TRIUMF

Status of T2K

Canada
TRIUMF
U. Alberta
U. British Columbia
U. Regina
U. Toronto
U. Victoria
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany
U. Aachen

Italy
INFN, U. Roma
INFN, U. Napoli
INFN, U. Padova
INFN, U. Bari

Japan
Hiroshima U.
ICRR
ICRR Kashiwa
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U.
Osaka City U.
U. Tokyo

Poland
A.Soltan, Warsaw
H.Niewodniczanski, Cracow
T.U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

Russia
INR

South Korea
N.U. Chonnam
U. Dongshin
N.U. Gyeongsang
N.U. Kyungpook
U. Sejong
N.U. Seoul
U. Sungkyunkwan

Spain
IFIC, Valencia
U.A. Barcelona

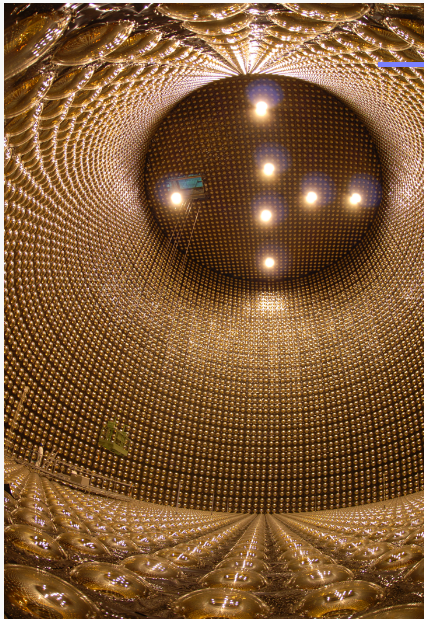
Switzerland
U. Bern
U. Geneva
ETH Zurich

UK
Imperial C. London
Queen Mary U.L.
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury

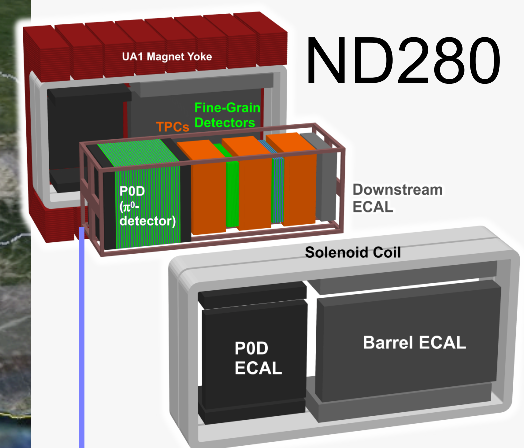
USA
Boston U.
BNL
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
U.C.Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Akira Konaka (TRIUMF/ICRR)

T2K experiment



Super-Kamiokande



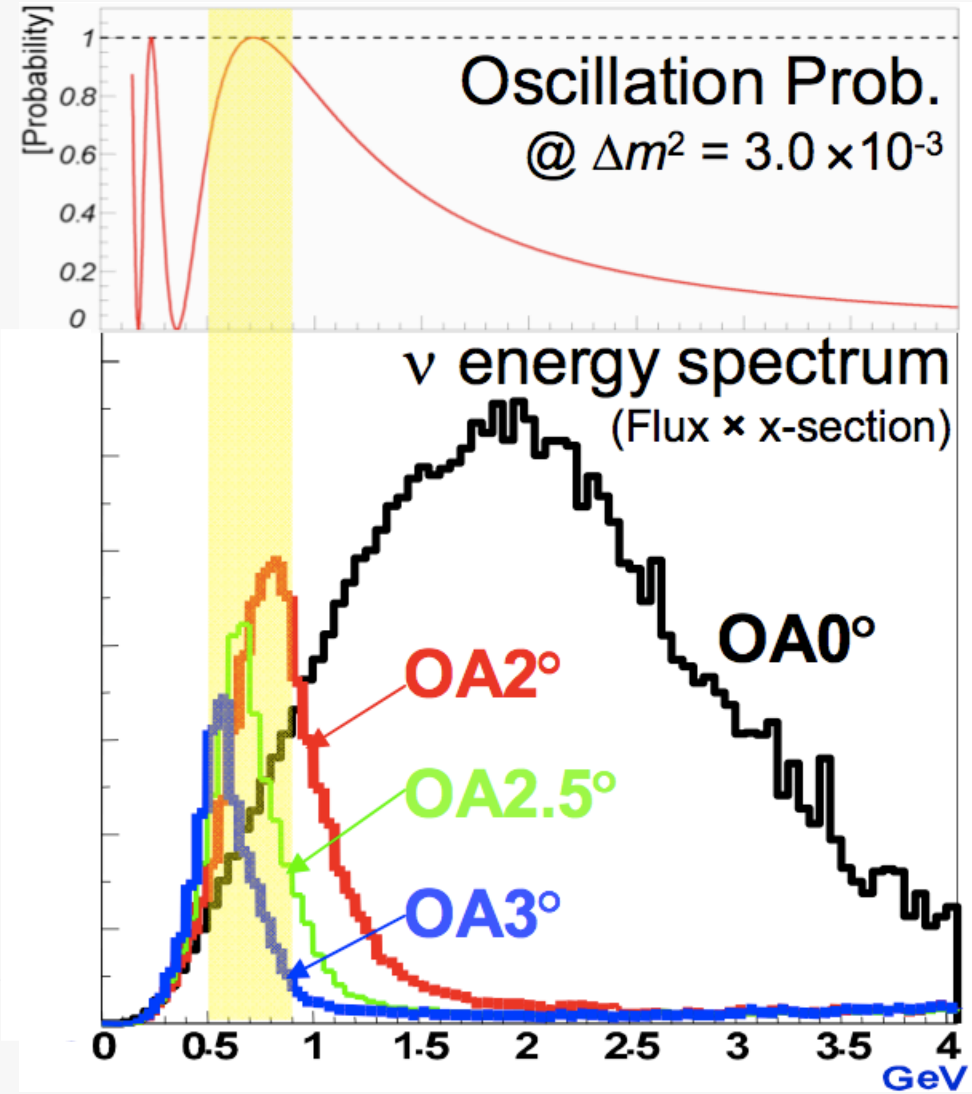
- Long baseline neutrino oscillation experiment from Tokai to Kamioka.
- $\nu_\mu \rightarrow \nu_e$ appearance to measure θ_{13}, which leads to CP violation studies.

Off-axis neutrino beam

- Narrow band beam tuned at the oscillation maximum
  - Off-axis ν beam (2.5 deg.)
  - Maximize ν oscillation
  - Suppress backgrounds from high energy tail, beam ν_e
- Sub-GeV ν beam (0.5-1GeV)
  - CCQE($\nu_\mu n \rightarrow \mu p$) dominates Eν reconst. by μ momentum

$$E_\nu = \frac{2E_l m_N - m_l^2}{2(m_N - E_l + P_l cos\theta_l)}$$

  - Works well for water Cerenkov (Super-K)



Neutrino oscillation

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

- Very small neutrino mass
  - See-saw mechanism at GUT scale?
- Large mixing angles, different from quark sector
  - Hint for the origin of flavor symmetry (at GUT scale)?
- Far detector is also sensitive to proton decay

Quark mixing (CKM matrix)

$$\begin{array}{cc} & \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{array}{c} d \\ s \\ b \end{array} & \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \end{array} \begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} \cos\theta_{13} & 0 & \cos\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\cos\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \end{array} \begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Almost diagonal

Cabbibo angle

$\sin\theta_{23} = A\lambda^2$ $\sin\theta_{13}e^{-i\delta} = A\lambda^3(\rho - i\eta)$ $\sin\theta_{12} = \sin\theta_C = \lambda \sim 0.2$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 - \frac{A^2\Lambda^2}{2} & A\Lambda^2 \\ 0 & -A\Lambda^2 & 1 - \frac{A^2\Lambda^2}{2} \end{pmatrix} \begin{pmatrix} 1 & 0 & A\Lambda^3(\rho - i\eta) \\ 0 & 1 & 0 \\ A\Lambda^3(\rho - i\eta) & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 - \frac{\Lambda^2}{2} & \lambda & 0 \\ -\lambda & 1 - \frac{\Lambda^2}{2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Large lepton mixing (PMNS)

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Tri-Bimaximal?

$$\sin^2\theta_{12} = \frac{1}{3}$$
$$\sin^2\theta_{23} = \frac{1}{2}$$
$$\sin^2\theta_{13} = 0$$

$$|\nu_3> = \frac{1}{\sqrt{2}}(-|\nu_\mu> + |\nu_\tau>)$$
$$|\nu_2> = \frac{1}{\sqrt{3}}(|\nu_e> + |\nu_\mu> + |\nu_\tau>)$$
$$|\nu_1> = \frac{1}{\sqrt{6}}(2|\nu_e> - |\nu_\mu> - |\nu_\tau>)$$

Tri-bimaximal?

$$
\begin{array}{cc}
 & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} &
\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}
\end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{pmatrix} \cos\theta_{13} & 0 & \cos\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\cos\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}
\end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
\end{array}
$$

$$
\sin^2\theta_{23} = \frac{1}{2} \qquad \sin^2\theta_{13} = 0 \qquad \sin^2\theta_{12} = \frac{1}{3}
$$

$$
\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}
\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{3}} & \sqrt{\frac{2}{3}} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

Breaking at $O(\lambda,\lambda^2)$~0.1 level like CKM?

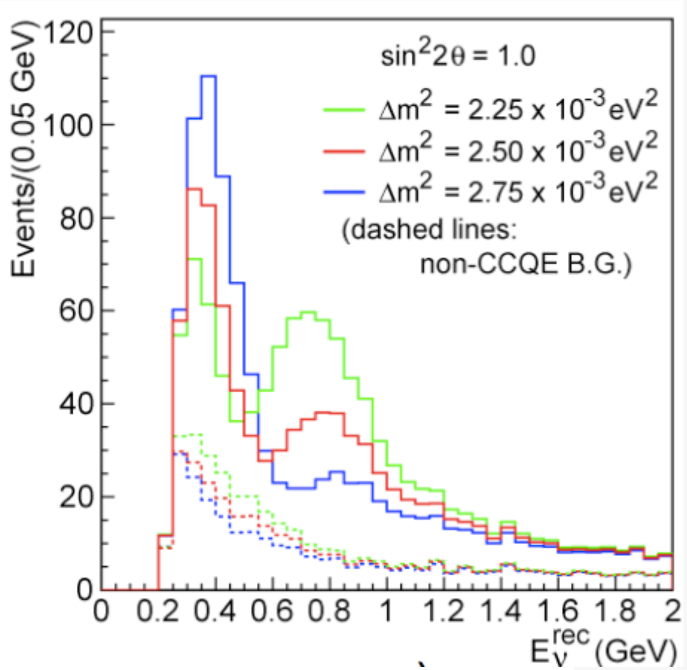
$\sin\vartheta_{23}$: ν_μ disappearance (Long baseline ν)

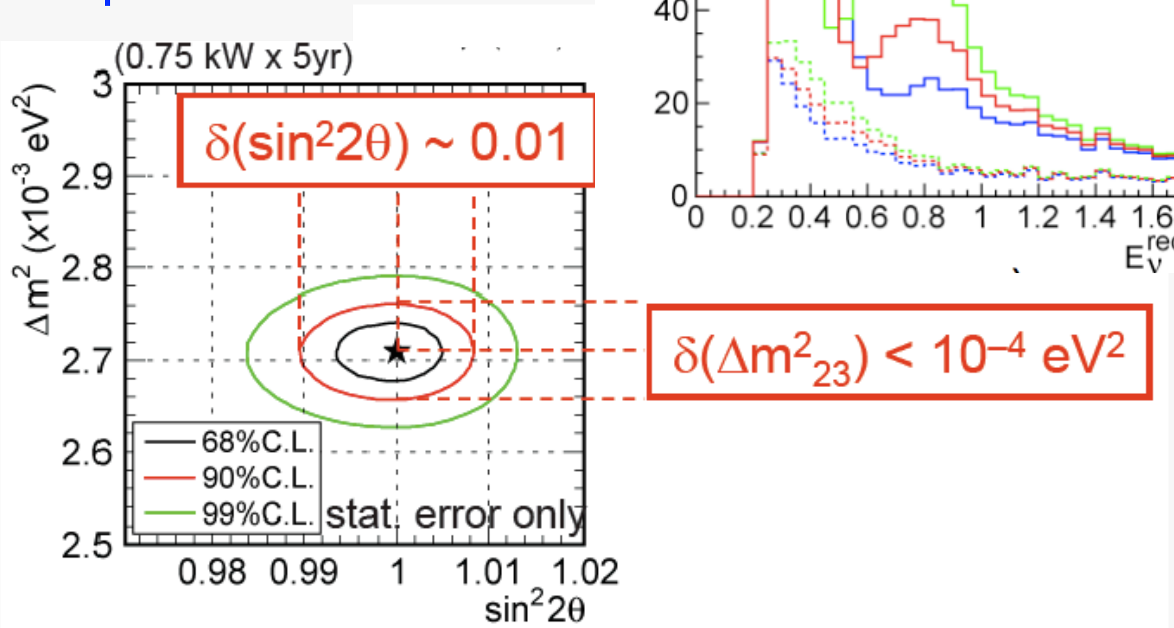
$\sin\vartheta_{13}$: $\nu_\mu \rightarrow \nu_e$ appearance (LBL), ν_e disappearance (reactor ν)

$\sin\vartheta_{12}$: ν_e disappearance (solar ν, reactor ν)

ν_μ disappearance

- $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2 L/E_\nu)$
  $\sin^2 2\theta_{23} = 1$ or <1?
- Oscillation pattern in SuperK rate
  $\sin^2 2\theta_{23}$: Depth of E_ν dip
  Δm^2_{23} : Position of E_ν dip
- 5 year sensitivity
  $\partial(\sin^2 2\theta_{23}) \approx 0.01$
  $\partial(\Delta m_{23}{}^2) \approx 0.0001\,\mathrm{eV}^2$





ν_e appearance

- $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E_\nu)$ + CP viol.+...

  $\theta_{13} \neq 0$?

- 90% CL sensitivity

  $\sin^2 2\theta_{13} \sim 0.006$ for 750kWx5yr

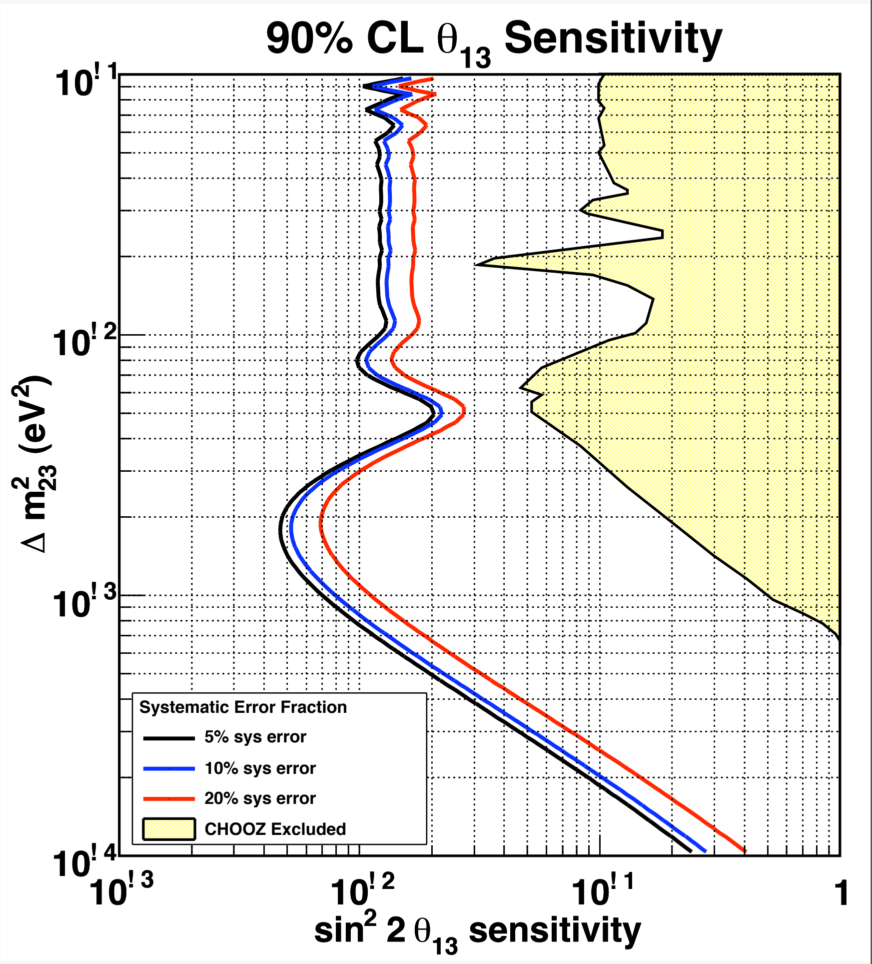
Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	Total	
0.1	10	13	23	103
0.01				10

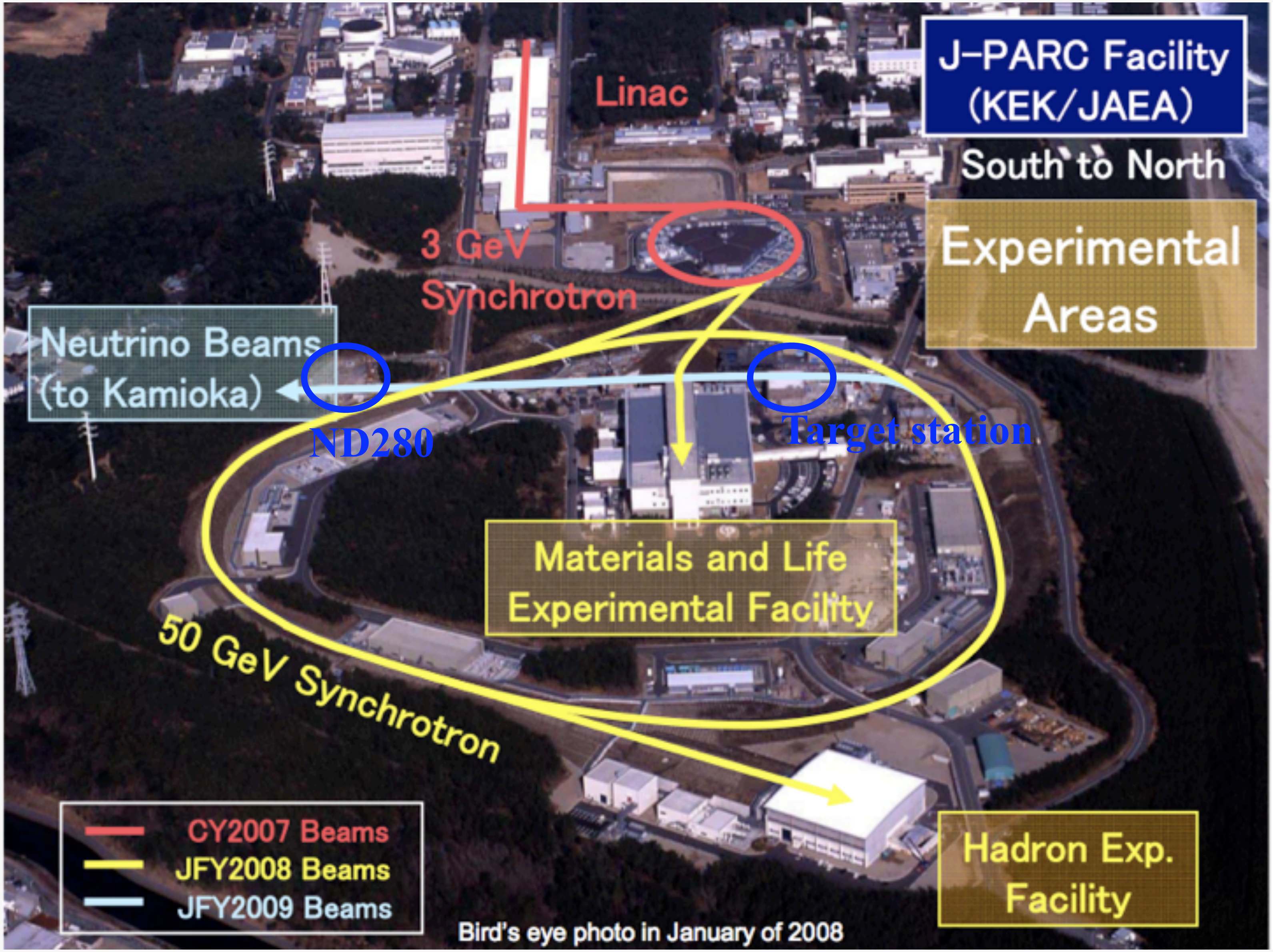
- CP viol. contribution not small

  CP study in the 2nd phase

  Complementary to reactor θ_{13}



J-PARC

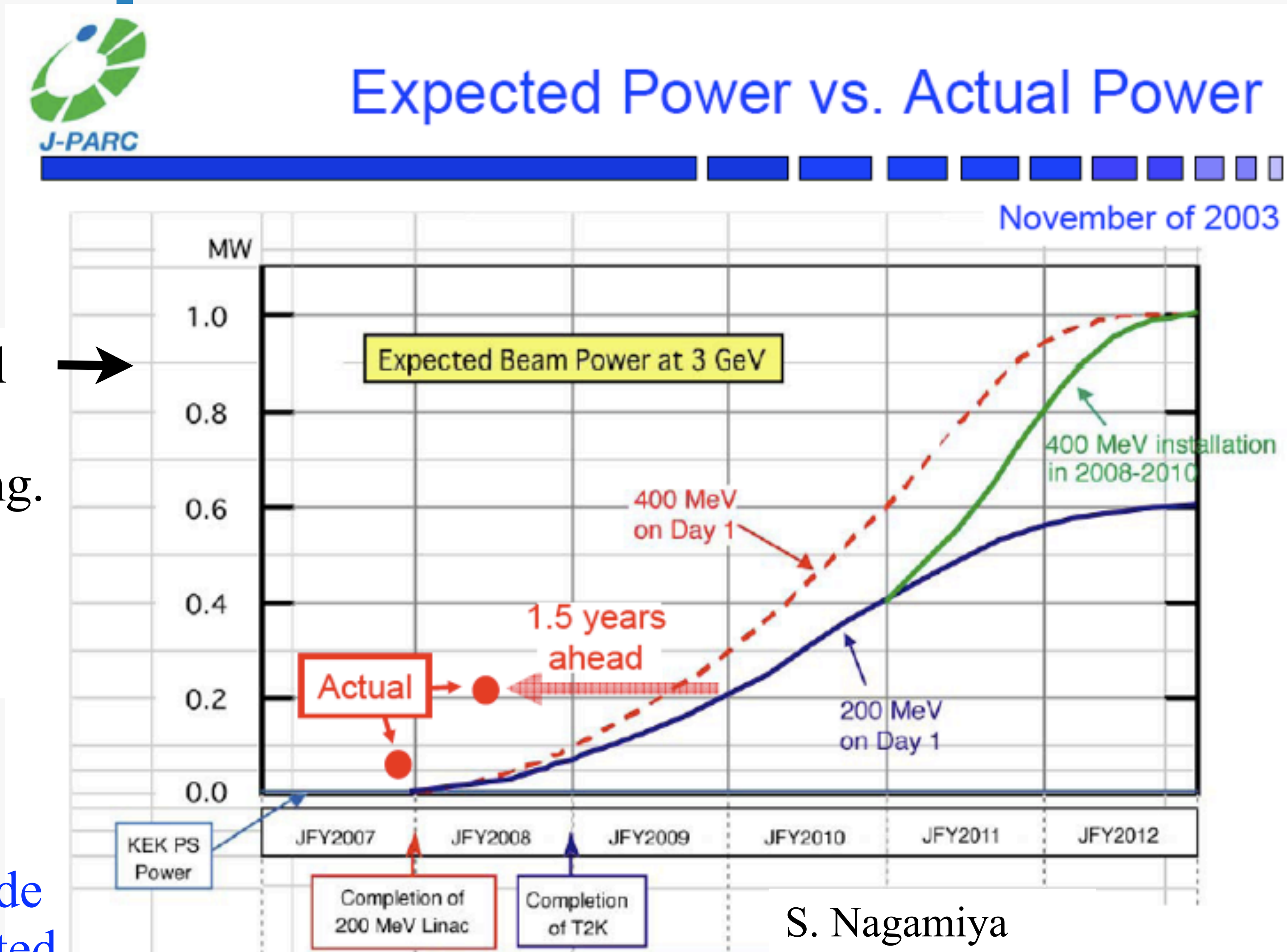


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
ND280
Target station
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

MW class proton beam

- High intensity
  - Large number of protons per bunch
    - space-charge effect to be controlled
  - Rapid cycling
    - high gradient RF : FINEMET magnetic alloy (new!)
- Control beam loss for hands-on maintenance
  - Good monitoring and control of the beam
    - good reproducibility, residual gas monitor
  - Imaginary transition energy
    - first large accelerator to adopt this
- Beamline
  - Large aperture magnets to reduce beam loss
  - Remote maintenance at the target station

Beam power ahead of schedule



Design goal
0.75MW
at Main Ring.
Eventually
upgrade to
→ **3-4MW**

Linac upgrade
funding started

S. Nagamiya
@ICFA seminar

K.Nishikawa @ FNAL users meeting

Beam commissioning has been accomplished on schedule,
BUT with low intensity.
Real challenge toward the power frontier machine just started.

1. Many issues (unreliable components, design etc.) to be solved
2. Beam must be provided to the users
3. Power upgrade should be also accomplished steadily.

K.Nishikawa @ FNAL users meeting

Beam commissioning has been accomplished on schedule,
BUT with low intensity.
Real challenge toward the power frontier machine just started.

1. Many issues (unreliable components, design etc.) to be solved
2. Beam must be provided to the users
3. Power upgrade should be also accomplished steadily.

Three serious issues

- RFQ discharge problem: identified problems in vacuum, material, and fabrication. Are there more problems?
- RF core long term stability problem: Thermal stress : analysis/design
- Stability of MR power supply and beam loss

K.Nishikawa @ FNAL users meeting

Beam commissioning has been accomplished on schedule,
BUT with low intensity.
Real challenge toward the power frontier machine just started.

1. Many issues (unreliable components, design etc.) to be solved
2. Beam must be provided to the users
3. Power upgrade should be also accomplished steadily.

Three serious issues

- RFQ discharge problem: identified problems in vacuum, material, and fabrication. Are there more problems?
- RF core long term stability problem: Thermal stress : analysis/design
- Stability of MR power supply and beam loss
  - Clearly need major improvements for MW operation
  - No problem for fast extraction with a level of 100kW operation
  - Need more stability for slow extraction

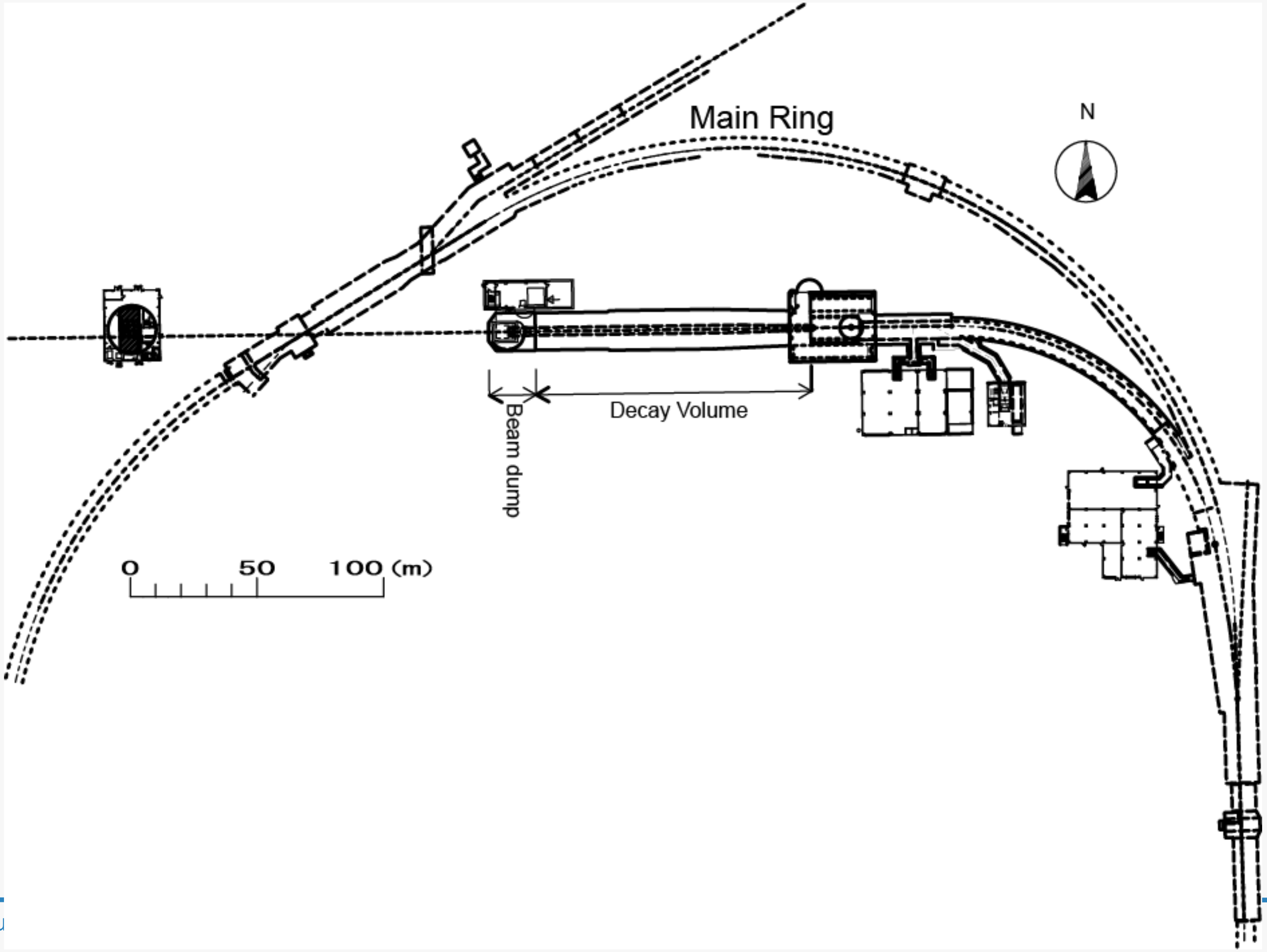
K.Nishikawa @ FNAL users meeting

Neutrino

1. **Early achievement of 100kW run (for 10^7 sec, in 2010)**
2. **Work on power upgrade scenario from 100 to 750kW.(2011~)**
3. **The above second step should be the base of the MW-class power frontier machine.**

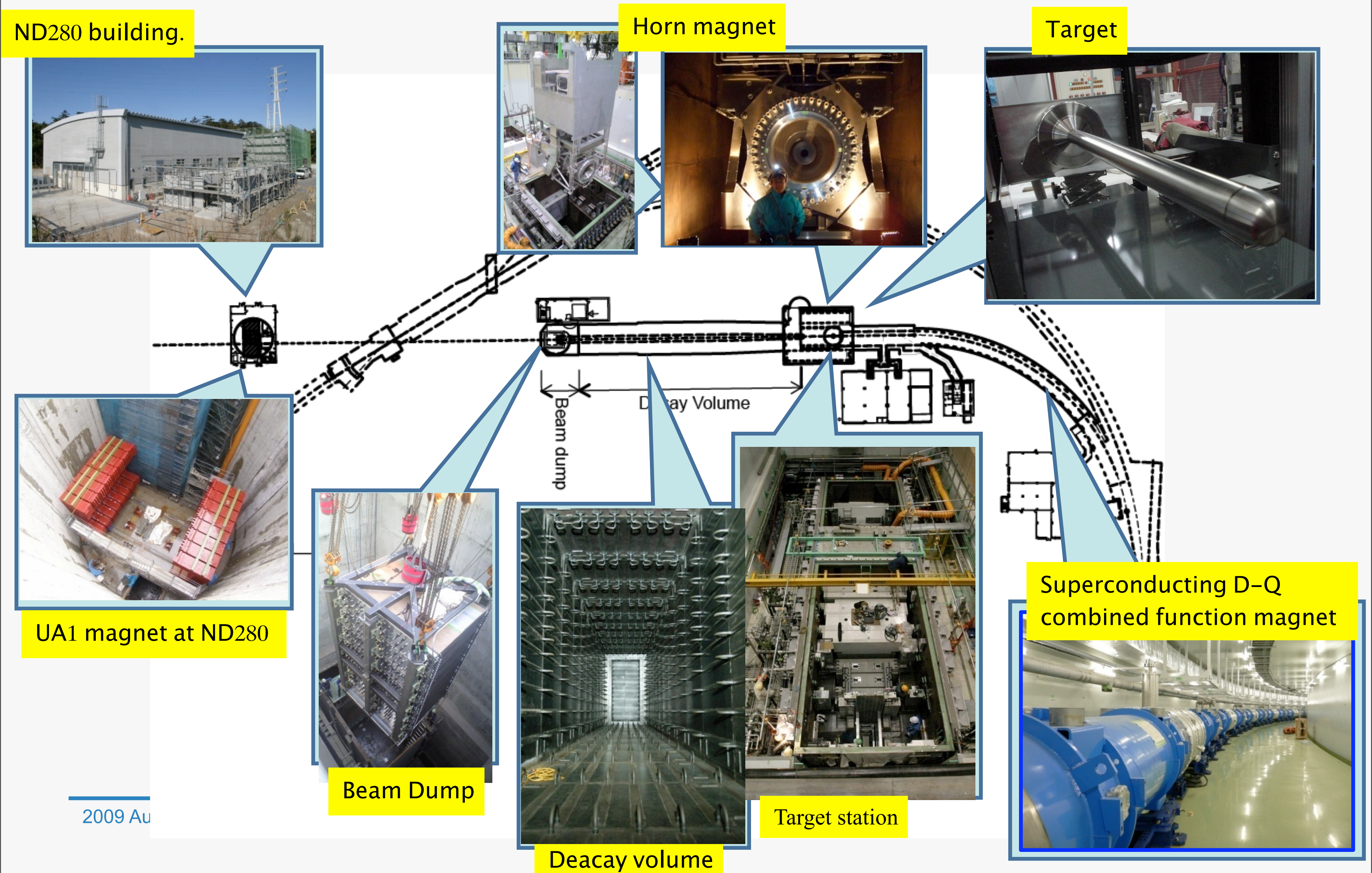
Neutrino beamline

- **5 year construction 2004~2009**

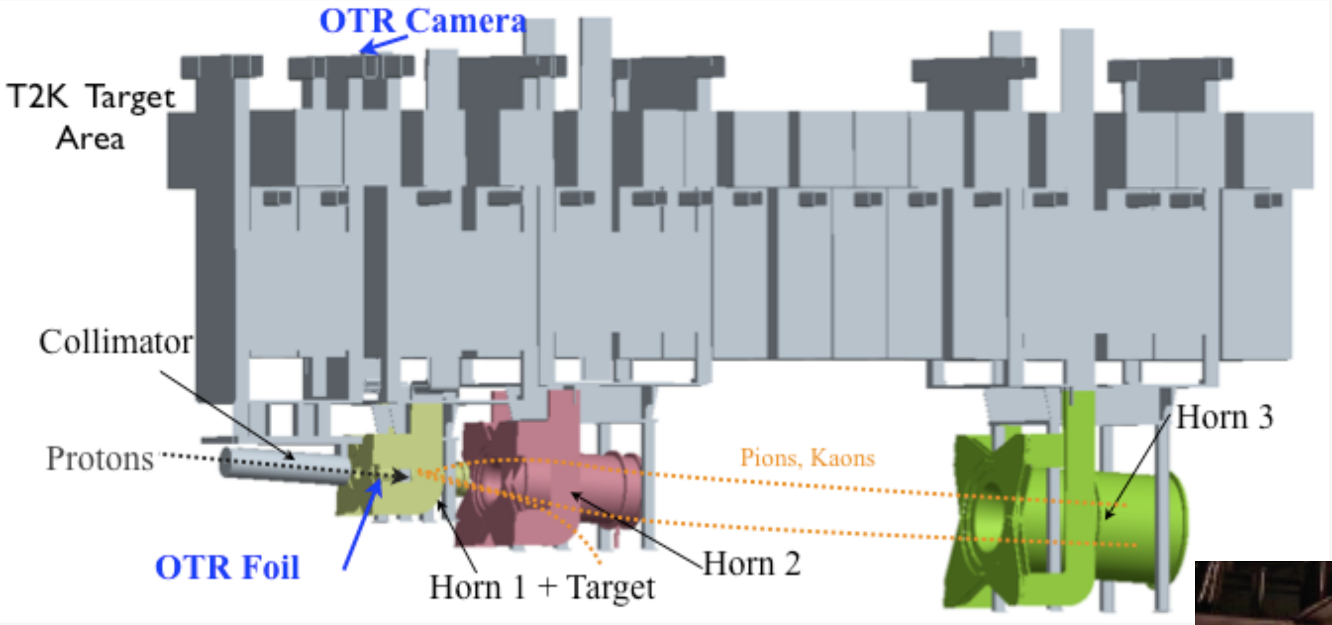


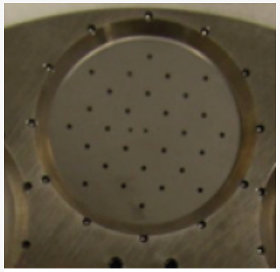
Neutrino beamline

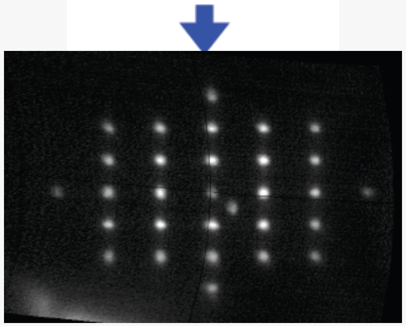
- 5 year construction 2004~2009

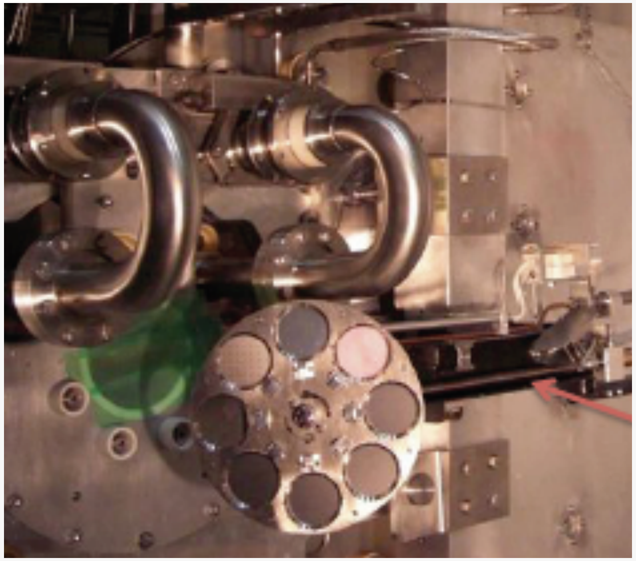


Optical Transition Radiation (OTR) monitor





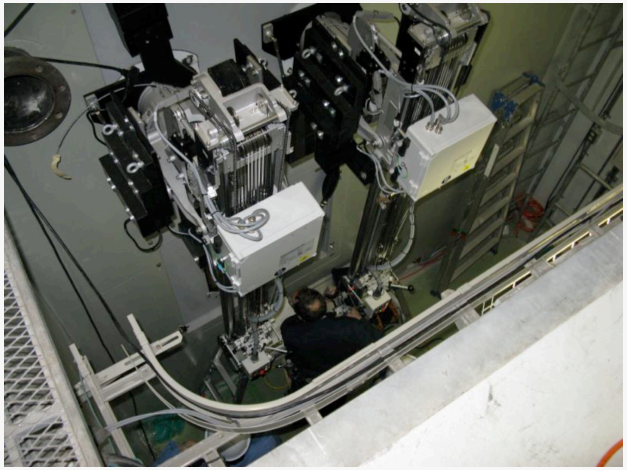
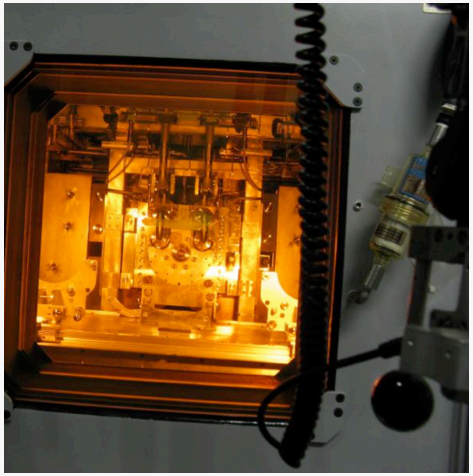




- Beam profile monitor in front of the 1MW target
- OTR light from Ti foil is transferred to rad-hard camera through shielding

Remote maintenance at target station

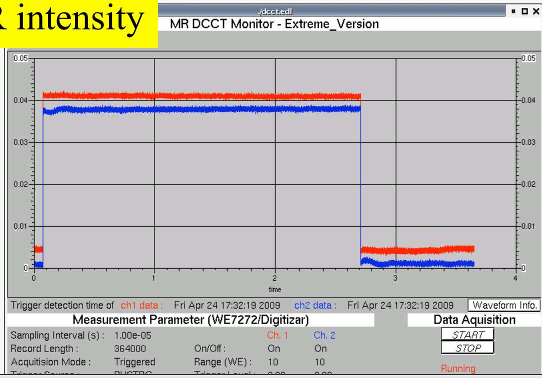
- Horn, target, and monitors are supported from the top with iron/concrete shieldings in between.
- Remote crane to bring each component to the service cell
  Maintenance work done using manipulator in the cell
  Sophisticated replacement mechanism developed for each component, in particular the target.

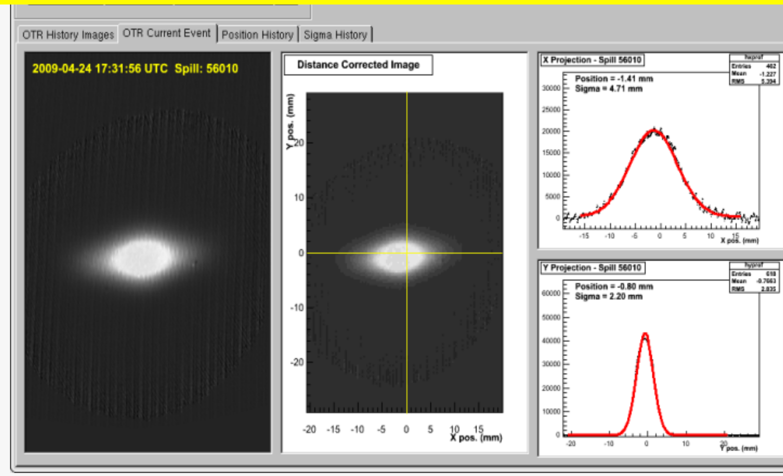

T2K beamline started operation!

After ~10 shots for tuning, proton beam hit around target center

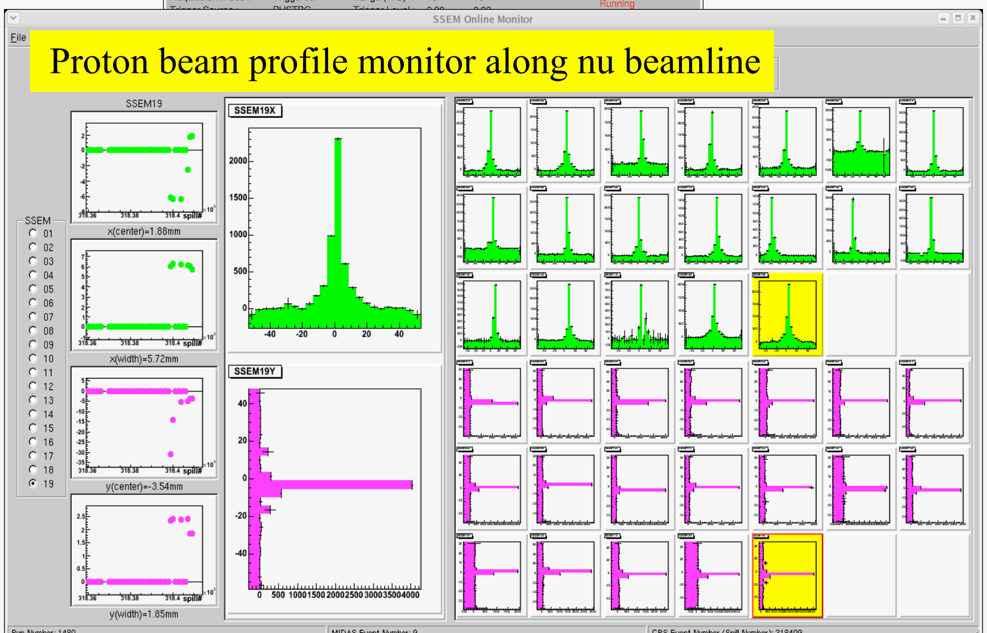
MR intensity



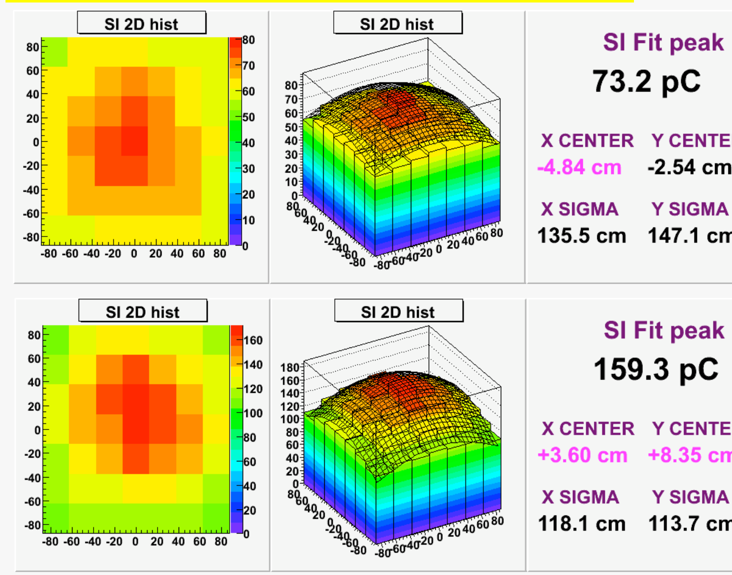
OTR detector just in front of target (fluorescence plate)



Proton beam profile monitor along nu beamline



Muon monitor (Silicon detector) profile



Horn Off

Horn 250kA

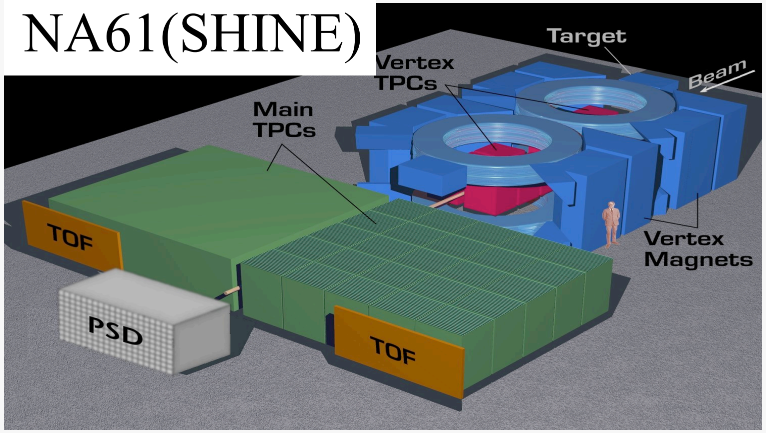
Neutrino facility commission

- Successful commission of the beamline
  - Tuning of extraction parameters to 0.3mm/0.04mrad
  - Beamline orbit was tuned to within 3mm level
  - Combined function SC magnet worked well
    - FODO lattice transport beam even with 2cm offset
- All the beam monitors worked as expected
- Horn focus was demonstrated with one horn
  - Rest of the two horns will be installed in summer
- Passed the government radiation safety inspection
  - 0.14kW (1.7×10^{11} p/bunch/6sec) operation for 40min.
  - 1.13 kW (7.1×10^{11} p/bunch/6sec x2bunches) for 30 sec.

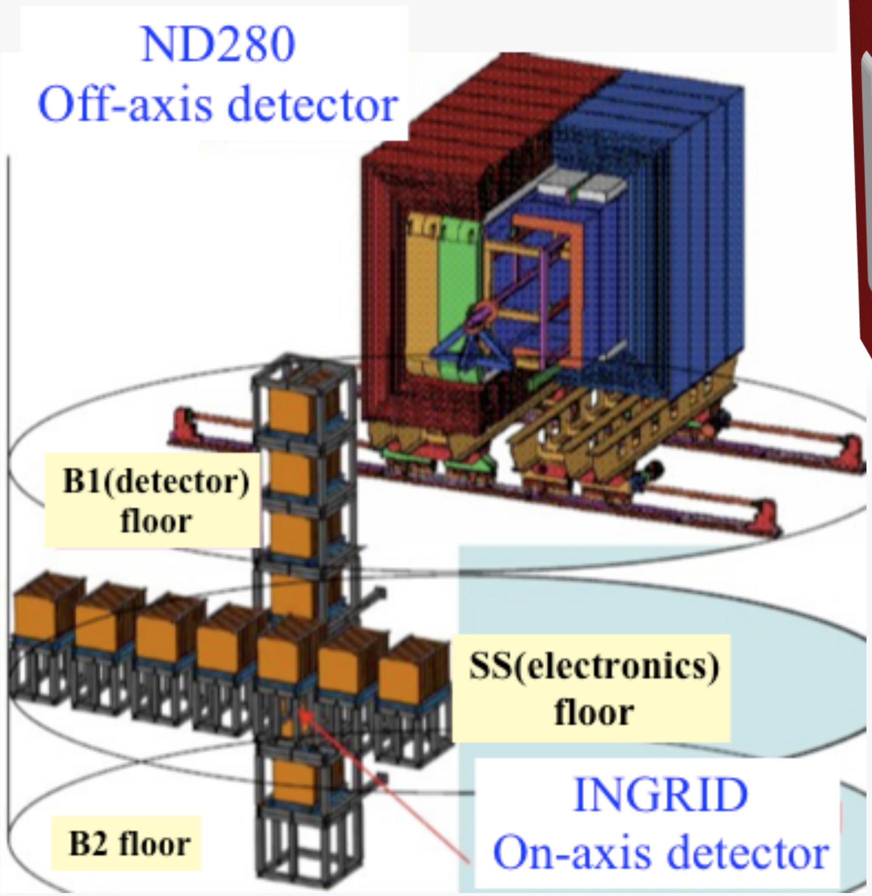
Expected Beam analysis

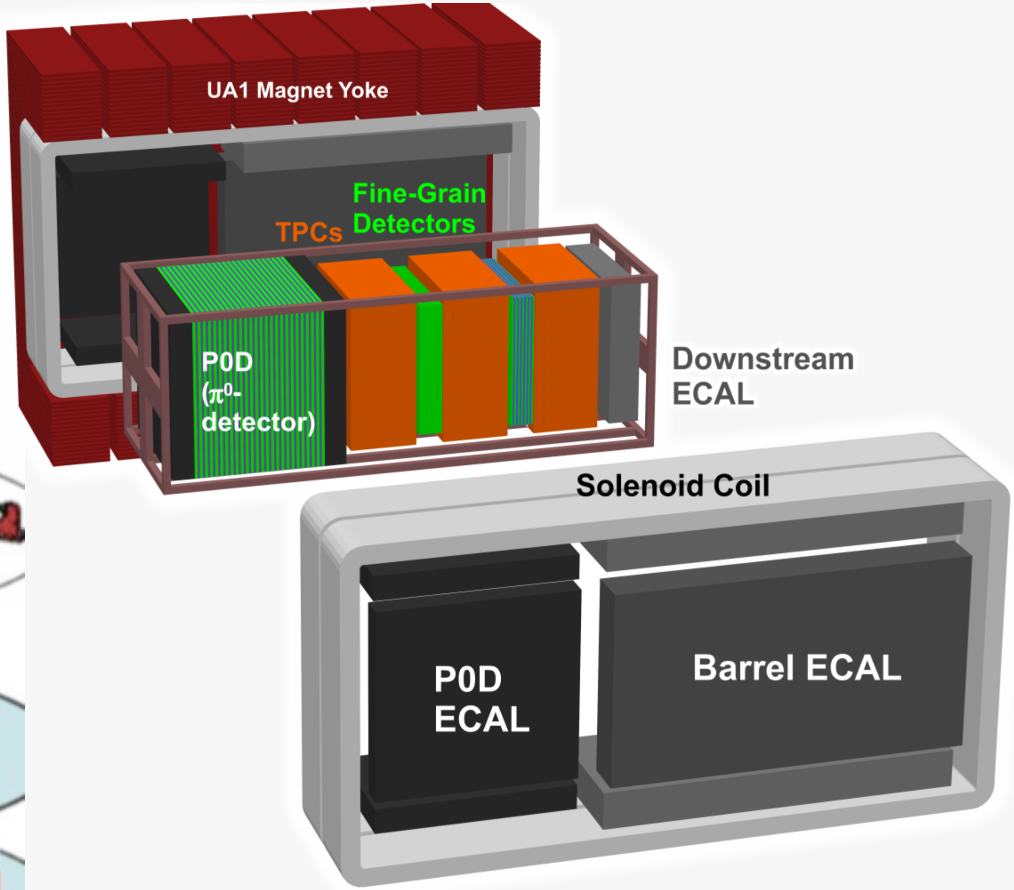
- Near to far extrapolation
  - Beam direction measurements $\Delta\theta$=1mrad
    - Beam position at the target (OTR): 1mm→1mrad
    - Muon monitor behind the beam dump: 5cm→1mrad
    - On axis near detector : 25cm→1mrad
    - Neutrino energy peak at near detector : 2%→1mrad
  - Parent π momentum distribution
    - Hadron production by NA61 (data analysis in progress)
    - Near to far extrapolation is not so strongly dependent on P_π
- Monitor beam stability

NA61(SHINE)

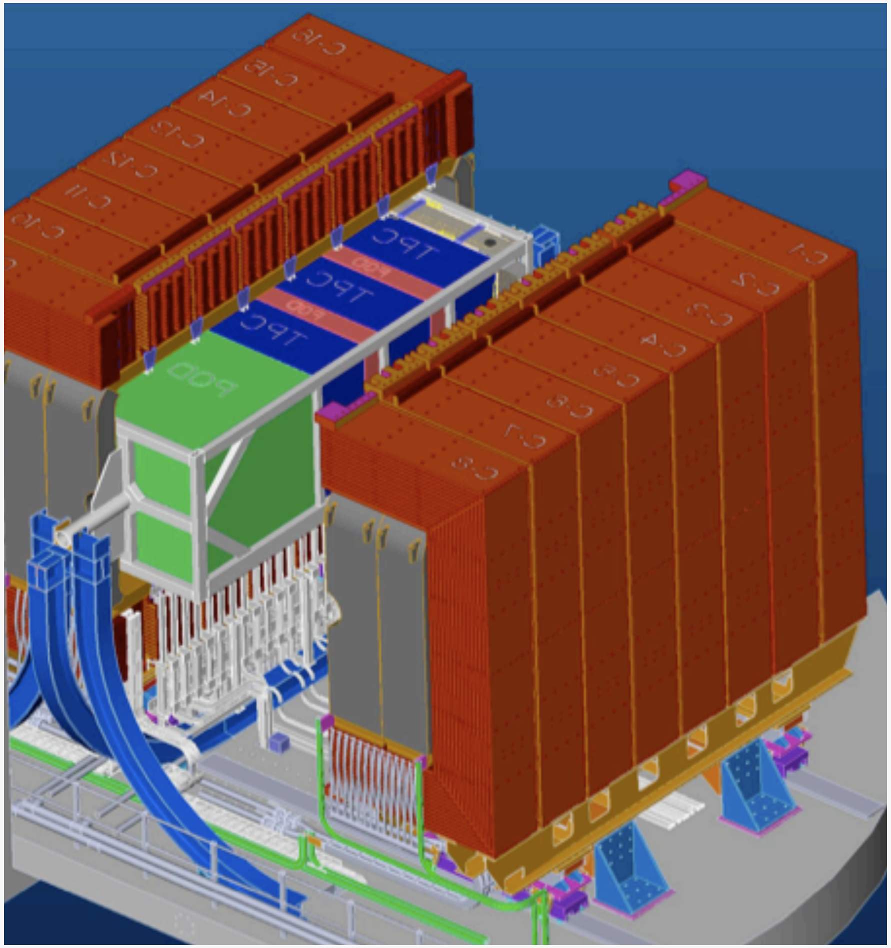


Near detector (ND280)

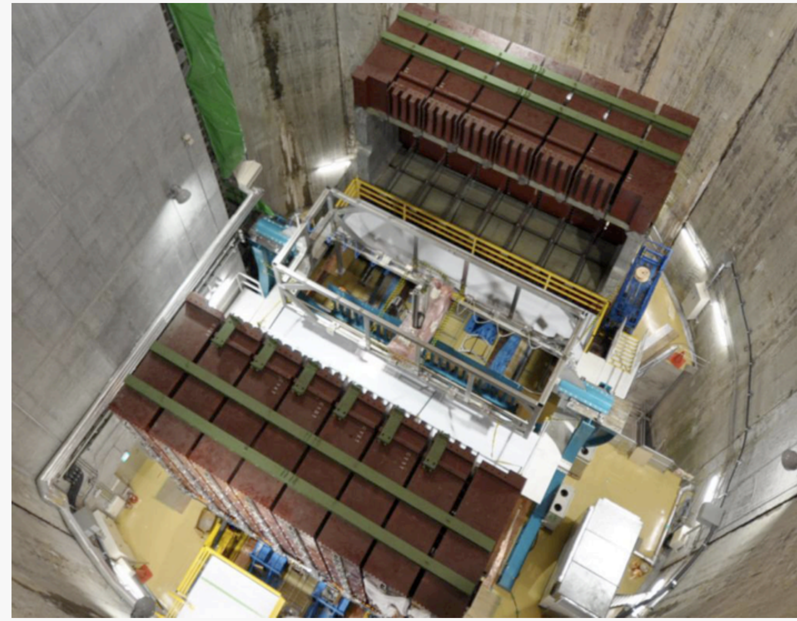




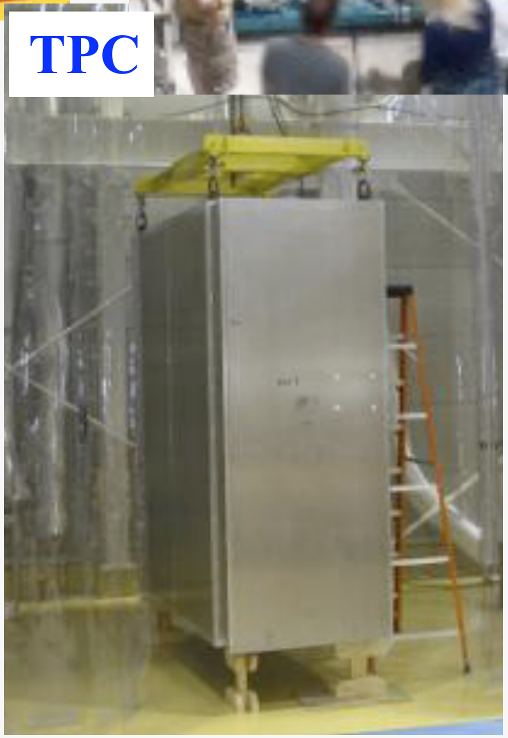
Off-axis near detector

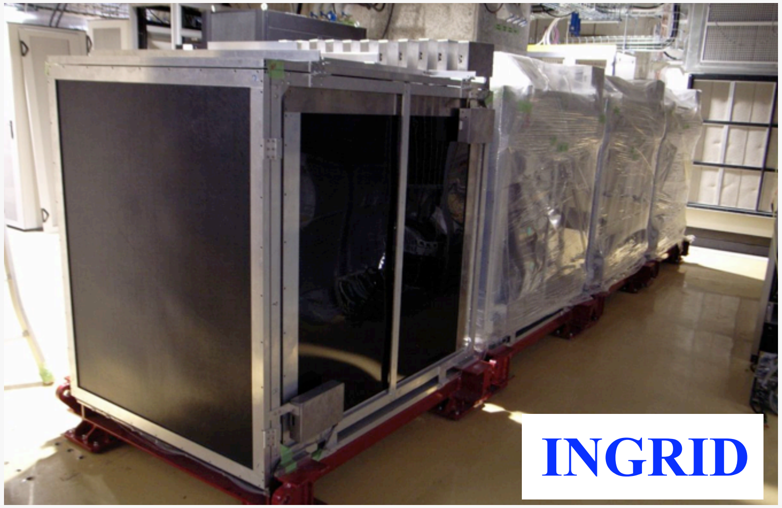


Neutrino detectors surrounded by the UA1 magnet from CERN



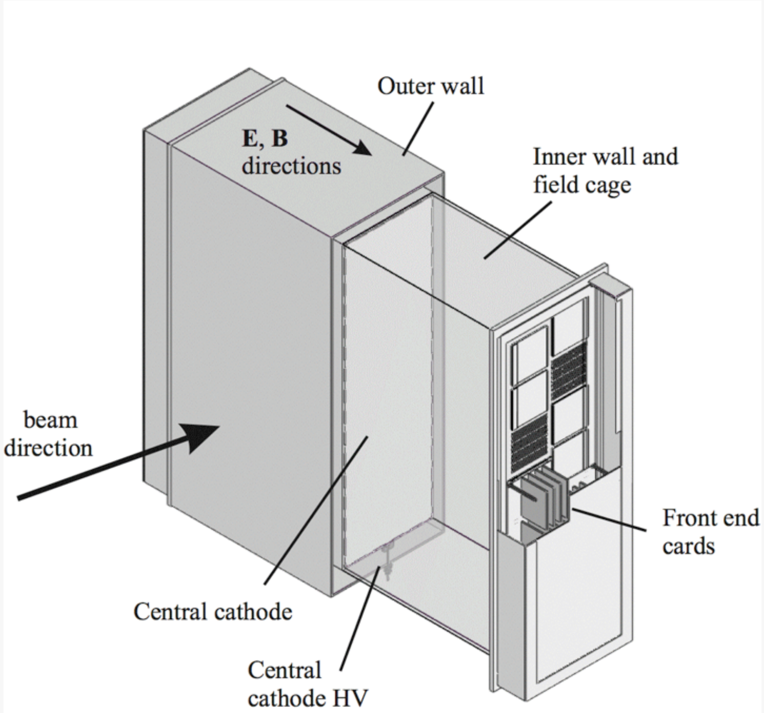
Near detector components

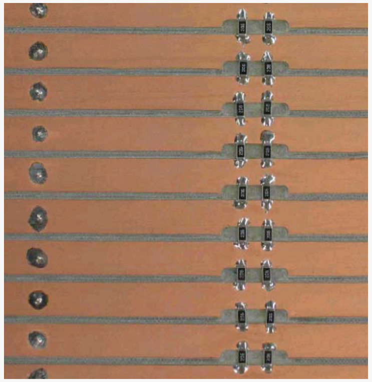




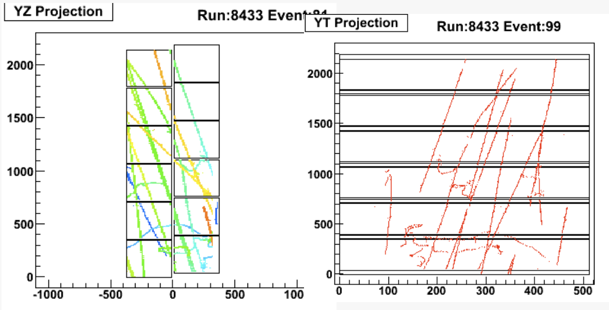
Time Projection Chamber (TPC)

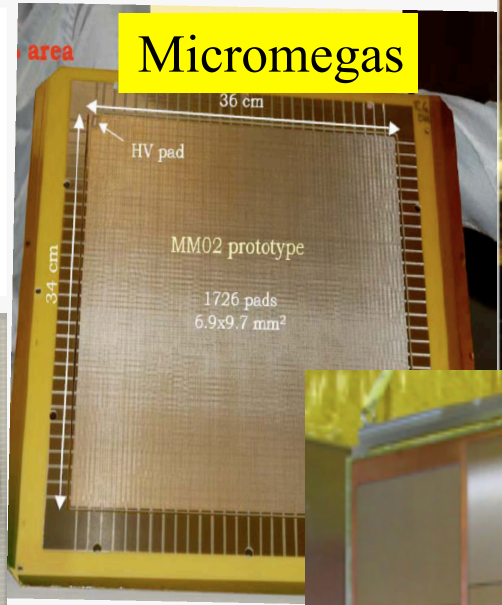
- Requirements
  - momentum resolution<10%
  - dE/dx resolution <10%
  - Energy scale resol. <2%
- Design
  - Double box structure
  - Cupper clad G10/rohacel
    - remove cupper between strips using router
  - Micromegas readout
  - Custom ASIC with SCA (AFTER)
  - Ar-CF_4-iC_4H_{10} (inner) and CO_2 (outer)
    - ΔP<0.1mb between inner and outer volume

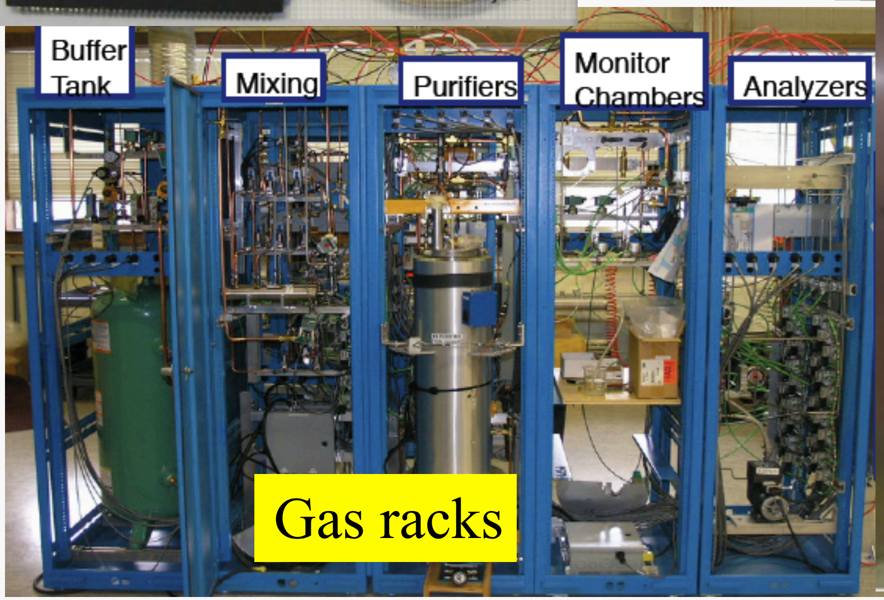


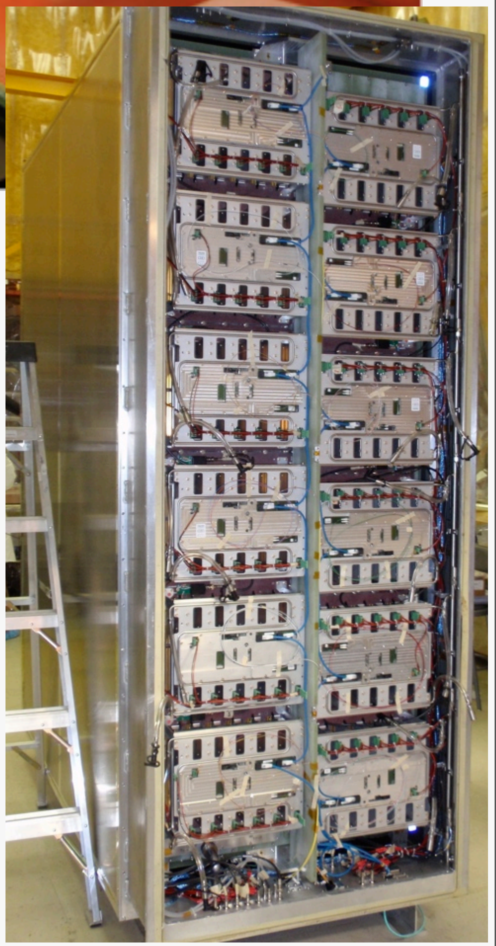


TPC construction

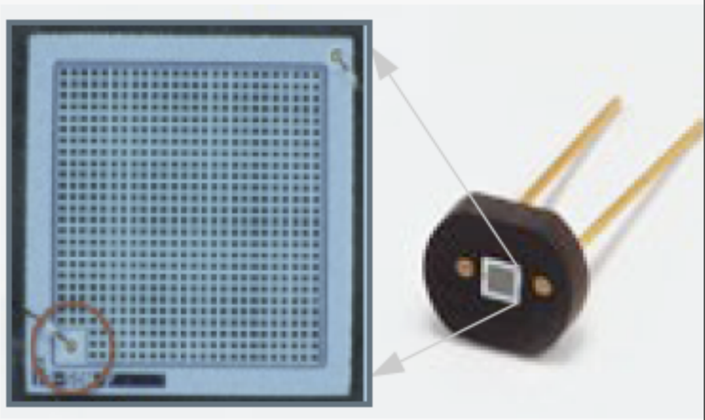




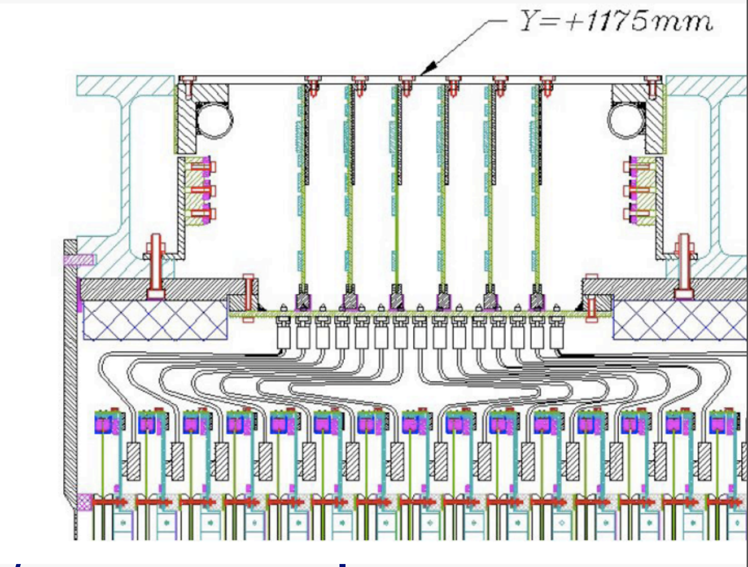




Fine Grained Detector (FGD)

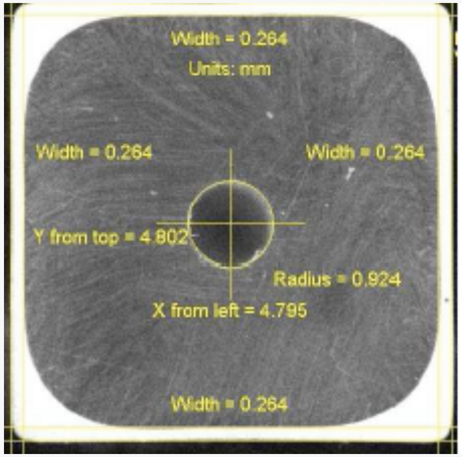


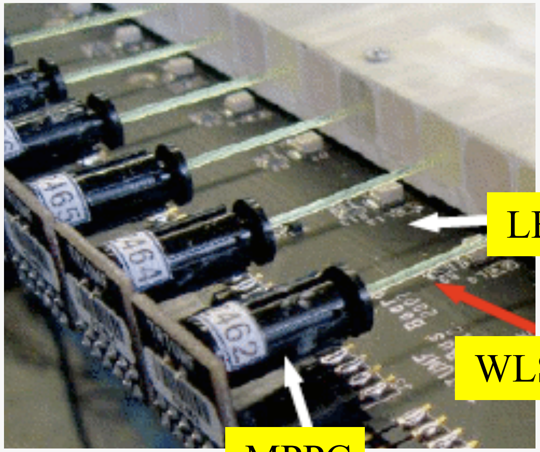
- Target mass for ν interaction
  - 2mx2mx30cm (<1 int. length)
  - one with water layers
- Detect secondaries around vertex
  - Fine granurality (1cmx1cm)
  - Extruded scinti. with WLS fiber
  - MPPC (SiPM) readout
    Photon counting
  - 10μsec-50MHz wave form digitizer for Michel electron (AFTER ASIC)
  - <$50/channel for sensor/electronics/powersupply



FGD construction

Extruded scintillator



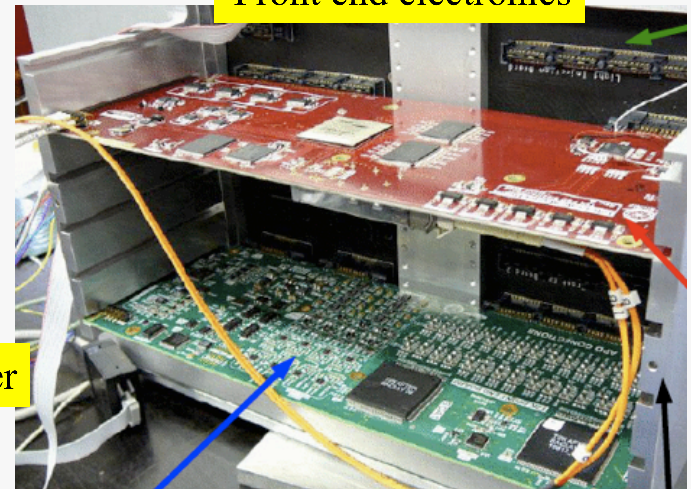


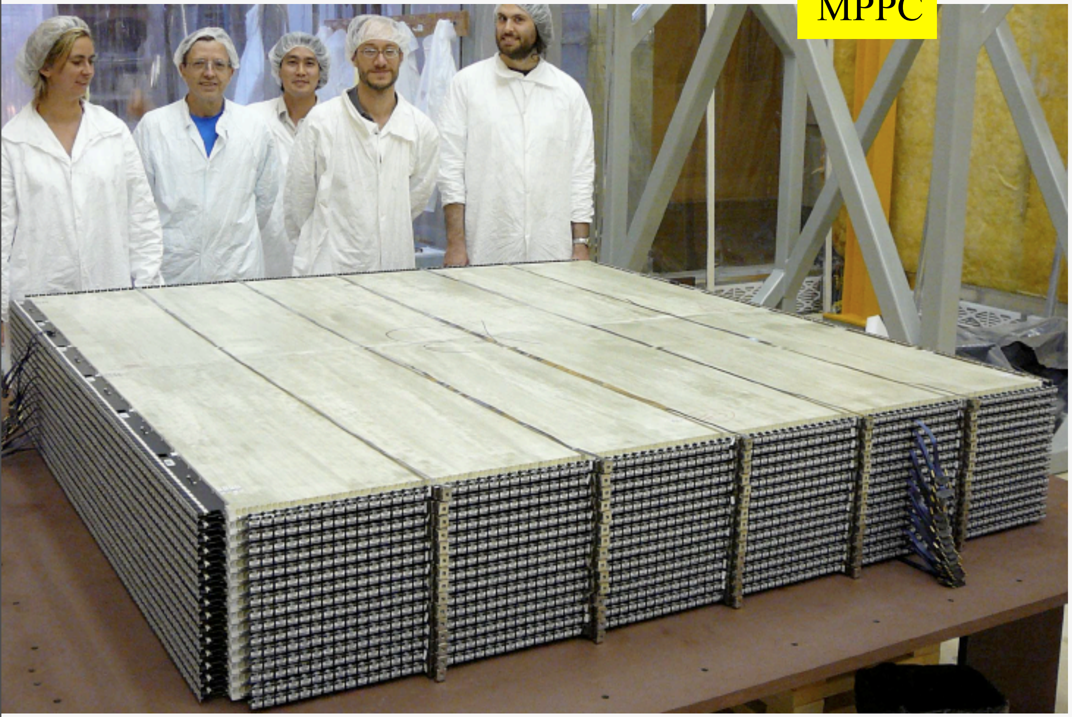
LED

WLS fiber

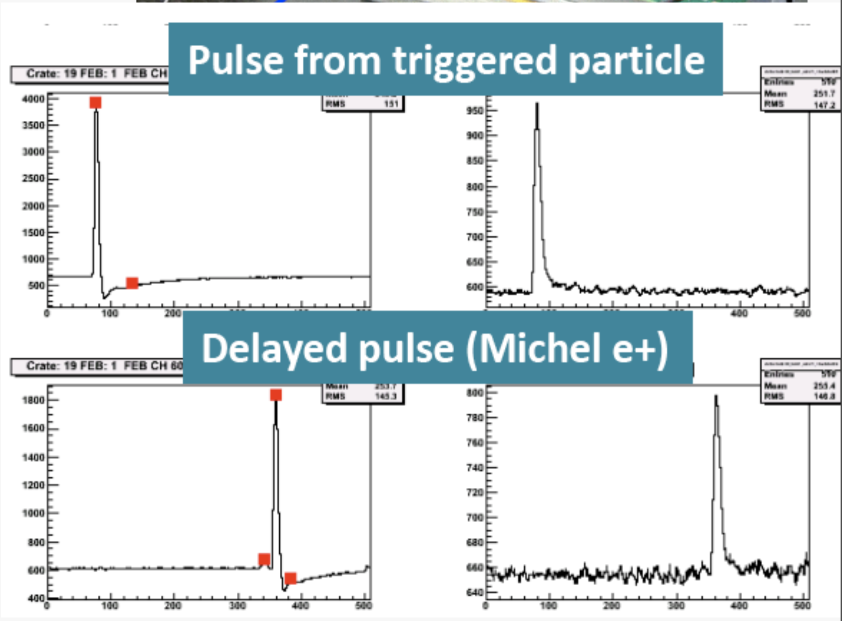
MPPC

Front end electronics





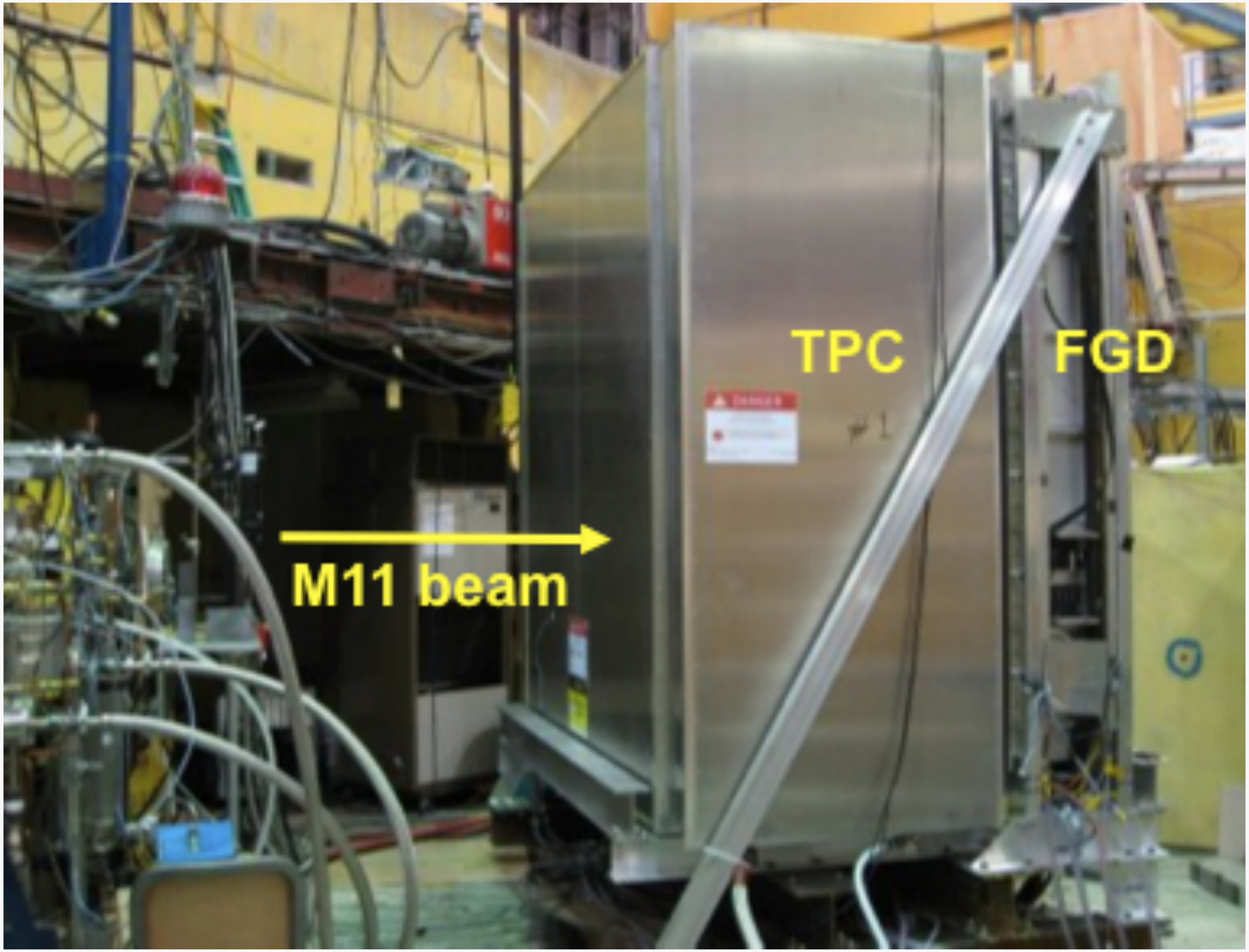
Pulse from triggered particle



Delayed pulse (Michel e+)

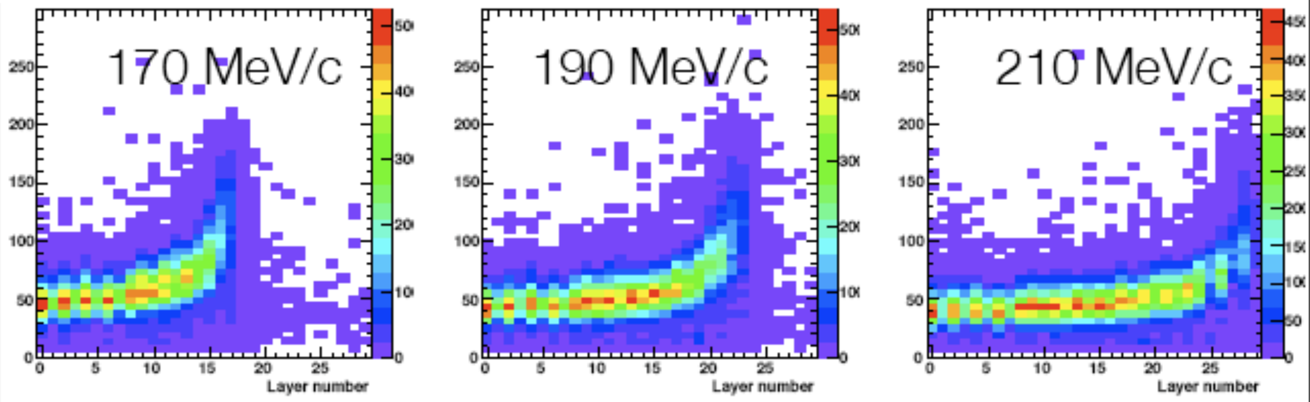
8.5k ch of 50MHz waveform

FGD/TPC beam test at TRIUMF

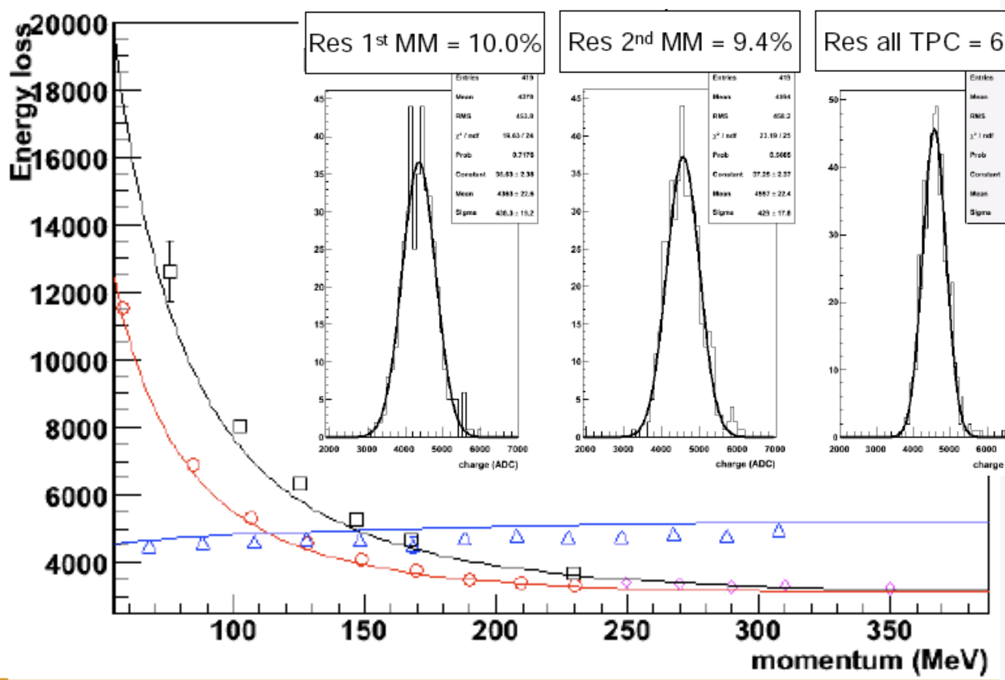


M11 Beam test results

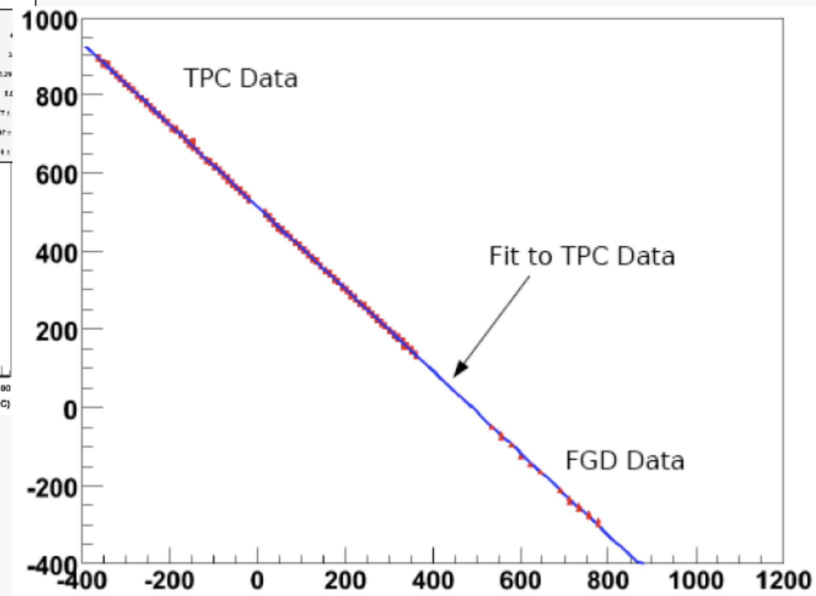
FGD Energy vs. range for muons



TPC dE/dx

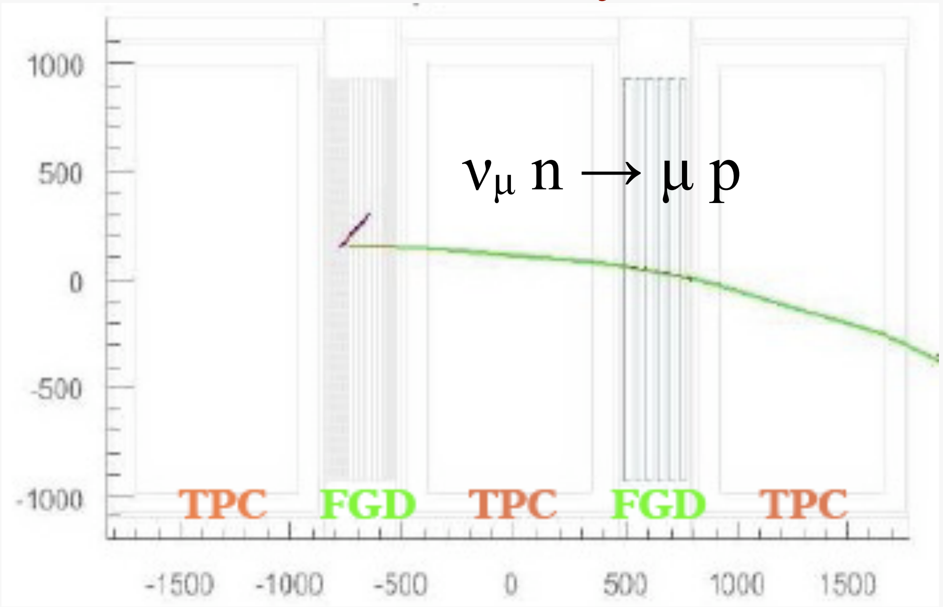


TPC/FGD track match



Flux and cross section study

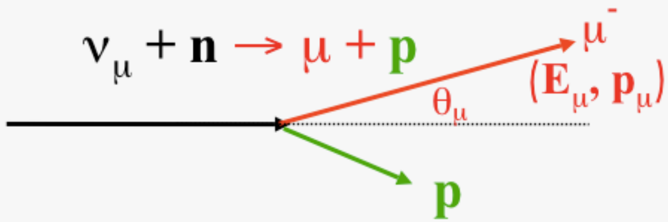
- Detect both leptons and hadrons
  - Clean particle identification
    - Momentum, dE/dx, downstream Ecal
  - Understand hadronic/nuclear uncertainties
    - Vertex activitie detection
    - “Kinematic” & “Calorimetric” ways



Two ways to reconstruct Eν

- **Kinematic way**

$$\nu_\mu + \mathbf{n} \rightarrow \mu + \mathbf{p}$$



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

  - Method used at low energy e.g. SuperK, MiniBooNE
  - Only μ information is needed and little hadronic uncertainty ⇒ **TPC** for PID and P_μ
  - Nuclear uncertainties, such as Fermi motion, Pauli blocking

- **Calorimetric way**

$$\nu_\mu + \mathrm{A} \rightarrow \mu + \mathrm{p} + (\mathrm{A\text{-}1})$$

$$E\nu = E\mu + Ep + M_{(A\text{-}1)} - M_A$$

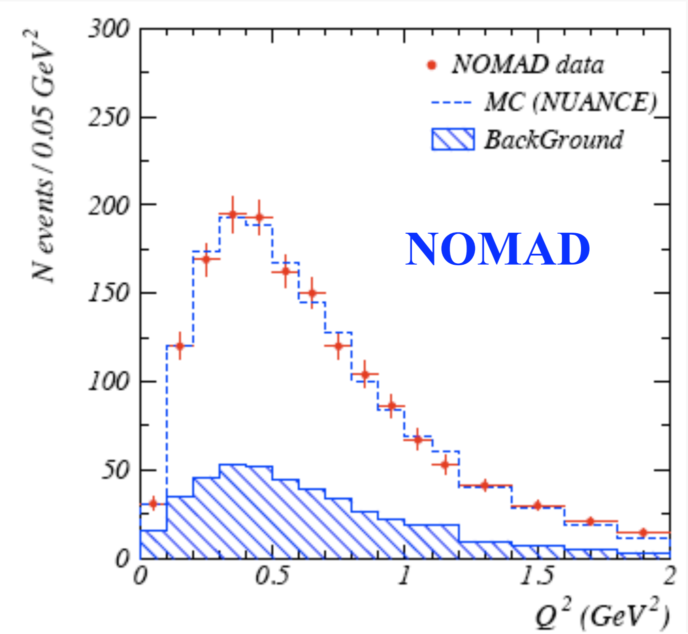
  - Method used at high energy e.g. MINOS, OPERA
  - Nucleus carries little energy ⇒ avoid nuclear uncertainty
  - Uncertainty in hadron (proton) energy measurement ⇒ Detect/identify each hadrons

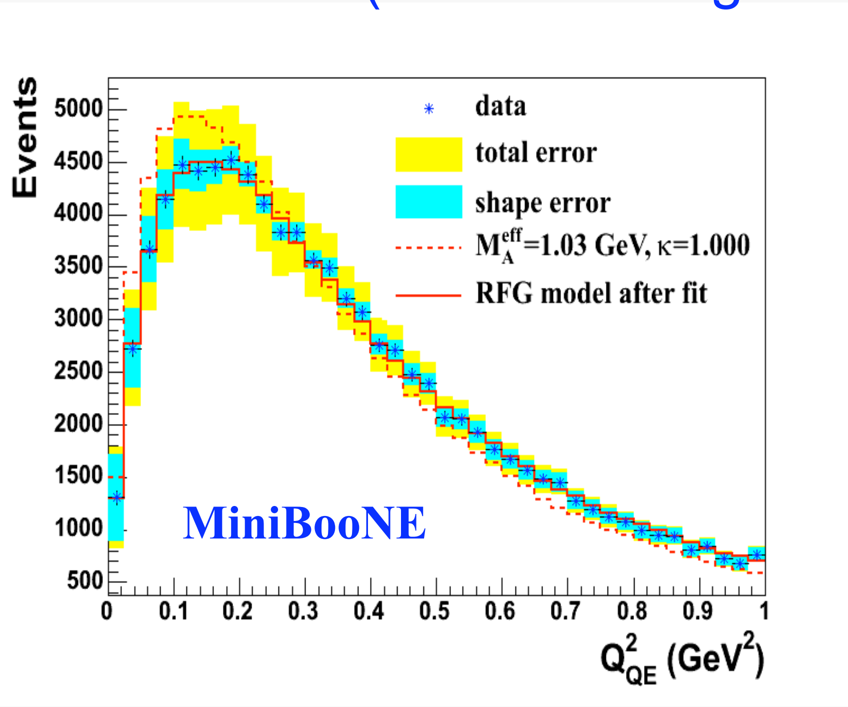
    FGD around the vertex
    TPC detects before interaction

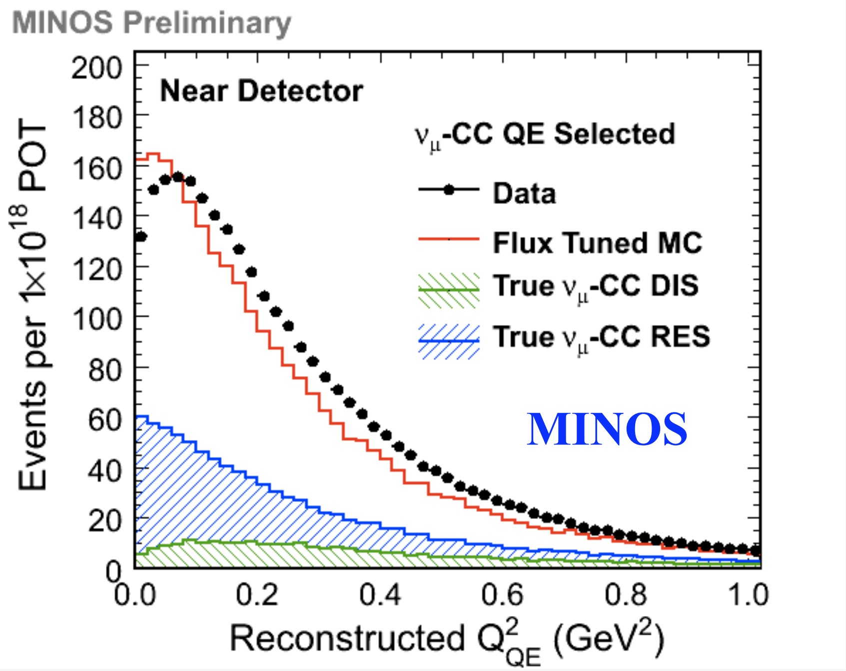
Comparing two method to untangle the nuclear and hadronic uncertainties

CCQE Q^2 distrib.

- Enhancement at high Q^2 region for K2K, SciBooNE, MiniBooNE and MINOS, but consistent for NOMAD.
  Larger effective M_A?
- Deficit at low Q^2 region
  Nuclear effect (Pauli blocking etc.)?

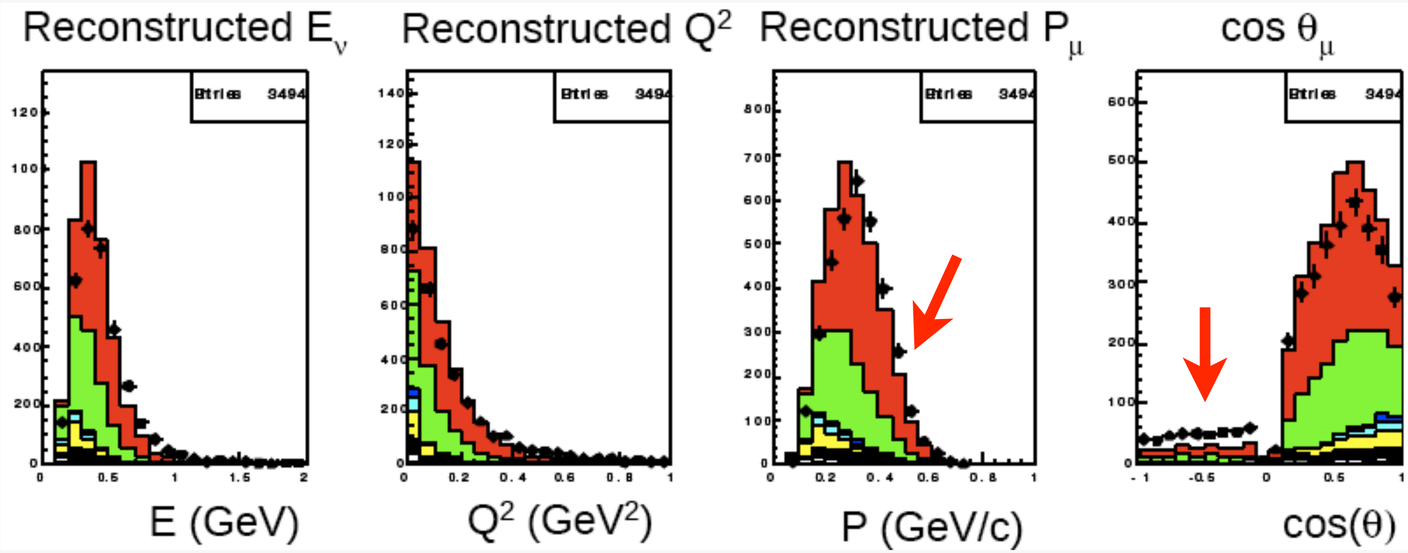






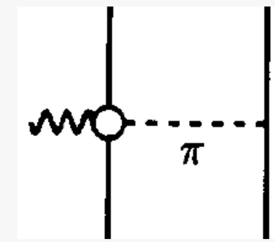
SciBooNE CCQE

SciBooNE CCQE single track data: Preliminary result at NuINT09

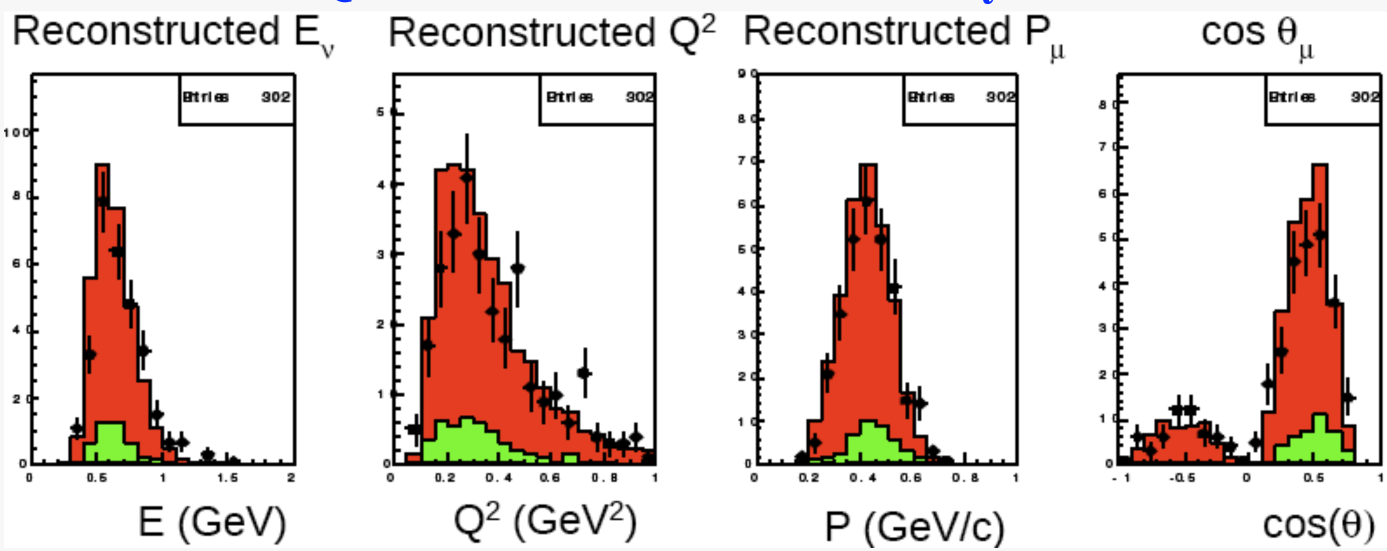


Enhancement with no proton tag

π-exhange current?

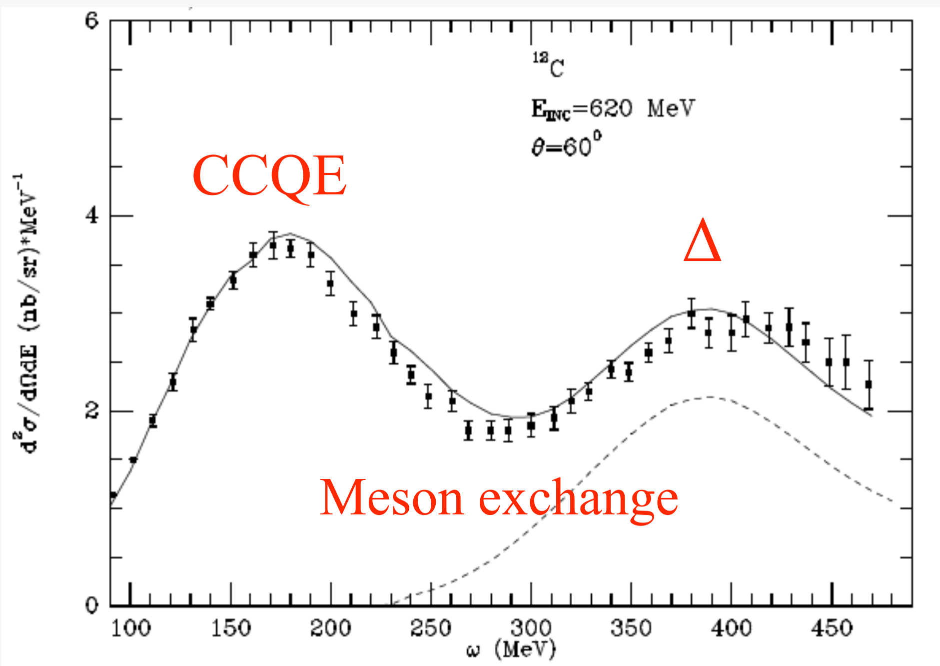


SciBooNE CCQE two track data: Preliminary result at NuINT09

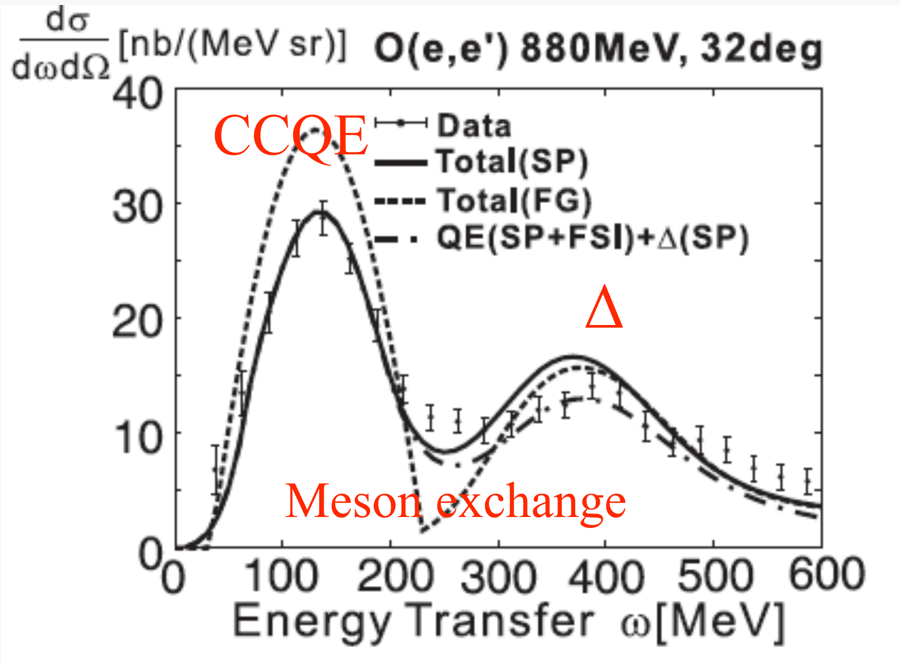


Electron scattering models

NPA627(1997)543

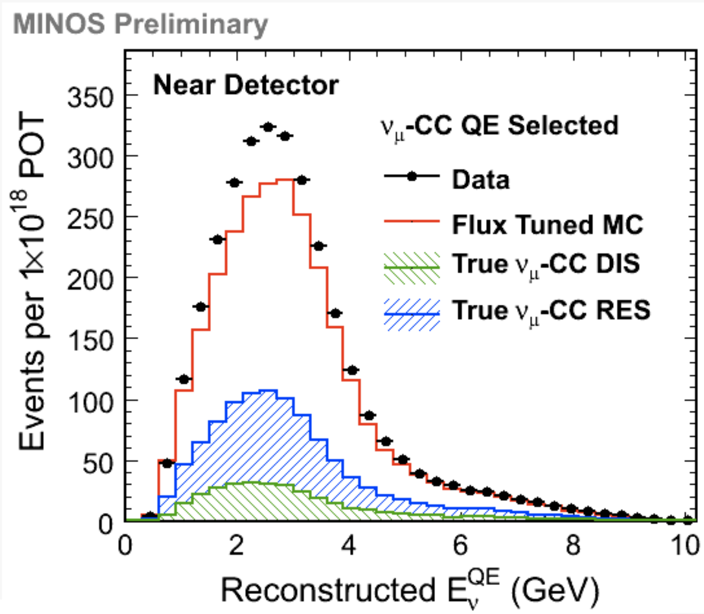


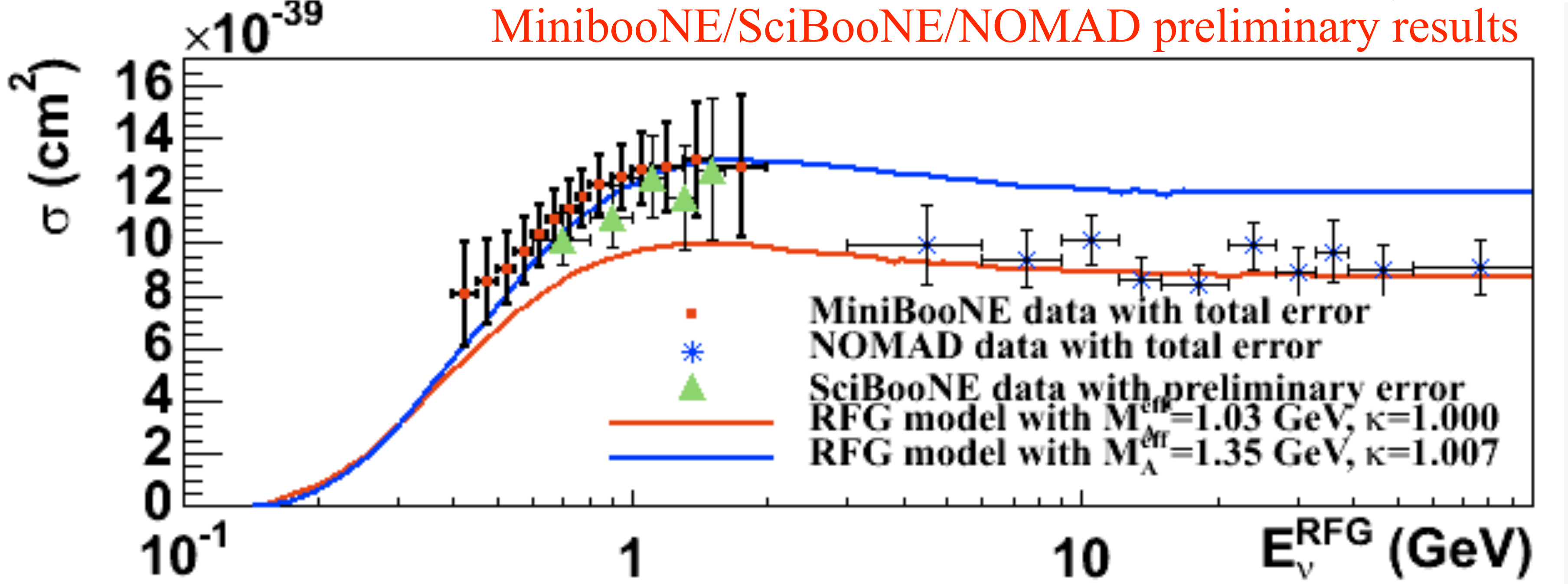
hep-ph/0705.3884



CCQE cross section

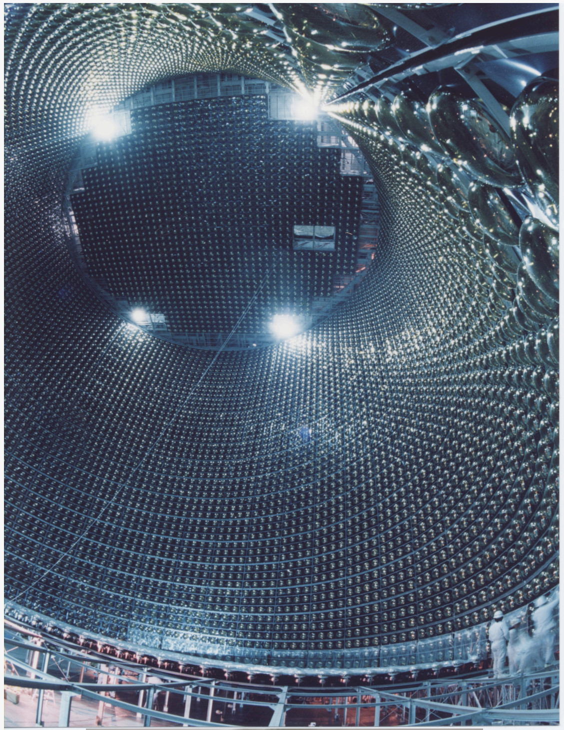
- Cross section is larger than MC up to a few GeV but OK for NOMAD (consistent with large effective M_A)
- Meson exchange current? Nuclear/hadronic effects need to be understood!





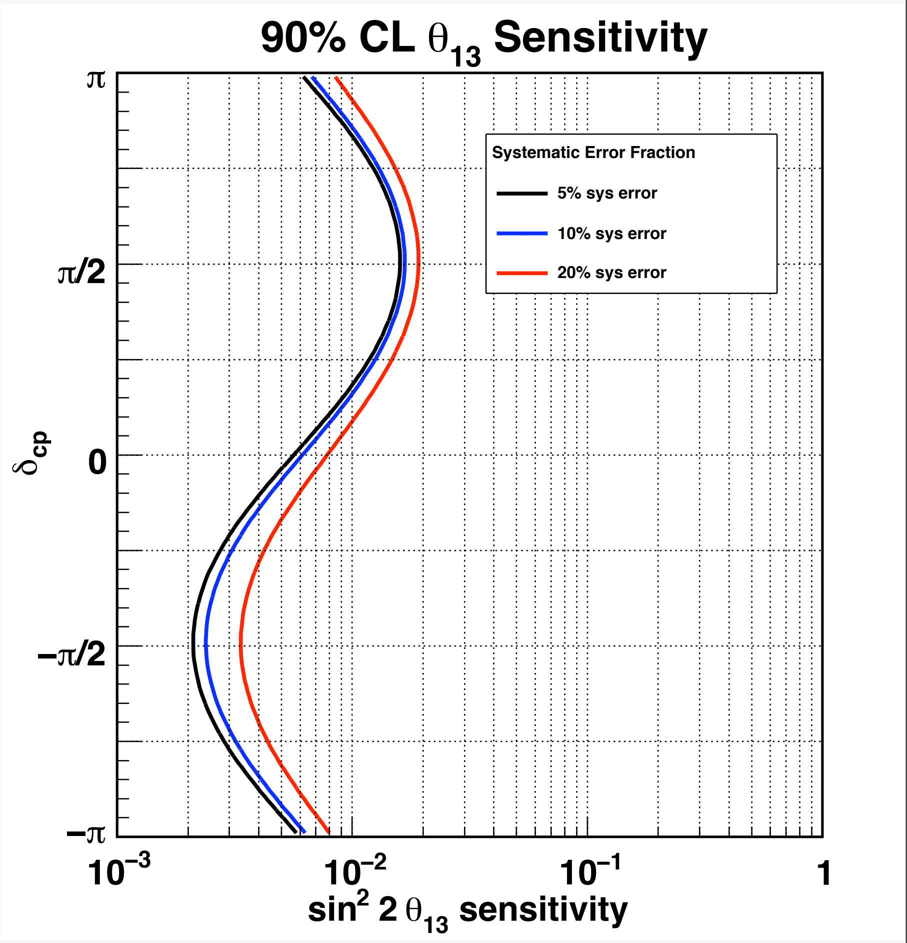
Super-Kamiokande

- SK fully recovered (2006) SK-III
  - PMT's with acrylic/FRP cover
- Electronics/DAQ upgrade SK-IV
  - High speed, deadtime-less
  - Software update and detailed calibration is getting ready.
  - Took T2K trigger data during the beamline commissioning.



Future of T2K

- New far/intermediate detectors for CP
  Water Cerenkov or Liquid Argon
  - **Hyper-K (300km)**
  - Korea (1100km)
  - Okinoshima (600km)
  - 2km detector
- Accelerator upgrades
  - 400MeV linac
  - Faster cycling, more #p
- Future depends on the size of θ_{13}



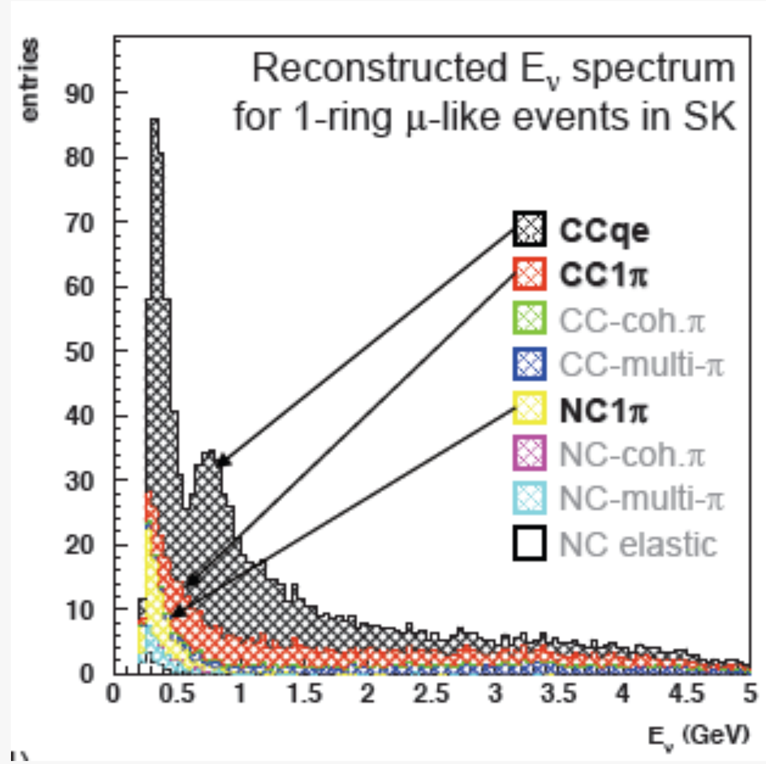
Summary

- T2K accelerator/beamline commissioned in 2009
  - Accelerator worked well but some concerns
    - New RFQ to be installed in summer 2010
  - All the beamline component worked, including the combined function superconducting magnet
    - Commissioning with three horns to take place this fall
- Near detector construction/installation is on schedule to be redy for the physics run in Dec.09 or Jan.2010
  - 100kW(13% of design) x 10^7sec is expected in 2010
  - New technologies (e.g. MPPC, Micromegas)
- SK-IV is up and running
- Physics results expected in a year or two!

Backup slides

Expected SK analysis

- Input cross sections from ND280, miniBooNE etc.
  - ν_μ disappearance
    - CC1π, NC1π
    - Very sensitive to π momentum
  - ν_e appearance
    - NC1π^0, beam ν_e
- Calibration of the SK responses
  - Optical parameters
  - PMT response
  - More stringent study may be required

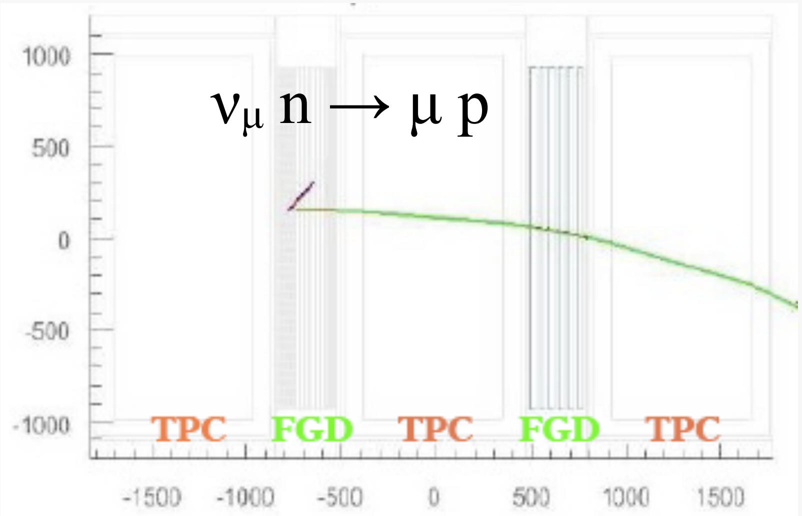


Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	Total	
0.1	10	13	23	103
0.01				10

Expected ND280 analysis

- (ν flux) x (cross section)
  - CCQE : hadronic/nuclear uncertainties
    - "Kinematic" & "Calorimetric" ways
    - Peak energy provides ν direction
  - Electron ID for ν_e detection
    - TPC dE/dx, downstream Ecal
- Background cross sections
  - CC1π :
    - P_π and PID (dE/dx) by TPC [π entering TPC]
    - E_π and PID (dE/dx, Michel) by FGD [π stop in FGD]
  - NC1π^0 : P0D, Ecal

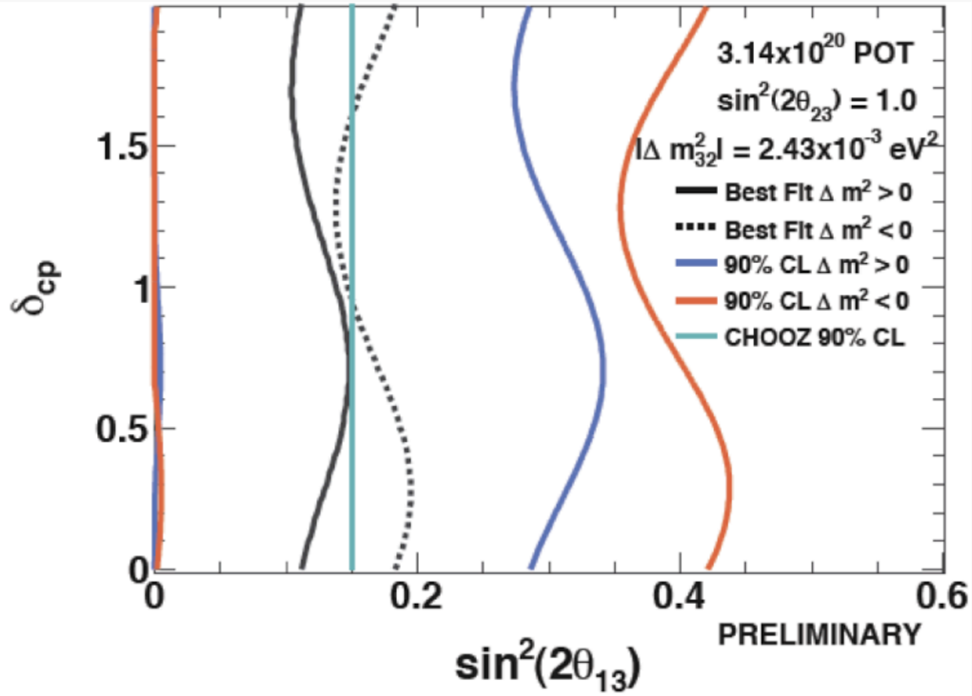


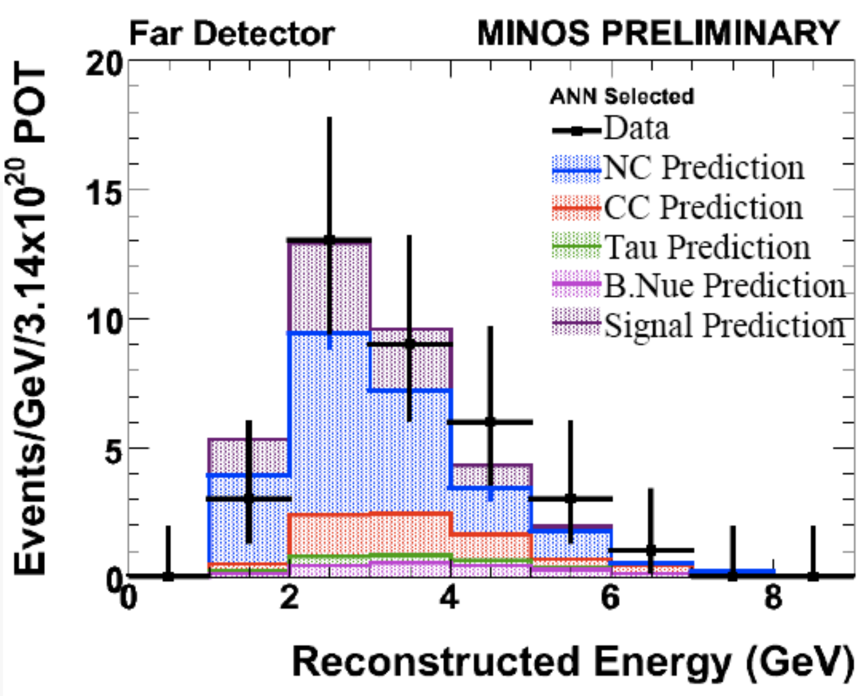
MINOS ν_e appearance result

Far Background: 27±5(stat)±2(sys)

Far Data: 35 events

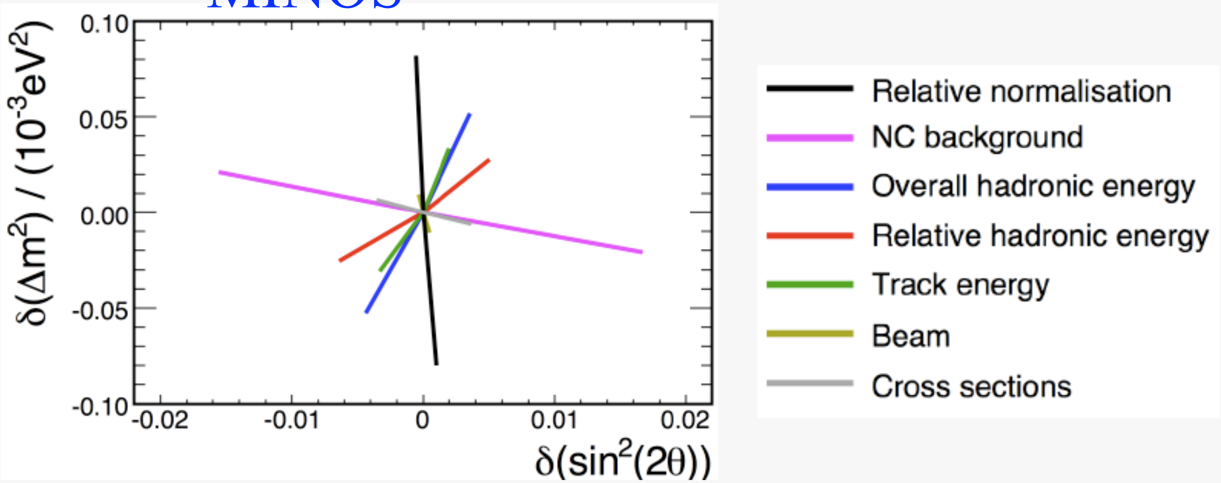
1.5σ excess above background



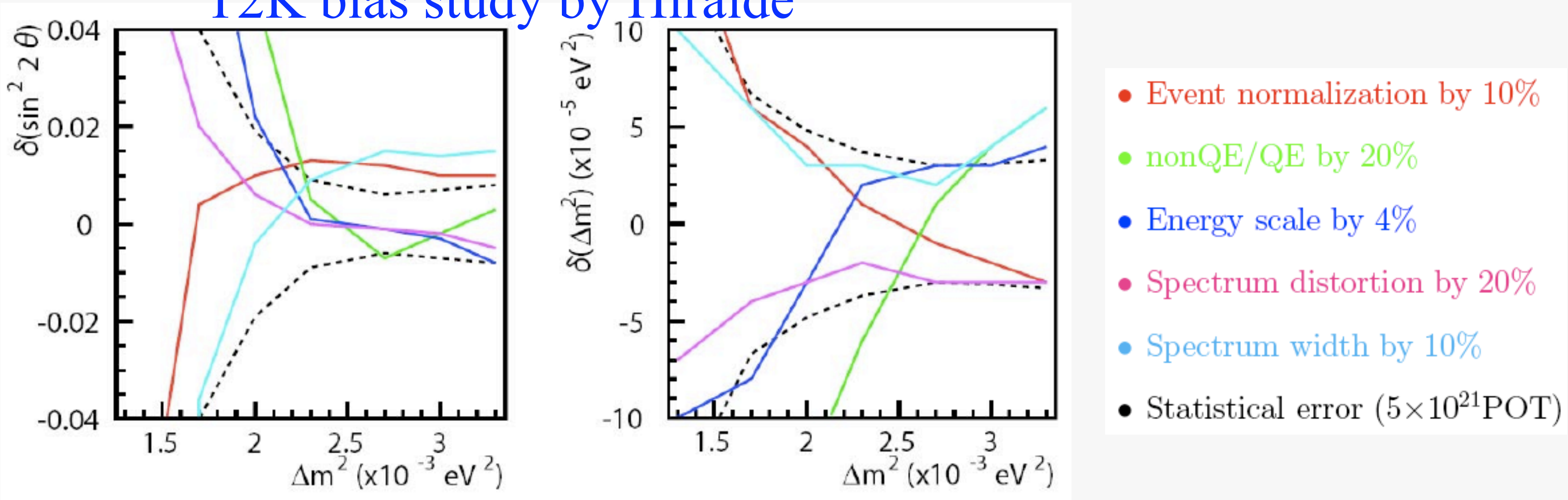


Systematic uncertainties

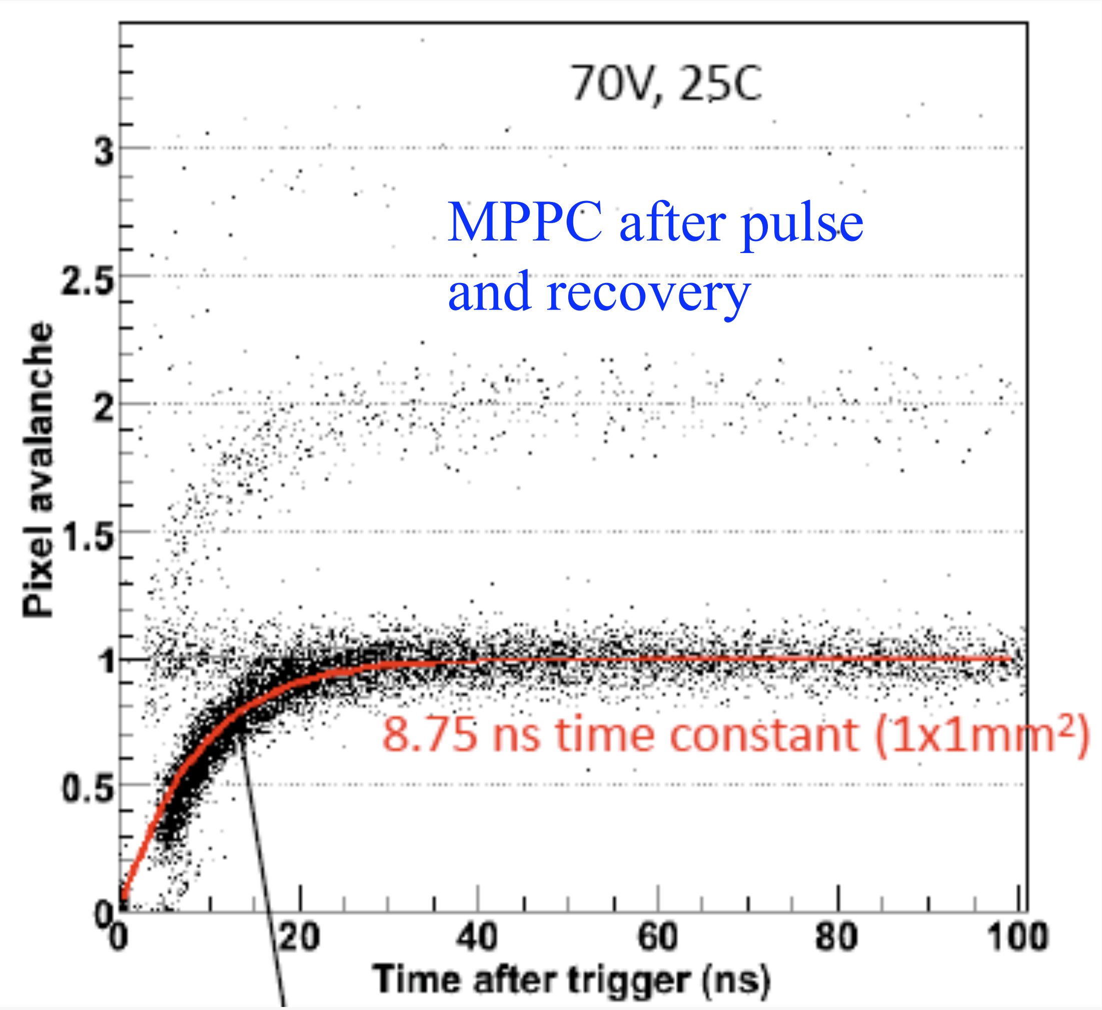
MINOS



T2K bias study by Hiraide

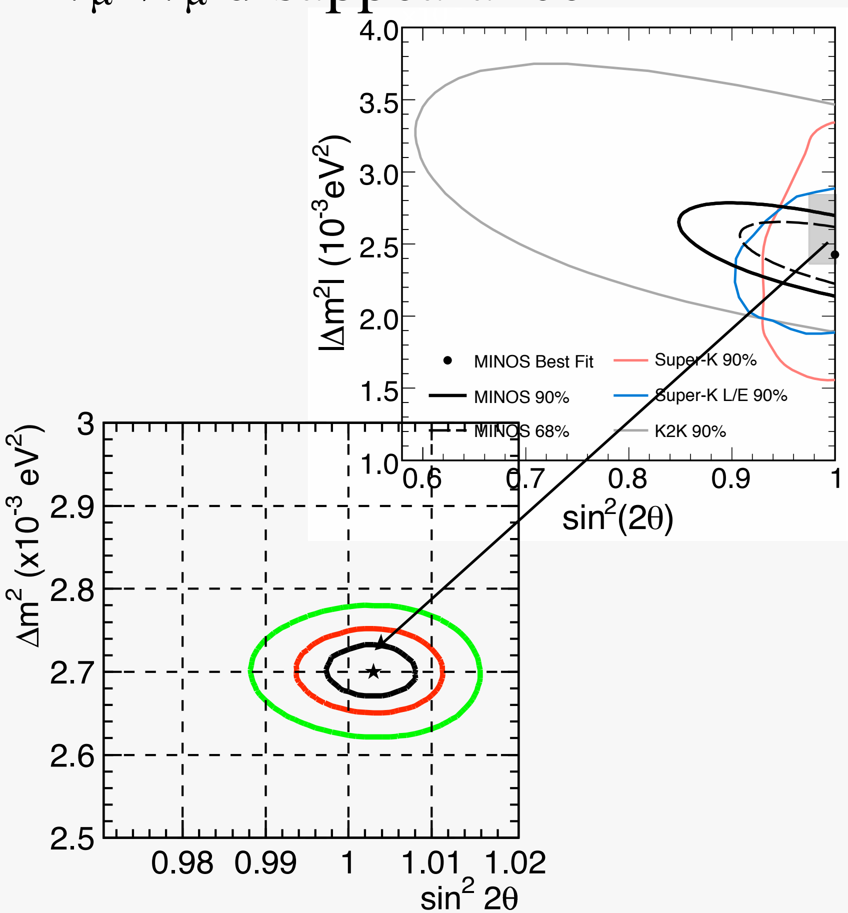


MPPC studies

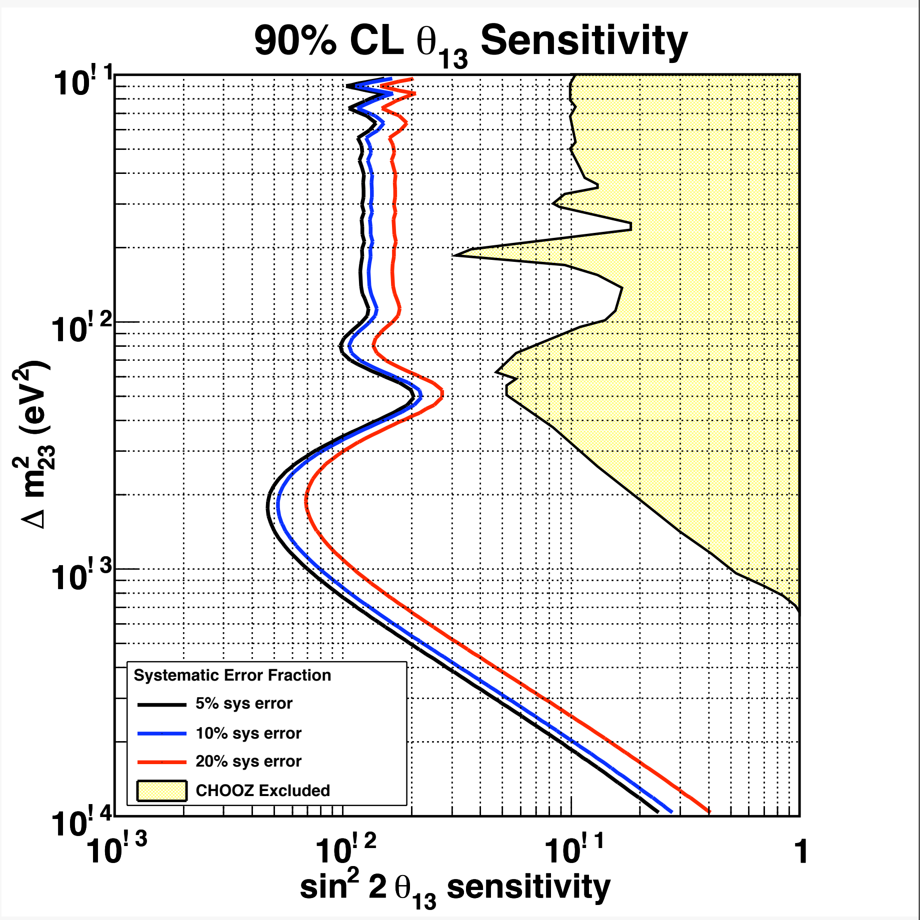


Sensitivities

$\nu_\mu \rightarrow \nu_\mu$ disappearance



$\nu_\mu \rightarrow \nu_e$ appearance



- Precision measurement of θ_{23} and Δm^2_{23}
- 20 times improvement in sensitivity in $\sin^2 2\theta_{13}$