FACULTÉ DES SCIENCES

UNIVERSITÉ DE GENÈVE

Neutrino properties from experiments

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What we know about neutrinos

3 flavours e,μ,τ, weakly interacting

Flavour universality = interactions are equal

Neutrinos oscillate = flavour can change!

Massive but very light!

Squared mass differences measured

$$\Delta m_{21}^2 \simeq +8\text{x}10^{-5}\, eV^2 \qquad \Delta m_{32}^2 \simeq 2\text{x}10^{-3}\, eV^2$$

Mixing parameters measured

$$\theta_{23} \simeq 45^\circ \qquad \theta_{12} \simeq 32^\circ \qquad \theta_{13} < 7^\circ$$

Neutrino mixing matrix

Relates weak states $\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$ with mass states

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & 0 & 0\\ 0 & e^{-i\alpha/2} & 0\\ 0 & 0 & e^{-i\beta/2}\end{pmatrix}$$

"Atmospheric" "Reactor" "Solar" "0νββ"

Equivalent of CKM matrix for quarks

Neutrino mixing matrix

Relates weak states $\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$ with mass states

Connection!

?

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & 0 & 0\\ 0 & e^{-i\alpha/2} & 0\\ 0 & 0 & e^{-i\beta/2}\end{pmatrix}$$

$\theta_{23} \sim 45^0$
"Atmospheric",
Super-K, K2K, MINOS

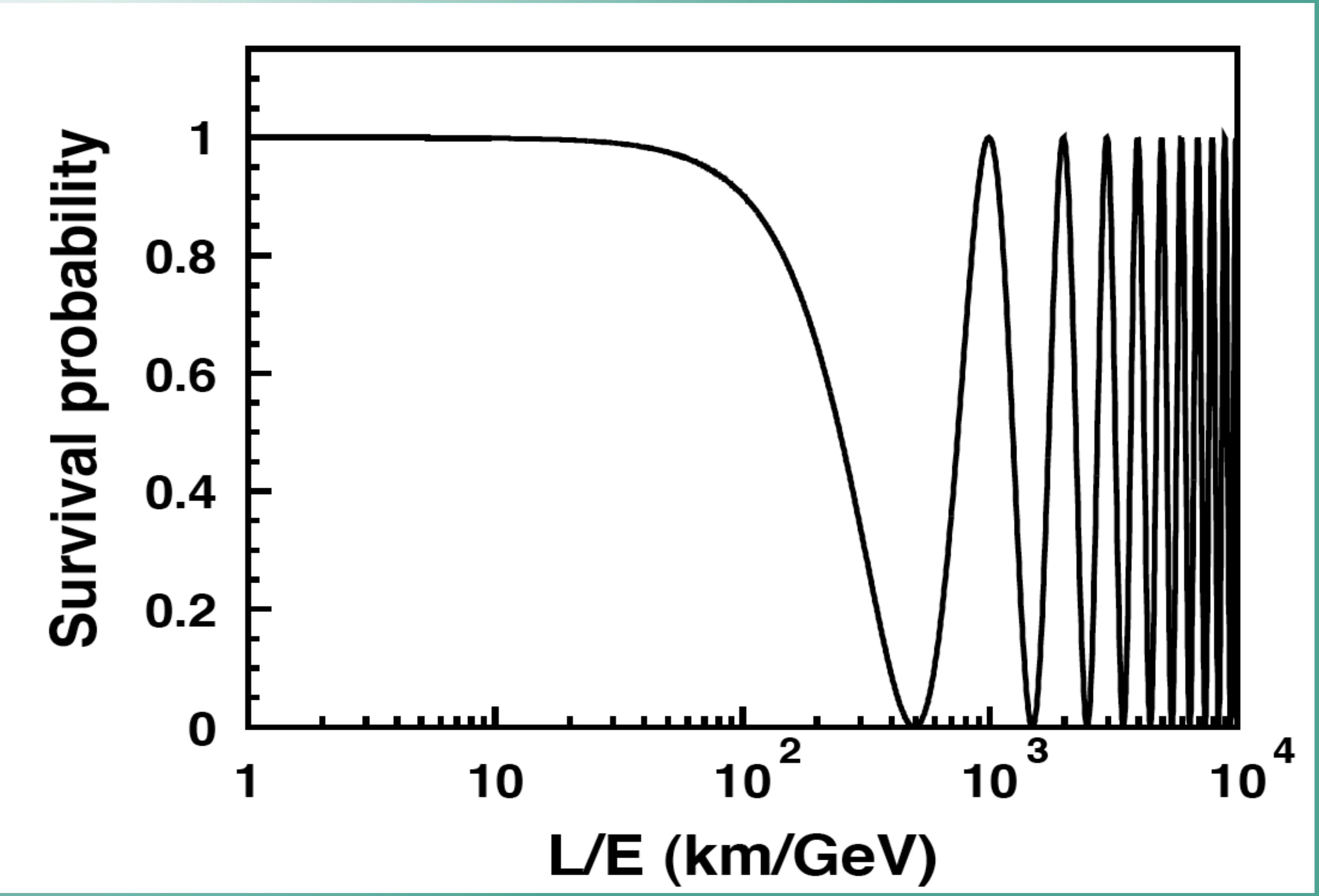
$\theta_{13} < 7^0$
"Reactor"
Chooz

$\theta_{12} \sim 32^0$
"Solar"
SNO, Super-K,
Borexino, KamLAND

Unknown
"0νββ"

Mass states lead to oscillations

- Since they propagate at different speeds they will shift in phase as they go
- The corre-sponding weak state propability will therefore change



$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m_{23}^2 L / E)$$

Mass states lead to oscillations

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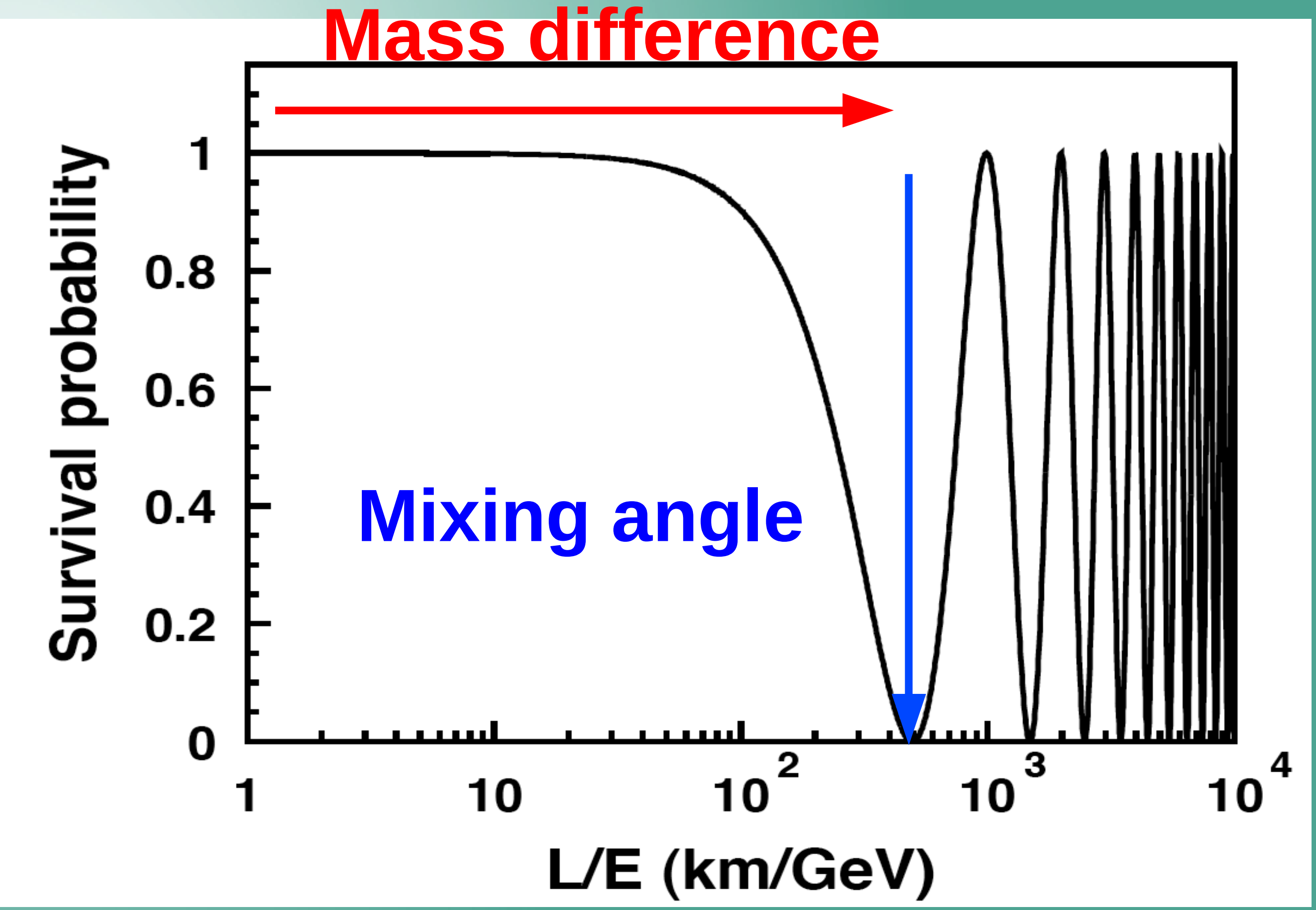
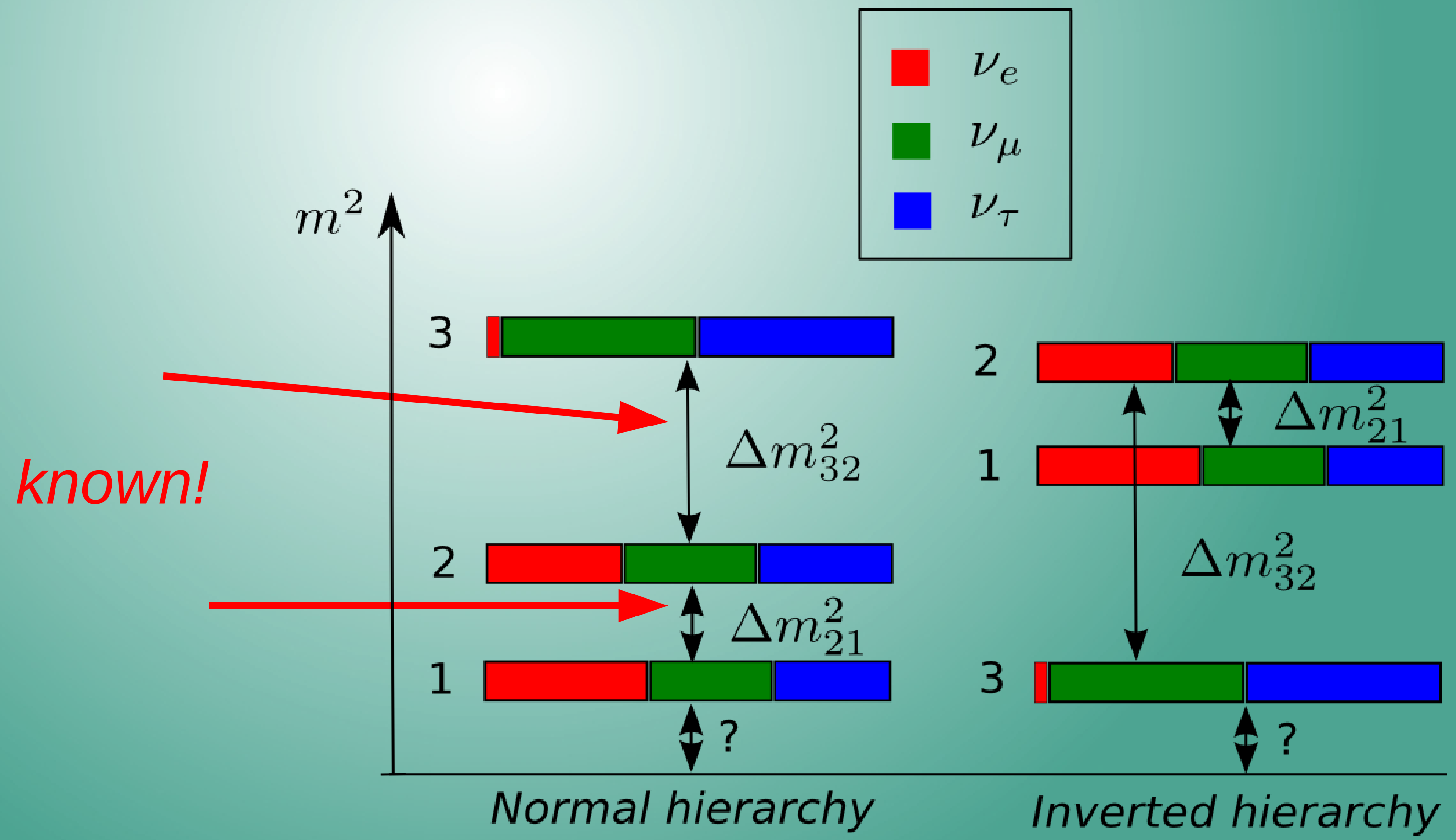


$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m_{23}^2 L/E)$$

What we don't know about neutrinos

- Absolute mass!
- Mass hierarchy
- Dirac / Majorana nature? LN-violation?
- Value of the CP-violating phase δ_{CP}
- Is $\theta_{13} > 0$?
- Asymptotic form of mixing matrix
- Number of sterile neutrinos (if any)

Mass hierarchy



Both hierarchies allowed by data

Structure of the mixing matrix

The matrix elements seem to indicate a tribi-maximal scenario, meaning 2 is an even mix of e,μ,τ and 3 is an even mix of μ,τ

$$U_{PMNS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

but how close to this ideal case is the real matrix?

If the matrix is tribimaximal,
then it's real and $\delta_{CP} = 0$

Dirac or Majorana

Neutrino masses introduce L-R transitions

If neutrinos are Dirac particles there should exist 2 sterile (unobserved) neutrinos N aside of the ordinary ones

$$\upsilon_L, N_R \qquad \bar{\upsilon}_R, \bar{N}_L$$

If they are Majorana particles then

$$N_R = \bar{\upsilon}_R \qquad \bar{N}_L = \upsilon_L$$

(which implies lepton number violation),
and we need only the 2 observed particles

$$\upsilon_L, \upsilon_R$$

CP violation

Implies that the amplitudes for the (vacuum) oscillations

$$\nu_\mu \rightarrow \nu_e \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

are different due to a non-zero δ_{CP}

(CPT conservation demands that the amplitudes for

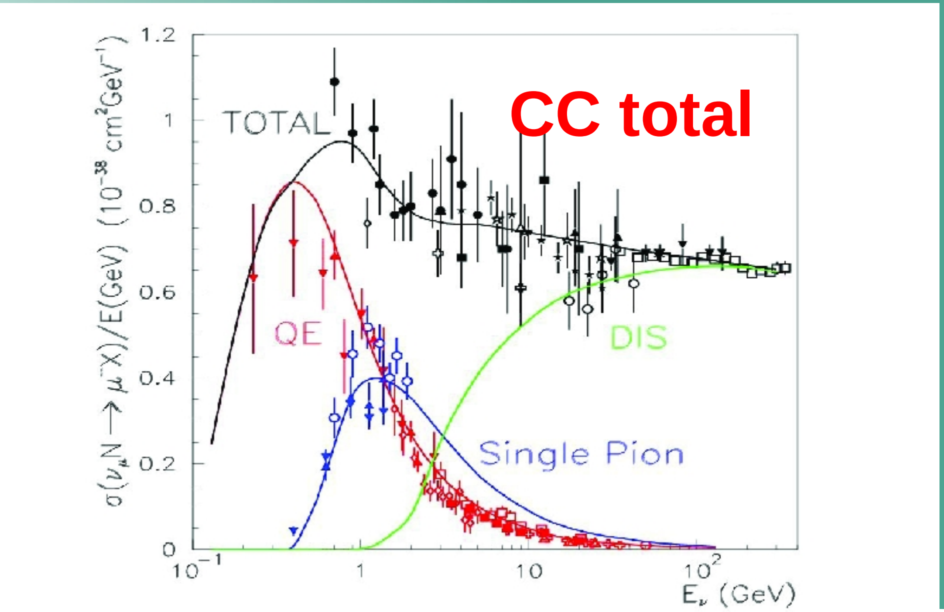
$$\nu_\mu \rightarrow \nu_\mu \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

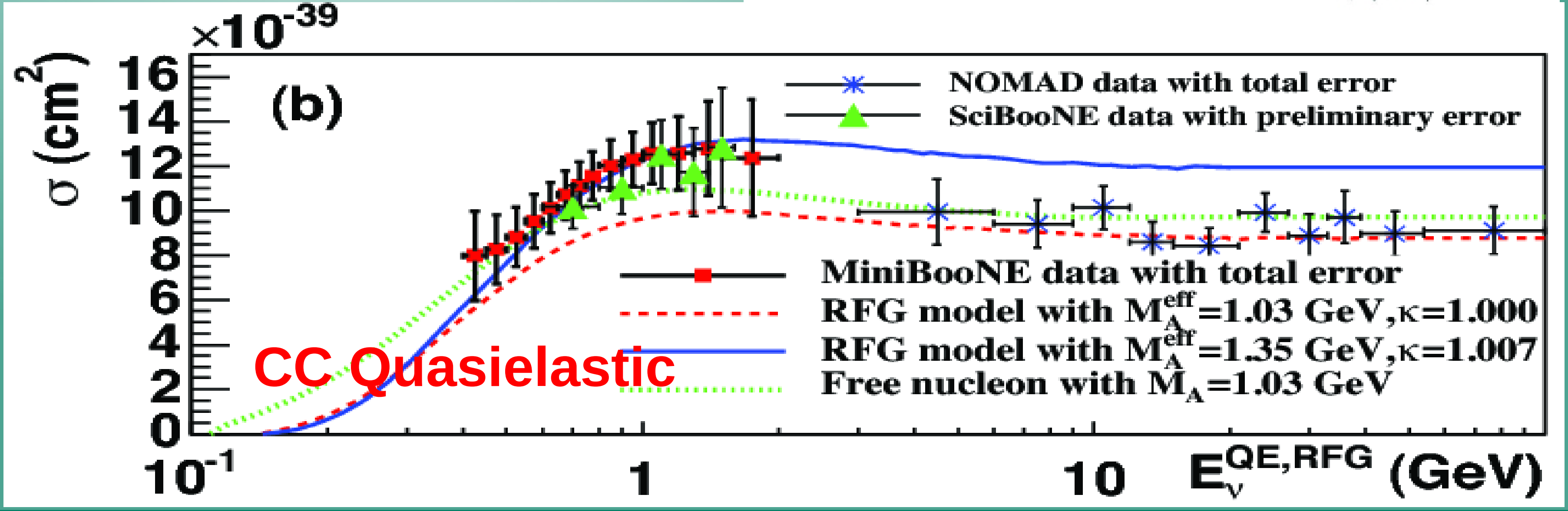
remain identical. CPT violated if neutrinos and antineutrinos have different masses)

Recent results

Neutrino interactions

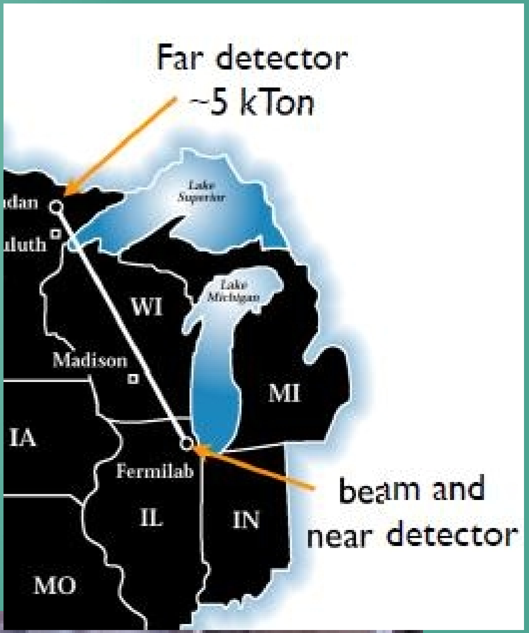
- Better precision needed for osc. experiments
- Experimental results seem to diverge
- Measure flux X cross-section
- **MiniBooNE/SciBooNE** data fits within syst. with **NOMAD**?





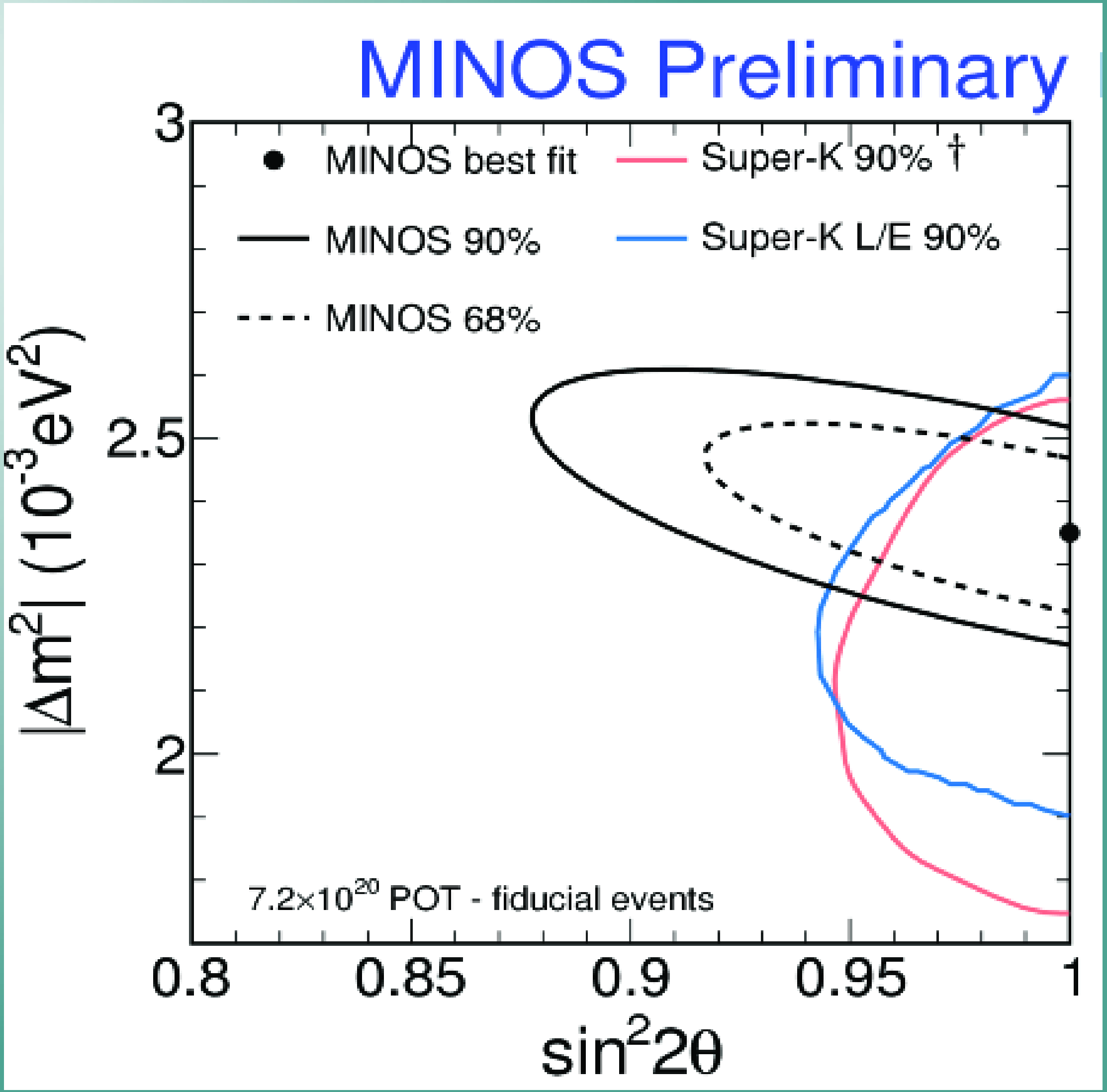
MINOS long baseline

- Muon (anti) neutrino beam experiment
- Fermilab NuMI beam line, L/E 500 km/GeV
- ND 1 km, FD 735 km
- Measure ν_μ and $\bar{\nu}_\mu$ disappearance, osc. vs decay/decoherence
- Mixing to sterile neutrinos?
- NC disappearance?



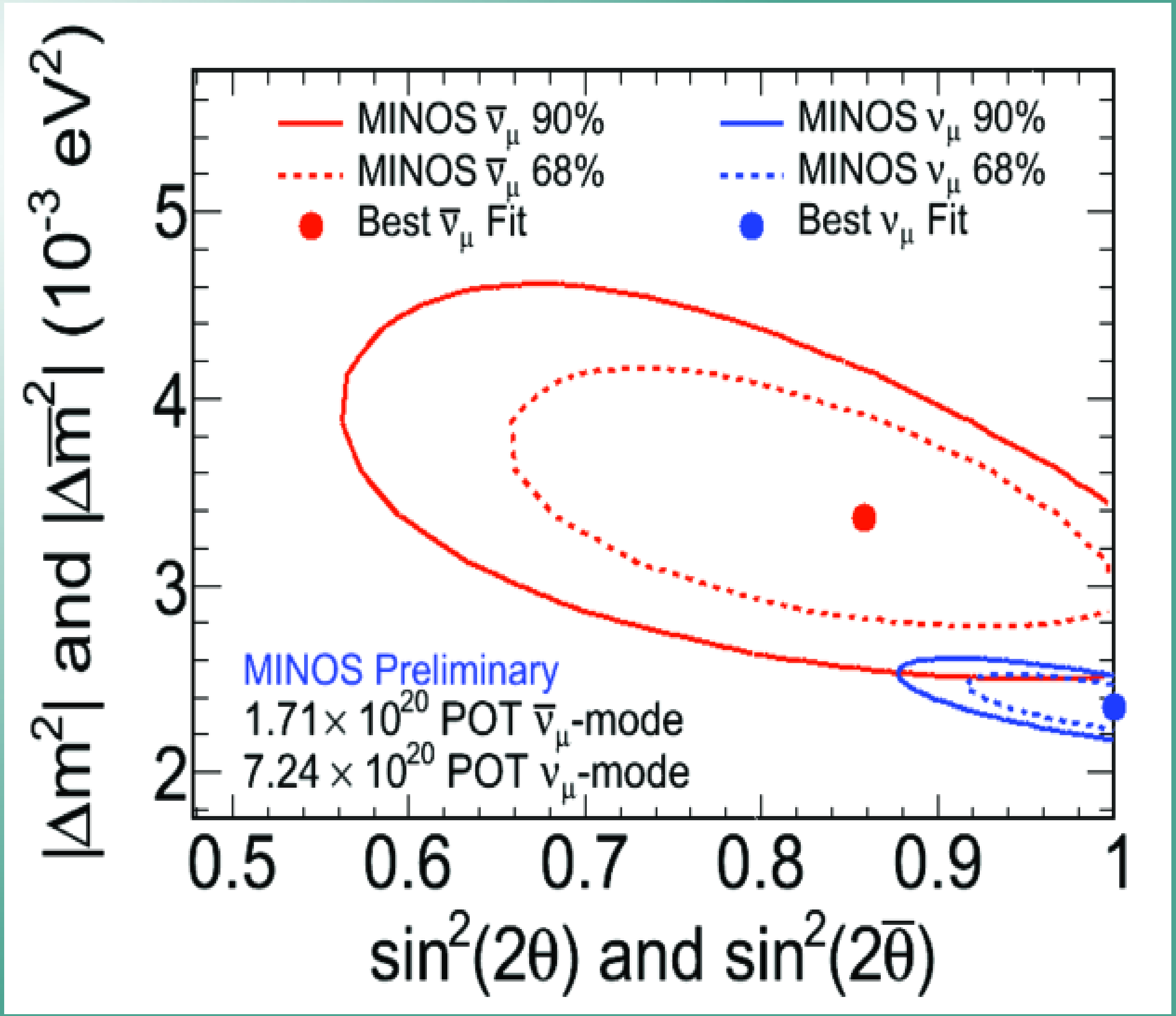
MINOS ν_μ disappearance results

- Muon neutrinos oscillate to tau and “disappear” from beam (=undetected)
- An experimental result that nicely matches the Super-K observation of atmospheric neutrinos



MINOS $\bar{\nu}_\mu$ disappearance results

- The two regions only just overlap
- Uncertainty dominated by statistics → more data needed
- CPT conservation requires osc. to be the same!



MINOS ν_e appearance results

- Normal hierarchy

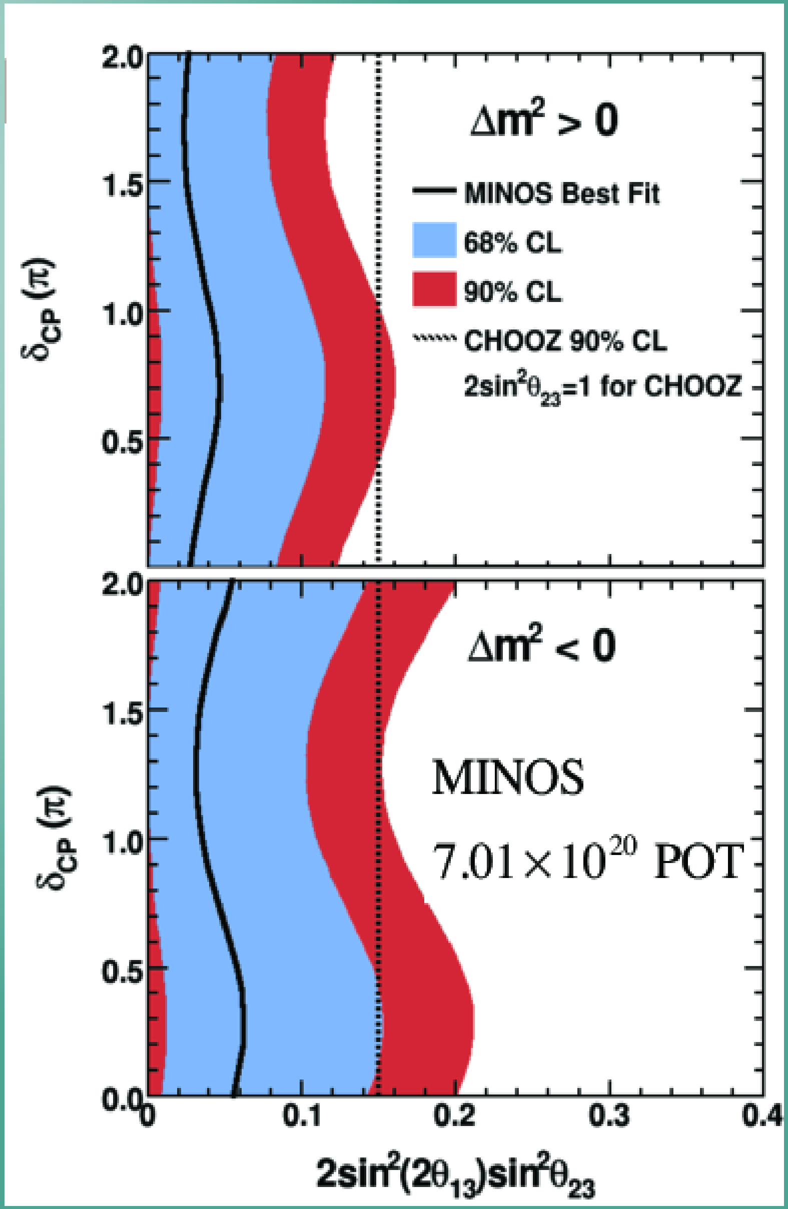
$$\sin^2(2\theta_{13}) < 0.12$$

- Inverted hierarchy

$$\sin^2(2\theta_{13}) < 0.20$$

Both assumes: $\sin^2(2\theta_{23}) = 1$

$$\Delta m^2_{32} = 2.43\text{x}10^{-3} eV^2$$

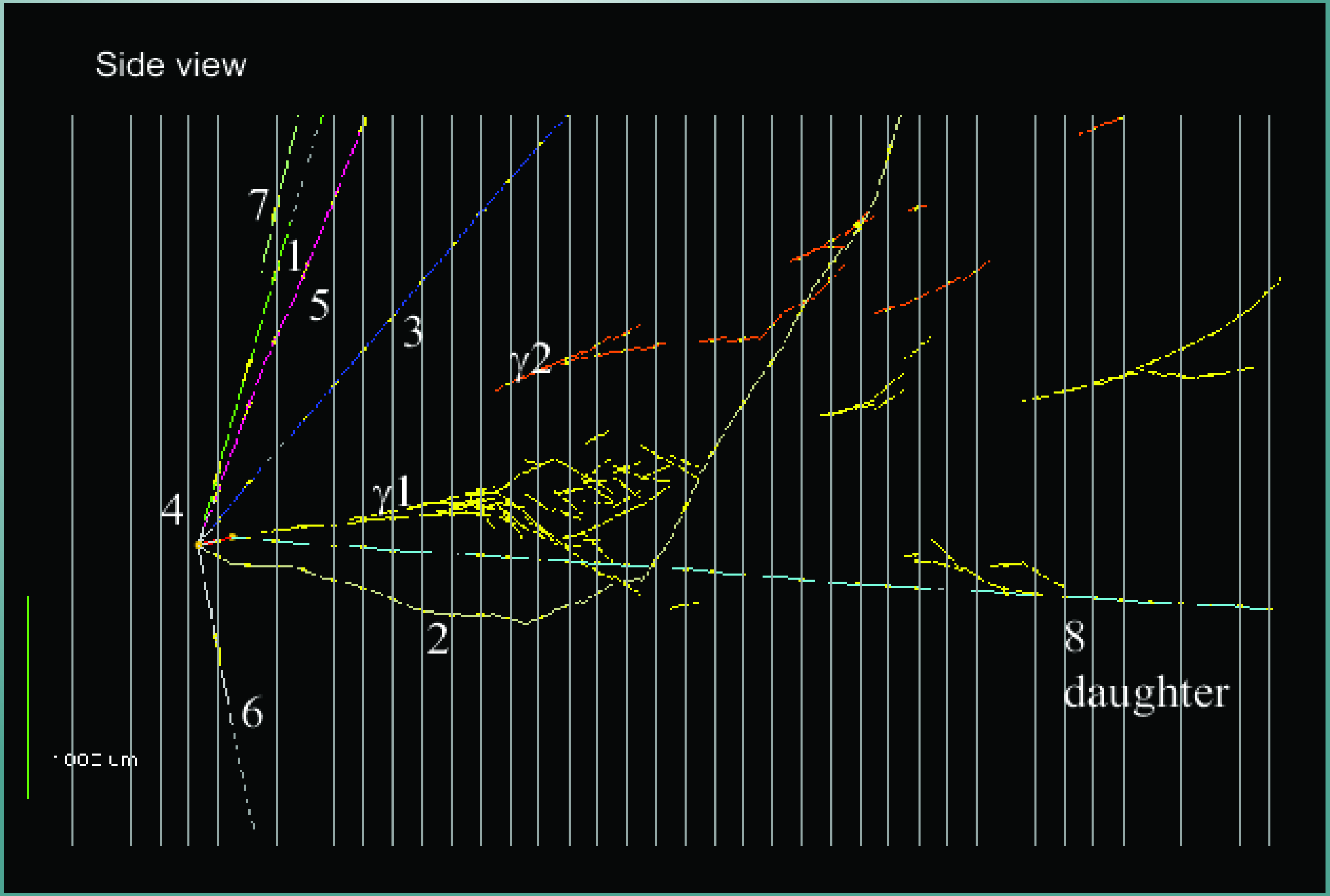


Opera

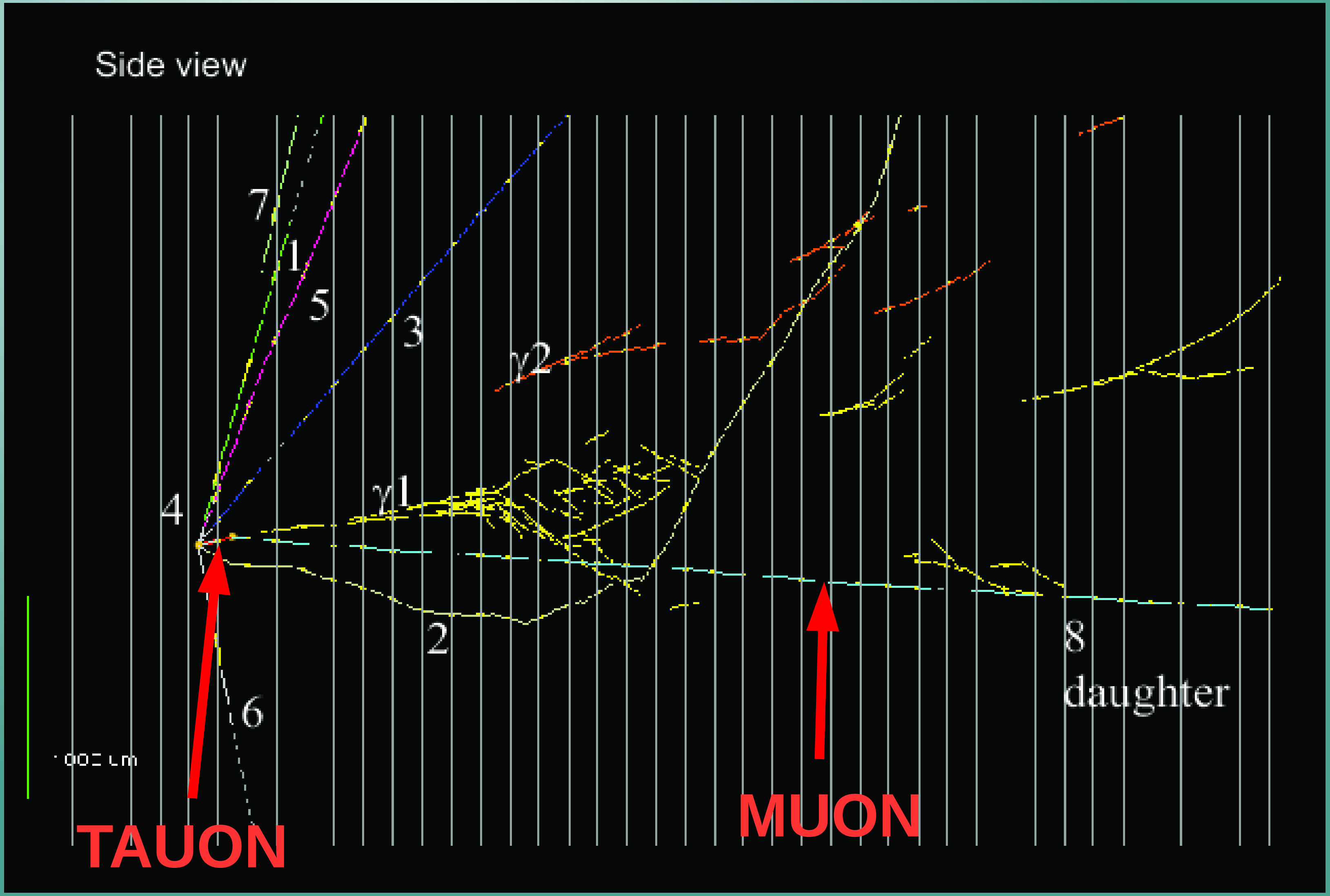
- Beam of muon neutrinos produced at CERN
- Beam observed at LNGS (L = 732 km)
- Goal: to observe the oscillation to tau neutrinos

- *Important for the exclusion of exotic models like decay and decoherance etc.*

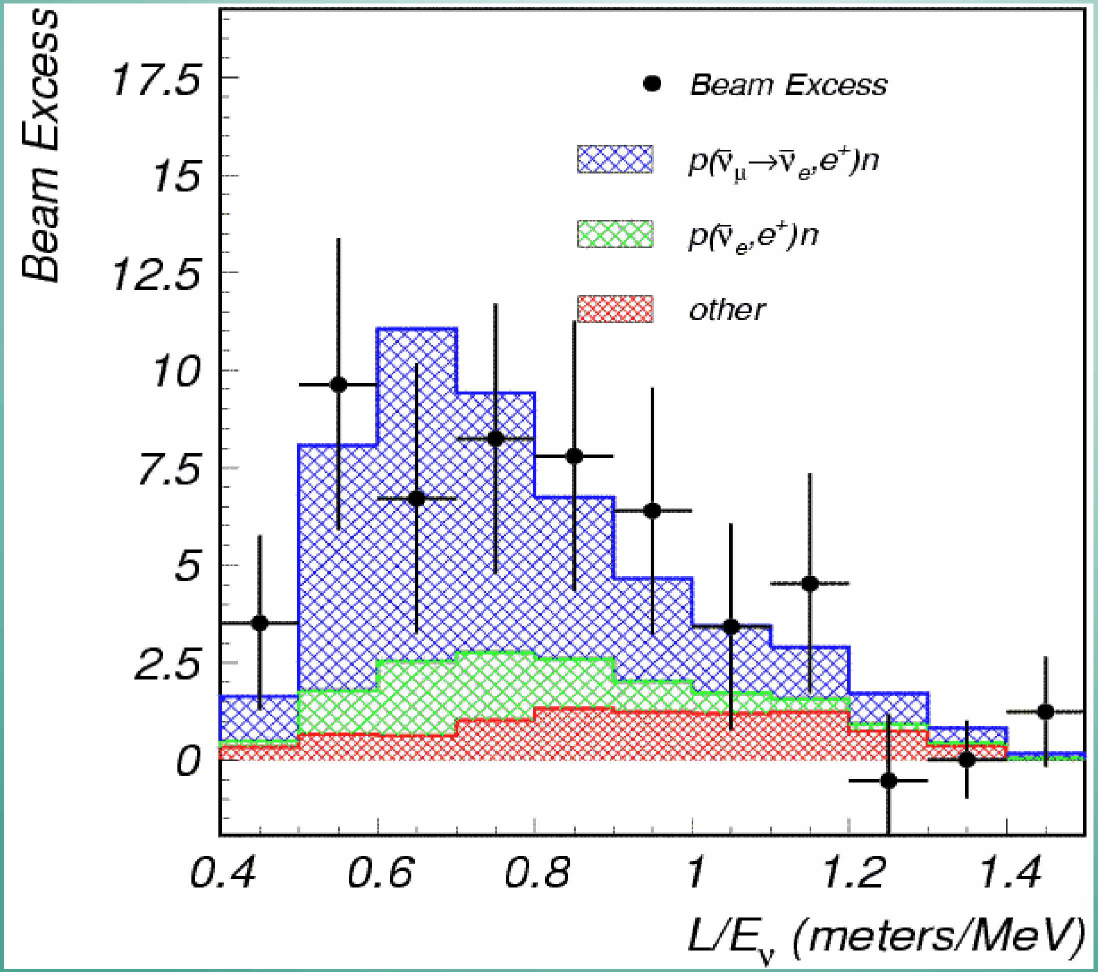
Opera result: one $\nu_\mu \rightarrow \nu_\tau$ event seen



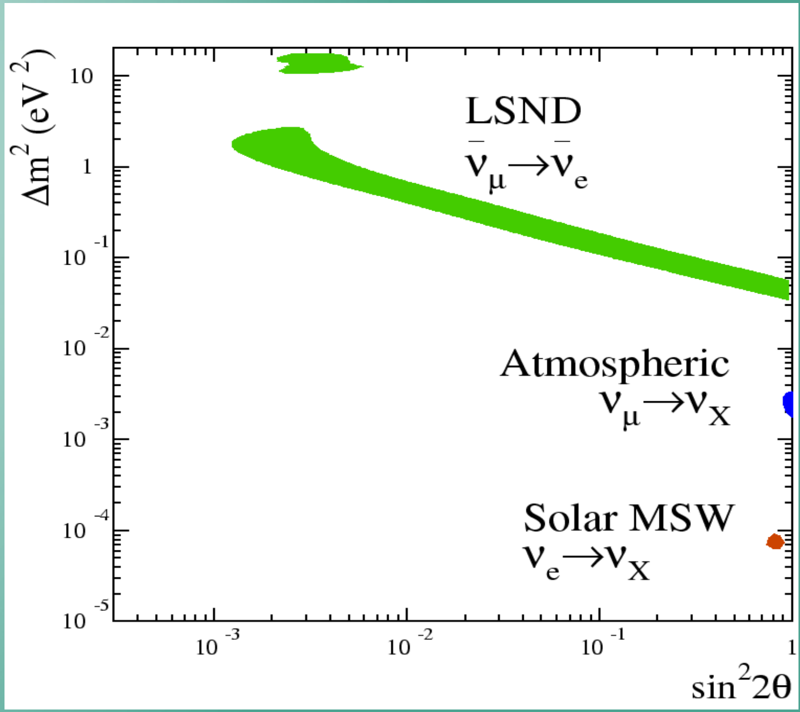
Opera result: one $\nu_\mu \to \nu_\tau$ event seen



LSND anomaly (2001)



$$\Delta m_{32}^2 + \Delta m_{21}^2 + \Delta m_{13}^2 \neq 0$$

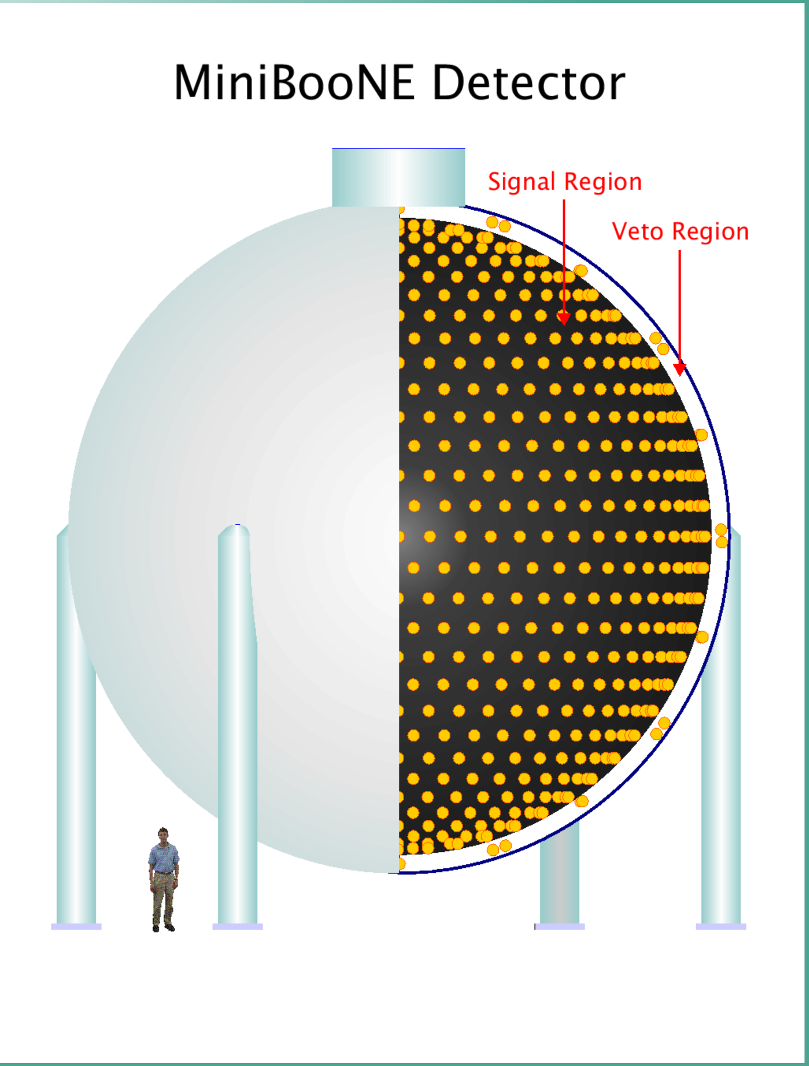


Appearance of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam:
3 sigma excess

Not possible to fit these 3 oscillations into a consistent model without adding sterile neutrinos or requiring CPT-violation: $m_\nu \neq m_{\bar{\nu}}$

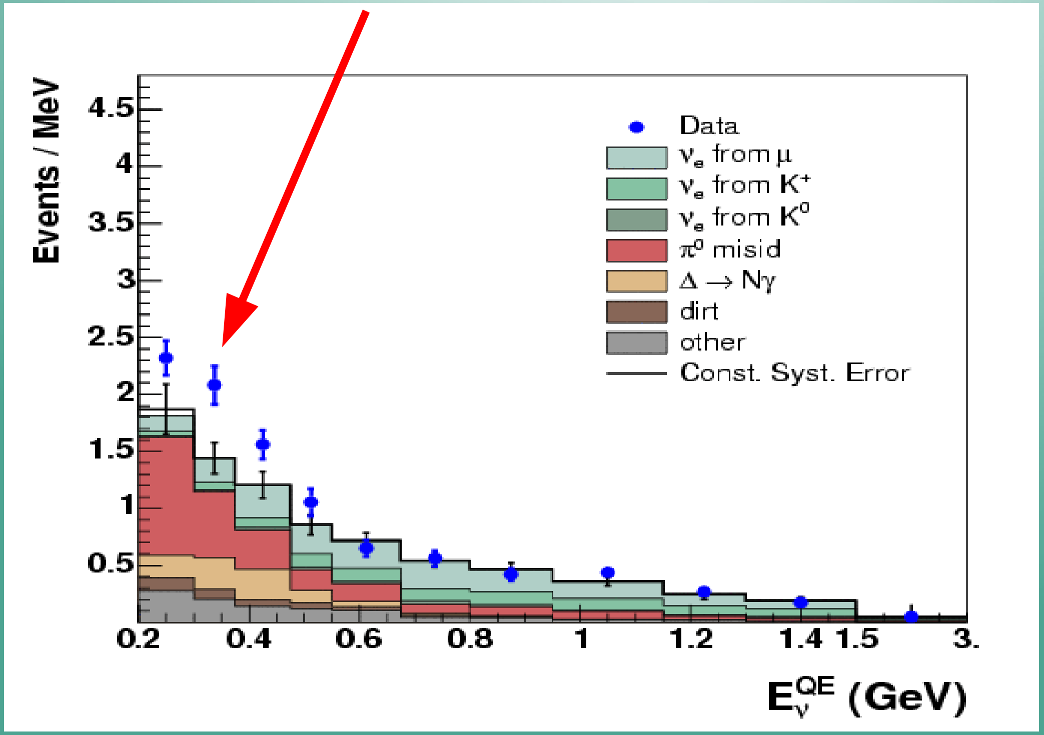
MiniBooNE short baseline

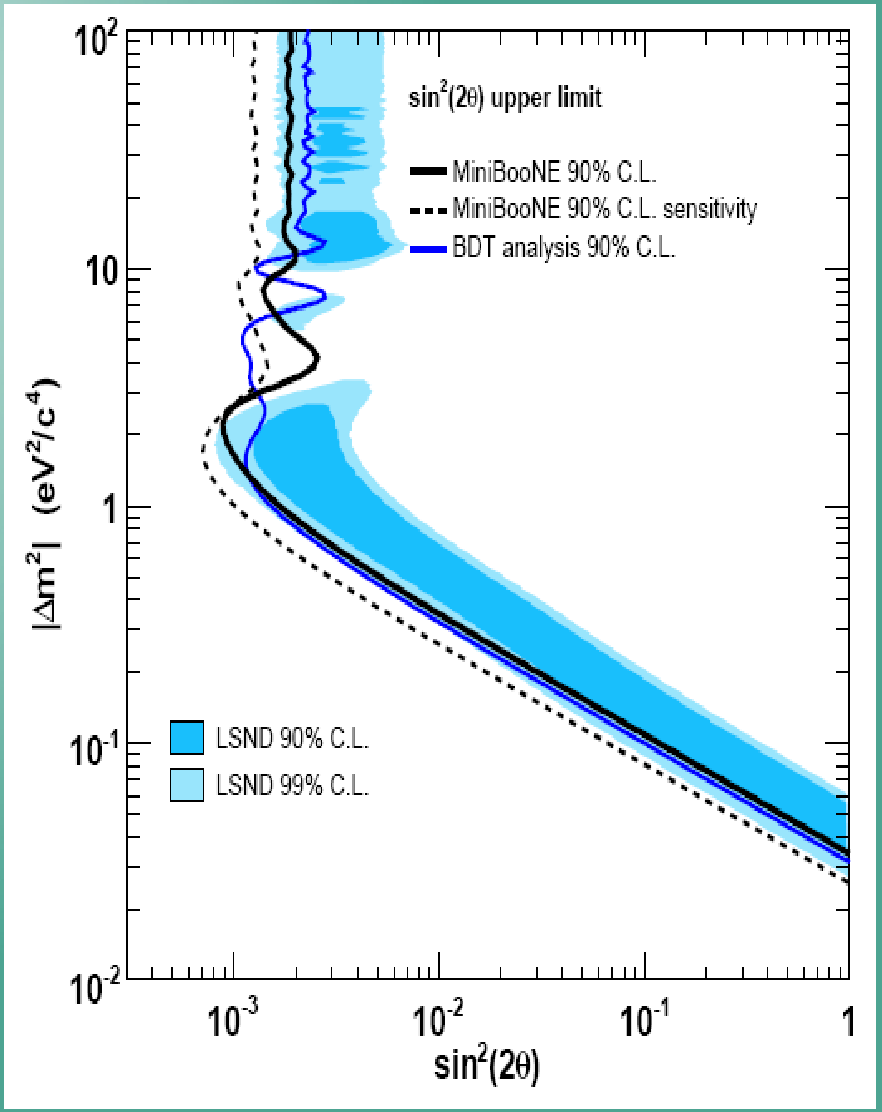
- Designed to test the LSND anomaly
- Muon (anti) neutrino beamline
- 500 m, 500 MeV, L/E ~1
- Search for electron (anti) neutrino appearance
- No near detector



MiniBooNE results: neutrino mode

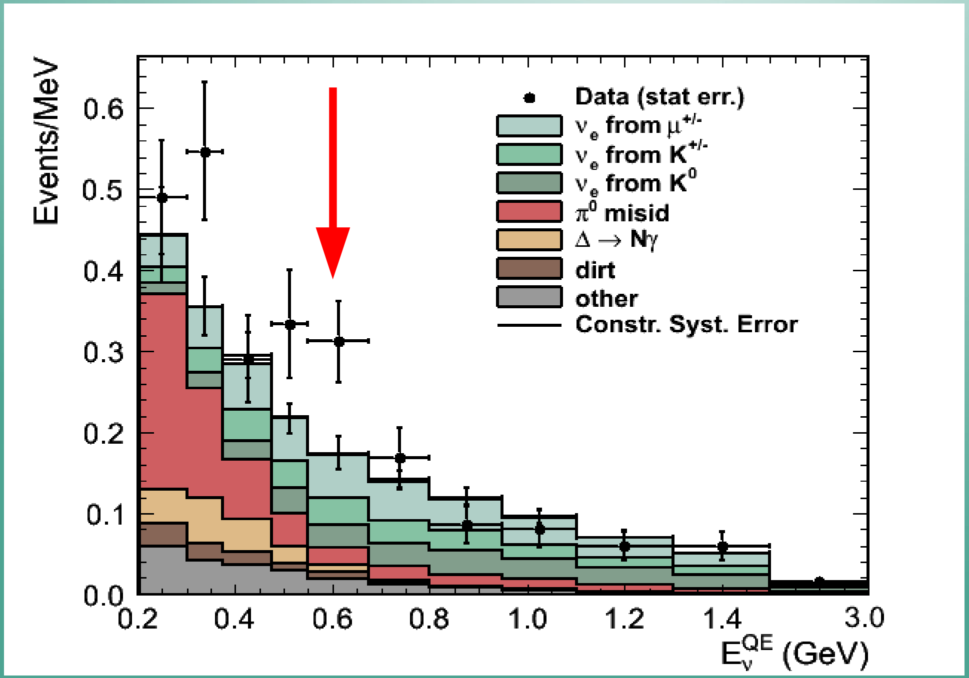
- Inconsistent with LSND!
- Excess observed at low energy (unexplained)!

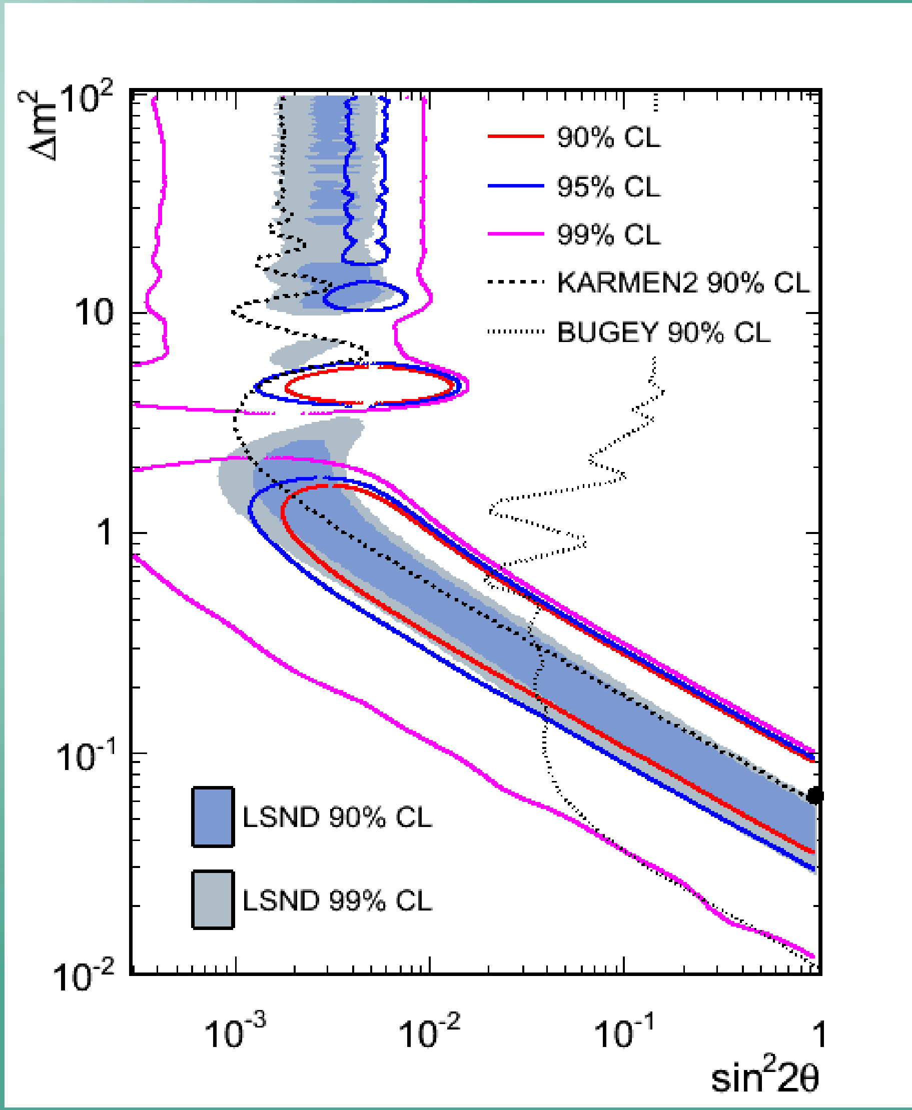




Antineutrino mode: anomaly still there?

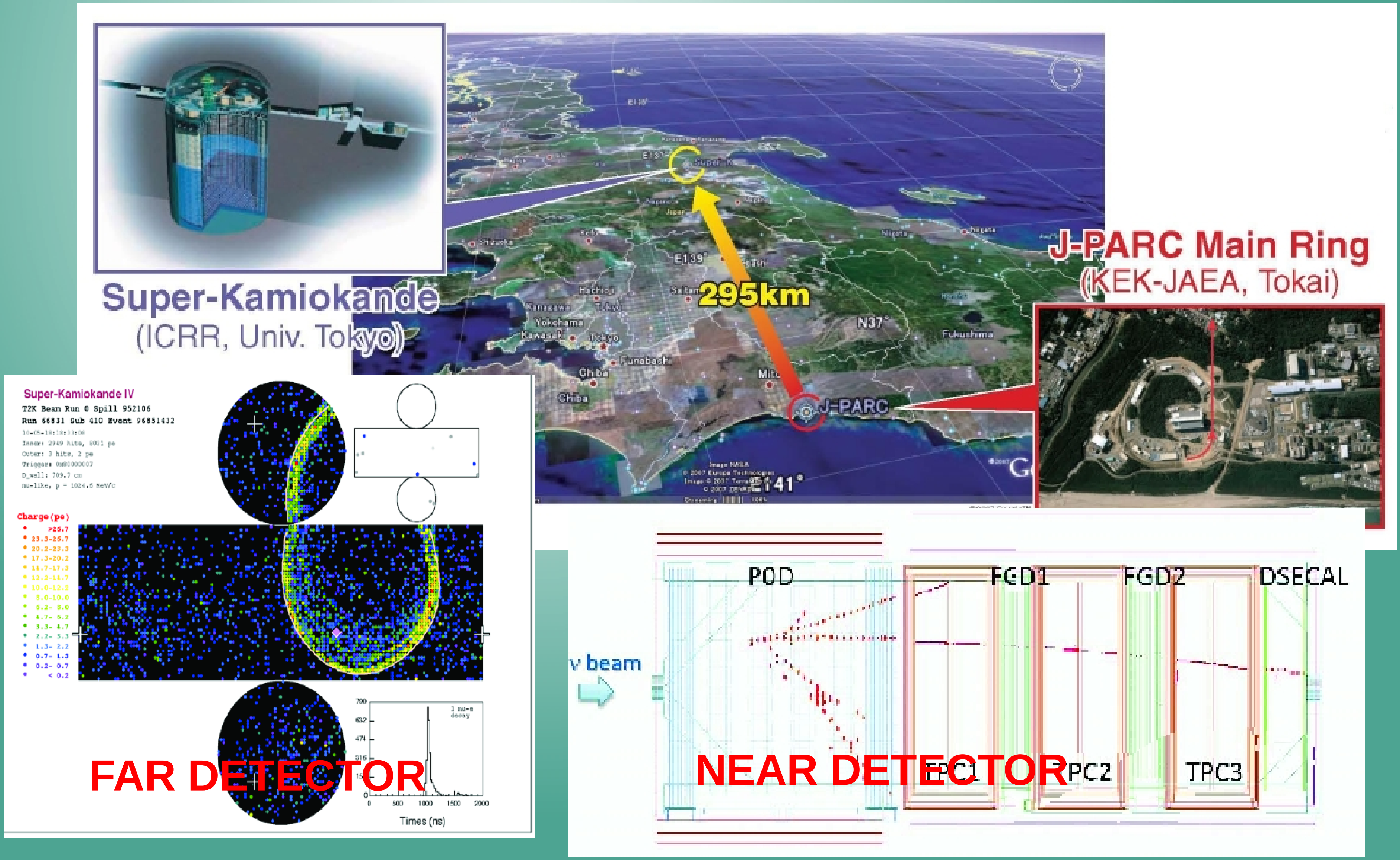
- Data don't exclude LSND
- 3% consistent with null
- Suggests sterile neutrinos?



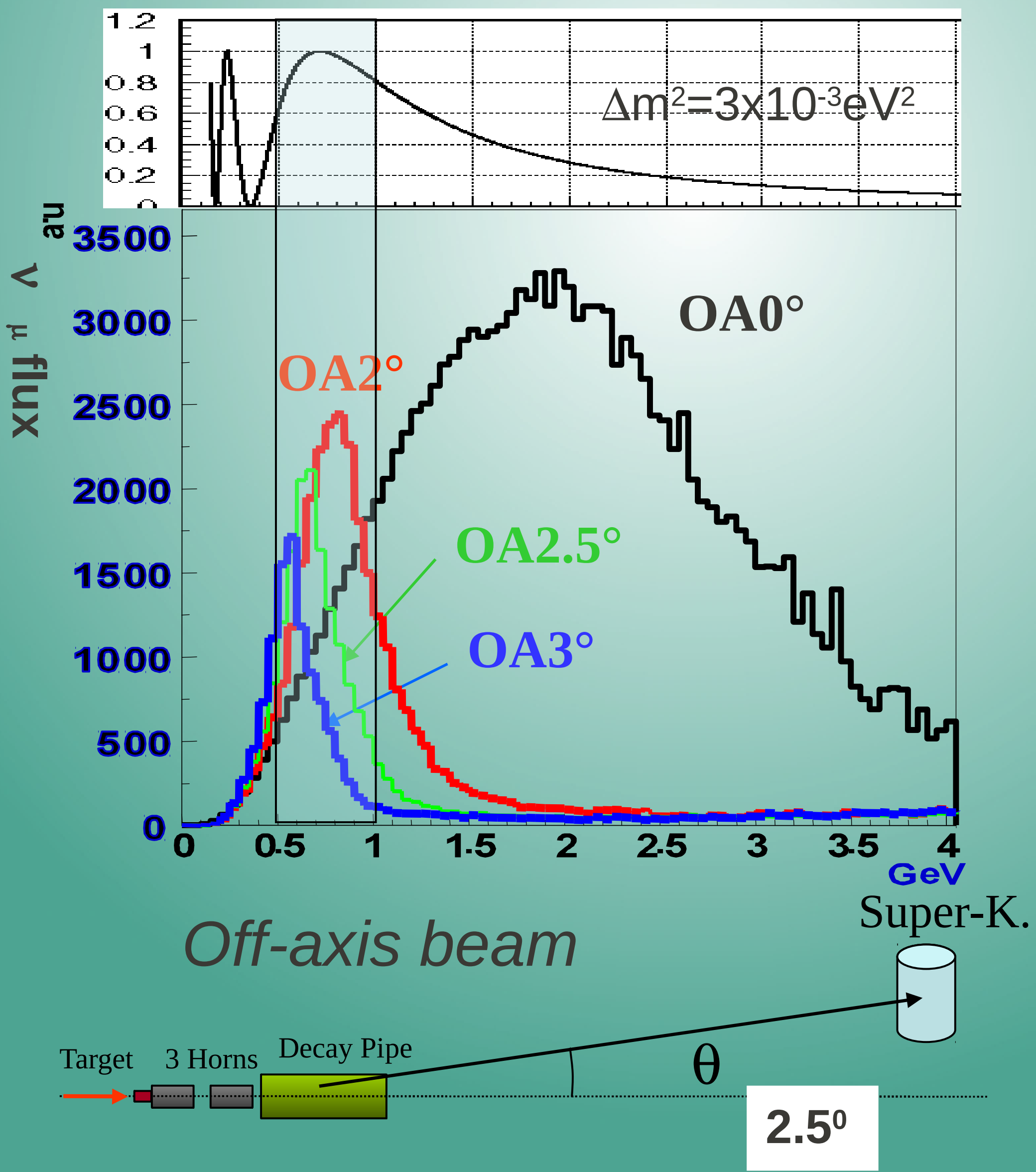


Coming results

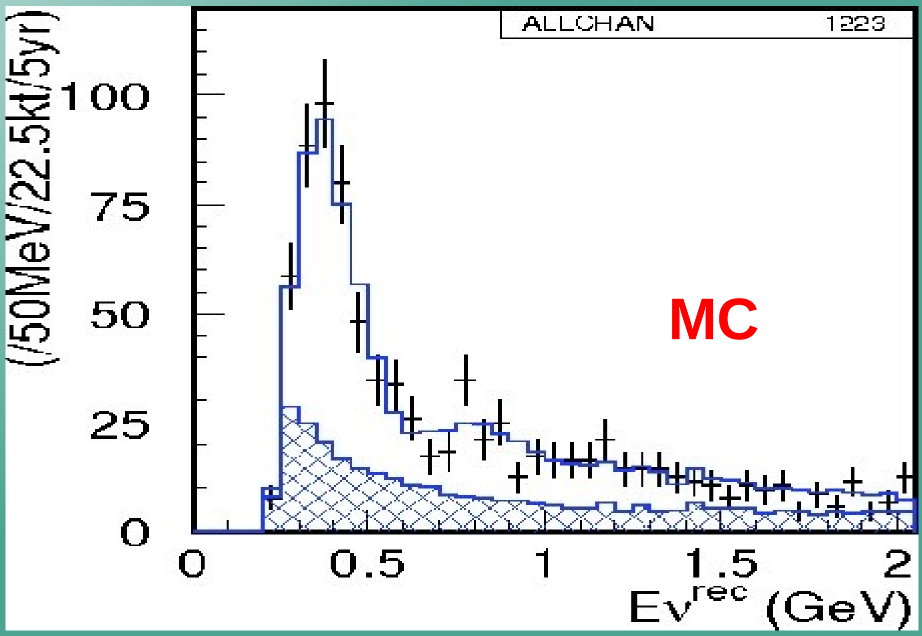
T2K – next generation ν_μ beam



T2K optimized to measure θ_{13}

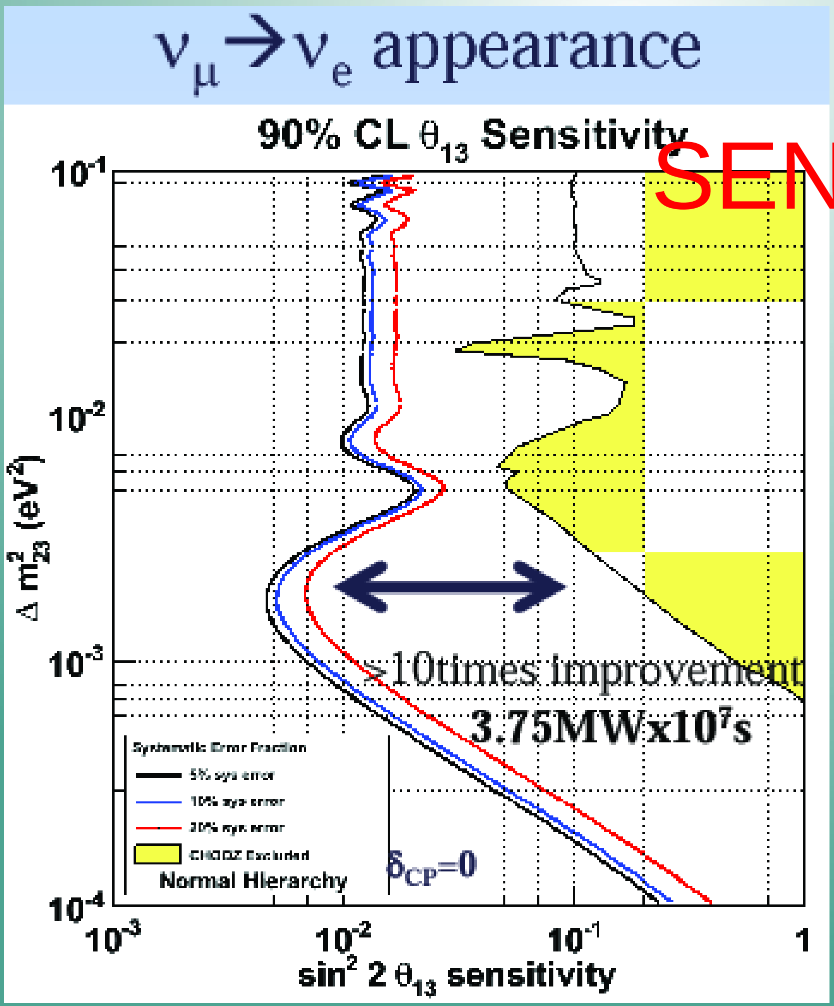


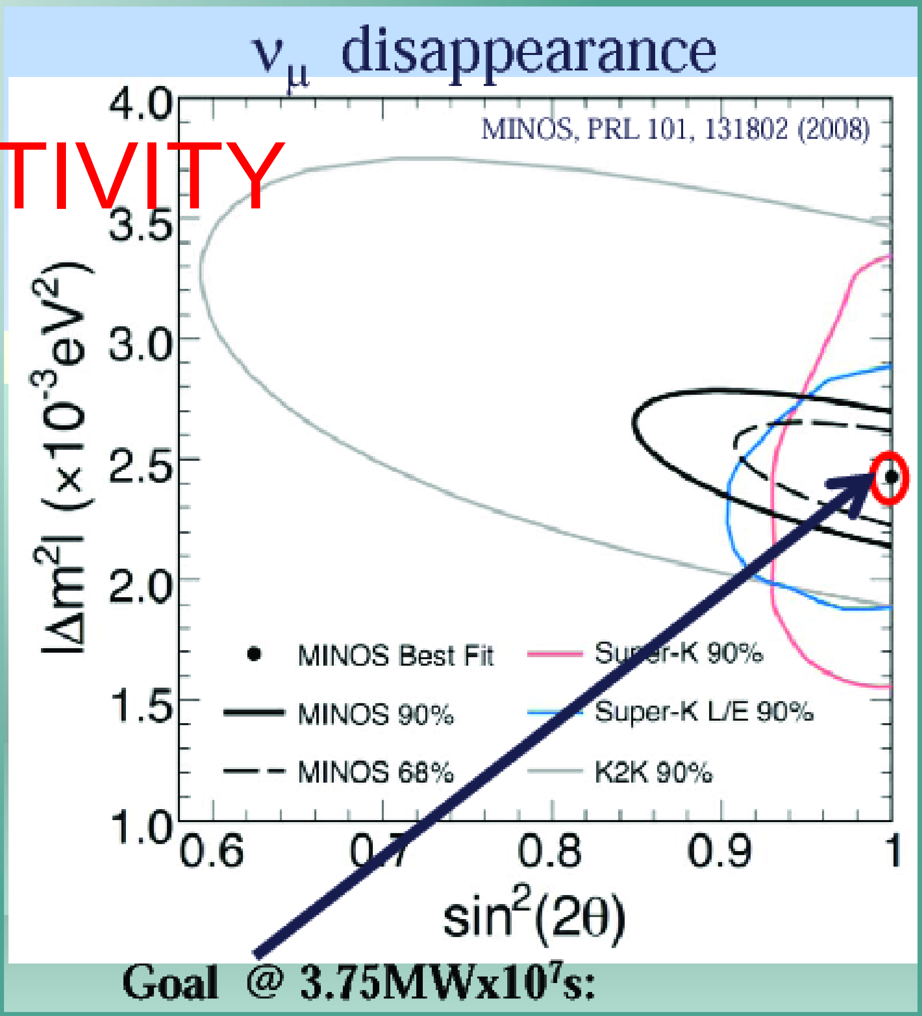
- Data from the ND is used to get an expected spectrum, which compared to FD observation yields oscillation parameters



T2K is taking oscillation data ...

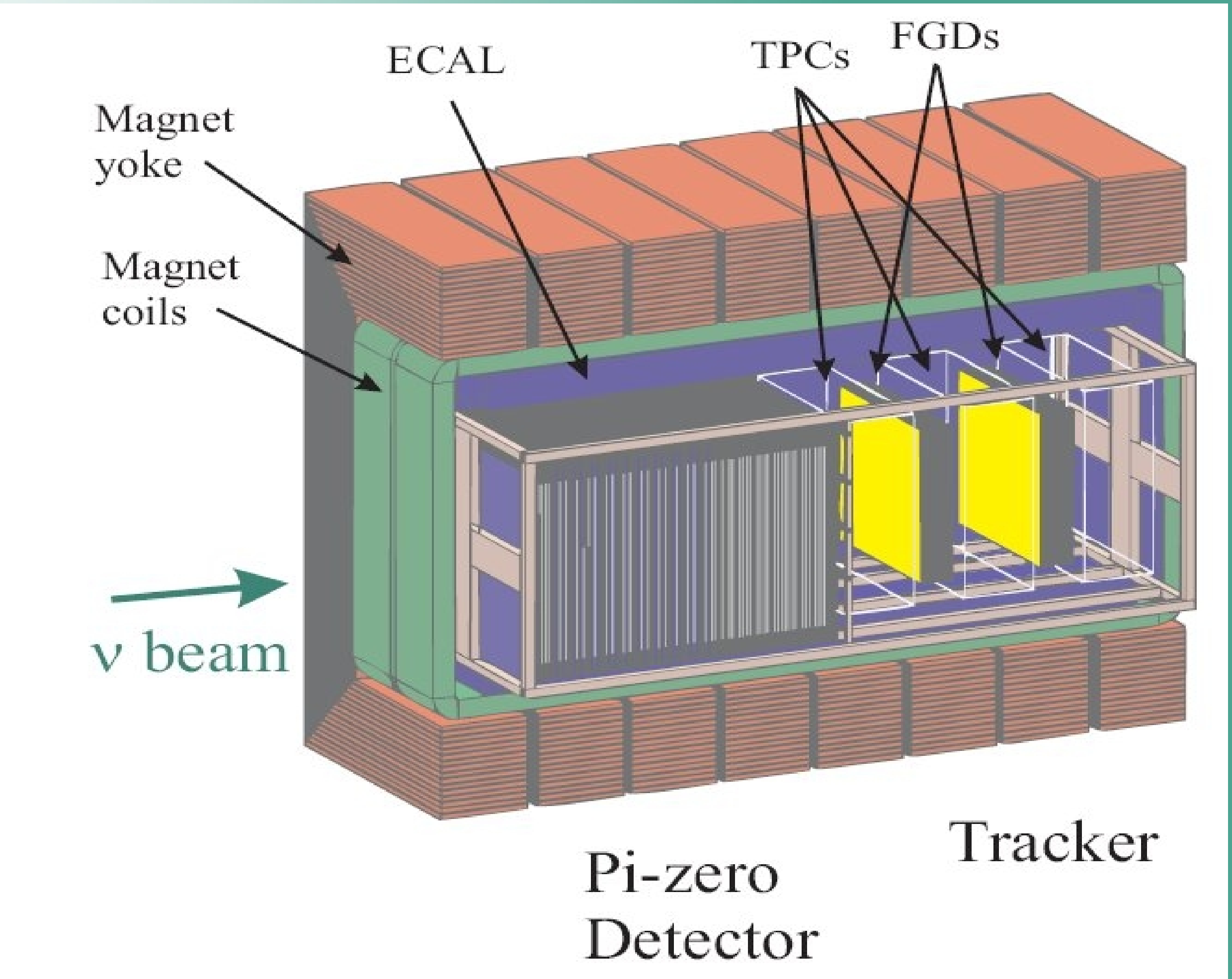
SENSITIVITY





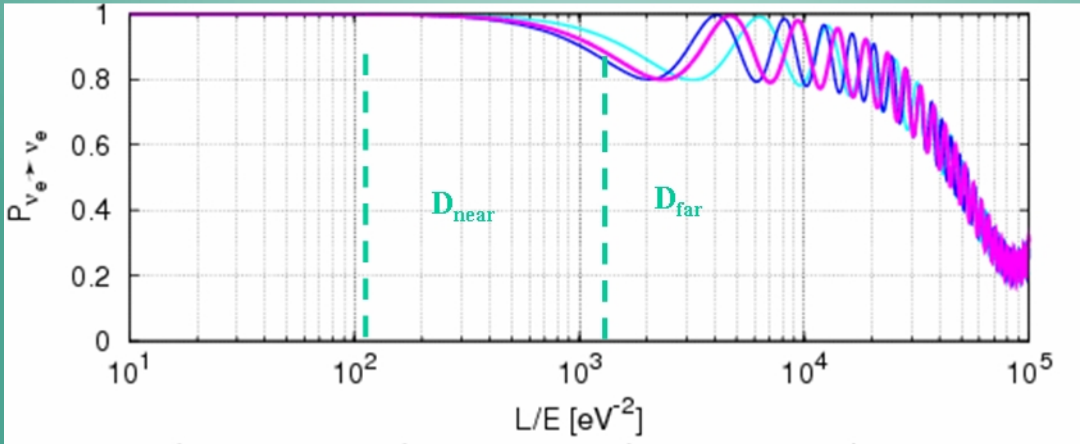
… and interaction data

- The near detector is capable of studying neutrino-nucleus interactions
- Also gives a precise flux prediction for the neutrino beam at Super-K



Double Chooz and **Daya Bay**

- "Reactor" experiments, use electron antineutrinos from nuclear power plants
- Low energy ~MeV
- Short baseline ~ 1 km
- Both soon taking data!

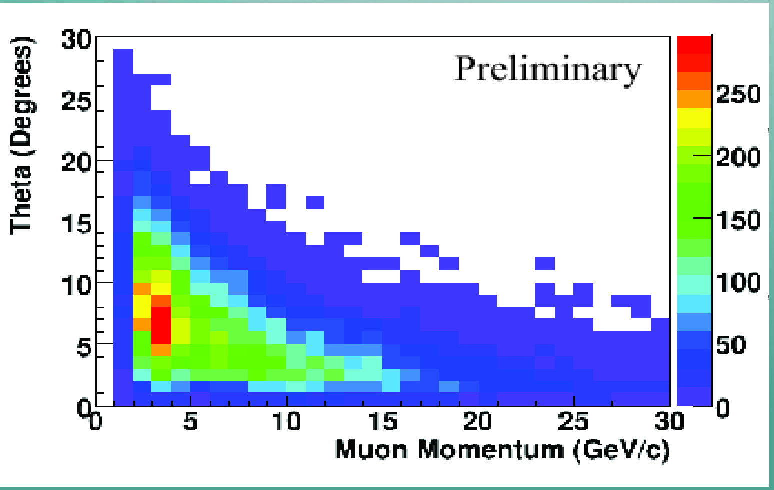


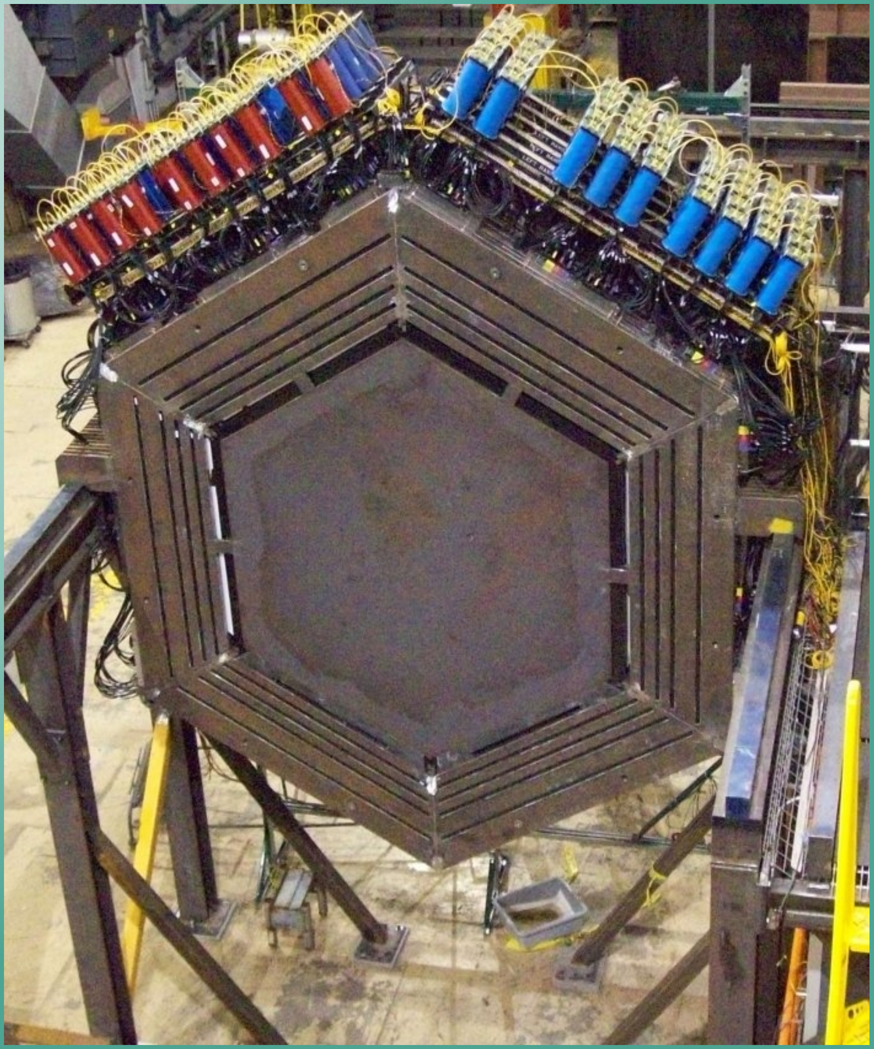
- Technique already tested in **Chooz**
- Detect via inverse β-reaction in water tanks
- Extract θ_{13} from the strength of antineutrino disappearance

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2(2\theta_{13}) X$$
$$\sin^2(1.27 \Delta m^2_{23} L/E)$$

MINERνA taking data

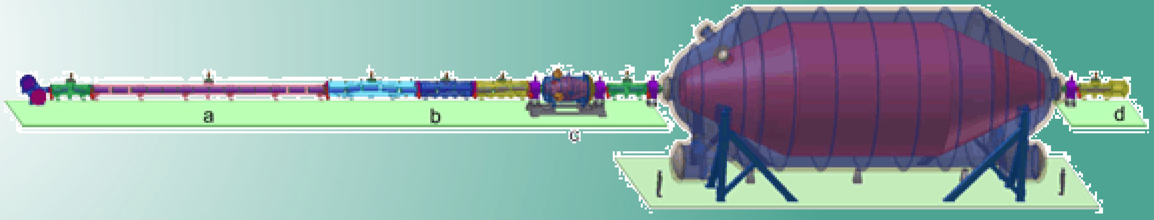
- Designed to measure neutrino-nucleus interactions at low energies
- Running on the MINOS beamline, where info on the muons are taken

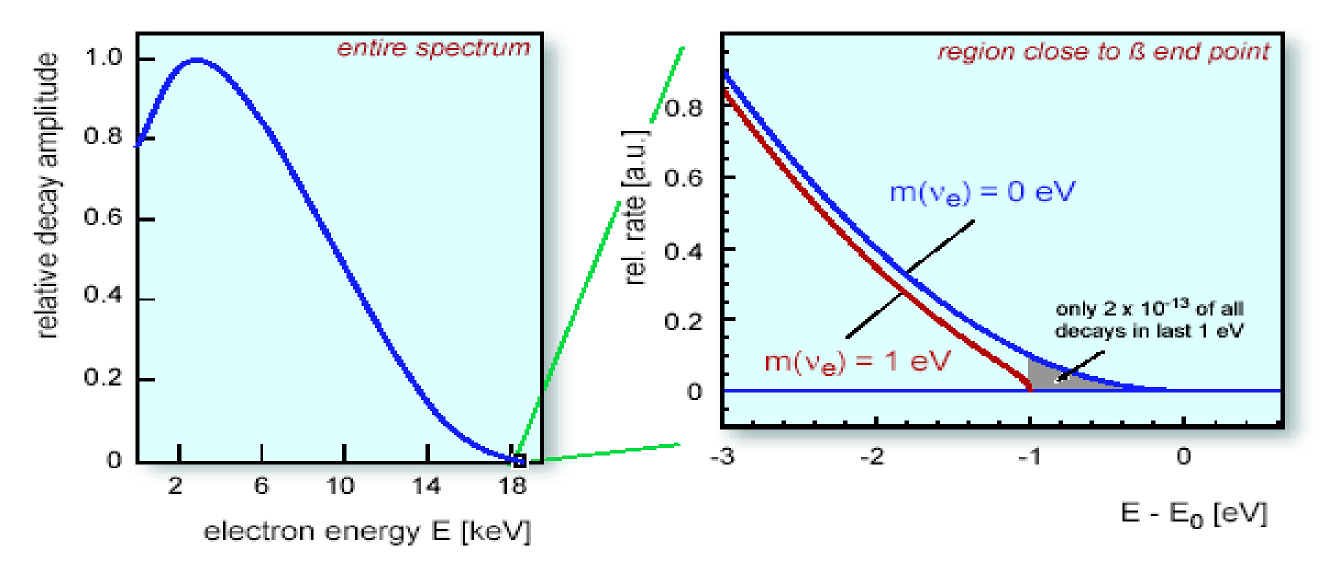




KATRIN: neutrino mass data soon

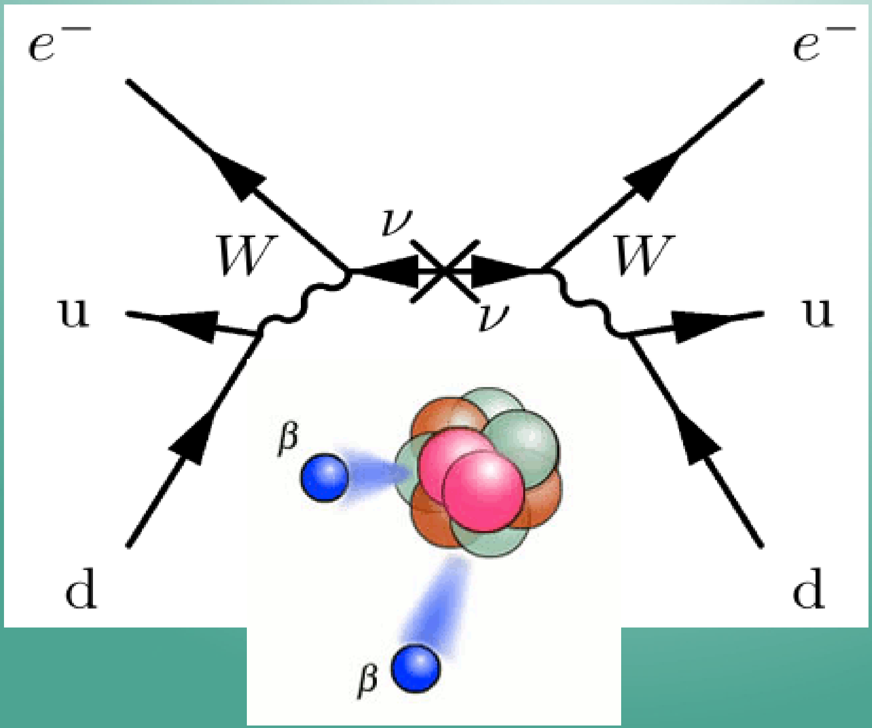
- Will study the mass of the electron neutrino from β-decay of ^3H (Tritium)
- Sensitivity is 0.2 eV
- Looks for the endpoint of the spectrum
- A direct mass measurement!

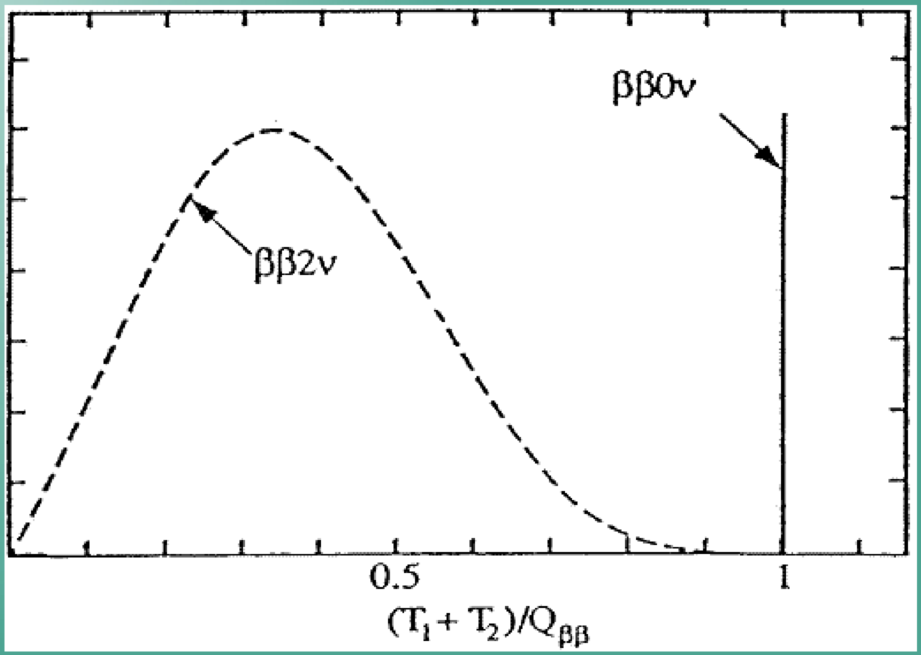




0νββ decay

- Experiments look for LNV processes in nuclei: (A,Z) → (A,Z+2) + 2e⁻

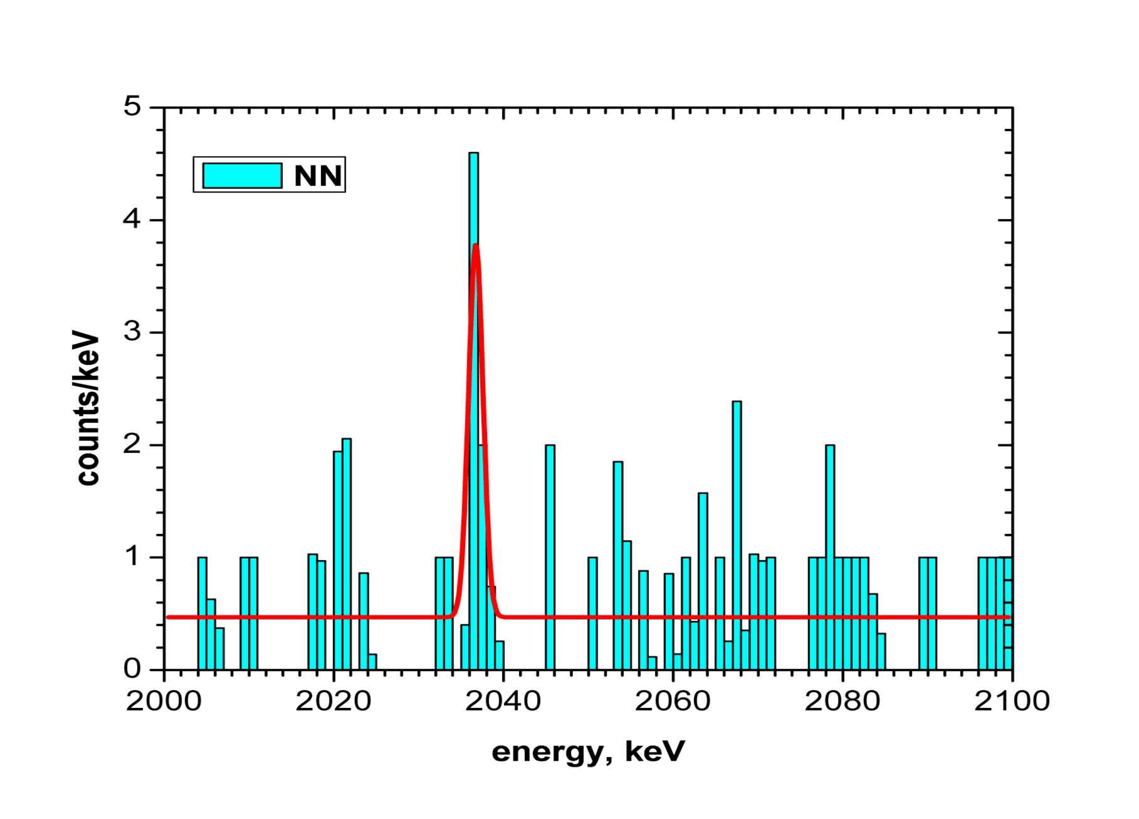




0νββ discovery claim (2001)

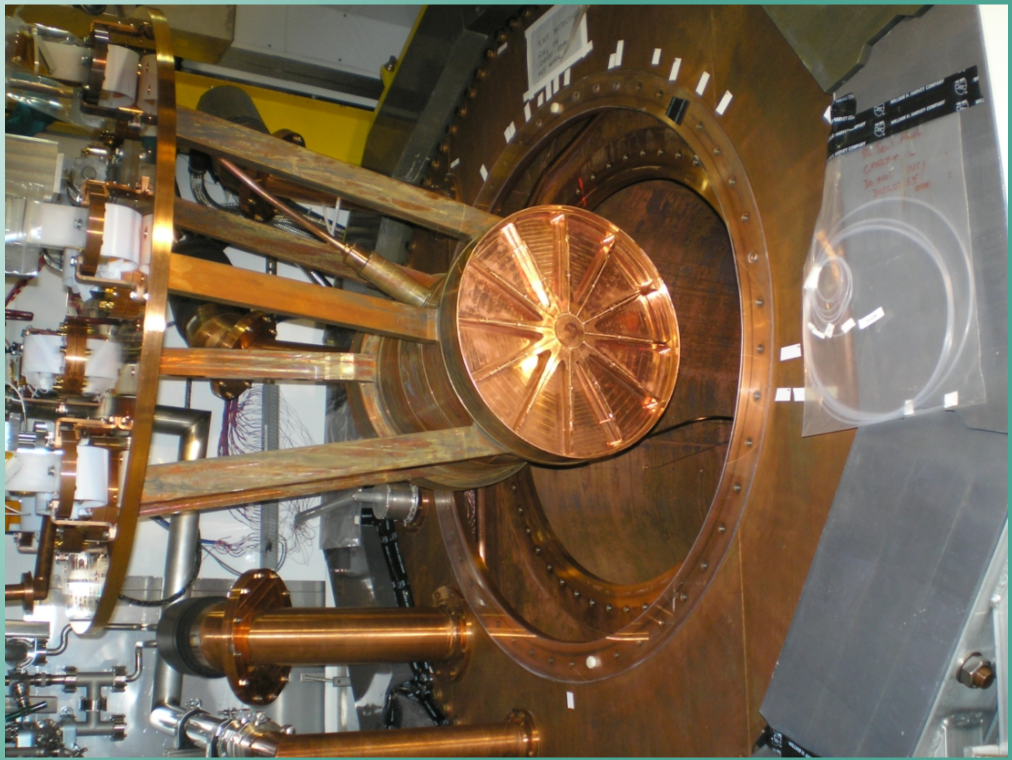
- The famous claim by Klapdor-Kleingrothaus et al. with data from **Heidelberg-Moscow** exp.

- Claim not refuted or confirmed by other experiments (yet)
- Remains quite controversial in the community



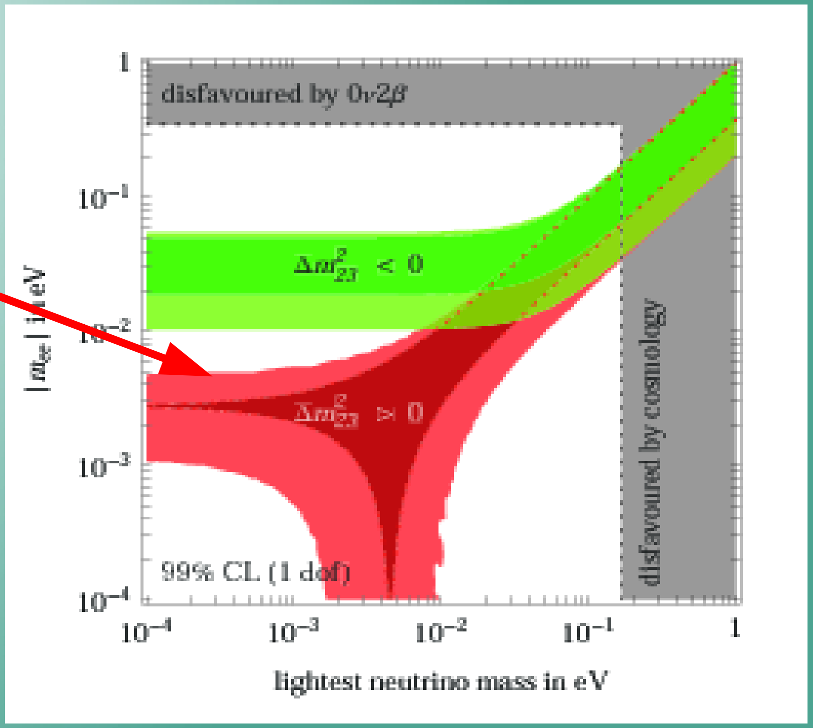
0νββ searches ongoing

- **EXO**, a Liquid Xe TPC with Ba^{2+} tagging
- Taking data now!
- In 2 years sensitive to a Majorana mass of 0.1 eV
- Ge experiments **Majorana** and **GERDA** also in the start pits



0νββ and mass hierarchy

- A detected signal below 0.01 eV would tell us that the mass hierarchy is normal, since the degeneracy is broken
- If a signal lies above, neutrino mass input is needed

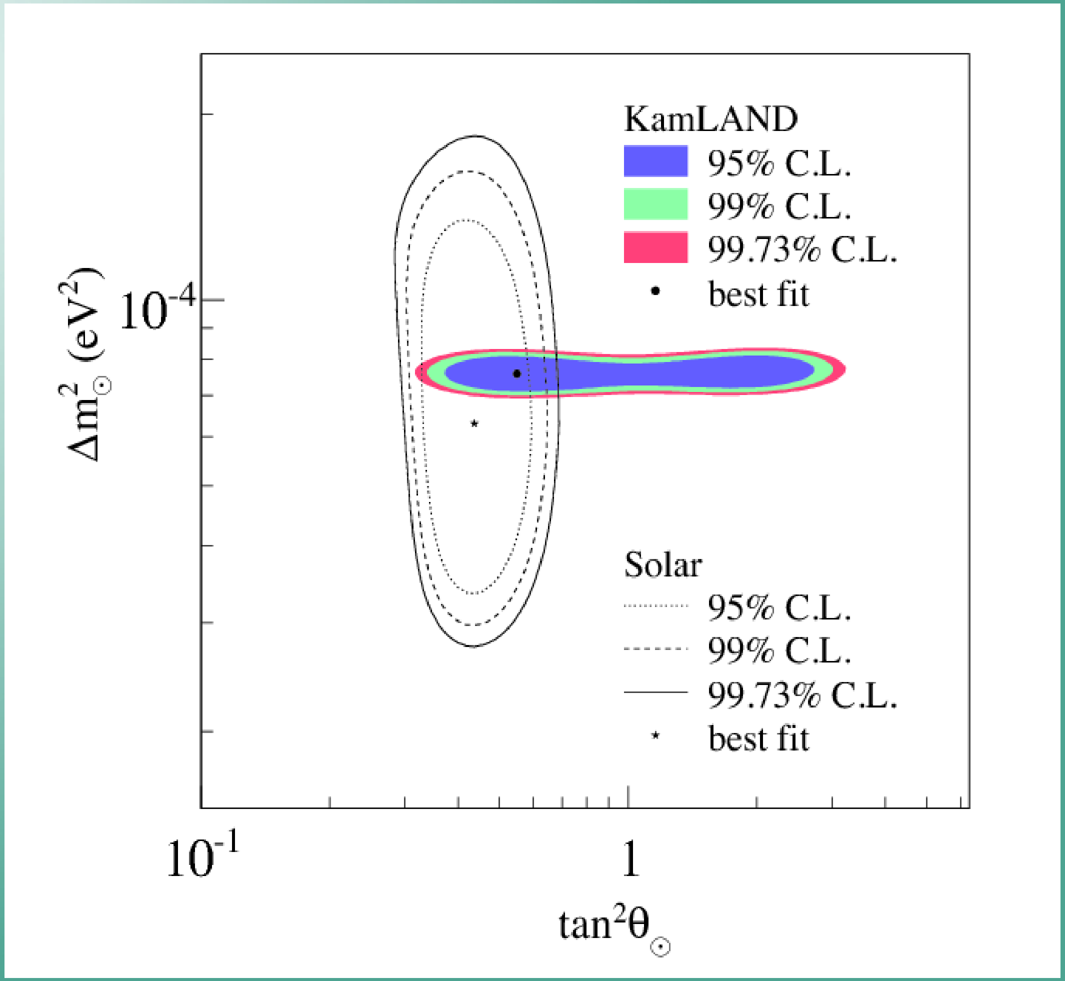


Summary

- Exciting scenarios exist in the neutrino sector: CPV, CPTV, LNV, sterile neutrinos?
- Oscillations now firmly established
- Measurement of θ_{13} soon to come
- Precision measurements of the other angles
- Neutrino masses still further away
- As always: stay tuned!

“Solar” mixing term θ_{12}

- Oscillation of electron neutrinos to muon or tau neutrinos
- First observed by SNO and Super-K
- Later confirmed by the KamLAND experiment using antineutrinos from 53 reactors with long baseline
- Long baseline ~180 km sensitive to Δm^2_{21}



“Reactor” mixing term θ_{13}

- Measured by **Chooz** (1999)
- Oscillation of electron antineutrinos to muon or tau neutrinos
- Neutrinos produced in two nearby reactors
- Short baseline (~1 km) sensitive to Δm_{32}^2