

Recent results from the T2K long baseline neutrino experiment

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For the T2K collaboration



The T2K Collaboration



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Outline

1. Introduction to neutrino oscillations
2. Overview of the T2K experiment
3. Data collected by T2K
4. Oscillation analysis method
 1. Neutrino flux and cross section prediction
 2. Near detector measurements
 3. Far detector selection and systematics
5. Results: ν_μ disappearance and ν_e appearance
6. Future plans and summary

What is neutrino oscillation?

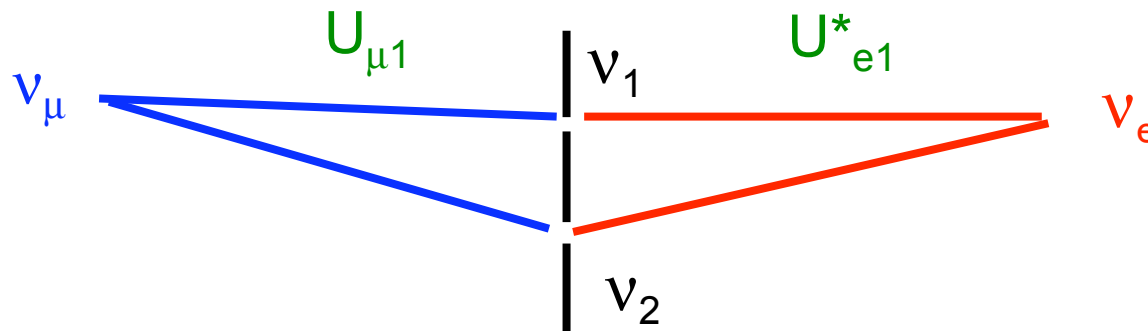
In the Standard Model, we have three charged leptons: e , μ , τ and three neutral leptons, called neutrinos: ν_e , ν_μ , ν_τ

Neutrinos “oscillate” as the flavor eigenstates are not the same as the mass eigenstates. Like a double slit experiment; the neutrino mass eigenstates propagate differently, resulting in an interference pattern.

Given an initial flavor eigenstate of ν_μ , observation some time later will yield a combination which:

- 1) has maximal ν_e (constructive interference) or
- 2) has only ν_μ (destructive interference)

The amount of interference is governed by the mixing matrix, U



No mass means no interference is possible

A refresher on neutrino mixing

The flavor state of the neutrino, ν_α , is related to the mass states, ν_i , by a mixing matrix, $U_{\alpha i}$

$$|\nu_i\rangle = \sum U_{\alpha i} |\nu_\alpha\rangle$$

Since there are three observed flavors of neutrinos (ν_e, ν_μ, ν_τ), U contains three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and a CP violating phase δ .

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

“Atmospheric”: $\theta_{23} \sim 37^\circ - 53^\circ$

“CP sector”: $\theta_{13} < 11^\circ$

“Solar”: $\theta_{12} \sim 34^\circ$

Rather different from quark mixing:

- Nearly diagonal unitary matrix
- Small angles:

$$\theta_{12}^{\text{CKM}} \sim 13.0^\circ, \quad \theta_{23}^{\text{CKM}} \sim 2.3^\circ, \quad \theta_{13}^{\text{CKM}} \sim 0.2^\circ$$

Open questions:

- Is θ_{23} exactly 45 degrees, or not?
- Is θ_{13} non-zero? yes!
- Is there CP violation in the neutrino sector?

Neutrino oscillation

Because of neutrino mixing, as the neutrinos propagate, the mass states interfere:

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

Probability to observe ν_β after starting in flavor state ν_α depends on:

- L (km): Distance the neutrino has travelled
- E (GeV): Energy of the neutrino
- Δm^2 (eV²): Difference of the square of the mass eigenvalues $\Delta m_{ij}^2 = m_i^2 - m_j^2$

At the atmospheric $\Delta m_{32}^2 \sim 10^{-3}$ eV², a beam of ν_μ will:

“disappear” into other neutrino flavors

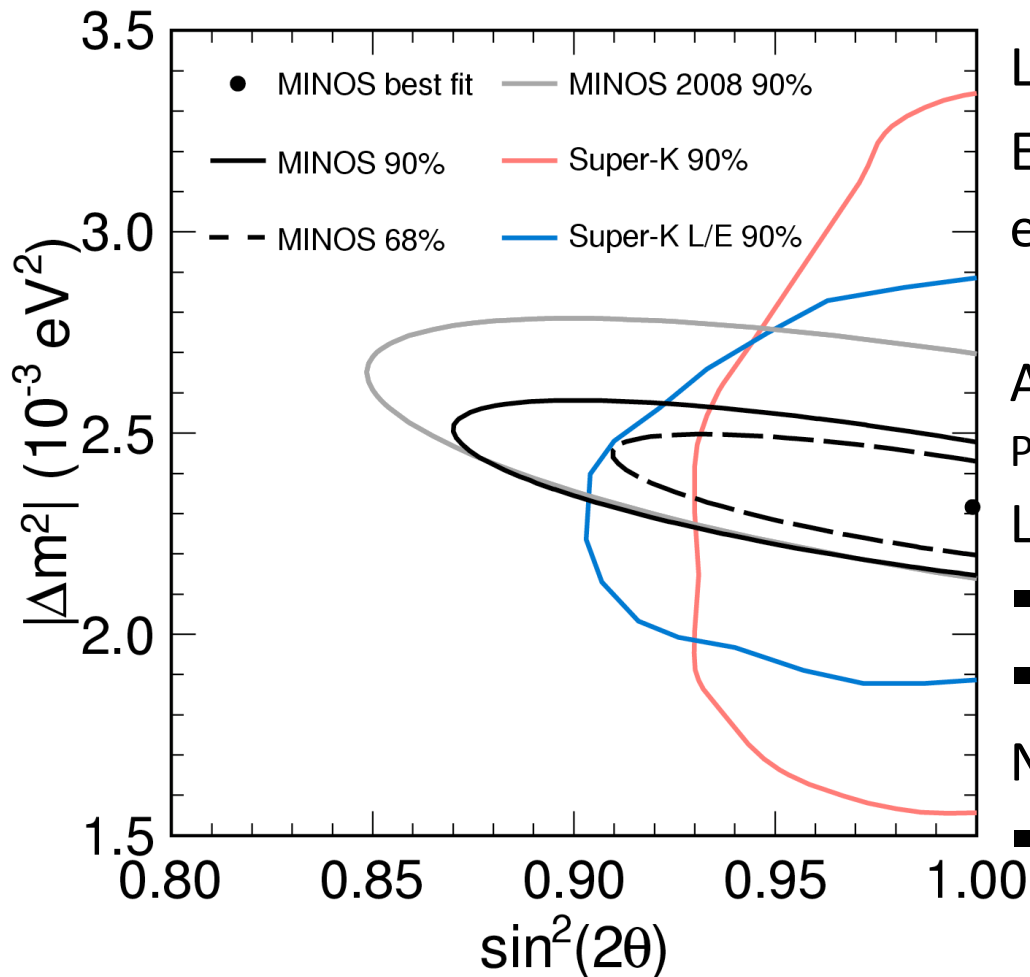
$$P(\nu_\mu \rightarrow \nu_{x \neq \mu}) \cong \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

A small fraction of ν_e will “appear”

$$\Delta m_{31}^2 \sim \Delta m_{32}^2$$

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

Measurements of Δm^2_{32} and θ_{23}



L, E are determined from neutrino source
 Extract $|\Delta m^2|, \sin^2 2\theta$ based on rate,
 energy spectrum after oscillation

Accelerator-produced neutrino beam (MINOS)
 Phys. Rev. Lett. 101, 131802 (2008)

$L=735\text{km}, E(\text{peak}) \sim 3 \text{ GeV}$

- $\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{23} > 0.90$ (90% CL)

New result (2011) 1103.0340 [hep-ex]

- $\Delta m^2_{32} = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$ (68% CL)

Atmospheric neutrinos (Super-Kamiokande)
 Phys.Rev.D71:112005,2005; hep-ex/0501064

$L \sim 15\text{km}-13,000\text{km}, E \sim 100 \text{ MeV}-10 \text{ TeV}$

- $1.5 < \Delta m^2_{32} < 3.4 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{23} > 0.92$ (90% CL)

$$P(\nu_\mu \rightarrow \nu_{x \neq \mu}) \cong \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$$

ν_e appearance and δ_{CP}

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \left(\frac{\Delta m_{31}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\alpha = \Delta m_{12}^2 / \Delta m_{32}^2 \sim 0.04$$

$$\Delta m_{31}^2 \sim \Delta m_{32}^2$$

Subleading terms depend on δ_{CP} differently for neutrinos (-) and antineutrinos (+)

Sakharov's conditions require CP violation and baryon number violation

A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)]

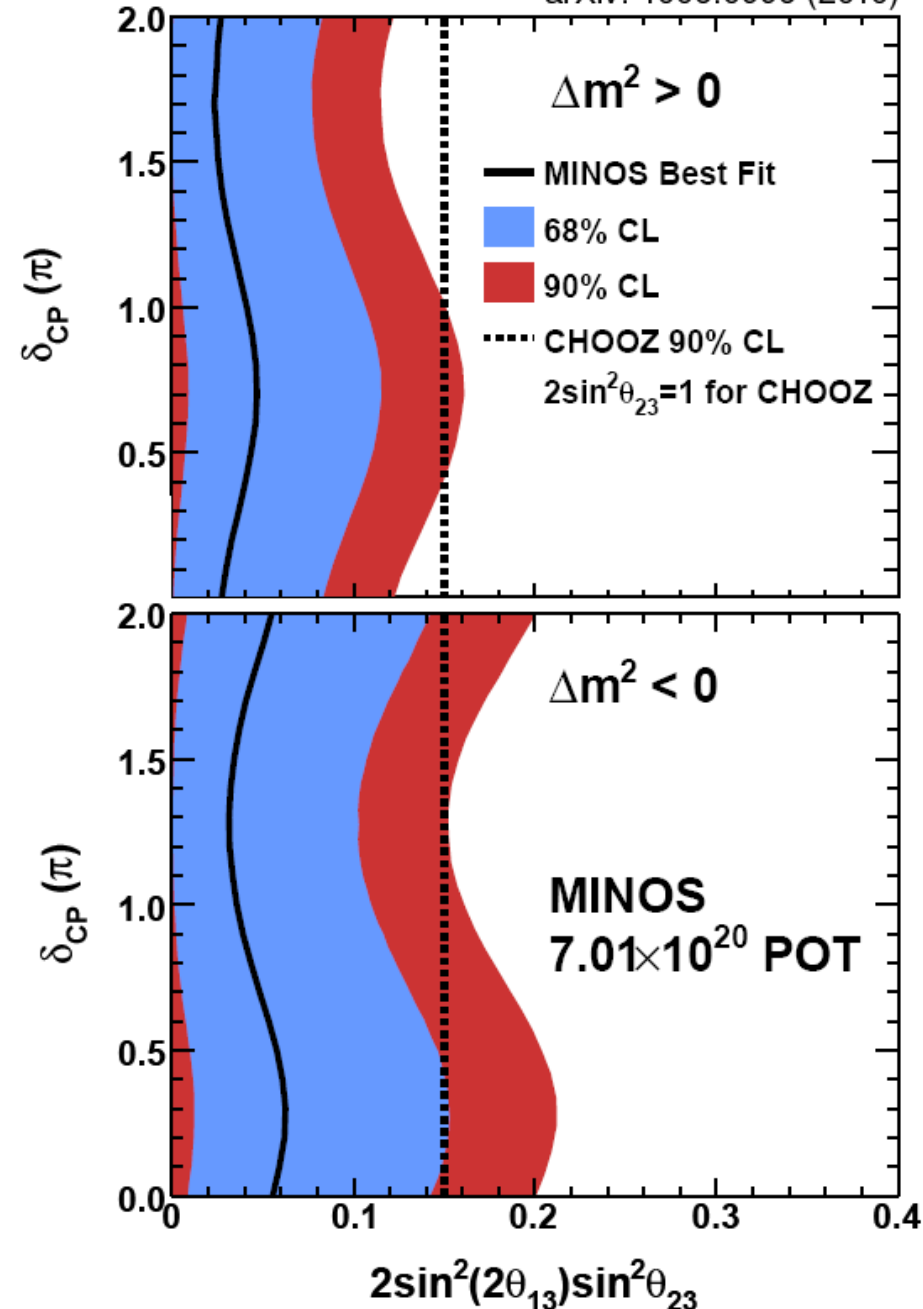
- CP violation in heavy, right handed neutrino decays creates lepton number asymmetry which can be converted to baryon number asymmetry (leptogenesis)

M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986)

- CP violation with light neutrinos is suggestive of CP violation of the hypothetical heavy neutrino; see saw mechanism gives light neutrino mass and heavy partner

Measurements of θ_{13} (prior 2011)

arXiv: 1006.0996 (2010)



ν_e appearance:

$$P(\nu_{\mu} \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Accelerator-produced neutrino beam (MINOS)
Phys.Rev.D82:051102,2010; hep-ex/1006.0996

$L=735\text{km}$, $E(\text{peak}) \sim 3 \text{ GeV}$

- $2\sin^2\theta_{23}\sin^22\theta_{13} < 0.12$ (90% CL)
- ν_e and ν_{μ} interact differently in matter which alters the oscillation probability
- “matter effects” depend upon $\text{sign}(\Delta m^2)$ called the mass hierarchy
 - $m_3 > m_1$ implies $\Delta m_{31}^2 > 0$ (normal)
 - $m_3 < m_1$ implies $\Delta m_{31}^2 < 0$ (inverted)
- MINOS is sensitive to this effect and so the limit depends on which hierarchy is assumed

Measurements of θ_{13} (prior 2011)

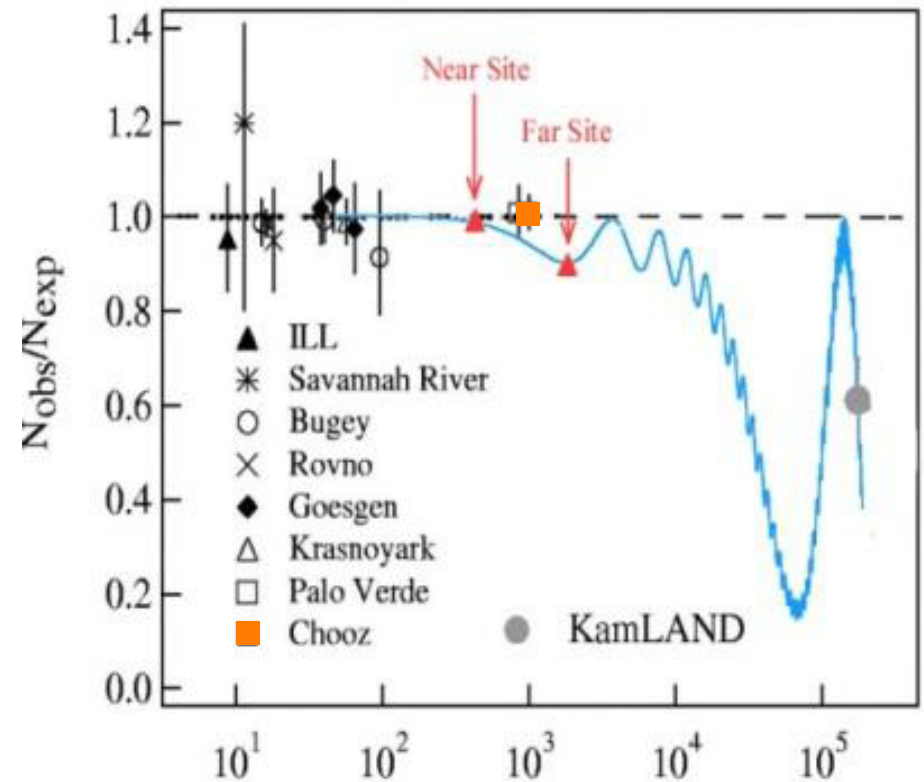
$\bar{\nu}_e$ disappearance:

$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

- Deficit of antineutrinos from reactors
- Detect antineutrinos via inverse beta decay, prompt electron signal and delayed neutron capture

CHOOZ experiment

- Single detector at $L \sim 1$ km, $E \sim 3$ MeV
 - $\sin^2 2\theta_{13} < 0.15$ at $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$
- Eur.Phys.J.C27:331-374,2003; hep-ex/0301017



J.K.Jang for RENO @ PH2012

Name	Site	Thermal power	Distance near/far (m)	Target Mass (tons)	Sensitivity $\sin^2 2\theta_{13}$ 90%C.L.
Double Chooz	France	8.7 GW	410/1050	8.3/8.3	0.03
RENO	Korea	17.3 GW	290/1380	16/16	0.02
Daya Bay	China	17.4 GW	360,500/1985,1613	40,40/80	0.01

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The Tokai-to-Kamioka (T2K) experiment

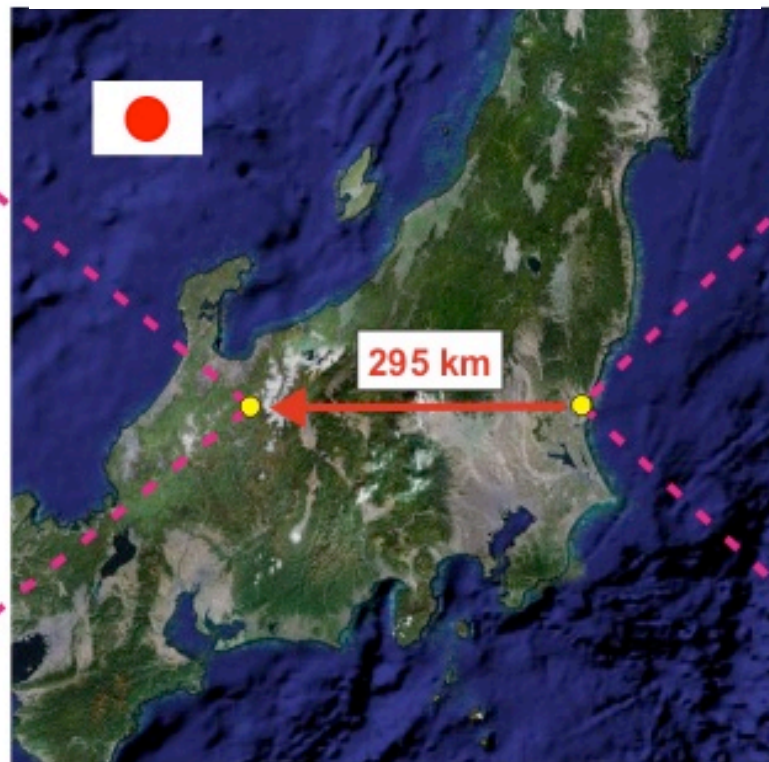
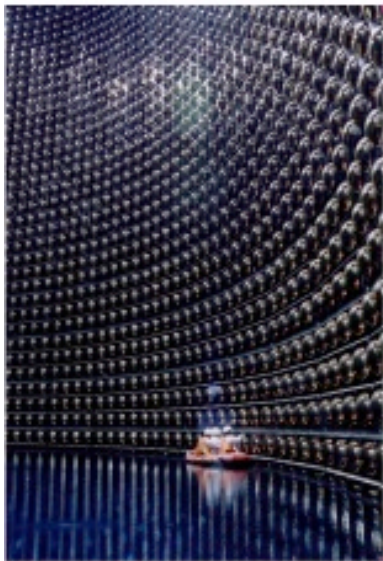
T2K is designed to measure oscillations at the atmospheric Δm^2 :

- Measure ν_μ disappearance ($\Delta m^2_{32}, \theta_{23}$)
- Aim to discover ν_e appearance (θ_{13})

Produce a beam of ν_μ on one side of Japan and detect it on the other

Far detector:

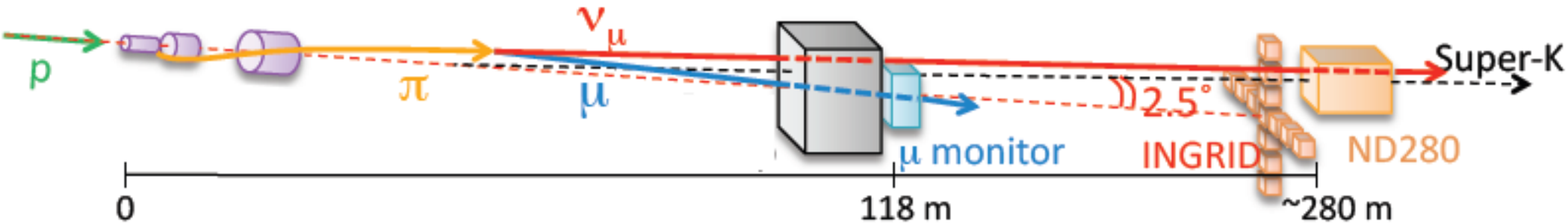
Super-Kamiokande
located near Kamioka



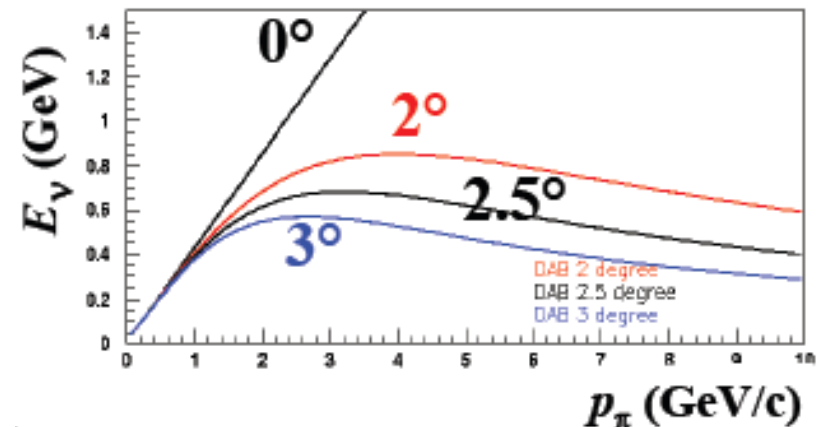
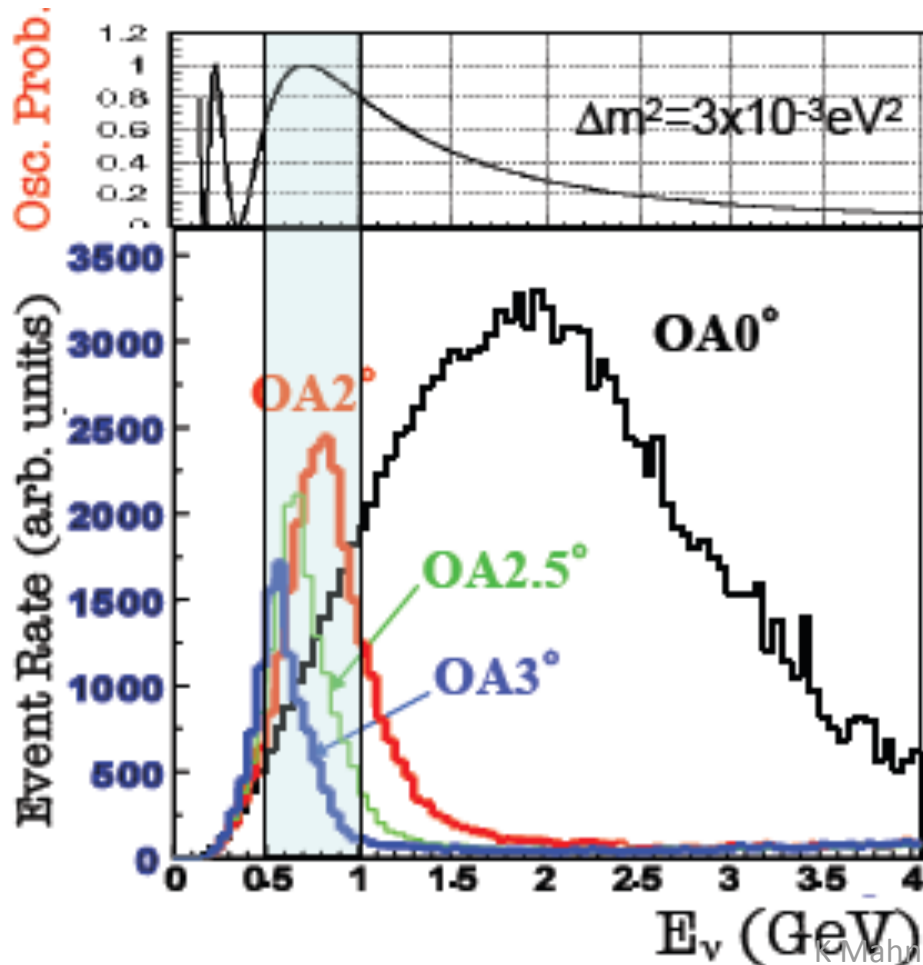
Beam source and near detectors:
J-PARC accelerator complex
located in Tokai-mura



Creating an (offaxis) neutrino beam



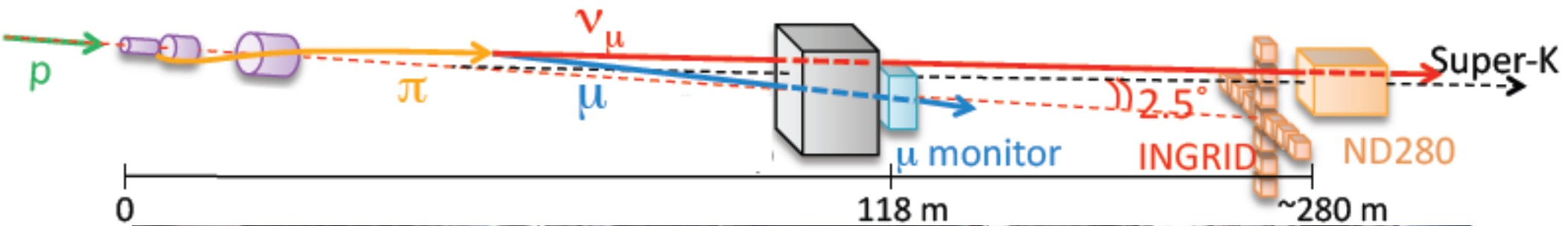
Primary protons hit a target (carbon) producing secondary mesons (π , K) which decay to a tertiary ν_μ beam



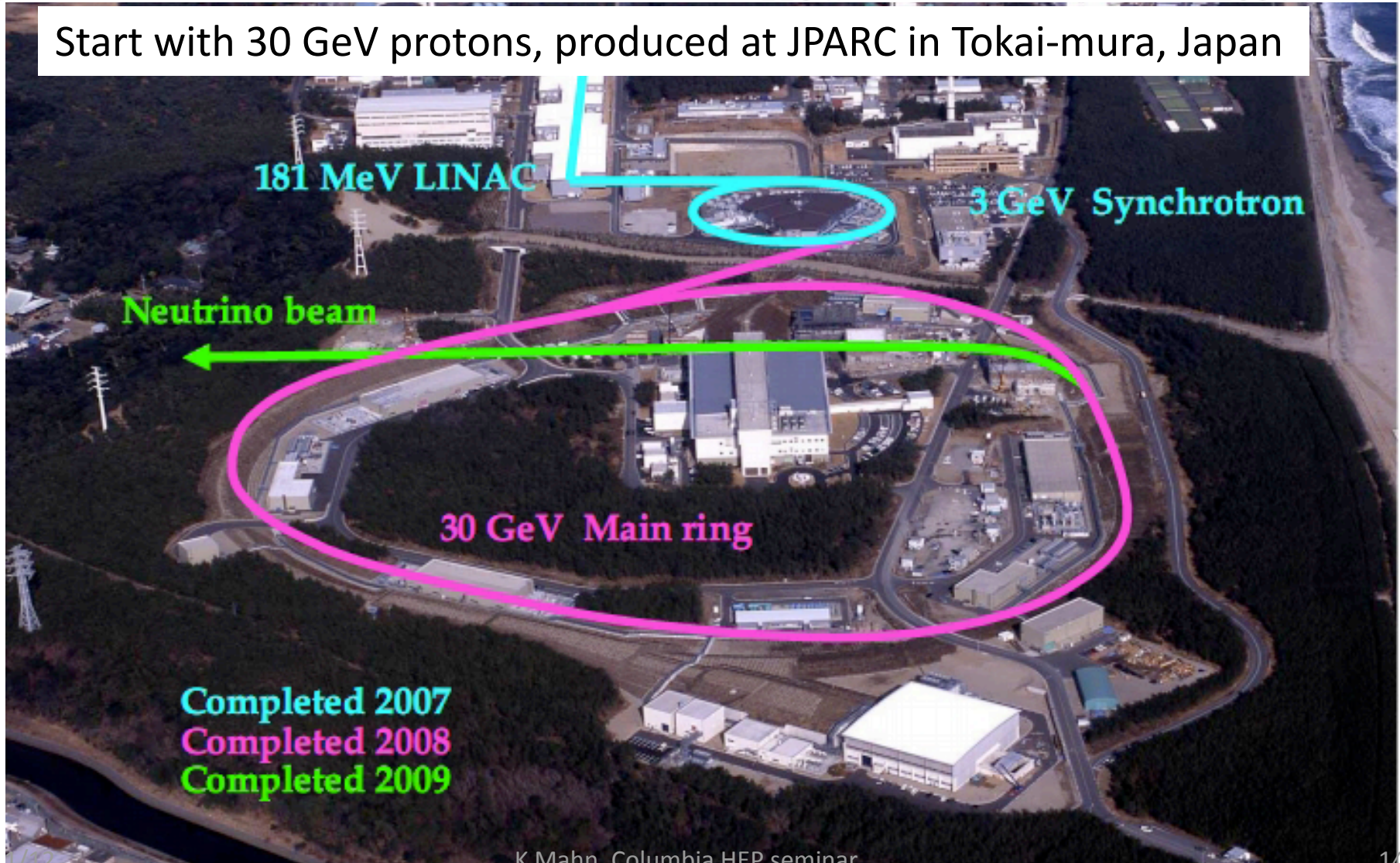
At angles away from the parent pion's direction, the neutrino energy is independent of pion momentum, resulting in a narrower neutrino energy spectrum

Peak corresponds to oscillation maximum
Reduces backgrounds from higher energy neutrino interactions

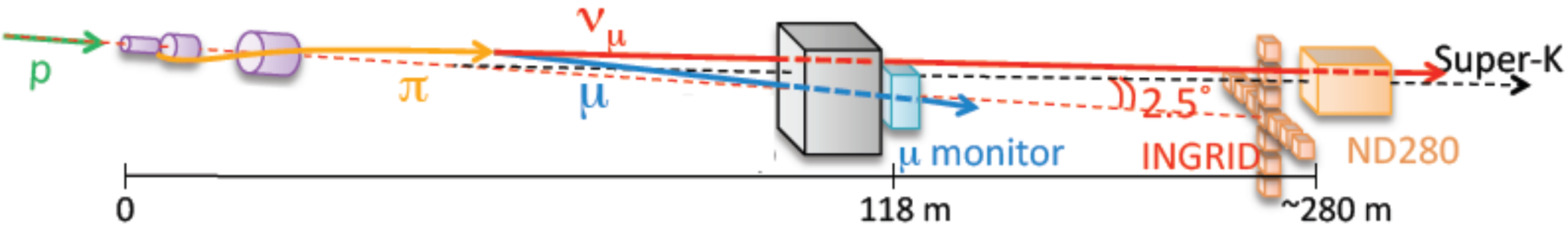
The proton beam



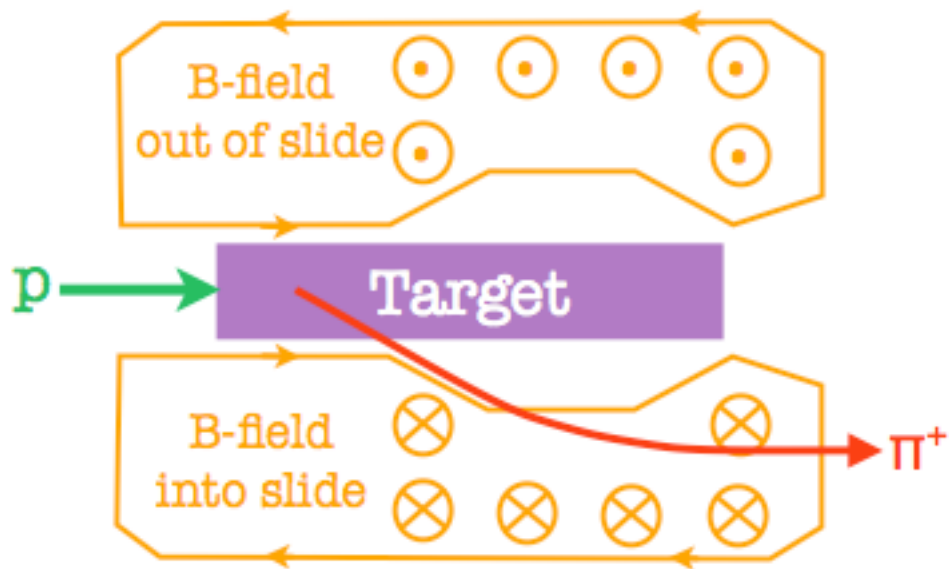
Start with 30 GeV protons, produced at JPARC in Tokai-mura, Japan



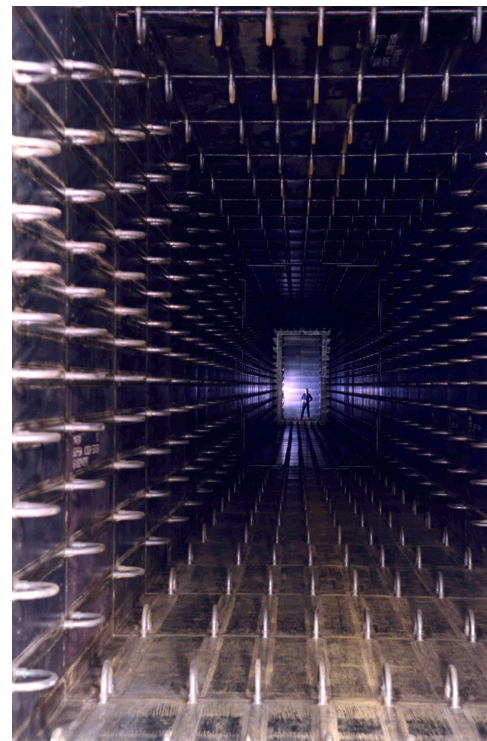
Secondary beam of mesons



The protons hit a 91 cm long graphite target, producing pions and kaons
 The mesons are focused by three magnetic "horns"



then decay in a 100m long decay volume



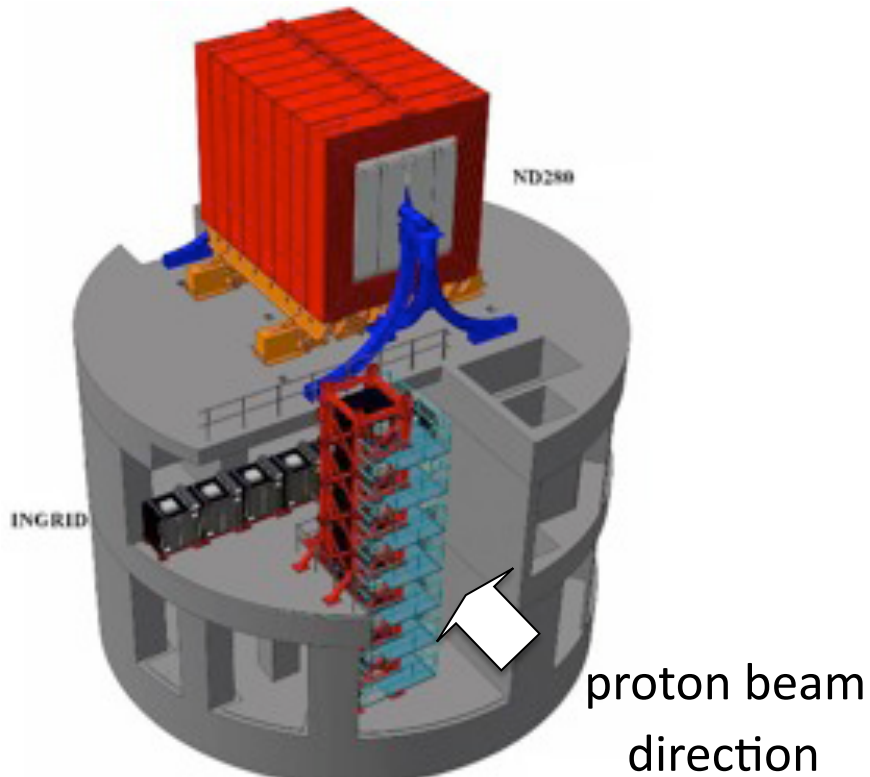
The muons are sampled using a pair of muon monitors as a real-time neutrino beam monitor

Neutrino detectors of T2K

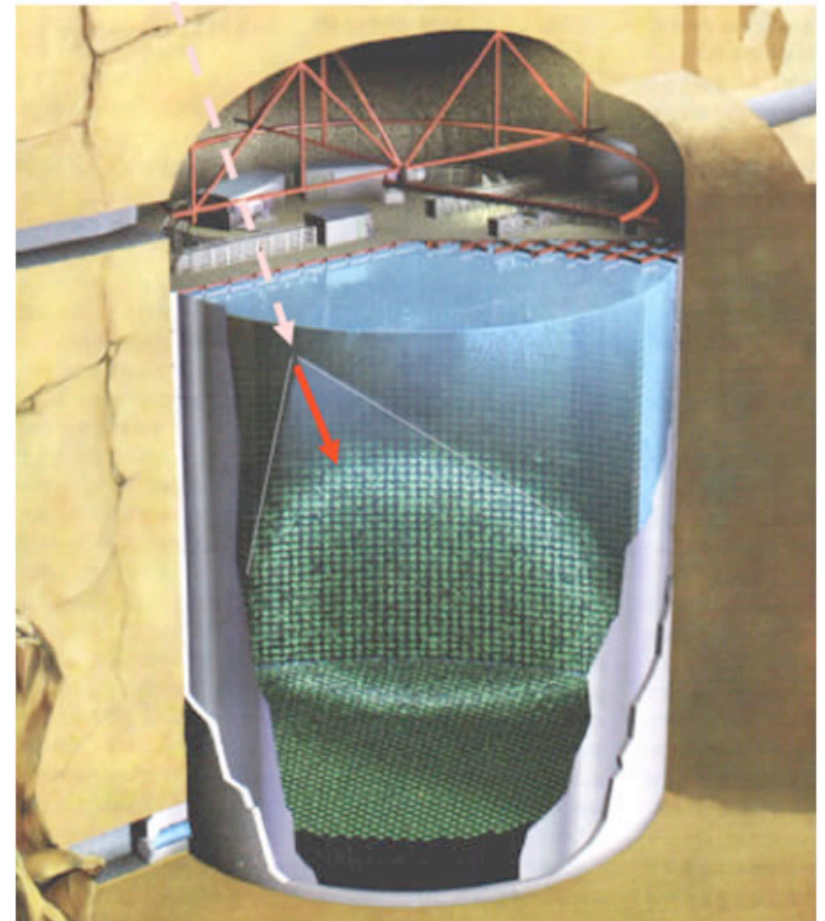
Neutrino detectors measure ν_μ , ν_e candidates before and after oscillation:

Off-axis ND280 detectors @ 280m:

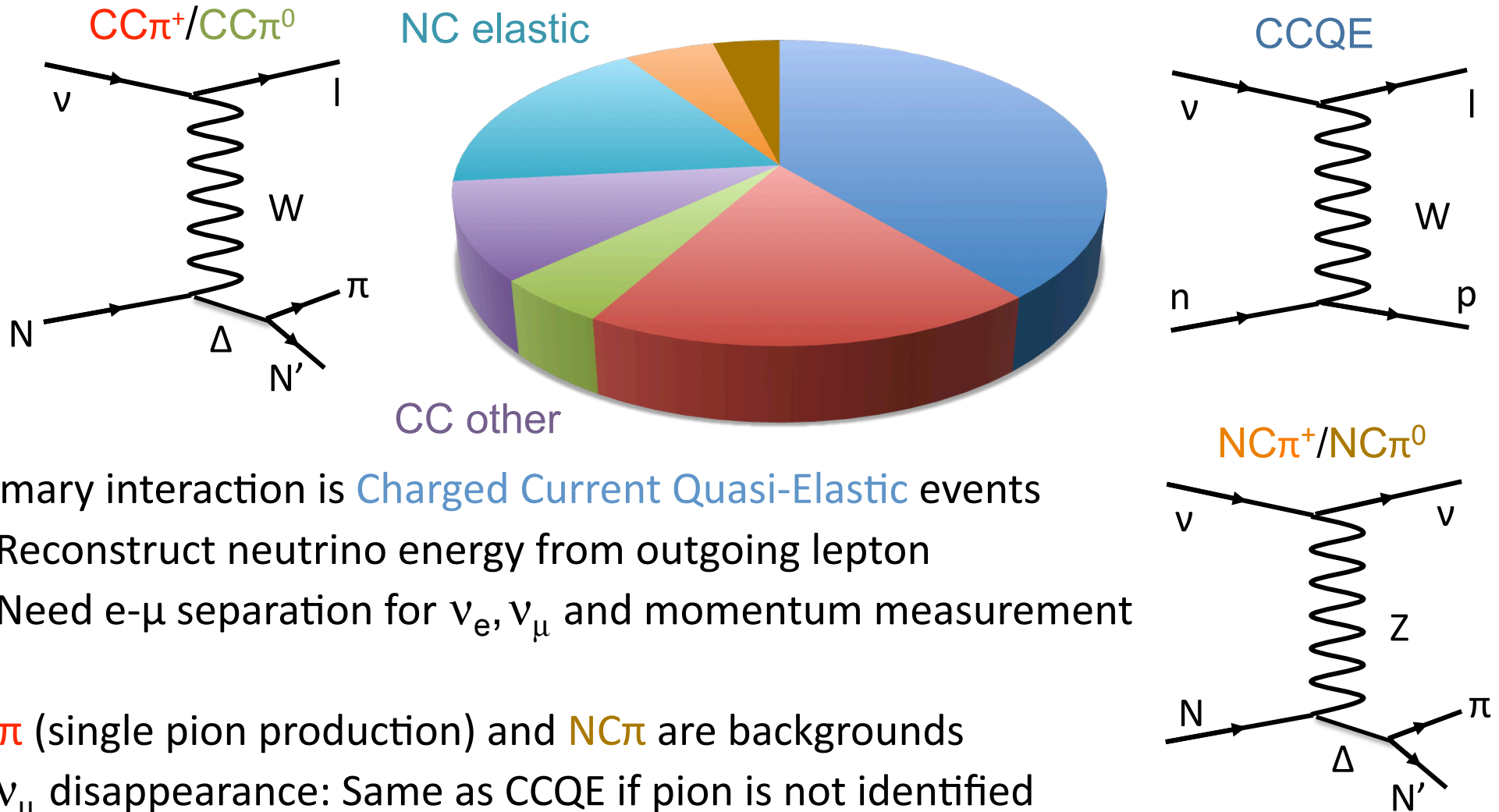
Off-axis Super-Kamiokande @295km:



On-axis INGRID detector @280m:



Neutrino interactions at T2K



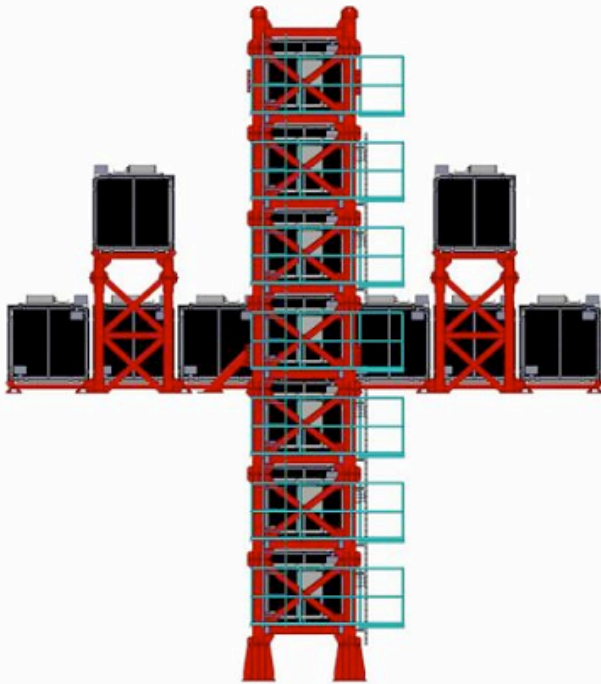
Primary interaction is **Charged Current Quasi-Elastic** events

- Reconstruct neutrino energy from outgoing lepton
- Need e- μ separation for ν_e, ν_μ and momentum measurement

CC π (single pion production) and **NC π** are backgrounds

- ν_μ disappearance: Same as CCQE if pion is not identified
- ν_e appearance: NC backgrounds are flux dependant and can mimic a CC ν_e interaction
- Final state interactions also alter how the underlying event is observed, e.g. absorption or charge exchange of π^+

On-axis Interactive Neutrino GRID (INGRID)



16 modules arranged in a cross

- X-Y iron-scintillator layers, 7.1 tons each

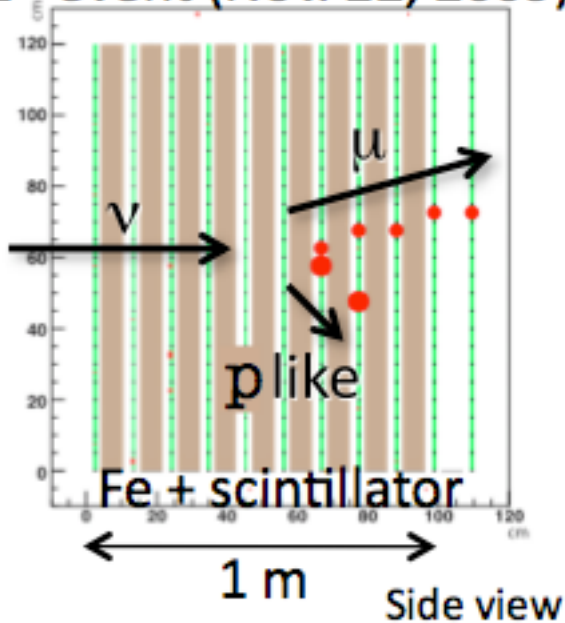
Count neutrino interactions in each module to determine neutrino rate vs. position

Extract beam direction better than 0.5 mrad

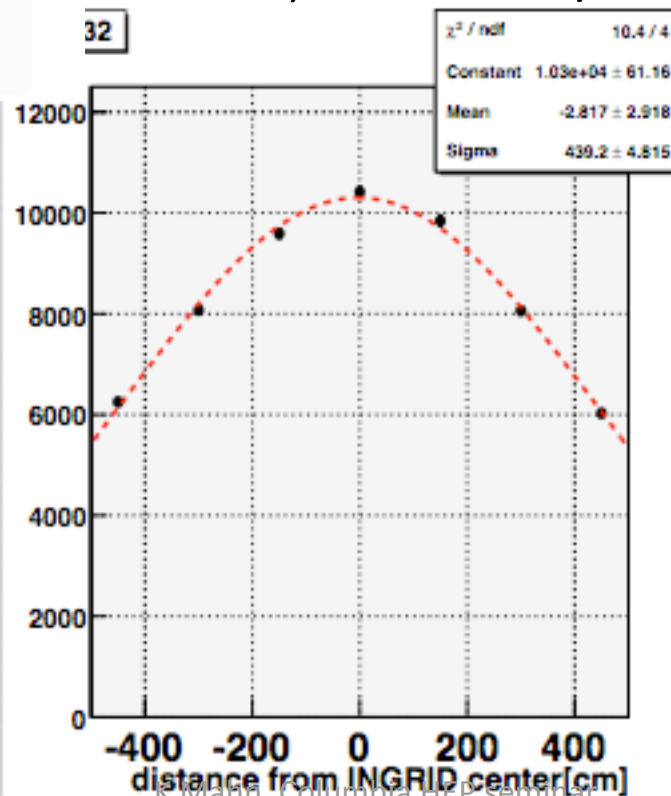
Monitor of neutrino beam vs. time

- $\sim 1.5 \nu / 10^{14}$ protons on target
- $\sim 10,000$ events / day

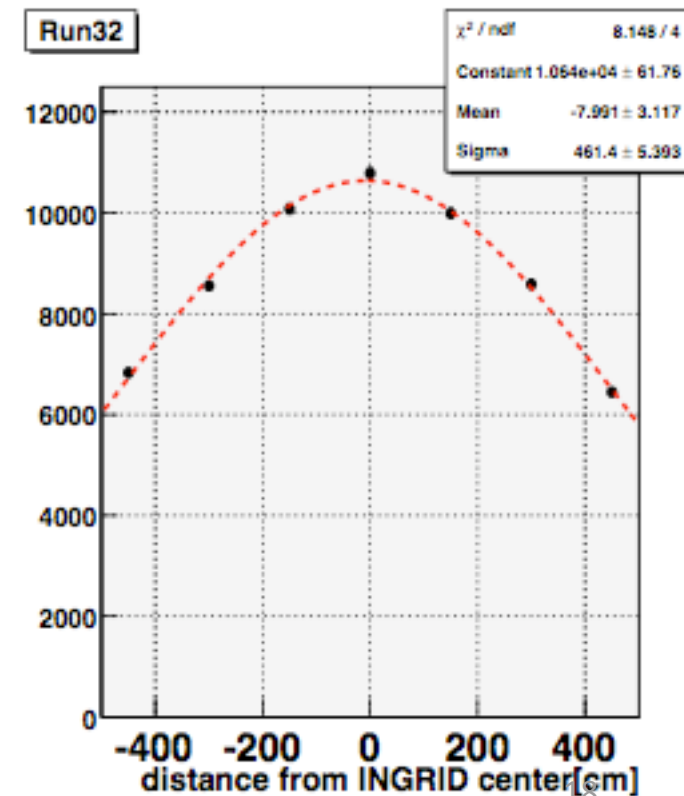
1st event (Nov. 22, 2009)



32



Run32



Off-axis ND280 detector complex

Suite of near detectors sit within UA1 (B=0.2T, 850 tons) magnet just above INGRID

- Current analysis use the Tracker to measure the unoscillated CC ν_μ rate
- Future analyses will use ECals, POD and SMRD

Side Muon Range Detector

87x17x0.7cm instrumented scintillator in magnet yoke
Active veto, cosmic trigger

Electromagnetic

Calorimeters

X-Y Pb/scintillator planes

POD, Barrel, TPC3

Tag photons, e from

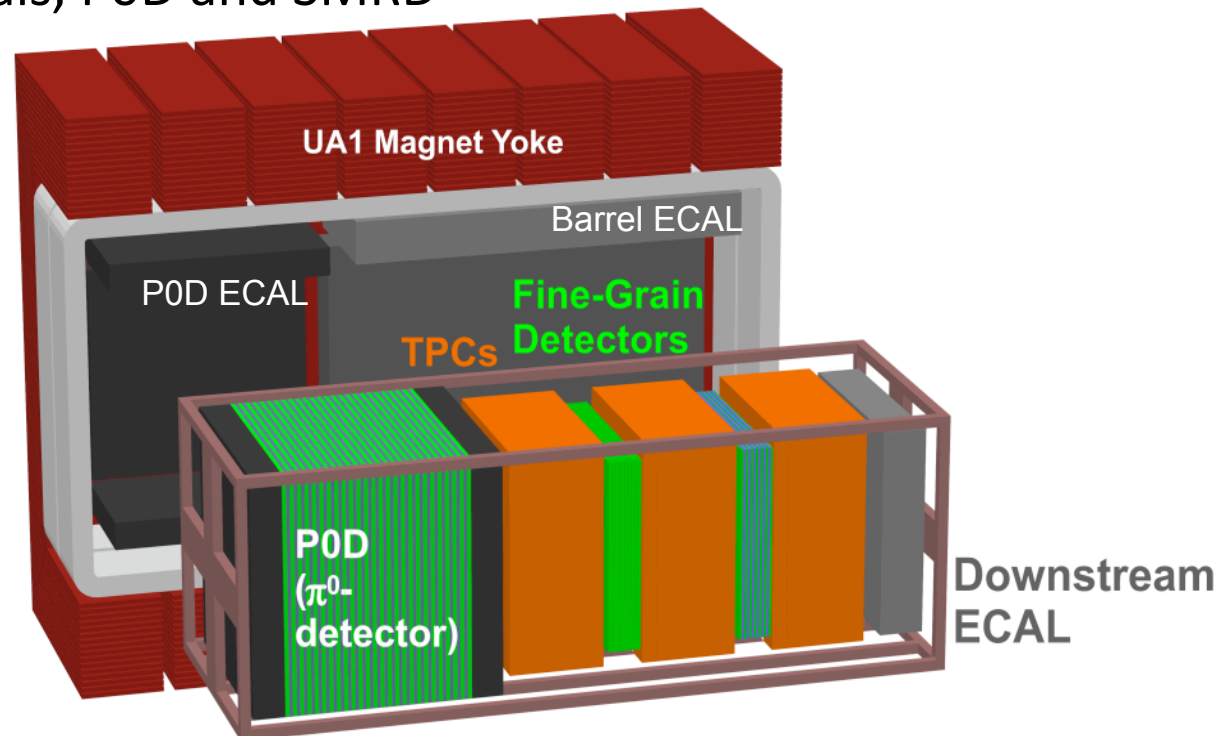
Tracker and POD

Pi-zero Detector (POD)

Pb/brass/scintillator planes with water bags (13.3 tons)

Neutrino interaction target (CH+H₂O)

Photons, electrons shower separable from MIPs



Tracker (FGD)

2 Fine Grained Detectors
XY scintillator sandwich
Neutrino interaction target (CH, CH+H₂O, 1.1 tons each)
Detailed vertex information
Particle ID from energy loss

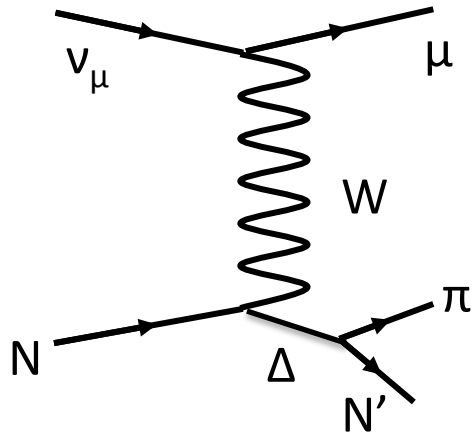
Tracker (TPC)

3 Time Projection Chambers
Field cage within a box filled with 95% Ar 3% CF₄ 2% isobutane
Momentum from curvature
Particle ID from energy loss

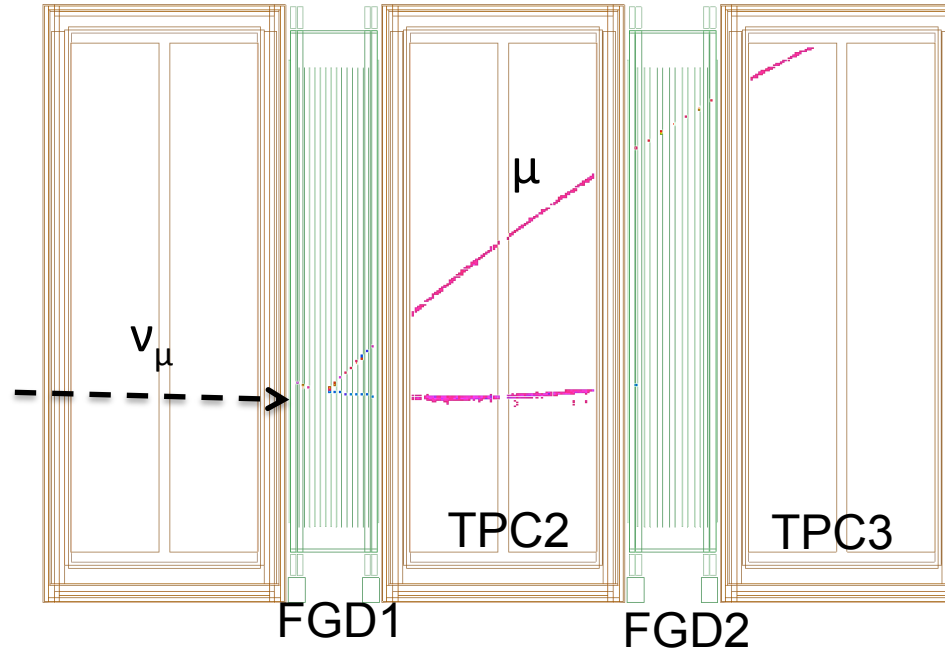
Example neutrino interactions in ND280

CC 1π

charged current
single pion production

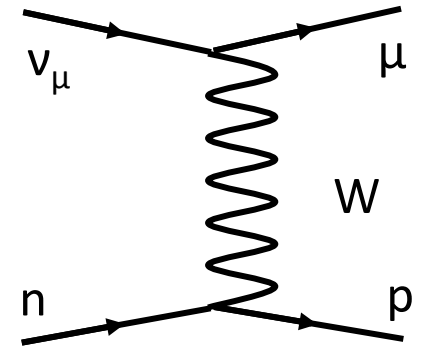


CC neutrino interaction candidate

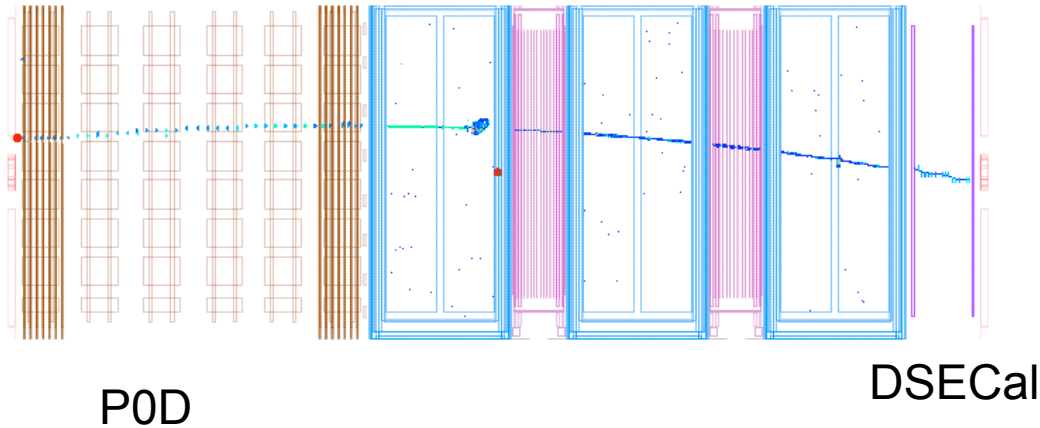


CCQE

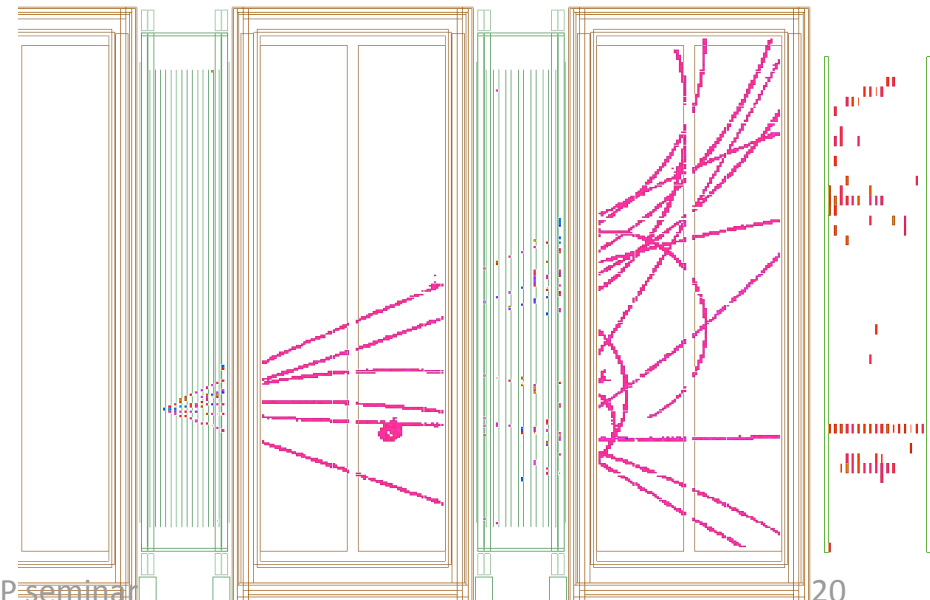
charged current
quasi-elastic



Neutrino interaction upstream of ND280



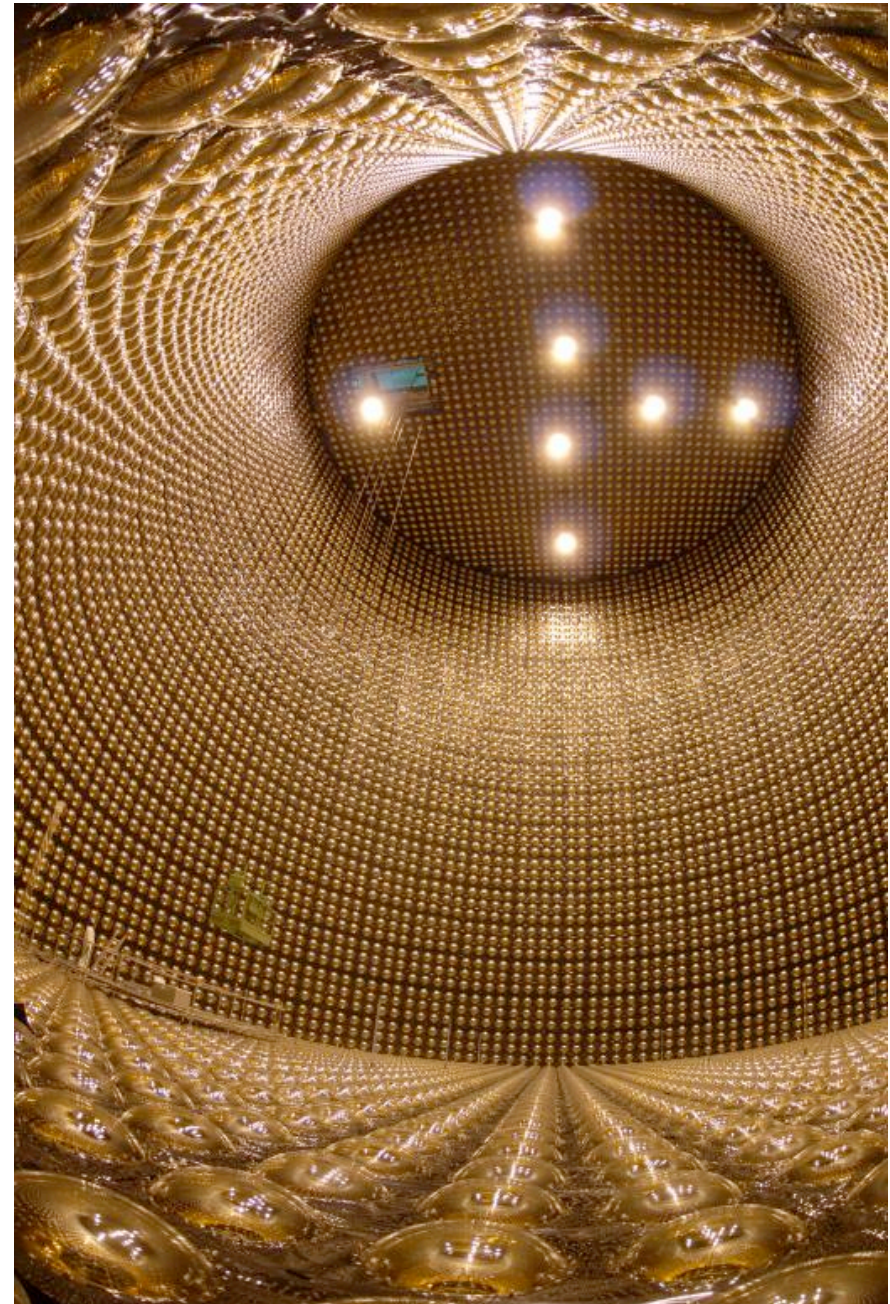
Deep inelastic scattering candidate



T2K far detector: Super-Kamiokande

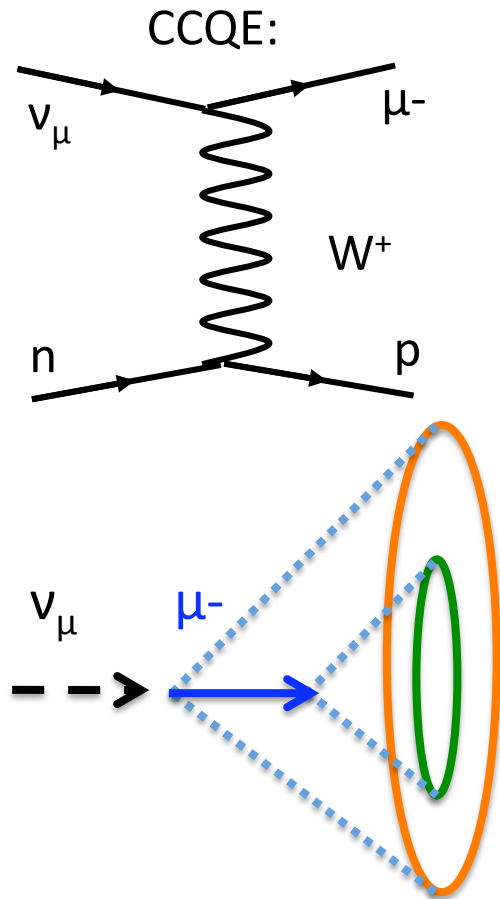
295km away is the T2K far detector,
Super-Kamiokande (“Super-K”)

- 50kton water Cherenkov detector
(22.5kton fiducial mass)
- 39.4 m diameter, 41.4 m tall cylindrical tank
- 11,129 inner photomultiplier tubes (PMTs)
(40% photocathode coverage)
- 1885 veto PMTs located on the outside
of the tank reject events entering the tank
- Cosmic ray rate in Kamioka mine is 1.77Hz
at 2700m water equivalent

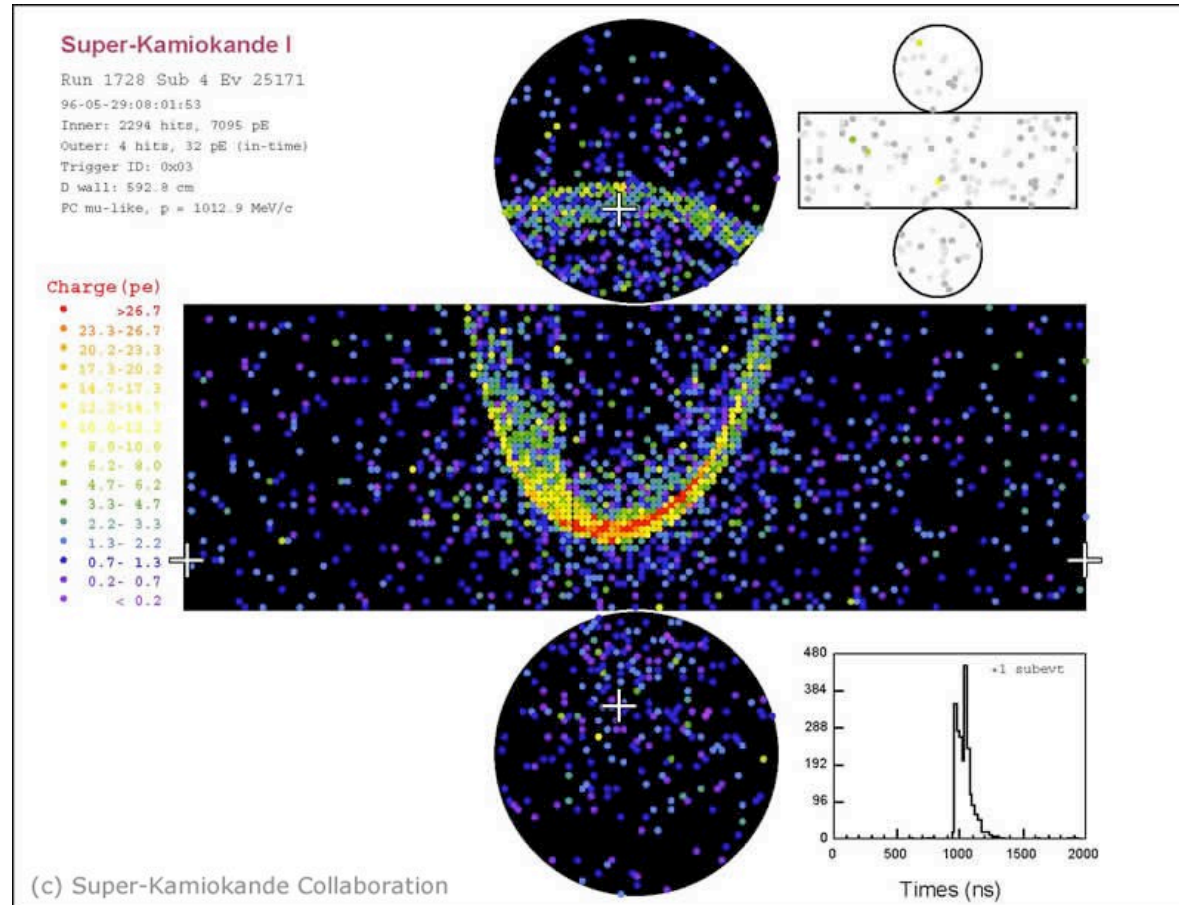


Neutrino events in Super-K

Cherenkov light emitted at a fixed angle produces ring(s) on the tank wall, recorded by PMTs



Data event in Super-K: single muon



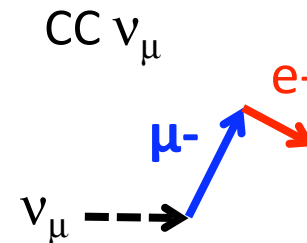
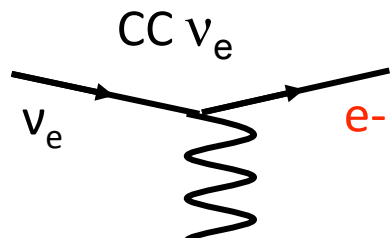
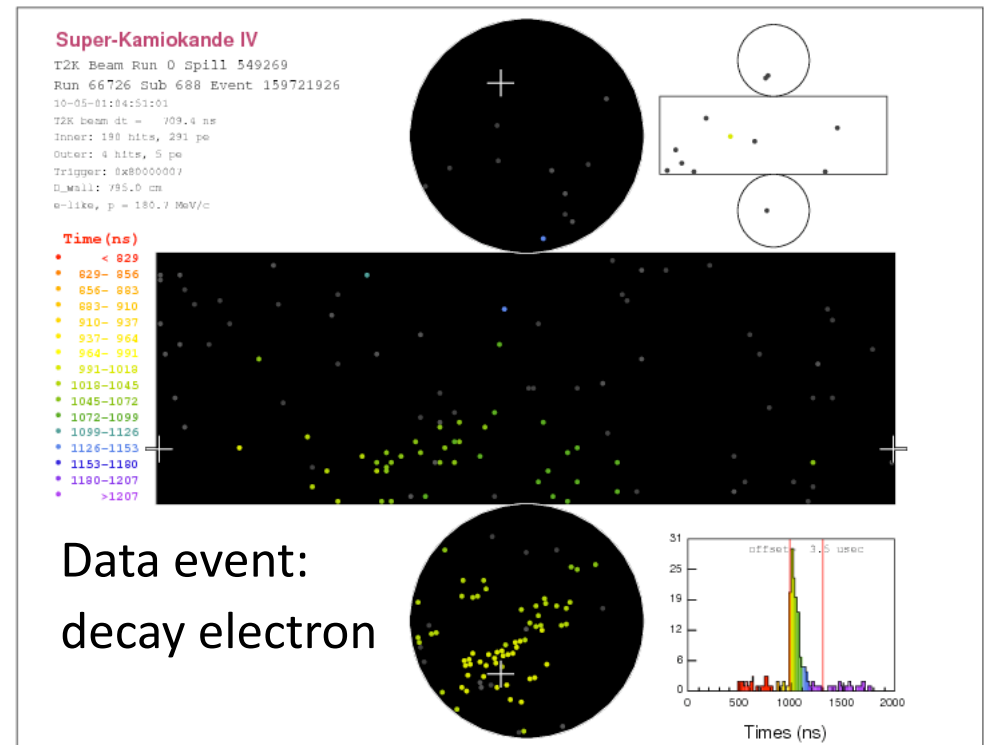
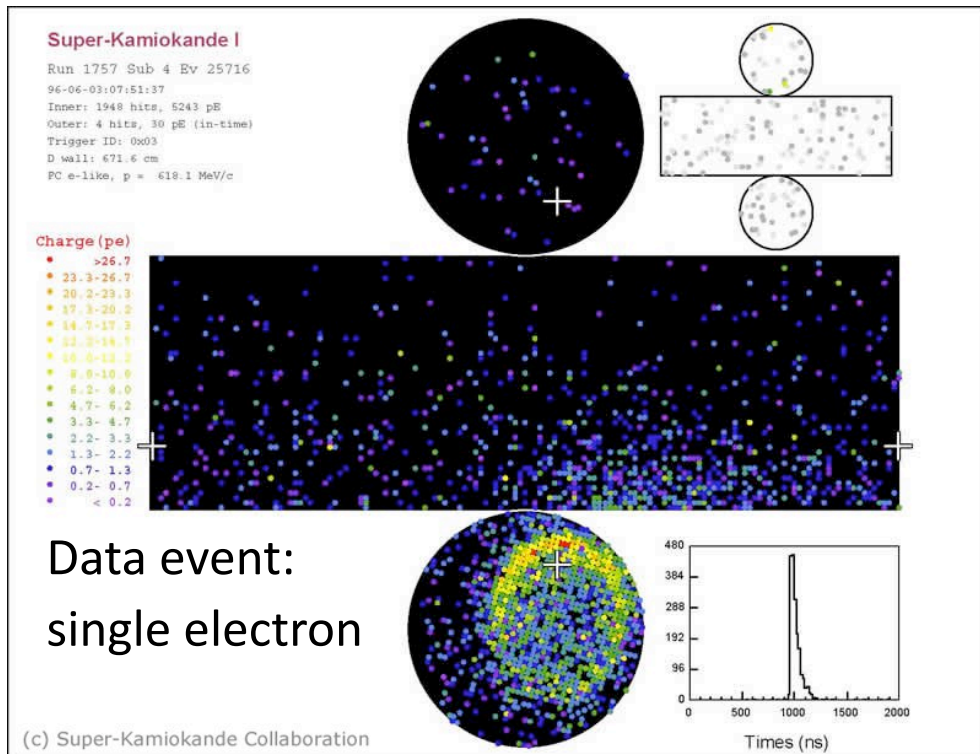
Muons from CC interactions produce well defined rings

Angle, momentum can be reconstructed from PMT charge, time information

Neutrino events in Super-K

Electrons produce “fuzzy” rings, due to multiple scattering and showering

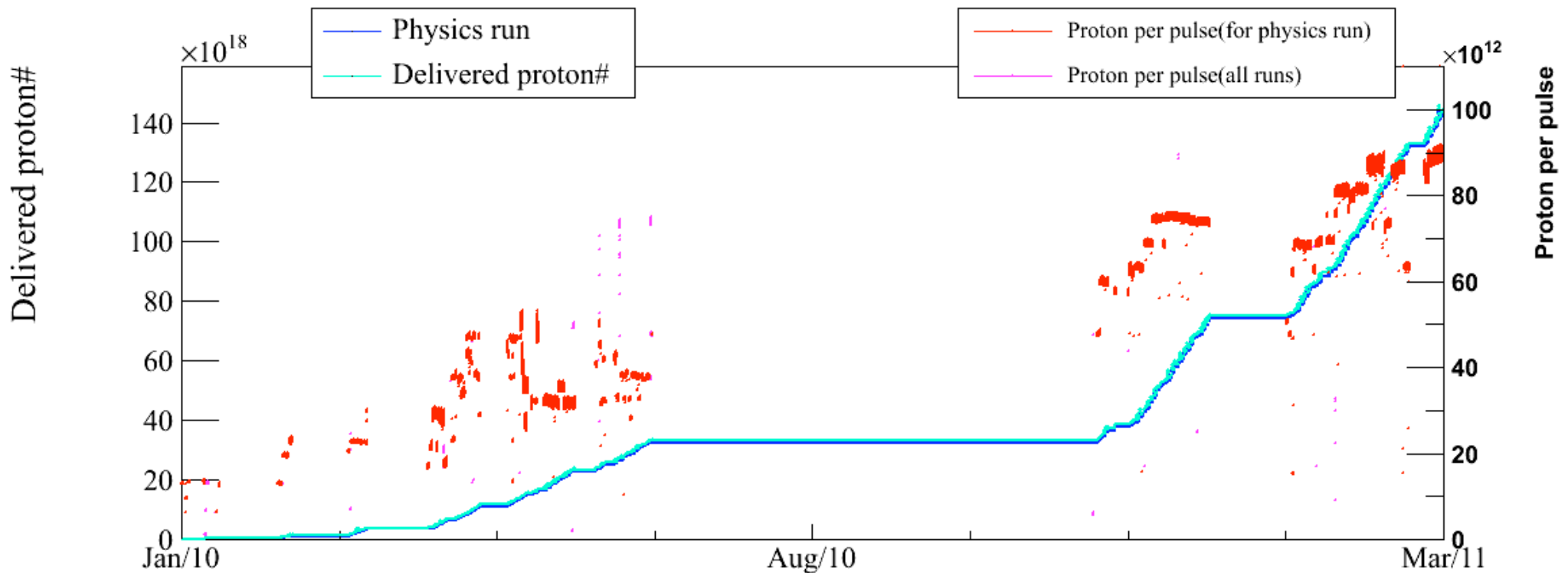
- CC ν_e events produce an electron (left)
- Ability to tag electrons from μ decay from CC ν_μ (right)



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Data collected



Run I: Jan 2010 – June 2010

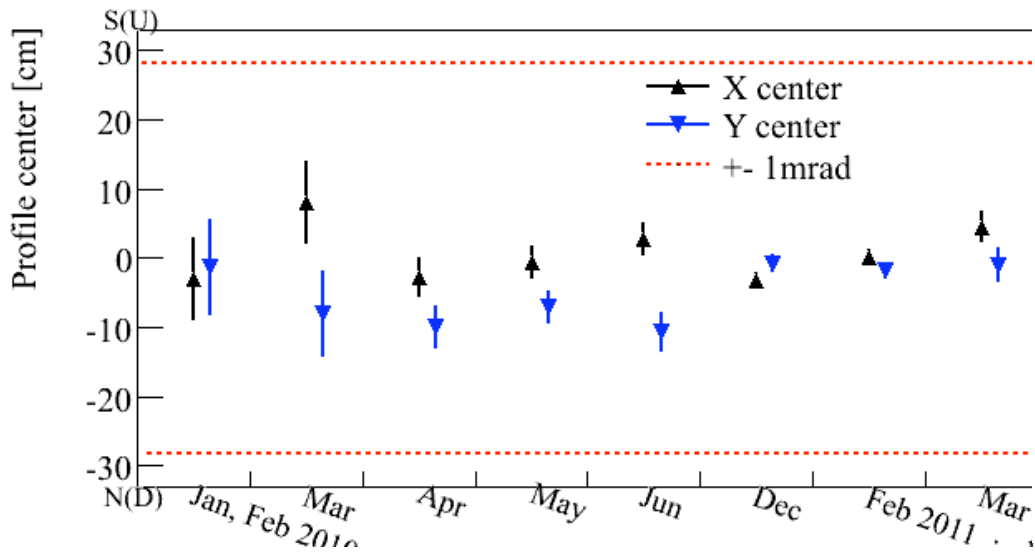
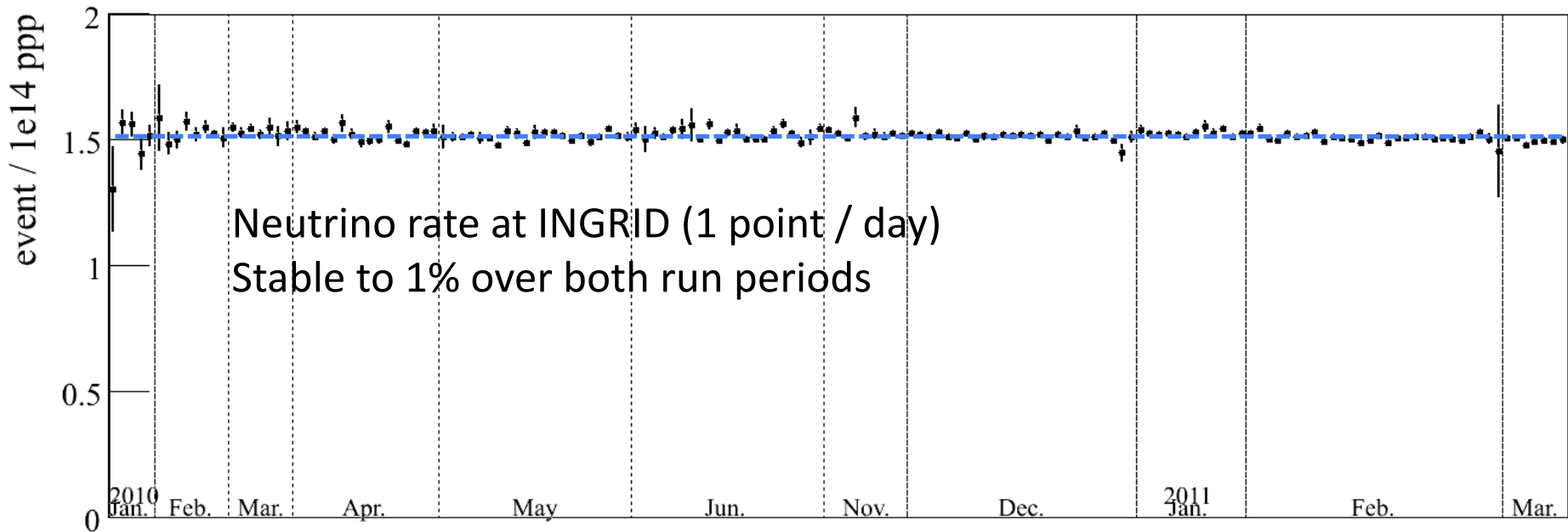
6 bunches / spill / 3.54s
Stable running at 3.3×10^{13} POT/spill
(≈ 54 kW) with maximum at 100kW

Run II: Nov 2010-Mar 2011

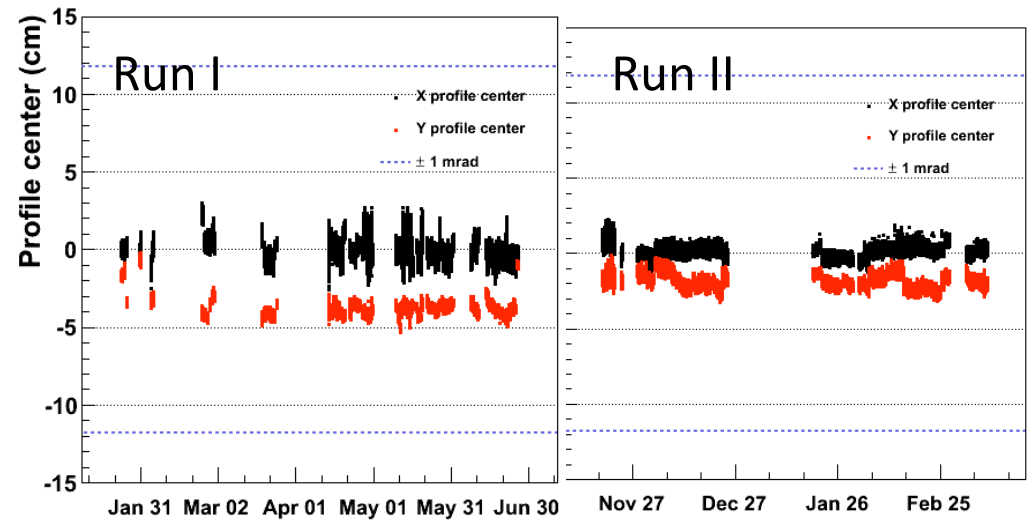
8 bunches / spill / 3.04s
Stable running at 145 kW

Run I + Run II protons on target = $(0.32 + 1.11) \times 10^{20}$
= 1.43×10^{20} POT (2% of T2K goal)

Neutrino beam stability



Beam direction (x and y) at INGRID
Stable to <1 mrad



Beam direction (x and y)
with the muon monitor
Stable to <1 mrad

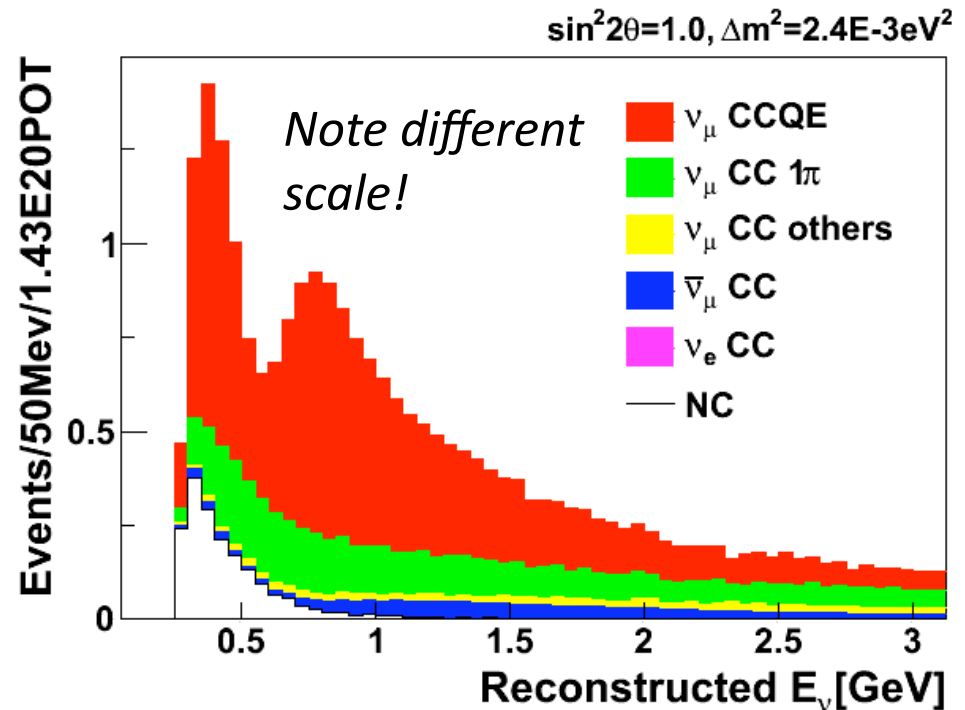
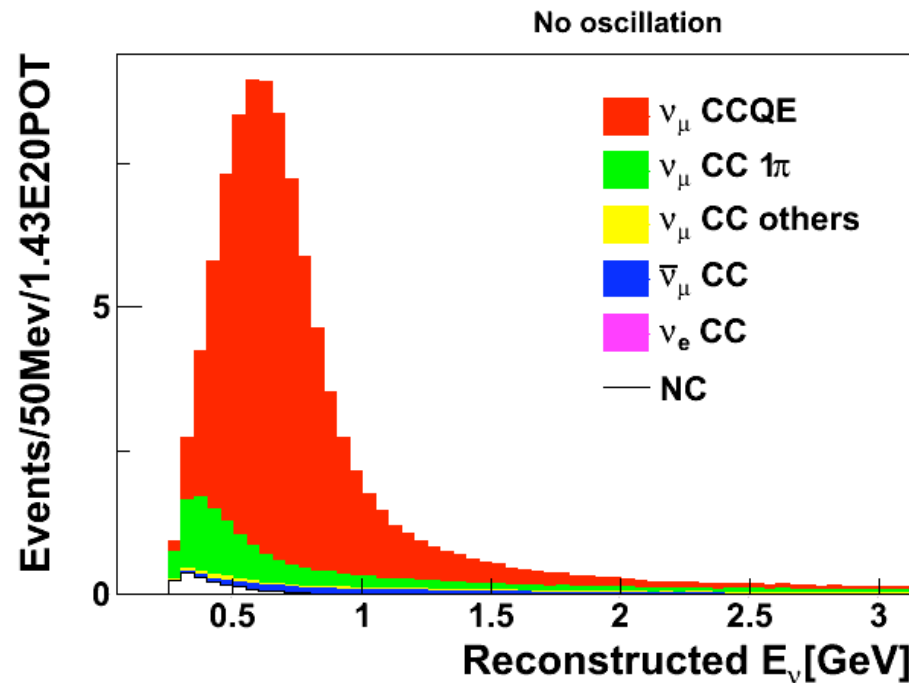
Outline

1. Introduction to neutrino oscillations
2. Overview of the T2K experiment
3. Data collected by T2K
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T2K oscillation analysis method

For a fixed baseline ($L=295\text{km}$) oscillation probabilities depend on the neutrino energy E_ν

$$P(\nu_\mu \rightarrow \nu_{x \neq \mu}) \cong \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$$



Disappearance observable as distortion to neutrino energy spectrum and reduction of overall rate at far detector

Appearance is a small excess of electron neutrino candidates over background (counting experiment)

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

T2K oscillation analysis method

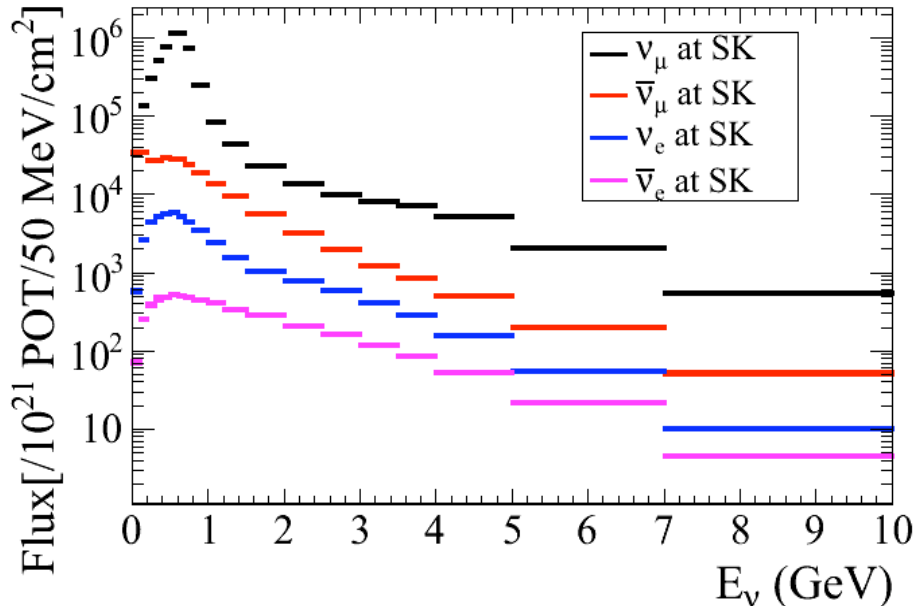
$$N'_{FD} = R_{ND}^{data}(CC \nu_{\mu}) \times \frac{N_{FD}}{R_{ND}^{exp}(CC \nu_{\mu})}$$

$$\frac{N_{FD}}{R_{ND}^{exp}} = \frac{\int \Phi_{\nu_{\mu}}^{FD} \times \sigma \times \epsilon_{FD} \times P(\nu_{\mu} \rightarrow \nu_x) dE_{\nu}}{\int \Phi_{\nu_{\mu}}^{ND} \times \sigma \times \epsilon_{ND} dE_{\nu}}$$

* Formula is a simplification, ignores summations over neutrino flavor types and interaction modes

- Calculate unoscillated event rate using flux (Φ), cross section (σ) predictions and detector (ϵ) efficiencies
- Correct far detector ν_{μ} spectrum (N'_{FD}) by observed ND280 rate $R(CC \nu_{\mu})$ to reduce flux, cross section uncertainties and set normalization
- Extract $\Delta m^2, \sin^2 2\theta_{23}$ oscillation parameters from a fit to N'_{FD}

Neutrino flux prediction



Geant3/FLUKA based flux prediction

Unoscillated flux at Super-K is ν_μ

- Also $\bar{\nu}_\mu$ ($\sim 6\%$) and
- ν_e components ($\sim 1\%$)

Neutrinos at peak from π^+ decay,
high energy flux from K decay

Prediction and uncertainties are determined by **external** or **in-situ** measurements

Use of ND constraint reduces flux uncertainties by a factor of 2

Largest uncertainty is π , K production from the target, constrained by NA61 exp't

Flux uncertainties (%)	ND	ν_e bkrd	ν_e / ND
Proton beam	2.2%	0.0%	2.2%
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Other hadronic interactions	9.7%	9.5%	1.5%
Meson focusing, beam direction	2.8%	2.2%	0.8%
Total	15.4%	16.1%	8.5%

Total ν_μ signal/ND uncertainty: 4.8%

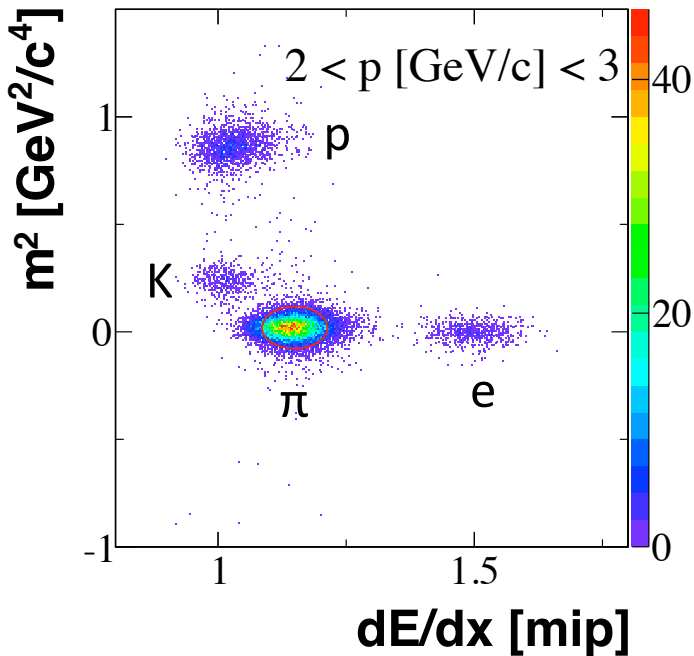
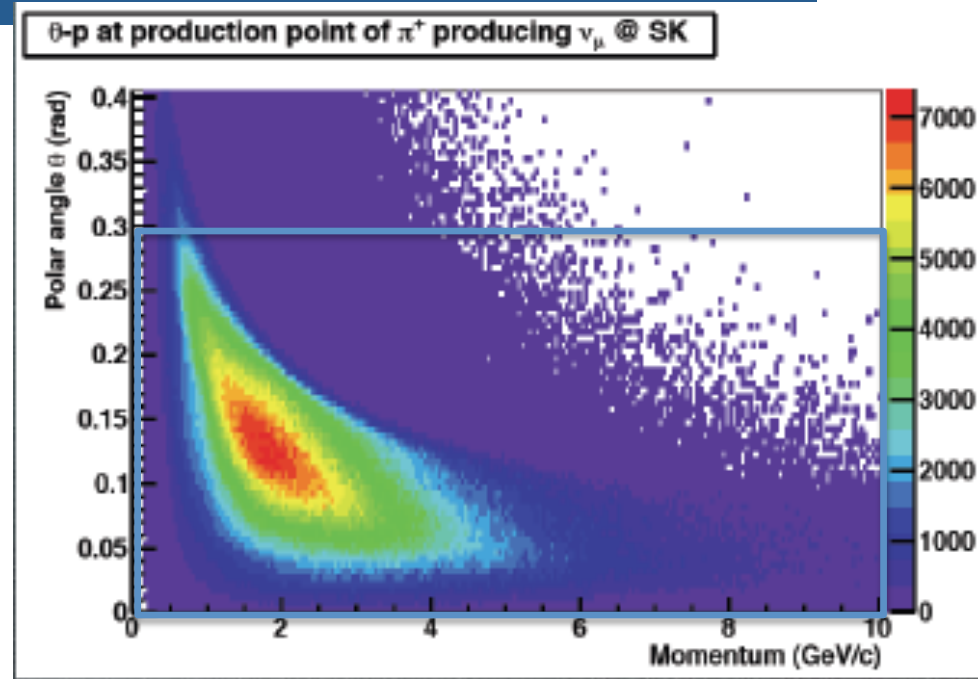
@ $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \sin^2 2\theta_{23} = 1.0$

π production from p+C

NA61/SHINE experiment at CERN
 Designed to measure hadron production

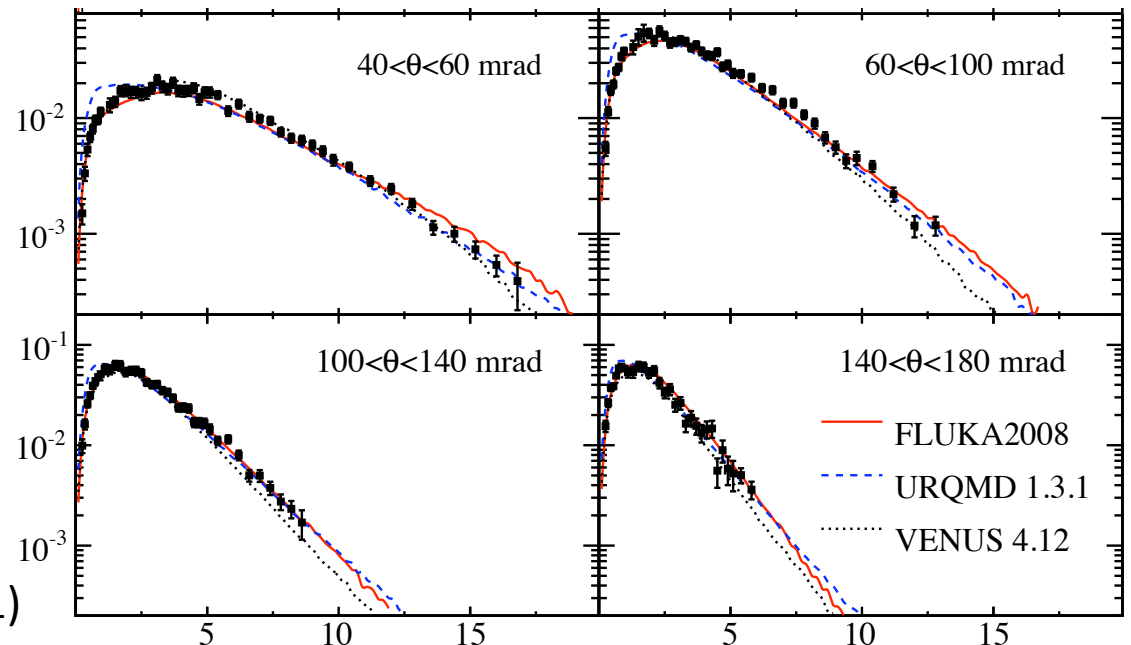
30 GeV p beam on:
 thin target (2cm) in 2007-2009 run
 T2K replica target (91cm, 1.9λ) in 2010 run

Use TOF and dE/dx to select pions



$$\frac{1}{\sigma_{\text{prod}}} \frac{d\sigma}{dp} \text{ [1/GeV/c]}$$

Differential pion multiplicity reproduces simulation



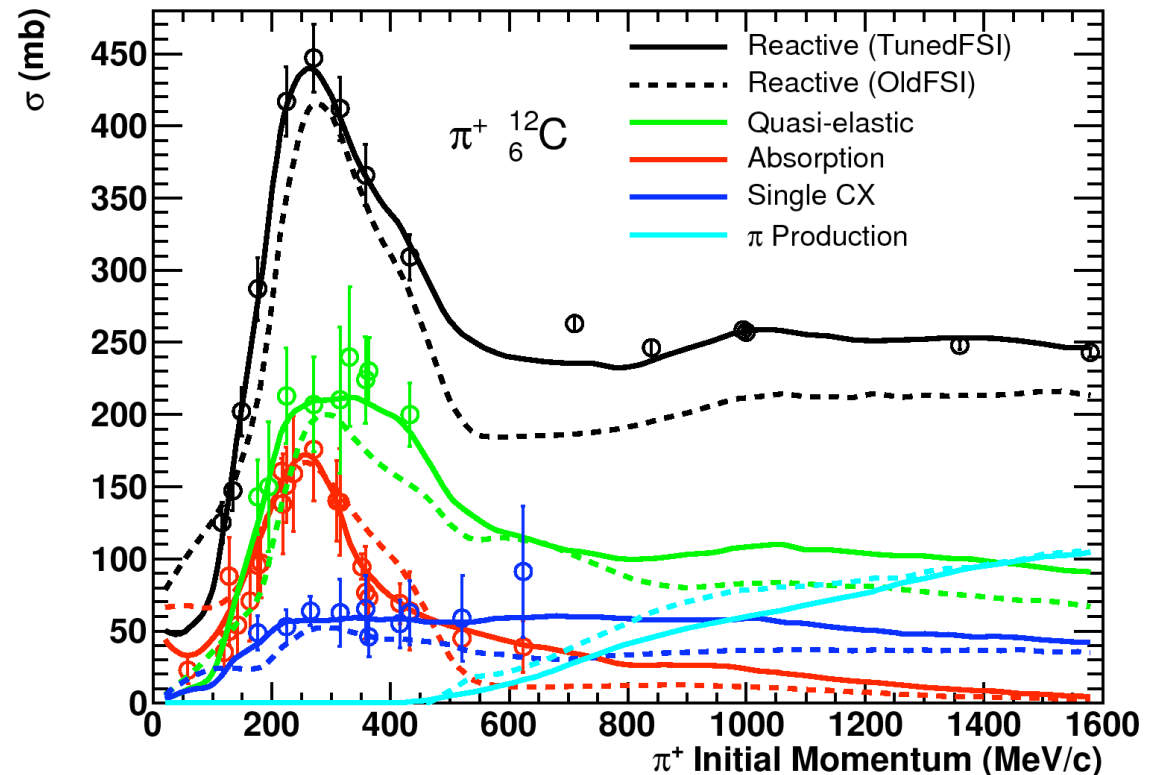
N.Abgrall et al., Phys.Rev.C 84, 034604 (2011)
 arXiv:1102.0983 [hep-ex]

Neutrino interaction uncertainties

Cross section model, uncertainties set from external data at $E_\nu \sim 1$ GeV
e.g. MiniBooNE, SciBooNE, K2K and constrained by ND280 rate

σ uncert. (%) (after ND)	ν_μ signal	ν_e bkrd
CCQE nuclear model (@lowE)	2.5%	3.1%
CC1 π	+0.4% -0.5%	2.2%
CC coherent π	-	3.1%
CC other	+4.1% -3.6%	4.4%
NC all	0.9%	-
NC1 π^0	-	5.3%
NC coherent π	-	2.3%
NC other	-	2.3%
$\sigma(\nu_e)$	N/A	3.4%
Final State Interactions (FSI)	6.7%	10.1%
Total	+8.3% -8.1%	14.0%

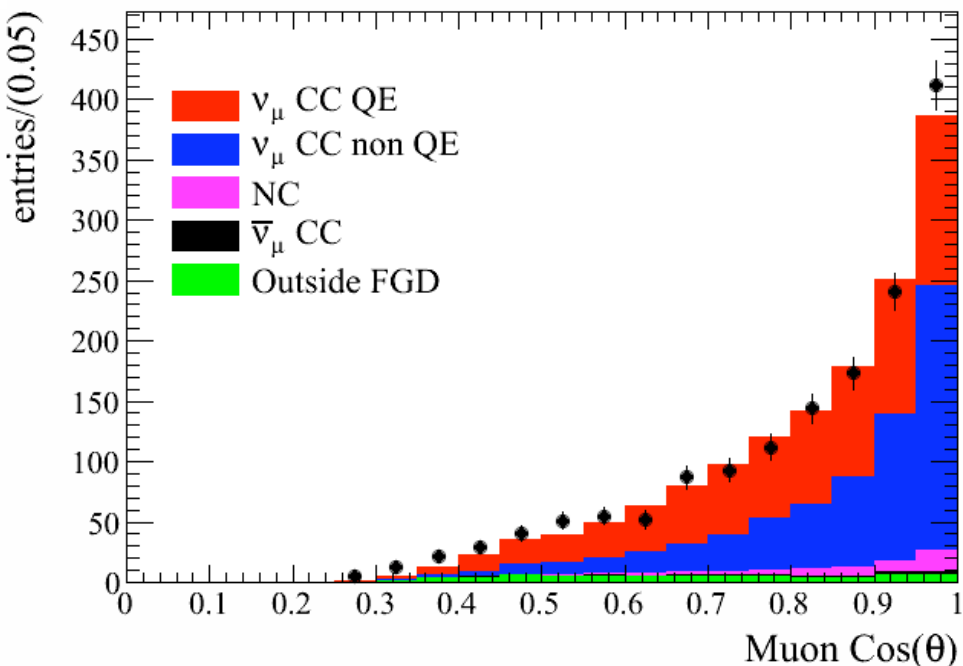
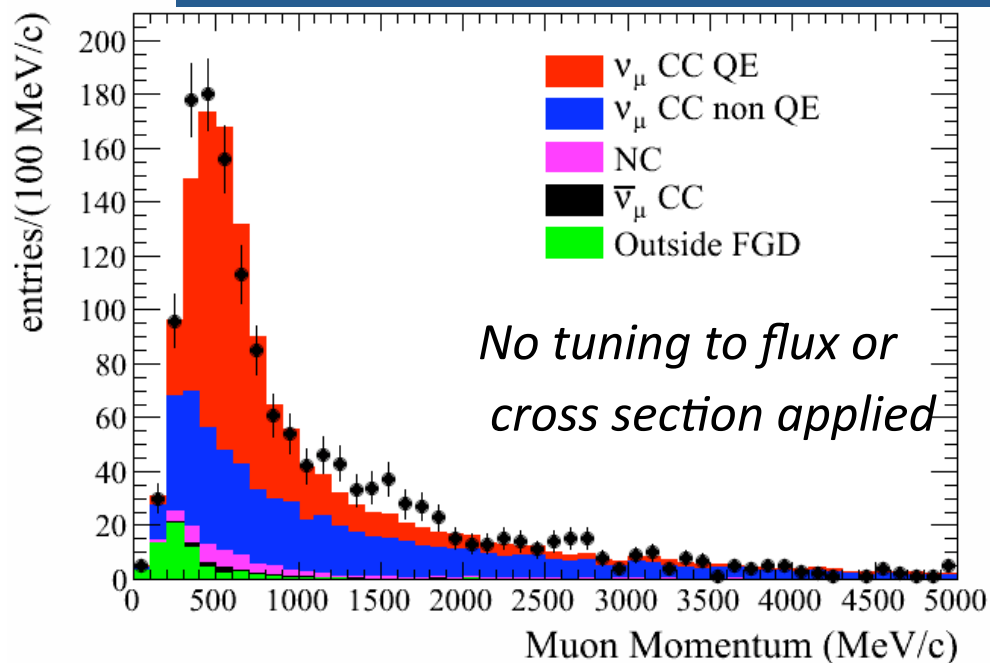
External data on π^+ interaction cross sections



- FSI alters the energy dependence of how backgrounds are reconstructed
- Modify π re-interaction probabilities within cross section model according to external data to determine FSI uncertainty

ν_μ signal @ $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2 \sin^2 2\theta_{23} = 1.0$

ND280 CC ν_μ sample



Dataset shown here: 2.88×10^{19} POT

Reconstructed momentum and angle of the CC ν_μ candidates:

1. Require no tracks in TPC1 (veto ν interactions upstream of FGDs)
2. Select events which originate in FGD1 or FGD2 fiducial volume
3. Use the highest momentum, negative TPC2 or TPC3 track
4. Select μ from TPC dE/dx information to determine flavor of neutrino

Rate used to normalize expected number of events at far detector:

$$R(\text{data/MC}) = 1.036 \pm 0.028 \text{ (stat)}$$

$${}^{+0.044}_{-0.037} \text{ (detector sys)}$$

$$\pm 0.038 \text{ (xsec model)}$$

Basic neutrino event selection at far detector

Basic neutrino selection (precuts)

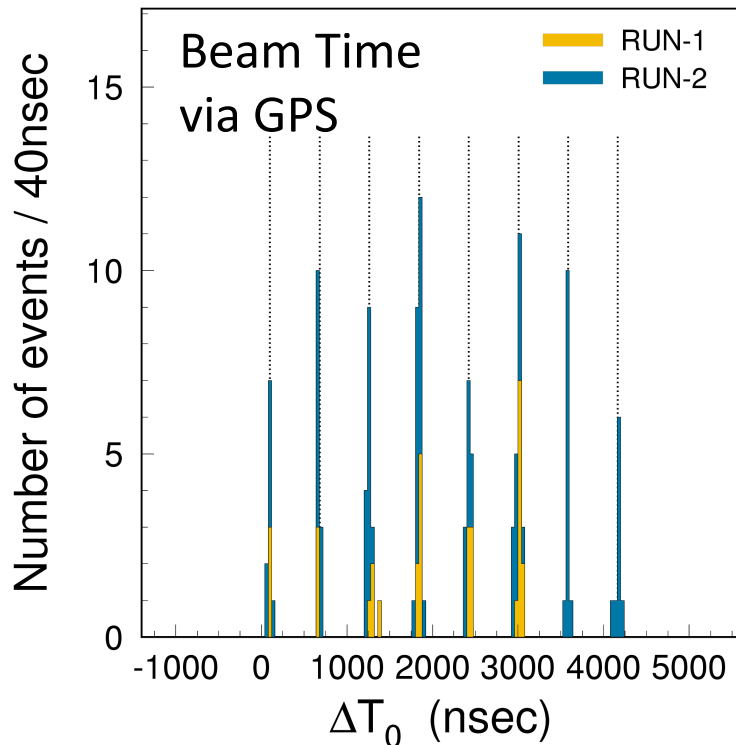
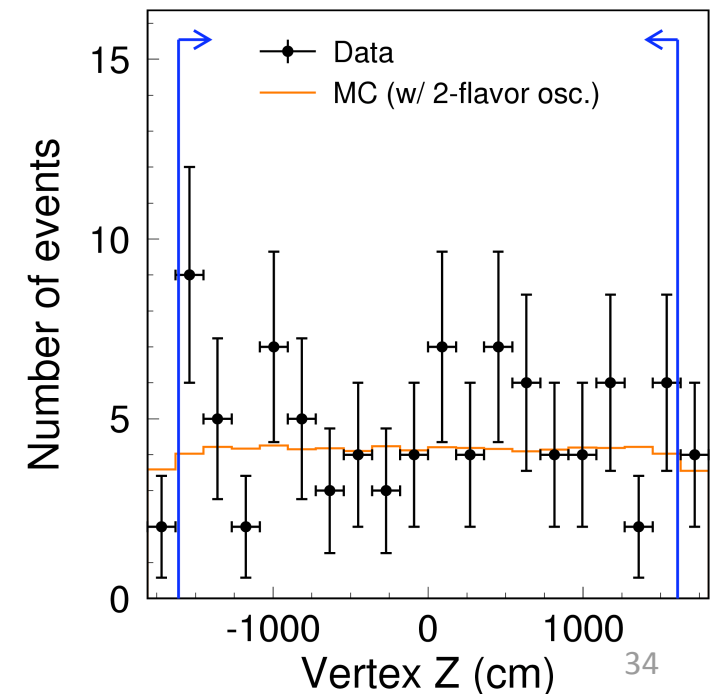
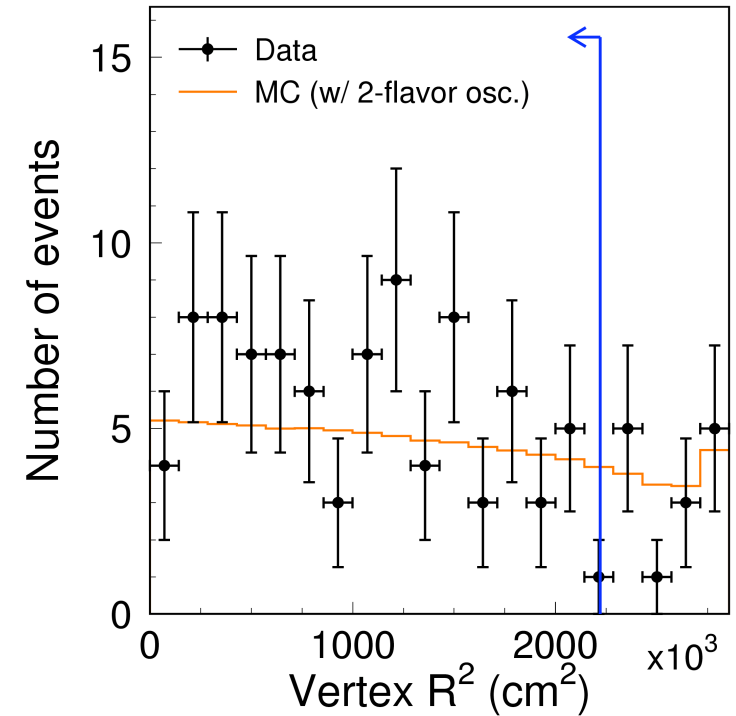
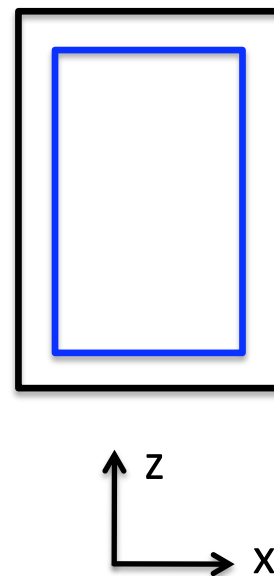
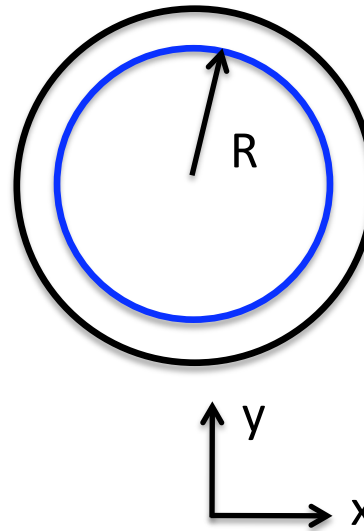
Event time within beam window

No activity in the veto

Visible $E > 30$ MeV

Reconstructed vertex > 2 m from wall

Single reconstructed ring

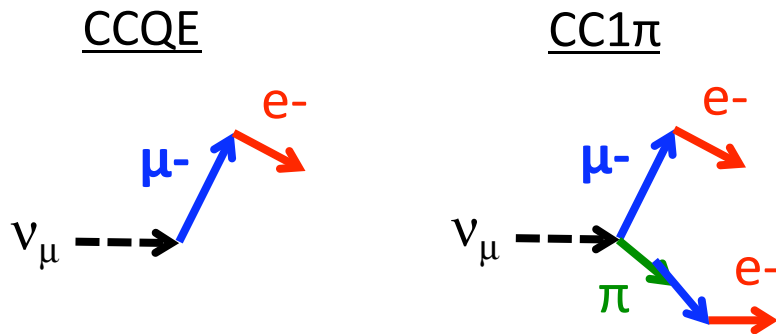


Events are consistent with expectation

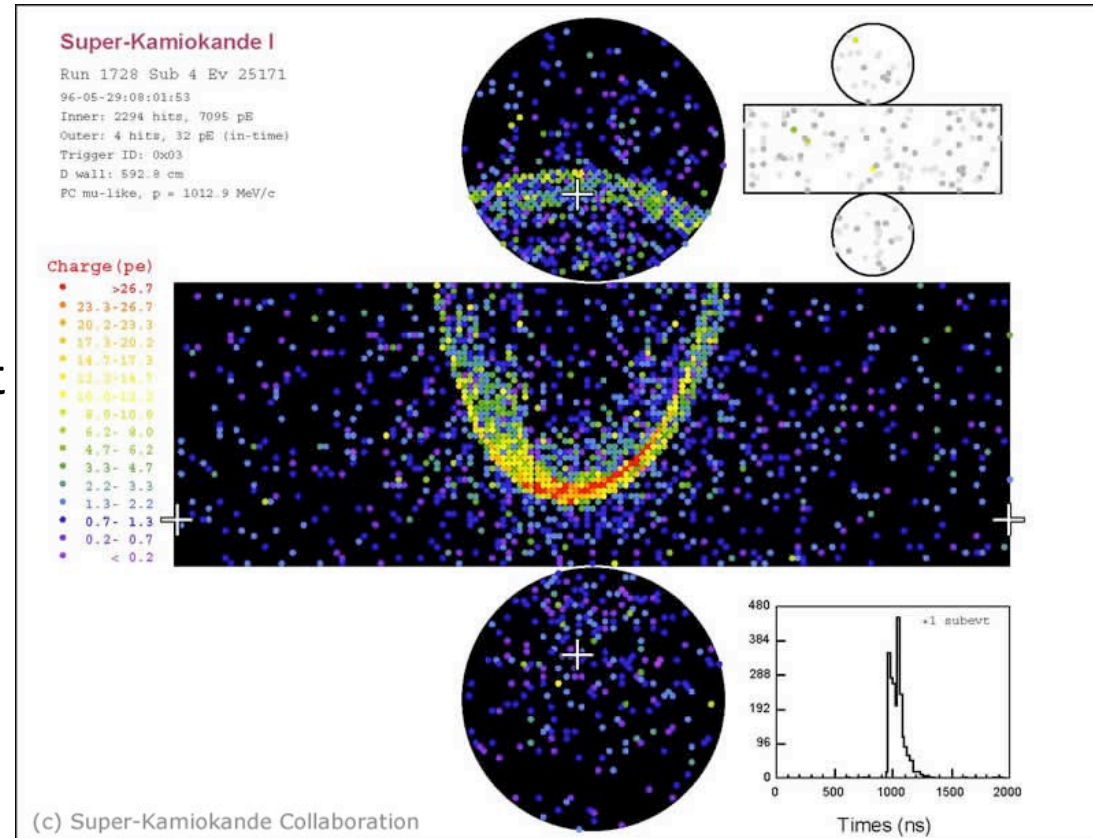
T2K far detector ν_μ event selection

Select CCQE ν_μ candidates:

1. Apply basic neutrino selection
2. Muon-like ring
 - a) Sufficient momentum for e- μ separation
3. 0 or 1 decay electrons, to reject CC1 π
 - a) Search for low energy electron events after primary event



Data event in Super-K: single muon



Signal CCQE ν_μ Efficiency = 72%

Background CCnonQE Rejection = 79%

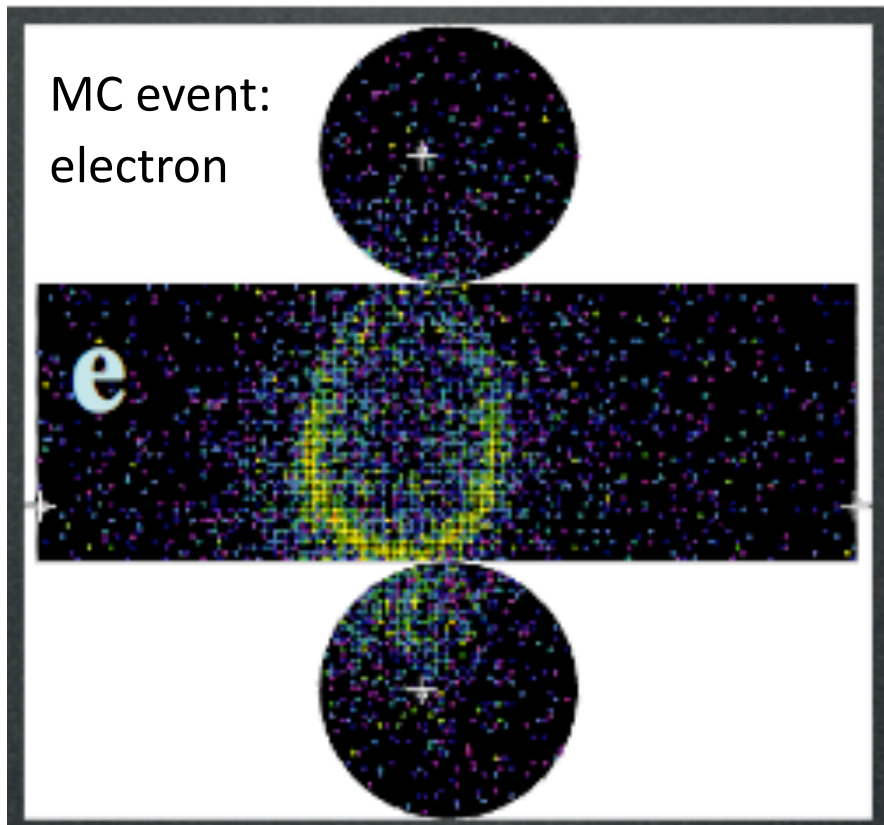
T2K far detector ν_e event selection

Similar selection for CC ν_e candidates:

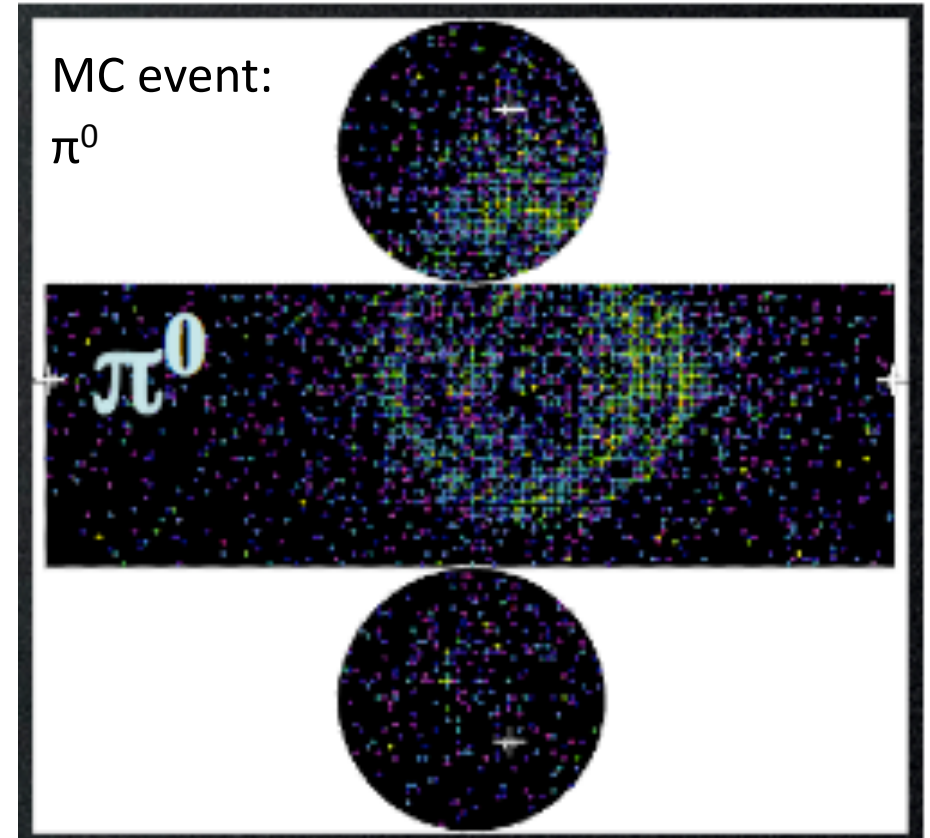
- Basic neutrino selection
- Single electron-like ring
- 0 decay electrons (reject CC ν_μ)
- Remove $E_\nu > 1.25$ GeV events as beam CC ν_e have higher average energy than signal

Additional background from NC π^0 events, where π^0 decay to two photons (electron-like rings)

- Calculate invariant mass assuming 2nd ring, and reject invariant mass consistent with π^0



Signal efficiency: 66%



Rejection efficiency for all NC bkrds: 99%

T2K far detector selection uncertainties

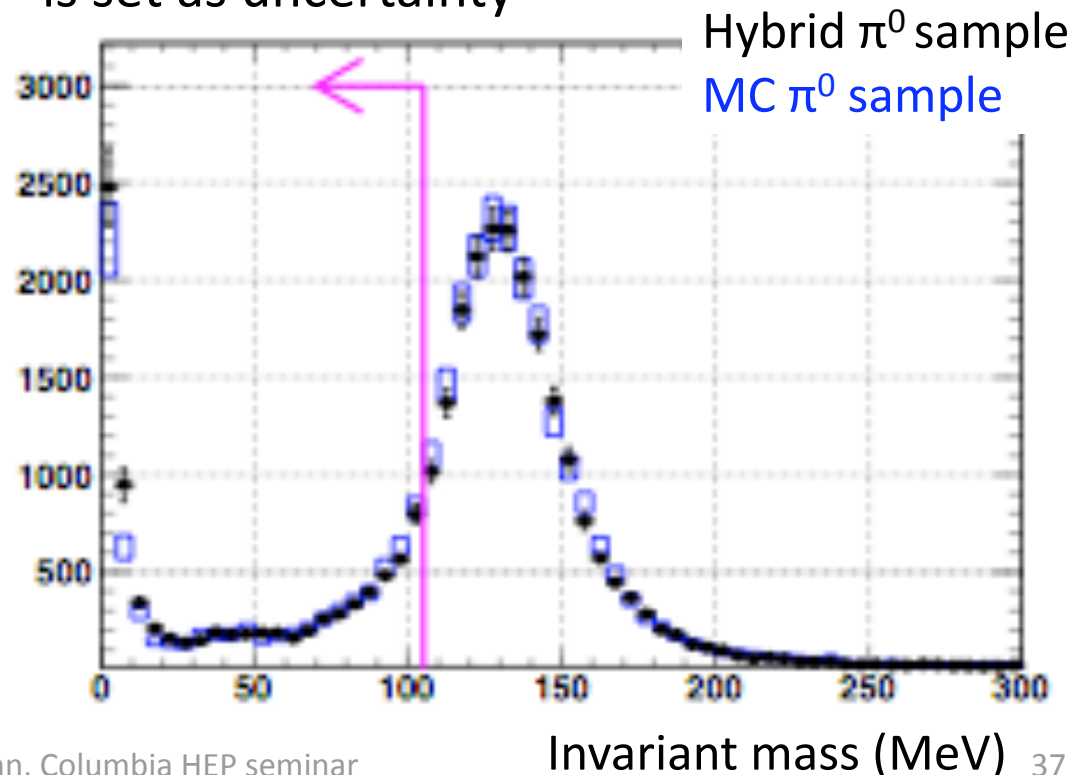
detector uncertainties (%)	ν_e signal	ν_e bkgd
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass	5.1%	8.7%
π^0 rejection	-	3.6%
Fiducial volume	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron eff	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

Total uncertainty for ν_μ analysis: 10.3%
(predominantly ring counting)

Evaluated with atmospheric ν control samples

Evaluated with a special control sample

- Select an atmospheric ν_e candidate or decay electron event
- Add a simulated photon to the event to create a “hybrid π^0 ”
- Difference in π^0 rejection efficiency between hybrid sample and pure simulated π^0 sample is set as uncertainty



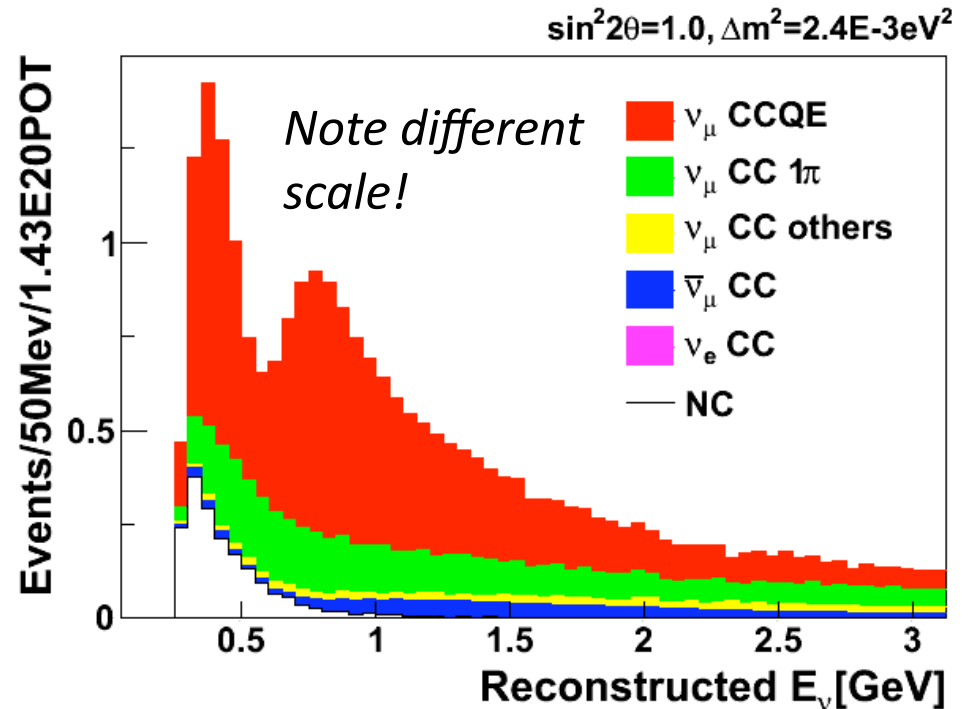
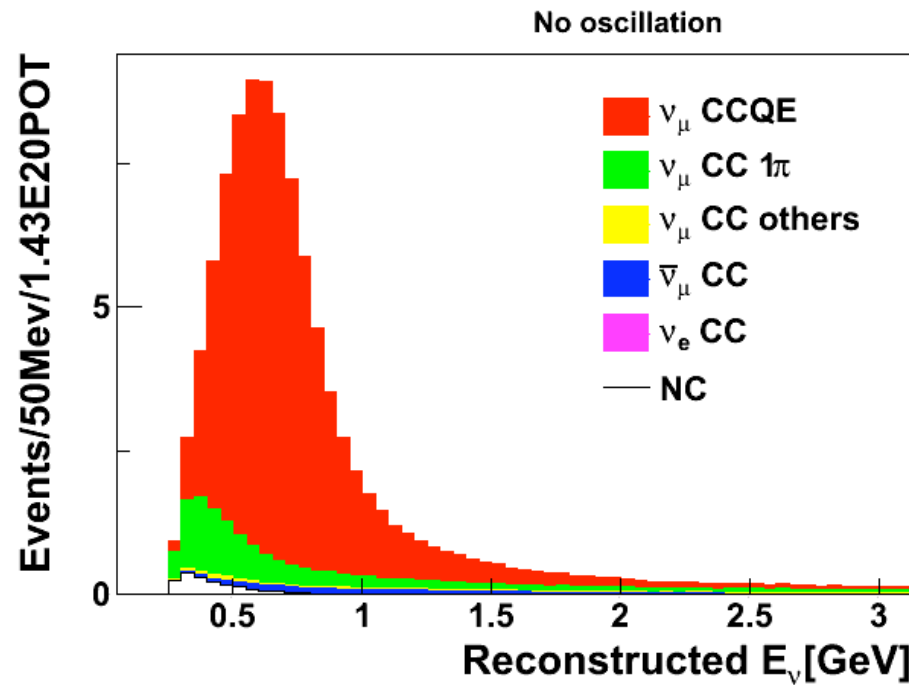
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T2K ν_μ disappearance method

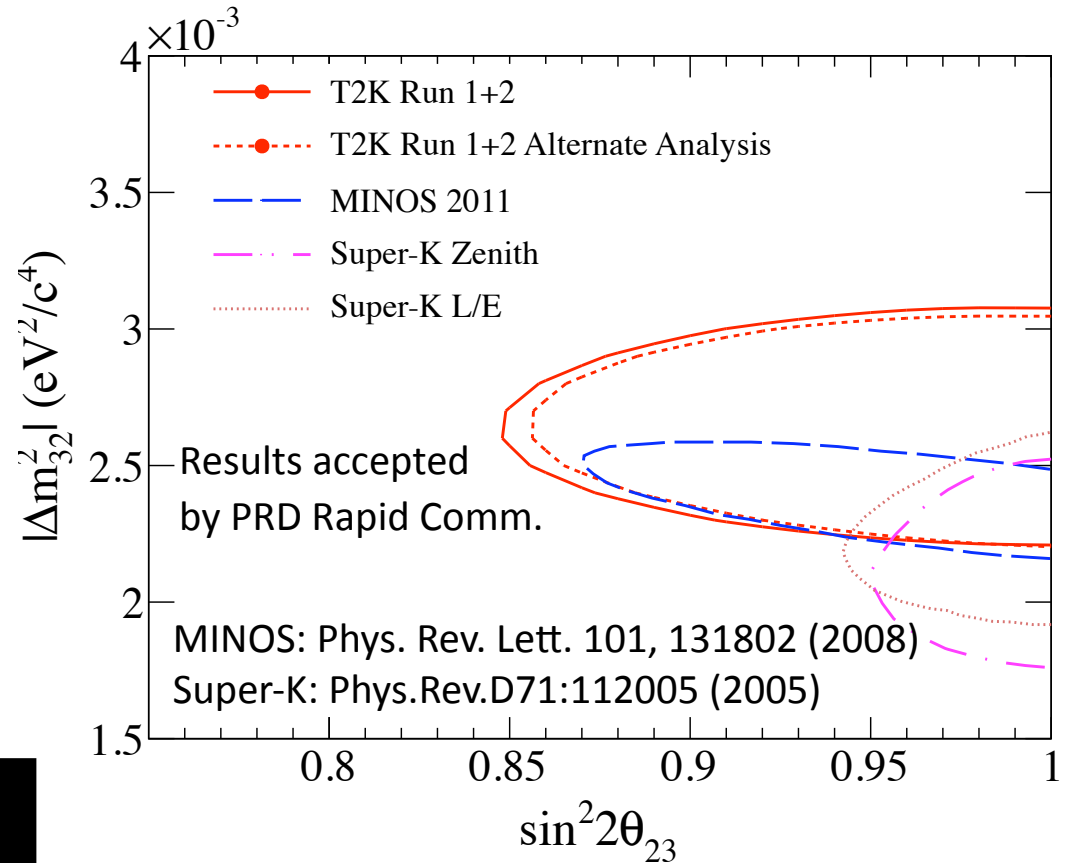
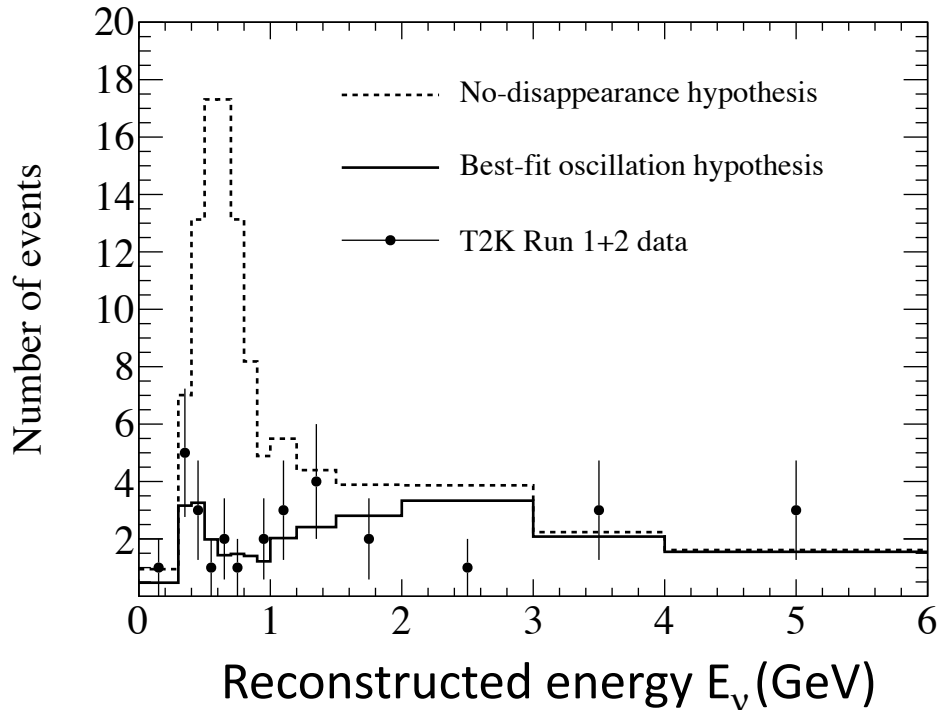
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$$P(\nu_\mu \rightarrow \nu_{x \neq \mu}) \cong \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$$



Disappearance observable as distortion to neutrino energy spectrum and reduction of overall rate at far detector

ν_μ disappearance results



Summary of uncertainties	ν_μ signal $\Delta m^2_{23} = 2.4 \times 10^{-3} \text{ eV}^2$ $\sin^2 2\theta_{23} = 1.0$
ν flux	$\pm 4.8\%$
ν interactions	$+8.3 - 8.1\%$
Near detector	$+6.2 - 5.9\%$
Far detector	$\pm 10.3\%$
Total	$+15.4 - 15.1\%$

- 31 events pass ν_μ selection criterion
- $103.6^{+13.8}_{-13.4}$ expected for no osc, excluded at 4.5σ
- Fit E_ν distribution for 2 flavor osc. parameters (binned χ^2 fit)
- Best fit: $|\Delta m^2_{32}| = 2.65 \times 10^{-3} \text{ eV}^2$
 $\sin^2 2\theta_{23} = 0.98$

ν_e appearance at T2K

Extract $\sin^2 2\theta_{13}$ by comparing observed number of ν_e candidates to expectation (counting experiment)

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Signal (ν_μ to ν_e osc)	# events
@ $\sin^2 2\theta_{13}=0.1, \delta_{cp}=0$	4.11

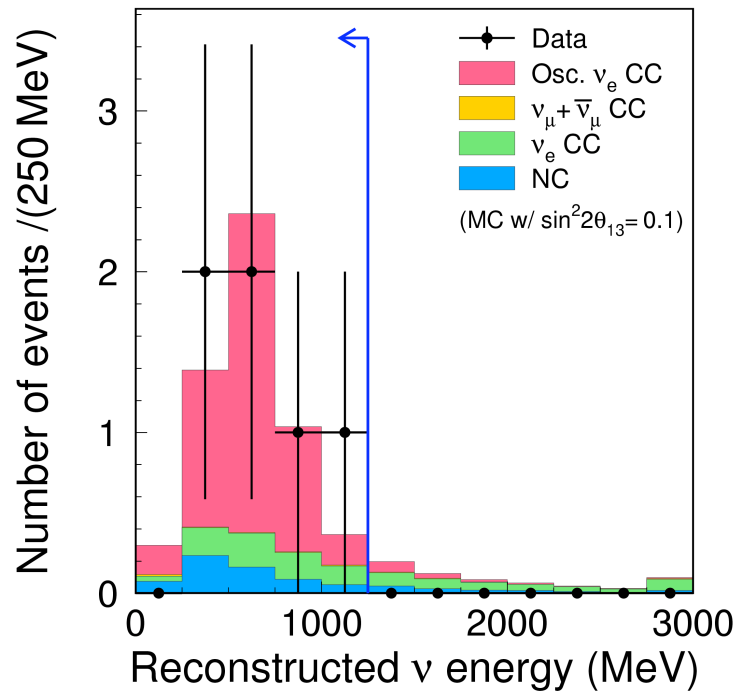
Background	# events
beam ν_e	0.76
ν_μ CC background	0.03
NC background	0.61
osc through θ_{12}	0.09
total:	1.49 ± 0.34 (sys)

ν_e signal @ $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2, \sin^2 2\theta_{23} = 1.0$

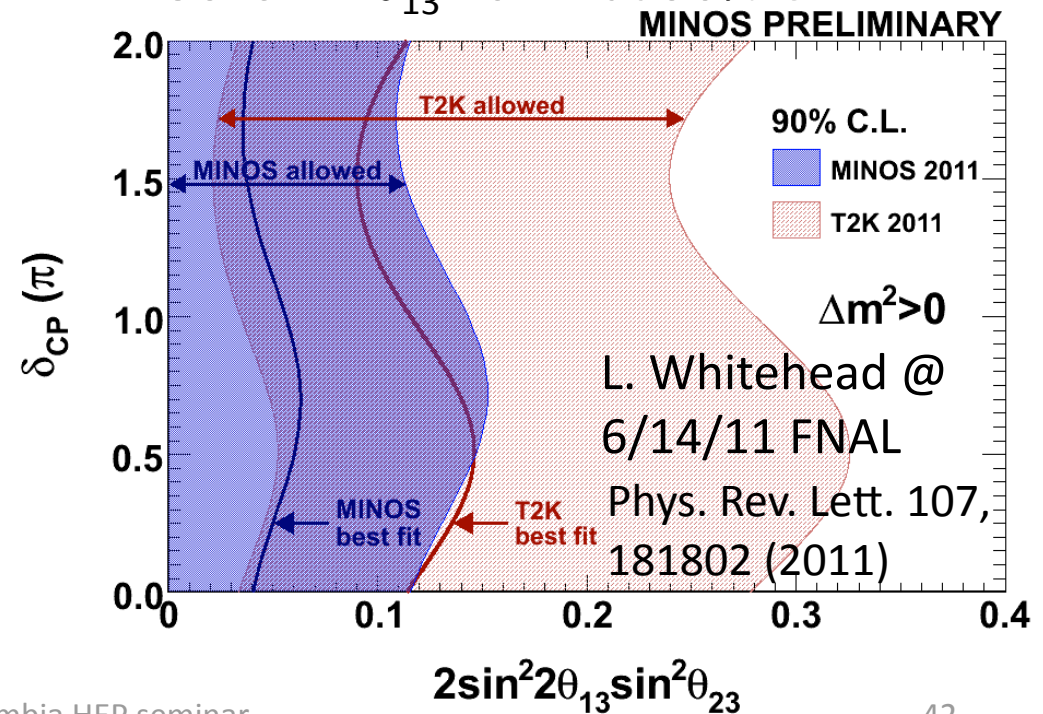
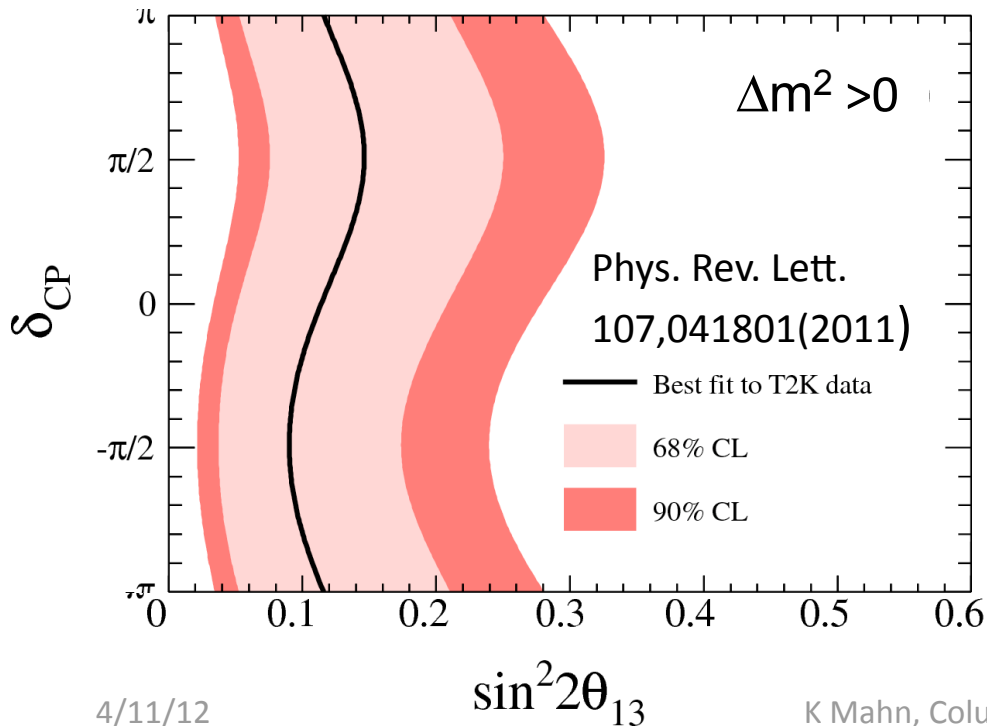
Event predictions normalized by ND280

Uncertainties	ν_e bkrd	ν_e sig+bkrd
ν flux	$\pm 8.5\%$	$\pm 8.5\%$
ν interactions	$\pm 14.0\%$	$\pm 10.5\%$
Near detector	+5.6 -5.2%	+5.6 -5.2%
Far detector	$\pm 14.7\%$	$\pm 9.4\%$
Total	+22.8 -22.7%	+17.6 -17.5%

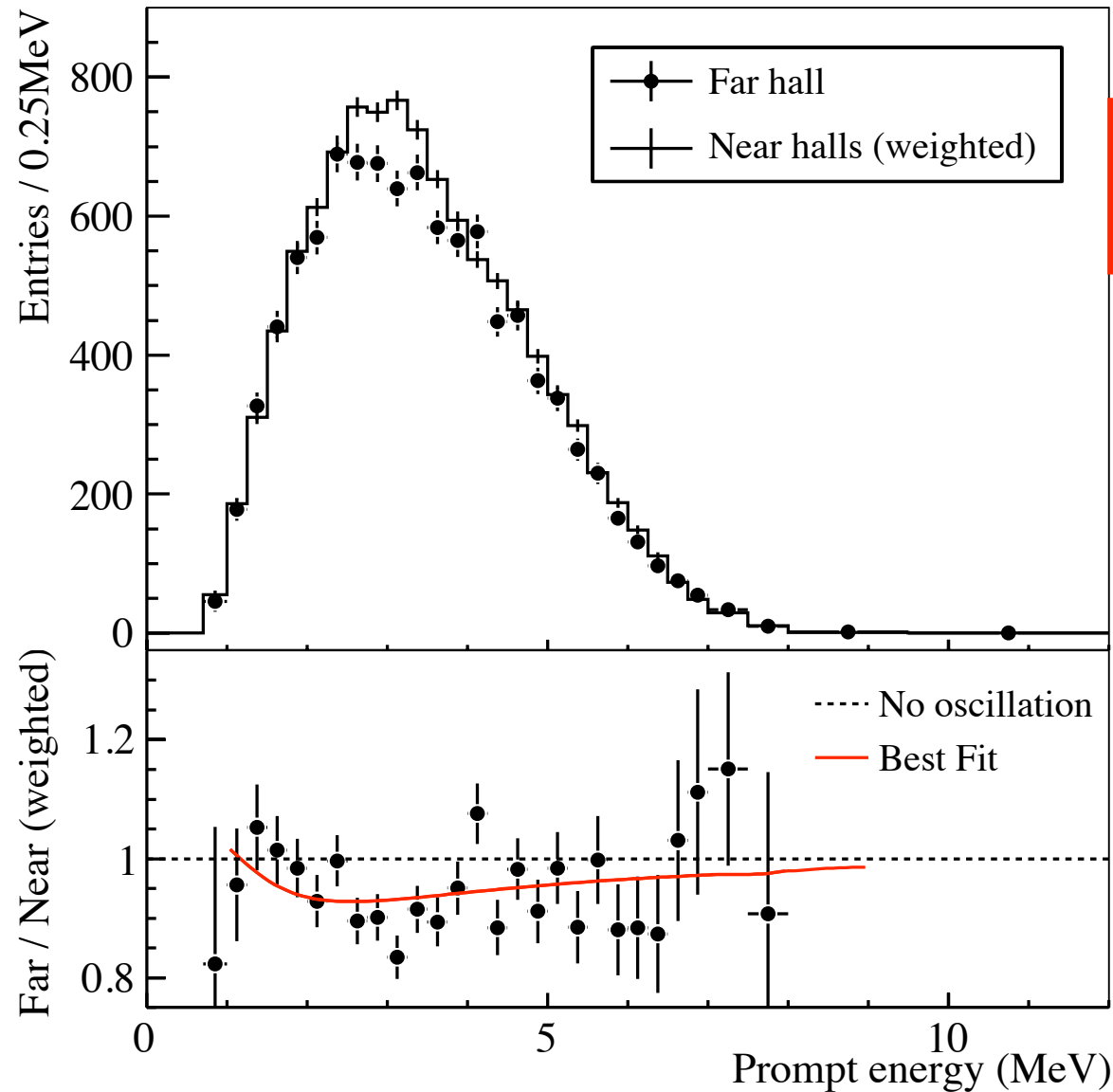
ν_e appearance results



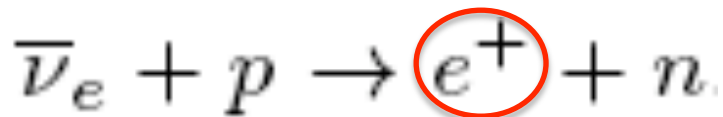
- 6 candidate events observed for background of 1.49 ± 0.34
- Probability to see 6 events or more for $\sin^2 2\theta_{13} = 0$ is 0.007 (2.5σ equivalent)
- For $|\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{ eV}^2$; $\sin^2 2\theta_{23} = 1$
Best fit: $\sin^2 2\theta_{13} = 0.11$
 $0.03 < \sin^2 2\theta_{13} < 0.28$ at 90% C.L.
- Recent results are consistent with T2K:
MINOS: $\sin^2 2\theta_{13} < 0.12$ at 90% C.L.



Results from reactor experiments



arXiv:1203.1669v1, submitted to PRL



$\bar{\nu}_e$ disappearance:

$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

- Double Chooz:
Dec 2011, arXiv:1112.6353
 $0.017 < \sin^2 2\theta_{13} < 0.16$ at 90% C.L.
- Daya Bay (right)
Mar 2012, arXiv:1203.1669v1
 $\sin^2 2\theta_{13} = 0.092$
 $\pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
- RENO:
April 2012
 $\sin^2 2\theta_{13} = 0.103$
 $\pm 0.013(\text{stat}) \pm 0.011(\text{syst})$

Evidence for Non-zero θ_{13}

Implications of a large θ_{13}

Long baseline experiments depend on δ_{CP} and θ_{13} :

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

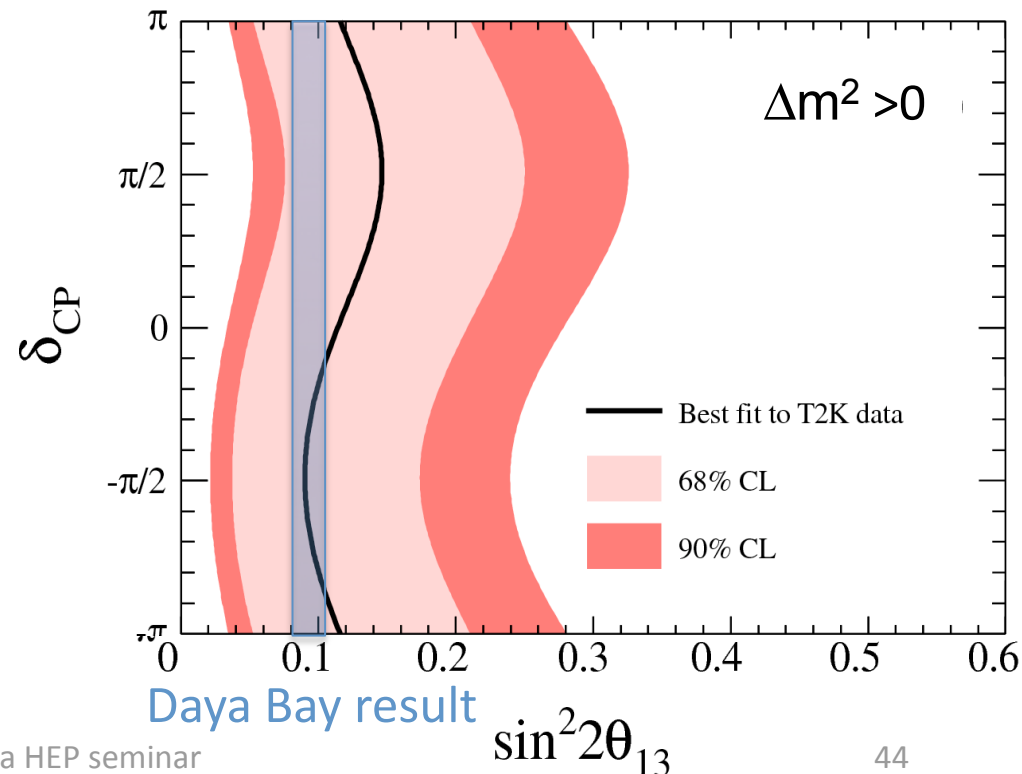
$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \left(\frac{\Delta m_{31}^2 L}{4E} \right) \quad \text{neglecting matter effects and mass hierarchy}$$

$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \left(\frac{\Delta m_{31}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Reactor experiments are pure measurements of θ_{13} :

$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

- Comparisons between long baseline experiments and reactor experiments can eventually constrain values of δ_{CP}



Implications of a large θ_{13}

Long baseline experiments depend on δ_{CP} and θ_{13} :

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \left(\frac{\Delta m_{31}^2 L}{4E} \right) \quad \text{neglecting matter effects and mass hierarchy}$$

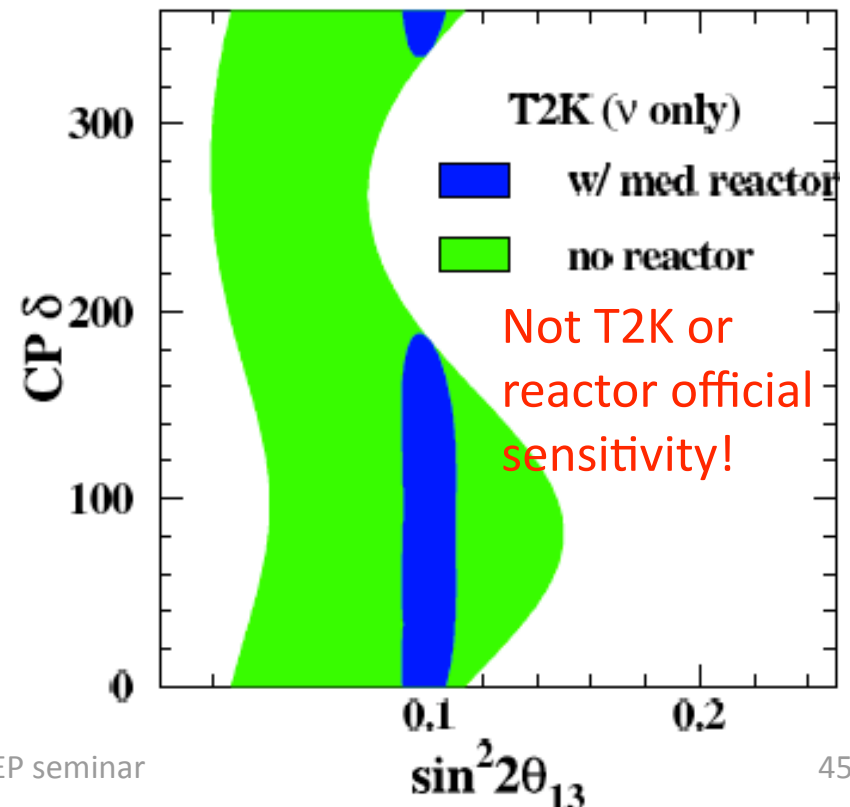
$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \left(\frac{\Delta m_{31}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Reactor experiments are pure measurements of θ_{13} :

$\delta_{CP}=90\text{deg}$

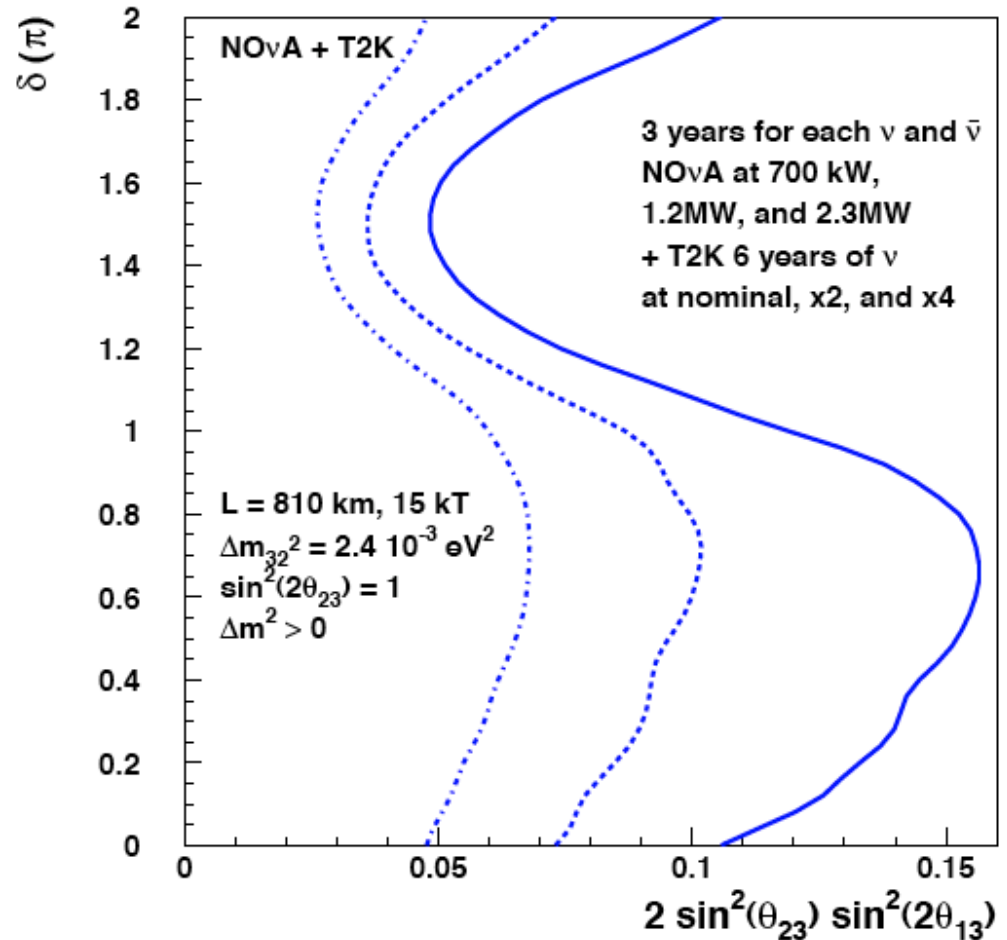
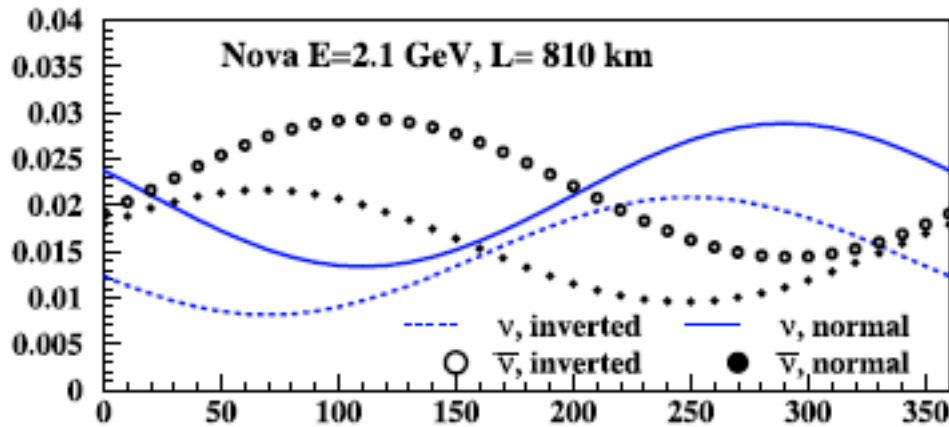
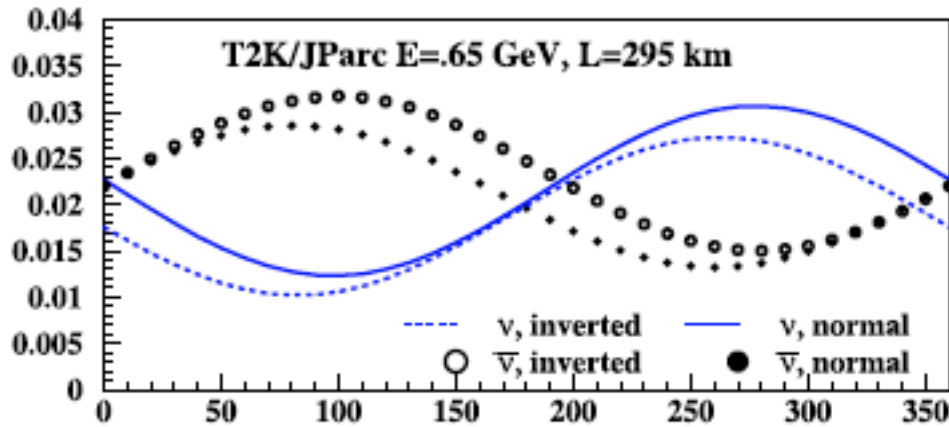
$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

- Comparisons between long baseline experiments and reactor experiments can eventually constrain values of δ_{CP}
Int. J.Mod. Phys. A 21, 3825 (2006), hep-ex/0409028



Implications of a large θ_{13}

- Combinations between long baseline experiments at different baselines is also sensitive to mass hierarchy and δ_{CP}
- Atmospheric neutrino measurements also sensitive as well (i.e. Hyper-K LOI)



Oscillation probability comparison including matter effects (assumes $\sin^2 2\theta_{13} = 0.05$)
 Int. J.Mod. Phys. A 21, 3825 (2006), hep-ex/0409028

G. Feldman, for Nova experiment
 arXiv:hep-ex/0503053

Searches for CP violation

Long baseline exp'ts can extract δ_{CP} by comparing ν_e appearance to $\bar{\nu}_e$ appearance:

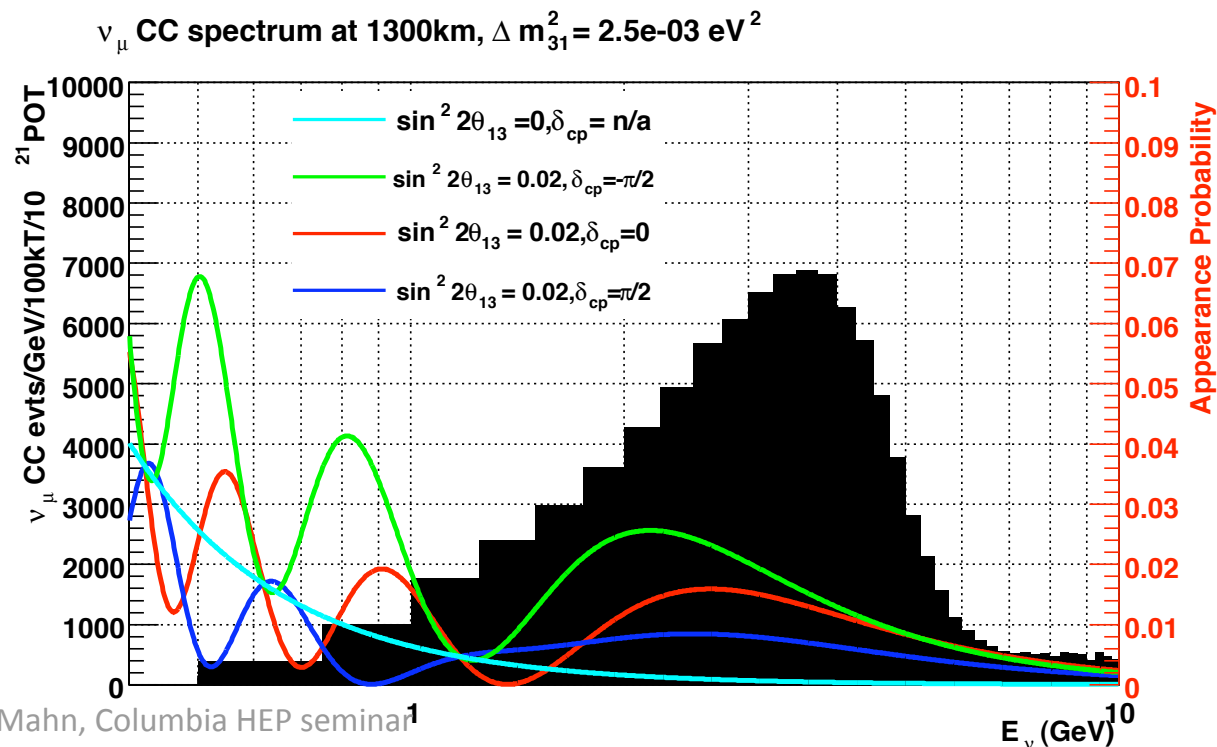
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

Can produce a predominantly antineutrino beam by switching polarity of magnetic focusing horns to focus π^- instead of π^+

Future long baseline experiments will require very intense sources of neutrinos and very large far detectors to make

a determination of δ_{CP} at $>3\sigma$

- LBNE (right)
proposal: arXiv:1110.6249
 - Hyper-Kamiokande
proposal: arXiv:1109.3262
 - LAGUNA, Daedalus, and more
- Large θ_{13} increases signal,
but decreases A_{CP}



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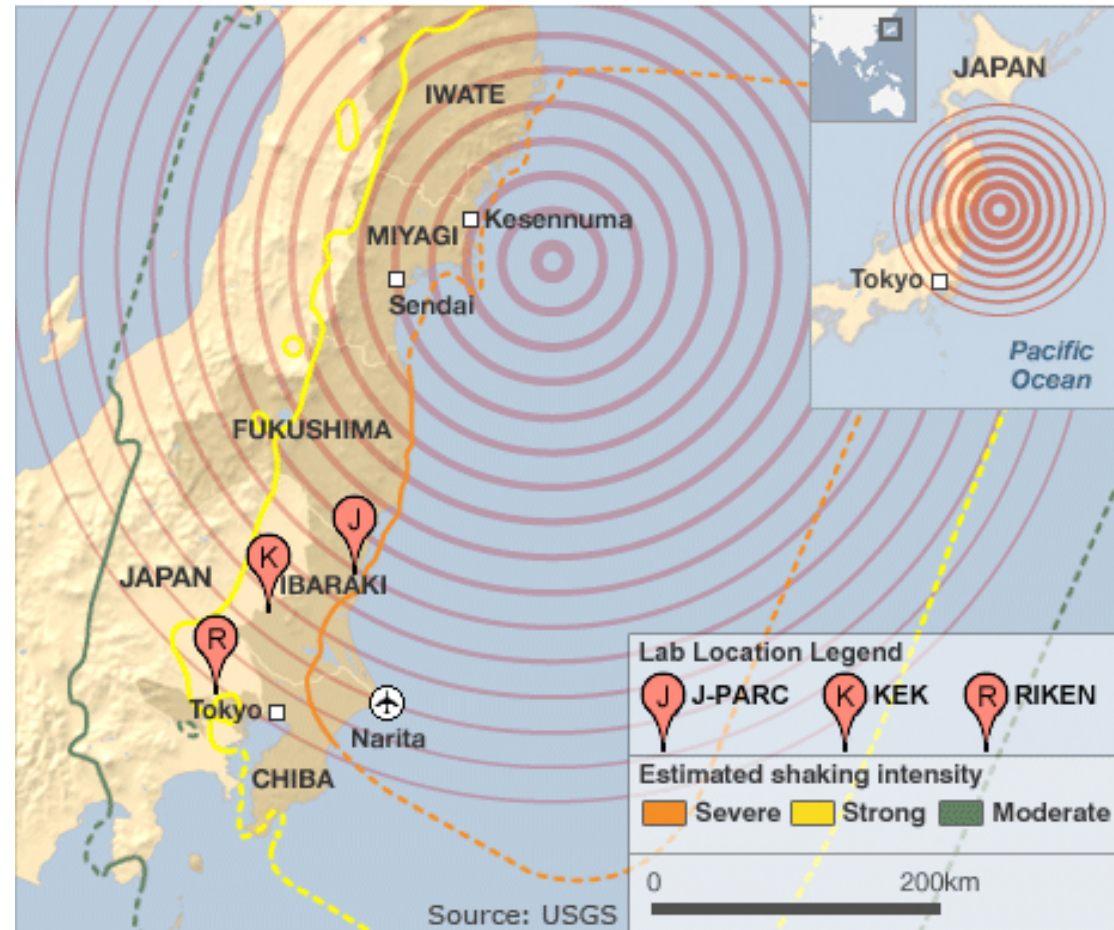
Earthquake and T2K

On March 11th, 2011, Japan experienced a severe earthquake followed by a tsunami

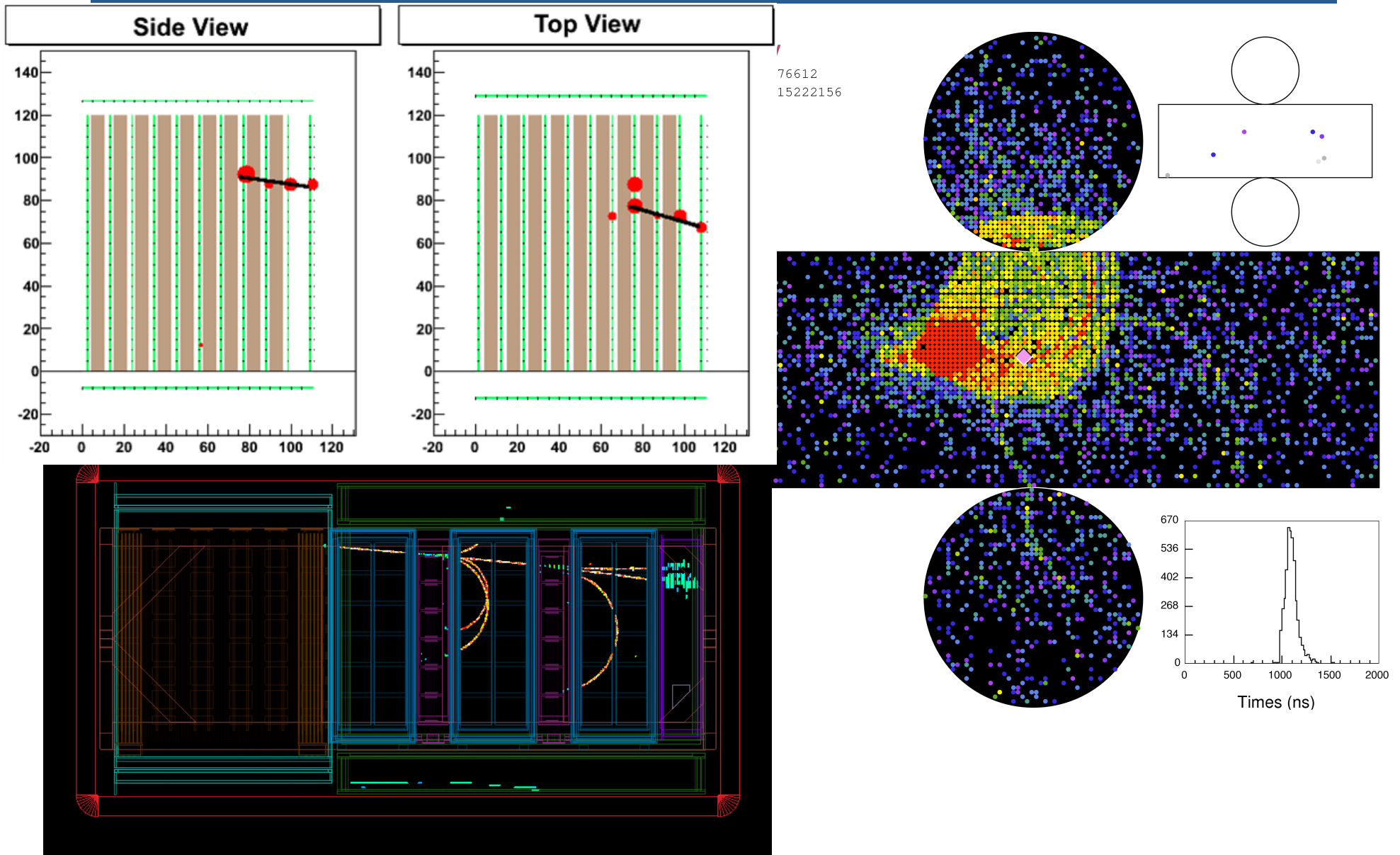
- Magnitude 9 earthquake on Richter scale, magnitude 6+ at J-PARC
- The tsunami did not reach J-PARC
- Accelerator was not operating (maintenance day)
- No reported injuries to T2K collaborators or J-PARC employees

T2K experiment status:

- Repairs made to infrastructure and accelerator
- Minor repairs and recommissioning of J-PARC near detectors successful
- First beam in late Dec 2011
- T2K run scheduled for ~4 months prior to summer 2012 shutdown



First neutrinos post-earthquake!



Enormous amount of work by collaborators, labs (KEK, J-PARC) and funding agencies) to make this happen, to which we are very grateful

Improvements to the oscillation analysis

Neutrino flux:

- NA61 results with K production
- NA61 results with replica target

Neutrino interactions:

- Add newer external data results
- e/π scattering data for FSI model

Error source	ν_e bkrd	ν_μ signal $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$ $\sin^2 2\theta_{23} = 1.0$
ν flux	± 8.5	± 4.8
ν interactions	± 14.0	+8.3 -8.1
Near detector	+5.6 -5.2	+6.2 -5.9
Far detector	± 14.7	± 10.3
Total	+22.8 -22.7	+15.4 -15.1

ND280 (near) detector:

- Include CC ν_μ spectrum information
- Improved CC ν_e measurement with ECal information; POD HE ν_e
- CCQE, CC π^+ , NC π^0 cross section measurements; O vs. C targets

Super-K (far) detector:

- Improved selection cuts, reconstruction for background separation
- Improved detector uncertainties and calibration techniques

▪ Include spectrum information

Summary

The T2K experiment is designed to make precision measurements of:

- ν_μ disappearance ($\Delta m^2_{32}, \theta_{23}$)
- ν_e appearance (θ_{13})

With dataset prior to the earthquake (2% of design POT)

- Preliminary ν_μ disappearance results are inconsistent with no-oscillation at 4.5σ and consistent with previous experiments (MINOS, Super-K, K2K)
- 6 candidate ν_e events were observed with expected background is 1.49 ± 0.34 (2.5σ equivalent indication of θ_{13}) and consistent with recent results from MINOS, Double Chooz, Daya Bay

T2K has resumed running to confirm the observation of non-zero θ_{13}

- Run period of ~ 4 months prior to 2012 summer shutdown of accelerator
- Improvements to all aspects of the analysis

Observation of large, non-zero θ_{13} key to future experiments which will probe CP violation in the neutrino sector. Exciting time to be in neutrino physics!

Backup slides

Pictures of JPARC, May 2011

<http://www.kek.jp/intra-e/Introduction/column/110509map.html>

Map of the damages at Tokai Campus (J-PARC)

- ① Linac
- ② 3GeV Synchrotron
- ③ 50GeV Synchrotron
- ④ Main Control Room
- ⑤ Material and Life Sciences Experimental Facility
- ⑥ 3 NBT
- ⑦ Neutrino Experimental Facility
- ⑧ Hadron Experimental Facility
- ⑨ Accelerator-Driven Transmutation Experimental Facility



3 GeV synchrotron power station



Road near 3 GeV RCS



LINAC



Neutrino Hall AC

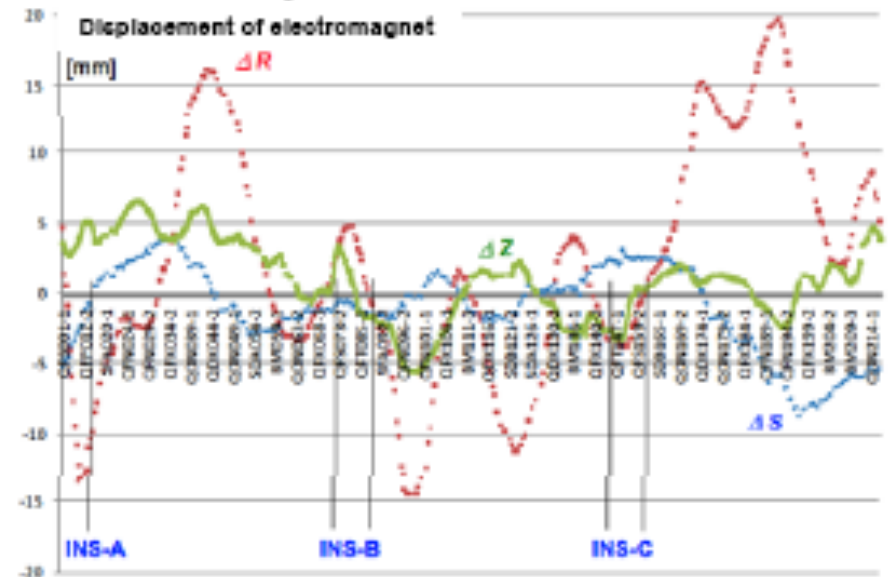
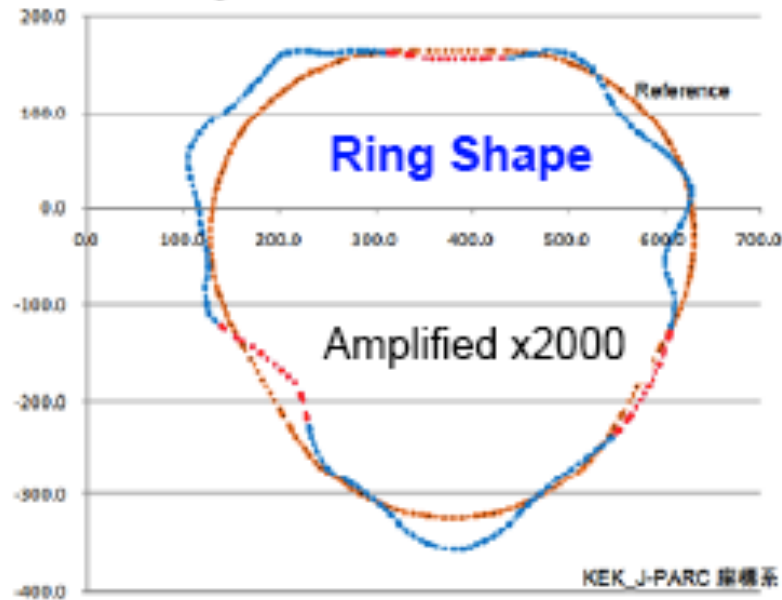


Neutrino beam dump

Pictures of JPARC, July 2011

<http://j-parc.jp/en/topics/2011/en.html>

Preliminary Results of Circumference Measurement by Laser Trucker



- It appeared there was a large misalignment in both horizontal and vertical directions.
- ~20 electromagnet mounts shifted more than a limit of simple adjustment.
- All electromangets will be realigned. Three teams will be done between August and October.



Road near 3 GeV RCS



Neutrino beam dump

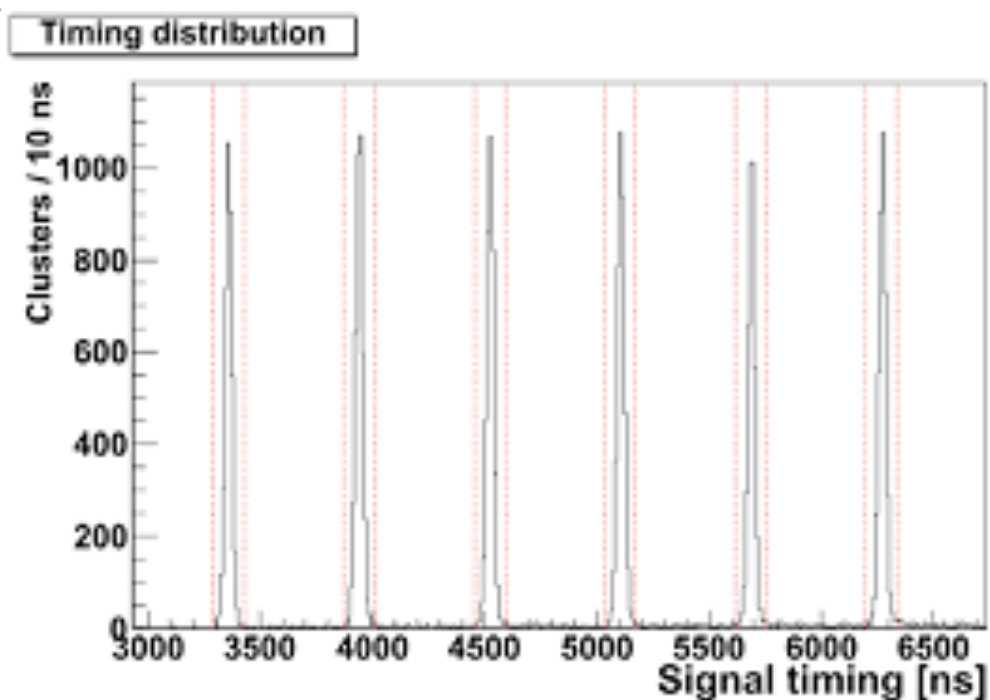
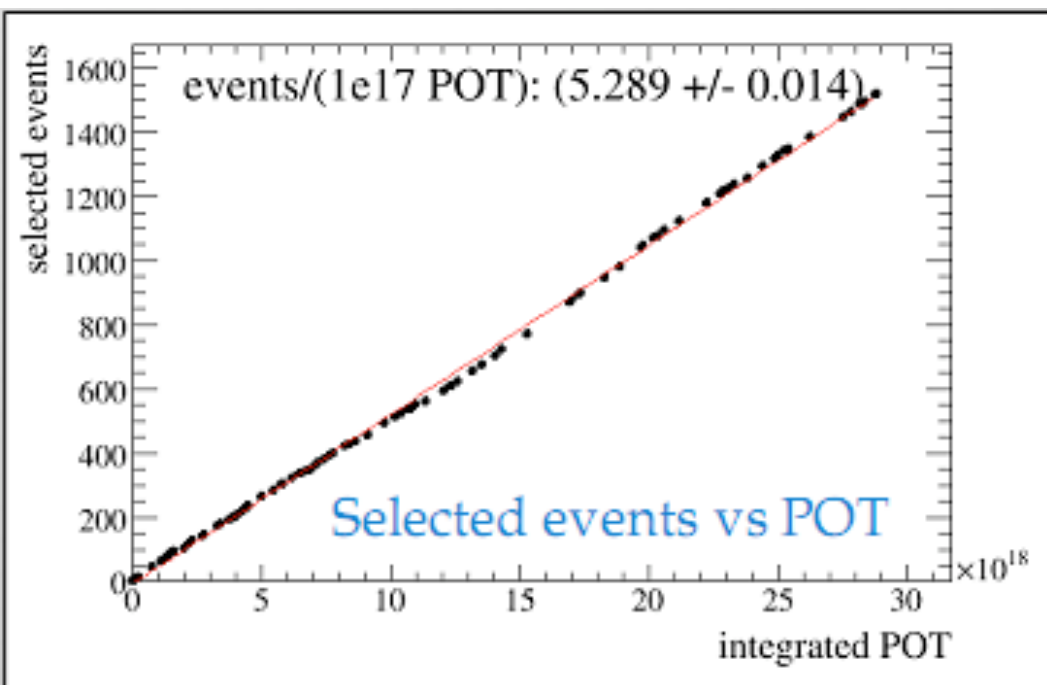
ND280 performance

Low rate of broken channels

Events / POT stable

Timing consistent with beam (FGD)

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



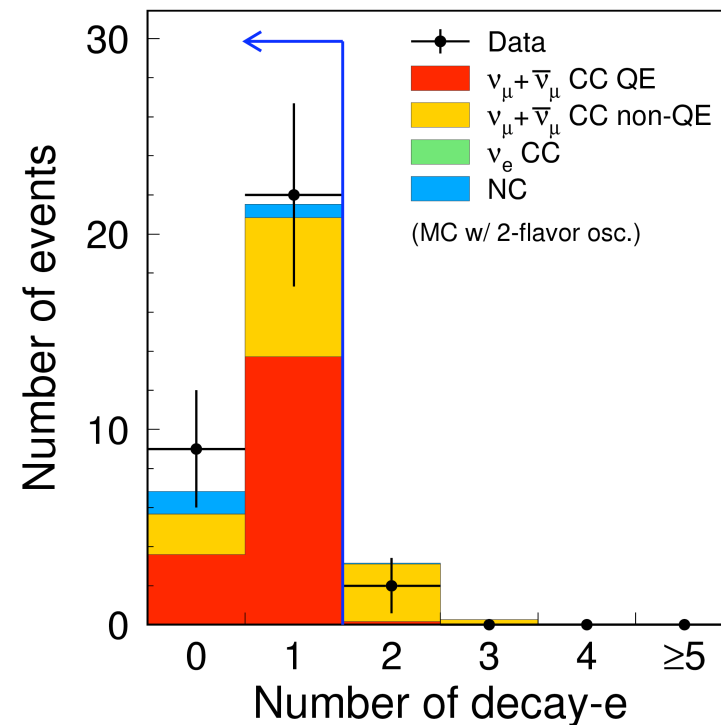
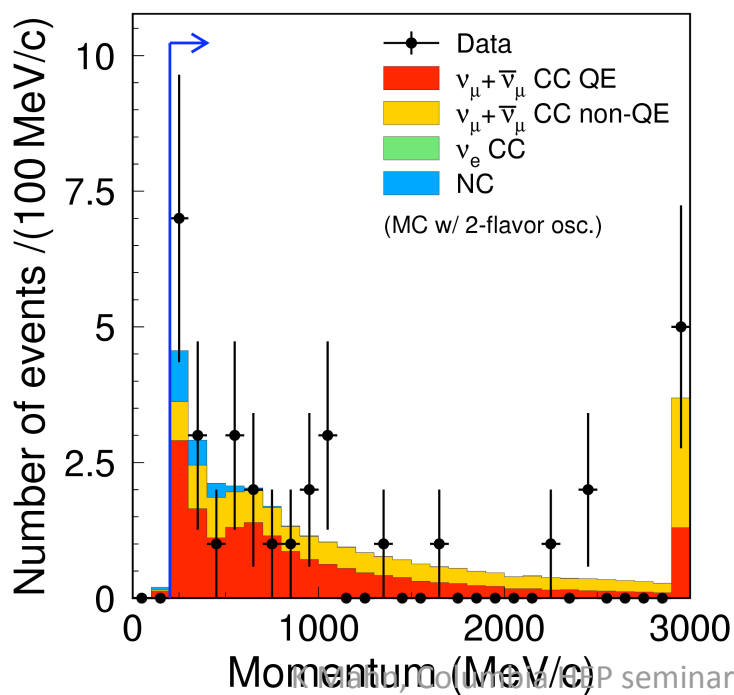
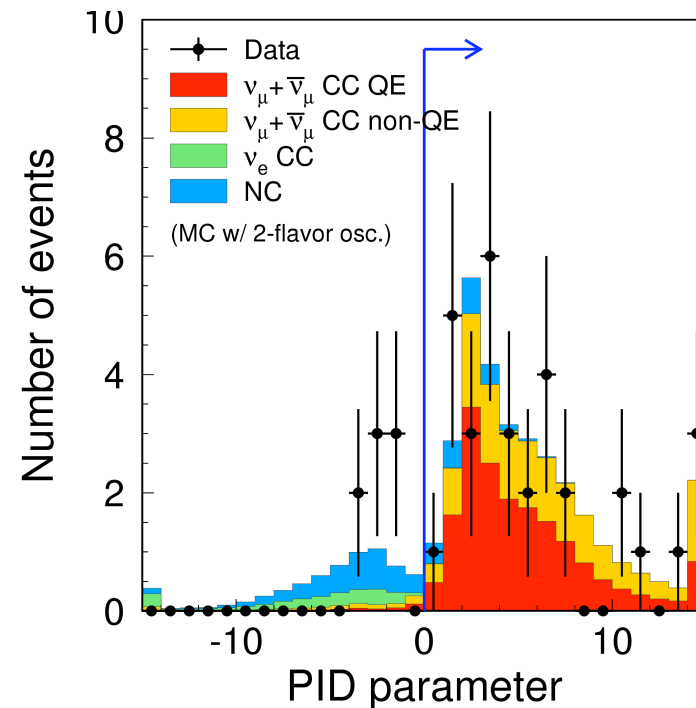
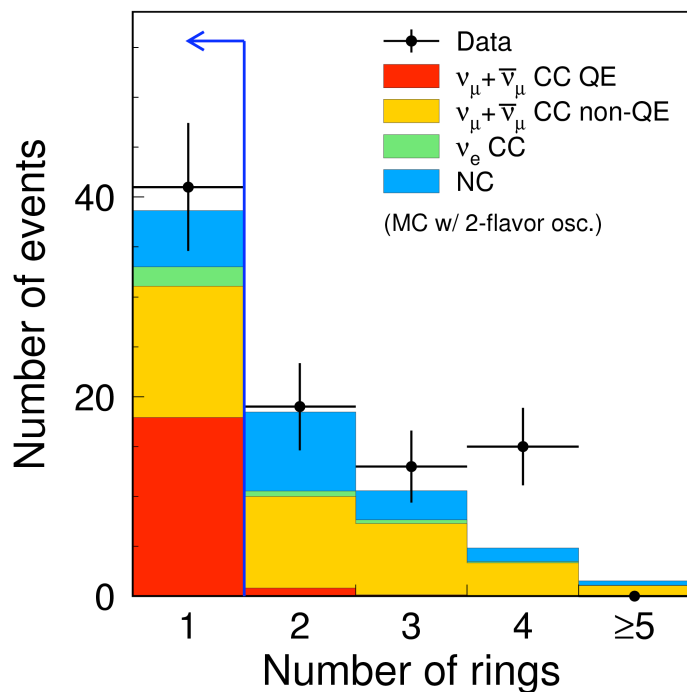
ν_μ selection

Single-ring

μ -like

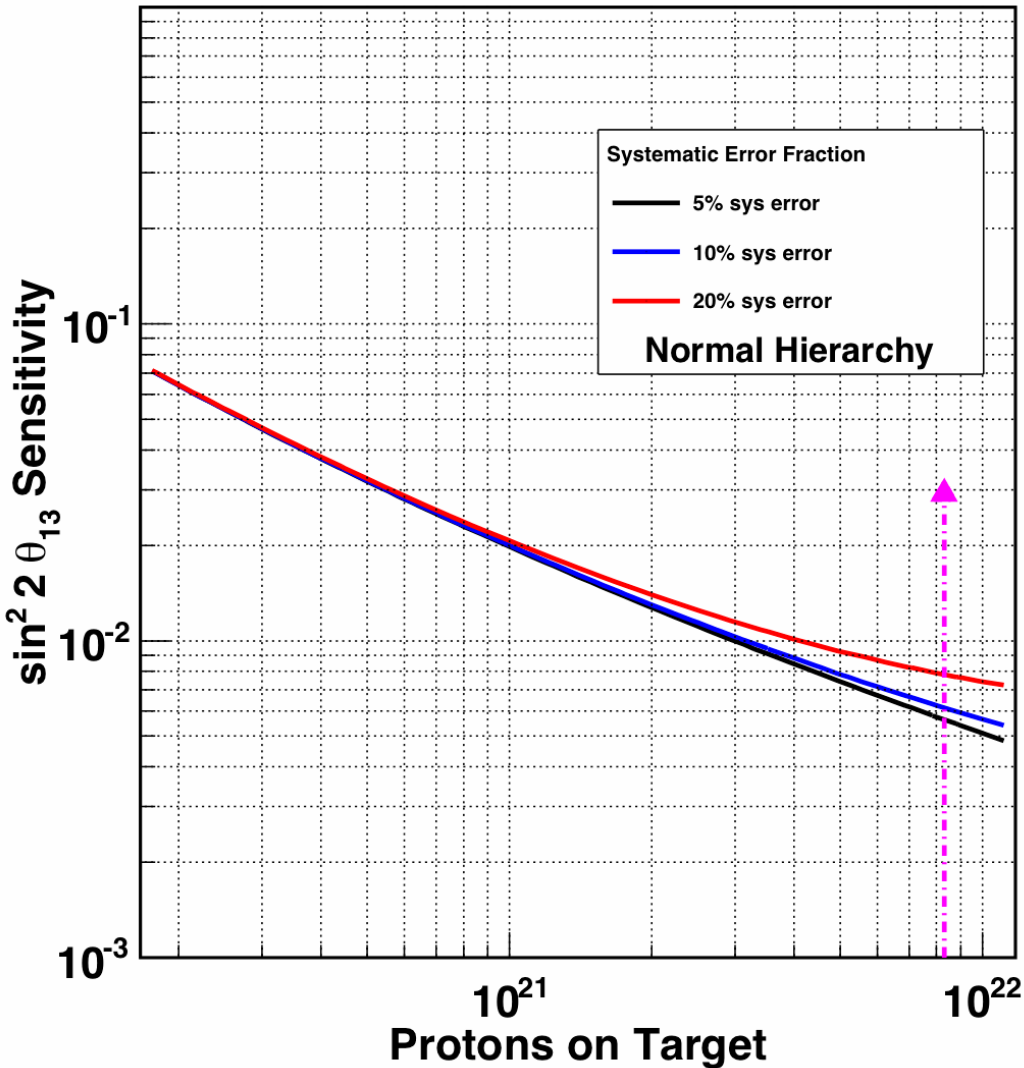
$P_\mu > 200$ MeV/c

$N(\text{decay-e}) \leq 1$

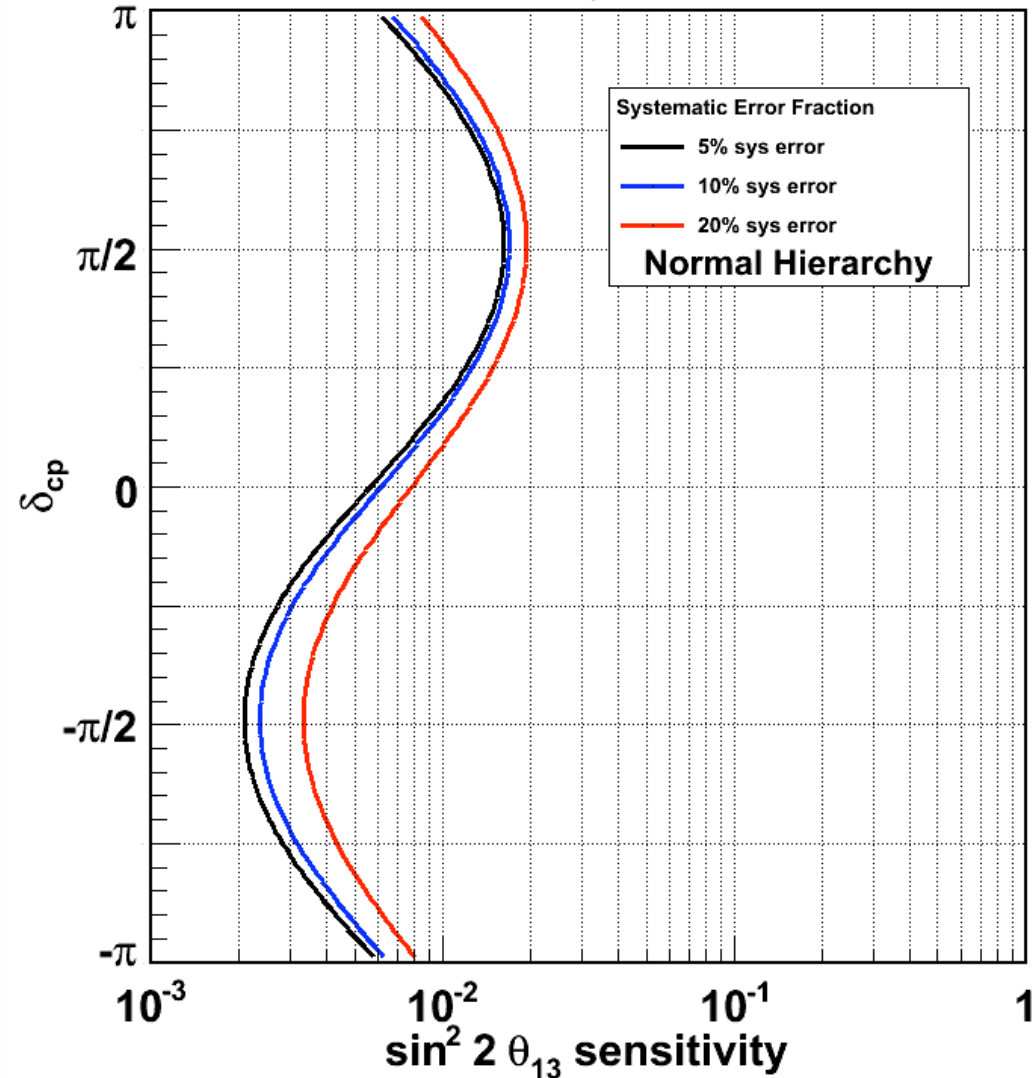


Future ν_e appearance sensitivity

90% CL θ_{13} Sensitivity



90% CL θ_{13} Sensitivity

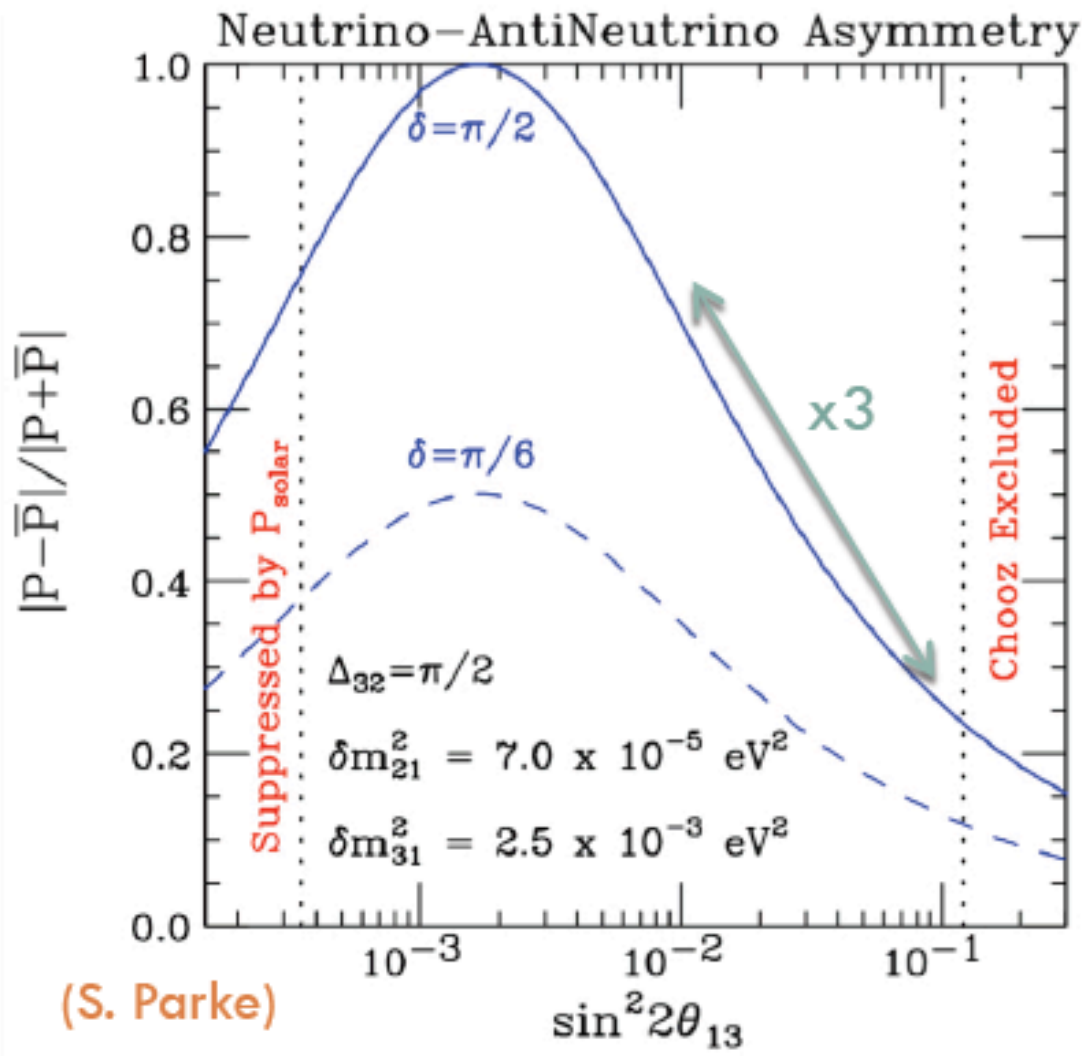


Pink line is final POT goal of T2K

Implications of large θ_{13} on future programme

Slide from Sam Zeller's talk (informal discussion at FNAL about T2K results)

<https://indico.fnal.gov/conferenceDisplay.py?confId=4546>



- the asymmetry

$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

is proportional to $\sim 1/\sin\theta_{13}$

- the asymmetry gets smaller as θ_{13} increases

$$\left. \begin{array}{l} \sim 75\% \text{ for } \sin^2 2\theta_{13} = 0.01 \\ \sim 25\% \text{ for } \sin^2 2\theta_{13} = 0.10 \end{array} \right\} \delta_{CP} = \pi/2$$

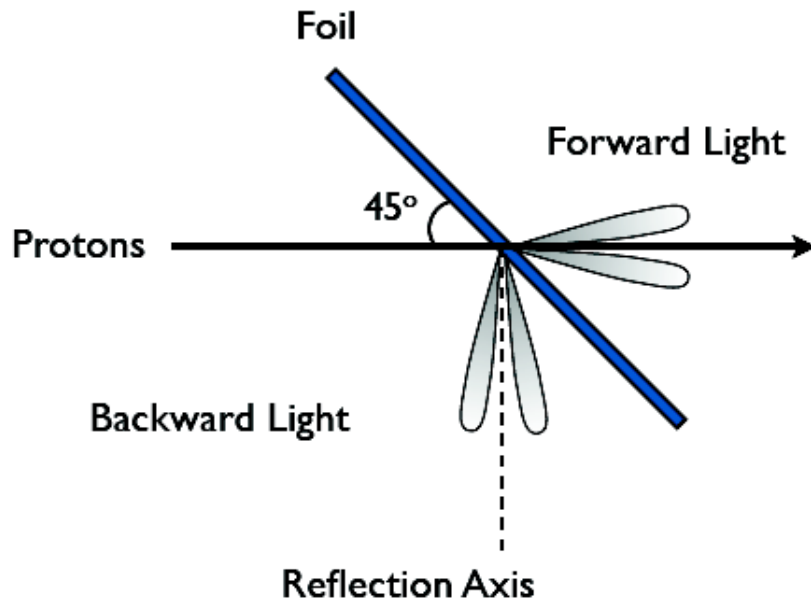
factor ~ 3 reduction in CP asymmetry
(independent of baseline)

- signal rate increases w/ θ_{13}
factor ~ 10 increase from 0.01 to 0.1
so $\times 3$ improvement in stat sig of signal

(ignoring matter effects & backgrounds for now)

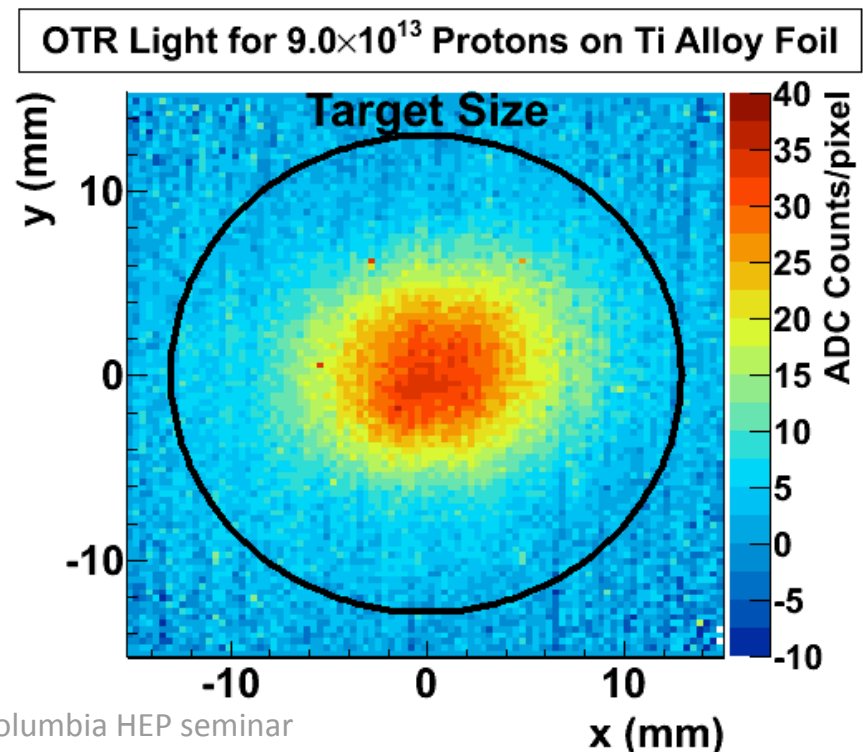
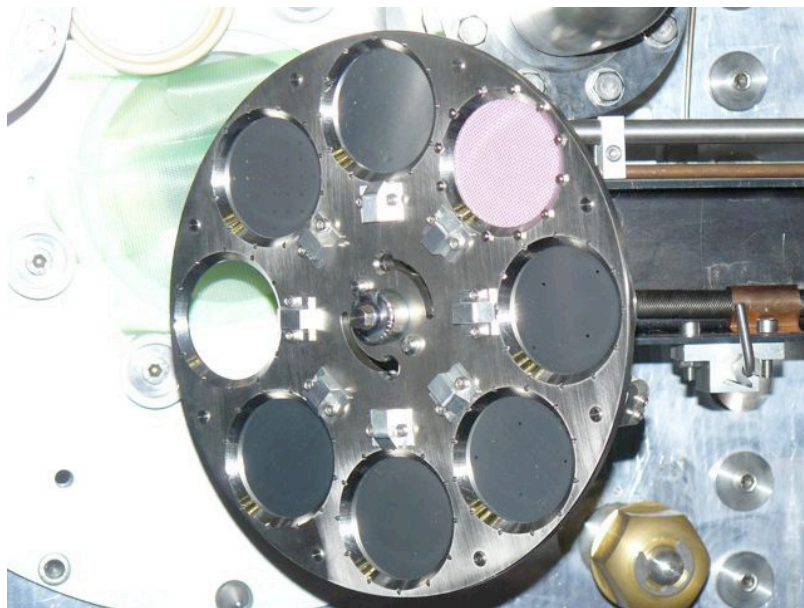
Proton beam monitoring

Multiple beam monitors measure the proton beam on the way to the neutrino target

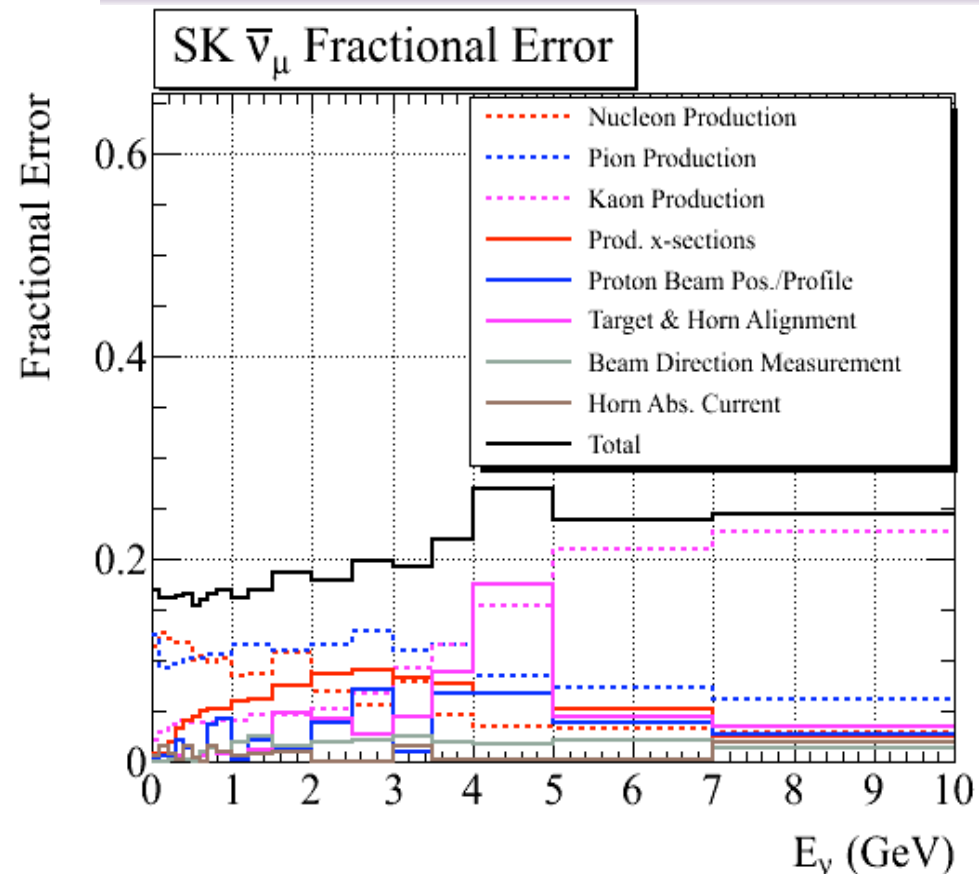
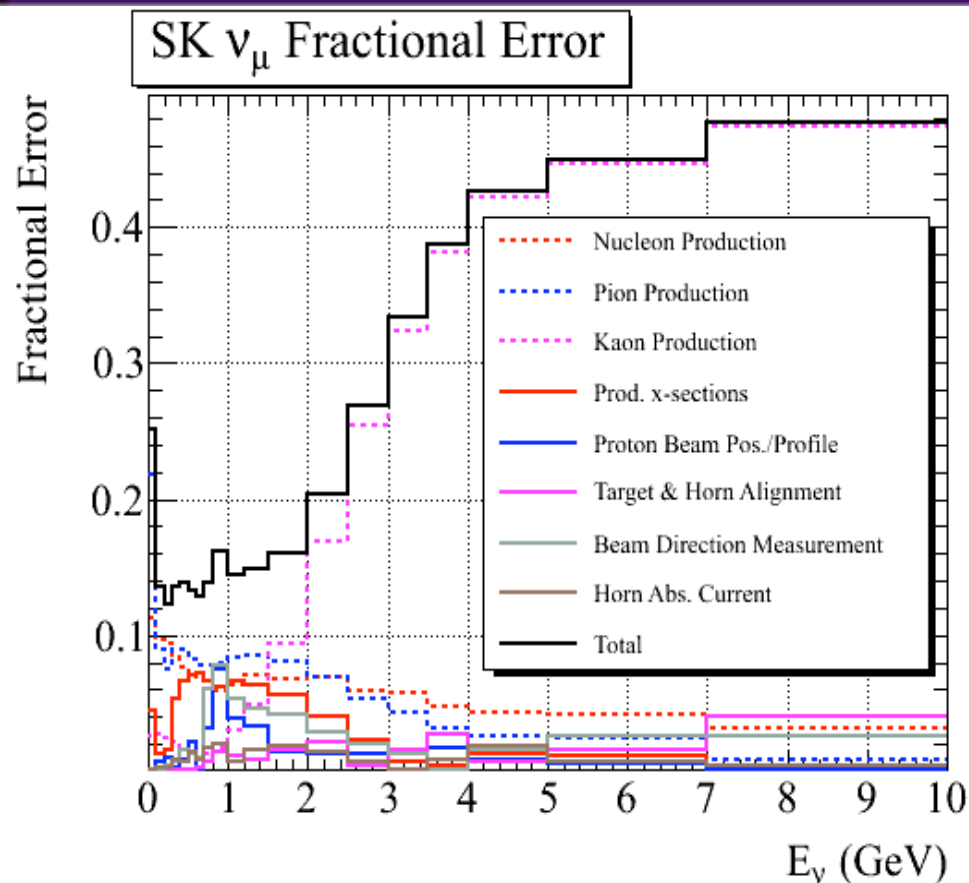


Optical Transition Radiation is produced by the protons as they pass through a thin Ti foil in front of the neutrino target.

The light is emitted perpendicular to the beam direction, and is recorded with a 40mm camera. OTR light is used to determine the beam profile and position on the target.

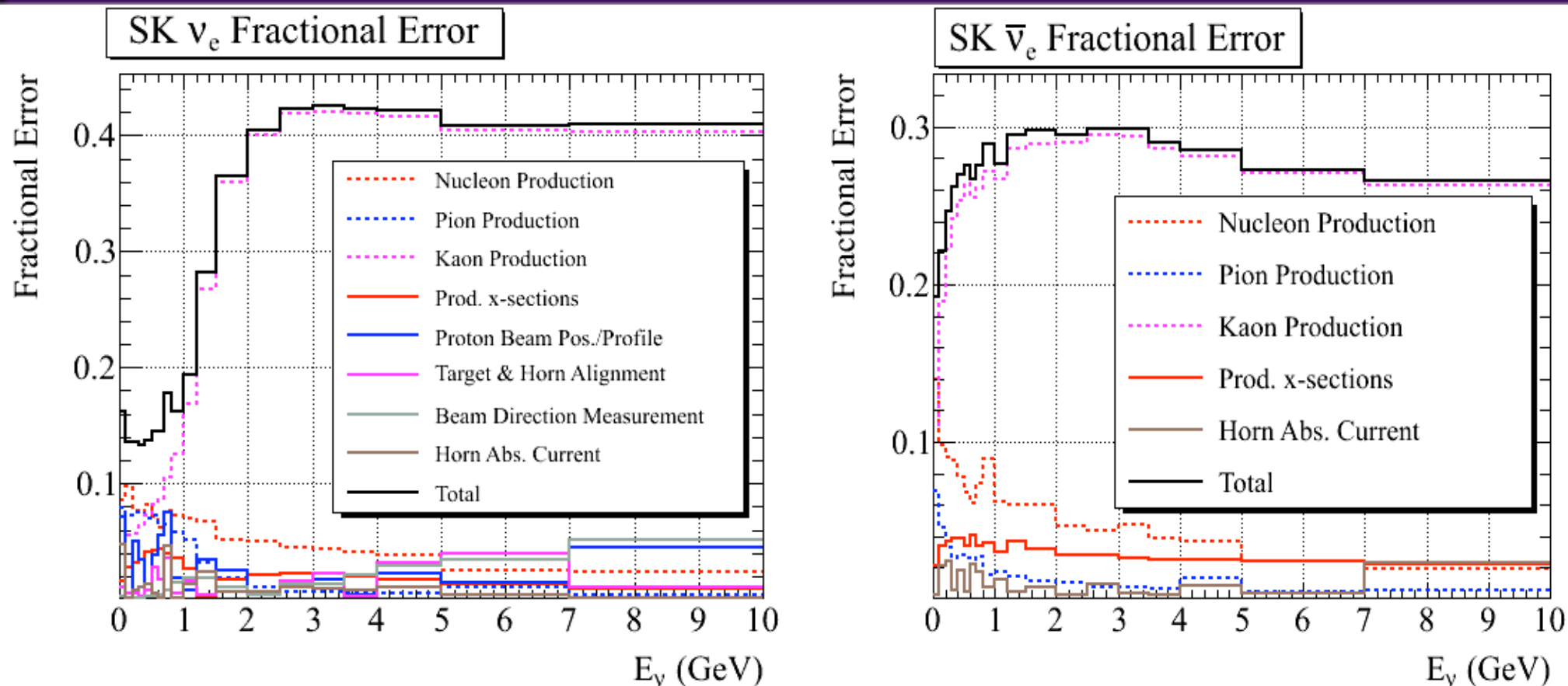


SK Systematic Error Envelopes



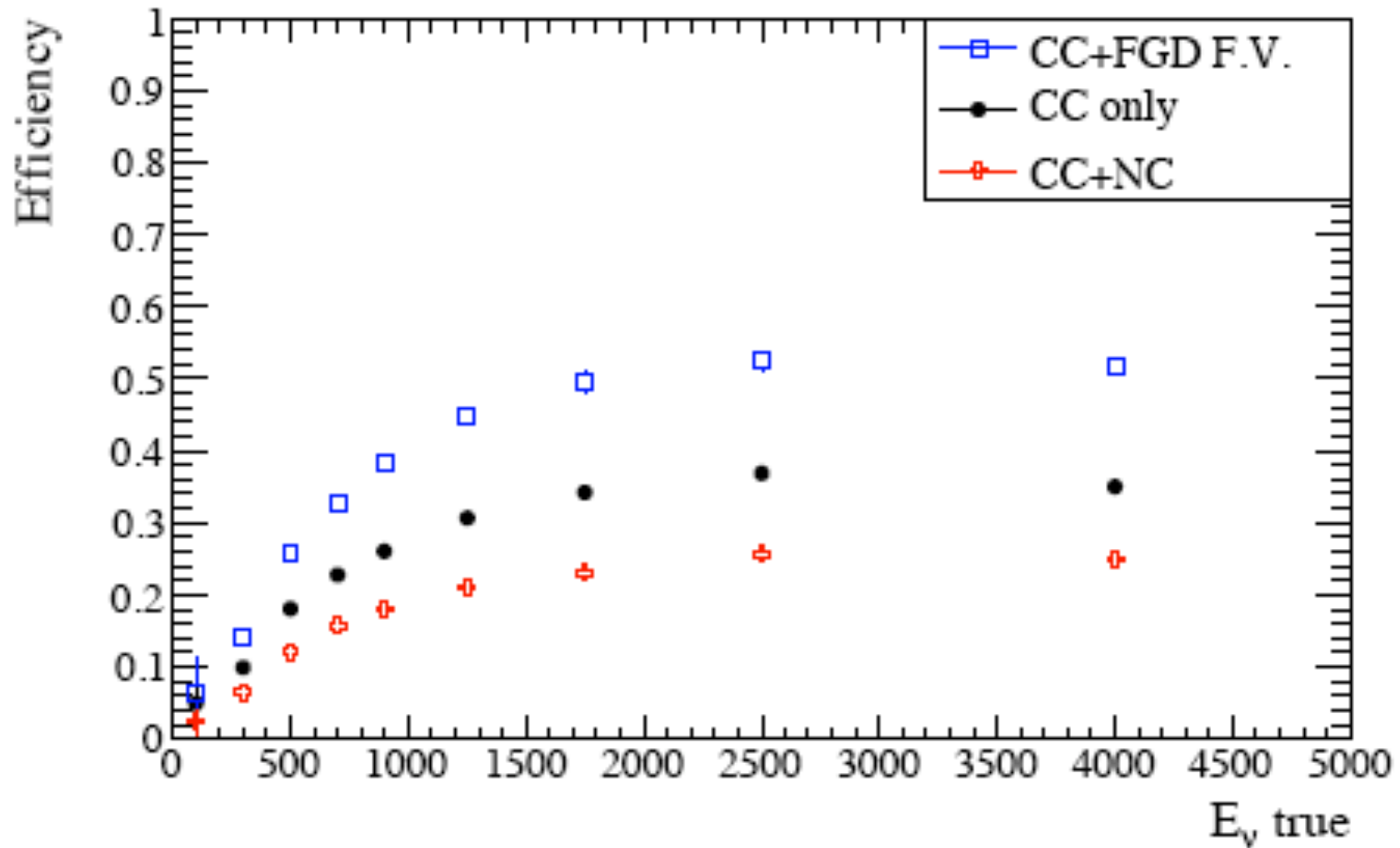
Error envelopes show the fractional error in each neutrino energy bin, but do not show correlations between bins. Error types described on slide 16.

SK Systematic Error Envelopes



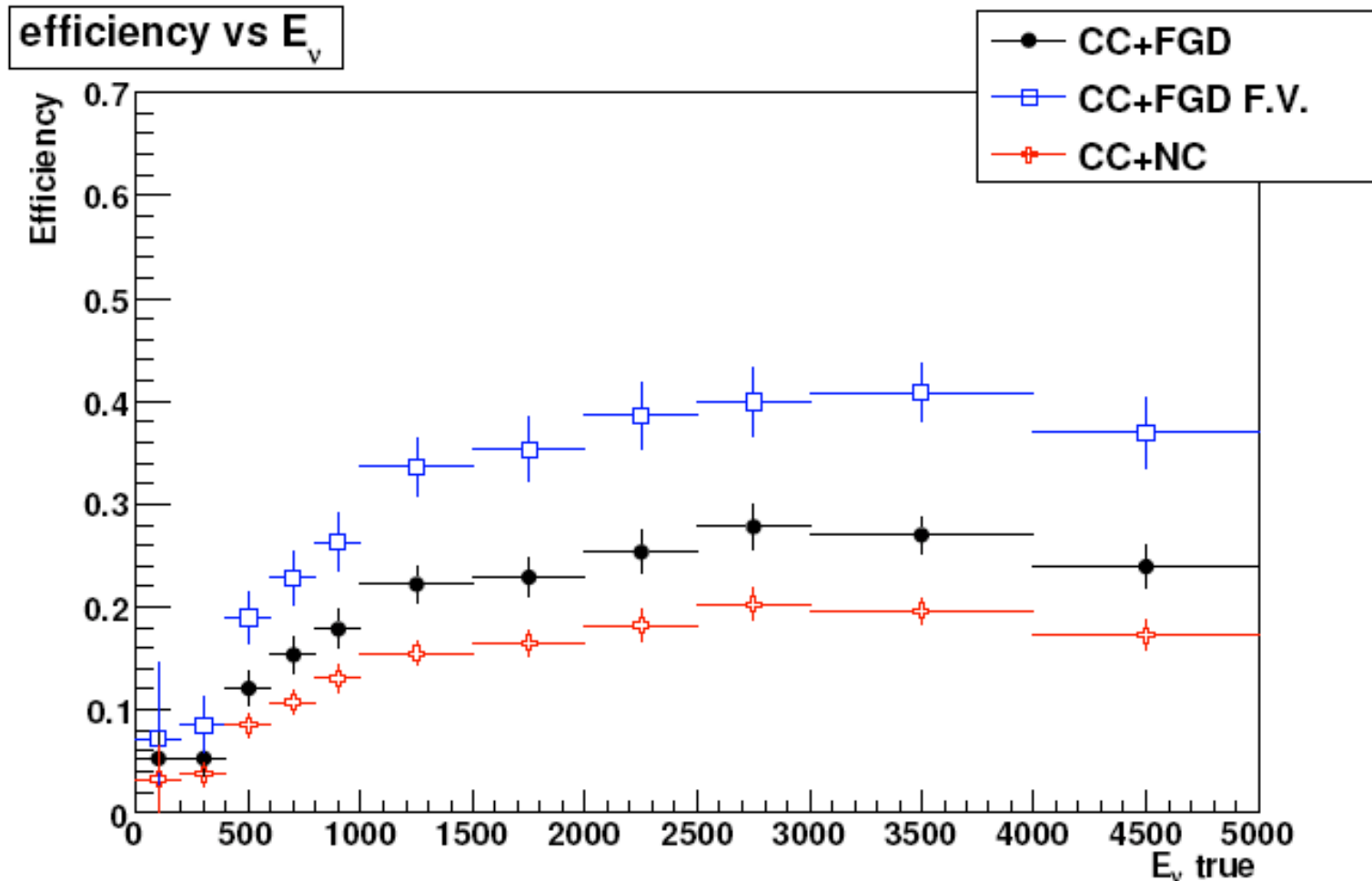
Error envelopes show the fractional error in each neutrino energy bin, but do not show correlations between bins. Error types described on slide 16.

Efficiency of CC ν_μ events



Overall efficiency for CC ν_μ : $38.3 \pm 0.2\%$ within FGD FV

Efficiency of CC ν_e events

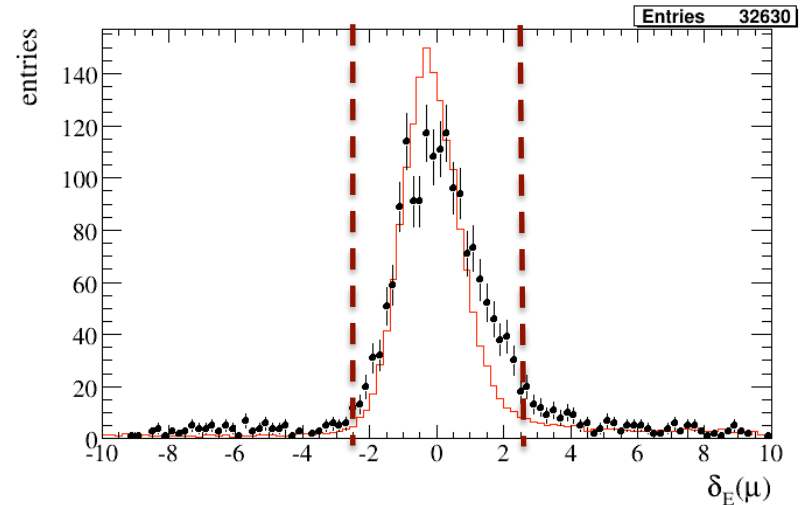
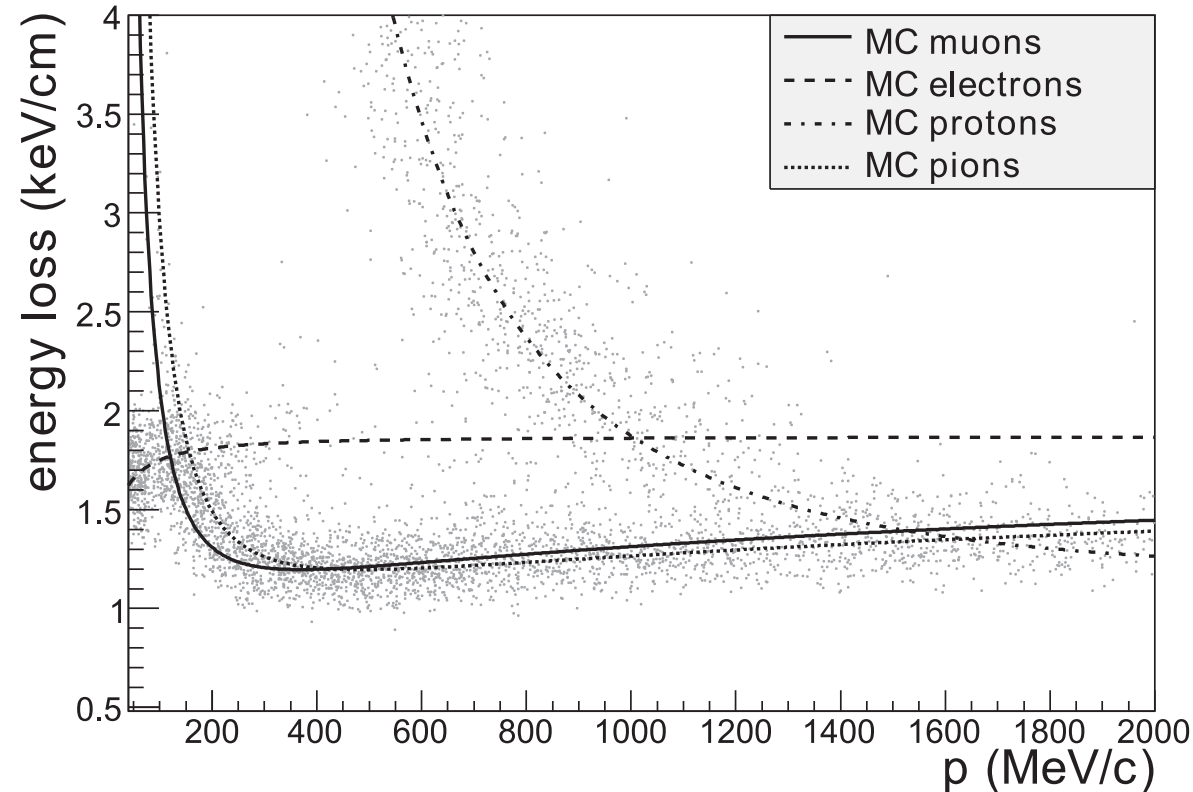


Overall efficiency for CC ν_e : $21.5 \pm 0.6\%$ (<2 GeV, within FGD FV)

Eff diff between ν_e and ν_μ is due to:

- More stringent PID cuts (large mu misID reduction required)
- Large background at low energy from decay e and photons

TPC dE/dx particle ID



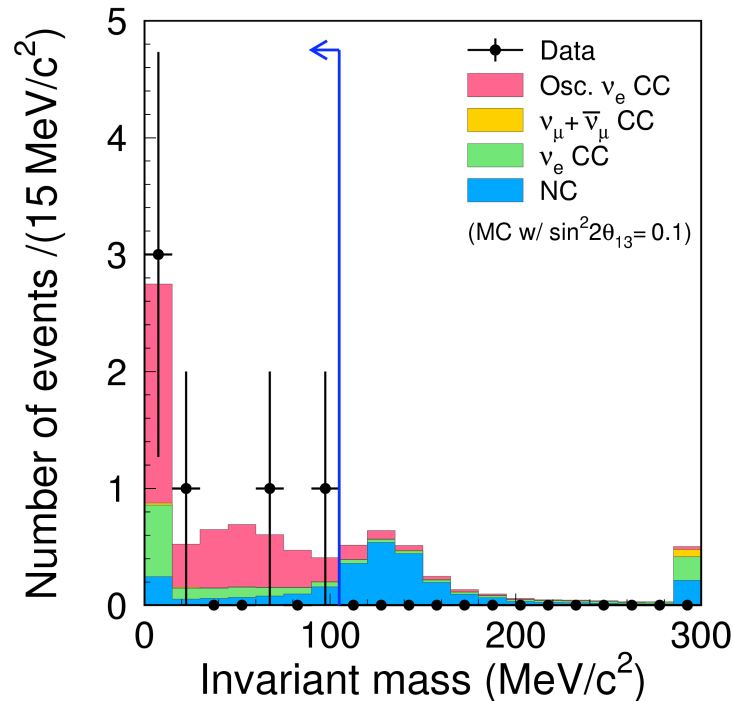
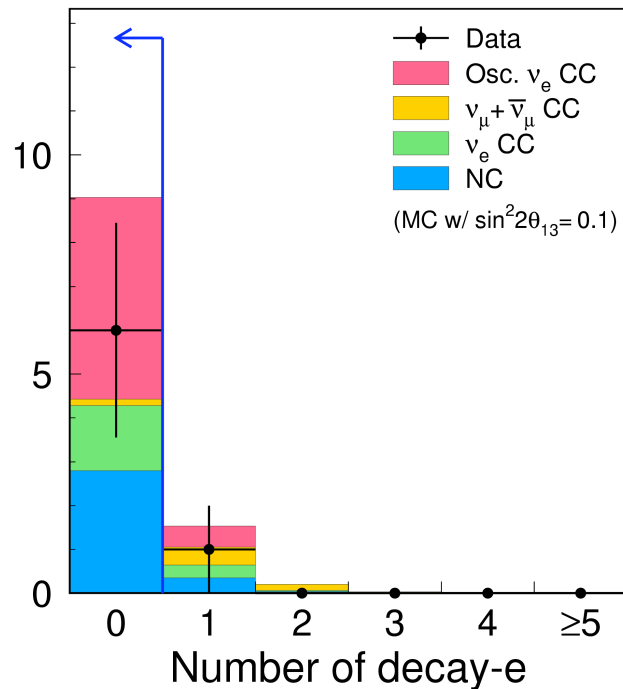
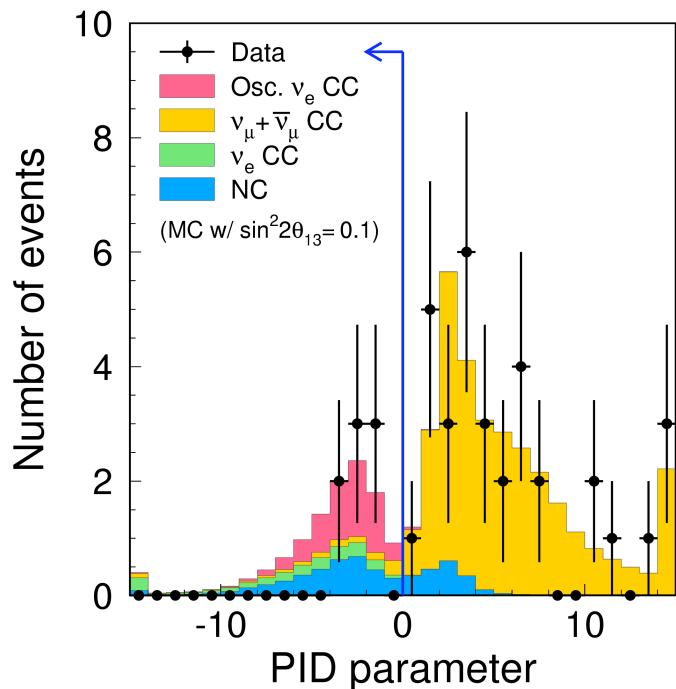
PID "pull" variable

Energy loss of the particle (dE/dx) can be used to separate particle type

dE/dx resolution for MIPs is 8%

Probability for a muon between 0.2 and 1.0 GeV to be identified using dE/dx as an electron is less than 0.2%

ν_e events after cuts



ν_e selection

Visible energy > 100 MeV

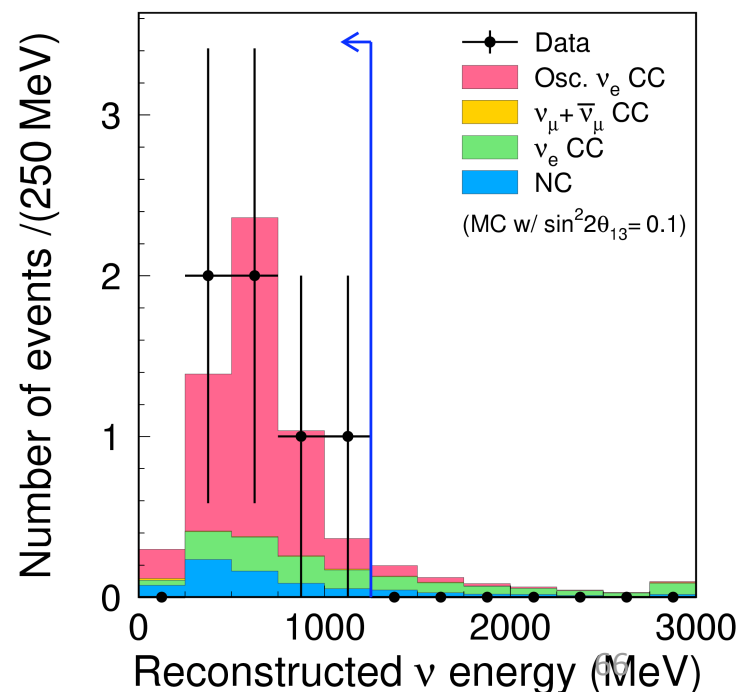
e-like ring

No decay electron

Invariant mass < 105 MeV/c²

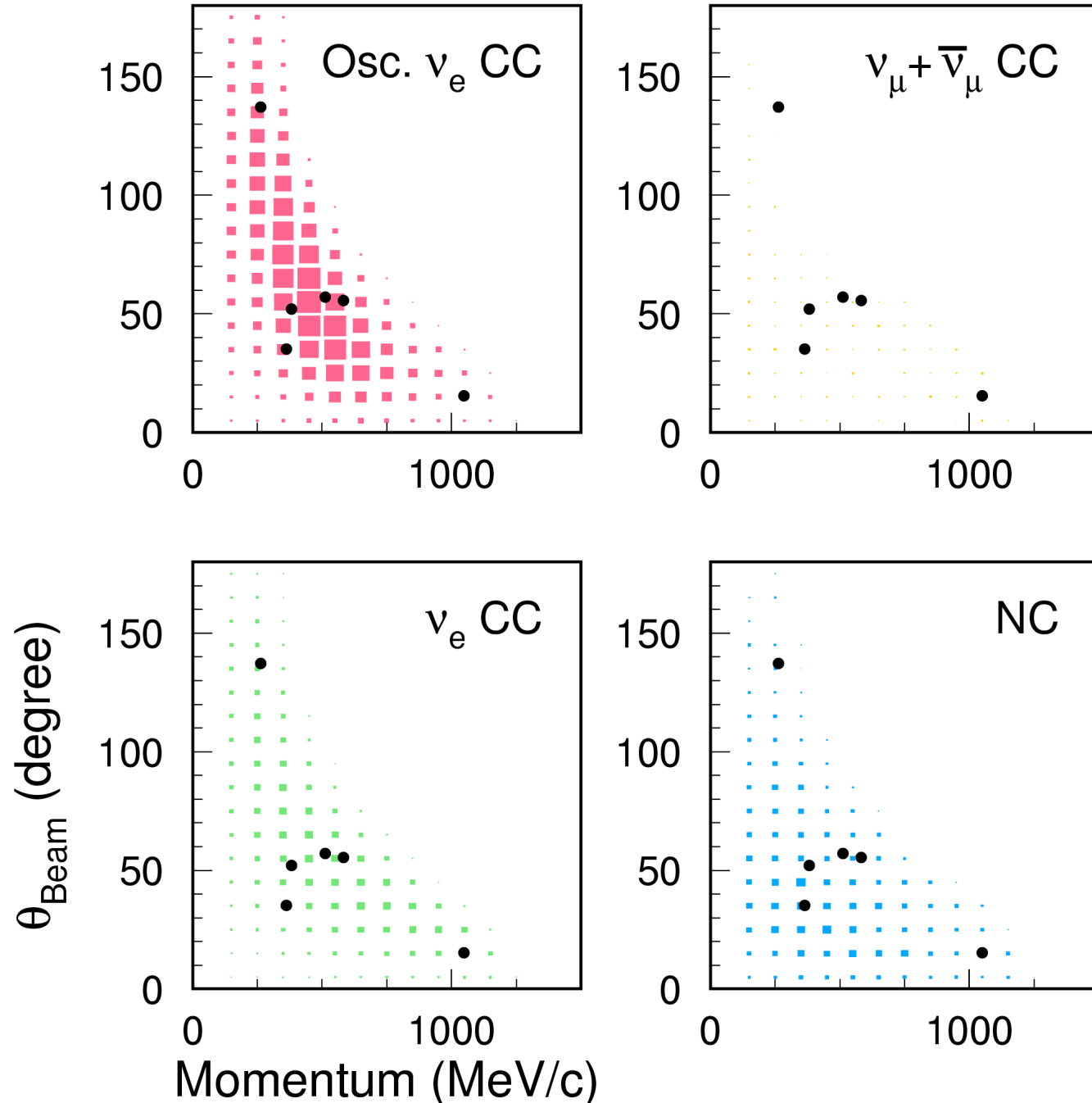
$E_\nu < 1250$ MeV

6 candidate events
observed
for background of
 1.49 ± 0.34

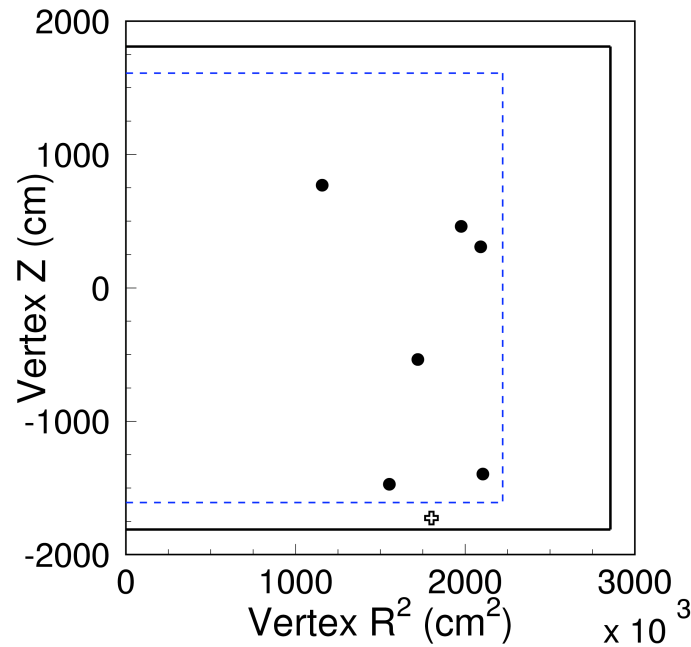
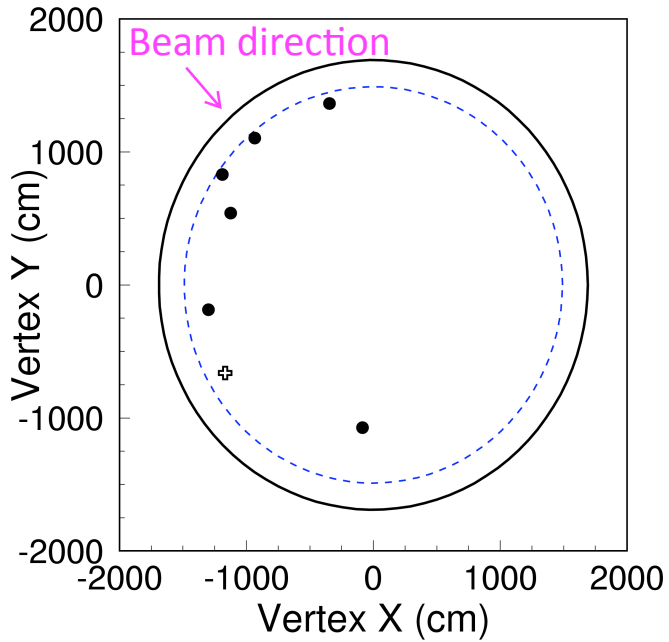


Basic distributions of ν_e candidates

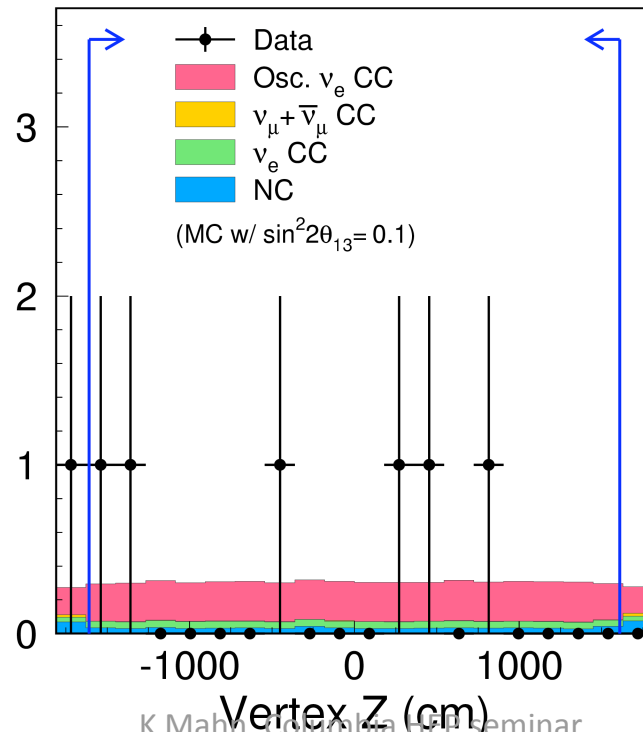
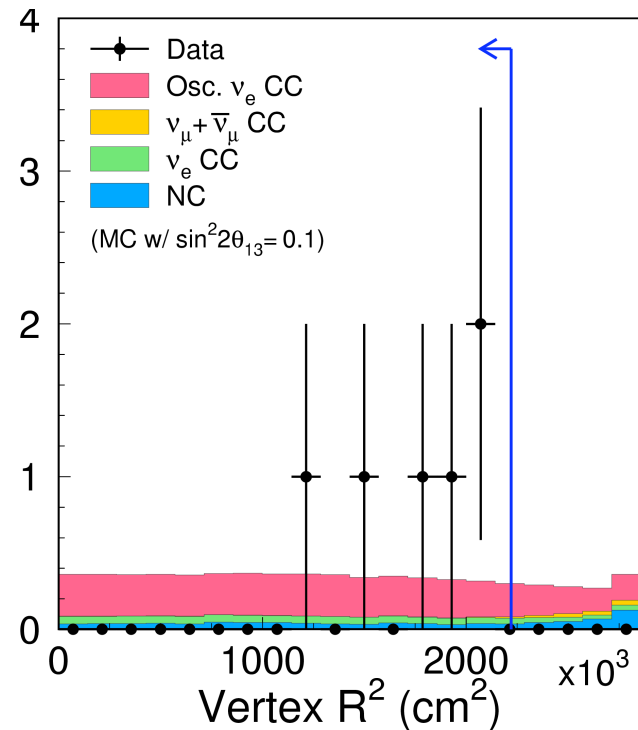
Momentum, angle with respect to beam direction distributions are reasonable



Basic distributions of ν_e candidates



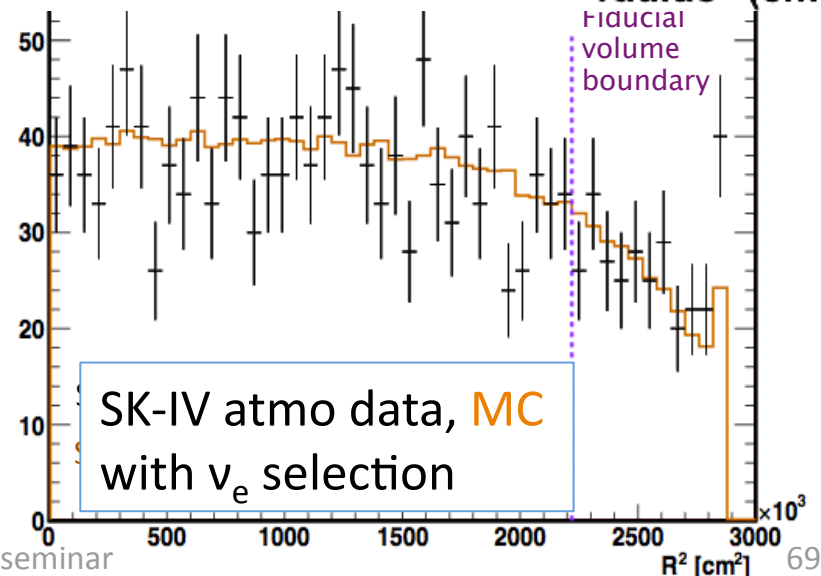
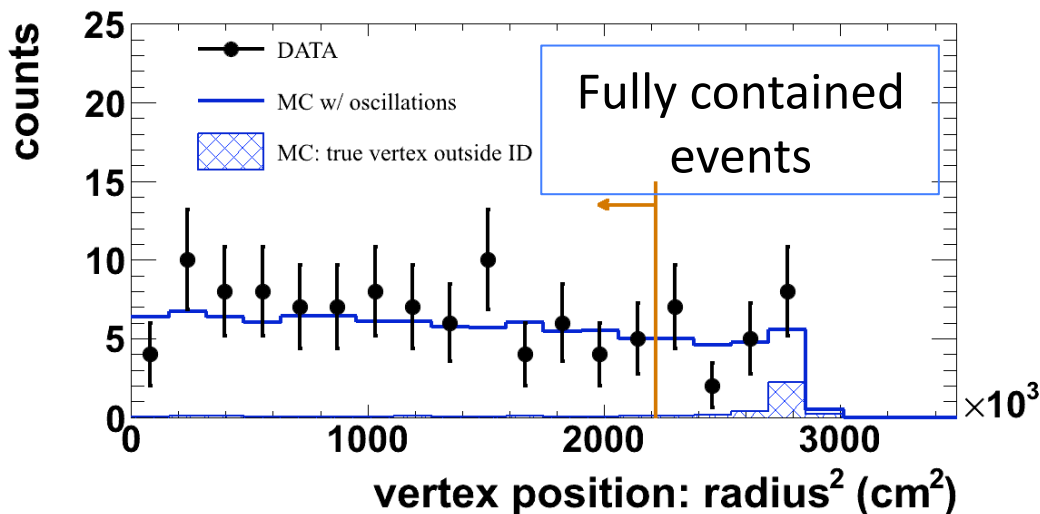
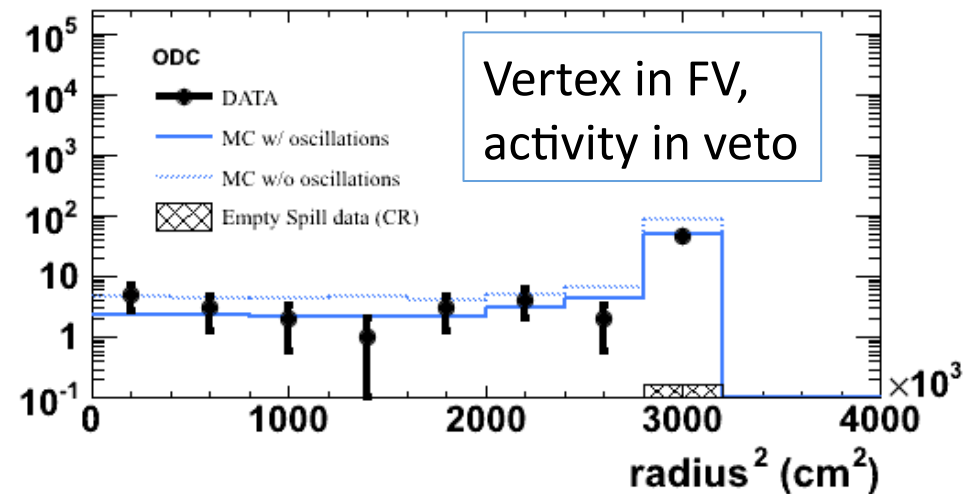
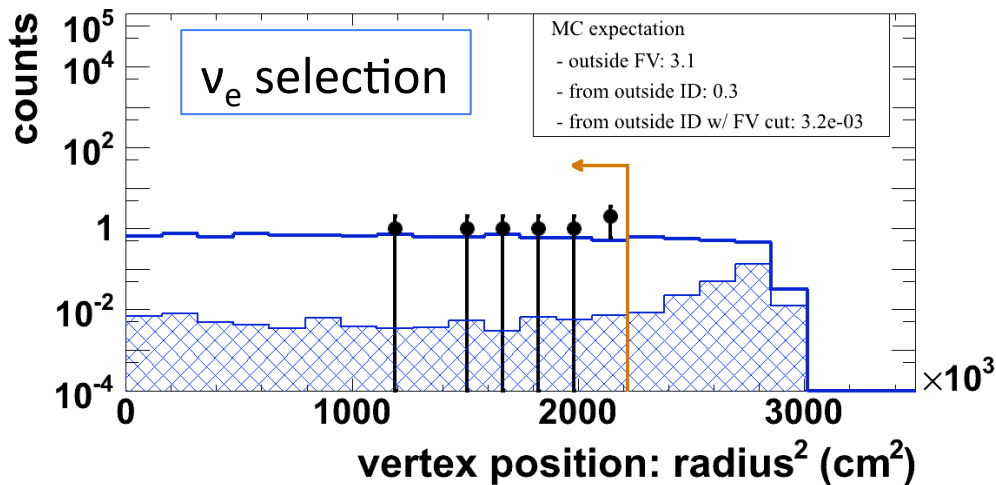
Clustering of candidates
at high R in beam direction
KS test of R^2 variable is 3%
(does not include beam dir)



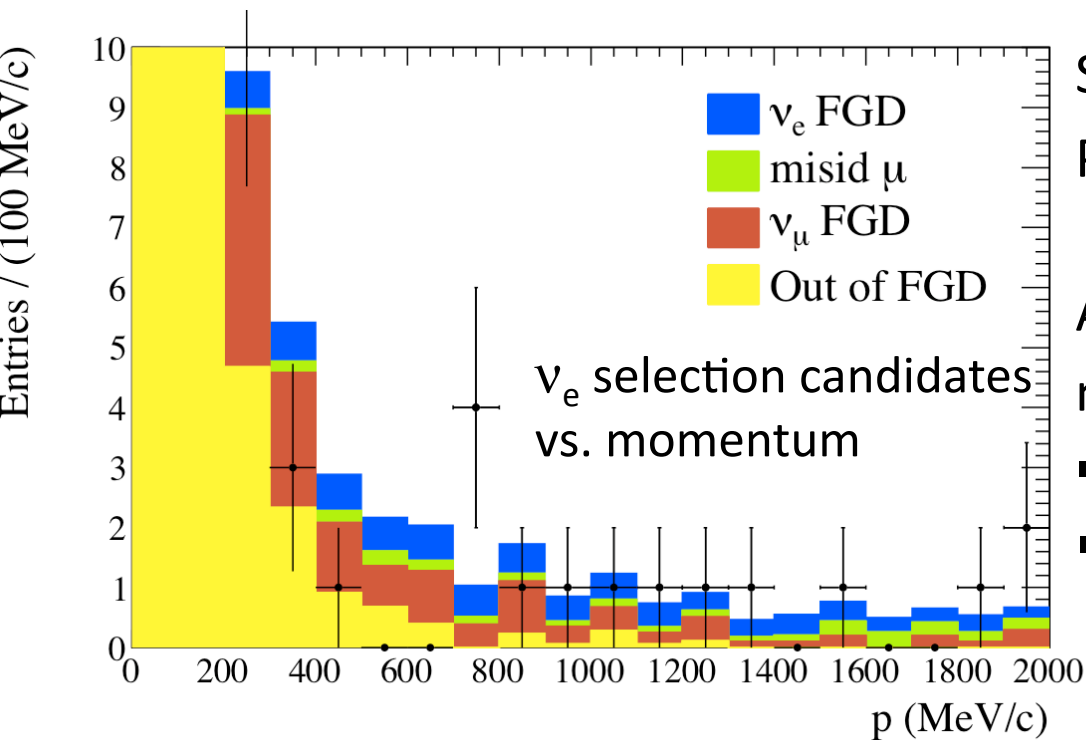
Beam backgrounds at high radius

MC simulates neutrino interactions upstream of the detector (e.g. π^0 production)

- Only 1 ν_e event cut by FV selection (no excess of ν_e events outside FV)
- Dedicated sample of events entering tank (with activity in veto) agree
- No bias to radial distribution of atmospheric sample under T2K ν_e selection



ND280 beam ν_e rate cross-check (I)



Select ν_e candidates at ND280 with TPC PID to check rate of intrinsic beam ν_e

Additional backgrounds to ν_e selection, measured via control samples

- μ misidentified as e
- e from photon conversion (photons emitted in ν_μ interactions in FGD and other subdetectors)

Ratio of observed ν_e / ν_μ events is consistent with untuned prediction

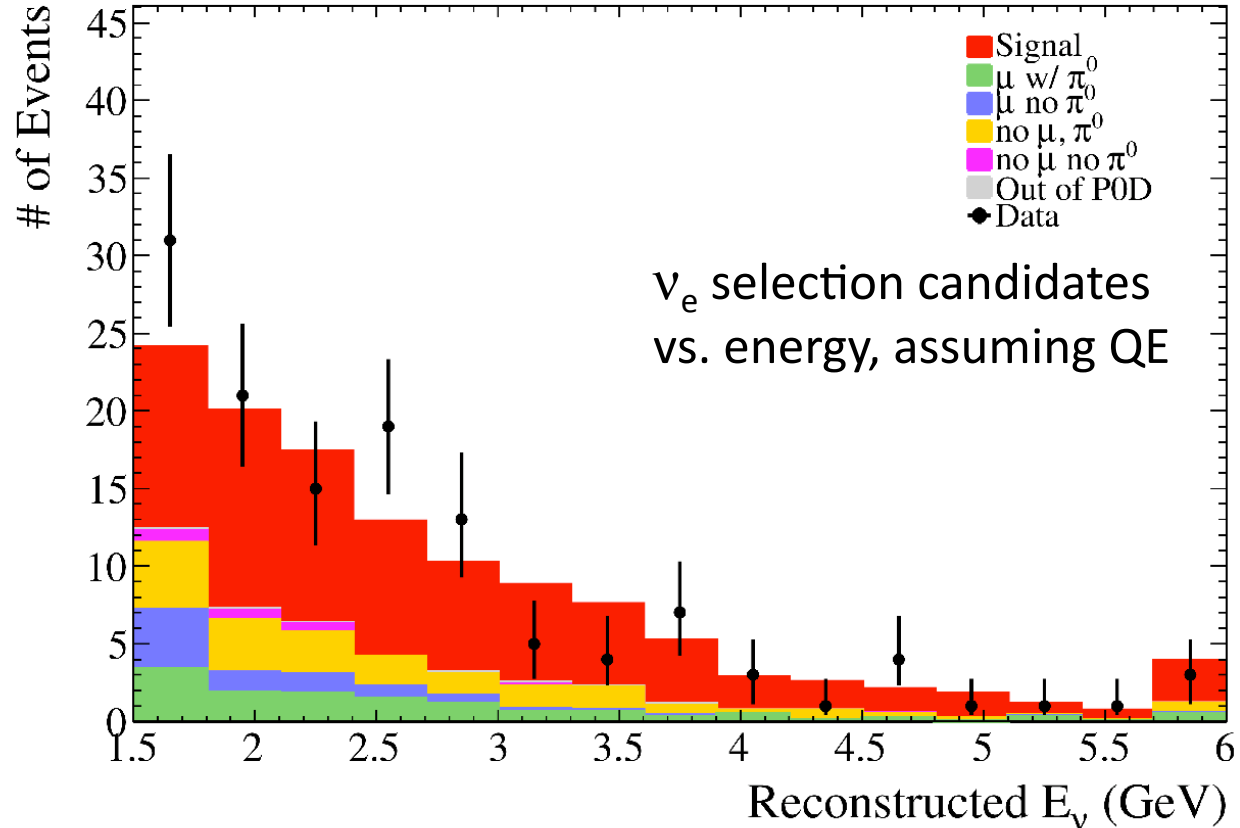
$$N(\nu_e) / N(\nu_\mu) = R(e:\mu) = 1.0\% \pm 0.7\% \text{ (statistics)} \pm 0.3\% \text{ (systematics)}$$

$$R(e:\mu, \text{data}) / R(e:\mu, \text{MC}) = 0.6 \pm 0.4 \text{ (statistics)} \pm 0.2 \text{ (systematics)}$$

Improvements to the analysis:

- Improved rejection of backgrounds with ECals
- More data: 2.88×10^{19} POT shown here

ND280 beam ν_e rate cross-check (II)



Select high energy CC ν_e candidates within the POD:

- Reconstructed track matched in x,y with vertex in FV consistent with an single EM shower (reject π^0 multiple photon showers and muons)
- Primary backgrounds are HE π^0 events

Consistent with current untuned MC:

$$\text{data-bkrd(MC)/sig(MC)} = R = 1.19 \pm 0.15(\text{statistics}) \pm 0.26(\text{systematics})$$