NEW ν_e Appearance Results from the T2K Experiment

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13 June 2012

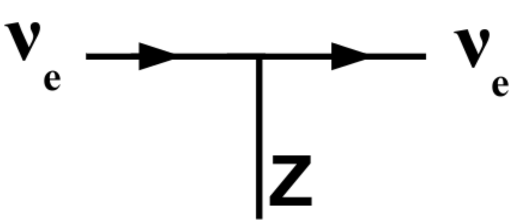
Outline

- Physics motivation: Neutrinos & Oscillations
- Overview of the T2K experiment
- Data taking at T2K
- ν_e analysis:
  - Selection criteria
  - Expected backgrounds
  - Systematic uncertainty
  - New data set
- New oscillation results
- Summary & conclusions

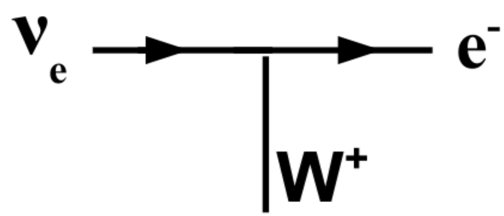
Neutrino Basics

- Weakly interacting isospin partners of charged leptons

Neutral current



Charged current



- Standard model includes three massless stable neutrinos, but...

As early as fifty years ago, discussions of massive neutrinos and oscillations had begun!

a) The weak neutrinos must be re-defined by a relation

$$\left.\begin{aligned} \nu_e &= \nu_1 \cos\delta - \nu_2 \sin\delta, \\ \nu_\mu &= \nu_1 \sin\delta + \nu_2 \cos\delta. \end{aligned}\right\} \qquad (2\cdot 18)$$

The leptonic weak current (2·9) turns out to be of the same form with (2·1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e \rightleftarrows \nu_\mu$ induced by the interaction (2·10). If the mass difference between ν_2 and ν_1, i.e. $|m_{\nu_2} - m_{\nu_1}| = m_{\nu_2}$*) is assumed to be a few Mev, the transmutation time $T(\nu_e \rightleftarrows \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast neutrinos with a momentum of ~Bev/c. Therefore, a chain of reactions such as[10)]

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad (2\cdot 19a)$$

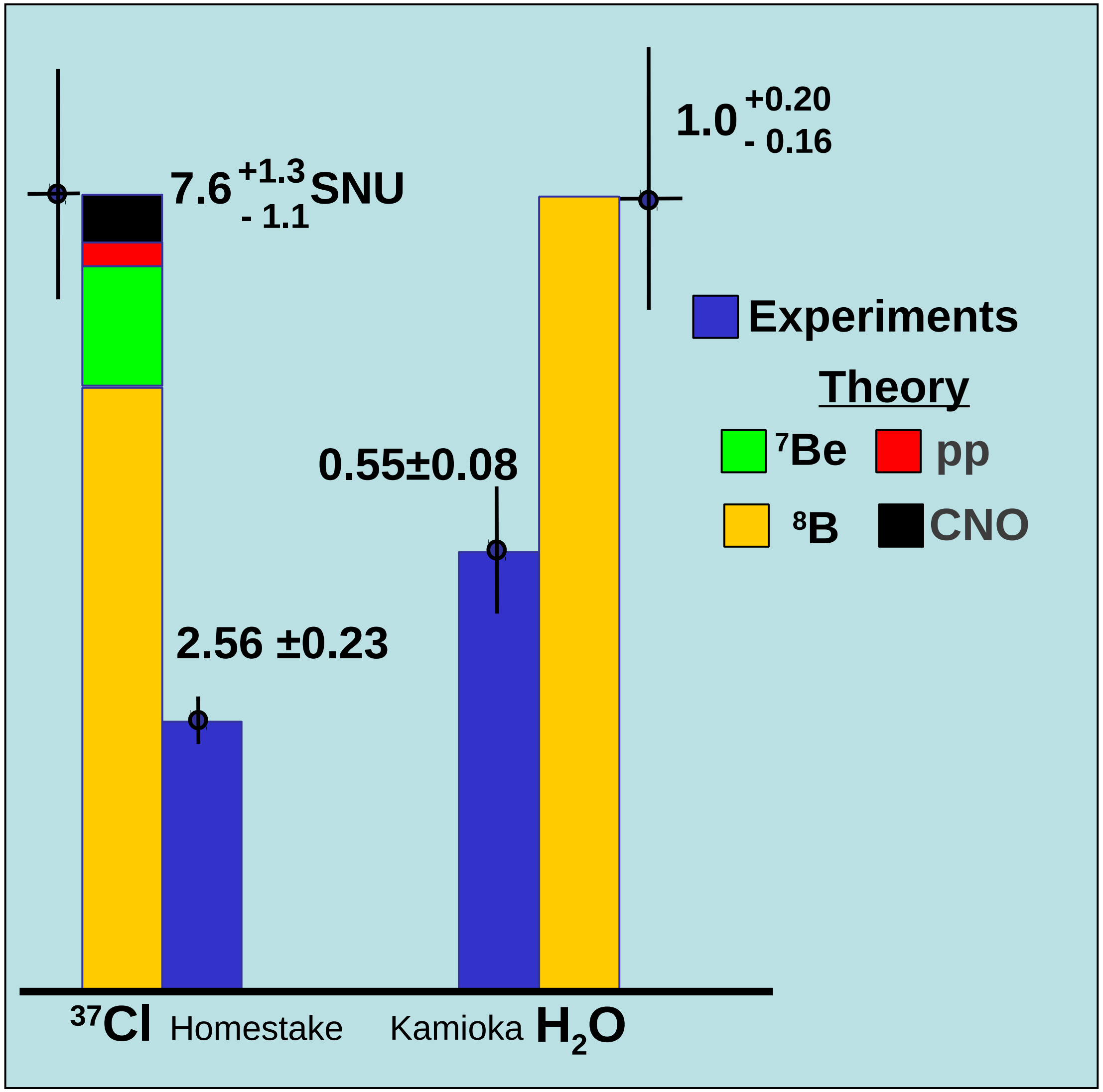
$$\nu_\mu + Z(\text{nucleus}) \to Z' + (\mu^- \text{ and/or } e^-) \qquad (2\cdot 19b)$$

is useful to check the two-neutrino hypothesis only when $|m_{\nu_2} - m_{\nu_1}| \lesssim 10^{-6}$ Mev

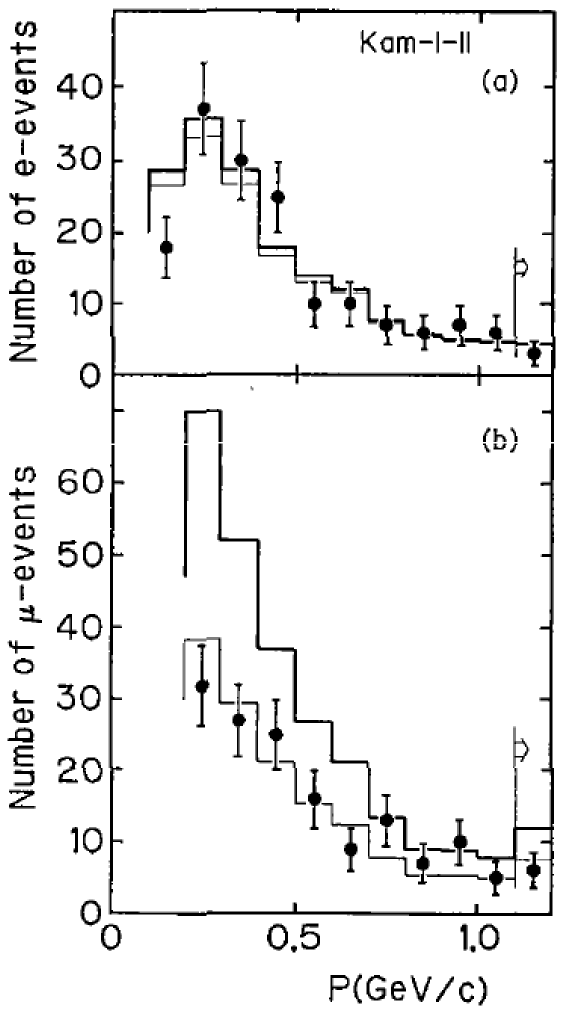
Maki, Nakagawa, Sakata (June 1962)

Early Hints of Oscillation

Solar Neutrinos

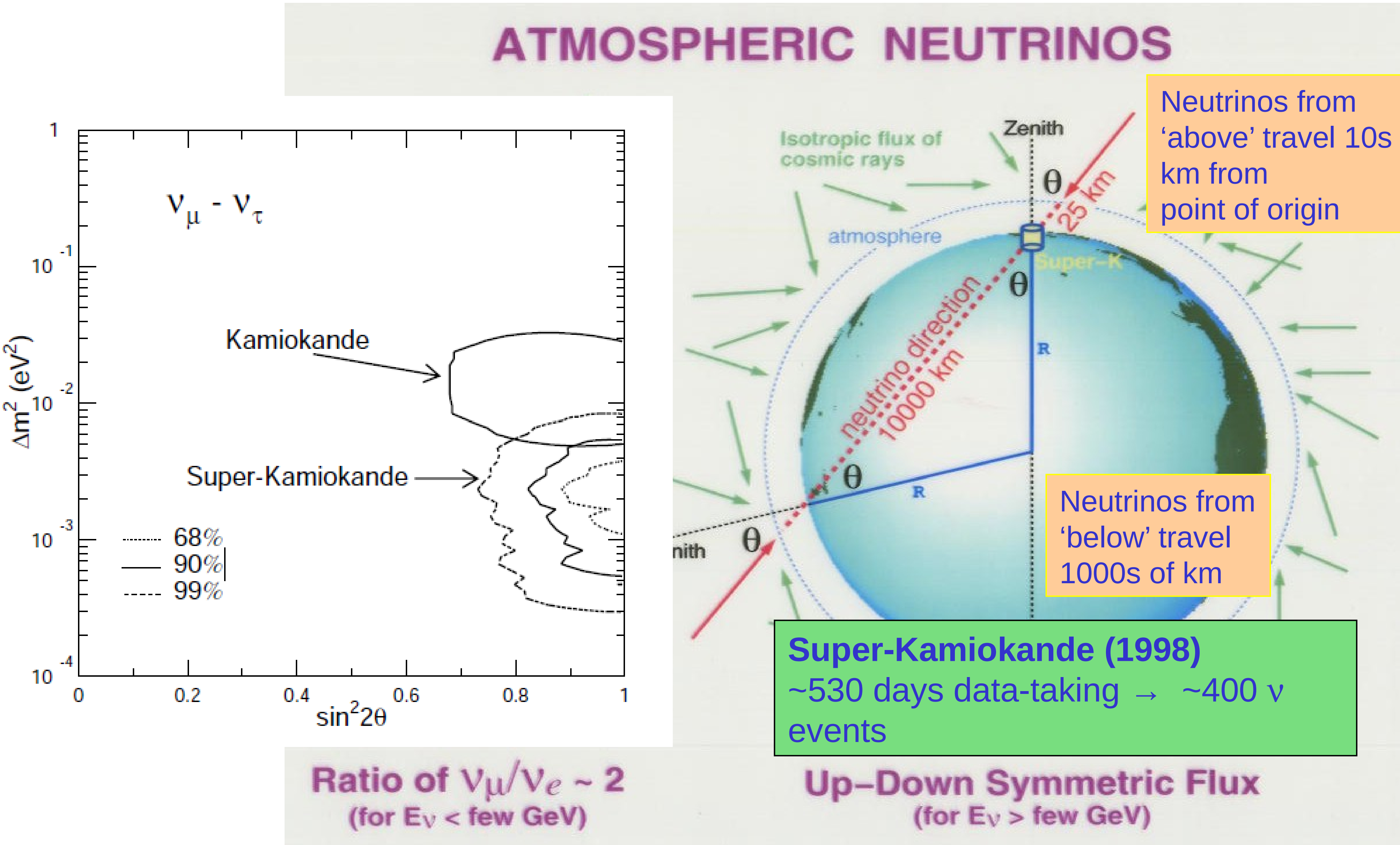


Atmospheric Neutrinos



Kamiokande (1992)

1998: Neutrino Mass!



Neutrinos from 'above' travel 10s of km from
point of origin

Neutrinos from 'below' travel 1000s of km

Super-Kamiokande (1998)
~530 days data-taking → ~400 ν events

Oscillation Basics

- Neutrinos have mass!

Flavour eigenstates: ν_e, ν_μ, ν_τ **Mass eigenstates:** ν_1, ν_2, ν_3

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle$$

- Produced and interact as flavour eigenstates;

propagate as mass eigenstates: $$|\nu_l(L)\rangle = \sum_{i=1}^{3} U_{li} e^{-i m_i^2 L/2E} |\nu_i(0)\rangle$$

where:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillations Probability

- Parameterization of the PMNS matrix U_{li} :

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

- Contains a CP violating phase (δ)

- Oscillation probability depends on energy (E), distance travelled (L), the mixing matrix (U), and the difference in the squares of the neutrino masses (Δm^2)

$$P_{\alpha\to\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Experimental Probes

- Parameterization of the PMNS matrix U_{li} :

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

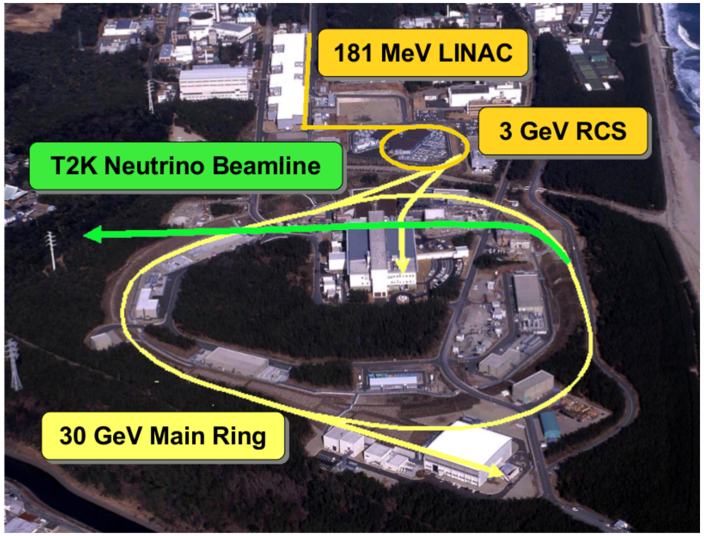
Probed with atmospheric neutrinos, long baseline accelerator neutrinos (1998 onwards)

Probed with solar neutrinos, long baseline reactor neutrinos (2001 onwards)

Probed with: long baseline accelerator neutrinos, short baseline reactor neutrinos (unknown at start of last year!)

2010 – 2012: Race For θ_{13}

Two types of experiments:



1) Long baseline accelerator expts:

Look for ν_e appearance in a ν_μ beam

→ MINOS, T2K, NOνA

2) Short baseline reactor expts:

Look for $\overline{\nu_e}$ disappearance

→ Double Chooz, Daya Bay, RENO

Measuring θ_{13}

Long baseline accelerator: Sensitive to θ_{13}, δ, mass hierarchy

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \;& \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}} \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
&+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
&-8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
&+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

CP violating (flips sign for anti-ν)

Solar

Matter

where:

$C_{ij} = \cos(\theta_{ij})$

$S_{ij} = \sin(\theta_{ij})$

$\Delta_{ij} = \Delta m_{ij} (L/4E)$

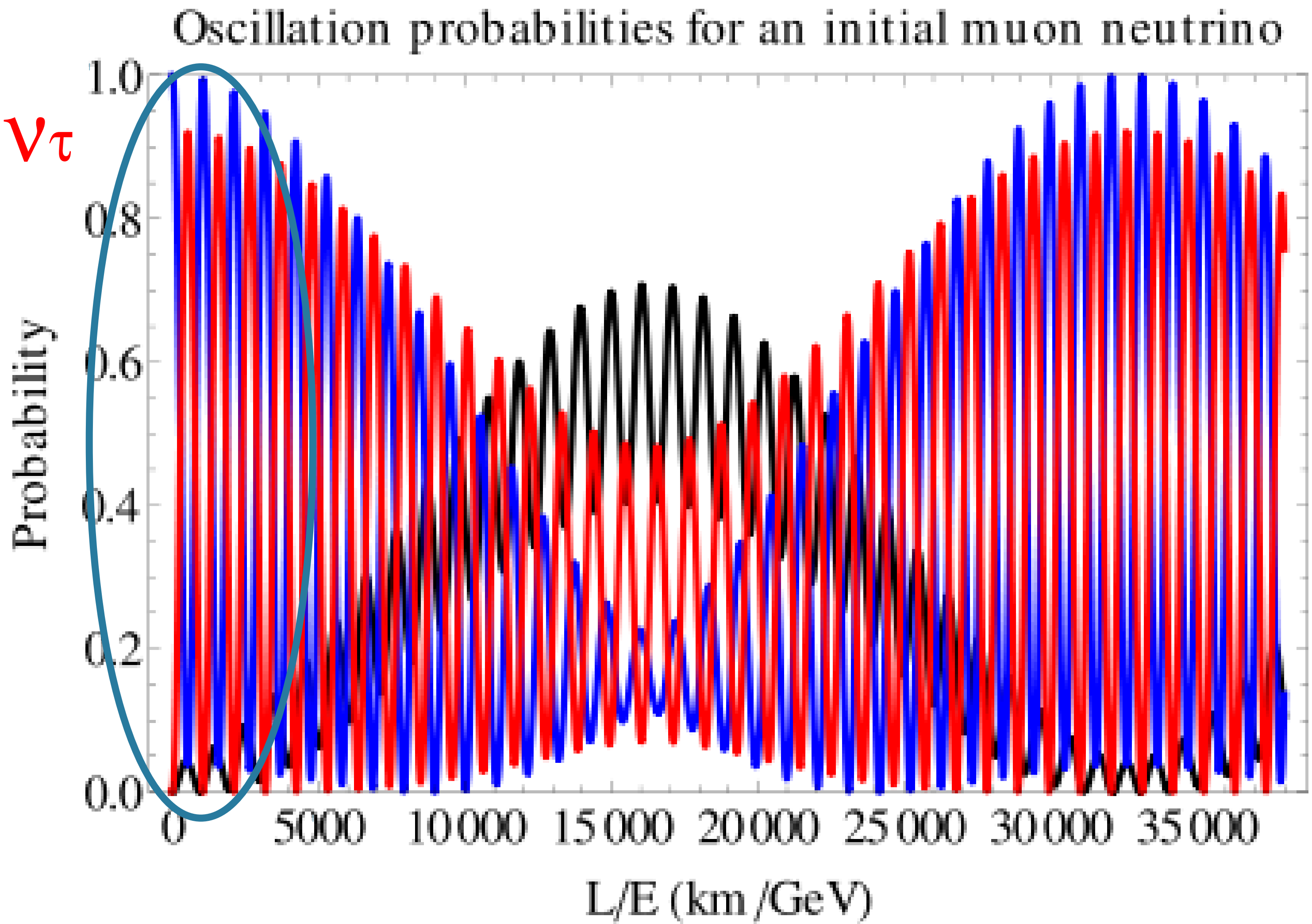
Short baseline reactor: Sensitive only to θ_{13}

$$P_{\mathrm{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m_{31}^2 L/E)$$

Oscillation @Accelerators

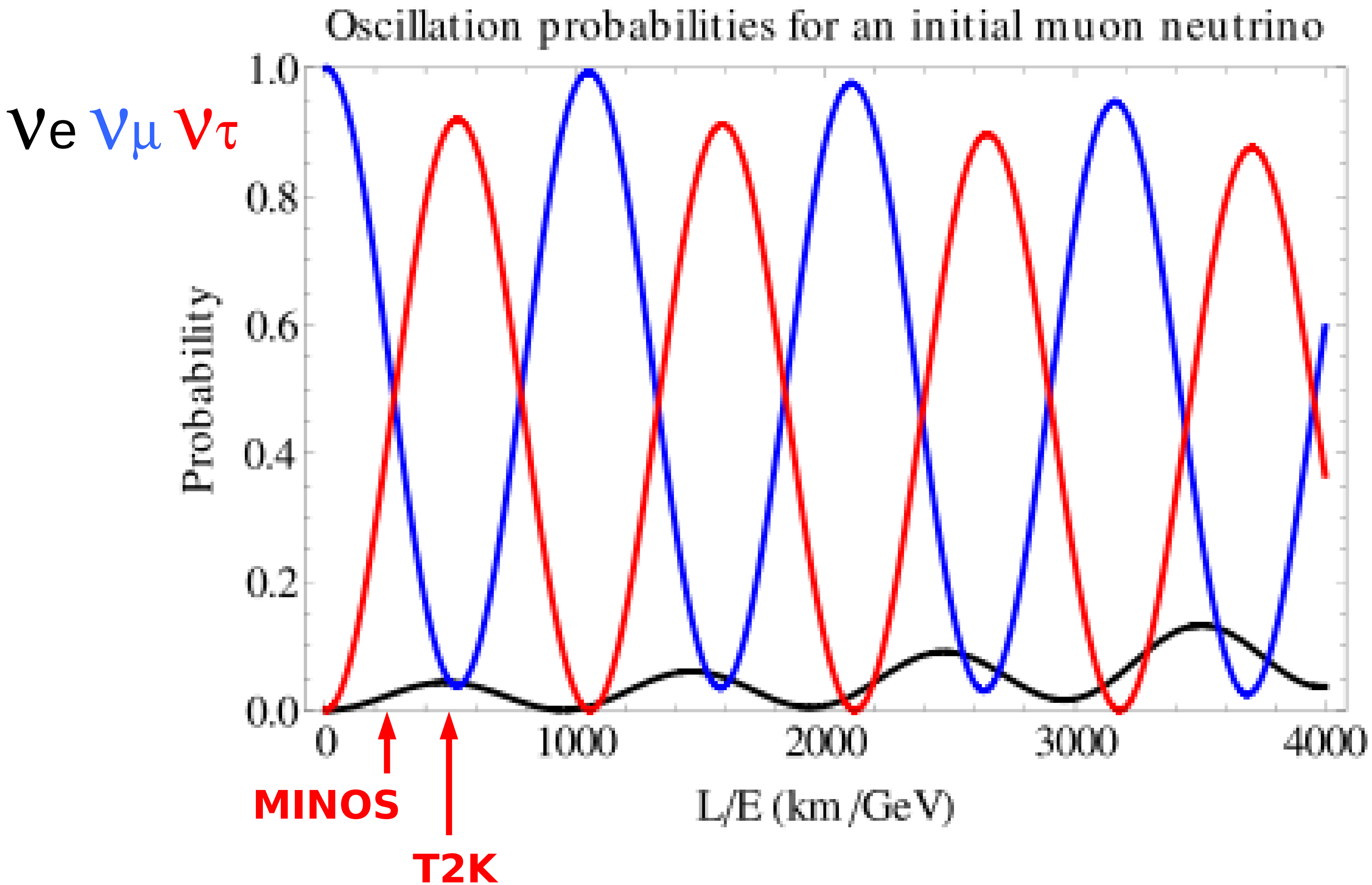
Long baseline accelerator: Sensitive to θ_{13}, δ, mass hierarchy

ν_e ν_μ ν_τ

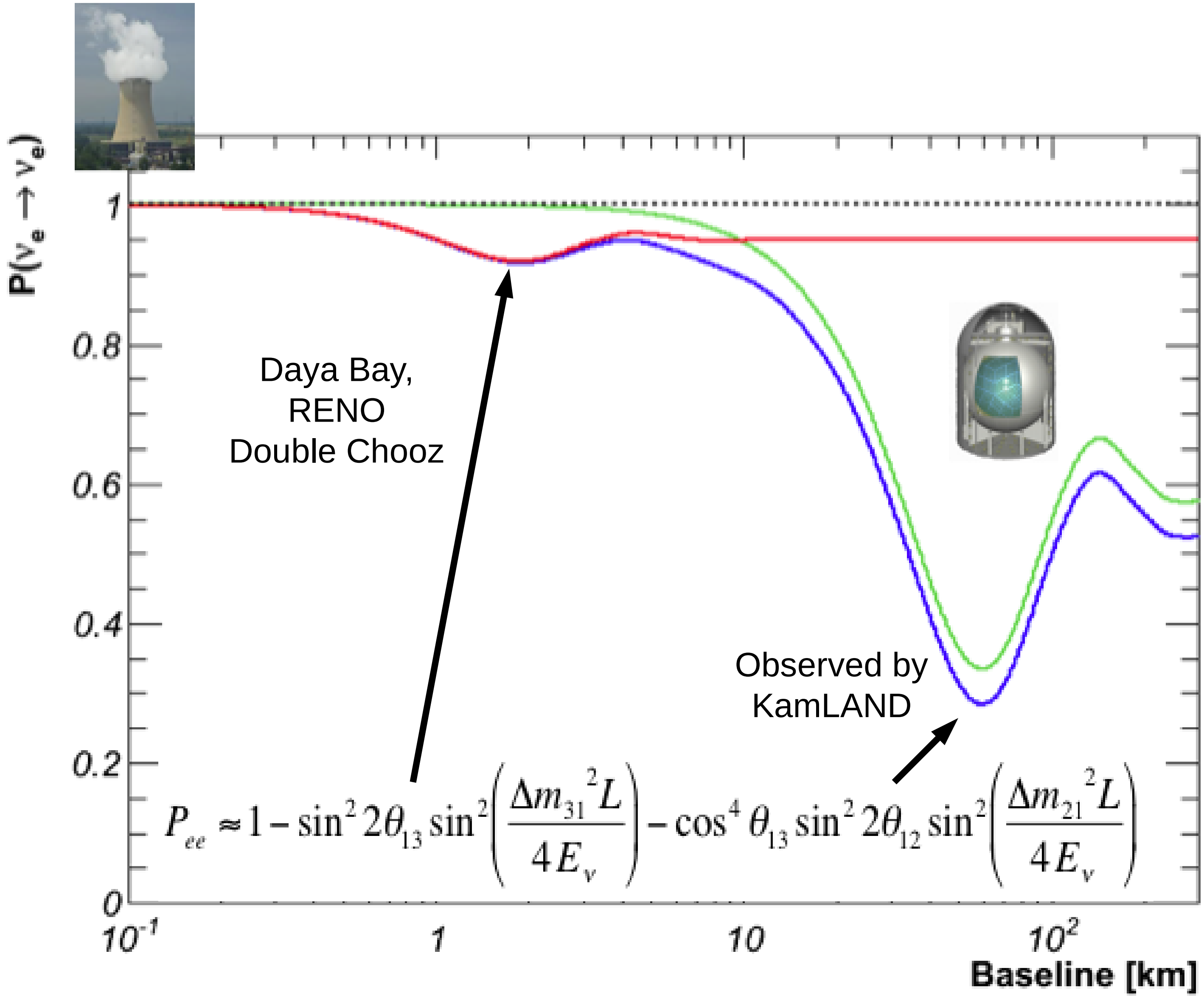


Oscillation @Accelerators

Long baseline accelerator: Sensitive to θ_{13}, δ, mass hierarchy



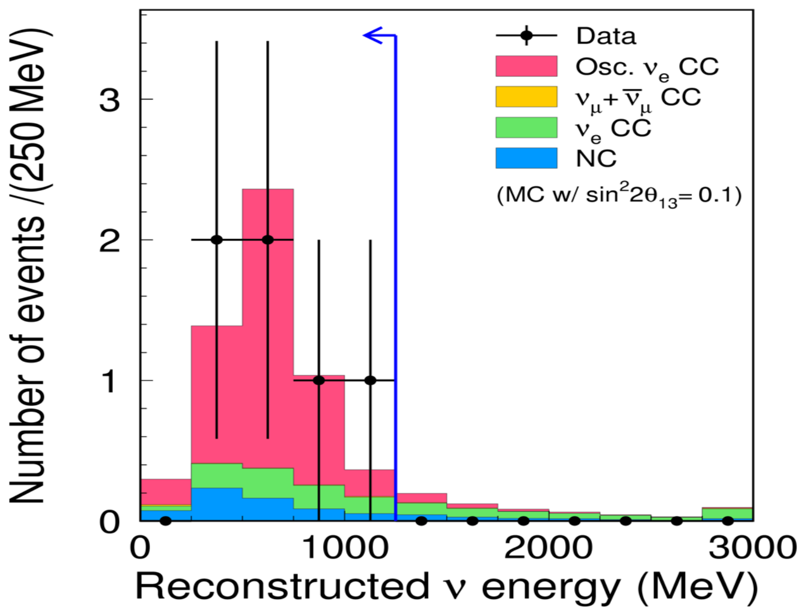
Oscillation @Reactors

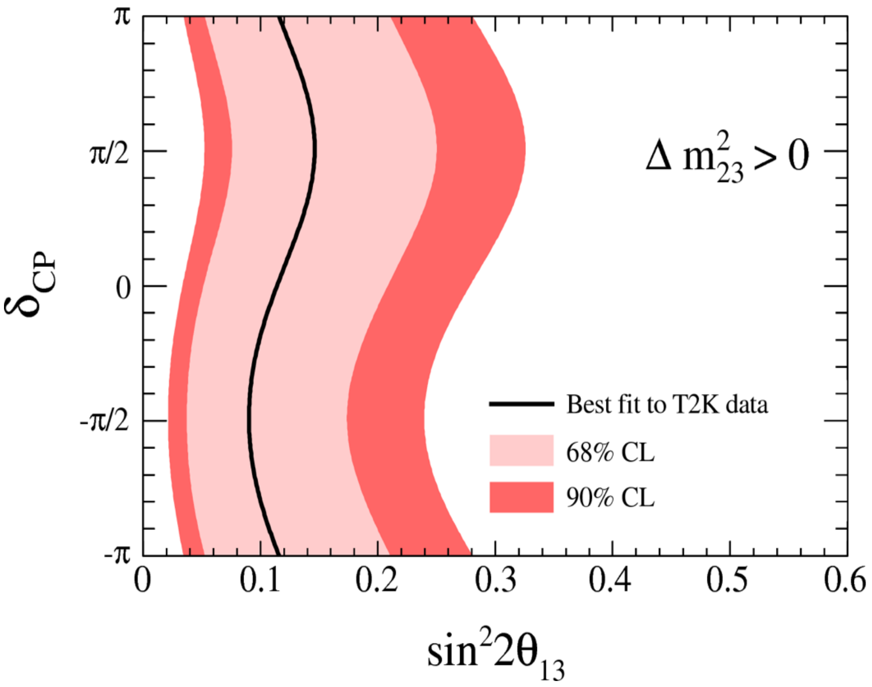


θ_{13} Results: Accelerators

<u>One year ago today:</u> T2K announces first indications of θ_{13}

June 13th 2011 – Six electron neutrino events are observed,
with 1.5 ± 0.3 background events expected



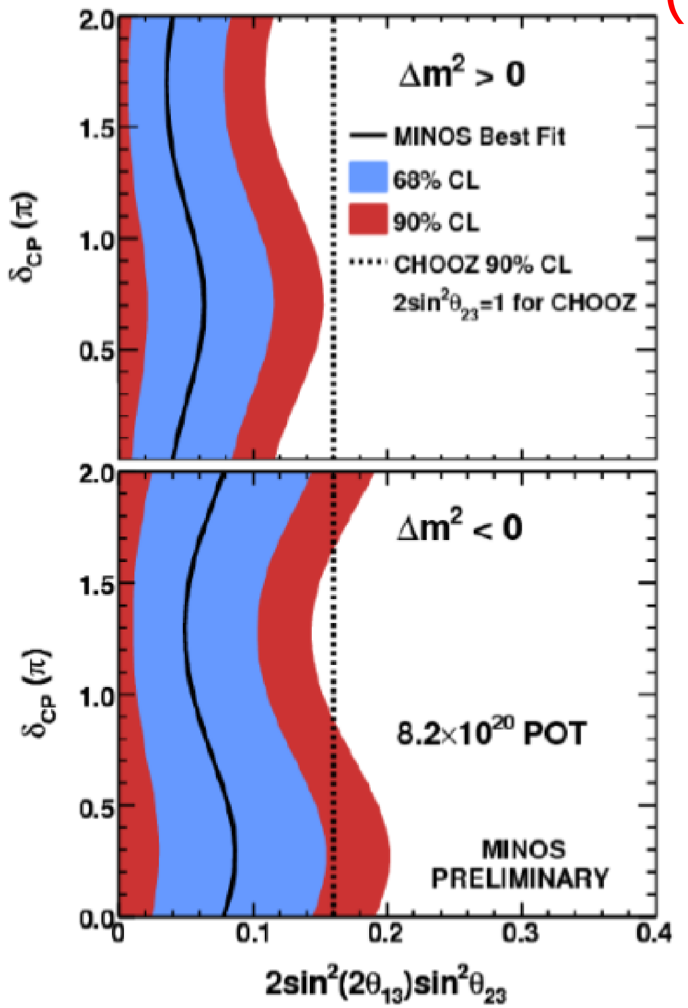


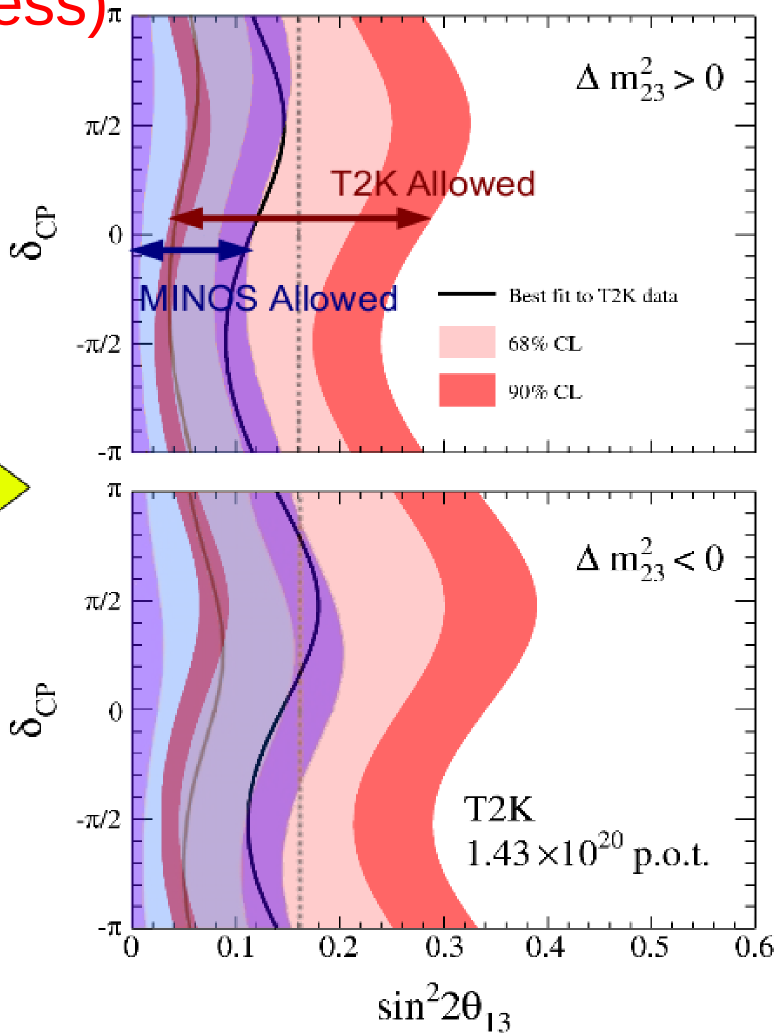
P-value (assuming no oscillations) is 0.007, or 2.5σ.

θ_{13} Results: Accelerators

<u>One week later:</u> MINOS sees 62 evts w/ 49.5 ± 2.8 (sys) ± 7.0 (stat) BG

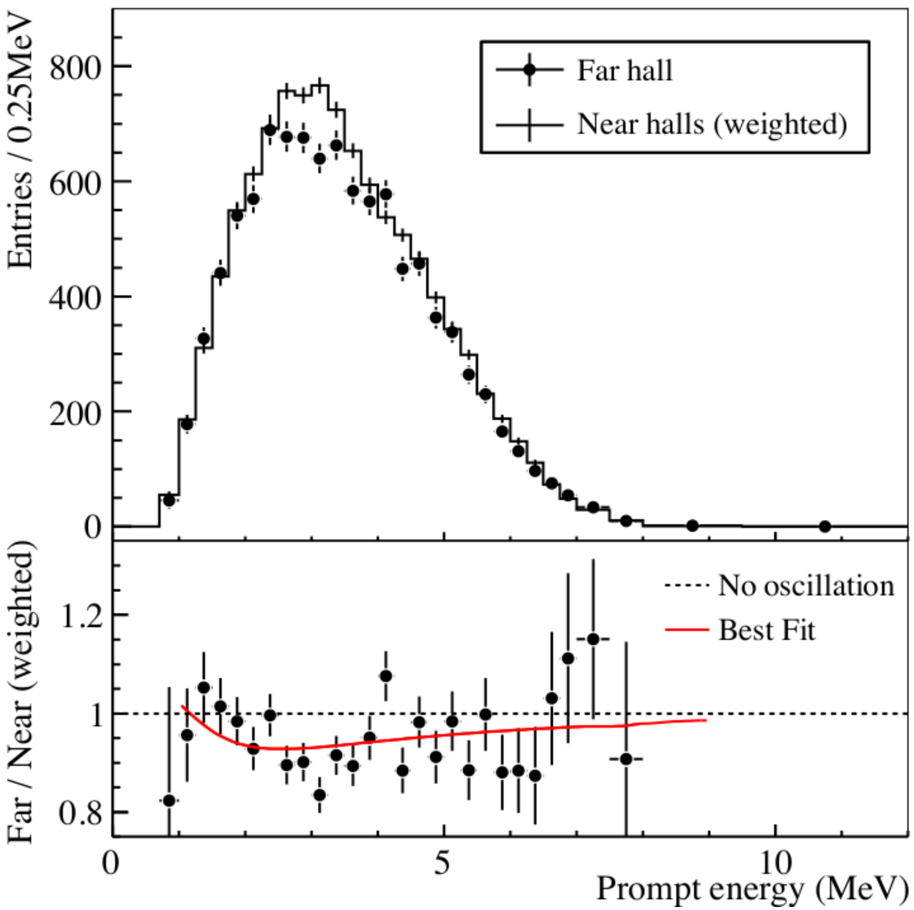
(1.7σ excess)





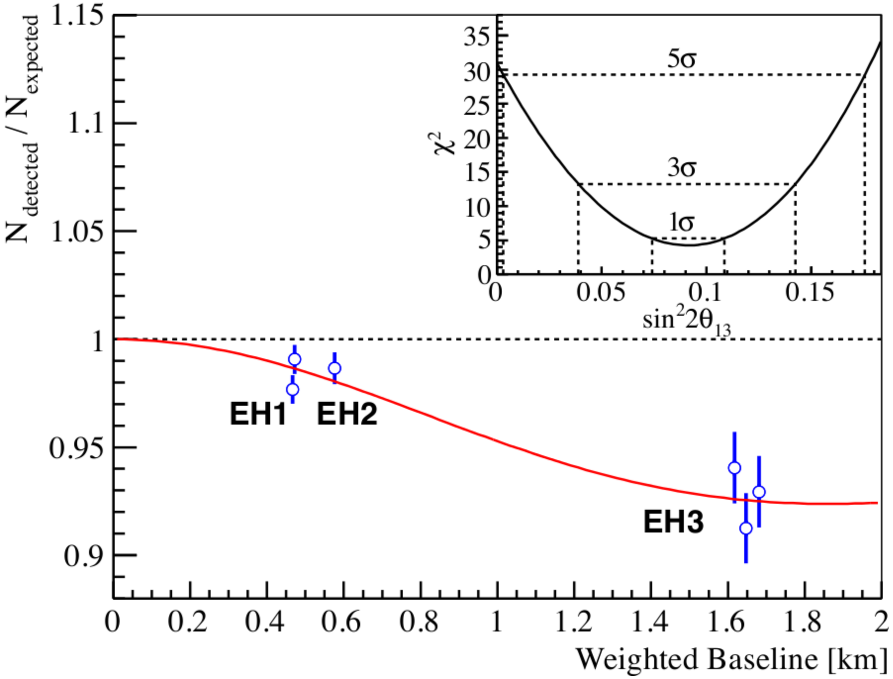
Significant overlap of T2K and MINOS 90% C.L. allowed regions

March 2012: **Daya Bay first to see θ_{13} via disappearance channel**



$\sin^2(2\theta_{13}) = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{sys})$

($\theta_{13} = 0$ excluded at 5.2σ)



Similar results followed one month later from RENO

Oscillation Parameters

- Standard parameterization for Dirac neutrinos has:
  3 mixing angles, 2 mass square differences, 1 CP phase

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

- What do we know?

$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$ $\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5}$ eV^2 SK, SNO, KamLAND

$\sin^2(2\theta_{23}) > 0.92$ (90% C.L.) $\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 SK, K2K, MINOS

$\sin^2(2\theta_{13}) = 0.103 \pm 0.017$ T2K, MINOS, Daya Bay, RENO

Open Questions

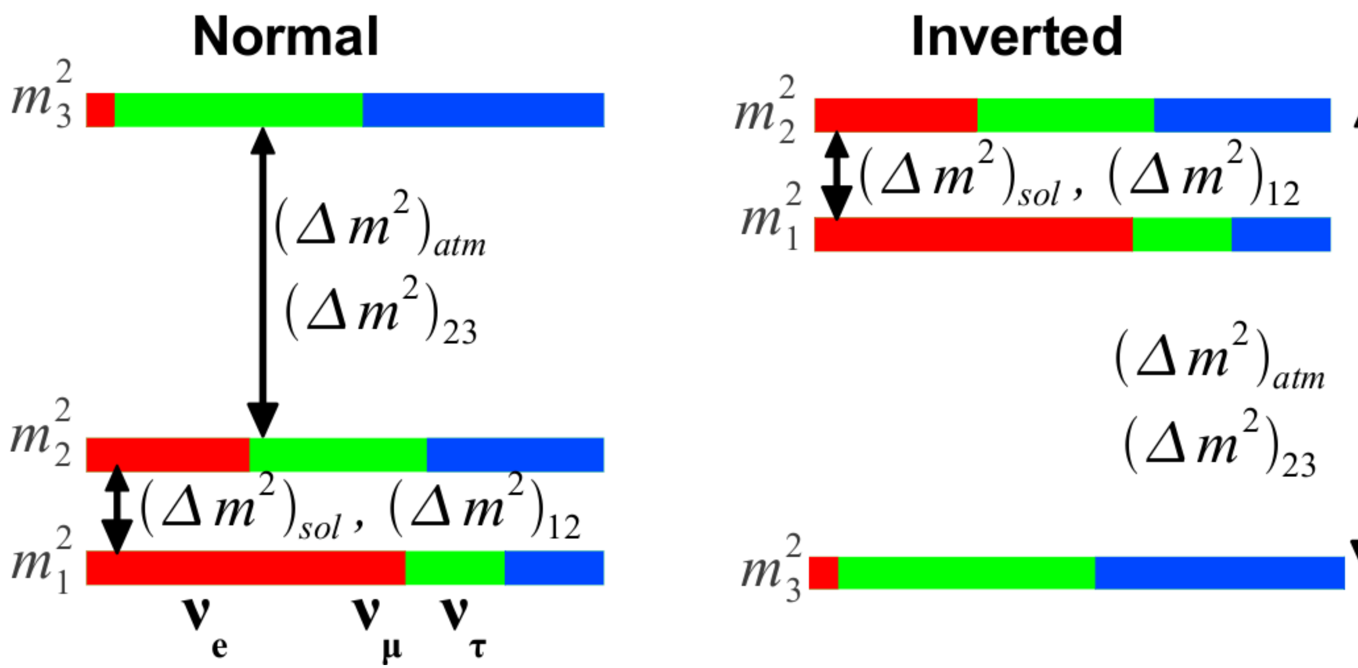
- **Q:** What do we still need to know?
- **A:** Two big questions in front of us now:

1) What is the CP violating phase δ?
2) What is the mass hierarchy?

Ambiguity in sign of

$$m_3^2 - m_2^2$$

Two possible mass hierarchies



→ Electron neutrino appearance can help answer both questions!

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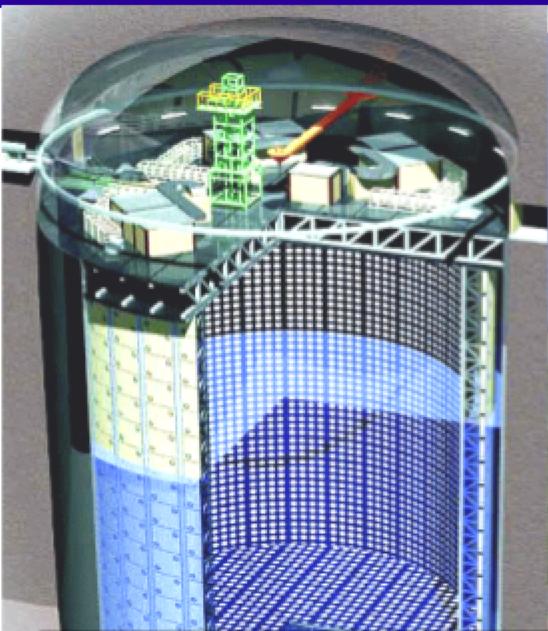
Tokai to Kamioka (T2K)

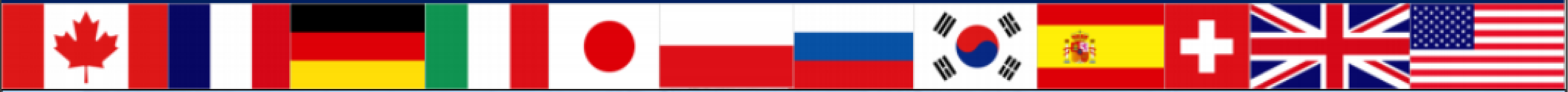


Super-Kamiokande 22.5 kton (fiducial) water cherenkov detector at 295 km

J-PARC: 30 GeV proton beam, design power of 750 kW

- Experimental goals:
  - Search for ν_e appearance ← Focus of this talk
  - Precision ν_μ disappearance
  - Other (ν cross sections, sterile ν searches, etc.)

The T2K Collaboration



~500 collaborators, 59 institutes, 12 countries

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

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

Germany
U. Aachen

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

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

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

Russia
INR

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

Spain
IFIC, Valencia
IFAE(Barcelona)

Switzerland
U. Bern
U. Geneva
ETH Zurich

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

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

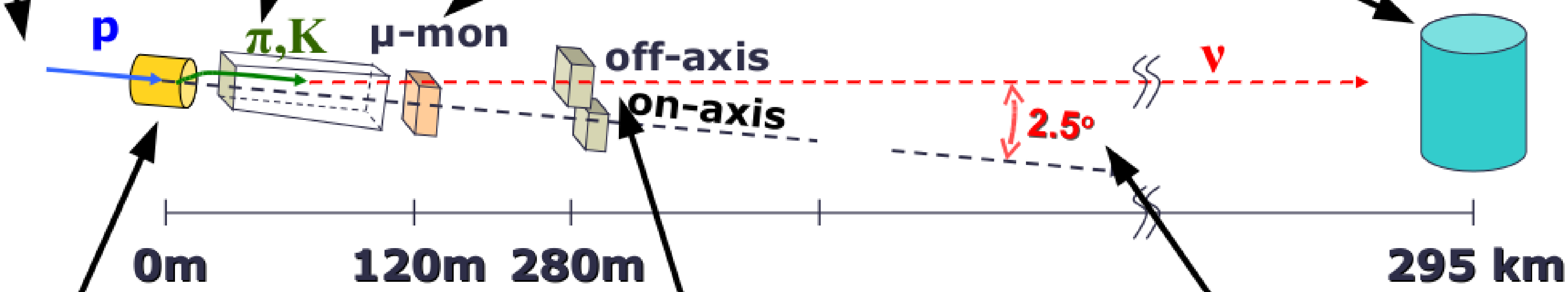
Experimental Overview

30 GeV proton beam from J-PARC

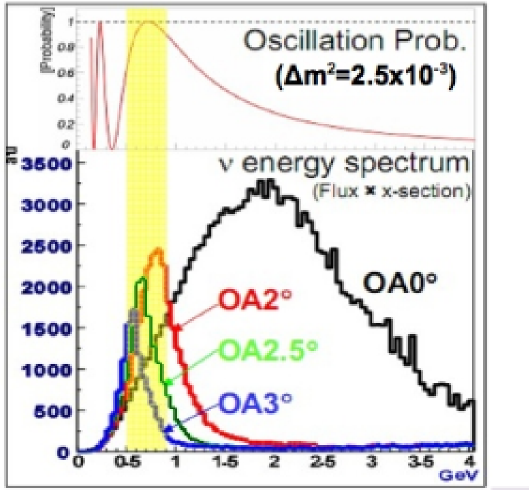
Pions, kaons, muons decay in 96 m decay volume

MUMON measures muons from pion decay

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



Off-axis = narrow band beam



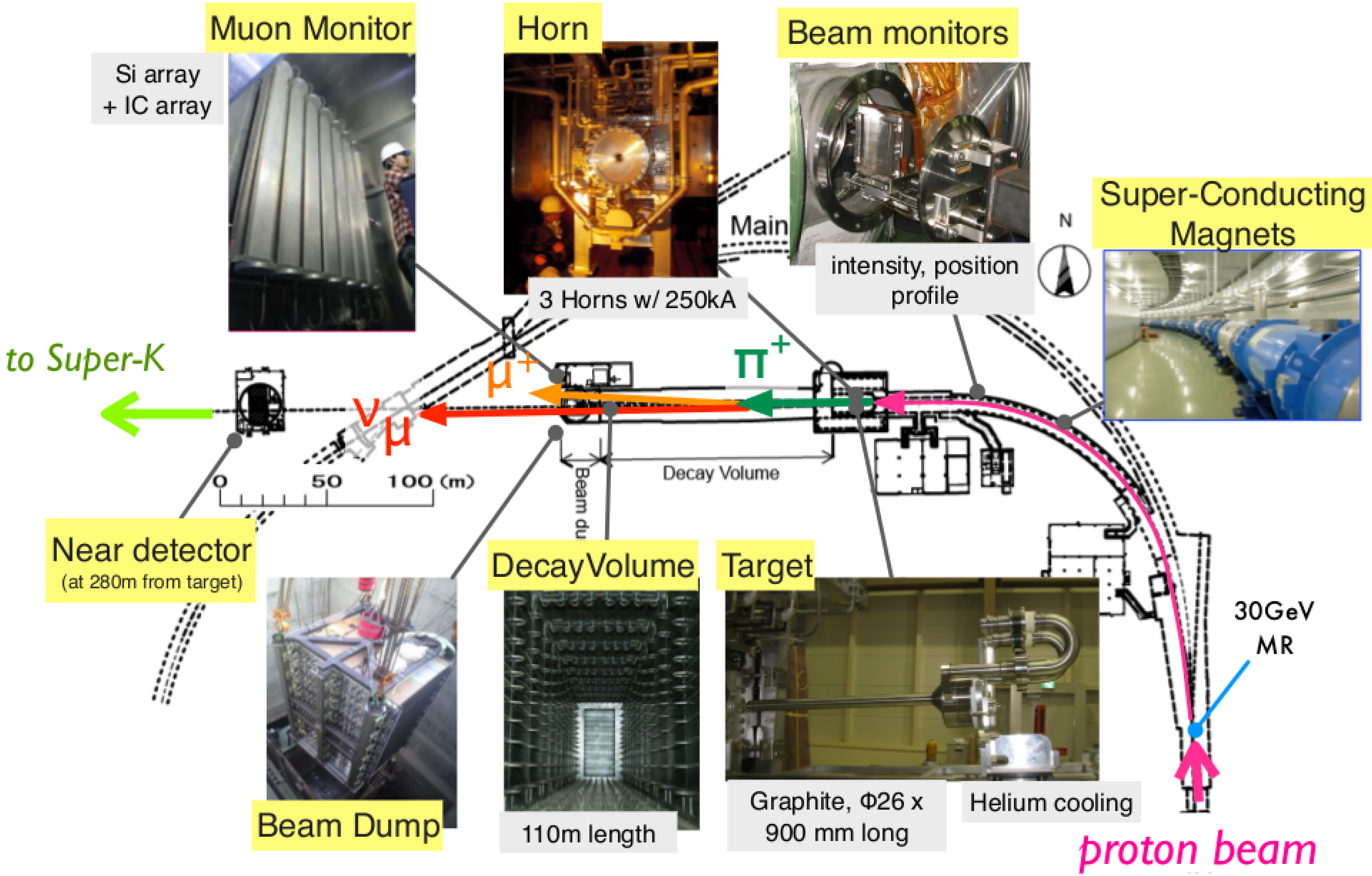
Beam on graphite target

3 magnetic horns focus positively charged hadrons

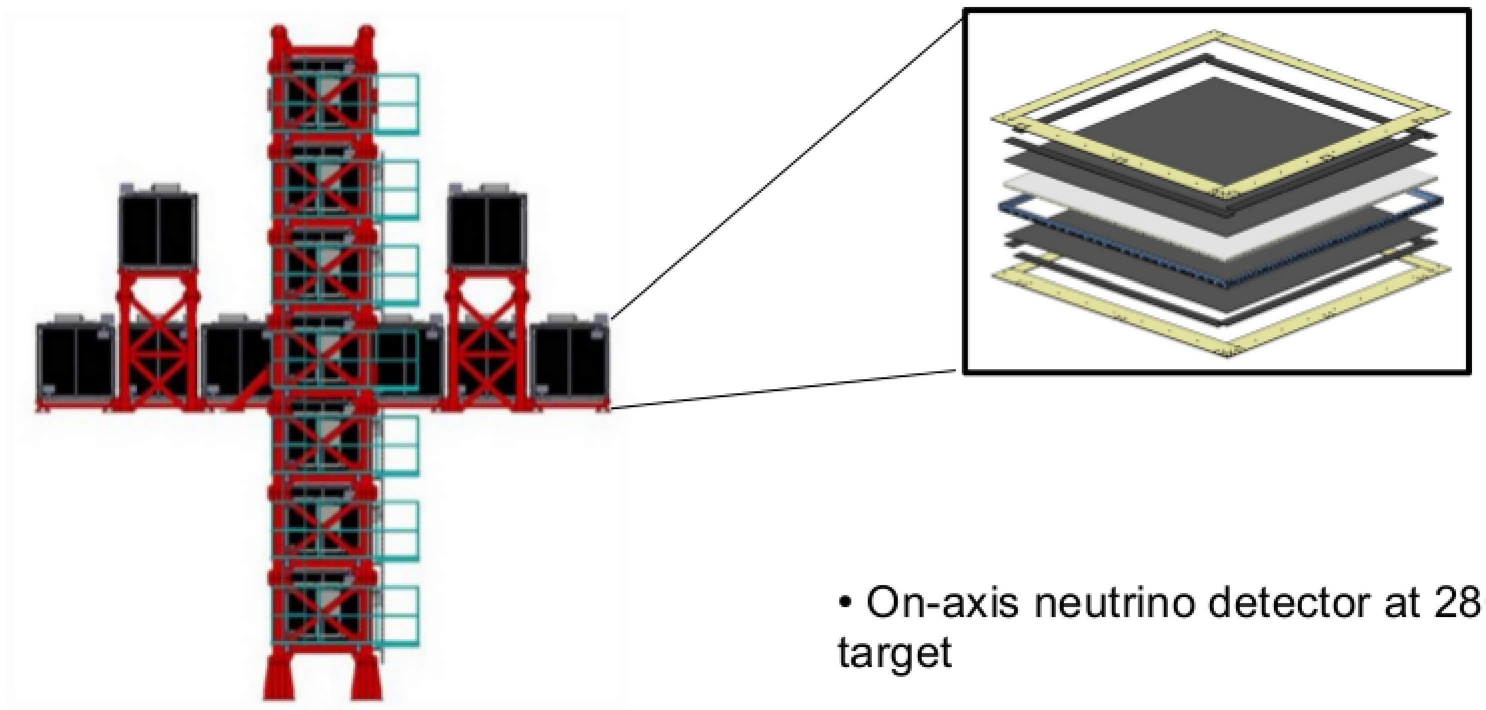
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

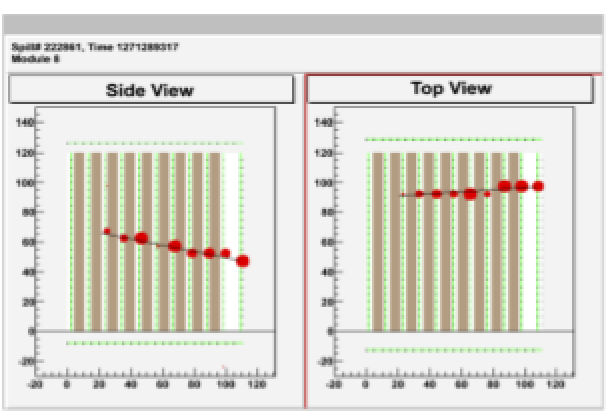
Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions

J-PARC Neutrino Beamline



INGRID (on-axis detector)





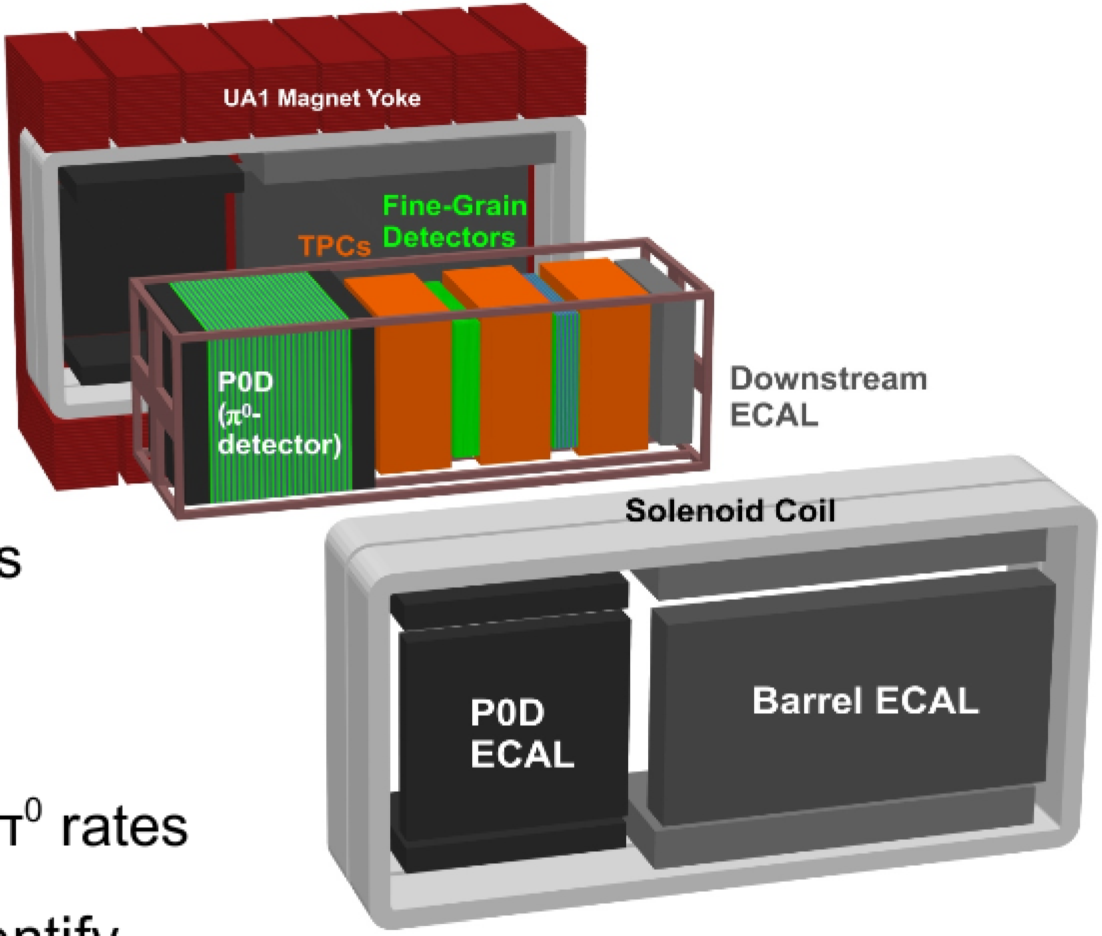
- On-axis neutrino detector at 280 m from target
- 16 modules (14 in cross configuration)
- Modules consist of iron and scintillator layers
- Measures neutrino beam profile and rate

ND280 (off-axis near detector)

- 0.2 T UA1 magnet

Used in this analysis

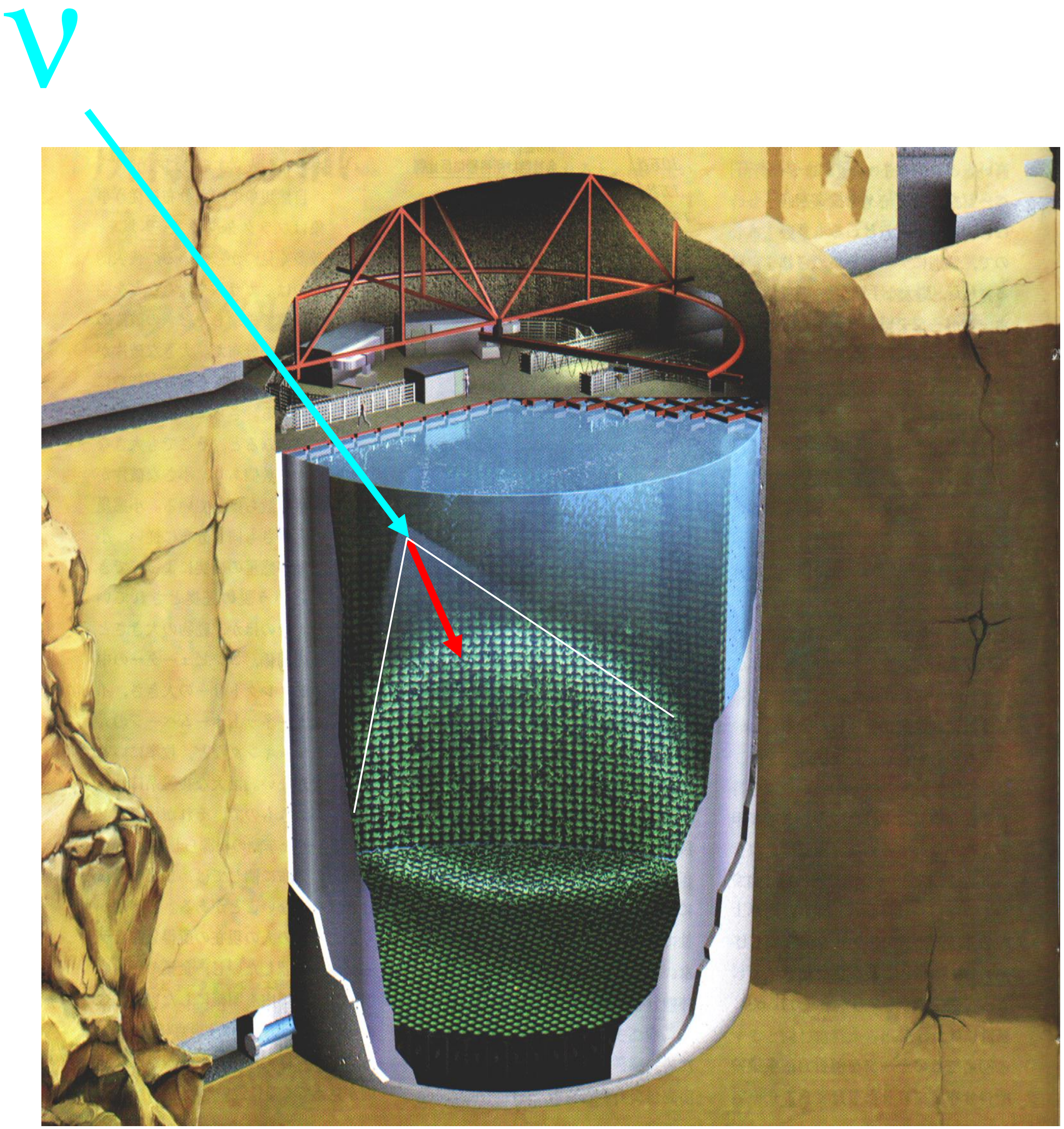
- Fine Grained Detectors (FGD) – neutrino target mass and tracking
- Time Projection Chambers (TPC) – momentum and dE/dx measurements



Important for future analyses

- POD π^0 detector – measures NC π^0 rates
- Electromagnetic calorimeters – identify electrons, photon reconstruction
- SMRD muon detector installed in the magnet yoke – muon range detector to improve muon ID

Super-Kamiokande (far)



- 50,000 tonne water Chereknov detector
- 22.5 kton fiducial mass
- Inner Detector (ID) has 11,129 inward facing 50cm PMTs for ~40% coverage
- Outer Detector (OD) has 1885 20cm PMTs; OD used as passive shielding and active veto
- Stable operation for many years
- Good reconstruction in energy range of T2K beam

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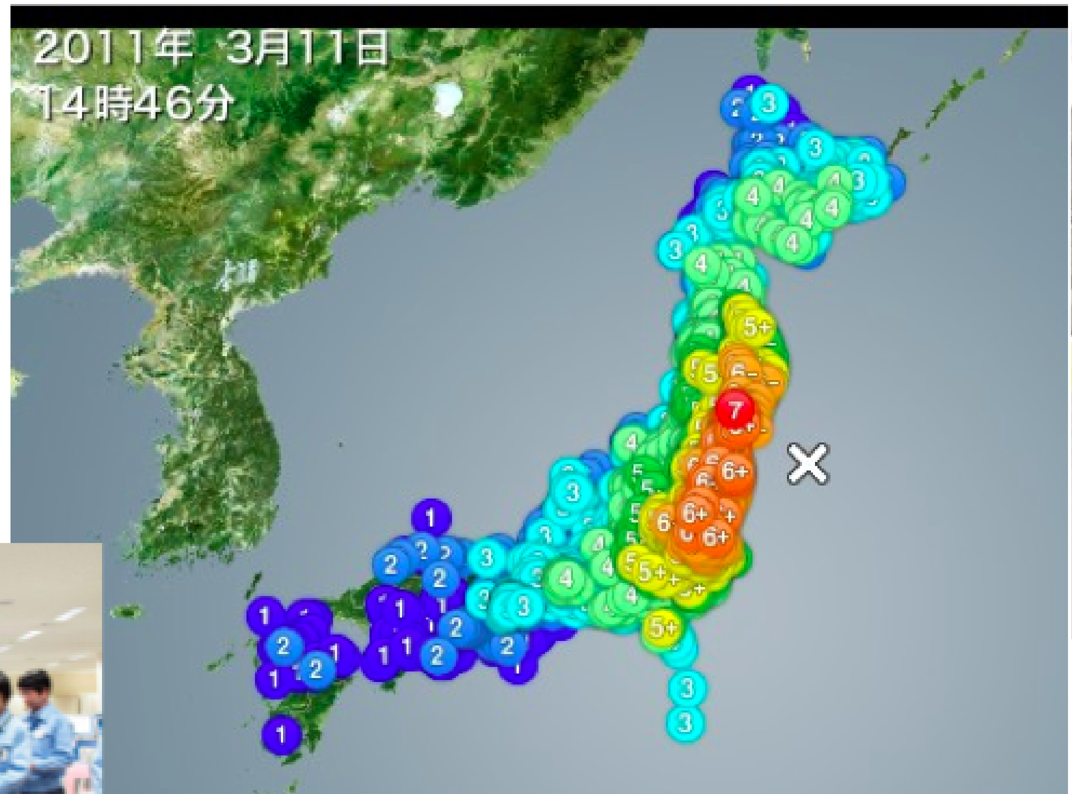
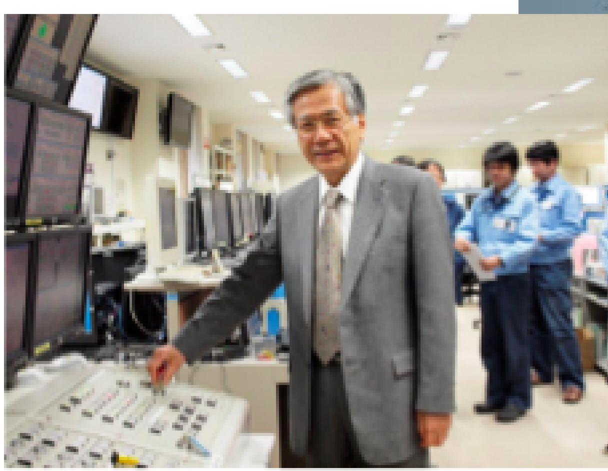
T2K: We're Back!

After taking data from January 2010, T2K was shut down by the Great Eastern Japan Earthquake and Disaster on March 11th 2011.

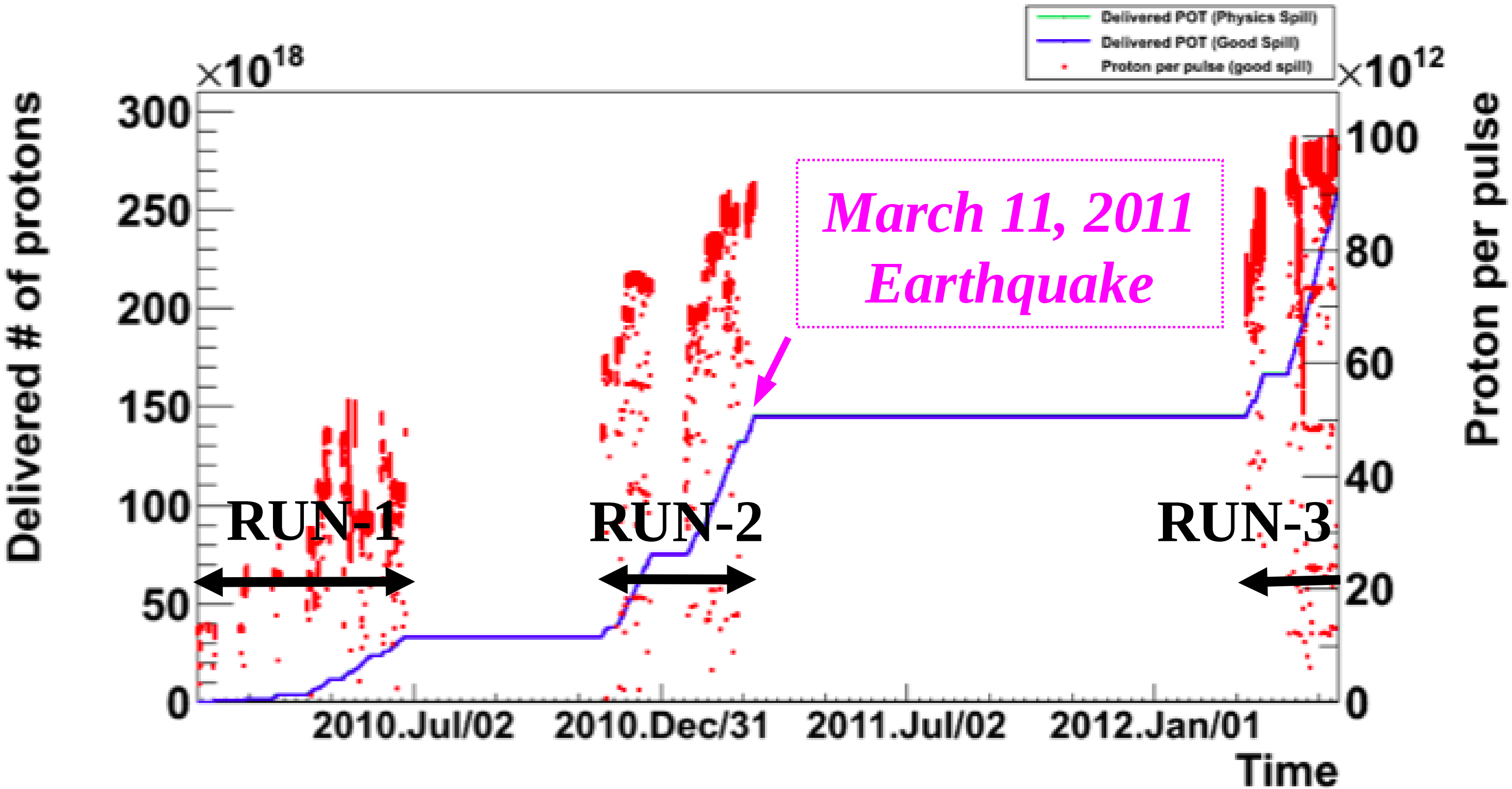




09:30 Key was on.

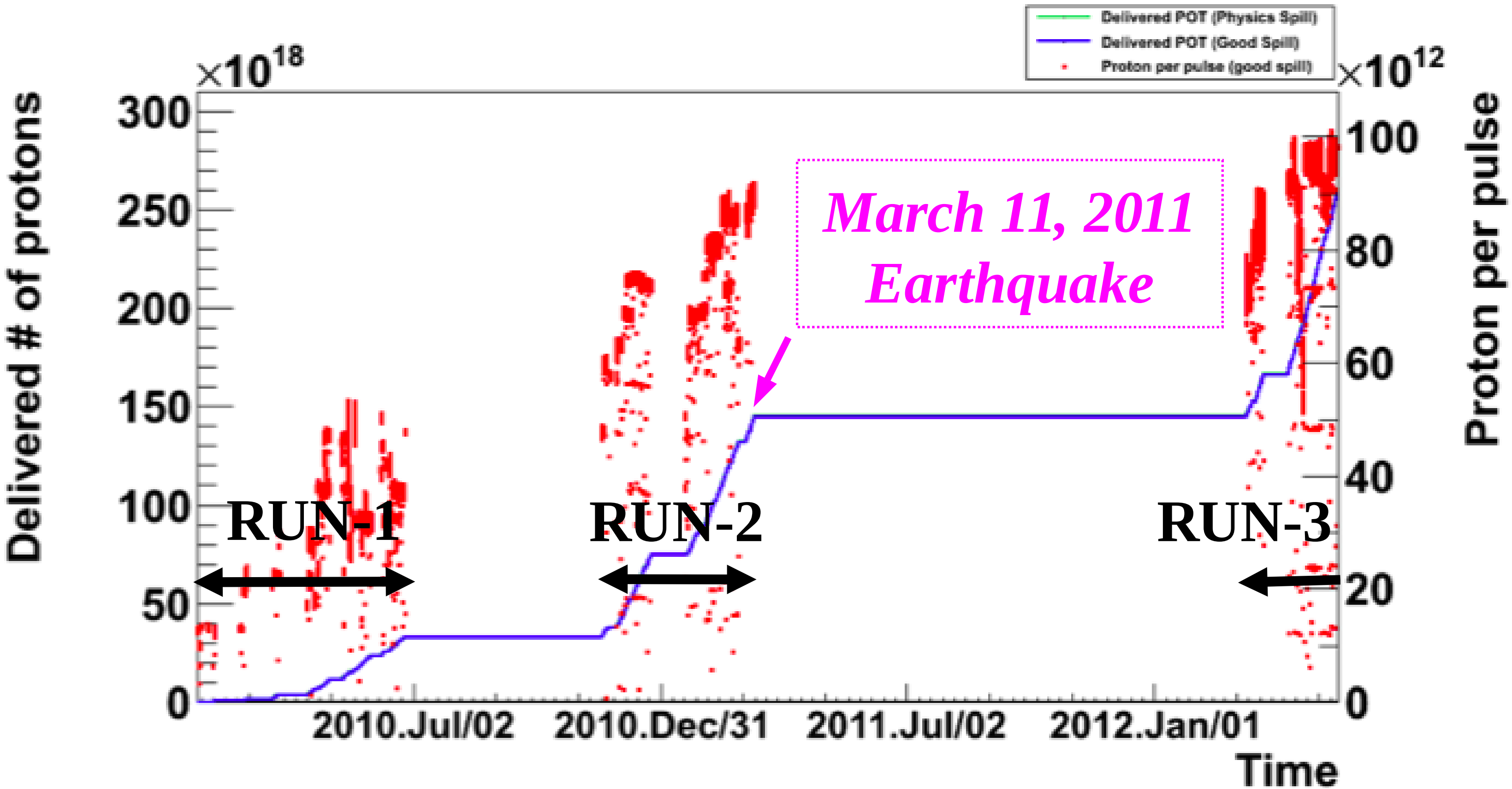
On Dec.9, 2011, J-PARC LINAC operation restarted!!!
On Dec.24, 2011, Neutrino events observed at T2K-ND280!!
On Mar.9, 2012, physics quality data-taking resumed! (Run 3)

Instantaneous Luminosity

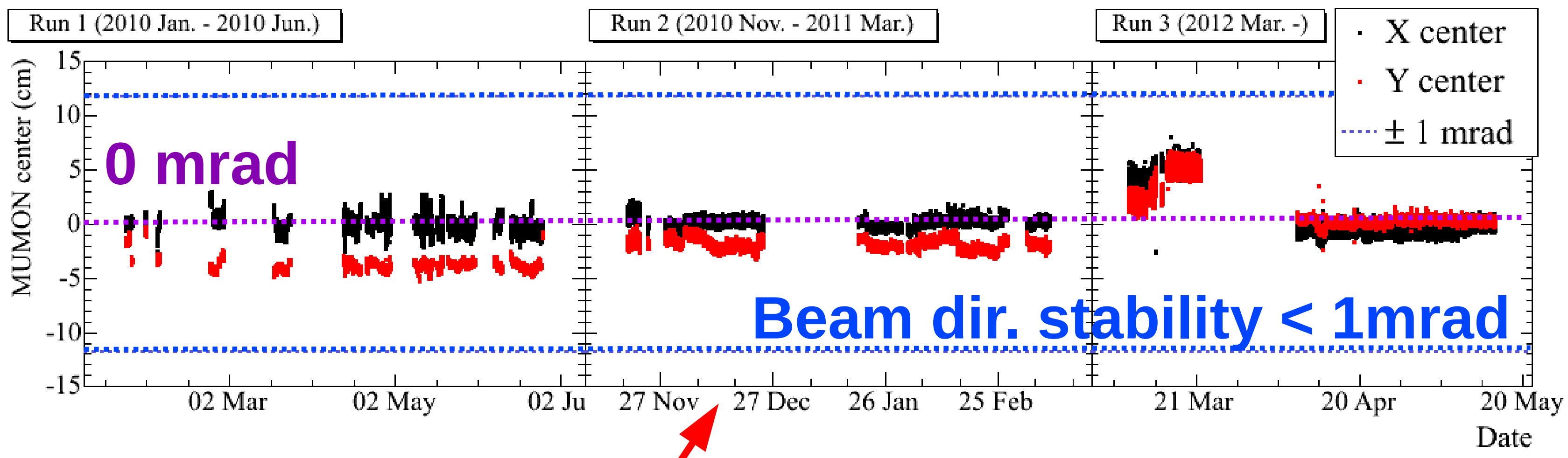


- Achieved **190 kW** of continuous running in Run 3
  - Compared to 145 kW in Run 2 and 50 kW in Run 1
  - Increased pulse repetition rate, bunches per pulse, protons per bunch
  - 10^{14} protons per pulse (world record)

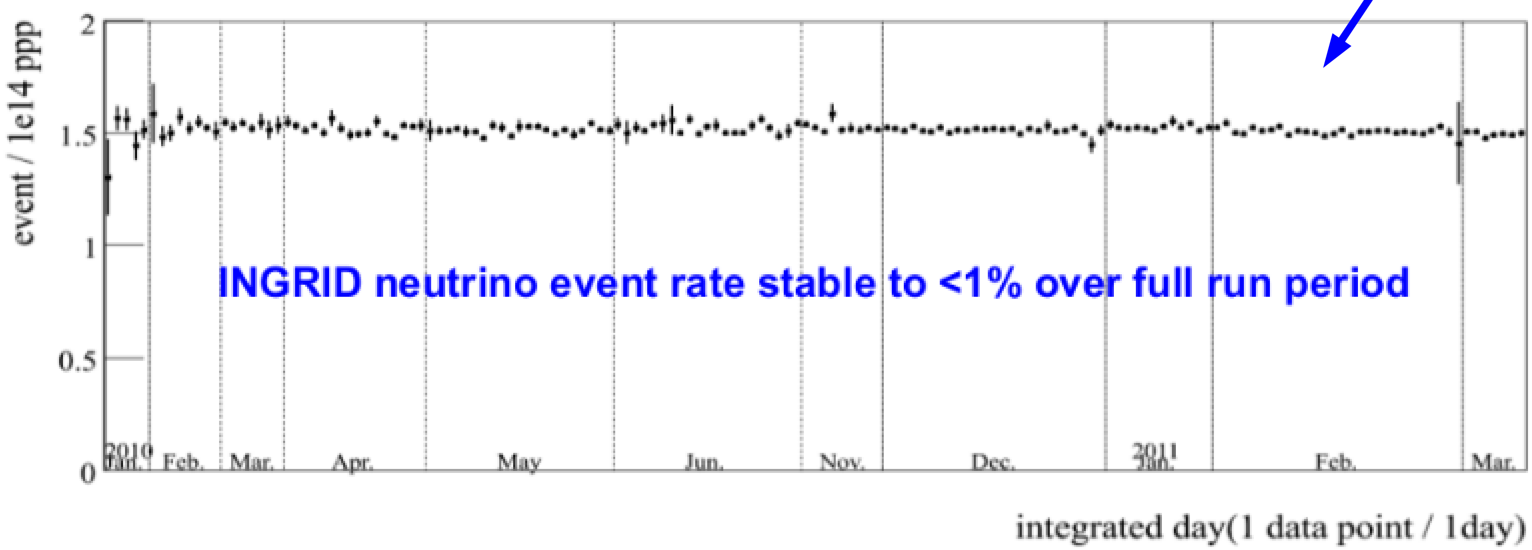
Integrated Luminosity



- Run 1 – 3 data sets = 2.56 x 10^{20} P.O.T. for SK analysis
  - Run 1: 0.32 x 10^{20} P.O.T. (2010)
  - Run 2: 1.11 x 10^{20} P.O.T. (2010 - 2011)
  - Run 3: 1.12 x 10^{20} P.O.T. (to May 15th 2012)
- Thus far, ~4% of the total data has been collected (assuming design goal)



Beam is quite stable in **space** (1 mrad tolerance) and **time** (within 1%)



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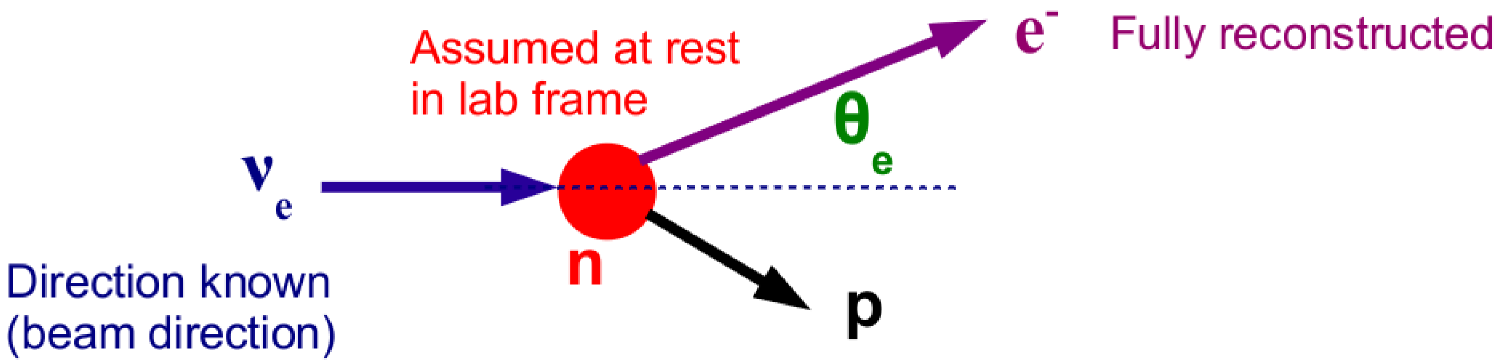
Reconstructing ν Energy

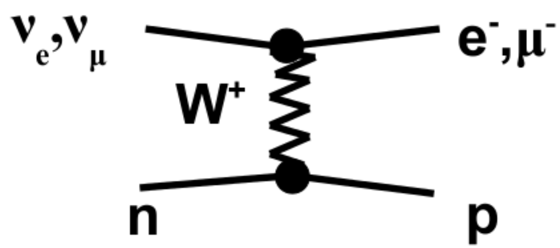


$$E_{\nu}^{QE}=\frac{2M_nE_e-(M_n^2+m_e^2-M_p^2)}{2[M_n-E_e+\sqrt{E_e^2-m_e^2}\cos\theta_e]}$$

- Only final state lepton is reconstructed
- Neutrino energy can be determined with certain assumptions:
  - Neutrino direction is known (beam direction)
  - Recoil nucleon mass is known (use neutron mass)
  - Target nucleon is at rest (not quite true; introduces smearing)

Neutrino Interactions

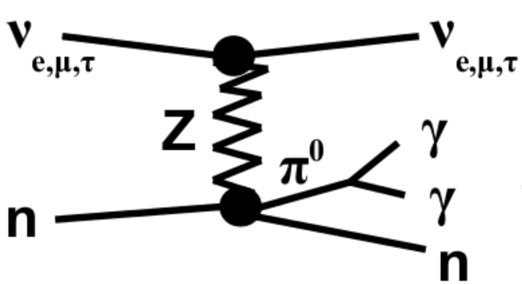
- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:



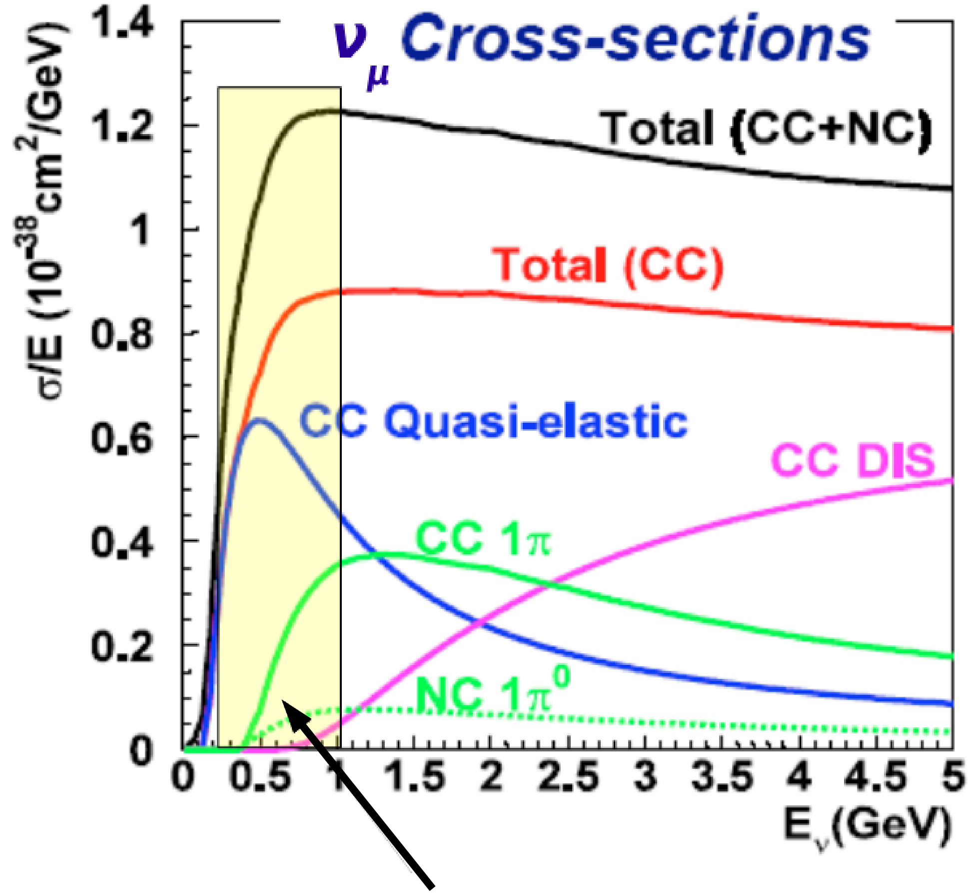
T2K signal at SK

- Also significant CC contribution with pion in final state

- NCπ^0 is a major background mode from electron appearance:



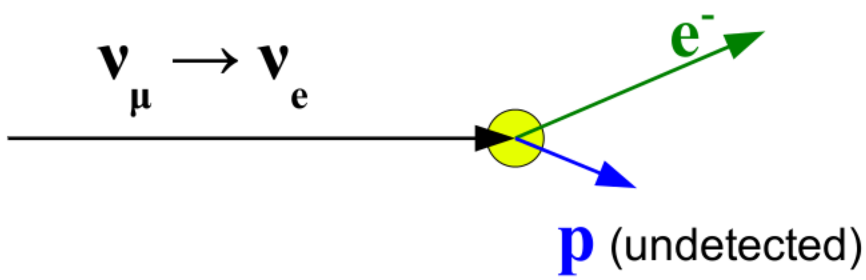
Photons from π^0 can fake electron signal

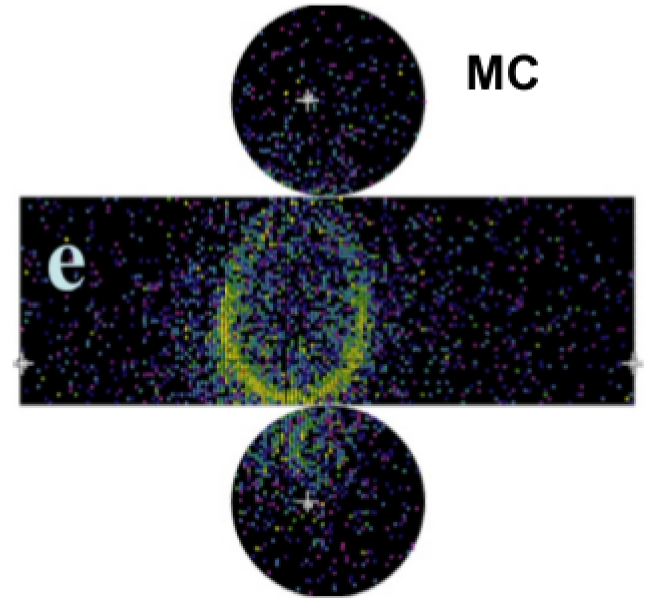


T2K beam peak energy

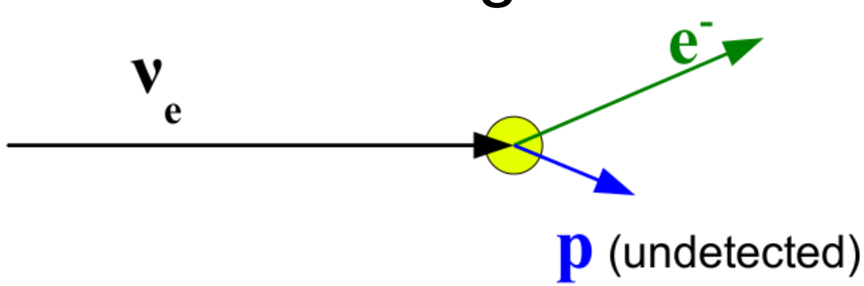
ν_e Signal & BG (at SK)

- Oscillation signal:



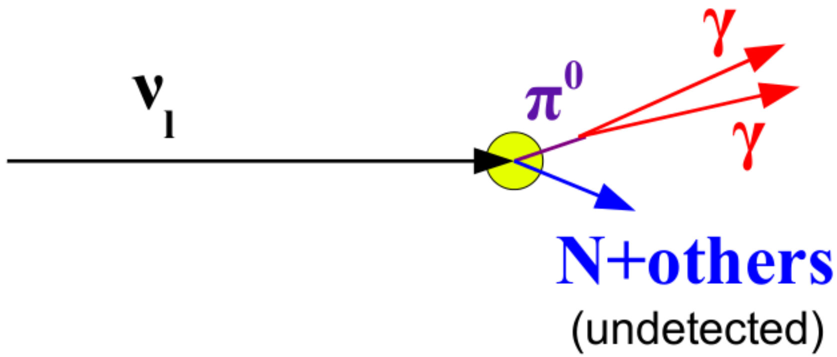


- Beam ν_e background:

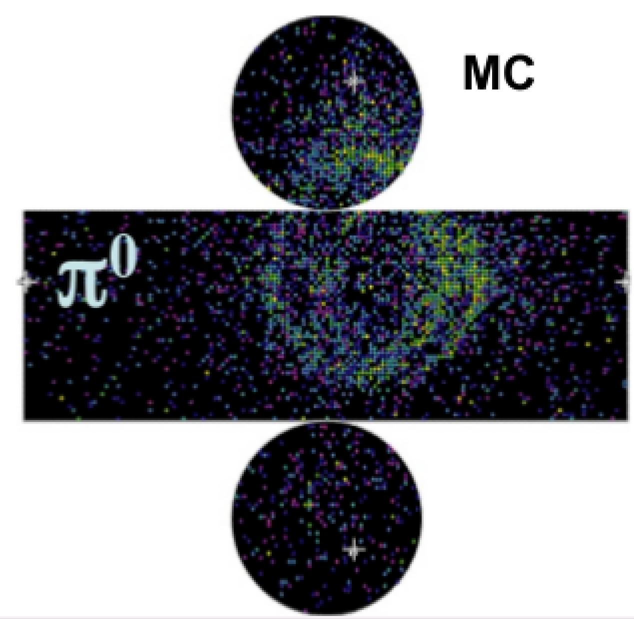


Beam background has harder energy spectrum

- Neutral current π^0 background:



Can be removed by identifying second photon ring



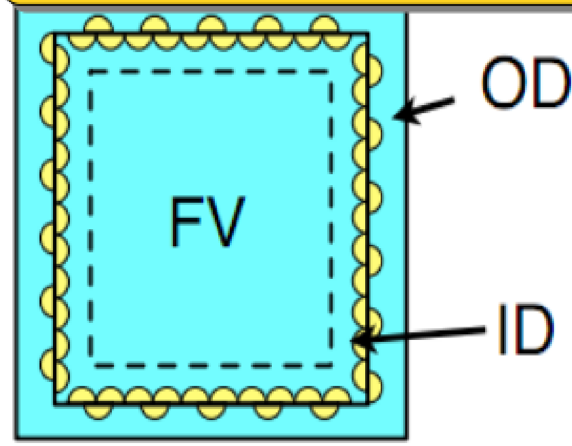
SK ν_e Event Selection

Select a single ring e-like sample, minimize beam and NCπ^0 backgrounds

Optimized for current statistics

Cuts fixed before looking at data

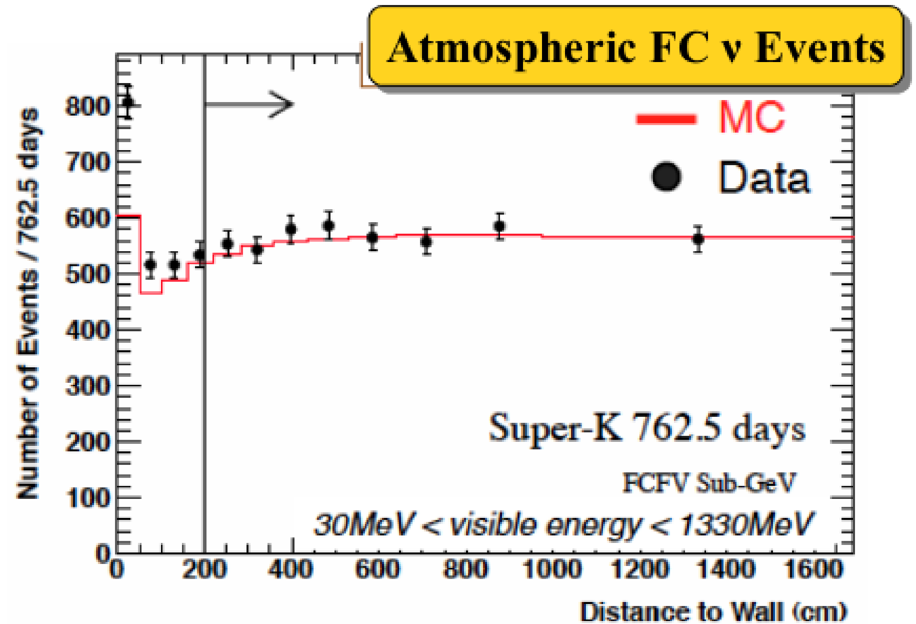
SK cross section view



1. Event falls in beam timing window, is fully contained in the inner detector (ID) (no activity in the OD)

2. Event vertex is >200 cm from the ID wall (fiducial volume cut)

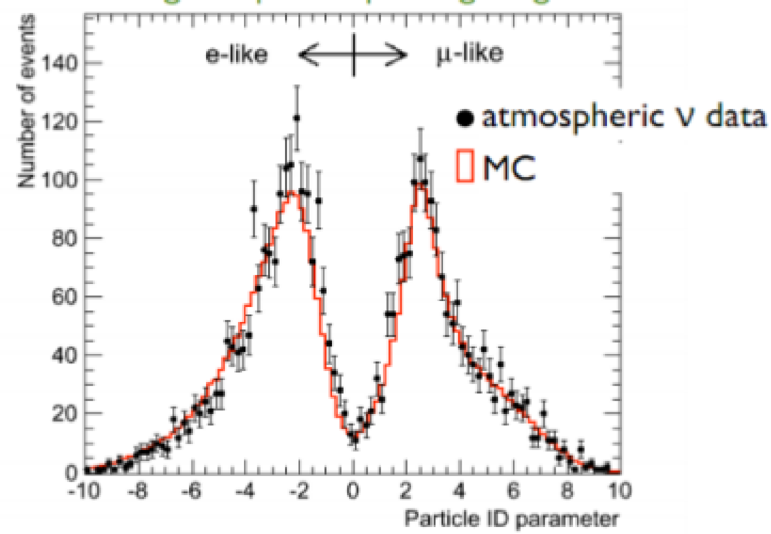
   - If particle direction is towards nearest wall: ring size ~ PMT spacing
   - Rejects events originating in OD
   - 22.5 kton within fiducial volume



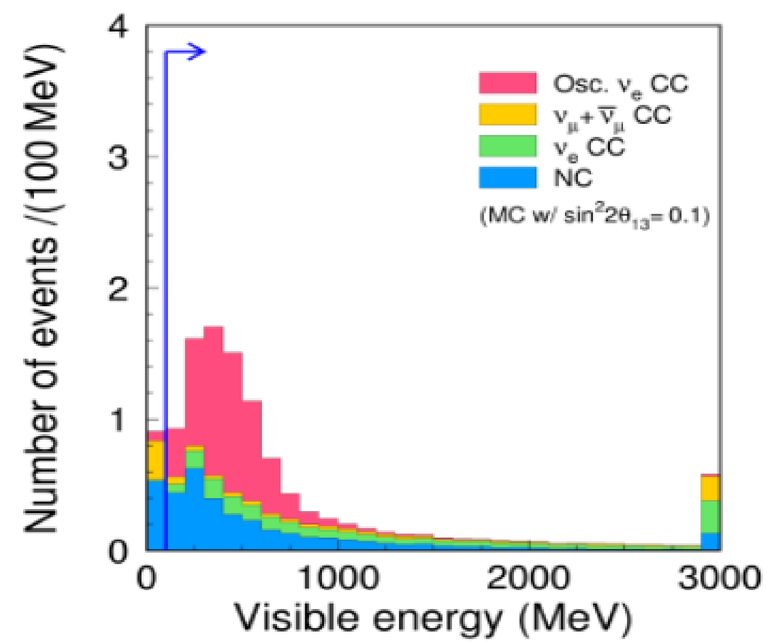
SK ν_e Event Selection

3. Select a single e-like ring
   - Particle ID based on ring shape
   - Good e/μ separation
   - Performance understood on atm. sample
   - ~1% probability to mis-ID μ as e

Particle identification using ring shape & opening angle

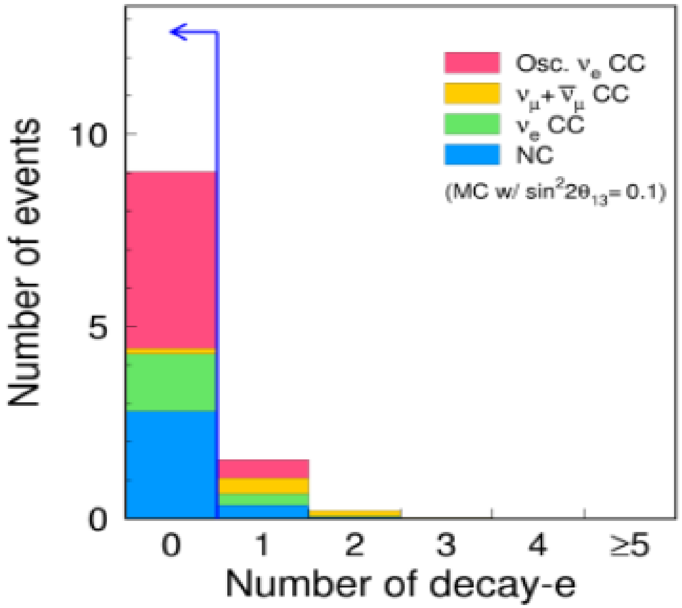


4. Visible energy > 100 MeV
   - Low energy events = NC background and electrons from μ decay

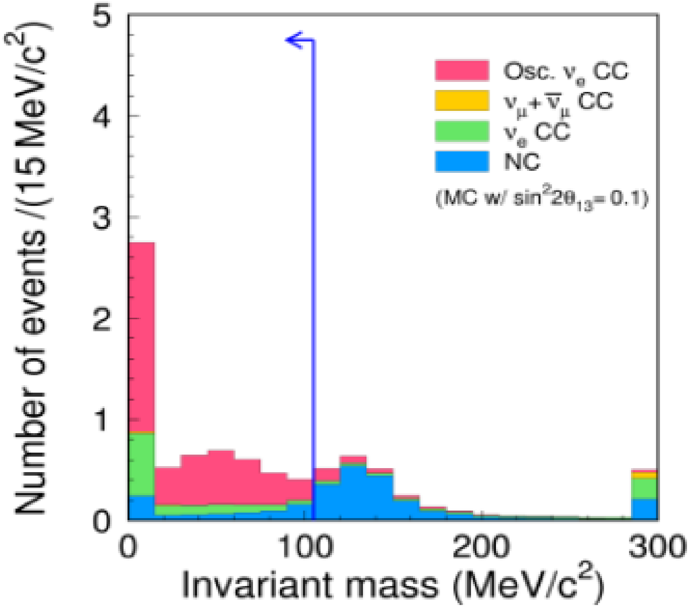


SK ν_e Event Selection

5. No decay electrons
   - Reject based on delayed activity in SK
   - Rejects events with μ or π below threshold or misidentified as electron



6. π^0 mass cut, M_{inv} < 105 MeV/c^2
   - Calculate invariant mass with 2-ring hypothesis for each event
   - Rejects $NC\pi^0$ background



SK ν_e Event Selection

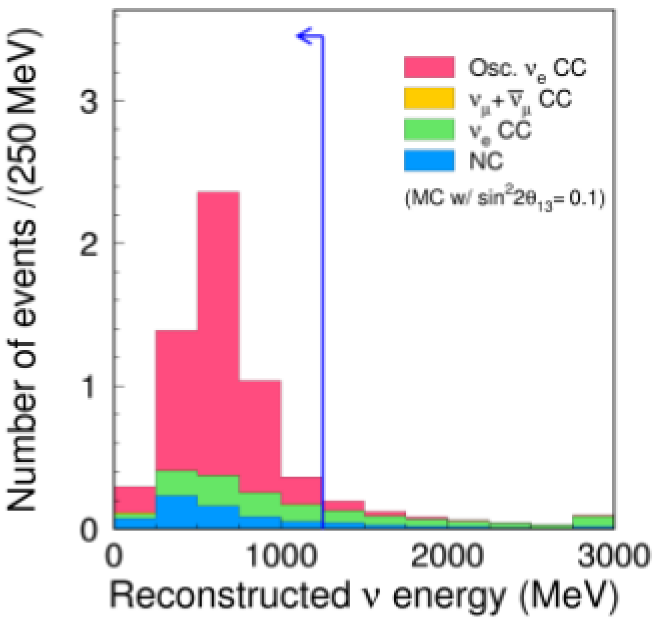
7. Reconstructed neutrino energy < 1250 MeV
   - Reject higher energy intrinsic beam background from kaon decays

Signal Efficiency = 66%

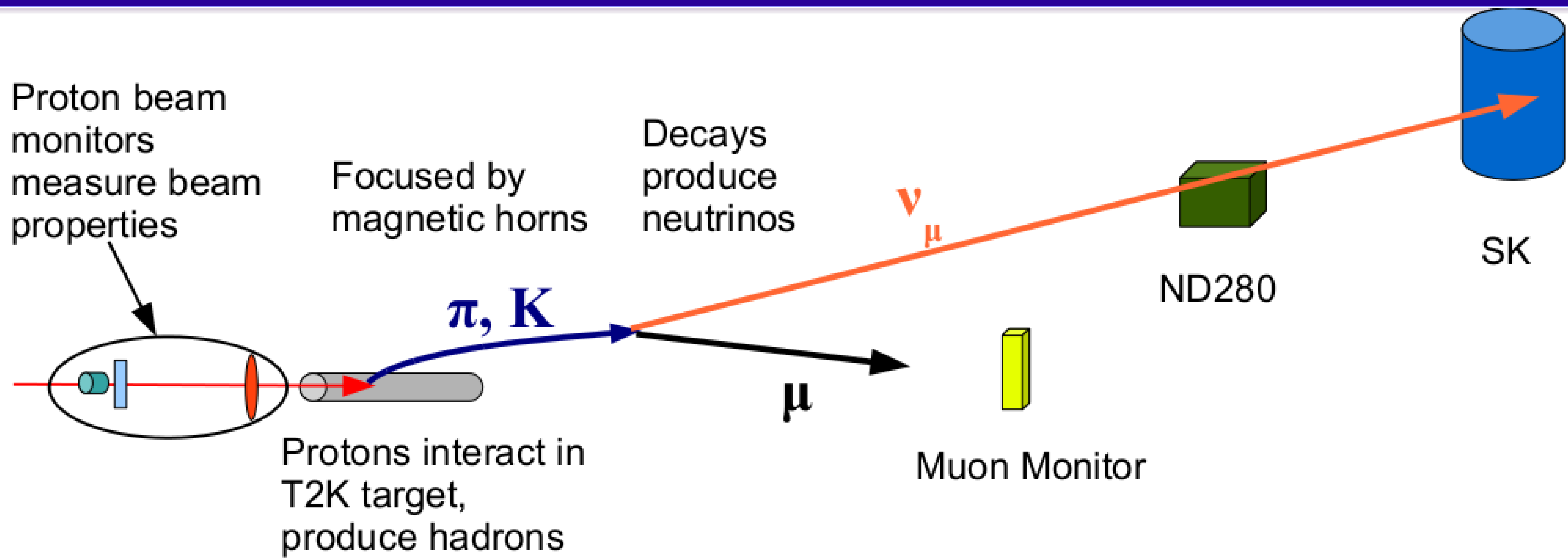
Background Rejection:

77% for beam ν_e

99% for NC



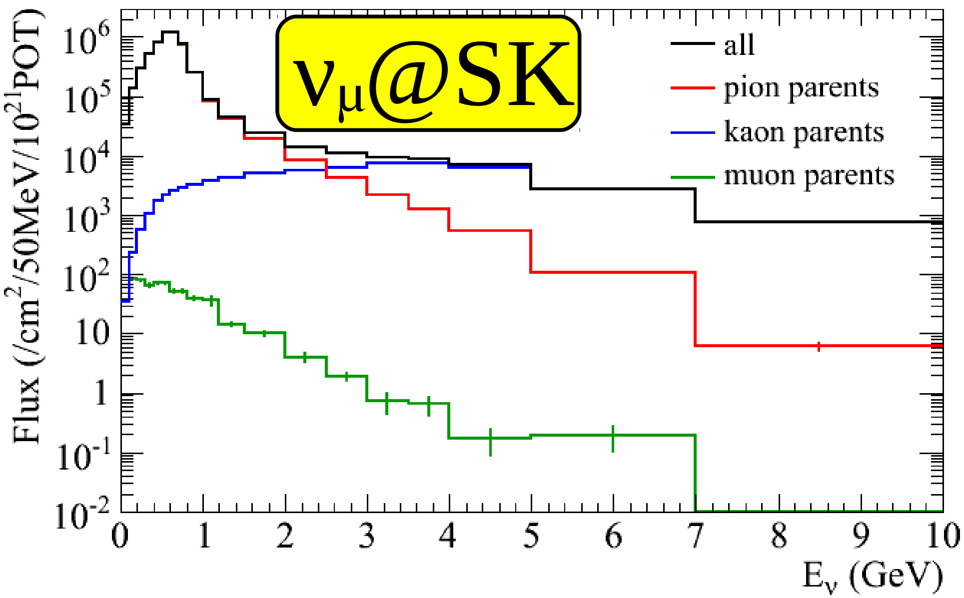
Modelling Neutrino Flux

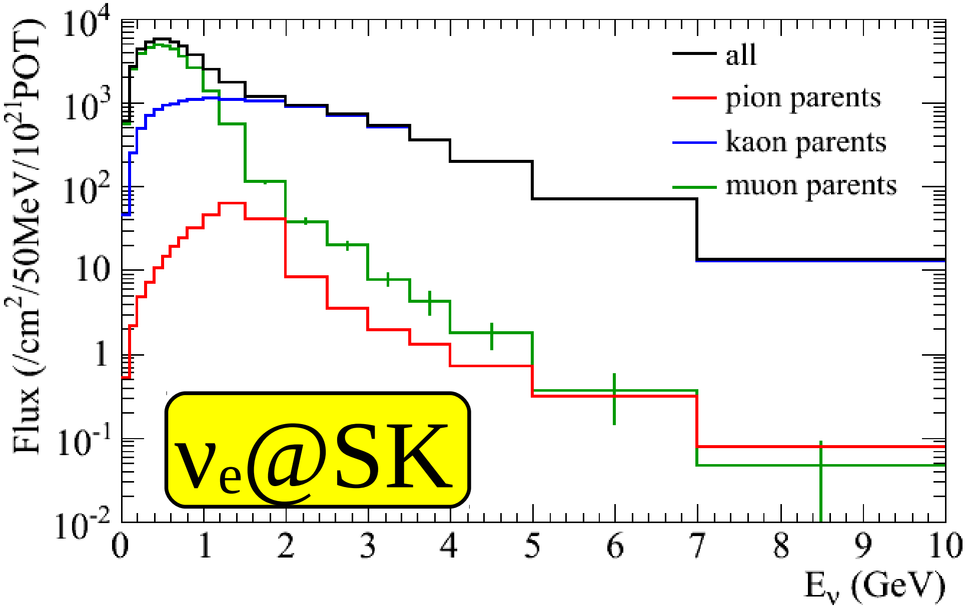


Flux Simulation:

- Proton beam monitor measurements as inputs
- In Target Hadron Production:
  - NA61 experimental (at CERN) data to model $\pi^{\pm}$ production
  - Kaon production, other hadron interactions – model with FLUKA
- Out of target interactions, horn focusing, particle decays
  - GEANT3 simulation
  - Interaction cross sections are tuned to existing external data

Neutrino Flux Predictions





- Muon neutrino flux around oscillation maximum predominantly from pion decays
- Intrinsic electron neutrino flux in beam from muon and kaon decays ~1% of total flux below 1 GeV
  - Dominant source around oscillation maximum is from muon decays

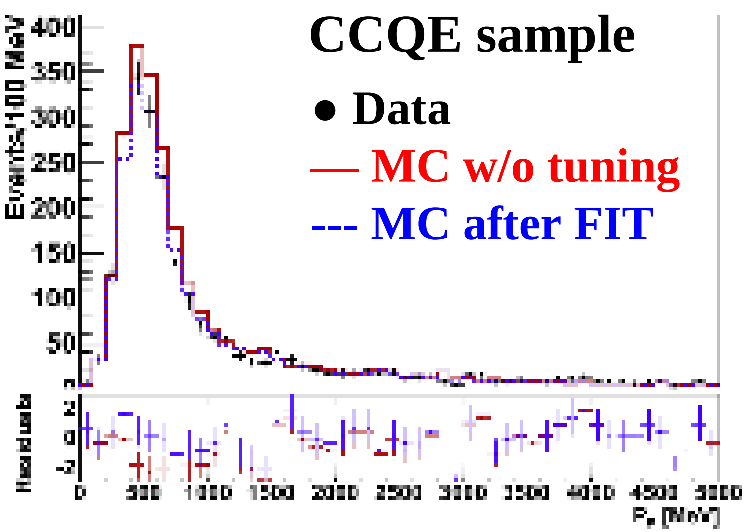
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

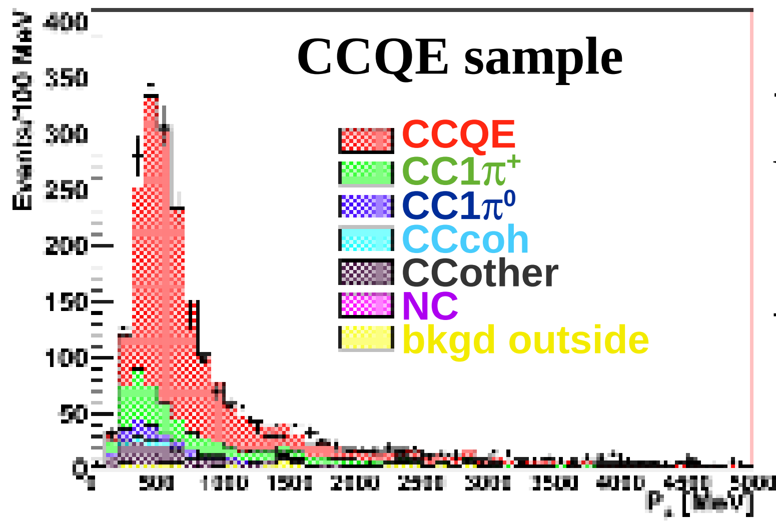
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

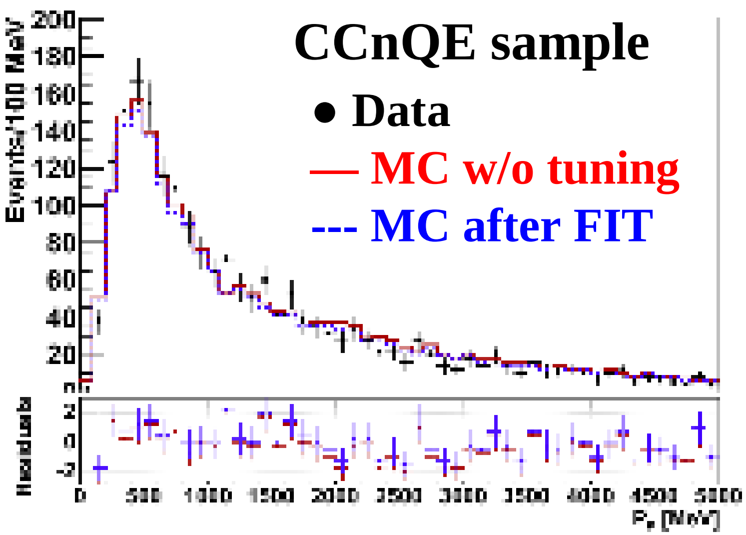
Flux depends on pion production

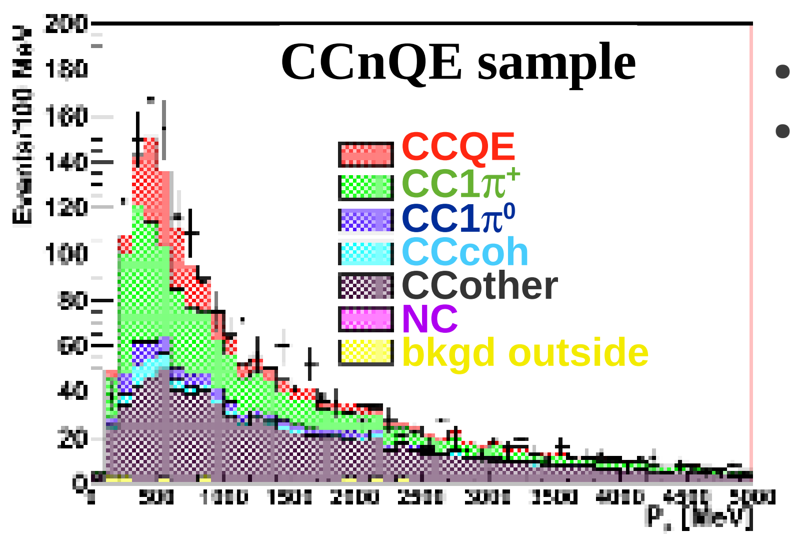
ND280 Inclusive ν_μ Sample

Measurements using Run 1+2 data (1.08 x 10^{20} P.O.T.):









ND280 events are used to constrain the flux and ν cross sections.

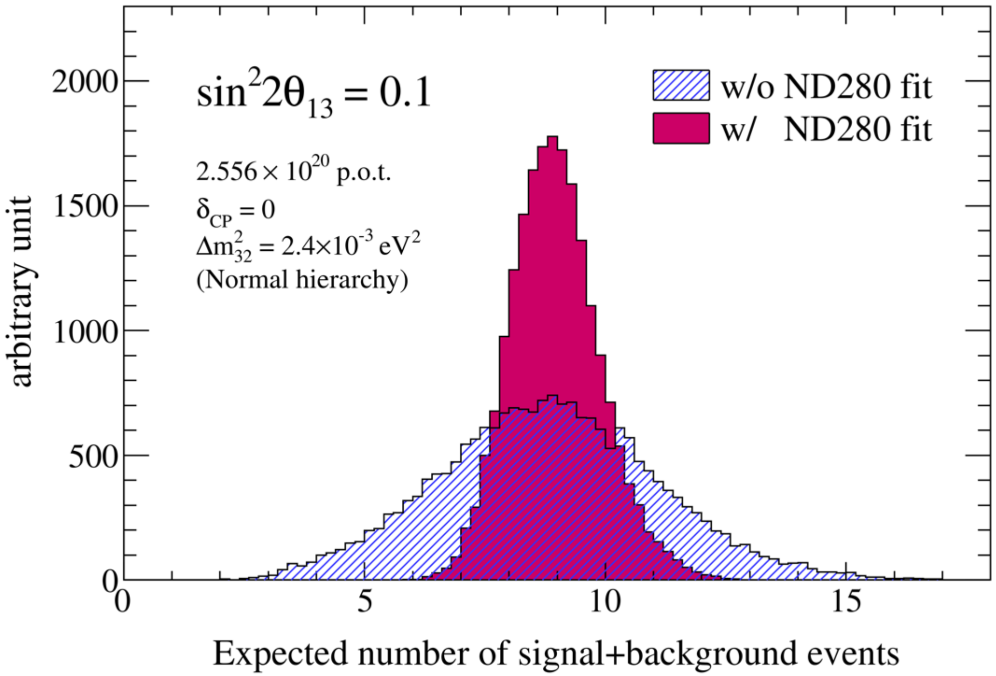
ND280 event selection:

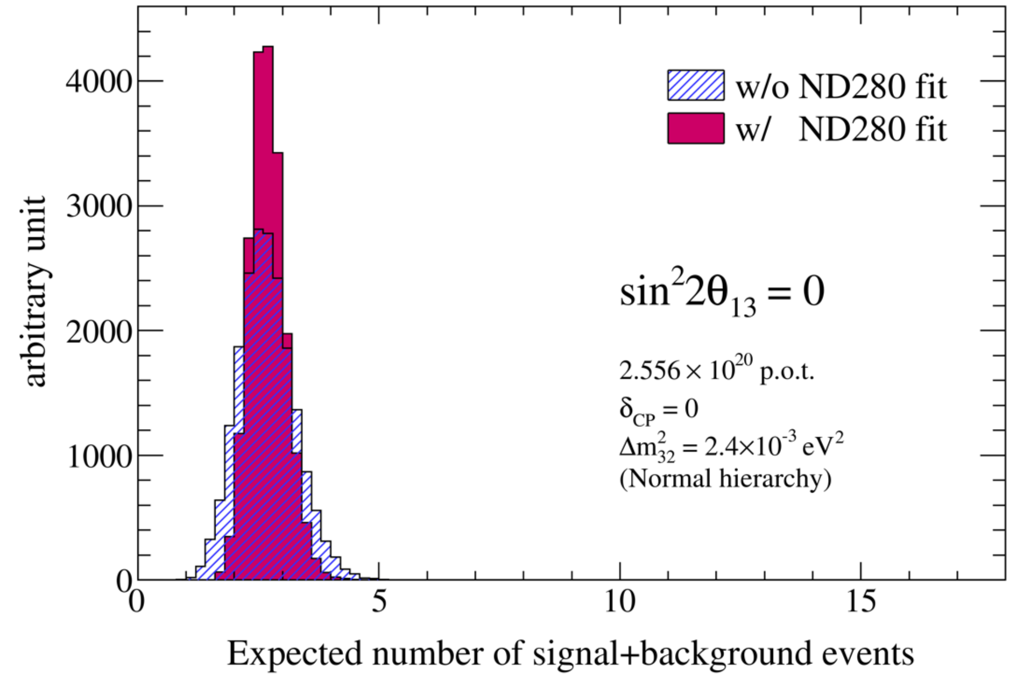
- Good negative track in fiducial volume
- Upstream TPC hit
- Muon ID by TPC (for CCQE events)
- 1 FGD-TPC track
- No decay-e in FGD

For CCQE selection:

- **40% efficiency**
- **72% purity**

SK Expectation





Predicted # of Events	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
Total	**9.07±0.93**	**2.73±0.37**
ν_e signal	6.60	0.15
ν_e background (beam org.)	1.32	1.42
ν_μ background (~NCπ^0)	1.02	1.02
anti-ν background	0.13	0.14

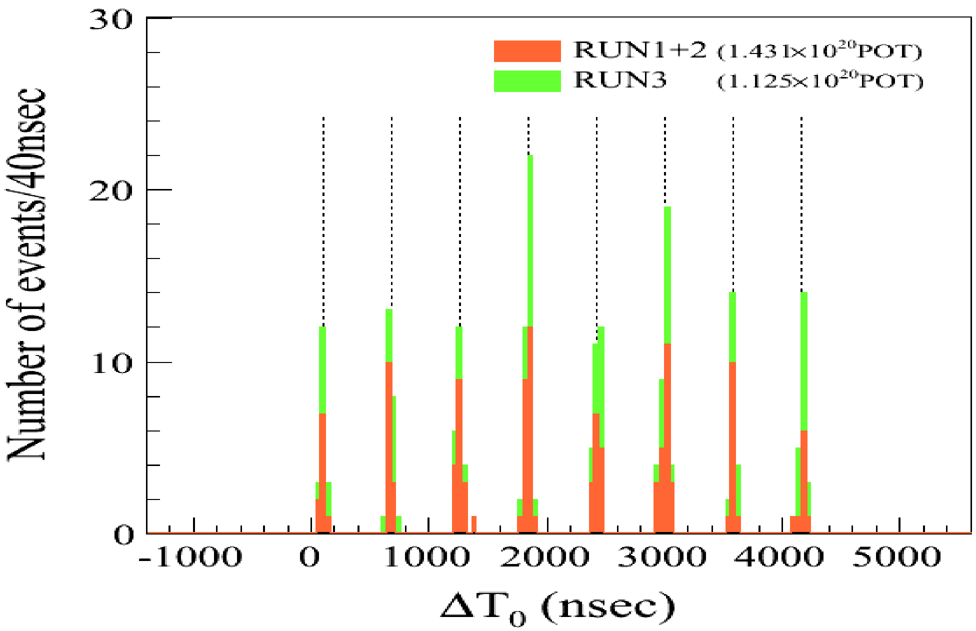
Systematic Err.	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
Flux+Xsec in T2K fit	5.7%	8.7%
Xsec (from other exp.)	7.5%	5.9%
SK + FSI	3.9%	7.7%
Total	**10.3%**	**13.4%**

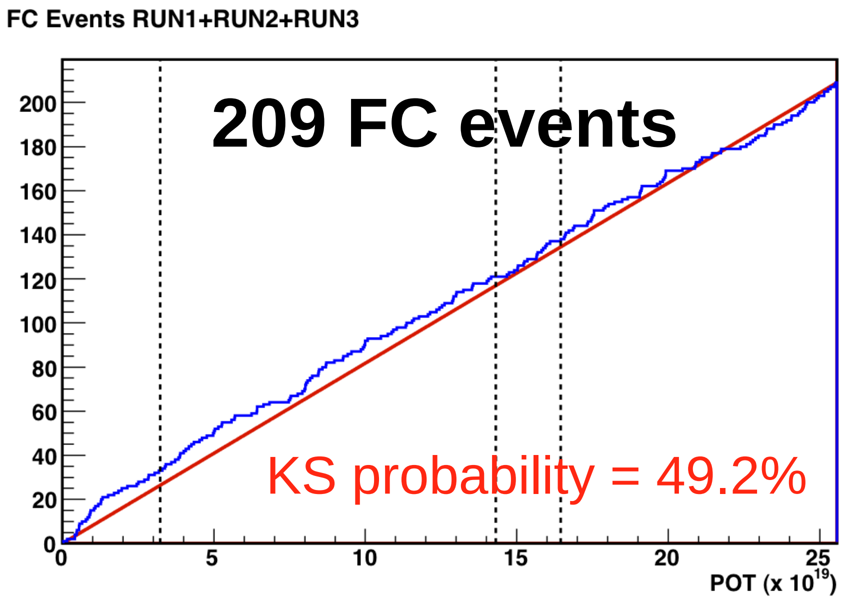
Large improvement from 2011 analysis:

~18% for $\sin^2(2\theta_{13}) = 0.1$

~23% for $\sin^2(2\theta_{13}) = 0.0$

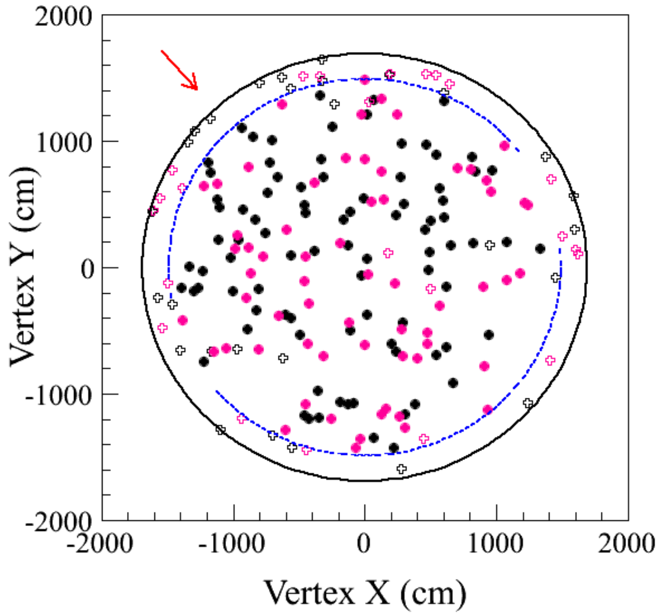
- SK synchronized to beam timing w/ GPS
- SK events fully contained in ID show clear beam time structure
- Non-beam BG estimated from timing sidebands; event rate is negligible (~0.04 events in current data set)



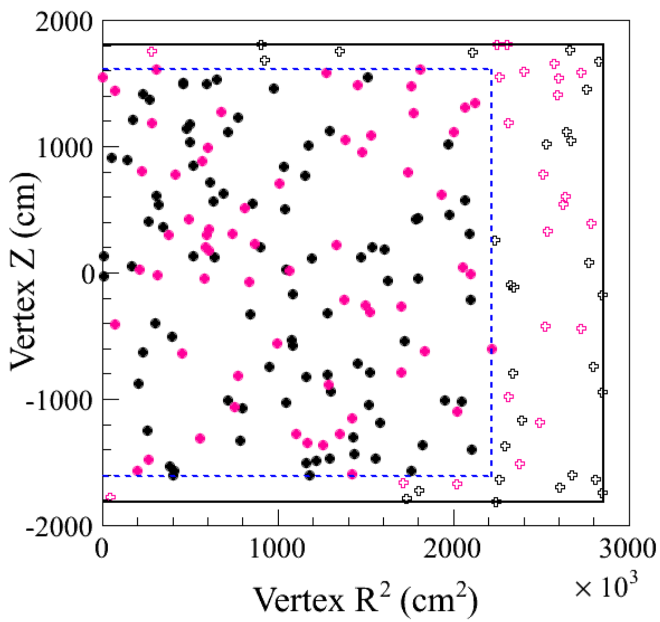


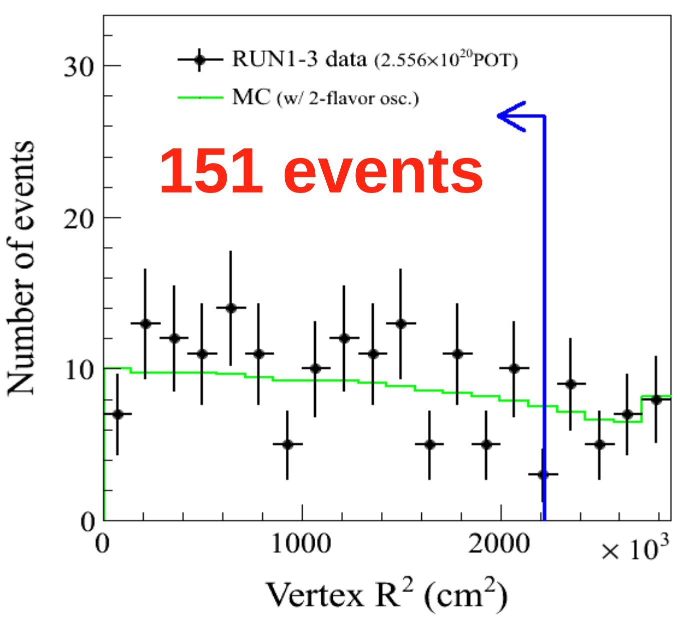
In total, there are 209 events in the current data sample that are in time with the beam and fully contained within the SK inner detector (Step 1 of the data reduction)

SK Data: Spatial Distrib.



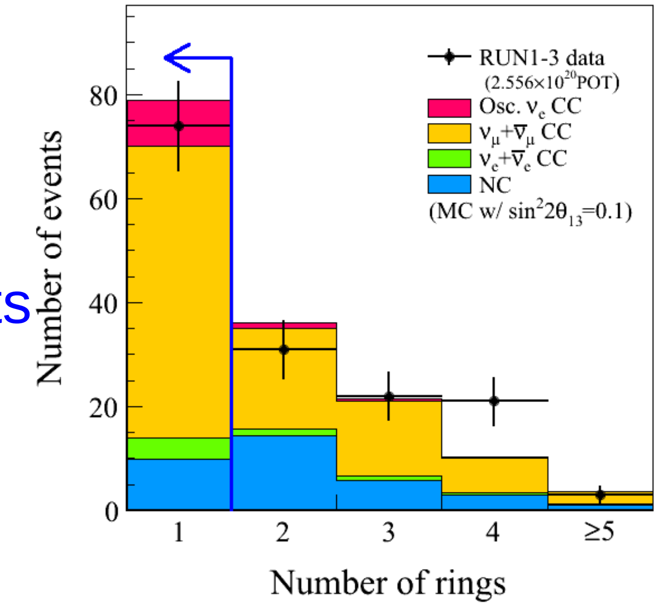
- Vertex distributions shown in horizontal (XY) and vertical (Z vs. R^2) planes
- Beam direction marked by arrow
- No anomalous behaviour in distribution
- After fiducial volume cut applied, 151 events remain in the data

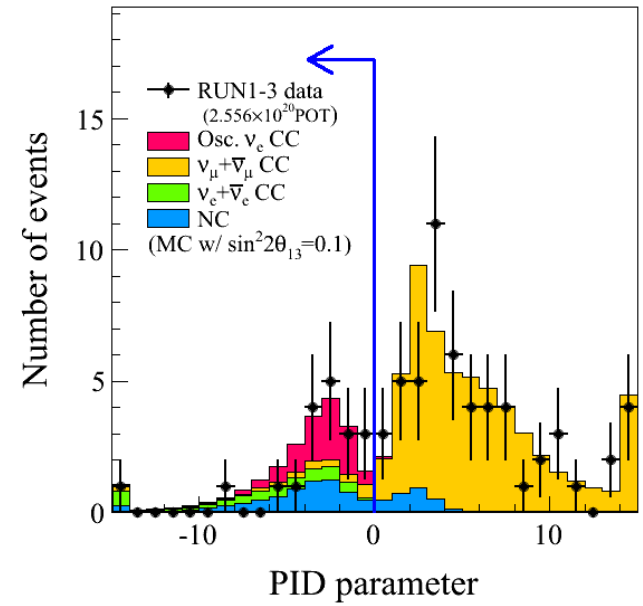




SK ν_e Data Reduction

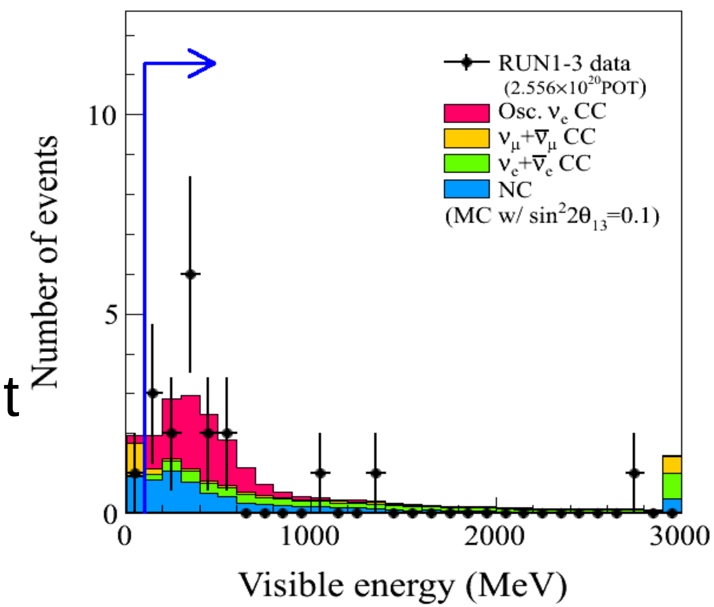
Step 3:
Single e-like ring
151 → 19 Events

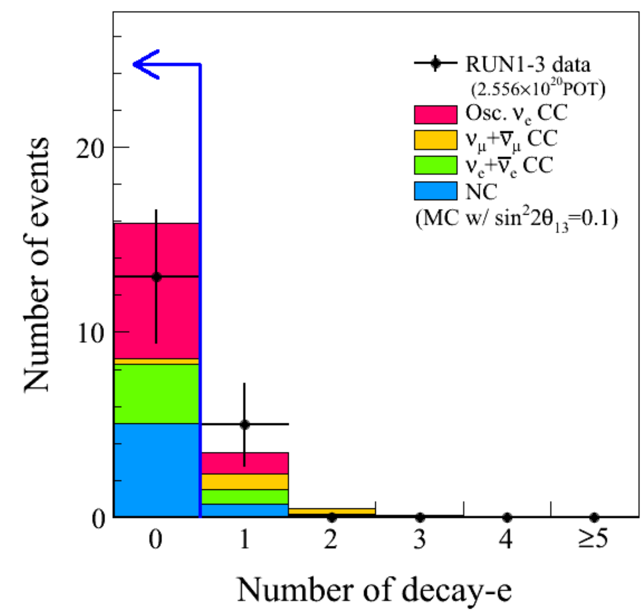




Step 4:
Visible energy cut
19 → 18 Events

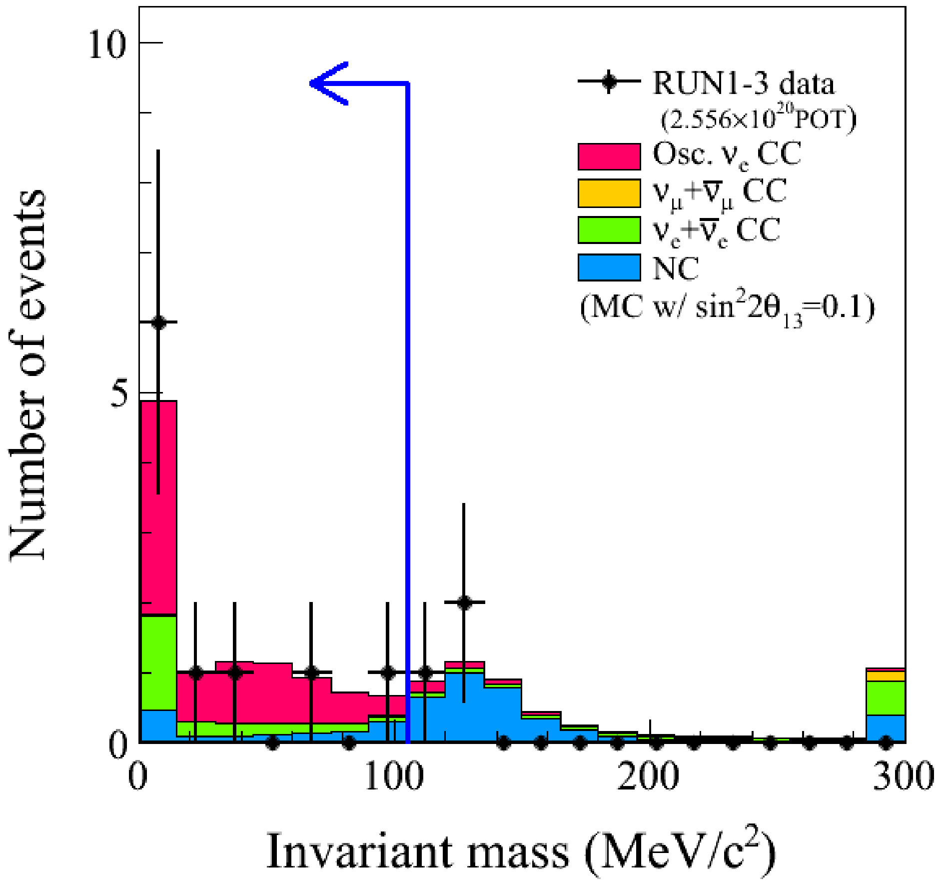
Step 5:
Decay electron cut
18 → 13 Events



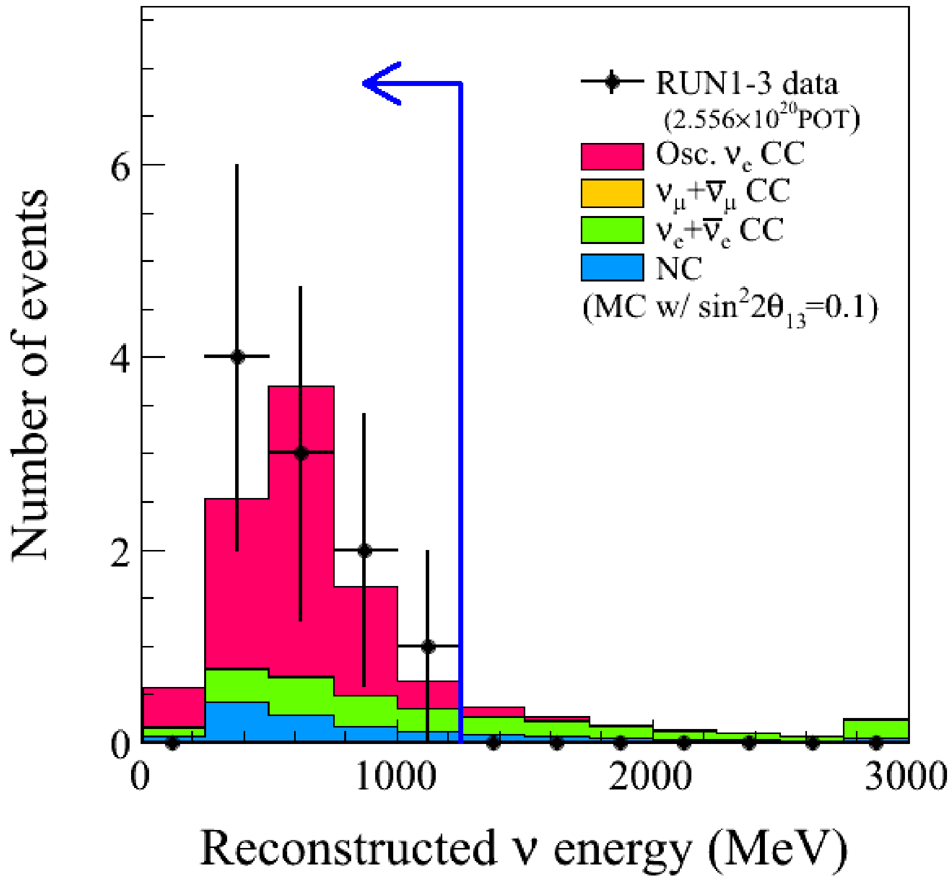


SK ν_e Candidate Sample

Step 6: π^0 mass cut
13 → 10 Events

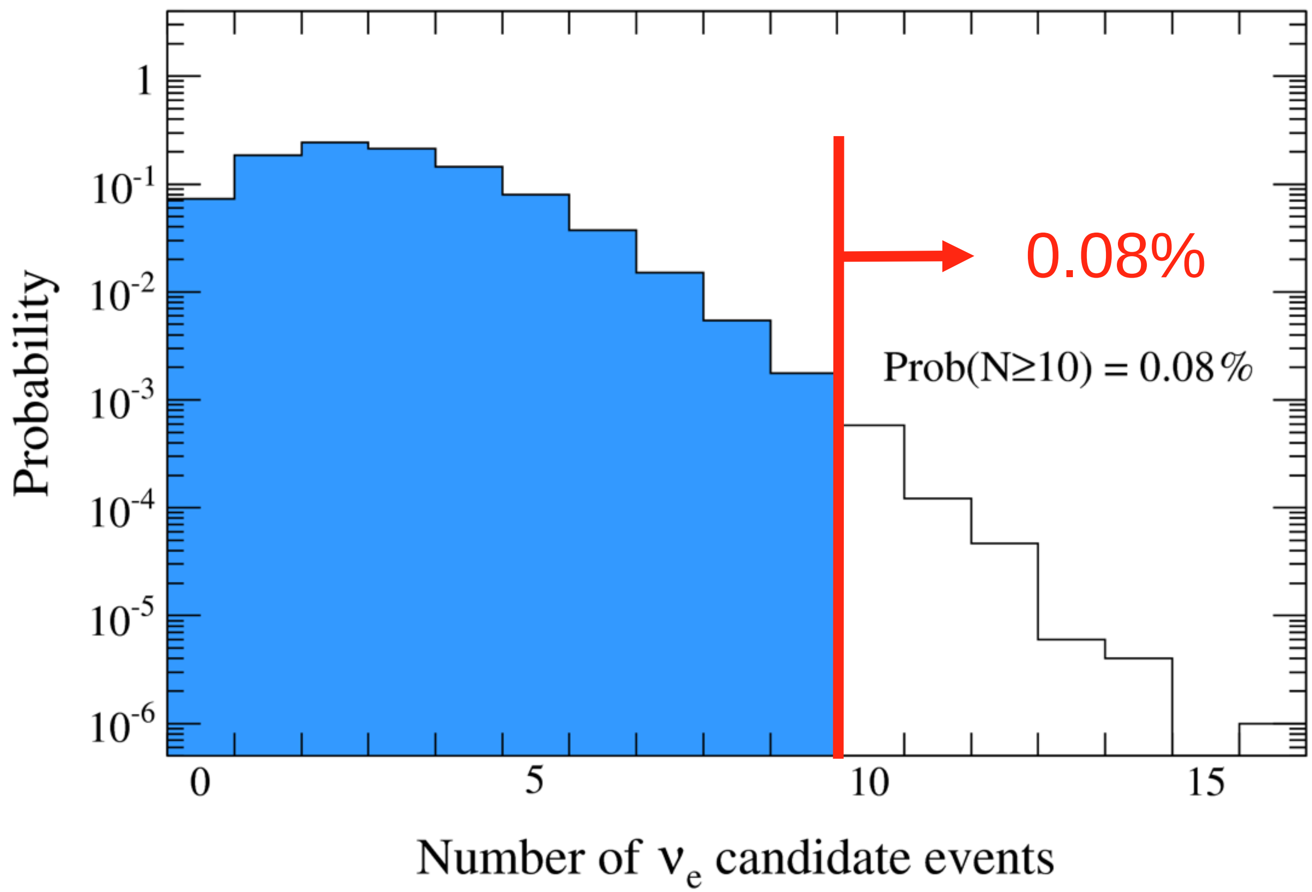


Step 7: Reconstructed energy cut
10 → 10 Events



After ν_e selection is applied → 10 candidate events remain!
(Recall, background expectation is 2.73 ± 0.37 events)

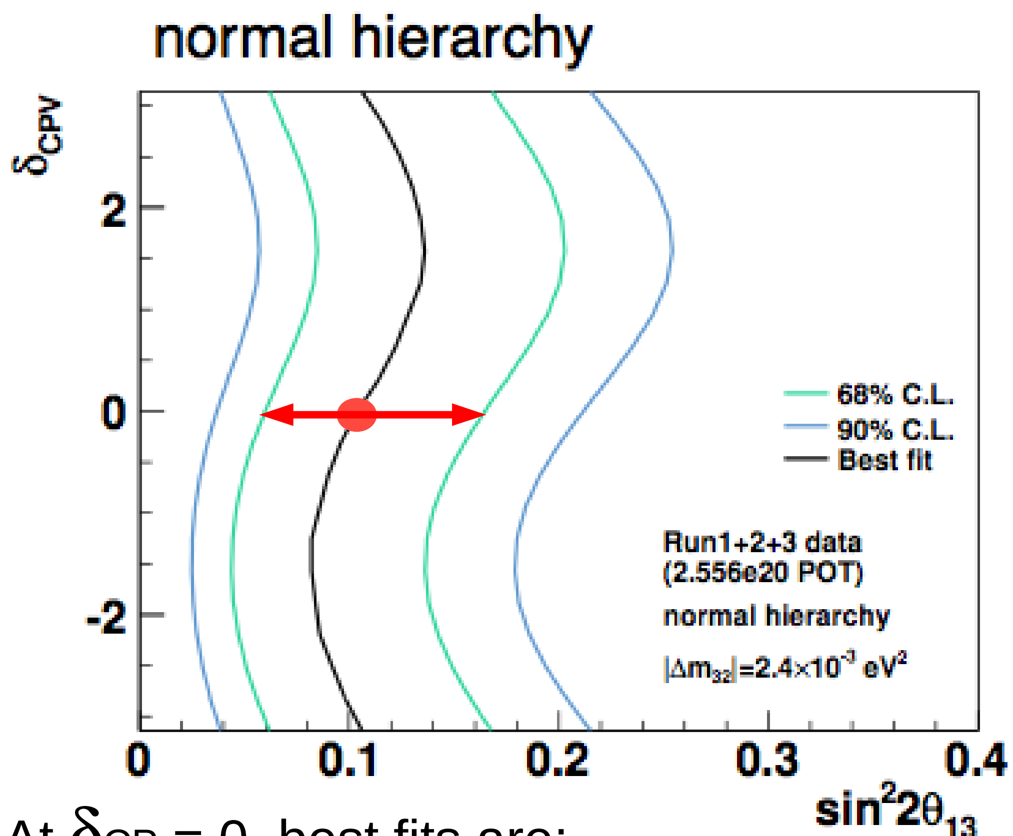
Evidence of appearance!

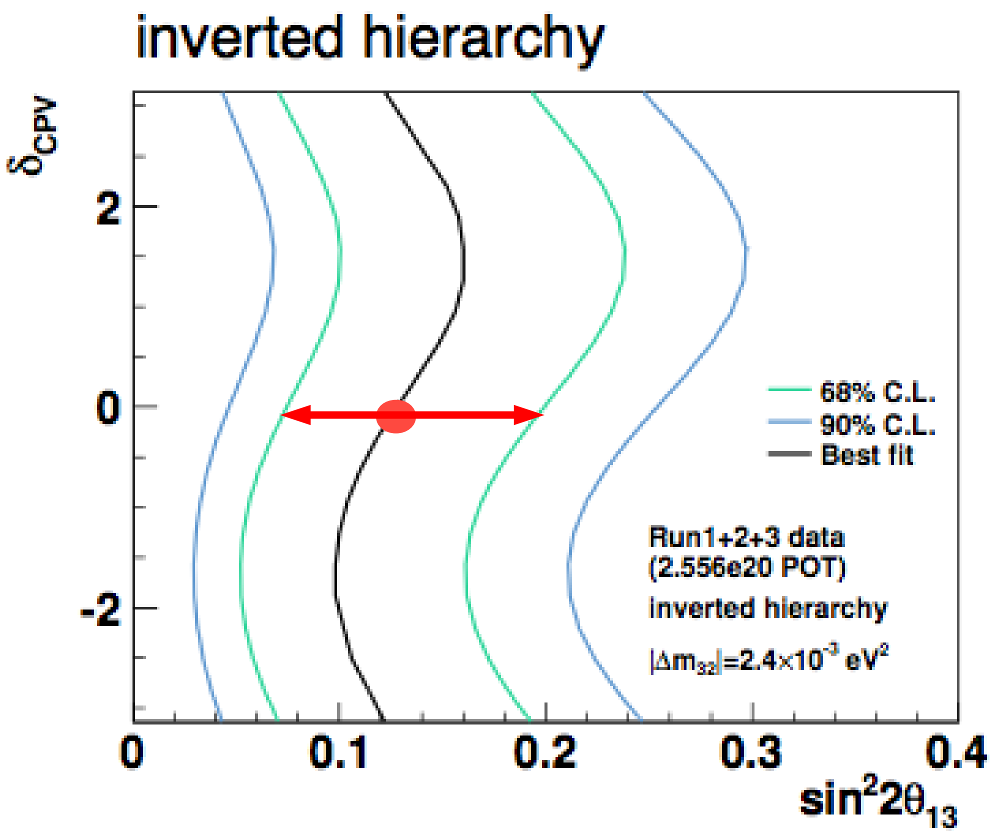


- The p-value to observe 10 or more events with 2.73 ± 0.37 BG is 0.0008 (equivalent to 3.2σ)
- This confirms the T2K 2011 result [PRL 107, 041801 (2011)]
- **We now have first evidence of ν_e appearance!**

For $\sin^2(2\theta_{13}) = 0$, probability to observe ≥ 10 events = 0.0008

Assuming $\sin^2(2\theta_{23}) = 1.0$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2





At $\delta_{CP} = 0$, best fits are:

$\sin^2(2\theta_{13}) = 0.104^{+0.060}_{-0.045}$

$\sin^2(2\theta_{13}) = 0.128^{+0.070}_{-0.055}$

Outline

- Physics motivation: Neutrinos & Oscillations
- Overview of the T2K experiment
- Data taking at T2K
- ν_e analysis:
  - Selection criteria
  - Expected backgrounds
  - Systematic uncertainty
  - New data set
- New oscillation results
- **Summary & conclusions**

Future Plans

- **Short term:**
  - Results from data collected up to summer shutdown ready soon
  - Update on ν_μ disappearance results coming shortly
    - Increased precision on θ_{23} necessary to probe CP violation
  - Precision measurements of neutrino cross sections

- **Medium term:**
  - Continue running at higher beam power:
    - ~8e20 POT (2013) → ~1.2e21 POT (2014) → ~1.8e21 POT (2015)
  - Sterile neutrino searches
  - More precise measurements of ν_e appearance to evaluate sub-leading effects, such as CP violation and the mass hierarchy!

- **Long term:**
  - Anti-neutrino running?
  - Hyper-Kamiokande?

Summary & Conclusions

- In 2011, 6 electron neutrino appearance candidate events were observed (p-value = 0.007), which indicated $\theta_{13} \neq 0$
- This year, J-PARC resumed operation after recovering from the Great East Japan Earthquake of March 2011. T2K resumed taking physics data with a beam power of ~190 kW
- Based on 2.56 x 10^{20} POT collected at SK by May 2012, a total of 10 electron neutrino appearance candidate events were observed:
  - p-value = 0.0008 (3.2σ)
  - $\sin^2(2\theta_{13}) = 0.104^{+0.060}_{-0.045}$ (for normal hierarchy assumption)
  - The systematic uncertainty is greatly reduced! (~10%)
- **First evidence for electron neutrino appearance!**
- This result opens the possibility of probing CP violation in the lepton sector, as well as determining the neutrino mass hierarchy

Back Up Slides

SK Particle Identification

Muons:

• Minimal scattering

• Ring has sharp edges

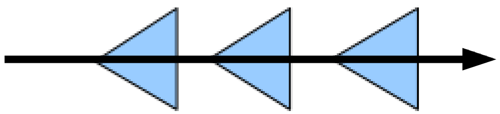
Electrons

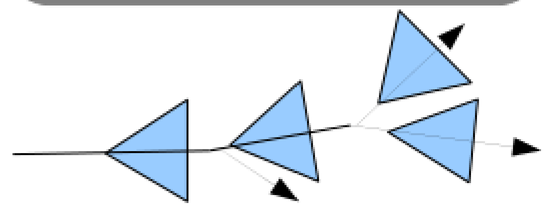
• Electromagnetic shower

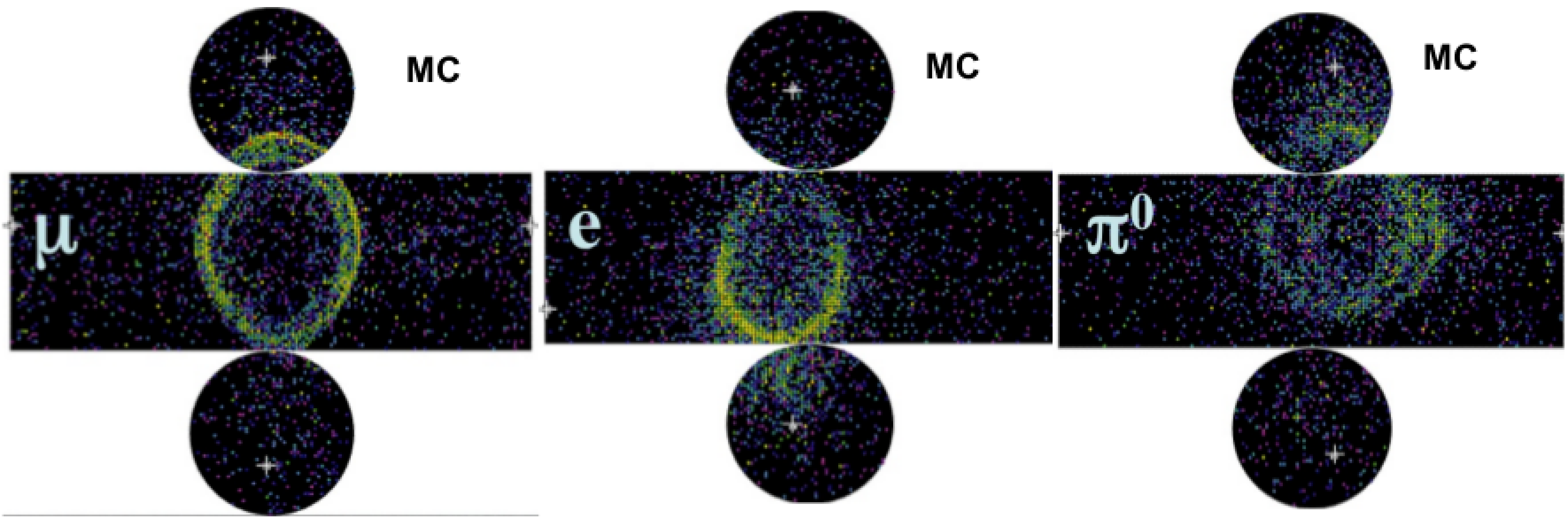
• EM scattering makes a "fuzzy" ring

Neutral Pions

• γs from π^0 decays shower and look like electrons

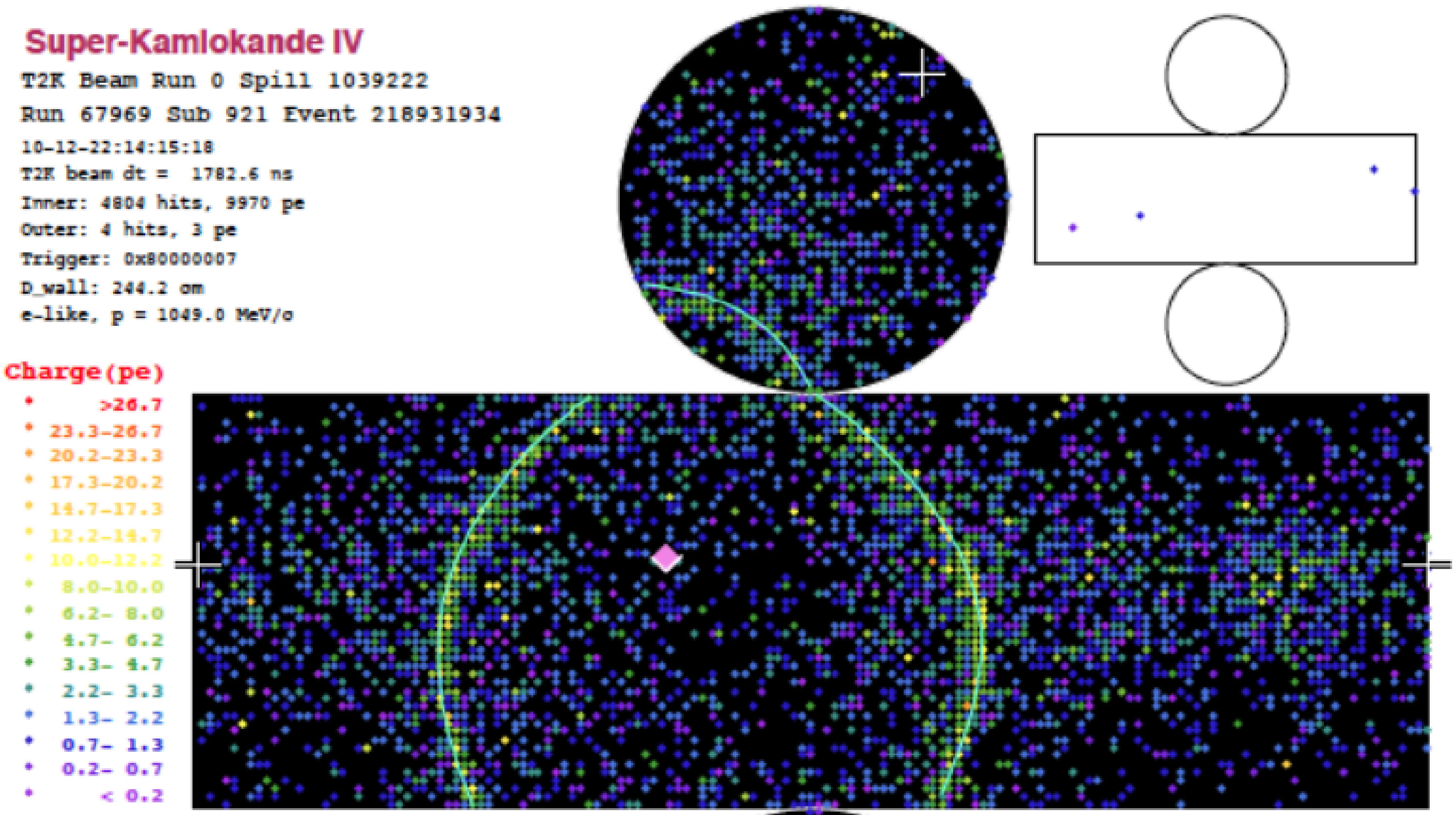




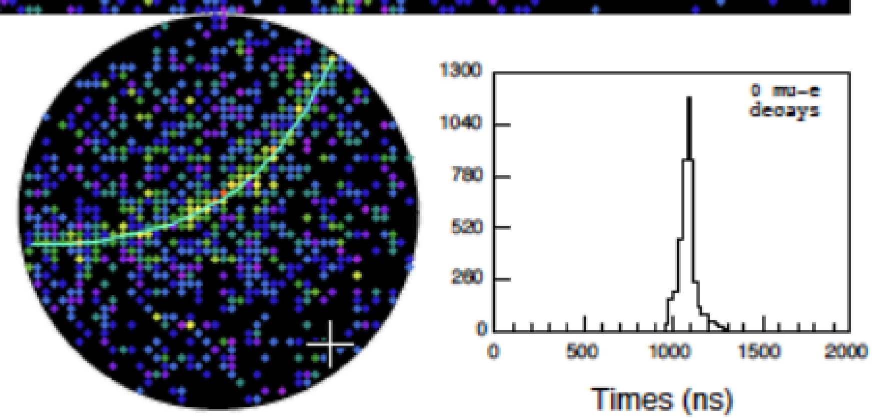


- Reliable PID particularly crucial to electron appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s

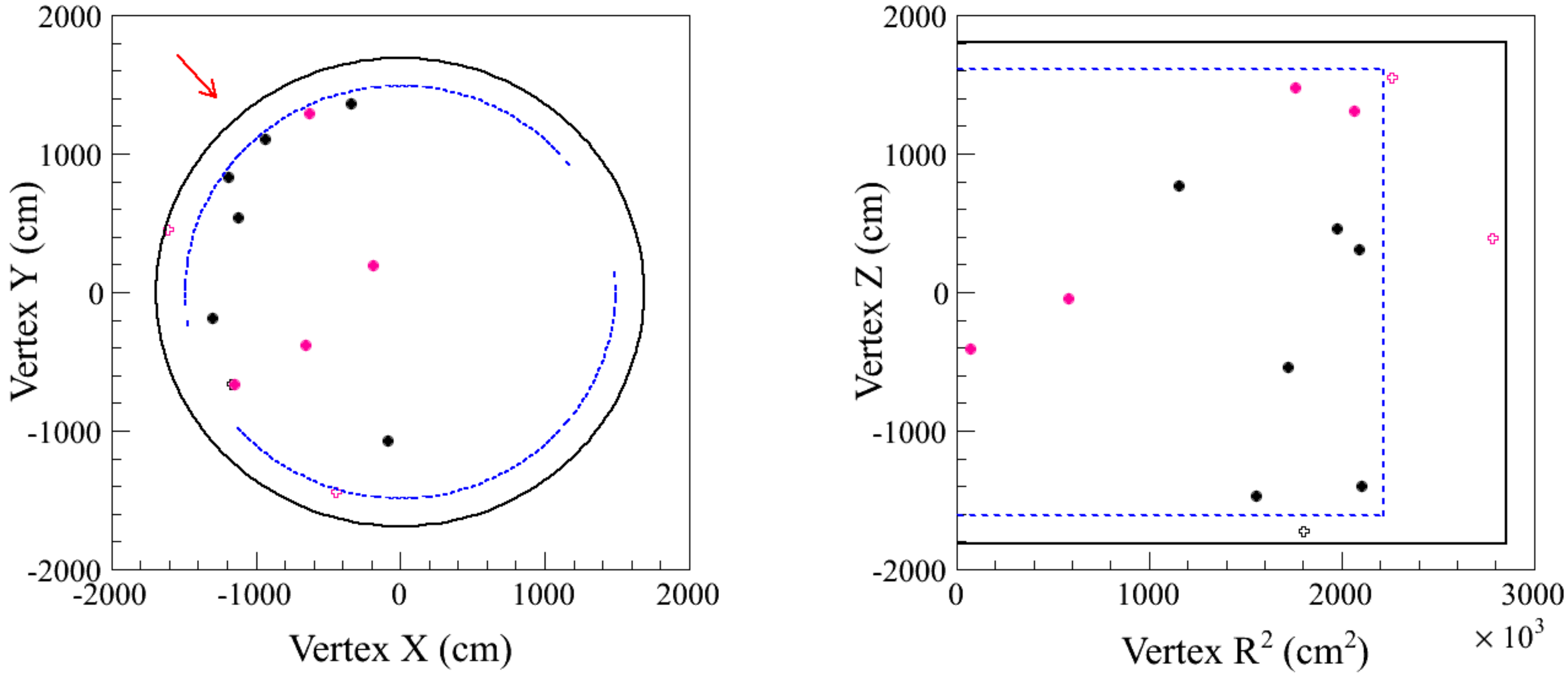
A Typical ν_e Candidate



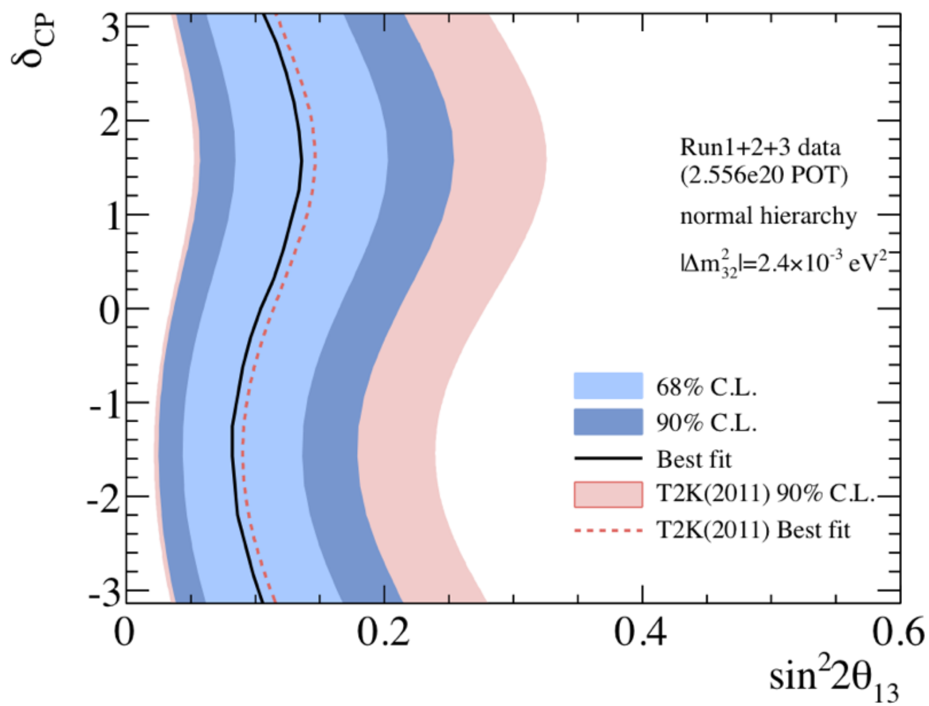
visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV

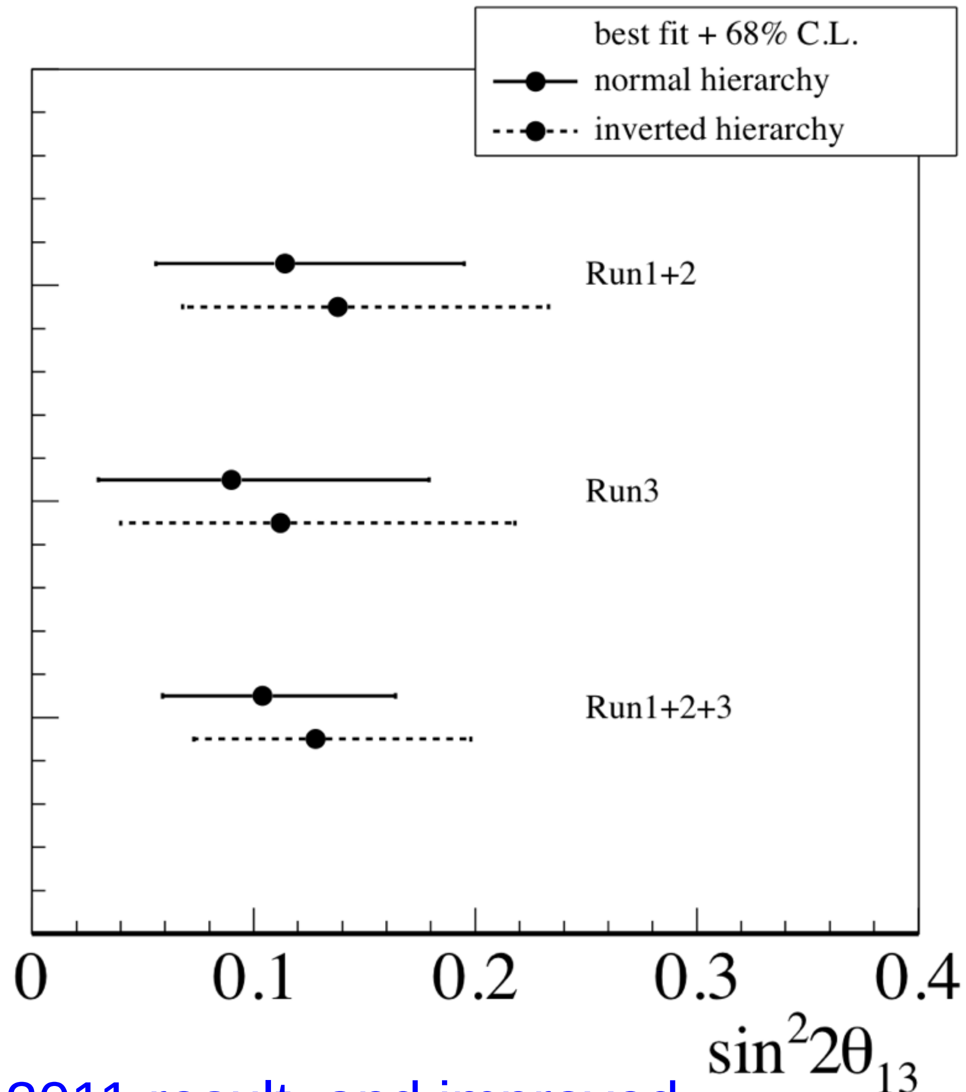


Vertex Distributions



2011 and 2012 Results





- The current result is consistent with the 2011 result, and improved
- The result with only 2012 data is also consistent with the 2011 result