# Overview of Recent Results From the T2K Experiment

**New Trends in High-Energy Physics**


**October 2-8, 2016**

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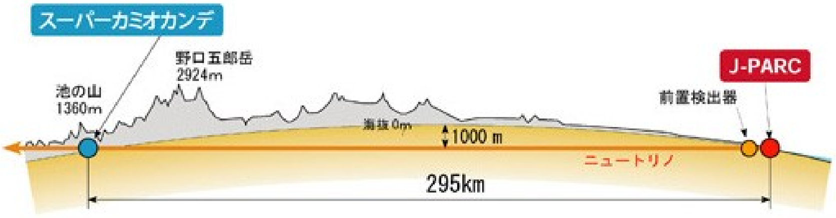
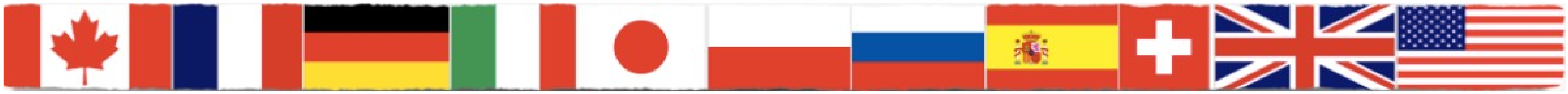
(Representing the T2K collaboration)

# Outline

- Motivation
- T2K Experimental Overview
- Oscillation Results:
  - Muon (+Anti-)Neutrino Disappearance
  - Electron (+Anti-)Neutrino Appearance
  - Joint Fits
- Other Physics
- Prospects, Outlook and Summary



# Motivation

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

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

Atmospheric & accelerator:
$\theta_{23} \sim 45^\circ$
$(\Delta m_{23})^2 \sim 2.4\times 10^{-3}$ eV$^2$

Interference:
$\theta_{13} \sim 9^\circ$ and $\delta_{CP}$=??

Solar & reactor:
$\theta_{12} \sim 34^\circ$
$(\Delta m_{12})^2 \sim 8\times 10^{-5}$ eV$^2$

**Muon neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$) :**

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1-\cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2\left(\frac{\Delta m^2_{31} L}{E_\nu}\right) \longrightarrow$$

**Sensitive to:**
**$\theta_{23}$, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$)**
( $\Delta m^2_{32} = m^2_3 - m^2_2$ )

**Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$):**

Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2\theta_{23}}\boxed{\sin^2 2\theta_{13}}\frac{\sin^2(\boxed{\Delta}(1-A))}{(1-A)^2} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2 A\Delta}{A^2}$$

Expanded under small $\theta_{13}$,$\alpha$

$$+\alpha\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\frac{\sin((1-A)\Delta)}{1-A}\frac{\sin A\Delta}{A}\cos(\boxed{\delta}+\Delta) \longrightarrow$$

CP Violation!

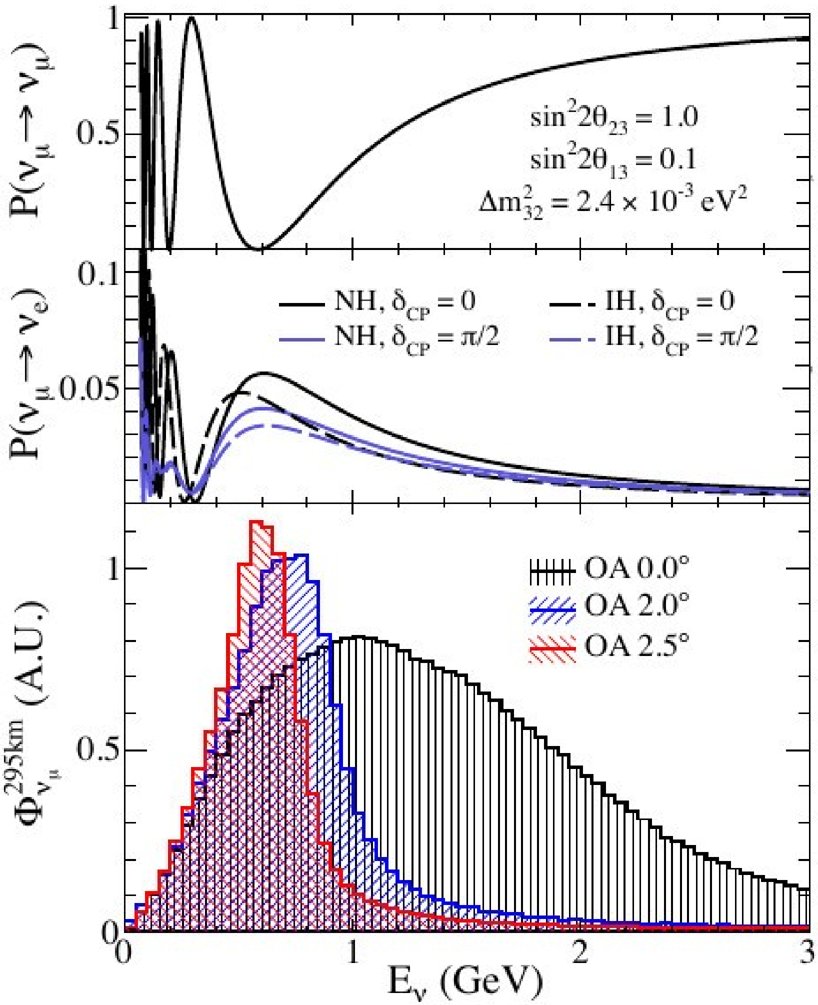
$$A = \pm 2\sqrt{2} G_F n_e E \Delta m^2_{31} \qquad \Delta = \frac{\Delta m^2_{31} L}{E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Hierarchy?

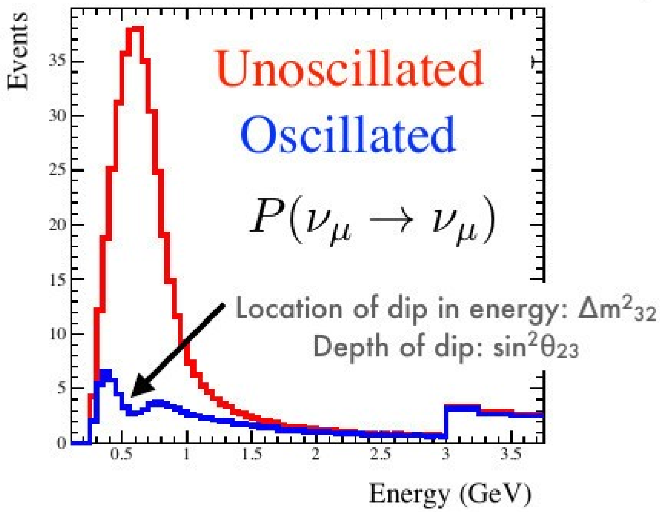
**Sensitive to:**
**$\theta_{13}$, $\delta_{CP}$, $\theta_{23}$, $\Delta m^2_{31}$**

Depends on sign of mass difference: *i.e.* Mass Hierarchy

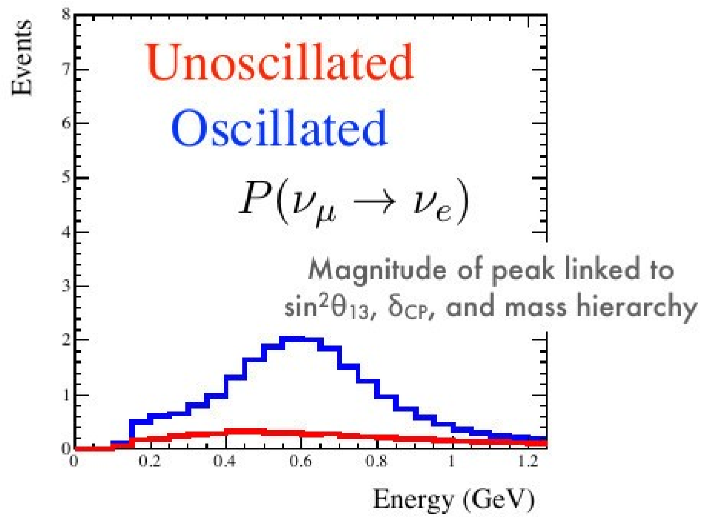
# Motivation



$\sin^2 2\theta_{23} = 1.0$
$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$
$P(\nu_\mu \to \nu_\mu)$
NH, $\delta_{CP} = 0$
IH, $\delta_{CP} = 0$
NH, $\delta_{CP} = \pi/2$
IH, $\delta_{CP} = \pi/2$
$P(\nu_\mu \to \nu_e)$
OA 0.0°
OA 2.0°
OA 2.5°
$\Phi^{295km}_{\nu_\mu}$ (A.U.)
$E_\nu$ (GeV)

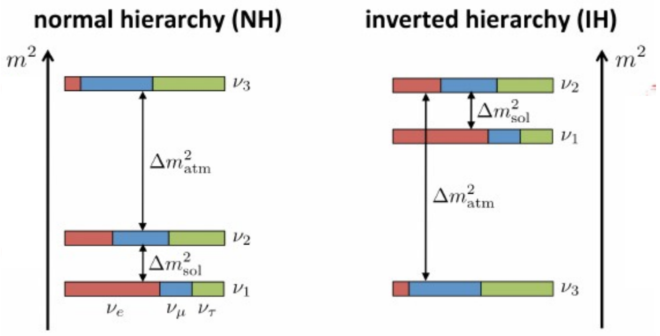
Unoscillated
Oscillated
$P(\nu_\mu \to \nu_\mu)$
Location of dip in energy: $\Delta m^2_{32}$
Depth of dip: $\sin^2\theta_{23}$
Events
Energy (GeV)

Unoscillated
Oscillated
$P(\nu_\mu \to \nu_e)$
Magnitude of peak linked to
$\sin^2\theta_{13}$, $\delta_{CP}$, and mass hierarchy
Events
Energy (GeV)

# What We Don't Know?

- **Value CP-Violating Phase:** $\delta$
- **$\theta_{23}$ Maximal? Octant? (< or > 45$^0$)**
- **Sign of the mass difference:**
  - **Normal Hierarchy (NH) > 0**
  - **Inverted Hierarchy (IH) < 0**



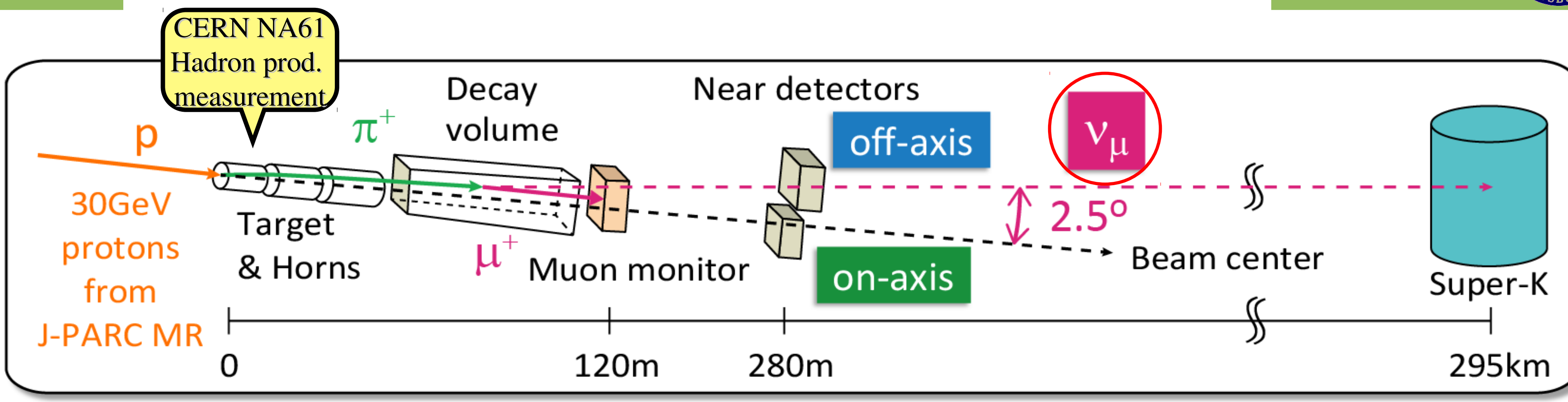

- **Are there any more ν's? (sterile)**
- **Are Neutrinos Dirac or Majorana?**

# The T2K Experiment
## (Tokai to Kamioka)


**Goals:**

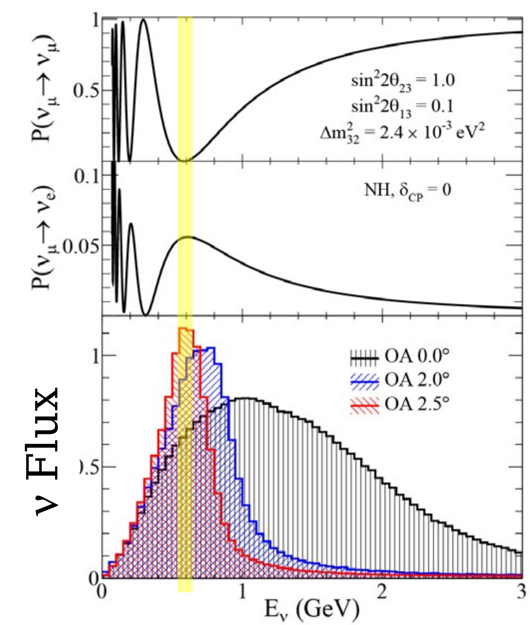
- Study $\nu_e$ and $\bar{\nu}_e$ appearance $(\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e)$: Explore $\delta_{CP}$ and $\theta_{13,\,23}$
- Precision measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance: Explore $\theta_{23}$ and $\Delta m^2_{23}$

# Overview of T2K: Beam

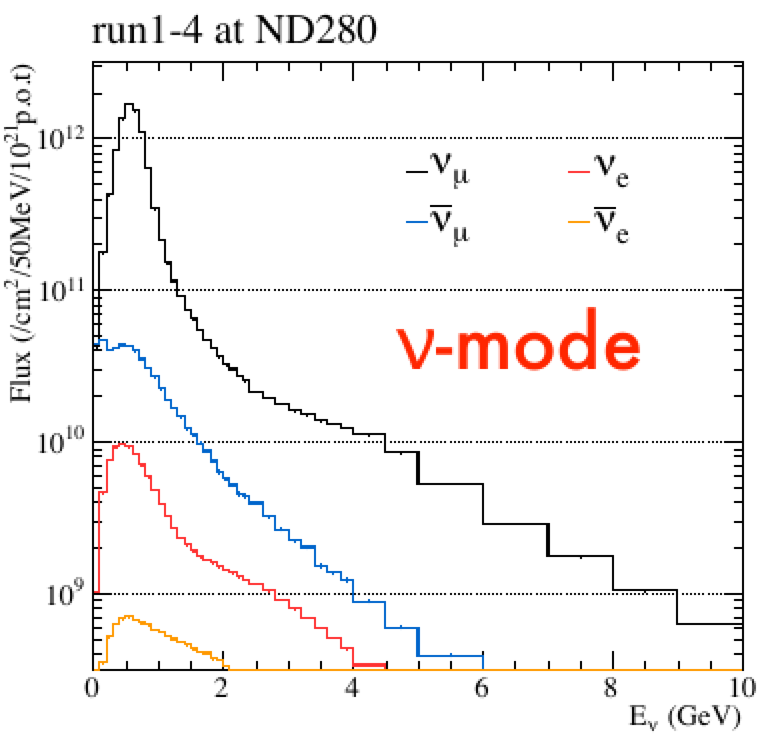


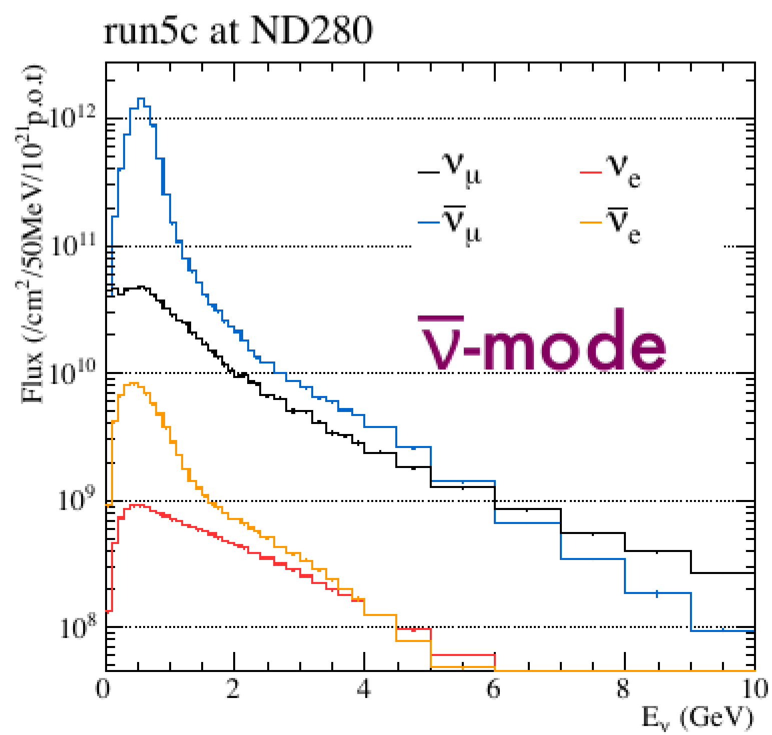

## First Use of Off-axis $\nu_\mu$ Beam:

- Intense & high-quality beam (Beam direction stability < 1mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low-energy narrow-band beam
- Can choose between ν and $\bar{\nu}$ by changing current direction in horns
- $E_\nu$ peak around oscillation maximum (~0.6 GeV)
- Small high-energy tail → reduces feed-down background events
- π,K production at target was measured using CERN NA61 exp.



# Beam Configurations

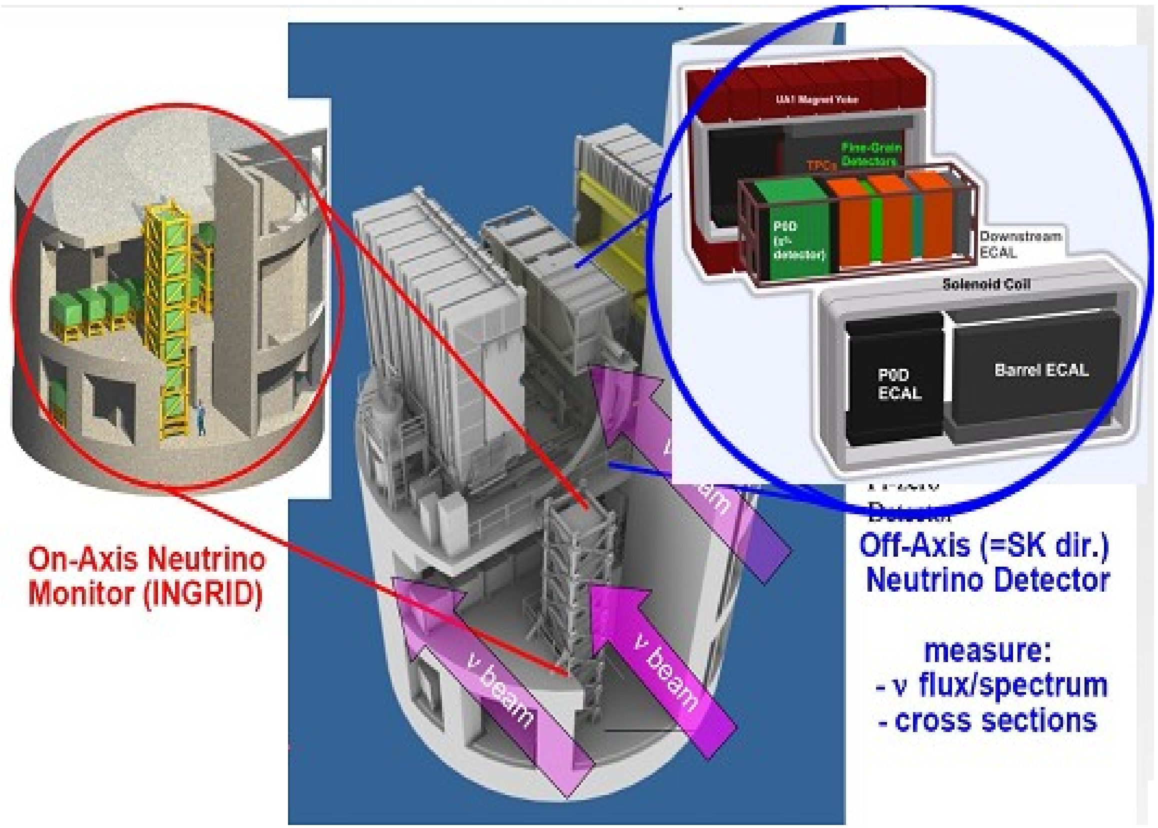



ν – mode known as "forward horn current" (FHC) or "positive focusing" (PF)

$\bar{\nu}$ – mode known as "reverse horn current" (RHC) or "negative focusing" (NF)

# Overview of T2K: Near Detectors(ND280)

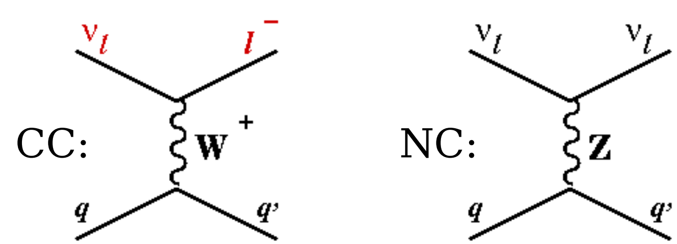



**On-Axis Detector (INGRID) Monitor ν:**

- **Beam direction**
- **Beam Intensity**

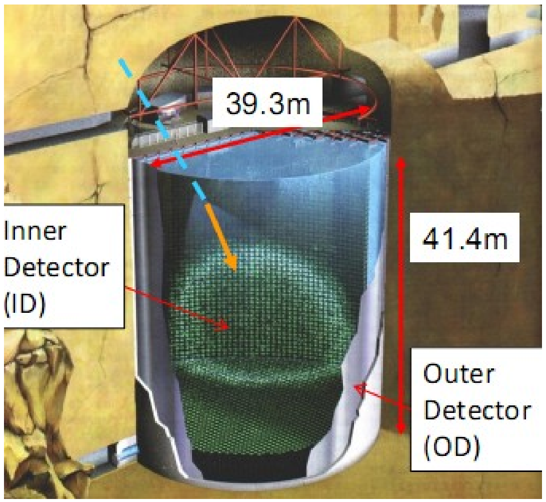
**Off-Axis Detector:**

- **In SK Direction**
- **Measure:**
  - **ν flux**
  - **Cross-section measurements using water targets to reduce systematic errors on oscillation parameters**

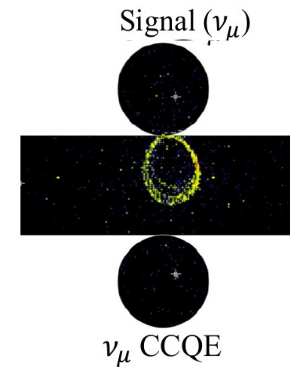


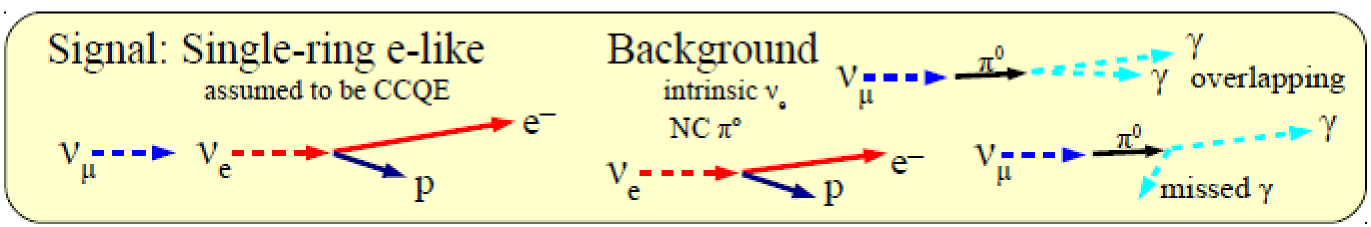

→ Used for monitoring of beam, flux constraints and systematic error reduction

# The T2K Far Detector: Super-Kamiokande

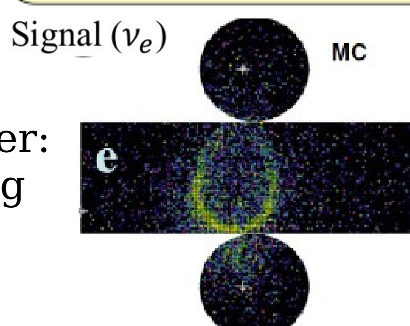



- 50 kiloton Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- High $\nu_e$ signal efficiency plus high $\pi^0$ rejection
  - 32 kiloton inner volume (22.5 kiloton fiducial)
  - 2 meter wide outer region to identify entering particles
- Probability to misidentify muon as electron is small
- GPS time recorded in real-time for every spill
  - Associate events with J-PARC (beam)

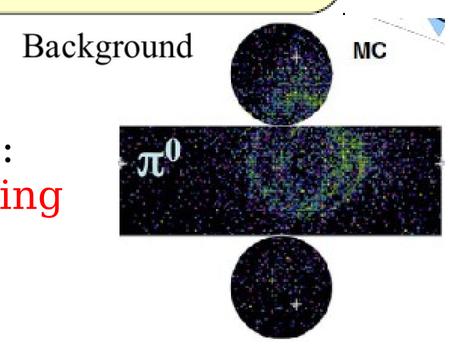


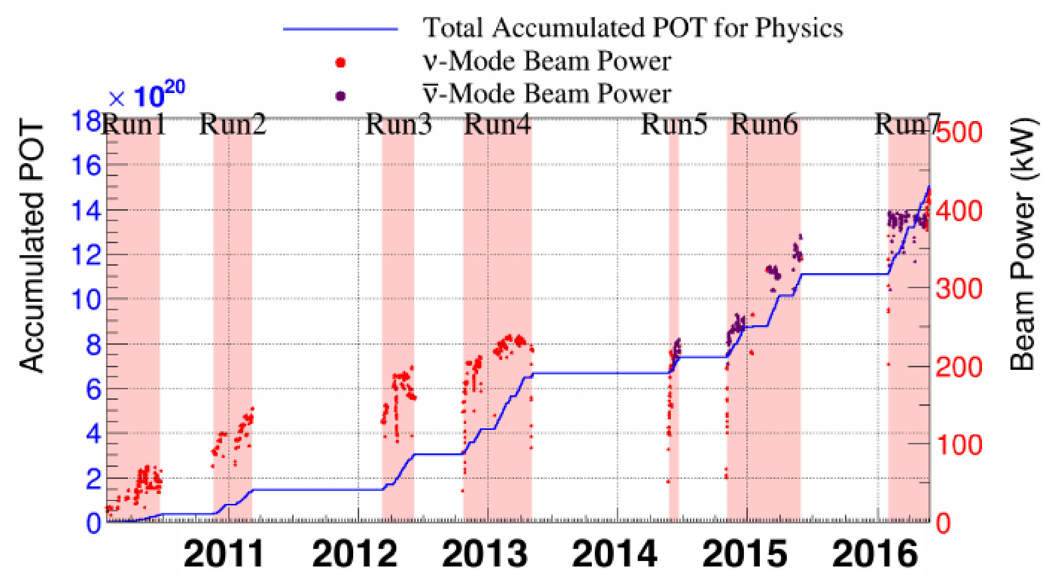

1 EM Shower:
1 Fuzzy Ring




2 EM Showers:
2 or 1 Fuzzy Ring



# Analyzed Data: Run 1-7



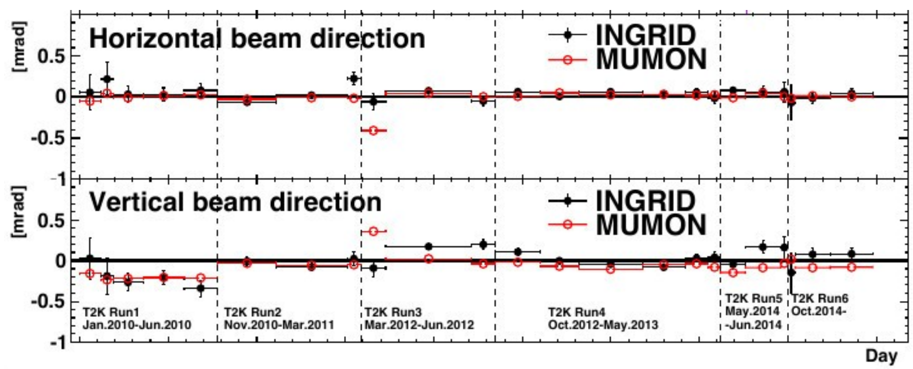

Full data (as of May 27, 2016)

→ ν-mode: $7.48 \times 10^{20}$ POT

→ $\bar{\nu}$-mode: $7.47 \times 10^{20}$ POT

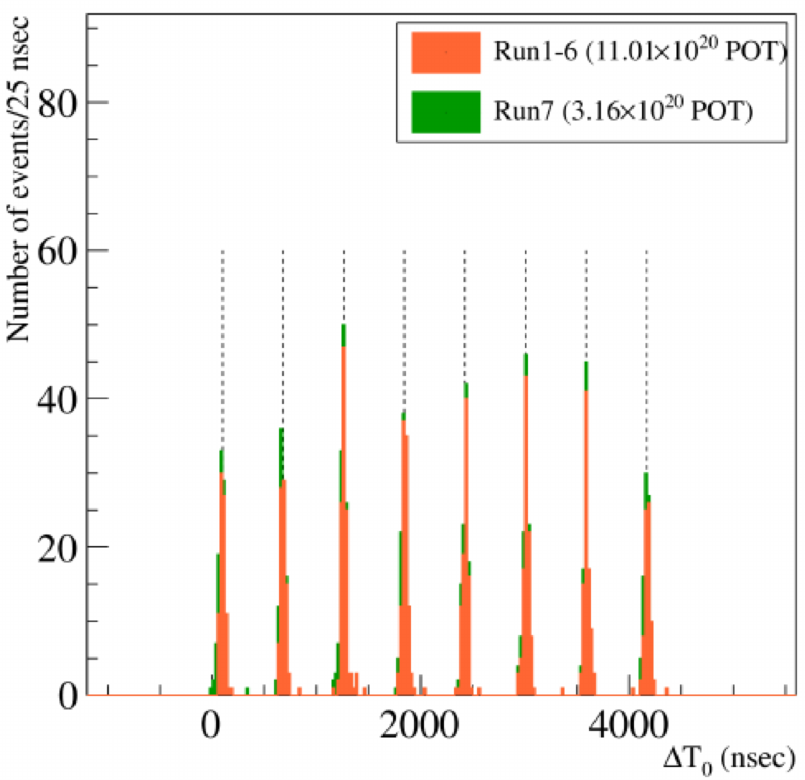
(POT – Protons on Target)

Required Beam direction stability achieved (< 1mrad)



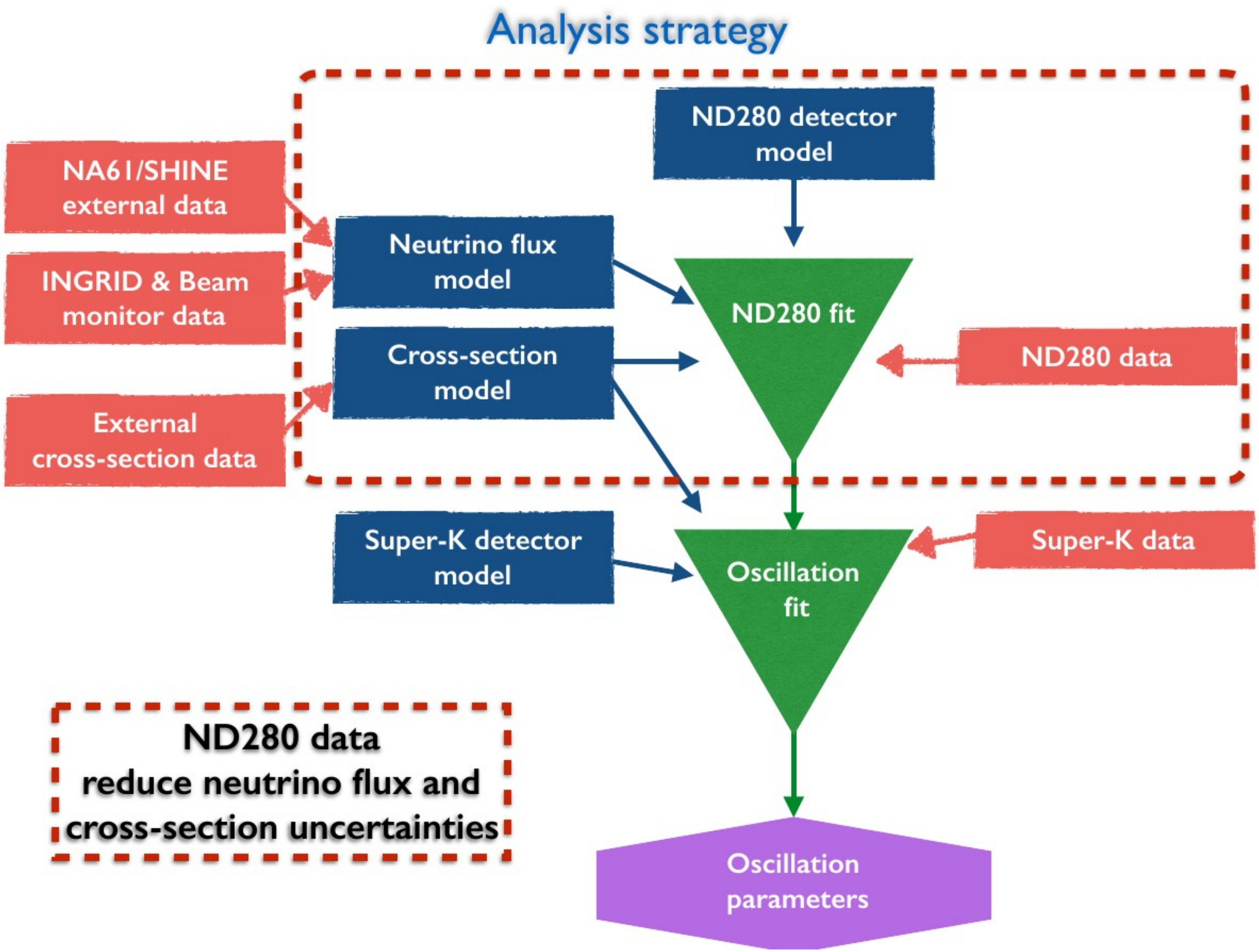
# Far Detector (SK): Event Timing

- T2K beam timing
  - Time window of (−2μs, +10μs)
- Fully Contained (FC) definition
  - No signal in Outer Detector (OD)
- Fiducial volume definition:
  - Vertex > 2 m from wall




(JPARC: 8 bunches/spill)

# Oscillation Parameter Fitting Procedure



# Oscillation Results

**First the disappearance (anti-)neutrino results…**

(Test for CPT Violation or a search for non-standard ν interactions)

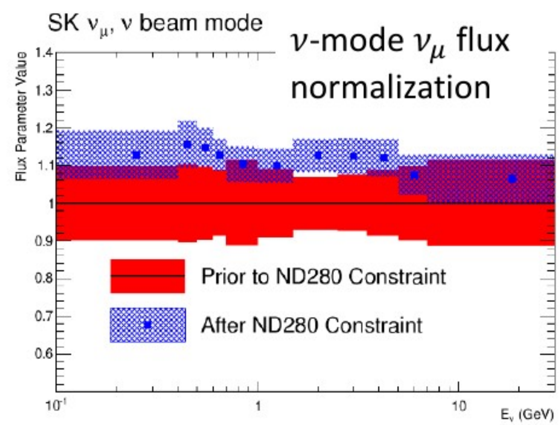
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2\left(\frac{\Delta m^2_{31} L}{E_\nu}\right)$$

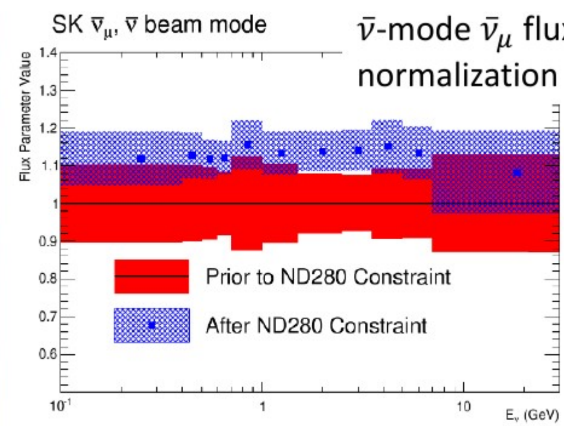
**Sensitive to:**
**$\theta_{23}$, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$ )**

- $\theta_{23}$ **Maximal? Octant? (< or > $45^0$)**

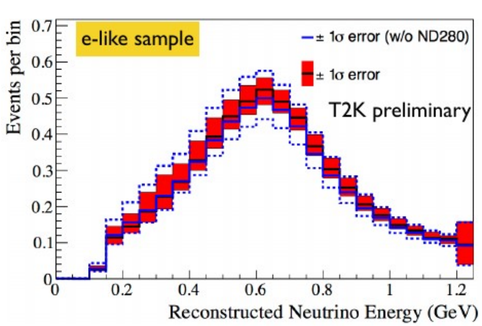
# Flux & $\nu$ Background Constraints using ND280

- Select charged-current (CC) events in ND280
- Separate into 3 categories (CCQE, CC Resonance, CC DIS)
  - Parameters from simultaneous fit of 3 samples
  - Used for prediction of Super-K neutrino spectrum w/o oscillation



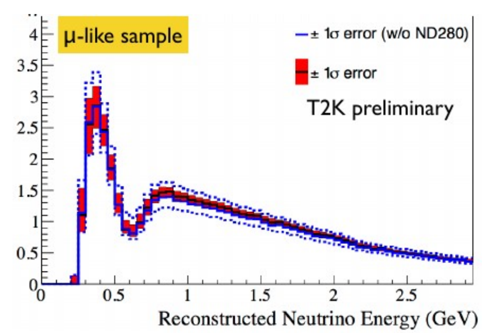

ND280 constraint provides significant reduction of uncertainty at Super-K:
Increases the effectiveness of each proton on target – Don't need to run as long!




(Appearance)

| Total $\delta N_{SK}/N_{SK}$ | | | |
|---|---|---|---|
| **Beam mode** | **sample** | **ND280 constrained** | **w/o ND280** |
| neutrino | μ-like | 5.03% | 12.0% |
| neutrino | e-like | 5.41% | 11.9% |
| anti-neutrino | μ-like | 5.22% | 12.5% |
| anti-neutrino | e-like | 6.19% | 13.7% |

20



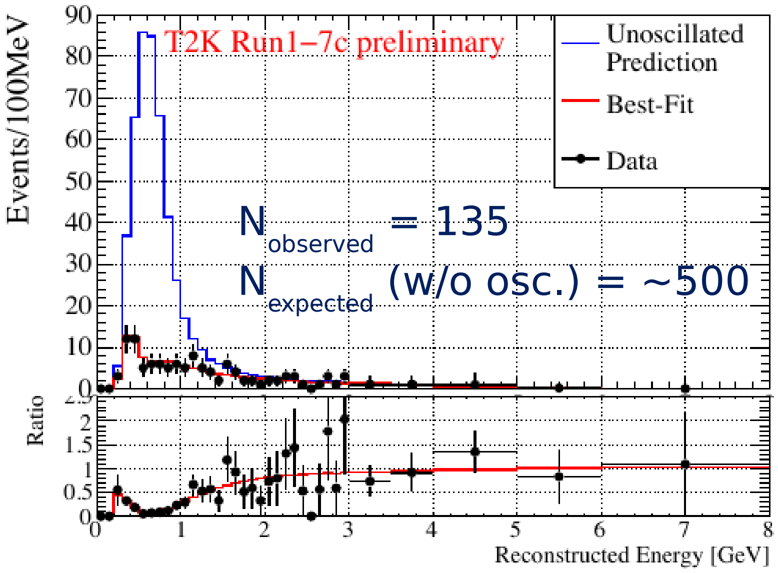

(Disappearance)

# T2K: Disappearance Event Selection

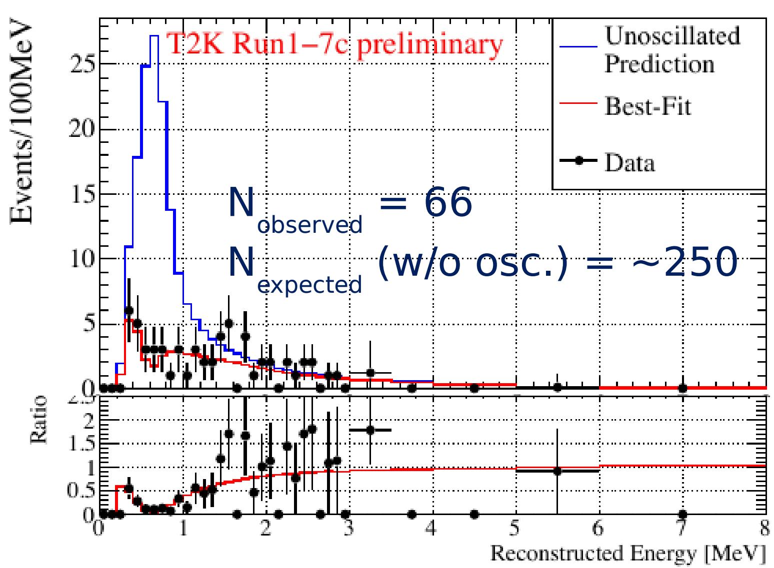
**$\nu_\mu$ ($\bar{\nu}_\mu$) event selection (Disappearance):**

- Fully contained fiducial volume
- Single-ring μ-like event
- $p_\mu$ > 200 MeV/c
- # of decay electron ≤ 1

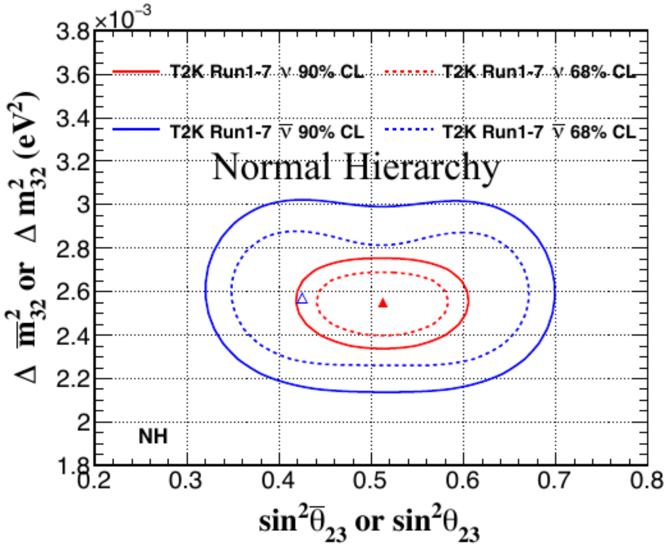
$\nu_\mu$

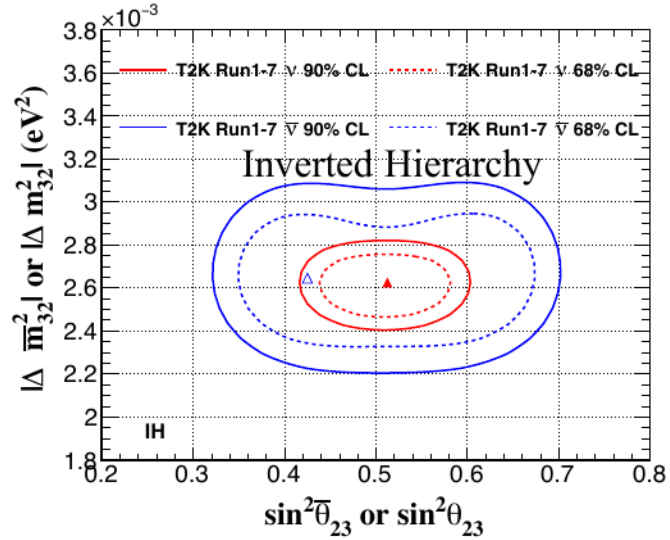



$\bar{\nu}_\mu$

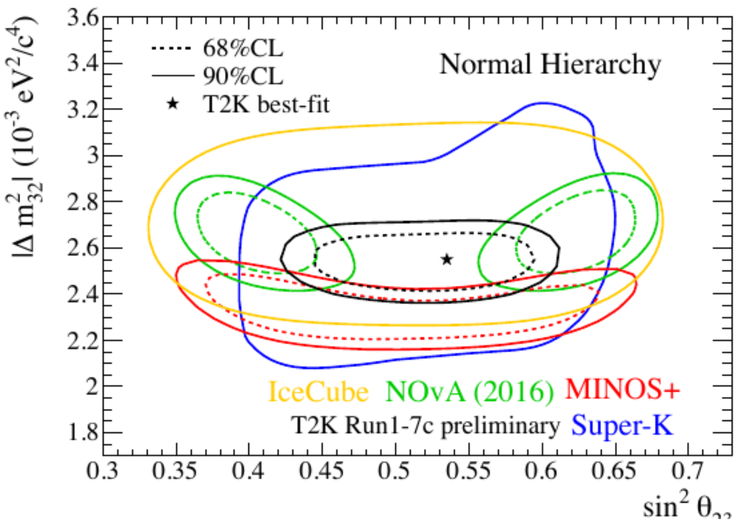


# Disappearance: Comparison between ν and $\bar{\nu}$




No obvious difference between ν and $\bar{\nu}$ observed... And we're consistent with maximal mixing ($\Theta_{23}$=45°)




Comparison to other experiments

| | NH | IH |
|---|---|---|
| $\sin^2\theta_{23}$ | $0.532^{+0.046}_{-0.068}$ | $0.534^{+0.043}_{-0.007}$ |
| $\lvert\Delta m^2_{32}\rvert$ (×$10^{-5}$ eV$^2$/c$^4$) | $254.5^{+8.1}_{-8.4}$ | $251.0^{+8.1}_{-8.3}$ |

# Oscillation Results

## Appearance (anti-)neutrino results…

Appearance

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2\theta_{23}}\boxed{\sin^2 2\theta_{13}}\frac{\sin^2(\boxed{\Delta}(1-A))}{(1-A)^2} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2 A\Delta}{A^2}$$

Expanded under small $\theta_{13},\alpha$

$$+\alpha\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\frac{\sin((1-A)\Delta)}{1-A}\frac{\sin A\Delta}{A}\cos(\boxed{\delta}+\Delta)$$

$$A = \pm 2\sqrt{2}G_F n_e E \Delta m^2_{31} \qquad \Delta = \frac{\Delta m^2_{31}L}{E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Hierarchy?

CP Violation!

**Sensitive to:**
**$\theta_{13}$, $\delta_{CP}$, $\theta_{23}$, $\Delta m^2_{31}$**

- **CP-Violating Phase: $\delta$**

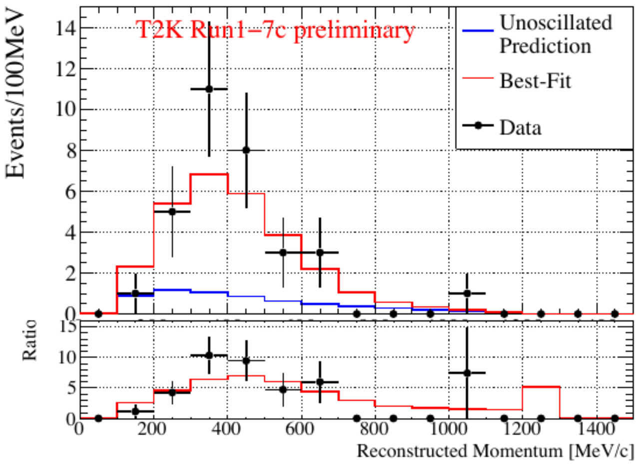
# T2K: Appearance Event Selection

**$\nu_e$ ($\bar{\nu}_e$)event selection (Appearance):**

- Fully contained fiducial volume
- Single-ring e-like event
- Evisible > 100 MeV, Erec < 1250 MeV
- # of decay electron = 0
- $\pi^0$ rejection cut

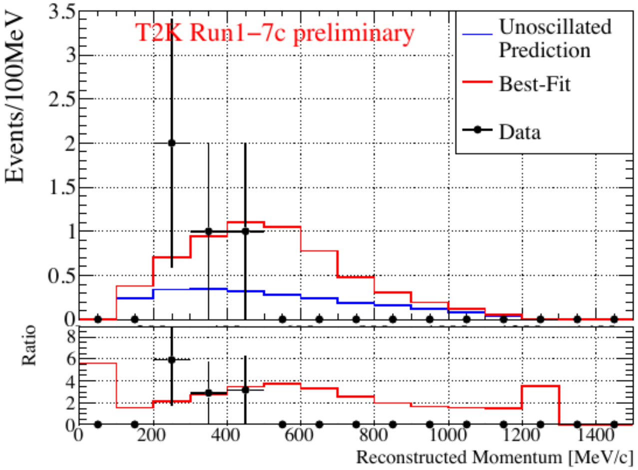
| | $\delta_{cp} = -\pi/2$ (NH) | $\delta_{cp} = 0$ (NH) | $\delta_{cp} = +\pi/2$ (NH) | $\delta_{cp} = \pi$ (NH) | Observed |
|---|---|---|---|---|---|
| $\nu_e$ | 28.7 | 24.2 | 19.6 | 24.1 | 32 |
| $\bar{\nu}_e$ | 6.0 | 6.9 | 7.7 | 6.8 | 4 |

$\nu_e$




32 events observed

$\bar{\nu}_e$




4 events observed

# Expected # of events($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$):

$\nu_\mu$:

| | |
|---|---|
| ν-mode run | 135.8 |
| $\bar{\nu}$-mode run | 64.2 |

(Observed
135
66)

$\nu_e$:

| | | $\delta_{CP} = -\pi/2$ | $\delta_{CP} = 0$ | $\delta_{CP} = +\pi/2$ | $\delta_{CP} = \pi$ |
|---|---|---|---|---|---|
| $\nu$-mode run | Normal | 28.7 | 24.2 | 19.6 | 24.1 |
| | Inverted | 25.4 | 21.3 | 17.1 | 21.3 |
| $\bar{\nu}$-mode run | Normal | 6.0 | 6.9 | 7.8 | 6.8 |
| | Inverted | 6.5 | 7.4 | 8.4 | 7.4 |

| | $\delta_{CP} = -\pi/2$ | $\delta_{CP} = 0$ | $\delta_{CP} = +\pi/2$ | $\delta_{CP} = \pi$ |
|---|---|---|---|---|
| $\bar{\nu}_\mu \to \bar{\nu}_e$ | 2.8 | 3.8 | 4.8 | 3.8 |
| $\nu_\mu \to \nu_e$ | 1.0 | 0.9 | 0.7 | 0.8 |
| other bkg. | | 2.2 | | |

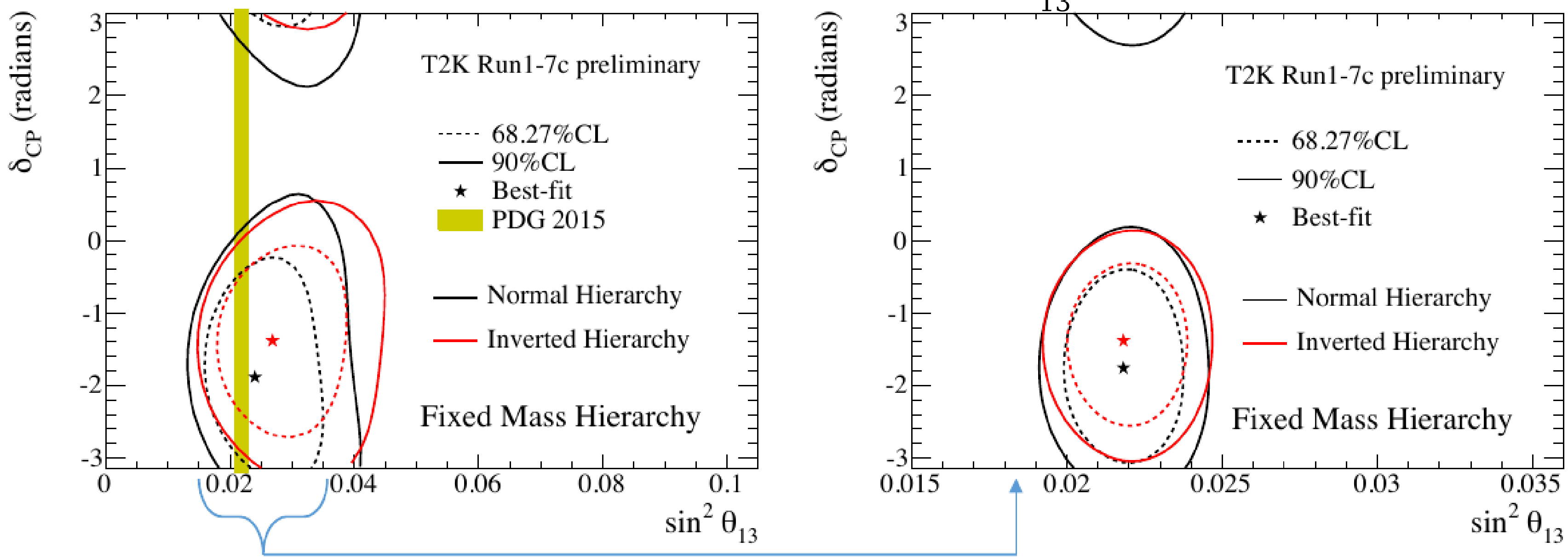
(Observed
32

4)

# Joint Fits ($\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$): $\delta_{CP}$ *vs* $\Theta_{13}$

T2K-Only

T2K Result with Reactor Constraint [$\sin^2(2\theta_{13}) = 0.085 \pm 0.005$]

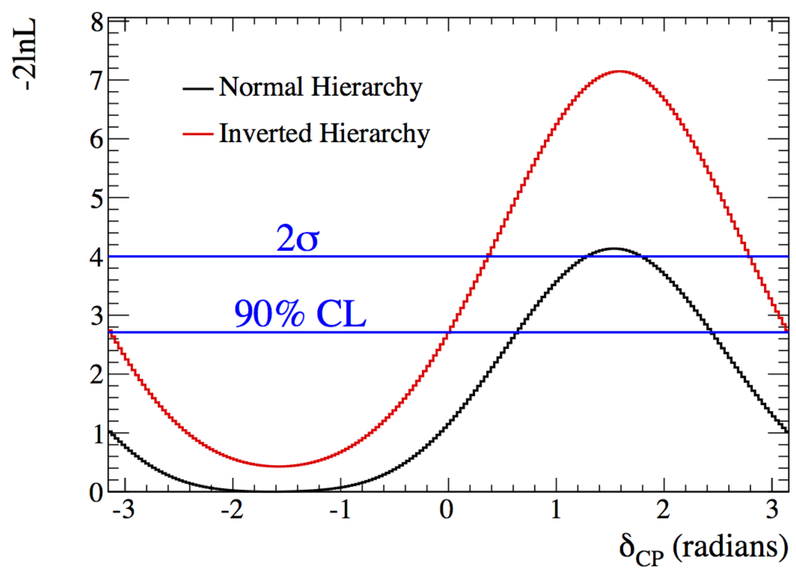



- T2K results consistent with reactor results
- Data prefer maximal CPV: $\delta_{CP}=-\pi/2$
  - Even though statistics are small $\bar{\nu}_e$ results reinforce maximal CPV observed for $\nu_e$ data

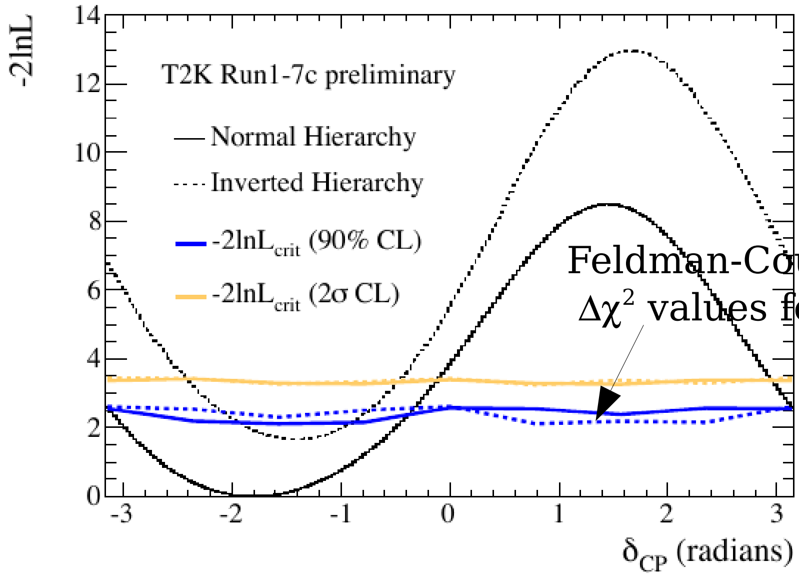
# Joint Fits ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$): $\delta_{CP}$ Sensitivity

T2K result with reactor constraint $\sin^2(2\theta_{13}) = 0.085 \pm 0.005$

**Sensitivity (Simulation)**




**Measurement (Data)**




90% Confidence Interval:

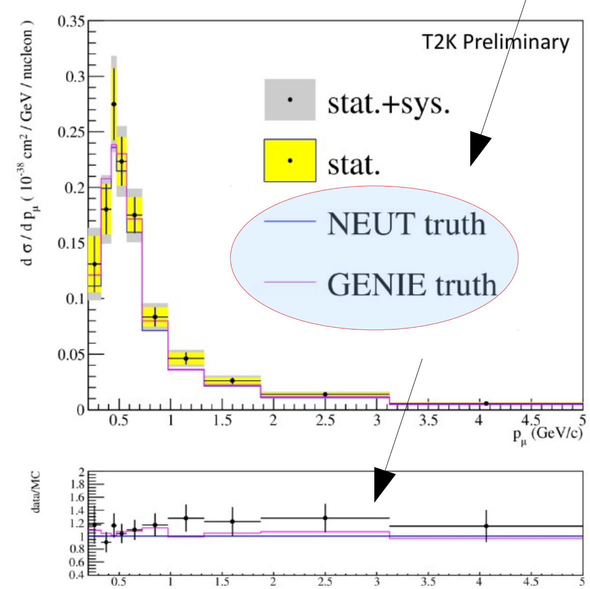
- Normal mass ordering: [-3.13 rad. , -0.39 rad. (-179°,-22°)]
- Inverted mass ordering: [-2.09 rad. , -0.74 rad. (-120°, -42°)]

**→ Slight Preference for NH over IH**

# T2K(ND280) ν Cross-Section Measurements
## (Selected Results)

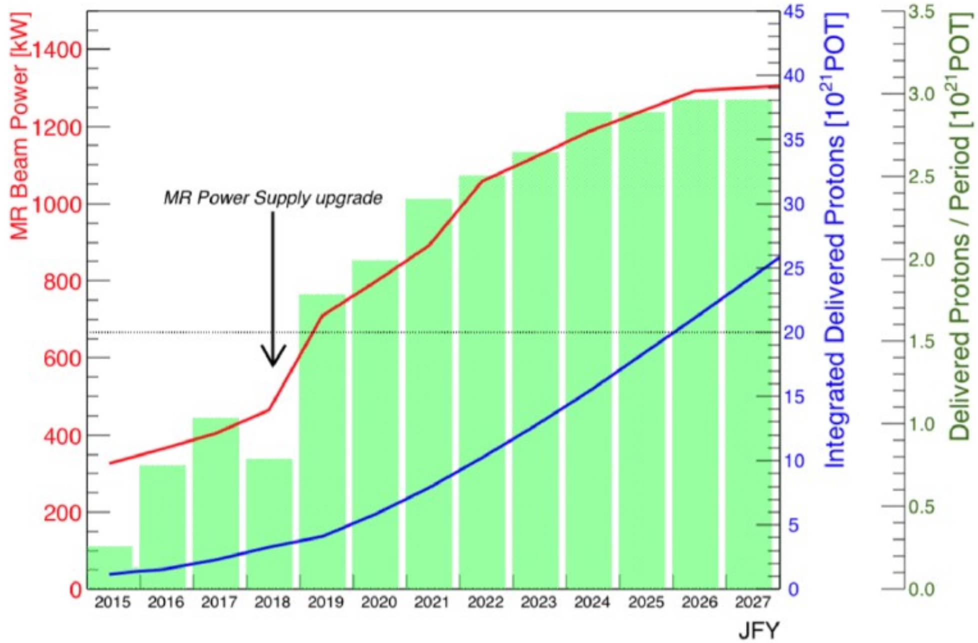
- T2K near detector suite(ND280/INGRID) can measure cross sections in addition to its direct role in oscillation analyses:
  - Important in their own right: Understand how ν's interact with matter
  - Reduce the systematic errors in oscillation analyses – improve MC models
    - We're now in an era of precision measurements in ν physics

- INGRID $\nu_\mu$ CC Inclusive on iron : PRD 93 072002
- INGRID $\nu_\mu$ CCQE on carbon : PRD 91 112002
- ND280 $\nu_\mu$ CC0π on carbon: PRD 93 112012
- ND280 $\nu_\mu$ CC0π on water
- ND280 $\nu_\mu$ CC1$\pi^+$ on Carbon
- ND280 $\nu_\mu$ CC1$\pi^+$ on Water : arXiv:1605.07964
- ND280 $\nu_\mu$ CC coherent π+ production on Carbon : arXiv:1604.04406
- ND280 $\bar{\nu}_\mu$ CC Inclusive on Carbon
- ND280 $\nu_e$ CC Inclusive on Carbon : PRL 113 241803

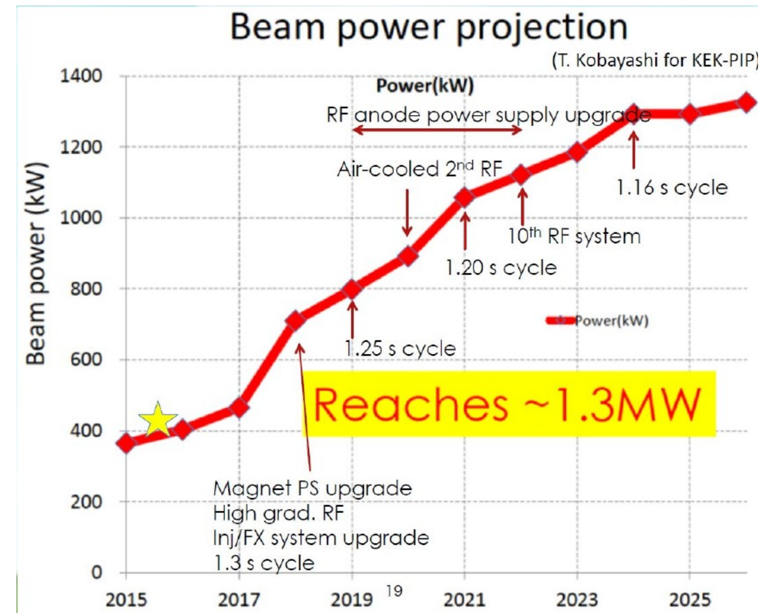



- **More to Come**

# Future Prospects: T2K II



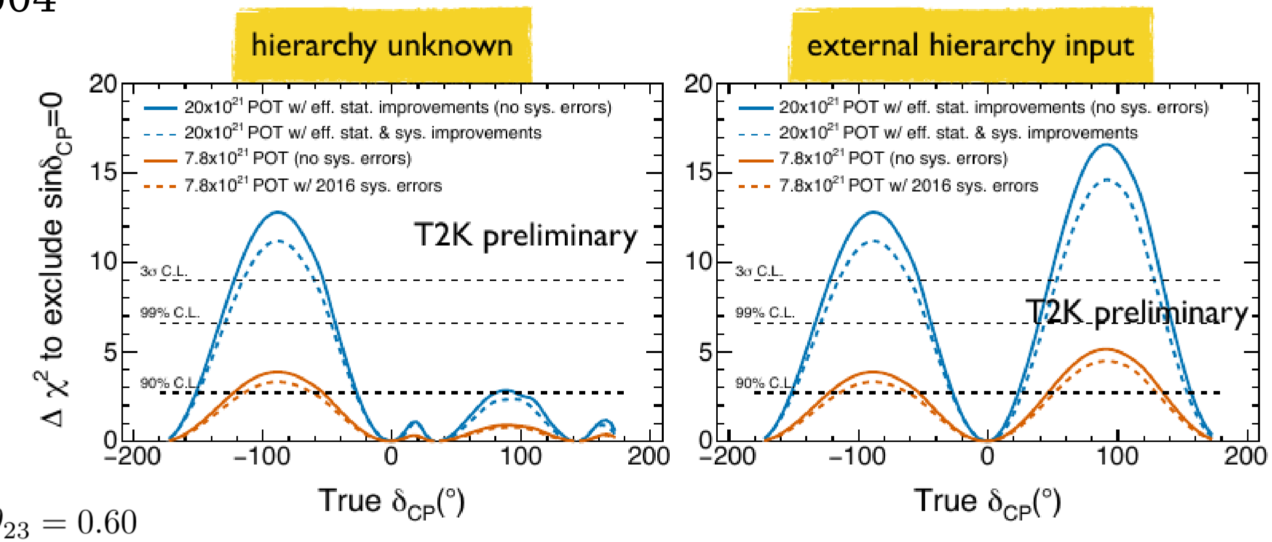

J-PARC Intensity Upgrade Plan:



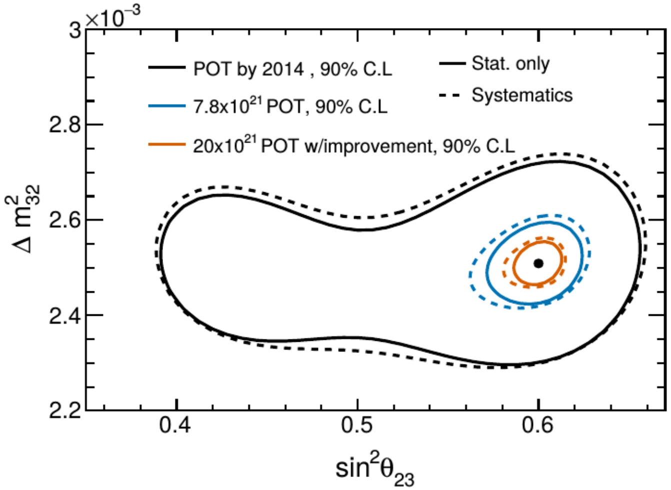

- Presently T2K approved for $7.8\times10^{21}$ POT
  - Projected to reach around 2020
- 1st stage of J-PARC main ring power supply upgrade approved
  - Major step in achieving > 1 MW beam power (currently 420 kW)
- T2K-II extends T2K accumulated POT to $20\times10^{21}$ POT
  - With further accelerator and beam-line upgrades expect 1.3 MW
  - Goal could be reached in 2026

# T2K II Sensitivity

arXiv:1607.08004




Assuming true $\sin^2\theta_{23} = 0.60$




## Goals:

- ~3σ sensitivity to CP violation for favorable (and currently favored) parameters
- Precise measurement of $\theta_{23}$:
    - Octant resolution if $\theta_{23}$ at the edge of currently allowed region
    - Otherwise measure $\theta_{23}$ with a resolution of 1.7° or better

# Summary and Outlook

- T2K has accumulated a total of $1.51\times10^{21}$ POT (split equally in $\nu$ and $\bar{\nu}$ mode) (~19% of T2K's approved POT)
- Joint analysis across all modes of oscillation $\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance has been performed
  - Constraints from near detector (ND280) measurements incorporated
  - These data show a preference for maximal $\theta_{23}$ mixing, $\delta_{CP}$ ~$-\pi/2$ and NH
    - Manifested by "maximal" $\nu_\mu/\bar{\nu}_\mu$ disappearance, "large" $\nu_e$ appearance, "small" $\bar{\nu}_e$ appearance
- Stable beam power @420 kW achieved this year
  - Approved upgrades for >700 kW operation
  - A proposed extension of T2K(T2K II):
    - Accelerator and beam line upgrades to improve beam power to 1.3 MW
      - Allowing $20\times10^{21}$ POT to be accumulated by ~2026
    - Primary goals are >3σ sensitivity to CPV and < 2° resolution on $\Theta_{23}$

**→ Stay Tuned: More oscillation results to come…**

# The T2K Collaboration

***Canada***
TRIUMF
U. Alberta
U.B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

***France***
CEA Saclay
IPN Lyon
LLR E. Poly.
LPHE Paris

***Germany***
Aachen U.

***Italy***
INFN U. Bari
INFN U. Napoli
INFN U. Padova
INFN U. Roma

***Japan***
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Met. U.
U. Tokyo

***Poland***
IFJ PAN Cracow
NCBJ Warsaw
U. Silesia Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

***Russia***
INR

***Spain***
IFAE Barcelona
IFIC Valencia

***Switzerland***
ETH Zurich
U. Bern
U. Geneva

***United Kingdom***
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary London
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

***USA***
Boston U.
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
UC Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

***500 members***
***59 Institutions***
***11 Countries***

# Backup Slides

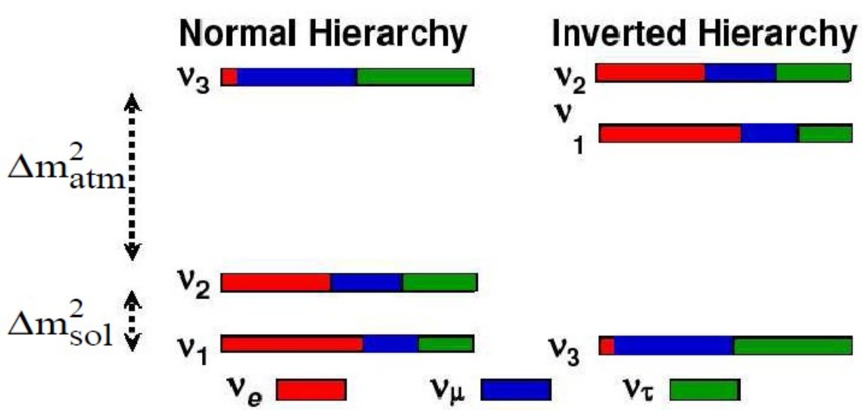
# What Do We Know?

Solar+KamLAND → $\theta_{12} \sim 34^0$

SK, MINOS, T2K, NOνA → $\theta_{23} \sim 45^0$

Daya Bay, Reno, Double Chooz → $\theta_{13} \sim 9^0$

(T2K: $\theta_{13} \neq 0 \rightarrow$ In Appearance Channel)




$\Delta m^2_{21} = (7.65 + \pm 0.23) \times 10^{-5}$ eV$^2$

sign of the mass difference, $\Delta m^2_{21} > 0$.

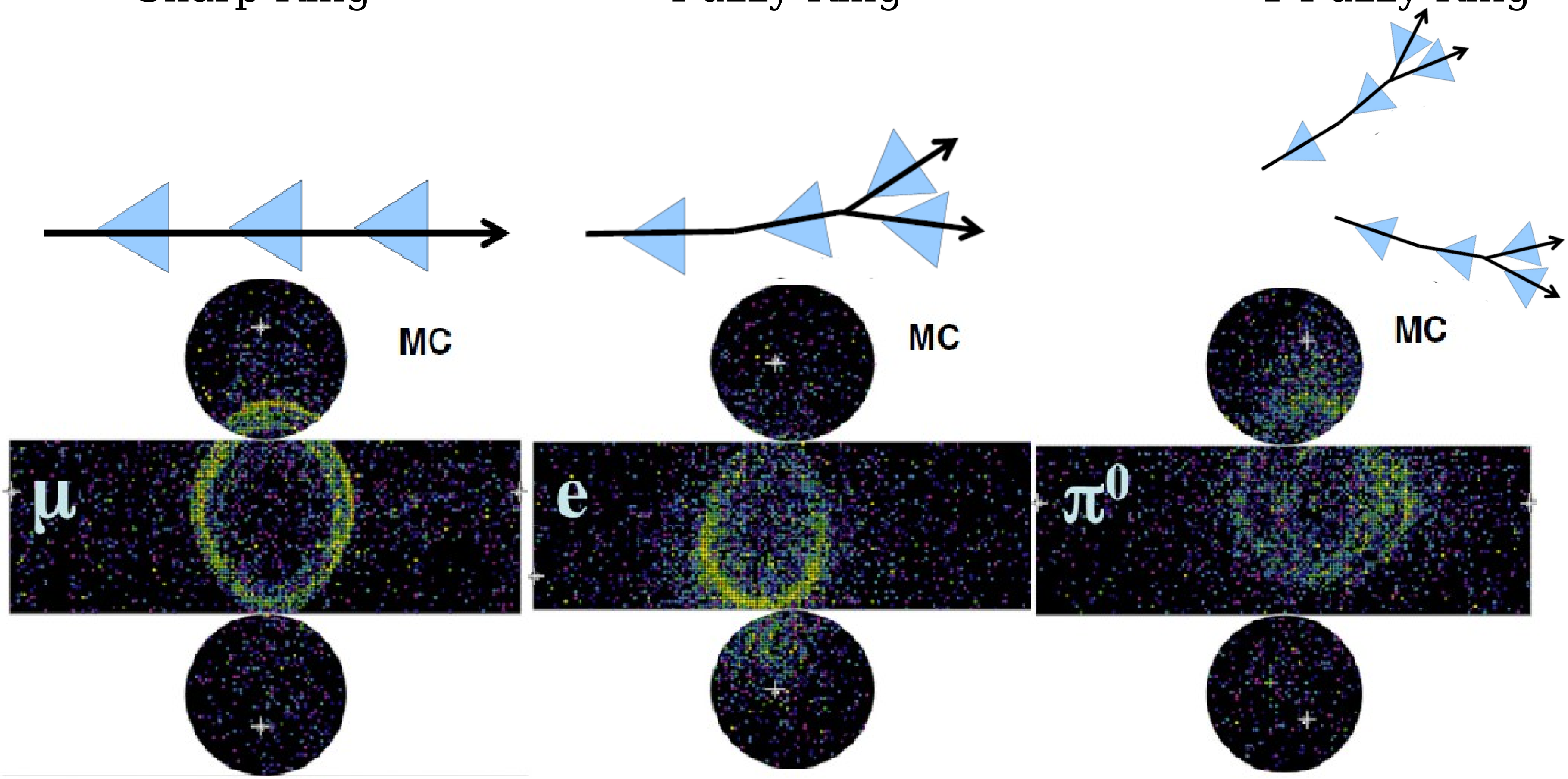
$\Delta m^2_{32} (\approx \Delta m^2_{31}) = (2.40 \pm 0.12) \times 10^{-3}$ eV$^2$

# Far Detector: Particle ID

MS Small:
Sharp Ring

EM Shower:
Fuzzy Ring

2 EM Showers:
> 1 Fuzzy Ring



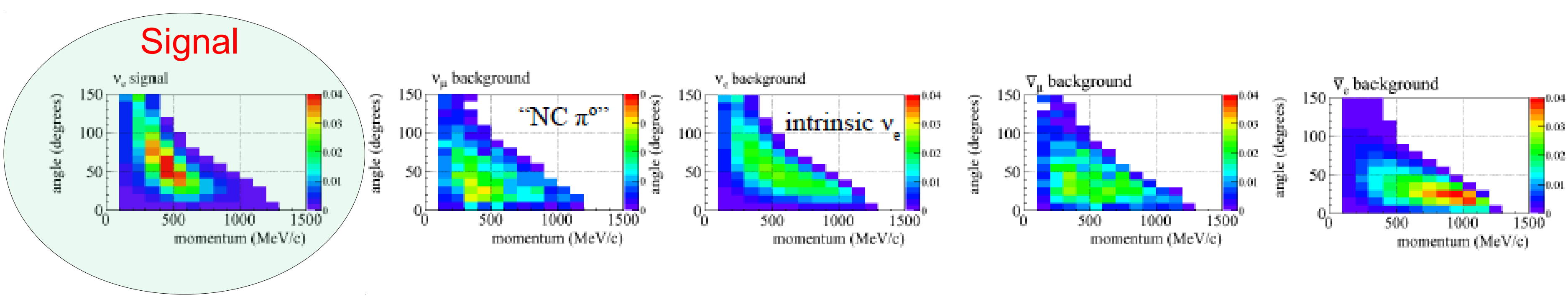
# $\nu_\mu \rightarrow \nu_e$: Oscillation Parameters

**Three analysis methods used:**

- Maximum likelihood Fit using 2D-distributions of electron momentum & angle → Result presented here
- Maximum likelihood Fit using reconstructed neutrino energy distribution
- “Rate Only” analysis → Single energy bin using Feldman-Cousins technique

→ All three methods result in consistent values

Using method 1: Differences in electron momentum and angle distributions allow signal and background separation and exploits detector measured variables:

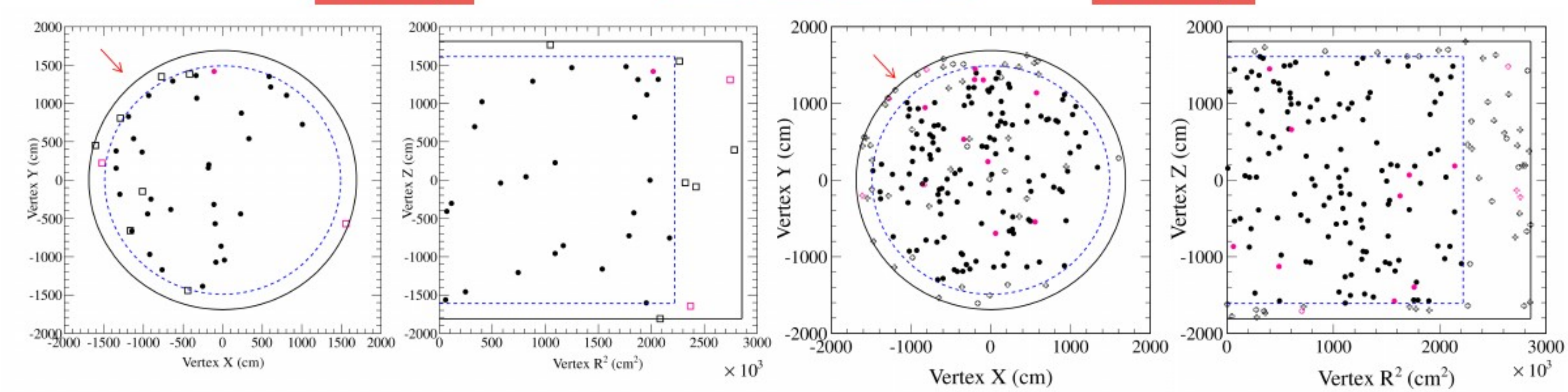


# SK Vertex Distributions

ν beam mode

e-like sample

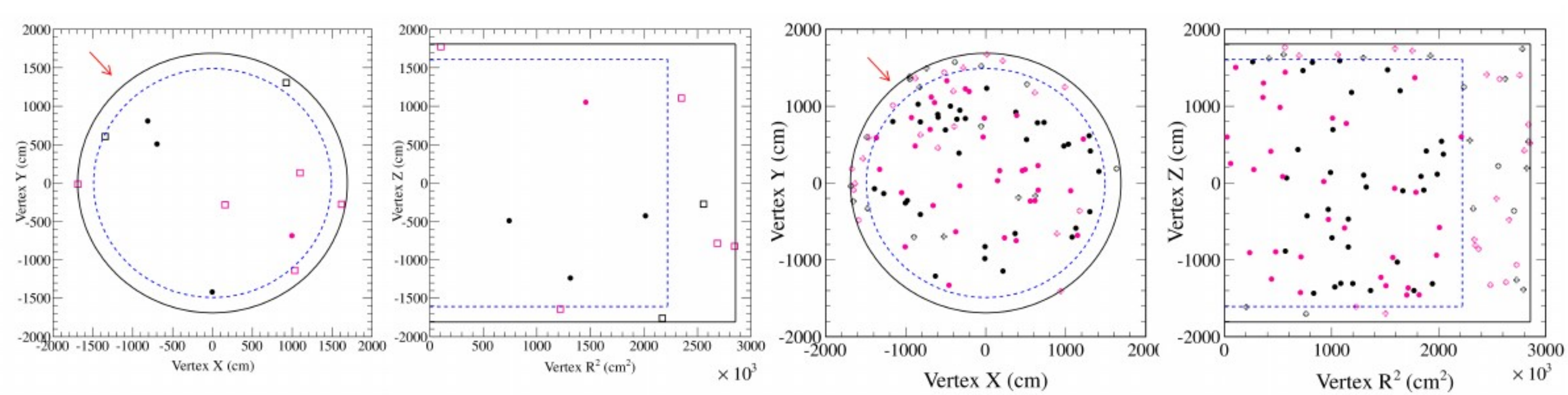
μ-like sample



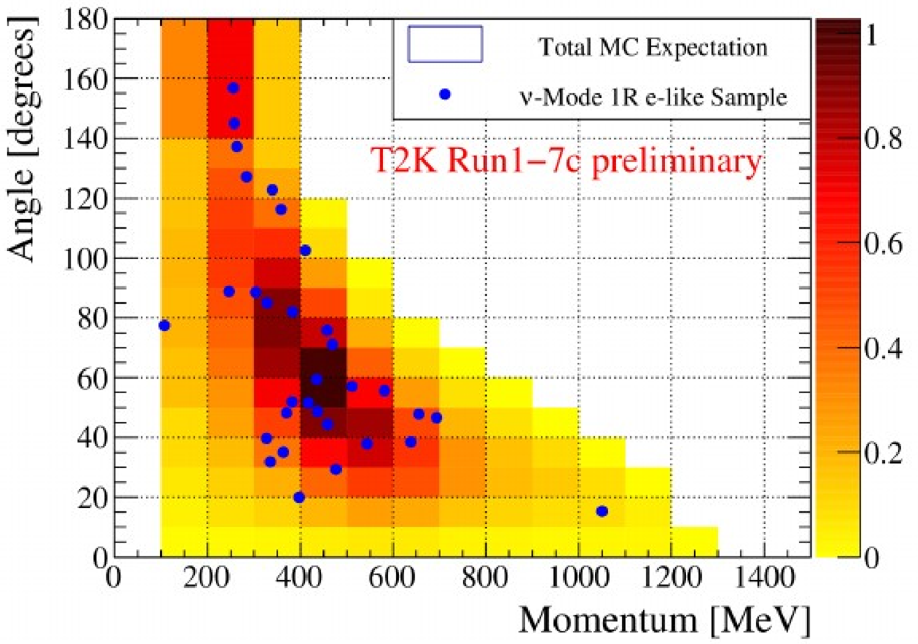

$\bar{\nu}$ beam mode

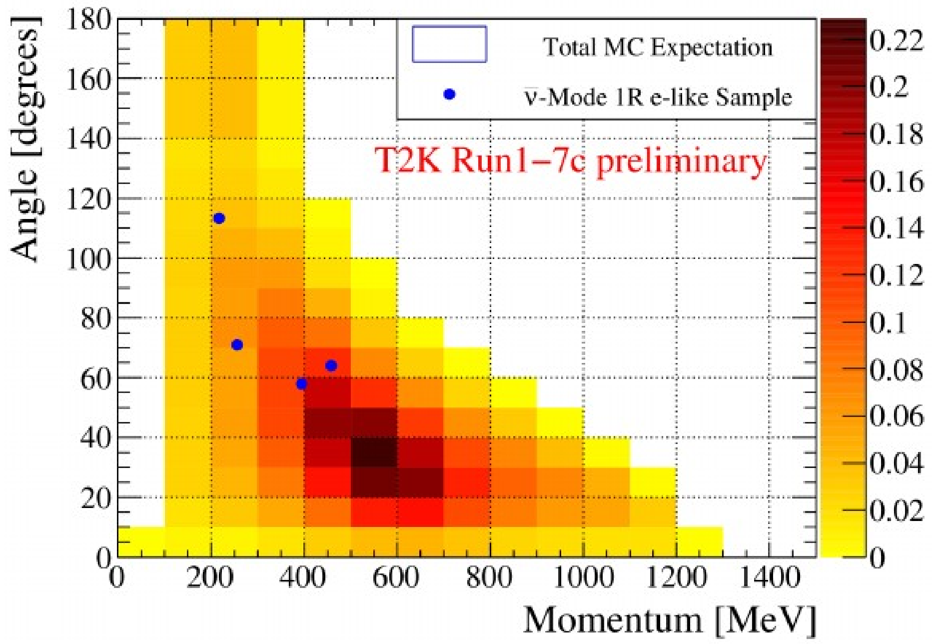
e-like sample

μ-like sample

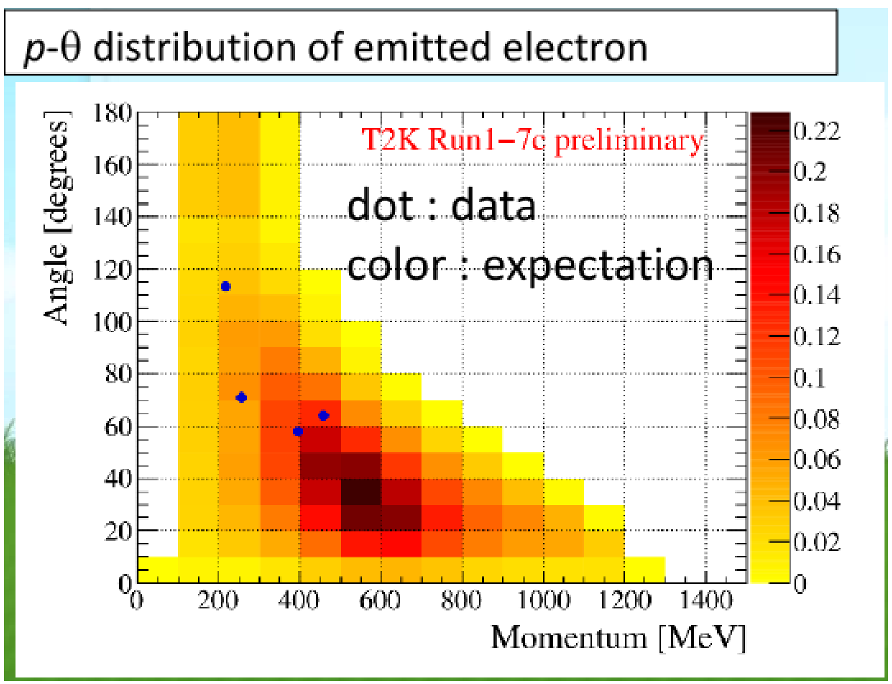


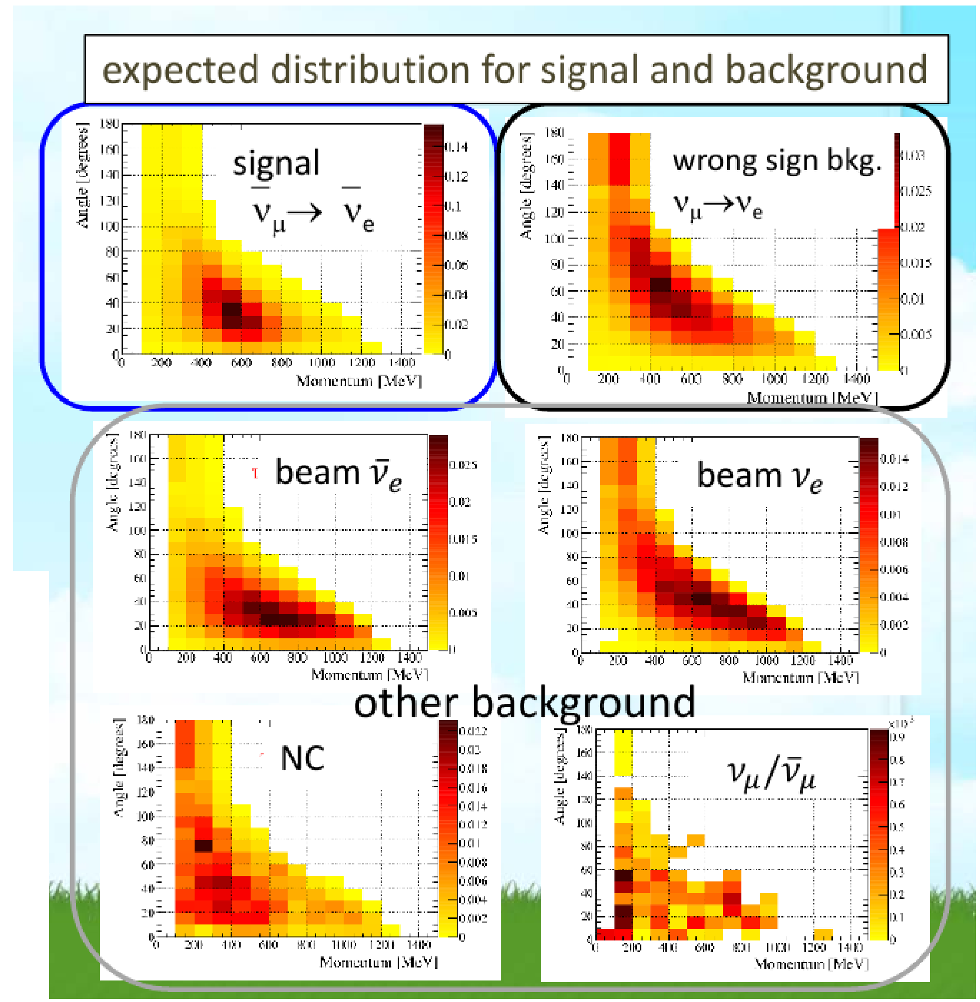
# p-θ distributions of selected 1R e-like events at SK



# $\bar{\nu}_e$ selection: Signal & Background



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