Neutrino Production and Interaction Modeling for Long Baseline Neutrino Experiments

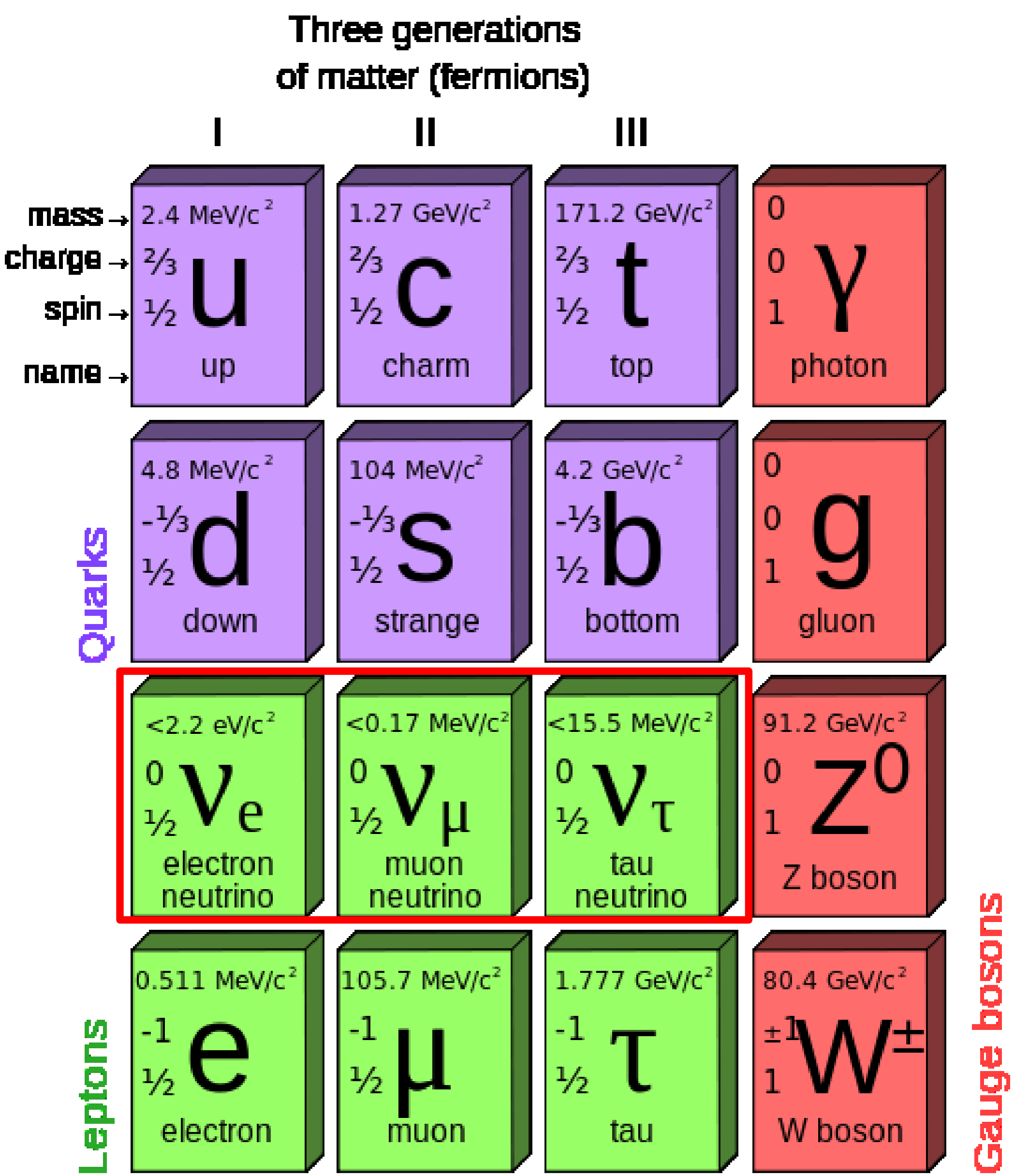
Mark Hartz
(University of Toronto, York University)

Kavli Institute for the Physics and Mathematics of the Universe,
Seminar, February 4, 2013

Outline

1. Introduction to neutrino oscillations
2. The T2K experiment
3. Neutrino flux modeling for T2K
4. Neutrino interaction modeling for T2K
5. T2K near detector constraint on flux and interaction models
6. Challenges for future T2K measurements and Hyper-K

Neutrinos in the Standard Model



Neutrinos:

Carry no electrical or color charge

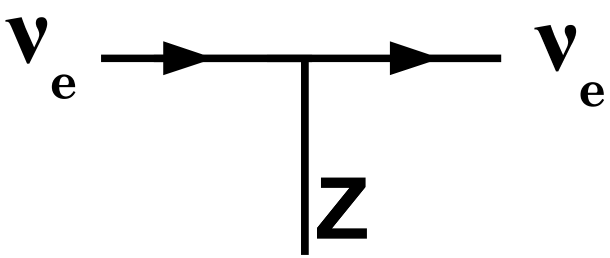
Interaction via the weak force

Small mass (<0.3 eV)

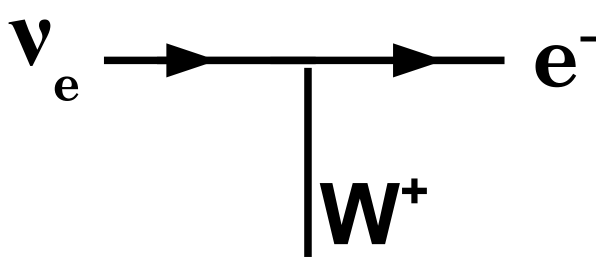
Neutrino Interactions

• Weakly interacting isospin partners of charged leptons:

Neutral current (NC)



Charged current (CC)



From an experimental perspective:

Detection of lepton in the final state:

• Charged lepton in CC interactions can be detected

• Neutrino in NC interactions is not detected

Mass of lepton in the final state:

• Mass of charged lepton in CC interactions limits the kinematically allowed space of the interaction

• Neutrinos are effectively massless at energy scales of interest

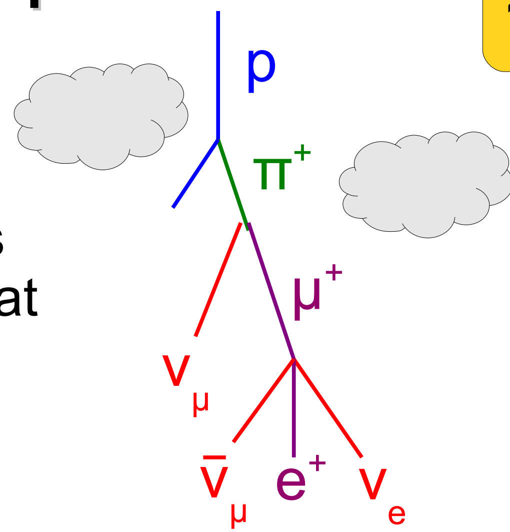
Neutrino Sources

Where do the neutrinos that we study come from?

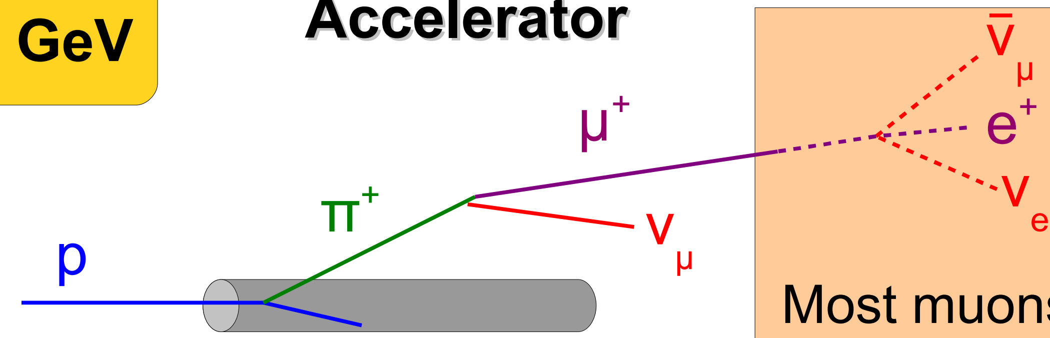
~1-10 GeV

Atmospheric

Cosmic ray showers produce pions and muons that decay to neutrinos



Accelerator



Most muons absorbed before decaying

Proton beam from accelerator collides with fixed target

~ 1-10 MeV

Solar

$$\ldots$$
$$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$$
$$\ldots$$
$$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$
$$\ldots$$

Produced in fusion reactions inside sun.

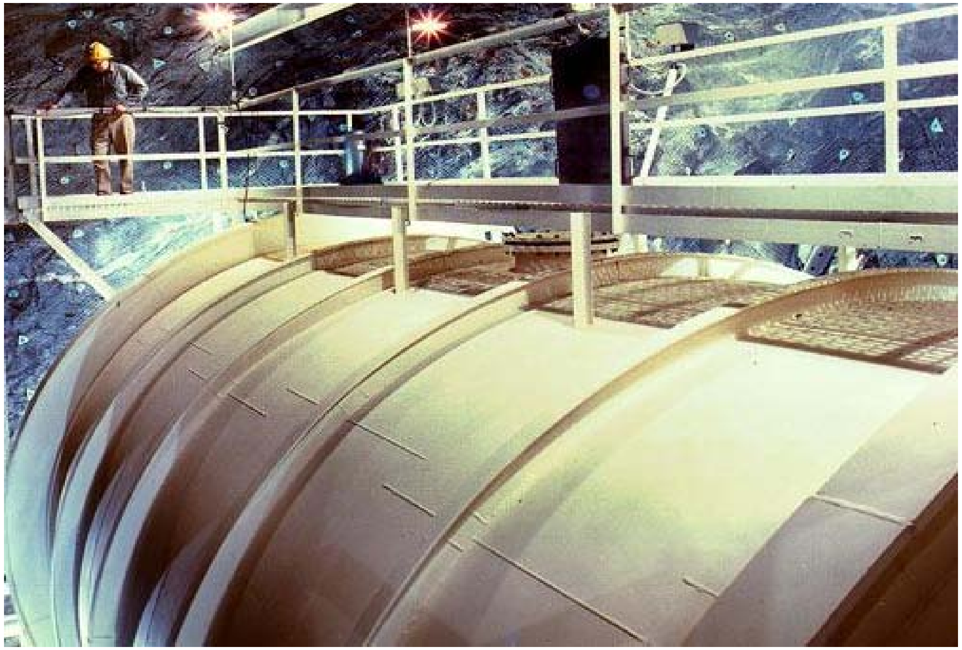
Energy thresholds matter for experiments

Reactor

$\bar{\nu}_e$ From β decay of isotopes in nuclear reactors

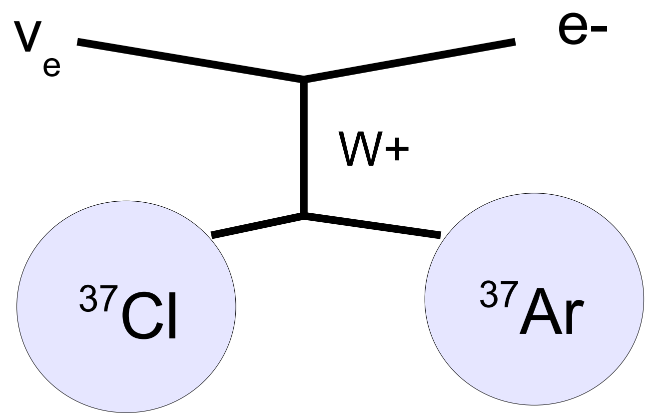
The Solar Neutrino Anomaly

The Homestake Experiment



PRL 20, 1205–1209 (1968)
Astrophys.J. 496 (1998) 505-526

Neutrino interactions in 615 tons of C_2Cl_4 cleaning fluid

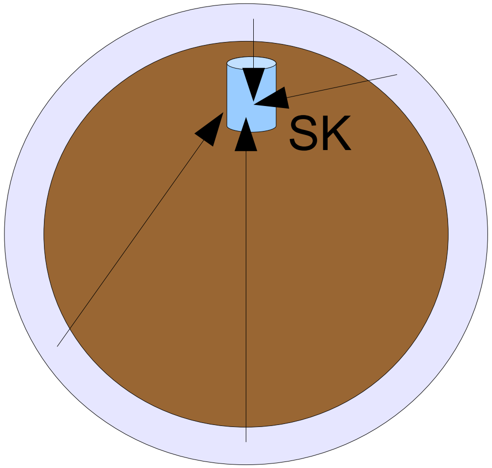


Electron neutrinos from the sun detected by production of ^{37}Ar from charged current scattering off of ^{37}Cl (group led by Raymond Davis Jr.)

Measured rate was 1/3 of expected rate based on calculations of J. Bahcall **(Phys. Rev. Lett., 12, 300)**

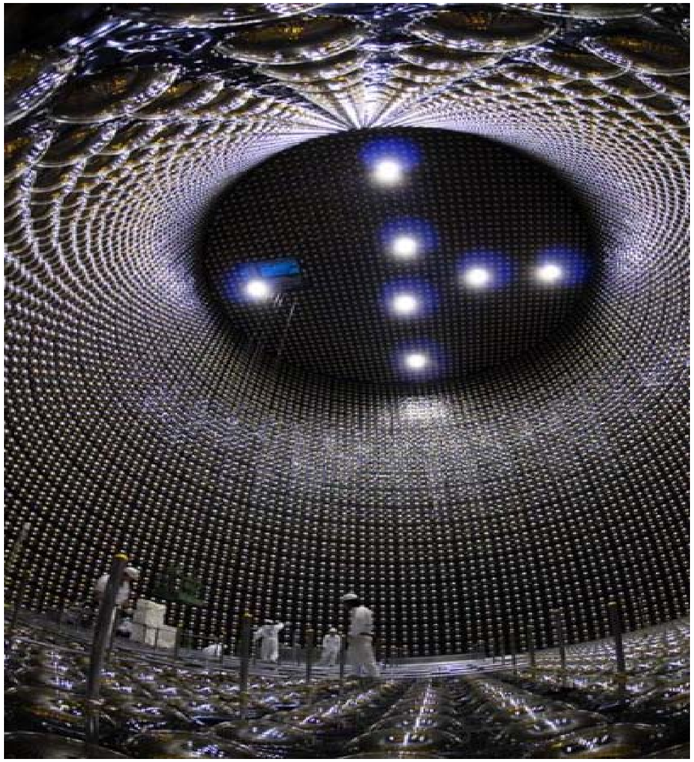
Was this a problem in the experiment, solar model or something else?

Atmospheric Neutrino Anomaly

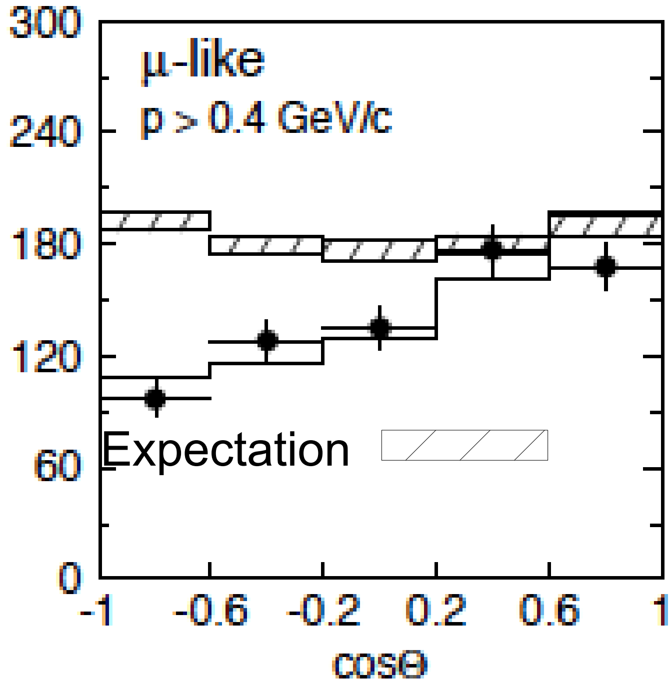


50 kton water Cherekov detector

Detect muon and electron neutrinos produced in cosmic ray showers



Phys. Rev. Lett. 81, 1562 (1998)



Deficit of muon neutrinos observed, depends on neutrino energy and distance traveled

Can this and the solar anomaly be explained? Yes, if the neutrinos are massive and mix.

Neutrino Mixing & Oscillations

- Parameterization of mixing with the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix U_{li}:

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

(Atmospheric) (Solar)

- δ is phase that can can cause CP violation
- Probability to oscillate depends on energy (E), distance traveled (L), the mixing matrix U and the differences in the squared neutrino masses :

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

Observed deficits are original flavor oscillating to another undetected flavor

Knowledge of Oscillation Parameters

Three mixing angles, two mass squared differences, CP phase

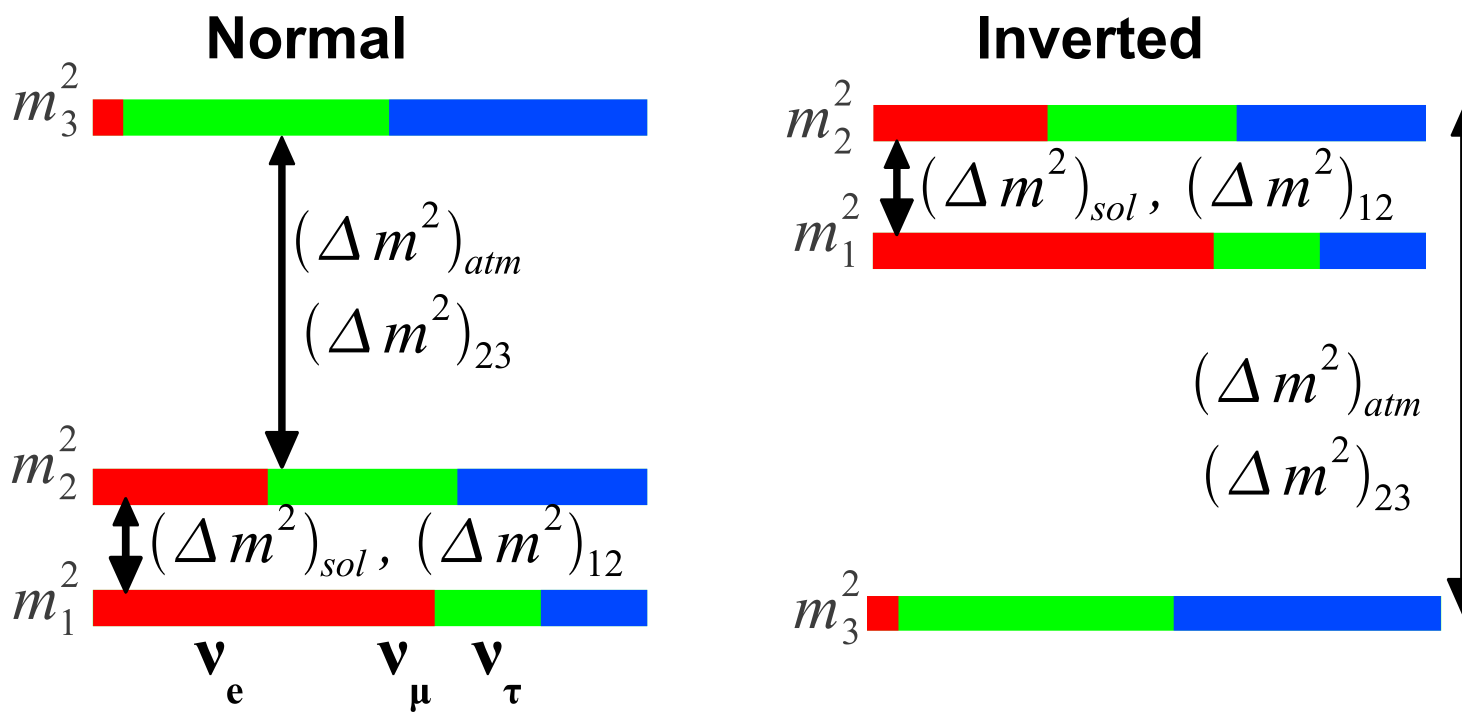
$\sin^2(2\theta_{12}) = 0.86 \pm 0.02$ $\qquad \Delta m^2_{12} = 7.50 \pm 0.20 \times 10^{-5}\ eV^2$ SNO, KAMLAND, SK

$\sin^2(2\theta_{23}) > 0.95\ \ (90\%\ \ C.L.)$ $\qquad \Delta m^2_{23} = 2.32 \pm 0.12 \times 10^{-3}\ eV^2$ SK, K2K, MINOS

Ambiguity in sign of

$m_3^2 - m_2^2$

Two possible mass hierarchies



$\sin^2(2\theta_{13}) < 0.12\ \ (90\%\ \ C.L.)$ MINOS, CHOOZ (As of 2010)

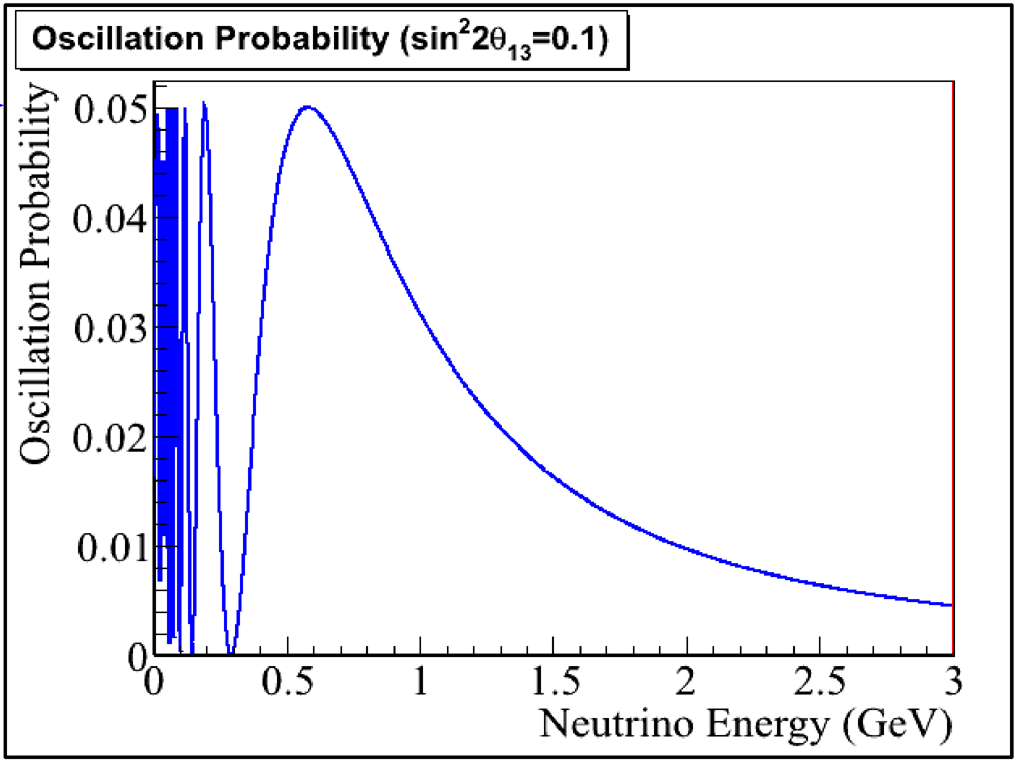
$\delta_{CP} = ?$

Electron Neutrino Appearance

Accelerator based experiments - access to θ_{13} through oscillations of muon neutrinos to electron neutrinos:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{32}^2 L}{4E_\nu} + \text{subleading terms}$$

ν_e appearance probability for T2K baseline (L=295 km) and $\sin^2(2\theta_{13})$=0.1 (ignoring subleading terms)



Design experiment with ν_μ beam peaked at first oscillation maximum

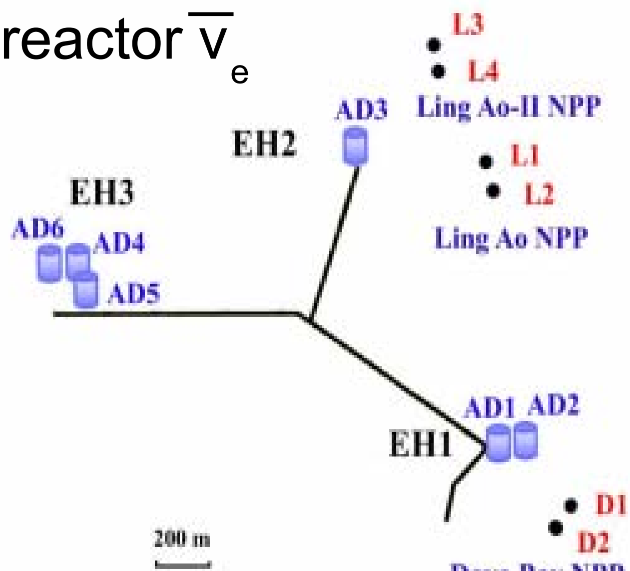
Search for ν_e appearance

Recent Success in Measuring θ_{13}

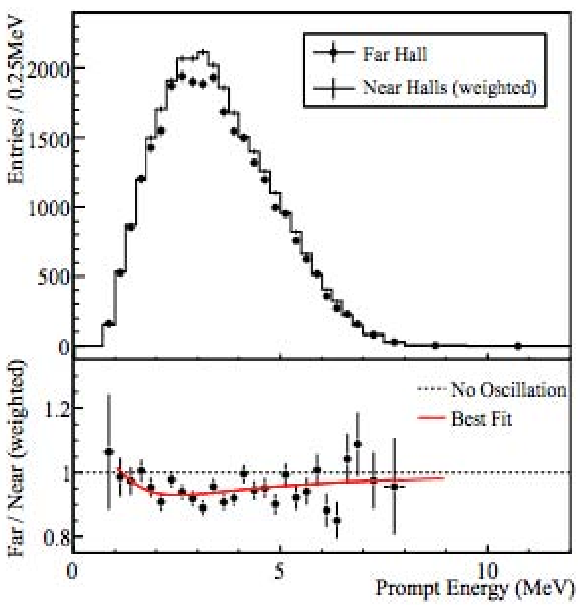
- June 2011 – T2K observes 6 electron neutrino candidates when 1.5±0.3 (syst.) are expected from background
  - $\theta_{13}=0$ is disfavored at 2.5σ **Phys. Rev. Lett. 107 (2011) 041801**

- March 2012 – Daya Bay observes a >5σ deficit in reactor $\bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2(1.27\frac{\Delta m^2_{31} L}{E})$$



- Deficits confirmed at high significance by RENO and Double Chooz experiments



Updated Daya Bay measurement in October 2012
arXiv:1210.6327

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat.) \pm 0.005(syst.)$$

Measuring δ

Full appearance probability includes term that goes as sin(δ):

$$\propto \pm \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta$$

Sign flip for neutrino vs. antineutrino

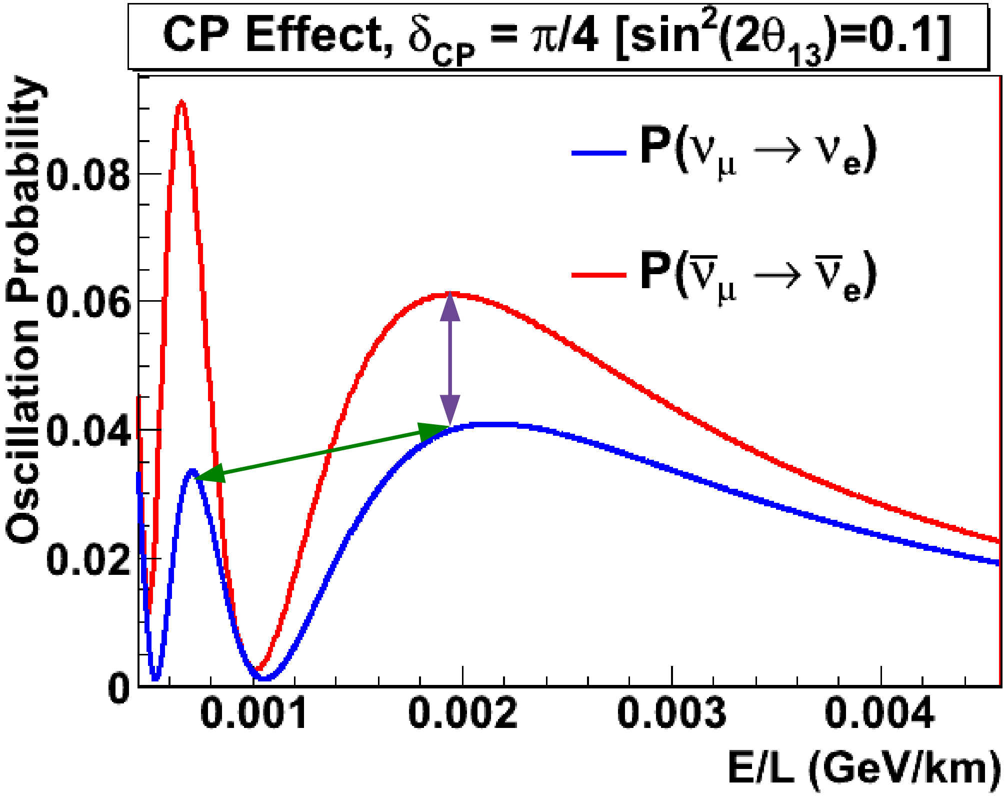
Need non-zero value for all three mixing angles including θ_{13}

Two ways to measure δ:

1. neutrino vs. antineutrino appearance probability

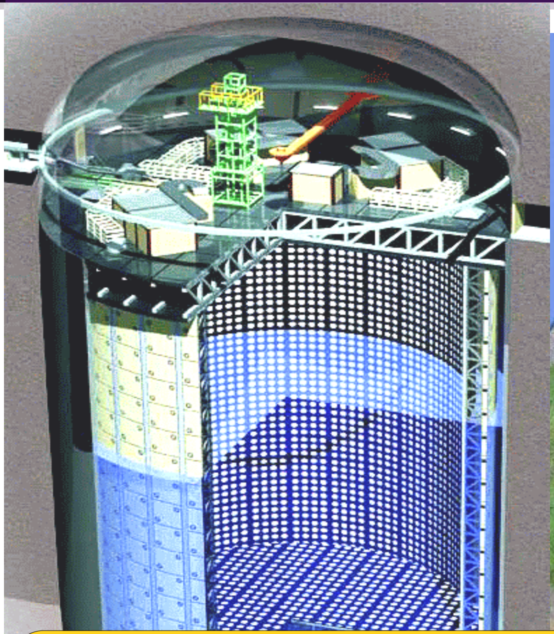
$$\boxed{A_{CP} \equiv \frac{P - \overline{P}}{P + \overline{P}} \approx \frac{\Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta}$$

2. 1^{st} vs 2^{nd} oscillation maximum for neutrino mode

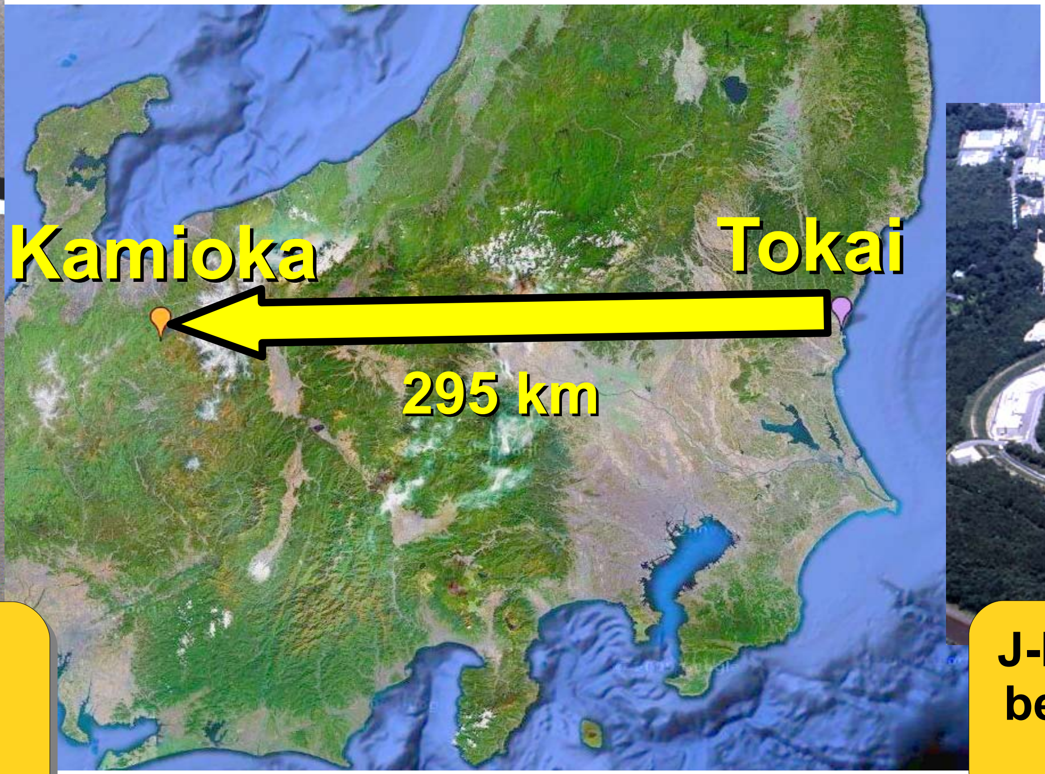


The T2K Experiment

T2K (Tokai to Kamioka) Experiment



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



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

- Experiment's immediate goals:
  - Search for ν_e appearance: $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4 E_\nu}$
  - Precision ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2 L}{4 E_\nu}$

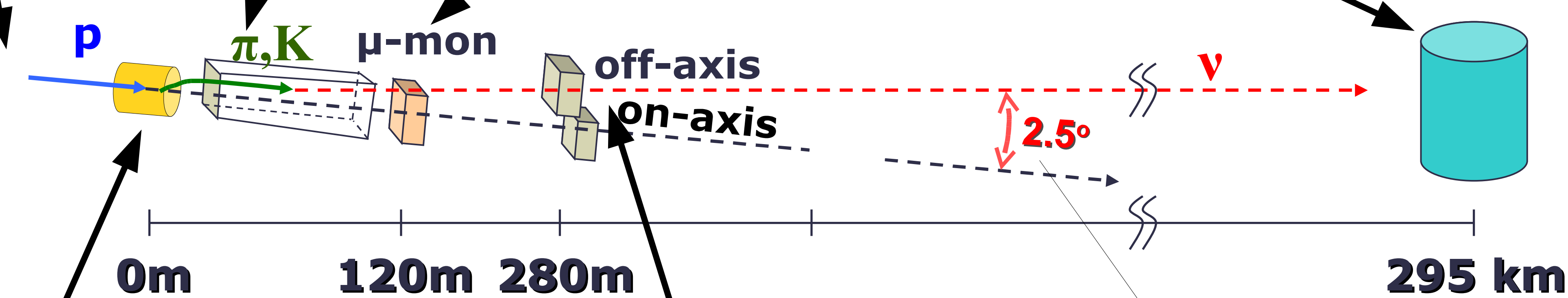
T2K Overview

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

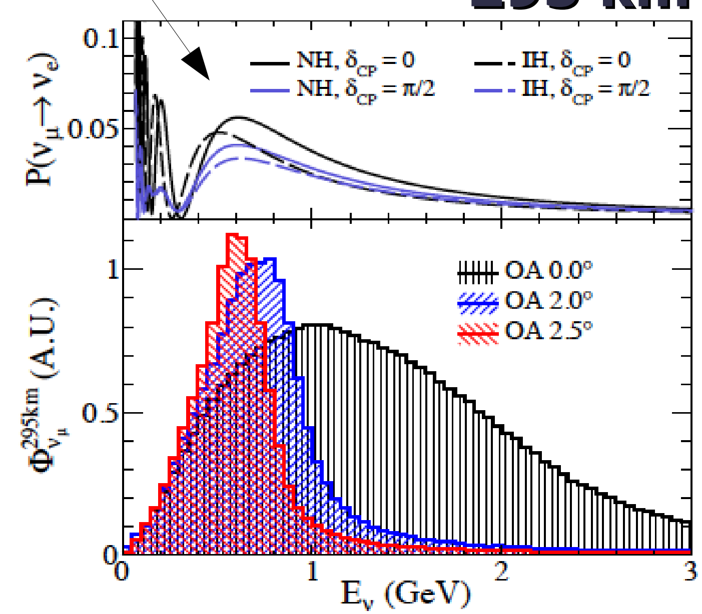


Beam on graphite target

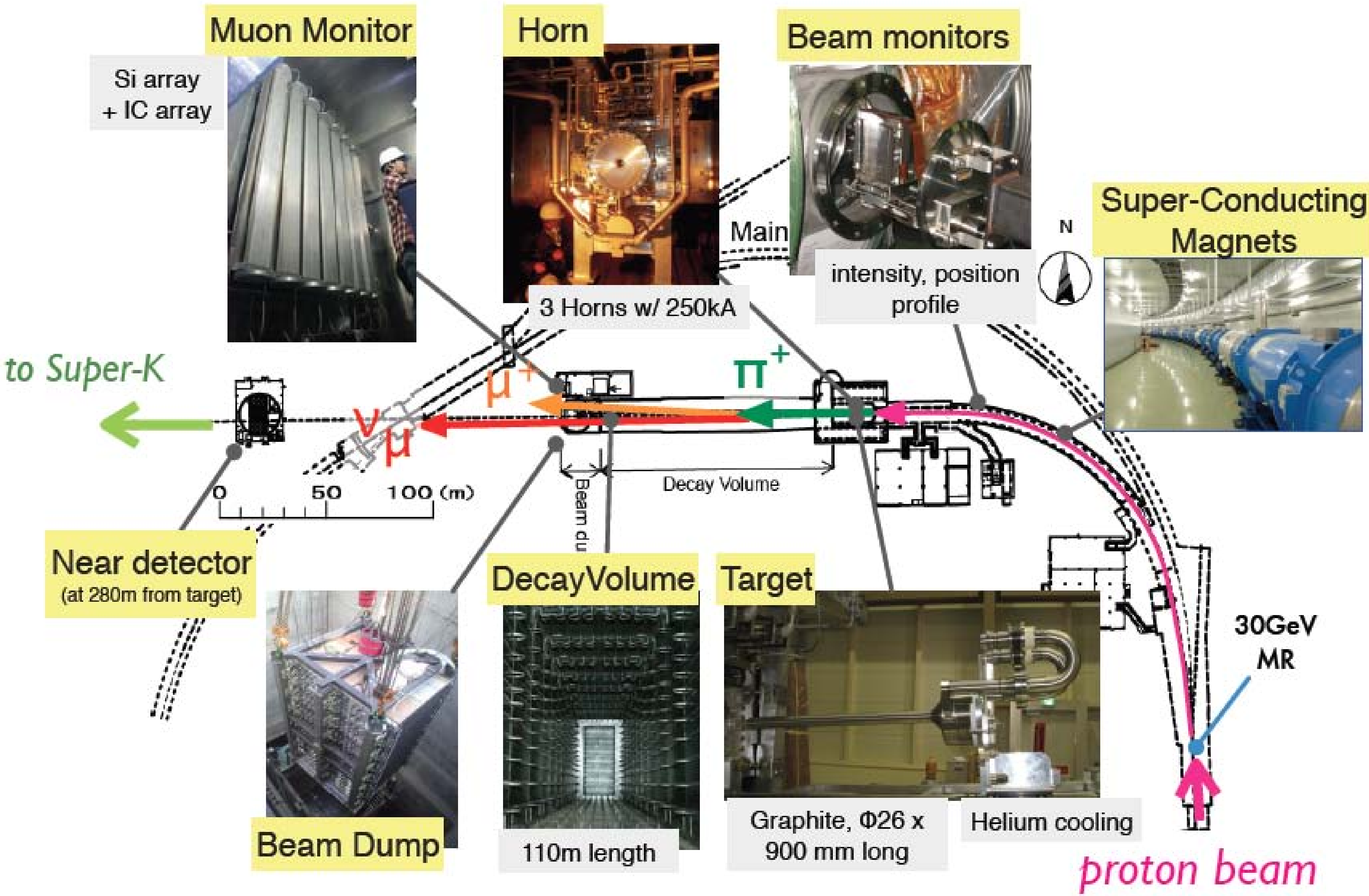
3 magnetic horns focus positively charged hadrons

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

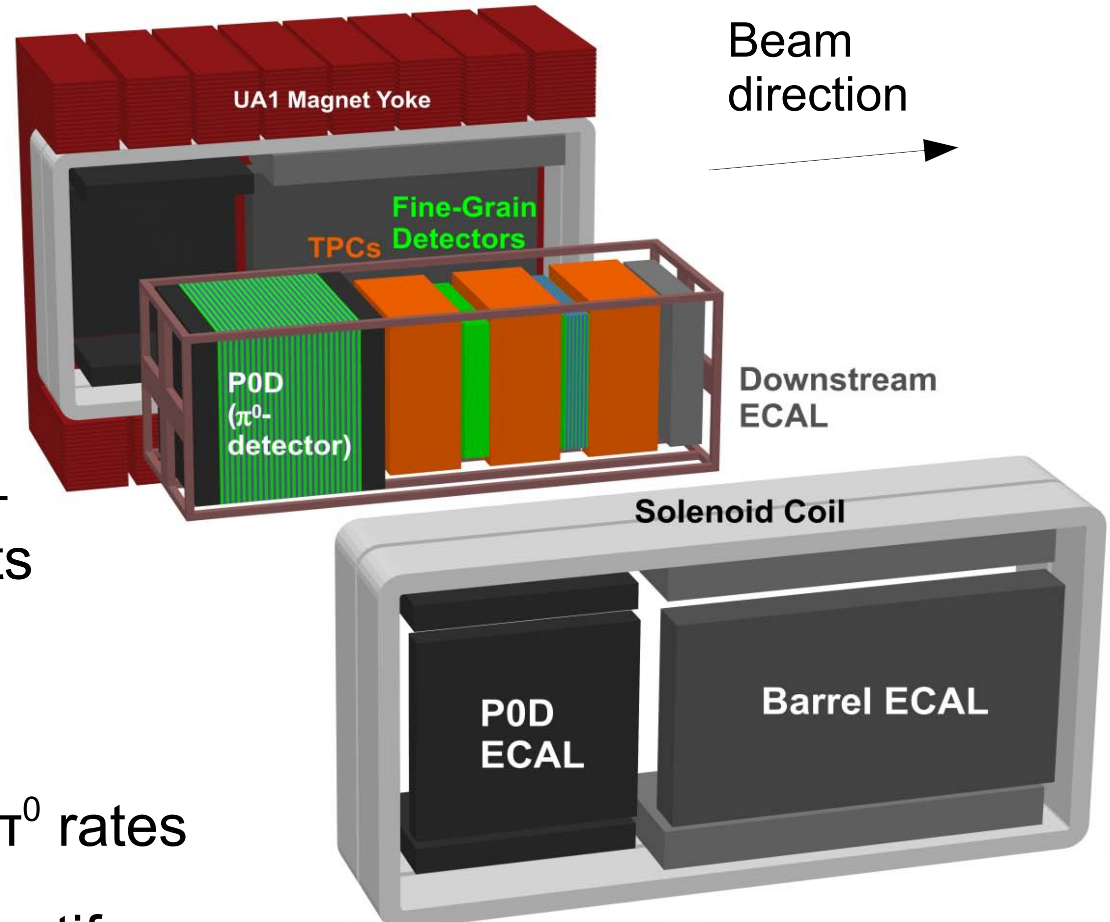
Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions



J-PARC Neutrino Beam Line



ND280 (Near) Off-axis Detector



- 0.2 T UA1 magnet

Used in this analysis

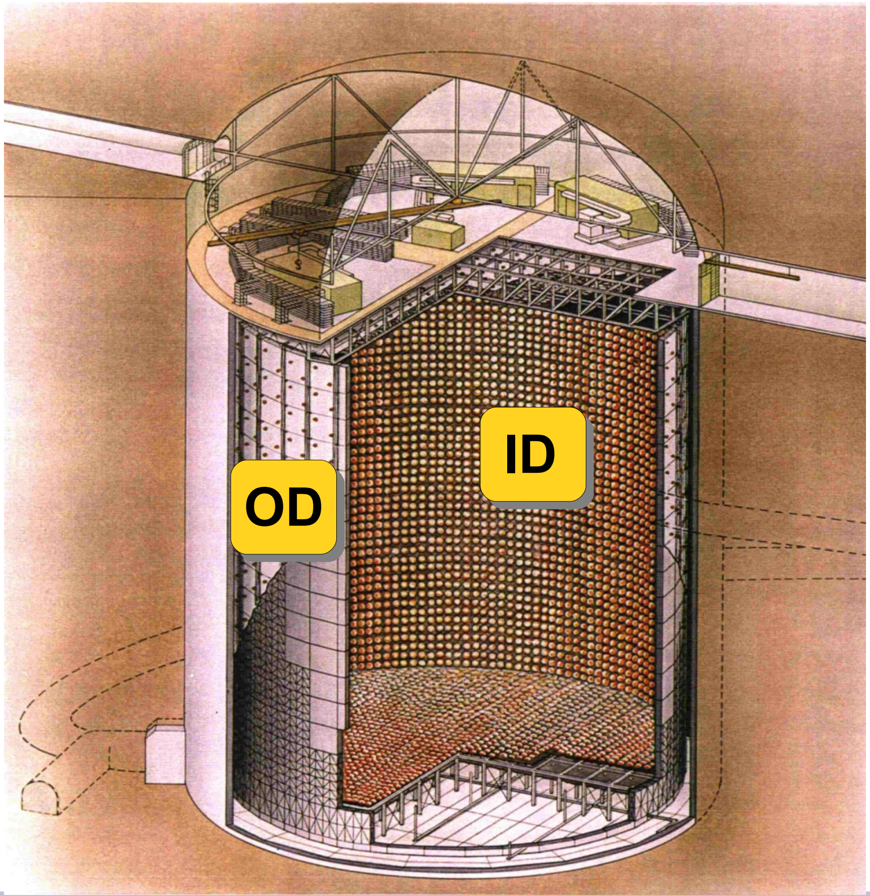
- Fine Grained Detectors (FGD) – neutrino target mass and tracking
- Time Projection Chambers (TPC) – momentum and dE/dx measurements

Important for future analyses

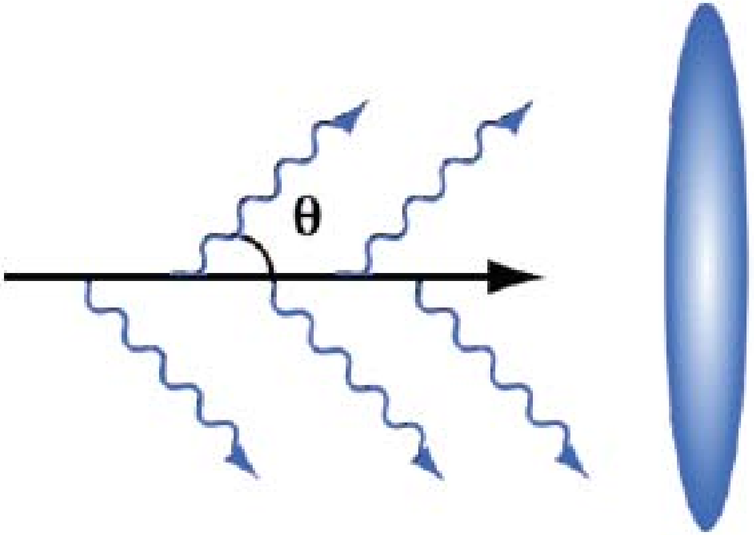
- P0D π^0 detector – measures NC π^0 rates
- Electromagnetic calorimeters – identify electrons, photon reconstruction
- SMRD muon detector installed in the magnet yoke – muon range detector to improve muon ID

SK (Far) Detector

- 50 kton (22.5 kton fiducial volume) water cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range (GeV)

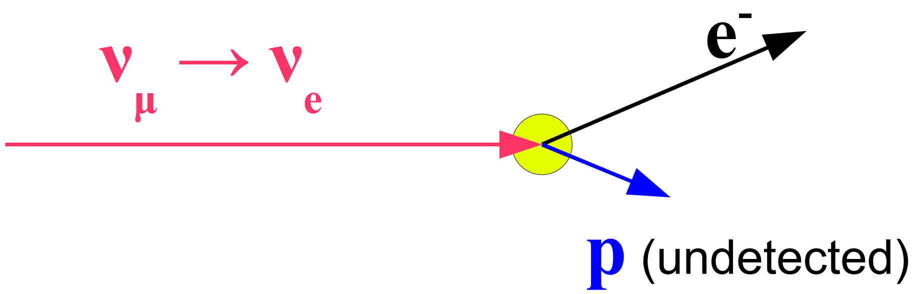


Cherenkov light produces a ring detected by the PMTs



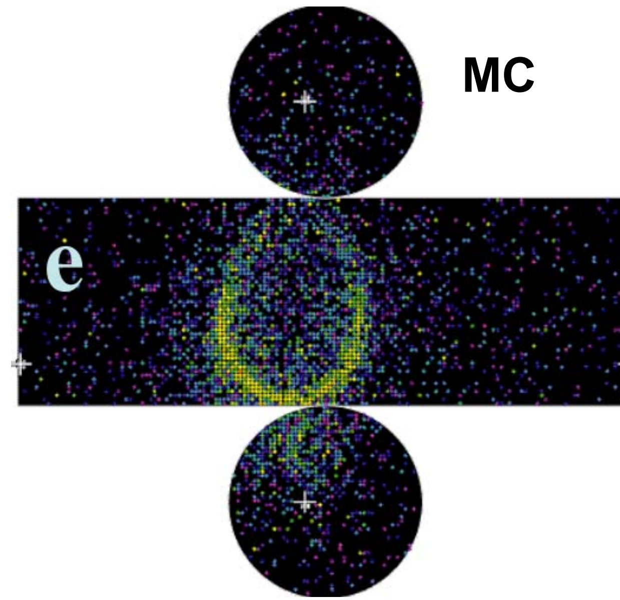
ν_e Signal & Background at SK

Oscillation Signal:

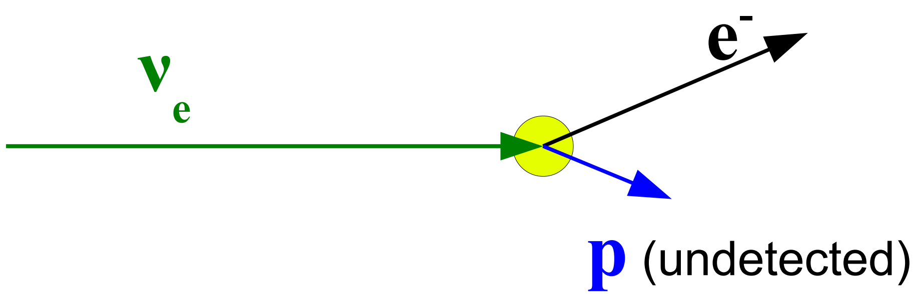


Identical for given neutrino energy.

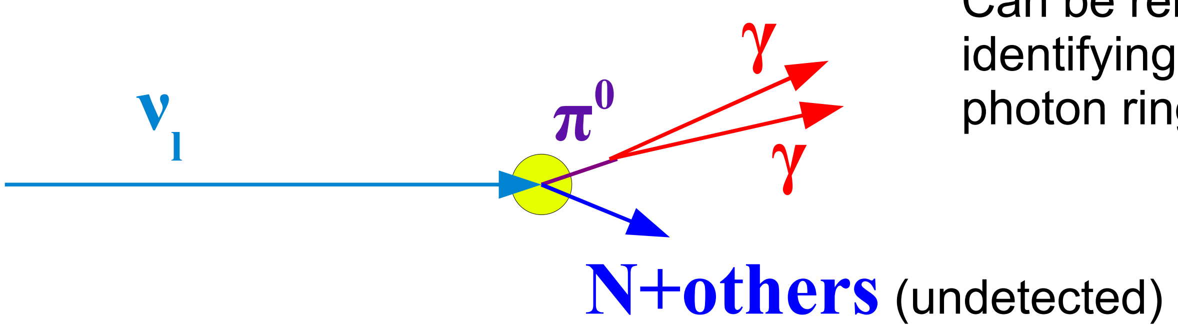
Beam background has harder spectrum



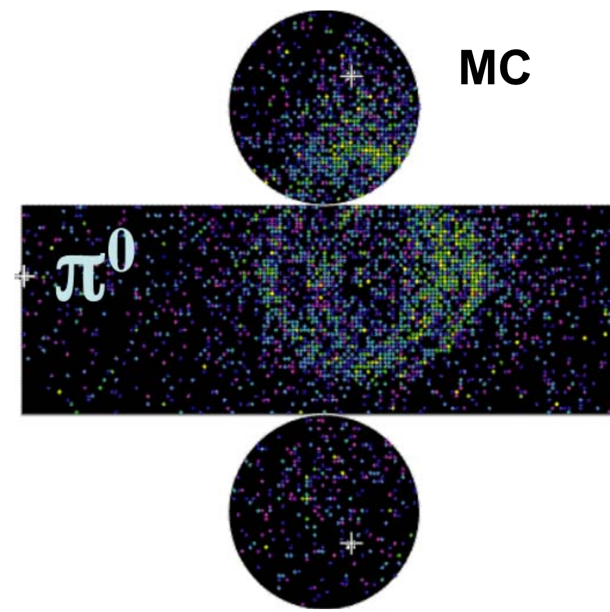
Beam ν_e Background:



Neutral Current π^0:



Can be removed by identifying second photon ring



Oscillation Measurement

Measure the event rate at the far detector: $N_{SK}^{data}(p_l, \theta_l)$

May be binned by lepton kinematics

Build an event rate prediction:

$$N_{SK}^{pred}(p_l,\theta_l)=\int_{E_\nu} P_{osc}(E_\nu)\cdot \boxed{\Phi_{SK}^{\nu_\mu(\nu_e)}(E_\nu)\frac{d\sigma(E_\nu,p_l,\theta_l)}{dE_\nu}}\cdot \epsilon_{SK}(p_l,\theta_l) M_{SK}\, dE_\nu$$

Apply fitting procedures to extract the oscillation parameters

Uncertainties on the flux and interaction models propagate to uncertainties on the fitted oscillation parameters

These models and uncertainties are derived from external data and T2K near detector data

Near Detector Constraint Flow

Prior flux model from NA61, proton beam monitors, etc.

Prior models tuned on external data

Prior Cross Section Model from external neutrino and hadron scattering data

Normalization uncertainty in energy and flavor bins

M_A, p_F, etc., model comparisons, normalization errors

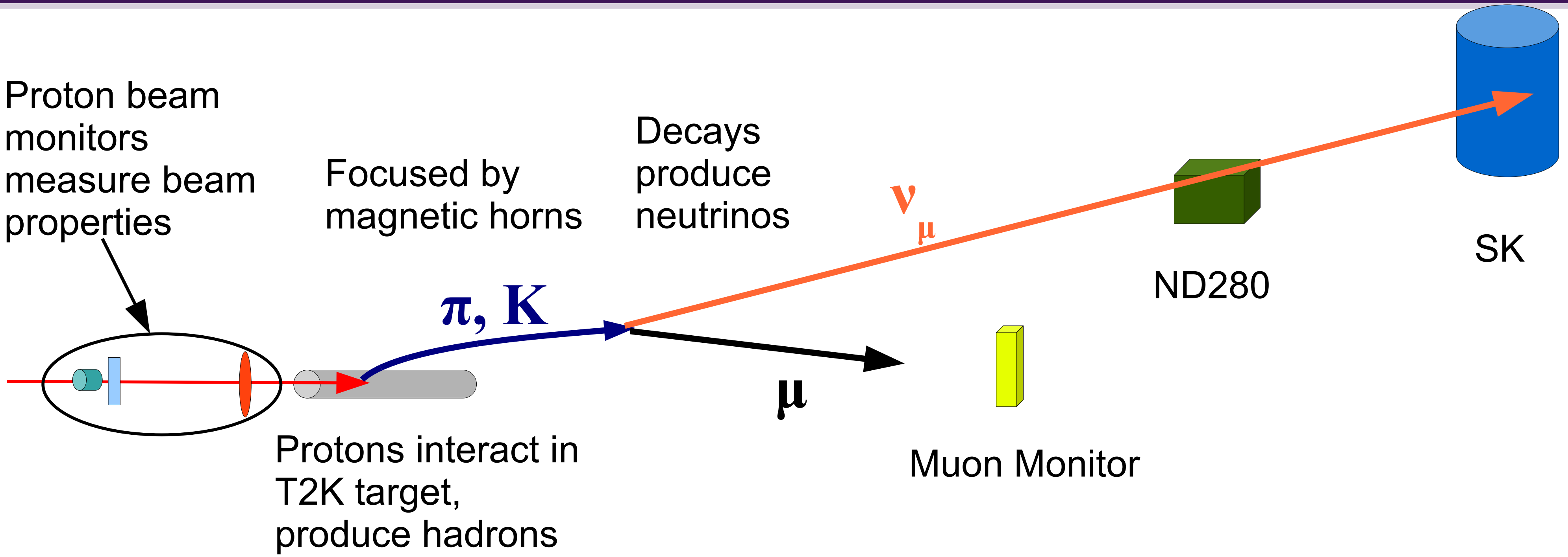
Fit of ND280 data places further constraints on the flux and cross section models.
Fit ν_μ interactions in the FGD1

Marginalize ND280 detector systematic errors and any cross section uncertainties with no cancellation

Use constrained flux and cross section models to predict SK event rates

Flux Model

Neutrino Flux and Modeling

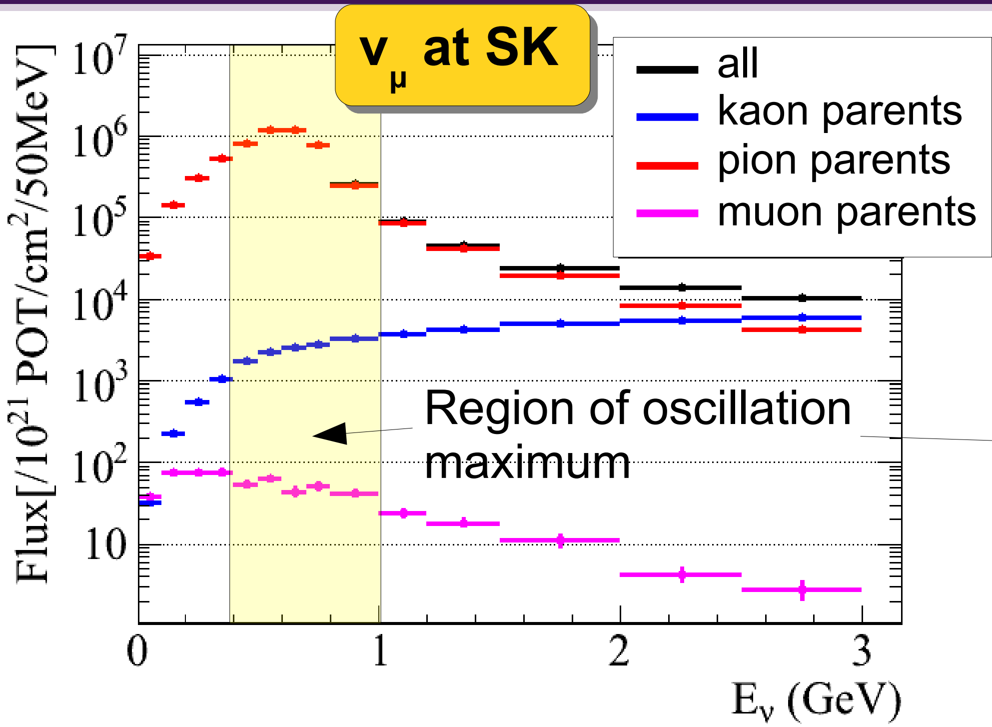


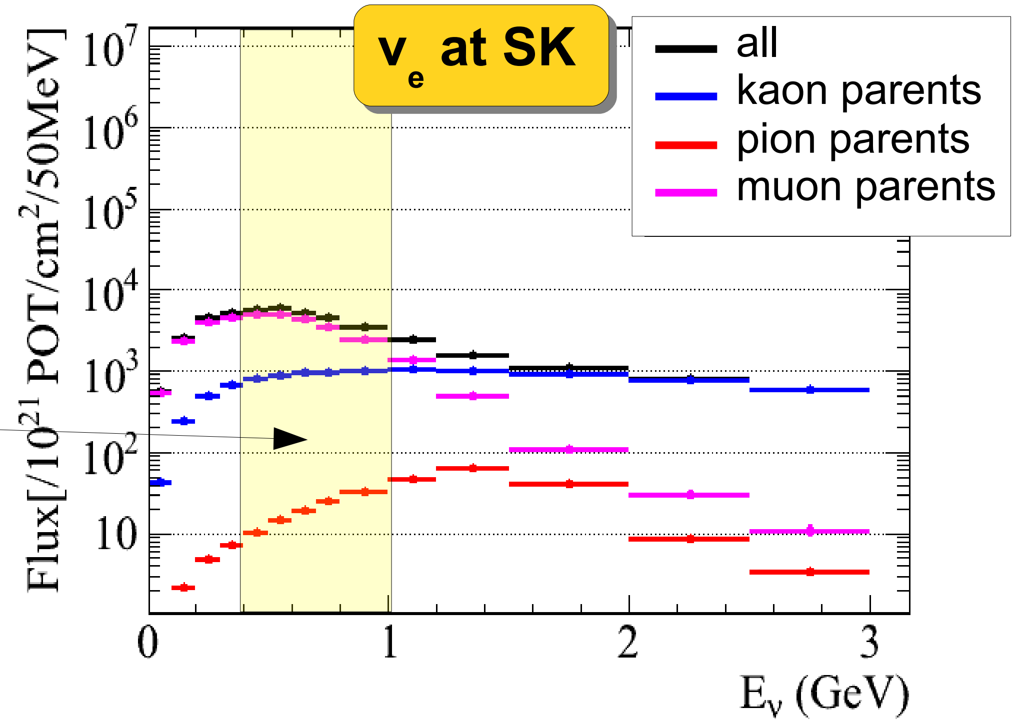
Flux Simulation:

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

Flux prediction description published in:
Phys. Rev. D 87, 012001 (2013)

Neutrino Flux Prediction





- 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

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

Flux depends on pion production

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

Importance of Beam Monitoring

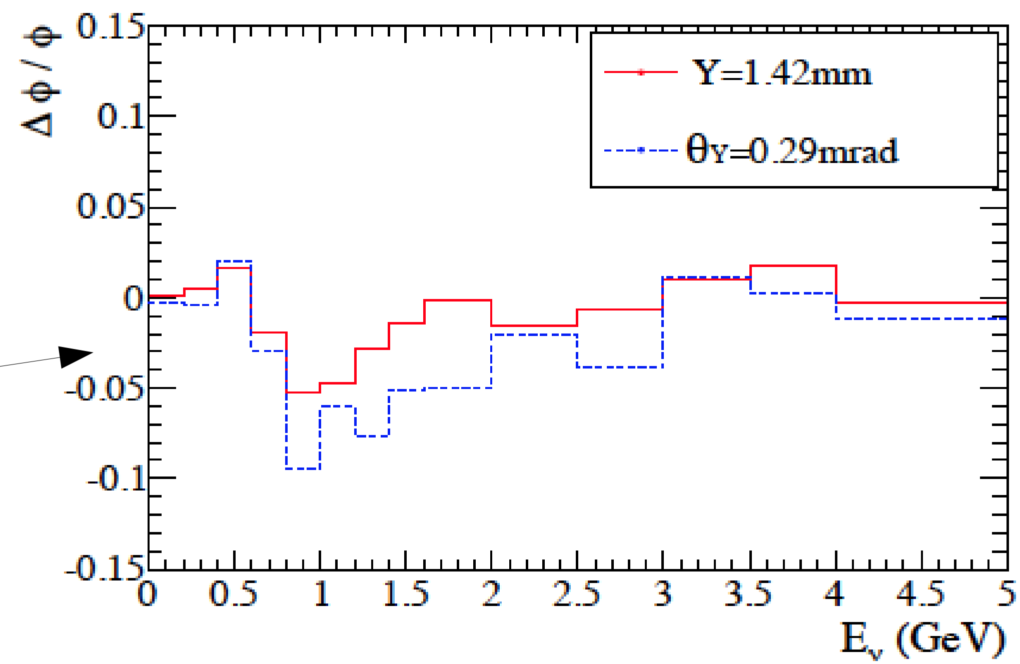
Measured properties of the proton beam → inputs to the flux simulation

Current transformers: measure beam current (absolute normalization)

Beam profile monitors: measure the beam direction, width and divergence in the transverse plane

0.5 mm shift of beam position at the target face corresponds to ~10 MeV shift in the peak of the flux spectrum

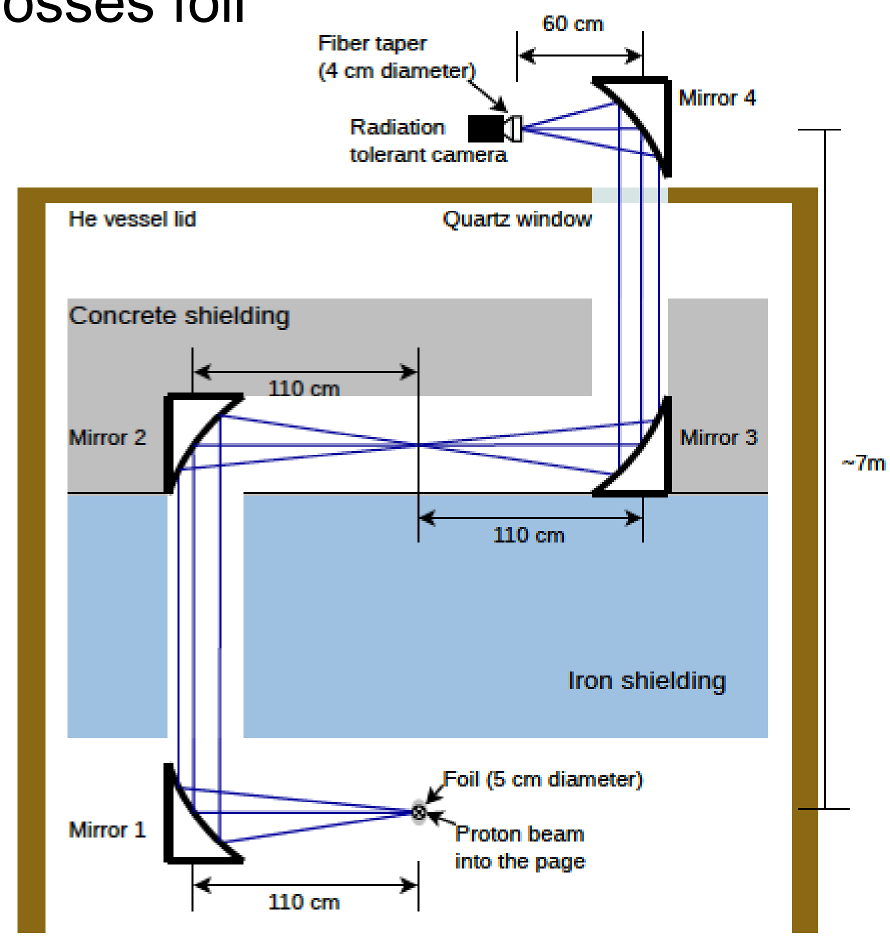
Fractional change to flux for 1σ shifts of the beam position and direction

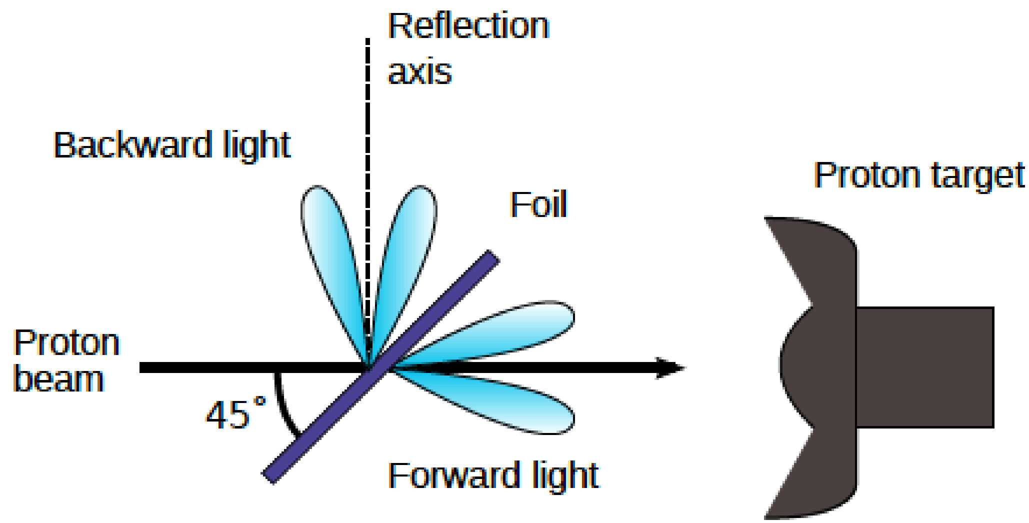


The OTR Monitor

Place a titanium foil 30 cm upstream of the T2K target

Optical **T**ransition **R**adiation produced when proton beam crosses foil





Transport light through shielding with 4 parabolic mirrors

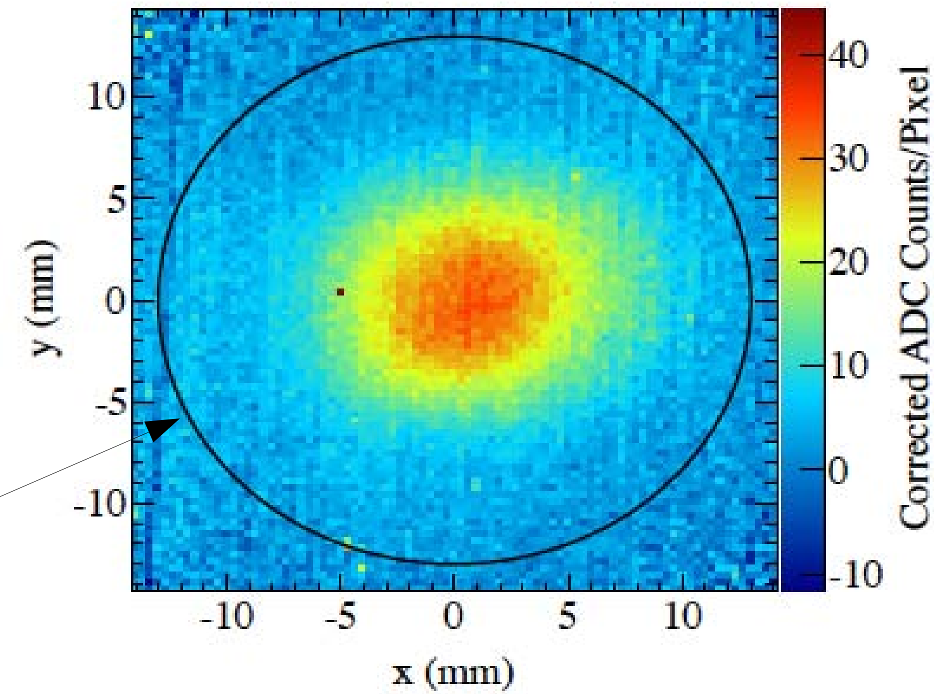
Image light with a radiation hard camera to measure proton beam profile

Description published
Nucl. Instrum. Meth. A Vol. 703, 45 (2013)
10.1016/j.nima.2012.11.044

OTR Monitor Performance

Example OTR for a $9x10^{13}$ proton beam spill

Can make precise measurement of the beam position on the target



Dominant uncertainties are from the alignment of the monitor

Can measure beam position and width to 0.5 mm

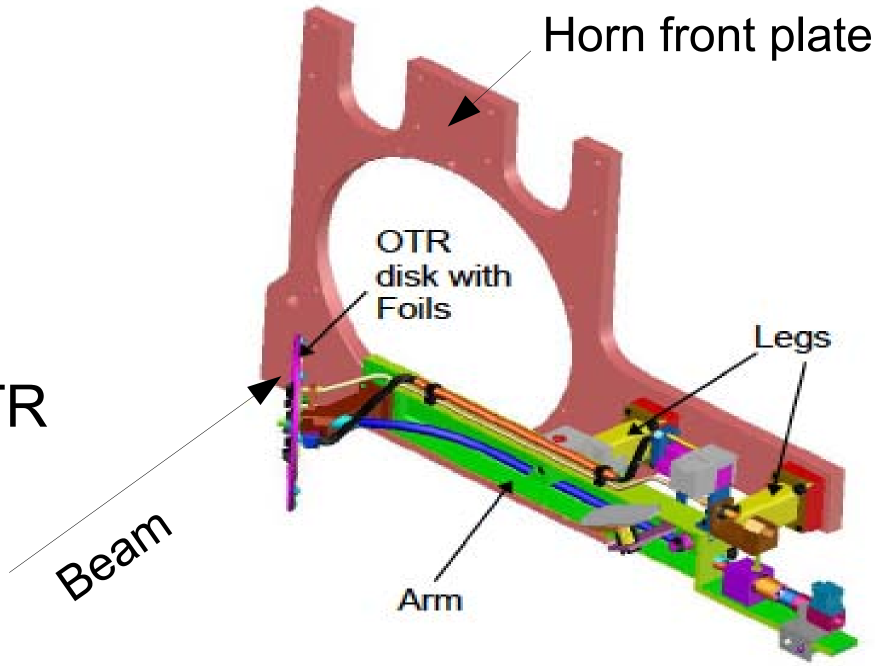
Table 4: Sources of systematic uncertainties for single spill OTR measurements.

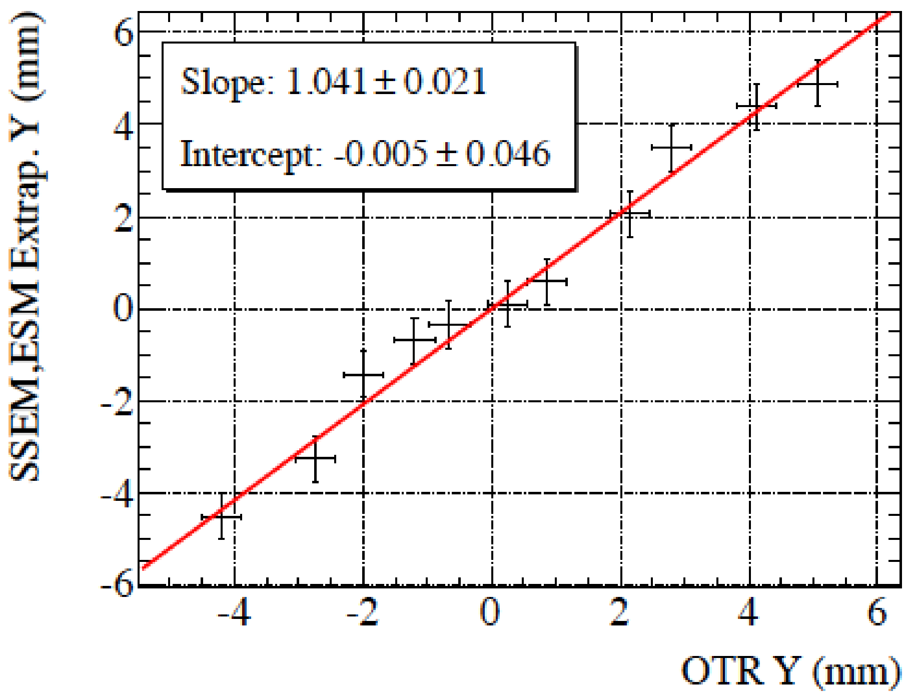
Source	$\delta x(\mu m)$	$\delta y(\mu m)$	$\delta\sigma_x(\mu m)$	$\delta\sigma_y(\mu m)$
Calib. foil alignment	302	300	87	102
Signal model	5	3	436	376
Background model	90	115	10	31
Fitter bias	4	15	105	140
Calib. light alignment	210	251	46	38
Pixel charge decay	101	84	19	30
Distortion correction	29	39	83	111
Others sources	95	57	79	85
Total	404	432	473	441

The OTR Monitor Post-Earthquake

The OTR foils system is attached to the front plate of the first T2K horn (which also contains the target)

If horn/target moved relative to upstream proton beam monitors, OTR should move with them



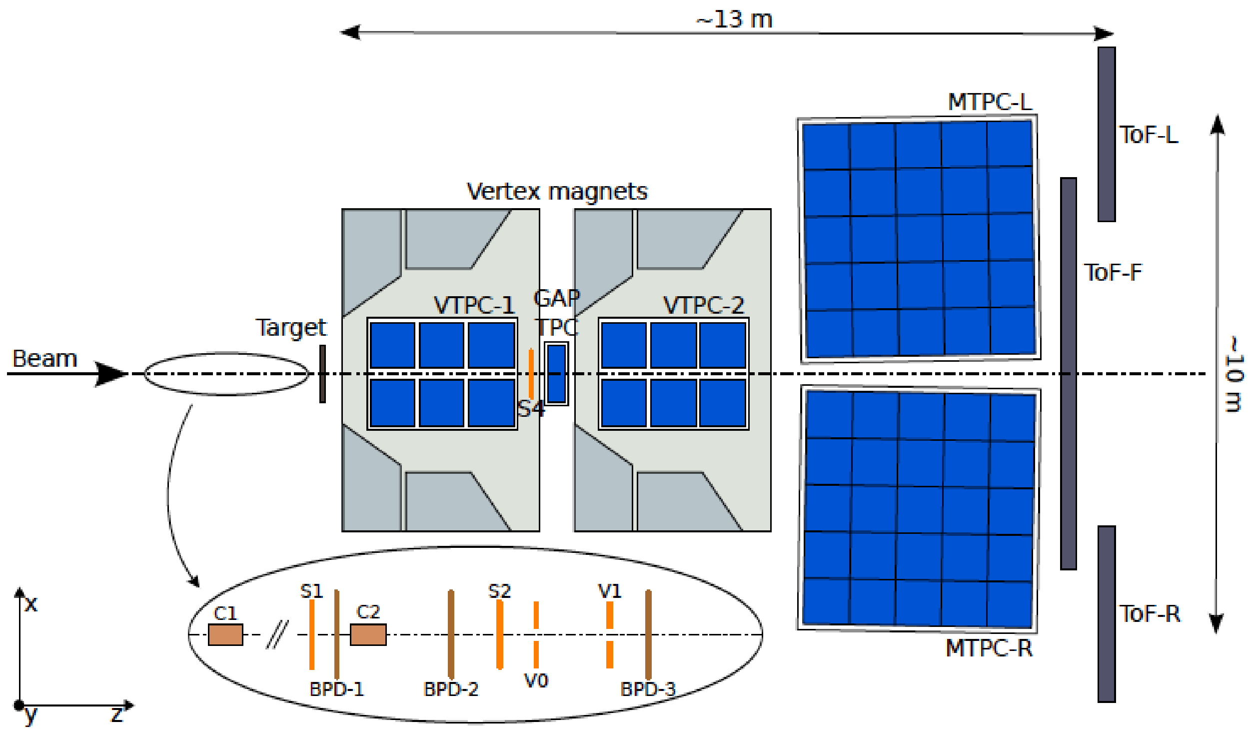


Post-earthquake check:

- Scan the beam across the target
- Check consistency of OTR measurement with extrapolation from upstream monitors
- Good consistency!

NA61 Hadron Production Measurments

Large acceptance spectrometer and time-of-flight detectors



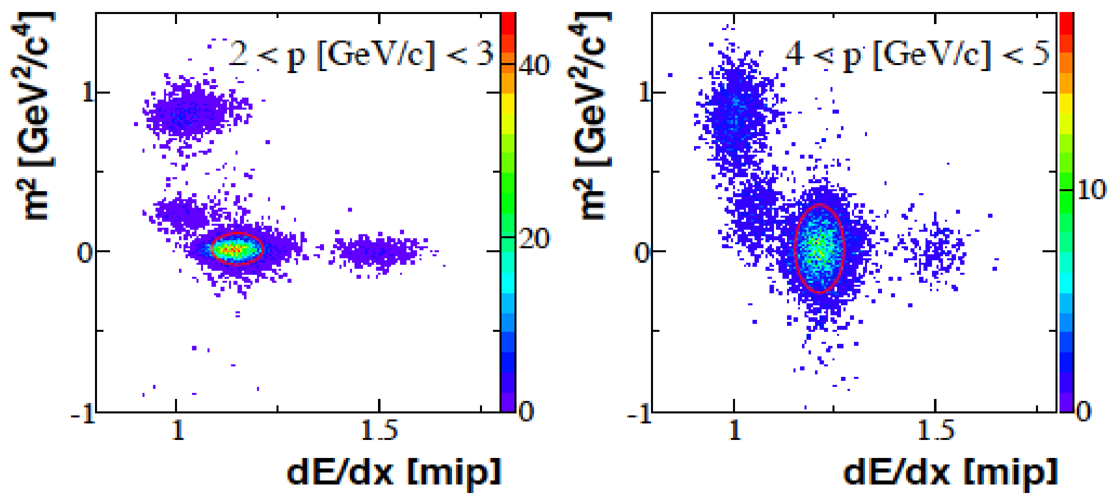
30 GeV proton beam to match T2K

Two target types:

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

Pions and kaons production from thin target used in this analysis

Good TOF and dE/dx performance allows for particle separation

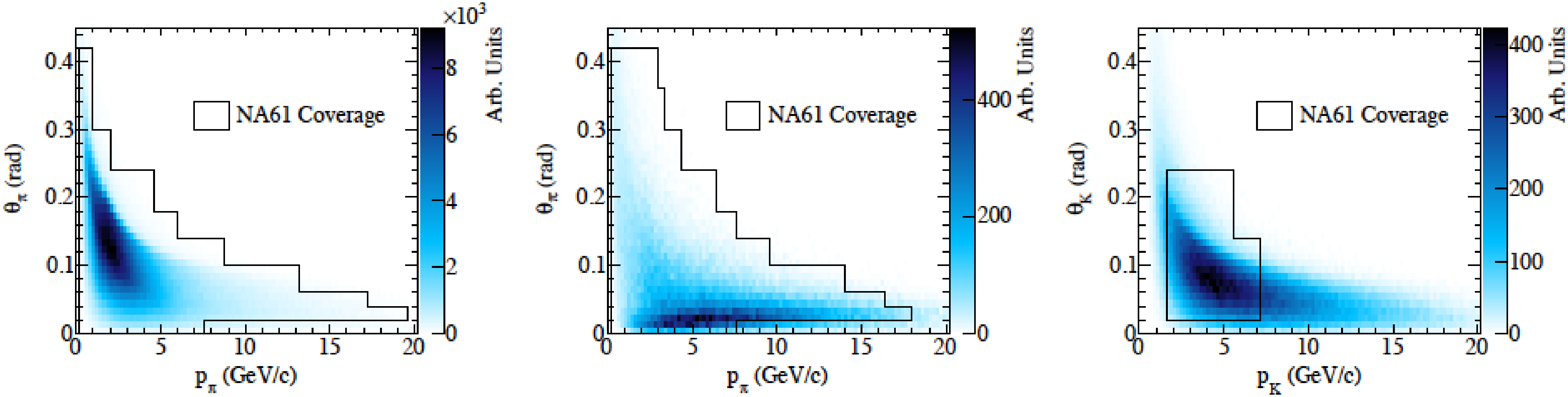


NA61 Measurements

Measure 30 GeV proton cross section on carbon: $\sigma_{prod} = 229.3 \pm 9.2 \quad mb$

Measure differential production of $\pi^{\pm}$ and K^{+}

Phys. Rev. C 84, 034604 (2011)
Phys. Rev. C 85, 035210 (2012)



(a) π^+ (b) π^- (c) K^+

The phase space for which NA61 makes measurements has excellent overlap with the phase space of hadrons that contribute to the T2K flux (blue)

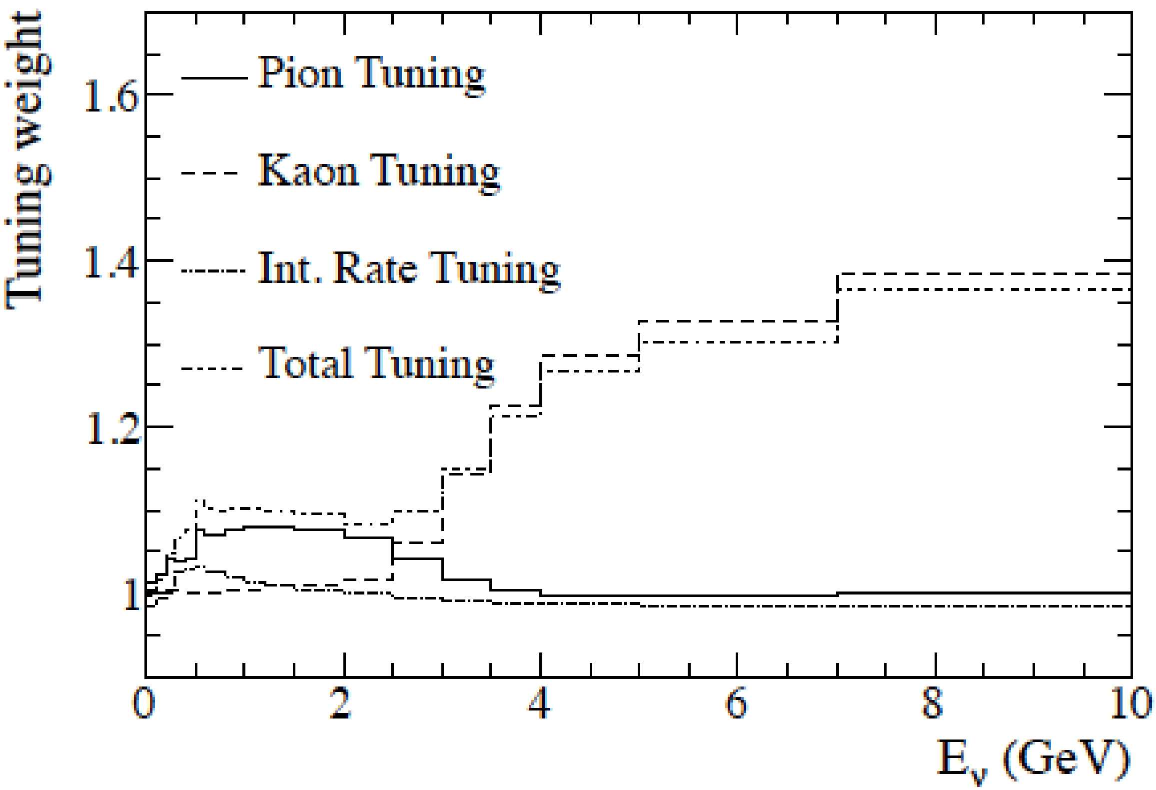
We tune the hadron interactions in the flux simulation to match the NA61 data, propagate uncertainties from the data

Hadron Production Tuning

Effect of pion production tuning is ~8% for flux near spectrum peak

Effect of kaon tuning is ~30% at high energy (FLUKA model underestimates the kaon production)

We also tune the inelastic cross sections for hadrons in the GEANT3 simulation – few % effect

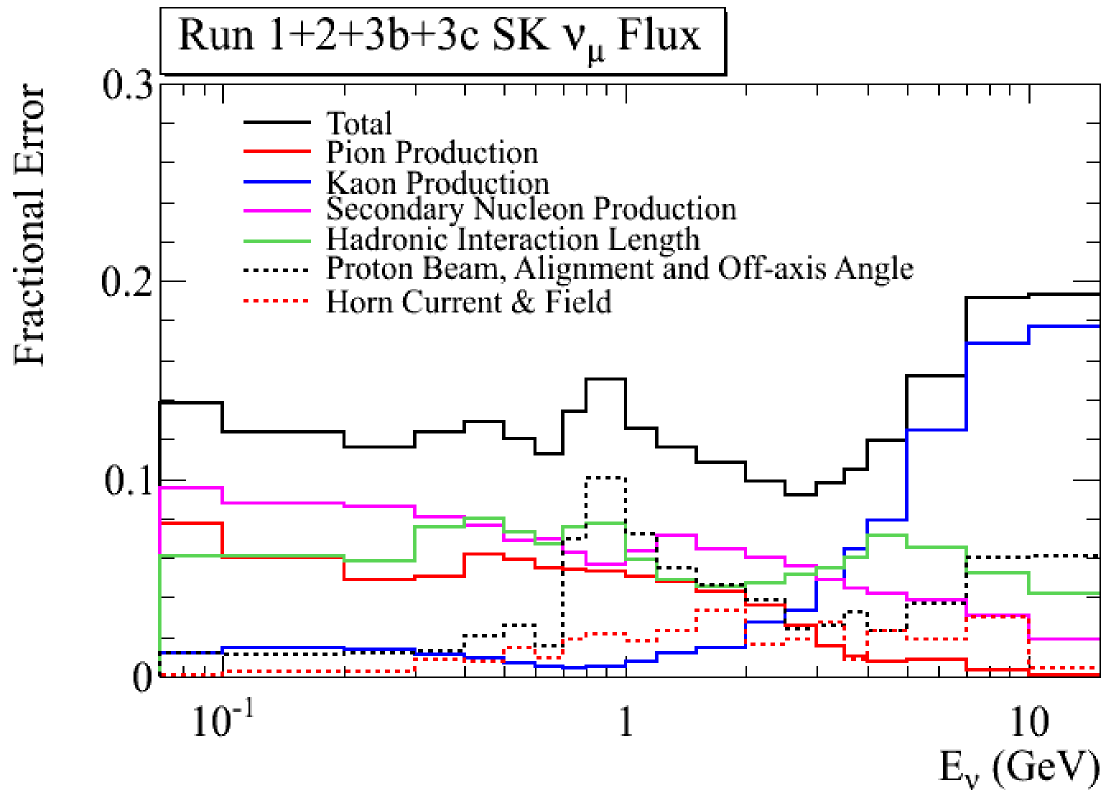


Flux Uncertainties

Flux prediction is controlled to 15% near the spectrum peak

Dominant uncertainties are in the hadron interaction model

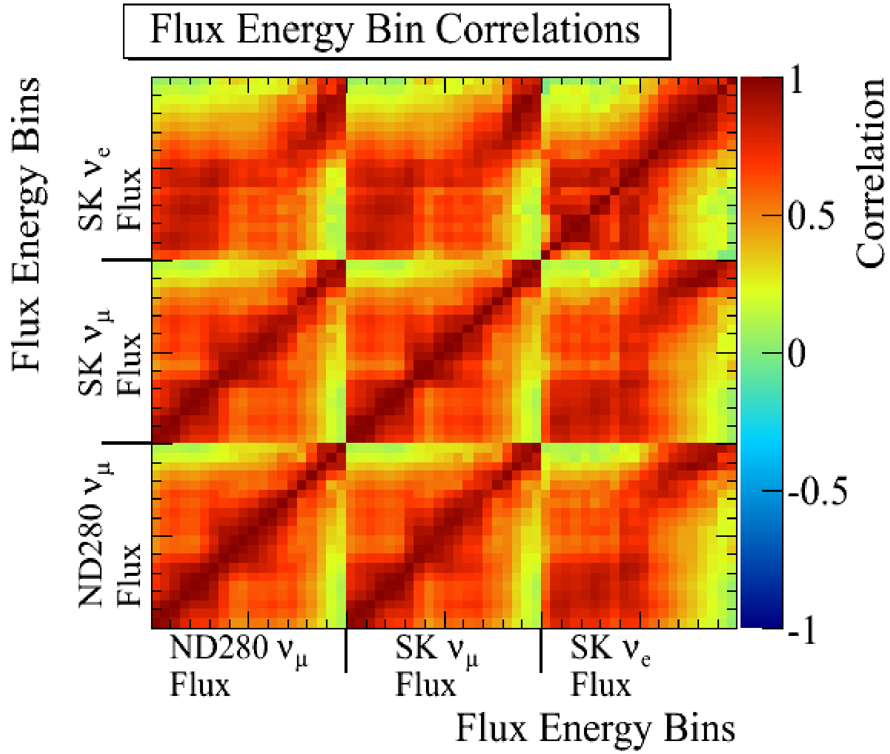
- Propagated from data uncertainties
- Discrepancies between data sets
- Data vs model discrepancies



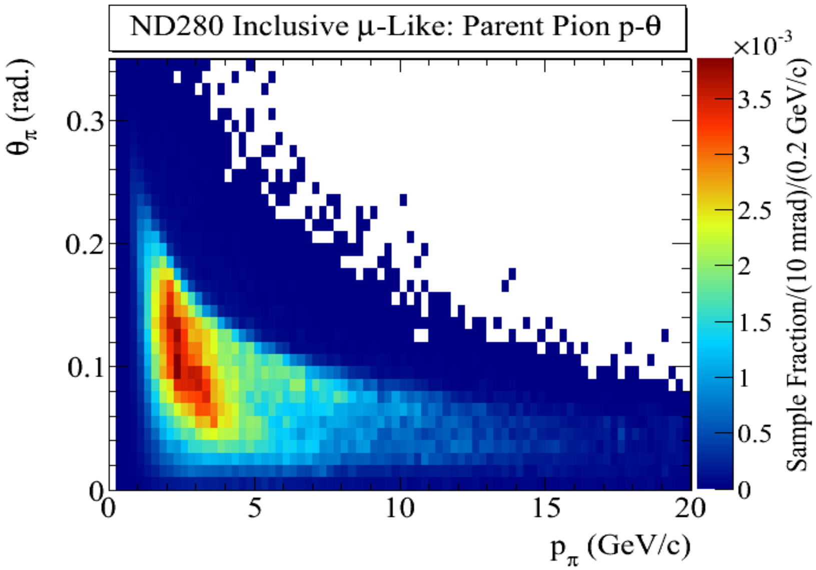
Flux Uncertainty Correlations

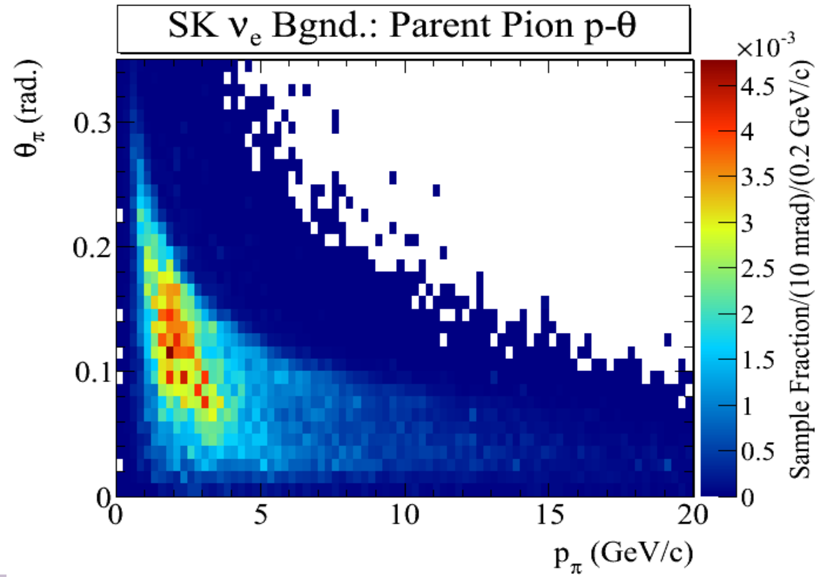
We evaluate the full covariance between bins of the flux prediction at ND280 and SK

Have significant correlations between the ν_μ and ν_e flux predictions – Can constrain the intrinsic ν_e with ν_μ measurements



Significant overlap in the parent pion phase space



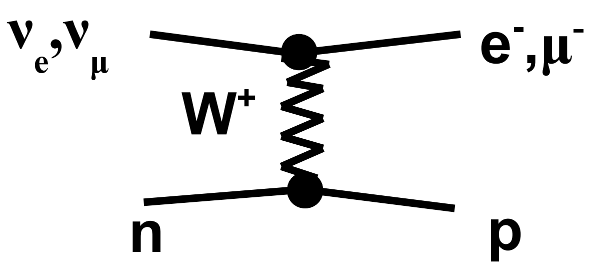


Cross Section Model

Neutrino Interactions at T2K

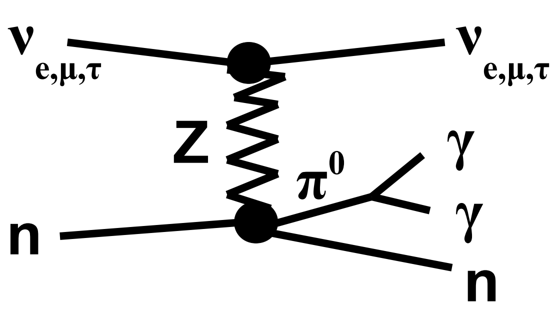
In region of interest for T2K:

Large contribution from charge current quasi-elastic (CCQE)



T2K signal at SK

NCπ^0 is significant background mode:



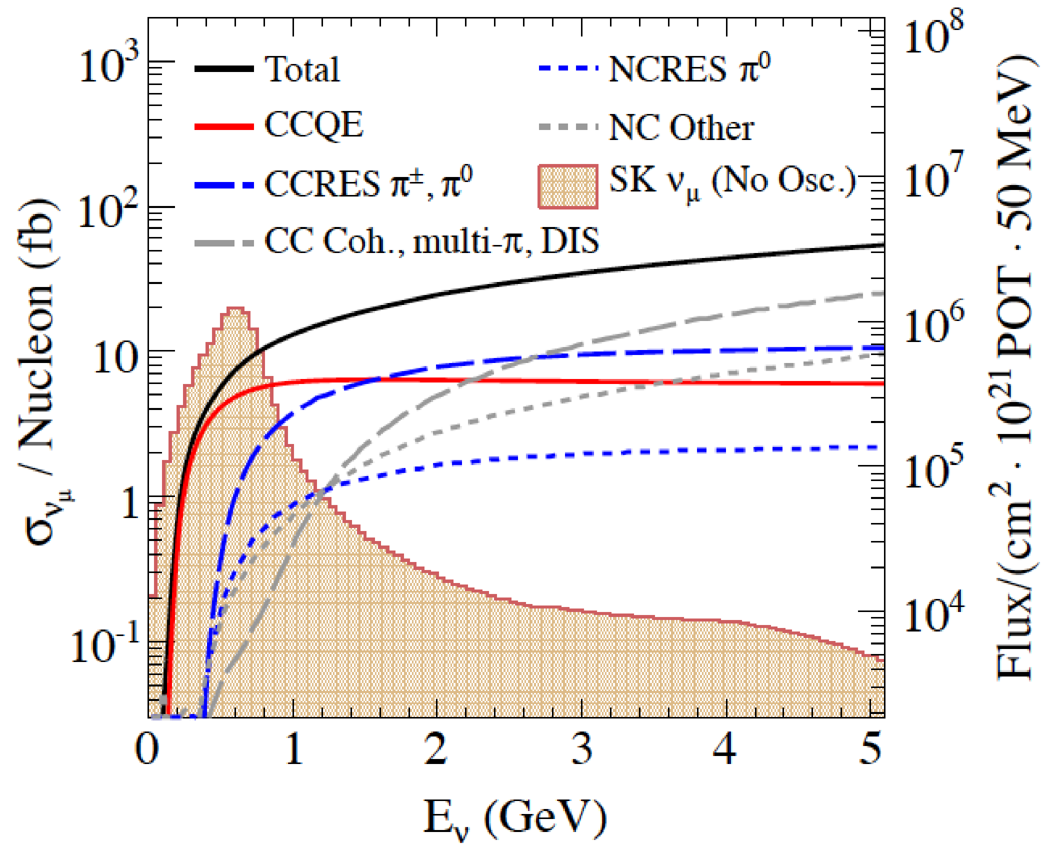
Photons from π^0 can fake an electron

NEUT Neutrino Interaction Generator

Y. Hayato, Acta Phys. Pol. B 40, 2477 (2009)

Use the NEUT interaction generator developed for SK atmospheric analysis

- Interactions of neutrinos on quasi-free nucleons in various nuclei
- CCQE: Relativistic fermi gas model of nucleus, vector and axial-vector form factors for the nucleon
- Pion production: Rein and Sehgal model. Dominant production is by the Δ(1232) resonance.
- Final state interactions: cascade model simulates interactions of hadrons in the nucleus



Cross Section Parametrization

We want to tune the NEUT interaction model based on our near detector data

Define a set of semi-empirical and empirical parameters and set central values and uncertainties based on external data

CCQE Cross Section	
M_A^{QE}	The mass parameter in the axial dipole form factor for quasi-elastic interactions
x_1^{QE}	The normalization of the quasi-elastic cross section for $E_\nu < 1.5$ GeV
x_2^{QE}	The normalization of the quasi-elastic cross section for $1.5 < E_\nu < 3.5$ GeV
x_3^{QE}	The normalization of the quasi-elastic cross section for $E_\nu > 3.5$ GeV
Nuclear Model for CCQE Interactions (separate parameters for interactions on O and C)	
x_{sf}	Smoothly changes from a relativistic Fermi gas nuclear model to a spectral function model
p_F	The Fermi surface momentum in the relativistic Fermi gas model
Resonant Pion Production Cross Section	
M_A^{RES}	The mass parameter in the axial dipole form factor for resonant pion production interactions
$x_1^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu < 2.5$ GeV
$x_2^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu > 2.5$ GeV
$x^{NC1\pi^0}$	The normalization of the NC1π^0 cross section
$x_{1\pi E_\nu}$	Varies the energy dependence of the 1π cross section for better agreement with MiniBooNE data
W_{eff}	Varies the distribution of $N\pi$ invariant mass in resonant production
$x_{\pi-less}$	Varies the fraction of Δ resonances that decay or are absorbed without producing a pion
Other	
$x^{CCcoh.}$	The normalization of CC coherent pion production
$x^{NCcoh.}$	The normalization of NC coherent pion production
$x^{NCother}$	The normalization of NC interactions other than NC1π^0 production
$x_{CCother}$	Varies the CC multi-π cross section normalization, with a larger effect at lower energy
$\vec{x}_{FSI}$	Parameters that vary the microscopic pion scattering cross sections used in the FSI model
x_{ν_e/ν_μ}	Varies the ratio of the CC ν_e and ν_μ cross sections

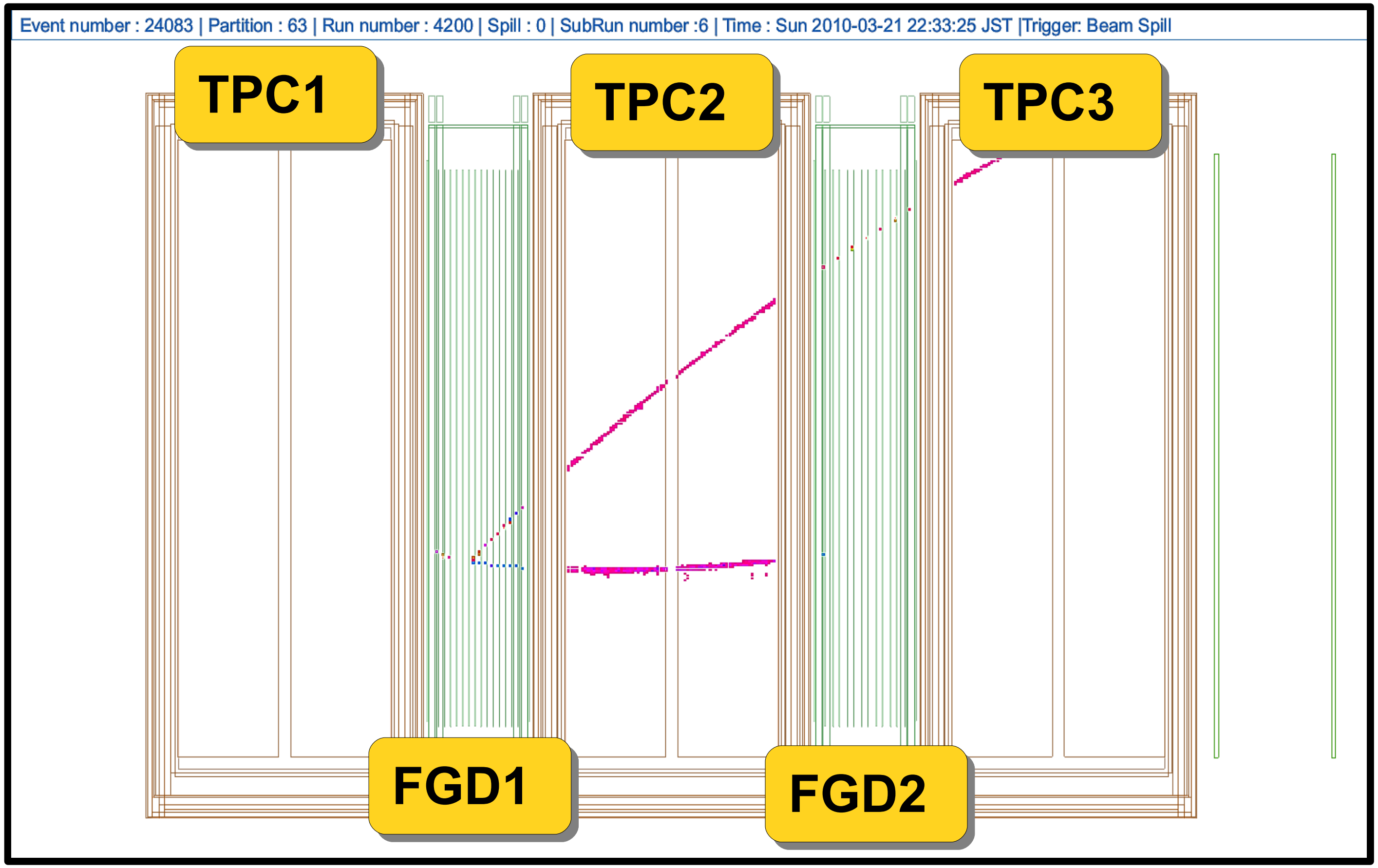
ND280 Data and Constraint

ND280 Tracker ν_μ Sample

Interactions in the FGD1

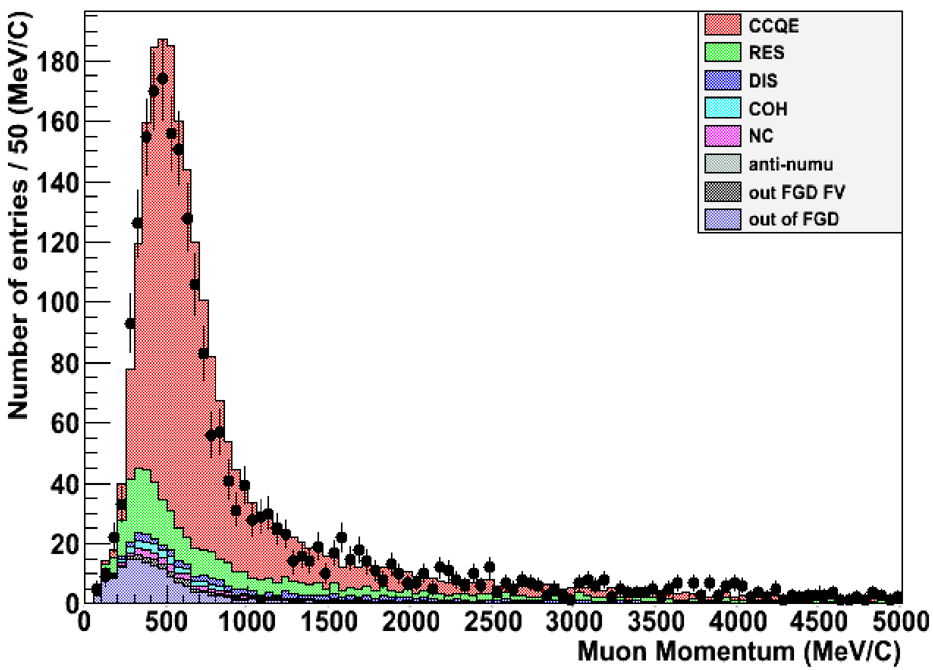
Highest momentum negative track in TPC2 is identified as muon by dE/dx

Split into CCQE-like and CCnonQE-like samples – based on presence of additional tracks that could be pions, or Michel electron candidates in FGD1

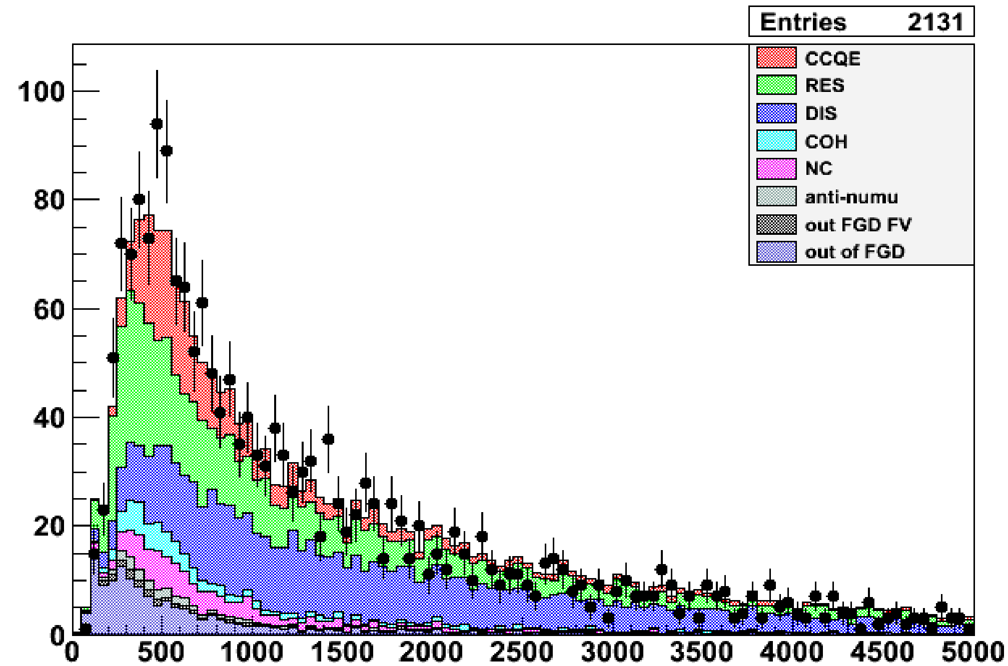


ND280 Tracker ν_μ Data

CCQE Enhanced Selection



CCnonQE Enhanced Selection



For 1.08×10^{20} POT:

2352 CCQE-like events

2132 CCnonQE-like events

The CCQE-like selection gives a sample that is 70% CCQE in the NEUT based simulation

Fit to ND280 Tracker Data

Data is divided into 20 muon p,cosθ bins for each selection (40 bins total)

Construct a binned likelihood that depends on nuisance parameters that vary the neutrino flux and cross section models, as well as the detector model

Flux, cross section and detector nuisance parameters

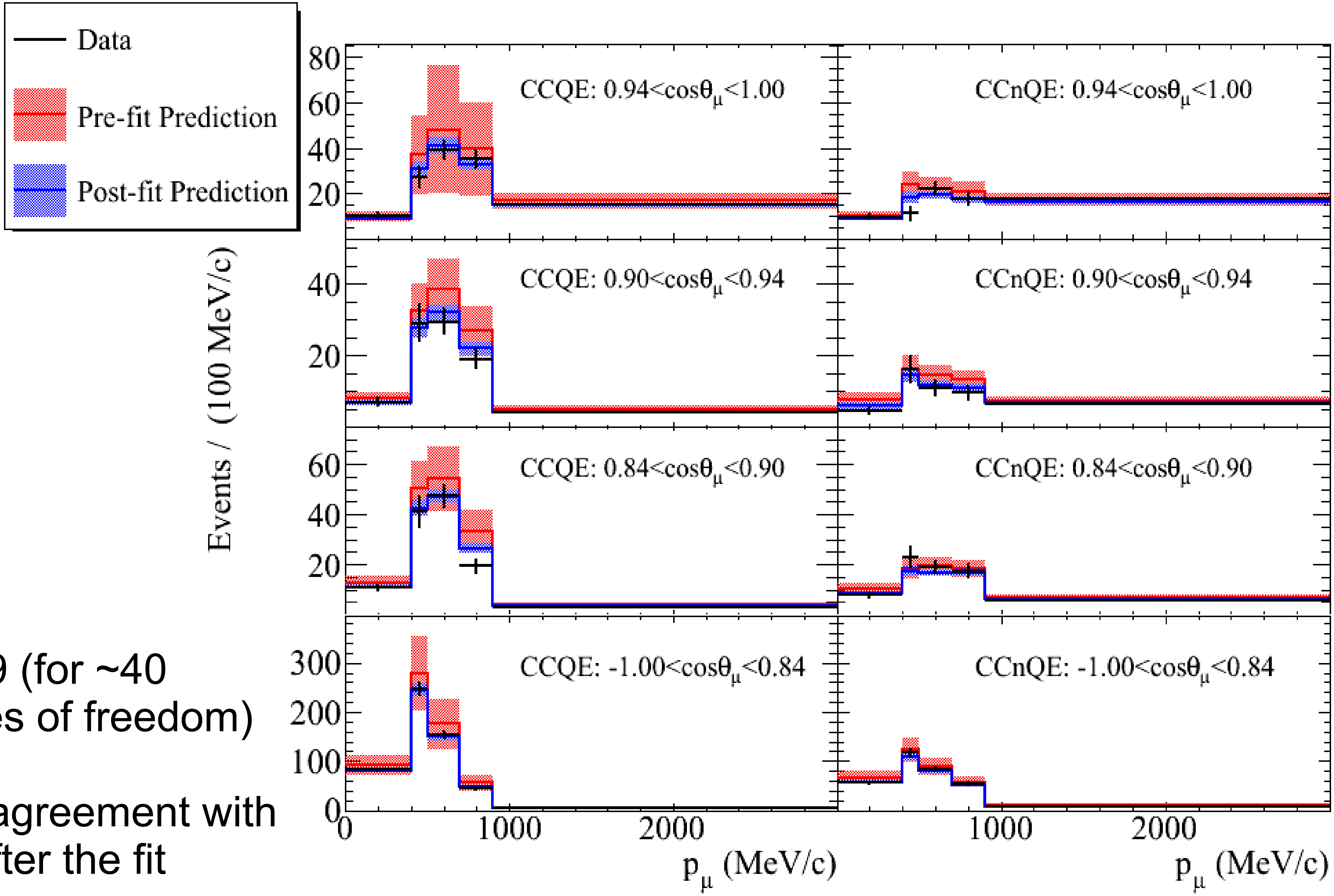
$$-2\ln(L)=2\sum_{i}^{p,\theta\ bins} N_i^{pred}(\boxed{\vec{b},\vec{x},\vec{d}})-N_i^{data}+N_i^{data}\ln[N_i^{data}/N_i^{pred}(\vec{b},\vec{x},\vec{d})]$$

$$\left.\begin{aligned}&+\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins}(1-b_i)(V_b^{-1})_{i,j}(1-b_j)+\sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars}(x_i^{nom}-x_i)(V_x^{-1})_{i,j}(x_j^{nom}-x_j)\\&+\sum_{i}^{p,\theta\ bins}\sum_{j}^{p,\theta\ bins}(1-d_i)(V_d(\vec{b},\vec{x})^{-1})_{i,j}(1-d_j)+\ln\left(\frac{|V_d(\vec{b},\vec{x})|}{|V_d^{nom}|}\right)\end{aligned}\right\}$$

Prior constraints on the nuisance parameters

Maximize the likelihood while varying the nuisance parameters

Results of Fit to ND280 Tracker Data



$\Delta\chi^2$=29 (for ~40 degrees of freedom)

Good agreement with data after the fit

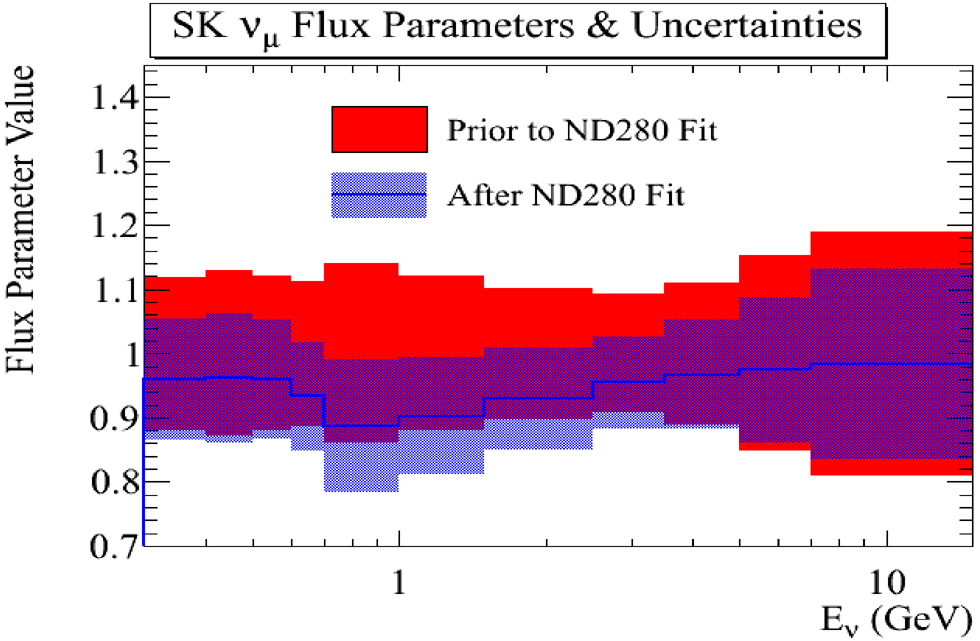
Fitted Parameter Values

Constrained cross section parameters used to predict SK event rates

	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CC1π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40

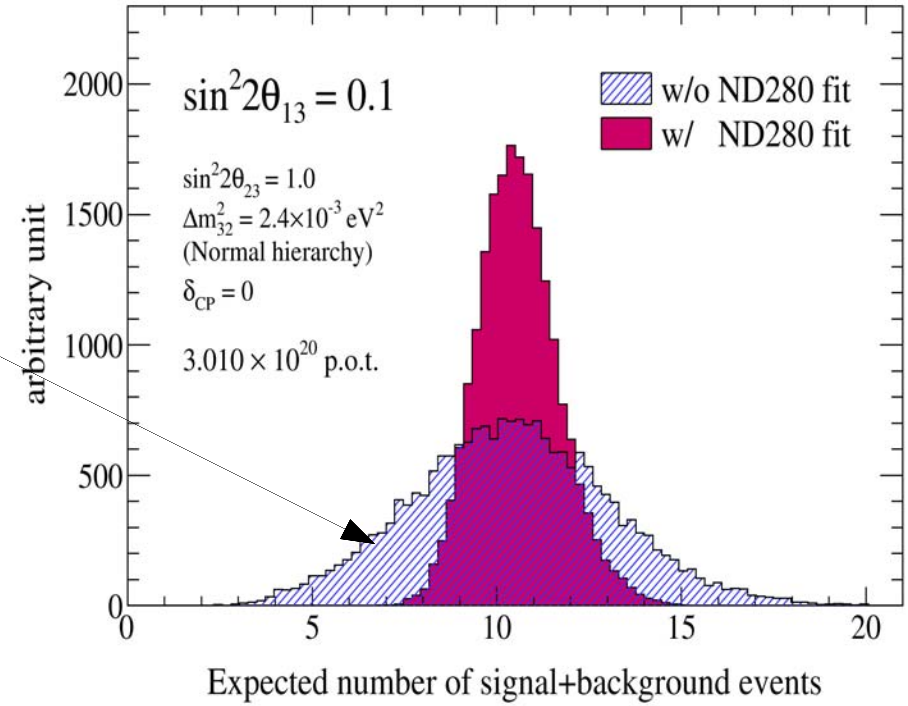
Prior value and uncertainty from fit to MiniBooNE single pion samples

The flux prediction is decreased, but within its prior uncertainty



Effect on SK Prediction

Uncertainty of 26% on the signal+background prediction is reduced to 10% by using the constraint from the near detector data



Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

Uncertainties from parameters constrained by fit to ND280 data

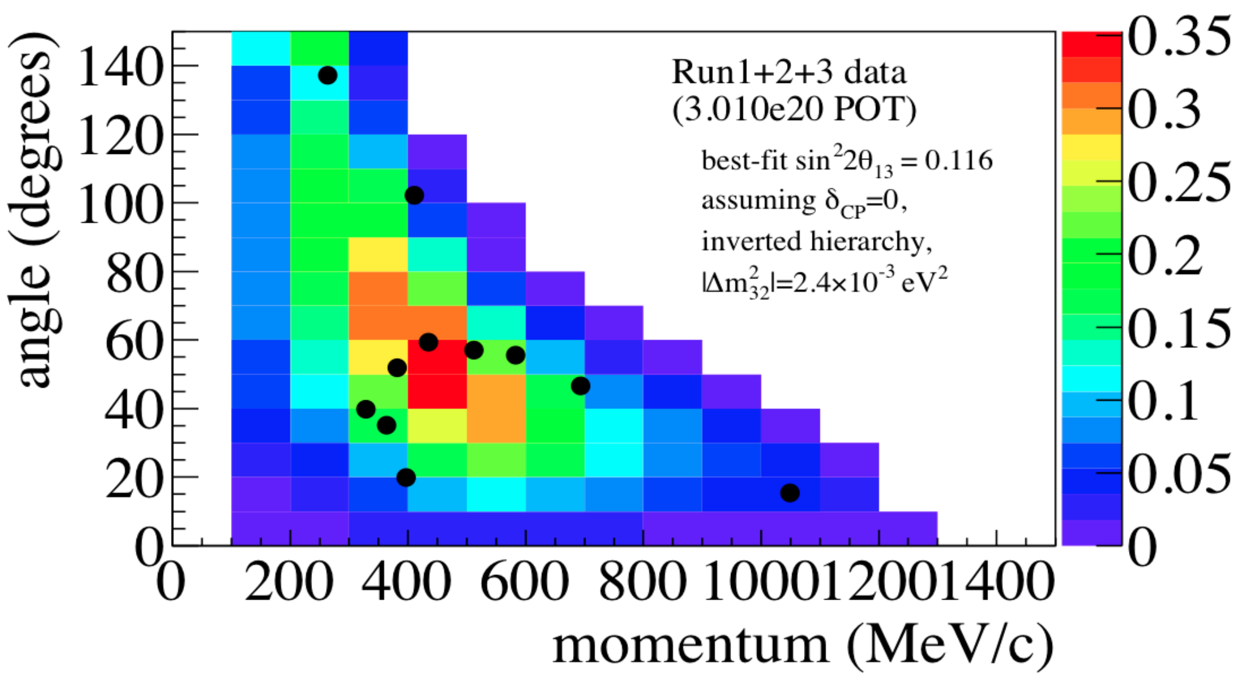
Appearance Fit Results

Event category	The predicted number of events $\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22	10.71
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background	1.21	1.21
$\overline{\nu}_\mu$ background	0.07	0.07
$\overline{\nu}_e$ background	0.09	0.09

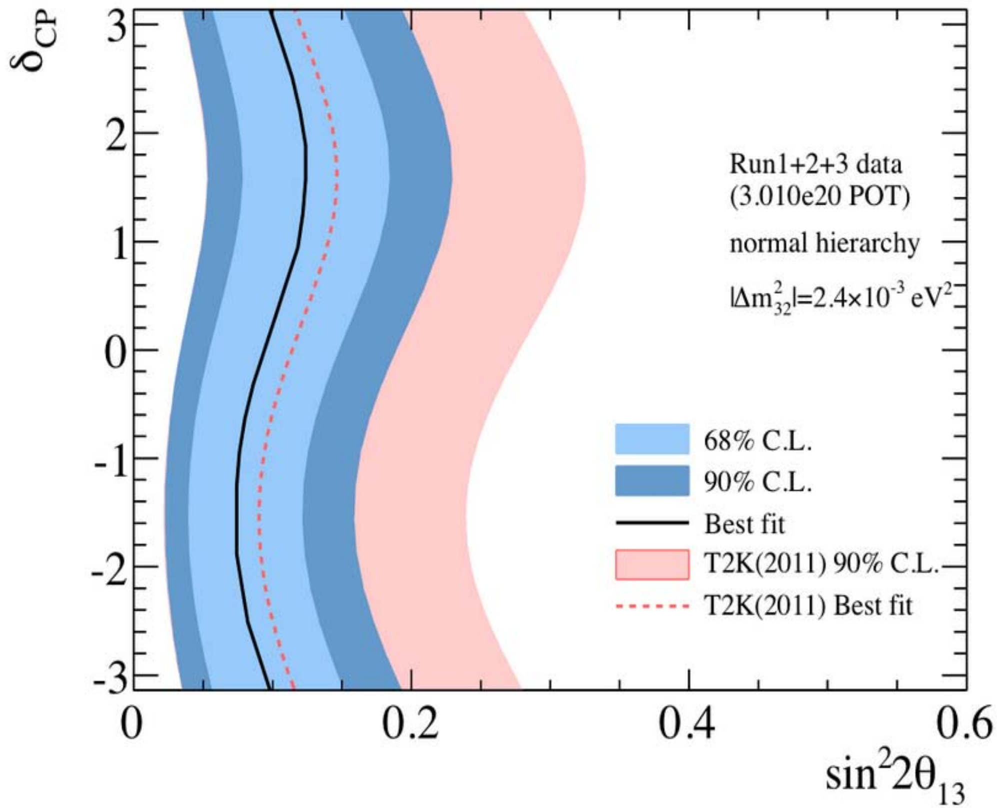
Predominantly neutral current

For 3.01×10^{20} POT
11 events observed!

Electron p,θ for 11 observed events and best fit prediction



Oscillation Parameter Results



All with $\sin^2(\theta_{23})$ fixed to 0.5

Result is consistent with 2011 T2K result with reduction in error band (largely from increased statistics)

New T2K results for the disappearance measurement are coming soon

Normal hierarchy		
Best fit value of $\sin^2 2\theta_{13}$	0.094	0.11
90 % C.L. allowed region	$0.033 < \sin^2 2\theta_{13} < 0.188$	$0.03 < \sin^2 2\theta_{13} < 0.28$
68 % C.L. allowed region	$0.054 < \sin^2 2\theta_{13} < 0.147$	$0.05 < \sin^2 2\theta_{13} < 0.21$
Inverted hierarchy		
Best fit value of $\sin^2 2\theta_{13}$	0.116	0.14
90 % C.L. allowed region	$0.041 < \sin^2 2\theta_{13} < 0.228$	$0.04 < \sin^2 2\theta_{13} < 0.34$
68 % C.L. allowed region	$0.067 < \sin^2 2\theta_{13} < 0.179$	$0.07 < \sin^2 2\theta_{13} < 0.26$

The Future

T2K's Future

Current schedule of J-PARC protons delivered to T2K

What we expect by summer 2013 → June 2013

Expected ultimate exposure → June 2021

Period	Accumulated Protons On Target	Beam Power
June 2012	3.1×10^{20}	170 kW
June 2013	7.8×10^{20}	200 kW
June 2014	1.2×10^{21}	250 kW[1]
June 2015	1.8×10^{21}	250 kW
June 2016	2.5×10^{21}	300 kW
June 2017	3.2×10^{21}	300 kW
June 2018	3.9×10^{21}	300 kW
June 2019	5.5×10^{21}	700 kW[2]
June 2020	7.1×10^{21}	700 kW
June 2021	8.8×10^{21}	700 kW

Will have ~30x the current POT

If all in neutrino mode, expect ~300 appearance candidates

Statistical errors <10% - need to work to reduce systematic uncertainties

T2K Appearance Error Breakdown

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3

Total= 5.7

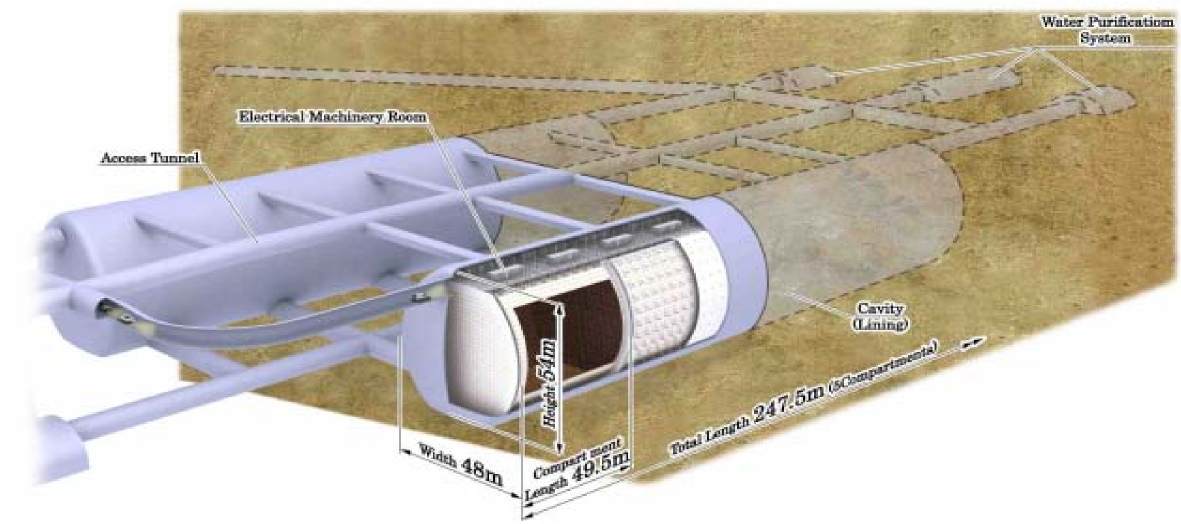
Constrained by fit to ND280 data

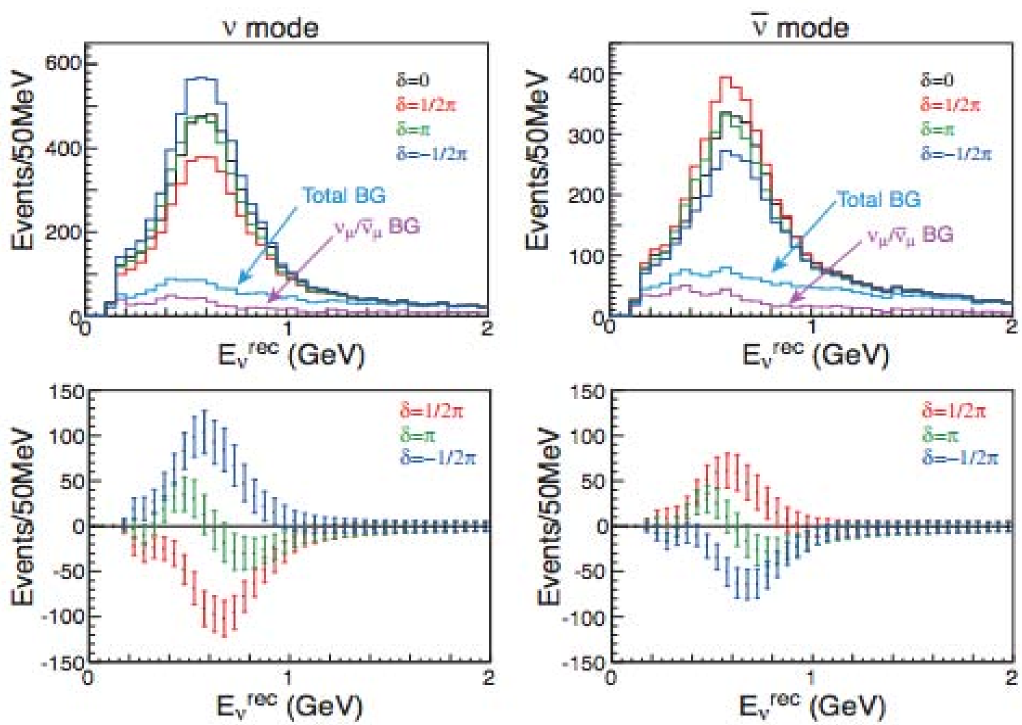
Nuclear model uncertainties. Near detector data on O targets to constrain & improved model

Need measurement of ν_e cross section

Final state looks CCQE-like, but larger energy transfer to hadronic system

Beyond T2K





Hyper-K – proposed 1 Megaton water Cherenkov detector

Same baseline from J-PARC accelerator as SK

Measure δ_{CP} by running with both neutrino and antineutrino beams

Appearance signal candidates for 1.5 years neutrino mode and 3.5 years antineutrino mode (1.6 MW beam)

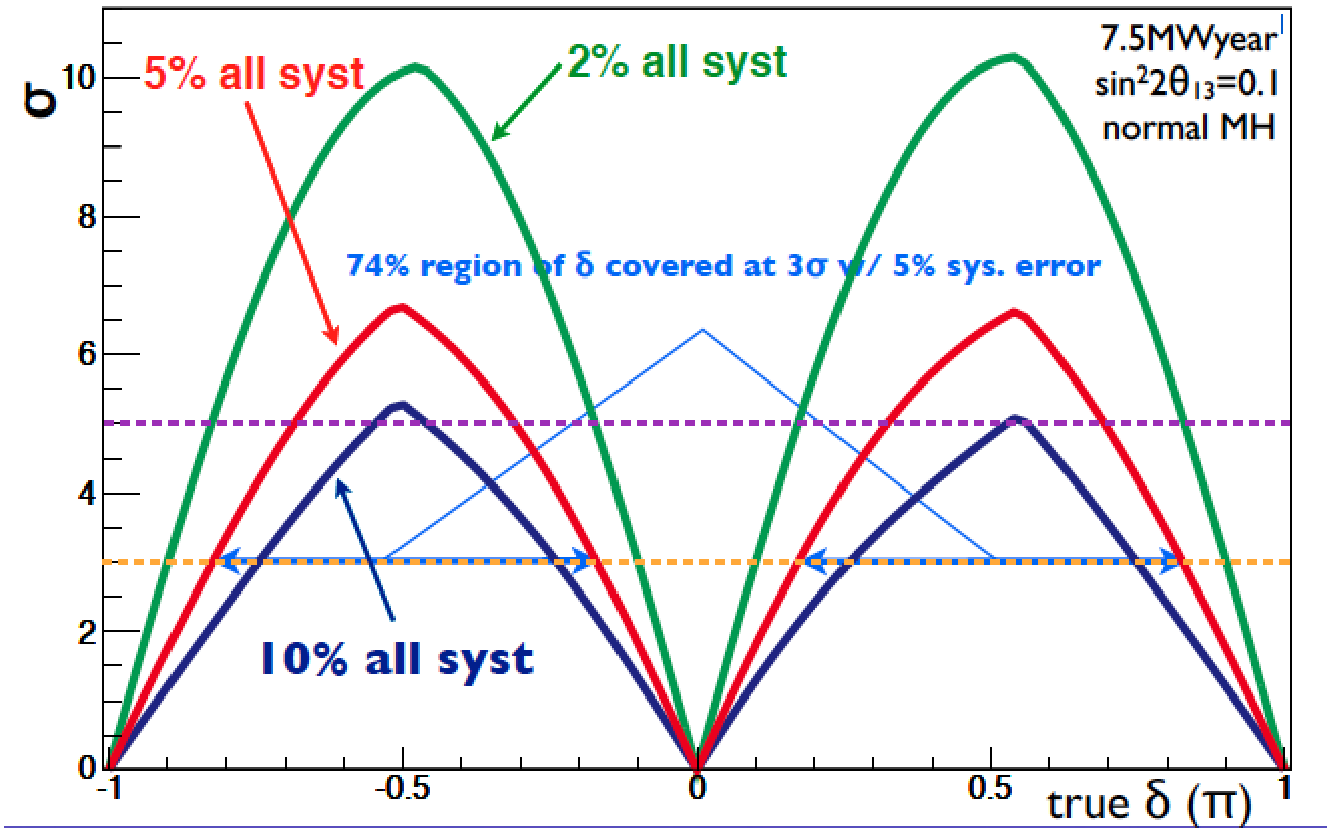
($\sin^2 2\theta_{13}$=0.1)

Hyper-K LOI:

arXiv:1109.3262

Hyper-K Sensitivity

M. Yokoyama
2nd Open Meeting for the Hyper-K Project



With 5% systematic uncertainties, can exclude non-CP violating case for 74% of the values of δ_{CP} at 3σ

Clear improvement if systematics are reduced to 2%

It is a waste of the statistical power in the Hyper-K data sets if we can only achieve 5% systematic errors

Need to study T2K performance and consider how uncertainties can be reduced

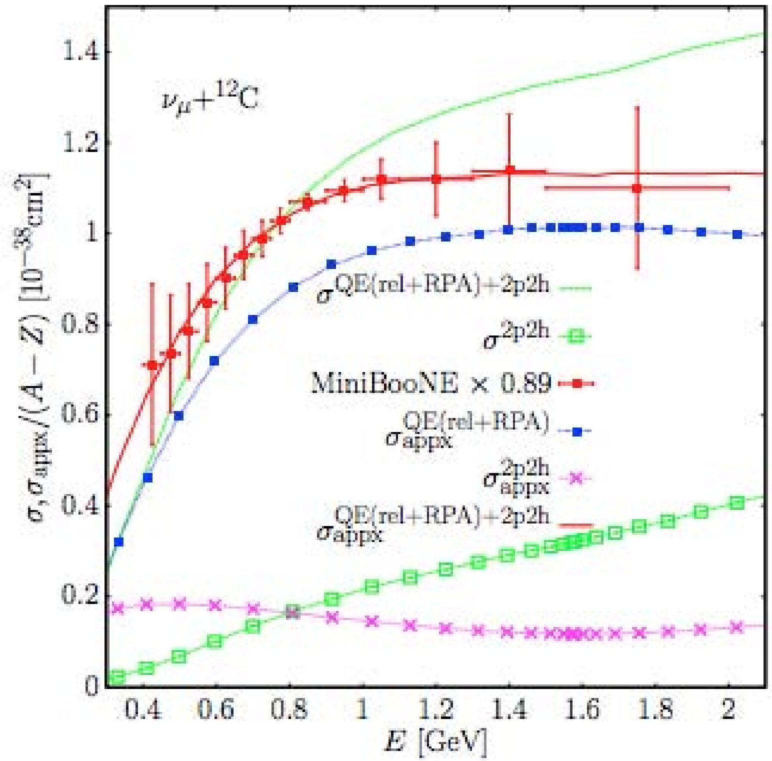
Discuss two important uncertainties on the following slides...

Multinucleon Interactions

Current neutrino interaction generators model scattering off of a single bound nucleon

Some evidence of electron scattering off correlated nucleons – Jlab sees multinucleon final states ~20% of the time

Nieves, et. al.
Phys.Rev. D85 (2012) 113008



In water Chereknov detectors, nucleons are typically below threshold, not detected – multinucleon looks like QE

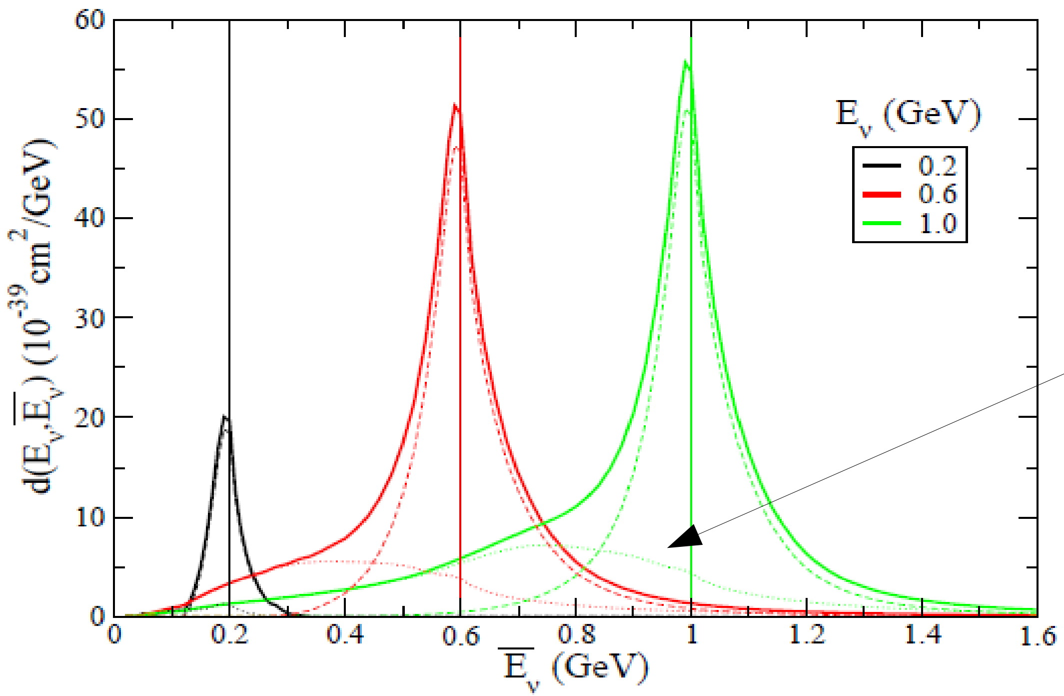
May explain why MiniBooNE sees an excess over predictions for the QE cross section and extracts an axial mass of 1.35 GeV

Energy Reconstruction

Relationship between the lepton kinematics and neutrino energy is important:

- We measure the lepton
- The oscillation probability depends on the neutrino energy

If we reconstruct the neutrino energy of multinucleon interactions under the QE assumption, the distribution is biased



Martini et. al.
np-nh multinucleon model
arXiv:1211.1523

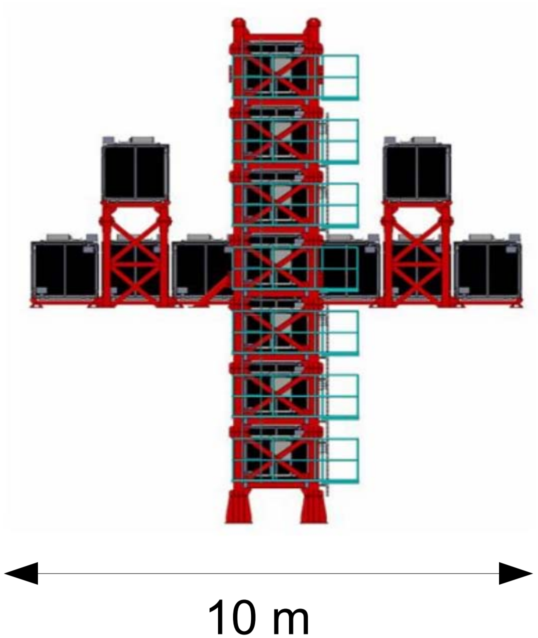
Low side tail is from multinucleon interactions

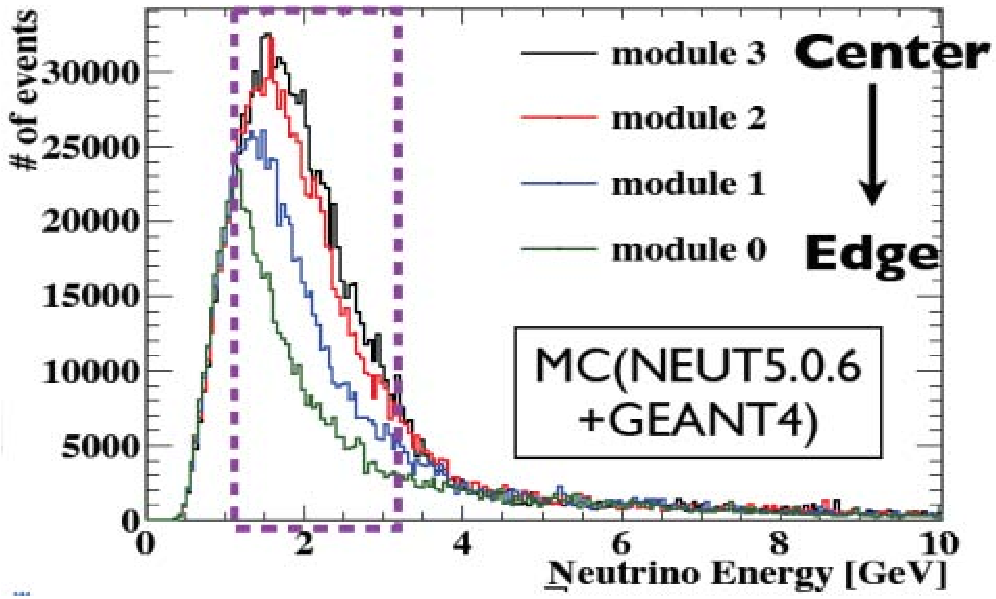
Measuring the Multinucleon Effect

Can investigate the lepton in the final state

- In ideal case of mono-energetic neutrino beam, we can directly measure the relationship between the lepton and neutrino
- In practice the beam has a broad spectrum that “smears” these effects
- Can we use the off-axis effect to “unfold” the spectrum smearing?

Already being done with T2K INGRID on-axis detector





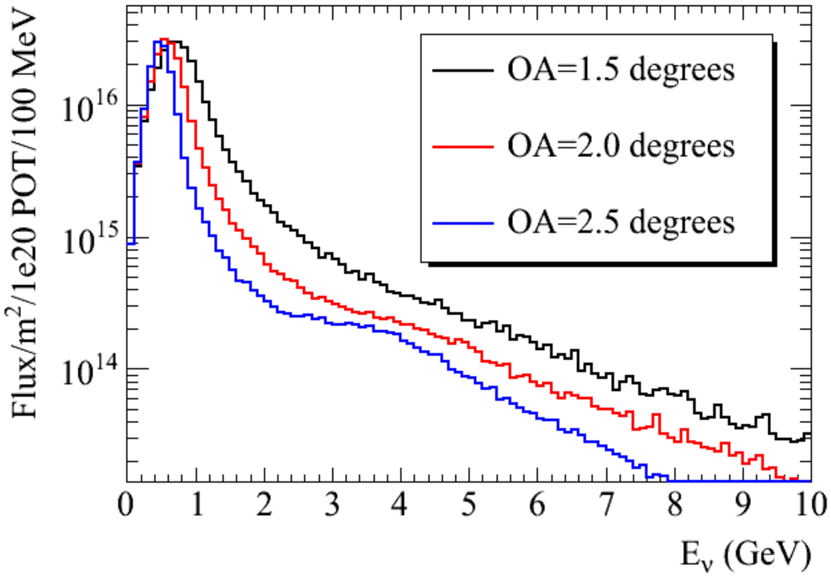
Extend to larger off-axis angles → lower energy

Application to Larger Off-axis Angles

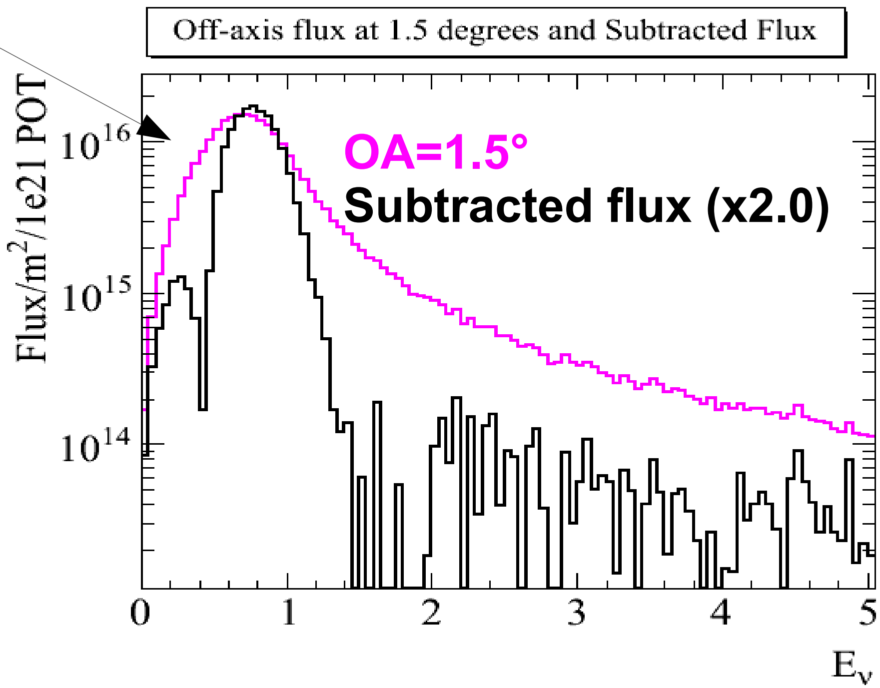
Ongoing studies by K. McFarland and M. Hartz to apply method over a larger range of off-axis angles

Principle of method can be seen in simple linear combinations of the fluxes

$$\phi_{\mathrm{sub}} = \phi(1.5^{\circ}) - 0.34\,\phi(1.0^{\circ}) - 0.42\,\phi(2.5^{\circ})$$



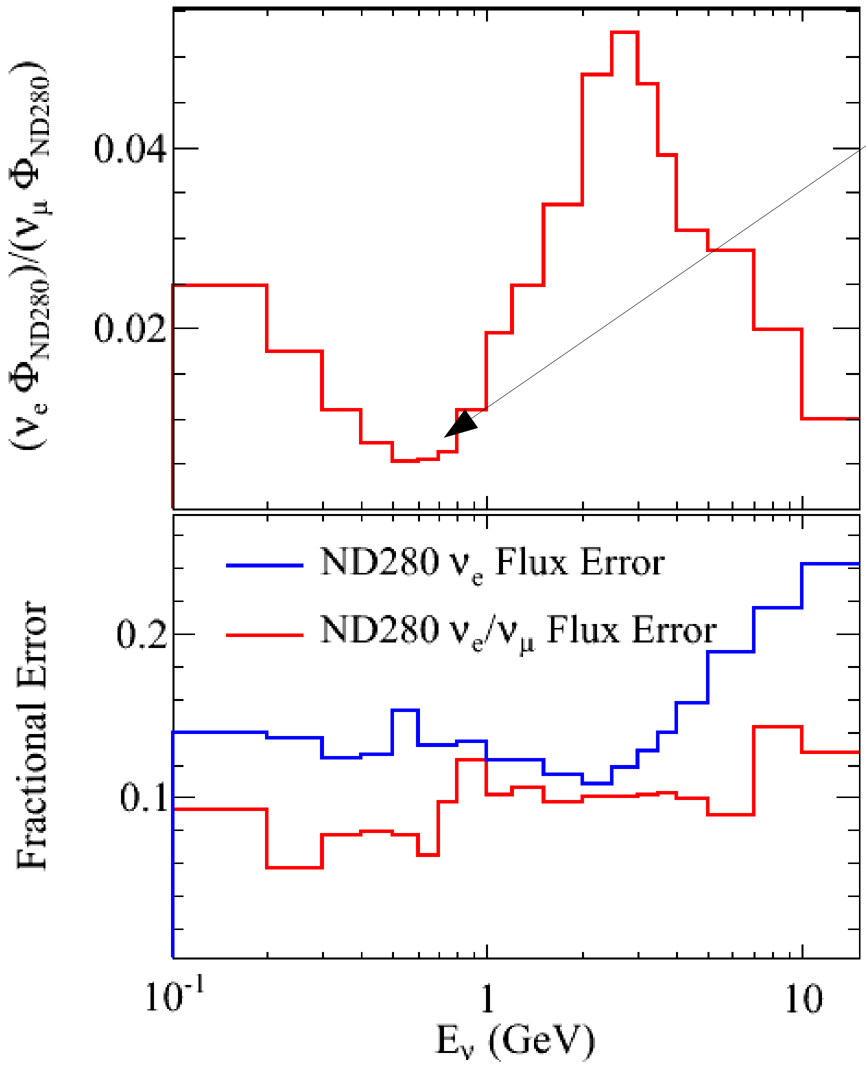
In practice, we will attempt to use a simultaneous fit to pseudo-experiments from a range of off-axis angles to extract model independent relationships between the neutrino energy and lepton kinematics



Stay tuned for more!

Measuring the ν_e Cross Section

Can we measure the ν_e cross section to a few % or better at near detectors using the intrinsic ν_e contamination?



The intrinsic ν_e contamination of the flux is <1% near the peak

Need to reduce backgrounds from NCπ^0 and misidentified muons

Flux uncertainty relative to ν_μ is important – Since near detector constraint comes from ν_μ interactions

Reduced by almost ½ compared to ν_e uncertainty

Irreducible off-axis angle uncertainties – 2 vs 3 body decay

Proposed T2K 2 km WC Detector

A 1 kton water Cherenkov detector for T2K was proposed, but not built

From proposal: studied the measurement of the ν_e contamination

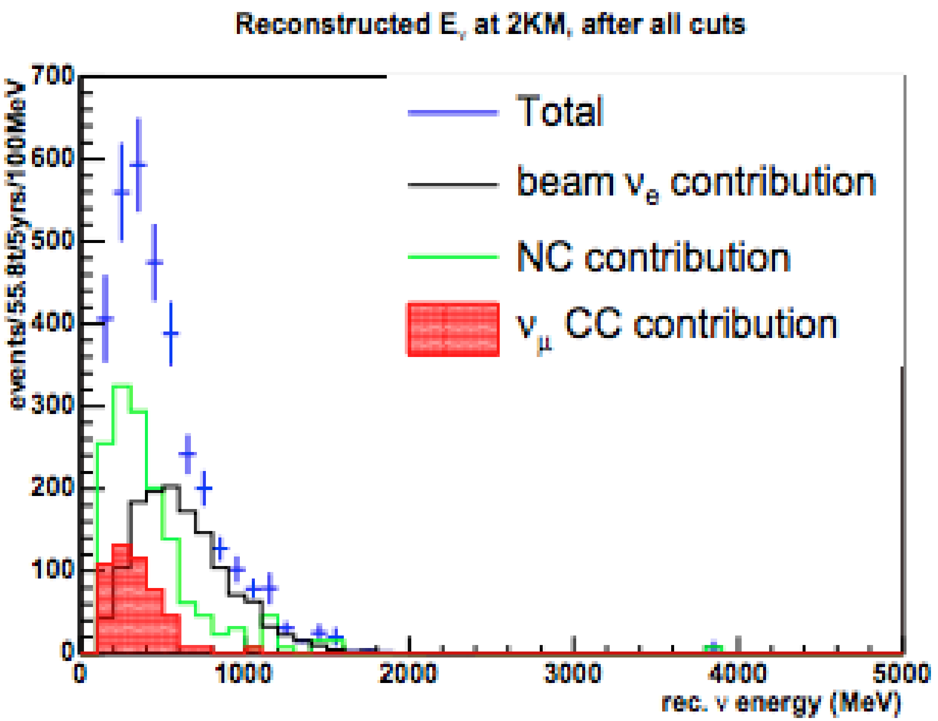
879 ν_e events with reconstructed energy between 0.35 and 0.85 GeV

NC background 641

CC ν_μ background 213

Conclusion: need more statistics and better electron separation from muons and π^0

For 5×10^{21} POT, 55.8 ton FV



ND280 ν_e Measurement

Selection:

Interactions in both FGDs

Select electron candidates from dE/dx in the TPC

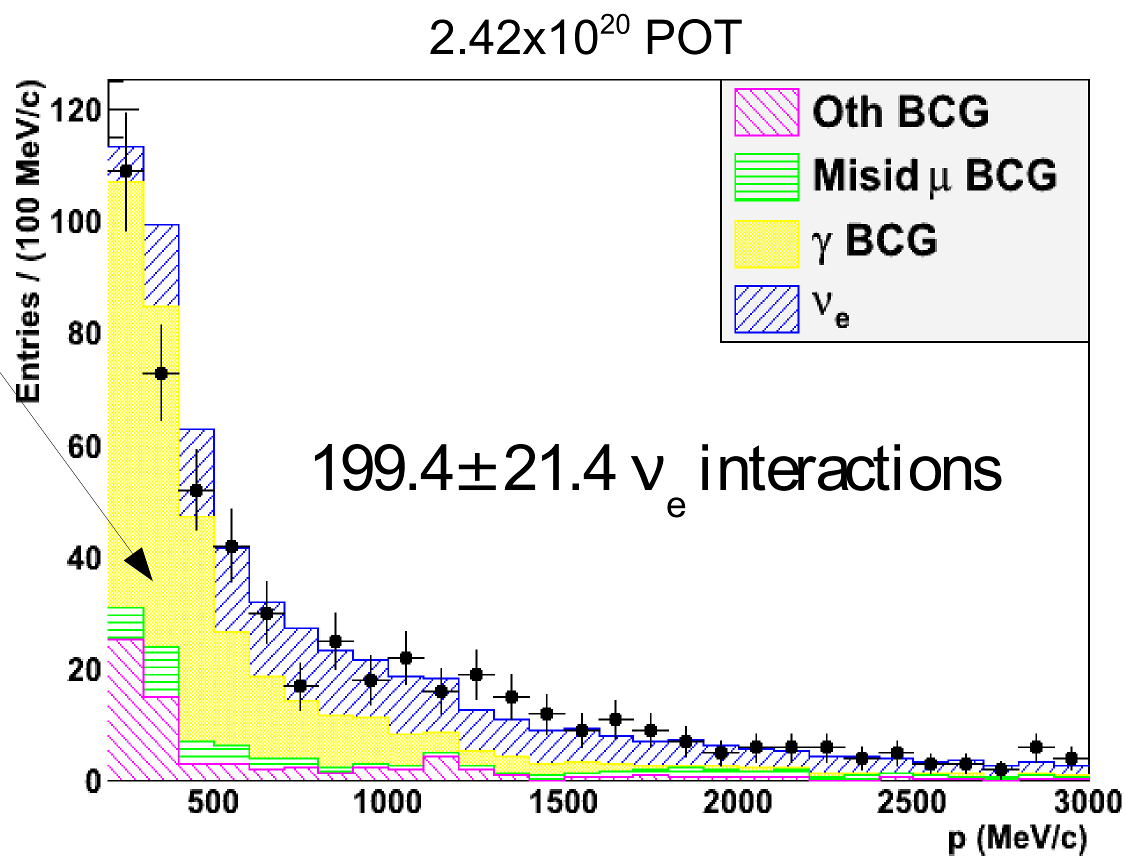
If electron candidate interacts in ECAL, require electron like shower

Reject events with additional electron track consistent with photon conversion

Large photon conversion background at low momentum

Most electrons from higher energy neutrinos produced in kaon decays (~80%)

Need to reduce the photon conversion background – use activity at the interaction vertex?

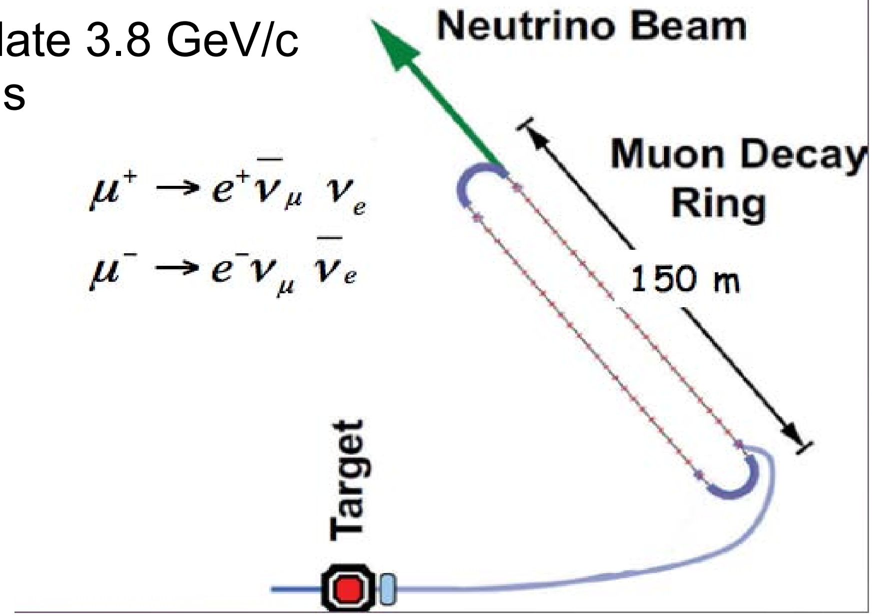


Muon Storage Ring

νSTORM is a proposed muon storage ring at Fermilab

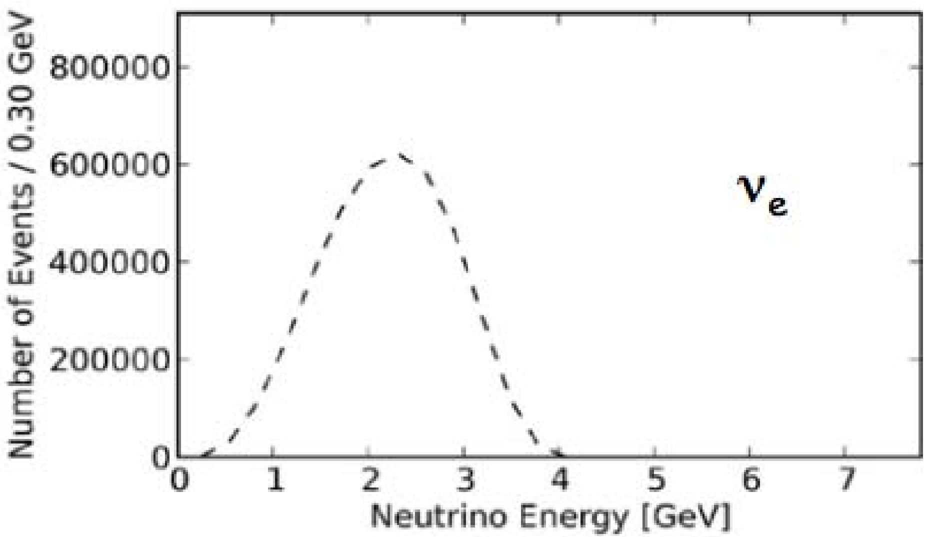
For details, see A Bross's slides at NuInt12

Circulate 3.8 GeV/c muons



Circulating muon beam:

- Half of neutrinos are ν_e
- Intensity of beam can be measured to <1% with current transformers



Current proposed muon momentum produces a higher energy spectrum than T2K or HK

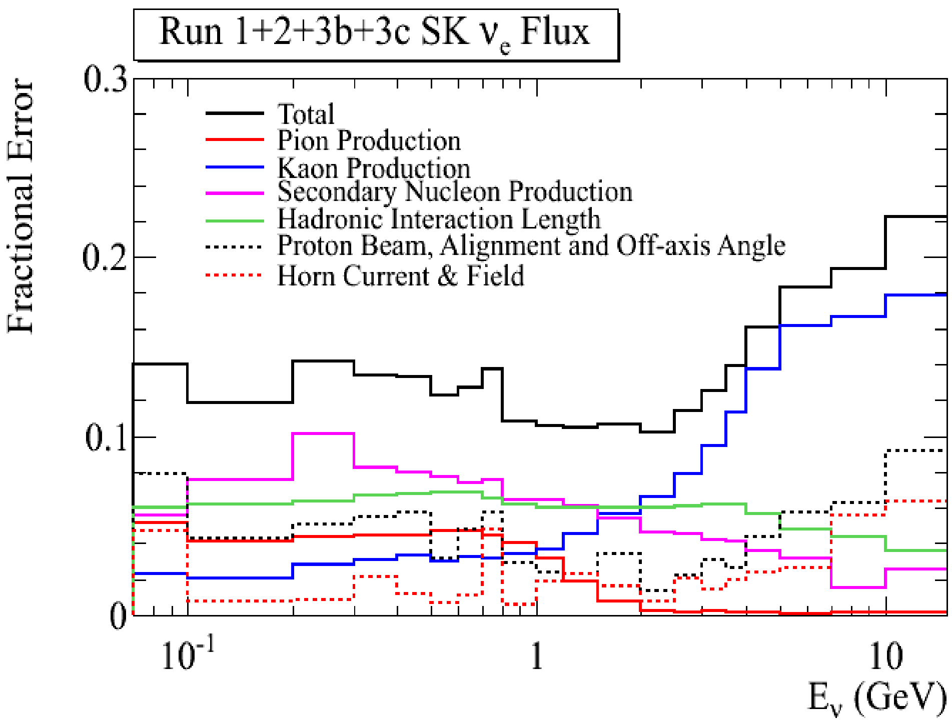
Can be tuned to select and circulate lower momentum muons

Conclusions

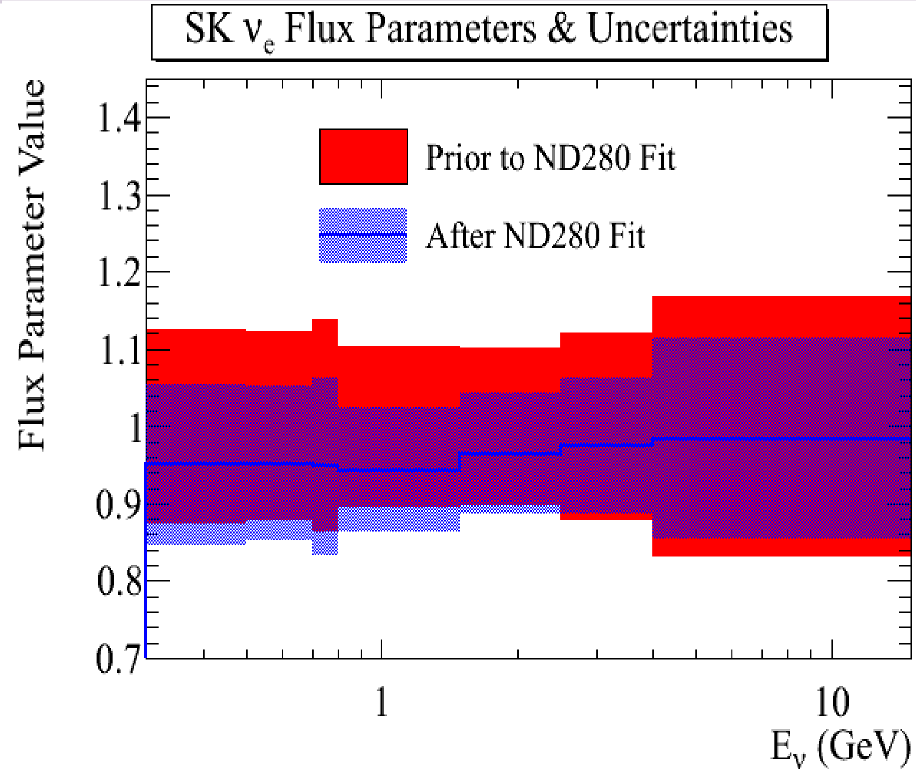
- Uncertainties on neutrino flux and cross section modeling are dominant systematic uncertainties for current experiments such as T2K
- T2K has used ex-situ and in-situ data to control these uncertainties at the 10% level
- To achieve its ultimate sensitivity, T2K must reduce systematic uncertainties to the 5% level
  - Near detector measurements on oxygen, study of multinucleon cross sections
  - Measurement of the electron neutrino cross section, but it is difficult
- Next generation experiments such as Hyper-K require systematic uncertainties <5%
  - Achieving this will be a challenge
  - Need novel ideas for cross section measurements, and need to starting work on this now!

Backup Slides

Electron Neutrino Uncertainties

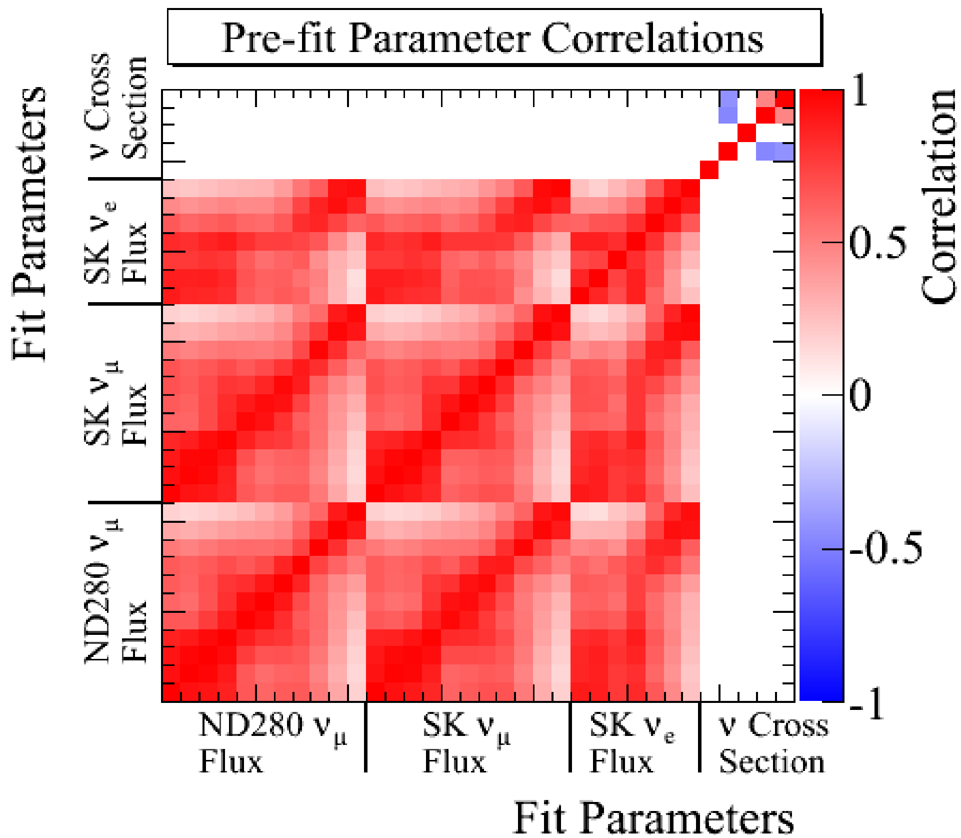


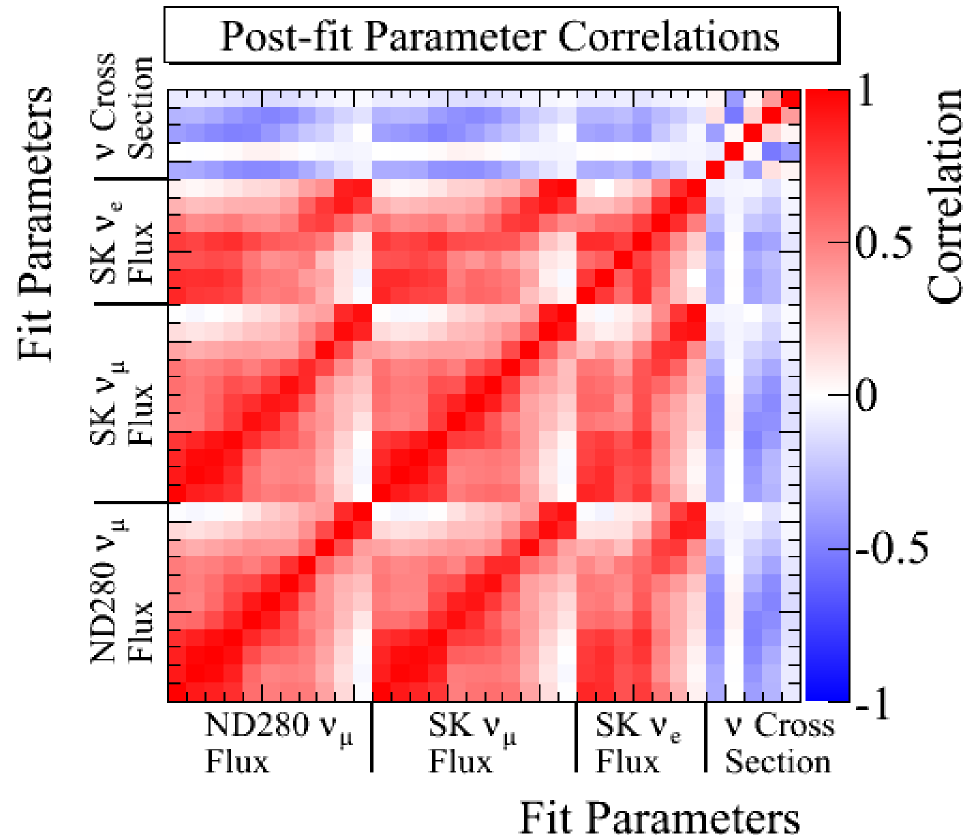
Prior uncertainties at SK



Central value and error band before and after the ND280 fit

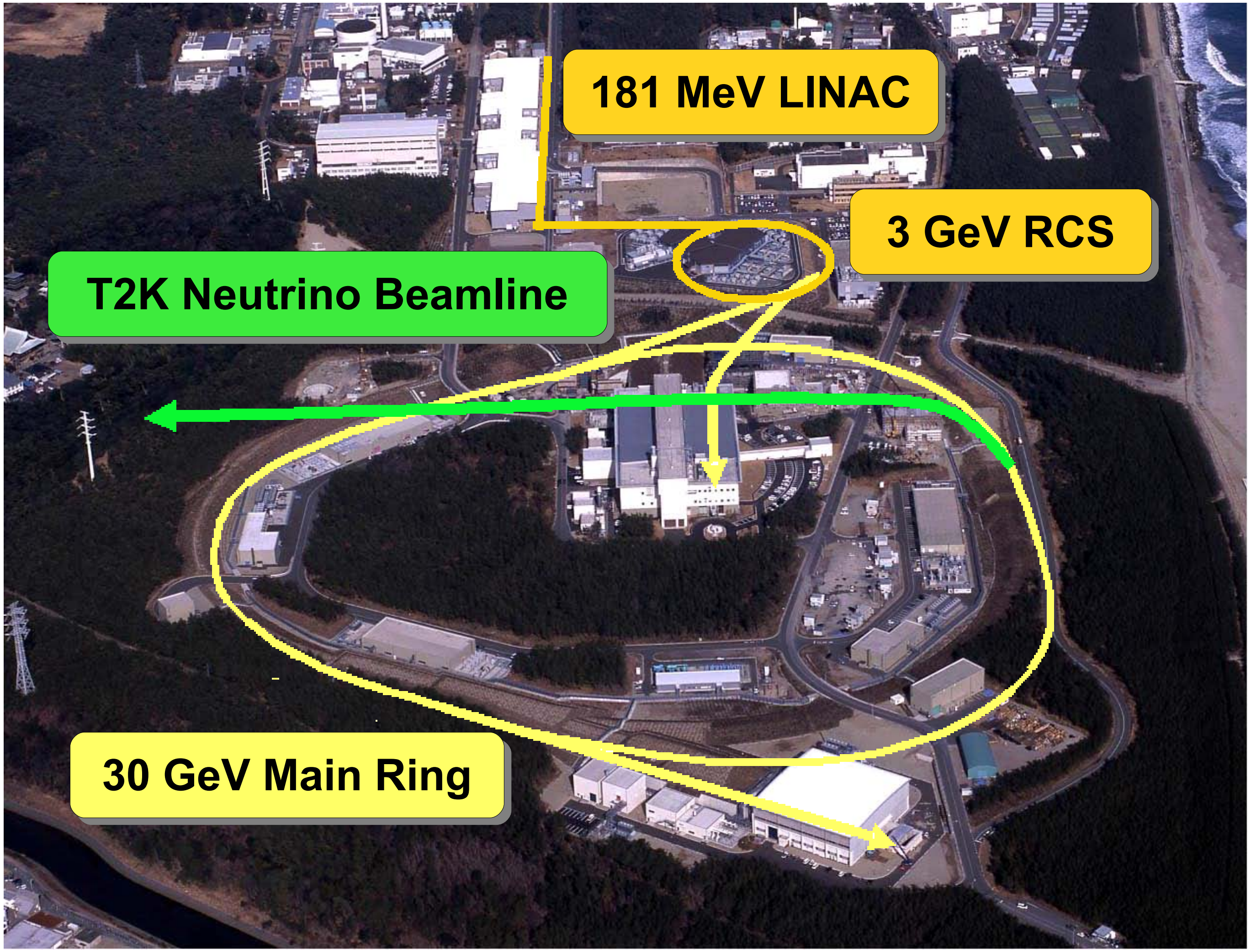
Fitted Parameter Correlations





Cross section parameters are: M_A^{QE}, M_A^{RES}, CCQE low energy normalization, CC1π low energy normalization and NC1π^0 normalization

J-PARC Accelerator



- Located in Tokai village
- Completed in 2009
- Accelerator Design/Performance
    - Design goal of 750 kW
    - 30 GeV protons to neutrino beamline
    - Reached 145 kW before earthquake

Measuring ν_μ Disappearance

T2K can measure θ_{23} and Δm^2_{23} through ν_μ disappearance:

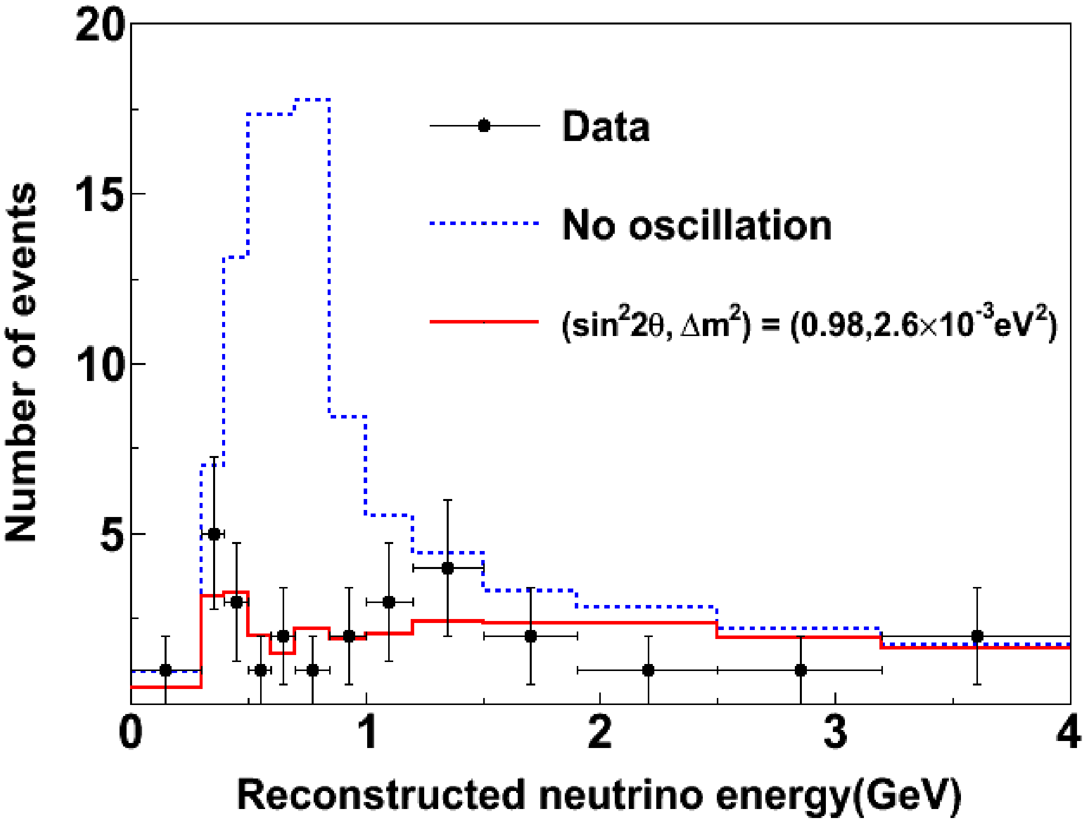
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\boxed{\theta_{23}} \sin^2 \frac{\boxed{\Delta m^2_{32}} L}{4 E_\nu}$$

Similar to ν_e appearance analysis, but now select muon like events at SK

$1.43\text{x}10^{20}$ POT

104 expected if no oscillations

31 events observed



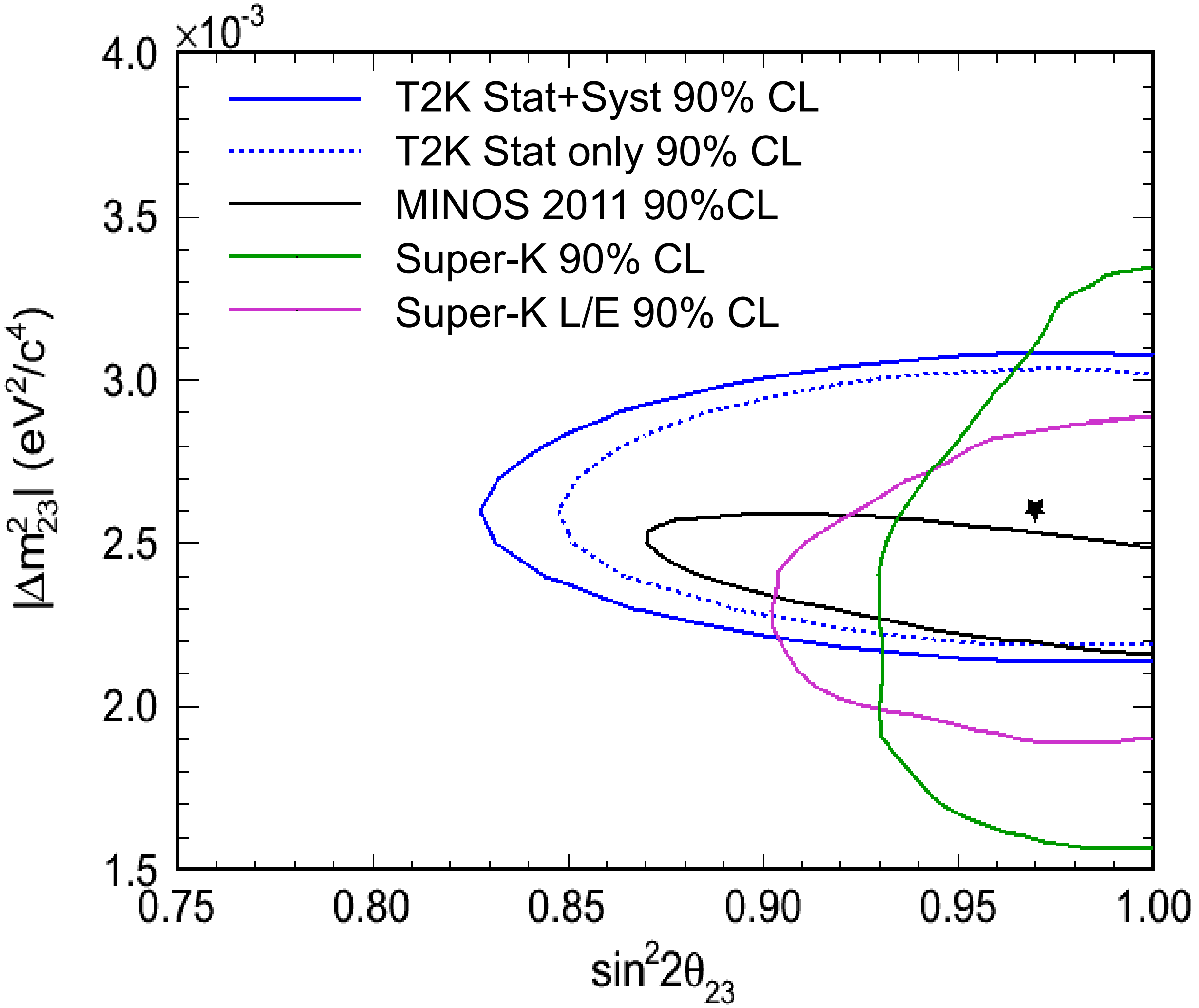
Interpreting the Results

Can produce an allowed region in the $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$ plane

Results are consistent with those from MINOS and SK atmospheric

With just 2% of exposure, already becoming competitive with existing measurements

Phys. Rev. D85 (2012) 031103



ν_e Cross Section Uncertainty

We measure the ν_μ rate at the near detector and use it to predict the $\nu_\mu \rightarrow \nu_e$ rate at the far detector

Rely on model to extrapolate from ν_μ interaction cross section to ν_e interaction cross section

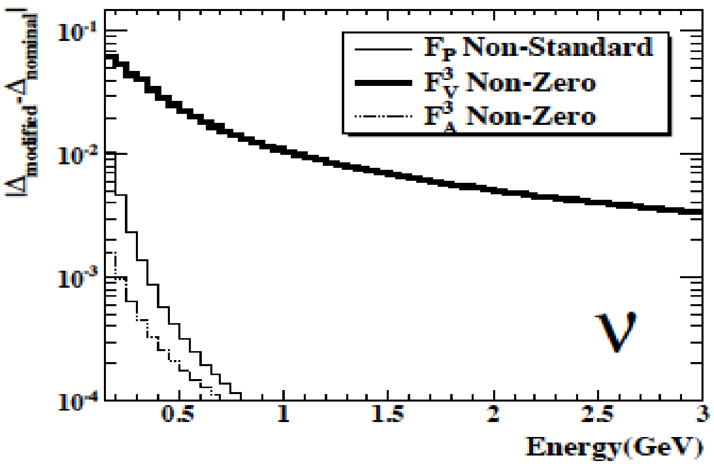
What is the uncertainty in the extrapolation?

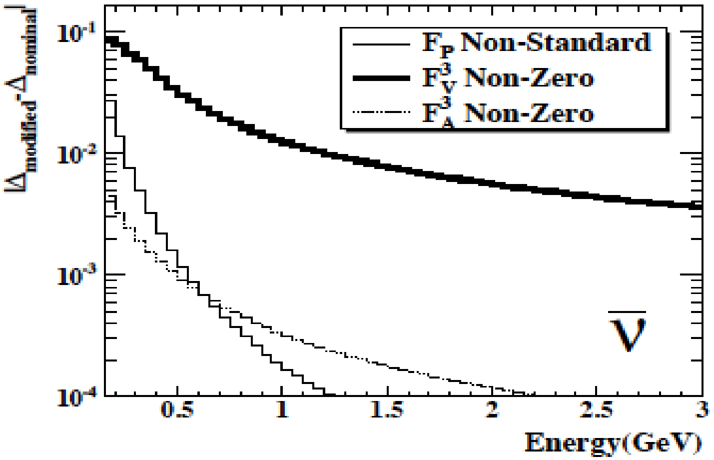
M. Day, K. McFarland **Phys.Rev. D86 (2012) 053003**

Study sub-leading terms of the QE cross section in the impulse approximation that depend on the lepton mass and not well measured form factors

Uncertainty on the cross section is at ~2% near T2K peak energy

Also look at radiative corrections that are not currently included in neutrino generators. Differences of order 10%





Why not measure the ν_e cross section?

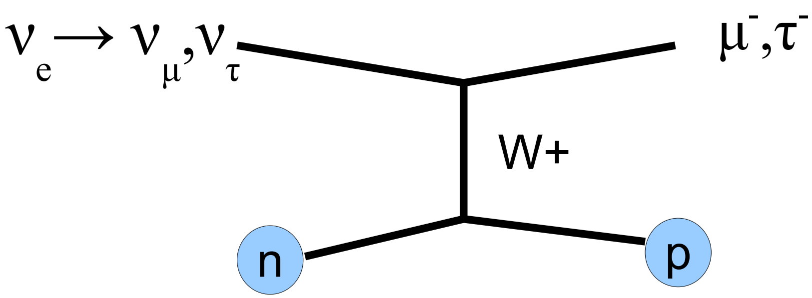
How are Parameters Measured?

Homestake	Deficit of solar ν_e in CC interactions
SK	Deficit of atmospheric ν_μ ($\bar{\nu}_\mu$) in CC interactions
SNO	Deficit of solar ν_e in CC interactions, confirm total rate with NC interactions
KamLAND	Deficit of reactor $\bar{\nu}_e$ in CC interactions
K2K	Deficit of accelerator ν_μ in CC interactions
MINOS	Deficit of accelerator ν_μ ($\bar{\nu}_\mu$) in CC interactions

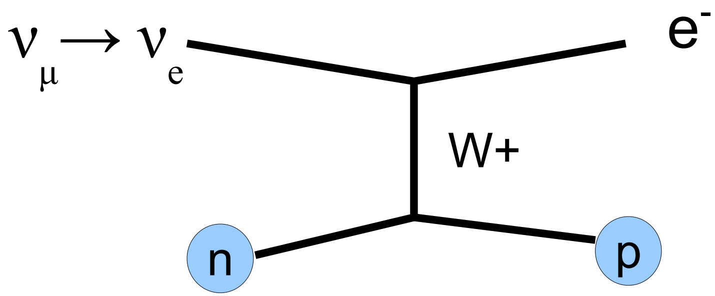
Why are all the measurements of deficits in the original neutrino flavor?

Shouldn't we detect the flavor to which the neutrino has oscillated to confirm the model?

What About Neutrino Appearance?

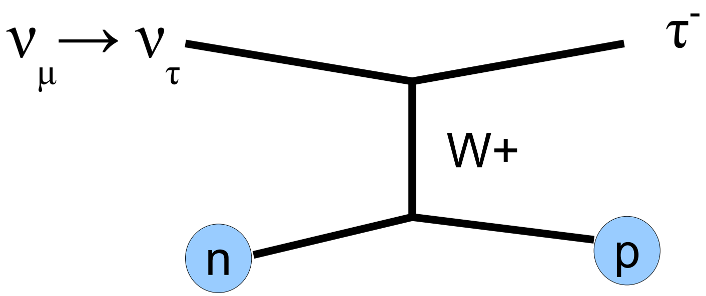


The muon (tau) is too heavy at m_μ=106 MeV/c^2 to be produced by neutrinos with energy E_ν~10 MeV



Disfavored by mixing angles: ν_μ mostly oscillate to ν_τ

Need well designed experiment (T2K)



Need high energy beam to produce tau with mass m_τ=1.78 GeV/c^2 (OPERA)

Particle Identification at SK

Muons:

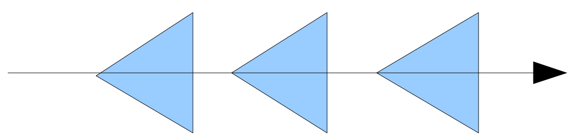
- Minimal scattering
- Ring has sharp edges

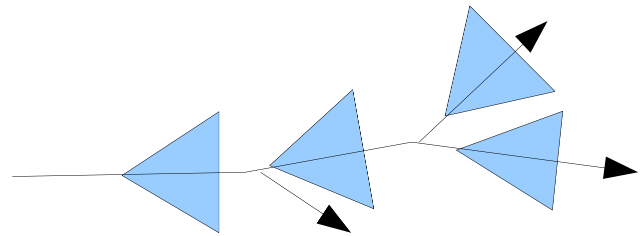
Electrons

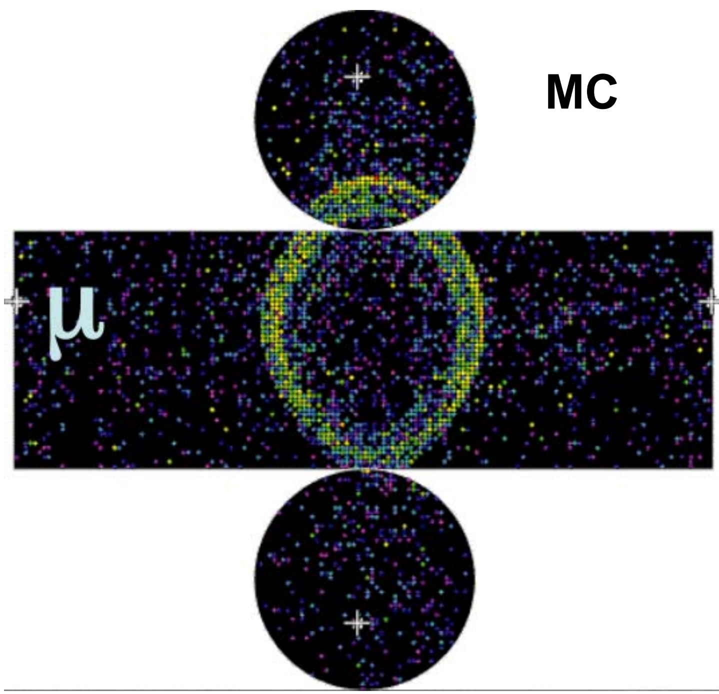
- Electromagnetic shower
- ”Fuzzy” ring

Neutral Pions

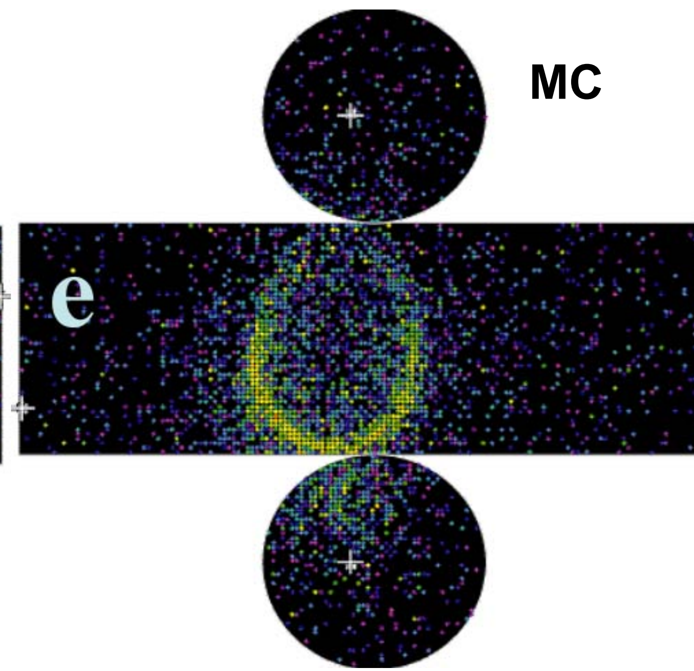
- γs from π^0 decays shower and look like electrons



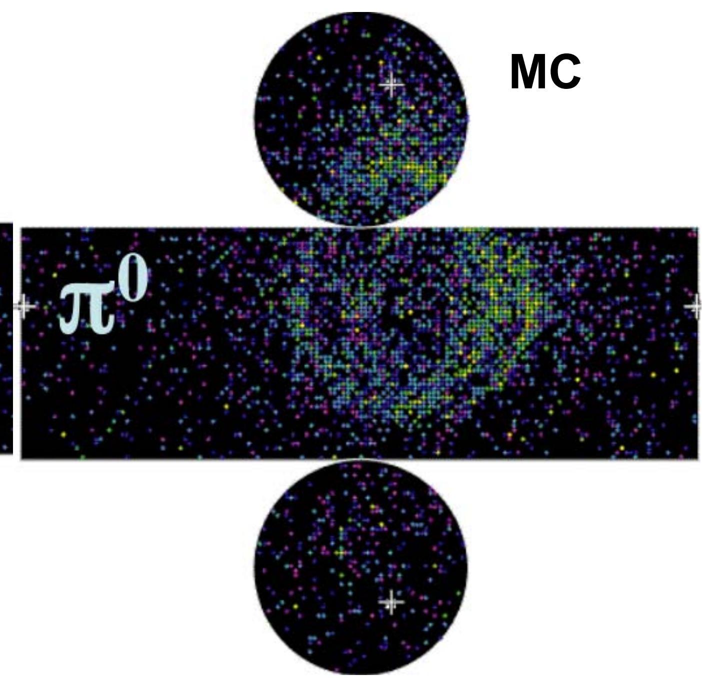




MC

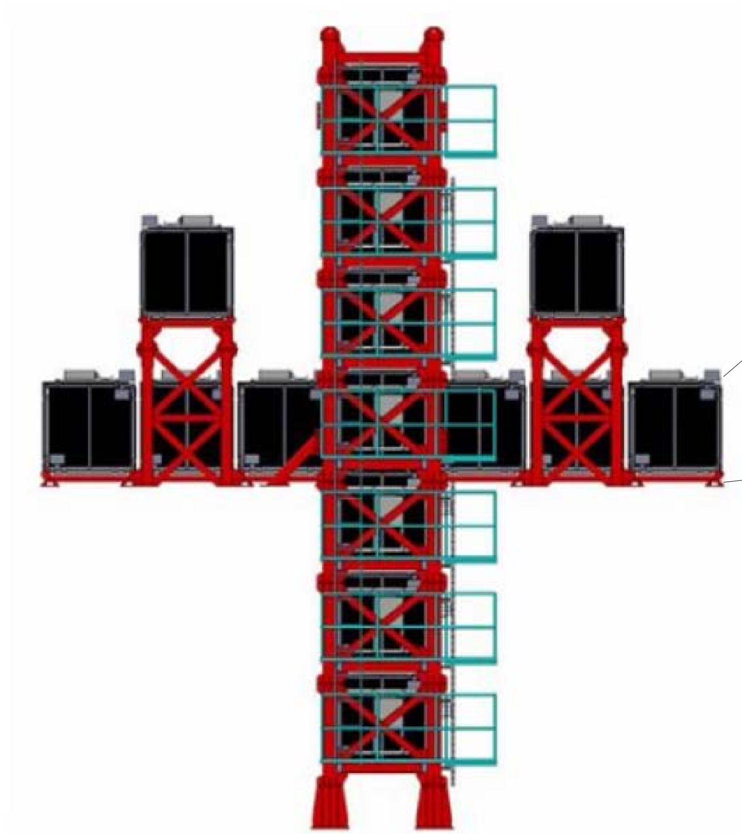


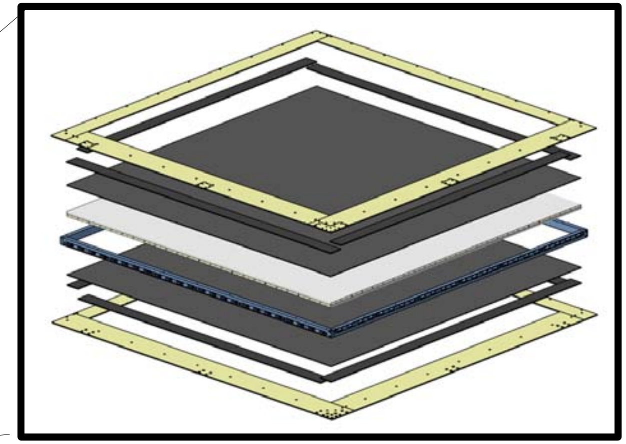
MC

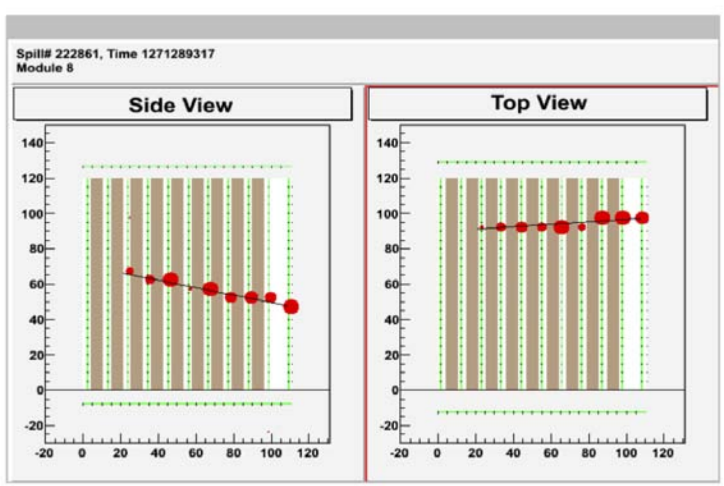


MC

INGRID On-axis Detector





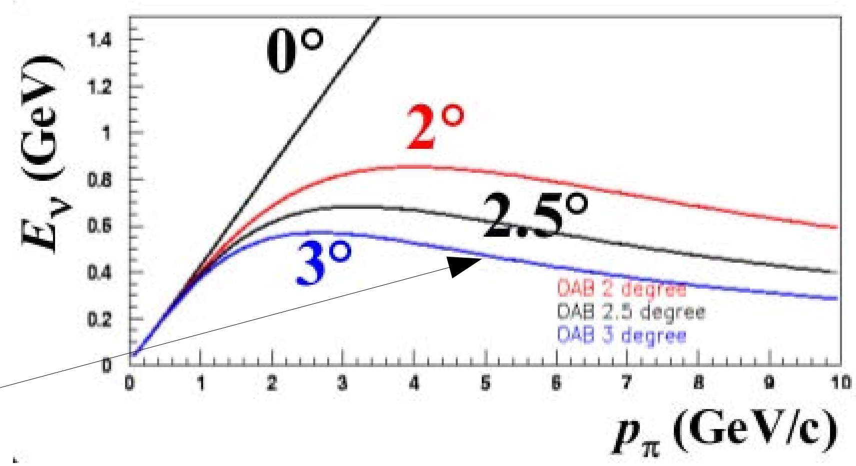


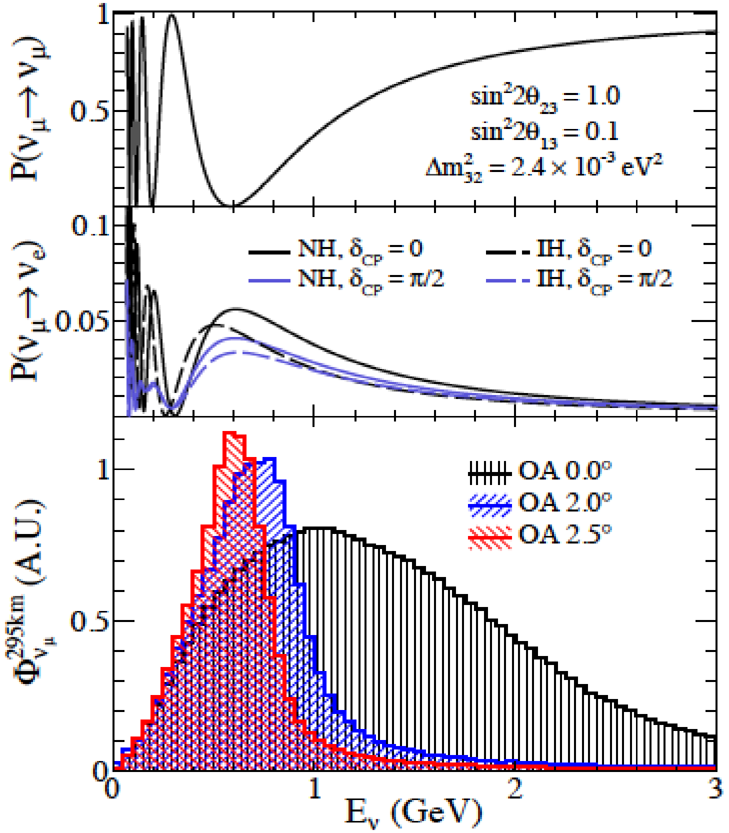
- On-axis neutrino detector at 280 m from target
- 16 modules (14 in cross configuration)
- Modules consist of iron and scintillator layers
- Measures neutrino beam profile and rate

Why Off-axis?

- Pion decay kinematics:
  - In pion direction, neutrino energy proportional to pion momentum
  - At non-zero angles, weak dependence on pion momentum
- 2.5° off-axis angle gives narrow band beam peaked at the first oscillation maximum
  - More statistics in the oscillation region
  - Less feed-down from backgrounds at higher energy

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



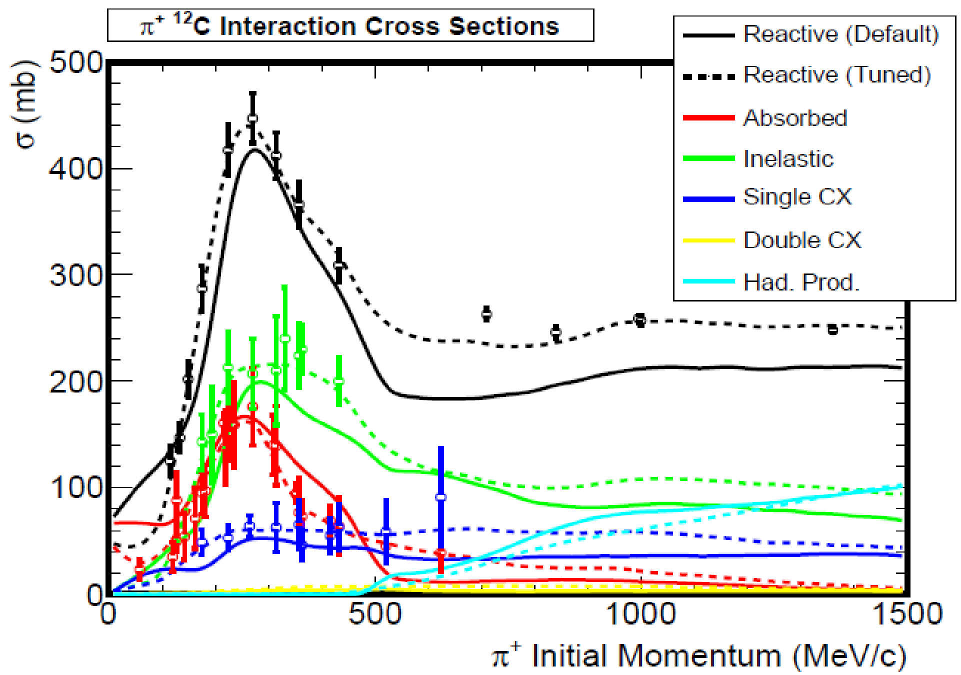


Final State Interactions

- Pions produced in the ν interactions can interact in the target nucleus:
  - Absorption - no pion in final state
  - Production - additional pions in the final state
  - Charge exchange - change of pion charge
- Microscopic (internal to nucleus) pion interaction model employed in NEUT
- Tune microscopic model to reproduce macroscopic pion scattering data

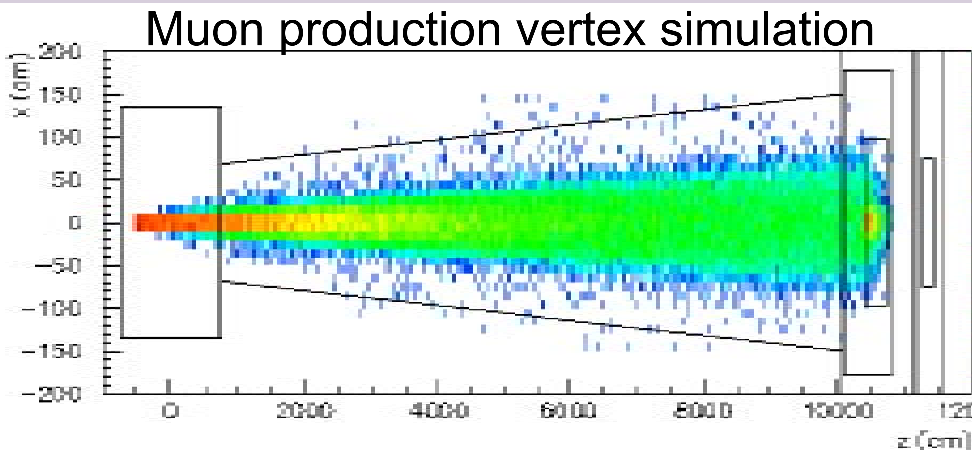
Tuning: vary microscopic mean free path for different interaction types and vary models

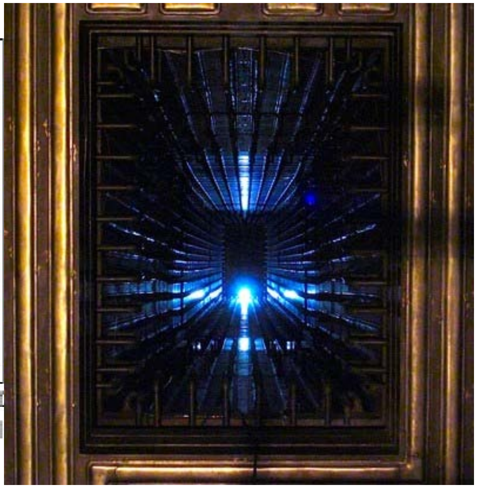
Tuned (dotted lines) in much better agreement with data



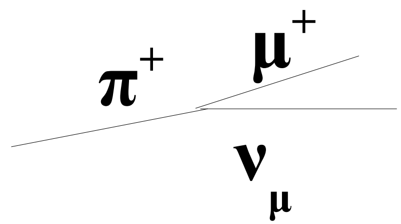
Decay Volume and MUMON

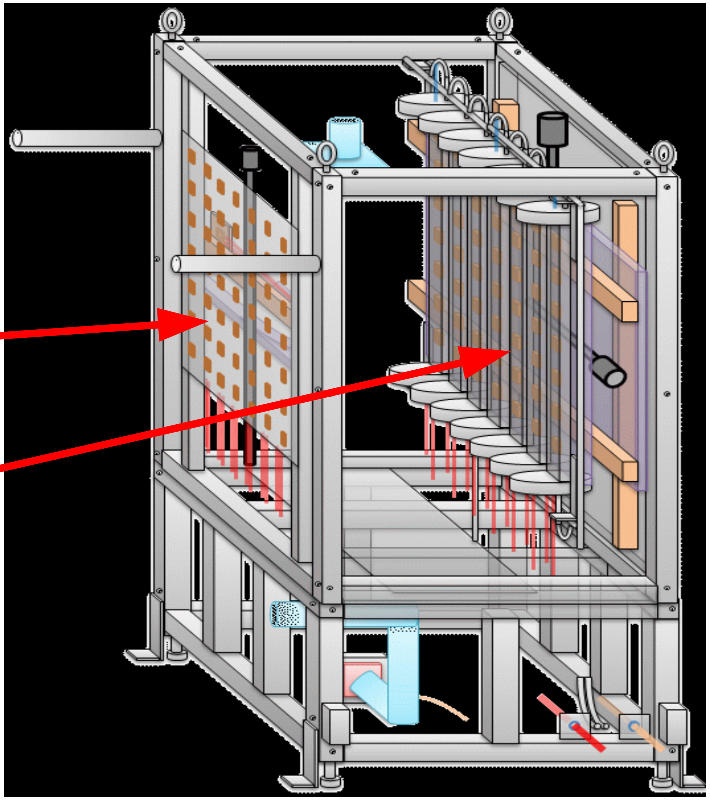
- Pions (and other particles) decay in 100 m long decay volume:



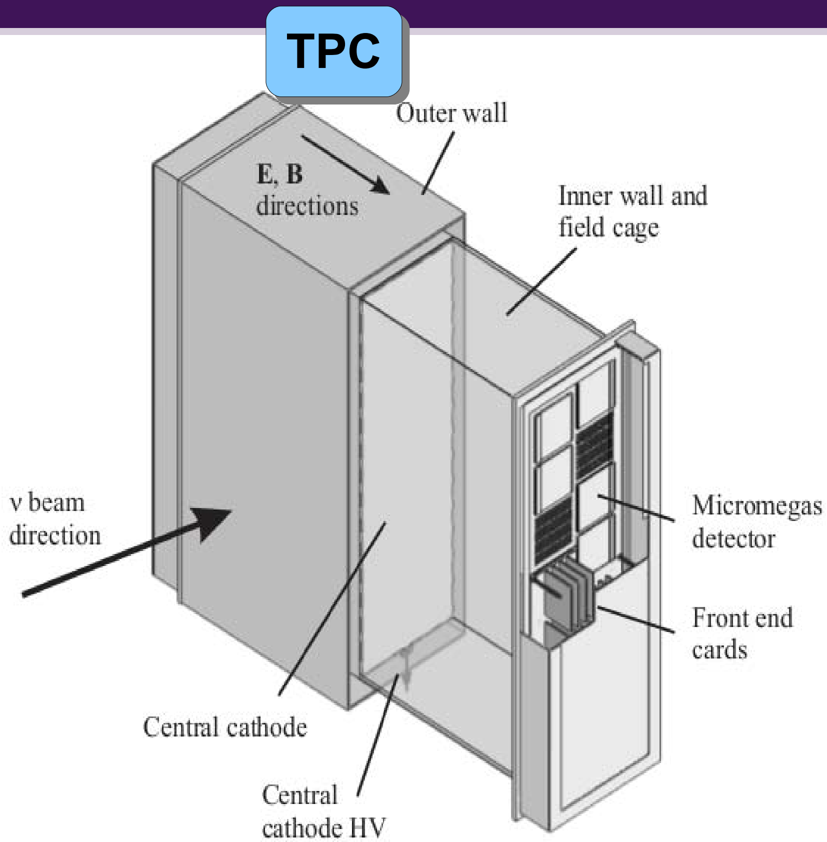


- MUMON muon monitor
  - Measures muons from pion decays
  - Si PIN photodiodes sensitive at low intensity, but radiation damage
  - Ionization chambers less suseptible to rad. damage
  - Measure beam shape and direction

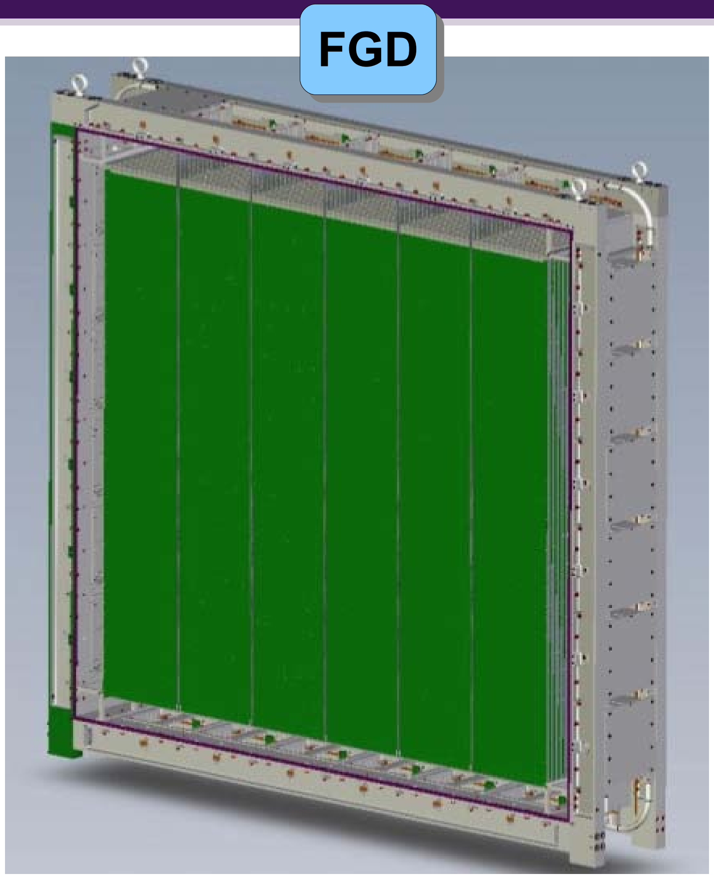




ND280 Tracker

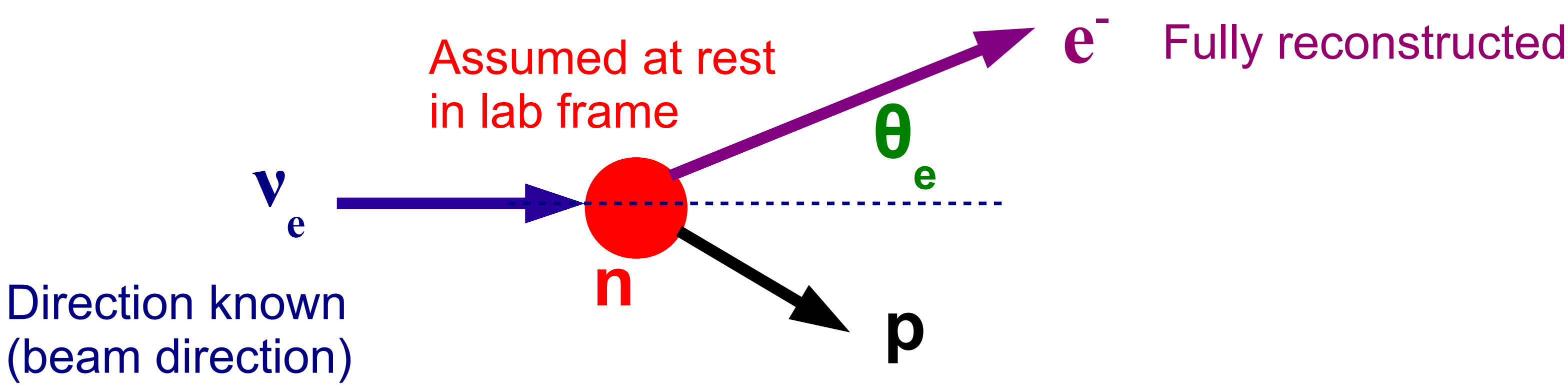


- Track charged particles in magnetic field
- 10% momentum resolution at 1 GeV/c



- Neutrino target: 2.2 tonnes of material (including water targets)
- Tracking of particles

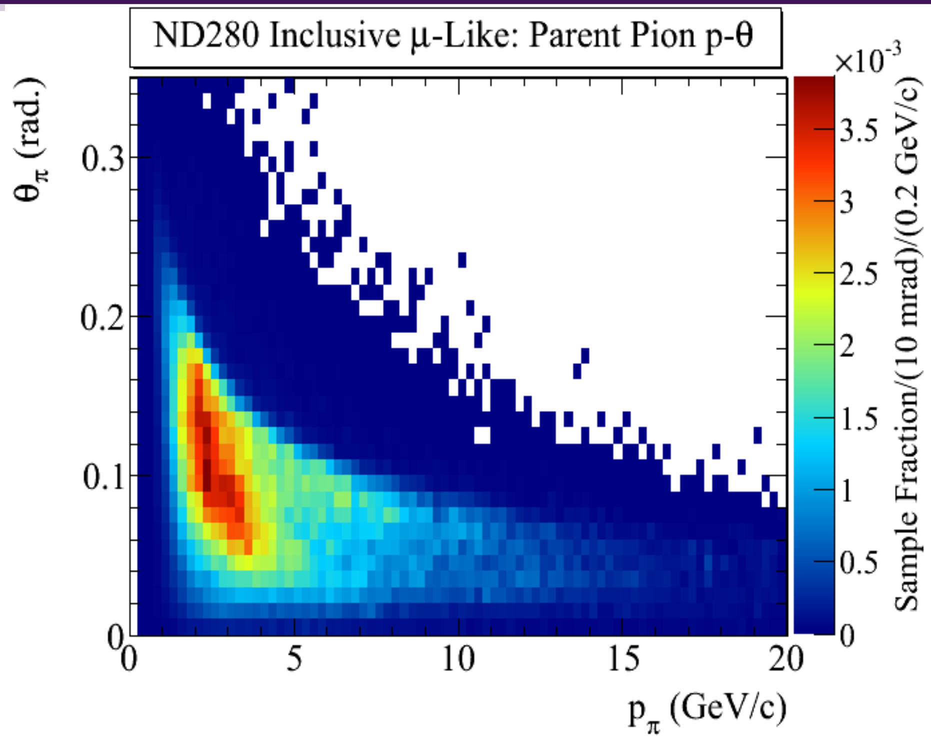
Reconstructing the ν Energy

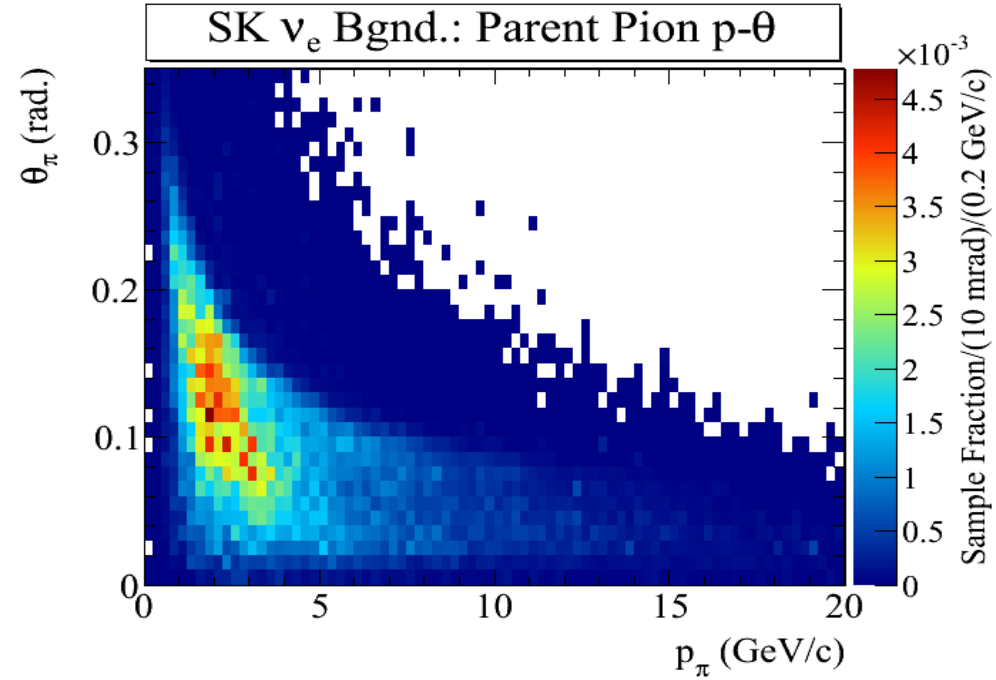


$$E_\nu^{QE} = \frac{2M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2[M_n - E_e + \sqrt{E_e^2 - m_e^2}\cos\theta_e]}$$

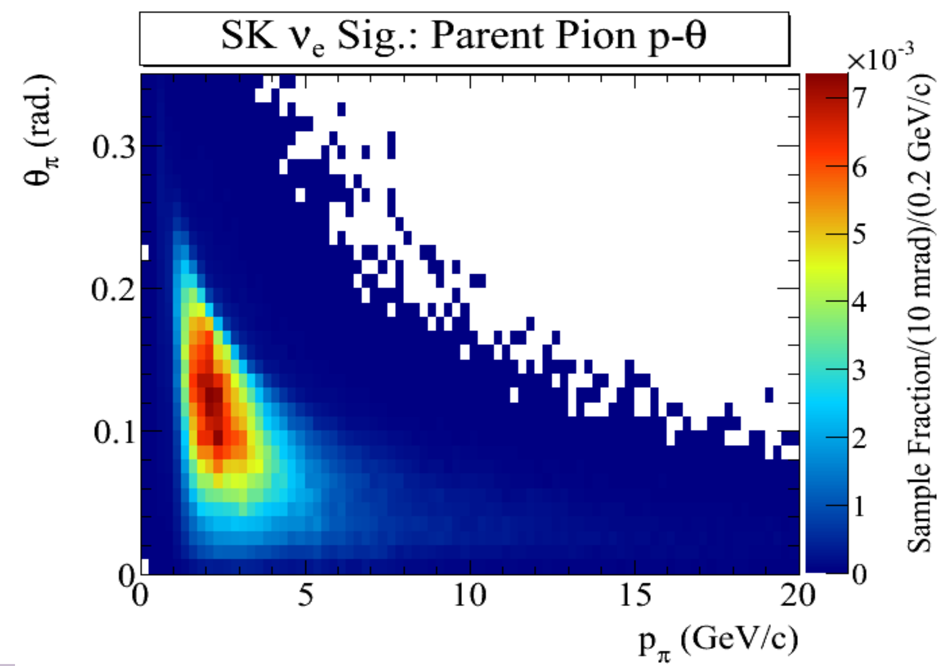
- Only lepton in final state is reconstructed
- Can determine neutrino energy with assumptions:
  - Neutrino direction is known (beam direction)
  - Recoil nucleon mass is known
  - Target nucleon is at rest – not exactly true, adds smearing to energy

Parent Pion Phase Space





Plots show the p-θ distribution of parent pions contributing to the ND280 (upper left), SK nu_e background (upper right) and SK nu_e signal (lower left) samples. Plots are normalized to by the sample size, so the z axis is sample fraction. θ is the polar angle relative to the beam direction



The T2K Collaboration

~500 collaborators, 57 institutes, 11 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

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