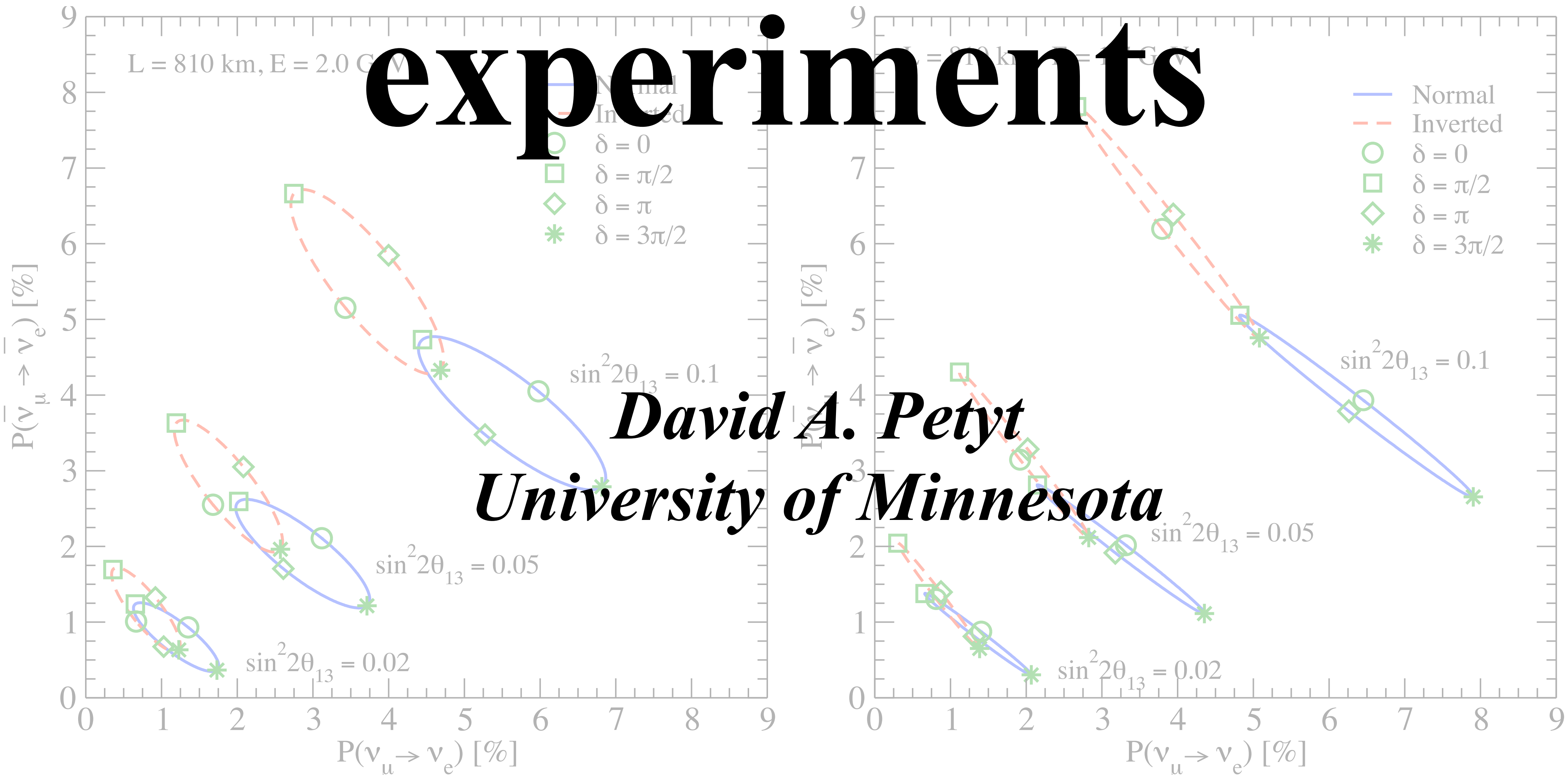
Review of long-baseline neutrino oscillation experiments



Reference: arXiv:0710.0554v2 (2008)

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University of Minnesota

45th Karpacz Winter School in Theoretical Physics
February 1-12 2009

Overview of the talk

- Brief history of the neutrino
- Neutrino oscillations - theoretical and experimental considerations
- Open questions in neutrino oscillation physics
- Past and present long-baseline experiments
- Near and long-future long-baseline experiments
- Summary and outlook

The neutrino in particle physics

The Discoveries

1930: "Invisible particle" postulated by Pauli

1933: Neutrino named by Fermi, theory of Weak interactions

1956: Reines/Cowan experiment observes Electron neutrino

1962: Observation of Muon Neutrino

1977: Observation of tau lepton - 3 lepton flavours

1991: Z line-width analysis at LEP → 3 light neutrinos

2001: Discovery of Tau Neutrino by DONUT

The Anomalies

1969: "Missing" solar neutrinos in Homestake experiment. *Confirmed in 1989-92 by Kamiokande, SAGE and GALLEX*

1988: Kamiokande observes deficit of atmospheric muon neutrinos. *Confirmed 1995-1998 by MACRO, Soudan 2, Super-Kamiokande*

1995: LSND anomaly - sees excess of ν_e in muon neutrino beam. *Disfavoured by MiniBoone analysis in 2007*

Neutrino oscillations

- Neutrino flavour oscillations possible if neutrinos have non-zero and non-degenerate masses.

flavour eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

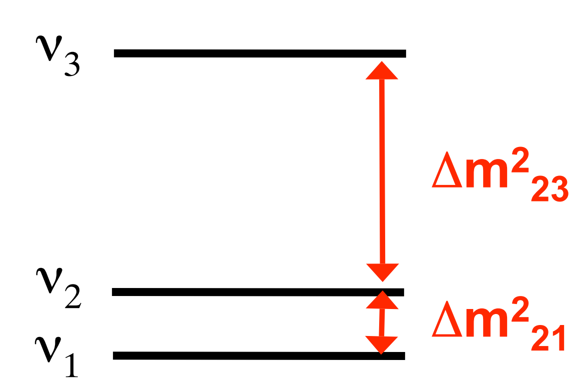
mass eigenstates

PMNS Unitary mixing matrix

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

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

Neutrino mass hierarchy



Two flavour formalism

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

mixing amplitude

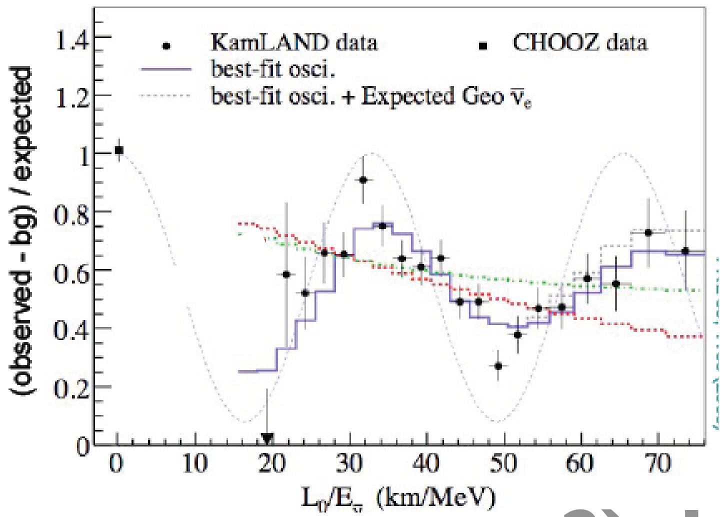
phase

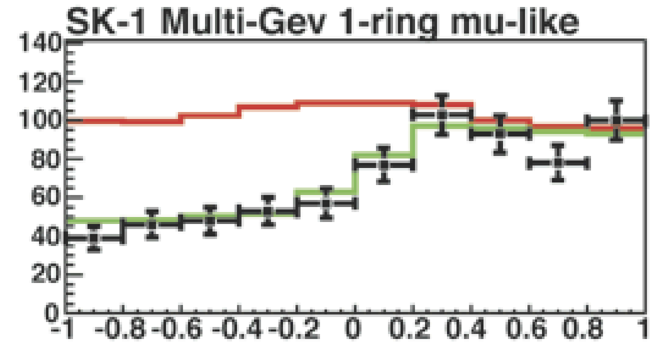
experimental variables

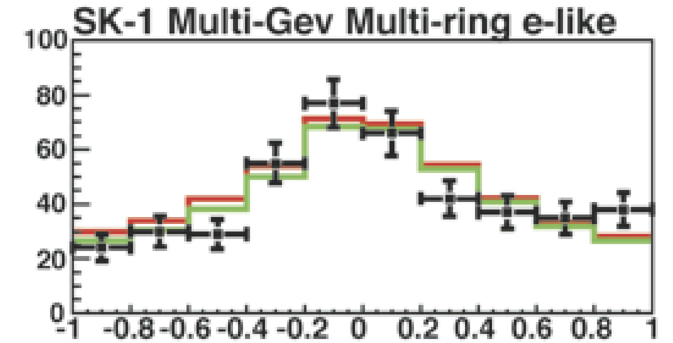
Neutrino oscillations - theory vs experiment

Solar Neutrinos+Kamland | **Atmospheric neutrinos**

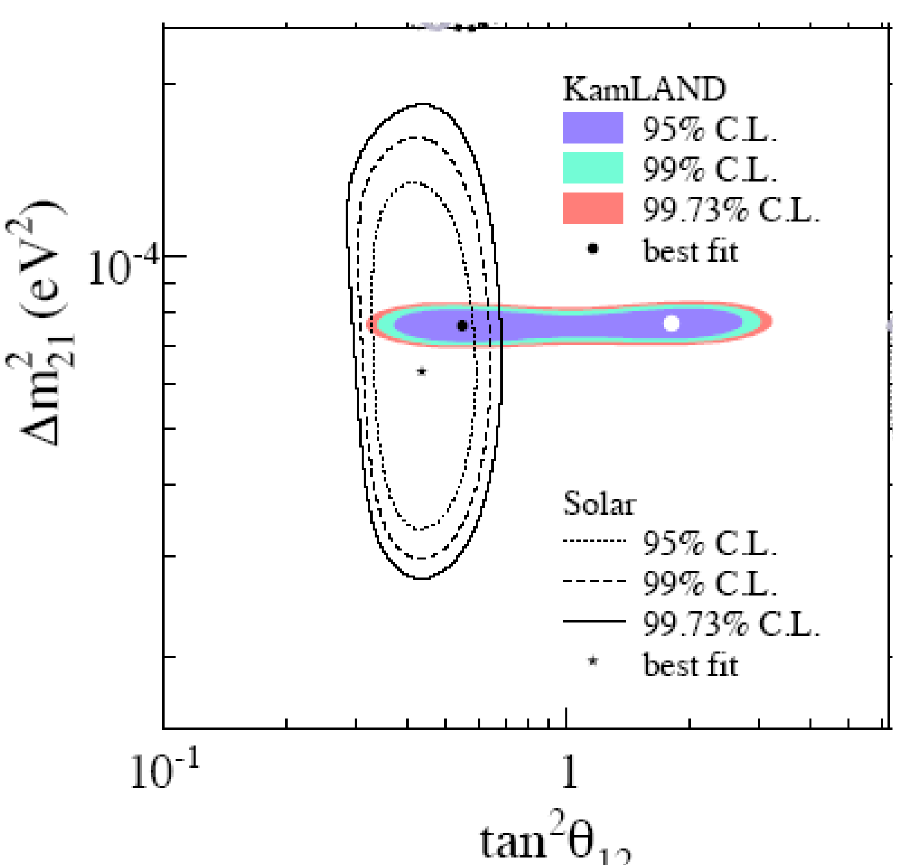
1) neutrino disappearance as a function of L/E

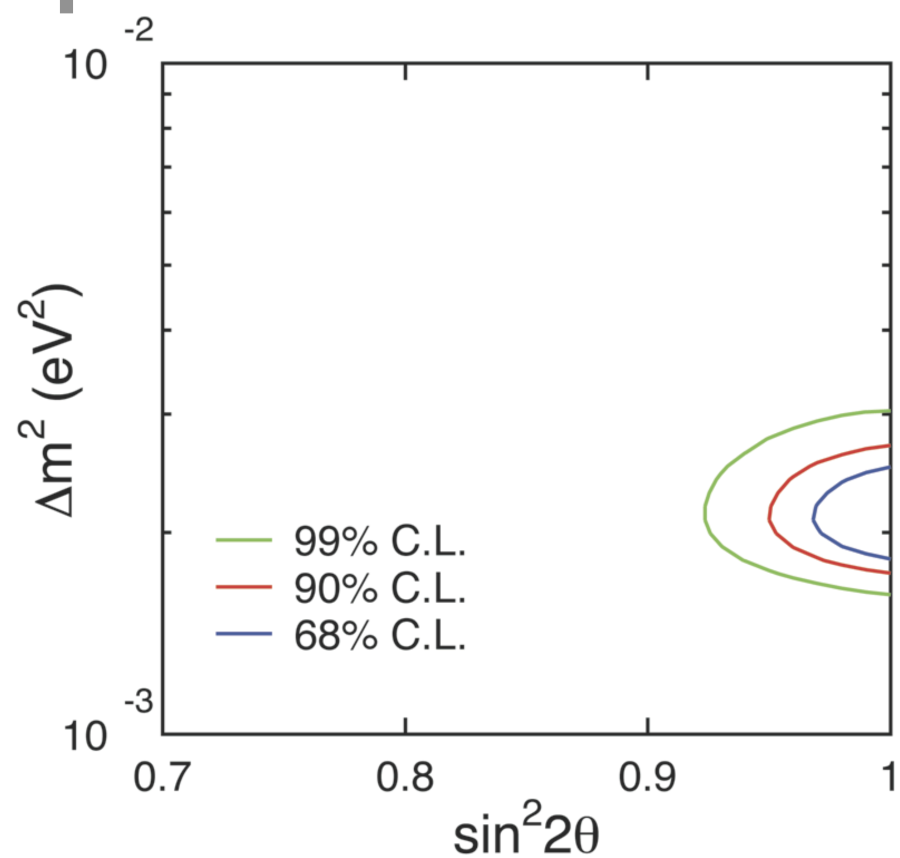






2) derived oscillation parameters





Phenomenon of neutrino oscillations well-established

Nobel Prize in Physics 2002: R. Davis Jr, M. Koshiba

Long-baseline experiments

- Explore neutrino oscillation phenomena using controlled beams produced by particle accelerators

- Optimise beam energy and experimental baseline to maximise sensitivity in region of oscillation phase space suggested by atmospheric neutrino data

- Two classes of search:

  - **Disappearance measurement:** search for a deficit of neutrinos of a given flavour (typically ν_μ) as a function of energy and neutrino path length

  - **Appearance measurement:** search for the appearance of neutrino of flavour ν_x, due to $\nu_\mu \rightarrow \nu_x$ oscillations

Two-detector approach

- Most long-baseline experiments adopt a two-detector approach:
  - A ***Near detector*** (or set of detectors) close to the neutrino source to measure the beam flux and composition in the absence of oscillations
  - A ***Far detector*** to measure the neutrino spectrum and flavour composition after the neutrinos have travelled sufficient distance to oscillate
- Although there are significant uncertainties in the prediction of the absolute beam flux and cross-sections, these are common to interactions in both Near and Far detectors.
  - By comparing events in the two detectors, one can significantly cancel these uncertainties.
  - The goal of long-baseline experiments is therefore make the fullest use of the Near detector data to predict the neutrino flux in the Far detector, using the Monte Carlo to make the required acceptance corrections.

Open questions

that can be addressed by long-baseline experiments

- Is the atmospheric neutrino disappearance signature $\nu_\mu \rightarrow \nu_\tau$?
  - are there light sterile neutrinos?
  - Can we verify the oscillation pattern?
- What is the value of the third mixing angle, θ_{13}?
- Is the mixing angle θ_{23} maximal?
- What is the ordering of neutrino masses?
- Is there CP violation in the neutrino sector?

Past/Current experiments

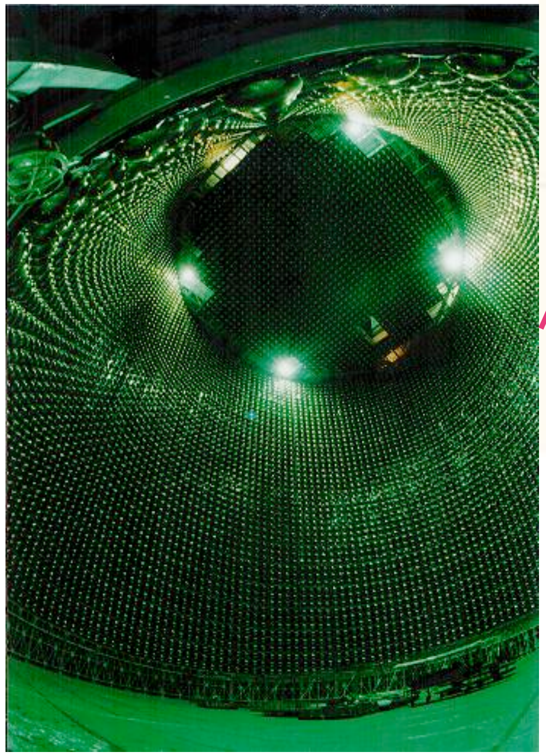
K2K: 1999-2004
MINOS: 2005-present
CERN-Gran-Sasso: 2007-present

List of experiments and goals

- The principal goals of the first generation of long-baseline accelerator neutrino experiments was/is:
  - K2K (1999-2004): confirm the oscillation signal observed in atmospheric neutrinos.
  - MINOS (2005+): make precision <10% measurement of the oscillation parameters, confirm oscillation pattern
  - OPERA (2007+): confirm $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis by directly observing τ decay signatures
- Secondary goals:
  - search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (ALL)
  - search for active→sterile oscillations (MINOS)

The K2K experiment

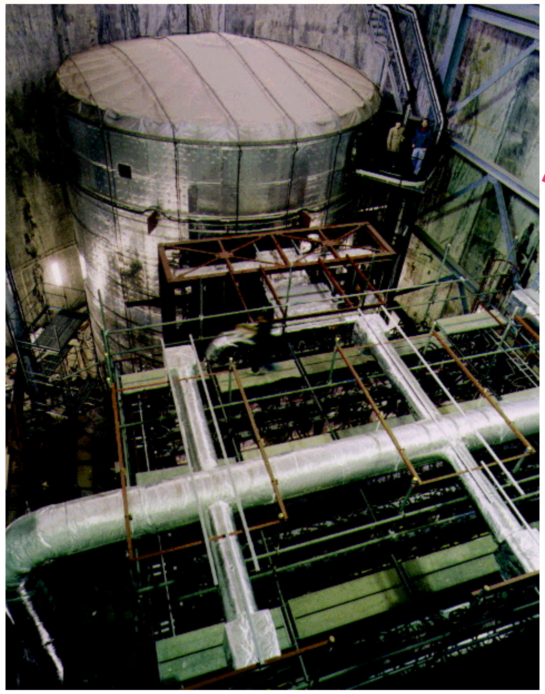
- The first long-baseline neutrino oscillation experiment using accelerator neutrinos



Far Detector

Super-Kamiokande

50 kT Water Cerenkov



Near Detectors

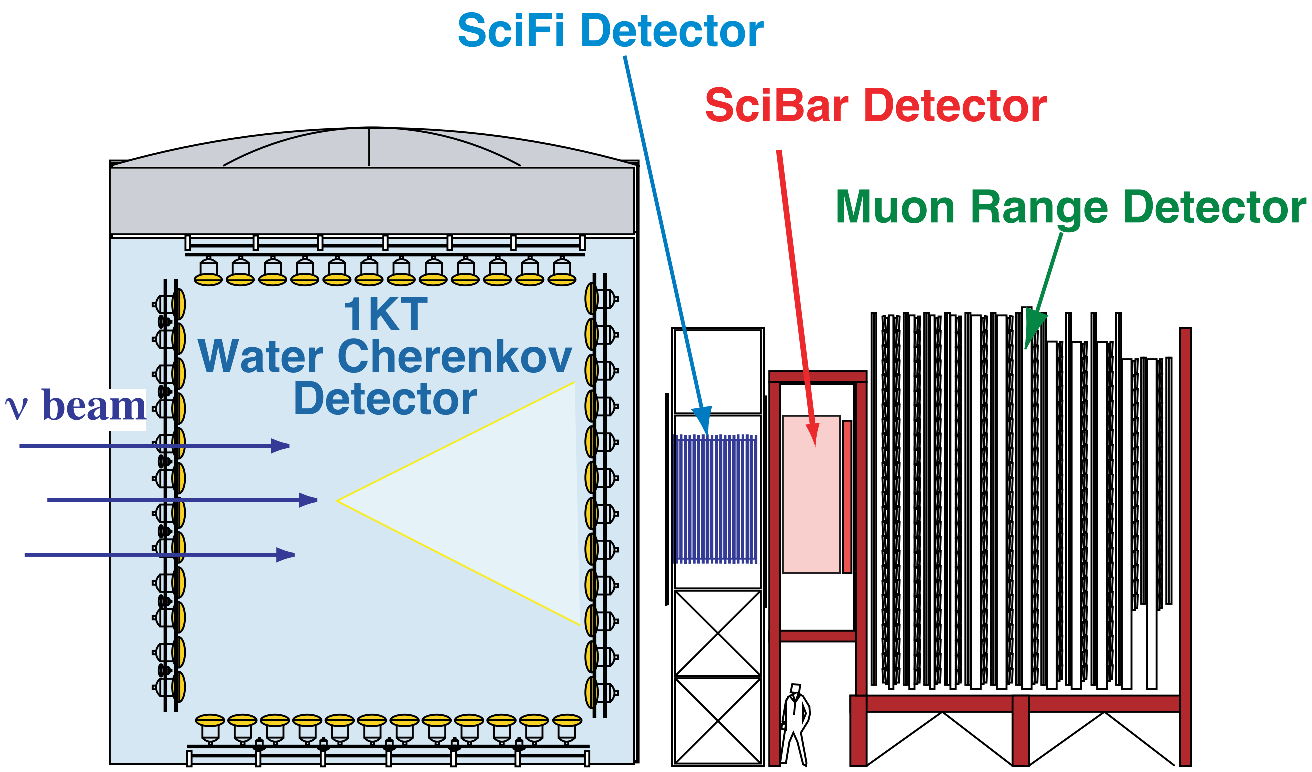
Neutrino Beam

12 GeV PS at KEK

K2K physics goals and near detectors

- 12 GeV protons from KEK PS produce pure ν_μ beam with mean neutrino energy ~1 GeV
  - together with the baseline from KEK to Super-K of 250 km, this allows an investigation of ν_μ disappearance in the Δm^2 range 10^{-3} to 10^{-2} eV^2 → **check of Super-K atm. ν results using controlled neutrino beam**

K2K near detector suite



- Neutrino flux measured by a suite of Near detectors:

1kT Water Cerenkov: smaller version of Super-K, uses same particle ID and reconstruction algorithms

Sci(ntillating) Fi(bre) detector: high resolution device for measuring charged tracks from neutrino interactions. Measures rates of QE and inelastic events

Sci(ntillating) Bar detector: high resolution, totally active device. Good sensitivity for low monentum charged particle tracks. Contains downstream EM calorimeter for measuring π^0 production and beam ν_e content

Muon range detector: 12 layers of iron/drift tubes (~2m iron thickness) for muon range measurement. Acceptance: 0.3-2.8 GeV

K2K analysis and physics results

- K2K prediction of ν_μ flux at Super-K:

$$\Phi_{SK}=\Phi_{ND} \times R_{FN}$$

measured flux at Near location

Far/Near flux ratio
from HARP particle production data, validated by K2K beam MC and K2K pion monitor data

- Results based on exposure of $0.922\text{x}10^{20}$ POT (June 1999-Nov 2004)
  - observed **112** μ-like events in Super-K, expected **158.1**
  - spectral distortion seen in FD E_ν spectrum of 58 single ring μ-like events

Oscillation parameters:

$Sin^2 2\theta > 0.6$ (90% C.L., 2 dof)

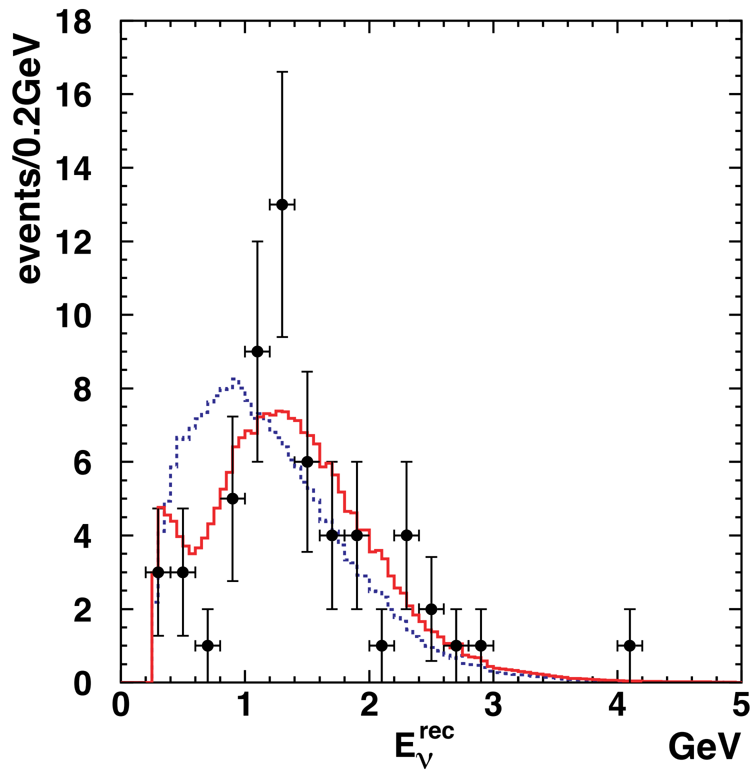
$1.9 < \Delta m^2 < 3.1\text{x}10^{-3}$ eV^2

(90% C.L., at $Sin^2 2\theta = 1$)

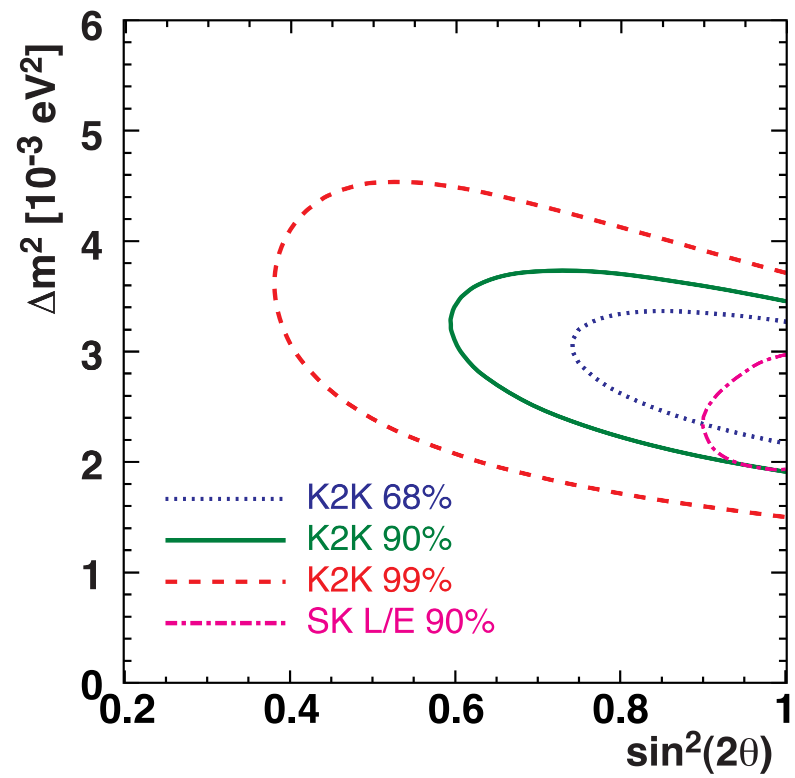
Best fit=$2.8\text{x}10^{-3}$ eV^2, 1.0

confirms earlier Super-K atm. ν result

E_ν spectrum of single-ring events

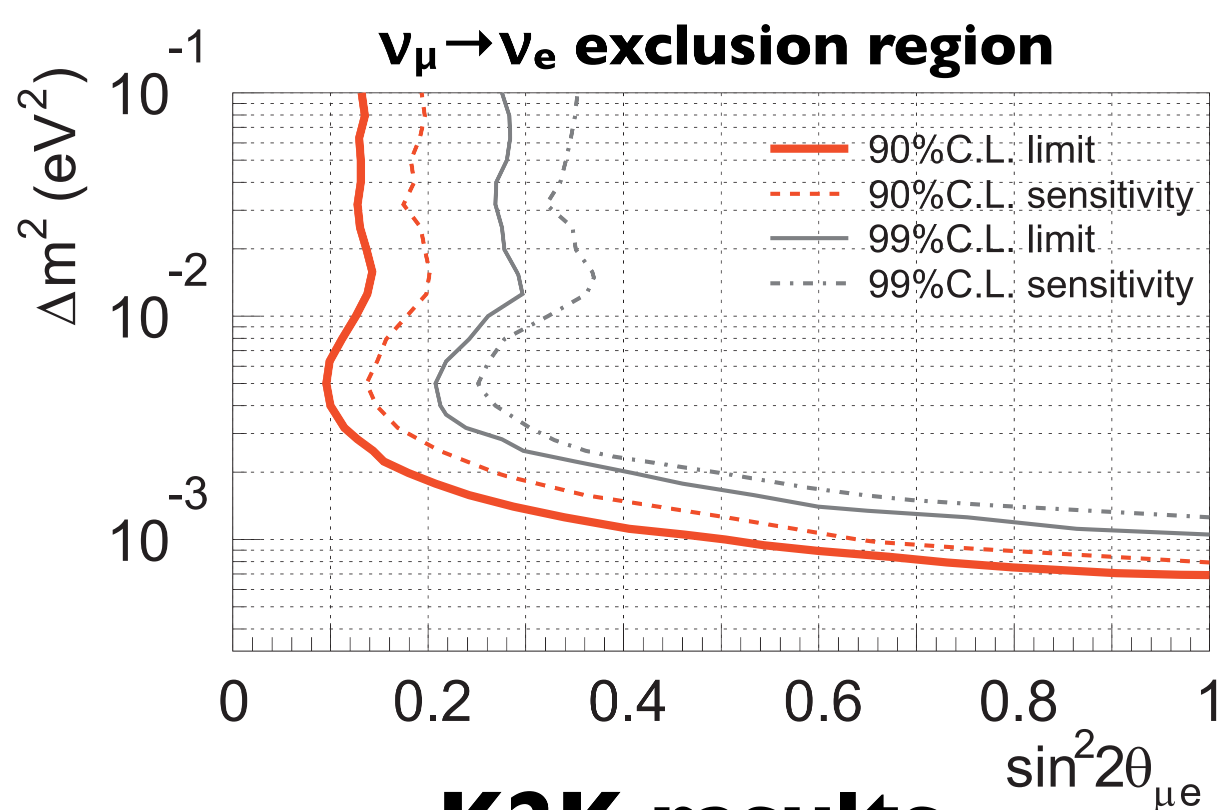


$\nu_\mu \rightarrow \nu_\tau$ allowed region



K2K results - ν_e

- Search for e-like (fuzzy) rings originating from ν_e CC QEL events
  - excess over background (π^0 from ν_μ interactions or beam ν_e) would be evidence for $\nu_\mu \rightarrow \nu_e$
- After all selection cuts, **1** candidate event observed, consistent with background estimate

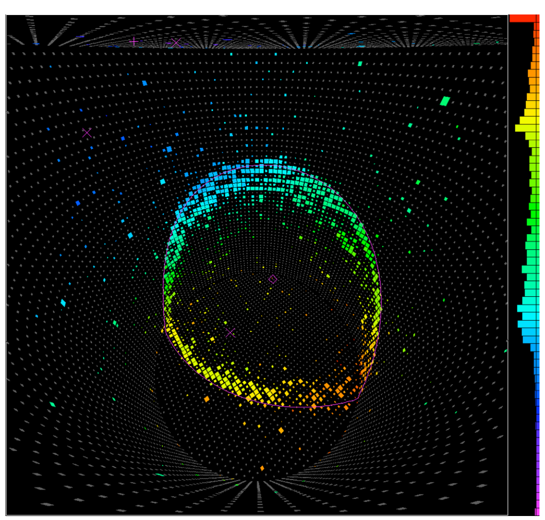


K2K results

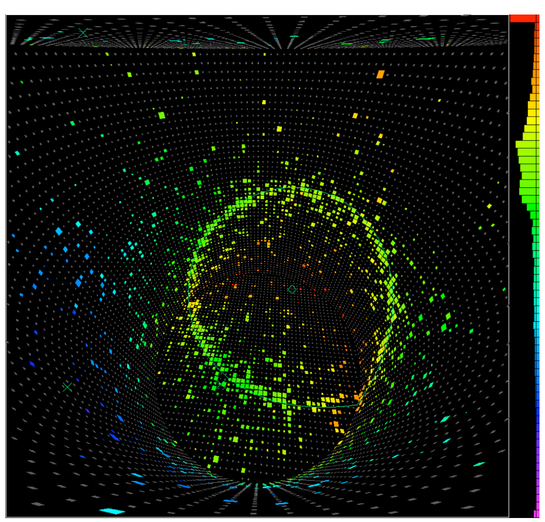
$\sin^2 2\theta_{\mu e} < 0.13$ (90% C.L. at $\Delta m^2 = 2.8 \times 10^{-3}$)

$\sin^2 2\theta_{13} < 0.26$ (90% C.L. at $\Delta m^2 = 2.8 \times 10^{-3}$)

using $\sin^2 2\theta_{\mu e} = 2\sin^2 2\theta_{13}$



μ-like



e-like

Existing limit from CHOOZ

$\sin^2 2\theta_{13} < 0.1$ (90% C.L. at $\Delta m^2 = 2.8 \times 10^{-3}$)

Phys. Rev. D 74, 072003 (2006). (nu_mu disappearance - long writeup)
Phys. Rev. Lett. 96, 181801 (2006). (nu_e appearance)
Phys. Rev. Lett. 90, 041801 (2003). (first oscillation results)

The MINOS experiment

- **MINOS (Main Injector Neutrino Oscillation Search)**
- Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector
  - A Near detector at Fermilab to measure the beam composition and energy spectrum
  - A Far detector deep underground in the Soudan Mine Minnesota, to search for evidence of oscillations

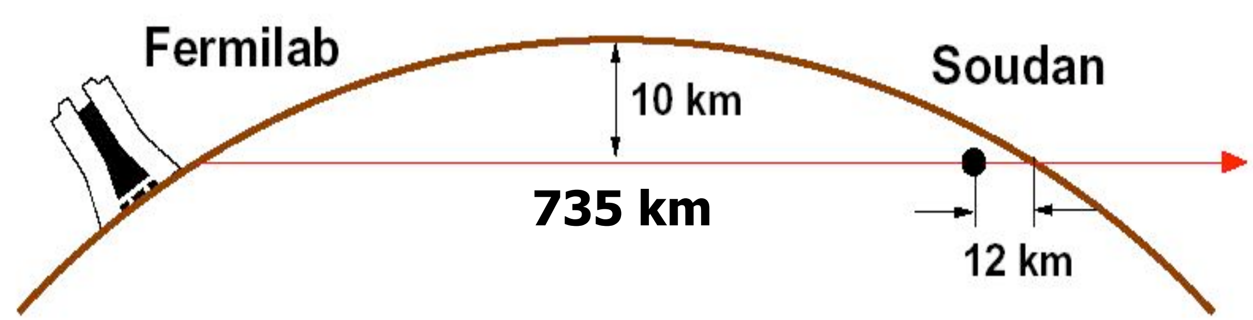
Primary physics goals:

Precise measurement of $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters

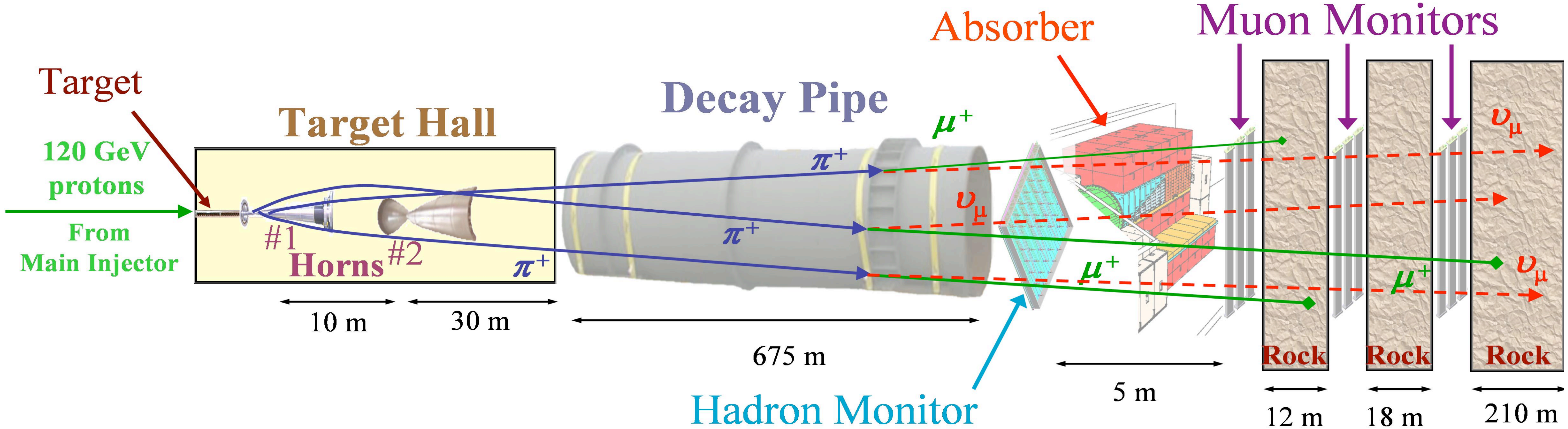
Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations

The MINOS Collaboration, 2003

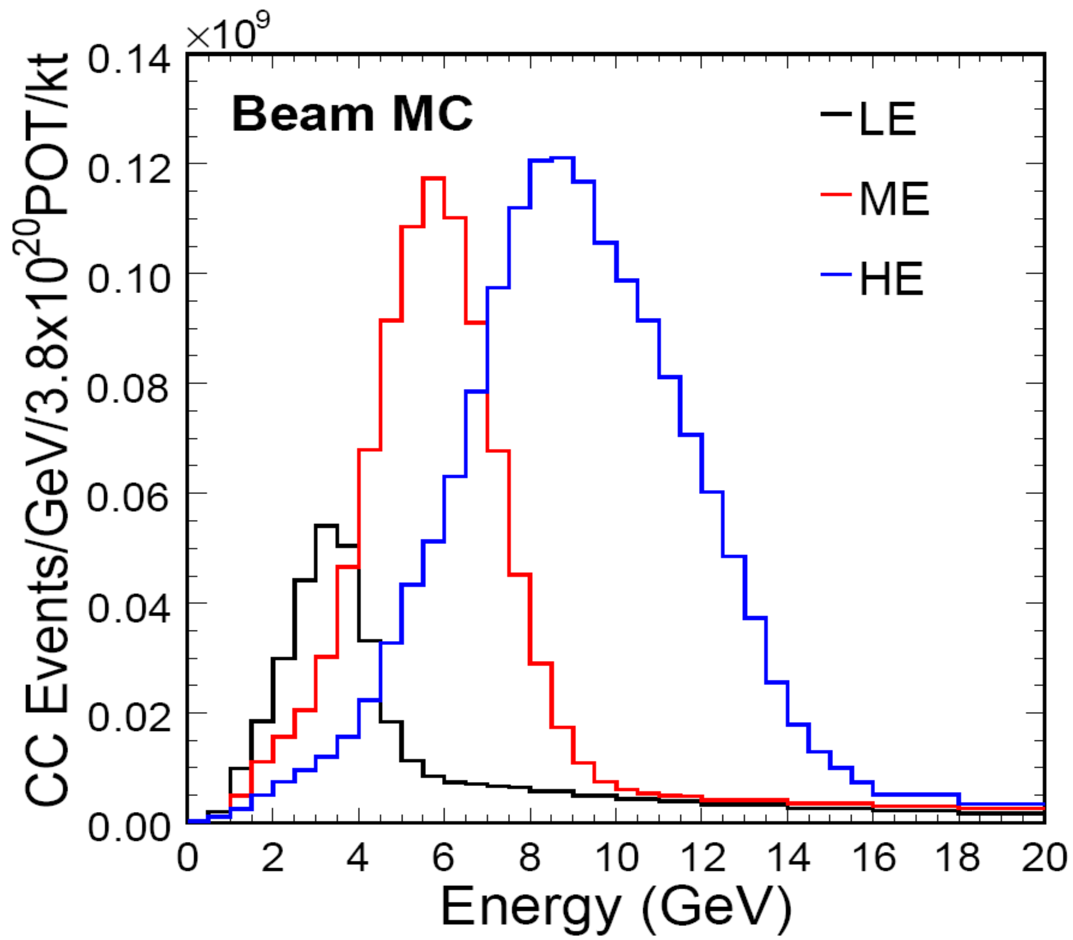
29 institutions, 165 scientists



The NuMI neutrino beam



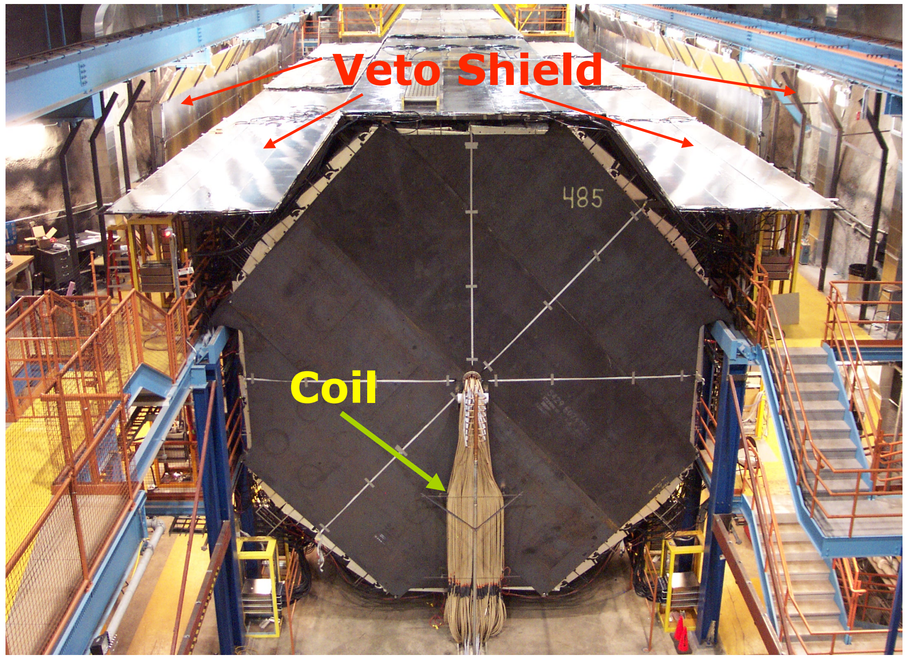
- Neutrino beam produced by 120 GeV protons striking a graphite target:
  - π and K decays produce a 98.5% pure ν_μ beam
- Neutrino energy spectrum can be changed by moving target position relative to first horn:
  - Most of the running has been in the low energy **"LE-10"** position, which is optimum for measuring the oscillation parameters
  - Some running in higher energy positions for beam tuning and systematics studies



The MINOS detectors

"Two functionally identical detectors"

Far Detector at Soudan



Data taking since ~ September 2001. Installation complete in July 2003.

Near Detector at Fermilab

Plane installation fully completed on Aug 11, 2004

Far Detector	Near Detector
5.4 kton mass, 8×8×30m	1 kton mass 3.8×4.8×15m
484 steel/scintillator planes	282 steel and 153 scintillator planes
(x 8 multiplexing)	(x 4 multiplexing after plane 120)
VA electronics	Fast QIE electronics

Magnetised steel - B ~1.2T

Multi-pixel (M16,M64) PMT readout

GPS time-stamping to synch FD data to ND/Beam

Continuous *untriggered* readout of whole detector (only during spill for the ND)

Interspersed light injection (LI) for calibration

Software triggering in DAQ PCs (Highly flexible : plane, energy, LI triggers in use)

Spill times from FNAL to FD trigger farm

MINOS results - ν_μ disappearance

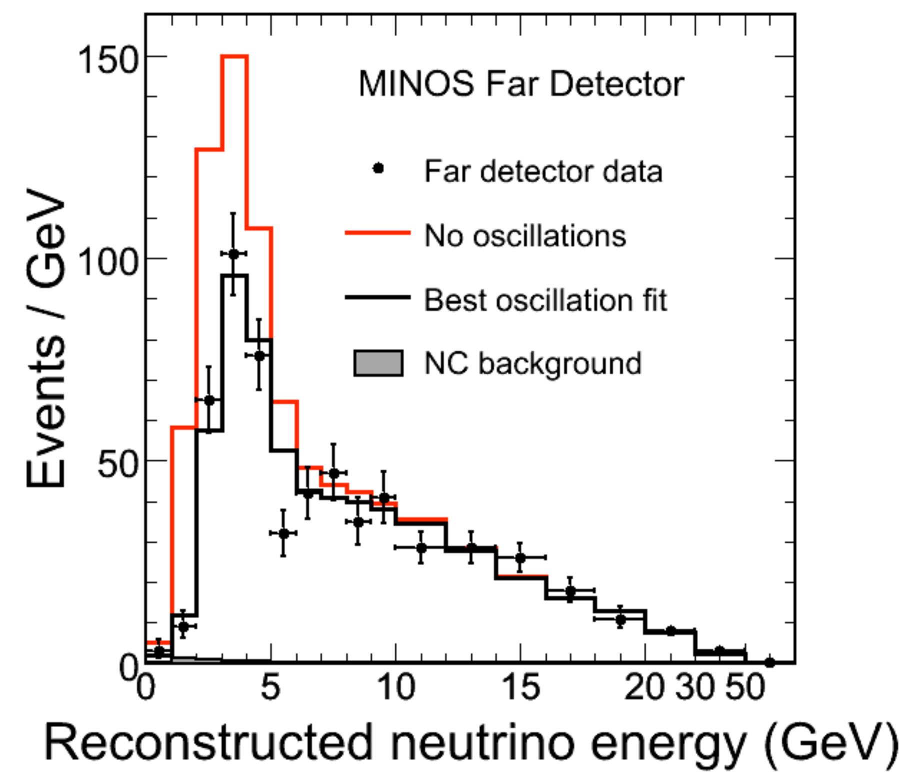
- Analysis based on the following datasets:
  - **3.2×10^{20} POT** in "Low energy" (LE) configuration
  - **1.5×10^{19} POT** in "High energy" (HE) configuration
- Results:
  - LE: 730 events observed, expected 936
  - HE: 118 events observed, expected 129
  - strong energy-dependent suppression observed
- Oscillation parameters:

$\sin^2 2\theta > 0.9$ (90% C.L., 1 dof)

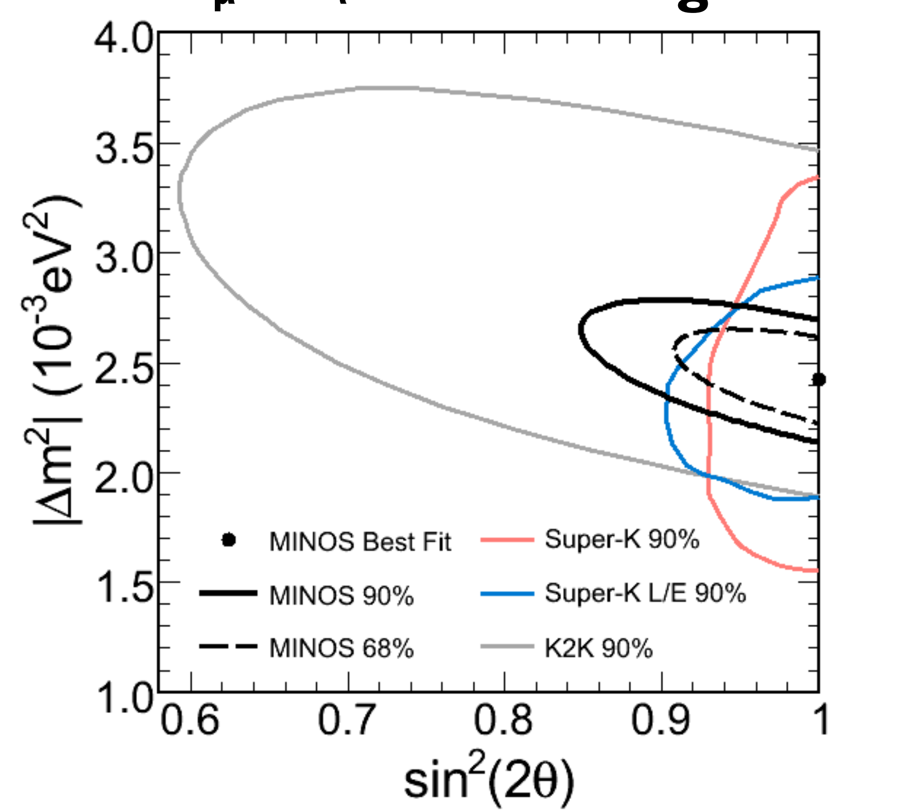
$\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2
(90% C.L., 1 dof)

Best fit=2.43×10^{-3} eV^2, 1.0

E_ν spectrum (LE+HE combined)



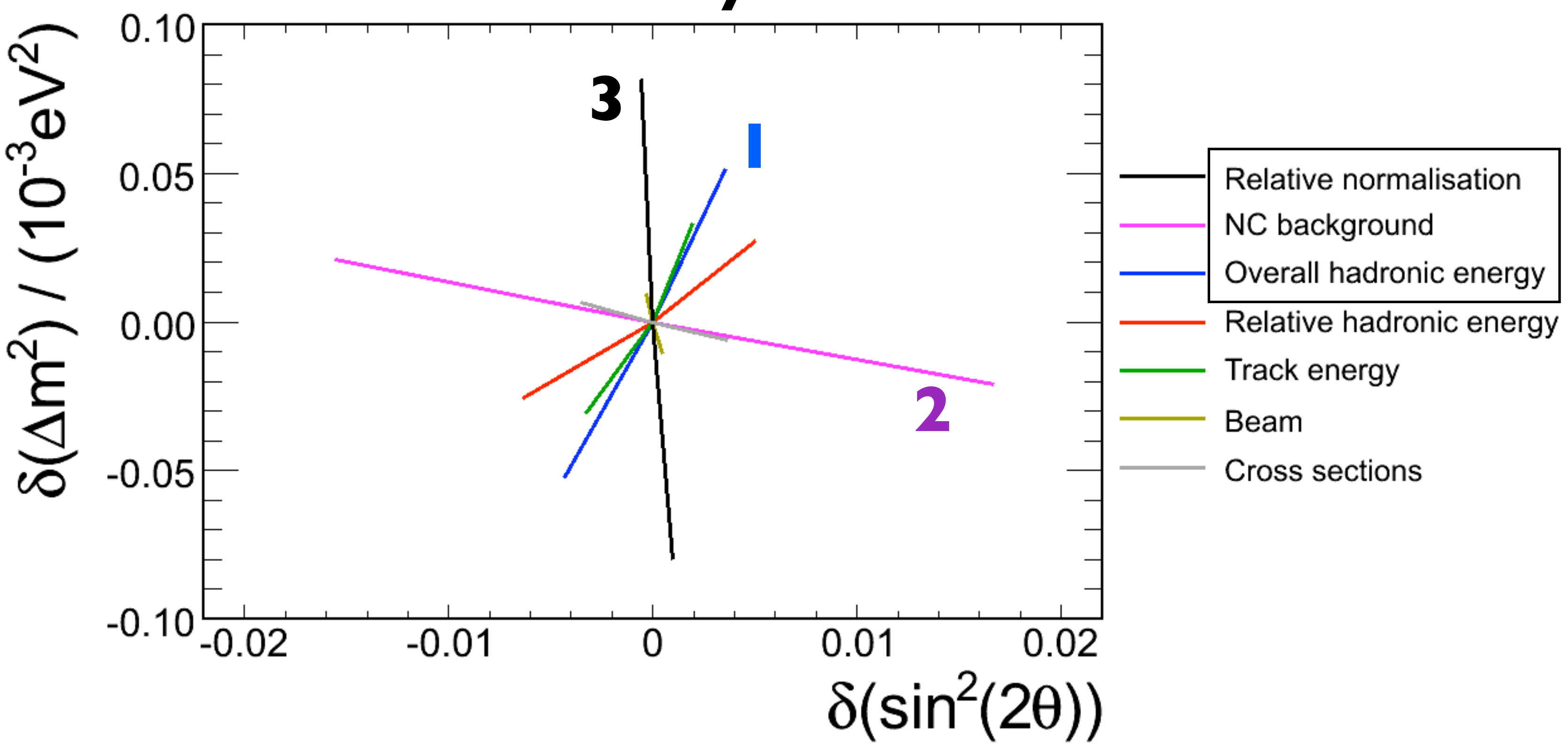
$\nu_\mu \rightarrow \nu_\tau$ allowed region



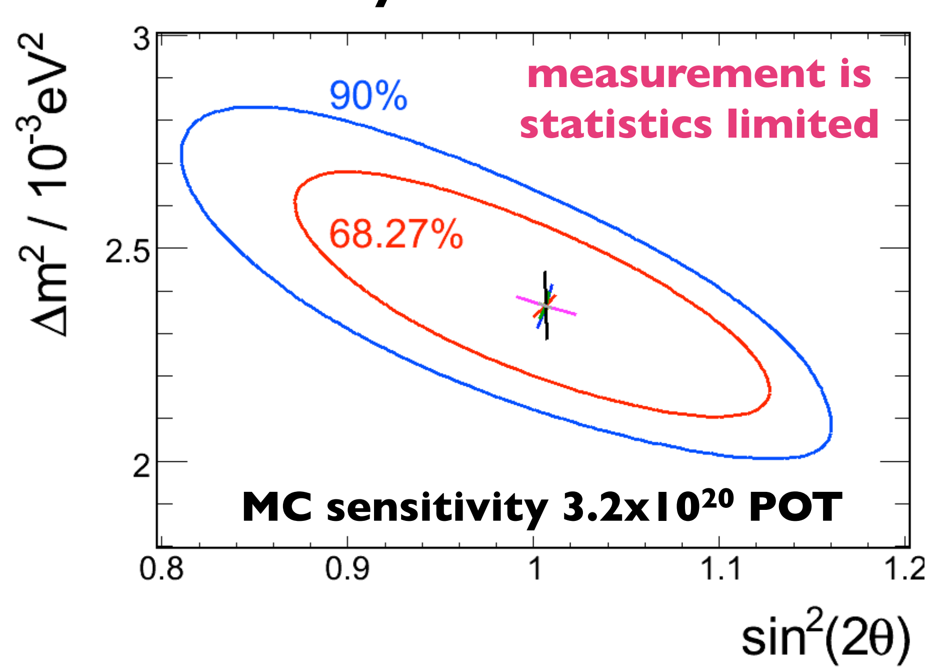
MINOS systematic errors

- Major sources of systematic error in ν_μ disappearance measurement:
  1. hadronic energy scale
  2. NC background uncertainty
  3. Near/far normalisation
- Effect of beam and cross-section uncertainties is minimised in this measurement, due to significant cancellation from ND to FD

MC determination of systematic errors



Comparison of statistical and systematic errors

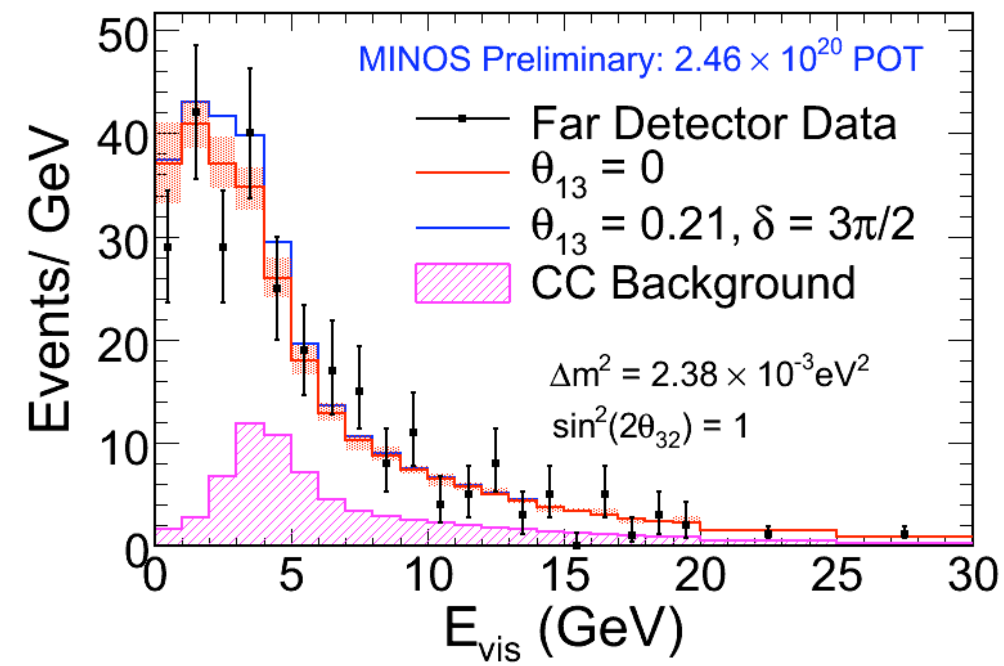


Other MINOS analyses

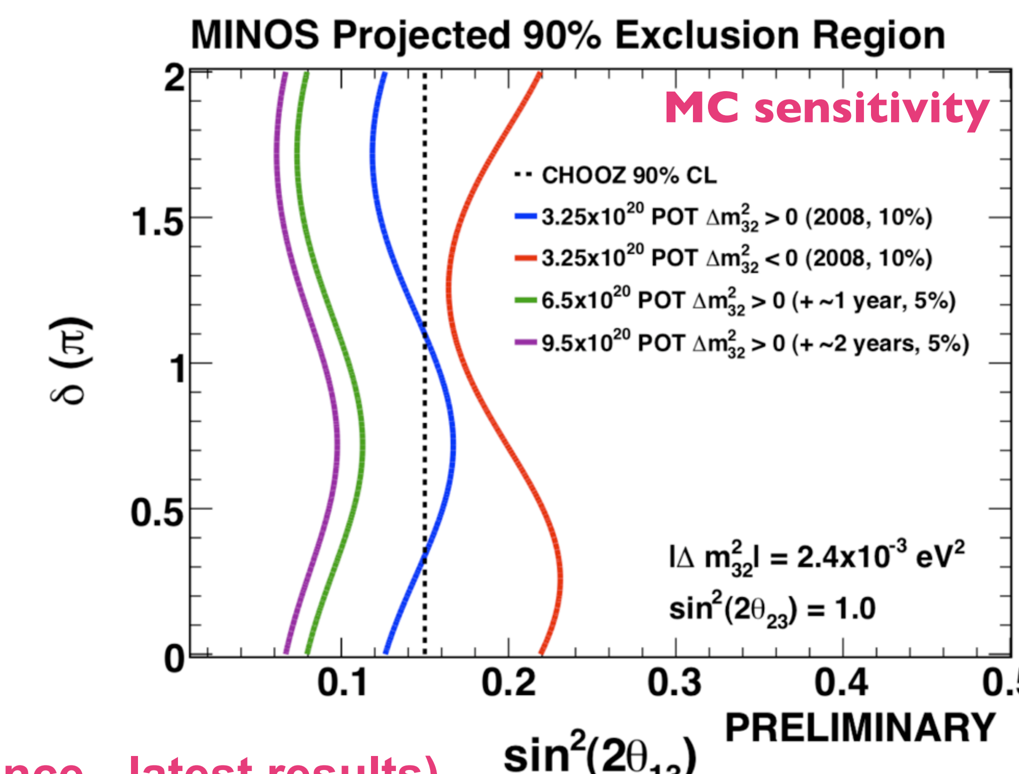
- Sensitive to the presence of active/sterile neutrino oscillations by searching for a deficit of NC interactions in the Far detector
- Set a limit on the parameter f_s - the fraction of ν_μ that oscillate to $\nu_{sterile}$ at the atm. ν mass scale
- No evidence for $\nu_\mu \rightarrow \nu_{sterile}$ oscillations seen:

$f_s < 0.68$ (90% C.L., 1 dof)

Best fit $fs = 0.28^{+0.25}_{-0.28}$ (68% C.L., 1 dof, $\theta_{13}=0$)



- Also sensitive to $\nu_\mu \rightarrow \nu_e$ by searching for excess of EM-like events in the Far detector
  - with Run I+RunII dataset, MINOS sensitivity comparable to CHOOZ limit.
  - Analysis ongoing - <u>first results this year</u>



Phys. Rev. Lett. 101, 131802 (2008) (nu_mu disappearance - latest results)
Phys. Rev. Lett. 101, 221804 (2008) (sterile neutrino search)
Phys. Rev. D 77: 072002 (2008). (nu_mu disappearance - long writeup)
Phys. Rev. Lett. 97, 191801 (2006). (first oscillation results)

Confirming the oscillation pattern

- Examine energy dependence of ν_μ oscillated/unoscillated spectrum ratio to test alternative models of ν_μ disappearace
- Decay/Decoherence disappearance probabilities are exponential functions of energy:
  - **no "dips" in spectrum ratio**
  - **slower "rise" at high energy**

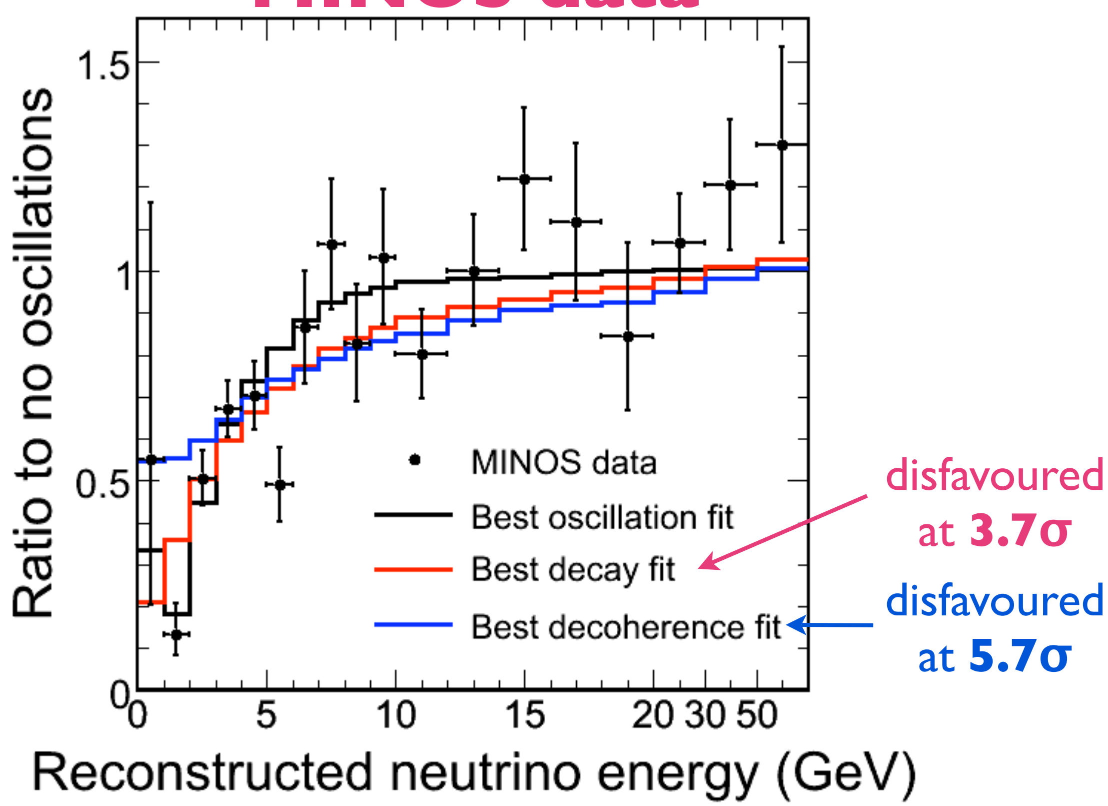
Neutrino Decoherence

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{\sin^2 2\theta}{2}\left(1 - e^{-\frac{\mu^2 L}{2E}}\right)$$

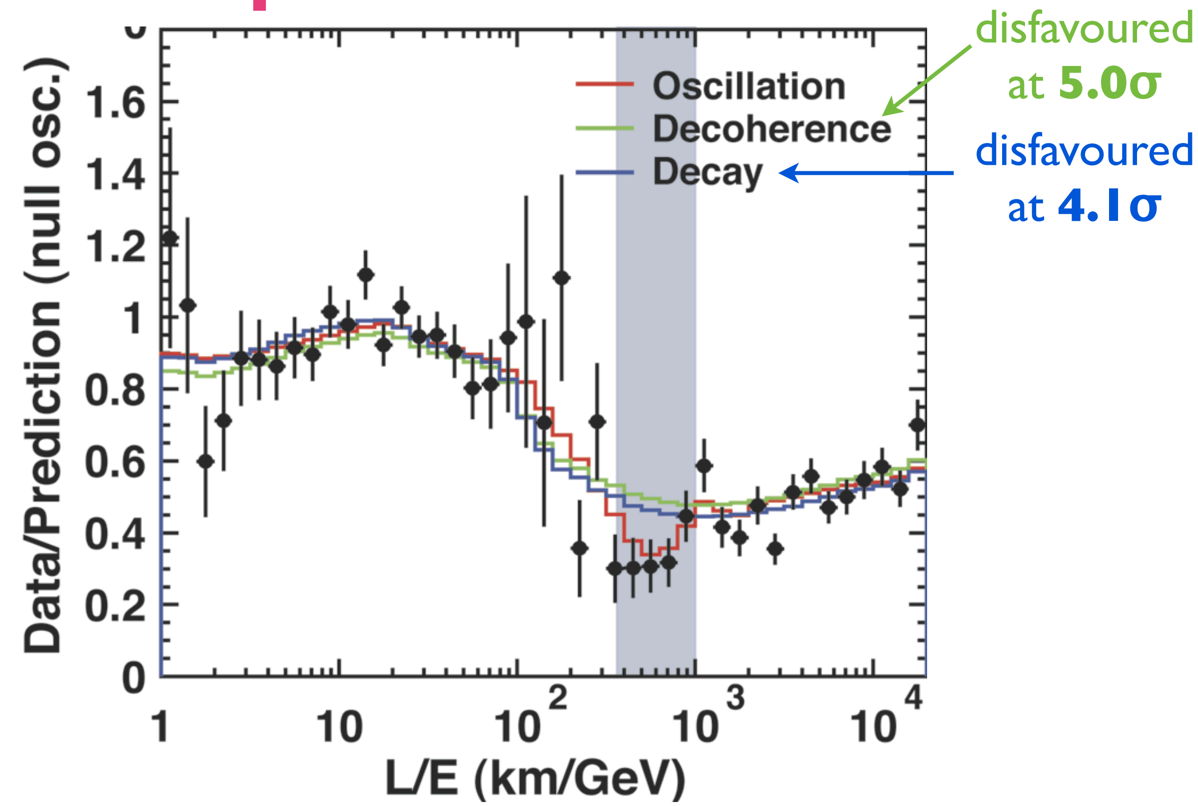
Neutrino Decay

$$P(\nu_\mu \to \nu_\mu) = (\sin^2\theta + \cos^2\theta e^{-\frac{\alpha L}{2E}})^2$$

MINOS data



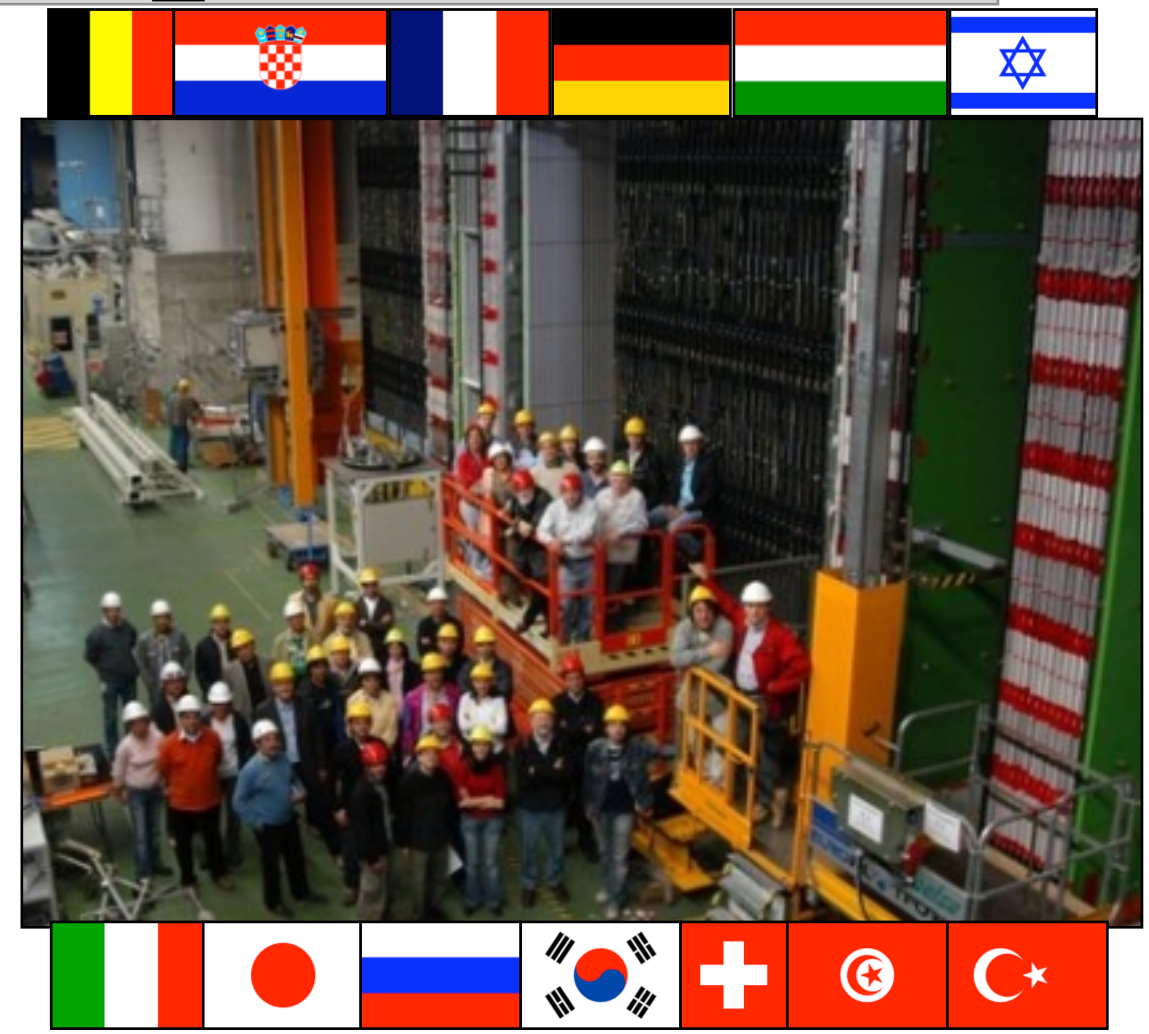
Super-K atm. ν data

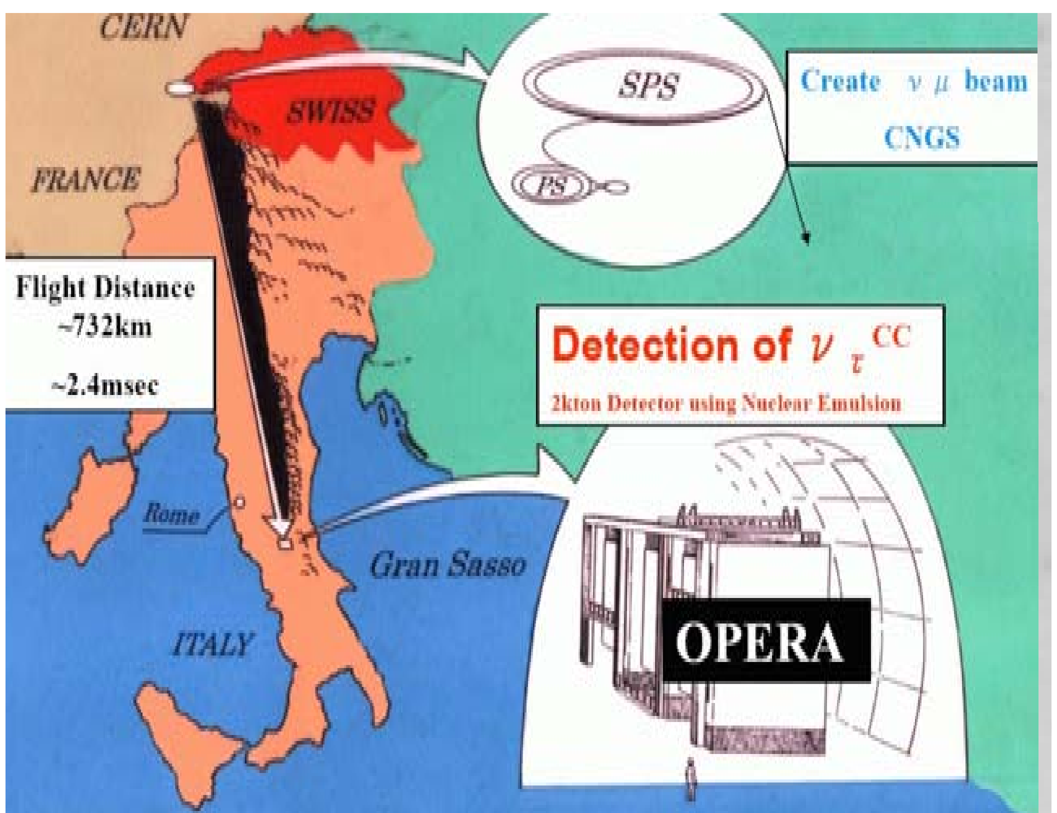


Current data disfavours pure decay/decoherence at >4σ

The OPERA experiment

- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations via τ appearance signature in nuclear emulsion



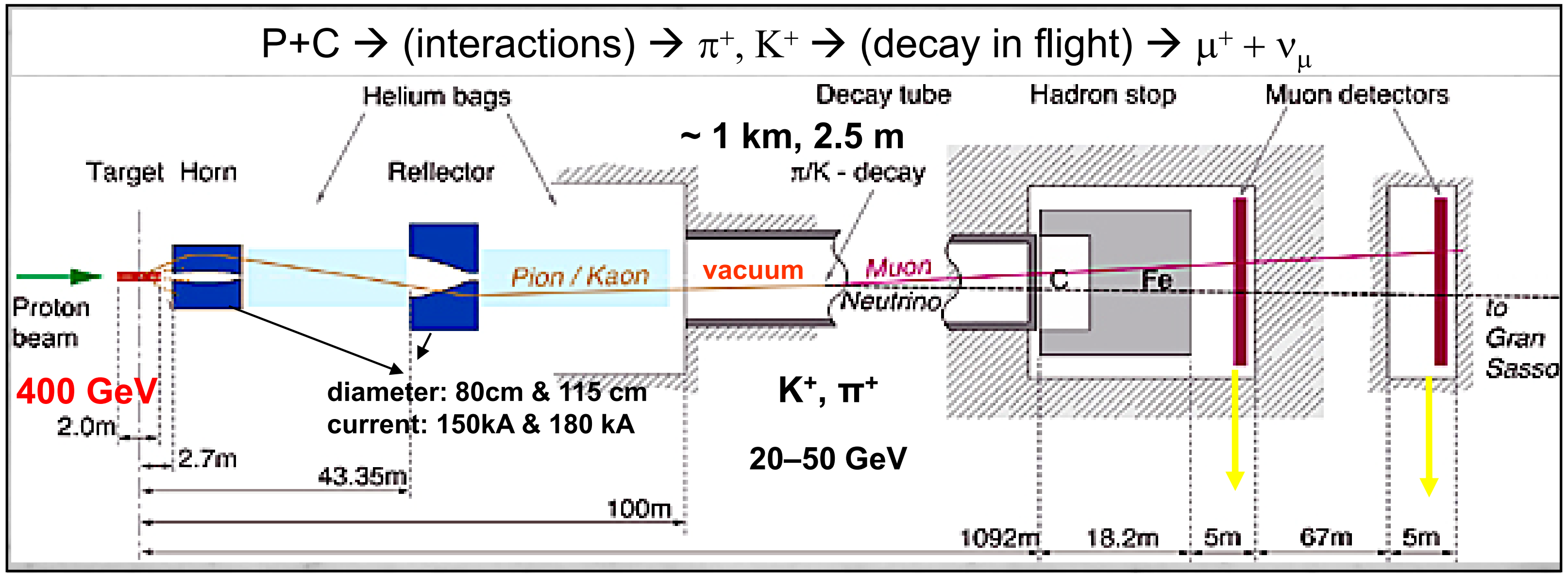


- Uses neutrino beam produced by CERN SPS and a large emulsion/tracking detector situated in Gran Sasso
  - baseline = 732 km

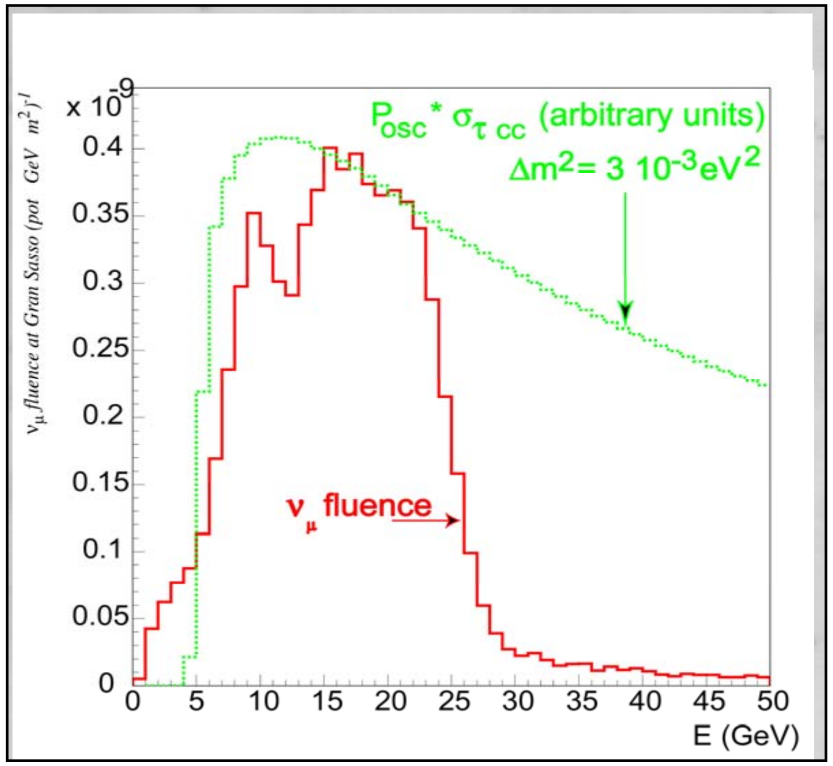
LNGS Beam

- High energy Wide-band beam, optimised for τ appearance

LNGS beamline



ν_μ CC spectrum at Gran Sasso



Beam parameters

$<E_{\nu\mu}>$	17 GeV
$(\nu_e+\overline{\nu}_e)/\nu_\mu$	0.87%
$\overline{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible
p.o.t./year	4.5×10^{19}

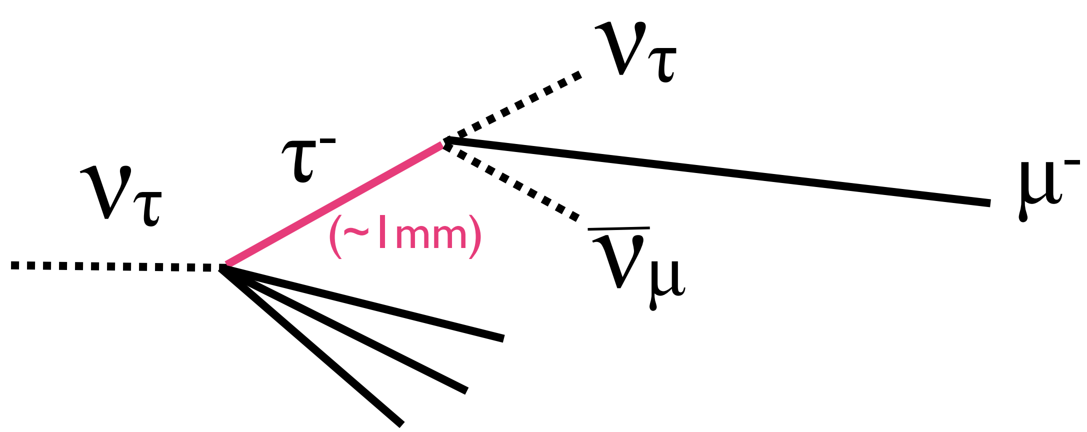
2007 run: 8.24×10^{17} POT
2008 run: 1.782×10^{19} POT

ν_τ CC events @ Gran Sasso(1.35kT, 5 years):

80 ($\Delta m^2=2\times10^{-3}$ eV^2)
180 ($\Delta m^2=3\times10^{-3}$ eV^2)

Signal and background

- Search for "kink" signature - secondary vertex caused by decay of τ



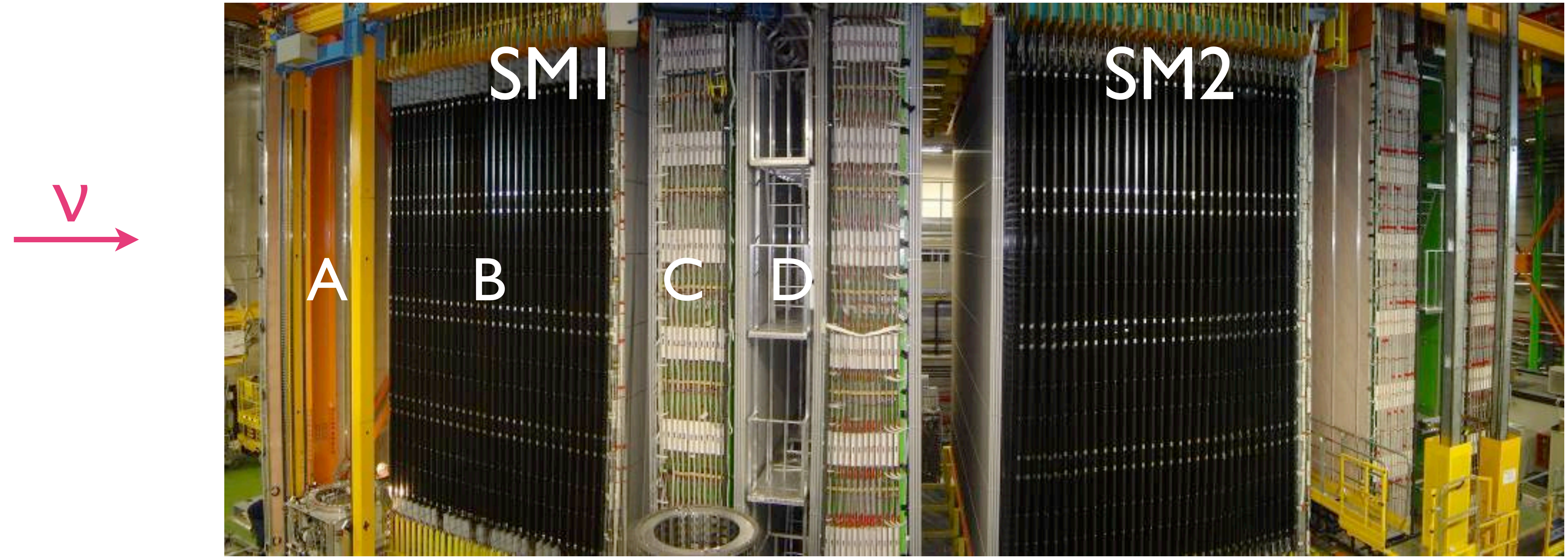
Decay channel	Detection efficiency(%)	Branching ratio(%)	Signal ($\Delta m^2=2.5\times10^{-3}$)	Background
$\tau\to\mu$	17.5	17.7	2.9	0.17
$\tau\to e$	20.8	17.8	3.5	0.17
$\tau\to h$	5.8	49.5	3.1	0.24
$\tau\to 3h$	6.3	15	0.9	0.17
ALL	effxBR=10.6%		**10.4**	**0.75**

5 year exposure @4.5x10^{19} POT/year

- Principal backgrounds:
  - charm decays
  - hadron re-interaction in lead
  - large angle muon scatters

OPERA Detector

Hybrid emulsion/tracking detector - 2 identical supermodules



total target mass: 1.35kT

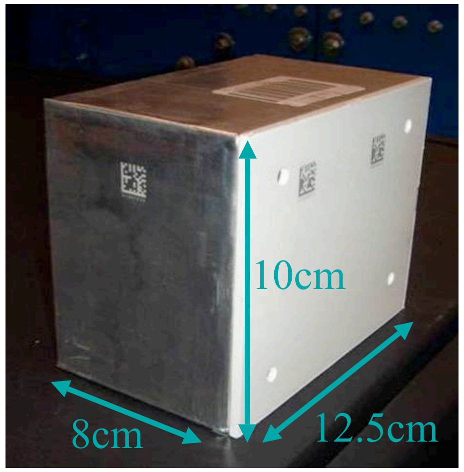
A: glass RPC veto

B: target + target tracker
77500 Pb/emulsion bricks in 29 "walls"
31 XY tracking planes (solid scintillator+ WLS readout)

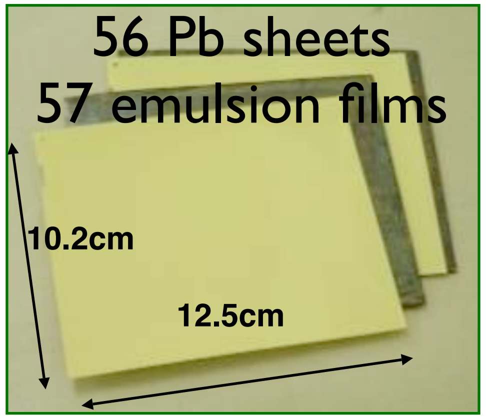
C: high precision tracker
6x4-fold layers of drift tubes

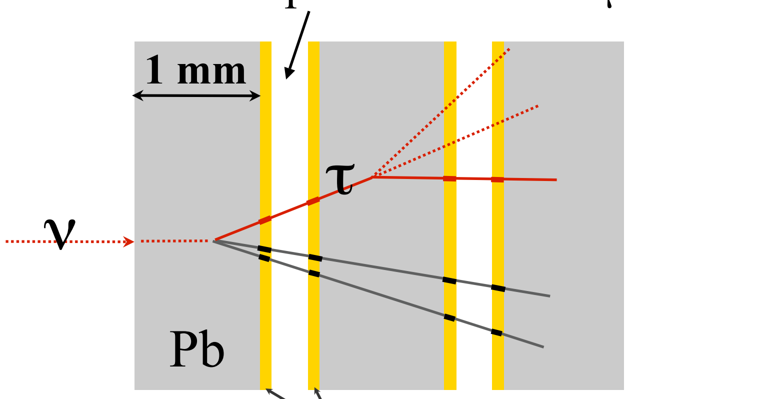
D: dipole magnet
1.53 T field
22 planes of RPCs (XY readout)

Pb/emulsion brick



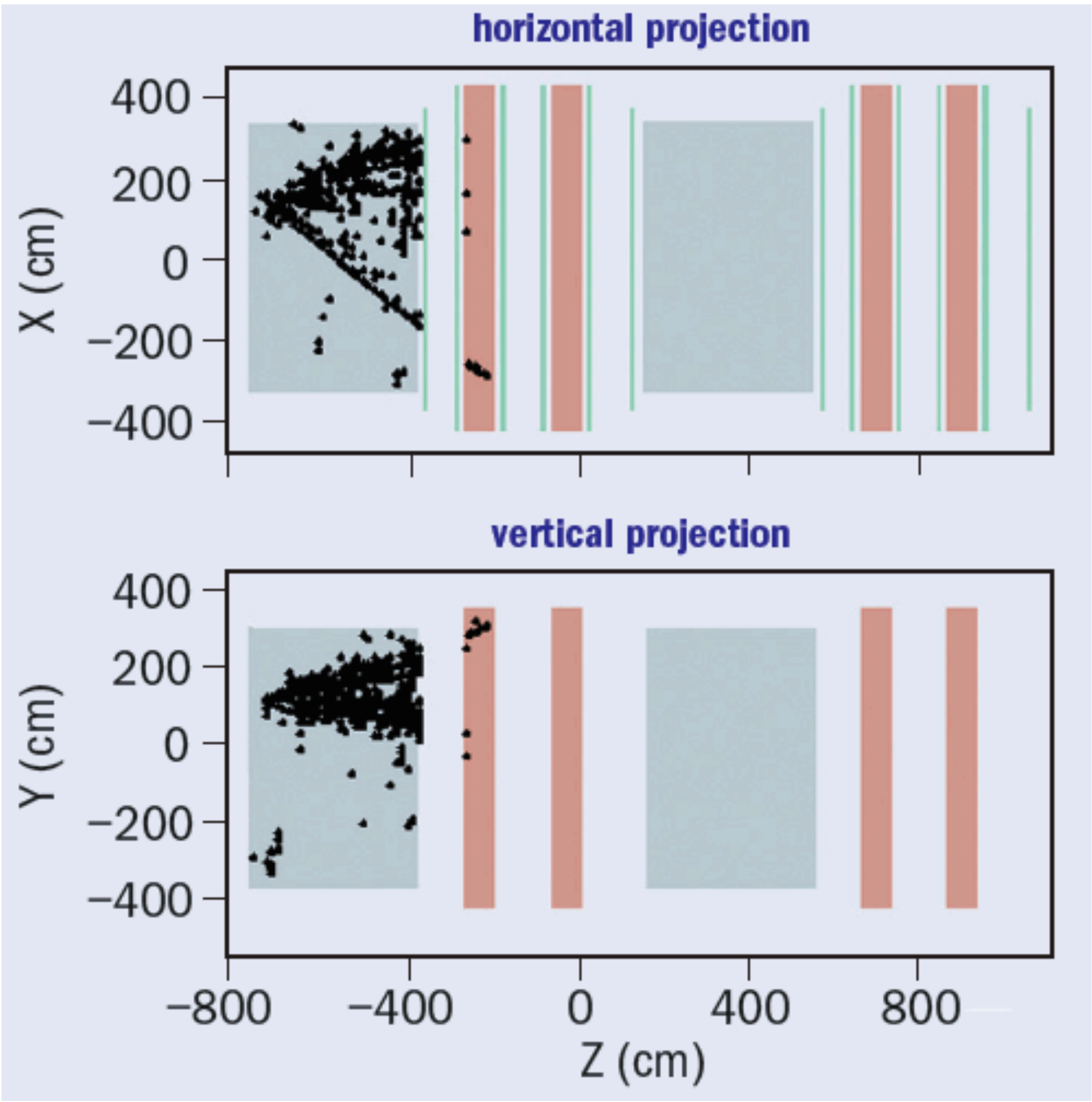
Pb/emulsion layers



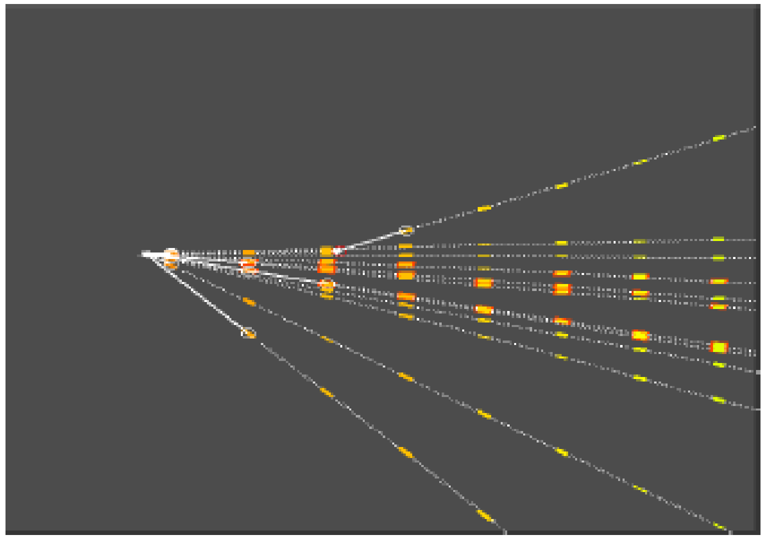


OPERA observed events

ν_μ charged-current interaction



charm candidate



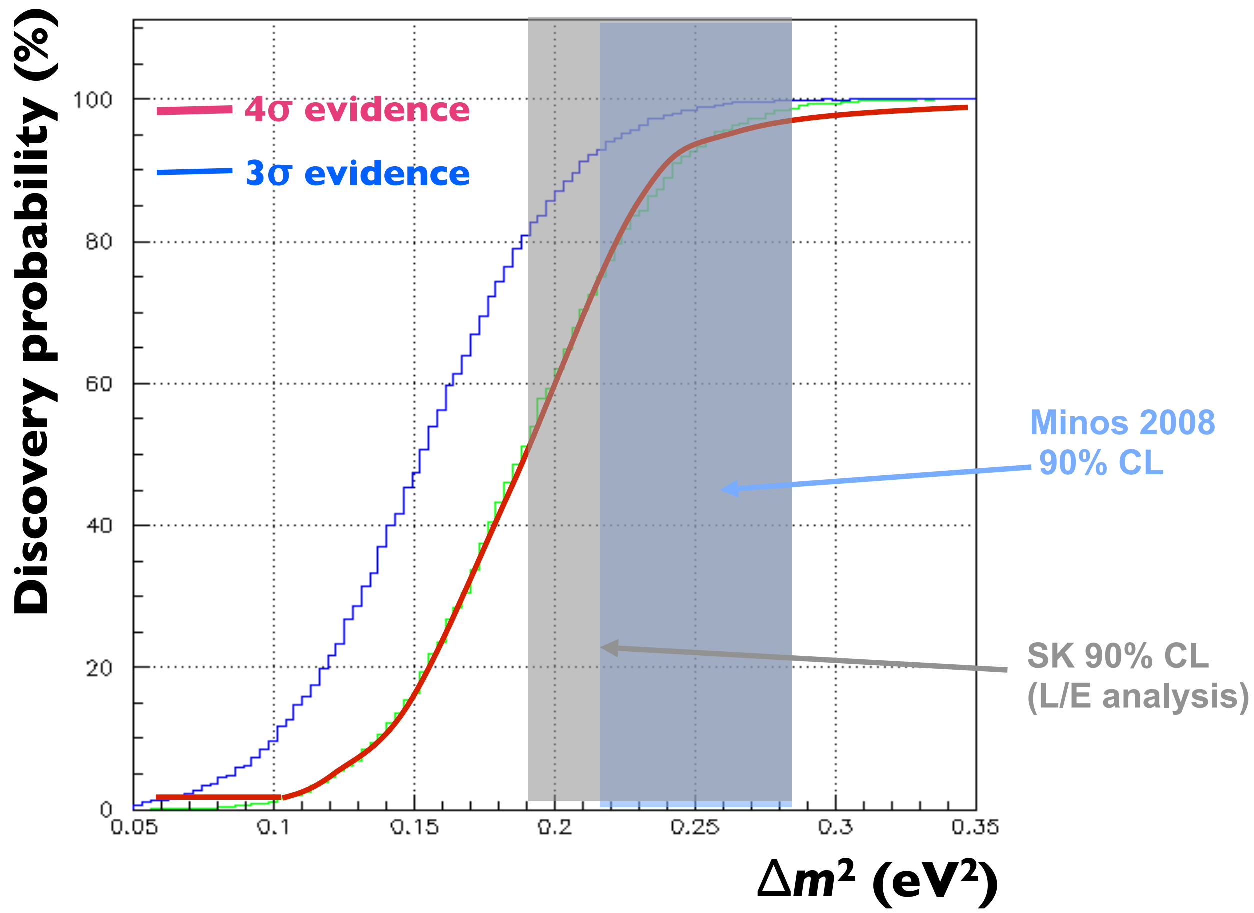
Flight lenght: 3247.2 μm
θ_{kink}: 0.204 rad
$P_{daughter}$: 3.9 (+1.7 -0.9) GeV
P_T: 796 MeV (> 606 MeV)

- Emulsions to be scanned are first tagged by charged tracks in tracking system, as well as removable emulsion films glued to exterior of bricks

Current data - see 2 charm candidates, with an expectation of ~2

OPERA sensitivity

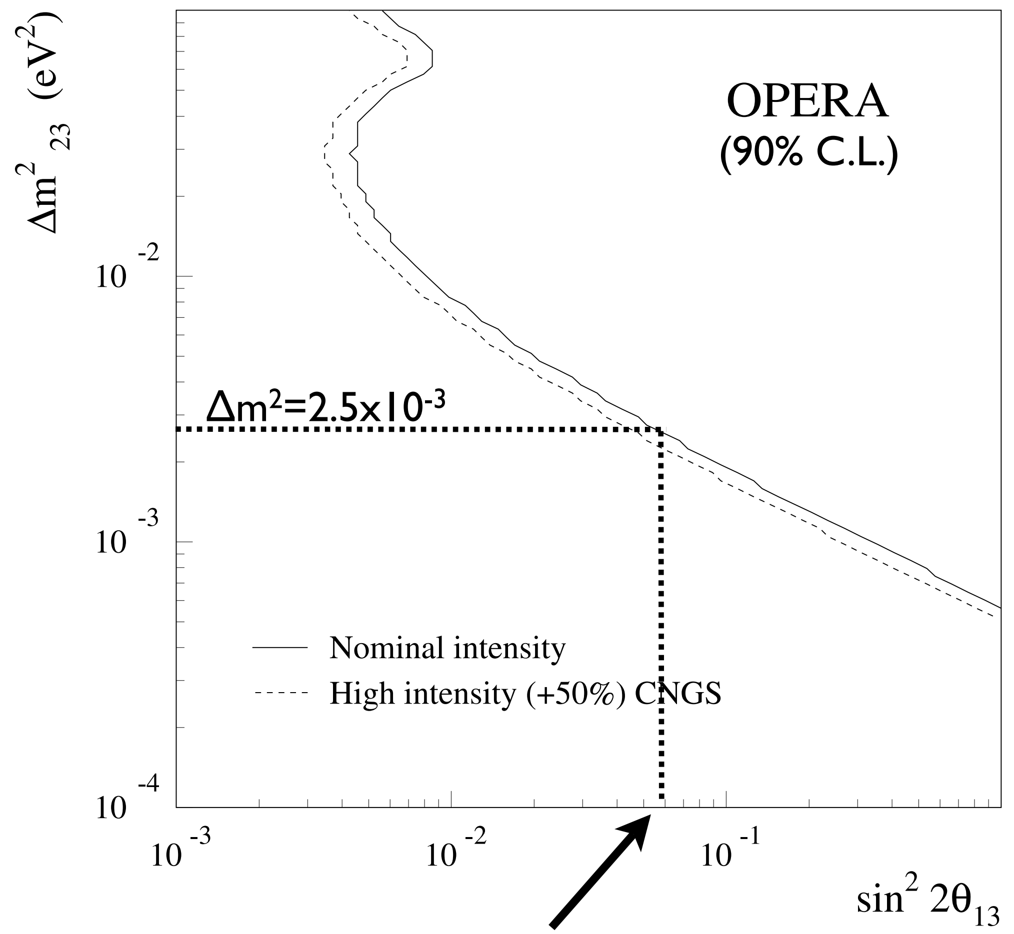
$\nu_\mu \rightarrow \nu_\tau$



probability to observe 3σ(4σ) effect after 5 year run

Current dataset should contain 1-2 ν_τ decays - analysis ongoing!

$\nu_\mu \rightarrow \nu_e$



can set limit of $\sin^2 2\theta_{13} < 0.06$ @ 90% C.L.

c.f. CHOOZ limit: $\sin^2 2\theta_{13} < 0.14$ @ 90% C.L.

θ_{13} (deg)	$\sin^2 2\theta_{13}$	Signal $\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$, $\tau \rightarrow e$	ν_μ CC	ν_μ NC	ν_e CC
9	0.095	9.3	4.5	1.0	5.2	18
7	0.058	5.8	4.6	1.0	5.2	18
5	0.030	3.0	4.6	1.0	5.2	18

5 year exposure @4.5x10^{19} POT/year

Near-Future experiments

Tokai-to-Kamiokande (T2K)
Fermilab-Nova

Goals of near-future experiments

- Search for non-zero θ_{13}
  - goal is sensitivity down to 1%
- Search for leptonic CP violation
  - only observable if $\theta_{13} >> 1\%$
  - requires neutrino+anti-neutrino running
- Determine sign of Δm^2
  - via CP violation and matter effects
- Higher precision measurements of 23 sector
  - 1% precision on $\sin^2 2\theta_{23}$ - search for $\theta_{23} < 45$ deg

$\nu_\mu \to \nu_e$ oscillation probability

- Three-flavour oscillations in matter:

atmospheric ν term

Reference: arXiv:0710.0554v2 (2008)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & \sin^2\theta_{23}\; \sin^2 2\theta_{13}\, \frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\,\Delta_{31}^2 \\
& + \sin 2\theta_{23}\; \sin 2\theta_{13} \sin 2\theta_{12}\, \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\,\Delta_{31}\, \frac{\sin(aL)}{(aL)}\,\Delta_{21}\; \cos(\Delta_{31}+\delta) \\
& + \cos^2\theta_{23}\; \sin^2 2\theta_{12}\, \frac{\sin^2(aL)}{(aL)^2}\,\Delta_{21}^2,
\end{aligned}
$$

interference term

$$\Delta_{ab} = \Delta m^2_{ab} L/4E$$

solar ν term

$$a = G_F N_e/\sqrt{2}$$

matter effects

size of matter effect proportional to L

Note: $P(\nu_\mu \to \nu_e)$ is a function of both θ_{13} and δ

multiple measurements needed to break degeneracies!!

Transformations

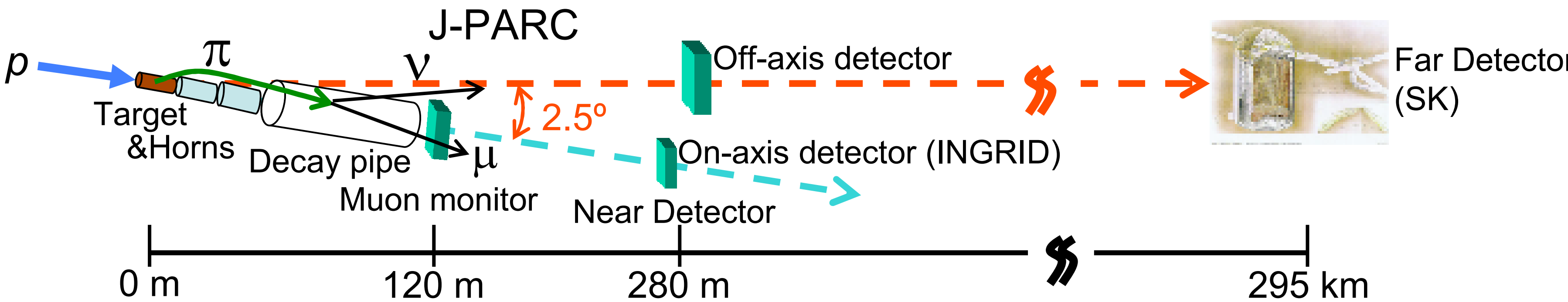
Anti-neutrinos: $a \longrightarrow -a \quad \delta \longrightarrow -\delta$

Inverted hierarchy: interference term changes sign

T2K - Tokai to Kamiokande

- New beamline using 50 GeV protons from JPARC facility in Tokai, directed to existing Super-Kamiokande detector

  - <u>beam aimed 2.5 degrees “off-axis” to maximise flux at low energy</u>



High beam power:

~0.77MW in phase 1

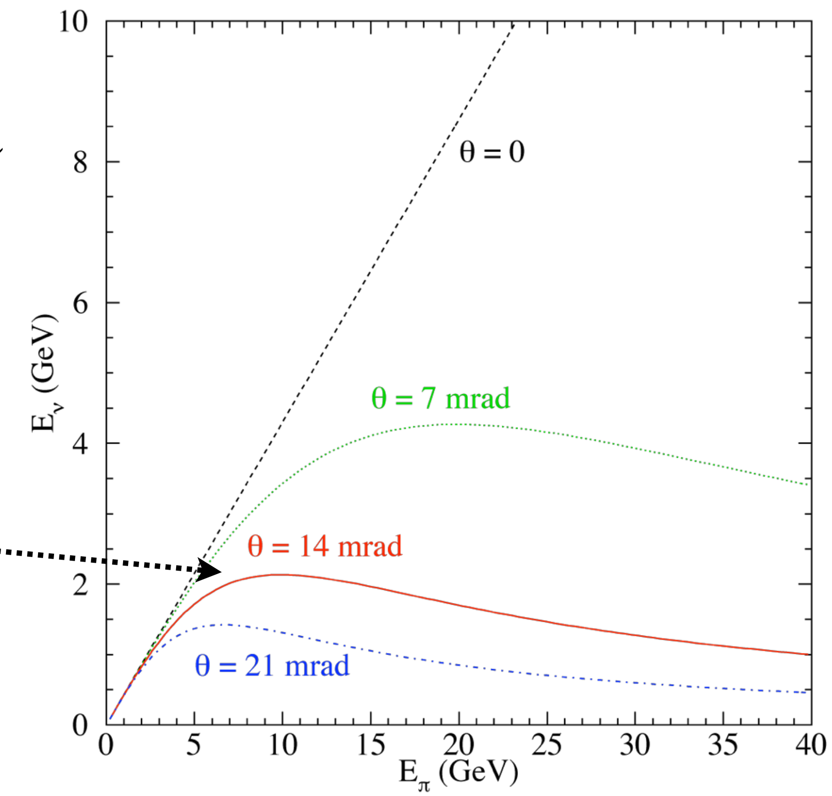
→1600 ν_μ events/yr in SK

Off-axis beam and near detectors

- Off-axis concept:
  - neutrino energy is related to parent pion energy via the decay angle, θ:

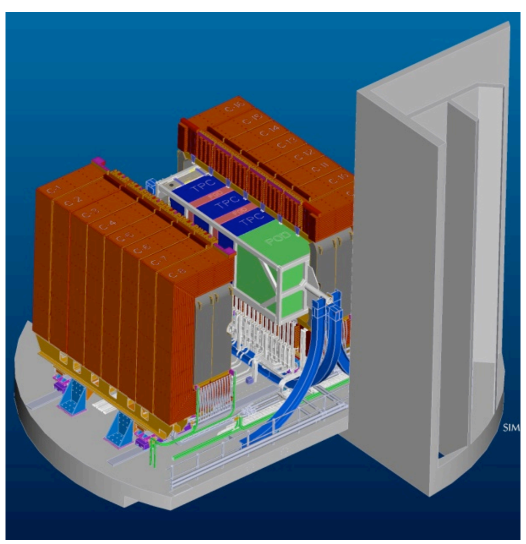
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = E_\pi / m_\pi$$

  - for θ~14mr, neutrino energy largely independent of parent pion energy → enhance low energy neutrino flux, suppress high energy tail



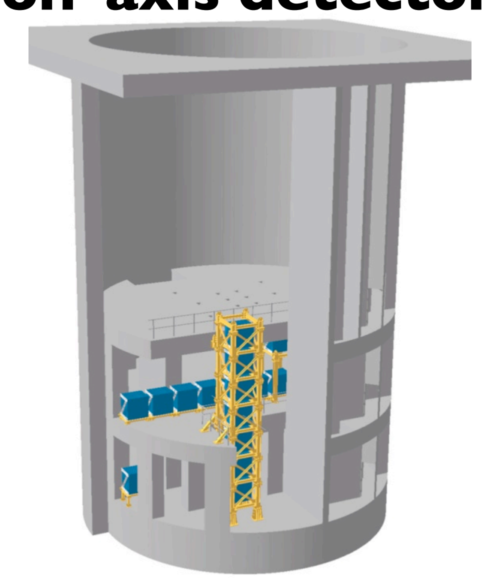
- T2K Near Detectors @280 m:

off-axis detector

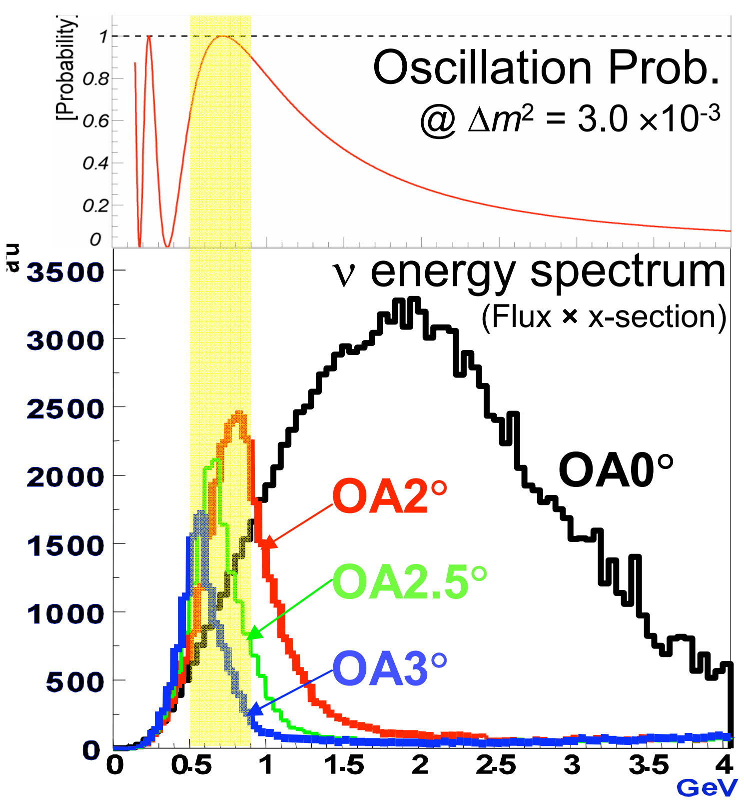


fine-grained detector:
scintillator/TPC tracking: measure x-sections
π^0 background measurement
EM calorimeter and muon ranger

on-axis detector

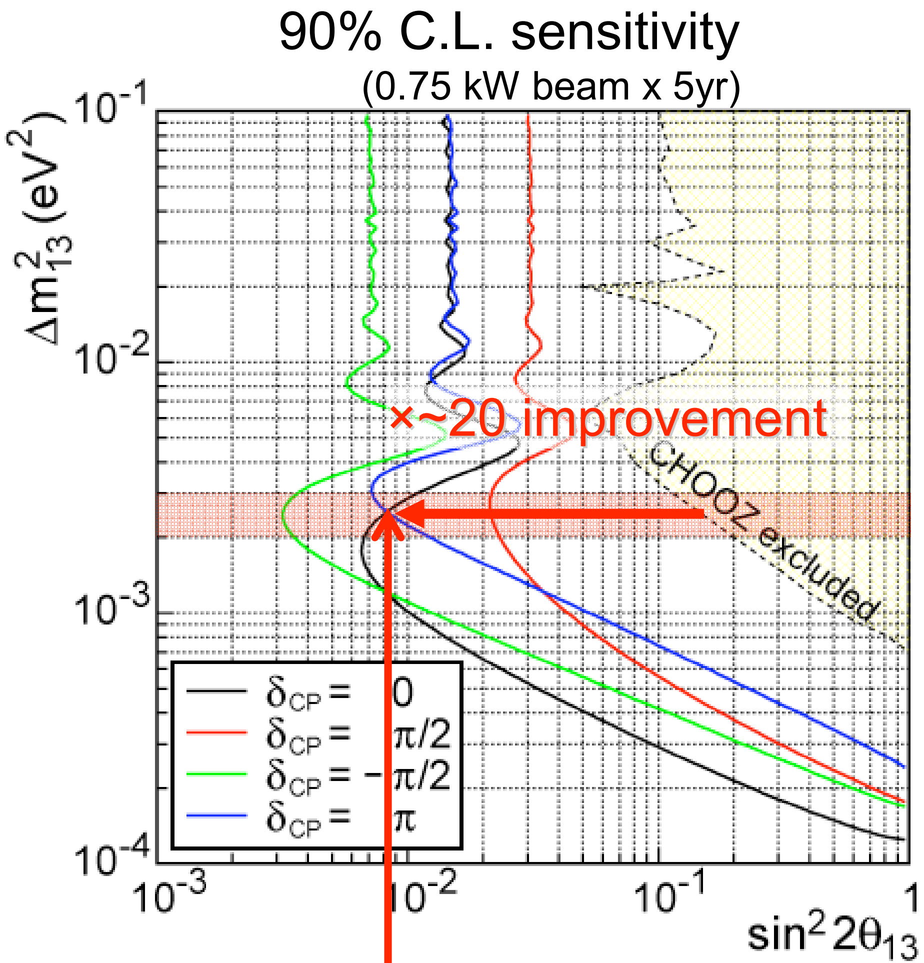


iron/scintillator detector
beam monitoring/beam direction measurements



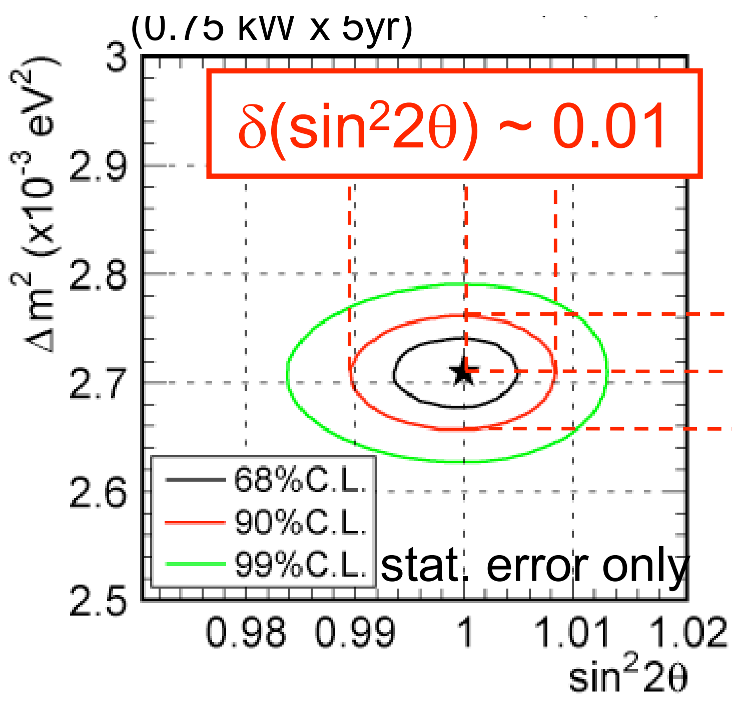
T2K physics measurements

ν_e appearance



$\sin^2 2\theta_{13}$ ~ 0.008 (δ_{CP} = 0,π)

ν_μ disappearance



$\delta(\sin^2 2\theta)$ ~ 0.01

Achievable precision
(@ Δm^2 ~ 2.5×10^{-3} eV^2)
when stat. error dominates

$\delta(\Delta m^2_{23}) < 10^{-4}$ eV^2

5 year sensitivities:

1% for $\sin^2 2\theta_{13}$

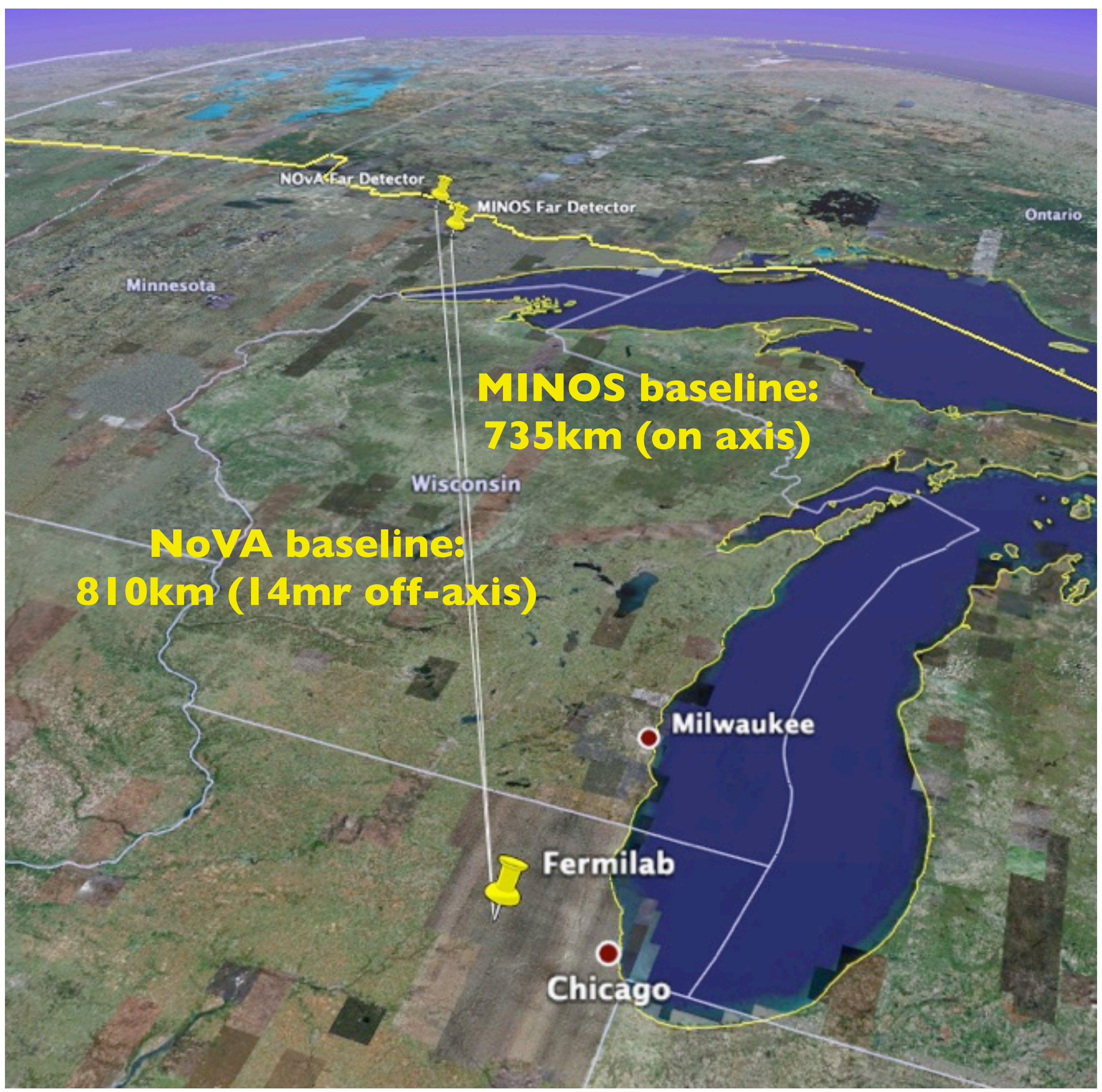
better than 1% precision on $\sin^2 2\theta_{23}$ and Δm^2_{23}

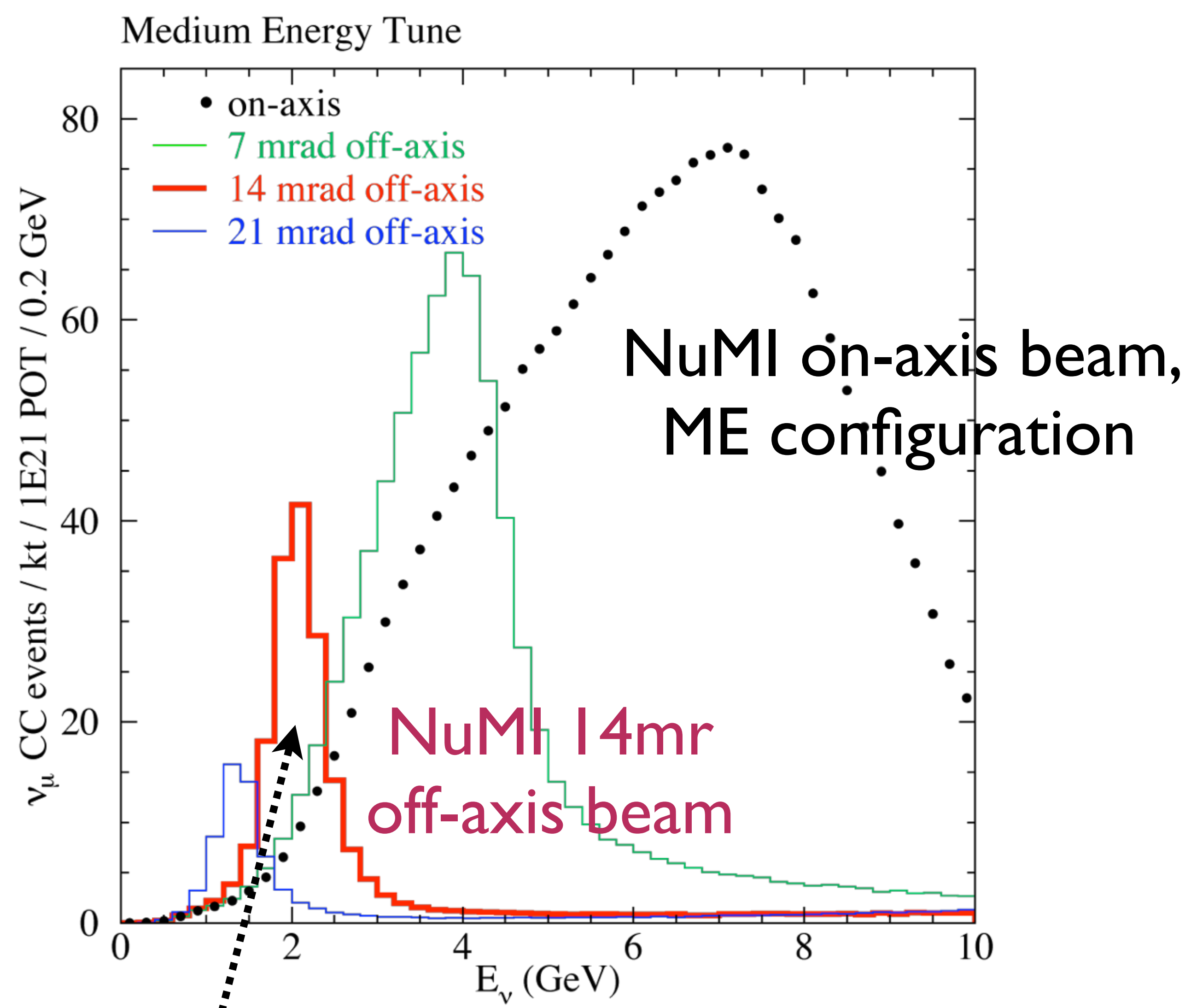
T2K timeline

- Beam:
  - Linac commissioned and beam injected into main ring
  - Beam accelerated to 30 GeV (JPARC startup energy)
  - first neutrino beam anticipated April 2009
- Detectors:
  - Super-K refurbished (PMT replacement) with upgraded electronics
  - on-axis ND ready for first beam in April 2009
  - off-axis detector installation Summer 09
- First physics results anticipated in 2010

The NOνA experiment

- NOνA = **N**uMI **O**ff-axis **ν**eutrino **A**ppearance
  - search for ν_e appearance using a new detector situated in North Minnesota, 14 mr off-axis from an upgraded NuMI beam

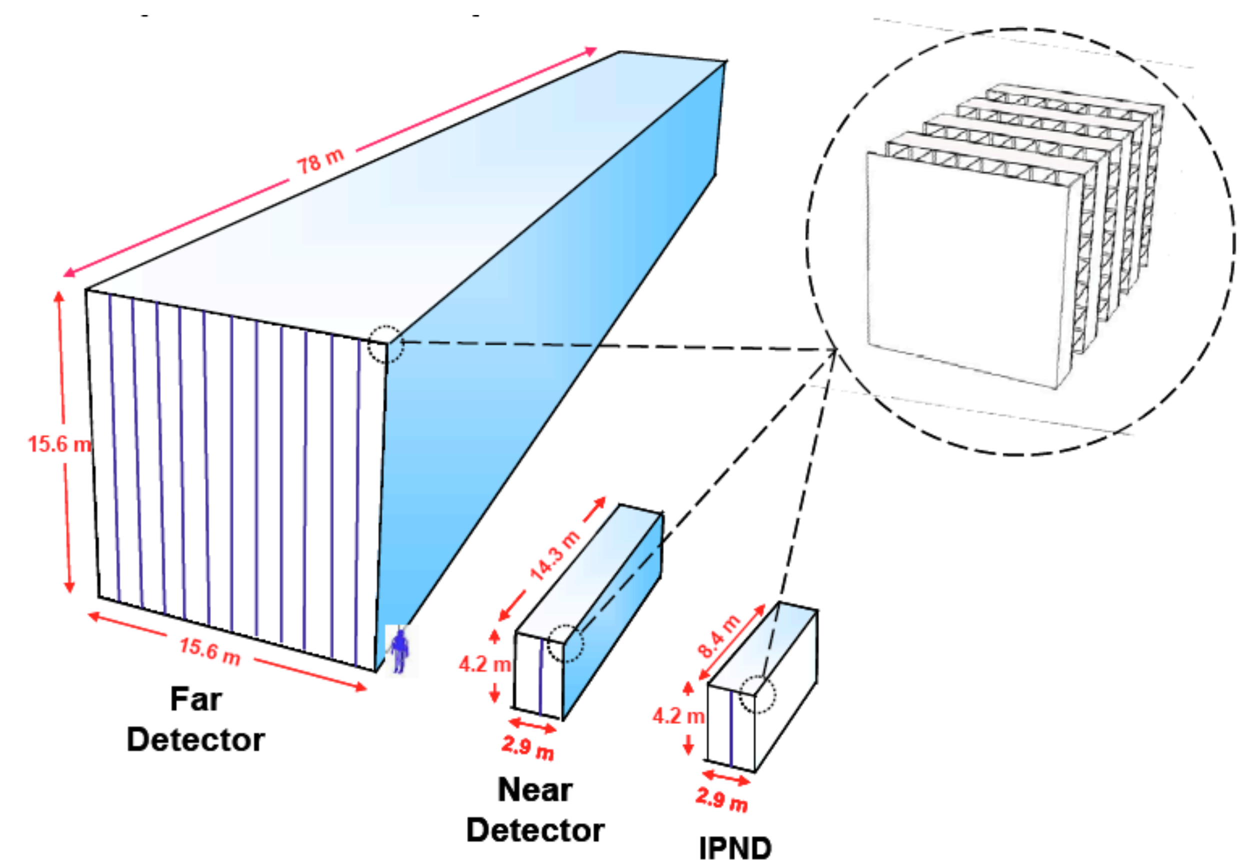




Off-axis beam significantly increases flux at 1st oscillation maximum, suppresses high energy tail

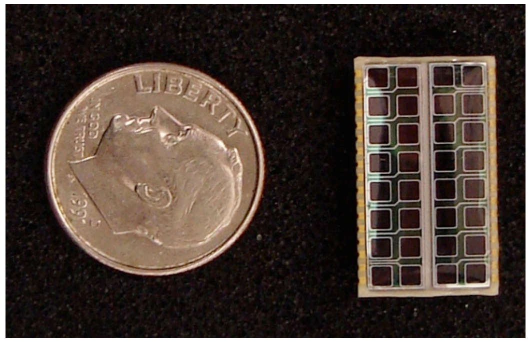
The NoVA detectors

- NoVA Far Detector:
  - 15 kt "totally active detector"
    - PVC "cellular" extrusions filled with liquid scintillator, arranged in planar geometry
    - WLS readout to APD photodiodes (high QE)
    - good electron ID capability (1 plane = 0.15 X_0)



- NoVA Near Detector
  - smaller version (215 T) of FD, situated 14mr off-axis, 1km from beam
    - integration prototype (IPND) will form part of ND

Avalanche photodiode

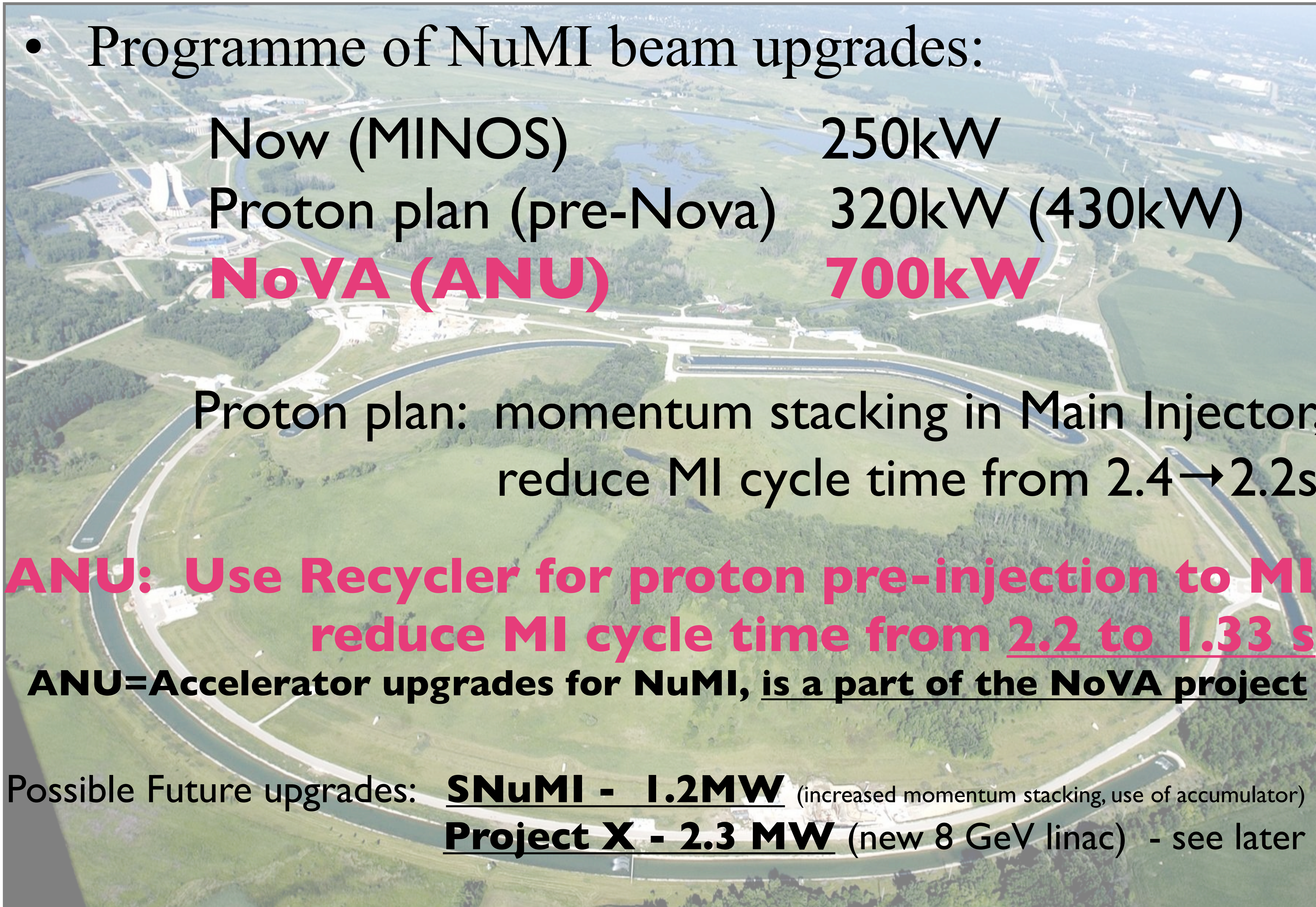


32 channels, 80% QE

PVC extrusions

cell cross-section: 3.9x6.6cm

NuMI beam upgrades



- Programme of NuMI beam upgrades:

Now (MINOS)	250kW
Proton plan (pre-Nova)	320kW (430kW)
NoVA (ANU)	**700kW**

Proton plan: momentum stacking in Main Injector,
reduce MI cycle time from 2.4→2.2s

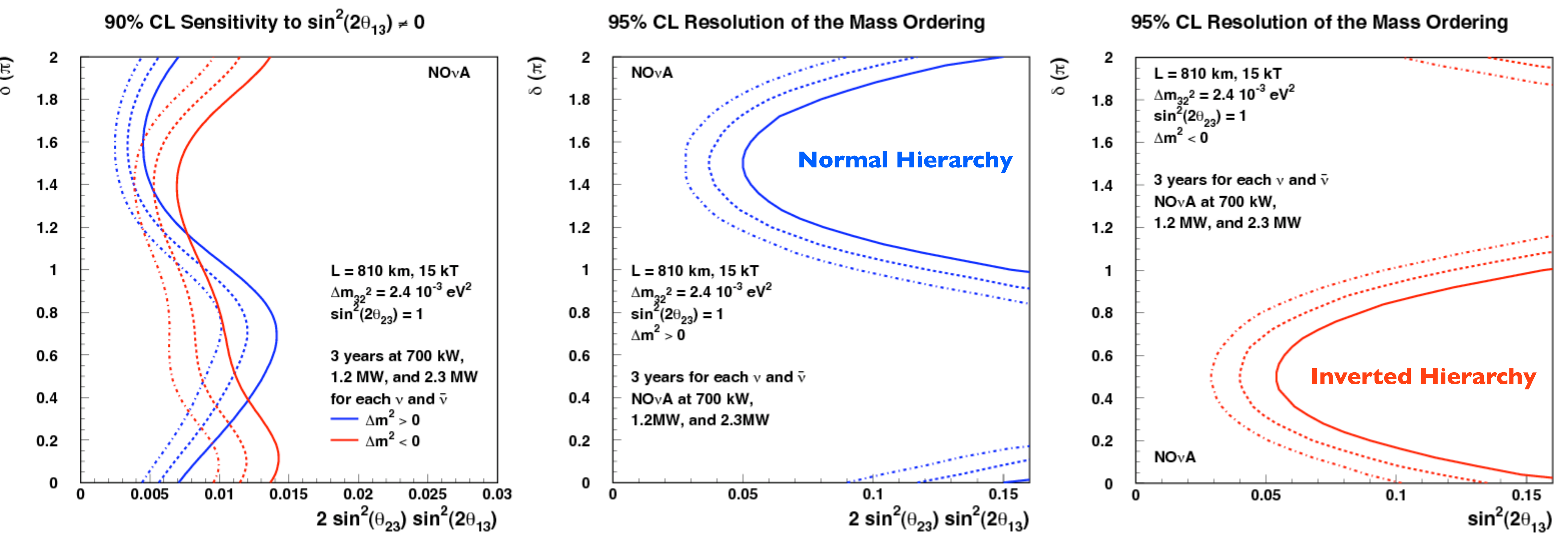
ANU: Use Recycler for proton pre-injection to MI
reduce MI cycle time from 2.2 to 1.33 s

ANU=Accelerator upgrades for NuMI, is a part of the NoVA project

Possible Future upgrades: **SNuMI - 1.2MW** (increased momentum stacking, use of accumulator)
Project X - 2.3 MW (new 8 GeV linac) - see later

NoVA sensitivity

- Sensitivity down to ~1% in $\sin^2 2\theta_{13}$
- Longer baseline → 3x matter effects of T2K
  - first opportunity to determine mass hierarchy over a significant region of phase space

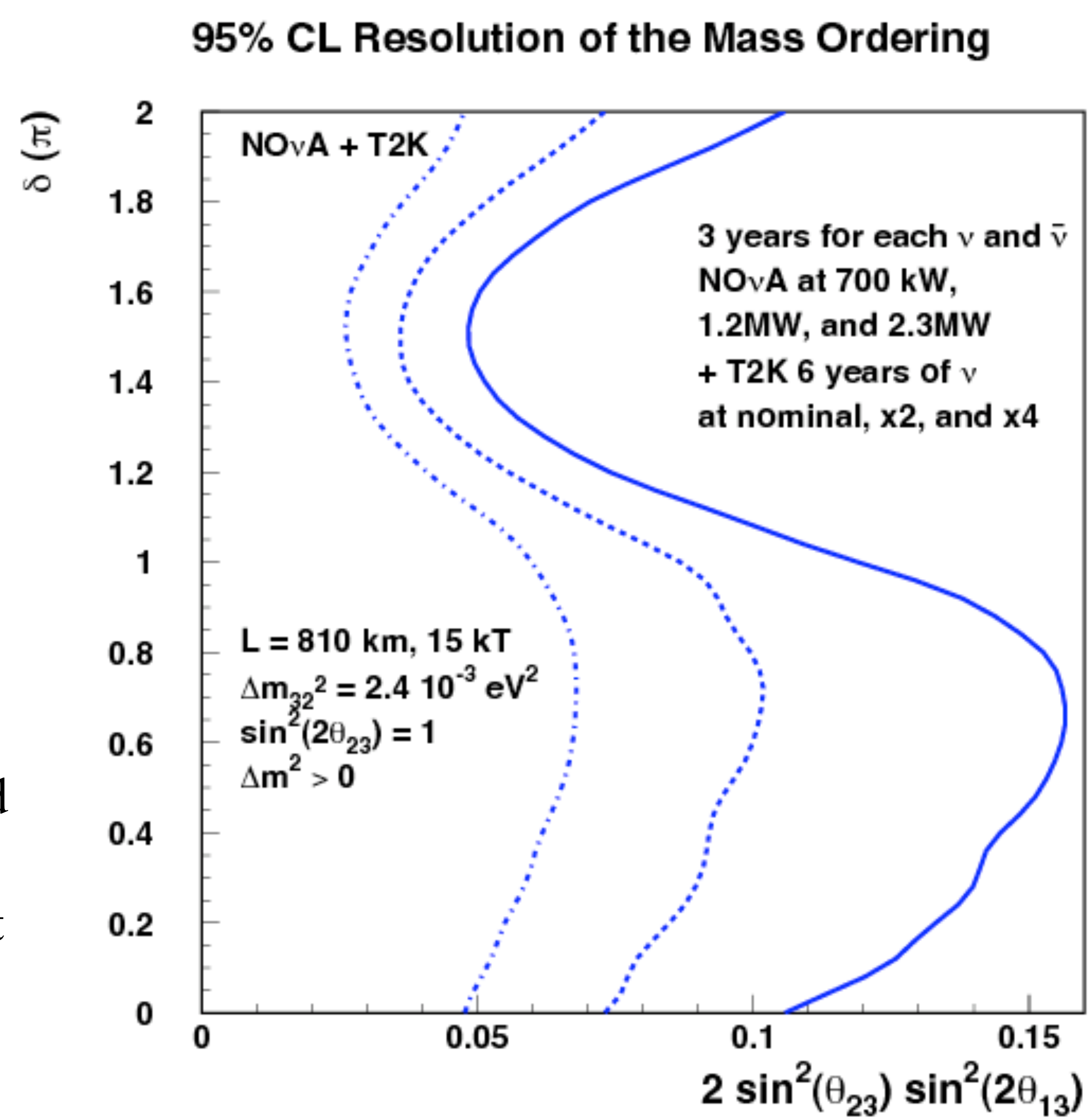


<u>Both neutrino and antineutrino running</u>

NoVA/T2K complementarity

Use of 2 experiments with different baselines (and matter effects) can help break parameter degeneracies inherent in single measurements

- **Region δ>π:**
  - NOvA resolves the hierarchy on its own through a comparison of measurements using neutrino and anti-neutrinos.
- **Region δ<π:**
  - *combination of:*
    - T2K's measurement using neutrinos at the first oscillation maximum which is little affected by matter effects
    - NOvA's measurement at the first oscillation maximum using neutrinos which is strongly affected by matter effects



Far-future experiments (proposed)

Far-future needs

- High beam power (neutrino flux):
  - conventional “super-beams” up to 2MW
- Massive detectors (event rate, ν_e detection capability):
  - 100kT→1MT scale
    - R&D into Water Cerenkov and Liquid Argon detector technologies
      (Higher mass) (Higher efficiency)
- Longer baselines
  - 1000km+
    - enhanced matter effects at first oscillation maximum
    - possibility to observe second oscillation maximum, where matter effects are suppressed → possibility to distinguish between CP violation and matter effects

Far-Future projects: Japan

T2KK - Tokai to Kamioka/Korea

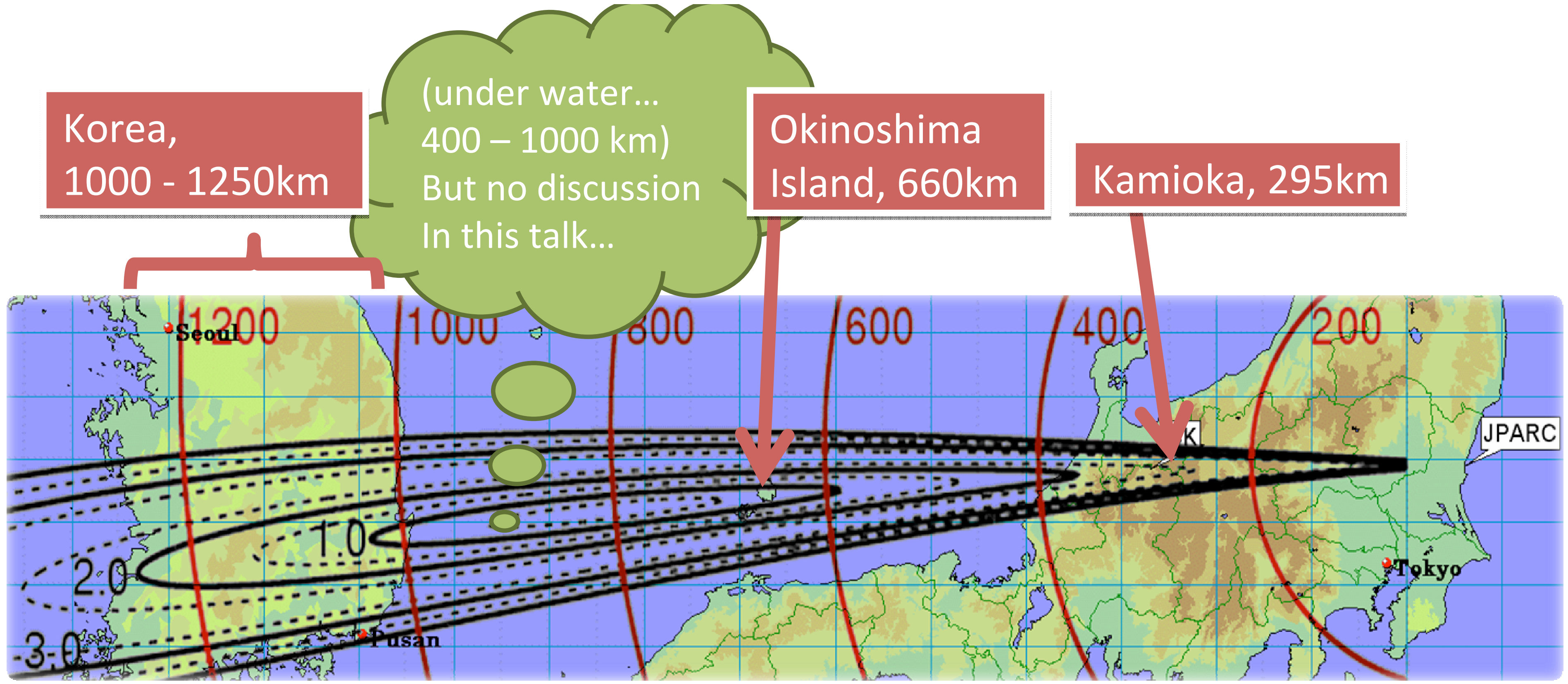


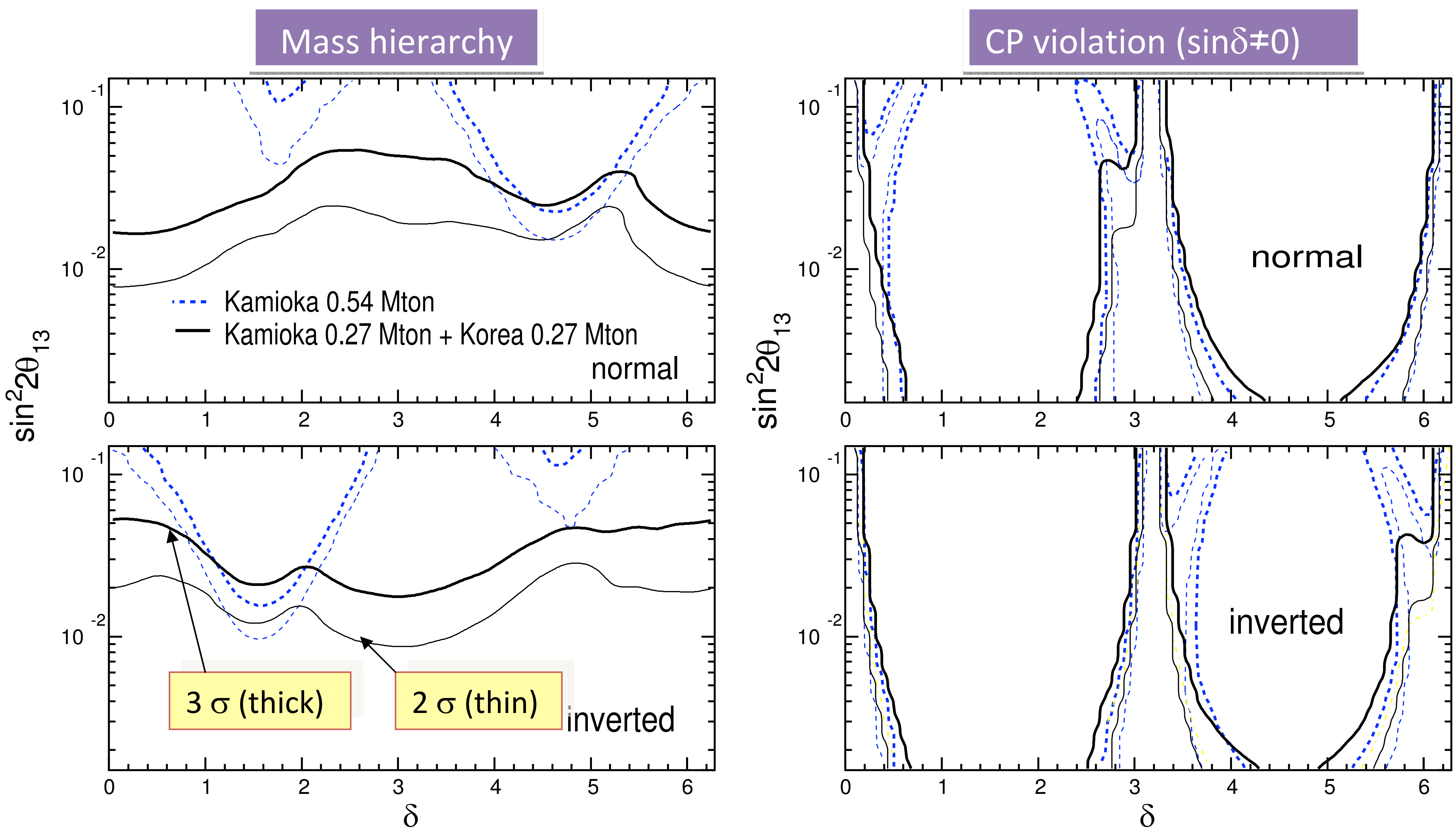
Fig: Senda NP04

- Massive detectors (0.27MT fiducial Water Cerenkov) located at Kamioka (1st oscillation max) and Korea (2nd oscillation max)
  - also studying 0.1MT liquid argon detector designs
- Accelerator upgrades → beam power 1.66 MW

T2KK sensitivity

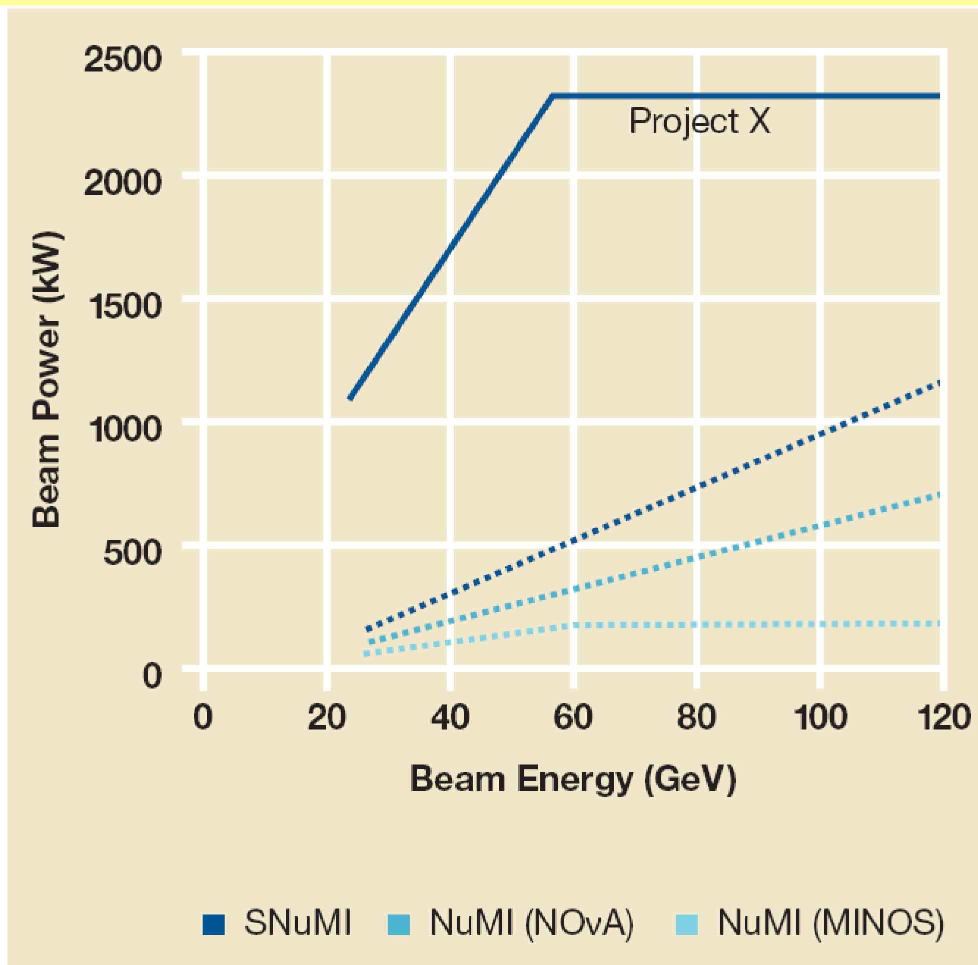
hep-ph/0504026

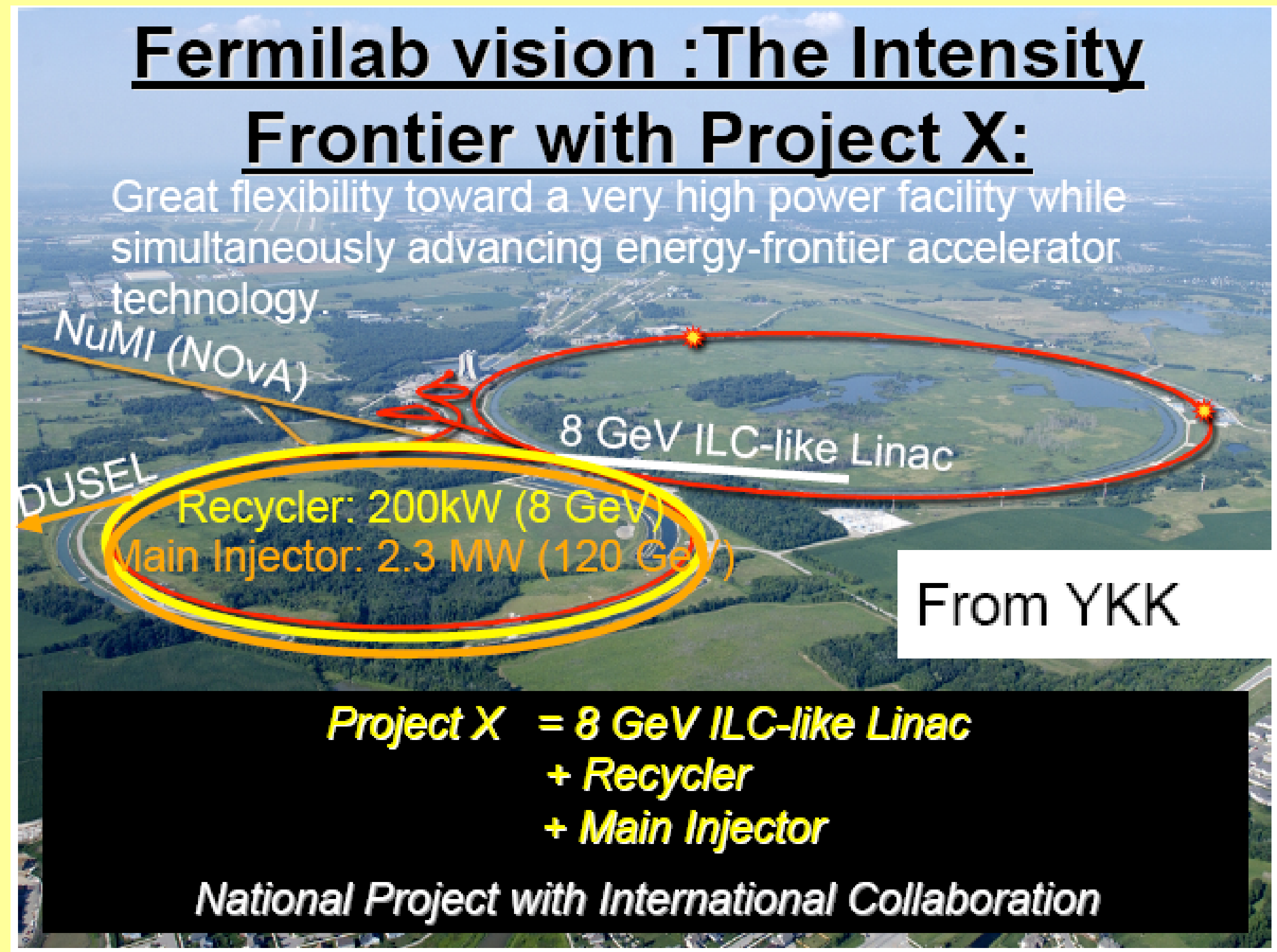
0.27 Mton fid. Mass at Kamioka and Korea (water Ch)
4 years ν beam + 4 years anti-ν beam, 4MW, 2.5 deg Off-axis



3σ sensitivity to mass hierarchy for $\sin^2 2\theta > 0.02$

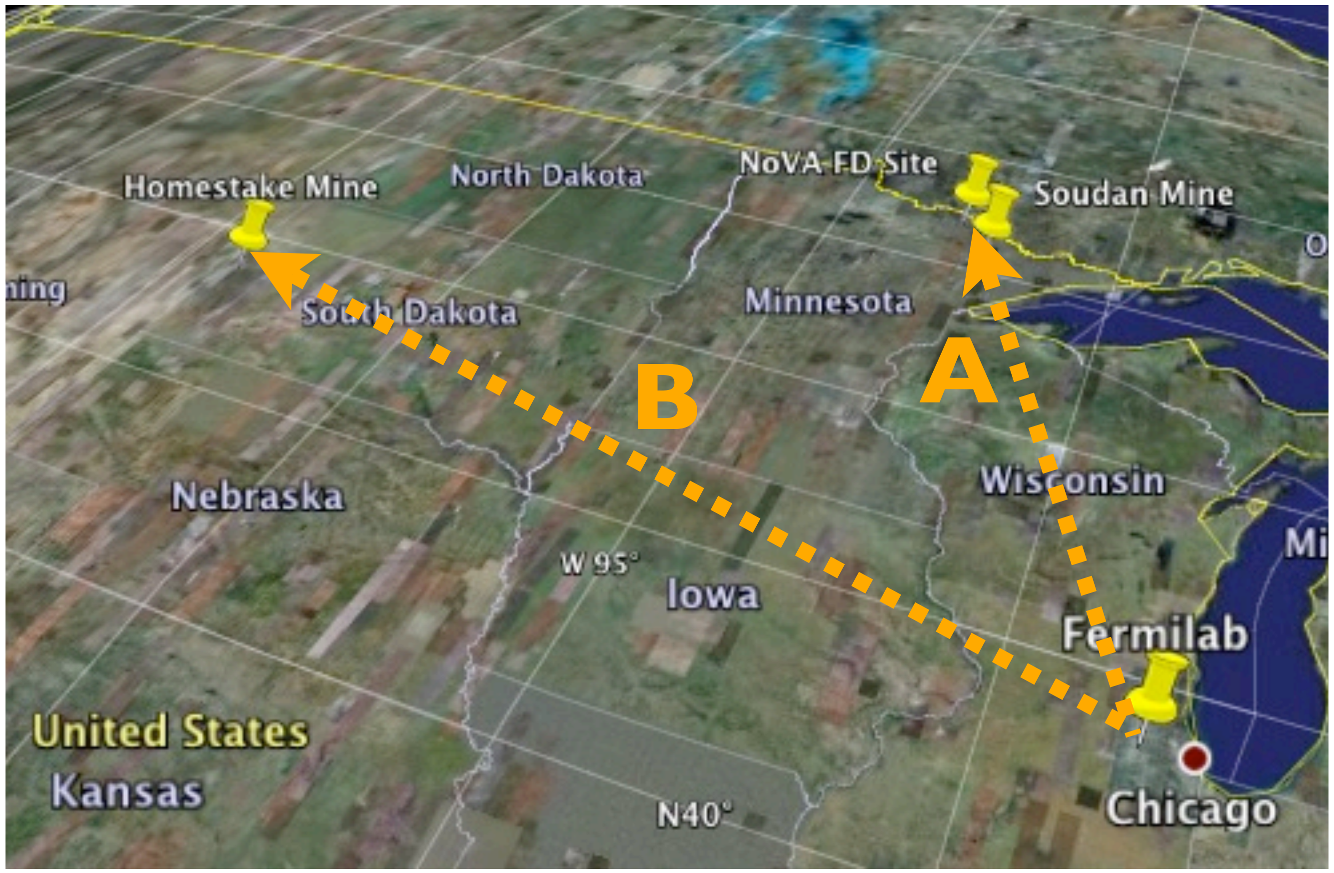
Far-Future projects: USA





- High intensity beam using new super-conducting 8 GeV linac (ILC-like technology)
  - proposed next step in FNAL neutrino beam upgrade beyond ANU (NoVA) and Super-NuMI

Fermilab beamline options



A: Upgrade existing Off-axis narrow band beam to NoVA site (810 km)

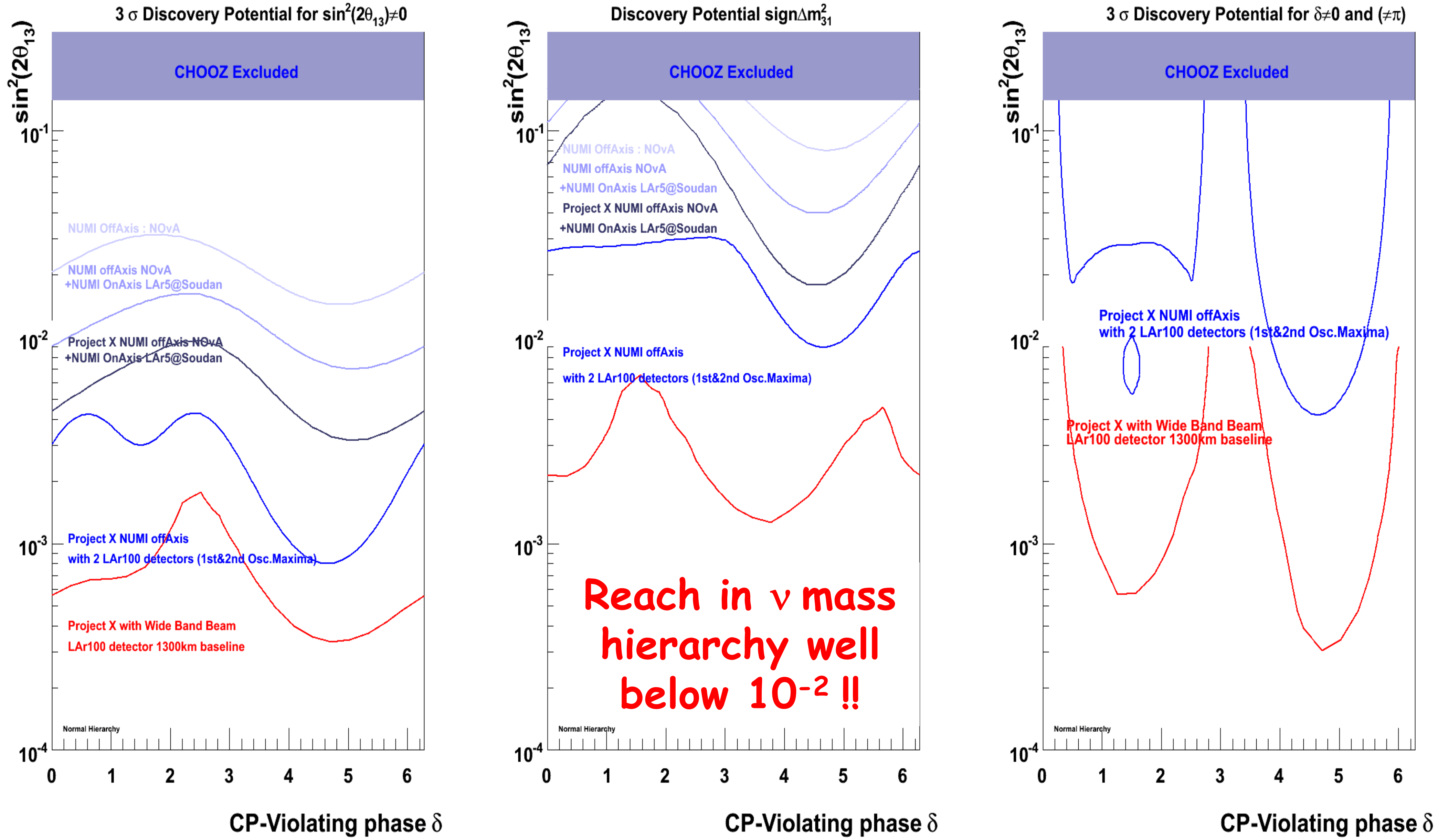
B: New Wide-Band beam to DUSEL/Sanford Lab (Homestake mine) (1300 km)

- Detector considerations:
  - 300kT Water Cerenkov; 100kT Liquid Argon

Staged approach: ArgoNeut→MicroBoone→5kT LAr

Project X sensitivities

Physics Reach : FNAL to DUSEL with 0.1 Mton LAr



NOvA - NOvA+5ktLAr - NOvA+5ktLAr+PX - NOvA+100kt LAr +PX

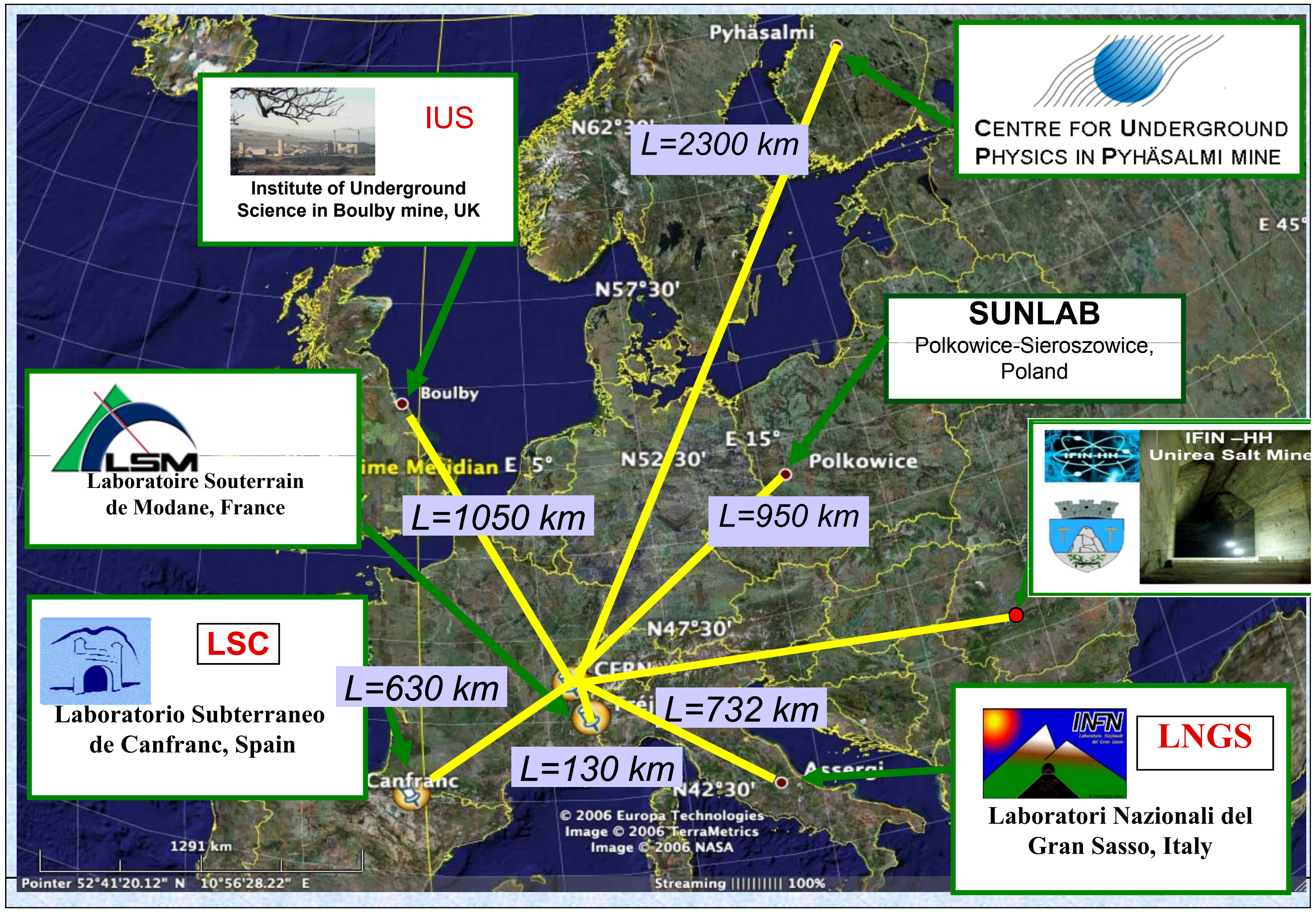
100ktLAr (OR 300kt WC) +New WBB+PX at DUSEL

Slide courtesy N. Saoulidou

Far-Future projects: Europe

- Large-scale multi-purpose detector design studies underway
  - 0.5 MT Water Cerenkov, 100kT LAr, 50kT liquid scintillator.
- High intensity beams:
  - conventional super-beams
  - beta beams (ν_e)
- Further future: neutrino factory beams (ν_μ and ν_e) and longer baselines

- **LAGUNA** [cfr talk by Th. Patzak, contact person for France] Started
  Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics
  - Several institutions participating to WP2-Underground Infrastructures and Engineering and WP4-Science Impact and Outreach
- **EUROnu** (ranked 1st among FP7 Insfrastructure proposals !) Started
  A High Intensity Neutrino Oscillation Facility in Europe Study
  - Physics performance of Water Cherenkov detector to measure neutrino oscillation parameters with SuperBeam and BetaBeam, including detailed response and backgrounds



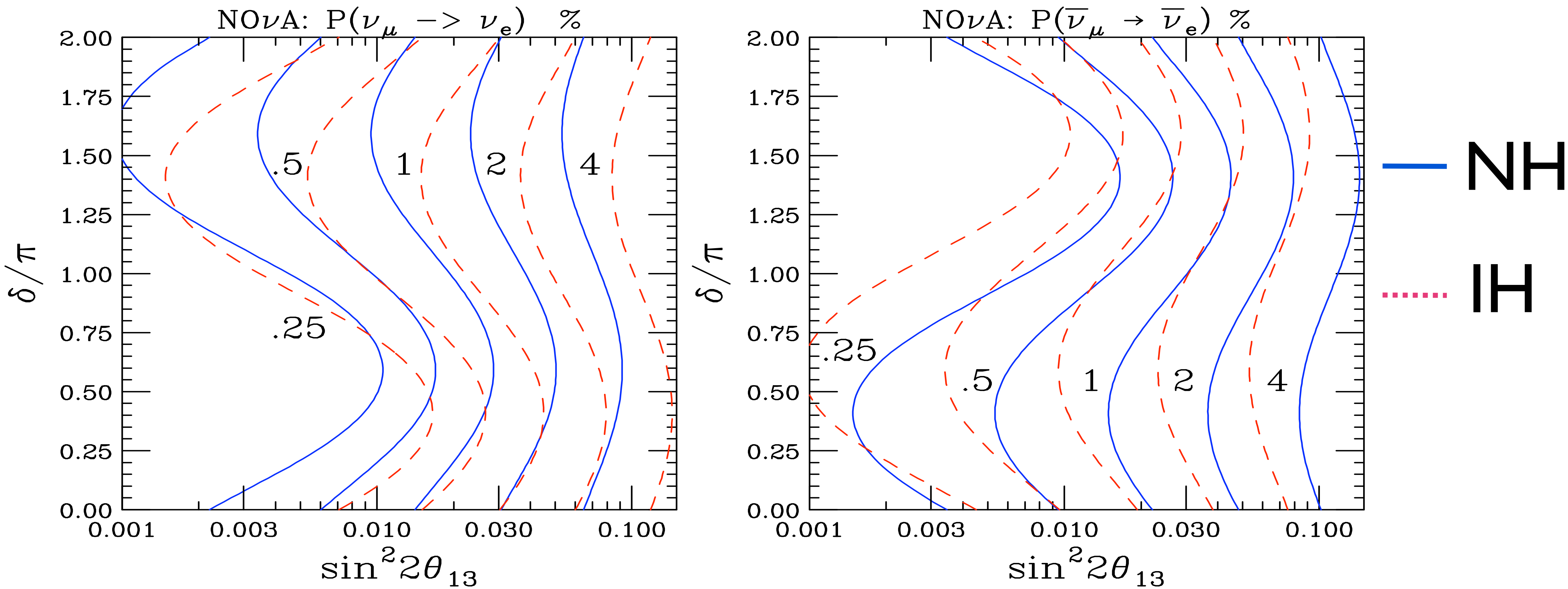
Summary and Prospects

- Paradigm shift (since 1998):
  - phenomenon of neutrino oscillations is now well-established. No longer talk of neutrino "anomalies"
- Now entering the measurement phase of the PMNS matrix in long-baseline experments:
  - *Current generation:* Precision measurement of 2-3 sector, verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis. First chance at observing non-zero θ_{13}
  - *Next generation:* Focussed on search for non-zero θ_{13} (down to 1% level). Possibility of resolving mass hierarchy if nature is kind
  - *Far-future:* Push θ_{13} search to 10^{-3} level. Search for CP violation

Difficult (but exciting) challenges ahead - a range of experiments and approaches will be required

Back-up slides

Iso-probability contours



Reference: arXiv:0710.0554v2 (2008)

CPT symmetry

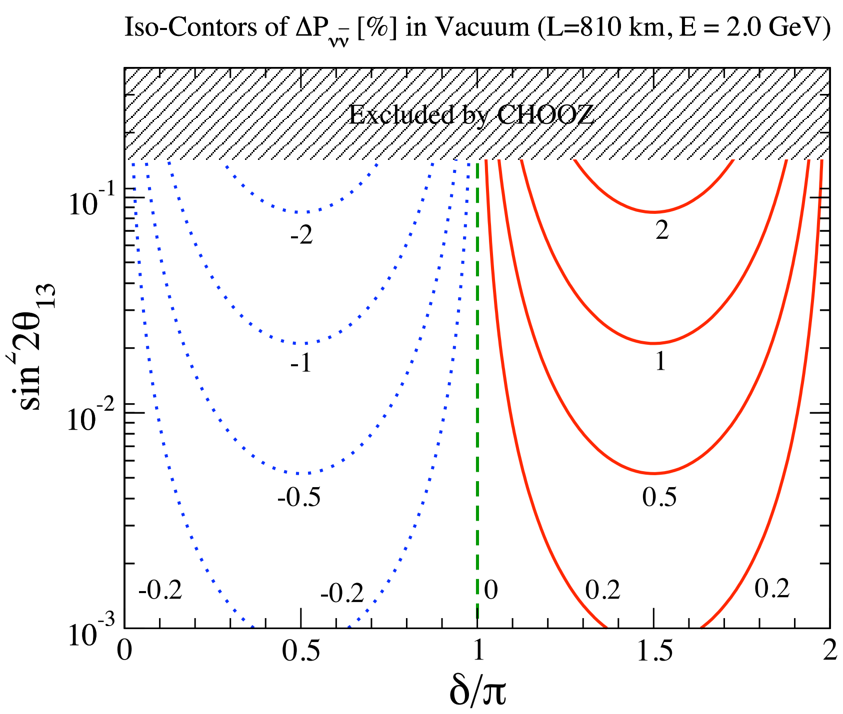
$$P(\nu_\mu \to \nu_e)(\delta, NH) = P(\bar{\nu}_\mu \to \bar{\nu}_e)(2\pi - \delta, IH)$$

difference between NH/IH → size of matter effect

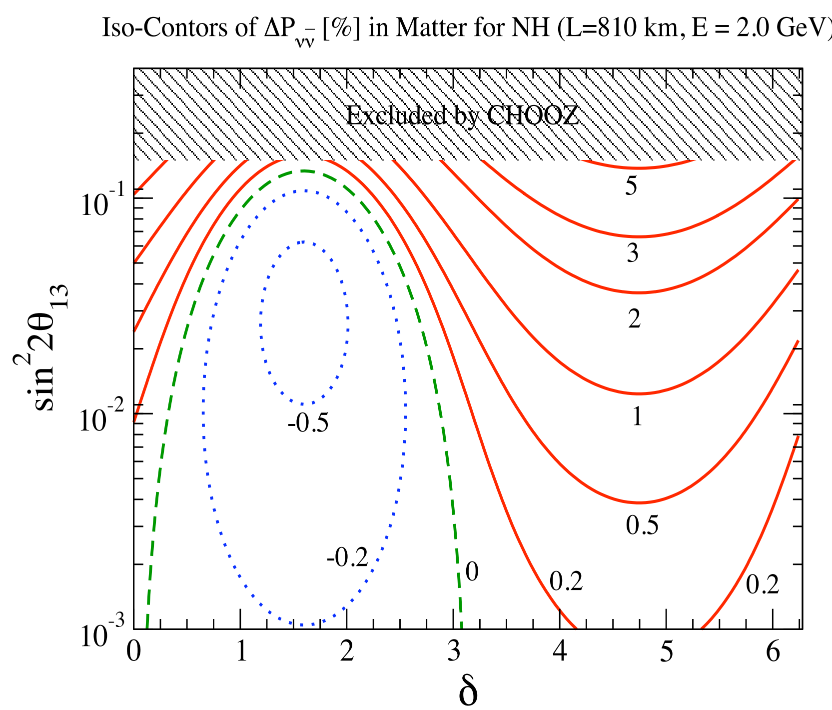
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Iso-contours: fractional difference between neutrino and anti-neutrino probabilities

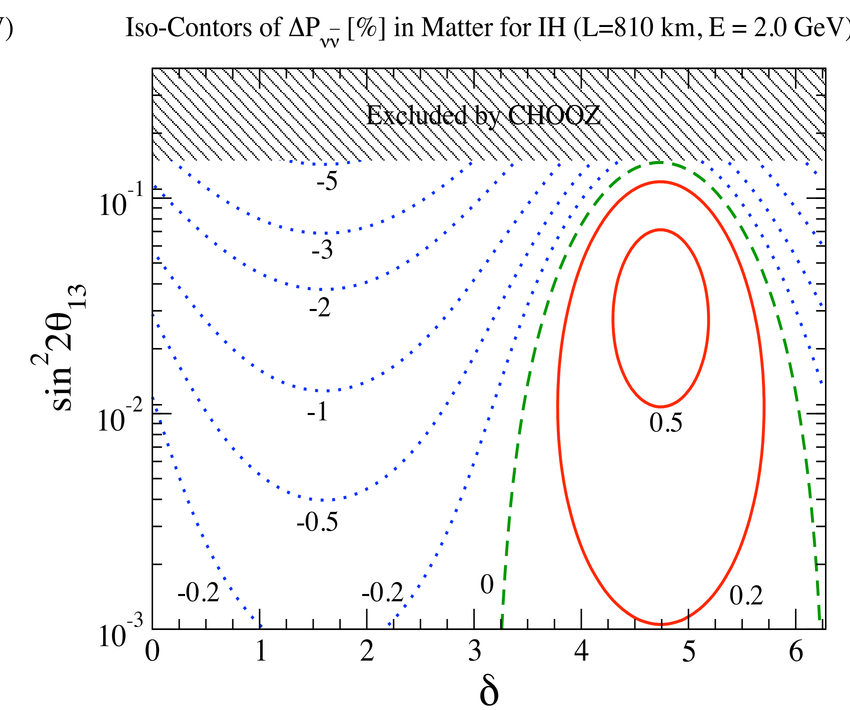
No matter effects



Normal Hierarchy: matter effects



Inverted Hierarchy: matter effects



Reference: arXiv:0710.0554v2 (2008)

matter effects enhance fractional difference for one sector of δ and suppress it in the other

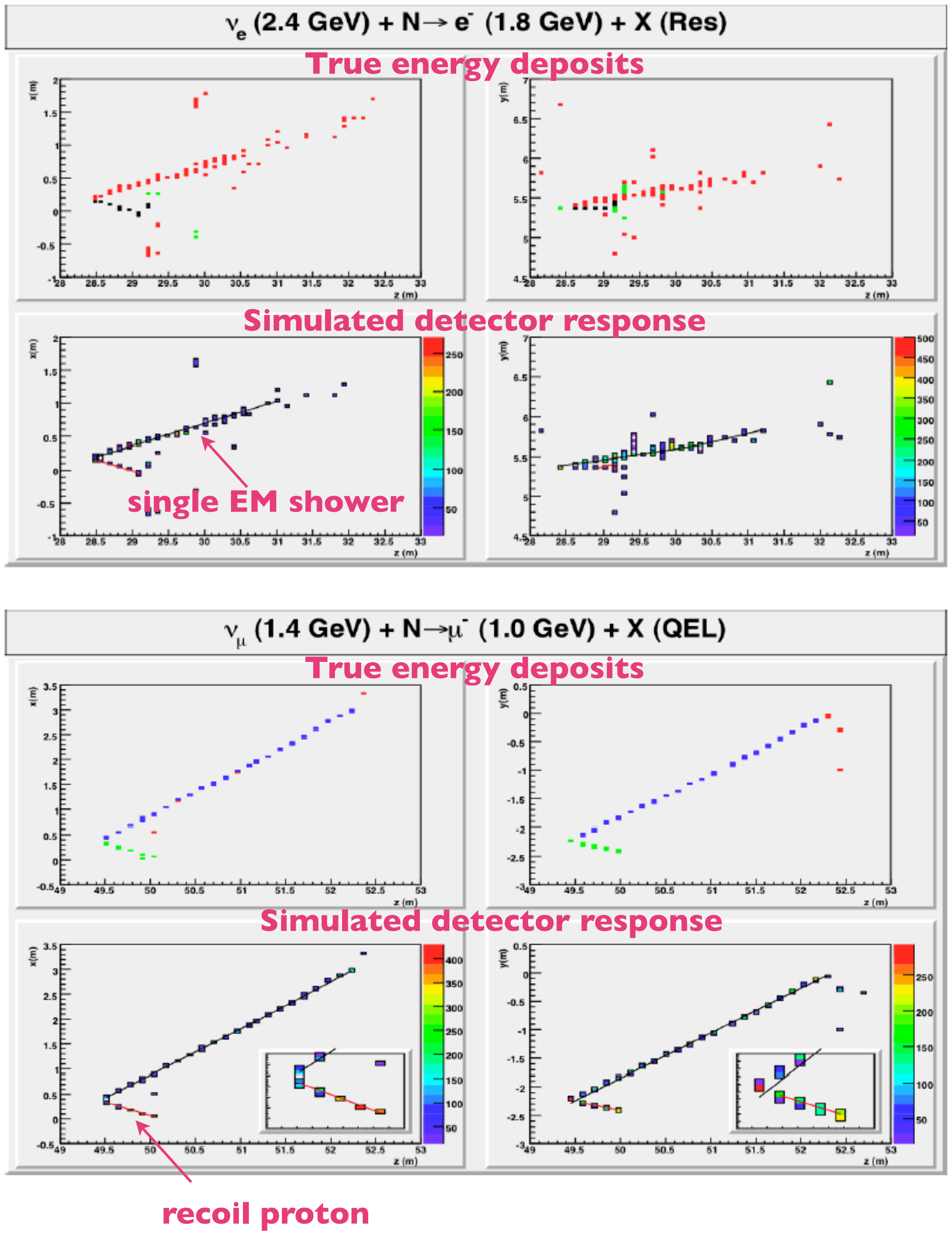
illustrates ambiguity between matter effects and CP violating effects

NoVA physics measurements

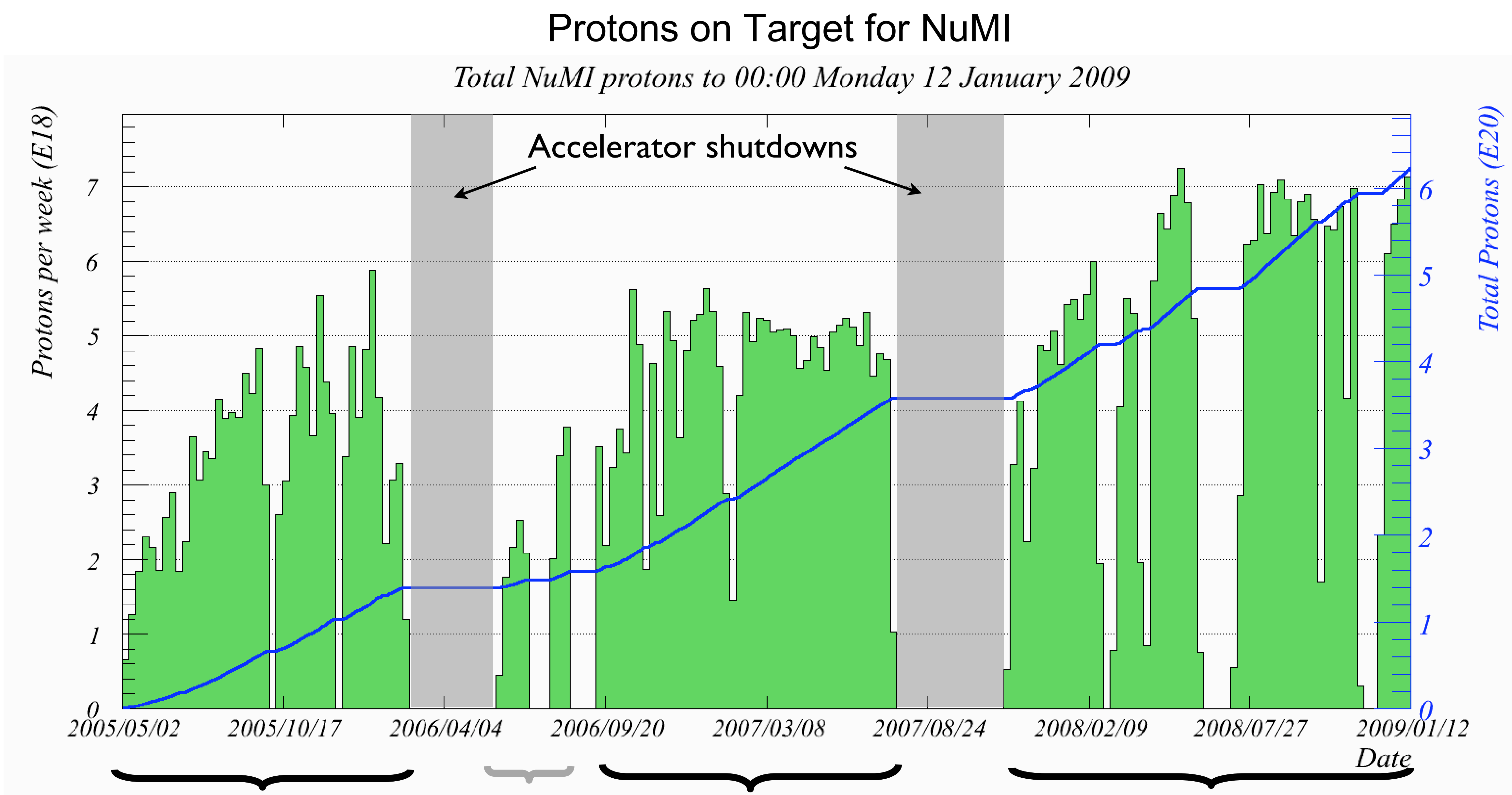
- Principal measurement is search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations.
  - good spatial resolution allows separation between ν_e signal and NC π^0 background events

- Secondary goals are precision measurements of θ_{23} sector via ν_μ disappearance

Simulated events



NuMI beam delivery and analysis datasets



RUN I - 1.27x10^20 POT

Higher energy beam running

RUN II - 1.9x10^20 POT

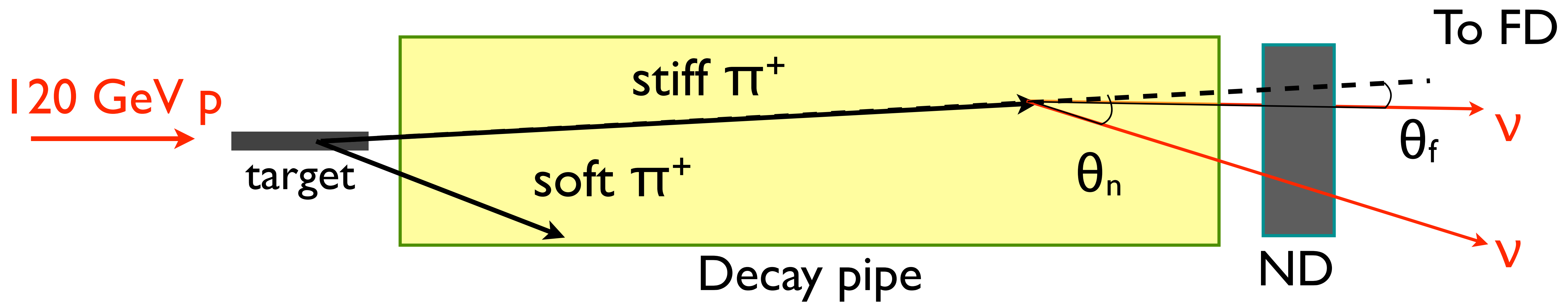
RUN III - >2.5x10^20 POT (not yet analysed)

This analysis: Run I + Run II - 3.2x10^20 POT

Extrapolating the flux

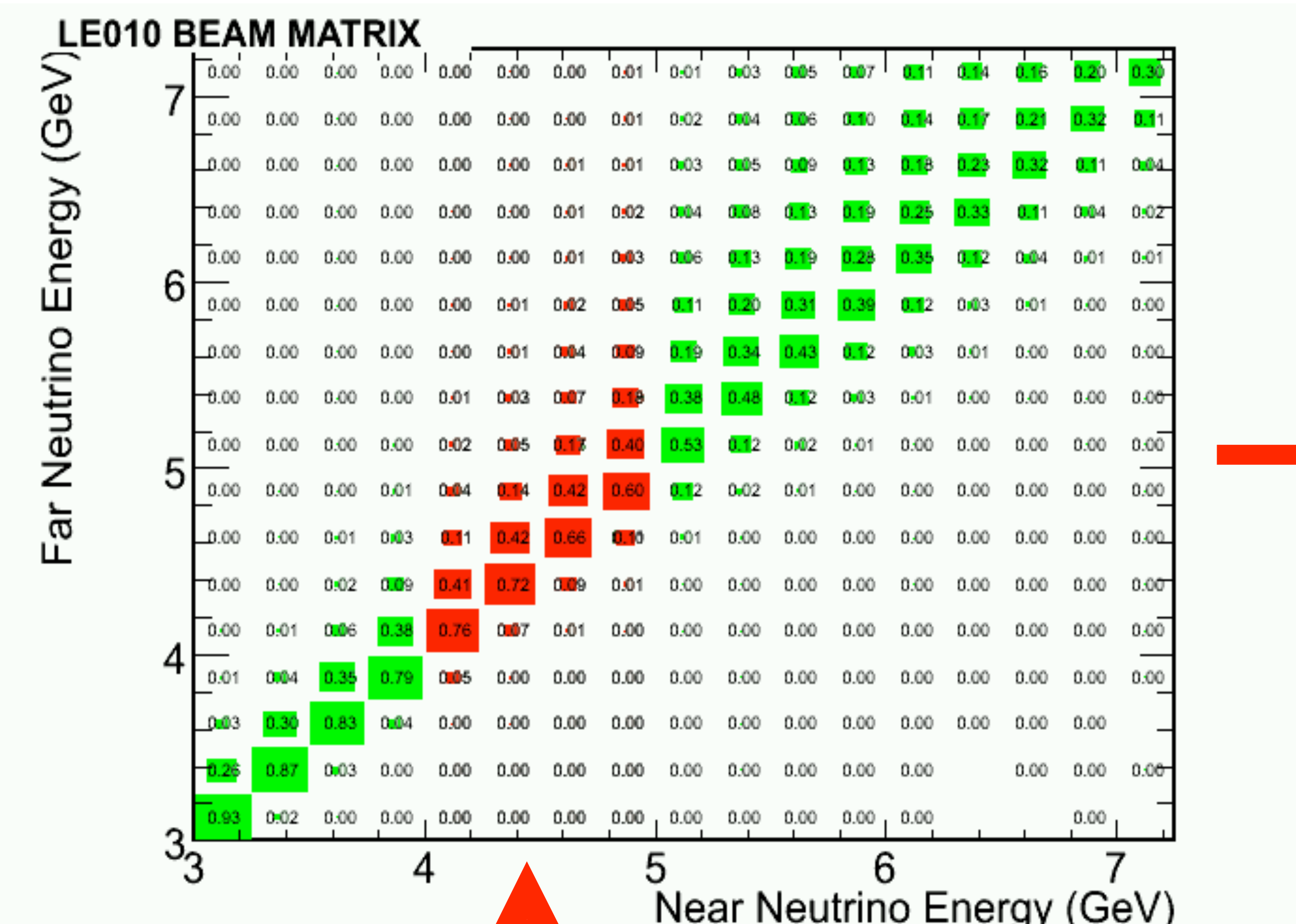
- Directly use the MINOS Near detector data to perform the extrapolation between Near and Far, **using the Monte Carlo to provide necessary corrections due to energy smearing and acceptance.**

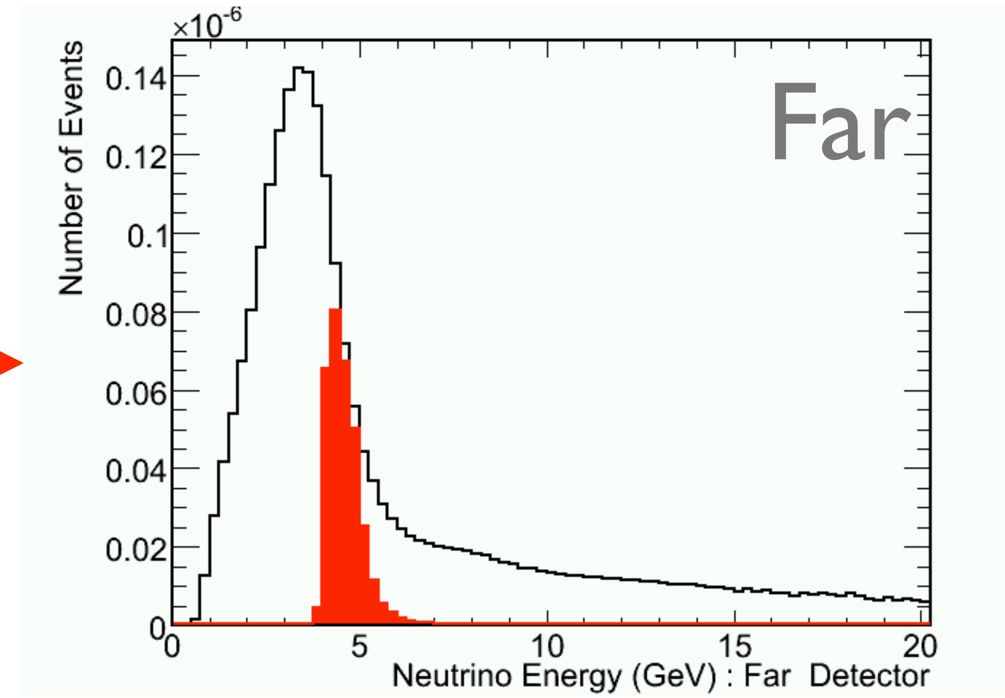
- Use the knowledge of **pion decay kinematics and the geometry of the beamline** (extended neutrino source, seen as point-like from the Far Detector) **to predict the Far detector energy distribution from the measured Near detector distribution**

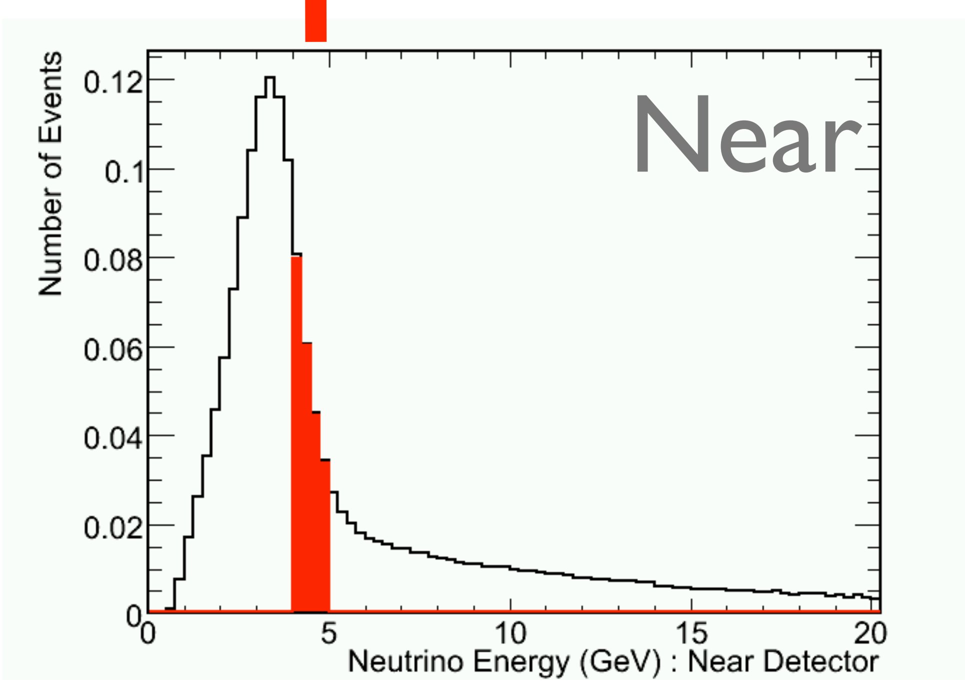


- This method is known as the "**Beam Matrix**" method.

The Beam Matrix

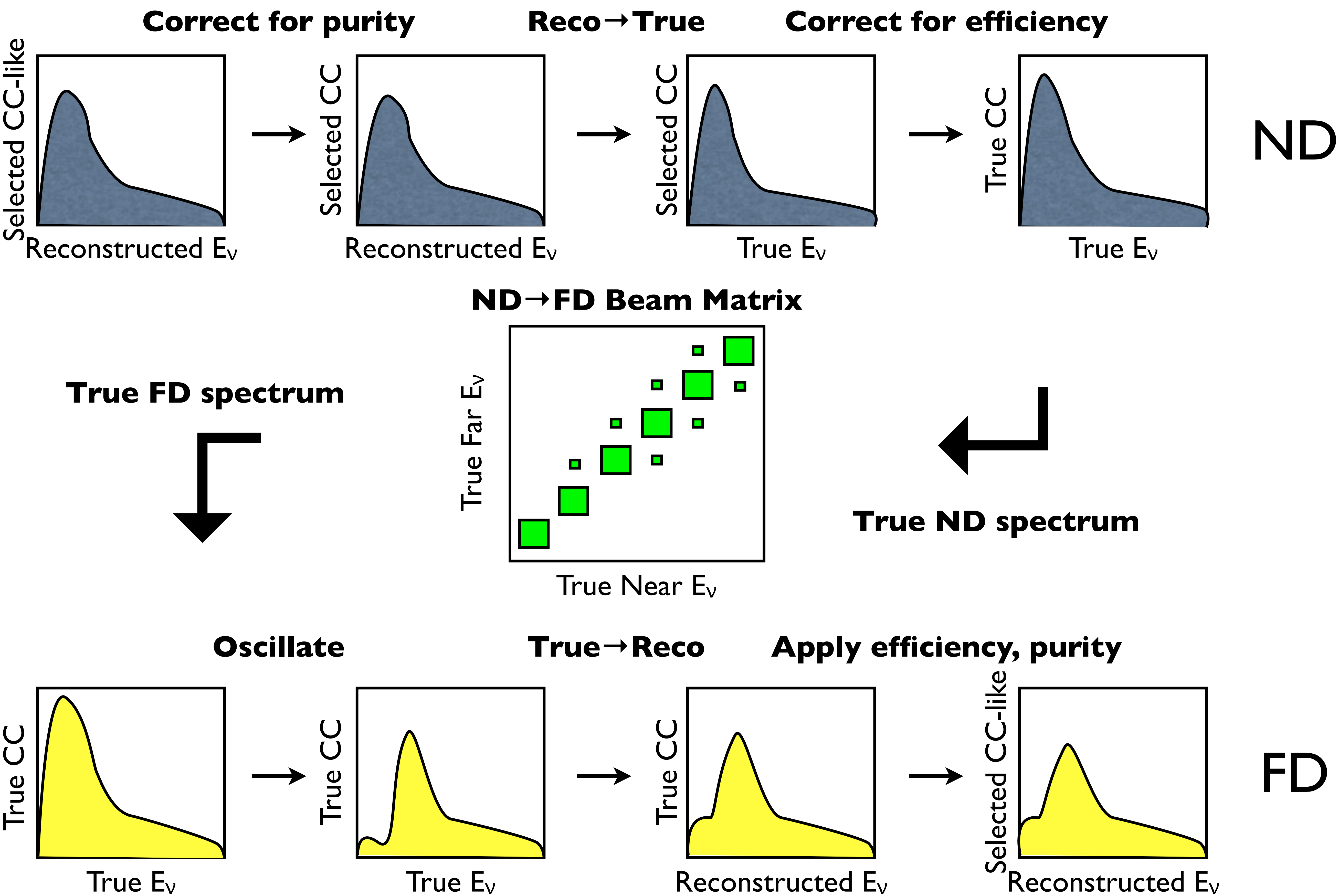




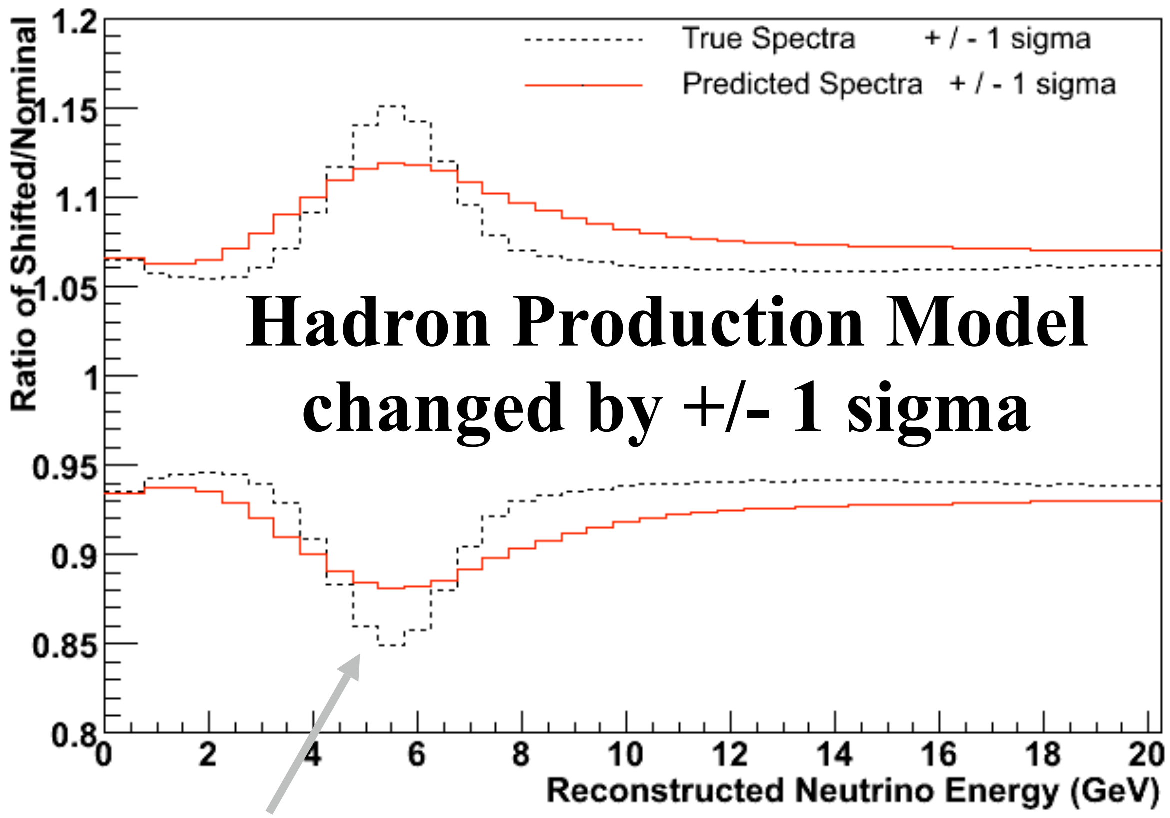


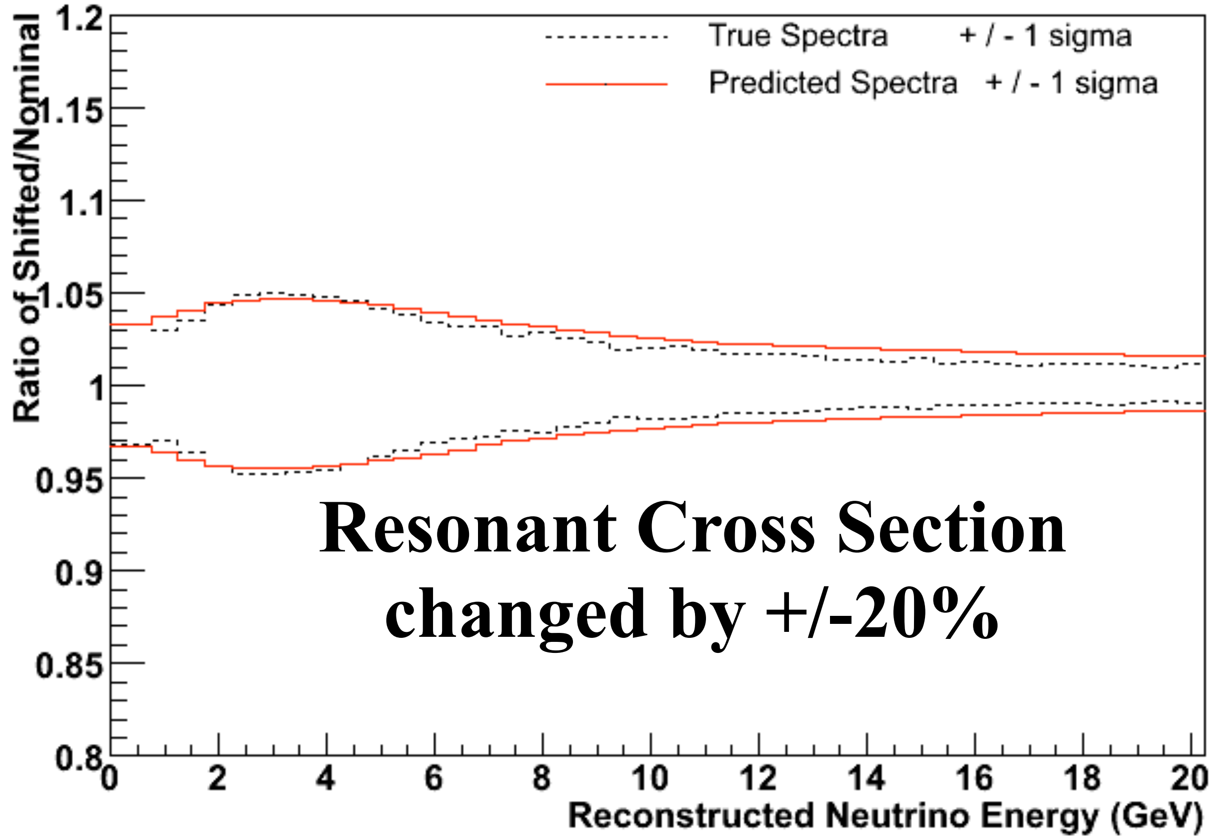
- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry.
- Beam Matrix provides a very good representation of how the near and far detector spectra relate to each other.

Steps in the Beam Matrix method



MINOS: Cancelling systematic errors





- We have investigated (using MC) the effect of systematic uncertainties on the predicted FD spectrum. The plots above illustrate uncertainties in beam modelling and neutrino cross-sections
  - the dashed lines show the magnitude of the systematic effect introduced to our reconstructed energy spectrum (relative to nominal MC)
  - the red lines show the predicted spectrum in these two cases, when the Beam Matrix method is used to extrapolate from Near-Far
  - the true and predicted spectra are very close, indicating that the effect of these systematics largely cancel when this method is used.

K2K energy spectrum

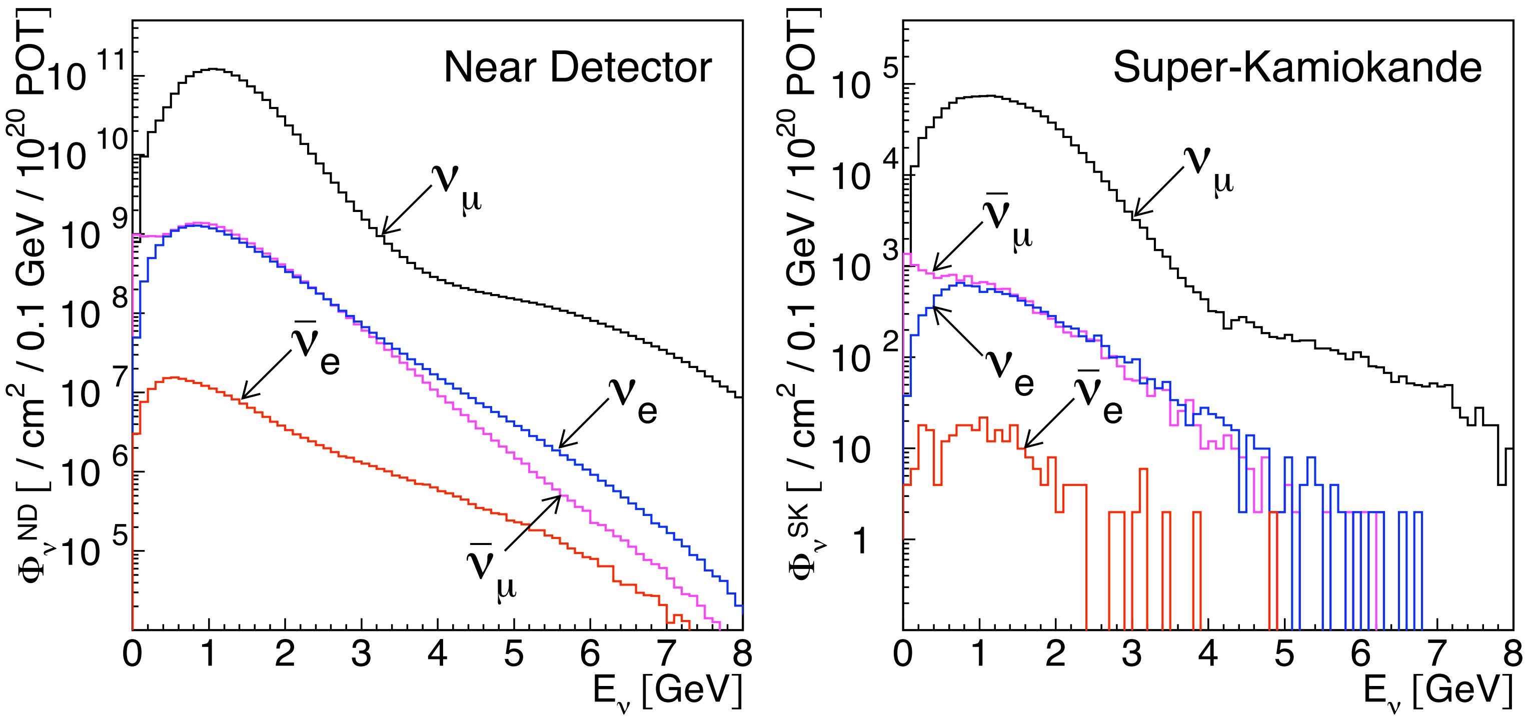
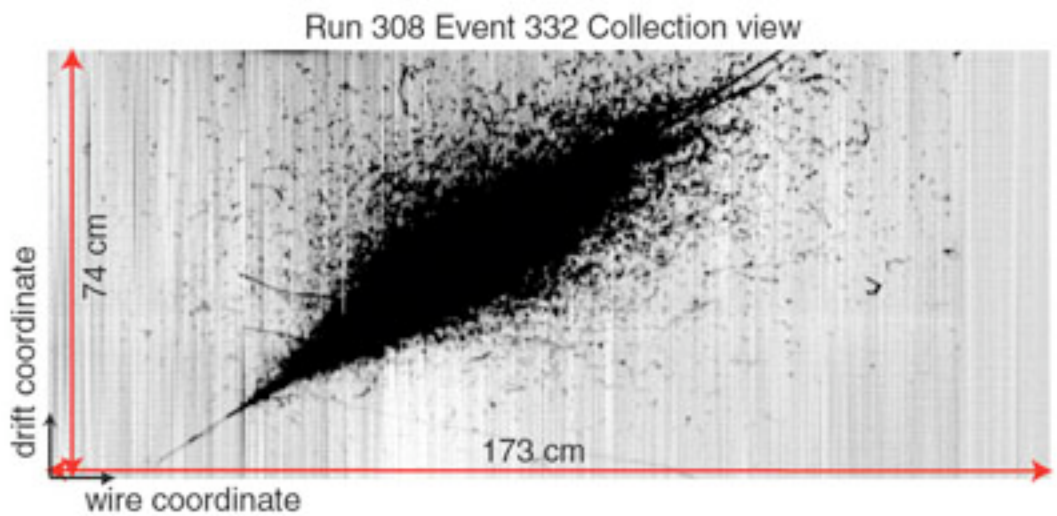


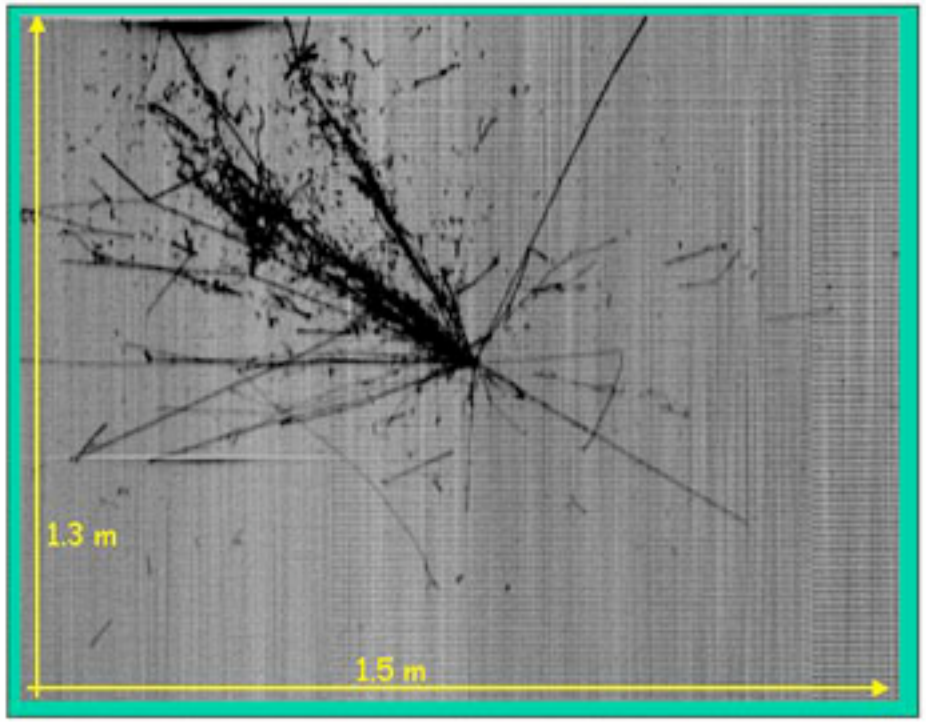
FIG. 6: The energy spectrum for each type of neutrino at ND (left) and SK (right) estimated by the beam MC simulation. The neutrino beam is 97.3% (97.9%) pure muon neutrino with contaminations of $\nu_e/\nu_\mu \sim 0.013$ (0.009), $\overline{\nu}_\mu/\nu_\mu \sim 0.015$ (0.012), and $\overline{\nu}_e/\nu_\mu \sim 1.8 \times 10^{-4}$ (2.2×10^{-4}) at ND (SK).

ICARUS

- 600t LAr detector, being installed in Gran Sasso
- High resolution images: multi-purpose detector:
  - Long-baseline neutrinos (CNGS)
  - solar/atmospheric neutrinos
  - proton decay
- Expected to be ready for data taking in 2009



Broad Electromagnetic Shower

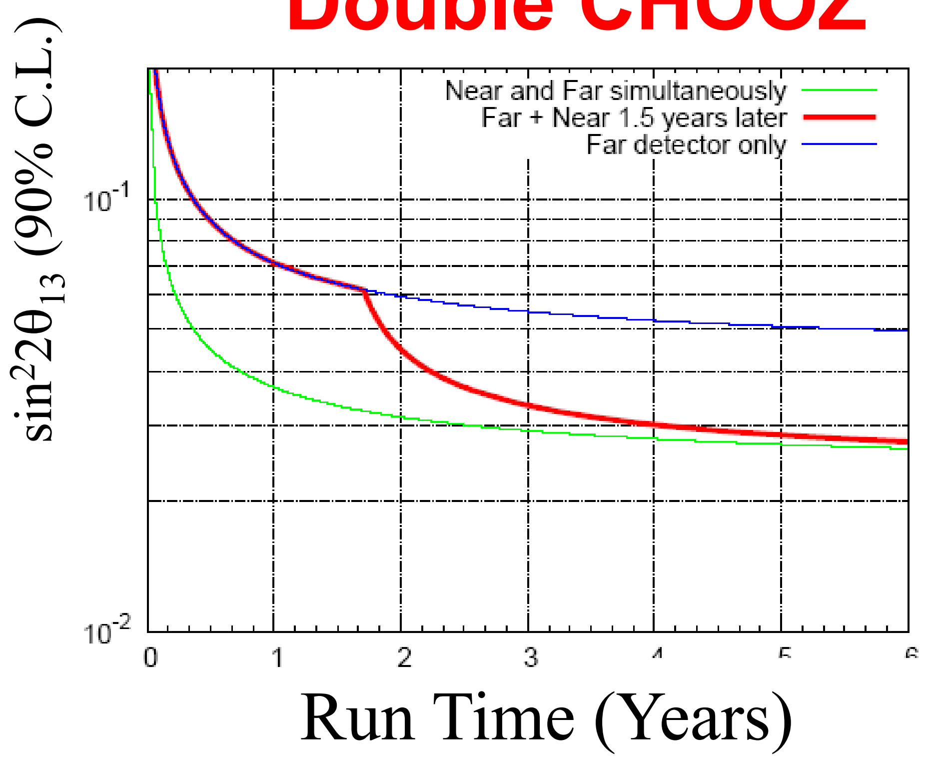


ICARUS T600: June2001 - Pavia Test

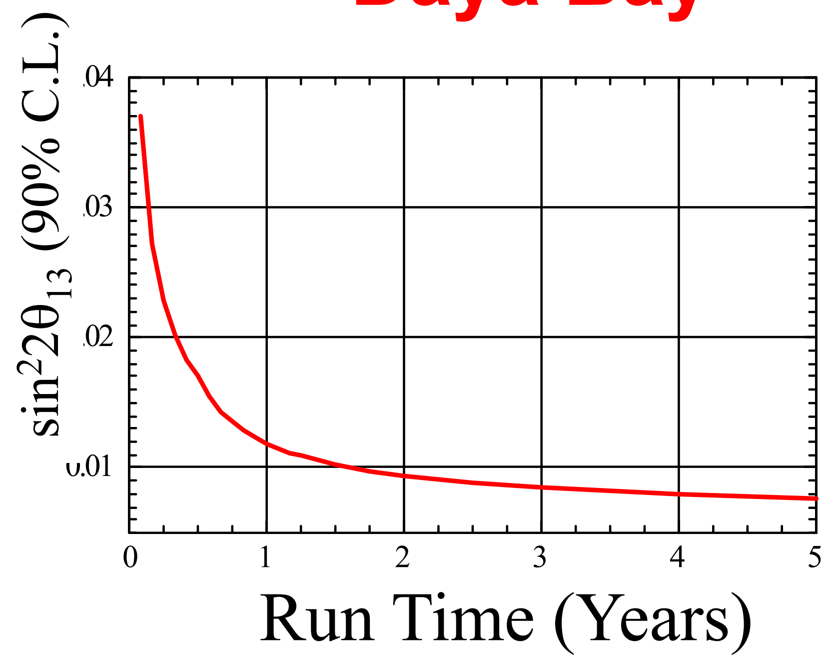
Cosmic ray interaction in LAr

Reactor experiments

Double CHOOZ



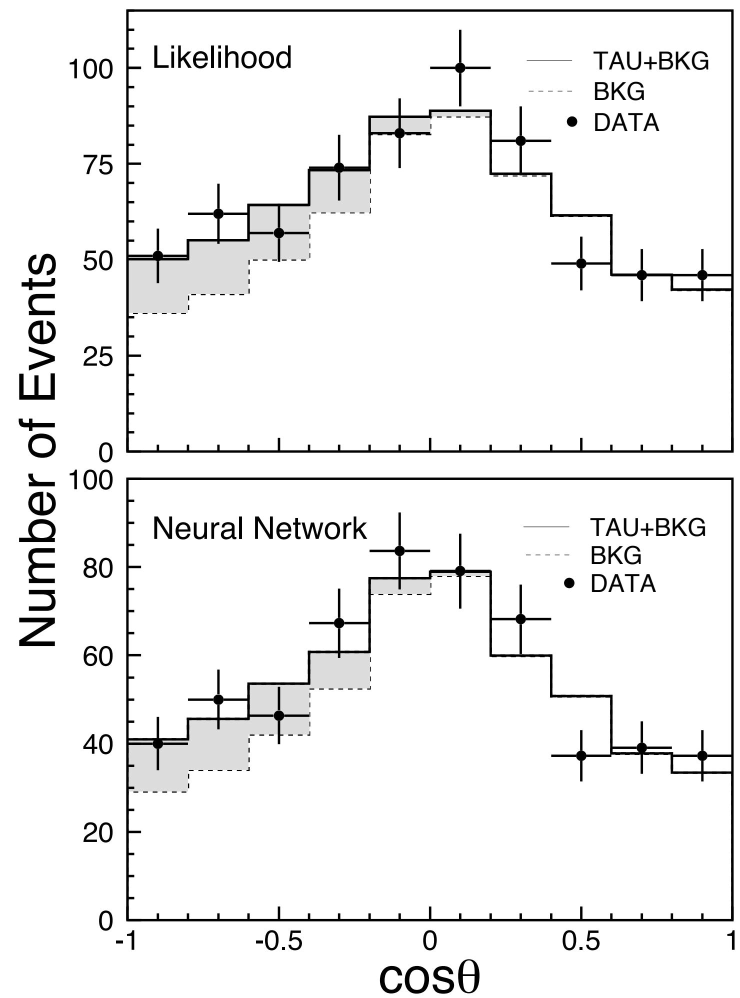
Daya Bay



- Next generation of reactor experiments coming online in the next 2 years:
  - Double CHOOZ - start mid 2009 (no ND)
  - Daya Bay - Start commissioning in 2010
- Combine near and far detector results to reduce systematic errors
- <u>Aiming for sensitivity to $\sin^2 2\theta_{13} \sim 1\%$</u>

Super-K ν_τ evidence

- Statistical search for τ appearance in atmospheric ν
  - focus on hadronic decays of τ
  - construct discriminants based on visible energy, number of Cerenkov rings, sphericity etc
- Search for an excess of events over background in the upward-going τ-enriched event sample
- Observe an excess consistent with ν_τ appearance: 2.4 sigma effect



Systematic uncertainties for expected ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis (23 error terms)	21.6	20.2
Tau related:		
Tau neutrino cross section	25.0	25.0
Tau lepton polarization	7.2	11.8
Tau neutrino selection efficiency	0.4	0.5
LH selection efficiency	4.8	–
NN selection efficiency	–	3.0
Total:	32.6	34.4

Systematic uncertainties for observed ν_τ	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis:		
Flux up/down ratio	6.5	5.7
Flux horizontal/vertical ratio	3.6	3.2
Flux K/π ratio	2.4	2.8
NC/CC ratio	4.3	3.8
Up/down asym. from energy calib.	1.4	< 0.1
Oscillation parameters:		
$0.0020 < \Delta m^2_{23} < 0.0027$ eV^2	+5.8 −2.6	+8.8 −3.3
$0.93 < \sin^2 2\theta_{23} < 1.00$	−3.3	−3.9
$0.0 < \sin^2 2\theta_{13} < 0.15$	−20.6	−17.9
Total:	+10.7 −22.9	+12.0 −20.3

ν_τ appearance signal

$$138 \pm 48(stat)^{+15}_{-32}(sys)$$

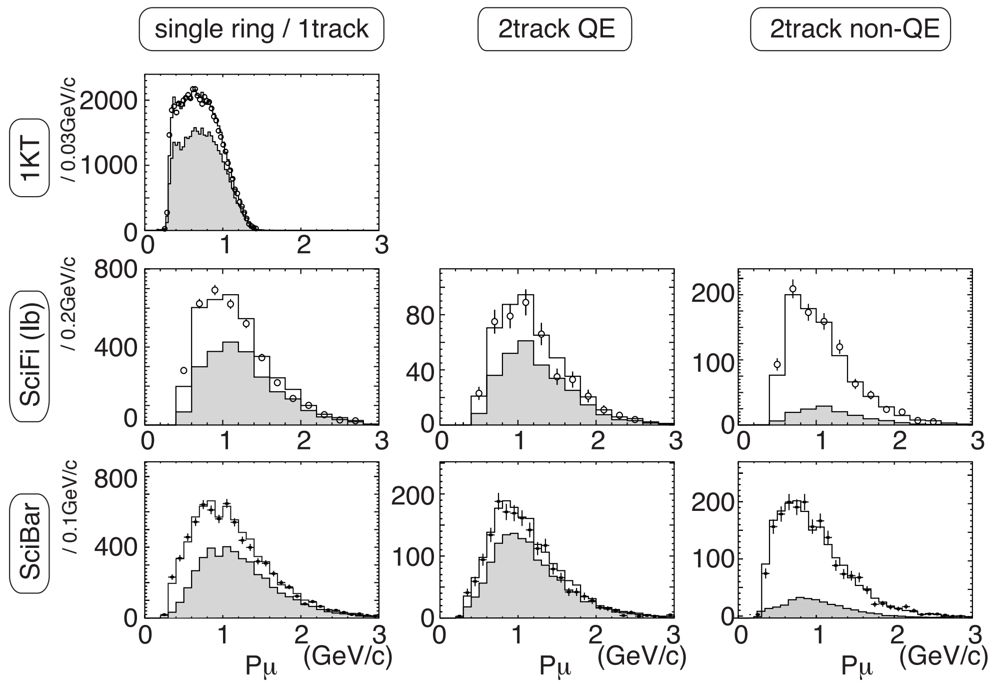
Expectation for $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2

$$78 \pm 26(sys)$$

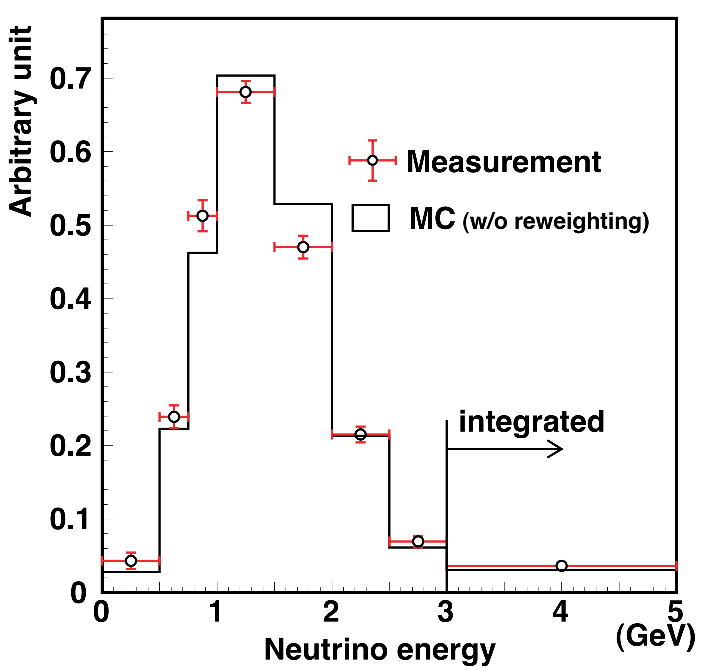
K2K spectrum and systematic errors

ND spectrum

Fits to ND p_μ distributions

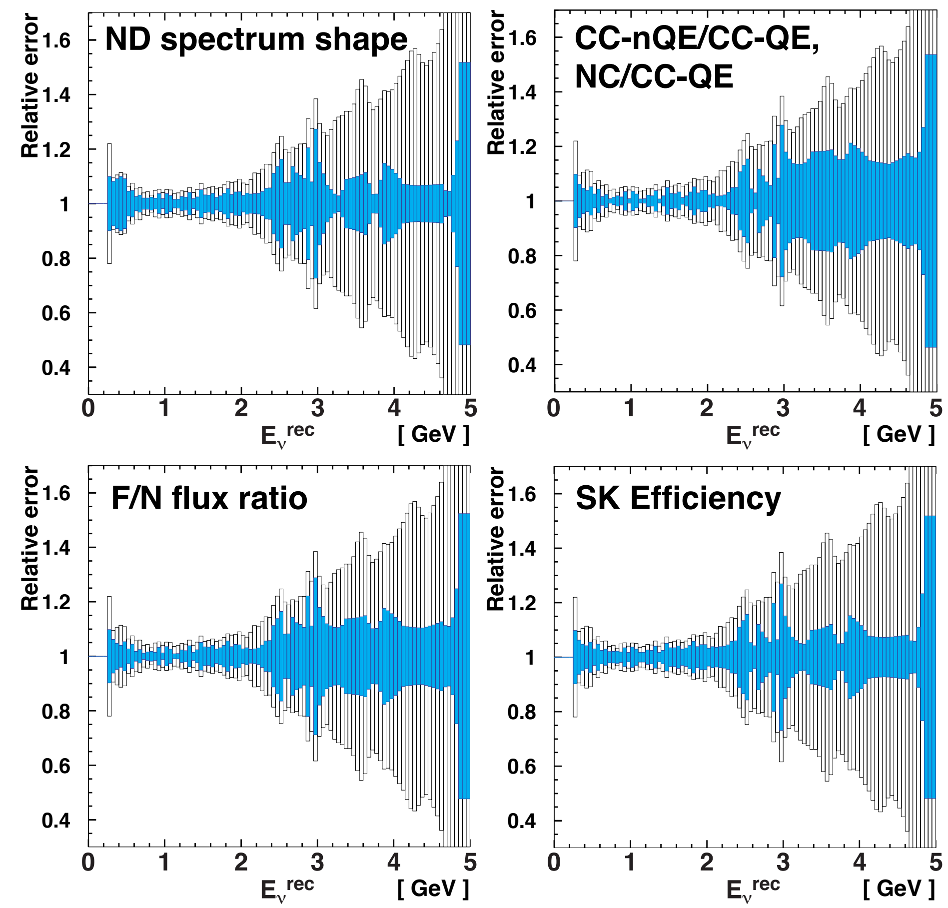


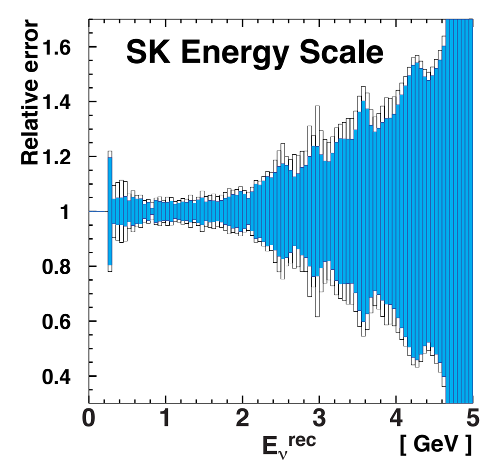
ND energy spectrum after fit vs nominal MC



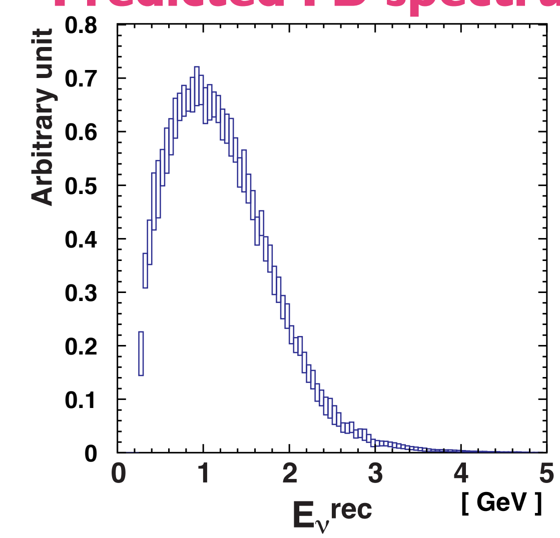
FD spectrum

Effect of systematic errors on FD spectrum





Predicted FD spectrum



$\theta_{13}>0$?

Hints of $\theta_{13} > 0$ from global neutrino data analysis

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Nailing down the unknown neutrino mixing angle θ_{13} is one of the most important goals in current lepton physics. In this context, we perform a global analysis of neutrino oscillation data, focusing on θ_{13}, and including recent results [*Neutrino 2008, Proceedings of the XXIII International Conference on Neutrino Physics and Astrophysics, Christchurch, New Zealand, 2008* (unpublished)]. We discuss two converging hints of $\theta_{13} > 0$, each at the level of $\sim 1\sigma$: an older one coming from atmospheric neutrino data, and a newer one coming from the combination of solar and long-baseline reactor neutrino data. Their combination provides the global estimate

$$\sin^2\theta_{13} = 0.016 \pm 0.010 \ (1\sigma)\,,$$

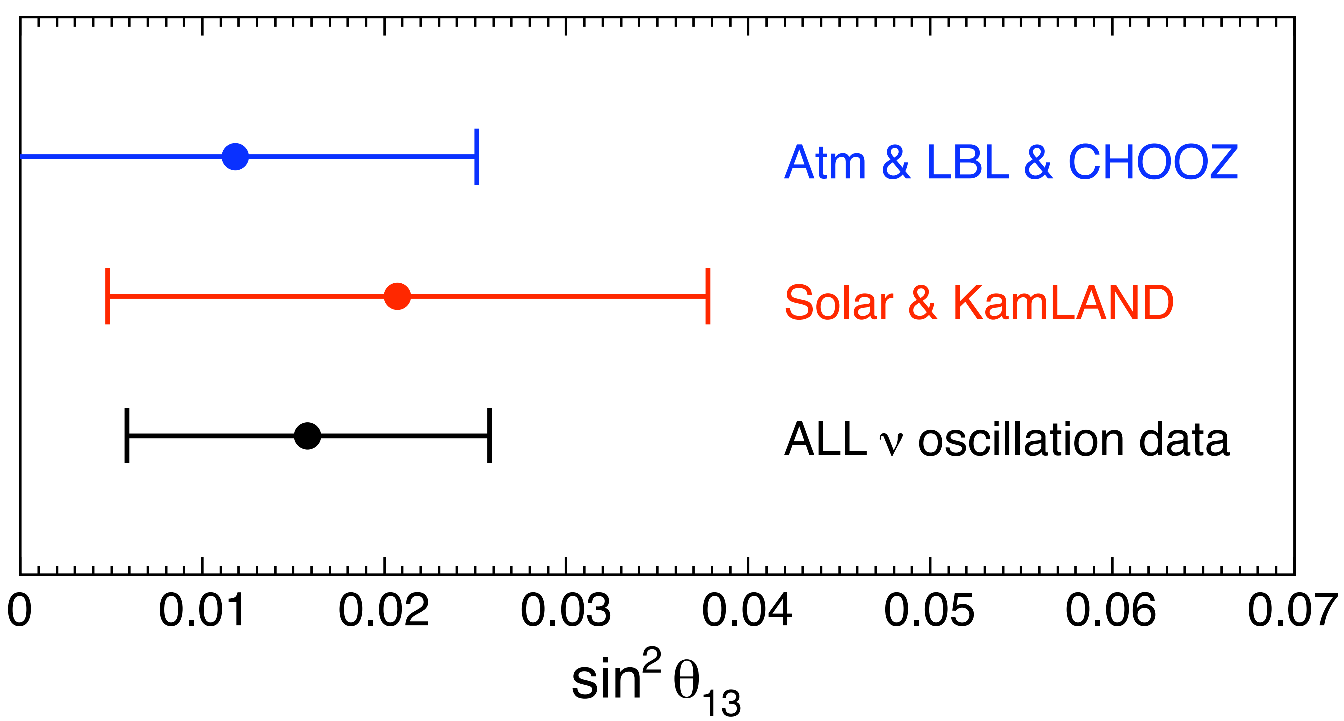

FIG. 2: Global ν oscillation analysis: Allowed 1σ ranges of $\sin^2\theta_{13}$ from different input data.