Recent Neutrino Oscillation Results from T2K

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NNN15

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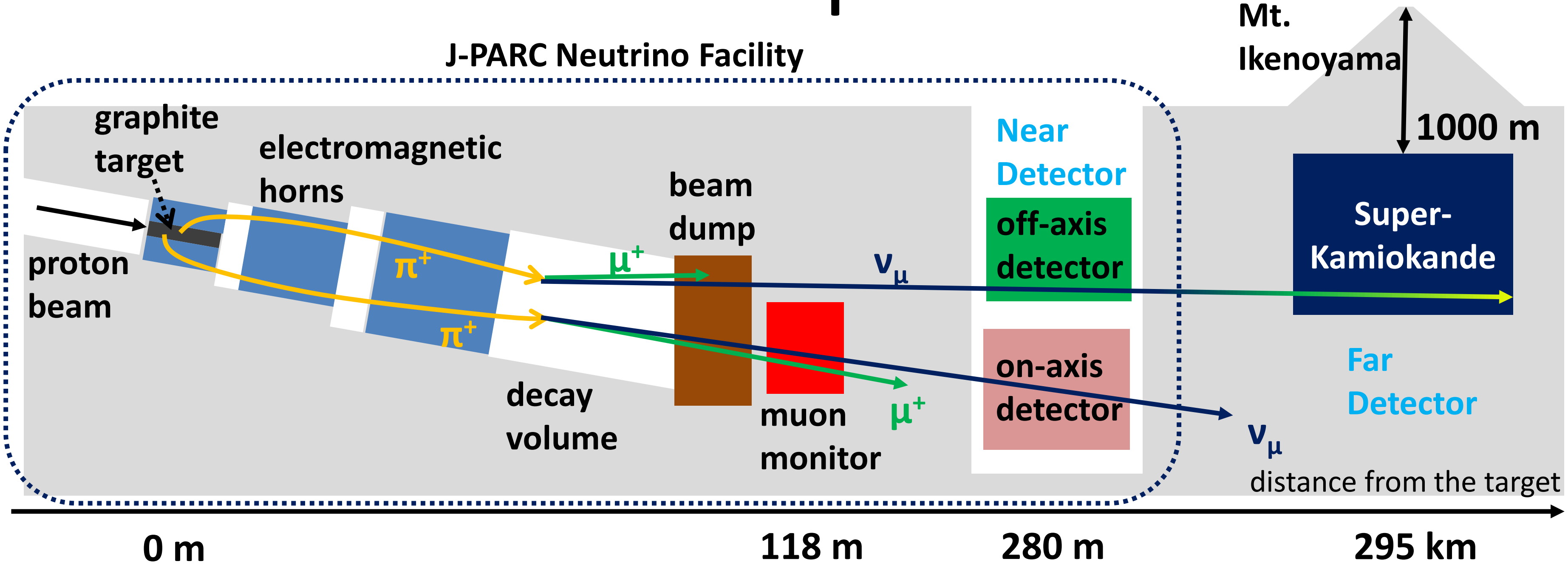
Outline

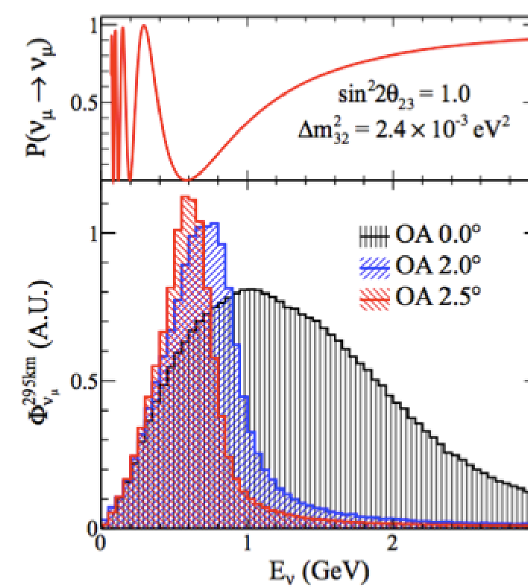
- The Tokai-to-Kamioka (T2K) experiment
- Highlights from ν-mode joint fit
- Analysis overview
  - Neutrino flux prediction
  - Near Detector measurements

- Oscillation results in $\bar{\nu}$**-**mode
  - Event selection at far detector ($\bar{\nu}_\mu$, $\bar{\nu}_e$)
  - systematic uncertainties ($\bar{\nu}_\mu$, $\bar{\nu}_e$)
  - **$\bar{\nu}_\mu$ disappearance** ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)
  - **$\bar{\nu}_e$ appearance** ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

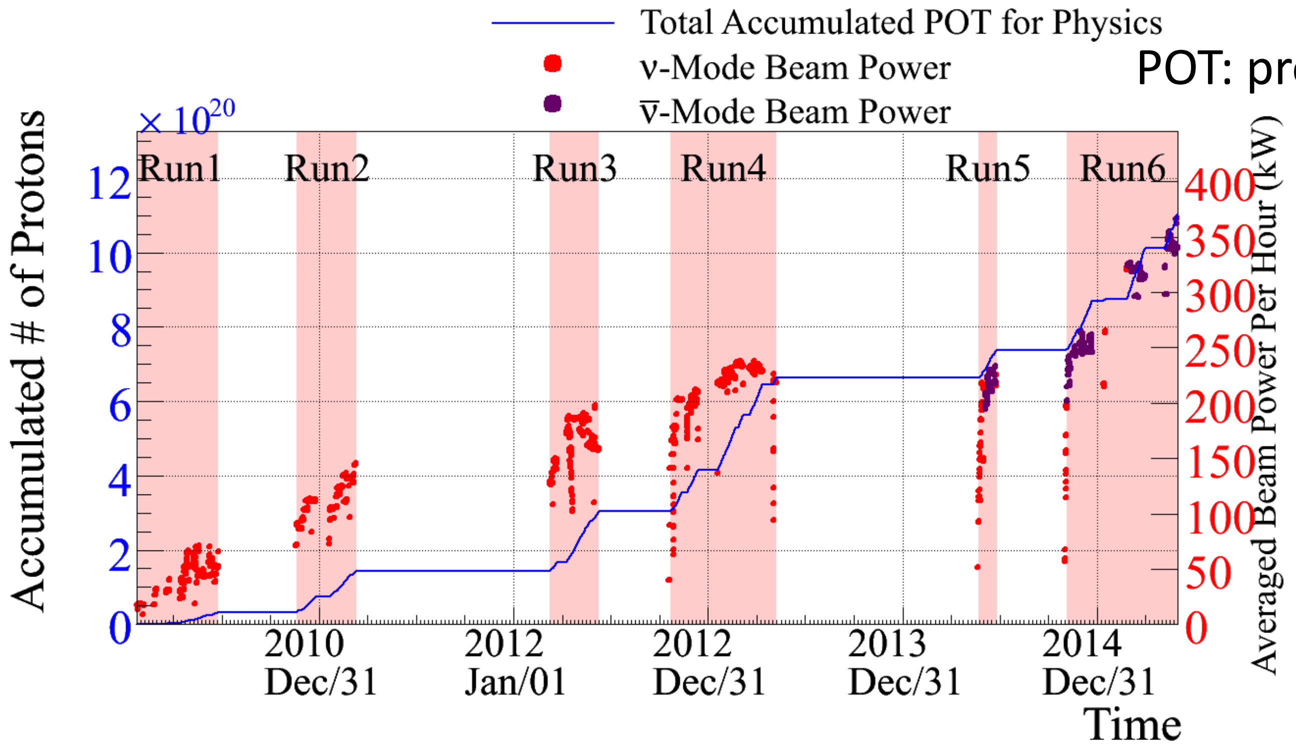
The T2K experiment



- off-axis beam to far detector (Super-K) and off-axis near detector (ND280)
  - generate narrow-band beam
    - enhance signal events at oscillation peak
    - reduce high energy neutrino backgrounds



Data taking



POT: protons on target

- Beam power is increasing and achieved ~**350** kW beam

✓ Integrated data so far:

7.09×10^{20} for ν-mode, 4.04×10^{20} for $\bar{\nu}$-mode

✓ used data for this oscillation analysis

off-axis ND : $\bar{\nu}$-mode 5.82×10^{20} POT, $\bar{\nu}$-mode 4.30×10^{19} POT

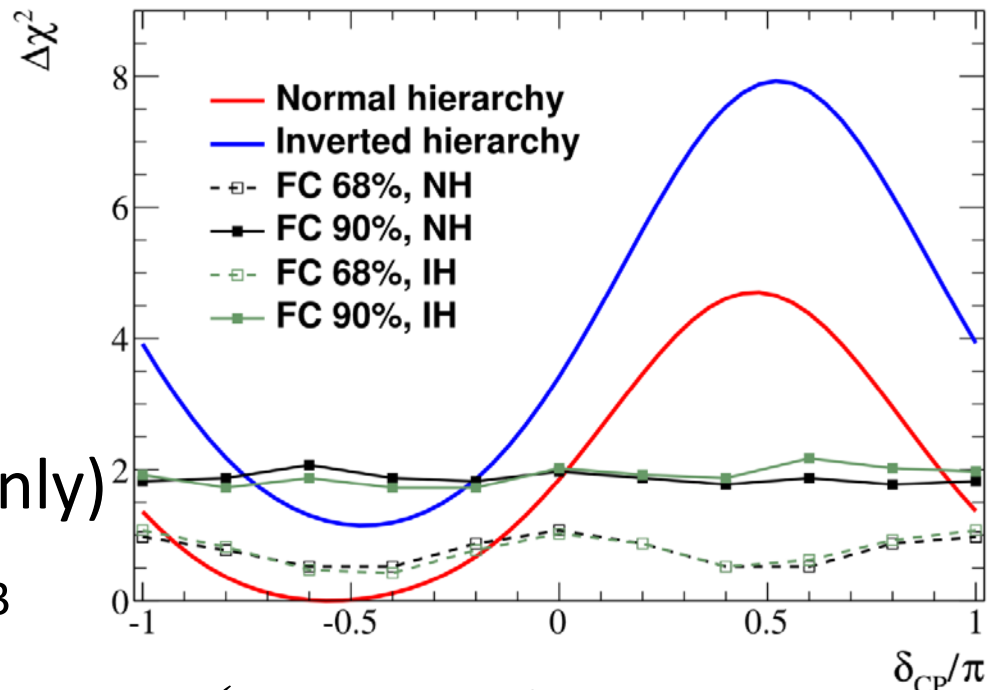
FD : $\bar{\nu}$-mode 4.01×10^{20} POT (all data so far)

Highlights from ν-mode joint fit

- simultaneous fit of $\nu_e + \nu_\mu$ samples
  - First δ_{CP} constraint

- use T2K RUN1-4 data
  - 6.6×10^{20} POT (ν-mode only)
- Inclusion of PDG 2013 θ_{13}
  - $\sin^2\theta_{13} = 0.0243 \pm 0.0026$

- Best fit value ~ -π/2, slightly favor normal hierarchy
  - Significance is not large and we have to take more data



✓ 90% C.L. excluded region
[0.15π, 0.83π] (normal hierarchy)
[-0.08π, 1.09π] (inverted hierarchy)

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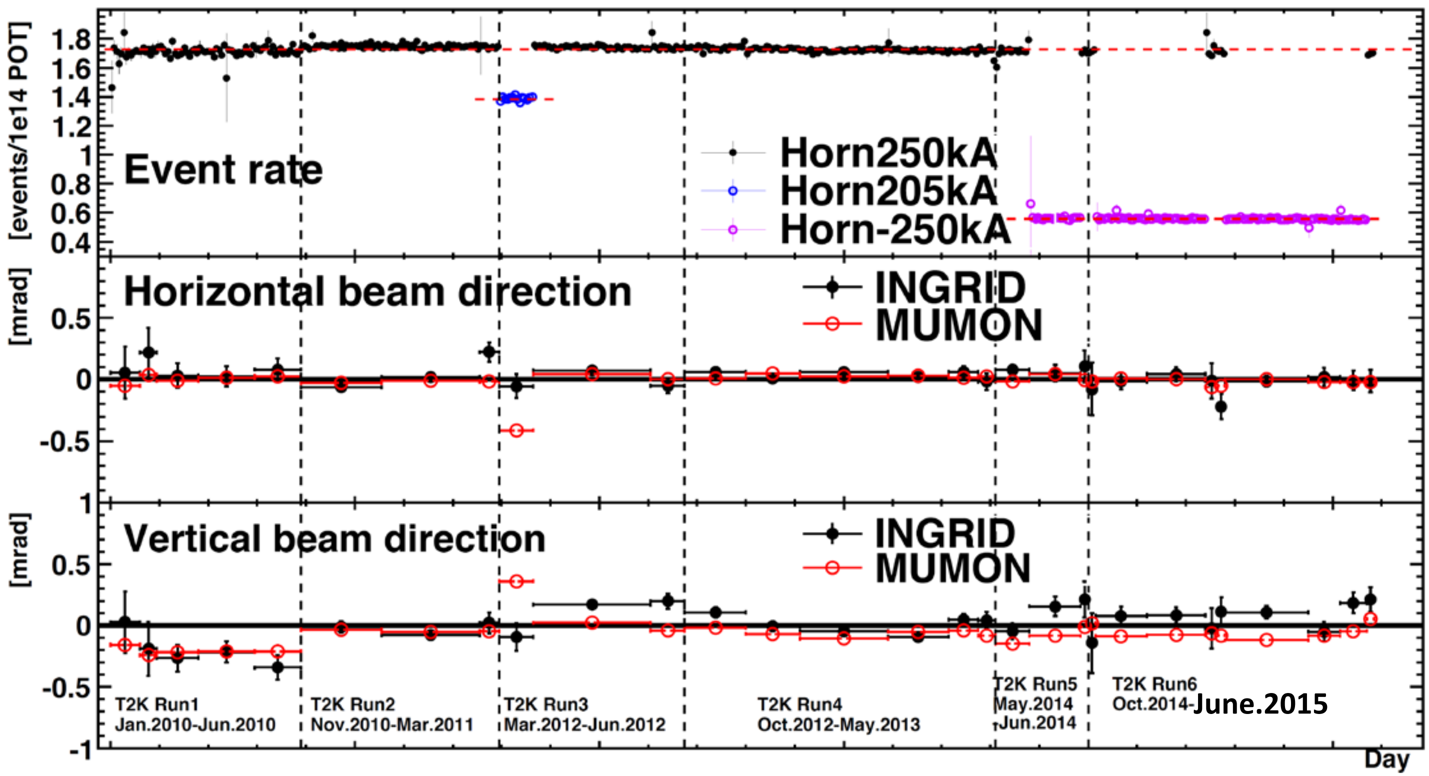
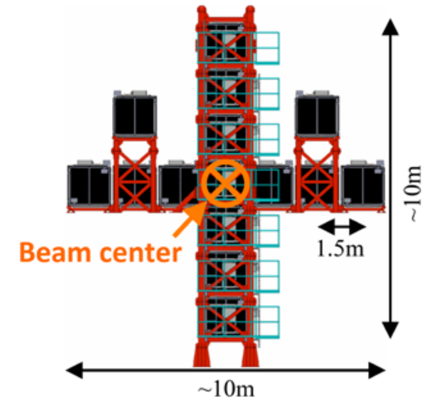
Beam stability

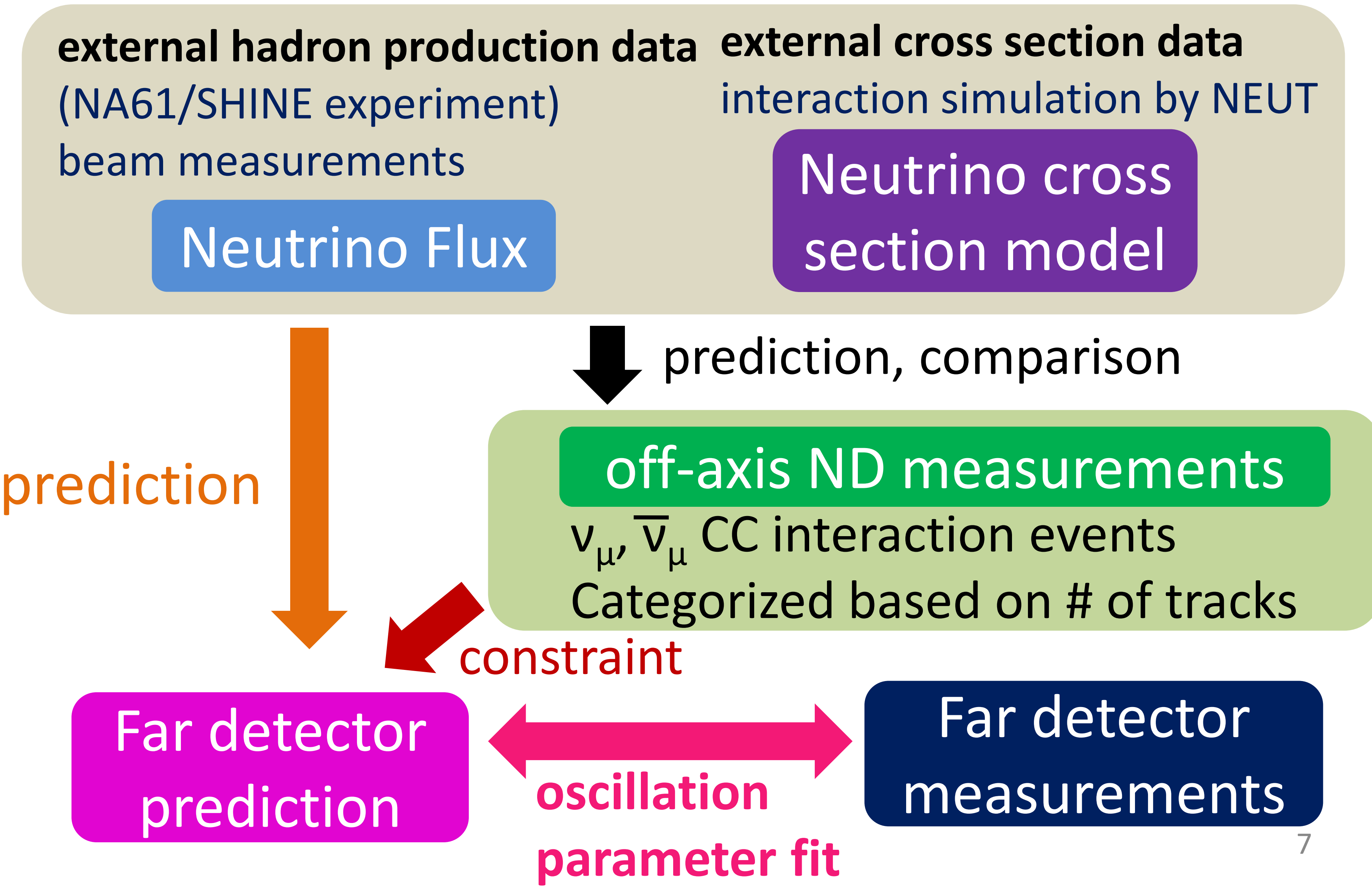


INGRID @ on-axis (0°)



- ✓ Event rate is stable to ~1% level
- ✓ Beam direction is stable within much better than 1 mrad
  - 1 mrad shift corresponds to ~2% shift of peak energy of ν flux

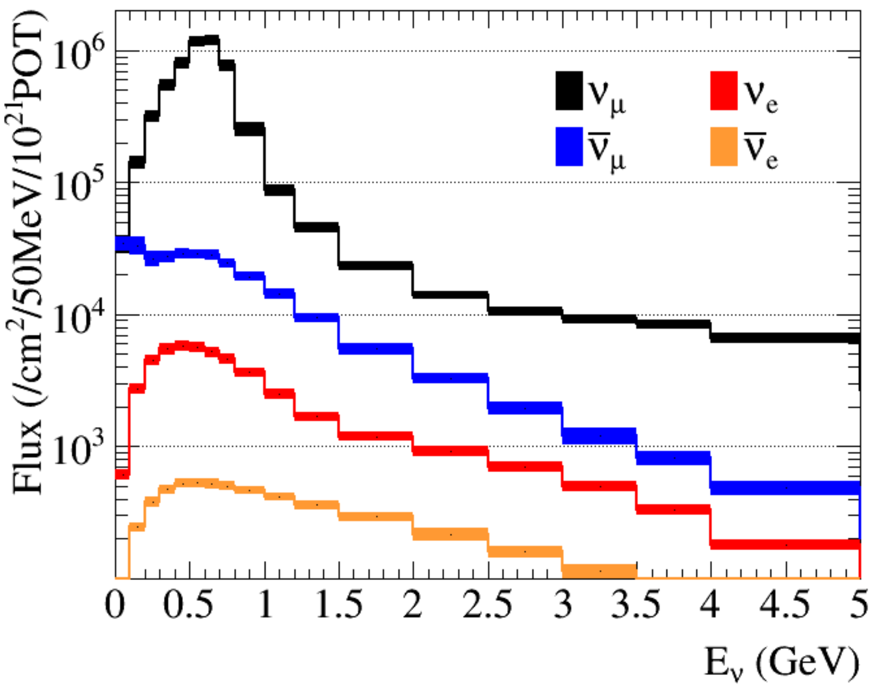
Analysis strategy

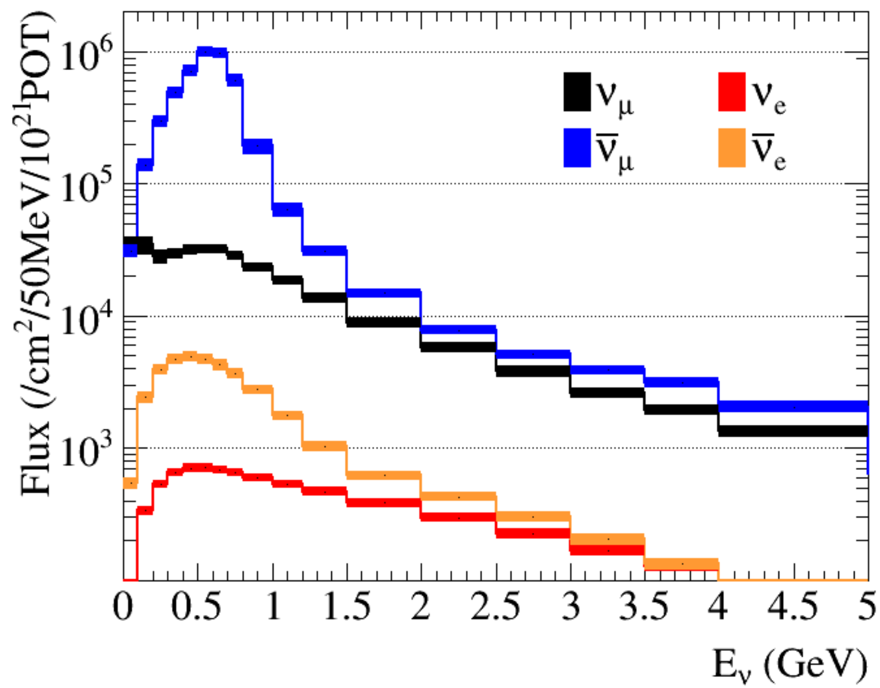


Neutrino flux prediction

ν mode $\bar{\nu}$ mode

box indicates size of the systematic uncertainty

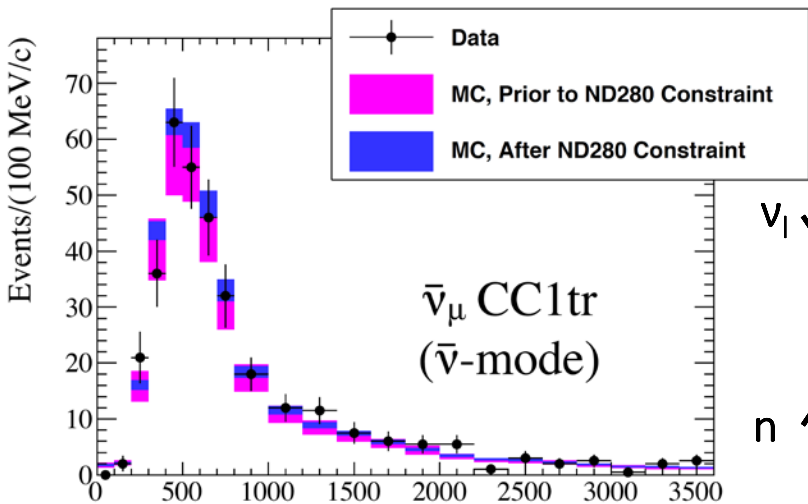


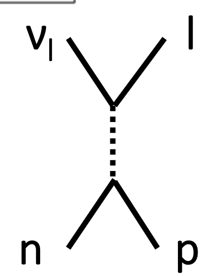


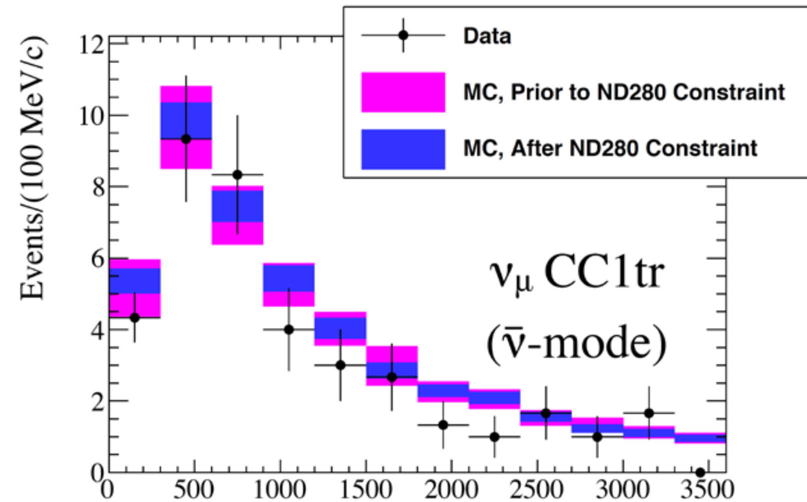
- Larger “wrong-sign” component in $\bar{\nu}$-mode
  - especially in higher energy region
  - ~3% at peak energy (~600 MeV)
- ~9% uncertainty at peak energy

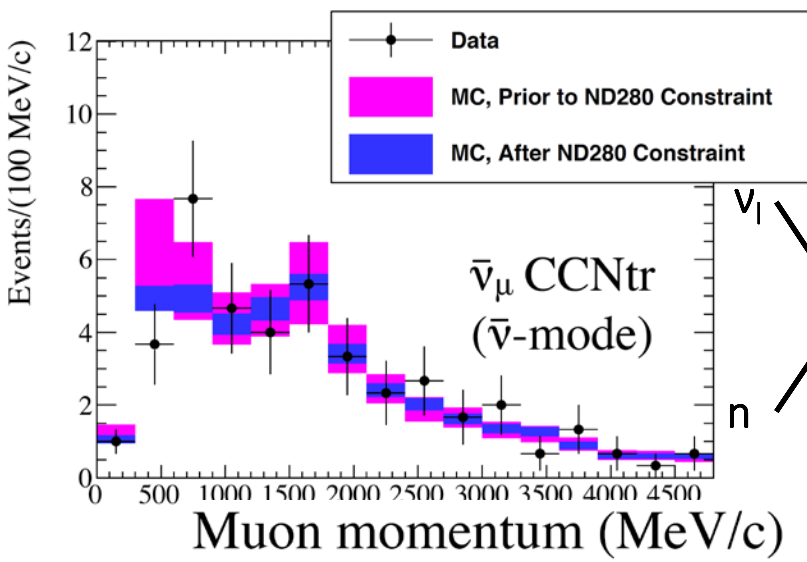
Near detector measurements

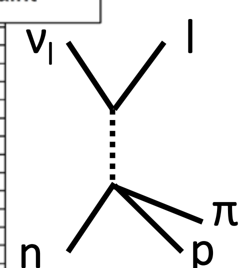
- $\bar{\nu}$-mode subsamples: CC1Track, CCNTracks (for $\bar{\nu}_\mu$, ν_μ) momentum distributions

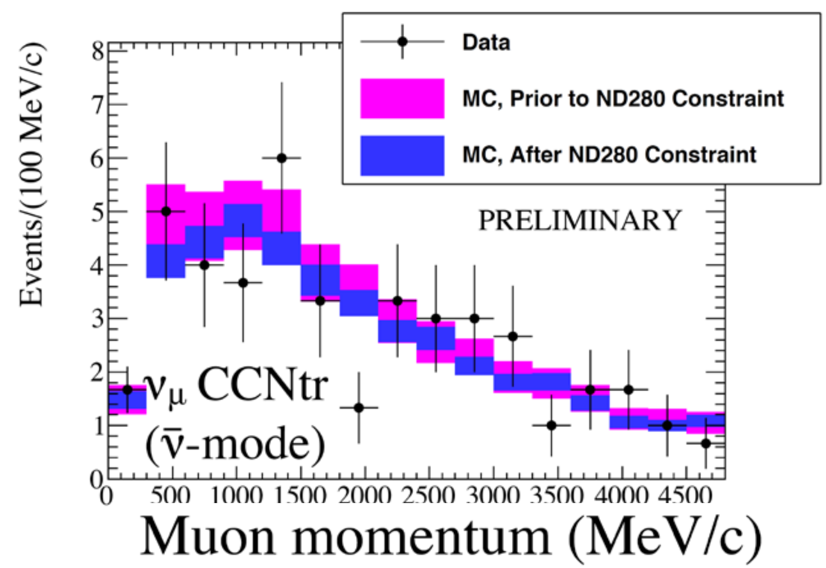






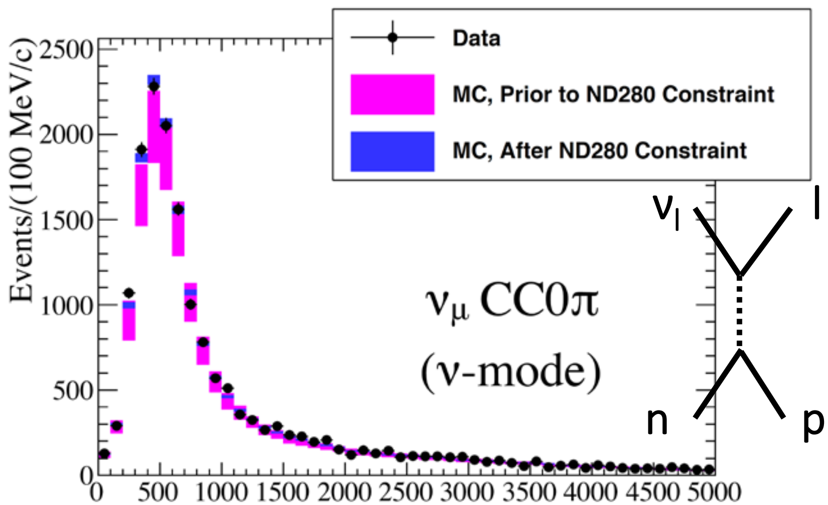


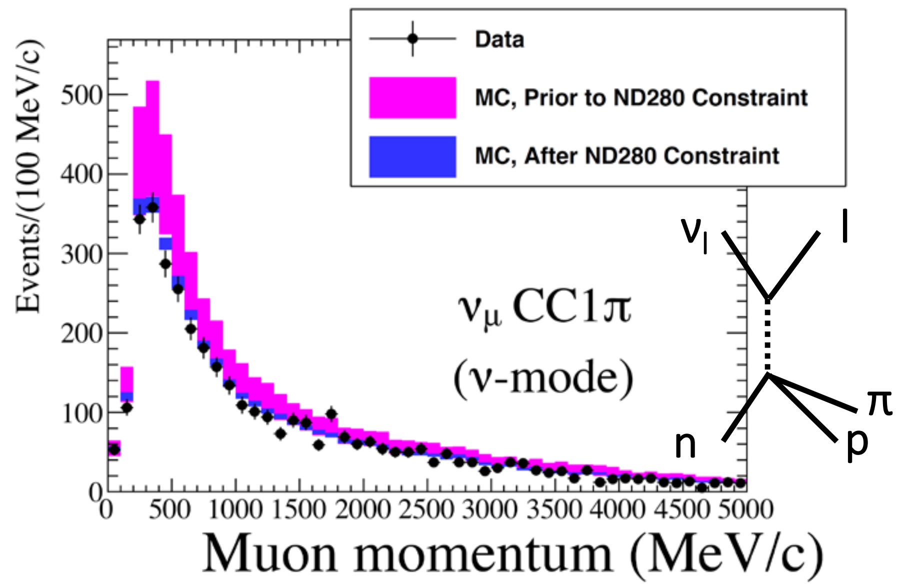


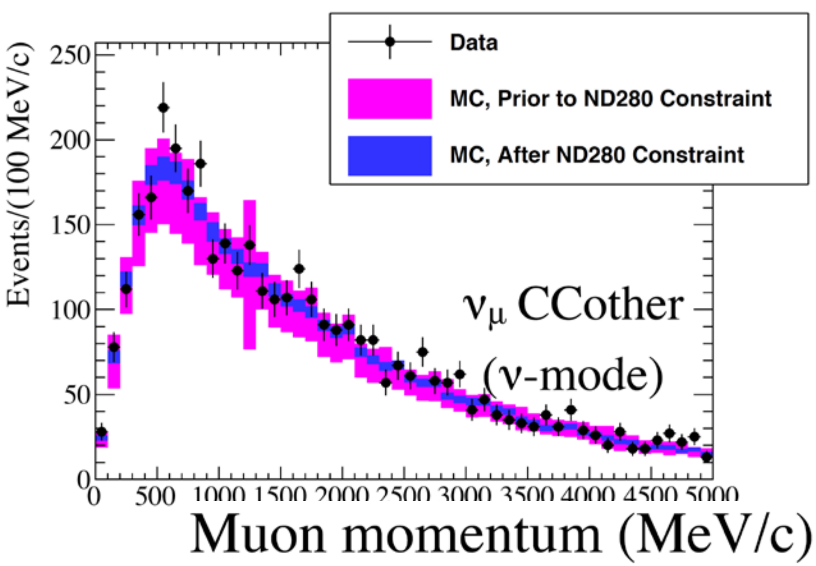


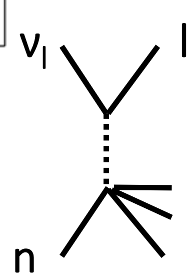
Near detector measurements

- ν-mode subsamples: CC0π, CC1π$^+$, CCother（ν_μ）
- finer categorization than $\bar{\nu}$-mode due to larger amount of data





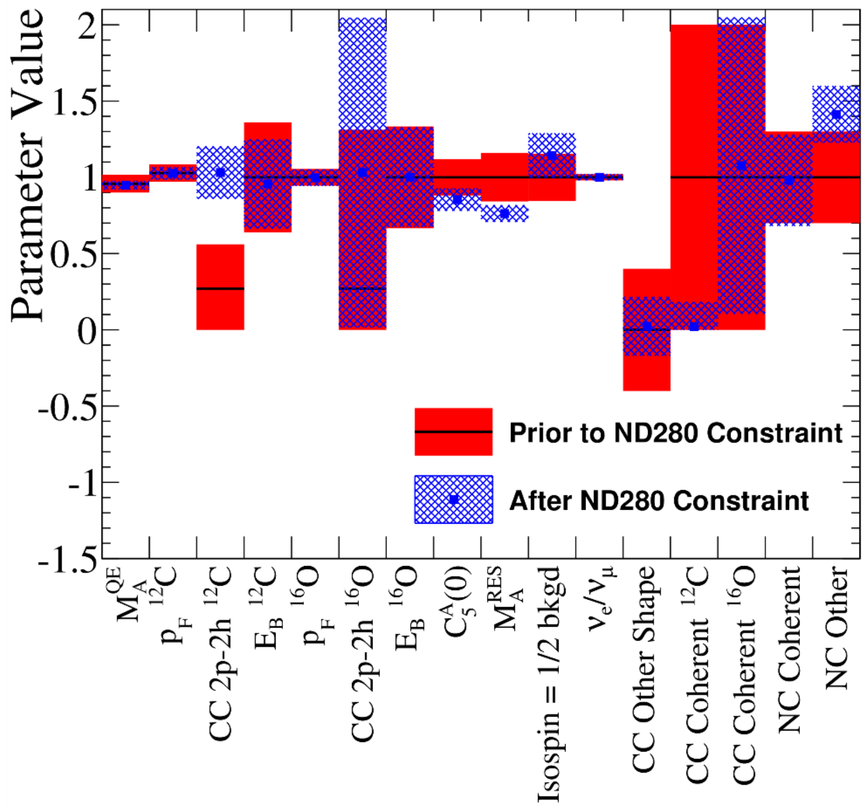




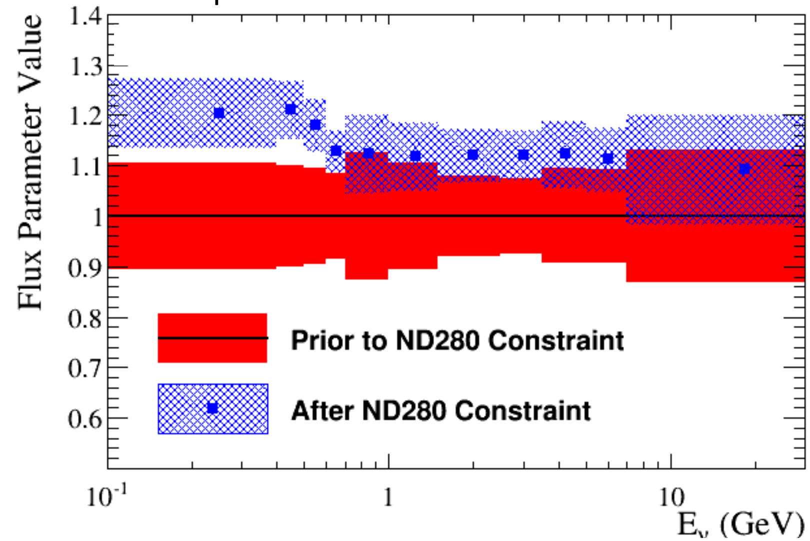
- Constrain flux and cross-section uncertainties due to correlation between ND and FD

ND analysis results

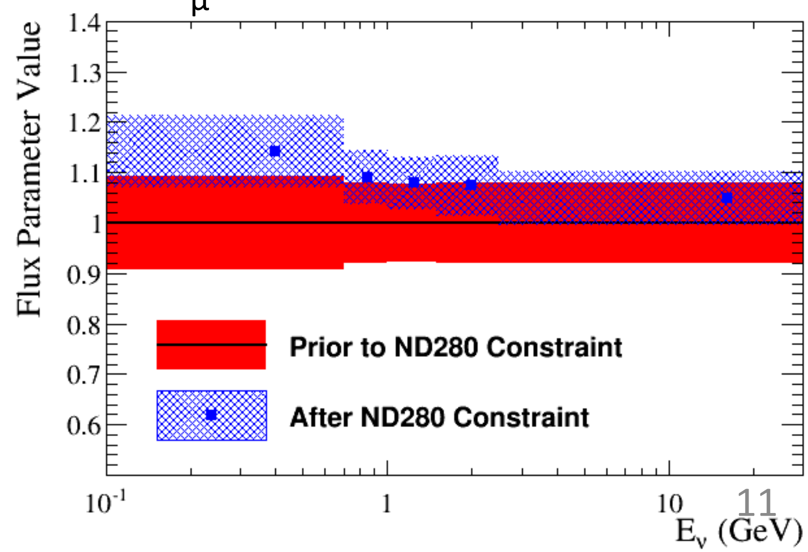
cross-section parameters



$\bar{\nu}_\mu$ flux in $\bar{\nu}$-mode at far detector



ν_μ flux in $\bar{\nu}$-mode at far detector

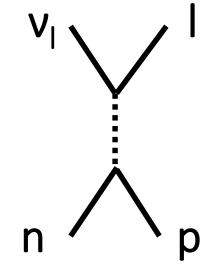


- constrain flux and cross-section uncertainties
  - nuclear-dependent parameters are hardly constrained (^{12}C is used for ND and ^{16}O for FD)

Event selection at far detector

- enhance CCQE 1-Ring μ/e event
- Event selection method in $\bar{\nu}$-mode data is same as that in neutrino ν-mode data

CCQE

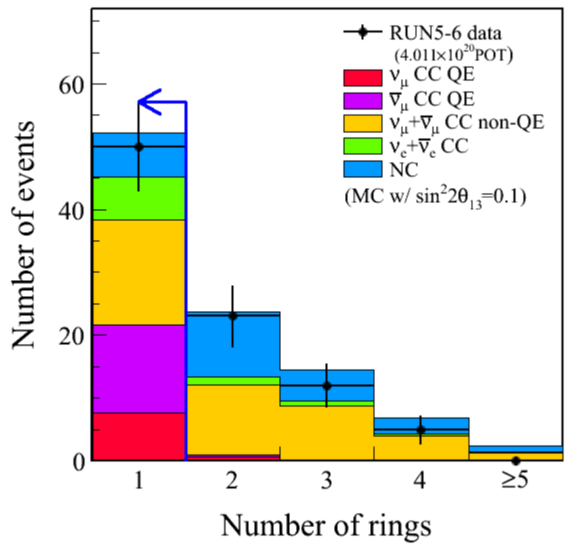


ν_μ	ν_e
Beam timing selection	
Fully contained in fiducial volume (FCFV)	
1-Ring μ-like	1Ring e-like
p_μ > 200 MeV/c	$E_{visible}$ > 100 MeV
# of decay electron ≤ 1	# of decay electron = 0
	0 < E_{rec} < 1250 MeV
	π^0 cut

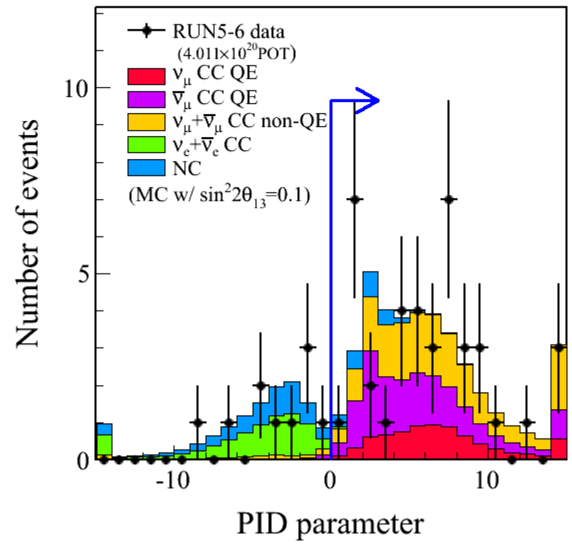
Far detector
Super-Kamiokande

$\bar{\nu}_\mu$ event selection at far detector

1 : 1-Ring

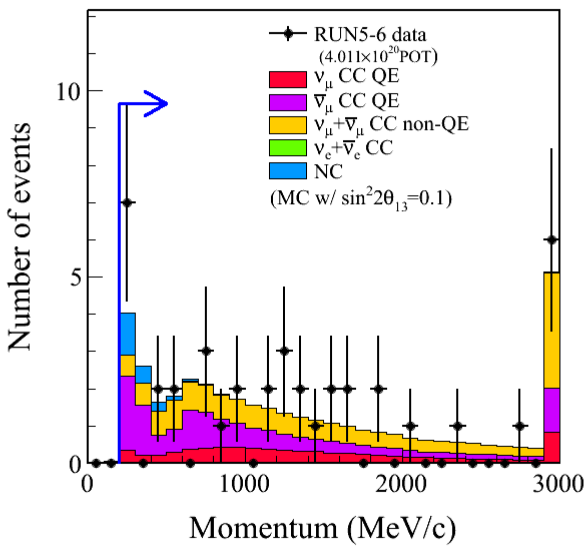


2 : μ-like Ring

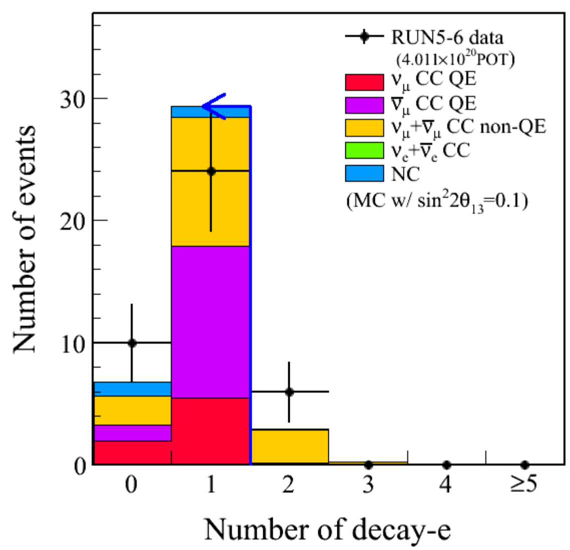


- MC assumes maximal disappearance

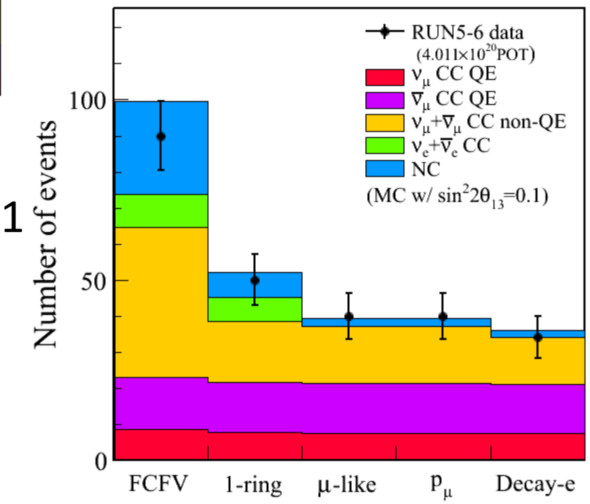
3 : momentum>200MeV/c



4 : # of decay electron ≦ 1



Summary

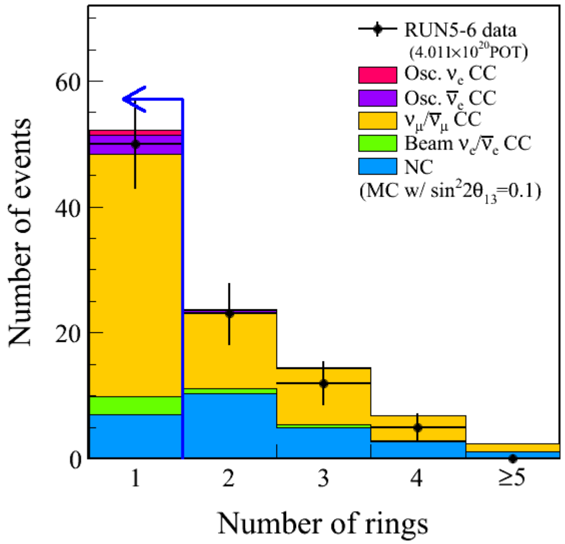


34 events observed

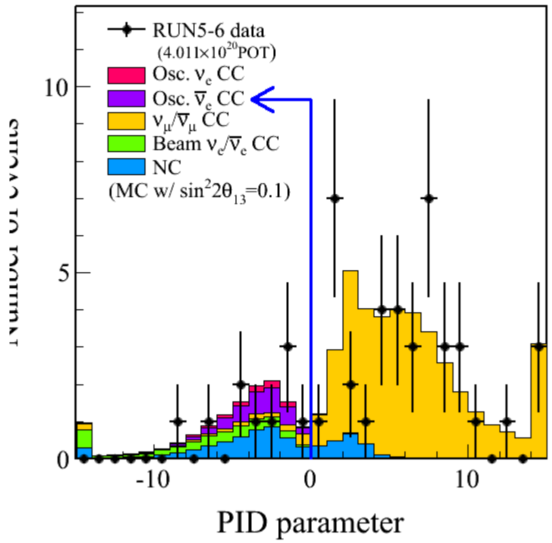
- 103.6 events expected in no oscillation case

$\bar{\nu}_e$ event selection at far detector

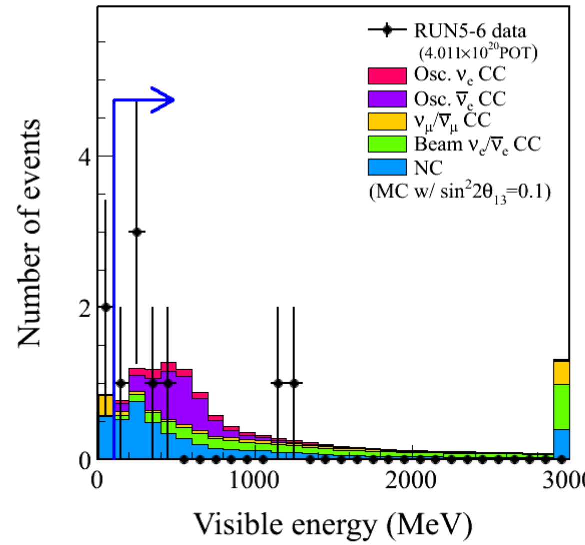
1 : 1-Ring



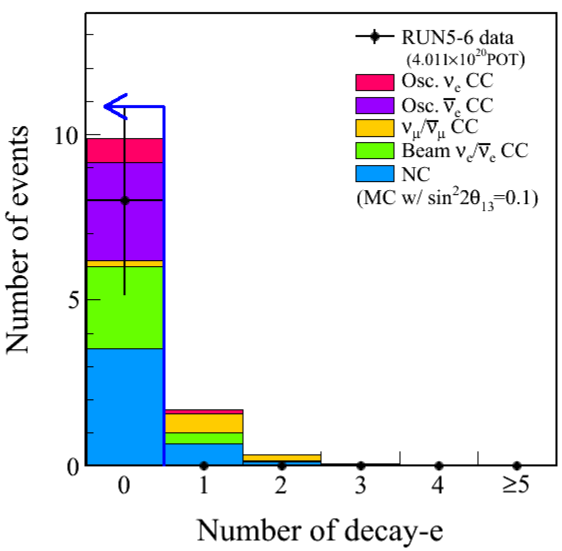
2 : e-like Ring



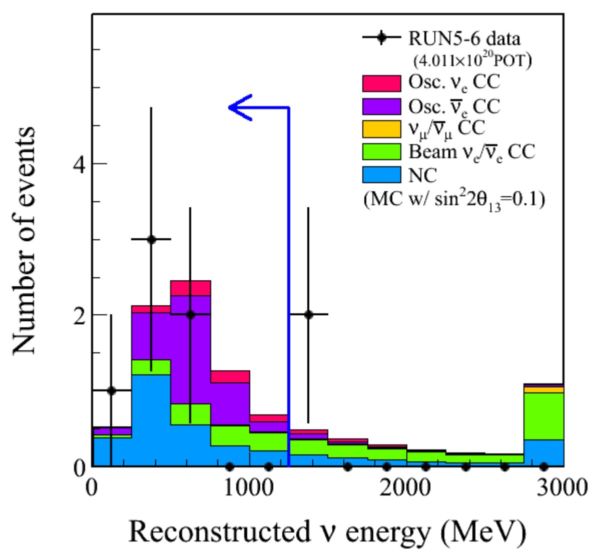
3 : visible energy > 100MeV



4 : # of decay electron = 0



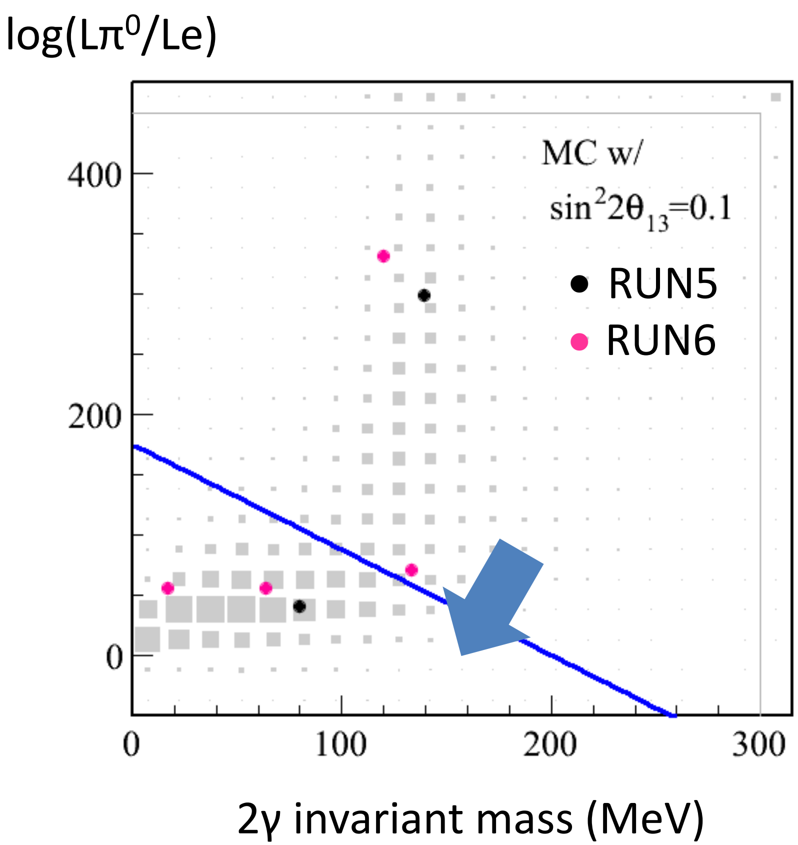
5 : reconstructed energy < 1250MeV



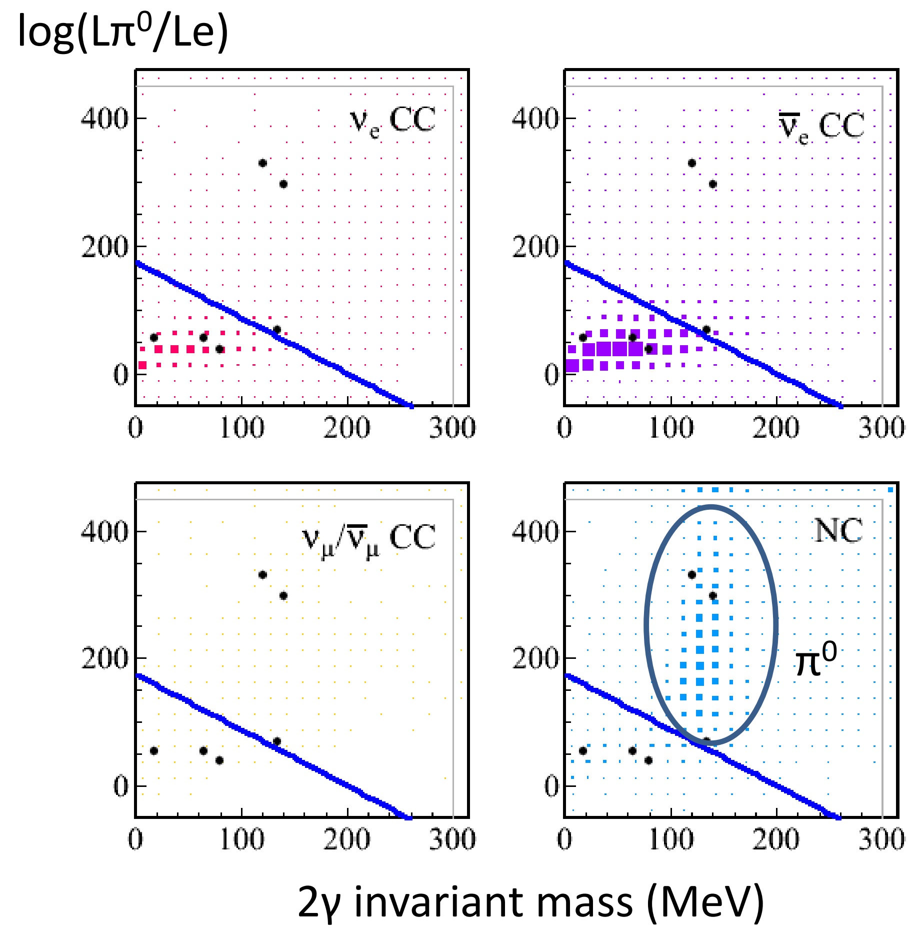
- MC assumes $\sin^2 2\theta_{13}$=0.1, δ_{CP}=0

$\bar{\nu}_e$ event selection (continued)

6: π^0 cut



divided into interaction modes



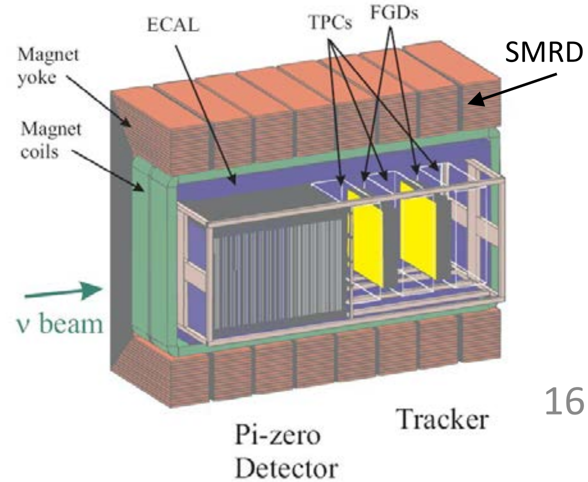
3 events observed

Systematic uncertainties

- Values in brackets are uncertainties **without** ND measurements

1σ error on # of event prediction		$\bar{\nu}_\mu$	$\bar{\nu}_e$
ν flux and cross section	(flux) × (cross section common to ND280)	3.4% (9.2%)	3.0% (9.4%)
	cross section (FD only, include ↓)	10.0 %	9.8%
	multi-nucleon effect on oxygen	9.5%	9.3%
Final or Secondary Hadronic Interaction		2.1%	2.2%
far detector		3.8%	3.0%
total		11.6% (14.4%)	11.0% (13.5%)

- Uncertainties from flux and cross section common to ND are decreased
- Dominant uncertainties come from cross section particular to FD
- Analysis of FGD2 (contain **water** target) will decrease these uncertainties



Muon antineutrino disappearance

- Search for CPT violation
- signals : $\bar{\nu}_\mu \to \bar{\nu}_\mu$, backgrounds : all the others include $\nu_\mu \to \nu_\mu$

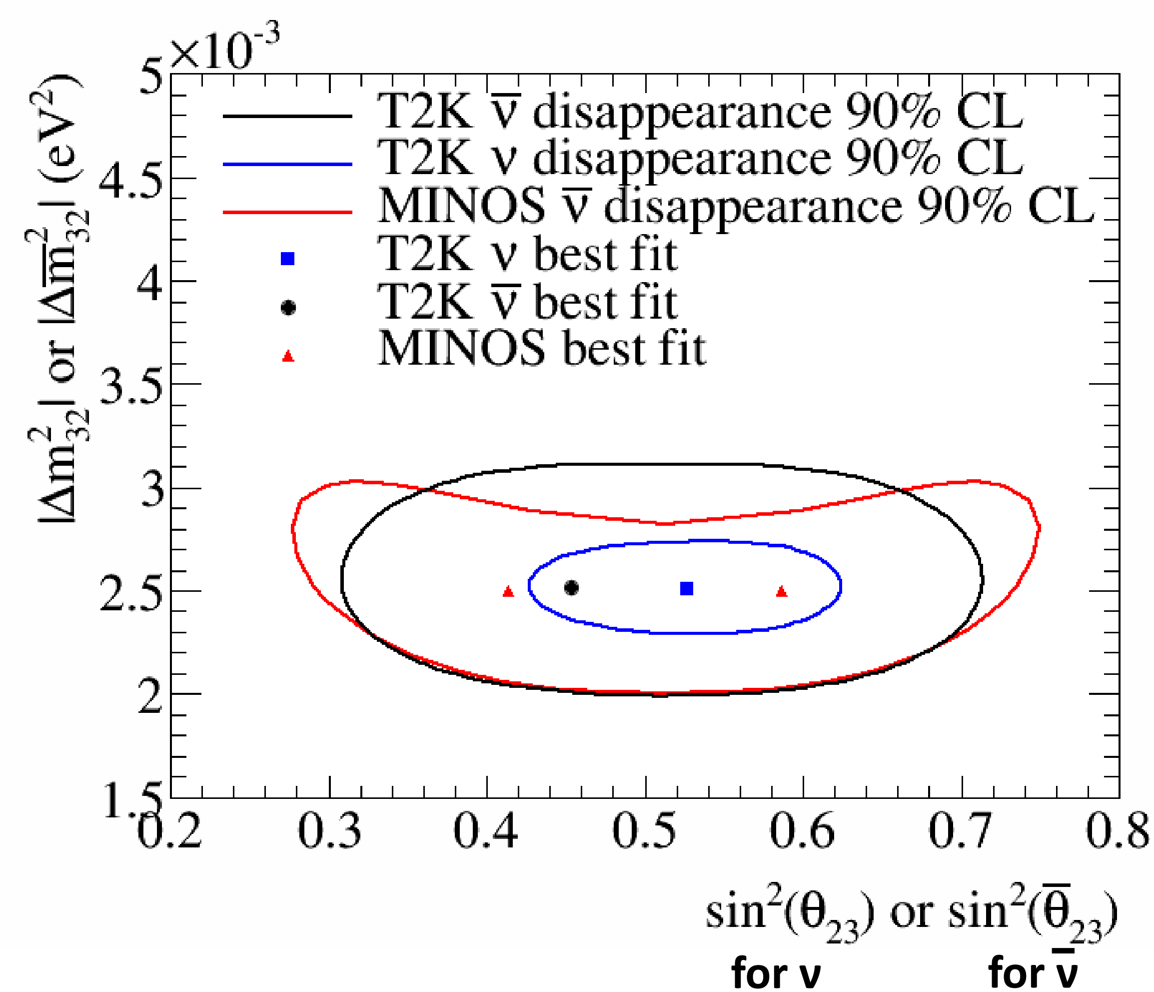
- Use different θ_{23} 、Δm^2_{23} for neutrinos and antineutrinos

  - fix oscillation parameters other than θ_{23}、Δm^2_{23}
  - use values from PDG2014 and past T2K ν-mode results

Parameter	Value
Δm^2_{21}	7.53×10^{-5} eV^2
Δm^2_{32}	2.51×10^{-3} eV^2
$\sin^2 \theta_{23}$	0.527
$\sin^2 2\theta_{12}$	0.846
$\sin^2 2\theta_{13}$	0.0967
δ_{CP}	-1.55
Earth matter density	2.6 g/cm^3
Mass hierarchy	normal
Baseline length	295 km

- Maximum Likelihood method considering number of events, shape (reconstructed energy), systematics

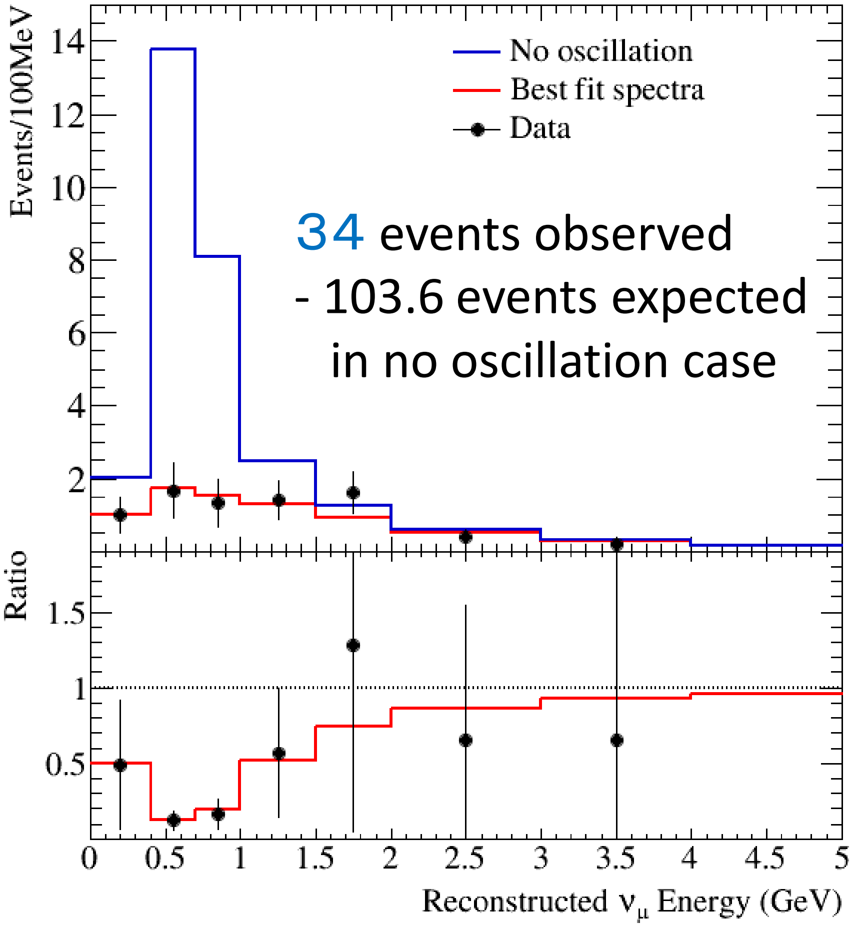
$\bar{\nu}_\mu$ disappearance result

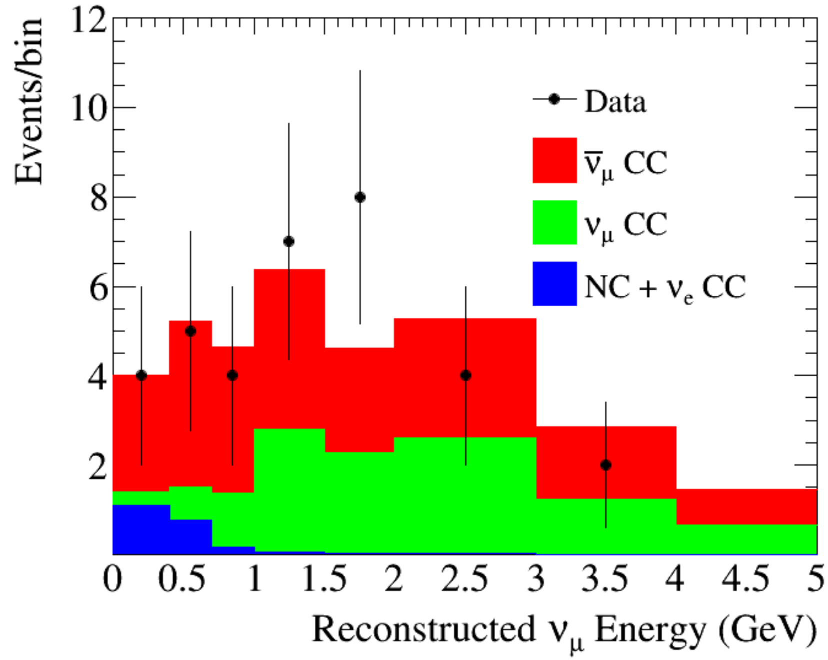


- Best-fit point and 1σ error
  - $\sin^2\bar{\theta}_{23}$: 0.45+0.19-0.07
  - $\Delta\bar{m}^2_{32}$: (2.51+0.29-0.26) $\times 10^{-3}$ eV^2

- consistent oscillation parameters between ν and $\bar{\nu}$
- compatible precision with other experiments

reconstructed neutrino energy





- Clear oscillation dip is observed

$\bar{\nu}_e$ appearance

- expected number of events: depend on δ_{CP} and mass hierarchy

4.01×10^{20} POT	δ_{CP}=-90°	δ_{CP}=0°	δ_{CP}=90°
normal hierarchy	3.73	4.32	4.85
inverted hierarchy	4.18	4.85	5.45

1.96 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal + 1.77 background events

observed events : **3**

- Introduce a discrete parameter β

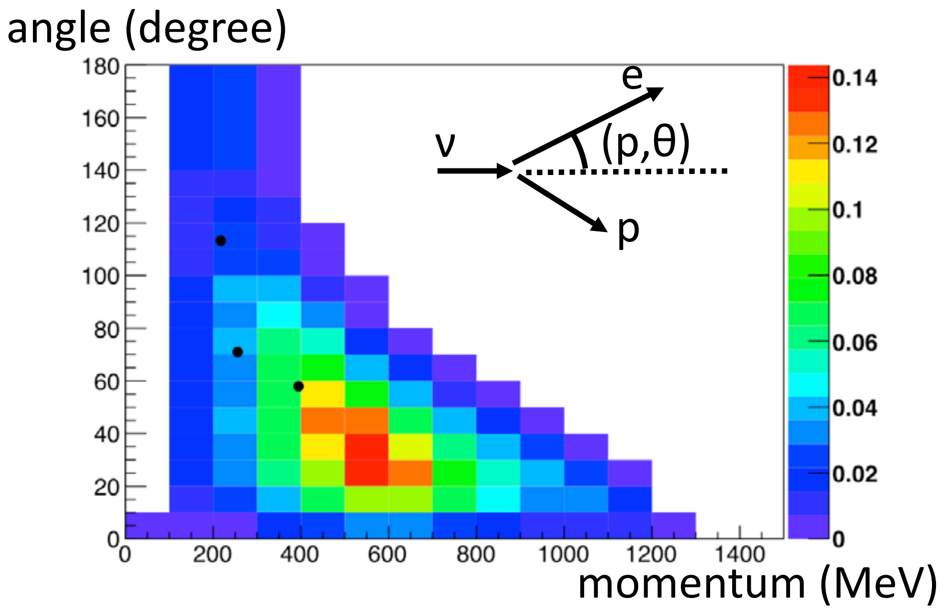
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- β=0 hypothesis : no $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation (background only)
- β=1 hypothesis : nominal $\bar{\nu}_e$ appearance

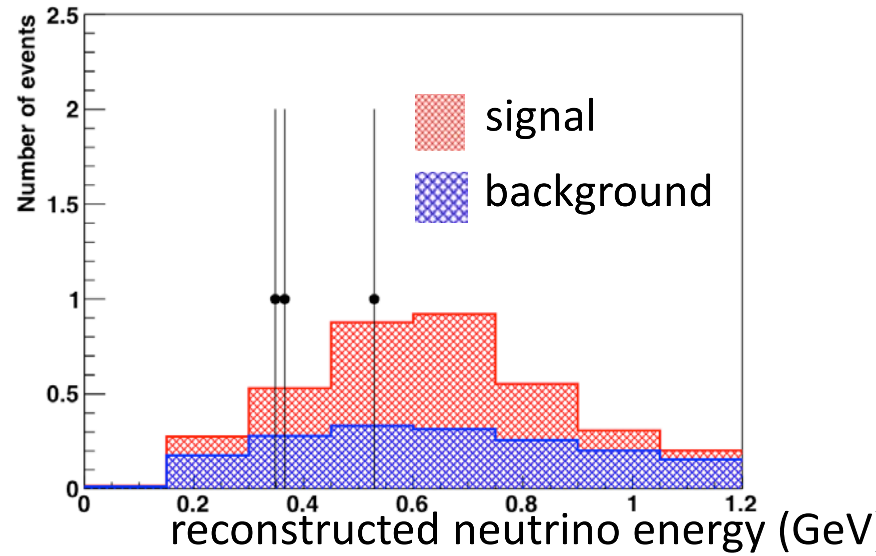
$\bar{\nu}_e$ appearance result

- independent analyses using different shape information

momentum-angle distribution



reconstructed energy distribution



calculate $\Delta\chi^2$ (= $-2\log(L(\beta=0)/L(\beta=1))$) for data and toy experiments

Then, compare them and calculate *p*-value

used information	data $\Delta\chi^2$	data *p*-value
# of event + p-θ	-1.16	0.335
# of event + E_{rec}	0.16	0.159

✓ we can not distinguish $\beta=0$ and $\beta=1$ hypotheses
- more data needed

Summary

- T2K took 1.1×10^{21} POT data in total
- ν-mode $\nu_e + \nu_\mu$ joint fit analysis with reactor constraint
  - first constraint to δ_{CP}
- First oscillation analyses with $\bar{\nu}$-mode are shown.
  - $\bar{\nu}_\mu$ disappearance
    - **34** μ-like antineutrino candidates are observed.
    - Consistent with ν-mode results
  - $\bar{\nu}_e$ appearance
    - **3** e-like antineutrino candidates are observed.
- These analyses are statistically limited

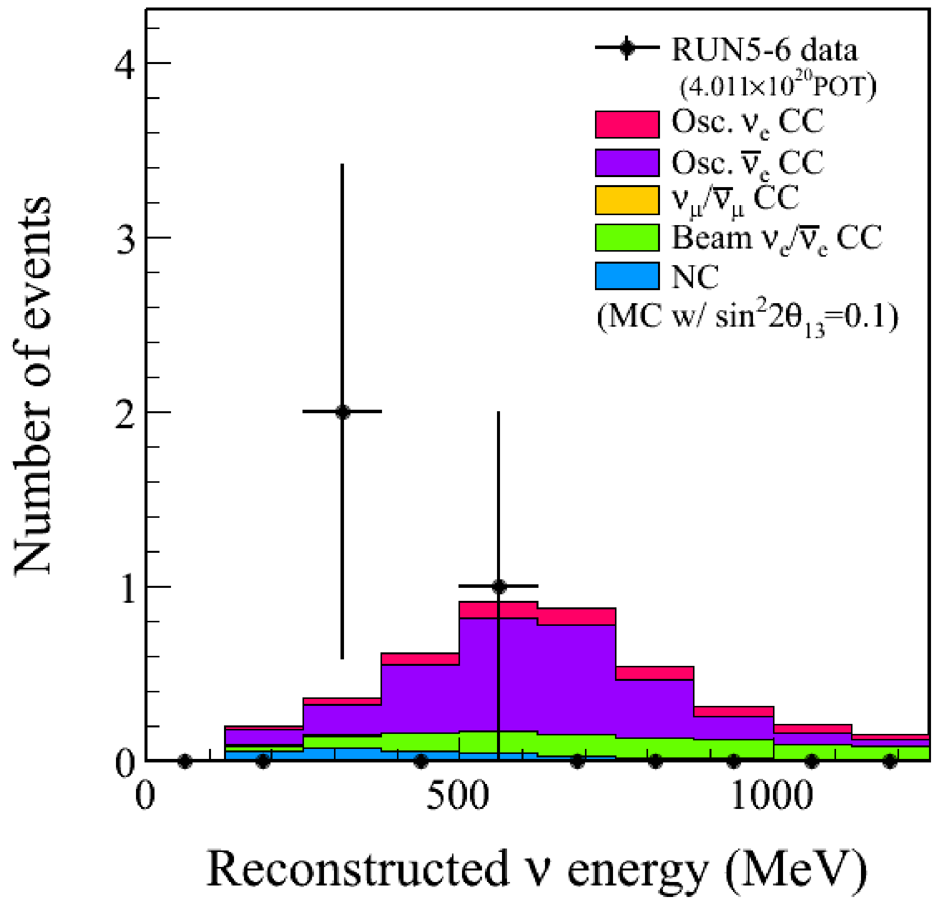
- Overall systematic uncertainties was presented by Bravar yesterday.

  https://indico.bnl.gov/contributionDisplay.py?contribId=40&confId=1282

Back up

$\bar{\nu}_e$ reconstructed energy distribution

after all selection applied



$\bar{\nu}_\mu$ disappearance result