First oscillation results from the T2K experiment

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(on behalf of the T2K collaboration)

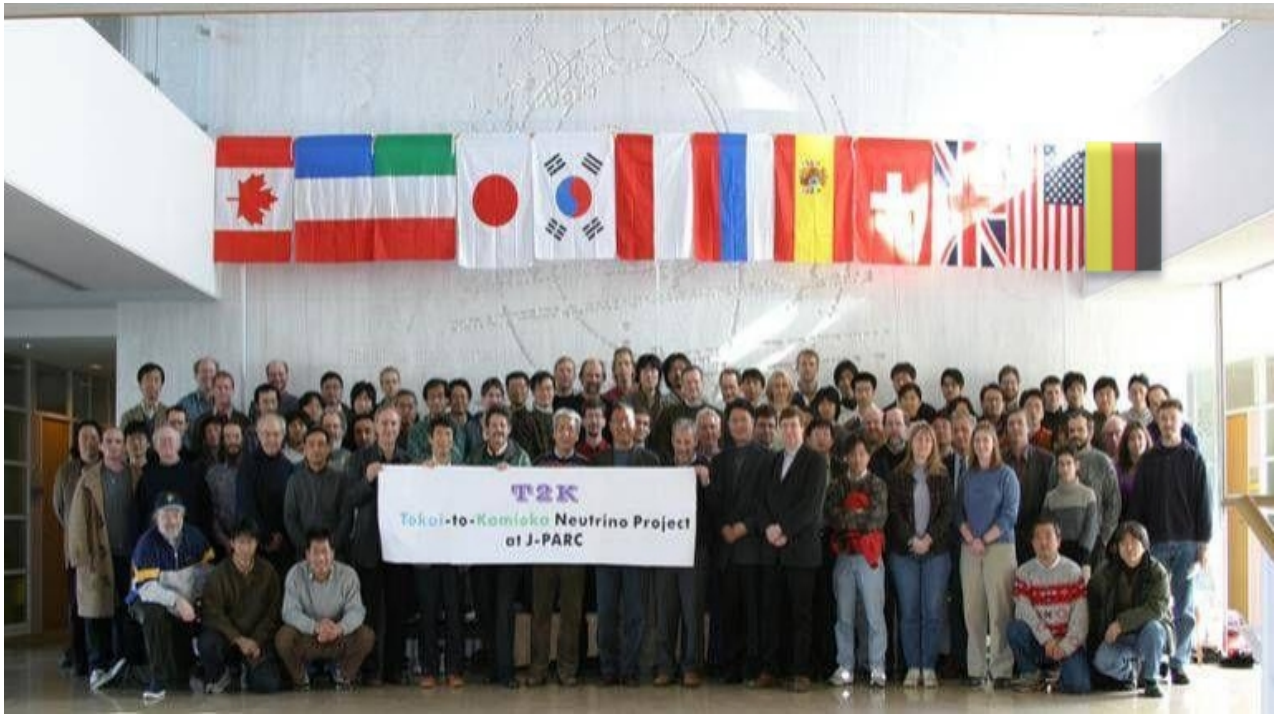
Fermilab - March 22, 2011

J-PARC/T2K status

- J-PARC and surrounding area were affected by the March 11 earthquake
  - roads and buildings have suffered visible damage
- The tsunami did not reach the lab
- No T2K collaborators or J-PARC staff were injured
  - all foreign collaborators left Tokai area safely within a few days of the disaster
- The reactors at the JAEA site in Tokai are fine
- Electricity is still limited and no drinking water
- Preliminary inspection has been carried out, but no thorough survey yet until power is restored

Outline

- Neutrino oscillation status and goals
- T2K experiment design and concept
- T2K experiment components
- Results from the first physics run: January-June 2010
- Future prospects



~500 members
59 institutions
12 countries:
Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, US (Boston U., Colorado S.U., Duke U., Louisiana S.U., Stony Brook U., UC Irvine, U. Colorado, U. Pittsburgh, U. Rochester, U. Washington)

Neutrino mixing/oscillation status

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

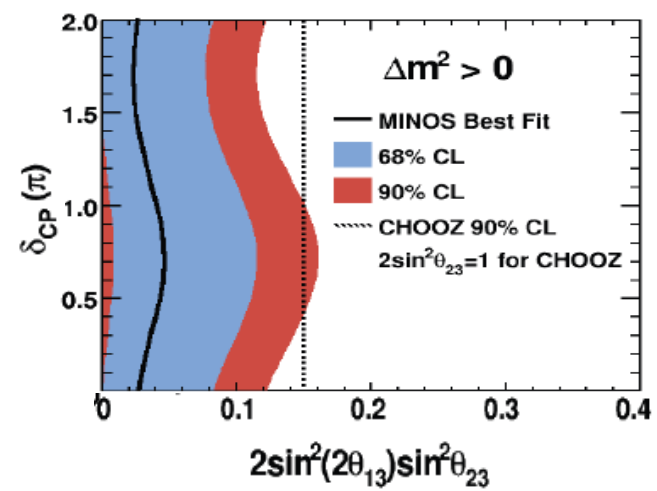
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}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

Atmospheric & accelerator:
$\theta_{23} \sim 45^o$
$(\Delta m_{23})^2 \sim 2.5\text{x}10\text{-}3\ eV^2$

Interference:
$\theta_{13} < 10^o$ (CHOOZ/MINOS)
δ_{CP} unknown

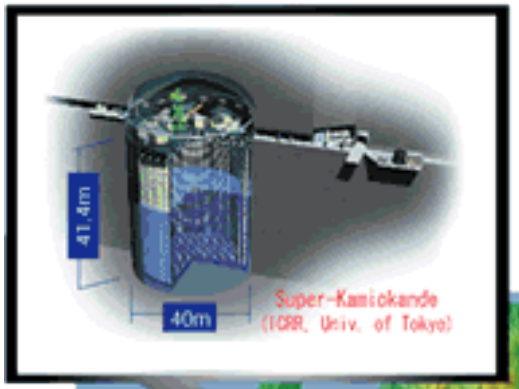
Solar & reactor:
$\Theta_{12} \sim 34^o$
$(\Delta m_{12})^2 \sim 8\text{x}10\text{-}5\ eV^2$

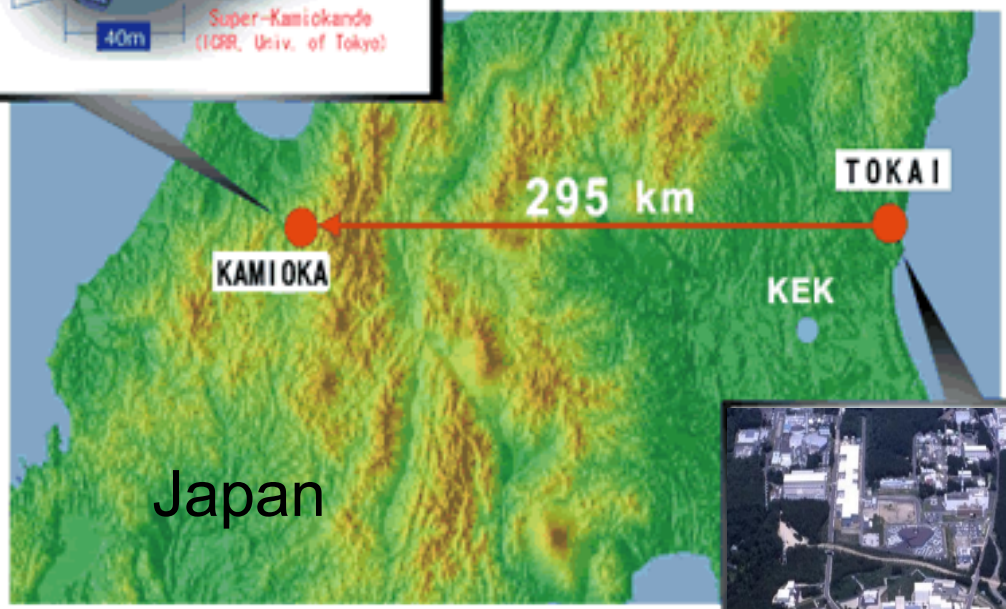
Goal of next generation experiments:
- measure θ_{13} and δ_{CP} (if $\theta_{13} \neq 0$)
- mass hierarchy ($\Delta m^2_{23} > 0$?)
- θ_{23} maximal (45°)?

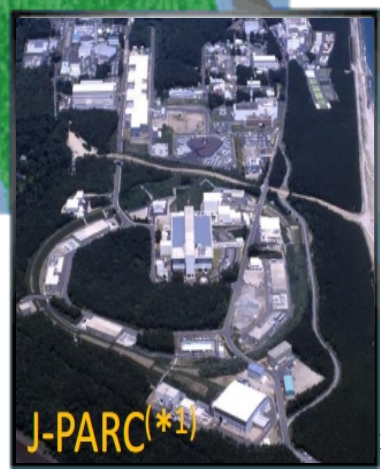


Tokai-to-Kamioka experiment

Far detector:
SK IV (50 kton)







Neutrino beam originates at
J-PARC, Tokai
30-GeV 750 kW proton beam

Main objectives:

- Measure/improve limit on θ_{13} ($\nu_\mu \rightarrow \nu_e$ appearance)

  $\theta_{13} \neq 0$ would allow to explore CPV in leptonic sector

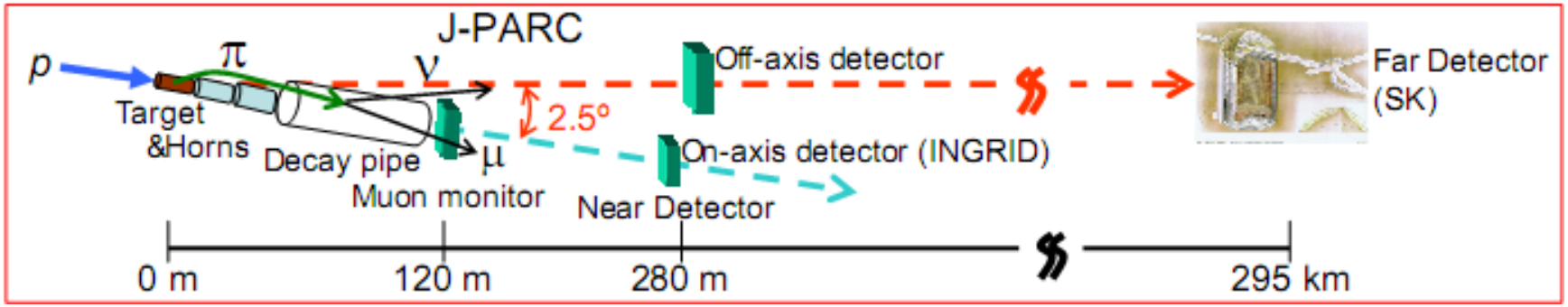
- Improve measurement of Δm^2_{23} and θ_{23} ($\nu_\mu \rightarrow \nu_\mu$ disappearance)

Requirements:

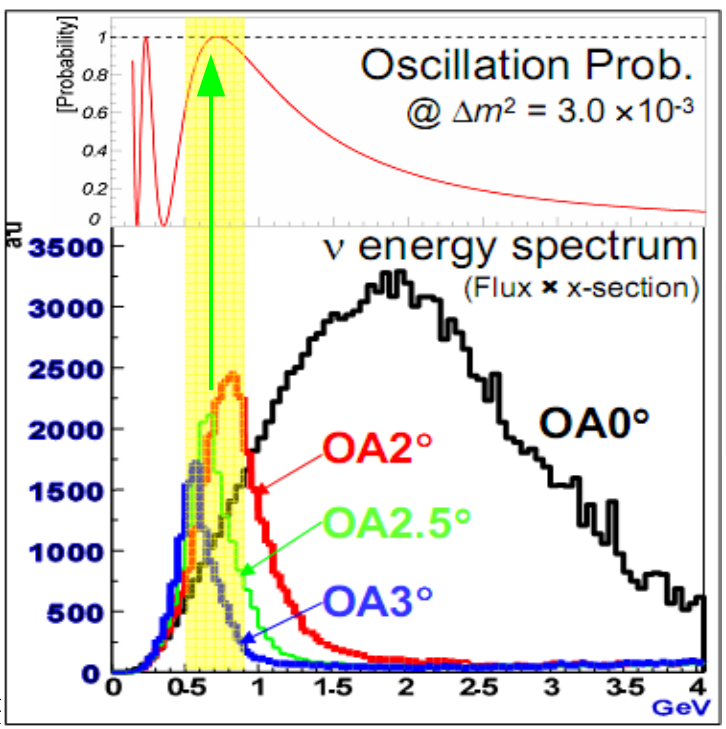
- Very intense ν beam
- Massive far detector
- Long baseline (295 km)
- Near detector (ν flux and composition near source)
- Off-axis design
  - enhance sensitivity at oscillation maximum
  - reduce intrinsic background

T2K off-axis concept

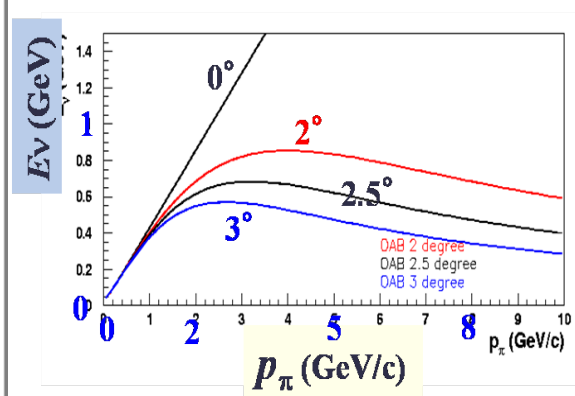
- T2K is the first long baseline ν experiment using an off-axis beam



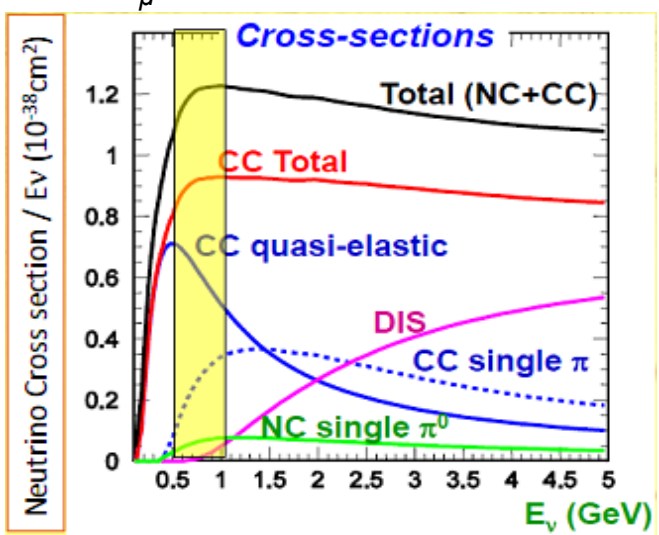
- The beam is aimed 2.5° off the direction of Super-Kamiokande



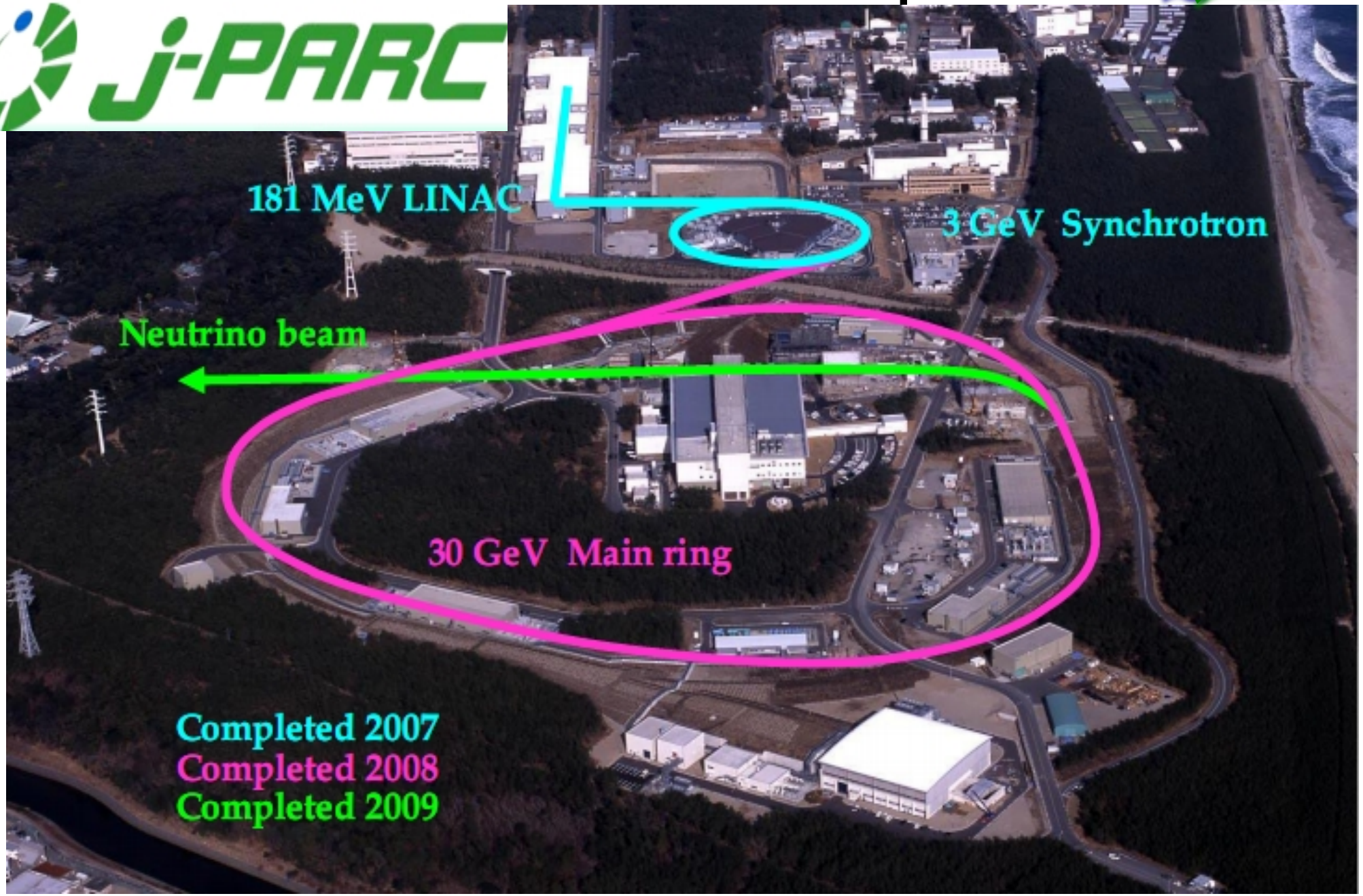
- This produces a narrow beam with peak energy (~600 MeV) tuned to first oscillation maximum ($\Delta m^2_{13} L/4E_\nu \approx \pi/2$)
- Helps to eliminate high energy tail: reduced background from non-QE interactions and NC feed down from high energy ν_μ



First T2K result



Accelerator complex



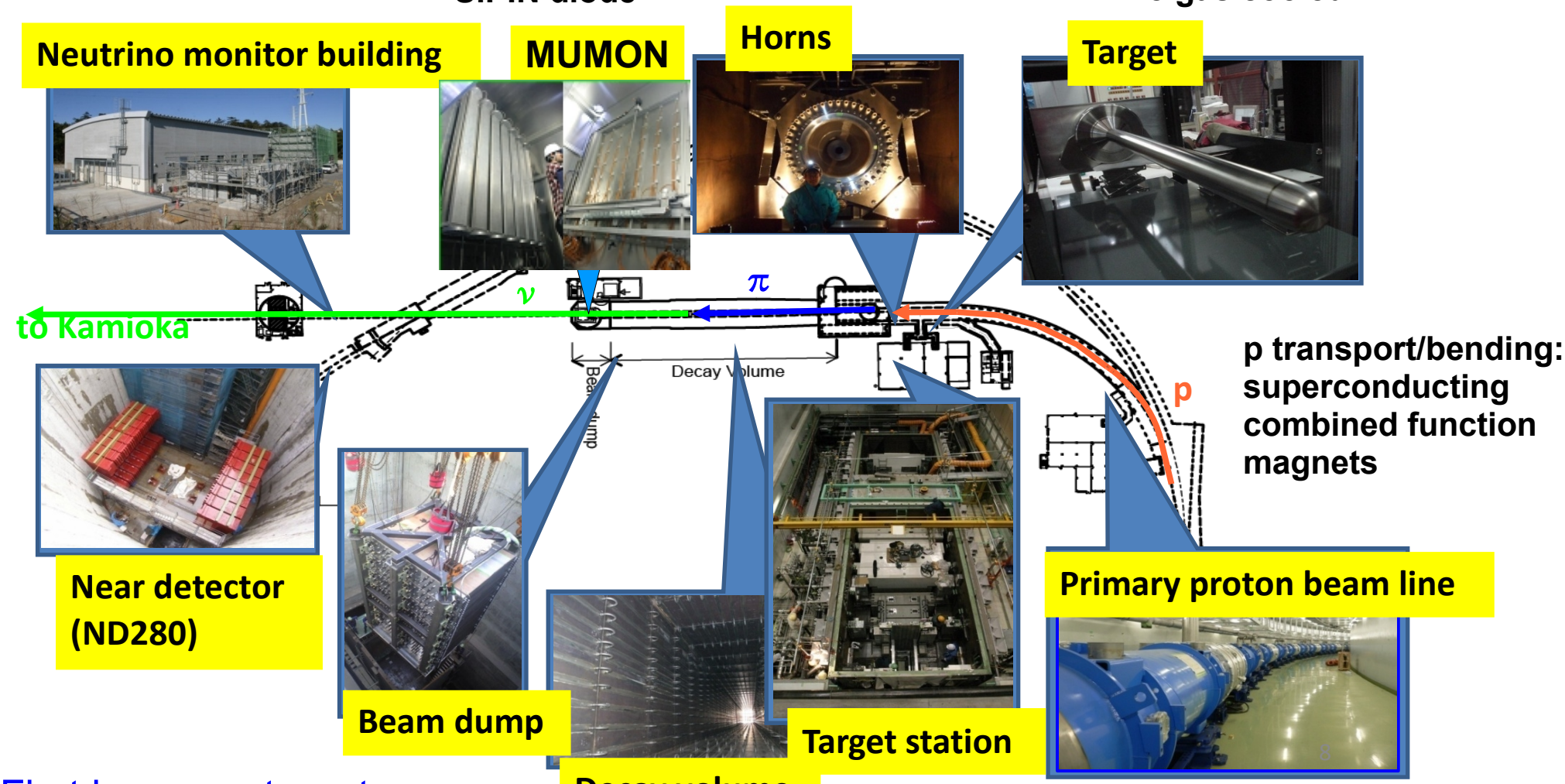
Neutrino beam line

Conventional beam:
p+C → π → ν+μ

Muon monitors:
Ionization chambers
+ SiPIN diode

3 focusing horns
(250 kA)

Target:
graphite (ø26mm x 90cm)
He gas cooled



p transport/bending:
superconducting
combined function
magnets

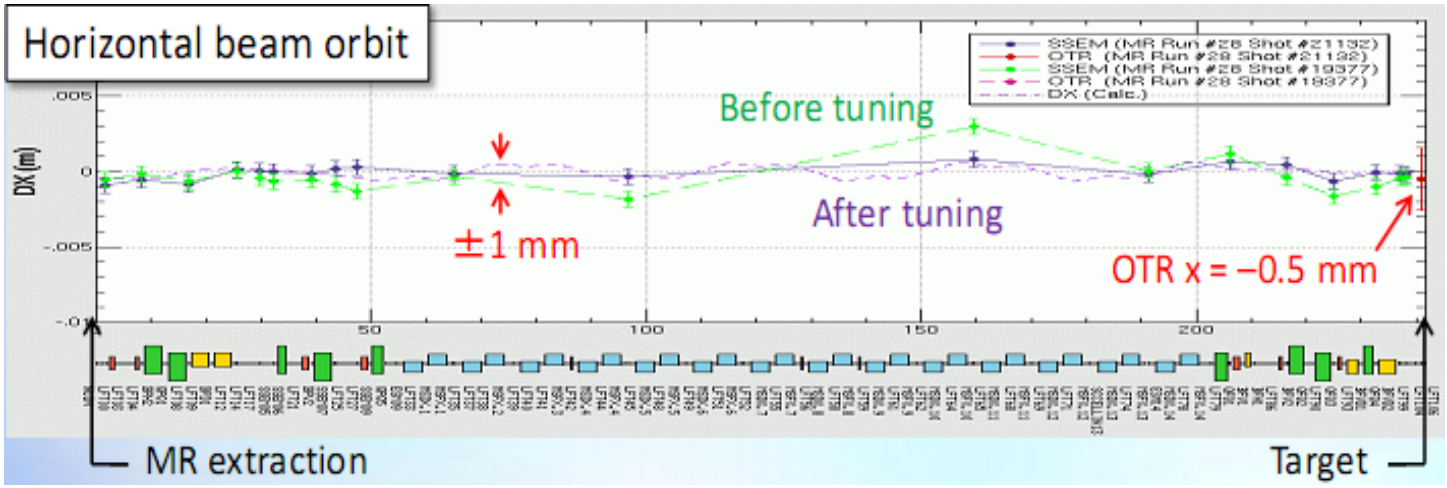
First beam on target:
April 23, 2009

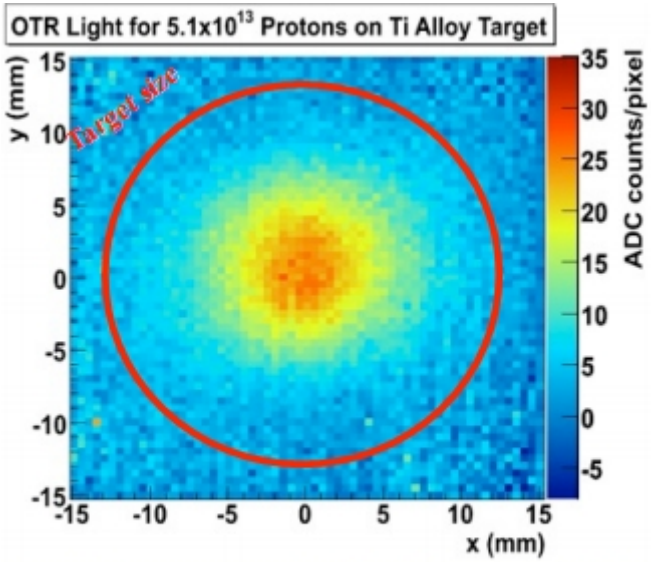
Decay volume (96 m)
He filled

Fast p extraction: 6-8 bunches/spill,
581 ns separation, 3.0-3.5 s spill period

Beam monitors

Proton beam precisely tuned (<2mm) to minimize beam loss, and control direction of secondary beam

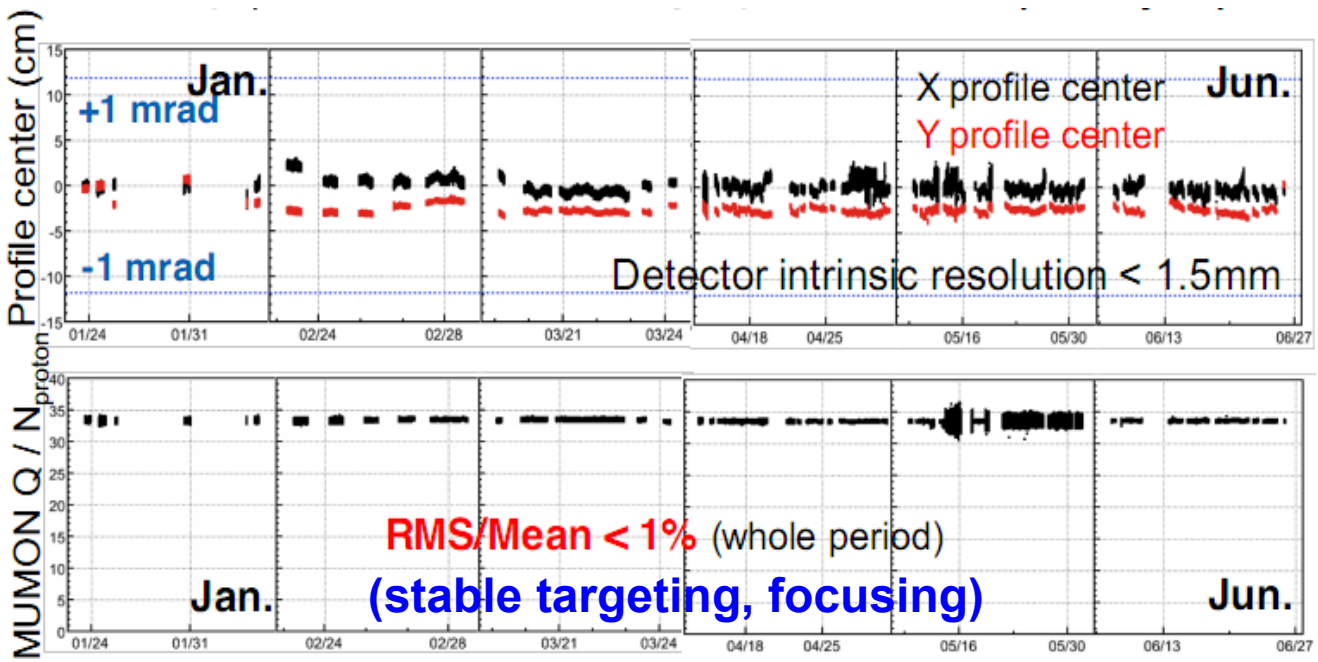




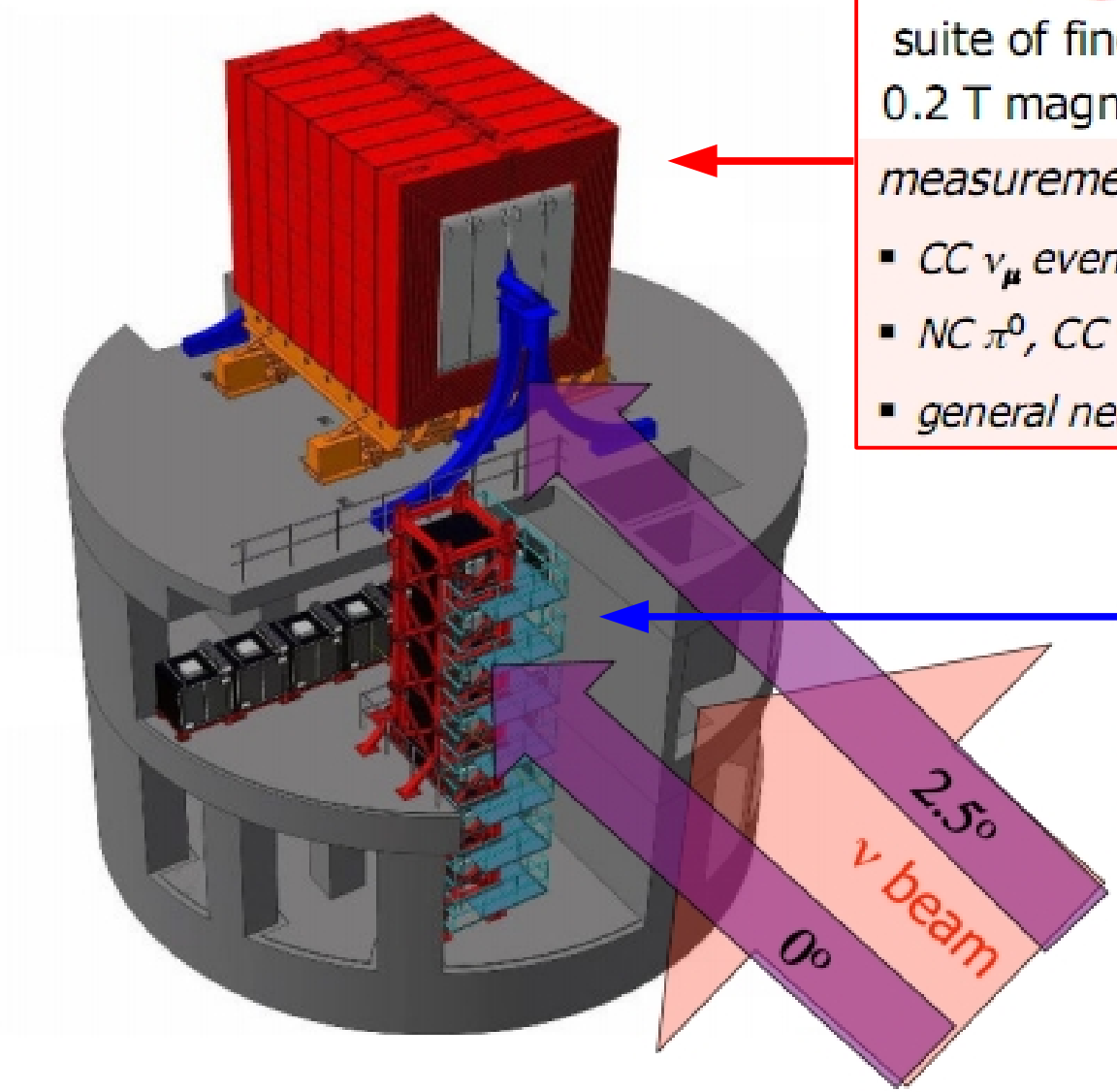
Optical transition radiation detector (OTR) immediately upstream of target:

Muon monitors (Si PIN and ionization chambers):

- Measure secondary beam direction and intensity spill-by-spill
- Direction is well within 1mrad ($\Delta\Phi$ ~ 2%/mrad at the peak energy)



Near detector complex



Off-Axis (ND280)
suite of fine grain detectors/tracker in 0.2 T magnetic field (UA1/NOMAD magnet)

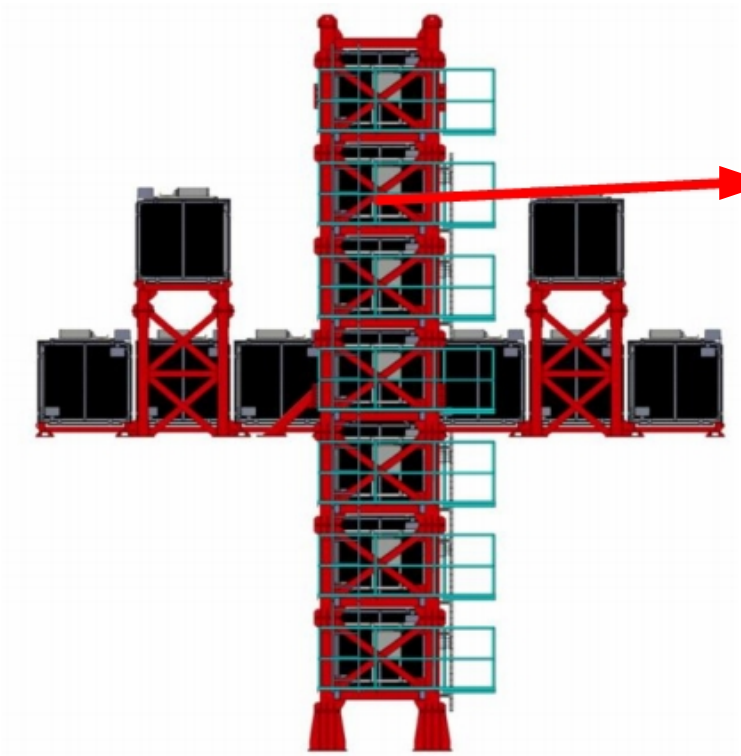
measurements of

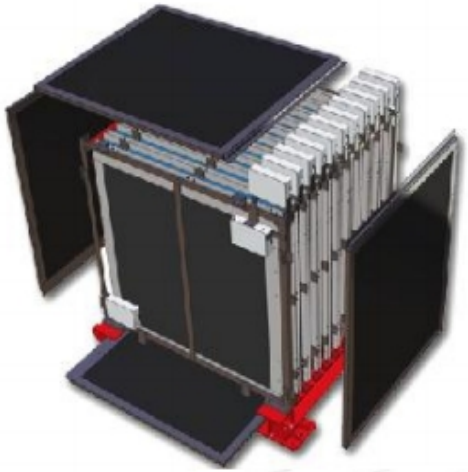
- *CC ν_μ events* (normalization, ν_μ disappearance)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

On-axis (INGRID)
scintillator-iron detectors

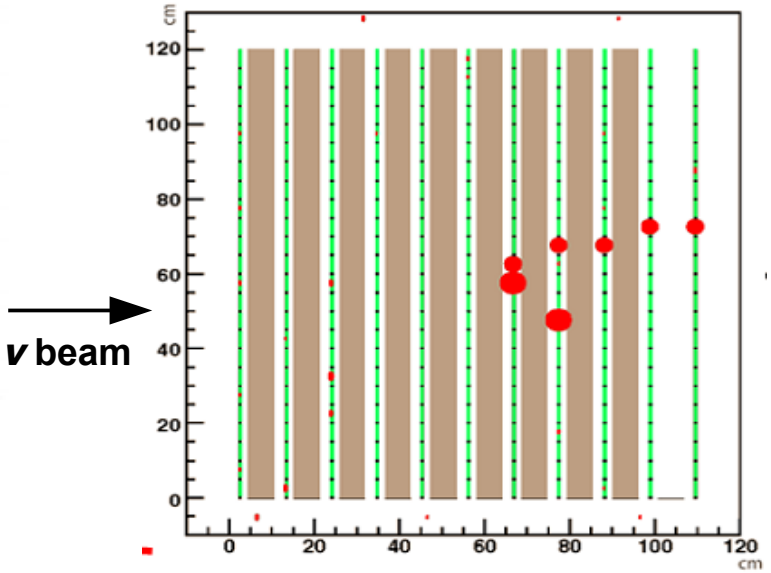
measurement of beam profile

INGRID: on-axis near detector

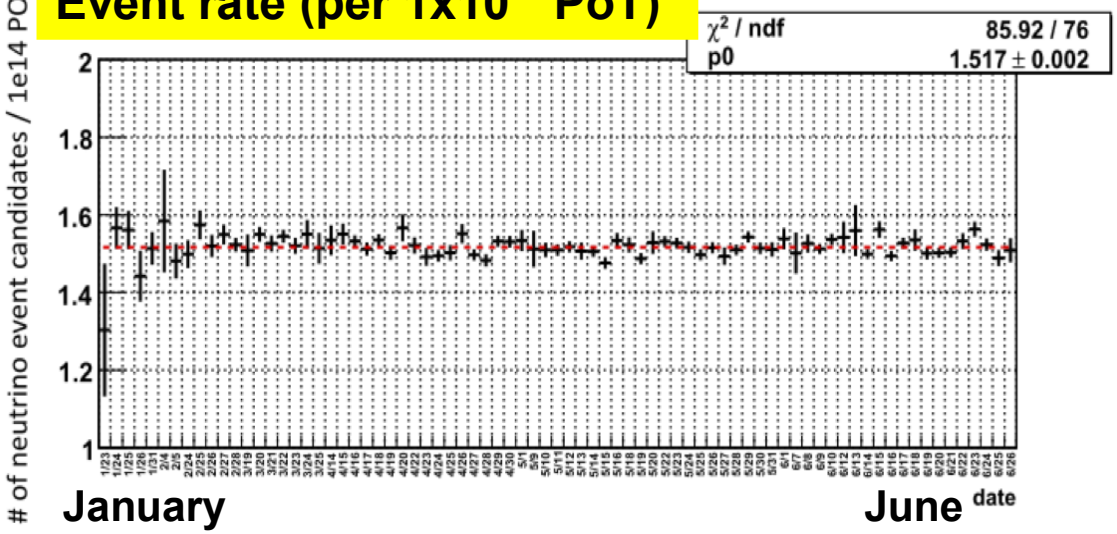




Typical event in one module



Event rate (per 1x10^{14} PoT)



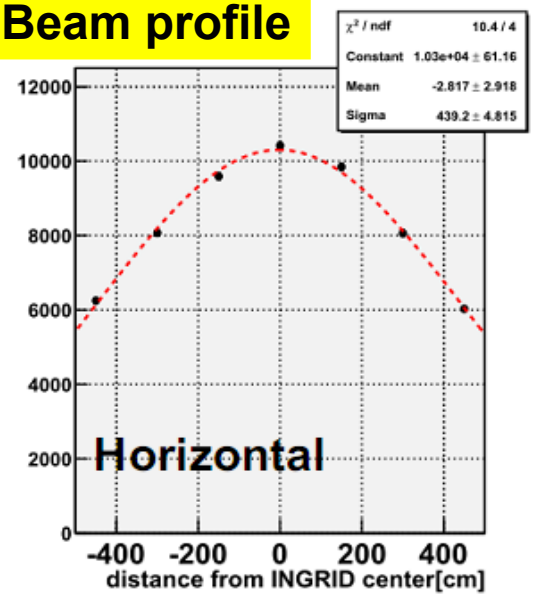
7+7 horizontal/vertical + 2 off-cross + 1 proton (no iron) modules

- alternating scintillator/iron planes + veto planes (7 tons/module)
- coverage 10x10 m^2
- 700 interactions/day (@ 50kW)

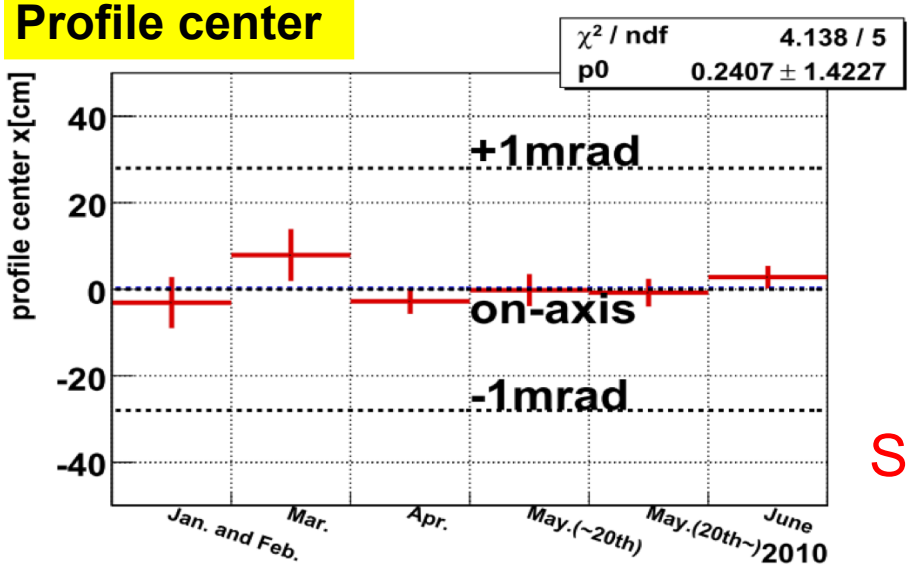
INGRID performance

- Measures ν-beam direction, profile, intensity using inclusive CC interaction

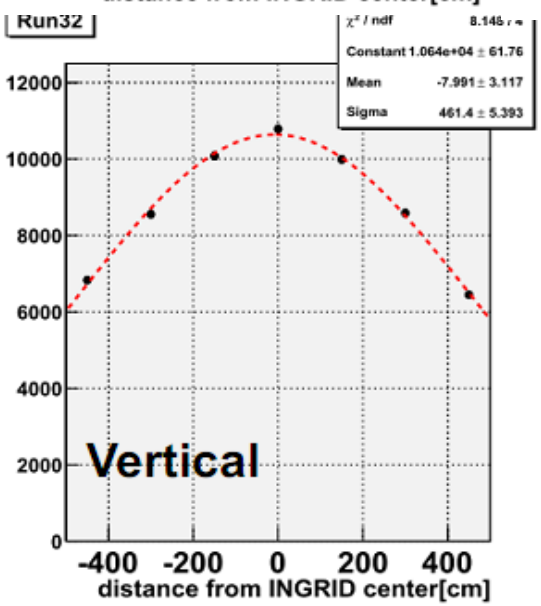
Beam profile

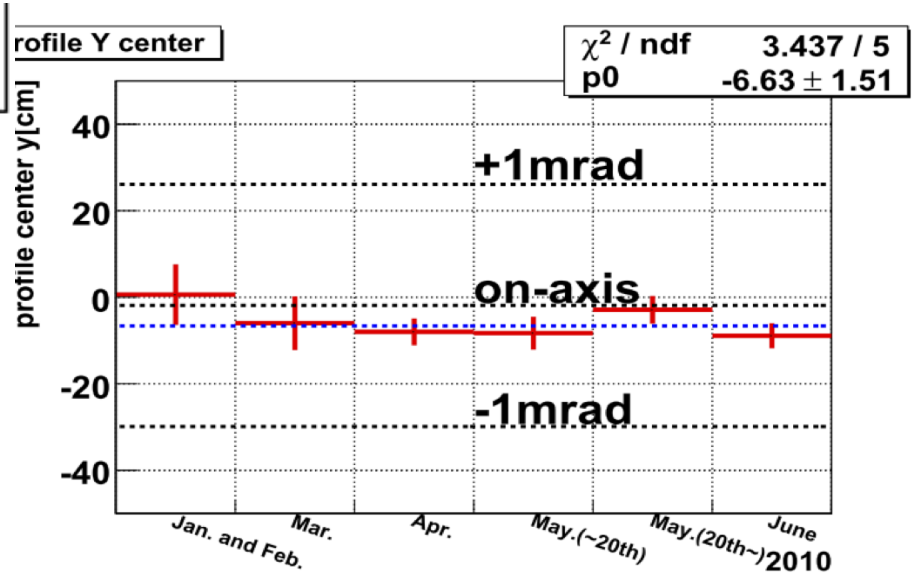


Profile center



Beam position is stable over run period





SK off-axis angle:

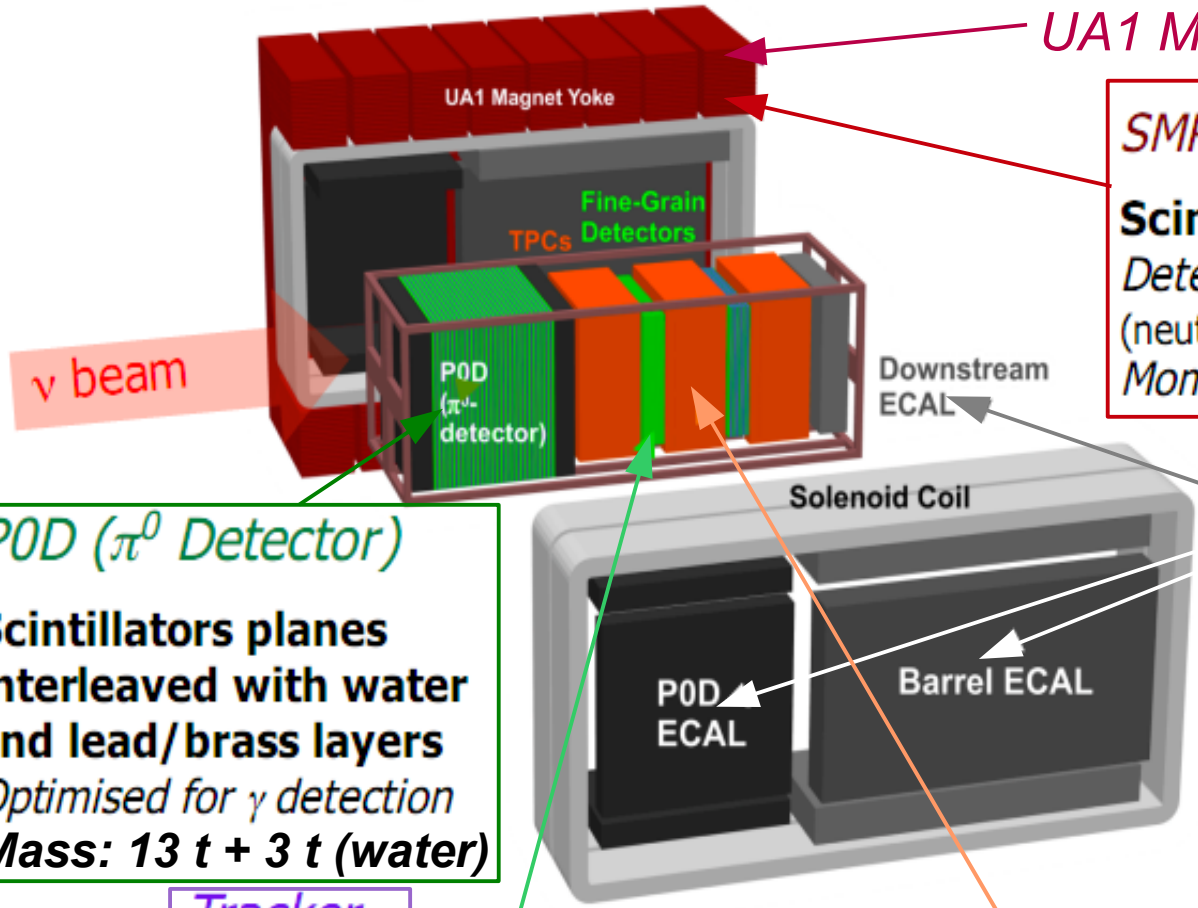
2.519 ± 0.021 degrees

R(data/MC):

1.073 ± 0.001(stat)

± 0.040(syst)

ND280: off-axis near detector



UA1 Magnet: 0.2 T

SMRD (Side Muon Range Detector)

Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)

Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection
Mass: 13 t + 3 t (water)

P0D, Barrel and DownStream ECAL

Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

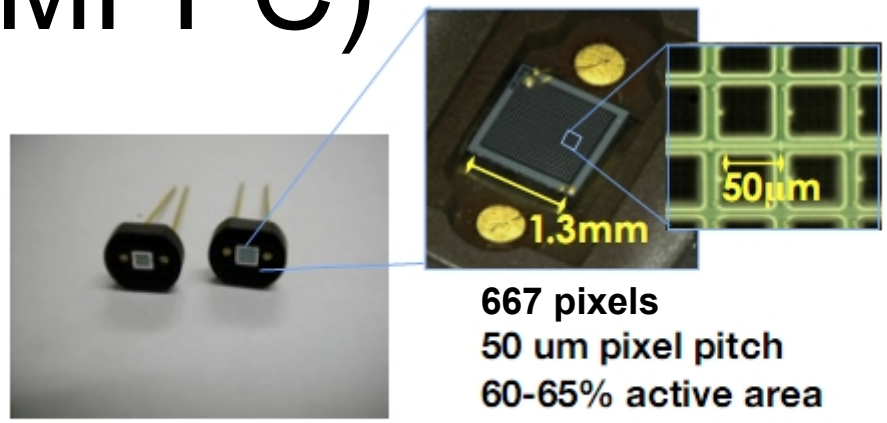
Tracker

2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

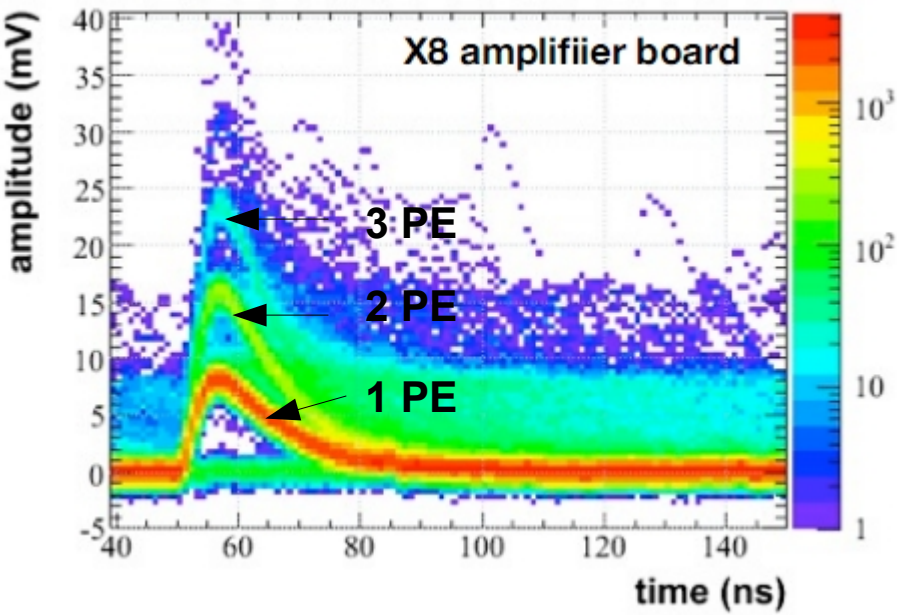
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

FGD1: 1t & FGD2: 0.5 t (scint) + 0.5 t (water)

Multi-Pixel Photon Counters (MPPC)

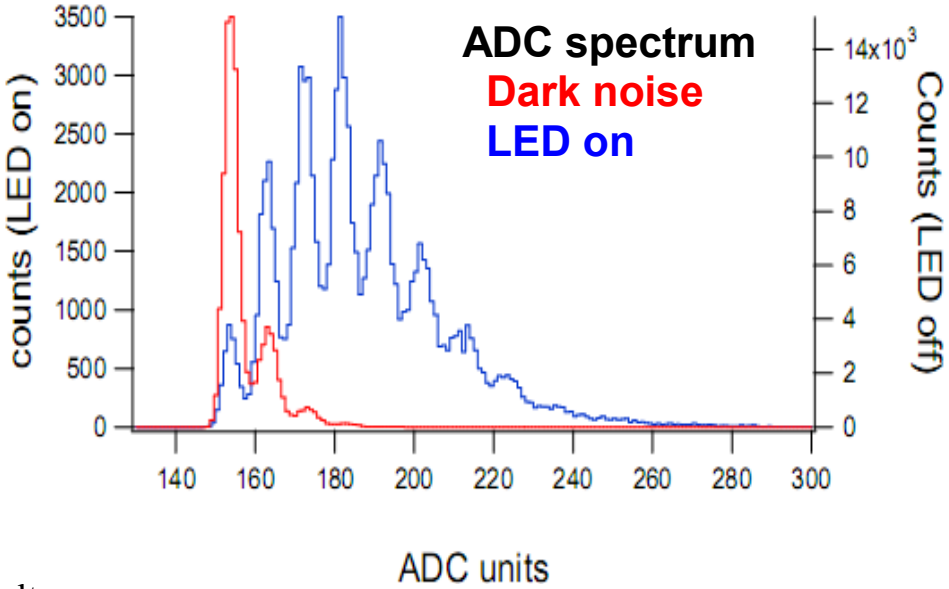


667 pixels
50 um pixel pitch
60-65% active area
Pixel capacitance : 97.5 fF
Passive quenching 150 MΩ
Pixel RC cnst~13 ns



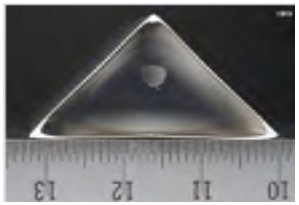
T2K is the first experiment to use MPPCs at a large scale (~56000 pieces)

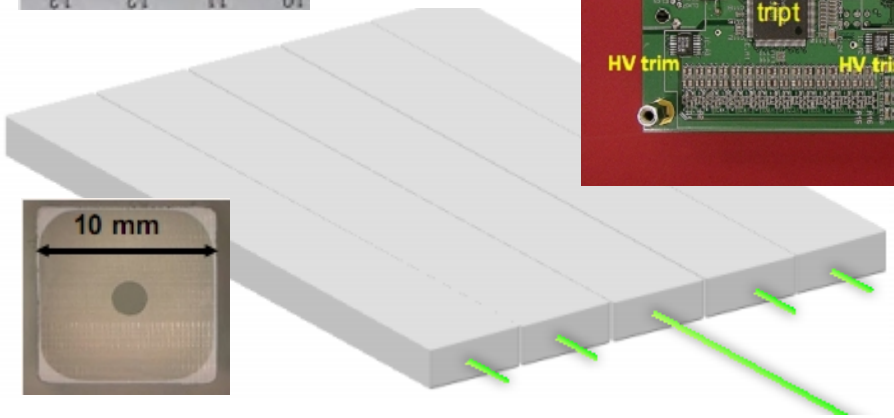
- operated in limited Geiger mode (~1V above breakdown voltage)
- nominal gain: 7.5×10^5
- insensitive to magnetic field
- PDE (500 nm): ~20%
- thermal noise: 500 MHz (20C)
- cross talk and after pulsing: ~15%

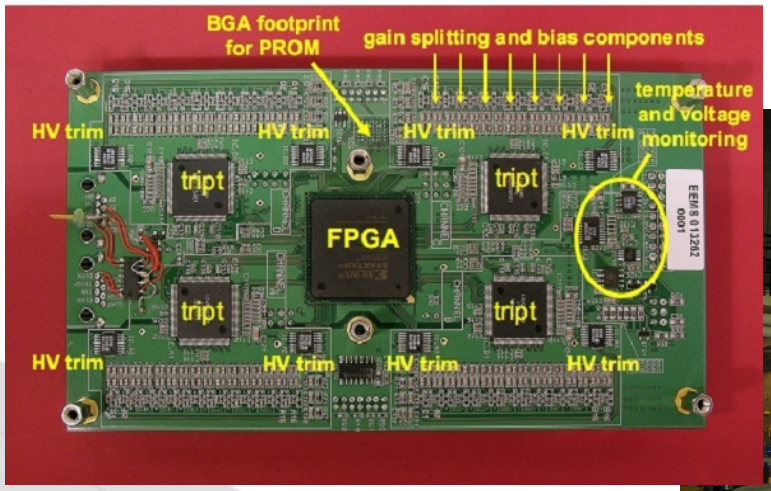


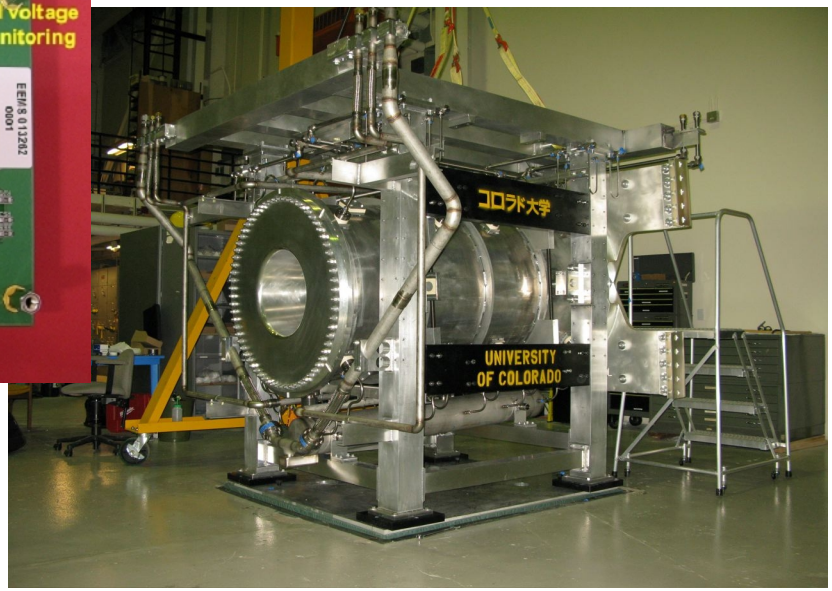
Fermilab connection

- Horn-2 development/construction – MiniBooNE experience
- Scintillator extrusion R&D – in particular P0D scintillator bars (same as MINERvA's) were produced in Lab 6 (PPD/Tech Center)
- Fiber mirrors for P0D/FGD (PPD/Tech Center)
- Front-end Electronics for P0D/ECal/SMRD: Trip-t ASIC based read out (D0, MINERvA – PPD/EED)



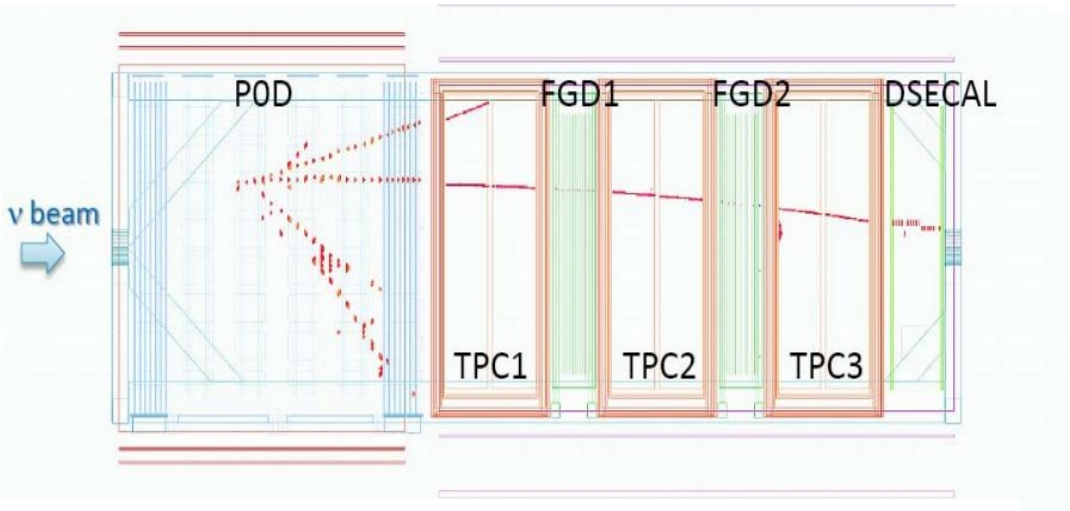




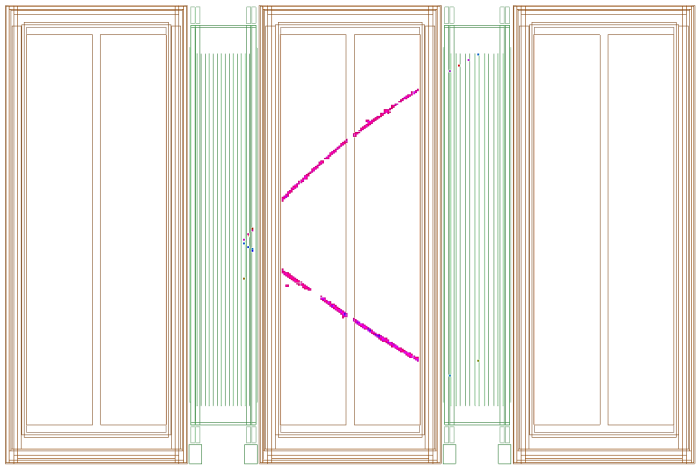


ND280 event gallery

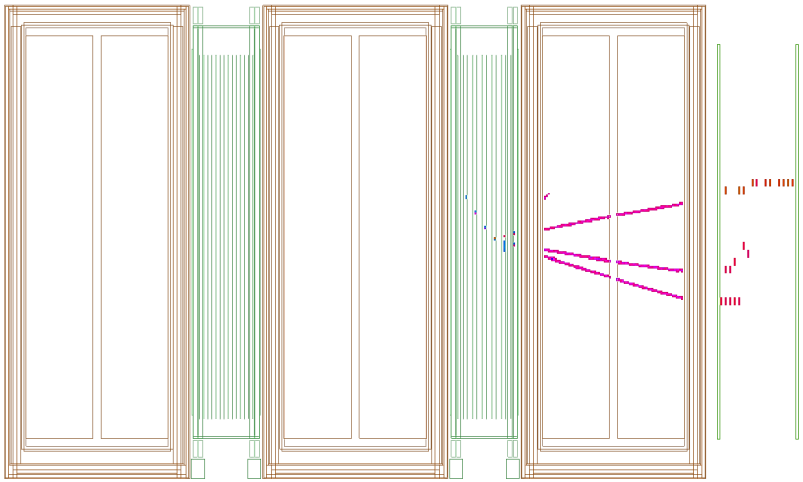
DIS candidate in P0D



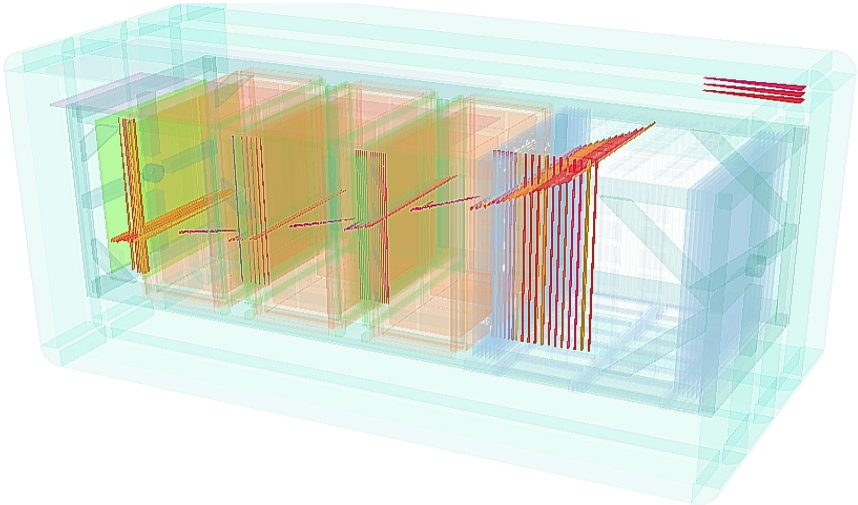
ν_μ CCQE candidate in FGD1



ν_μ CC1π candidate in FGD2

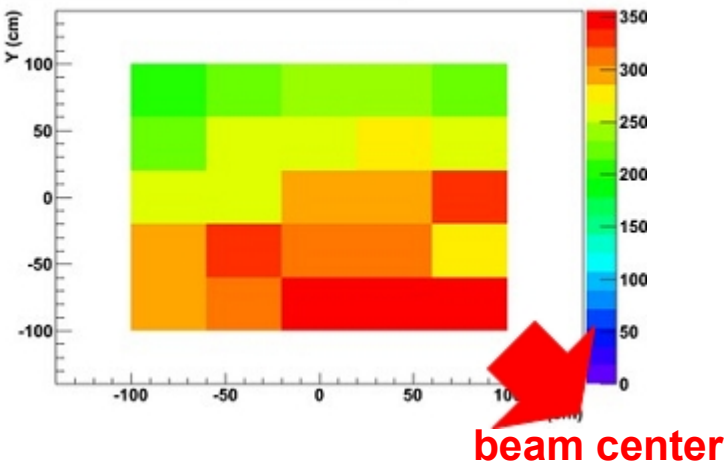


Cosmic-ray muon



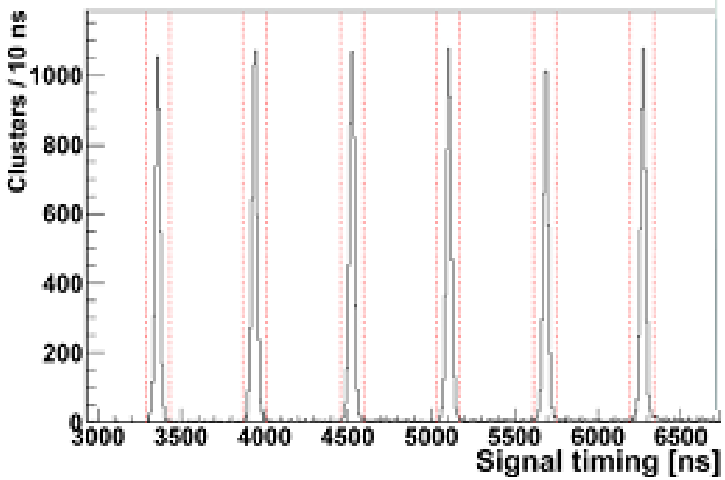
ND280 performance

P0D vertex position (x-y)

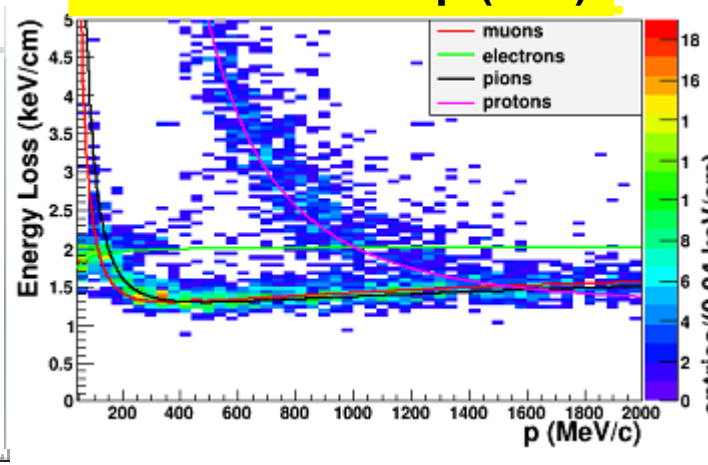


Detector	Channels	Bad ch.	Bad fraction
ECAL (DSECAL)	22,336 (3,400)	35 (11)	0.16% (0.32%)
SMRD	4,016	7	0.17%
P0D	10,400	7	0.07%
FGD	8,448	20	0.24 %
INGRID	10,796	18	0.17 %
TPC	124,416	160	0.13 %

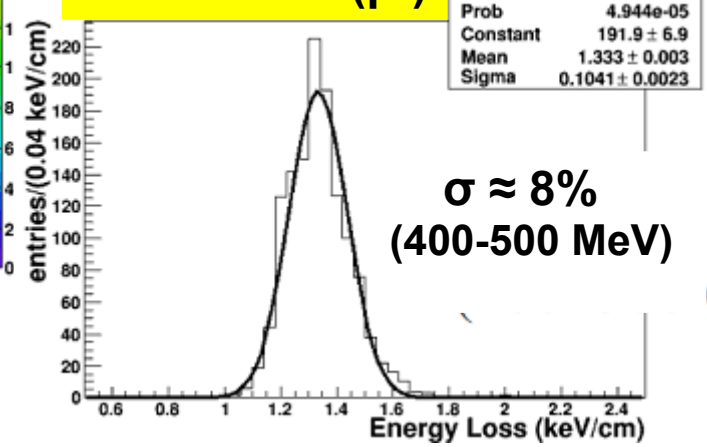
FGD cluster timing



TPC: dE/dx vs p (+ve)



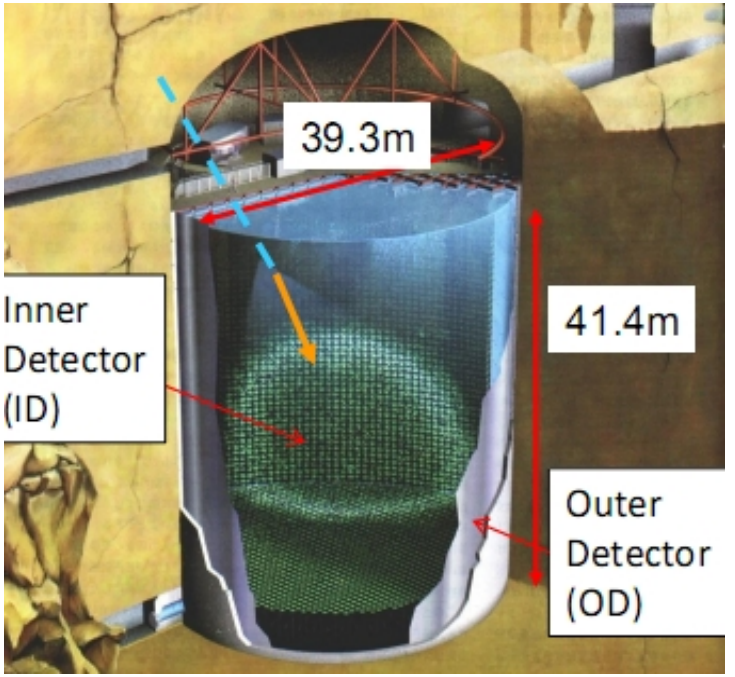
TPC: dE/dx (μ^-)

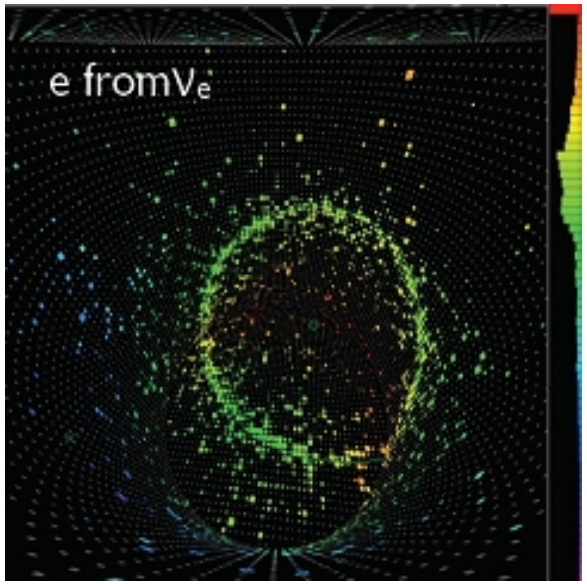


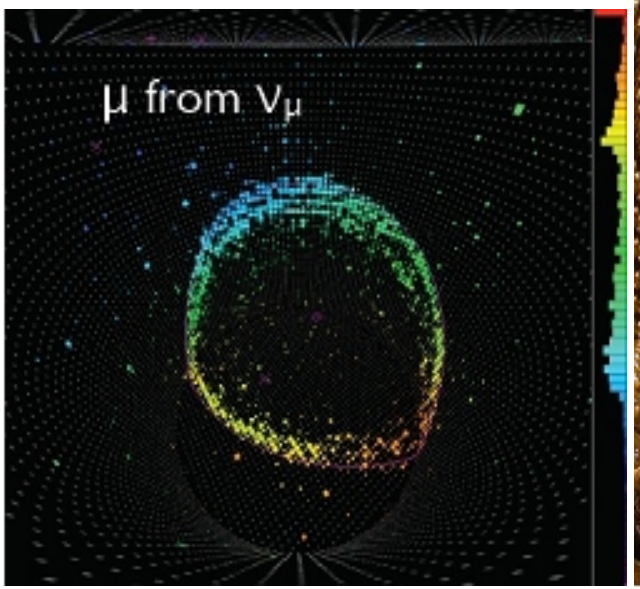
σ ≈ 8%
(400-500 MeV)

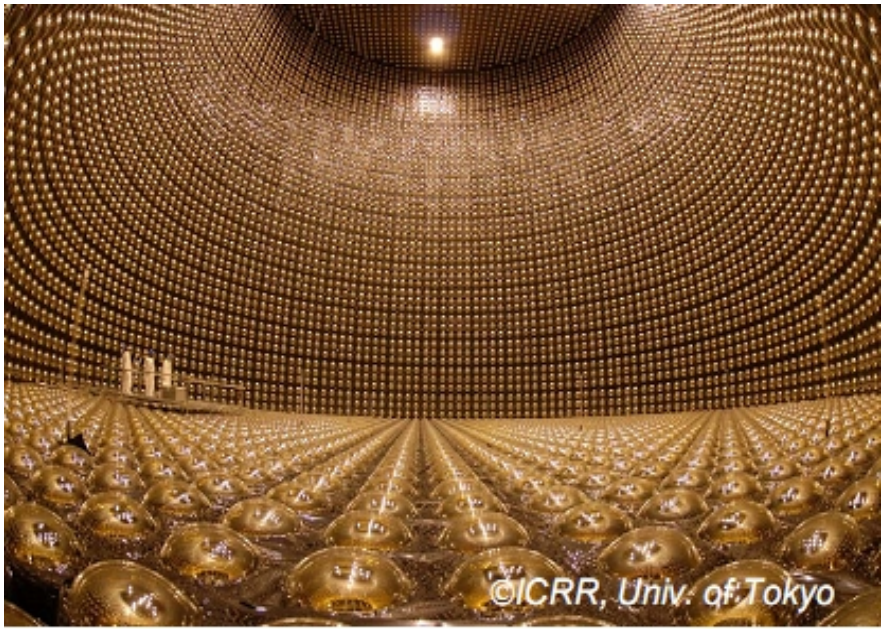
Far detector: Super Kamiokande IV

- 50 kton (22.5 kton fiducial) water Cherenkov det.
- ID: 11k 20" PMT (40% photo coverage); OD: 2k 8" veto PMT (optically isolated from ID)
- New readout electronics and DAQ (no dead time) – improved decay-electron tagging
- GPS based event timing – record events within 500 μs around spill
- Very efficient e/μ separation (~99% at 0.6 GeV)

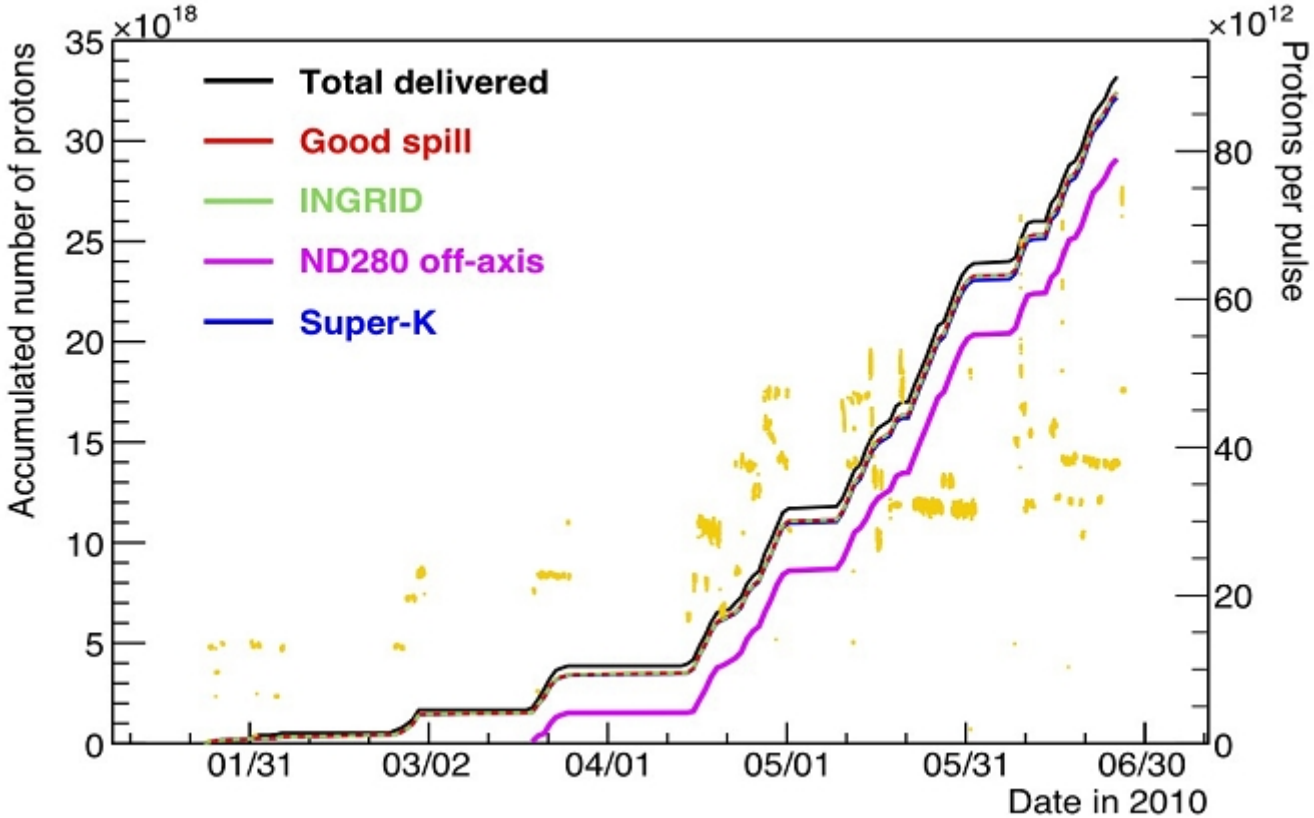








2010a data



- Data collected January – June 2010
- Total Super-K data: 3.23×10^{19} PoT (15.5 kW x 10^7s)
- 6 bunches / spill / 3.54s
- Stable running at 3.8×10^{13} PoT/spill (≈54 kW) shots up to 100 kW

Analysis strategy of 2010a data

Flux prediction

- Proton beam data
- External hadron production data

ND280 measurement

- Inclusive ν_μ CC selection
- $R_{data/MC} = N^{data}_{ND280} / N^{MC}_{ND280}$

Cross sections

- Interactions models
- External data

SK measurement

- Event selection (ν_μ and ν_e)
- Estimate expected events
- Correct normalization using ND measurement:

$$N^{exp}_{SK} = R_{data/MC} \times N^{MC}_{SK}$$

- Evaluate systematics
- Extract oscillation parameters

Current analysis does not use the near det. spectrum or the near/far extrapolation

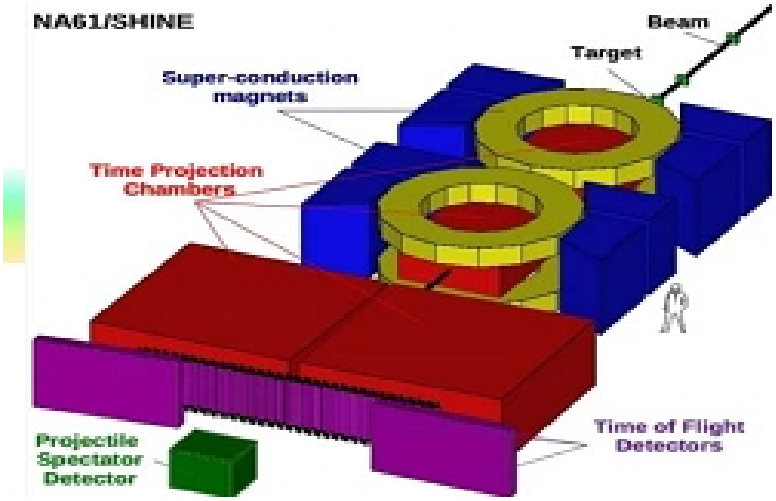
Flux constraint

NA61/Shine experiment in CERN

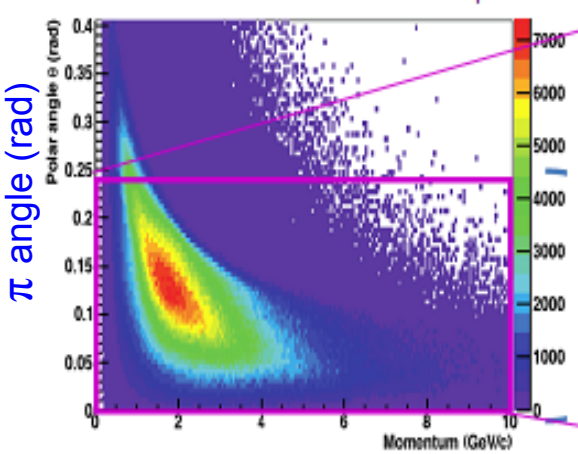
Constrain hadron production in target for beam simulation (FLUKA[1])

1) G. Battistoni et al., AIP Conf. Proc. 896 (2007) 31

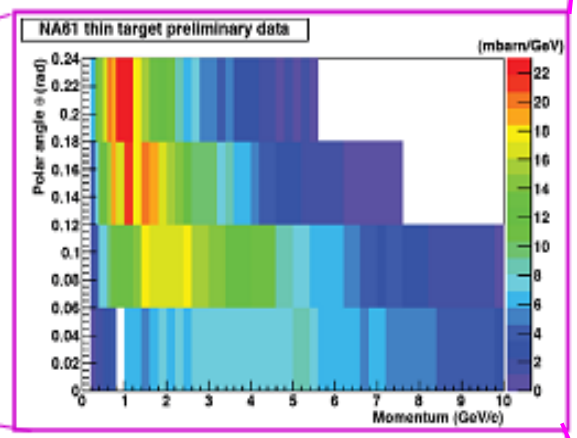
- p+C interaction on thin (2cm) target (2007-2009) and T2K replica (2010)
- pion production in MC is corrected based on preliminary results (Dec 2009)



MC(T2K):π^+ produce ν_μ @ SK

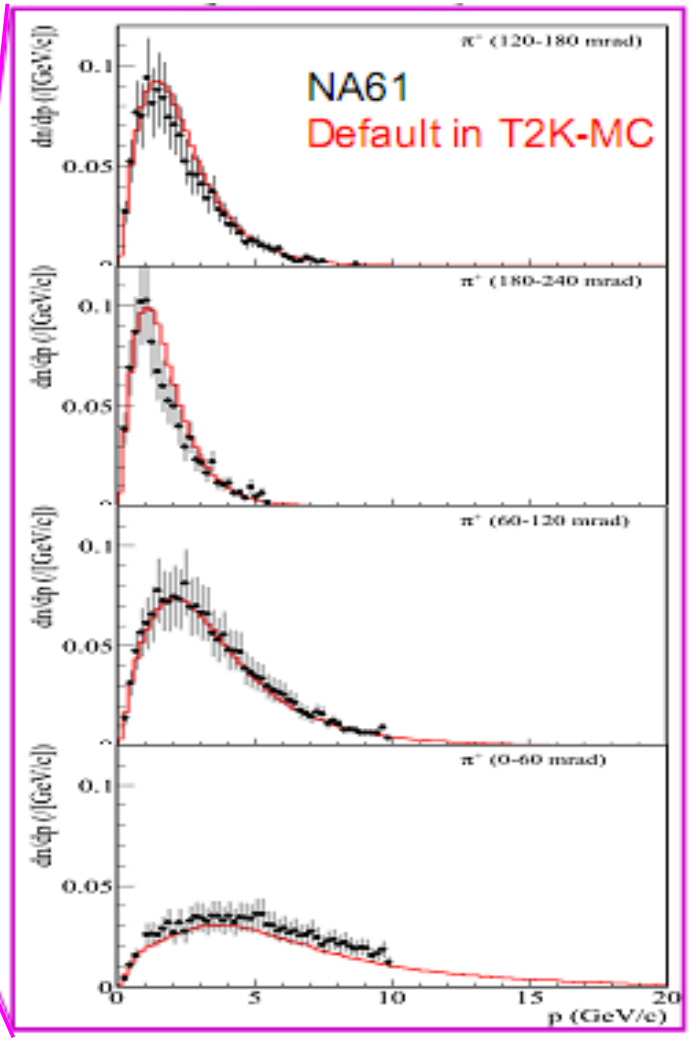


NA61 2007 data: π^+



π angle (rad)

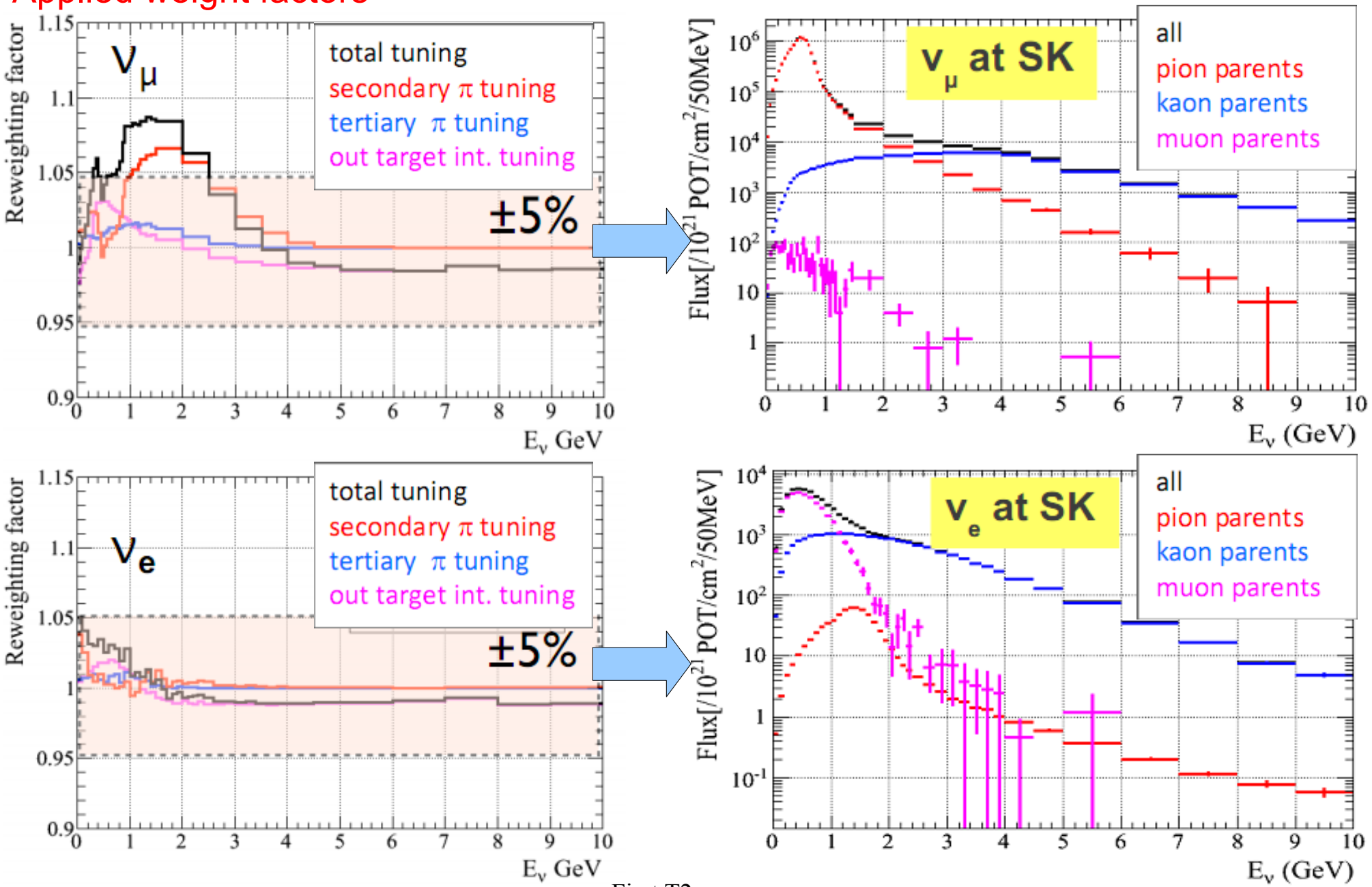
π momentum (GeV)



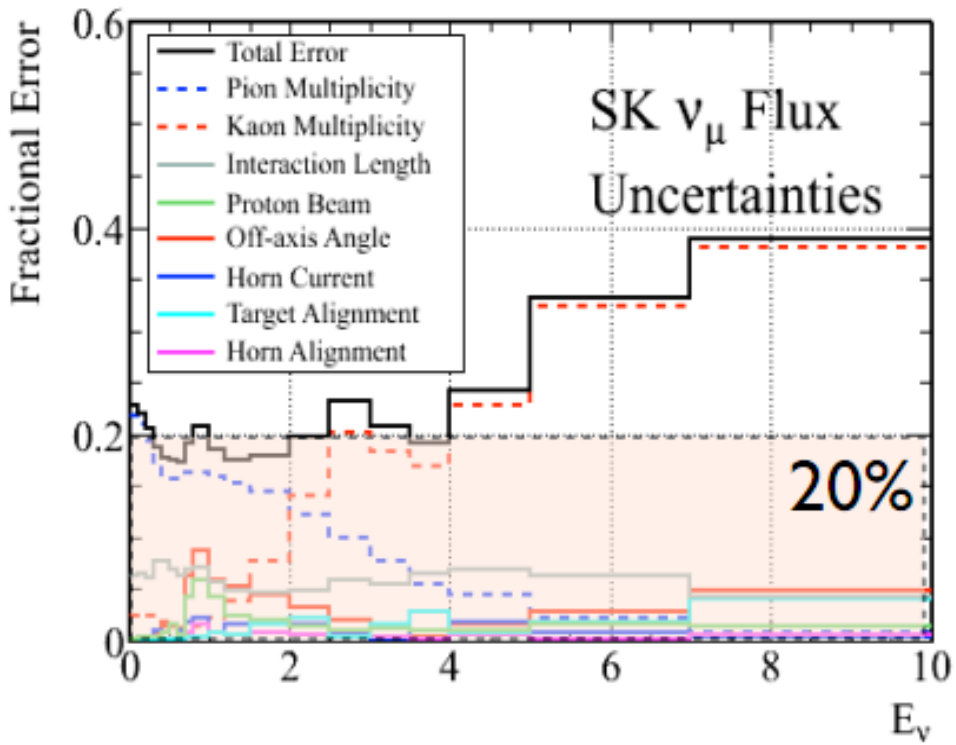
Flux prediction

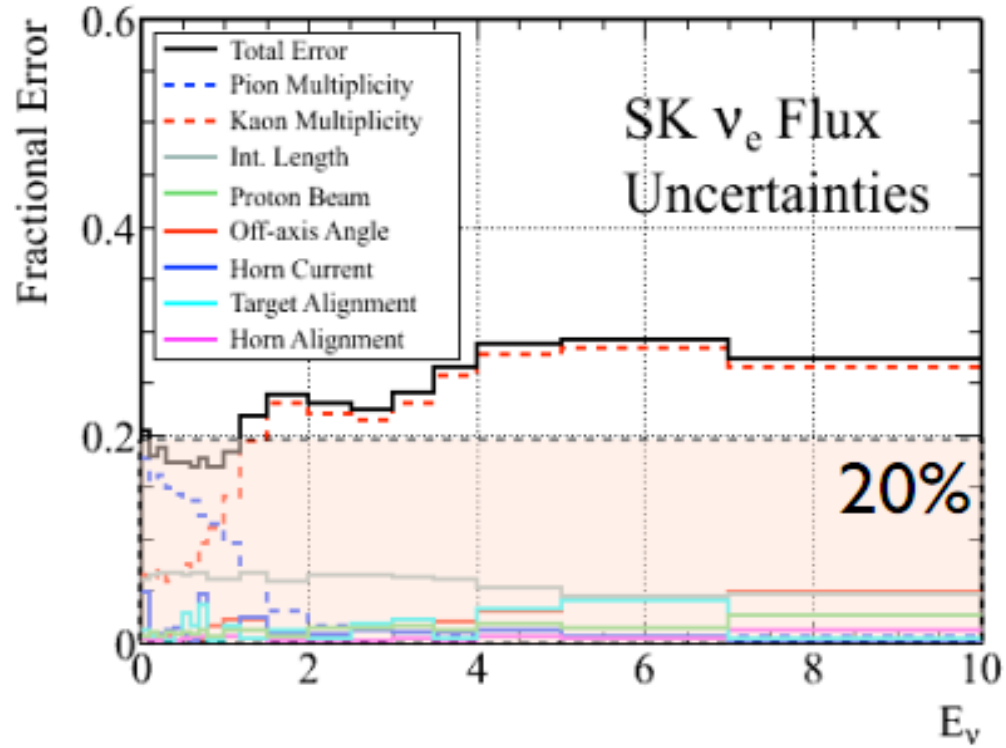
Applied weight factors

Tuned neutrino fluxes



Flux uncertainties





- Dominant uncertainty: pion (at low E) and K (at high E) production (20-40%)
- Flux related uncertainty in the normalization ratio $N_{SK}^{MC} / N_{ND}^{MC}$ is smaller (~7% for ν_μ and 12% for ν_e)
  - estimated by changing the systematic parameters by 1σ in the beam simulation

ν interaction uncertainty

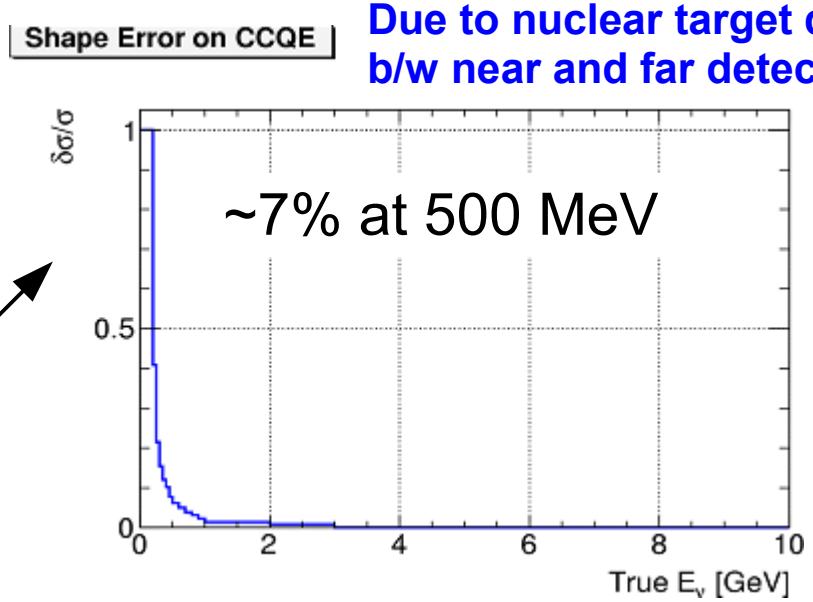
- Estimated from parameter variations in MC models and comparisons with data (K2K, MiniBooNE, SciBooNE, MINOS)

For electron appearance analysis:

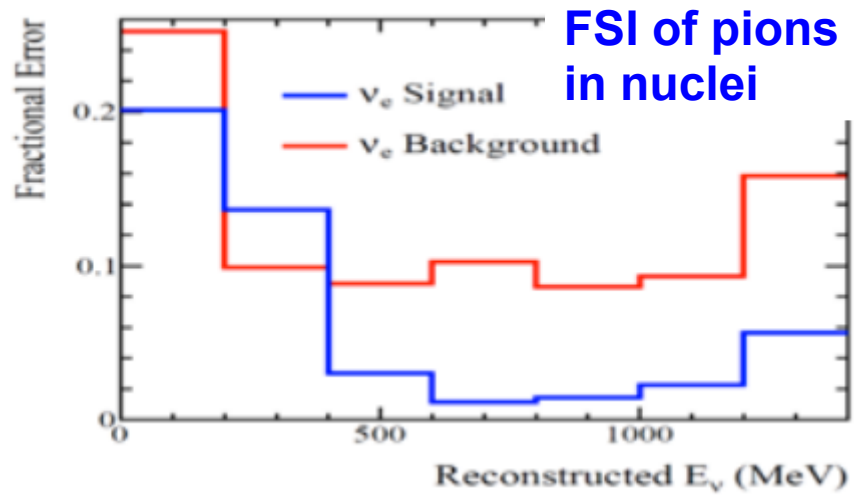
Category	Error [%]	
CC QE	Depends on true neutrino energy	
CC 1π	30 (E_ν<2 GeV)	20 (E_ν>2 GeV)
CC coherent π	100	
CC other	30 (E_ν<2 GeV)	25 (E_ν>2 GeV)
NC $1\pi^0$	30 (E_ν<1 GeV)	20 (E_ν>1 GeV)
NC coherent	30	
NC other	30	
FSI error	Depends on reconst. neutrino energy	
$\sigma(\nu_e)/\sigma(\nu_\mu)$:	6%	

Uncertainties on the ratio relative to CCQE

Most errors considered correlated b/w near and far detectors



Due to nuclear target diff. b/w near and far detector

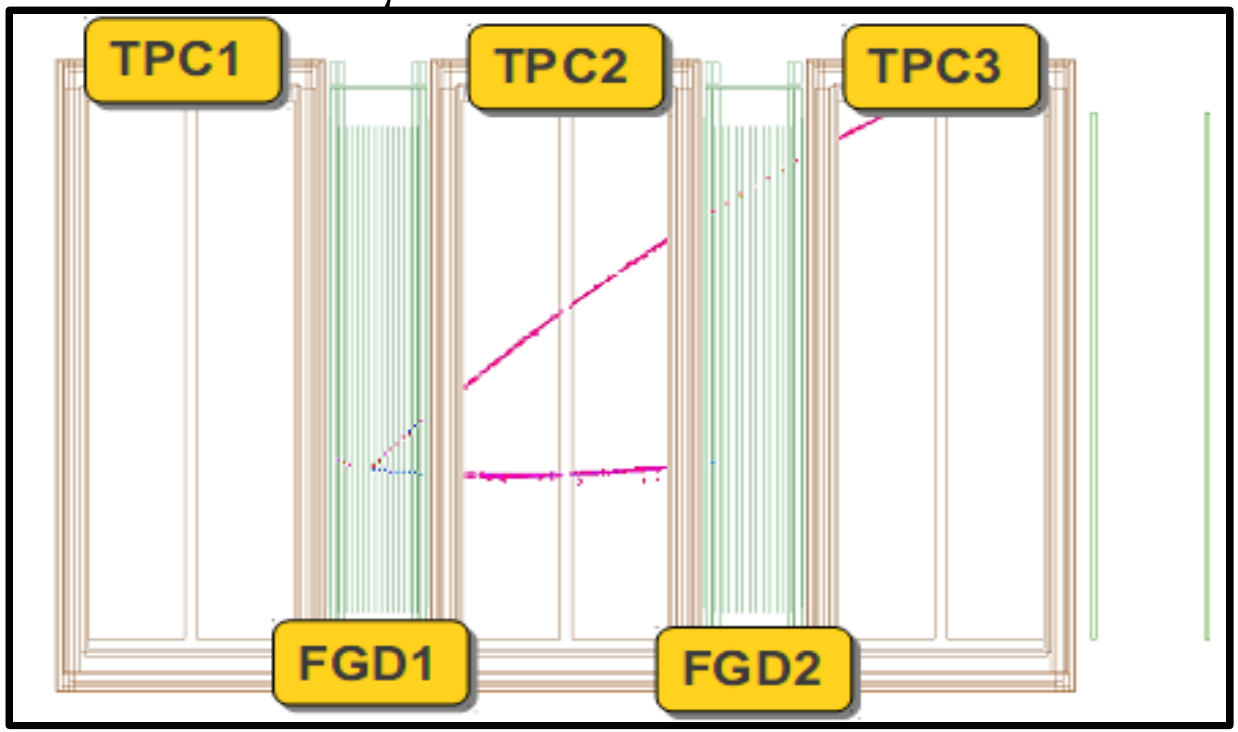


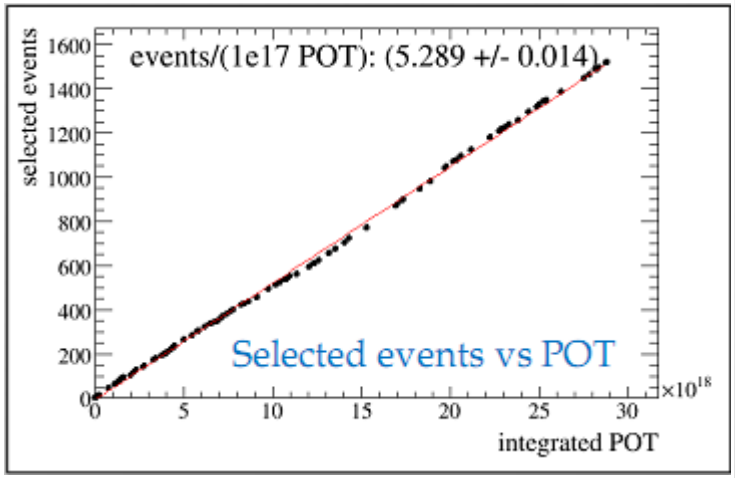
FSI of pions in nuclei

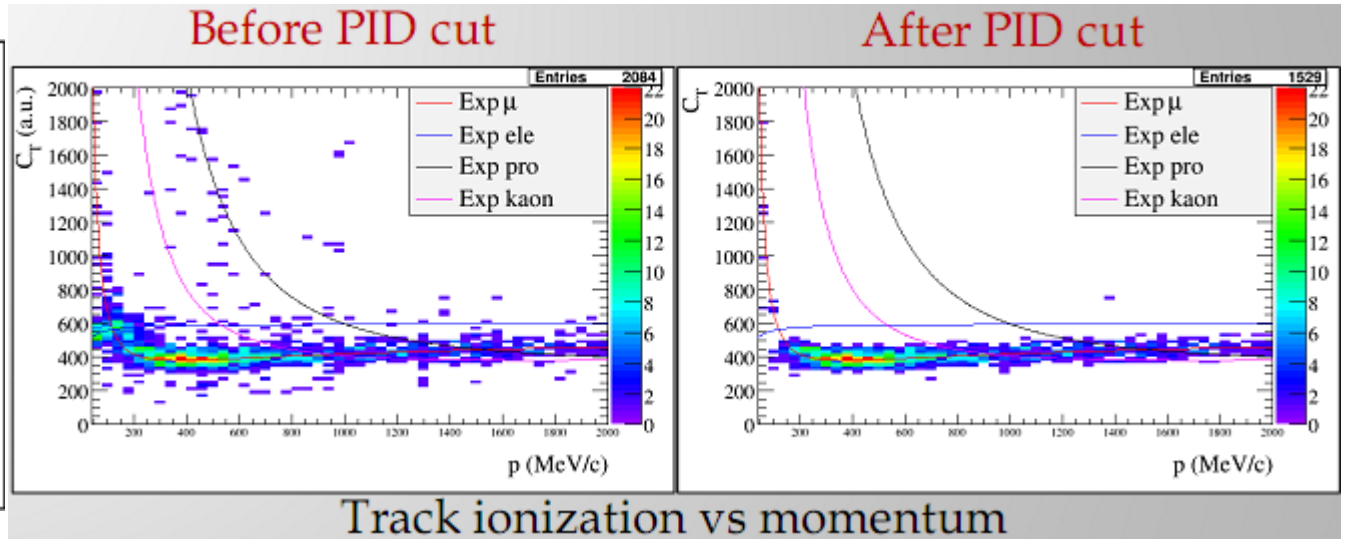
ND280 inclusive ν_μ CC selection

Event Selection

- No track in TPC 1
- ≥1 negative charge track in TPC 2 (or 3)
- Track starts in FV of FGD1 or FGD2
- TPC PID

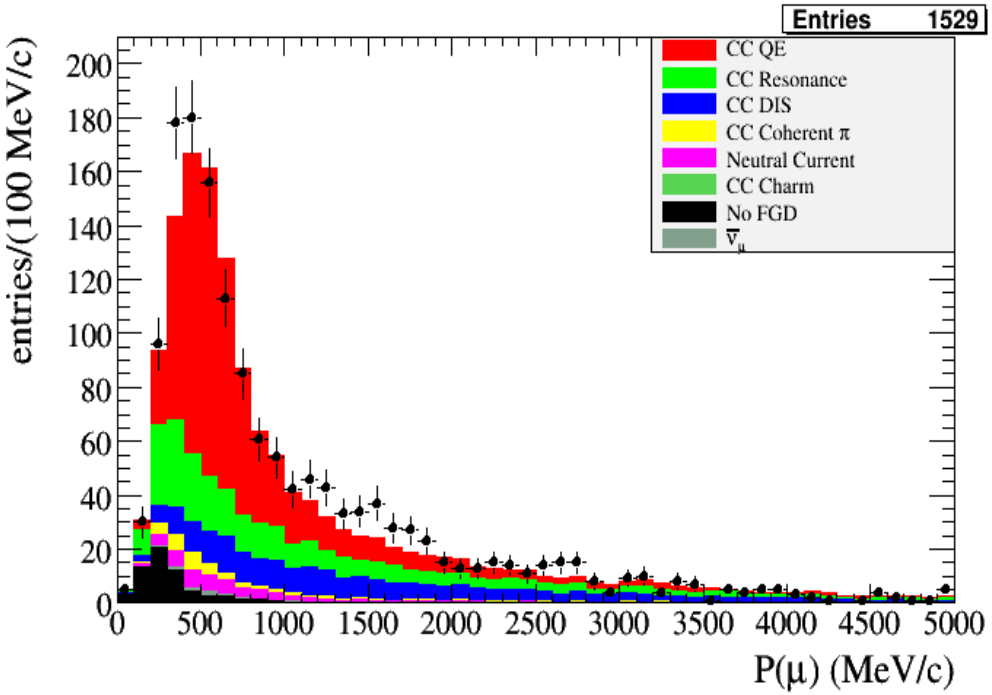


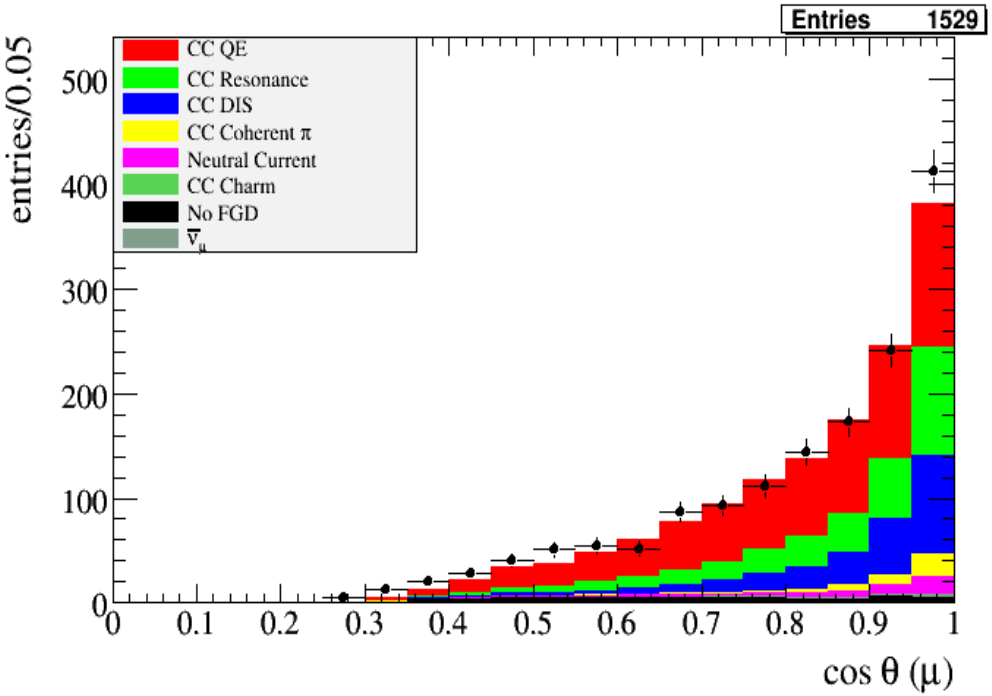




ND280 data vs. MC

Comparison with MC prediction (NEUT normalized to 2.88×10^{19} PoT)



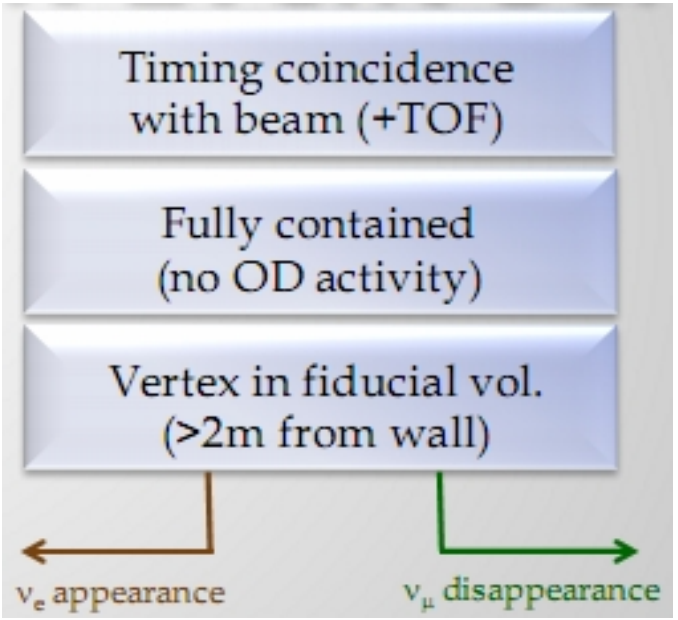


$$R_{data/MC} = 1.061 \pm 0.028(stat.)^{+0.044}_{-0.038}(det.\,sys.) \pm 0.039(phys.\,model)$$

Includes:
TPC-FGD matching, dE/dx pull distributions, TPC tracking efficiency

Far detector event selection

Pre-selection:



ν_e selection

- $E_{vis} > 100$ MeV
- 1 e-like ring
- No decay electron
- Forced 2nd ring ($m_{inv} < 105$ MeV/c^2)
- $E_\nu^{reco} < 1250$ MeV

ν_μ selection

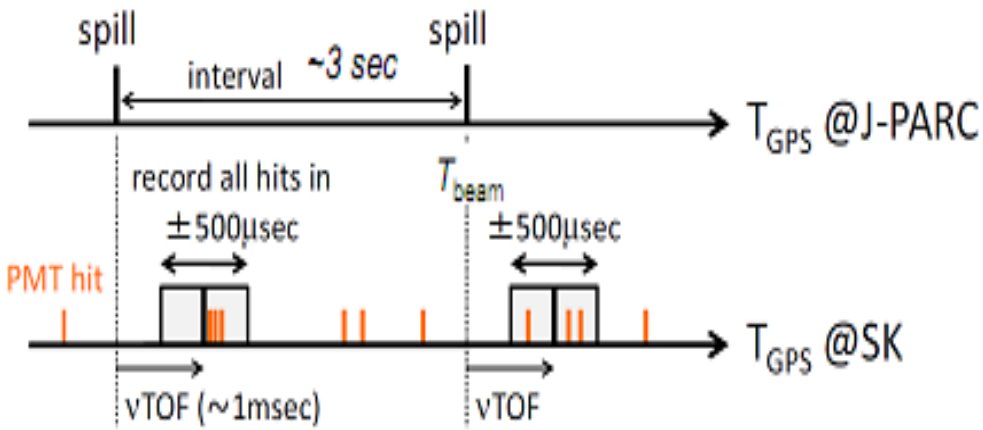
- $E_{vis} > 30$ MeV
- 1 μ-like ring

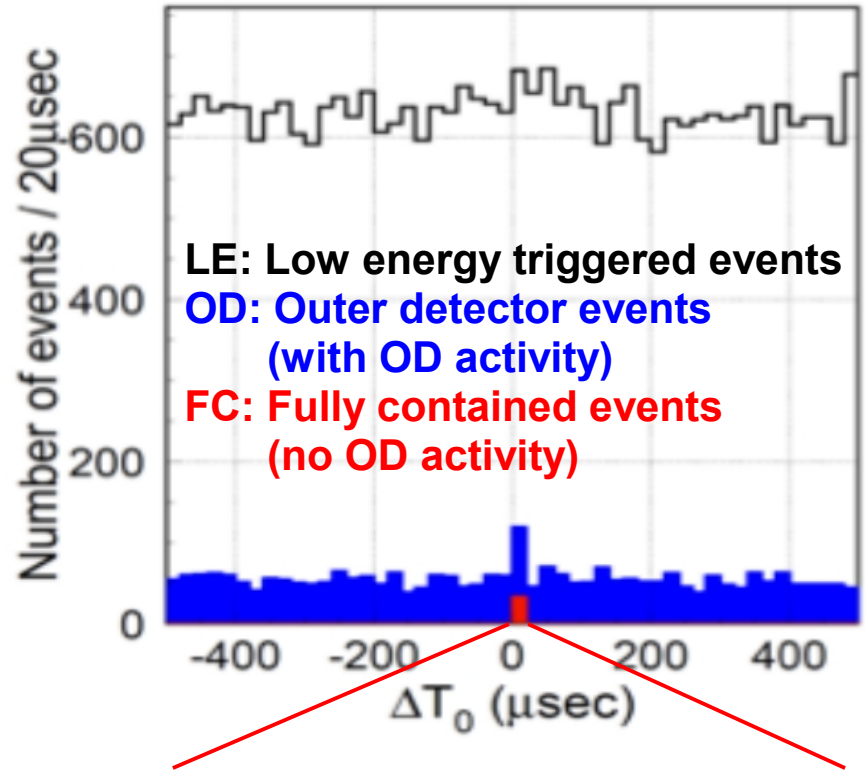
- Unbiased event selection
- Set in advance from previous experience with SK detector

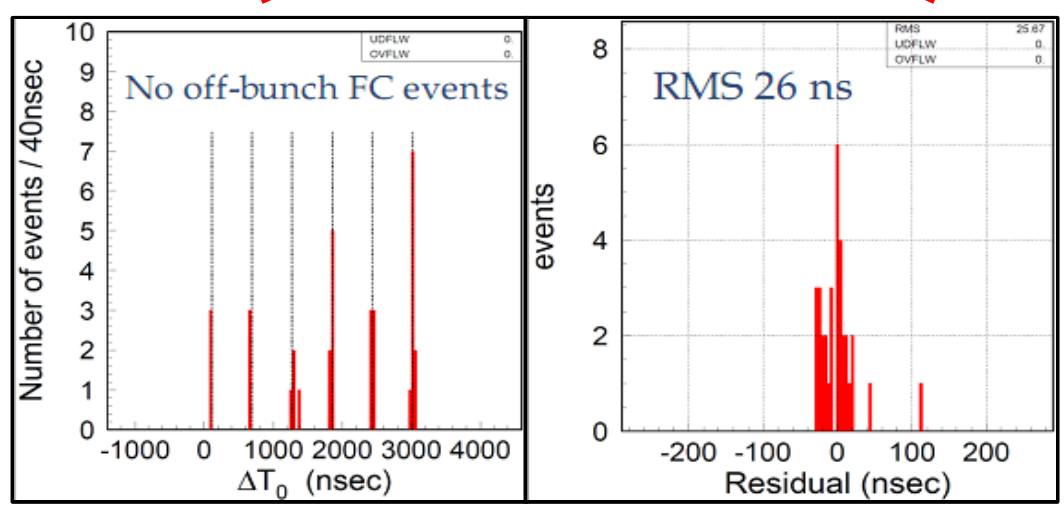
SK event timing

Dead-timeless DAQ:

- all hits within +/- 500 μs window around beam spill arrival time to SK recorded
- time between SK and JPARC synchronized by GPS





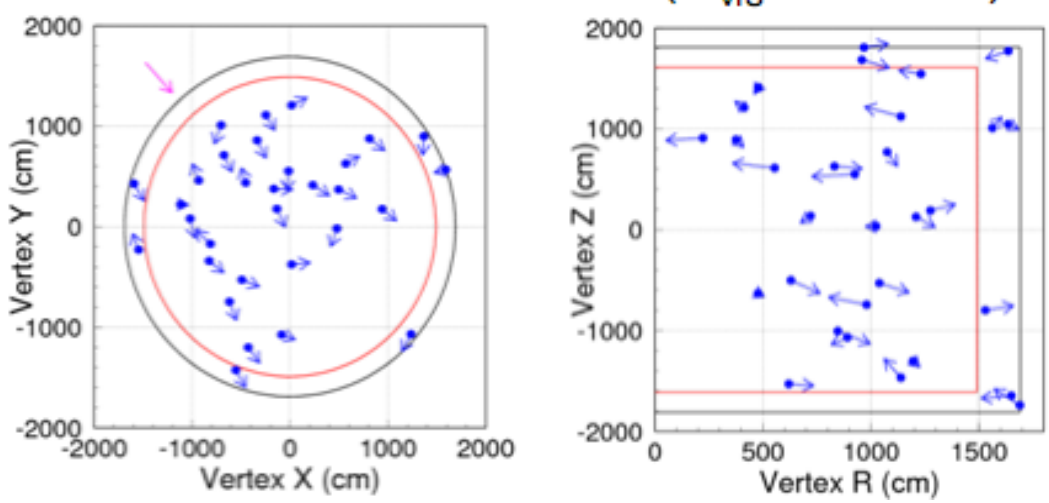


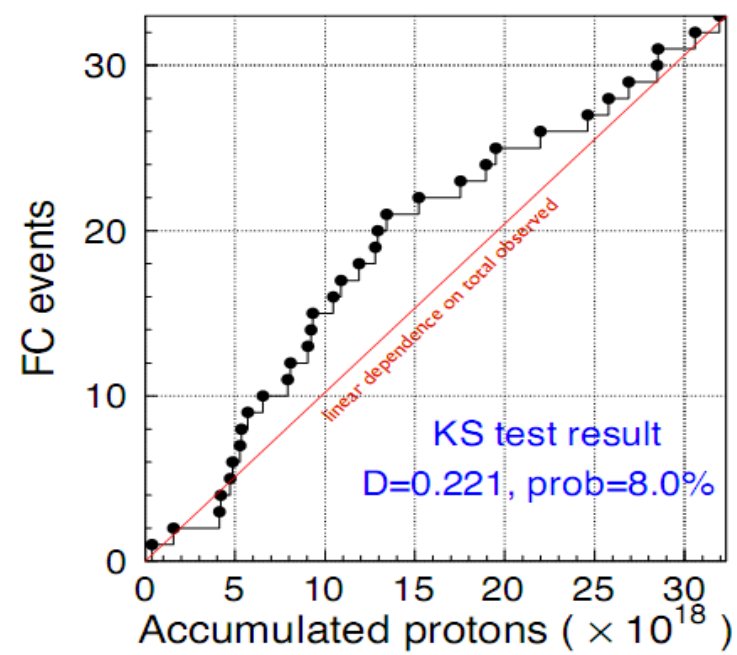
FC events clearly show the beam spill structure

SK pre-selection: FC/FV

T2K-SK events	Data	MC		BG (12μs window)
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011

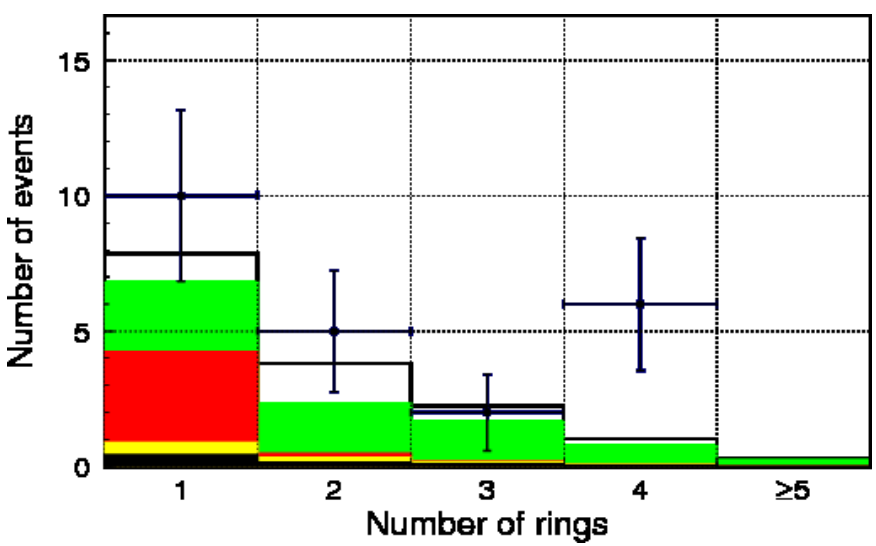
Event vertex distribution (E_{vis}>30MeV)



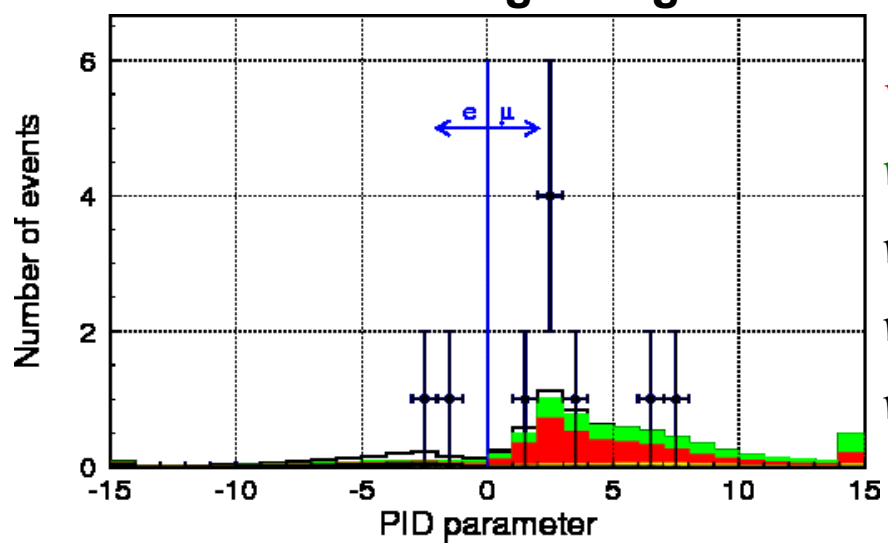


SK pre-selection: ring counting and PID

T2K-SK events	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	8	24.5 ±3.9	7.1 ±1.3
Single-ring e-like (P_e>100MeV/c)	2	1.5 ±0.7	1.3 ±0.6
Multi-ring	13	10.2	8.0



single-ring events



ν_μ CC QE

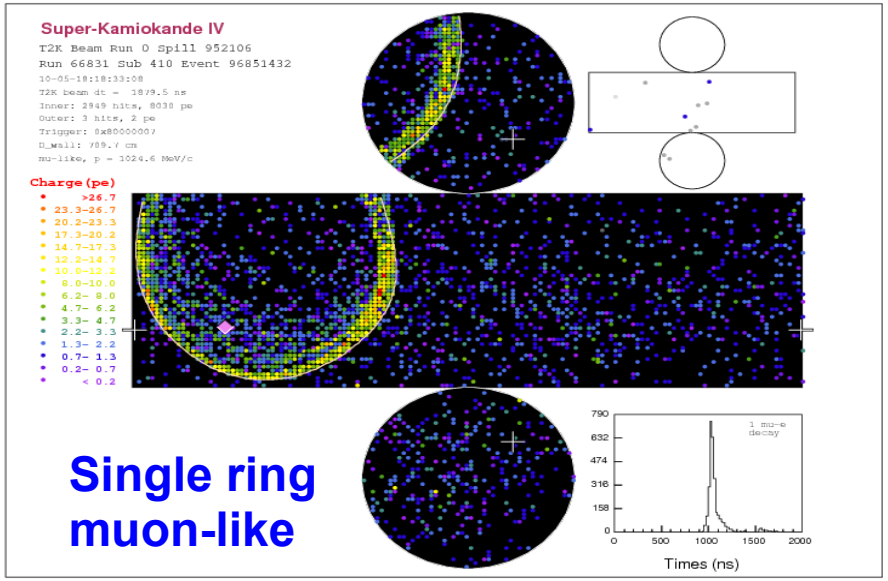
ν_μ CC non-QE

ν_μ (yellow)

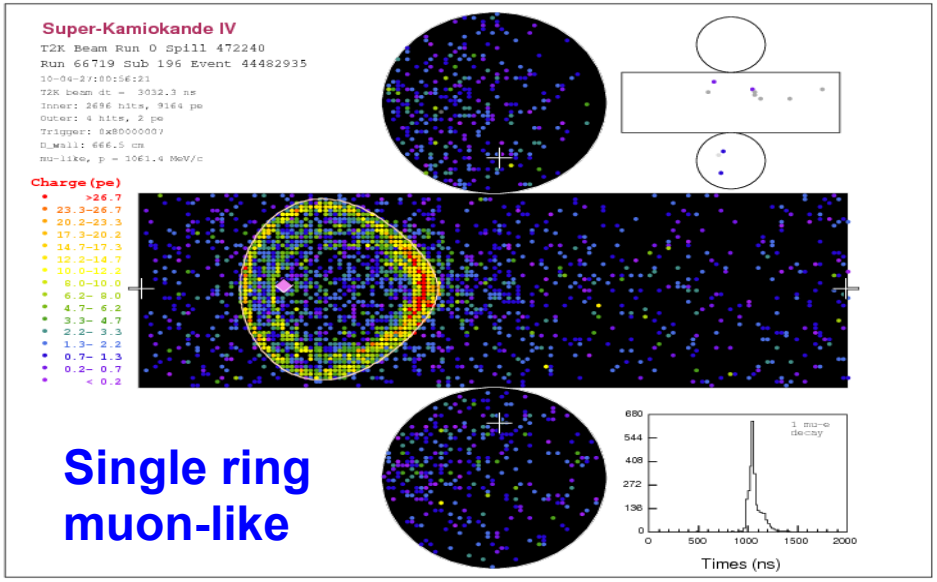
ν_e (black)

$\nu_{\mu/\tau}$ NC (white)

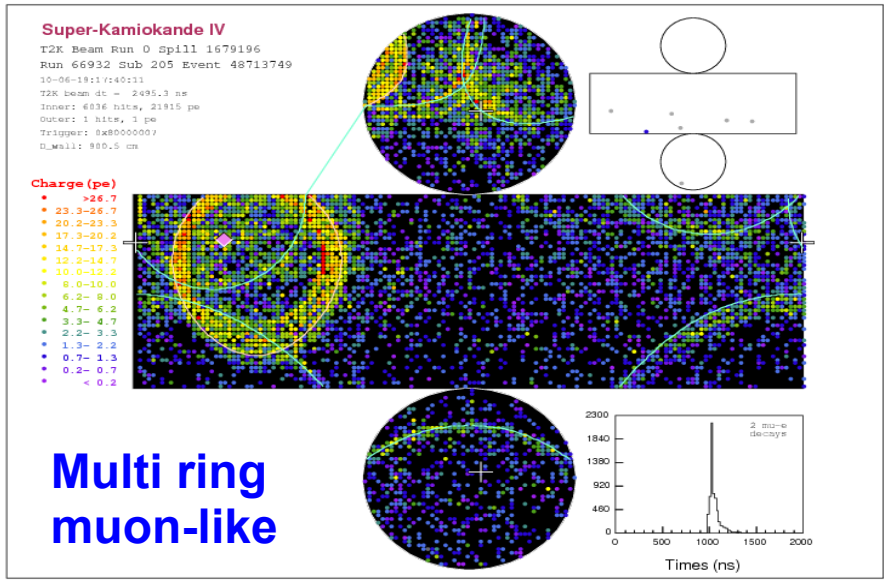
SK event gallery



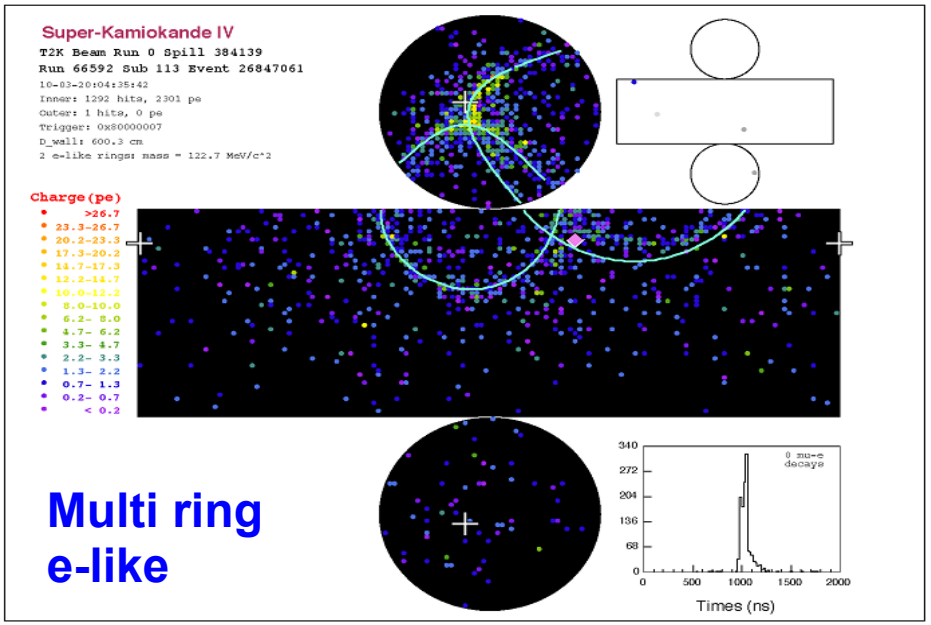
Single ring muon-like



Single ring muon-like



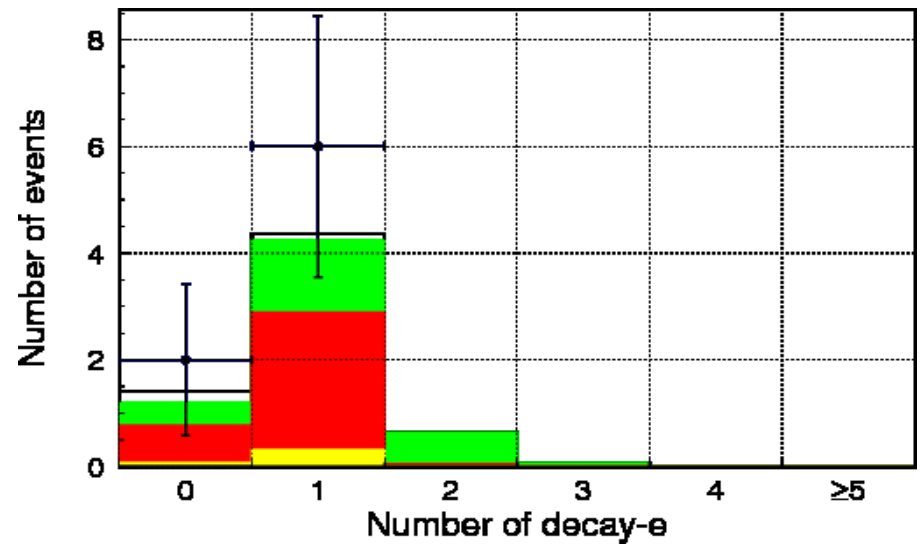
Multi ring muon-like

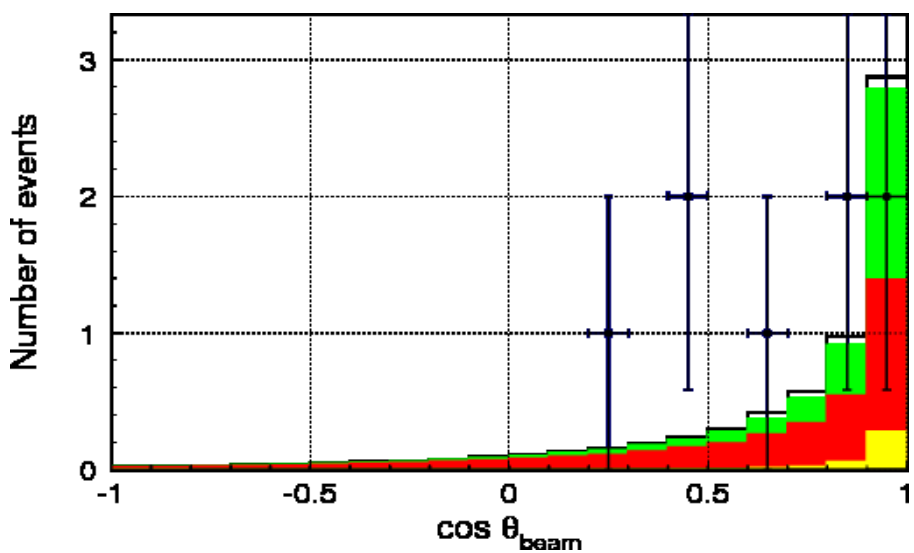


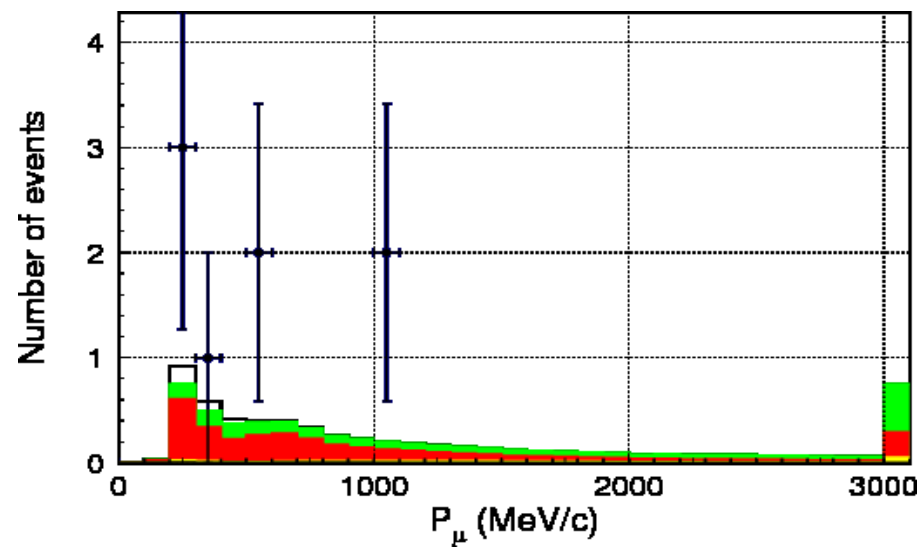
Multi ring e-like

Single-ring ν_μ events

T2K-SK events	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	8	24.5 ±3.9	7.1 ±1.3
N(decay e) < 2 (E_{rec} < 10 GeV)	8	22.8 ±3.2	6.3 ±1.0

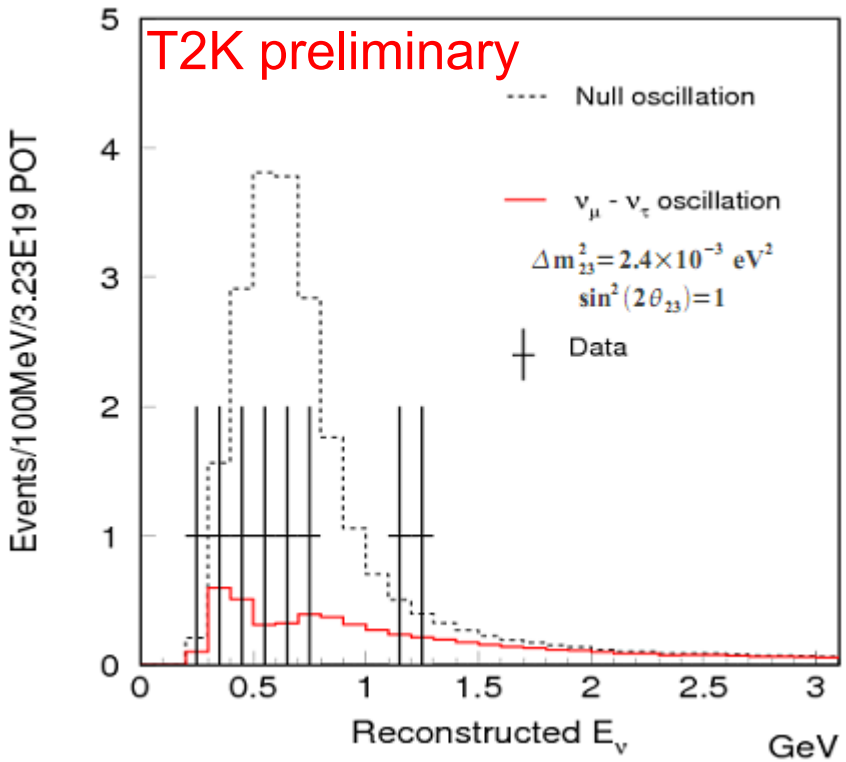






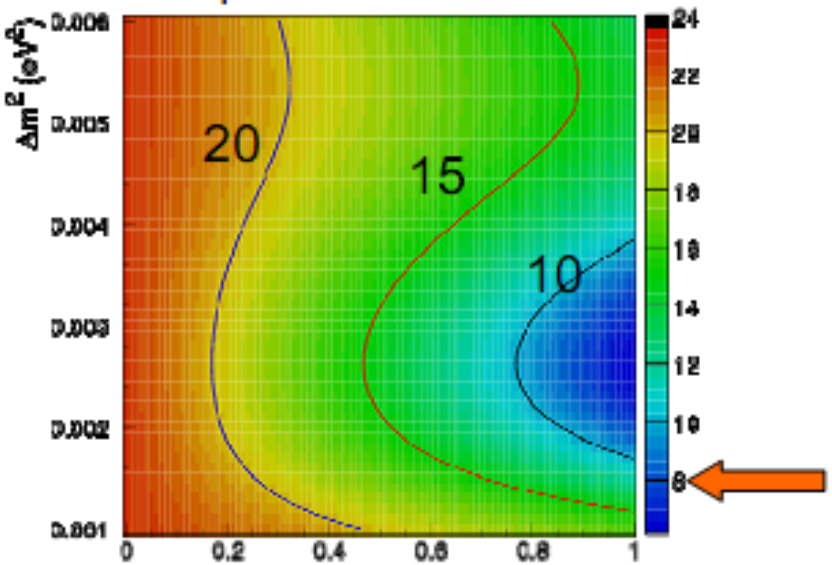
MC: ν_μ CC QE , ν_μ CC non-QE, $\bar{\nu}_\mu$ (yellow), ν_e (black), $\nu_{\mu/\tau}$ NC (white)

ν_μ disappearance analysis

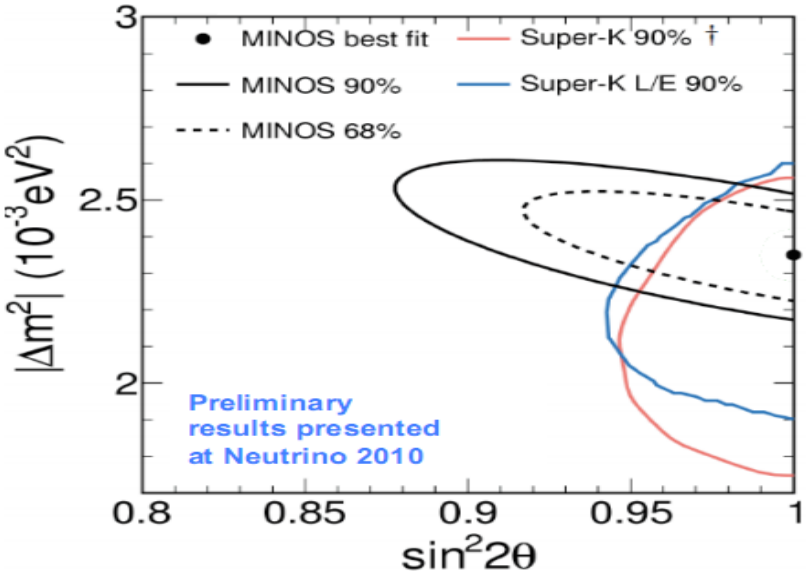


consistent with earlier MINOS and SK measurements

Expected # of events as a function of Oscillation parameters.



8 events observed



Final ν_e event selection

T2K-SK events	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$ $\theta_{13}=0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7
Single-ring e-like (P_e>100MeV/c)	2	1.5 ±0.7	1.3 ±0.6

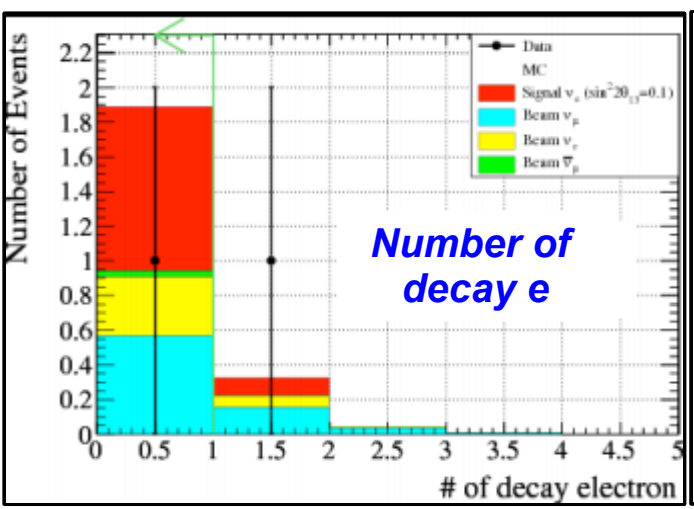
Additional background rejection:

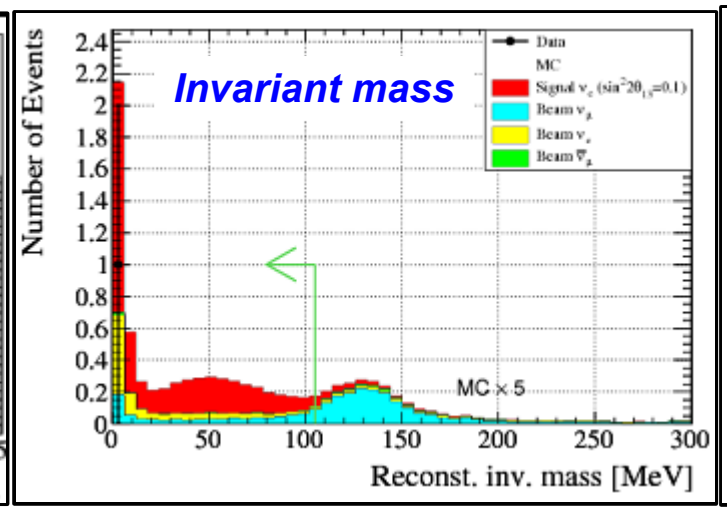
- no decay electron
- $m_{\gamma\gamma}$ < 105 MeV assuming second ring exist
- reconstructed Ev < 1250 MeV

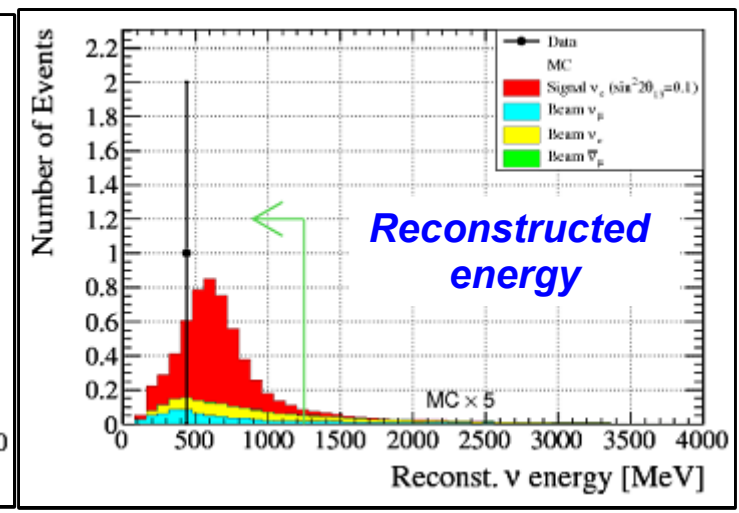
65.9% efficiency for signal

One candidate ν_e event remains!

T2K preliminary

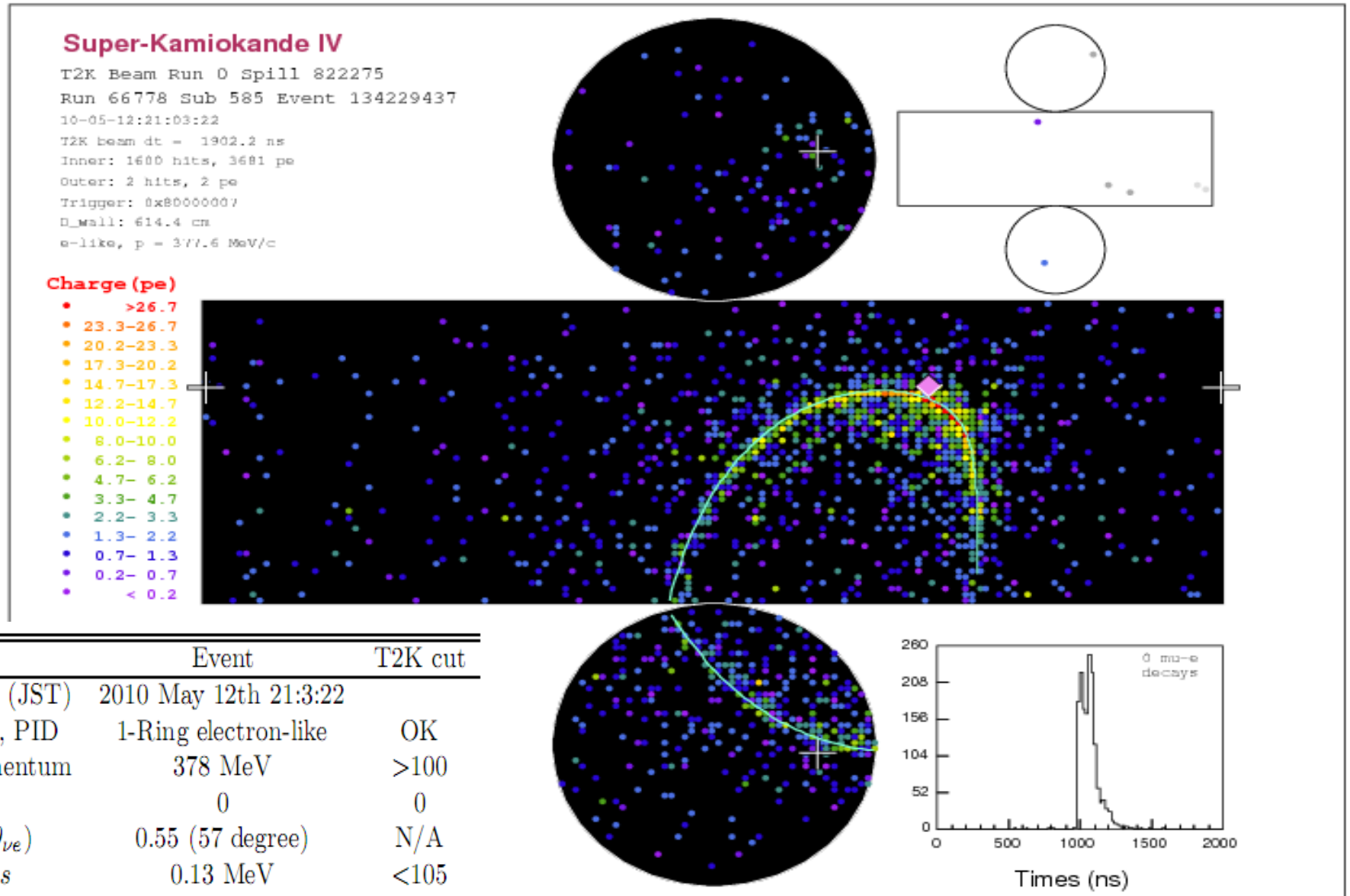






ν_e event candidate

T2K preliminary



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

Total systematic uncertainty for ν_e

- Estimated combined systematic error on ν_e events

T2K preliminary

Error source	N_{SK}^{sig}	N_{SK}^{bkg}	N_{SK}^{s+b}	N_{ND}	N_{SK}^{bkg}/N_{ND}	N_{SK}^{s+b}/N_{ND}
SK Efficiency	$\pm$ 7.60	$\pm$ 15.81	$\pm$ 9.47	$\pm$ 0.0	$\pm$ 15.81	$\pm$ 9.47
Cross section	$\pm$ 9.66	$\pm$ 13.90	$\pm$ 9.88	$\pm$ 8.37	$\pm$ 14.17	$\pm$ 10.61
Beam Flux	$\pm$ 21.97	$\pm$ 18.12	$\pm$ 20.49	$\pm$ 19.83	$\pm$ 9.17	$\pm$ 11.88
ND Efficiency	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$	$^{+5.60}_{-5.16}$
Overall Norm.	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 0.00	$\pm$ 2.70	$\pm$ 2.70
Total	$\pm$ 25.17	$\pm$ 27.77	$\pm$ 24.64	$^{+22.23}_{-22.13}$	$^{+23.95}_{-23.85}$	$^{+19.55}_{-19.43}$

When constrained by ND normalization

$\Delta m^2_{23}=2.4\cdot 10^{-3}\,eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$

23.9% background only

19.5% background + signal ($\sin^2 2\theta_{13}=0.1$)

Expected ν_e events

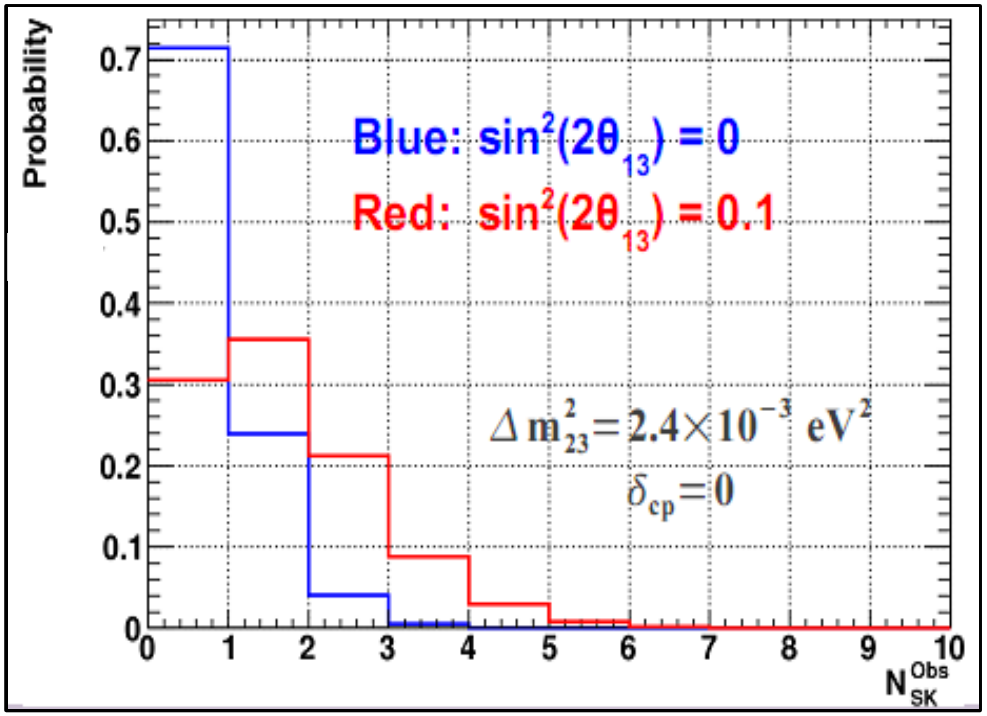
Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**

$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$

Expected background + signal if $\sin^2 2\theta_{13}=0.1$:
1.20 ± 0.23 (syst.)

Probability of observing N events (including systematic uncertainty)

T2K preliminary



Probability of observing ≥1 events if $\theta_{13}=0$: 29%

ν_e oscillation limits

- Two independent analysis method to derive limits and sensitivity (confidence interval construction differs)

A: Feldman-Cousins

B: Classical one-sided limit

90% limits/sensitivity (Δm^2_{23}=2.4x10^{-3} eV^2, δ=0)

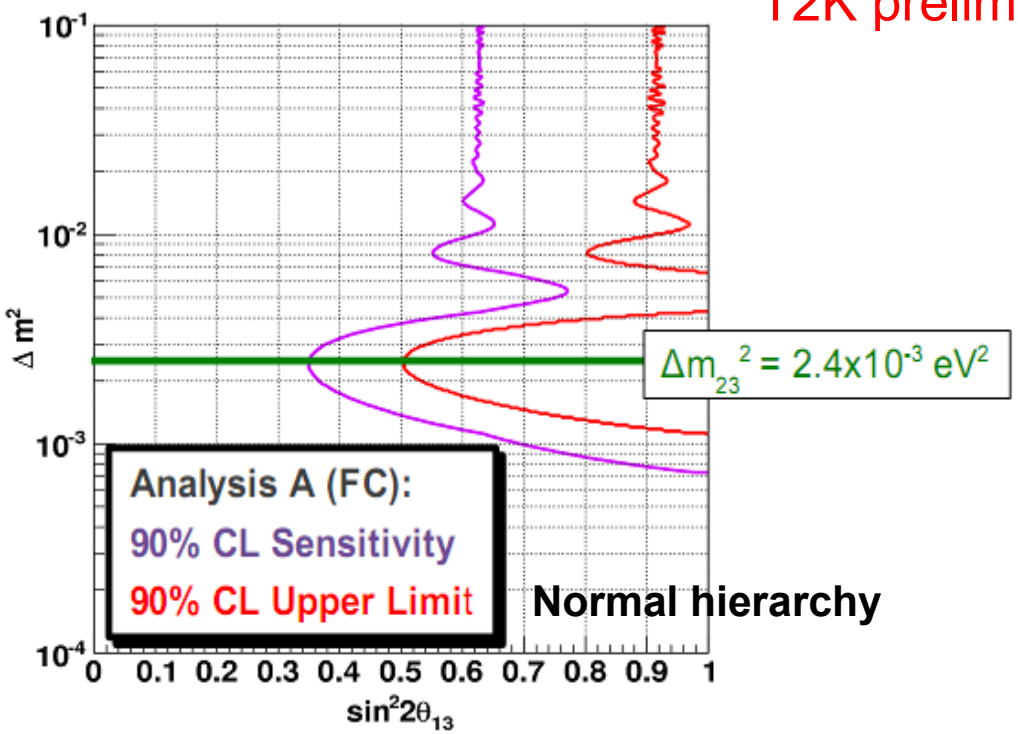
A

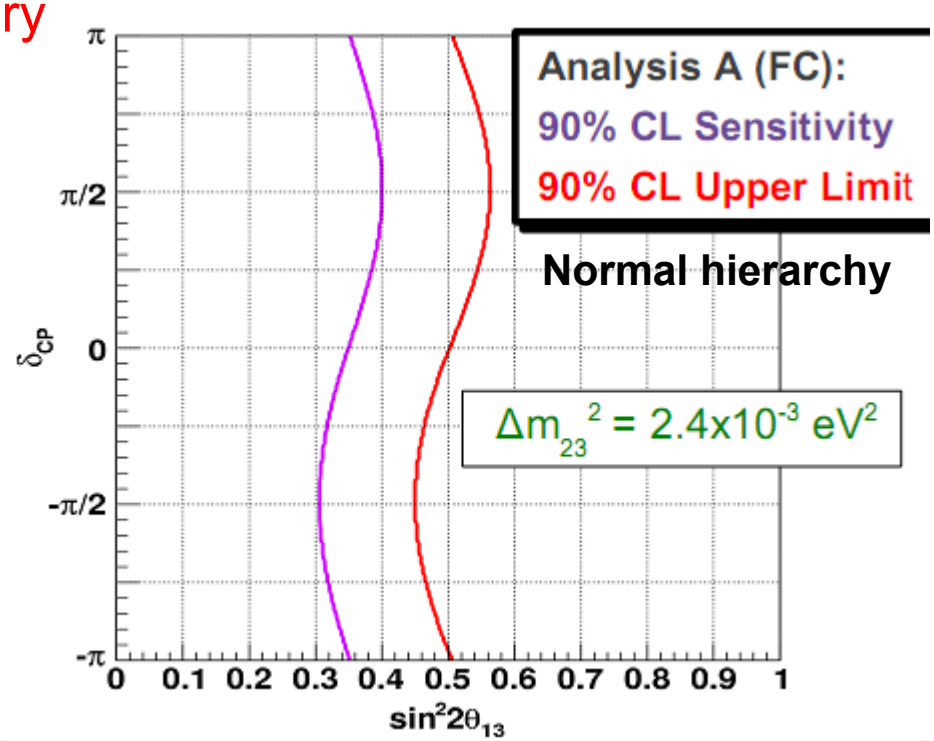
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

B

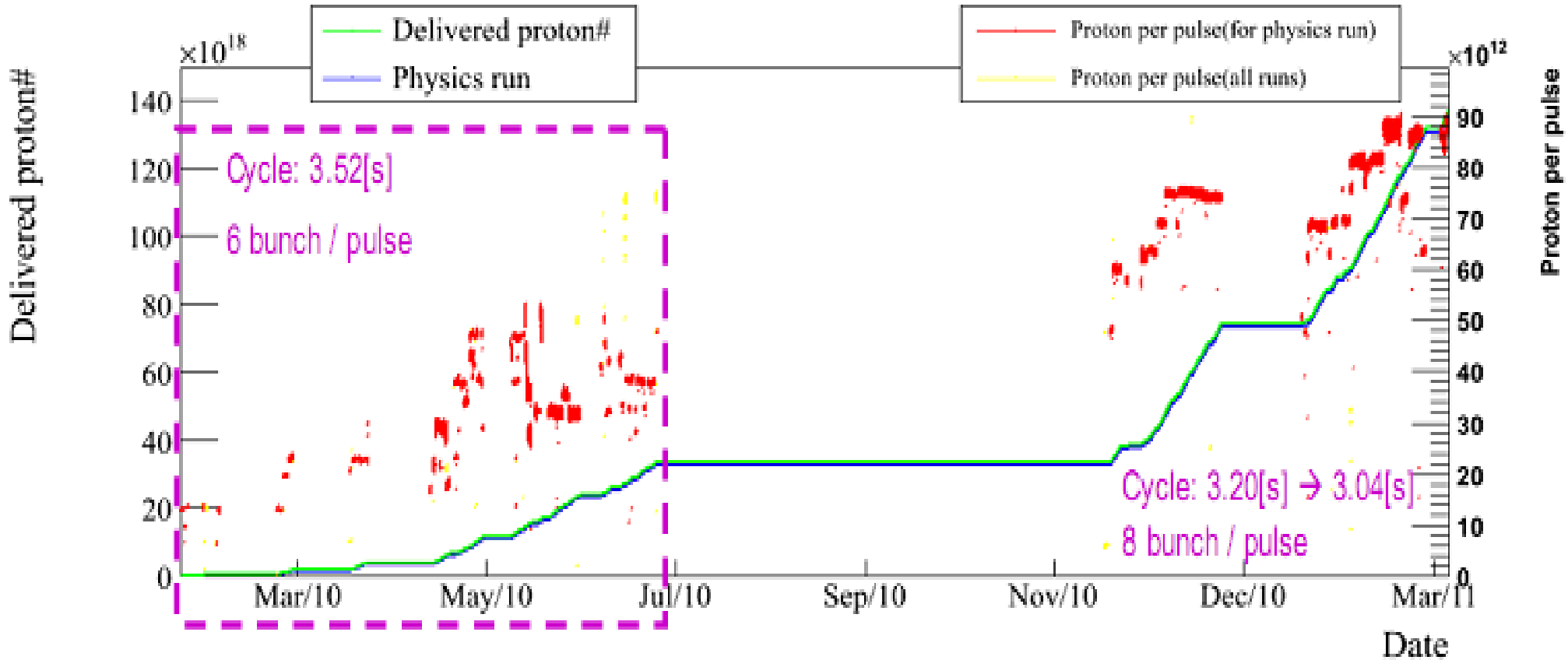
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39

T2K preliminary





Future prospects

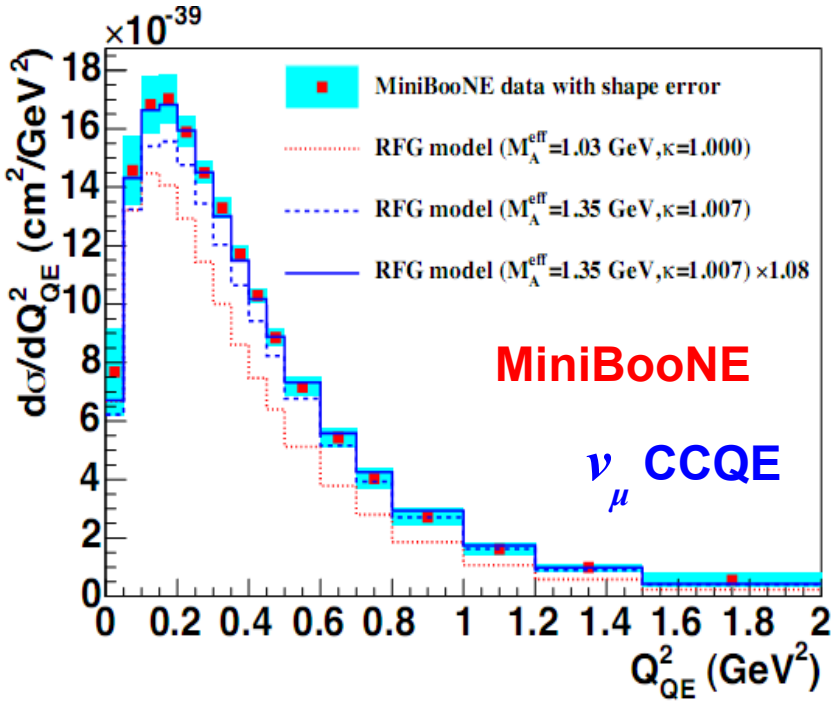


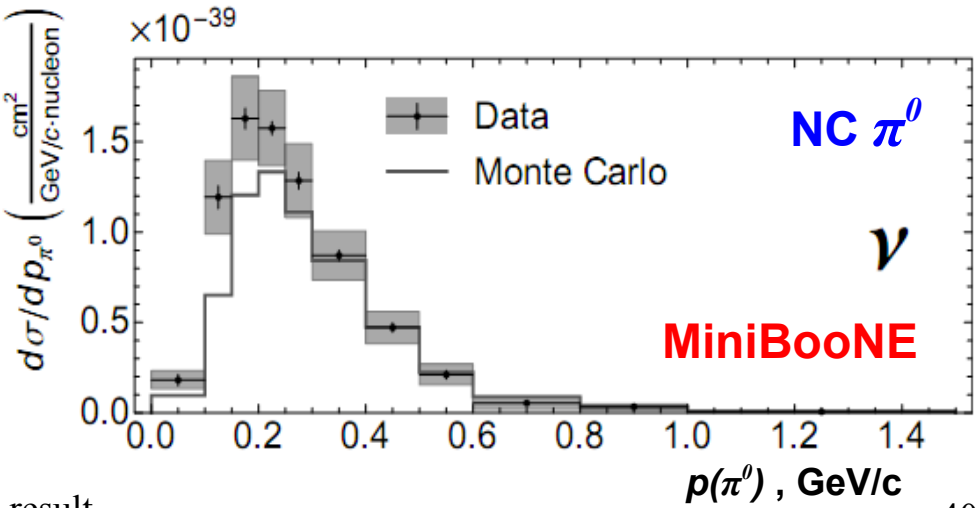
Run 2010b (from Nov 2010 – March 2011):

- 9.3×10^{13} p/spill (8 bunches/spill/3.04s)
- Max beam power: ~145 kW (MR losses limit beam power)
- Total data collected up to Mar 11: 1.45×10^{20} PoT (inc. 2010a)

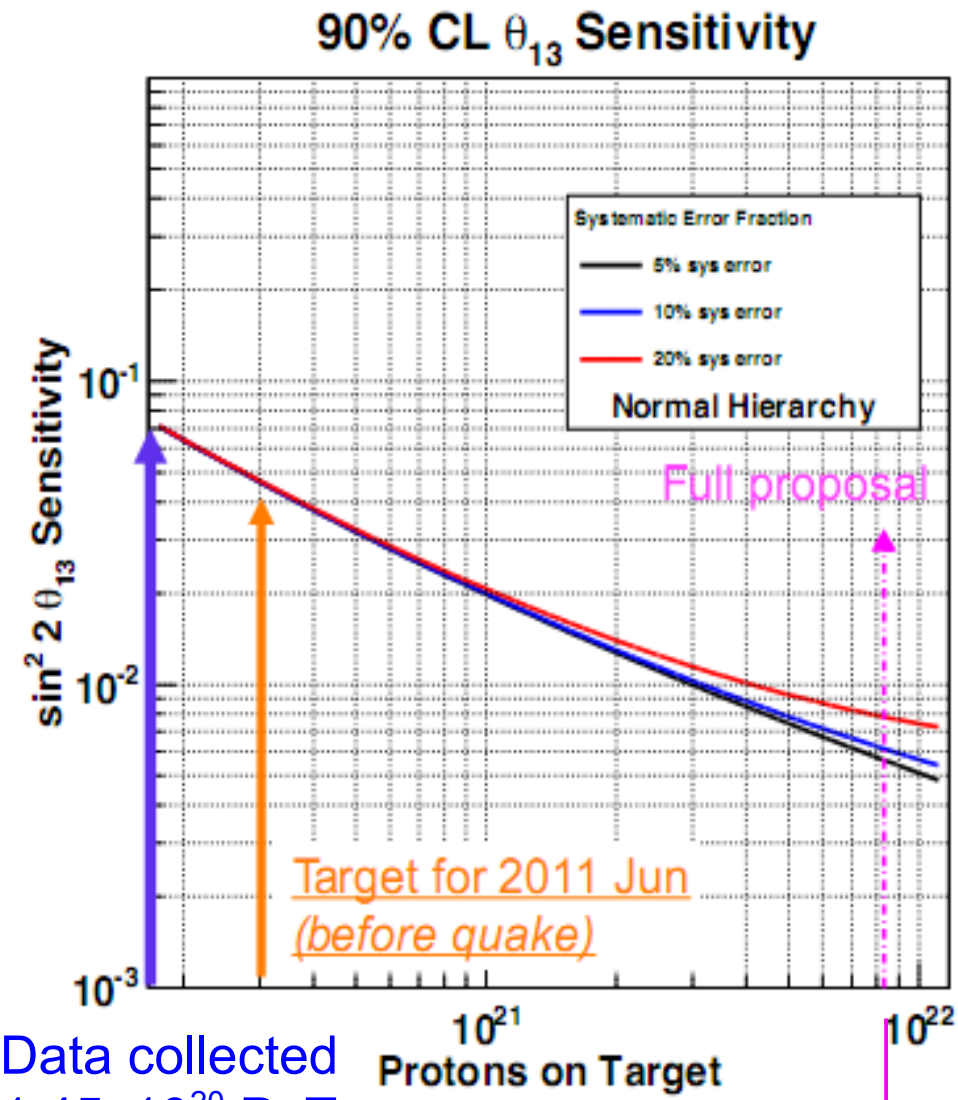
Future analysis improvements

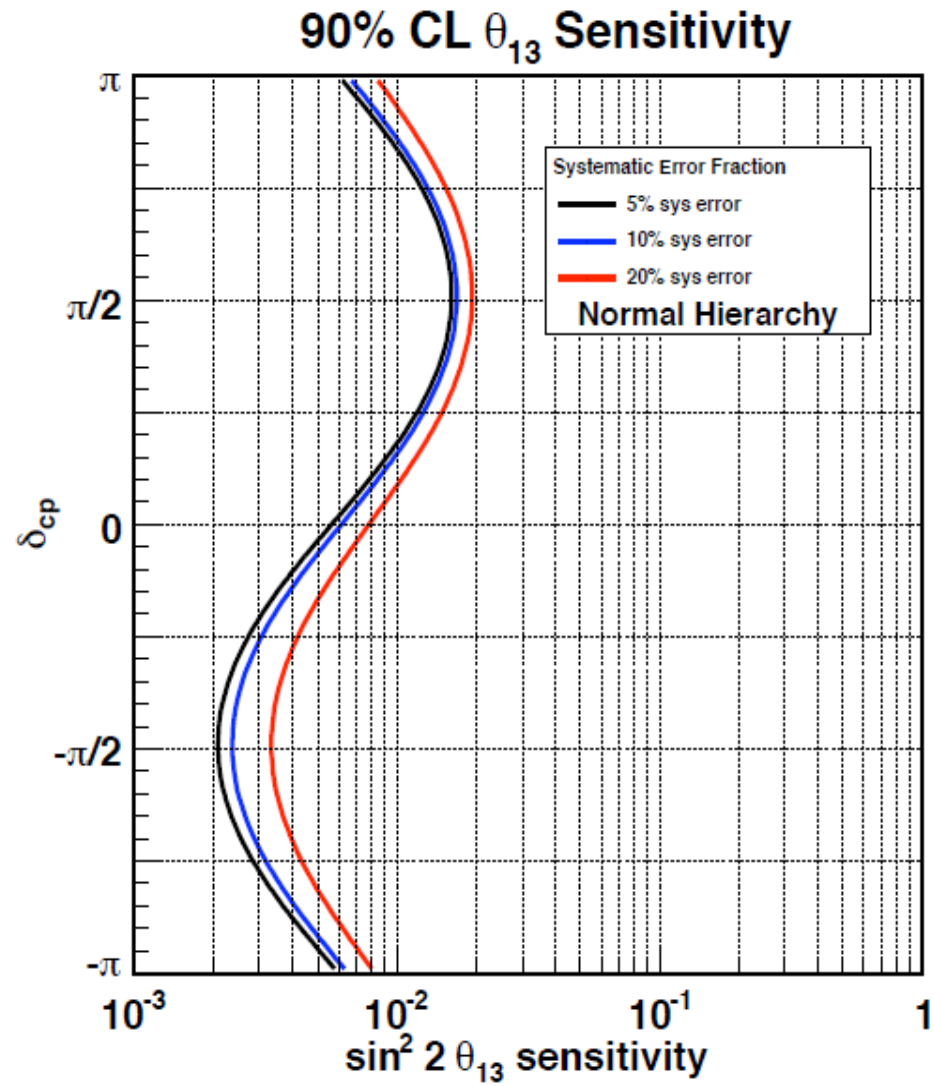
- Reduce flux systematics: new results from NA61 (esp. K meson)
- ν spectral information from ND280 and near/far extrapolation to reduce model dependence
- Measure NC π^0 and beam e^- background in ND280
- Incorporate new internal/external cross section measurements as they become available: ND280, Sci/Mini/MicroBooNE, MINERvA





Future θ_{13} sensitivity





Data collected
1.45×10^{20} PoT

4.5x 2010a data (½ of target)

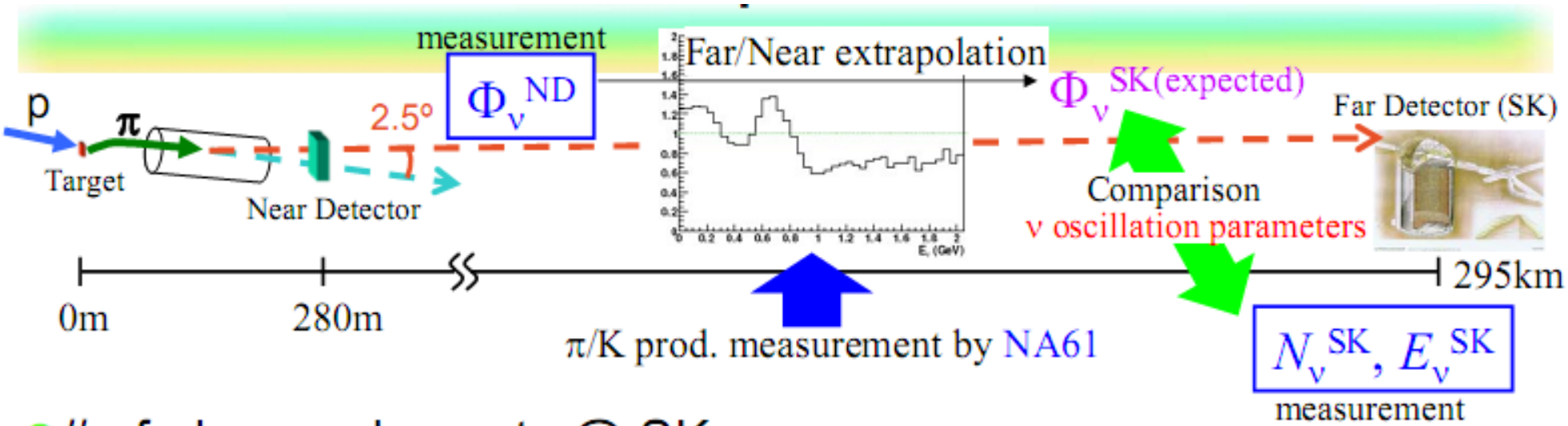
with 8.8×10^{21} P0T (750 kW x 5×10^{7}s)

Summary

- T2K: first high intensity, off-axis long-baseline neutrino oscillation experiment to measure ν_e appearance and improve ν_μ disappearance parameters
- Data taking started in January 2010
- First $\nu_\mu \rightarrow \nu_e$ oscillation result based on physics run from Jan-June 2010 (3.23×10^{19} P0T data)
  - observe 1 ν_e candidate (expected background is 0.30±0.07)
  - observed 8 ν_μ candidates – consistent with osc. parameters from MINOS
- Analysis of the 1.45×10^{20} PoT collected before March 11 earthquake is underway
  - expected sensitivity better than the current MINOS/CHOOZ limit

Extra slides

Analysis concept



- # of observed events @ SK:

  $N\nu e^{SK} = P(\nu_\mu \rightarrow \nu_e) \times \Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ interaction})$

- $\Phi^{SK}(\nu_\mu) \times \sigma(\nu \text{ int.}) = R(SK/ND) \times \Phi^{ND}(\nu_\mu) \times \sigma(\nu \text{ int.})$

  $= R(SK/ND) \times N\nu_\mu^{ND}$ ← ND measurement.

- $R(SK/ND)$: Far to Near flux extrapolation.
  - Targeting condition: Measured by proton beam monitors.
  - p_π, θ_π distribution : Measured by CERN NA61

"Beam MC"

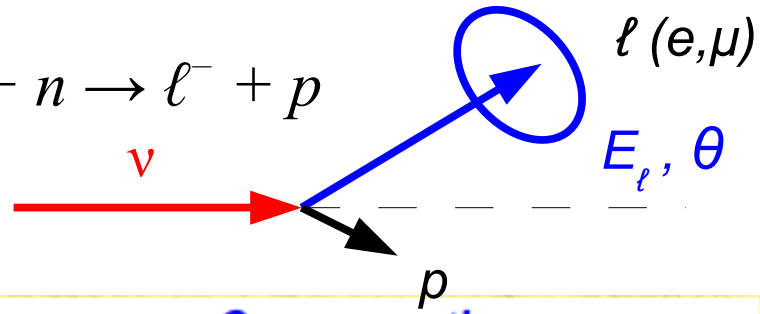
E_ν measurement

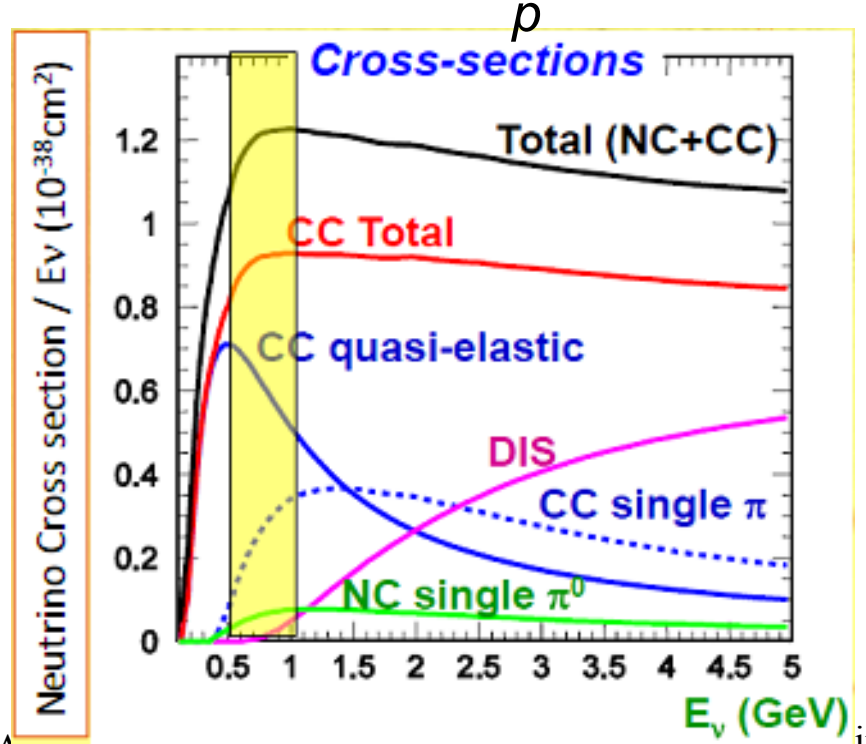
Charge Current Quasi-elastic interaction dominates at the T2K energy

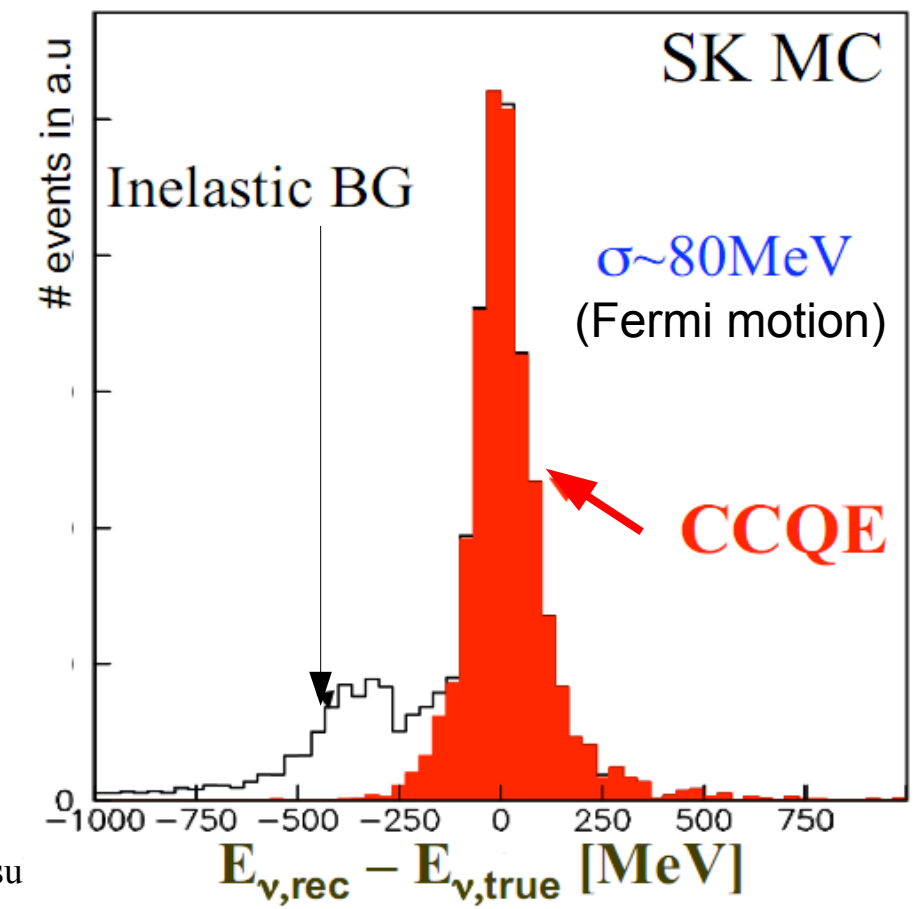
- E_ν can be reconstructed from the energy and angle of the charged lepton

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

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

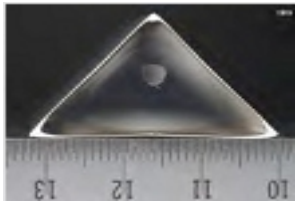




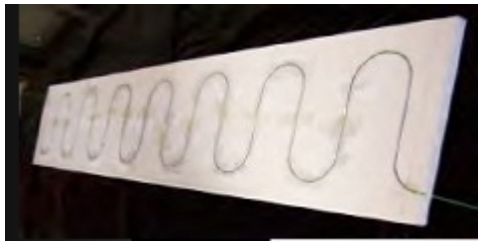


ND280: off-axis near detector

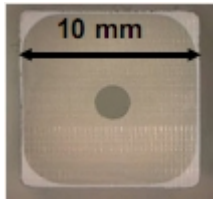
Pi0 detector (P0D): target
40 x-y scintillator planes
(~10k scint. bars)
Middle: scint+H_2O bags (11t)
Front/back: calorimeter
(veto and γ catcher)
Pb+Scint (6.4t)

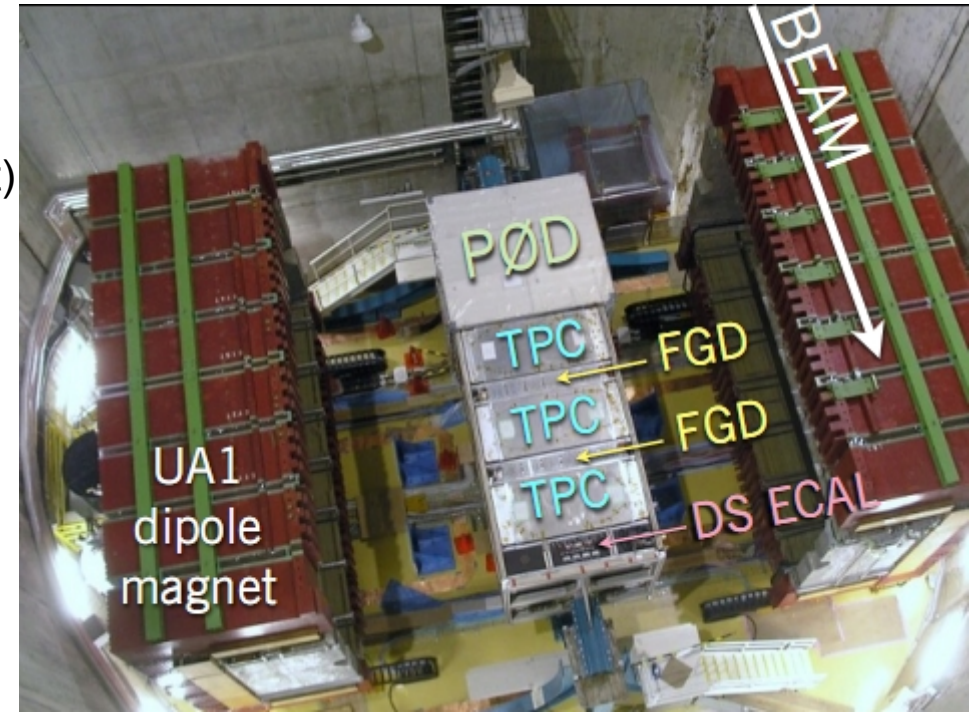


SMRD: μ range, veto
cosmic trigger
~2k scint. counters
(87x17x0.7 cm3)

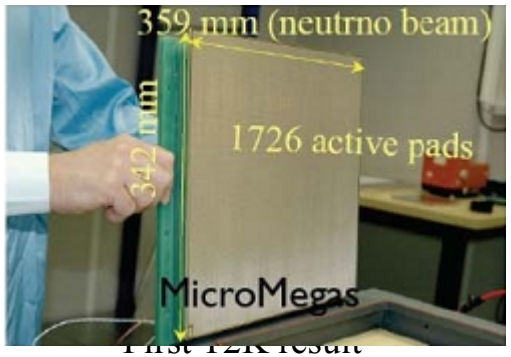


Fine Grained Detectors (FGD):
x-y scintillator planes
(~8.4k scint. bars)
+ H_2O (in FGD2)



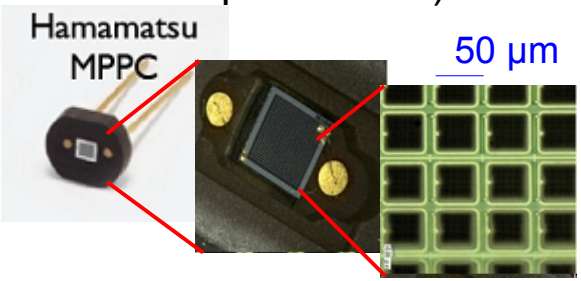


Time Projection Chambers (TPC):
wireless readout with MicroMegas
(7x10mm^2 pads) ~124k channels
5σ e/μ separation, $\sigma_p/p < 10\%$

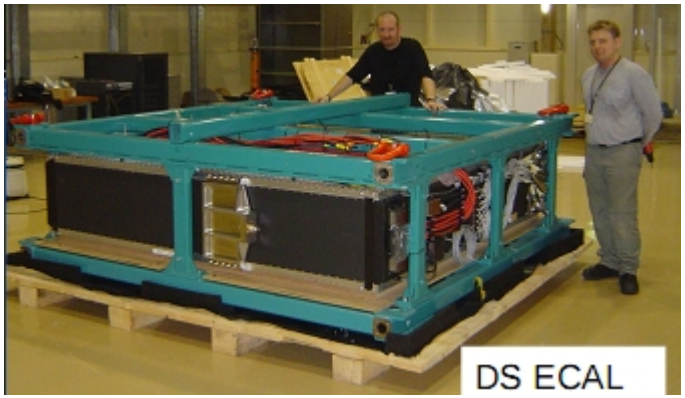


First T2K result

Scintillator detectors read out
via WLS fiber coupled to
Si MPPC (667 pixel
avalanche photodiode)



ECal: x-y fine grained
Pb+Scint. (4x1 cm^2)
~21k scint. bars (total)
$\sigma E/E \sim 7.5\%/\sqrt{E}$



SK systematics

- SK selection systematic uncertainties – estimated using cosmic-ray, muons, atmospheric neutrino, and hybrid π0 samples

Error source	Signal	Background
Normalization	1.4 %	1.4%
Energy scale	0.3	0.5
Ring counting	3.9	8.4
Muon PID		1.0
Electron PID	3.8	8.1
POLfit mass cut	5.1	8.7
Decay electron finding	0.1	0.3
π^0 rejection		5.9
Total:	7.6%	15.8%

Beam systematics

- Uncertainties in the neutrino flux prediction

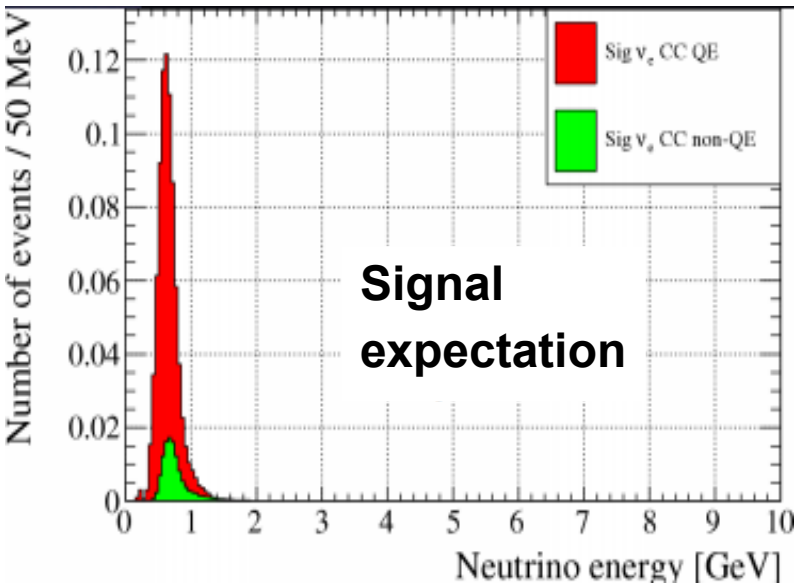
Source	Uncertainty	Change at Peak	Max Change(<3GeV)
Pion Multiplicity	20%	16%	22%
Kaon Multiplicity	20-25%	1%	20%
Prod. Cross Sections	10-50%	7%	8%
Proton Beam	0.5mm, 0.3mrad	3%	9%
ν Beam Direction	0.44mrad	1%	8%
Target Alignment	1.3mrad	<1%	1%
Horn Alignment	1mm	1%	3%
Horn Current	5kA	2%	2%
Horn Field Asym,	1.25%	0.5%	1%

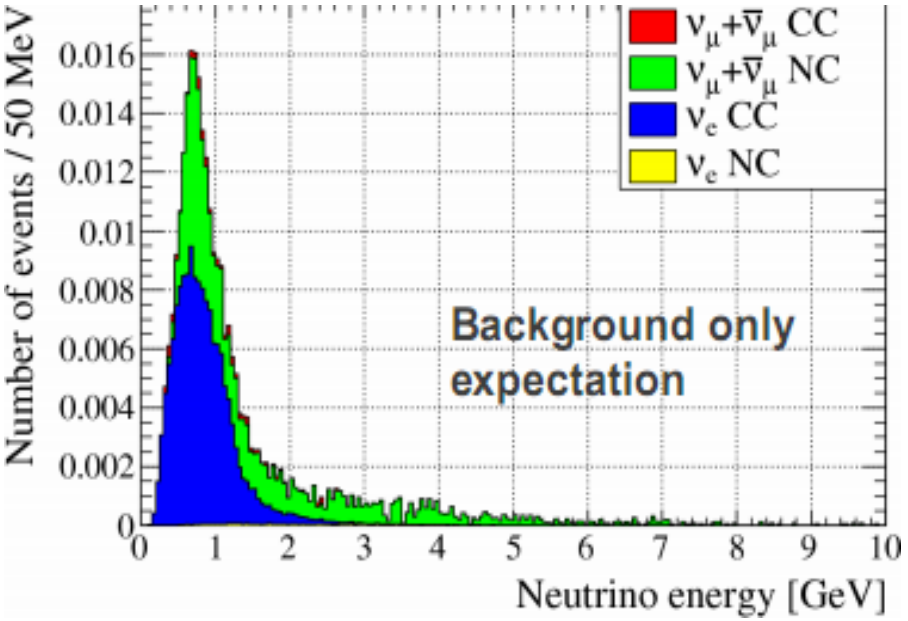
Neutrino model systematics

- Variations of NEUT MC parameters

Source	Central Value	Variations
M_A^{QE} [(GeV/c)^2]	1.21	± 0.2
M_V^{QE} [(GeV/c)^2]	0.84	± 0.1
M_A^{RES} [(GeV/c)^2]	1.21	± 0.2
M_V^{RES} [(GeV/c)^2]	0.84	± 0.1
M_A^{COH} [(GeV/c)^2]	1.0	± 0.5
CCQE p_F [MeV/c]	225	± 25
CCQE E_B ^{16}O [MeV]	26.6	$+23.2$
CCQE κ	1.00	$+0.007$
DIS Bodek-Yang Corr.	on	off
$^{\dagger}\pi$: absorption		$^{+60}_{-40}\%$
$^{\dagger}\pi$: inelastic		$^{+60}_{-40}\%$
$^{\dagger}\pi$: charge exchange		$\pm 60\%$
$^{\dagger}\pi$: π production		$\pm 50\%$
Δ absorption	20%	$\pm 20\%$
π/Δ abs. $\rightarrow$ nN	off	on

Expected ν_e events

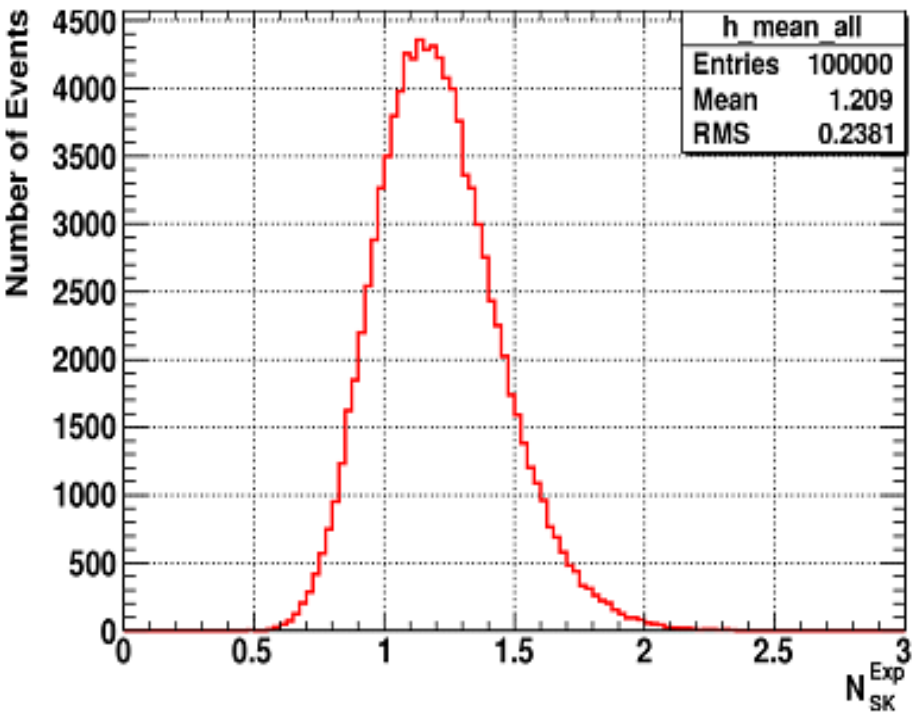




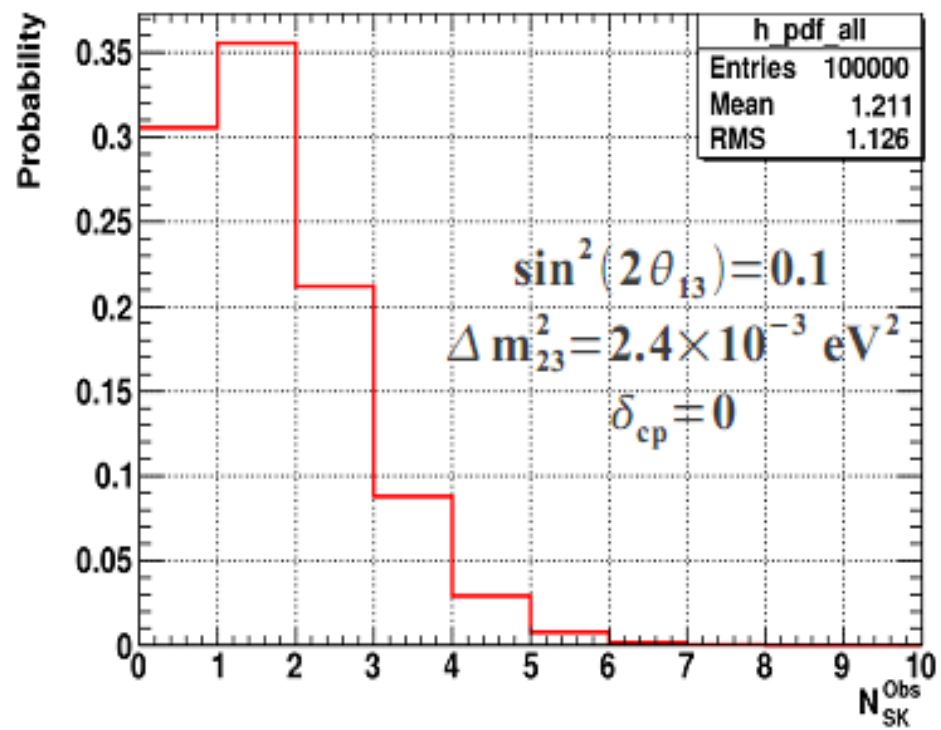
$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$

Probability distributions

- Example distributions generated with toy MC at a specific oscillation point



Number of expected SK events (signal + backg) with systematic uncertainties included



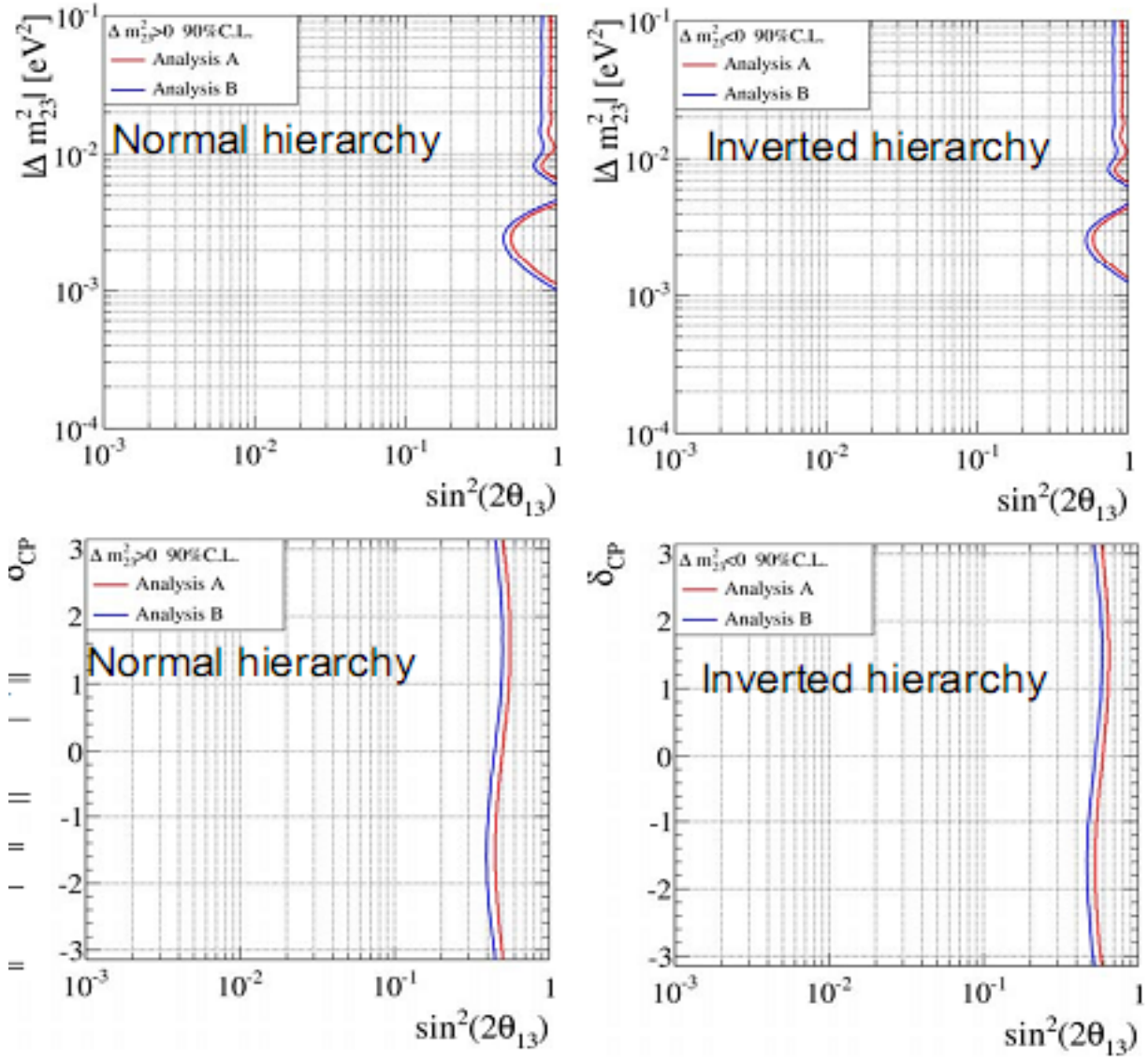
Probability of observing N events at SK (signal + backg) after statistical fluctuation

ν_e oscillation limits

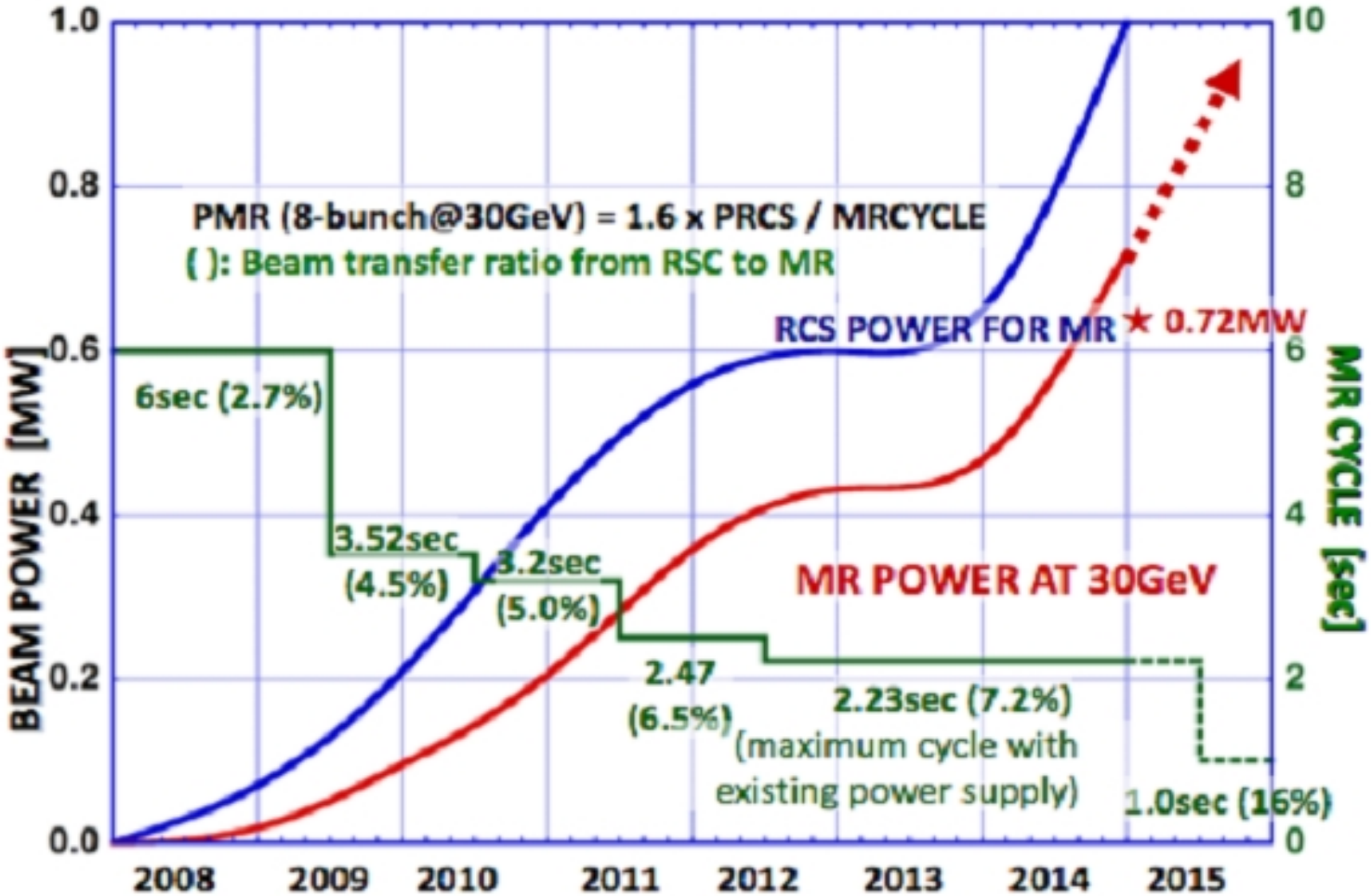
T2K preliminary

A: Feldman-Cousins

B: Classical one-sided limit



Accelerator power

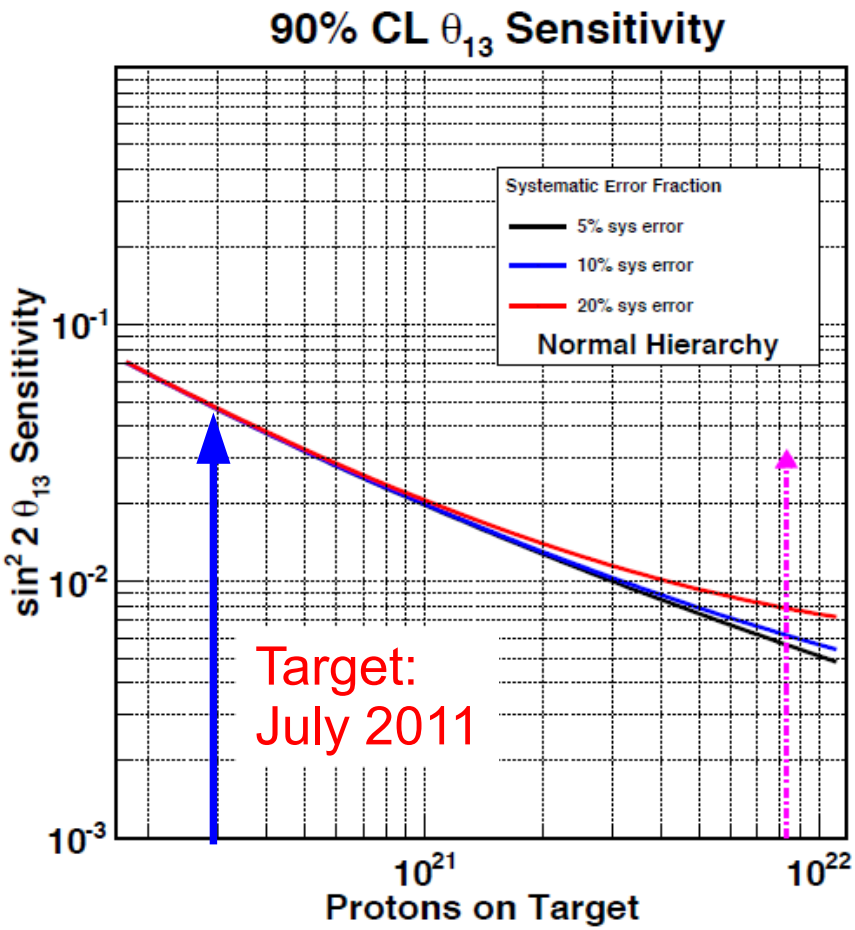


Ultimate sensitivity

- ν_e appearance:

$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)

5 x 0.75 MW x 10^7s (8.3 x 10^{21} PoT)

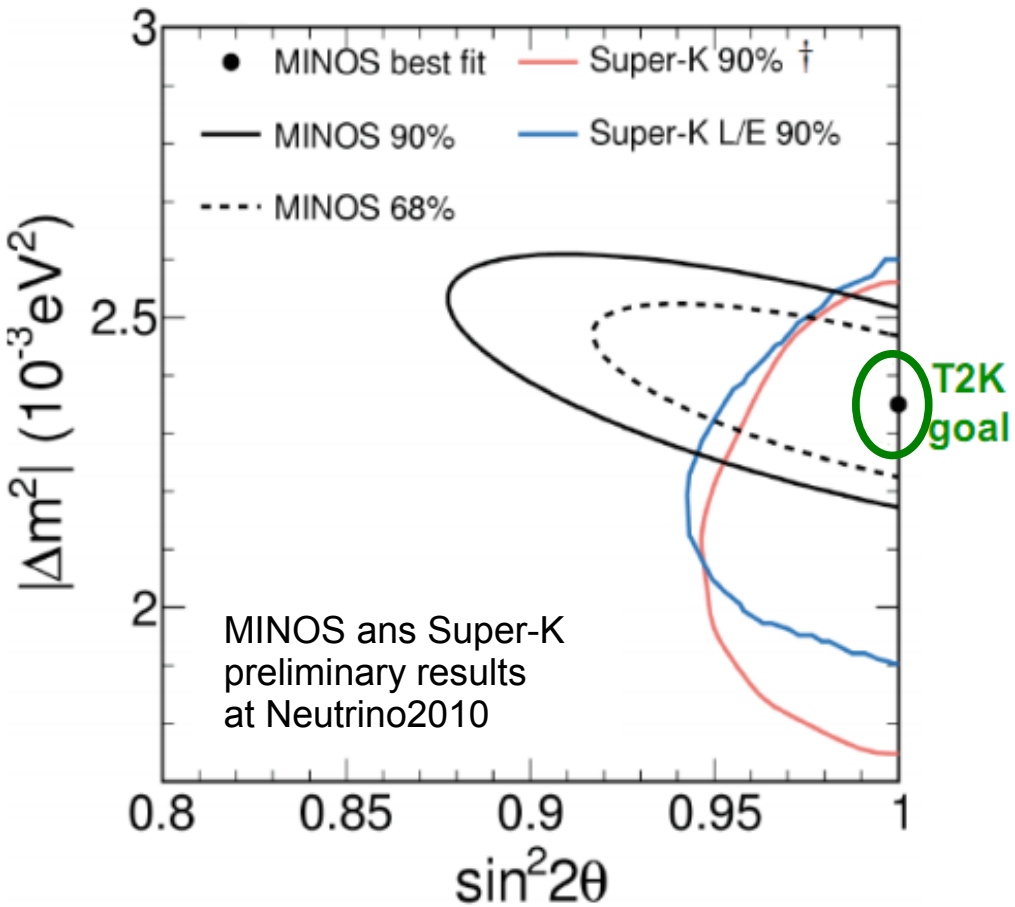


(Δm^2_{23}=2.4x10^{-3} eV^2, δ_{CP}= 0)

- ν_μ disappearance:

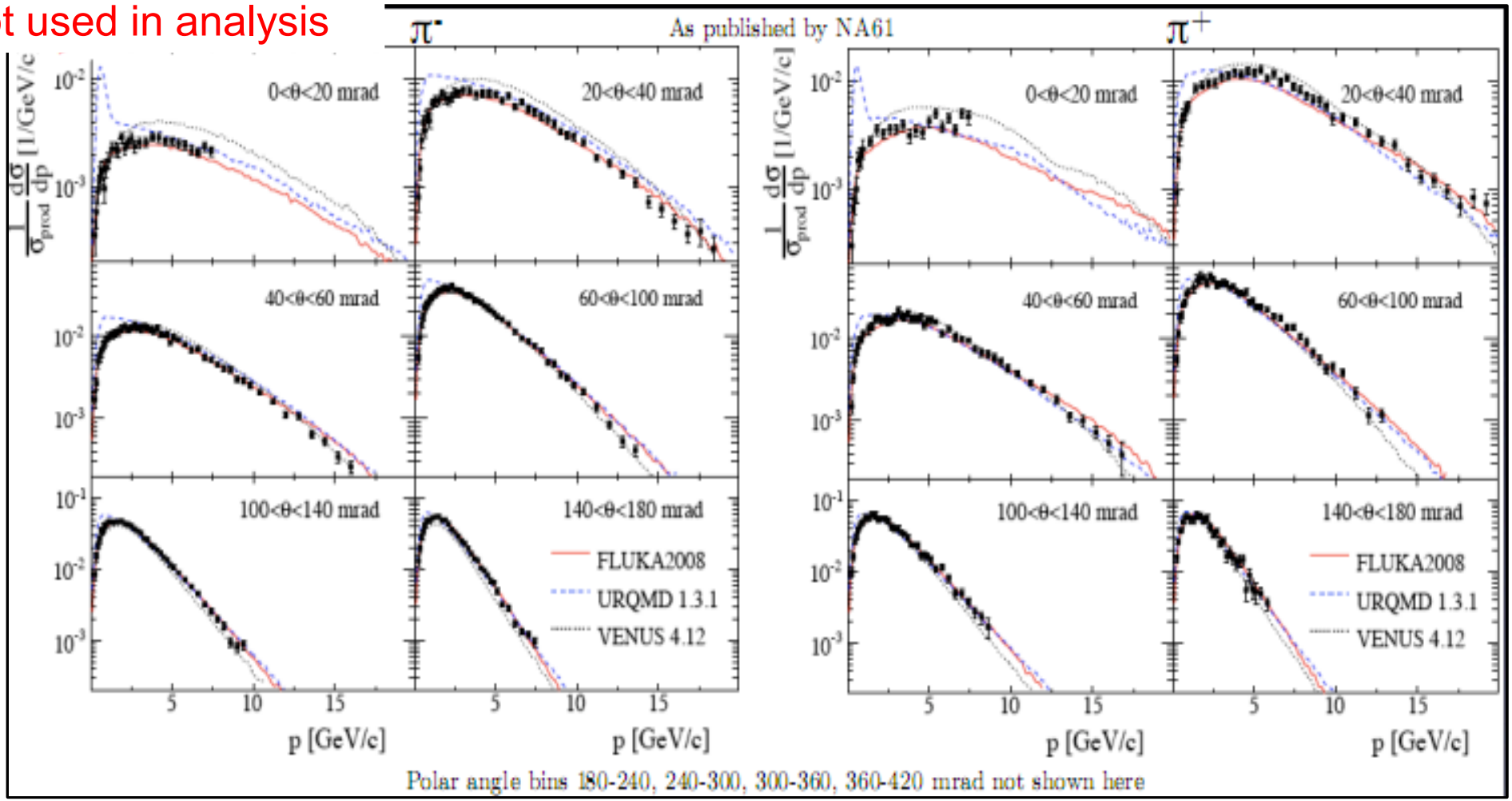
$\delta(\sin^2 2\theta_{23}) \approx 0.01$ & $\delta(\Delta m^2_{23}) < 1\times10^{-4}$ eV^2 (90% C.L.)

5 x 0.75 MW x 10^7s (8.3 x 10^{21} PoT)



New NA61/Shine results

Pre-print: arXiv:1102.0983 (hep-ex) submitted to Phys. Rev. C

- estimated systematic error ~6%

Not used in analysis