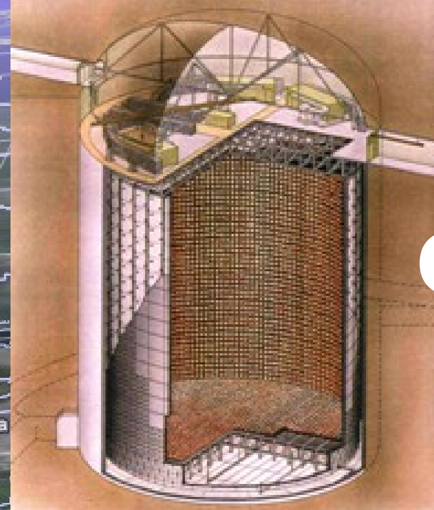


New Results From The T2K Neutrino Oscillation Experiment

Scott Oser
for the T2K collaboration

University of British Columbia

SSP 2012
Groningen

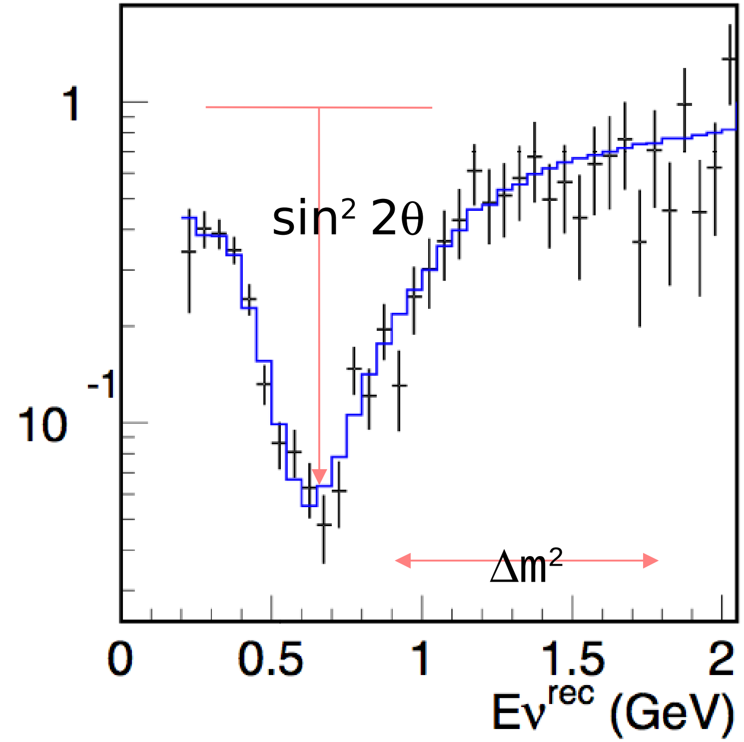
Neutrino Flavour Oscillation

Because a flavour eigenstate produced by a weak interaction is a mix of mass eigenstates which, if $m_1 \neq m_2$, propagate with different kinematics, oscillation can occur.

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu(t)\rangle = e^{i\sqrt{p^2+m_1^2}\,t}\cos\theta\,|\nu_1\rangle + e^{i\sqrt{p^2+m_2^2}\,t}\sin\theta\,|\nu_2\rangle$$

$$\mathrm{Prob}\left(\nu_\mu \rightarrow \nu_\mu\right) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$



Units: [L] = km; [E] = GeV;
Δm^2 = [eV^2]

Three Flavour Neutrino Mixing

3x3 unitary matrix relating mass eigenstates to flavour eigenstates can be parametrized by four angles

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

Measured with atm and LBL ν

Measured with reactor and LBL ν

Measured with solar, reactor ν

$\theta_{23} \approx \pi/4$ $\theta_{13} \approx \pi/20$ $\theta_{12} \approx \pi/6$

Compare to identical parameterization of CKM matrix ...

$\theta_{23} \approx \pi/76$ $\theta_{13} \approx \pi/870$ $\theta_{12} \approx \pi/14$

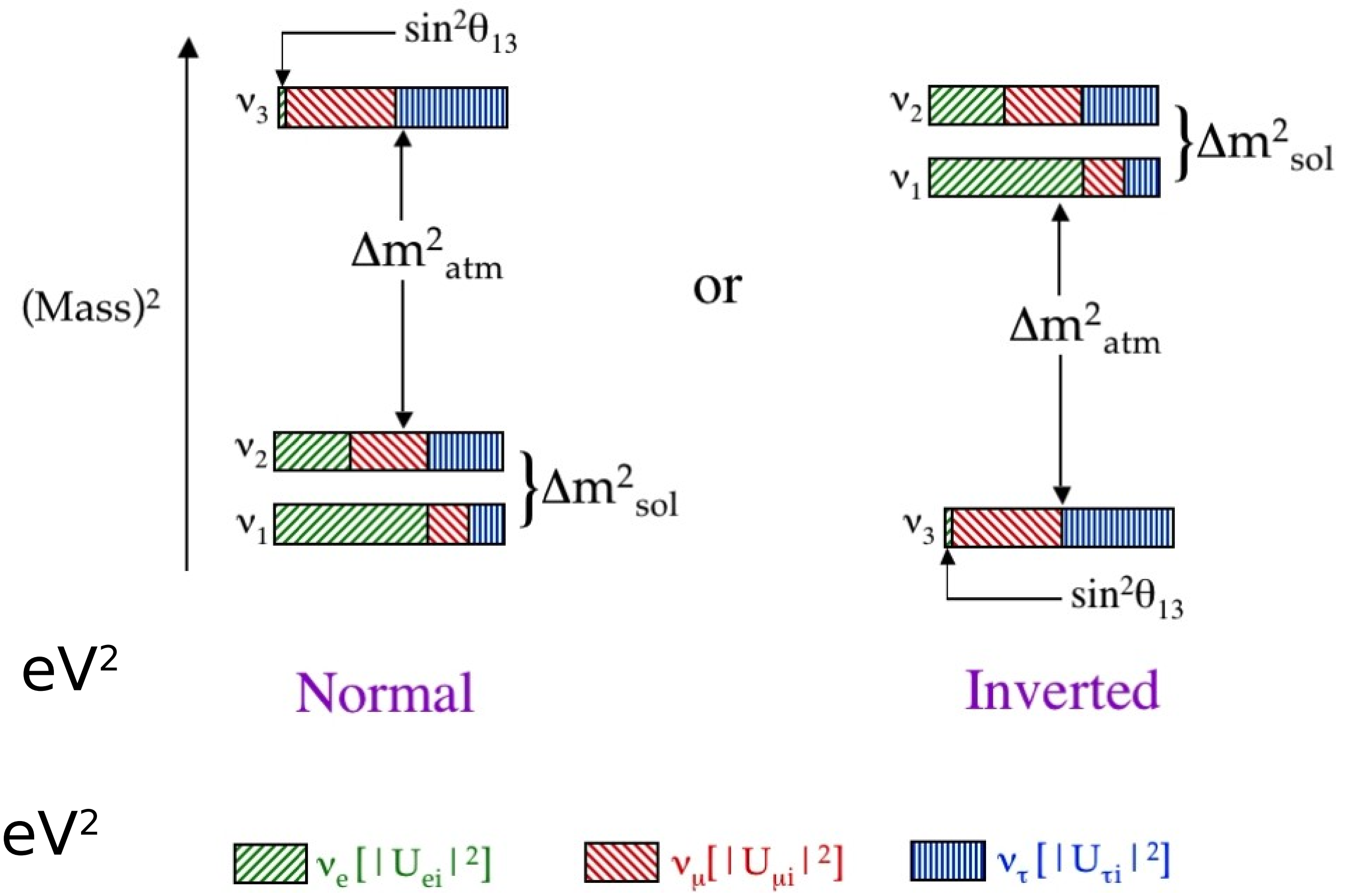
Mass Hierarchy

Currently unknown:

- δ_{CP}
- sign of the mass hierarchy

$\Delta m^2_{atm} = 2.4 \times 10^{-3}$ eV^2

$\Delta m^2_{sol} = 7.6 \times 10^{-5}$ eV^2



θ_{13} and ν_e Appearance

The observed oscillations of atmospheric and long-baseline ν's seem to be $\nu_\mu \to \nu_\tau$. What about $\nu_\mu \to \nu_e$?

For oscillations involving ν_2 and ν_3 (atmospheric, long baseline), the limiting factor for $\nu_\mu \to \nu_e$ is how much ν_3 couples to electrons in CC weak interactions. To first order, in the absence of matter and CP effects, at oscillation maximum this probability is:

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23}$$

$$\approx 1/2 \sin^2 2\theta_{13}$$

Observing this is the main goal of T2K.

CP Violation and ν_e Appearance

CP symmetry requires $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$

For ν_e appearance at Δm^2_{32}:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m^2_{12} L \sin 2\theta_{12}}{4E_\nu \sin\theta_{13}} \sin\delta_{CP}$$

modulo matter effect corrections (small at T2K)

Only δ_{CP} now unknown---this could be a big asymmetry!

Our universe is made of matter but not anti-matter.
CP violation is a requirement for producing a cosmological asymmetry.
Regular quark CP violation not enough---is this the missing piece?

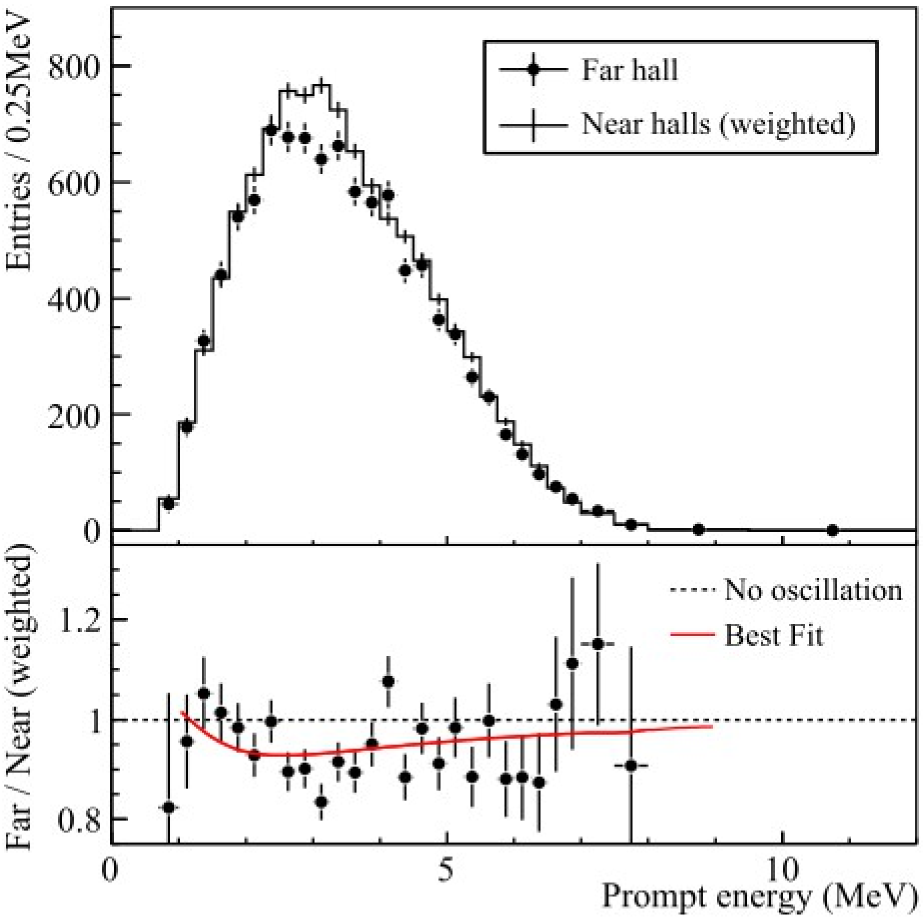
Notable recent θ_{13} measurements

T2K (June 2011): $\sin^2 2\theta_{13} \approx 0.11 \pm 0.044$ (2.5σ excess, assuming δ_{CP}=0, normal hierarchy. PRL 107, 041801)

Daya Bay reactor experiment (arXiv:1203.1669, March 2012):

$\sin^2 2\theta_{13} \approx 0.092 \pm 0.016 \pm 0.005$
(5.2σ deficit)
Updated: $0.089 \pm 0.010 \pm 0.005$

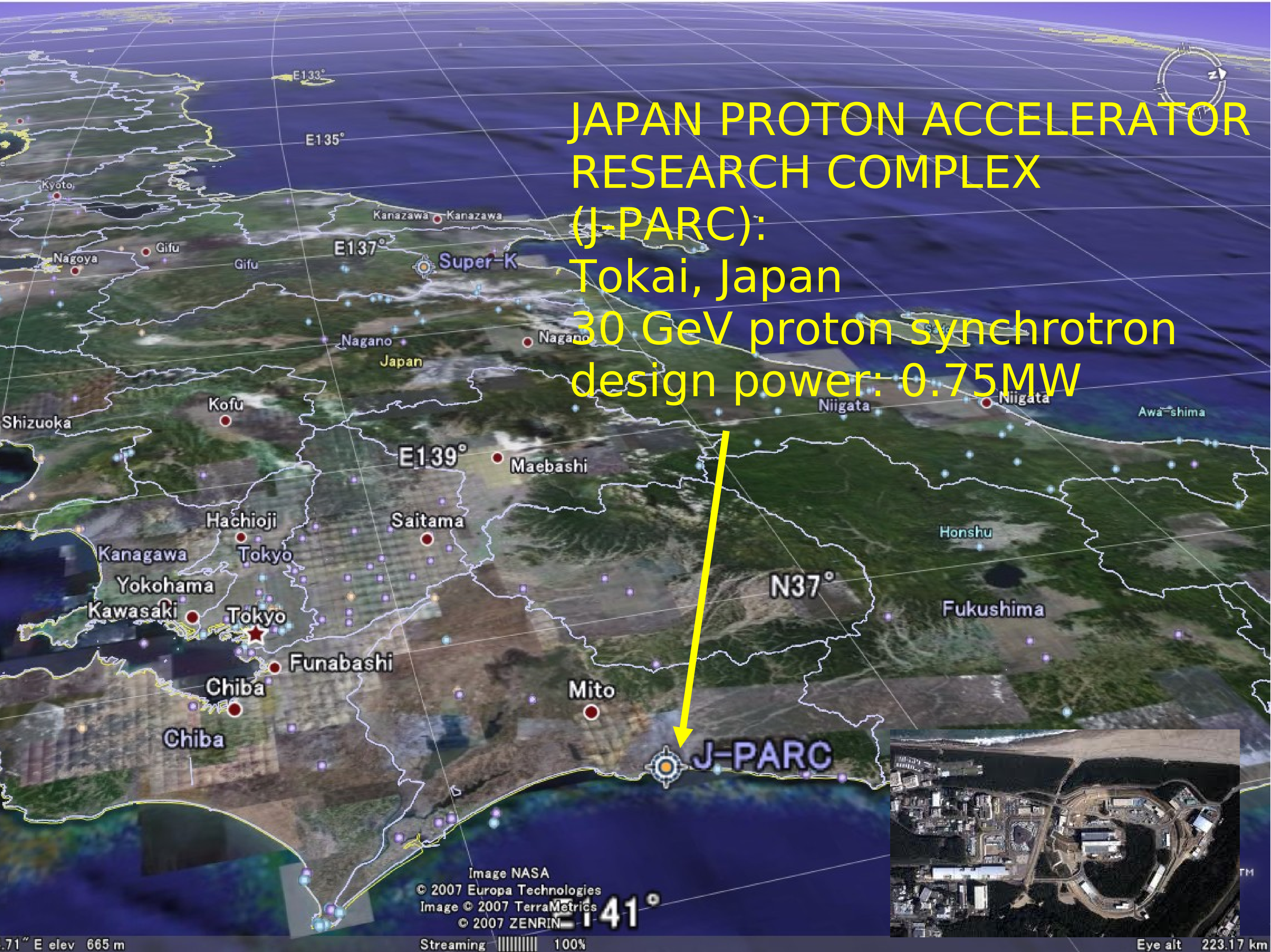
Daya Bay disappearance effect

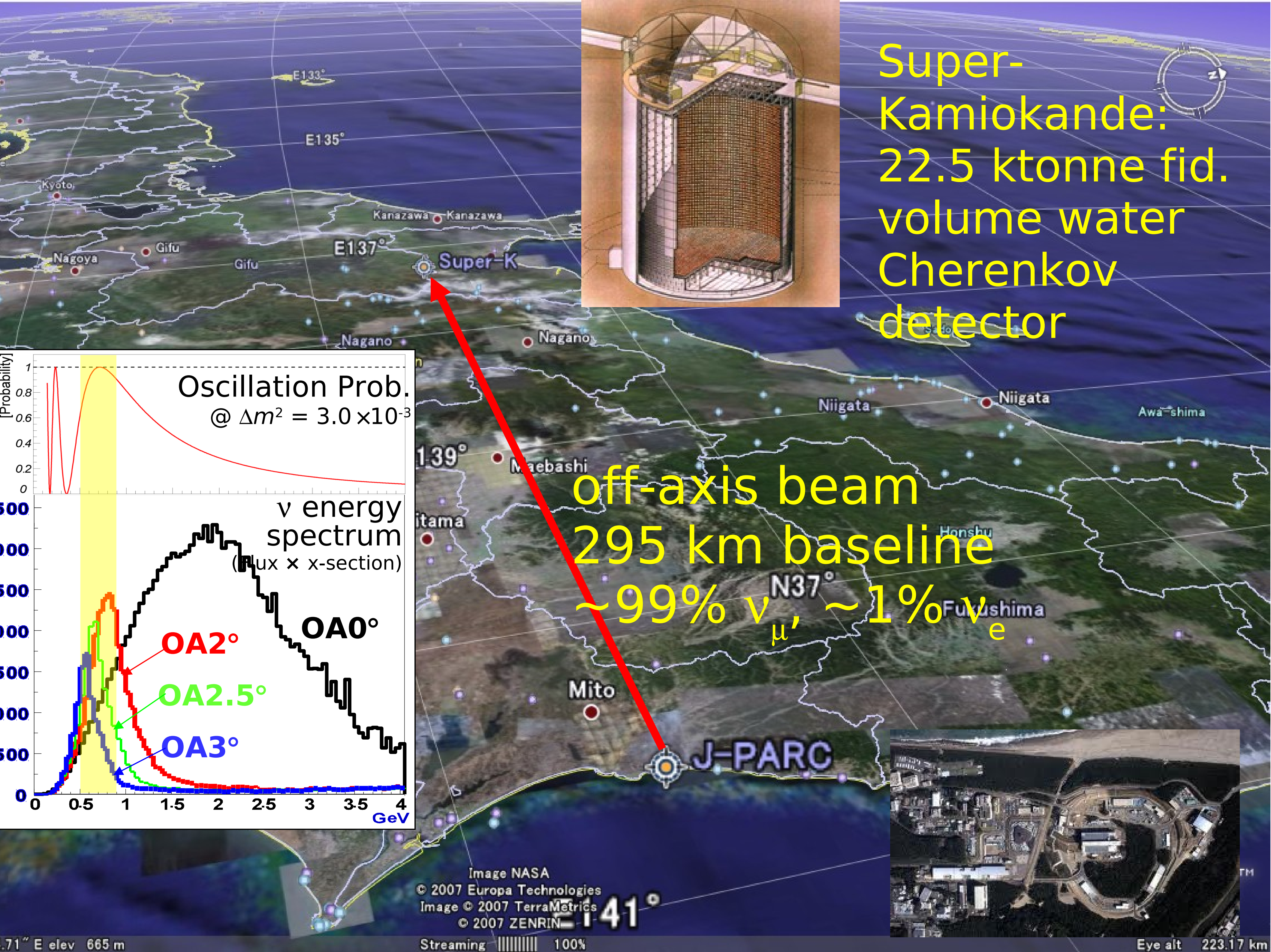


RENO reactor experiment (arXiv:1204.0626, April 2012):

$\sin^2 2\theta_{13} \approx 0.113 \pm 0.013 \pm 0.019$
(4.9σ deficit)

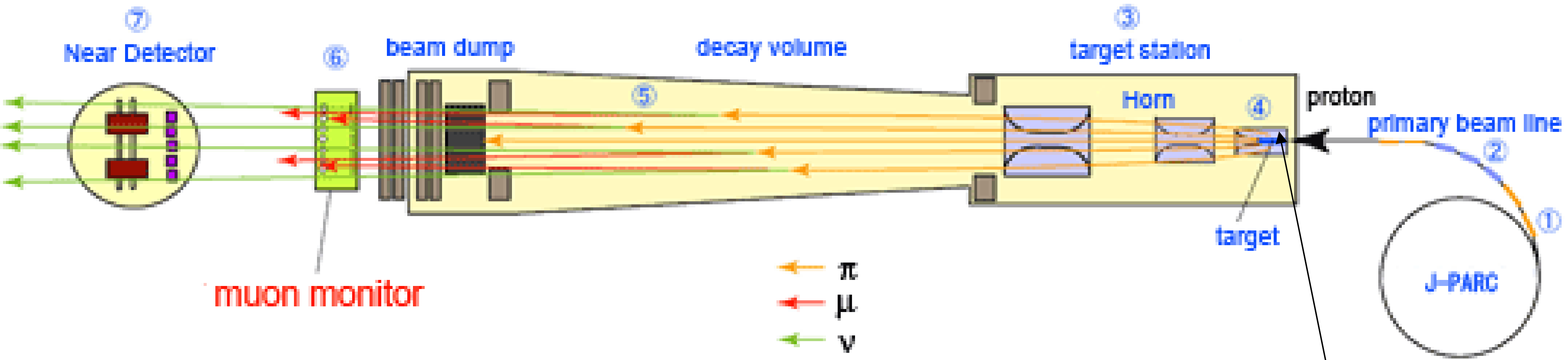
JAPAN PROTON ACCELERATOR RESEARCH COMPLEX (J-PARC):
Tokai, Japan
30 GeV proton synchrotron
design power: 0.75MW




Super-Kamiokande: 22.5 ktonne fid. volume water Cherenkov detector
off-axis beam
295 km baseline
~99% ν_μ, ~1% ν_e
Oscillation Prob.
@ Δm^2 = 3.0 ×10^{-3}
ν energy spectrum
(flux × x-section)
OA0°
OA2°
OA2.5°
OA3°
GeV
Super-K
J-PARC
Kanazawa
Gifu
Nagoya
Kyoto
Nagano
Niigata
Maebashi
Mito
Fukushima
Honshu
Awa-shima
E133°
E135°
E137°
139°
N37°
41°
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
elev 665 m
Streaming 100%
Eye alt 223.17 km

Sophisticated near detectors 280m from proton target

T2K Neutrino Beam

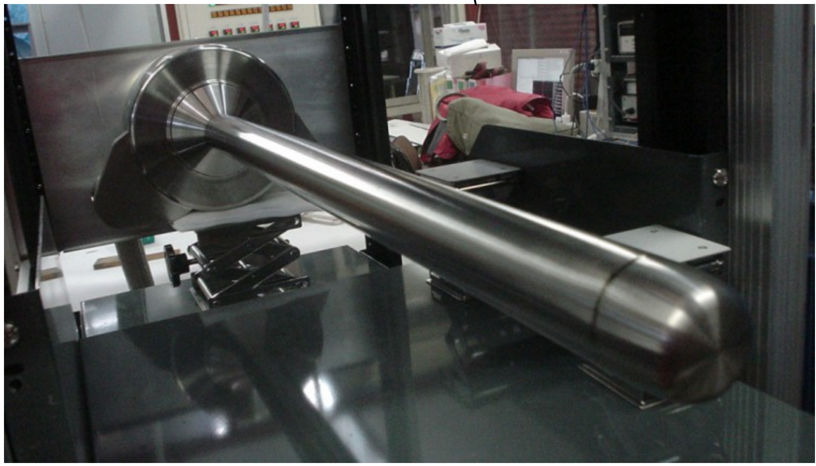


30 GeV protons hit graphite target

3 magnetic horns focus π^+, defocus π^-.

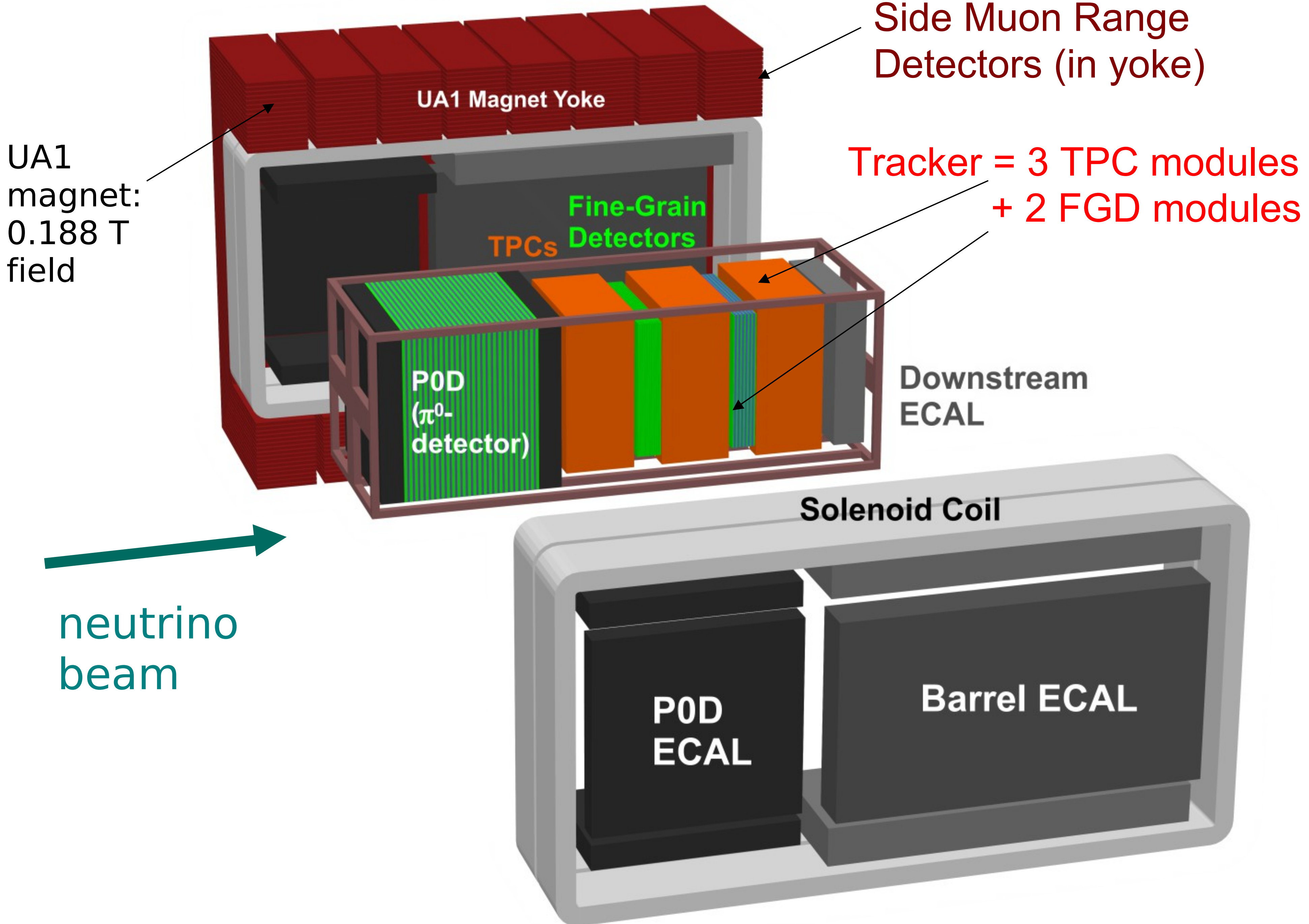
$\pi^+ \longrightarrow \mu^+ + \nu_\mu$ in 96m long decay pipe

μ monitor at far end of beam dump: fluence: $10^8\ \mu/cm^2$/spill at 750 kW (projected eventual beam power)



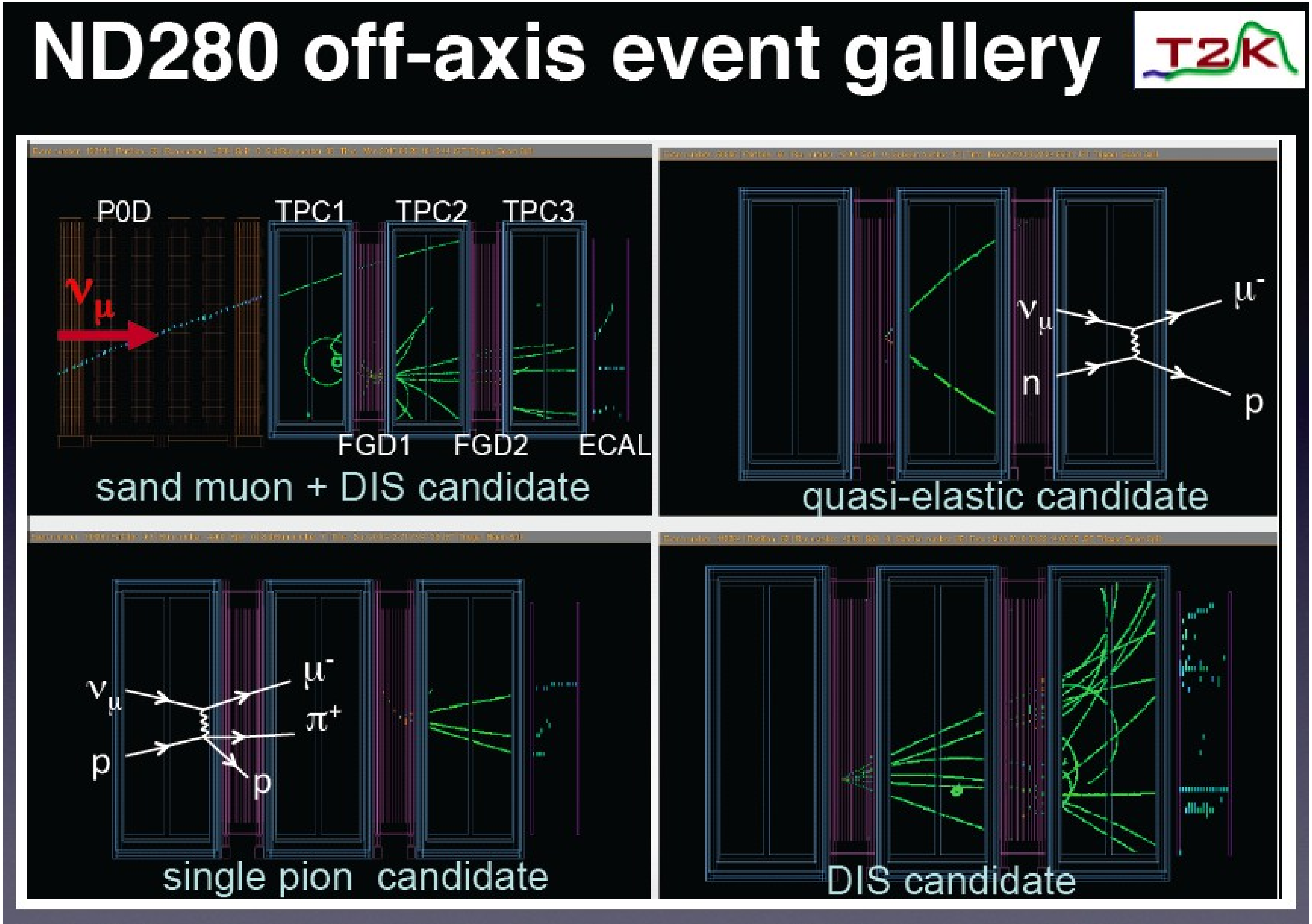
T2K's 90cm graphite target

Off Axis Near Detector

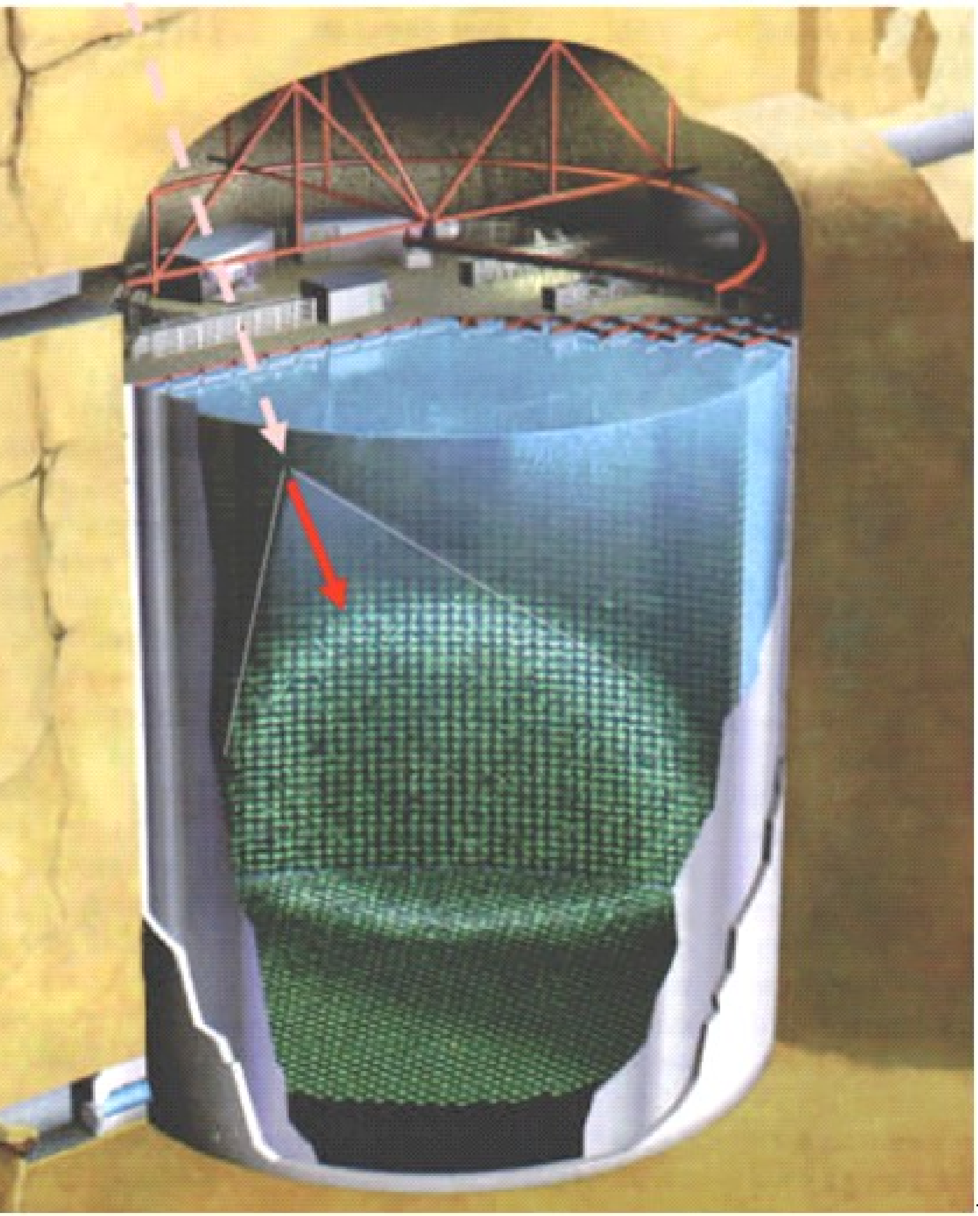


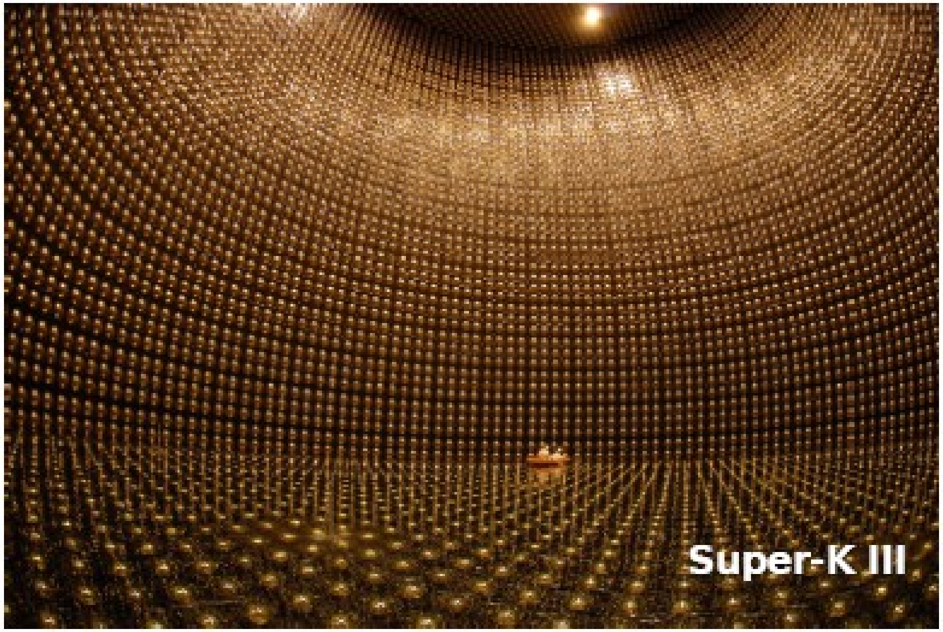
Measure flux and spectrum before neutrinos oscillate.

Near detector interactions



Super-Kamiokande





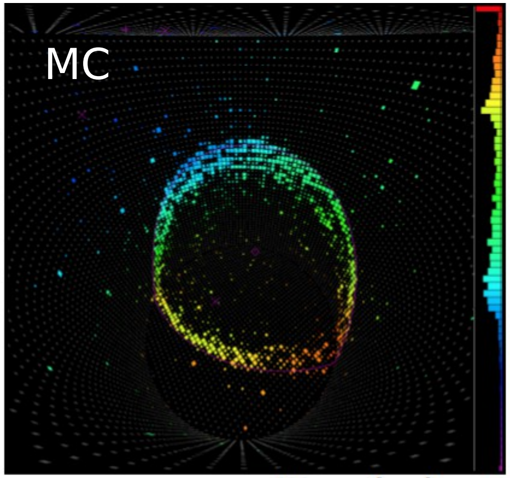
Large water Cherenkov detector

22.5ktonne water fiducial mass

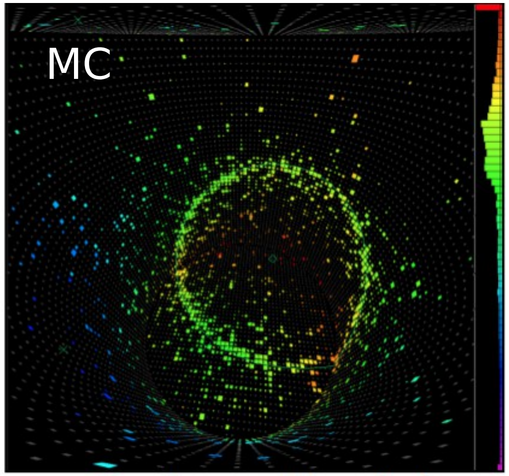
~11,000 phototubes

T2K Event Selection at Super-K

Super-K measures CCQE ν_μ or ν_e events for key T2K measurements.



muon-like (ν_μ)



electron-like (ν_e)

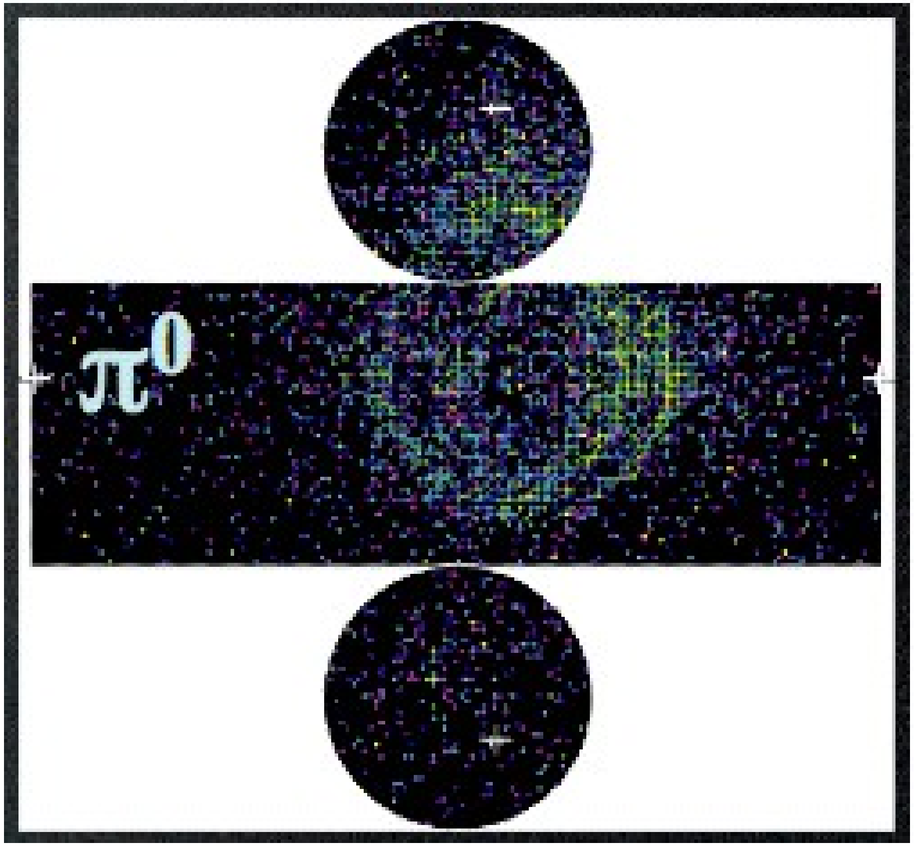
- Some challenges:
  - Understanding the irreducible background from beam ν_e
  - Understanding background ν_μ interactions that might mimic signal ν_μ or ν_e interactions, such as

    $\nu_\mu + n \rightarrow \nu_\mu + n + \pi^0$: NC1pi0 (ν_e background)

Backgrounds to ν_e Appearance

1. Intrinsic beam ν_e:
   - reduce with E cut
   - measure at ND

2. π^0 production, if one γ from $\pi^0 \rightarrow \gamma\gamma$ is not detected at Super-K:
   - better ID algorithms
   - measure at ND
   - measure π^0 in SK



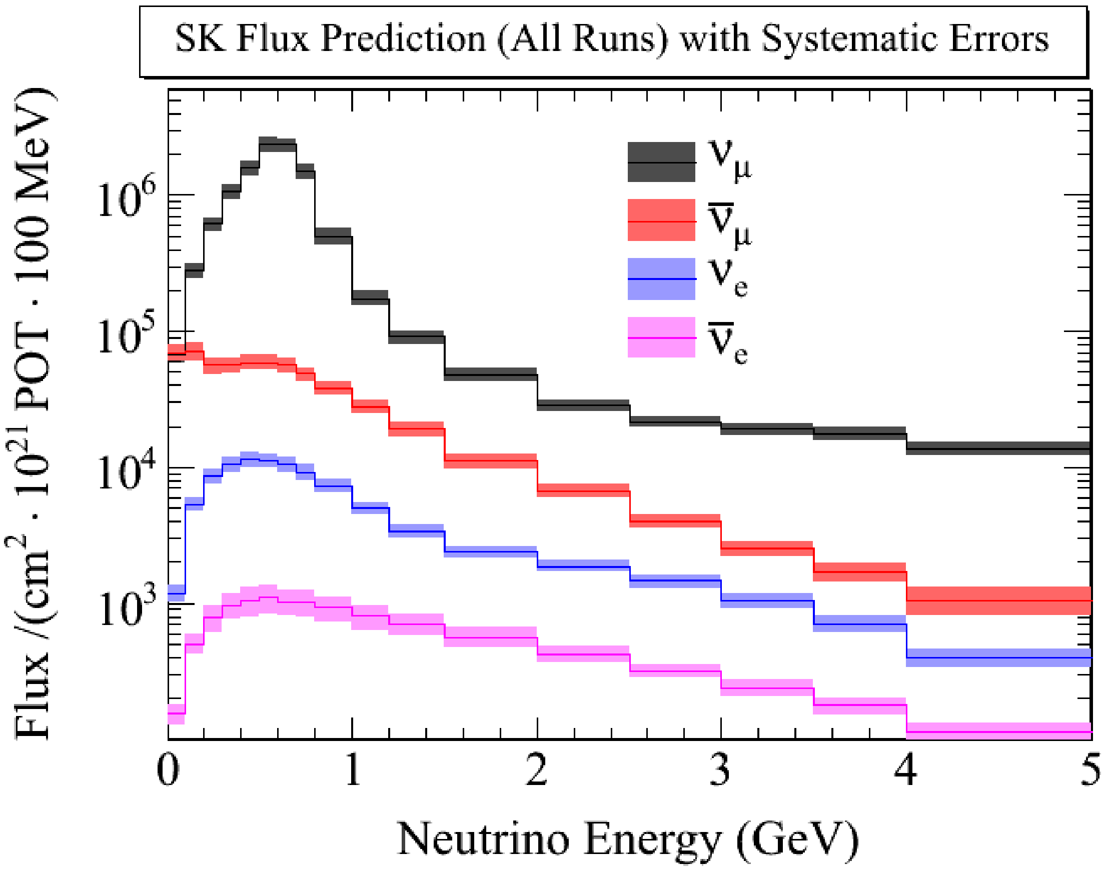
MC π^0 event at Super-K

Analysis Strategy

- Predict event rates and distribution at Super-K as function of θ_{13} and δ_{CP}.
  - Beam Monte Carlo and neutrino interaction models provide baseline prediction
  - Use near detector measurements to normalize flux ⊕ cross-section to data
- Select ν_e events at Super-K
- Compare observed ν_e distribution to prediction and fit for preferred θ_{13}.

Beam Flux Predictions

Flux uncertainty derived from experimental data on hadronic production. Pion and kaon production tuned to external data, especially NA61, which measured these on replica T2K target. Tuned GEANT3 simulation of production on graphite target used to predict fluxes at near and far detectors.



Major uncertainties are secondary nucleon production, hadronic interaction length, and pion production.

Beam flux uncertainty at SK is 11%, before adding near detector constraint.

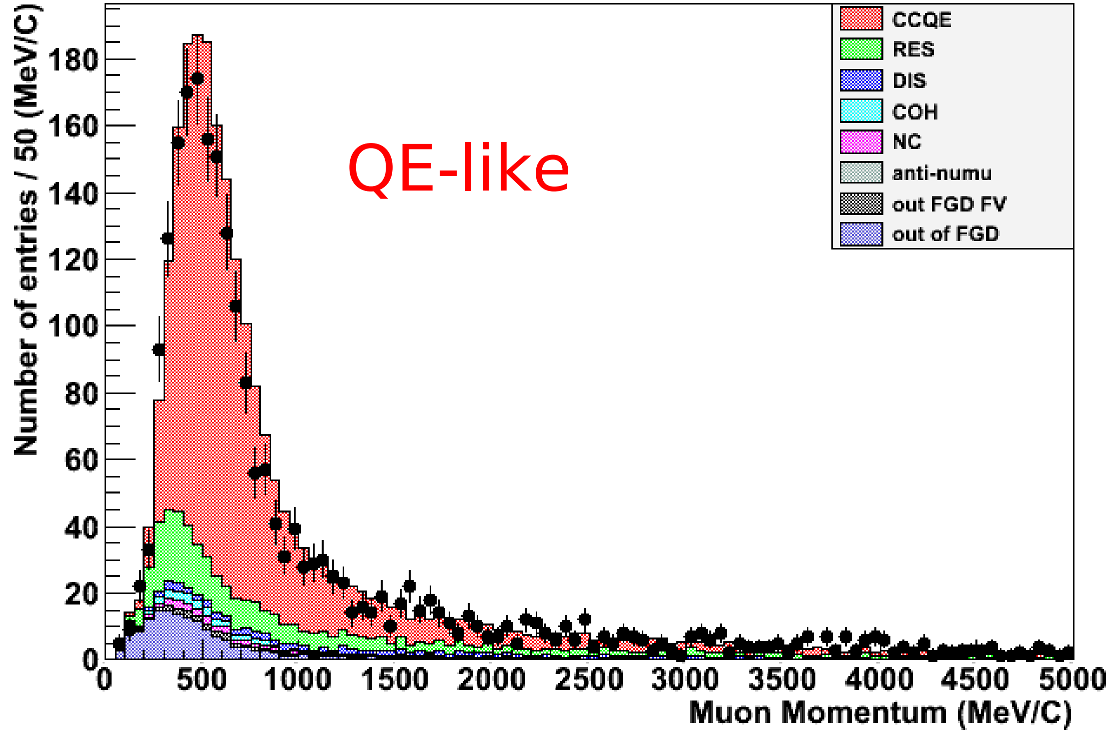
Full correlation matrix between near and far detector fluxes is produced.

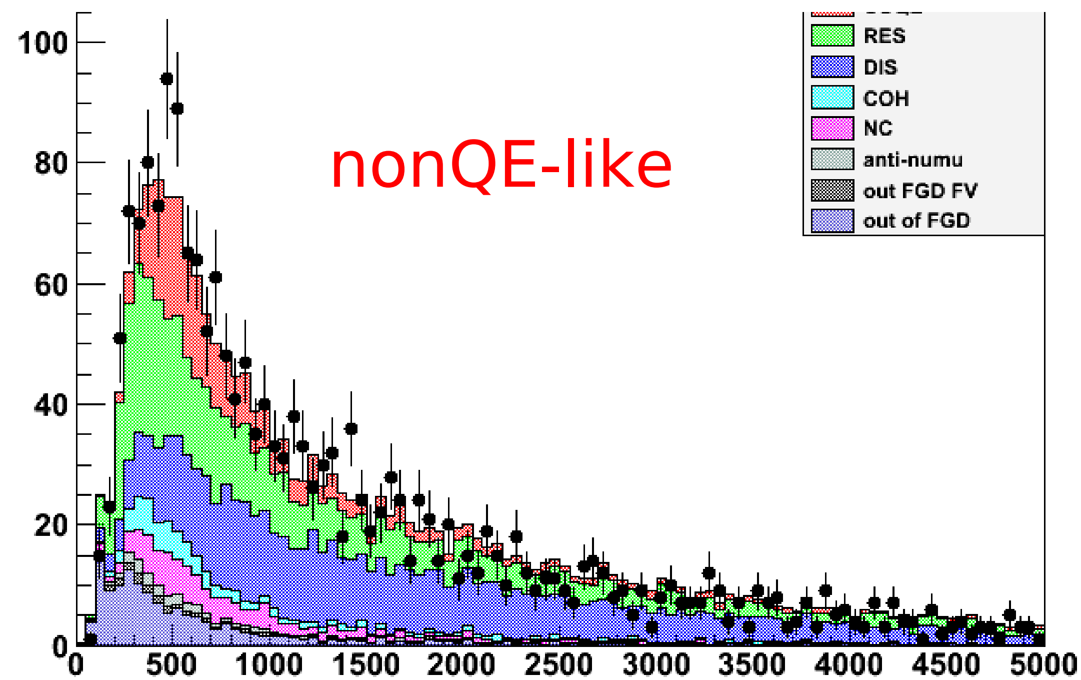
Near Detector Spectrum Measurement

Select CC events in 1st FGD: muon-like dE/dx in TPC, negative curvature, start of track in FGD fid. volume, no upstream tracks

Divide into CCQE-like and nonQE-like sample: QE-like if no 2nd track in TPC & no Michel electron in FGD.

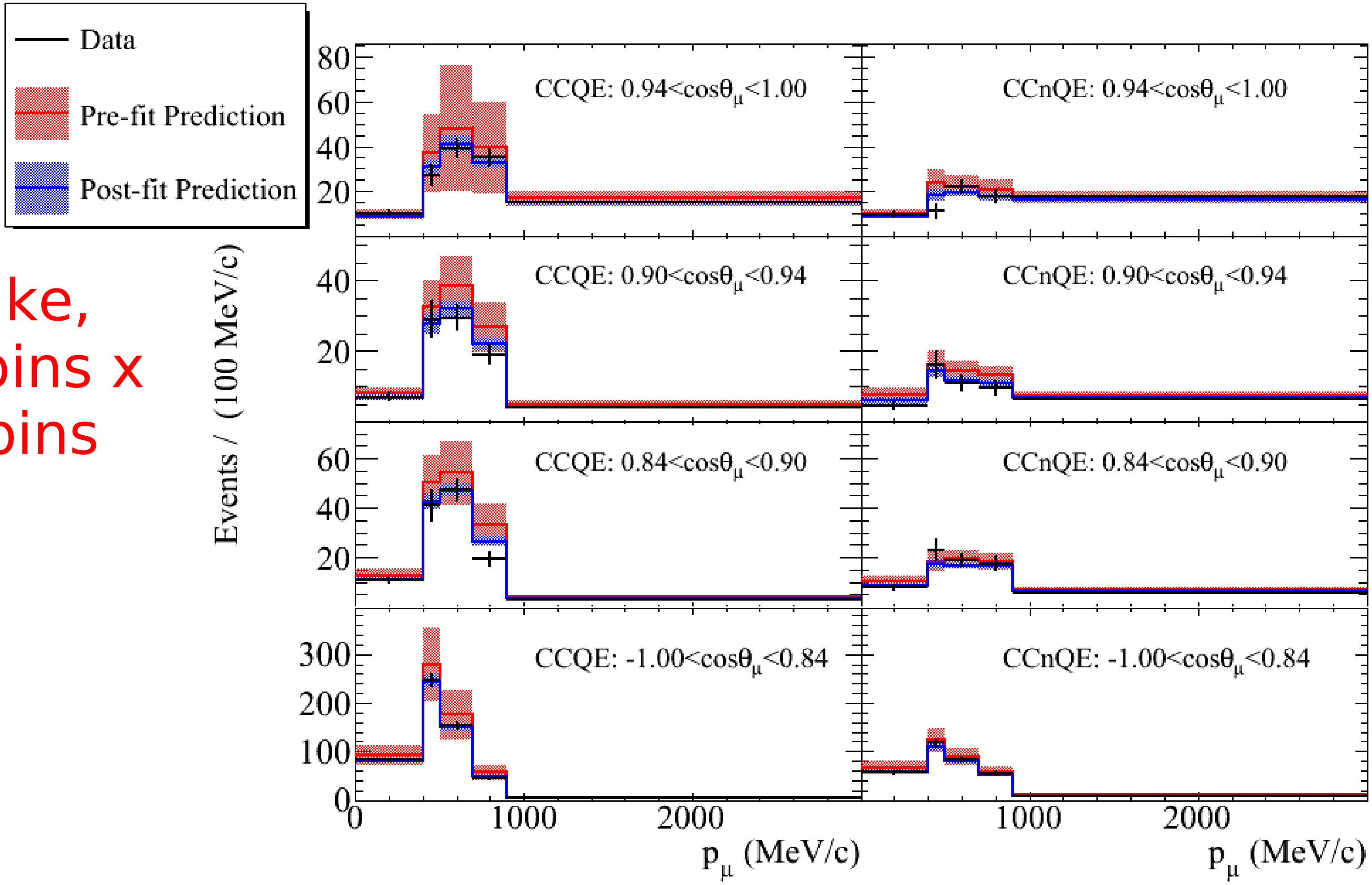
Measure the muon track's momentum and angle, and use the p,θ distribution for both QE-like and nonQE-like events to constrain flux and cross-section





Near Detector Distributions

QE-like,
4 θ bins x
5 p bins



nonQE-like,
4 θ bins x
5 p bins

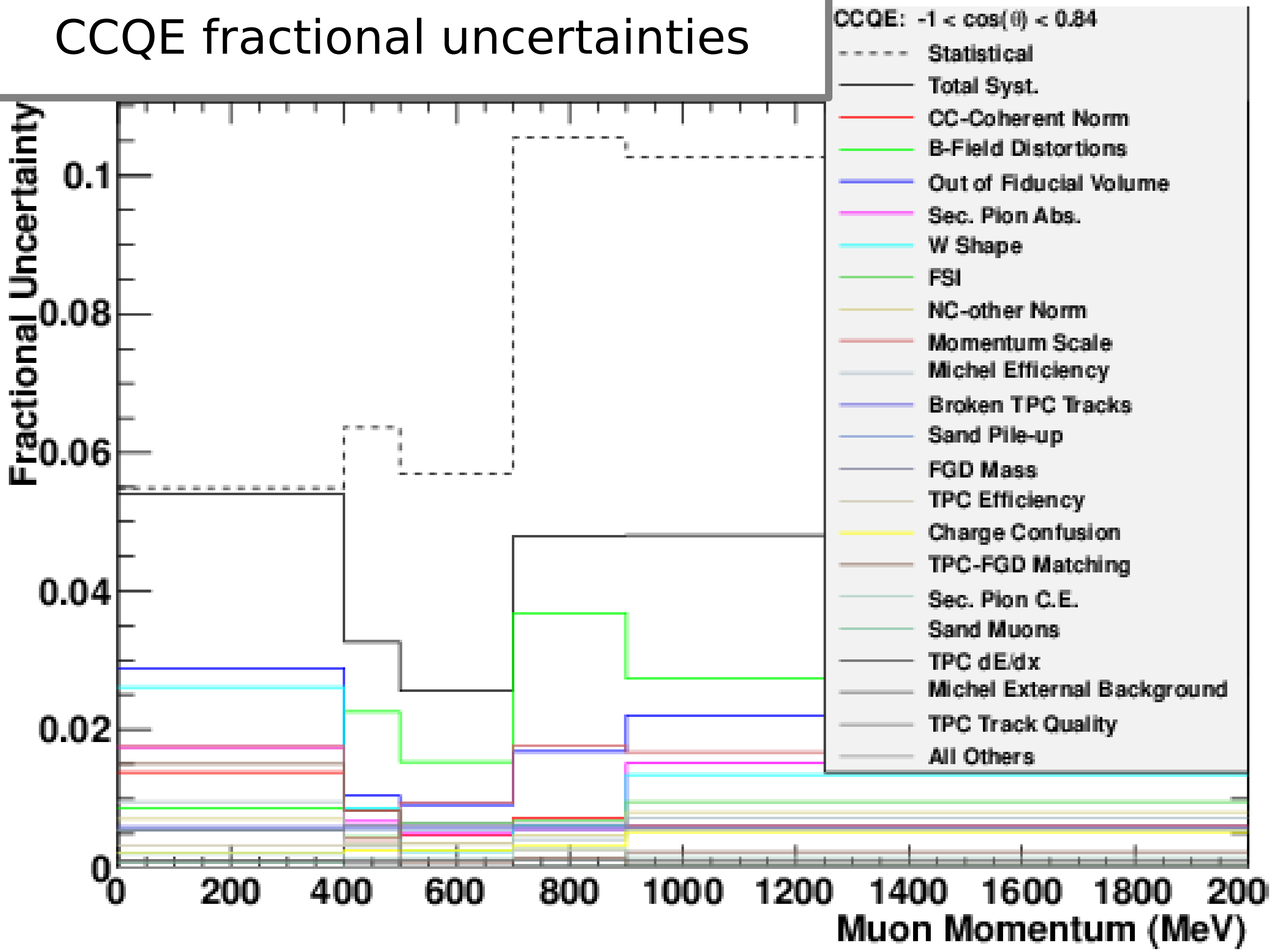
QE sample constrains spectral shape, flux, and cross-section:

$$E_\nu^{\mathrm{rec}} = \frac{(M_n - V_{nuc}) \cdot E_e - m_e^2/2 + M_n \cdot V_{nuc} - V_{nuc}^2/2 + \left(M_p^2 - M_n^2\right)/2}{M_n - V_{nuc} - E_e + P_e \cos\theta_{\mathrm{beam}}}$$

NonQE-like sample fixes backgrounds, cross-section inputs

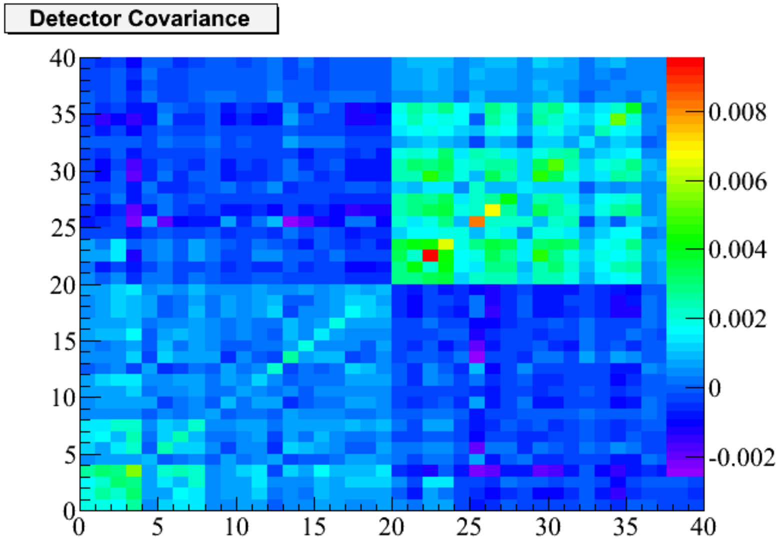
Near Detector Systematics

CCQE fractional uncertainties



Statistics-limited analysis.
Major detector systematics:
* non-uniform B field
* secondary interactions
* background from interactions outside of FGD

Full 40x40 detector covariance matrix produced for all systematic uncertainties.



Joint fit of beam and near detector data for fluxes and cross-sections

Beam inputs:
binned energy spectra for all flux components; covariances between ND280 and SK fluxes

+

ν interaction model:
parametrized cross-sections for all relevant modes;
Error estimates from fits to external data.
NEUT + reweighting

=

Predicted # of events in ND bins as a Function of flux and cross-section parameters

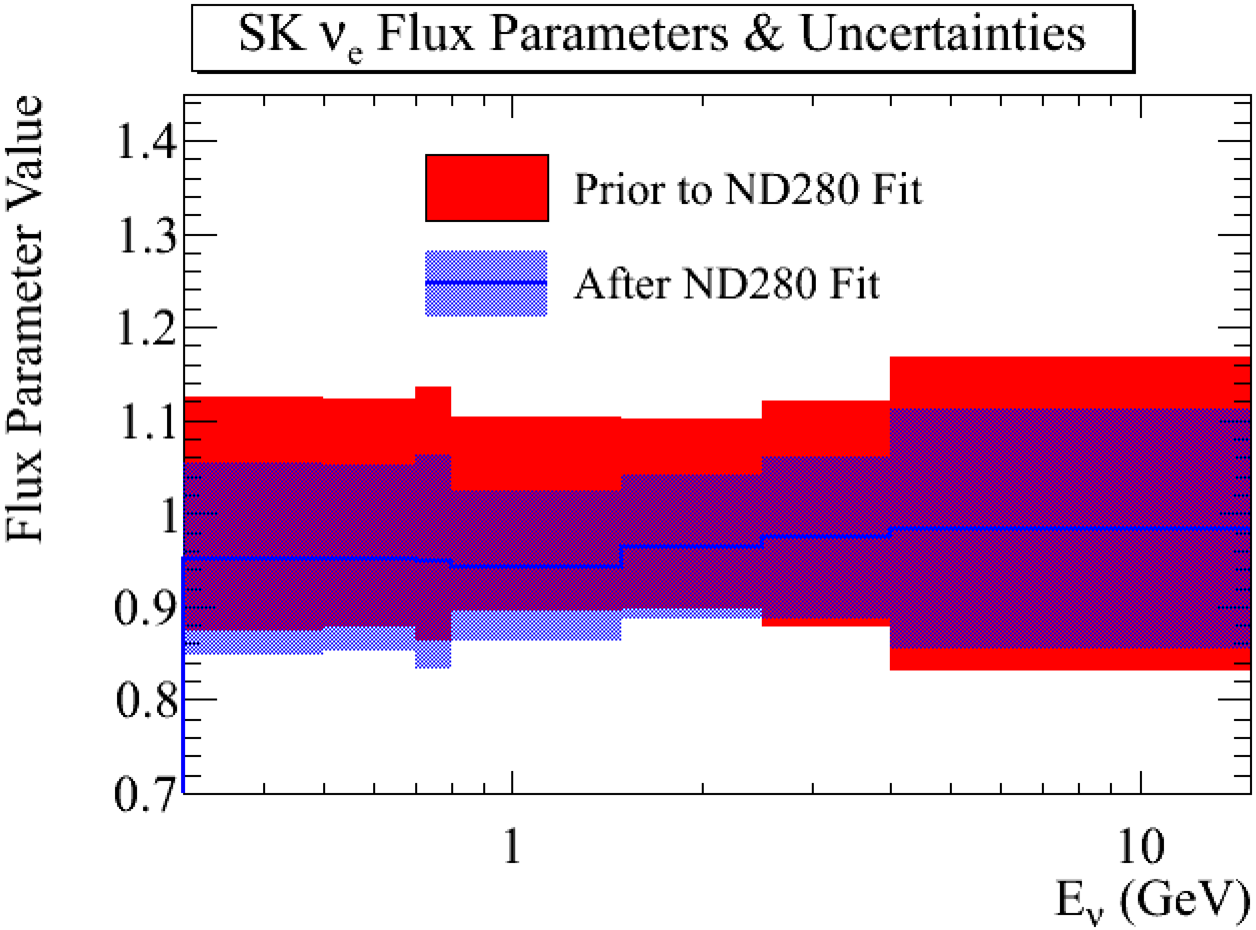
↕

Near detector data:
Number of events in 20 p_μ,θ_μ bins for QE-like and nonQE-like samples,
+ full error matrix.

Maximum likelihood fit to ND data to determine flux and cross-section reweightings. Beam model prediction and external cross-section measurements serve as priors in fit.

Result: updated flux, cross-section values and uncertainties at SK

Reduction in uncertainty from ND fit



Near detector data constrains combination of flux x cross-sections.

Flux at ND is highly correlated with flux at SK, since ν's are produced by the same decaying particles in the beam.

Event totals	QE-like	nonQE-like
ND Data	2352	2132
Predicted, pre-fit	2694±275(flux)±469(xsec)	2348±235(flux)±238(xsec)
Predicted, post-fit	2363±79 (flux + xsec)	2130±107 (flux + xsec)

Neutrino Interaction Model

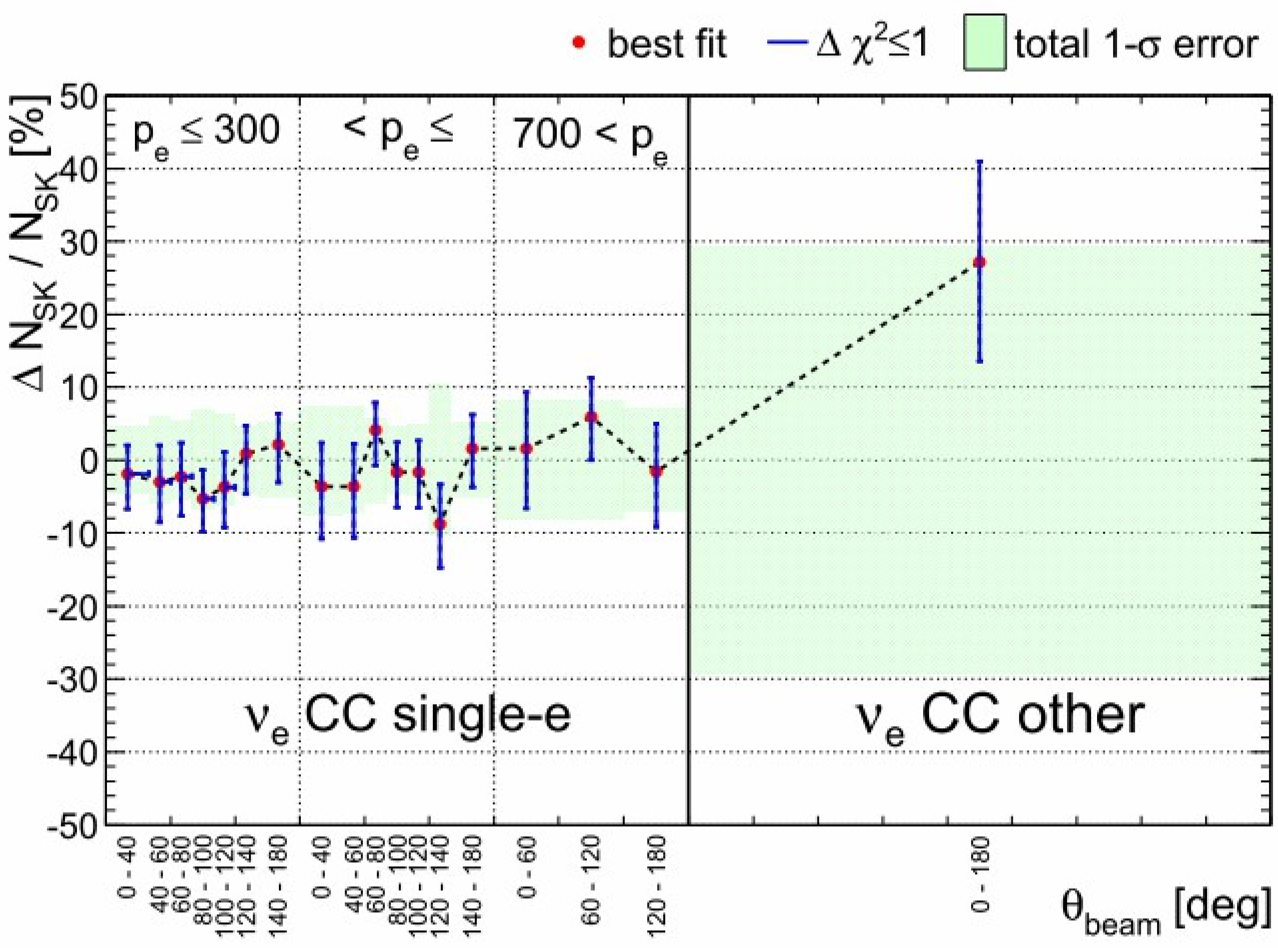
Our primary neutrino interaction model is NEUT, with GENIE used as a cross-check.

Previous data from Mini-BooNE, K2K, and other experiments used to constrain parametrized cross-section model.

Parameter	Prior Value	Prior Error	Fitted Value	Fitted Error
M_A^{QE} (GeV)	1.21	0.45	1.186	0.194
M_A^{RES} (GeV)	1.16	0.11	1.137	0.095
CCQE E1	1.0	0.11	0.941	0.087
CCQE E2	1.0	0.30	0.917	0.230
CCQE E3	1.0	0.30	1.182	0.252
CC1π E1	1.63	0.43	1.665	0.283
CC1π E2	1.0	0.40	1.101	0.297
NC1π^0 Norm.	1.19	0.43	1.222	0.396
Spec. Function	0 (off)	1 (on)	0.038	0.205
p_F (MeV/c)	217	30	224.6	23.5
CC Other Shape (GeV)	0.0	0.4	-0.048	0.352

CCQE model is based on relativistic Fermi gas model of nucleus, with empirical normalization factors to span uncertainties in data. Comparison to spectral function model included as uncertainty.

Super-K Detector Systematics



N_{SK} error

Detector efficiency systematics are determined primarily from atmospheric neutrino data.

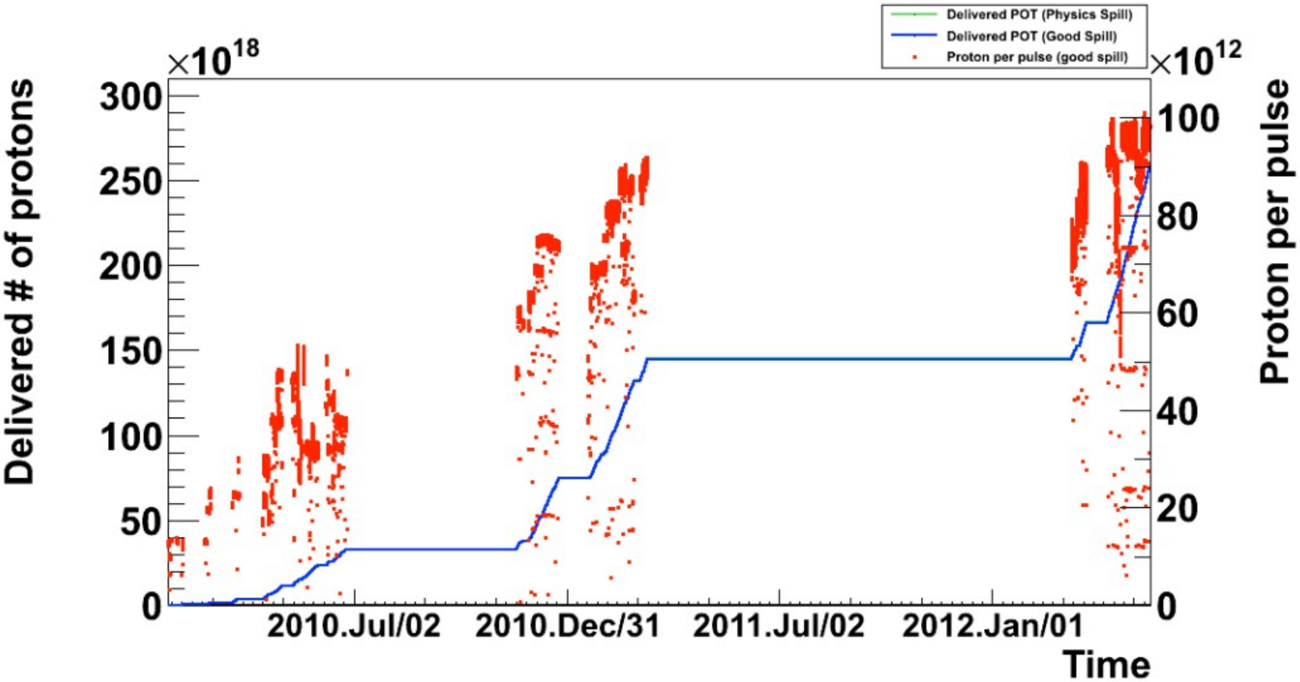
π^0 mis-ID studied with hybrid electron + MC γ sample

Systematic uncertainties evaluated as function of electron direction & momentum

Event	Systematic error	
	$\sin^2 2\theta_{13}$=0.1	$\sin^2 2\theta_{13}$=0
Signal	2.6%	2.6%
Background	9.4%	9.0%
Sig+BKG	3.3%	8.5%

T2K Data Set (until 2012 May 15)

	Run Periods			
	Run 1	Run 2	Run 3b	Run 3c
Protons on Target ($\times 10^{20}$)	0.323	1.108	0.214	0.911



Peak beam power: 190kW

Total POT used in analysis: 2.56×10^{20}

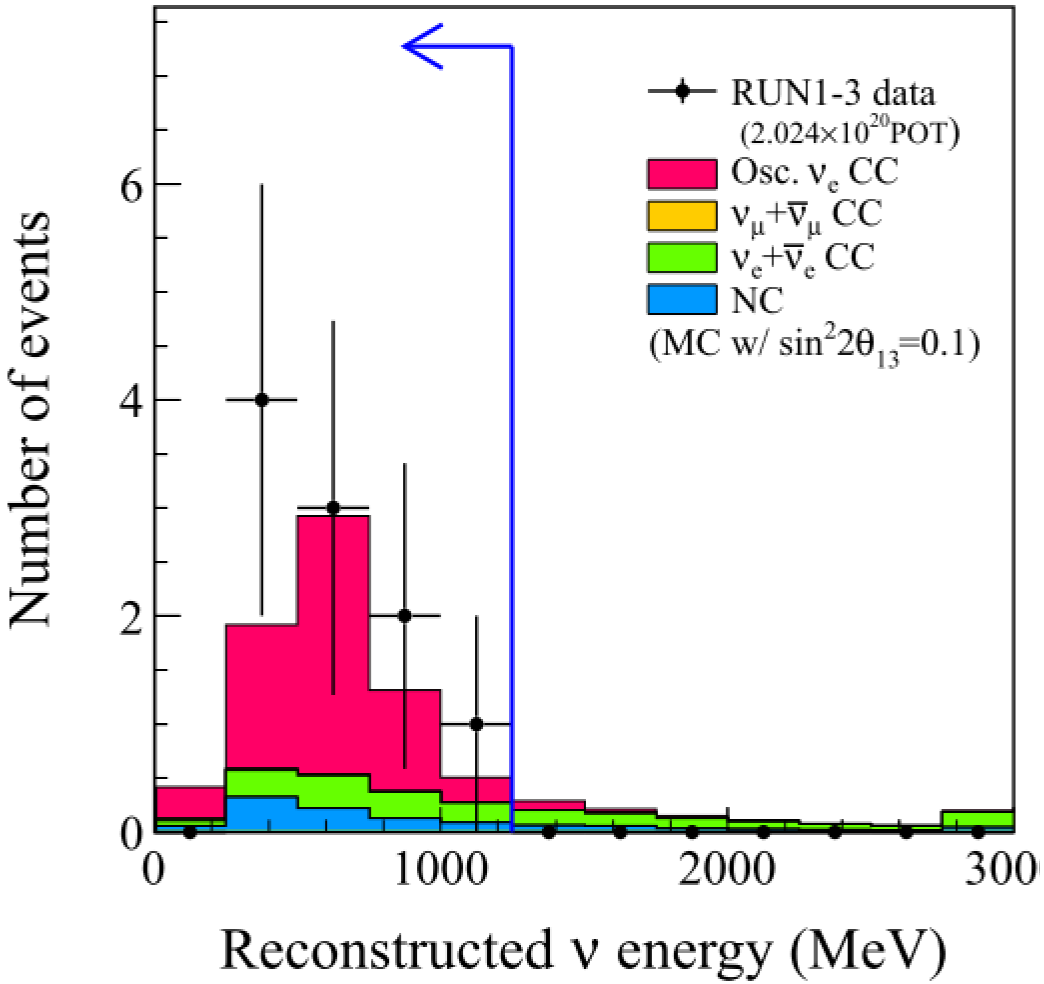
Near detector constraint from just Run 1+2 only

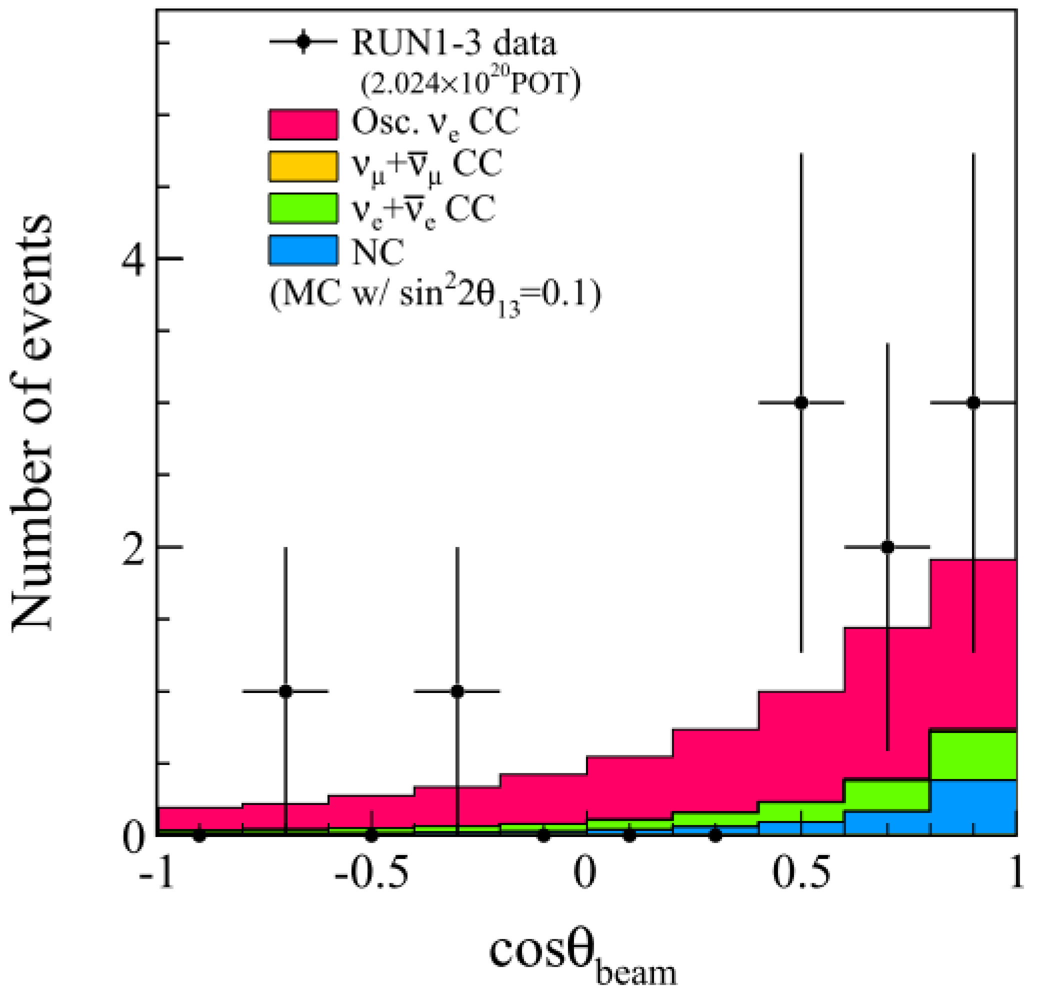
T2K event selection cuts at SK

Selection cuts optimized on MC and fixed before data-taking.

1. Event is fully contained in SK fiducial volume (22.5ktonne)
2. Number of rings found = 1
3. Ring has electron-like particle ID
4. Visible energy > 100 MeV
5. No decay electrons
6. π^0 cut: fit for best 2^{nd} ring that can be found, and demand that invariant mass of two rings is < 105 MeV/c^2
7. Reconstructed neutrino energy (assuming CCQE kinematics) is <1250 MeV.

Selected T2K ν_e events in SK





	The predicted number of events	
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	2.73	9.07
ν_e signal	0.15	6.60
ν_e background	1.42	1.32
ν_μ background	1.02	1.02
$\bar{\nu}_\mu$ background	0.06	0.06
$\bar{\nu}_e$ background	0.08	0.07

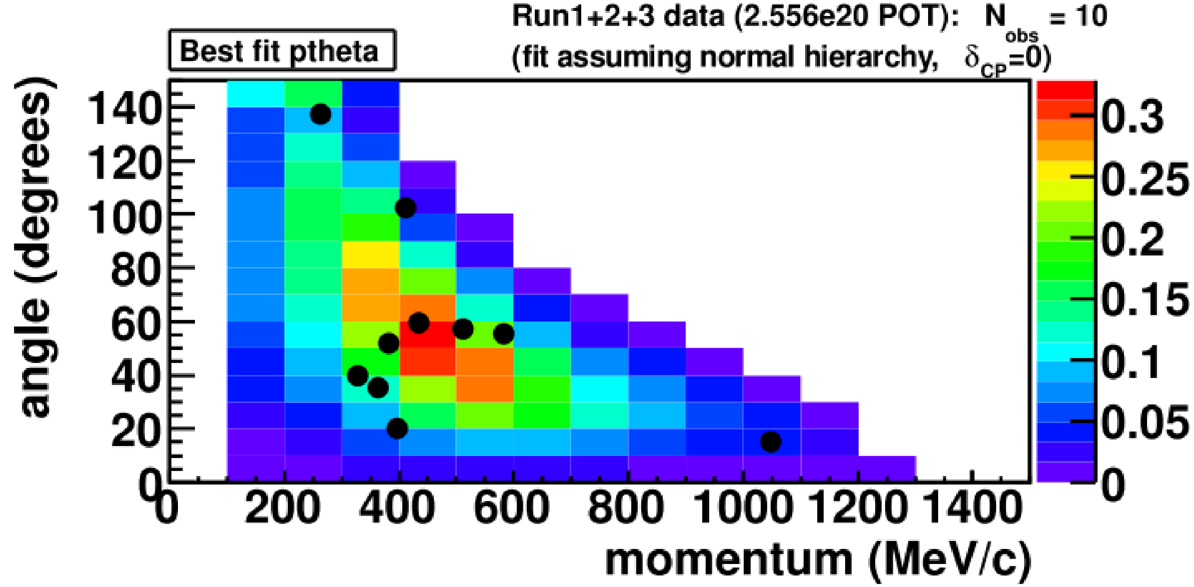
Observed: 10 events

Expected (θ_{13}=0): 2.73±0.37

Probability of 2.73 fluctuating to ≥10 events: 8.2×10^{-4} (3.2σ)

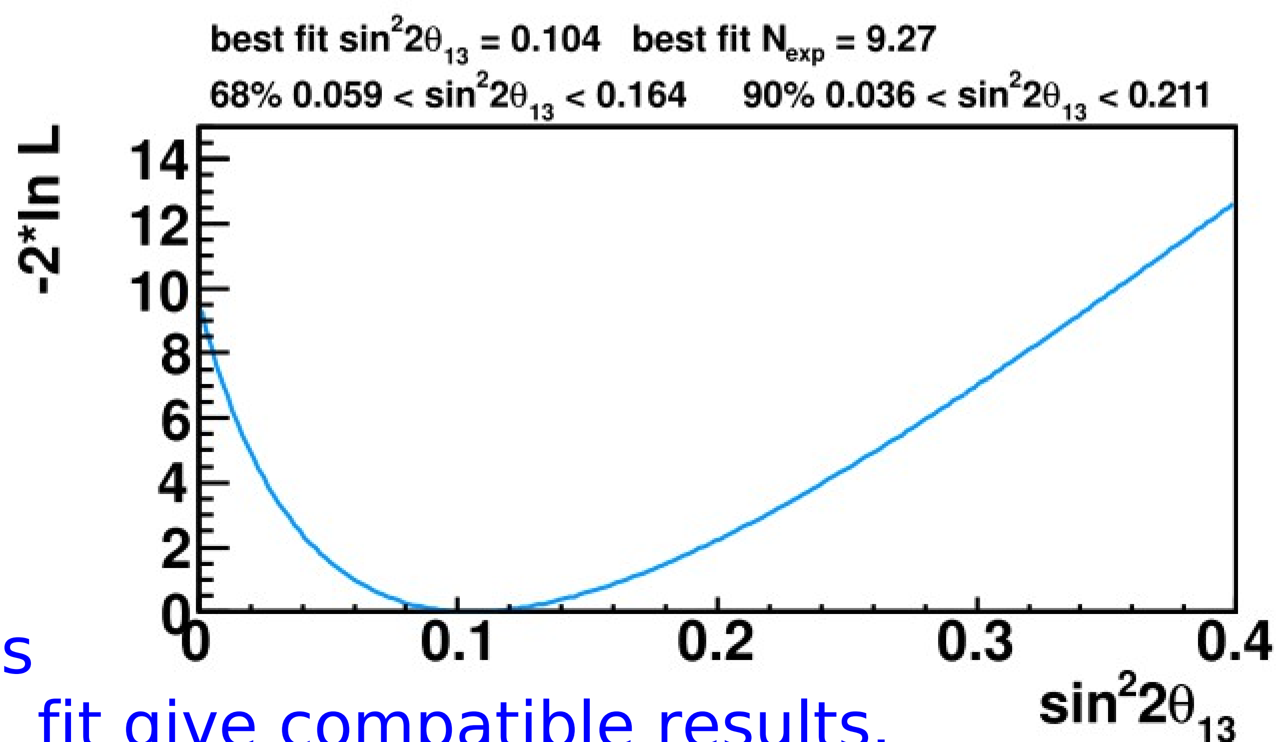
Oscillation Fit

We fit the p_e,θ_e distribution to templates for signal and background to determine θ_{13}, using a maximum likelihood fit.



Signal and background have different distributions in these variables.

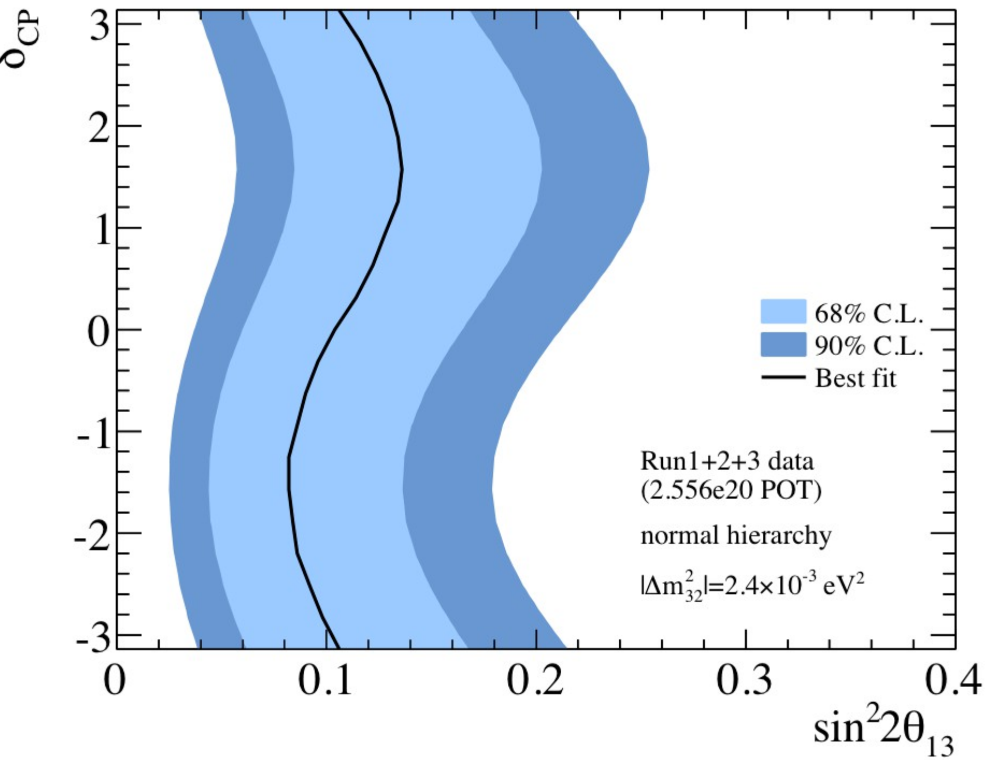
Best-fit:
$\sin^2 2\theta_{13} = 0.104$
(for normal hierarchy, $\delta_{CP}=0$)



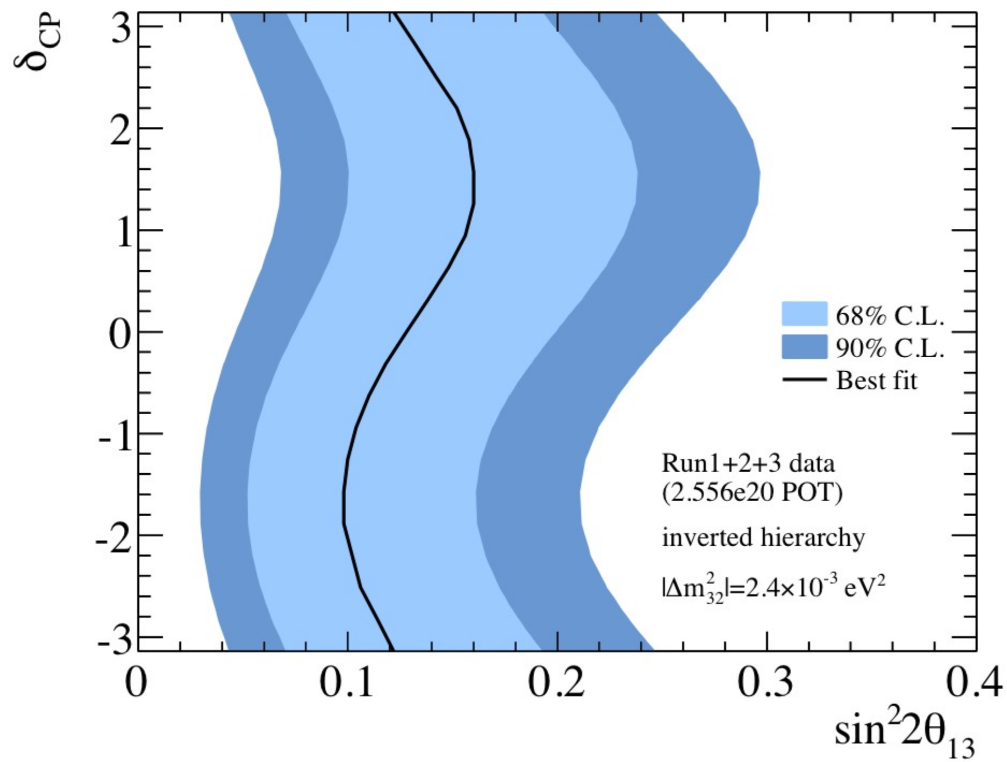
Alternate fits using rates only or reconstructed E_ν fit give compatible results.

Oscillation parameter limits

Normal hierarchy

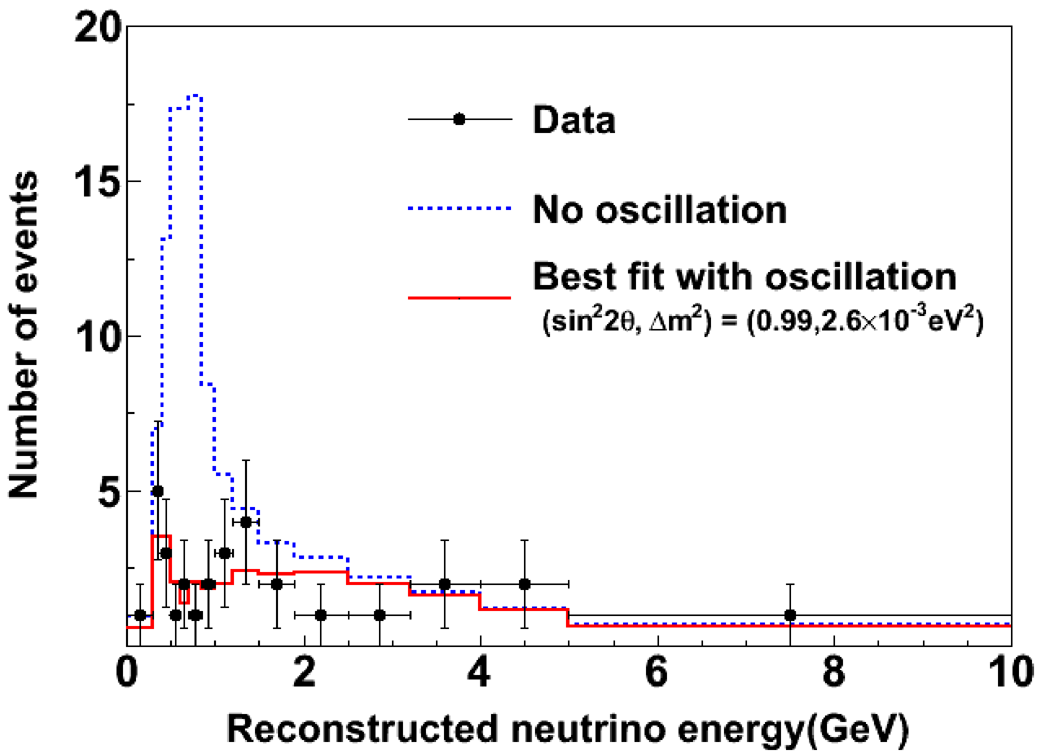


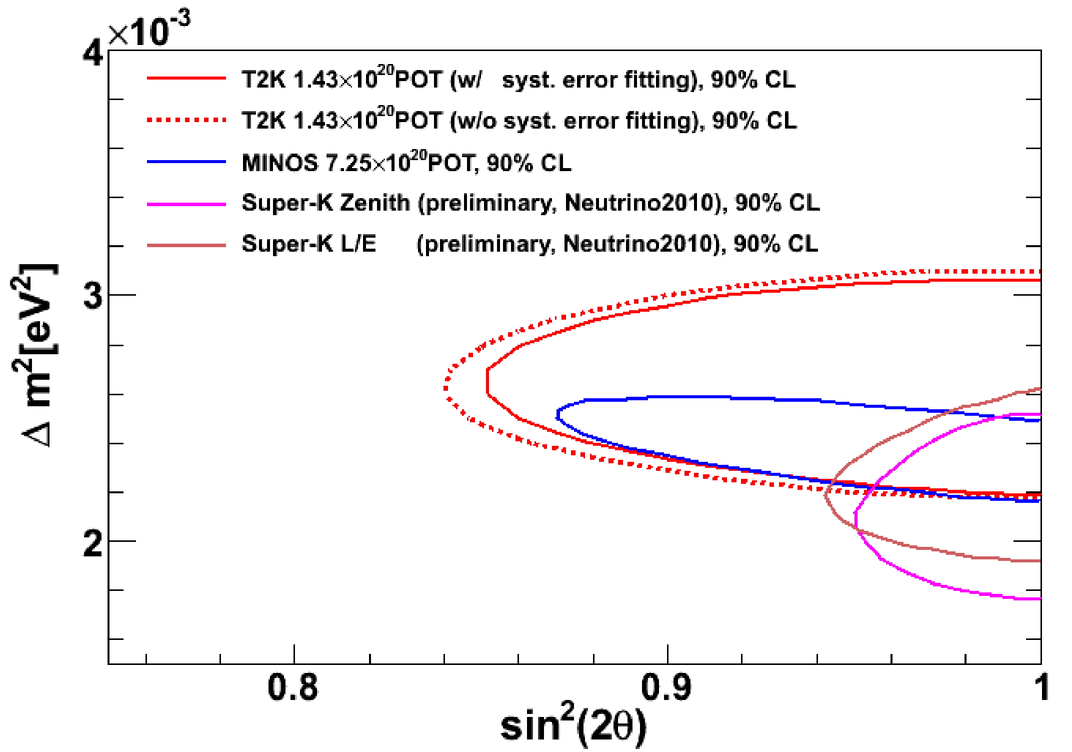
Inverted hierarchy



Best-fit values for both normal and inverted mass hierarchy are very close to values inferred from reactor neutrino data.

ν_μ disappearance result: Runs 1+2





With only 1/50th of its final data set T2K is already competitive on atmospheric neutrino mixing parameters. Significant improvements in θ_{23}, tests of maximal mixing expected.

PHYSICAL REVIEW D 85, 031103(R) (2012) arXiv:1201.1386

Conclusions

T2K has nearly doubled its data set since the March 2011 earthquake, and has significantly upgraded the analysis.

New analysis uses full near detector spectrum measurement, improved beam systematics, reduced Super-K systematics, and momentum/angular distributions at Super-K.

Latest data from T2K excludes $\theta_{13}=0$ at 3.2σ.

Results are consistent with past T2K and recent reactor neutrino results, and open the door to CP studies using long-baseline neutrino beams.

Backup slides

Matter Effects and ν_e Appearance

Matter effects modify the oscillation formula. Because the Earth is made of electrons and not heavier leptons, the effective "index of refraction" for ν_e is different than that for ν_μ. At the oscillation maximum, the ν_e appearance probability changes to:

$$P(\nu_\mu \rightarrow \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

where

$$E_R = \frac{\Delta m_{32}^2}{2\sqrt{2} G_F N_e} = \pm 11\, GeV$$

The sign of the matter effect is opposite for neutrinos and anti-neutrinos, and depends on the sign of Δm^2 as well.

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

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

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

leading term

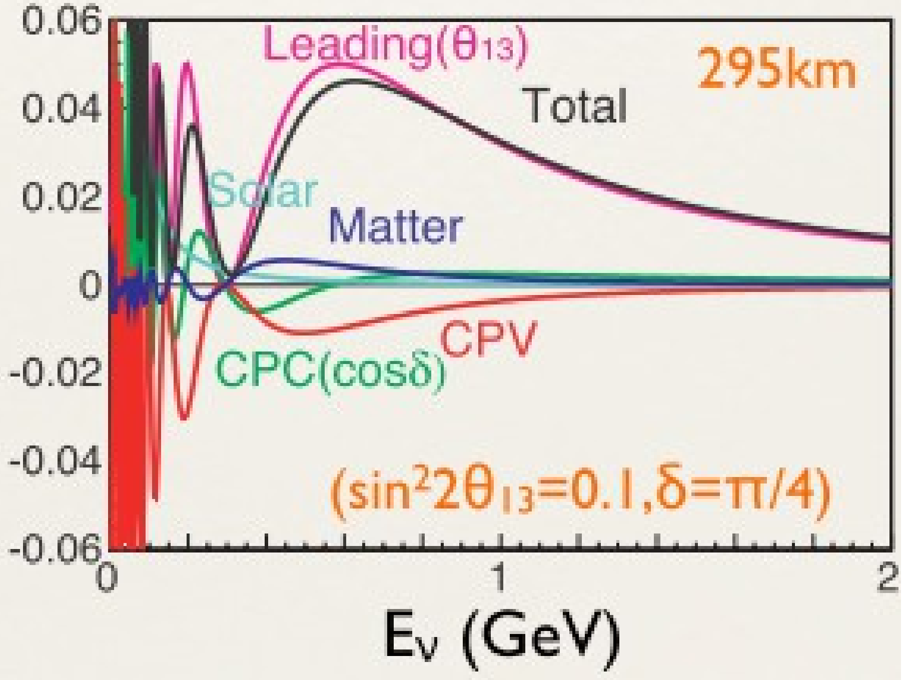
CP violating (flips sign for anti-ν)

Solar

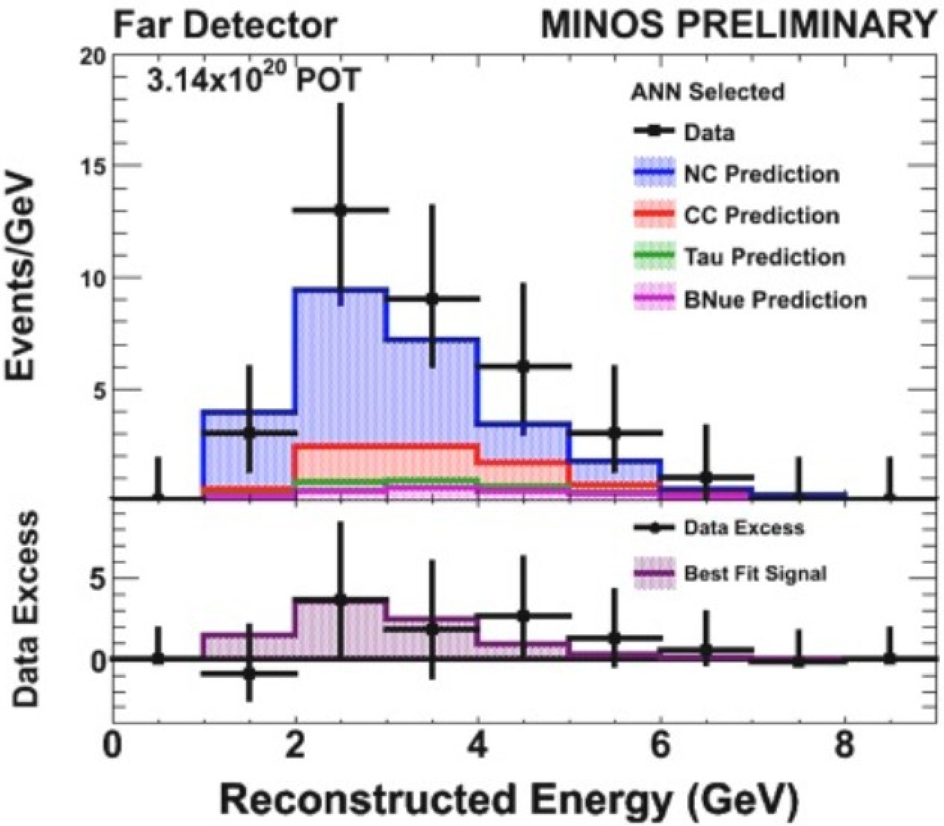
Matter

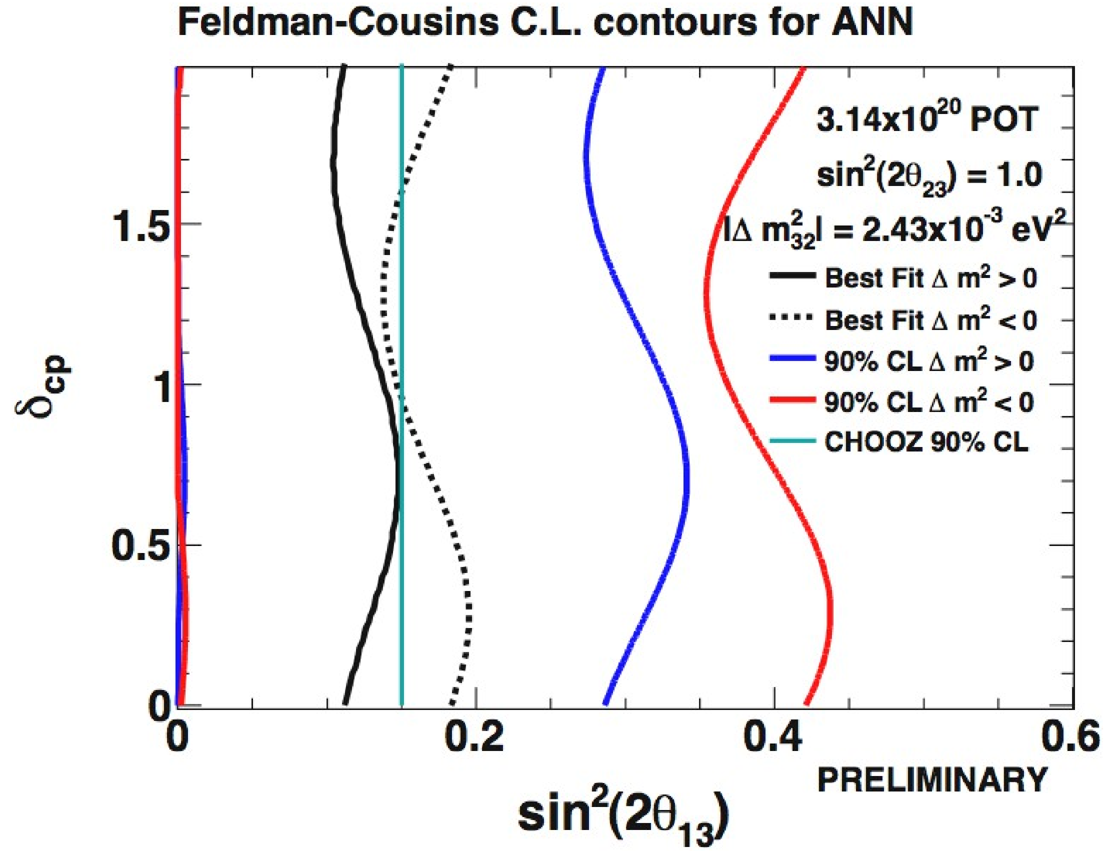
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m_{23}^2 \frac{L}{E}\right)$$

- ***Rich Physics in ν_e appearance***
  [θ_{12}, θ_{13}, θ_{23}, δ_{CP}, Δm_{21}^2, Δm_{31}^2, Δm_{32}^2]
  - ***CP violation***
  - ***Matter effect***
  - ***(Sterile neutrinos) or new physics***



θ_{13}: MINOS



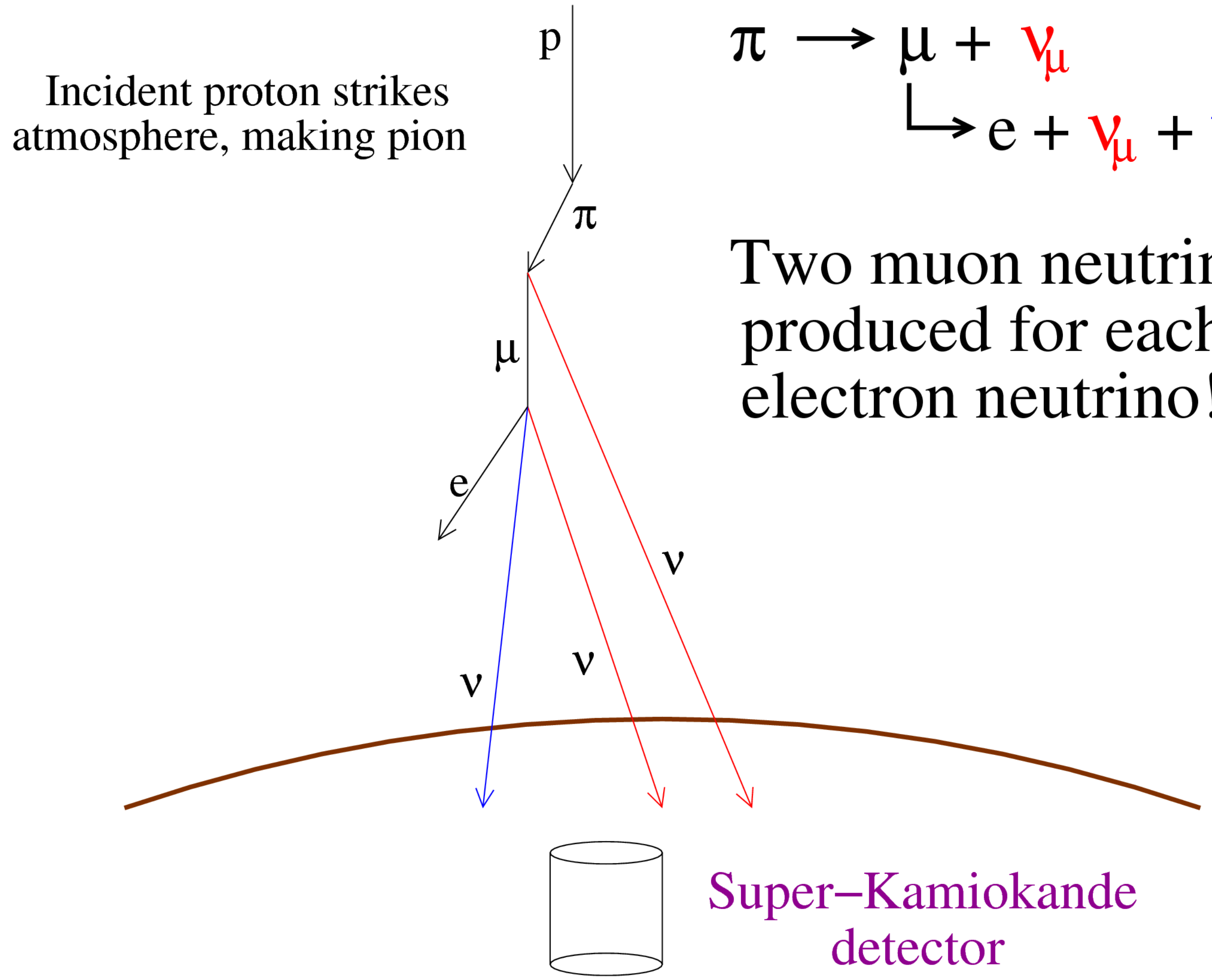


MINOS $\nu_\mu \rightarrow \nu_e$: saw 35 events, expected background 27 ± 5 ± 2

$$\sin^2 2\theta_{13} = 0.078^{+0.079}_{-0.064}$$

PRL 107, 101802 (2011)

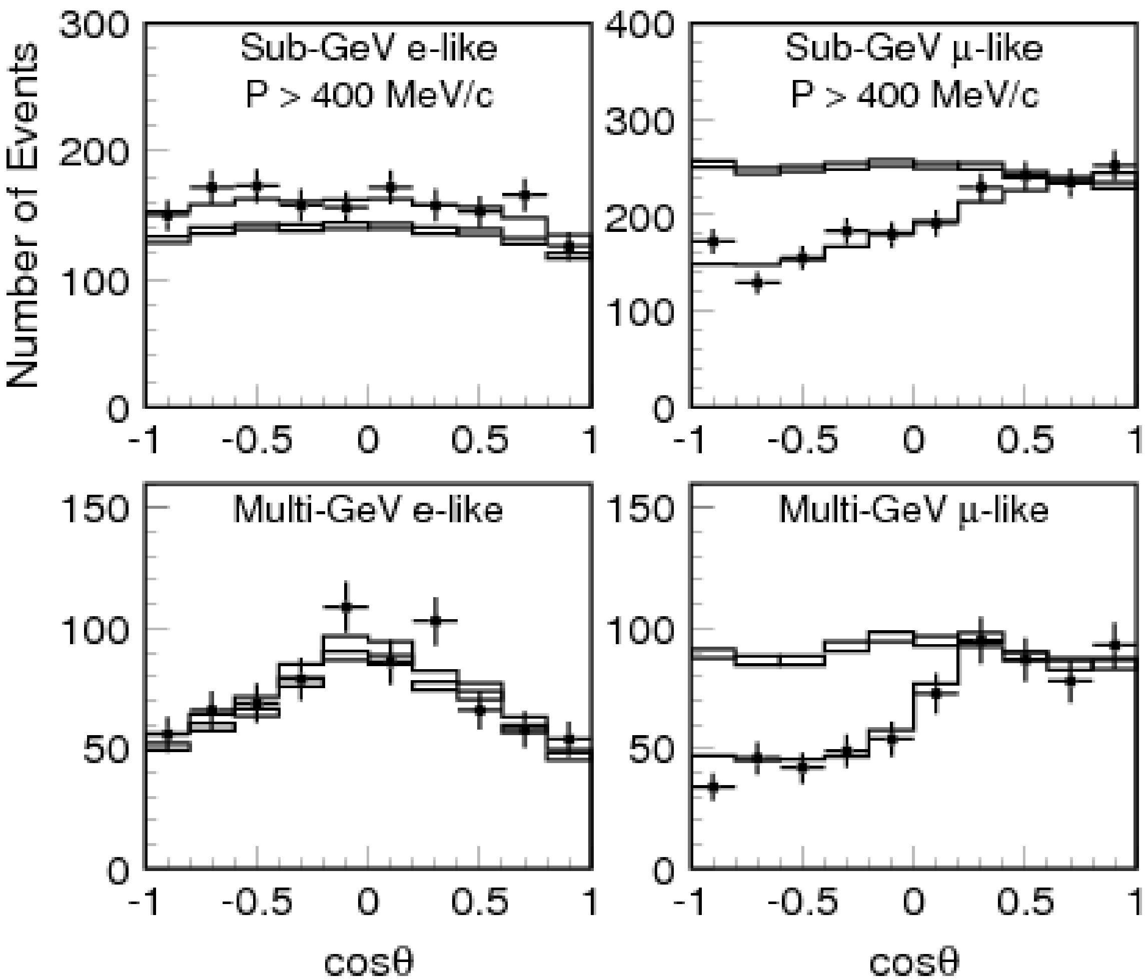
Atmospheric Neutrinos

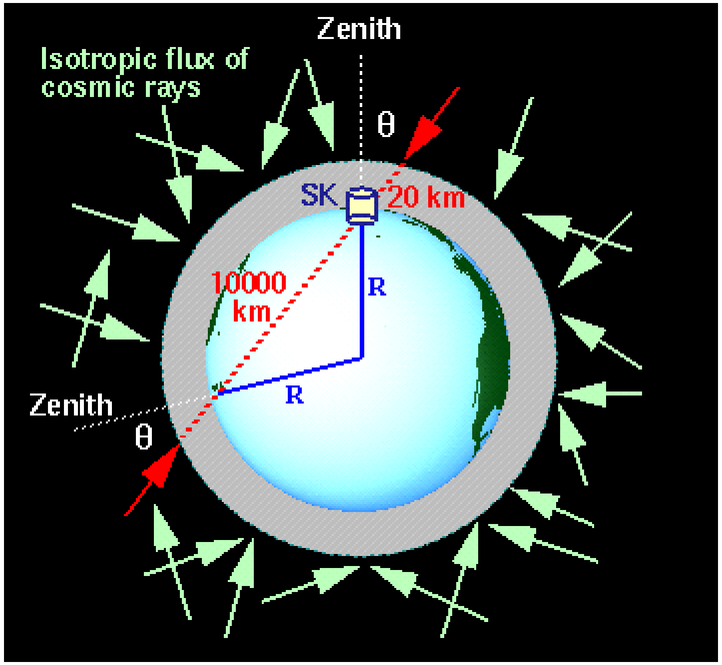


$$\pi \longrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

Two muon neutrinos produced for each electron neutrino!

Super-K atmospheric ν results





Deficit of upward-going ν_μ relative to downward-going.

No deficit for ν_e.

Seems like $\nu_\mu \rightarrow \nu_\tau$

PRL 93:101801, 2004
PRD 71:112005, 2005

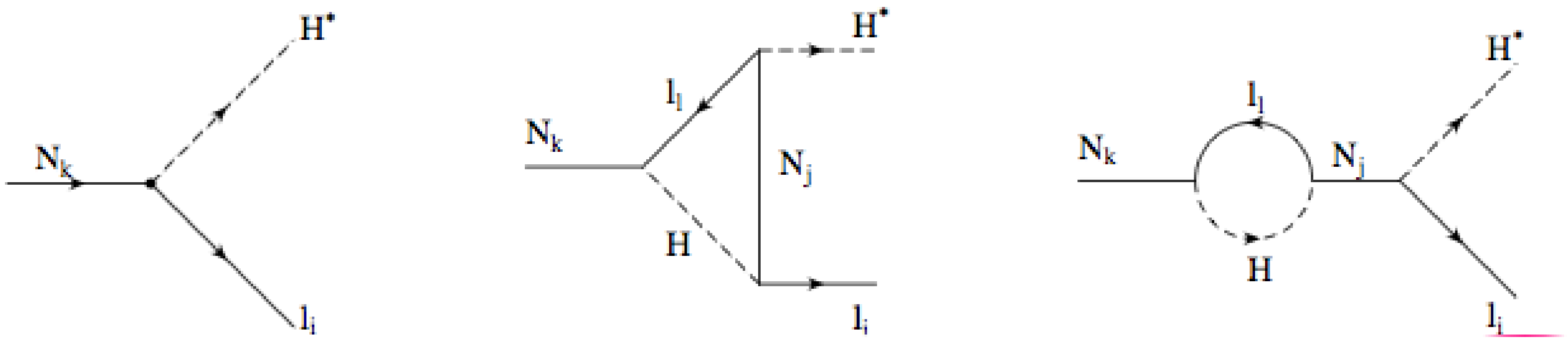
Leptogenesis

CP violation in quark sector not enough to explain observed matter-antimatter asymmetry in universe.

Neutrino mixing provides another possible source of CPV.

- Standard Leptogenesis: decays of RH neutrinos (CPV in decay)

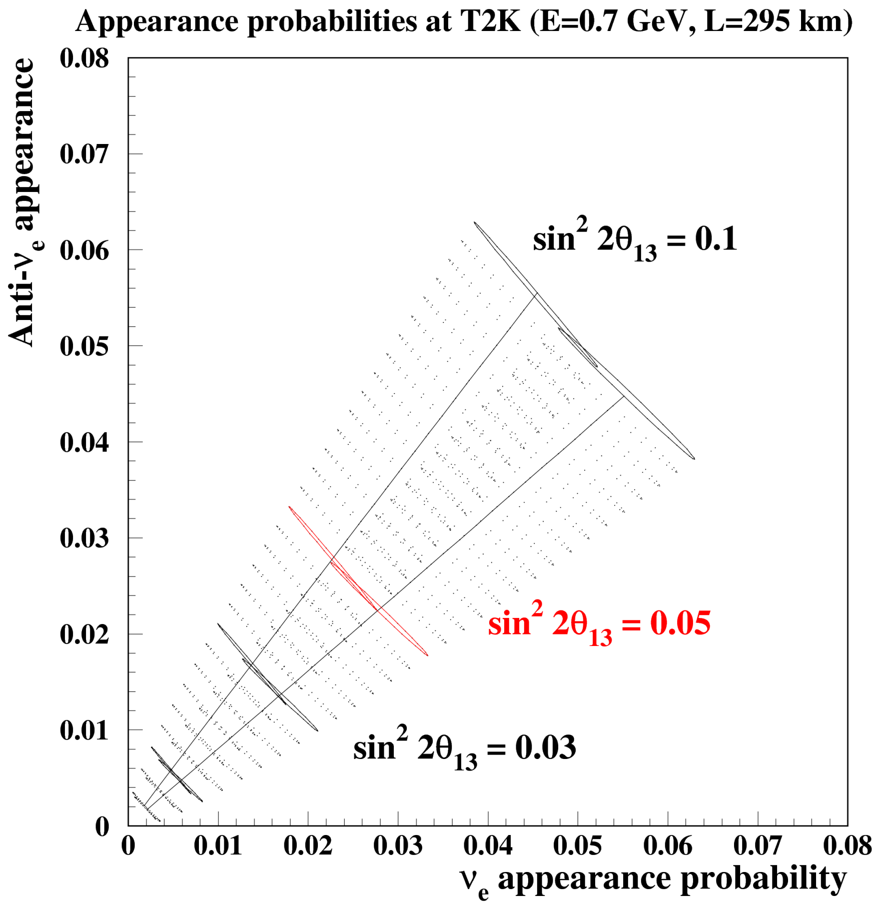
  Quantum interference of tree diagram and one-loop diagram

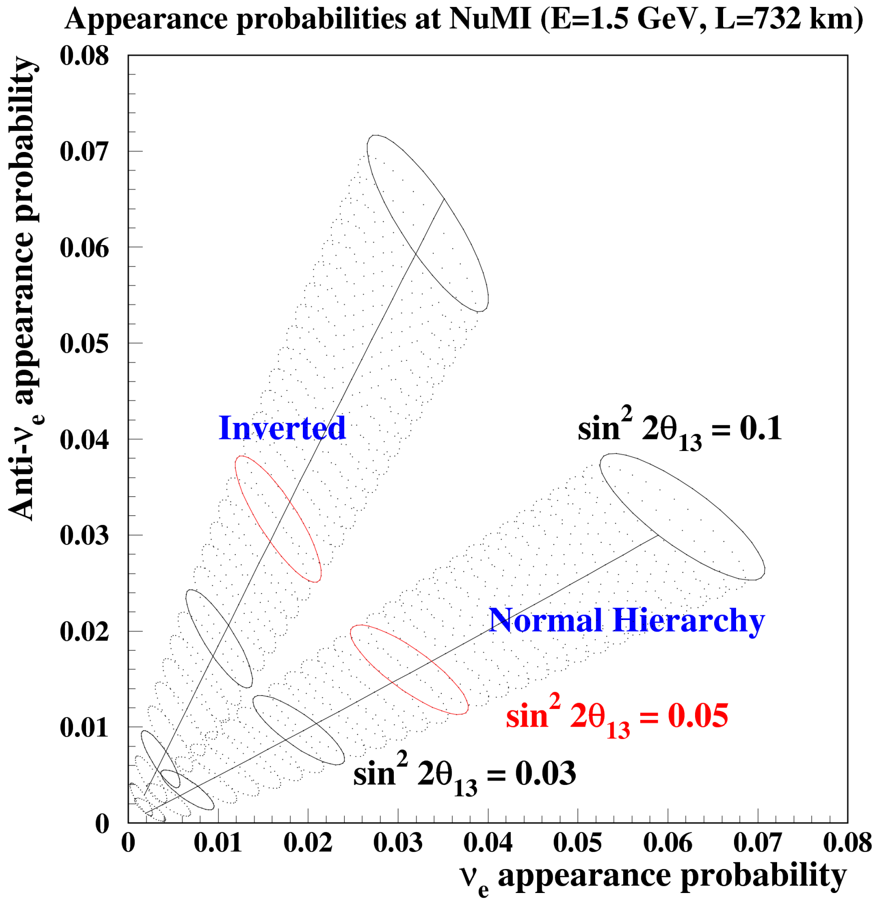


Usual scenario: decay of heavy Majorana neutrinos Phys.Lett B 174, 45 (1986)
Many alternates, eg. leptogenesis with only Dirac ν's PRL 89:271601 (2002)

Relation of δ_{CP} to leptogenesis is model-dependent, but observation of leptonic CP violation is an important milestone.

CP Violation and Matter Effects





Significant parameter degeneracies will require multiple experiments to disentangle.

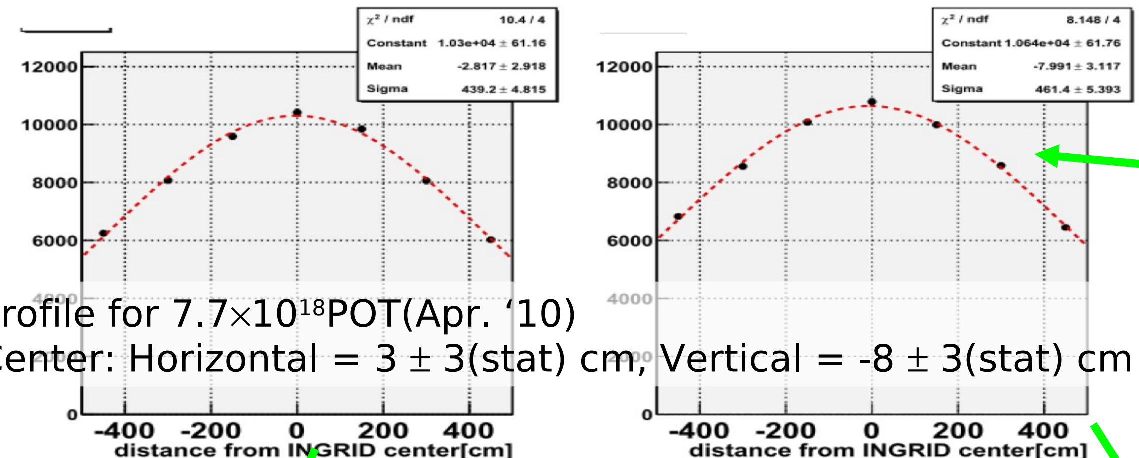
Beam Flux Uncertainties

$\sin^2(2\theta_{13})=0.1$ $\Delta m^2_{32}=2.4\times10^{-3}$ eV^2 $\sin^2(2\theta_{23})=1.0$

	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.56	1.90
Proton Beam, Alignment & Off-axis Angle	3.45	2.08	1.75
Horn Current and Magnetic Field	1.40	1.16	1.39
Total	10.04	10.94	4.78

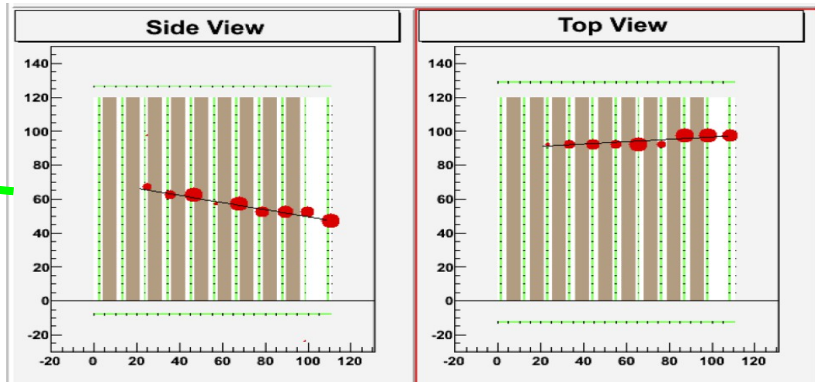
Beam direction: INGRID

- 7+7 array of the scintillator trackers with iron target.
- Distance from target = 279m (V) / 283m (H)
  → 10cm center shift ≡ 0.04mrad
- Beam direction from 2010 Jan. ~ Jun.
  - Horizontal: +0.01±0.05(stat.)±0.33(syst.) mrad
  - Vertical : -0.24±0.05(stat.)±0.37(syst.) mrad

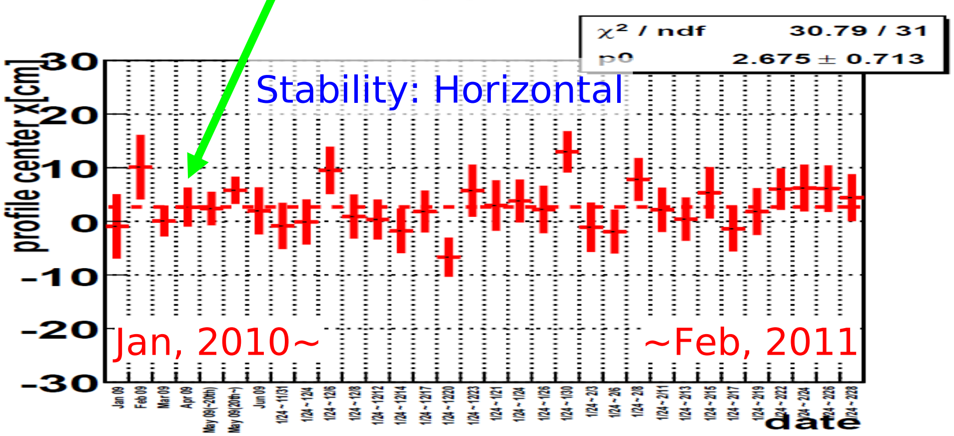


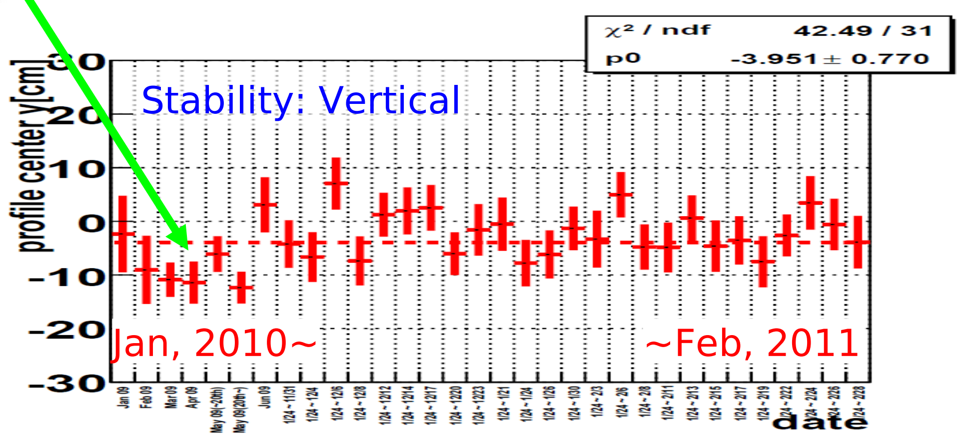
Profile for 7.7×10^{18}POT(Apr. '10)

Center: Horizontal = 3 ± 3(stat) cm, Vertical = -8 ± 3(stat) cm

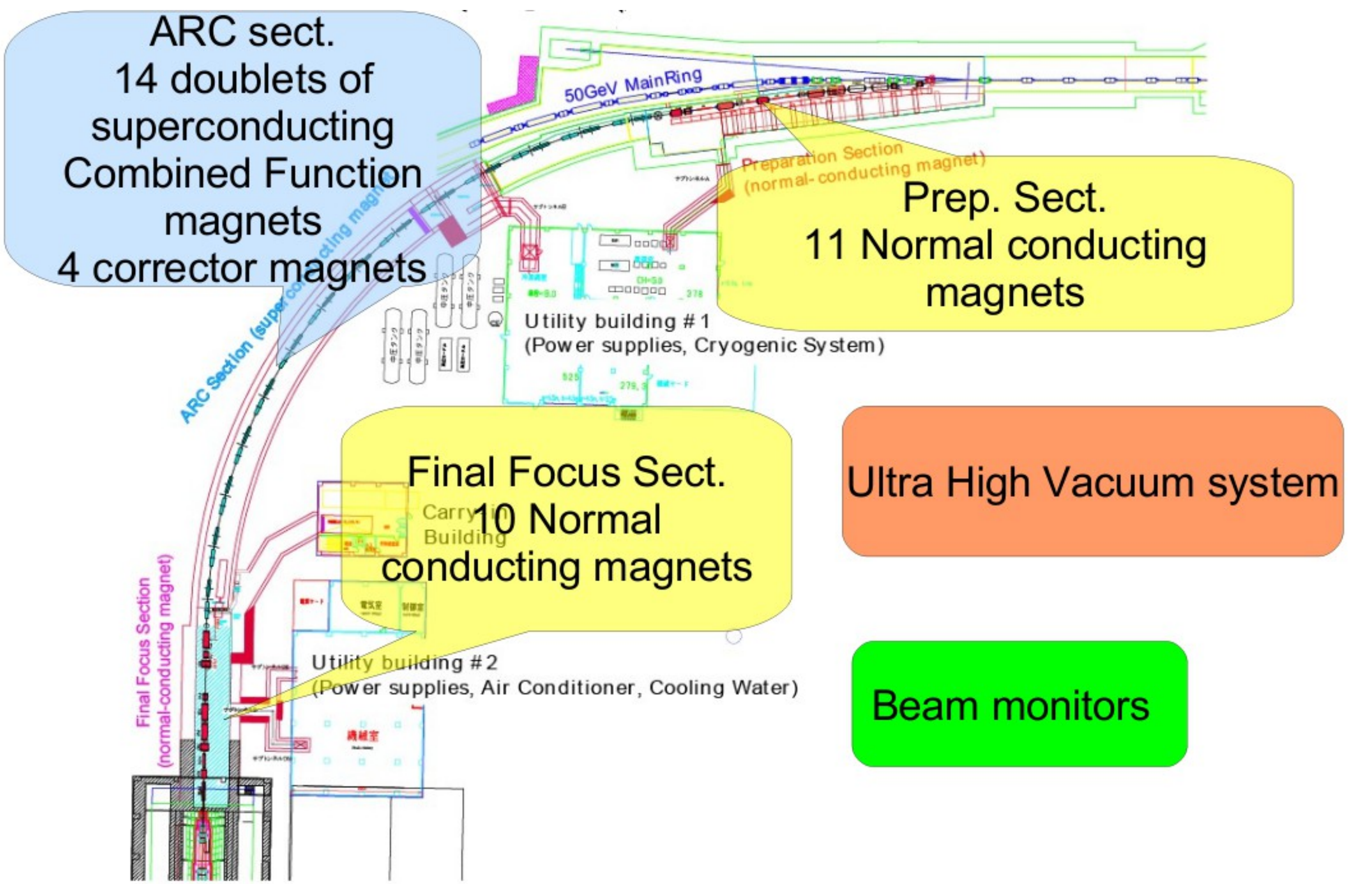


Event display

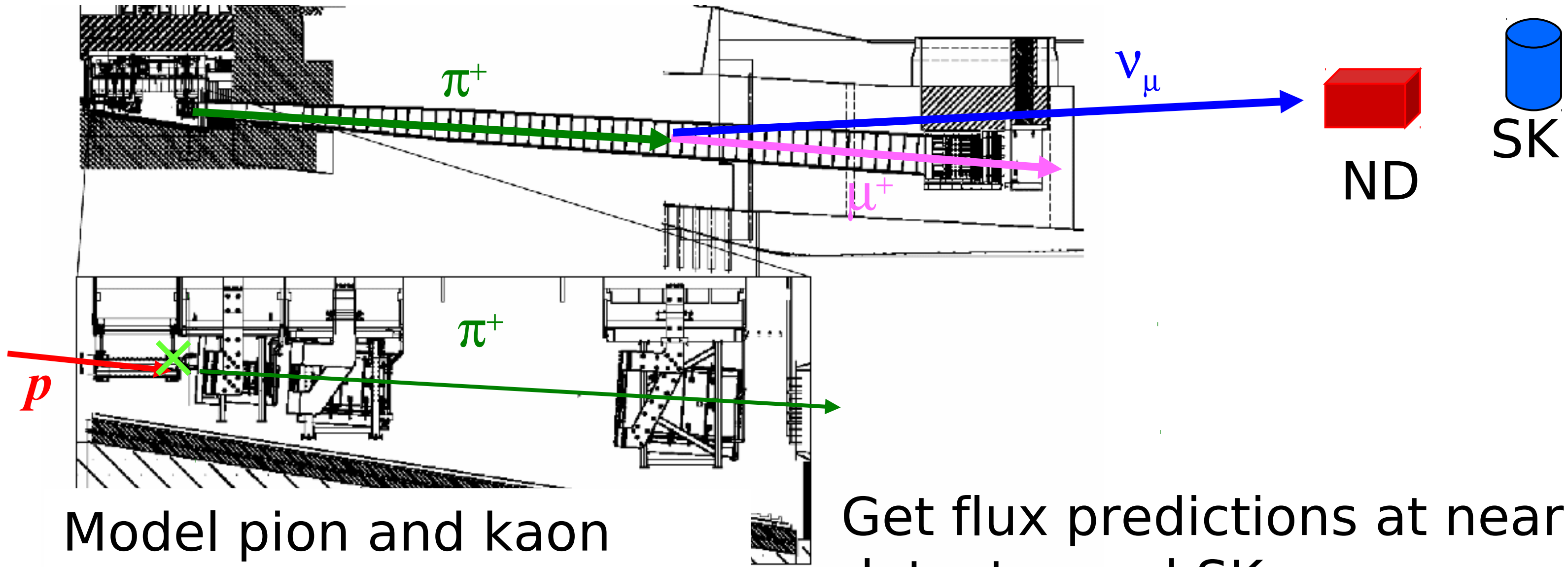




Neutrino Beamline



T2K: Flux prediction (Beam MC)

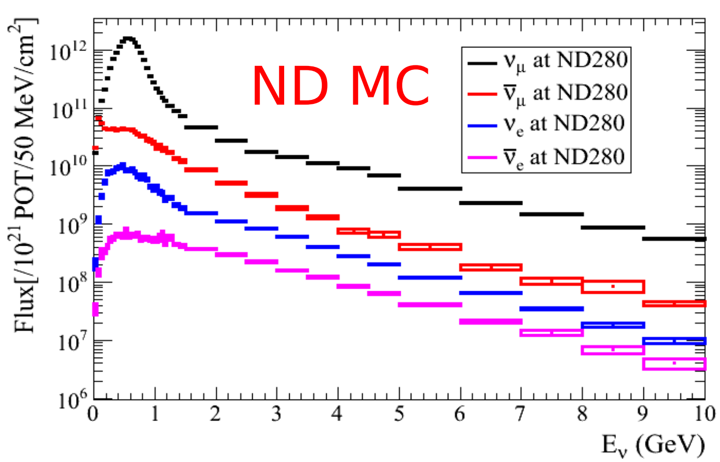


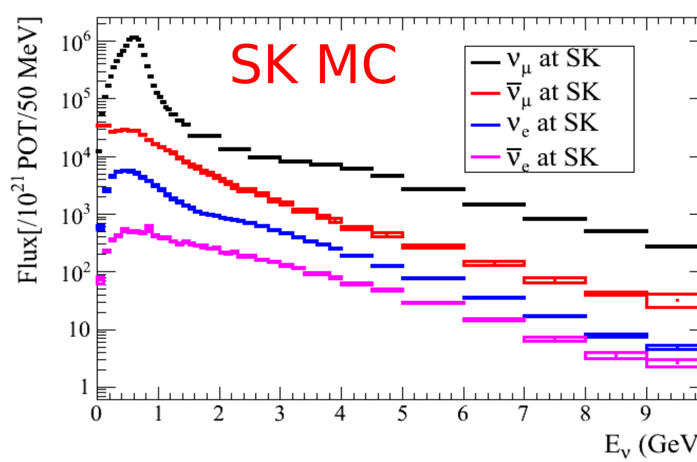
Simulate hadron production on target using FLUKA simulation

Model pion and kaon propagation and decay through horns and beamline

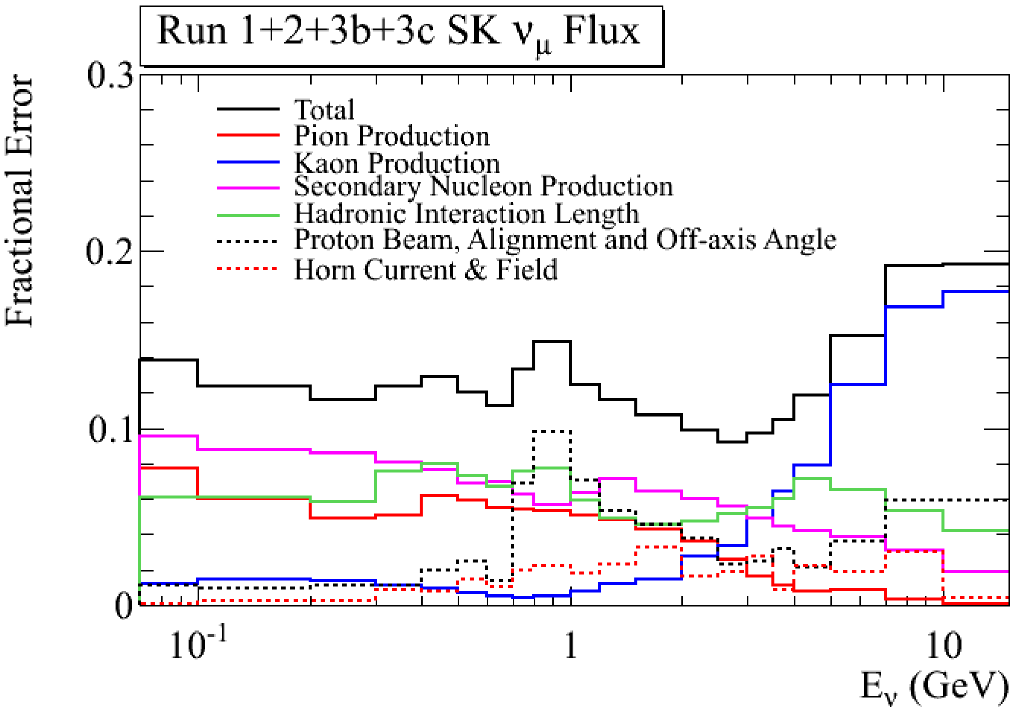
Get flux predictions at near detector and SK

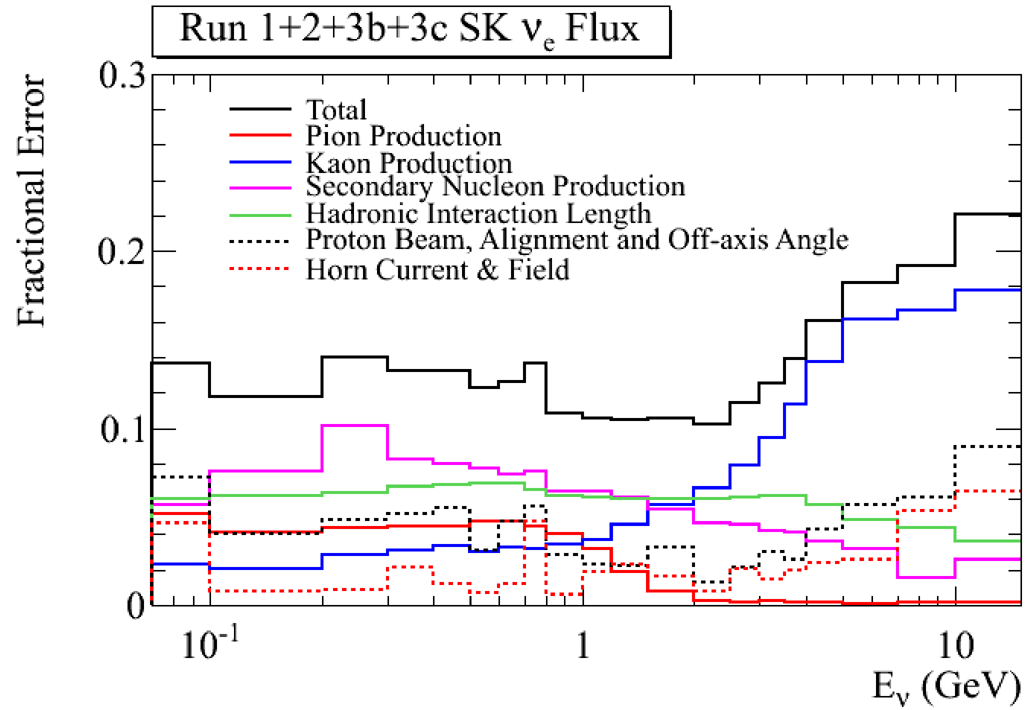
Particle production cross sections tuned to external data from NA61 and others.



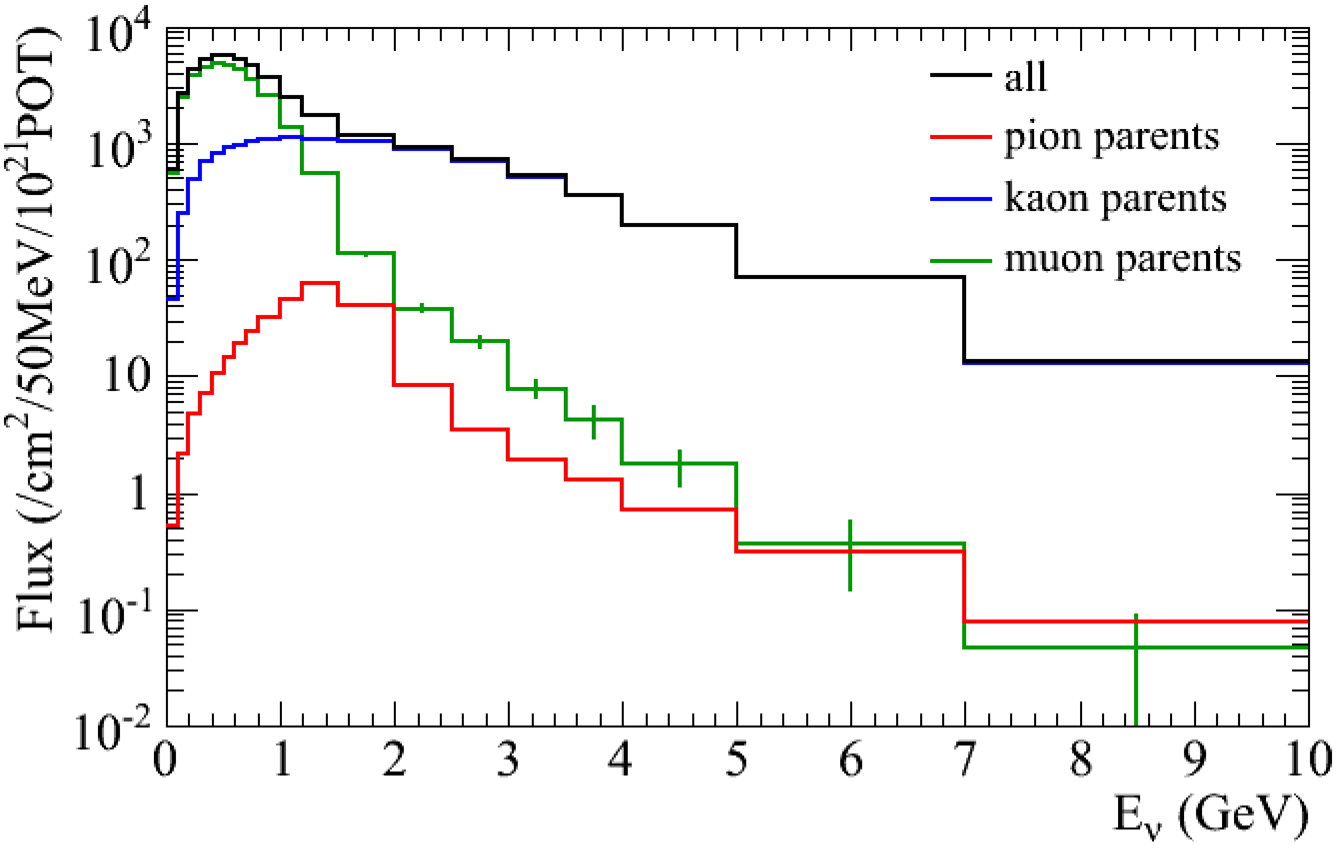


Flux uncertainties for ν_μ and ν_e

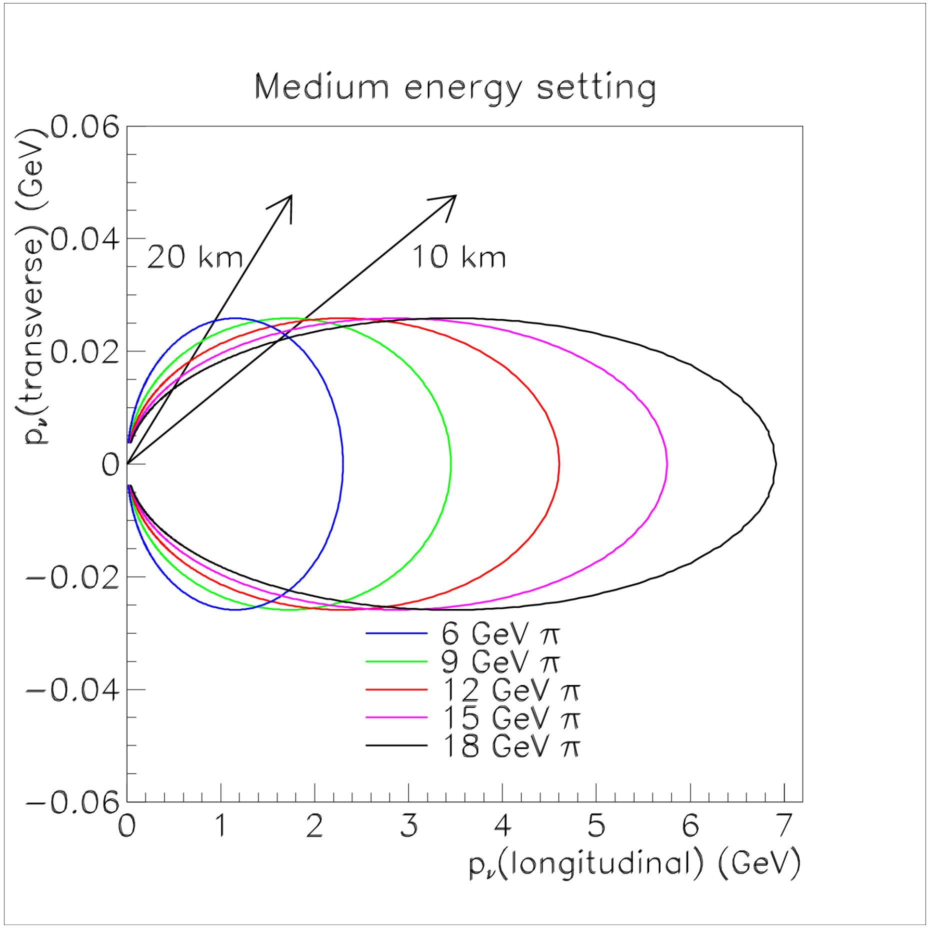


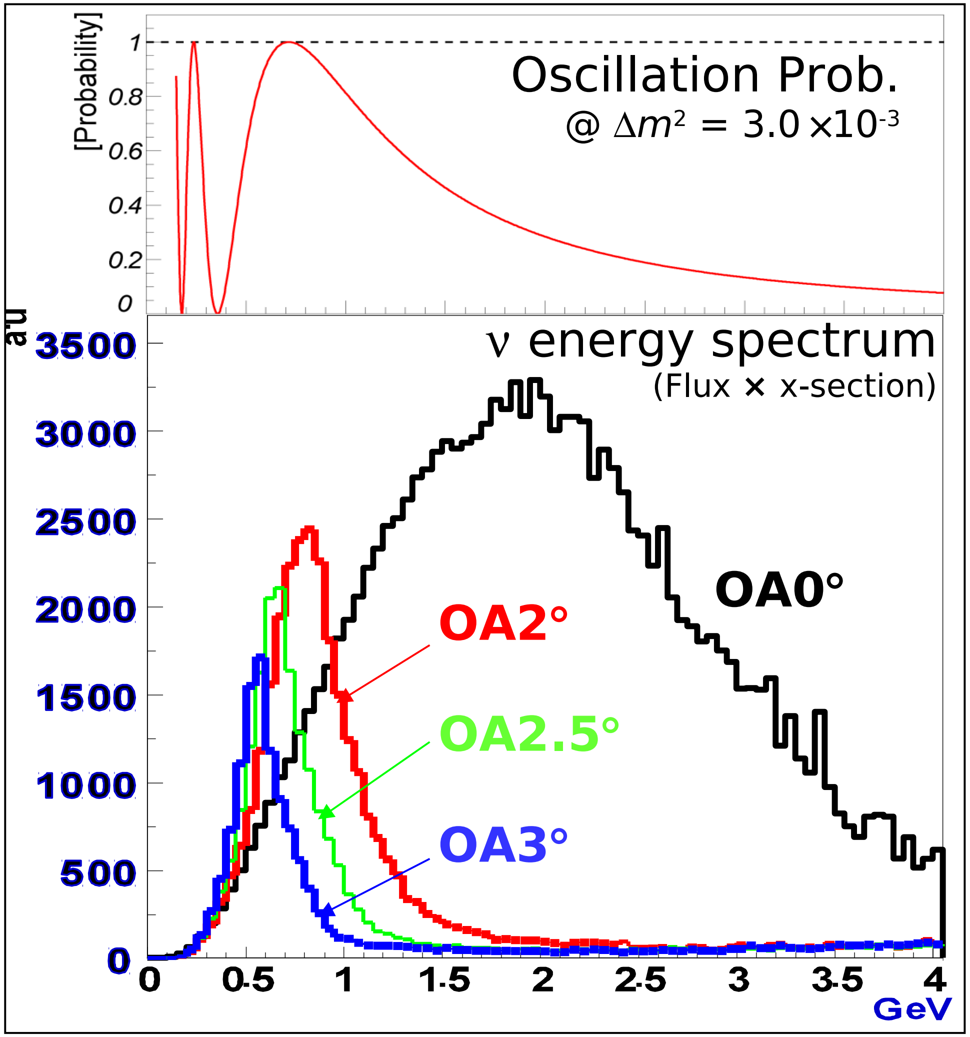


Parent particles of beam ν_e background



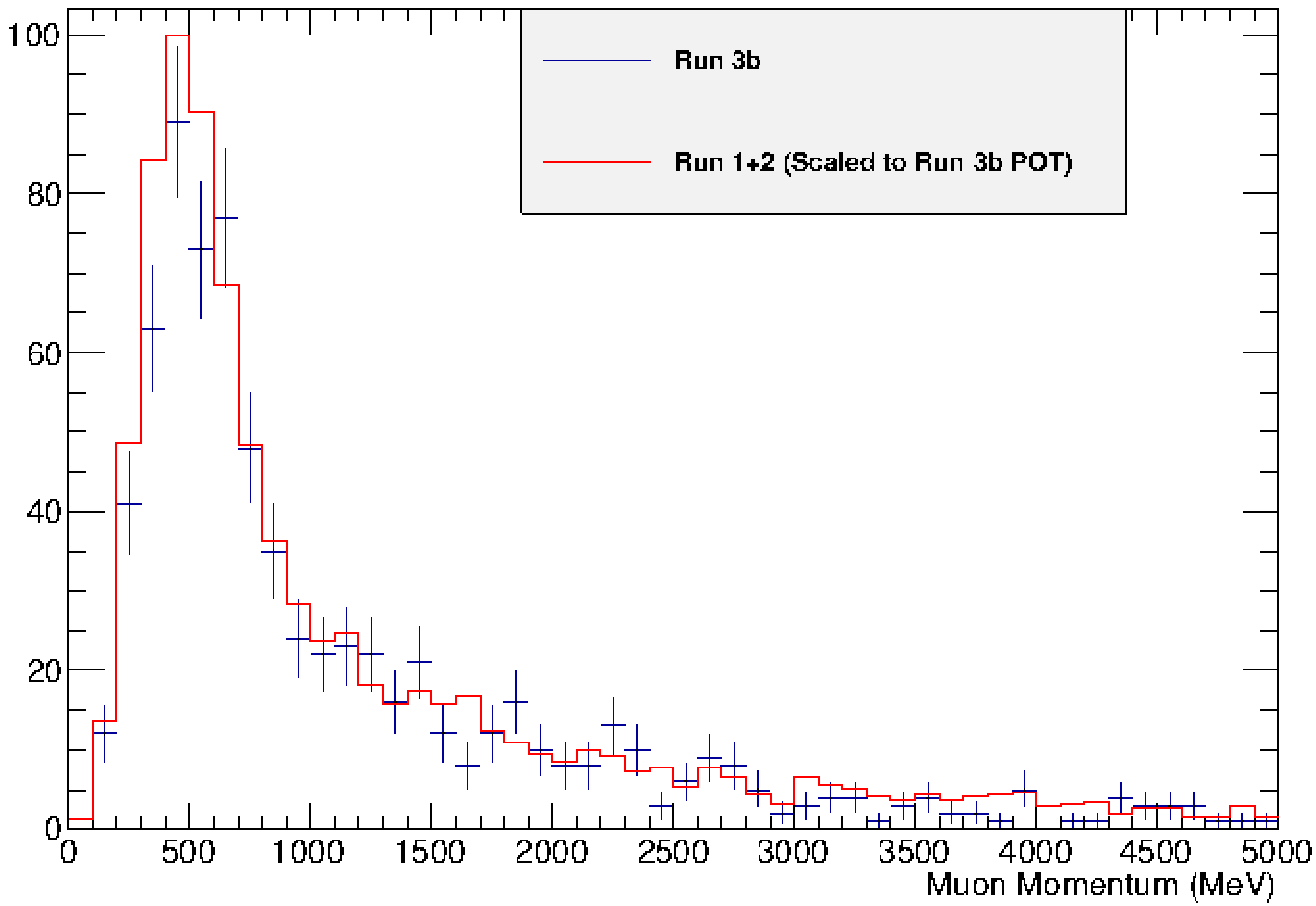
Off-Axis Beam Principle





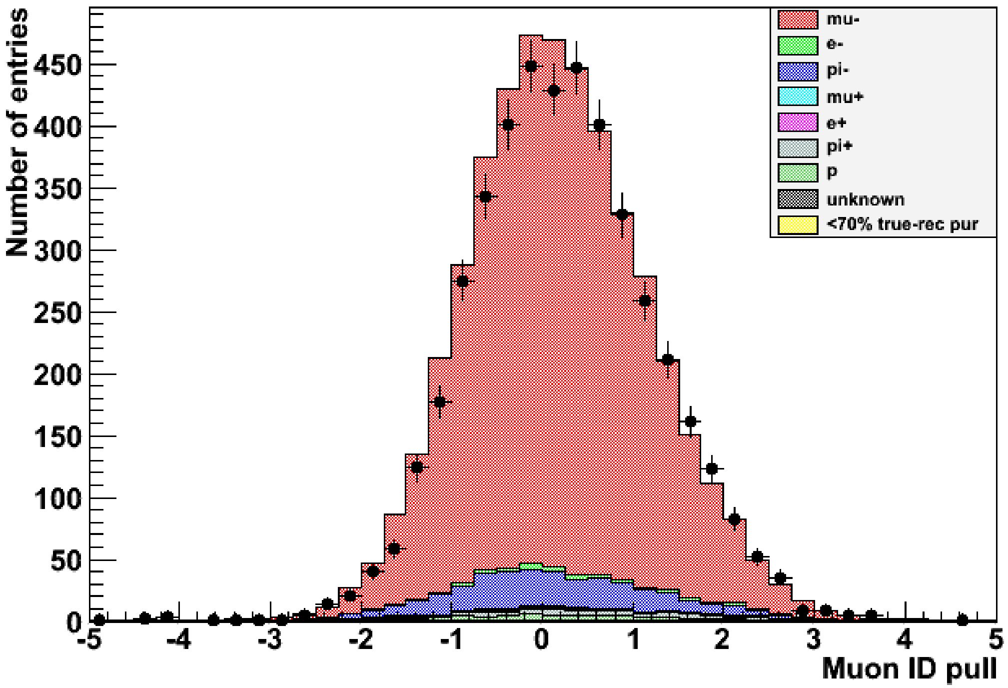
Off-axis beam: more flux near peak oscillation energy, less flux at higher energies where ν_e backgrounds are produced.

Near Detector Run 3 vs. Run 1+2 comparison

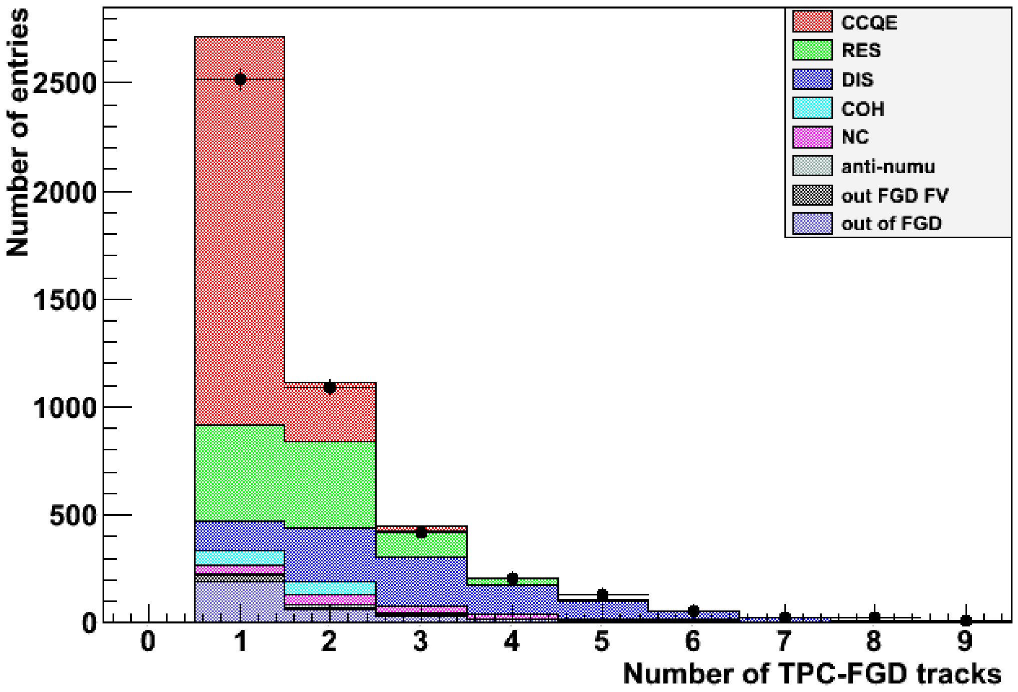


Check	Sample	P-value
Rate Consistency	Run3 versus Run1+2	0.989
Shape Consistency	Run3 versus Run1+2	0.561

ND280 selection cut distributions

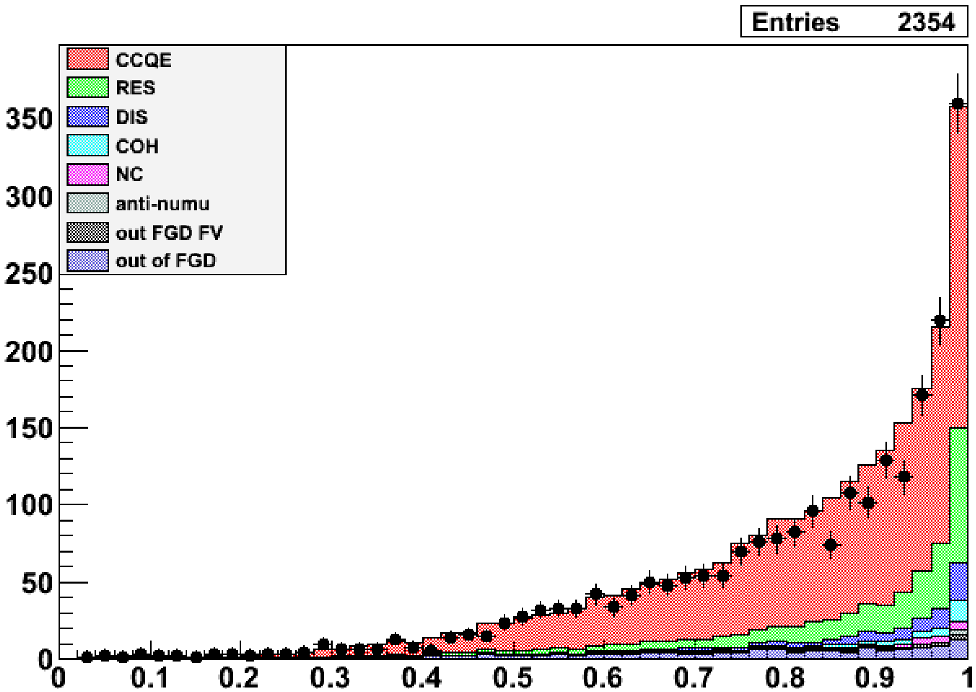


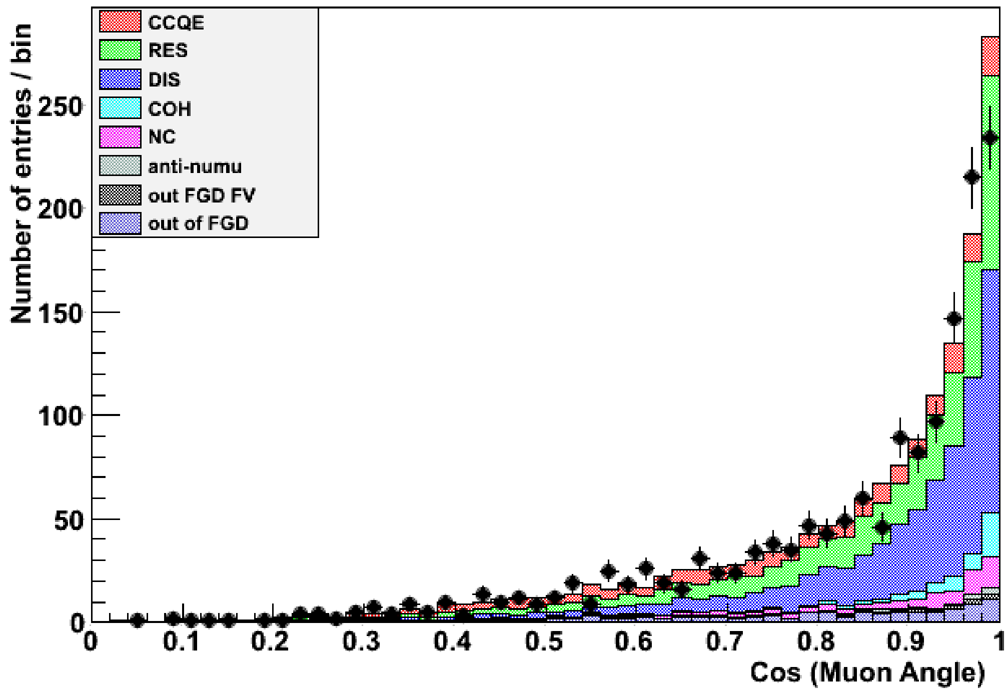
TPC dE/dX particle ID



Number of TPC-FGD tracks

Near Detector angular distributions





QE-like

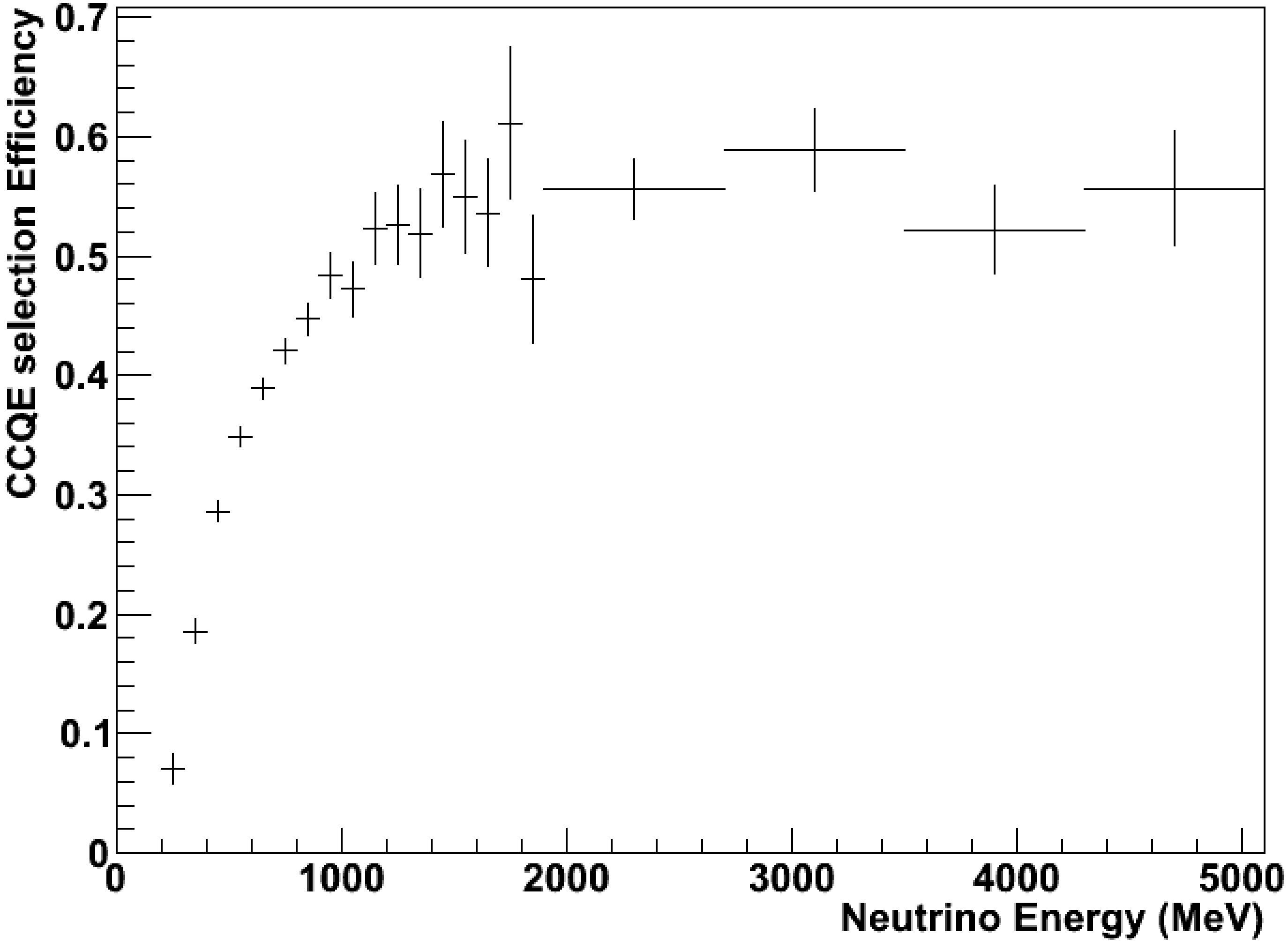
nonQE-like

Technically plot is Run2 only, since Run 1+2 wasn't available

ND280 detector systematics

Systematics	Sample	Error (%)
Track quality	Beam data/MC	0.1
TPC single track eff.	Beam data/MC	0.5
TPC double track eff.	Beam data/MC	0.6
TPC particle ID (PID)	Beam data/MC	0.1
TPC momentum scale	External measurements	0.5
TPC mom. distortion	Special MC	~1-7
TPC mom. resolution	Beam data/MC	2.0
TPC-FGD match. eff.	Sand interact. + cosmics	<1
Fiducial mass	External measurements	0.7
Charge mis-ID	Beam data/MC	<0.3
Michel electron eff.	Cosmics	0.5
Cosmic rays	Special MC	0.1
Sand interactions	Special MC	1.5
Out-of-fiducial volume	Several samples	~1-9

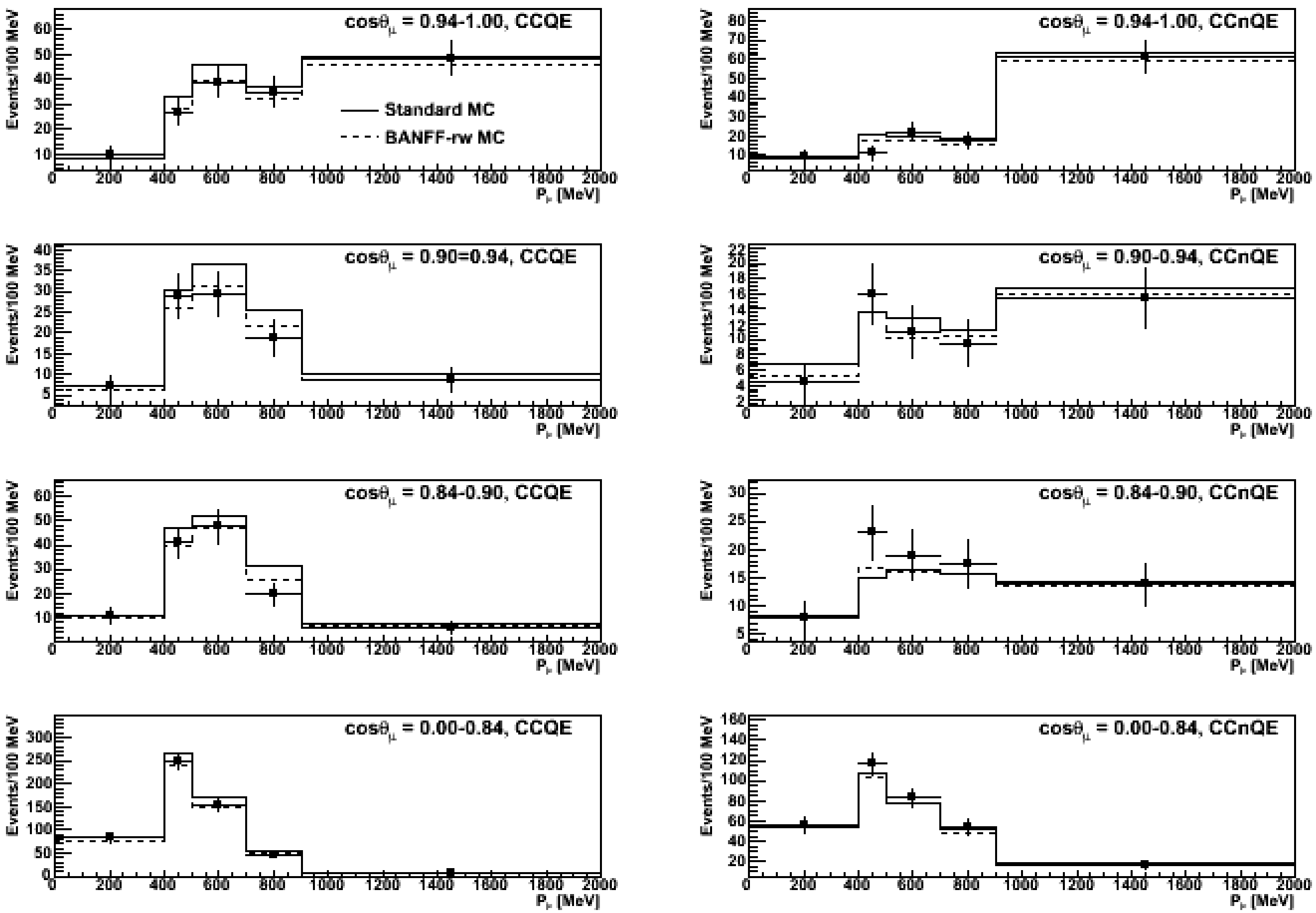
CCQE selection efficiency in ND



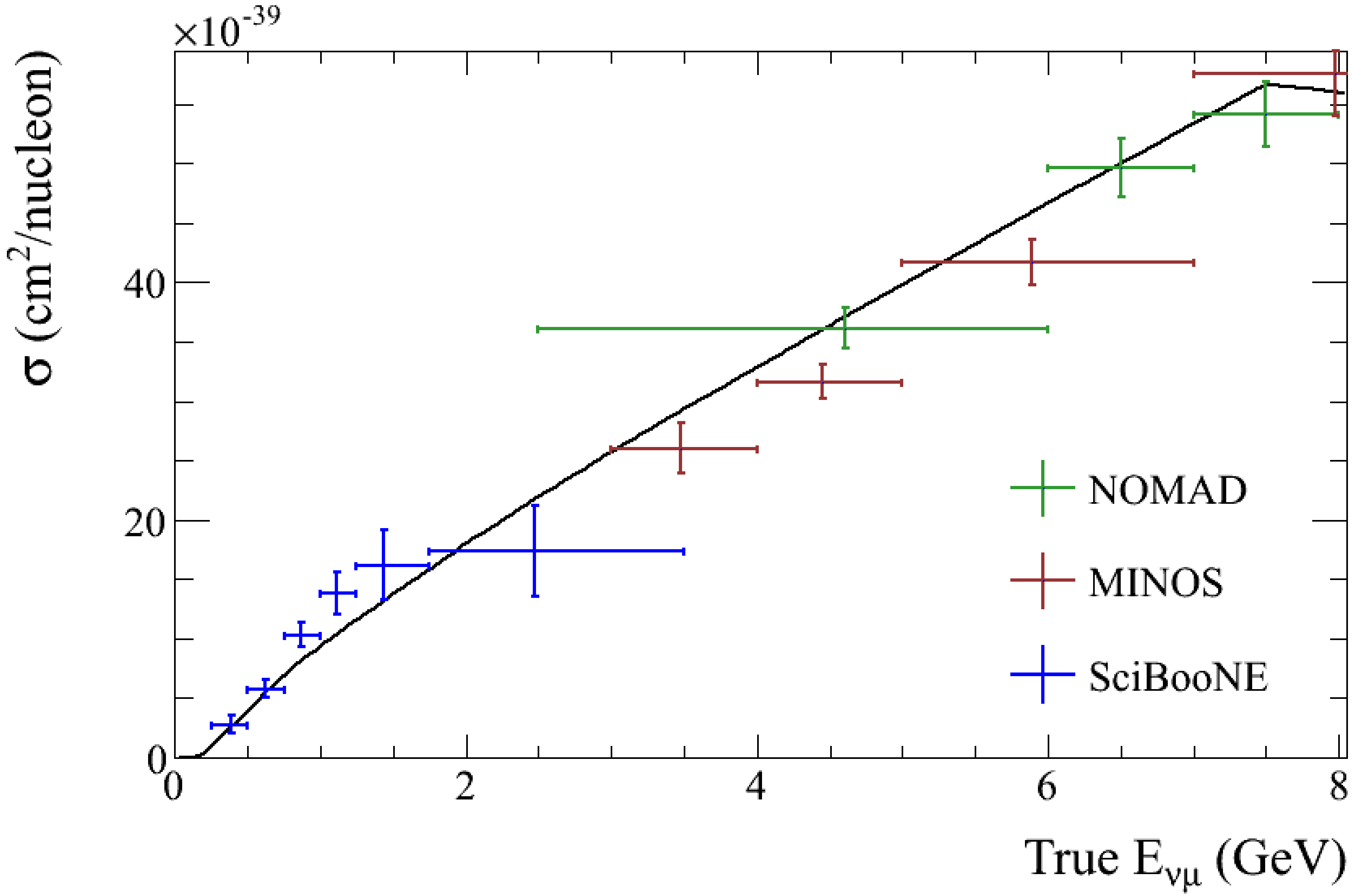
ND selection table

Cut	Data Run1	MC Run1	Data Run2	MC Run2
CC Inclusive Selection				
Good negative track in FV	2479	2347.9	6358	6148.8
Upstream TPC veto	1741	1800.7	4502	4749.6
PID cut	1202	1266.2	3283	3440.6
CCQE Sub-Sample Selection				
TPC-FGD track = 1	664	727.4	1853	1989.9
No Michel electron	619	676.0	1735	1858.8

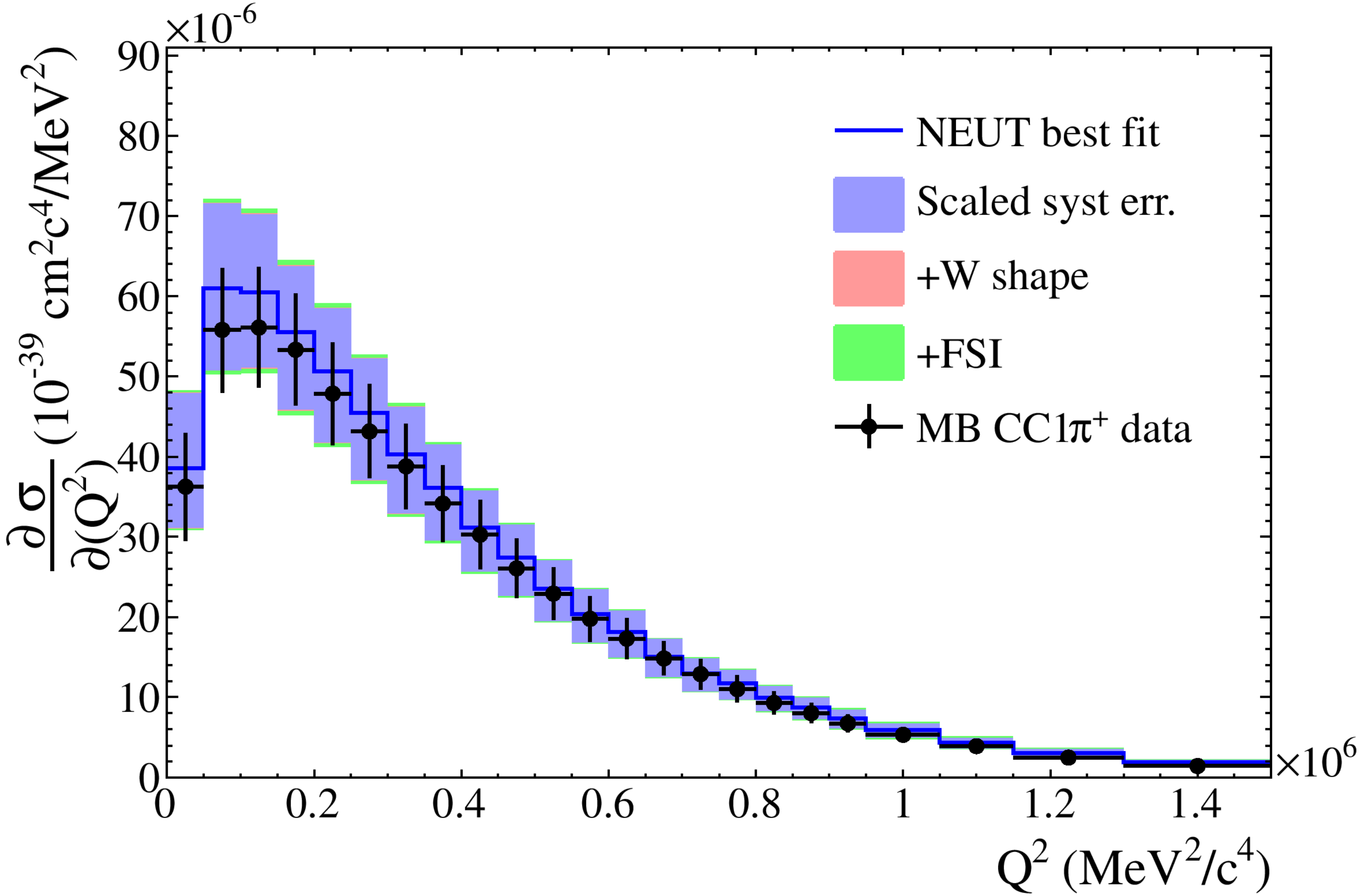
Comparison of ND280 data to MC after tuning with fit results



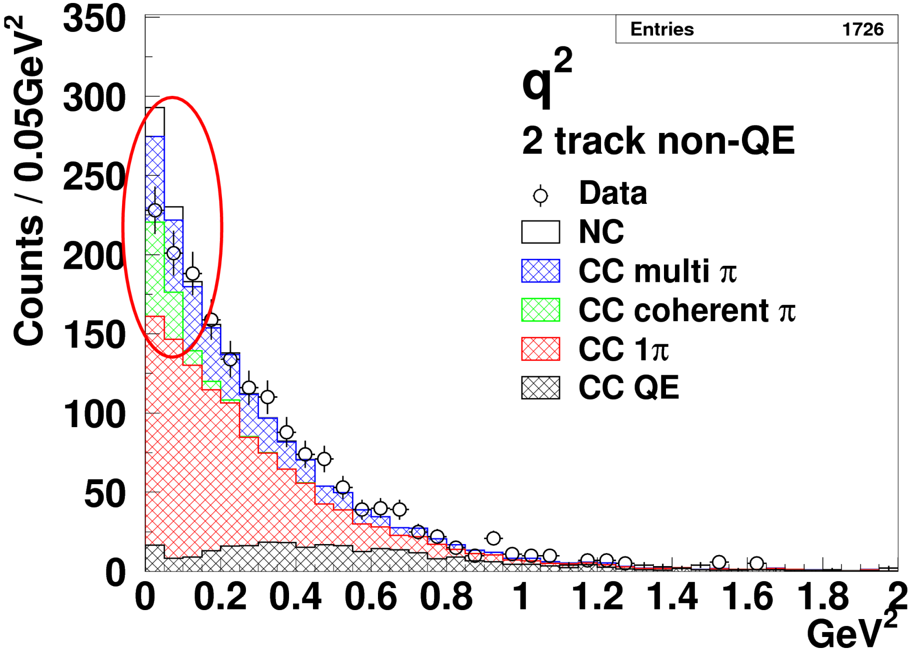
NEUT bare (nucleon level) inclusive CC cross-section vs. energy



CC1π q² distribution for best fit



Nuclear Effects



Data from K2K Scibar detector shows poor agreement in q^2 distribution for events selected as being not CCQE

The neutrino world's version of a QCD background ... are there ain't no such thing as asymptotic freedom at these energies!

Nuclear effects quite important in modelling neutrino interactions: binding energy, Fermi motion, Pauli blocking, coherent scattering off of entire nucleus ...

Data anomalies abound!

May be different for different nuclei.

T2K general likelihood fit

$$\ln[L(\vec{b},\vec{x},\vec{o}|\vec{M}_{ND280},\vec{M}_{SK})] = \ln[P(\vec{M}_{ND280}|\vec{b},\vec{x})] + \ln[P(\vec{M}_{SK}|\vec{b},\vec{x},\vec{o})] + \ln[\pi(\vec{b})] + \ln[\pi(\vec{x})]$$

$$\pi(\vec{b}) = (2\pi)^{-k/2}|V_b|^{-1/2}e^{-\frac{1}{2}\Delta b(V_b^{-1})\Delta b^T}$$

$$\ln[L(\vec{b},\vec{x},\vec{o}|\vec{M}_{ND280},\vec{M}_{SK})] = \ln[P(\vec{M}_{ND280}|\vec{b},\vec{x})] + \ln[P(\vec{M}_{SK}|\vec{b},\vec{x},\vec{o})] - \frac{1}{2}\Delta b(V_b^{-1})\Delta b^T - \frac{1}{2}\Delta x(V_x^{-1})\Delta x^T$$

T2K beam+ND likelihood fit

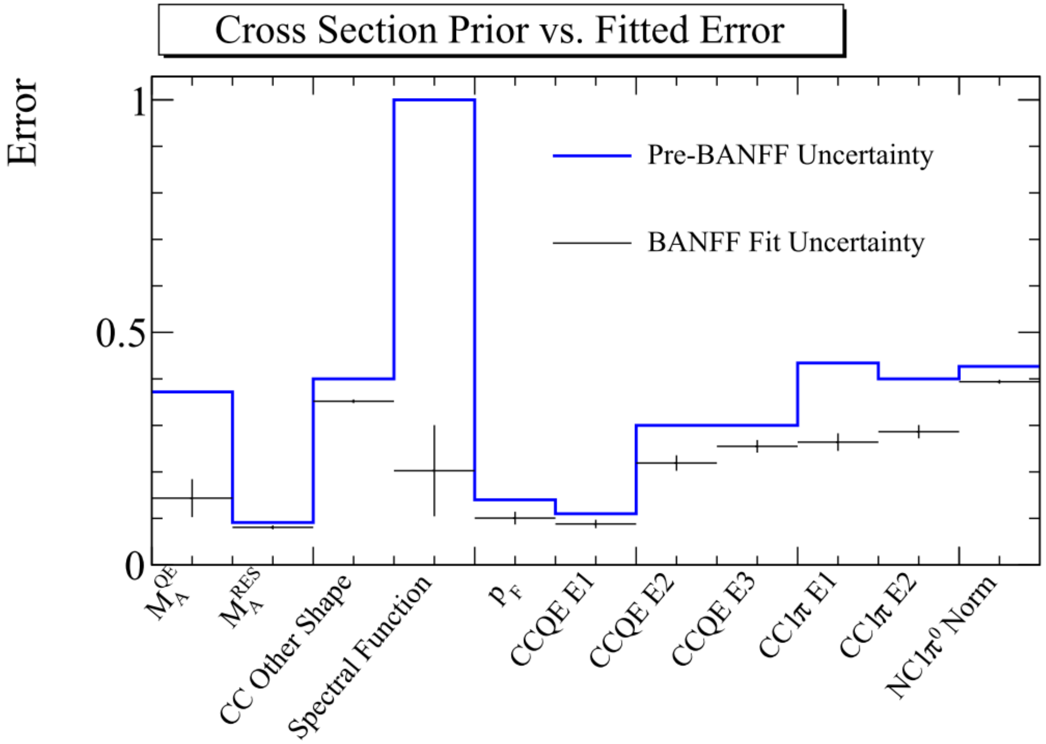
$$\ln[L(\vec{b},\vec{x}|\vec{M}_{ND280})] = \ln[P(\vec{M}_{ND280}|\vec{b},\vec{x})] - \frac{1}{2}\Delta b(V_b^{-1})\Delta b^T - \frac{1}{2}\Delta x(V_x^{-1})\Delta x^T$$

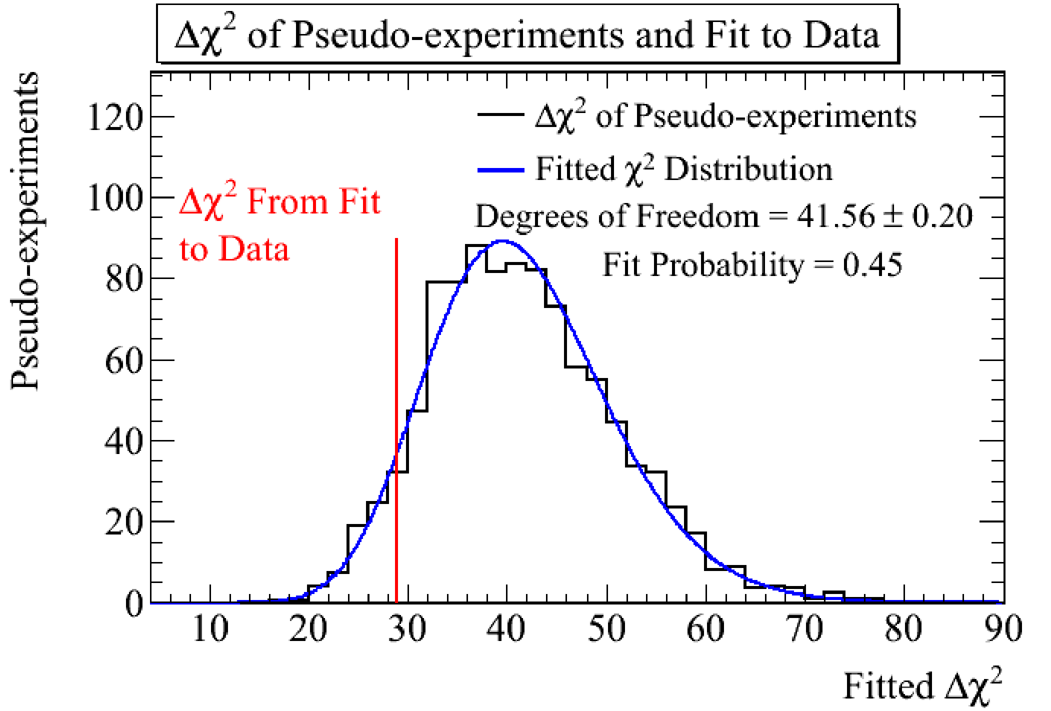
$$\Delta\chi^2_{ND280} = 2\sum_i^{Nbins} N_i^p(\vec{b},\vec{x},\vec{d}) - N_i^d + N_i^d ln[N_i^d/N_i^p(\vec{b},\vec{x},\vec{d})] +$$

$$\sum_i^{E_\nu bins}\sum_j^{E_\nu bins} \Delta b_i(V_b^{-1})_{i,j}\Delta b_j + \sum_i^{xsecpars}\sum_j^{xsecpars} \Delta x_i(V_x^{-1})_{i,j}\Delta x_j +$$

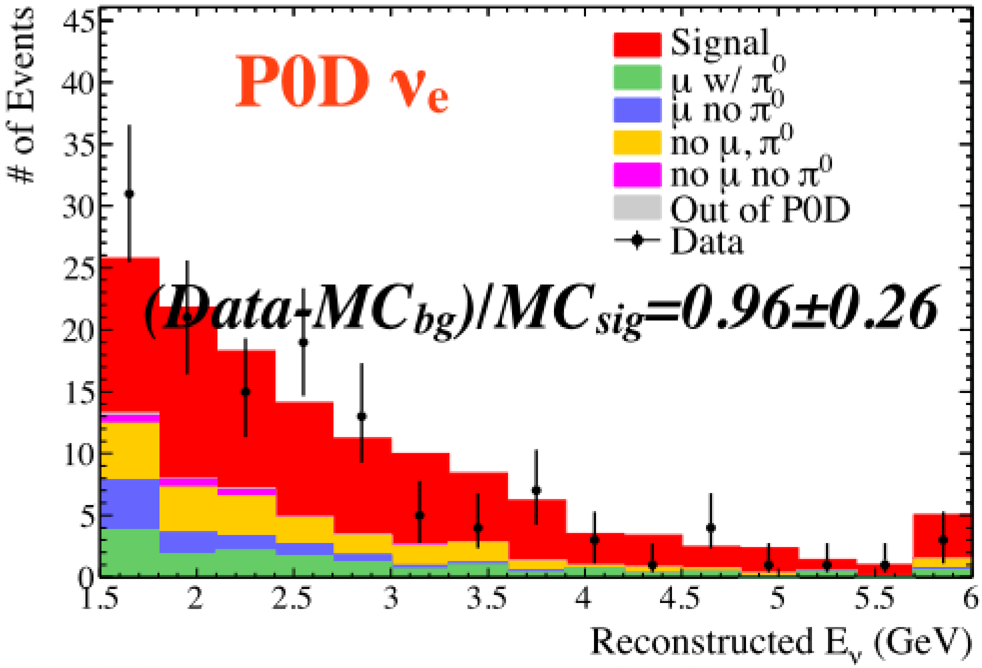
$$\sum_i^{Nbins}\sum_j^{Nbins} \Delta d_i(V_d(\vec{b},\vec{x})^{-1})_{i,j}\Delta d_j + ln(\frac{|V_d(\vec{b},\vec{x})|}{|V_d^{nom}|})$$

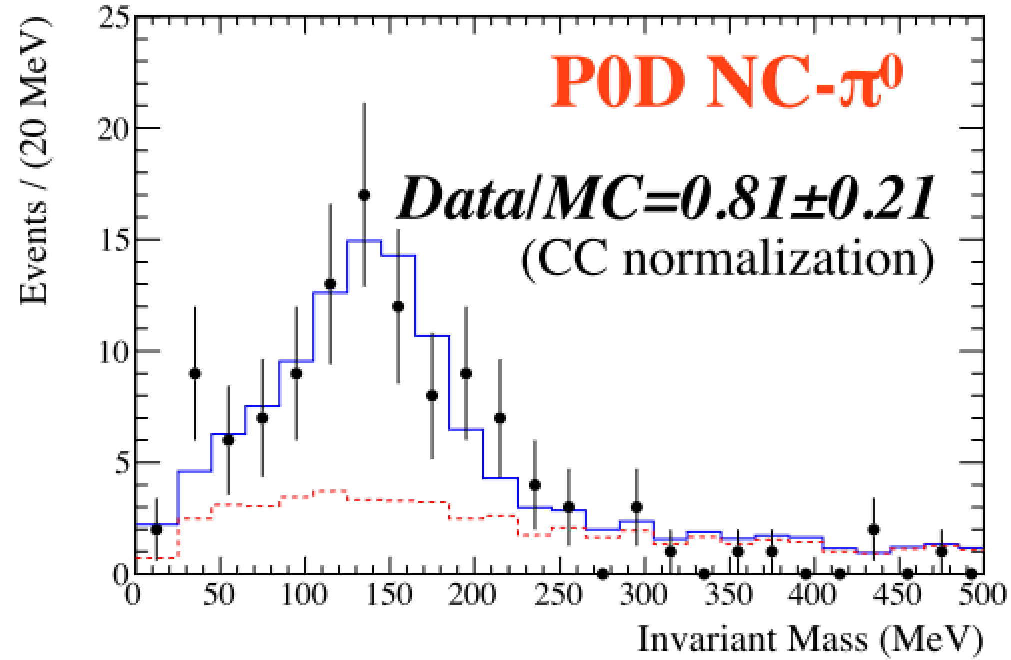
Beam+ND fit results

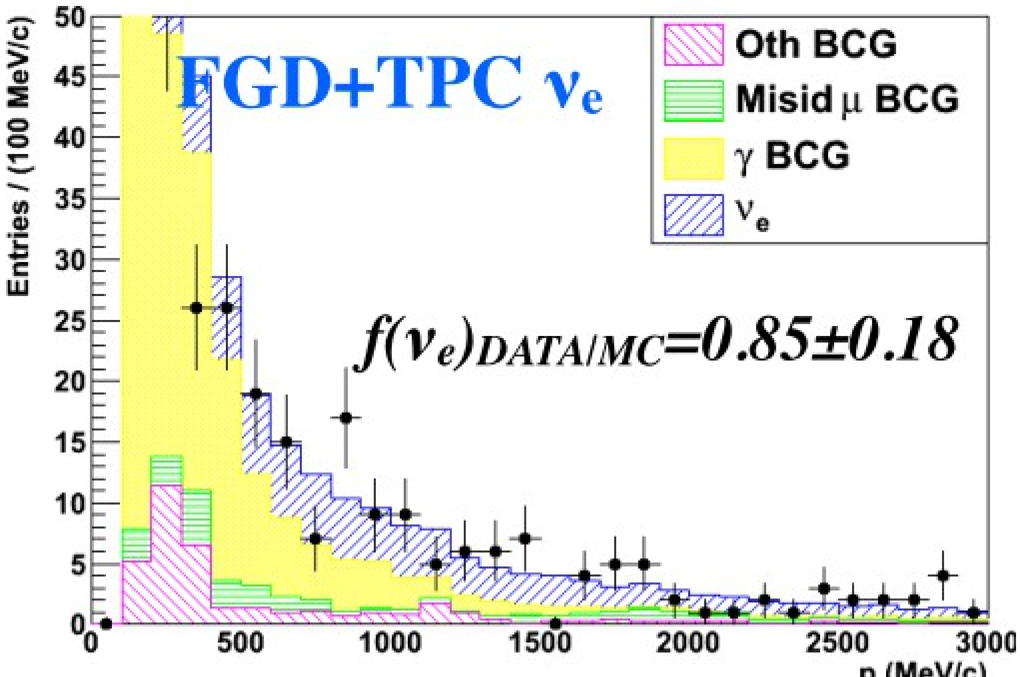




ND280 background measurements



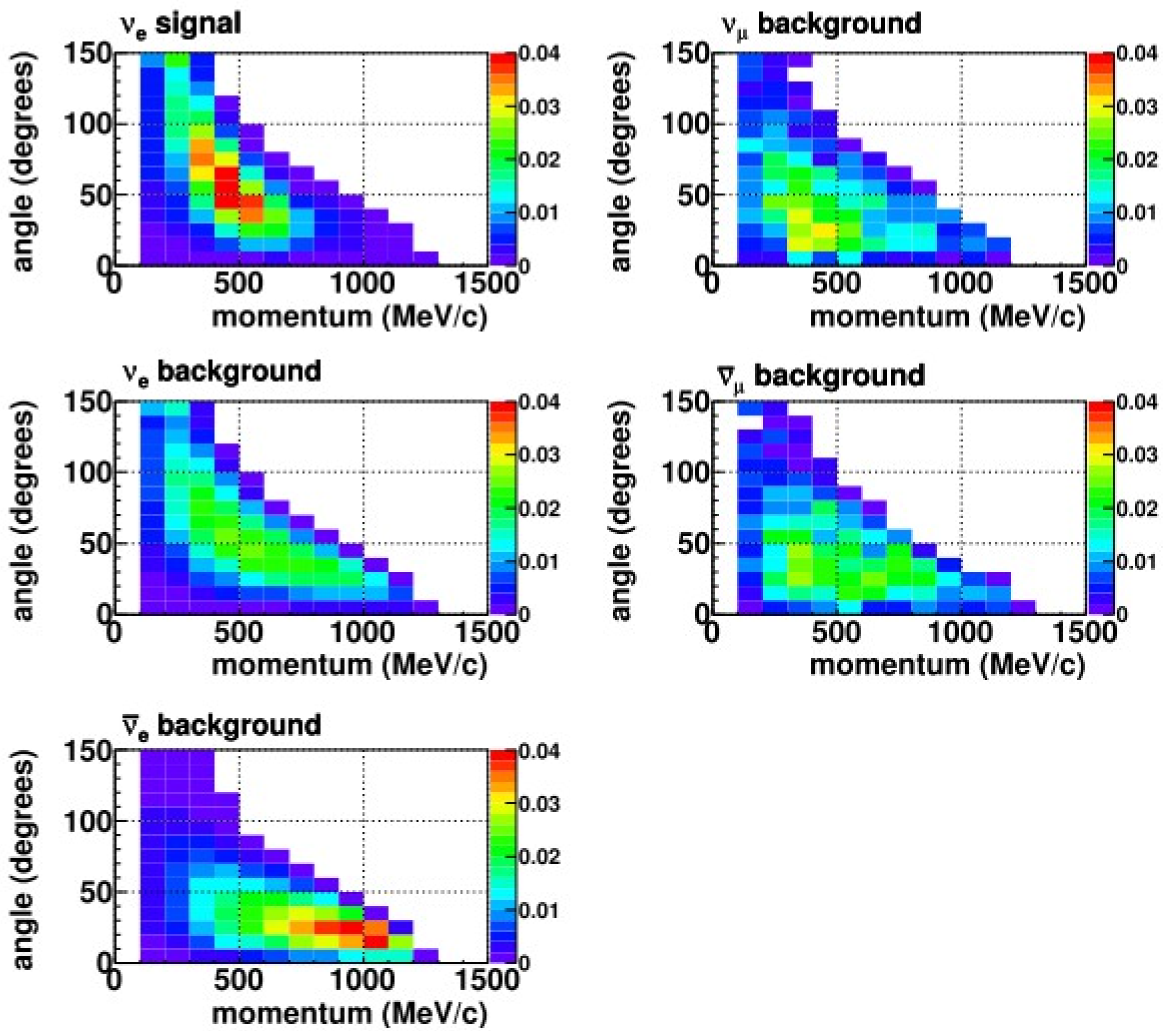




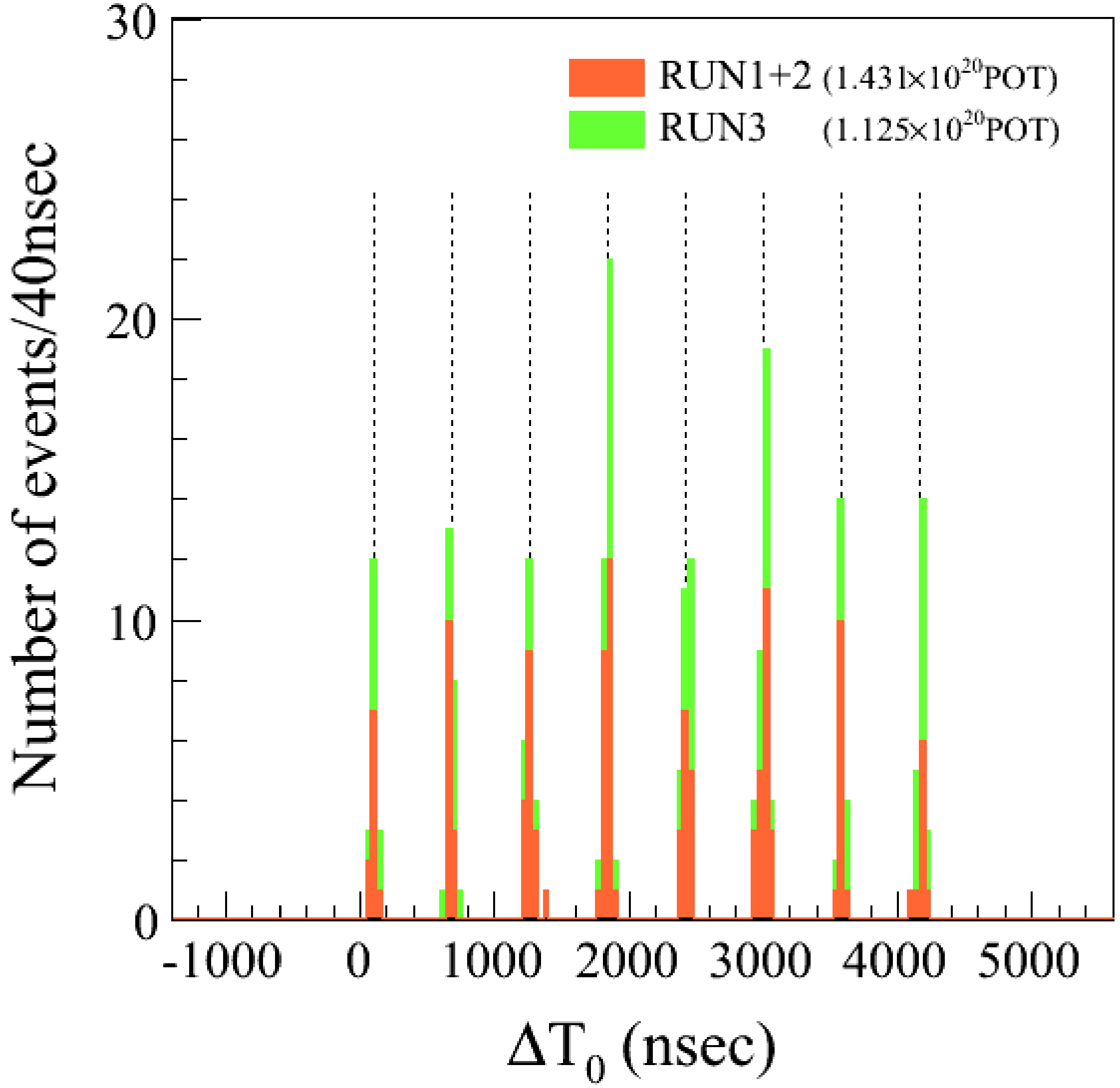
In-situ measurements of electron neutrino component of beam and π^0 production rate in ND280.

Used as cross-checks at present.

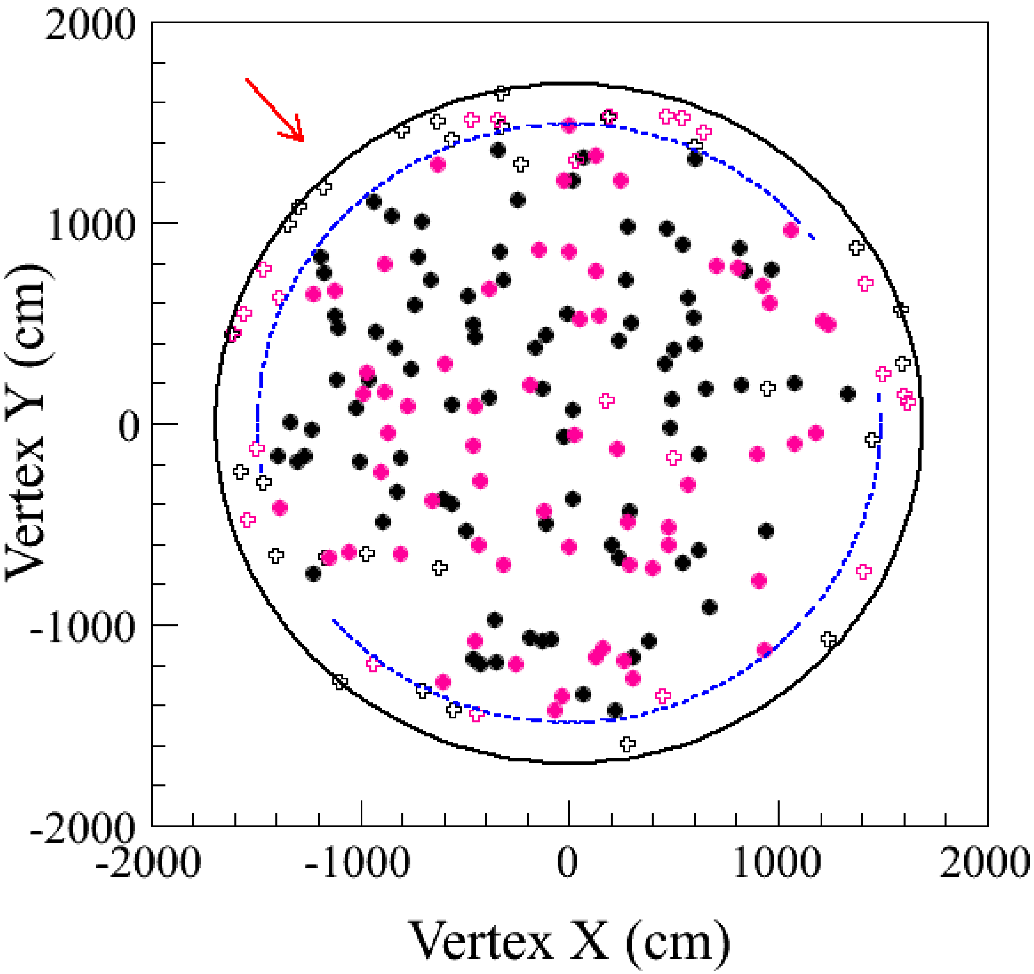
p_e, θ_e PDFs for signal and backgrounds in oscillation fit



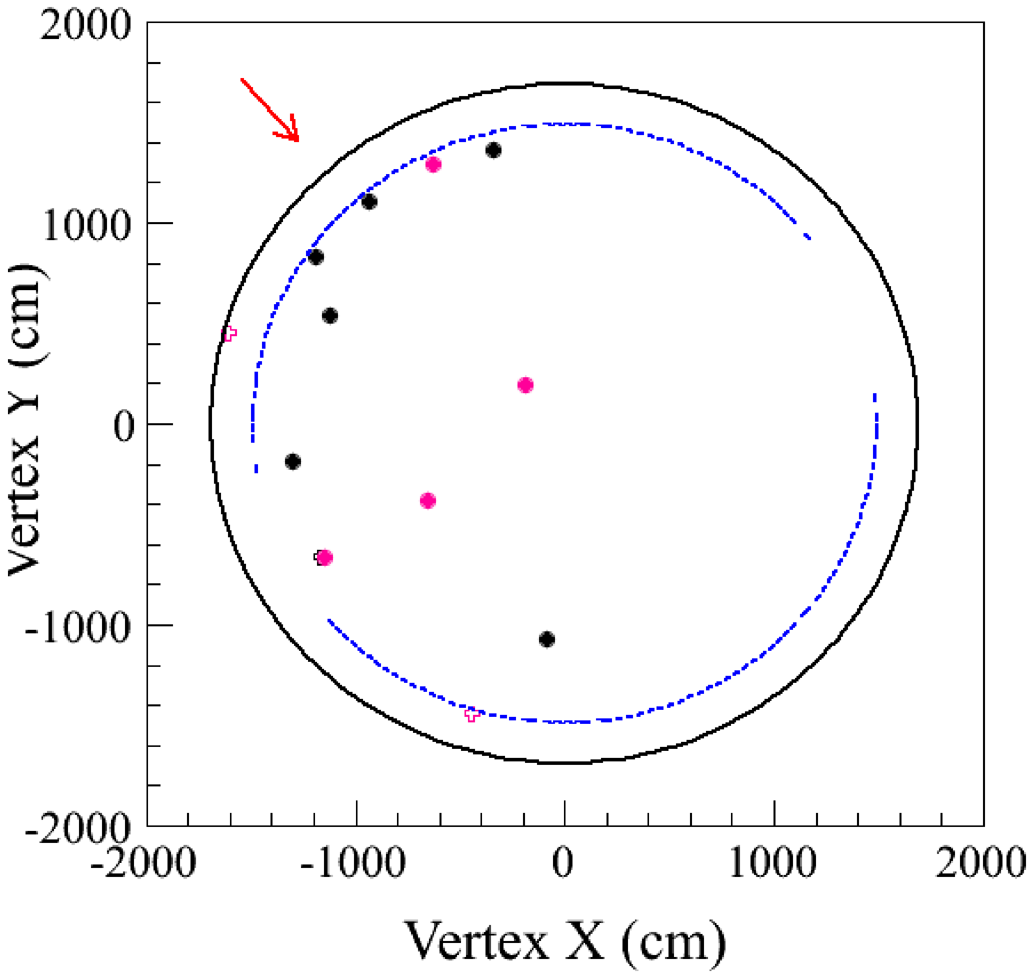
Event timing for fully contained events at Super-K



Event distributions at Super-K

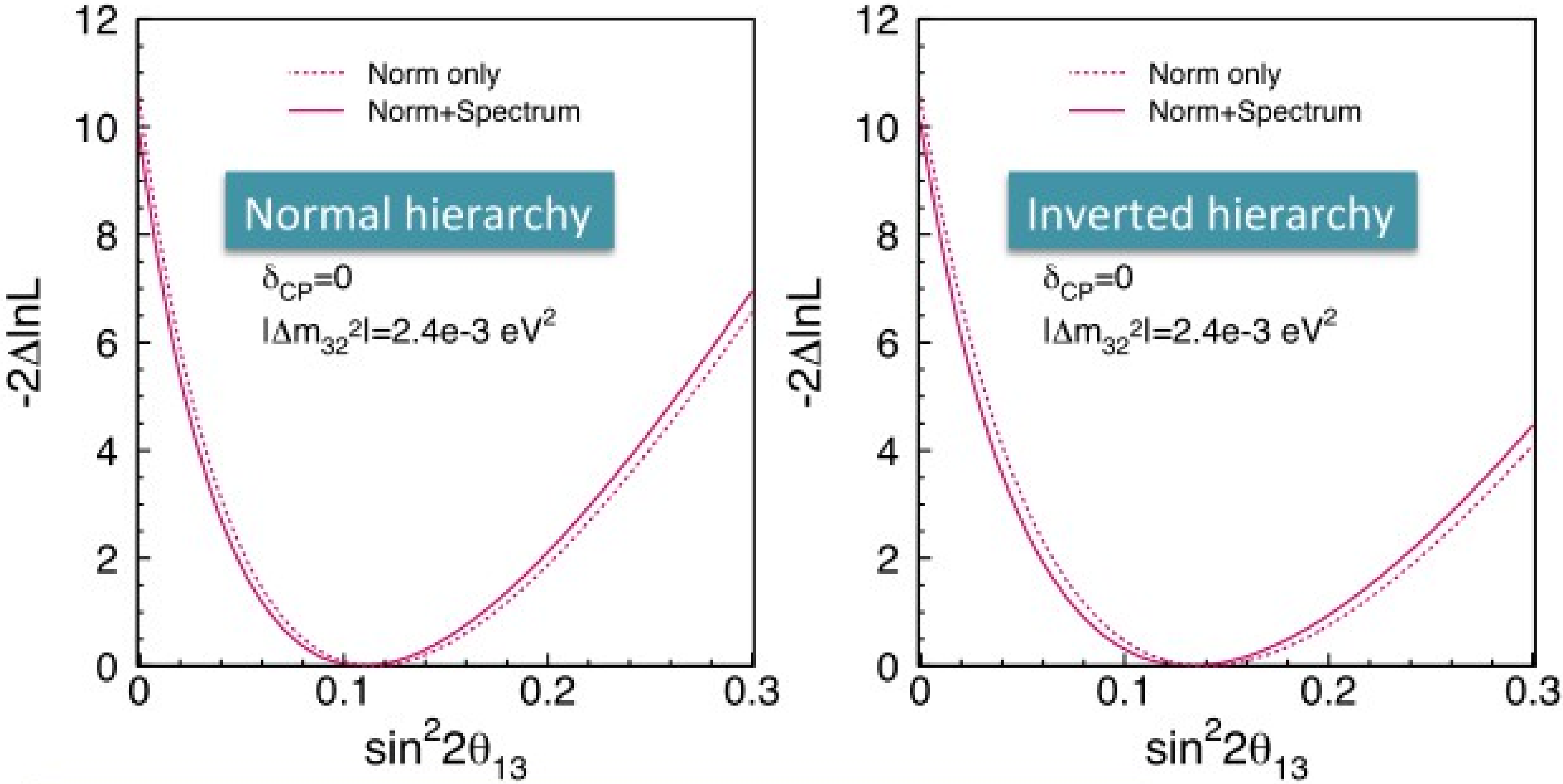


All fiducial volume events with E>30MeV



ν_e candidate events

Results from fit to reconstructed E_ν

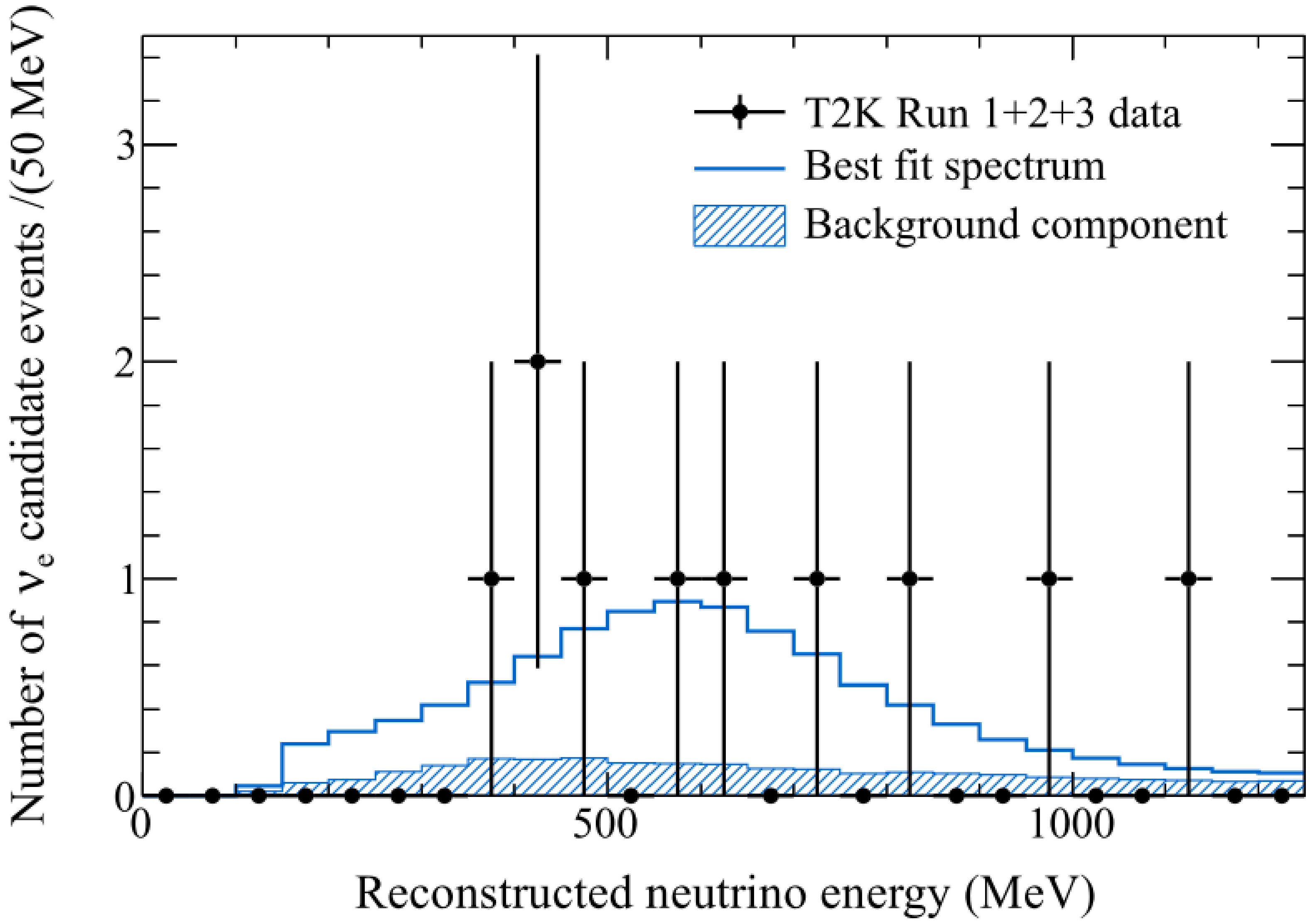


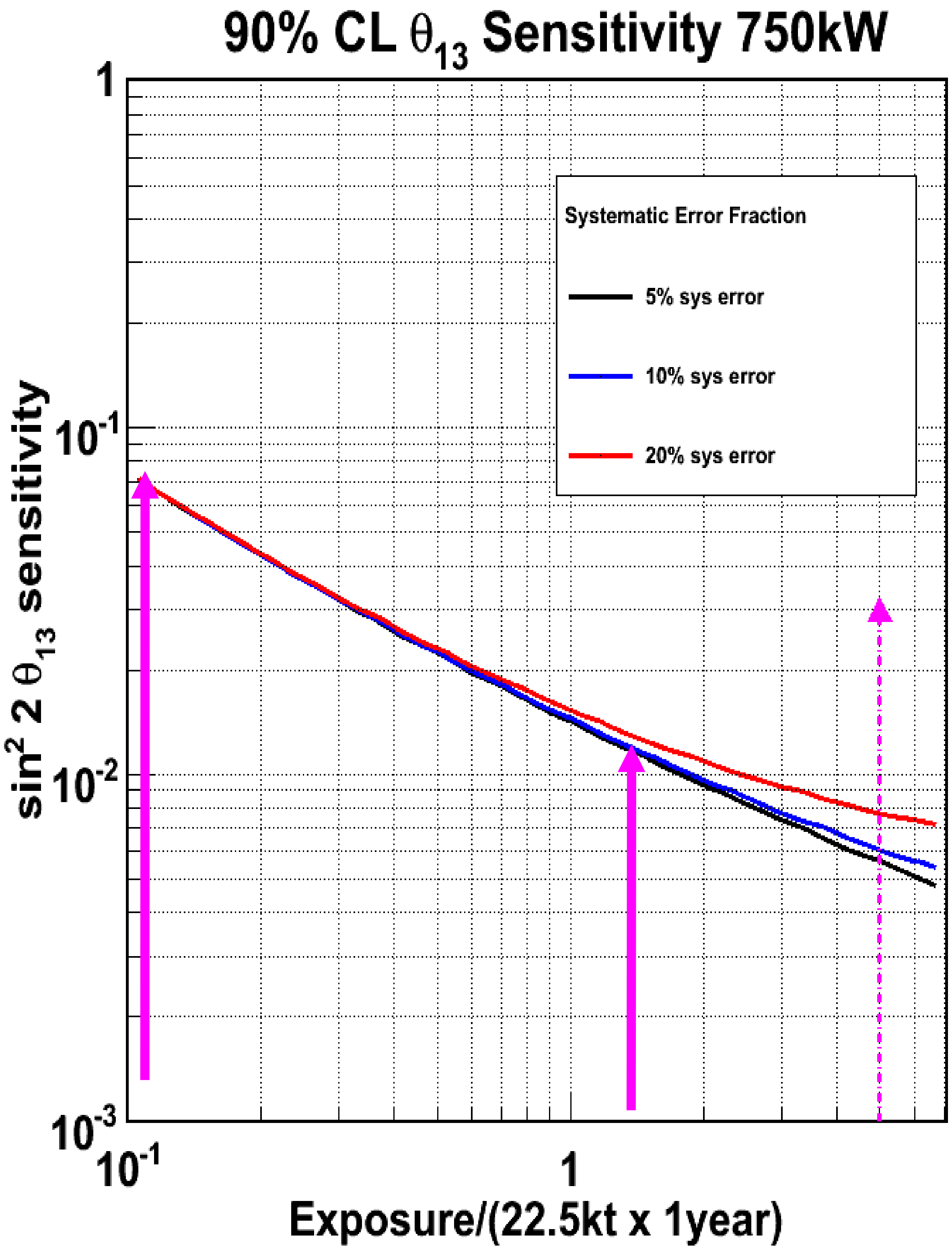
	Normal hierarchy	Inverted hierarchy
Best fit	0.11	0.13
68 % C.L.	0.06 - 0.17	0.08 - 0.20
90 % C.L.	0.04 - 0.21	0.05 - 0.26

N_{exp} @ best fit for NH

9.7 events

Reconstructed E_ν spectrum





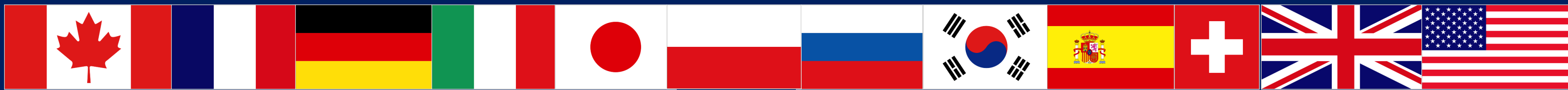
Ultimate Sensitivity

Ultimately we aim for 750kW x $5x10^7$ s, which should push down to $\sin^2 2\theta_{13}$ = .006 (90% CL)

This would be 5 years of running at full power.

Intermediate target is $\sin^2 2\theta_{13} = 0.013$

The T2K Collaboration



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