Accelerator-based Neutrino Physics

Lecture 2

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Outline

Lecture 2: the present

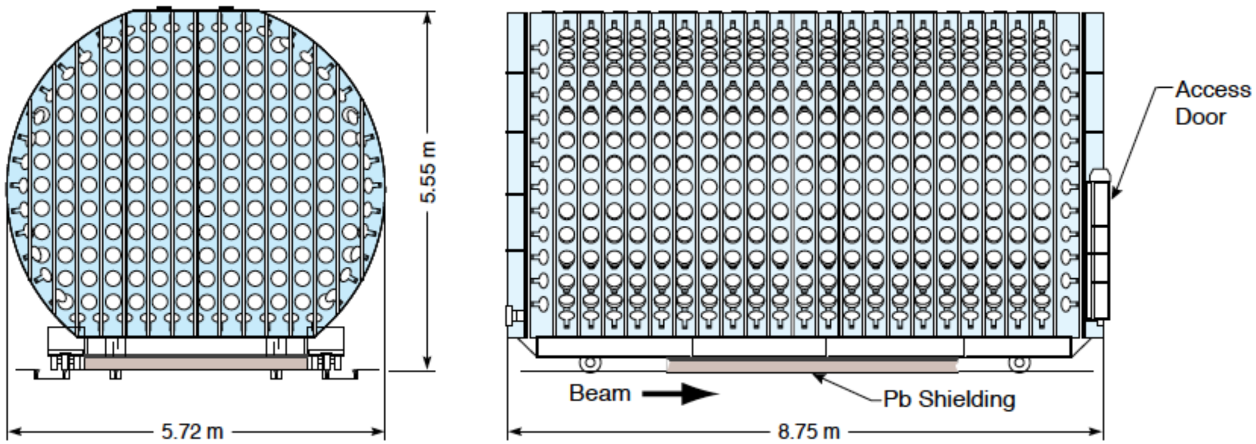
3. Accelerator-based neutrino oscillation experiments
   - 3.1 Short-baseline neutrino experiments: LSND, KARMEN, NOMAD, CHORUS, MiniBooNE
   - 3.2 Long-baseline neutrino experiments: K2K, MINOS, CNGS, T2K, NOvA

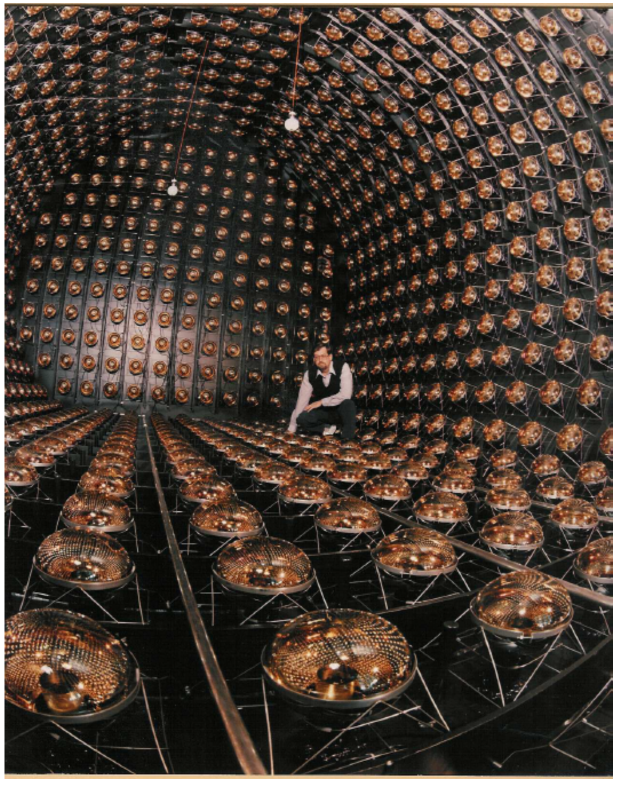
3.1 Short Baseline Oscillation Experiments

"Light Sterile Neutrinos: a White Paper", arXiv:1204.5379

LSND

- LSND: Los Alamos Scintillator Neutrino Detector
  - Operated at the LAMPF accelerator at Los Alamos: 1 mA proton current at 798 MeV from 1993-1998
  - Detector: 167 tons dilute liquid scintillator (with both a Cherenkov and scintillator signal) at 30 m from ν source
  - Around 1500 PE for 45 MeV e^- (280 PE in Cherenkov ring)





LSND

- Neutrinos from π^+ and μ^+ decay at rest (DAR):

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

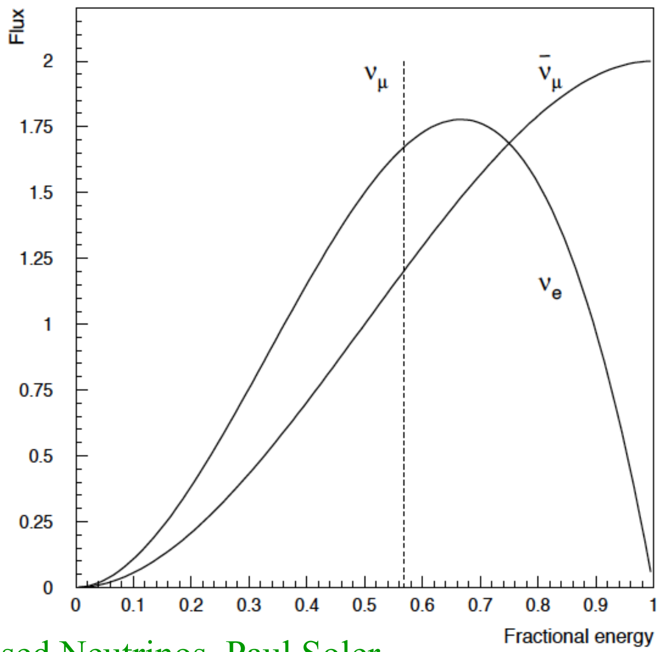
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

  – The π^- and μ^- are stopped in the Fe shield and Cu dump
  – The $\bar{\nu}_e$ flux is ~ 8×10^{-4} of ν_μ flux in $20<E_\nu<52.8$ MeV

- Oscillation signal:

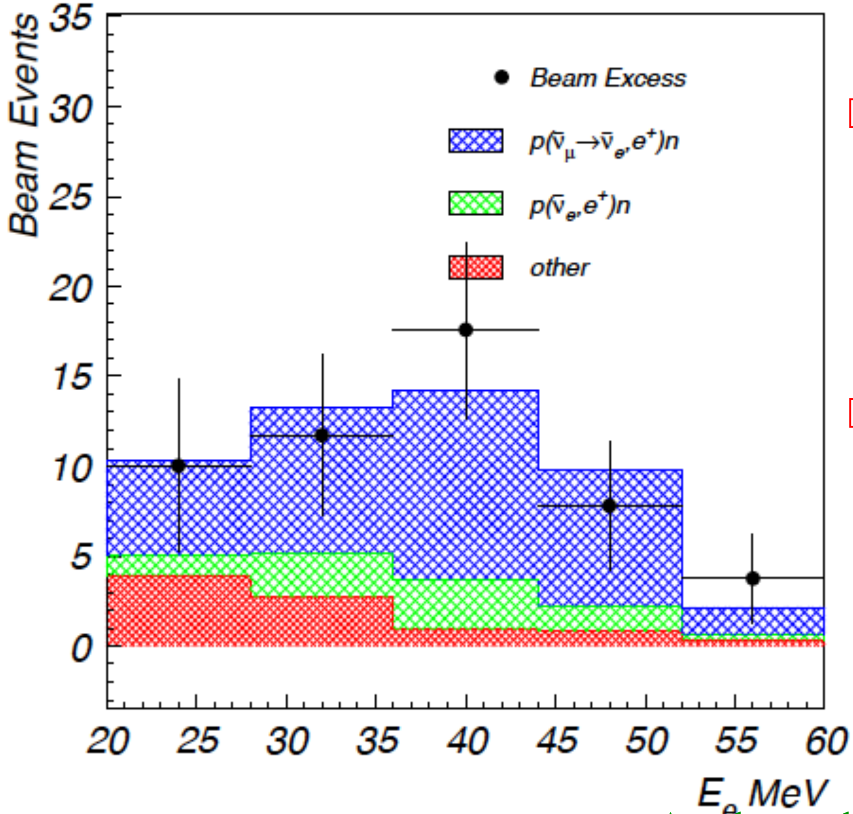
$$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

$$\bar{\nu}_e p \rightarrow e^+ n$$



LSND

- LSND results from DAR:
  - Beam on-off excess: 117.9 ± 22.4 events
  - Background: μ^- DAR and $\bar{\nu}_e p \to e^+ n$ 19.5 ± 3.9 events
  - Background: π^- DIF and $\bar{\nu}_\mu p \to \mu^+ n$ 10.5 ± 4.6 events



- Excess: 87.9 ± 22.4 ± 6.0 events

$$P(\nu_e \to \nu_\mu) = (0.264 \pm 0.067 \pm 0.045)\%$$

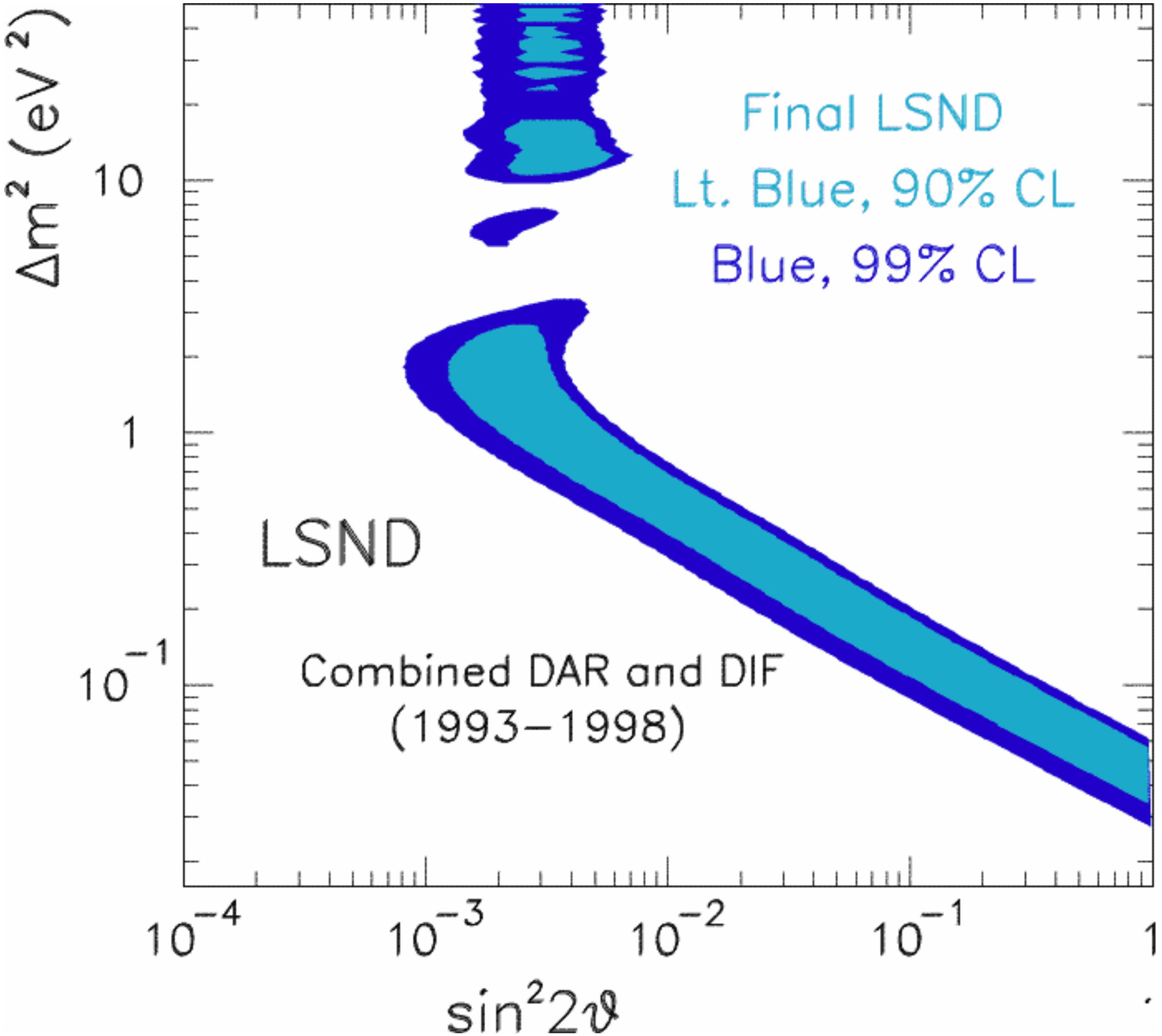
3.3σ evidence

- Oscillation parameters:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L_\nu}{E_\nu}\right)$$

LSND

- Final LSND results from DAR and DIF:



Includes also an analysis of decay in flight (DIF) pions that confirms oscillations

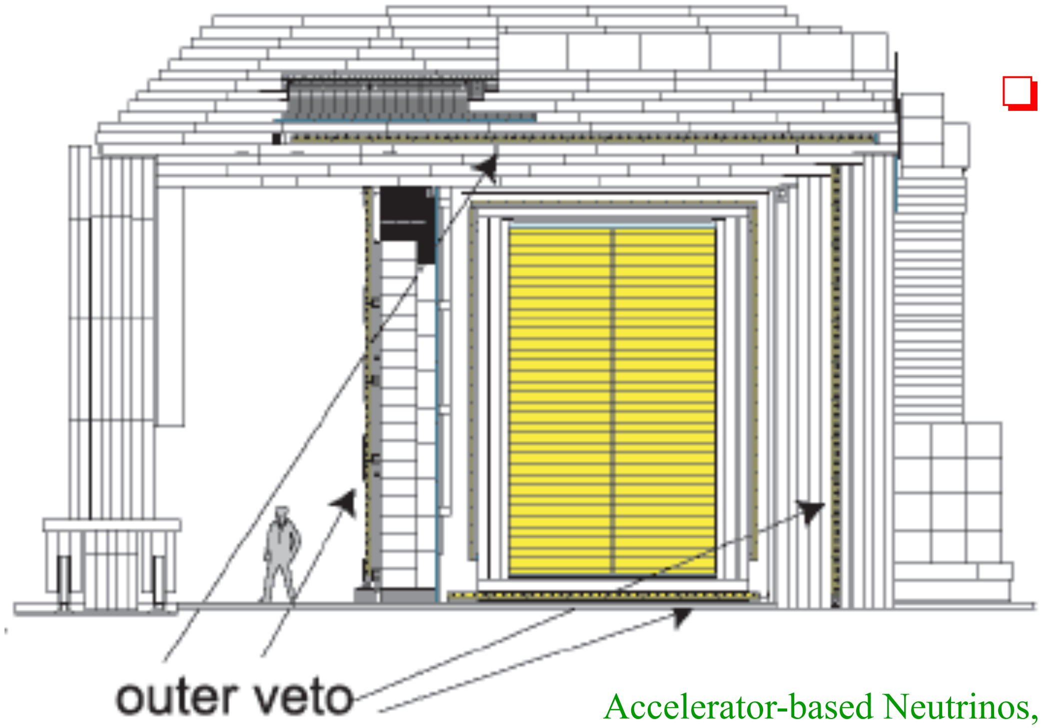
Interpretation: Neutrino oscillation to a fourth (sterile) neutrino, which oscillates back to another flavour

$$\bar{\nu}_\mu \rightarrow \nu_4 \rightarrow \bar{\nu}_e$$

$$\sin^2 2\theta = 4\left|U_{\mu 4} U_{e 4}\right|^2$$

KARMEN

- KARMEN: KArlsruhe-Rutherford Medium Energy Neutrino experiment
  - Operated at ISIS at RAL (UK) with 200 uA proton current at 800 MeV from 1993-1998
  - Detector: 56 tons liquid scintillator, 17.7 m from ν source



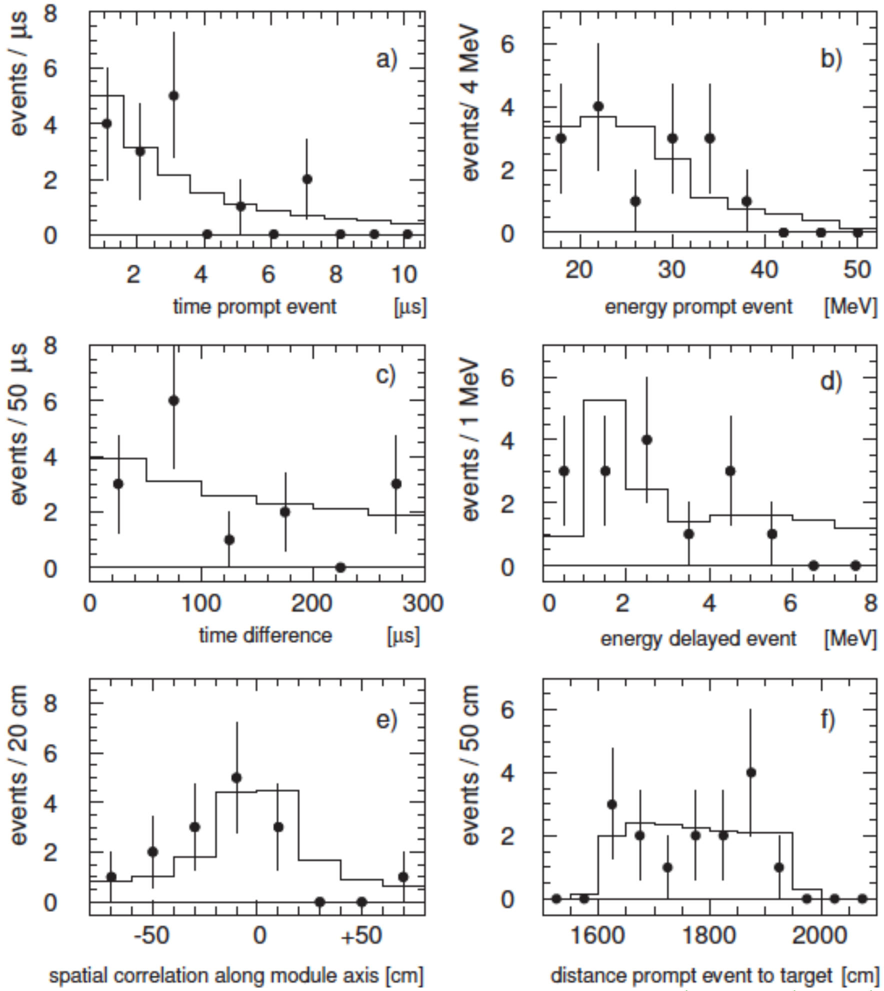
- Same oscillation signal:

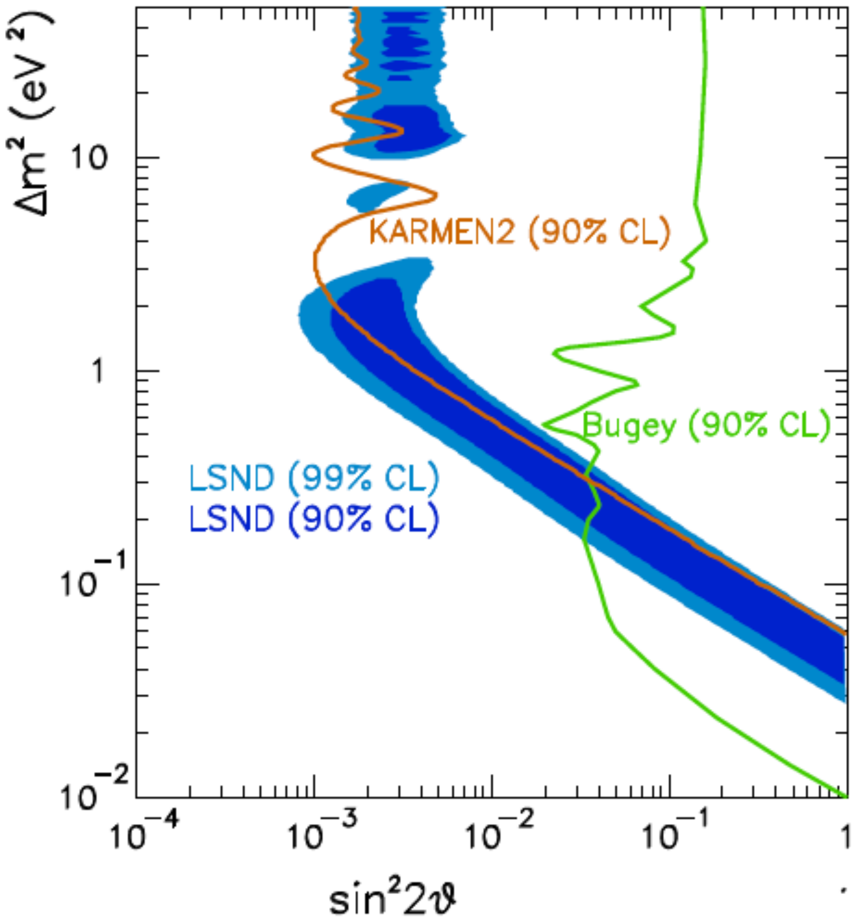
$$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

$$\bar{\nu}_e p \rightarrow e^+ n$$

KARMEN

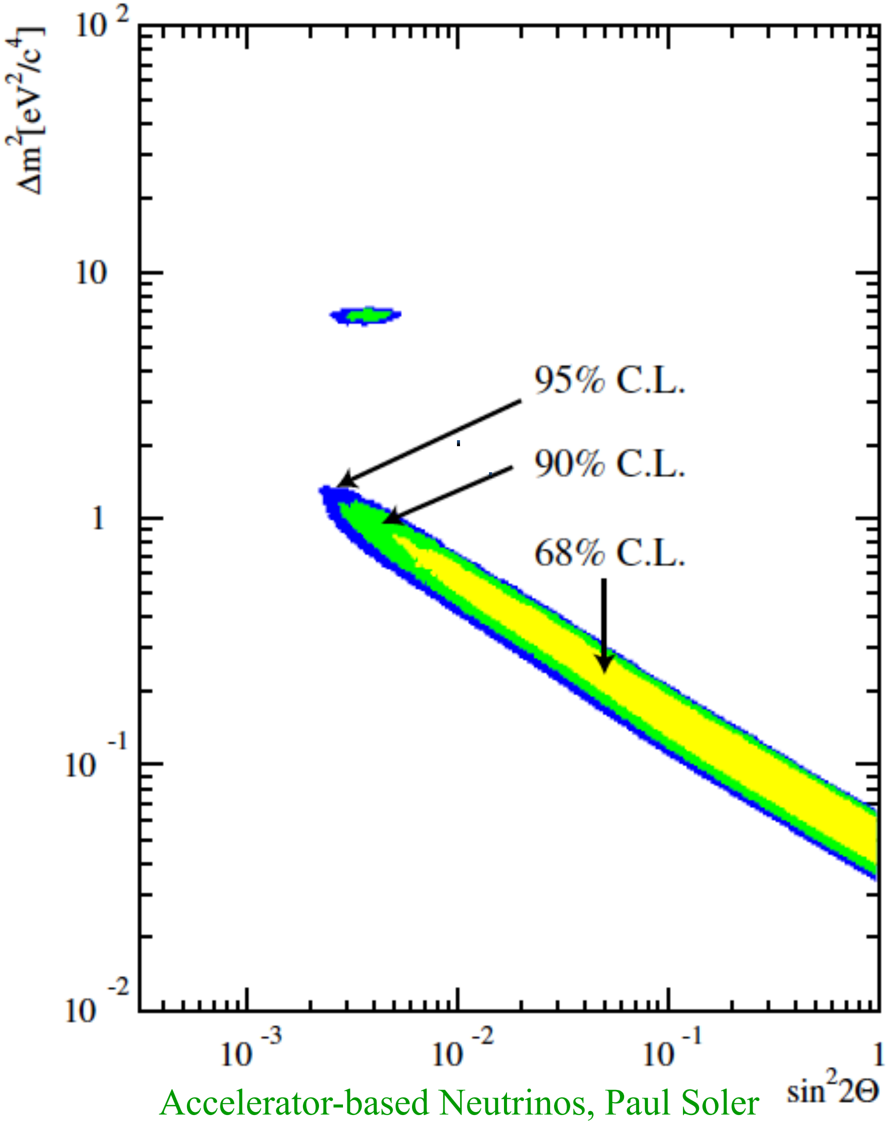
- KARMEN results: **Compatible with no oscillation**
  - Observed: 15 events; background: 15.8 ± 0.5 events





Combined LSND + KARMEN

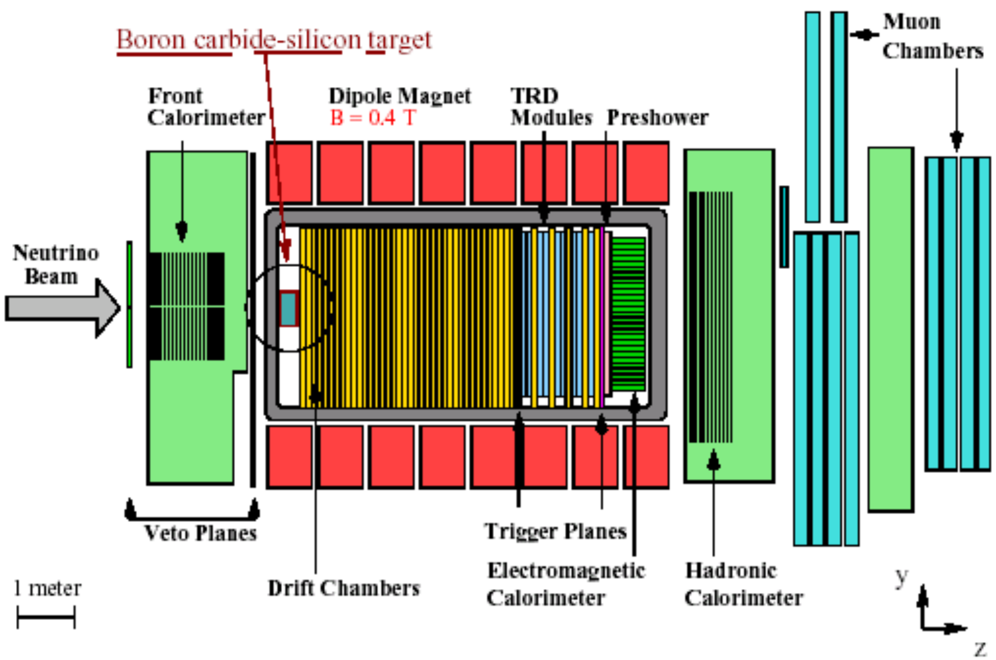
- Combined analysis LSND + KARMEN



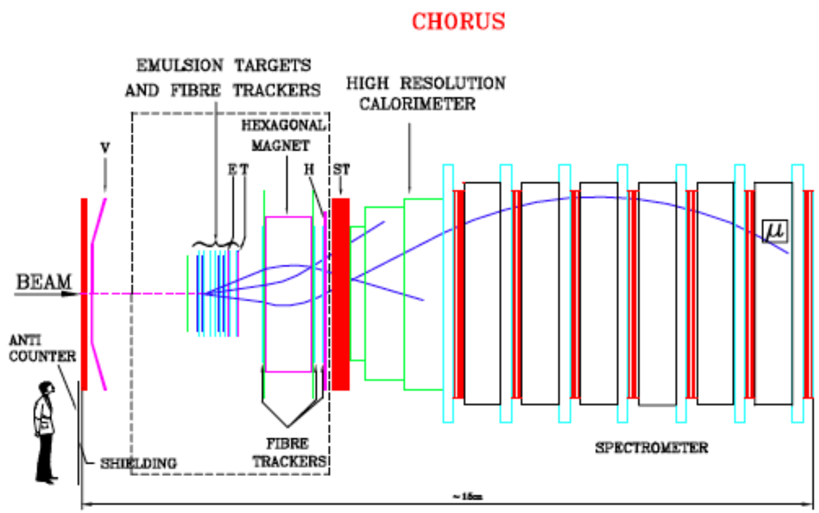
NOMAD and CHORUS

- NOMAD and CHORUS: search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in a short baseline experiment (1 km) at CERN WANF
  - NOMAD: through kinematic properties of taus
  - CHORUS: searching for tau kinks in emulsions

NOMAD



CHORUS



NOMAD and CHORUS

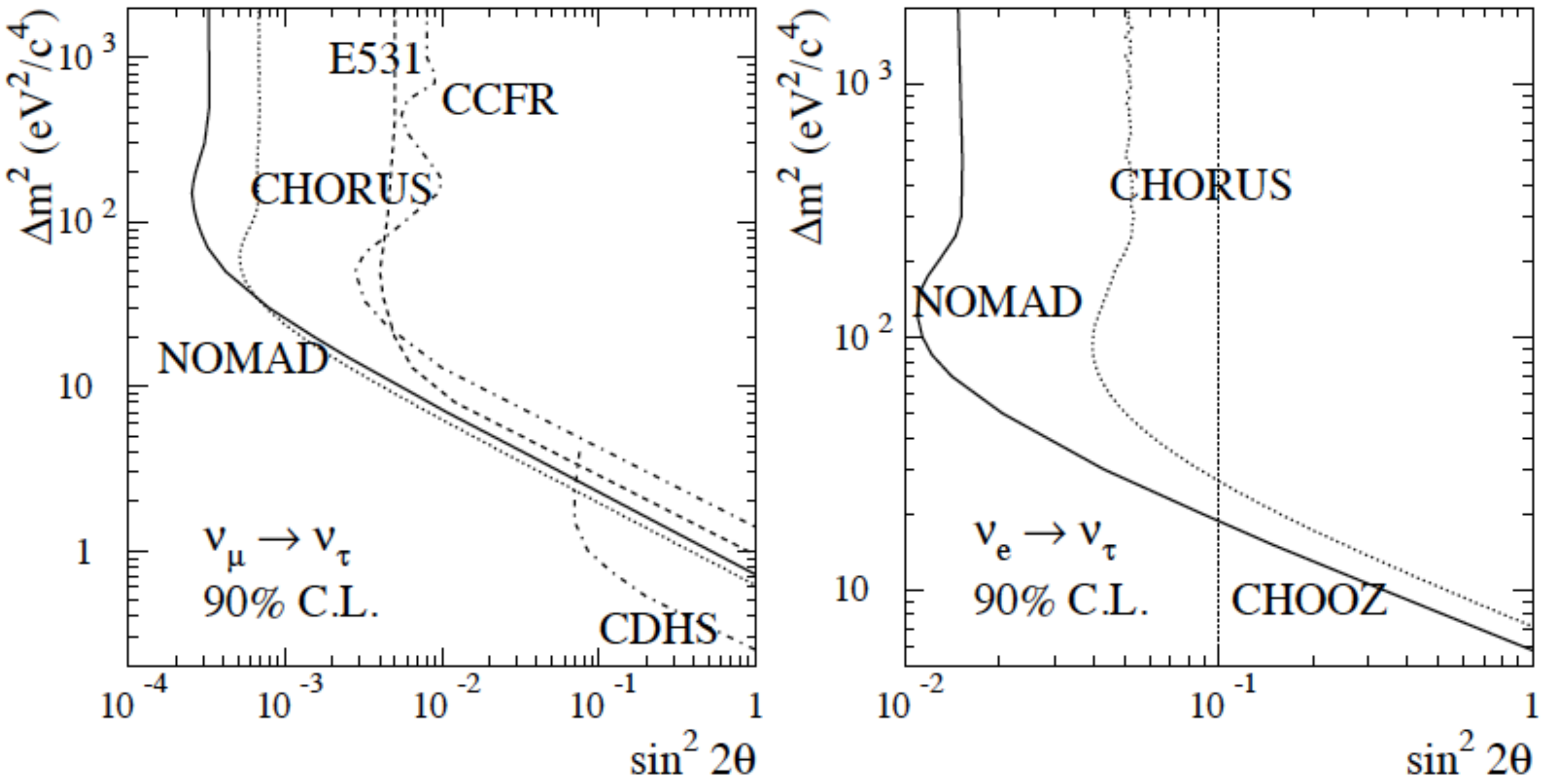
- NOMAD and CHORUS set most stringent limits on short baseline $\nu_\mu \leftrightarrow \nu_\tau$ oscillations $\Delta m^2 > 0.7\ eV^2$

$P(\nu_\mu \leftrightarrow \nu_\tau) < 1.63 \times 10^{-4}\ (90\%\ CL)$

$\sin^2 2\theta < 3.3 \times 10^{-4}\ (90\%\ CL)$

$P(\nu_e \leftrightarrow \nu_\tau) < 0.74 \times 10^{-2}\ (90\%\ CL)$

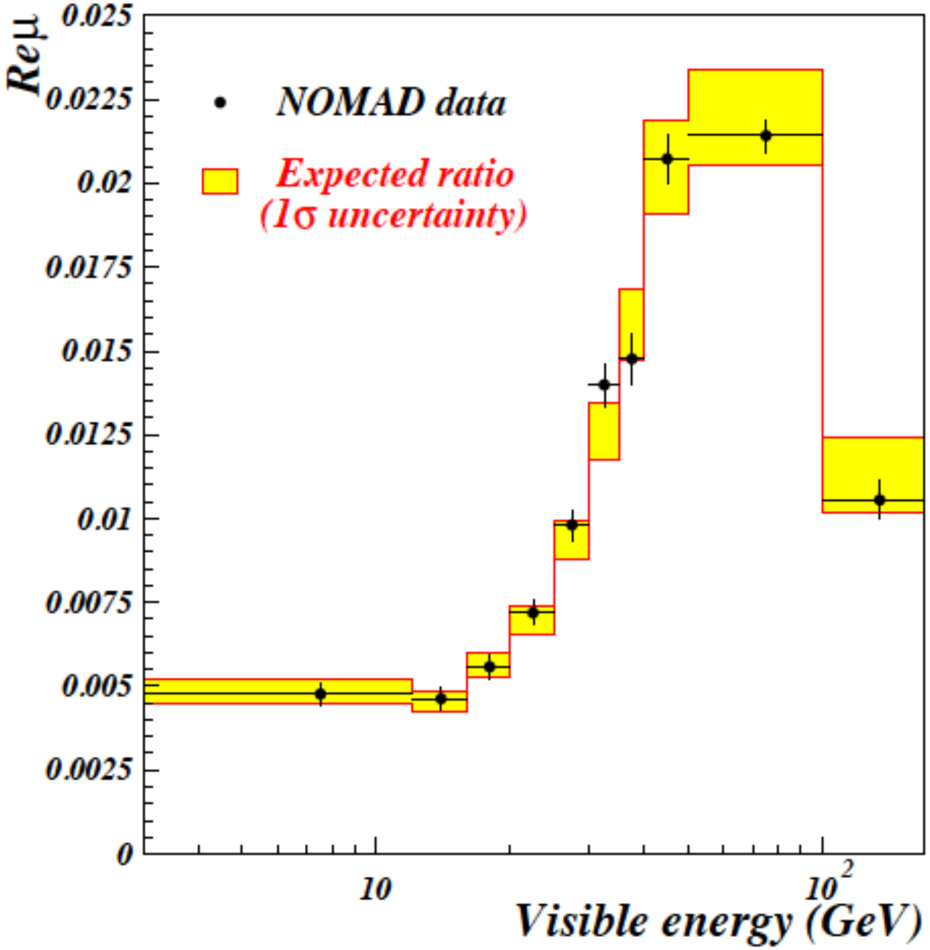
$\sin^2 2\theta < 1.5 \times 10^{-2}\ (90\%\ CL)$

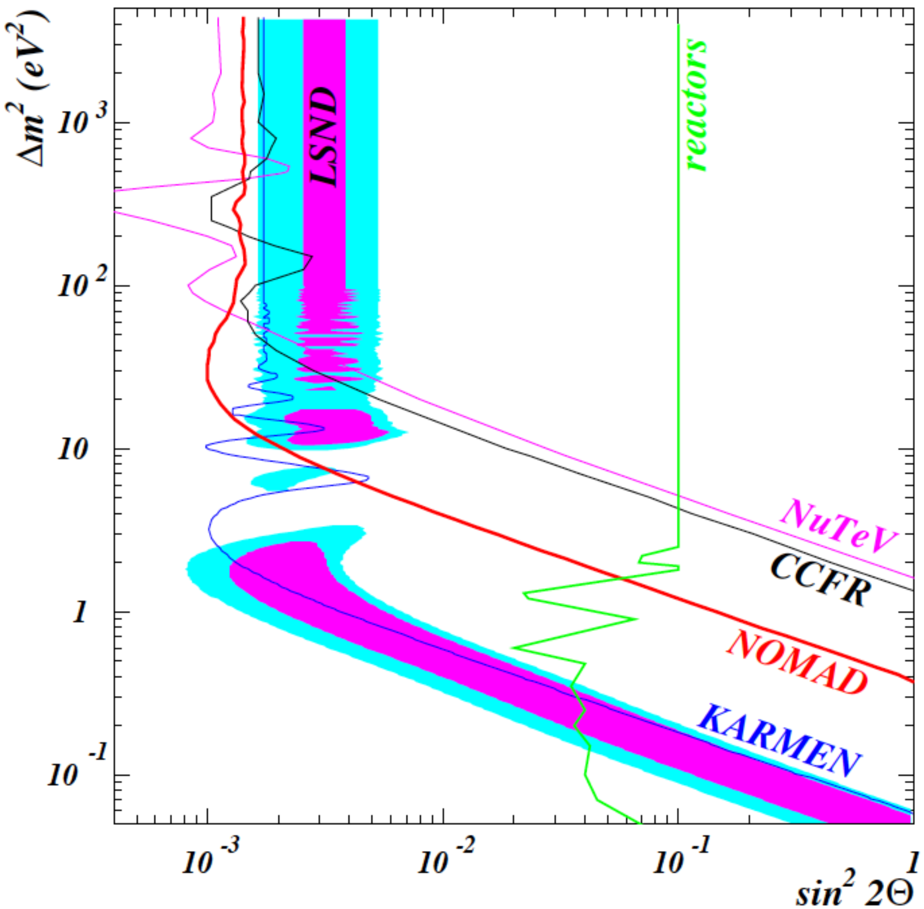


NOMAD

- NOMAD $\nu_\mu \leftrightarrow \nu_e$ oscillation search

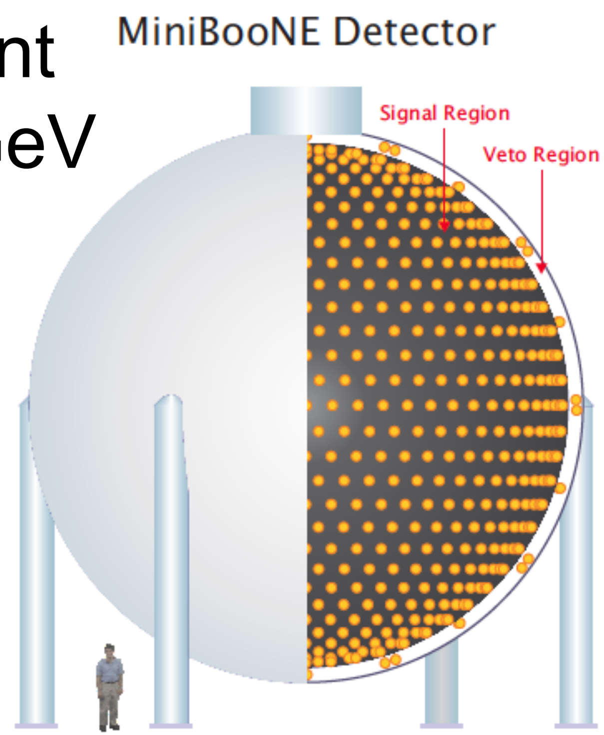
$$\sin^2 2\theta < 1.4 \times 10^{-3} \;\; \Delta m^2 < 0.4\, eV^2 (90\%\, CL)$$

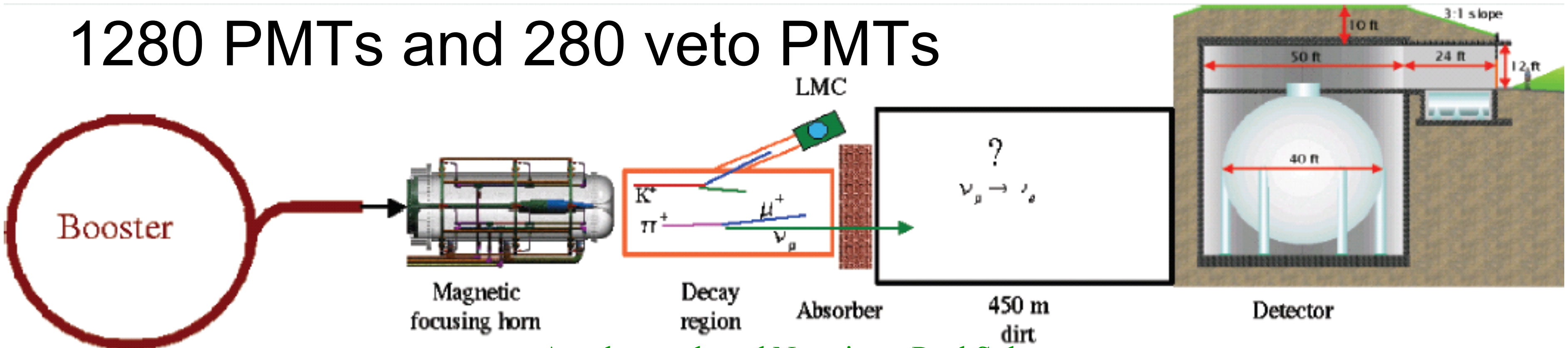




MiniBooNE

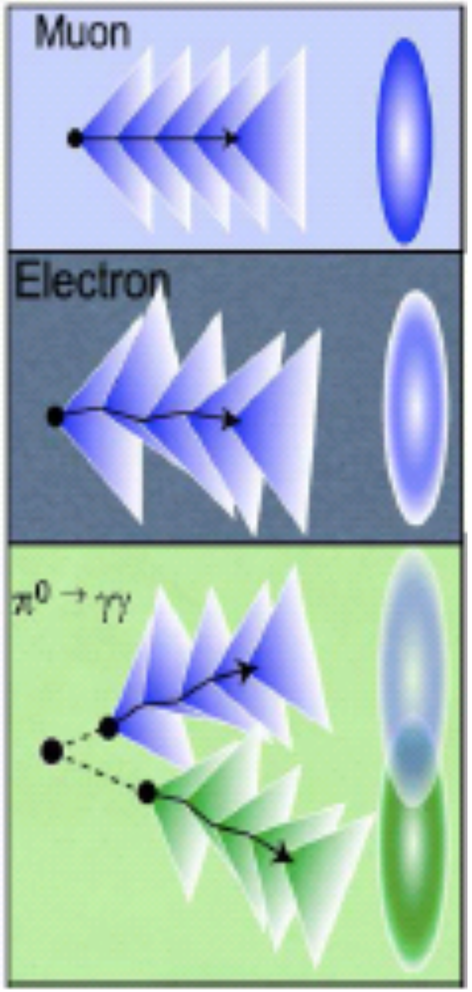
- MiniBooNE is a neutrino experiment at the Fermilab Booster fed by 8 GeV protons on 71 cm Be target
- It was designed to test the LSND anomaly by searching for $\nu_\mu \leftrightarrow \nu_e$ oscillations
- The detector is 12.2 m diameter and has 800 tons scintillator with 1280 PMTs and 280 veto PMTs

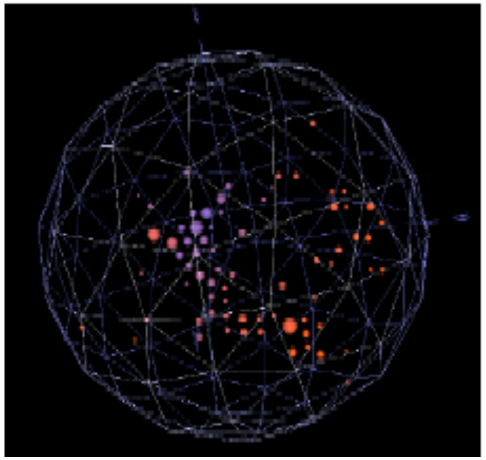




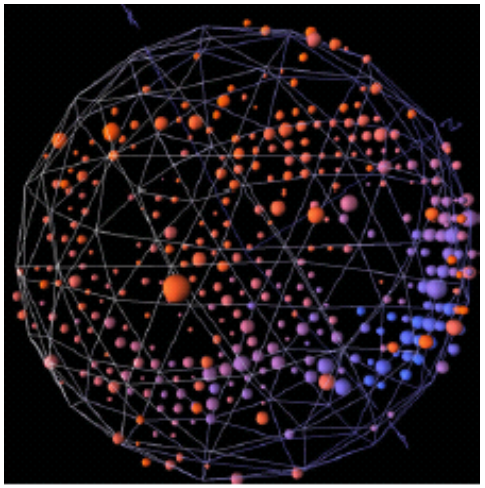
MiniBooNE

- MiniBooNE measures $\nu_e C \rightarrow e^- X$ charged current quasi-elastic (CCQE) events

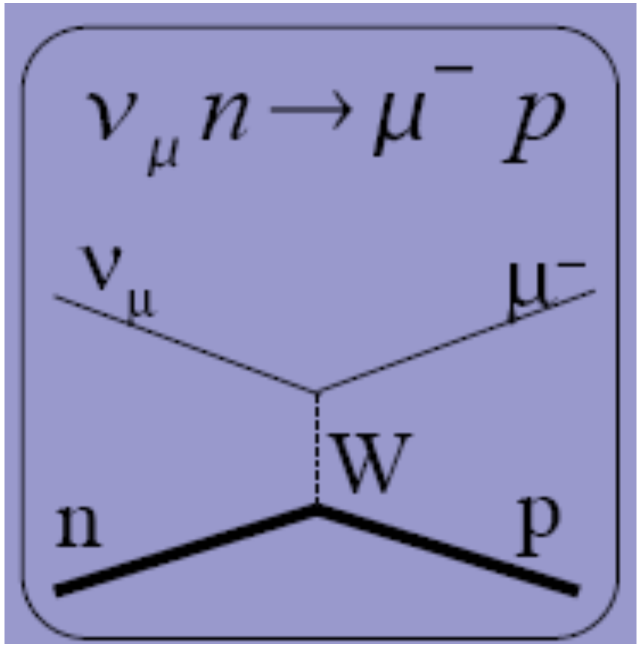




Michel electron

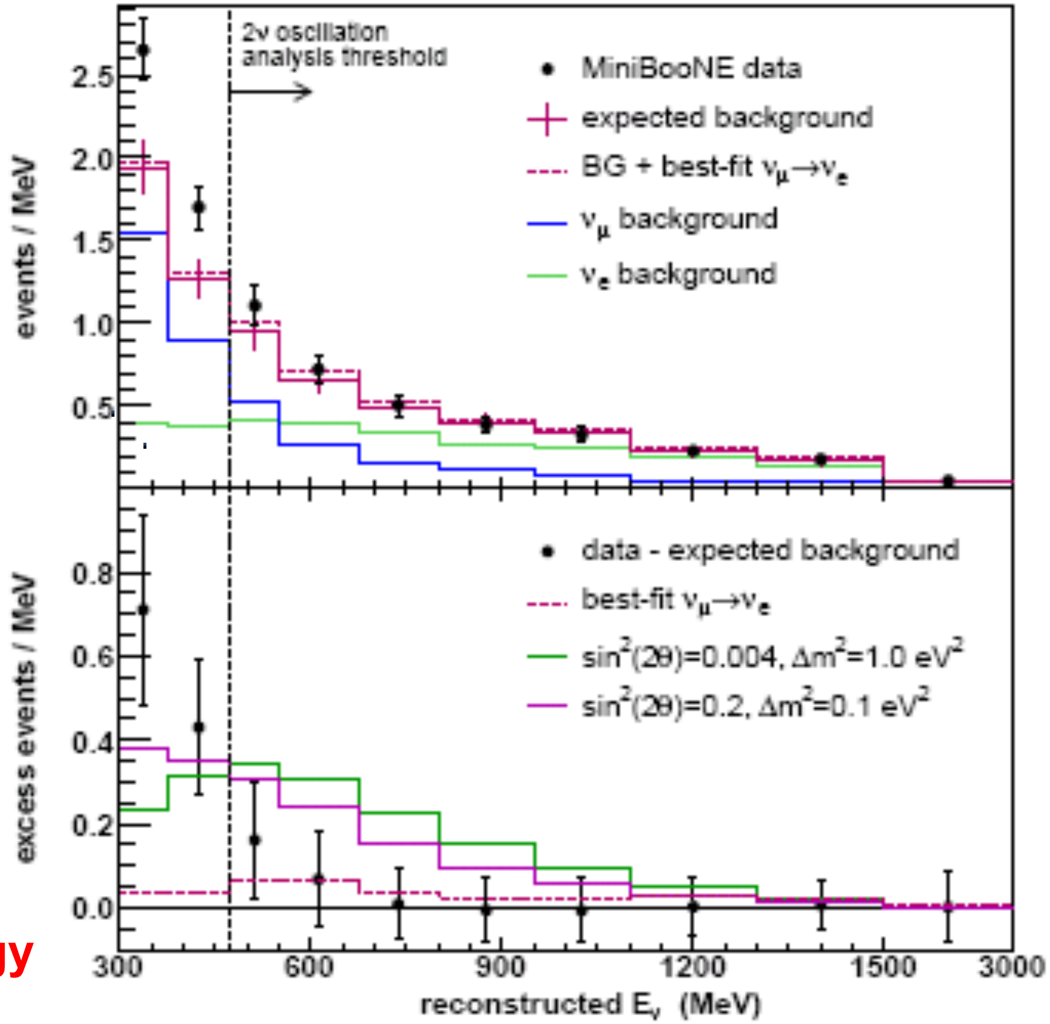


π^0 event



MiniBooNE

- MiniBooNE relies on knowing:
  - Flux of neutrinos, using HARP pion yields
  - CCQE cross-section
  - ν_e background from μ, π and K decay
  - NC backgrounds (eg: π^0, Δ resonance)



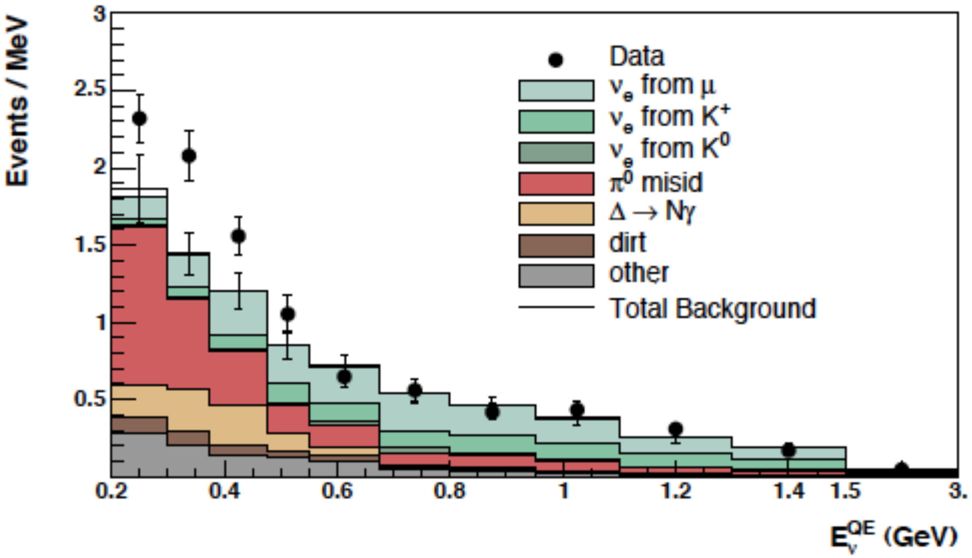
Blind analysis: tune cuts outside signal region until good fit. When satisfied open box

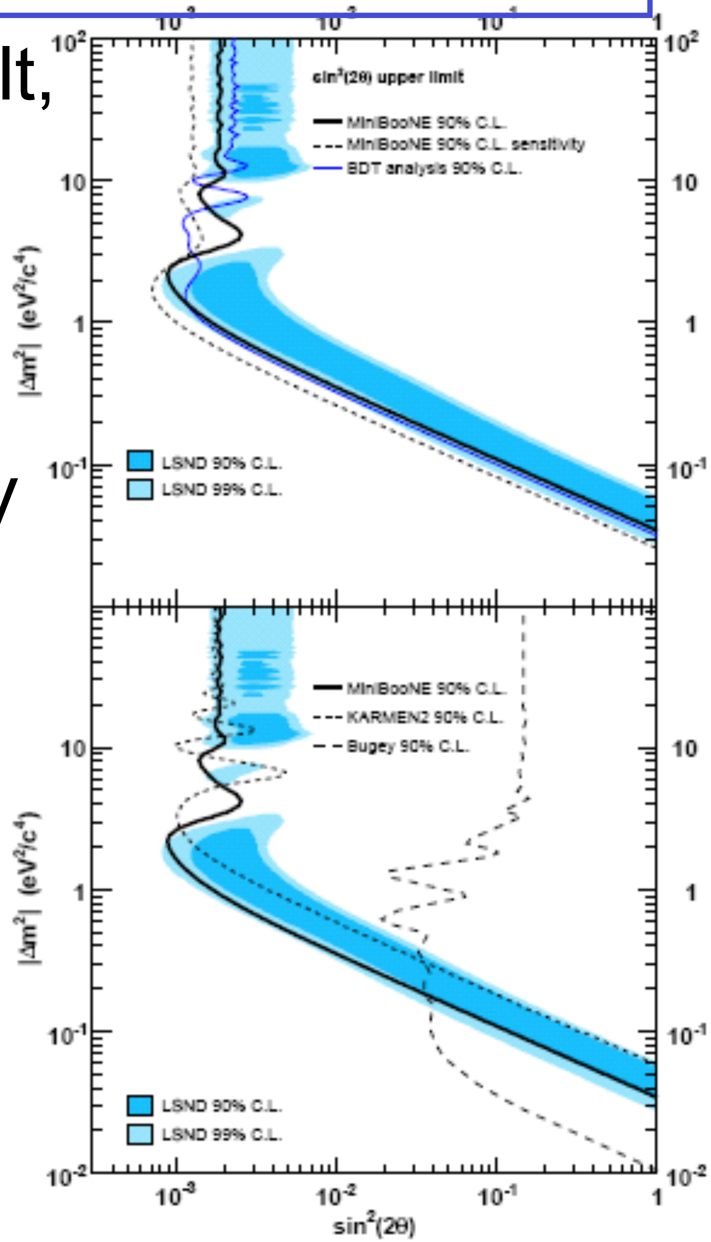
Results published June 2007.

No excess of ν_e events in ν_μ energy window but excess at low energy

MiniBooNE

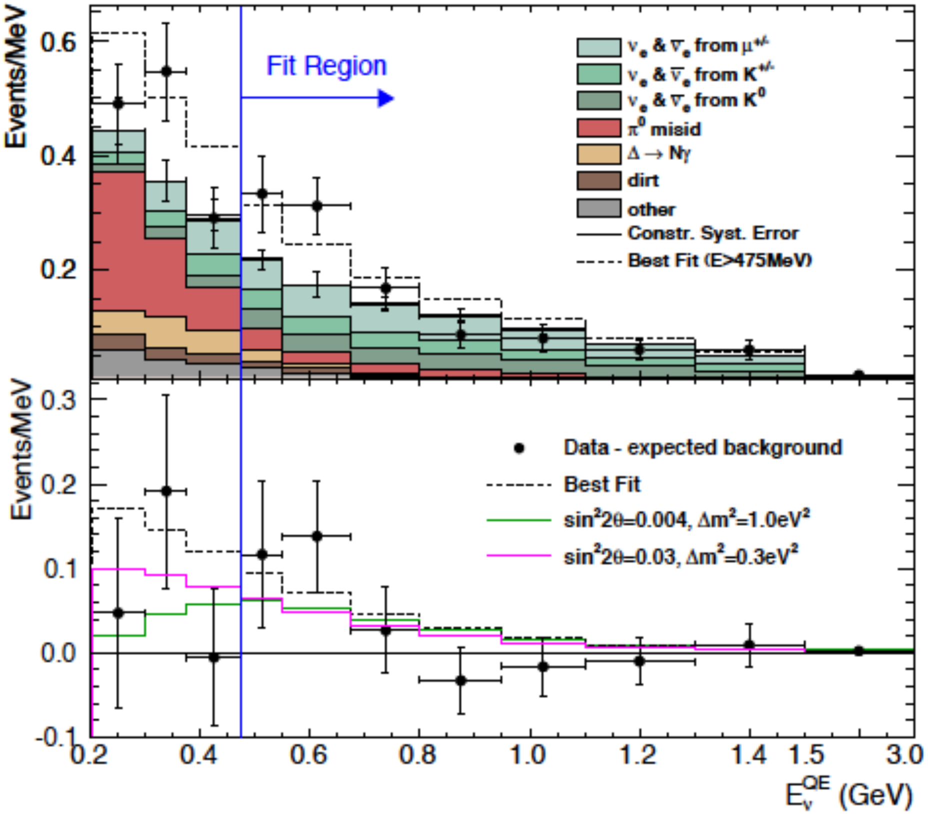
- Based on "null" oscillation result, MiniBooNE set upper limits
- Nearly excluded all of the available $\sin^2 2\theta - \Delta m^2$ space
  Phys. Rev. Lett. 98 (2007) 231801
- However, excess 200-475 MeV remains unexplained
  Phys. Rev. Lett. 102 (2009) 101802

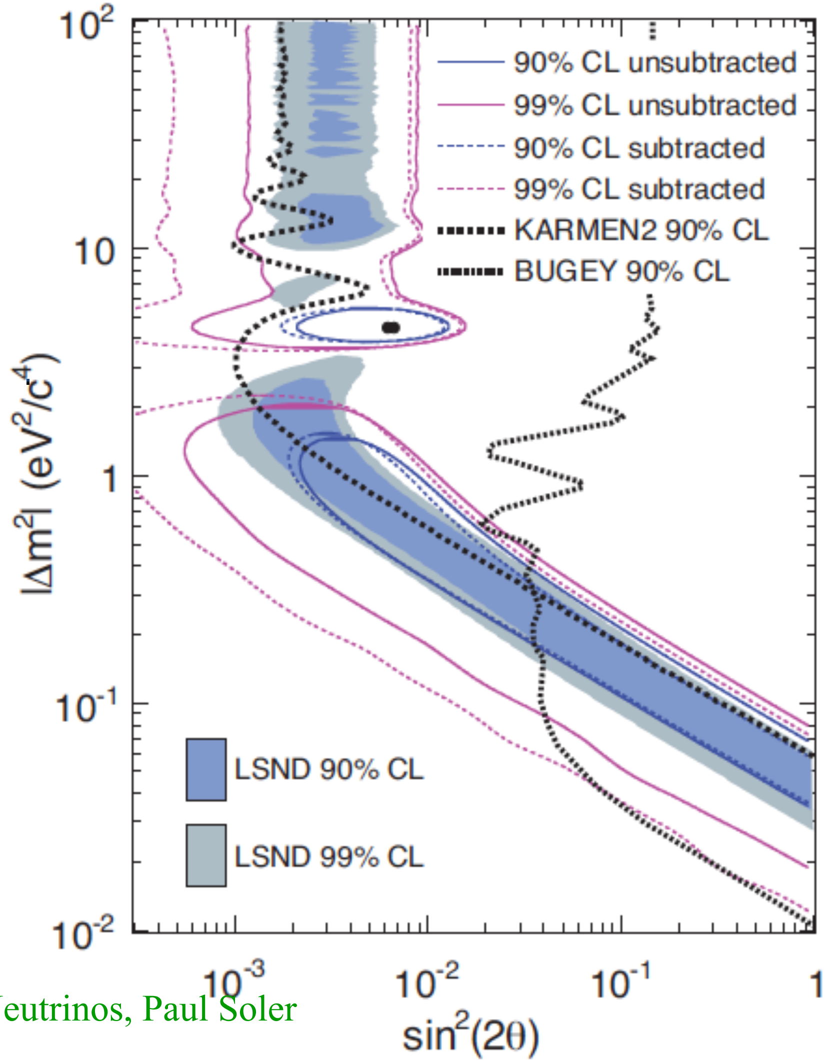




MiniBooNE

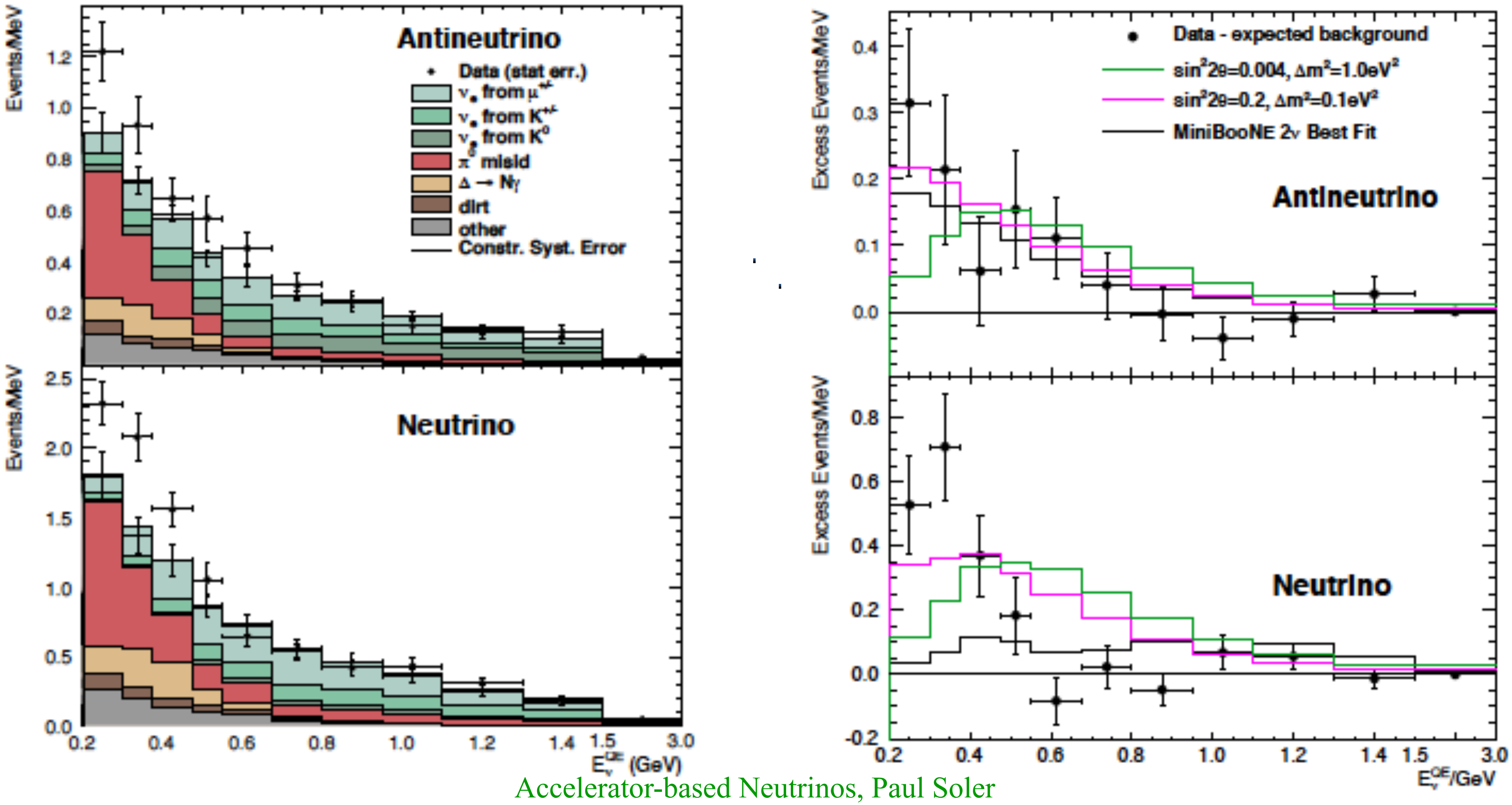
- Antineutrino data then also showed an excess compatible with LSND **Phys. Rev. Lett. 105 (2010) 181801**





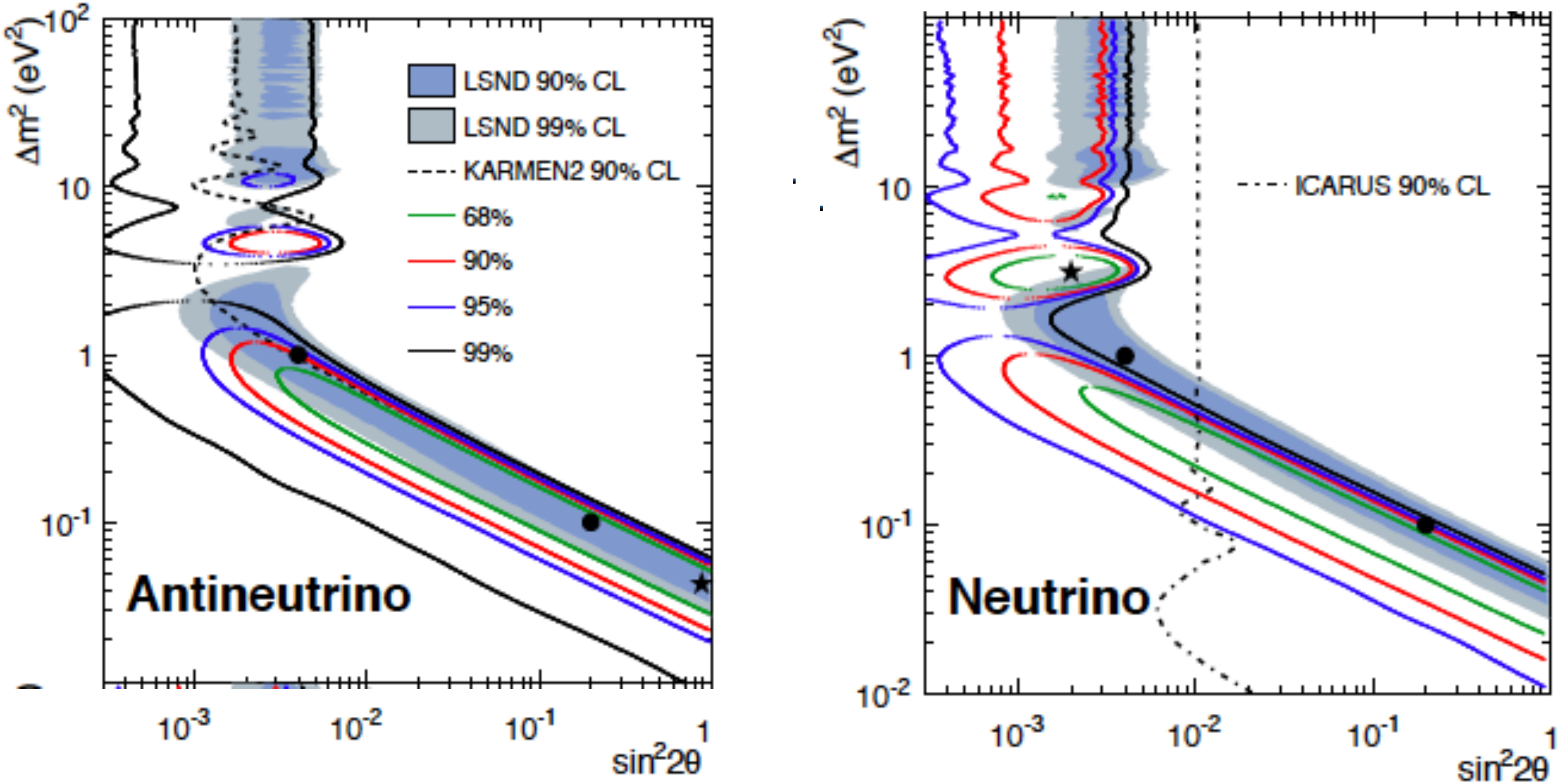
MiniBooNE

- Latest MiniBooNE paper suggests excess in both neutrinos and antineutrinos **Phys. Rev. Lett. 110 (2013) 161801**



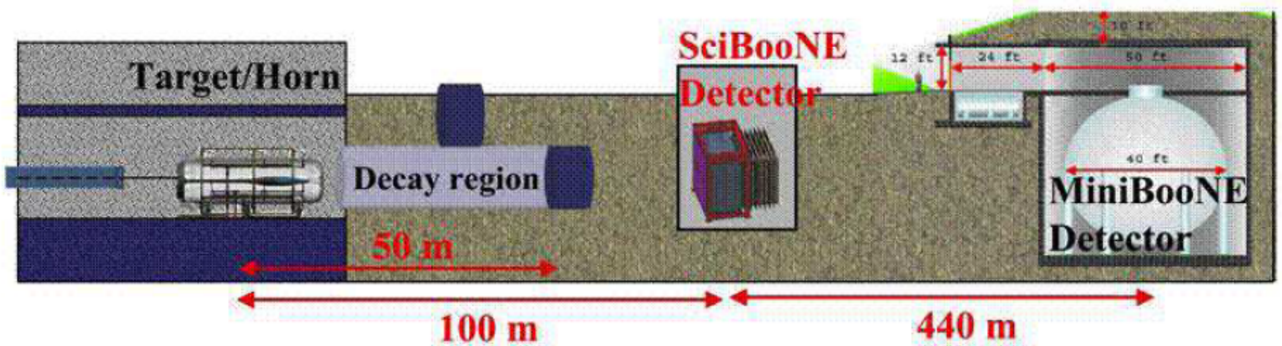
MiniBooNE

- Latest MiniBooNE paper suggests excess in both neutrinos and antineutrinos **Phys. Rev. Lett. 110 (2013) 161801**
  - Interpreted as neutrino oscillations compatible with LSND



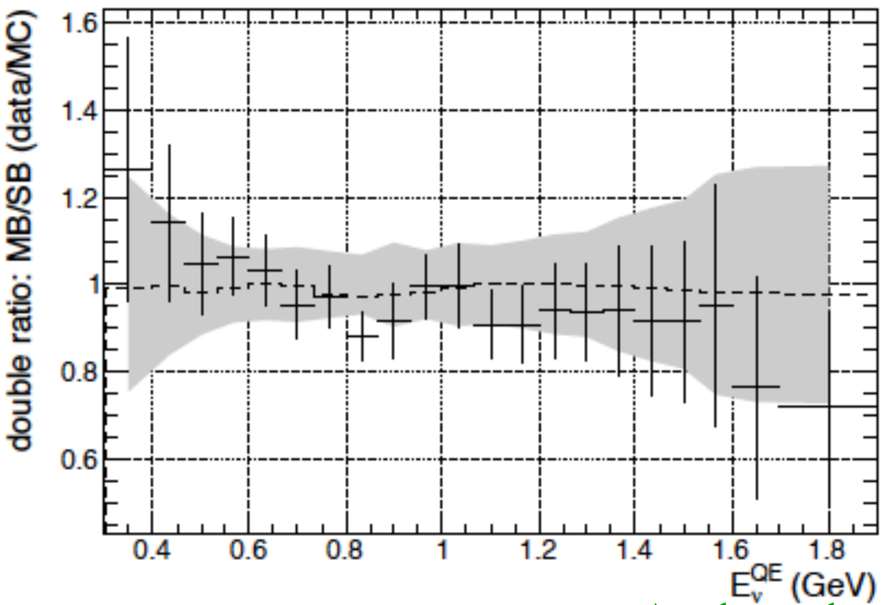
MiniBooNE

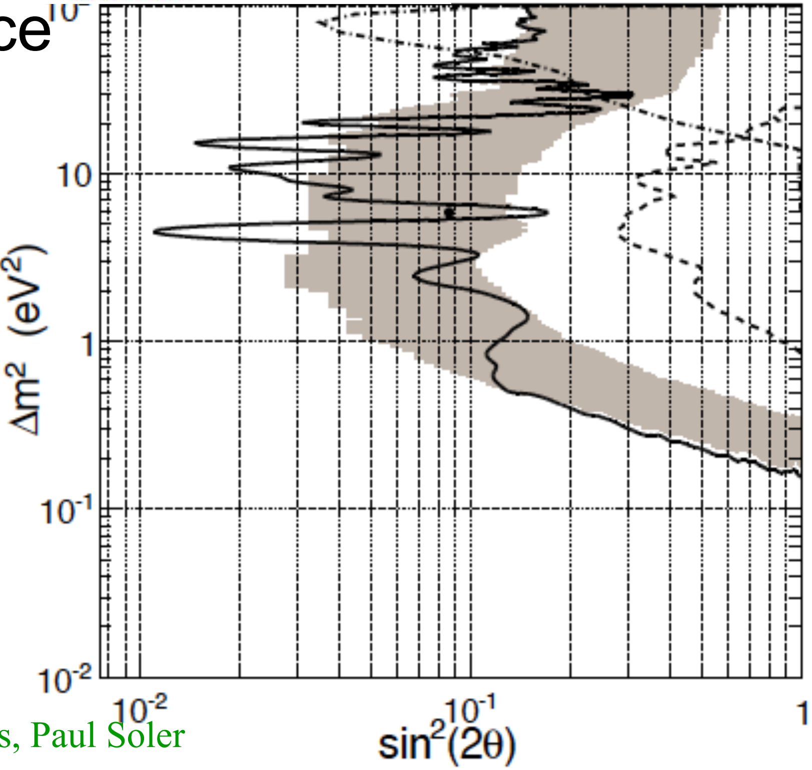
- MiniBooNE/SciBooNE joint disappearance analysis



  - No evidence of $\bar{\nu}_\mu$ disappearance

Phys. Rev. D 86 (2012) 052009





Compatibility of short baseline data

- Is all the short baseline data compatible?
  - Fit to neutrino and antineutrino excess in tension with two neutrino oscillation **Maltoni, EPS-HEP (2013), Stockholm**
  - Fit to one extra neutrino m_4 in tension with disappearance

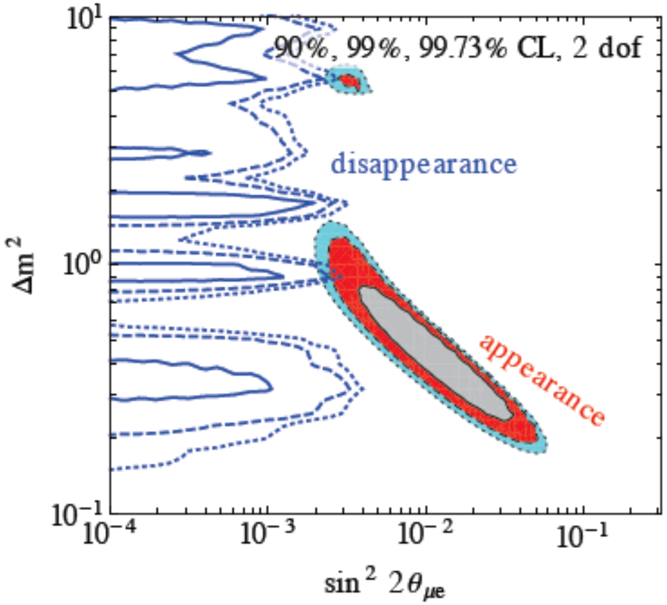
$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E};$$

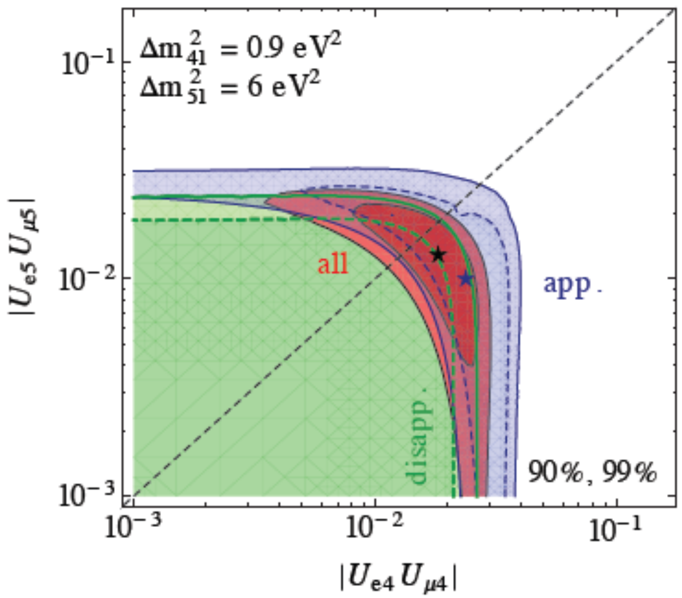
  - Fit to two extra neutrinos m_4 and m_5 is better, but not great

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$

3+1

JHEP 1305 (2013) 050



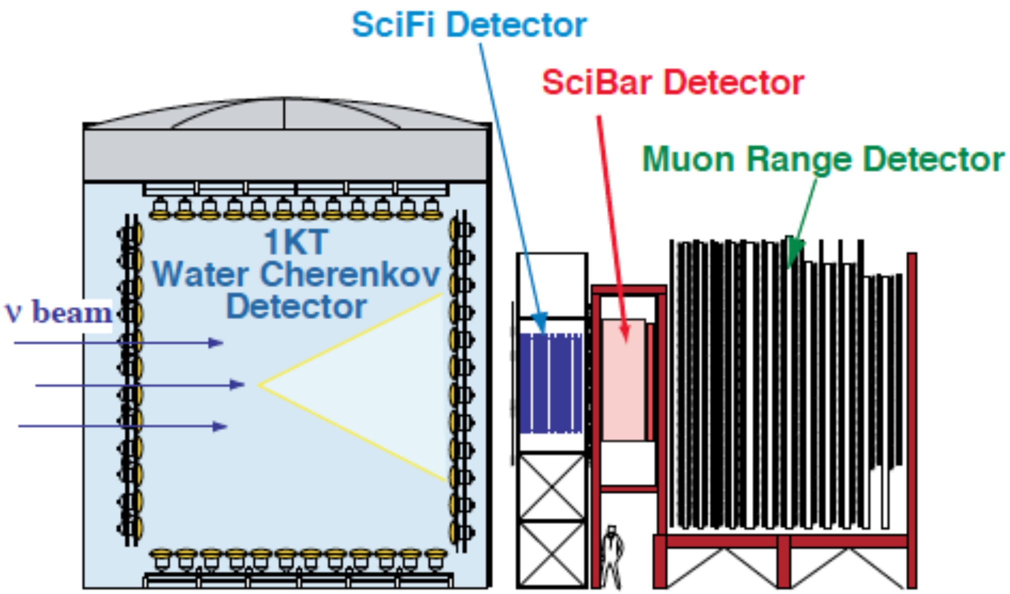


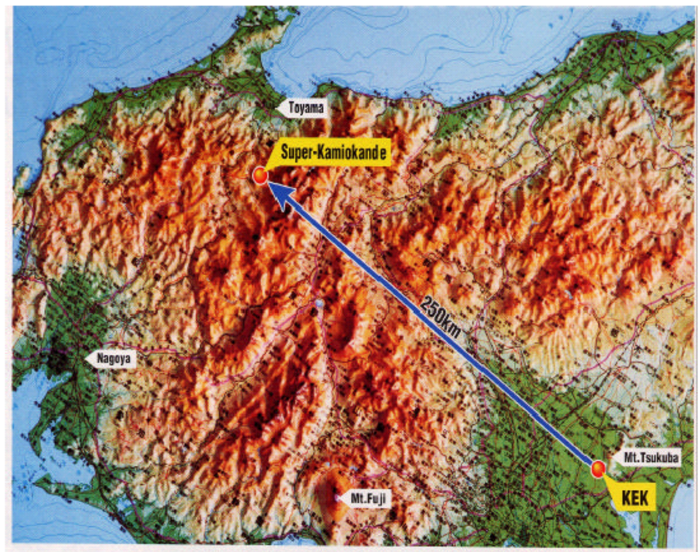
3+2

3.2 Long Baseline Oscillation Experiments

K2K: first long baseline experiment

- K2K is first long baseline neutrino oscillation experiment, from KEK to Kamioka mine: L=250 km
  - Beam 12 GeV protons on Al, two horns: $\langle E_\nu \rangle = 1.4\ GeV$
  - Near detector at KEK: water Cherenkov, SciFi, SciBar, muon range detector
  - Far detector: SiuperKamiokande

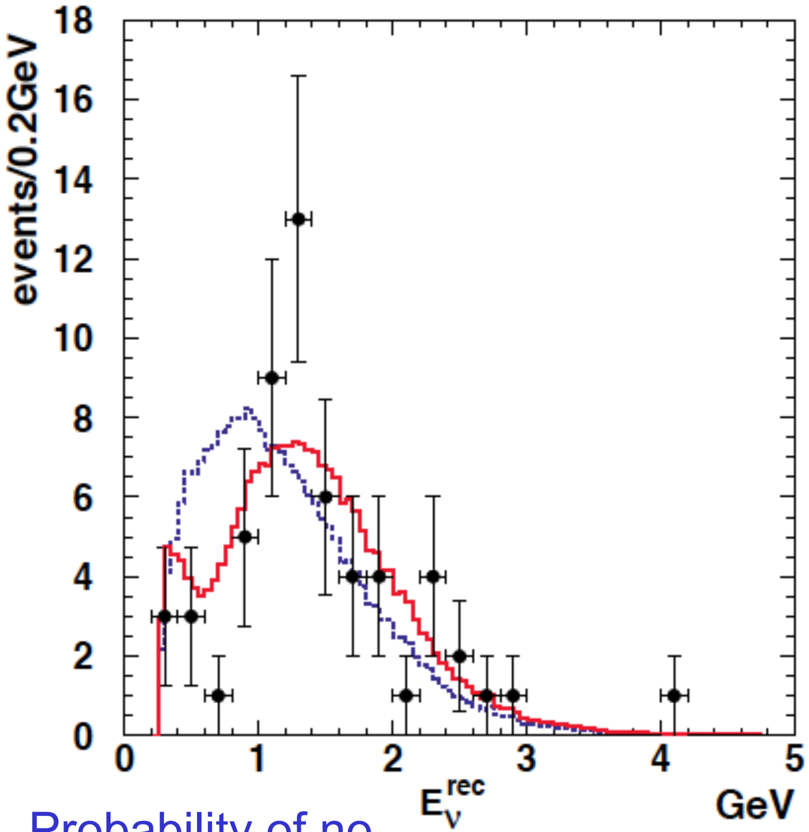


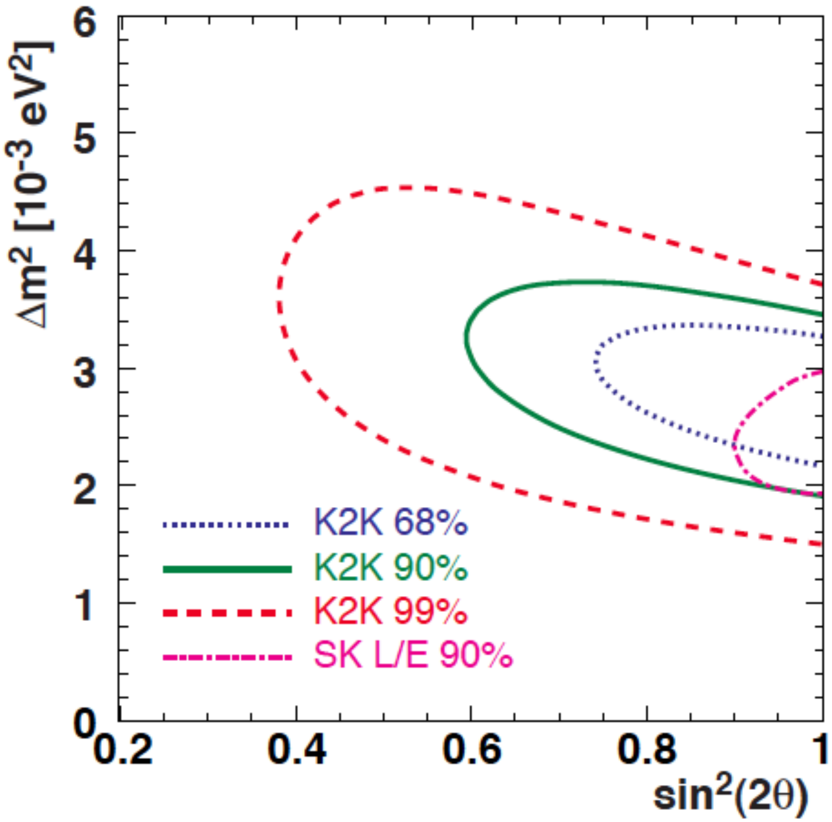


K2K: first long baseline experiment

- K2K results:
  - Observed SuperK: 112 events
  - Expected SuperK: $158.1^{+9.2}_{-8.6}$

Compatible with Super-K atmospheric Oscillation parameters.





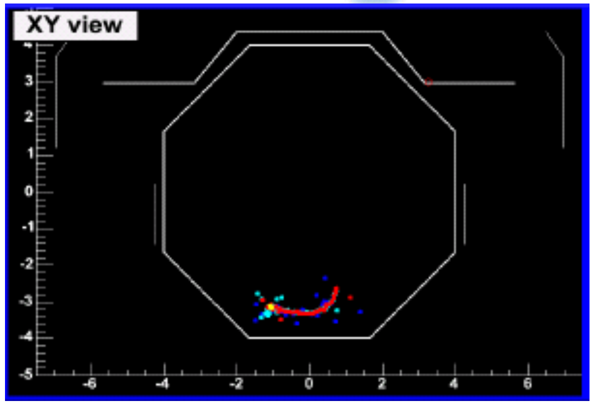
Probability of no oscillation 0.0015% (4.3σ)

MINOS

- MINOS: long baseline neutrino oscillation experiment, from Fermilab to Soudan (Mn) mine L=730 km
  - Beam: 120 GeV protons from Main Injector on graphite target to produce neutrino beam focused by two horns
  - Near and far detectors: iron-scintillator magnetic spectrometers
  - Started running January 2005

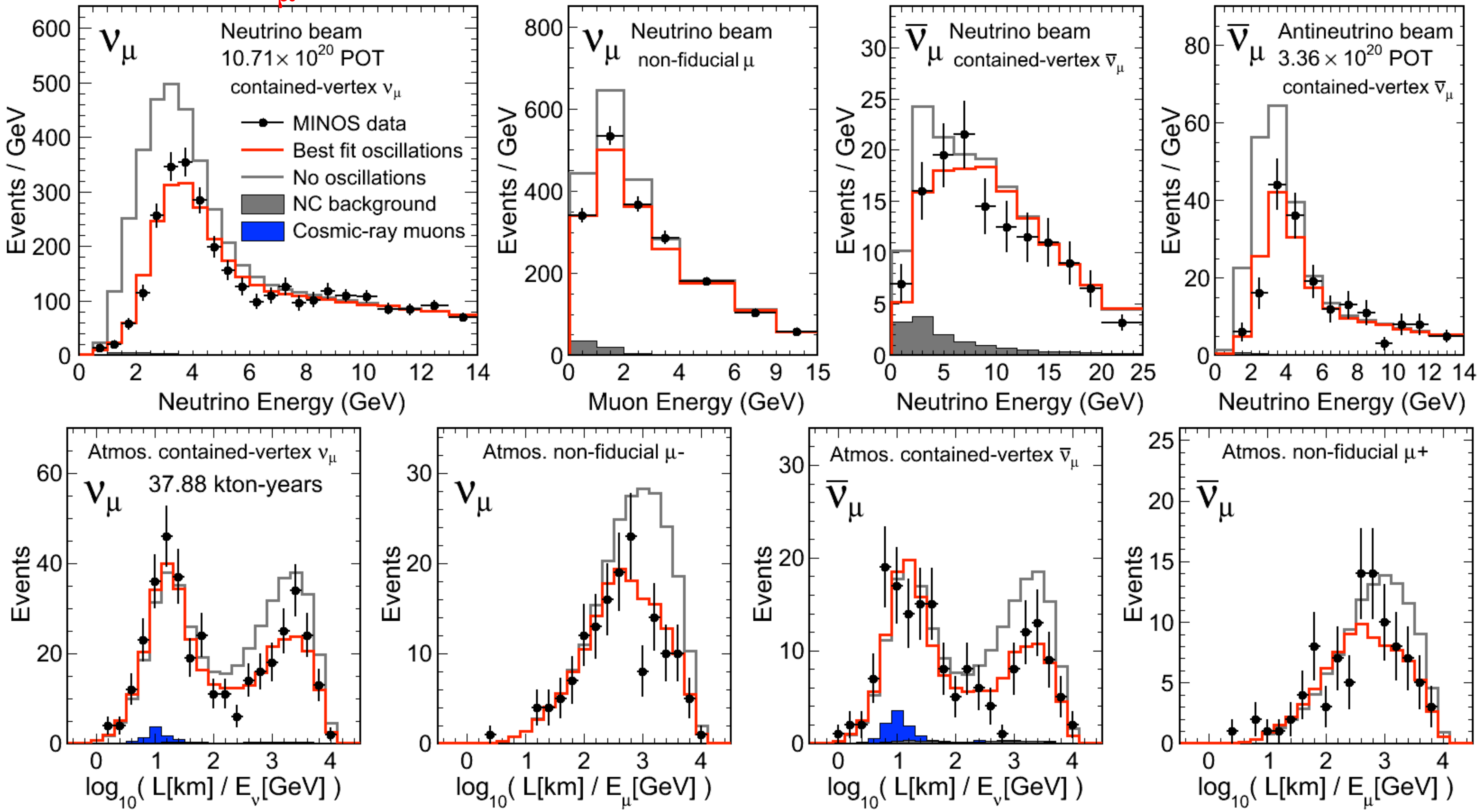
Near detector: 980 tons

Far detector: 5400 tons



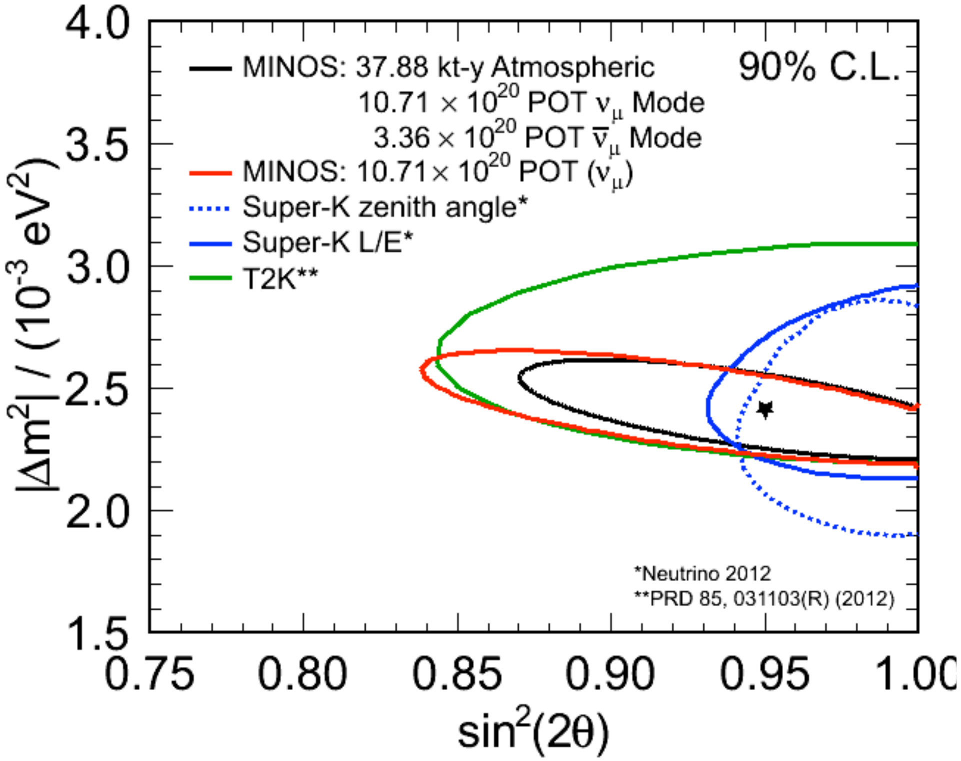
MINOS

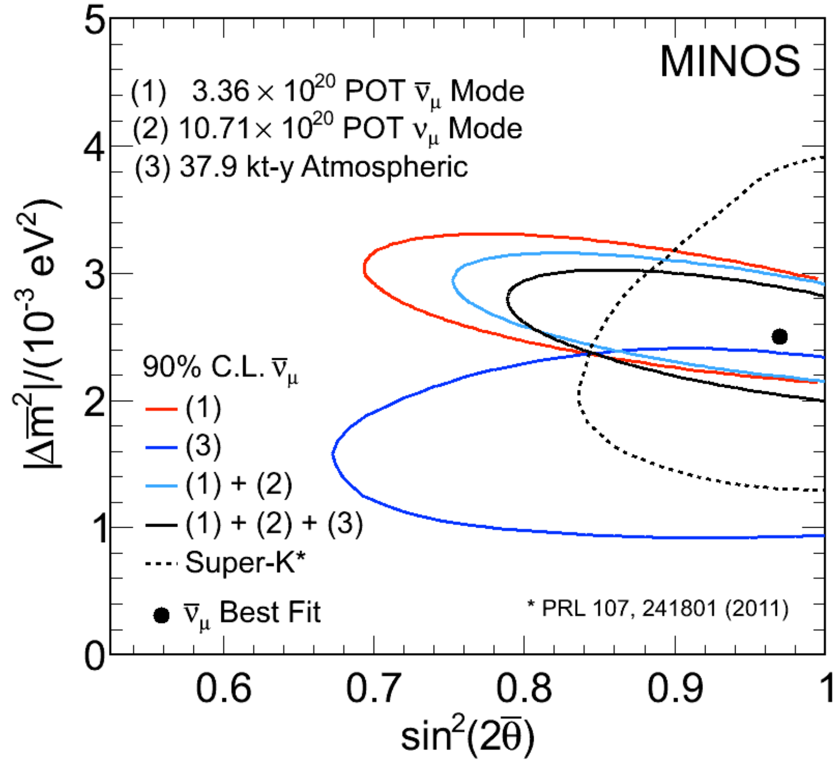
MINOS ν_μ disappearance and atmospheric results:



MINOS

MINOS ν_μ disappearance and atmospheric results:





Discovery ν_μ disappearance.

Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations

$$\Delta m^2 = \left(2.41^{+0.09}_{-0.10}\right) \times 10^{-3}\ eV^2$$

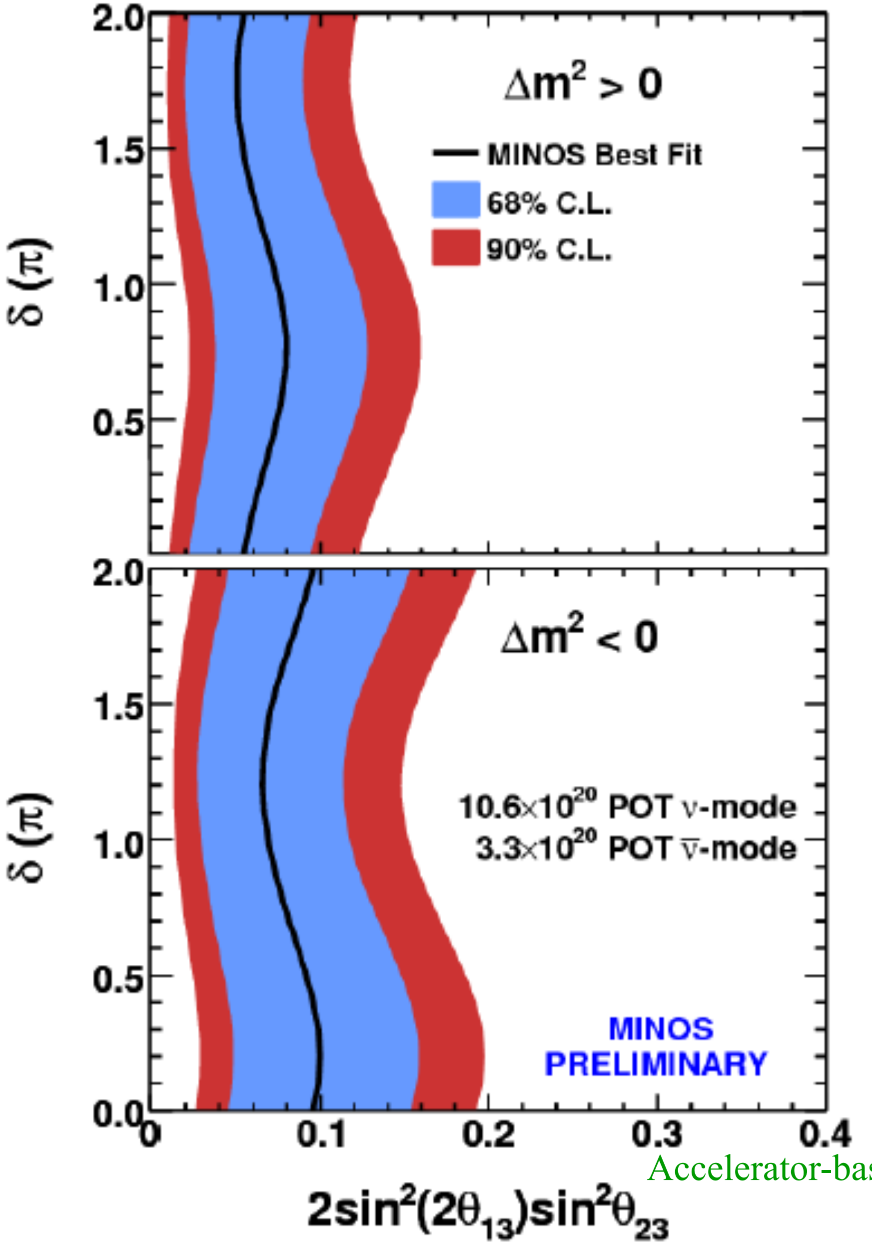
$$\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$$

Neutrino parameters consistent with antineutrino parameters

$$\Delta m^2 = \left(2.50^{+0.23}_{-0.25}\right) \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta = 0.97^{+0.03}_{-0.08}$$

MINOS ν_e results



Cannot distinguish between ν_e and anti-ν_e events, so we perform a combined analysis:

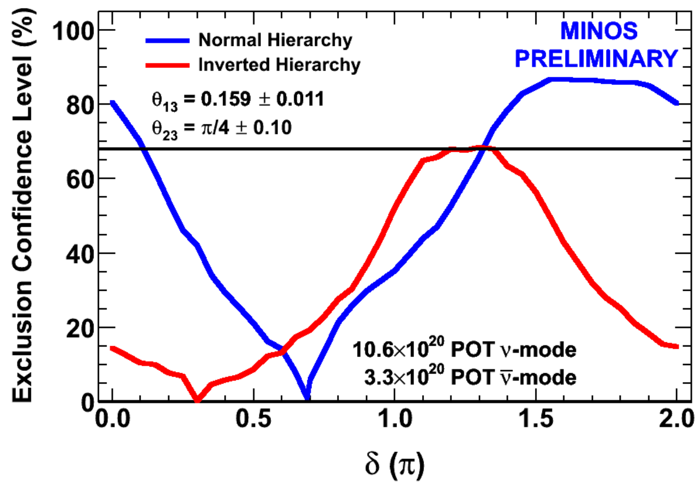
At $\delta_{CP} = 0$ and $\theta_{23} < \pi/4$

- Assuming normal hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$
$$0.01 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.12 \quad \text{(90\% C.L.)}$$

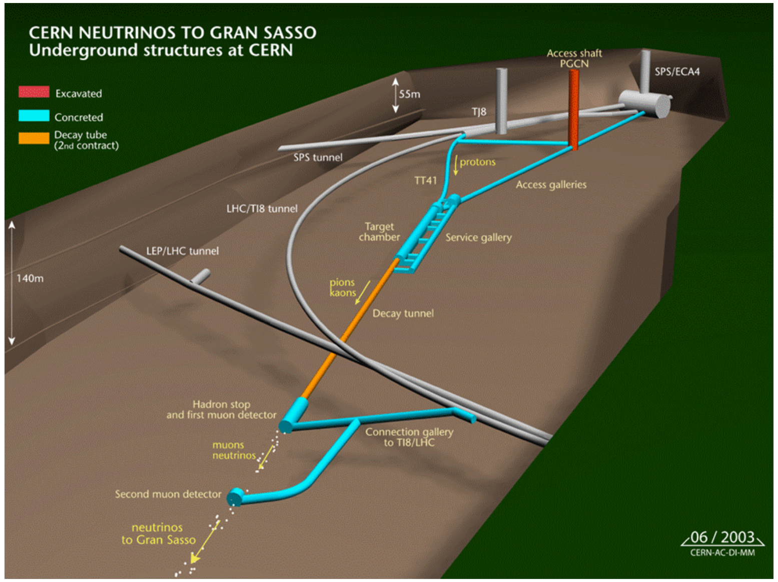
- Assuming inverted hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$
$$0.03 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.18 \quad \text{(90\% C.L.)}$$

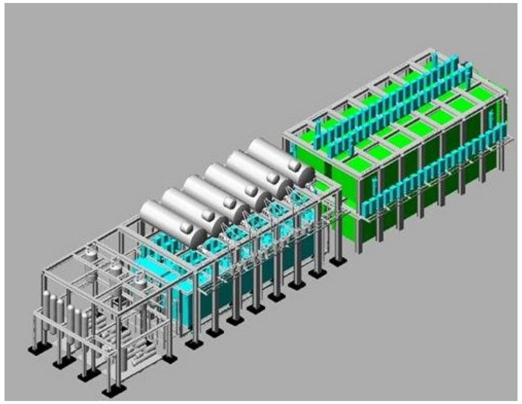


CERN-Gran Sasso

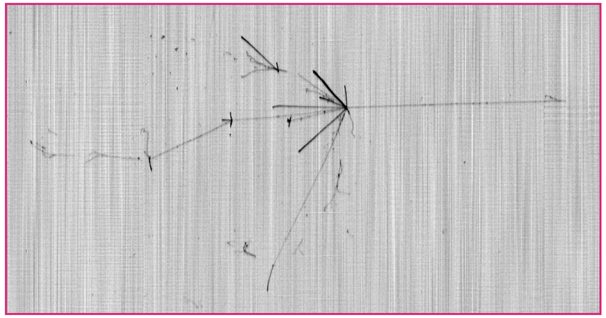
- CNGS: CERN to Gran Sasso (Italy). L= 732 km, <E> = 30 GeV. Started in 2006.



- ICARUS (600 ton liquid argon TPC): kinematic selection of ν_τ



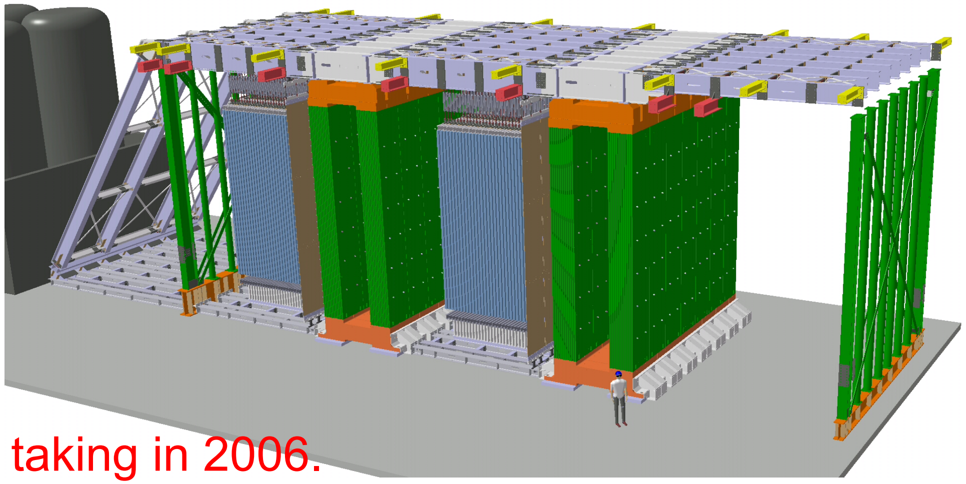
Started data taking 2010

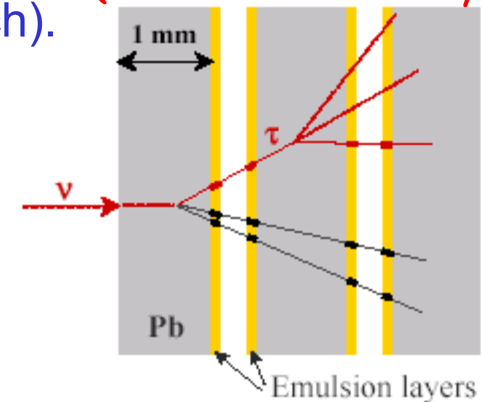


206,336 "ECC bricks"
(56 Pb/Emulsion layers)

- OPERA (1.8 kton emulsion based ν_τ appearance search).

ν beam



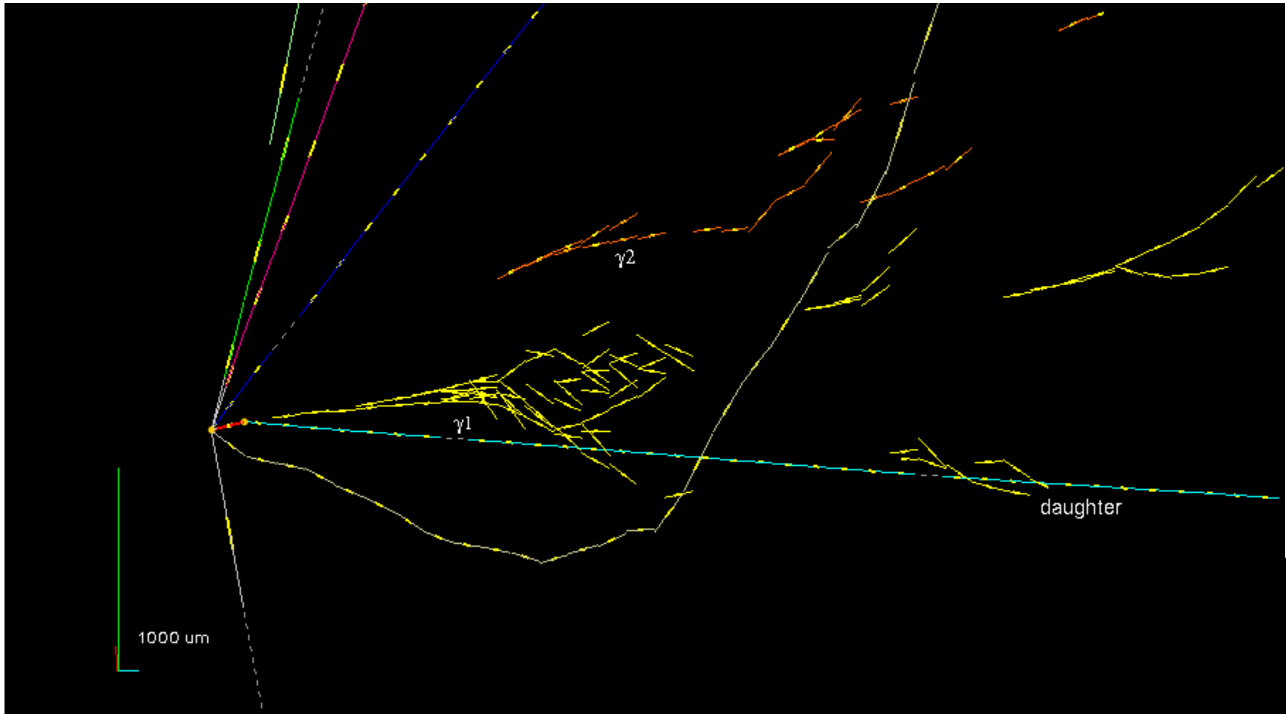


6.6 ν_τ signal events
(Δm^2=1.9x10^{-3}eV^2)

Started data taking in 2006.

Accelerator based oscillation expts (cont)

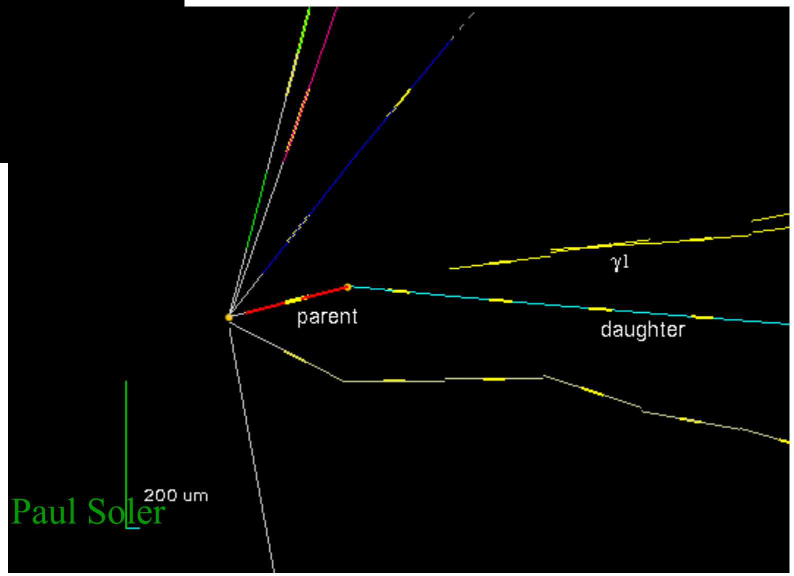
- OPERA: first tau candidate found in 2010



Consistent with τ decay to ρ:

$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \rho(\pi^-\pi^0) + \nu_\tau$$

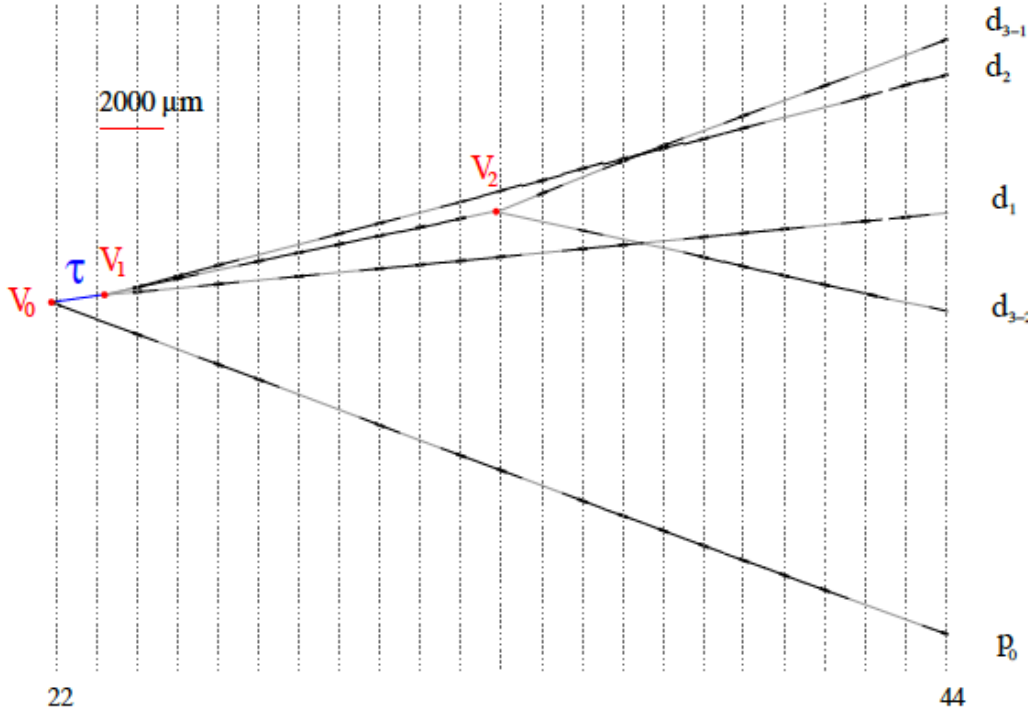


Background: 0.045±0.020

Event significance: 2.36σ

Accelerator based oscillation expts (cont)

- OPERA: two more candidates found



Consistent with:

$$\tau^- \rightarrow h^+ h^- h^- \nu_\tau$$

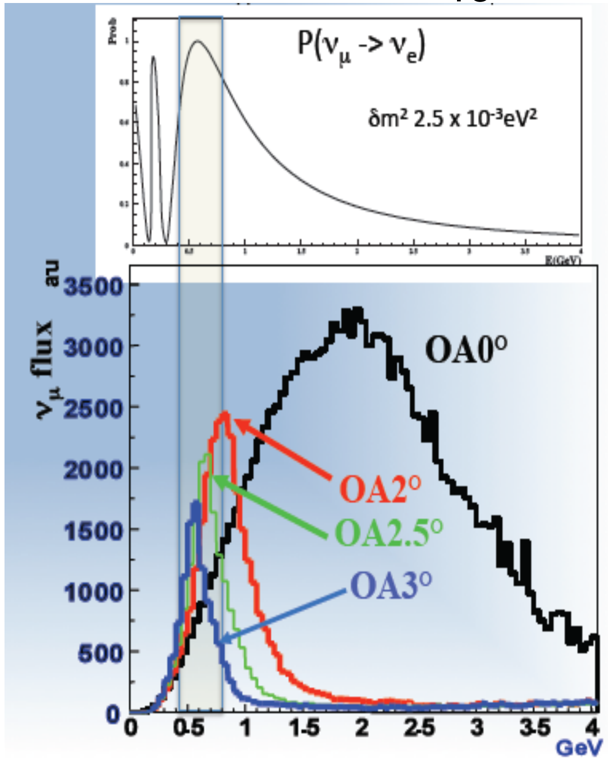
Third event consistent with: $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

Three events found, probability of background = 7×10^{-4}

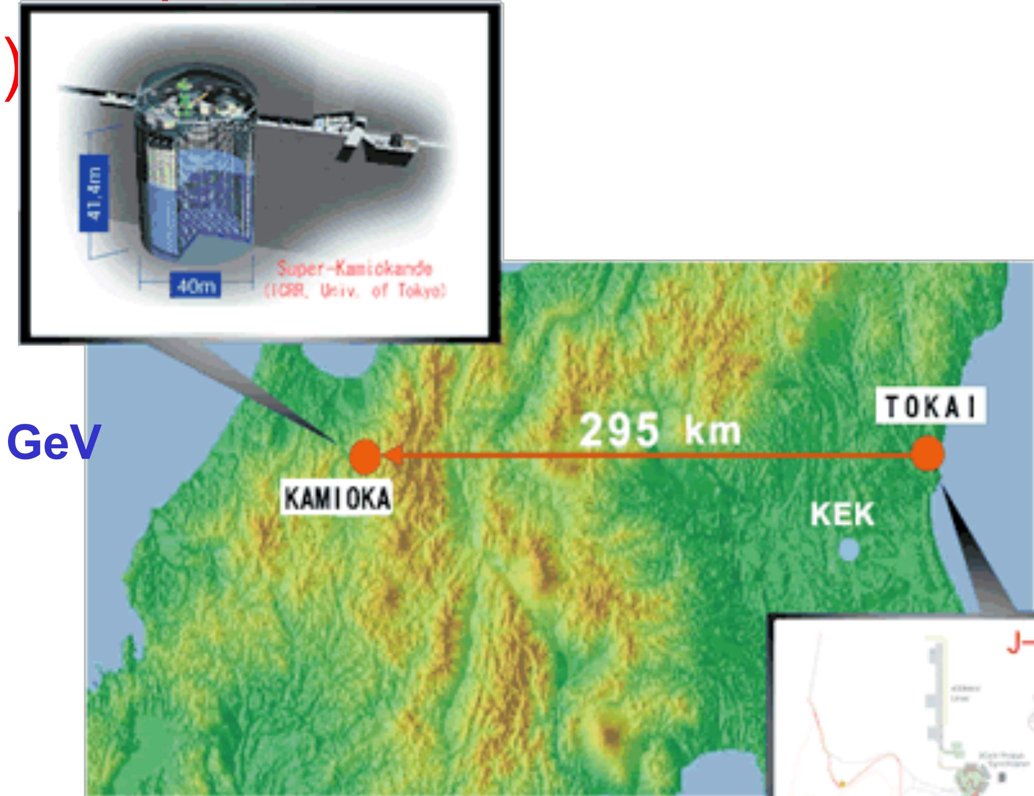
Significance of three events: 3.5σ

The search for θ_{13}: T2K

- The next goal in neutrino oscillation physics is the confirmation of θ_{13} – first step towards CP violation
- T2K (Tokai-to-Kamioka)
  - First off-axis beam to discover θ_{13}: 2.5°



E_ν=0.6 GeV

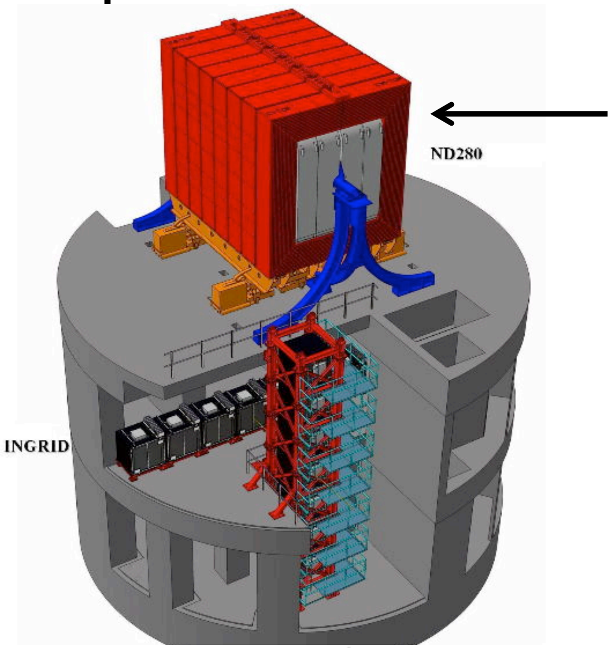


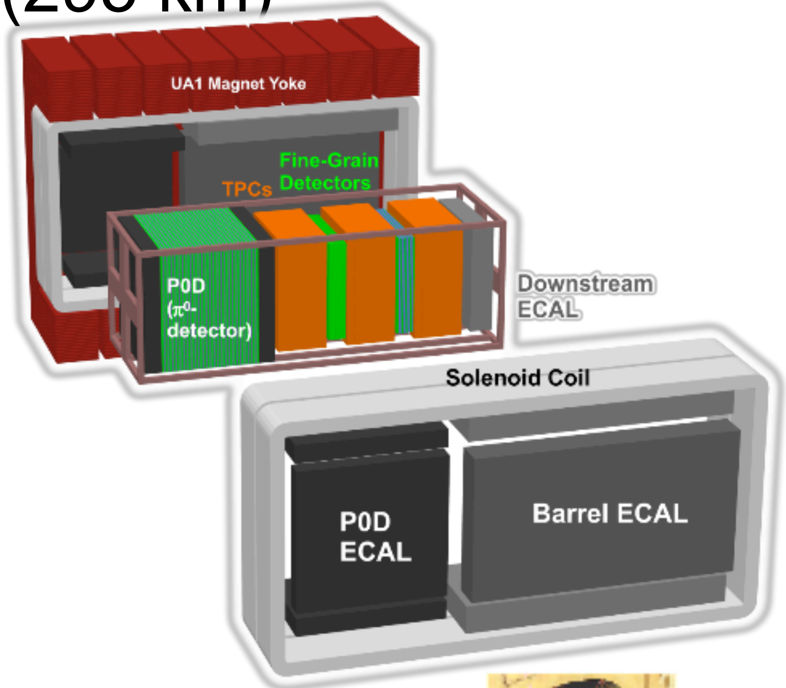
Off-axis: narrower energy band:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2\left(E_\pi - p_\pi \cos\theta\right)}$$

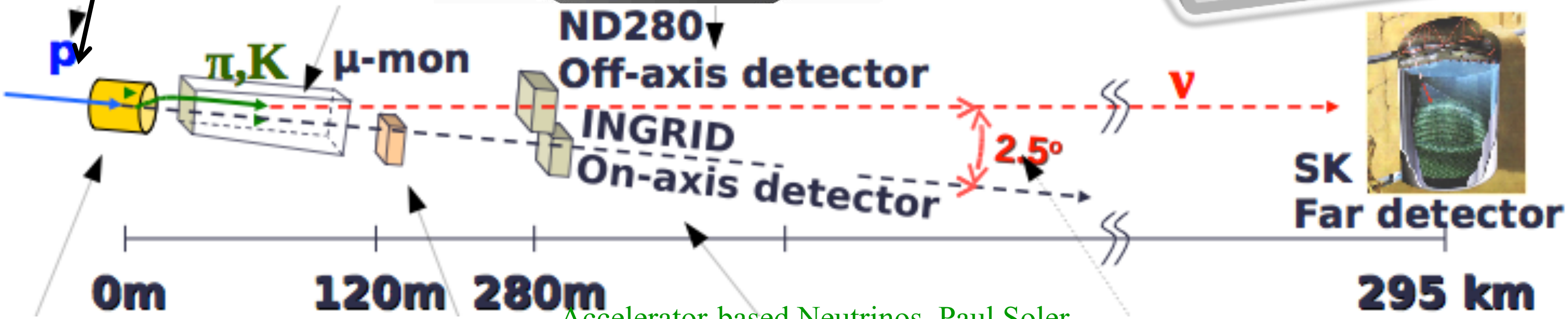
T2K Detectors

- Near detectors: μ-mon, INGRID and ND280
- Far detector: Super-Kamiokande (295 km)



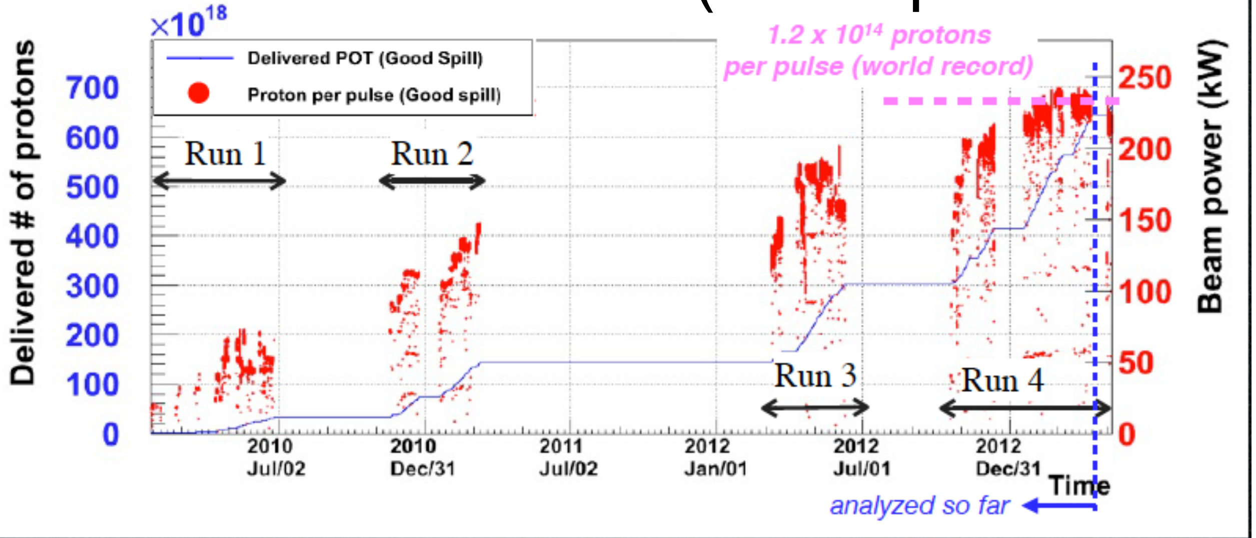


30 GeV protons from J-PARC

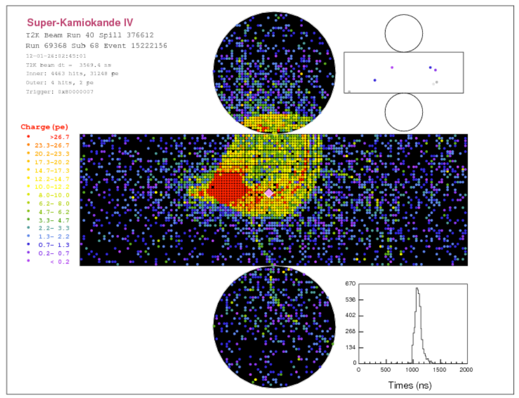


T2K Detectors

- Runs 1 and 2: 1.43×10^{20} POT (2% expected data)



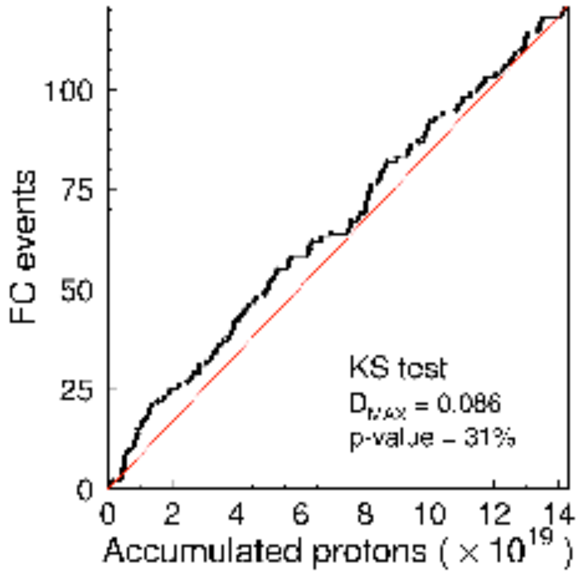
  - Run cut short by devastating earthquake and tsunami that hit Japan on 11 March 2011
  - Accelerator damaged and repaired
  - Facility was recovered and T2K started data taking again on 24 Dec 2011 (without horn)
  - Resumption full data taking March 2012
  - Now have runs 3 and 4



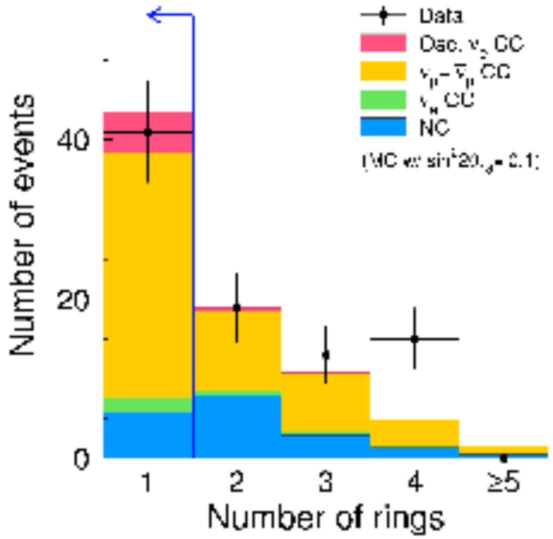
T2K electron neutrino appearance

- First analysis:

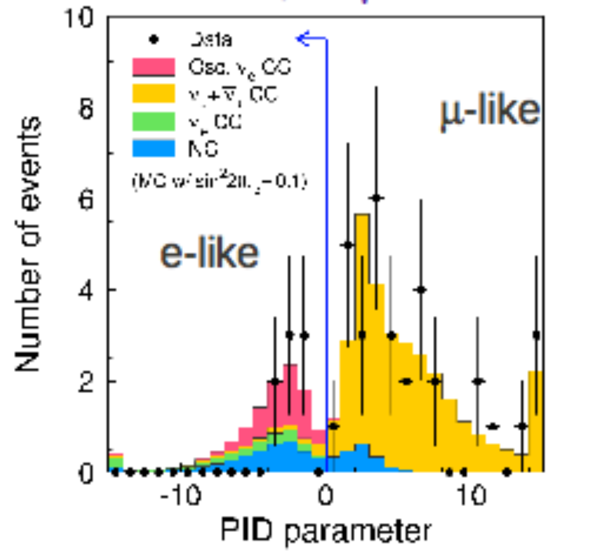
88 FCFV events



41 single ring events

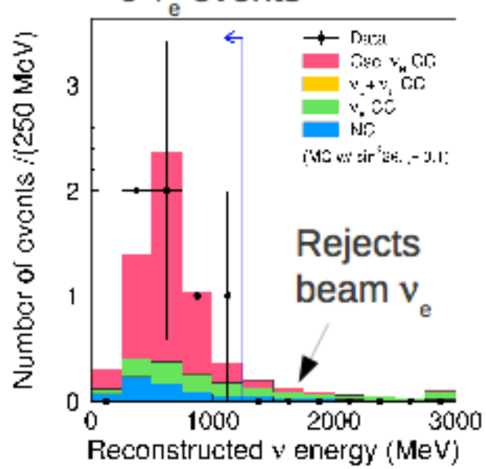


8 e-like events, 33 μ-like events



  - Finally, 6 events survive cuts(1.5±0.3) unoscilllated background
  - If $\sin^2 2\theta_{13}$=0.1 then 5.5 events would have survived cuts

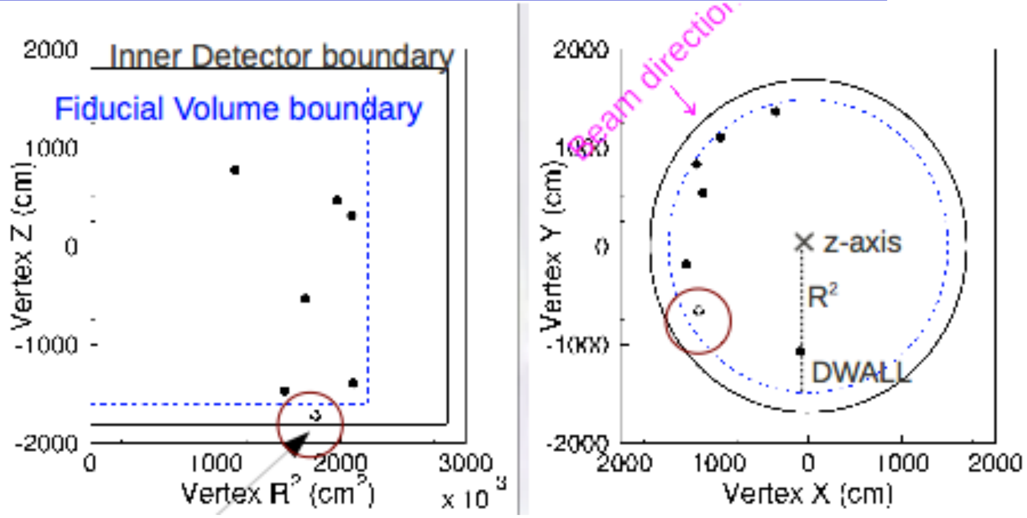
6 ν_e events



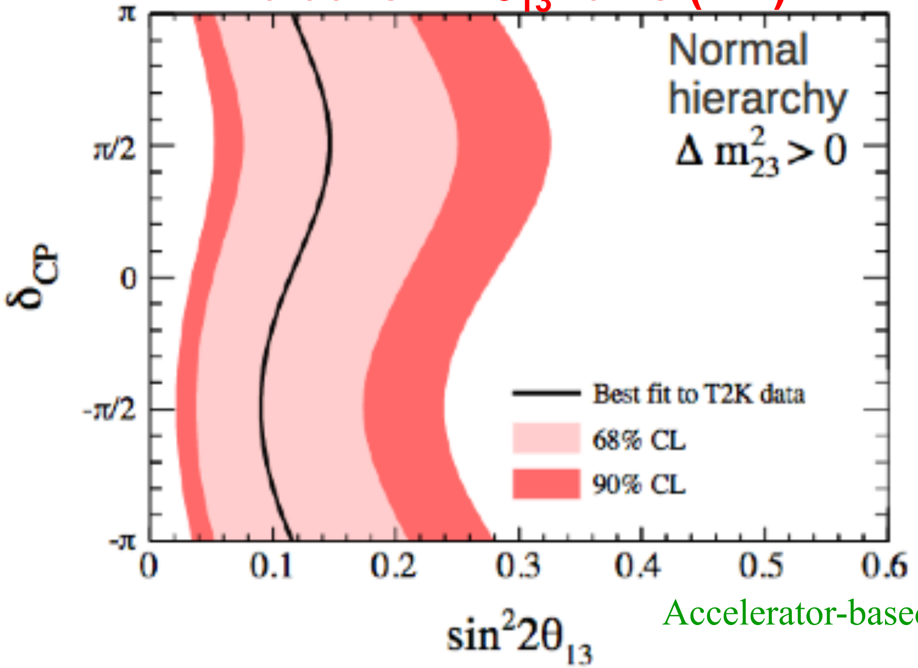
T2K electron neutrino appearance

- Events close to fiducial volume edge, but no evidence for bias
- Final sensitivity of θ_{13} as a function of CP phase δ:

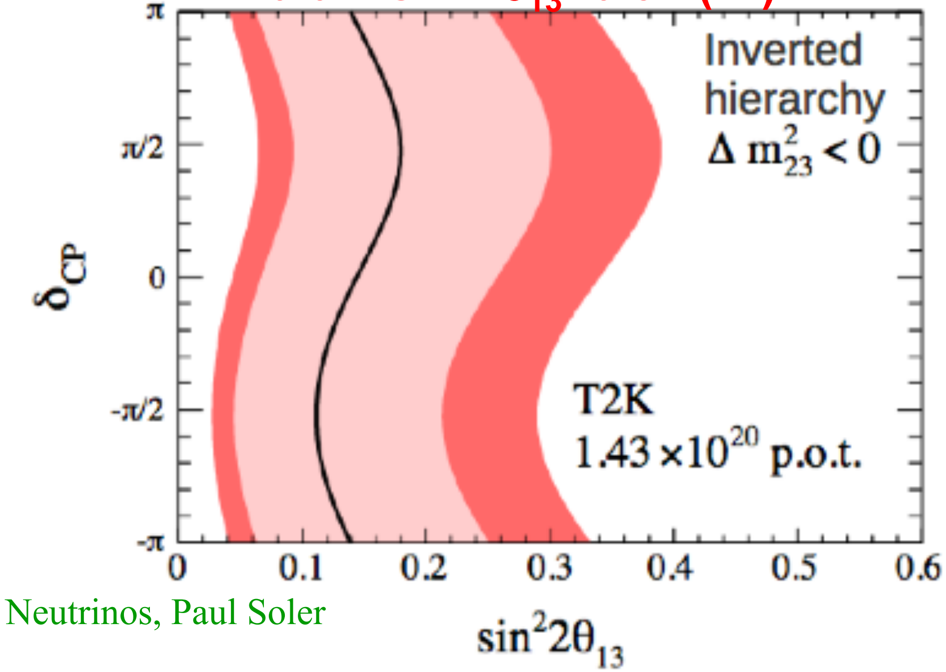
PRL 107, 041801, (2011)



$0.03<\sin^2 2\theta_{13}<0.28$ (NH)



$0.04<\sin^2 2\theta_{13}<0.34$ (IH)



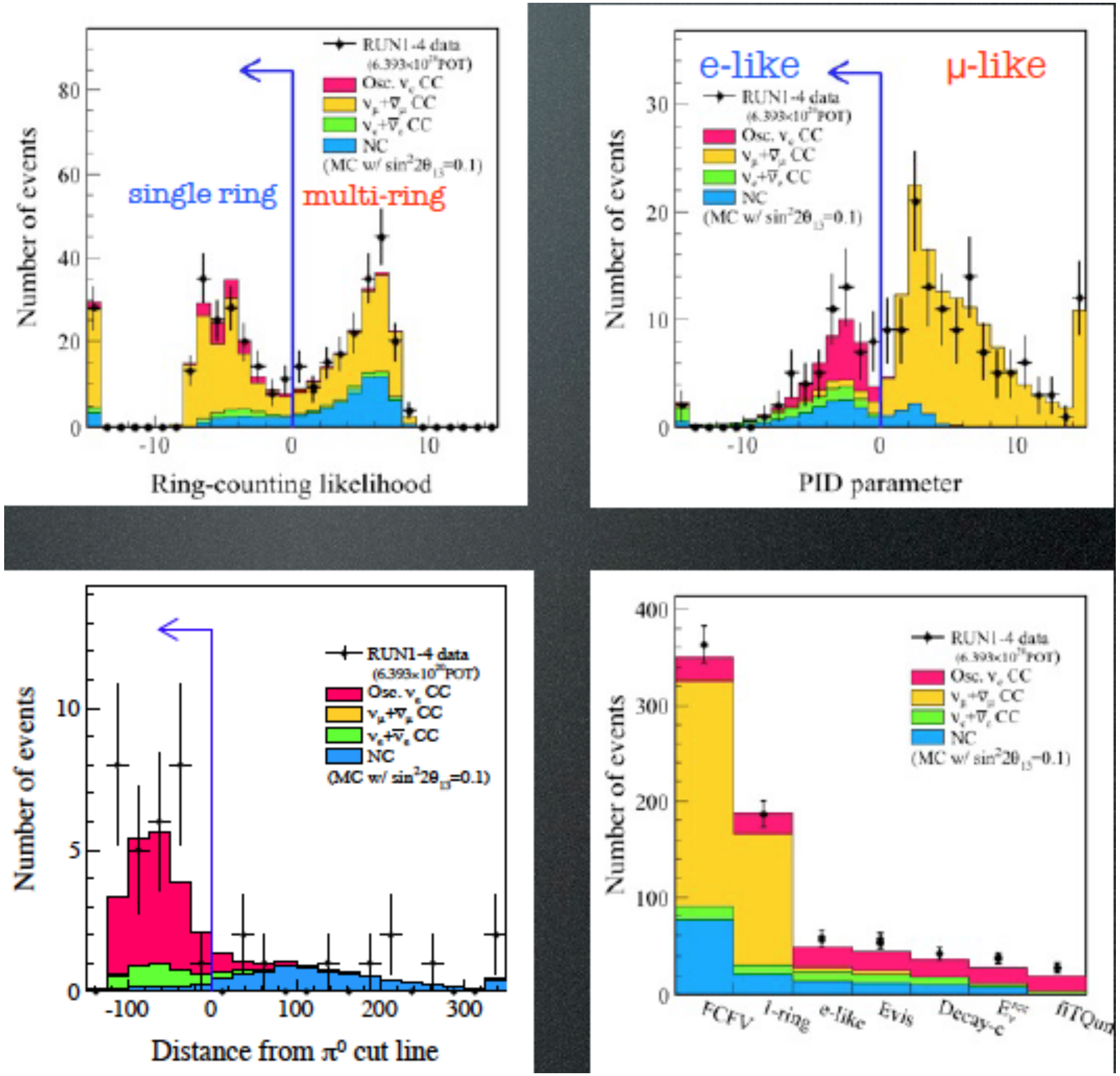
T2K new electron neutrino analysis

- Events selection:

Wilking, EPS-HEP (2013) Stockholm

ν_e Selection Cuts

- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- $0 < E_\nu < 1250$ MeV

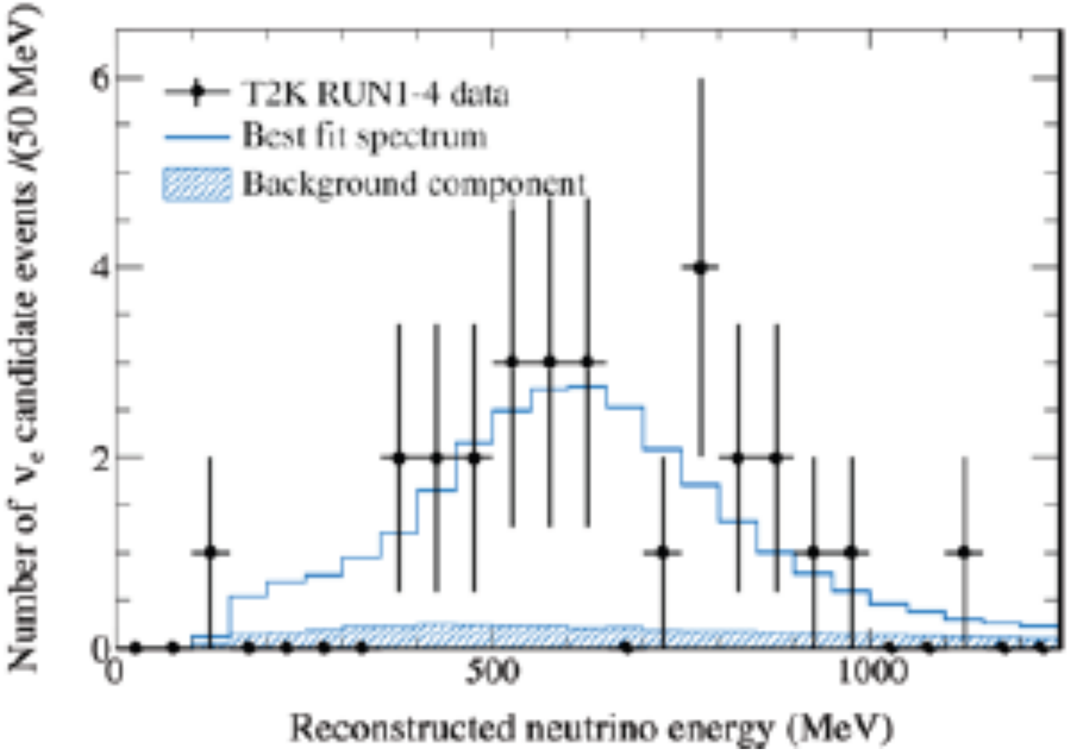


T2K new electron neutrino analysis

- Events that survive cuts: 28 events
  - Expect: 20.4 ± 1.8 events
  - Background: 4.64 ± 0.53 events

Wilking, EPS-HEP (2013) Stockholm

7.5σ sensitivity



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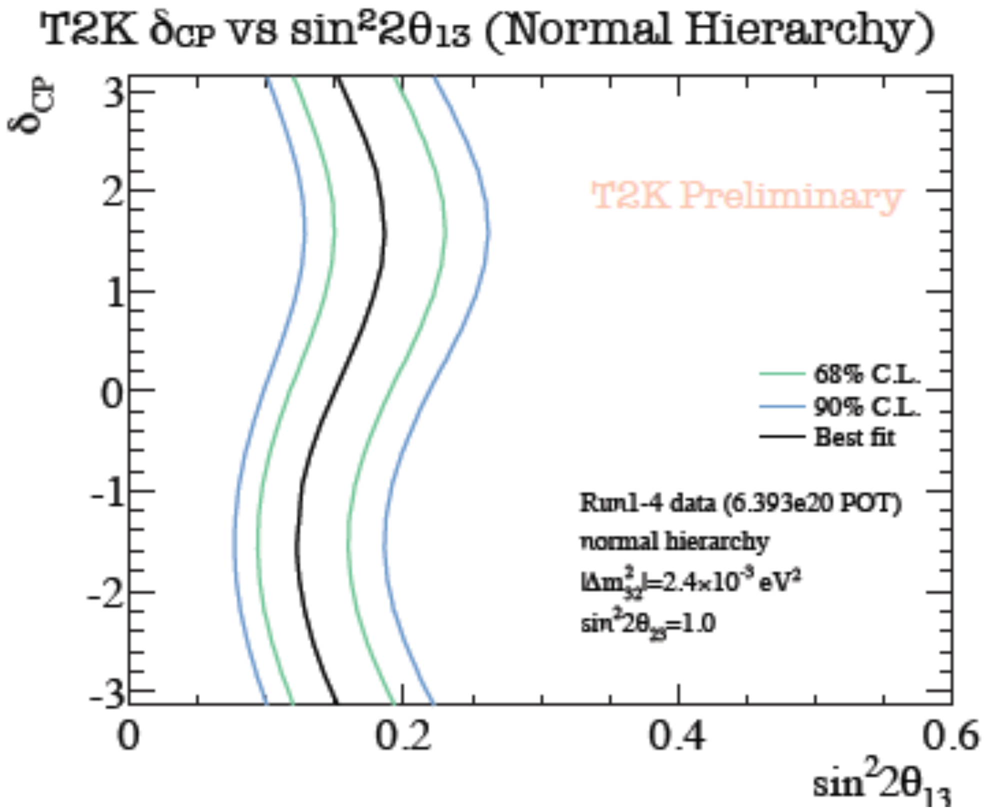
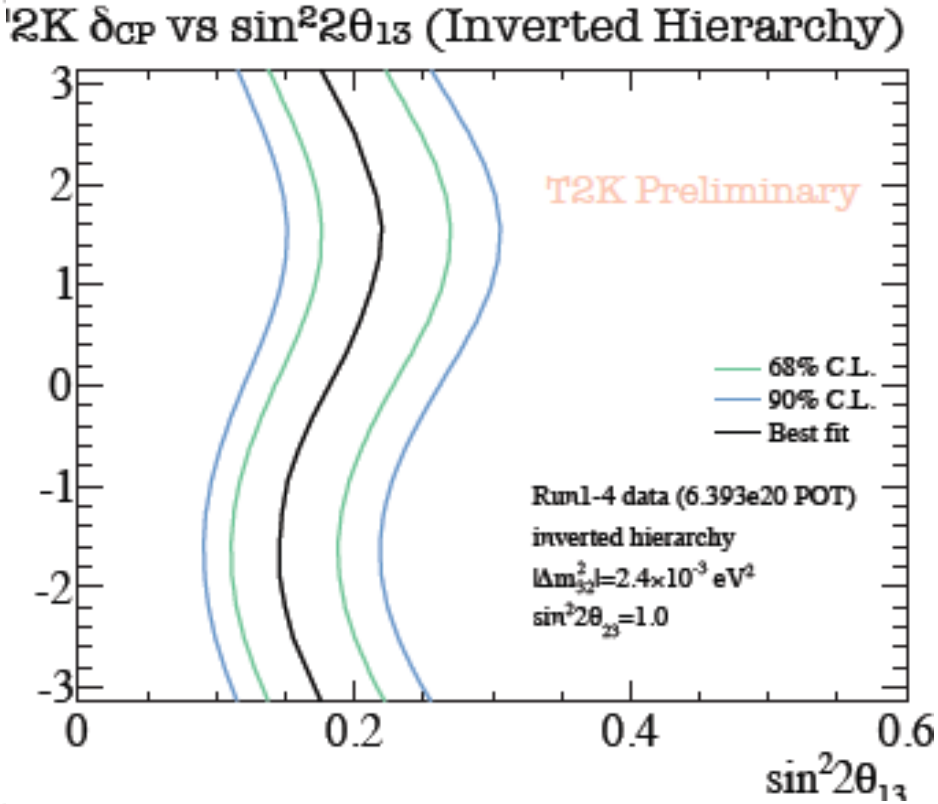
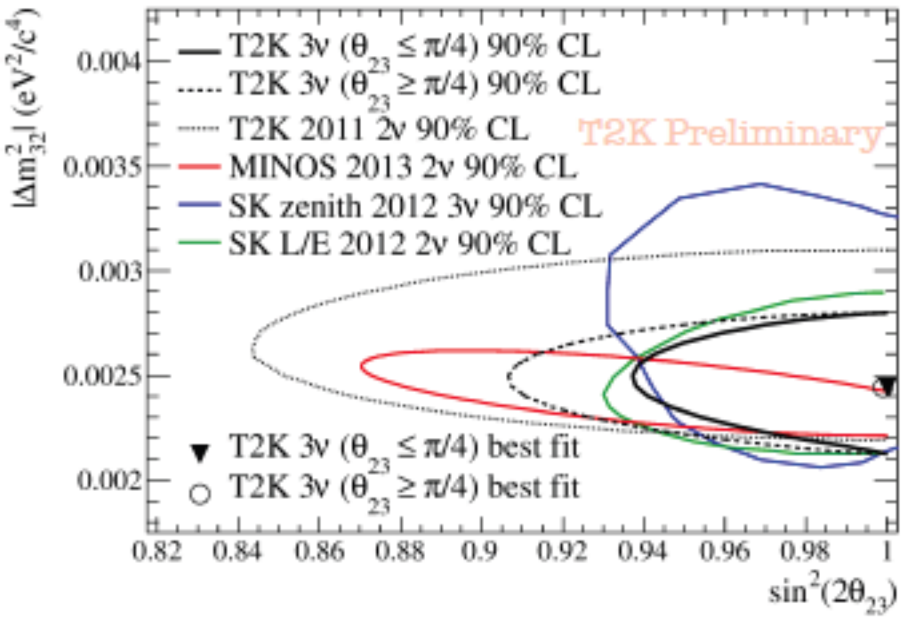


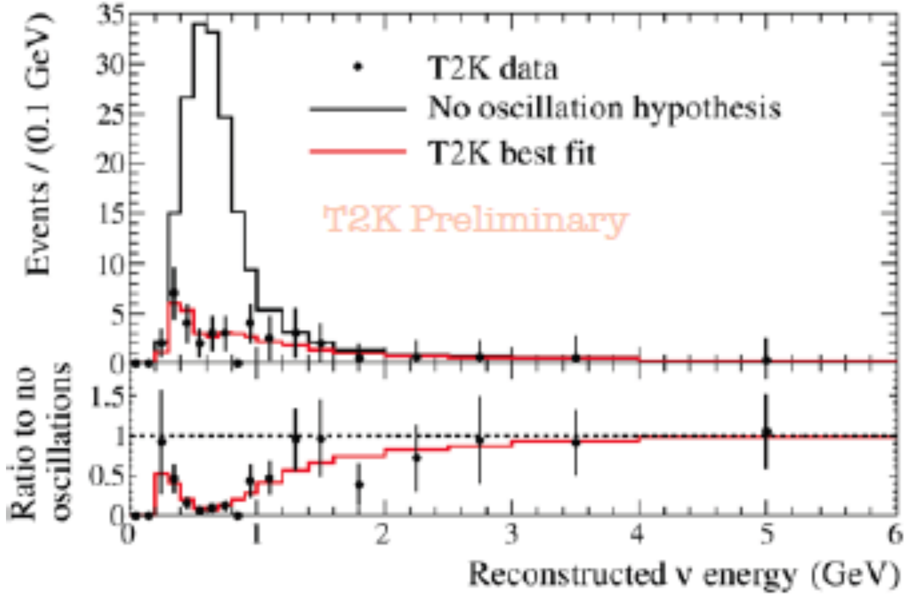


T2K ν_μ disappearance

- Updated disappearance analysis

Wilking, EPS-HEP (2013) Stockholm





Previous published T2K paper: arXiv: 1201.1386

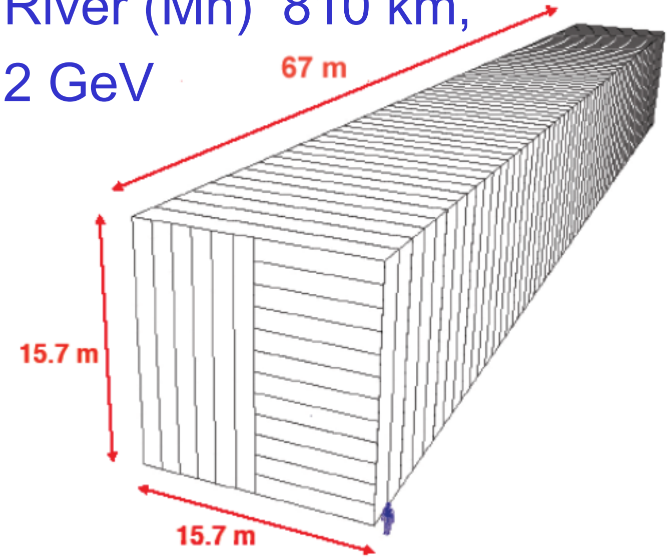
$\sin^2 2\theta_{13}=0.99$
$\Delta m^2_{32}=2.63\times10^{-3}$

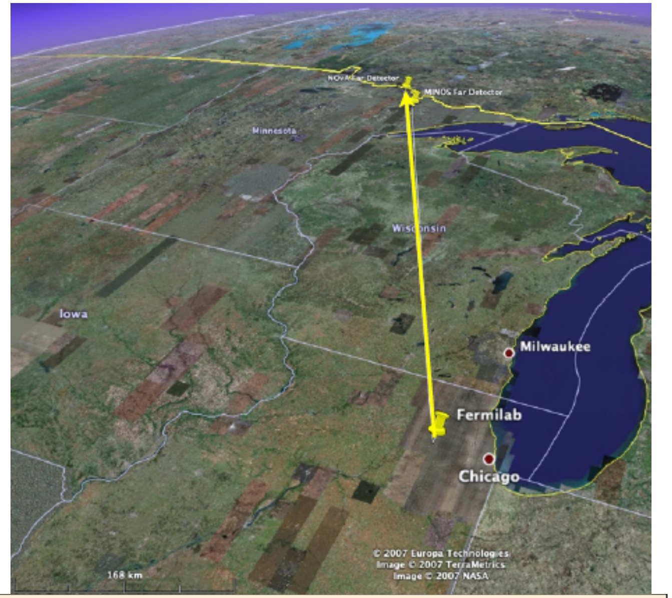
NOVA neutrino appearance

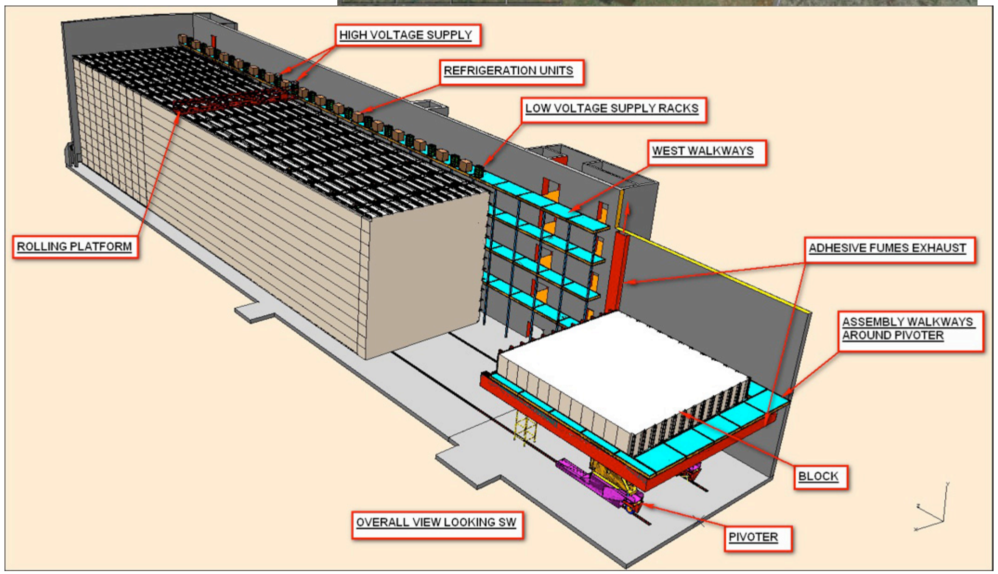
- Fermilab to Ash River (Mn) 810 km,
  - 14 mrad, ~2.2 GeV

14 kt liquid scintillator detector

Under construction



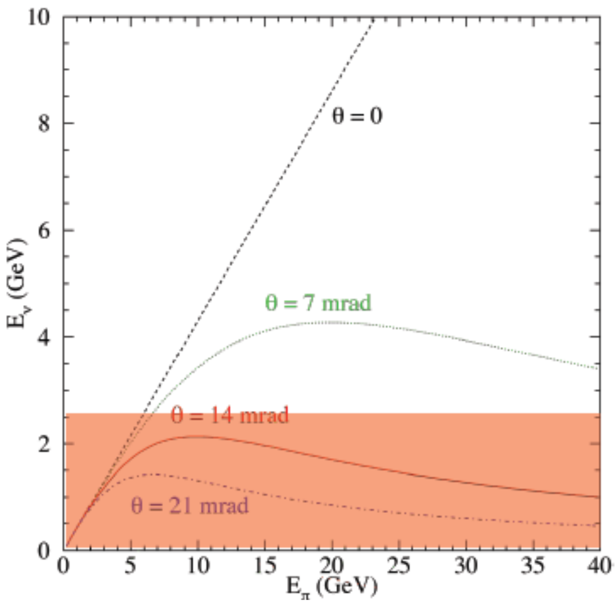




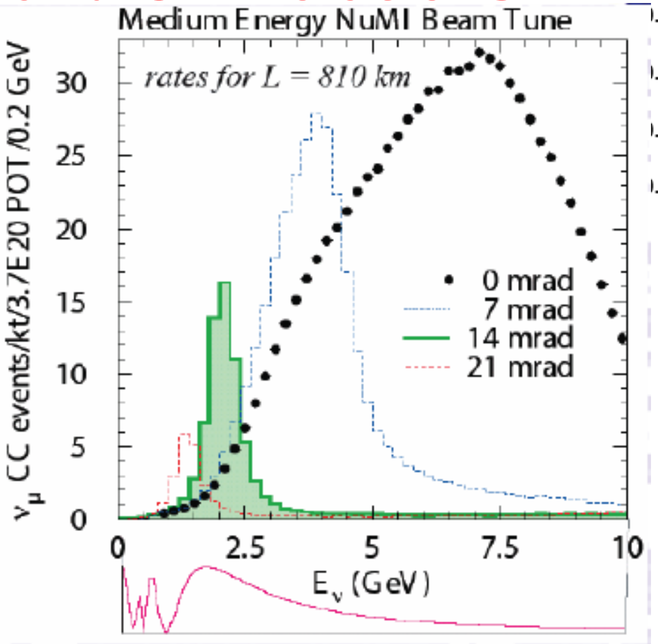
Over 2 kton of NOvA detector instrumented taking cosmics

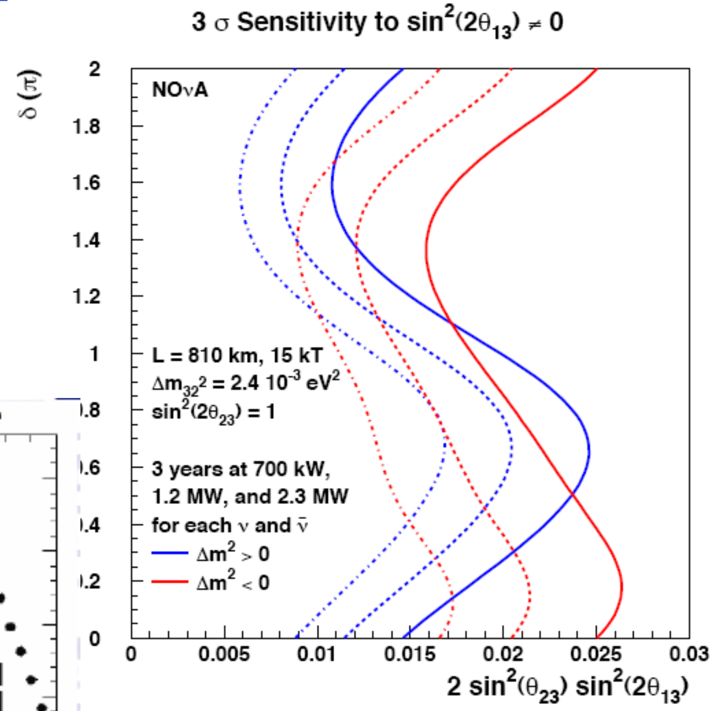
NOVA neutrino experiment

- Fermilab to Ash River (Mn) 810 km,
  - 14 mrad, ~2.2 GeV



Main goals: θ_{13}, mass hierarchy and CP violations





On track to commence summer 2014