Making use of ν_e from muon storage ring

Brief review on T-violation and neutrino factory, and NuTRISTAN

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Hokkaido Workshop on Particle Physics at Crossroads
@Hokkaido University

- Three generation and CP violation
- Why T-violation instead of CP violation
- Review on NuFACT
- Towards “Nu”TRISTAN

1.Three generation and CP Violation

Long (long ?) ago, there was question whether neutrinos are massive and hence there is a lepton mixing.

Theory :

G321 (SM) ->G3221->G422 (Pati-Salam) -> SO (10) GUT

Neutrinos are massive since "RH neutrinos" are introduced.

Dirac mass with RH neutrino (SM singlet fermion) and possibly very small masses due to seesaw mechanism

$$G_{321} \equiv SU(3)\times SU(2)_L \times U(1)_Y \to G_{3221} \equiv SU(3)\times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{matrix} u_L^c \\ d_L^c \end{matrix} \longrightarrow Q_L^c = \begin{pmatrix} u_R^c \\ d_R^c \end{pmatrix}$$

$$(3, 2, \tfrac{1}{6}) \longrightarrow (3, 2, 1, \tfrac{1}{6}) \qquad \begin{matrix} (\bar{3}, 1, -\frac{2}{3}) \\ (\bar{3}, 1, \frac{1}{3}) \end{matrix} \longrightarrow (\bar{3}, 1, 2, -\tfrac{1}{6})$$

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{matrix} \blacksquare \\ e_L^c \end{matrix} \longrightarrow L_L^c = \begin{pmatrix} \nu_L^c \\ e_L^c \end{pmatrix}$$

$$(1, 2, -\tfrac{1}{2}) \longrightarrow (1, 2, 1, -\tfrac{1}{2}) \qquad (1, 1, 1) \longrightarrow (1, 1, 2, \tfrac{1}{2})$$

By noting that the ratio of U(1) is 1:-3 $SU(3)\times U(1) \to SU(4)$ $G_{3221} \to G_{422}$

$$\Rightarrow (4, 2, 1) \qquad \Rightarrow (\bar{4}, 1, 2)$$

Since $\mathrm{SU}(4)\simeq\mathrm{SO}(6)$ & $\mathrm{SU}(2)\times\mathrm{SU}(2)\simeq\mathrm{SO}(4)$

$$\mathrm{G}_{422}\subset\mathrm{SO}(10)$$

All particle of one generation is unified into ONE PARTICLE

$$\mathrm{SO}(10)\ 16$$

We have Standard Model singlet which can be interpreted as RH neutrino

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Experiment:

Solar Neutrino Deficit

Not enough neutrinos coming from the sun

& Atmospheric Neutrino Anomaly

Counts of Neutrino from atmosphere is strange

Both can be explained by Neutrino oscillation with

large lepton mixing ,,,

However …

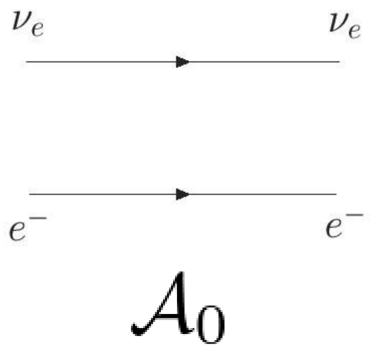
Pathological preconceptions that

Mixing MUST be small

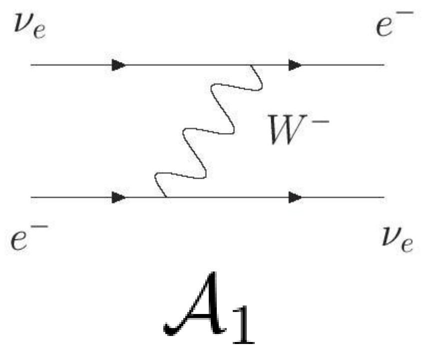
though it may be natural because of GUT …

The Savior = Matter effect =
MSW (Mikeyev Smirnov and Wolfenstein) effect

Refraction phenomeno when neutrino goes through matter like the sun and the earth



Go through



Forward Scattering

Propagating in matter
We cannot distinguish them
-> They interfere each other

$$\mathcal{M} = \mathcal{A}_0 + \mathcal{A}_1 \to |\mathcal{M}|^2 = \mathcal{A}_0^2 + 2\mathrm{Re}\left(\mathcal{A}_0 \mathcal{A}_1^*\right)$$

$$\mathcal{A}_1 \simeq G_F(\bar{\psi}_e \gamma^\mu \psi_{\nu_e})(\bar{\psi}_{\nu_e} \gamma_\mu \psi_e) = G_F(\bar{\psi}_e \gamma^\mu \psi_e)(\bar{\psi}_{\nu_e} \gamma_\mu \psi_{\nu_e})$$

Non relativistic limit

$$\to G_F(\bar{e}\gamma^0 e)(\bar{\nu}_e \gamma_0 \nu_e)$$

Modulation of **electron neutrino** energy

Framework of standard 3 flavor ν oscillation in matter

Here, matter density is constant.
$+$ for ν, $-$ for $\bar{\nu}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(\bar{\nu}_e)\\ \nu_\mu(\bar{\nu}_\mu)\\ \nu_\tau(\bar{\nu}_\tau)\end{pmatrix} = \left[U\mathrm{diag}(0,\Delta E_{21},\Delta E_{31})U^\dagger + \mathrm{diag}(\pm A,0,0)\right]\begin{pmatrix}\nu_e(\bar{\nu}_e)\\ \nu_\mu(\bar{\nu}_\mu)\\ \nu_\tau(\bar{\nu}_\tau)\end{pmatrix}$$

$$= \widetilde{U}^{(\pm)}\mathrm{diag}(\tilde{E}_1^{(\pm)},\tilde{E}_2^{(\pm)},\tilde{E}_3^{(\pm)})\widetilde{U}^{(\pm)\dagger}\begin{pmatrix}\nu_e(\bar{\nu}_e)\\ \nu_\mu(\bar{\nu}_\mu)\\ \nu_\tau(\bar{\nu}_\tau)\end{pmatrix}$$

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

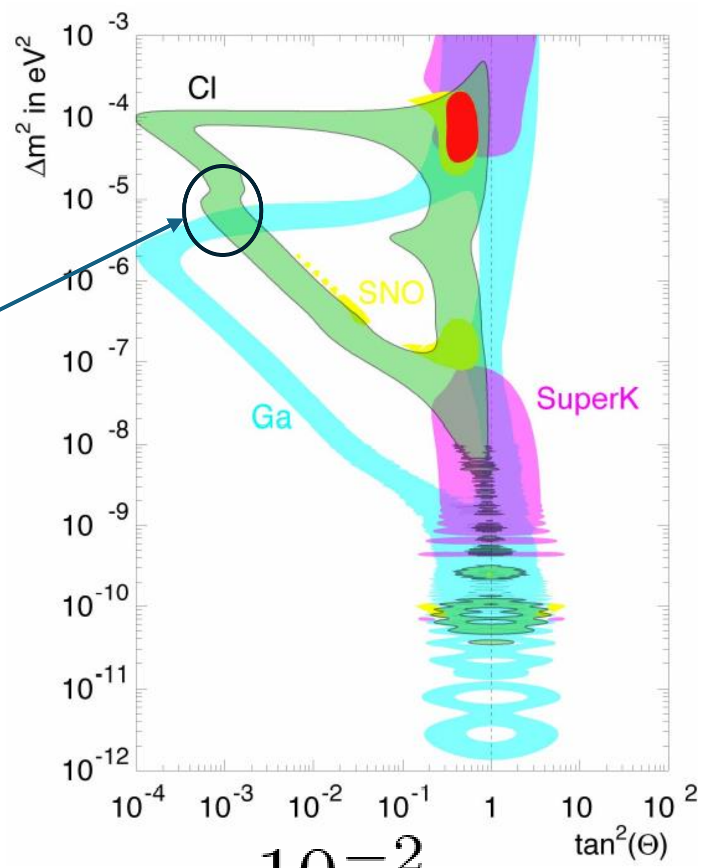
CP phase

Matter effect saved the small mixing partially.

Solar neutrino deficit could be explained by small mixing.
In the sun, with an appropriate parameter for neutrinos, even with small mixing, effectively they mix largely.

Fredman NOON2004

Large mixing also explains with matter effect appropriately …



10^{-2}

At the beginning
Small mixing was prefered
even with Kamiokande.

However Atomospheric Neutrino anomaly was not …

Oscillation probability in matter

$$P\left(\nu_\alpha(\bar{\nu}_\alpha) \to \nu_\beta(\bar{\nu}_\beta)\right)$$

$$= \delta_{\alpha\beta} - 4\sum_{j>k} Re[\widetilde{U}^{(\pm)}{}_{\beta j}\widetilde{U}^{(\pm)}{}^{*}_{\alpha j}\widetilde{U}^{(\pm)}{}^{*}_{\beta k}\widetilde{U}^{(\pm)}{}_{\alpha k}]\ \sin^2\left(\frac{\Delta\tilde{E}^{(\pm)}_{jk}L}{2}\right)$$

$$+2\sum_{j>k} Im[\widetilde{U}^{(\pm)}{}_{\beta j}\widetilde{U}^{(\pm)}{}^{*}_{\alpha j}\widetilde{U}^{(\pm)}{}^{*}_{\beta k}\widetilde{U}^{(\pm)}{}_{\alpha k}]\sin\left(\Delta\tilde{E}^{(\pm)}_{jk}L\right)$$

CP-violation

$$P\left(\nu_\alpha \to \nu_\beta\right) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Complicated contributions of matter effect and CP phase δ

T-violation

$$P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\nu_\beta \to \nu_\alpha\right)$$

Not complicated contributions of matter effect and CP phase δ

2.CP Violation? T Violation?

Phys.Rev.D 55 (1997) 1653-1658 Arafune, JS

Phys.Rev.D 56 (1997) 3093-3099, Phys.Rev.D 60 (1999) 119905 (erratum) Arafune, Koike, JS

Nucl.Instrum.Meth.A 451 (2000) 36-41 JS

1996-

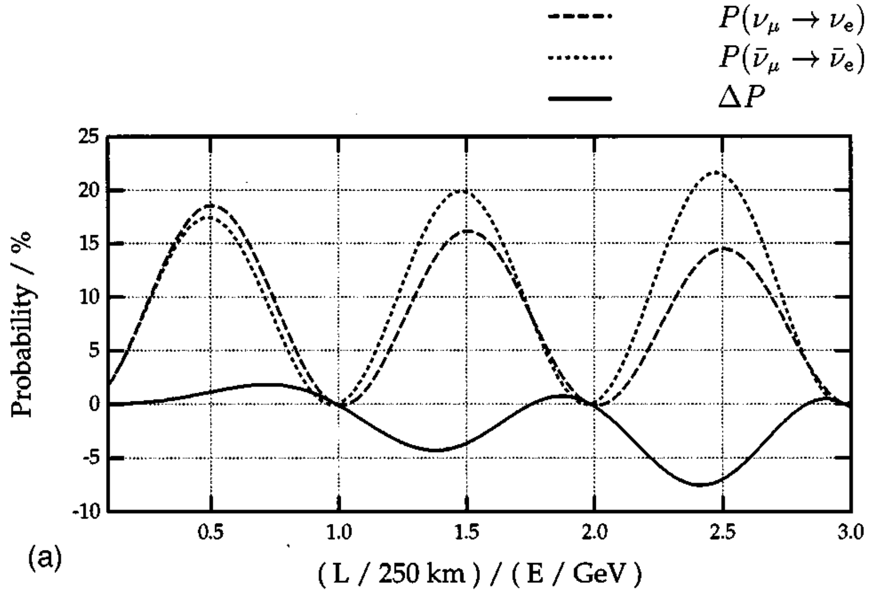
Theory :: Small mixing is believed

but Solar ν (θ_{12}) Small->Large , Atm (θ_{23}) Large

Last mixing (θ_{13}) upper bound $\sim$ 0.1

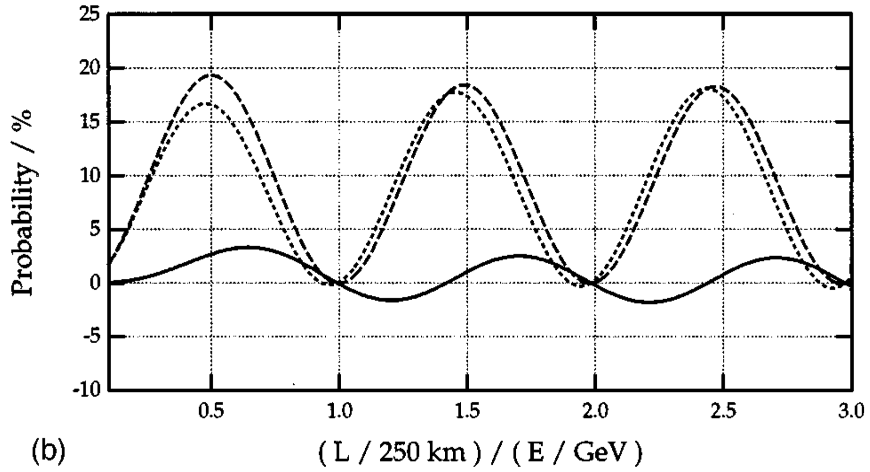
Experiment :: K2K under construction

If both are large, CP violation can be observed in K2K !?



(a)

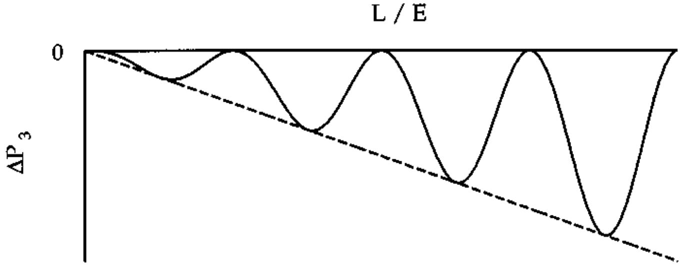
$$\delta = \frac{\pi}{2}$$



(b)

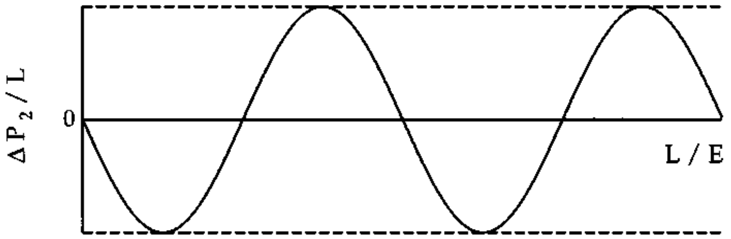
$$\delta = 0$$

We discussed if we observe CPV effect in near future ecperiment with “Maximum parameter”



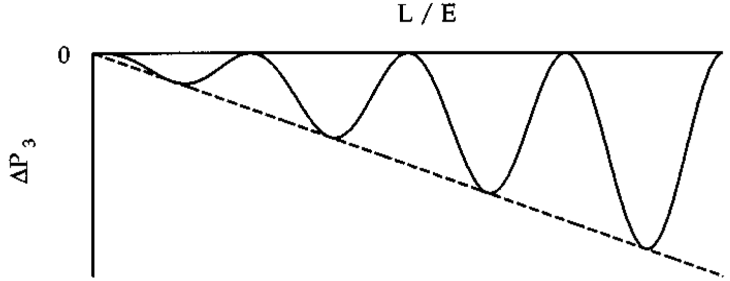
(c)

Includint to observe not only first maximum but this envelope



(b)

Matter effect



(c)

CPV

If we observe only first maximum can we distinguish them clearly ?

On the contrary T violation is very clear !!

Oscillation probability in matter

$$P\left(\nu_\alpha(\bar{\nu}_\alpha) \to \nu_\beta(\bar{\nu}_\beta)\right)$$
$$= \delta_{\alpha\beta} - 4\sum_{j>k} Re[\widetilde{U}^{(\pm)}{}_{\beta j}\widetilde{U}^{(\pm)}{}^*_{\alpha j}\widetilde{U}^{(\pm)}{}^*_{\beta k}\widetilde{U}^{(\pm)}{}_{\alpha k}]\ \sin^2\left(\frac{\Delta\tilde{E}^{(\pm)}_{jk}L}{2}\right)$$
$$+2\sum_{j>k} Im[\widetilde{U}^{(\pm)}{}_{\beta j}\widetilde{U}^{(\pm)}{}^*_{\alpha j}\widetilde{U}^{(\pm)}{}^*_{\beta k}\widetilde{U}^{(\pm)}{}_{\alpha k}]\sin\left(\Delta\tilde{E}^{(\pm)}_{jk}L\right)$$

CP-violation

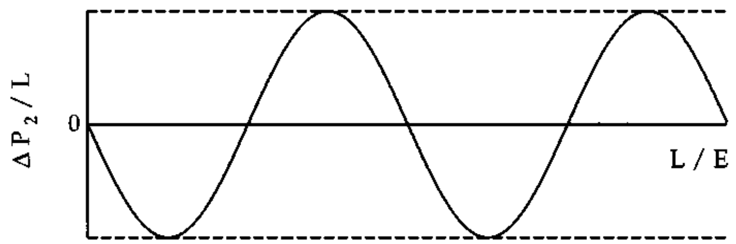
$$P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right)$$

Complicated contributions of matter effect and CP phase δ

T-violation

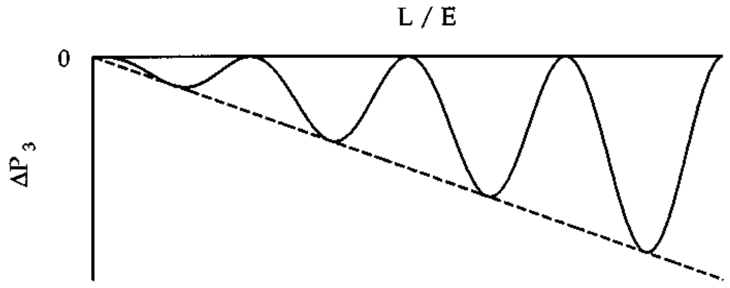
$$P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\nu_\beta \to \nu_\alpha\right)$$

Not complicated contributions of matter effect and CP phase δ



(b)

Matter effect



(c)

CPV

If we observe only first maximum can we distinguish them clearly ?

On the contrary T violation is very clear !!

However we need ν_e

Kuno-san told me it is easy to get !! It's from muon beam !!

First step for muon collider

3. Neutrino Factory

Phys.Rev.D57:6989-6997,1998; Erratum-ibid.D59:039903,1999 S.Geer

Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential

Basic Concept

大艦巨砲主義 policy of using large ships as a weapon

Game of number of events

1. Charged Current Cross Section $\sigma_{\nu(\bar{\nu})N} \sim 0.67(0.34) \times 10^{-38}\mathrm{cm}^2 E_{\nu(\bar{\nu})}[\mathrm{GeV}]$

Proportional to neutrino energy -> **Higher energy !** for high statistics

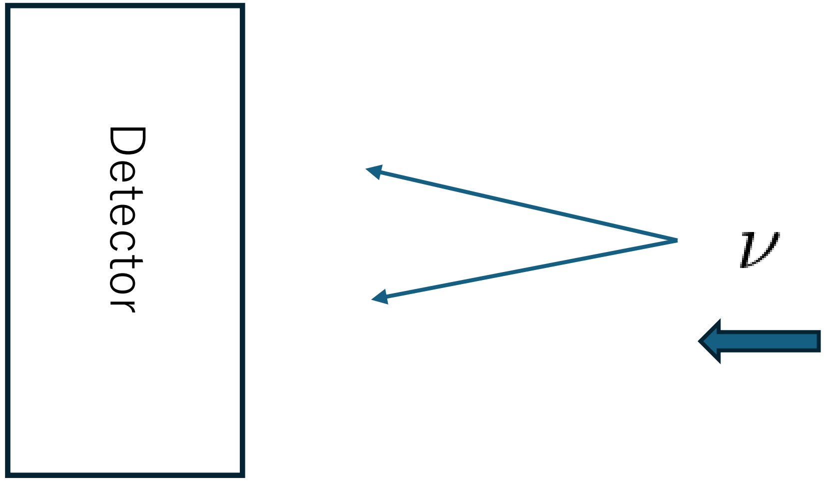
2.Oscillation Probability $\sim \sin^2 \frac{\delta m^2 L}{E}$

Higher energy = **Longer distance** to keep osc. max.

longer distance = smaller flux naively $flux \propto 1/L^2$

However neutrinos from high energy muon are focused forward

$$flux \propto E^2/L^2$$

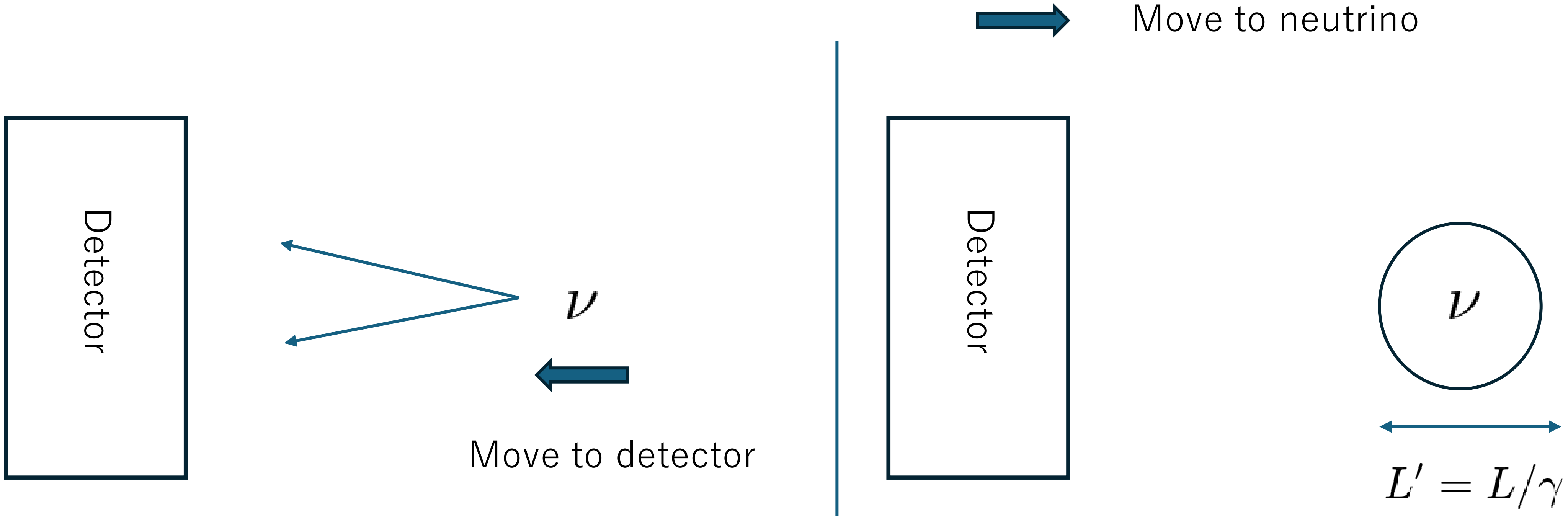


Lab. Frame :
Beam is forcused

longer distance = **smaller flux** naively $flux \propto 1/L^2$

However neutrinos from high energy muon are focused forward

$$flux \propto E^2/L^2$$



Lab. Frame :
Beam is forcused

Rest Frame of neutrino:
Distance is $L' = L/\gamma$

Diametor of
neutrino wave fn.

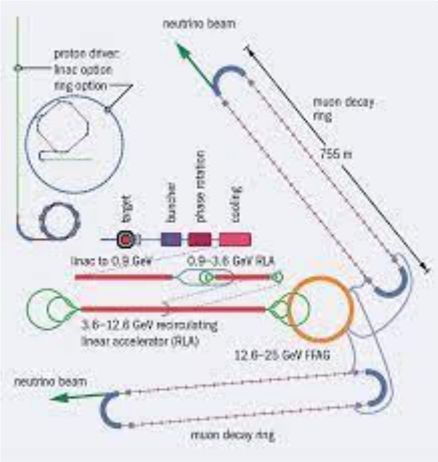
As a total, appearance event proportional to neutrino (parent muon) energy

-> longer baseline $\because L \propto E$ 30-50 GeV

3000km? 9000km?

Long decay volume

$\gamma \sim 300-500, \tau_\mu \sim 10^{-3}\mathrm{s}, d \sim 300\mathrm{km}$



CERN Courier

Wrong sign muon

signal muon (from oscillatated neutrino) has opposite charge

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

$$\nu_\mu \rightarrow \nu_\mu, \nu_\mu + N \rightarrow \mu^- + X$$ "Correct" sign = No osciilation

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\mu + N \rightarrow \mu^+ + X$$ "Wrong" sign = Osciilation

Pros & Cons

Pros Number of events

Cons If making use of quasi elastic , # of event is constant of E

Mater effect is uncontrolled

Many Earth Model. PREM is just one of models

High energy and Longer baseline is really meaningful ?

Charge Identification ?

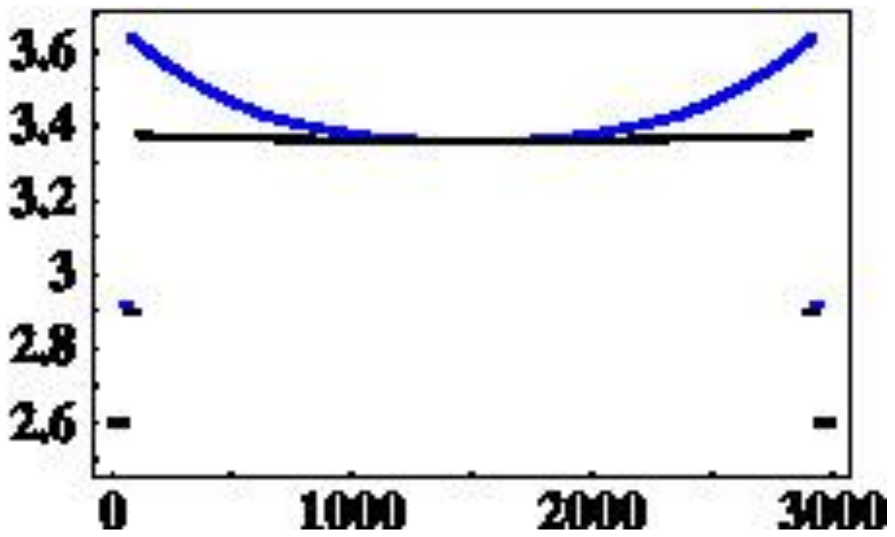
Several ideas …. E.g.

$$\mu^+ \rightarrow \bar{\nu}_\nu + \nu_e + e^+,\ e^+ + e^- \rightarrow 2\gamma\ (511\mathrm{keV})$$

And others

Matter effect in very long baseline

Phys.Rev.D 67 (2003) 053003 • e-Print: hep-ph/0211095 [hep-ph]
Toshihiko Ota & JS



Matter density profile for 3000km baseline
Ak135-f (blue) vs PREM (black)

Fatal to observe CPV

4. ν TRISTAN

- *To observe CPV phase, T-violation is robust against matter effect*
- *Low energy neutrino is welcome against matter effect*

➡ Oscillation of electron neutrino from μTRISTAN

ν TRISTAN

Pros

Electron neutrino

Same baseline with T2K

Not so long
Neutrino go through only crust

Listen carefully to Sugama's talk

Answer Fundamental Question

CPT Theorem holds ?

Comparison between CP and T Violation

Cons Charge Identification ?

5. Summary

- CP Phase is the last piece. Measurement itself is important
- To measure it T violation is ideal since robust against matter effect
- muTRISTAN offers an opportunity to measure T Violation. Baseline is same as T2K !
- Comparison with CP violation is CPT test too!