Life After ν_e Appearance: What's NEXT for T2K ?

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Neutrino Mixing

- Neutrinos have mass!

Flavour eigenstates: ν_e, ν_μ, ν_τ
(interaction)

Mass eigenstates: ν_1, ν_2, ν_3
(propagation)

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

1998 onwards:
Probed with atmospheric neutrinos, long baseline accelerator neutrinos (SK, K2K, MINOS)

2001 onwards:
Probed with solar neutrinos, long baseline reactor neutrinos (SK, SNO, KamLAND)

First measured in 2011 – 2012:
Short baseline reactor neutrinos (Daya Bay, RENO, DoubleChooz); Long baseline accelerator neutrinos (T2K, MINOS, NOvA)

Experimental Probes

- For Dirac neutrinos, standard parameterization of the PMNS matrix U_{li} (for Dirac neutrinos) has:

  3 mixing angles, 2 mass square differences, 1 CP phase

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

$\sin^2(2\theta_{23}) > 0.95$ (90% C.L.)
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}$ eV^2

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
$\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5}$ eV^2

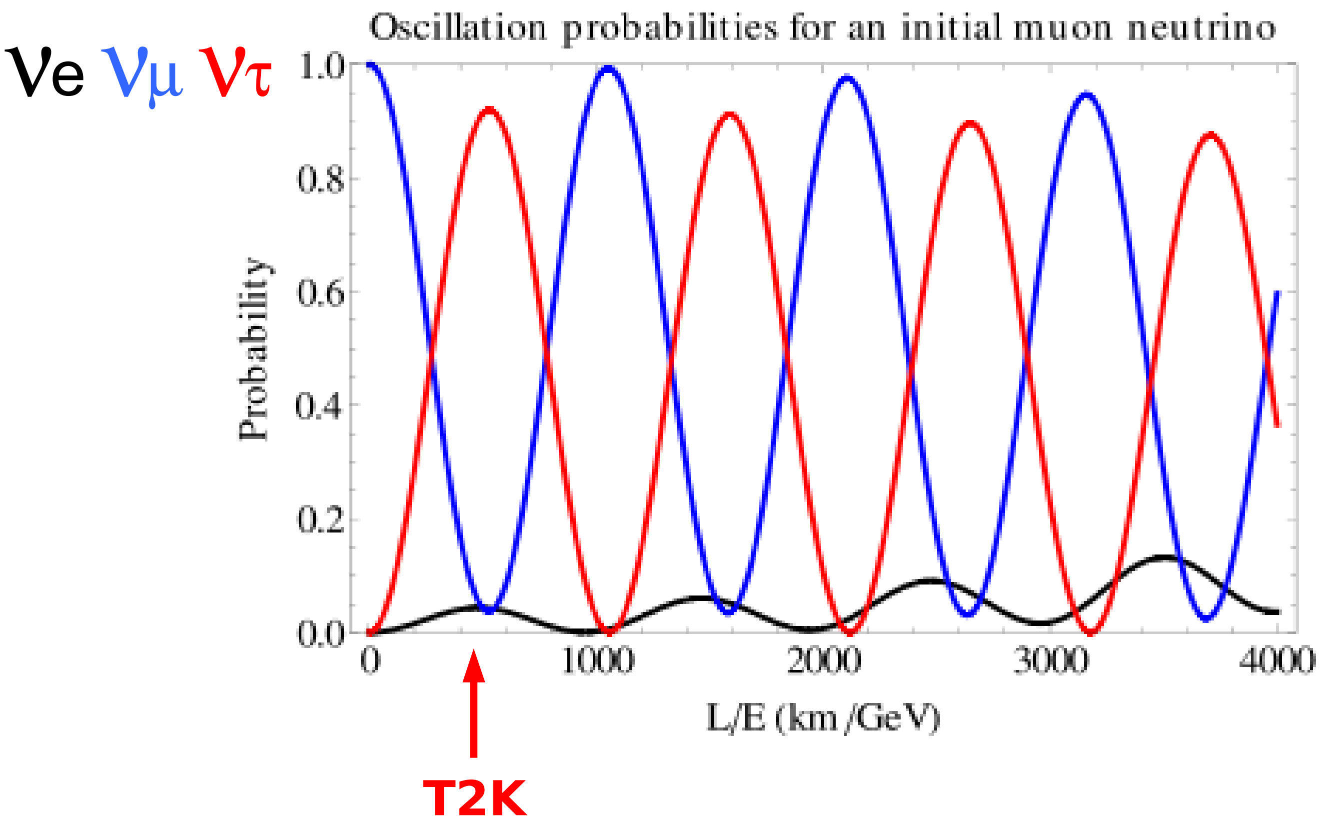
$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

What is the octant of θ_{23}? What is the mass hierarchy?

What is the CP violating phase δ?

Oscillation @Accelerators

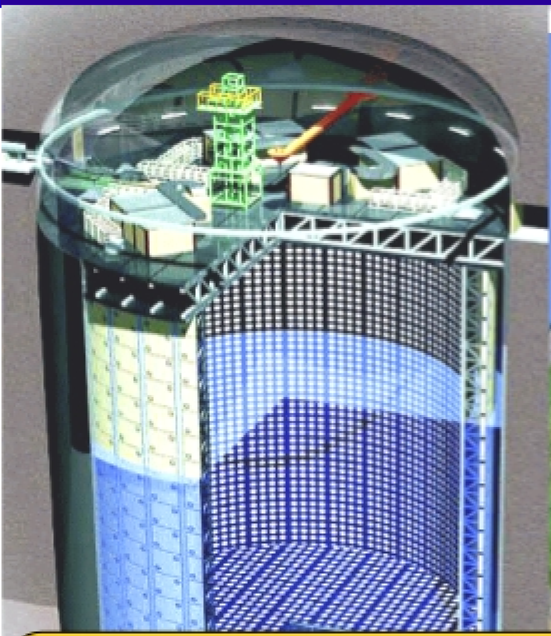
Long baseline accelerator: Sensitive to θ_{13}, θ_{23}, δ, mass hierarchy



$$P_{\mu\to\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P_{\mu\to e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

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 (and non-zero θ_{13})**
  - Precision ν_μ disappearance
  - Other (ν cross sections, sterile ν searches, etc.)

T2K Collaboration

~ 500 members, 59 Institutes, 11 countries

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

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

Germany
Aachen U.

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

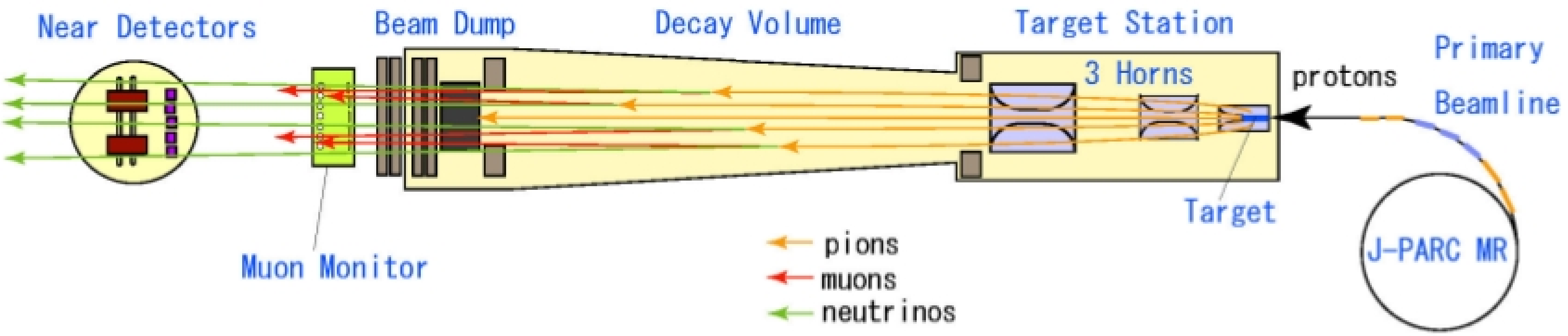
Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

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

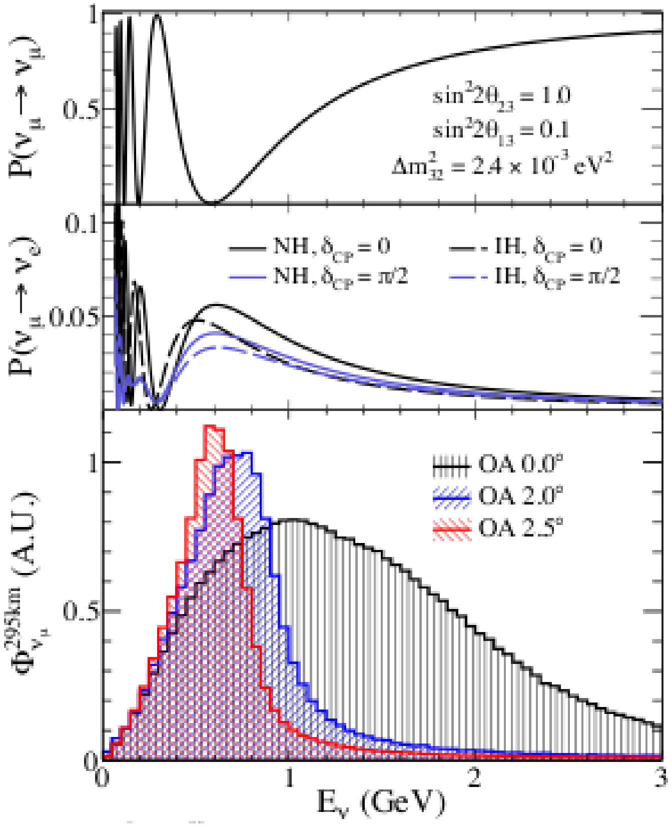
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Neutrino Beam

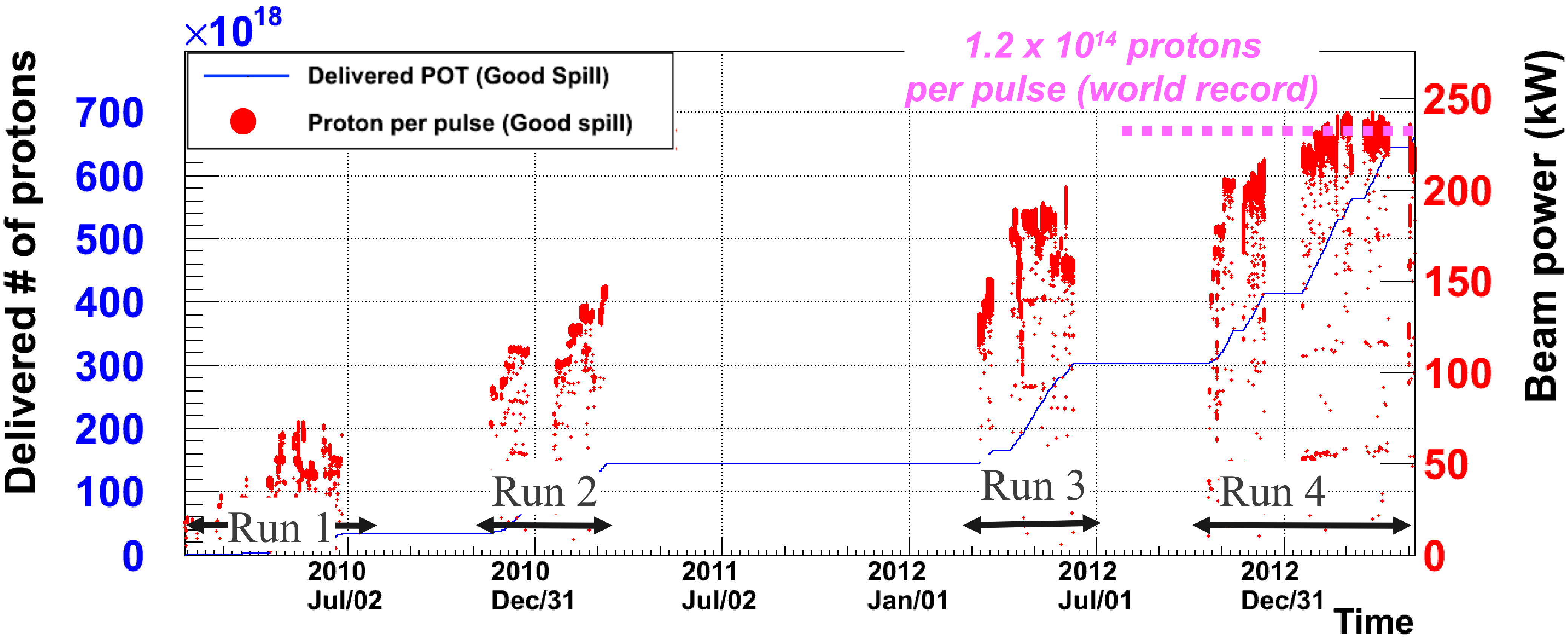


T2K is the first experiment to use an **off-axis** neutrino beam:

- Enhances signal at oscillation maximum
- Reduces backgrounds from other energies



Data Taking

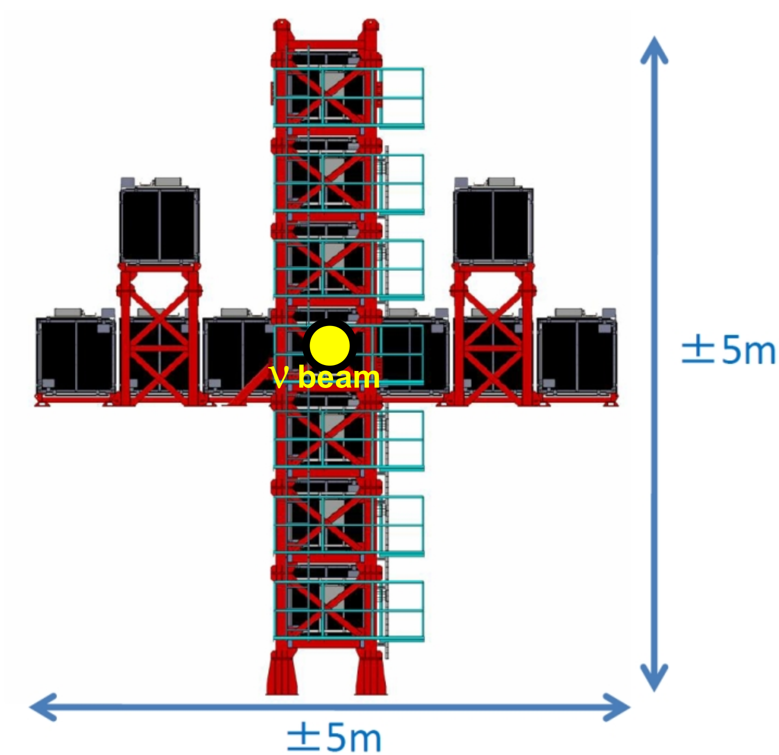


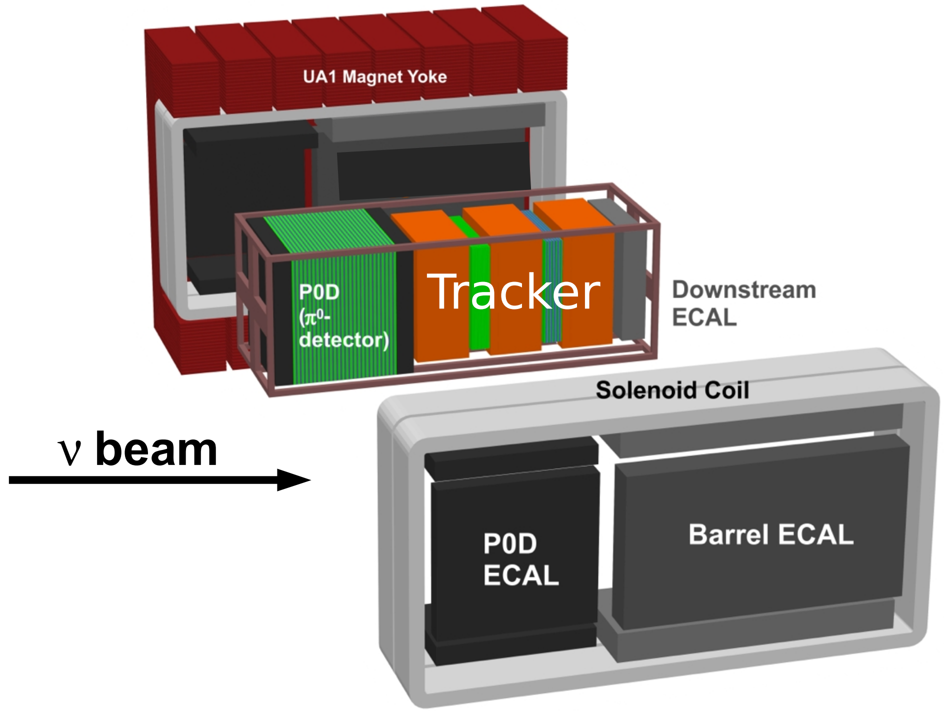
- **NEW!** Full Run 1 – 4 data sets published last week!
  - 6.57 x 10^{20} P.O.T. for SK analysis (6.39 x 10^{20} P.O.T. shown this Summer)
  - Previous ν_e appearance result (2012) used 3.01 x 10^{20} P.O.T. → Statistics increased by factor >2!
- Thus far, ~8% of the total data has been collected (assuming design goal)
- Instantaneous luminosity of 220 kW (1.2 x 10^{14} protons per pulse) → **World record!**

Near Detector Suite

INGRID (On-axis)

- 16 modules of iron and scintillator
  → 14 in “cross” configuration
- Monitors beam profile and rate

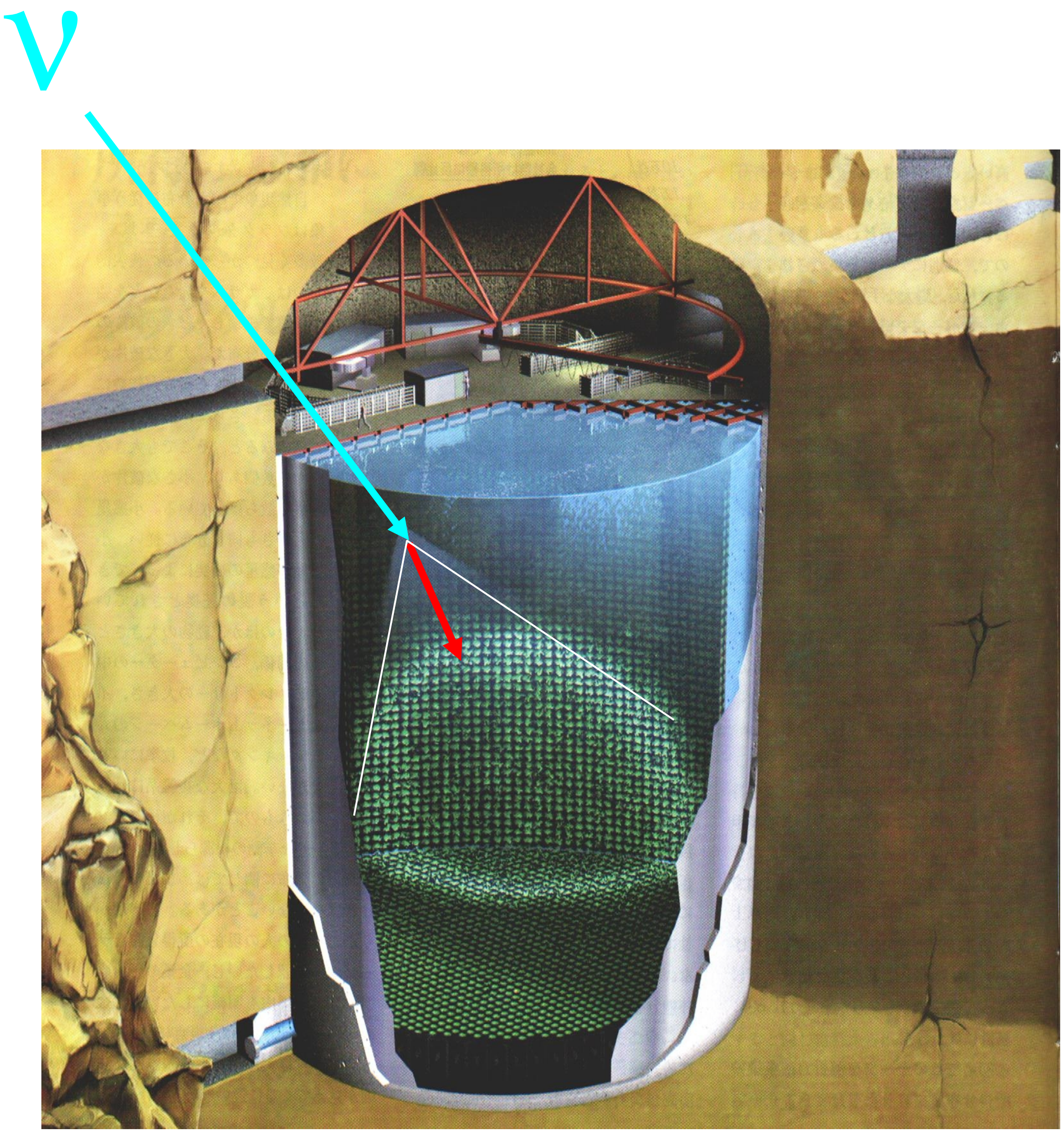




ND280 (Off-axis)

- Sits in 0.2 T magnetic field
- Tracker comprised of:
  - 2 Fine-Grain Detectors (FGDs)
    → 1.6 t plastic scintillator primary target
    → Detailed vertex information
  - 3 Time Projection Chambers (TPCs)
    → Track momentum from curvature
    → Particle identification from dE/dx

Super-Kamiokande (far)



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

SK Particle Identification

Muons:

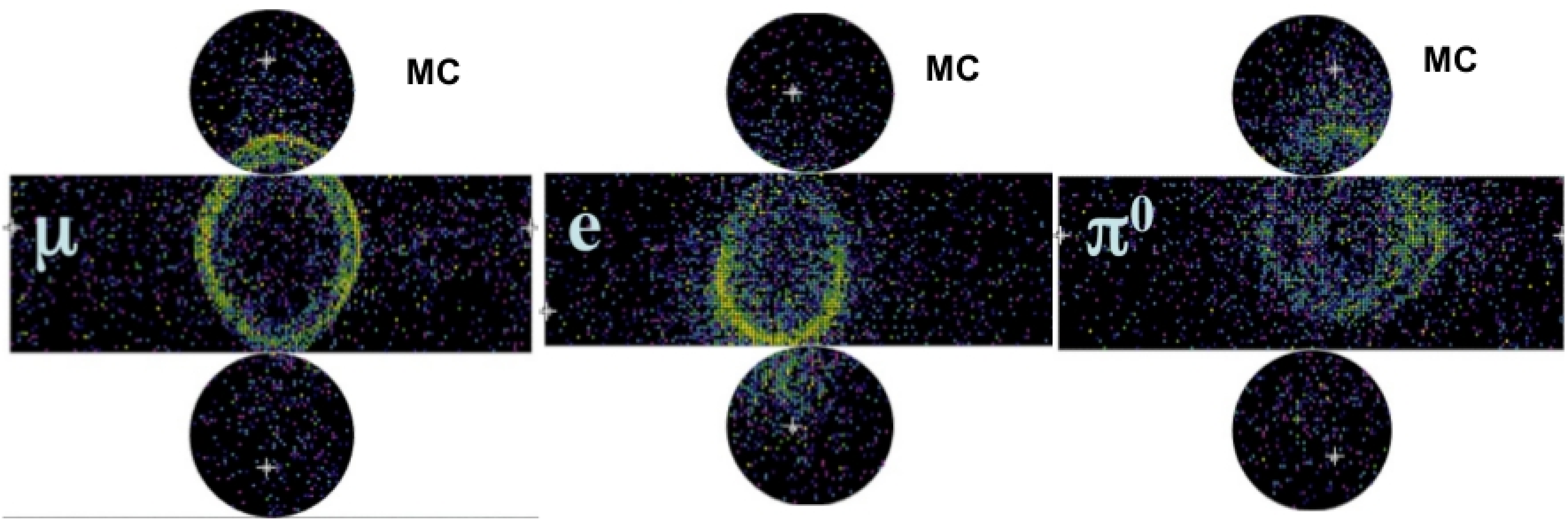
- Minimal scattering
- Ring has sharp edges

Electrons

- Electromagnetic shower
- EM scattering makes a "fuzzy" ring

Neutral Pions

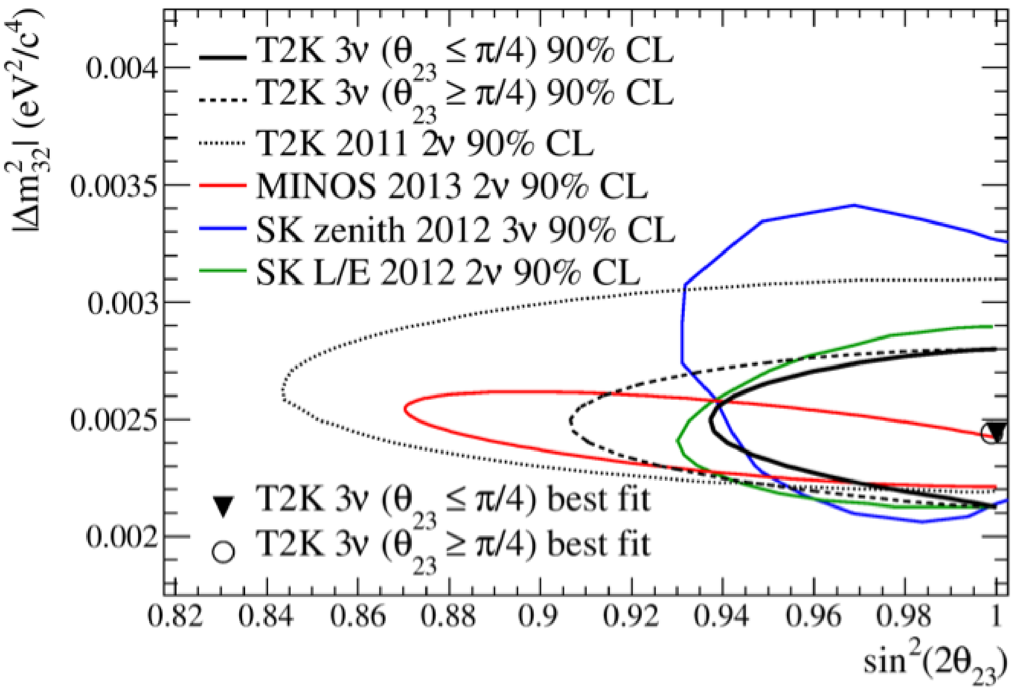
- γs from π^0 decays shower and look like electrons

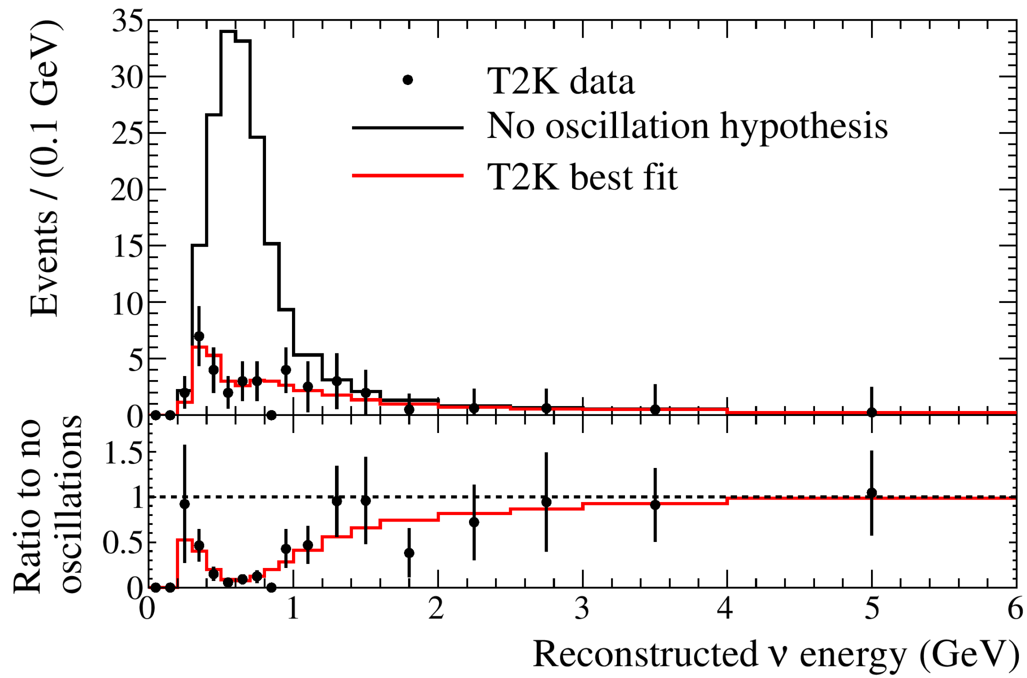


- Reliable PID particularly crucial to ν_e appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s

T2K: What's New?

- Last week was a good week for T2K!
  - Nov 19: New ν_e results paper (full 6.57×10^{20} P.O.T.) sent to arXiv (1311.4750) & submitted to PRL
  - Nov 19: New ν_μ results paper (3.01×10^{20} P.O.T.) published: *Phys. Rev. Lett.* **111:211803** (2013)



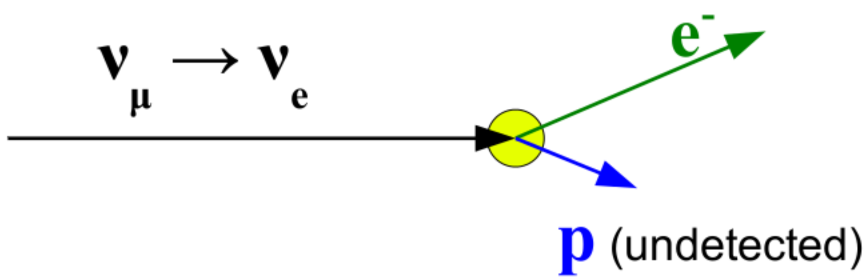


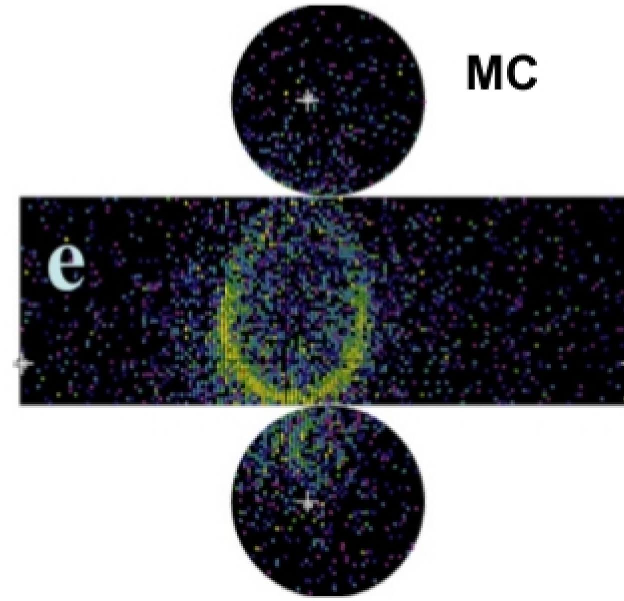
- Without oscillation 205 ± 17 events expects; 58 events observed
- Best fit: $\sin^2(\theta_{23}) = 0.514 \pm 0.082$ (consistent with maximal mixing)
- New ν_μ disappearance results coming soon
- All future results will be reported as $\sin^2(\theta_{23})$ NOT $\sin^2(2\theta_{23})$ to remove octant ambiguity

New ν_e Appearance Results

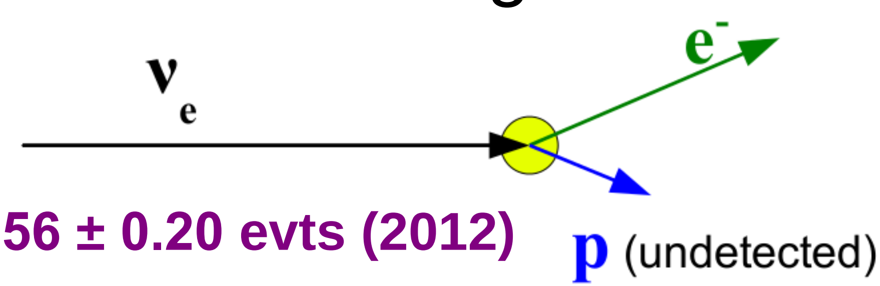
T2K

- Oscillation signal:





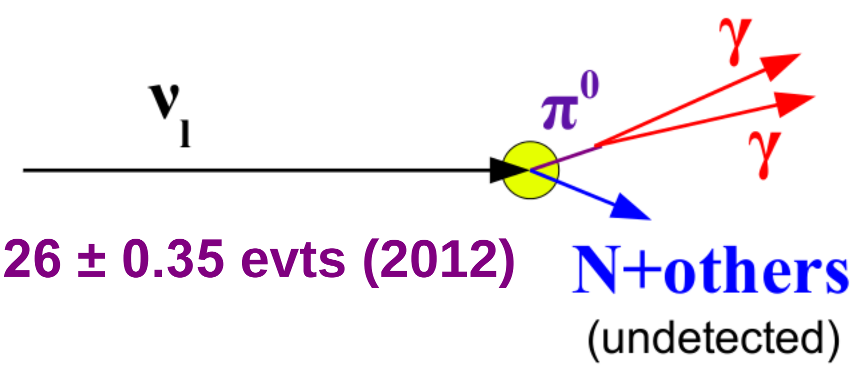
- Beam ν_e background:



1.56 ± 0.20 evts (2012)

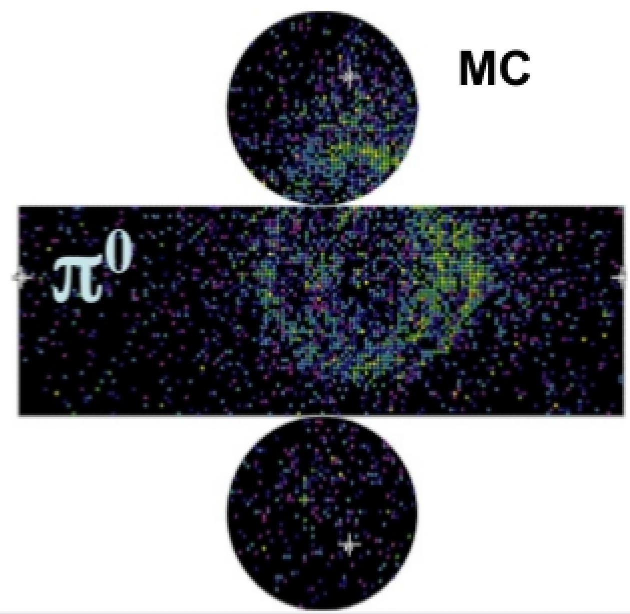
Beam background has harder energy spectrum

- Neutral current π^0 background:



1.26 ± 0.35 evts (2012)

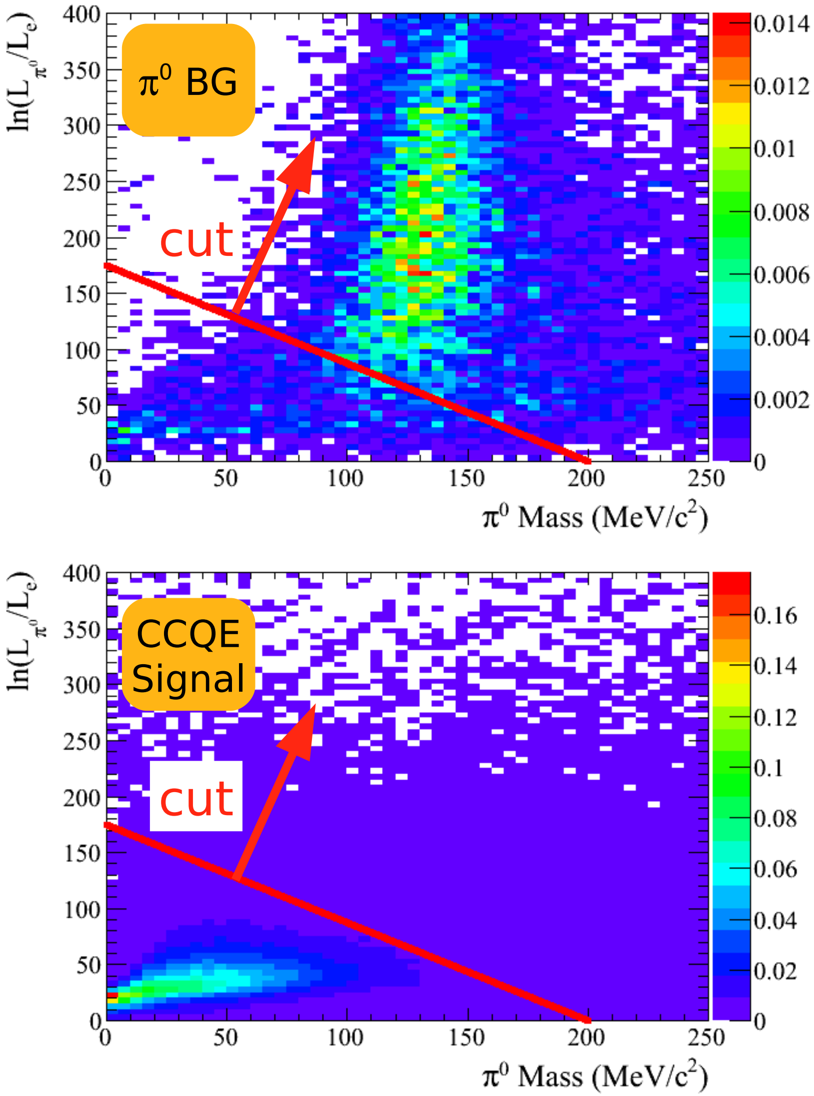
Can be removed by identifying second photon ring



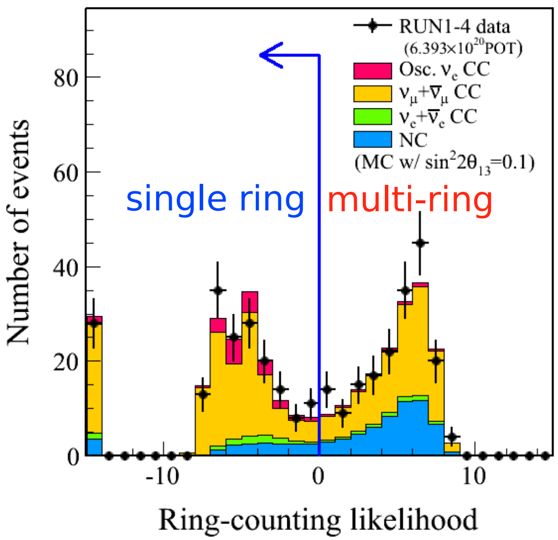
Improved π^0 Rejection

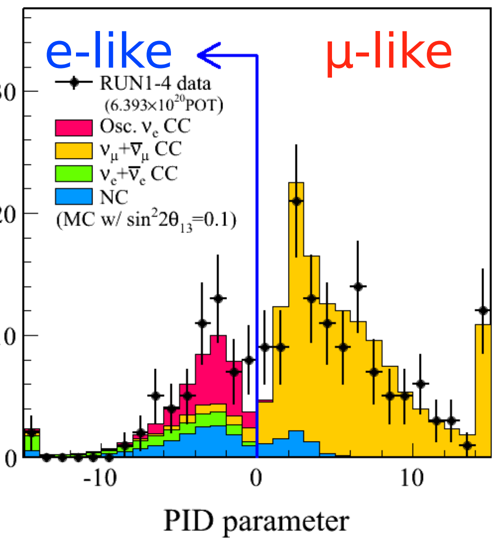
- New likelihood fitter (fiTQun) used to distinguish electrons from π^0
- Assumes two electron-like rings produced at a common vertex
- Uses 12 parameters in fit:
    - Vertex (X, Y, Z, T)
    - Directions (θ_1, φ_1, θ_2, φ_2)
    - Momenta (p_1, p_2)
    - Conversion lengths (c_1, c_2)
- This 2D cut **removes 70% of the π^0 background remaining** after previous selection (POLfit) applied (for same signal efficiency)
- Total background is reduced by 27%
- 6.74 BG events → 4.92 BG events expected
  (in full Run 1 – 4 dataset)

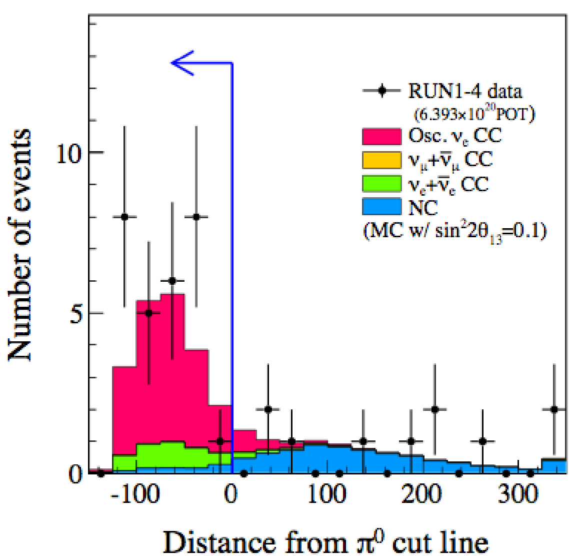
Likelihood Ratio vs π^0 Mass
(T2K Monte Carlo)

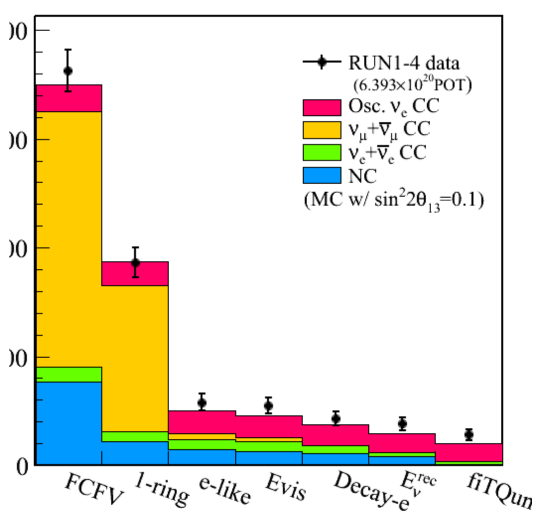


T2K-SK ν_e Event Selection





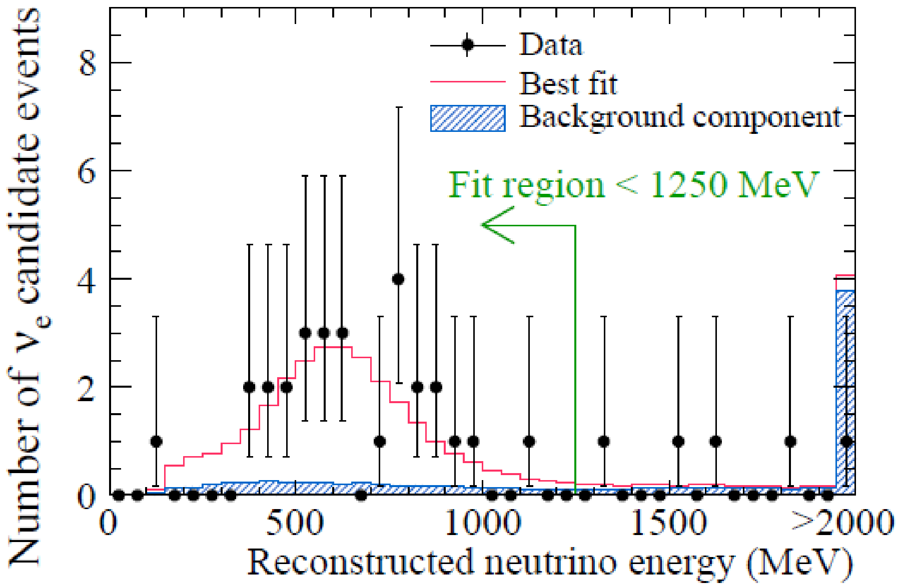


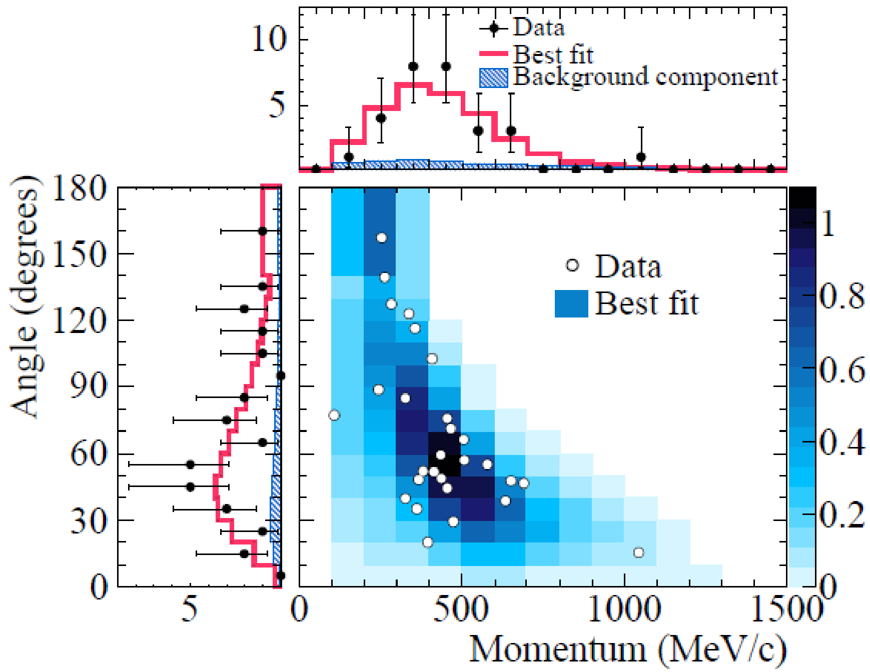


ν_e Selection Criteria

- \# clustered veto hits < 16
- Distance to wall > 200 cm
- \# of rings = 1
- PID of ring is e-like
- Visible energy > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- $0 < E_\nu < 1250$ MeV

ν_e Appearance Analysis



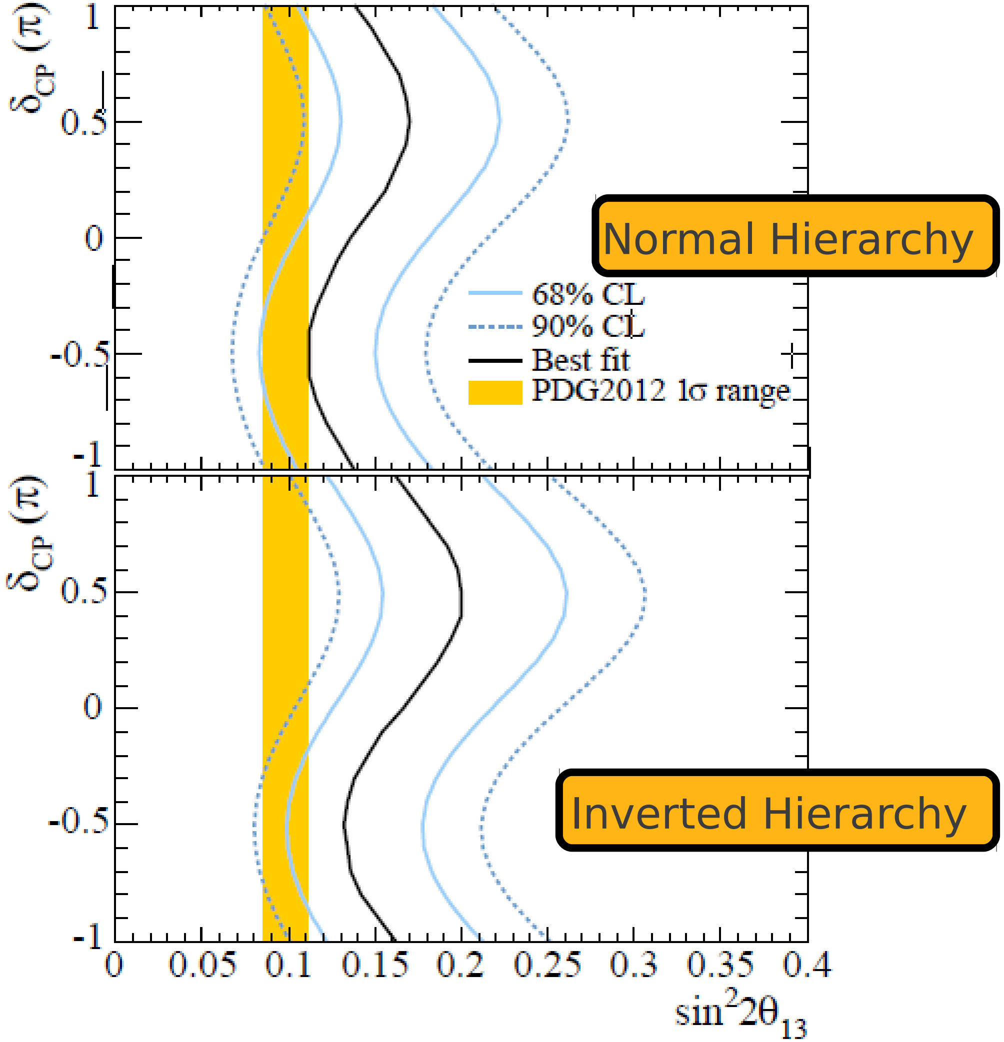


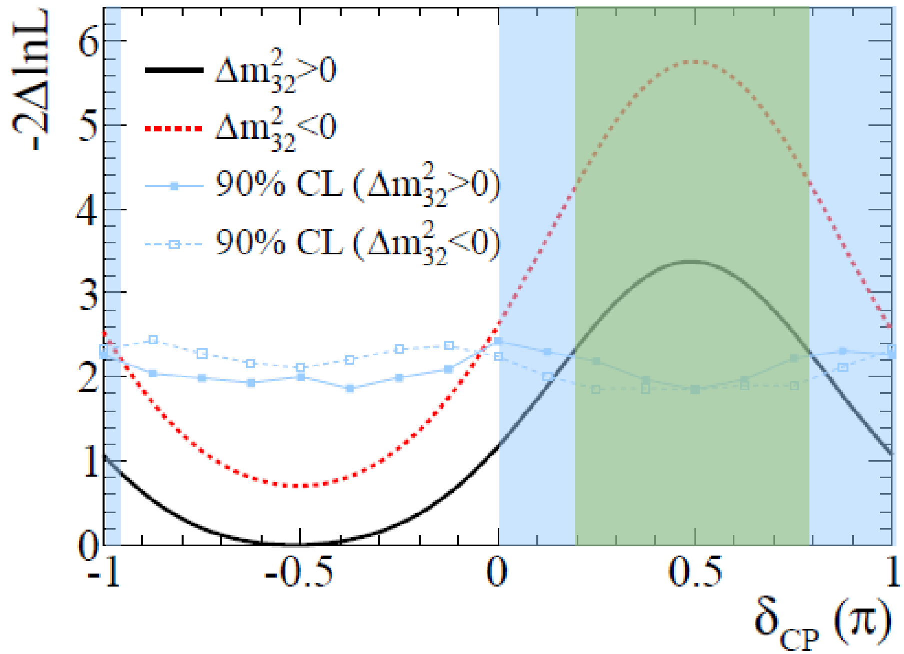
- Expected background:
  - 4.92 ± 0.55 events
- With the following assumptions:
  - $\sin^2(2\theta_{13}) = 0.1$
  - $\sin^2(2\theta_{23}) = 1$
  - $\delta_{CP} = 0$
  - normal mass hierarchy

  the expected signal is:
  - 21.6 ± 1.8 events
  - **5.5σ sensitivity to exclude $\theta_{13} = 0$**
- Oscillation parameters were extracted with two parallel analyses:
  - Using the 1D Eν distribution (top)
  - Using the 2D p-θ distribution (bottom)

ν_e Appearance Results

- **28 ν_e events observed** (recall 21.6 ± 1.8 expected for $\sin^2(2\theta_{13}) = 0.1$)
- Comparison to null hypothesis gives 7.3σ significance for $\theta_{13} \neq 0$



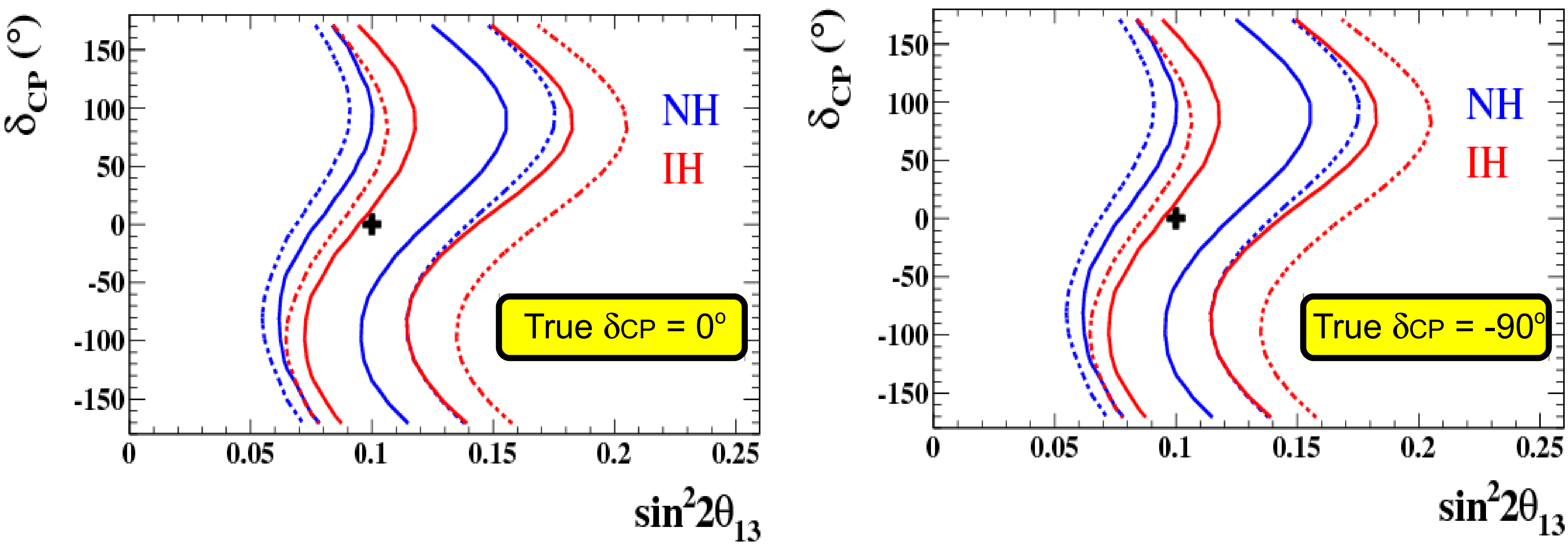


Tension with θ_{13} measurement at reactors gives some sensitivity to δ

- Some regions excluded at 90% CL
- $\delta = -\pi/2$ preferred for both hierarchies

What's Next?

- Original design for T2K is 7.8 x 10^{21} P.O.T. of ν running **>10x more data**
- Future sensitivity studies have been performed for full data set:



Truth parameters for this Monte Carlo study include:

- Normal hierarchy and maximal mixing
- $\sin^2(2\theta_{13}) = 0.1$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

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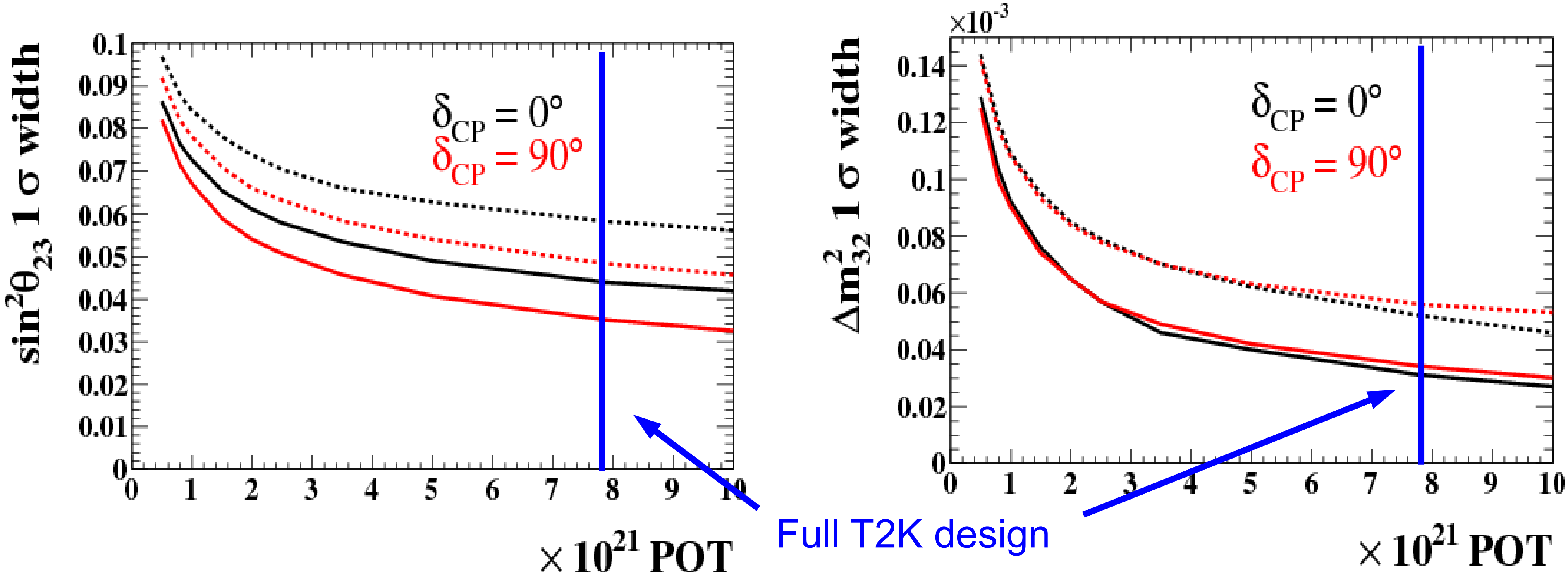

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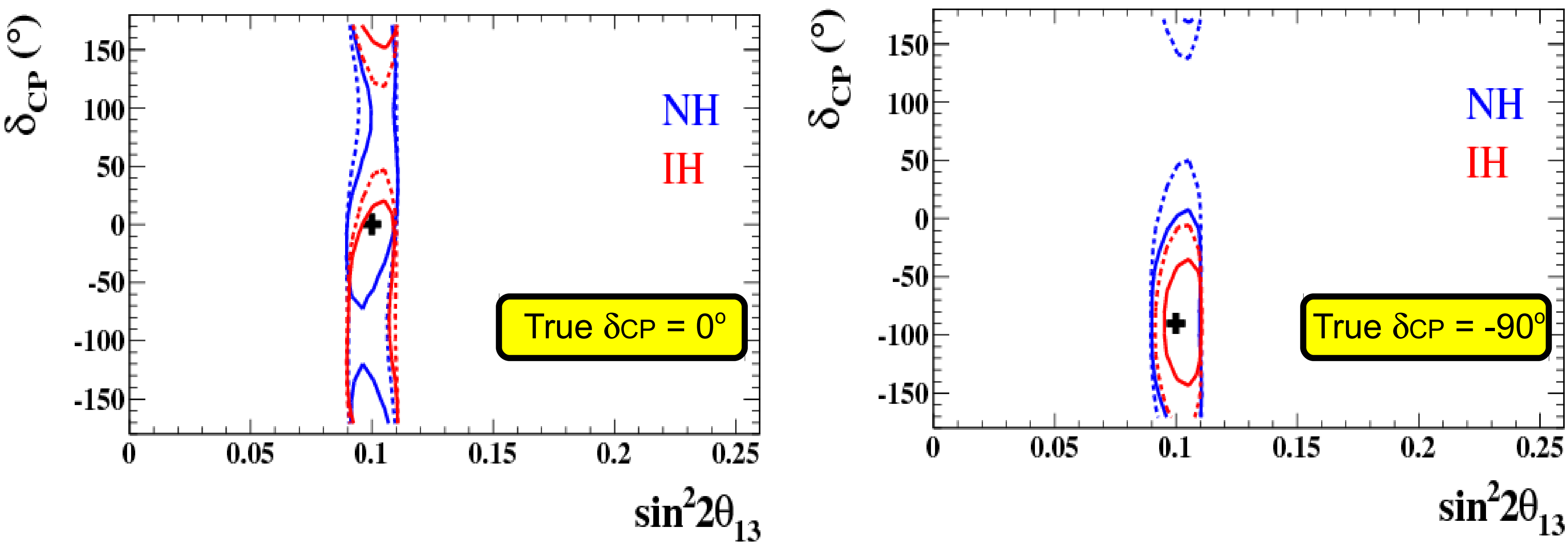
- Normal hierarchy and maximal mixing
- $\sin^2(2\theta_{13}) = 0.1$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Can We Do Better?

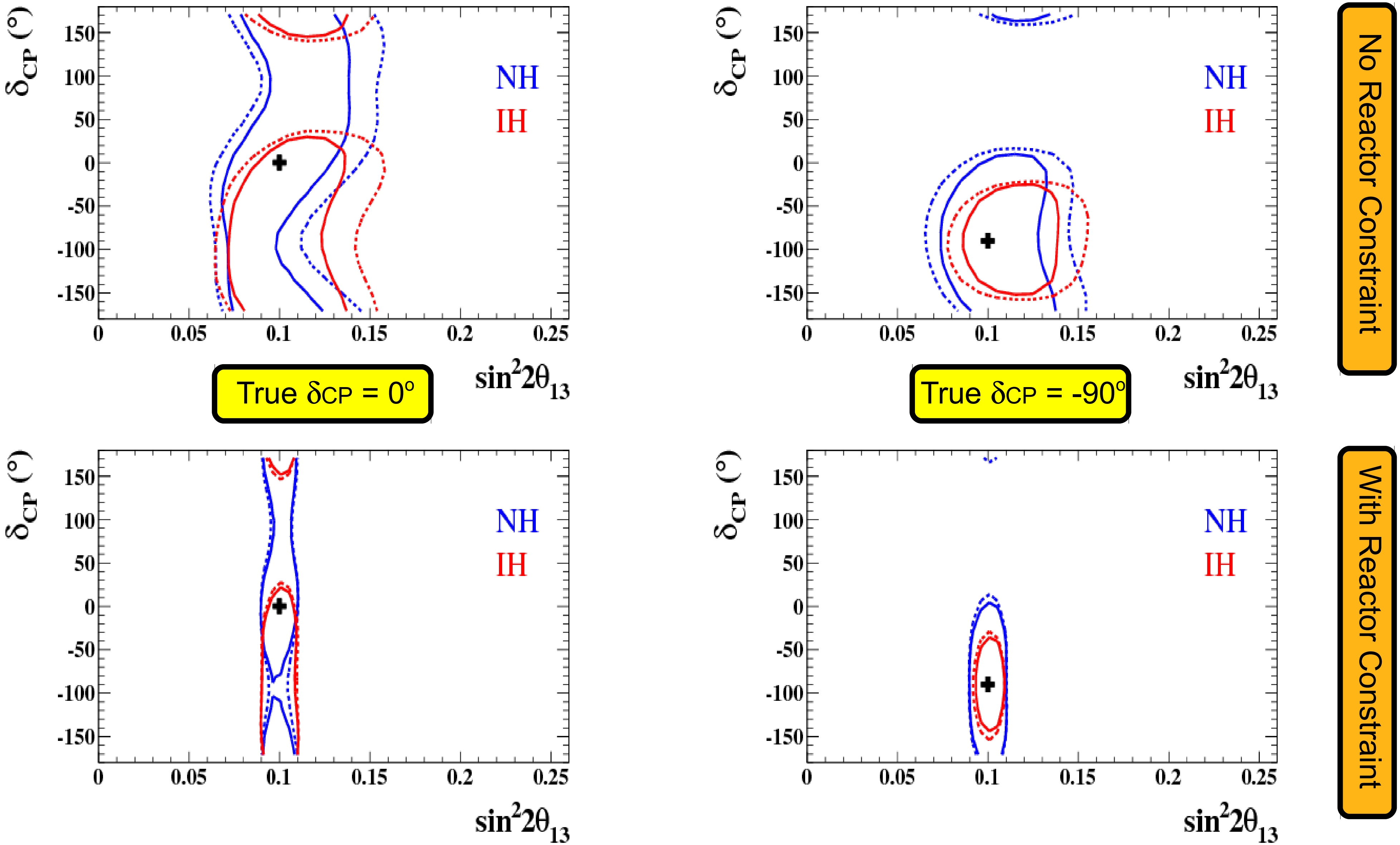
- Can include ultimate reactor sensitivity to θ_{13} as a constraint:
  - ➔ Uses anti-ν_e disappearance for direct measurement of θ_{13}



- Original T2K design anticipated long search for tiny (maybe zero) θ_{13}
- Nature was kind / we got lucky → θ_{13} is large!
- Can modify design to increase sensitivity to other paramters (*e.g.,* δ_{CP})
- **<u>One idea:</u> Run both ν and anti-ν beams!**

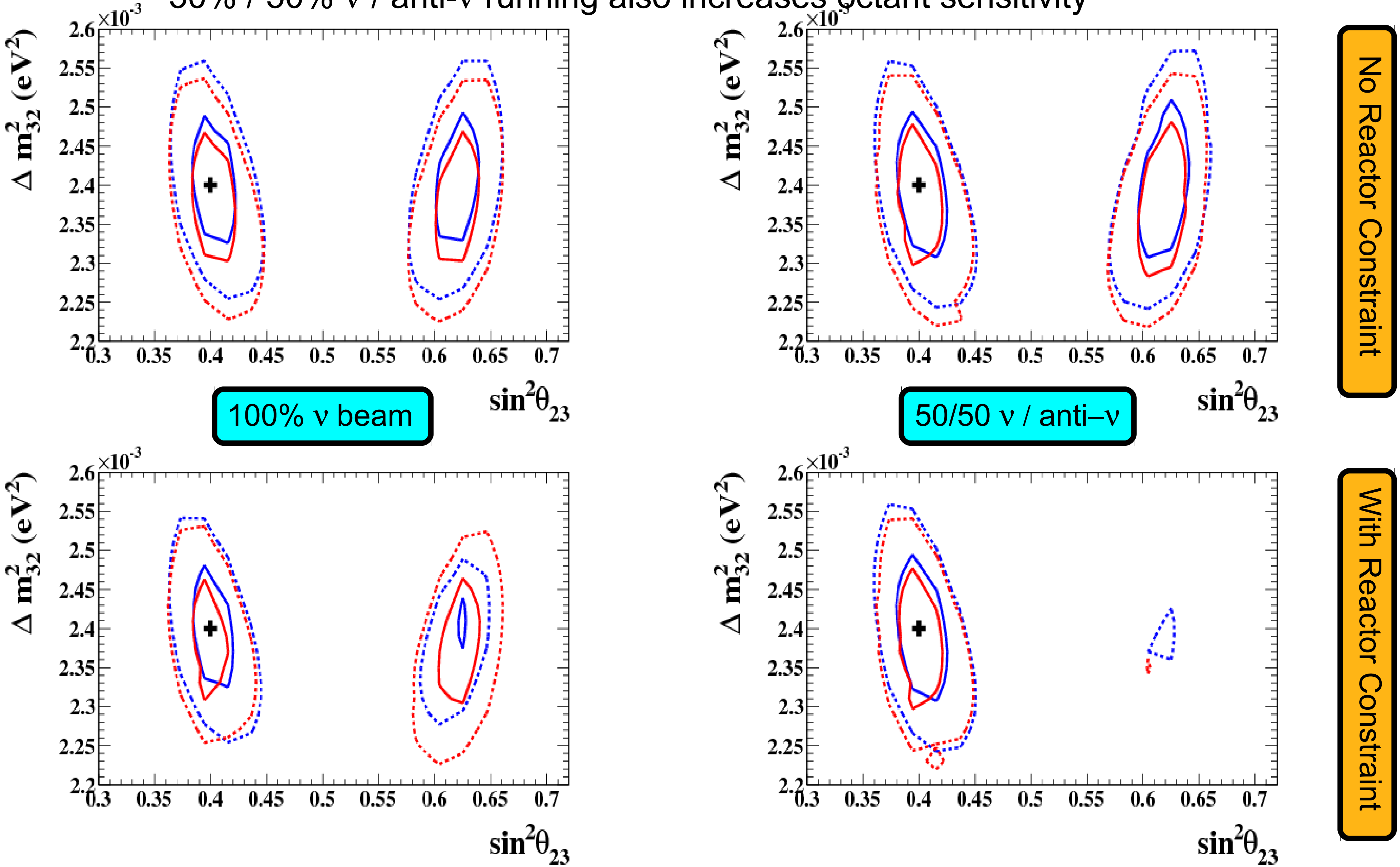
Can We Do EVEN Better?

T2K sensitivity running 50% with ν beam and 50% with anti-ν beam



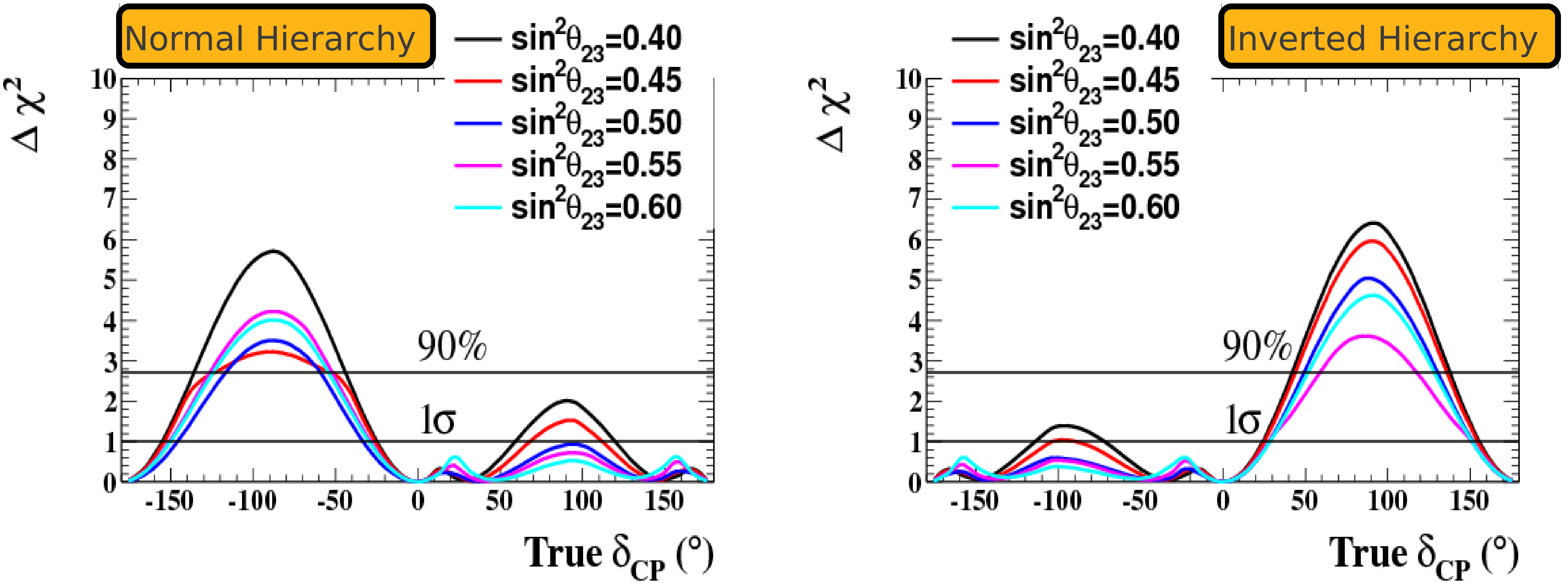
Can We Do EVEN Better?

50% / 50% ν / anti-ν running also increases octant sensitivity



Ultimate CPV Sensitivity

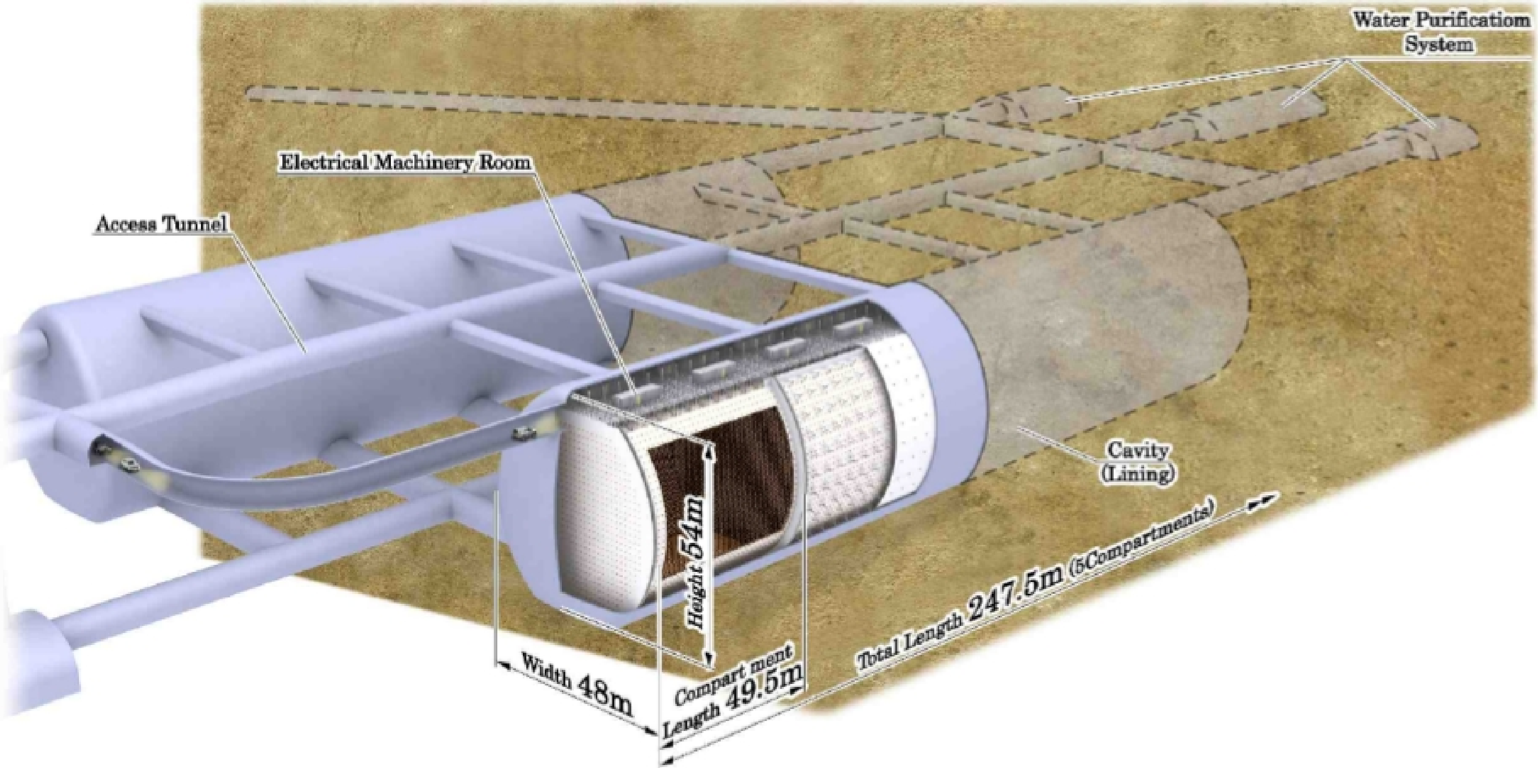
- Sensitivity plotted as a function of true δ_{CP}



- Many values can be ruled at at 90% C.L.
- Need bigger experiment to achieve 3σ evidence or beyond, unless we get very lucky!

What's NEXT NEXT?

- **Hyper-Kamiokande:** A 1,000,000 tonne water Cherenkov detector



- Plan to build in Japan: Construction from 2017/18; physics running from 2022
- Rich physics programme, incl. atmospheric ν, solar ν, proton decay, etc.
- Long baseline accelerator neutrinos from J-PARC ("T2HK")
- Currently writing proposal for UK involvement → **NOW** is an excellent time to join!

Summary & Conclusions

- **First observation of electron neutrino appearance!**
  - T2K has measured ν_e appearance in a ν_μ beam
  - $\theta_{13} = 0$ is excluded at the 7.3σ level (assuming $\delta_{CP} = 0$ and $\theta_{23} = 45°$)
- Measurements of ν_μ becoming competetive → New results coming soon!
- A total exposure of 6.57 x 10^{20} P.O.T. has been collected & analysed, more than doubling the data sample used for the Run 1 – 3 (2012) analysis
- Nature has been kind; with our "primary goal" already achieved, we are looking at changing the nature of T2K running to increase sensitivity to mass hierarchy and CP violation
- Future sensitivity studies indicate that running both ν and anti-ν will enhance T2K's physics potential
- In the longer term, we need more statistics → Hyper-Kamiokande!

BACK UP SLIDES

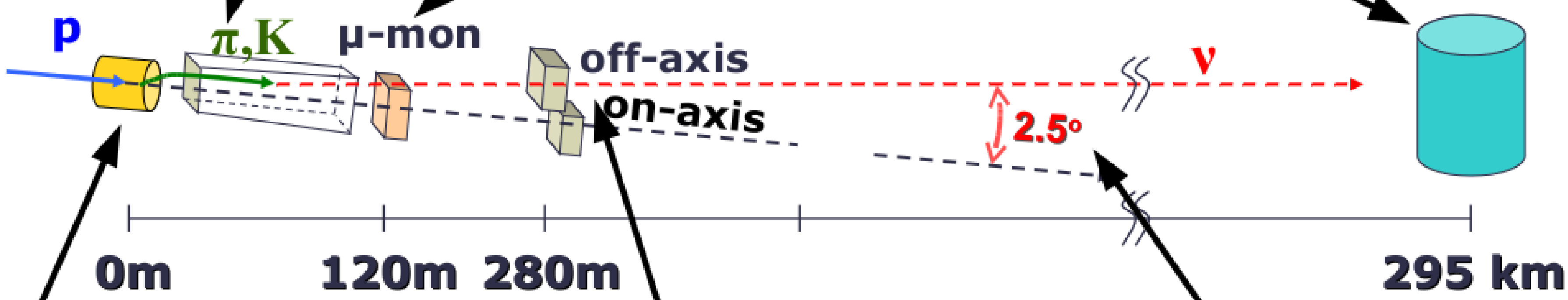
Experimental Overview

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

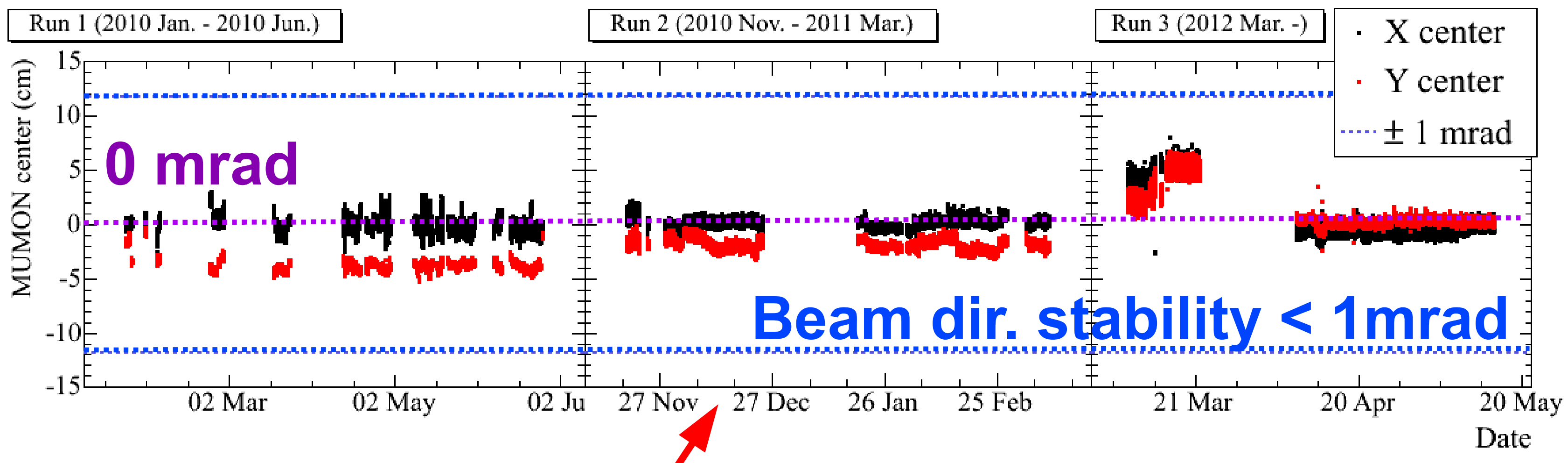
Beam on graphite target

3 magnetic horns focus positively charged hadrons

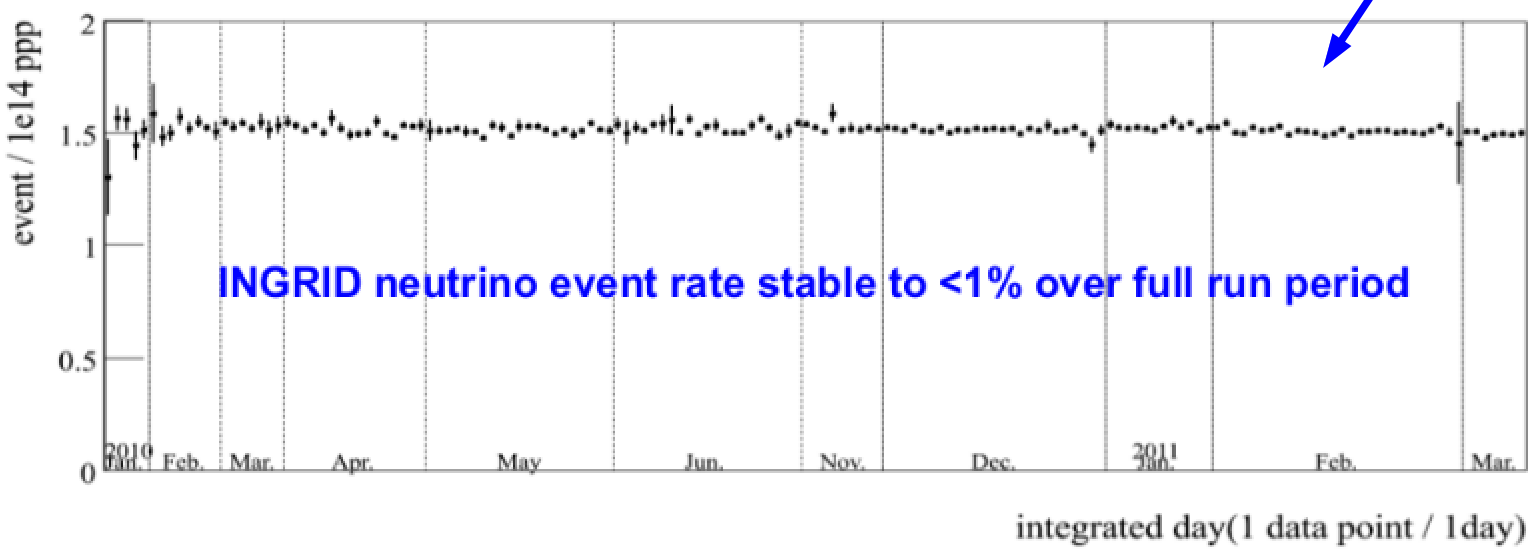
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

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

Beam Stability: Rate & Direction



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



Near Detector Constraint

GOAL: Constrain neutrino flux & cross section parameters used for oscillation prediction (via MC) at T2K far detector

Error on Far Detector ν_e Prediction
(After Near Detector Constraint)

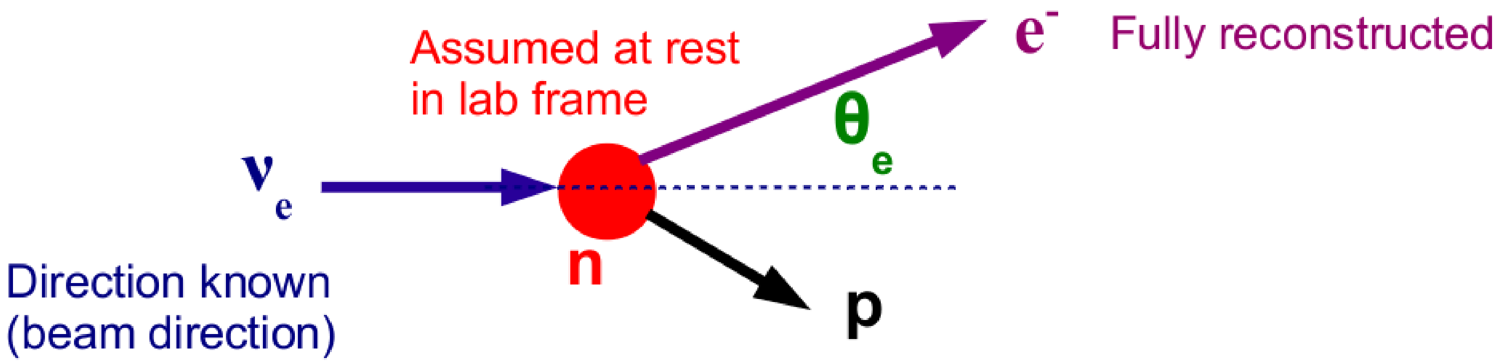
	Runs 1-3 (2012)	Runs 1-3 (2013)	Runs 1-4 (2013)
$\sin^2 2\theta_{13}=0.1$	4.7%	3.5%	3.0%
$\sin^2 2\theta_{13}=0.0$	6.1%	5.2%	4.9%

Error on Cross Section Parameters
(After Near Detector Constraint)

Parameter	Runs 1-3 (2012)	Runs 1-4 (2013)
M_A^{QE} (GeV/c^2)	1.27 ± 0.19	1.22 ± 0.07
M_A^{RES} (GeV/c^2)	1.22 ± 0.13	0.96 ± 0.06
CCQE Norm.	0.95 ± 0.09	0.96 ± 0.08
CC1π Norm.	1.37 ± 0.20	1.22 ± 0.16

- Significant reduction for event rate errors at the far detector
- Uncertainties on the *cross section & flux* parameters have been reduced

Reconstructing ν Energy

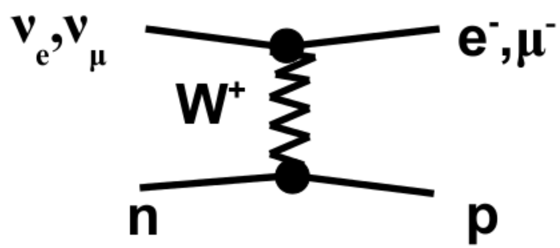


$$E_\nu^{QE} = \frac{2M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2[M_n - E_e + \sqrt{E_e^2 - m_e^2}\cos\theta_e]}$$

- 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

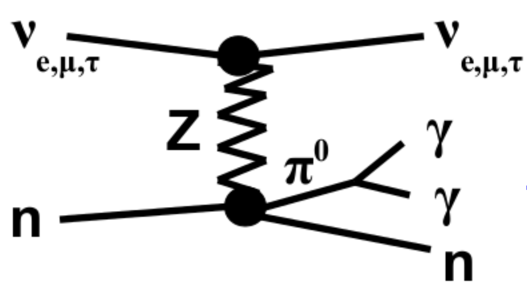
- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:



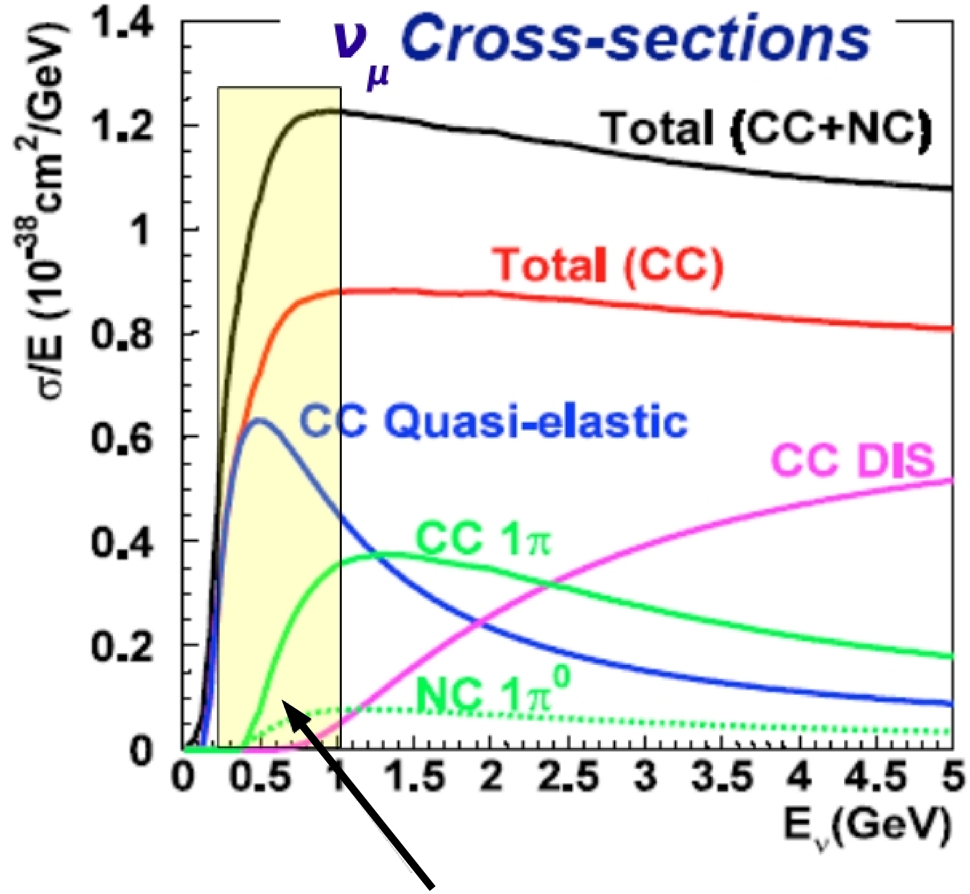
T2K signal at SK

- Also significant CC contribution with pion in final state

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

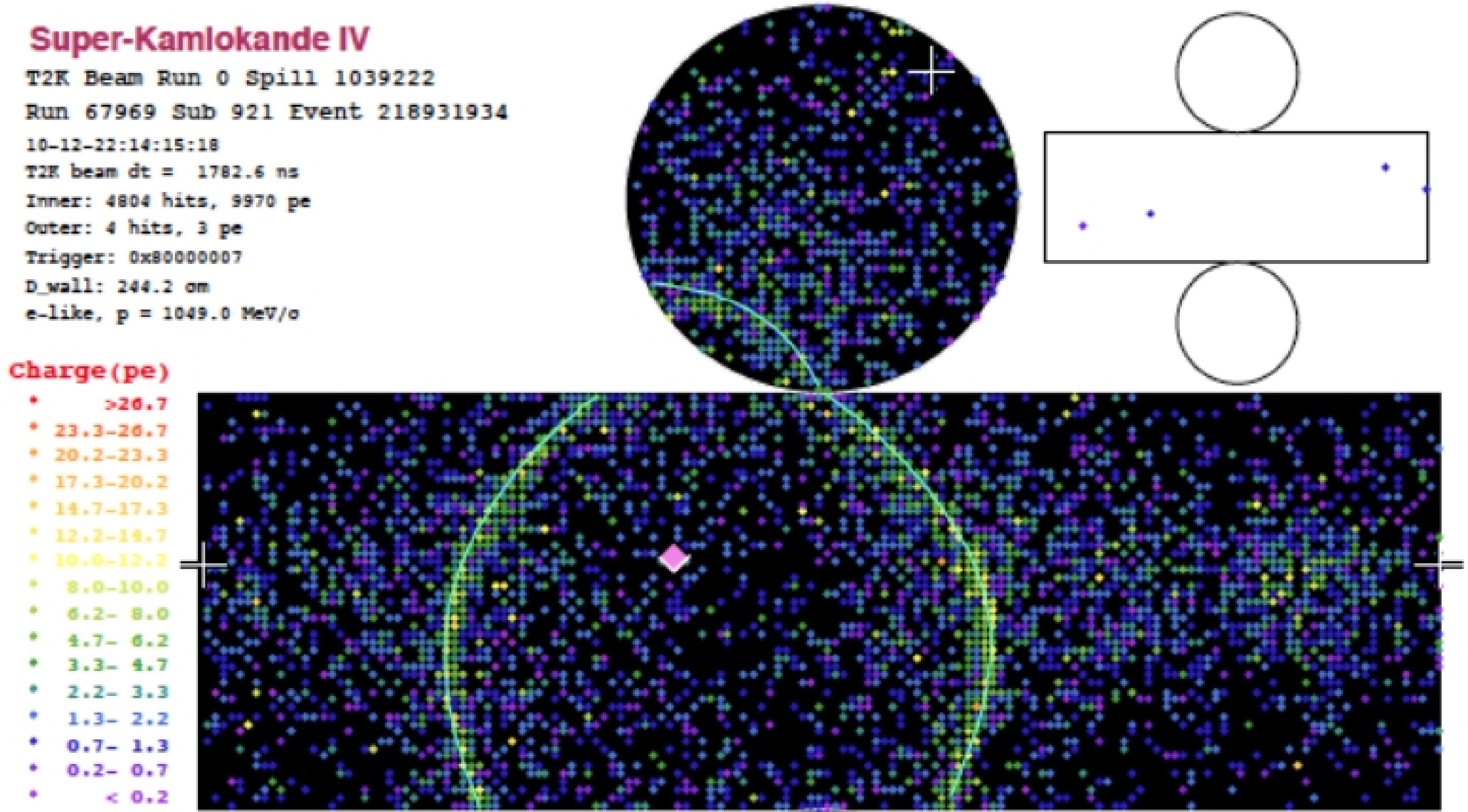


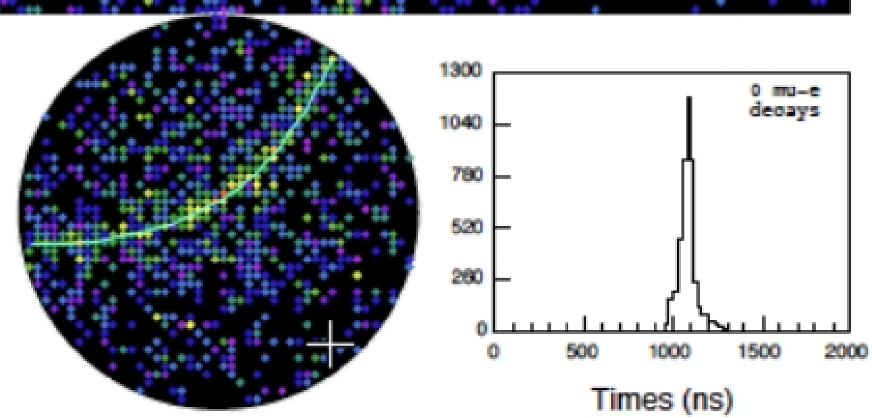
Photons from π^0 can fake electron signal



T2K beam peak energy

A Typical ν_e Candidate

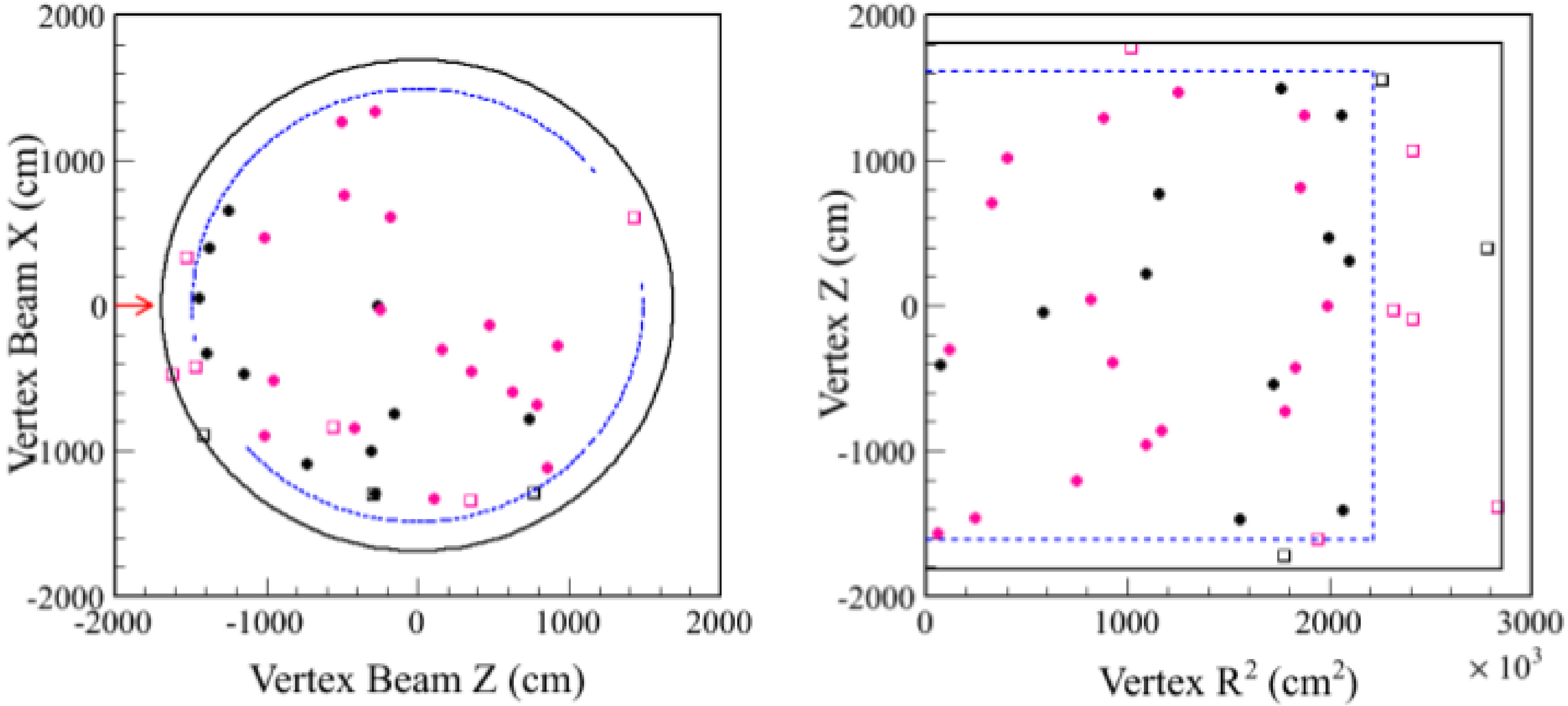




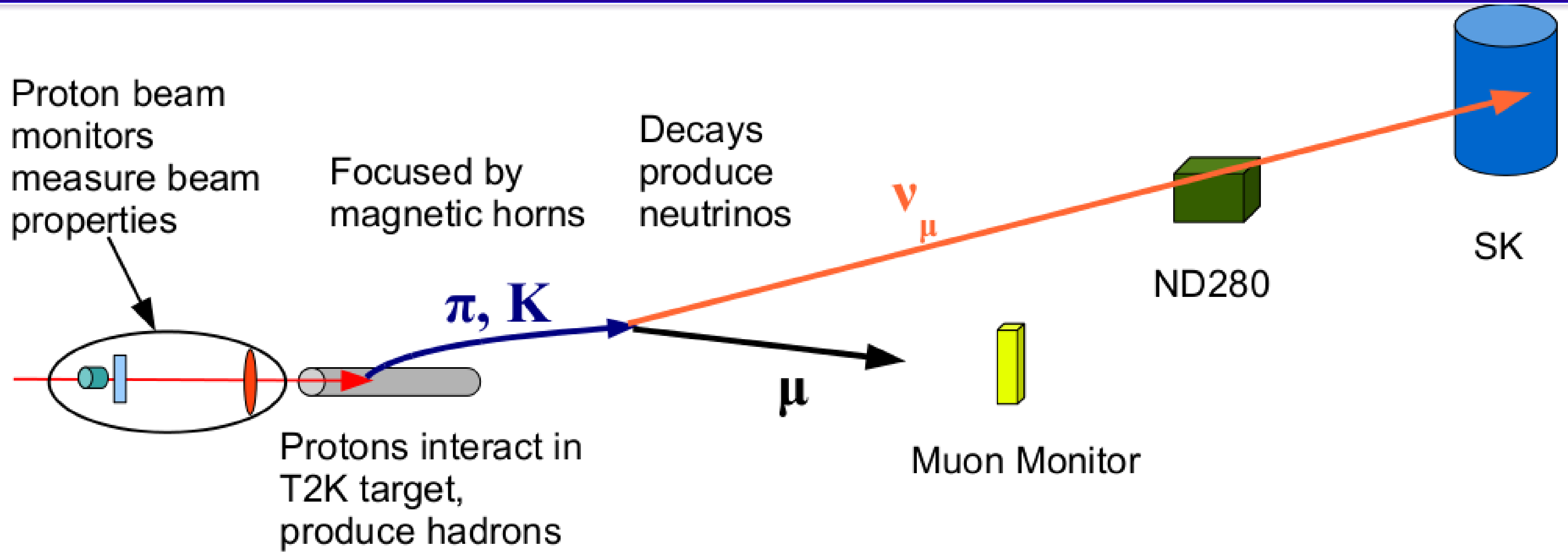
visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV

ν_e Vertex Distributions

Vertex distributions for ν_e candidates at the far detector:



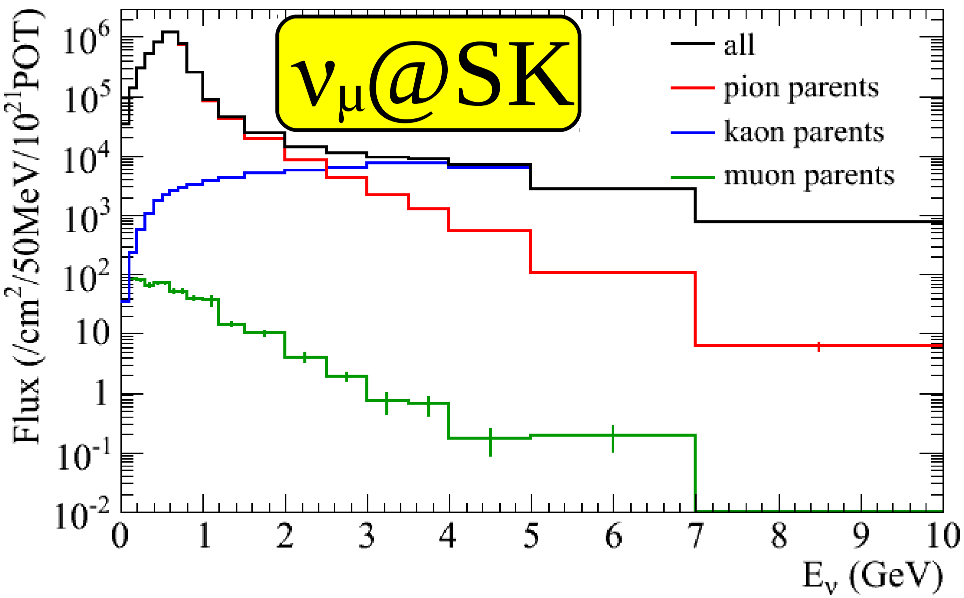
	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall beam$_{\parallel}$	6.04%	85.6%	8.93%
$R^2 + Z$	32.4%	98.1%	64.5%

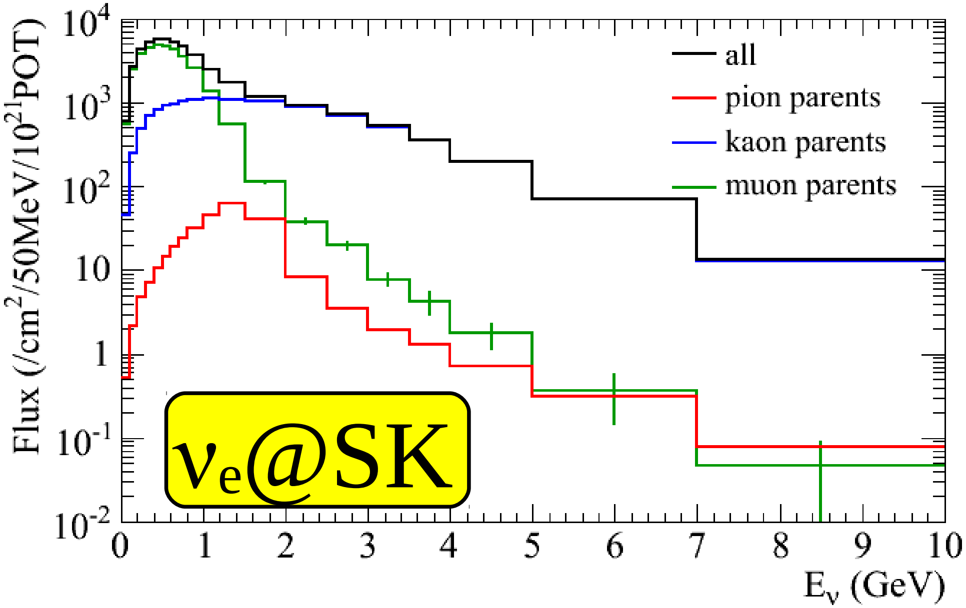


Flux Simulation:

- 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





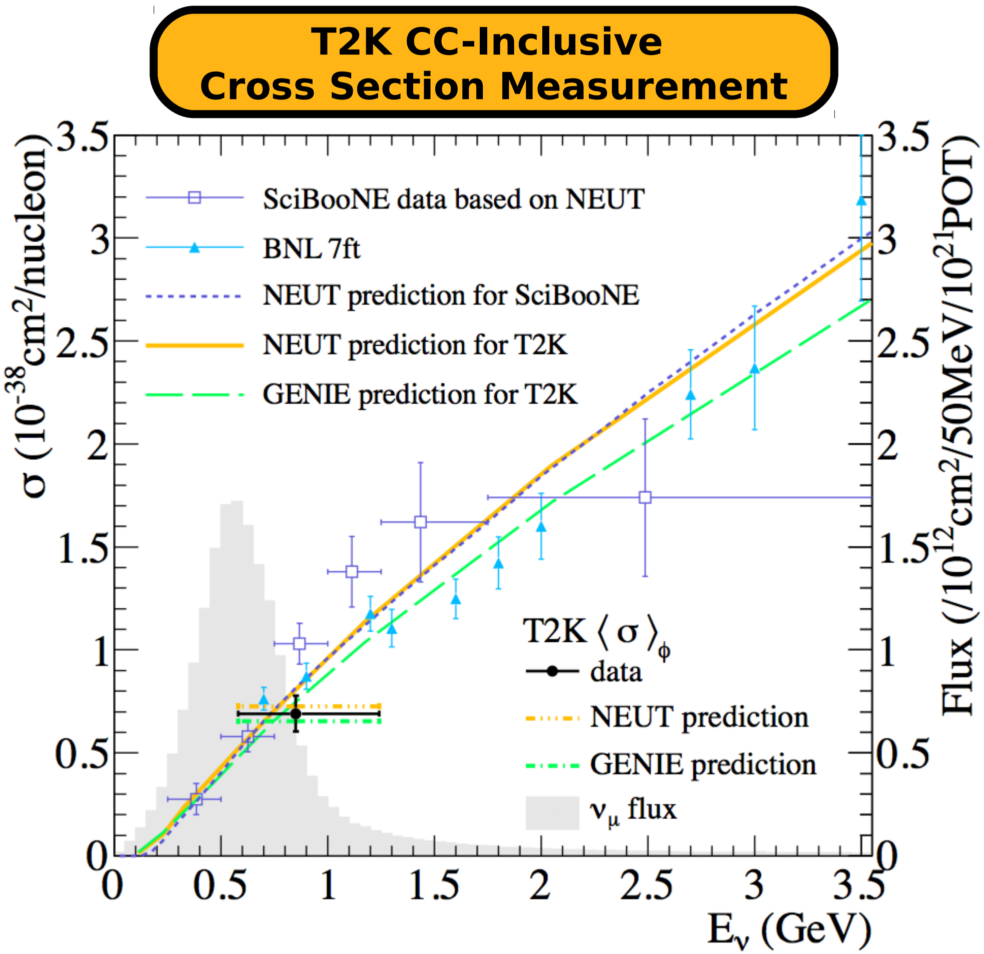
- Muon neutrino flux around oscillation maximum predominantly from pion decays
- Intrinsic electron neutrino flux in beam from muon and kaon decays ~1% of total flux below 1 GeV
  - Dominant source around oscillation maximum is from muon decays

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

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

Flux depends on pion production

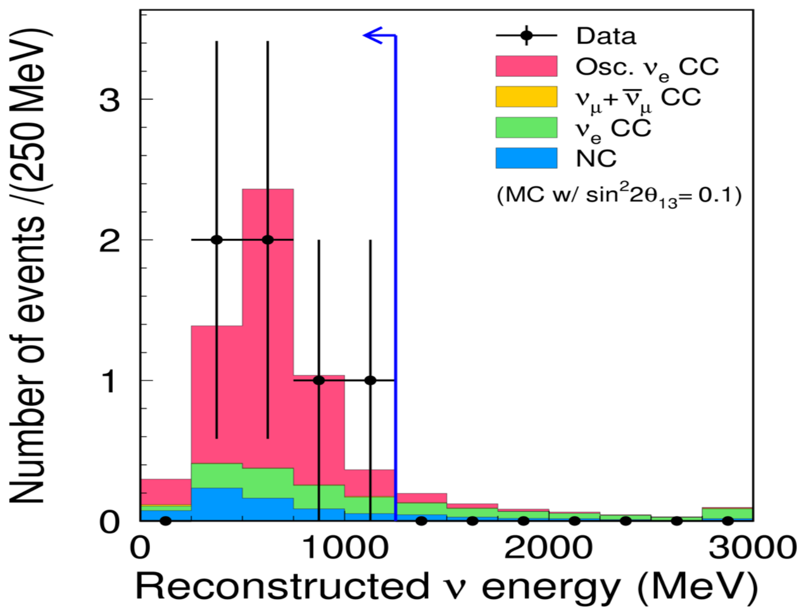
Other T2K Results: Cross Sections

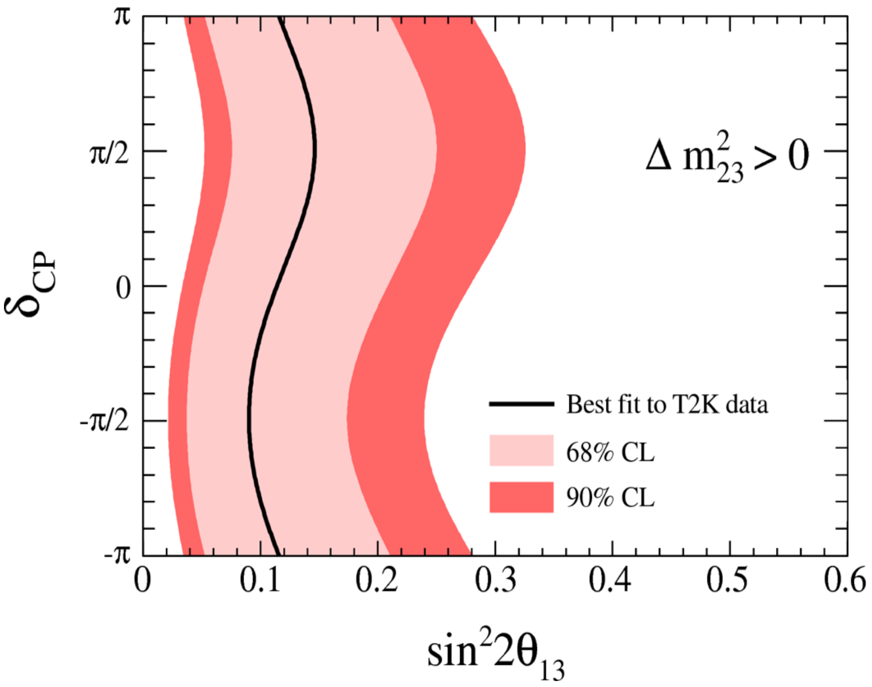


- The near detectors can also be used to make cross section measurements
- The T2K charged current inclusive cross section measurement was published earlier this year:
  - Phys. Rev D **87:092003** (2013)
  - Uses same near detector event selection as 2012 osc. analysis
- The CCQE sample from the 2012 osc. analysis has been used to measure $\sigma_{CCQE}(E_\nu)$
- Additional cross section results expected soon...

θ_{13} Results: Accelerators

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



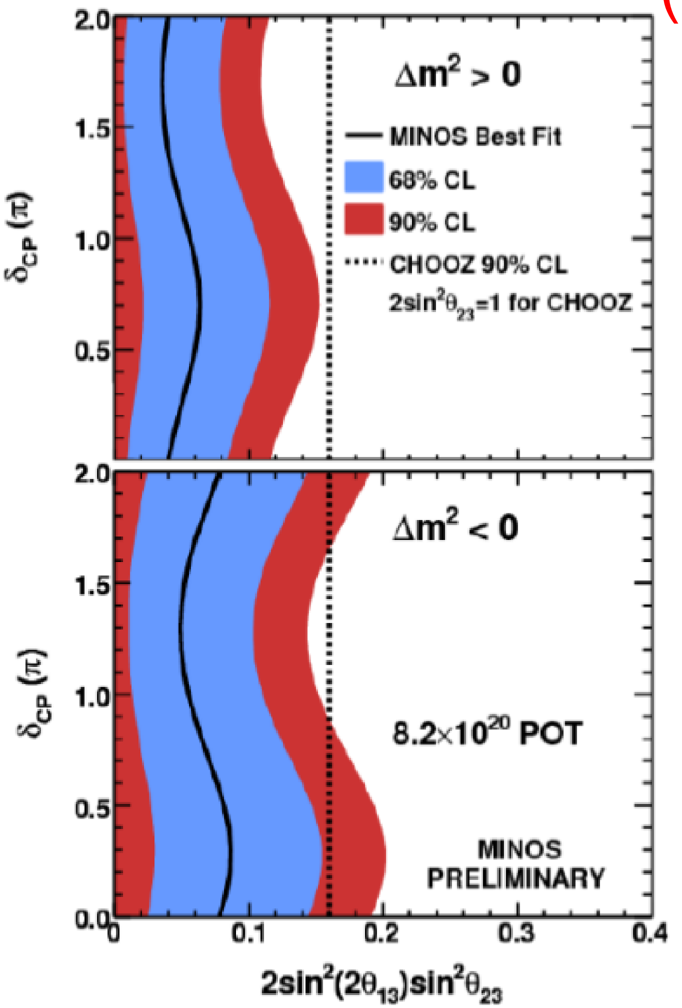


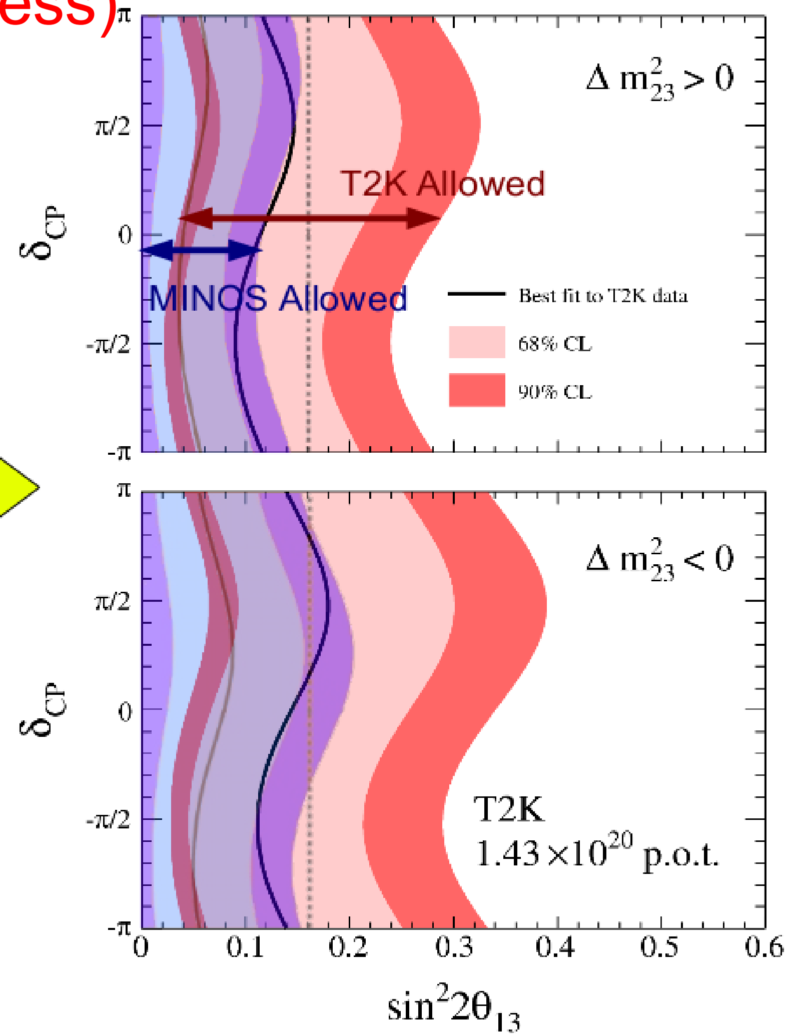
P-value (assuming no oscillations) is 0.007, or 2.5σ.

θ_{13} Results: Accelerators

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

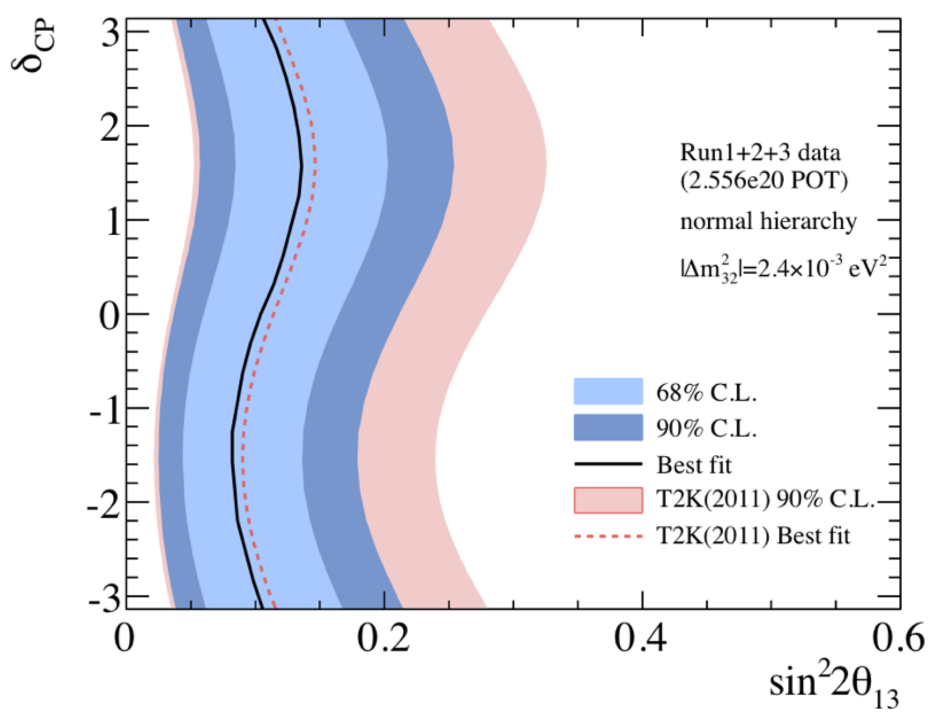
(1.7σ excess)

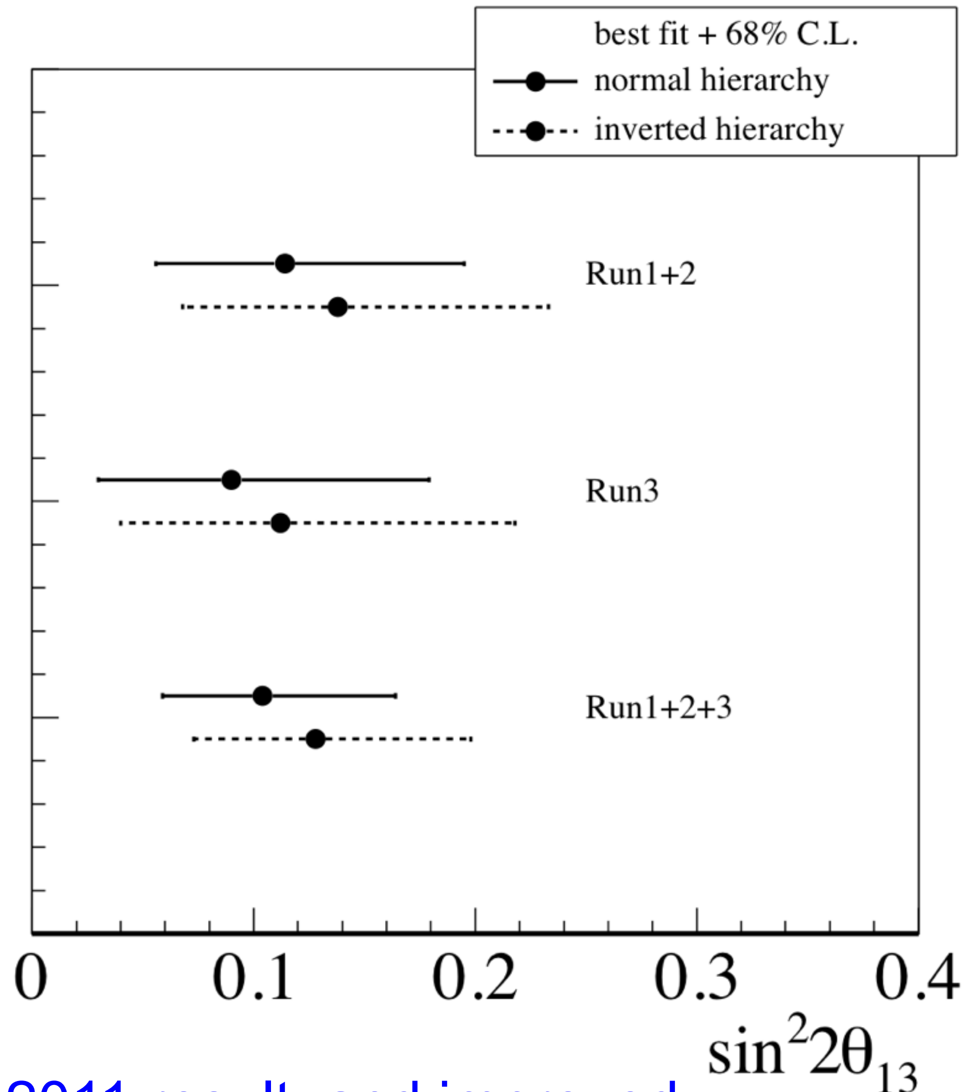




Significant overlap of T2K and MINOS 90% C.L. allowed regions

2011 and 2012 Results

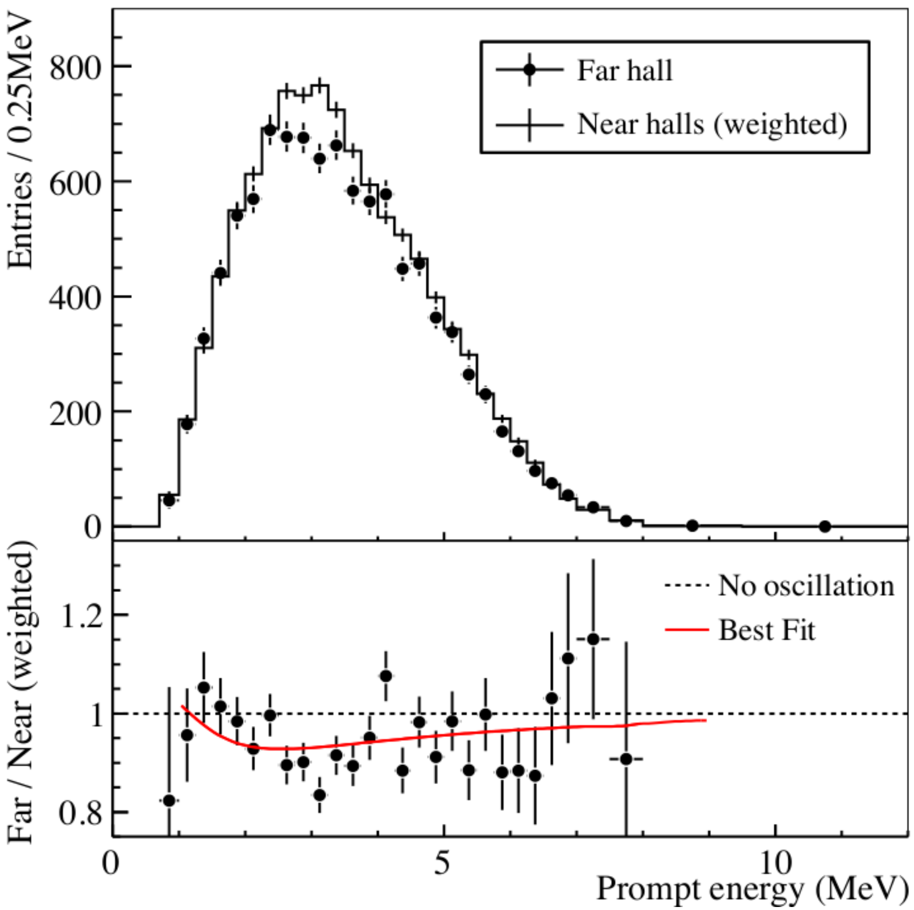




- The current result is consistent with the 2011 result, and improved
- The result with only 2012 data is also consistent with the 2011 result

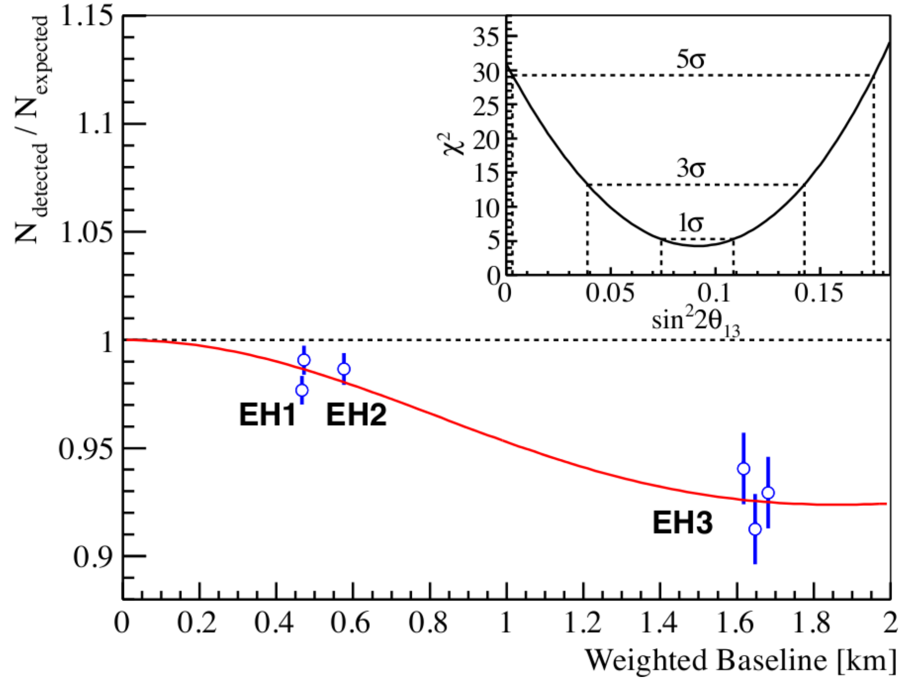
θ_{13} Results: Reactors

<u>March 2012:</u> 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