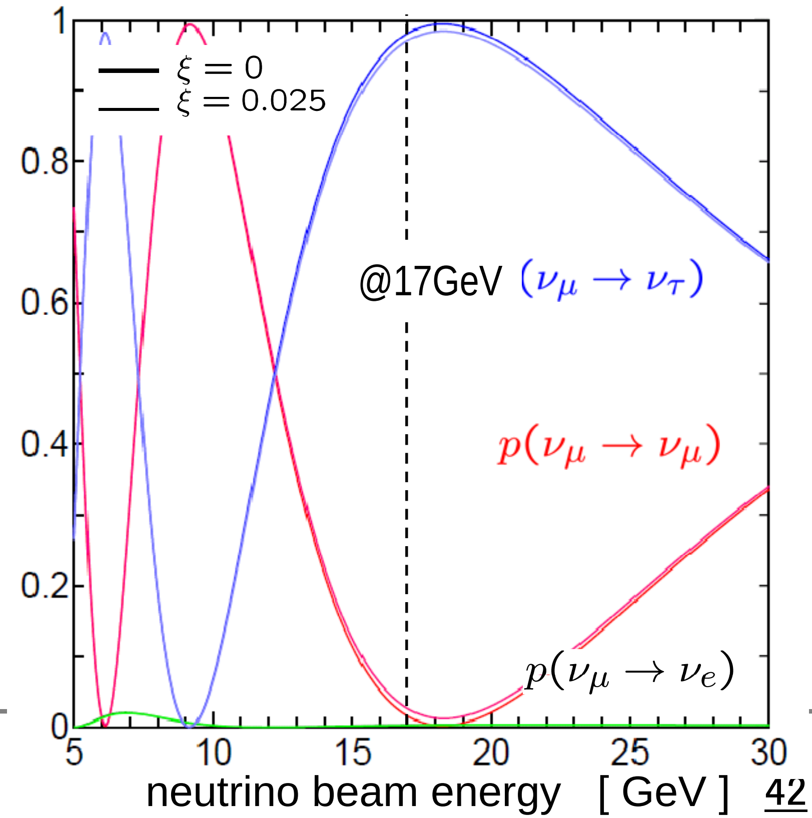
$\sin(2\theta_{atm}) = \sin\theta_{23}\cos\theta_{13} \approx \sin\theta_{23}$

matter density $= 4.6\ g/cm^3$	$\sin^2(2\theta_{atm}) = 1$	$\delta m^2_{31} = 2.5\times10^{-3}\ eV^2$
CP phase $\delta = 0$	$\tan^2(\theta_{sun}) = 0.40$	$\delta m^2_{21} = 8.0\times10^{-5}\ eV^2$
	$\sin^2(2\theta_{rct}) = 0.16$	

normal hierarchy

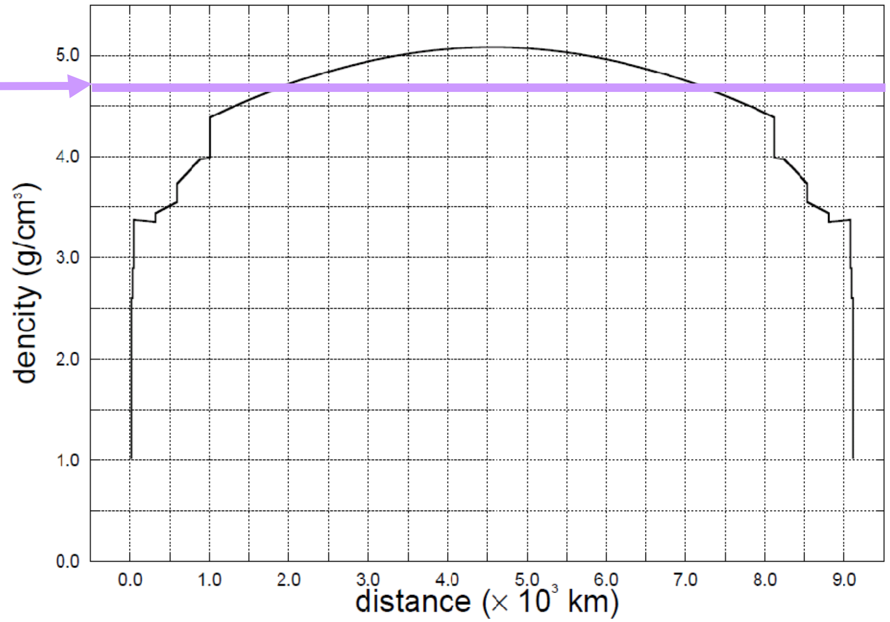


inverted hierarchy

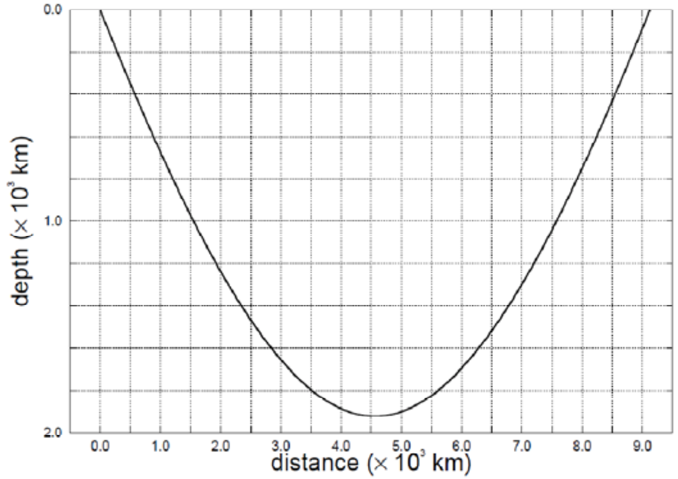


Matter Profile

density (FNAL⇔HK)



depth (FNAL⇔HK)



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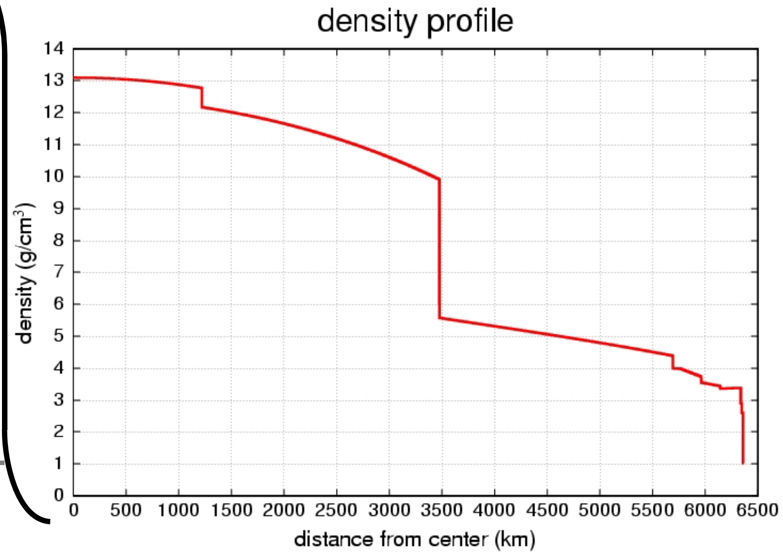

average matter density

$$\rho = 4.6 \text{ g/cm}^3$$