New results from the T2K long baseline neutrino experiment

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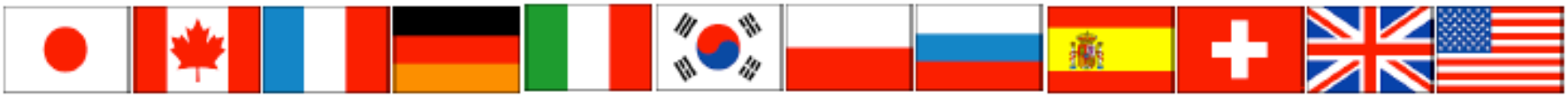
TRIUMF

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 strategy
    1. Neutrino flux
    2. Neutrino interactions
    3. Near detector measurements
    4. Far detector selection and systematics
5. ν_μ disappearance results
6. ν_e appearance results
7. Future of the T2K experiment
8. Future determination of θ_{13} (and CP violation?)

A refresher on neutrino mixing

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

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

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

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

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

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

"Atmospheric": θ_{23} ~37°-53°

"CP sector": θ_{13} <11°

"Solar": θ_{12} ~34°

Quark mixing: unitary matrix, small angles: θ^{CKM}_{12}~13.0°, θ^{CKM}_{23}~2.3°,θ^{CKM}_{13}~0.2°

- Is θ_{23} exactly 45 degrees, or not?
- Is θ_{13} zero, or just small?
- Is there CP violation in the neutrino sector? Is it large?
- Is the mixing matrix unitary?

Neutrino oscillation: ν_μ disappearance

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

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

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 (eV^2): Difference of the square of the mass eigenvalues

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

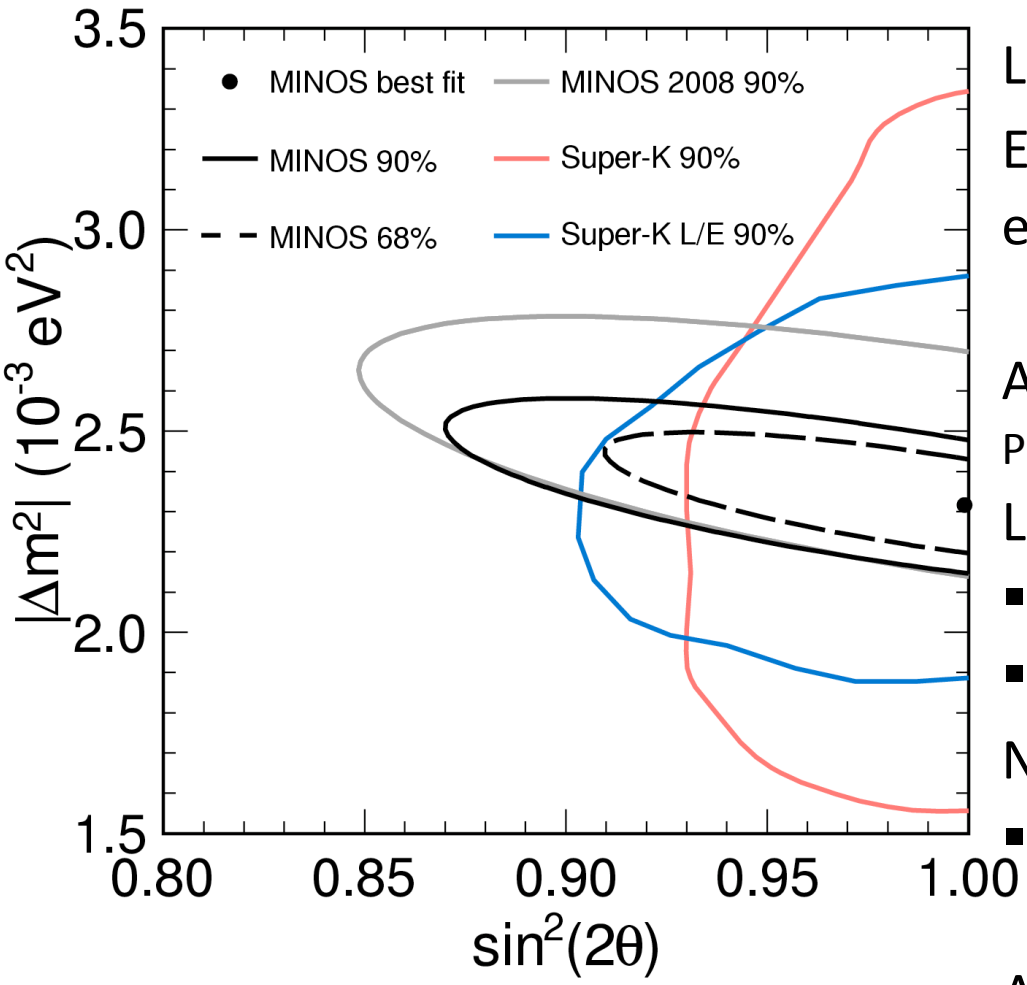
"Atmospheric": $\Delta m^2_{23} = 2.4 \times 10^{-3}\ eV^2$

"Solar": $\Delta m^2_{12} = 7.59 \times 10^{-5}\ eV^2$

Probability for ν_μ oscillating into ν_x :
Start with ν_μ beam, will observe less at a later time, called "ν_μ disappearance"

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

Existing measurements of ν_μ disappearance



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=735km, E(peak) ~3 GeV

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

New result (2011) 1103.0340 [hep-ex]

- $\Delta m^2_{23} = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV^2 (68% CL)

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

Atmospheric neutrinos (Super-Kamiokande)

Phys.Rev.D71:112005,2005; hep-ex/0501064

L~15km-13,000km, E~100 MeV-10 TeV

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

Neutrino oscillation: ν_e appearance

Probability for ν_μ oscillating into ν_e (ν_e appearance in ν_μ beam)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

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

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

$\alpha = \Delta m^2_{12}/\Delta m^2_{23} \sim 0.04$

$\Delta m^2_{31} \sim \Delta m^2_{23}$

Subleading terms depend on δcp differently for neutrinos (-) and antineutrinos (+)

Sakharov's conditions require CP violation and baryon number violation

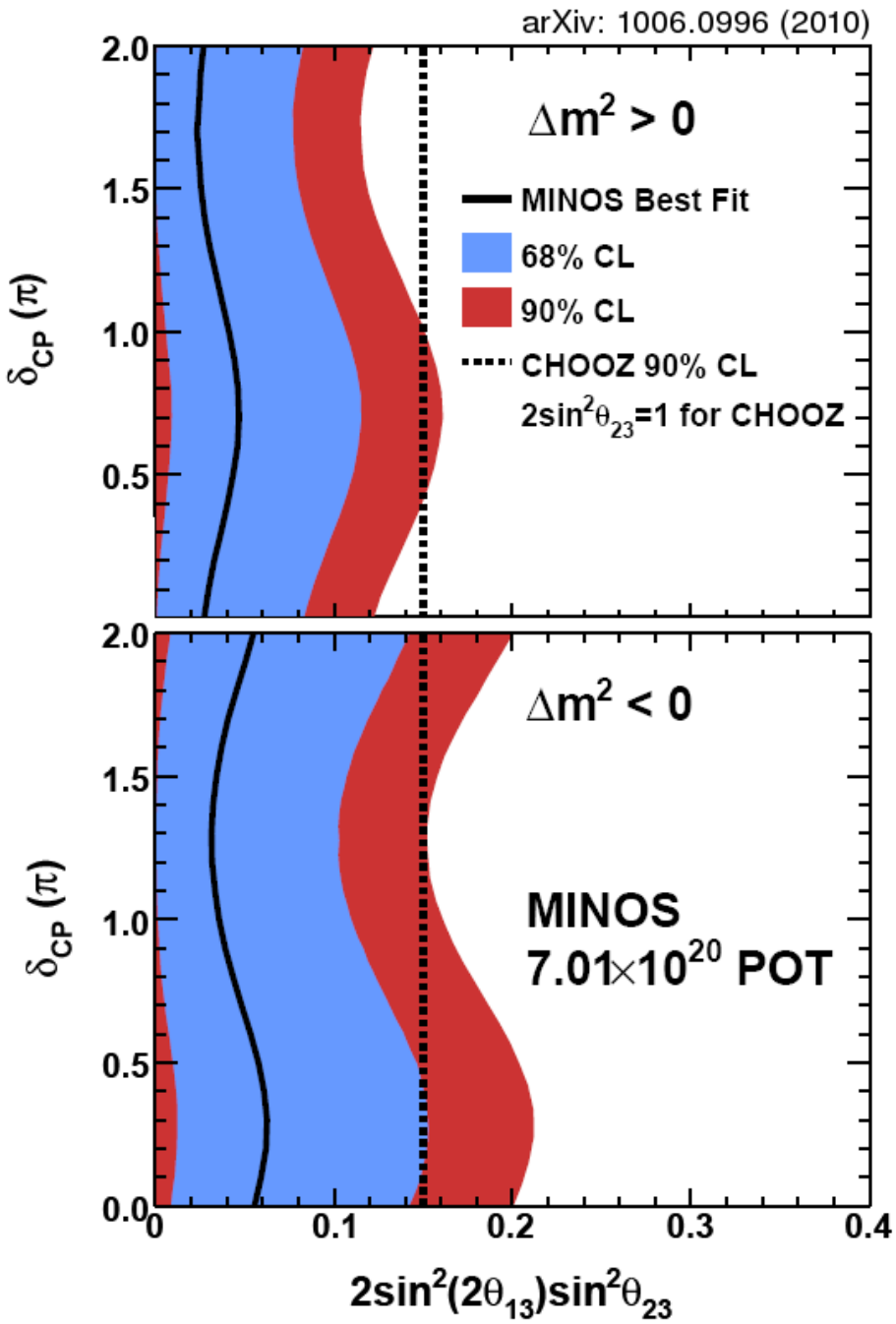
A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)]

- 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

Existing measurements of ν_e appearance



Accelerator-produced neutrino beam (MINOS)

Phys.Rev.D82:051102,2010; hep-ex/1006.0996

L=735km, E(peak) ~3 GeV

- $2\sin^2\theta_{23}\sin^2 2\theta_{13} < 0.12$ (90% CL)
- ν_e and ν_μ interact differently in matter which alters the oscillation probability
- "matter effects" depend upon sign(Δm^2), called the mass hierarchy

  $m_3 > m_1$ implies $\Delta m^2_{31} > 0$ (normal)

  $m_3 < m_1$ implies $\Delta m^2_{31} < 0$ (inverted)
- MINOS is sensitive to this effect and so the limit depends on which hierarchy is assumed

Reactor $\overline{\nu}_e$ disappearance (CHOOZ)

Eur.Phys.J.C27:331-374,2003; hep-ex/0301017

L~1 km, E~3 MeV

- $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2

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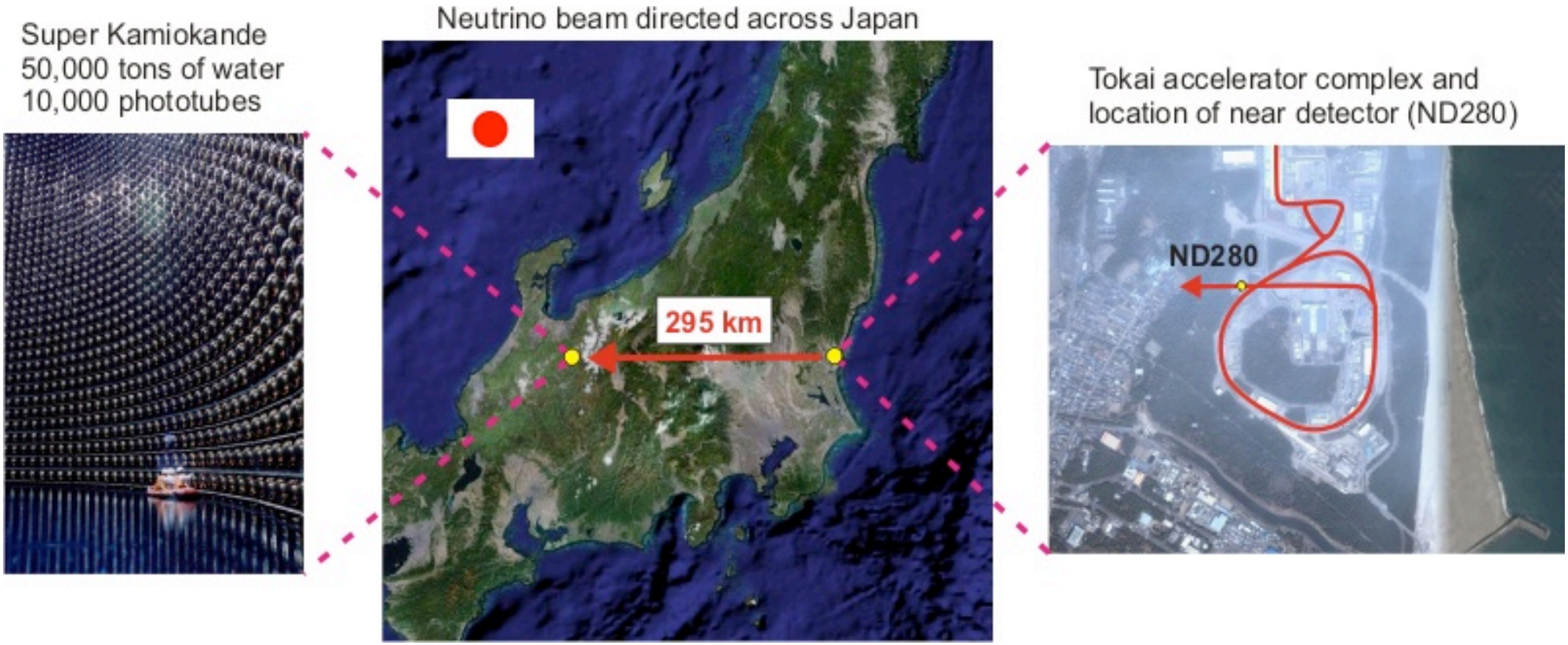
The T2K experiment

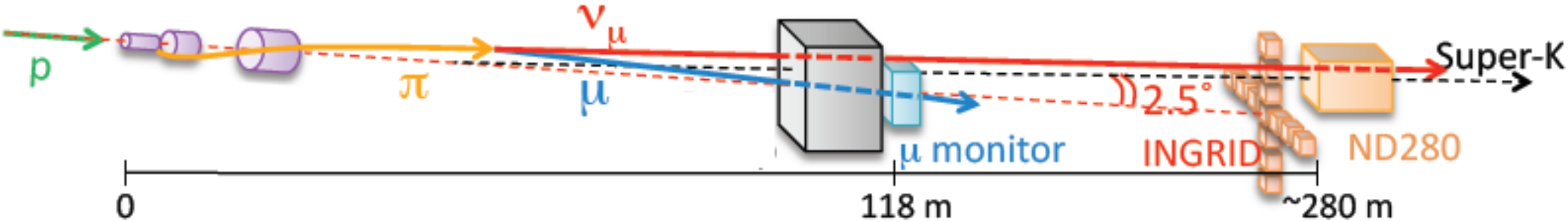
T2K is designed to measure oscillations at the atmospheric Δm^2 :

- Measure ν_μ disappearance (Δm^2_{23}, θ_{23})
- Discover ν_e appearance? (θ_{13})

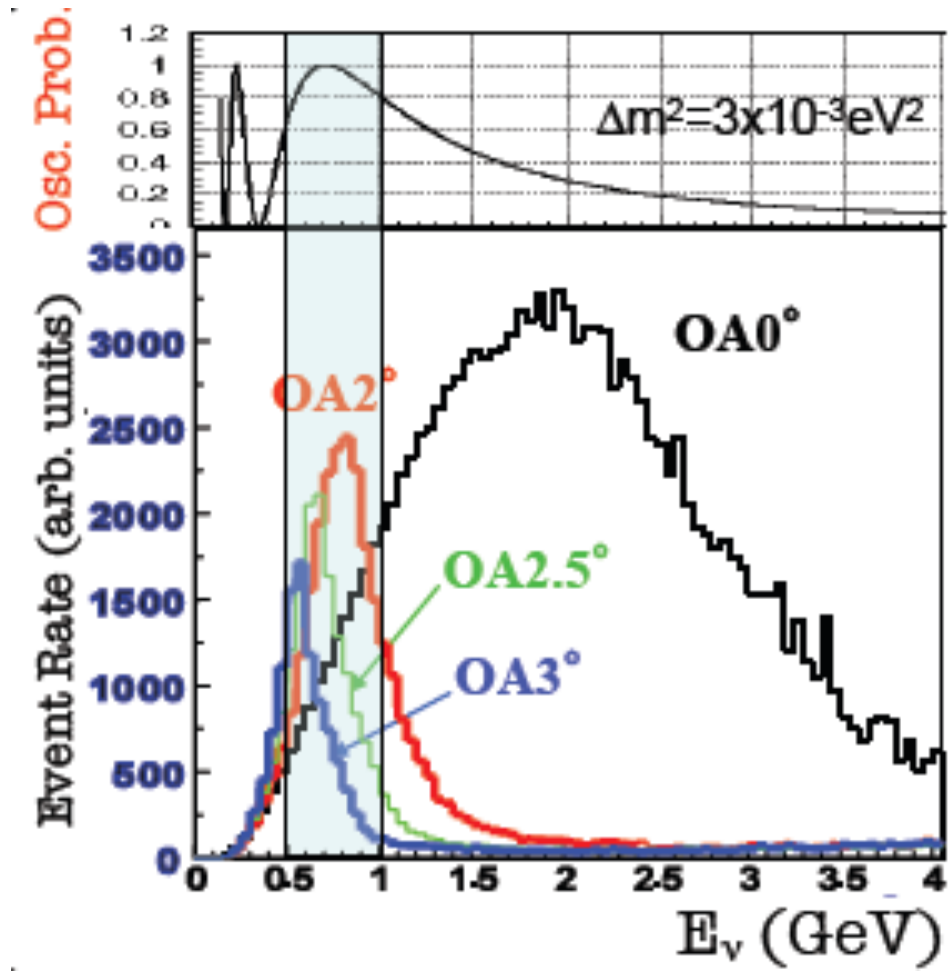
Produce a beam of ν_μ on one side of Japan and detect it on the other

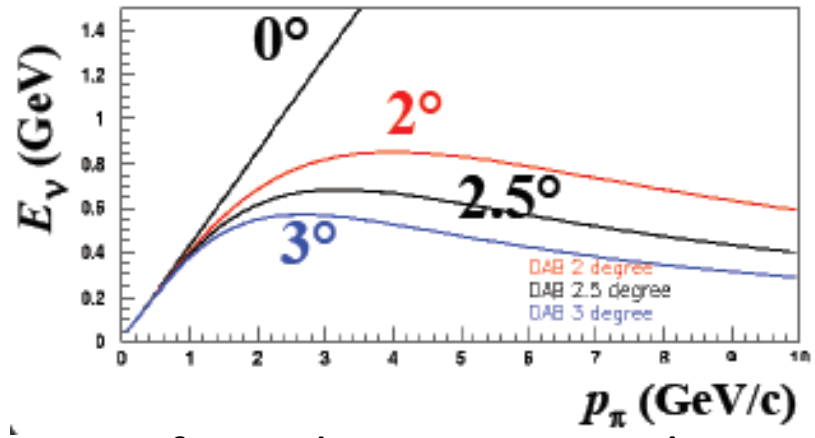


Creating an (offaxis) neutrino beam



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

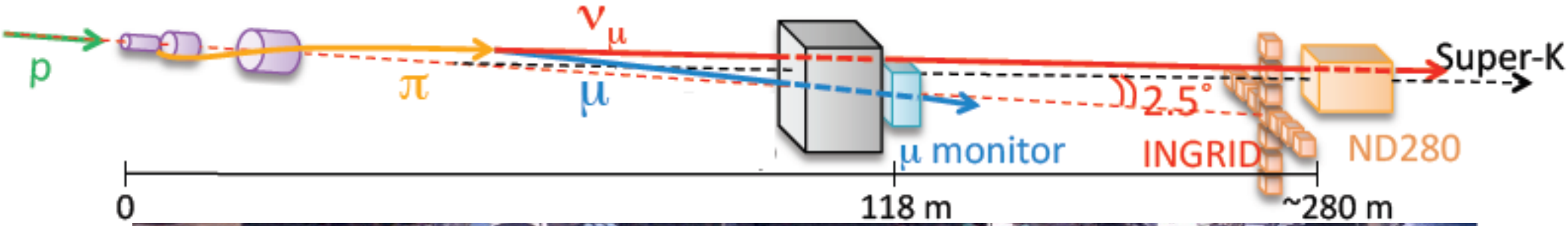




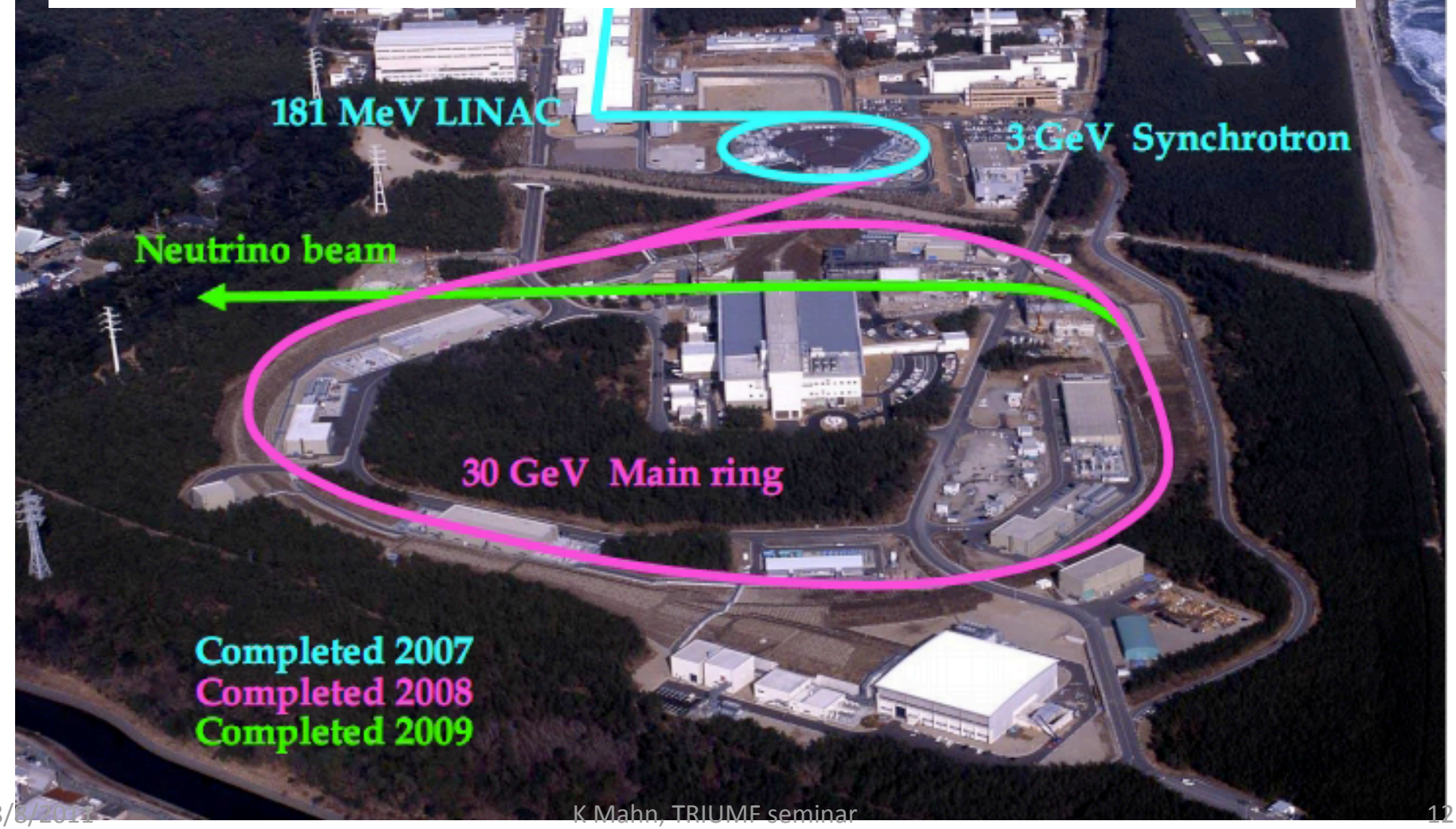
At angles away from the parent pion's direction, the neutrino energy is independent of pion momentum, resulting in a narrower neutrino energy spectrum

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

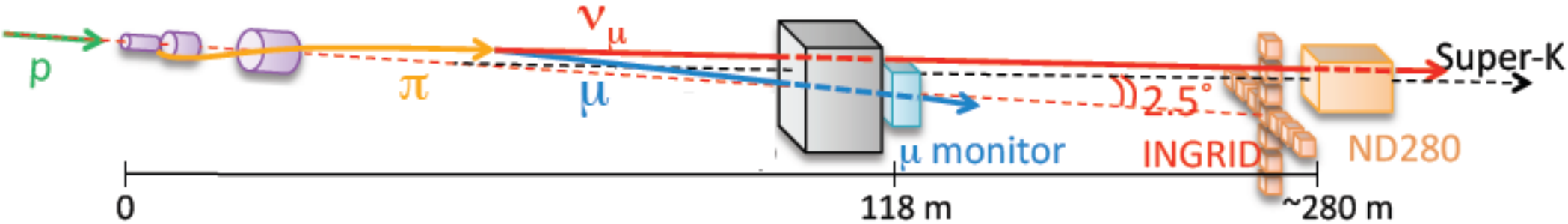
The proton beam



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

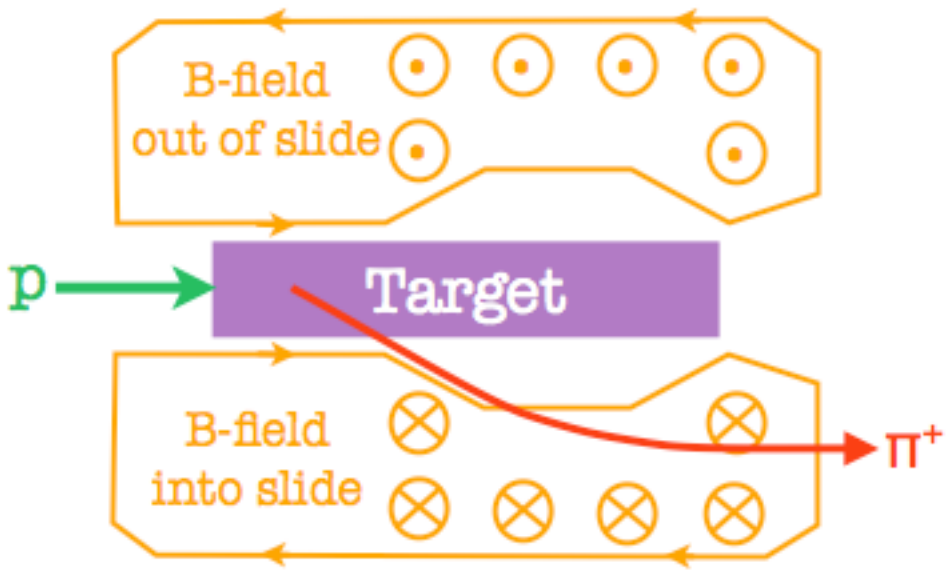


Secondary beam of mesons



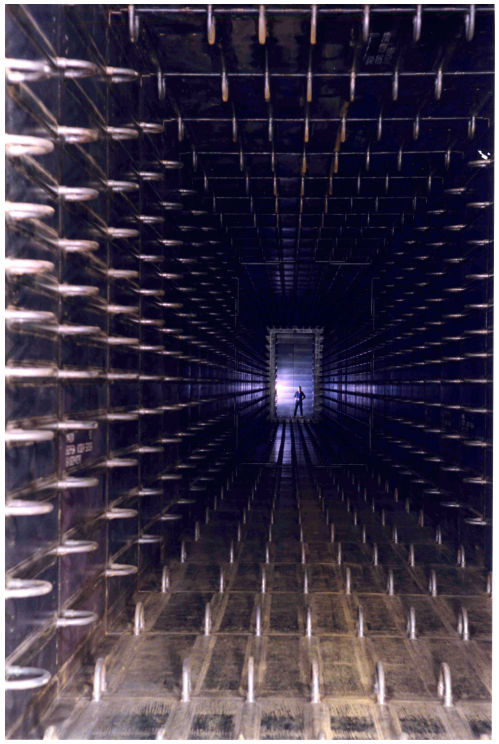
The protons hit a 91 cm long graphite target, producing pions and kaons

The mesons are focused by three magnetic ``horns”



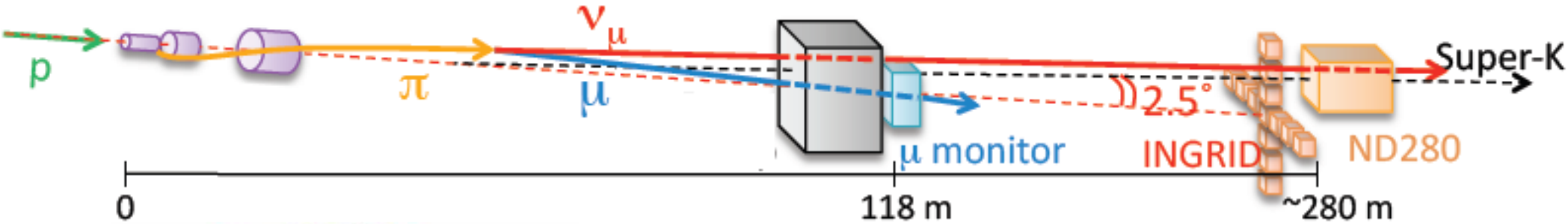
then decay in a 100m long decay volume

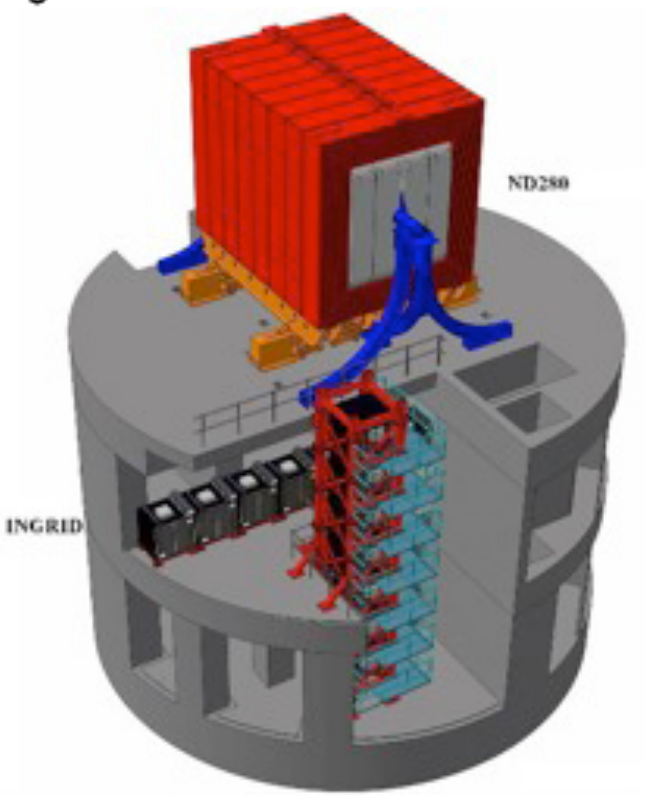
$$\pi \rightarrow \mu \ + \nu_\mu$$



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

Neutrino detectors





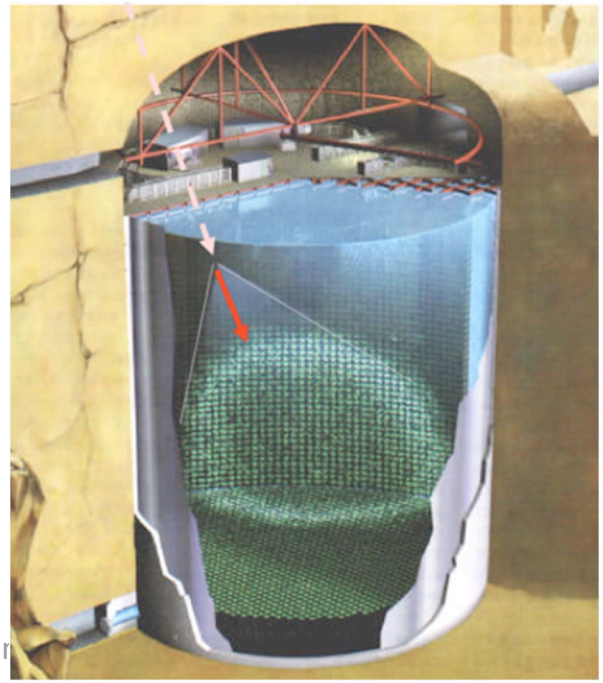
<u>On-axis with the INGRID detector</u>

Determine neutrino beam direction

<u>Off-axis with the ND280 detectors</u>

Measure the unoscillated ν_μ and ν_e rates

Constrain background processes

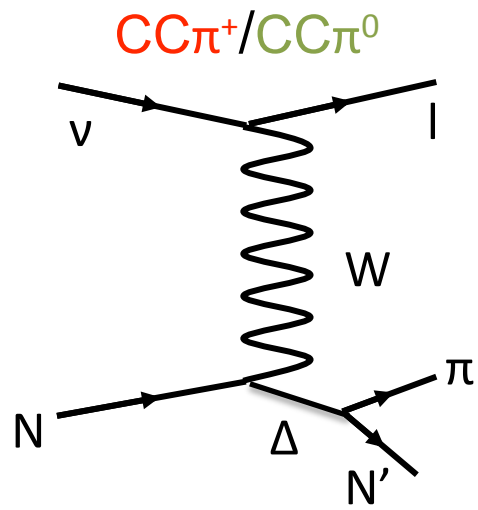


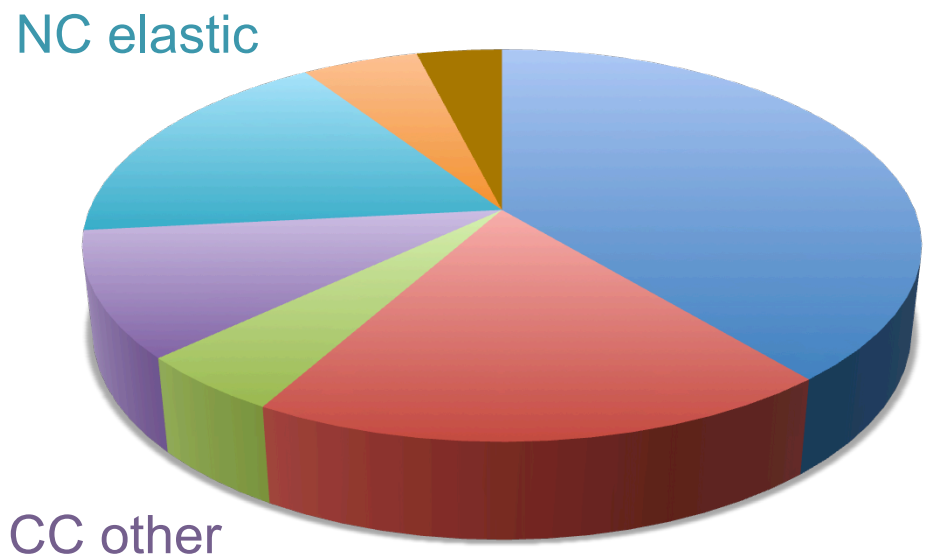
<u>Off-axis@295km with Super-Kamiokande</u>

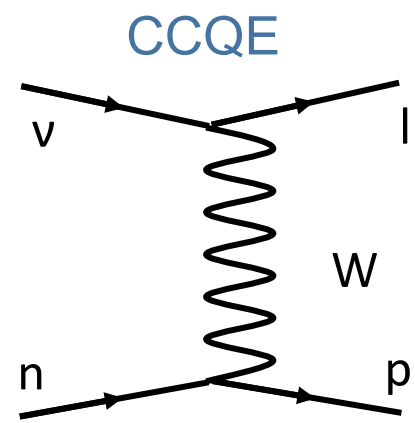
Extract oscillation parameters

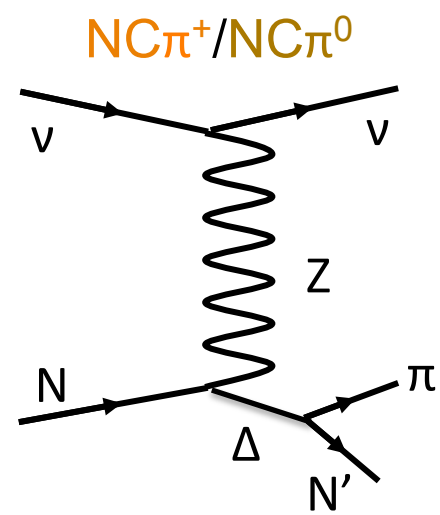
from ν_μ, ν_e rates

Neutrino interactions at T2K









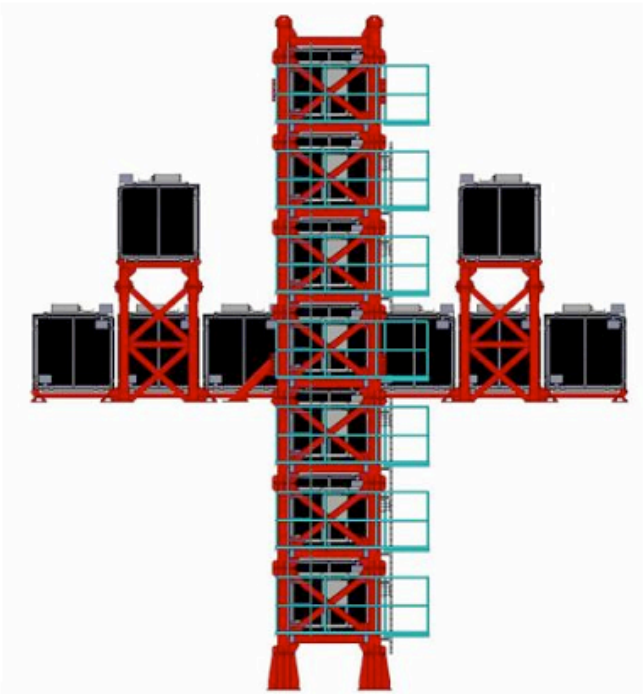
Primary interaction is Charged Current Quasi-Elastic events

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

CCπ (single pion production) and NCπ 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

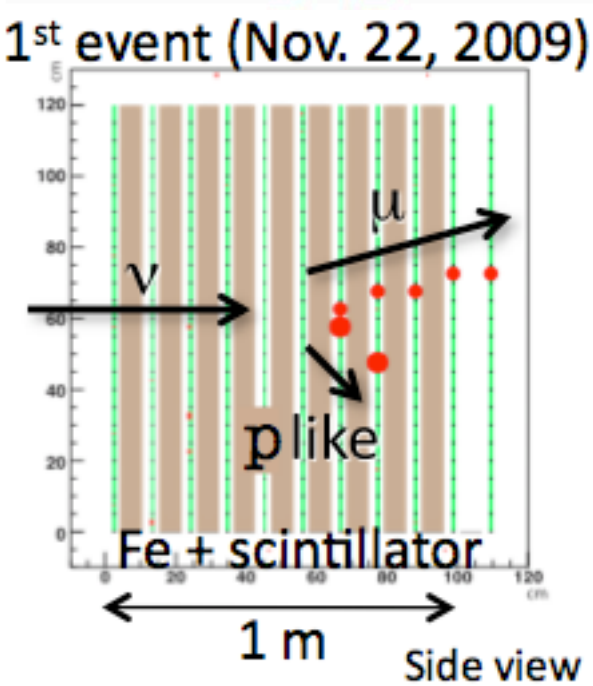
- X-Y iron-scintillator layers, 7.1 tons each

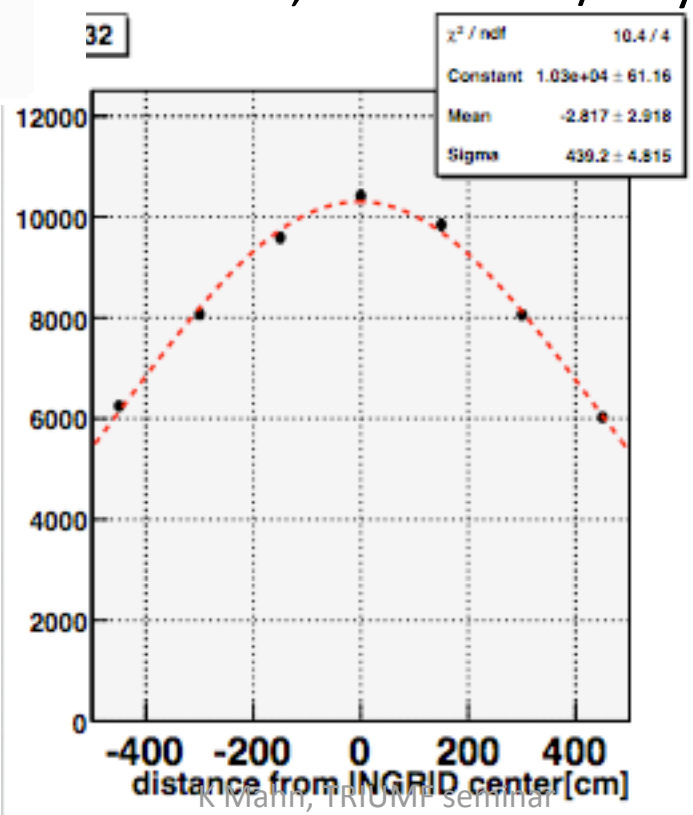
Count neutrino interactions in each module to determine neutrino rate vs. position

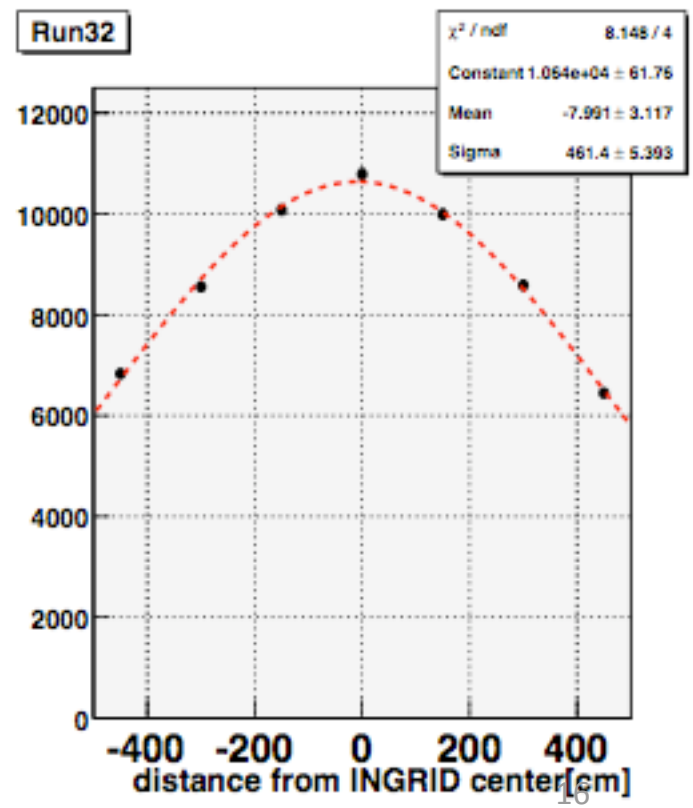
Extract beam direction better than 0.5 mrad

Monitor of neutrino beam vs. time

- ~1.5 ν / 10^{14} protons on target
- ~10,000 events / day







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, P0D and SMRD

Side Muon Range Detector

87x17x0.7cm instrumented scintillator in magnet yoke

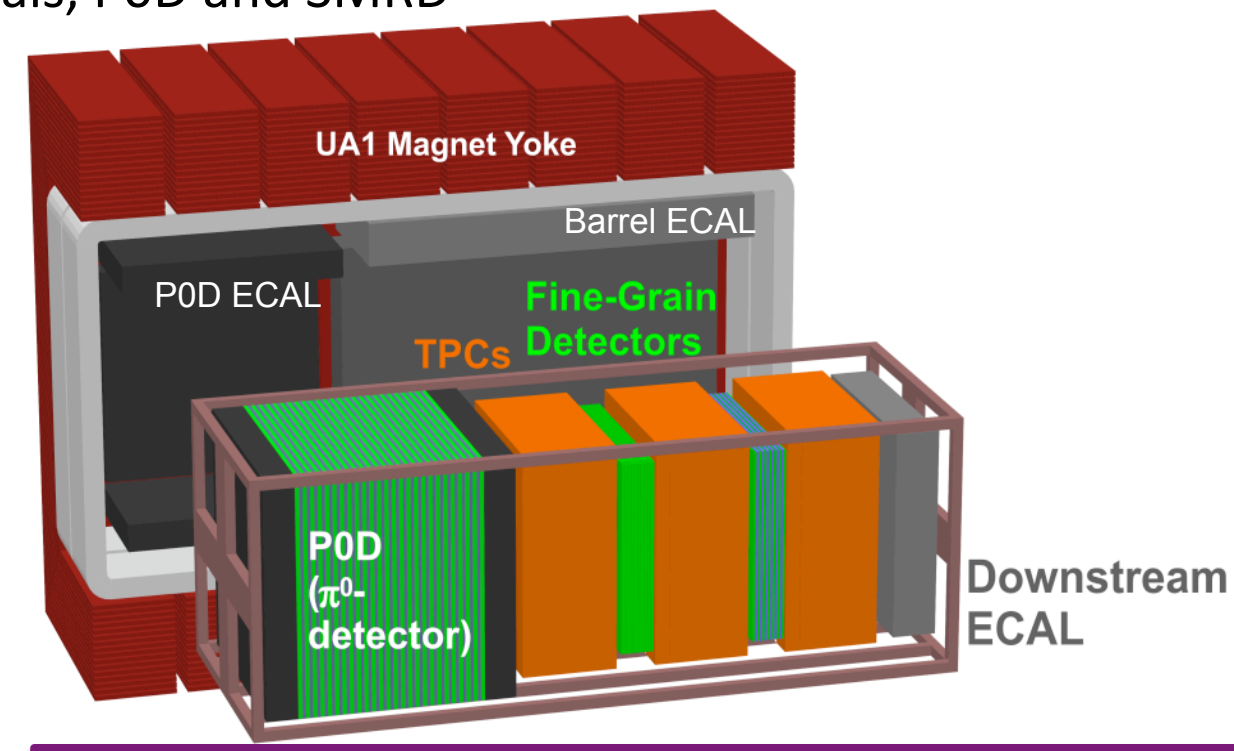
Active veto, cosmic trigger

Electromagnetic Calorimeters

X-Y Pb/scintillator planes

P0D, Barrel, TPC3

Tag photons, e from Tracker and P0D



Pi-zero Detector (P0D)

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

Neutrino interaction target ($CH+H_2O$)

Photons, electrons shower separable from MIPs

Tracker (FGD)

2 Fine Grained Detectors

XY scintilator sandwich

Neutrino interaction target

(CH, $CH+H_2O$, 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% CF_4

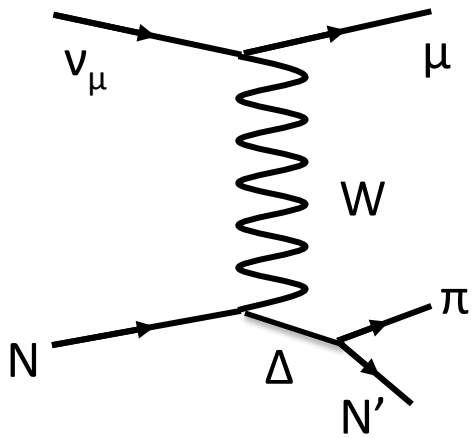
2% isobutane

Momentum from curvature

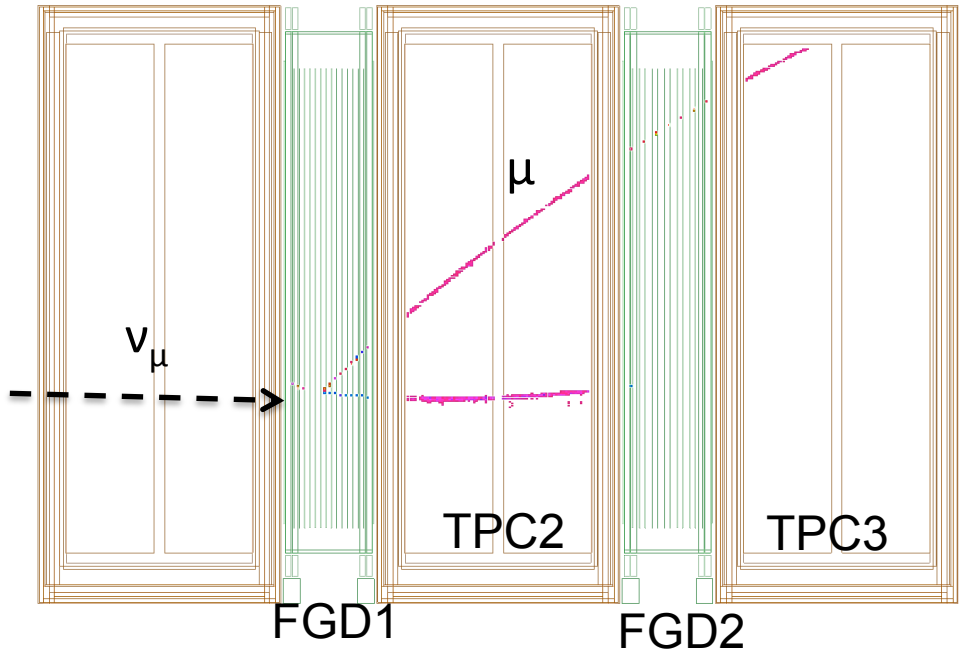
Particle ID from energy loss

Example neutrino interactions in ND280

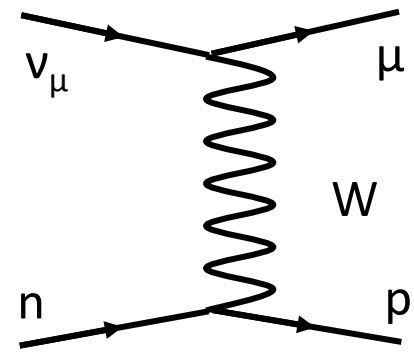
CC 1π
charged current
single pion production



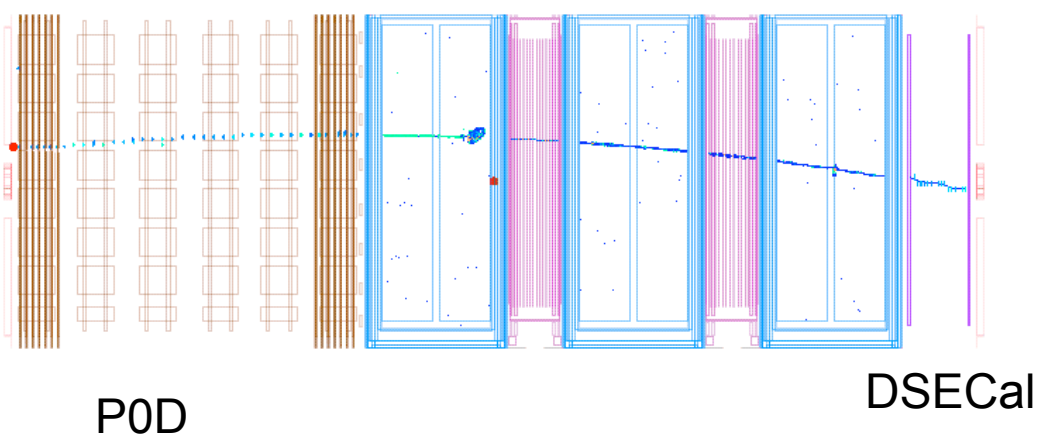
CC neutrino interaction candidate



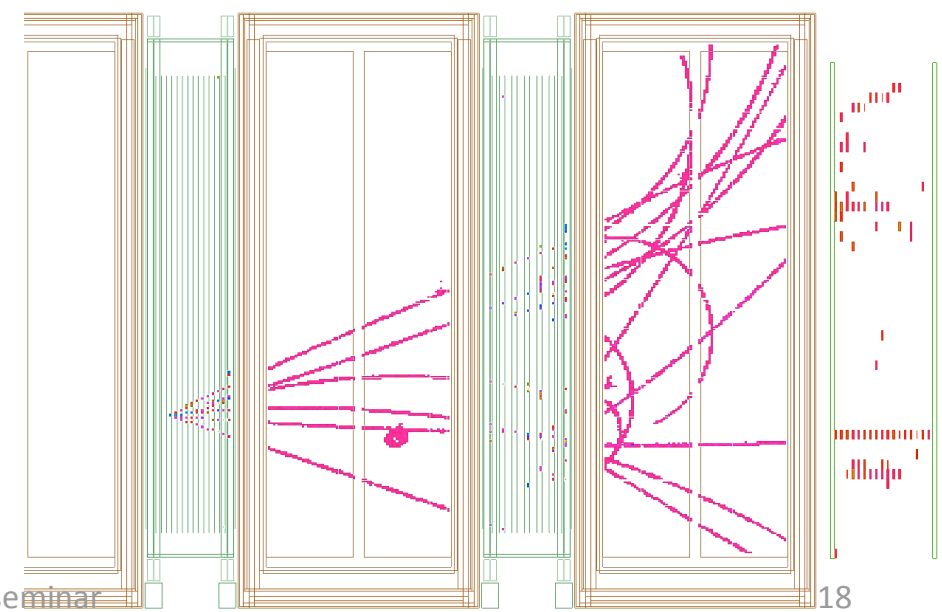
CCQE
charged current
quasi-elastic



Neutrino interaction upstream of ND280



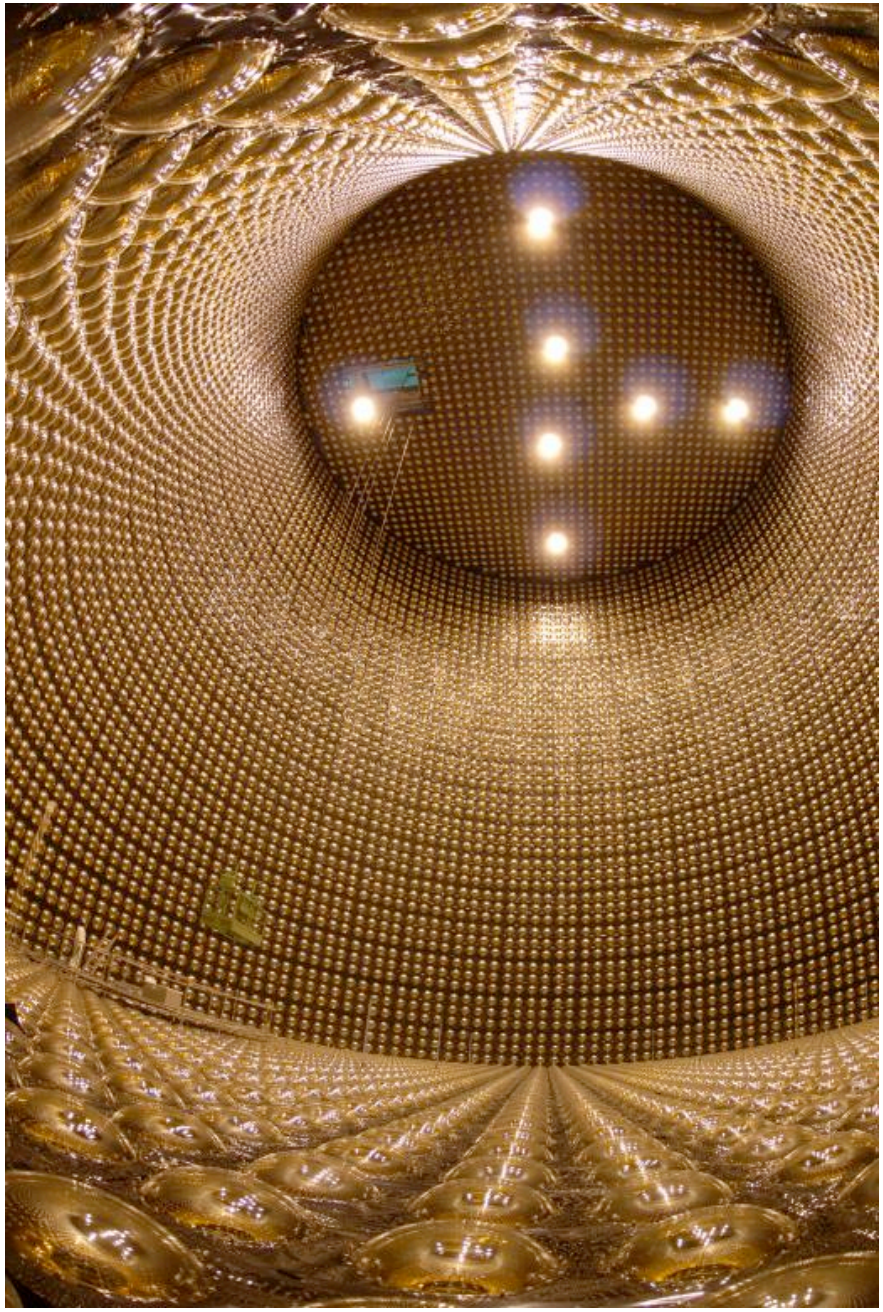
Deep inelastic scattering candidate



T2K far detector: Super-Kamiokande

295km away is the T2K far detector, Super-Kamiokande ("Super-K'')

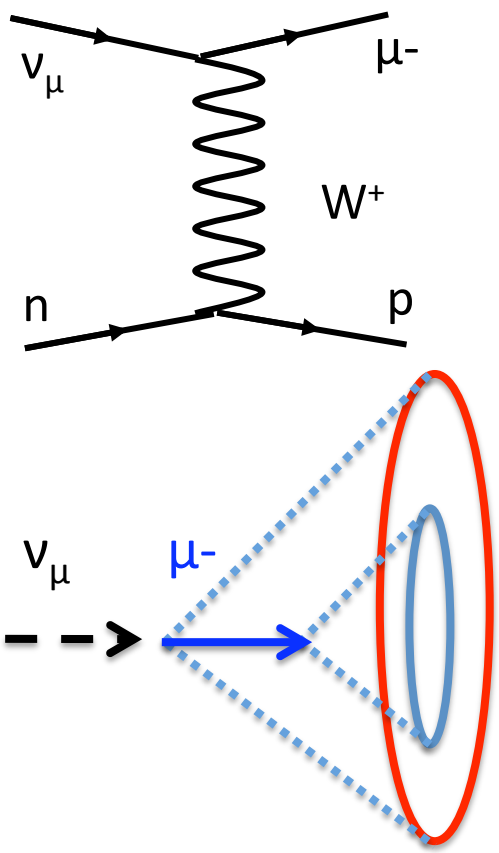
- 50kton water Cherenkov detector (22.5kton fiducial mass)
- 39.4 m diameter, 41.4 m tall cylindrical tank
- 11,129 inner photomultiplier tubes (PMTs) (40% photocathode coverage)
- 1885 veto PMTs located on the outside of the tank reject events entering the tank
- Cosmic ray rate in Kamioka mine is 1.77Hz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



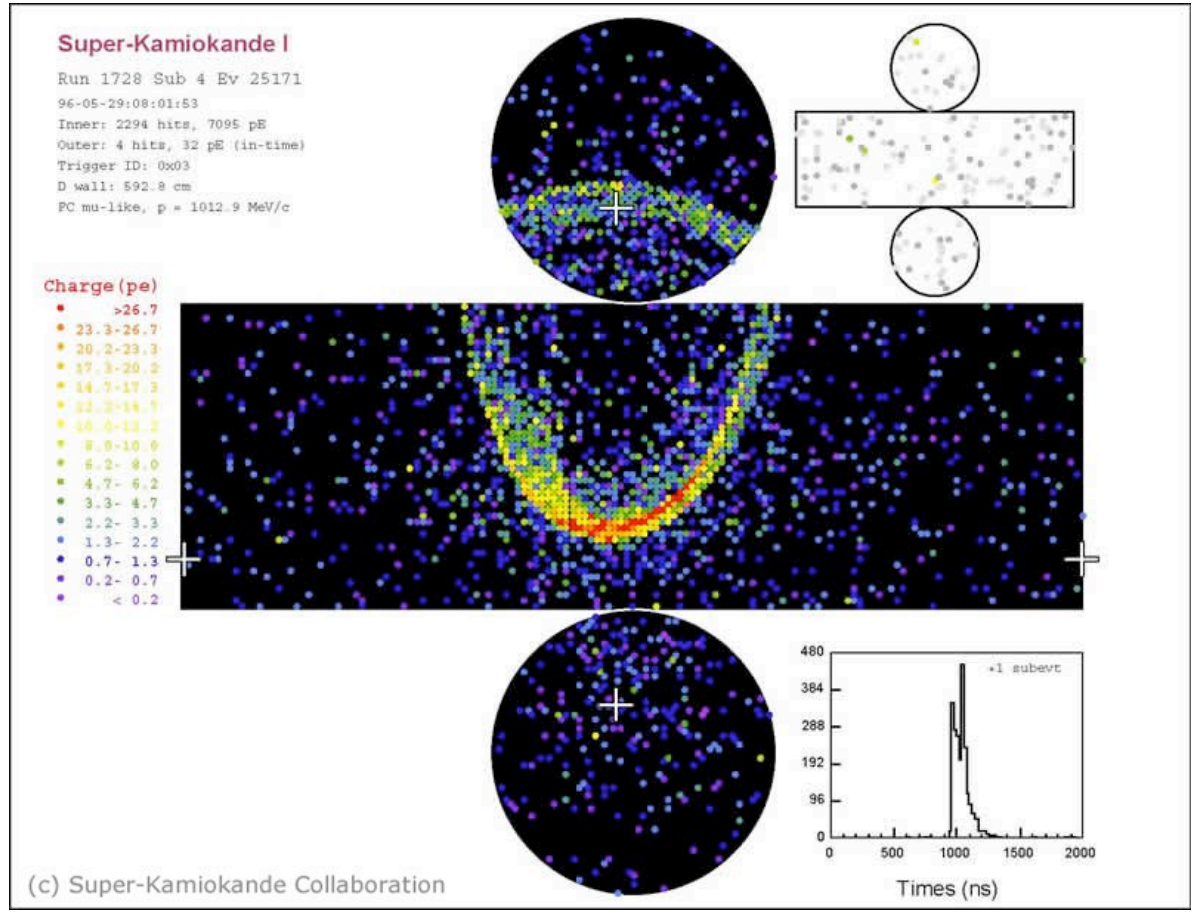
Neutrino events in Super-K

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

CCQE:



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

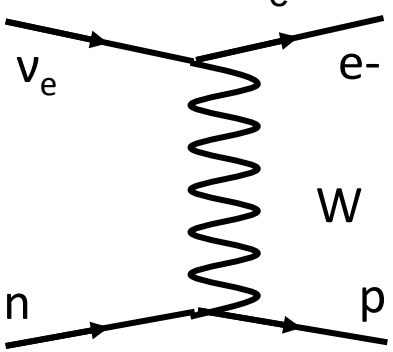
Electrons produce ``fuzzy'' rings, due to multiple scattering and showering

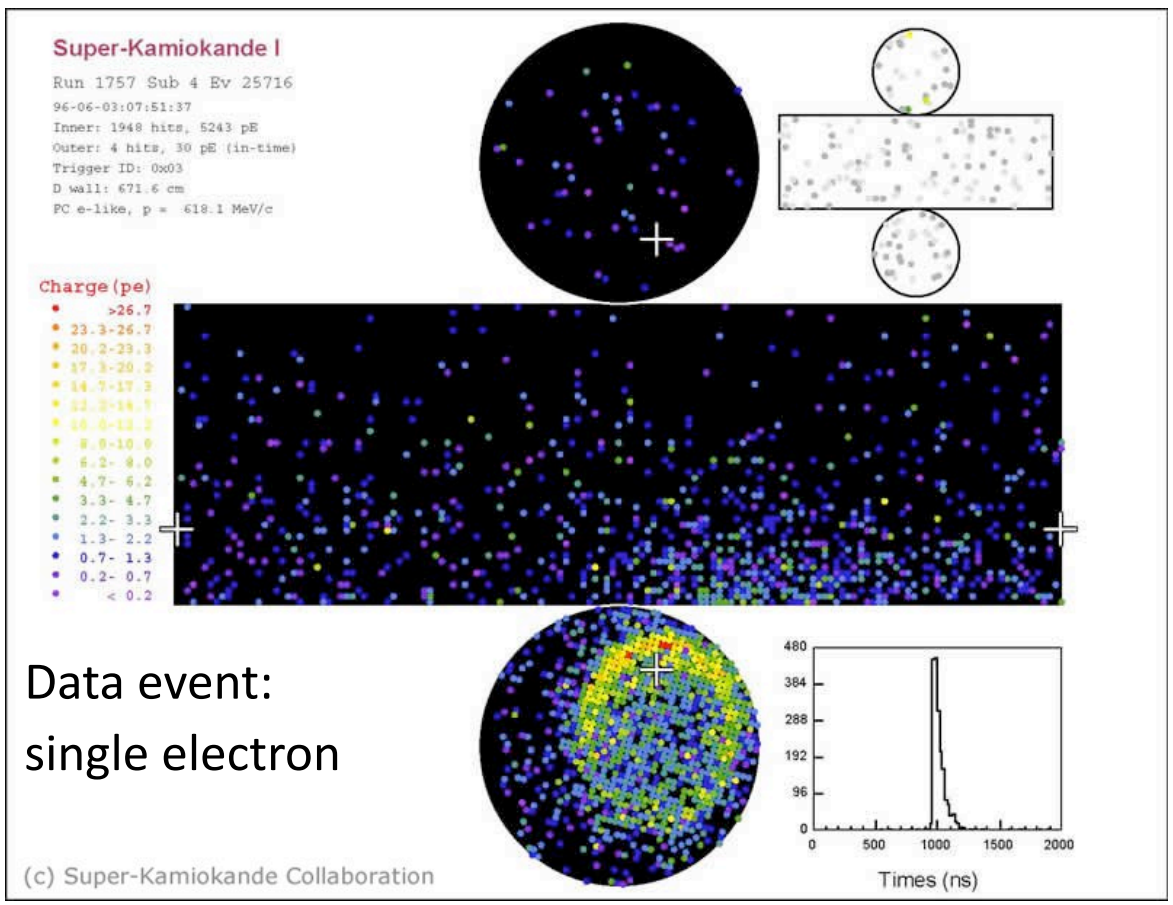
- CC ν_e events produce an electron
- Ability to tag electrons from μ decay from CC μ (deadtime-less DAQ)

Neutral pions produce two electron-like rings from decay photons

If one ring is not reconstructed, mimics CCQE ν_e signal

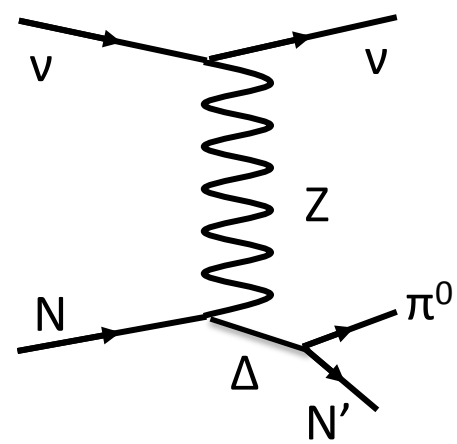
CCQE ν_e





Data event:
single electron

NCπ^0:



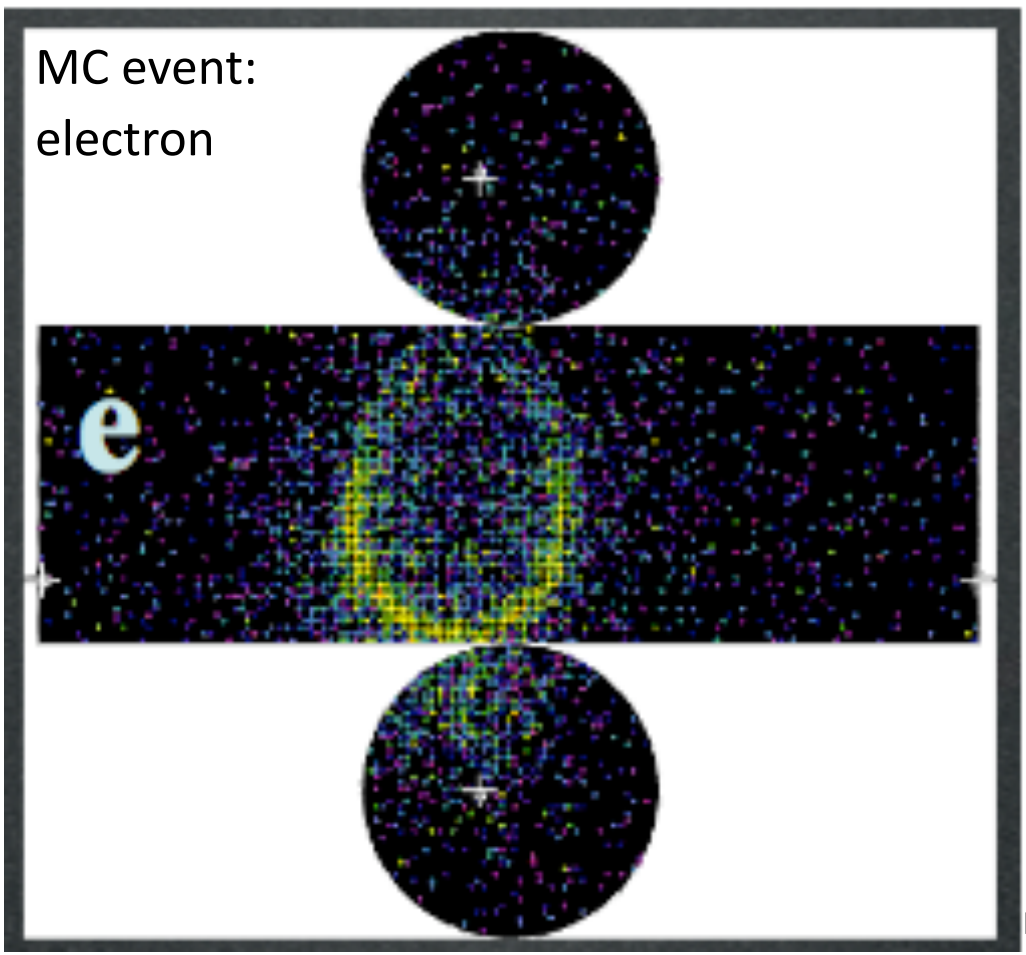
NC π^0 background rejection

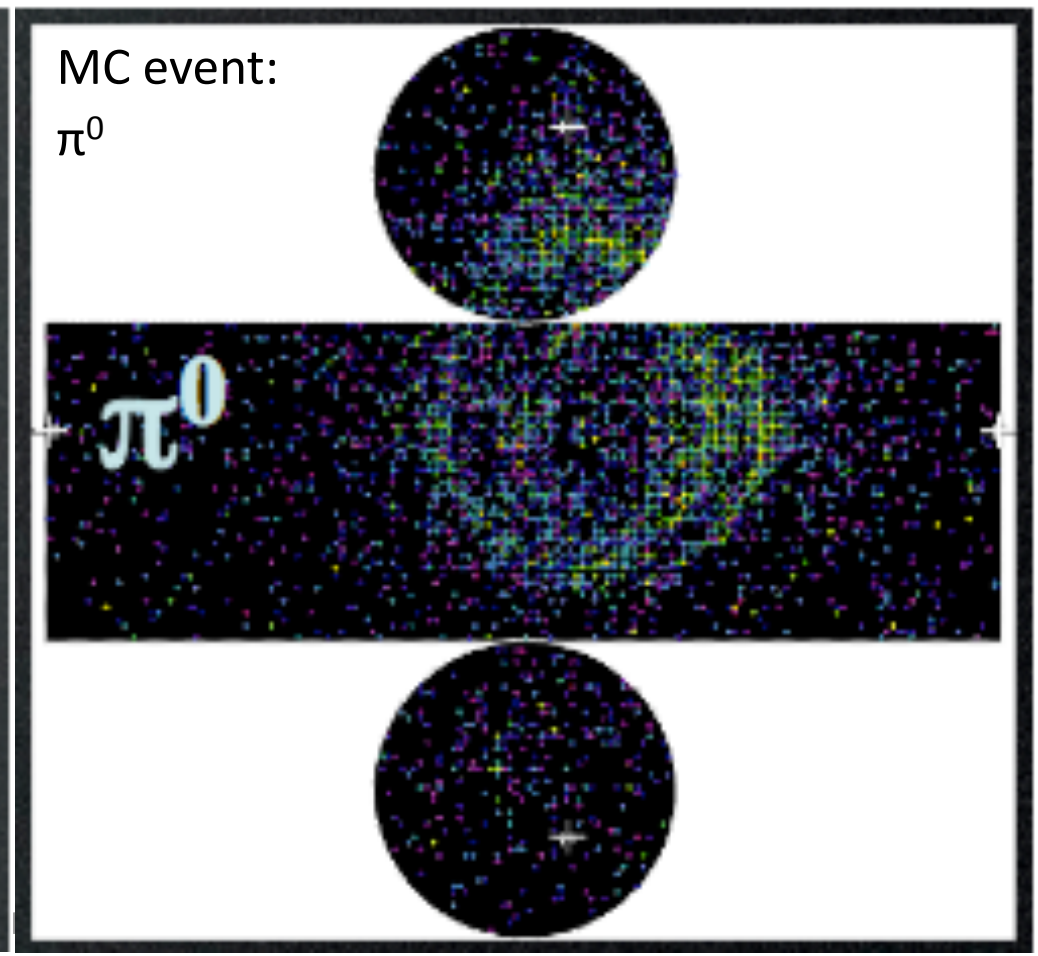
Scan over possible second ring directions and energies for a faint second ring

Select best match for observed light pattern

Cut on resulting invariant mass of two rings (m π^0) or $L_{2\gamma}/L_e$

Events with two true rings will have an invariant mass consistent with π^0





Outline

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3. Data collected by T2K
4. Oscillation analysis strategy
    1. Neutrino flux
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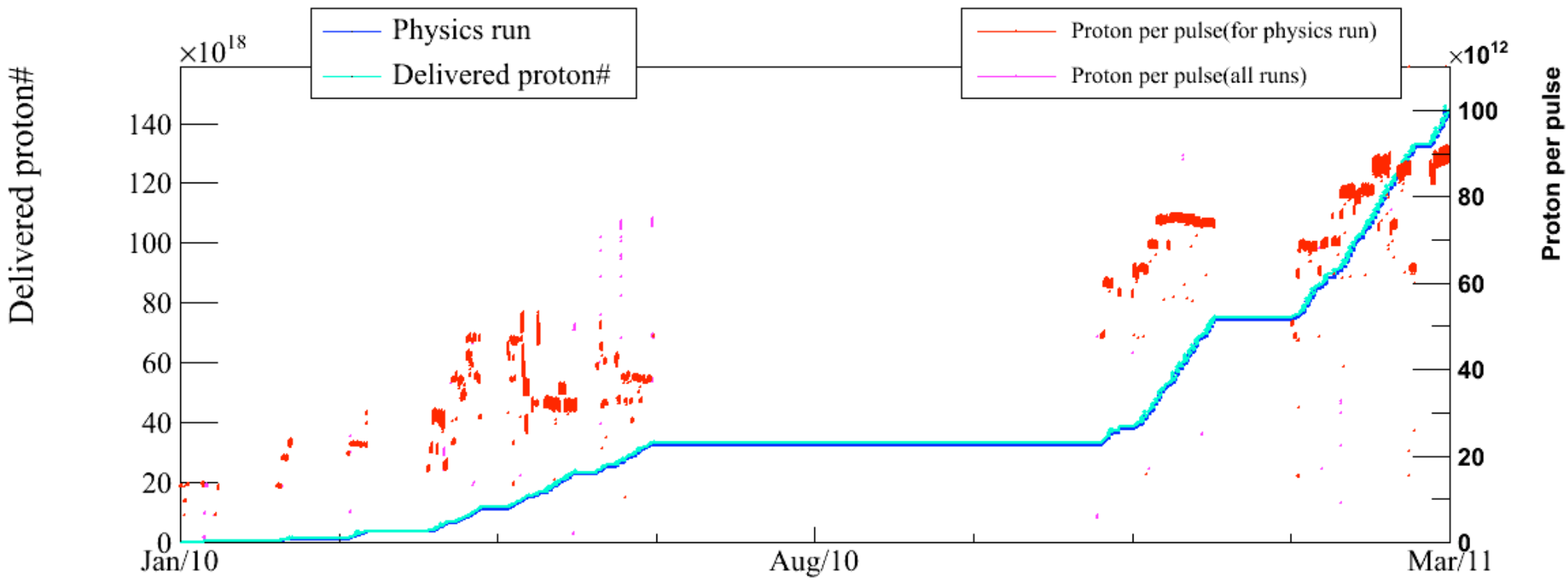
Data collected

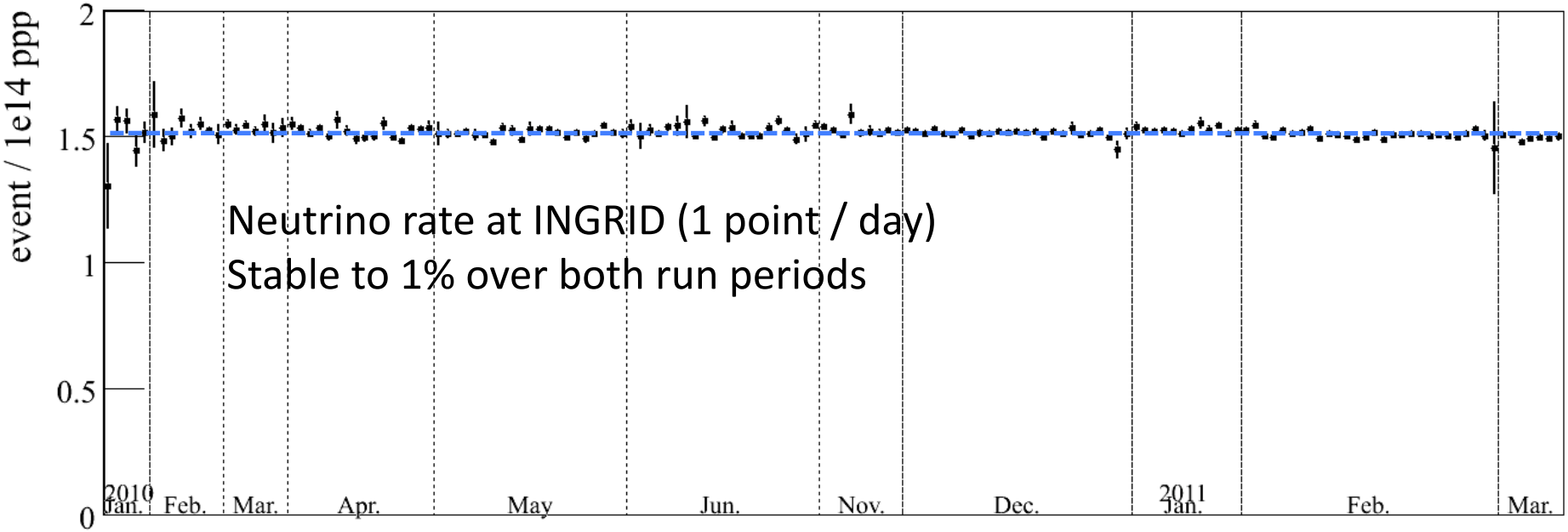


<u>Run I: Jan 2010 – June 2010</u>
6 bunches / spill / 3.54s
Stable running at 3.3 x 10^{13} POT/spill
(≈54 kW) with maximum at 100kW

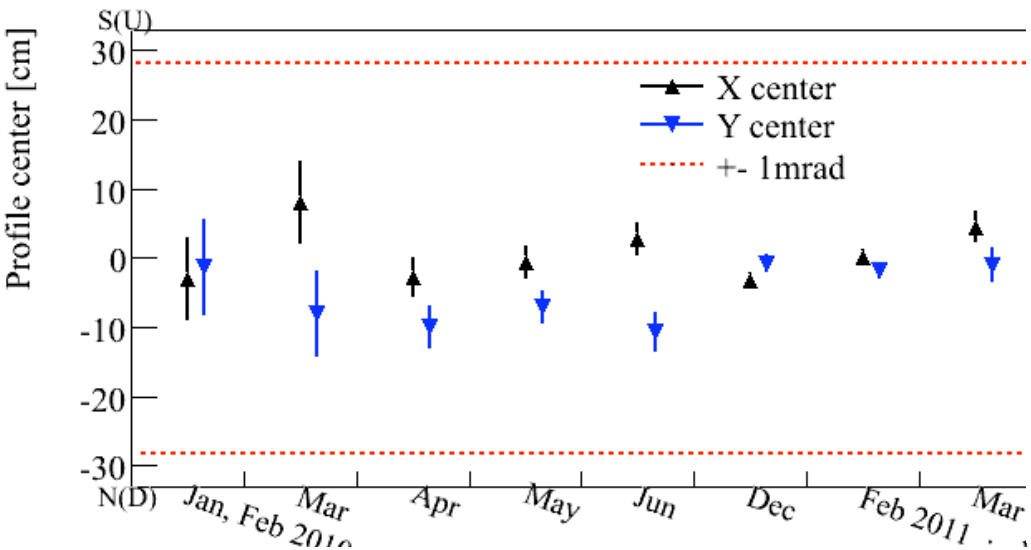
<u>Run II: Nov 2010-Mar 2011</u>
8 bunches / spill / 3.04s
Stable running at 145 kW

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

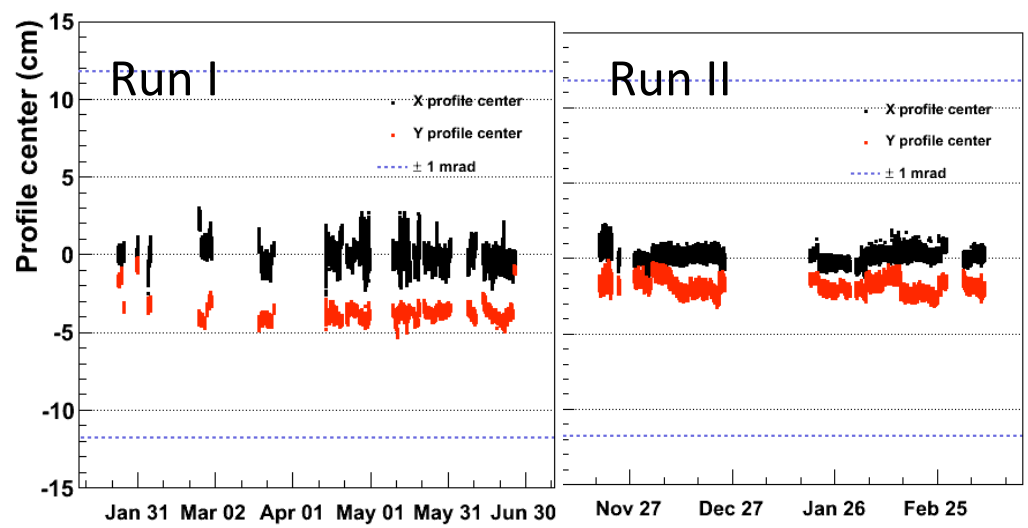
Neutrino beam stability



Neutrino rate at INGRID (1 point / day)
Stable to 1% over both run periods



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



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

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Analysis strategy

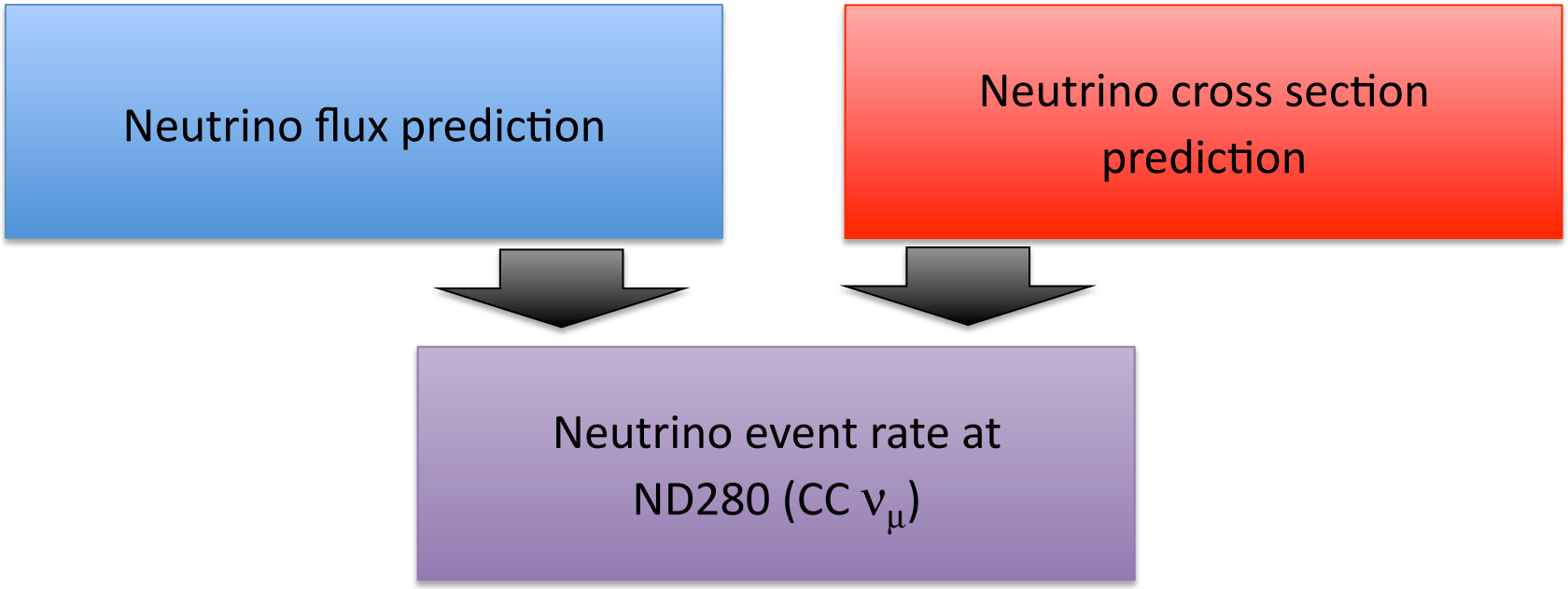
Neutrino flux prediction

Predict the flux from measurements of beam or external data
(e.g. hadron production off the target)

Neutrino cross section prediction

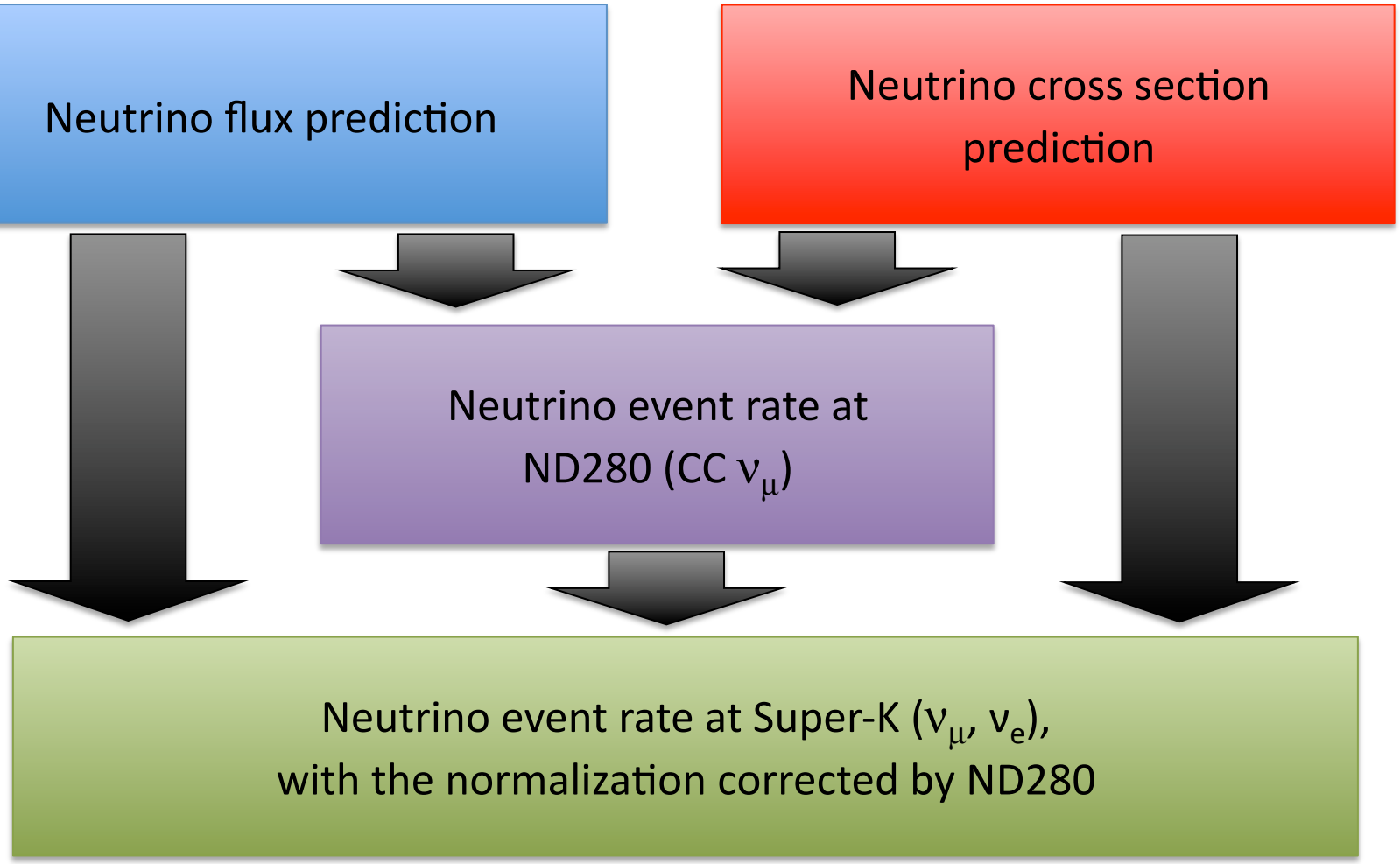
Predict the cross section based on measurements of neutrino interactions at $E\nu$~1 GeV

Analysis strategy



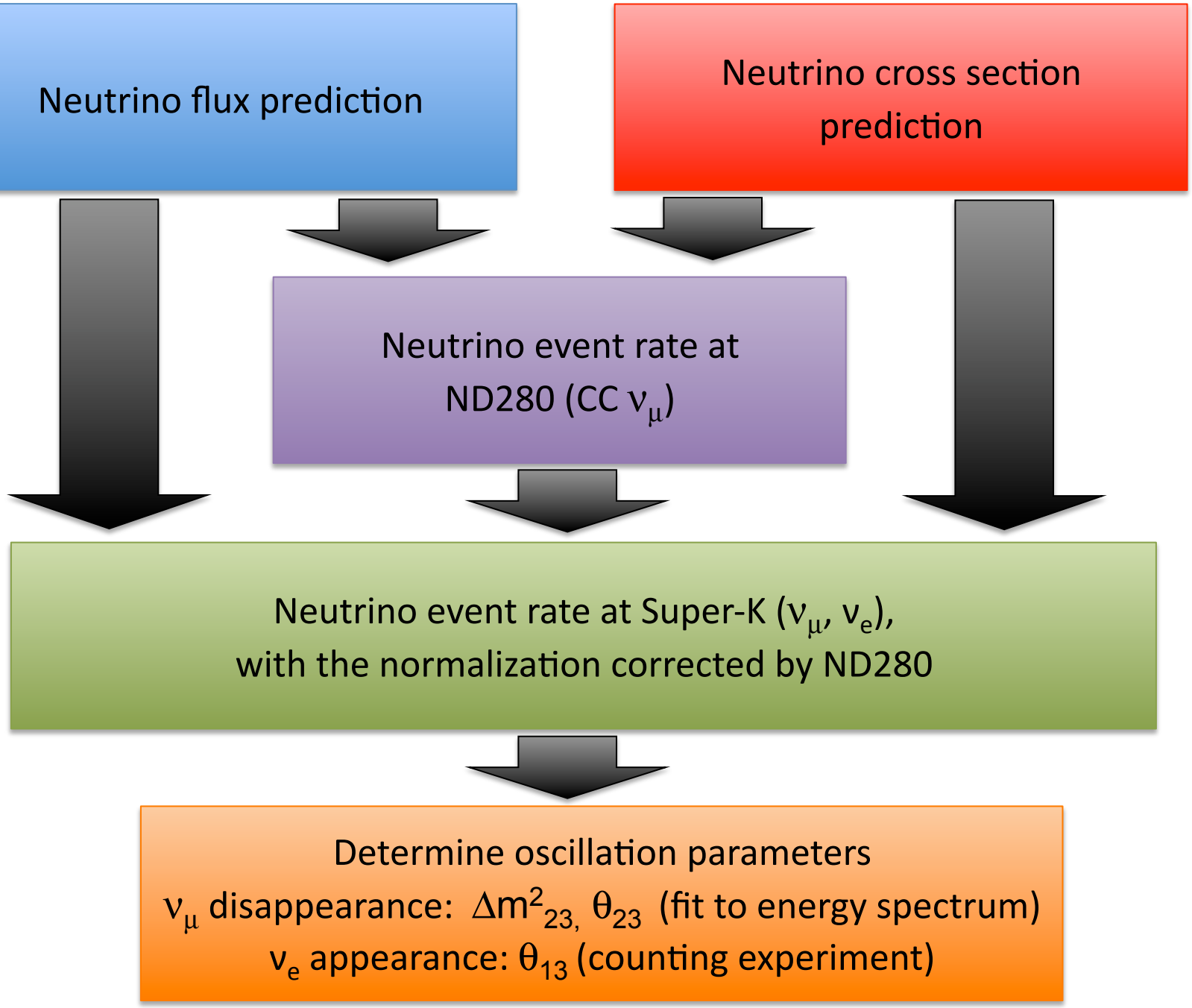
Compare prediction to inclusive ND280 CC ν_μ selection
Extract a ratio of the rate R(CC ν_μ) between data and MC

Analysis strategy



Correct the rate at Super-K by the normalization measured at ND280 and constrain the uncertainties

Analysis strategy



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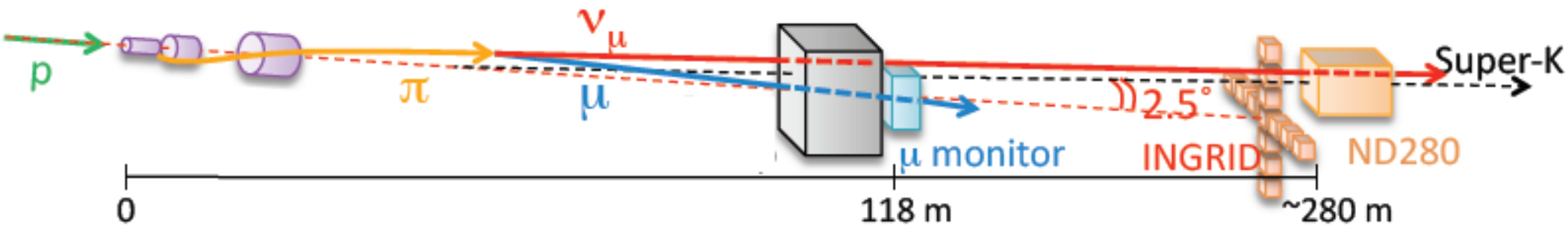
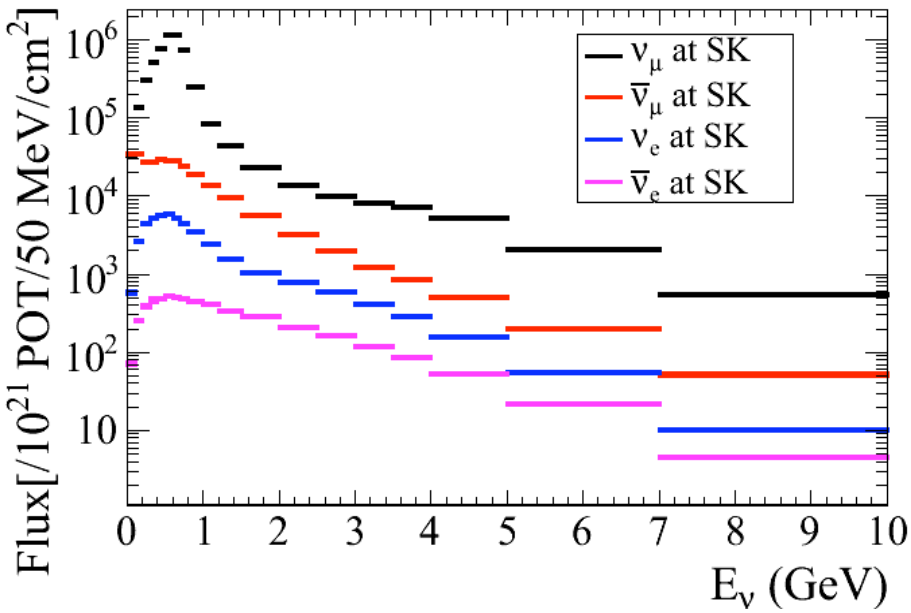
Neutrino flux prediction



Geant3/FLUKA based flux prediction



Unoscillated flux at Super-K is ν_μ

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

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

Uncertainties are constrained with external measurements or in-situ monitors

Largest uncertainty is π, K production from the target (NA61 experiment)

	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) 4.8% after ND rate applied @ $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2 $\sin^2 2\theta_{23} = 1.0$

π production from p+C

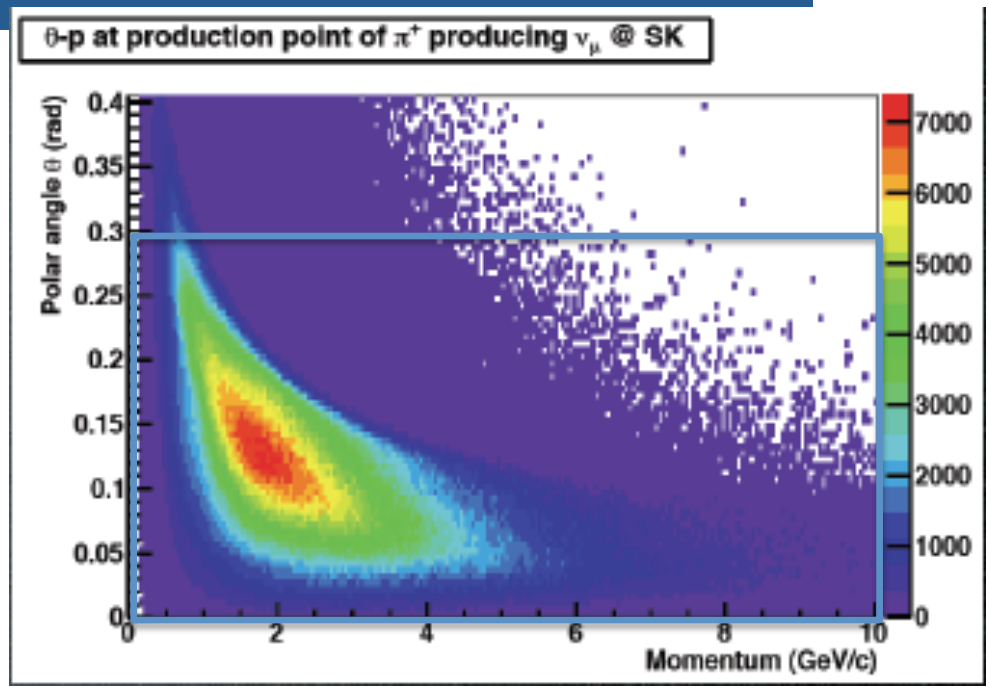
NA61/SHINE experiment at CERN

Designed to measure hadron production

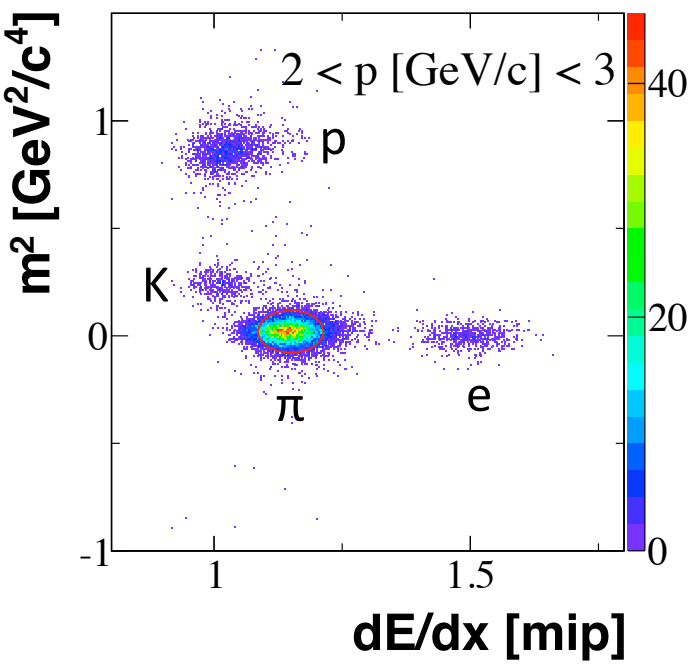
30 GeV p beam on:

thin target (2cm) in 2007-2009 run

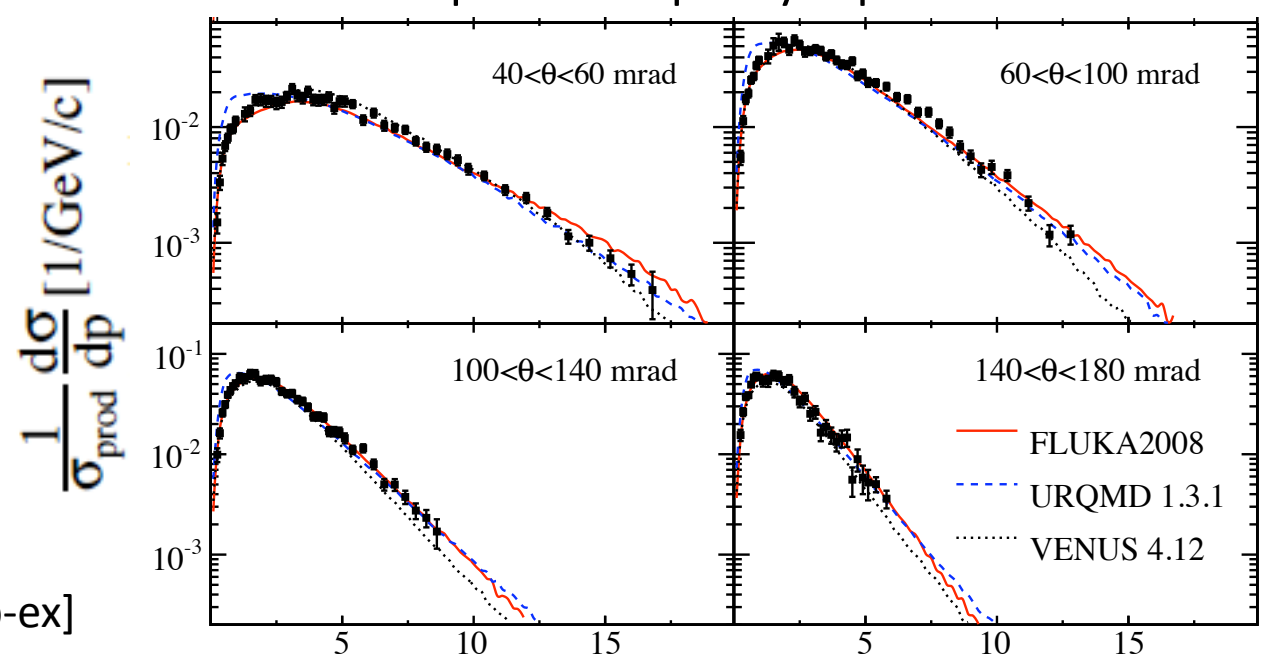
T2K replica target (91cm, 1.9λ) in 2010 run



Use TOF and dE/dx to select pions



Differential pion multiplicity reproduces simulation



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

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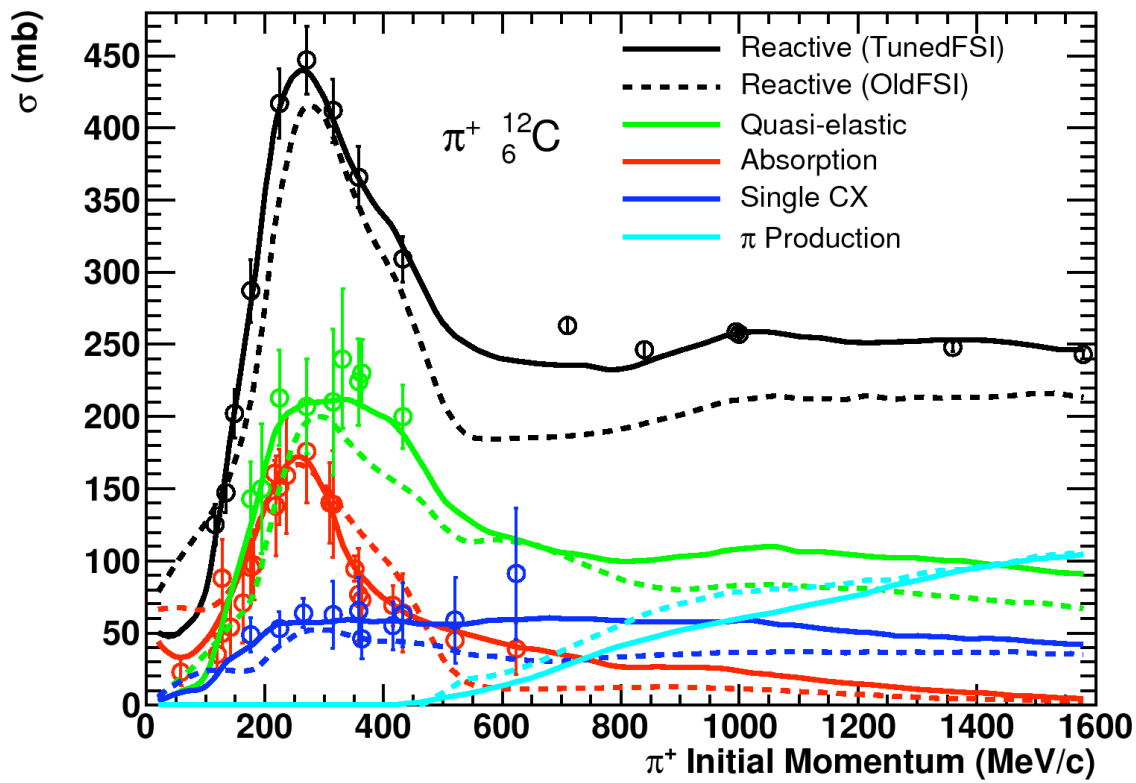
Neutrino interaction uncertainties

Cross section model, uncertainties set from external data at E_ν ~ 1 GeV e.g. MiniBooNE, SciBooNE, K2K

	ν_μ signal	ν_e bkrd
CCQE nuclear model (@lowE)	2.5%	3.1%
CC1π	+0.4% -0.5%	2.2%
CC coherent π	-	3.1%
CC other	+4.1% -3.6%	4.4%
NC all	0.9%	-
NC1π^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



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

ν_μ signal @ Δm^2_{23} =2.4 x 10^{-3} eV^2 $\sin^2 2\theta_{23}$=1.0

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    2. Neutrino interactions
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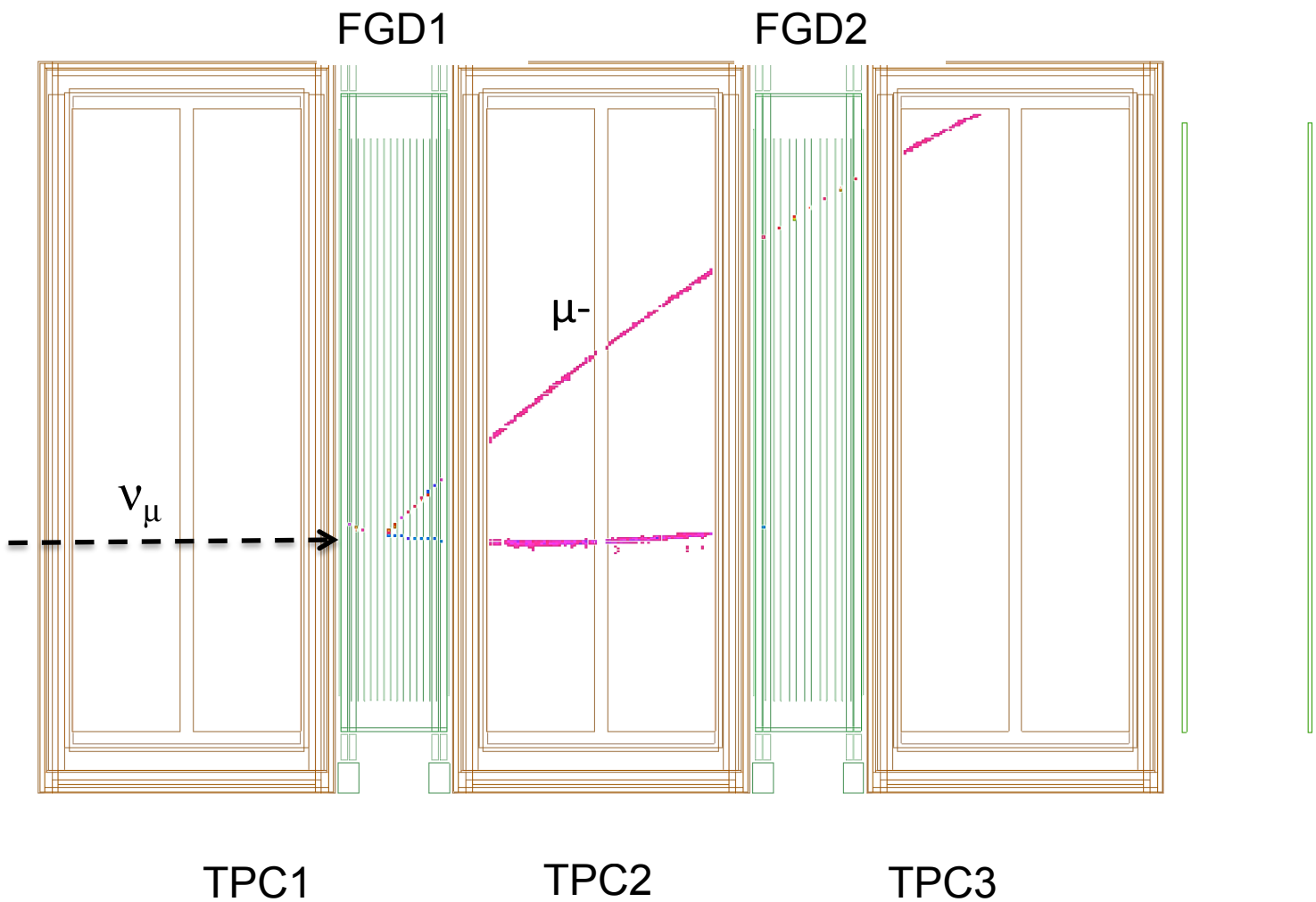
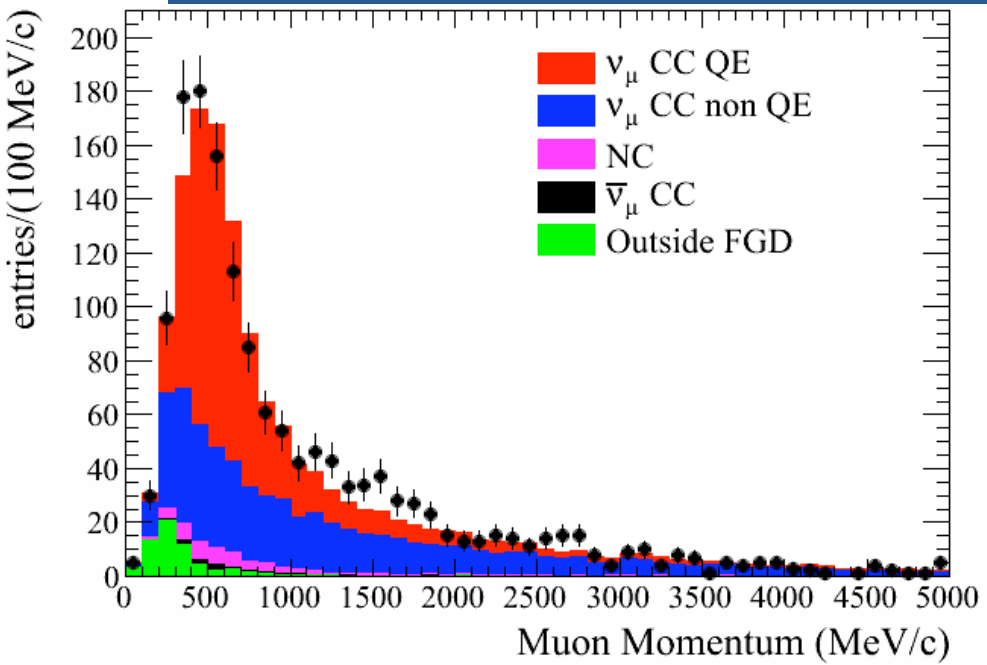
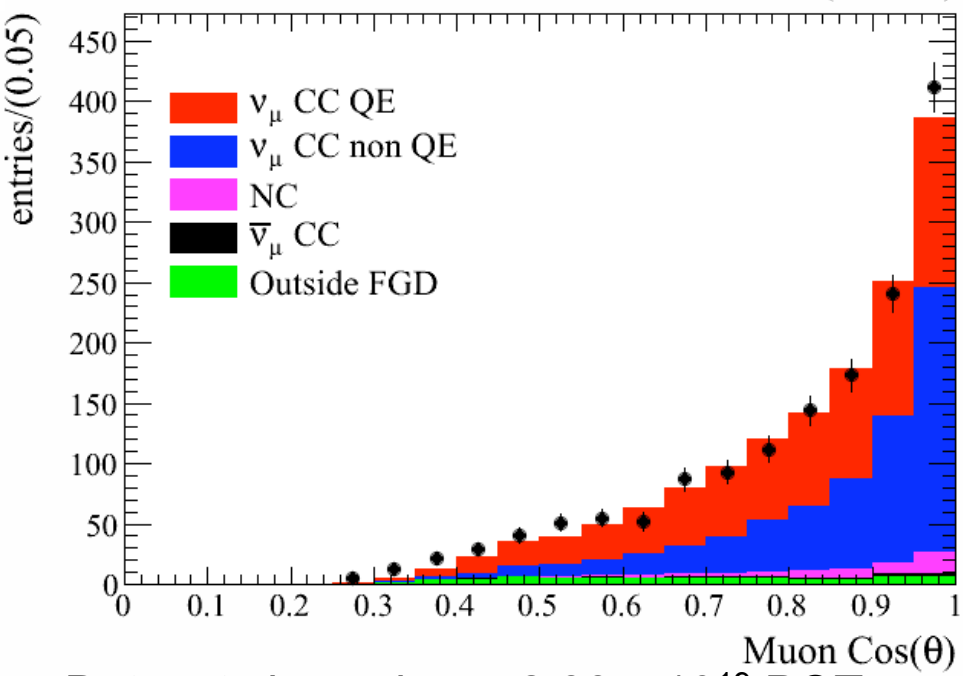
Basic CC ν_μ selection in ND280



1. Require no tracks in TPC1 (veto P0D, sand ν interactions)
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

ND280 CC ν_μ sample





Dataset shown here: 2.88 x 10^{19} POT

Reconstructed momentum and angle of the CC ν_μ candidates after selection

- CC ν_μ purity: 91%
- CCQE purity: 49%

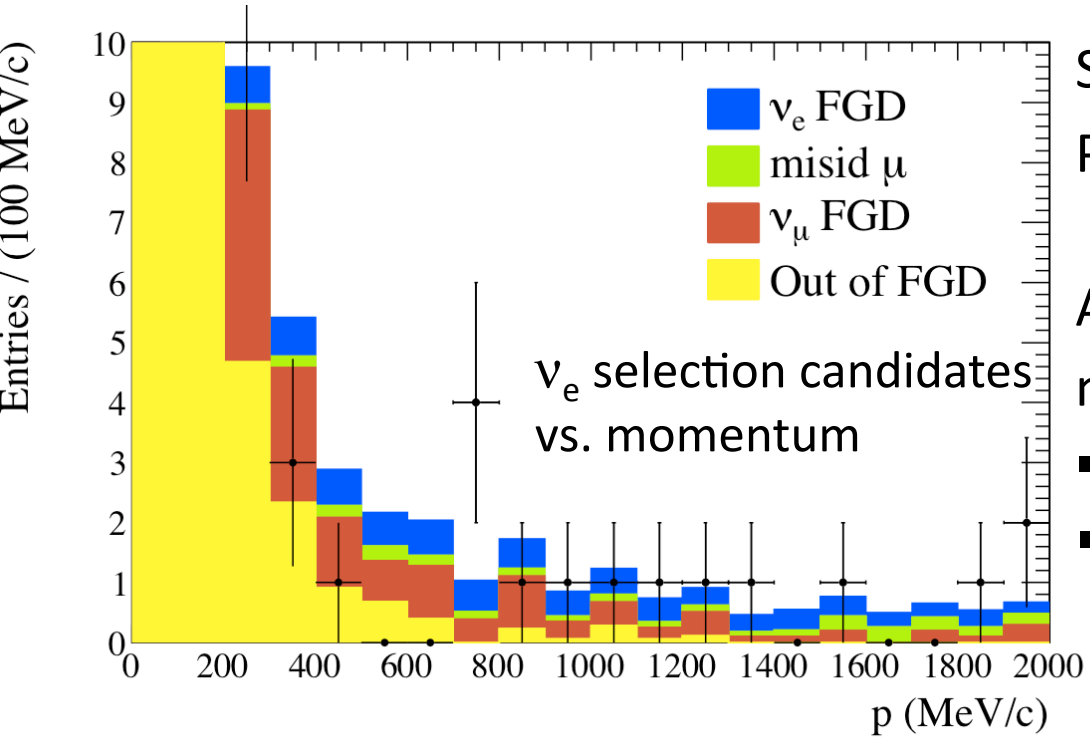
No tuning to flux or cross section applied

R(data/MC) = 1.036 ± 0.028 (stat)
$^{+0.044}_{-0.037}$ (detector sys)
± 0.038 (xsec model)

Rate used to normalize expected number of events at far detector

Flux uncertainties on ν_e appearance analysis reduced by factor of 2 as a result

ND280 beam ν_e rate cross-check



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

$N(\nu_e)/ N(\nu_\mu) = R(e:\mu) = 1.0\% \pm 0.7\%$ (statistics) $\pm 0.3\%$ (systematics)
$R(e:\mu, \text{data}) / R(e:\mu, \text{MC}) = 0.6 \pm 0.4$ (statistics) ± 0.2 (systematics)

Improvements to the analysis:

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

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    2. Neutrino interactions
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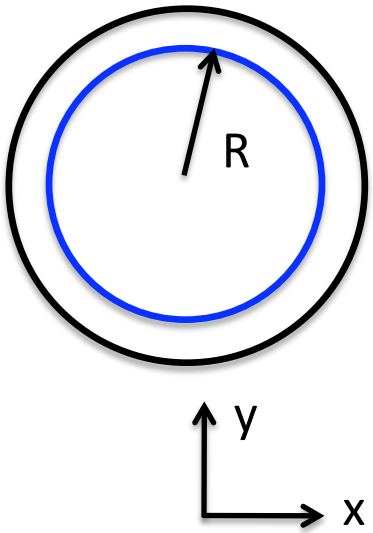
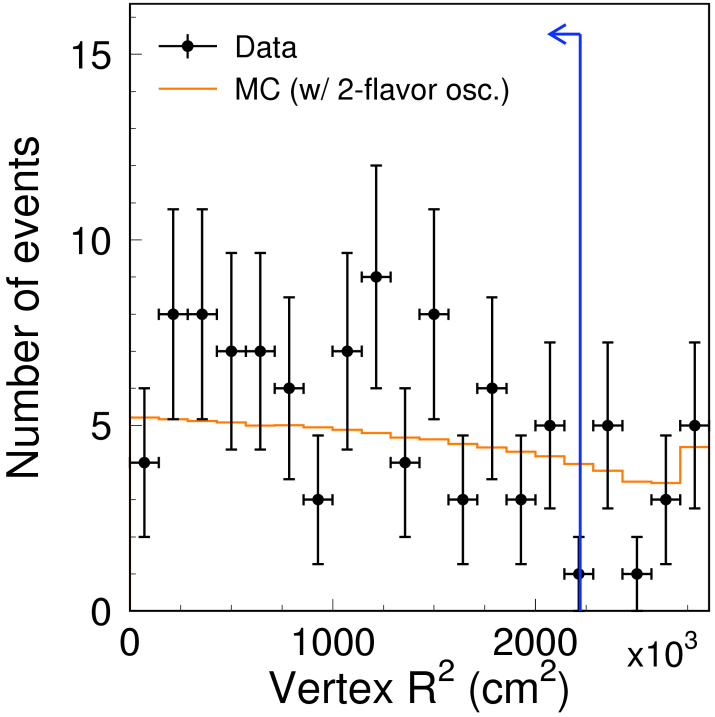
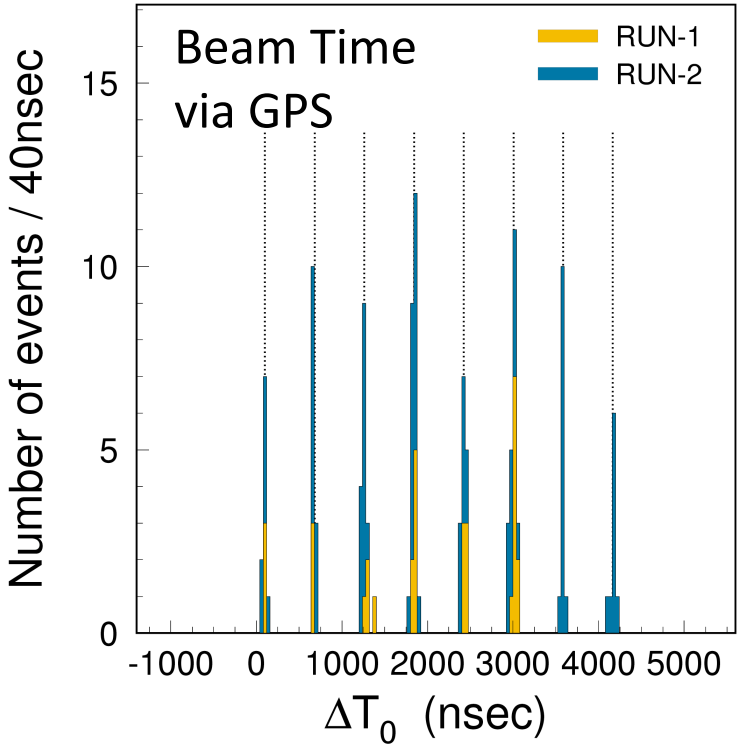
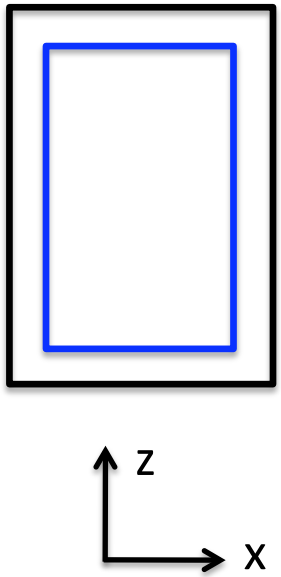
Basic neutrino event selection at Super-K

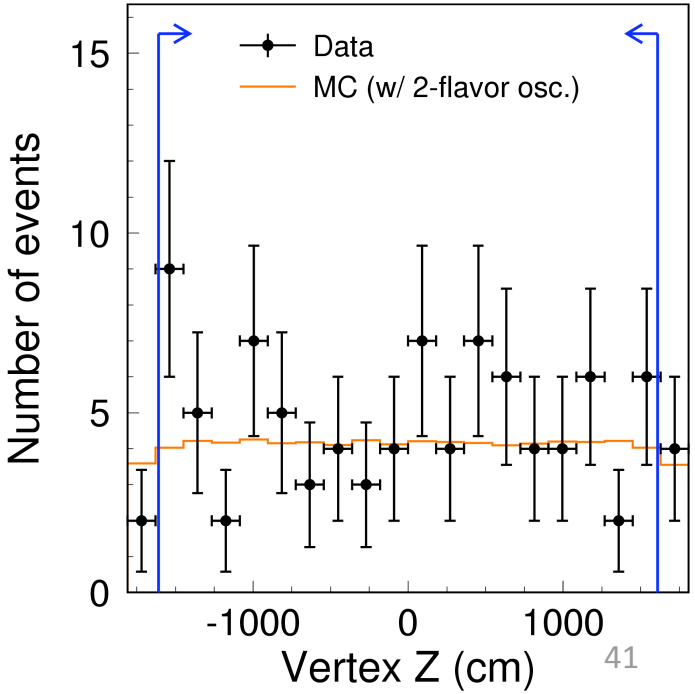
Basic neutrino selection (precuts)
Event time within beam window
No activity in the veto
Visible E > 30 MeV
Reconstructed vertex >2m from wall
Single reconstructed ring











Events are consistent with expectation

ν_μ and ν_e selection at Super-K

ν_μ selection
1. μ-like ring
2. p_μ >200MeV/c
3. 0 or 1 decay electron

Signal CCQE ν_μ Efficiency = 72%
Background CCnonQE Rejection = 79%

1. Select muon-like ring (CC ν_μ)
2. Sufficient momentum for μ PID
3. Reject CC1π with decay electron cut
   - CCQE: $\mu \rightarrow e$
   - CC1π: above plus $\pi \rightarrow \mu \rightarrow e$

ν_e selection
1. Visible energy > 100 MeV
2. e-like ring
3. No decay electron
4. Invariant mass < 105 MeV/c^2
5. Eν <1250 MeV

Signal ν_e Efficiency = 66%
Background Rejection:
- 77% for beam ν_e
- 99% for NC

1. Energy above μ, $\pi \rightarrow e$, $n \rightarrow \gamma$ threshold
2. Select electron-like ring (CC ν_e)
3. Reject CC ν_μ with decay electron cut
4. Remove NCπ^0 background events
   - Calculate invariant mass assuming 2nd ring
   - Reject invariant mass consistent with π^0
5. Beam CC ν_e have higher average energy than signal CC ν_e

Super-K selection uncertainties

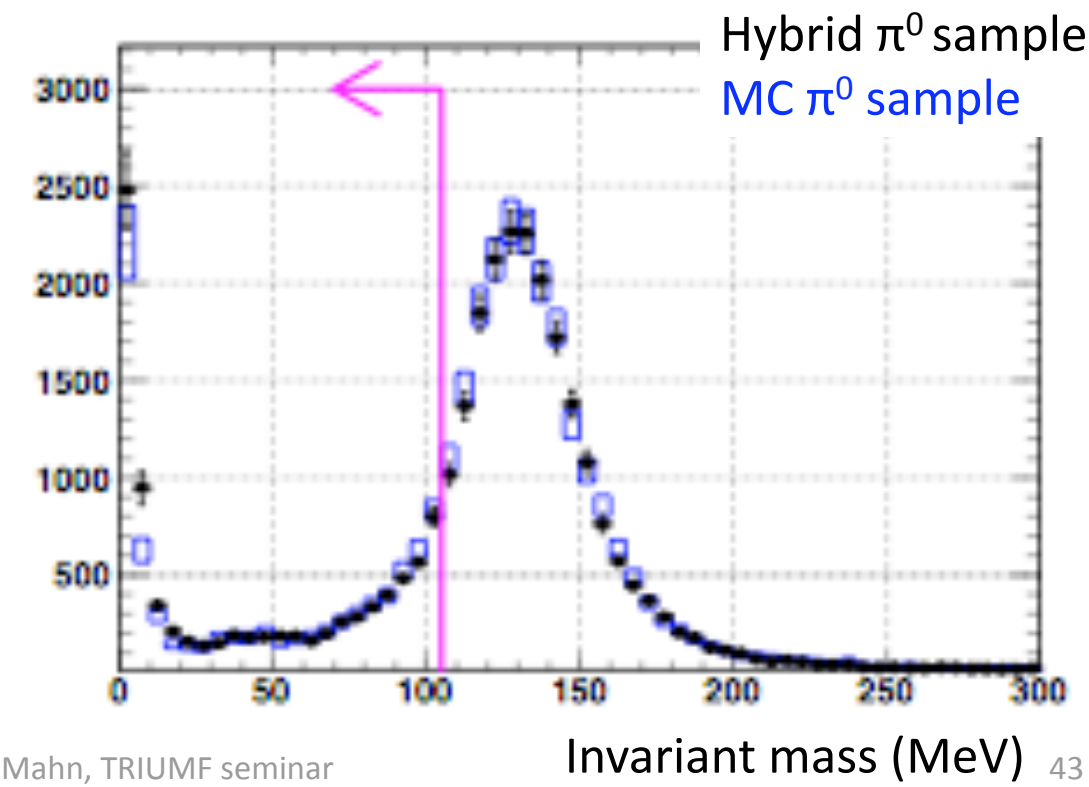
Error source	ν_e signal	ν_e bkgd
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass	5.1%	8.7%
π^0 rejection	-	3.6%
Fiducial volume	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron eff	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

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
- 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



Outline

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2. Overview of the T2K experiment
3. Data collected by T2K
4. Oscillation analysis strategy
    1. Neutrino flux
    2. Neutrino interactions
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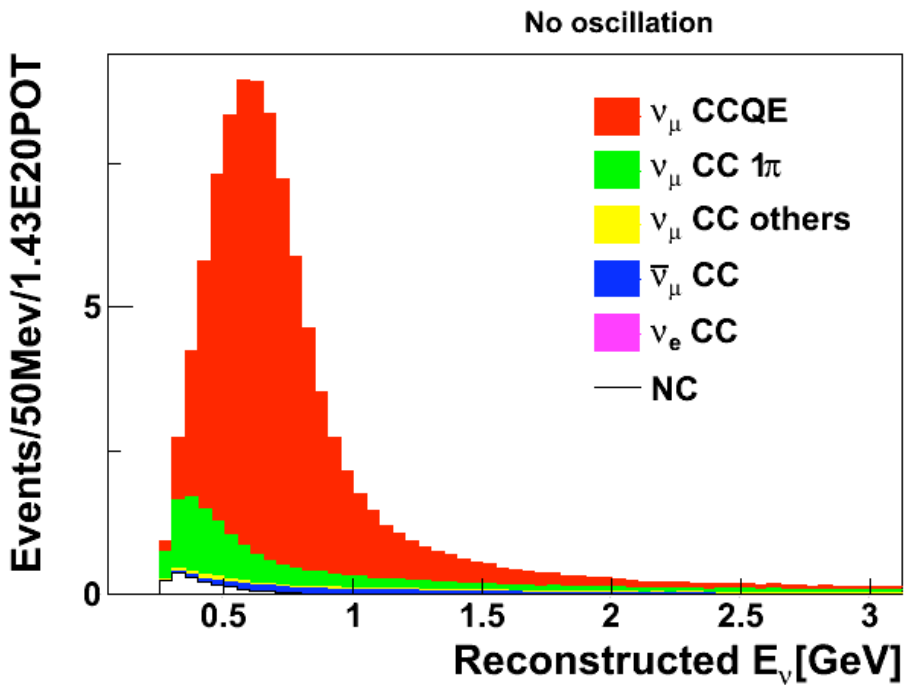
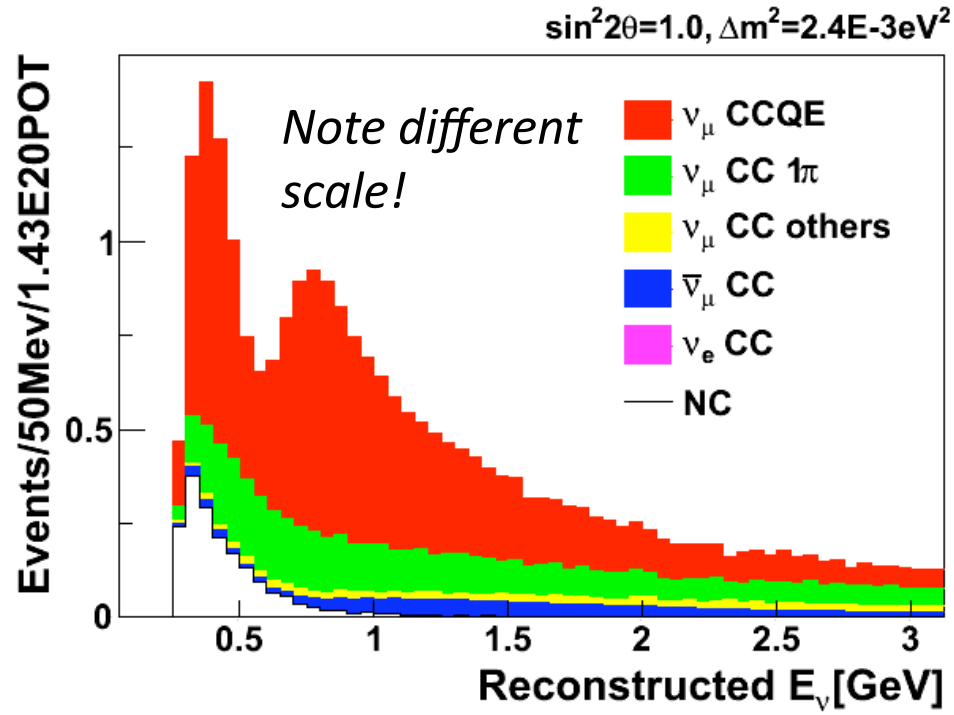
ν_μ disappearance at T2K

For a fixed baseline (L=295km) oscillation probability is different for neutrinos of different energies

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





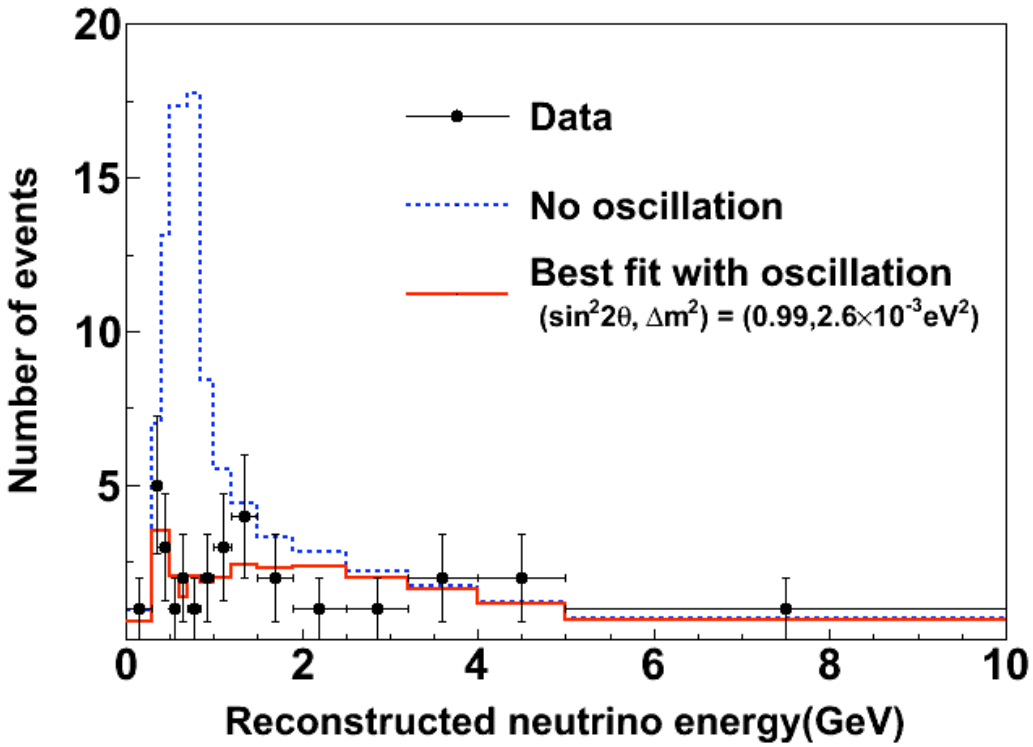
Reconstruct neutrino energy from outgoing muon kinematics assuming QE interaction:

$$E_\nu^{QE} = \frac{2M'_n E_\mu - [M'^2_n + m^2_\mu - M^2_p]}{2[M'_n - E_\mu + p_\mu \cos\theta_\mu]}$$

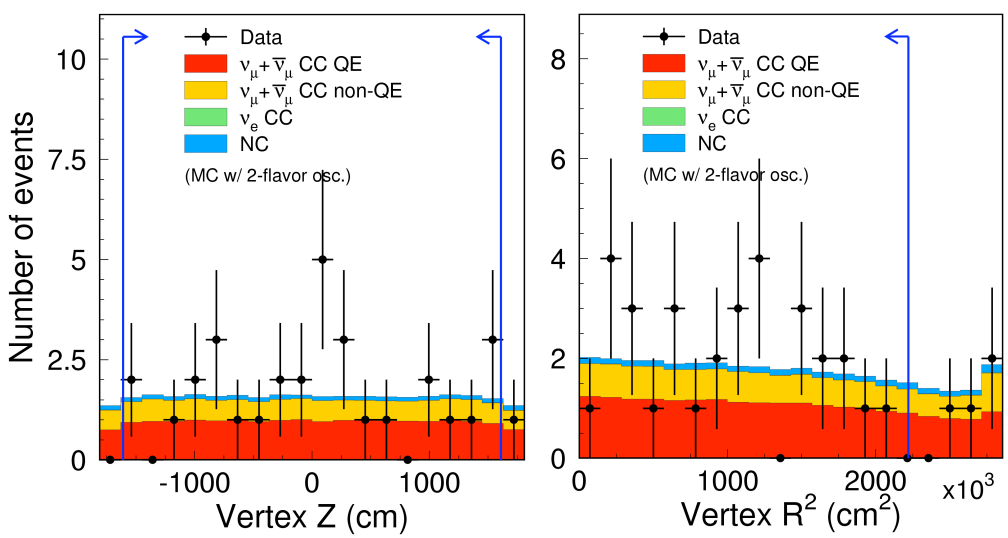
Extract Δm^2, $\sin^2 2\theta_{23}$ from observed change in overall rate and spectrum

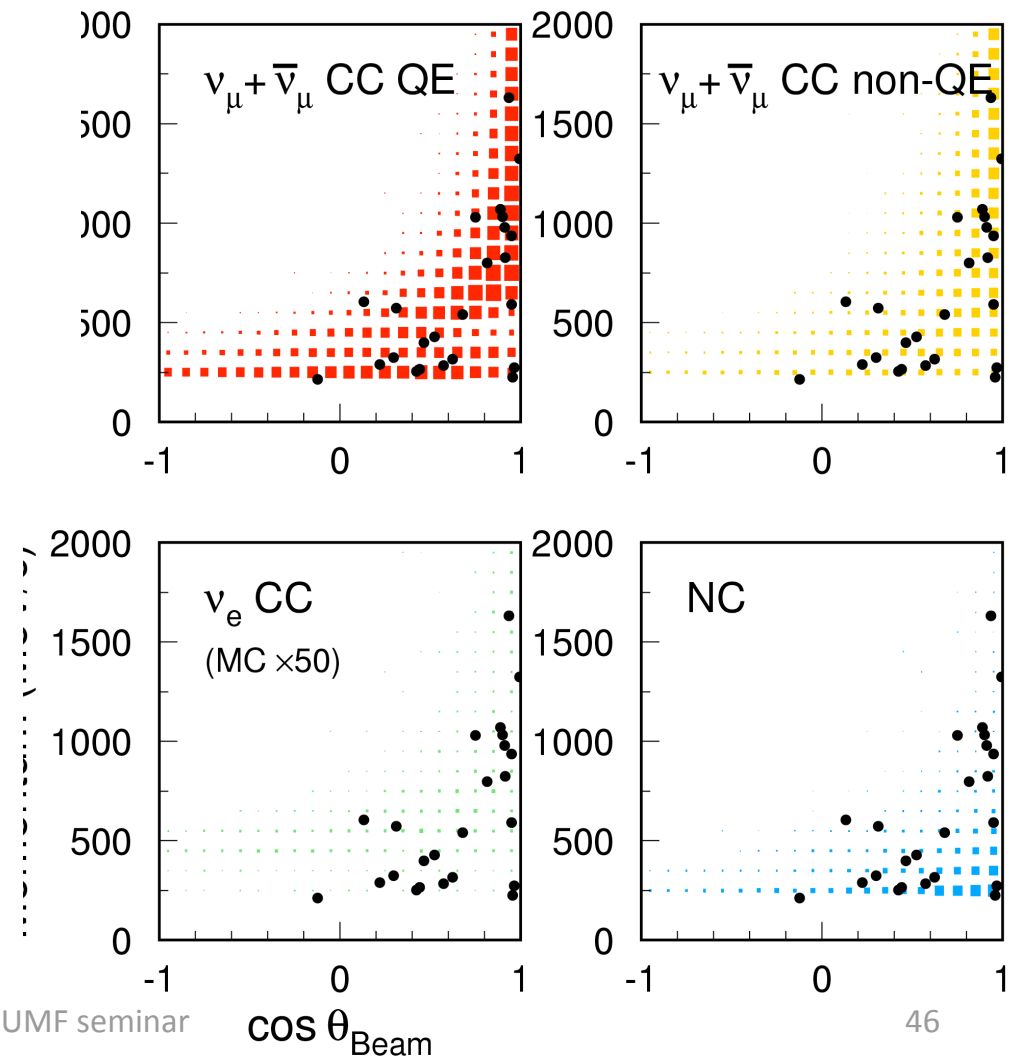
Backgrounds are events where pion is unobserved (absorbed) or mistaken for muon

ν_μ disappearance results



31 events pass ν_μ selection criterion;
$103.7^{+16.6}_{-16.2}$ expected with
no oscillations is excluded at 4.5σ
No clustering in momentum, angle, radius
according to background





ν_μ disappearance results

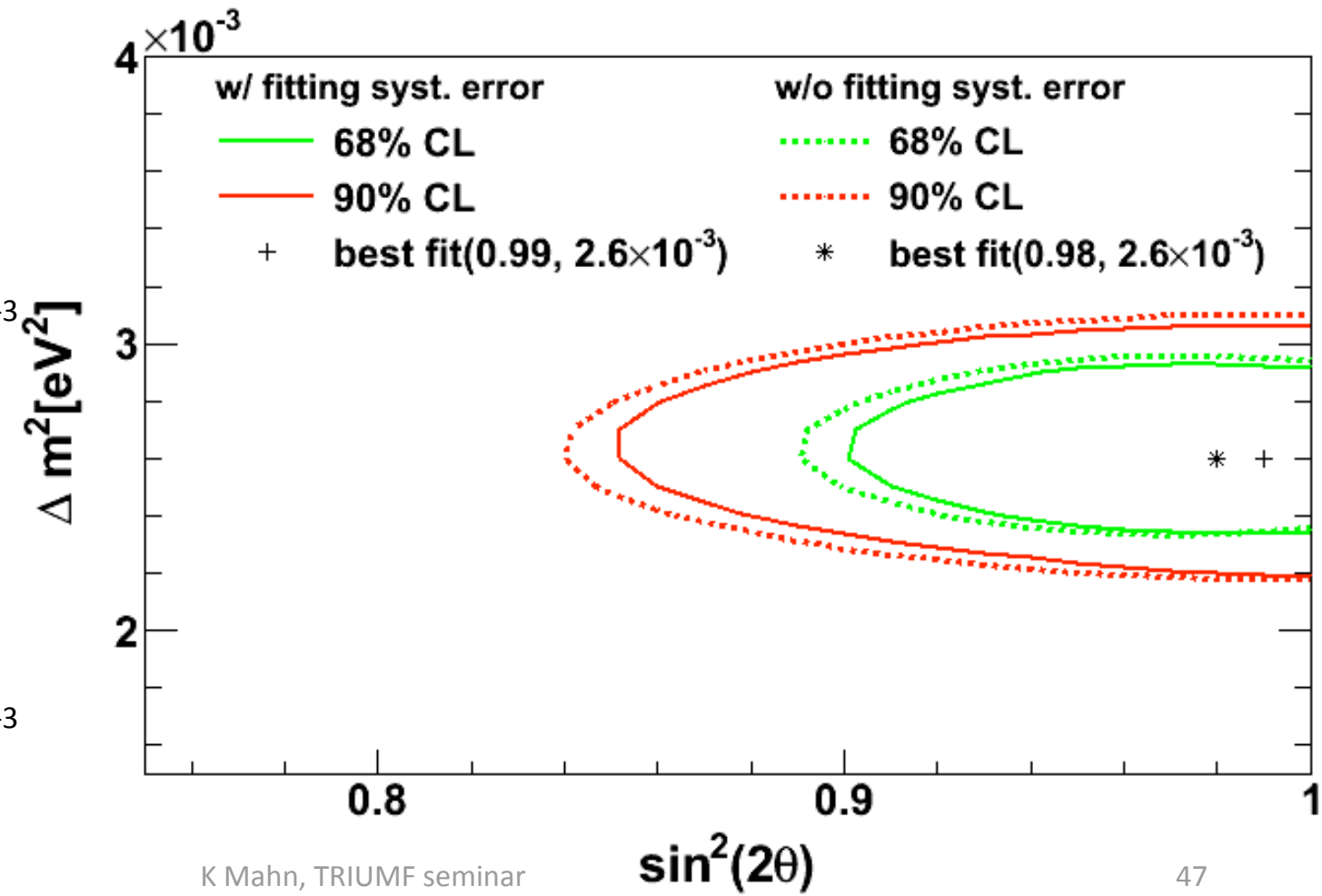
Two independent, 2 flavor, oscillation fits are consistent

- Method A: Maximum likelihood fit to normalization, spectrum shape, systematic parameters constrained in fit
- Method B: χ^2 minimization fit over binned energy spectrum

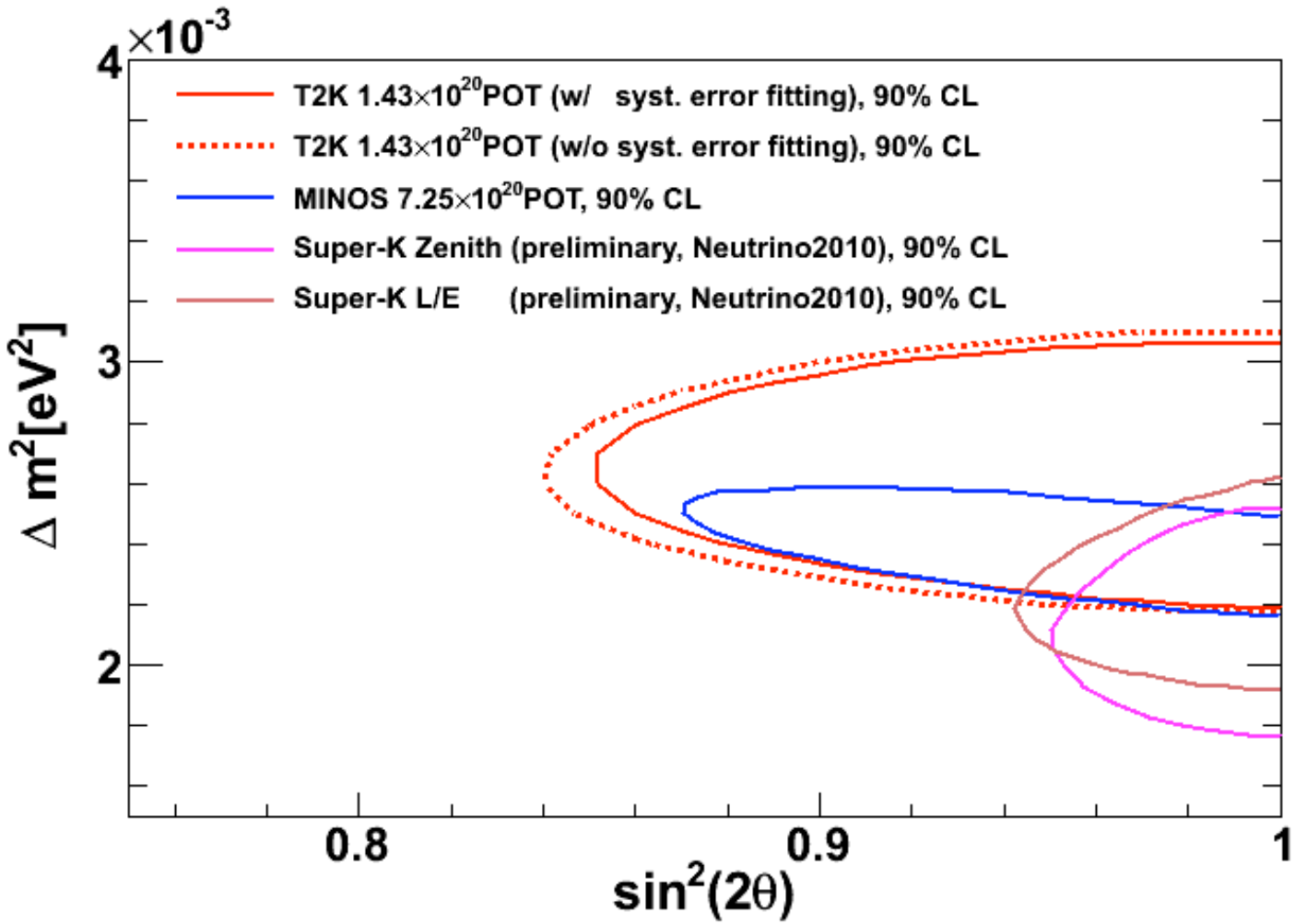
Both use Feldman-Cousins unified method to determine confidence intervals

<u>Method A (solid)</u>
Best fit: $\sin^2 2\theta_{23} = 0.99$,
$|\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV^2
90%CL: $\sin^2 2\theta_{13} > 0.85$
$2.1 < |\Delta m^2| (\text{eV}^2) < 3.1 \times 10^{-3}$

<u>Method B (dashed)</u>
Best fit: $\sin^2 2\theta_{23} = 0.98$,
$|\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV^2
90%CL: $\sin^2 2\theta_{13} > 0.84$
$2.1 < |\Delta m^2| (\text{eV}^2) < 3.1 \times 10^{-3}$



Comparison to previous results



Consistent with previous measurements of ν_μ disappearance (MINOS, Super-K)

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6. ν_e appearance results
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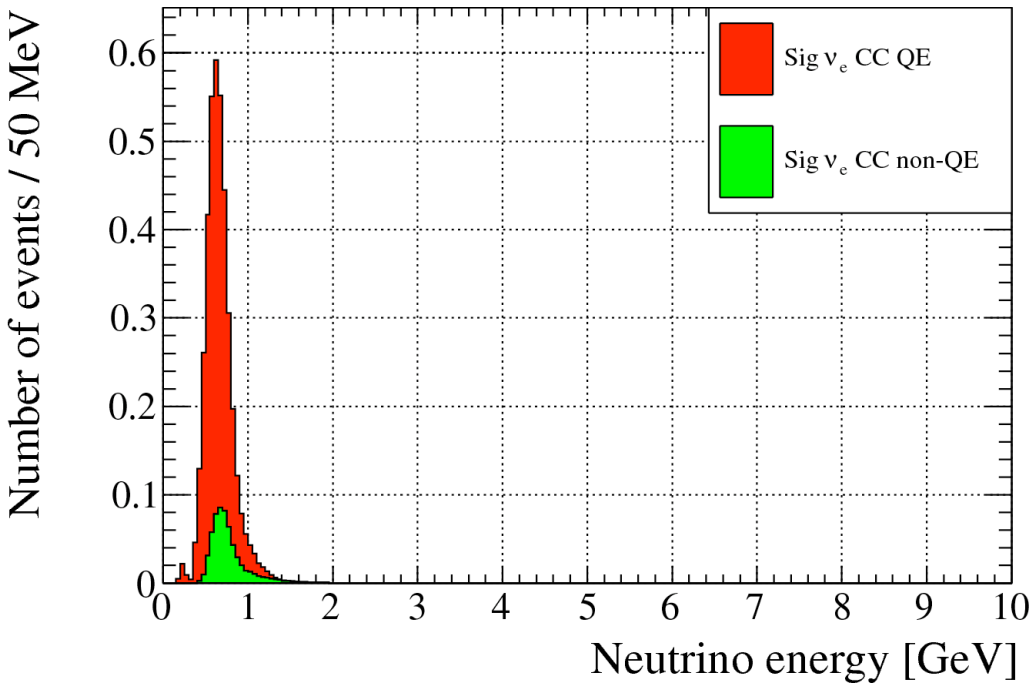
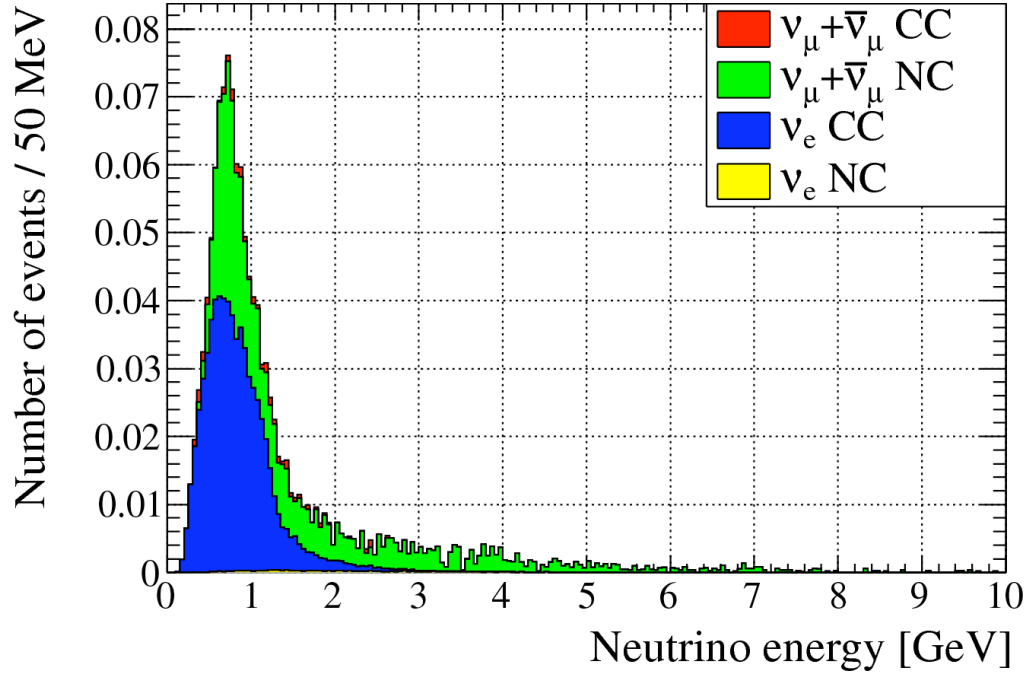
8. Future determination of θ_{13} (and CP violation?)

ν_e appearance at T2K

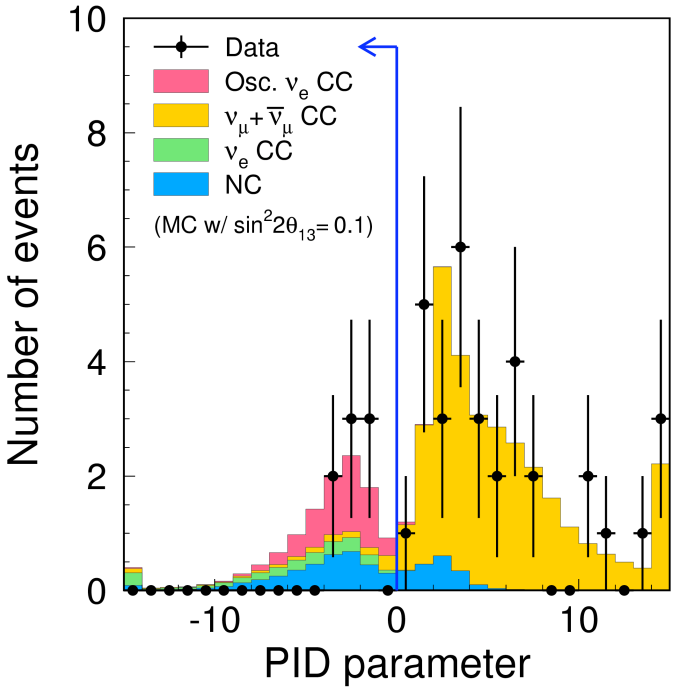


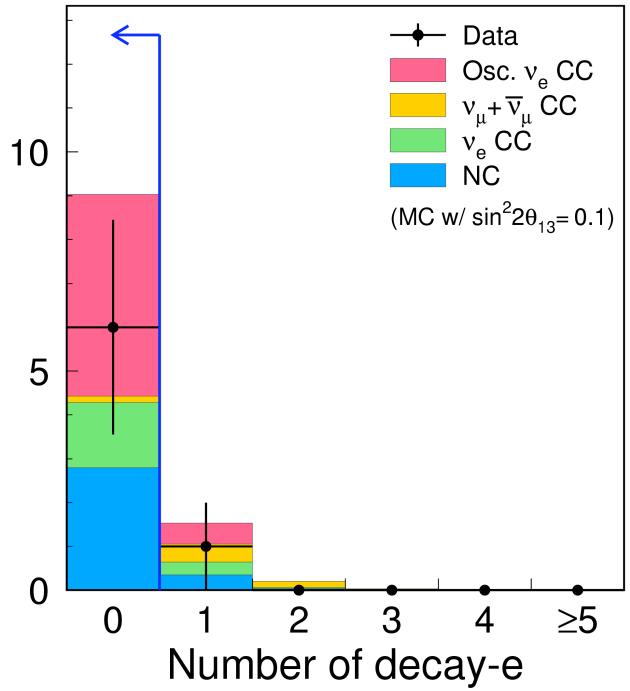


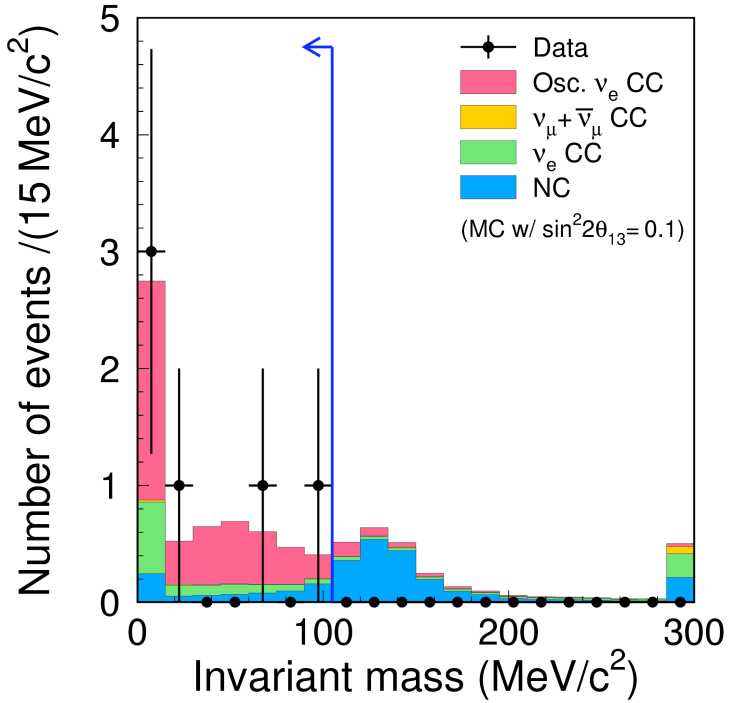
Signal (ν_μ to ν_e osc)	# events
@$\sin^2 2\theta_{13}$=0.1,δcp=0	4.11

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 events after cuts

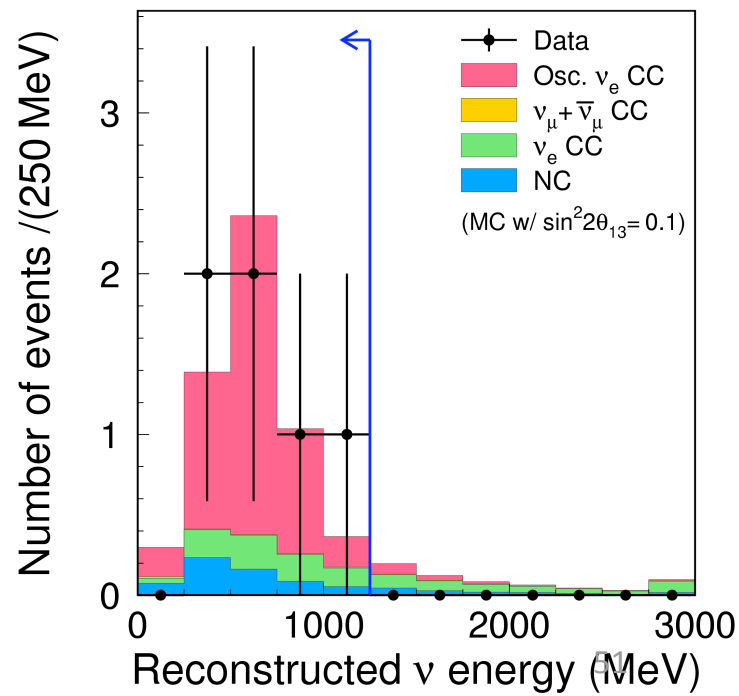






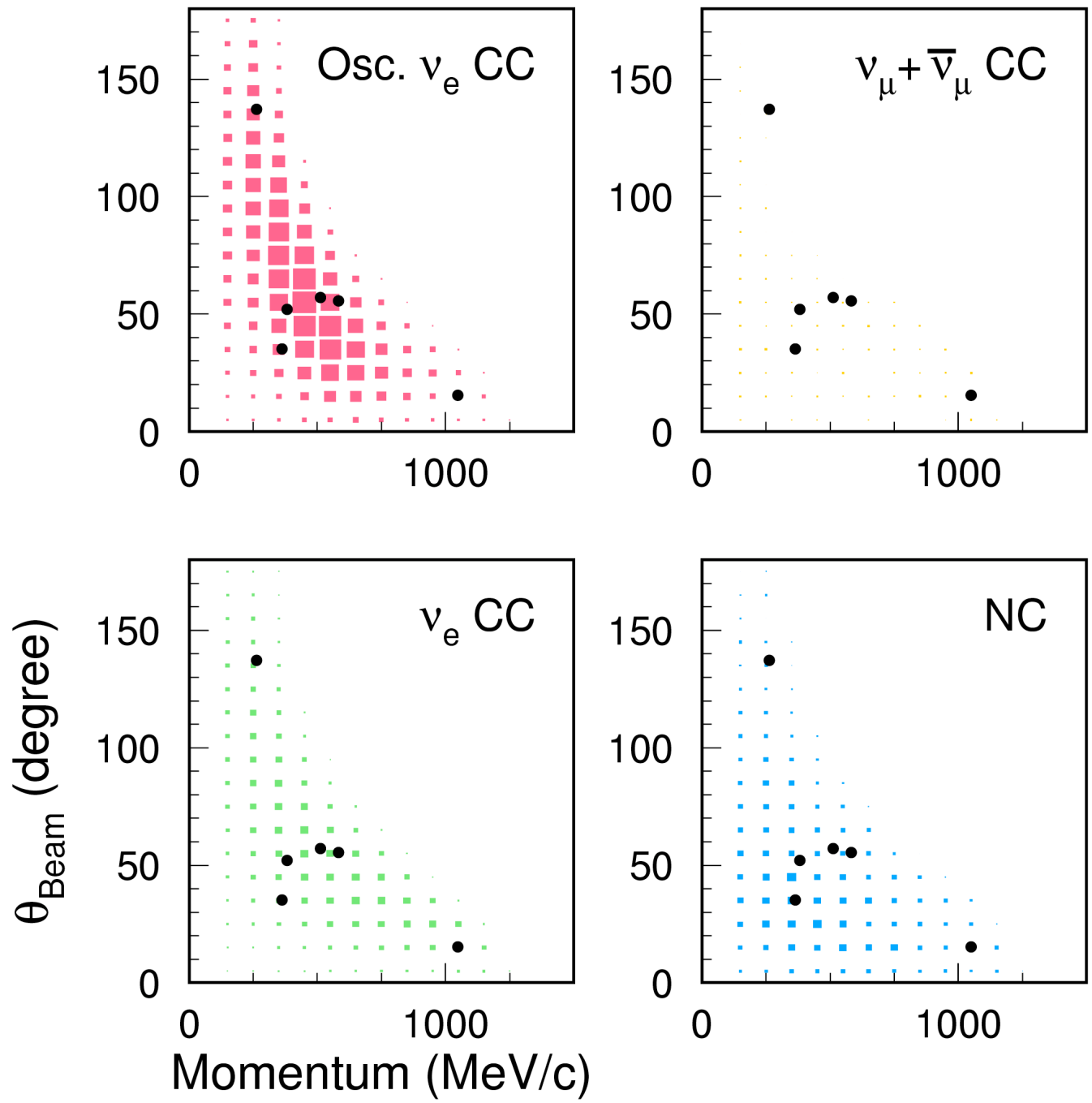
ν_e selection
Visible energy > 100 MeV
e-like ring
No decay electron
Invariant mass < 105 MeV/c^2
Eν <1250 MeV

6 candidate events observed for background of 1.49 ± 0.34

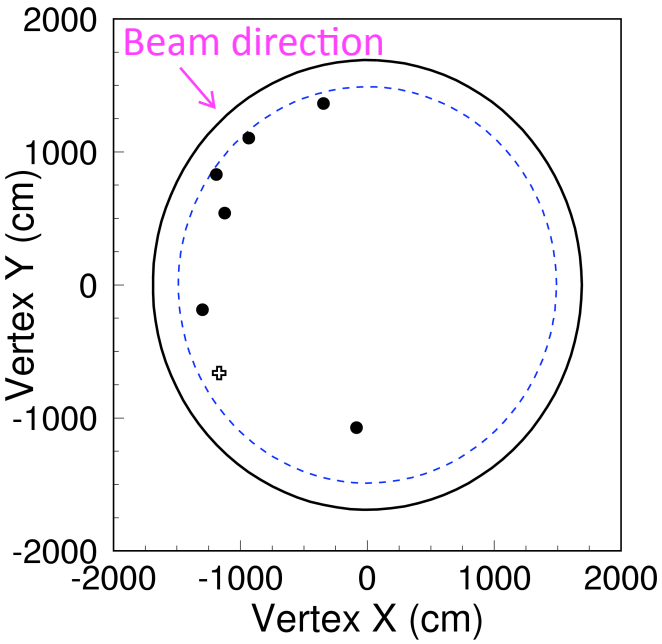


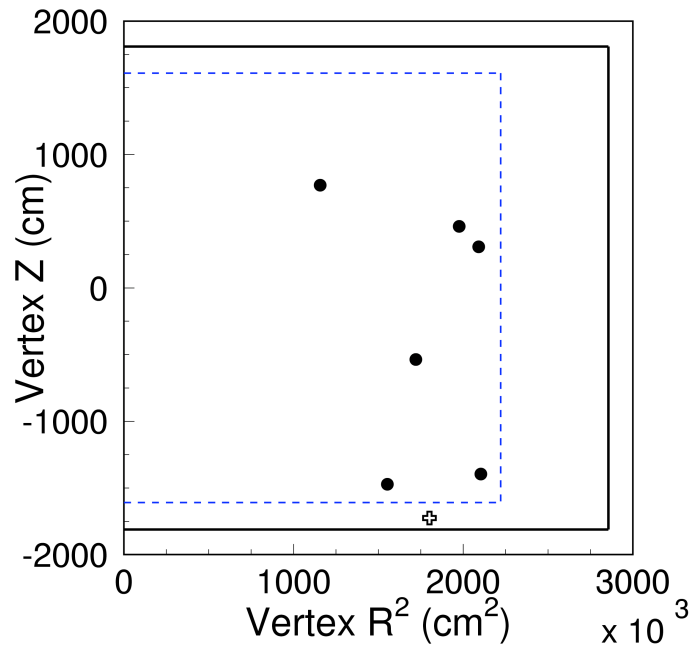
Basic distributions of ν_e candidates

Momentum, angle with respect to beam direction distributions are reasonable



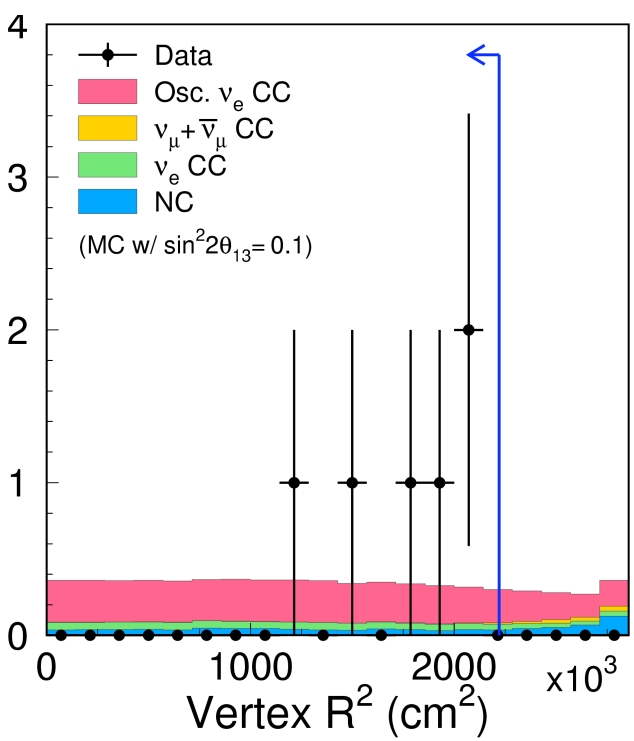
Basic distributions of ν_e candidates

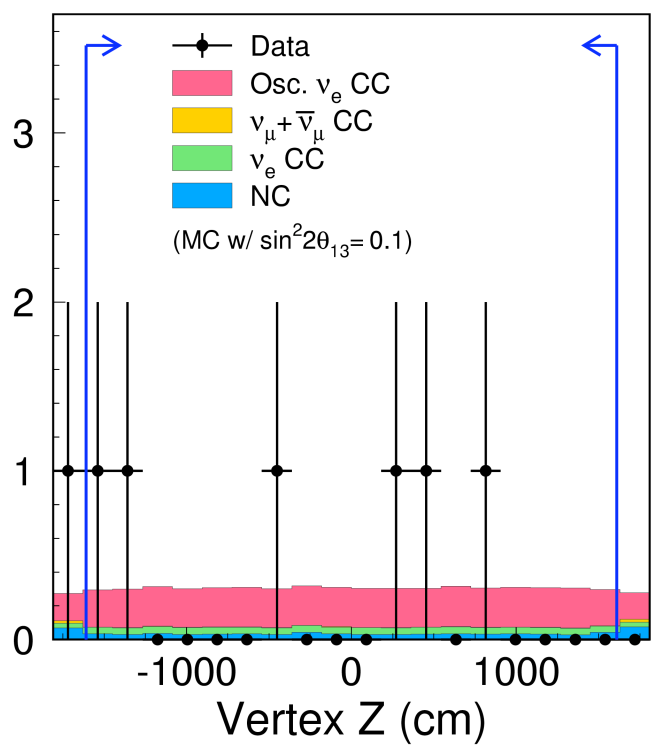




Clustering of candidates at high R in beam direction

KS test of R^2 variable is 3% (does not include beam dir)

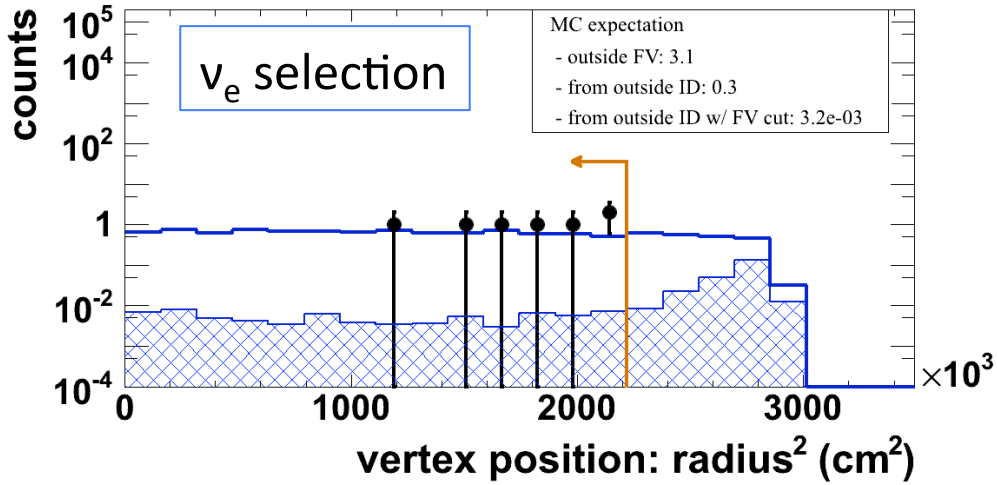


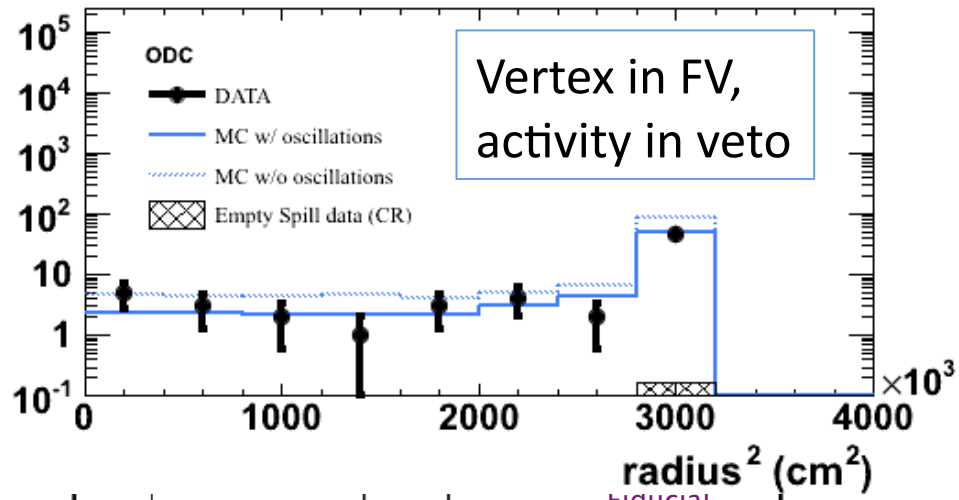


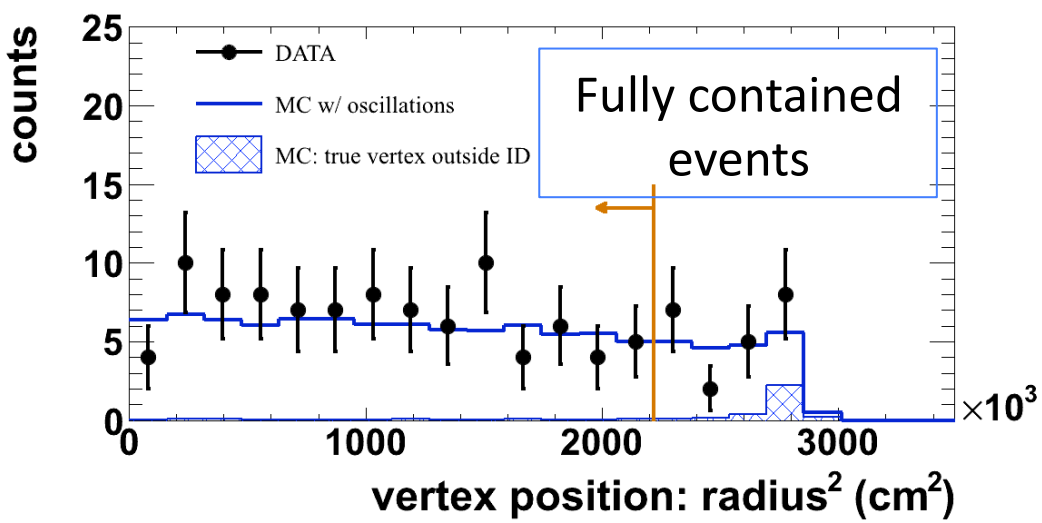
Beam backgrounds at high radius

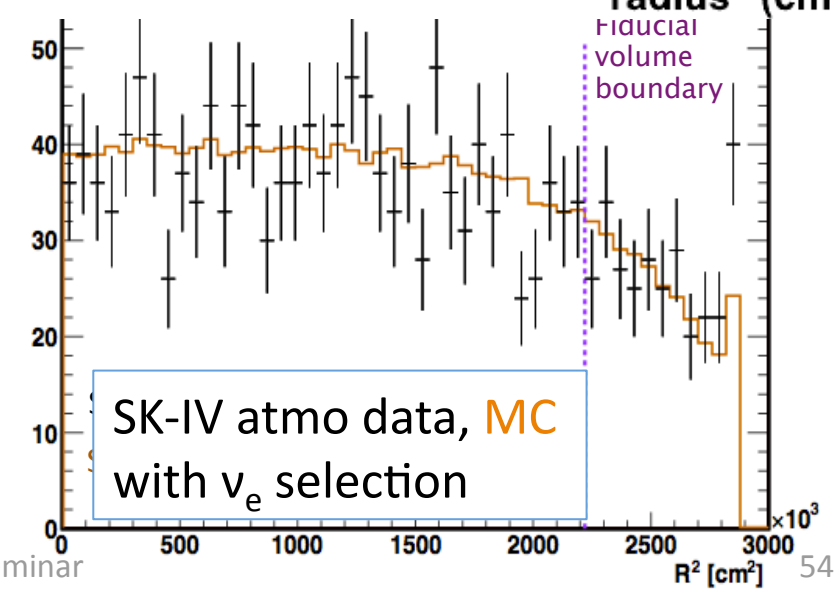
MC simulates neutrino interactions upstream of the detector (e.g. π^0 production)

- 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

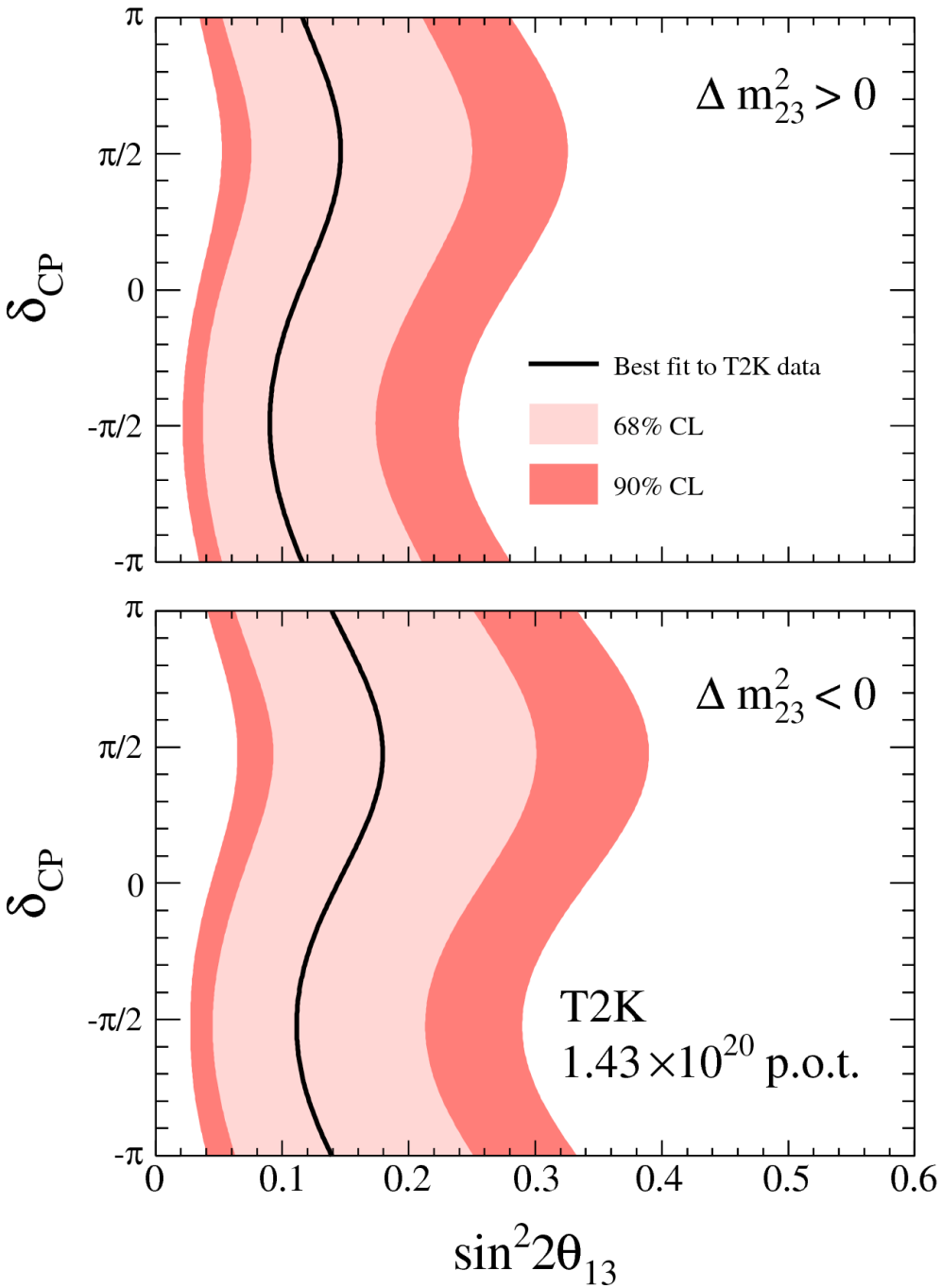








ν_e appearance interpretation



Probability to see 6 events or more for for $\sin^2 2\theta_{13}=0$ is 0.007 (2.5σ equivalent)

Feldman-Cousins unified method
For $|\Delta m^2_{23}|=2.4 \times 10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1$

<u>Normal hierachy ($\Delta m^2 > 0$), $\delta cp=0$</u>
best fit $\sin^2 2\theta_{13} = 0.11$
$0.03 < \sin^2 2\theta_{13} < 0.28$ at 90% C.L.

<u>Inverted hierachy ($\Delta m^2 < 0$), $\delta cp=0$</u>
best fit $\sin^2 2\theta_{13} = 0.14$
$0.04 < \sin^2 2\theta_{13} < 0.34$ at 90% C.L.

Phys. Rev. Lett. 107, 041801 (2011)

Excitement in the press

BBC Mobile | News | Sport | Weather | Travel

NEWS SCIENCE & ENVIRONMENT

June 15th 2011

Neutrino particle 'flips to all flavours'

June 23rd 2011

The Economist

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World politics | Business & finance | Economics | Science & technology | Culture | Blogs | Debate

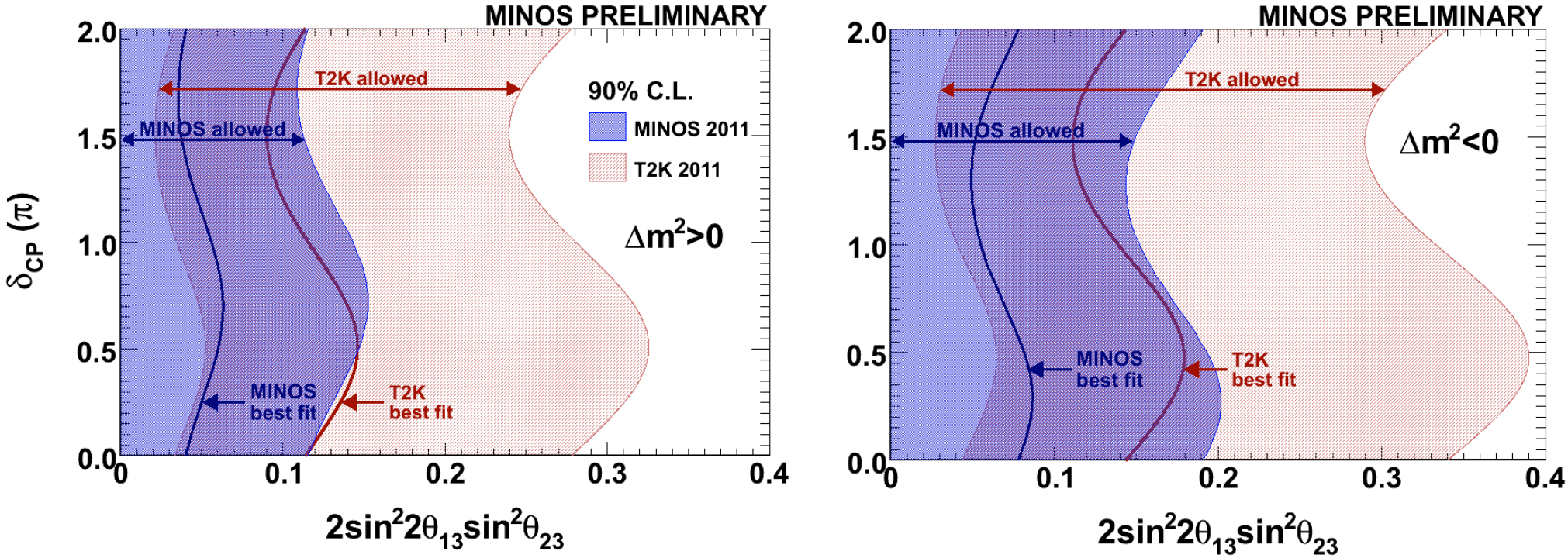
All Science & technology | Technology Quarterly

Neutrinos

Delta force

A study of neutrinos may explain why things are made of matter, not antimatter

Comparison with new results from MINOS



L. Whitehead, Fermilab Wine and Cheese:
http://theory.fnal.gov/jetp/talks/MINOSNue_2011June24.pdf

MINOS produced updated ν_e appearance results two weeks after T2K

Overlay (not combined fit) of results indicates consistency

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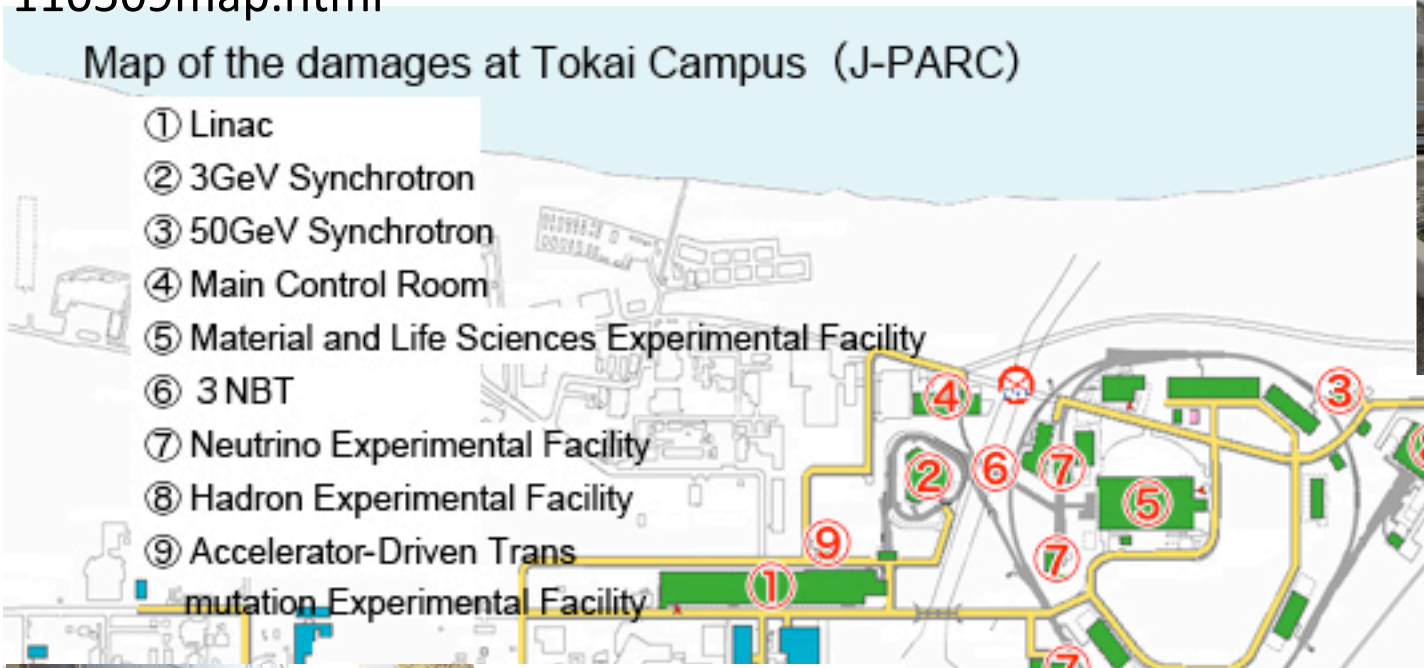
Pictures of JPARC, May 2011

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




3 GeV synchrotron power station


Road near 3 GeV RCS


LINAC

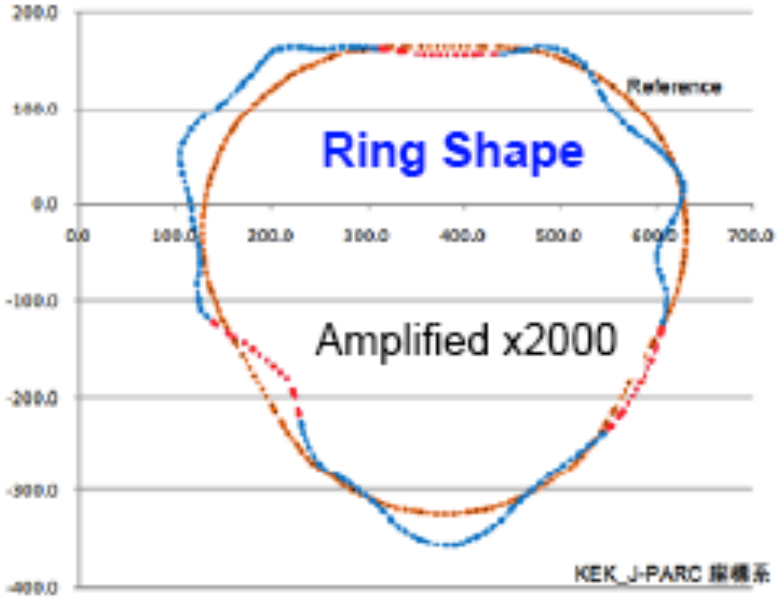

Neutrino Hall AC

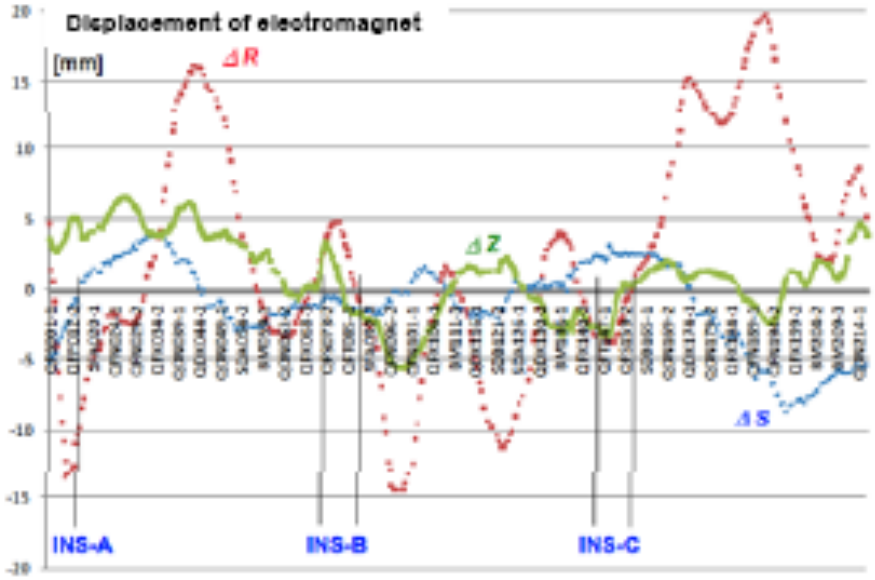

Neutrino beam dump

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

Near term plan for T2K

Plan is to resume experiment to make a determination of θ_{13}, nonzero or not

- Accelerator is scheduled to resume in December
- Neutrino facility (near detector and beamline) are scheduled to be ready in November
- ND280 detectors were recommissioned and are operational
- 3rd horn was moved to remote handling cell and is OK

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

がんばれ、日本!

Keep it up, Japan!

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 Δm^2_{23} =2.4 x 10^{-3} 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; P0D HE ν_e
- CCQE, CCπ^+, NCπ^0 measurements; O vs. C

Super-K (far) detector:

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

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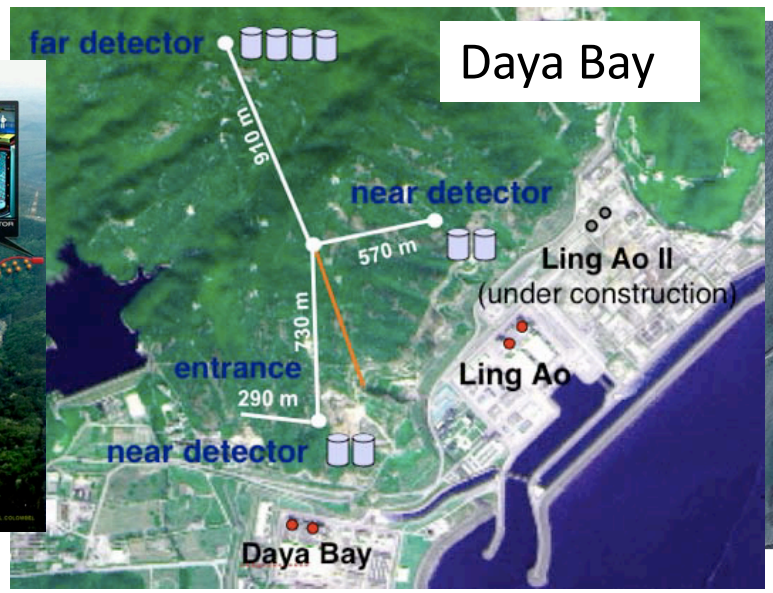
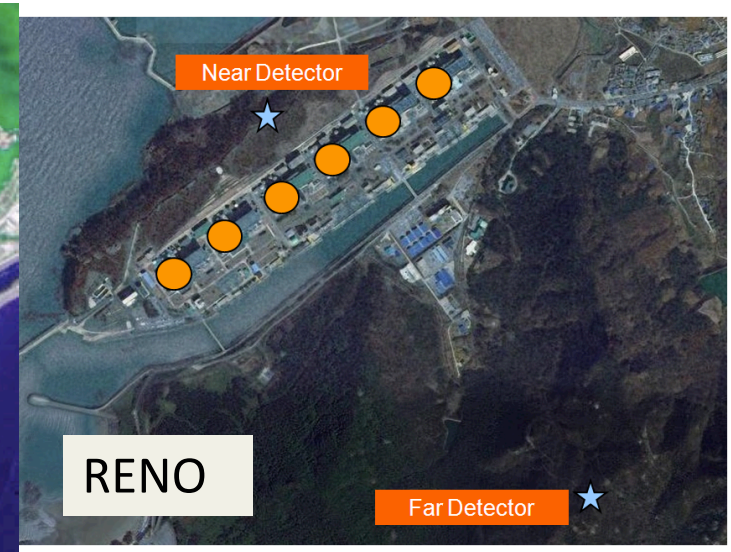
Other ways to measure θ_{13}

Measure θ_{13} with $\bar{\nu}_e$ disappearance from intense MW reactor sources

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

Use multiple detectors at different positions from reactor for a <1% measurement





Double Chooz is taking data with far detector since Dec 2010, near in 2012

Daya Bay detectors starts data taking this summer with near detector, all in 2012

Eventual sensitivity: $\sin^2 2\theta_{13} \sim 0.03 - 0.01$

Future measurements of δ_{CP}

Long baseline experiments (T2K second phase, LBNE) can extract δ_{CP} by comparing ν_e appearance to $\bar{\nu}_e$ appearance:

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

T2K creates a predominantly antineutrino beam by switching polarity of magnetic focusing horns to focus π^- instead of π^+

Can combine results from a reactor with T2K (ν mode) to constrain values of δ_{CP} as long baseline experiments depend on δ_{CP} and θ_{13}; reactors measure only θ_{13}
Int. J.Mod. Phys. A 21, 3825 (2006), hep-ex/0409028

Future long baseline experiments require very intense sources of neutrinos and or very large far detectors to make a determination of δ_{CP} at >3σ

Summary

The T2K experiment is designed to make precision measurements of:

- ν_μ disappearance (Δm^2_{23}, θ_{23})
- ν_e appearance (θ_{13})

With dataset prior to the earthquake:

- 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, expected background is 1.49 ± 0.34

T2K will resume running to establish if θ_{13} is nonzero or not, conclusively

- Neutrino facility (beam, near detectors) ready to operate by November
- Accelerator is scheduled to resume in December 2011

T2K leads an exciting worldwide program in precision neutrino physics:

- Is θ_{23} maximal?
- Is θ_{13} nonzero?
- Is there CP violation in the neutrino sector?

Backup slides

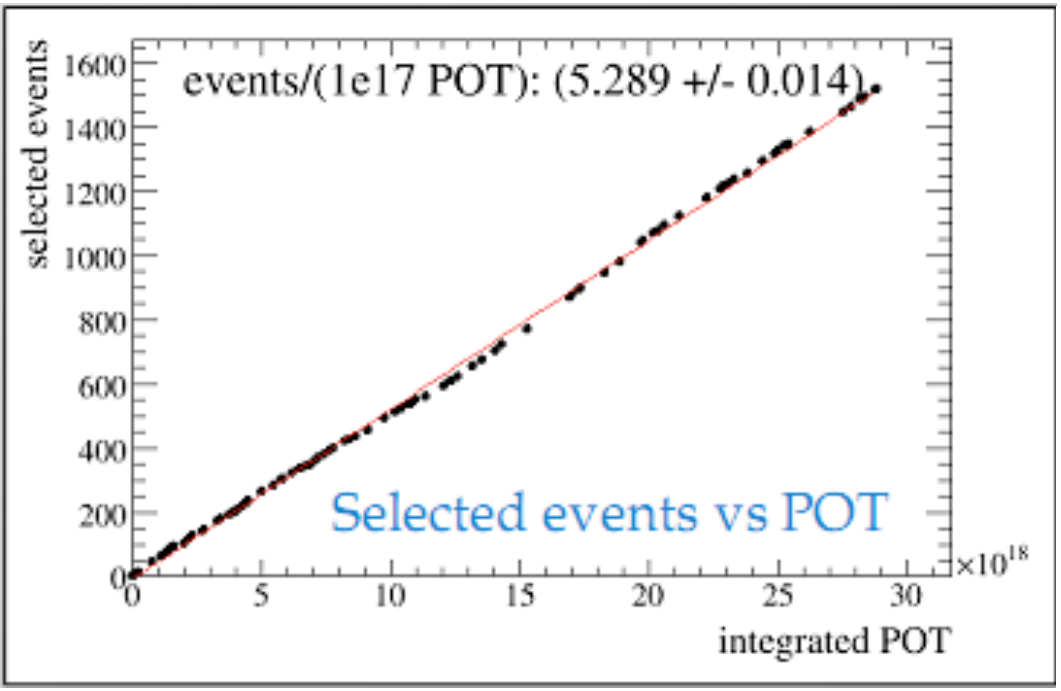
ND280 performance

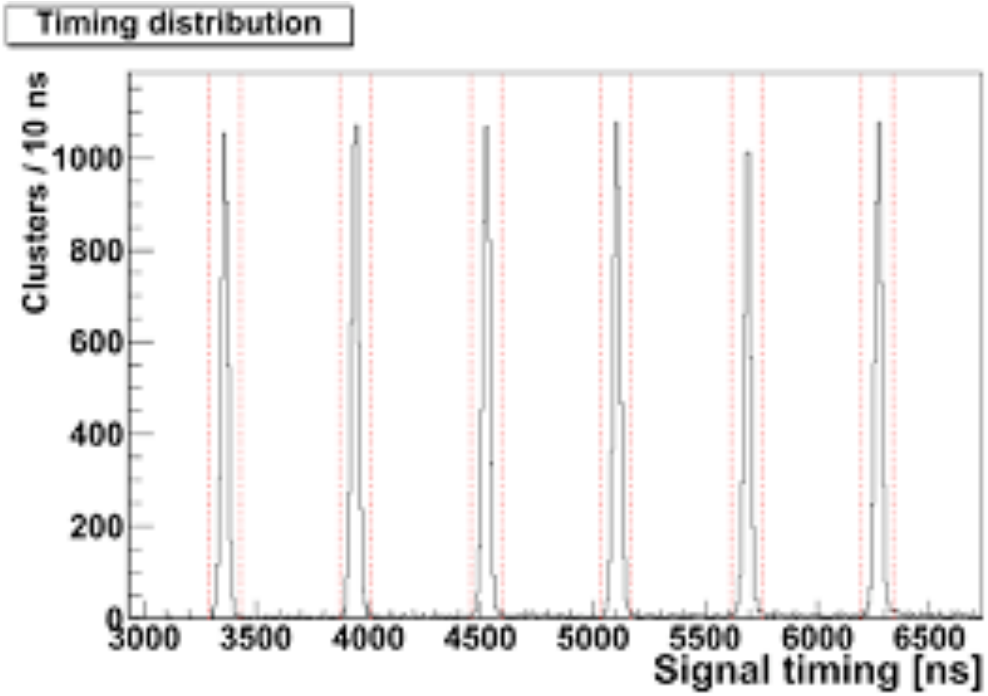
Low rate of broken channels

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%
P0D	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 (all cuts)

	Data	MC w/ 2-flavor oscillation					MC w/o osc.
		Total	ν_μCCQE	ν_μCC non-QE	ν_eCC	NC	
Interaction in FV	-	**141**	24.0	43.7	3.2	71.0	243
FCFV	**88**	**74.1**	19.0	33.8	3.0	18.3	166
Single-ring	**41**	**38.7**	17.9	13.1	1.9	5.7	120
μ-like	**33**	**32.0**	17.6	12.4	< 0.1	1.9	112
P_μ > 200 MeV/c	**33**	**31.8**	17.5	12.4	< 0.1	1.9	111
N(decay-e) ≤ 1	**31**	**28.4**	17.3	9.2	< 0.1	1.8	104
Efficiency	-	**20 %**	72 %	21 %	0.4 %	3 %	43 %

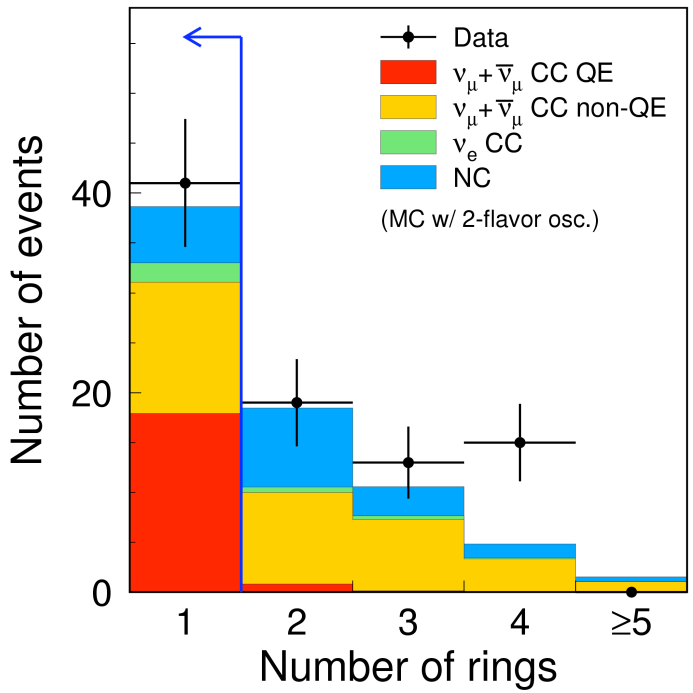
ν_μ selection

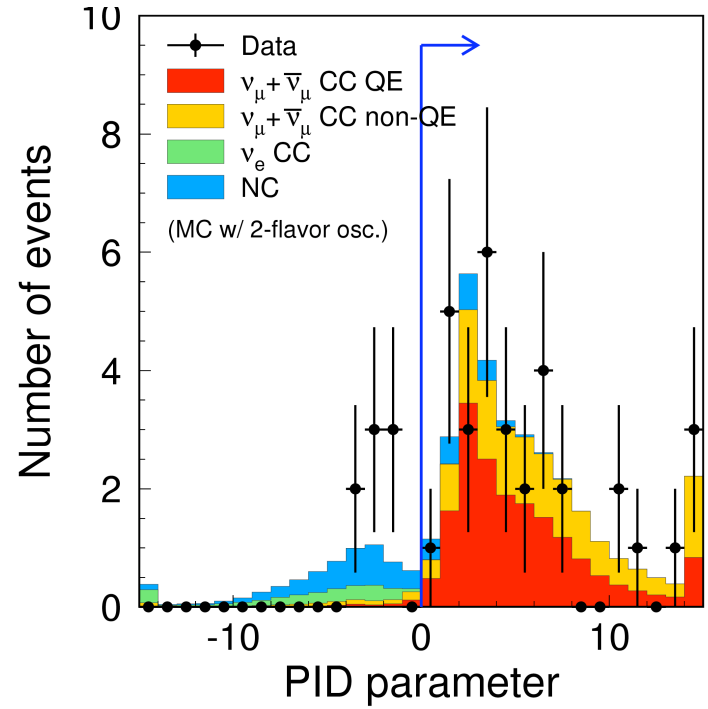
Single-ring

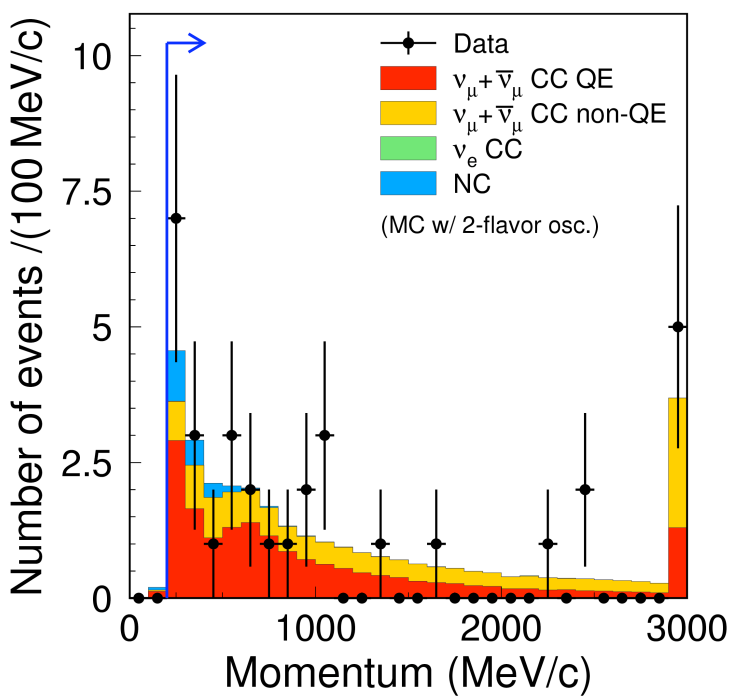
μ-like

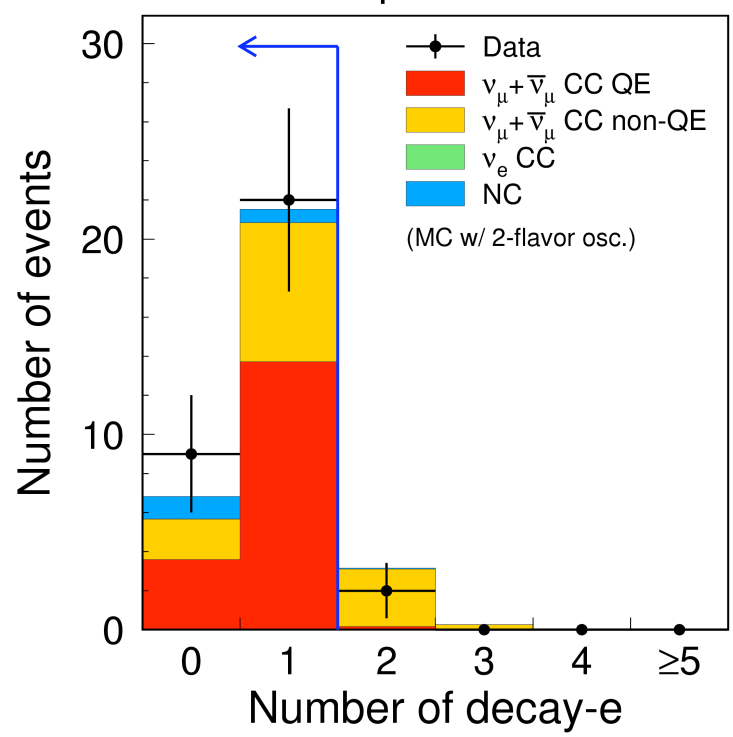
$P_\mu > 200$ MeV/c

N(decay-e) ≤ 1







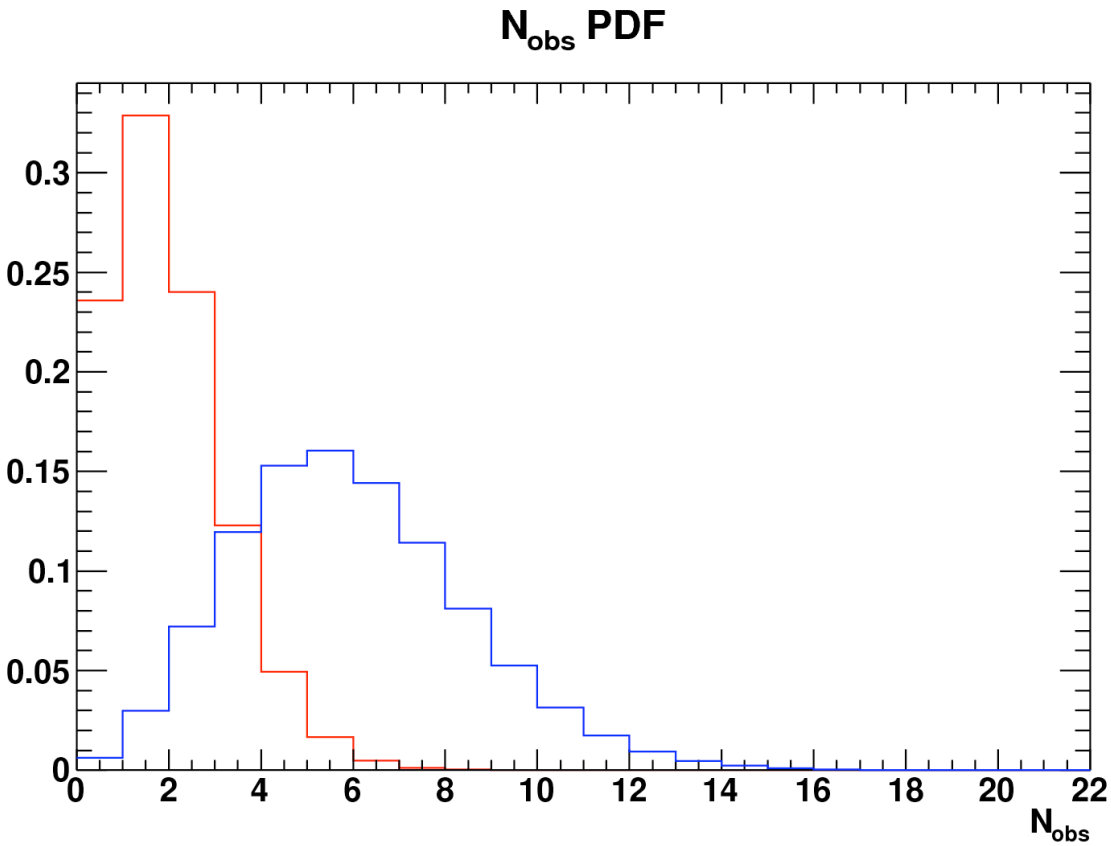


ν_e selection (all cuts)

	Data	BG expectation				$\nu_\mu \rightarrow \nu_e$ expect.
		Total	ν_μCC	ν_eCC	NC	
Interaction in FV	-	**141.3**	67.2	3.1	71.0	6.2
FCFV	**88**	**73.6**	52.4	2.9	18.3	6.0
Single-ring	**41**	**38.3**	30.8	1.8	5.7	5.2
e-like	**8**	**6.6**	1.0	1.8	3.7	5.2
E_{vis} > 100 MeV	**7**	**5.7**	0.7	1.8	3.2	5.1
No decay-e	**6**	**4.4**	0.1	1.5	2.8	4.6
M_{inv} < 105 MeV/c^2	**6**	**1.9**	0.04	1.1	0.8	4.2
E_ν^{rec} < 1250 MeV	**6**	**1.3**	0.03	0.7	0.6	4.1
Efficiency	-	**1 %**	< 0.1 %	23 %	1 %	66 %

ν_e appearance results

6 candidate events are observed

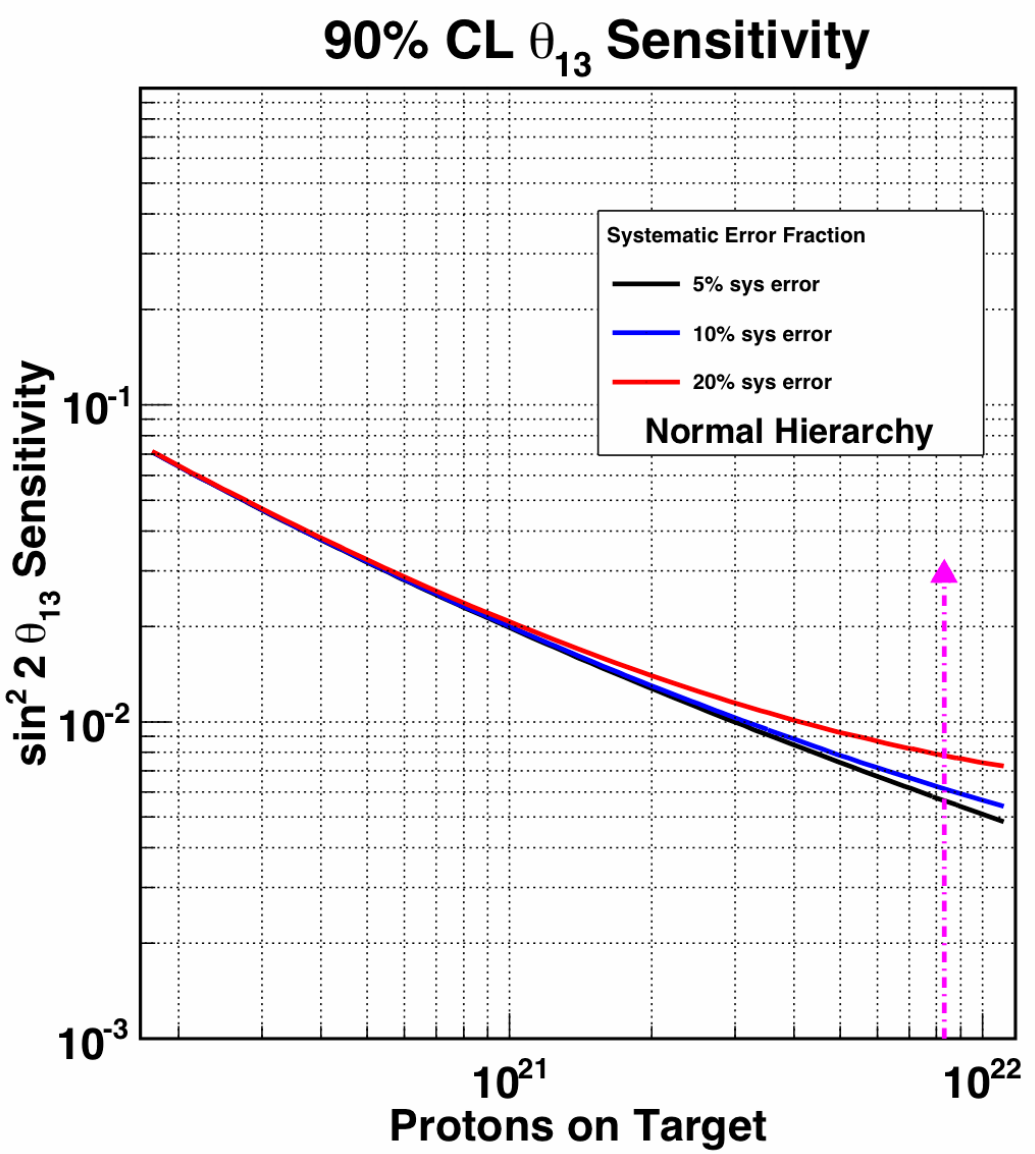


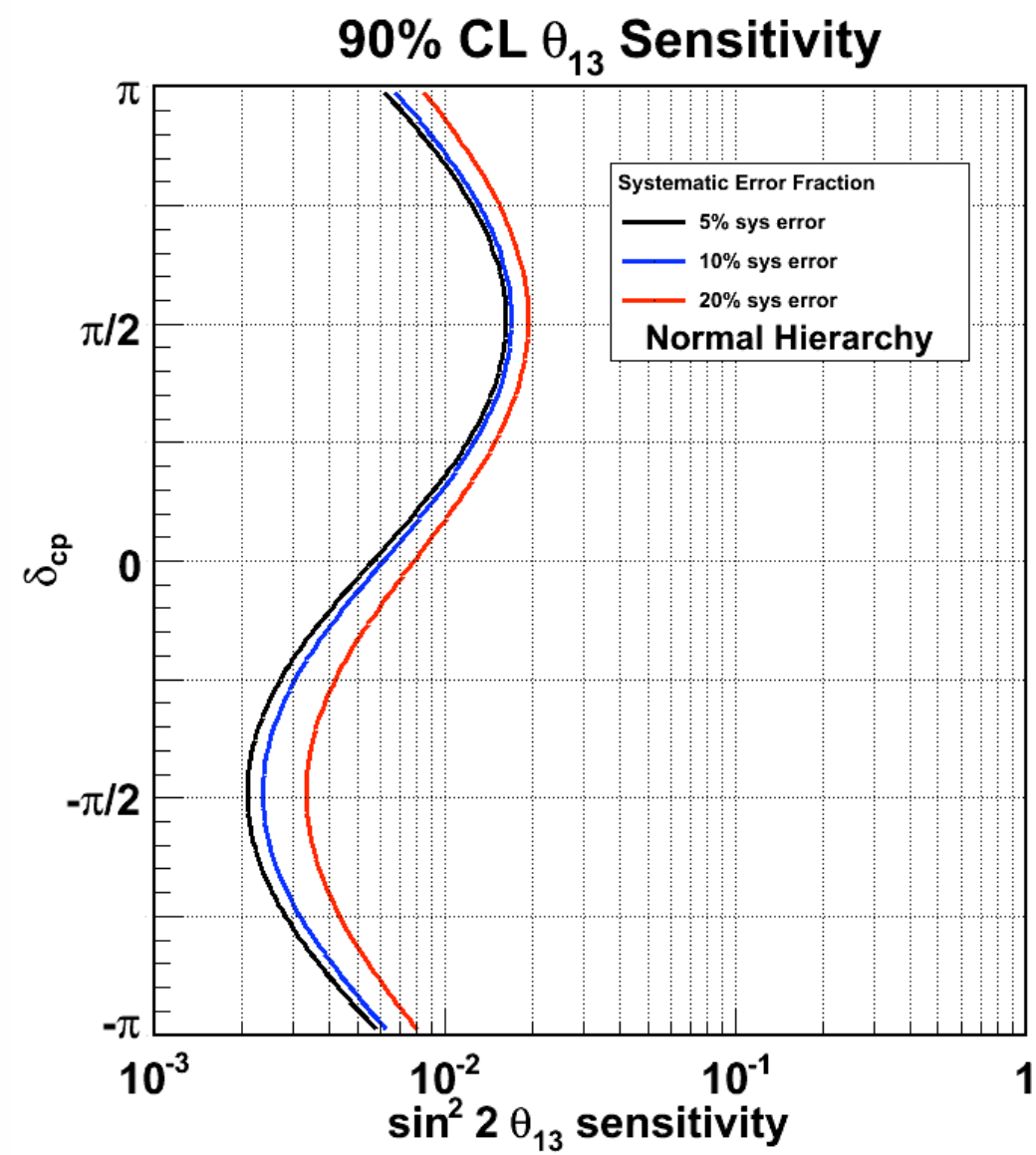
Blue: $\sin^2 2\theta_{13}=0.1$
Red: $\sin^2 2\theta_{13}=0$

$\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$
$\delta cp=0$

PDF for expected number of Super-K ν_e events, including statistical and systematic errors

Future ν_e appearance sensitivity

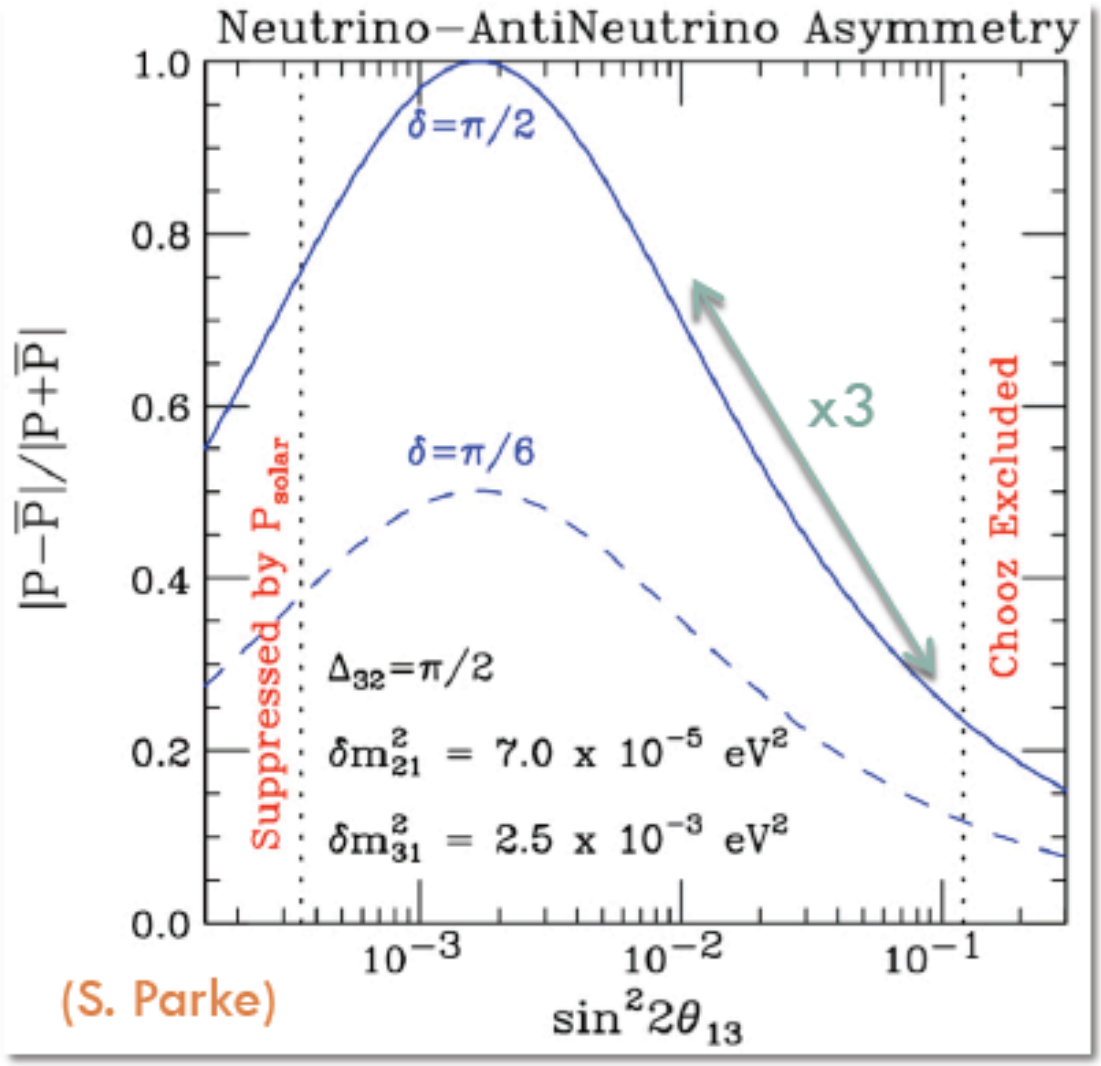




Pink line is final POT goal of T2K

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



(ignoring matter effects & backgrounds for now)

- **the asymmetry**

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

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

- **the asymmetry gets smaller as θ_{13} increases**

~75% for $\sin^2 2\theta_{13}=0.01$
~25% for $\sin^2 2\theta_{13}=0.10$
} $\delta_{CP}=\pi/2$

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 x3 improvement in stat sig of signal

Calculation of expectation at SK

$$N_{SK}^{\exp} = R_{ND}^{\mu,Data} \times N_{SK}^{MC} / R_{ND}^{\mu,MC}$$

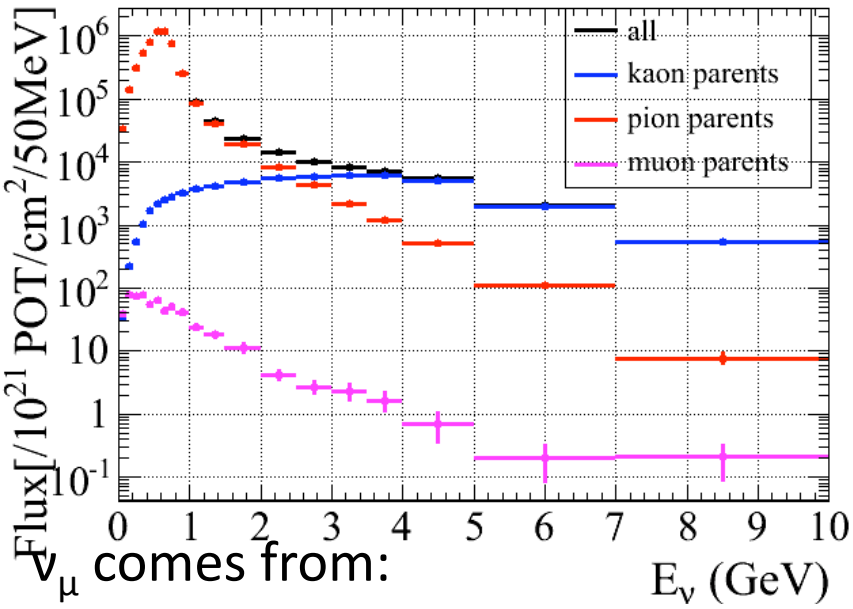
Ignoring sums over neutrino flavors, interaction modes

$$\frac{\int \Phi_{\nu_\mu(\nu_e)}^{SK}(E_\nu) \cdot P_{osc}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\, dE_\nu}{\int \Phi_{\nu_\mu}^{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\, dE_\nu}$$

- ND280 statistical uncertainty
- Flux uncertainty → expect cancellation in ratio
- Neutrino interaction cross section uncertainties
- SK reconstruction, selection uncertainties
- ND280 reconstruction, selection uncertainties

Slide from Mark Hartz's FNAL seminar

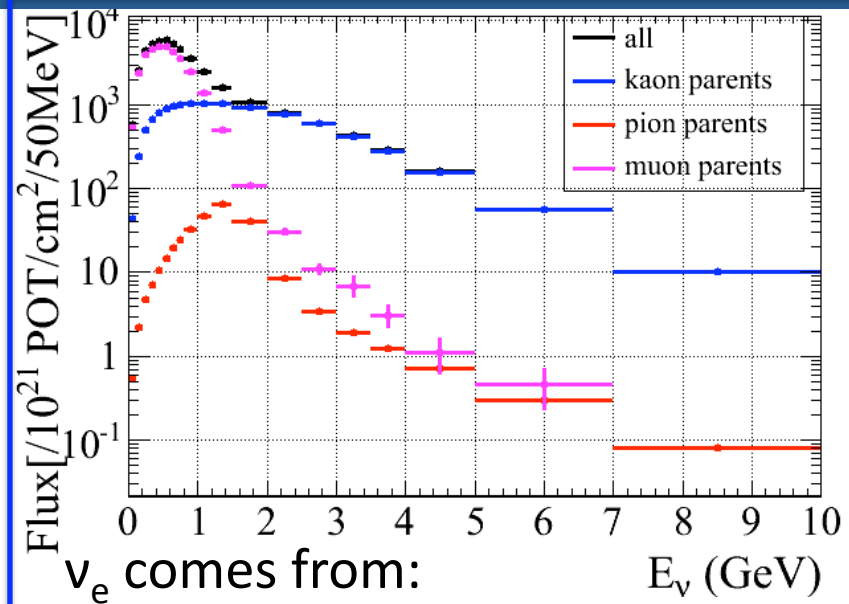
Neutrino flux prediction



ν_μ comes from:

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

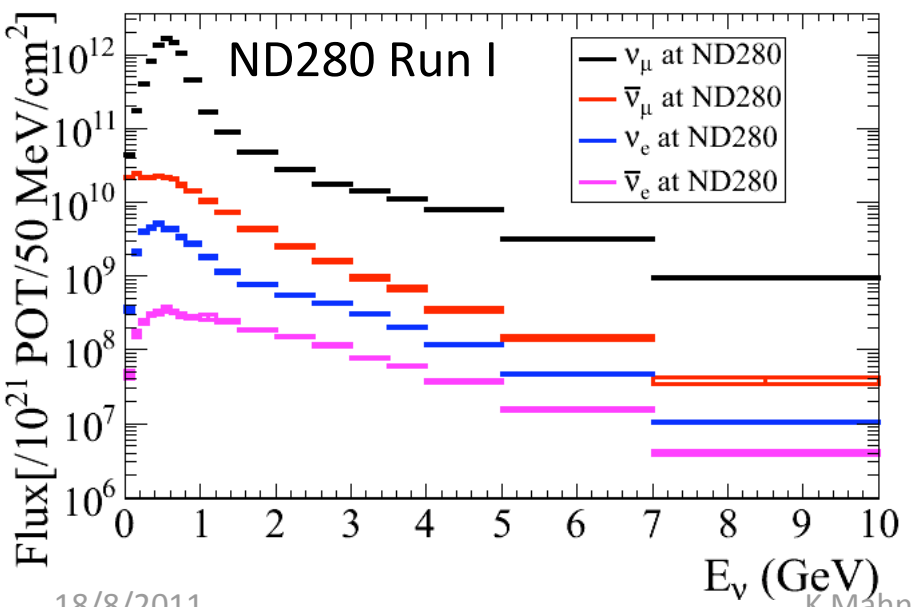
HE tail from $K \rightarrow \nu_\mu$ decay (E_ν >2.5 GeV)

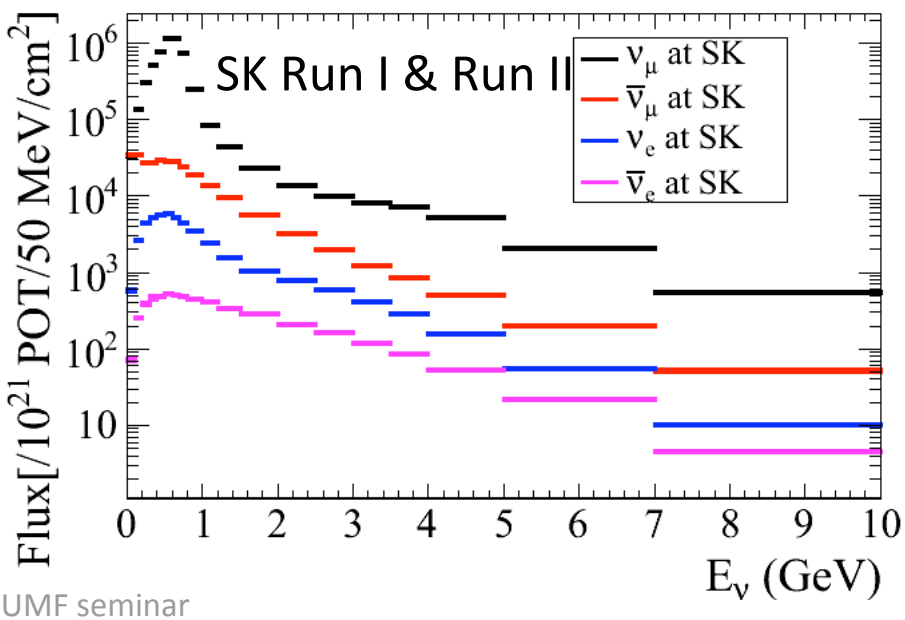


ν_e comes from:

$\pi \rightarrow \mu \rightarrow \nu_e$ decay chain (E_ν < 1.5 GeV)

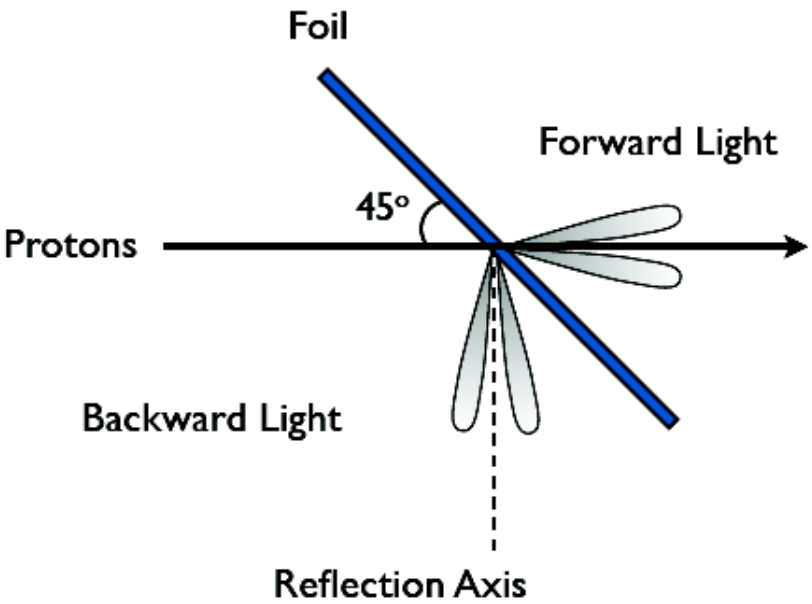
$K \rightarrow \nu_e$ decay (E_ν >1.5 GeV)



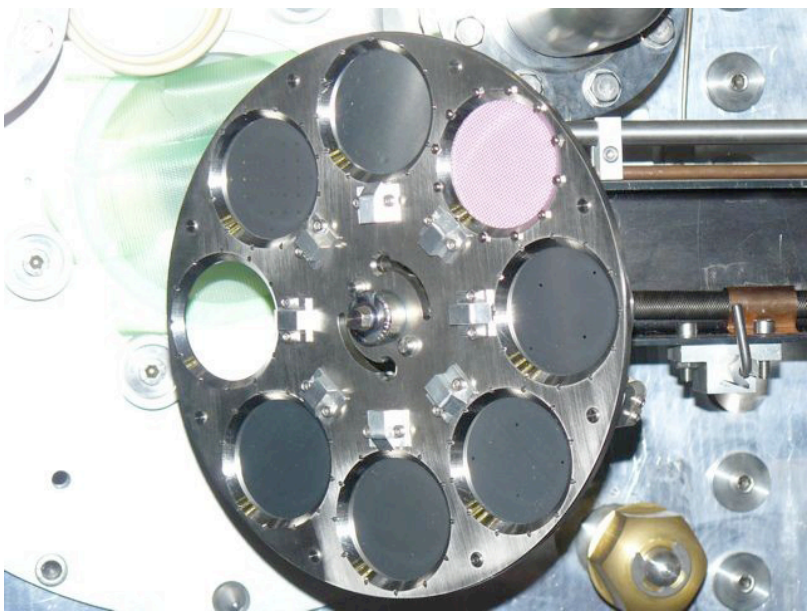


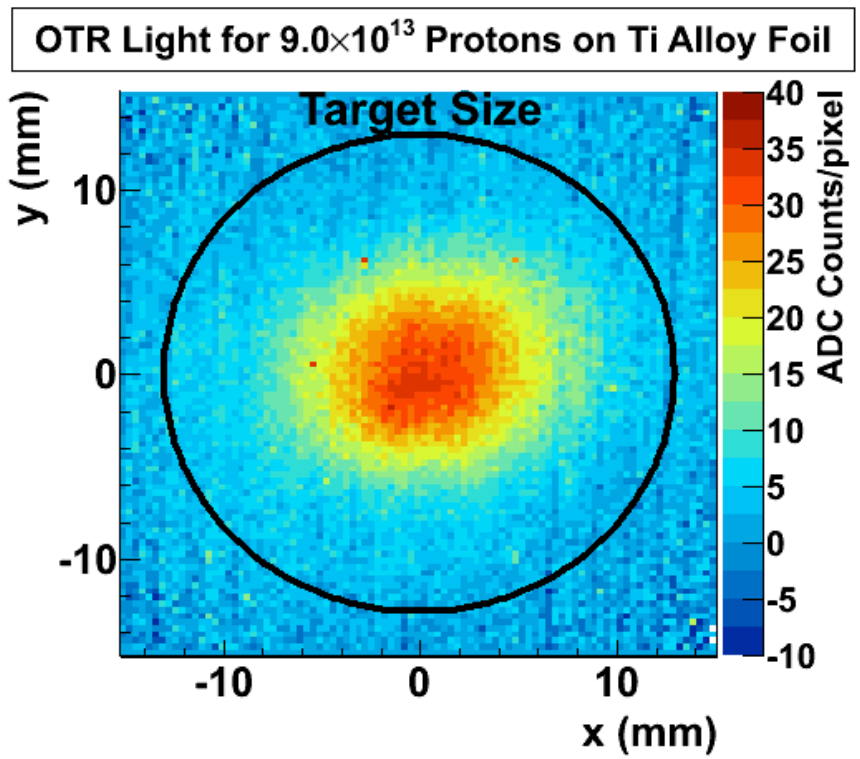
Proton beam monitoring

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

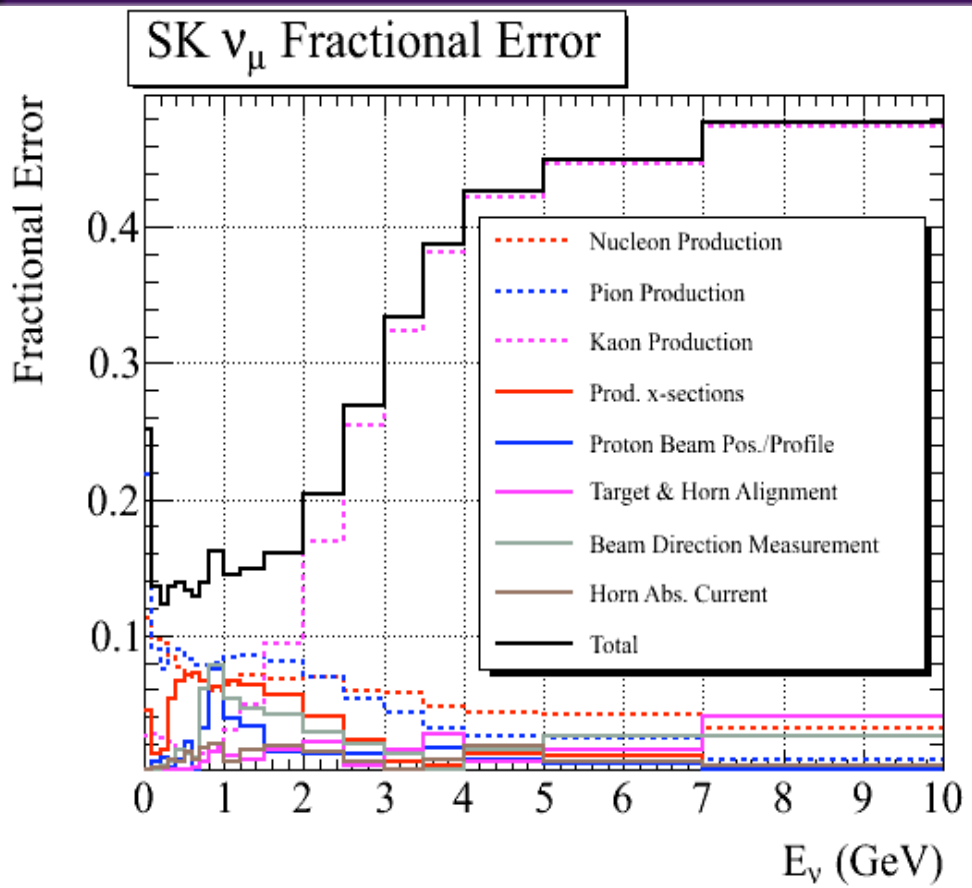


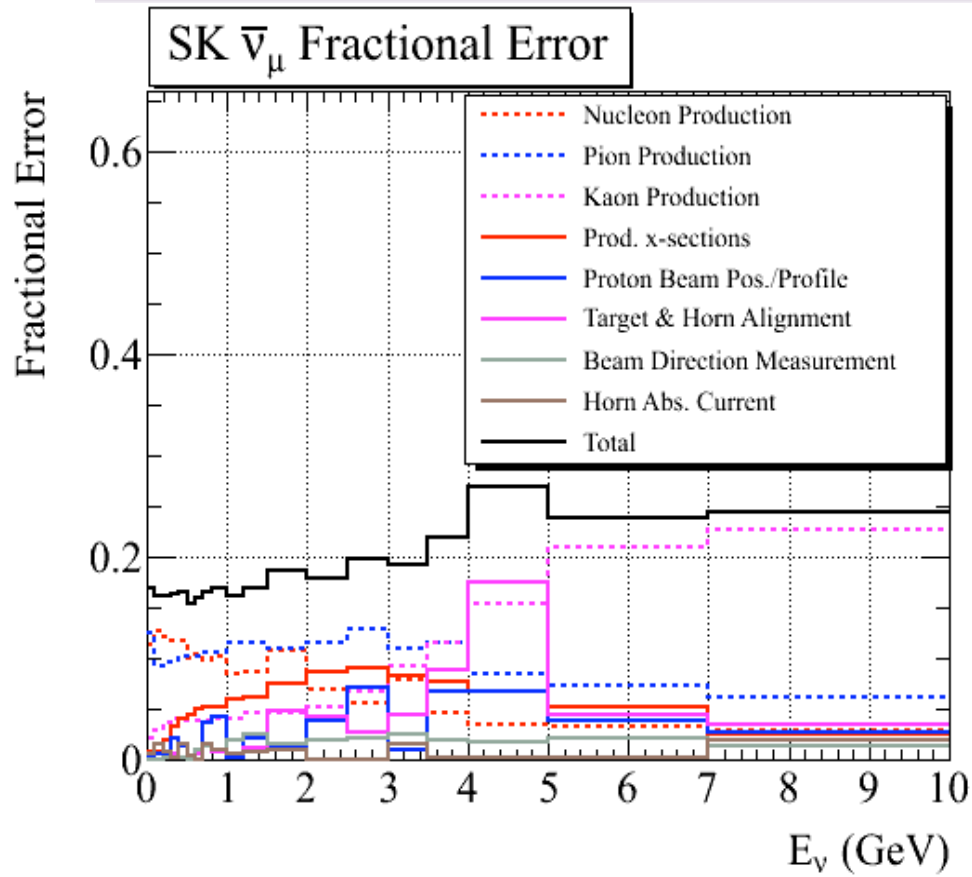
Optical Transition Radiation is produced by the the protons as they pass through a thin Ti foil in in front of the neutrino target.
The light is emitted perpendicular to the beam direction, and is recorded with a 40mm camera
OTR light is used to determine the beam profile and position on the target





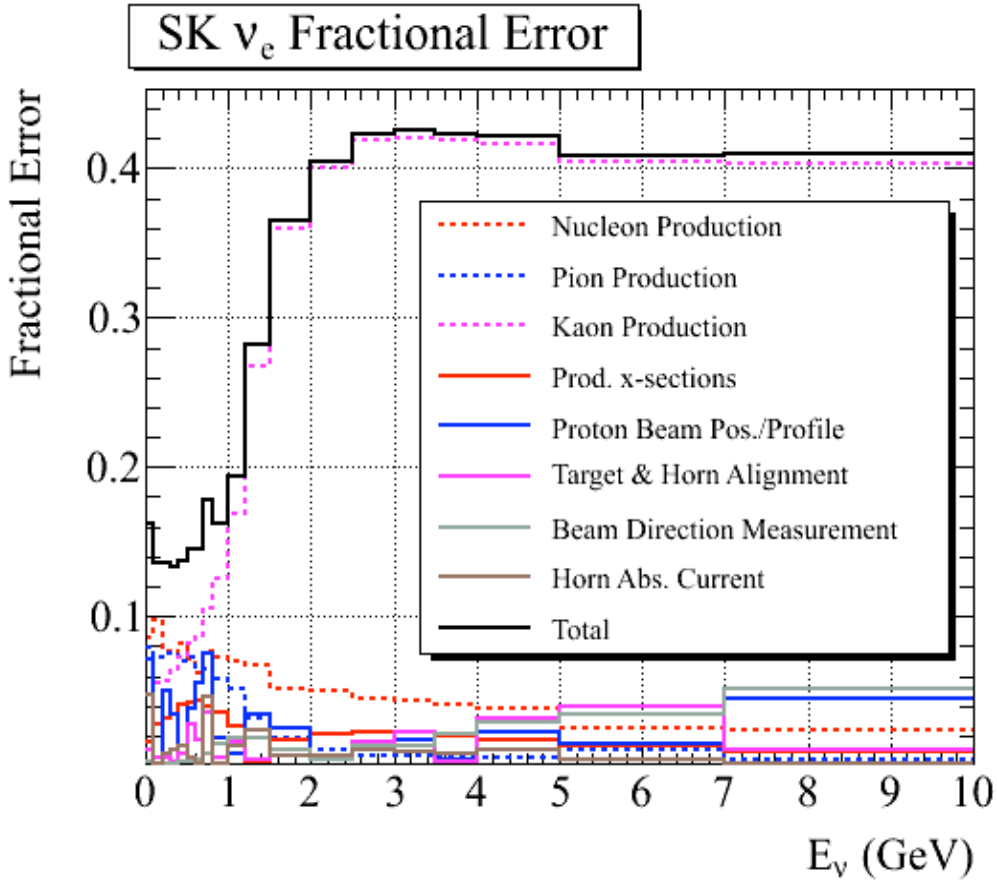
SK Systematic Error Envelopes

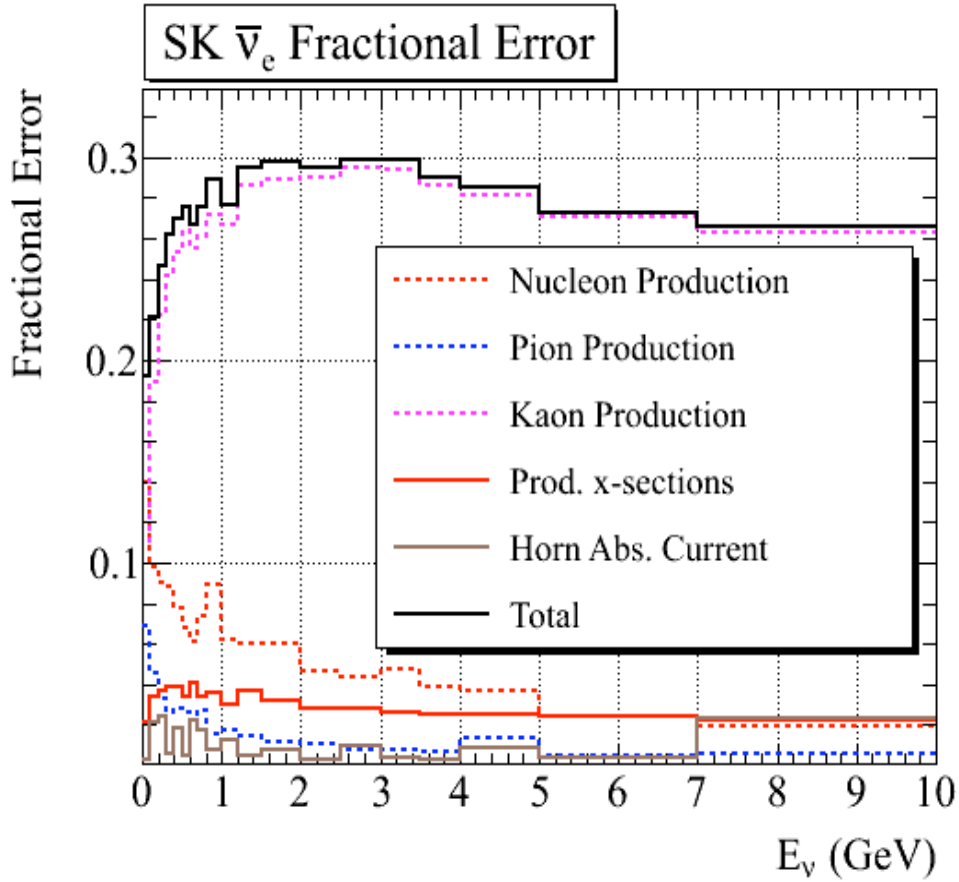




Error envelopes show the fractional error in each neutrino energy bin, but do not show correlations between bins. Error types described on slide 16.

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.

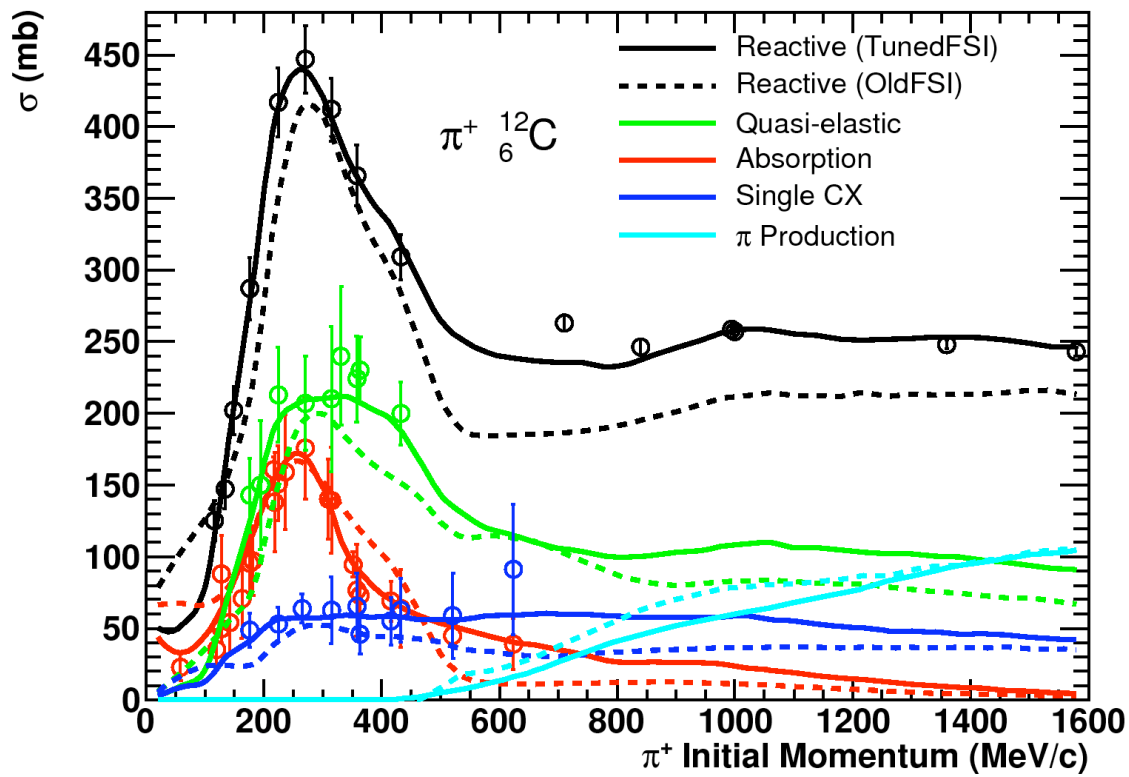
Neutrino interaction uncertainties

	ν_μ signal	ν_e bkrd
CCQE shape	2.5%	3.1%
CC1π	+0.4% -0.5%	2.2%
CC coherent π	-	3.1%
CC other	+4.1 -3.6%	4.4%
NC all	0.9%	-
NC1π^0	-	5.3%
NC coherent π	-	2.3%
NC other	-	2.3%
$\sigma(\nu_e)$	N/A	3.4%
FSI	6.7%	10.1%
Total	+8.3 -8.1%	14.0%

ν_μ signal assumes:

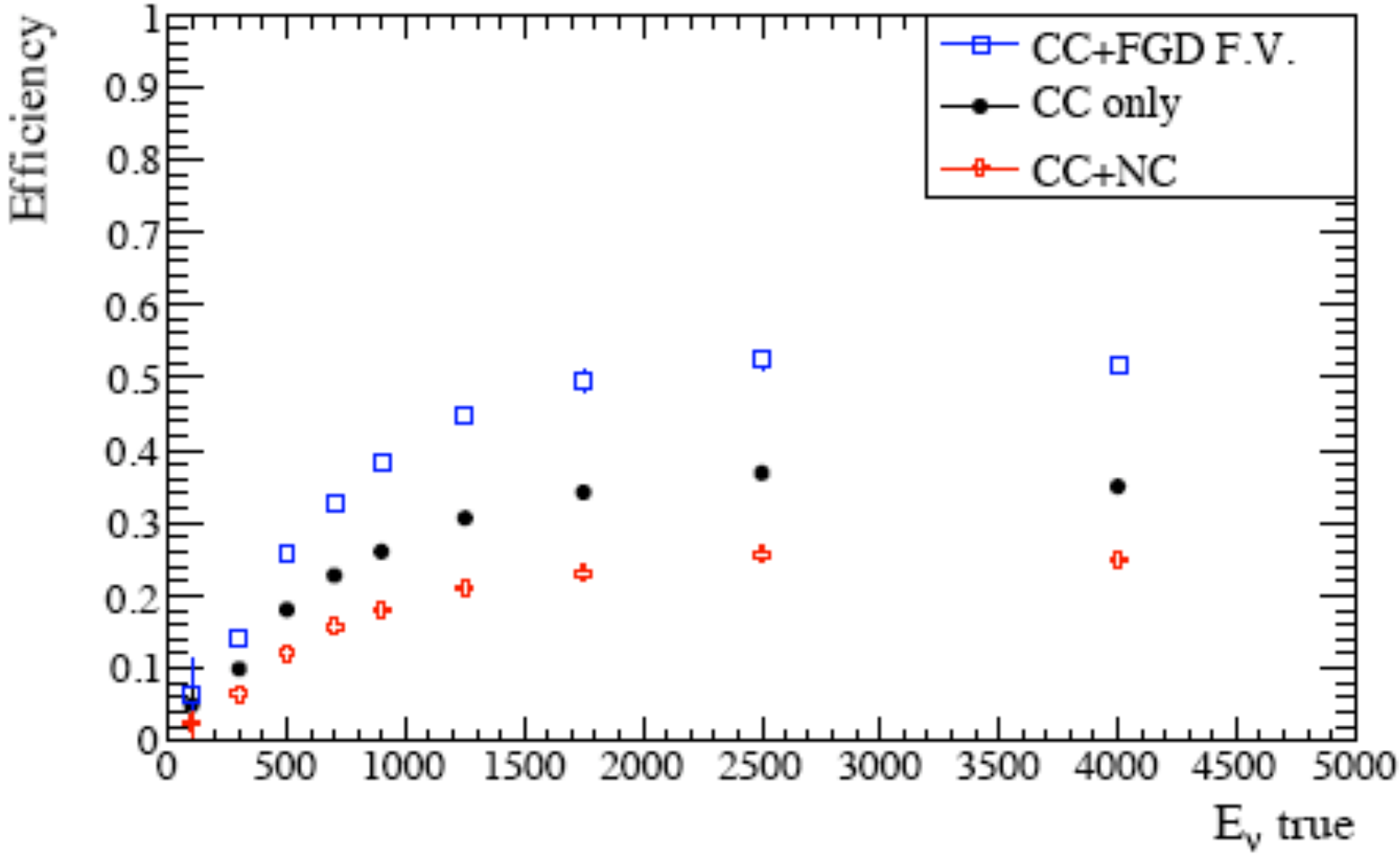
$\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2 $\sin^2 2\theta_{23} = 1.0$

External data on π^+ interaction cross sections



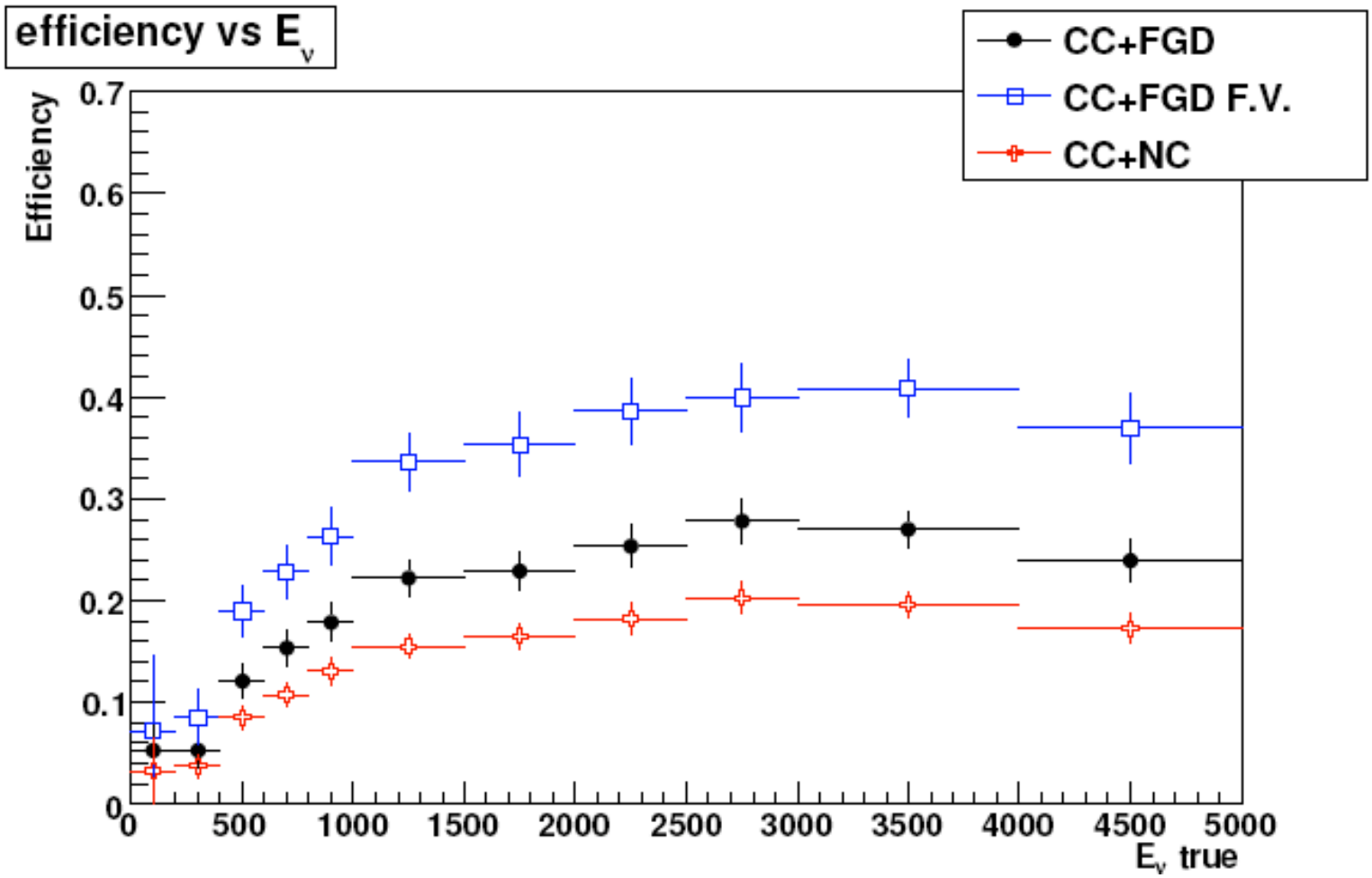
- FSI: Modify π re-interaction probabilities within cross section model according to external data to determine FSI uncertainty
- Alters the energy dependence of how backgrounds are reconstructed

Efficiency of CC ν_μ events



Overall efficiency for CC ν_μ: 38.3 ±0.2% within FGD FV

Efficiency of CC ν_e events

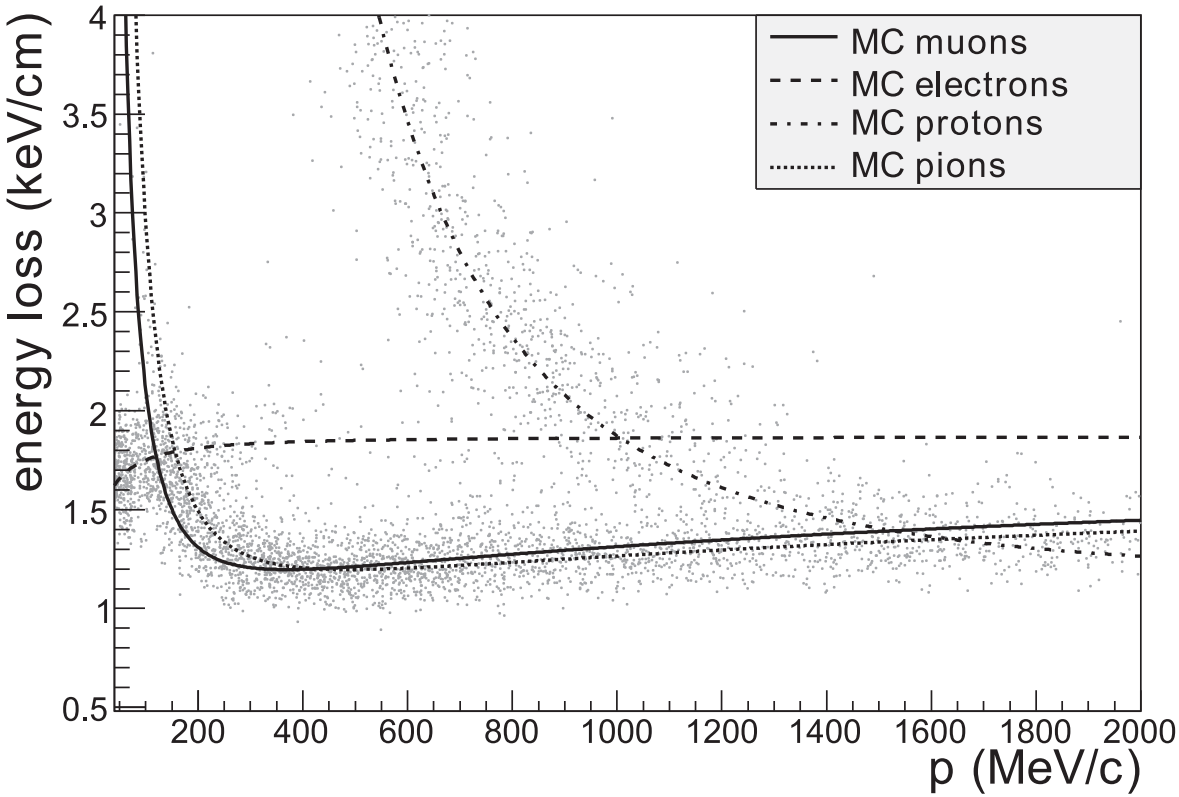


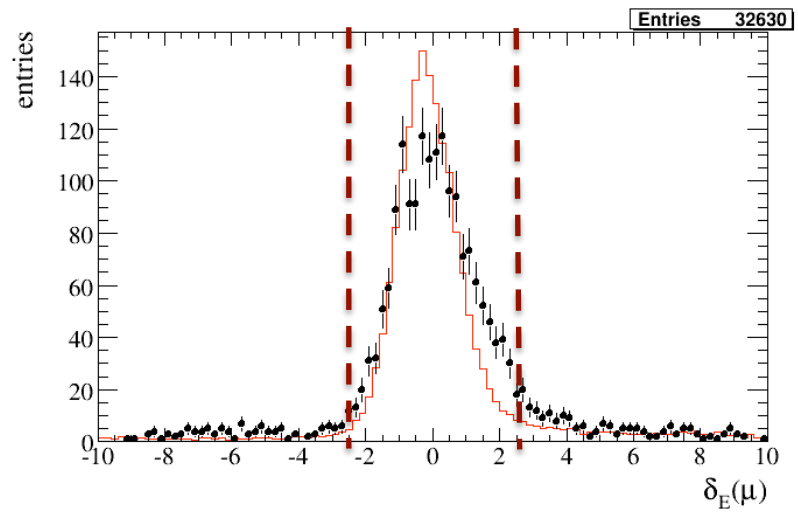
Overall efficiency for CC ν_e: 21.5 ±0.6% (<2 GeV, within FGD FV)

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

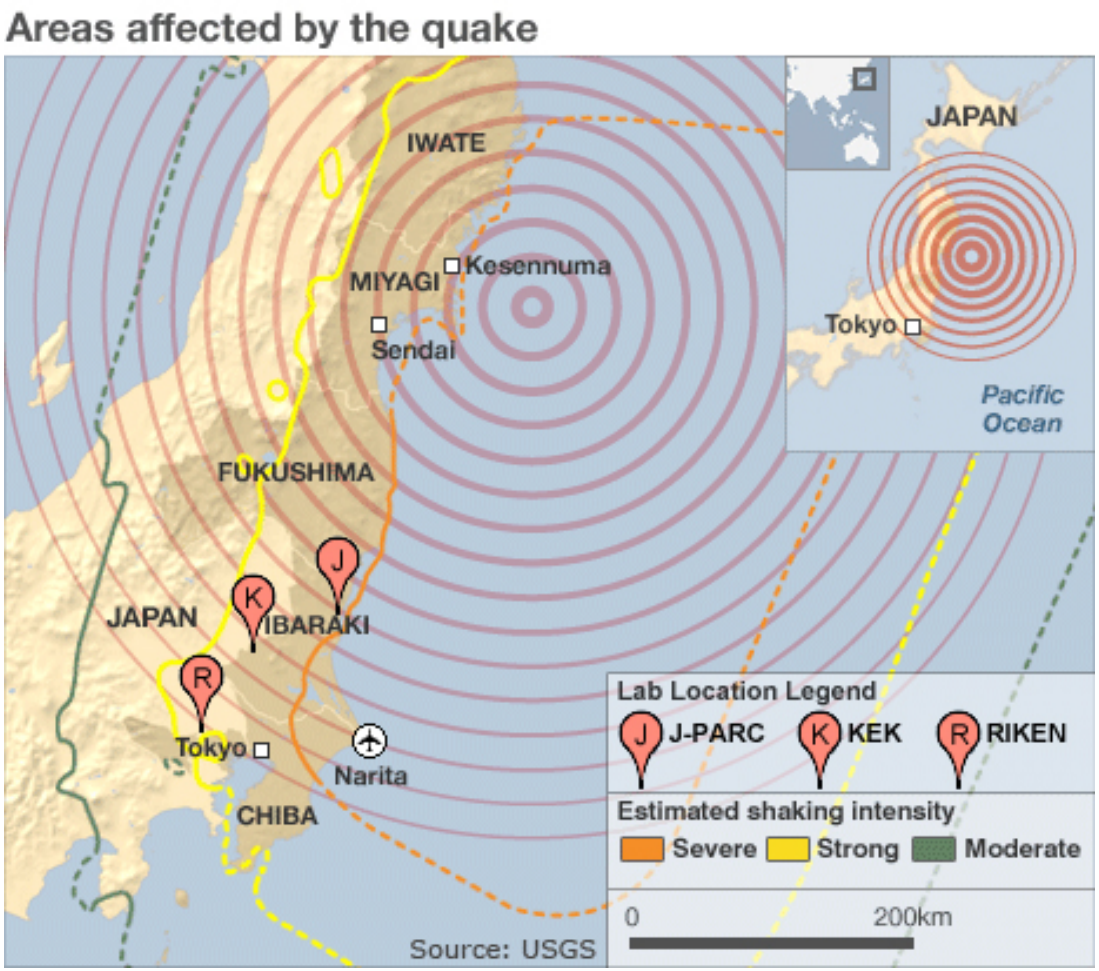
dE/dx resolution for MIPs is 8%

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%

Earthquake in Japan

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

- Magnitude 9 earthquake on Richter scale
- Magnitude 6+ at JPARC
- The tsunami did not reach JPARC
- Accelerator was not operating (maintenance day)



No reported injuries to members of the T2K collaboration or to JPARC employees

A reminder about neutrinos

In the Standard Model, there are three neutrinos: ν_e, ν_μ, ν_τ
paired with an associated charged lepton partner: e, μ, τ

Neutrinos interact via the weak force (W, Z bosons)

To detect neutrinos:
Need "nothing" coming in

Detect the outgoing lepton to determine neutrino flavor (CC only)

Nucleus can be excited or additional particles emitted (NC or CC)