Istituto Nazionale di Fisica Nucleare

THE STERILE NEUTRINO PUZZLE:
new experimental results and the global analysis

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SEMINARIO GENERALE

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OUTLINE

- **Introduction**

- **The disappearance ν_e / $\bar{\nu}_e$ experiments**
  → the reactor experiment
  → the radioactive artificial source experiment
  + constrains from solar data

- **The disappearance ν_μ / $\bar{\nu}_\mu$ experiments**
  → the accelerator experiment (MINOS/MINOS+)
  + constrains from atmospheric data

- **The ν_μ → ν_e appearance experiments**
  → LSND and the latest results from MiniBoone

- **Global analysis**

- **Future prospective**

THE 3 flavor STANDARD SCENARIO

The Standard Model of neutrino oscillations solved the solar anomalies

Pontecorvo- Maki –Nakagawa –Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 1} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Measured parameters:

	Any Ordering
	3σ range
$\theta_{12}/^\circ$	$31.42 \to 36.05$
$\theta_{23}/^\circ$	$40.3 \to 51.5$
$\theta_{13}/^\circ$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

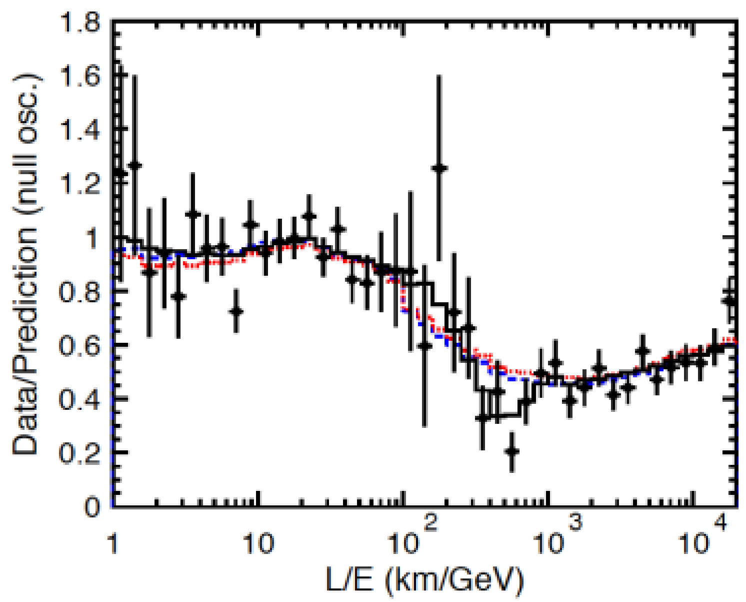
$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k} |\nu_k\rangle$$

In 2 flavor:

$$\begin{aligned} \psi \ &= \ \left(\cos^2\theta e^{-i(E_1 t - \vec{p_1}.\vec{x})} + \sin^2\theta e^{-i(E_2 t - \vec{p_2}.\vec{x})}\right)\nu_e - \\ &\left(\cos\theta\sin\theta\left(e^{-i(E_1 t - \vec{p_1}.\vec{x})} - e^{-i(E_2 t - \vec{p_2}.\vec{x})}\right)\right)\nu_\mu . \end{aligned}$$

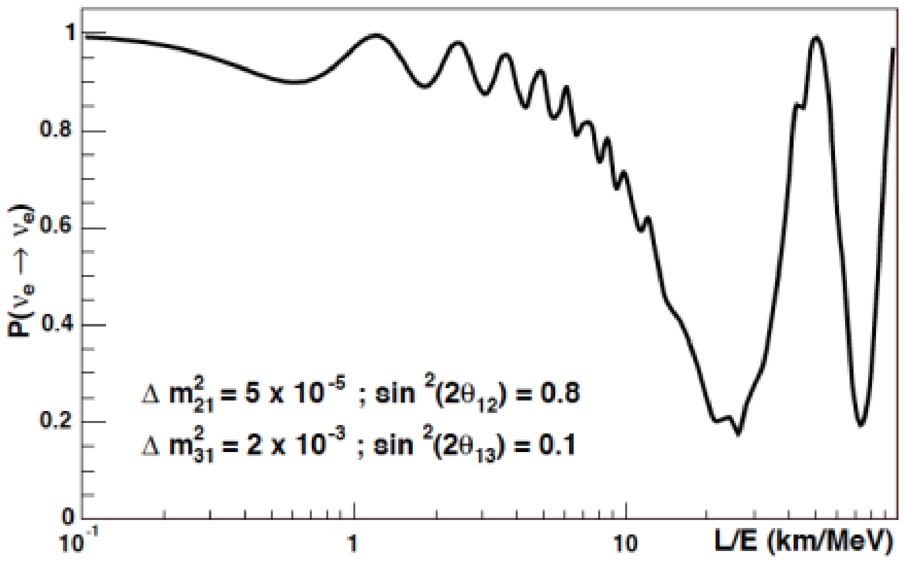
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

SNO and KamLand experiments



THE 3 flavor OSCILLATIONS

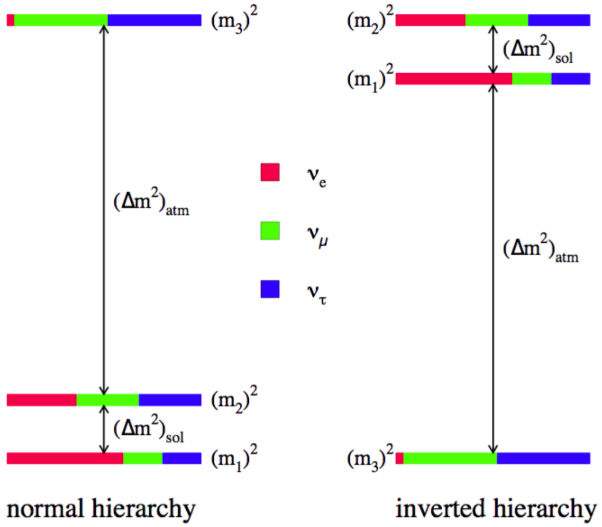
Oscillation probabilities



$$P(\nu_e \to \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\left(\frac{\Delta m^2_{21}\, L}{4E_\nu}\right) +$$

$$-4|U_{e1}|^2|U_{e3}|^2 \sin^2\left(\frac{\Delta m^2_{31}\, L}{4E_\nu}\right) - 4|U_{e2}|^2|U_{e3}|^2 \sin^2\left(\frac{\Delta m^2_{32}\, L}{4E_\nu}\right)$$

$$|\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \gg |\Delta m^2_{21}|$$



$$P(\nu_e \to \nu_e) \simeq 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21}\, L}{4E_\nu}\right) - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32}\, L}{4E_\nu}\right)$$

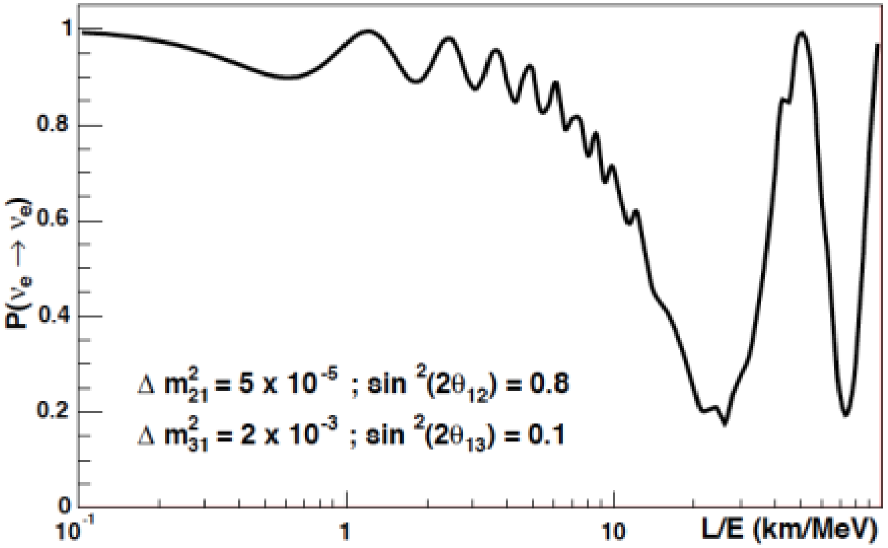
If L/E >10 km/MeV

If L/E ≈ 1-2 km/MeV

Each experiment is sensitive to a L/E region

- SOLAR DATA on ν_e Δm^2_{12}
- ATMOSPHERIC DATA on ν_μ Δm^2_{32}
- REACTOR and ACCELERATOR experiments for the matrix elements (mixing angles): θ_{13}

THE ANOMALIES



3 flavor standard oscillations does not occur at short baseline!

the anomalies at short baseline:

- GalleX, SAGE — 1.9 m - 0.6 m
- Reactors — 10 -100 m
- LSND — 30 m
- MiniBoone — 540 m

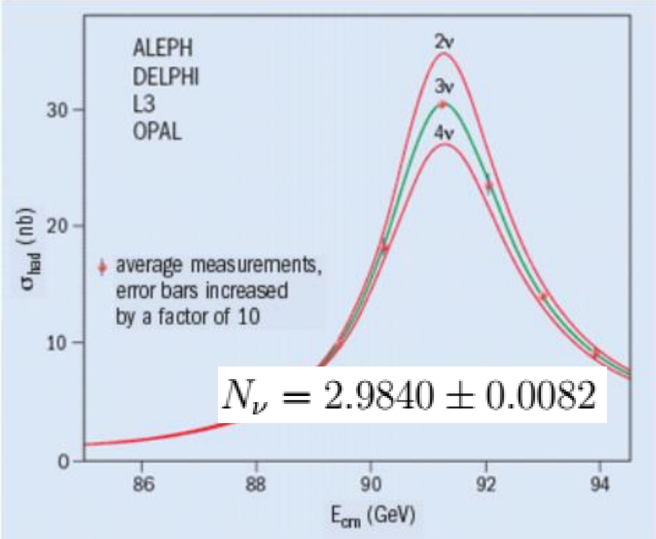
GalleX, SAGE and Reactors: ν_e Deficit

LSND and MiniBoone: $\nu_\mu \to \nu_e$ Appearance

cannot be explained by the same matrix

The new hypothesis: other oscillations?...other neutrinos?

- This time the neutrino must be sterile (not week interaction)
- The PNMS matrix is not unitary !?



THE NEW HYPOTHESIS

Which experimental tests?

The new matrix 3+n x 3+n

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

The Short Base Line approximation

no oscillations due to the standard 3 flavor

P depends only on the terms $U_{\alpha i}$ Δm^2_{i1} with $i \geq 4$

The ν_e DISAPP

$$P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2_{41}L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

The ν_μ DISAPP

$$P_{\mu\mu}^{\mathrm{SBL},3+1} = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\frac{\Delta m^2_{41}L}{4E} = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

The $\nu_\mu \rightarrow \nu_e$ APP

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e}^{\mathrm{SBL},3+1} = 4|U_{\mu 4}U_{e4}|^2\sin^2\frac{\Delta m^2_{41}L}{4E} = \sin^2 2\theta_{\mu e}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

The Long Base Line approximation

the effect of the sterile neutrino can be seen as a global flux reduction

$$P_{\nu_\alpha\to\nu_\alpha}^{\mathrm{LBL},3+2} = \left(1-\sum_{i=3}^{5}|U_{\alpha i}|^2\right)^2 + \sum_{i=3}^{5}|U_{\alpha i}|^4 + 2\left(1-\sum_{i=3}^{5}|U_{\alpha i}|^2\right)|U_{\alpha 3}|^2\cos(2\phi_{31}) \qquad \phi_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}$$

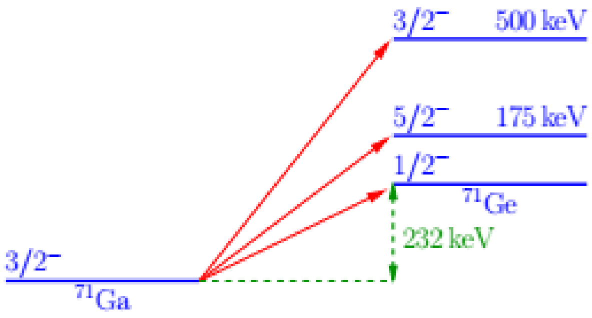
ν_e DISAPPEARANCE: the radioactive source experiments

Radioactive source ^{51}Cr ^{37}Ar in GALLEX and SAGE detectors

	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098

1991-1997

L=1.9 m　　　0.6 m



$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

The cross section changed during the years!

From Bahlcall cross section

$$\sigma_B(^{51}\mathrm{Cr}) = 58.1 \times 10^{-46}\,\mathrm{cm}^2$$
$$\sigma_B(^{37}\mathrm{Ar}) = 70.0 \times 10^{-46}\,\mathrm{cm}^2$$

to larger cross section

$$\sigma = \sigma_{gs}\left(1 + \xi_{175}\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{gs}} + \xi_{500}\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{gs}}\right)$$

with
$$\sigma_{gs}(^{51}\mathrm{Cr}) = 55.3 \times 10^{-46}\,\mathrm{cm}^2$$
$$\sigma_{gs}(^{37}\mathrm{Ar}) = 66.2 \times 10^{-46}\,\mathrm{cm}^2$$

The ratio between observed and expected events

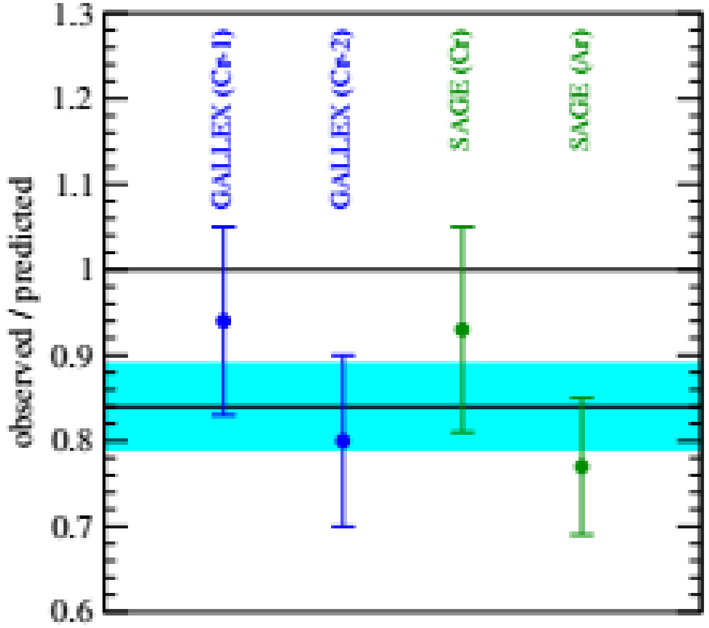
The values depend on the cross section

	G1	G2	S1	S2	AVE
R_B	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$

ν_e DISAPPEARANCE: the radioactive source experiments

The final results

$$\text{GALLEX:} \begin{cases} R_1(\text{Cr}) = 0.94 \pm 0.11 \\ R_2(\text{Cr}) = 0.80 \pm 0.10 \end{cases} \qquad \text{SAGE:} \begin{cases} R_3(\text{Cr}) = 0.93 \pm 0.12 \\ R_4(\text{Ar}) = 0.77 \pm 0.08 \end{cases}$$

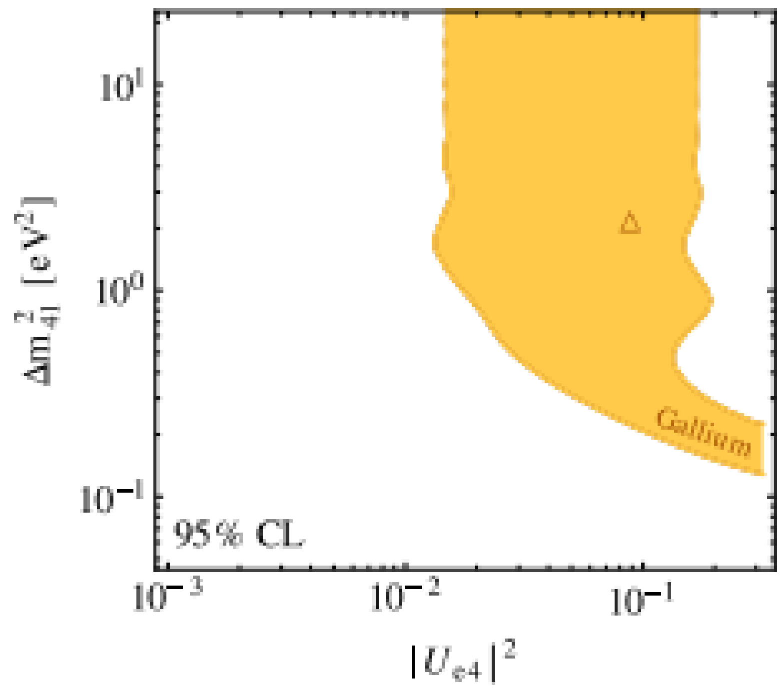


Fitting the 4 values with the same flux:

$$r_{\min} = 0.84^{+0.054}_{-0.051}\,, \qquad \Delta\chi^2_{r=1} = 8.72 \quad (2.95\sigma)$$

The ν_e DISAPP

$$P_{ee}^{\text{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2_{41} L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m^2_{41} L}{4E}$$



$\bar{\nu}_e$ DISAPPEARANCE: the reactor experiments

Many experiments observing $\bar{\nu}_e$ from reactor at short distance: **E → few MeV and L < 100 m**

Reactor code for flux estimation

First generation: Bugey and others
observed a ratio smaller than 1

Latest results: RENO, DANSS, NEOS, Daya Bay
Independent on the flux
Near/Far detector comparison!
New codes for fluxes for distinguish the isotope
New analysis fixed and free flux

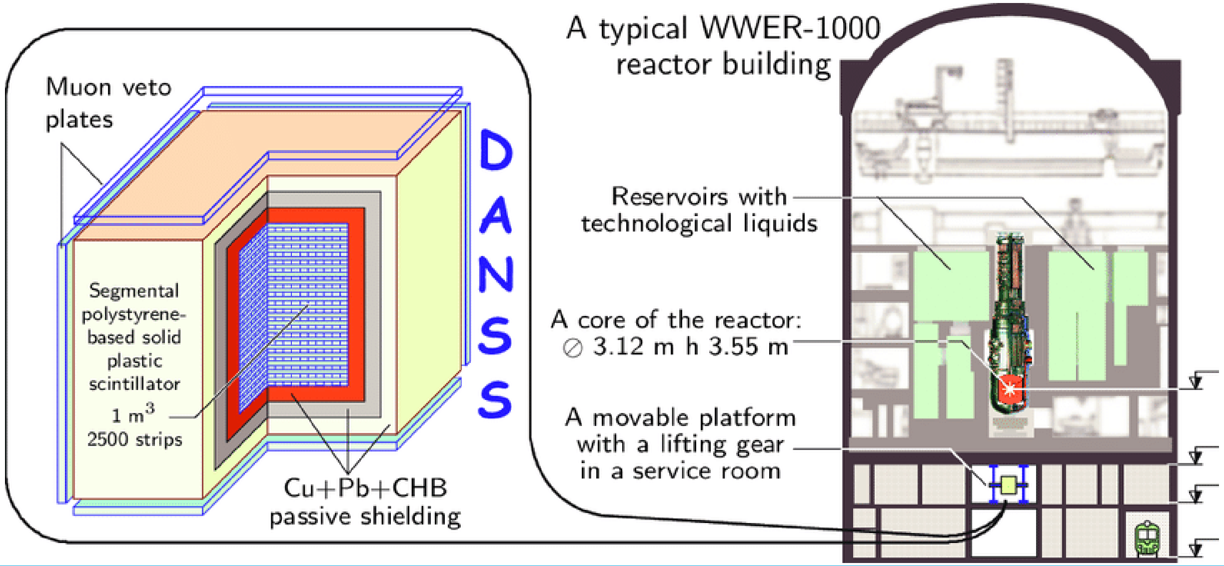
New results in the future
PROSPECT- STEREO

Fission reactors release about 10^{20} ν_e GW s^{-1} from beta decay of fission product ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U

The emitted antineutrino spectra is

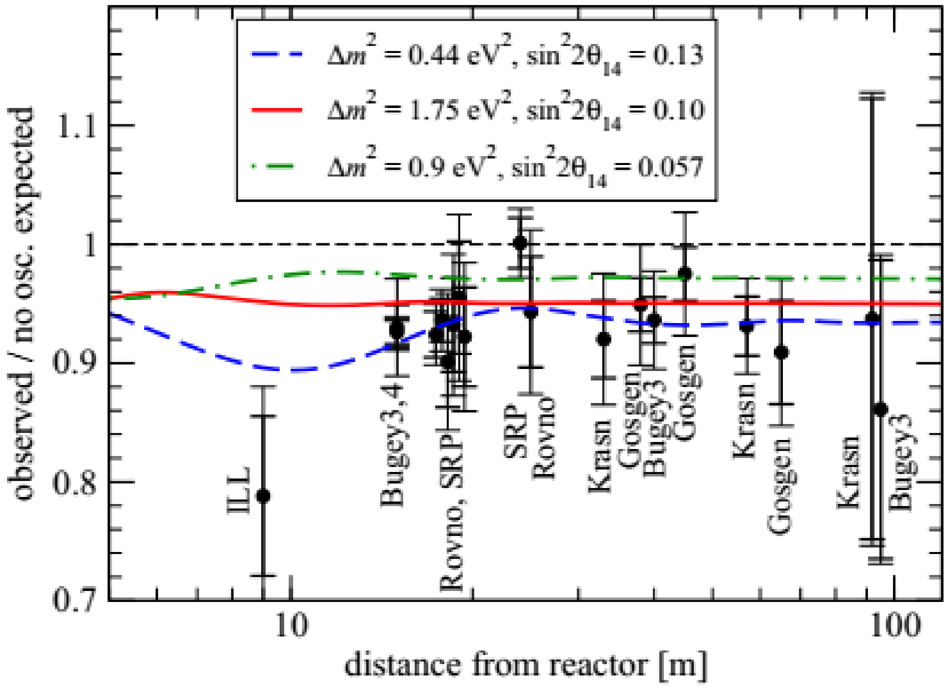
$$S_{tot}(E_\nu) = \sum_k f_k S_k(E_\nu)$$

summed on the fuel composition (different for each experiment!)



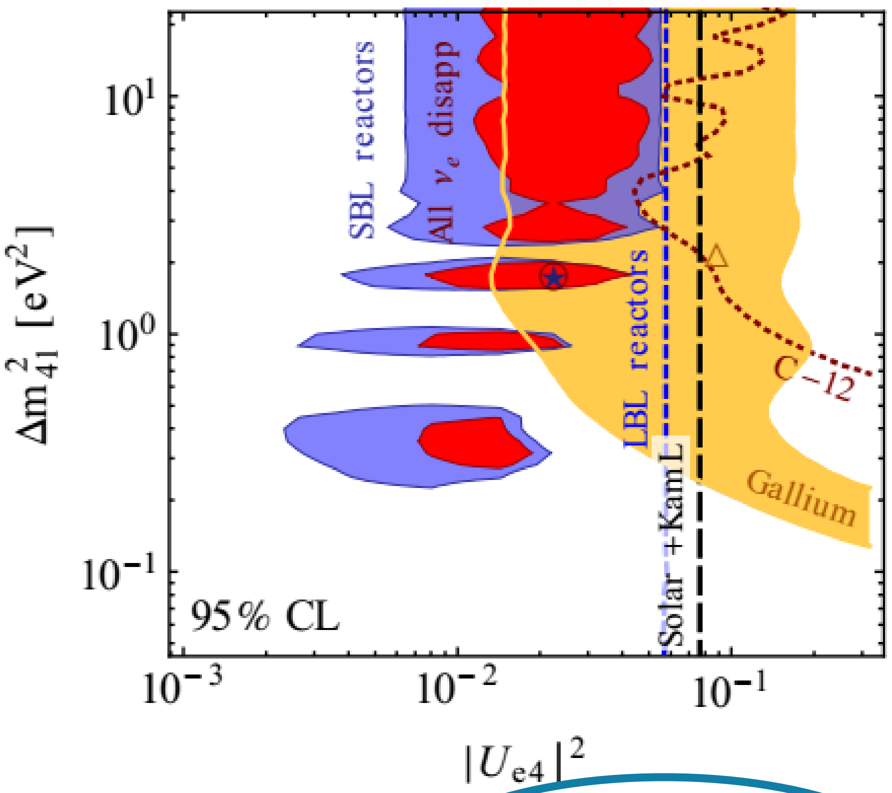
$\overline{\nu}_e$ DISAPPEARANCE: the reactor experiments

First generation results… … and combined fit



NO visible dependence on L

→ $\Delta m^2 >\sim 1\ eV^2$



The neutrino flux uncertainties is not included in the bars

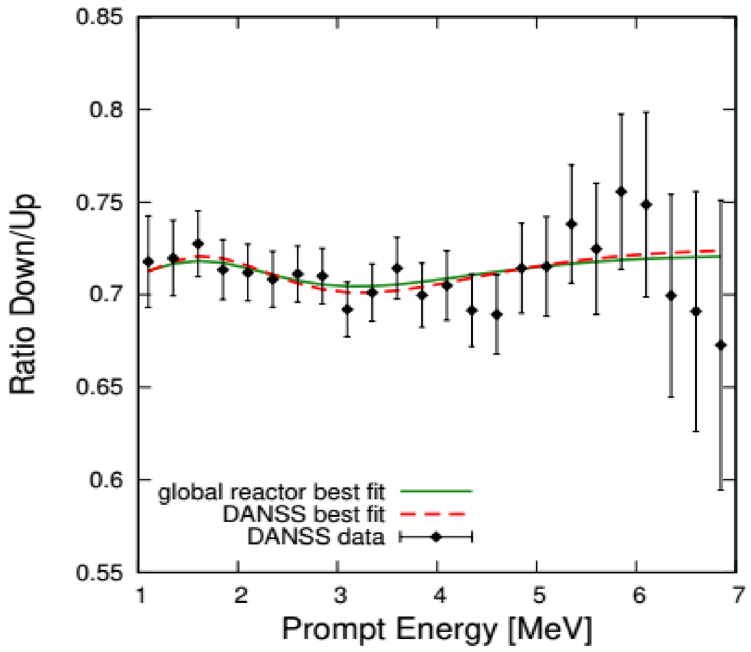
	Δm^2_{41}	Δm^2_{51}	θ_{14}	θ_{15}	χ^2_{min} (GOF)	$\Delta\chi^2_{3+1}$ (CL)	$\Delta\chi^2_{no\text{-}osc}$ (CL)
SBLR	0.46	0.87	0.12	0.13	53.0/(76-4) (95%)	5.3 (93%)	14.3 (99.3%)
SBLR+gal	0.46	0.87	0.12	0.14	60.2/(80-4) (90%)	3.8 (85%)	17.8 (99.9%)

$\overline{\nu}_e$ DISAPPEARANCE: the reactor experiments

Second generation experiments: results independent on the neutrino flux

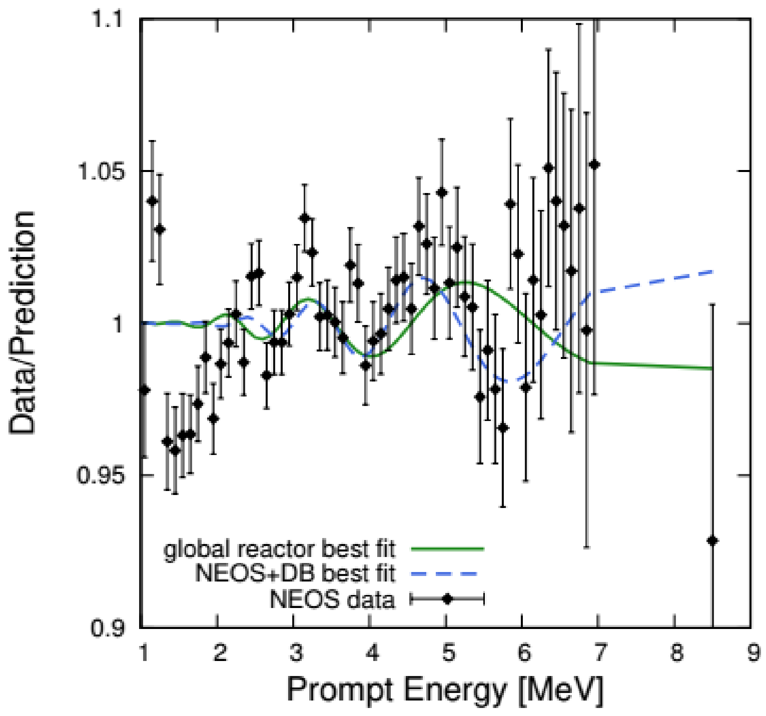
DANSS movable detector

at L=10.7 m and L=12.7 m



$$\Delta m^2_{41} = 1.32\ \text{eV}^2,\ \sin^2\theta_{14} = 0.012\ \text{for DANSS}$$

NEOS normalized to Daya-Bay flux



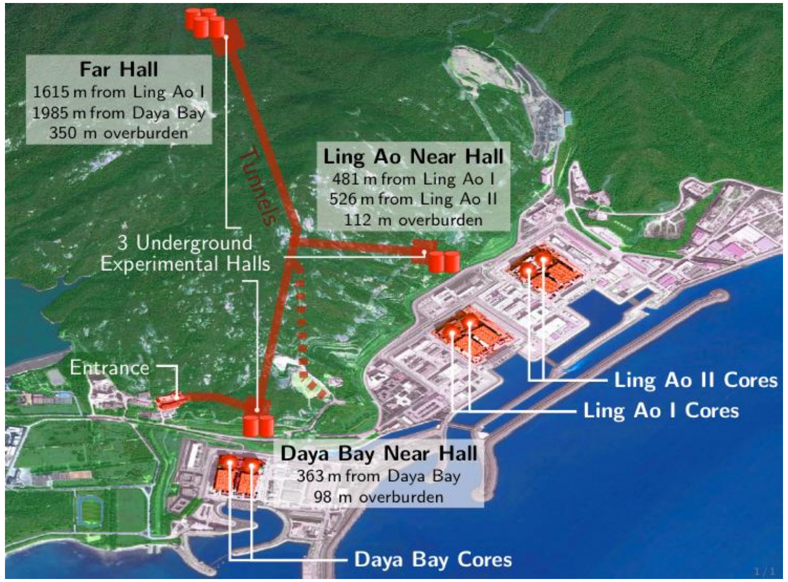
$$\Delta m^2_{41} = 1.78\ \text{eV}^2,\ \sin^2\theta_{14} = 0.013$$

No oscillation hypothesis discarded at **3.3 σ** in the **free flux** analysis (free normalization of the 4 main comp.) and at **3.5 σ** in the **fixed flux** analysis

$\overline{\nu}_e$ DISAPPEARANCE: the reactor experiments

Second era experiments: flux composition study

2016-2017



RENO Daya Bay Double CHOOZ:

observed a bump at 5 MeV

It is not due to sterile neutrino
It is a flux feature suggesting that the flux is not completely understood!

Daya-Bay:

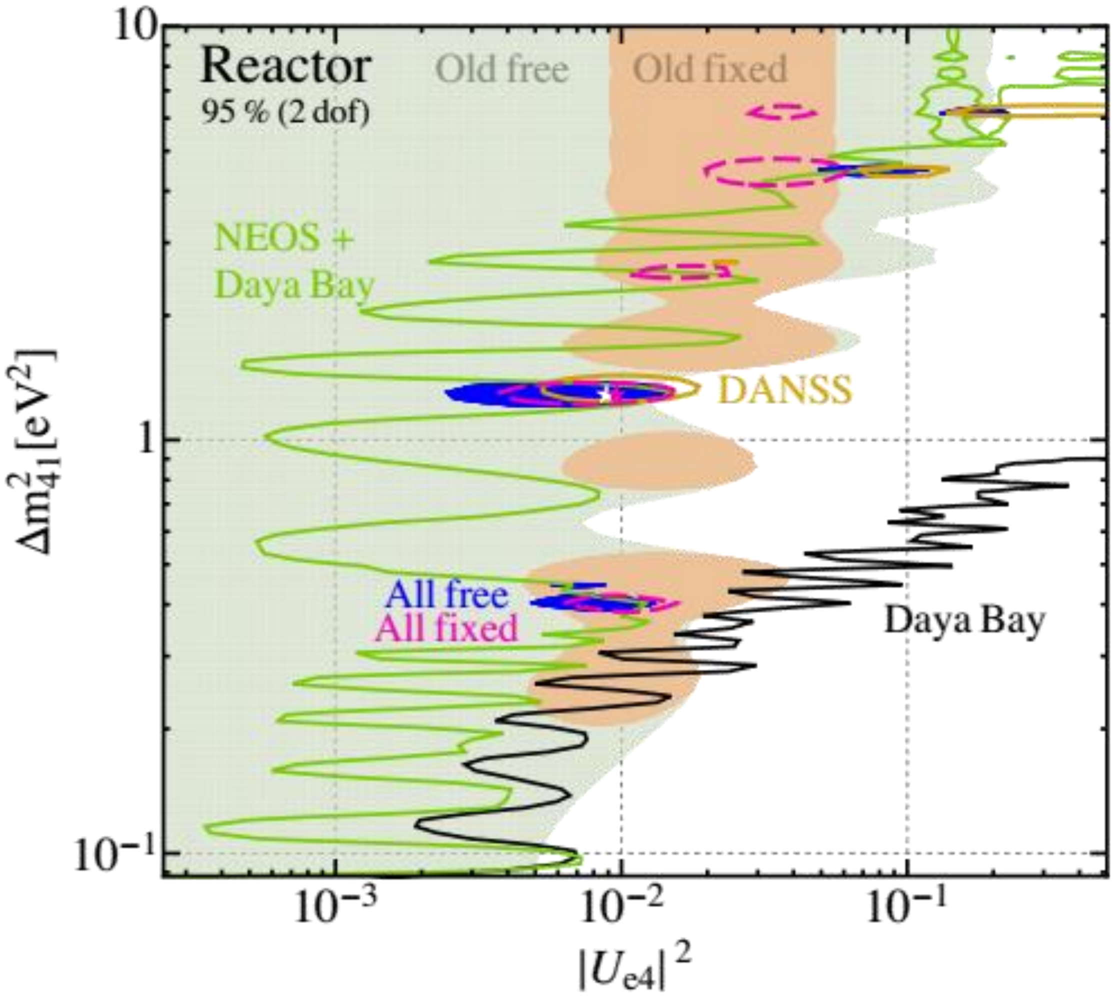
by using **the time evolution** of the observed reactor **anti-neutrino spectra** and the known evolution of the reactor **fuel composition**

measurements of **the individual neutrino fluxes** from the two most important fissible isotopes ^{235}U and ^{239}Pu

- The anomaly stems mainly from ^{235}U and not for ^{239}Pu
- the hypothesis no-oscillation and free neutrino flux normalization is preferred at 2.7 σ versus the flux prediction and sterile neutrino hypothesis

→ small tension with the global reactor data!

$\overline{\nu}_e$ DISAPPEARANCE: all reactor experiments



- Old and new reactor anomaly quite in agreement
- Tension between DANS – NEOS and Daya Bay data
- The conclusion does not depend on the flux

The sterile neutrino hypothesis became less strong but it is not excluded!

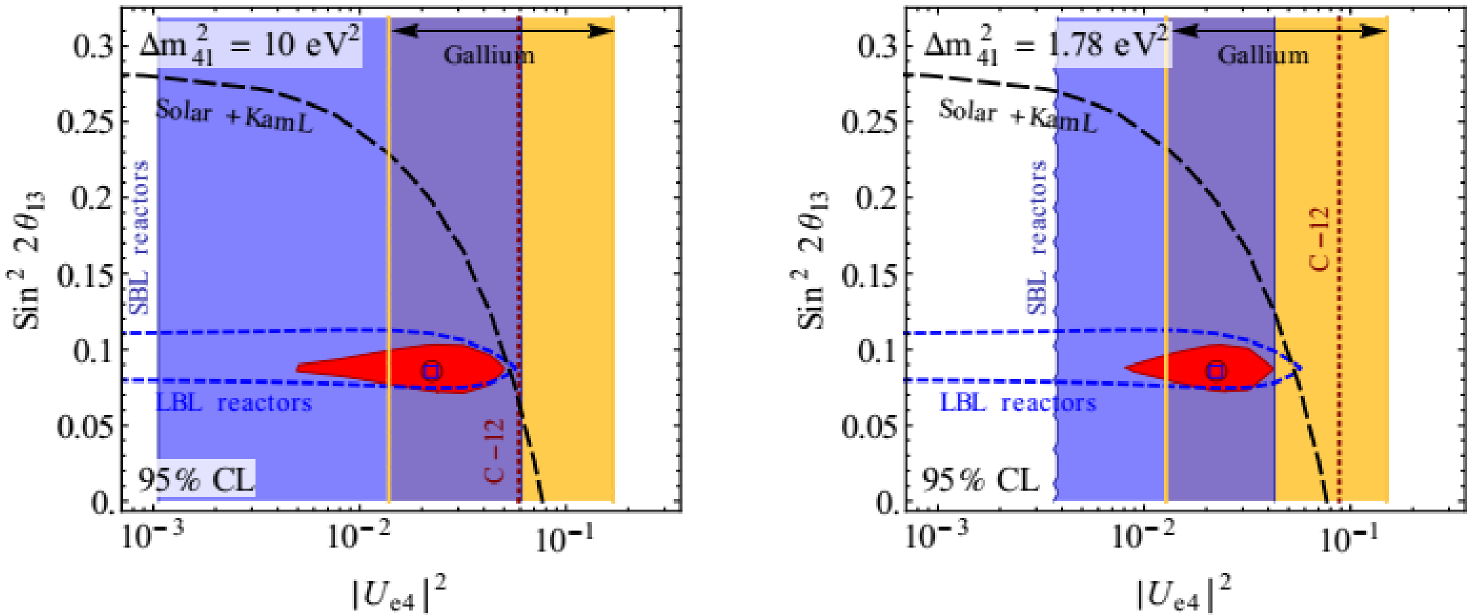
ν_e DISAPPEARANCE: other constrains

Solar neutrinos:

- ν_e survival probability — constrain on U_{e4} (θ_{24} and θ_{34})
- Neutral Current data — sensible to $\nu_x \rightarrow \nu_s$ oscillation

both the sterile neutrino and the θ_{13} oscillation results in a global flux reduction

Δm^2_{21} Δm^2_{31} **fixed**



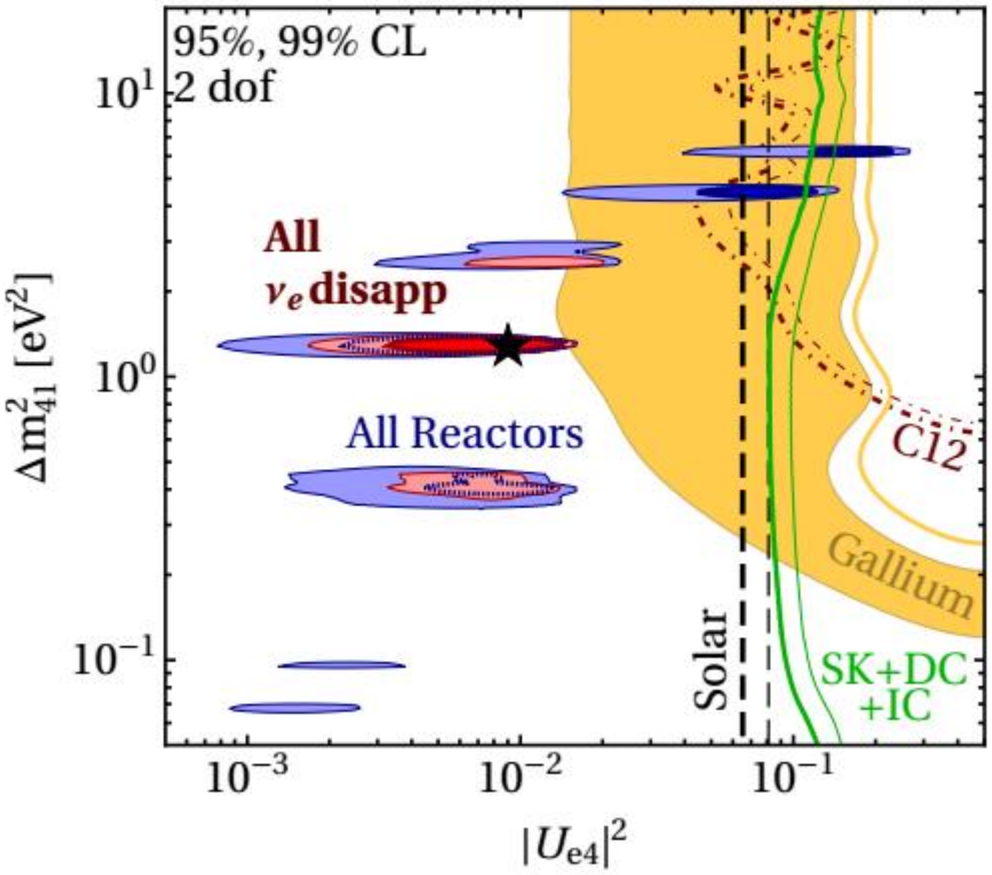
complementarity between short baseline and Long BaseLine

θ_{13} is not dependent on the sterile oscillation and can be fixed!

ν_e DISAPPEARANCE: the GLOBAL ANALYSIS

Gallex + Reactor + Solar

Analysis	Δm^2_{41} [eV^2]	$\|U^2_{e4}\|$	χ^2_{min}/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 – 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 – 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 – 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 – 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 – 6)	17.5	3.8σ



An hint for the sterile exists!

ν_μ DISAPPEARANCE: introduction

$$P_{\mu\mu}^{\mathrm{SBL},3+1} = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

Accelerator neutrino:

→ **MINOS and MINOS+** comparison between FAR and NEAR in both the Charge Current $U_{\mu4}$ and Neutral Current $U_{\tau4}|$

Short and Long Base Line!

→ **MiniBoone**

Short base Line

Atmospheric neutrino:

→ **Super-Kamiokande**

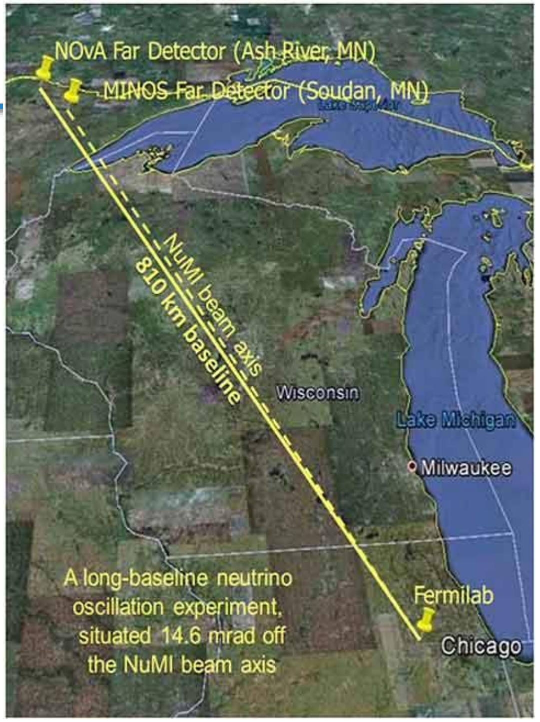
The sterile neutrino influence the normalization effect on $P_{\mu\mu}$ survival $U_{\mu4}$
but the e events and mu events have a correlated error…

Long Base Line!

→ **IceCube**

with matter effect: independent on $U_{\mu4}$

ν_μ DISAPPEARANCE: MINOS and MINOS+



Ratio between far and near spectrum

MINOS and MINOS+ 7 GeV

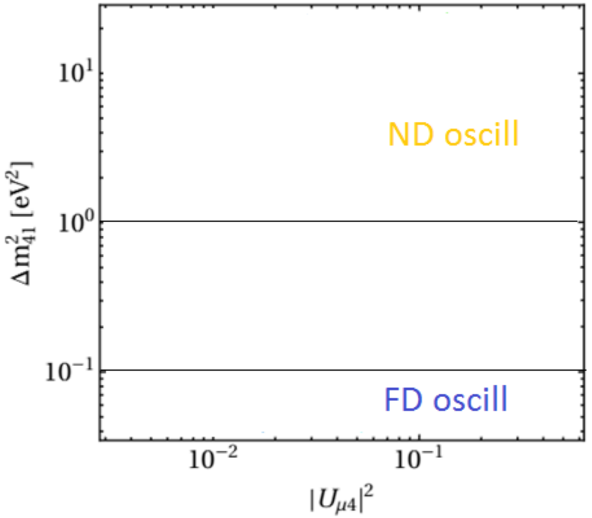
(energy higher than the maximal disappearance of 3 flavor)

- the sterile-driven oscillations are seen as an **energy-dependent modification to the FD spectra**
- the oscillation have a wavelength comparable to or shorter than the energy resolution of the detector so are seen as a **deficit in the event rate**, constant in energy
- **oscillations occur in the ND** along with rapid oscillations averaging in the FD

Near: 1 Km $\Delta m^2_{41} \sim 1\text{–}100\ \text{eV}^2$

Far: 735 km $\Delta m^2_{41} \sim 10^{-3}\text{–}10^{-1}\ \text{eV}^2$

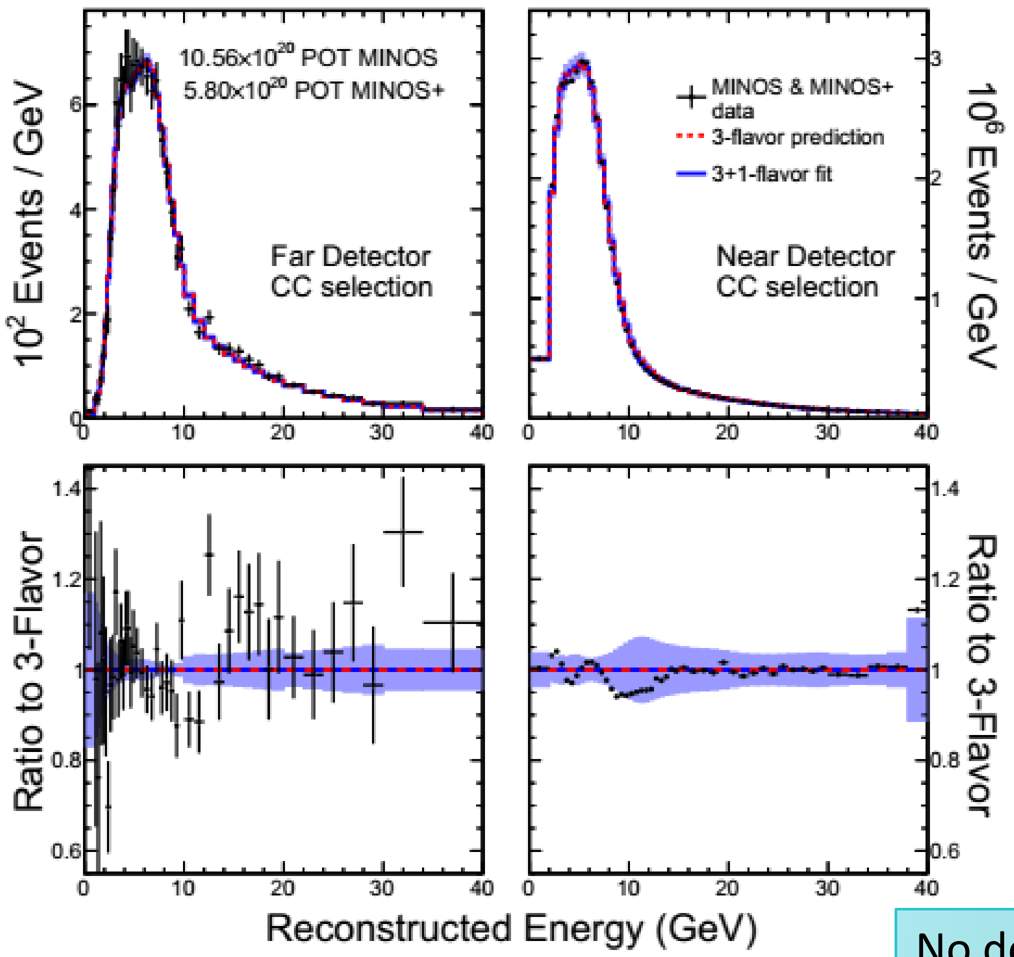
The oscillation pattern could be observed

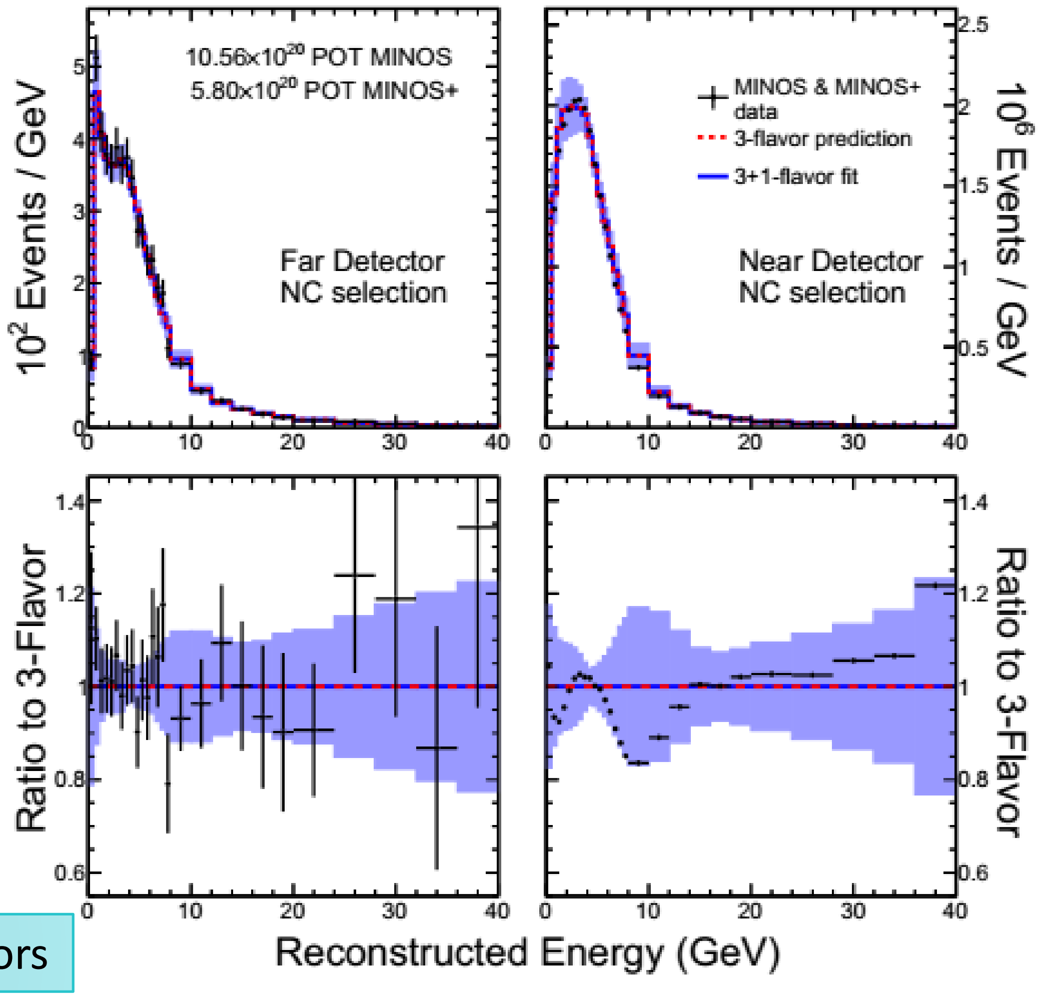


Two data sets: CC channel and NC channel

ν_μ DISAPPEARANCE: MINOS and MINOS+ data

Charge Current data set and Neutral Current data set





No deviation from 3 flavors

ν_μ DISAPPEARANCE: MINOS and MINOS+

Charge current

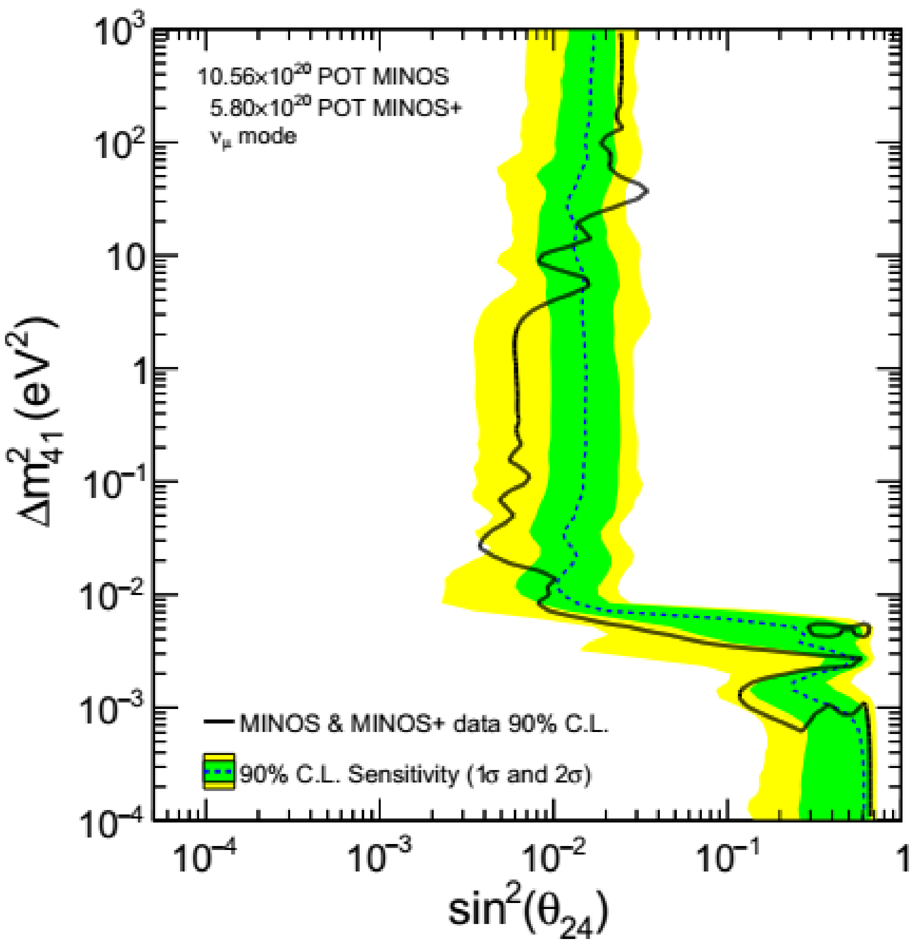
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right).$$

constrain on θ_{24}

Neutral current

$$P_{NC} = 1 - P(\nu_\mu \to \nu_s)$$
$$\approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$
$$+\frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin\left(\frac{\Delta m^2_{31} L}{2E}\right)$$

constrain on θ_{34} ($U_{\tau 4}$)



ν_μ DISAPPEARANCE: MiniBoone data

L=541 m from
proton target (BNB)

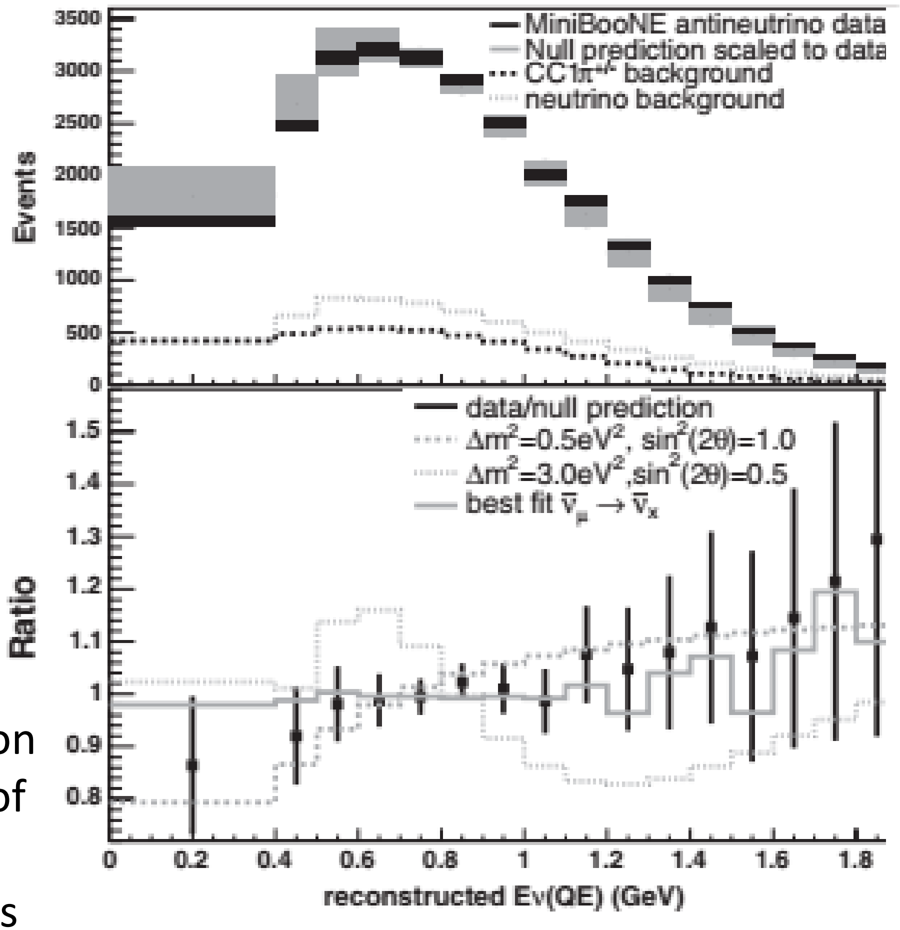
E= 200-1600 MeV

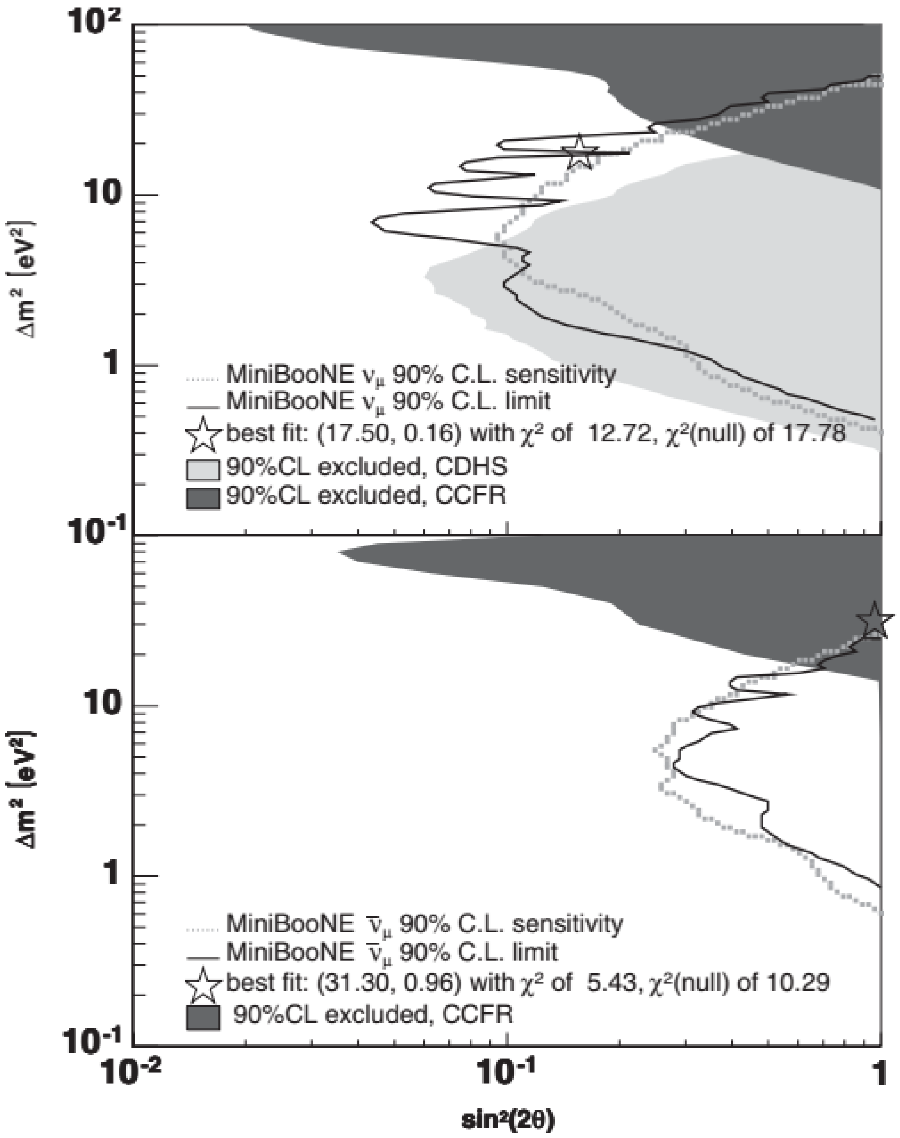
- Energy resolution 11%

In neutrino and anti-neutrino modes

The dominant systematics:

- CC-1π background contamination
- the neutrino flux (production of pions from p-Be interactions)
- CCQE cross section uncertainties





The χ^2 between data and null hypothesis is 17.78 /16 (34% prob.) consistent with no oscillation at 90% C.L.

ν_μ DISAPPEARANCE: IceCube

Active-sterile neutrino enhanced by MSW effect in matter:

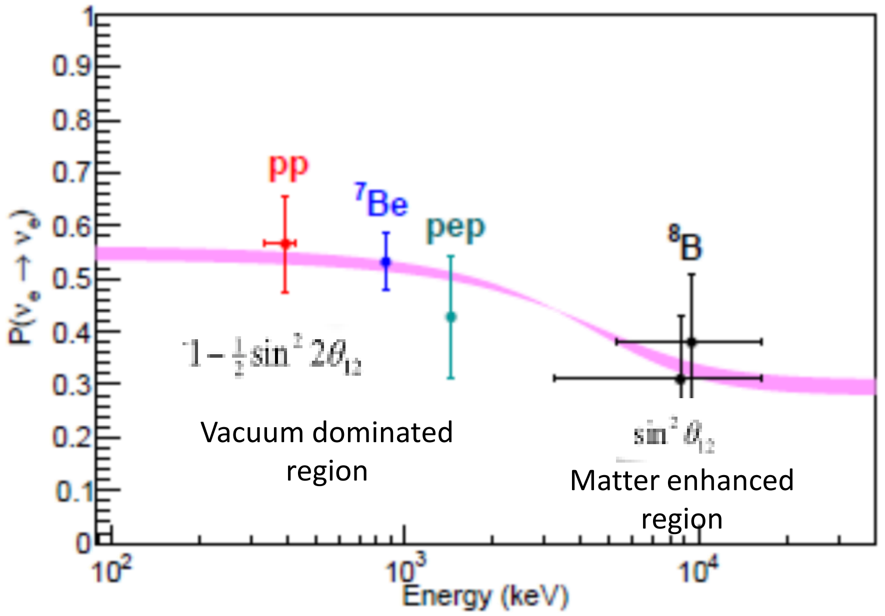
resonance at TeV high energy atmospheric neutrino IceCube

MSW effect: $\nu_e \rightarrow \nu_s$ oscillations in matter where the mass eigenstates are different

The resonance condition depends on the sign of Δm^2, density of the medium and neutrino energy

For instance for solar neutrino

$$E > \frac{\delta m^2 \cos 2\theta_{12}}{2\sqrt{2} G_F N_0} \approx \frac{\delta m^2 \cos 2\theta_{12}}{1.5 \times 10^{-11}\ \text{eV}} \approx 2\ \text{MeV}.$$



ν_μ DISAPPEARANCE: global analyis

IceCube searches for a maximal oscillation at TeV energies

2017

$$E_{res} = 5.3\ \text{TeV} \times \left(\frac{5\ \text{g/cm}^3}{\rho_\oplus}\right)\left(\frac{\Delta m^2_{41}}{1\ \text{eV}^2}\right)$$

$$\Delta E_{res} \sim \frac{\Delta m^2_{41} \sin^2 2\theta_{24}}{2V_{MSW}}$$

small resonance width

If **Δm^2_{41} >0** the resonance is expected in the antineutrino mode

The effect was not observed BUT how much is the sensitivity?

- IceCube cannot distinguish on an event-by event basis the neutrino/antineutrino
- Systematic uncertainties

Super-Kamiokande and DeepCore for ν_μ at GeV energies:

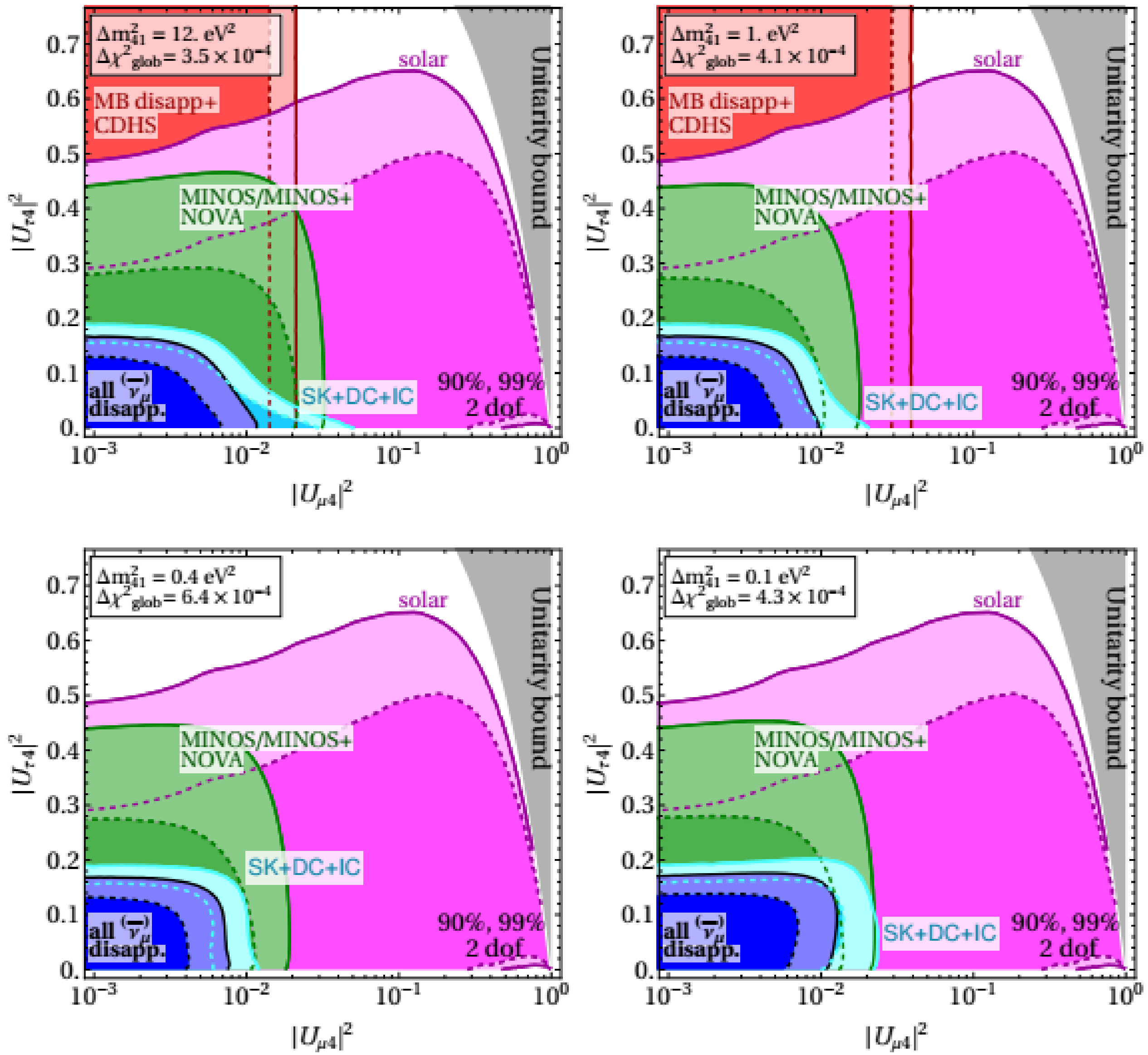
Constrains:

- on $U_{\mu 4}$ as global suppression of $P_{\mu\mu}$
- on $U_{\tau 4}$ zenith dependence of $P_{\mu\mu}$

CONSTRAIN ON $U_{\tau 4}$

$U_{\tau 4}$ controls the weight of the oscillation between $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ at the atmospheric scale

$$\begin{aligned} P_{\rm NC} &= 1 - P\left(\nu_\mu \to \nu_s\right) \\ &\approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \\ &\quad - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ &\quad + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \end{aligned}$$

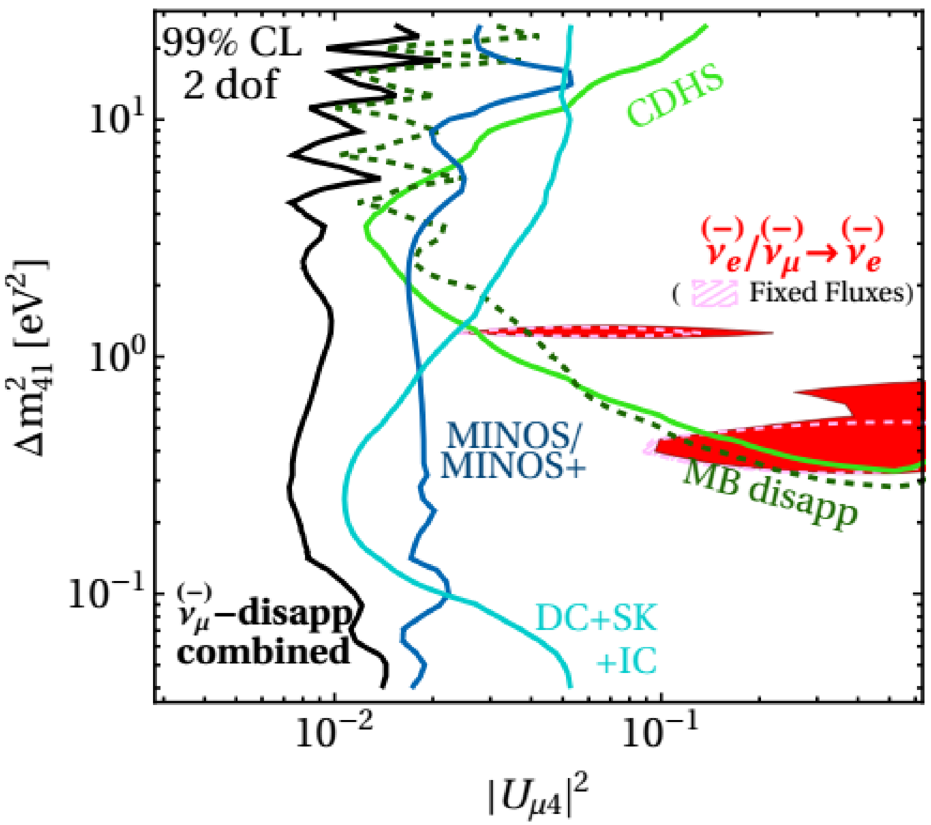


- from solar neutrino matter effect SNO
- from MINOS+ NC
- from atmospheric neutrino from neutral current

from atmospheric neutrino

$$|U_{\tau 4}|^2 < 0.13\,(0.17) \quad \text{at} \quad 90\%\,(99\%)\,\text{CL}.$$

ν_μ DISAPPEARANCE: global analyis



No anomaly was observed!

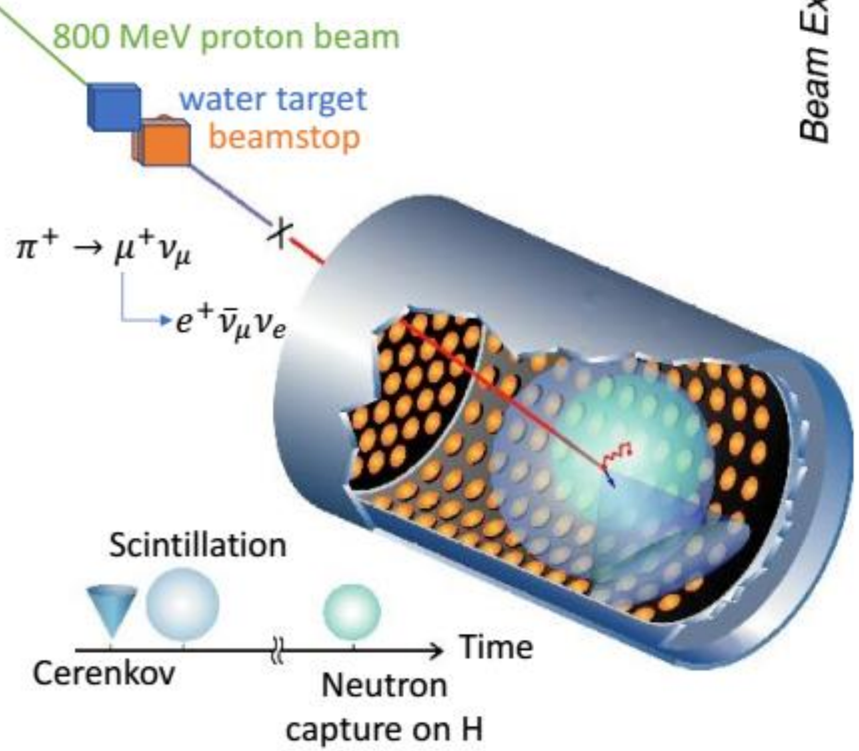
From direct searches (MINOS an MiniBoone) and from indirect searches
a big space of parameters is excluded!

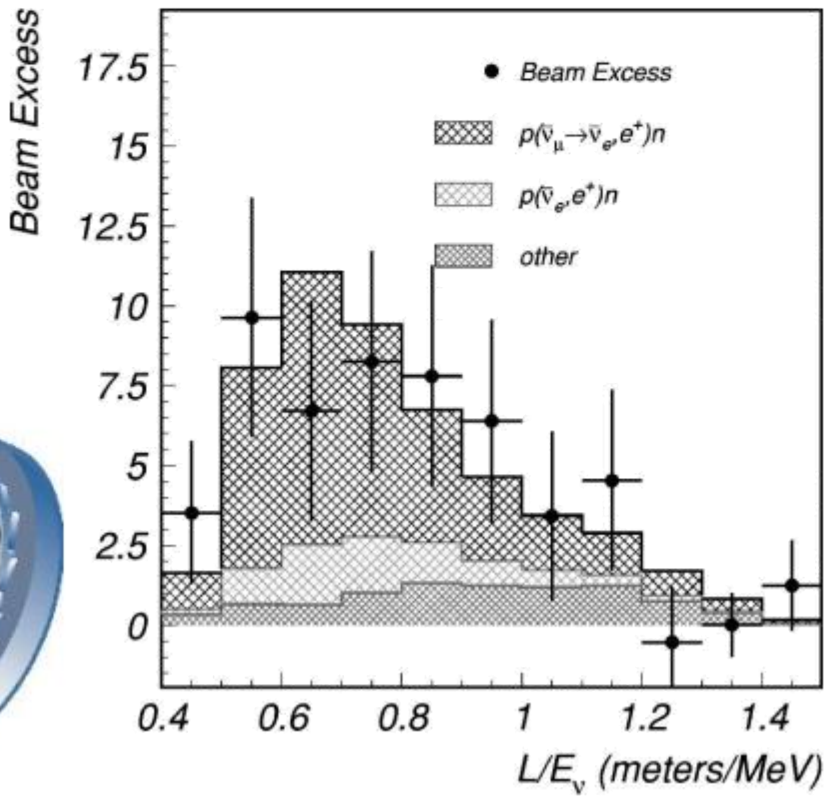
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ APPEARANCE: LSND

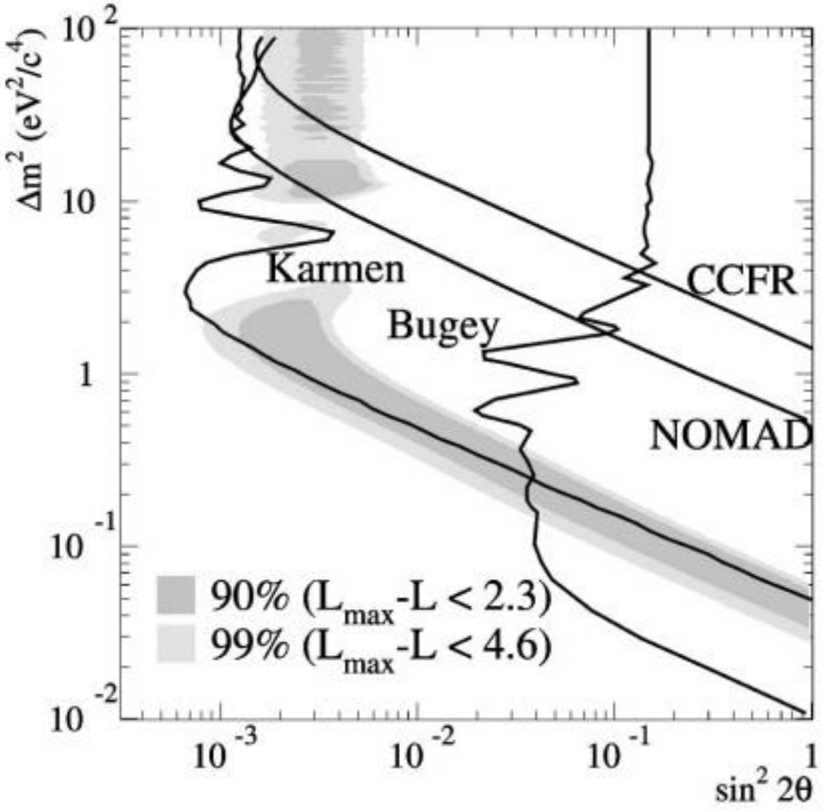
Liquid Scintillator Neutrino Detector searching for ν_e / $\overline{\nu}_e$

1993-1998

L=35 m
E=30 MeV





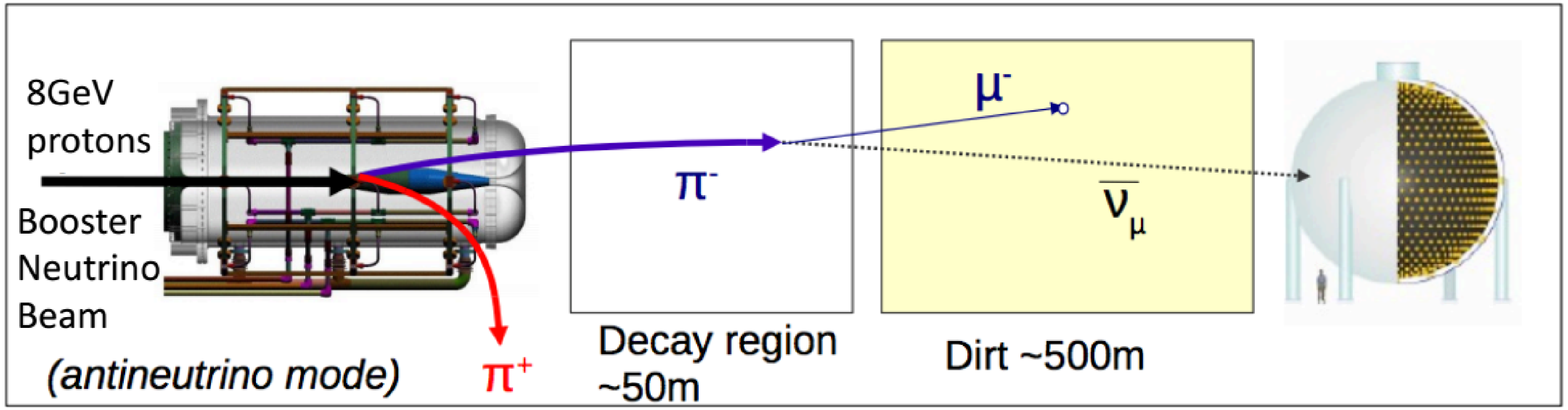


$\overline{\nu}_e p \rightarrow e^+ n$ **cross section well known**

$$P^{SBL,3+1}_{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e} = 4|U_{\mu 4} U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

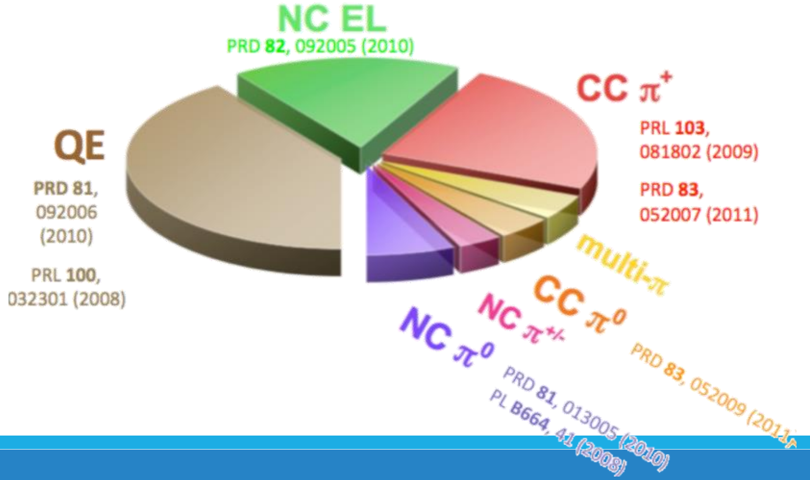
$\nu_\mu \to \nu_e$ APPEARANCE: MiniBoone

MiniBoone: L=541 m E=0.5 GeV from Booster Neutrino Beam at Fermilab



Detector:

12 m diameter sphere filled with 818 tons of pure mineral oil (CH2) and 1520 8-inch PMTs) directed Cherenkov light and isotropic scintillation light



15 years of data acquisition

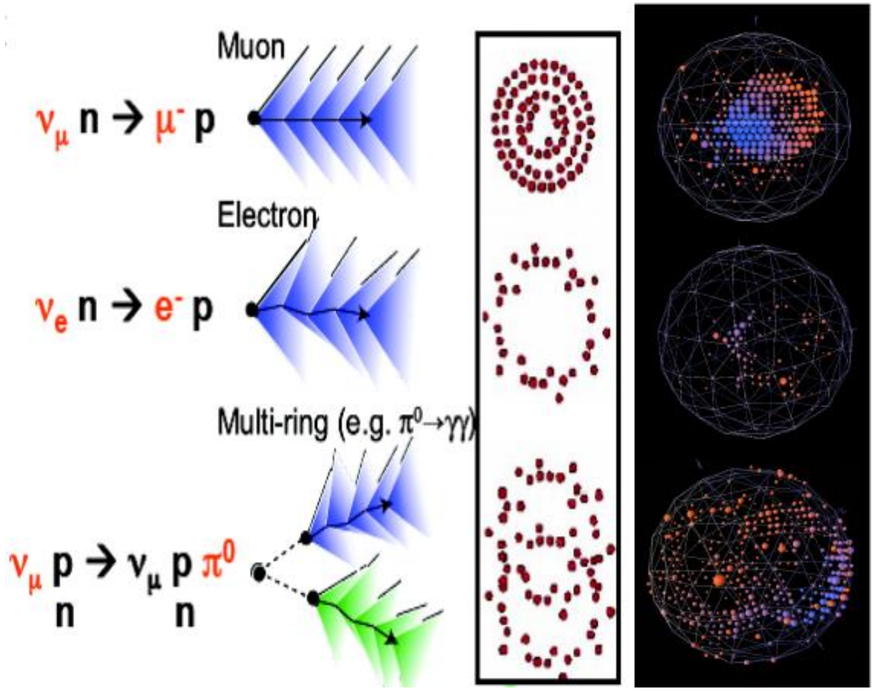
Beam stability at 2%   CCQE events

Energy range **200 MeV< Ev < 1250 MeV**

$\nu_\mu \rightarrow \nu_e$ APPEARANCE: MiniBoone

Particle identification

thanks to the Cherenkov light

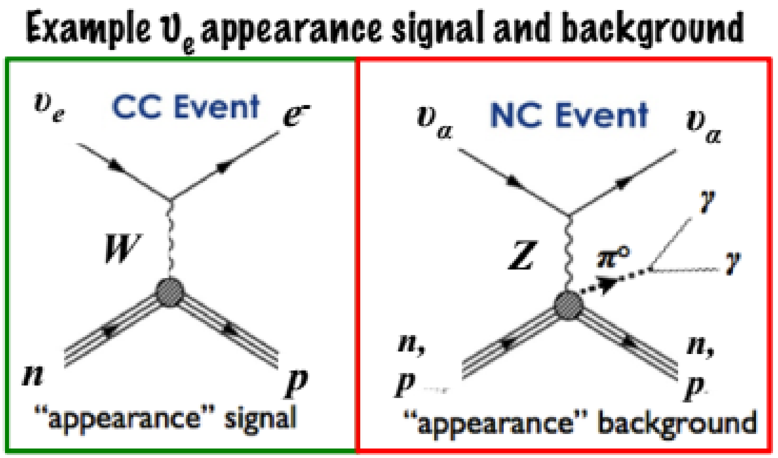


No identification between electron and photon

Background from:

- ν_e from K+
- ν_e from muon decay in 50 m
- External event background
- NC π^0 reconstructed as ν_e
- NC -> $\Delta\ \gamma$
- Wrong sign neutrino

- Charged-current events typically signal events
- Can use out-going lepton to tag neutrino flavor

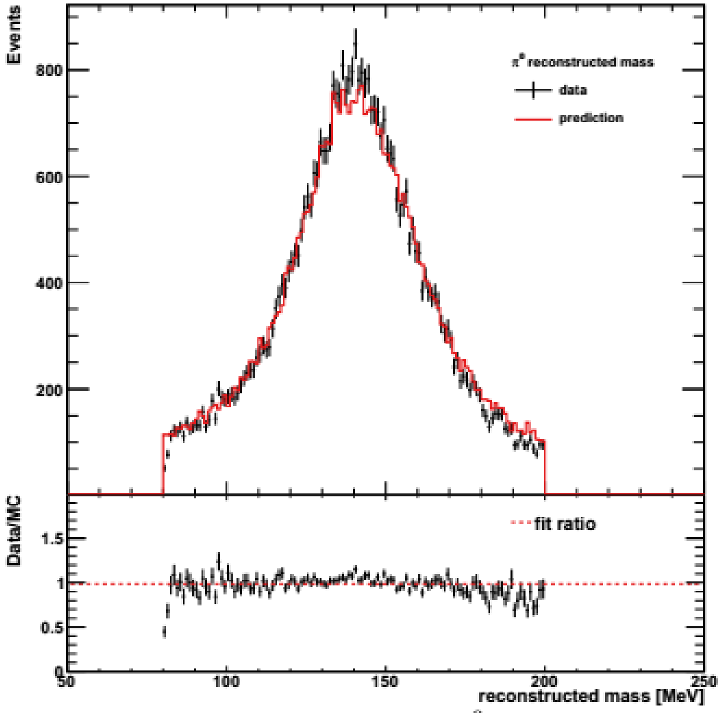


- Neutral-current events typically background events
- no way to tag the neutrino flavor

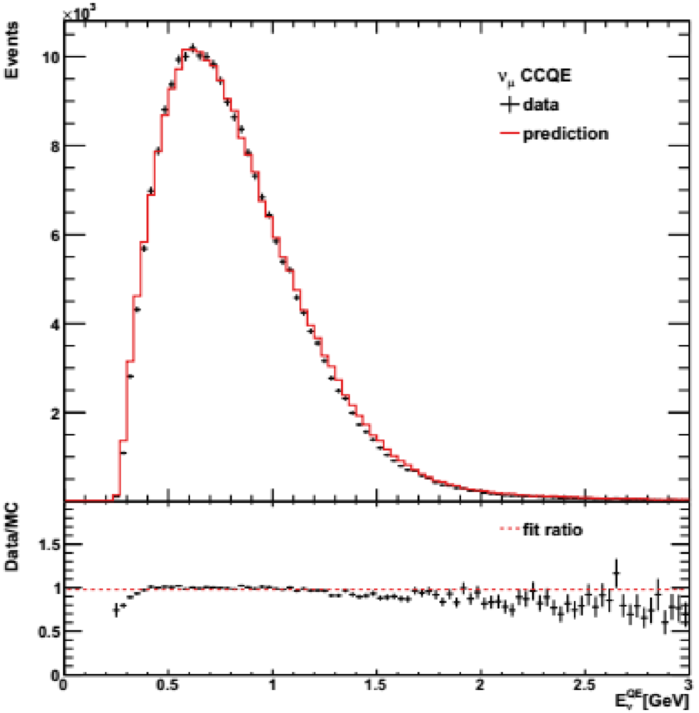
$\nu_\mu \rightarrow \nu_e$ APPEARANCE: MiniBoone

MC studies

$m_{\gamma\gamma}$ distribution

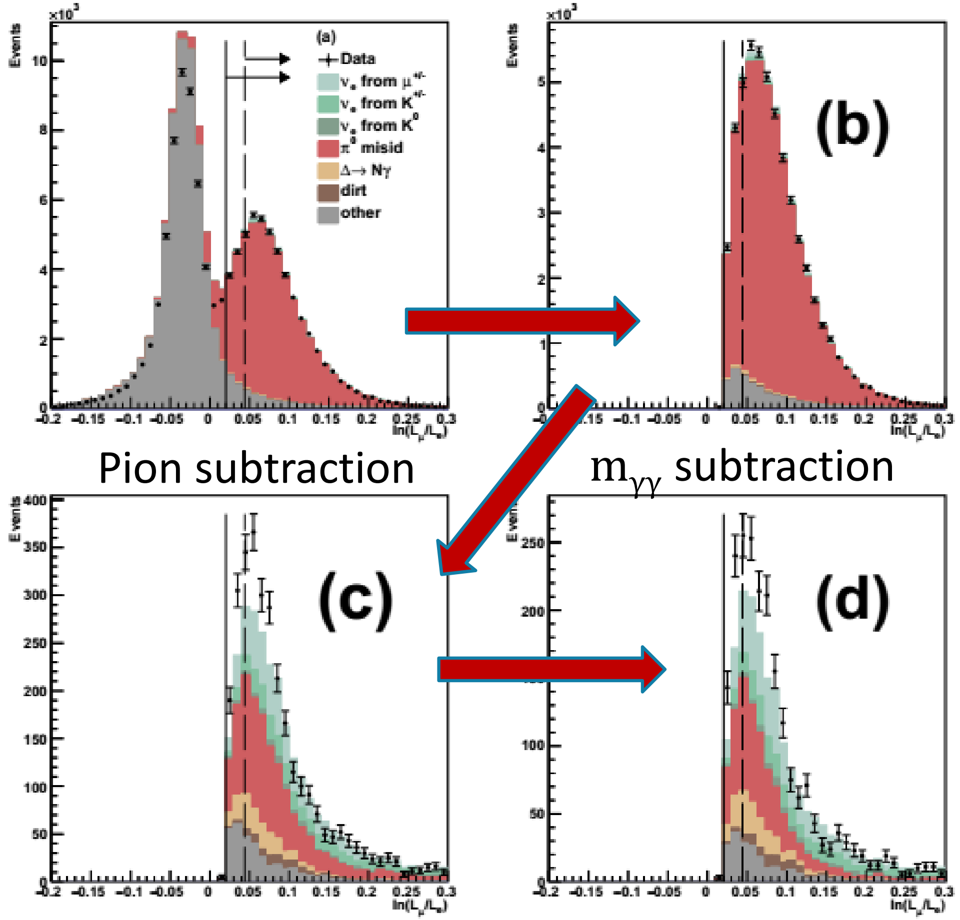


Energy distribution of ν_μ



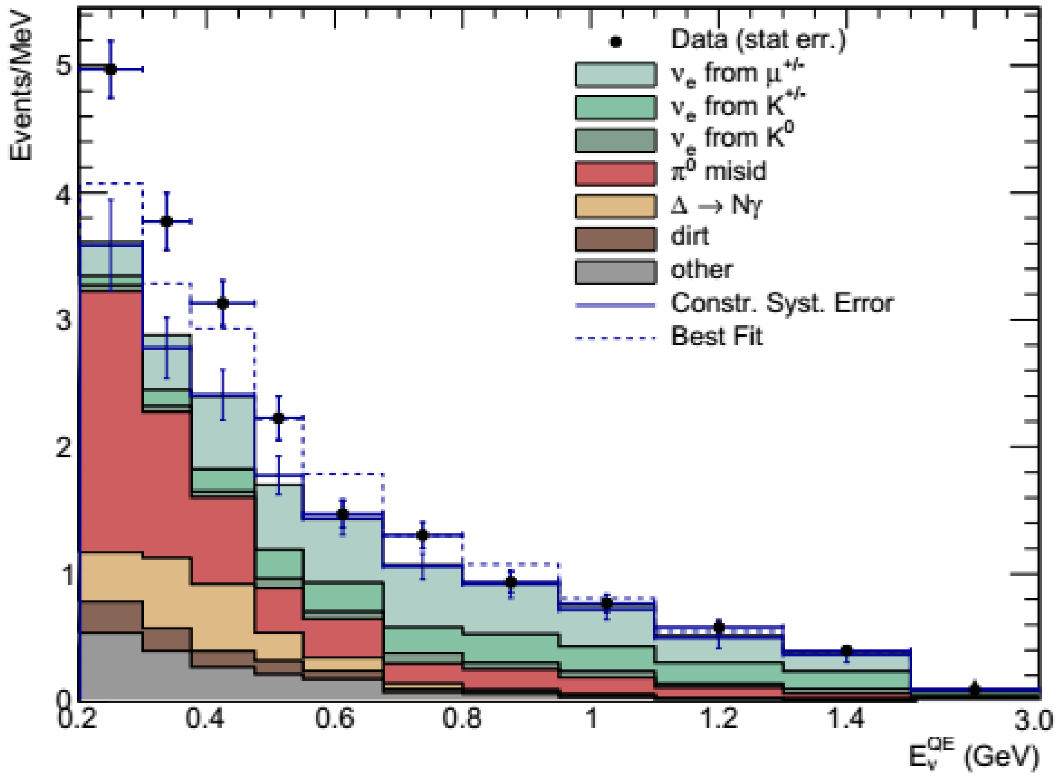
Data selection:

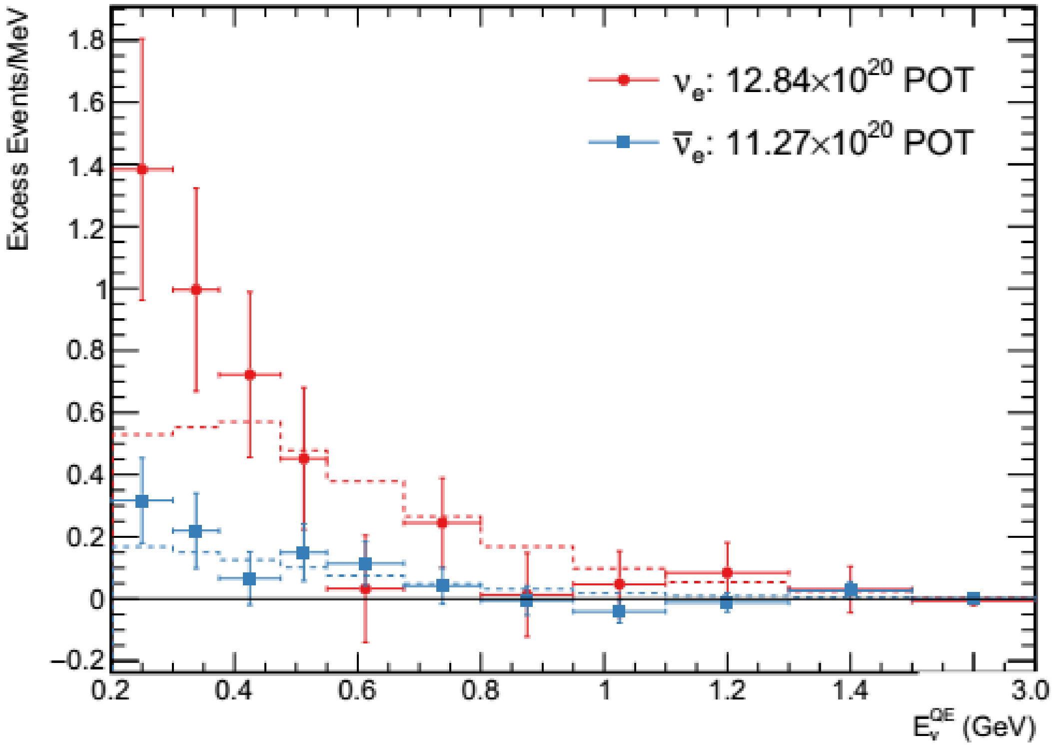
Muon subtraction



$\nu_\mu \rightarrow \nu_e$ APPEARANCE: MiniBoone

Latest results: **both in neutrino and antineutrino mode**





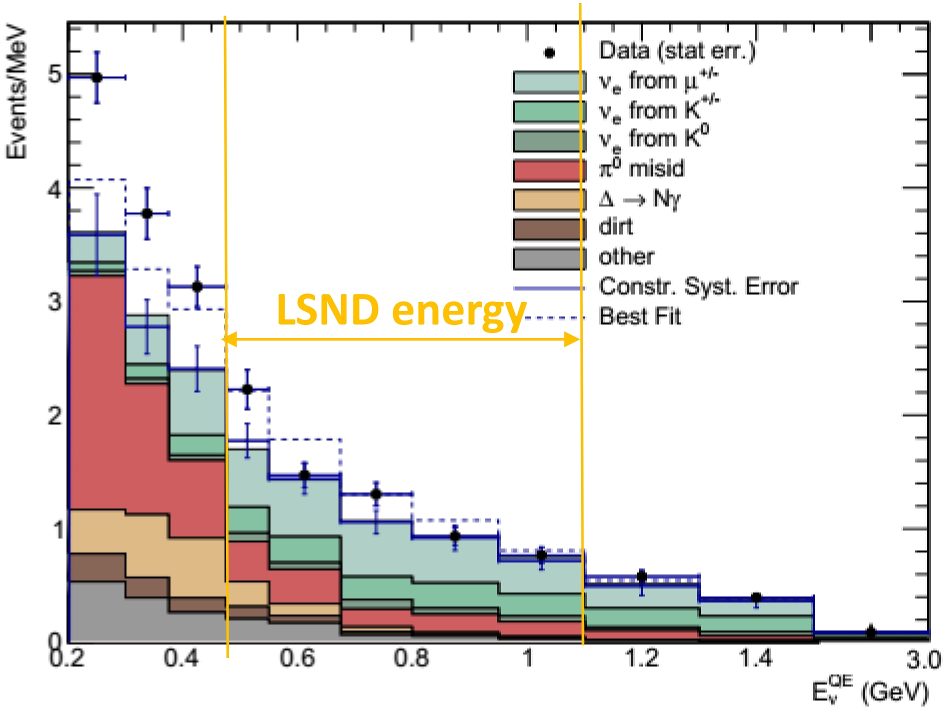
	POT	Excess	significance
Neutrino	12.84×10^{20}	381.2 ± 85.2	4.8
Antineutrino	11.27×10^{20}	79.3 ± 28.6	4.5
Combined			6.1

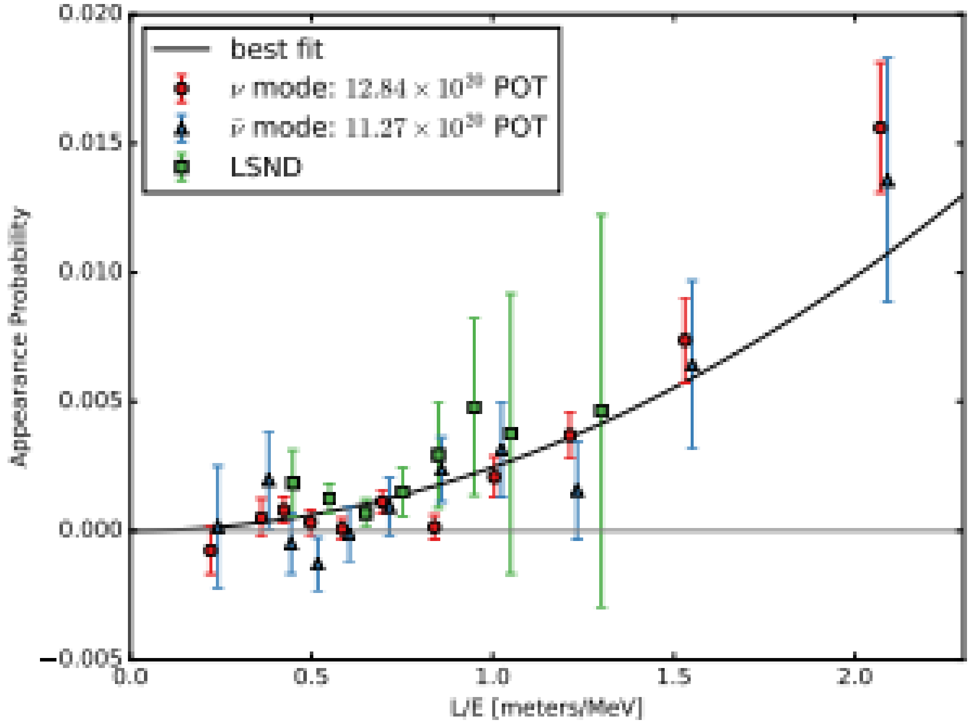
excess of ν_e / ν_e is observed!

$\nu_\mu \rightarrow \nu_e$ APPEARANCE: LNSD and MiniBoone

Comparison with LNSD

the two experiments have different neutrino energies, neutrino fluxes, reconstruction algorithm, backgrounds and systematic uncertainties.

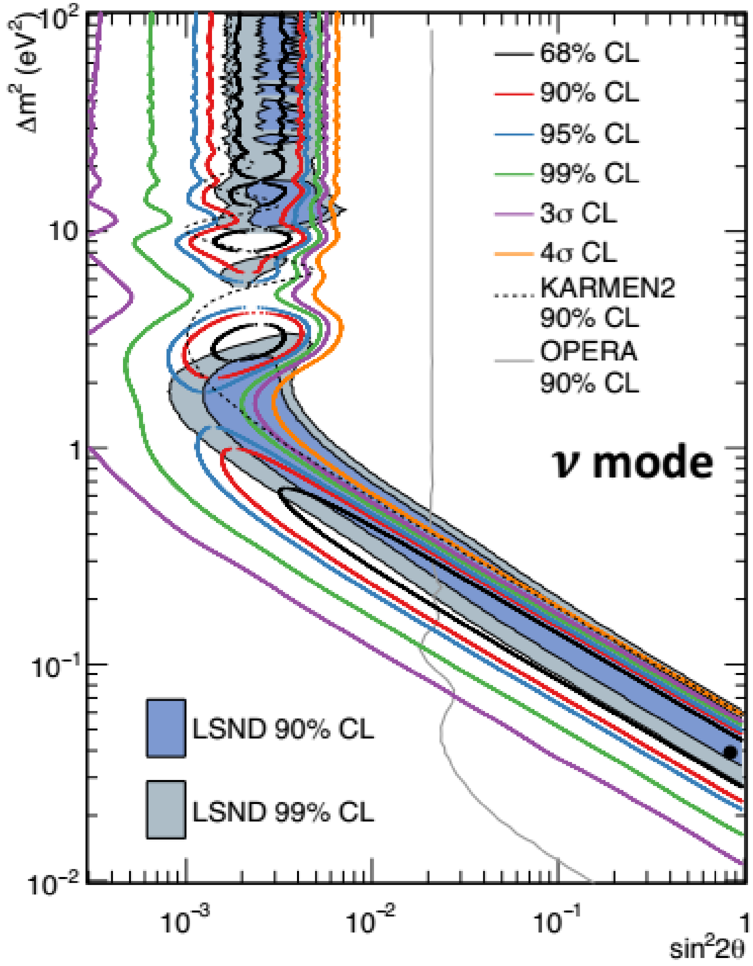




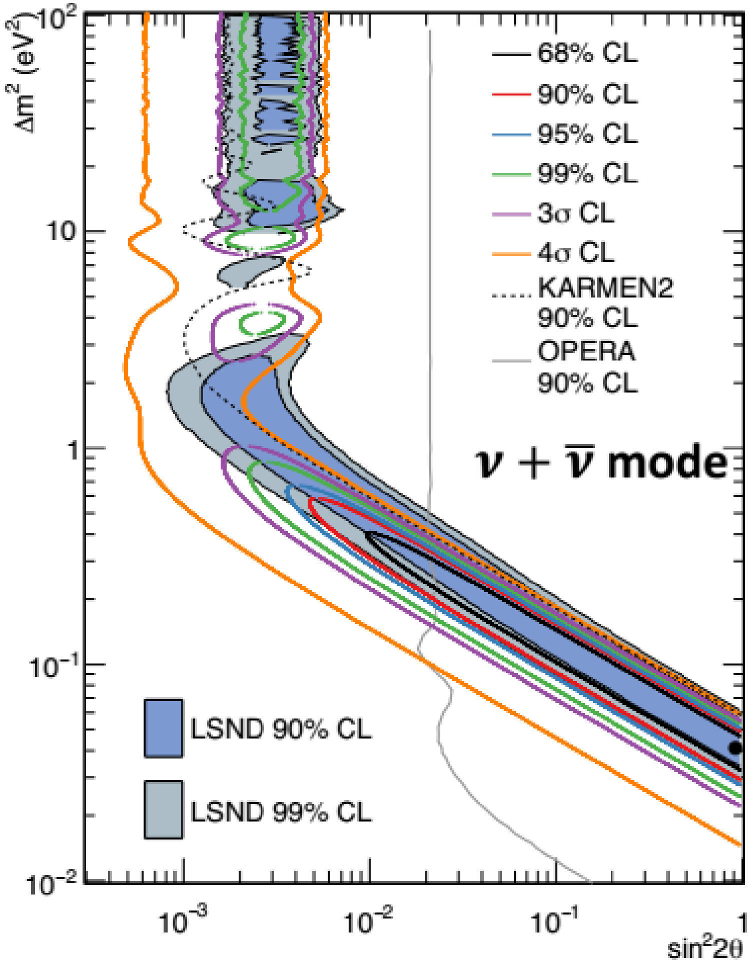
The significance of the combined LSND (3.8σ) and MiniBooNE (4.8 σ) excesses is 6.1 σ

$\nu_\mu \rightarrow \nu_e$ APPEARANCE: new global fit

Allowed regions



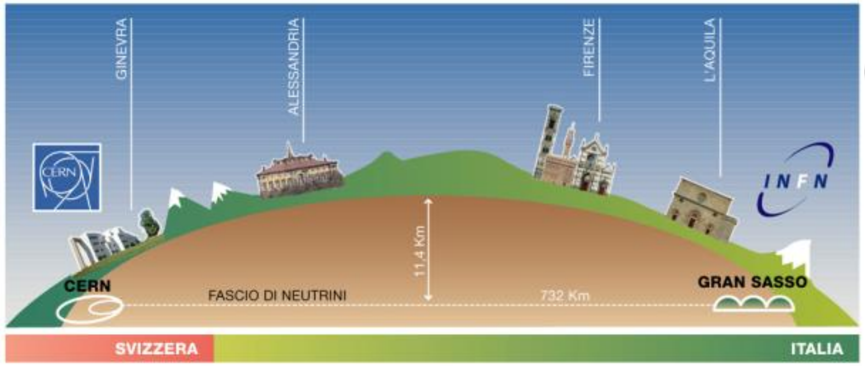
$$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$$
$$\chi^2/ndf = 10.0/6.6\ (\text{prob} = 15.4\%)$$



$$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$$
$$\chi^2/ndf = 19.5/15.4\ (\text{prob} = 20.1\%)$$

Best fit:
The big value for $\sin^2(2\theta)$ suggest that 3+1 is not the right scenario

$\nu_\mu \rightarrow \nu_e$ APPEARANCE: OPERA



OPERA experiment is based on nuclear emulsion detector

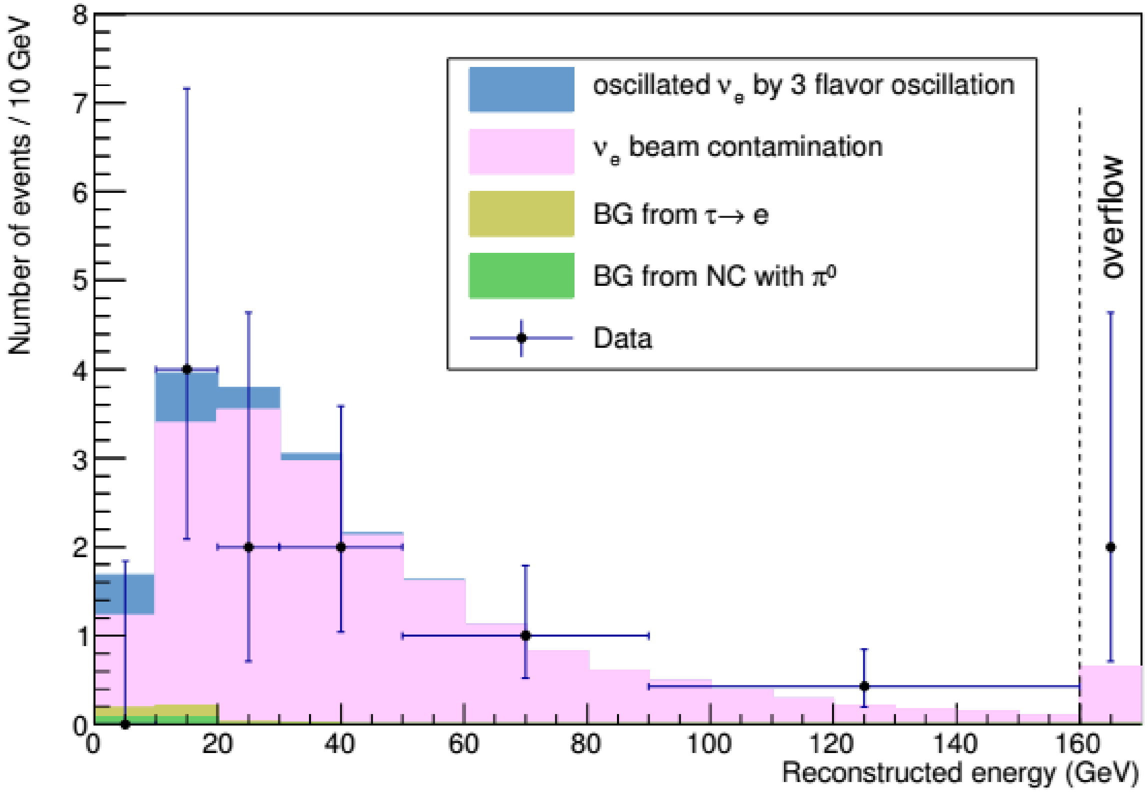
2012

Long baseline experiment
for $\nu_\mu \rightarrow \nu_\tau$

E= 20 GeV from CNGS beam
L= 730 km

Sensitivity for $\Delta m^2 > 0.01\ eV^2$

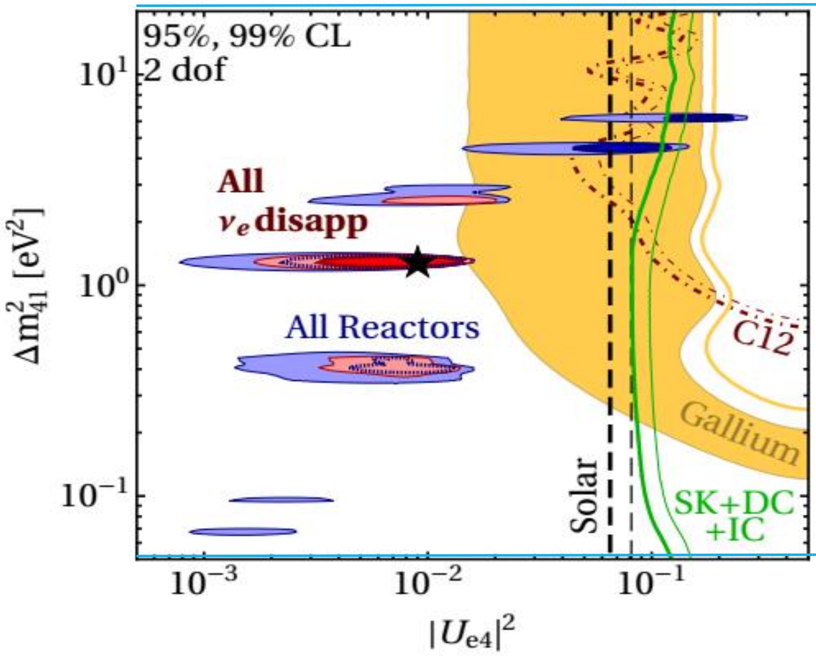
For sterile neutrino analysis:
ν_e from CC



The statistic is low but no excess was observed

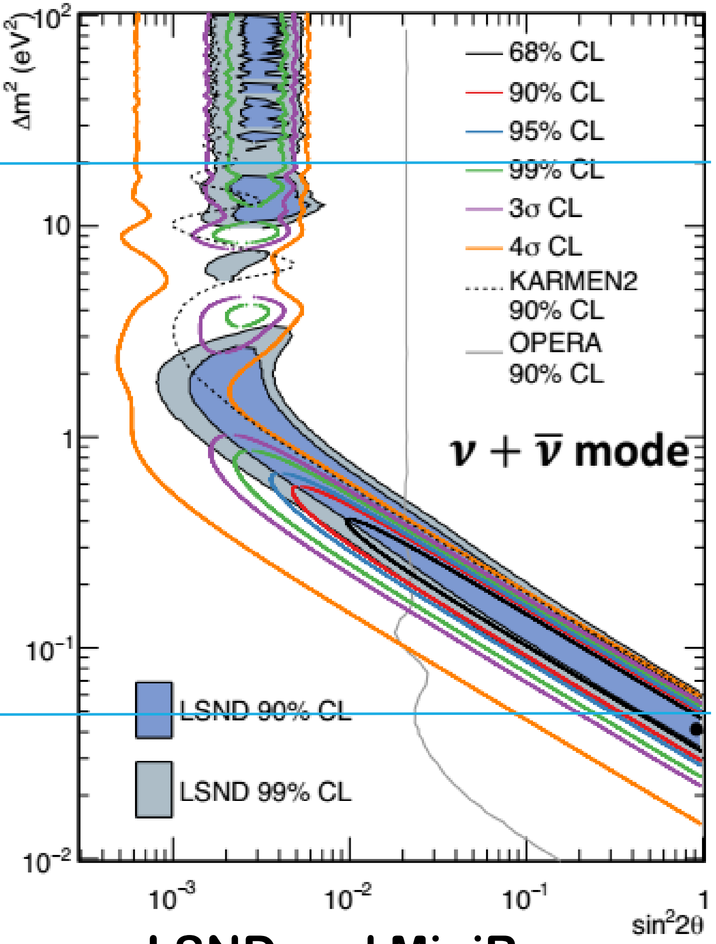
COMBINIG ALL TOGETHER

ν_e DISAPPEARANCE



Gallium and SBL reactor

$\nu_\mu \rightarrow \nu_e$ APPEARANCE



LSND and MiniBoone

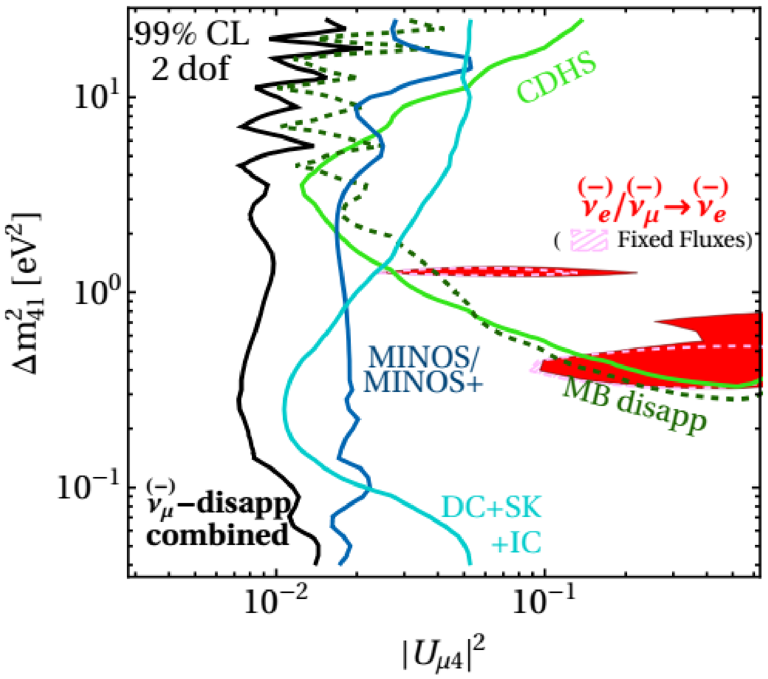
Both probe to the same range of Δm^2_{14}, but at different mixing angle

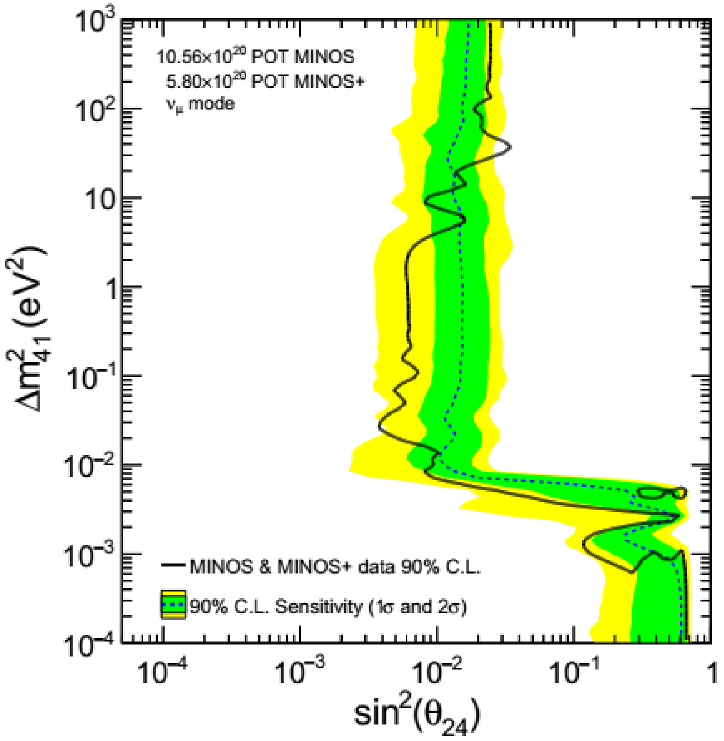
COMBINIG ALL TOGETHER

ν_μ DISAPPEARANCE

$$P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2 \text{ with } \begin{cases} |U_{e4}|^2 \propto P_{\nu_e\to\nu_e} \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu} \end{cases}$$

$$, P_{\nu_\mu\to\nu_e} > 0 \text{ requires } \begin{cases} P_{\nu_e\to\nu_e} > 0 , \\ P_{\nu_\mu\to\nu_\mu} > 0 ; \end{cases}$$





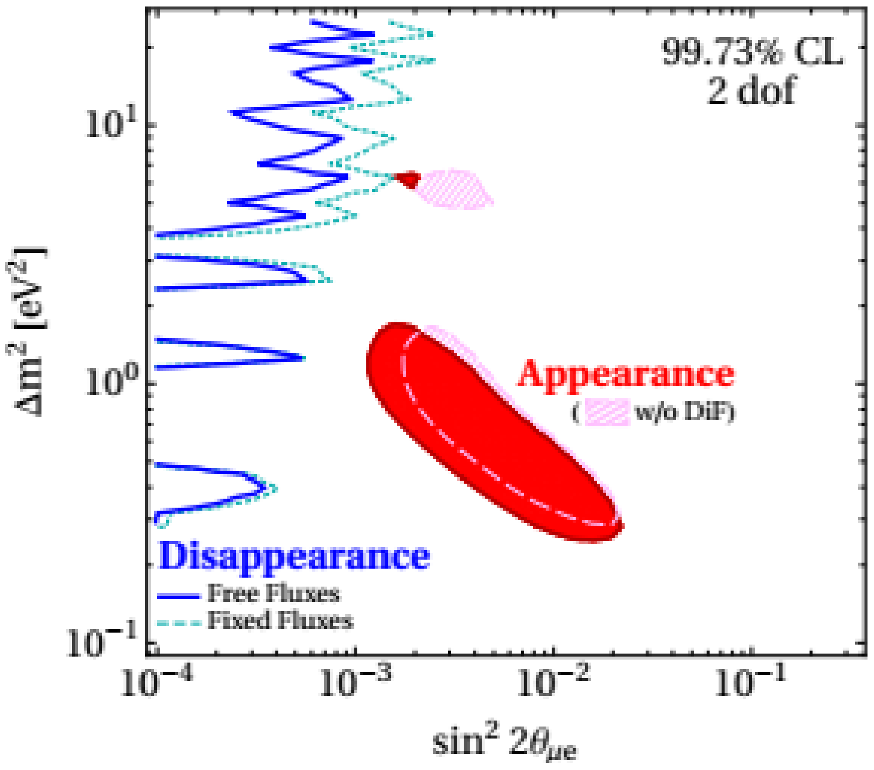
The sterile neutrino cannot explain all channels together!?

no anomaly is found in any disappearance data set

THE GLOBAL ANALYSIS

Combining all together…

Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	$\chi^2_{\rm min}$/dof	GOF	$\chi^2_{\rm PG}$	PG
appearance (DaR)	0.573	$4\lvert U_{e4}\rvert^2\lvert U_{\mu4}\rvert^2 = 6.97\times10^{-3}$		89.8/67	3.3%		
appearance (DiF)	0.559	$4\lvert U_{e4}\rvert^2\lvert U_{\mu4}\rvert^2 = 6.31\times10^{-3}$		79.1/–			
$\overset{(-)}{\nu}_\mu$ disapp	2×10^{-3}	0.12	0.039	468.9/497	81%		
Reactor fluxes fixed at predicted value ± quoted uncertainties							
$\overset{(-)}{\nu}_e$ disapp	1.3	0.1	–	552.8/588	85%		
Global (DiF)	6.03	0.2	0.1	1127/–		25.7	2.6×10^{-6}
Global (DaR)	5.99	0.21	0.12	1141/1159	64%	28.9	5.3×10^{-7}
Reactor fluxes floating freely							
$\overset{(-)}{\nu}_e$ disapp	1.3	0.095	–	542.9/586	90%		
Global (DiF)	6.1	0.20	0.10	1121/–		29.6	3.7×10^{-7}
Global (DaR)	6.0	0.22	0.11	1134/1157	68%	32.1	1.1×10^{-7}



There is a strong tension

The tension does not depend on:

DaR or DIF events for LNSD

Free or fixed flux for reactor experiments

sterile neutrino models **fail to simultaneously account** for **all** channels and data set!...This is robust!

THE GLOBAL ANALYSIS: conclusions

Is there any chance to reconcile?

- Each of these anomalies can be **individually** explained by sterile neutrinos

- sterile neutrinos still succeed in simultaneously explaining groups of anomalies

  sharing the same oscillation channel

- The sterile neutrino for the ν_e channel is not completely excluded

- The sterile neutrino as explanation for the appearance is excluded at 4.7 σ level

  or it is background or it is new physics!!

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

MORE STERILE NEUTRINOS?

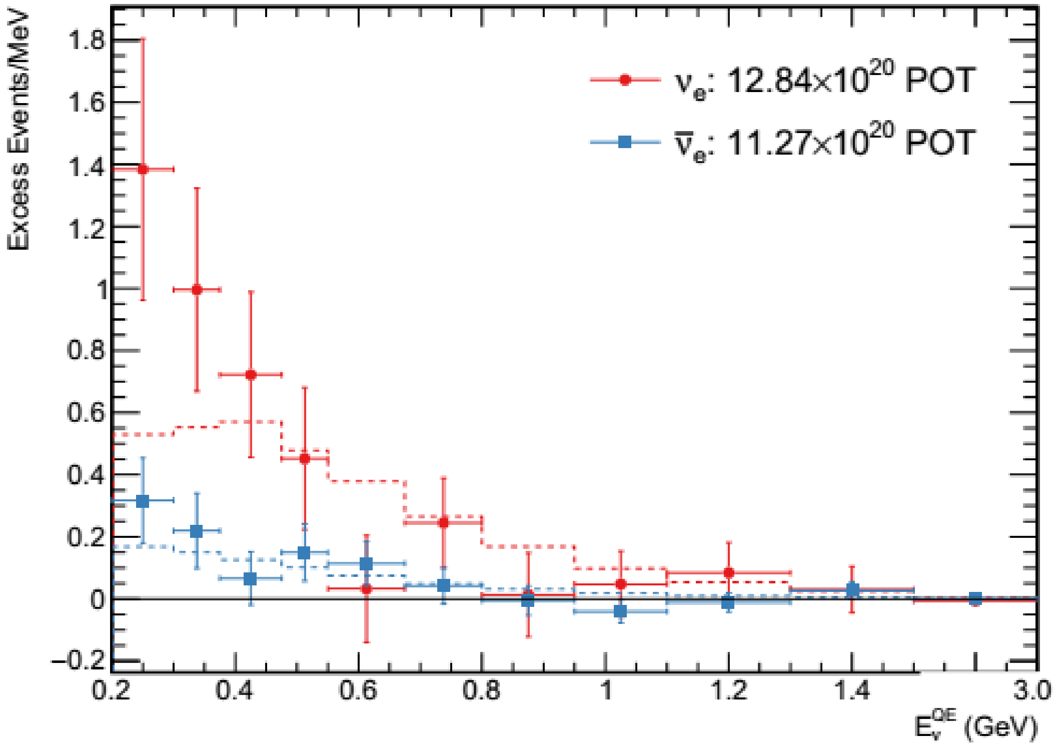
➢ **With 1 sterile neutrino**

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41}$$

for large energy $P_{\mu e}^{4\nu}$ drops as $1/E^2$

The MiniBoone excess is sharper! ($1/E^2$)

➢ **with 2 sterile neutrino** a better description of the MiniBoone low energy data can be achieved



BUT the same APP/DIS tension is not solved!!

quadratic suppression of the $\nu_\mu \rightarrow \nu_e$ oscillation amplitudes by constraints on the elements *Uei* and *Uμi* (*i* ≥ 4) from disappearance data remains equally true in scenarios with more than one eV-scale mass states.

3+ N do no present substantial advantages over the 3+1 model

DO NOT FORGET THE COSMOLOGY

Limits:

on number of neutrino species

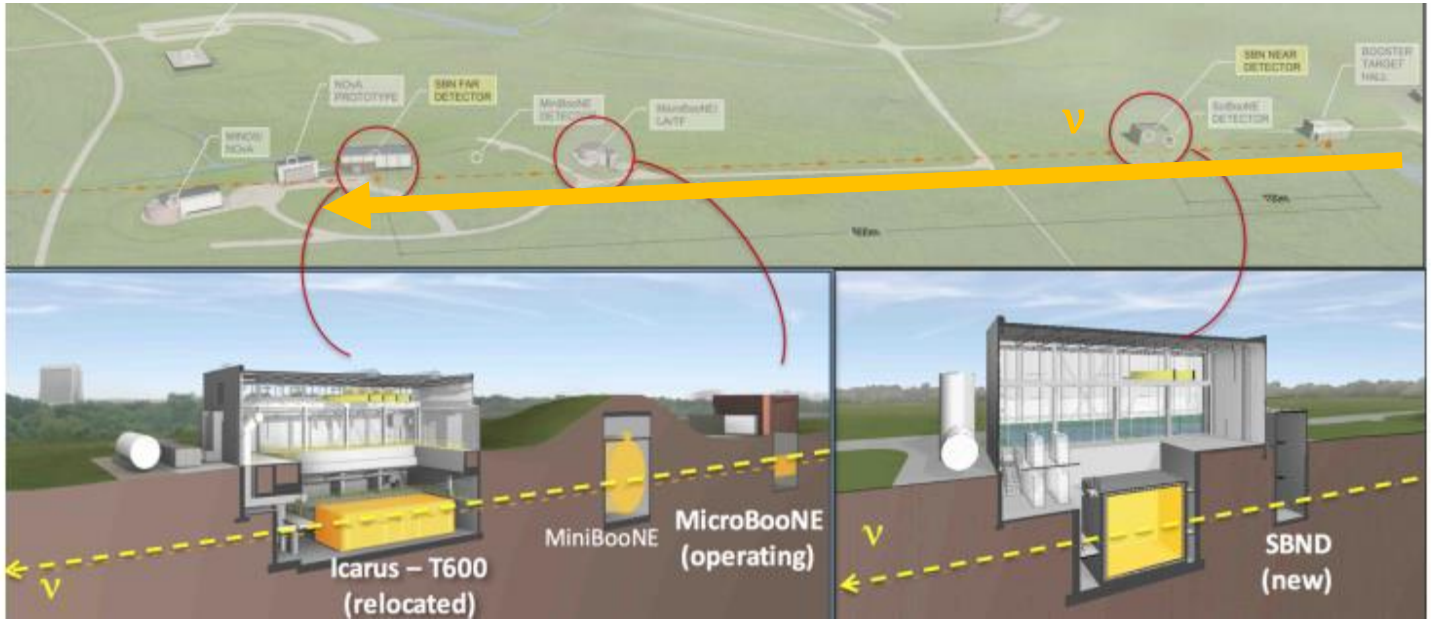
- If thermalized in the early Universe they contribute *N*eff (the number of relativistic degrees of freedom)
- There might be some hints for additional species coming mainly from CMB data.
  Depending on which additional cosmological data are used, *N*eff values ranging from
  $3.30^{+0.54}_{-0.51}$ to $3.62^{+0.50}_{-0.48}$ (95% CL)
- Constraints from Big Bang Nucleosynthesis on *N*eff.

on neutrino mass

- The sterile neutrino might give a large contribution to the **sum of neutrino masses**,
  which is constrained to be **below around 0.5 eV**.
- From **galaxy clustering** and structure formation and from Cosmic Microwave Background disfavor >0.3 eV!

- However how far one would need to deviate from the ΛCDM model in order to accommodate the sterile neutrino at eV scale remains under discussion

THE SHORT BASE LINE PROGRAM AT Fermilab

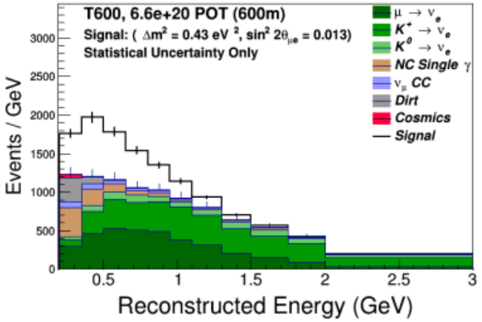


Short Baseline Near detector (SBND)

SBND is a **112 ton** active volume liquid argon time projection chamber(LArTPC).

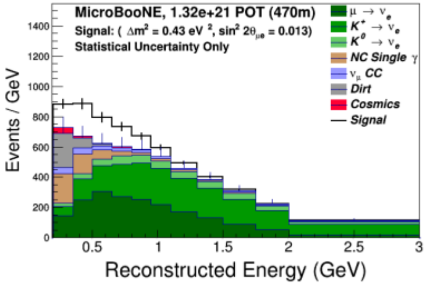
The detector is currently in the design phase and shortly it will be ready to run.

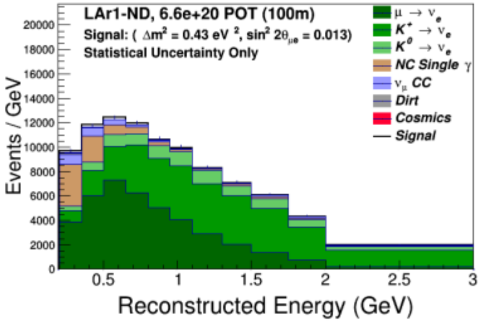
Short Baseline Far detector Icarus
760 ton LAr



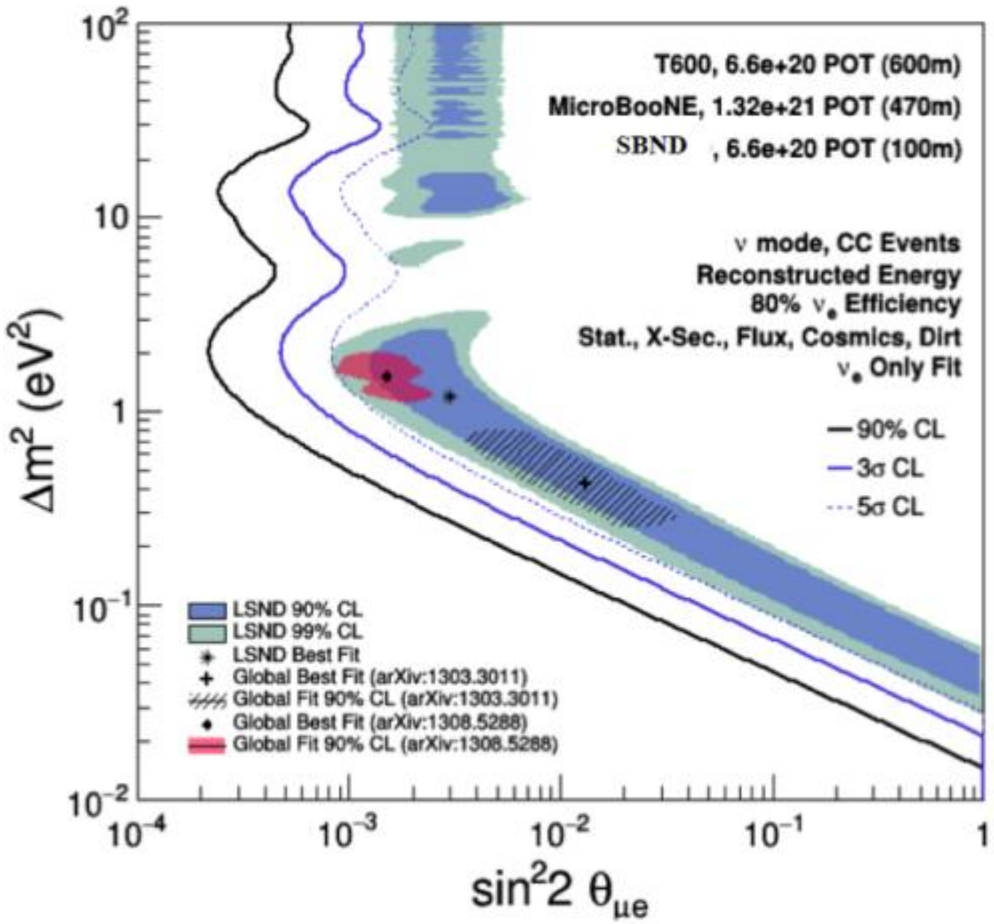
Intermediate detector
MicroBoone 170 ton LAr

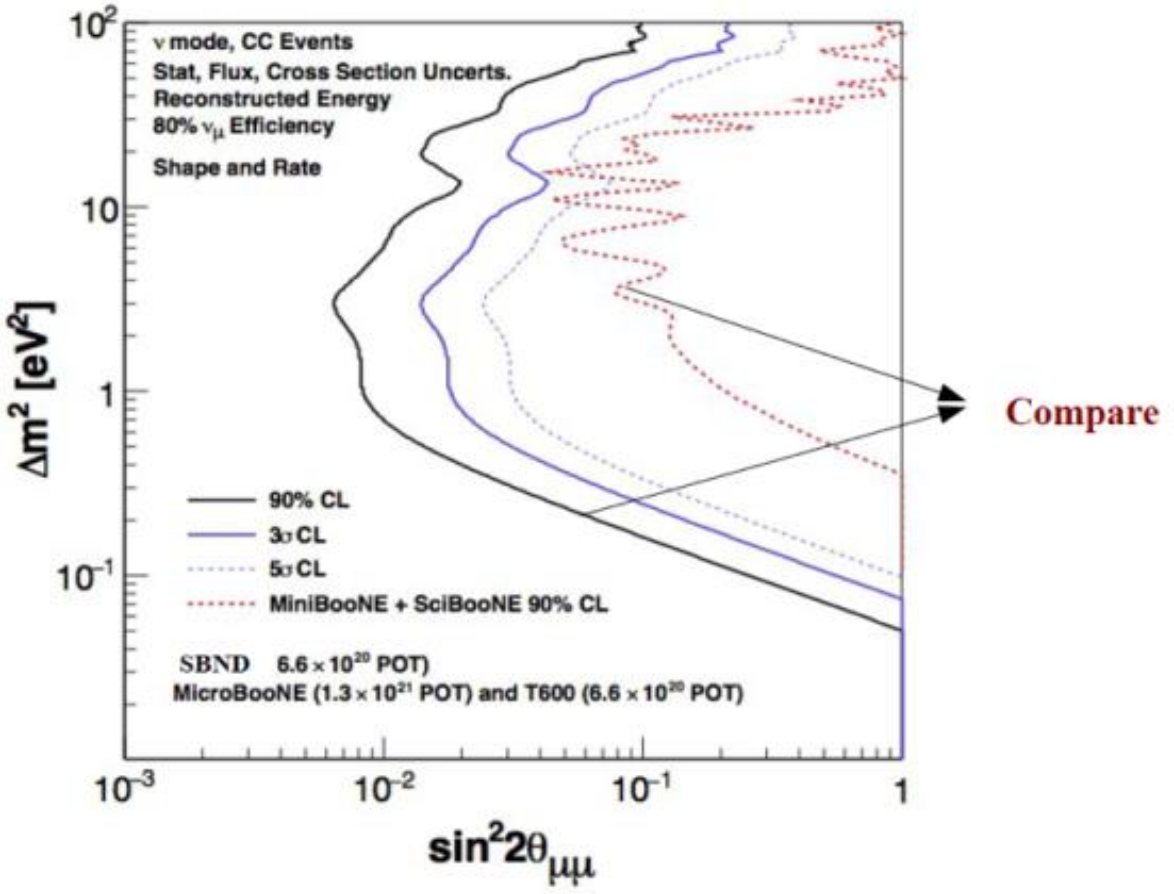
investigate the **low energy excess events**, measure a suite of low energy neutrino cross section.





THE SHORT BASE LINE PROGRAM AT Fermilab



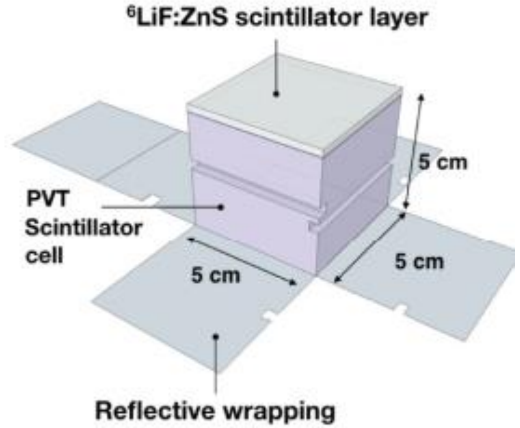


For clarifying both the **appearance** and the **disappearance** channels!

OTHER EXPERIMENTS

New detectors

SOLID and CHANDLER experiments



new segmented detector:
optically isolated cubes readout by fibers

for more **energy resolution** and **better background rejection**

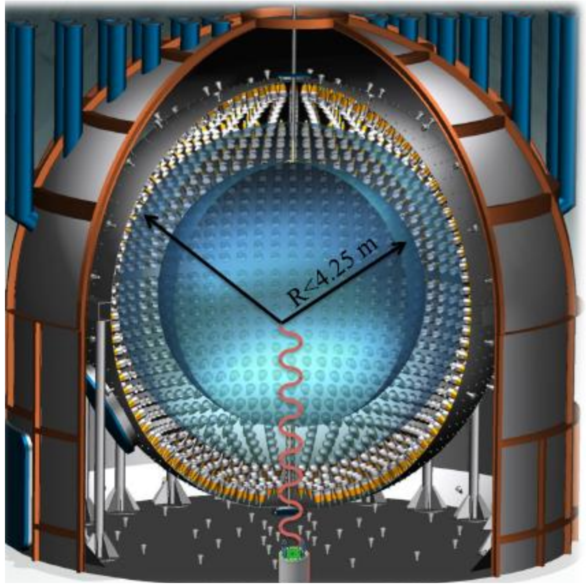
and reactor (BR2) with a **compact core** (~50 cm)

New sources

IsoDAR
Cyclotron proton beam to continuously produce ^{8}Li which decay beta producing $\bar{\nu}_e$

nuSTORM
for producing a well characterized beam of
ν_μ and $\bar{\nu}_e$ (or $\bar{\nu}_\mu$ and ν_e)

It is very difficult to produce a kCi artificial source



Our SOX would have been important!

CONCLUSIONS

ν_e disappearance experimental data suggest $\Delta m^2_{41} \approx 1.3\ \mathrm{eV}^2$ and $|U_{e4}| \approx 0.1$ 3σ level

ν_μ disappearance experimental results are strong in tension with the $\nu_\mu \rightarrow \nu_e$ appearance results: here the sterile neutrino hypothesis can be discarded 4.5 σ level

If all these results are confirmed: new physics is necessary

BUT new experimental results are necessary and …

...THE STORY CONTINUES!

Thanks for the attention!