The T2K Experiment

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Outline

- Neutrino Oscillations
- T2K Overview
- J-PARC
- Neutrino Beam Line
- Near Detector
- Super-K
- Outlook

Neutrino Oscillations

- Not expected. One of the biggest scientific discoveries of the last decade.
- Well established.
- Mass eigenstates (ν_1, ν_2, ν_3) are not the same as weak eigenstates (ν_e, ν_μ, ν_τ).

Simple Two-Generation Case

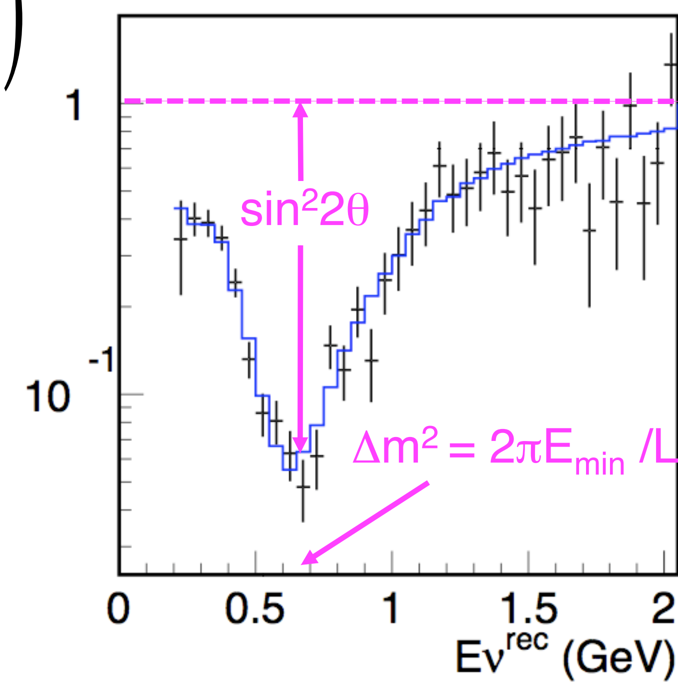
- Probability that a neutrino of energy E with initial flavor α is observed to still be of flavor α after traveling distance L:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 L \big/ 4E\right)$$

θ is a mixing angle

$$\Delta m^2 \equiv \Delta m_b^2 - \Delta m_a^2$$

can be negative



Three Generations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\sim \begin{pmatrix} 0.8 & 0.5 & ??? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}, \ c_{ij} = \cos\theta_{ij}$$

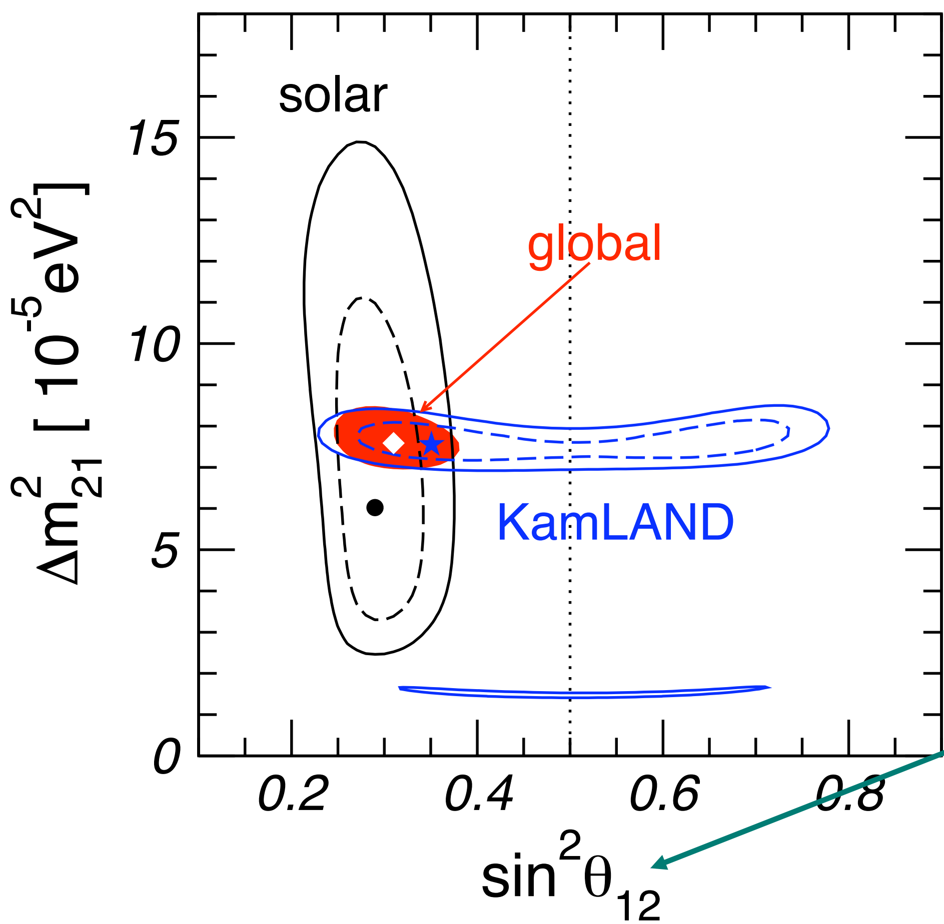
This is not a diagonal matrix!

Oscillation Parameters

- 3 mixing angles, θ_{12}, θ_{23}, θ_{13}
- 1 cp-violating phase δ
- 3 masses m_1, m_2, m_3 $\Rightarrow$ two independent Δm^2

What We Know – Solar

- Super-K, SNO, Gallex, GNO, Kamland (reactor)



$$\Delta m^2_{21} = \left(7.65^{+0.23}_{-0.20}\right) \times 10^{-5}\ eV^2$$

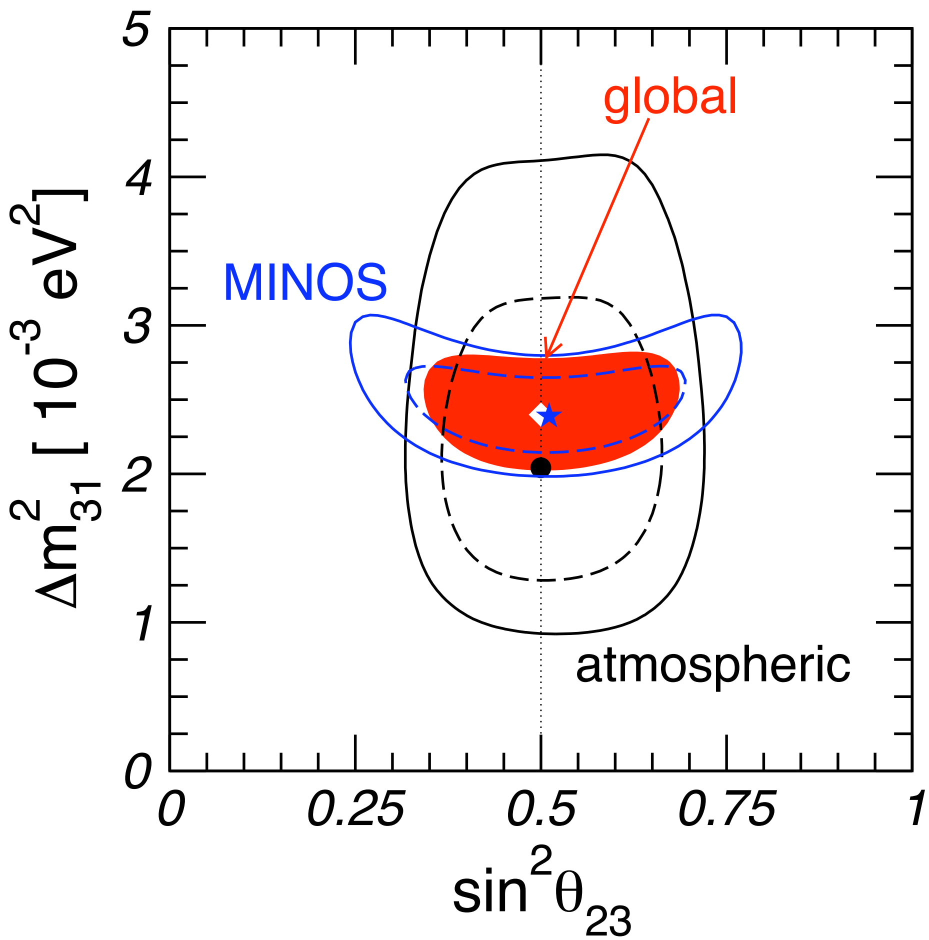
$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$$

not $\sin^2 2\theta$!

Schwetz, Tortola, Valle,
New J.Phys.10:113011,2008

What We Know – Atmospheric

- Super-K, (K2K), MINOS (FNAL long baseline)

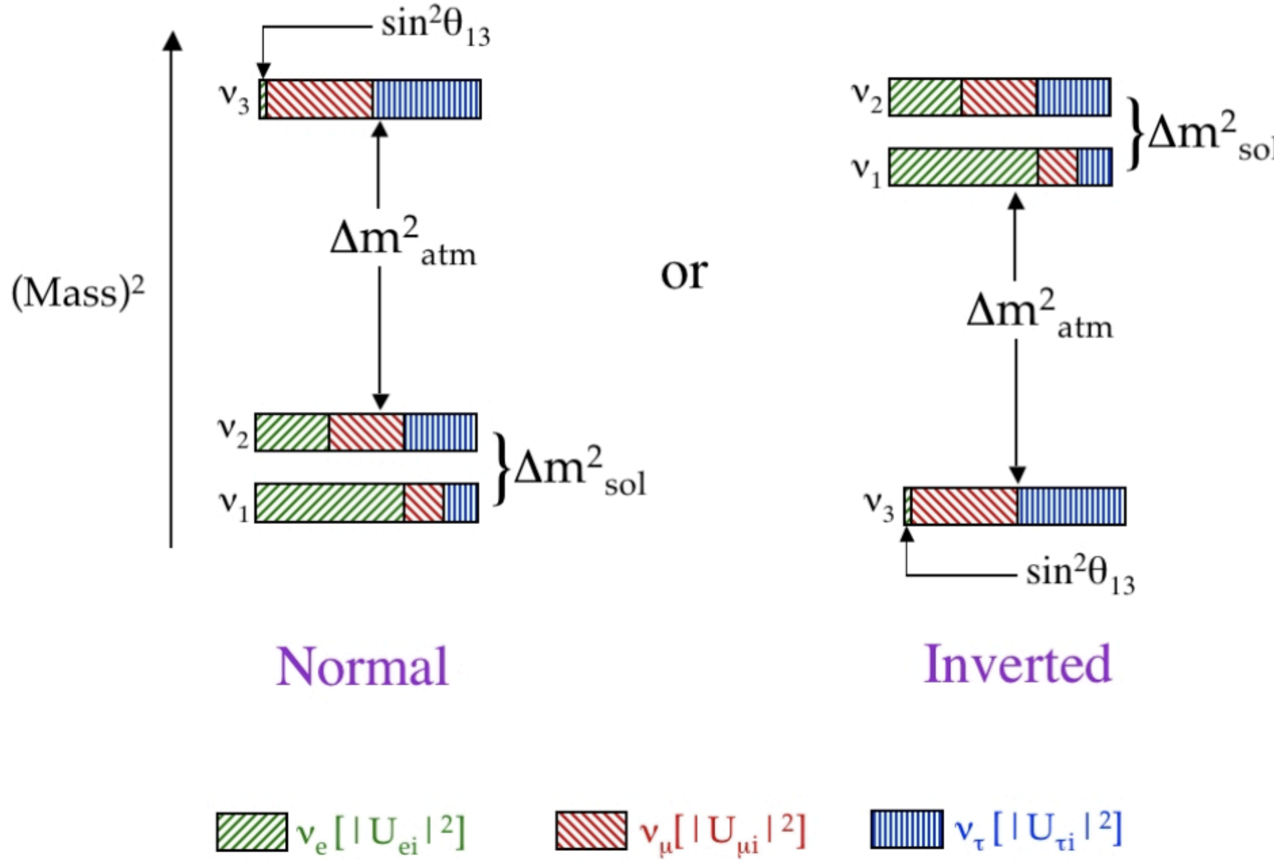


$$\left|\Delta m^2_{31}\right| = \left(2.40^{+0.12}_{-0.11}\right) \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

What We Don't Know

- sign of $\Delta m_{31}^2 \equiv m_3^2 - m_1^2$ (mass hierarchy)
- θ_{13}
- δ
- (Majorana)



Measuring θ_{13} via $\nu_\mu \rightarrow \nu_e$ Oscillations

- Dominant "atmospheric" oscillation is ν_μ to ν_τ.
  - τ are not reconstructed, so this is basically ν_μ disappearance.
- $\nu_\mu \rightarrow \nu_e$ can occur, but has not been observed.
  - complicated formula…

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

where

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \quad ,$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad ,$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad ,$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \quad .$$

and

$\Delta \equiv \Delta m_{31}^2 L / 4E$

$\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2 \approx \pm 0.03$

$x \equiv 2\sqrt{2} G_F N_e E / \Delta m_{31}^2 \approx \pm E / 11 GeV$

N_e = electron number density

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

where

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \quad ,$$

T_1 is dominant, ~ 0.5 at oscillation max

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad ,$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad ,$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \quad .$$

and

$\Delta \equiv \Delta m^2_{31} L / 4E$ — kinematic phase of oscillation

$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31} \approx \pm 0.03$ — α is small

$x \equiv 2\sqrt{2} G_F N_e E / \Delta m^2_{31} \approx \pm E / 11 GeV$

N_e = electron number density

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

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$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \quad .$$

This term does not depend on θ_{13}, but is small

and

$$\Delta \equiv \Delta m^2_{31} L / 4E$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31} \approx \pm 0.03$$

$$x \equiv 2\sqrt{2} G_F N_e E / \Delta m^2_{31} \approx \pm E / 11 GeV$$

N_e = electron number density

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

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and

$\Delta \equiv \Delta m^2_{31} L / 4E$

$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31} \approx \pm 0.03$

$x \equiv 2\sqrt{2} G_F N_e E / \Delta m^2_{31} \approx \pm E / 11 GeV$ ⇐ Matter effects are larger for NOνA (E ~ 2 GeV) than T2K (E ~ 0.6 GeV)

N_e = electron number density

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

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$$x \equiv 2\sqrt{2} G_F N_e E / \Delta m^2_{31} \approx \pm E/11 GeV$$

N_e = electron number density

All three of these terms depend on the mass hierarchy (sign of Δm_{31}^2)

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

δ only appears in product with $\sin 2\theta_{13}$

where

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP violating
$\delta \to -\delta$ for $\bar{\nu}$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \quad .$$

and

$$\Delta \equiv \Delta m_{31}^2 L / 4E$$

$$\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2 \approx \pm 0.03$$

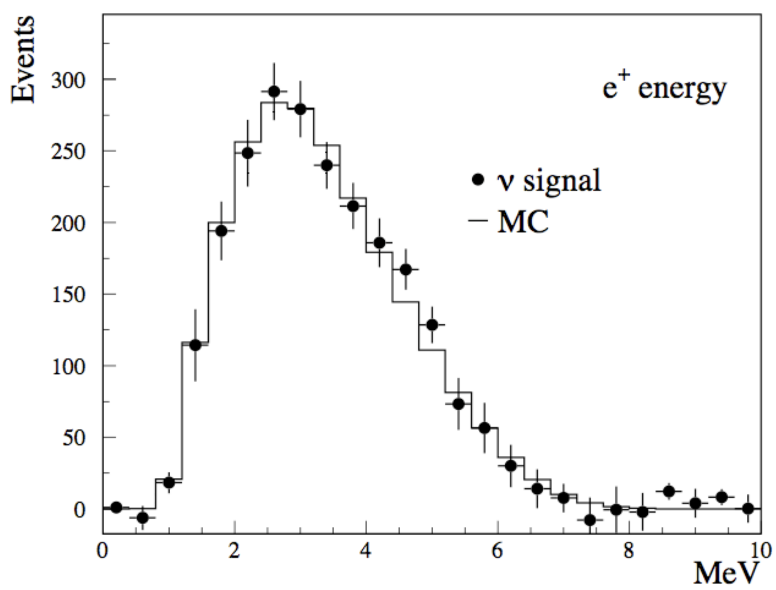
$$x \equiv 2\sqrt{2} G_F N_e E / \Delta m_{31}^2 \approx \pm E/11 GeV$$

$x \to -x$ for $\bar{\nu}$; can fake CPV

N_e = electron number density

Chooz Experiment

- Reactor experiment (1997-98) looking for ν_e disappearance. E_ν ~ 3 MeV, L ~ 1 km.
- $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2(\Delta m^2_{31} L/4E) + O(\alpha^2)$
  - Does not depend on δ, *x*, or mass hierarchy.

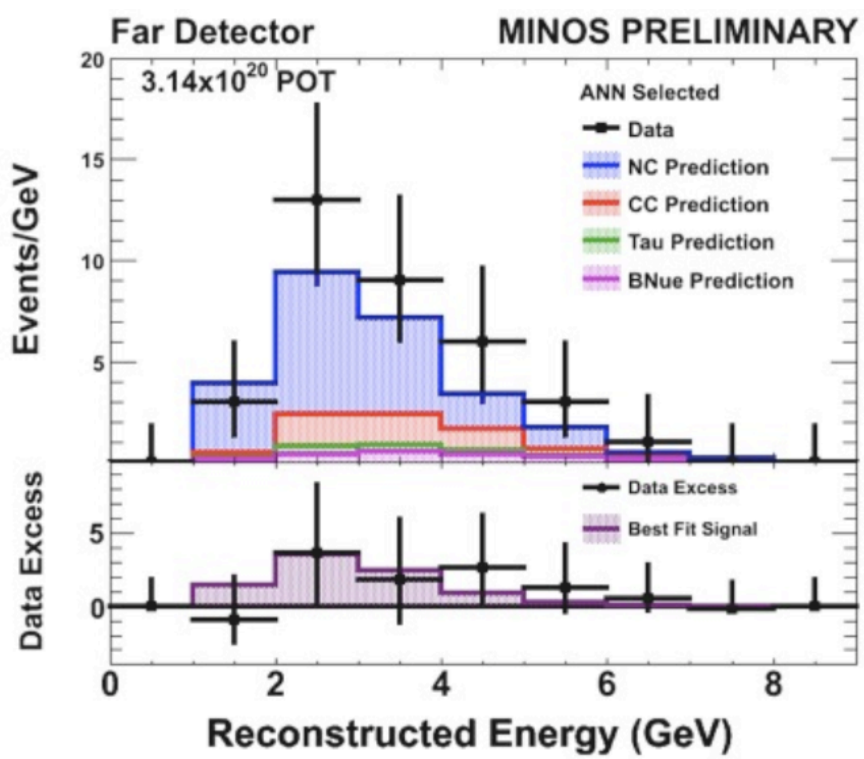


$\sin^2 2\theta_{13} < 0.15$ 90% CL

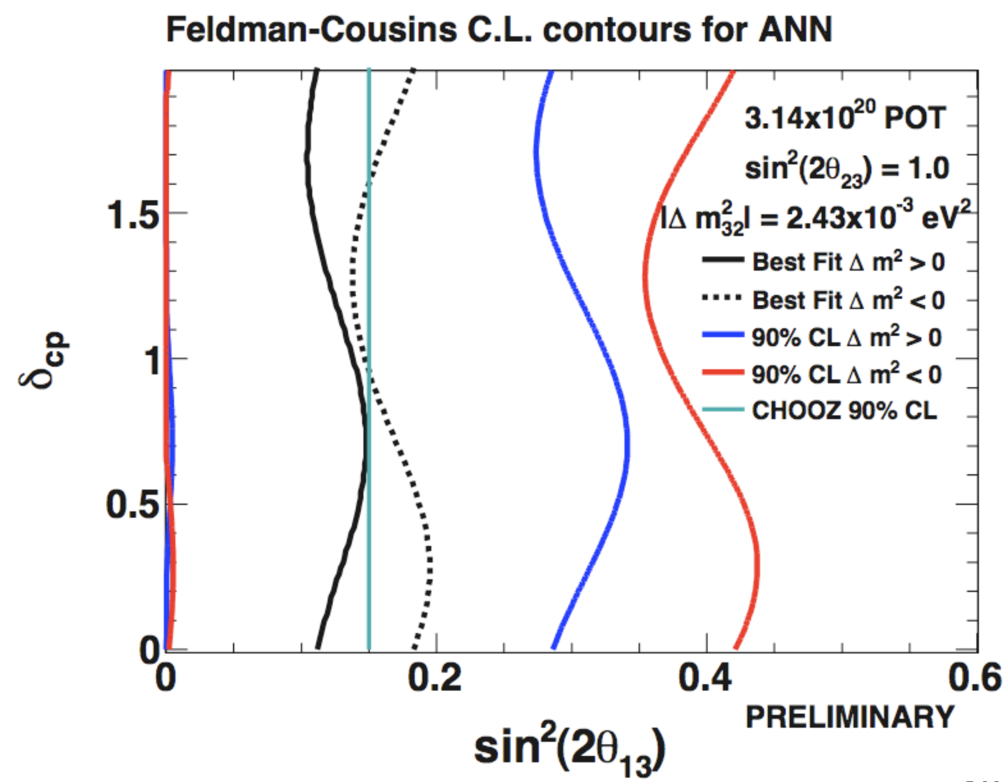
Double Chooz (upgrade with two detectors) aiming for sensitivity to ~0.03

MINOS Results on θ_{13}

- ν beam from NuMI (120 GeV), $E_\nu \sim 3$ GeV. Far detector in Soudan mine, 735 km. 4 kT fiducial.



35 events vs 27 ± 5 ± 2 background



Physics Goals of T2K

- Measure θ_{13}
- Improve measurements of θ_{23} and $|m_{31}^2|$

- *So is this the equivalent of a dedicated experiment to measure V_{ub}?*

Grand Unified Theories

- MNS Matrix:

$$V_{\rm PMNS} = \begin{pmatrix} 0.837e^{-i179^\circ} & 0.544e^{-i173^\circ} & 0.0566e^{i138^\circ} \\ 0.364e^{-i3.86^\circ} & 0.609e^{-i173^\circ} & 0.705e^{i3.45^\circ} \\ 0.408e^{i180^\circ} & 0.577 & 0.707 \end{pmatrix}$$

→ $\sin^2\theta_{\rm atm} = 1, \ \tan^2\theta_\odot = 0.422 \ \text{and} \ |U_{e3}| = 0.0566$

prediction for Dirac CP phase: δ = -46.9 degrees

$J_\ell = -0.0094$

Note that these predictions do NOT depend on *u* and ξ_0

- neutrino masses:

$$u_0 = -0.0593, \quad \xi_0 = 0.0369, \quad M_X = 10^{14} \text{ GeV}$$
$$m_1 = 0.0156 \text{ eV}, \quad m_2 = 0.0179 \text{ eV}, \quad m_3 = 0.0514 \text{ eV}$$

2 parameters in neutrino sector

- Majorana phases $\alpha_{21} = \pi \qquad \alpha_{31} = 0.$

predicting:3 masses,
3 mixing angles, 3 CP Phases

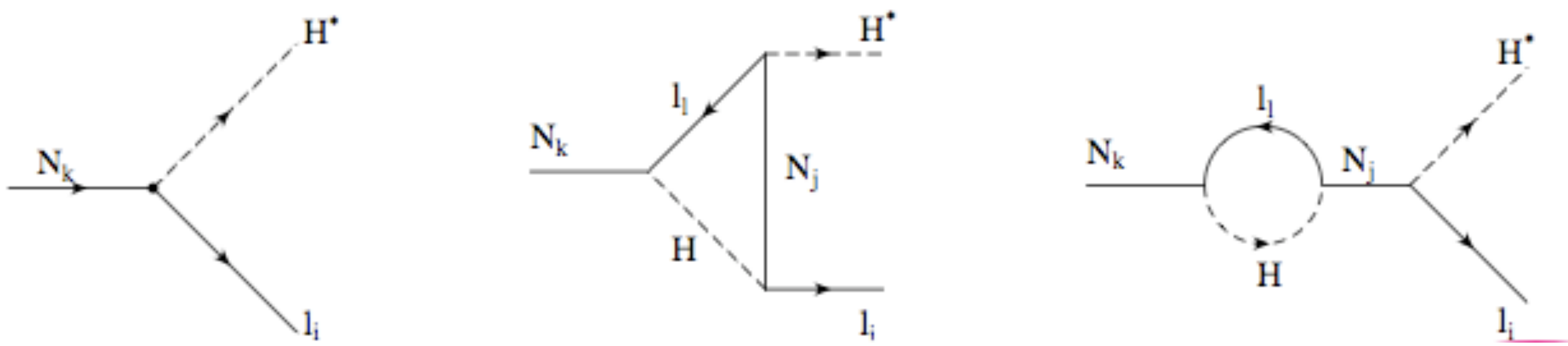
41

Mu-Chun Chen, Phys. Lett. B652 (2007) 34

Leptogenesis

- A CPV measurement could shed light on matter anti-matter asymmetry of the universe.
  - Standard Leptogenesis: decays of RH neutrinos (CPV in decay)

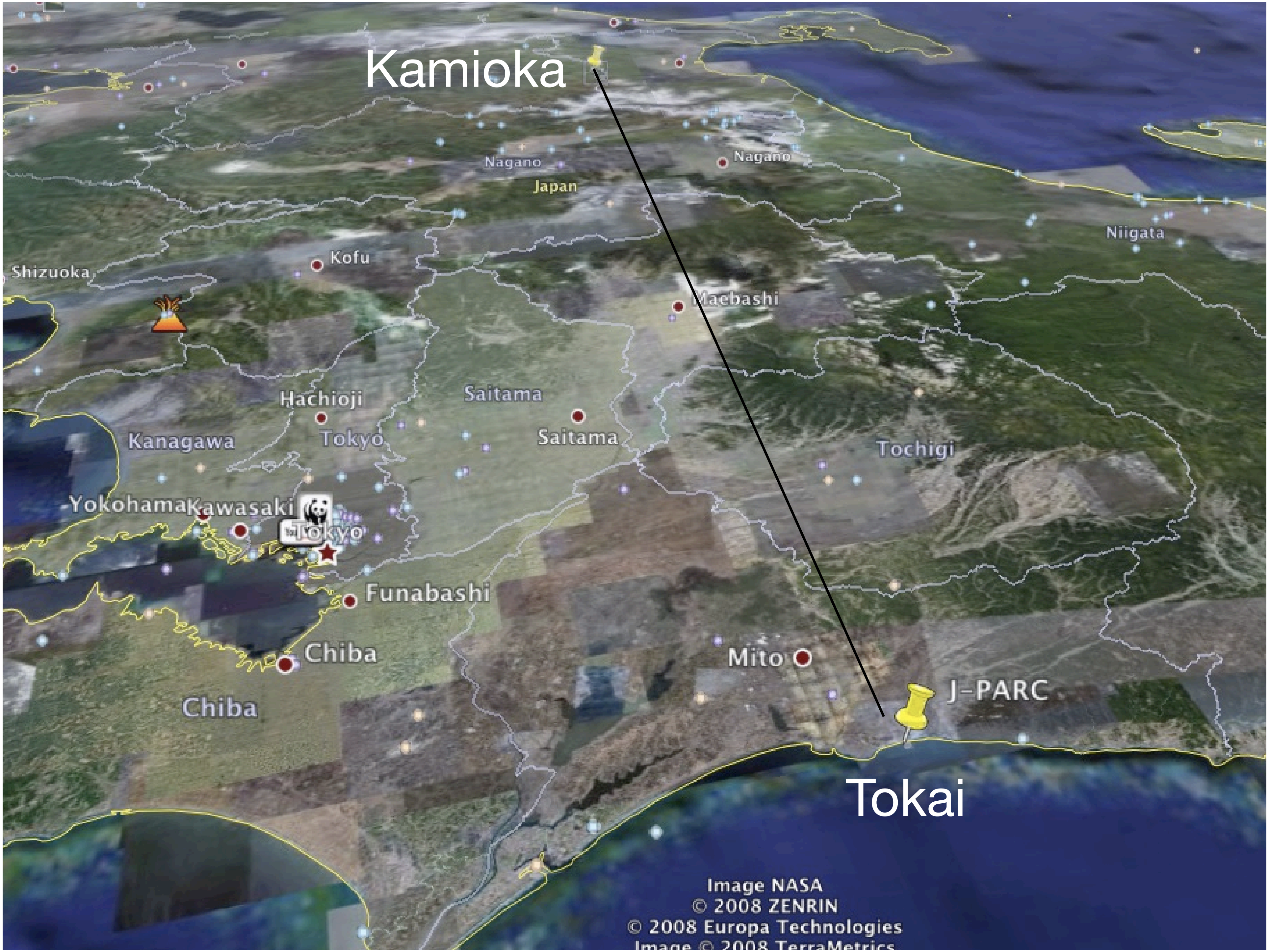
    Quantum interference of tree diagram and one-loop diagram



- There are models in which strong correlations exist between low-energy and high-energy mixing parameters.

M.-C.Chen & K.T. Mahanthappa, Phys. Rev. D71 (2005) 035001

T2K OVERVIEW


Kamioka
Nagano
Japan
Nagano
Niigata
Kofu
Shizuoka
Maebashi
Hachioji
Saitama
Kanagawa
Tokyo
Saitama
Tochigi
Yokohama
Kawasaki
Tokyo
Funabashi
Mito
Chiba
J-PARC
Chiba
Tokai
Image NASA
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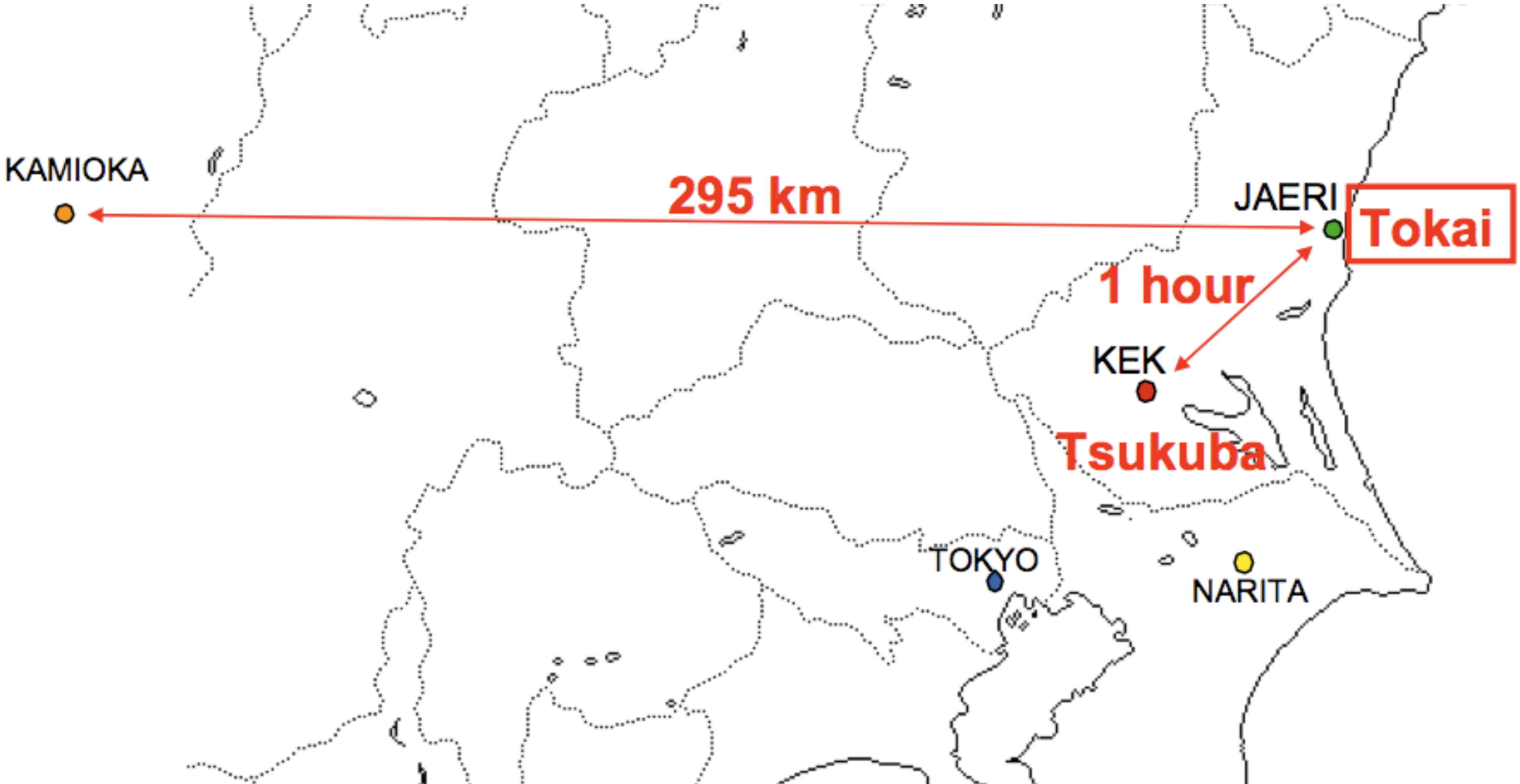
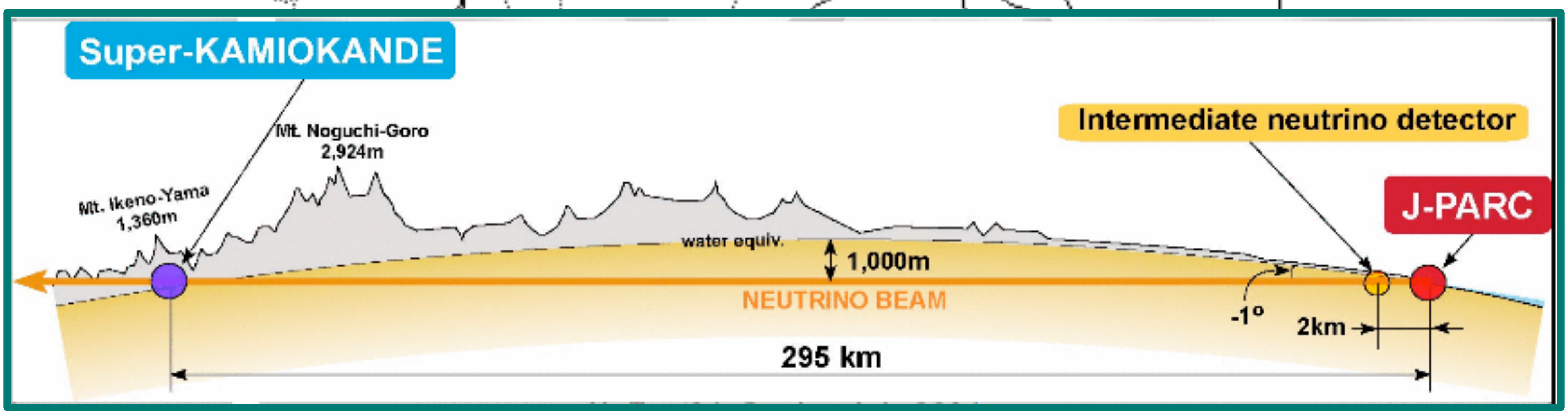
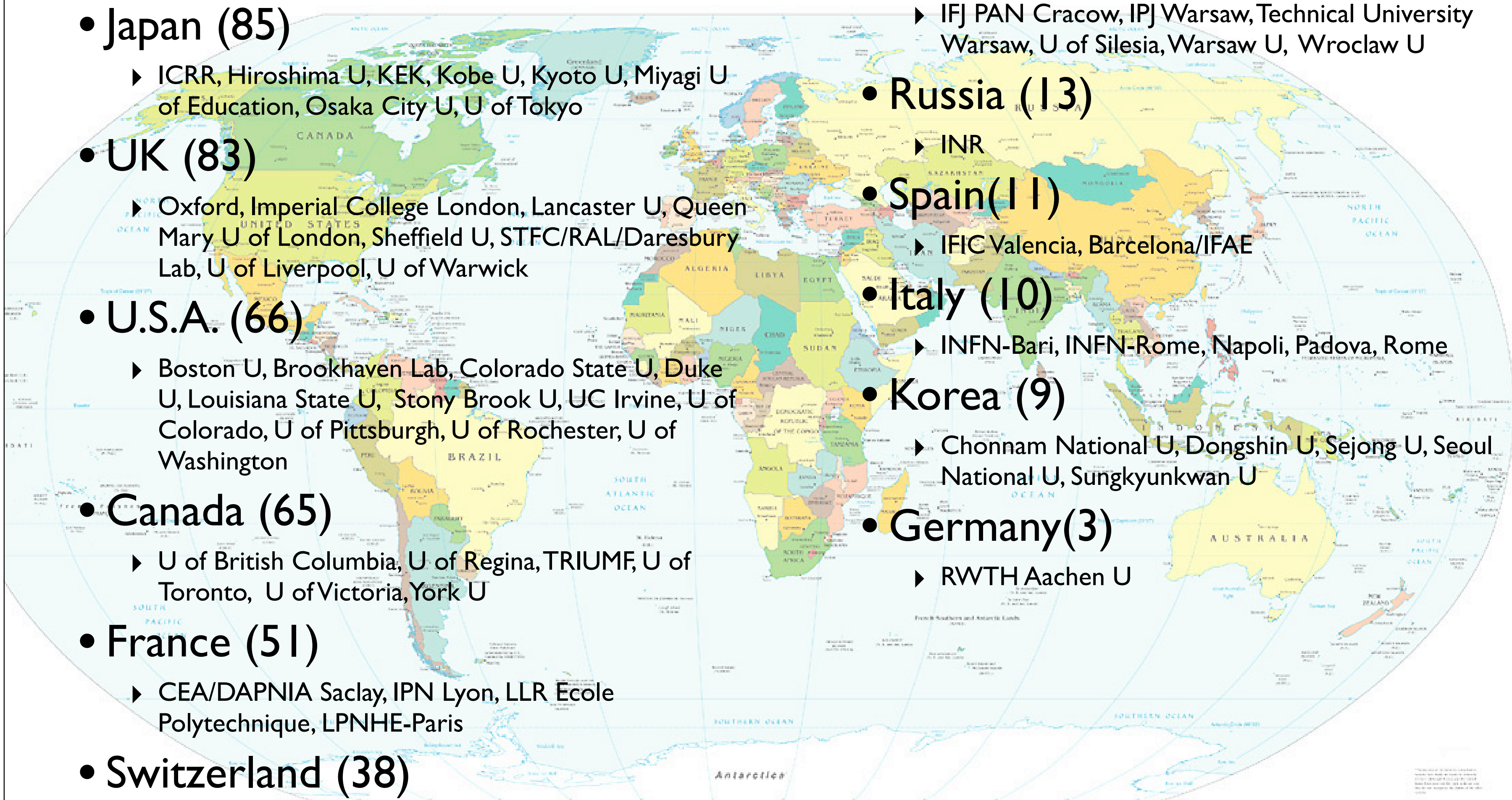

KAMIOKA
295 km
JAERI
Tokai
1 hour
KEK
Tsukuba
TOKYO
NARITA


Super-KAMIOKANDE
Mt. Noguchi-Goro
2,924m
Mt. Ikeno-Yama
1,360m
water equiv.
1,000m
NEUTRINO BEAM
Intermediate neutrino detector
J-PARC
-1°
2km
295 km

T2K Collaboration



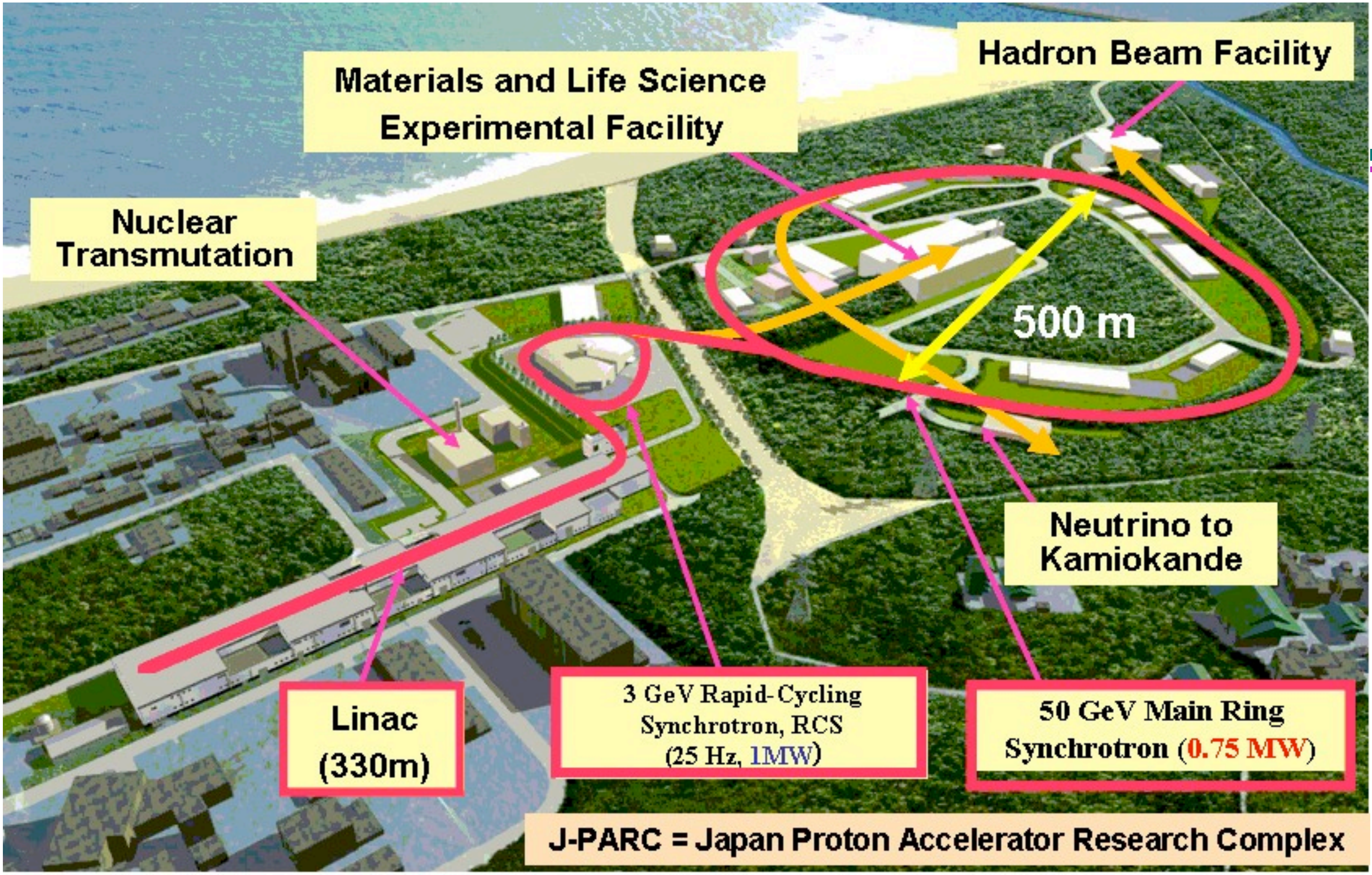
- ~400 people, (290 PhD physicists)
- Japan (85)
  - ICRR, Hiroshima U, KEK, Kobe U, Kyoto U, Miyagi U of Education, Osaka City U, U of Tokyo
- UK (83)
  - Oxford, Imperial College London, Lancaster U, Queen Mary U of London, Sheffield U, STFC/RAL/Daresbury Lab, U of Liverpool, U of Warwick
- U.S.A. (66)
  - Boston U, Brookhaven Lab, Colorado State U, Duke U, Louisiana State U, Stony Brook U, UC Irvine, U of Colorado, U of Pittsburgh, U of Rochester, U of Washington
- Canada (65)
  - U of British Columbia, U of Regina, TRIUMF, U of Toronto, U of Victoria, York U
- France (51)
  - CEA/DAPNIA Saclay, IPN Lyon, LLR Ecole Polytechnique, LPNHE-Paris
- Switzerland (38)
  - Bern, ETHZ, U of Geneva
- Poland(29)
  - IFJ PAN Cracow, IPJ Warsaw, Technical University Warsaw, U of Silesia, Warsaw U, Wroclaw U
- Russia (13)
  - INR
- Spain(11)
  - IFIC Valencia, Barcelona/IFAE
- Italy (10)
  - INFN-Bari, INFN-Rome, Napoli, Padova, Rome
- Korea (9)
  - Chonnam National U, Dongshin U, Sejong U, Seoul National U, Sungkyunkwan U
- Germany(3)
  - RWTH Aachen U

T2K Overview

- Measure θ_{13} using $\nu_\mu \rightarrow \nu_e$ oscillations.
  - » also significantly lower errors on $\sin^2 2\theta_{23}, \Delta m^2_{23}$
- Experiment has three components:
  - » Neutrino beam line, using 30 GeV p from J-PARC
  - » Near detector ND 280
  - » Far detector Super-K

  Not the same technology!
- 1^{st} stage: 100 kW × 10^7 sec [2 × 10^{20} p.o.t.]
  2^{nd} stage: 1 MW × 10^7 sec [2 × 10^{21} p.o.t.]
  full data set: 3.5 MW × 10^7 sec [7 × 10^{21} p.o.t.]

THE J-PARC FACILITY



Joint KEK / JAEA project

Tracks

1. **Godzilla Attacks Tokai - Japan's Energy Crisis** (M2)
2. Fateful Confrontation (M3)
3. Main Title (M4)

Accelerator Chain

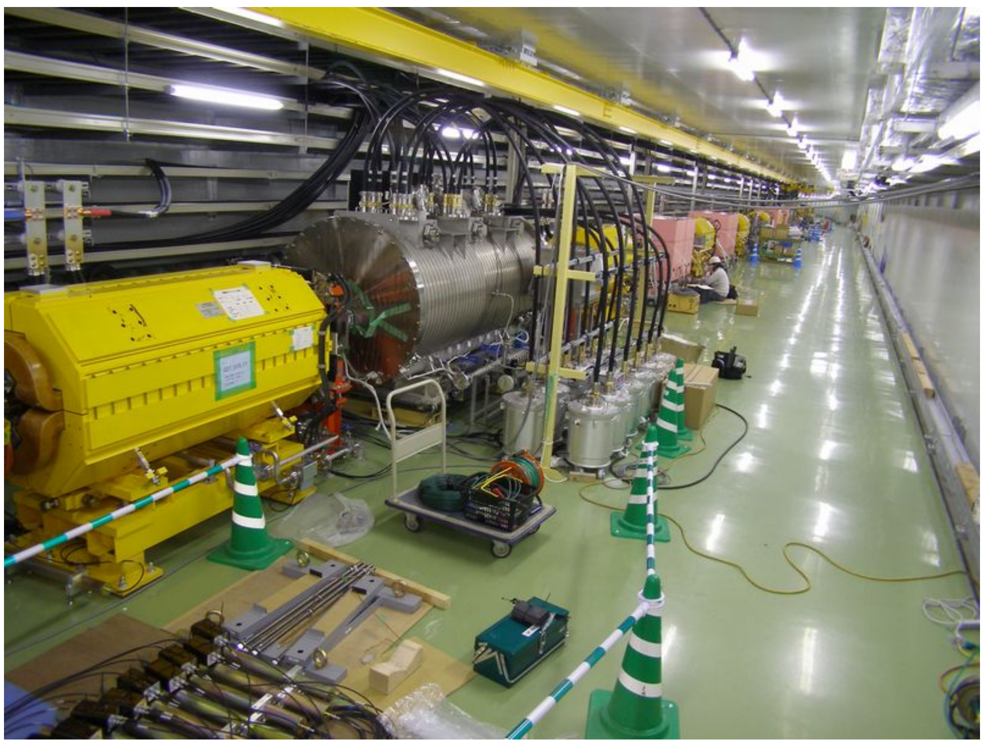
- Linac: Accelerates H^- to 180 MeV

Accelerator Chain

- Rapid-cycling synchrotron RCS: 1 MW of 3-GeV protons (mostly for spallation neutrons)
  - also serves as injector for main ring.

Accelerator Chain

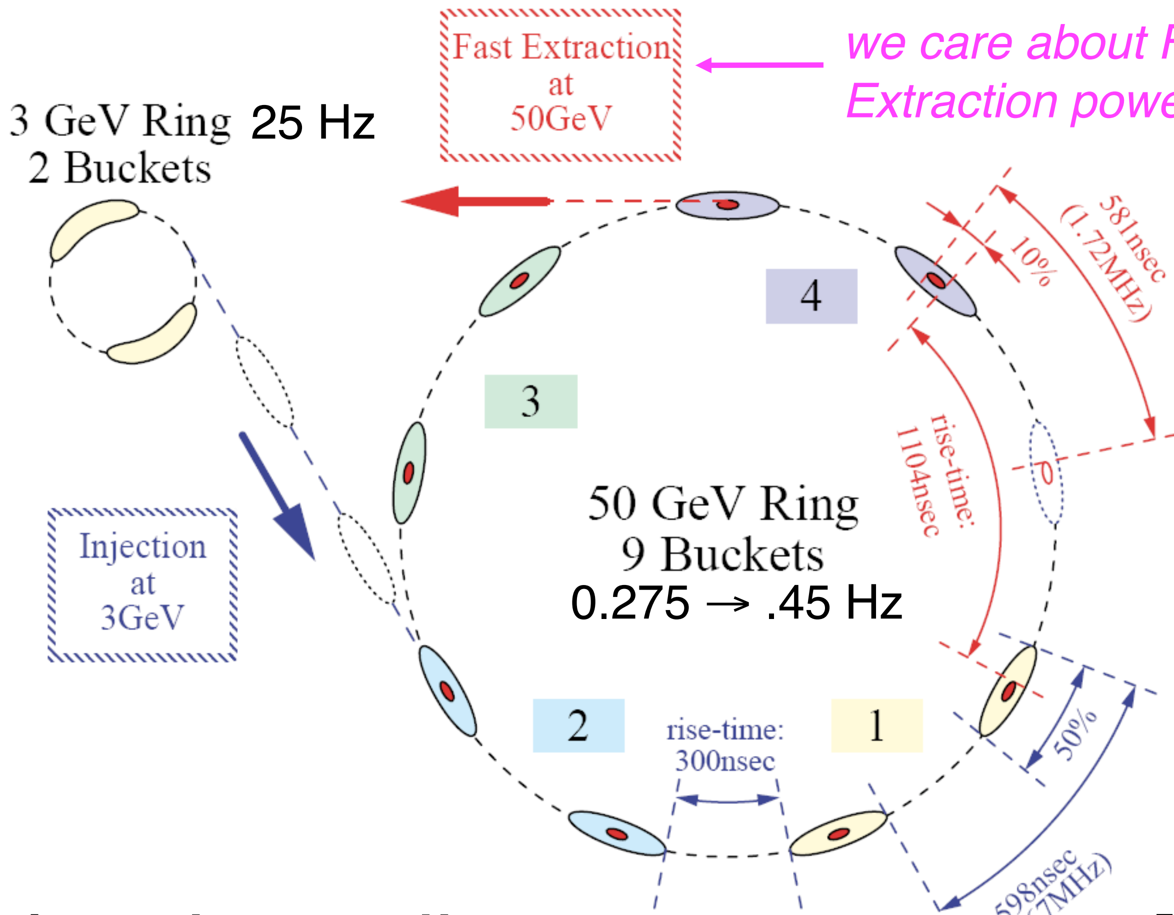
- Main Ring: synchroton accelerates from 3 GeV to 30 GeV. Protons for ν beamline (fast extraction) or for Kaon physics (slow extraction)



Note on Power

normally hear about 3 GeV power "1 MW"

we care about Fast Extraction power



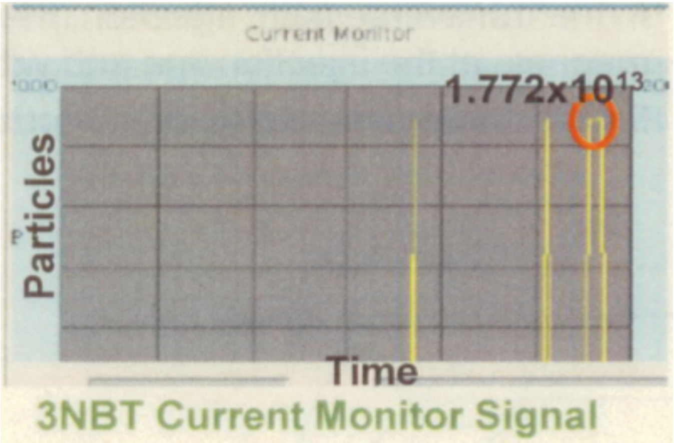
- 6 [8] bunches into ν line every 3.64 sec [2.2 sec]. Power = 0.33 P_{3GeV} [0.75 eventually]

Status


MLF : May, 2008
祝 中性子ビーム生成
J-PARC MLF
MR 3 GeV May, 2008
祝! MR!!!!
MR30GeV 加速成功
MR 30 GeV : Dec., 2008
祝 ハドロンビームライン
ビーム取り出し・輸送成功
Hadron Jan., 2009

Status

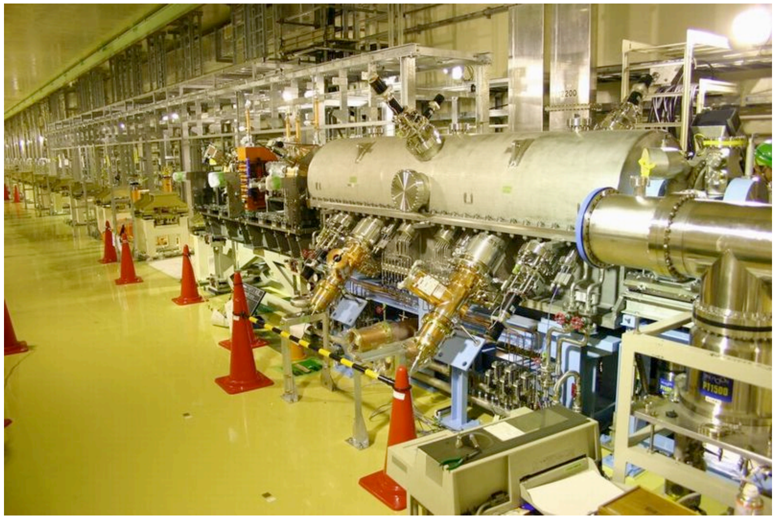
- 3 GeV RCS: 210 kW for 70 sec
  - limited by beam dump license.

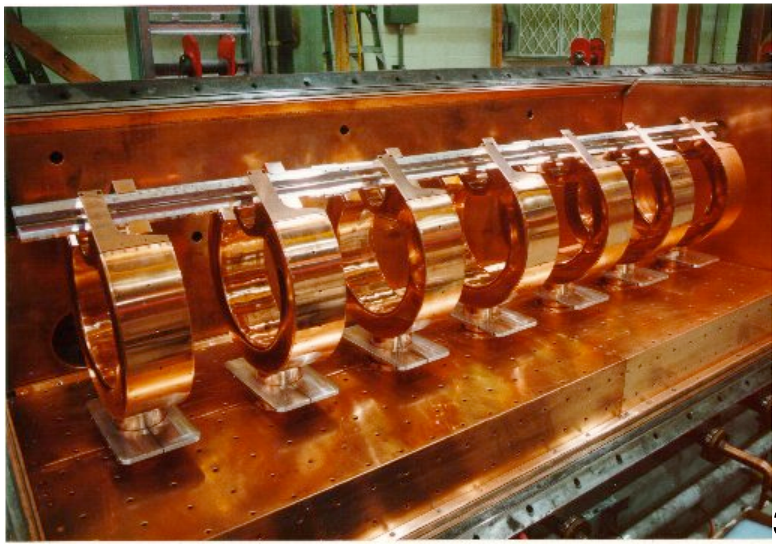


- Single bunch operation of MR at 30 GeV; fast extraction to ν line.
- However, front end of linac (Radio Frequency Quadrupole) is not so healthy…

RFQ Status

- Accelerates H^- to 3 MeV.
- Discharges started in Sept 08. Perhaps related to incorrect copper alloy, and/or inadequate vacuum (protons).





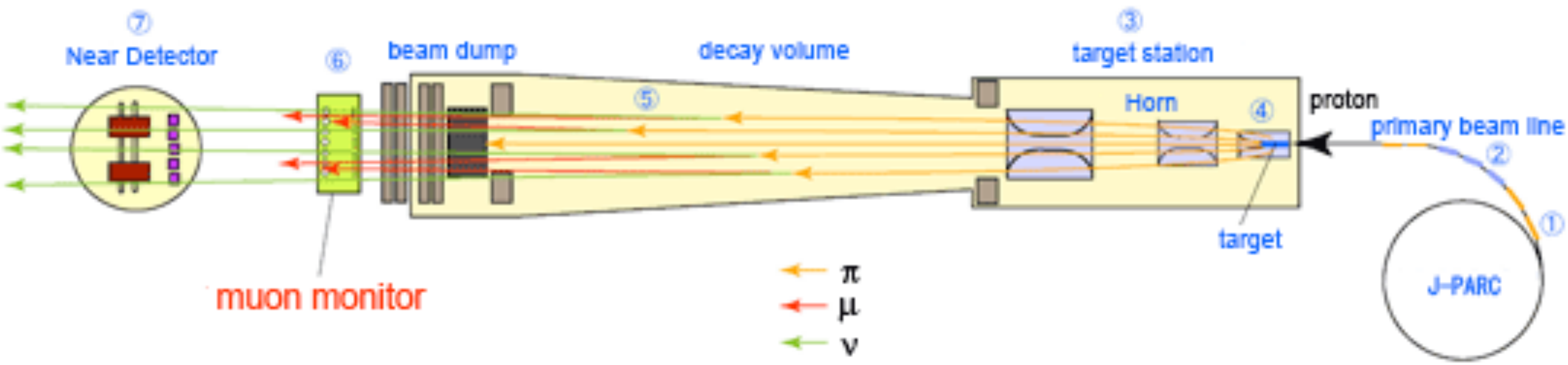
Interior of TRIUMF RFQ

RFQ Status II

- Currently limiting RCS (3 GeV) power to 20 kW
- Conditioning 5 hours per day; stable operation for 19 hours.
- Extra pumping being installed
- Replacement RFQ aimed for Spring 2010.

NEUTRINO BEAM LINE

Target Area

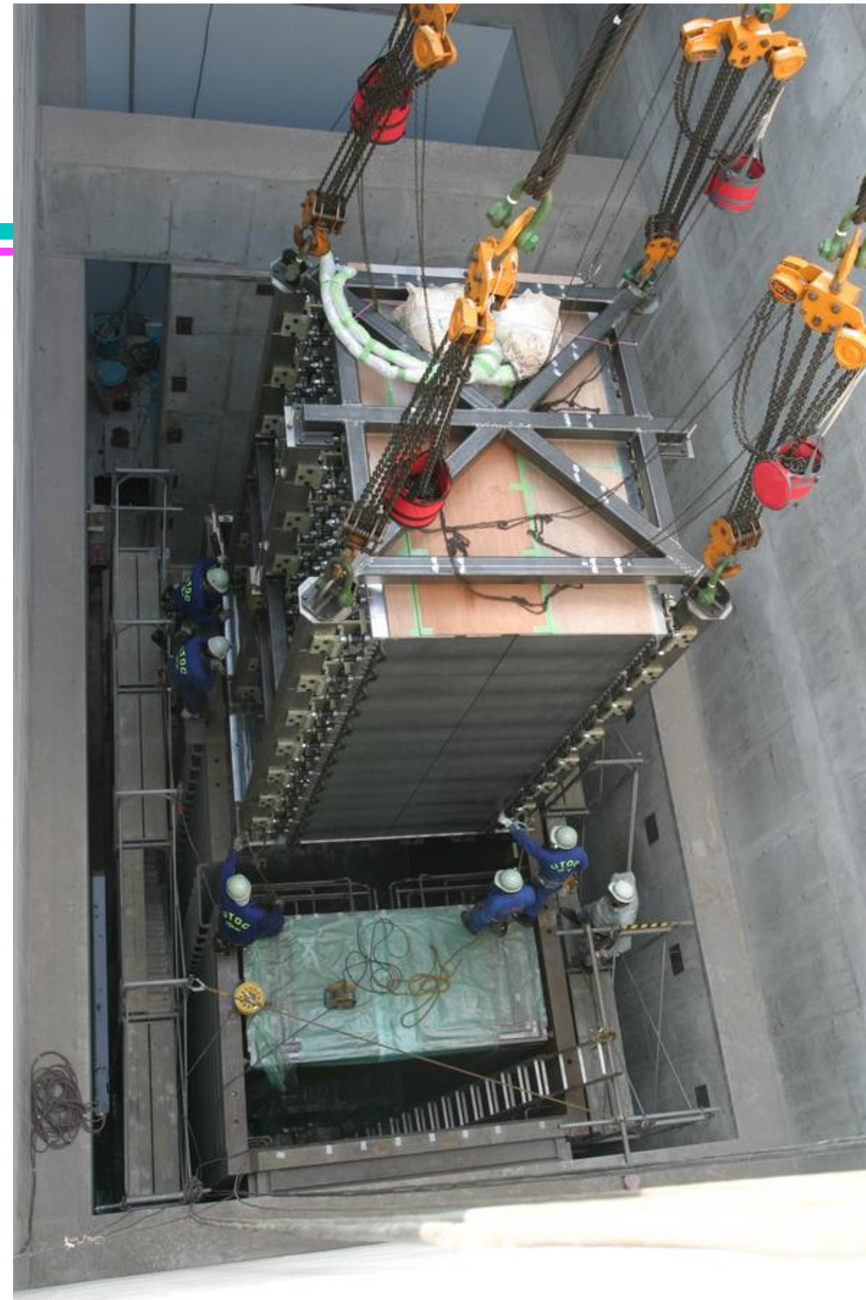


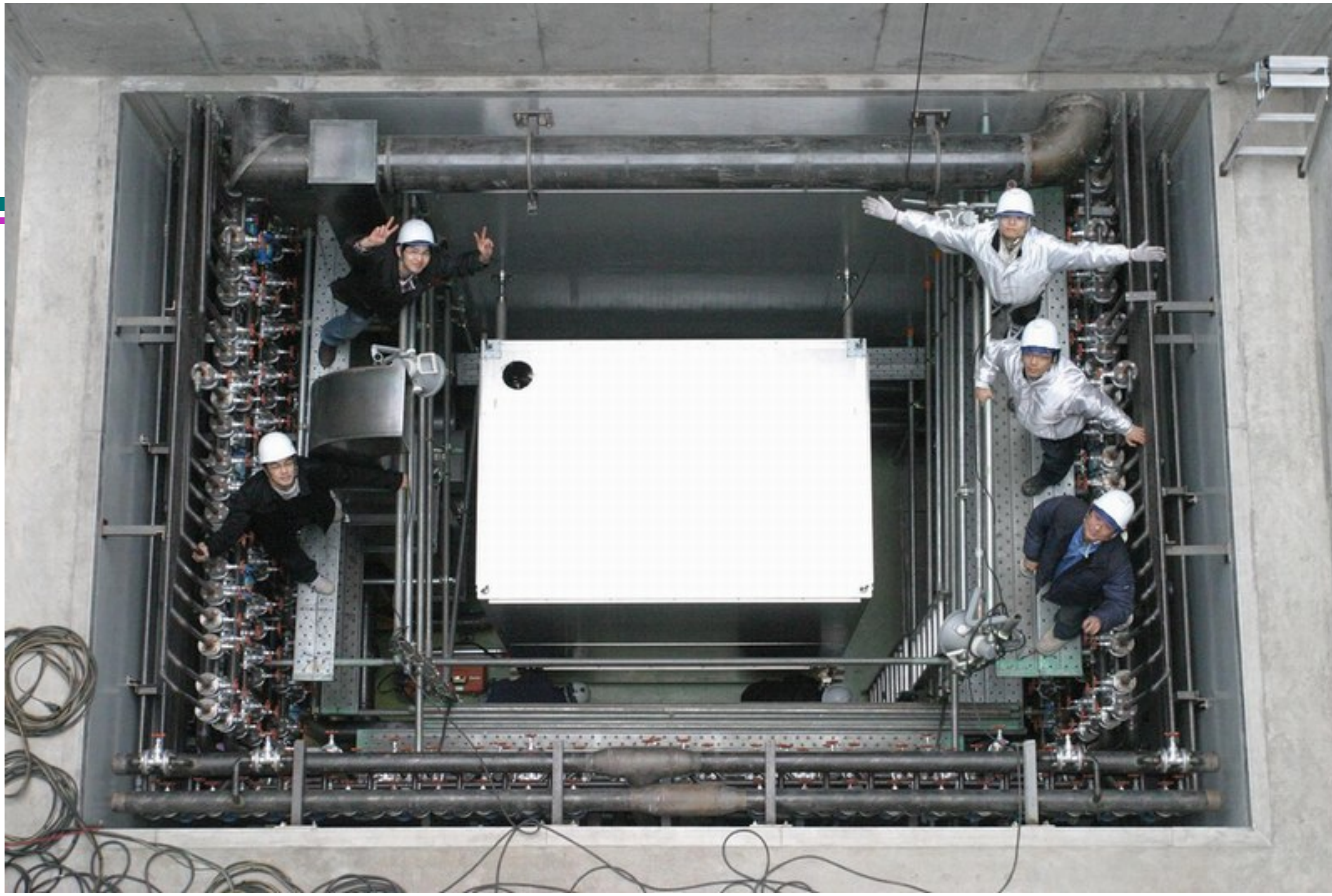
- 30 GeV protons strike 90 cm graphite target, creating $\pi^{\pm}$ and $K^{\pm}$.
- Three horns focus π^{+}, defocus π^{-}
- $\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$ in 110 m decay volume
- Muon monitor follows beam dump.

2^{nd} Horn

Inside the decay volume

Beam Dump



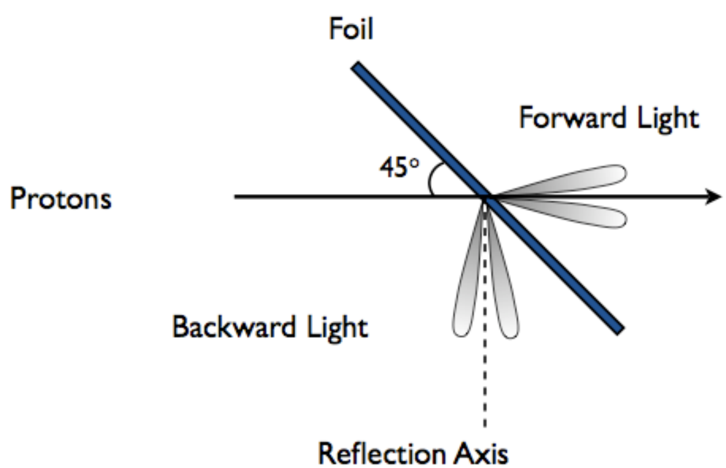


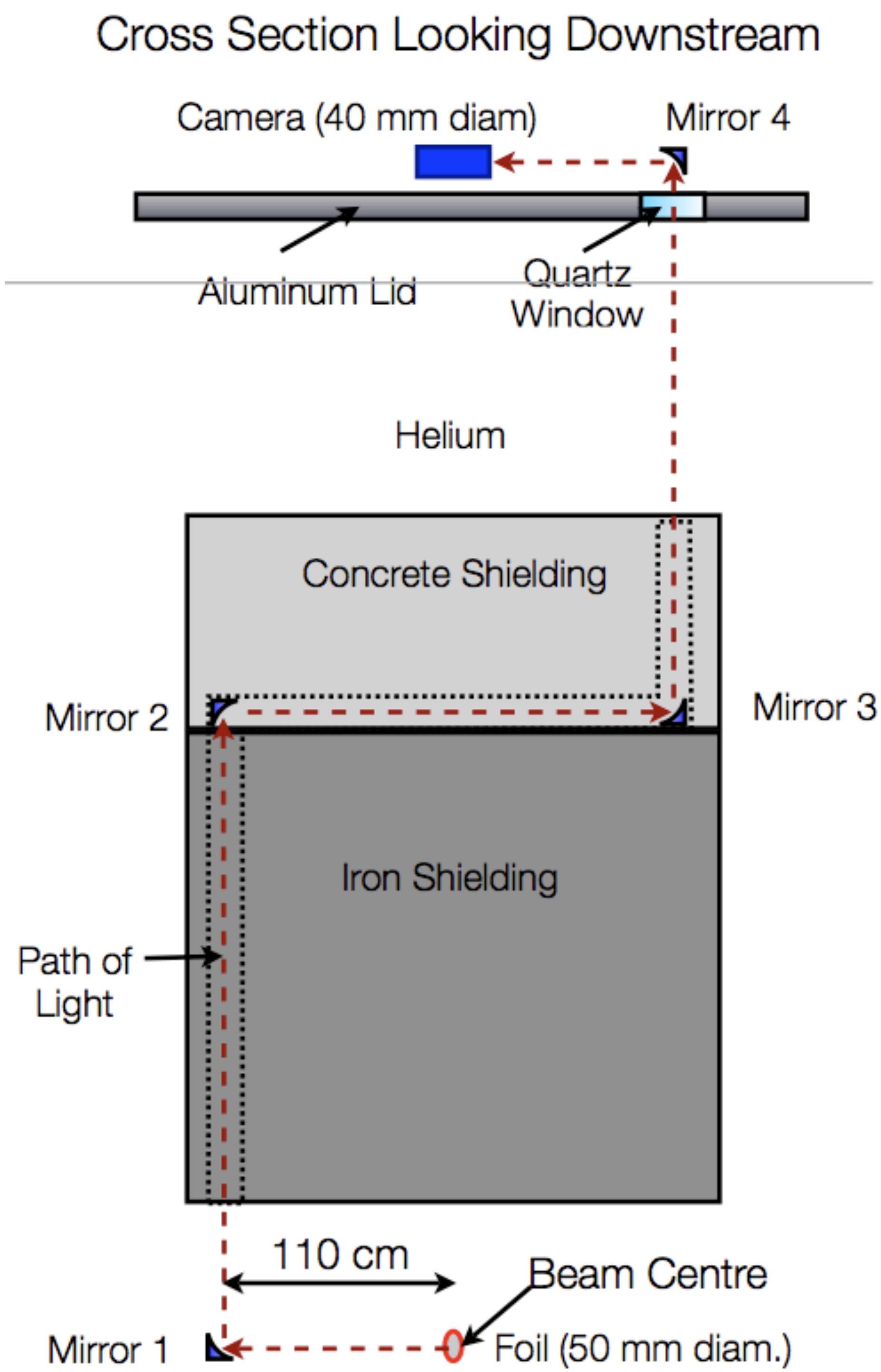
Muon Monitor

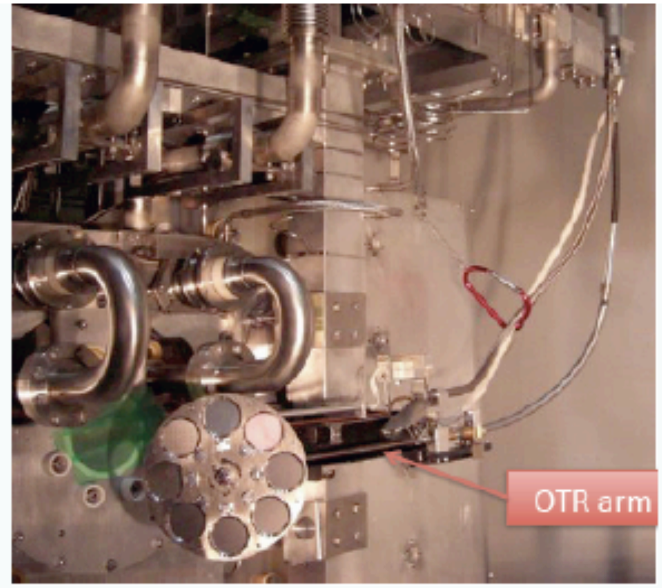
10^8 μ/cm^2/spill at full power
(after beam dump)

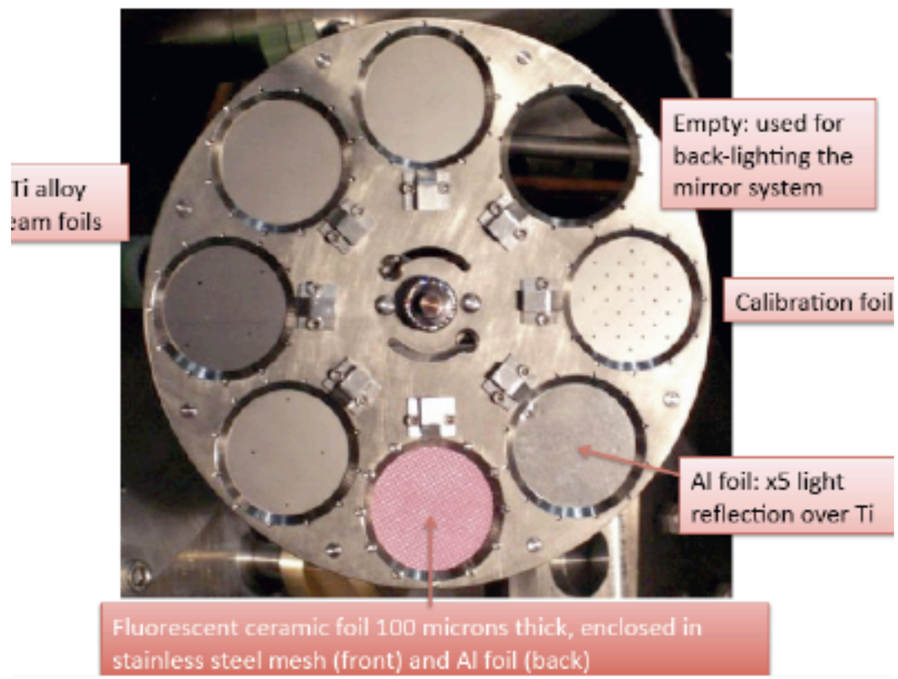
Monitoring the Beam Location

- Horns focus point-to-direction. Need to monitor beam location to ~1 mm to ensure correct ν beam direction.
- Optical Transition Radiation detector immediately in front of target.



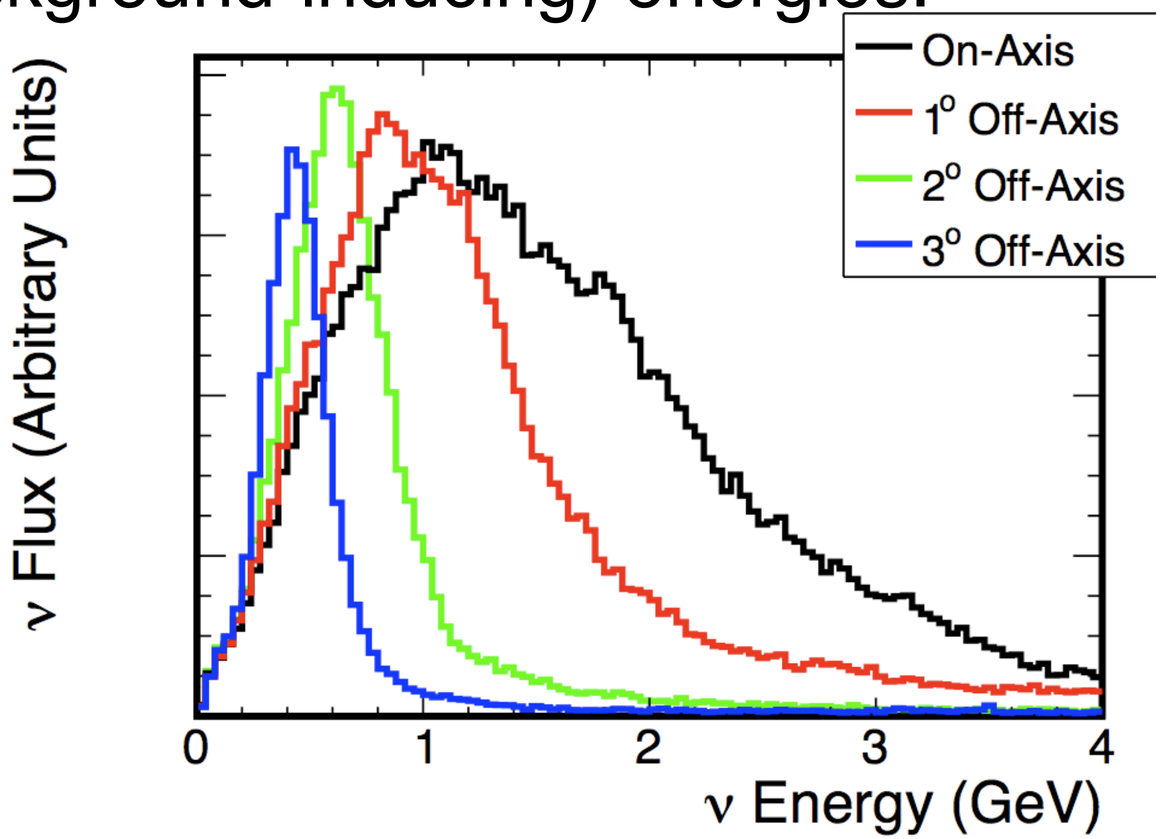

Cross Section Looking Downstream
Camera (40 mm diam)
Mirror 4
Aluminum Lid
Quartz Window
Helium
Concrete Shielding
Mirror 2
Mirror 3
Iron Shielding
Path of Light
110 cm
Beam Centre
Mirror 1
Foil (50 mm diam.)


OTR arm


Empty: used for back-lighting the mirror system
Calibration foil
Al foil: x5 light reflection over Ti
Fluorescent ceramic foil 100 microns thick, enclosed in stainless steel mesh (front) and Al foil (back)

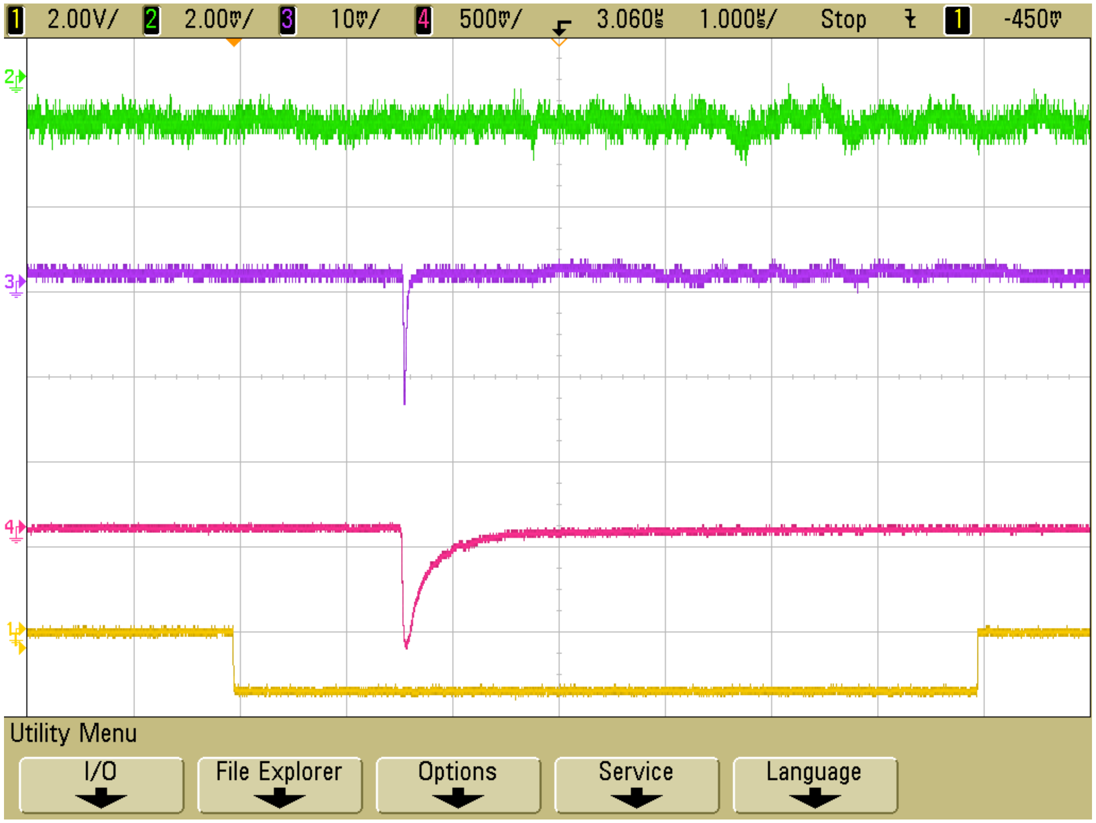
Off Axis Beam

- Super-K is 2.5° off the ν beam direction
  - higher flux at energy of interest; lower flux at higher (background-inducing) energies.



Status

- First beam on target April 23, 2009



signal in muon monitor

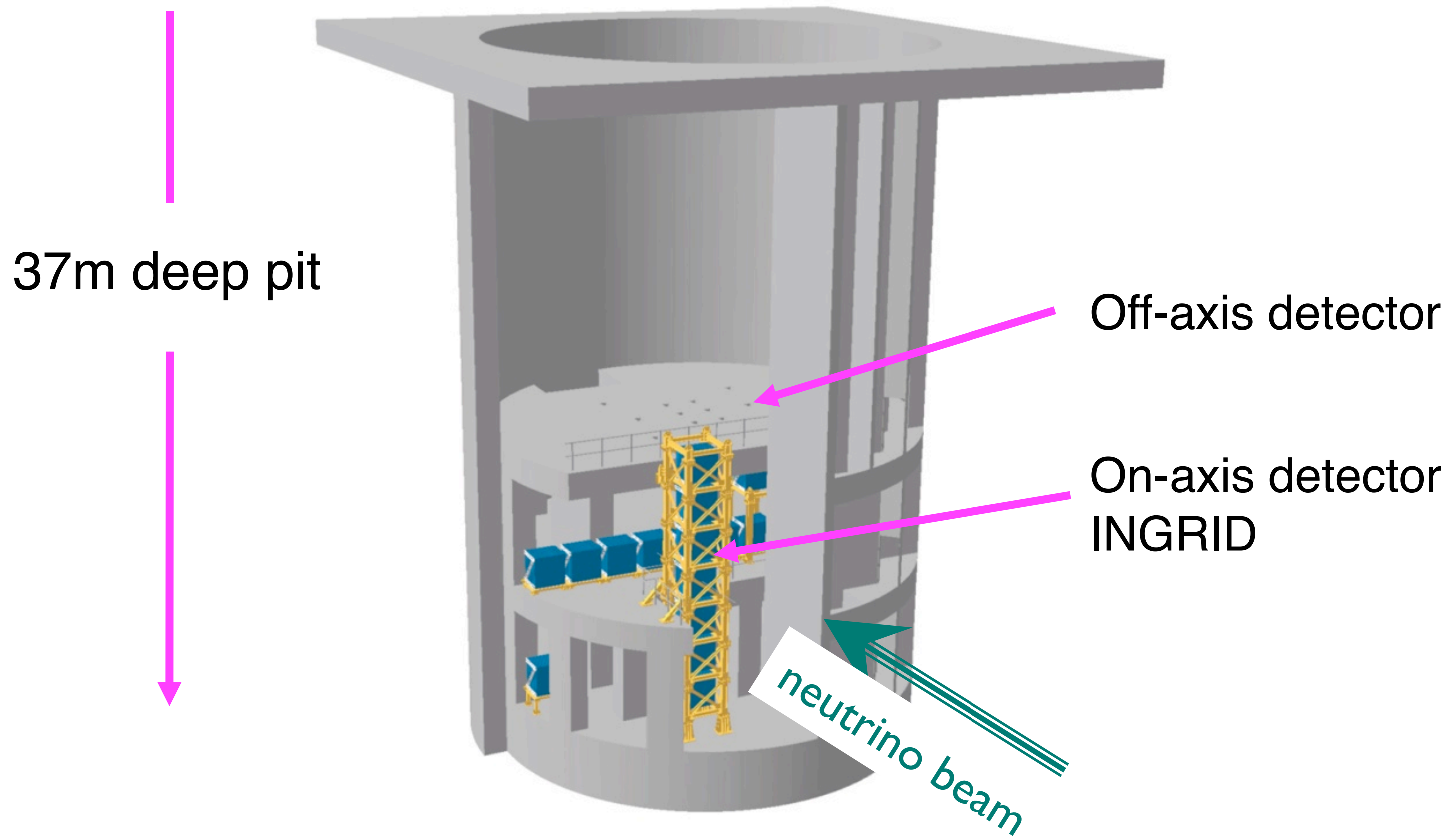
Commissioning

- Commission with low intensity, single pulses until official government inspection on May 28.
  - activation
- 2nd and 3rd horns then installed over next four months. Last remaining major components.
- Commission at higher power in the fall.

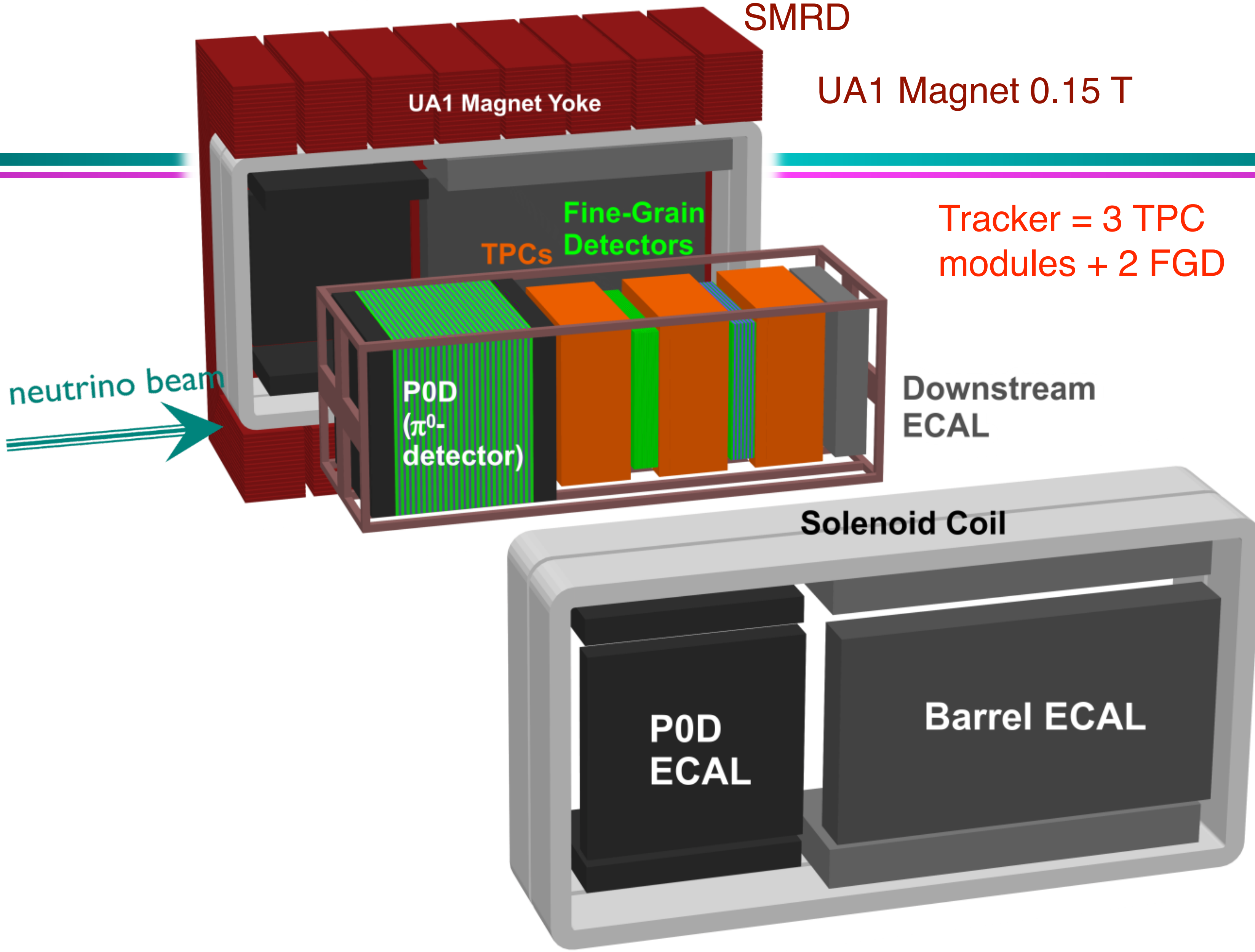
NEAR DETECTOR

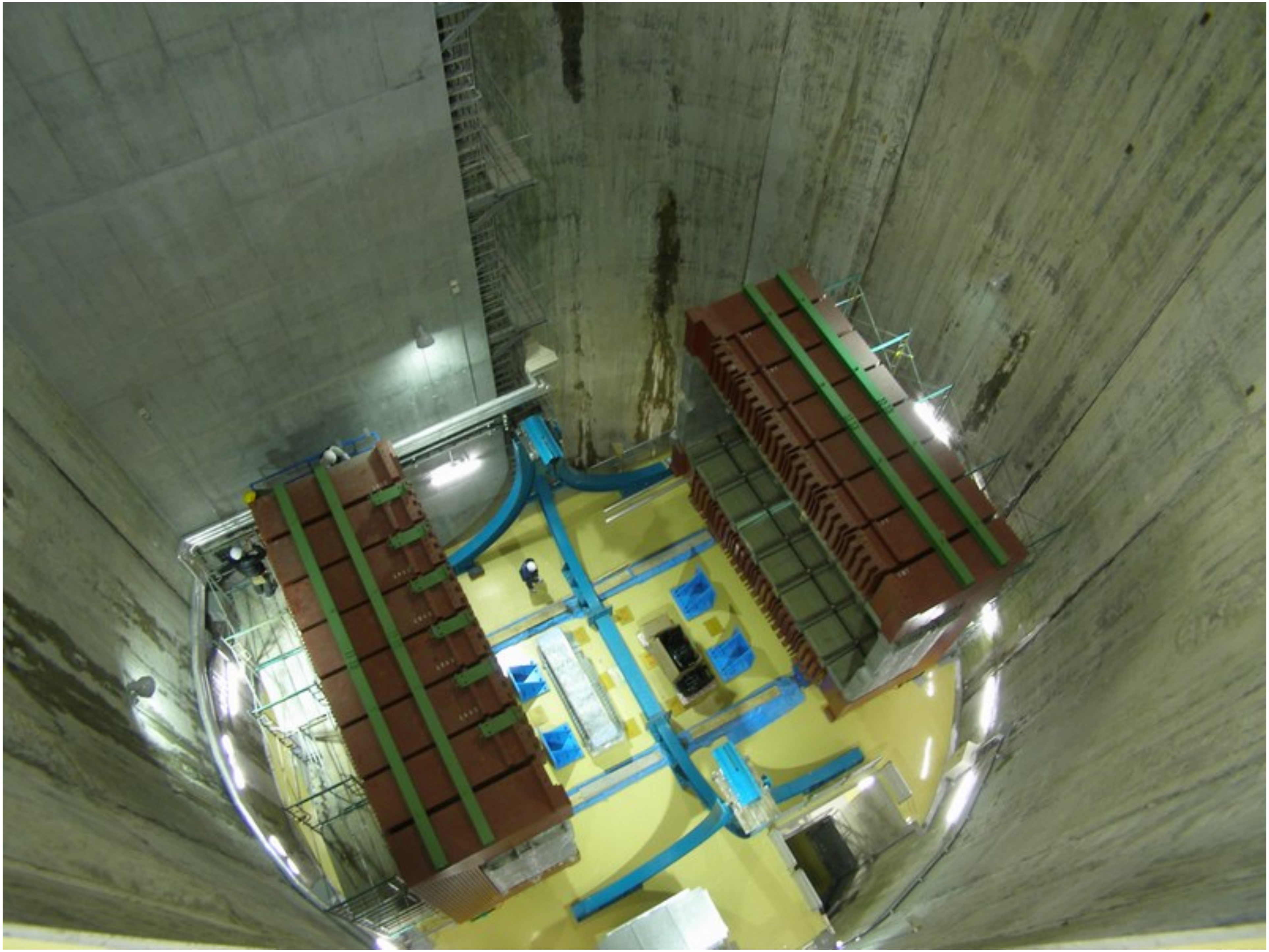
ND 280

- On- and off-axis detectors 280 m from target



Off Axis Detector





Goals of the Near Detector

- Measure ν beam direction
- Determine ν_μ flux and energy spectrum
- Study backgrounds to ν_e appearance (θ_{13})
- Study backgrounds to ν_μ disappearance

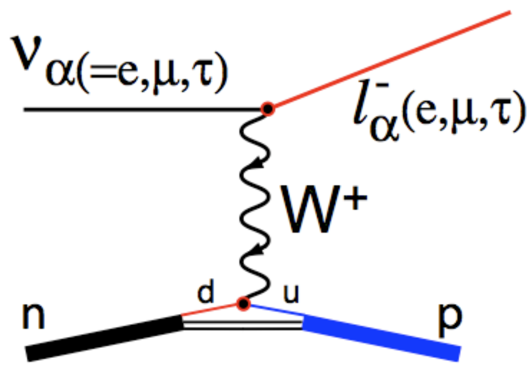
Ingrid – On-Axis Detector

- 16 modules × 10 tons; 10^5 interactions/day at full power ⇒ ~1 mrad precision on beam direction in a day.

scintillator bars/WLS fiber /iron layers/
Hamamatsu MPPC readout

Quasi-elastic ν Interactions

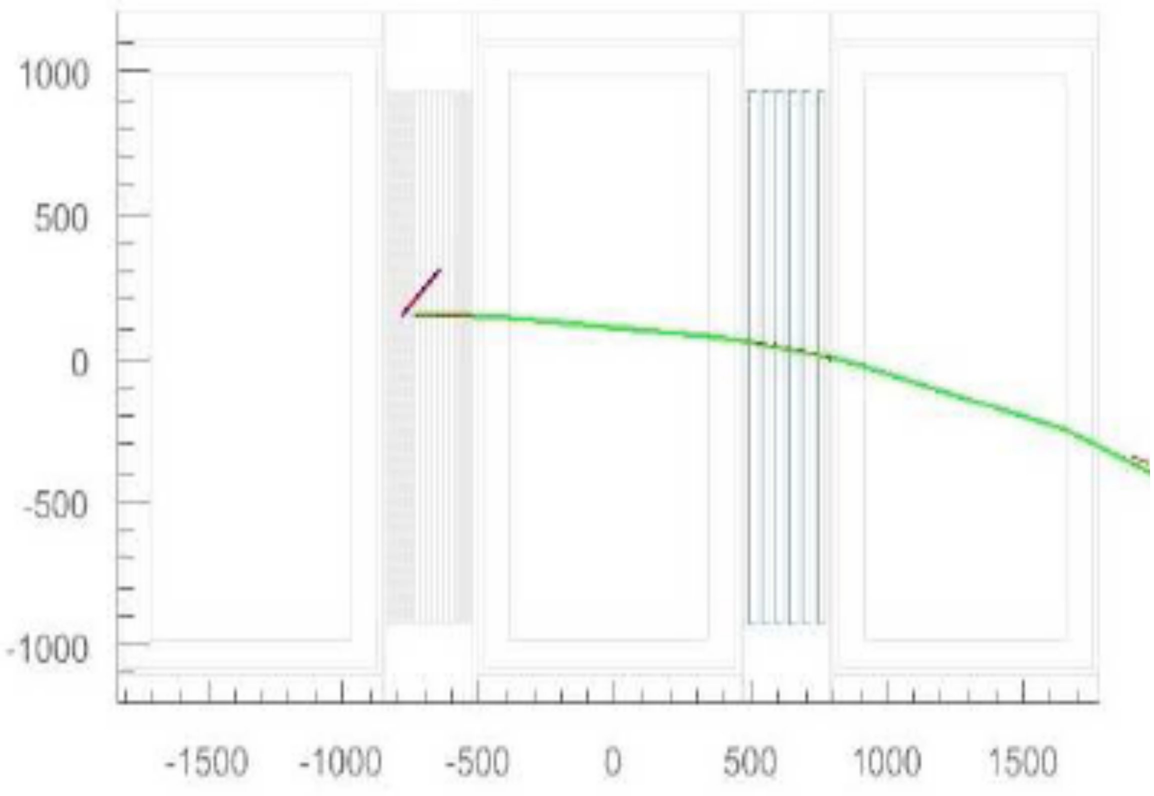
- "Golden Mode" for flux measurements: charged-current quasi-elastic CCQE $\nu\, n \rightarrow p\, \ell^-$

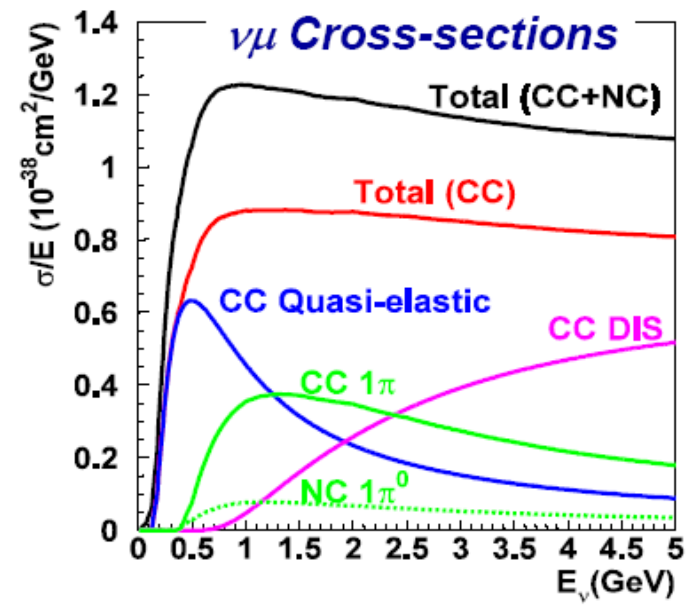


- lepton θ + momentum ⇒ neutrino energy, assuming target is at rest.
  - Not quite true — Fermi motion.

Simulated CCQE neutrino interaction:

$$n + \nu_\mu \rightarrow p^+ + \mu^-$$





Flux Measurements

- ~30k CCQE events in Tracker (FGD + TPC) fiducial volume in initial data set.
- Main background: charged current events with extra π^+ (often through Δ resonance)
  - » skewed kinematics
  - » constrain with proton angle
- ν_e ~0.5% of beam at ~0.6 GeV (oscillation maximum)

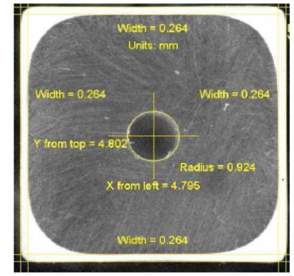
Backgrounds to Measurement of θ_{13} Using ν_e Appearance

- Intrinsic ν_e component of beam
- Neutral current production of π^0
  - $\nu_\mu N \to \nu_\mu \pi^0 N$
  - one photon is missed, other looks like an electron.
  - typically from neutrinos with energies above oscillation maximum.

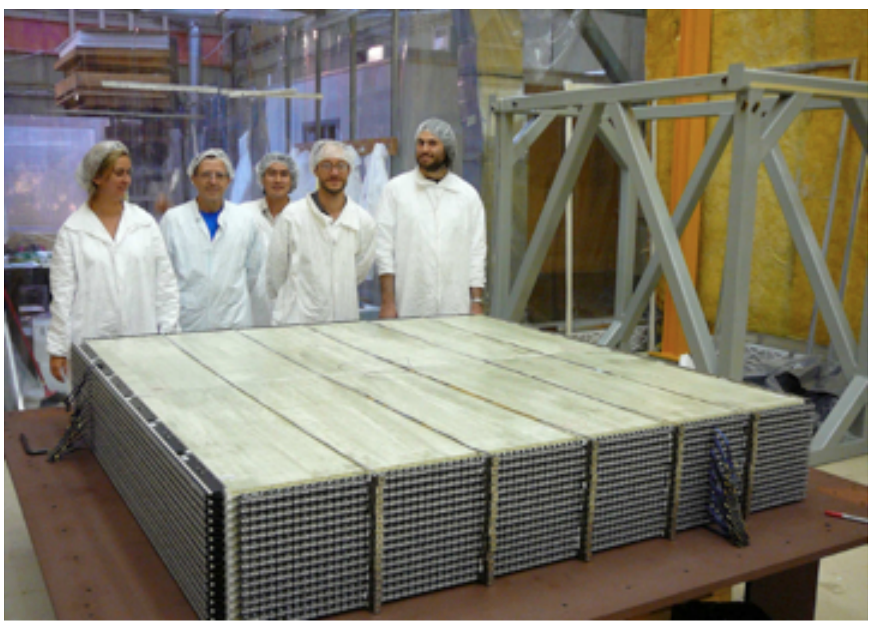
Nuclear Effects

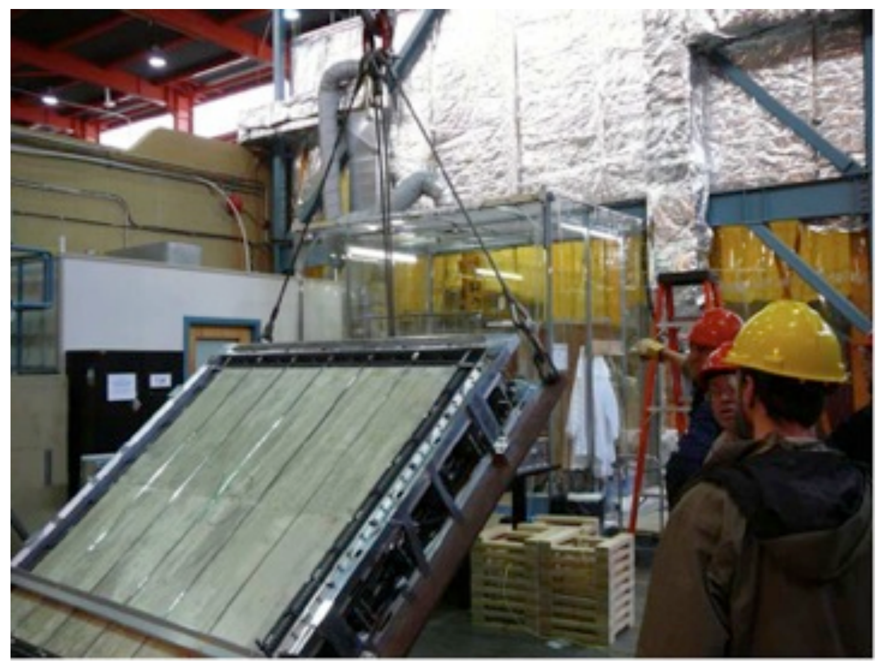
- Non-negligible hadronic interactions in nucleus.
  - rescattering, absorption, charge exchange
  - π^- mostly result from such interactions.
- Neutrino cross sections are not well known at these energies, so measure flux × cross section on water.

Fine Grain Detector — FGD



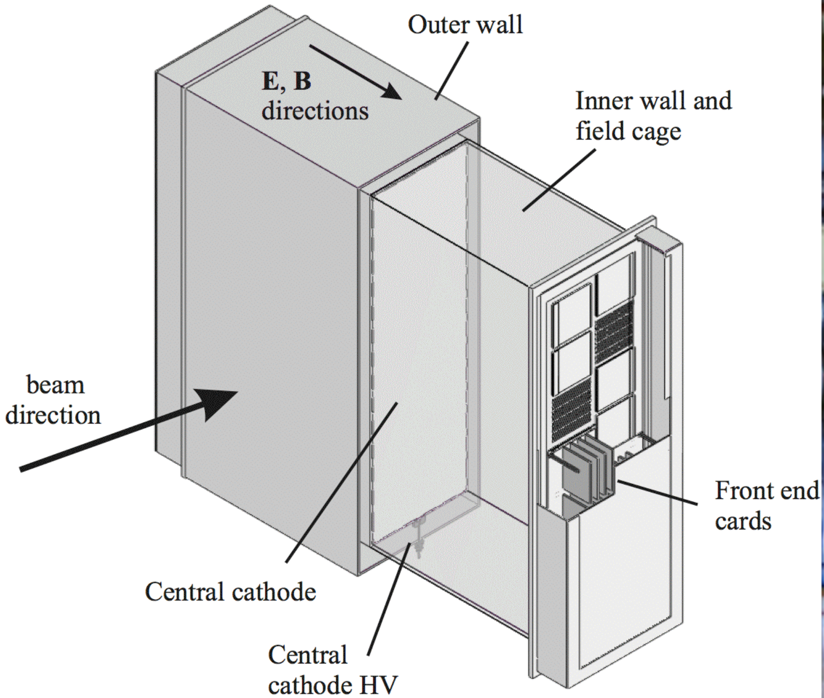
- Two modules, each ~1 ton.
  - 1 cm extruded scintillator bars/WLS/MPPCs
  - 2nd module also has water layers.
  - small bars ⇒ good proton reconstruction.



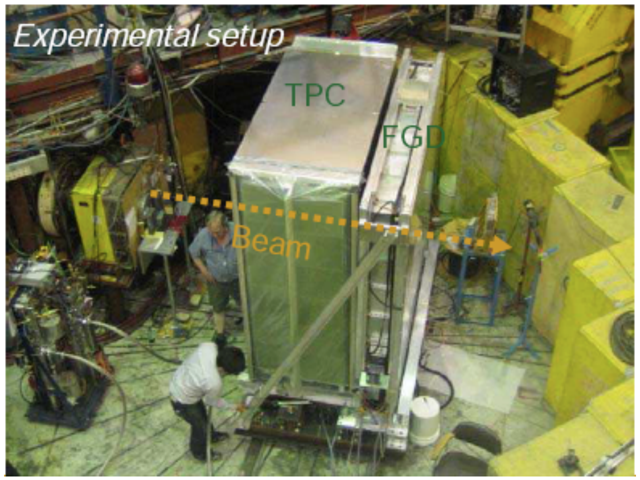


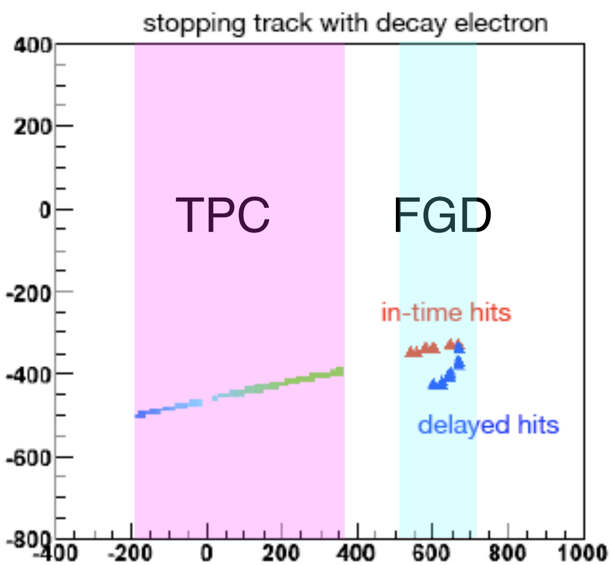
TPCs

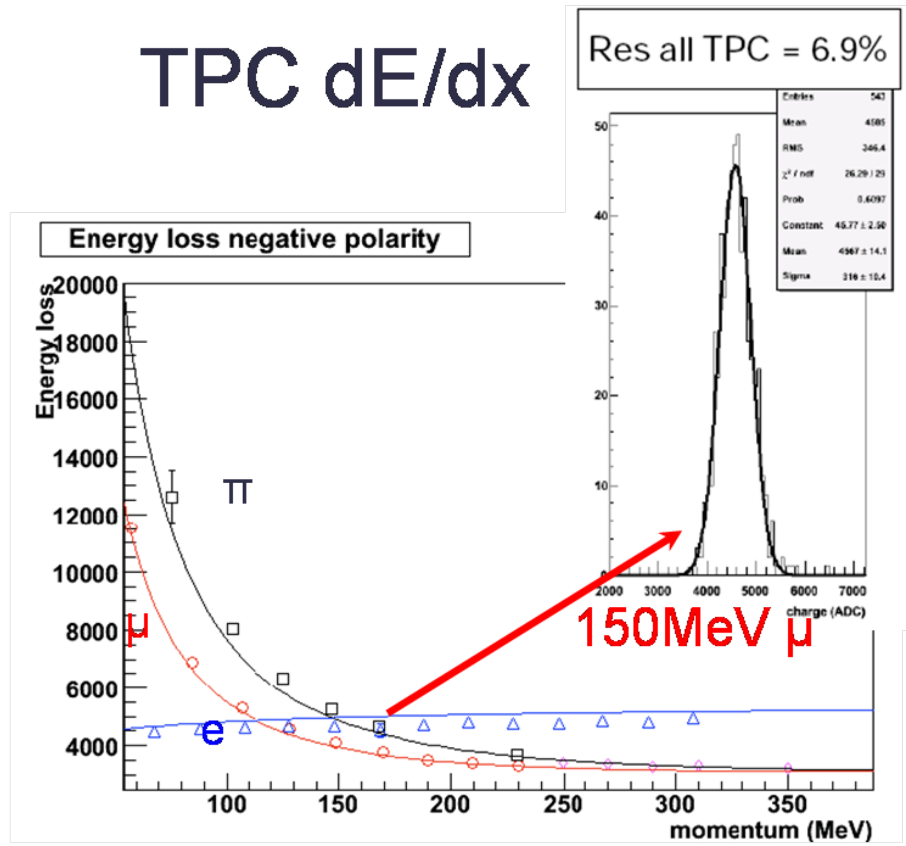
- Three rectangular TPCs with micromegas readout.
  - $\delta p/p$ ~10% at 1 GeV is adequate (Fermi motion)
  - Need to know momentum scale to 2%; distorts ν energy spectrum.
  - dE/dx gives >3σ μ/e separation 0.3–1 GeV


Outer wall
E, B
directions
Inner wall and
field cage
beam
direction
Front end
cards
Central cathode
Central
cathode HV

Tracker Beam Test at TRIUMF





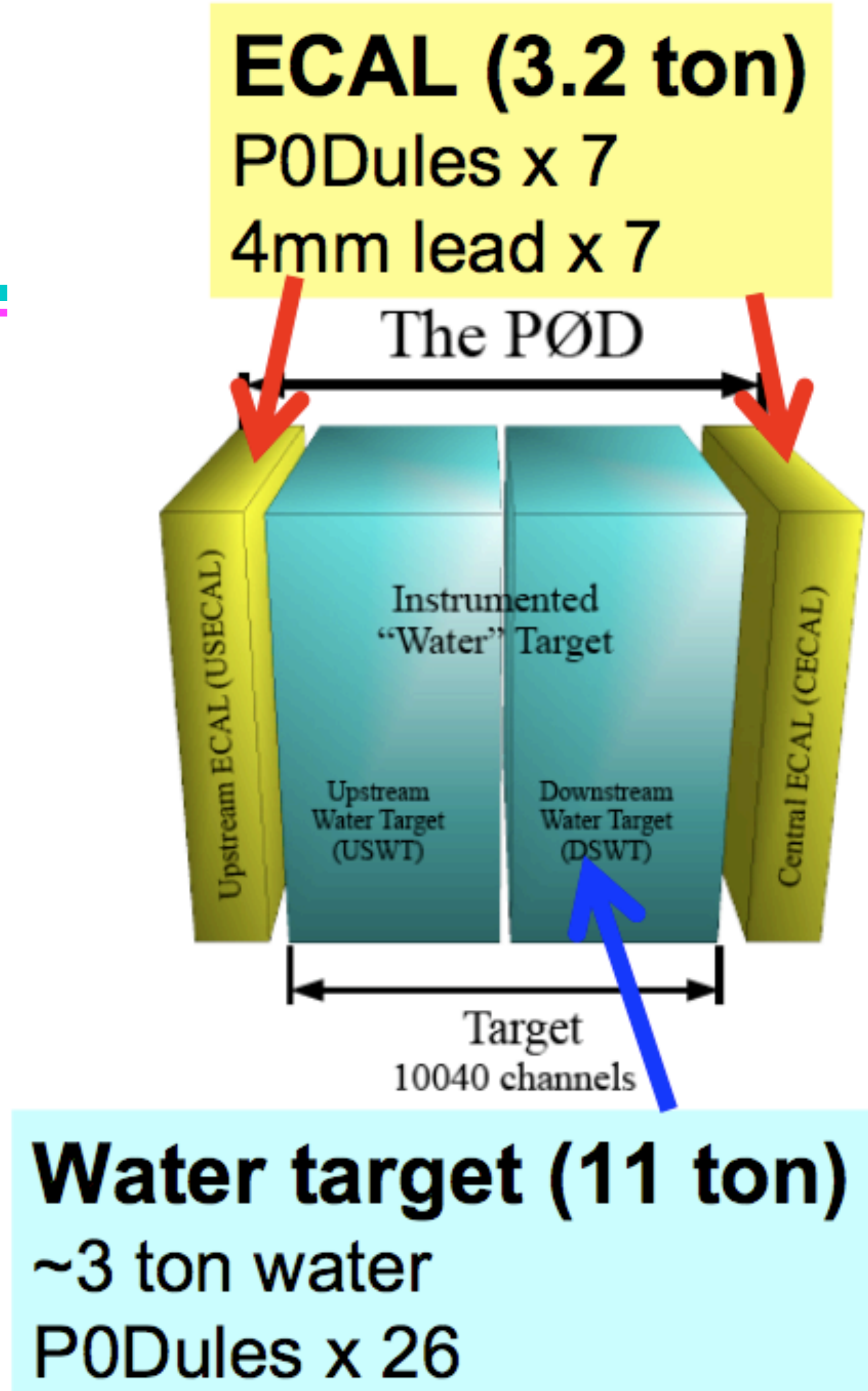


>5σ separation of e/μ for p>200MeV

Performance as expected

P0D

- Optimized to measure neutral current π^0 production on water.
- Triangular scintillator bars/WLS fibers/lead/water



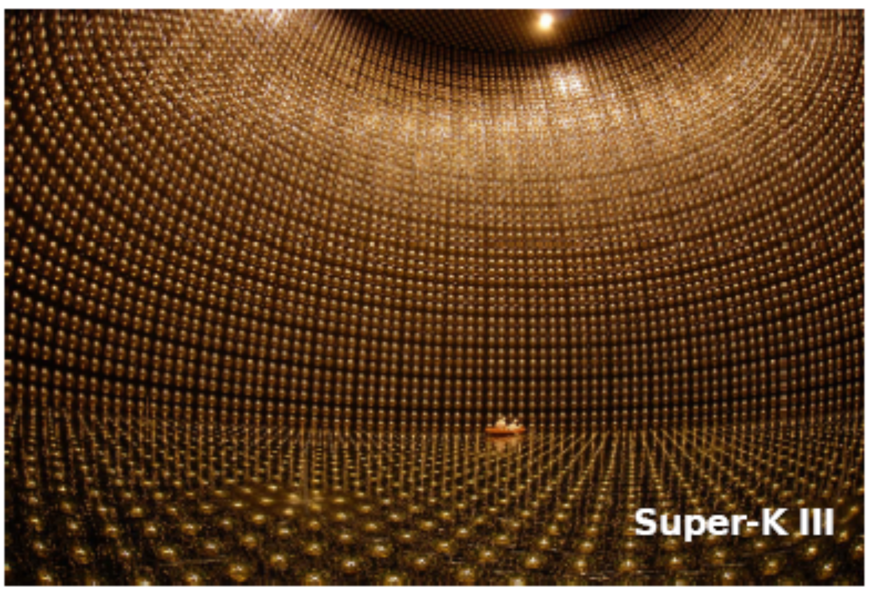
ND 280 Status

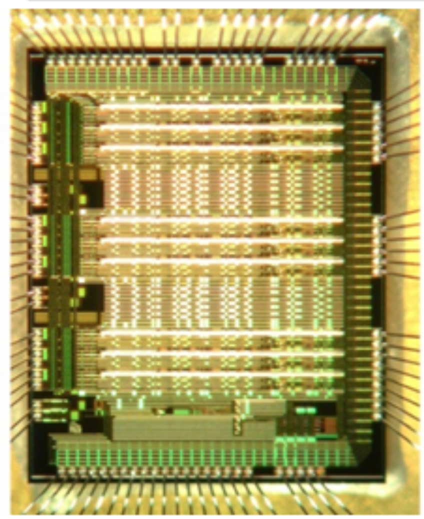
- Infrastructure installation in progress
- Magnetic field mapping in July
- P0D, FGD, downstream ECAL and two TPCs will arrive by July and be installed early October.
  - 3rd TPC should arrive December.
  - Full side (barrel) ECAL in Summer 2010.

FAR DETECTOR

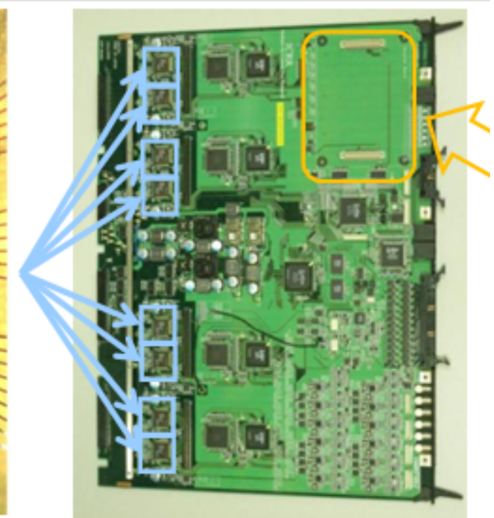
Super-K

- Large water Cherenkov detector: 50 kT total, 22.5 kT fiducial.
- In operation since 1996; SK-IV started Sept 08 with new electronics.





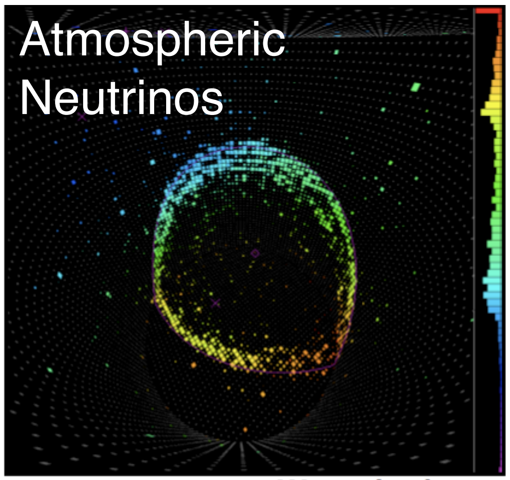
QTC
(Charge to Time Converter)



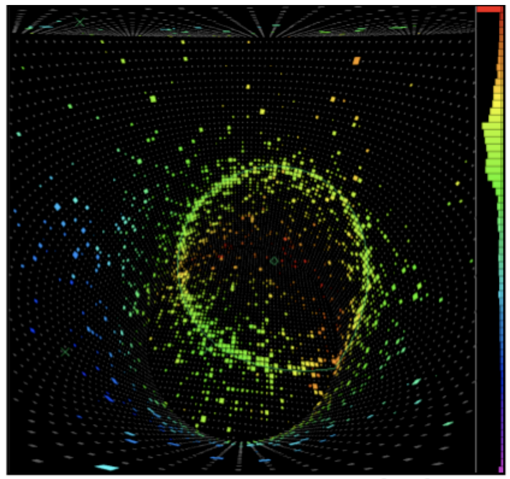
Front-End Board: Q-bee
= Qtc-based Electronics
with Ethernet

Super-K Signals

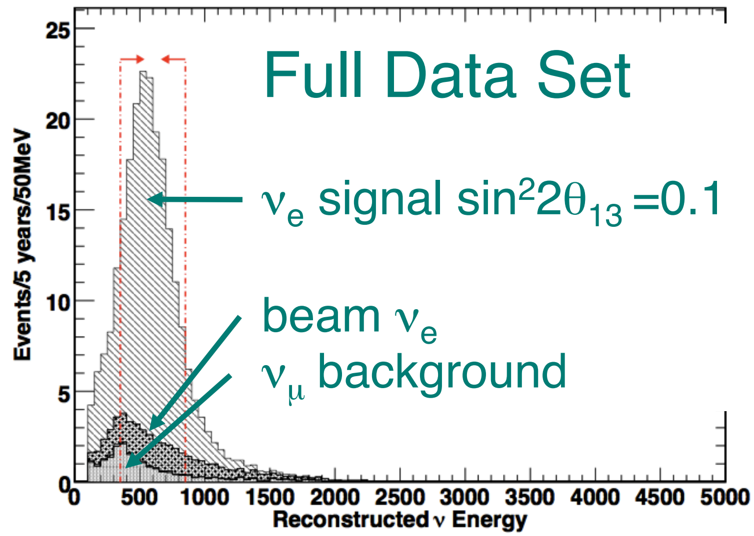
- CCQE for both ν_μ and ν_e spectra



muon-like (ν_μ)



electron-like (ν_e)



- Initial data set (fiducial):
  - ~100 ν_μ
  - ~9 ν_e for $\sin^2 2\theta_{13} = 0.1$ (~4 after cuts compared to ~0.8 background)

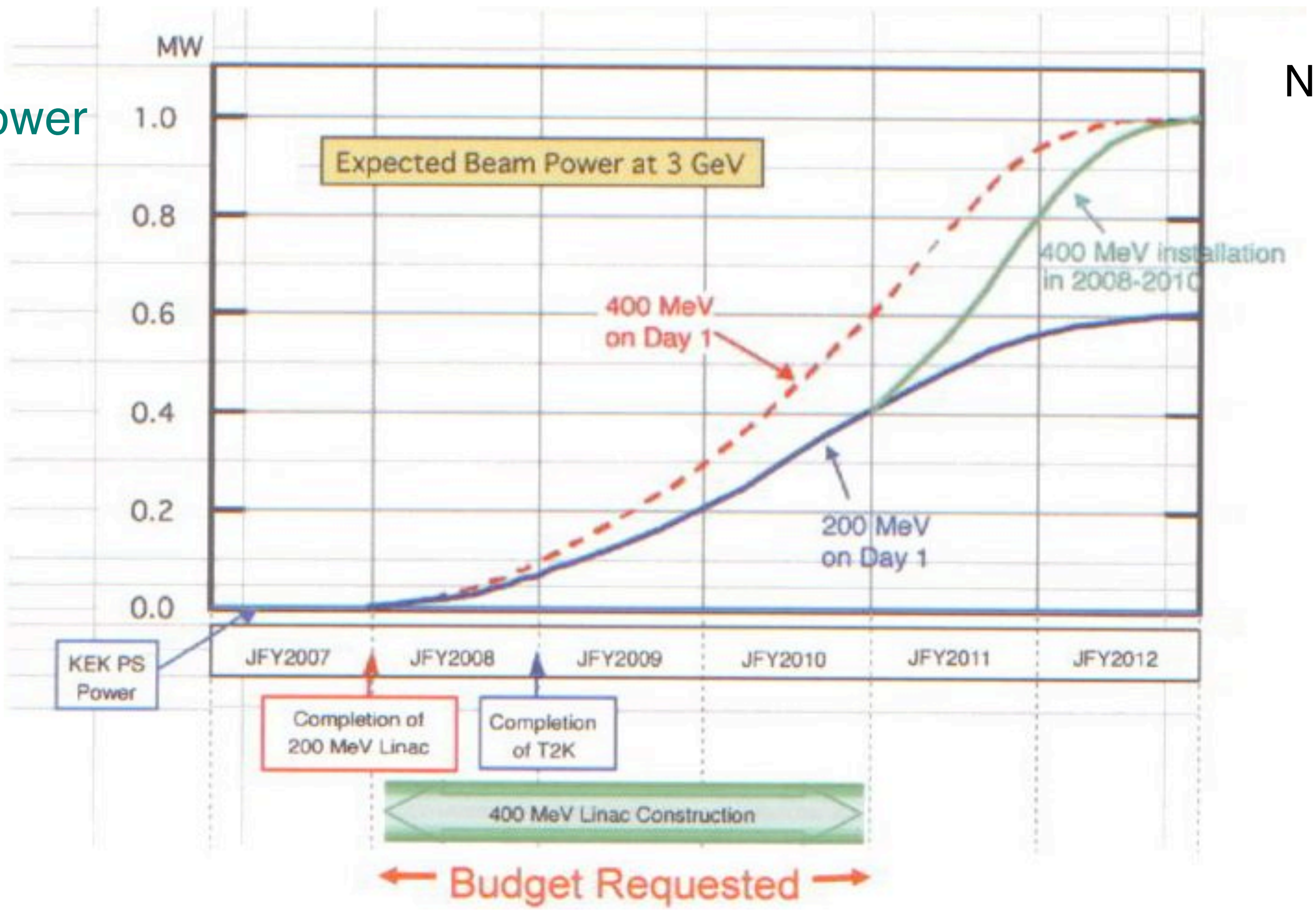
OUTLOOK

Expected Power

- First run starts Dec/Jan. Not clear if we will get the planned 100 kW on target until RFQ is replaced in Spring 2010.
  - also split run time between slow and fast extraction.
- It will take a while to get full 750 kW on target (= 1 MW @ 3 GeV).

Plan for Power Ramp

3 GeV Power

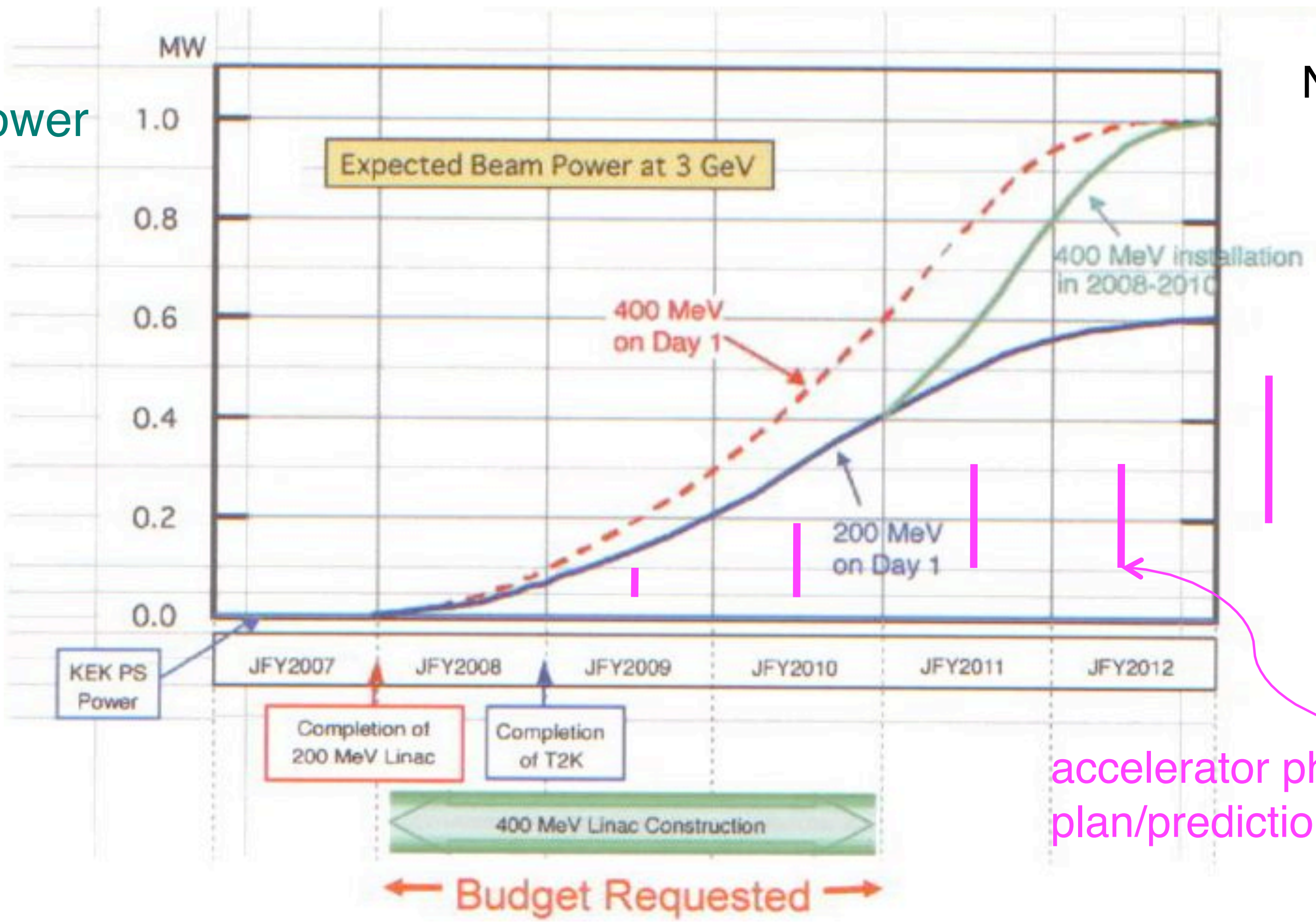


Nominal

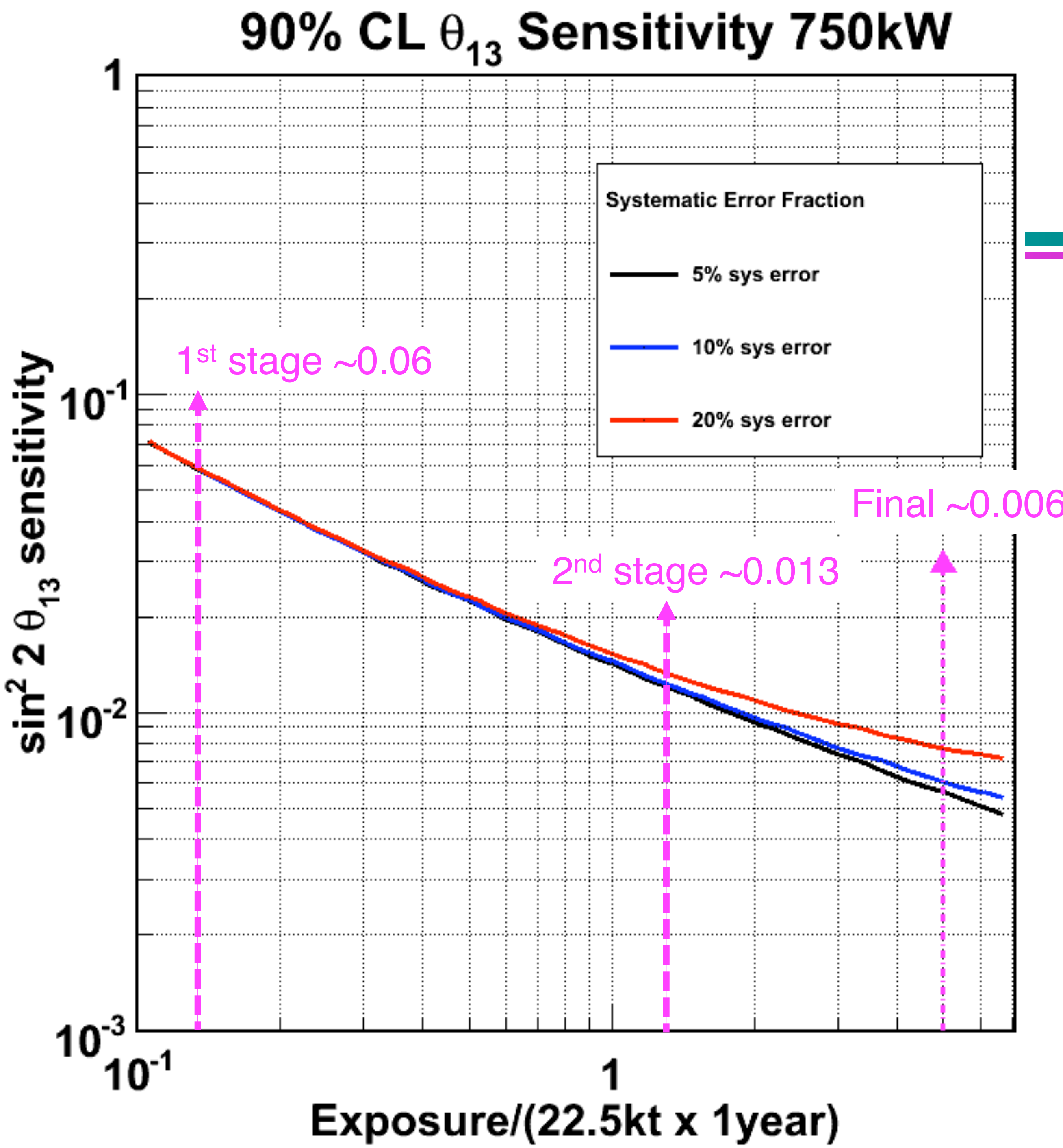
Plan for Power Ramp

3 GeV Power

Nominal



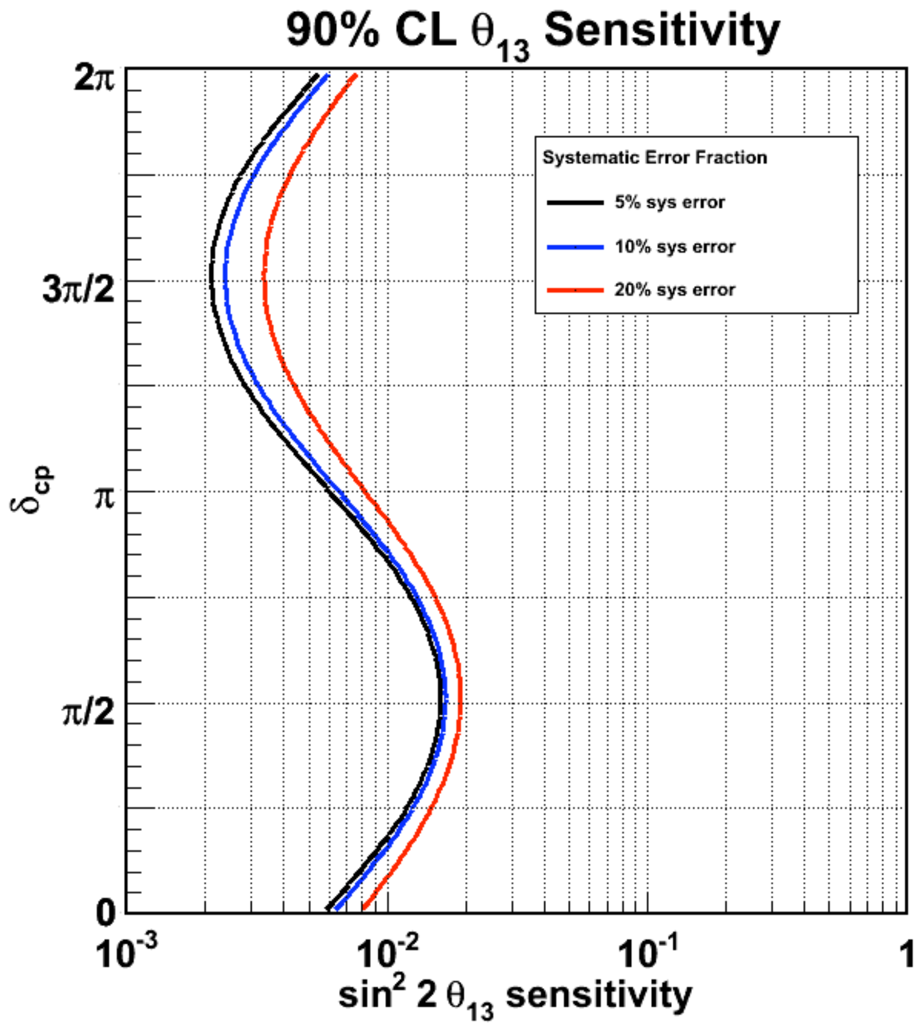
accelerator physicists plan/prediction



90% CL θ13 Sensitivity 750kW
sin² 2 θ13 sensitivity
Exposure/(22.5kt x 1year)
1
10-1
10-2
10-3
10-1
1
Systematic Error Fraction
5% sys error
10% sys error
20% sys error
1st stage ~0.06
2nd stage ~0.013
Final ~0.006

Dependence on δ_{CP}

- We actually measure a function of θ_{13}, δ_{CP} and matter effects/mass hierarchy.
- If we are lucky, compare with Double Chooz (no δ, no x) and NOνA (larger matter effects) to disentangle

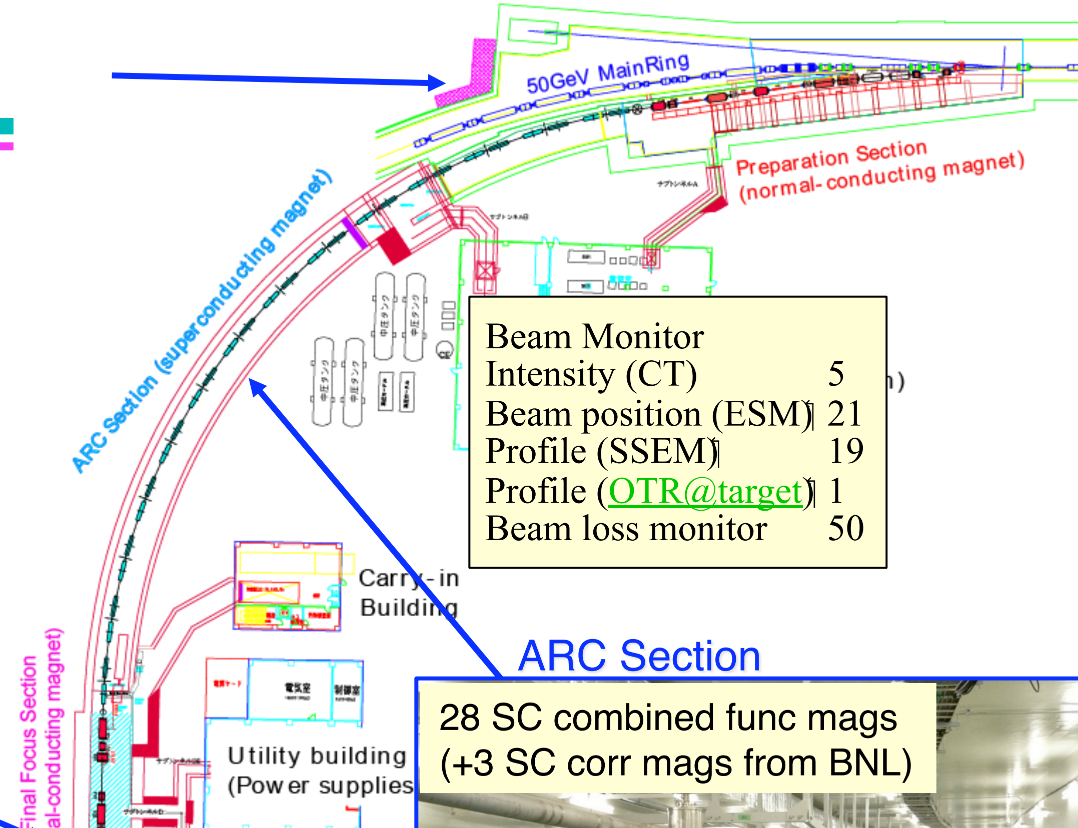


Summary

- J-PARC and T2K beam line commissioning is in progress and near detector installation will occur this summer.
- 1st stage result on θ_{13} (Summer 2010? 2011?) should surpass existing limits.
- Full dataset sensitivity to $\sin^2 2\theta_{13} \sim 0.01$.
  - but I hope we are not still talking about a limit at that time!

BACKUP

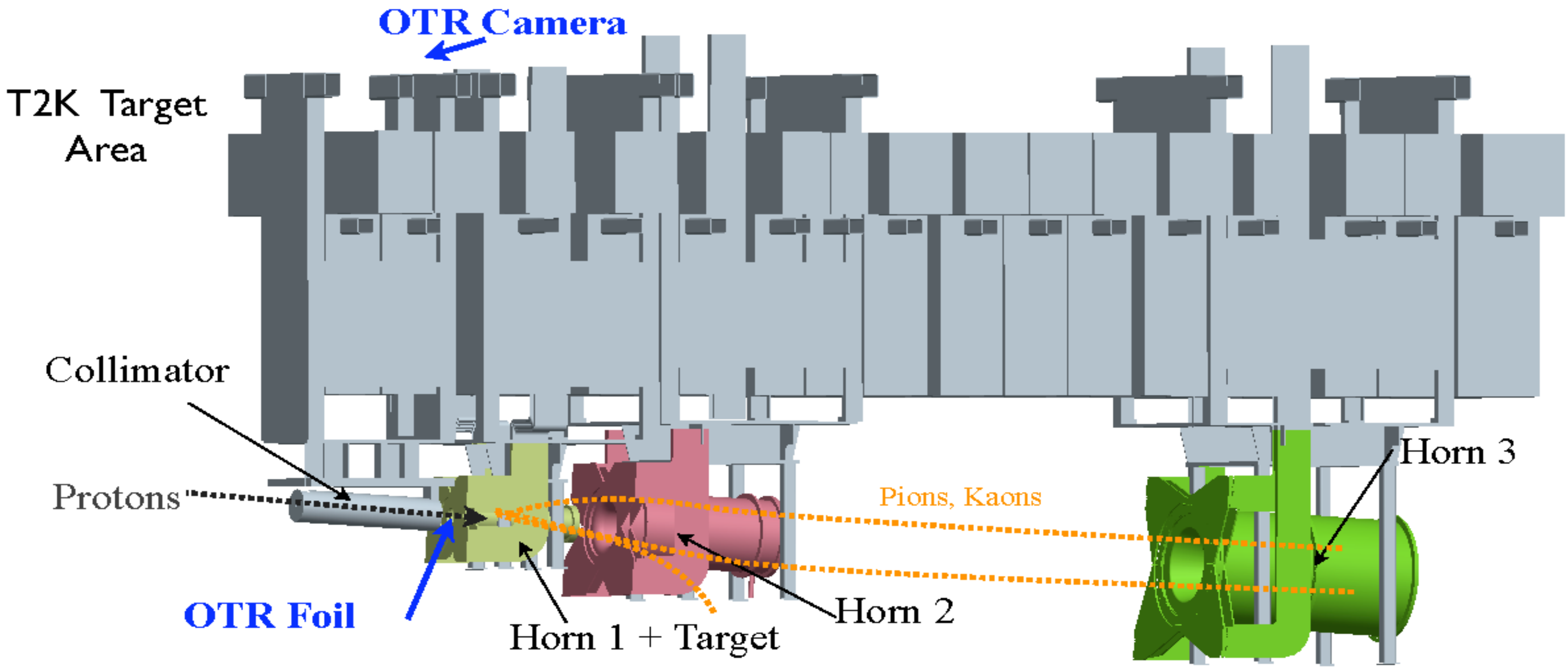
Primary Beam Line



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

10 NC mags

ARC Section


OTR Camera
T2K Target
Area
Collimator
Protons
Pions, Kaons
Horn 3
OTR Foil
Horn 1 + Target
Horn 2

Tri-bimaximal PMNS Matrix

- neutrino masses: triplet Higgs contribution

$$3_S = \frac{1}{3}\begin{pmatrix} 2\alpha_1\beta_1 - \alpha_2\beta_3 - \alpha_3\beta_2 \\ 2\alpha_3\beta_3 - \alpha_1\beta_2 - \alpha_2\beta_1 \\ 2\alpha_2\beta_2 - \alpha_1\beta_3 - \alpha_3\beta_1 \end{pmatrix} \qquad 1 = \alpha_1\beta_1 + \alpha_2\beta_3 + \alpha_3\beta_2$$

- neutrino masses: singlet contribution $1 = \alpha_1\beta_1 + \alpha_2\beta_3 + \alpha_3\beta_2$

- Resulting mass matrix:

$$M_\nu = \frac{\lambda v^2}{M_x}\begin{pmatrix} 2\xi_0 + u & -\xi_0 & -\xi_0 \\ -\xi_0 & 2\xi_0 & u - \xi_0 \\ -\xi_0 & u - \xi_0 & 2\xi_0 \end{pmatrix}$$

$$V_\nu^{\mathrm{T}} M_\nu V_\nu = \mathrm{diag}(u + 3\xi_0,\, u,\, -u + 3\xi_0)\frac{v_u^2}{M_x} \qquad U_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

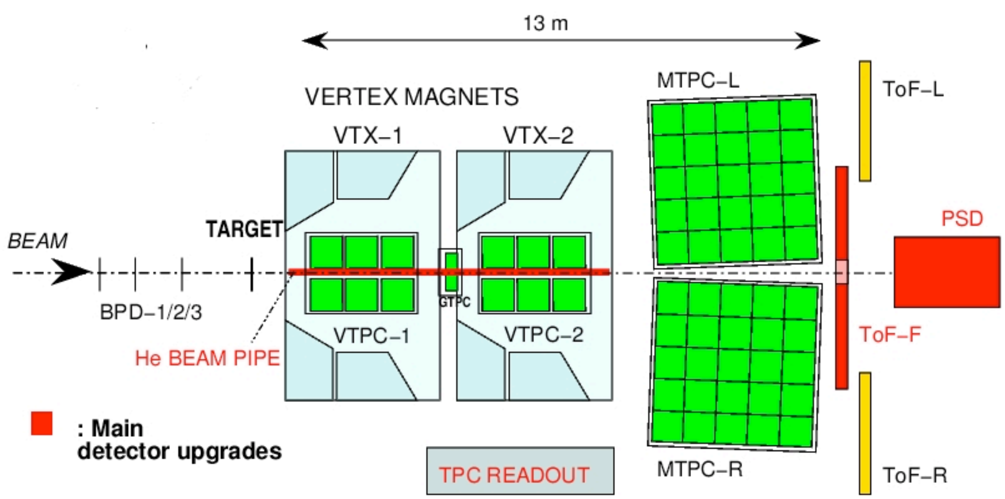
Form diagonalizable:
-- no adjustable parameters
-- neutrino mixing from CG coefficients!

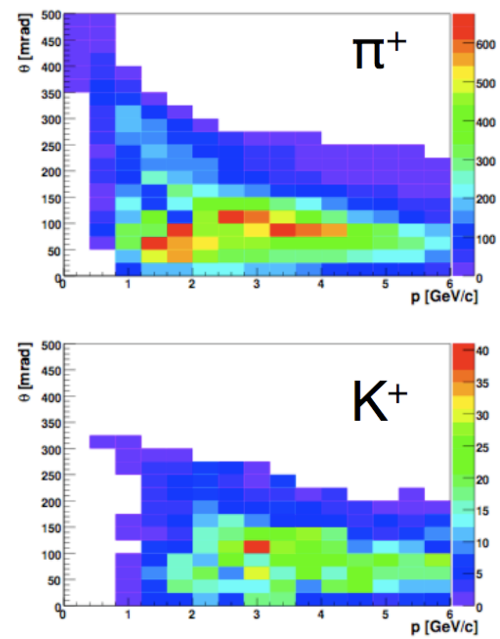
General conditions for Form Diagonalizablility
in seesaw: M.-C. C, S. F. King, arXiv:0903.0125

Mu-Chun Chen

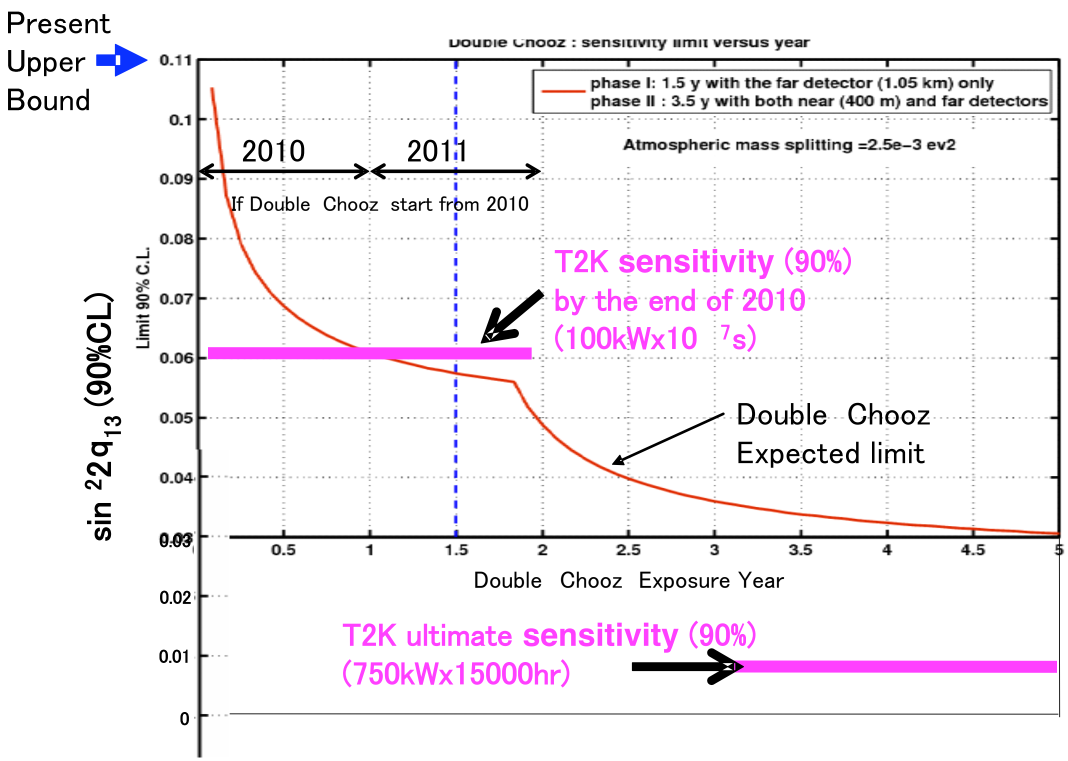
NA-61 at CERN SPS

- Beamline group is responsible for calculating the produced ν flux and spectrum.
- Results from NA-61 are important input. Hadron production using 30 GeV p on T2K target.
  - 3 week run in Aug 2009



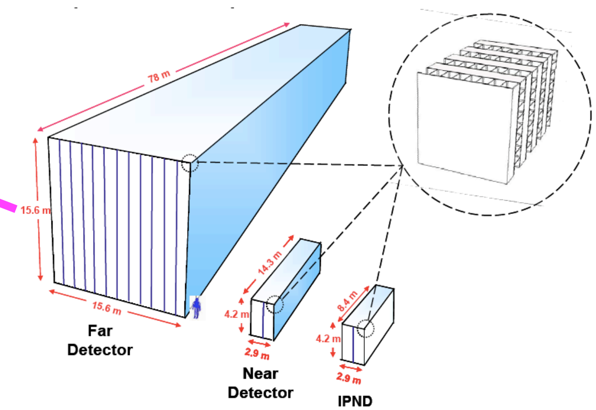


Competition from Double Chooz



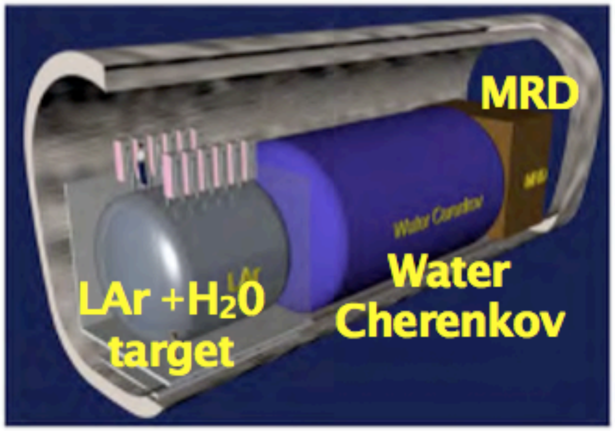
NOνA

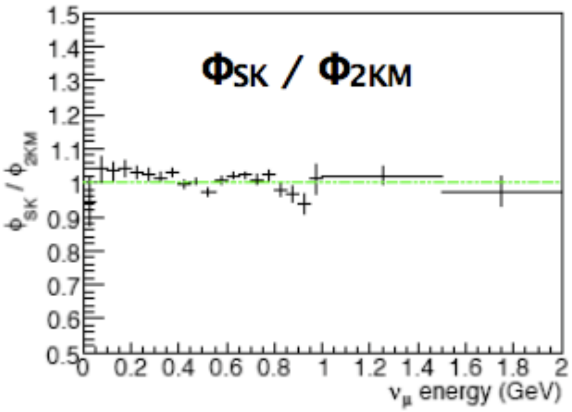
15 kT liquid scintillator
0.8 deg off axis
Ready January 2014

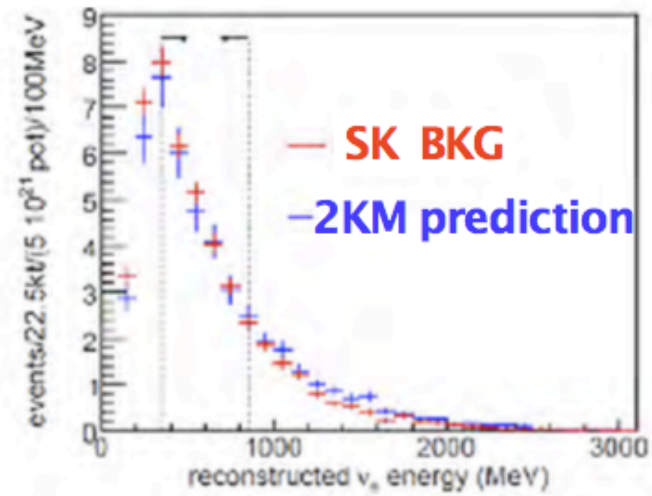


upgrade NuMI from
400 kW to 700 kW

2KM Proposal

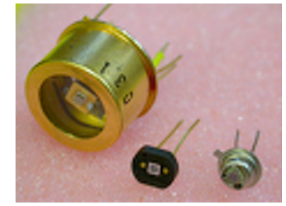






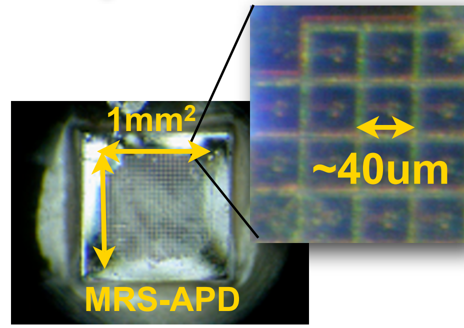
- Strengthen prediction of far detector flux through measurement (~2 km away) using :
  - Almost **same beam flux as far detector**
  - **Same target material**
  - **Same detector technology** and reconstruction analysis
- Check ND280+NA61 prediction before oscillation
- Combine ND280+2kM measurements
  - Reduce further the systematic errors
  - Understand better the ve backgrounds

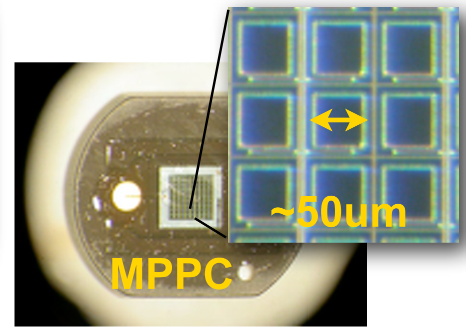
Novel type of photosensor : Geiger Mode multi- pixels APD



ND280 Scintillator Detectors Constraints :

- Magnetic Field
- Very tight space constraints
- Low light yield at end of WLS fibre
- High number of channels
- Detector operation 5 years



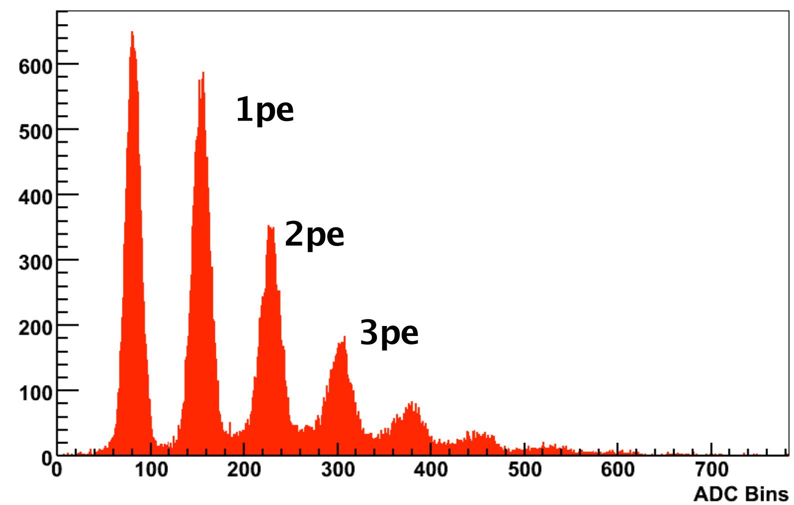


$$Signal = \sum_i Q_i^{pixel}$$

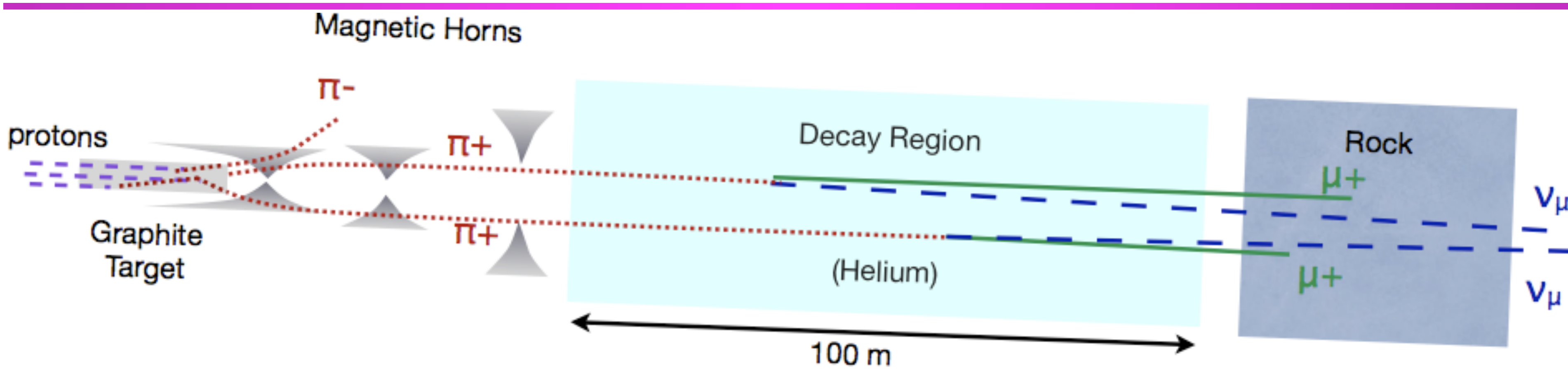
Photo-electron resolution
+ dynamic range combined in 1 sensor

GM-APDs

- Insensitive to magnetic field, tested to 4T
- Small (active area ~1mm^2)
- Bias voltage 50V
- Photon detection efficiency >20% at 500nm
- Gain G~ 5x10^5
- Low power consumption
- Dark count rate ~0.5MHz/mm^2 at 25°C
- Longevity OK



Target Area



- 30 GeV protons strike 90 cm graphite target, creating $\pi^{\pm}$ and $K^{\pm}$.
- Three horns focus π^{+}, defocus π^{-}
- $\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$ in 110 m decay volume
- Muon monitor follows beam dump.

Reactor experiments (Q13)

Site (proposal)	Power (GW)	Baseline Near/Far (m)	Detector Near/Far (t)	Overburden Near/Far (MWE)	Sensitivity to $\sin^2 2\theta_{13}$ (90%CL)	Operation year
Angra dos Reis (Brazil)	6.0	300/1500	50/500	200/1700	~0.006	unknown
Double Chooz (France)	8.7	400/1050	10/10	115/300	~ 0.03	Early 2010
Daya Bay (China)	17.4	360/500/ 1800	40/40/80	264/302/946	~ 0.008	Late 2010
Reno (S. Korea)	17.3	290/1380	15/15	200/540	~ 0.025	Early 2010