# T2K Results and Future Plans


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on behalf of the T2K Collaboration



XIII$^{th}$ International Workshop on Neutrino Factories, Super beams and Beta beams

CERN - 1$^{st}$, 5$^{th}$ and 6$^{th}$ Aug'11, UNIGE - 2$^{nd}$ - 4$^{th}$ Aug'11

# Outline

- **The T2K experiment**
  - Experimental set-up
  - Detectors
  - Performance

Accepted for publication in Nucl. Instrum. Methods arXiv:1106.1238v2 [physics.ins-det]

- **$\nu_e$ appearance analysis**
  - Analysis method
  - Results

Phys. Rev. Lett. 107, 041801 (2011) arXiv:1106.2822v1 [hep-ex]

- **$\nu_\mu$ disappearance analysis**
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Preliminary Results

- **Future plans**

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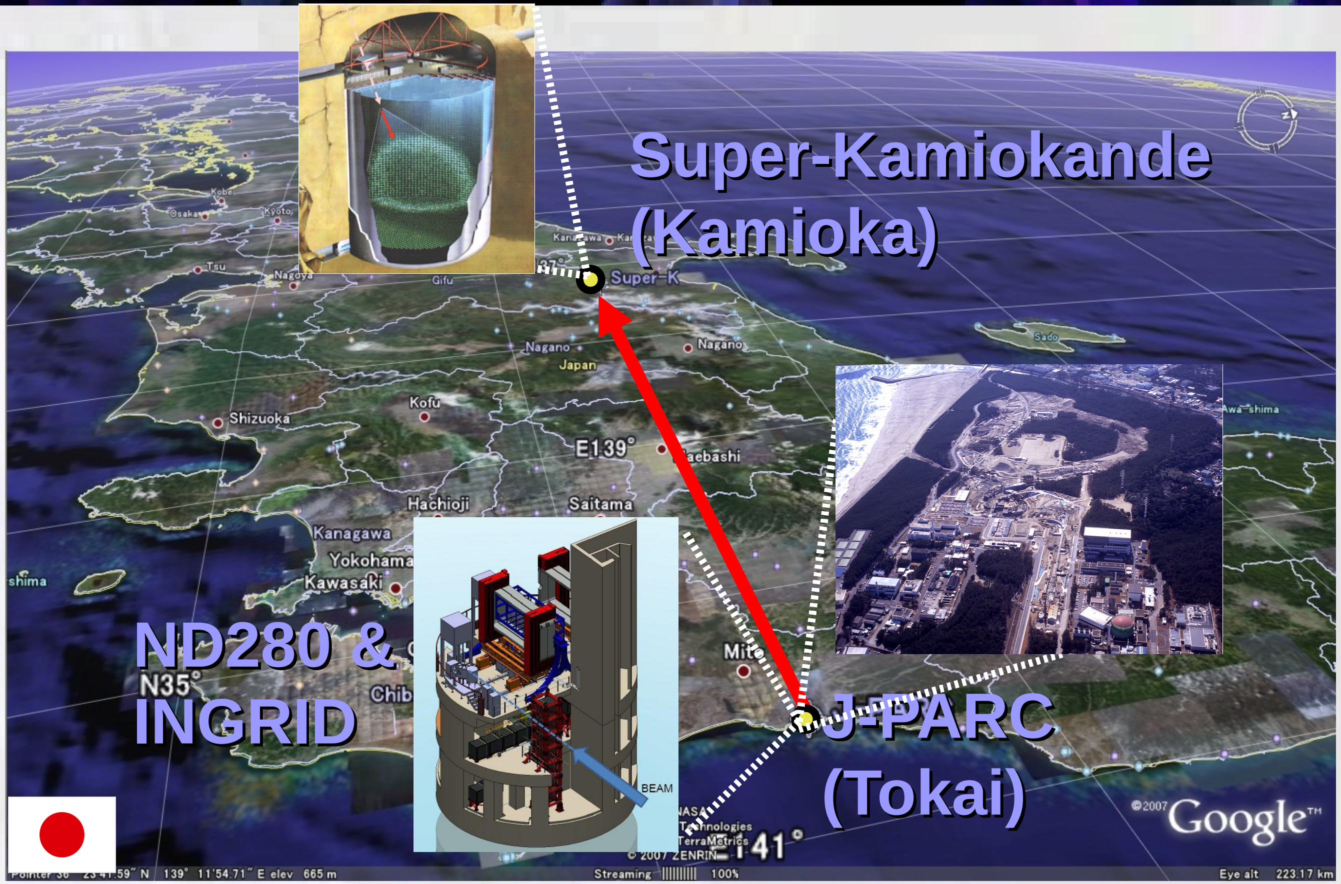
# The T2K Experiment




- Long baseline neutrino oscillation experiment (Tokai 2 Kamioka, T2K):
  - Near detectors: ND280 and INGRID (280m)
  - Far detector: SuperKamiokande (295Km)
- High intensity $\nu_\mu$ beam produced at J-PARC (Tokai)
- Main physics goals:
  - Discovery of $\nu_e$ appearance $\rightarrow$ determine $\theta_{13}$
  - Precise measurement of $\nu_\mu$ disappearance $\rightarrow$ $\theta_{23}$, $\Delta m^2_{23}$

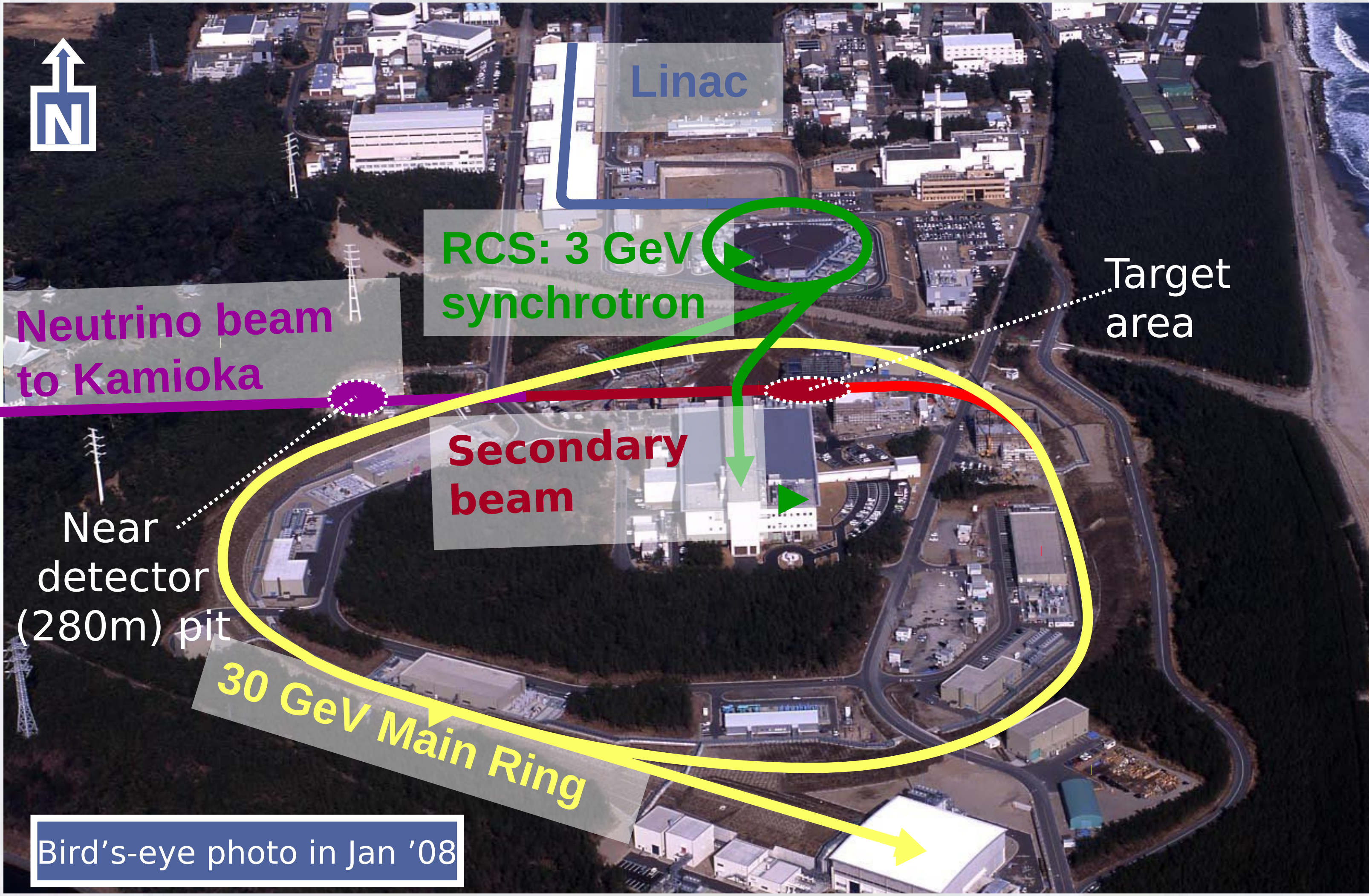
# J-PARC Accelerator

J-PARC: Japan Proton Accelerator Research Complex

Joint project of KEK & Japan Atomic Energy Agency (JAEA)

Located in Tokai-Mura

Construction: JFY 2001-2008




Accelerator design/performance

- Design goal of 750 kW - Reached 145 kW before earthquake
- 30 GeV protons to neutrino beamline

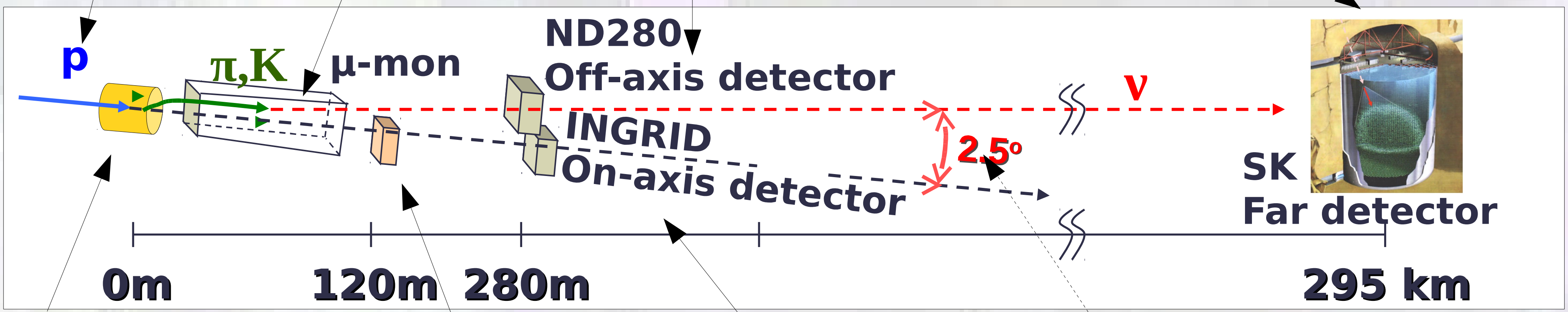
# T2K Experimental Overview

30 GeV proton beam from J-PARC

Pions, kaons, muons decay in 96m decay volume.

At 280 m, off-axis near detector: ND280 detector measures spectra for various neutrino interactions

Off-axis far detector at 295 km: Super Kamiokande (SK) water Cherenkov detector measures oscillated flux




Beam on graphite target. Three magnetic horns focus positively charged hadrons.

MUMON measures muons from pion decay.

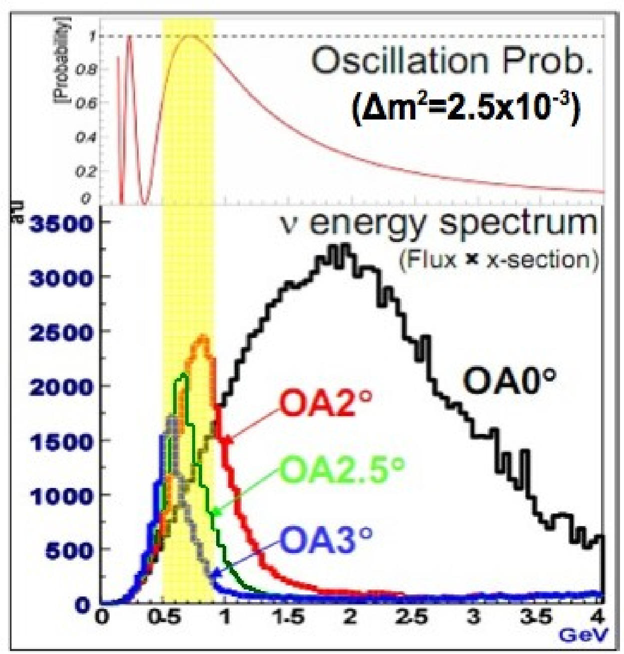
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Beam energy at osc. max: $E_\nu$ = 0.6 GeV

(based on L=295km and $\Delta m^2_{32}$)

Off-axis = narrow band beam

- Increase statistics @ osc. max
- Less feed-down from background at high energy tail



# INGRID on-axis near detector (280m)

See “The Status of the T2K Near Detectors”
Presented by Neil McCauley
WG2 Neutrino Cross-Sections and Detectors
Date, time: Aug 3, 14:25

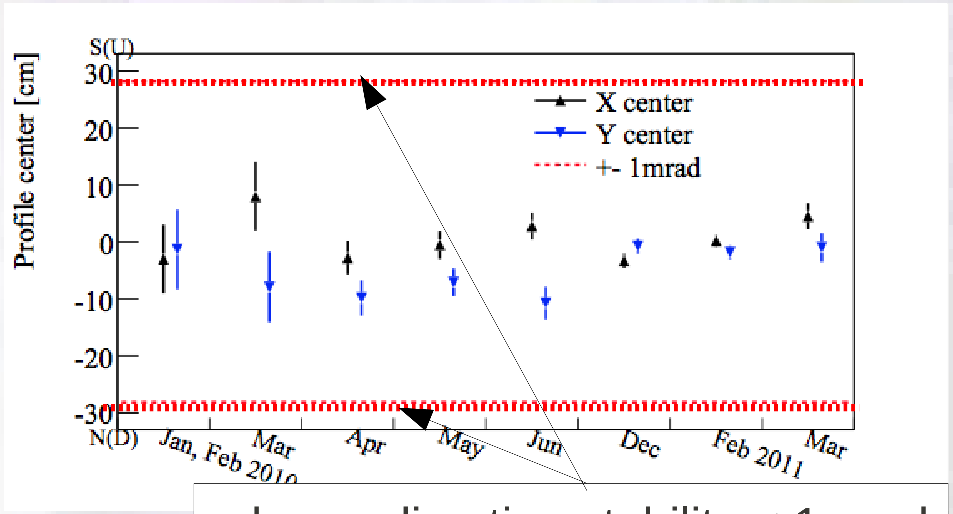
INGRID (on-axis detector 280m from target):

•Designed to measure neutrino interactions & beam profile (beam intensity, direction &stability)

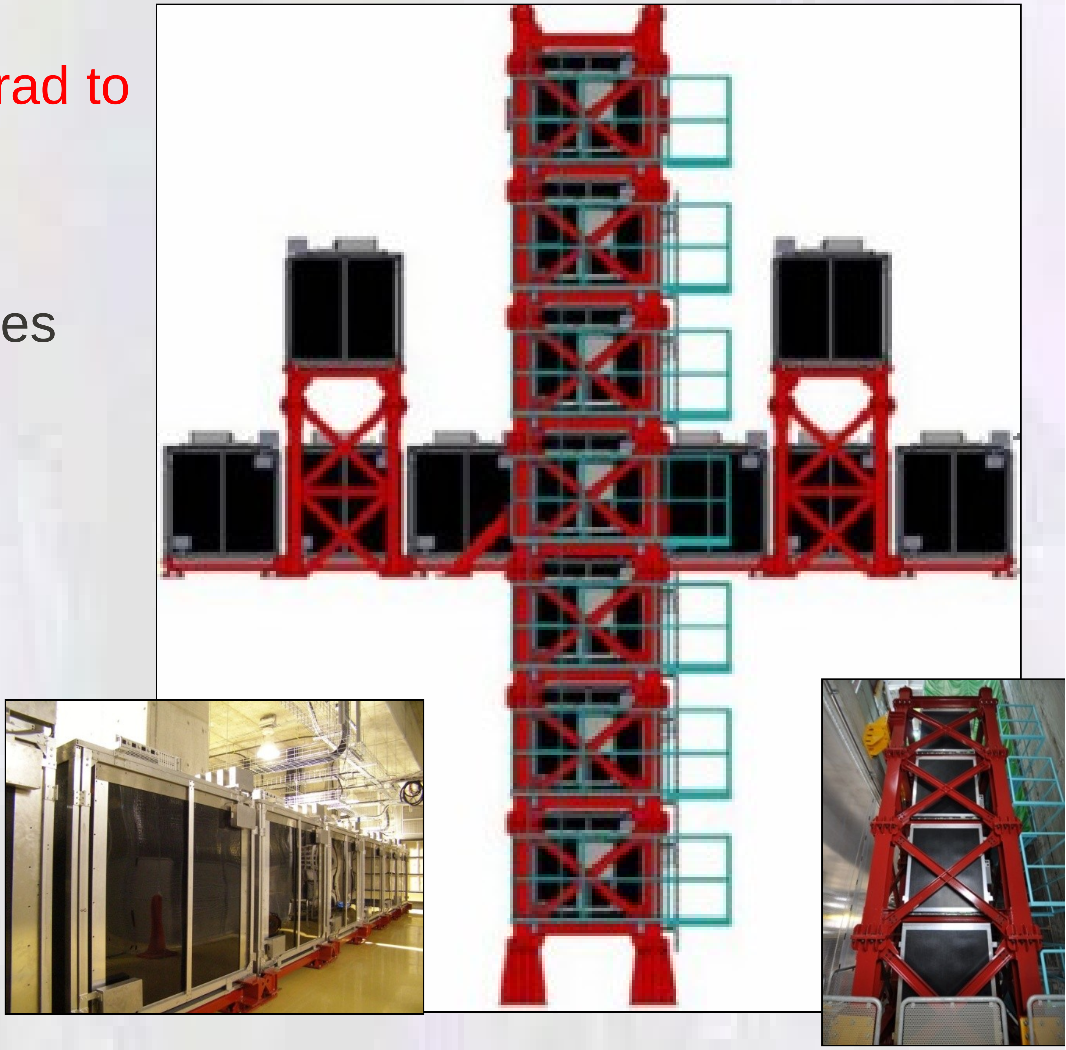
•Stability of beam direction requested <1mrad to keep the peak energy at SK stable δE<2%

•7 + 7 modules (iron/scintillator planes sandwiches) in cross shape (central modules on-axis) + 3 extra modules.

**Stability of ν beam direction well within 1 mrad:**




ν beam direction stability < 1mrad



# ND280 off-axis near detector (280m)

General purpose detector to measure: CC$\nu_\mu$ events (normalization, $E_\nu$ spectrum), CC$\nu_e$ events (background to $\nu_e$ appearance), general neutrino interactions.

Inner tracker: Used in ND280 analyses in this talk

**2 FGDs Fine Grained Detectors:**
Thin, wide scintillator planes.
**Provides active target mass.**
Optimized for p recoil detection.

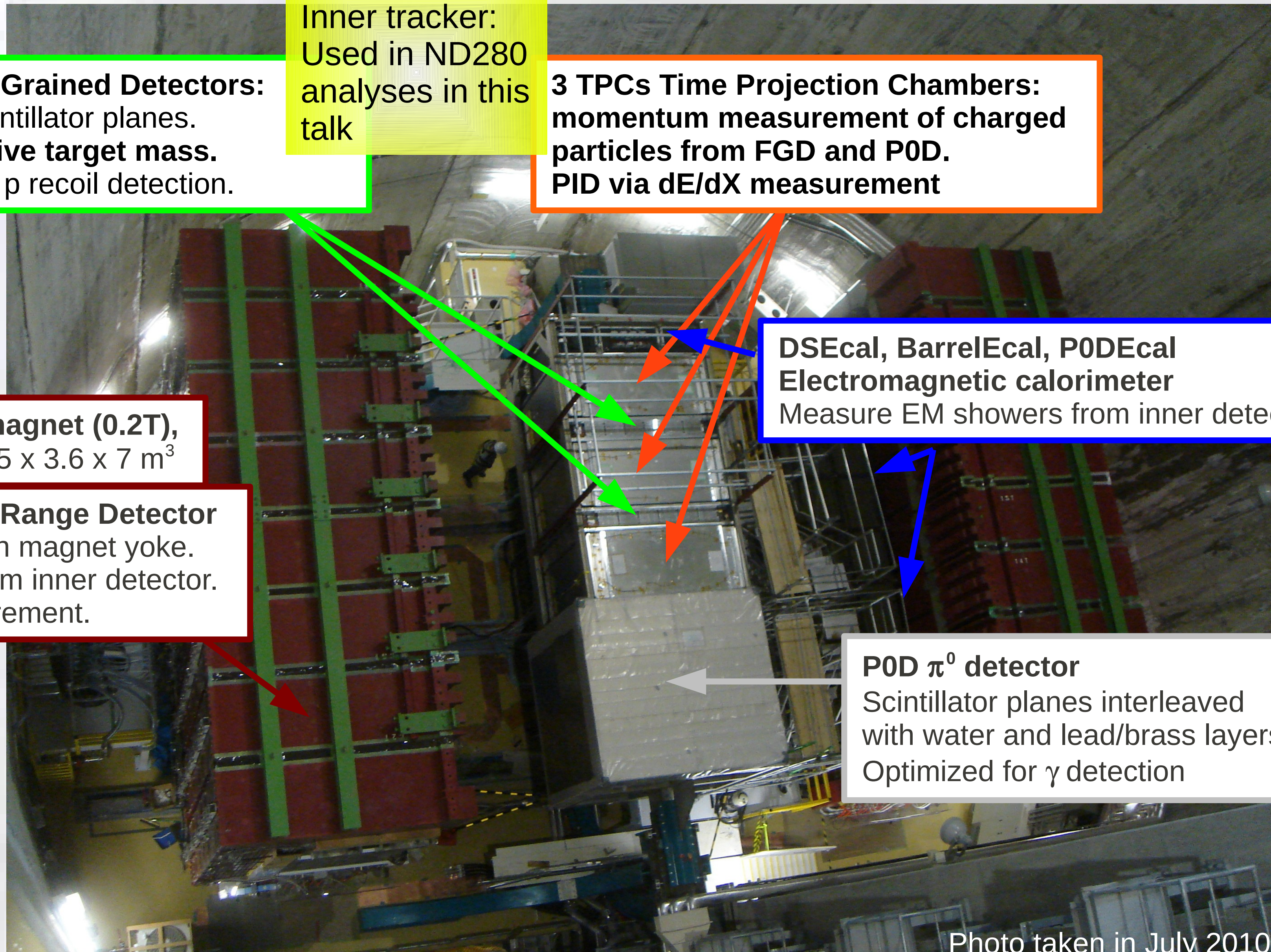
**3 TPCs Time Projection Chambers:**
**momentum measurement of charged particles from FGD and P0D.**
**PID via dE/dX measurement**

**DSEcal, BarrelEcal, P0DEcal**
**Electromagnetic calorimeter**
Measure EM showers from inner detector

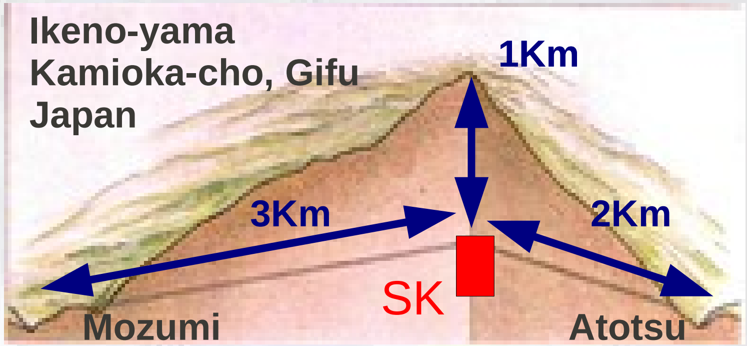
**UA1/NOMAD magnet (0.2T),**
Inner volume 3.5 x 3.6 x 7 $m^3$

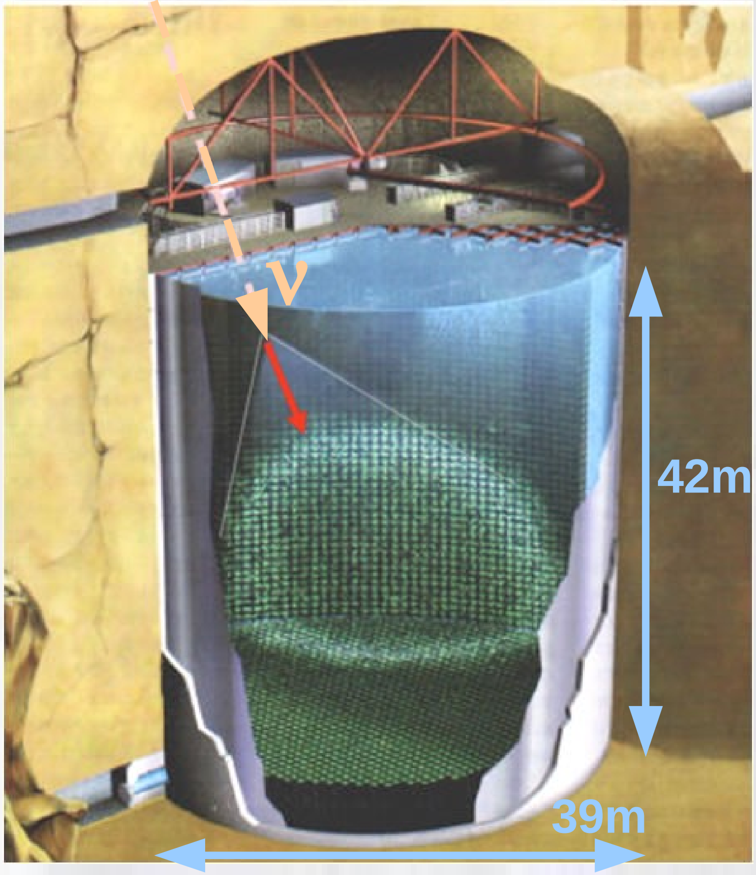
**SMRD Side Muon Range Detector**
Scintillator planes in magnet yoke.
Detector muons from inner detector.
Momentum measurement.

**P0D $\pi^0$ detector**
Scintillator planes interleaved with water and lead/brass layers
Optimized for $\gamma$ detection

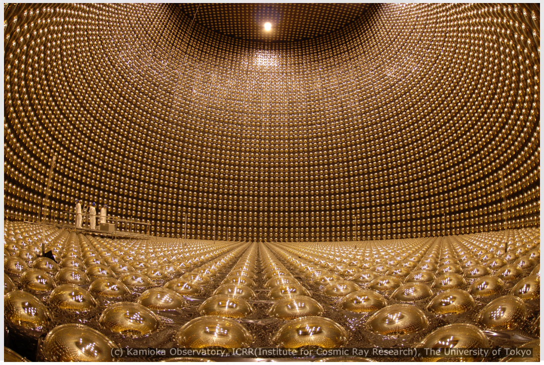


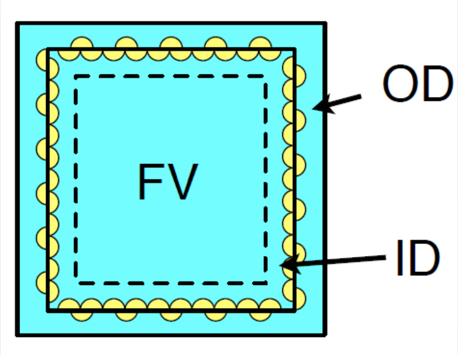
# Super Kamiokande off-axis far detector




- Water Cherenkov detector operational since 1996.
- Good electron/muon separation.
- Signal events are charged-current quasi-elastic interactions on $^{16}O$ nuclei.
- Total volume: 50kton (Fiducial volume: 22.5kton)
- 11129 20" PMTs in inner detector (ID), 40% photon coverage.
- 1885 8" PMTs in outer detector (OD) facing outward: veto cosmics, radioactivity, exiting events.
- T2K event trigger by accelerator timing sent online



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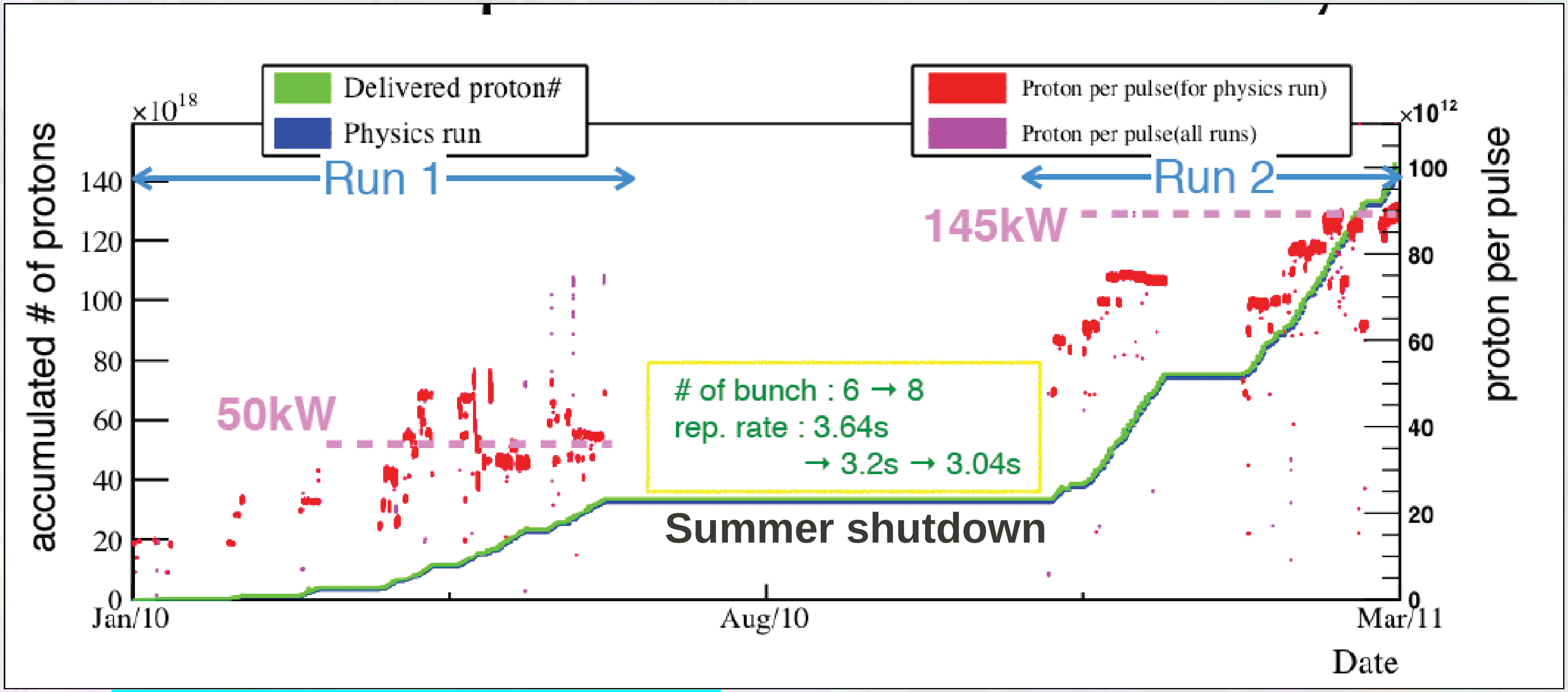
# T2K Dataset




Run1 (Jan-Jun 2010)
$3.23 \times 10^{19}$ POT for analysis
50 kW stable beam operation

Run2 (Nov 2010 - Mar 2011)
$11.08 \times 10^{19}$ POT for analysis
145 kW stable beam operation

- Started physics data taking Jan, 2010.
- Stable beam operation at 145kW achieved.
- Run1+Run2 datasets = $1.43 \times 10^{20}$ POT (~70 [kW x $10^7$s]) delivered.
- All data taken was analyzed.

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Preliminary Results

# T2K Oscillation Analysis Method

**Flux Prediction**
- Proton beam measurements
- Hadron production data

**ND280 Measurement**
- Inclusive CC $\nu_\mu$ measurement
- Output: $R_\mu^{ND,Data} / R_\mu^{ND,MC}$
- Cross-check: $N(\nu_e)/N(\nu_\mu)$

**Neutrino Cross Sections**
- Interaction Models
- External cross section data

**Super-Kamiokande Measurement**
- Select CC $\nu_\mu$ and $\nu_e$ candidates
- Compute $N_{MC}^{SK}$ w/o oscillations
- Adjust normalization with ND280:
- $N_{exp}^{SK} = (R_\mu^{ND,Data} / R_\mu^{ND,MC}) \times N_{MC}^{SK}$
- Compare with $N_{obs}^{SK}$ to evaluate oscillation parameters:
  - $\nu_e$ analysis: 1 bin (counting)
  - $\nu_\mu$ analysis: number of events and shape combined

# T2K Neutrino Flux and Modeling

**Flux Simulation:**

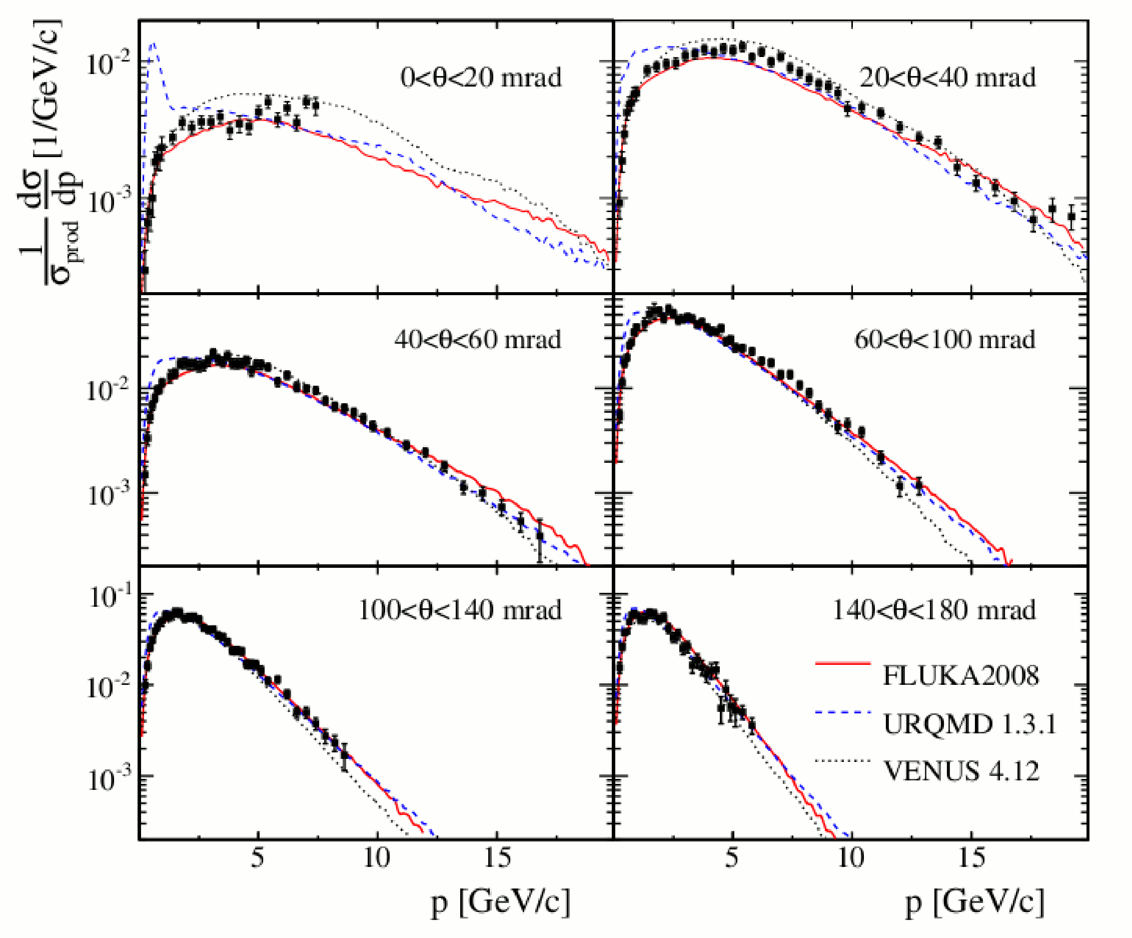
- Proton beam monitor measurements as inputs for actual beam profile & position

- Hadron production in target:
  - NA61 experimental (at CERN) data to model $\pi^{\pm}$ production – same proton energy and target material as T2K.
  - 5-10% systematic uncertainties on each NA61 point, 2.3% normalization factor
  - Kaon production, pions outside NA61 acceptance – model with FLUKA

- Out of target interactions, horn focusing, particle decays:
  - GEANT3 (GCALOR) simulation.
  - Interaction cross sections are tuned to existing external data

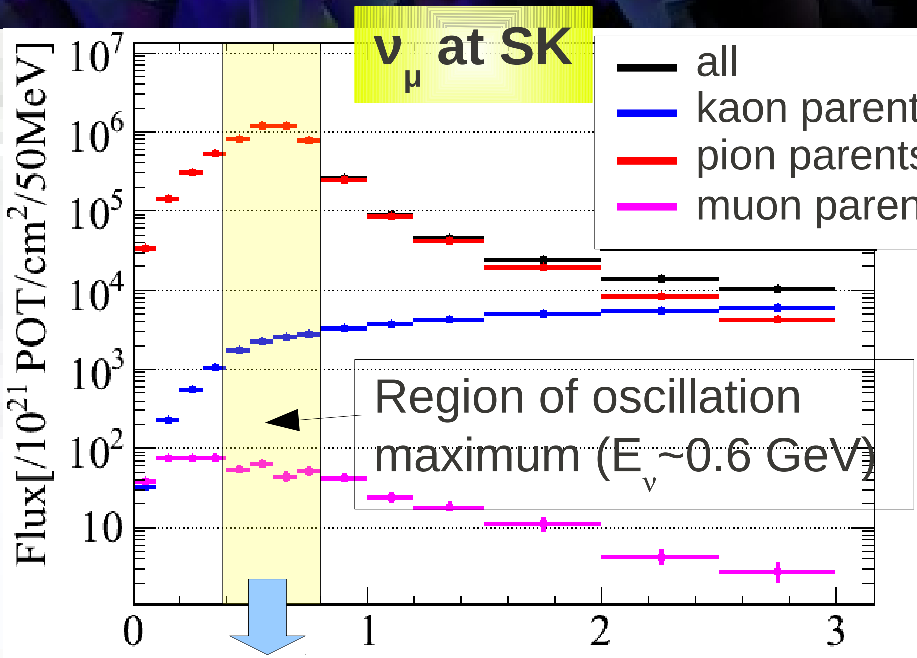
See “Predicting the Neutrino Flux at T2K”
Presented by Vyacheslav Galimov
WG2 Neutrino Cross-Sections and Detectors
Date, time: Aug 4, 15:05

NA61: Differential π production multiplicity in p+C @31GeV

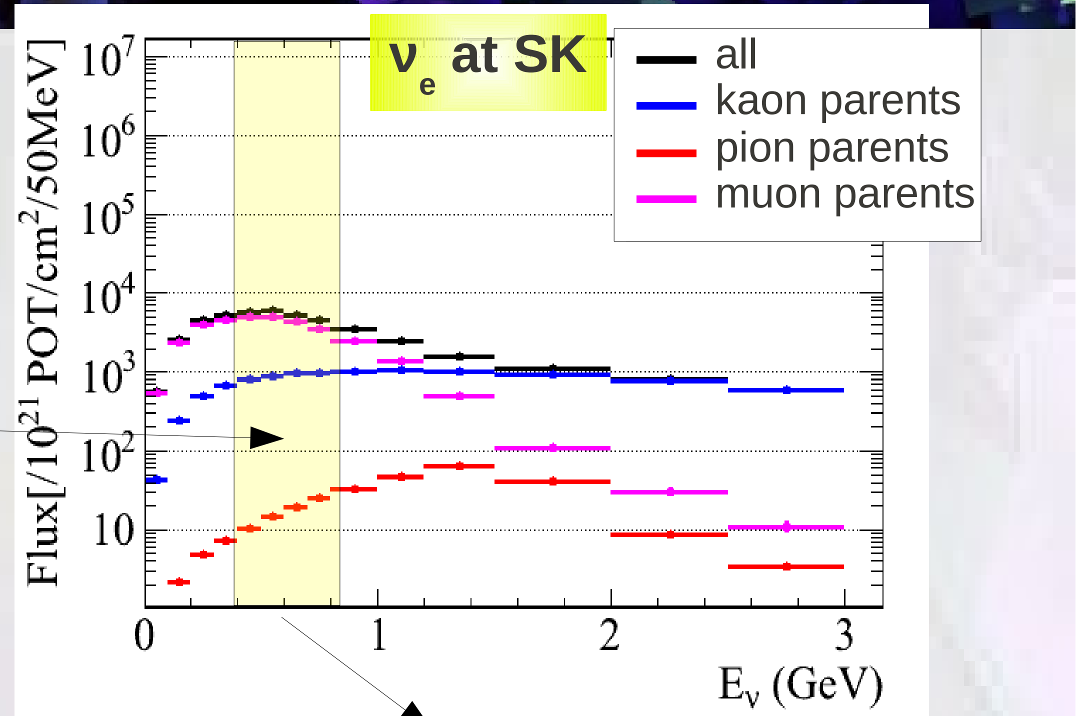



N.Abgrall et al., arXiv:1102.0983 [hep-ex] accepted by Phys.Rev.C (2011)

# T2K Neutrino Flux Prediction




$\nu_\mu$ flux mainly from $\pi$ decays




Total number of $\nu_\mu$ in ND280

Total number of $\nu_e$ in SK

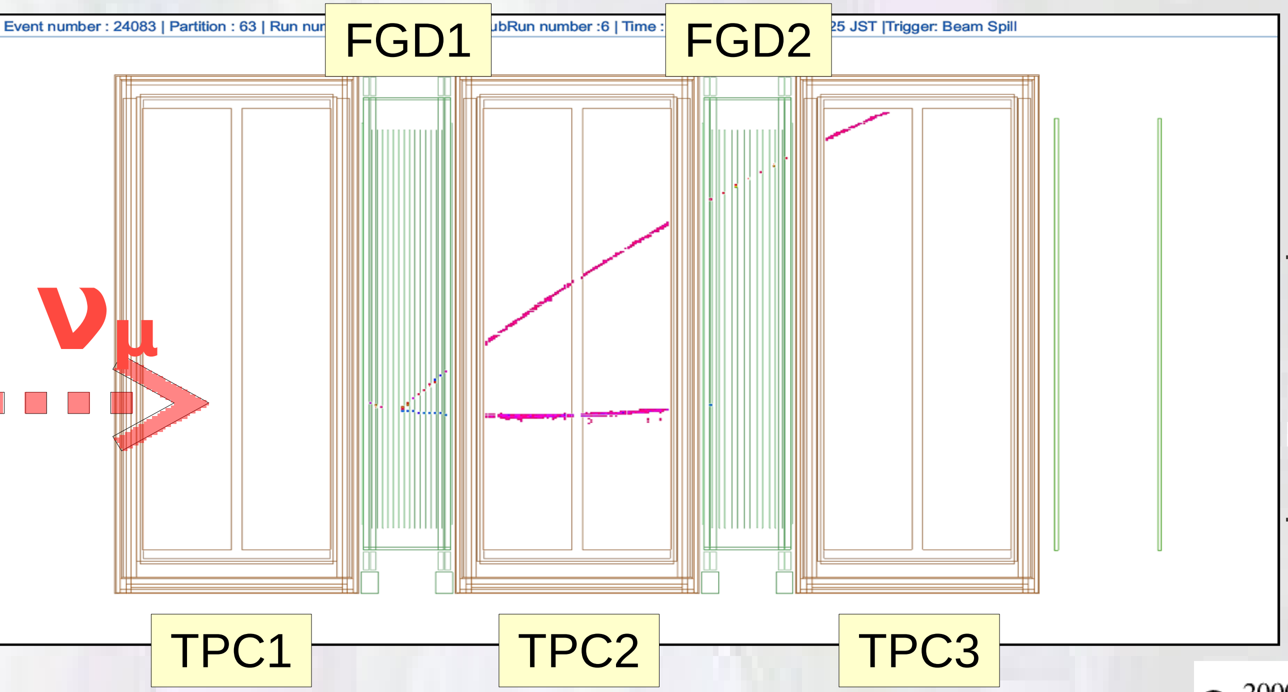
| Error source | $R_{ND}^{\mu,\,MC}$ | $N_{SK}^{MC}$ | $\frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$ |
|---|---|---|---|
| Pion production | 5.7% | 6.2% | 2.5% |
| Kaon production | 10.0% | 11.1% | 7.6% |
| Nucleon production | 5.9% | 6.6% | 1.4% |
| Production x-section | 7.7% | 6.9% | 0.7% |
| Proton beam position/profile | 2.2% | 0.0% | 2.2% |
| Beam direction measurement | 2.7% | 2.0% | 0.7% |
| Target alignment | 0.3% | 0.0% | 0.2% |
| Horn alignment | 0.6% | 0.5% | 0.1% |
| Horn abs. current | 0.5% | 0.7% | 0.3% |
| **Total** | **15.4%** | **16.1%** | **8.5%** |

- intrinsic $\nu_e$ flux (~1% of total):
  - mainly from $\mu$ decays:
    $\pi^+ \rightarrow \mu^+ (\rightarrow e^+ \, \nu_\mu \, \bar{\nu}_e) \nu_\mu$
  - NA61 pion measurement predicts the beam $\nu_e$ from the pion origin.

The uncertainty on the expected $\nu_e$ events at SK is significantly reduced when normalizing to the near detector

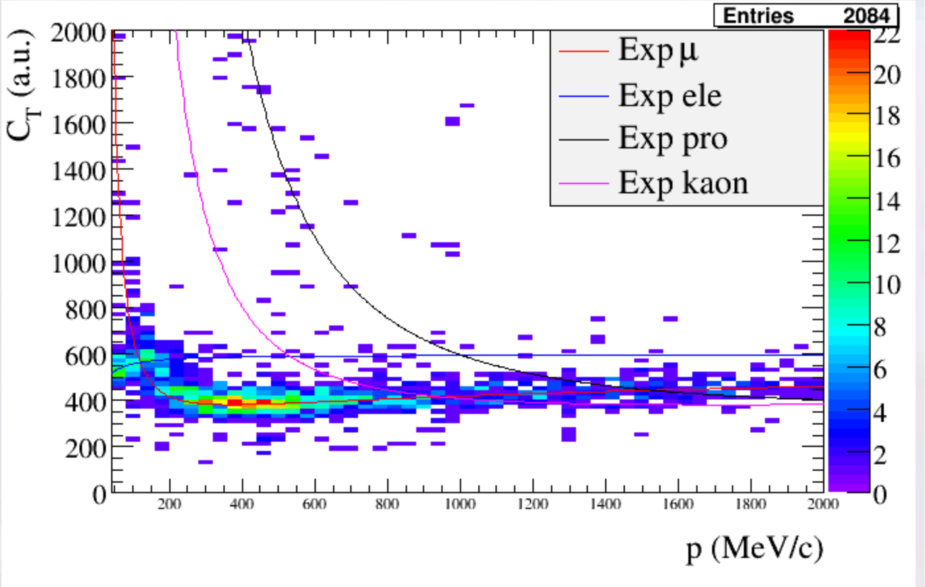
# Near Detector Analyses

- Measure inclusive CC$\nu_\mu$ event rate and $\nu_e$ beam component at the near off-axis detector ND280.




- Based on Run1 (2.9x10$^{19}$ POT)
- Select interactions in FGD producing at least 1 negative track in the downstream TPC → lepton candidates.
- Measure track momentum in the TPC.

dE/dx vs P (before TPC PID cut):



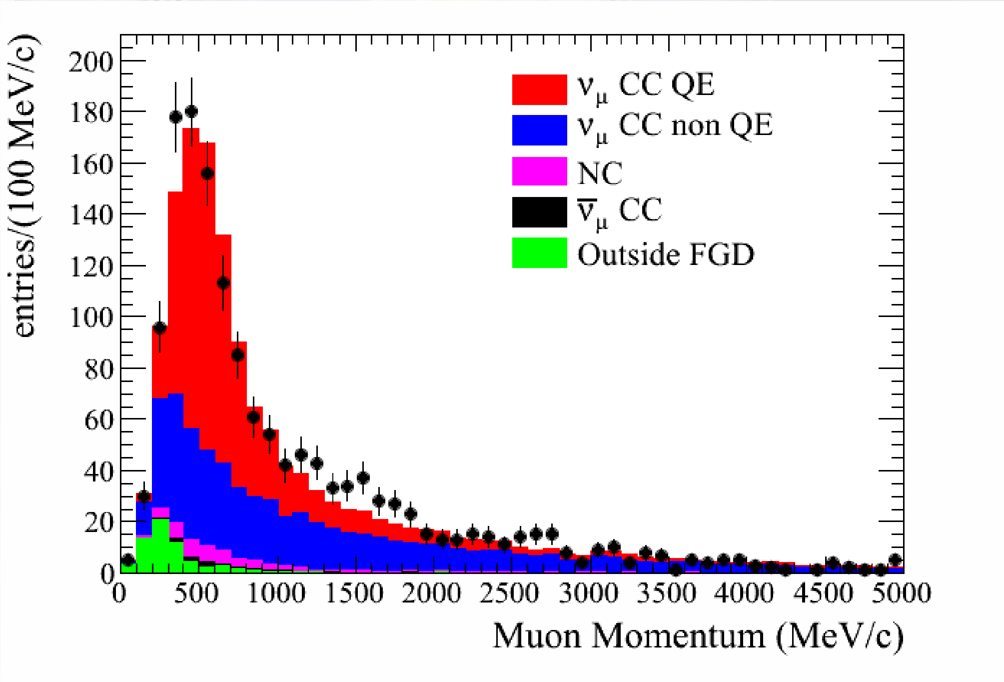

- Use TPC PID to select muons or electrons:

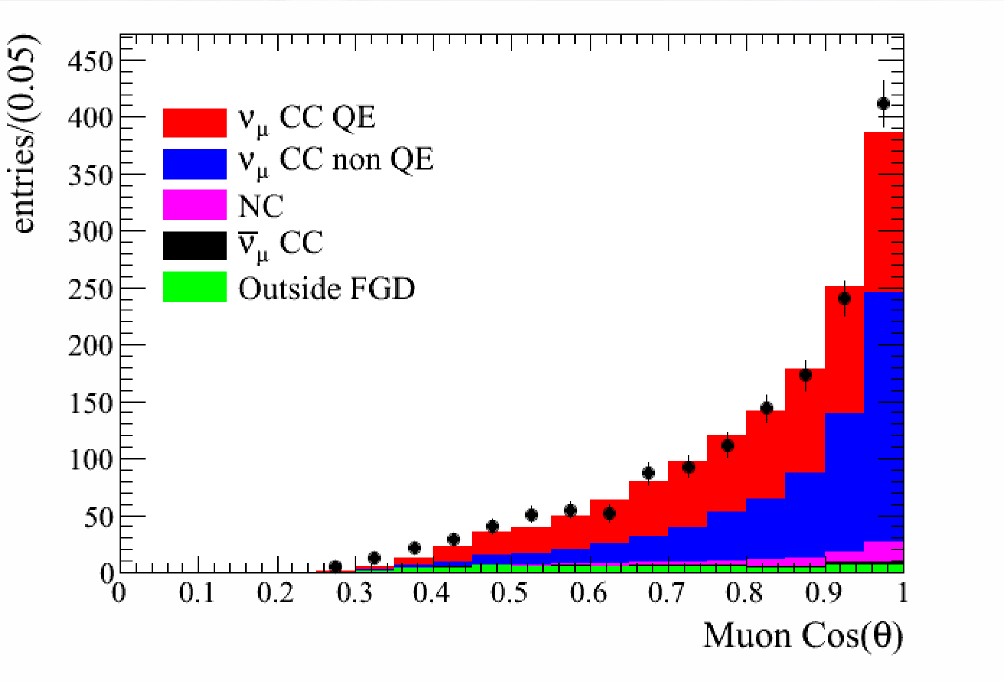
See "Neutrino Interaction Measurements Using the T2K Near Detectors"
Presented by Daniel Brooke-Roberge
WG2 Neutrino Cross-Sections and Detectors
Date, time: Aug 4, 15:05

# Inclusive CC$\nu_\mu$ analysis

- Selection of μ-like tracks requiring dE/dx in the TPC compatible with muons
- 90% purity and 38% efficiency in CC selection
- 1529 data events selected
- Good agreement between data and MC (NEUT)
- Dominant detector syst.: dE/dX pull width: 3.0%, TPC-FGD matching: 2.1%

POT normalized MC: NA61+FLUKA flux model, NEUT neutrino interaction model:




Ratio of the POT normalized rates of CC$\nu_\mu$ in data and MC:

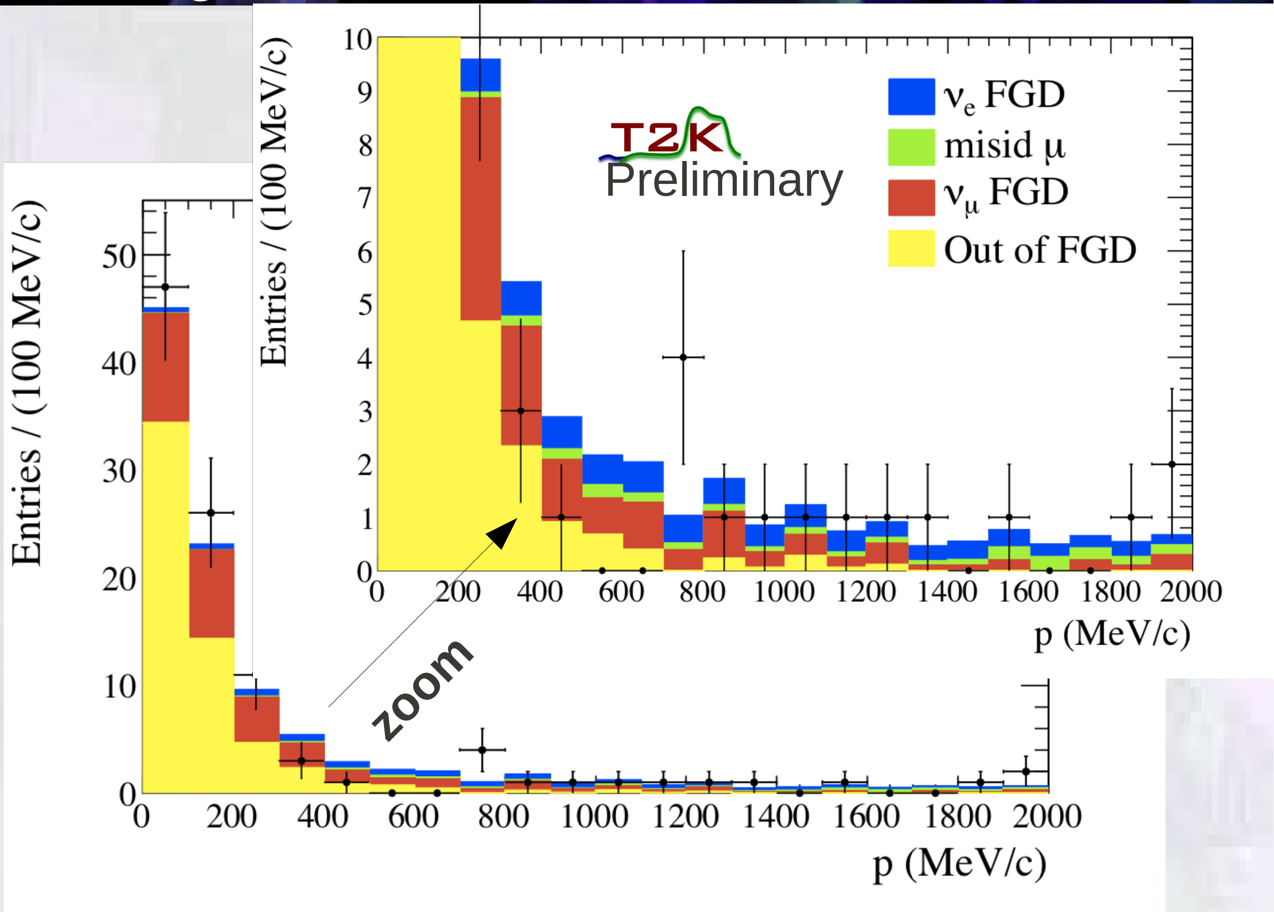
$$\frac{R_{ND}^{\nu\mu,DATA}}{R_{ND}^{\nu\mu,MC}} = 1.036 \pm 0.028\,(\text{stat.})\ ^{+0.044}_{-0.037}\,(\text{det. syst.}) \pm 0.038\,(\text{phys. syst.})$$

(neutrino interaction model)

Absolute cross section variation not included, but treated together with far detector in oscillation fit.

# Beam $\nu_e$ Analysis

- Beam $\nu_e$ main background to ($\nu_\mu \rightarrow \nu_e$) signal at SK
- Measured by selecting electrons via dE/dx in the TPC
- Background from mis-identified μ estimated from sand muons in data
- MC expectation for γ conversions constrained by control samples based on data




- Likelihood fit on electron momentum to measure number of observed $\nu_e$
- Ratio $\nu_e/\nu_\mu$ is:

$$R_{\nu e/\nu\mu} = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$$
$$< 2.0\% \text{ @ } 90\% \text{ C.L.}$$

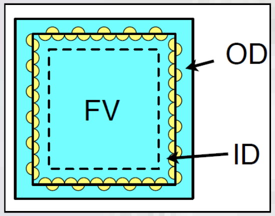
- Observed $\nu_e/\nu_\mu$ ratio $R_{\nu e/\nu\mu}$ at ND280 consistent with beam MC expectations

$$R^{data}_{\nu e/\nu\mu}/R^{MC}_{\nu e/\nu\mu} = 0.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$$

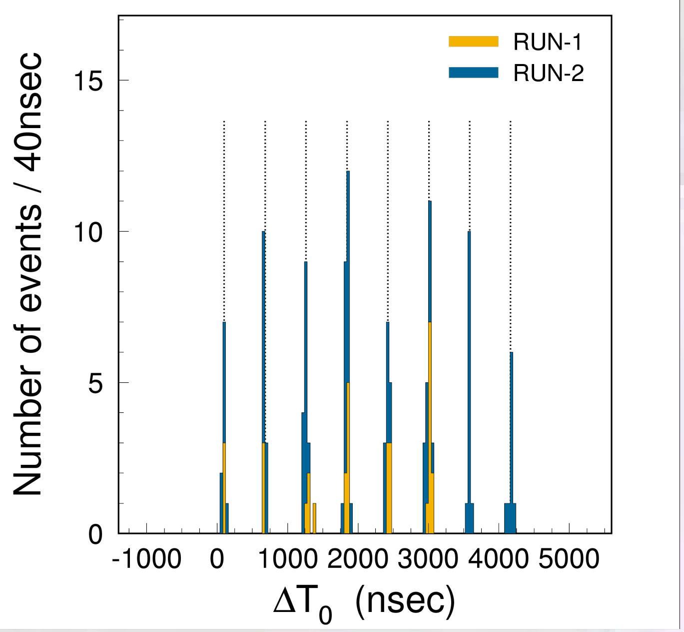
# T2K Far Detector Selection

Event selection for both $\nu_\mu$ and $\nu_e$:

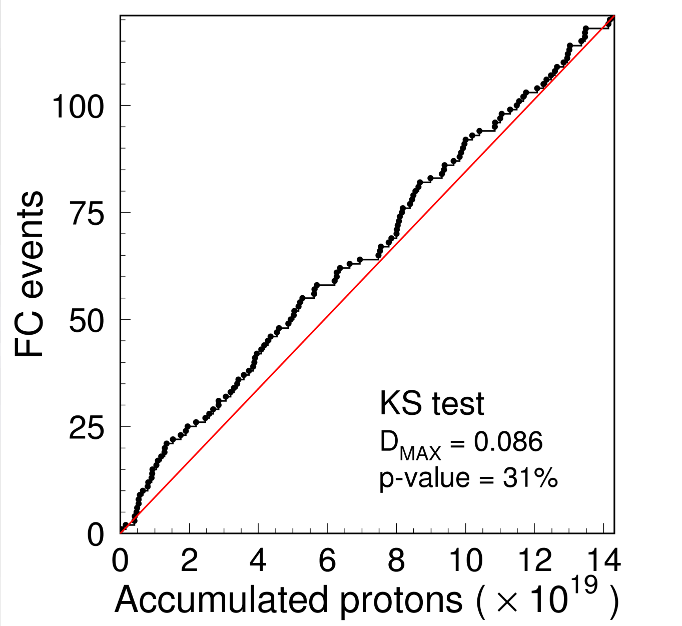
- SK synchronized to beam timing using GPS
- Fully contained (FC) events in the Inner Detector, minimal activity in the Outer Detector
- Starting in the Fiducial Volume (FCFV)
- Number of rings = 1
- PID algorithm to distinguish e-like and μ-like events



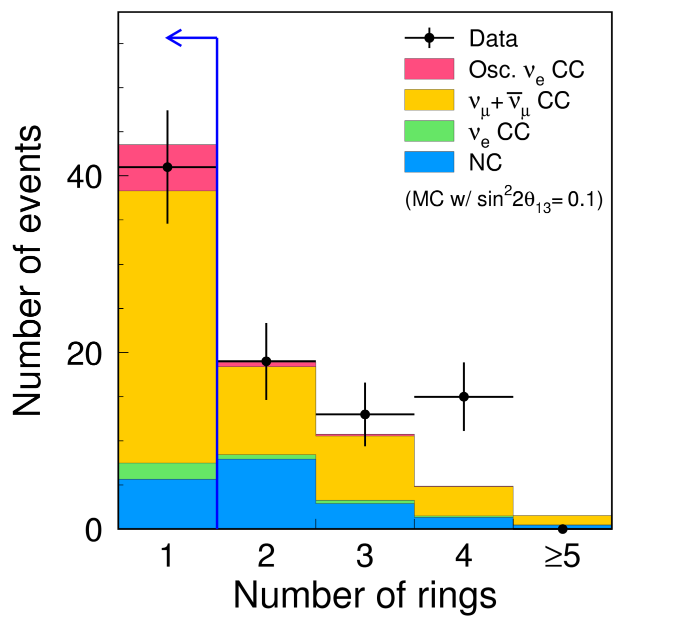

121 FC events



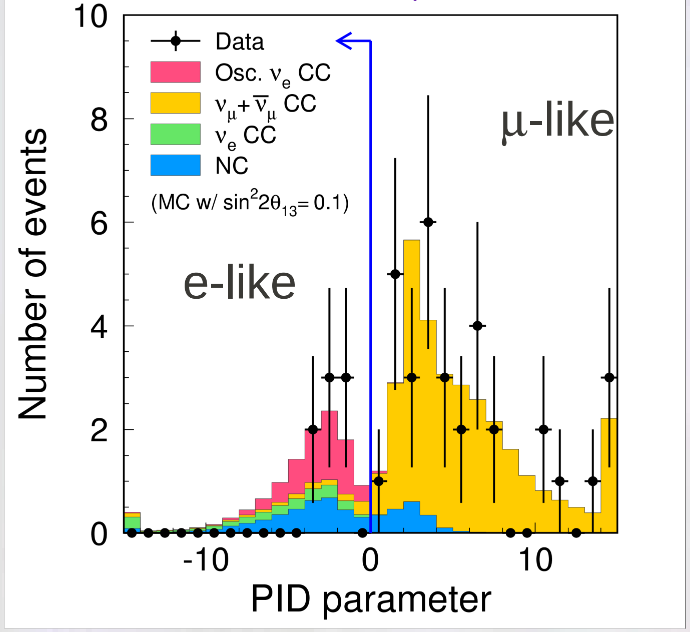

88 FCFV events




41 single ring events




8 e-like events, 33 μ-like events



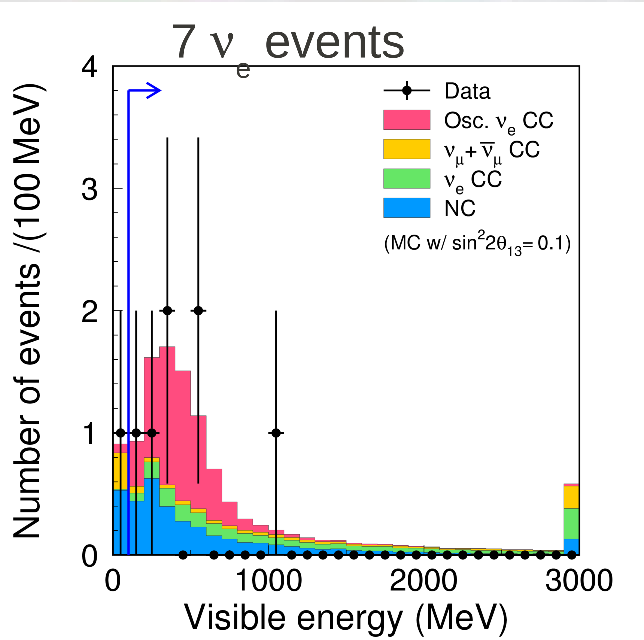
# T2K $\nu_e$ Results

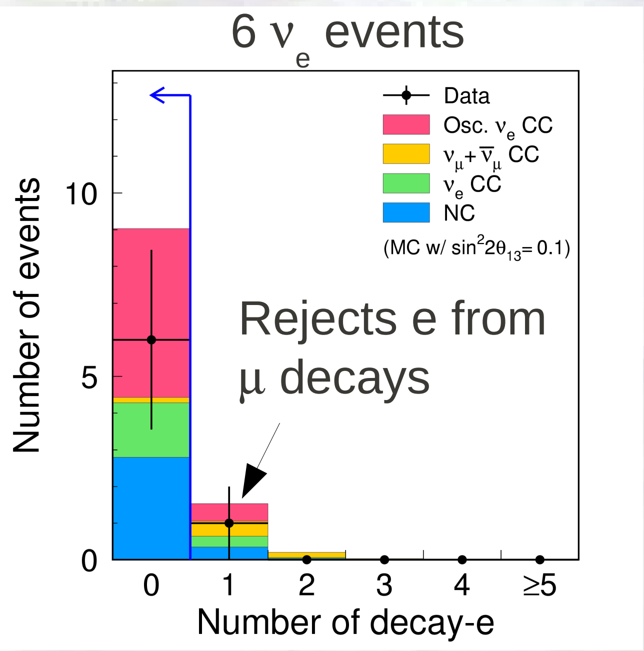
8 e-like PID-selected events. Four additional cuts:

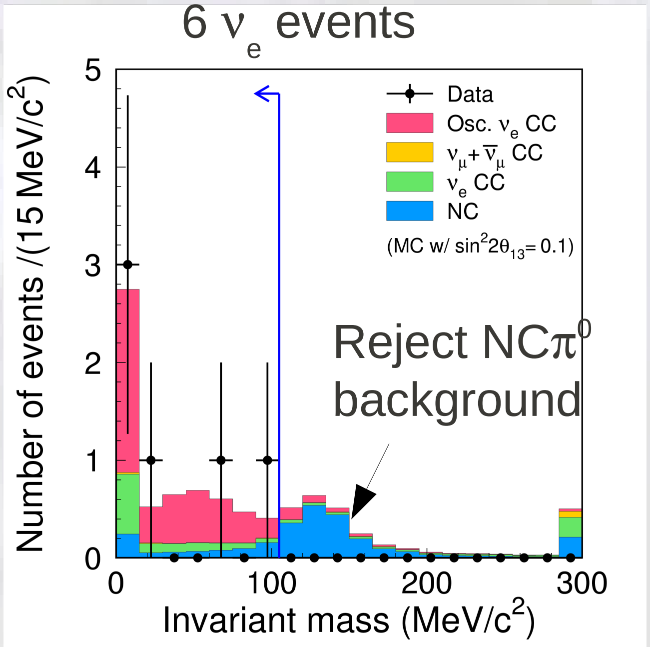
- Visible energy > 100 MeV
- Number of decay-electrons == 0
- Invariant mass < 105 MeV
- Reconstructed neutrino energy < 1250 MeV

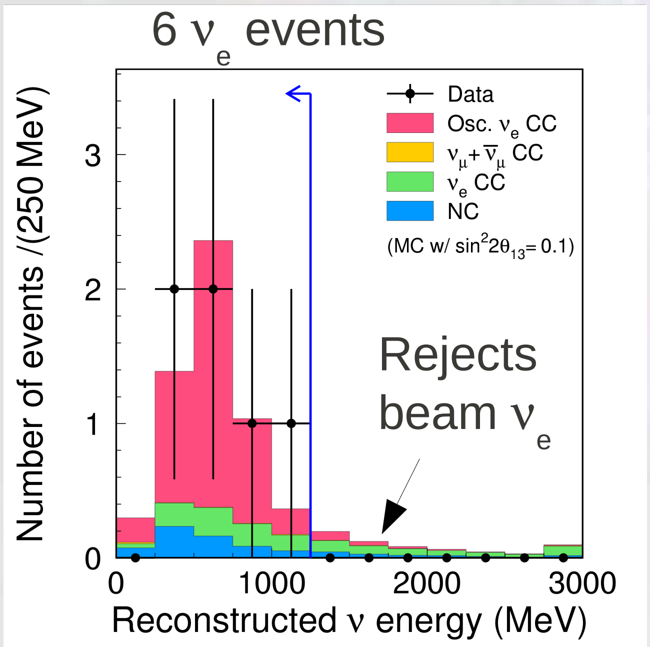
Signal efficiency: 66%,
Background rejection: 77% beam for $\nu_e$, 99% for NC

Observed $\nu_e$ data events: 6
Expected $\nu_e$ events: 1.5±0.3 (5.5±1.0) for $\sin^2 2\theta_{13}$ = 0(0.1)



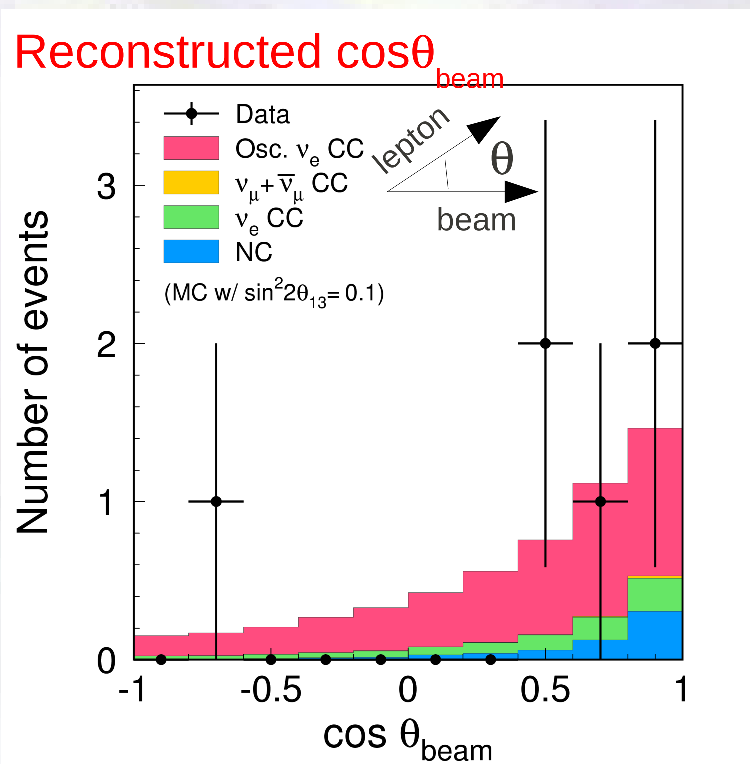



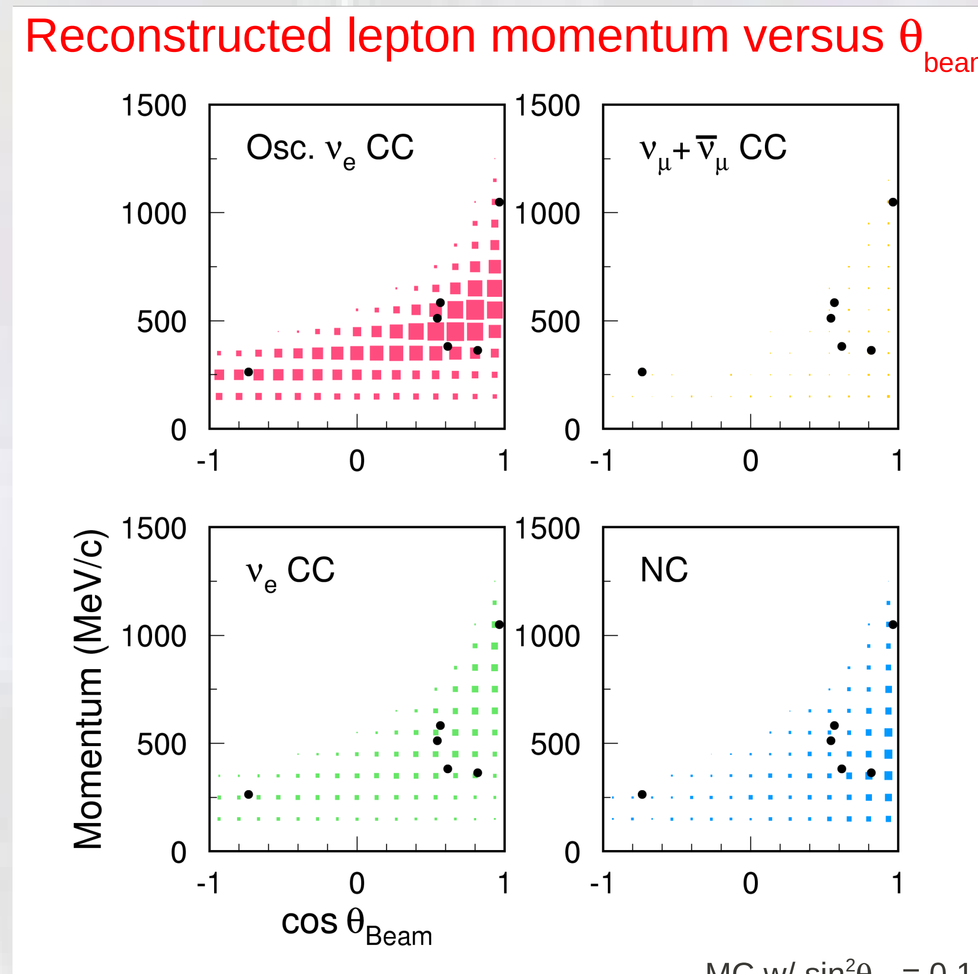
# $\nu_e$ Event Distributions

- Breakdown of expected events:

| $\sin^2 2\theta_{13}=0$ | Beam $\nu_e$ background | NC background | $\nu_\mu \to \nu_e$ (solar term) | Total |
|---|---|---|---|---|
| *The expected # of events at SK* | **0.8** | **0.6** | **0.1** | **1.5** |

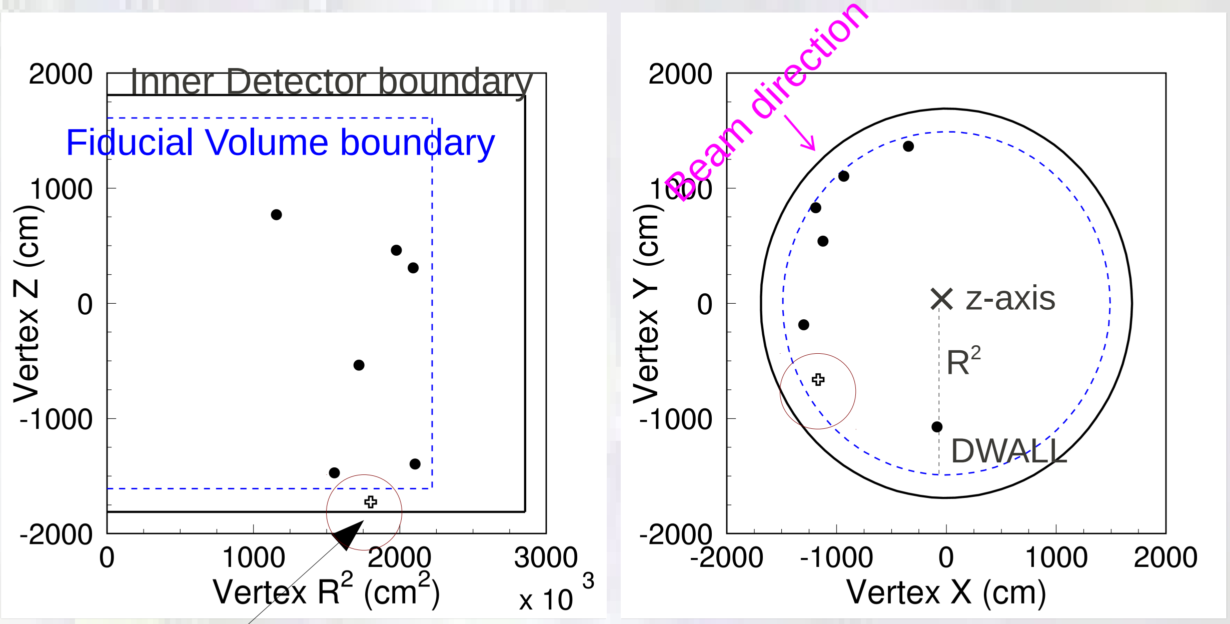
- Checking distributions of $\nu_e$ selected events:



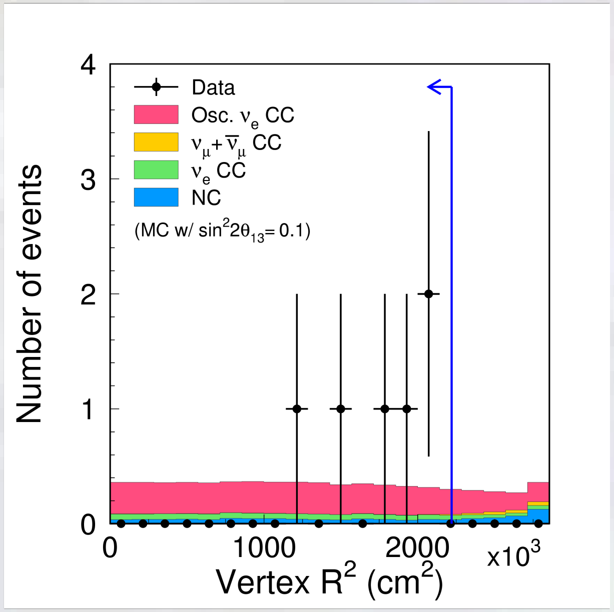



# $\nu_e$ Vertex Distributions

Vertex distribution of the 6 events → clustering at large R (in SK cylindrical coordinates).



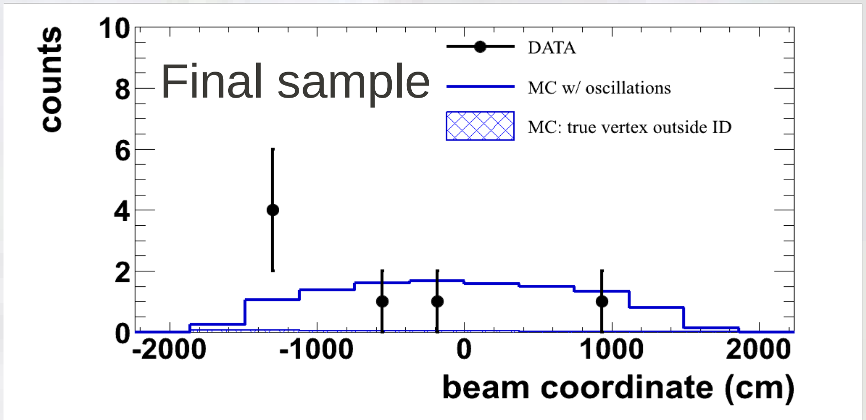

Kolmogorov-Smirnov test on the $R^2$ distribution → 3% p-value (other distributions have p-values 1-20%):

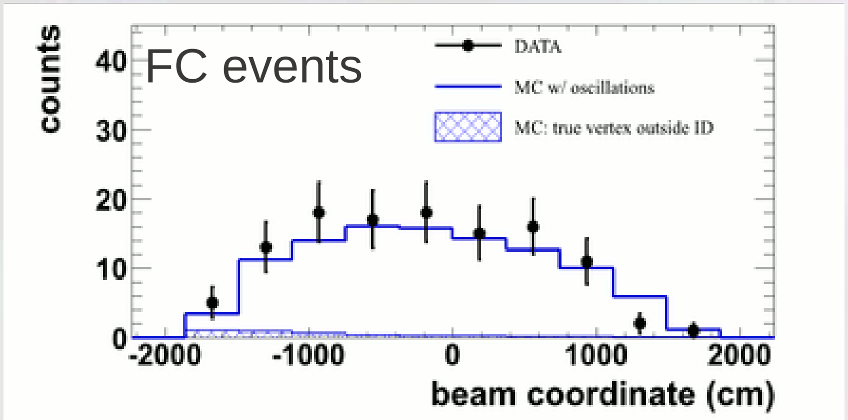



Only one event seen outside fiducial volume that passes all other cuts:

- if beam related background from outside FV, expect more events in this region.

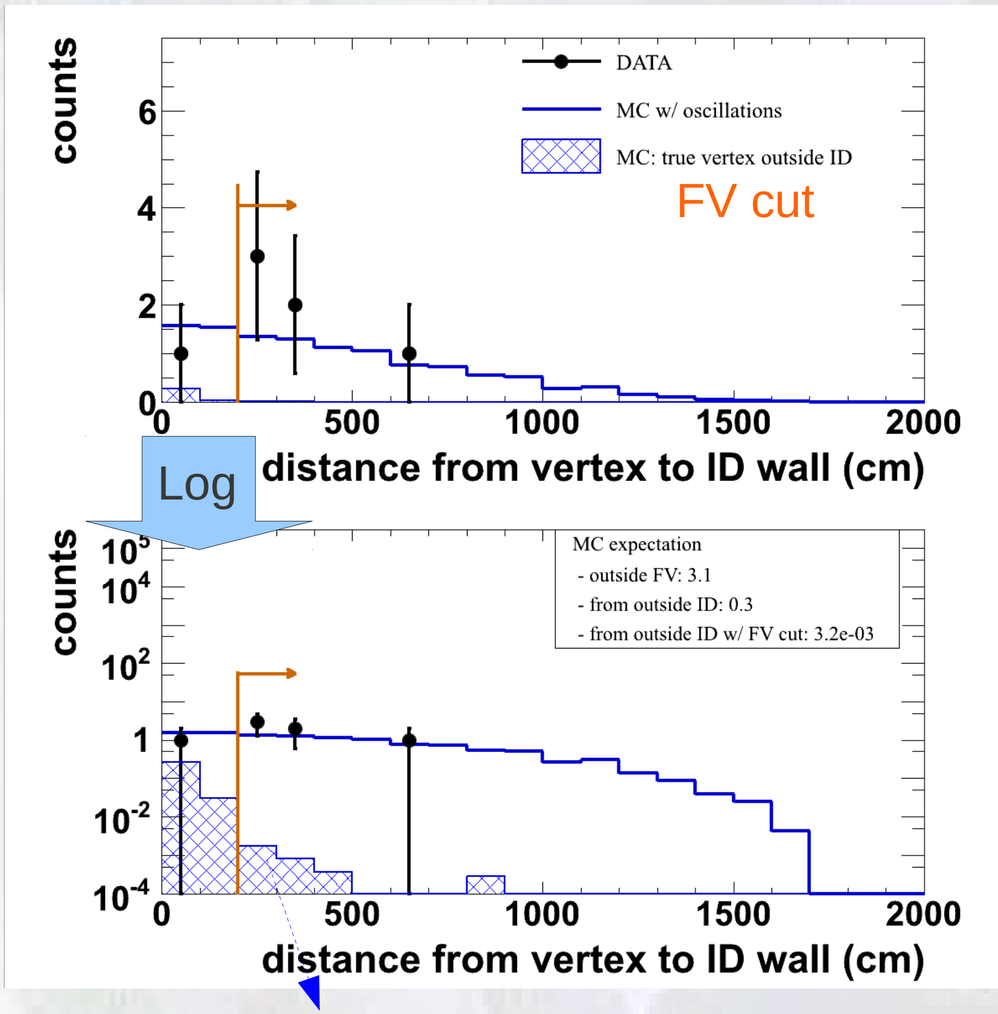
Vertex distribution along beam direction consistent with MC:



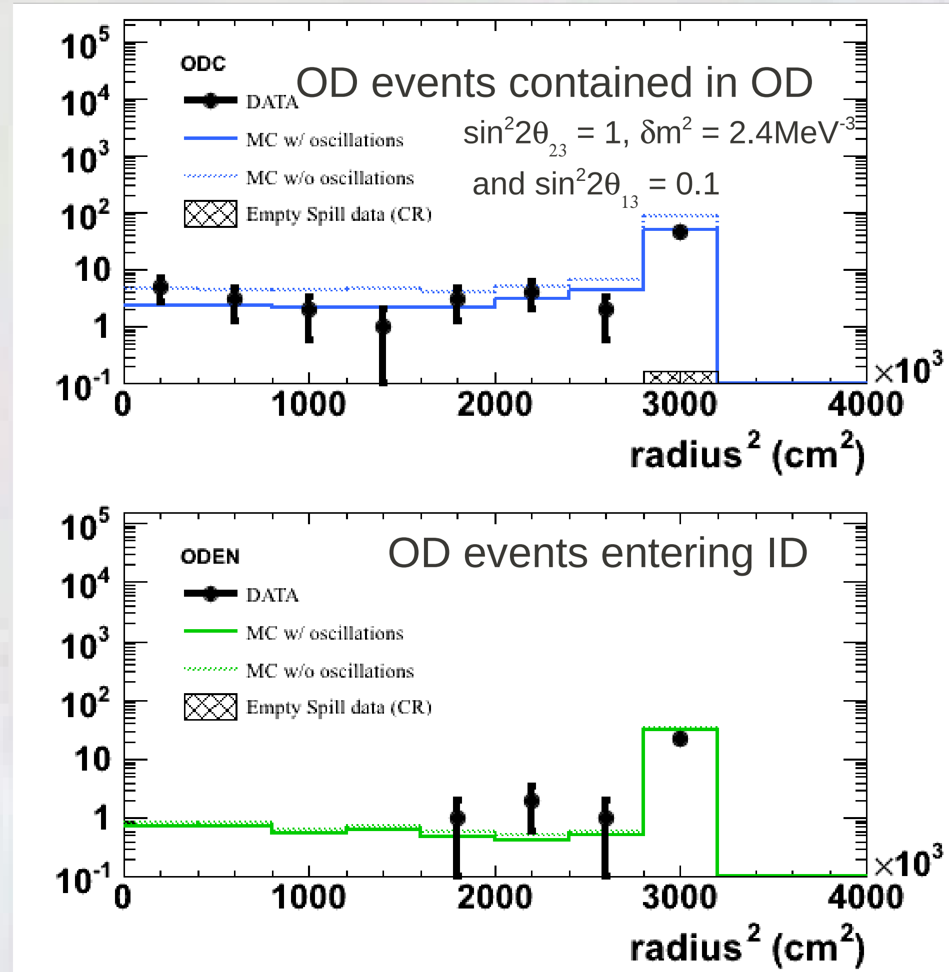



# $\nu_e$ Events OD Distributions

Vertices after FC cuts but w/o FV cut:




OD event vertex distributions:




From outside ID w/ FV cut: $3.2 \times 10^{-3}$ expected events.

No significant excess of events in OD

OD event distributions show no indication of contamination from outside ID

# Systematic Uncertainties

| Error source @ SK | $\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$ | $\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$ |
|---|---|---|
| $\pi^0$ rejection | - | 3.6% |
| Ring counting | 3.9% | 8.3% |
| Electron PID | 3.8% | 8.0% |
| Invariant mass cut | 5.1% | 8.7% |
| Fiducial volume cut etc. | 1.4% | 1.4% |
| Energy scale | 0.4% | 1.1% |
| Decay electron finding | 0.1% | 0.3% |
| Muon PID | - | 1.0% |
| **Total** | **7.6%** | **15%** |

Data-driven evaluation of uncertainties at the far detector

The total uncertainty on $N^{MC}_{SK\ tot.}$ is **14.7 %** ($\sin^2 2\theta_{13}=0$) (uncertainty on the background + solar term oscillated $\nu_e$)

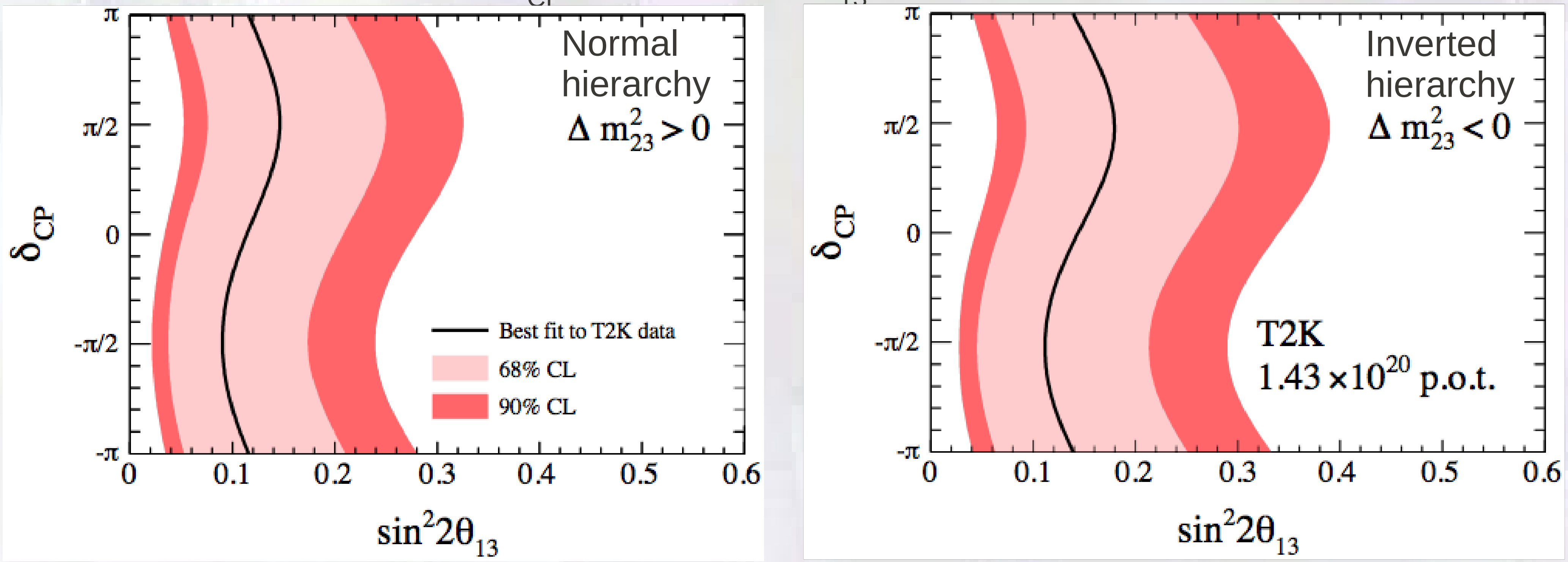
Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}=0$:

$N^{exp}_{SK\ tot.}$ = 1.5 ± 0.3 events for $\sin^2 2\theta_{13}=0$ (w/ 1.43 x $10^{20}$ POT)

| T2K Systematic errors | syst. error |
|---|---|
| (1) $\nu$ flux | $\pm 8.5\%$ |
| (2) $\nu$ cross section | $\pm 14.0\%$ |
| (3) Near detector | $^{+5.6}_{-5.2}\%$ |
| (4) Far detector | $\pm 14.7\%$ |
| (5) Near det. statistics | $\pm 2.7\%$ |
| Total $\delta N^{exp}_{SK}/N^{exp}_{SK}$ | $^{+22.8}_{-22.7}\%$ |

# T2K $\nu_e$ Appearance Analysis

- Probability of observing 6 events if $\sin^2(2\theta_{13})=0 \rightarrow$ 0.7% (2.5σ significance)
- Feldman-Cousins unified method used to construct the confidence intervals.
- Confidence intervals for $\delta_{CP}$ versus $\sin^2 2\theta_{13}$:




90% interval and best fit (for $\sin^2(2\theta_{23})=1$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV$^2$, $\delta_{CP}=0$):

**Normal hierarchy, δ=0:**
- Best fit: $\sin^2(2\theta_{13})=0.11$
- $0.03<\sin^2(2\theta_{13})<0.28$ @90% C.L.

**Inverted hierarchy, δ=0:**
- Best fit → $\sin^2(2\theta_{13})=0.14$
- $0.04<\sin^2(2\theta_{13})<0.34$ @90% C.L.



Published in Phys. Rev. Lett. 107, 041801 (2011)

# Outline

- **The T2K experiment**
  - Experimental set-up
  - Detectors
  - Performance

Accepted for publication in Nucl. Instrum. Methods arXiv:1106.1238v2 [physics.ins-det]

- **$\nu_e$ appearance analysis**
  - Analysis method
  - Results

Phys. Rev. Lett. 107, 041801 (2011) arXiv:1106.2822v1 [hep-ex]

- **$\nu_\mu$ disappearance analysis**
  - Analysis selection
  - Results

Preliminary Results

- **Future plans**

# T2K $\nu_\mu$ Results

- 33 μ-like events are selected with PID likelihood.

- Additional cuts:
  - Less than 2 decay electrons
  - Reconstructed μ momentum larger than 200 MeV

Expected final sample composition:

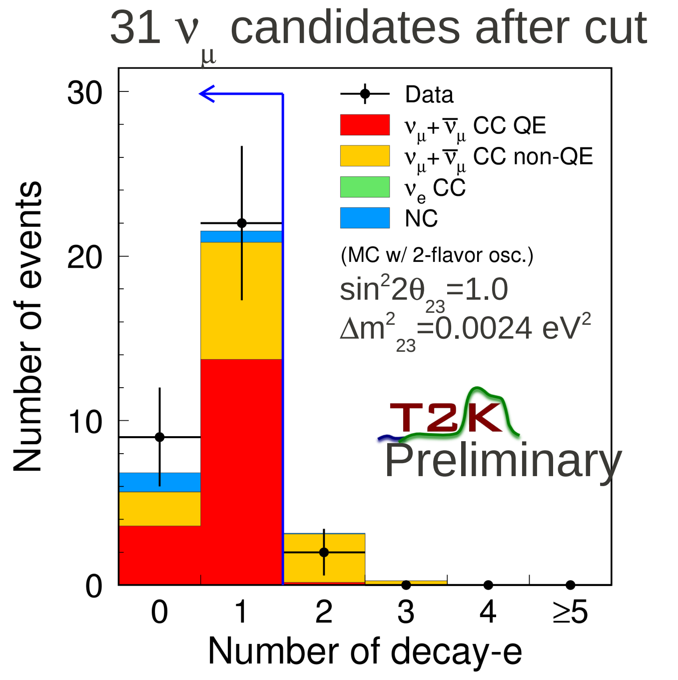
- CCQE(61%) CCnQE (32%), NC(6%), $\nu_e$(<1%)

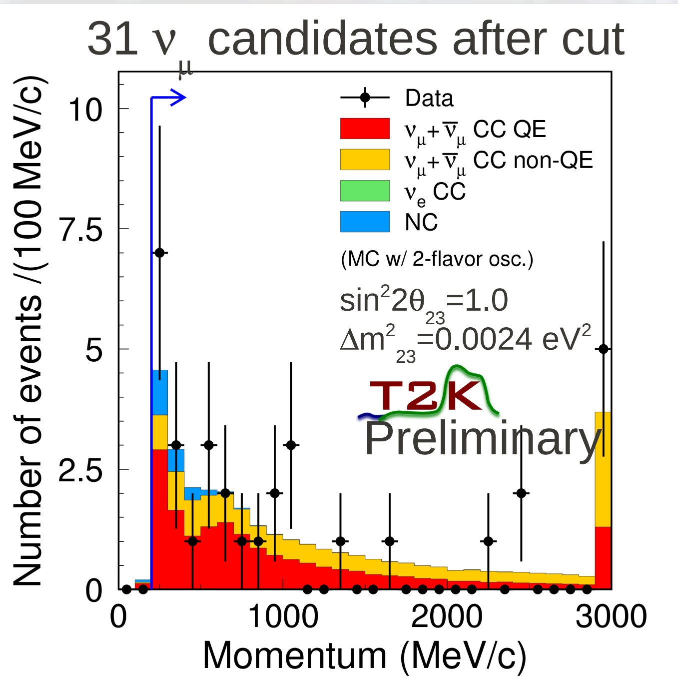
- 31 events pass all the selections, 104 expected w/o oscillations → null-oscillation hypothesis excluded at 4.5σ

Systematics on SK expected events:

$N^{SK}_{exp.}$ error table

| Error source | $\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$ | Null Oscillation |
|---|---|---|
| SK Efficiency | +10.3% 10.3% | +5.1% -5.1% |
| Cross section and FSI | +8.3% -8.1% | +7.8% -7.3% |
| Beam Flux | +4.8% -4.8% | +6.9% -5.9% |
| ND Efficiency and Overall Norm. | +6.2% -5.9% | +6.2% -5.9% |
| Total | +15.4% -15.1% | +13.2% -12.7% |

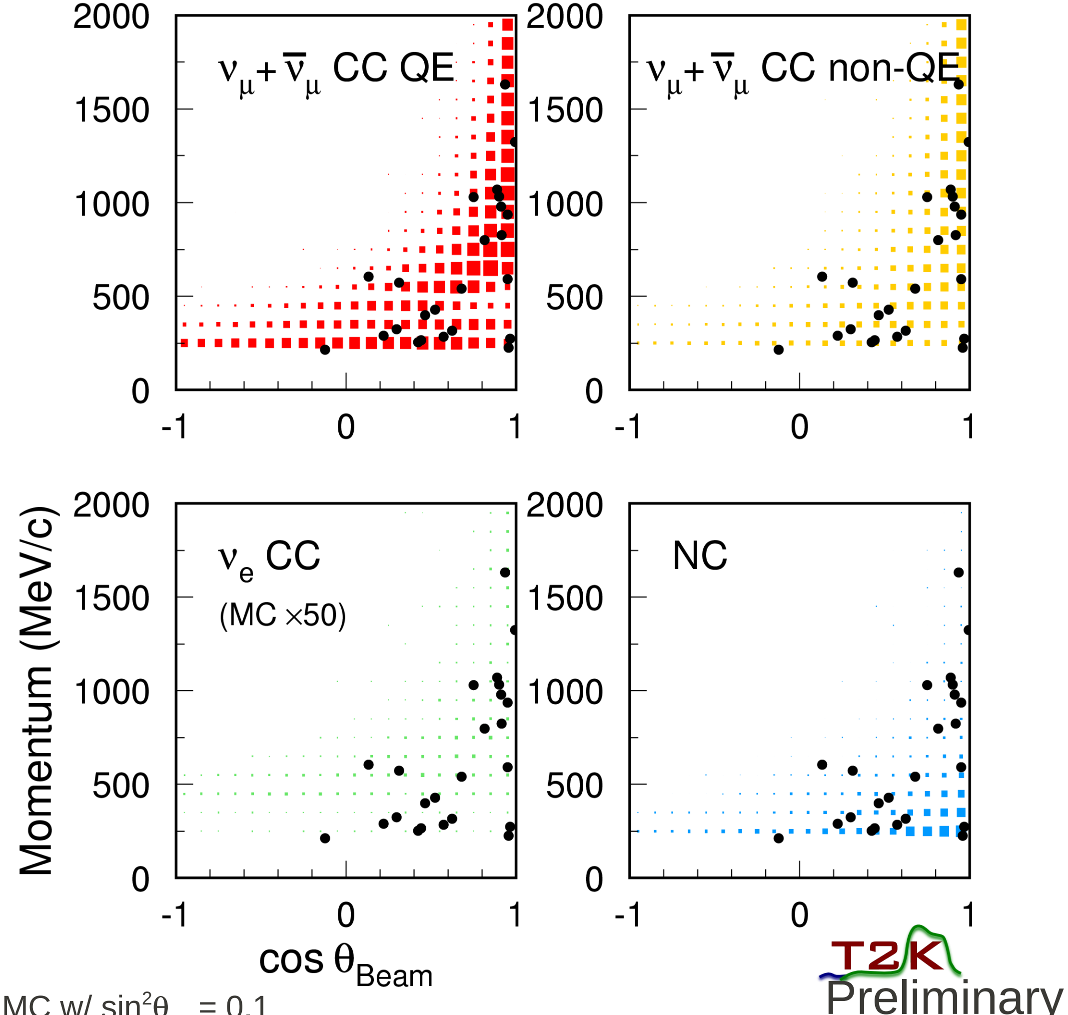


# $\nu_\mu$ Events

- Checking several distributions of $\nu_\mu$ events.
- No clustering of events at high R.

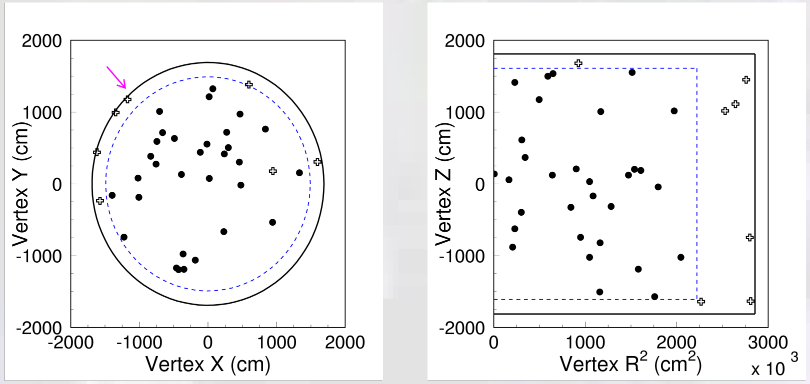
Reconstructed lepton momentum versus $\theta_{beam}$ with MC divided by neutrino species/interactions:

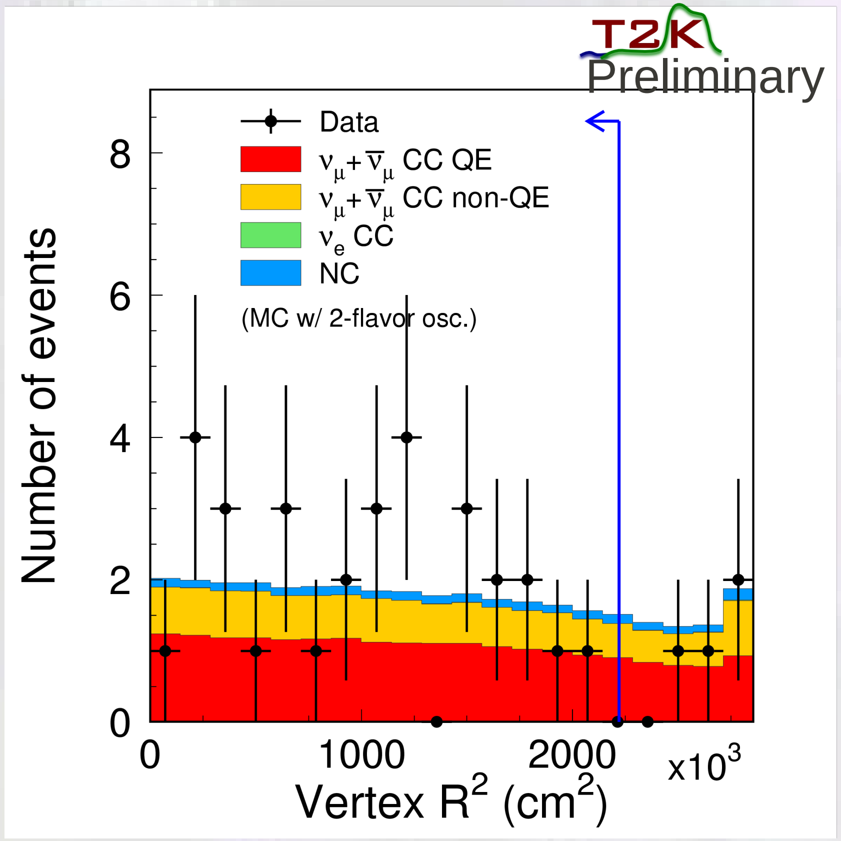



MC w/ $\sin^2\theta_{13}$ = 0.1

- MC events with $\sin^2 2\theta_{23}$=1.0 and $\Delta m^2_{23}$=0.0024 eV$^2$

Vertex Distributions:

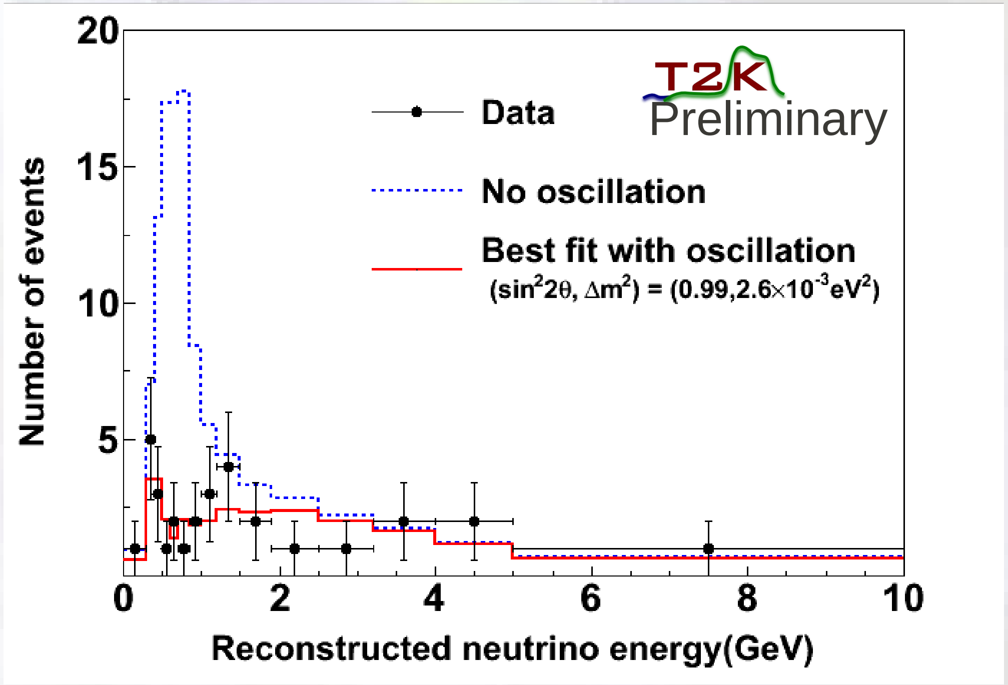


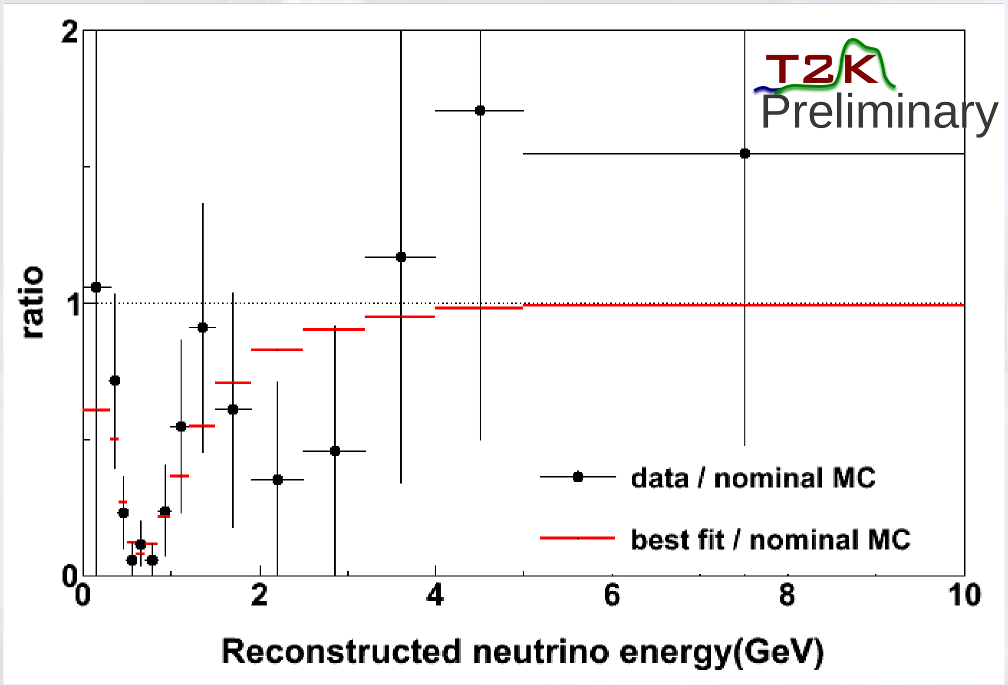
# T2K $\nu_\mu$ Energy Spectrum

- Oscillation parameters extracted from an oscillation fit on the reconstructed $E_\nu$
- The oscillation pattern due to the disappearance of $\nu_\mu$ is clearly visible in the reconstructed $E_\nu$

Reconstructed $E_\nu$




Reconstructed $E_\nu$ data/ MC (w/o oscill.) ratio



# T2K $\nu_\mu$ Disappearance Results

- Two independent oscillation fits to extract the oscillation parameters.
- Both use Feldman-Cousins unified method to build confidence intervals.
- Maximum likelihood (method A) and likelihood ratio (Method B) used.
- Main difference between the two fit results comes from the fit to the systematic parameters performed in method A.

Method A:

- Best fit:

$\sin^2(2\theta_{23})=0.99$, $|\Delta m^2_{23}|=2.6\times10^{-3}$ eV$^2$

- 90% C.L:

$\sin^2(2\theta_{23})>0.85$

$2.1\times10^{-3}<|\Delta m^2_{23}|(\mathrm{eV}^2)<3.1\times10^{-3}$

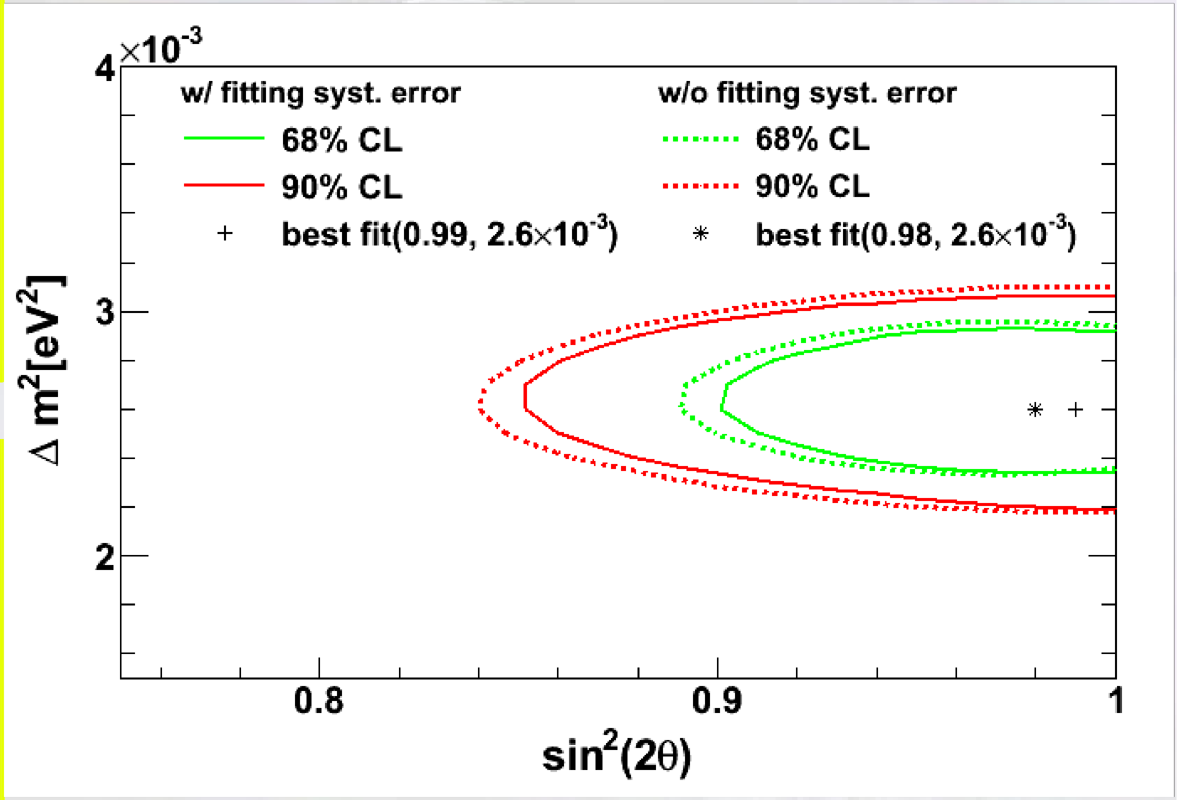
Method B:

- Best fit:
- $\sin^2(2\theta_{23})=0.98$, $|\Delta m^2_{23}|=2.6\times10^{-3}$ eV$^2$
- 90% C.L.:

sin2$(2\theta_{23})>0.84$

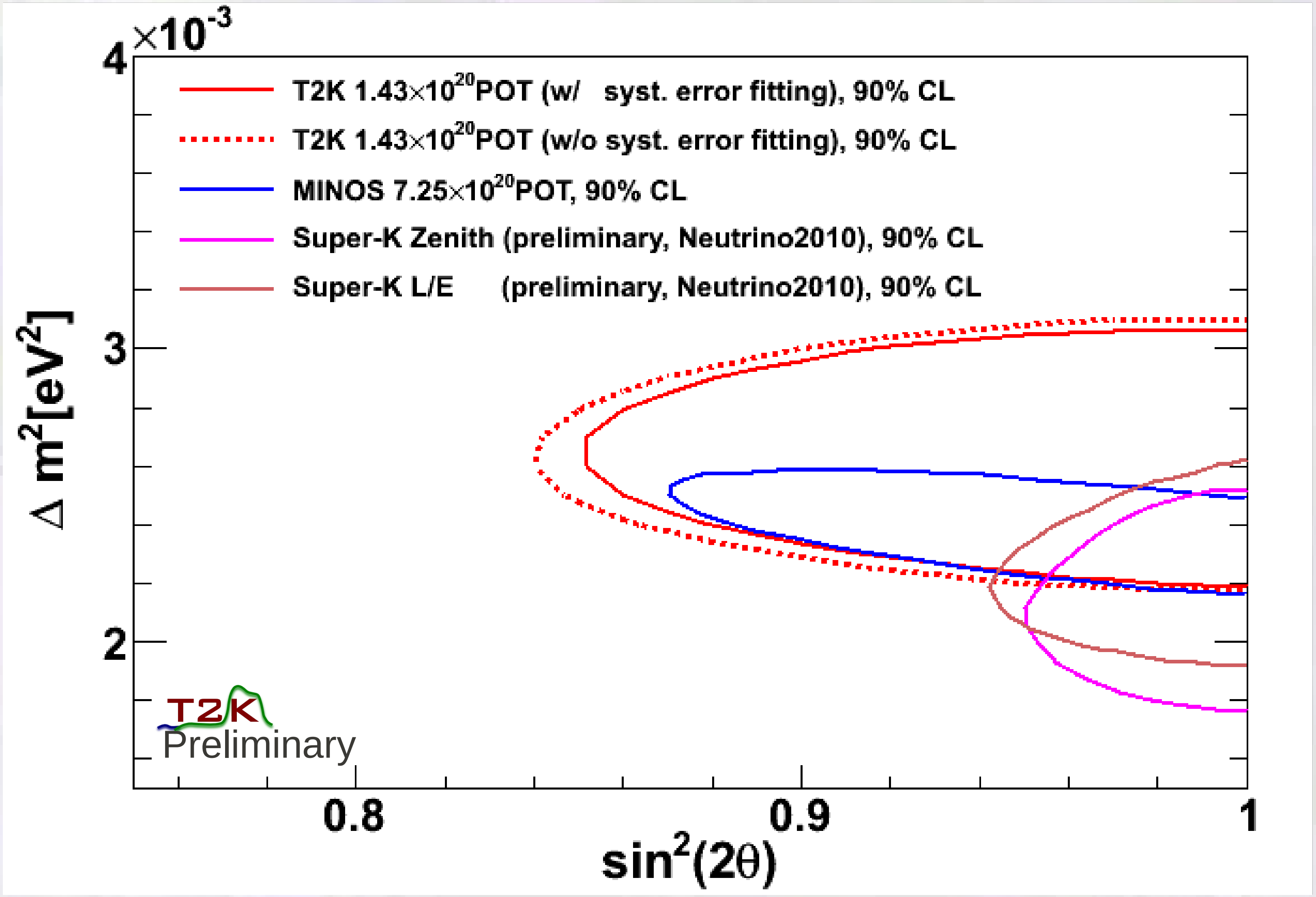
$2.1\times10^{-3}<|\Delta m^2_{23}|(\mathrm{eV}^2)<3.1\times10^{-3}$

Very good consistency between the two fits



# Comparison with SK and MINOS

•T2K results are in good agreement with results from SK and MINOS



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arXiv:1106.2822v1 [hep-ex]

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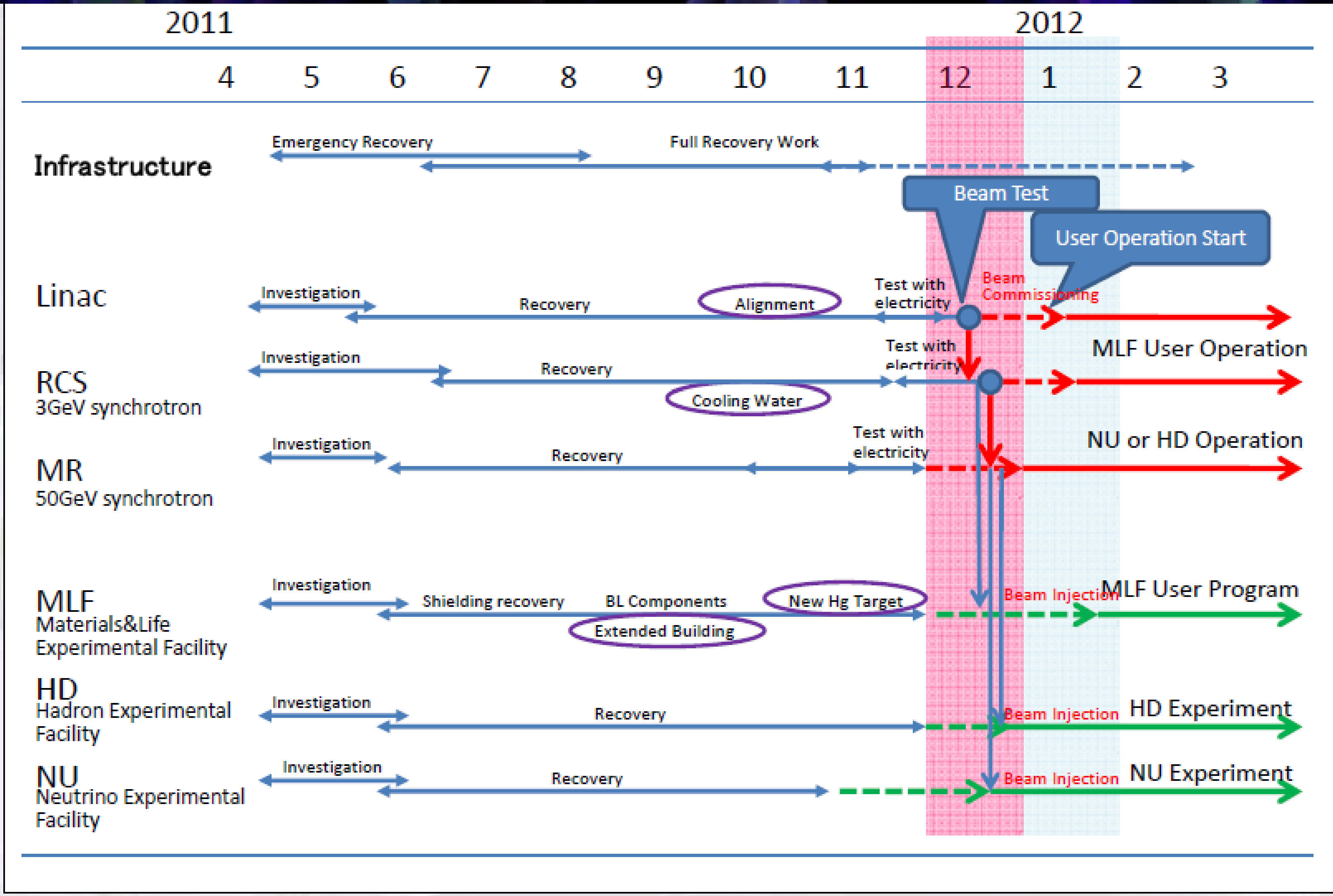
Preliminary Results

- **Future plans**

# J-PARC Recovery Schedule




Schedule updated on 2011-05-20

- J-PARC Earthquake hit at 14:46 on Mar. 11th.
- Recovery work started in March and it is proceeding steadily.
- No serious damages found on accelerator, beamline and near detectors
- SuperKamiokande not affected
- We will resume J-PARC operations in Dec. 2011

# Future Milestones

Highest priority is to firmly establish non-zero $\theta_{13}$ and its precise determination as quickly as possible.

We have 70 [kW$\times10^7$s] = $1.45\times10^{20}$ POT (2% of the approved goal)

We aim to have:

- By Summer 2013: ~0.5 [MW$\times10^7$s] ~ $1\times10^{21}$POT
  - Conclude non-zero $\theta_{13}$
  - >5sigma for present T2K central value

- Within a few years : ~ 1 [MW$\times10^7$s] ~ $2\times10^{21}$POT
  - $> 3$sigma for $\sin^2 2\theta_{13} > 0.04$

- Approved goal: 3.8 [MW$\times10^7$s] ~ $8\times10^{21}$POT
  - $> 3$sigma for $\sin^2 2\theta_{13} >\sim 0.02$

# Conclusions

Using the full dataset ($1.43 \times 10^{20}$ POT), two analyses presented:

**$\nu_e$ appearance analysis (Phys. Rev. Lett. 107, 041801 (2011) arXiv:1106.2822v1 [hep-ex])**:

- 6 events have been observed (1.5±0.3 expected)
- The probability of 6 events with $\theta_{13} = 0$ is 0.7% (2.5σ significance)
- This lead to a 90% confidence interval of $0.03(0.04)<\sin^2(2\theta_{13})<0.28(0.34)$ for normal (inverted) hierarchy & δCP=0

**$\nu_\mu$ disappearance analysis (new preliminary results):**

No oscillation hypothesis excluded at 4.5σ

$\sin^2(2\theta_{23})>0.85$ and $2.1 \times 10^{-3}<\Delta m^2_{23}$ ($eV^2$)$<3.1 \times 10^{-3}$ @ 90% C.L.

The experiment is currently recovering from the 11th March earthquake

Investigations done so far indicate that all damage is repairable

**Aim to restart JPARC operation in December 2011.**

# The T2K Collaboration

**Canada**
- U. Alberta
- U. B. Columbia
- U. Regina
- U. Toronto
- TRIUMF
- U. Victoria
- York U.

**France**
- CEA Saclay
- IPN Lyon
- LLR E. Poly.
- LPNHE Paris

**Germany**
- U. Aachen

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

**Japan**
- ICRR Kamioka
- ICRR RCCN
- KEK
- Kobe U.
- Kyoto U.
- Miyagi U. Edu.
- Osaka City U.
- U. Tokyo

**Poland**
- A. Soltan, Warsaw
- H.Niewodniczanski, Cracow
- U. Silesia, Katowice
- T. U. Warsaw
- U. Warsaw
- U. Wroclaw

**Russia**
- INR

**S. Korea**
- Chonnam N.U.
- Dongshin U.
- Seoul N.U.

**Spain**
- IFIC, Valencia
- U. A. Barcelona

**Switzerland**
- ETH Zurich
- U. Bern
- U. Geneva

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

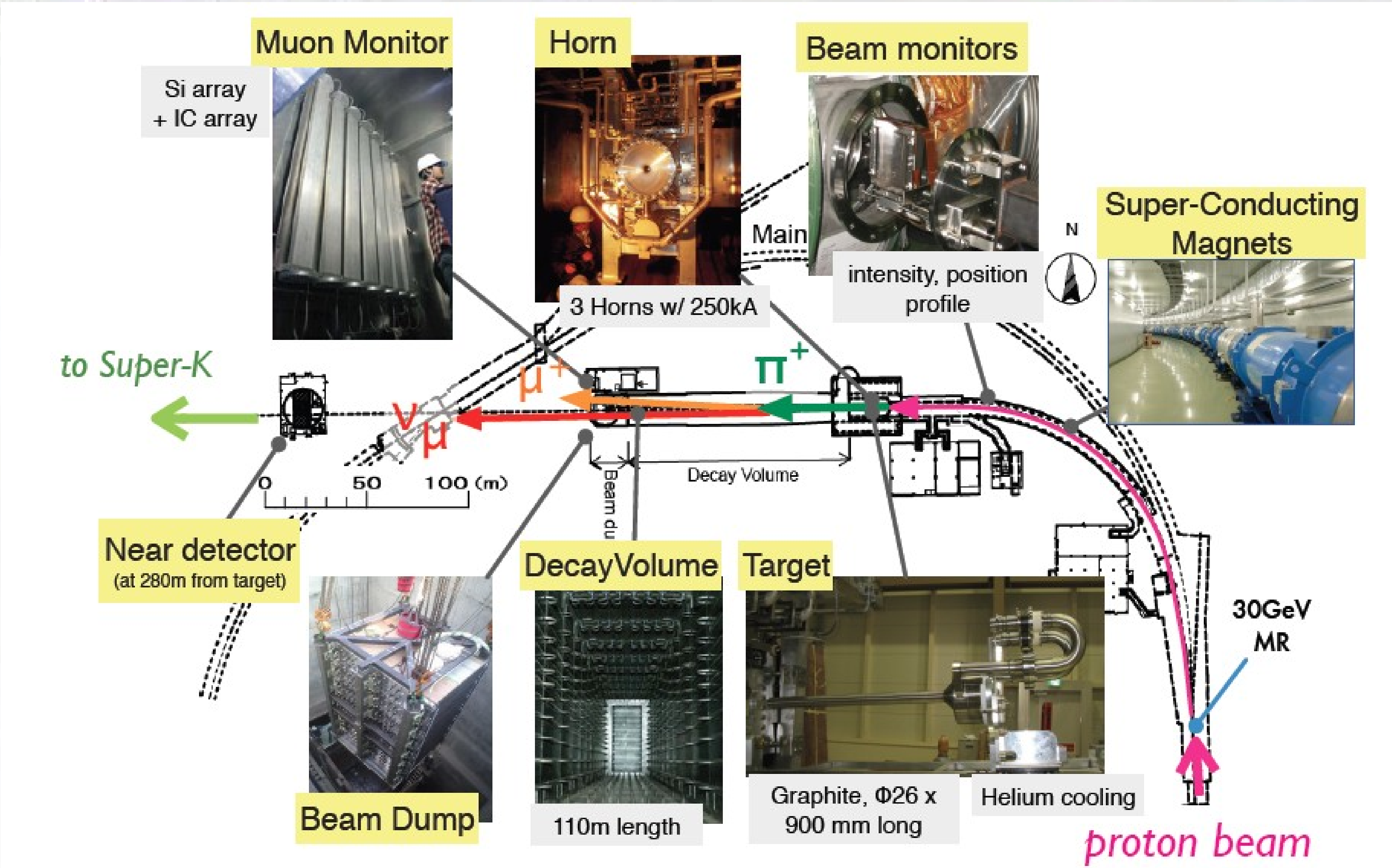
**USA**
- Boston U.
- B.N.L.
- Colorado S. U.
- U. Colorado
- Duke U.
- U. C. Irvine
- Louisiana S. U.
- U. Pittsburgh
- U. Rochester
- Stony Brook U.
- U. Washington

Near & Far sites: KEK/JAEA, ICRR

Total:
~500 members
59 institutes
12 countries

# Additional Slides

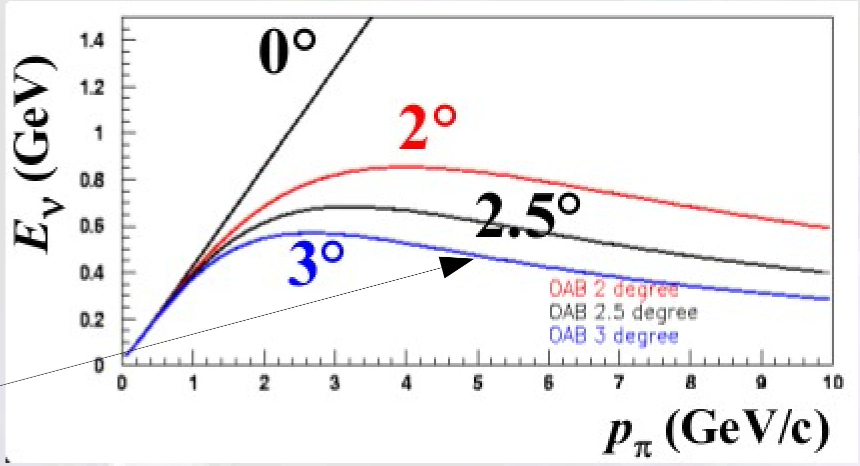
# J-PARC Neutrino Beam Line

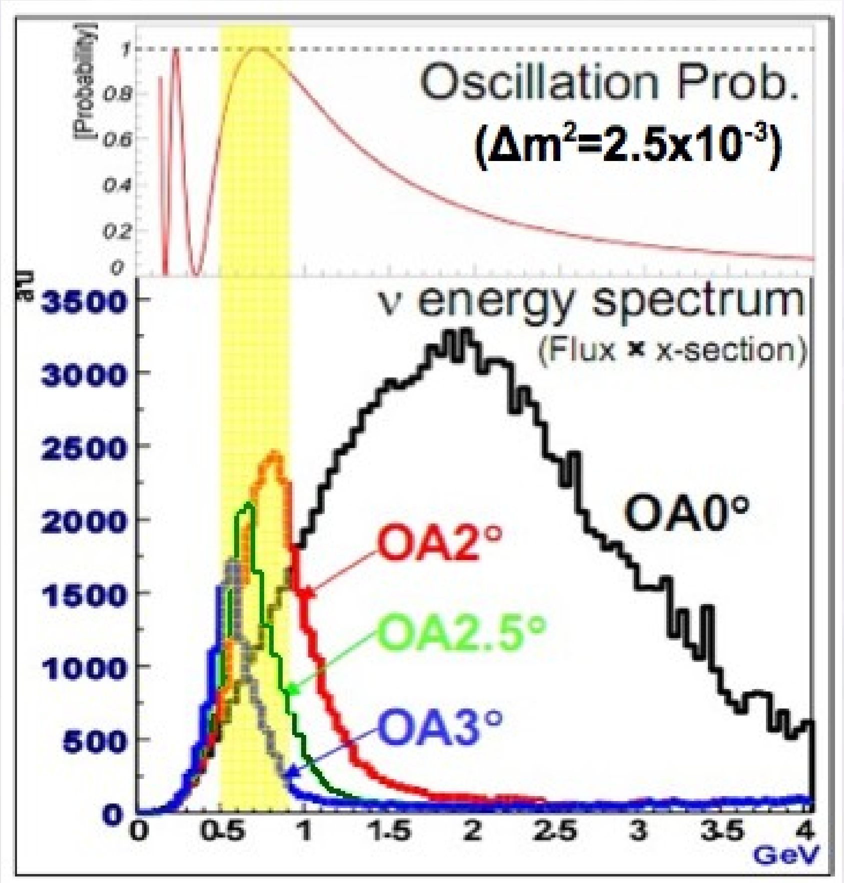


# Why Off-axis?

- Pion decay kinematics:
  - In pion direction, neutrino energy proportional to pion momentum
  - At non-zero angles, weak dependence on pion momentum
- 2.5° off-axis angle gives narrow band beam peaked at the first oscillation maximum (for L = 295 Km and $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$)
  - More statistics in the oscillation region
  - Less feed-down from backgrounds at higher energy

**Idea originally developed for long baseline proposal at BNL (E889)**

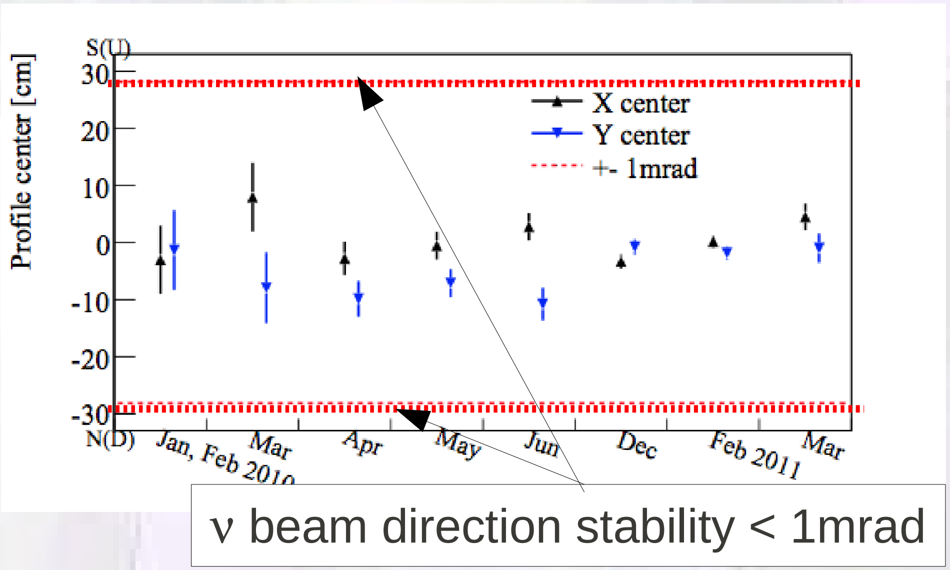


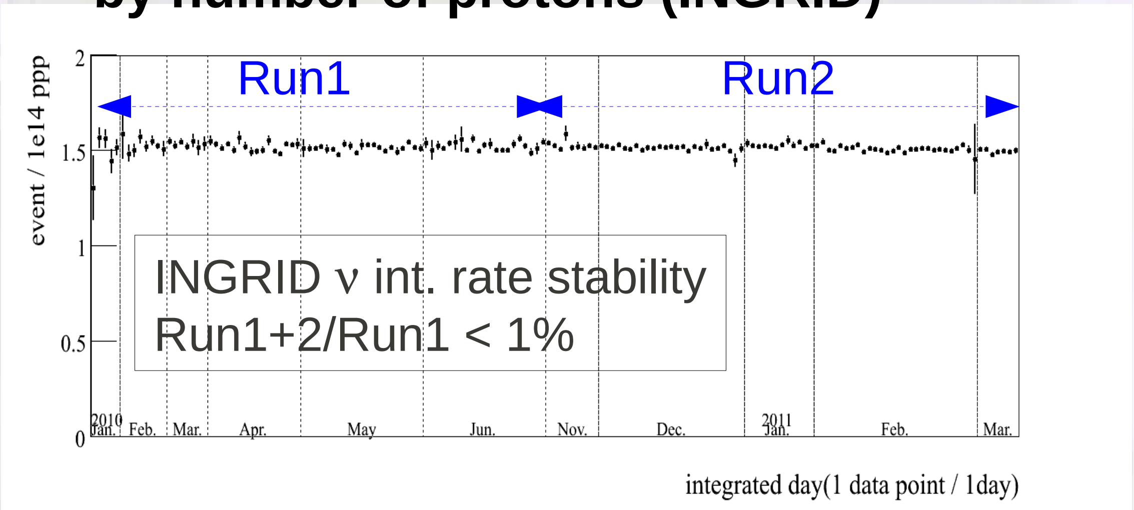
# ν Rate and Direction Stability

Necessary to keep the beam direction stable to ensure the stability of the neutrino peak energy: δ(dir)<1 mrad → δ(E)/E<2% @ SK

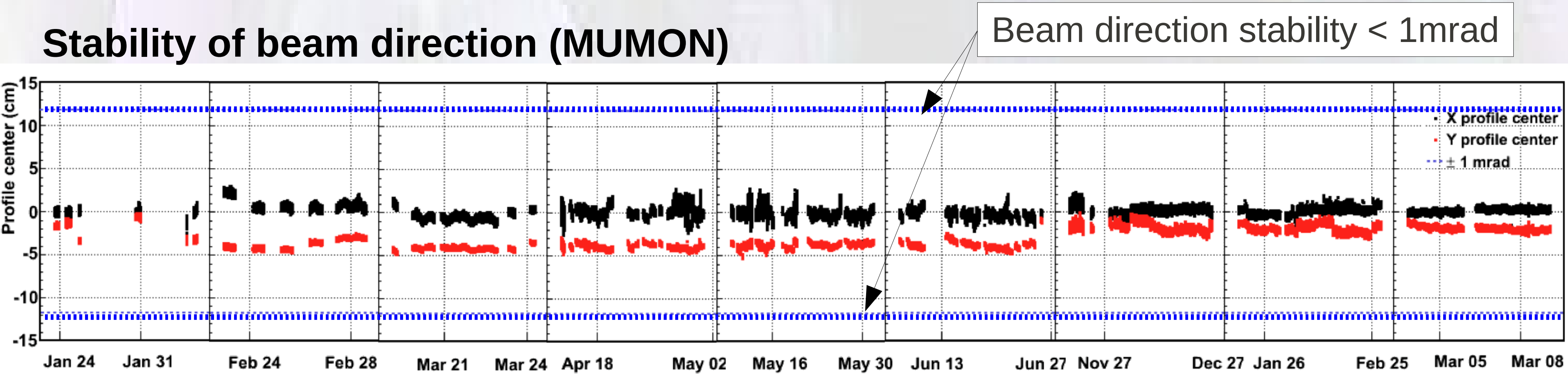
## Stability of ν beam direction (INGRID)




## Stability of ν interaction rate normalized by number of protons (INGRID)

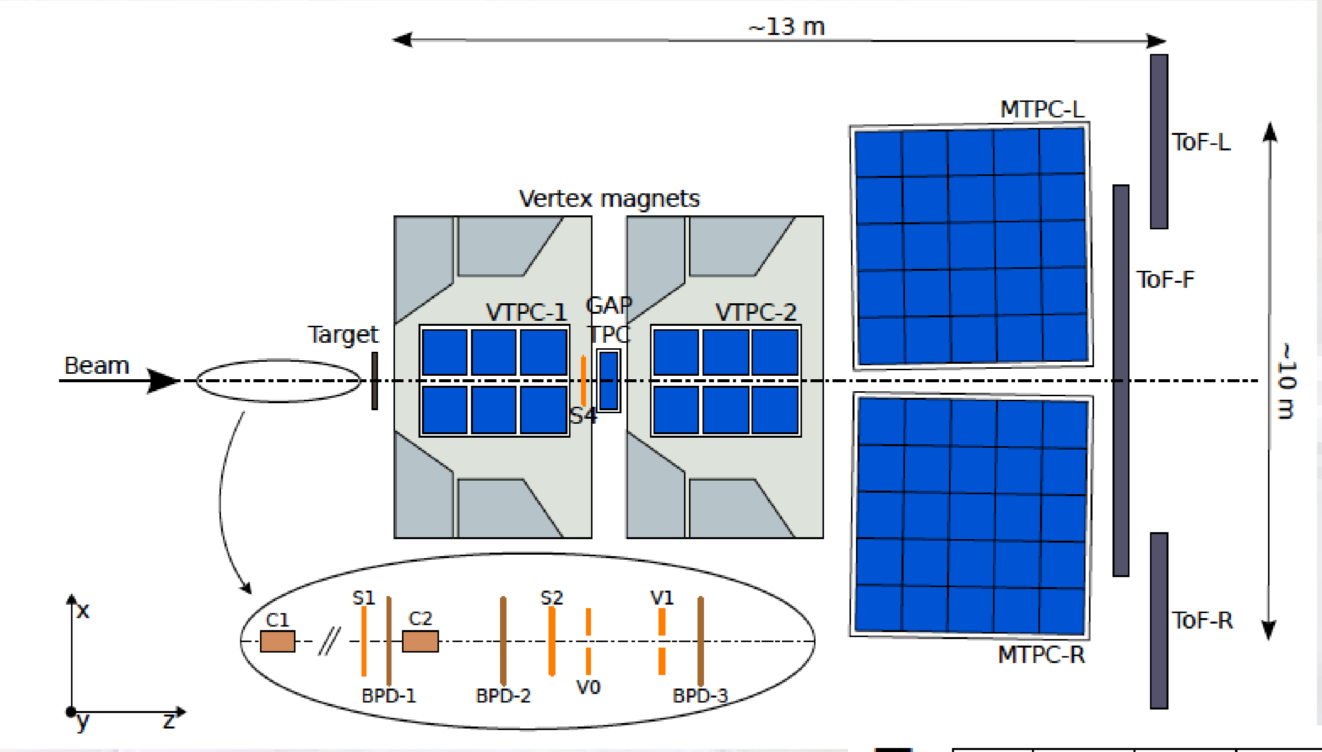



## Stability of beam direction (MUMON)



# NA61 Experiment

Large acceptance spectrometer and time-of-flight detectors



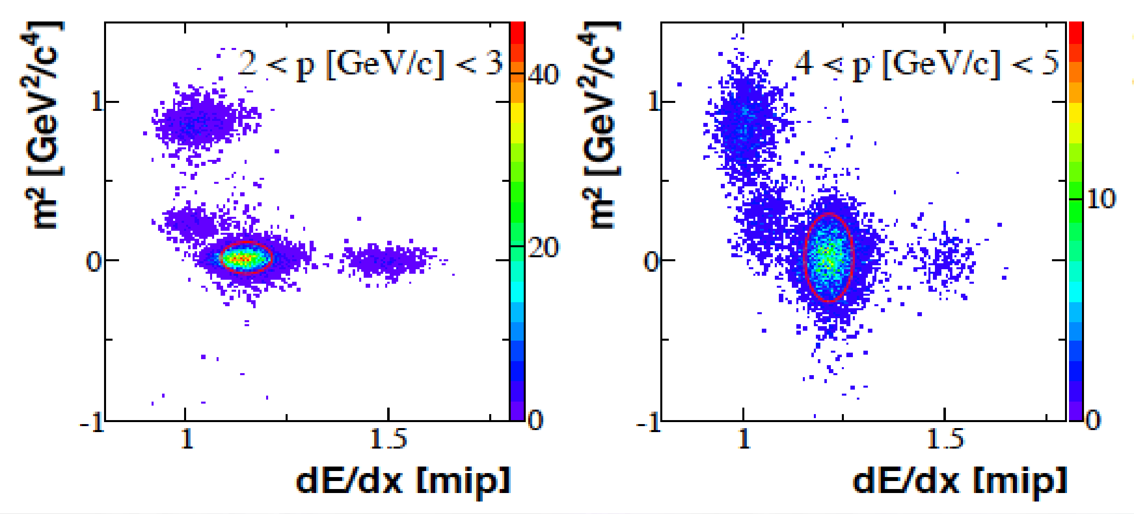

30 GeV proton beam to match T2K

Two target types:

1) 0.04 λ "thin target"
2) T2K replica "long target"

Pion production from thin target used in this analysis

Good TOF and dE/dx performance allows for particle separation



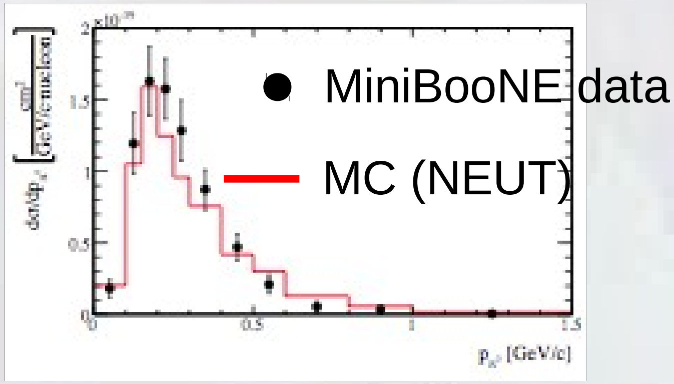
# Neutrino Interactions

Cross-section uncertainties are estimated by:

- Parameter variations in the model
- Different models
- Comparison to external data (MiniBooNE, SciBooNE, SK atmospheric)

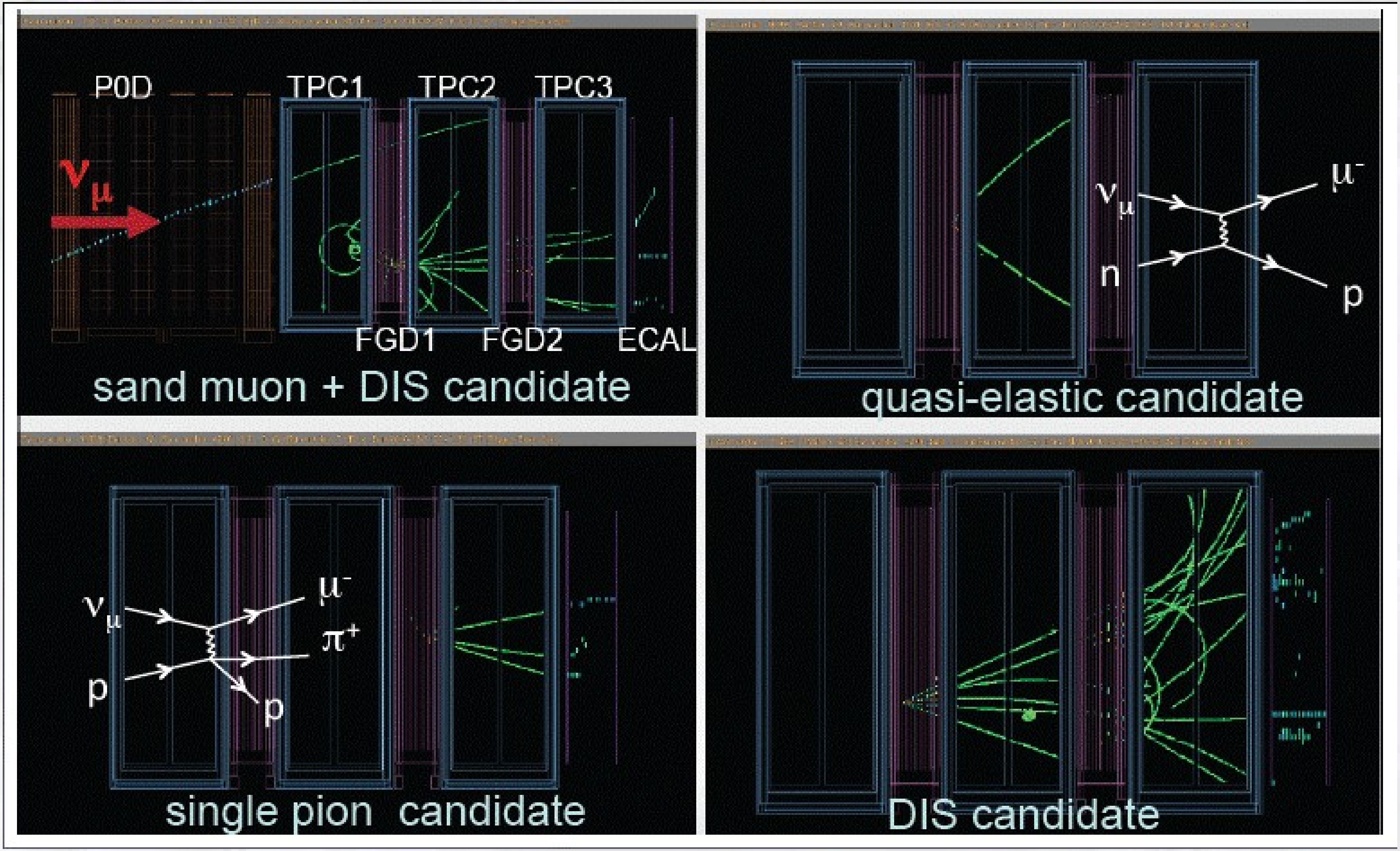
| Process | Cross section uncertainty relative to the CCQE total x-section |
|---|---|
| CCQE | energy dependent ($\sim \pm 7\%$ at 500 MeV) |
| CC $1\pi$ | 30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV) |
| CC coherent $\pi^0$ | 100% (upper limit from [30]) |
| CC other | 30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV) |
| NC $1\pi^0$ | 30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV) |
| NC coherent $\pi$ | 30% |
| NC other $\pi$ | 30% |
| Final State Int. | energy dependent ($\sim \pm 10\%$ at 500 MeV) |

Uncertainty of $\sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\%$

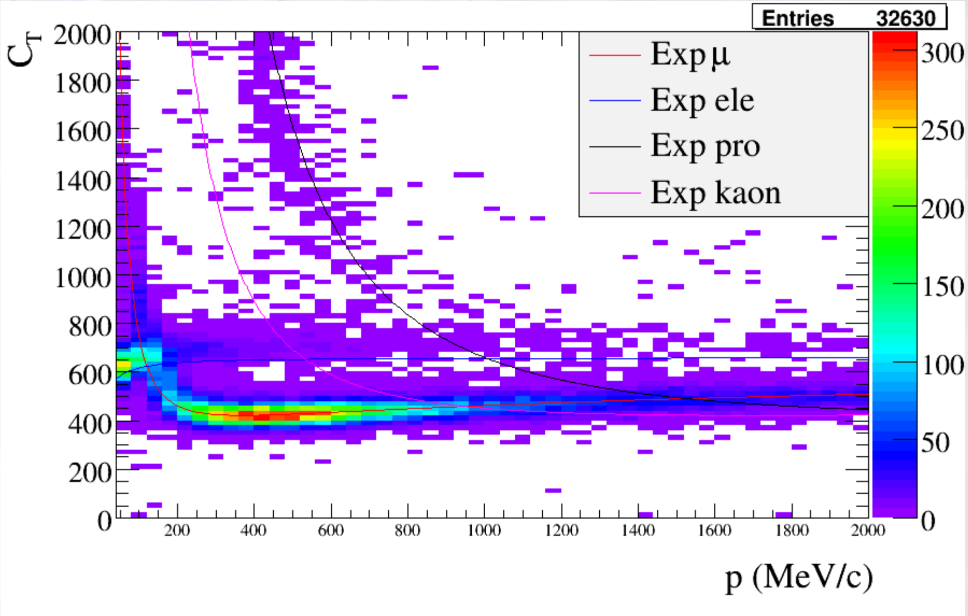


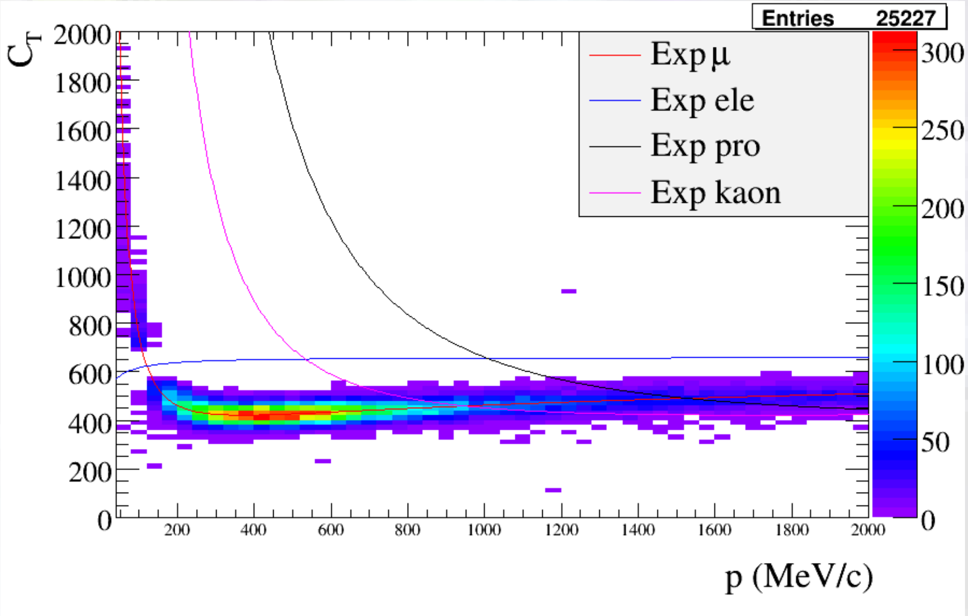

Total systematics:
14% for background to $\nu_e$ appearance, 8% to $\nu_\mu$ disappearance

# ND280 event gallery

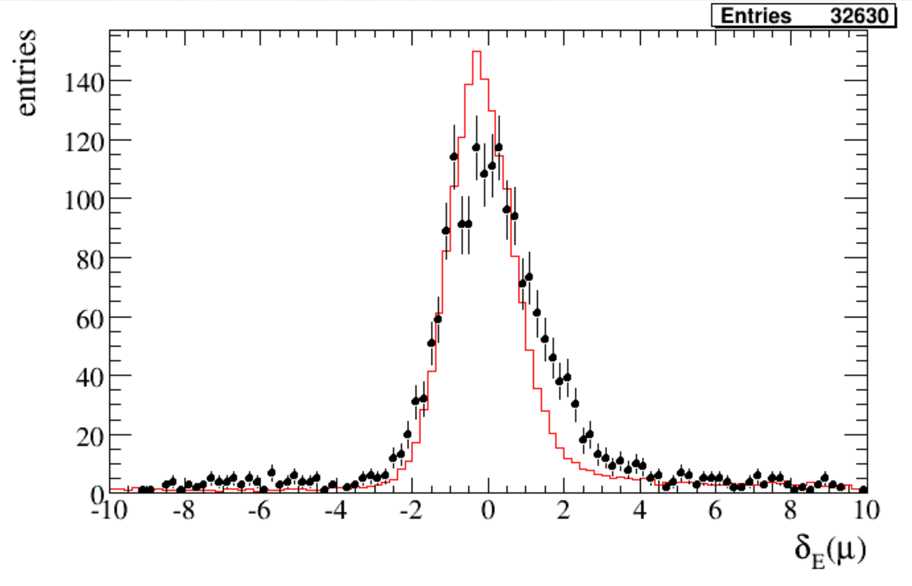


# Particle Identification in TPC

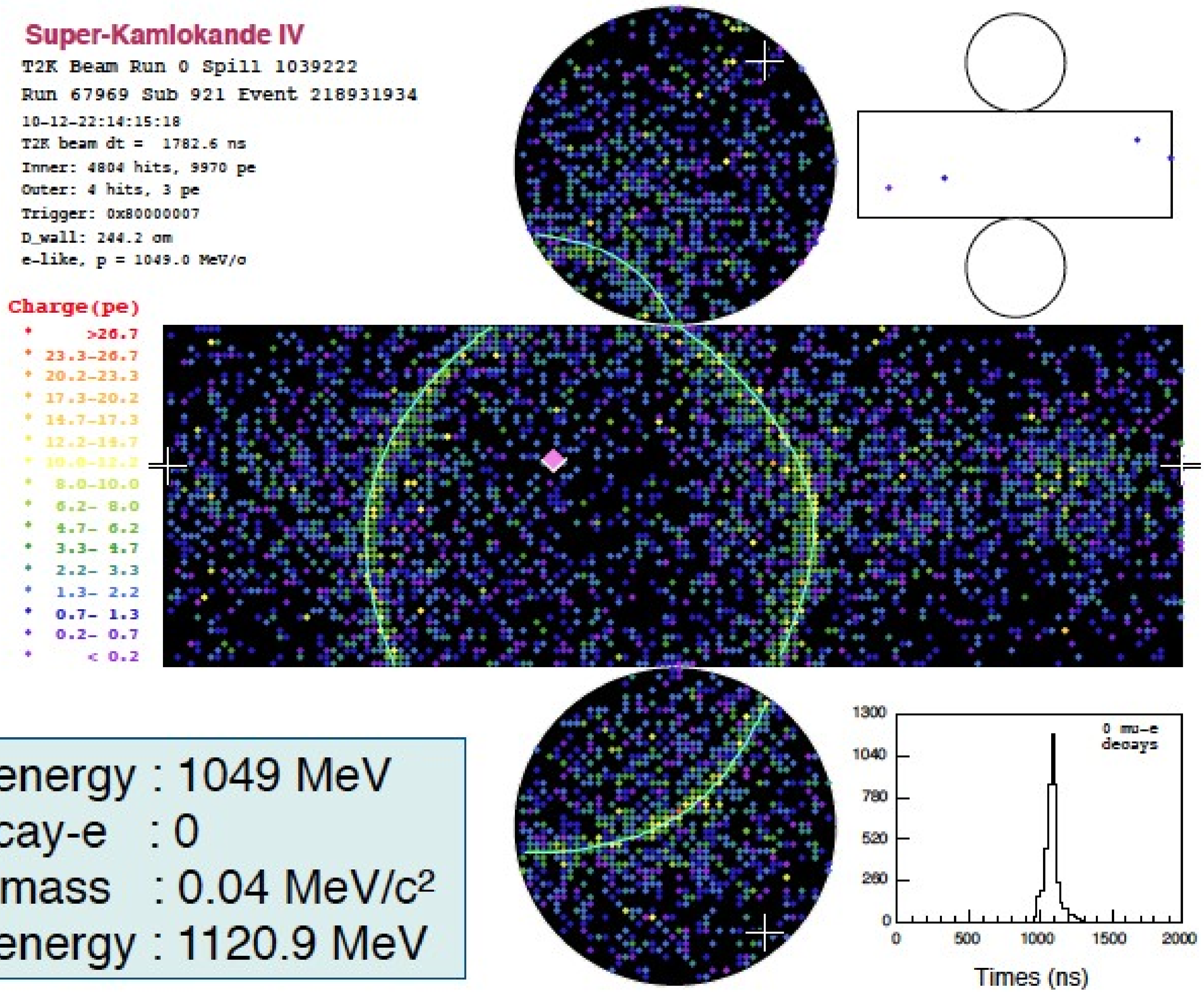



- PID in the TPC is accomplished comparing the particle dE/dX with the expected value for the predicted momentum.
- A pull is defined as the difference between the expected and measured value of the ionization rate divided by the deposited energy resolution.



# T2K $\nu_e$ Data Event Display




visible energy : 1049 MeV
\# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV

# Vertex Distribution Probabilities

- Though each vertex only has one vertex, there are many ways to look at them.
  - We have looked at the distributions defined in the next slide for FC and FCFV events.
- Can use KS test for the probability of the cumulative distribution
  - Concern about KS test for low statistics sample, so calculate probabilities from distributions of 100,000 toy MCs (assuming same number of events as our data)

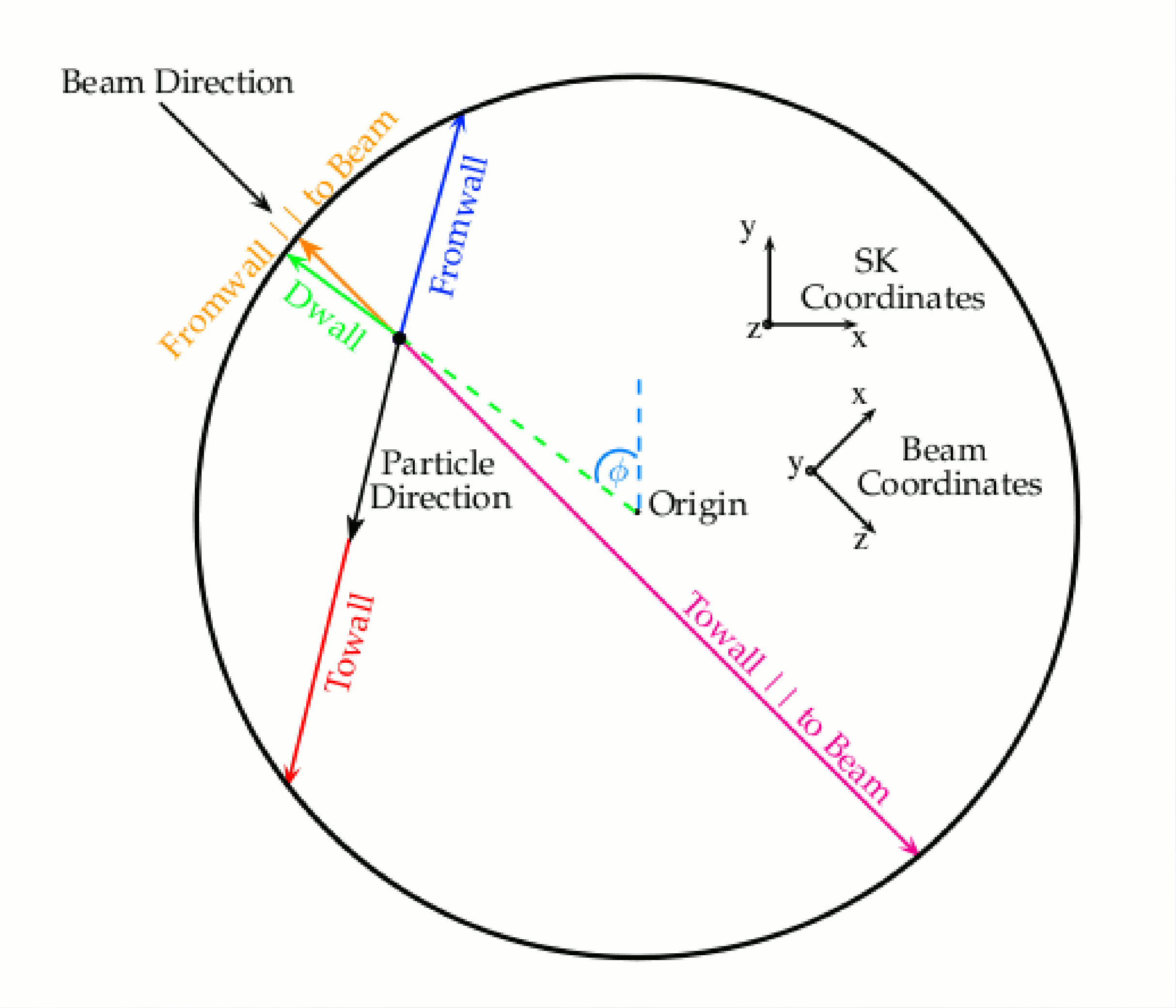
•Some of the most useful distributions:

| KS Toy MC Probabilities | 6 FCFV Events | 7 FC Events |
|---|---|---|
| Distance to nearest wall | 3.7% | 20.6% |
| From wall \|\| to beam | 0.14% | 1.4% |
| To wall \|\| to beam | 1.1% | 5.1% |
| $R^2$ | 3.1% | 10.9% |

For distributions relative to ID wall, it is more natural to include all 7 FC events

# Vertex Distribution Definition

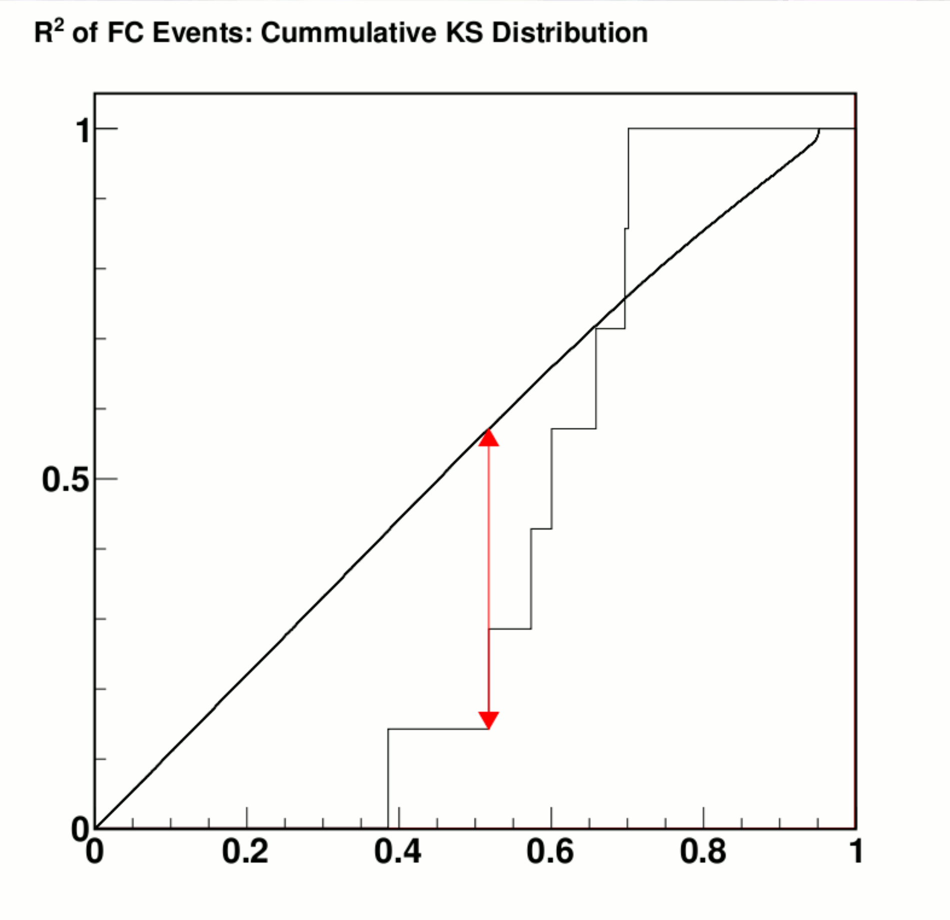
Cartoon showing what each vertex distribution looks like and defining the two coordinate system:

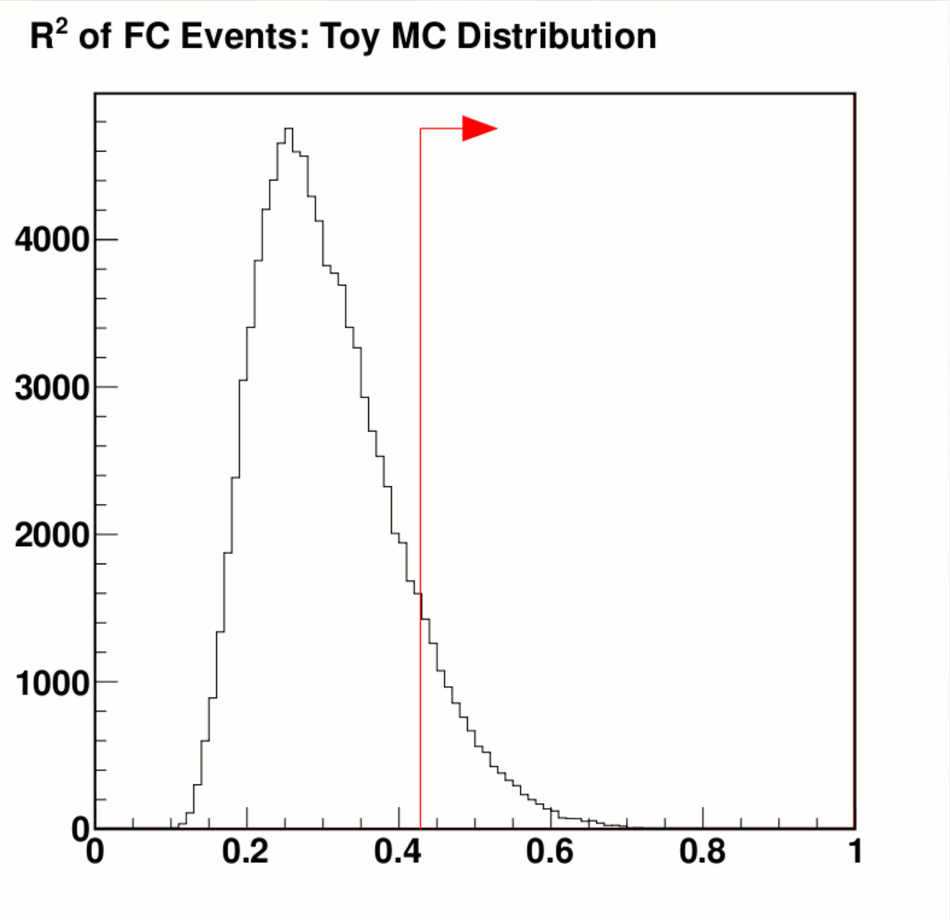


# KS + Toy MC example

Cumulative distribution to extract maximum cumulative distance

p-value comes from toy MCs' distribution of maximum cumulative distance



# MC Study of Sources Outside ID

Generated MC with events produced in material up to 550 cm outside of ID wall

**Sources of beam-induced background with True Vertex outside the ID**

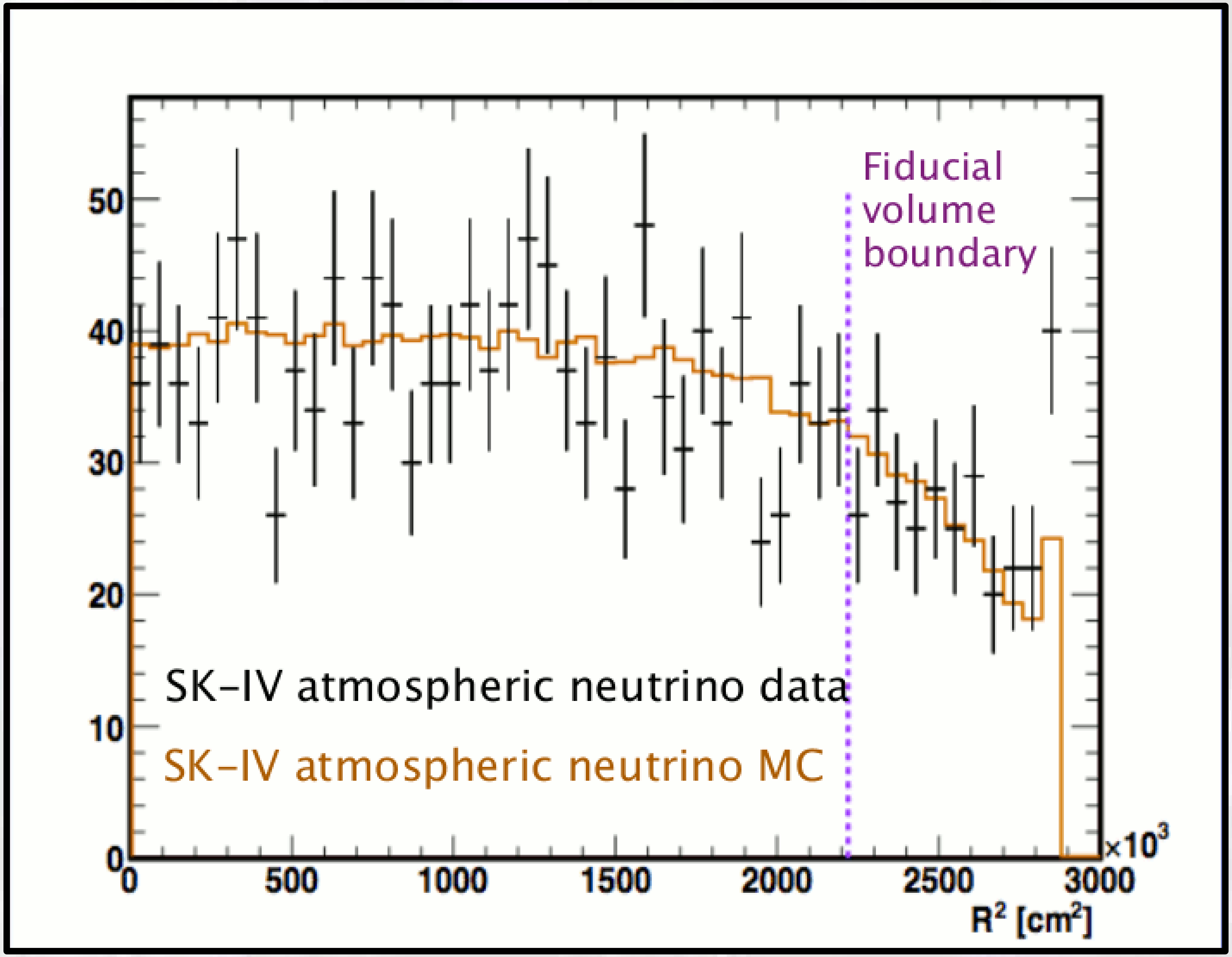
| Sample | Expected true vertex outside ID | Source of track, from MC truth* mis-id muon | pi0 photon | neutron | K-long | K-short |
|---|---|---|---|---|---|---|
| Nue Analysis Sample (w/ FV cut) | 3.16E-03 | 9% | 78% | 11% | 0.01% | <0.01% |
| Nue Analysis Sample (w/o FV cut) | 0.30 | 4% | 75% | 3% | <0.01% | <0.01% |

*percentages do not total to 100% because list here is not exhaustive
Expectation assumes $\sin^2\theta_{13} = 0.1,\ \Delta m^2 = 2.4 \times 10^{-3}\ \mathrm{eV}^2$.

No significant contribution to FCFV sample simulated sources outside of ID

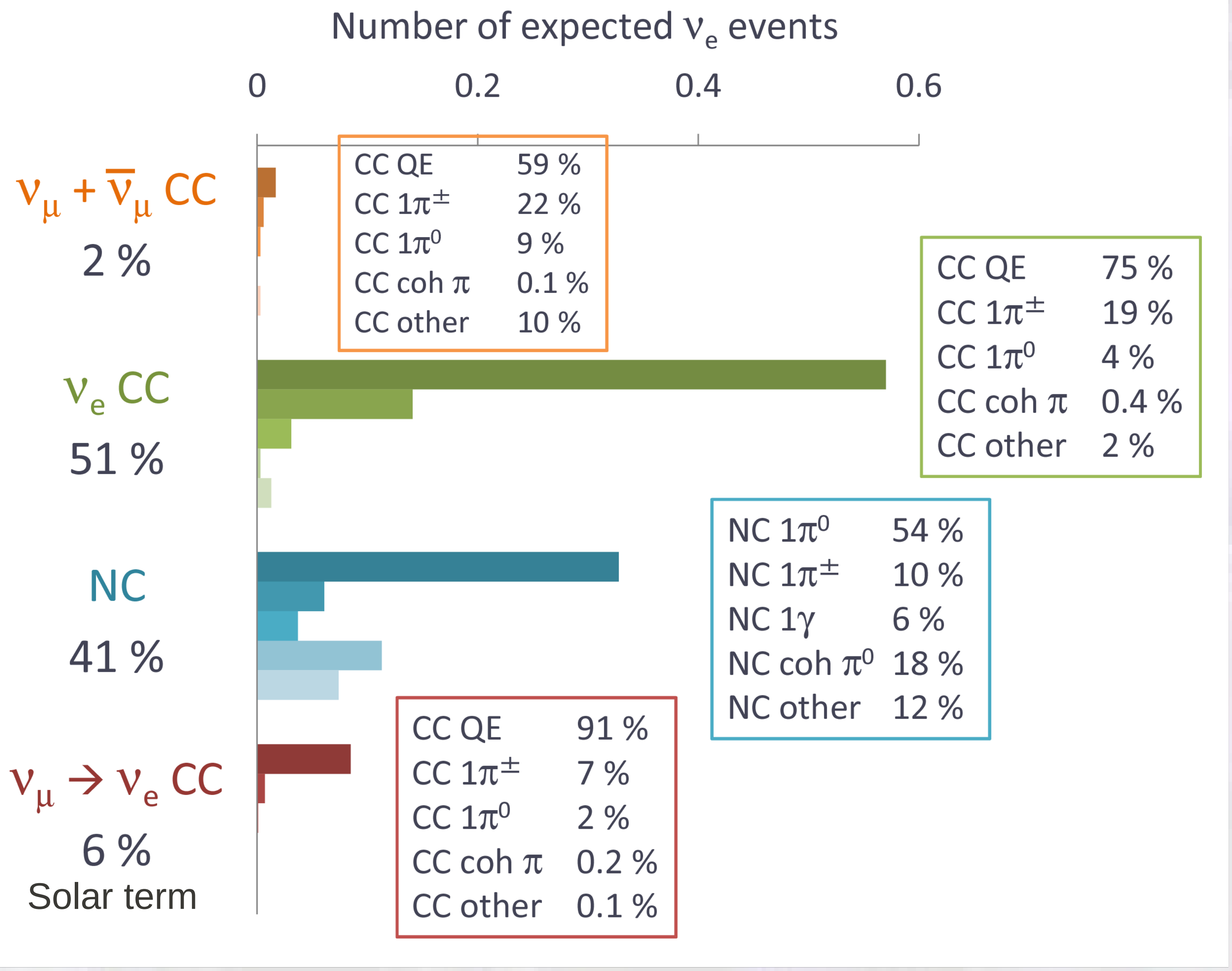
# Reconstruction @ SK

SK IV Sub-GeV e-like + T2K cuts → good agreement between data and MC inside and outside the FV



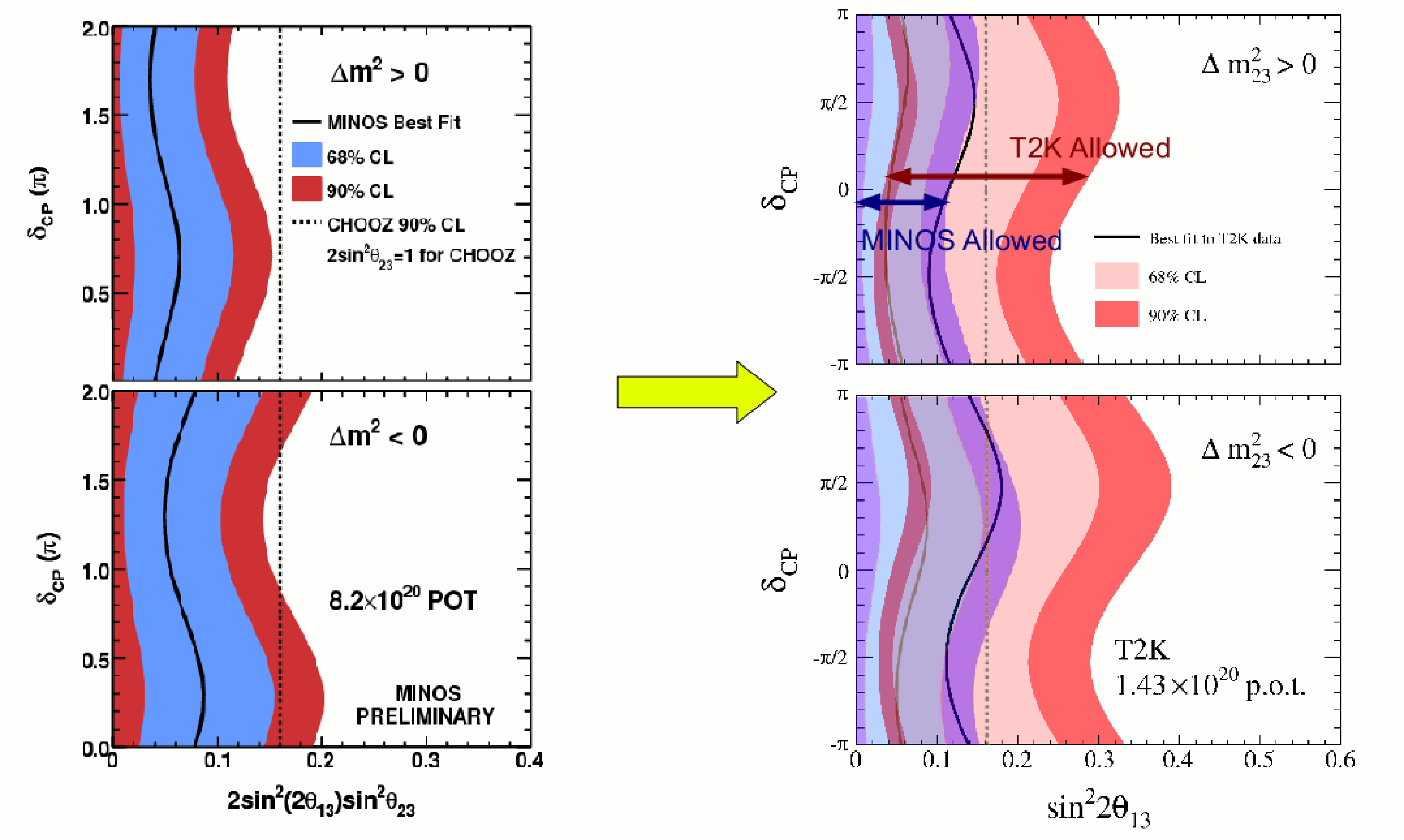
# Far Detector $\nu_e$ Background

$\sin^2(2\theta_{13}) = 0$



# $\nu_e$ Appearance Analysis

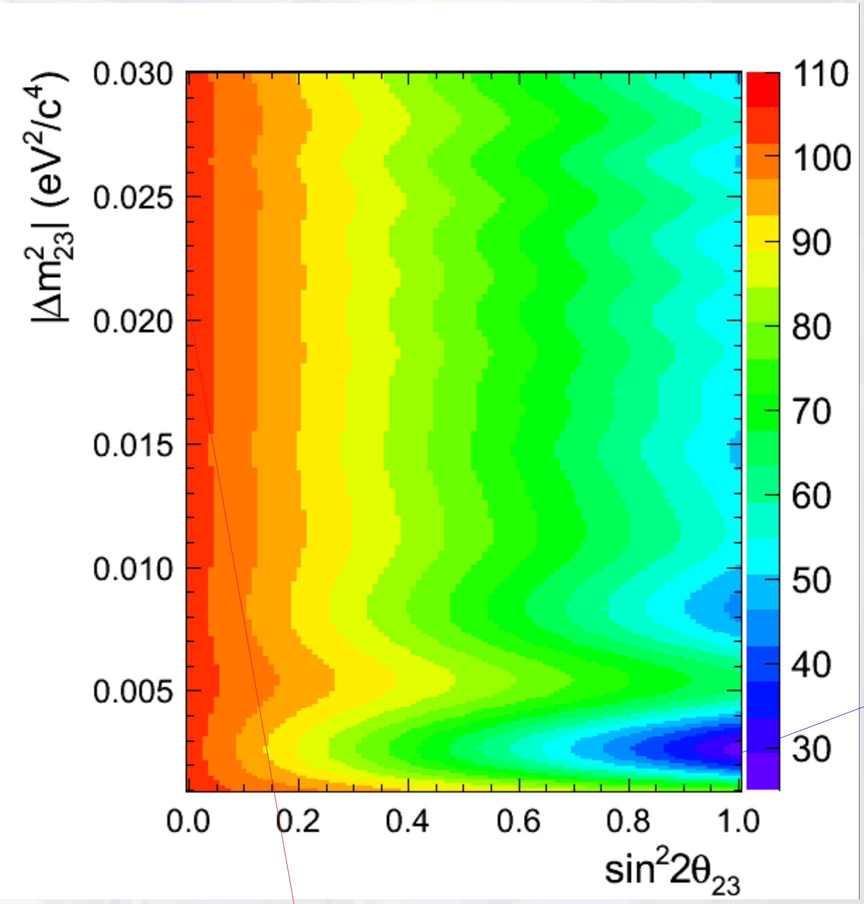
Comparison with MINOS:




Significant overlap of T2K and MINOS 90% CL allowed regions

# T2K $\nu_\mu$ Results

Number of SK expected events as a function of the oscillation parameters ($\Delta m^2_{23}$, $\sin^2(2\theta_{23})$):




$\sin^2 2\theta_{23}=1.0$ $\Delta m^2_{23}=0.0024$ $eV^2$

| | Data | MC w/ 2-flavor oscillation | | | | | | MC w/o osc. |
|---|---|---|---|---|---|---|---|---|
| | | Total | $\nu_\mu$CCQE | $\nu_\mu$CC non-QE | $\nu_e$CC | NC | | |
| Interaction in FV | - | **141** | 24.0 | 43.7 | 3.2 | 71.0 | | 243 |
| FCFV | **88** | **74.1** | 19.0 | 33.8 | 3.0 | 18.3 | | 166 |
| Single-ring | **41** | **38.7** | 17.9 | 13.1 | 1.9 | 5.7 | | 120 |
| $\mu$-like | **33** | **32.0** | 17.6 | 12.4 | < 0.1 | 1.9 | | 112 |
| $P_\mu$ > 200 MeV/c | **33** | **31.8** | 17.5 | 12.4 | < 0.1 | 1.9 | | 111 |
| N(decay-e) ≤ 1 | **31** | **28.4** | 17.3 | 9.2 | < 0.1 | 1.8 | | 104 |

$N^{exp}$ with oscillation: 28.4
$\sin^2 2\theta=1$, $\Delta m^2=2.4\times10^{-3}$ $eV^2$

$N^{exp}$ without oscillation: 104

# $\nu_\mu$ oscillation fit methods

- The oscillation fits are performed assuming a two flavour oscillation.
- We developed two independent oscillation fits to extract the oscillation parameters:

**Method A:**
Maximum likelihood with fitting of the systematics parameters:

$$L(sin^2 2\theta, \Delta m^2, \vec{f}) = L_{norm}(sin^2 2\theta, \Delta m^2, \vec{f}) \cdot L_{shape}(sin^2 2\theta, \Delta m^2, \vec{f}) \cdot L_{syst}(\vec{f})$$

$L_{norm}$ → Poisson distribution of the total number of events

$L_{shape}$ → un-binned spectrum shape

**Method B:**
Comparison of the observed spectrum with the expected spectrum varying oscillation parameters to minimize:

$$\chi^2 = 2\sum_{i=1}^{N}\left[n_i^{obs} \cdot ln\left(\frac{n_i^{obs}}{n_i^{exp}}\right) + n_i^{exp} - n_i^{obs}\right]$$

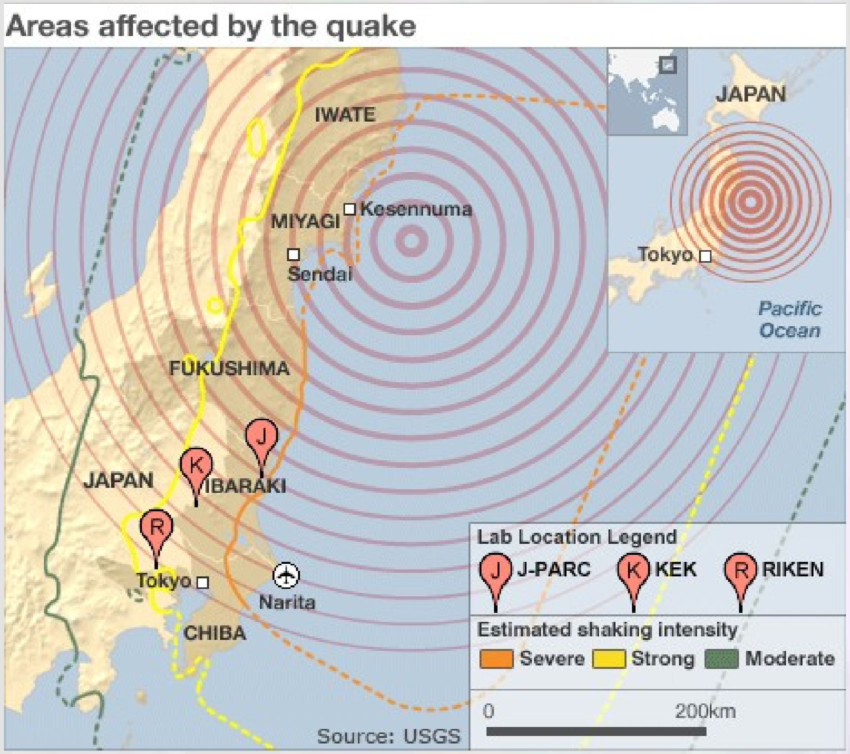
i = bin number in SK energy

$n_i^{obs(exp)}$ number of observed (expected) events in the i-th bin

In this method systematic *f* parameters are not fitted

# Earthquake on March 11th

Earthquake hit at 14:46 on Mar. 11th:
- Magnitude 9.0 in Richter scale
- Seismic intensity 6+ at Tokai
- No Tsunami reached J-PARC
- All electric power was stopped
- Maintenance day=Acc. not operated
- SuperKamiokande not affected



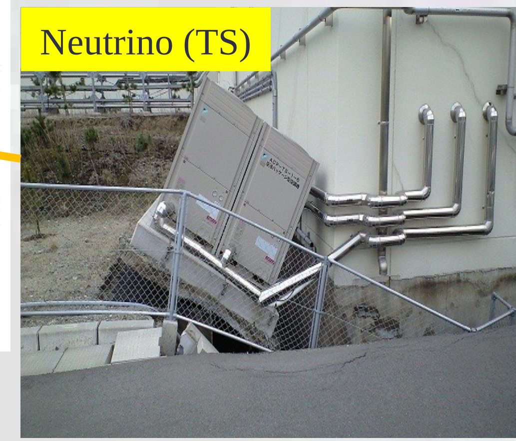

Damages
- Lots of subsidence happened here&there
- LINAC tunnel  sunk ~4cm at maximum, tunnel is bent
- RCS elec-power facility ground sink damaged the facility
- Big water leak into MR tunnel from big cracks → mostly fixed
- 1~2m drop of surrounding ground of neutrino facility
- No serious damages found on accelerator, beamline and near detectors components

Recovery work started in March and it is proceeding steadily.

# Ground Level Damage....

LINAC

RCS (elec yard)



Neutrino (TS)

**Severe subsidence here and there (1~2m depth)**
**Near by piping/cabling were damaged**

LINAC

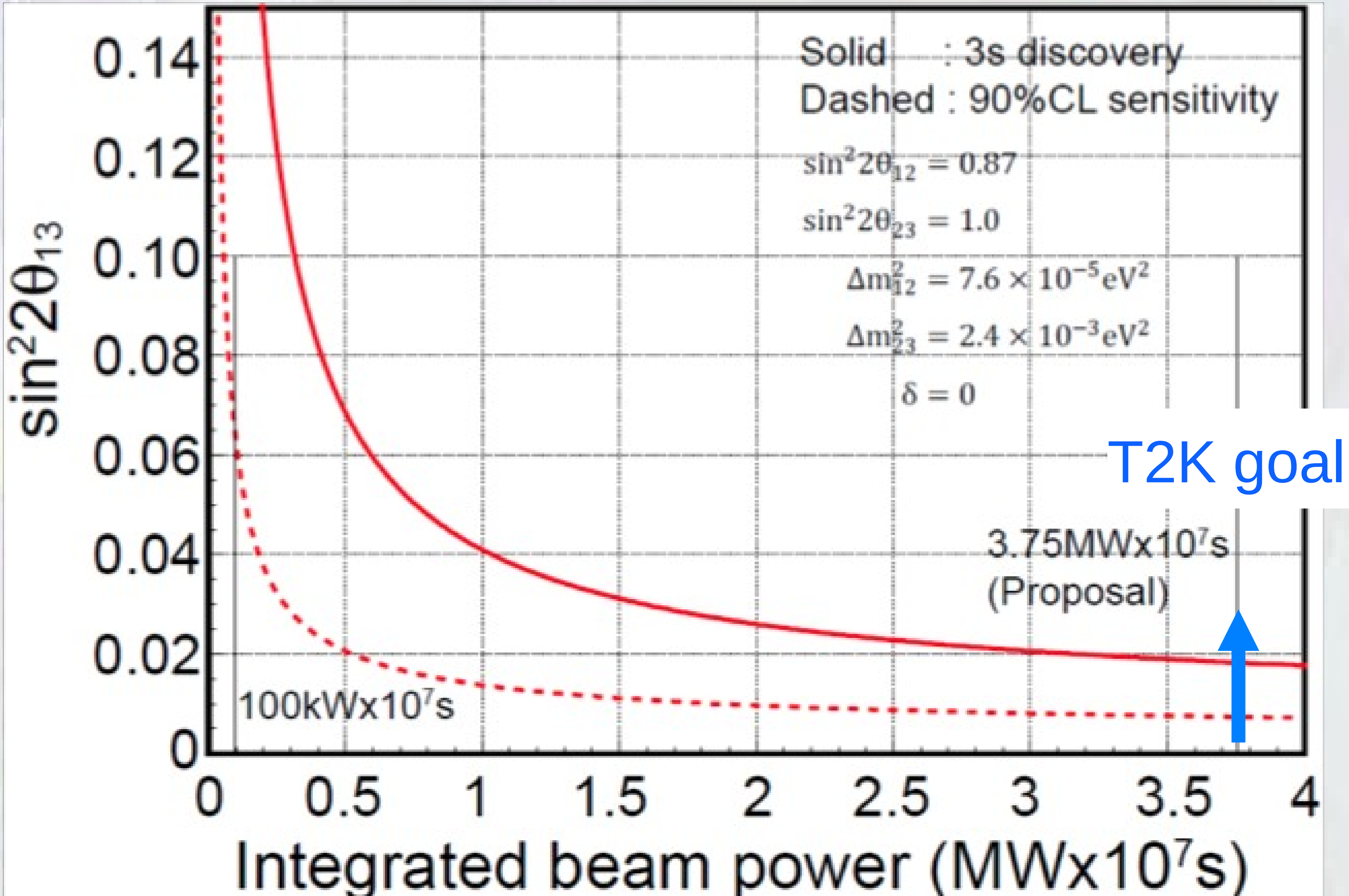
Neutrino (Dump)

Neutrino (Dump)

# ....Being Rapidly Repaired




# T2K $\theta_{13}$ Sensitivity




Final results with 3.75 x $10^7$ MW*sec (8 x $10^{21}$ POT)