Neutrino physics:

present status and

questions for the future

IOP: Particle Physics 2006

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1 – Outline

- Experimental data: evidence of neutrino oscillations
- Present status of neutrino physics
- Future questions and experimental program
- Conclusions

- We have compelling **evidence** of neutrino oscillations from atmospheric, solar, reactor and accelerator neutrino experiments.

- Neutrino oscillations require neutrino **masses** ($\Delta m^2 \neq 0$) and neutrino **mixing** ($\theta \neq 0$):

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \; \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$$

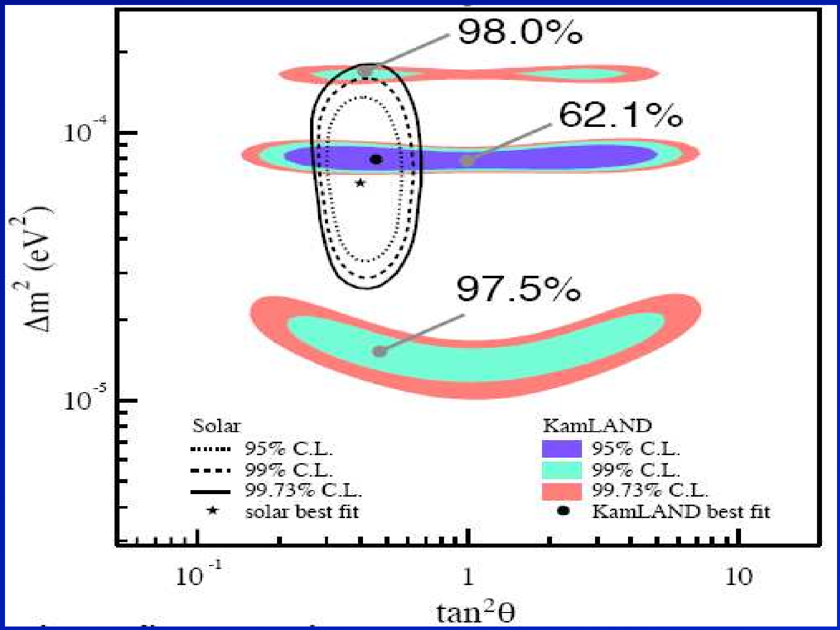
First evidence of Physics beyond the Standard Model.

2 – Neutrino oscillations - Experiments

• Solar neutrinos and KamLAND

The solar and KamLAND ν_e flux depletion can be explained in term of

$\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations.



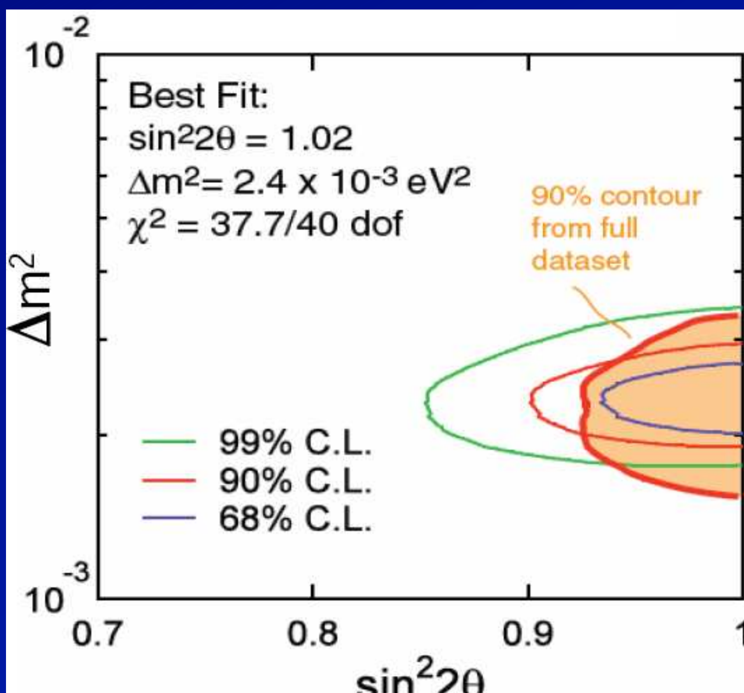
[SNO Coll., nucl-ex/0502021]

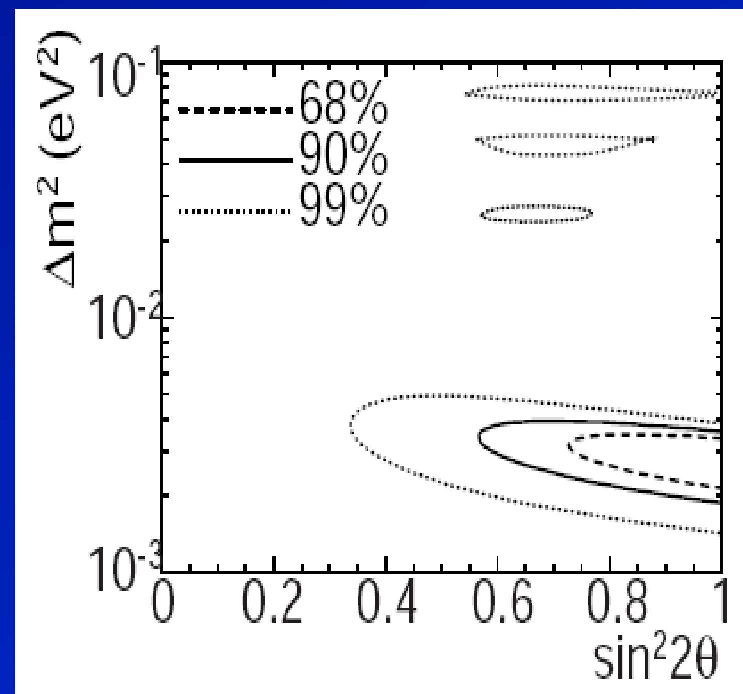
$$\Delta m^2_{\odot} = 8 \times 10^{-5}\,\mathrm{eV}^2 \quad \text{and} \quad \sin^2\theta_{\odot} = 0.31$$

• Atmospheric neutrinos

The SuperKamiokande (IMB, Kamiokande, MACRO, Soudan2) and **K2K** experiments data require

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations



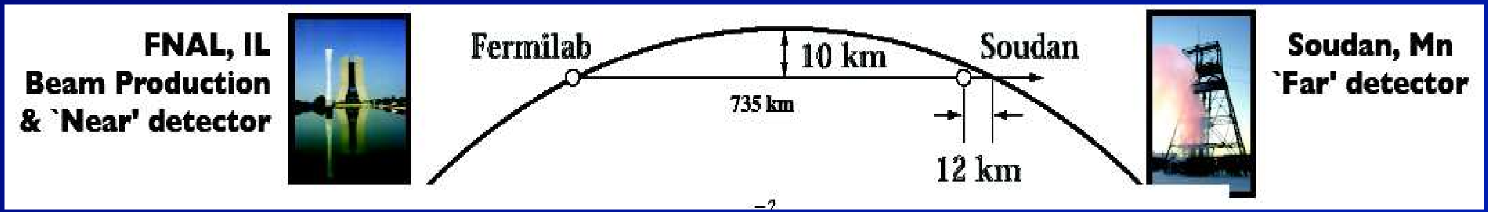


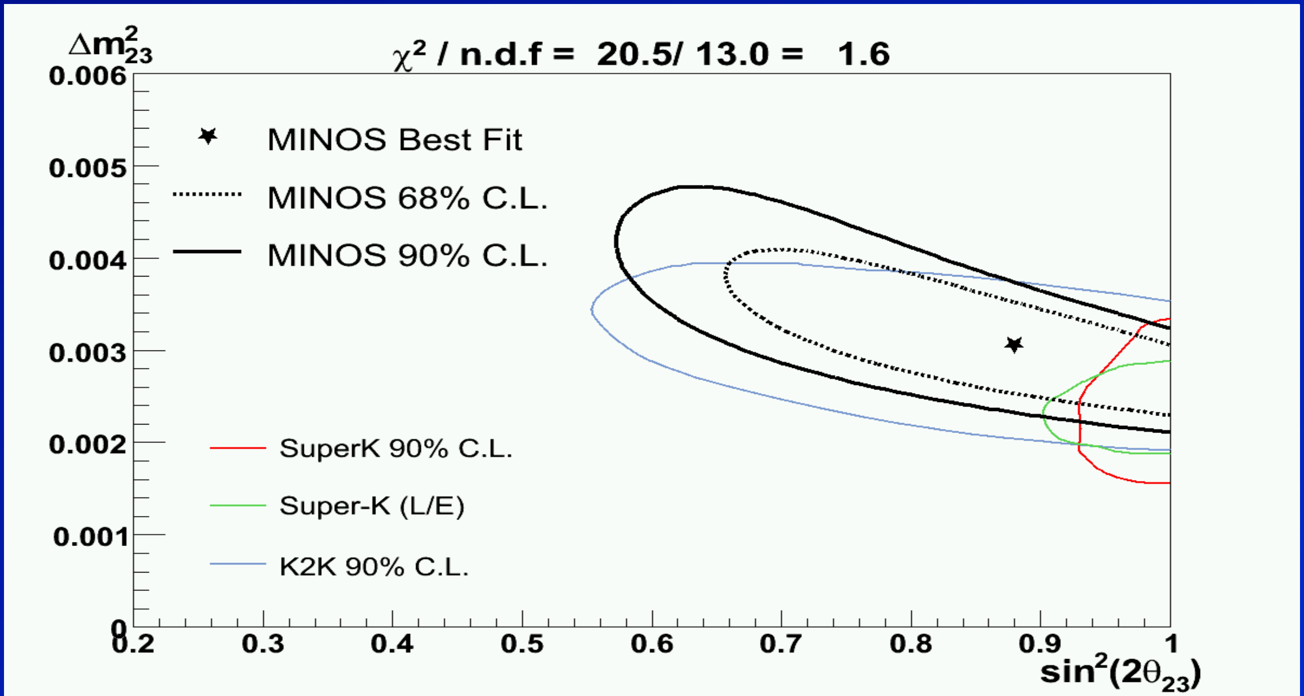
[Preliminary, Y. Suzuki @ Taup2005]

[K2K Coll., PRL 94 (2005) 081802]

$$\Delta m^2_{\rm A} = 2.5 \times 10^{-3}\,{\rm eV}^2 \quad \text{and} \quad \sin^2\theta_{\rm A} = 1$$

MINOS, (first data March 31), confirmed the oscillation hypothesis.

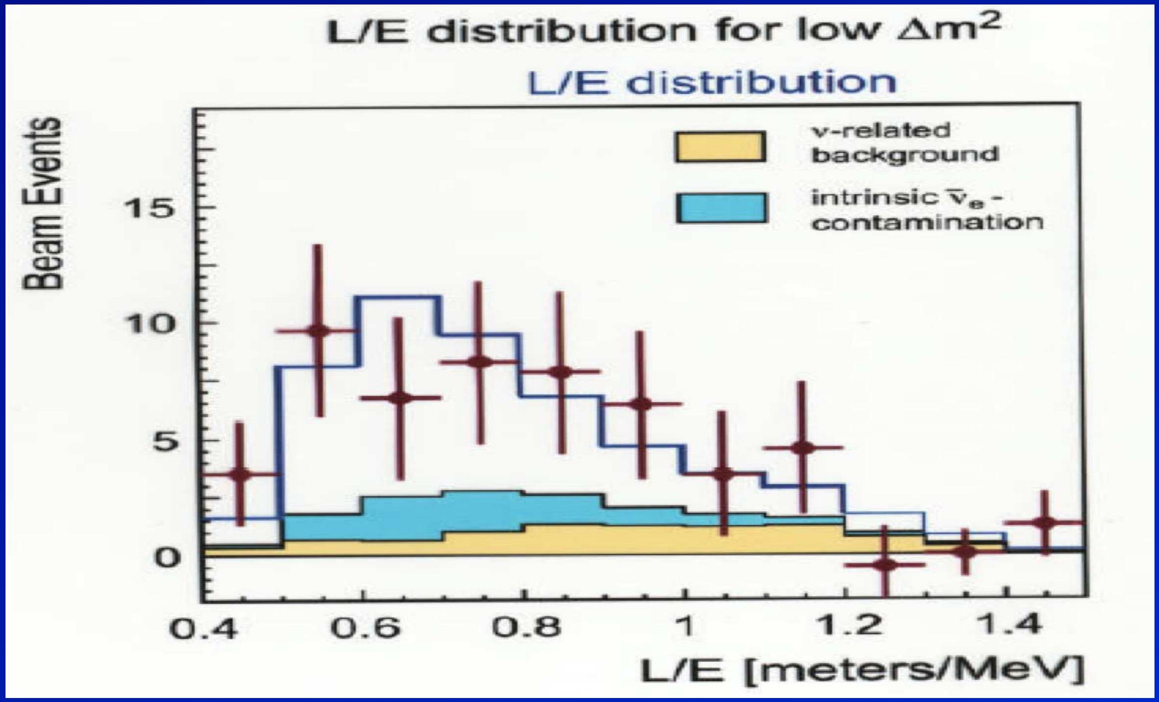




● LSND

The LSND exp took data from 1993 to 1998.

Accelerator neutrinos, ν_μ, ν_e and $\bar{\nu}_\mu$, were produced in π^+ and μ^+ decays. The LSND detector was located at a distance of 30 m. $\bar{\nu}_e$ were revealed.



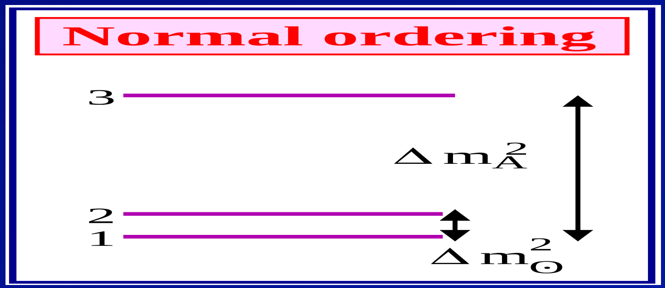
[LSND Coll., PRL 81 (1998) 1774]

LSND data cannot be explained with oscillations of 3 neutrinos:

Sterile neutrinos, new physics?????

3 – Present status of neutrino physics

$\Delta m^2_\odot \ll \Delta m^2_\text{A}$ implies at least **3 neutrinos**.



$$m_1 = m_\text{MIN}$$
$$m_2 = \sqrt{{m_\text{MIN}}^2 + \Delta m^2_\odot}$$
$$m_3 = \sqrt{{m_\text{MIN}}^2 + \Delta m^2_\text{A}}$$

$$m_3 = m_\text{MIN}$$
$$m_1 = \sqrt{{m_\text{MIN}}^2 + \Delta m^2_\text{A} - \Delta m^2_\odot}$$
$$m_2 = \sqrt{{m_\text{MIN}}^2 + \Delta m^2_\text{A}}$$

Measuring neutrino masses requires to know m_MIN and sign(Δm^2_{31}).

Mixing is described by a unitary matrix:

$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ Atm, Acc. $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase Reactor, Acc. $\theta < 12^o$ CPV Majorana phases

4 – Questions for the future

What are the fundamental questions for the present and the future?

1. Nature of neutrinos: Majorana vs Dirac?
2. Number of neutrinos: Are there sterile neutrinos?
3. Neutrino masses: absolute mass scale and type of hierarchy?
4. CP-violation: $\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$?

QUESTION 1: Nature of neutrinos.

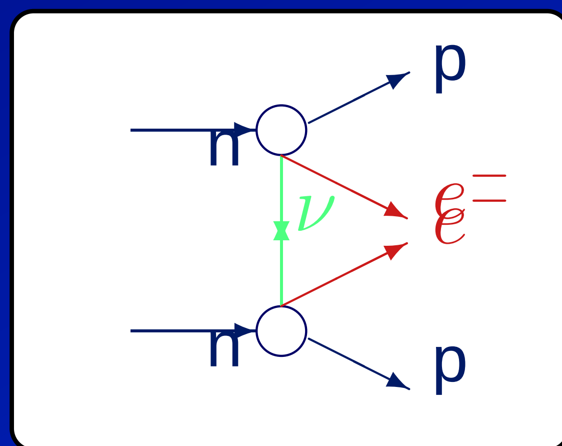
Neutrino can be either

Dirac	or	**Majorana**
lepton number conserved		lepton number broken

- The **nature of neutrinos** is directly related to the **fundamental symmetries** of elementary particles interactions.
- It provides important information on the **origin of neutrino masses**: in the see-saw mechanism neutrinos are predicted to be Majorana particles.
- Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism for generating the baryon asymmetry of the Universe.

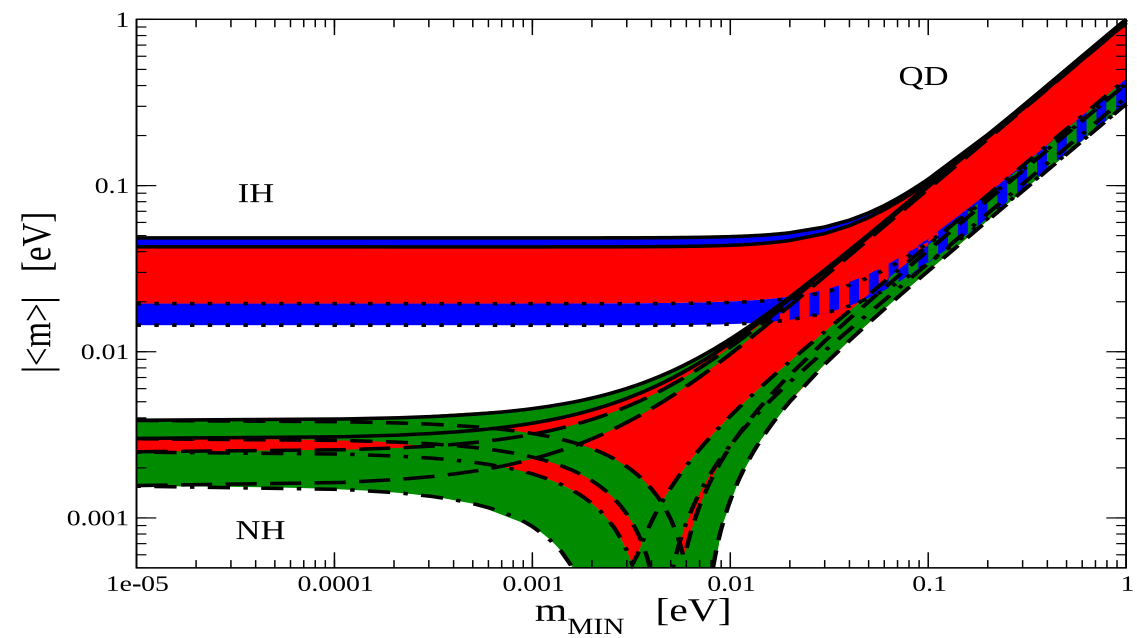
Neutrino oscillations are not sensitive to the nature of neutrinos.

The most sensitive process of all is $(\beta\beta)_{0\nu}$**-decay** ($(A,Z) \to (A,Z+2) + 2e^-$). It can proceed through the exchange of light Majorana neutrinos:



The half-life time, $\mathrm{T}_{0\nu}^{1/2}$, of the $(\beta\beta)_{0\nu}$-decay depends on **the effective Majorana mass parameter,** $|{<}\,m\,{>}|$:

$$|{<}\,m\,{>}| \;\equiv \left|\, m_1|U_{\mathrm{e}1}|^2 + m_2|U_{\mathrm{e}2}|^2 e^{i\alpha_{21}} + m_3|U_{\mathrm{e}3}|^2 e^{i\alpha_{31}} \,\right| .$$



[For ex., S.T. Petcov, A. Yu. Smirnov, PLB 322 (1994) 109; S.P., S.T. Petcov PLB 544 (2002) 239,...]

A positive signal would imply that

the lepton number is not a conserved symmetry in nature,

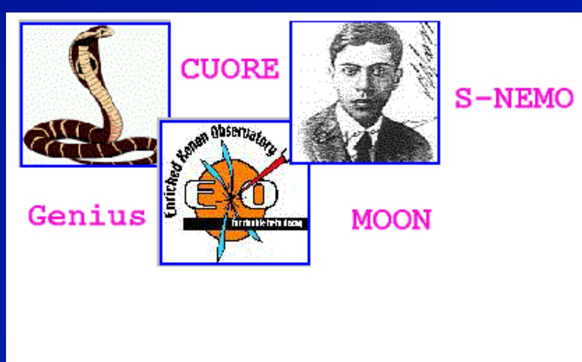
neutrinos are Majorana particles,

and it would give information on m_i and Majorana CP-V phases.

The present best limit on $|<m>|$ reads:

$|<m>| \; < (350 - 1050)\ \mathrm{meV}$	**Heidelberg-Moscow**
$|<m>| \; < (680 - 2800)\ \mathrm{meV}$	**NEMO3**
$|<m>| \; < (200 - 1050)\ \mathrm{meV}$	**CUORICINO**

Recently a claim of $(\beta\beta)_{0\nu}$decay discovery has been published [Klapdor-Kleingrothaus et al., PLB 586 (2004) 198]. It implies $|<m>| \; \simeq 200 - 600\ \mathrm{meV}$.



The sensitivity will be increased

to $|<m>| \; \sim 10 - 30\ \mathrm{meV}$,

in the new generation of experiments

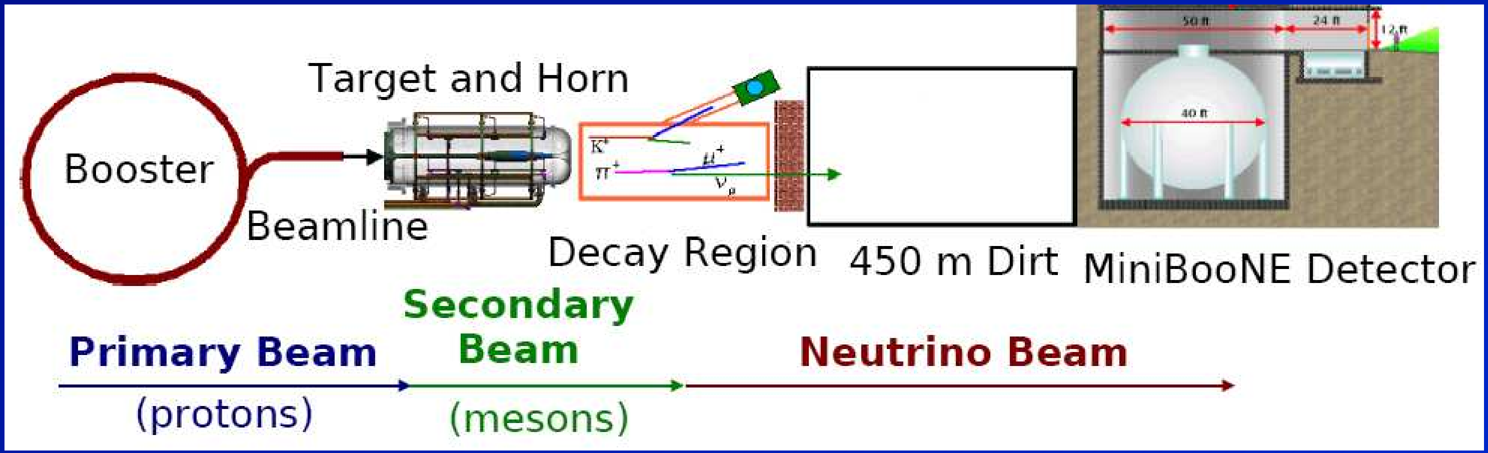
which is now under R&D and construction

(CUORE, SuperNEMO, EXO, GERDA, COBRA).

QUESTION 2: Number of neutrinos.

The LSND signal requires the existence of sterile neutrinos and maybe new interactions.

It is currently checked by the **MiniBOONE** exp.



[http://www-boone.fnal.gov]

Results are expected soon (sometime in 2006). Stay tuned!!!!.

QUESTION 3: Neutrino masses, m_1, m_2, m_3.

As we know only $\Delta m^2_\odot$ and $\Delta m^2_{\rm A}$, we need:

- the absolute mass scale ($m_{\rm MIN}$).
- the type of hierarchy ($sgn(\Delta m^2_{31})$).

Knowing the type of spectrum (NH, IH, QD) is crucial for understanding the origin of neutrino masses in the context of models Beyond the Standard Model.

- Direct mass searches in **tritium beta decay** exp. The present limit is $m_0 < 2.2$ eV (Troiztk and Mainz). KATRIN can reach a sensitivity to $m_0 \sim 0.2$ eV, covering all the QD spectrum.

Type of hierarchy

- $(\beta\beta)_{0\nu}$-decay: it can distinguish between different types of spectra (NH, IH, QD). The role of $\sin^2\theta_{13}$ is subdominant.

- atmospheric neutrino experiments: exploiting matter effects in magnetized or not detectors (Hyper-Kamiokande, INO).

- long baseline neutrino oscillation experiments exploiting matter effects. It depends crucially on the value of $\sin^2\theta_{13}$. Degeneracies arise with the CP-violating phase δ.

Neutrinos travelling through the Earth are affected by matter.

The mixing angle changes with respect to the vacuum case:

$$\sin 2\theta_m = \frac{(\Delta m^2/2E)\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}}$$

For $\Delta m^2 > 0$, mixing gets enhanced for neutrinos and suppressed for antineutrinos.

For $\Delta m^2 < 0$, the opposite happens.

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})$$

QUESTION 4: CP-violation.

If U is complex we have CP-violation:

$$P(\nu_l \to \nu_{l'}) \neq P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

- Establishing leptonic CP-V (δ) is a fundamental and challenging task.

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses.

The observation of neutrinoless double beta decay (L violation) and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

Determining CP-V and the type of hierarchy in LBL exp

The CP-asymmetry and the type of hierarchy will be searched for in future long base-line exp: $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu_\mu} \to \bar{\nu_e})$.

It is necessary to disentangle true CP-V effects due to the δ phase from the ones induced by matter: **degeneracies**.

$$\left.\begin{array}{l} \Delta m^2_{31}\,,\ \theta_{13}\,,\ \delta\,,\ \theta_{23} \\ \Delta m^{2\,\prime}_{31}\,,\ \theta'_{13}\,,\ \delta'\,,\ \theta'_{23} \end{array}\right\} \rightarrow P, \overline{P}$$

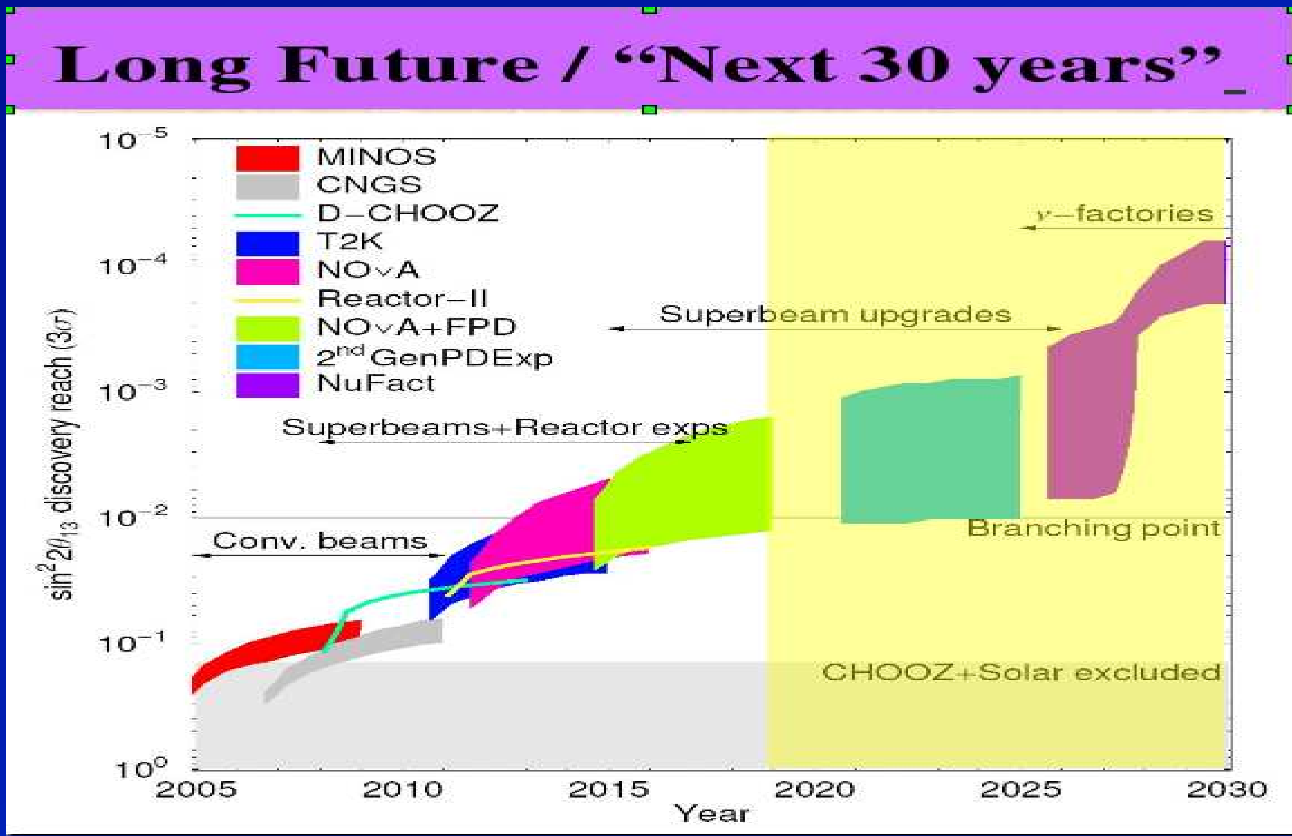
Degeneracies worsen the possibility of future experiments in resolving the type of hierarchy and the sensitivity to CP-violation.

Many future LBL ν oscillation exp will do precision studies.

1. Superbeams.

2. Neutrino factories.

3. Beta-beams.

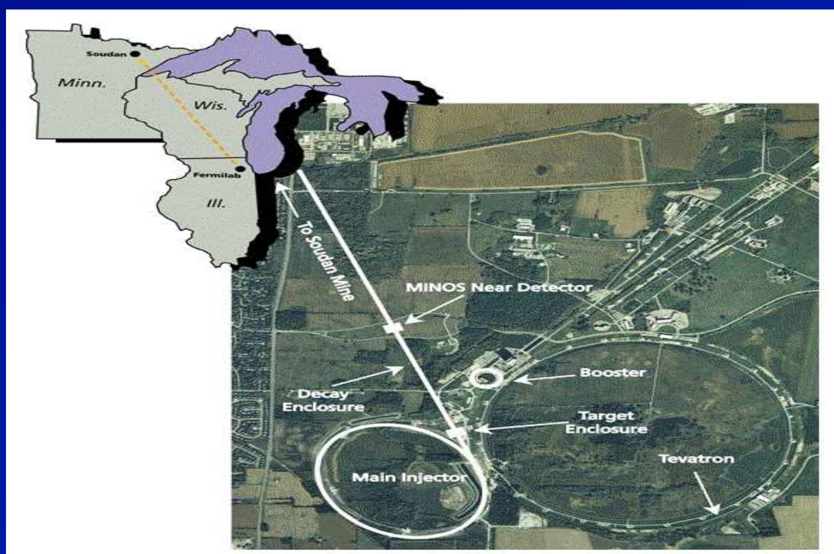


Superbeams (NOνA, T2K):

a very intense ν_μ beam produced in $\pi^\pm, K^\pm$ decays to search for ν_μ disappearance, ν_e appearance and ν_τ appearance.

Off-axis detector to achieve a narrow energy beam.

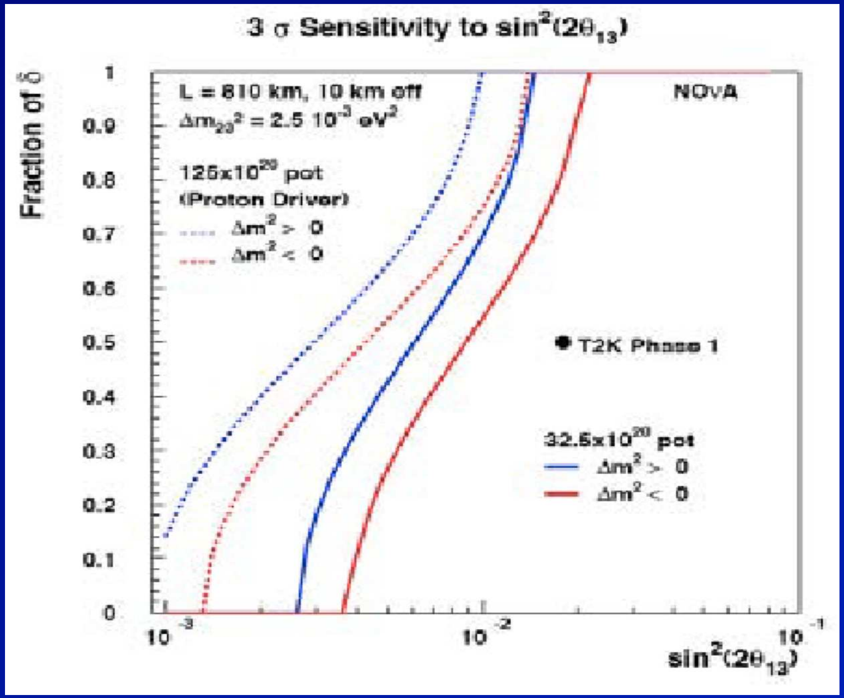
NOνA



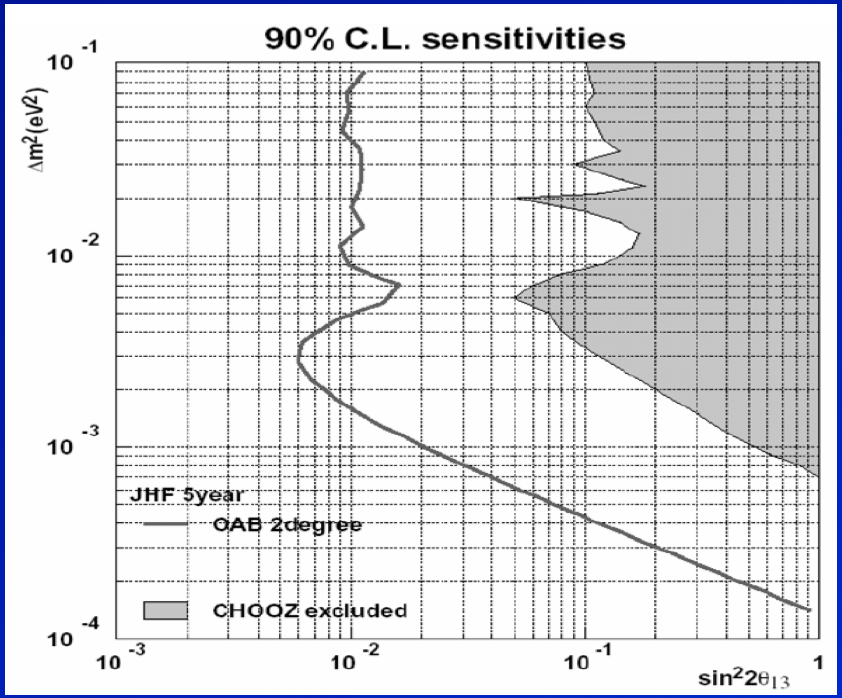
[http://www-nova.fnal.gov]

T2K

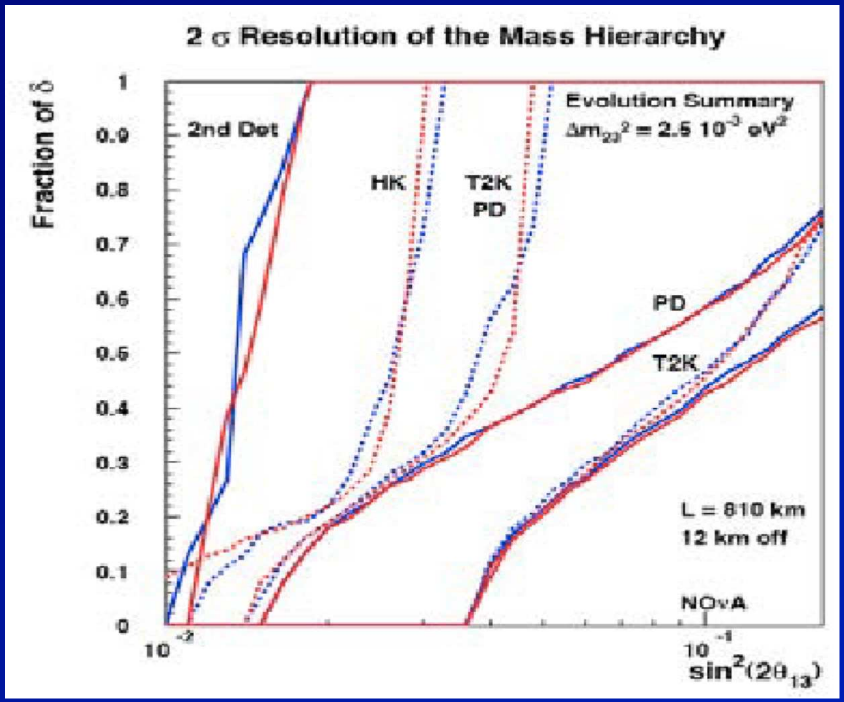
[http://neutrino.kek.jp/jhfnu/]

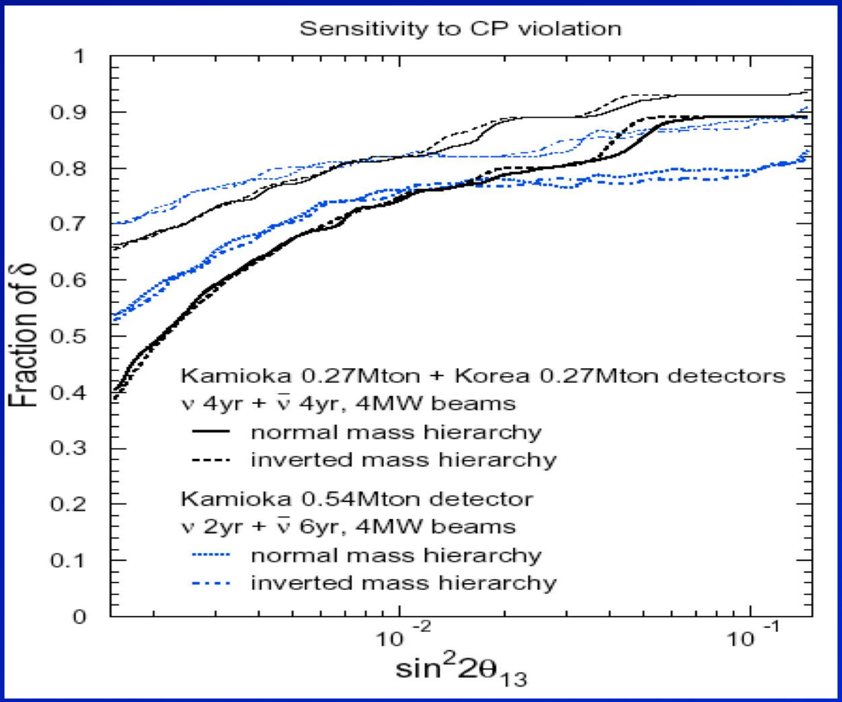


[NOνA proposal]



[T2K LOI]





[NOνA proposal]

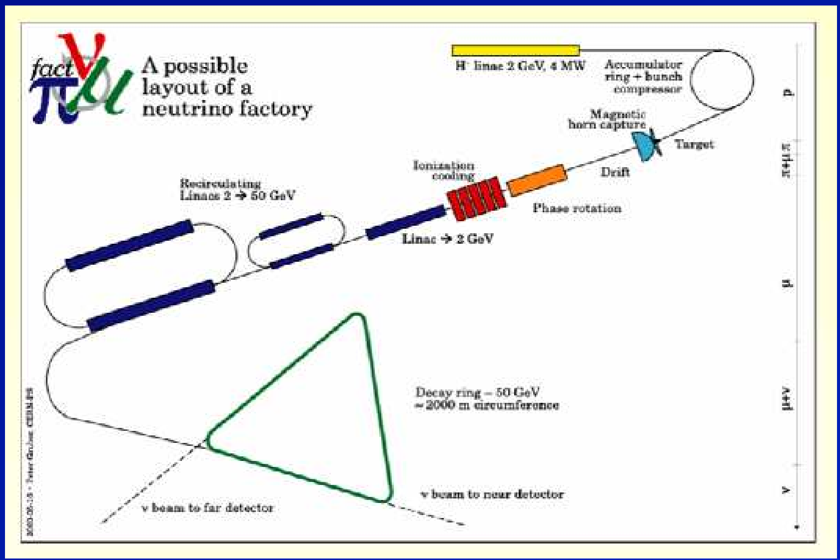
[M. Ishitsuka et al.]

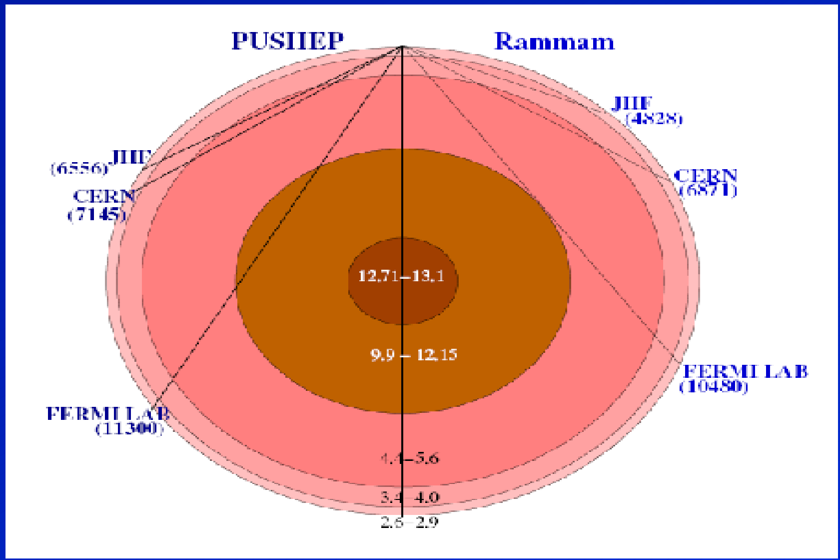
Neutrino factories:

ν_μ and ν_e are produced in very relativistic muon decays.

Energies of 20–50 GeV.

Distance 3000–7000 Km.





[INO proposal]

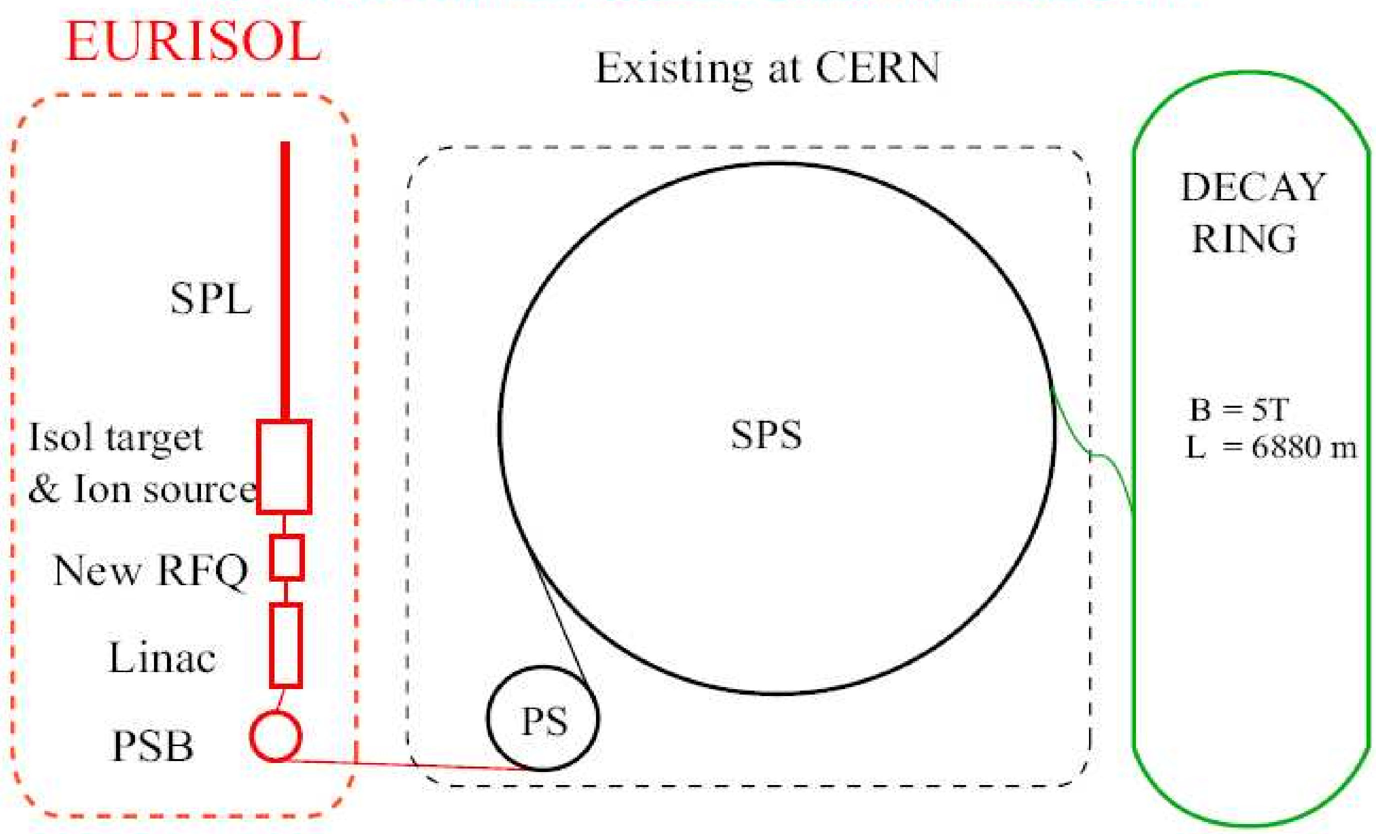
Beta-beams:

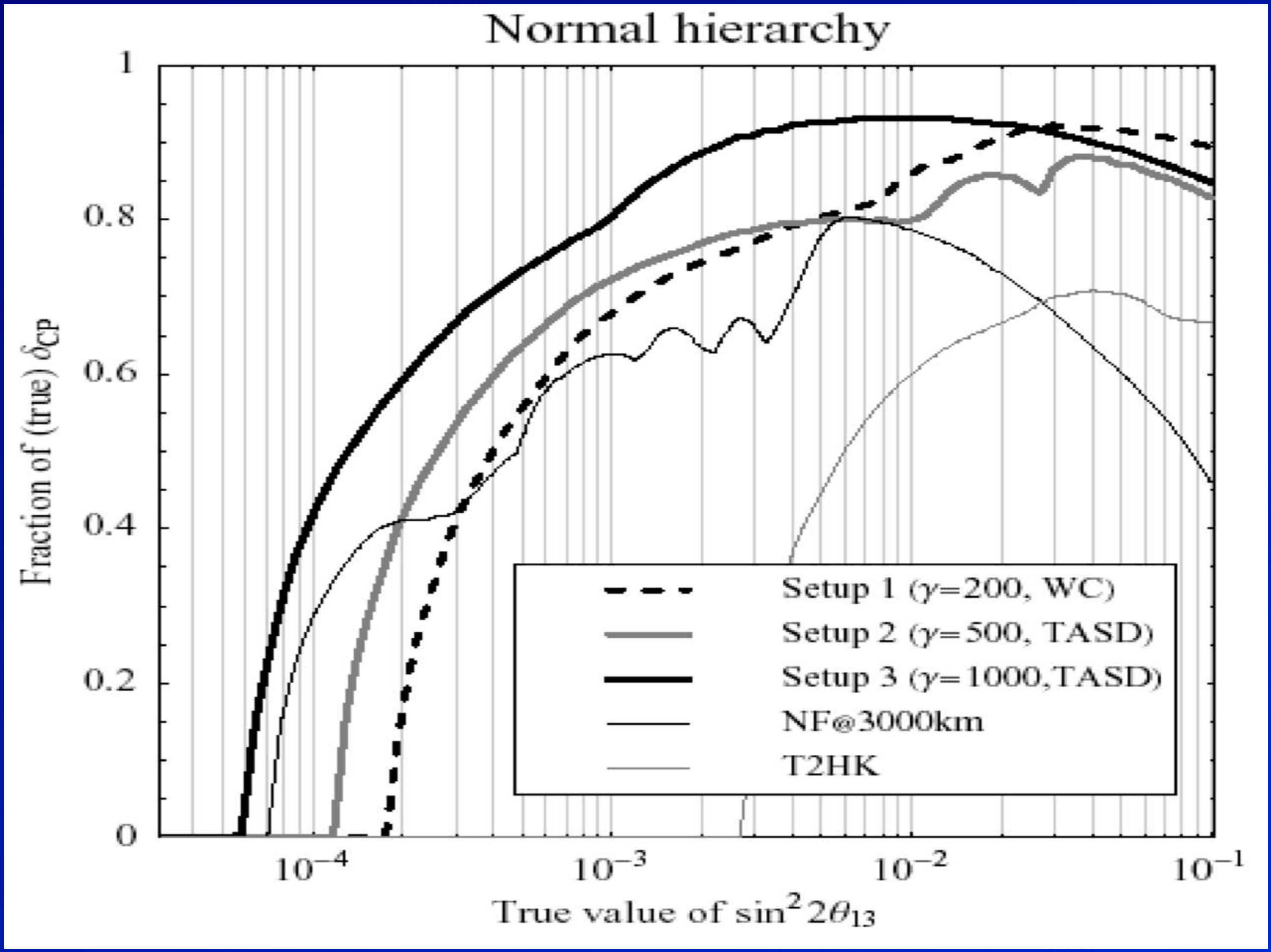
ν_e are produced by beta decay of accelerated ions.

Energies 200-2000 MeV.

Distance 100-1000 Km.

M. Lindroos et al., see http://beta-beam.web.ch/beta-beam





[P. Huber, M. Lindner, M. Rolinec and W. Winter]

5 – Conclusions

- We have strong evidence for neutrino oscillations. They imply that Neutrinos are massive ($\Delta m^2 \neq 0$) and that they mix ($\sin\theta \neq 0$).

Neutrino masses and mixing requires new physics beyond the SM.

- Questions for the future:

1. Nature of neutrinos: Majorana vs Dirac?
2. Number of neutrinos: Are there sterile neutrinos?
3. Absolute value of neutrino masses: mass scale and hierarchy?
4. CP-violation: $\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$?

- A wide experimental program is going to address these questions in the next future: $(\beta\beta)_{0\nu}$-decay experiments, LBL experiments.