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VIETNAM

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PRESENTS

A NU HOPE
EPISODE II

The ν Standard Model

- 3 light (m_i <1 eV) Majorana Neutrinos:

  $\Rightarrow$ only 2 δm^2

  $|\delta m^2_{atm}| \sim 2.5 \times 10^{-3}$ eV^2 and $\delta m^2_{solar} \sim +8.0 \times 10^{-5}$ eV^2

- Only Active flavors (no steriles):
  $e, \ \mu, \ \tau$

- Unitary Mixing Matrix:

  3 angles $(\theta_{12}, \ \theta_{23}, \ \theta_{13})$, 1 Dirac phase (δ),

  2 Majorana phases (α_2, α_3)

$(n \times n)$ unitary mixing matrix $\tilde{U}$ $\Rightarrow$ n^2 real parameters:

$$\frac{n(n-1)}{2} \text{ mixing angles}, \qquad \frac{n(n+1)}{2} \text{ phases}$$

In Dirac ν case: $n + (n-1) = 2n - 1$ phases unphysical – can be absorbed into redefinition of charged lepton and neutrino fields. Number of physical phases:

$$\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$$

In Majorana case – only n phases can be absorbed (redefinition of ν fields not possible) $\Rightarrow$ In addition to Dirac-type phases there are $(n-1)$ physical Majorana-type phases.

$$|\nu_\alpha\rangle_{flavor} = U_{\alpha i}|\nu_i\rangle_{mass}.$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $\beta\beta 0\nu$ decay

500km/GeV 15km/MeV

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}\begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

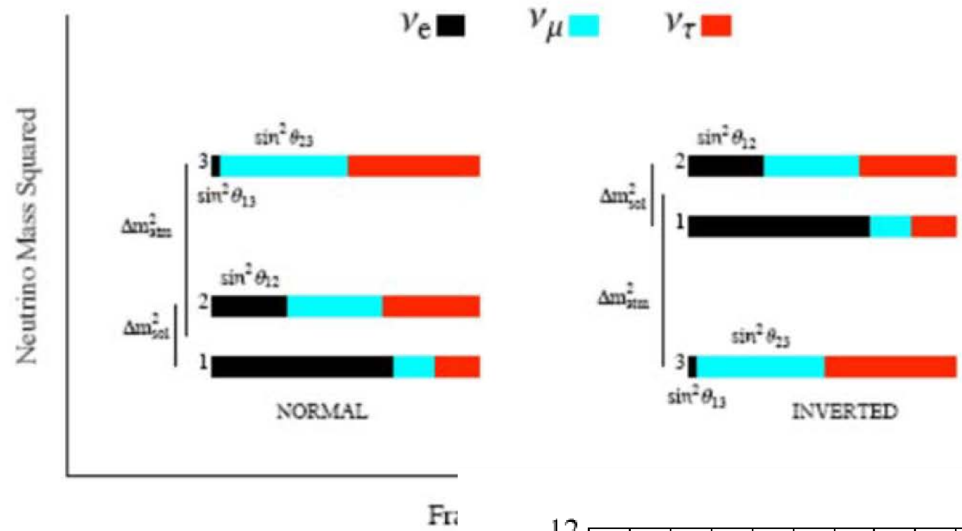
In oscillation phenomena,

the phases $\alpha_2,\ \alpha_3$ are unobservable $(U_{\alpha i}U^*_{\beta i})$

and also the value of m_{lite} is irrelevant (δm^2)

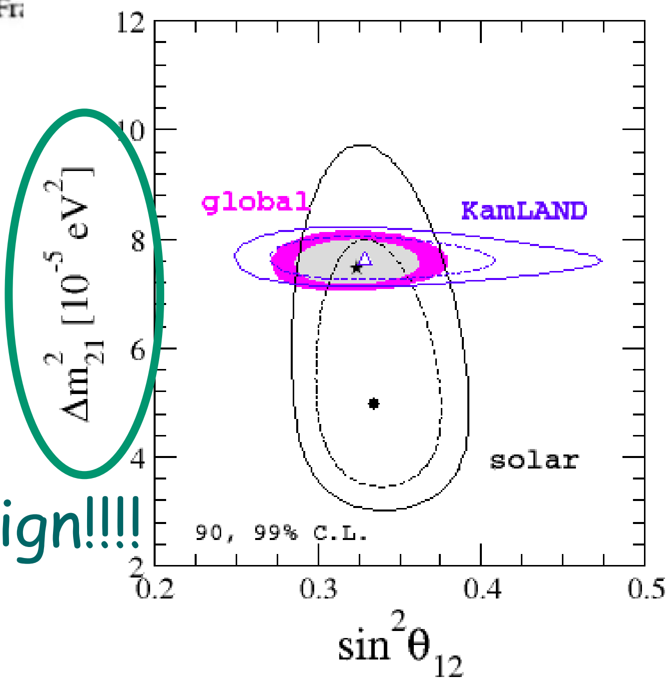
$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

(12)-Sector:



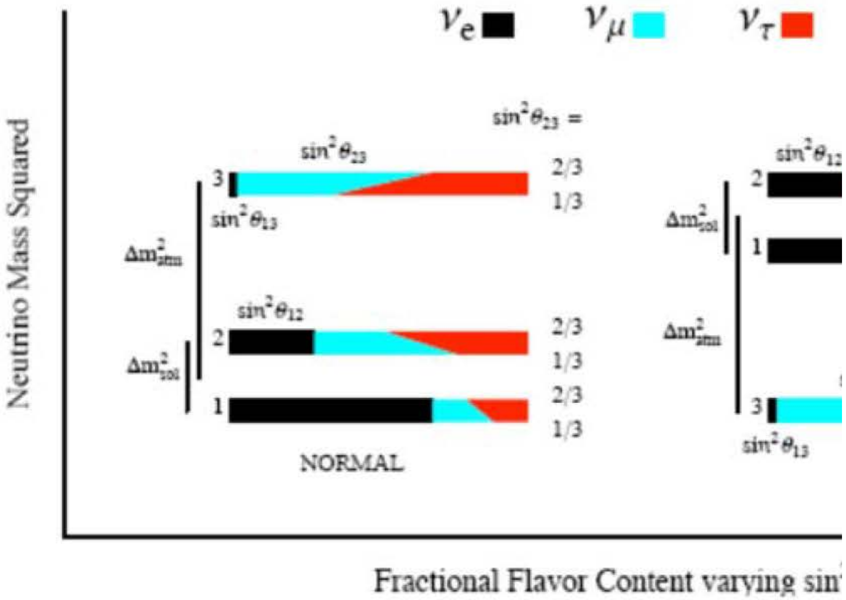
Δm^2_{21}: $[10^{-5}$ eV^2 $\quad 7.55^{+0.20}_{-0.16}$

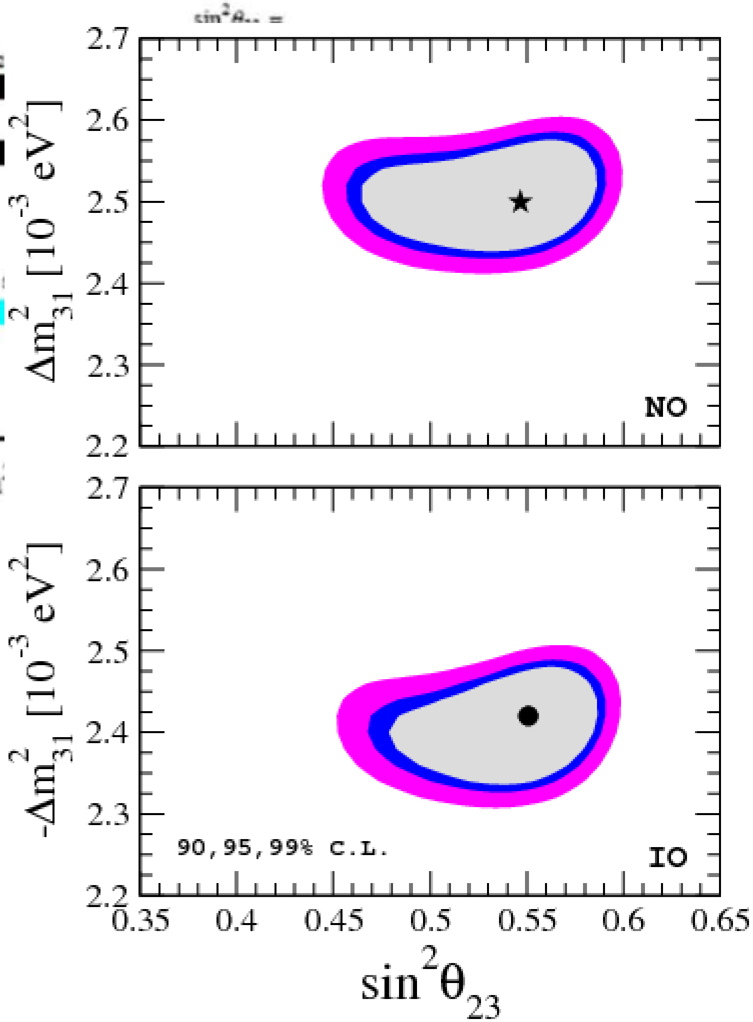
$\sin^2\theta_{12}/10^{-1} \quad 3.20^{+0.20}_{-0.16}$



notice the sign!!!!

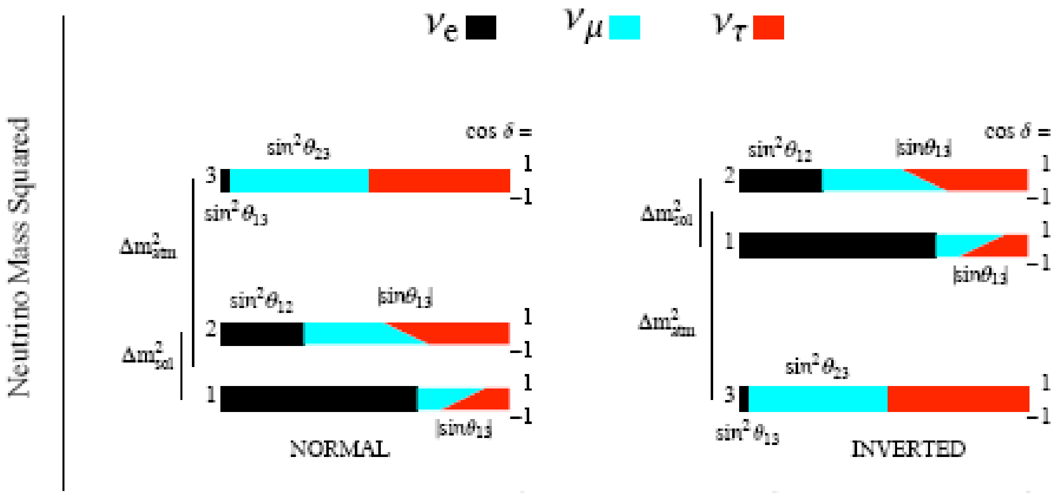
(23)-Sector:





$\lvert\Delta m^2_{31}\rvert$: [$10^{-3}$ eV^2] (NO)	2.50$\pm$0.03
$\lvert\Delta m^2_{31}\rvert$: [$10^{-3}$ eV^2] (IO)	$2.42^{+0.03}_{-0.04}$
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$

(13)-Sector:



$$P(\nu_e \to \nu_\mu) \approx -4U_{e1}U_{\mu 1}U_{e2}U_{\mu 2}\sin^2\Delta_{21} + 4U_{e3}^2U_{\mu 3}^2\sin^2\Delta_{32}$$

$$\approx \sin^2(2\theta_{13})\ \sin^2(2\theta_{23}\ )\ \sin^2(\ \Delta_{32}\ )$$

Invariant!

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2\sin^2\Delta_{21} - 4|U_{e1}|^2|U_{e3}|^2\sin^2\Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2\sin^2\Delta_{32}$$

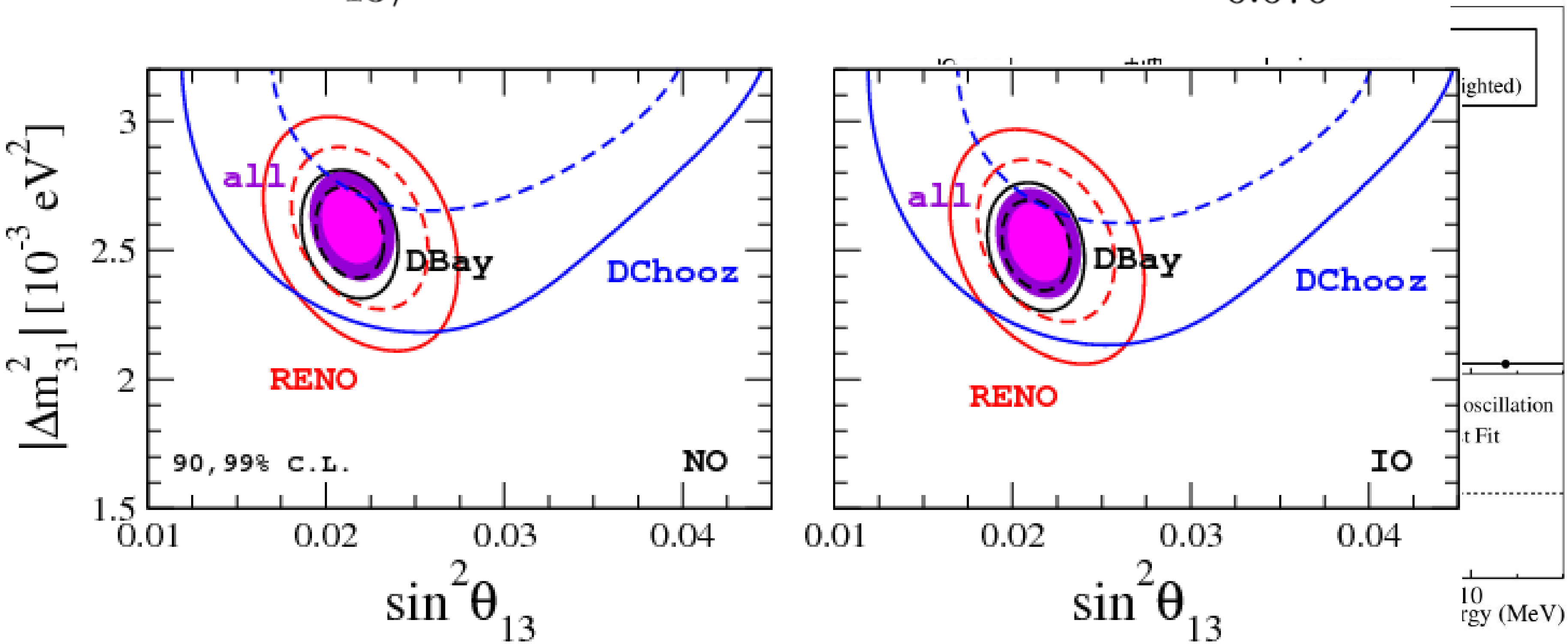
$$m_3^2 - m_1^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2)$$

$L_{32} \sim 0.8$ km

$$P(\nu_e \to \nu_e) \quad \approx\ 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

$L_{21} \sim 30$ km

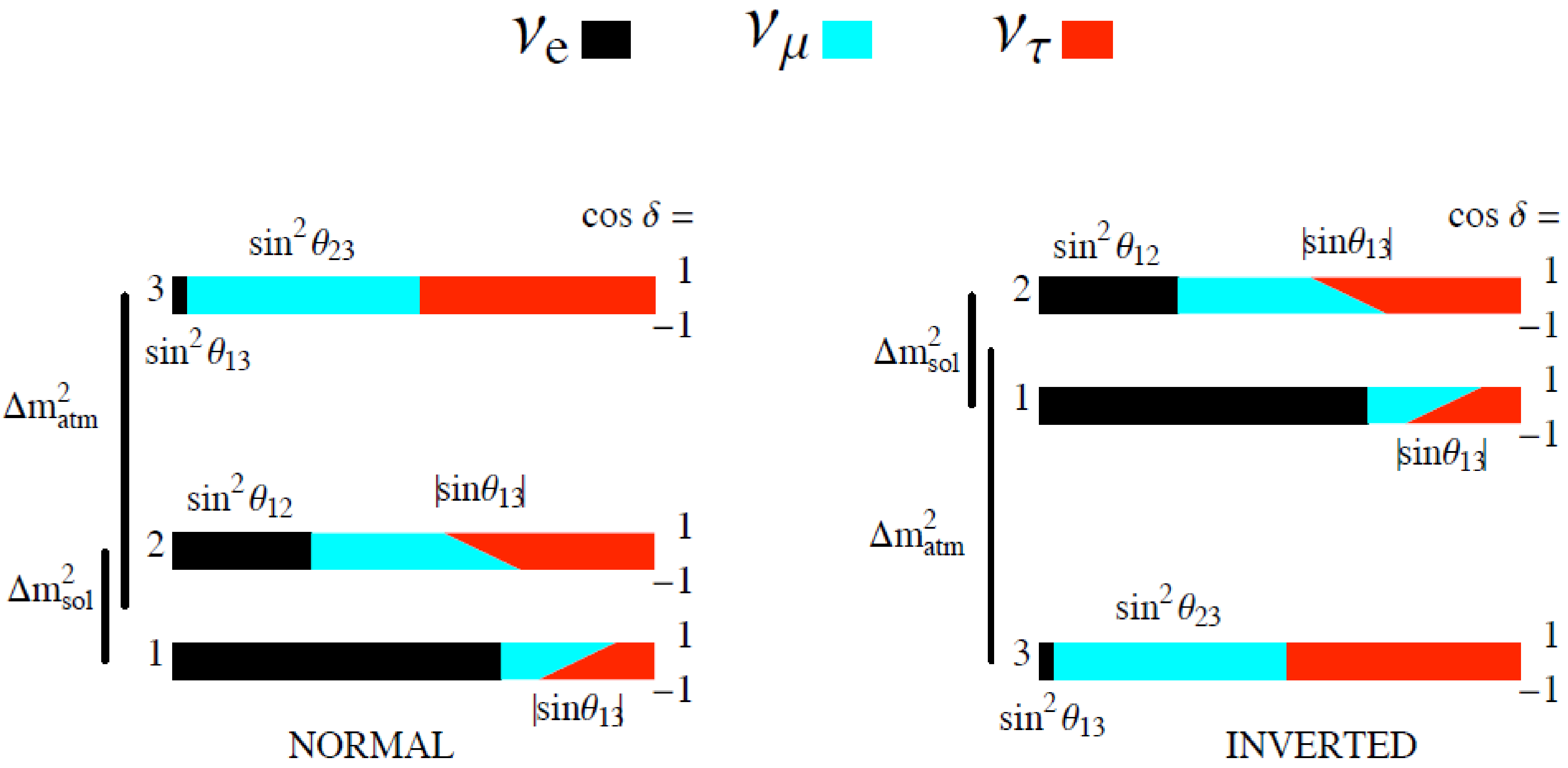
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$



- RENO
  - R=0.920 ± 0.009(stat) ± 0.014(syst) (4.9σ)
  - $\sin^2 2\theta_{13}$= 0.113±0.013(stat)±0.019(sys)

pectral distortion
onsistent with oscillation

What’s to be done …



We determined that $m(K_L) > m(K_S)$ by

- Passing kaons through matter (regenerator)
- Beating the unknown sign$[m(K_L) - m(K_S)]$ against the known sign[reg. ampl.]

We will determine the sign(Δm^2_{32}) by

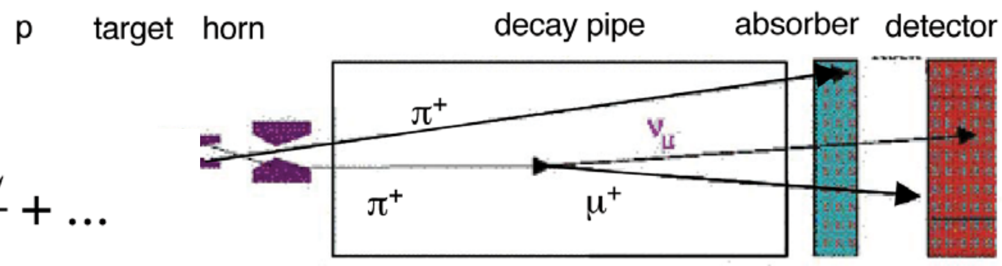
- Passing neutrinos through matter (Earth)
- Beating the unknown sign(Δm^2_{32}) against the known sign[forward $\nu_e\, e \longrightarrow \nu_e\, e$ ampl]

$$L \approx \frac{2\,\pi}{G_F n_e} \approx 1.16\ 10^4\ \mathrm{km}\left(\frac{1.69\ 10^{24}\ cm^3}{n_e}\right)$$

~~CP~~ :How we are going to do it ?

Accelerator experiments

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$



- Appearance experiment $\nu_\mu \rightarrow \nu_e$
- Measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields δ

<u>Remember what happens in the quark sector !!!</u>

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}L}{2}\right) && \equiv P^{atmos} \\
&+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}L}{2}\right) && \equiv P^{solar} \\
+\tilde{J} &\quad \cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) \frac{\Delta_{12}L}{2} \sin\left(\frac{\Delta_{23}L}{2}\right) && \equiv P^{inter}
\end{aligned}
$$

$$
(\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu})
$$

$$
\begin{aligned}
P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta \\
\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)
\end{aligned}
$$

The off axis idea

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Allows an
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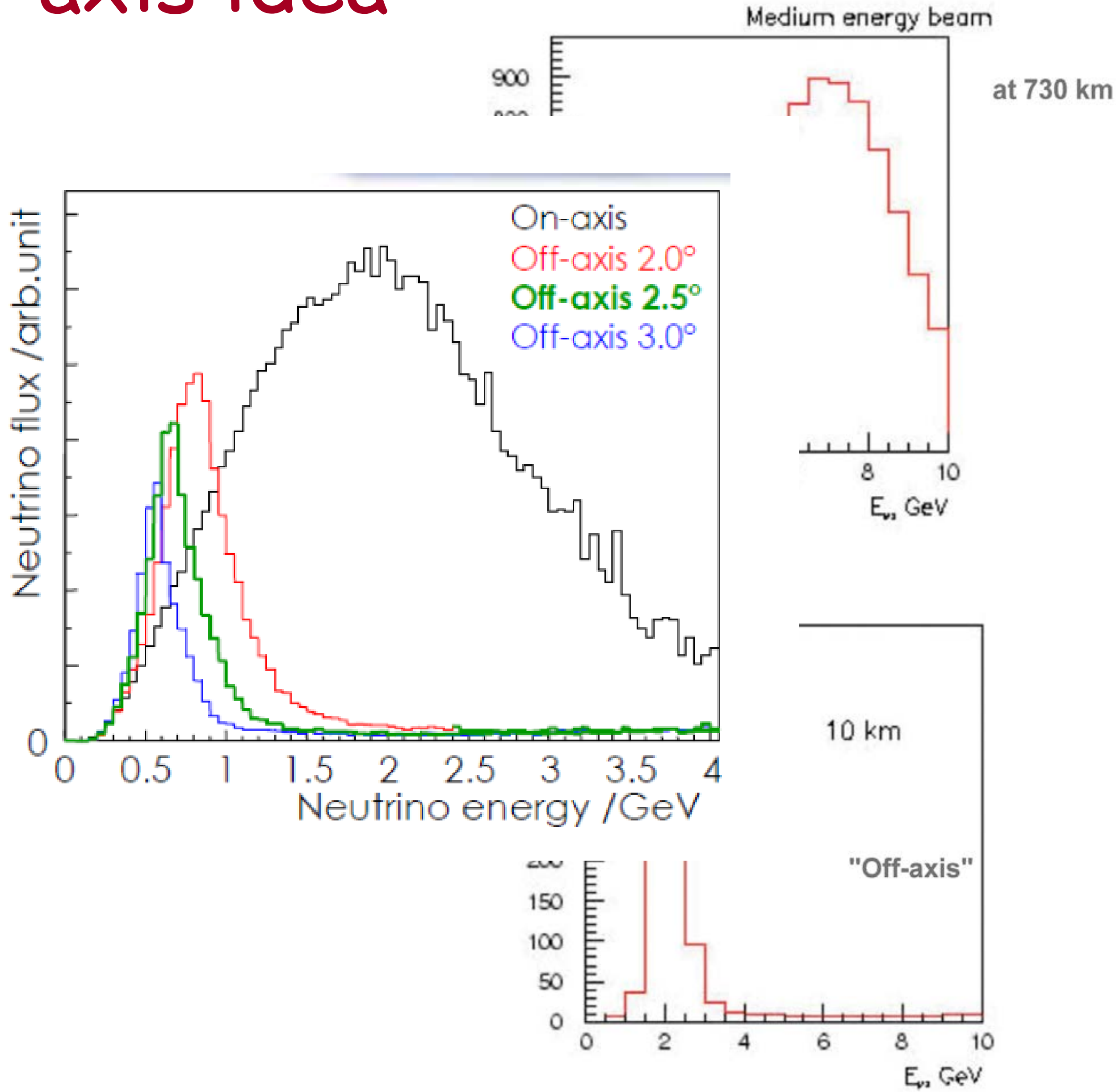
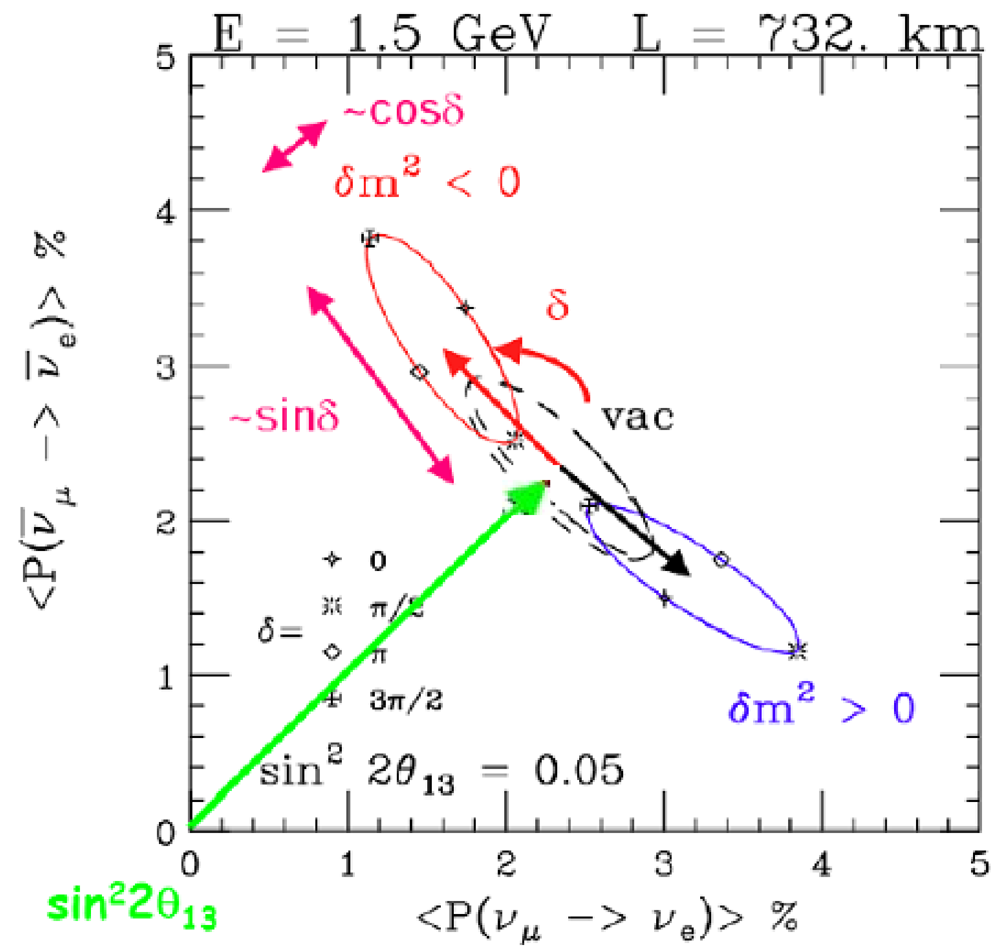
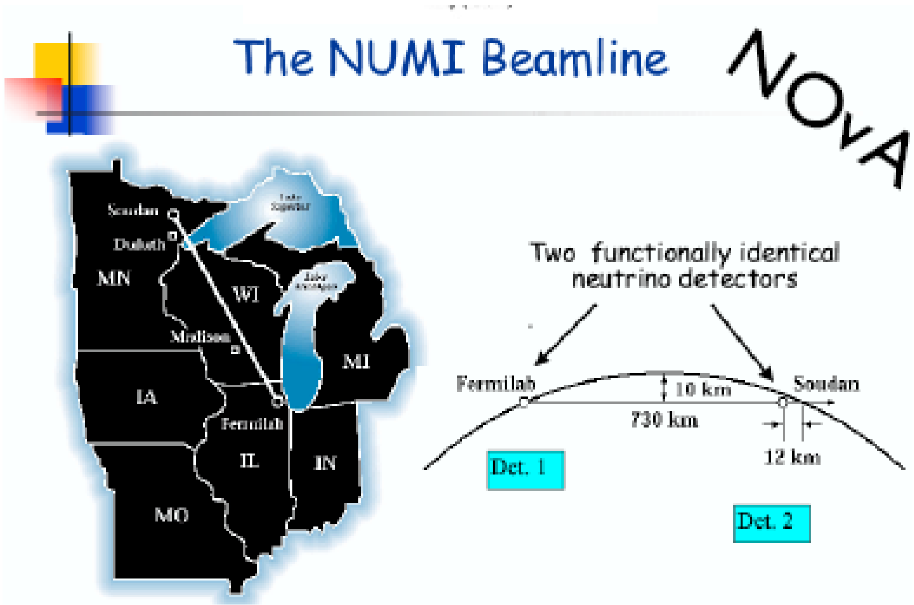


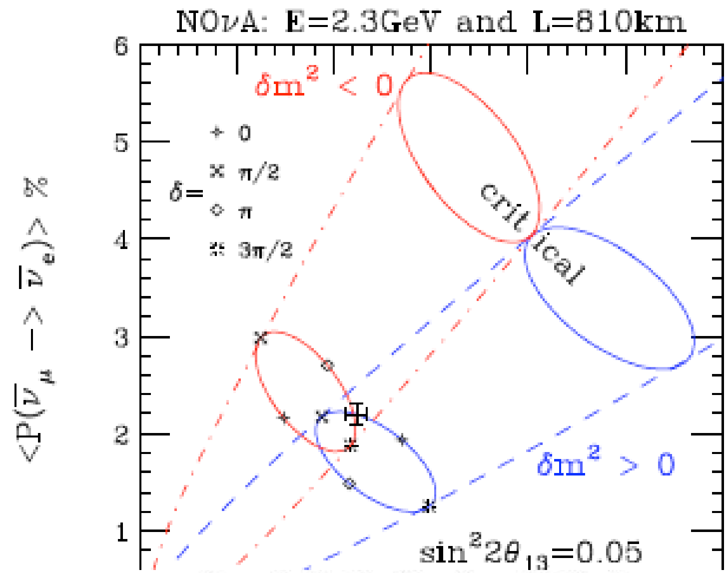
What will we get ?

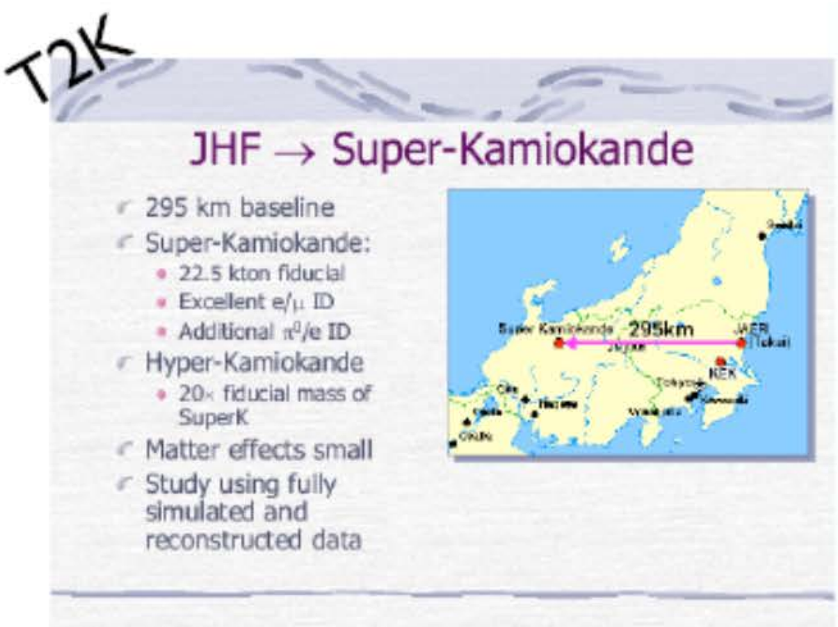


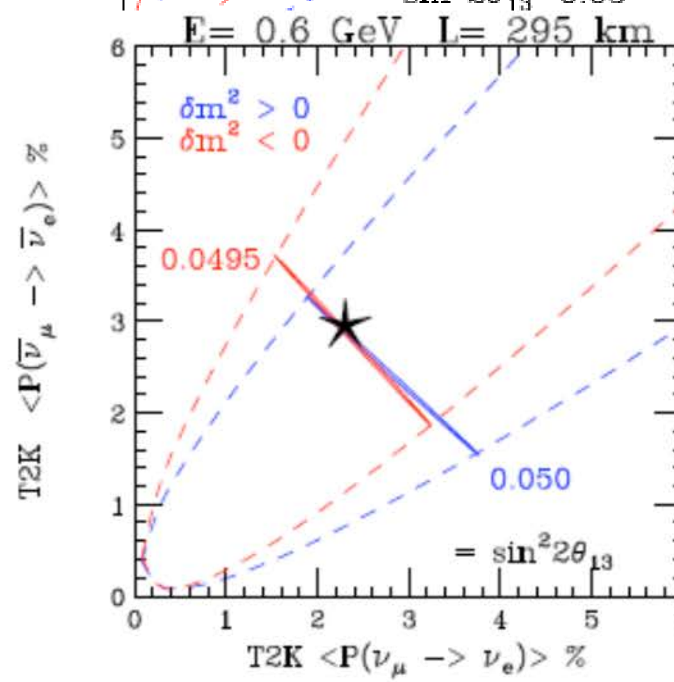
Minakata and Nunokawa

Neutrino v Anti-Neutrino One Expt.









Standard scenario: solar $\oplus$ atmos. with 3-ν

Let us assign:

$$\Delta m^2_{23} = m^2_3 - m^2_2 = \Delta m^2_{atmos}, \qquad \Delta m^2_{12} = m^2_2 - m^2_1 = \Delta m^2_{solar}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $\beta\beta 0\nu$ decay

$$V_{PNMS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix}$$

Solar and atmospheric anomalies approximately decouple as independent 2-by-2 mixing phenomena because

- Hierarchy between the two mass splittings: $|\Delta m^2_{atmos}| \gg |\Delta m^2_{solar}|$
- Small θ_{13}: $\sin\theta_{13} = V_{e3} \quad \leftrightarrow V_{ub}$

I. $E/L \sim \Delta m^2_{23}$:

$$P(\nu_e \to \nu_\mu) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\nu_e \to \nu_\tau) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\nu_\mu \to \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

Daya Bay θ_{13} miserably small !!!

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atmos}, \theta_{\rm atmos}),$$

II. $E/L \sim \Delta m^2_{12}$:

$$P(\nu_e \to \nu_e) \simeq c^4_{13} \left(1 - \sin^2 2\theta_{12} \, \sin^2 \left(\frac{\Delta m^2_{12}}{4E} \, L \right) \right) + s^4_{13}$$

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\rm solar}, \theta_{\rm solar})$$

When solar and atmospheric fits are done in the context of three families nothing changes too much

CP violation in neutrino oscillations

Can I have it ?

Vacuum oscillations ($W^{jk}_{\alpha\beta} \equiv [U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}]$)

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4\sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}]\,\sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{4\mathrm{E}_\nu}\right)$$

$$\pm \quad 2\sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}]\,\sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}}\,\mathrm{L}}{2\mathrm{E}_\nu}\right)$$

CP violation shows up as a difference between $P(\nu_\alpha \to \nu_\beta)$ and $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

By CPT:

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

CP and T-odd terms cancel in survival probabilities $\to$ need appearance measurements: $\alpha \neq \beta$

Observability of CP-violation $\leftrightarrow$ measurable CP-asymmetries:

$$A^{CP}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \quad A^{T}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha)}{P(\nu_\alpha \to \nu_\beta) + P(\nu_\beta \to \nu_\alpha)}$$

$$
\begin{aligned}
P(\nu_i \to \nu_j) &= P_{CP}(\nu_i \to \nu_j) + P_{\not{CP}}(\nu_i \to \nu_j) \\
P(\bar{\nu}_i \to \bar{\nu}_j) &= P_{CP}(\nu_i \to \nu_j) - P_{\not{CP}}(\nu_i \to \nu_j)
\end{aligned}
$$

$$
P_{CP}(\nu_i \to \nu_j) = \delta_{ij} - 4\mathrm{Re}J^{ji}_{12}\sin^2\Delta_{12} - 4\mathrm{Re}J^{ji}_{23}\sin^2\Delta_{23} - 4\mathrm{Re}J^{ji}_{31}\sin^2\Delta_{31},
$$

$$
P_{\not{CP}}(\nu_i \to \nu_j) = -8\sigma_{ij}\, J \sin\Delta_{12}\sin\Delta_{23}\sin\Delta_{31},
$$

$$
s_{12}\, c_{12}\, s_{13}\, c^2_{13}\, s_{23}\, c_{23}\, \sin\delta_{\mathrm{CP}}
$$

$$
\begin{aligned}
J^{ij}_{kh} &\equiv U_{ik}U^\dagger_{kj}U_{jh}U^\dagger_{hi} \\
\Delta_{ij} &\equiv \Delta m^2_{ij}L/4E \\
\sigma_{ij} &\equiv \sum_k \varepsilon_{ijk}
\end{aligned}
$$

CP(T)-odd terms the same for all $\alpha \neq \beta$:

$$A^{\mathrm{CP(T)-odd}}_{\nu_\alpha \nu_\beta} = \frac{2 \sin\delta\, c_{13} \sin 2\theta_{13} \overbrace{\sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E_\nu}}^{\text{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E_\nu}}^{atmos}}{P^{\mathrm{CP-even}}_{\nu_\alpha \nu_\beta}}$$

GIM suppressed in all the Δm^2 and all the angles, because if any of them is zero, the CP-odd phase is unphysical

- Minimize GIM suppression: $E/L \sim \Delta m^2_{atmos}$
- Effects of δ are more significant in subleading transitions: $\nu_e \rightarrow \nu_\mu (\nu_\tau)$:

$$P^{\mathrm{CP-even}}_{\nu_\mu \nu_\tau} = \text{unsuppressed in } \theta_{13} \text{ or } \frac{\Delta m^2_{12} L}{E_\nu}$$

$$P(\nu_\mu \to \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23}}{4E} L \right)$$

$$A^{\mathrm{CP(T)-odd}}_{\nu_\mu \nu_\tau} \sim \sin 2\,\theta_{13} \, \frac{\Delta m^2_{12} L}{E_\nu}$$

$$P^{\mathrm{CP-even}}_{\nu_e \nu_\mu(\nu_\tau)} = \text{suppressed in } \theta^2_{13} \text{ or } \left(\frac{\Delta m^2_{12} L}{E_\nu} \right)^2$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{12}}{4E} L \right)$$

$$A^{\mathrm{CP(T)-odd}}_{\nu_e \nu_\mu(\nu_\tau)} \sim \frac{\Delta m^2_{12} L / E_\nu}{\sin 2\theta_{13}} \text{ or } \frac{\sin 2\theta_{13}}{\Delta m^2_{12} L / E_\nu}$$

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= s_{23}^2\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{atmos} \\
&+ c_{23}^2\,\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta_{12}\,L}{2}\right) && \equiv P^{solar} \\
+\tilde J \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right)\,\frac{\Delta_{12}\,L}{2}\sin\left(\frac{\Delta_{23}\,L}{2}\right) && \equiv P^{inter}
\end{aligned}
$$

$$
(\tilde J \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}\ )
$$

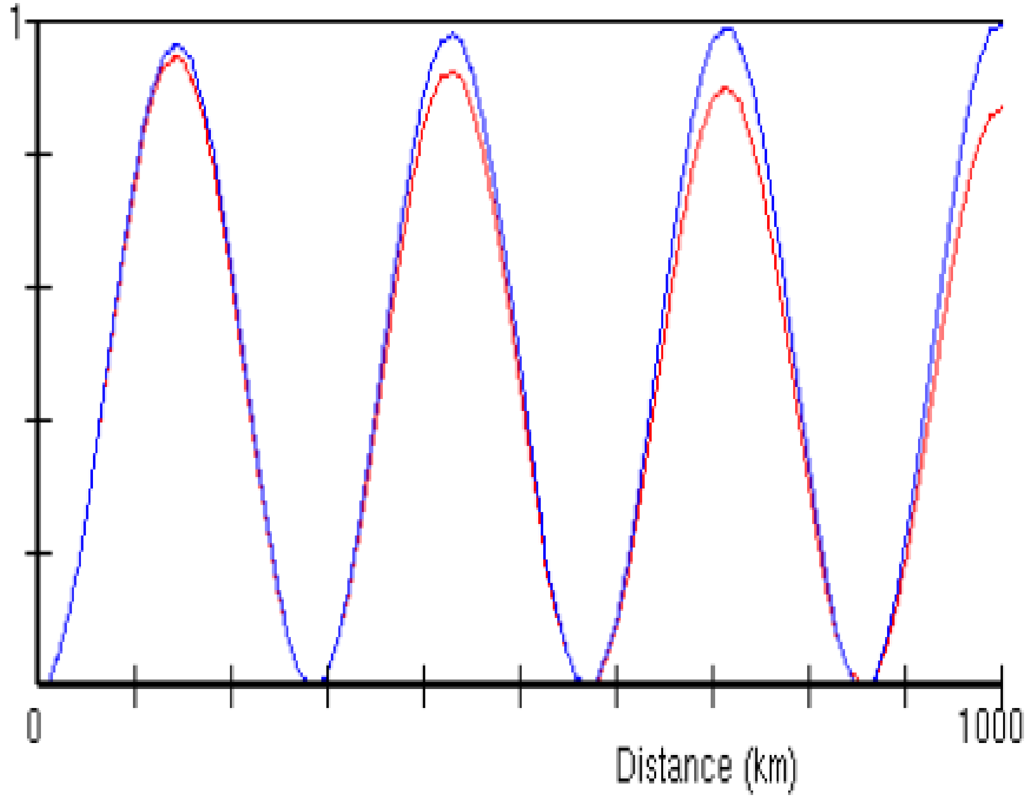
$$
P^{atmos} \gg P^{solar} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\Delta_{12}L}{\sin 2\theta_{13}}
$$

$$
P^{solar} \gg P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} \sim \frac{\sin 2\theta_{13}}{\Delta_{12}L}
$$

$$
P^{solar} \simeq P^{atmos} \quad \rightarrow \quad A^{CP,T}_{\nu_e\nu_\mu(\nu_\tau)} = O(1)
$$

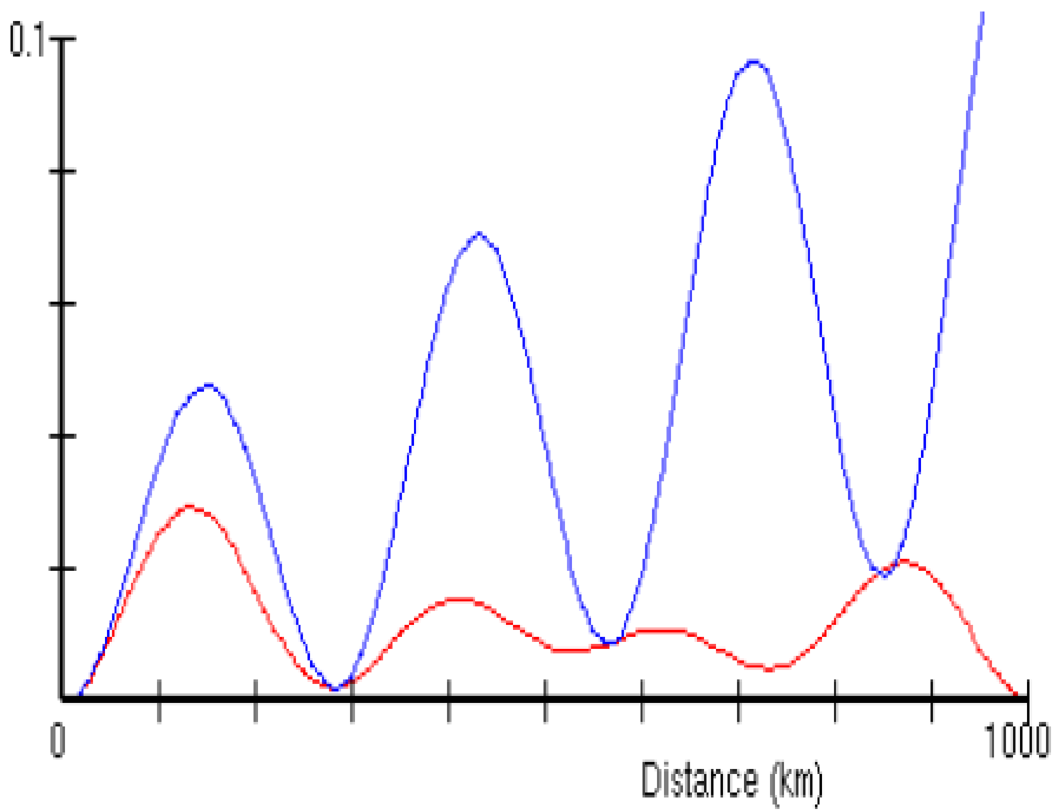
$E_\nu = 500\ \text{MeV} \quad \theta_{13} = 8^\circ \quad \delta = 90^\circ$

$P_{\nu_\mu \to \nu_\tau}$ vs. $P_{\bar{\nu}_\mu \to \bar{\tau}_\mu}$



$$E_\nu = 500 \text{ MeV} \quad \theta_{13} = 8^\circ \quad \delta = 90^\circ$$

$P_{\nu_e \to \nu_\mu}$ vs. $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$



The challenge

We need to measure for the first time small oscillation probabilities:
need more intense and purer ν sources

- **Superbeams** ν from K, π decay

$$\begin{aligned} \pi, K \rightarrow \quad & \nu_\mu \quad O(1\%)\, \nu_e\ \bar{\nu}_\mu; \\ & \nu_\mu \quad \rightarrow \nu_e \rightarrow e^- \\ & \qquad\quad \nu_e \rightarrow \nu_e \rightarrow e^- \end{aligned}$$

- **Neutrino factory** ν from muon decay

$$\begin{aligned} \mu^- \rightarrow e^- \quad & \nu_\mu \quad \bar{\nu}_e\,; \\ & \qquad\quad \bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ \\ & \nu_\mu \quad \rightarrow \nu_\mu \rightarrow \mu^- \end{aligned}$$

- **β-beams** from boosted heavy ions decays

$$\begin{aligned} {}^6He^{++} \rightarrow^6_3 Li^{+++}\ e^- \qquad & \bar{\nu}_e \\ & \bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ \end{aligned}$$

Matter Effects

The oscillation probabilities for three neutrino mixing in matter are not very illuminating. A particularly useful approximation is obtained for $E/L \sim \Delta m^2_{23}$ and to second order in the two small parameters: θ_{13} and Δm^2_{12} :

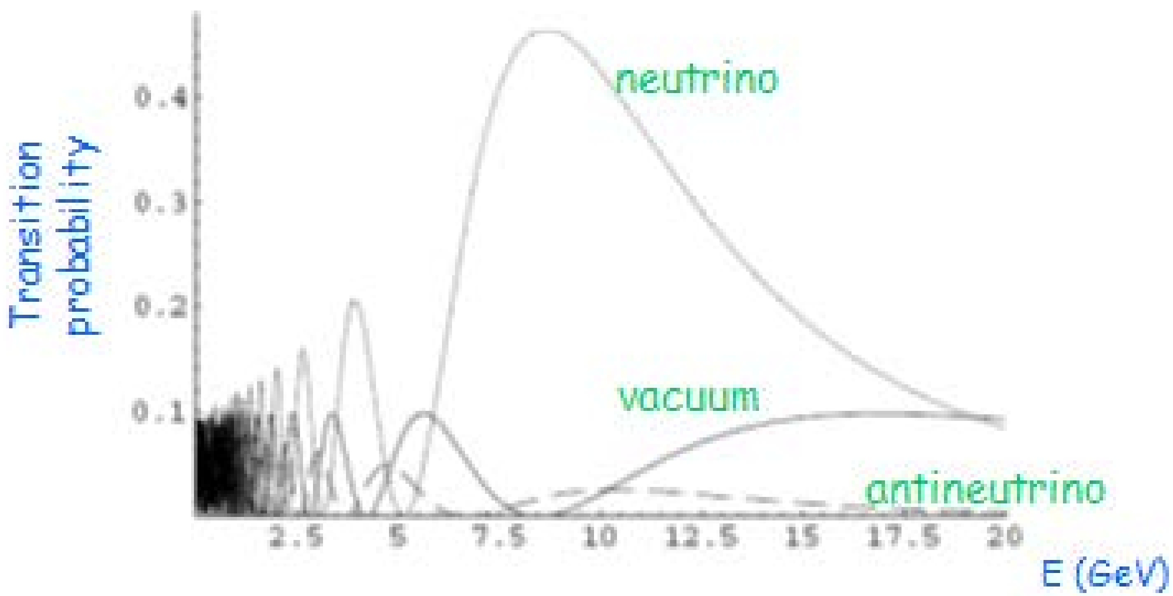
$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+ c^2_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$
$$+ \tilde{J} \frac{\Delta_{12}}{A} \sin\left(\frac{AL}{2}\right) \frac{\Delta_{13}}{B_\pm} \sin\left(\frac{B_\pm L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

$$B_\pm = |A \pm \Delta_{13}| \qquad \Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

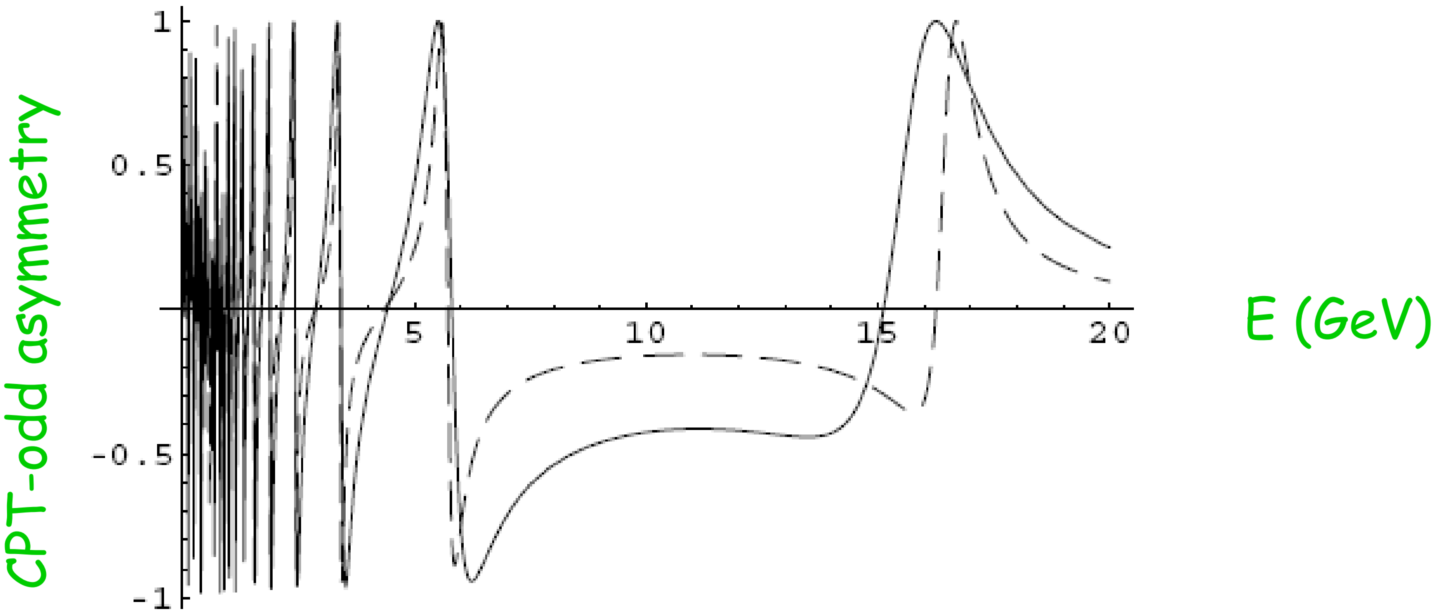
There is an MSW effect in θ_{13}! There is a huge enhacement of the ν or $\bar{\nu}$ (depending on the sign of Δm^2_{23}) channel if:

$$2E_\nu A \sim |\Delta m^2_{13}|, \quad E_\nu \sim 10 - 20 GeV$$

$$\sin^2(2\tilde{\theta}_{13}) = \frac{4s^2_{13}c^2_{13}\left(\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2}{\left(E - \cos 2\theta_{13}\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2 + 4s^2_{13}c^2_{13}\left(\frac{\Delta m^2_{13}}{\tilde{a}}\right)^2}$$



For very long baselines and atmospheric neutrinos...

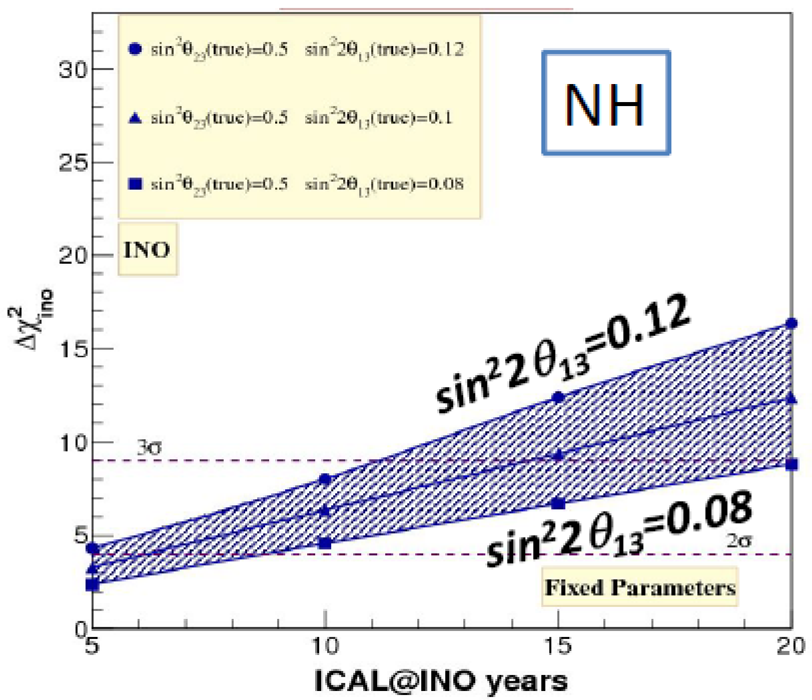


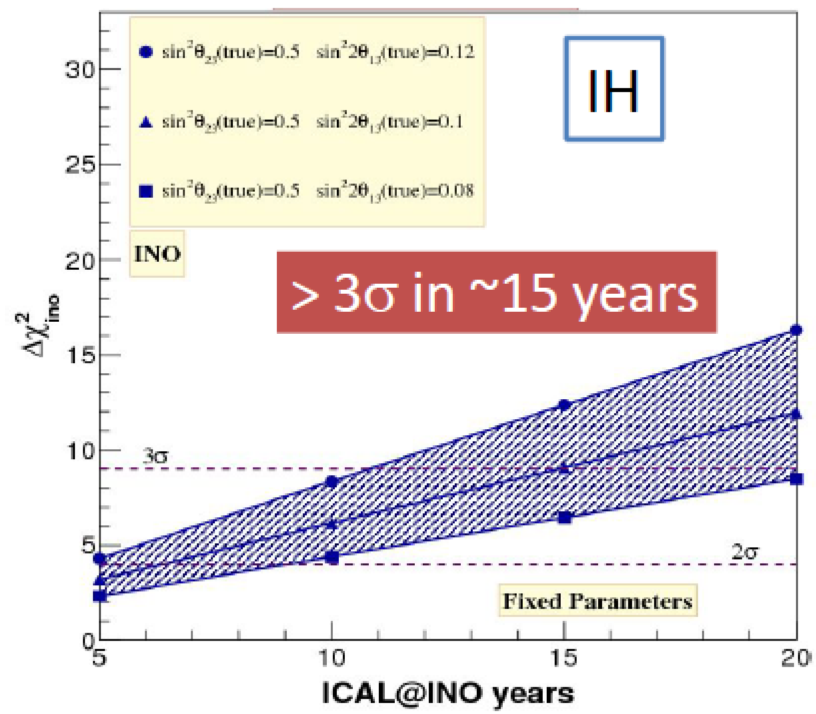
INO

The detector

- Magnetised iron calorimeter (~ 50kT)
- 140 horizontal (vertical) iron layers interspersed with Glass RPC
- Modular structure

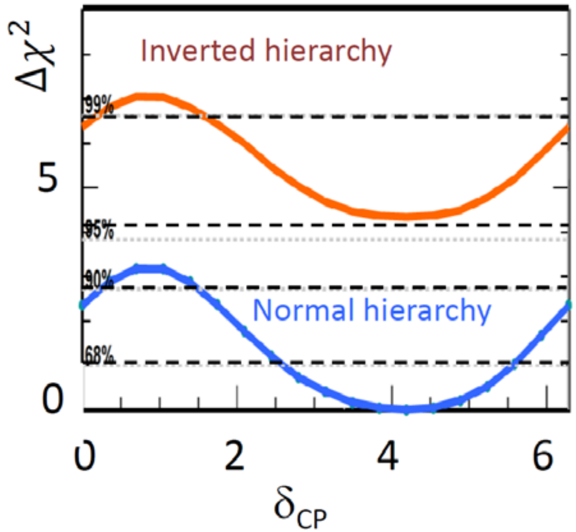
- Sensitive to muons
- Energy determination from
  - Track length
  - Track curvature in a magentic field
- Direction of parent neutrino from the track



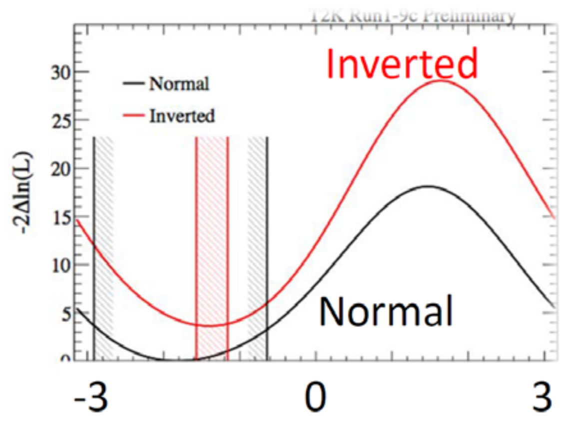


	DUNE	Hyper-K
Baseline	1300km ➔ Large matter effect (Good for MO)	295km ➔ Small matter effect
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. Ar TPC	Water Cherenkov

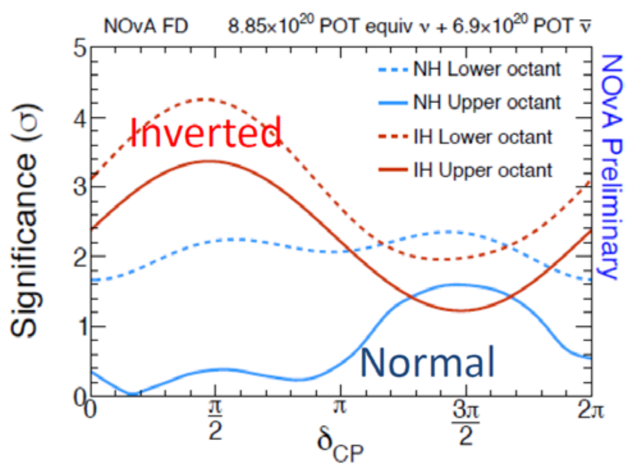
***Super-K** atmospheric (Y. Hayato)*



***T2K** (M. Wascko)*



***NOvA** (M. Sanchez)*



Neutrinos,

In and Beyond the Standard Model:

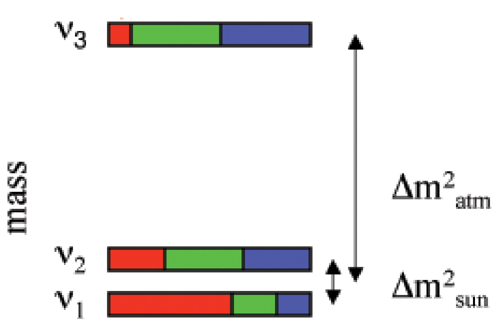
NEUTRINO MASS:

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad L/E = 500\ km/GeV$$

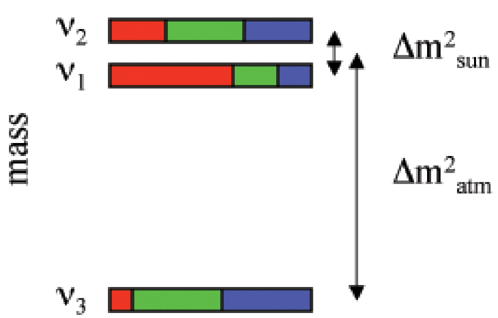
$$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2 \qquad L/E = 15\ km/MeV$$

$$\Downarrow$$

$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$

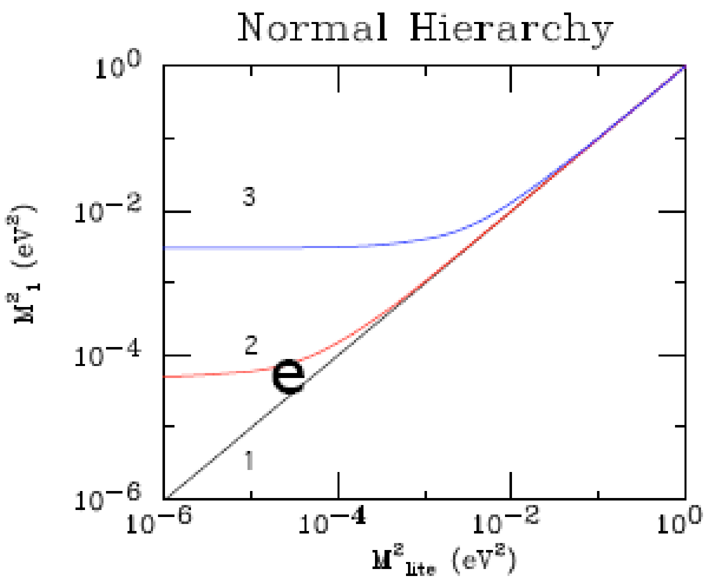


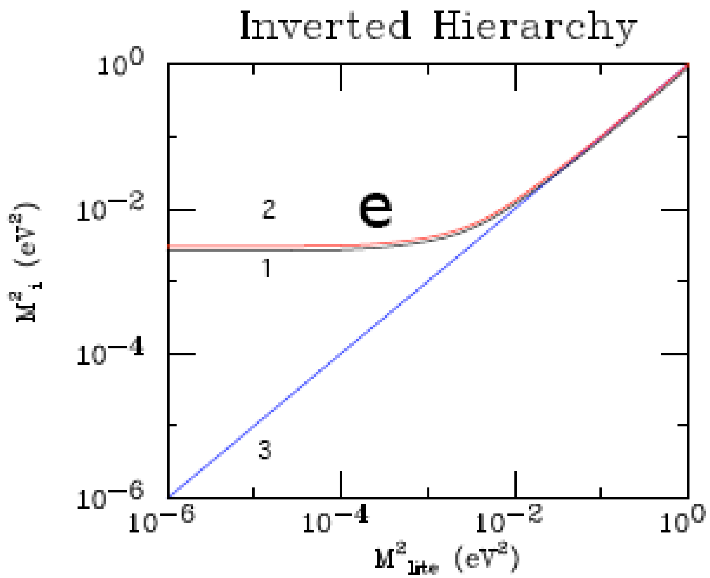
Normal mass hierarchy



Inverted mass hierarchy

Masses:

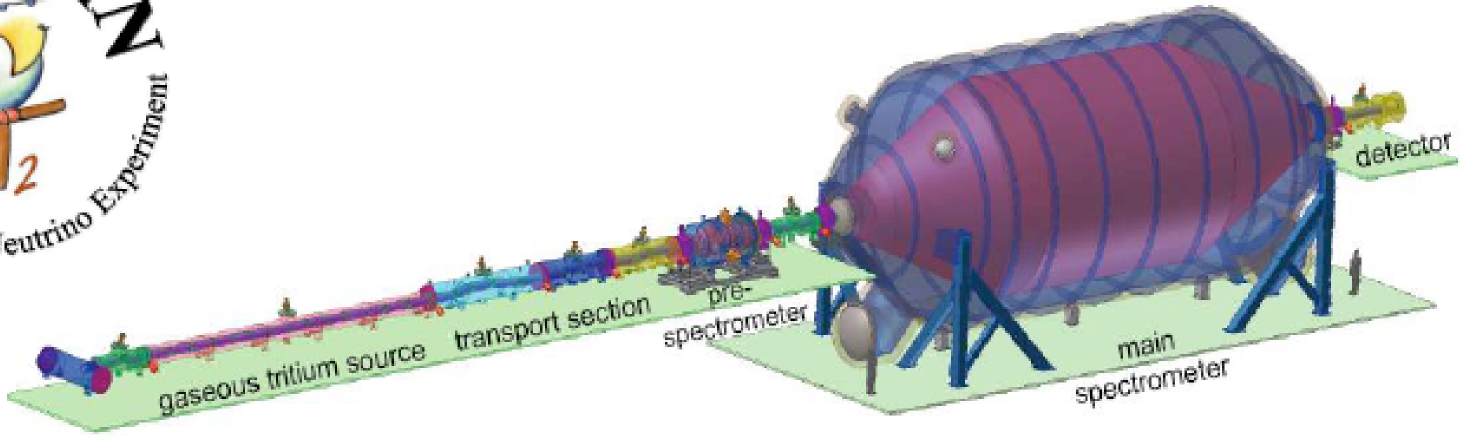


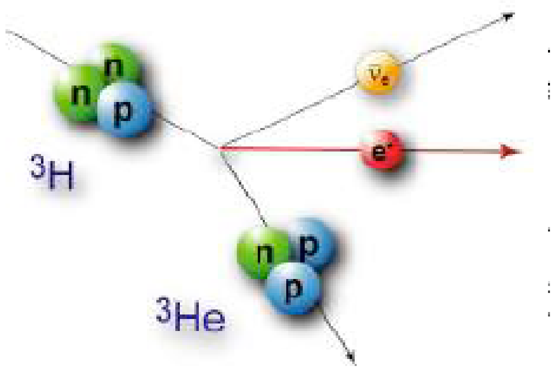


States 1 and 2 are ν_e rich.

KATRIN

Karlsruhe Tritium Neutrino Experiment



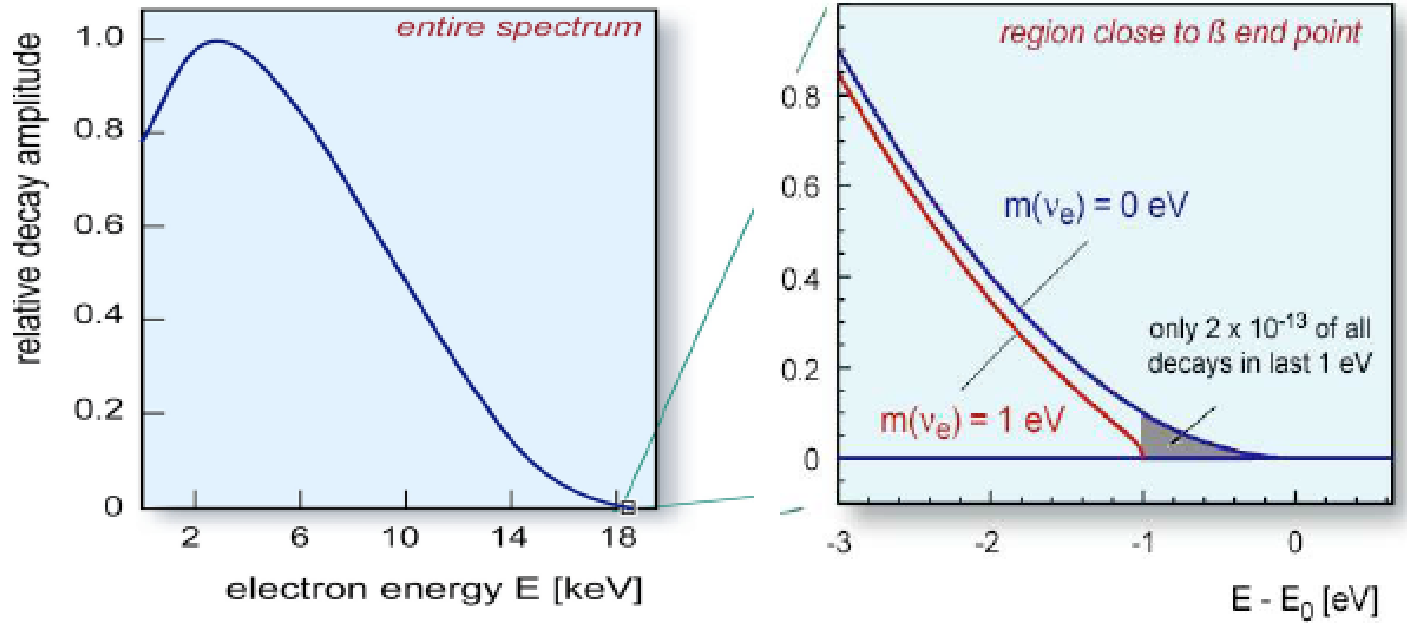


Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)

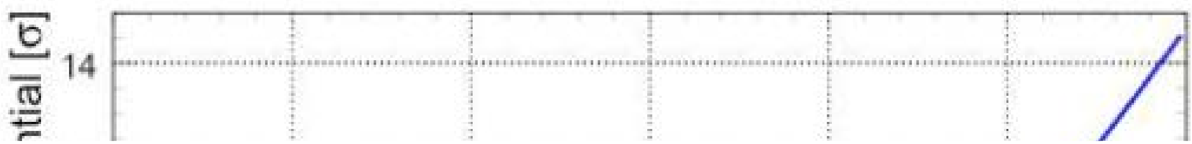


Decay Rate:

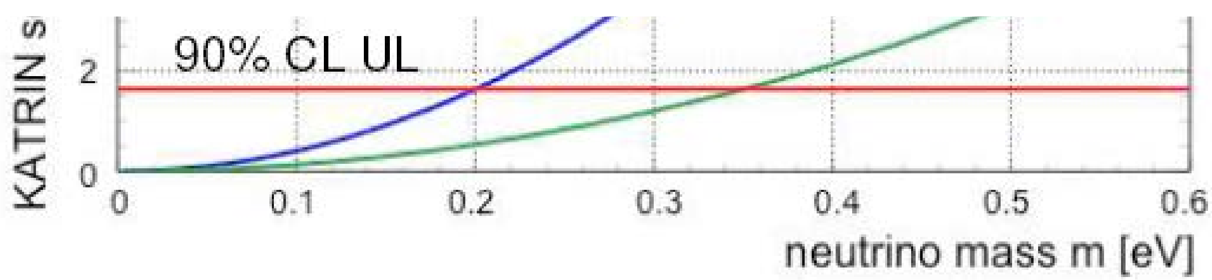
$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

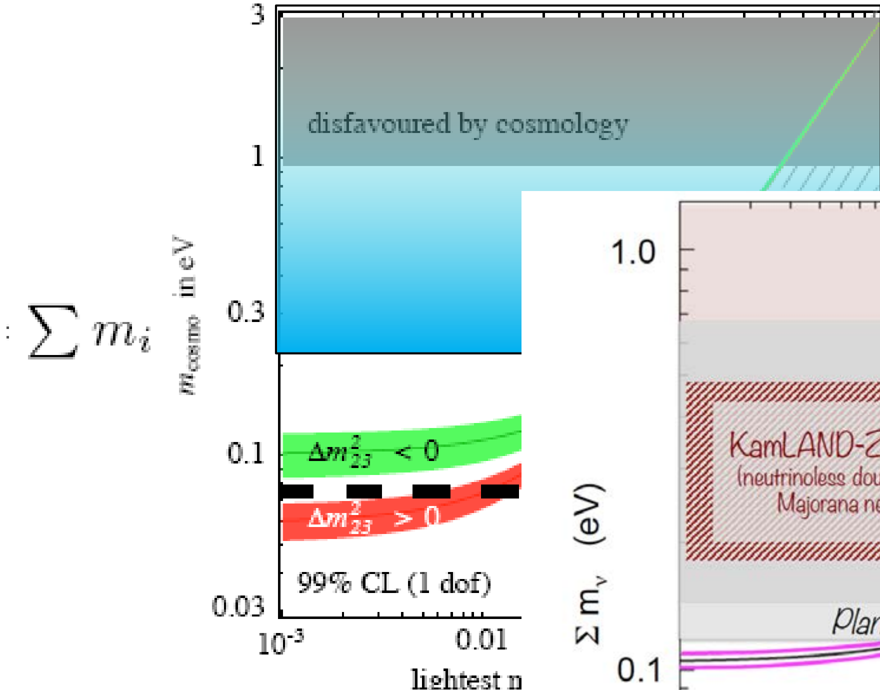
if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

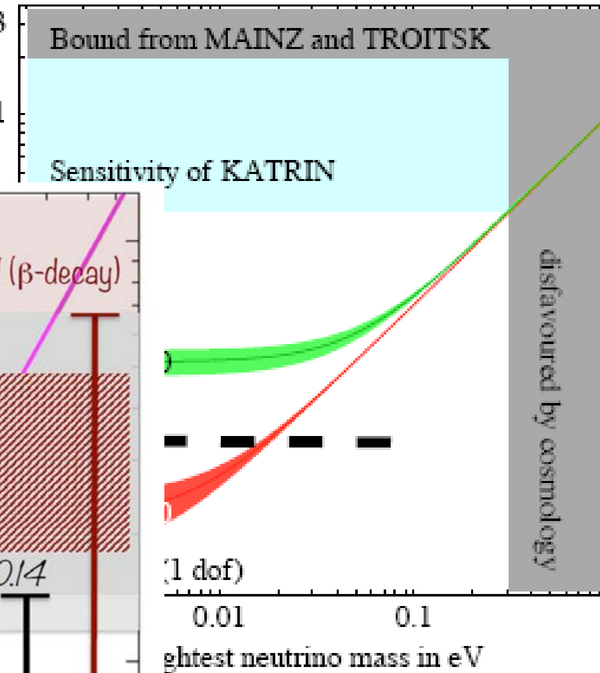
$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

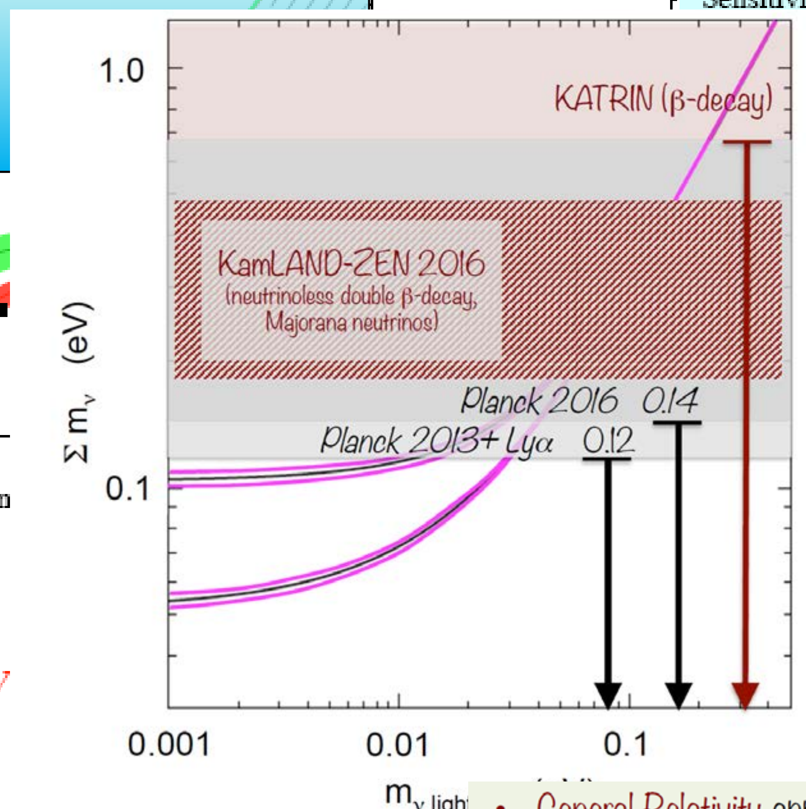


- Calibration and systematic error studies
- 2016+ neutrino mass measurements, $m_\nu < 2$ eV
- 2018+ neutrino mass measurements using an atomic tritium source, $m_\nu < 0.2$ eV









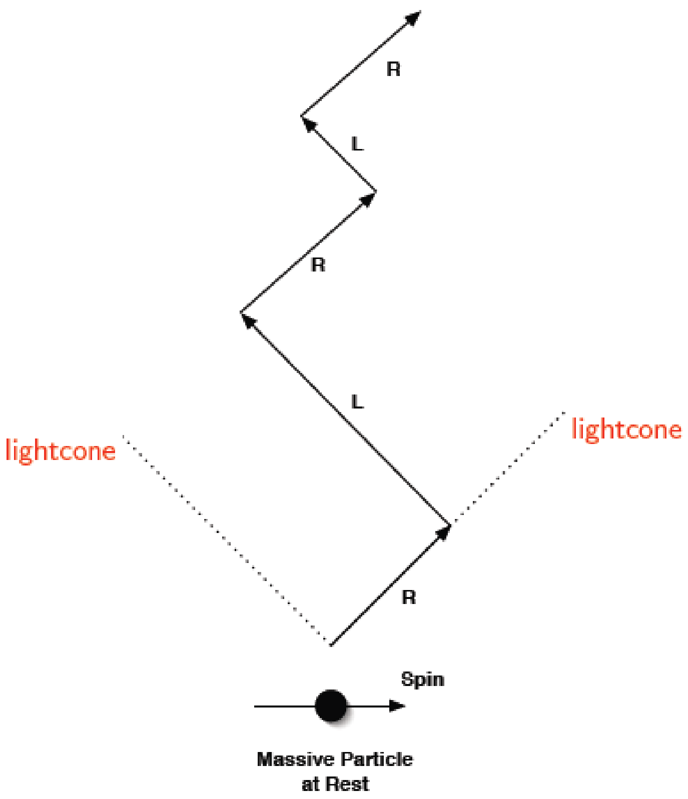
$\sum m_i \approx 2\ eV$ % of this number.

- General Relativity applies
- Neutrinos only interact weakly (no non-standard interactions)
- Universe reached thermal equilibrium before T ~ few MeV

Similarly, if Tritium decay exp

could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, t

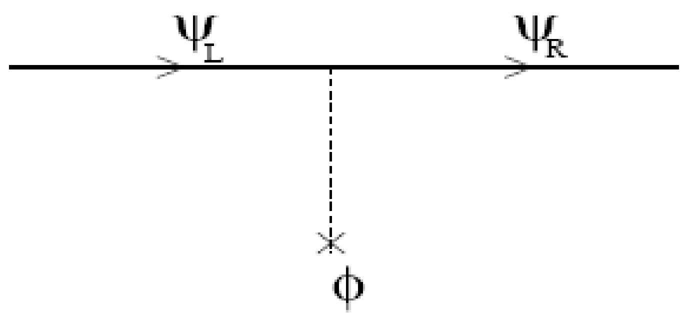
What is Fermion Mass ???



A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m\,\overline{\psi_L}\psi_R + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



$$\lambda_f\,\overline{\psi_L}\,\Phi\,\psi_R + h.c. \to m_f = \lambda_f\,v$$

Fermion Masses:

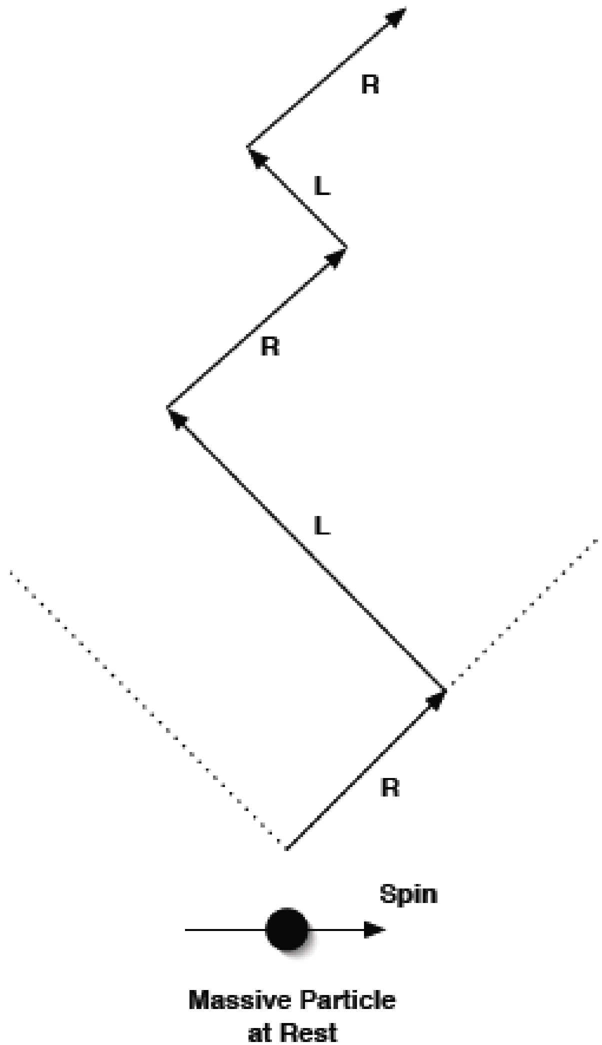
	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.

Mass couples L to R:



$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless   left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	$\boldsymbol{\nu_L}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_R}$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	$\boldsymbol{\nu_R}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_L}$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. ($\rightarrow M$)

ν_L to $\bar{\nu}_R$ $\qquad$ ν_L to ν_R

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$\bar{\nu}_R$ to $\bar{\nu}_L$ $\qquad$ ν_R to $\bar{\nu}_L$

Two Majorana neutrinos
with masses m_D^2/M and M

Seesaw:
Yanagida, Gell-man-
Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

The consequences of this alternative are profound:

- Physics beyond the SM at a scale M!

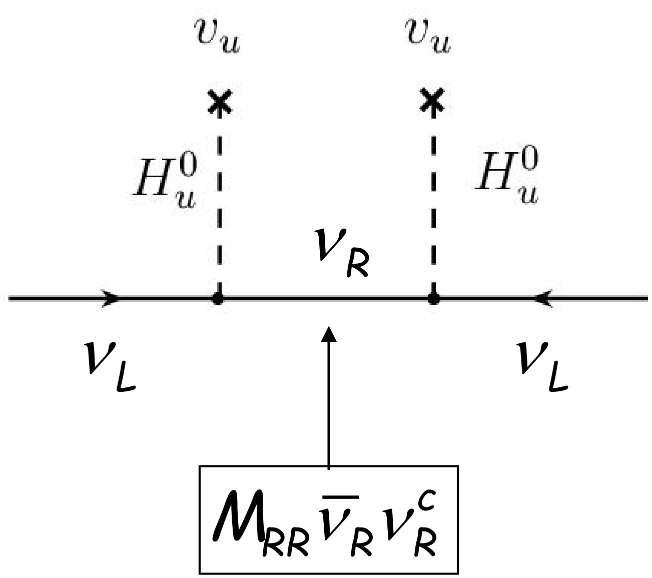
- Majorana fermions carry no conserved charge: L is violated !

$$\nu_L \to e^{i\alpha}\nu_L$$

does not leave the Majorana mass term invariant.
$\rightarrow$ Most welcome for baryogenesis: a mechanism to understand the matter-antimatter asymmetry in the Universe emerges naturally
$\rightarrow$ Most welcome by string theory: it is difficult to get global $U(1)$ charges conserved

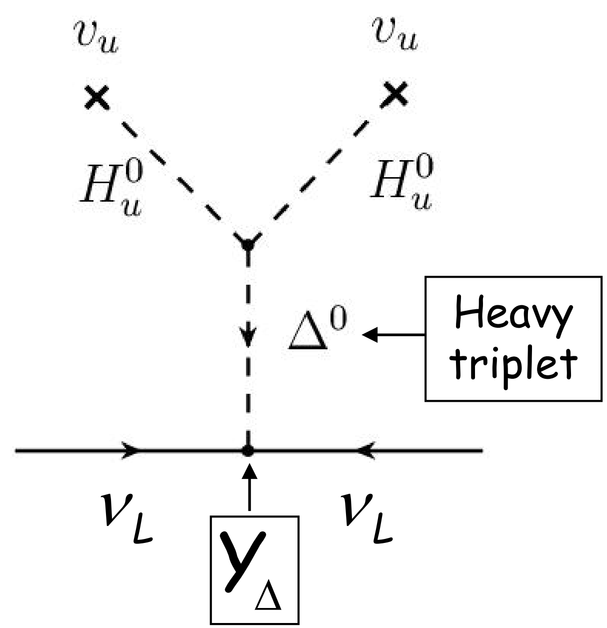
Types of see-saw mechanism

Type I see-saw mechanism



$$m_{LL}^{I} \approx -m_{LR}M_{RR}^{-1}m_{LR}^{T}$$

Type II see-saw mechanism



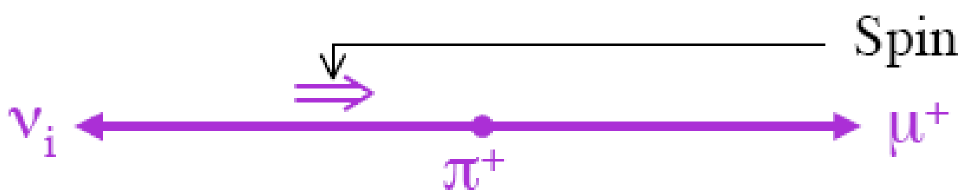
$$m_{LL}^{II}\overline{\nu}_L\nu_L^c \approx Y_\Delta \frac{v_u^2}{M_\Delta}$$

How Can We Demonstrate That $\overline{\nu_i} = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \rightarrow \ell^-$; $\bar{\nu} \rightarrow \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

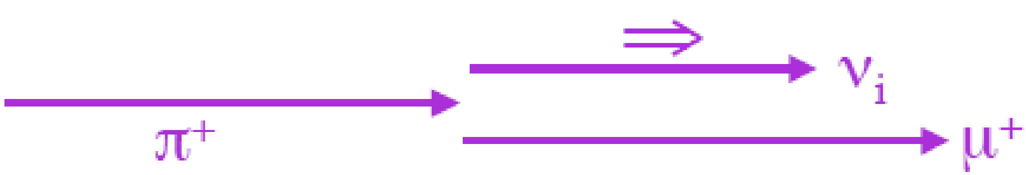
Produce a ν_i via—



Pion Rest Frame

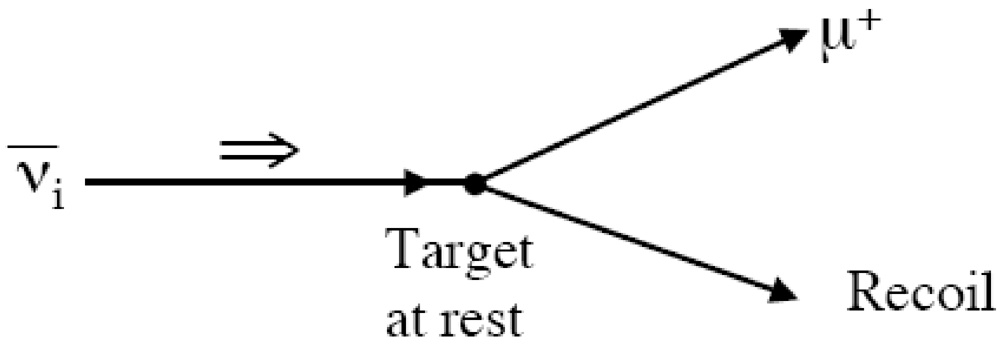
Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$



Lab. Frame

The SM weak interaction causes —



$\nu_i = \overline{\nu}_i$ means that $\nu_i(h) = \overline{\nu}_i(h)$.

helicity

If $\nu_i \xrightarrow{\Rightarrow} \; = \; \overline{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

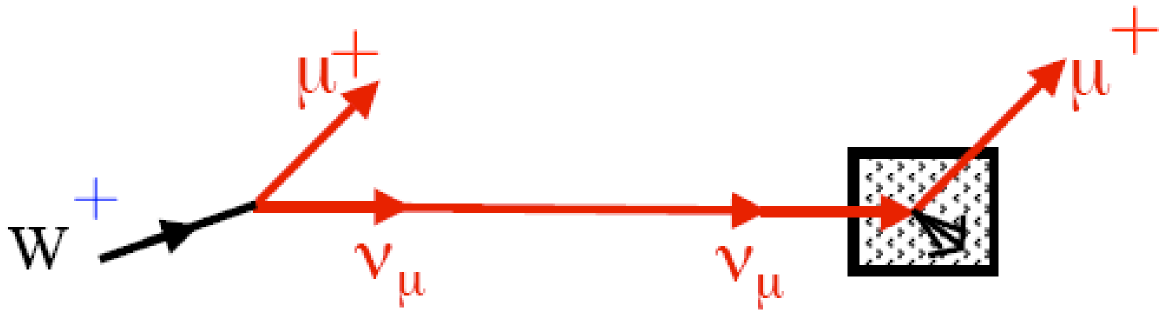
$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi \ (\text{Lab}) > 10^4 \ \text{TeV} \quad \text{if} \quad m_\nu \sim 1 \text{ eV}$$

Fraction of all π–decay that get helicity flipped

$$\approx \left(\frac{m_\nu}{E_\nu \ (\pi \text{ Rest Frame})} \right)^2 \sim 10^{-16} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

For Majorana Neutrinos

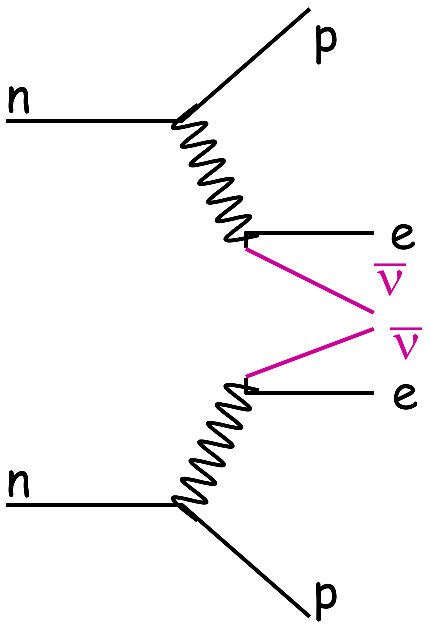


Not Observed

Allowed

BUT Suppressed by $\frac{m_\nu^2}{E^2} \sim 10^{-20}$!!!

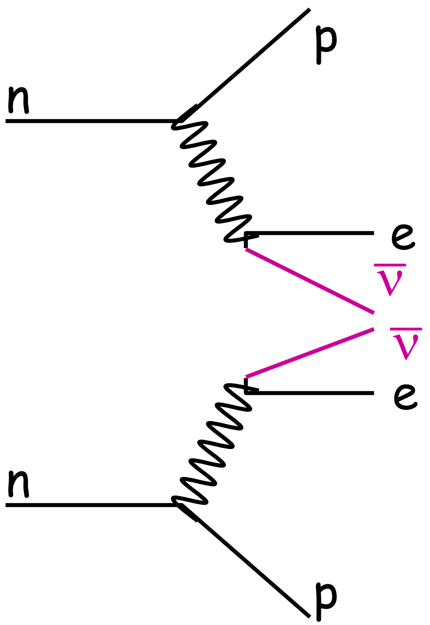
➢ How we can find out ?



SM double weak process

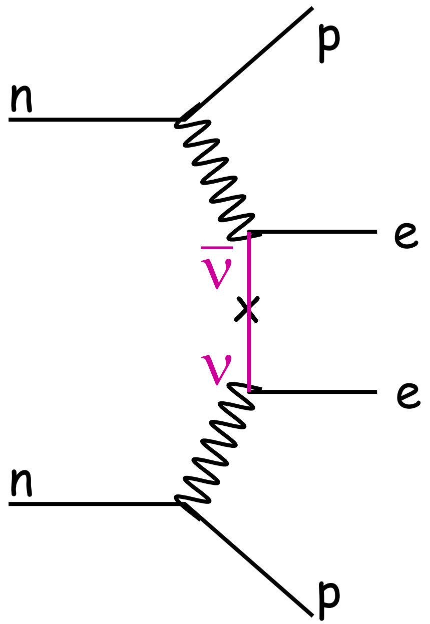
4 body decay: continuos spectrum for the e energy sum

➢ How we can find out ?



SM double weak process

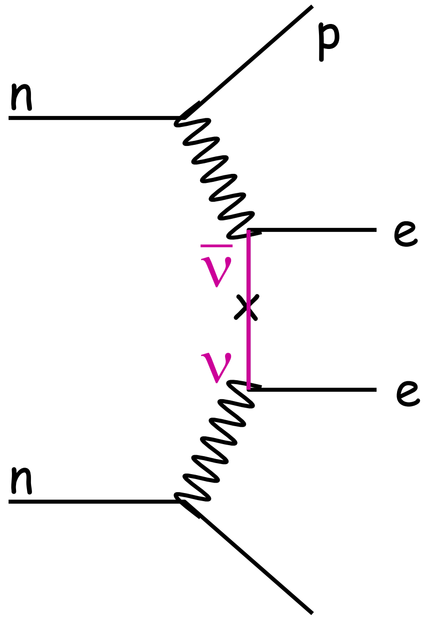
4 body decay: continuos spectrum for the e energy sum



Only allowed for Majorana ν

2 body decay: e energy sum is a delta

$\overline{\nu}_i$ is emitted (RH + O(m_i/E) LH)



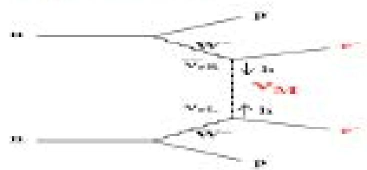
Amp[ν_i contribution] $\sim$ m_i

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right|$$

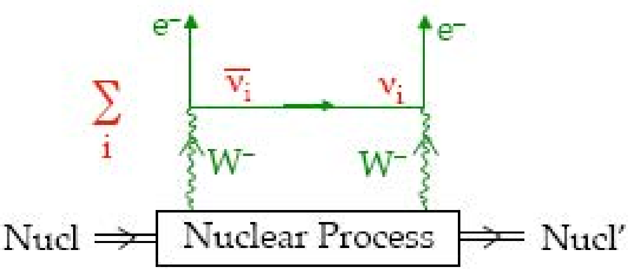
effective mass

Neutrinoless double beta decay

- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



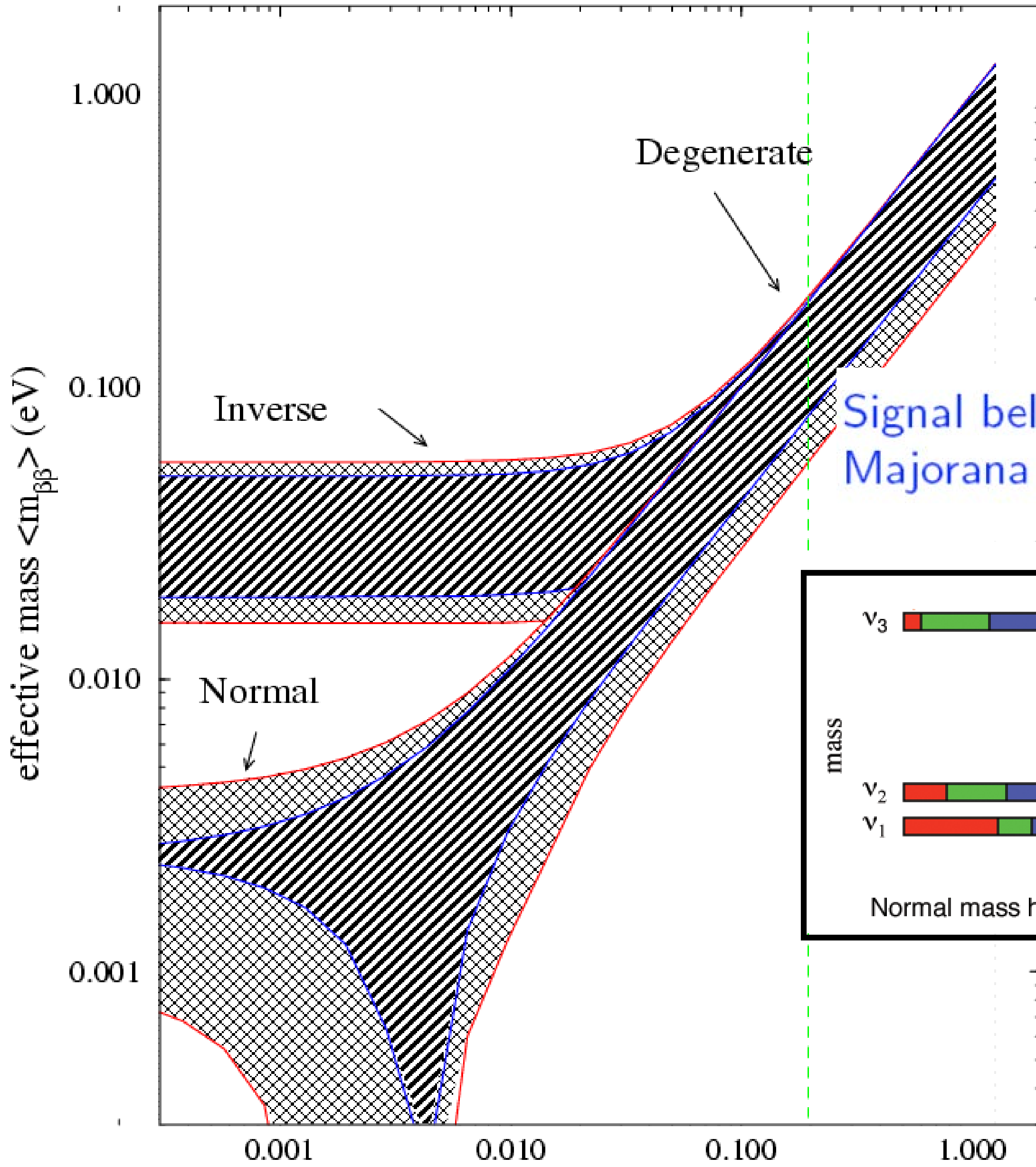
$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$
$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$



Effective neutrino mass in 0ν ββ decay

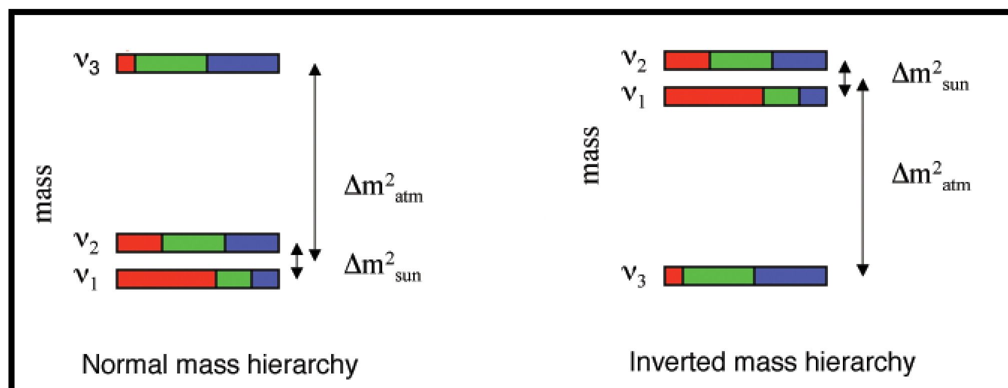
LMA solution, crosshatched region with errors

$$m_{\beta\beta} = \left| \sum m_i U_{ei}^2 \right|$$



dividing point $m_{\beta\beta} \approx 10meV$

Signal below ~ 10 meV would imply Majorana and Normal Hierarchy!



Test KK may look easy but nobody did it completely …

- 5 HP(
- Peak

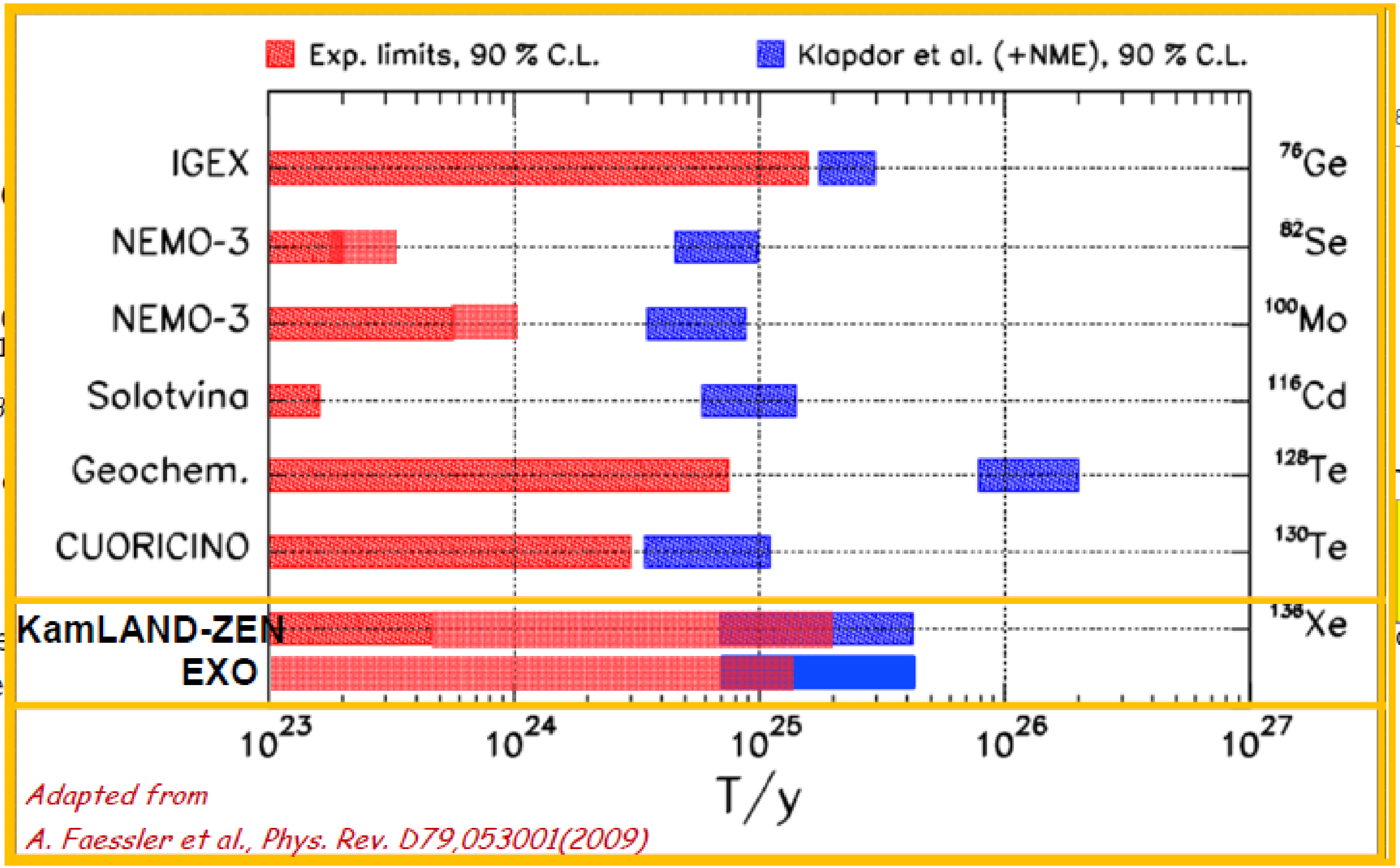
T

$\langle m_\beta$

- Probl

⇒ Ne

ne



Some exotic (and not so exotic) scenarios

Non standard neutrino interactions

CPT violation

Violations of Lorentz invariance

Non standard neutrino interactions

They can be described by effective four-fermion operators of the form

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\overline{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f'\right)$$

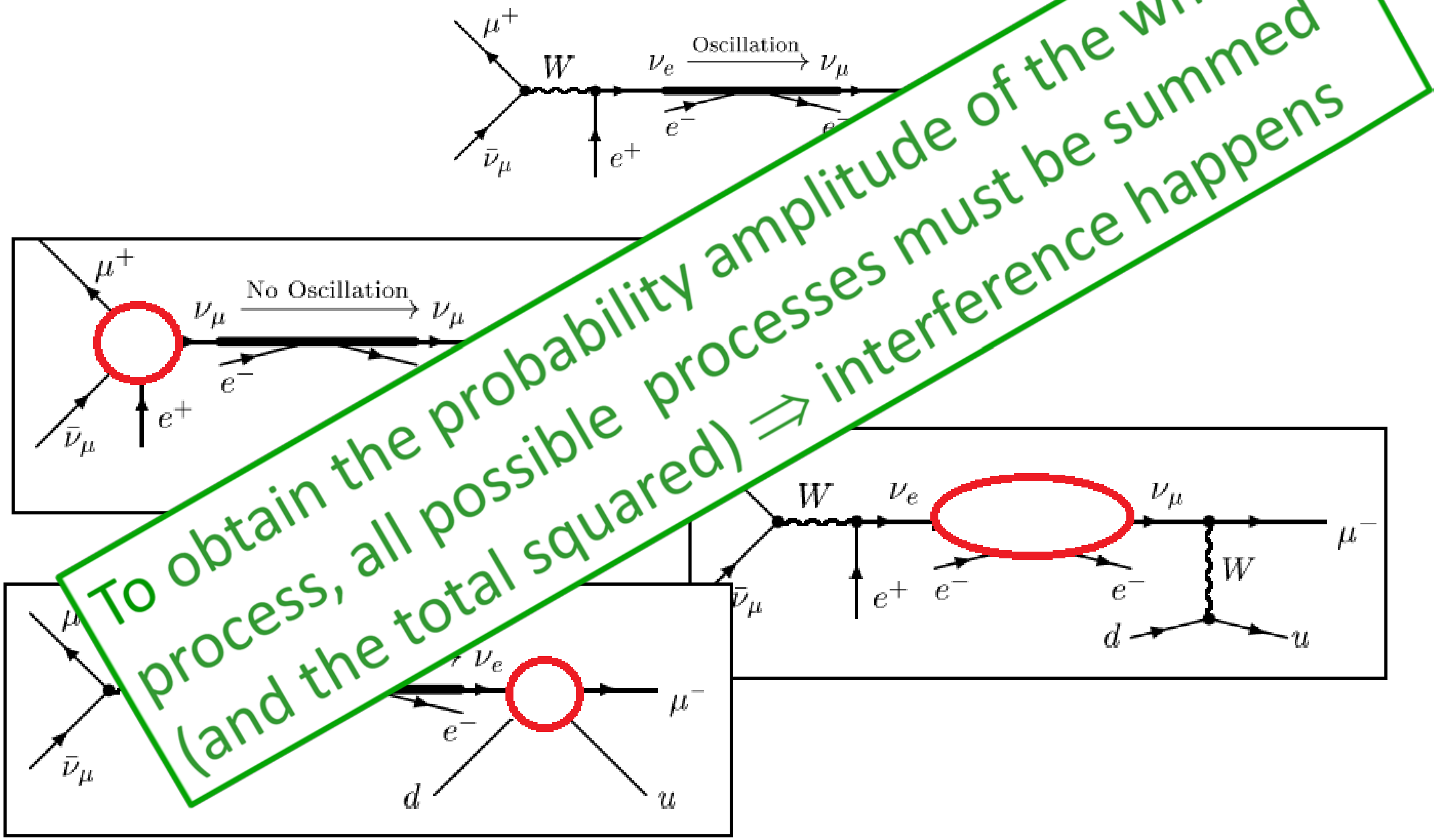
normalizing the operator with the Fermi constant

$$\varepsilon_{\alpha\beta} = \frac{M_W^2}{M^2_{NSNI}}$$

NSNI can appear at every step. It is therefore necessary to break down the analysis in three stages

- the production process
- the time evolution
- the detection process

Lets have a look at what is called the “golden ” channel



To obtain the probability amplitude of the whole process, all possible processes must be summed (and the total squared) $\Rightarrow$ interference happens

The system consists of an initial state

state of the parent particle

$A + T$

state of the target

intermediate state B

and a final state

state of the particle producing and identifiable event

$C + U$

unobserved particles

$$P\,(\,A + T \;\rightarrow C + U) = |\, \textstyle\sum_B \;\Phi(A, T; B; C, U)\;|^2$$

The system consists of an initial state

state of the parent particle

$A + T$

state of the target

intermediate state B

and a final state

state of the particle producing and identifiable event

$C + U$

unobserved particles

$$P\,(\,A + T \;\rightarrow C + U) = |\,\textstyle\sum_B\;\Phi(A, T; B; C, U)\;|^2$$

$$\boxed{P\,(\,A\;\rightarrow C) = \sum_{T,U} P(A + T \rightarrow C + U)}$$

Assuming that the amplitude $\Phi\,(A, T_o\,; B_o; C\,, U_o\,)$ is dominant

$P\,(A \rightarrow C) \approx P(A + T_o \;\rightarrow\; C + U_o)$

$= |\;\Phi\,(A, T_o\,; B_o; C\,, U_o)|^2$

$+\, 2\,\mathrm{Re}\left[\,\Phi\,(A, T_o\,; B_o; C\,, U_o)^*\,\sum_{B \neq B_o} \Phi\,(A, T_o\,; B; C\,, U_o\,)\right]$

$\cancel{+\;|\sum_{B \neq B_o} \Phi\,(A, T_o\,, B; C\,, U_o\,)\,|^2}$

For a neutrino factory : $A\;\rightarrow \mu$- $\quad C \rightarrow \mu$+

Production and detection involve charged current NSNI

$$\pi \longrightarrow \mu + \nu_\alpha$$

$$\mu^- \rightarrow e^- \; \nu_\mu \; \overline{\nu_\alpha}$$

$$n + \nu_\alpha \longrightarrow p + l_\beta$$

$$2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ud}\left(\bar{l}_\beta \gamma^\mu P_L \nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R} d\right) \qquad 2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{\mu e}\left(\bar{\mu}\gamma^\mu P_L \nu_\beta\right)\left(\bar{\nu}_\alpha \gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 2.6\cdot 10^{-5} & 0.078 & 0.013 \\ 0.011 & 0.016 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

bounds are $\sim \; 10^{-2}$

We are left "only" with neutral current NSNI

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma \cdots\right.$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta\cdots\end{pmatrix} \cdots \begin{pmatrix}\cdots & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \cdots & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

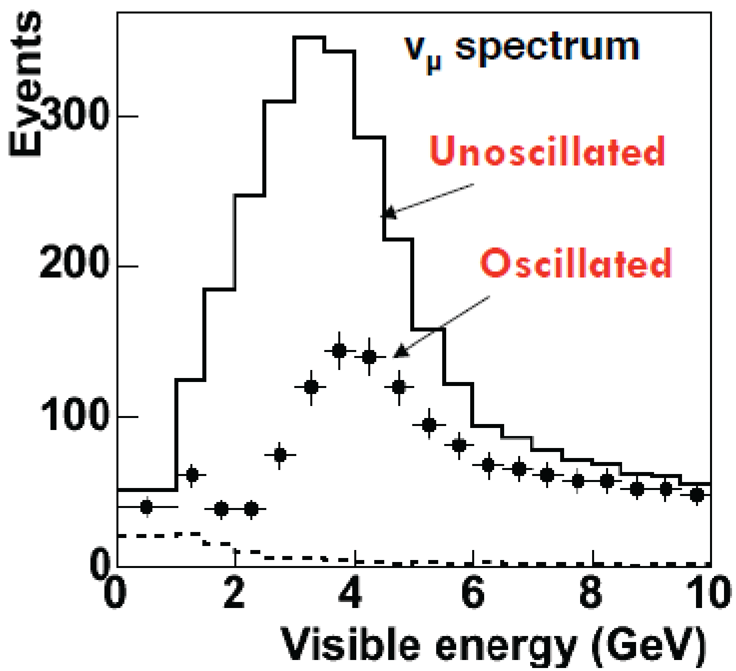
$$a \equiv 2\sqrt{2}G_F n_e E$$

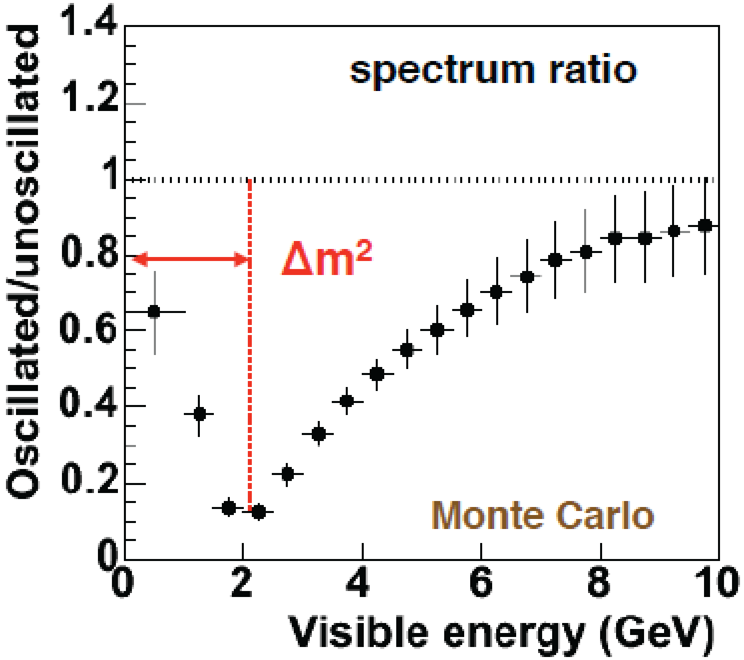
$$H = \cdots m^2_{32}\Big) U^\dagger + a\begin{pmatrix}\epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\Big]$$

Anomalies

the driving force in neutrino physics for 30+ years !!!!!

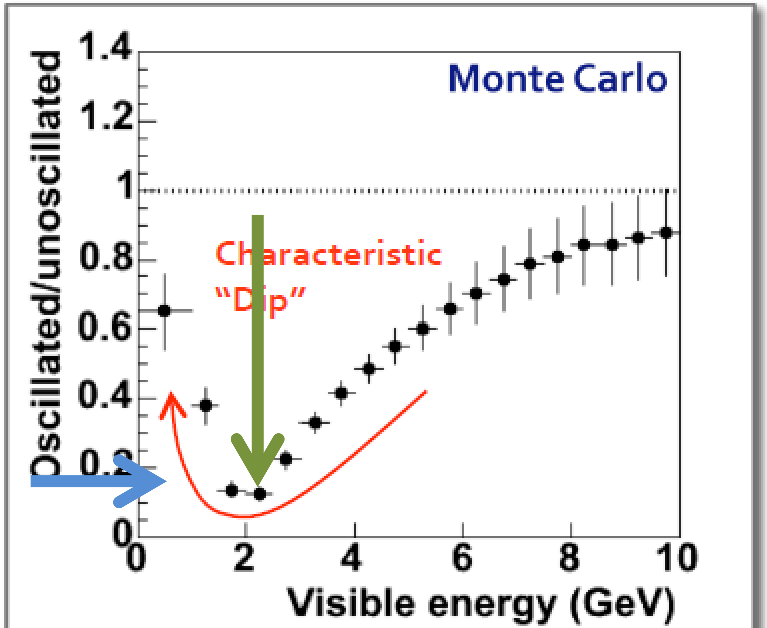
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L / E)$$





$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

$$\Delta m^2$$

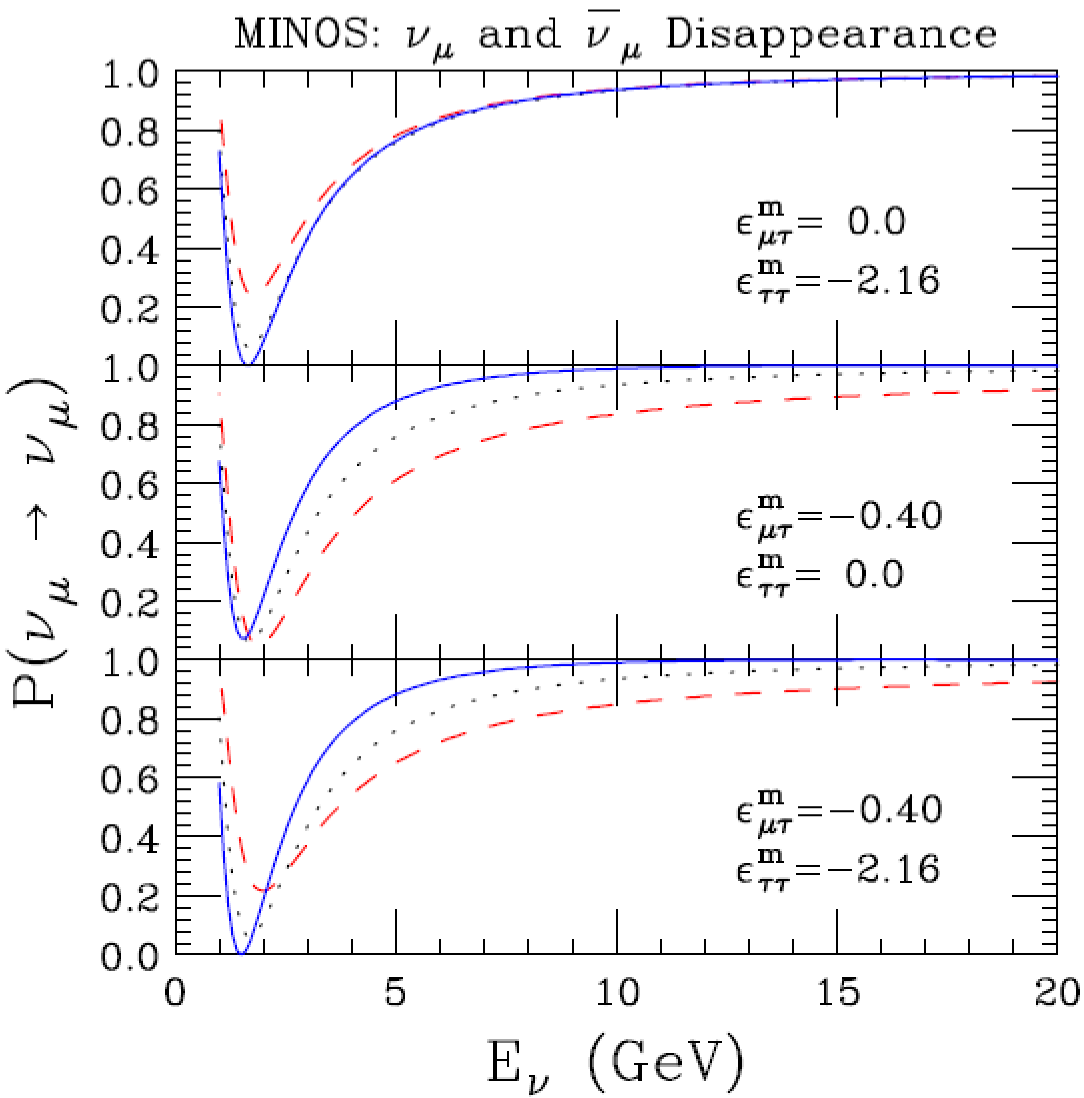


$\varepsilon_{\tau\tau}$ modifies the dissapearence probability near the first oscillation minimum, especially the depth of the minimum

$$sin^2(2\,\theta_{23})$$

neutrino

antineutrino



Kopp et al. 1009.0014

CPT violation

$$\frac{|\, m(K_0) - m(\overline{K_0}\,)\,|}{m_{K-av}} < 10^{-18}$$

$$m_{K-av} \approx \frac{1}{2}\ 10^{9}\ \text{eV}$$

$$(m(K_0) - m(\overline{K_0}\,)\ )(m(K_0) + m(\overline{K_0}\,)) < 2\ \ 10^{-18}\, m_{K-av}{}^{2}$$

$$|m^2(K_0)\ - m^2(\overline{K_0}\,)| \qquad \approx \frac{1}{2}\ \text{eV}^{\,2}$$

$$\boxed{|\ \Delta m^2 \text{ - } \overline{\Delta m^2}\ | \approx\ 10^{-6}\ -\ \ 10^{-3}\,\text{eV}^{\,2}}$$

Current bounds

- We use the same data (except atmospheric neutrinos) as for the global fit arXiv:1708.01186 to obtain

$$
\begin{aligned}
|\Delta m_{21}^2 - \Delta\overline{m}_{21}^2| &< 4.7 \times 10^{-5}\mathrm{eV}^2, \\
|\Delta m_{31}^2 - \Delta\overline{m}_{31}^2| &< 3.7 \times 10^{-4}\mathrm{eV}^2, \\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14, \\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.03, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.32,
\end{aligned}
$$

G.B., C. Ternes and M. Tortola, ArXiv:1712.01714

Distinguishing CPT violation from NSNI

The muon neutrino survival probability in matter can be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_\nu \sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right) .$$

in matter

$\Delta m_\nu^2 \cos 2\theta$ … $- \epsilon_{\tau\tau} A\,,$

$\Delta m_\nu^2 \sin 2\theta$ … $- 2\epsilon_{\mu\tau} A\,.$

$$4\Delta m^4 = \Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})$$

$$\sin^2(2\theta) = \frac{\left(\Delta m_\nu^2 \sin(2\theta_\nu) + \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu})\right)^2}{\Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})}$$

$$\begin{aligned} 2\epsilon_{\tau\tau}^m A &= \Delta m_\nu^2 \cos(2\theta_\nu) - \Delta m_{\bar\nu}^2 \cos(2\theta_{\bar\nu}) \\ 4\epsilon_{\mu\tau}^m A &= \Delta m_\nu^2 \sin(2\theta_\nu) - \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu}) \end{aligned}$$

Violations of Lorentz invariance

$$(h_{\mathrm{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^{\alpha} p_{\alpha} - (c_L)^{\alpha\beta} p_{\alpha} p_{\beta}\right]_{ab}$$

Violations of Lorentz invariance

Lorentz violation

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standard Lorentz covariant term

violates both CPT and Lorentz invariance

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standard Lorentz covariant term

violates both CPT and Lorentz invariance

As usual, the oscillation probability is governed by the difference of the eigenvalues of the effective hamiltonian.

$$\sin^2(\Delta_{ab} \; L/2)$$

$${m_{ab}}^2 L/E$$

$$(a^{\alpha})_{ab} \; L$$

$$(c^{\alpha\beta})_{ab} \; L \, E$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$

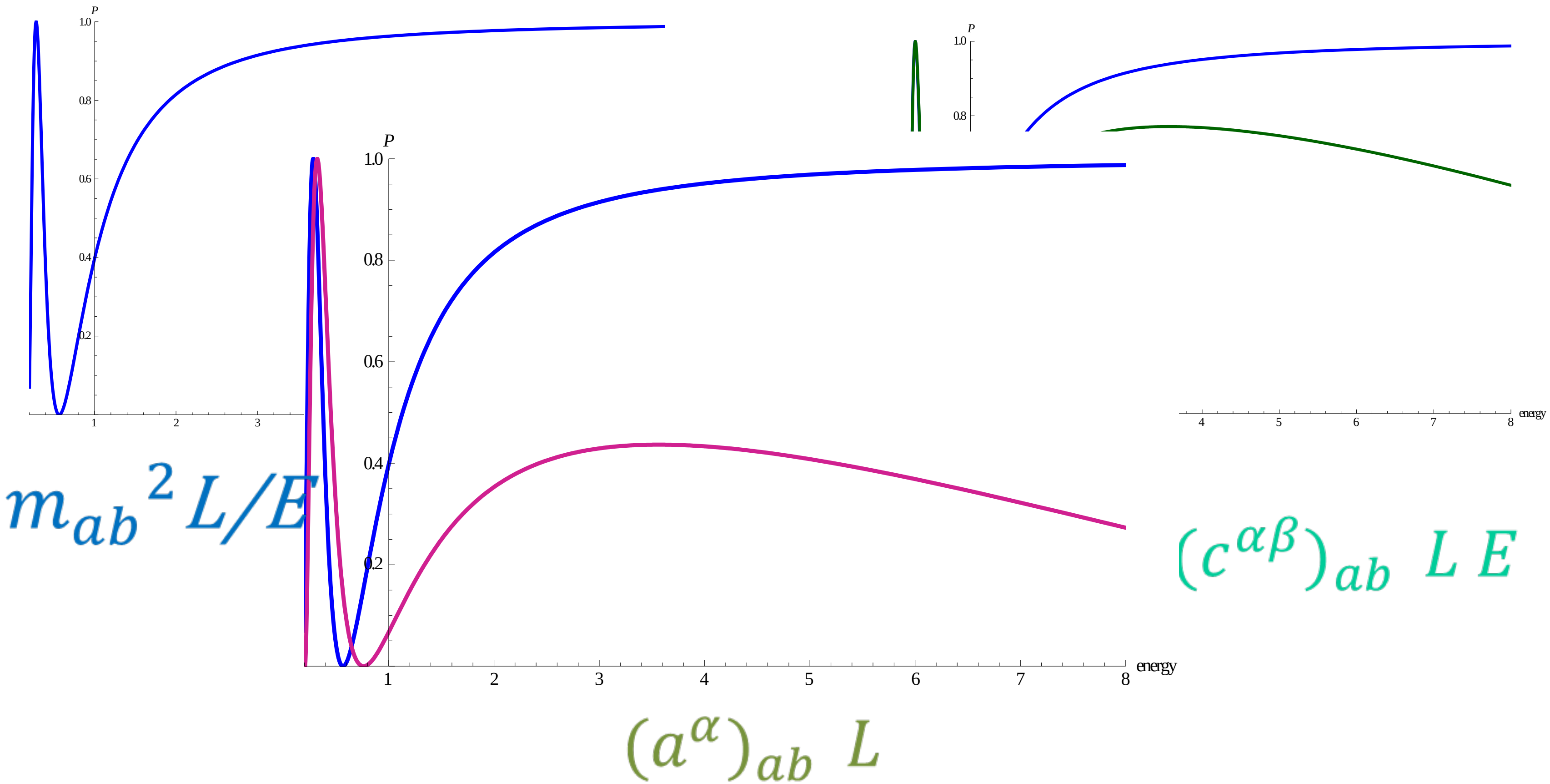


Table S4. Maximal sensitivities for the neutrino sector

$d=3$	**Coefficient**	$e\mu$	$e\tau$	$\mu\tau$	**Coefficient**	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	10^{-24} GeV	$\mathrm{Im}\,(a_L)^T$	–	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV	$\mathrm{Im}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-20} GeV
	$\mathrm{Re}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV	$\mathrm{Im}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-20} GeV
	$\mathrm{Re}\,(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	–	$\mathrm{Im}\,(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	–

$d=4$	**Coefficient**	$e\mu$	$e\tau$	$\mu\tau$	**Coefficient**	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}	$\mathrm{Im}\,(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-21}
	$\mathrm{Re}\,(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}	$\mathrm{Im}\,(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-21}
	$\mathrm{Re}\,(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}	$\mathrm{Im}\,(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-21}
	$\mathrm{Re}\,(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}	$\mathrm{Im}\,(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-21}
	$\mathrm{Re}\,(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}	$\mathrm{Im}\,(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-21}
	$\mathrm{Re}\,(c_L)^{ZZ}$	10^{-19}	10^{-16}	–	$\mathrm{Im}\,(c_L)^{ZZ}$	–	10^{-16}	–
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–	$\mathrm{Im}\,(c_L)^{TT}$	–	10^{-17}	–
	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}	$\mathrm{Im}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-22}
	$\mathrm{Re}\,(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}	$\mathrm{Im}\,(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-22}
	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	10^{-16}	–	$\mathrm{Im}\,(c_L)^{TZ}$	–	10^{-16}	–

Isotropic	**Coefficient**	**Sensitivity**	**Coefficient**	**Sensitivity**
	$\mathring{a}^{(3)}$	10^{-7} GeV	$\mathring{a}^{(3)}_{e\mu}$	10^{-20} GeV
	$\mathring{c}^{(4)}$	10^{-9}	$\mathring{c}^{(4)}_{e\mu}$	10^{-19}
	$\mathring{a}^{(5)}$	10^{-18} GeV^{-1}	$\mathring{a}^{(5)}_{e\mu}$	10^{-19} GeV^{-1}
	$\mathring{c}^{(6)}$	10^{-9} GeV^{-2}	$\mathring{c}^{(6)}_{e\mu}$	10^{-19} GeV^{-2}
	$\mathring{a}^{(7)}$	10^{-29} GeV^{-3}	$\mathring{a}^{(7)}_{e\mu}$	10^{-19} GeV^{-3}
	$\mathring{c}^{(8)}$	10^{-11} GeV^{-4}	$\mathring{c}^{(8)}_{e\mu}$	10^{-18} GeV^{-4}
	$\mathring{a}^{(9)}$	10^{-40} GeV^{-5}	$\mathring{a}^{(9)}_{e\mu}$	10^{-18} GeV^{-5}
	$\mathring{c}^{(10)}$	10^{-14} GeV^{-6}	$\mathring{c}^{(10)}_{e\mu}$	10^{-18} GeV[illegible]

V.Kostelecky and N. Russell
Rev.Mod.Phys. 83 (2011) 11
e-Print: revised Jan 2018

SUMMARY I

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

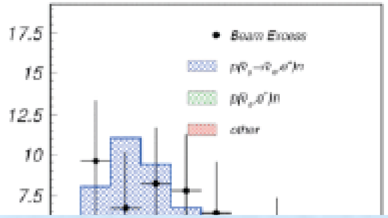
$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\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

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

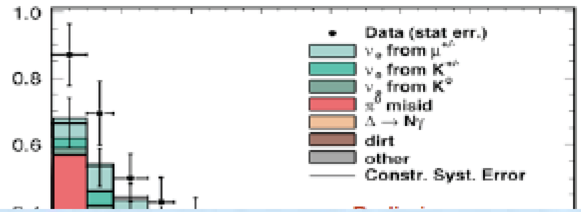
https://globalfit.astroparticles.es/

parameter	best fit $\pm$ 1σ	3σ range	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

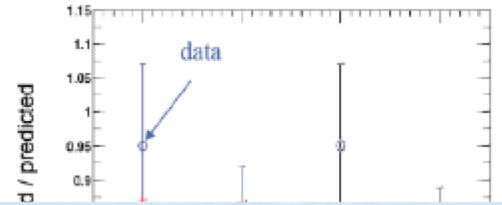
LSND



MiniBoone



Ga Anomaly



Long Baseline experiments producing data….

- Hints addressing these questions
- Next sets of data in the next couple of years will be critical!

T2K, MINOs+, NOvA, ICECUBE, PINGU, HyperK, JUNO, DUNE

Short Baseline anomalies persist….

- Many new experiments coming online to address these

MicroBooNE, SBND, ICARUS, OscSNS, IsoDAR, Prospect, Posiden, Nucifer, Solid, Stereo,…..

How are long baseline and short baseline related?

Direct Mass measurements

- Taking data and coming online

Katrin, Project 8, HOLMES, CRES, NUMEC, ECHO

- New Interactions, Surprises !!!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EPISODES III, IV, V
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