Physics Results from the first year of the T2K

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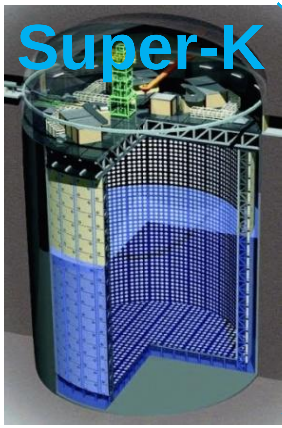
for T2K collaboration

Apr. 27th (2011) ICRR Seminar

Contents

- T2K experiment
- Experiment performance
- ν_e appearance analysis

T2K (Tokai to Kamioka)

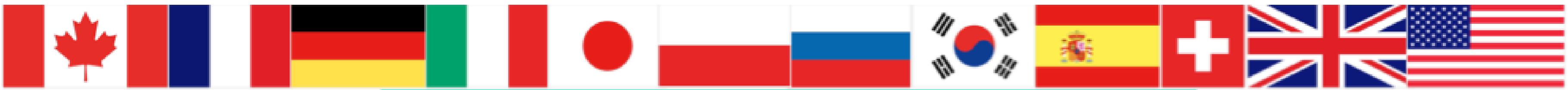


50-kt water Cherenkov
(22.5 kt fiducial)

30-GeV 750-kW proton beam

- **Long baseline neutrino oscillation experiment**
  - Intense ν_μ beam at **J-PARC**
  - Measure neutrino oscillation at **Super-K** (295 km away)
- **Goals**
  - Discovery for $\nu_\mu \rightarrow \nu_e$ (ν_e appearance)
  - Precise measurement of $\nu_\mu \rightarrow \nu_\tau$ (ν_μ disappearance)

The T2K Collaboration



~500 members, 61 Institutes, 12 countries

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U. Regina
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IPN Lyon
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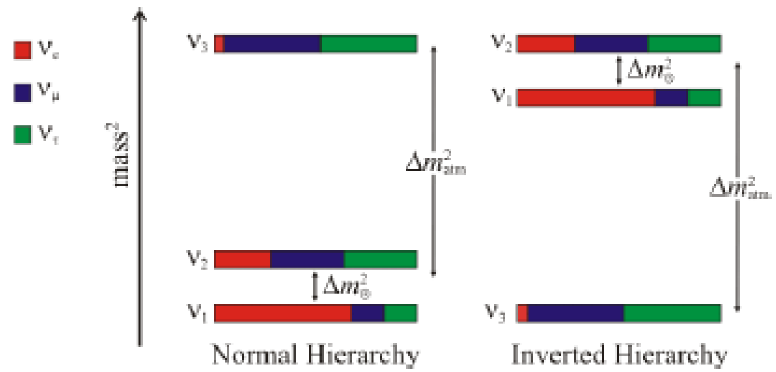
Neutrino Oscillation

flavor states ≠ mass states

ν mixing ~ 3 × 3 unitary matrix U_{PMNS}

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



U_{MNS}: 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 CP phase (δ)

2 mass differences ($\Delta m_{ij}{}^2 = m_i^2 - m_j^2$)

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

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

atm + accelerator (θ_{23}) **θ_{13}, δ_{cp}** **solar + reactor (θ_{12})**

What we know so far (90 % C.L.)

- **(1,2)**: $\theta_{12} = 34.4^{+1.3}_{-1.2}{}^\circ$, $\Delta m_{12}{}^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5}$ eV^2 (solar + reactor)
- **(2,3)**: $\theta_{23} = 37^\circ \sim 45^\circ$, $\Delta m_{23}{}^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 (atmospheric + accelerator)
- **(1,3)**: only upper limit, $\theta_{13} < 11^\circ$ (reactor(CHOOZ) + accelerator)
- **δ /sign of $\Delta m_{atm}{}^2$** : no information

Goal of T2K

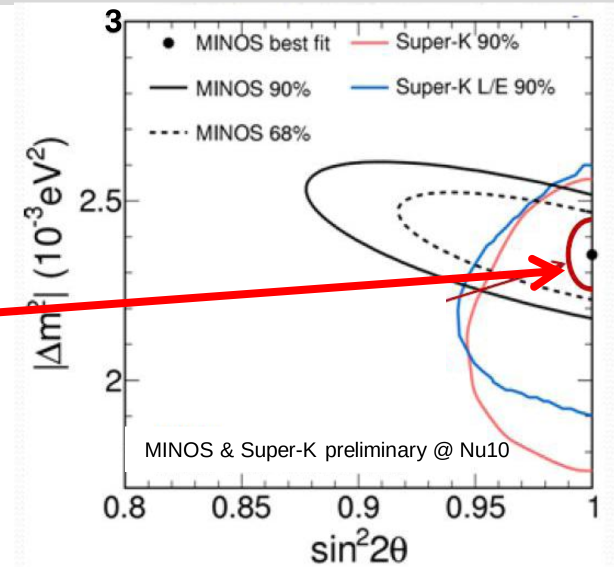
- **ν_μ disappearance**

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(1.27\Delta m^2_{23}\frac{L}{E}\right)$$

$$\approx 1 - \sin^2 2\theta_{23}\sin^2\left(1.27\Delta m^2_{23}\frac{L}{E}\right)$$

<u>T2K goal w/ 3.75 MW × 10^7s:</u>

$\delta(\Delta m_{23}^2) \sim 1\times10^{-4}$ eV^2, $\delta(\sin^2 2\theta_{23}) \sim 1\%$ (90% C.L.)



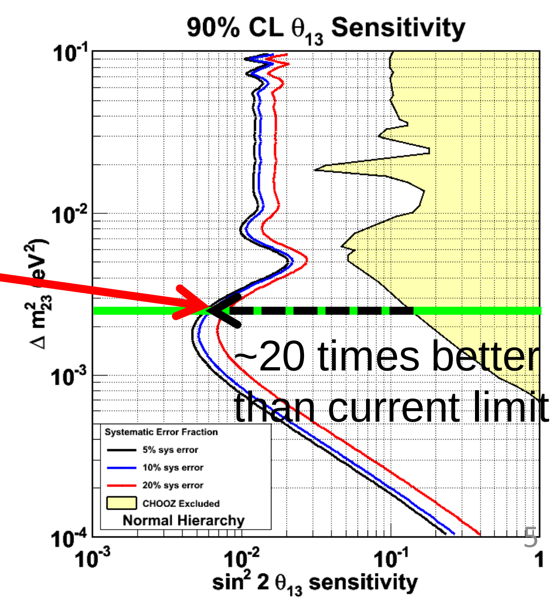
- **ν_e appearance**

$$P_{\mu\rightarrow e} \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(1.27\Delta m^2_{13}\frac{L}{E}\right)$$

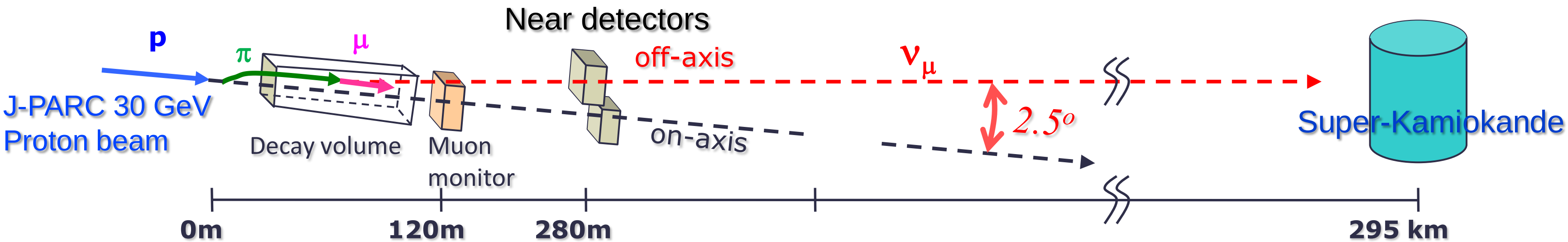
<u>T2K goal w/ 3.75 MW × 10^7s:</u>

$\sin^2 2\theta_{13}$ down to 0.006 (90% C.L.)

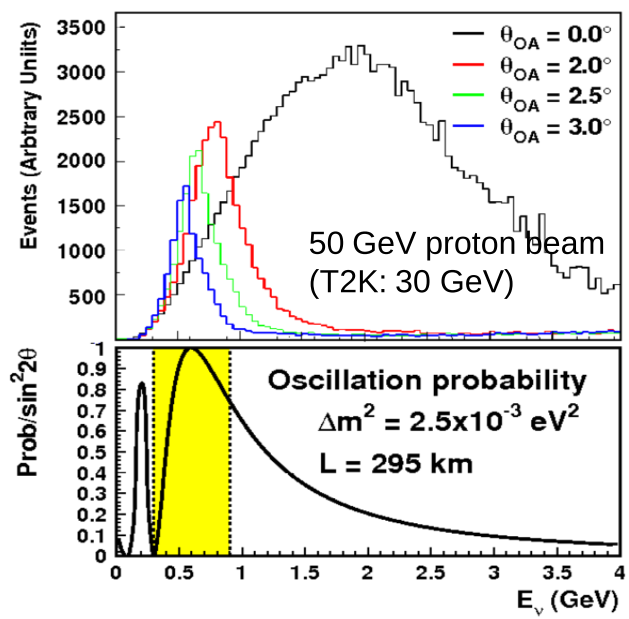
($\Delta m^2 \sim 2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$, δ_{CP}=0, normal hierarchy, 10% syst. error.)



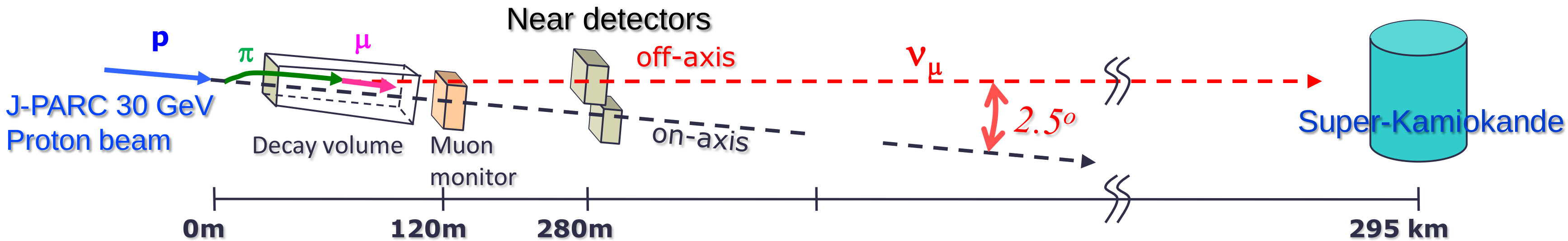
Off-Axis Neutrino Beam



- **T2K ν_μ beam**
  - **Oscillation maximum:** L=295km, Δm_{23}^2~2.4 × 10^{-3} eV^2 → **E_ν ~ 0.6 GeV**
  - **Signal:** Charged Current Quasi Elastic events
- **E_ν spectrum vs angle**
  - On-axis: large tail at high energy
  - Off-axis: narrow spectrum
- **Our choice: off-axis angle = 2.5°**
  - Increase flux at the oscillation maximum
  - Reduce high energy ν background from non-CCQE events
- **Small ν_e fraction** (~1%)

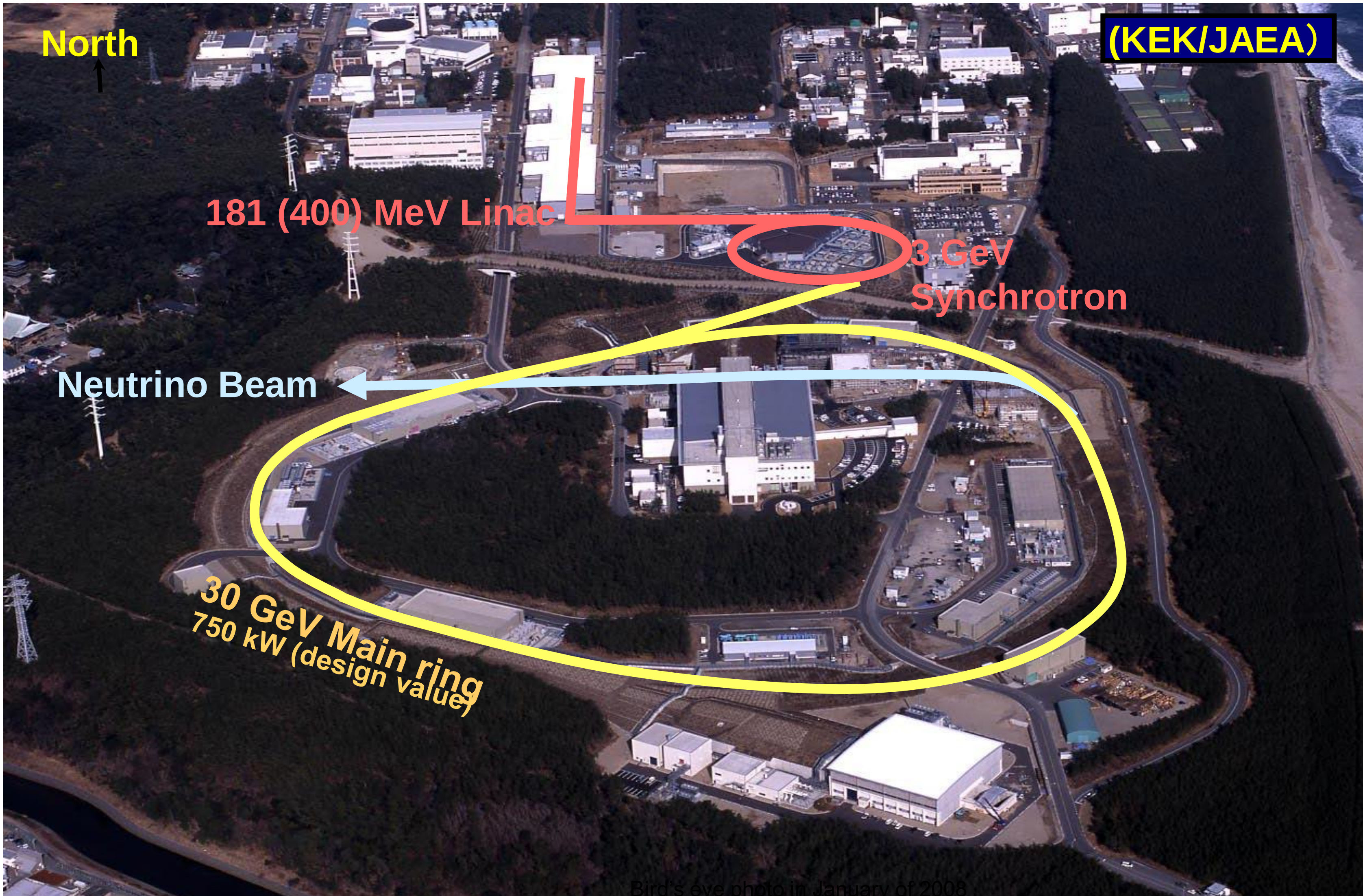


T2K Overview

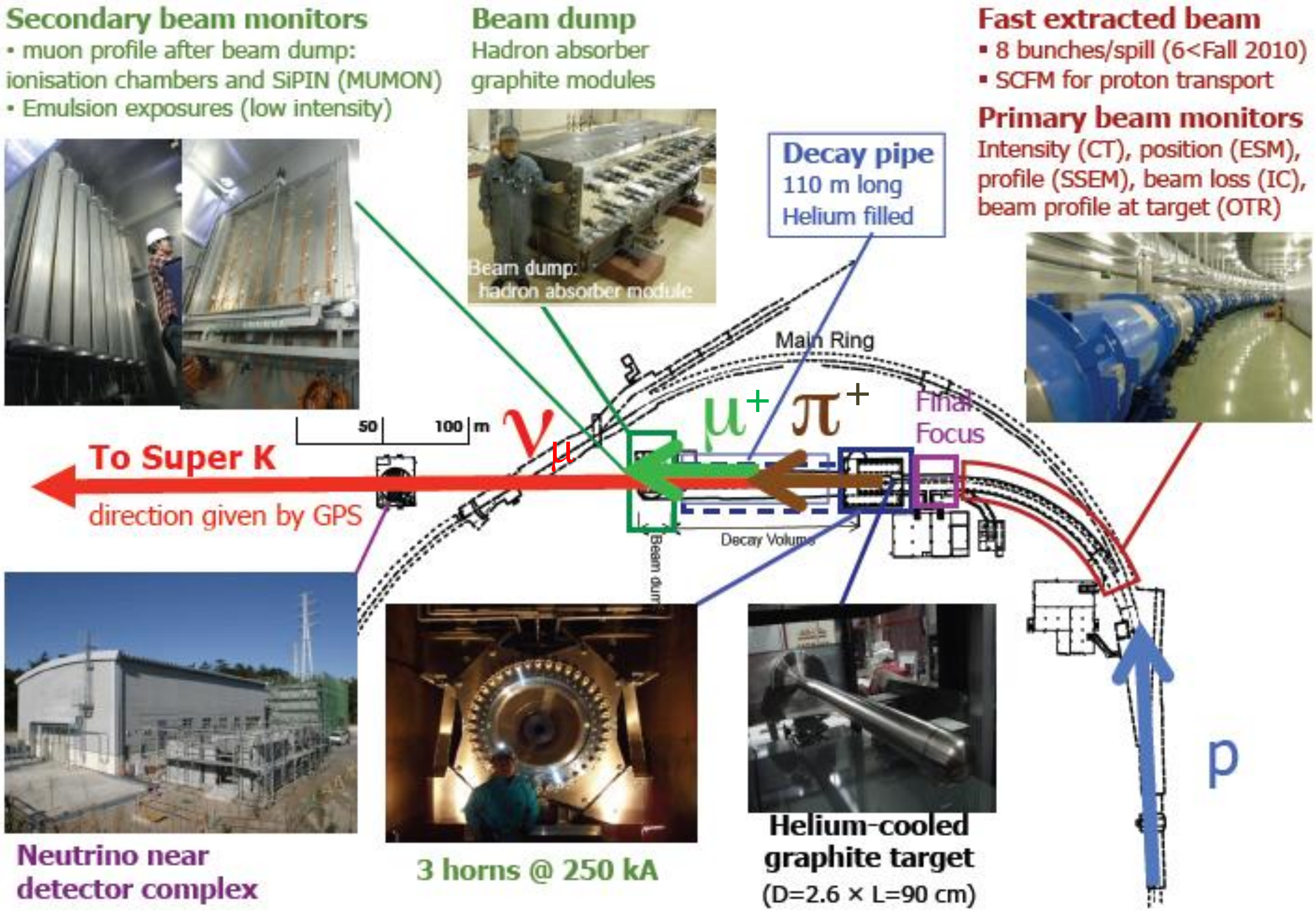


- **Beam monitoring**
  - Primary proton beam monitors (intensity, position, profile)
  - Muon monitor (**MUMON**) just after decay pipe: beam direction/intensity
- **Near detector @ 280m**
  - on-axis (**INGRID**): ν beam direction/intensity
  - off-axis (**ND280**): ν flavor/flux/spectrum/"cross section" measurement
- **Off-axis far detector @ 295km**
  - **Super-Kamiokande**: ν flavor/flux/spectrum measurement

The J-PARC facility

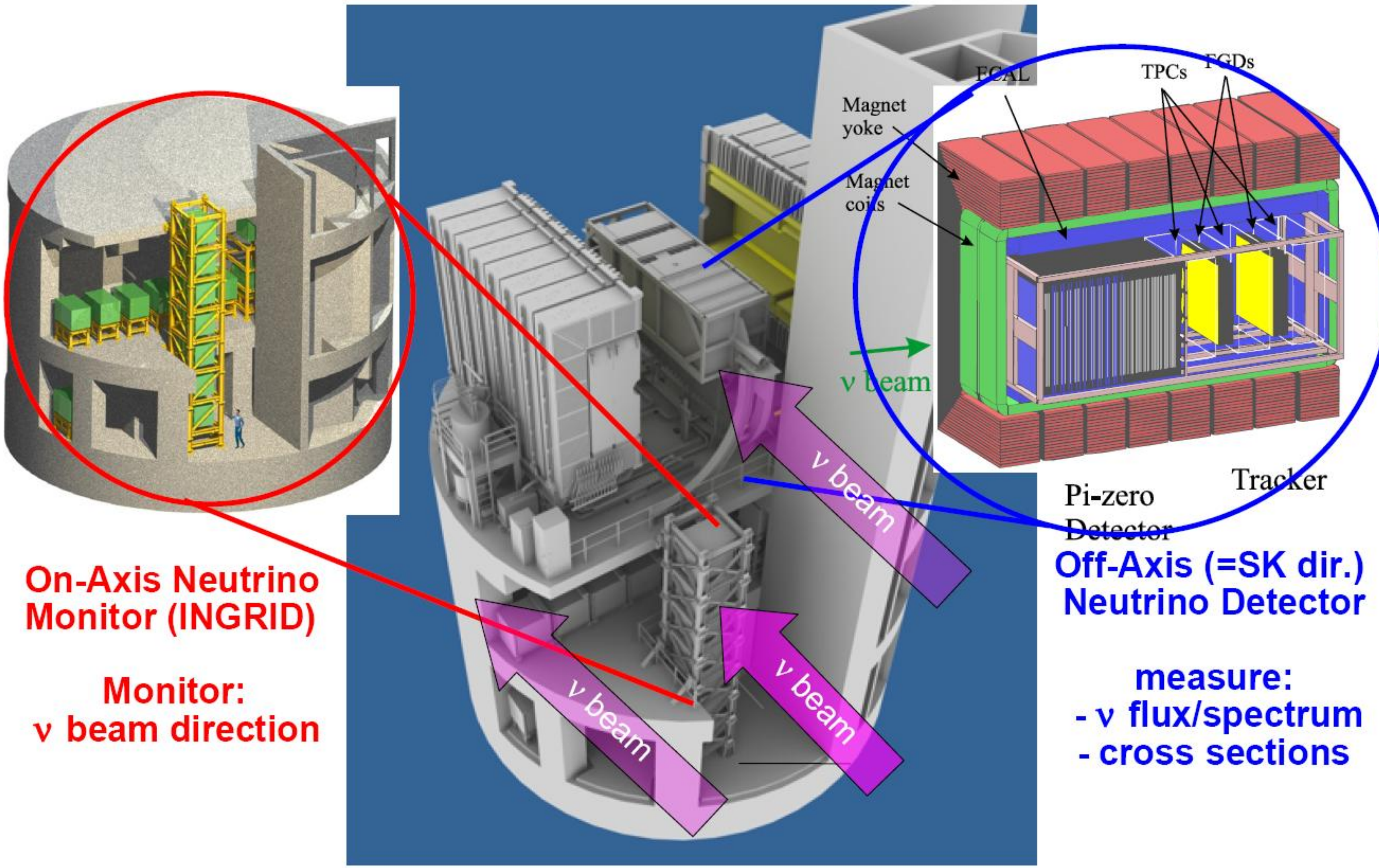


Beam Line



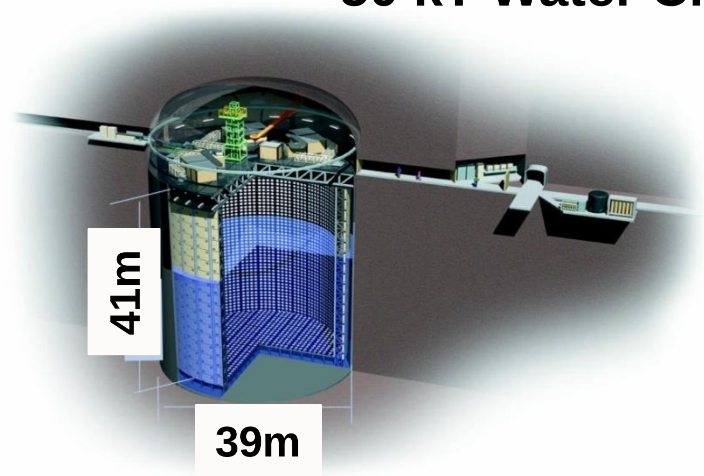
Secondary beam monitors
• muon profile after beam dump: ionisation chambers and SiPIN (MUMON)
• Emulsion exposures (low intensity)
Beam dump
Hadron absorber graphite modules
Beam dump: hadron absorber module
Decay pipe
110 m long
Helium filled
Fast extracted beam
▪ 8 bunches/spill (6<Fall 2010)
▪ SCFM for proton transport
Primary beam monitors
Intensity (CT), position (ESM), profile (SSEM), beam loss (IC), beam profile at target (OTR)
Main Ring
50
100 m
ν_μ
μ^+
π^+
Final Focus
To Super K
direction given by GPS
Decay Volume
Beam dump
p
Neutrino near detector complex
3 horns @ 250 kA
Helium-cooled graphite target
(D=2.6 × L=90 cm)

Near Detector: INGRID and ND280



Far detector: Super-Kamiokande

50 kT Water Cherenkov detector (22.5 kT fiducial mass)



Inner detector: 11,129 PMTs (20 inch)

Outer detector: 1,885 PMTs (8 inch)

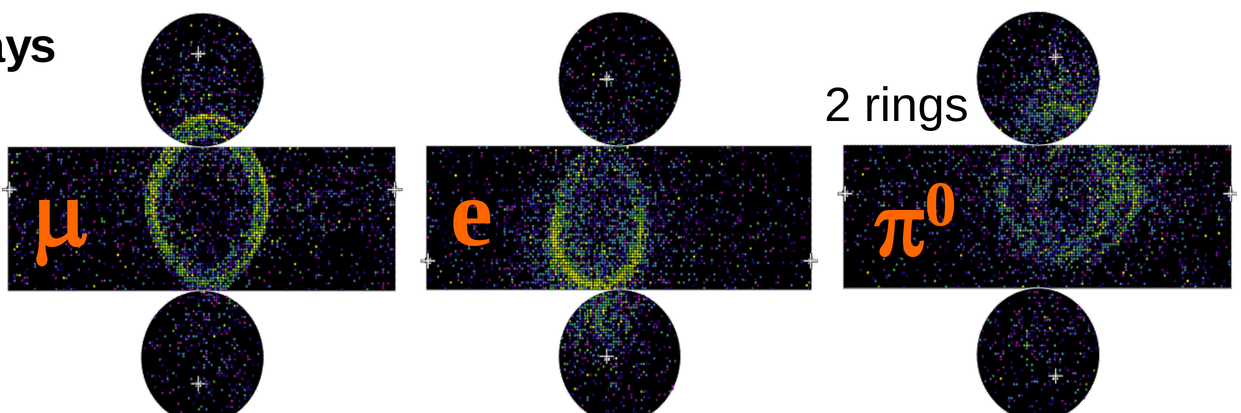
New electronics/DAQ (since 2008)

- Stably running
- Deadtime-less DAQ
  → Improve e-tagging (from μ decay) efficiency

Good e-like/μ-like separation:

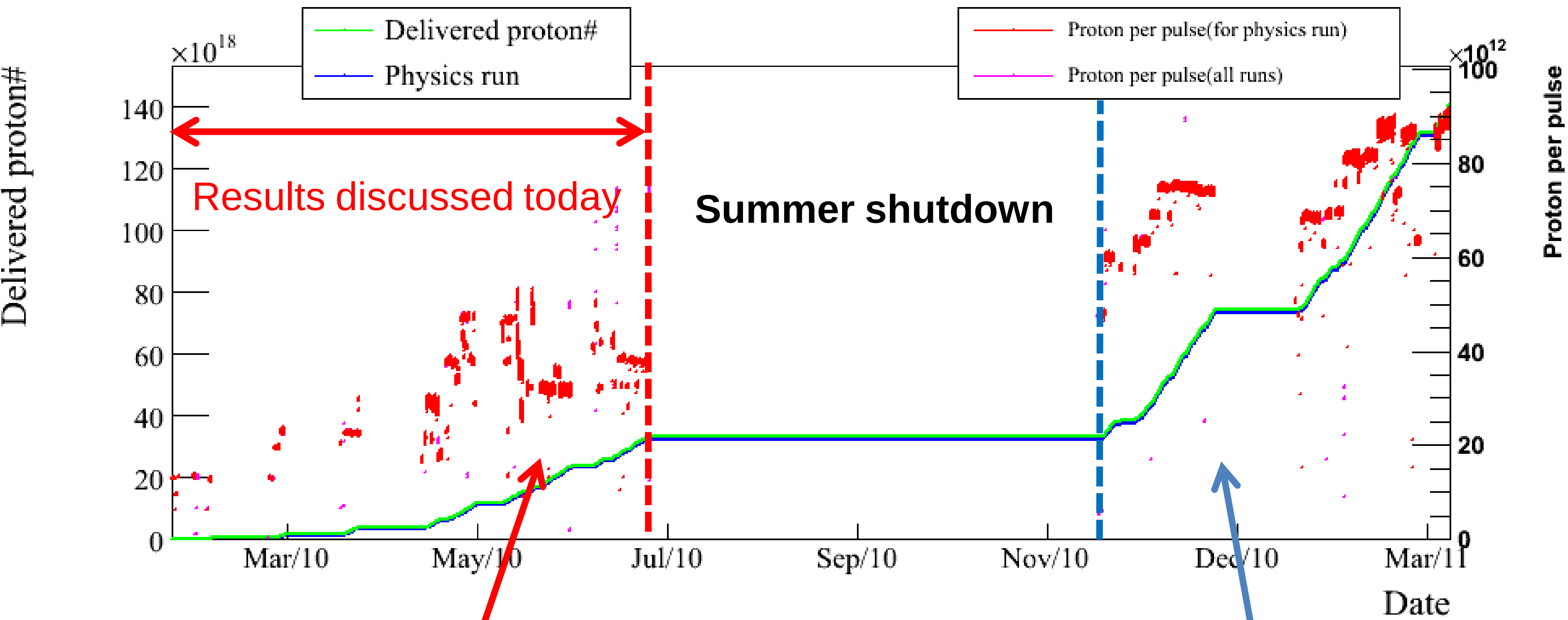
mis-PID probability ~ 1% π^0 background rejection

Event displays
(MC events)



EXPERIMENT PERFORMANCE

Delivered Protons



T2K run 1 **(Jan. to Jun. 2010)**

- **6 bunches/spill**, **3.5 s** spill period
- 3.23×10^{19} POT for T2K analysis
- ~**50 kW** operation

T2K run 2 (from Nov. 2010)

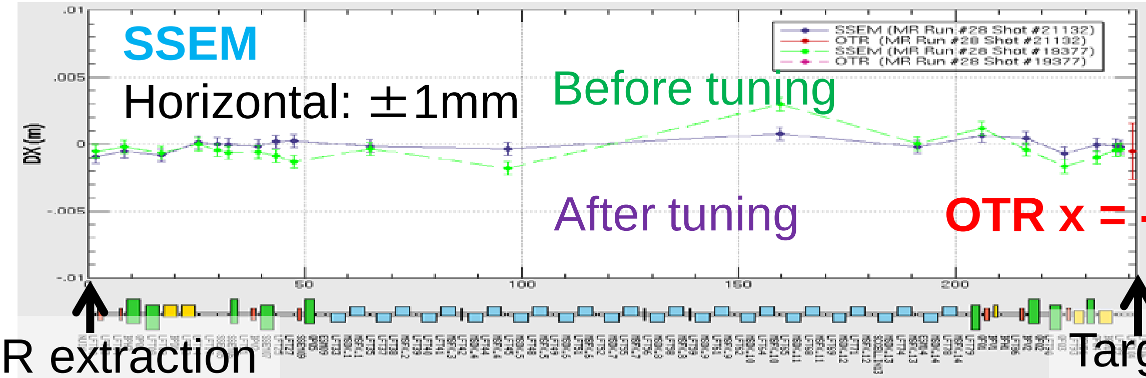
- **8 bunches, 3.2 s** spill period
- 1.45×10^{20} POT delivered
- reaches to ~**145 kW**

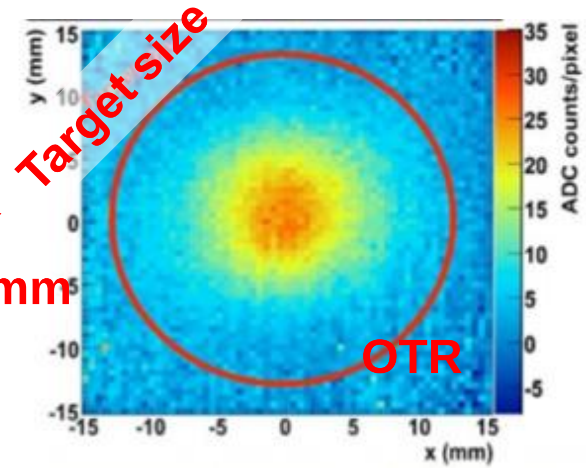
Beam Monitor Measurements

Primary proton beam monitoring

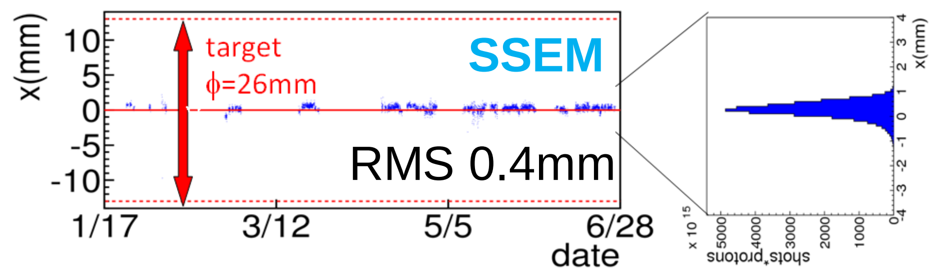
- **Beam orbit:** tuned within 2mm from design orbit.
  (Critical for controlling beam loss)

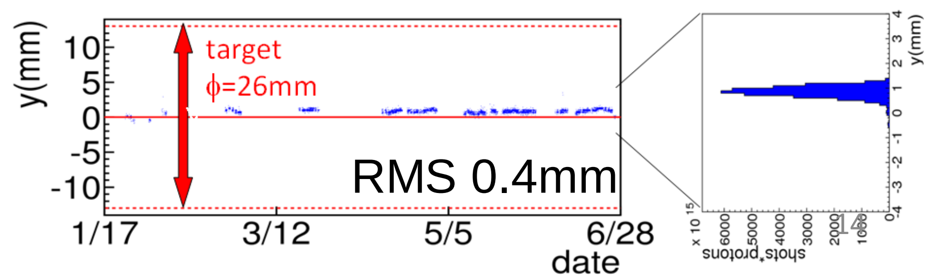
Proton beam hits center of target





- **Beam position on target:**
  Succeeded to control < 1mm during long term operation



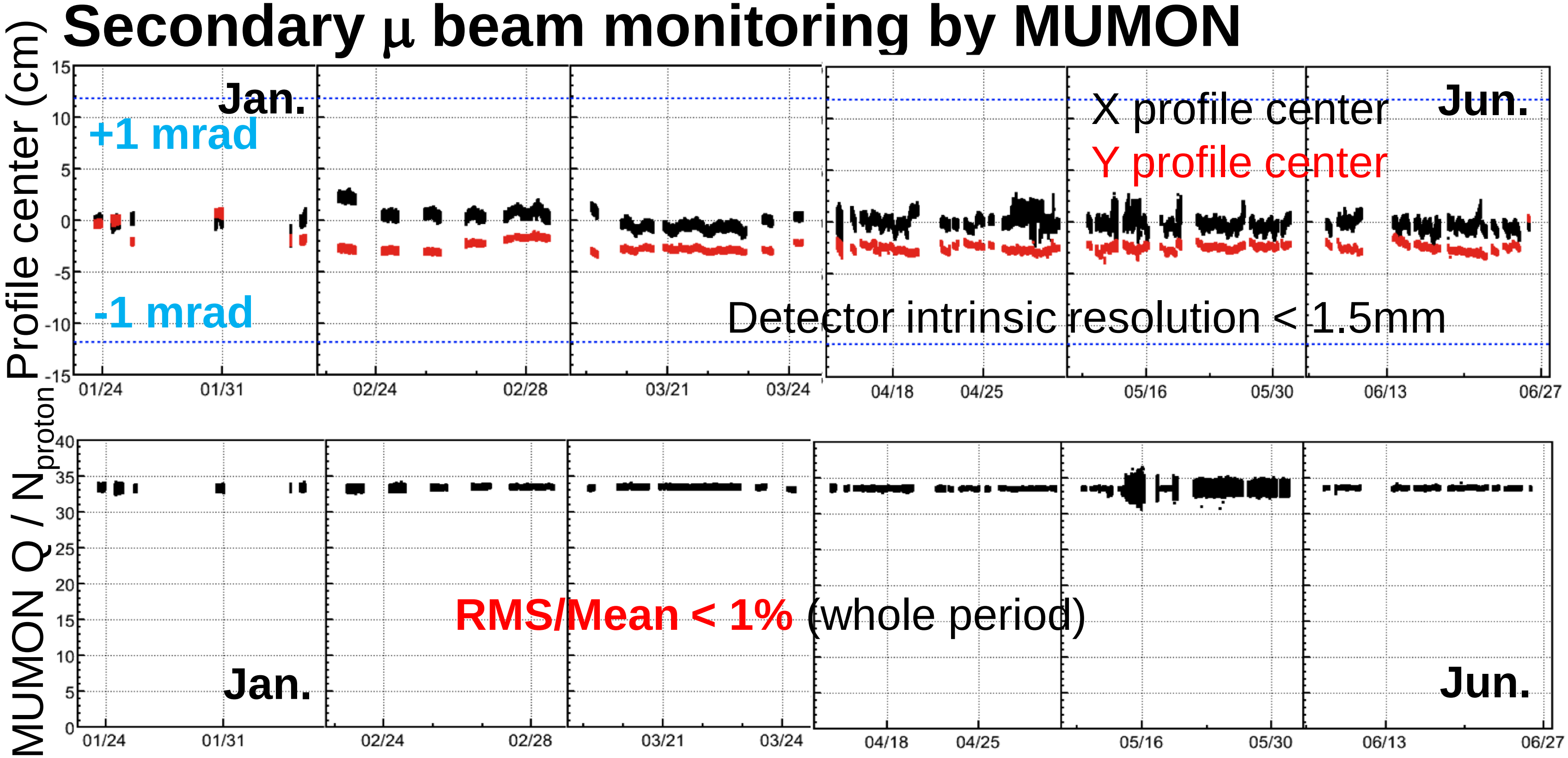


SSEM:
Segmented Secondary Emission Monitor

OTR:
Optical Transition Radiation detector

Beam Monitoring (MUMON)

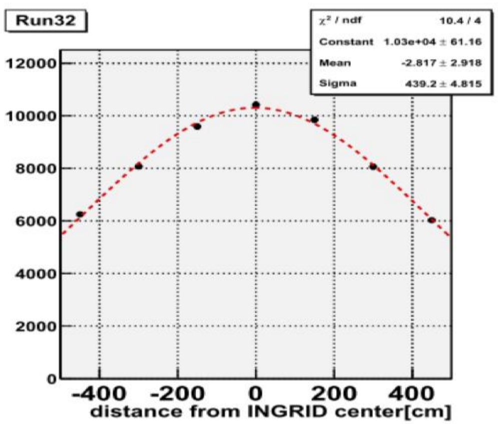
Secondary μ beam monitoring by MUMON

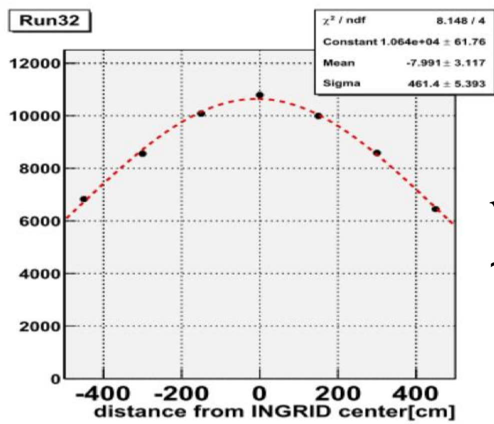


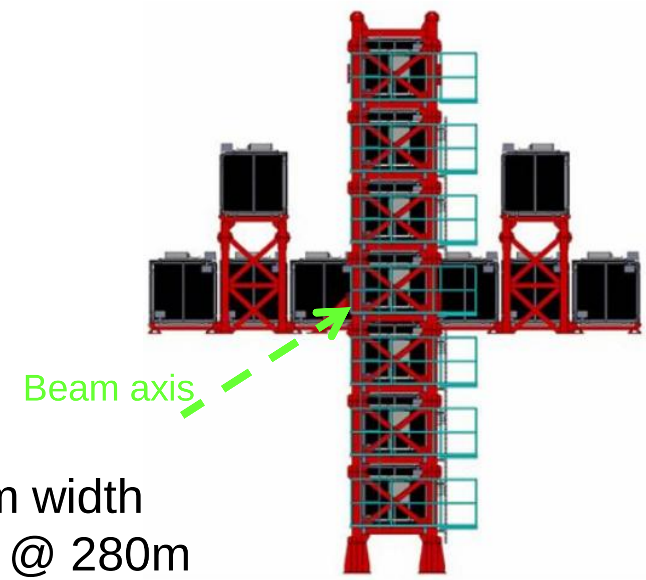
- **Beam direction** is controlled well within **1 mrad**. (1 mrad corresponds to 2% change in the SK flux at the peak energy, E_ν = 0.5 – 0.7 GeV)
- **Secondary beam intensity** (normalized by proton intensity) is stable within **1%** → reflects stability of targeting, horn focussing, etc

Neutrino Beam Monitoring (INGRID)

- Targeting efficiency of proton beam ~99%.
- ν Beam direction measured by INGRID from 2010 Jan. ~ Jun.
  - Horizontal: +0.01±0.05(stat.)±0.33(syst.) mrad
  - Vertical : -0.24±0.05(stat.)±0.37(syst.) mrad

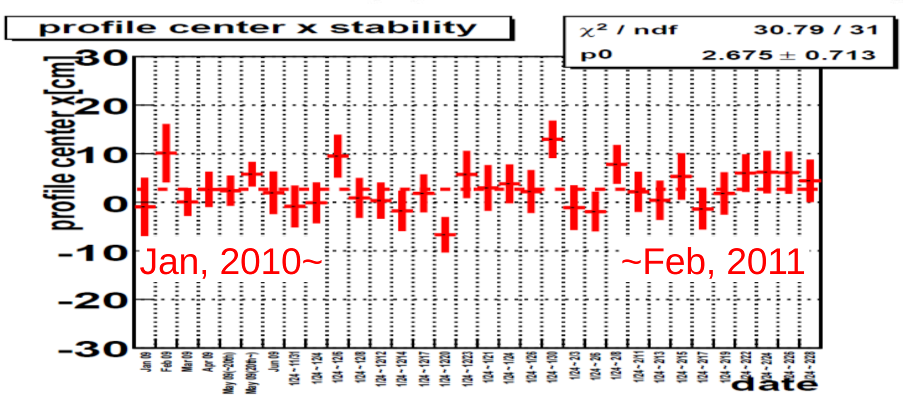


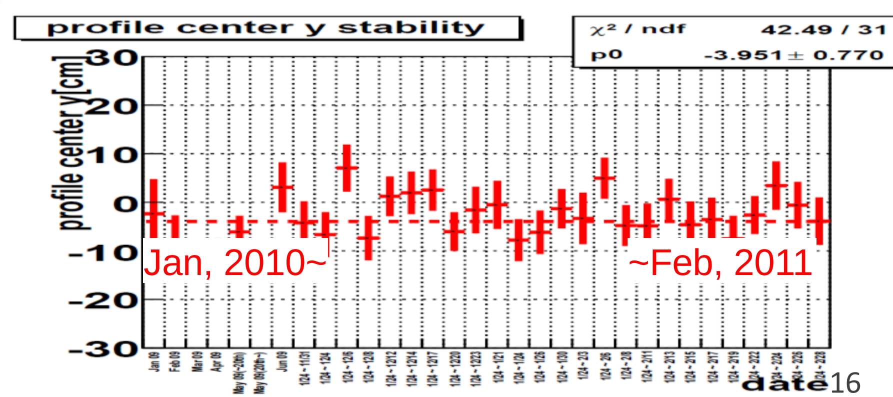




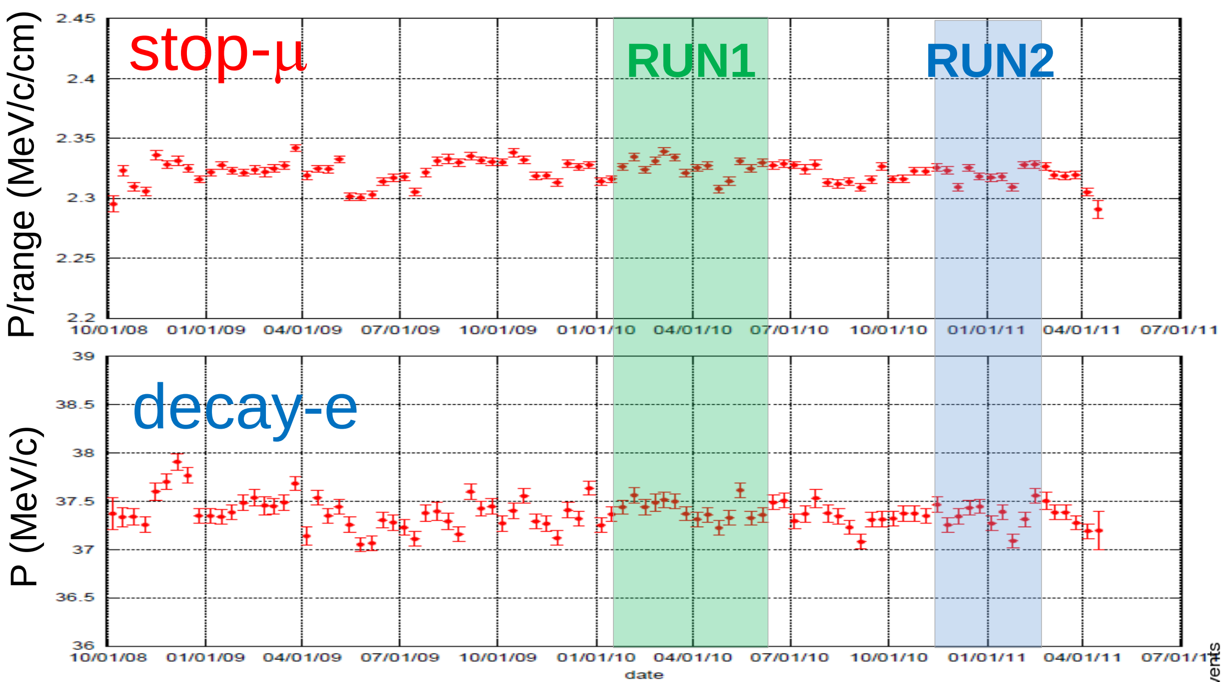
ν beam width ~4.5m @ 280m

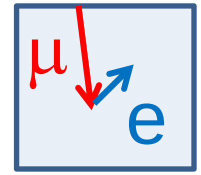
Stability: Vertical





Super-K Performance





Energy scale stability is checked using cosmic muon / decay-e

RMS/Mean ~ 0.4% for both samples during SK4

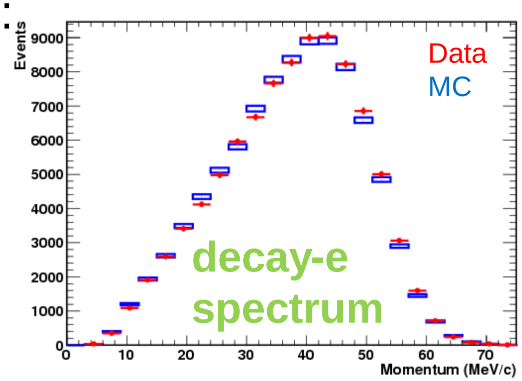
Reconstruction performance:

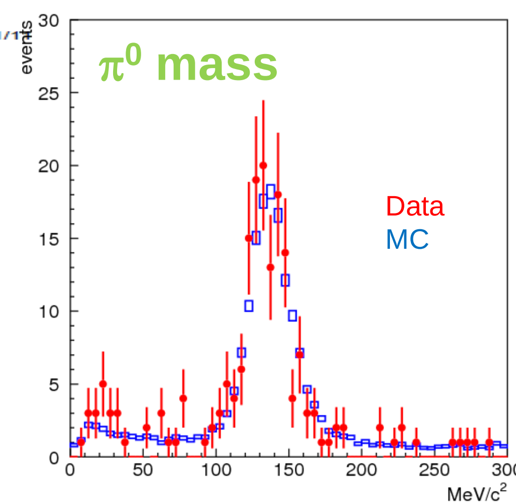
Energy scale:

cosmic μ/e, atm ν π^0

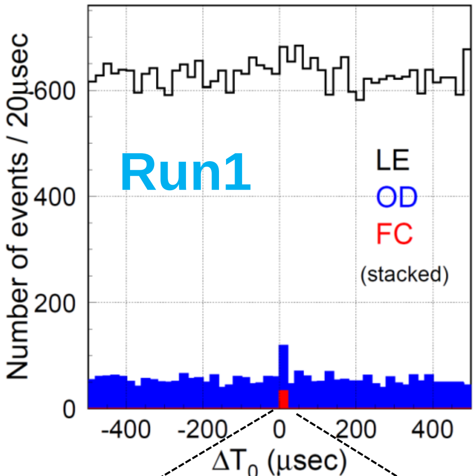
Ring-counting, PID, vertex :

cosmic μ, atm ν data





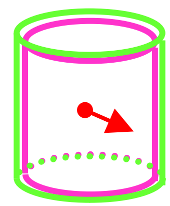
Observed Events at SK



Identify beam-induced events with GPS

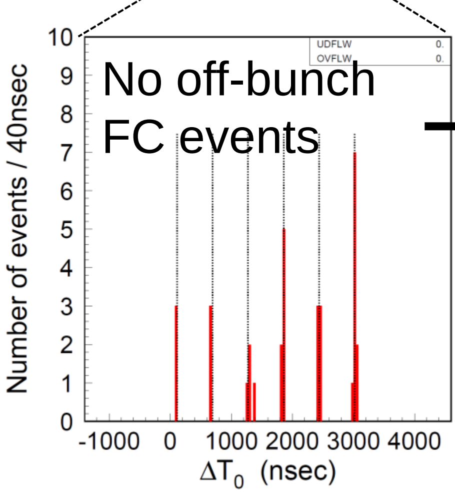
- Transfer beam spill information in real time
- Compare GPS time stamps of beam/SK trigger

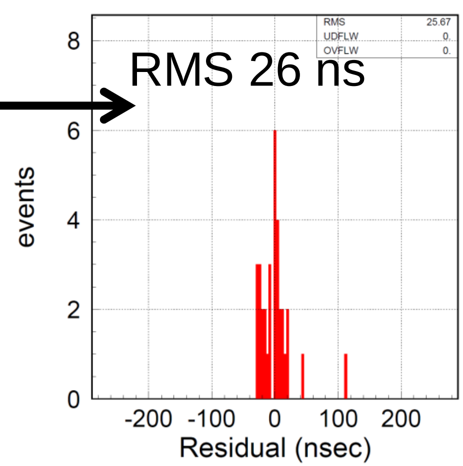
LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events



FC:
all particle contained in ID
no activity in OD

(T2K Run1: 3.23×10^{19} POT)





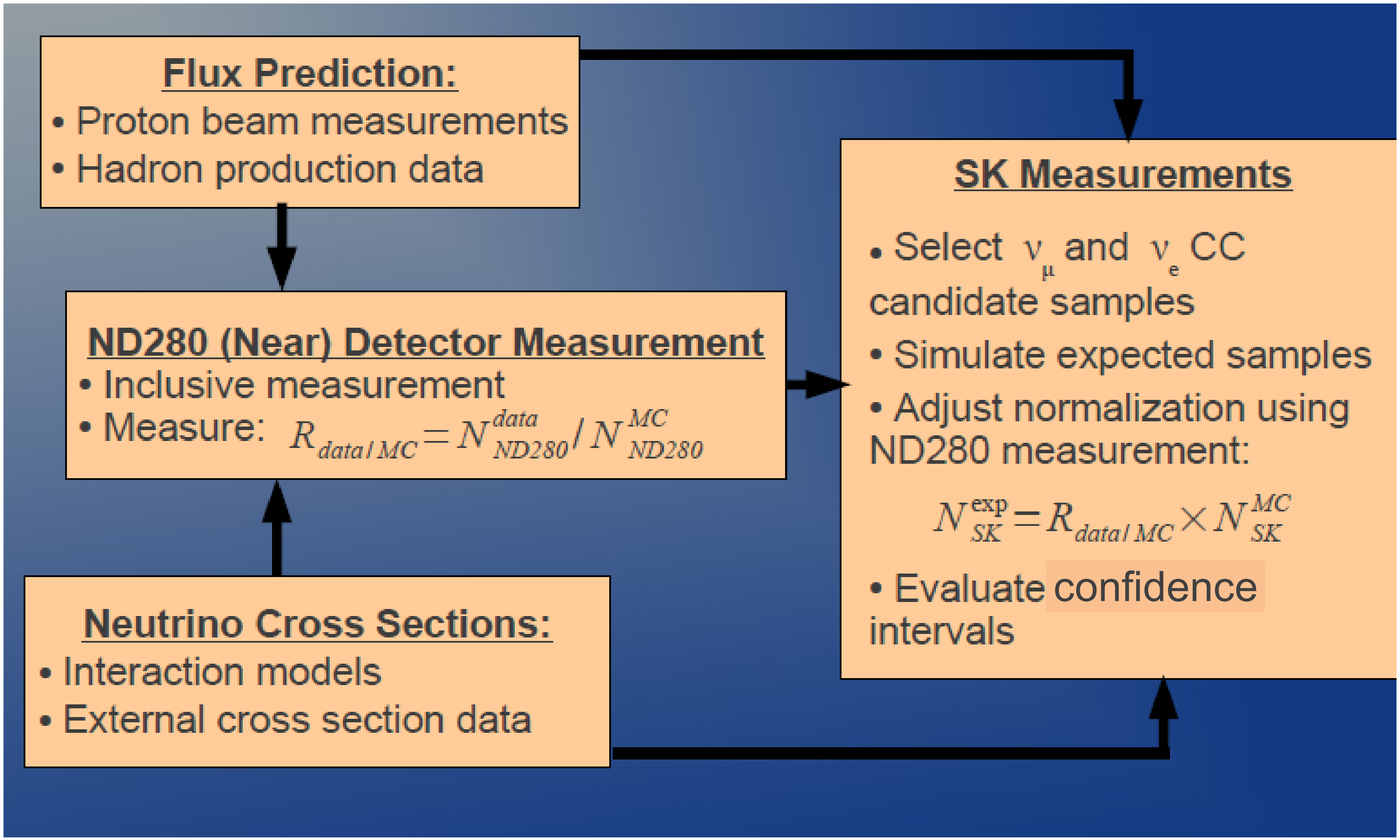
Cuts	Observed events	Expected BG
Fully Contained (FC)	33	~0.01
FC + FV cut + E_{vis} > 30 MeV	**23**	~0.001

ΔT_0=SK trigger time
- beam trigger time

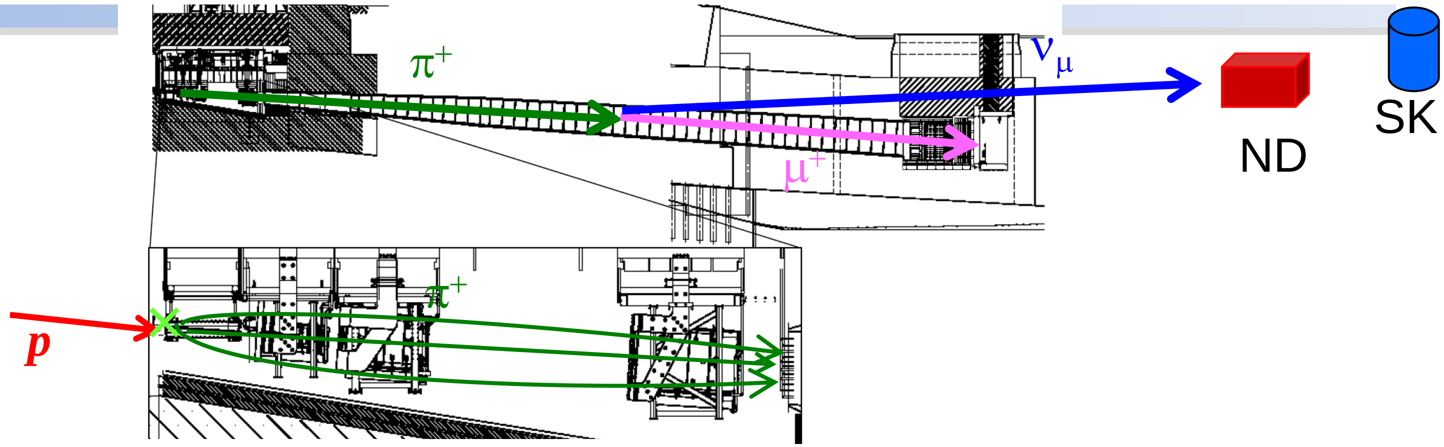
RUN1 OSCILLATION ANALYSIS

(Mainly ν_e appearance)

Analysis Strategy



Flux Prediction (Beam MC)



(1) Hadron production by p+C interaction and secondary interaction in target is simulated using FULKA framework.

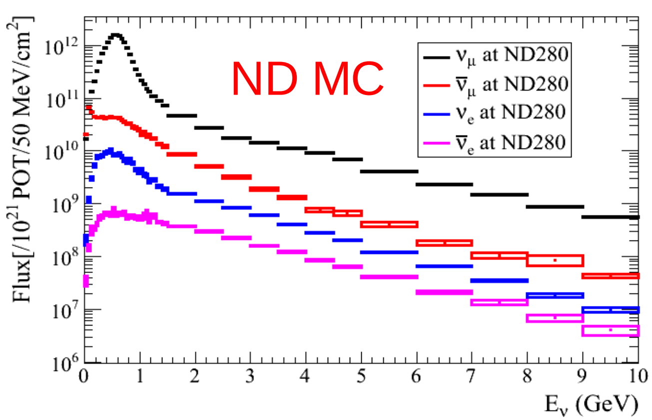
* Pion production cross section is corrected using NA61 data.

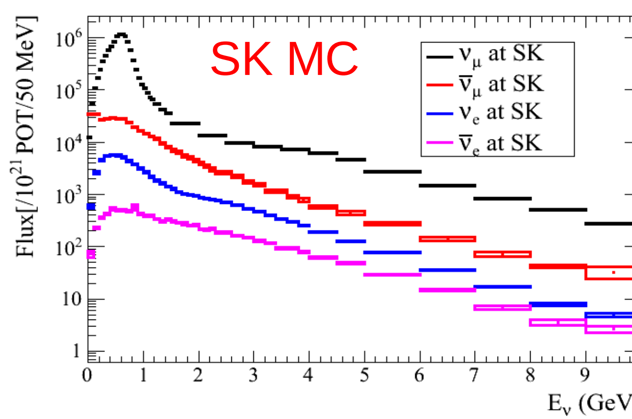
* Measured proton parameters is assumed.

(2) Propagation of produces hadrons (π, K, etc) including Horn focusing is simulated using GEANT3 framework.

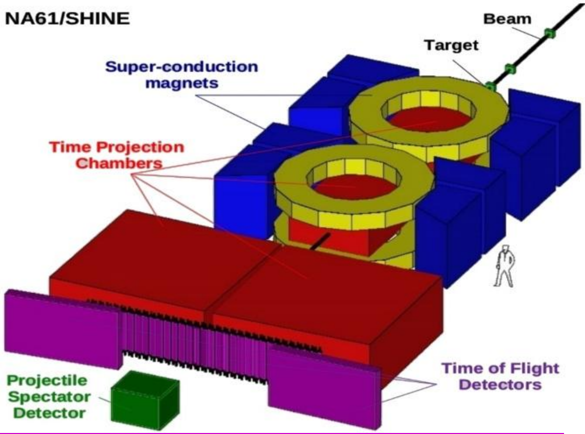
* Secondary interaction cross section is corrected using existing data by other experiments.

(3) ν producing decay is simulated.
Geometrical acceptance is calculated.
→ ν flux obtained at ND & SK, respectively



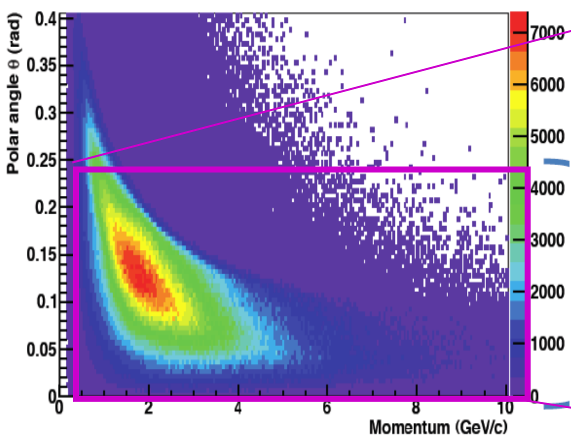


SHINE / NA61

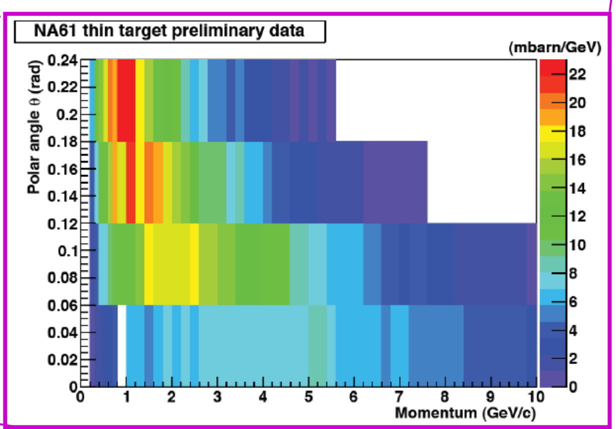


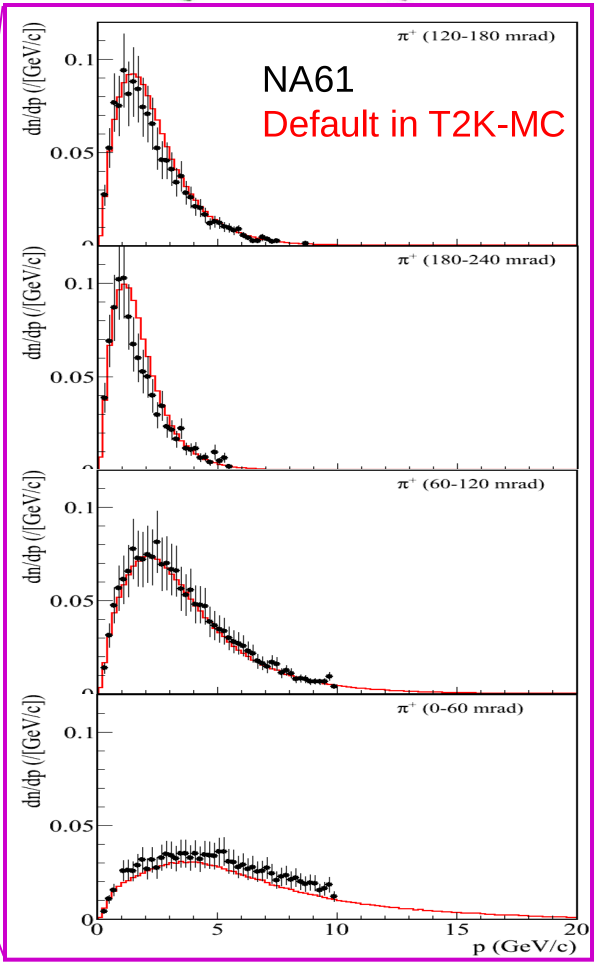
- SHINE experiment (CERN NA61)
  - Data was taken in 2007 and 2009.
    - p (30GeV) + C (target thin:2cm / thick: 90cm)
  - $\pi^{\pm}$ production model in T2K-MC is corrected by NA61 preliminary results which was released in Dec. 2009.
  - Systematic uncertainty
    - 10% : Inelastic p + C cross section
    - 20%: Pion multiplicity

MC(T2K):π^{+} produce ν_{μ} @ SK



NA61 2007 data: π^{+}

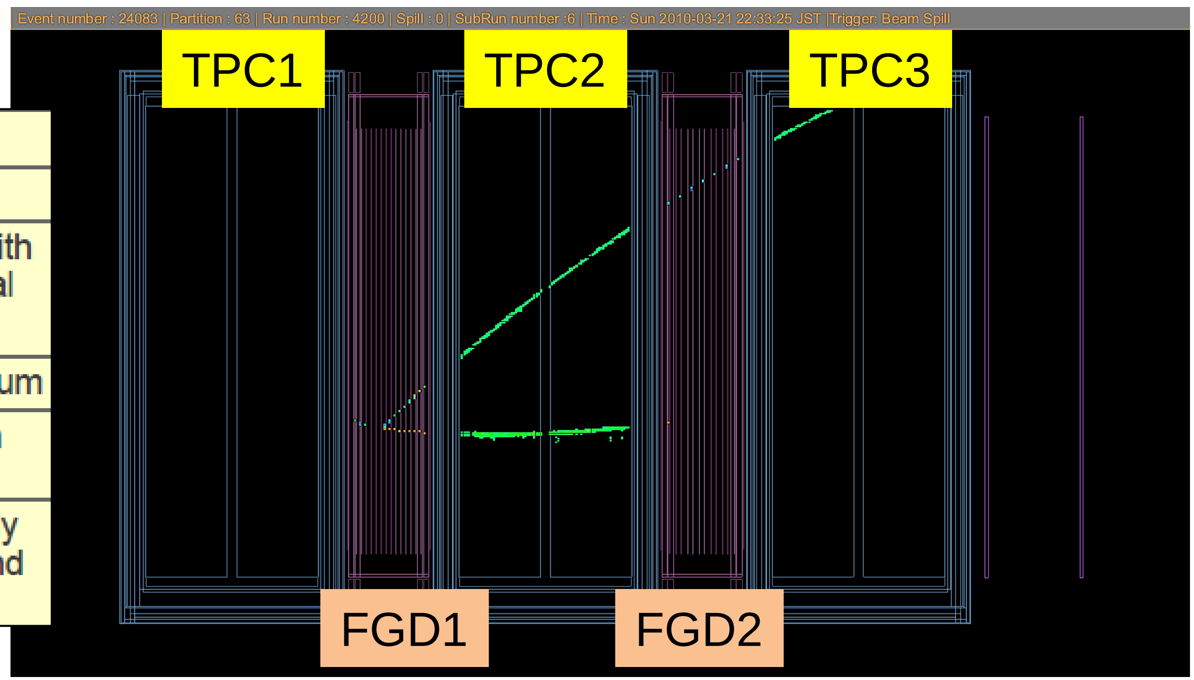




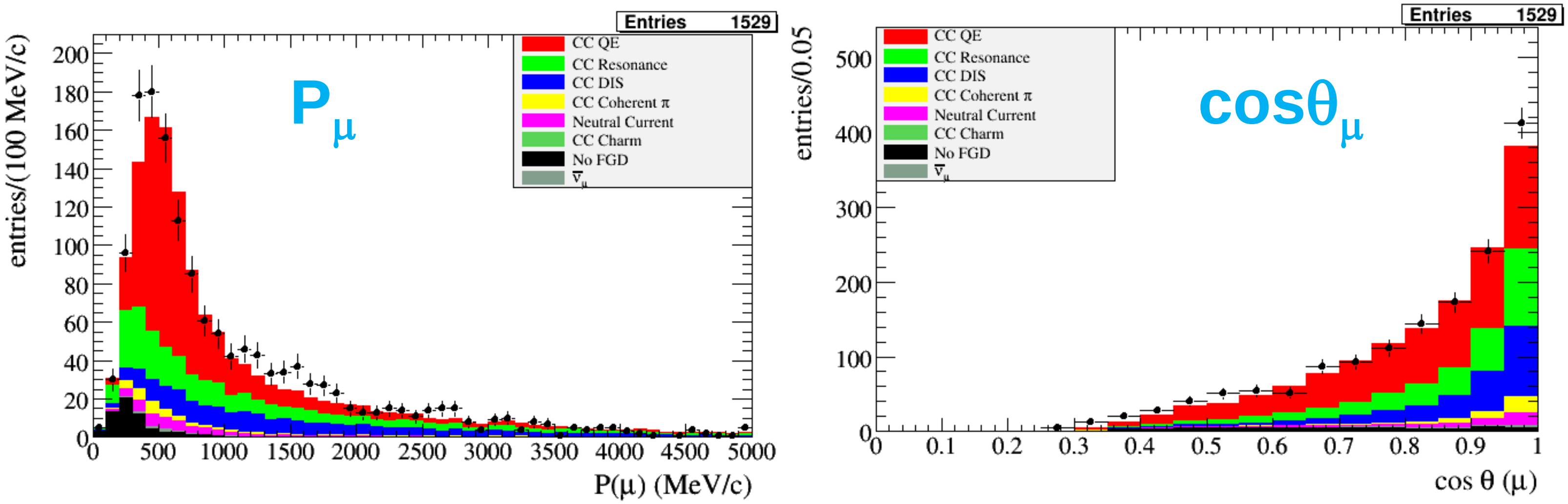
ND280 Analysis

- Use inclusive events with low level reconstruction
  - Track start from FGD, and dE/dx cut in TPC
  - 90% ν_μ purity, 50% CCQE

Event Selection
No tracks in first TPC
At least 1 track in second TPC with starting point in first FGD fiducial volume, p>50 MeV/c
Select track with highest momentum
TPC dE/dx cuts to select muon candidates, exclude electrons
If no tracks in second TPC, apply selection to third TPC and second FGD



ND280: Normalization DATA/MC



# of CC inclusive μ events

$$R_{Data/MC} = 1.061 \pm 0.028(stat.)^{+0.044}_{-0.038}(syst.) \pm 0.039(phys.)$$

Uncertainty on N_{exp}:

$$N^{SK}_{\exp} = \frac{N^{ND}_{Data}}{N^{ND}_{MC}} \times N^{SK}_{MC}$$

±2.7% by data statistics

$^{+5.6}_{-5.2}$ % by ND efficiency & phys.

ν_e Analysis: Signal and BGK

Signal : $\nu_\mu \rightarrow \nu_e$

- Main events: νe CCQE
- Event selection
  - Single-ring e-like PID
  - No delayed signal from π, μ
  - Eν ~ 600 MeV

BKG : Beam ν_e CC

- Small fraction (~1%) in beam
- But significant after reduction
- No pattern difference with signal
- Higher energy than signal
  - reduced by energy cut

BKG : Beam ν_μ CC

- Dominant fraction in beam
- Powerful rejection by:
  - Muon PID
  - Tag delayed electron signal

BKG : NC π^0 production

- $\pi^0 \rightarrow \gamma + \gamma$
- mis-reconst. of 2nd γ could be BKG
- Special π^0 fitter to find 2nd gamma
- Reduced by π^0 mass peak cut

ν_e Analysis: Selection Criteria

Basic neutrino selection
Fully contained events in inner detector
Visible energy > 30 MeV
Reconstructed vertex >2m from wall

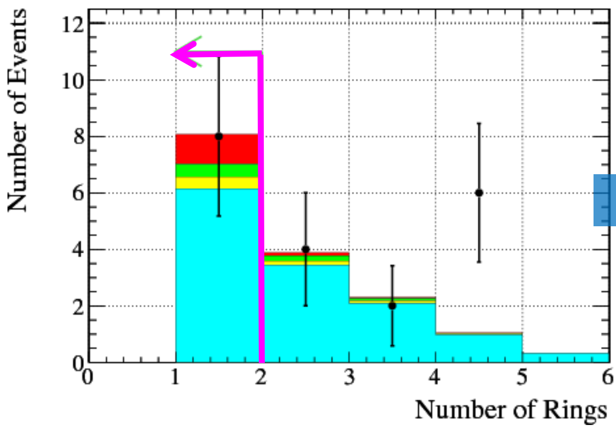
νe selection
Single Cherenkov Ring
Electron-like PID
Visible energy >100 MeV
No delayed electron signal
π^0 invariant mass < 105 MeV
Reconst. ν energy < 1250 MeV

$\nu\mu$ selection
Single Cherenkov Ring
Muon-like PID
Muon momentum > 200 MeV

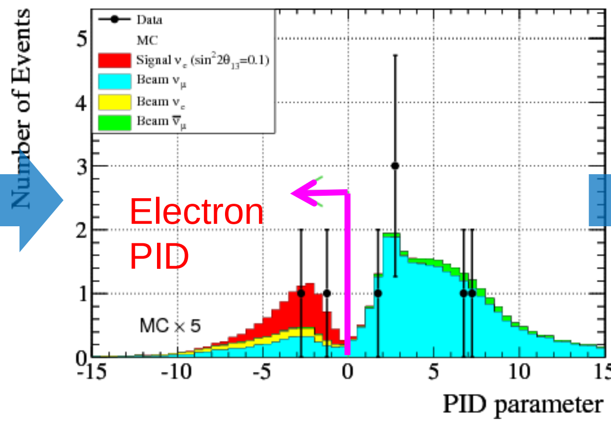
Cut criteria fixed before data open

ν_e Analysis: Event Selection

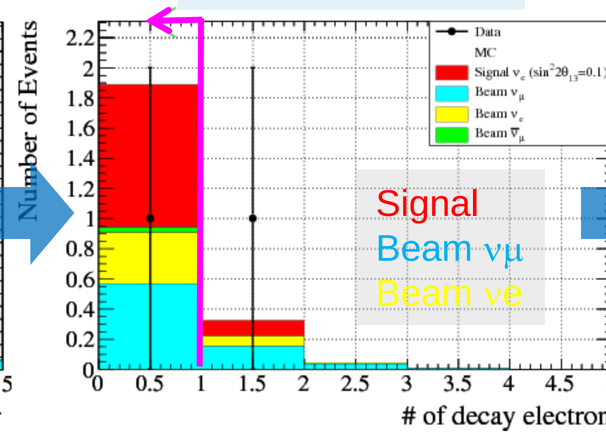
Number of Rings

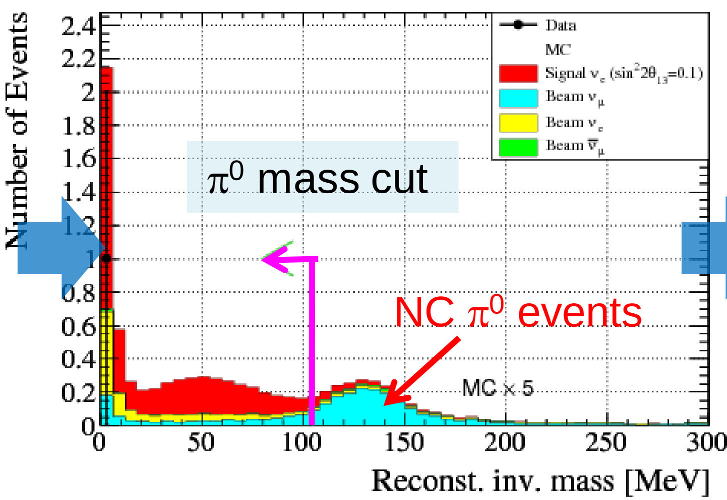


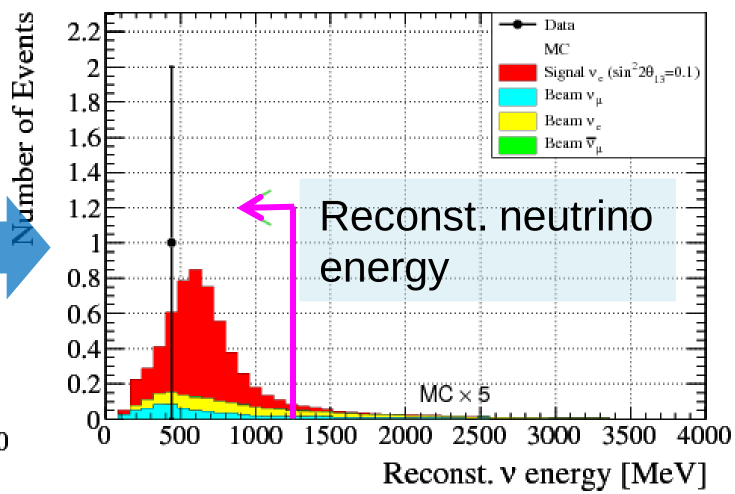
Particle ID



Decay electrons







Rejection:

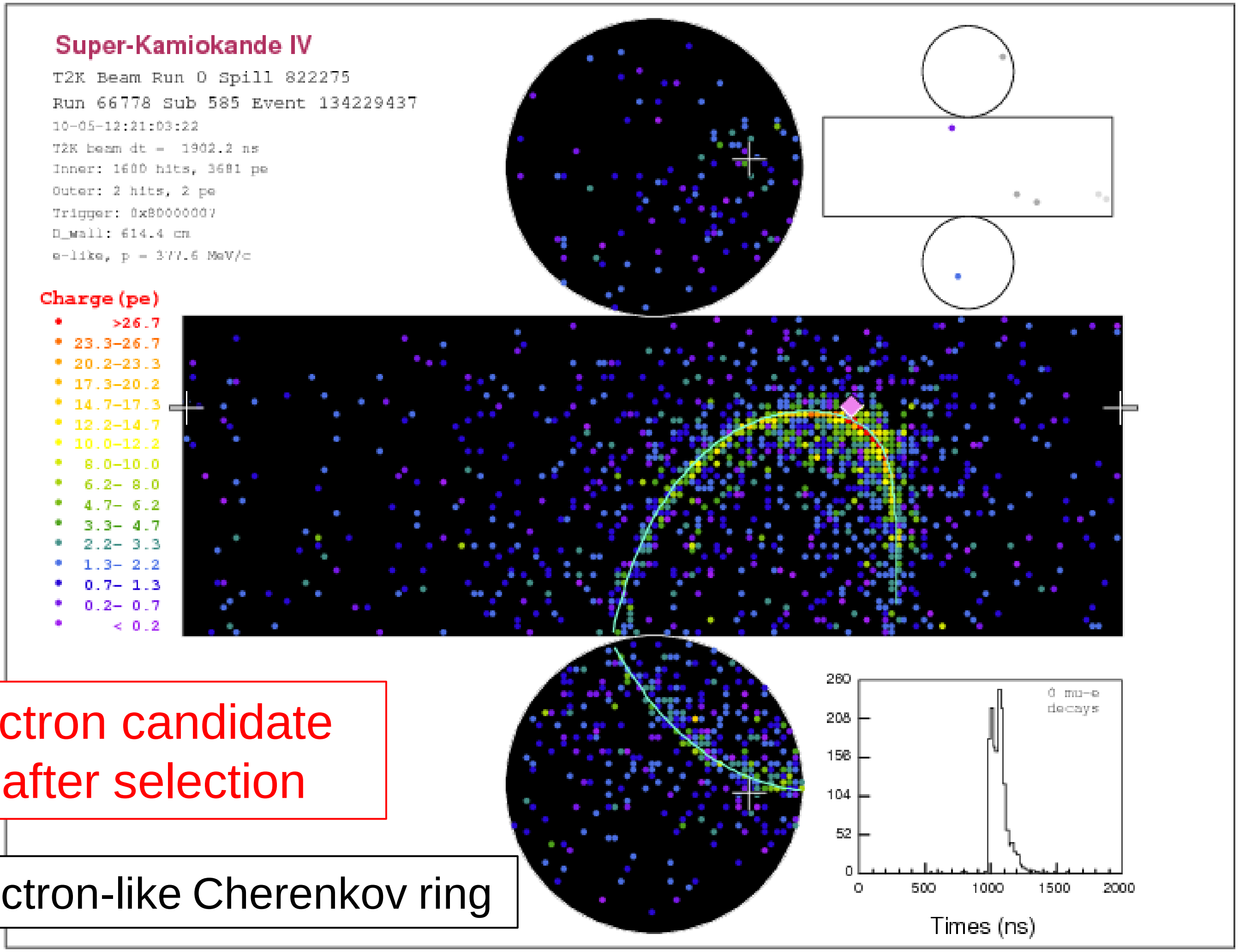
99% for νμ

79% for νe

Acceptance:

68% for signal

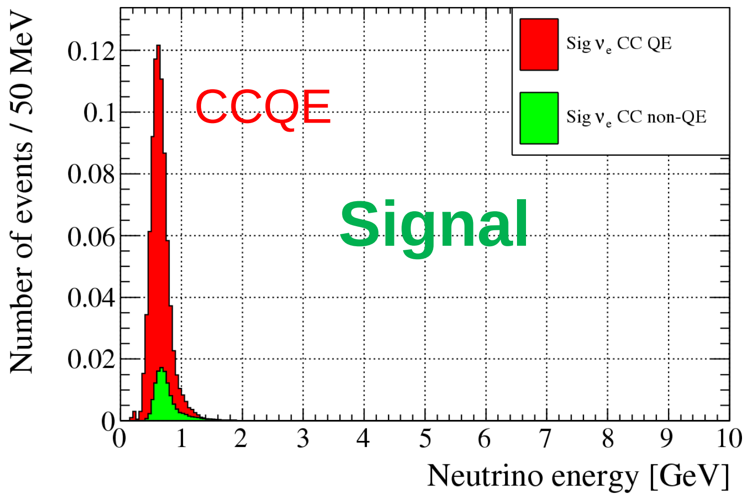
ν_e Analysis: Candidate Event

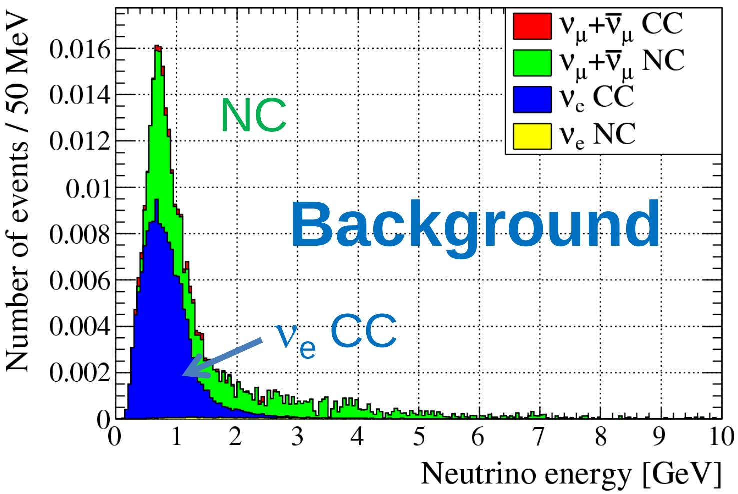


One electron candidate remains after selection

Clean electron-like Cherenkov ring

ν_e Analysis: MC Expectation and Syst. Error





Expected background		
νμ	0.13	NC 95%
anti-νμ	0.01	
νe	0.16	
Total	0.30 ± 0.07 (syst)	

Signal + background ($\sin^2 2\theta_{13}$=0.1)	
Total	1.20 ± 0.22 (syst)

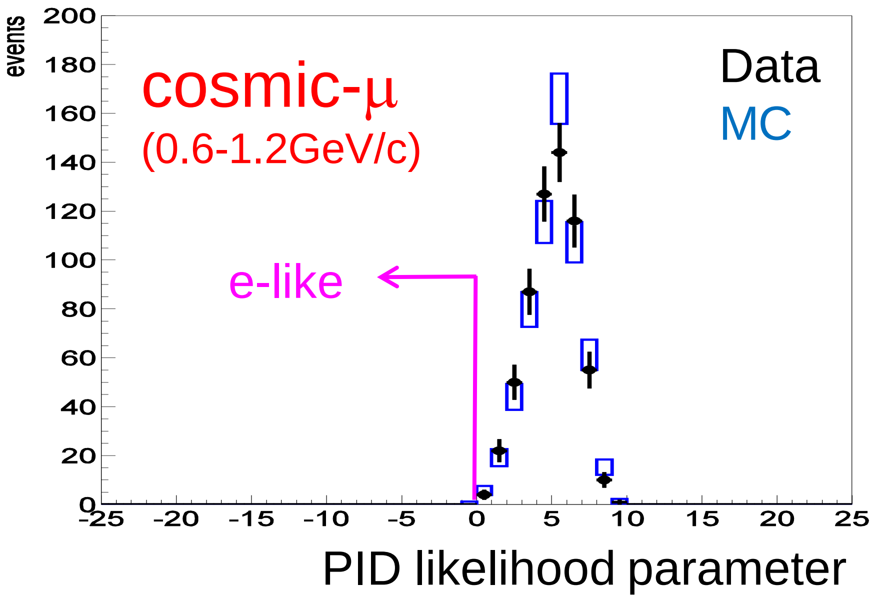
Error source	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 15.8	$\pm$ 9.5
Cross section	$\pm$ 14.3	$\pm$ 10.6
Beam Flux	$\pm$ 8.9	$\pm$ 11.9
ND Efficiency	$^{+5.6}_{-5.2}$	$^{+5.6}_{-5.2}$
Overall Norm.	$\pm$ 2.7	$\pm$ 2.7
Total	$^{+23.9}_{-23.8}$	$^{+19.5}_{-19.4}$

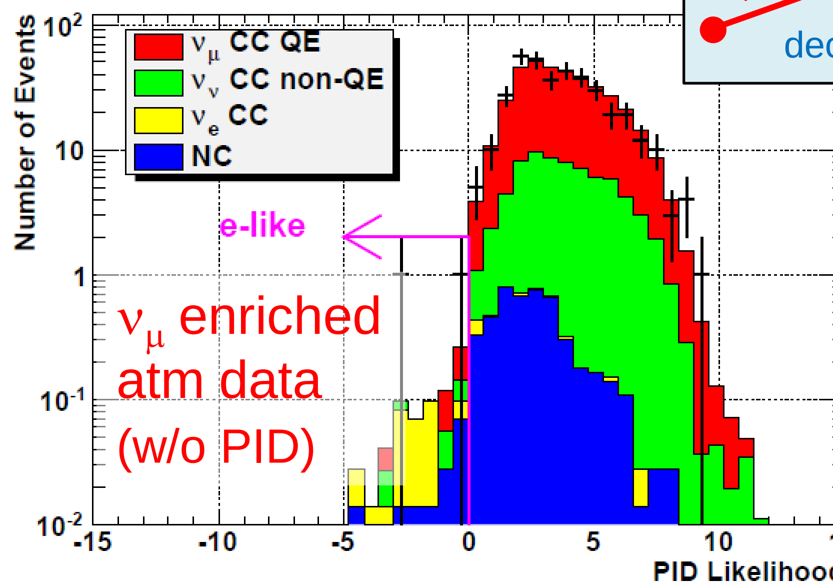
Syst. error ~24% (bkg only)
~20% (sig+bkg)

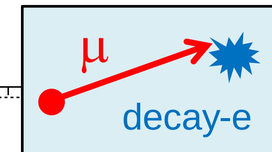
ν_e Analysis: Muon PID systematics

Understanding BKG error is important for ν_e analysis

ν_μ rejection by PID is studied with two method:



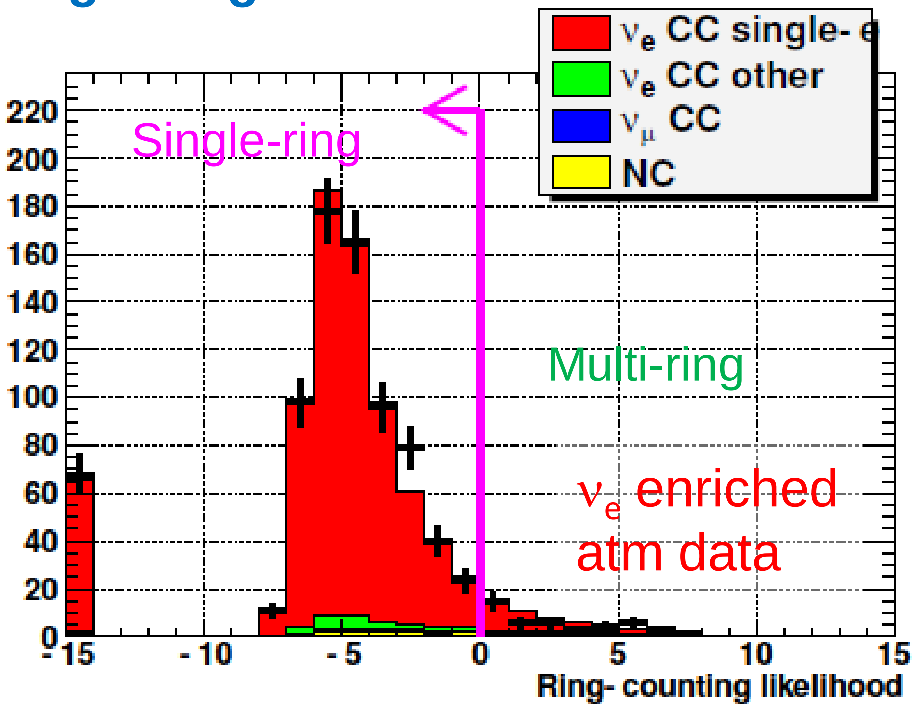




~99% rejection efficiency verified

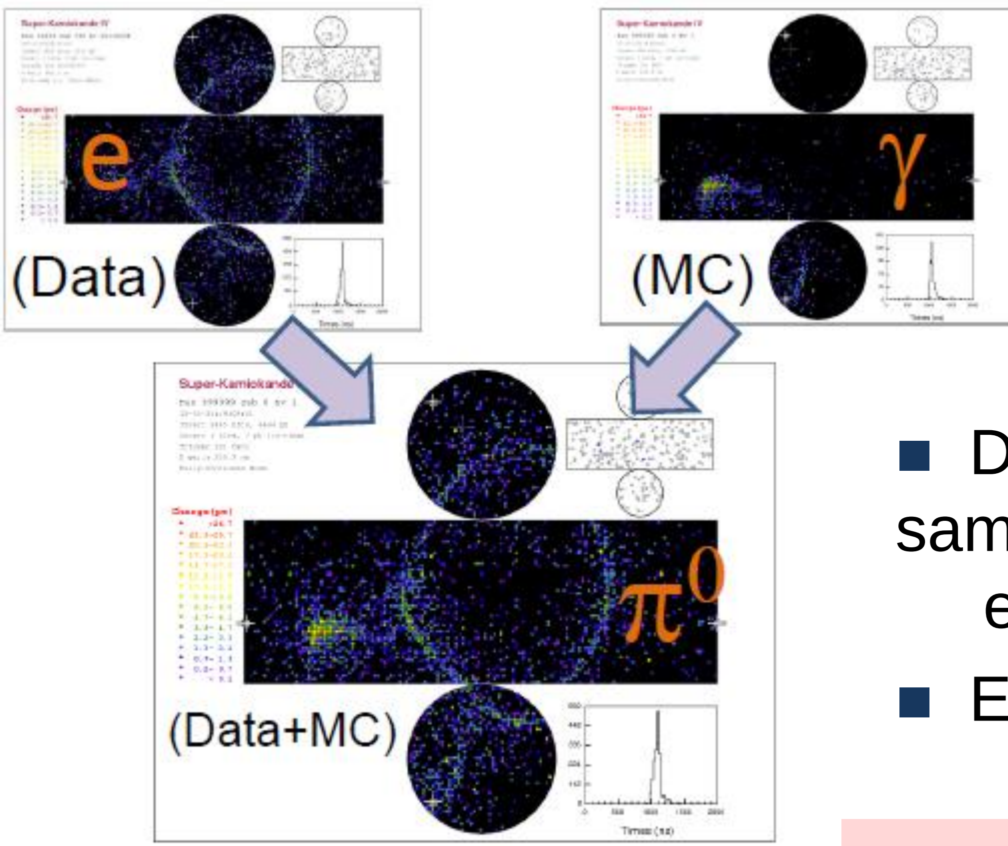
ν_e Analysis: ν_e Acceptance

Single ring selection :



- ν_e enhanced atm. ν sample requiring no decay electrons
- Compare selected / rejected ratio btwn Data-MC
- Efficiency and syst. error are confirmed

ν_e Analysis: π^0 Rejection Efficiency



π^0 is crucial background for ν_e search

$\pi^0 \to \gamma + \not{\gamma}$ → electron-like

- Develop composite π^0 sample using:
  electron data + gamma MC
- Estimate π^0 BKG error: 18%

Now we understand detector uncertainties for ν_e analysis !

ν_e Analysis: Upper Limit on $\sin^2 2\theta_{13}$

Oscillation analysis performed using # of candidates

Calc probability to observe 1 ev considering systematic error

Give θ_{13} upper limit by two statistical method:

A. Feldman-Cousins
B. Classical one-sided limit

A

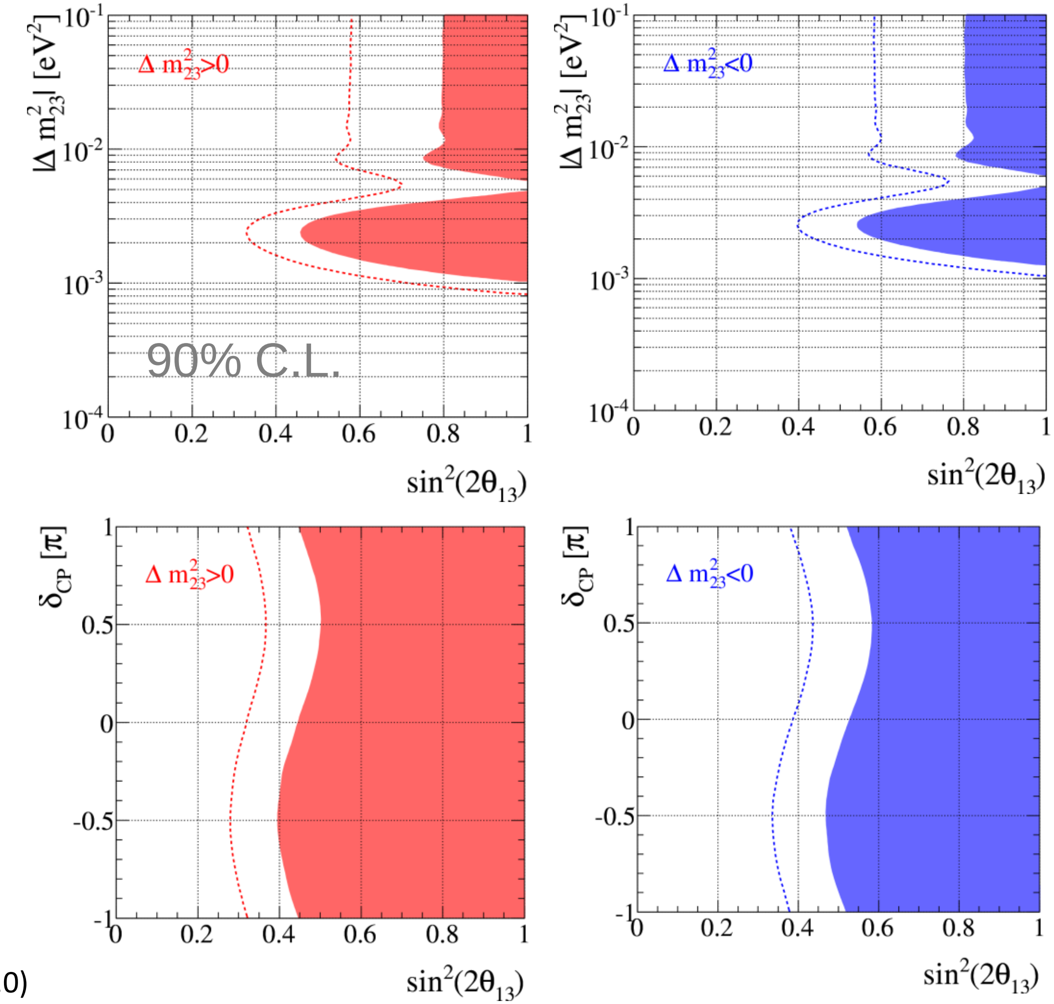
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

B

Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39

at $(\Delta m_{23}^2, \sin^2 2\theta_{23}, \delta_{cp}) = (2.4\times10^{-3}\text{eV}^2, 1.0, 0.0)$

Contours by statistical method B:



ν_μ Analysis: Selection Criteria

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$\nu\mu$ selection
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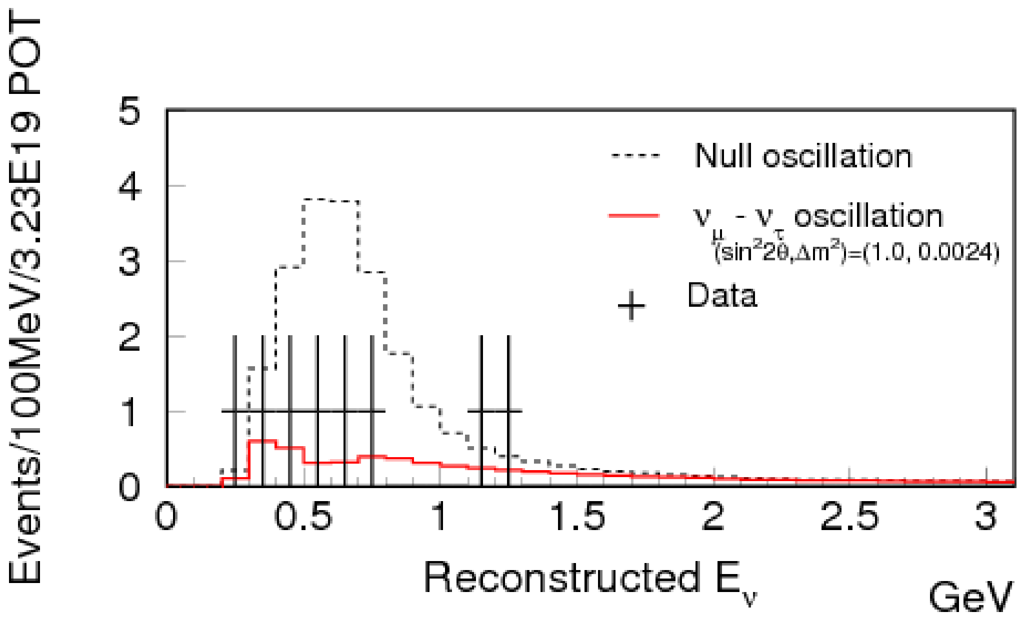
Muon-like PID
Muon momentum > 200 MeV

Cut criteria fixed before data open

ν_μ Analysis: Result

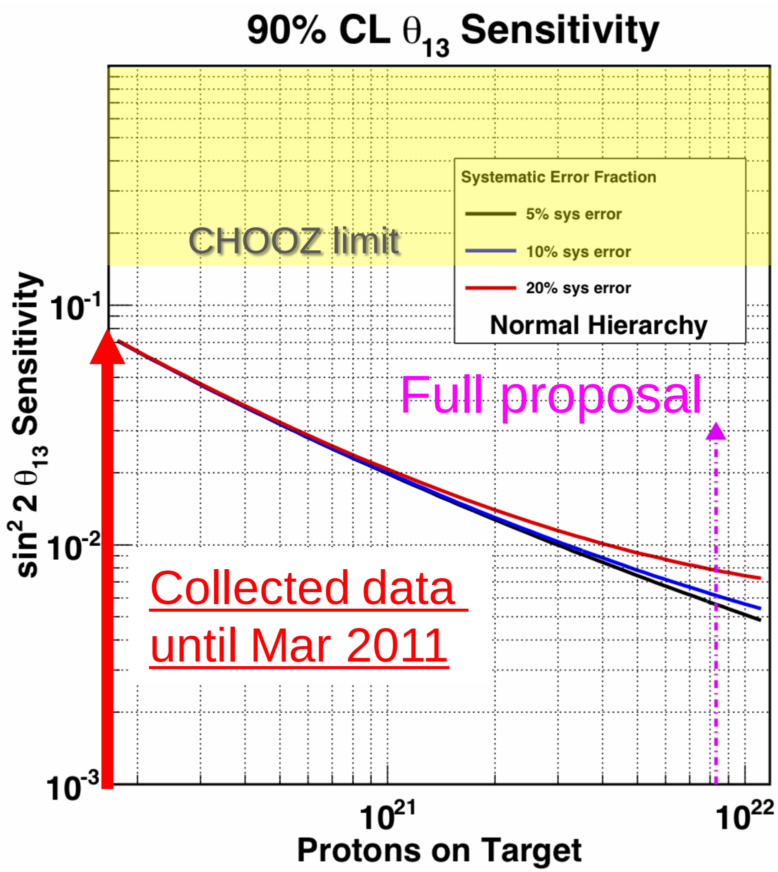


- Consistent with oscillated expectation
- Oscillation analysis is on-going including Run2 data

	# of Events
Data	8
Expected w/ osc.	6.3 ± 0.1 (syst)
Expected w/o osc.	22.8 ± 3.2 (syst)

$(\Delta m_{23}^2, \sin^2 2\theta_{23}) = (2.4\text{x}10^{-3}\text{eV}^2, 1.0)$

Prospects in 2011



- Collected 1.45 x 10^{20} POT until Mar. 2011
  - Data x 4.5 statistics increased
- Possible analysis improvement:
  - Syst. error reduction of beam flux using external hadron data
  - CCQE, spectrum measurements in ND280
  - ν_e spectrum analysis in oscillation analysis
- Will go into unexplored θ_{13} region

Summary

- T2K experiment aims precision measurement for:
  - $\nu\mu$ disappearance (Δm_{23}^2, θ_{23})
  - νe appearance (θ_{13})
- Analysis with first half year data (3.23×10^{19}POT) :
  - 8 $\nu\mu$ events observed (consistent with oscillation)
  - One νe candidate event observed for expected background 0.30 ± 0.07 (syst) events
  - Give upper limit on $\sin^2 2\theta_{13}$
- 1.45×10^{20} POT data collected until Mar. 2011
  - Analysis is ready, and still improving for maximum sensitivity