Accelerator Neutrino Oscillation Experiments

Status and Expectations over the next ~5 years

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Workshop on the European Strategy for Neutrino Physics
CERN, 1st October 2009

Neutrino mixing

Flavor eigenstates

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

Mass eigenstates

LONG BASELINE ACCELERATOR EXPERIMENTS

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
ν_μ Long BL

reactor Short BL
ν_μ Long BL

Solar
reactor Long BL

Majorana
??

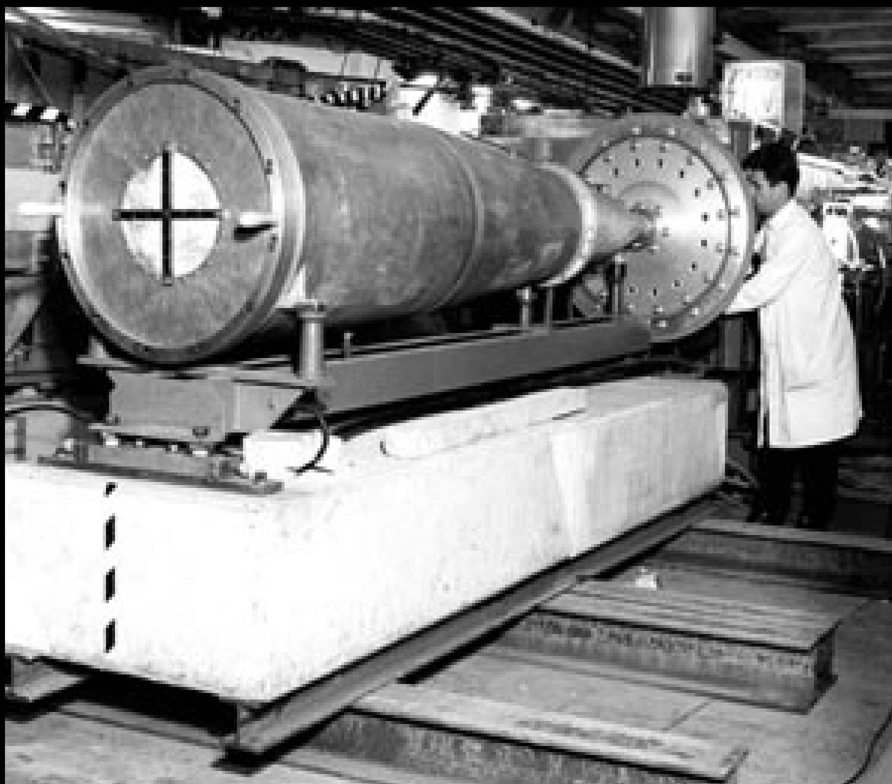
$$c_{ij} = \cos(\theta_{ij})$$

$$s_{ij} = \sin(\theta_{ij})$$

2-neutrino oscillation

$$P_{\alpha\beta} = \delta_{\alpha\beta} - \left(2\delta_{\alpha\beta} - 1\right)\sin^2(2\theta)\sin^2\left(1.27 \bullet \Delta m^2 \bullet \frac{L}{E}\right)$$

CERN is part of the history of neutrino beams
and
neutrino beams are part of CERN's discovery history



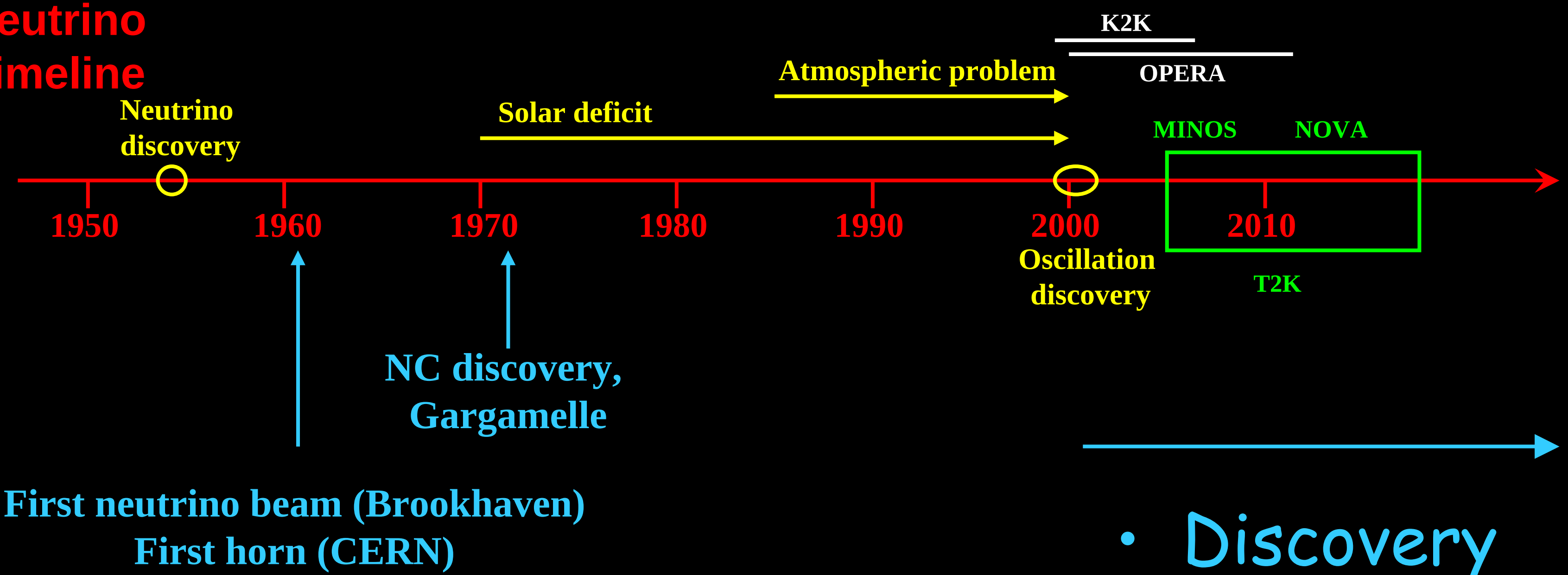
The 1st Neutrino Horn –
Van den Meer, CERN, 1961

Discovery of neutral currents,
Gargamelle, 1973

CNGS - MINOS – NOVA - T2K

Neutrino Long Baseline Experiments

Experimental Neutrino Timeline



- Discovery
- PMNS
- Precision
- CP search ?

Overview

2000

- K2K — Some European participation — completed
- OPERA — European experiment — running

First experiments
Proof of Long Baseline method
Confirmation of oscillations
Disappearance / Appearance
First measurements (2-3)

- MINOS — More European participation — running

Precision (2-3)
Neutrino - Antineutrino
Search for θ_{13}

- T2K — Strong European participation — Start running Dec 09
- NOVA — construction

Search for θ_{13}
Improved precision (2-3)
Hierarchy?
Pave the way for CP searches?

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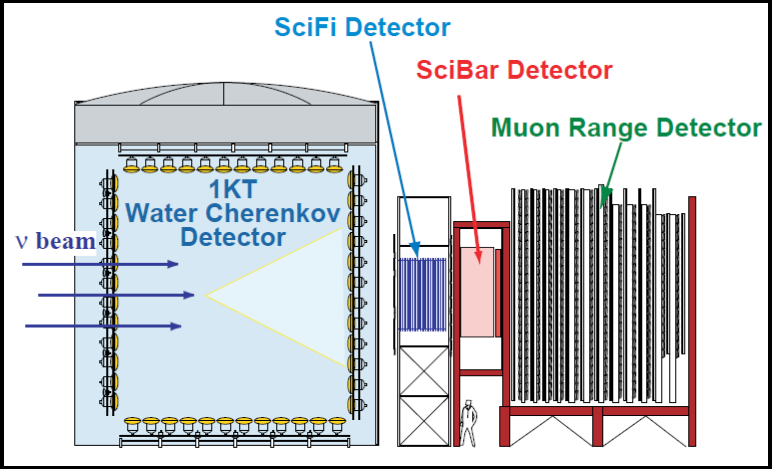
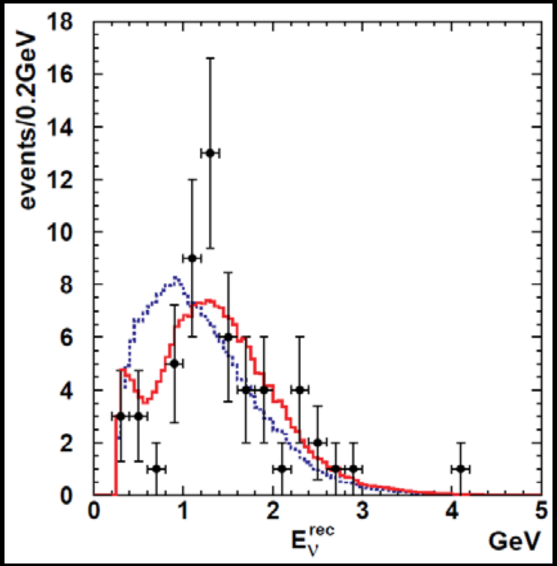
>2015

K2K: KEK to Kamioka

Near Detector



- KEK 12GeV proton beam
- Near Detector to characterize the neutrino beam
- Far Detector: 50kt Super-Kamiokande
- Baseline: 250km
- Neutrino energy: ~1GeV
- 1999-2006: 10^{20} P.O.T.
- Expected 92.3(54.4) muon-like events in S-K w/o(with) oscillations; observed 58
- Also fitted spectral distortion



$$1.9\times10^{-3} \leq \Delta m^2 \leq 3.5\times10^{-3}\ \mathrm{eV}^2\ (90\%\mathrm{CL}) \quad \text{for } \sin^2 2\theta=1$$

Phys. Rev. D 74, 072003 (2006)

OPERA

What we have directly observed elsewhere:

- Disappearance of ν_μ
- Most do not appear as ν_e

They must turn to ν_τ

BUT: no direct ν_τ appearance observation yet

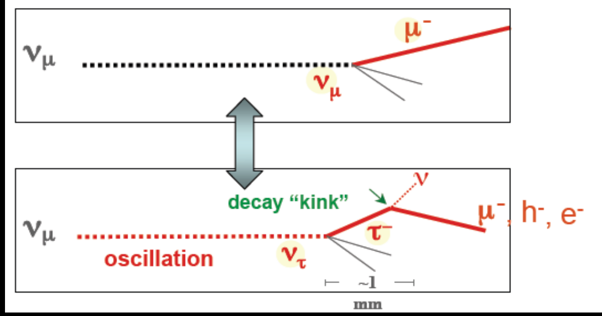
OPERA: search for ν_τ appearance in pure ν_μ beam

- Elegant but demanding technique
- Can produce textbook result assuming delivery of enough POT
- European Long Baseline experiment, substantial investment

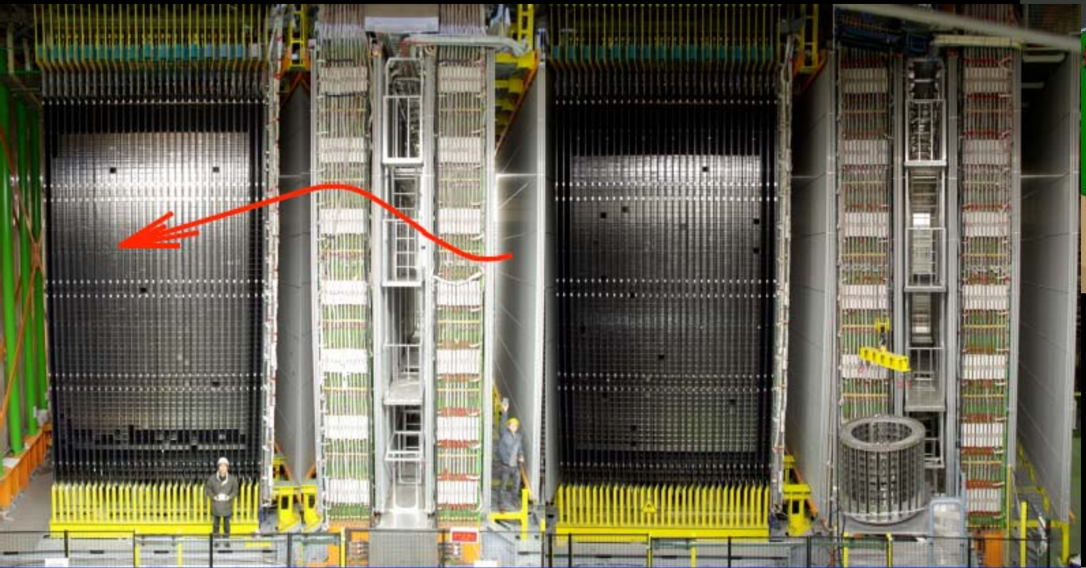
Timeline:

- 2000: SPSC proposal
- 2007: first CNGS neutrinos observed with partial detector
- 2008: Detector complete
- Approved for 2.25×10^{20}POT
- Today: 4.2×10^{19}POT delivered and recorded
- Possible by end 2010: $\sim 10^{20}$POT: expect 4.3 ν_τ events
- Proposed extension: 2011,12 to reach 2×10^{20}POT

OPERA (ii)

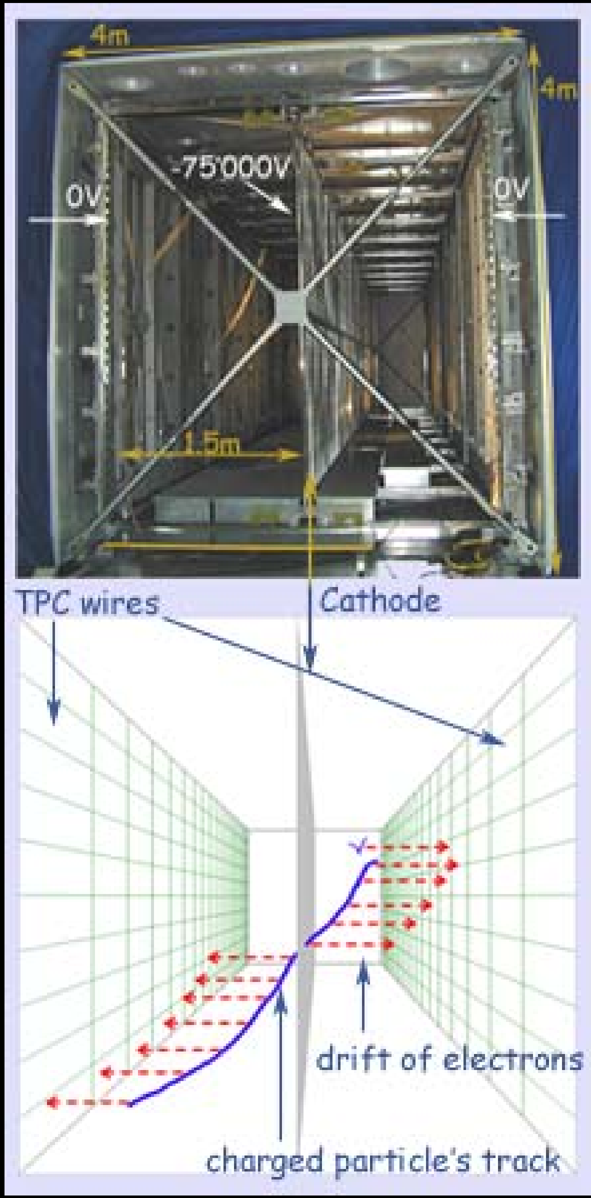


- CNGS beam: 400GeV protons from the SPS
- Almost pure ν_μ, <E>=17GeV
- Baseline (CERN to LNGS): 730km
- Topological τ identification using Emulsion Cloud Chamber technique taken to a new scale: 1.25kt, 150,000 "bricks"
- Electronic detectors and magnet for trigger and momentum measurement



ICARUS

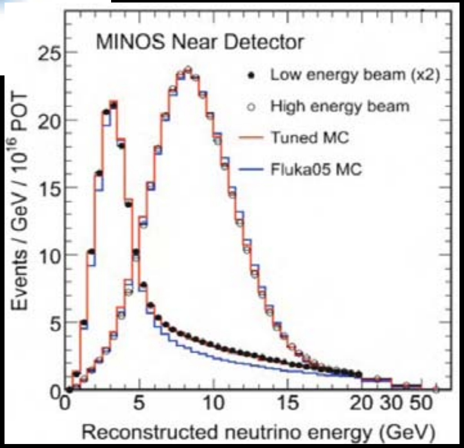
- T600: 2x300t LAr
- 3D event recording, vertexing, calorimetry, PID
- Exciting technology
- Also very challenging
- No beam data taken
- Physics prospects depend on ICARUS starting to take data soon and extension of CNGS run



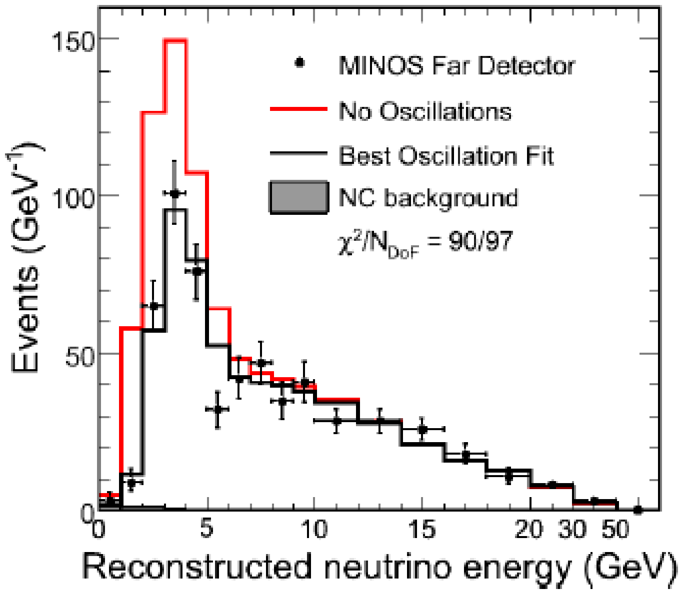
MINOS

- Fermilab beam, 120GeV Main Injector protons
- Typical beam power: 180kW
- Baseline: 735km (FNAL to Soudan, MN)
- Low and high E runs
- Data-taking since 2005
- Magnetized iron / scintillator tracking calorimeter detectors
- 5.4kt Far detector
- 0.98kt Near detector

- 7×10^{20}POT recorded
- 3×10^{20}POT analysed & presented
- Antineutrino running starting
  - 5σ observation of antineutrino oscillation in 1 year
- Mature experiment at the height of its productivity



MINOS – disappearance results



Unconstrained fit:

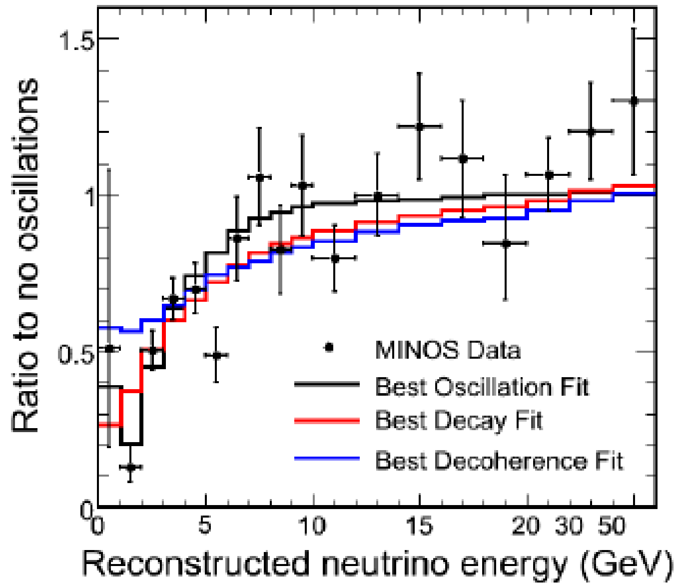
$|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

$\sin^2(2\theta) > 0.95$ [χ^2/ndof = 90/97, 68% C.L.]

Constrained ($\sin^2(2\theta)$=1.) fit:

$|\Delta m|^2 = 2.33 \times 10^{-3}\ eV^2$

$\sin^2(2\theta)$=1.07 [$\Delta\chi^2$=-0.6]



Decay

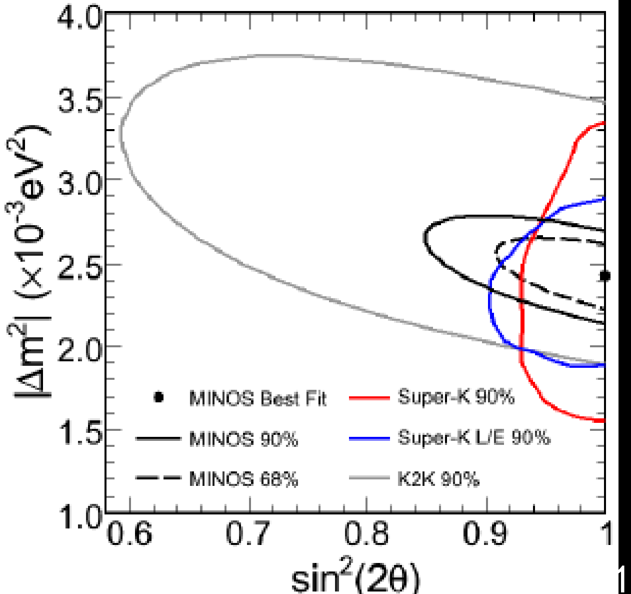
$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence

$\Delta\chi^2 = 33$

disfavored at 5.7σ

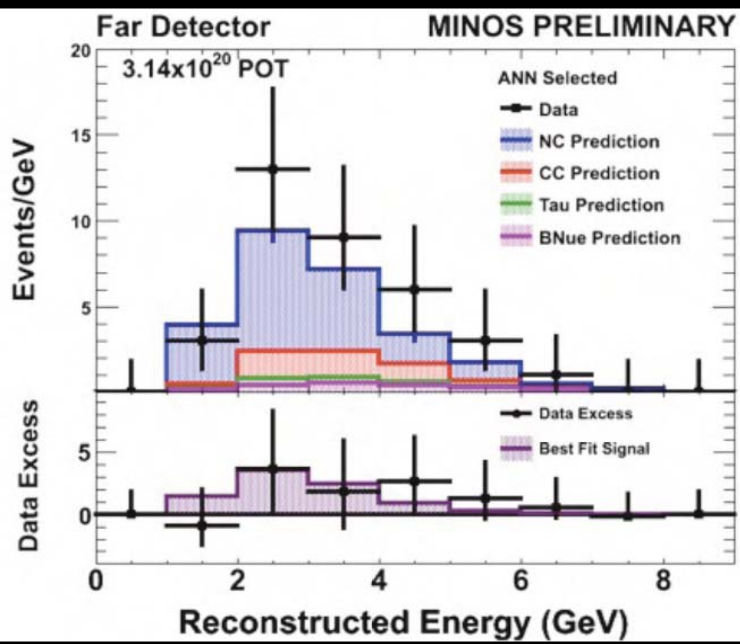


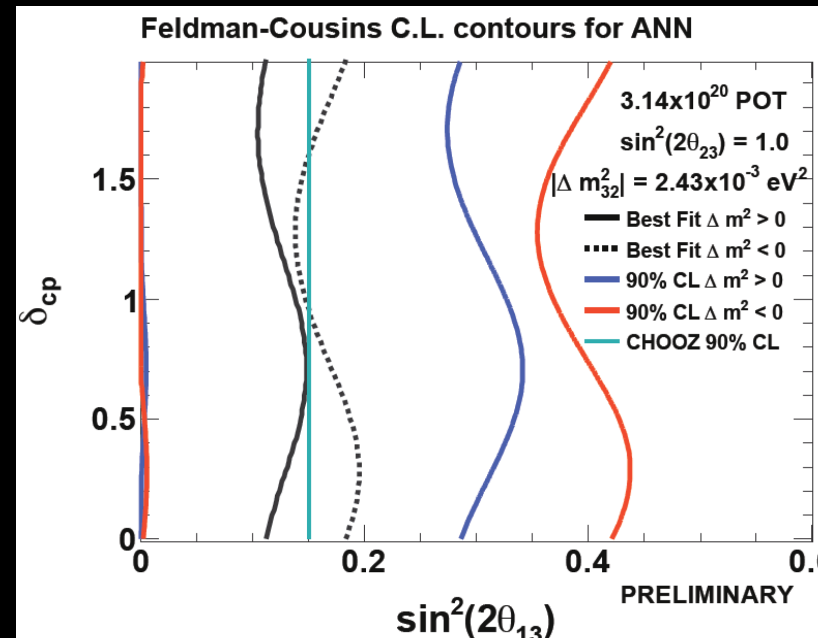
MINOS – appearance results

Observation 35 events

Expected Background 27±5(stat)±2(sys)

for 3.14×10^{20} POT



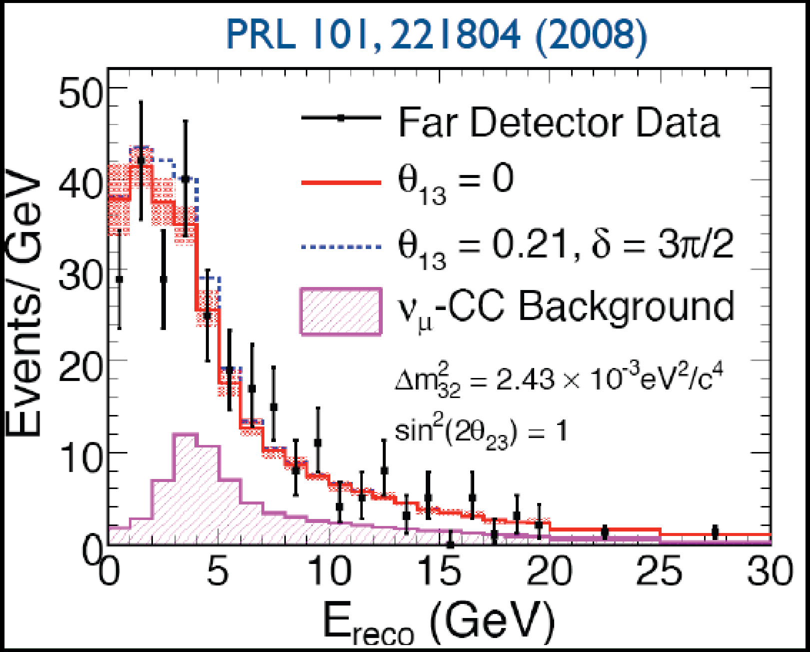


- normal hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) <$ 0.29 (90% CL)**
- inverted hierarchy, $\delta_{CP} = 0$: **$\sin^2(2\theta_{13}) <$ 0.42 (90% CL)**

Not conclusive (1.5σ); more statistics (double) to be analyzed
(My) current reading of this: after the first MINOS result we do not have any stronger limit than before
Early evidence and discovery by T2K (and Double-CHOOZ) remains a strong possibility

MINOS – other results

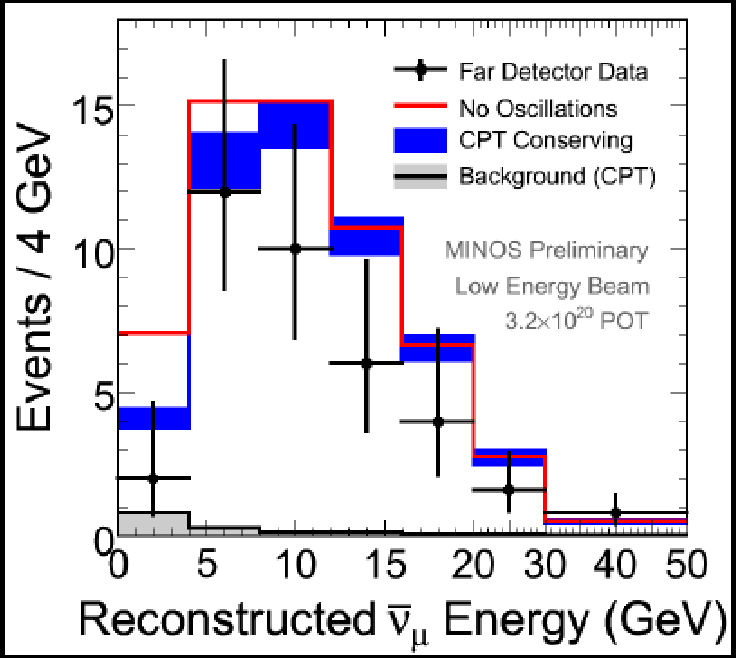
NC events, sterile neutrinos



Data consistent with no oscillations to sterile neutrinos

Muon antineutrinos

Magnetized detector allows separate detection of antineutrinos (7% of beam)



Data consistent with neutrino oscillation parameters

T2K

Canada
TRIUMF
U. of Alberta
U.of British Columbia
U. of Regina
U. of Toronto
U. of Victoria
York U.
France
CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE-Paris
Germany
RWTH Aachen U.
Italy
INFN Bari
INFN Roma
Napoli U.
Padova U.
Rome U.
Japan
Hiroshima U.
ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. of Edu
Osaka City U.
U. of Tokyo
Korea
Chonnam Nat'l U.
Dongshin U.
Sejong U.
Seoul Nat'l U.
Sungkyunkwan U.
Poland
A.Soltan
H.Niewodniczansk
Technical U.
U. of Silesia
Warsaw U.
Wroclaw U.
Russia
INR
Spain
IFIC, Valencia
U.A. Barcelona
Switzerland
Bern
ETHZ
U. of Geneva
UK
U. of Oxford
Imperial C. London
Lancaster U.
Queen Mary, U. of L.
Sheffield U.
STFC/RAL
U. of Liverpool
U. of Warwick
USA
Boston U.
BNL
Colorado State U.
Duke U.
Louisiana State U.
Stony Brook U.
U. of California, Irvine
U. of Colorado
U. of Pittsburgh
U. of Rochester
U. of Washington

- 477 members, 62 institutes, 12 countries
- 28 institutes from 7 European countries
- Approved in 2004
- First data December 2009
- Main objective: θ_{13}

T2K highlights

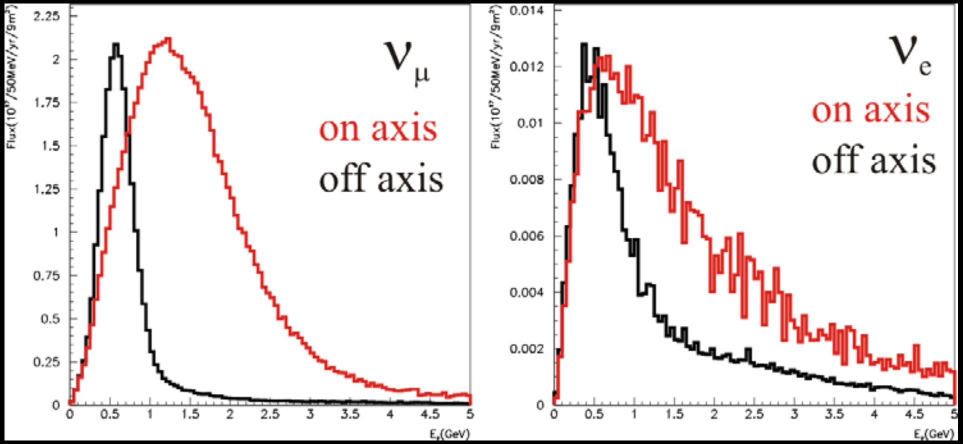
Main objectives

- Discovery: search for non-zero θ_{13}
  - Increase current sensitivity by ~10
- Precision: θ_{23} , Δm^2_{23}
  - World's most precise measurements

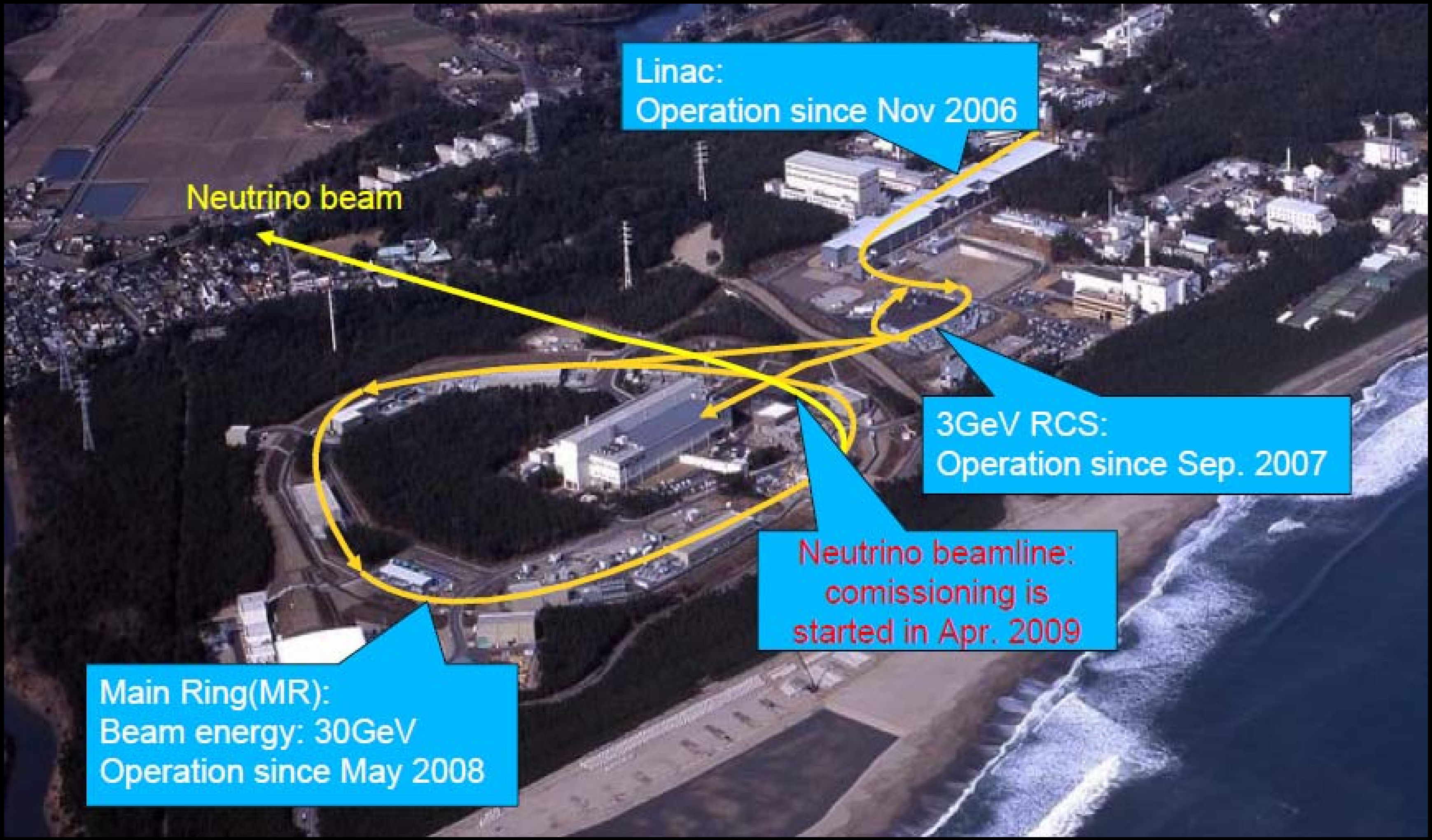
$$\sin^2 2\theta_{23} \rightarrow \quad \approx 1\% \qquad \qquad \Delta m^2_{23} \rightarrow \quad \approx 2\%$$

Off-axis beam (2.5°)

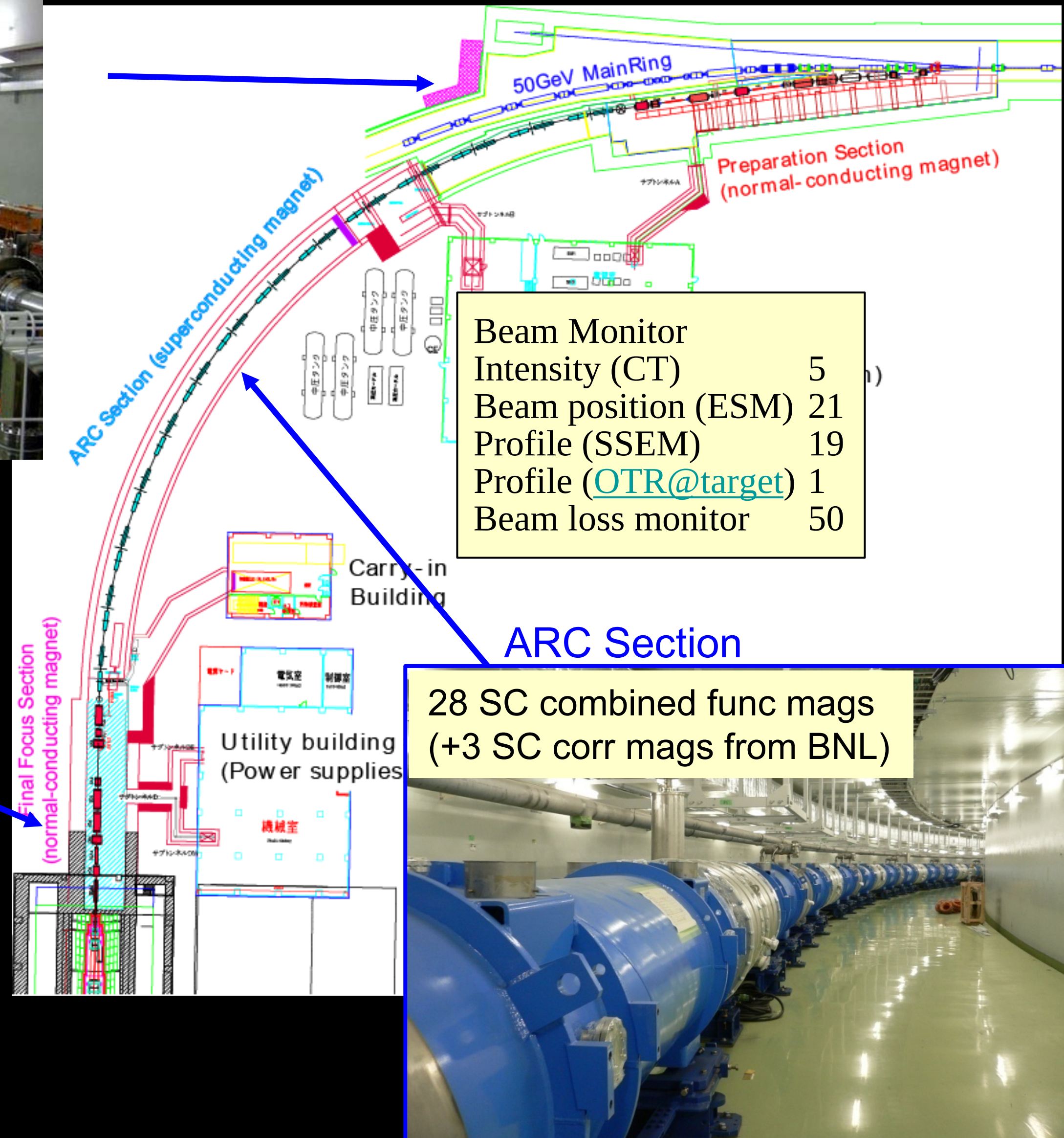
- Quasi-monochromatic ν_μ beam
- L/E tuned for max sensitivity
- Smaller intrinsic ν_e fraction
- Reduced high-E non-CCQE backgrounds



JPARC accelerator complex



Primary Beam-line

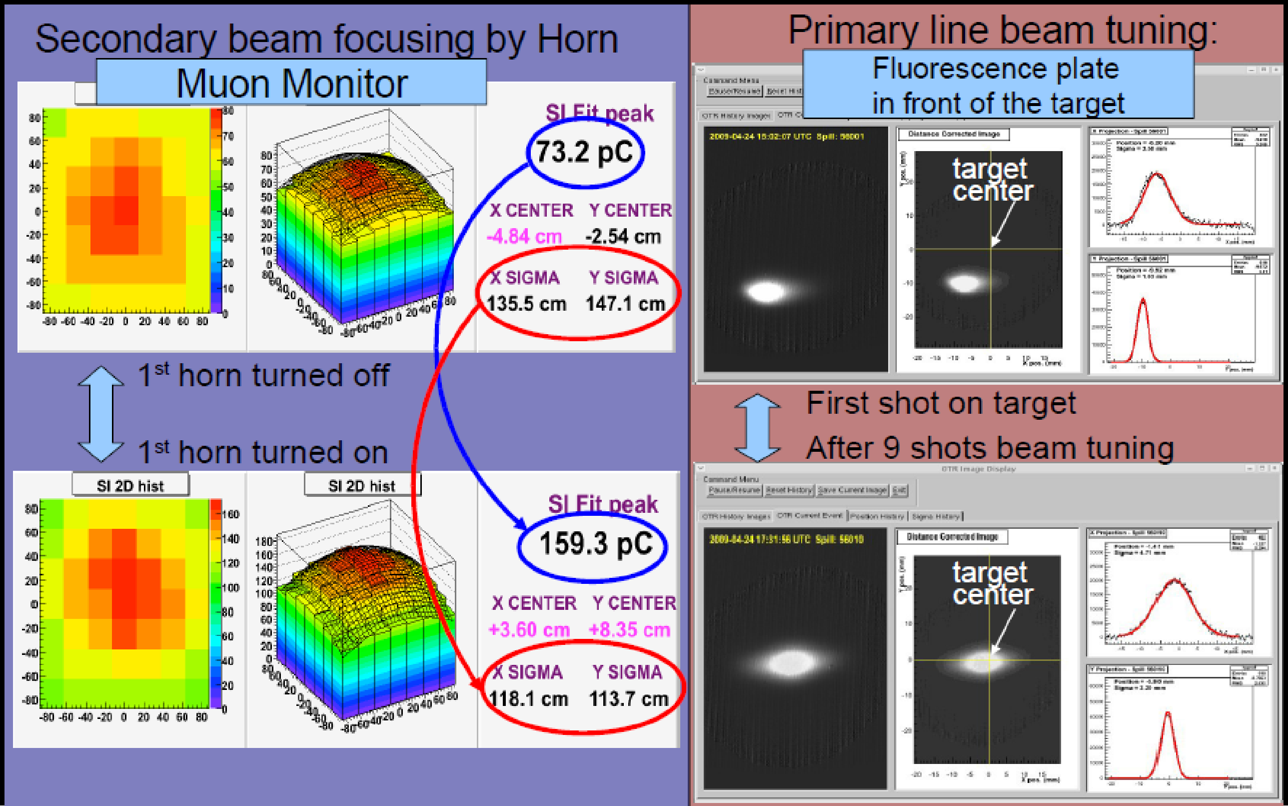


Beam Monitor	
Intensity (CT)	5
Beam position (ESM)	21
Profile (SSEM)	19
Profile (OTR@target)	1
Beam loss monitor	50

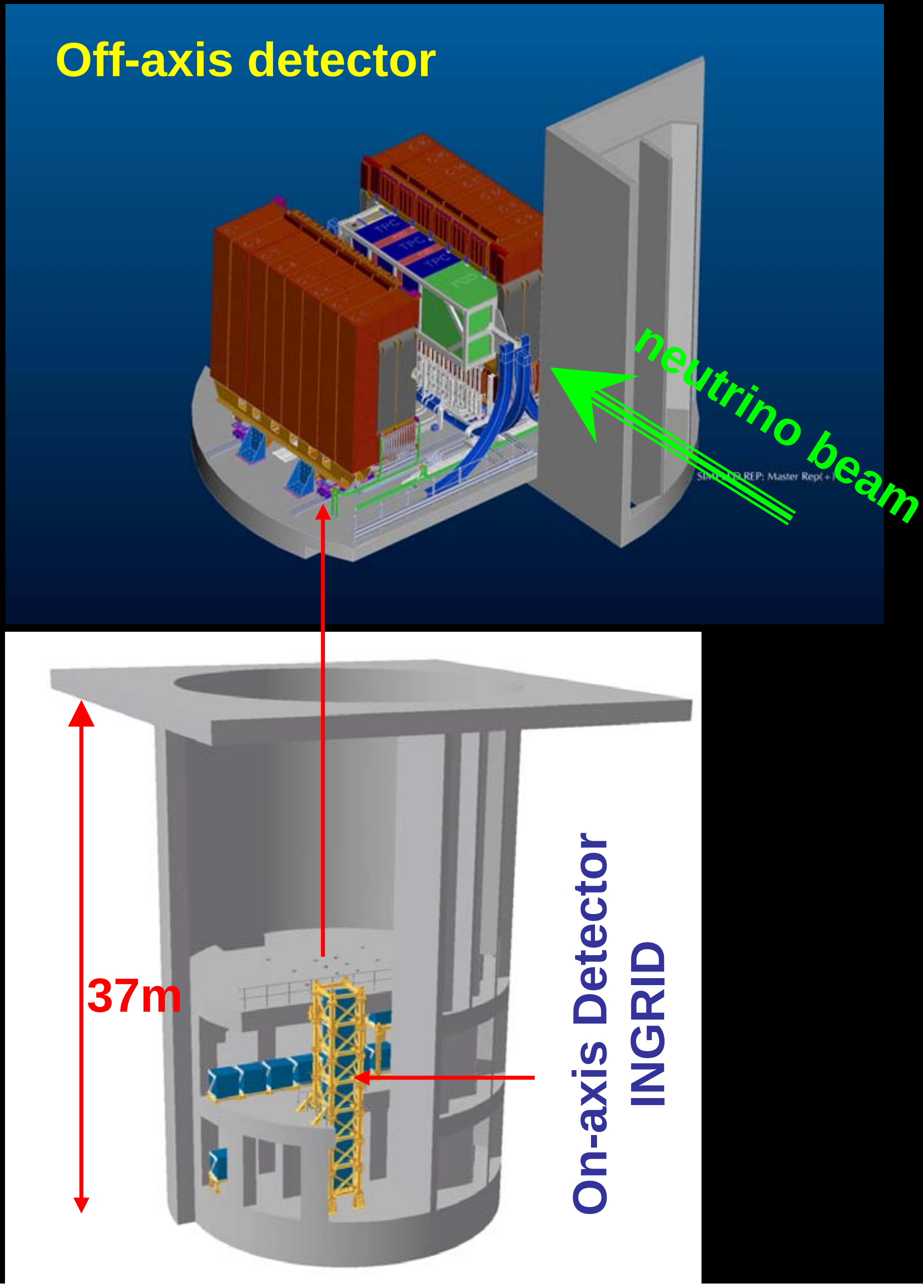
ARC Section

Neutrino Beam Line

- Primary beam line fully installed
- Commissioned (with 1 horn) in April 2009
- Signal in muon monitors from first shot
- *All 3 horns now installed*



The near detector: ND280



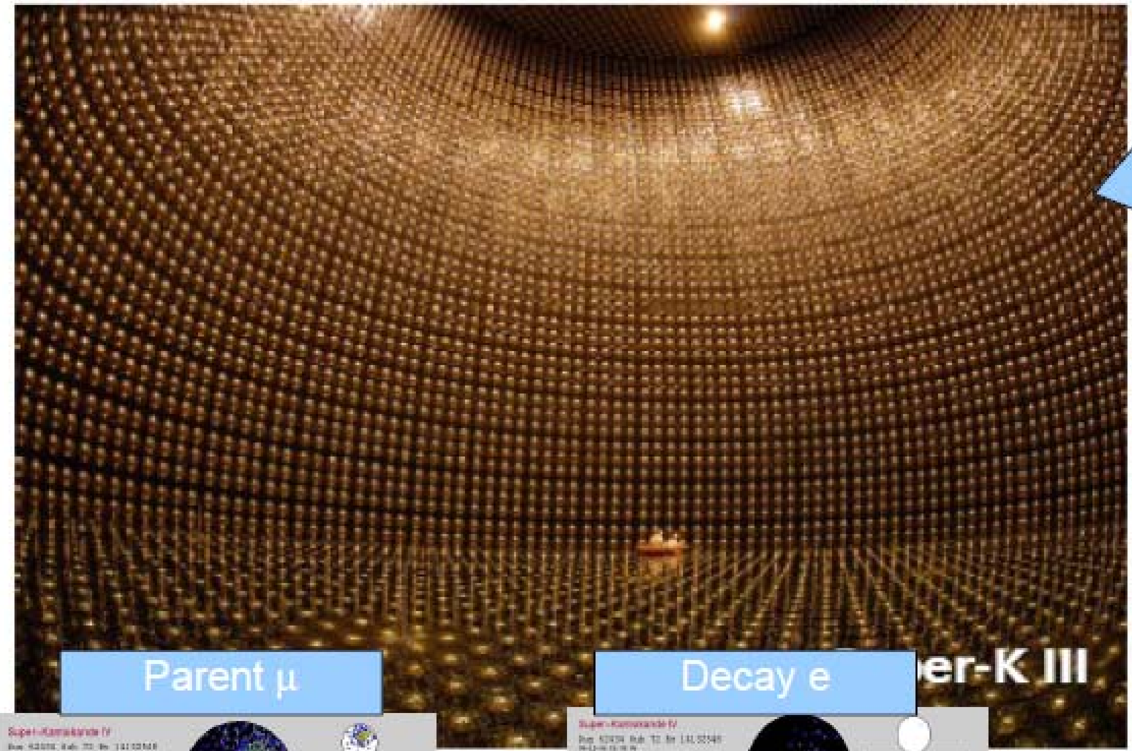
INGRID

- fully installed and operational

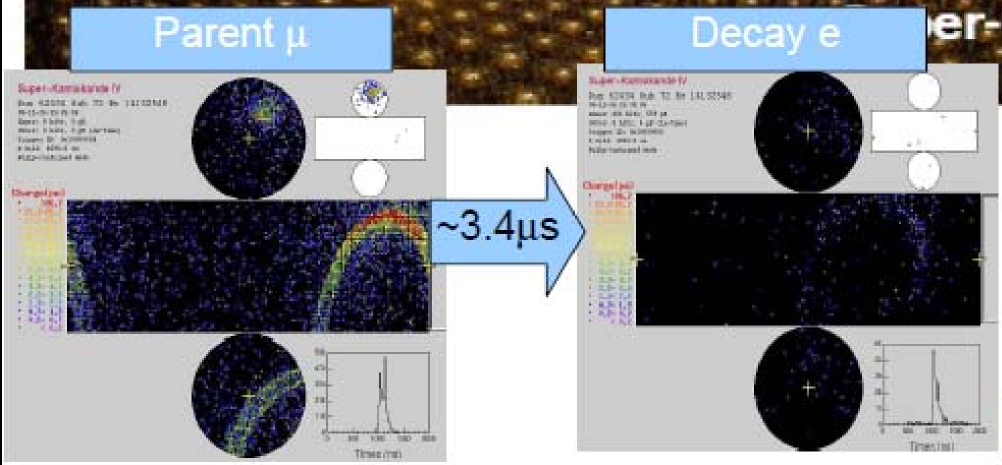
Off-axis detector

- Refurbished UA1 magnet: operational, field mapped
- SMRD: fully installed, commissioning
- POD: fully installed, commissioning
- FGD: installation this week
- DS ECAL: installation next week
- TPCs: 2 of 3 at JPARC, installation in October; third one in construction
- Barrel ECAL, POD ECAL: in construction, installation in 2010

Far Detector: Super-Kamiokande



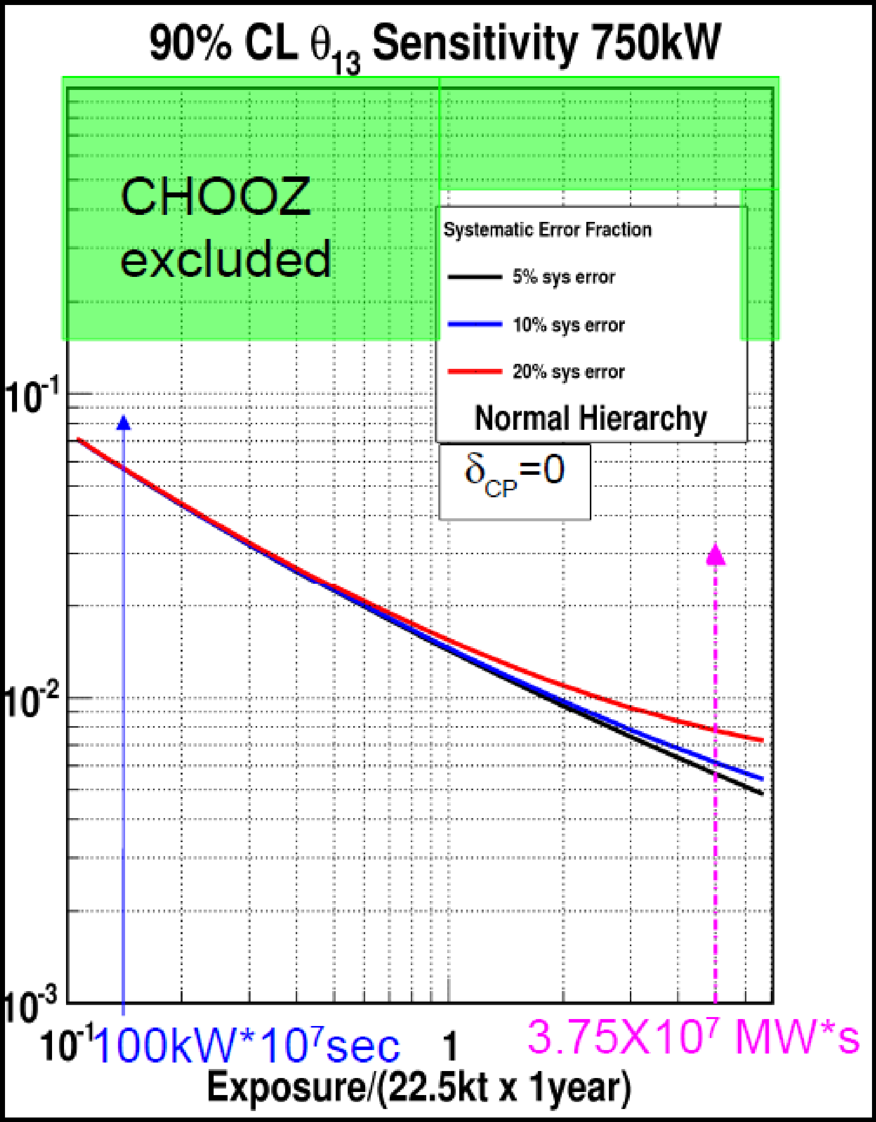
- ·50kt Water Cherenkov detector
- ·20”PMT x 10,000
- +Anti counter x 2000

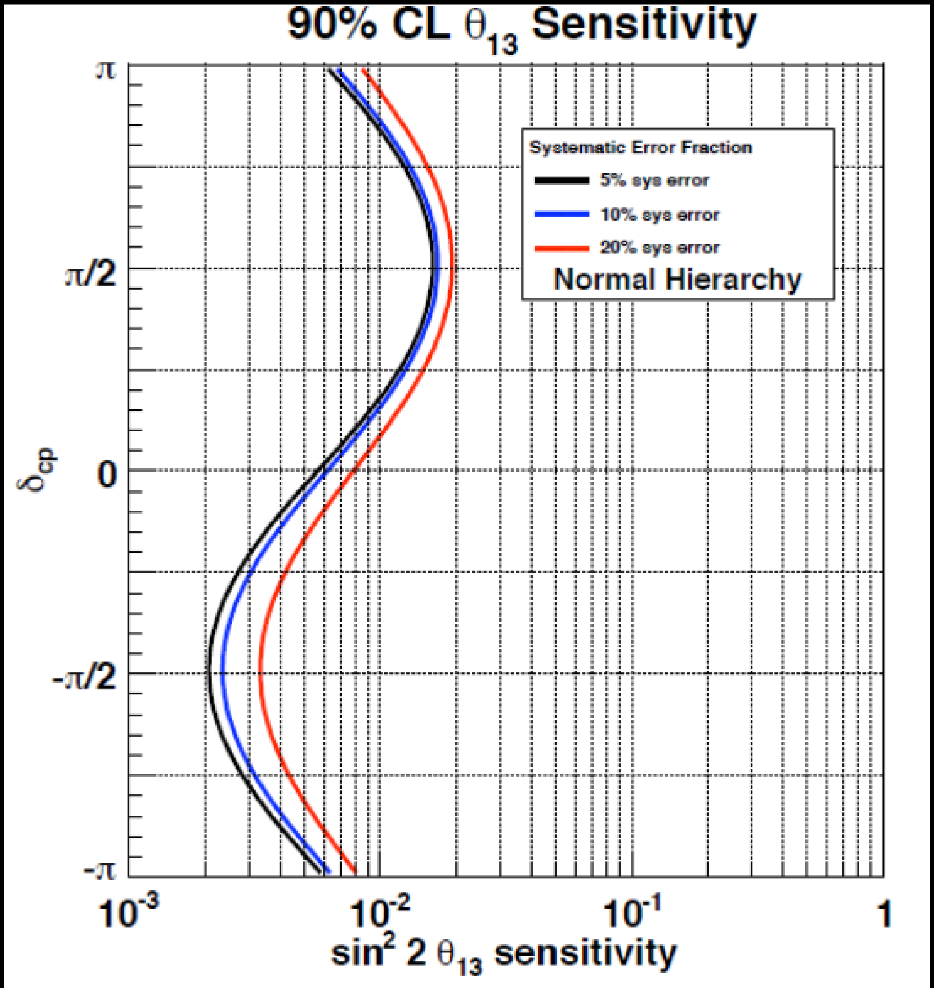


New electronics installed in summer of 2008. (SK-IV)

- Stable and dead time less DAQ
  → e.g. improvement of decay-e tagging efficiency
- Ready for T2K experiment

T2K appearance sensitivity

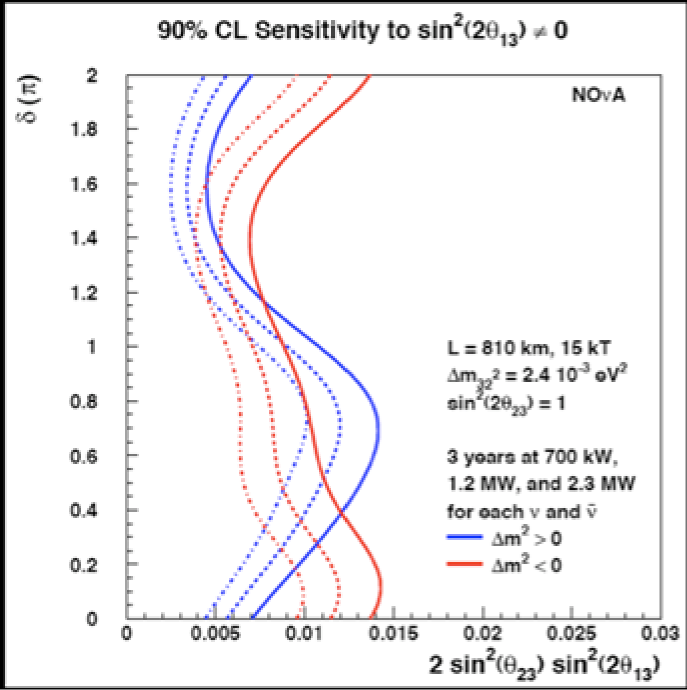




NOνA

- FNAL NuMI beam, Off-axis, 810kM
- NuMI beam upgrade to 700kW
- Liquid scintillator in 4cm x 6cm cells
- 14kton far detector
- 222ton near detector
- Funded in FY09 budget, ground breaking in far site started 1st May
- First data (2.5kton) 2012
- Full detector 2014

- Longer Baseline:
  - Mass Hierarchy (combinied with T2K)?



The next ~5 years

- If θ_{13}>0.01:
  - evidence very soon
  - firm observations by 2005
  - CP search will be open: new detectors, upgraded beams
- Europeans are participating in the θ_{13} search
  - BUT no experiment on European ground
  - How should we focus activities, what should the role of CERN be, so that Europe can be a major player in the CP-search phase?
- If no evidence of ν_e appearance by 2005
  - Need for new type of facilities (NF, BB)