NEUTRINO OSCILLATIONS: CURRENT EXPERIMENTAL VIEW

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NEUTRINO OSCILLATIONS: CURRENT EXPERIMENTAL VIEW

- Standard oscillation picture
- Current measurements in the 1-2 and 2-3 sectors
- θ_{13} and the future
- Anomalies

Neutrino oscillation probability in standard 3-neutrino picture

- The flavor eigenstates are related to the mass eigenstates by matrix *U*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing Matrix (aka MNSP Matrix)

- Probability for detecting particular flavor depends on the values in *U* and the Δm^2 between the neutrino mass states. In general:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin^2[1.27\Delta m^2_{ij}(L/E)]$$
$$-2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) sin[2.54\Delta m^2_{ij}(L/E)]$$

L=Distance in km,
E=Energy in GeV

Matrix Elements

$\Delta m^2_{ij} = m_i^2 - m_j^2$,
m=neutrino mass in eV

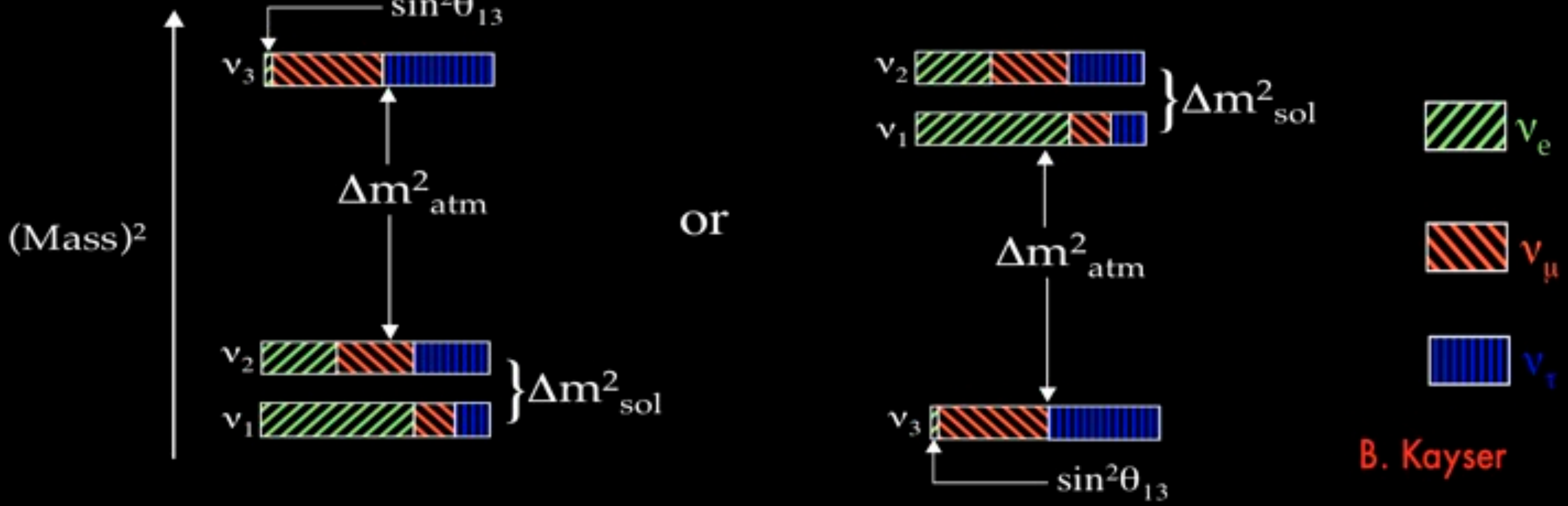
Parametrizing the matrix

- *U* is a basis transformation, and therefore a unitary matrix. Can be fully specified with four real numbers: three angles θ_{12}, θ_{13}, θ_{23} and one phase δ_{CP}:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $s_{ij} = sin(\theta_{ij})$ and $c_{ij} = cos(\theta_{ij})$

- As with quark mixing, *CP* violation is only possible if all three angles are nonzero.



B. Kayser

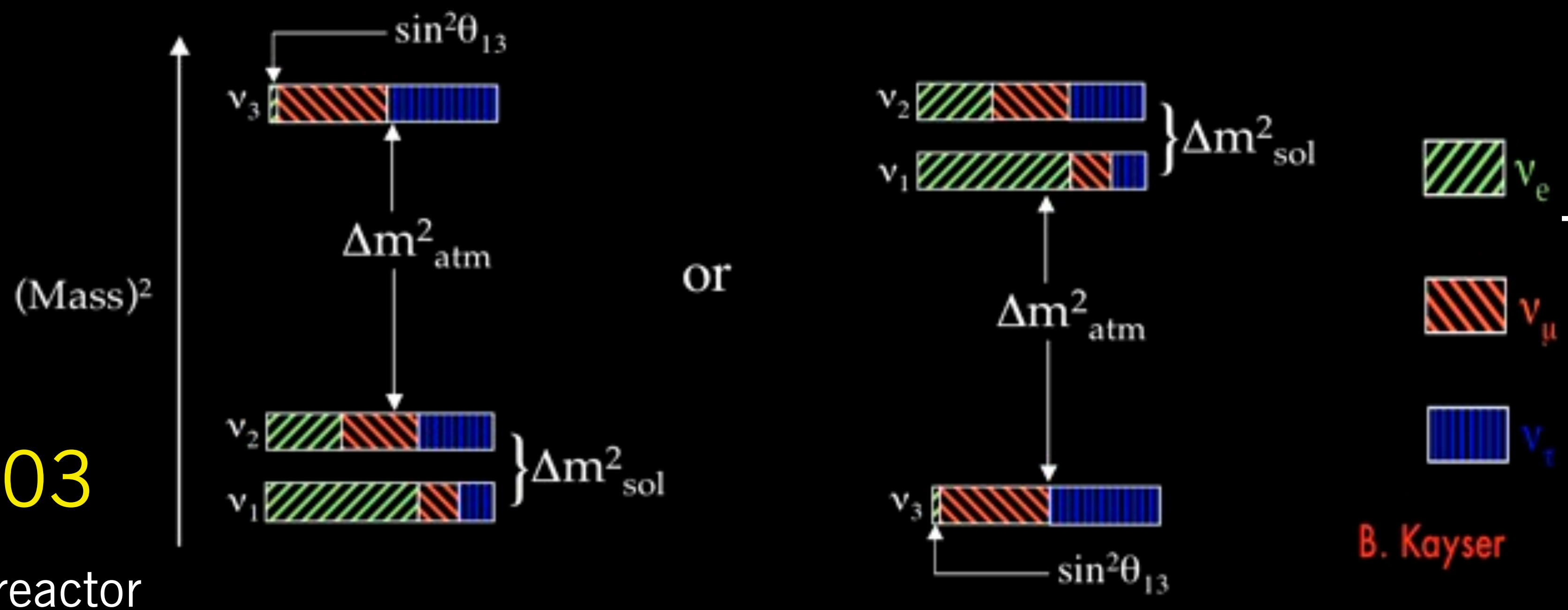
Character of the parameters

- Matrix is characterized by large mixing angles (unlike the quark sector)
- The hierarchy of masses and the large mixing angles mean that most experiments (up to now) could be analyzed by neglecting all but a single dominant oscillation mode -- reducing the transmutation probability to the simple

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

with mc^2 in eV and L/E in km/GeV.

Our "current" knowledge (PDG averages)



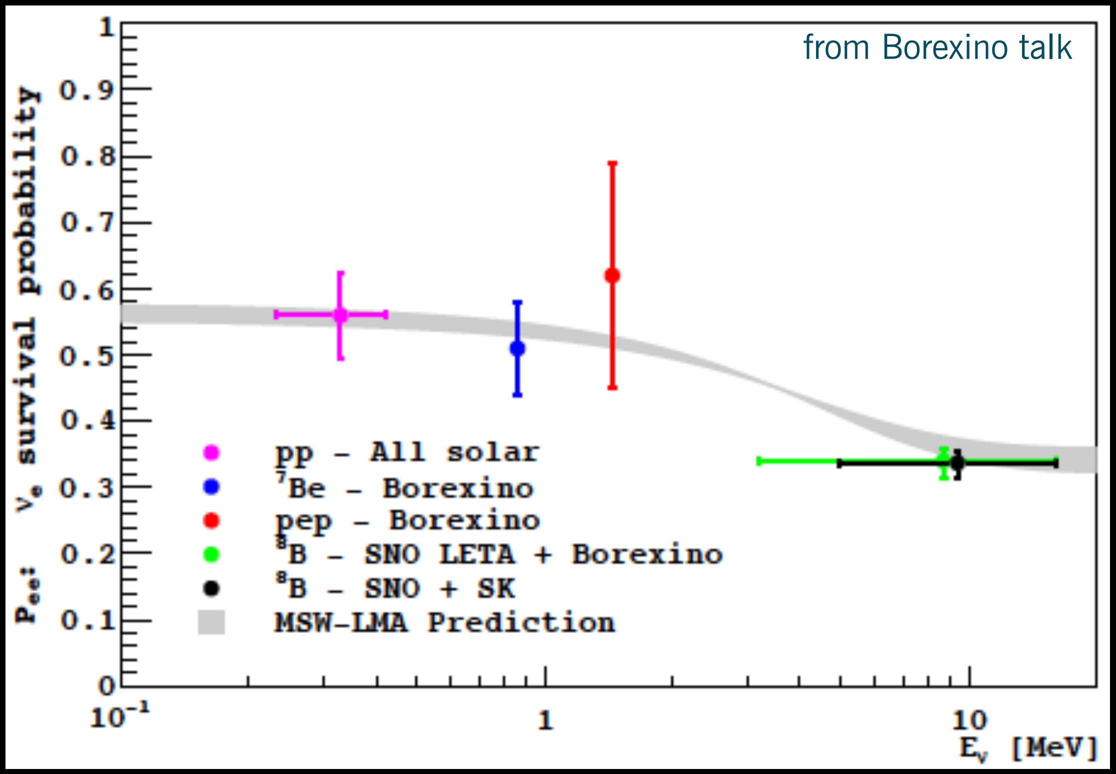
B. Kayser

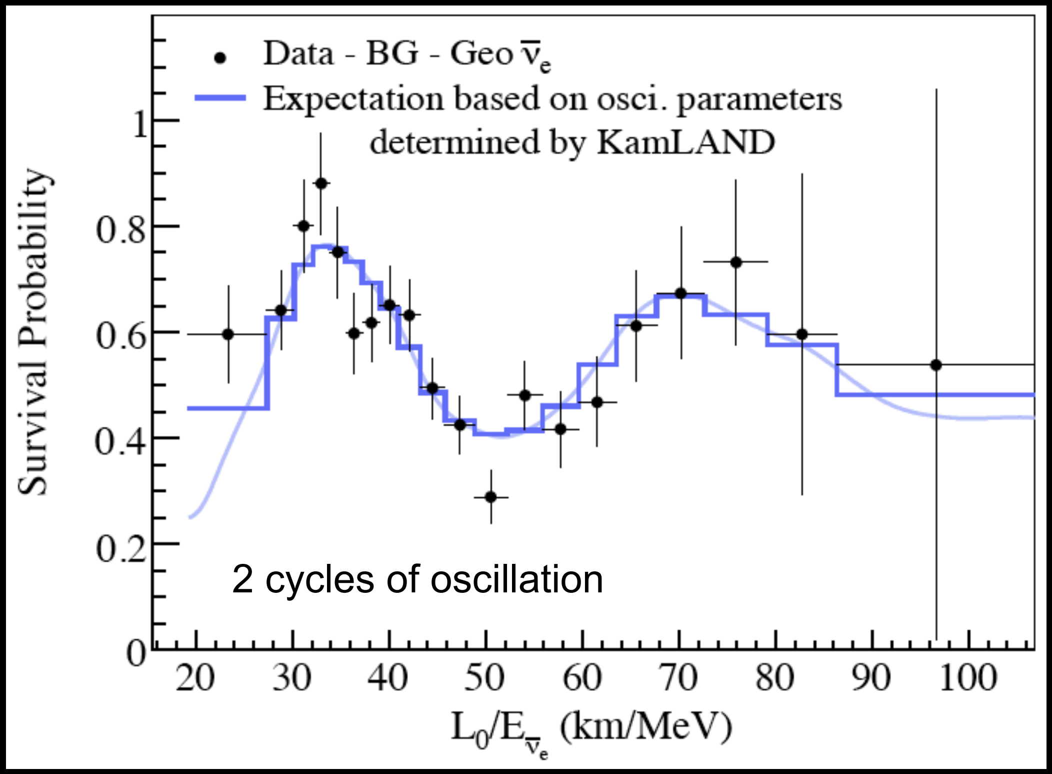
- $\sin^2(2\theta_{12}) = 0.87 \pm 0.03$
  - Solar neutrinos, long-baseline reactor
- $\Delta m^2_{21} = (7.59 \pm 0.20) \times 10^{-5}\,\mathrm{eV}^2$
  - Solar neutrinos, long-baseline reactor
- $\sin^2(2\theta_{23}) > 0.92$, CL=90%
  - Atmospheric neutrinos, long-baseline accelerator
- $|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\,\mathrm{eV}^2$
  - Atmospheric neutrinos, long-baseline accelerator; sign unknown
- $\sin^2(2\theta_{13}) < 0.15$, CL=90%
  - Short-baseline reactor, long-baseline accelerator
- δ_{CP}: No significant direct information
  - Long-baseline accelerator, neutrino factories?

Major new results in past year

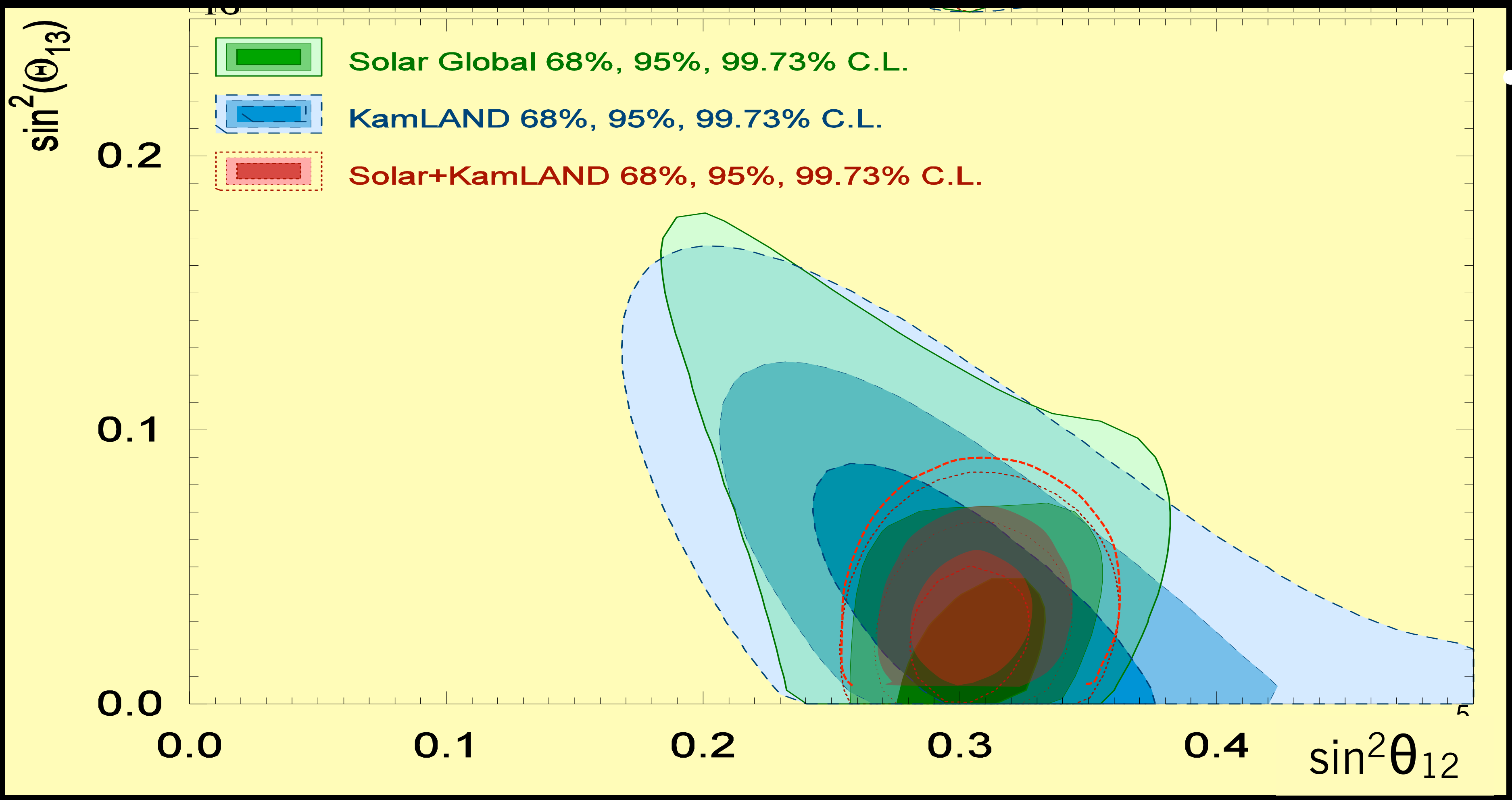
The “1-2” sector: data

- Observed in solar ν_e disappearance measurements, where matter effects in the sun are crucial for interpretation
- Long-baseline reactor measurement (KamLAND)


from Borexino talk


2 cycles of oscillation

1-2 sector mixing angle fit

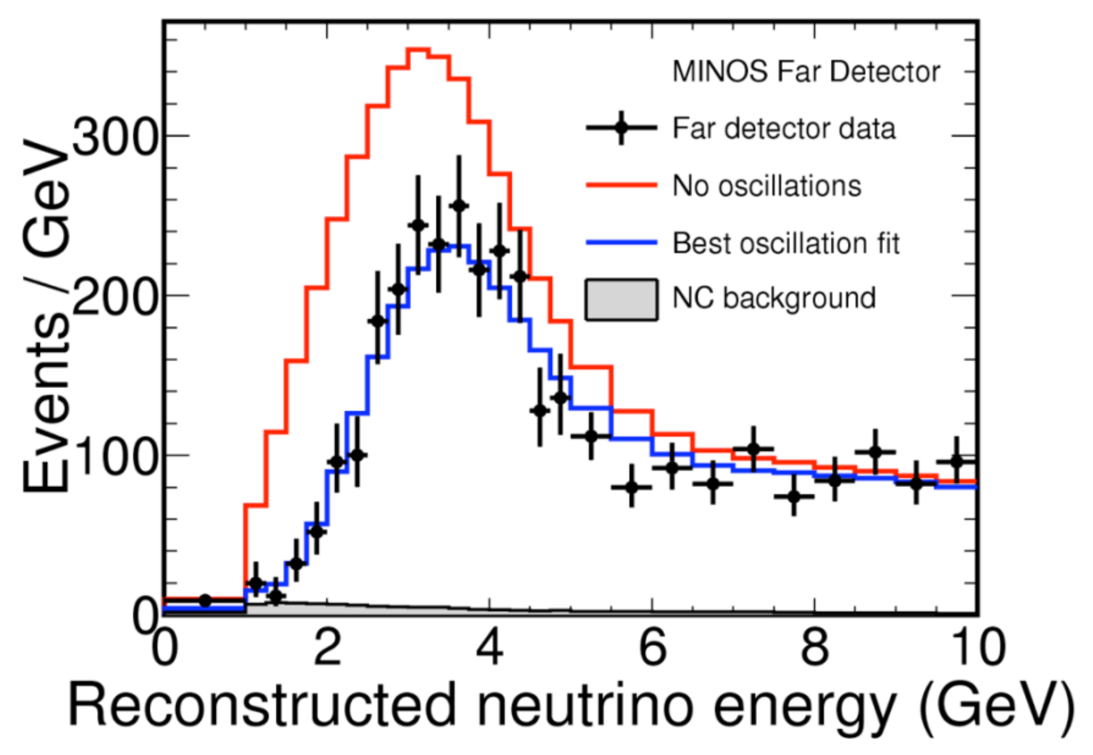


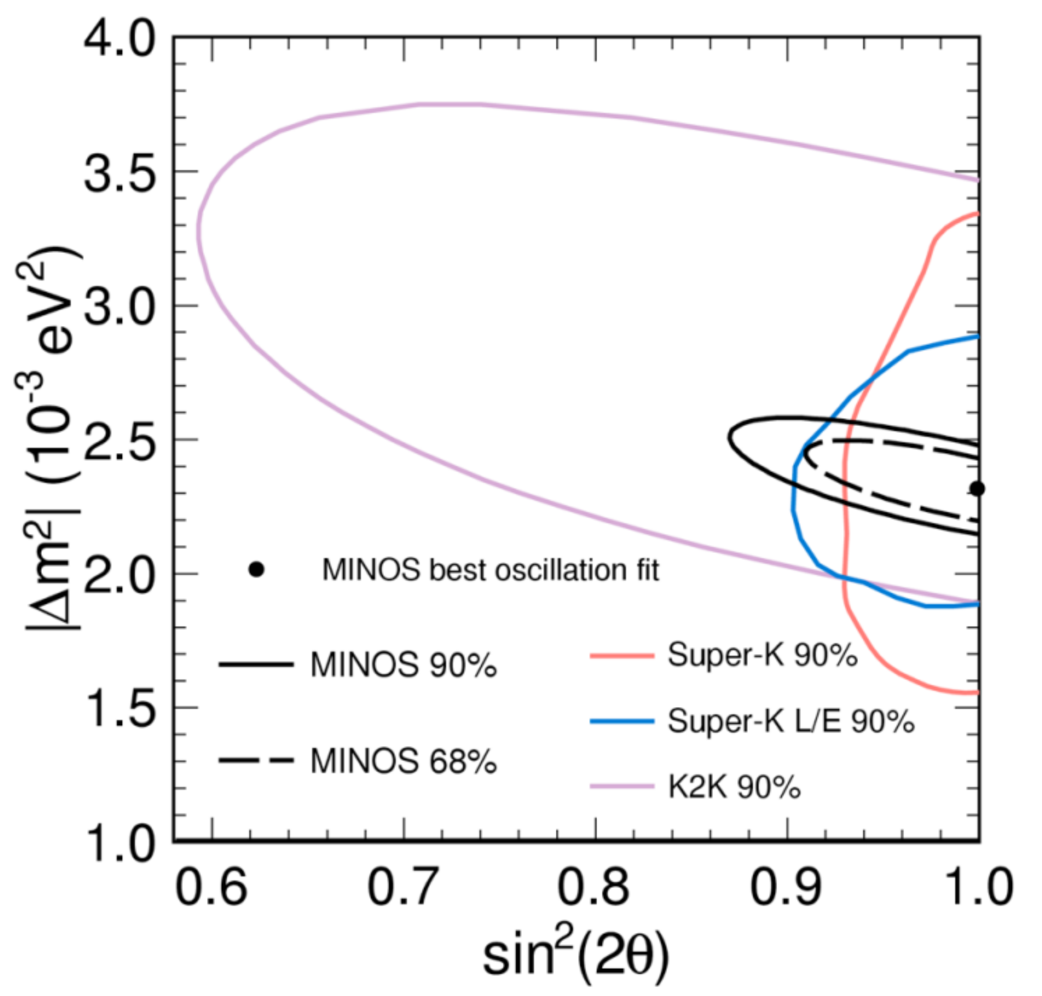
- Note: axes are $\sin^2\theta$, not $\sin^2(2\theta)$

- Mixing large but not maximal

The “2-3” sector

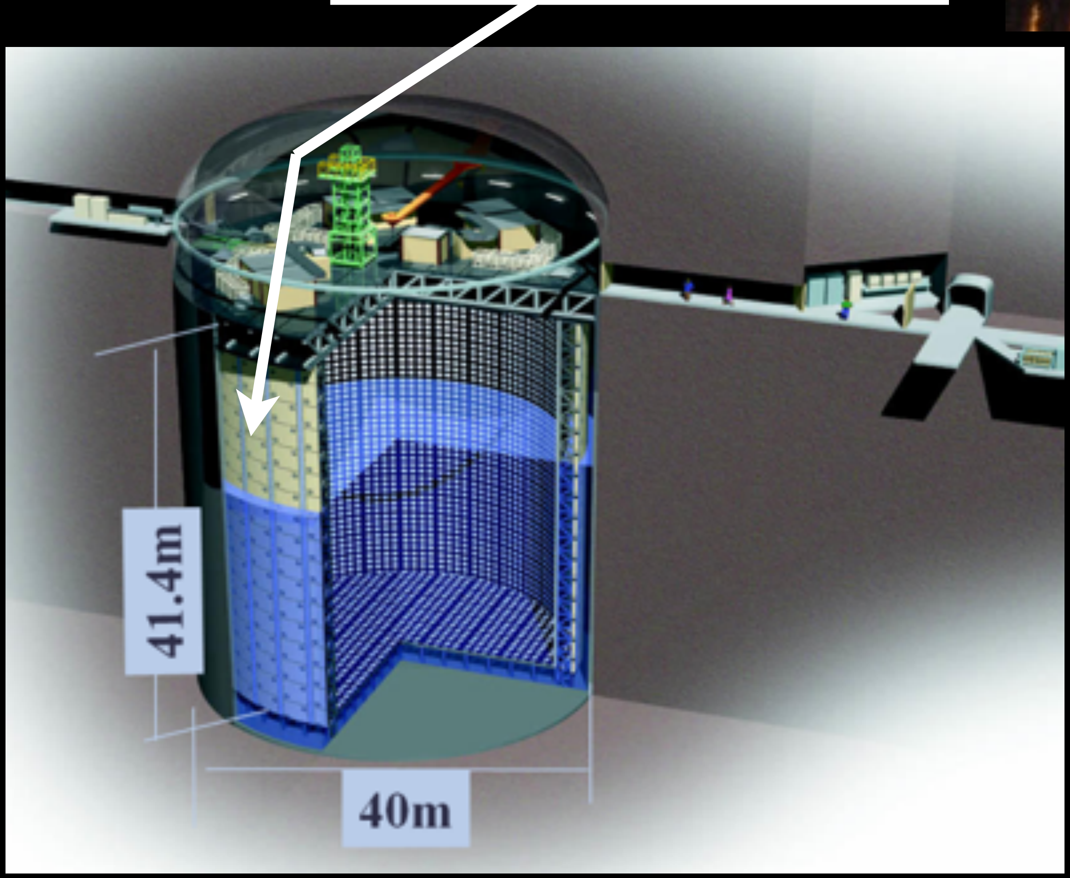
- Originally measured using atmospheric ν_μ disappearance (Super-Kamiokande 1998 and subsequent); now also with long-baseline accelerator measurements
- Super-K and MINOS (Fermilab) now have the most precise results on mixing angle and Δm^2 respectively
- Fits still favor maximal mixing!
- Dominant effect is $\nu_\mu \leftrightarrow \nu_\tau$ in standard oscillation picture





Super Kamiokande

- 50 kt water Cherenkov (22.5 kt fiducial)
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector

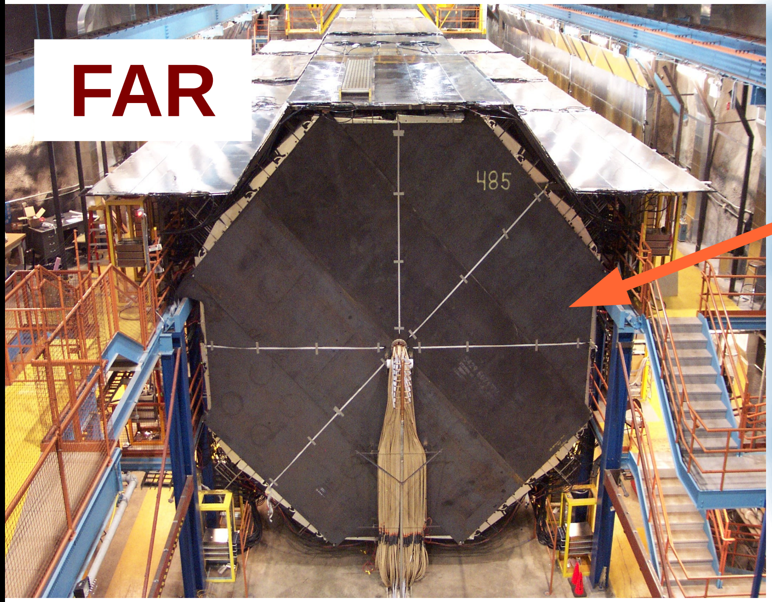


- Originally commissioned 1997
- Designed for proton decay and neutrino measurements
- Sensitive to solar neutrinos as well as atmospheric
- Now also used as far detector for T2K

MINOS long-baseline experiment

- Conventional ν_μ beam from pion/kaon decays in flight at Fermilab; 734 km baseline to far detector

alternating layers of steel plates and scintillator strips in a ~1.3 T toroidal magnetic field



735 km from the target
5.4 kilotons
8 m tall planes
486 planes (30 m)
700 m underground
Few ν interactions/day

1 km from the target
1 kiloton
~4 m tall planes
282 planes (15 m)
100 m underground
Few ν interactions/spill

L. Whitehead seminar

CPT test in 2-3 sector

Neutrino

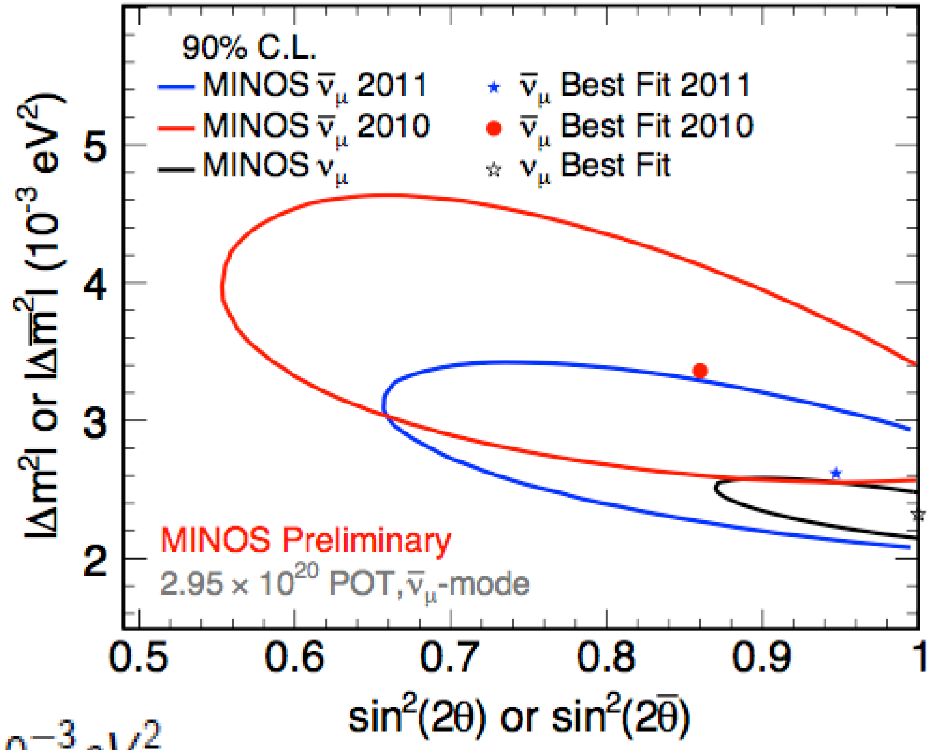
$$|\Delta m^2_{atm}| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$

$$\sin^2(2\theta_{23}) > 0.90(90\% CL)$$

Anti-neutrino

$$|\Delta \bar{m}^2_{atm}| = 2.62^{+0.31}_{-0.28}(stat) \pm 0.09(syst) \times 10^{-3} eV^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.11}_{-0.11}(stat) \pm 0.01(syst)$$

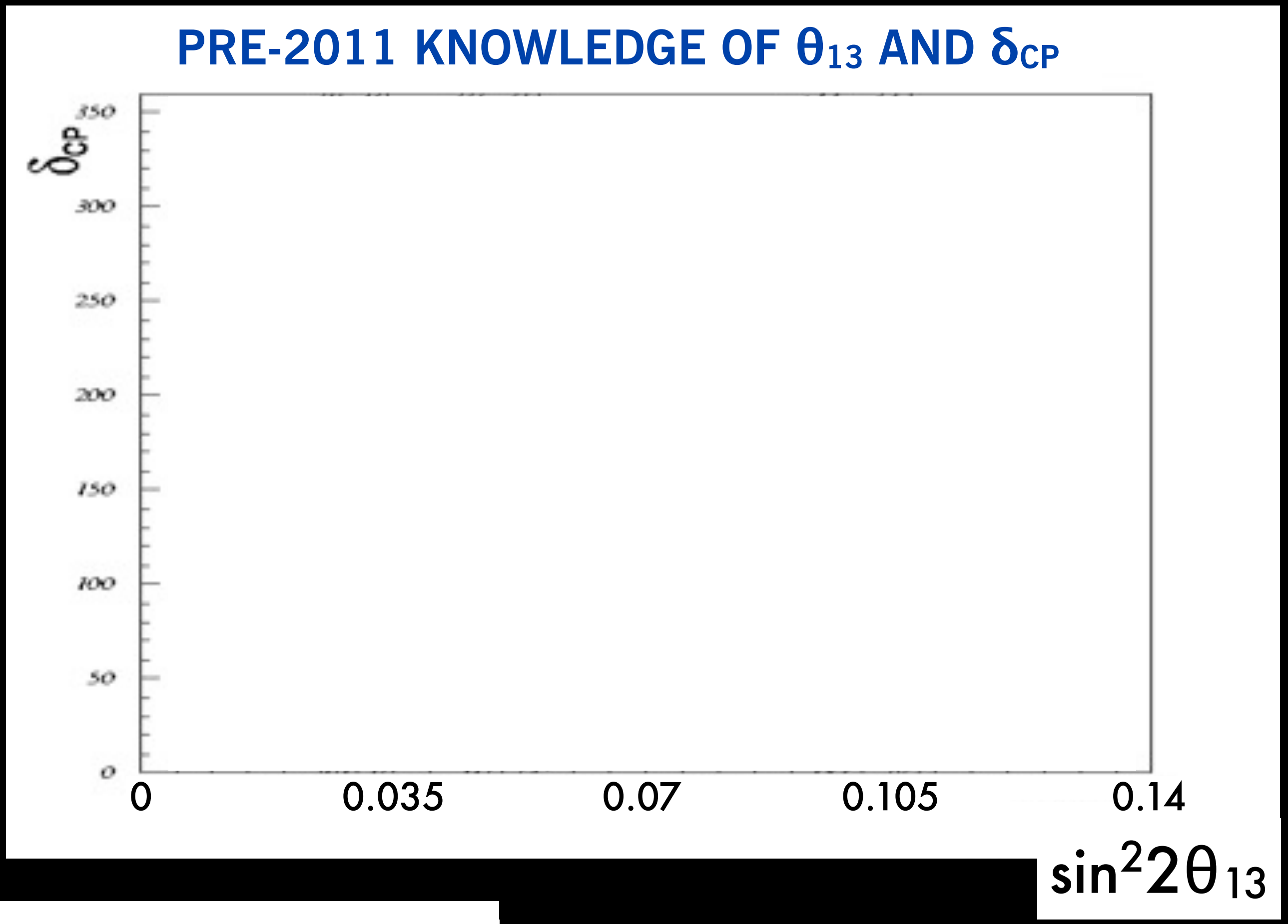


- MINOS tests consistency of disappearance parameters with neutrinos and antineutrinos. After a fluctuation caused some excitement, CPT test now looks OK.

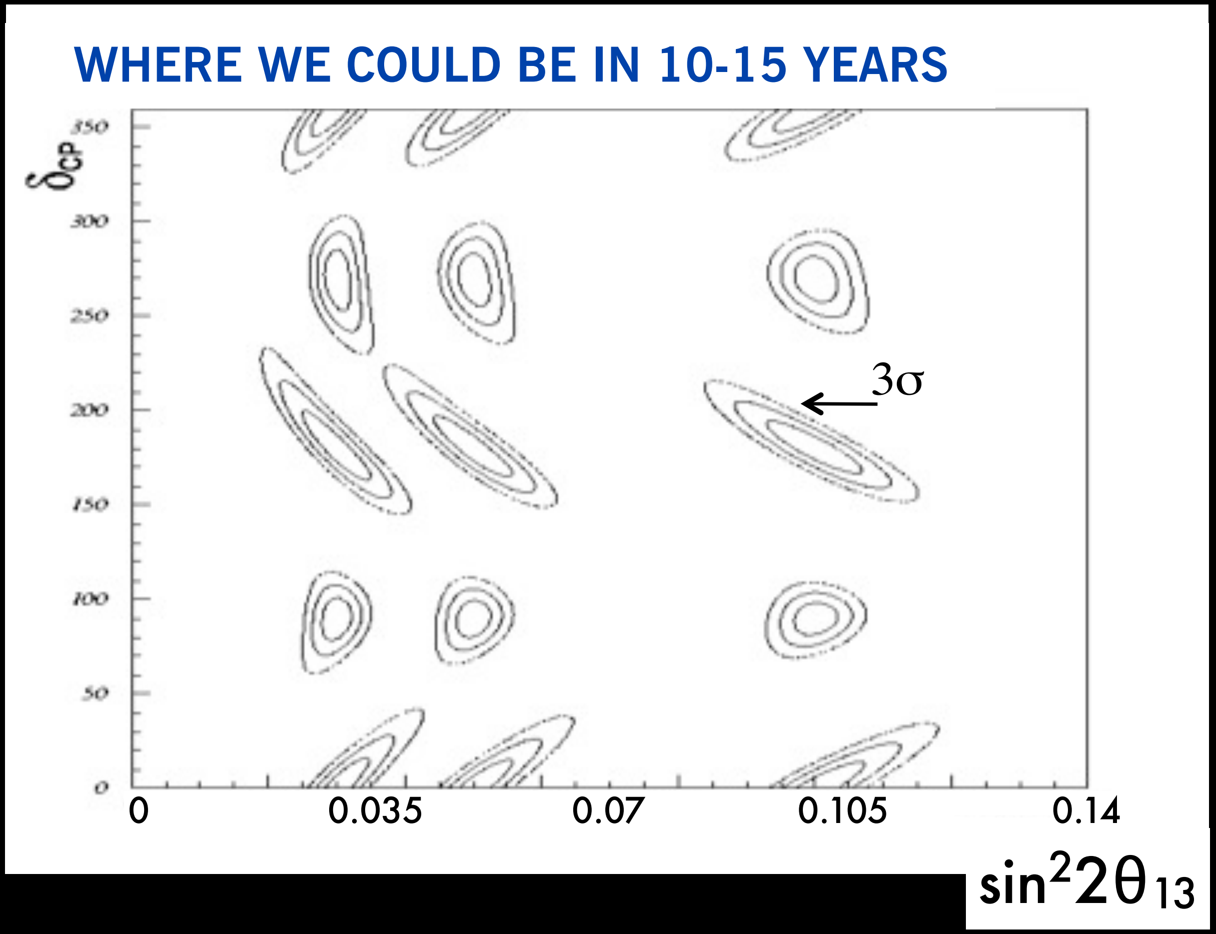
The year of θ_{13}

- Next-to-last “standard” oscillation parameter to be measured
- Non-zero value is essential for existence of *CP* violation in the standard three-neutrino picture
- Much of the present effort in neutrino experiments is aimed at this parameter

Goal is to get from:



to:



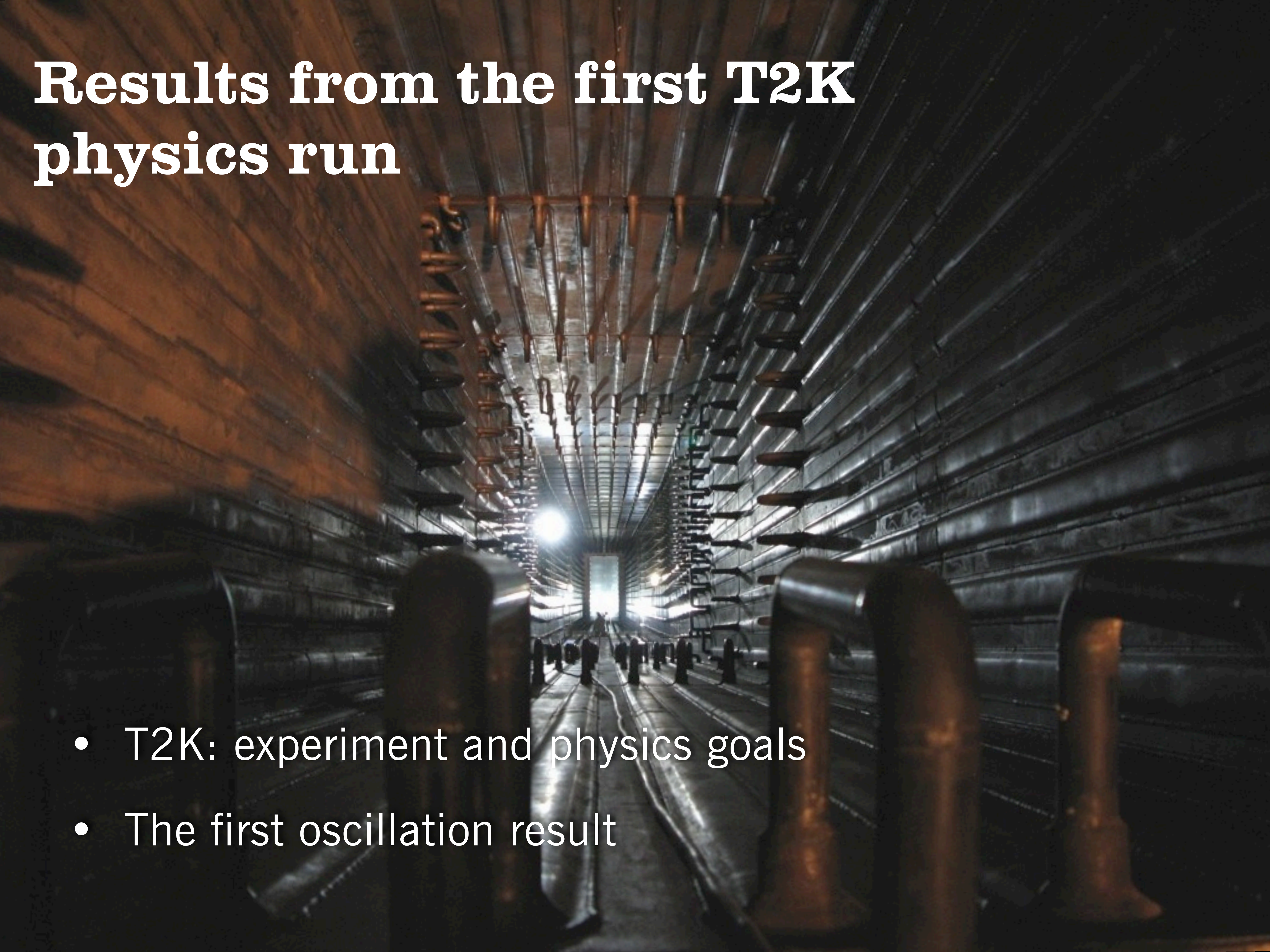
Two approaches:

- Search for $\nu_\mu \rightarrow \nu_e$ in long-baseline accelerator measurements
- Search for $\bar{\nu}_e$ disappearance at nuclear reactors

T2K and future neutrino oscillation experiments

- Present: T2K, MINOS, reactors
- Near future: NOvA
- Far future: LBNE, J-PARC ultimate experiments?

Results from the first T2K physics run

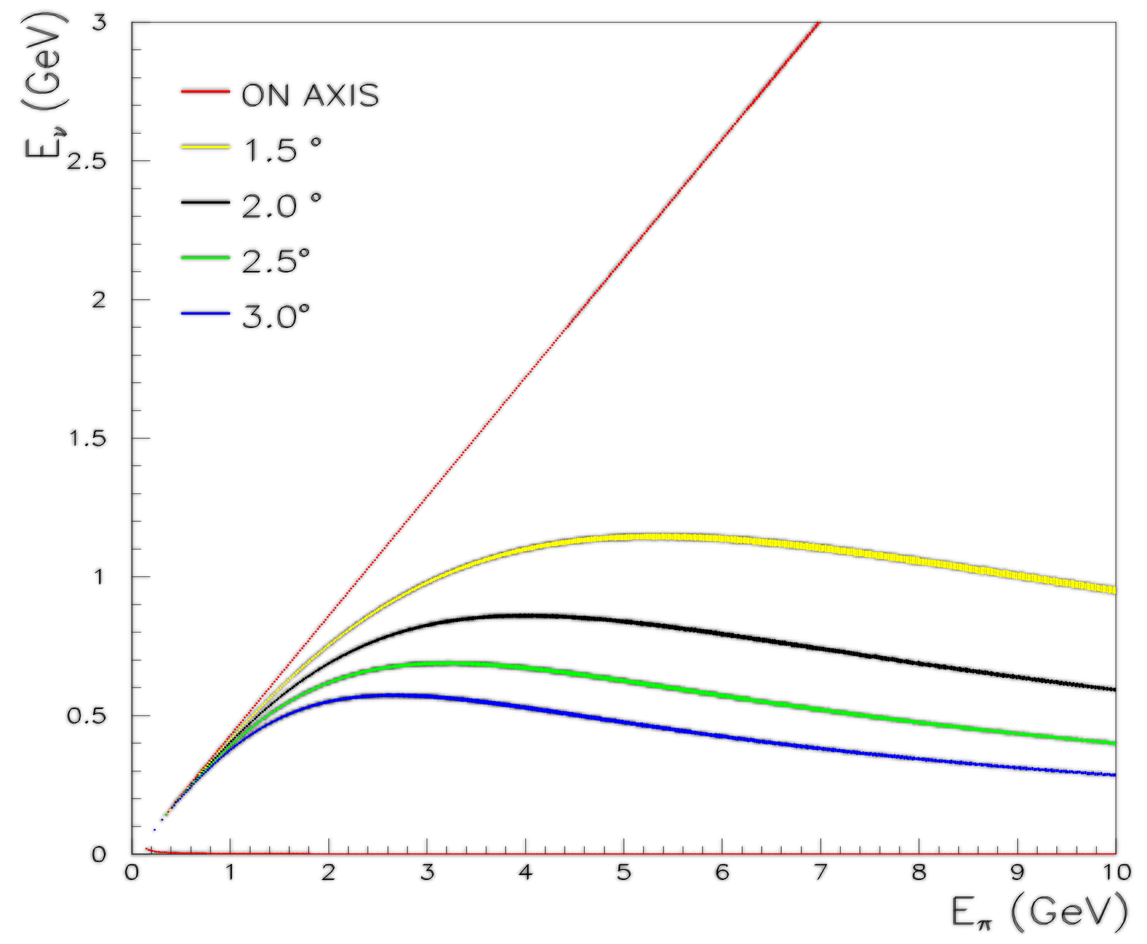


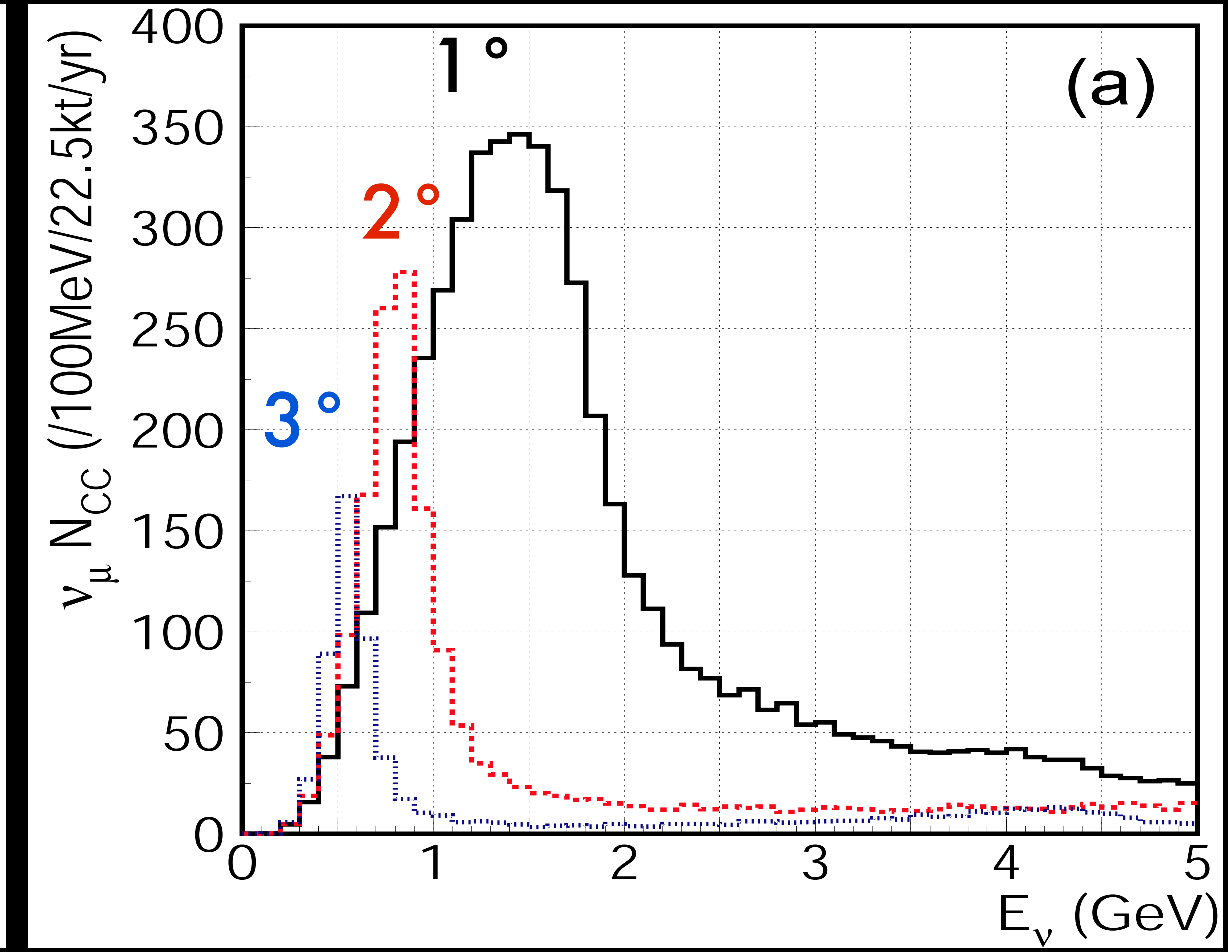
- T2K: experiment and physics goals
- The first oscillation result

T2K design and physics goals

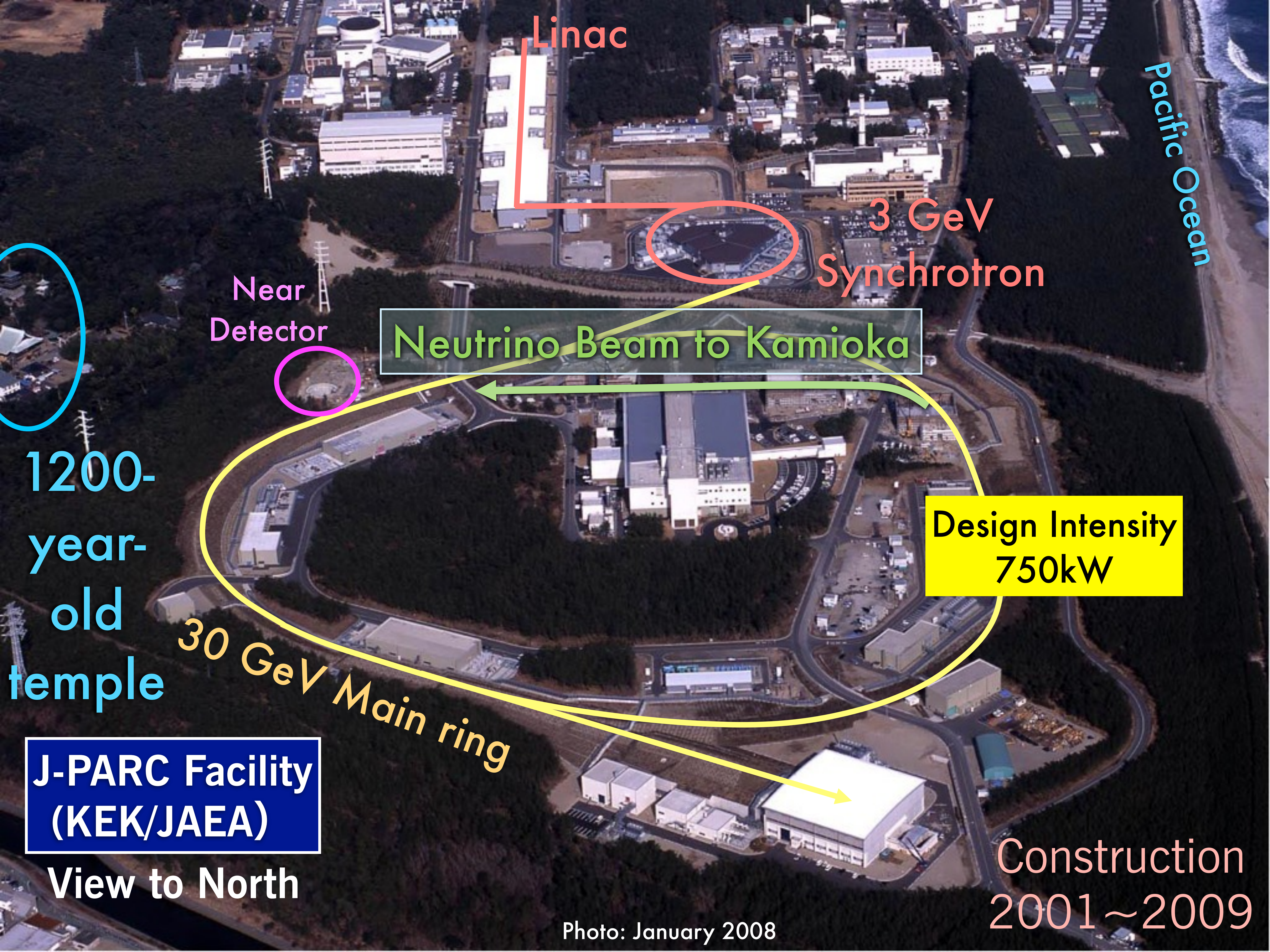
- Design:
  - First experiment to use off-axis technique to produce a narrow-band ν_μ beam
  - High-intensity 30 GeV proton beam from J-PARC sychrotron
  - Beam monitors to measure primary and secondary beam each pulse
  - On- and off-axis near neutrino detectors to characterize beam
  - Far detector Super-Kamiokande, 295 km baseline
- Initial physics goals:
  - Discover ν_e appearance and determine θ_{13}
  - Precise measurement of ν_μ disappearance θ_{23}, Δm^2_{23}
- Future:
  - Possible search for CP violation in lepton sector

Off-axis beam technique





- For wide range of pion momenta, E_ν depends more on decay angle than E_π
- Exploit to make narrow-band ν_μ beams by going off-axis
- At 295 km baseline, first oscillation maximum is at 570 MeV for $\Delta m^2 = 2.4 \cdot 10^{-3}$ eV^2 ⇒ T2K wants 2.5° off-axis angle



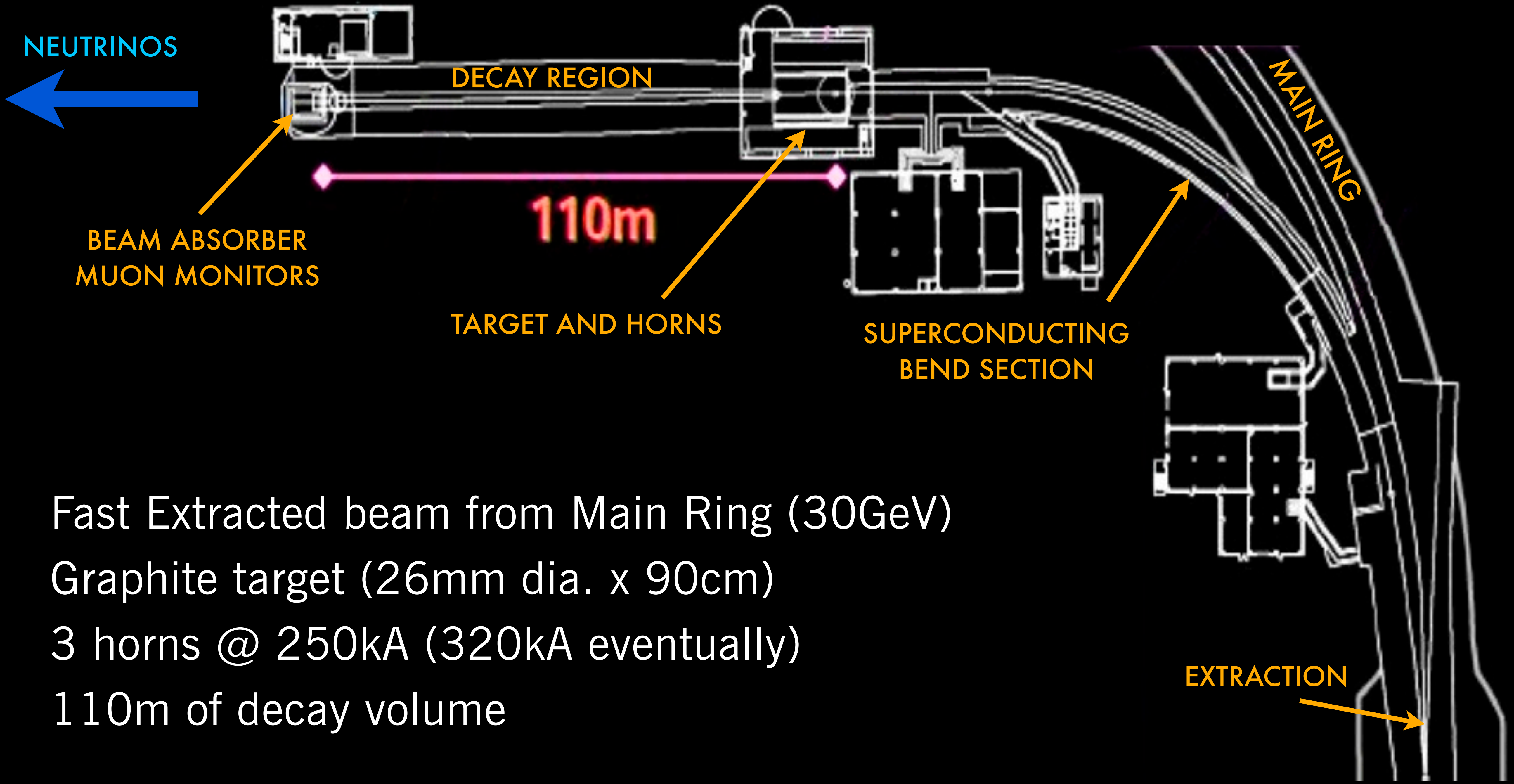
J-PARC Facility (KEK/JAEA)

View to North

Photo: January 2008

Construction 2001~2009

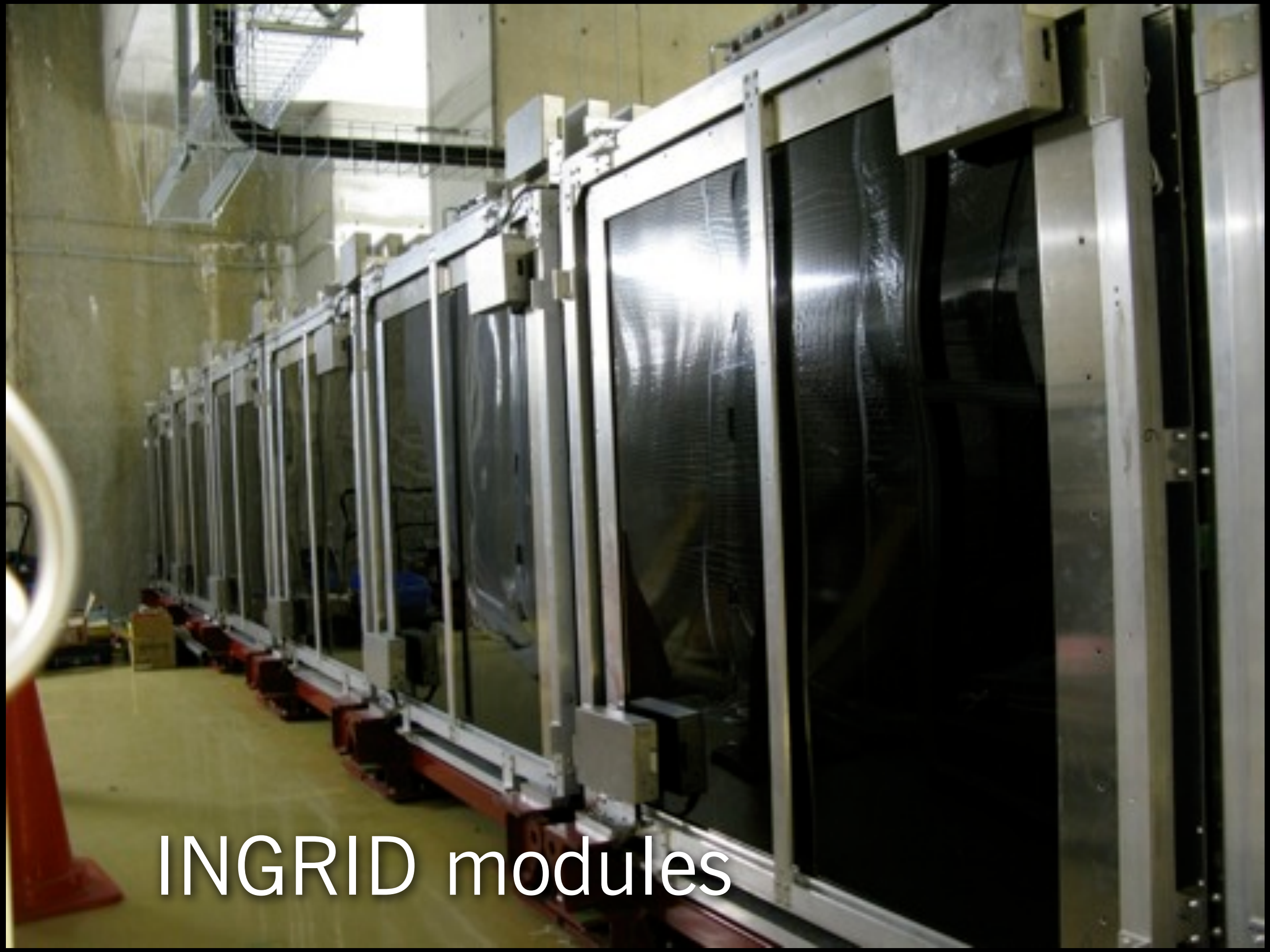
Neutrino Beam



- Fast Extracted beam from Main Ring (30GeV)
- Graphite target (26mm dia. x 90cm)
- 3 horns @ 250kA (320kA eventually)
- 110m of decay volume

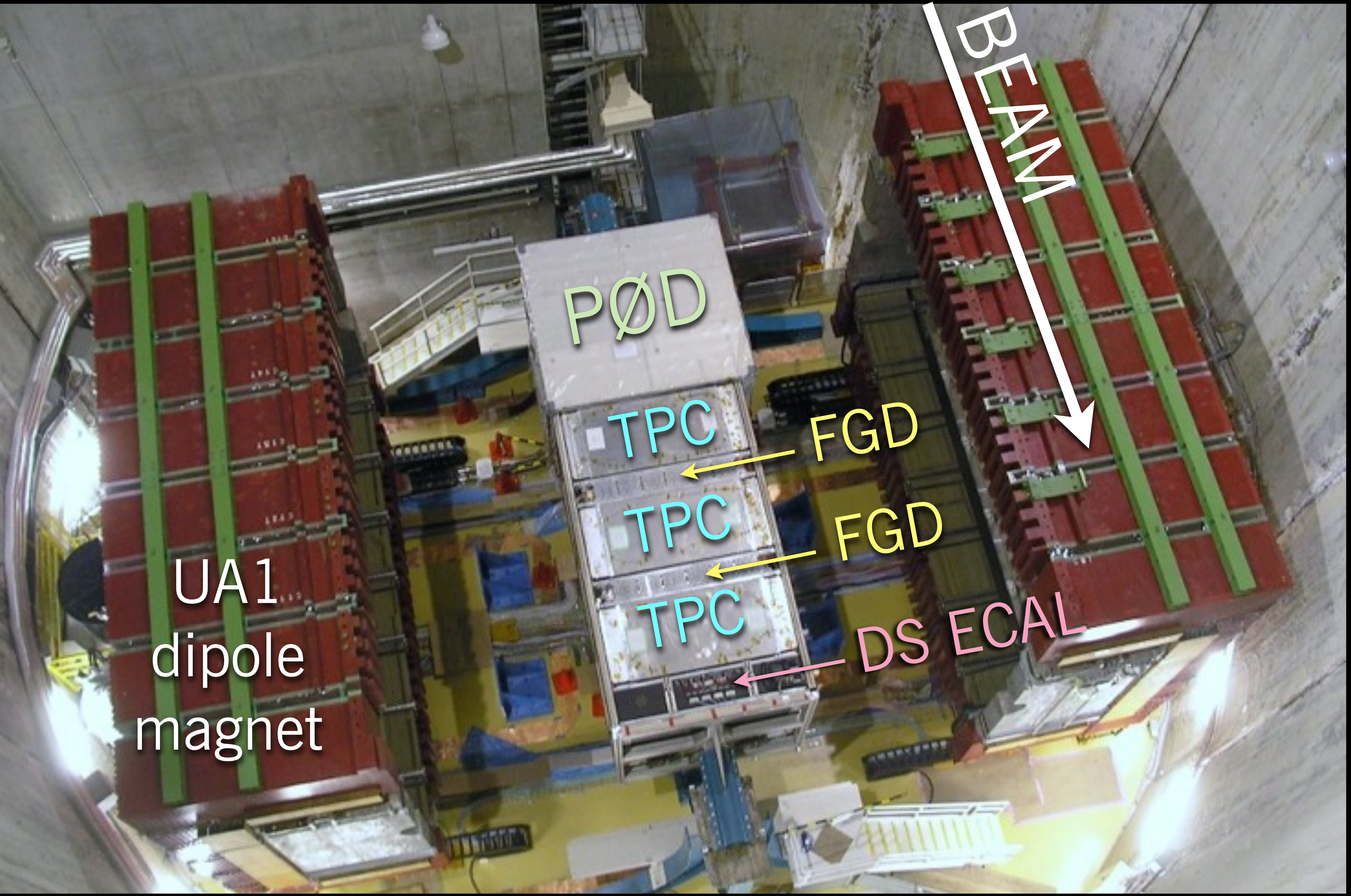
280m on-axis near detector: INGRID

- Array of 9-ton iron-scintillator neutrino detectors in cross shape centered on beam axis
- Designed to show neutrino beam profile, event rate, and precise measure of beam center/off-axis angle



INGRID modules

Off-axis Near Detector



- Pi Ø Detector (PØD): optimized for π^0 detection, includes H_2O target
- Tracker: 2 Fine-Grained Detectors (FGD), 3 TPCs: measure fluxes before oscillation
- ECAL: surrounding POD and Tracker, measure EM activity
- Side Muon Range Detector: in the magnet yokes, identify muons

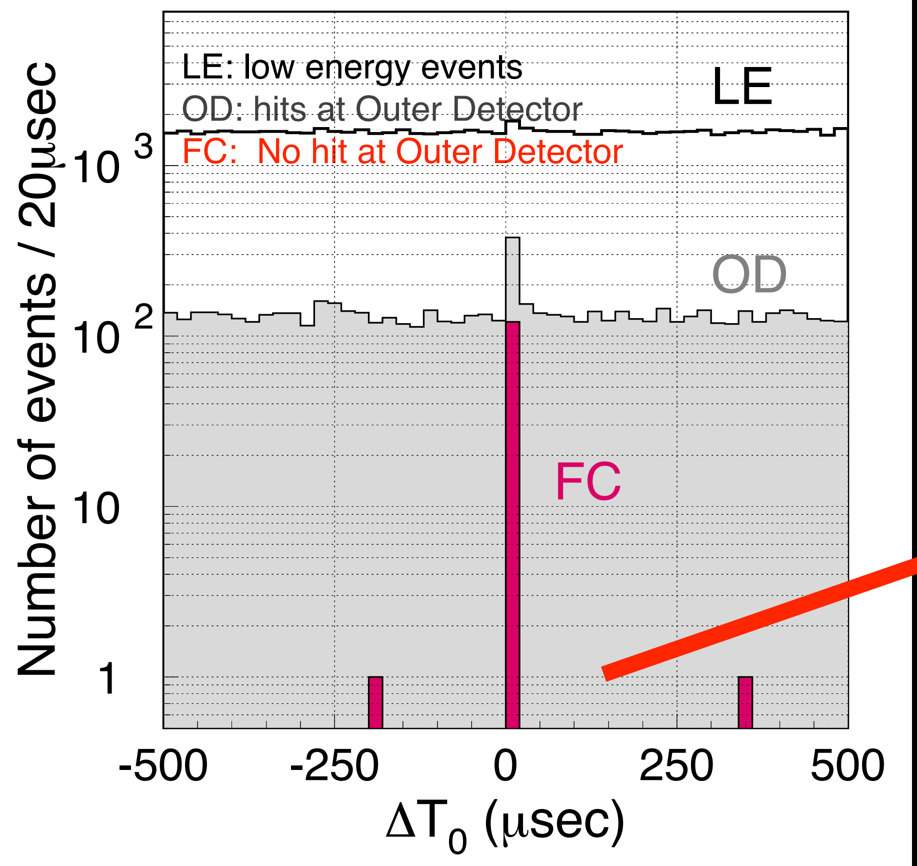
First neutrino physics runs

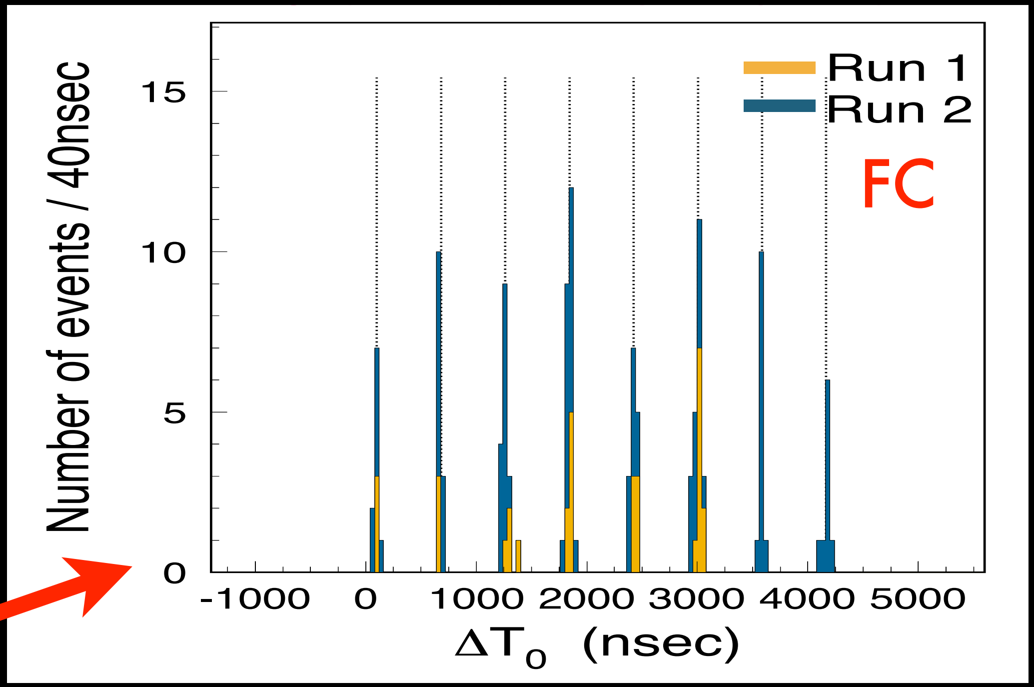
- Run 1: January-June 2010: $0.32 \cdot 10^{20}$ protons (16 kW$\cdot 10^{7}$ s)
- Run 2: November 2010-March 2011: $1.13 \cdot 10^{20}$ protons (54 kW$\cdot 10^{7}$ s)
    - Beam power up to 145 kW (most running around 50-100 kW)

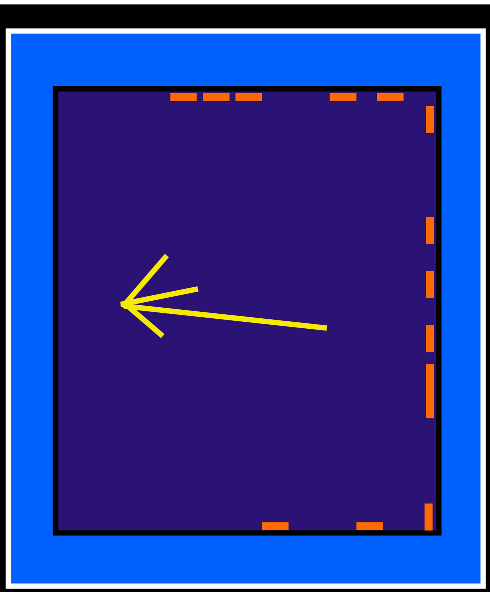
- March 11, 2011: earthquake and tsunami (1-year setback)

- Run 3: ongoing since March 2012:
    - Beam power approaching 200 kW; total has now surpassed $2 \cdot 10^{20}$ protons

Neutrino physics runs: Super-Kamiokande





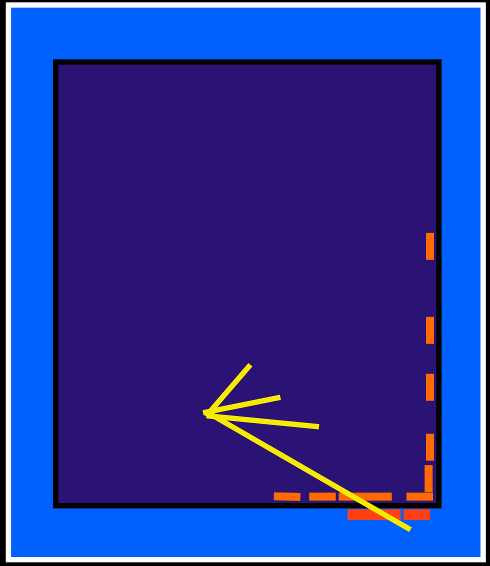


FC: Fully contained event

LE: Low energy triggered events

OD: Outer detector events

FC: Fully contained events



OD: Outer detector event

- Event time distribution clearly shows eight-bunch (six in Run 1) beam structure
- Observed # of fully contained events: 121
- Expected non-beam background: 2.3×10^{-3} events

First neutrino physics run: Super-Kamiokande

- SK analysis is very well established: generally looking for quasielastic scattering: $\nu_\ell n \to \ell^- p$

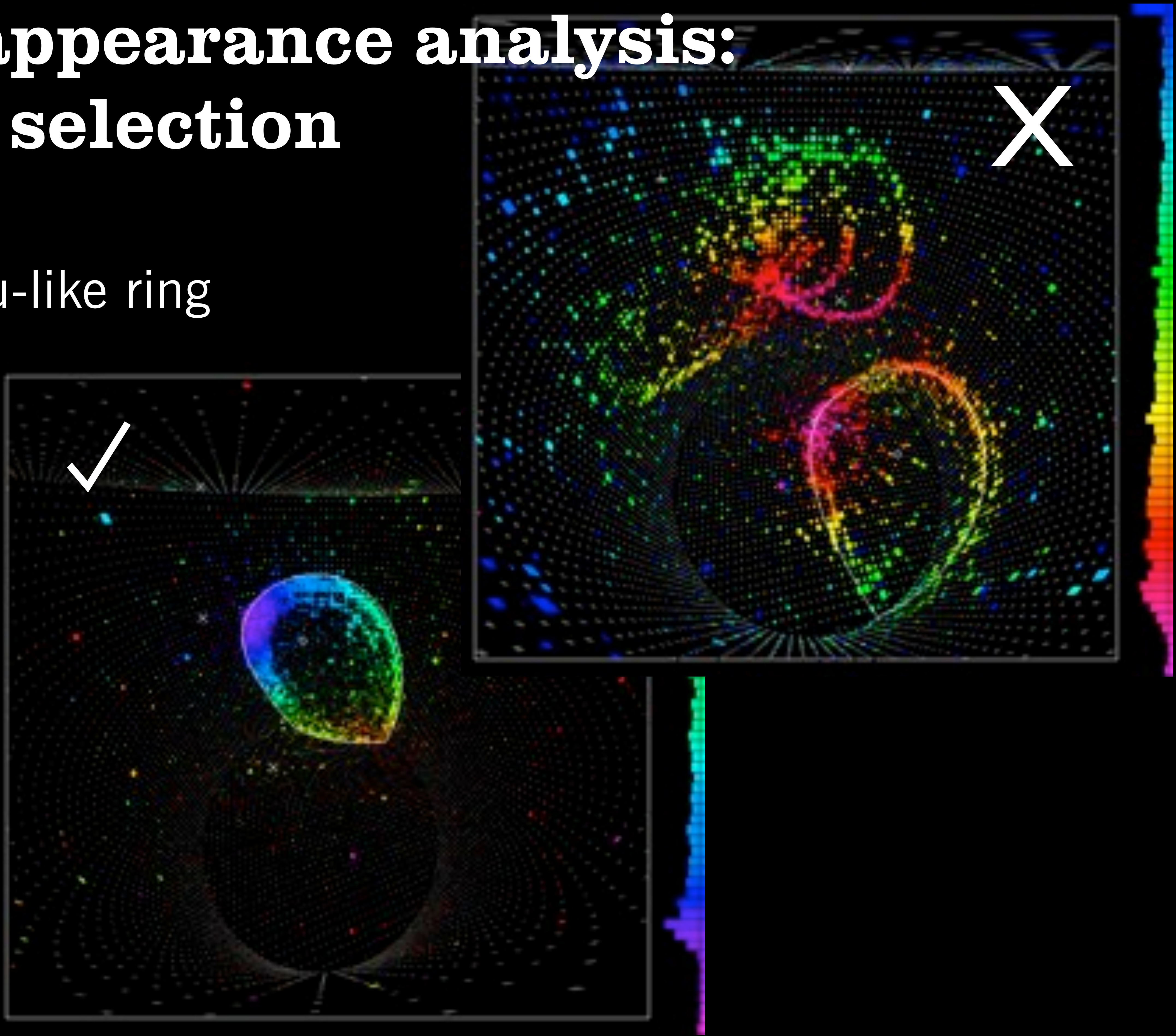
  where proton is below threshold.

- Event selection & cut values fixed before data collection for this run

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Number of rings = 1	
$E_{vis} > 30$ MeV	$E_{vis} > 100$ MeV
μ-like ring	e-like ring
0 or 1 decay electron	No decay electron
$p_\mu > 200$ MeV/c	Forced 2nd ring: $m_{\gamma\gamma} < 105$ MeV
	$E_\nu^{rec} < 1250$MeV

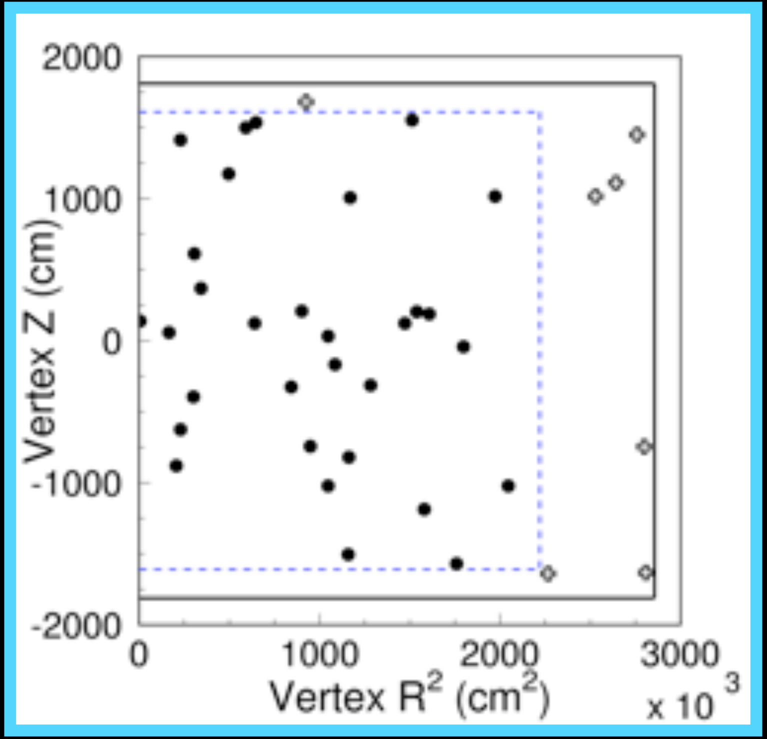
ν_μ disappearance analysis: CCQE selection

- One mu-like ring



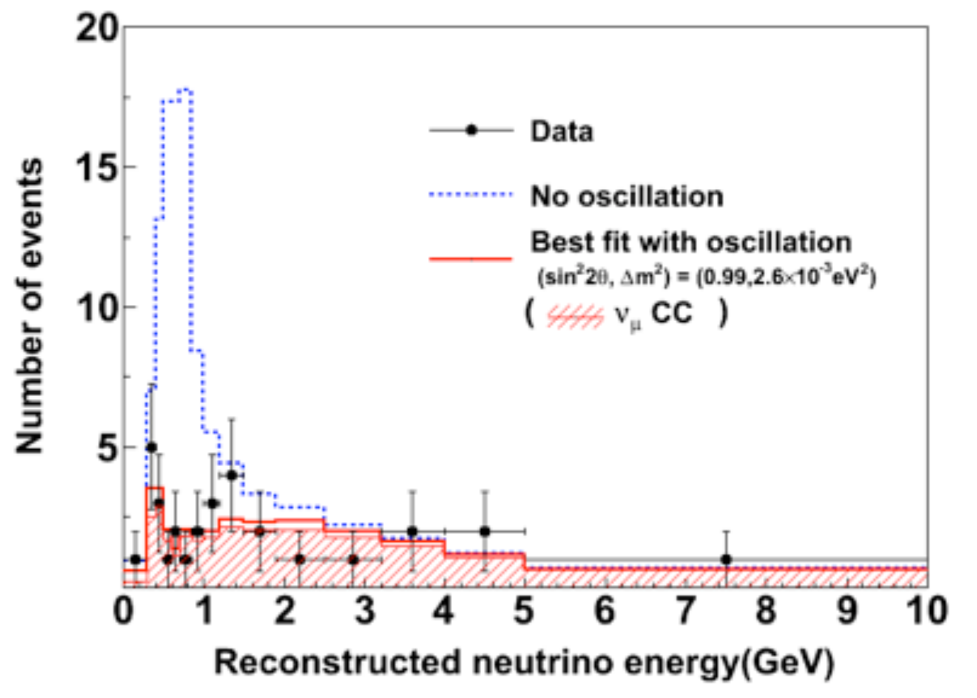
E_ν^{QE} and vertex distribution

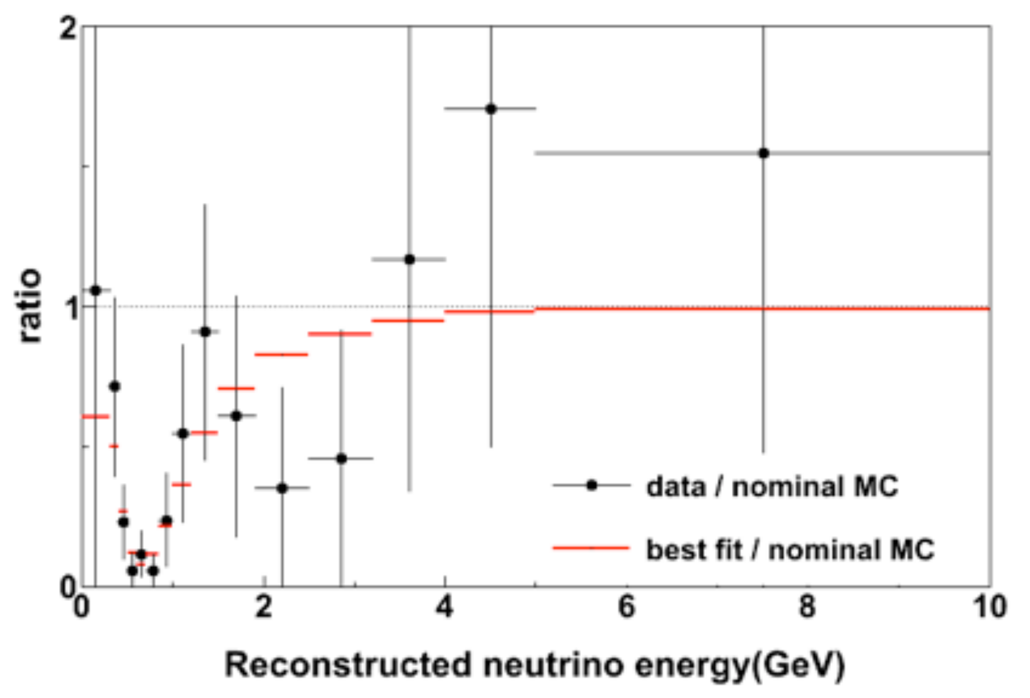
Vertex distribution (all cuts except fiducial)



Observed events consistent with past ν_μ disappearance measurements in:

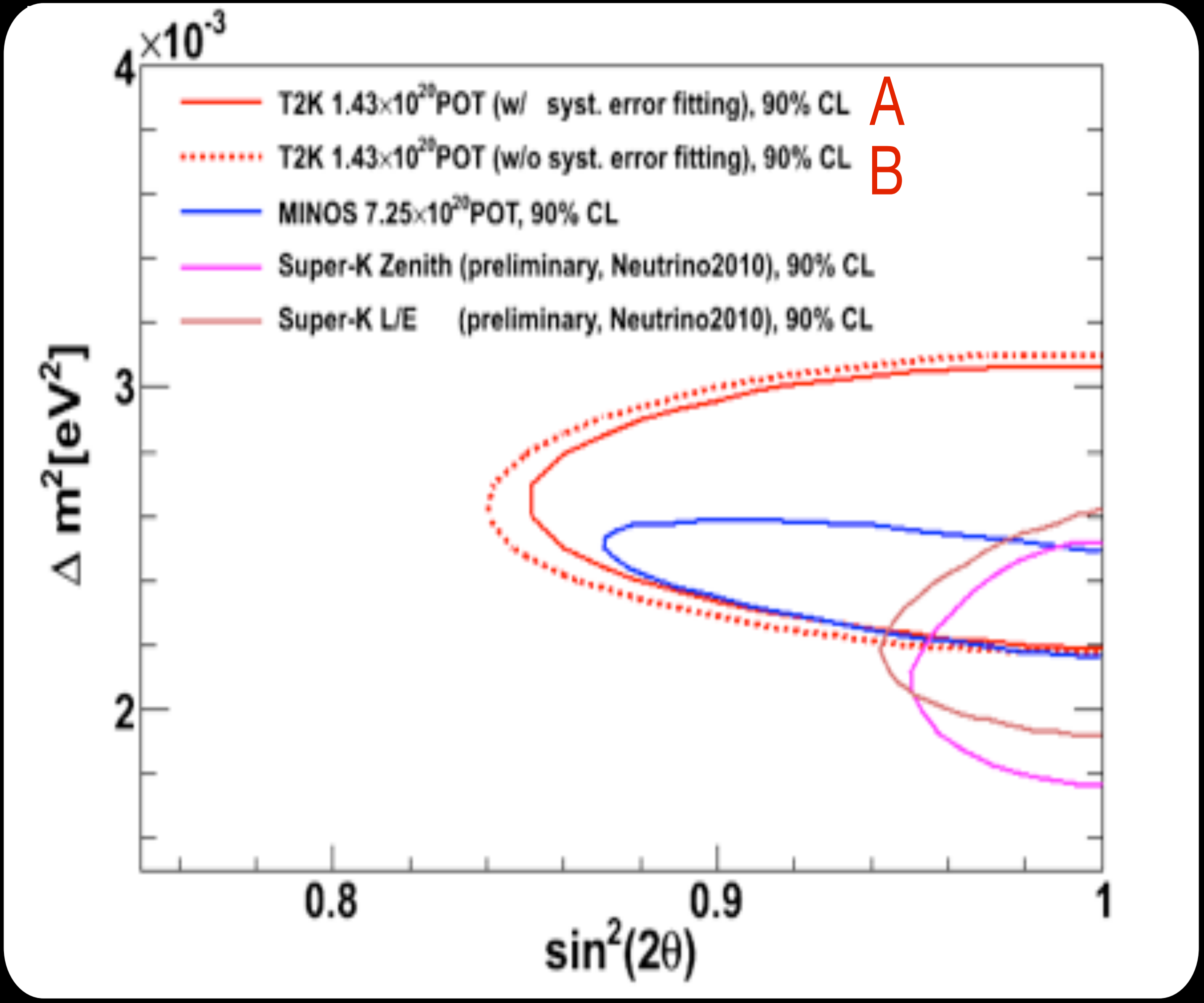
- number of events (4.5 σ from no-osc hypothesis)
- energy spectrum (oscillation pattern apparent)





Oscillation parameter fit

- Fit with 2-flavor model to extract parameters
- Two methods: “A” fits for systematic error parameters; “B” does not
- 90% CL for Method A(B)
  - $\sin^2 2\theta > 0.85$ (0.84)
  - $2.1\mathrm{x}10^{-3} < \Delta m^2(\mathrm{eV}^2) < 3.1\mathrm{x}10^{-3}$



Signal and background for ν_e appearance analysis

- Most common process at oscillation maximum (600 MeV) is *charged-current quasielastic scattering:*
  - $\nu_\ell + n \rightarrow \ell^- + p$
  - *e*/μ separation is mostly via ring shape; decay electron identification helps too
- Signature in Super-Kamiokande is a single Cherenkov ring, as proton usually below threshold
- Most common non-ν_e background is neutral-current π^0 production, where one photon has very low energy

First Run 1+2 ν_e appearance analysis strategy

- Predict neutrino fluxes using:
  - GEANT3-based beam MC
  - Hadron production measurements from CERN NA61

- Near detector analysis:
  - GEANT4-based detector MC
  - Inclusive charged-current event selection; no energy cut

- Predict flux at Super-K using beam MC
- Reweight by near detector Data/MC ratio for inclusive sample (no energy dependence)

- Far detector analysis:
  - GEANT3-based Super-K detector MC
  - Count events that pass appearance cuts
  - Compare this number to oscillated prediction, form confidence regions in oscillation parameter space

Far detector analysis: cuts

For ν_μ disappearance analysis	For ν_e appearance search
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (>2m from wall)	
Number of rings = 1	
E_{vis} > 30 MeV	E_{vis} > 100 MeV
μ-like ring	e-like ring
0 or 1 decay electron	No decay electron
p_μ > 200 MeV/c	Forced 2nd ring: $m_{\gamma\gamma}$<105 MeV
	E_ν^{rec} < 1250MeV

After all cuts:

- Signal efficiency 66% for fiducial volume
- Intrinsic ν_e background efficiency is 23%
- NC efficiency <1%

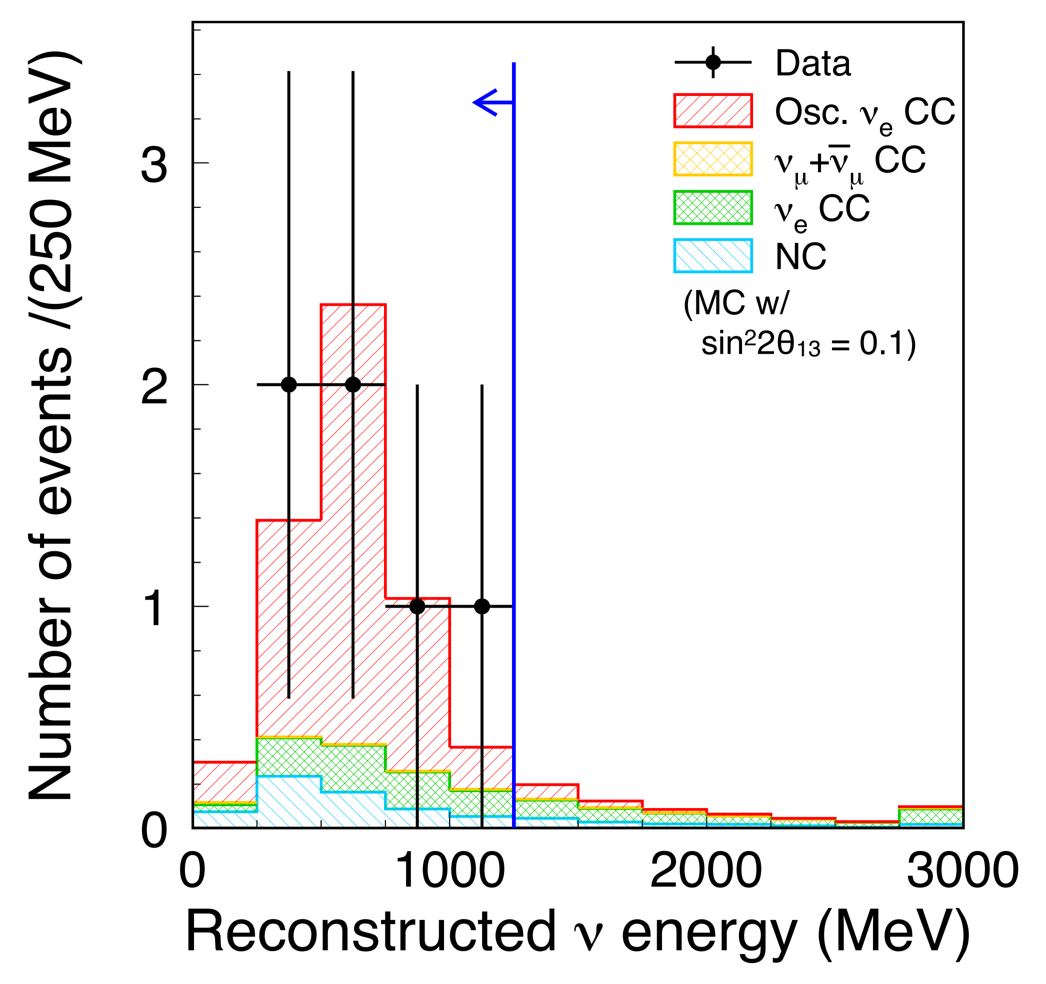
Predicted background and systematic error

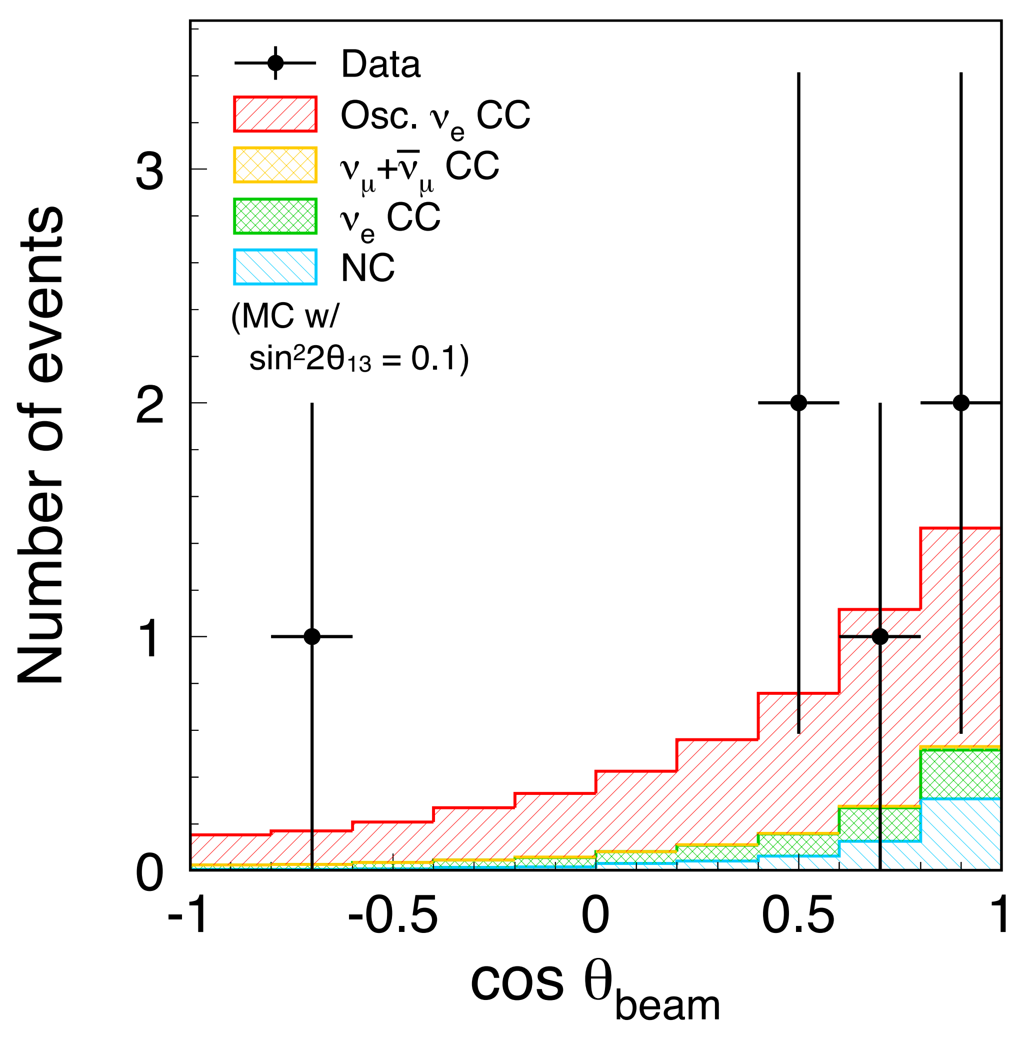
Beam intrinsic ν_e CC background	NC background	Δm_{21}^2 oscillations	Total background
0.8	0.6	0.1	1.5

Neutrino flux model	±8.5%
Neutrino interaction cross-sections	±14.0%
Near detector efficiencies/acceptance	+5.6/−5.2%
Far detector efficiencies/acceptance	14.7%
Near detector statistics	±2.7%
TOTAL	+22.8/−22.7%

- N_{SK} = 1.5 ± 0.3 events for $\theta_{13}=0$

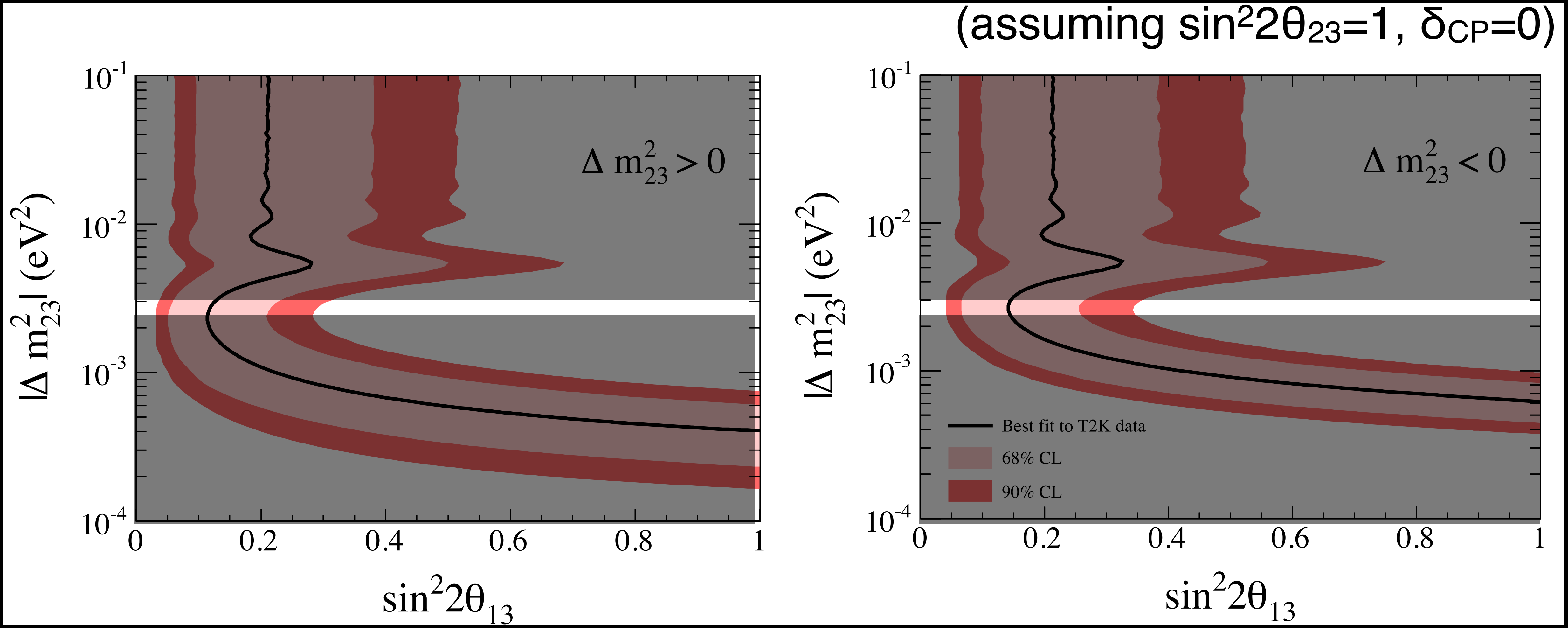
Final ν_e candidate events





- Six events remain after all cuts. Probability of ≥6 events with $\theta_{13}=0$ is 6.6×10^{-3}
- Events are well distributed in lepton angle (this variable is a decent proxy for Q^2 given the narrow-band beam)

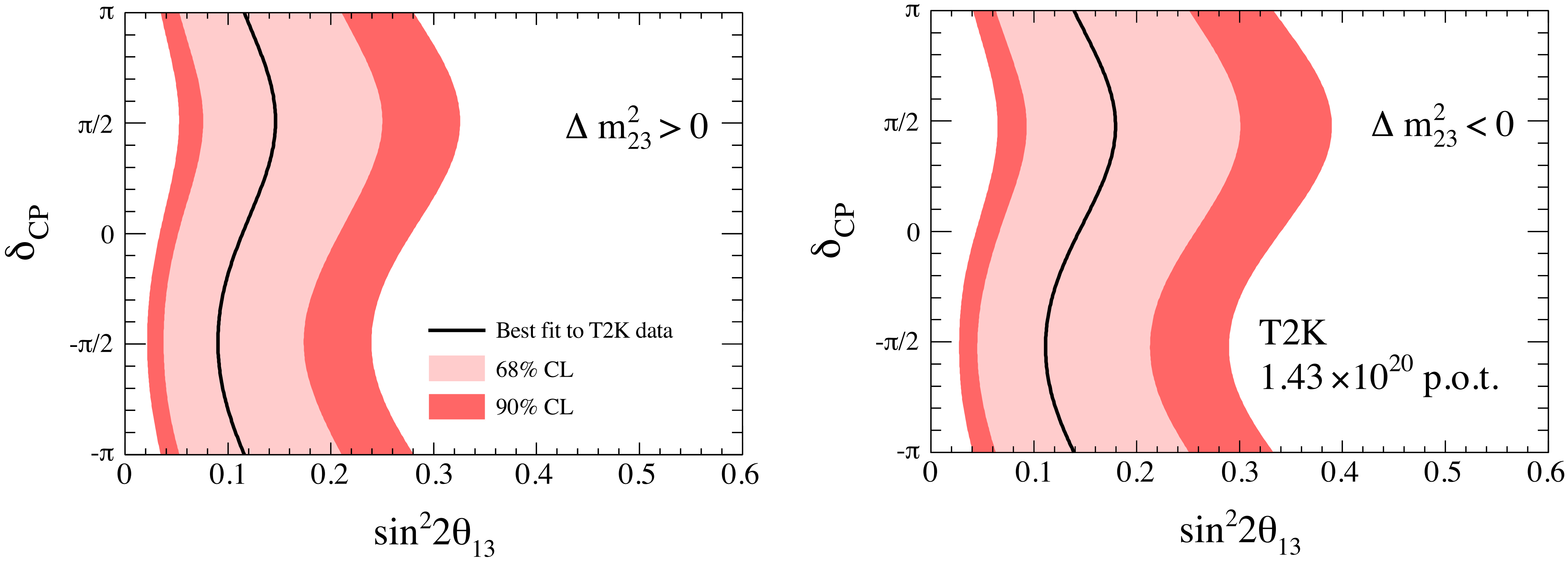
Fitting the result to an oscillation hypothesis: Feldman-Cousins bounds


(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

Note: only Δm^2 around $2\text{-}3\times10^{-3}$ allowed by other experiments

Fit depends somewhat on CP phase:

(assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1)

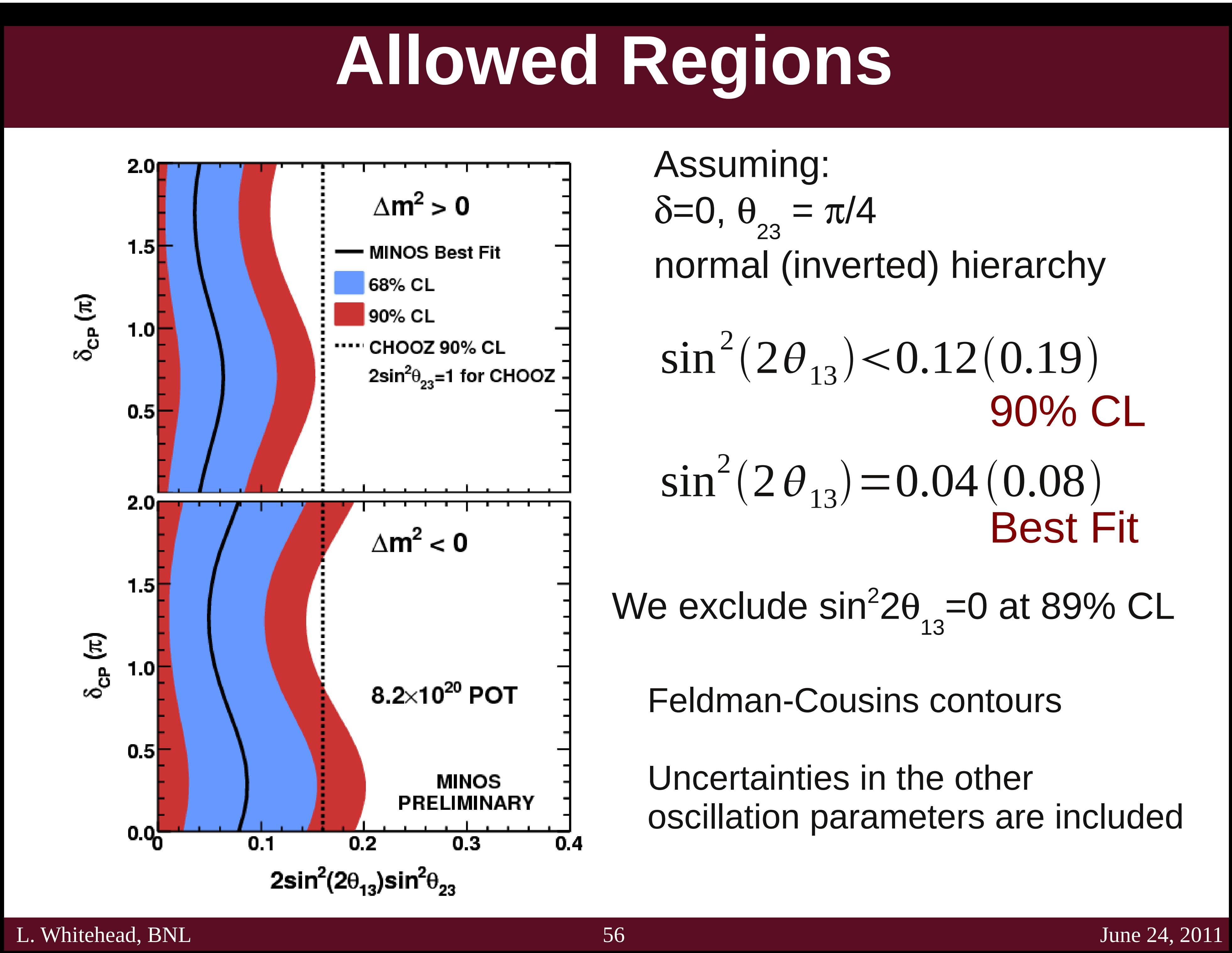


90% C.L. interval & Best fit point (assuming Δm^2_{23}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

- >0.15 is excluded by Chooz, MINOS

MINOS result



Allowed Regions

Assuming:
$\delta=0$, $\theta_{23} = \pi/4$
normal (inverted) hierarchy

$$\sin^2(2\theta_{13})<0.12(0.19)$$

90% CL

$$\sin^2(2\theta_{13})=0.04(0.08)$$

Best Fit

We exclude $\sin^2 2\theta_{13}=0$ at 89% CL

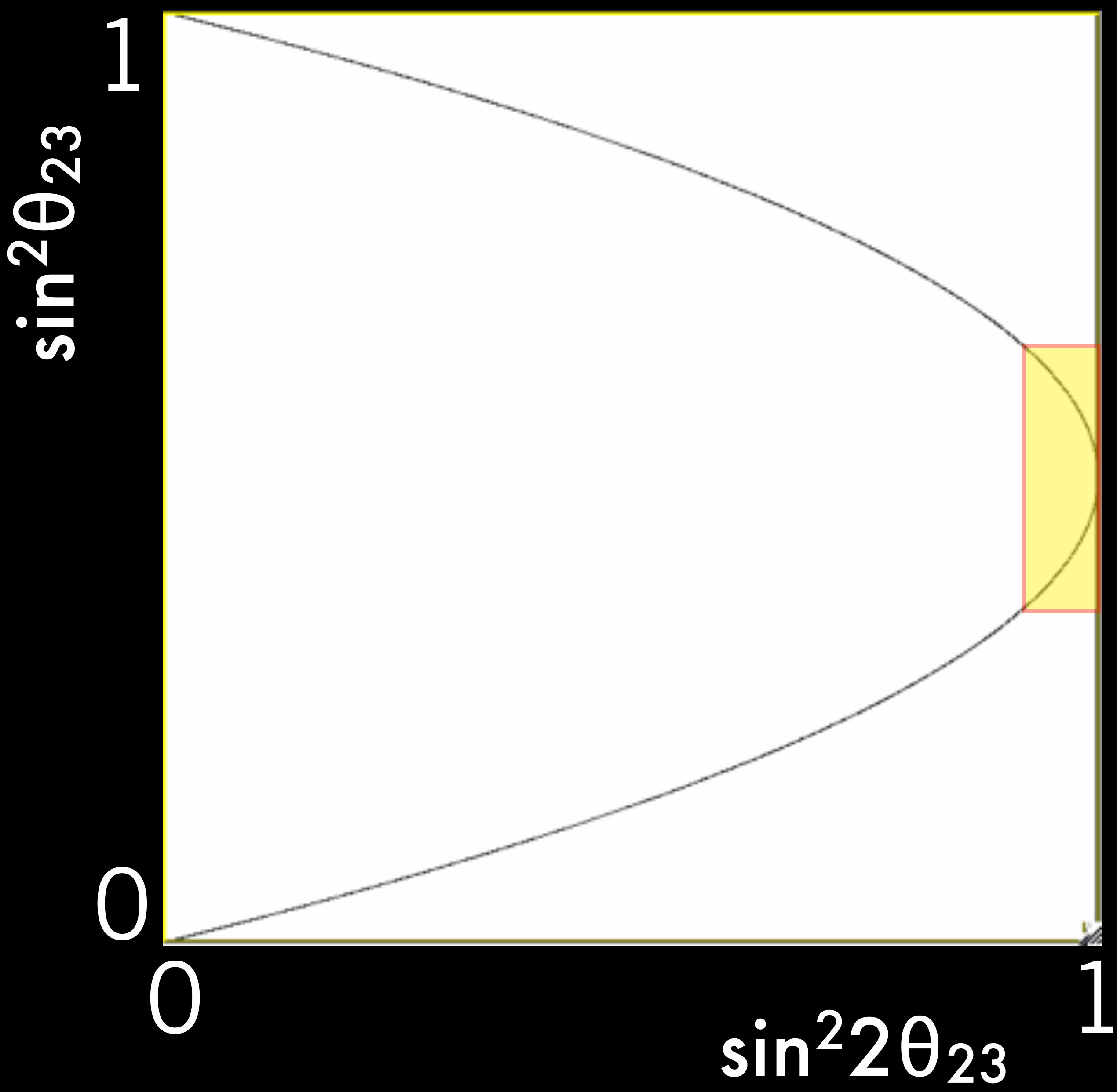
Feldman-Cousins contours

Uncertainties in the other oscillation parameters are included

- New analysis is significantly more sensitive than previous
- Result quite consistent with T2K
- Improves confidence that θ_{13} is nonzero

θ_{23} DEPENDENCE OF APPEARANCE RESULTS

- Appearance probability is approximately proportional to $\sin^2\theta_{23} \cdot \sin^2 2\theta_{13}$.
- PDG gives $\sin^2 2\theta_{23} < 0.92$ (90% CL)
- This gives $0.36 < \sin^2\theta_{23} < 0.64$
- Nearly factor of 2 allowed range!
- Reactor measurements do not depend on θ_{23}



New results: reactor-based measurements

- Actually, revival of a very old technique (the first to detect neutrinos).
- Reactor-based searches were the best θ_{13} limits until 2011
- Principle: fission products are too neutron-rich for stability, so β-decays result: copious $\bar{\nu}_e$ produced in few-MeV range
- Detection is via inverse beta decay
- Detect positron, delayed *n* capture
- Only $\bar{\nu}_e$ interact

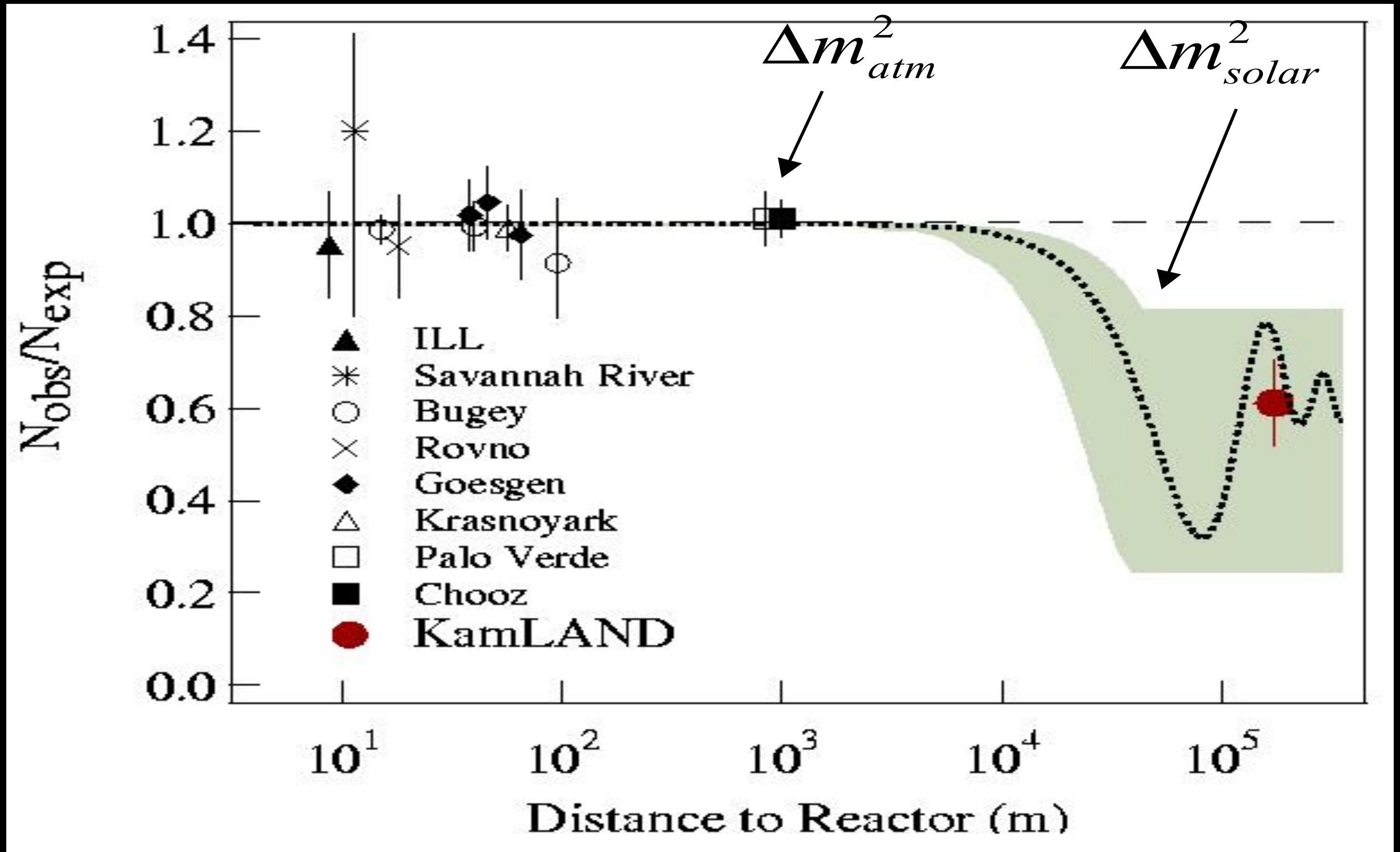
Physics goals of coming reactor experiments

- Determine θ_{13} via $\bar{\nu}_e$ disappearance at the atmospheric Δm^2 scale (~1km at these energies), pushing current limits by order of magnitude.
- In principle, result is cleaner than for $\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\Delta m^2_{13} \frac{L}{4E}\right) + f(\delta) + f(\text{matter})$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(\Delta m^2_{13} \frac{L}{4E}\right) + \text{small terms}$$

- However, need high statistics to establish disappearance effects, and need excellent understanding of cross-section (yes) and flux (maybe).

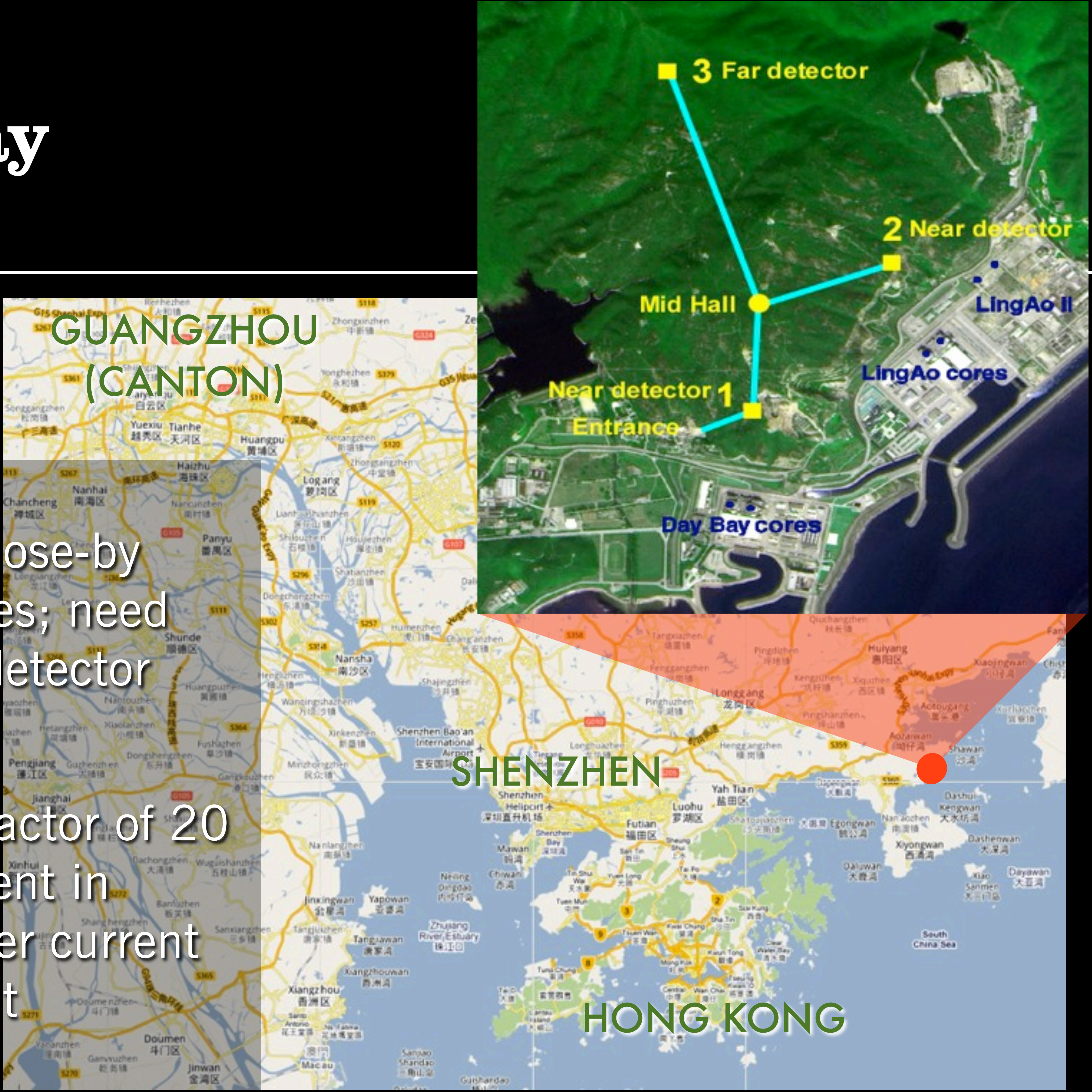


Current-generation reactor-based neutrino experiments

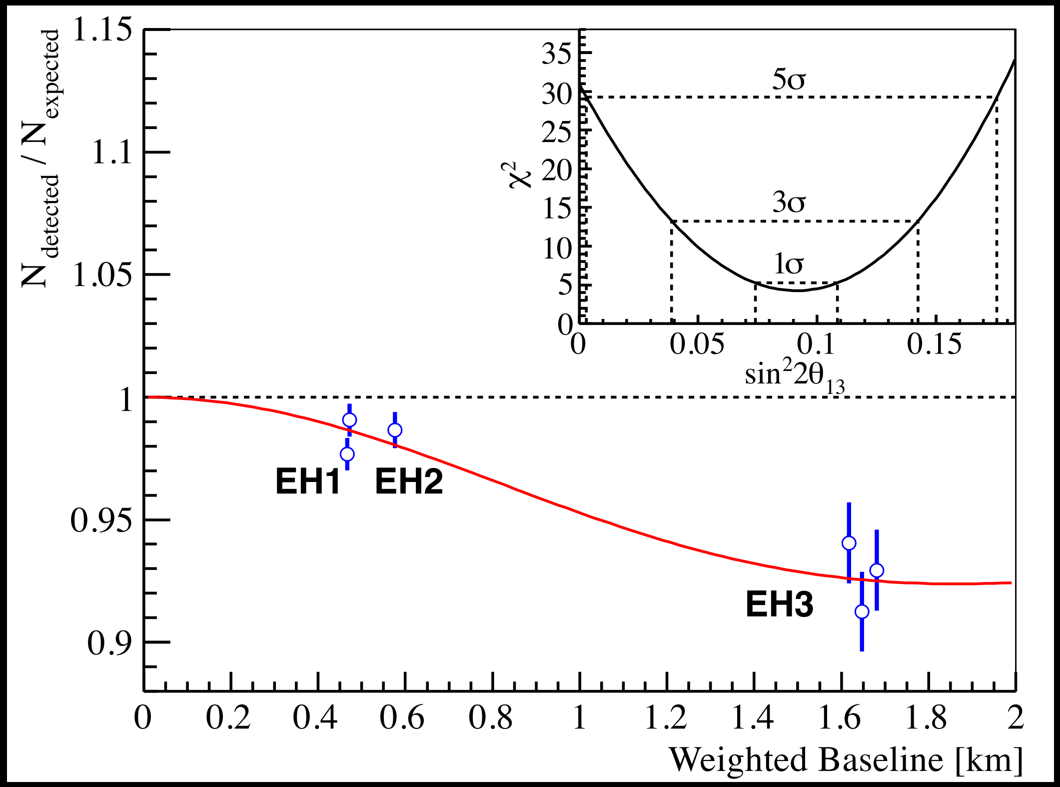
- Three sites have experiments in rapid development:
  - Double Chooz (France)
  - Daya Bay (China)
  - RENO (South Korea)
- Major improvements over previous experiments:
  - ***Near detectors to cancel flux uncertainties!***
  - Baseline selected specifically for (now known) Δm^2
  - Larger detectors, more powerful reactors
- Next speaker will provide details!

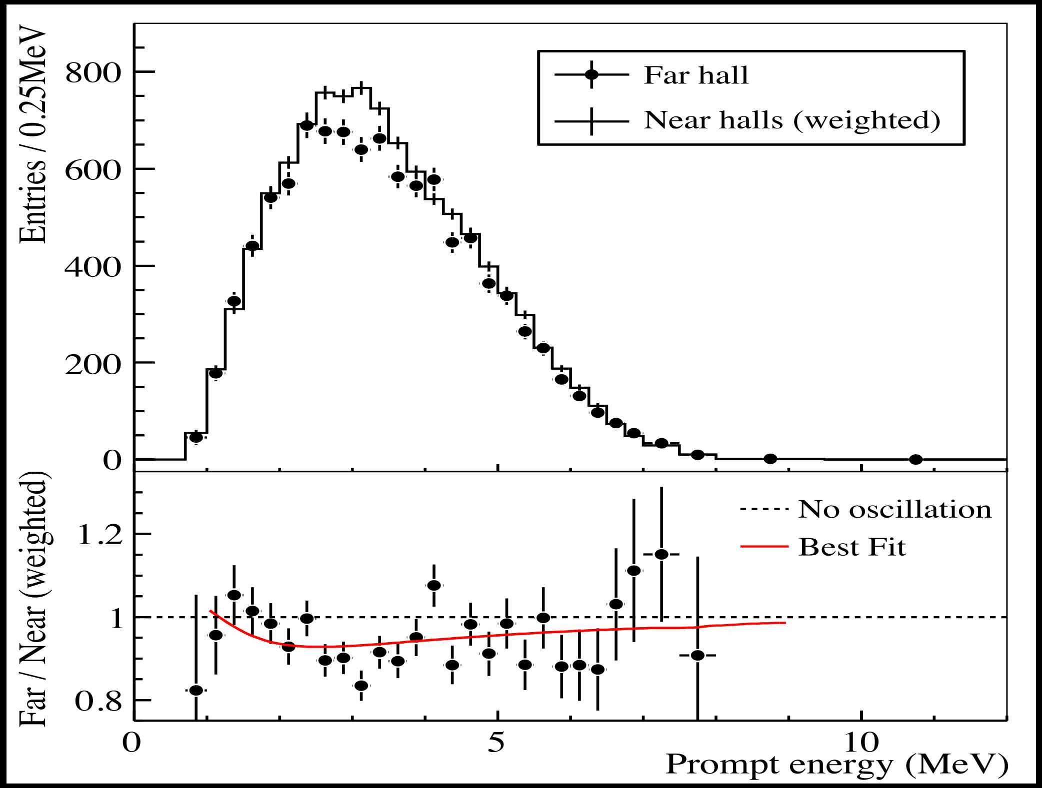
Daya Bay

- Multiple close-by reactor sites; need two near detector sites
- Planning factor of 20 improvement in $\sin^2\theta_{13}$ over current Chooz limit



Daya Bay: conclusive observation of $\theta_{13} \neq 0$



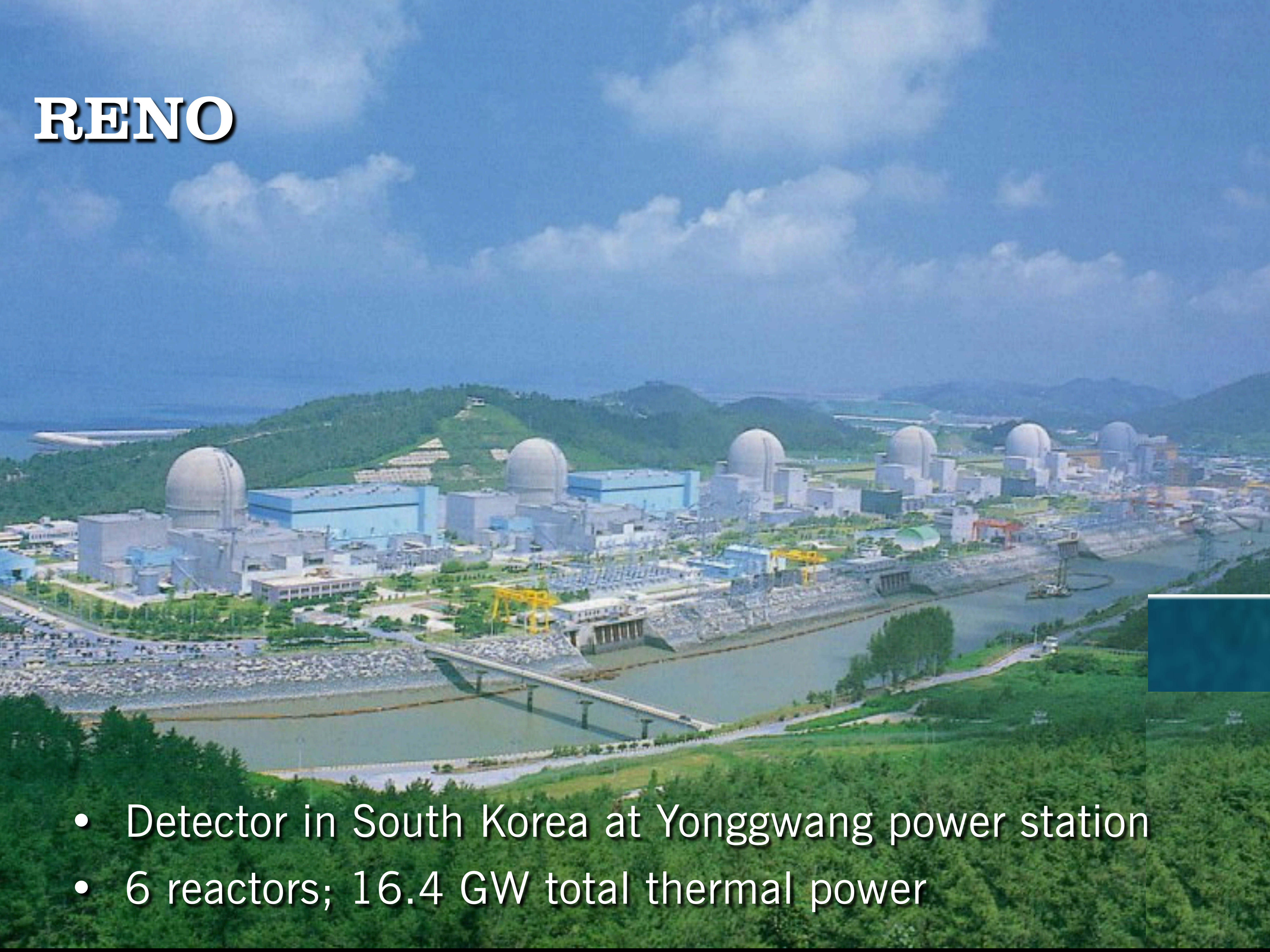


- Clear signal of disappearance of $\overline{\nu}_e$ at short baseline: must be Δm_{23}^2 scale effect.

- $\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

- Preprint 1203.1661 [hep-ex]

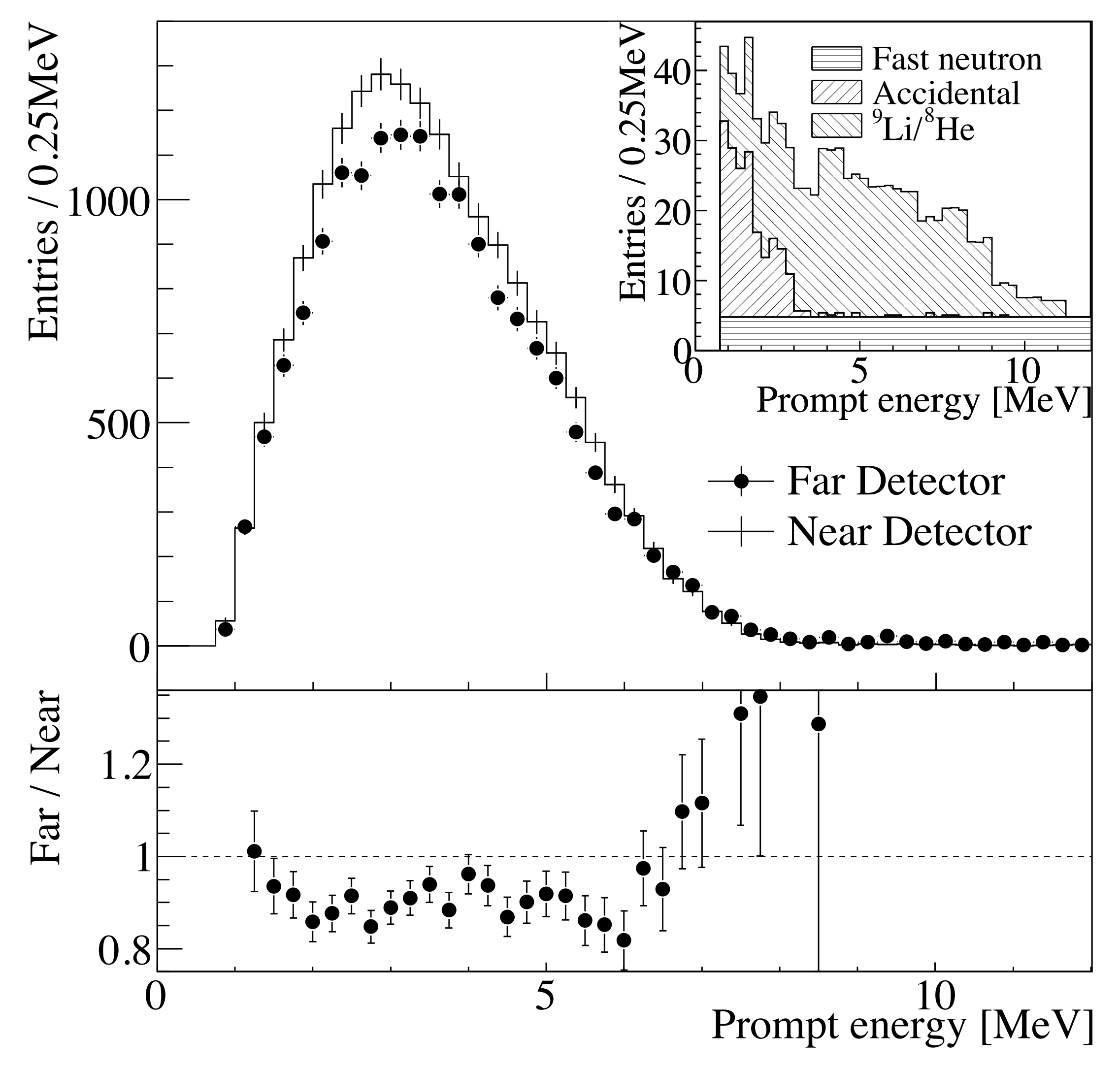
RENO



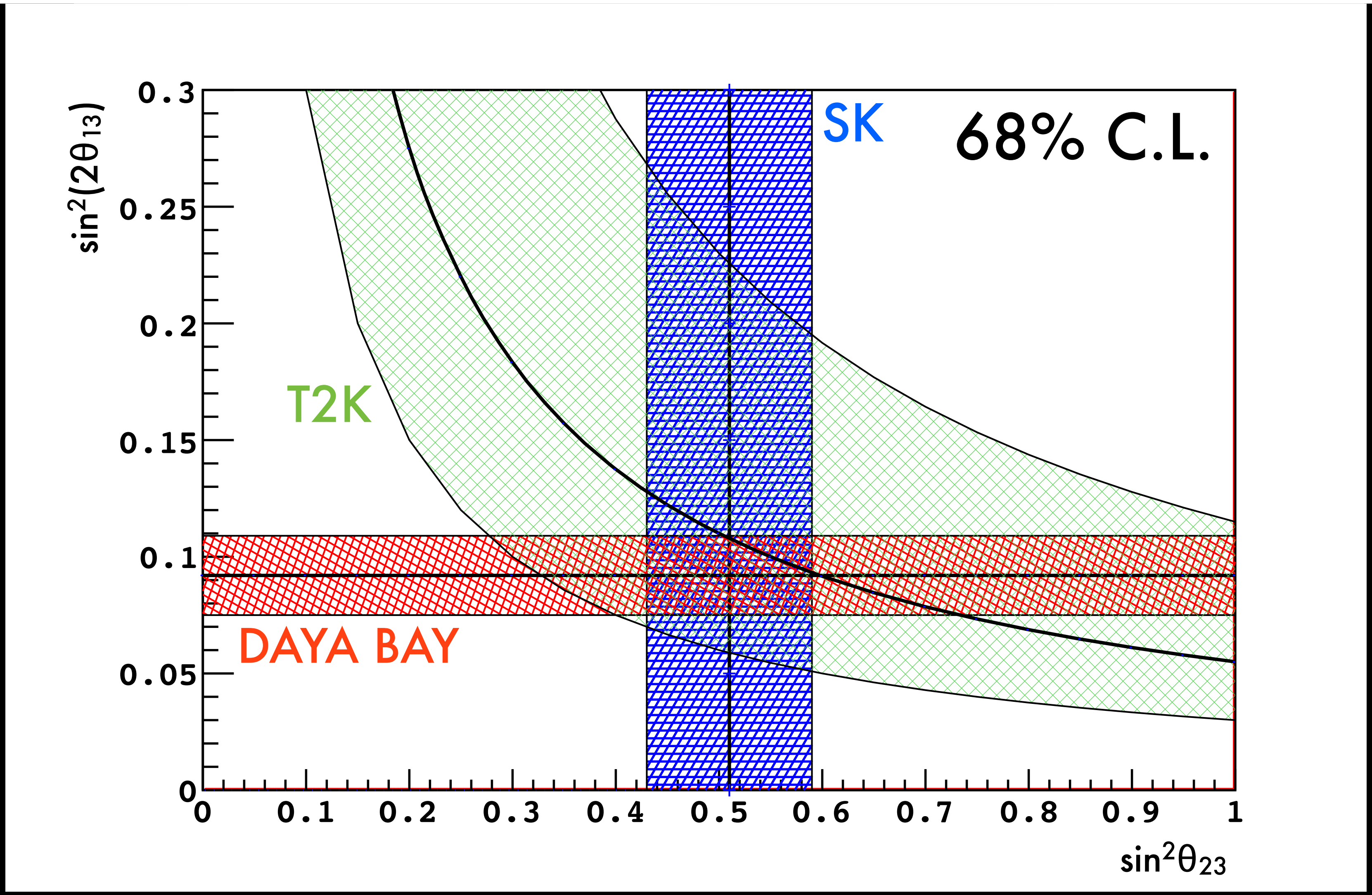
- Detector in South Korea at Yonggwang power station
- 6 reactors; 16.4 GW total thermal power

RENO first result

- First results released last month: arXiv:1204.0626
- Result consistent with Daya Bay:
- $\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat.) ± 0.019(syst.)

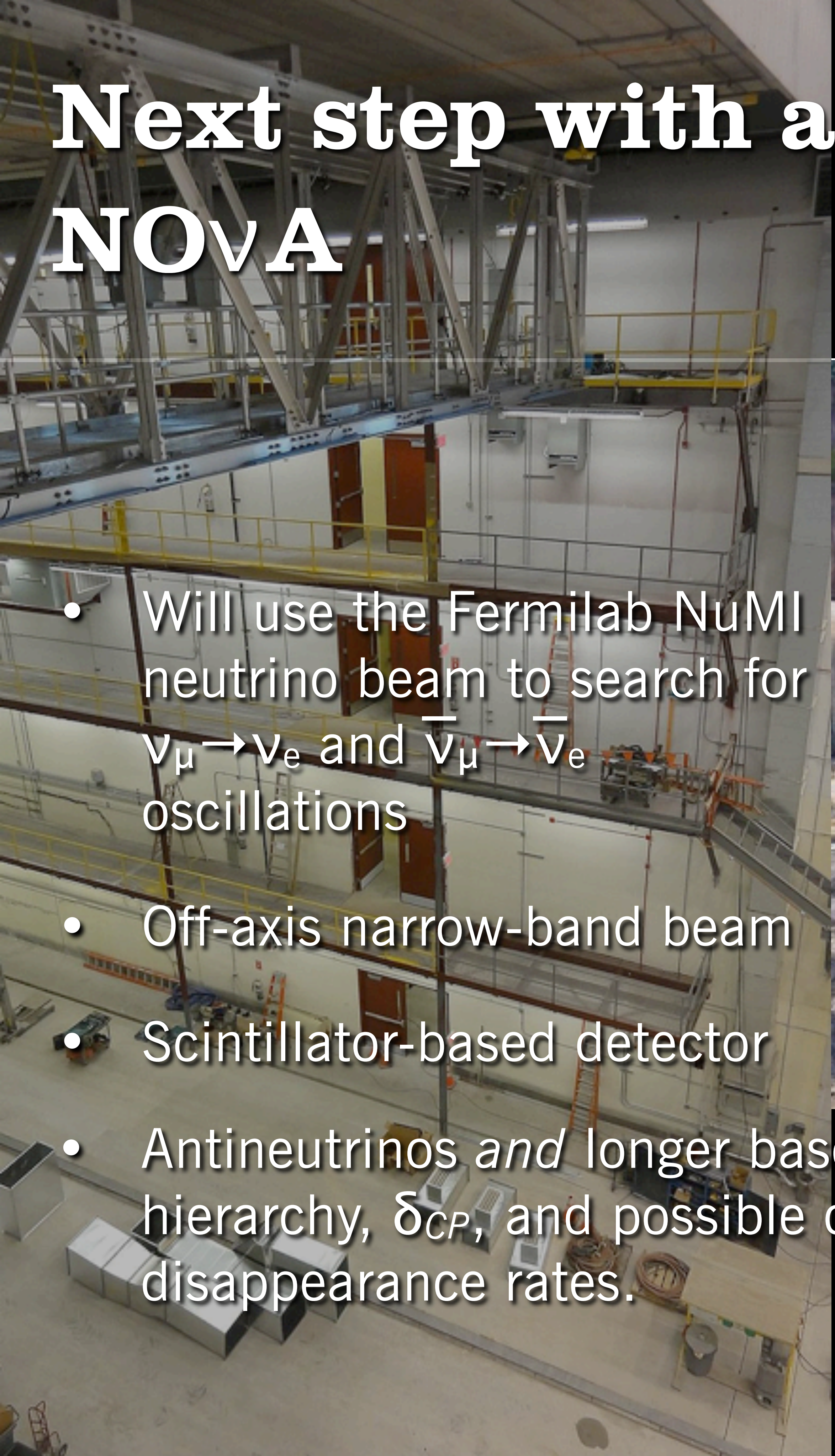


Putting the mixing angle results together



- Most precise single results for each parameter
- Some chance of distinguishing θ_{23} octant when T2K result gets more precise

Next step with accelerators: NOνA



- Will use the Fermilab NuMI neutrino beam to search for $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations
- Off-axis narrow-band beam
- Scintillator-based detector
- Antineutrinos *and* longer baseline: sensitive to neutrino mass hierarchy, δ_{CP}, and possible differences in neutrino and antineutrino disappearance rates.

Ultimate(?) long-baseline experiments

- Definitive resolution of mass hierarchy, CP violation over most of possible parameter space
- Multi-hundred kton scale detectors, megawatt-scale beams:
    - J-PARC to other sites in same beam
        - Okinoshima (liquid argon), Hyper-Kamiokande
    - Fermilab LBNE (Homestake)
    - LAGUNA: European proposal

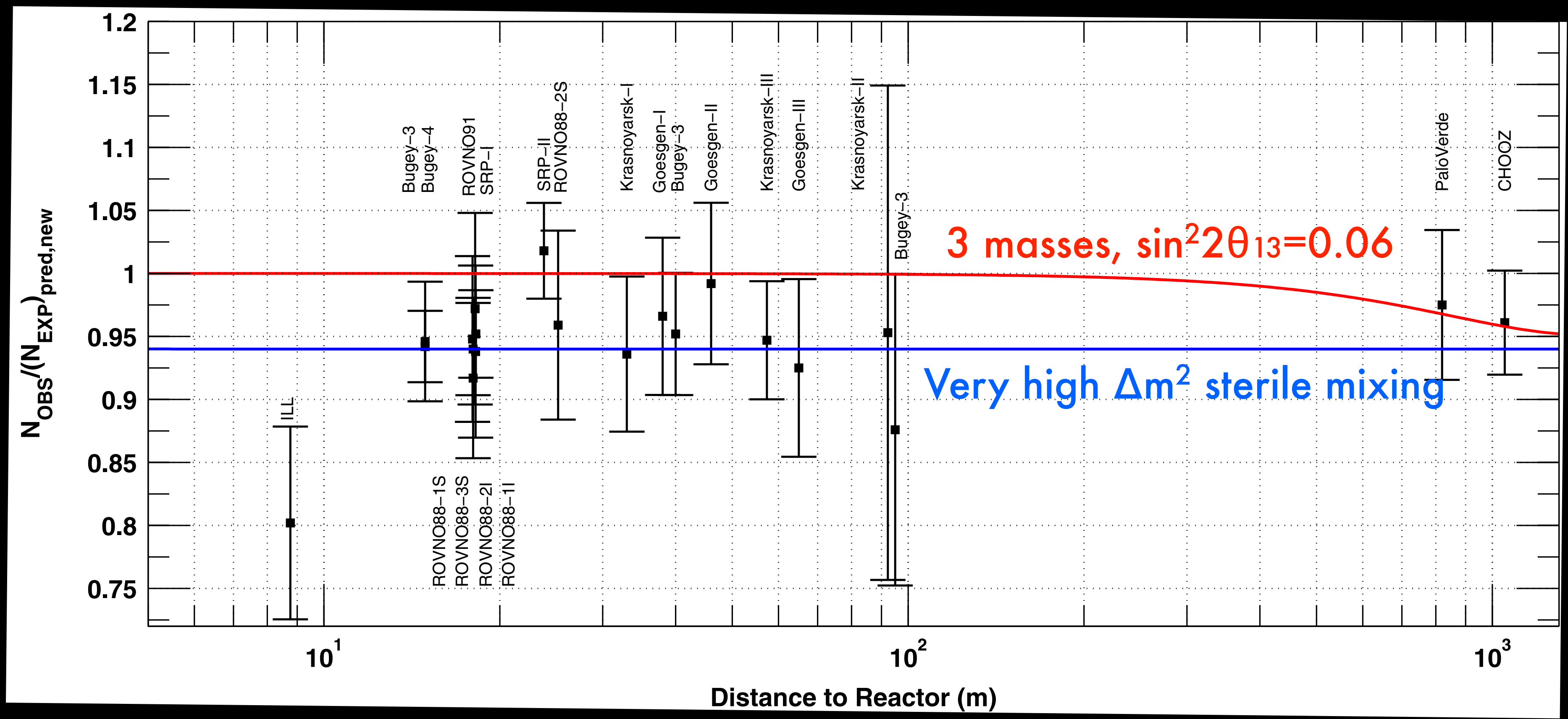
Anomalies

- Not all results right now fit cleanly into the 3-neutrino mixing model:
  - Reactor neutrino anomaly
  - Short-baseline accelerator anomalies
    - LSND
    - MiniBooNE

Reactor neutrino anomaly?

- New evaluation of reactor antineutrino flux per unit thermal power: G. Mention *et al.*, *Phys. Rev.* **D83** 073006 (2011)
- Predicted flux increases by 3%; average of experimental results now 0.943 ± 0.023 of prediction.

- Could indicate common systematic effect, or error in beta spectrum data
- Also consistent with sterile neutrino mixing at very high Δm^2



LSND

Liquid Scintillator Neutrino Detector

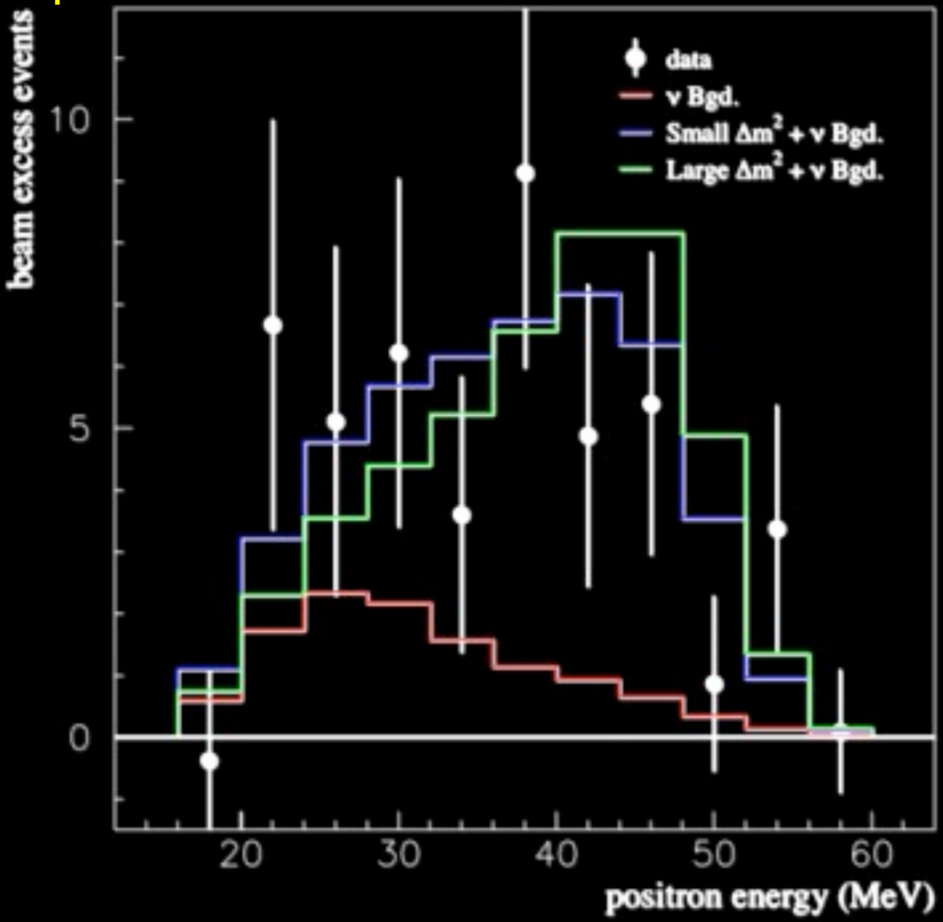
- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\overline{\nu}_\mu$ but no $\overline{\nu}_e$ (due to π^- capture).

Search for $\overline{\nu}_e$ appearance via reaction:

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

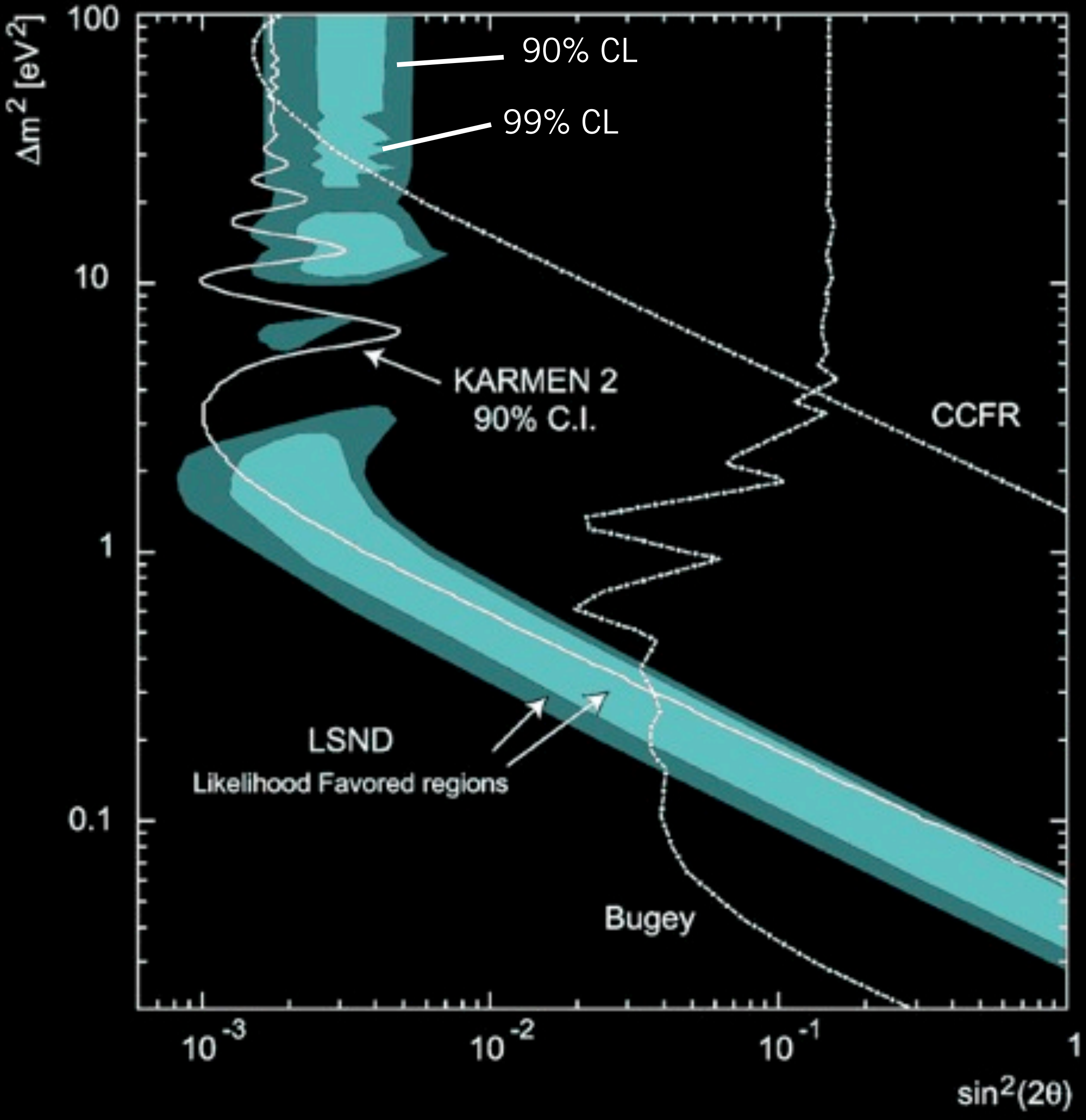
- Look for delayed coincidence of positron and neutron capture.
- Major background non-beam (measured, subtracted)
- 3.8 standard dev. excess above background.
- Oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.5 \pm 0.6_{\rm stat} \pm 0.4_{\rm syst}) \times 10^{-3}$$



LSND oscillation signal

- LSND "allowed region" shown as band
- KARMEN2 is a similar experiment with a slightly smaller L/E; they see no evidence for oscillations. Excluded region is to right of curve.



MiniBooNE: E898 at Fermilab

- Purpose is to test LSND with higher energy, different signature
- L=500 meters, E=0.5−1 GeV: same L/E as LSND.
- 800-ton mineral oil Cherenkov detector
- $\nu_\mu \to \nu_e$ oscillation signature is charged-current quasielastic scattering:

$$\nu_e + n \longrightarrow e^- + p$$

- Dominant backgrounds to oscillation:
  - Intrinsic ν_e in the beam

$$\pi \to \mu \to \nu_e \text{ in beam}$$
$$K^+ \to \pi^0 e^+ \nu_e,\ K_L^0 \to \pi^0 e^\pm \nu_e \text{ in beam}$$

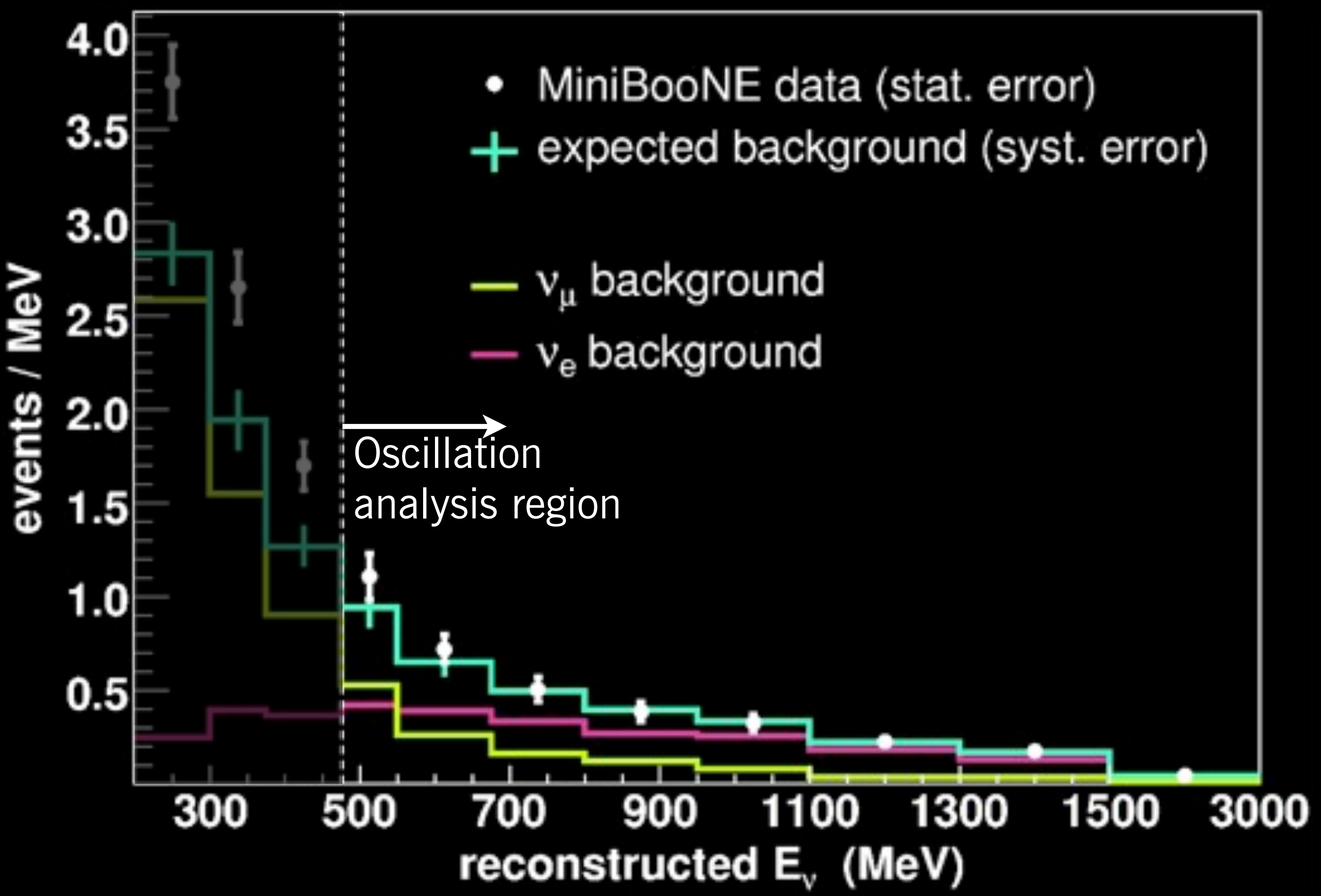
  - Particle misidentification in detector

Neutral current resonance:

$$\Delta \to \pi^0 \to \gamma\gamma \text{ or } \Delta \to n\gamma, \text{ mis-ID as } e$$

Neutrino Oscillations: 2007 result

- Sensitivity to LSND-type oscillations is strongest in 475 MeV < E < 1250 MeV range
- Data consistent with background in oscillation fit range
- Significant excess at lower energies: source unknown, consistent experimentally with either ν_e or single photon production



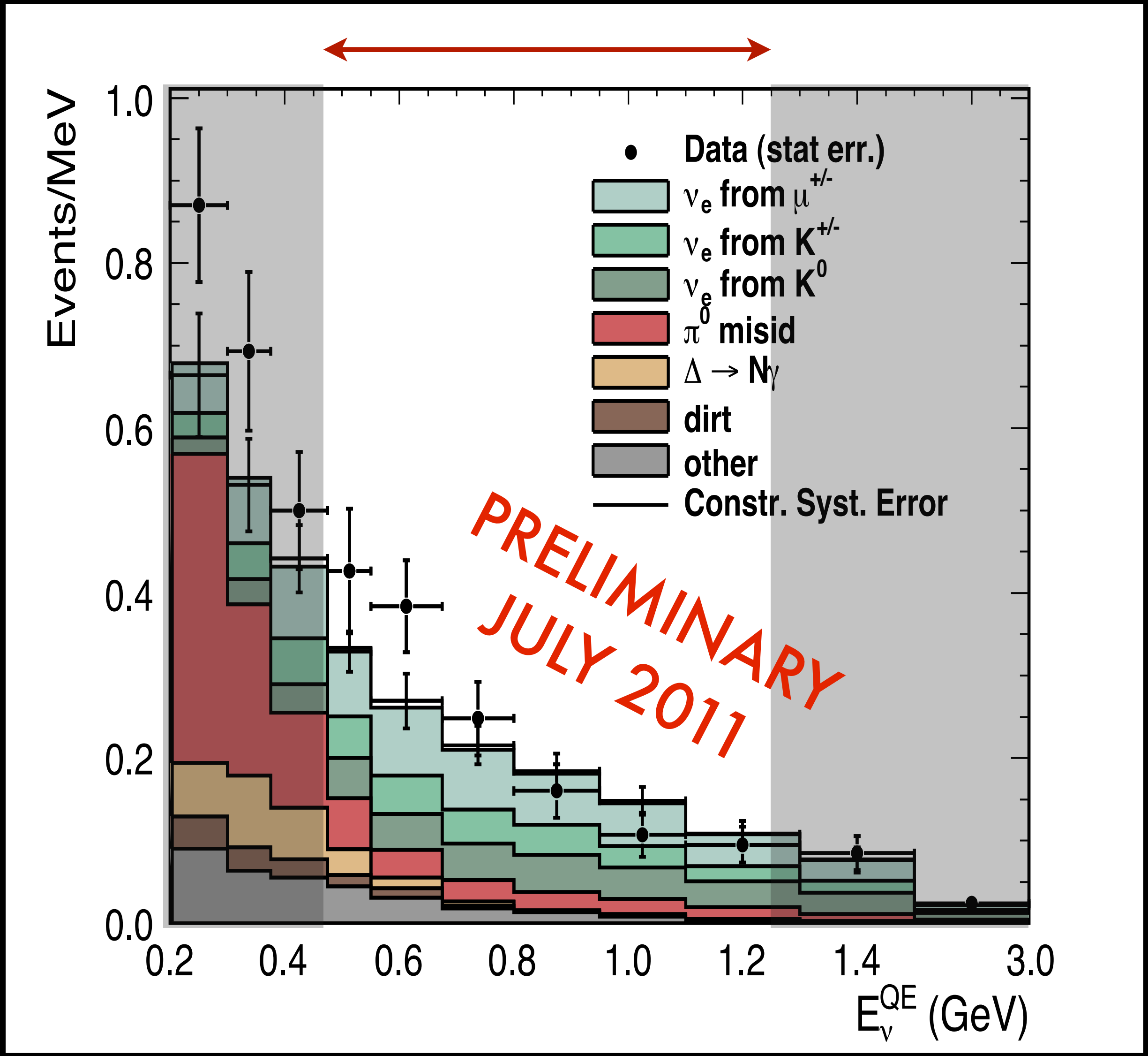
Oscillation analysis region

Oscillation search: *Phys.Rev.Lett*.**98**:231801 (2007)
Low-E excess: *Phys.Rev.Lett*.**102**:101802 (2009)

MiniBooNE antineutrino data: 8.58E20 POT

- 475 MeV $< E <$ 1250 MeV:
  - 151.7±15.0(syst) expected after fit constraints
  - 168 observed; excess 16.3±19.4 (total)
  - Oscillation hypothesis preferred to background-only at 91.1% confidence level.
  - Raw “one-bin” counting excess significance 0.84σ
- Excess in oscillation-sensitive region is reduced somewhat with new data; low-energy excess is more significant and resembles neutrino-mode data

475-1250 MeV
oscillation-sensitive region



How to resolve the anomalies?

- New Physics (sterile neutrinos, extra dimensions)
- “New” Physics (neutrino cross-sections, neutral-current photon production, …)
- New experiments
    - MicroBooNE: may be able to distinguish photons from electrons in low-energy excess region
    - Other new experiments?

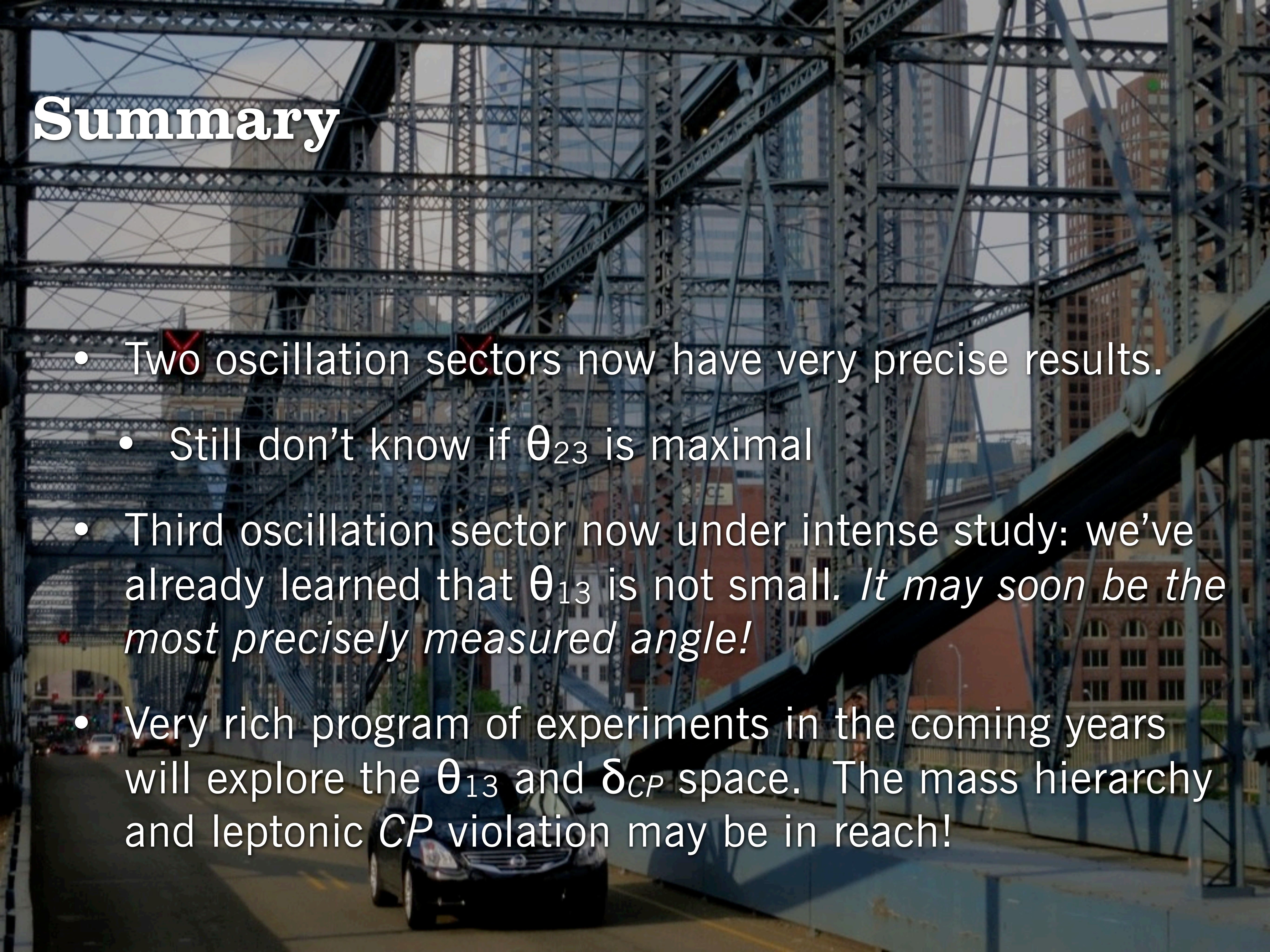
No time to discuss

- Proposed short-baseline experiments at FNAL, CERN to study parameter space regions associated with short-baseline anomalies: very exotic physics if *any* of these hold up to more precise studies

- Detector technology developments: liquid argon TPC experiments in particular are very active, hoping to scale up to multi-kiloton range: LBNE

- Neutrino interaction cross-section measurements: essential for understanding oscillations

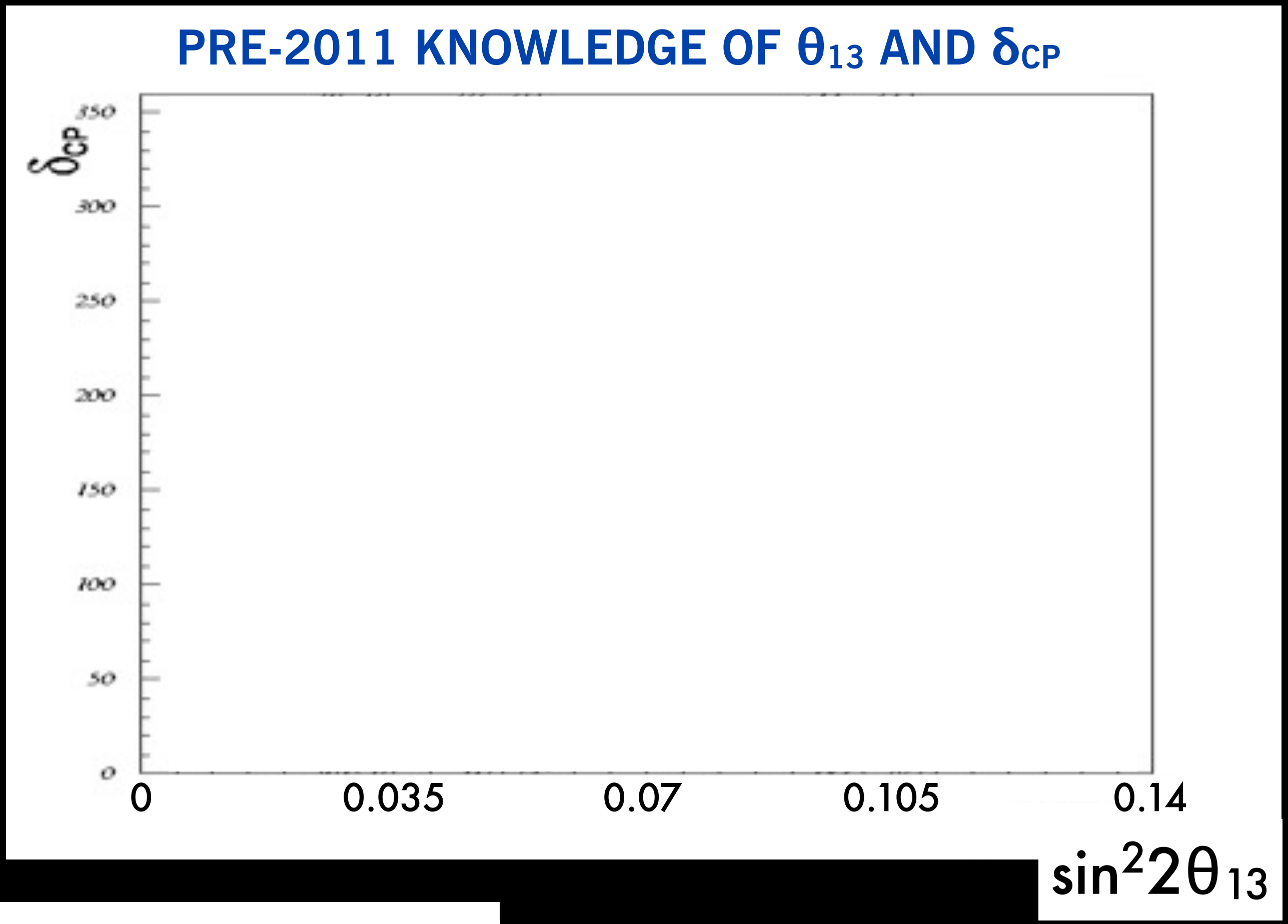
- Current and proposed large detectors are also proton decay detectors: positive results here could eclipse neutrino oscillations!



Summary

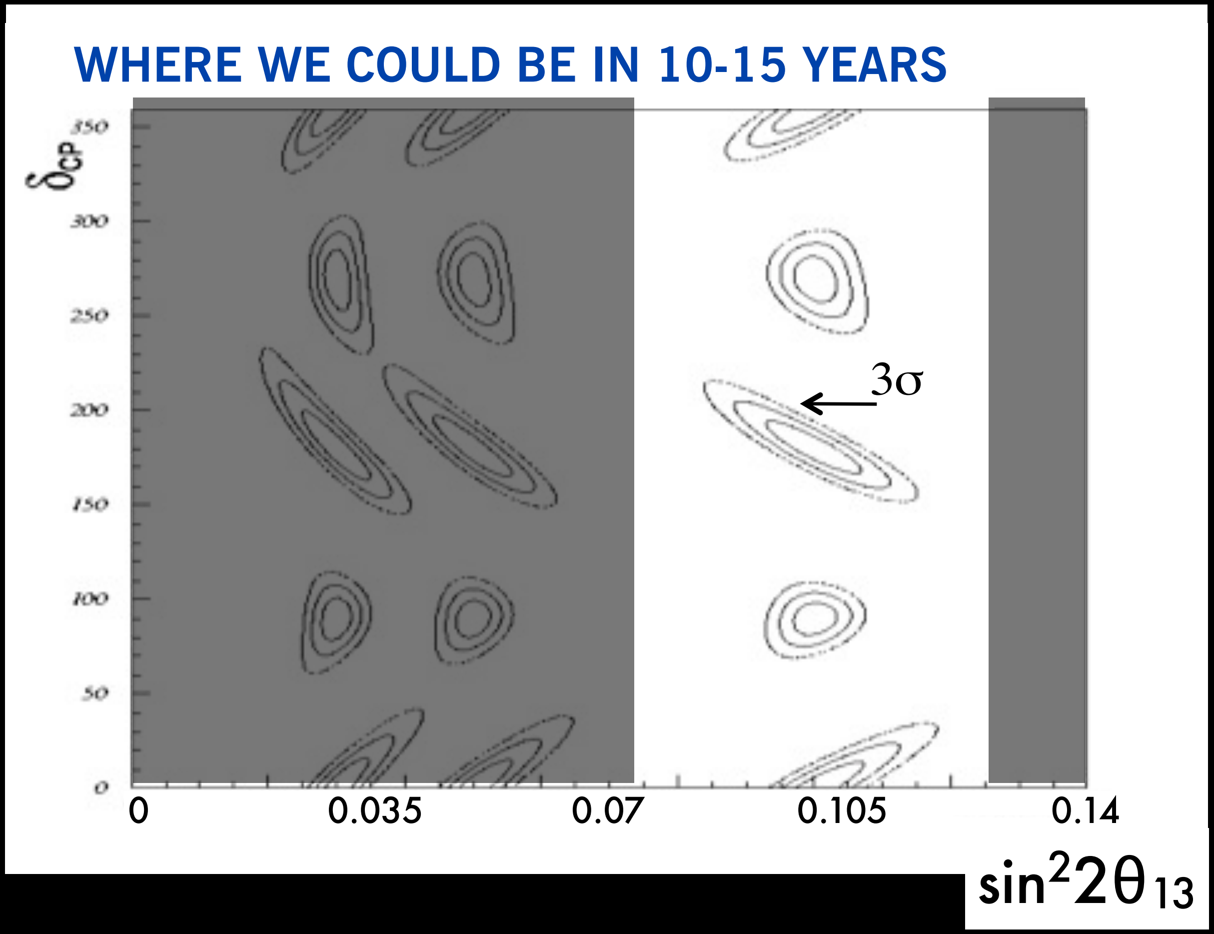
- Two oscillation sectors now have very precise results.
  - Still don’t know if θ_{23} is maximal
- Third oscillation sector now under intense study: we’ve already learned that θ_{13} is not small. *It may soon be the most precisely measured angle!*
- Very rich program of experiments in the coming years will explore the θ_{13} and δ_{CP} space. The mass hierarchy and leptonic *CP* violation may be in reach!

Goal is to get from:



PRE-2011 KNOWLEDGE OF θ_{13} AND δ_{CP}

to:



WHERE WE COULD BE IN 10-15 YEARS

...rapidly narrowing the parameter space already!