TRIUMF

Status of T2K

Long-baseline neutrino experiment

TRIUMF
Alberta
British Columbia
Regina
Toronto
Victoria
York

Akira Konaka (TRIUMF)

T2K collaboration

~400 collaborators, 65 institutes, 12 countries

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
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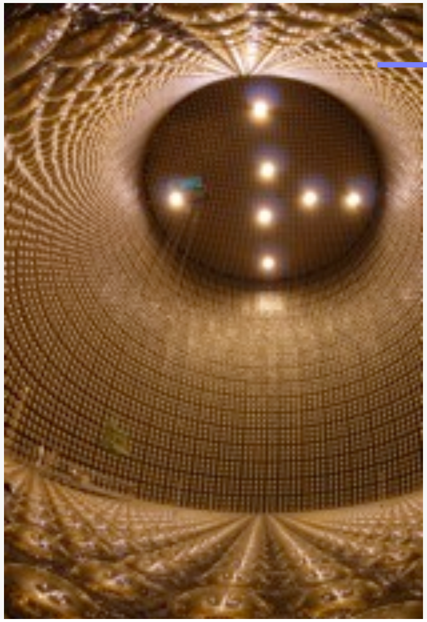
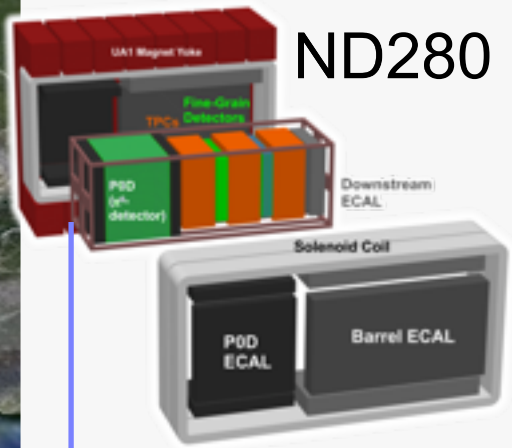
Lancaster U.
Liverpool U.
Oxford U.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury
USA
Boston U.
BNL
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
U.C.Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

T2K experiment



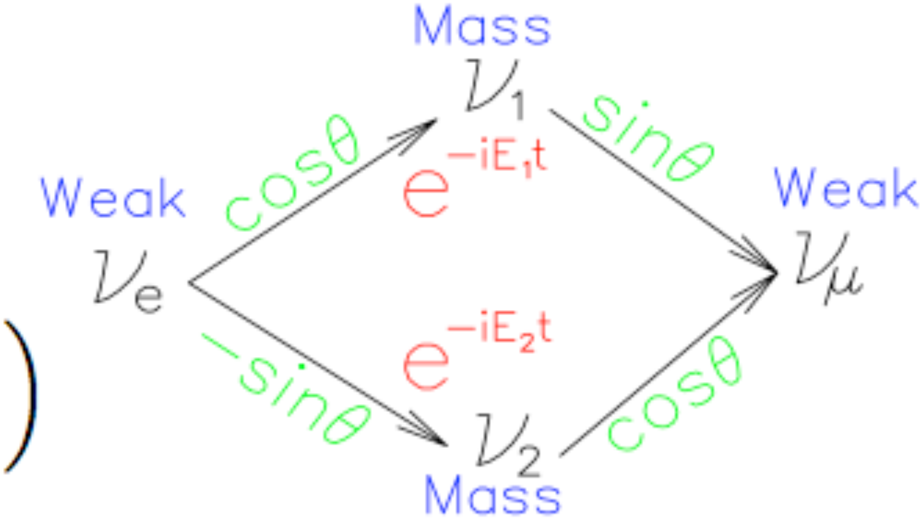
Super-Kamiokande



- 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.

Neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$\begin{aligned} P(\nu_e \to \nu_\mu) &= \left|\sin\theta\cos\theta\left(e^{-iE_1t} - e^{-iE_2t}\right)\right|^2 \\ &= \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L(km)}{E(GeV)} \end{aligned}$$

- Weak and mass eigenstates of neutrinos differs
- Quantum mechanical interference causes neutrino oscillation

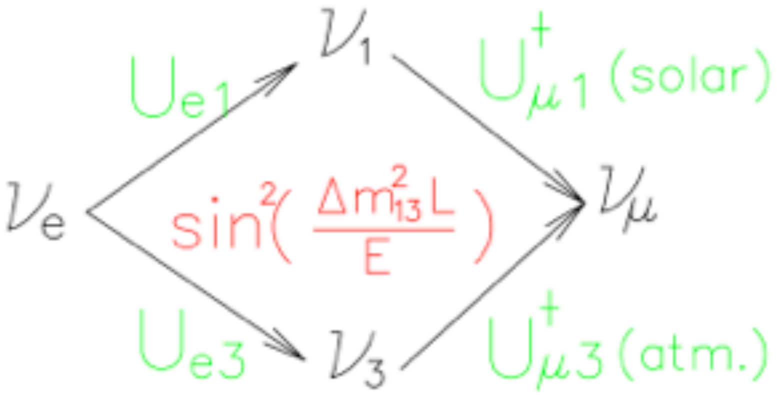
3 generation neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Leptonic CKM
(MNS matrix)

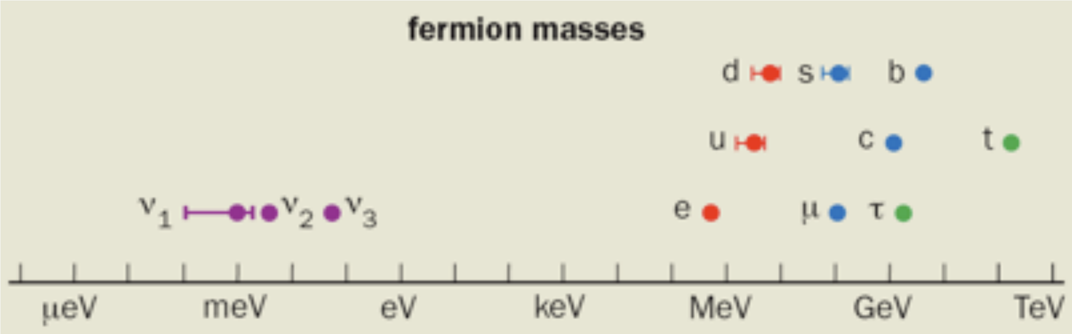
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \cos\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\cos\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_e \rightarrow \nu_\mu$ is suppressed
due to small Δm^2_{12}
$\Delta m^2_{13}(\theta_{13})$ term dominates



Why neutrino is interesting?

- Neutrino mass indicates new energy scale



- See-saw mechanism
  - Mixing of Dirac & Majorana mass explains small m_ν

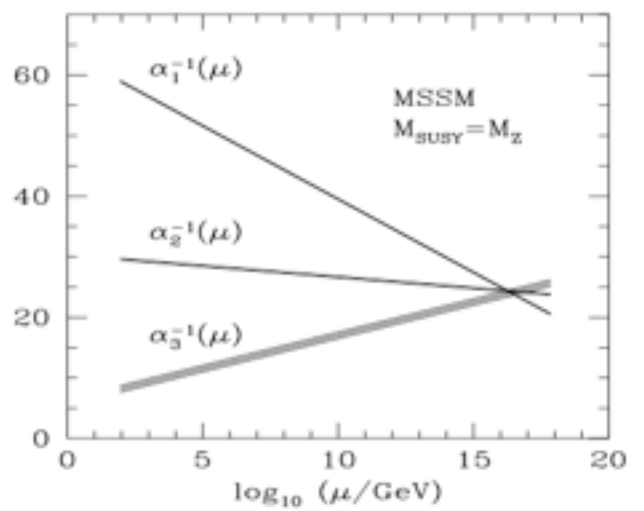
$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & m_D \\ \nu_R & m_D & M \end{array} \qquad m_{light} = \frac{m_D^2}{M}$$

  - Majorana mass is at GUT scale

$$M \sim \frac{m_D^2}{m_{light}} \sim \frac{(250GeV)^2}{\sqrt{2.5\times10^{-3}eV^2}} \sim 10^{15}GeV$$

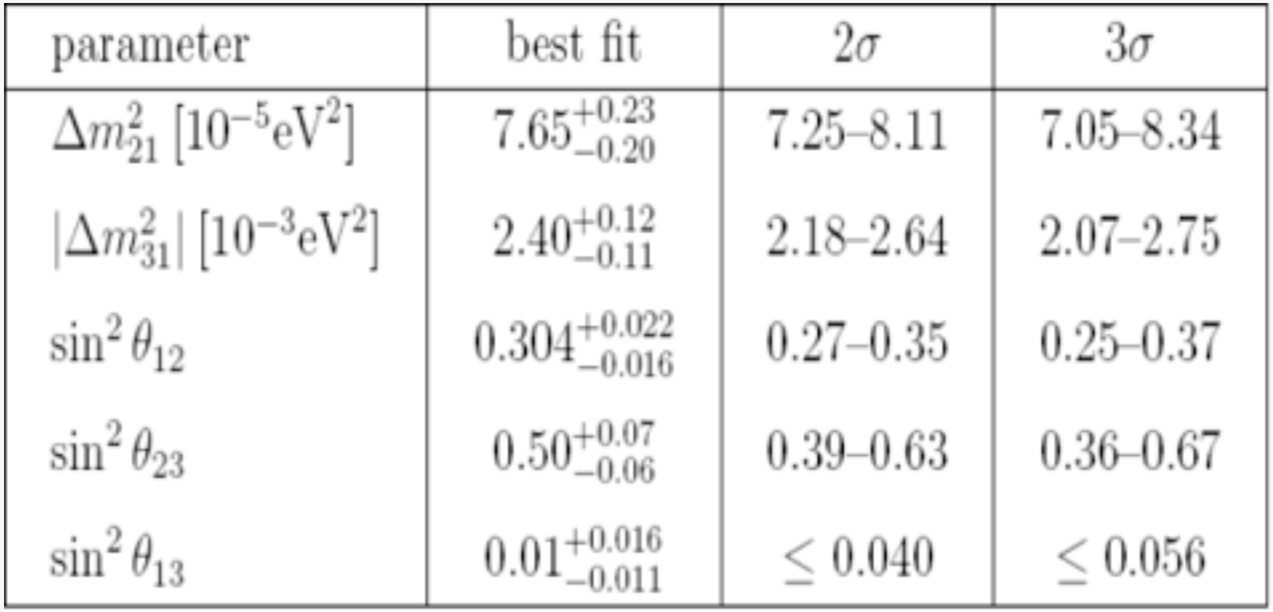
  - ~~CP~~ explains Baryon Asymmetry

Leptogenesis



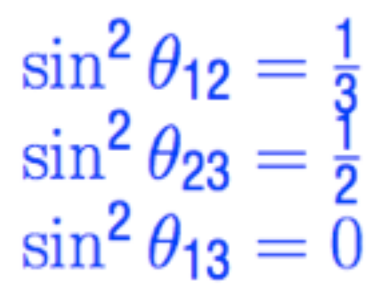
Large lepton mixing (PMNS)

Giving us information at GUT scale?

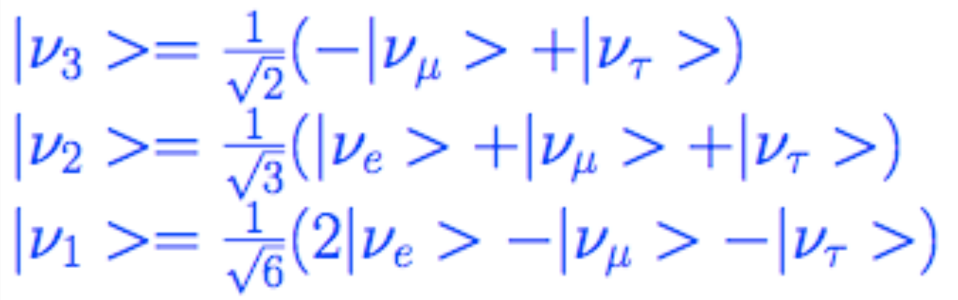


parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$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

Tri-Bimaximal?



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



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

Quark mixing (CKM matrix)

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

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

Almost diagonal

Cabbibo angle

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

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

Tri-bimaximal?

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

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

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

Breaking at O(λ,λ^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)

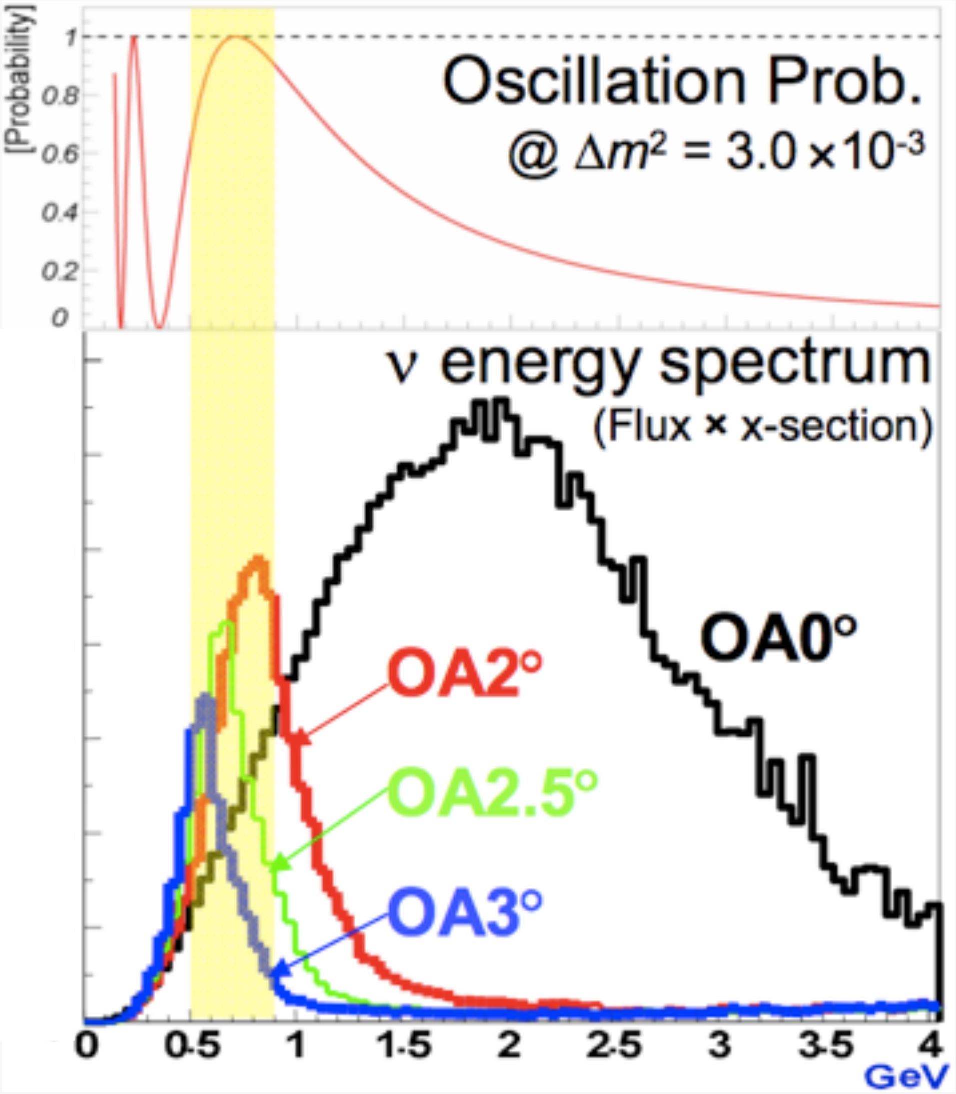
$\sin\vartheta_{12}$: ν_e disappearance (solar ν, reactor ν)

Basic idea of T2K experiment

- 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)



ν_μ disappearance

- $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2 L/E_\nu)$

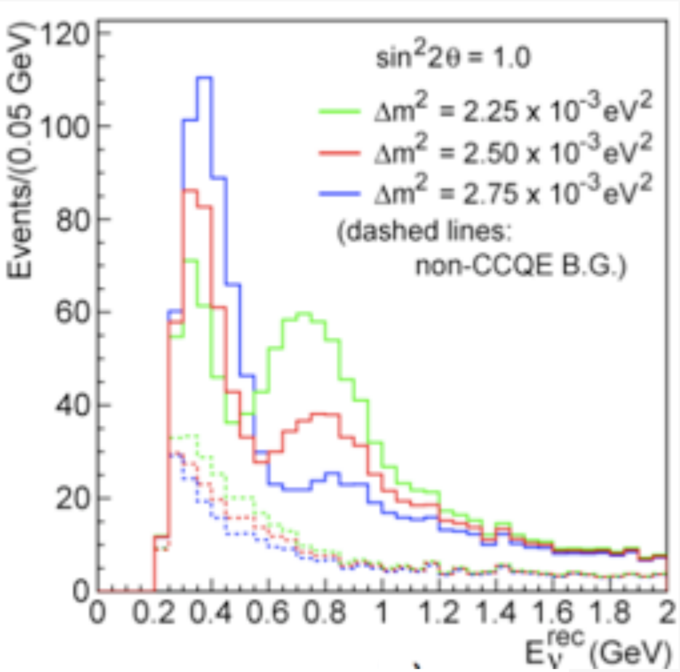
  $\sin^2 2\theta_{23} = 1$ or <1?
- Oscillation pattern in SuperK rate

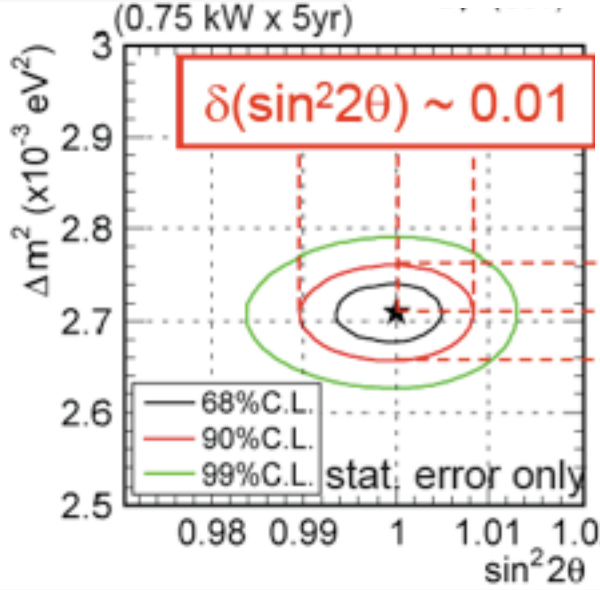
  $\sin^2 2\theta_{23}$: Depth of E_ν dip

  Δm^2_{23} : Position of E_ν dip
- 5 year sensitivity

  $\partial(\sin^2 2\theta_{23}) \approx 0.01$

  $\partial(\Delta m_{23}^2) \approx 0.0001 \text{eV}^2$

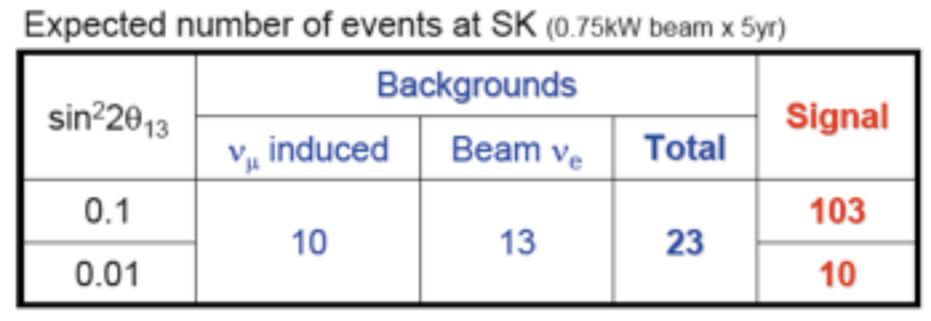




ν_e appearance

- $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{13}L/E_\nu)$+ CP viol.+...
  $\theta_{13} \neq 0$?

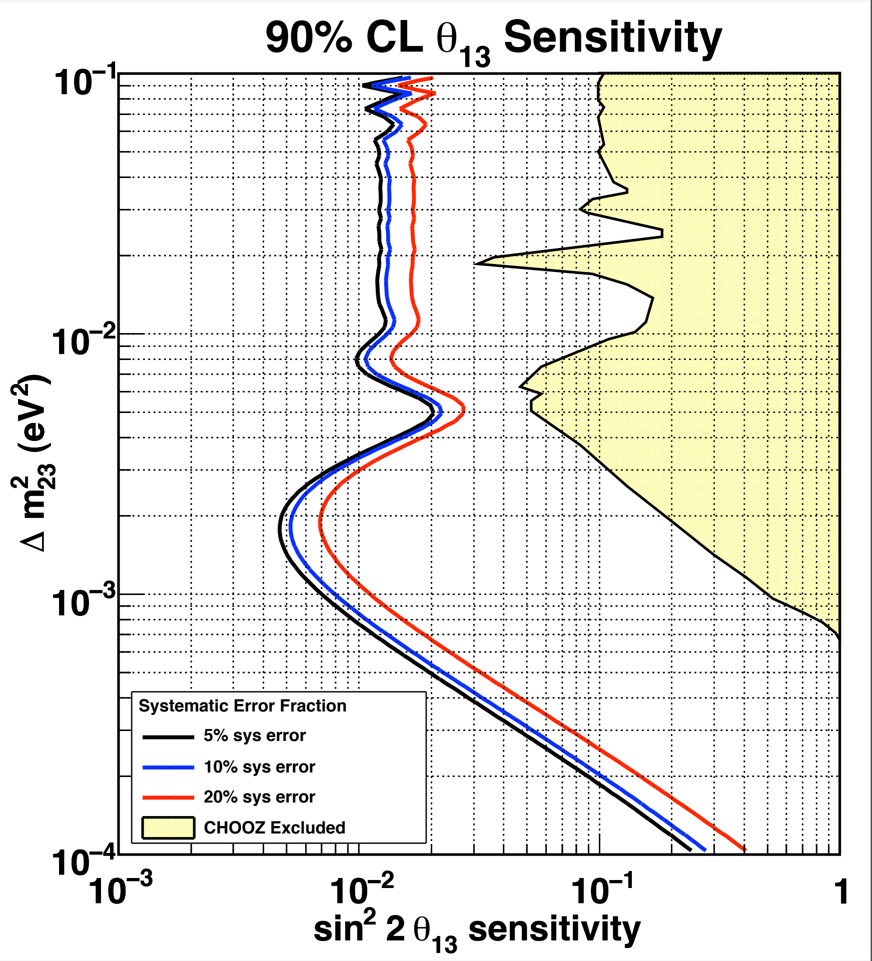
- 90% CL sensitivity
  $\sin^2 2\theta_{13} \sim 0.006$ for 750kWx5yr



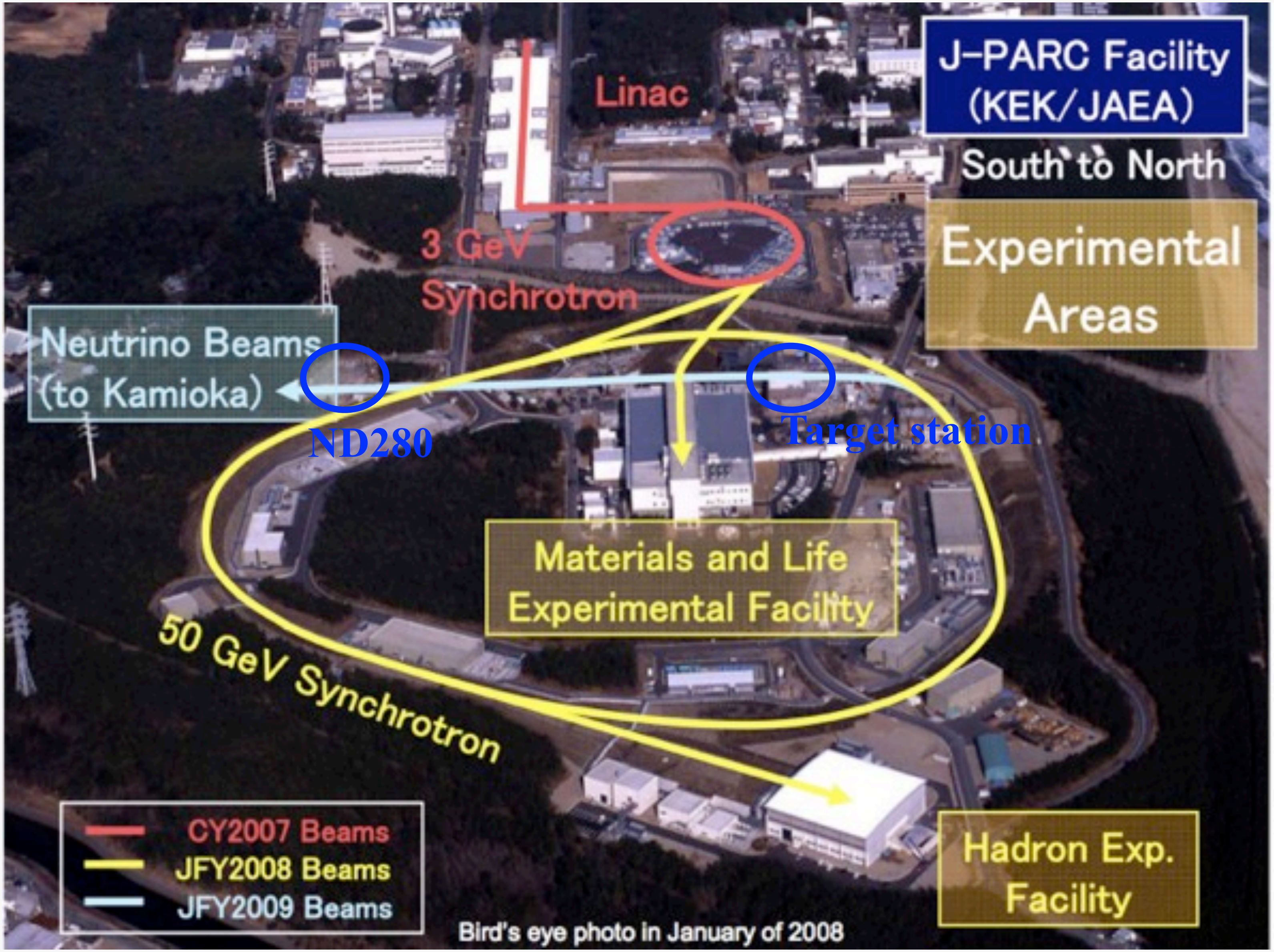
Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	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}

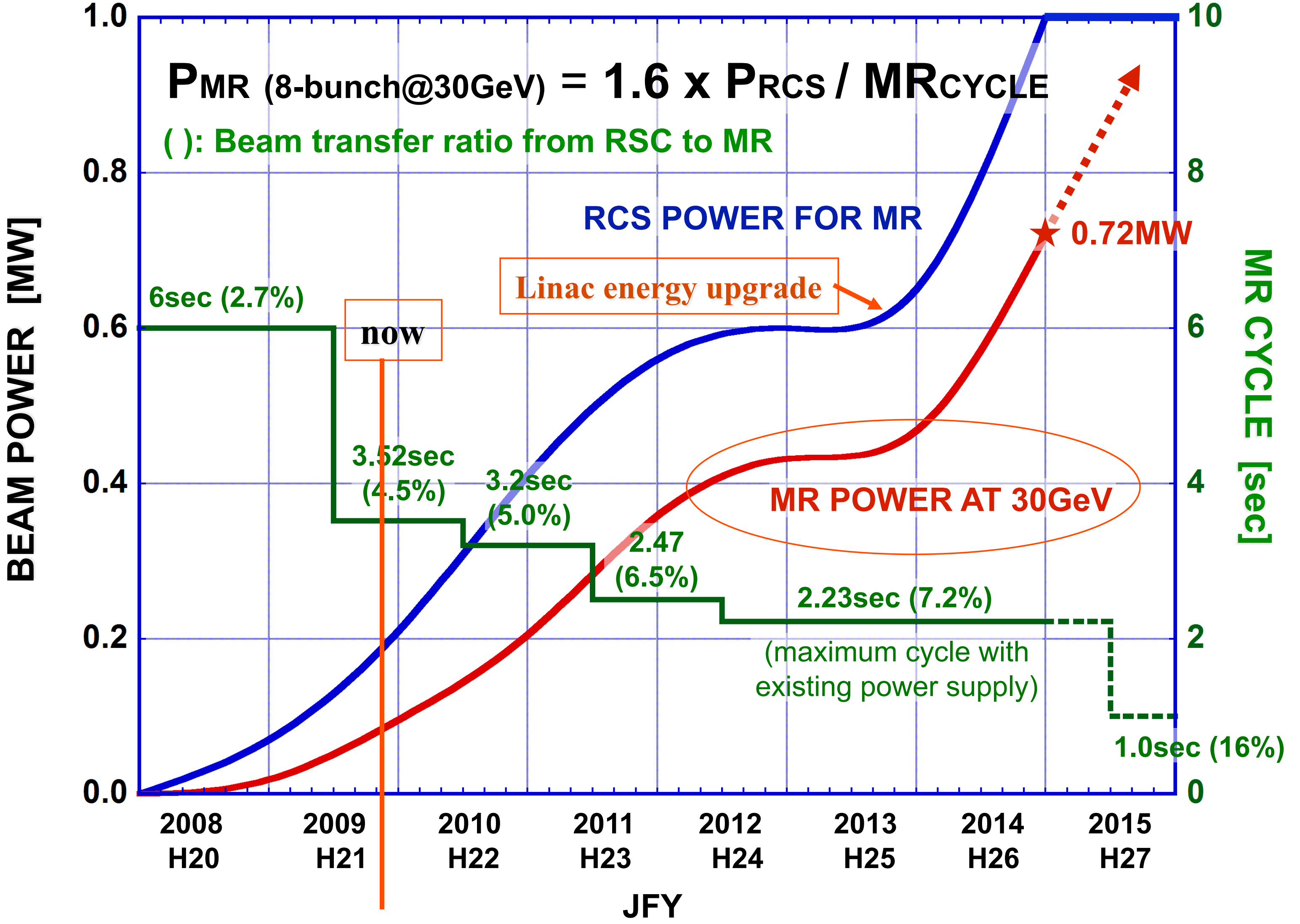


J-PARC

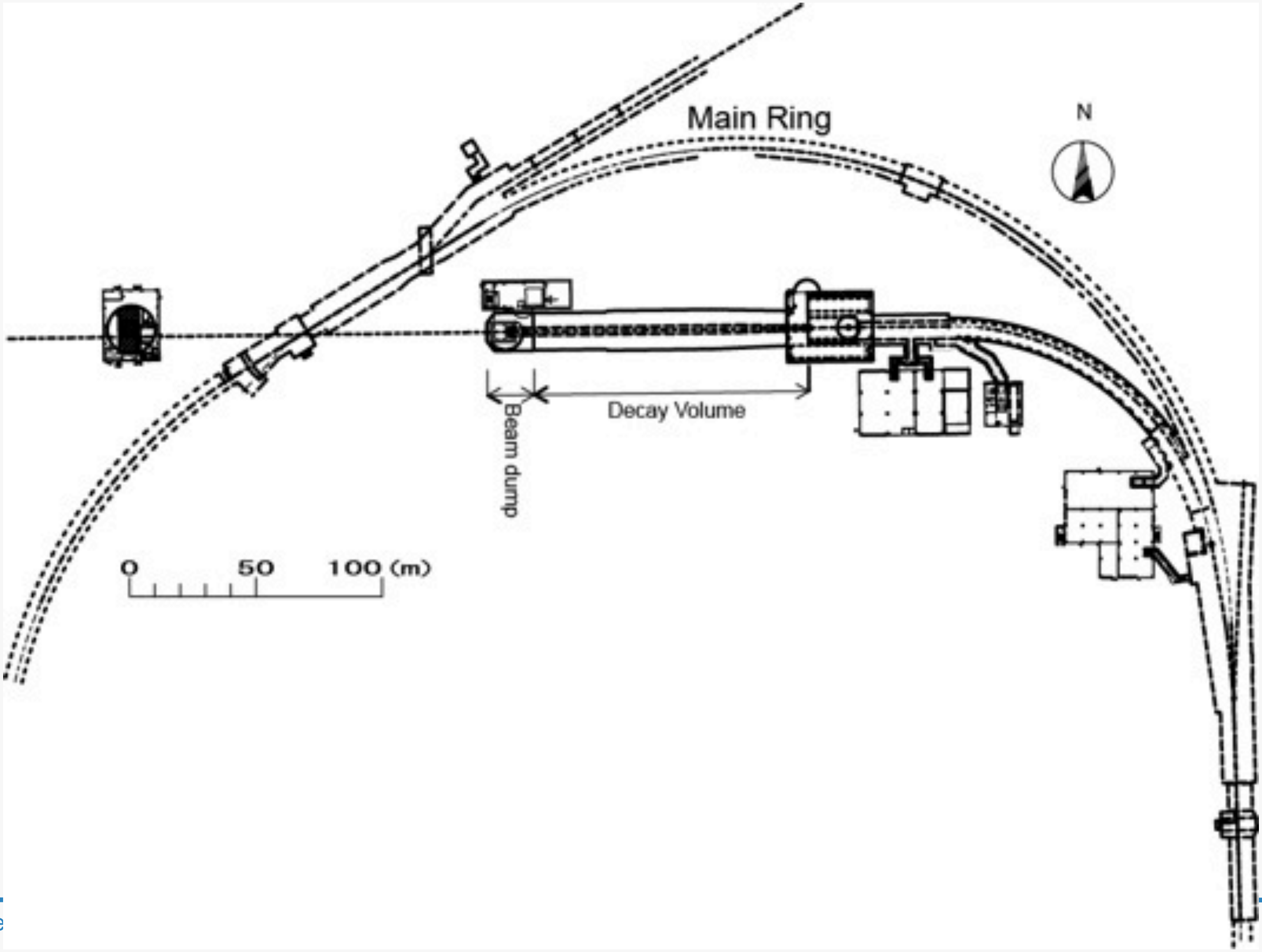


Bird's eye photo in January of 2008

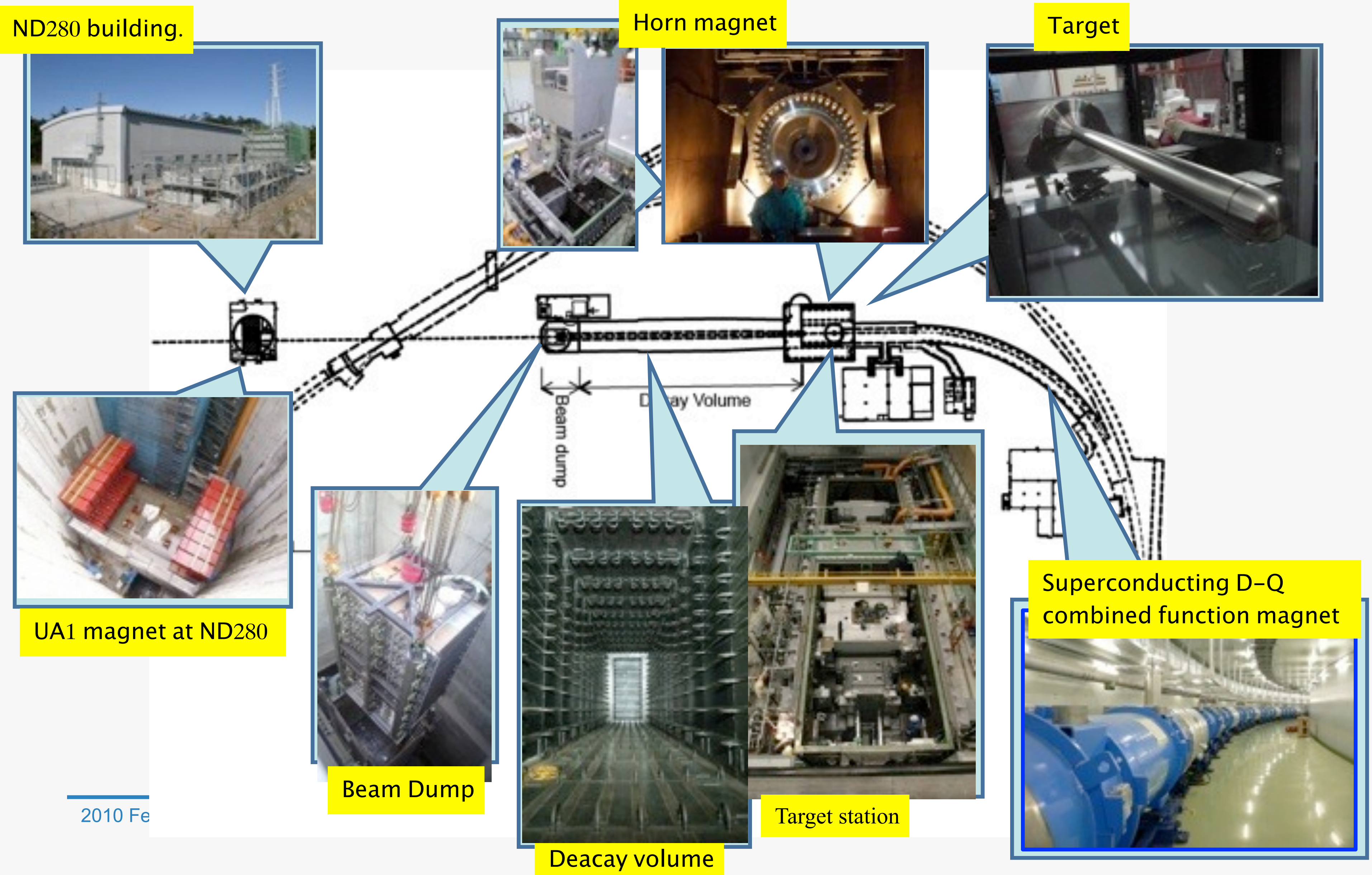
AN EXPECTED BEAM POWER CURVES FOR RCS AND MR FAST BEAM EXTRACTION



Neutrino beamline



Neutrino beamline



ND280 building.

Horn magnet

Target

UA1 magnet at ND280

Beam Dump

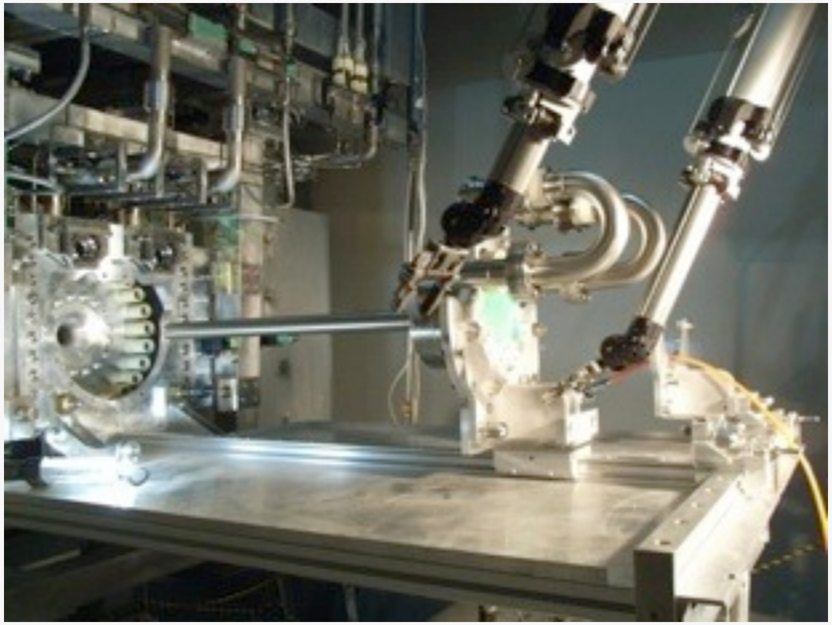
Deacay volume

Target station

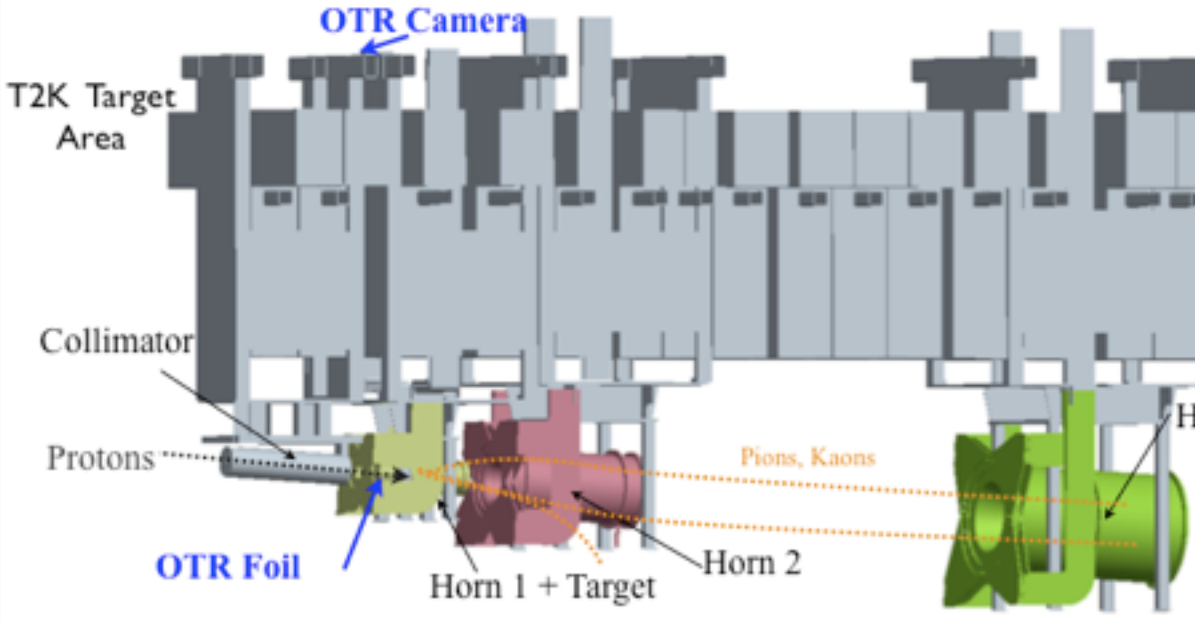
Superconducting D-Q combined function magnet

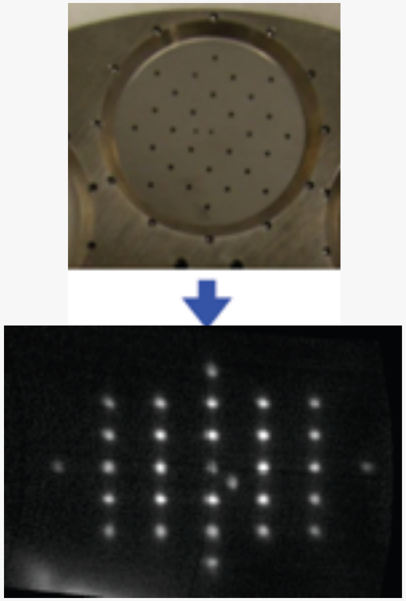
Target Remote Maintenance

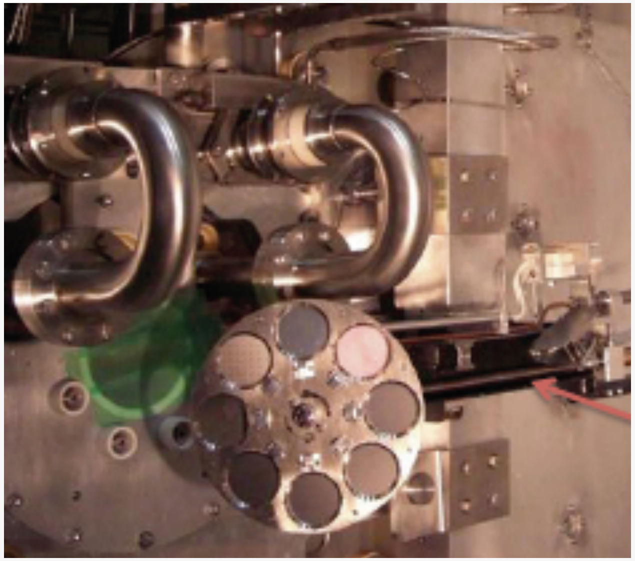
constructed by TRIUMF/RAL



Optical Transition Radiation (OTR) monitor

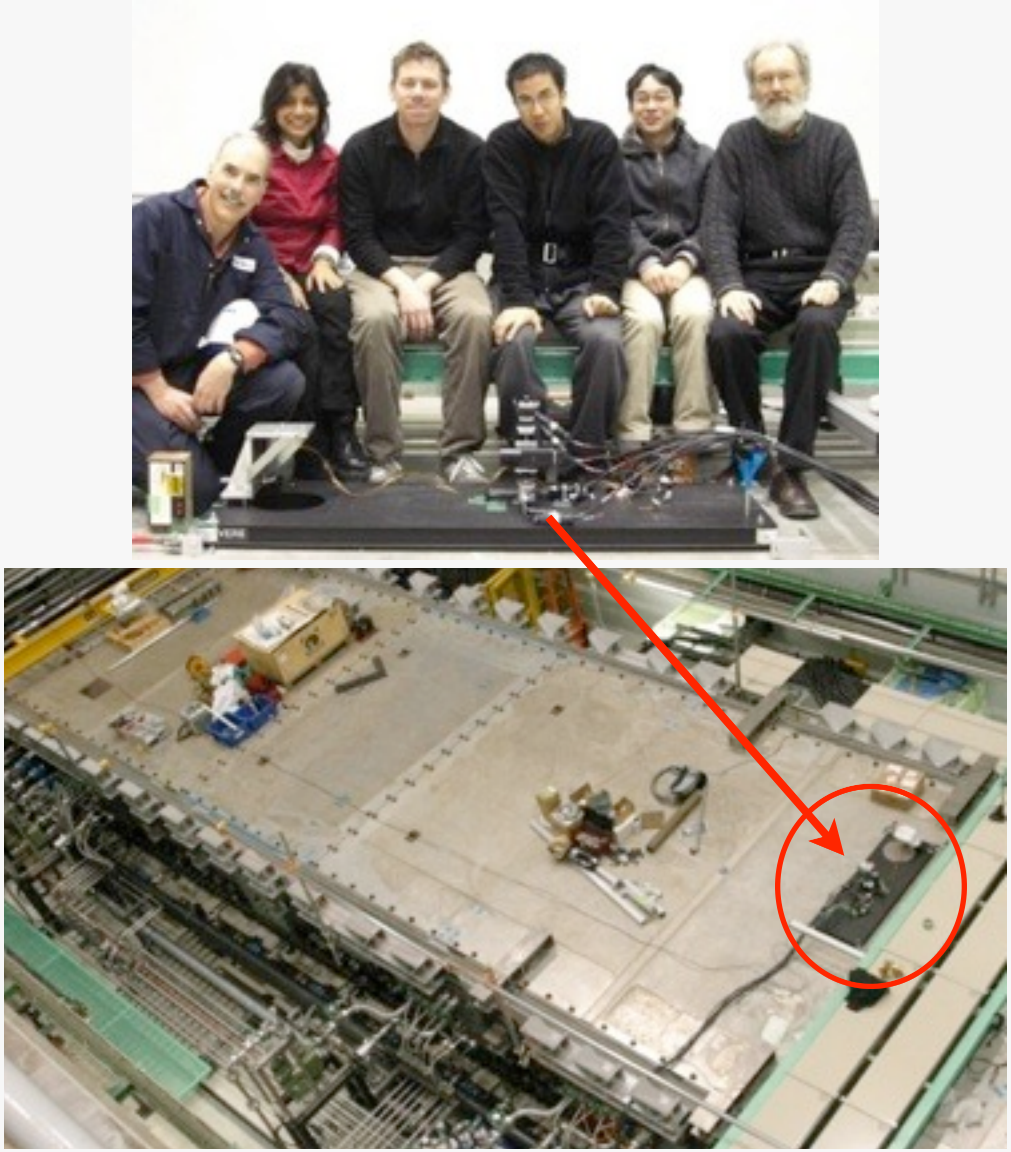






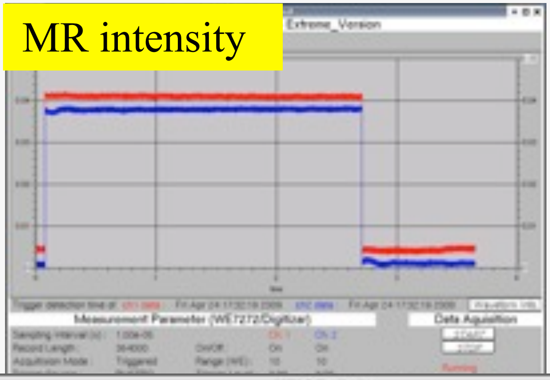
- Beam profile monitor in front of the 1MW target
- OTR light from Ti foil is transferred to rad-hard camera through shielding

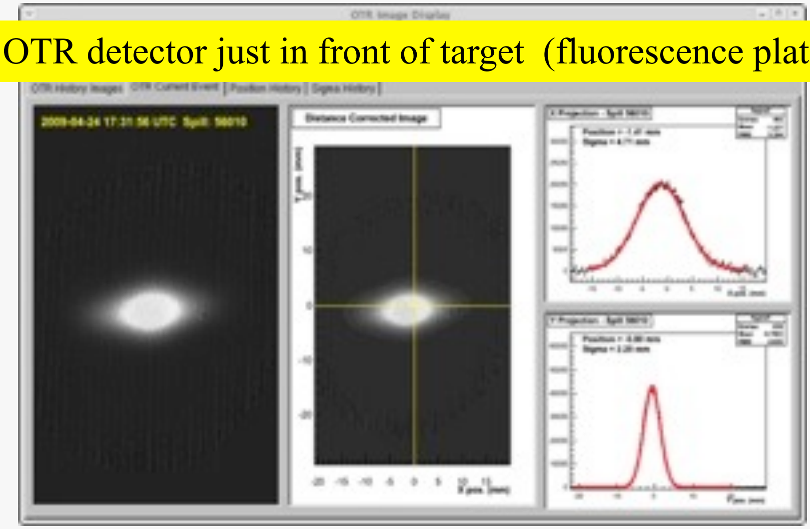
OTR

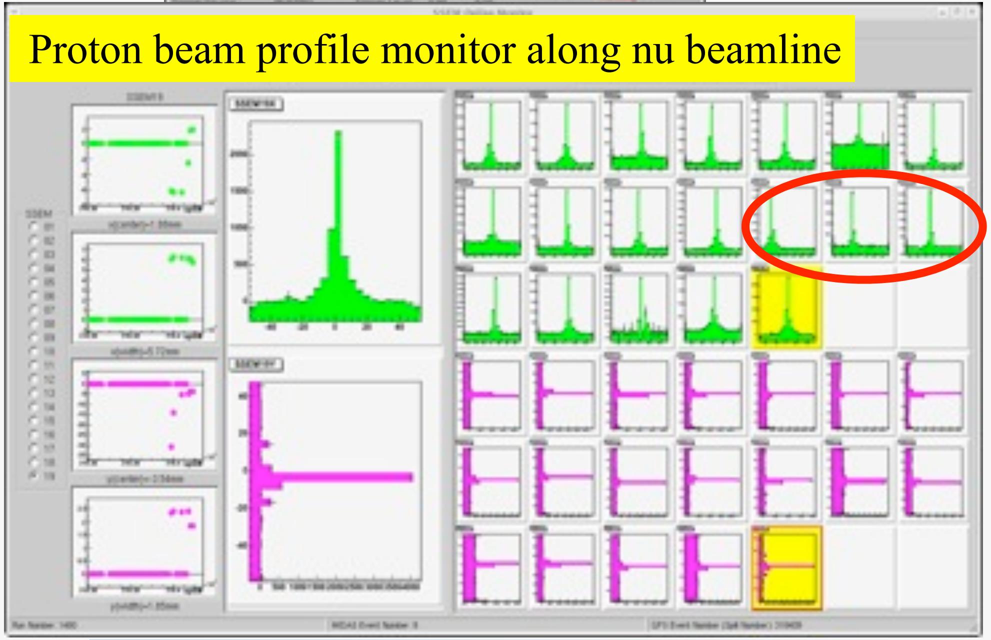


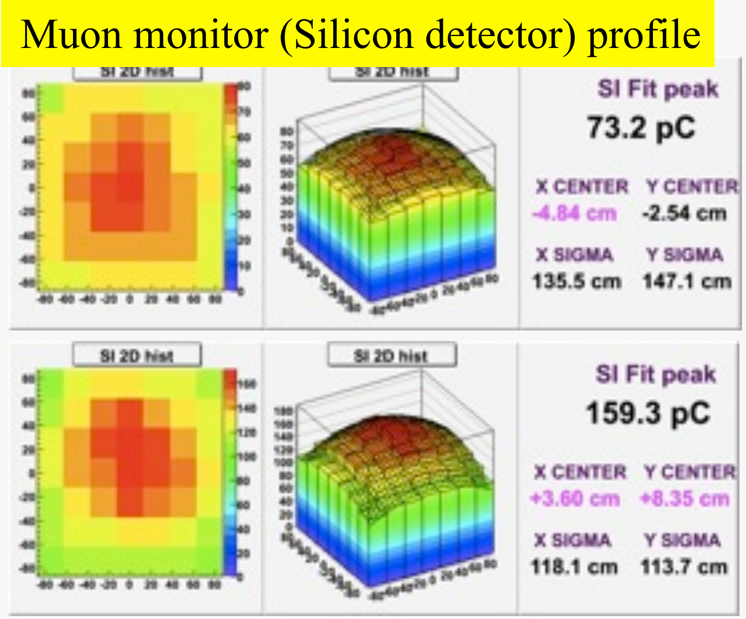
Beamline commissioning: April 09

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

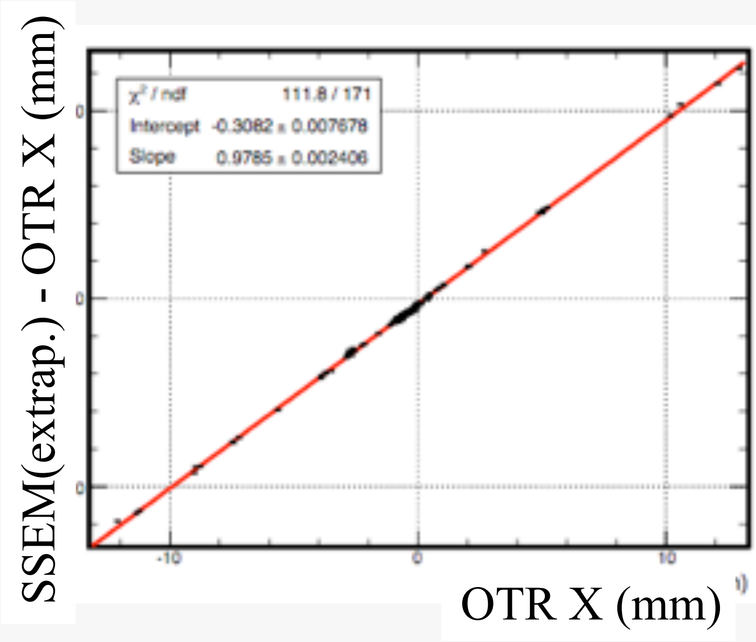
SI Fit peak
73.2 pC
X CENTER -4.84 cm
Y CENTER -2.54 cm
X SIGMA 135.5 cm
Y SIGMA 147.1 cm

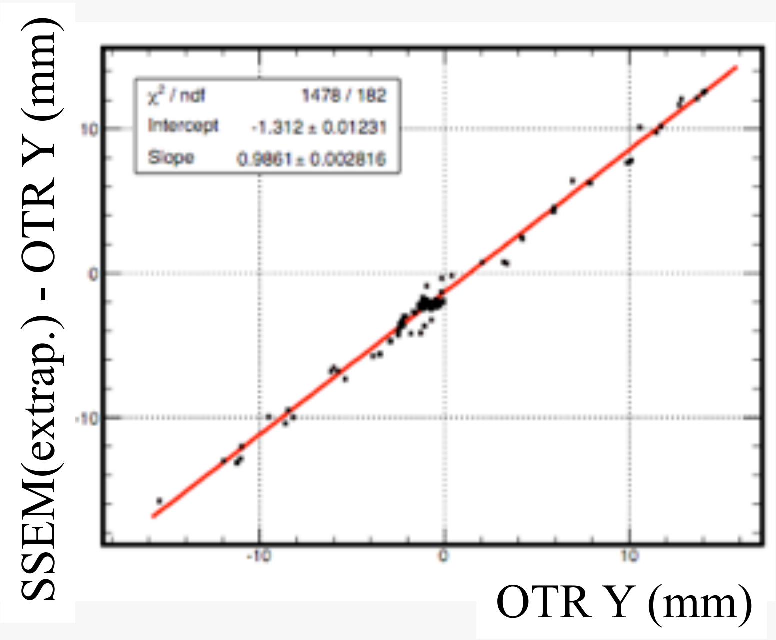
Horn 250kA

SI Fit peak
159.3 pC
X CENTER +3.60 cm
Y CENTER +8.35 cm
X SIGMA 118.1 cm
Y SIGMA 113.7 cm

Beam monitor analysis

- Detailed study of beam monitor alignment, rotation, coordinate system, etc.
  - Lead by Toronto/York postdoc and graduate students

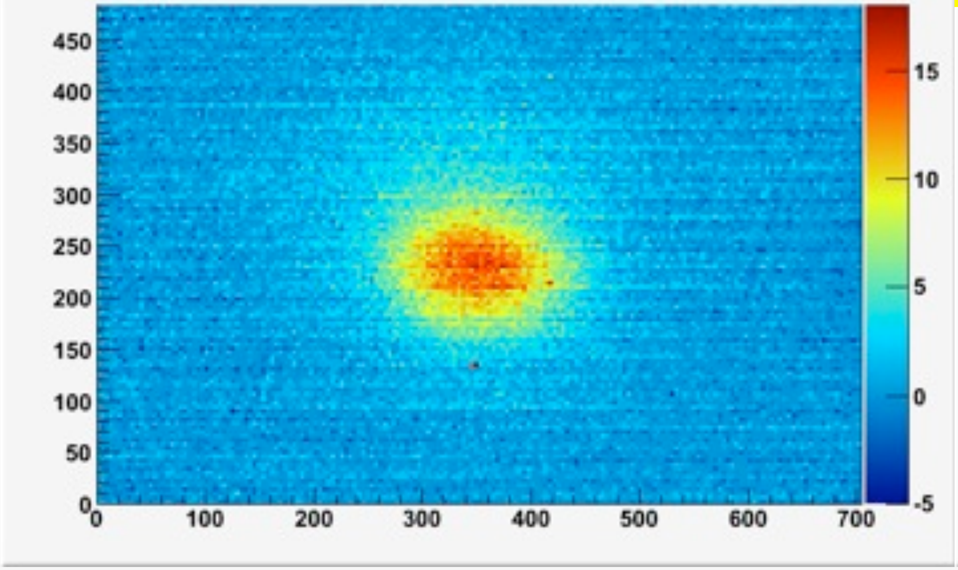




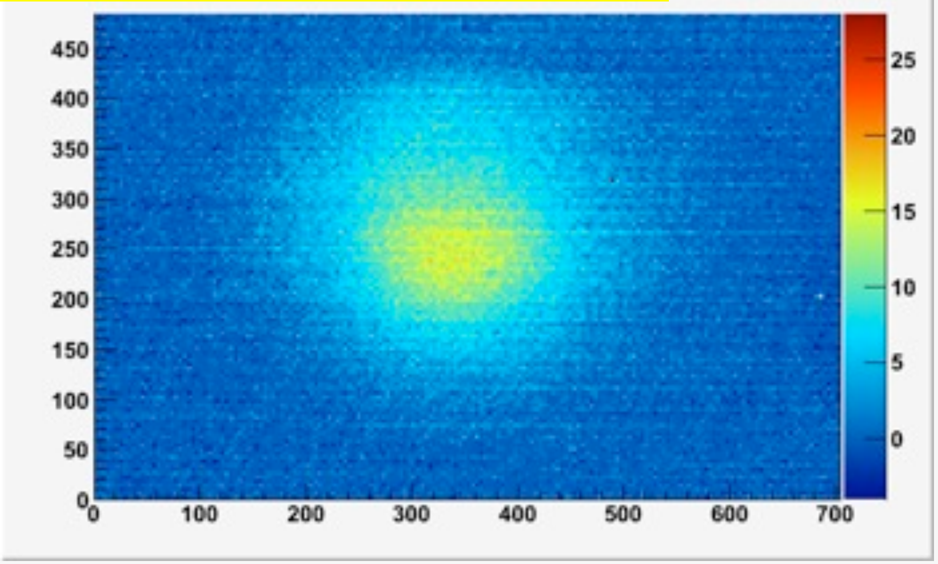
OTR light being used from Dec.09

As the beam intensity goes up, we use OTR foils instead of fluorescence ceramic plate

20kW beam on Al target

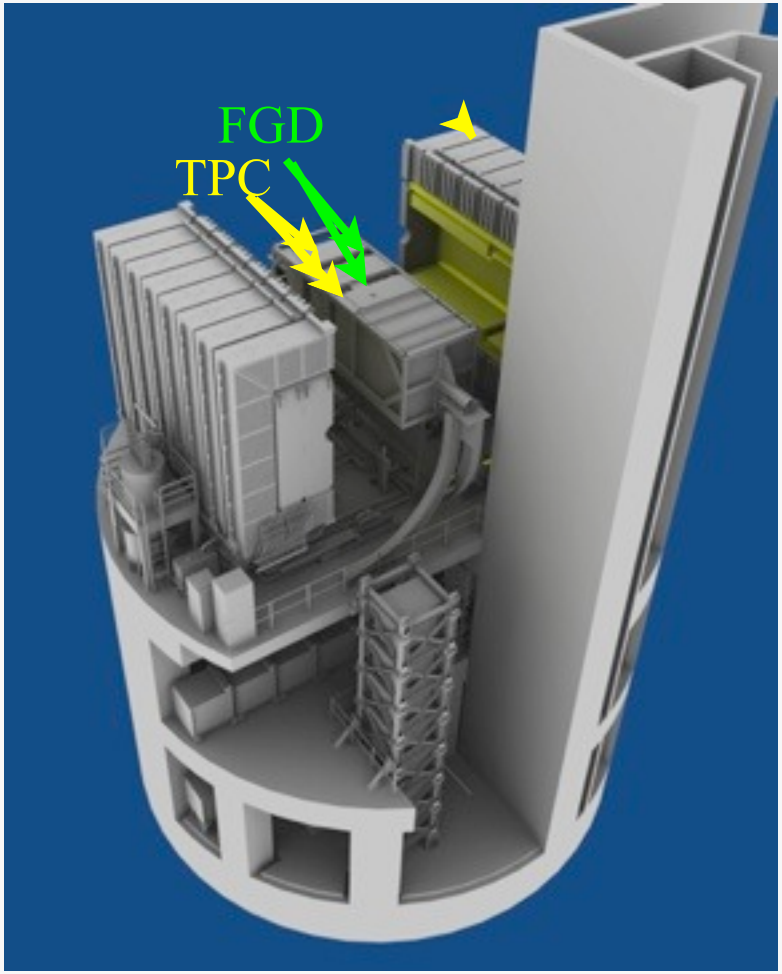


50kW beam on Ti target



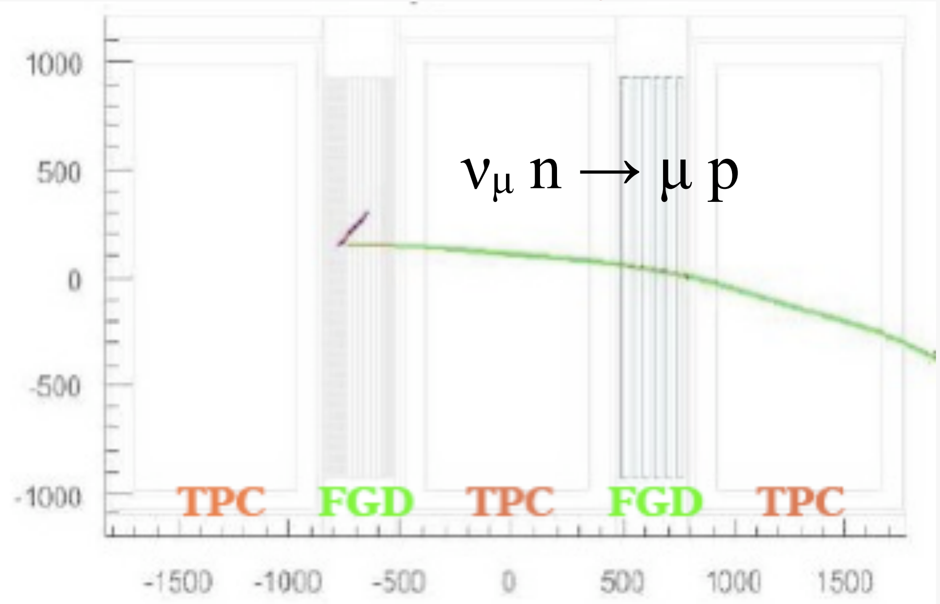
Off-axis near detector (ND280)

- Canada contributes TPC (time projection chamber) and FGD (fine grained detector) built at TRIUMF

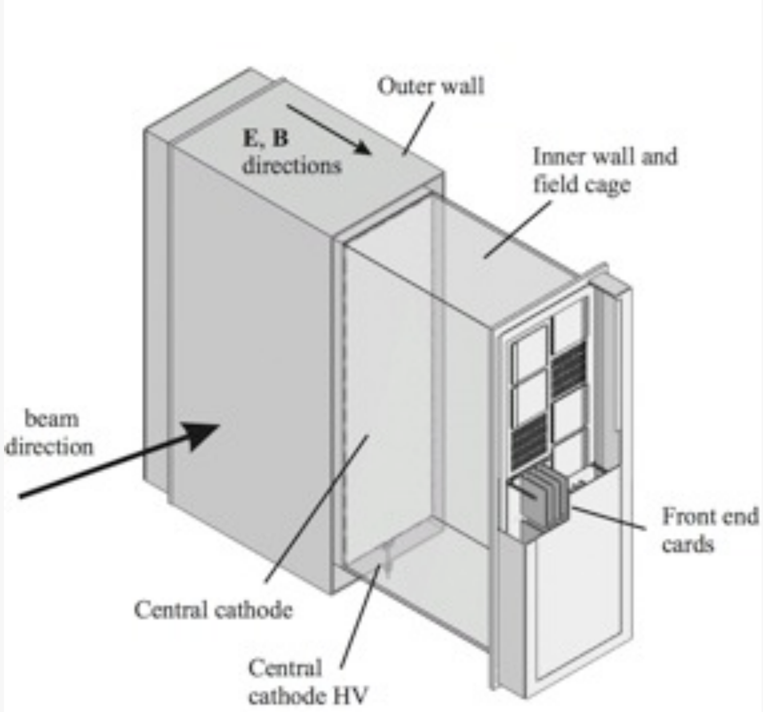


Flux and cross section study

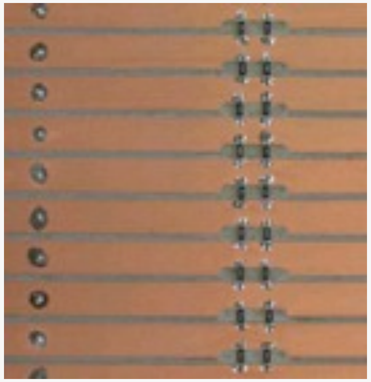
- Detect both leptons and hadrons
  - Clean particle identification
    - Momentum, dE/dx, downstream Ecal
  - Understand hadronic/nuclear uncertainties
    - Vertex activitie detection
    - “Kinematic” & “Calorimetric” ways



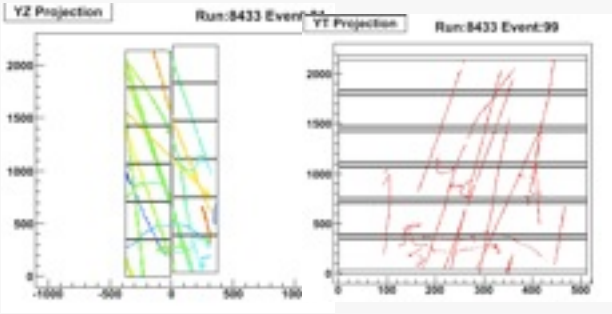
Time Projection Chamber (TPC)



- 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)
    - $\Delta P<0.1$mb between inner and outer volume



TPC construction

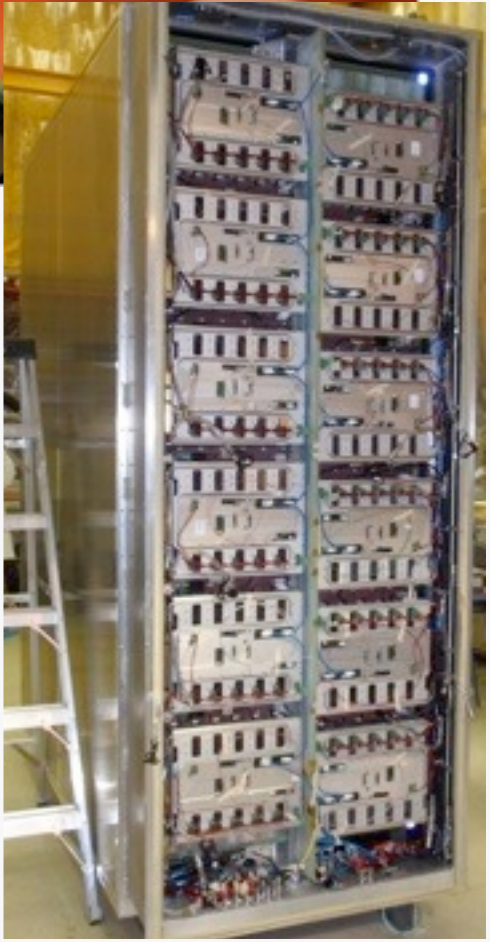


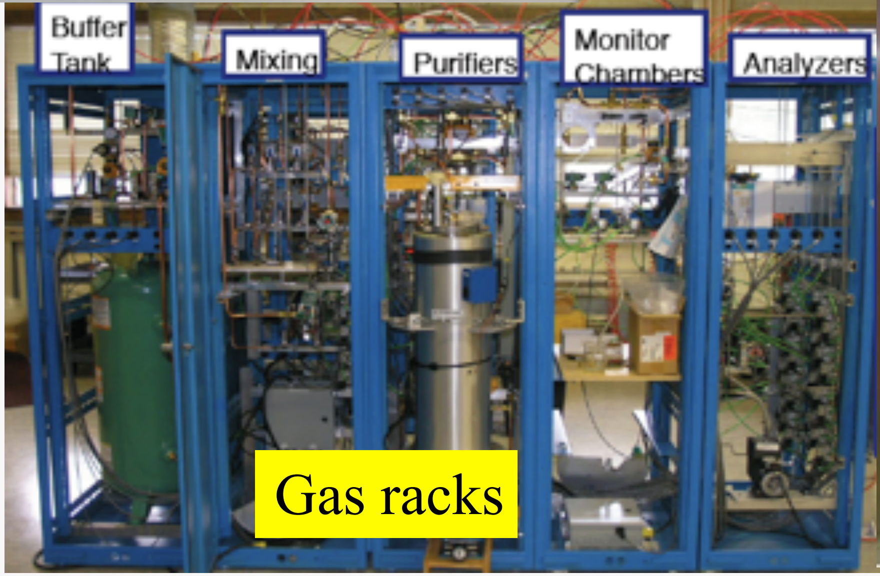
Technology:
AMS CMOS 0.35µm
Area: 7546µm x 7139 µm
Submission: 24 April 2006
Delivery: end of July
Package:
LQFP 160 pins; Plastic
dimensions: 30mm x 30mm
thickness: 1.4mm
pitch: 0.65mm
# of transistors: 400,000

AFTER ASIC

Micromegas

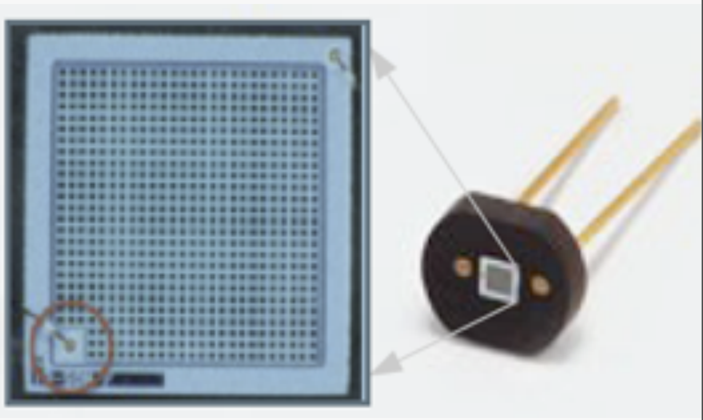
Centeal cathode with laser target



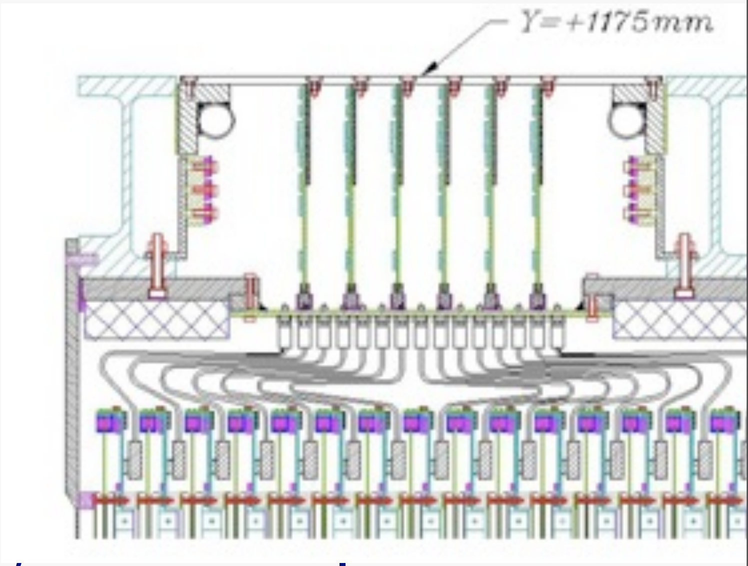


Gas racks

Fine Grained Detector (FGD)

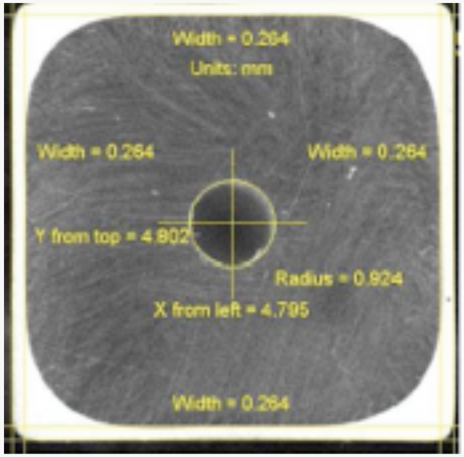


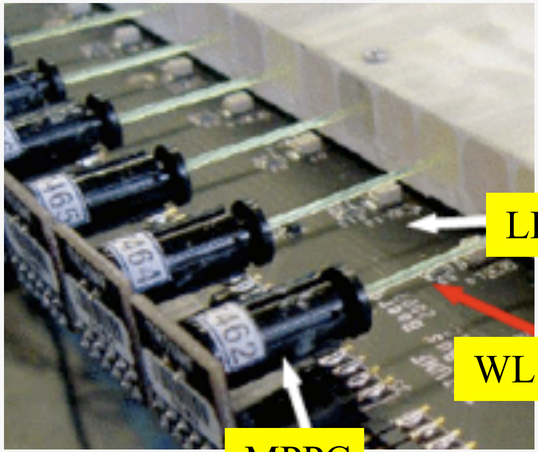
- Target mass for v interaction
  - 2mx2mx30cm (<1 int. length)
  - one with water layers
- Detect secondaries around vertex
  - Fine granurality (1cmx1cm)
  - Extruded scinti. with WLS fiber
  - MPPC (SiPM) readout
    Photon counting
  - 10μsec-50MHz wave form digitizer for Michel electron (AFTER ASIC)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



FGD construction

Extruded scintillator



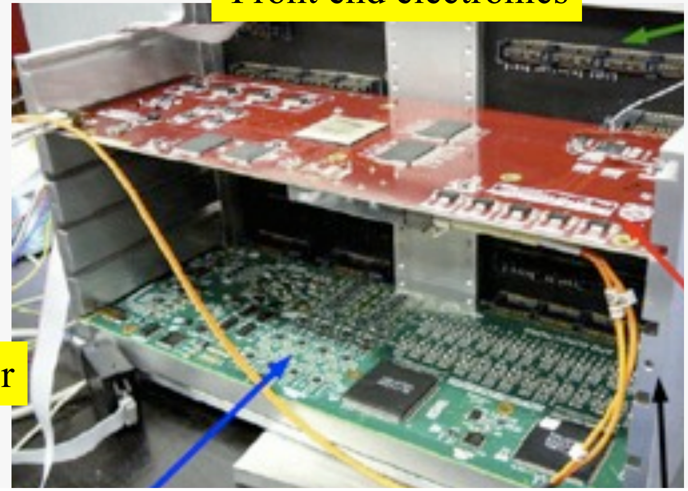


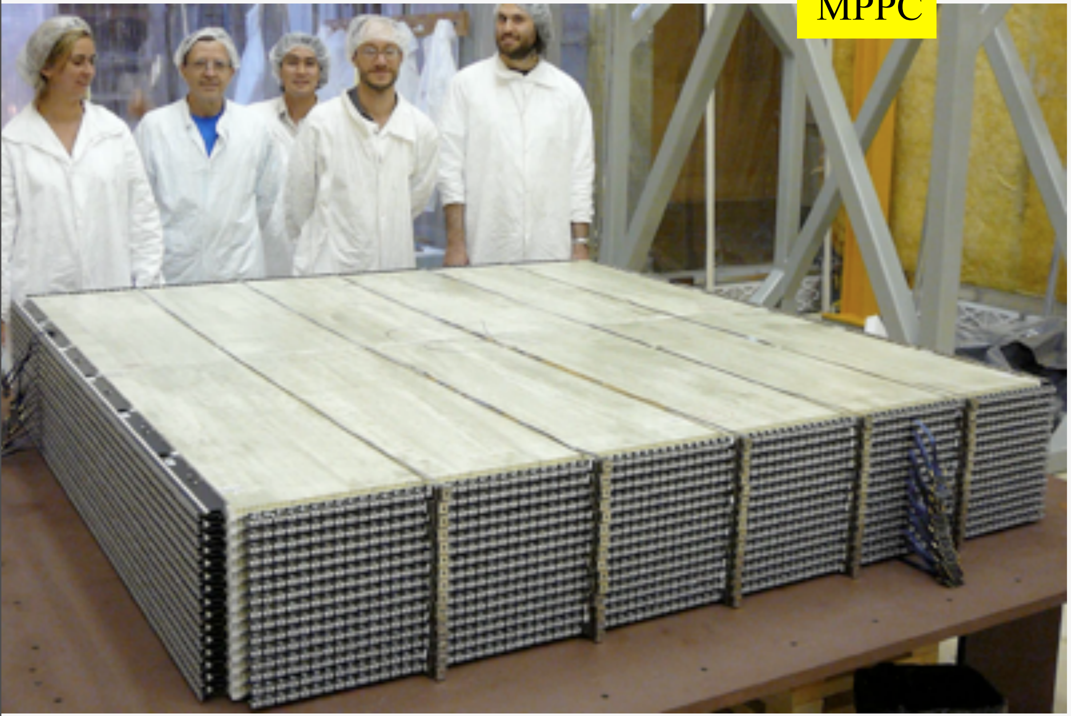
LED

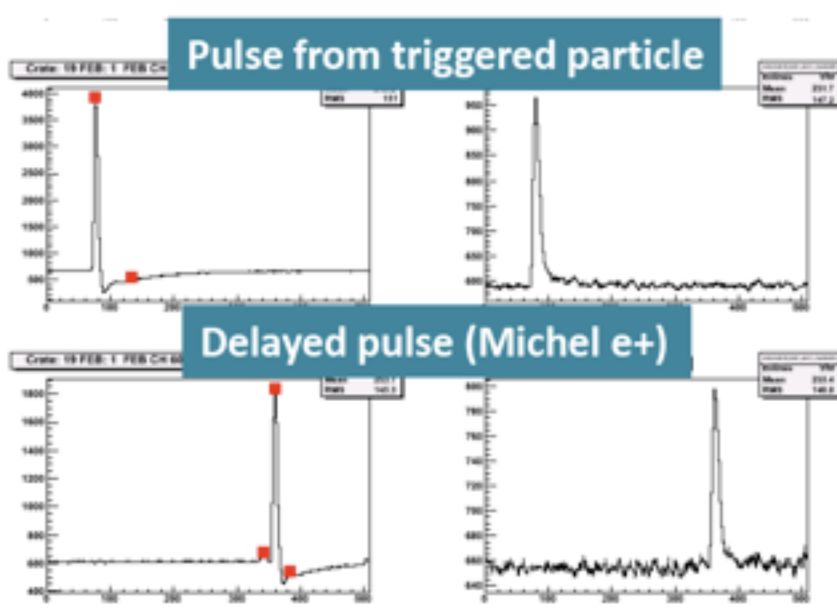
WLS fiber

MPPC

Front end electronics





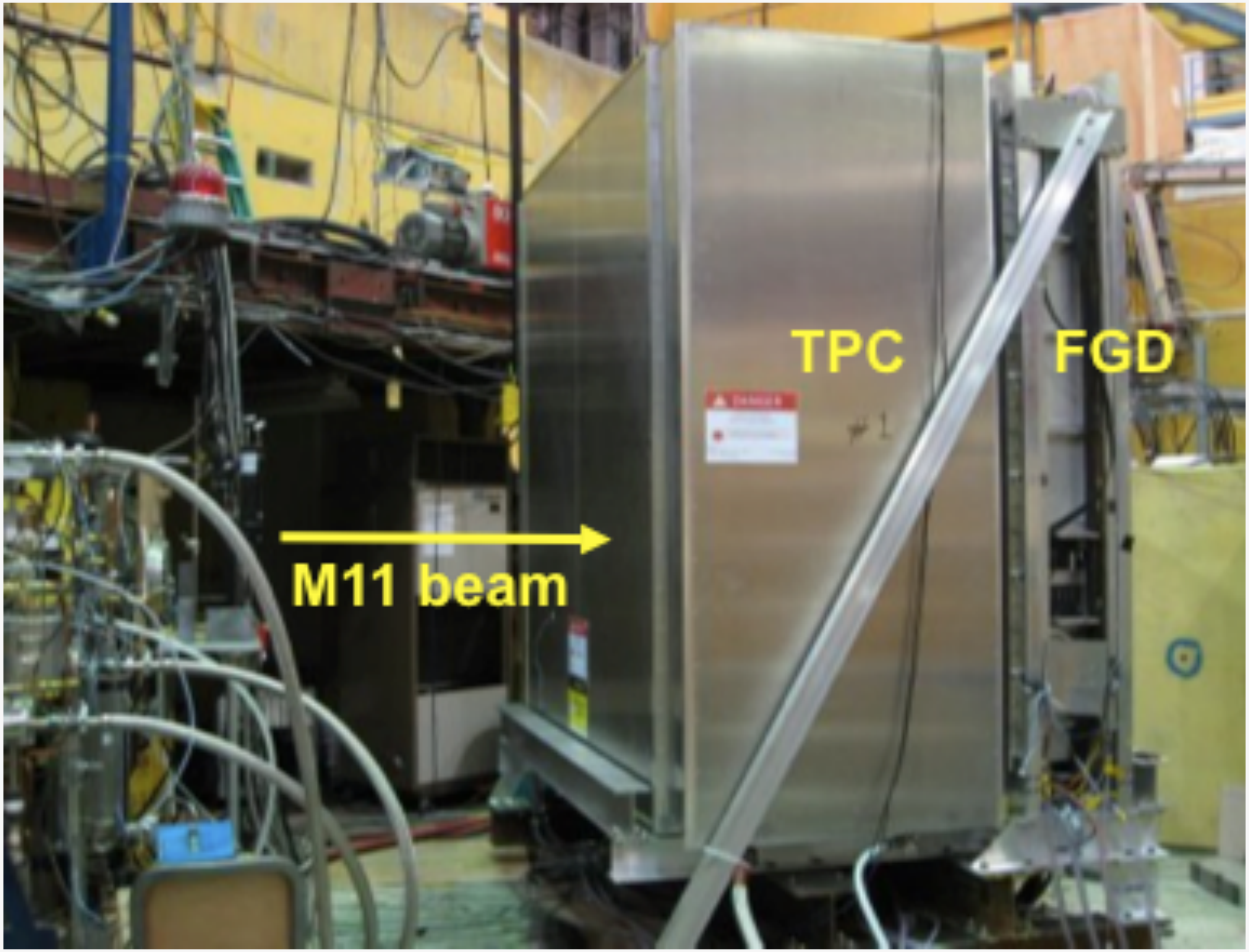


Pulse from triggered particle

Delayed pulse (Michel e+)

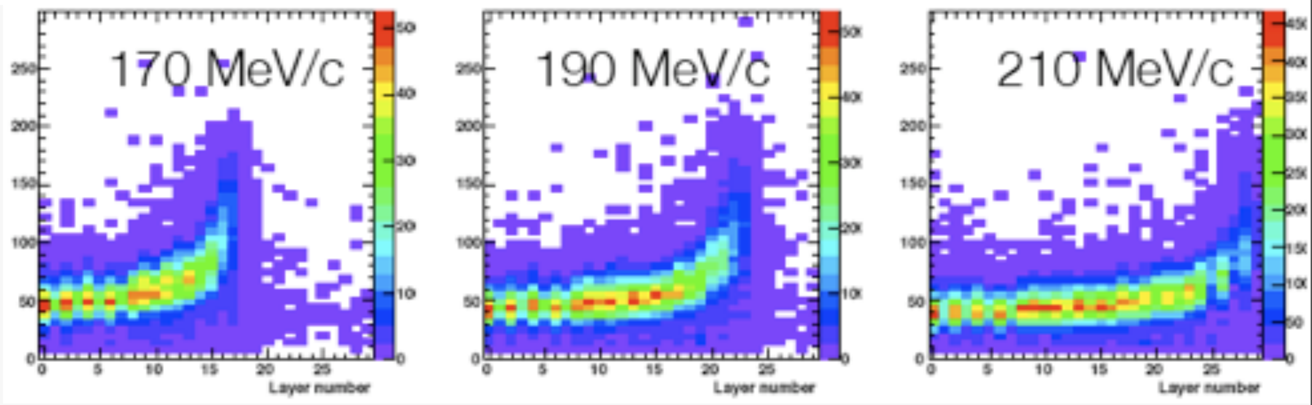
8.5k ch of 50MHz waveform

FGD/TPC beam test at TRIUMF

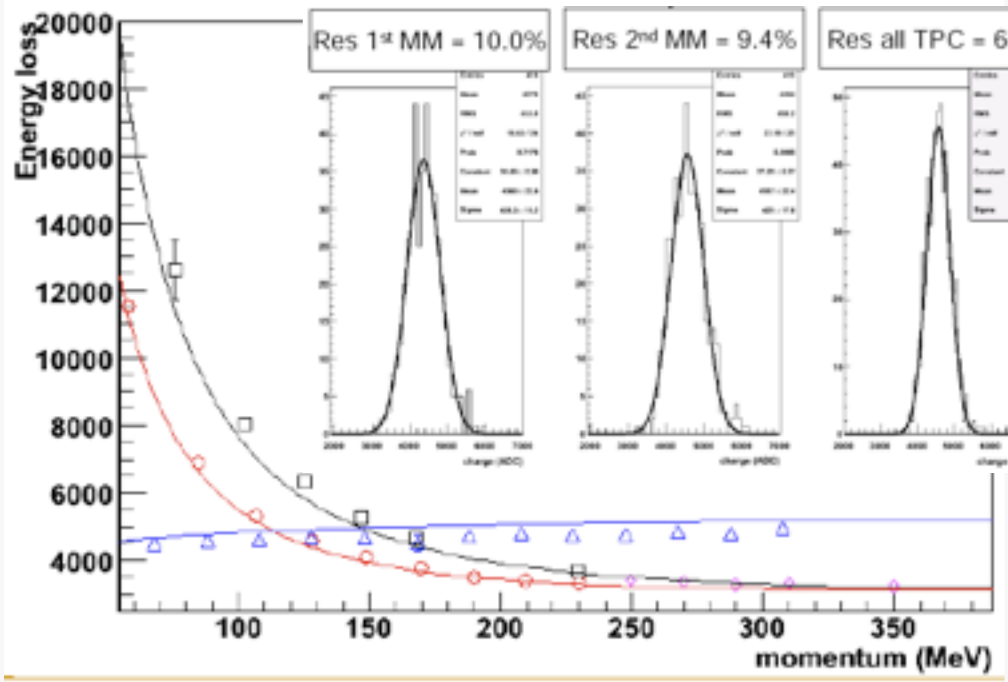


M11 Beam test results

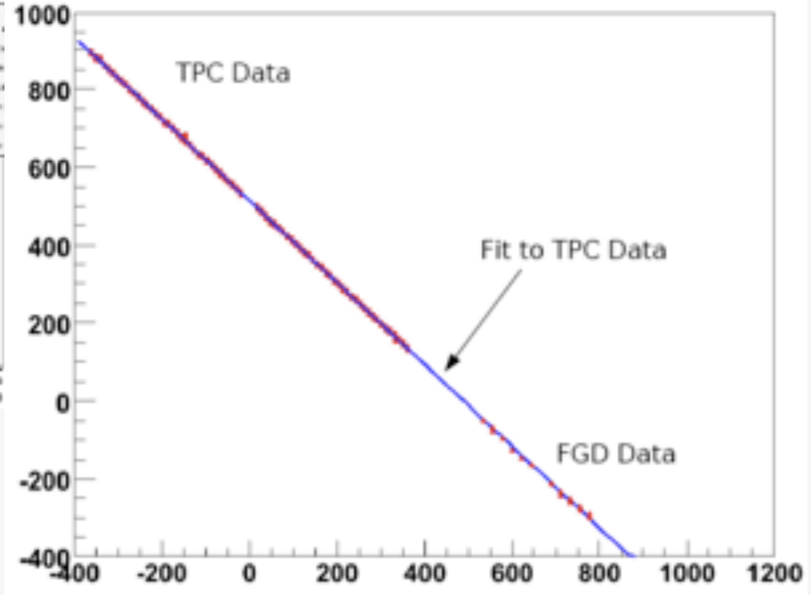
FGD Energy vs. range for muons



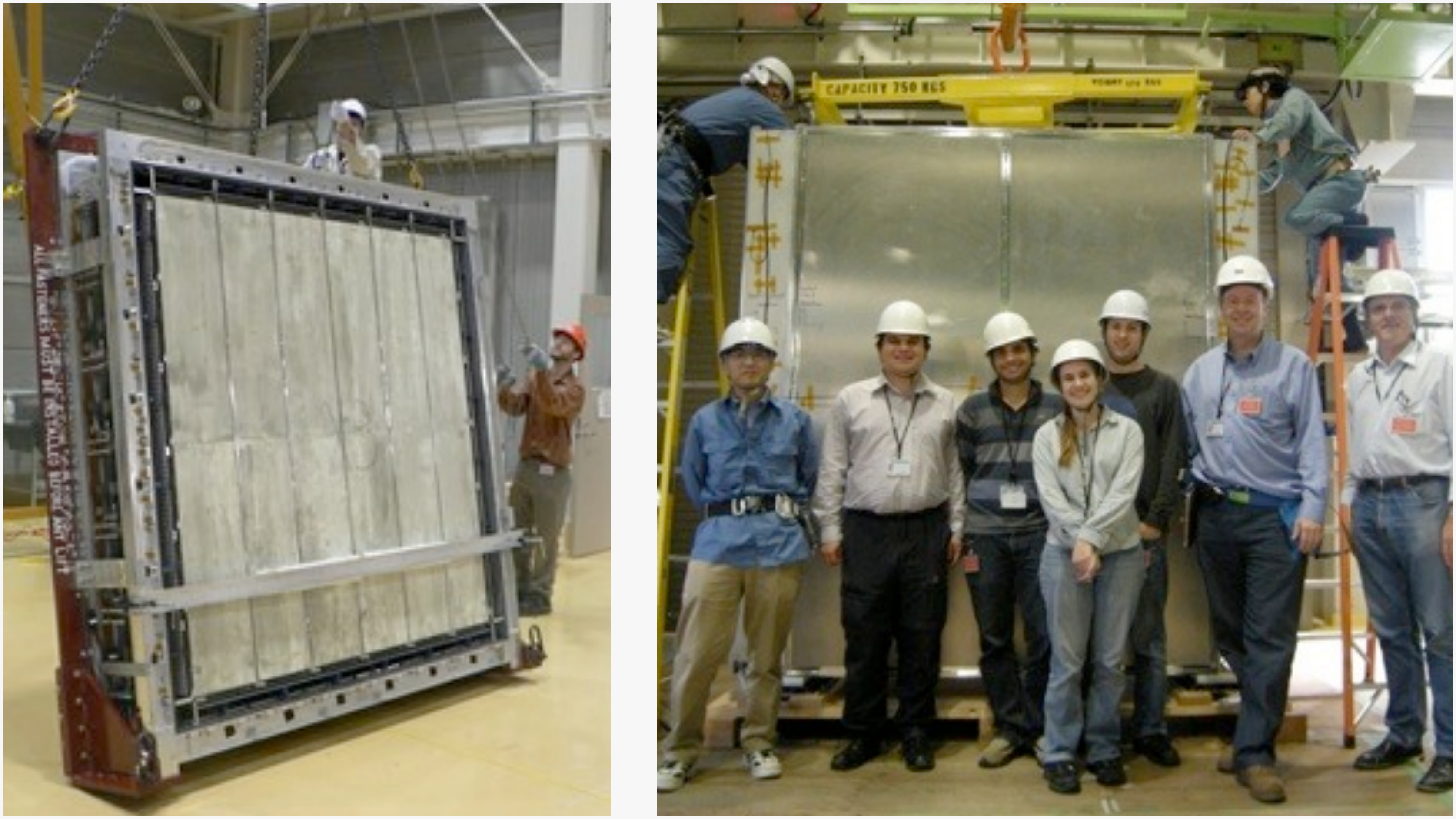
TPC dE/dx



TPC/FGD track match

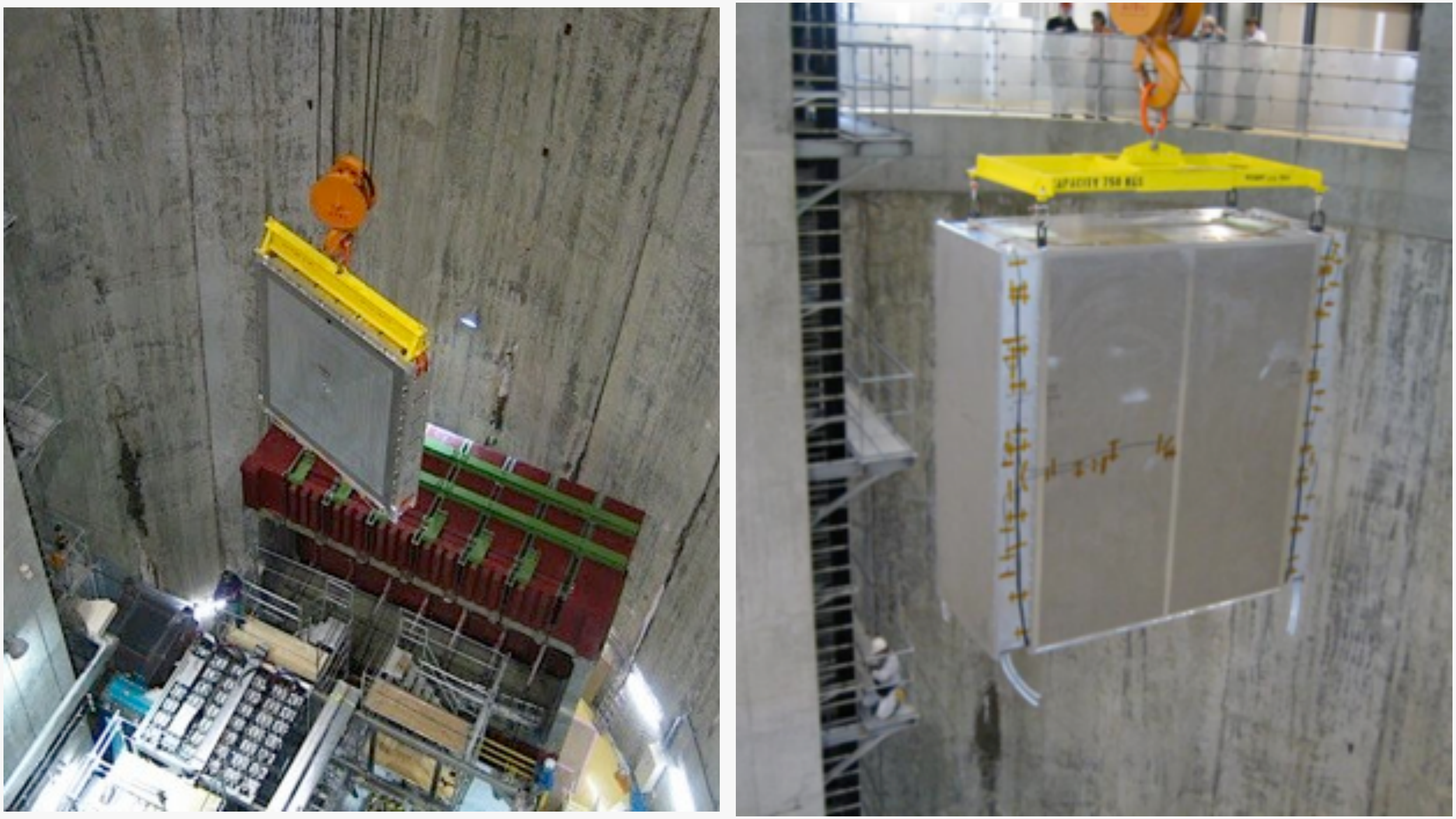


FGD/TPC assembly at J-PARC



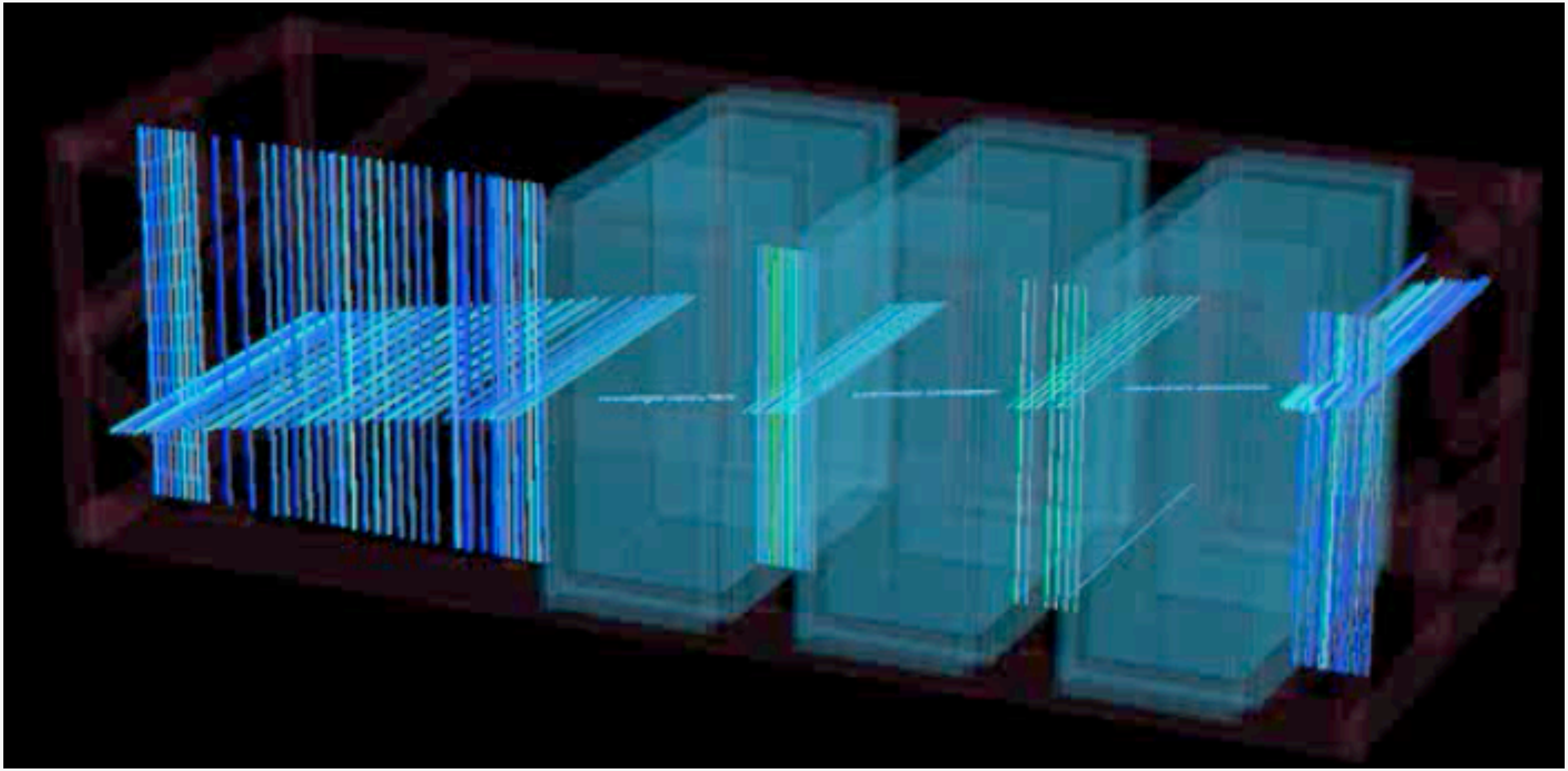
Students and postdocs with experts for assembly in summer ’09

FGD/TPC installed smoothly!

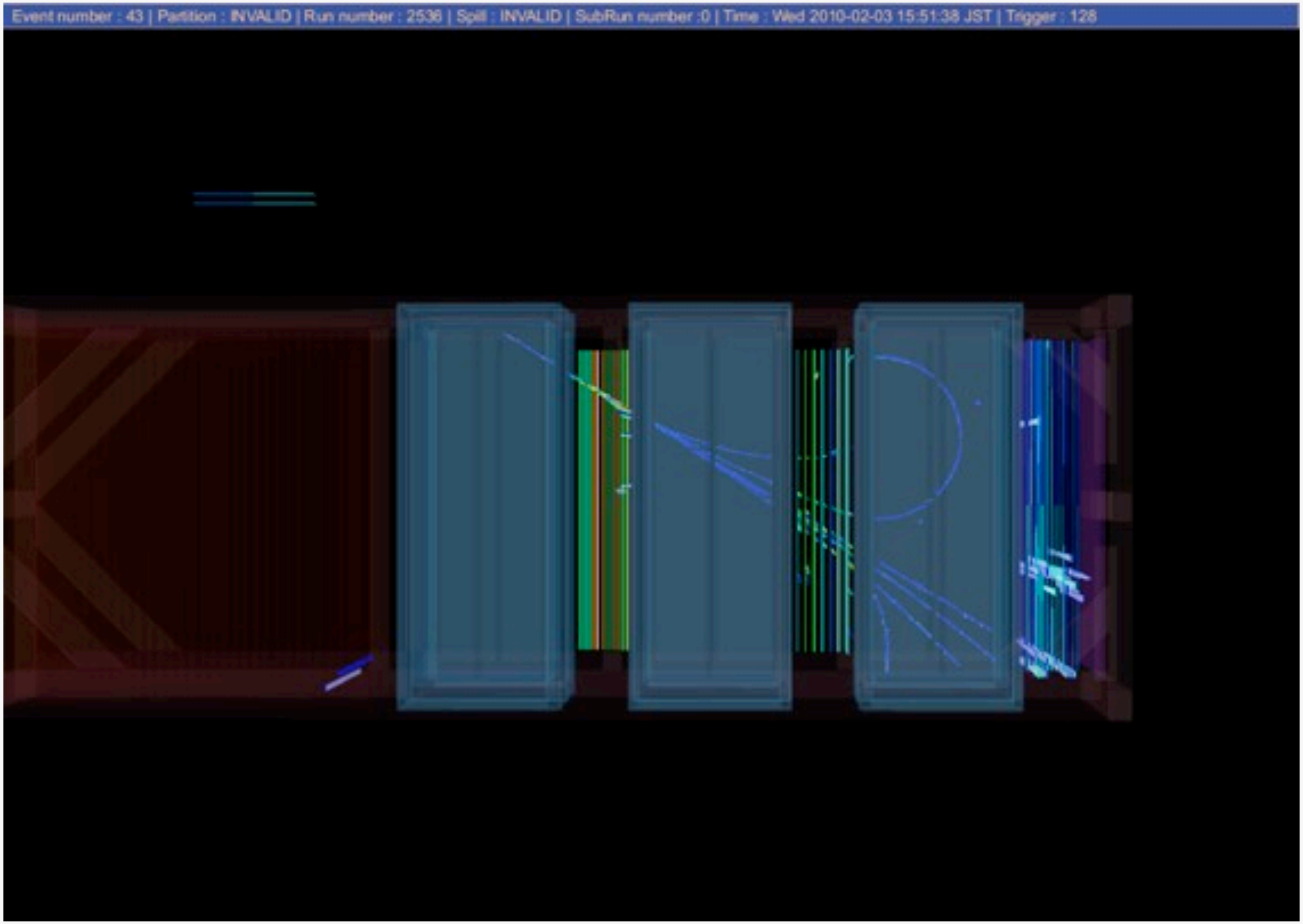


Why yes, that *is* Hiro Tanaka hitting the FGD with a hammer.

Neturino event on ND280
(on YouTube)

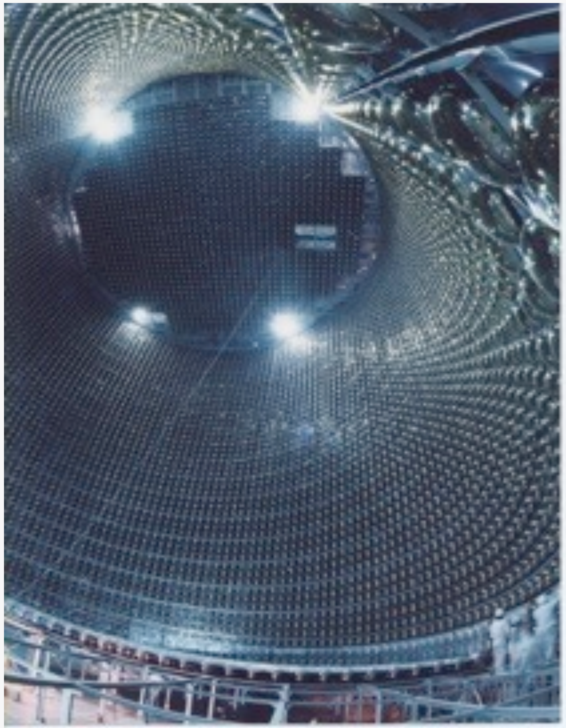


Cosmic event with magnet on (Yesterday's event!)



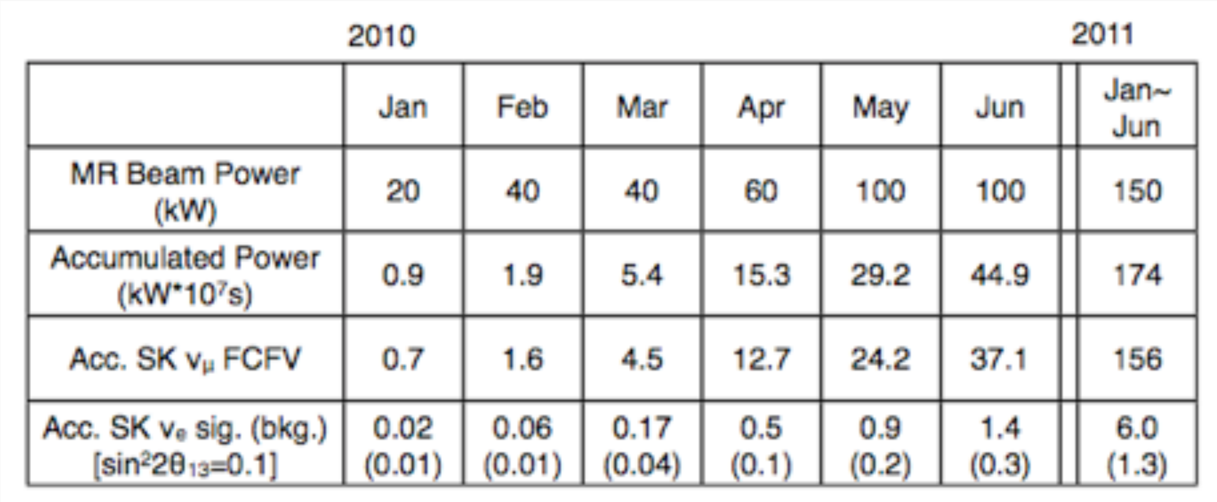
Event number : 43 | Partition : INVALID | Run number : 2536 | Spill : INVALID | SubRun number :0 | Time : Wed 2010-02-03 15:51:38 JST | Trigger : 128

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 ready.
  - Observation of T2K neutrino event is imminent.
- Study of optical response of PMT
  - Lead by Hiro Tanaka

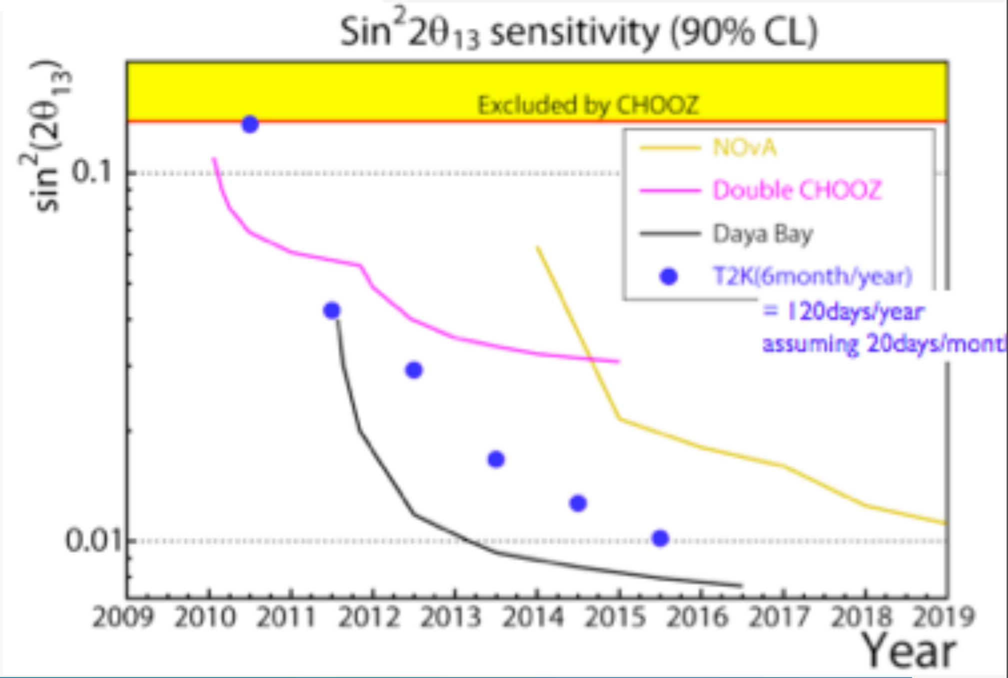
T2K run plan



	2010						2011
	Jan	Feb	Mar	Apr	May	Jun	Jan~ Jun
MR Beam Power (kW)	20	40	40	60	100	100	150
Accumulated Power ($kW*10^7s$)	0.9	1.9	5.4	15.3	29.2	44.9	174
Acc. SK ν_μ FCFV	0.7	1.6	4.5	12.7	24.2	37.1	156
Acc. SK ν_e sig. (bkg.) [$\sin^2 2\theta_{13}=0.1$]	0.02 (0.01)	0.06 (0.01)	0.17 (0.04)	0.5 (0.1)	0.9 (0.2)	1.4 (0.3)	6.0 (1.3)

Presentation at J-PARC PAC 2010

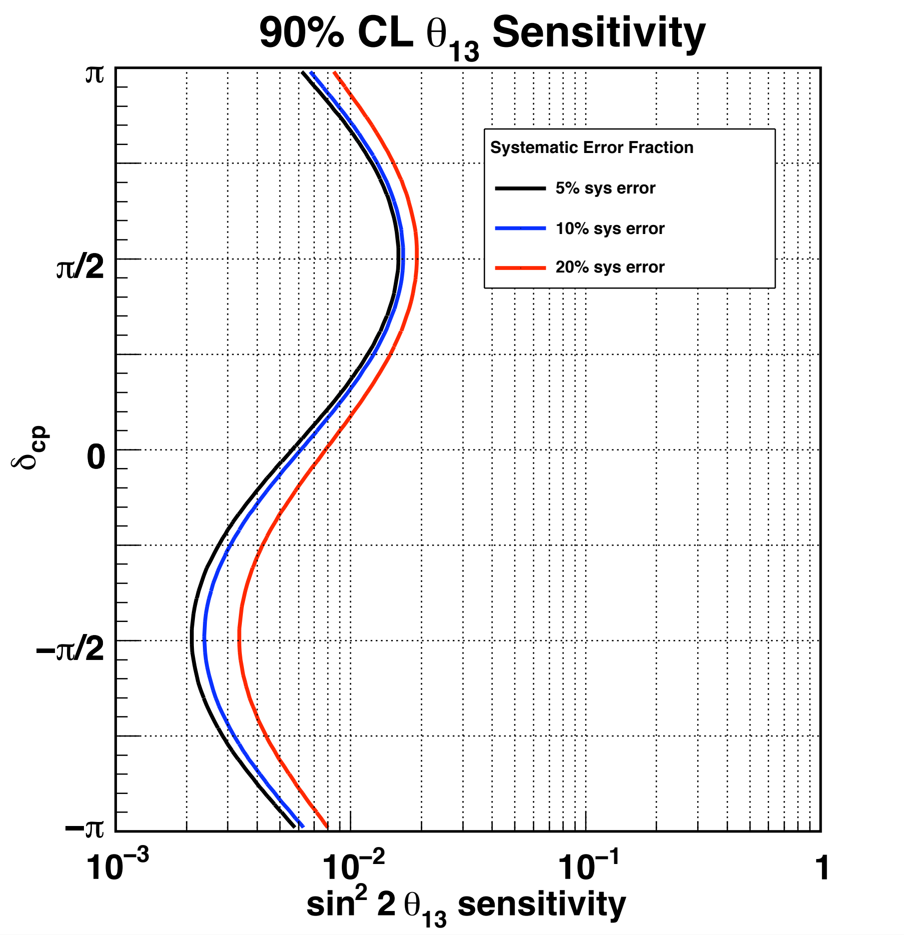
- Complementary to reactor projects
  - appearance
  - sensitive to CP
- Daya Bay
  - near detector ready 2010
  - far detector ready 2011



$\sin^2 2\theta_{13}$ sensitivity (90% CL)

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 intensity is gradually going up 20-50kW
  - Beamline compnents worked as designed
- Near detector installation completed in Dec.09.
  - First neutrino events observed.
  - Magnet commissioning is being completed.
  - 100kW(13% of design) x 10^7sec is expected in 2010
  - New technologies (e.g. MPPC, Micromegas)
- Far detector SK-IV is up and running
- Physics results expected in a year.
  - Canadian group is taking central role in detector construction, operation and analysis.

Backup slides

JFY 2010 KEK budget
(to be approved by Congress)

	JFY2009	JFY2010	
Total Budget	300M$	295M$	↓ 5M$
J-PARC	65M$	68M$	↑ 3M$
B Factory	50M$	45M$	↓ 5M$
Intern. Collab.	10M$	10M$	↓ 0.5M$
Others			
‘KEKB facility Improvement’	0	6M$	↑ 6M$

The cut was not substantial.
Thank you for your supports last year.

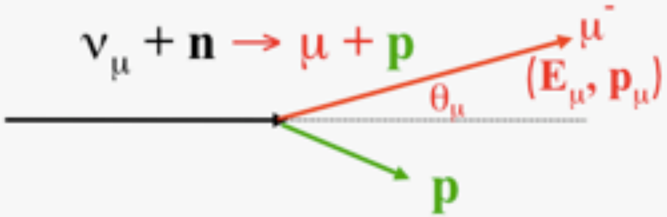
K.Nishikawa @ PAC

Leadership role towards physics

- Near detector (ND280)
  - run coordinator (Dean Karlen)
  - physics coordinator (Hiro Tanaka)
  - ν_μ convener (Scott Oser)
  - Calibration convener (Fabrice Retiere)
  - Software co-convener (Thomas Lindner)
- SK
  - Co-convener (Akira Konaka)
  - Graduate student (Patrick de Perio) at Kamioka
- Beam (mainly KEK/Kyoto group)
  - Canadian members lead the beam monitor analysis

Two ways to reconstruct Eν

- **Kinematic way**



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

  - 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**

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

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

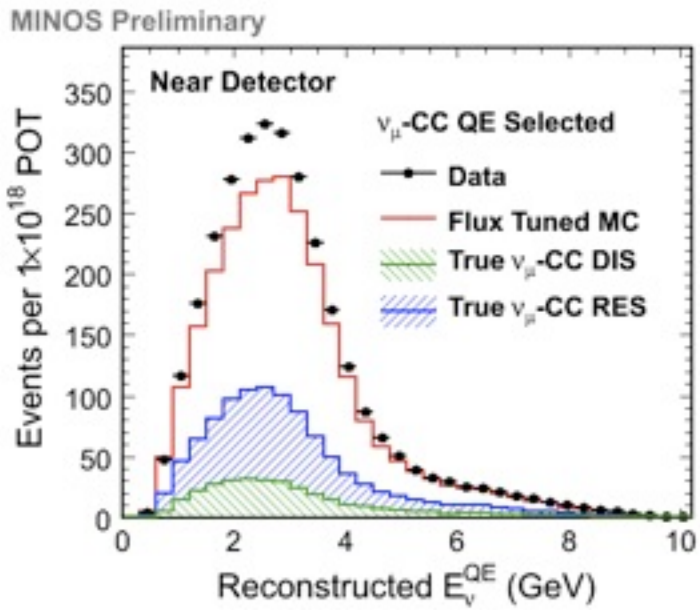
  - Method used at high energy e.g. MINOS, OPERA
  - Nucleus carries little energy ⇒ avoid nuclear uncertainty
  - Uncertainty in hadron (proton) energy measurement ⇒ Detect/identify each hadrons

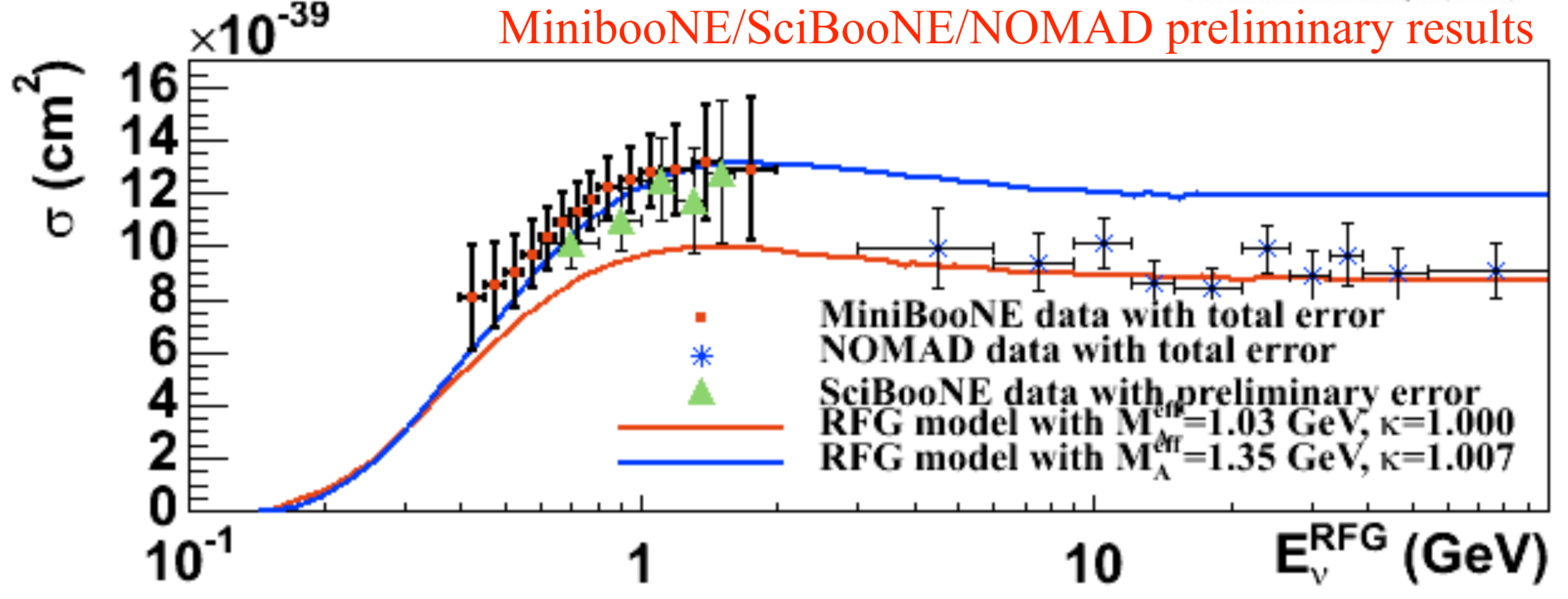
    FGD around the vertex
    TPC detects before interaction

Comparing two method to untangle the nuclear and hadronic uncertainties

CCQE cross section

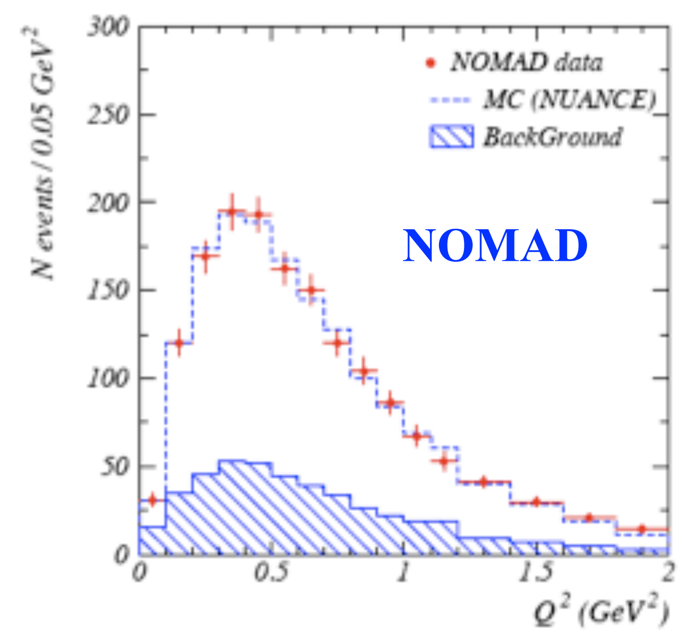
- Cross section is larger than MC up to a few GeV but OK for NOMAD (consistent with large effective M_A)
- Meson exchange current? Nuclear/hadronic effects need to be understood!

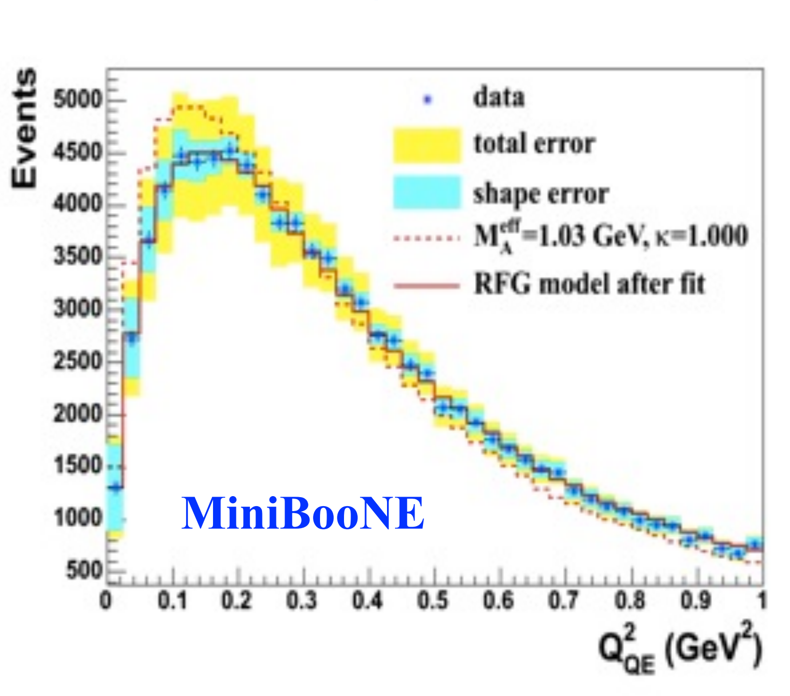


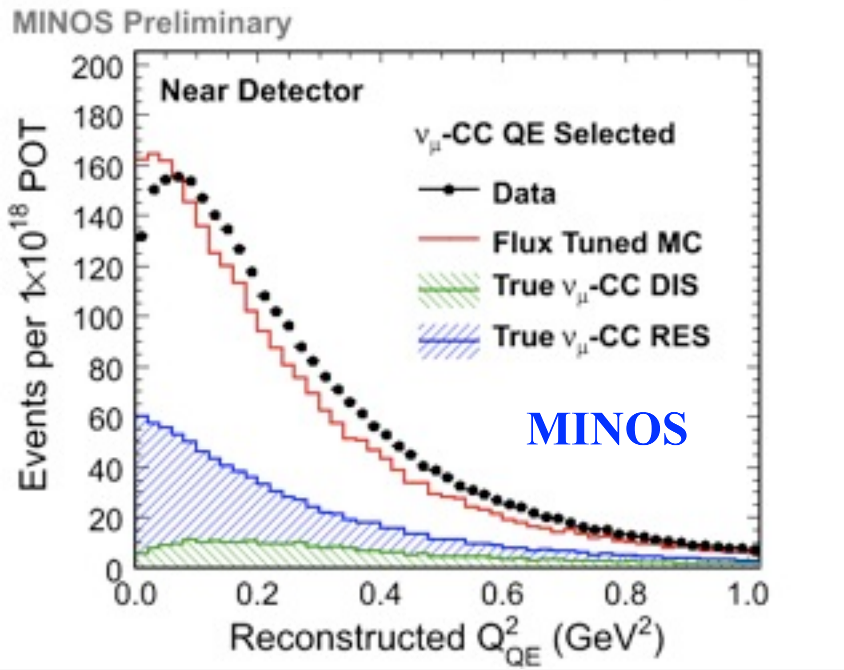

MiniooNE/SciBooNE/NOMAD preliminary results

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.)?

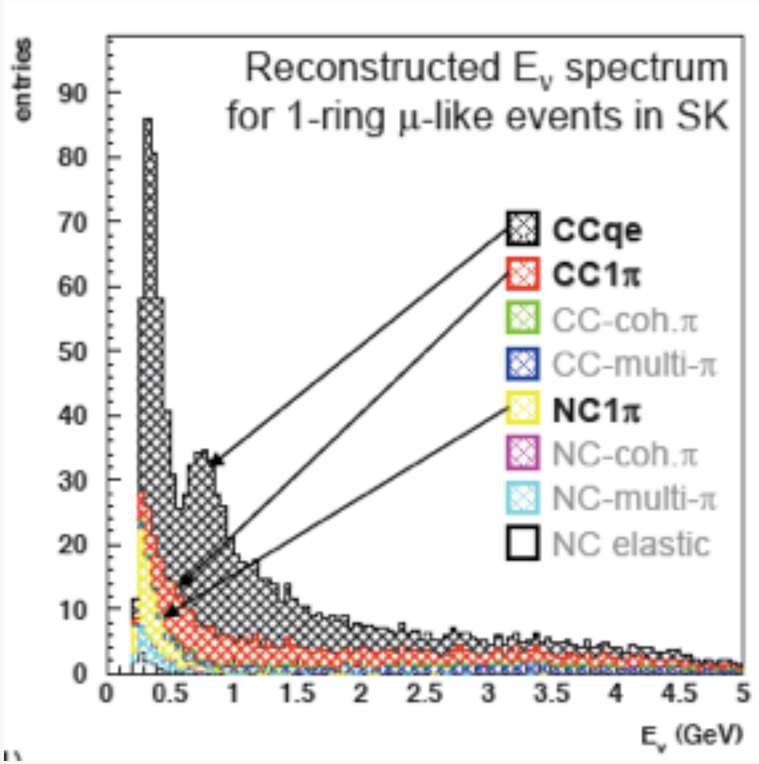


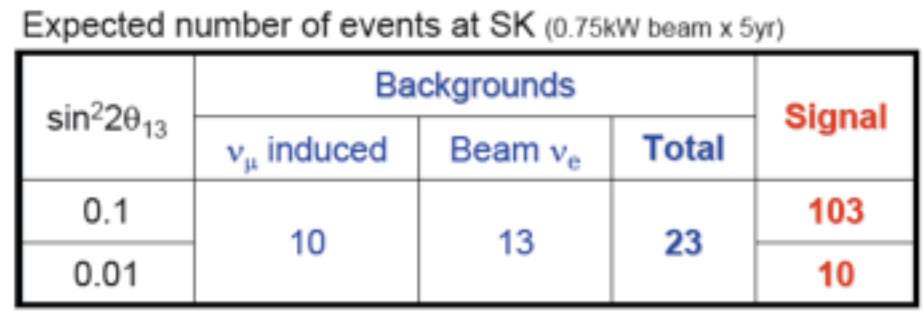




Expected SK analysis

- 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



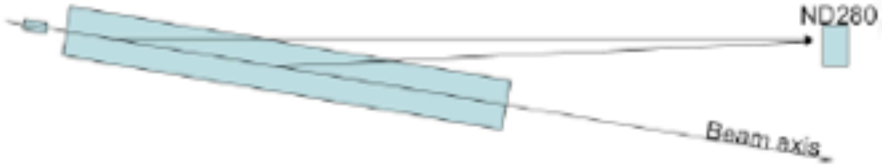


Expected number of events at SK (0.75kW beam x 5yr)

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

$R_{far/near}$ turns out to be robust against hadron production models

- E_ν of off-axis beam is insensitive to P_π



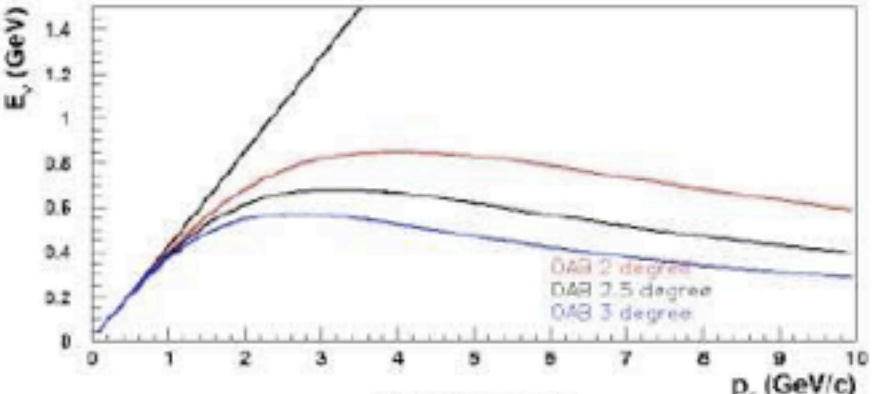
- Decay vertex distribution is also insensitive to P_π

$$\text{Yield} \propto [\text{Decay}]\times[\text{Solid angle}]$$
$$\propto e^{-z/\gamma\beta c\tau} \times \frac{1}{z^2+r^2}\,\frac{1}{4\pi\gamma^2(1-\beta\cos\theta)^2}$$

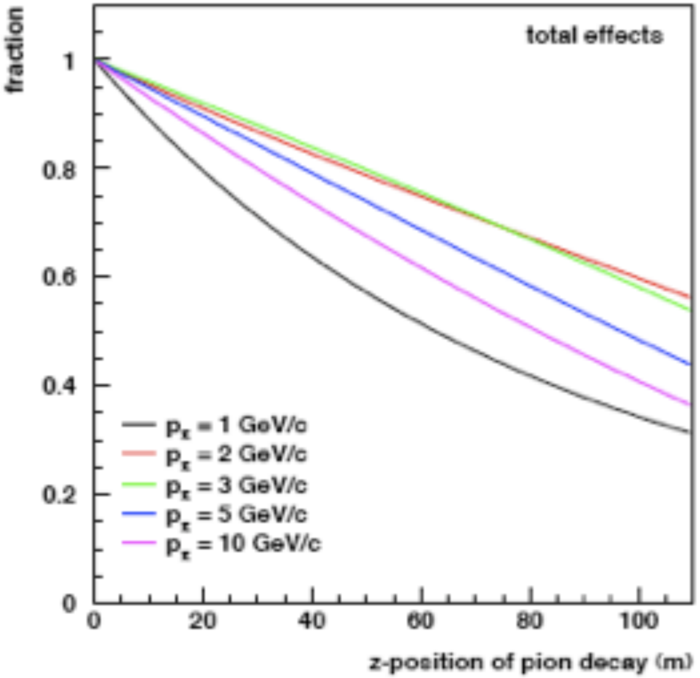
P_π dependences of decay and Lorentz factors cancels for horn focused P_π range of 1.5-4GeV.

Another advantage of off-axis beam!

⇒ $R_{far/near}$ difference between MARS and FLUKA is 2% at the peak and 5% in the tail, which is within the required uncertainty of $< 5\%$.

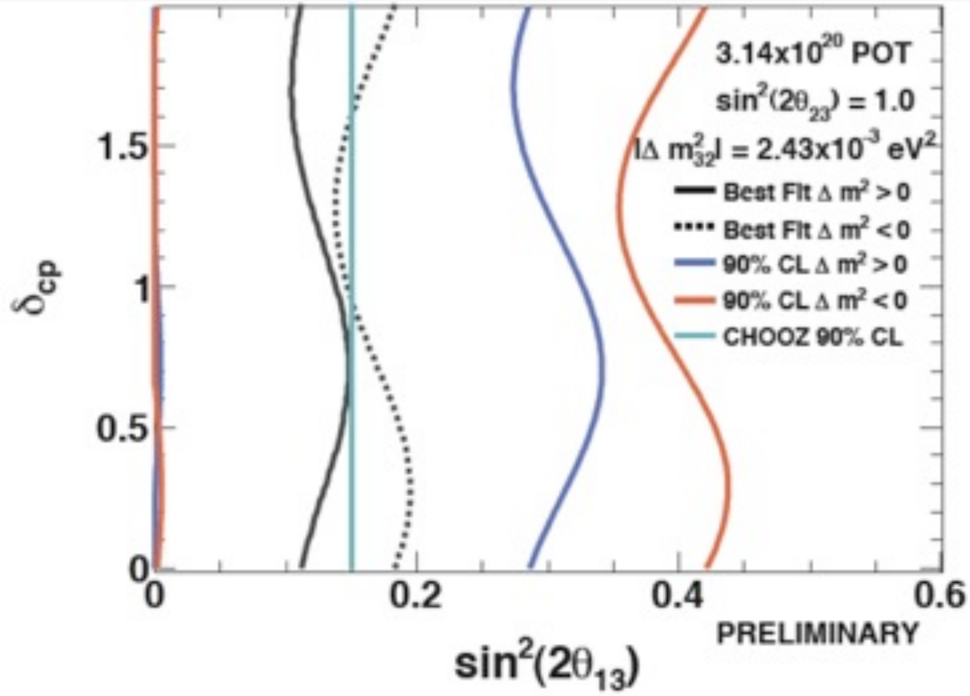


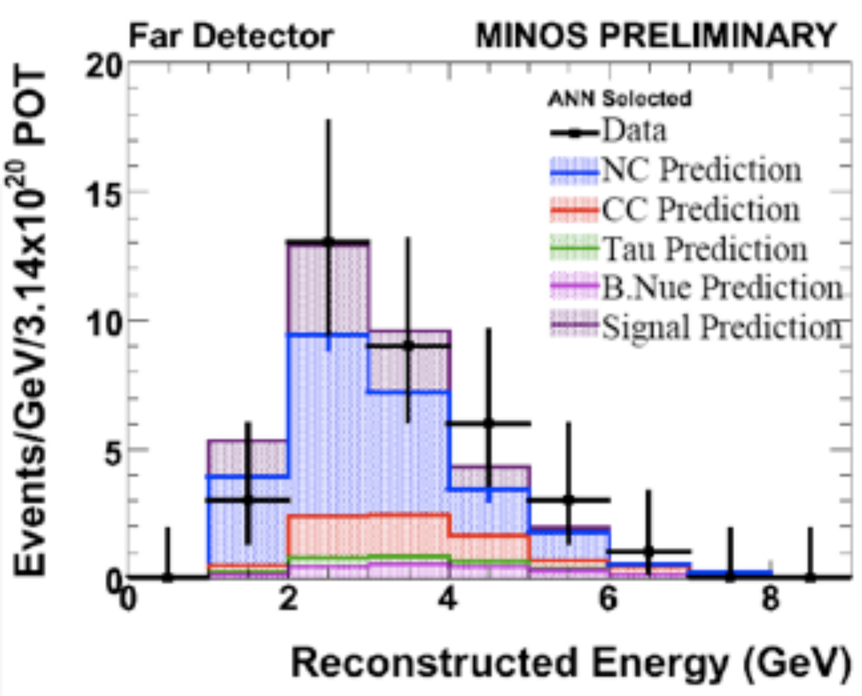
Off-Axis beam



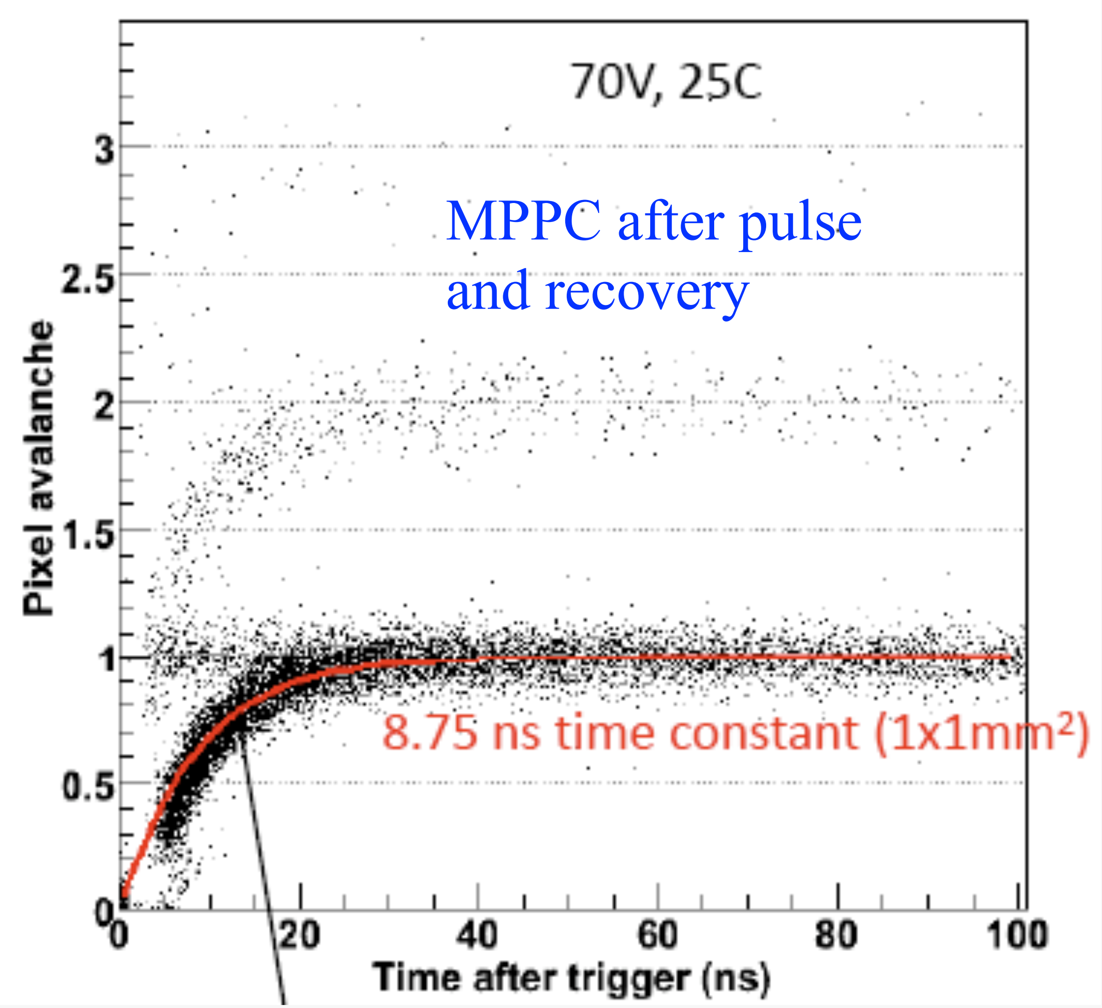
MINOS ν_e appearance result

Far Background: 27±5(stat)±2(sys)
Far Data: 35 events
1.5σ excess above background





MPPC studies



MPPC after pulse and recovery

8.75 ns time constant (1x1mm²)