Recent results from the T2K experiment

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on behalf of the T2K Collaboration

QUARKS-2018
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Outline

- Neutrino oscillations
- T2K experiment
- T2K analysis
- Recent results
- Near/far future
- Summary

Neutrino mixing (reminder)

- ✓Neutrinos of 3 flavors take part in the weak interactions: ν_e ($\bar{\nu}_e$), ν_μ ($\bar{\nu}_\mu$), ν_τ ($\bar{\nu}_\tau$); no definite mass;
- ✓3 flavor fields are linear combinations of 3 fields of massive neutrinos ν_1, ν_2, ν_3 (*Dirac* or *Majorana*);
- ✓The mixing can be described by the PMNS matrix (*Dirac* case) :

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\underset{\text{“solar”}}{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}\underset{\text{“reactor”}}{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}}\underset{\text{“atmospheric”}}{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}}_{\text{PMNS matrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS (≡ Pontecorvo-Maki-Nakagawa-Sakata) matrix

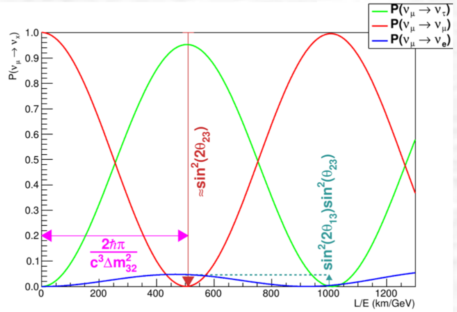
Neutrino oscillations

(for Dirac neutrinos)

C. Patrignani et al. (**PDG**), Chin. Phys. C, **40**, 100001 (**2016**) and 2017 update:

"Appearance" probability **$P(\nu_\alpha \to \nu_\beta)$** depends on

- ✓ **3** mixing angles **θ_{ij}**;
- ✓ **1** CPV phase **δ_{CP}**;
- ✓ **2** mass differences **Δm^2_{ij}**;
- ✓ **mass hierarchy** (ordering);
- ✓ neutrino energy **E** and path length **L**



$\sin^2\theta_{23} = 0.51 \pm 0.04$ (NH)
$\sin^2\theta_{13} = 0.0210 \pm 0.0011$
$\sin^2\theta_{12} = 0.307 \pm 0.013$

$\Delta m^2_{ij} \equiv m^2_i - m^2_j,\ i \neq j$

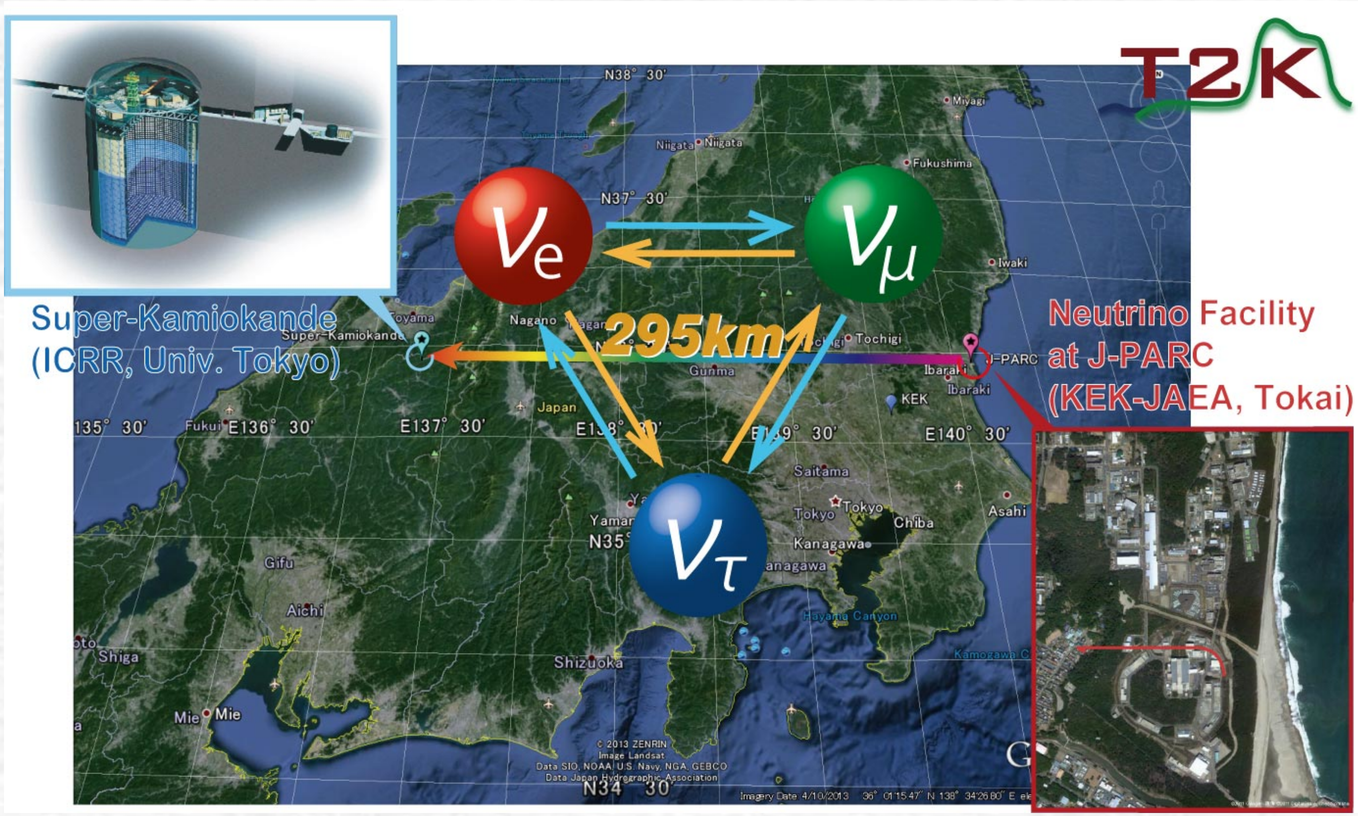
$\Delta m^2_{32} = (2.45 \pm 0.05)\ 10^{-3}\ \text{eV}^2$ (NH)
$\Delta m^2_{21} = (7.53 \pm 0.18)\ 10^{-5}\ \text{eV}^2$

Currently unknown:

- CP-violation: **δ_{CP}** = ?
- Mass Hierarchy (Ordering):
  $m_3 > m_2 > m_1$ (**NH**) or
  $m_2 > m_1 > m_3$ (**IH**)?
- **θ_{23} octant**: >45° or <45°?

[NH/IH = normal/inverted hierarchy]

T2K Experiment



T2K = Tokai-to-Kamioka
long-baseline accelerator neutrino experiment

T2K history and QUARKS

- Sergiev Posad, QUARKS-2008; Yu. Kudenko: commissioning of J-PARC, construction of the near detectors;

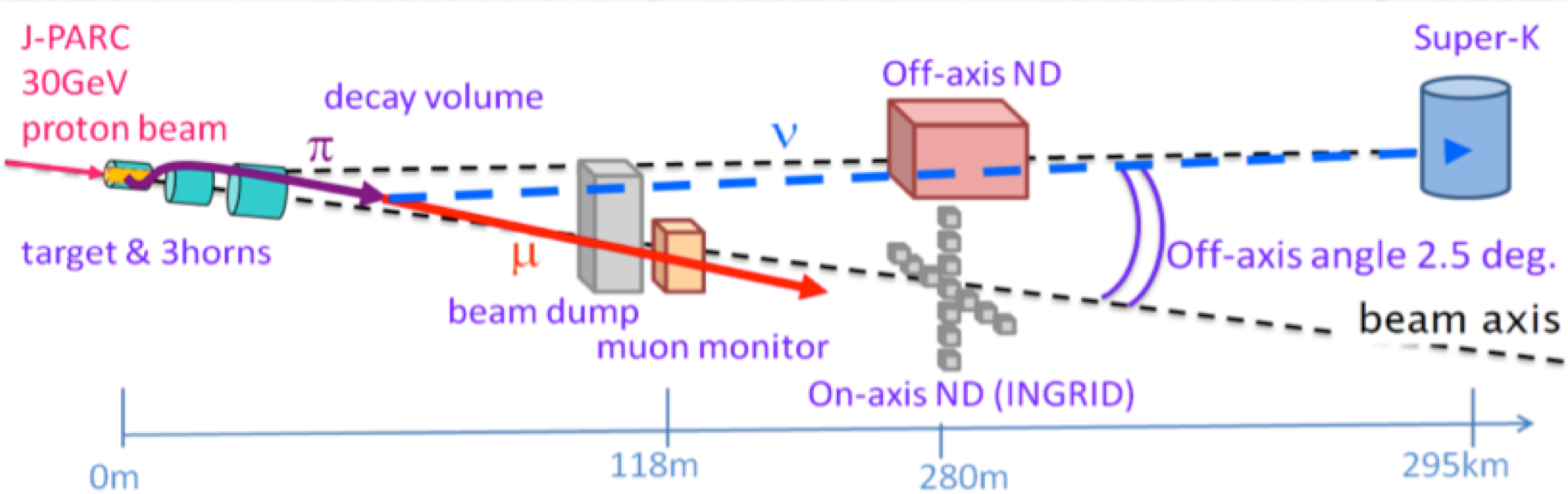
- Kolomna, QUARKS-2010; J. Kameda: start of data taking, first neutrinos;

- Yaroslavl, QUARKS-2012; M. Khabibullin: indication of $\nu_\mu \to \nu_e$ oscillations (3.2σ); 2.6×10^{20} POT (protons-on-target);

- Suzdal, QUARKS-2014; Yu. Kudenko: observation of $\nu_\mu \to \nu_e$ (7.3σ); 6.5×10^{20} POT; first constraints of δ_{CP}; start running in $\bar{\nu}$-mode;

- Pushkin, QUARKS-2016; M. Lawe: first results in $\bar{\nu}$-mode; 13.8×10^{20} POT (ν:51.5%; $\bar{\nu}$:48.5%)

T2K Setup



Protons hit the **target**: graphite rod (∅26 mm × 914 mm long, 1.8 g/cm^3)

$$\mathbf{p + C \rightarrow \pi^{+/-} + X}$$

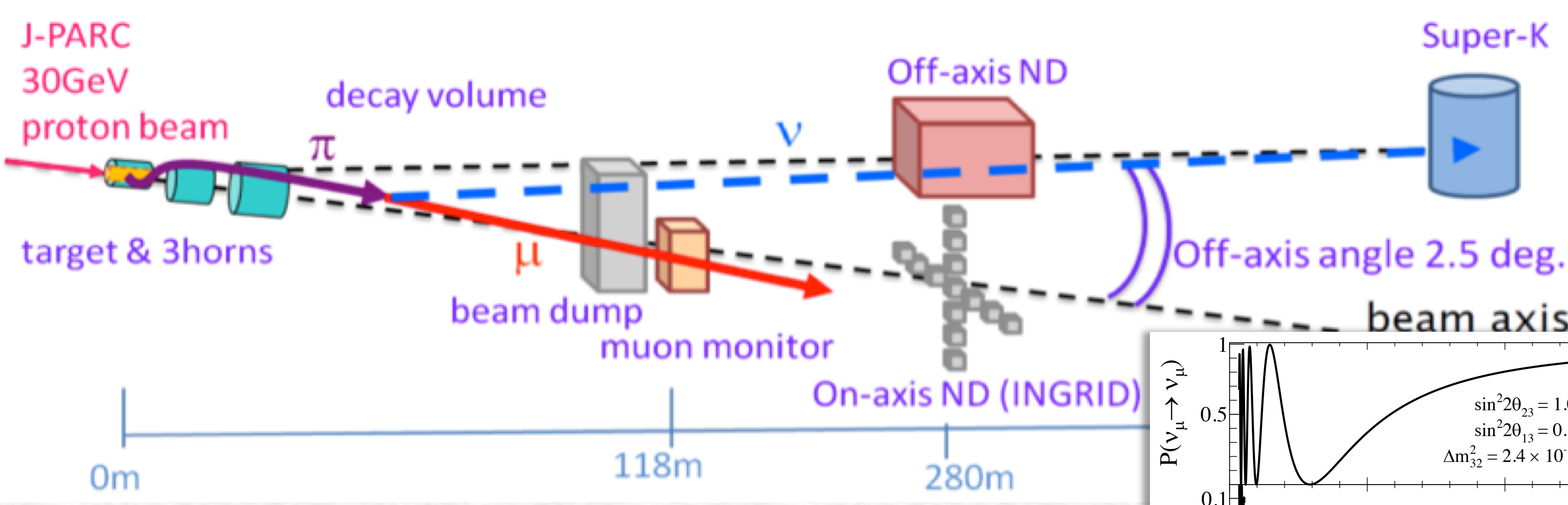
Three horns (+/−250 kA): collect and focus positive/negative pions

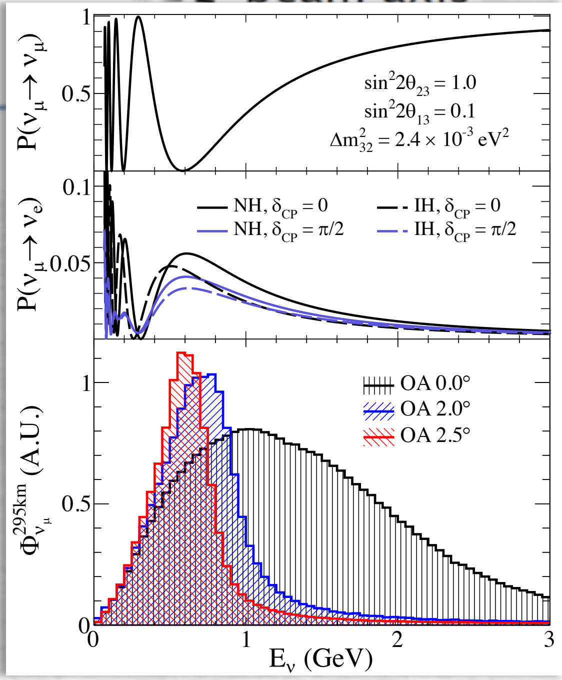
Decay Volume (96 m long, He ~1 atm.): $\pi^+ \rightarrow \mu^+ + \nu_\mu$; $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$;

Beam Dump: stops all the hadrons and muons with $p_\mu < 5$ GeV/c

Muon Monitors (ion. chambers and Si PIN diodes): measure the intensity and profile of the muons ($p_\mu > 5$ GeV/c) on the bunch-by-bunch basis

T2K Setup: off-axis beam



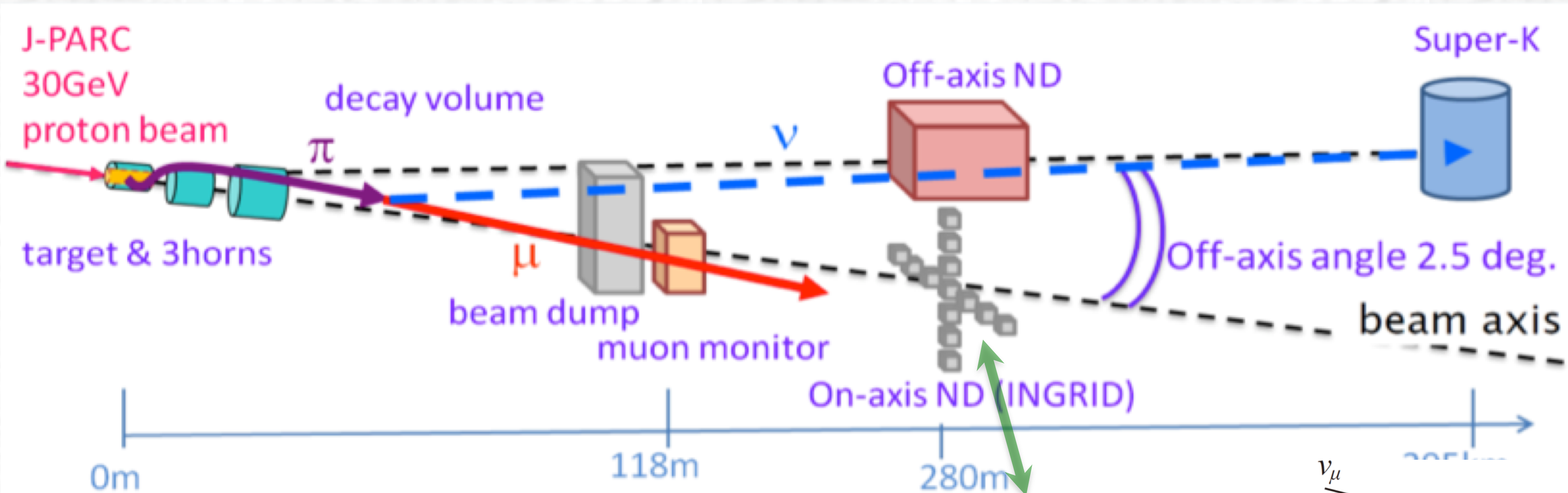


Off-axis idea: at small angles neutrinos have almost mono-energetic spectra

Off-axis angle can be tuned to get the maximal oscillation:

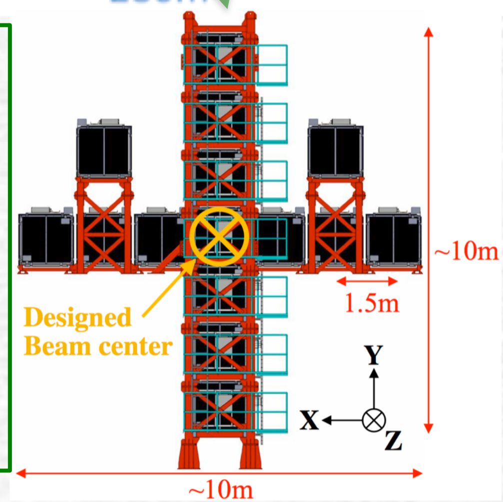
- 2.5° is best for **L**= 295 km and **E**$_\nu$ = 600 MeV
- suppression of the high energy tail

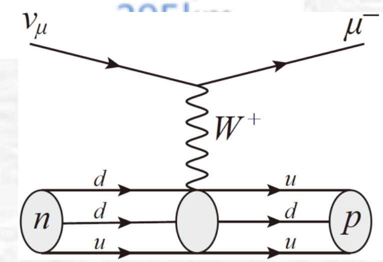
T2K near detectors: on-axis

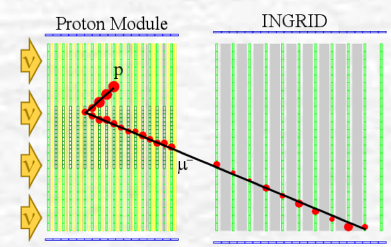


On-axis near detector **INGRID** (*Interactive Neutrino GRID*): plastic scintillators and iron (+ water module since 2017).

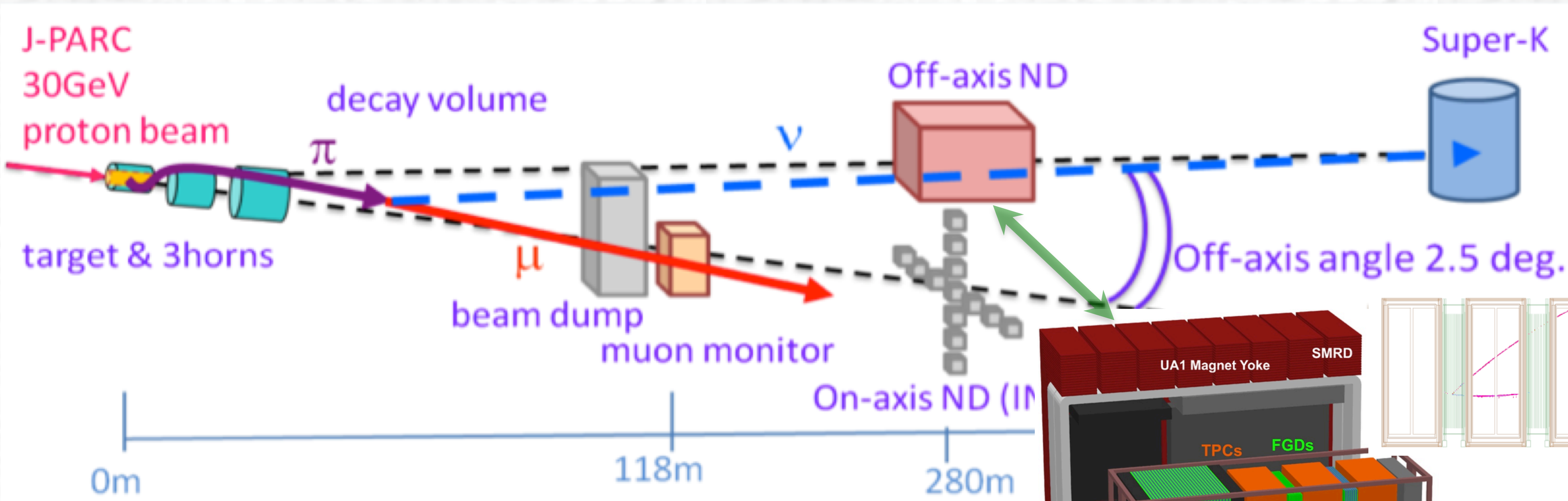
Measures neutrino beam rate, direction and cross sections.

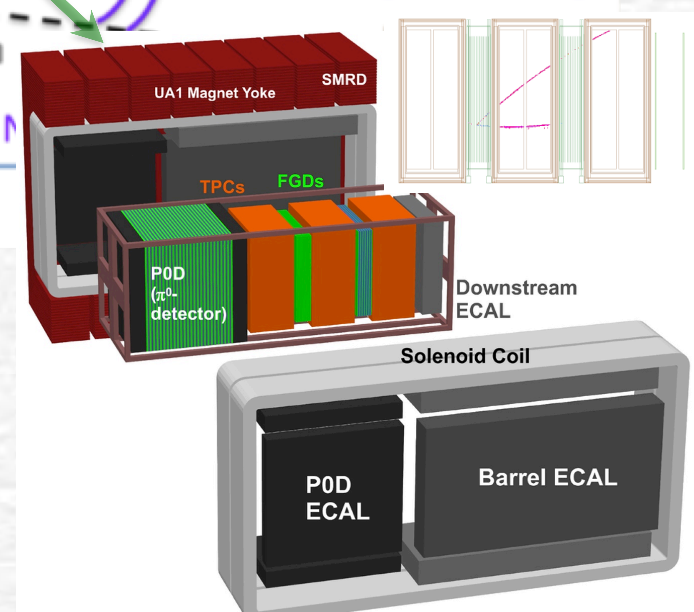






T2K near detectors: off-axis



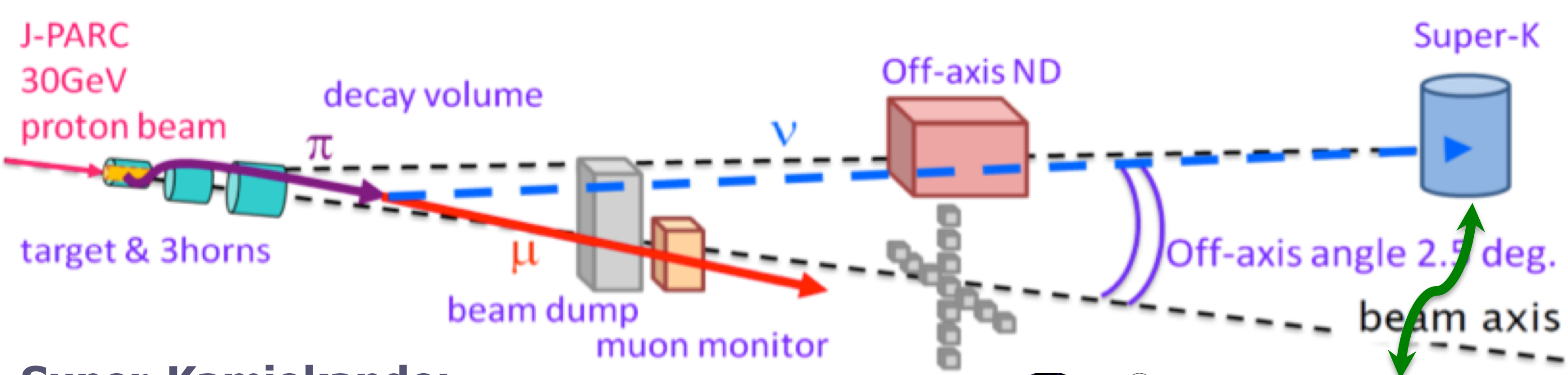


<u>Off-axis</u> near detector **ND280** measures neutrino beam properties before oscillations; constrains flux and cross-section parameters

- Tracker: Magnet (0.2 T)+3**TPC**s+2 **FGD**s
- **FGD1**: plastic scintillator; **FGD2**: +water
- P0D; ECaL; SMRD

[*TPC = Time Projection Chamber; FGD = fine-grained detector; P0D = π0 detector; ECaL = E/M Calorimeter; SMRD = Side Muon Range Detector*]

T2K far detector: Super-K



<u>Super-Kamiokande:</u>

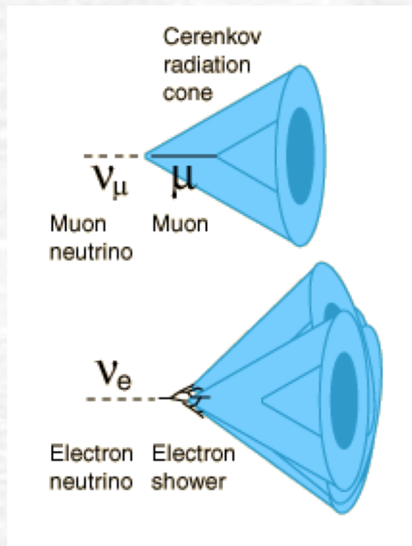
- ✓ 50 kT water Cherenkov detector @ 295 km;
- ✓ >99% μ/e separation;
- ✓ GPS synchronization with the J-PARC beam

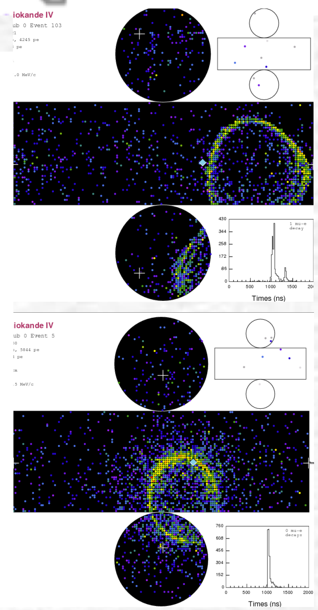
<u>Inner Detector</u> (ID):

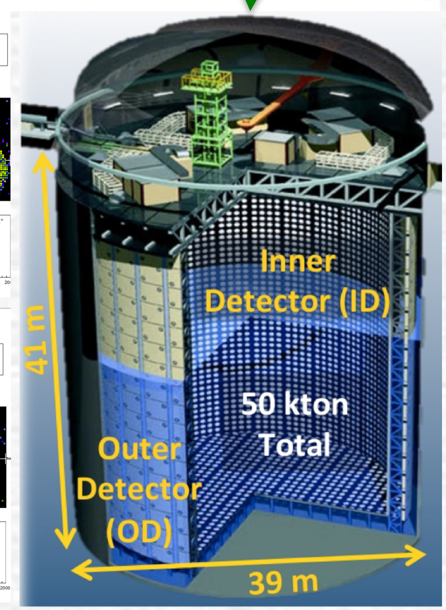
- ✓ >11000 PMTs (50 cm)
- ✓ 40% photo-coverage

<u>Outer Detector</u> (OD):

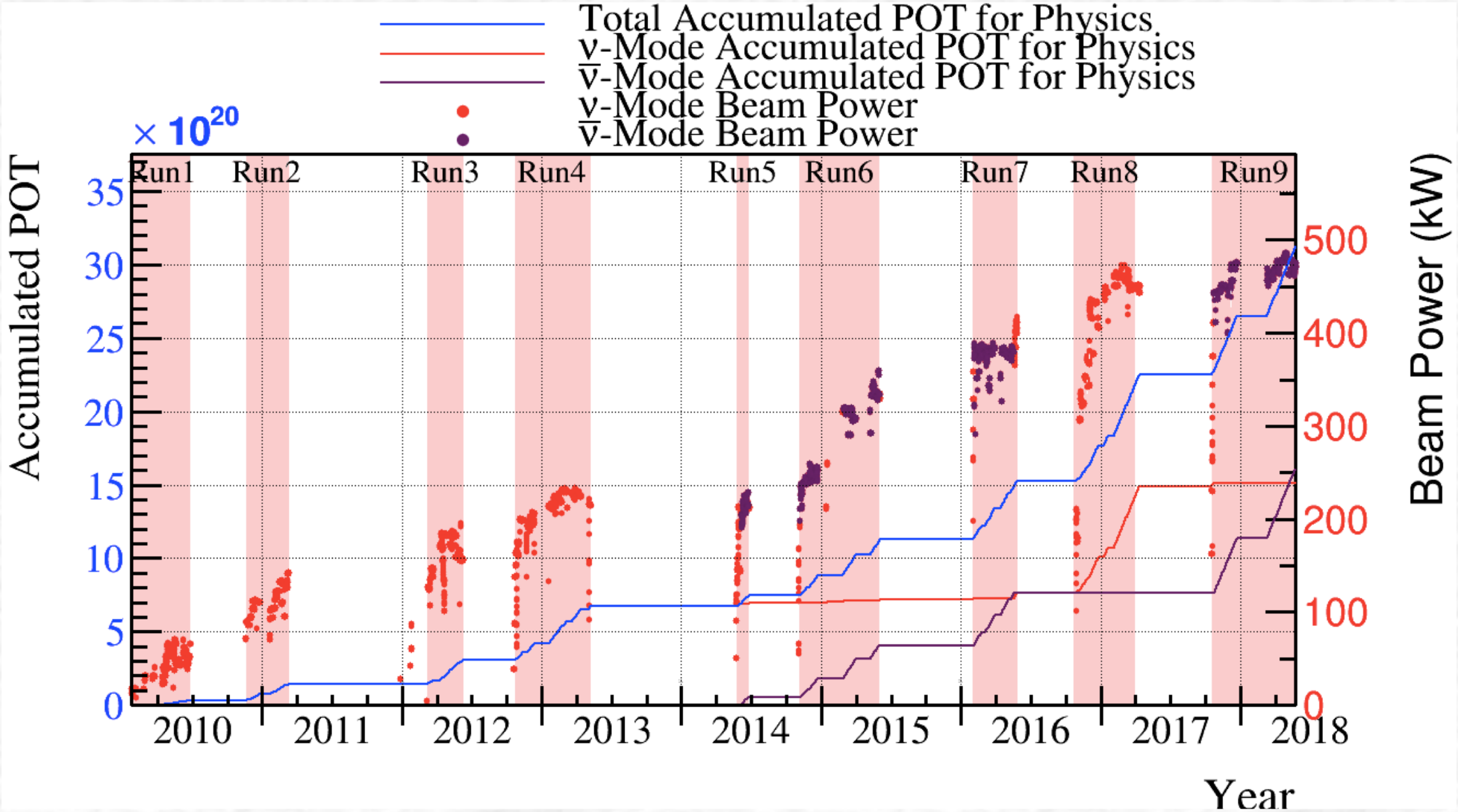
- ✓ ~2000 PMTs (20 cm)







T2K data (2010-2018)



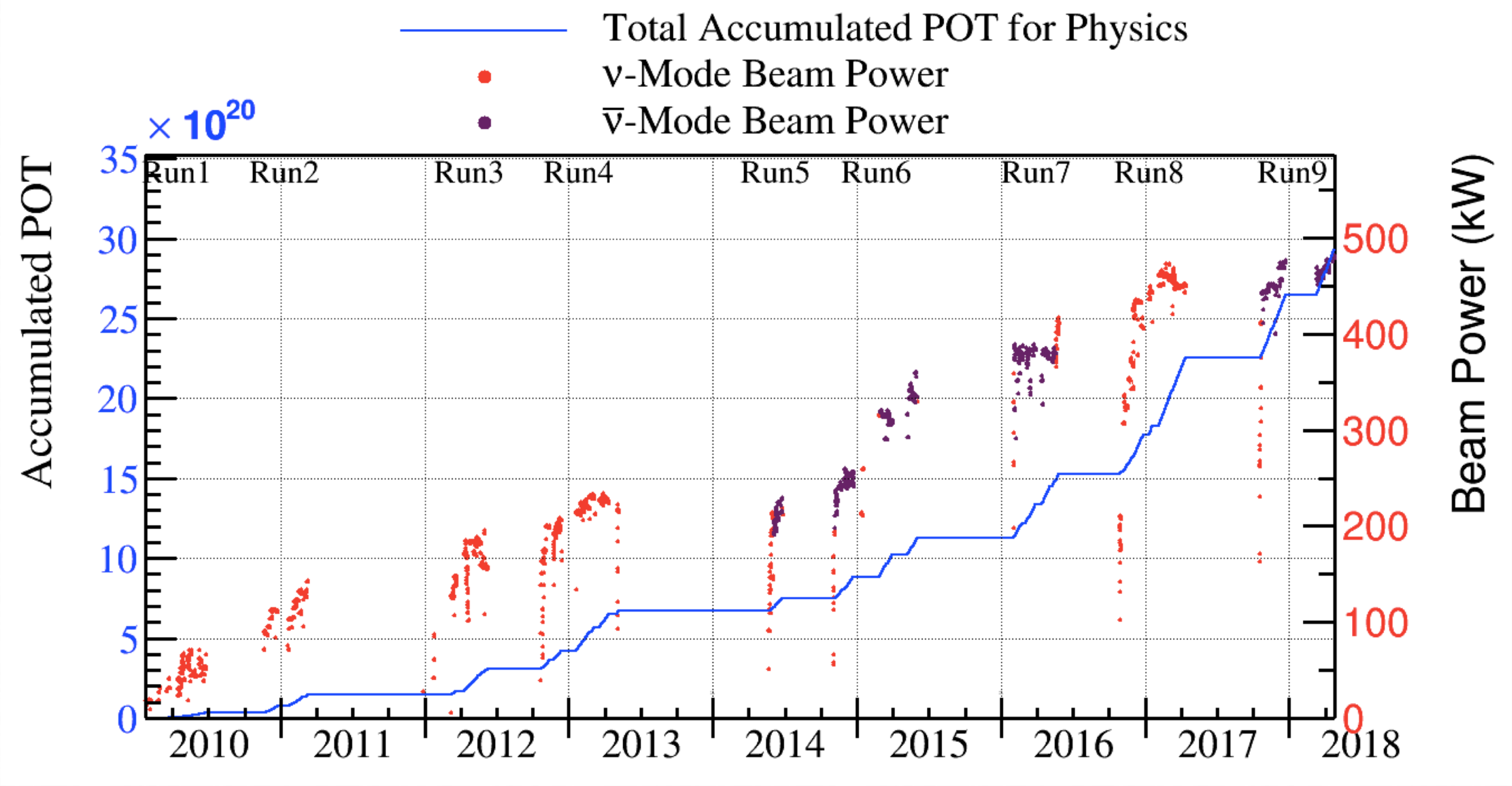
Current T2K statistics (end of May 2018): ~31.2×10^{20} protons-on-target (POT)

This talk: 22.3×10^{20} POT

14.7×10^{20} POT in neutrino mode

7.6×10^{20} POT in antineutrino mode

T2K data (2010-2018)



Current T2K statistics (end of May 2018): ~30.0 $\times 10^{20}$ protons-on-target (POT)

This talk: 14.7$\times 10^{20}$ POT in neutrino mode

7.6$\times 10^{20}$ POT in antineutrino mode

T2K oscillation analysis

Multi-step analysis:

- ✓ Prediction of neutrino flux at Super-K
- ✓ Near detector constraint of the flux and neutrino interaction parameters
- ✓ Selection and reconstruction of the Super-K data (new algorithm)
- ✓ Comparison of the observed Super-K data to predictions and retrieving oscillation parameters

T2K oscillation analysis

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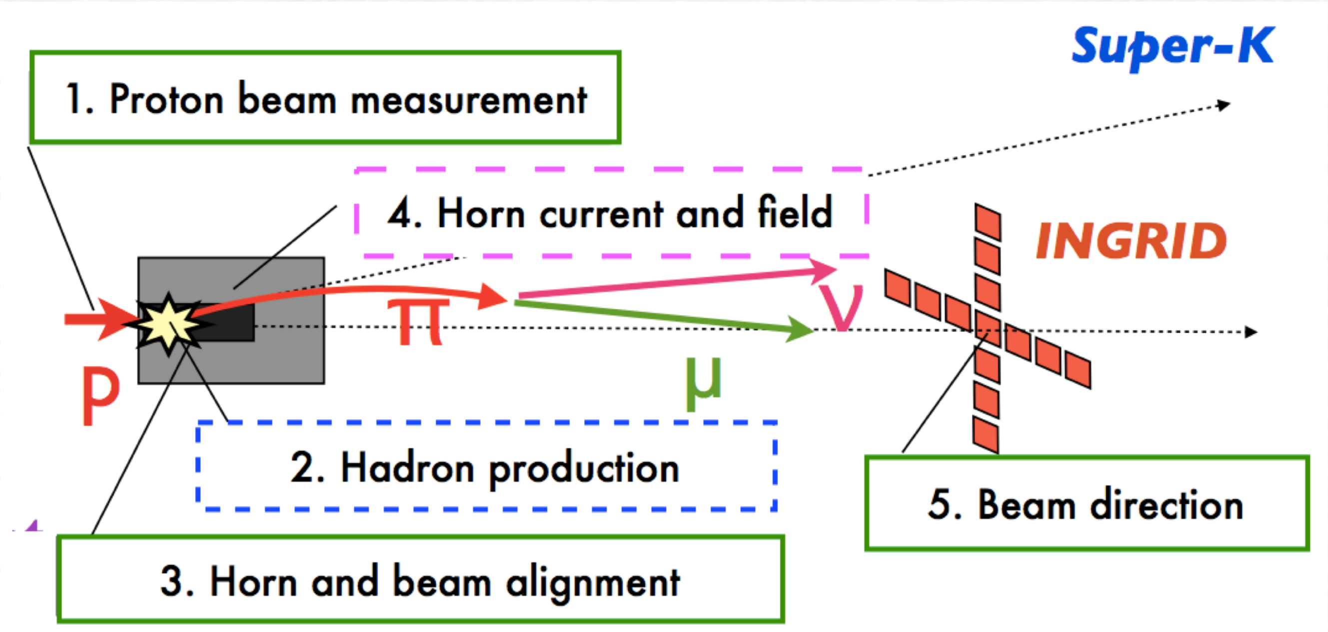
T2K neutrino flux prediction

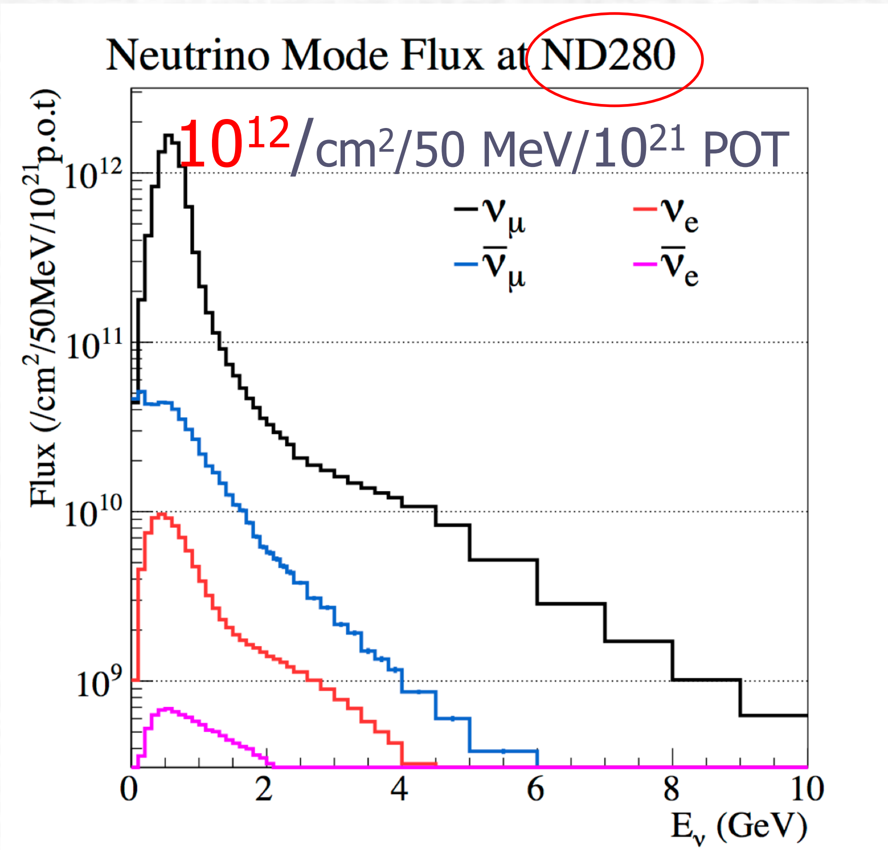
Neutrino flux calculations are based on

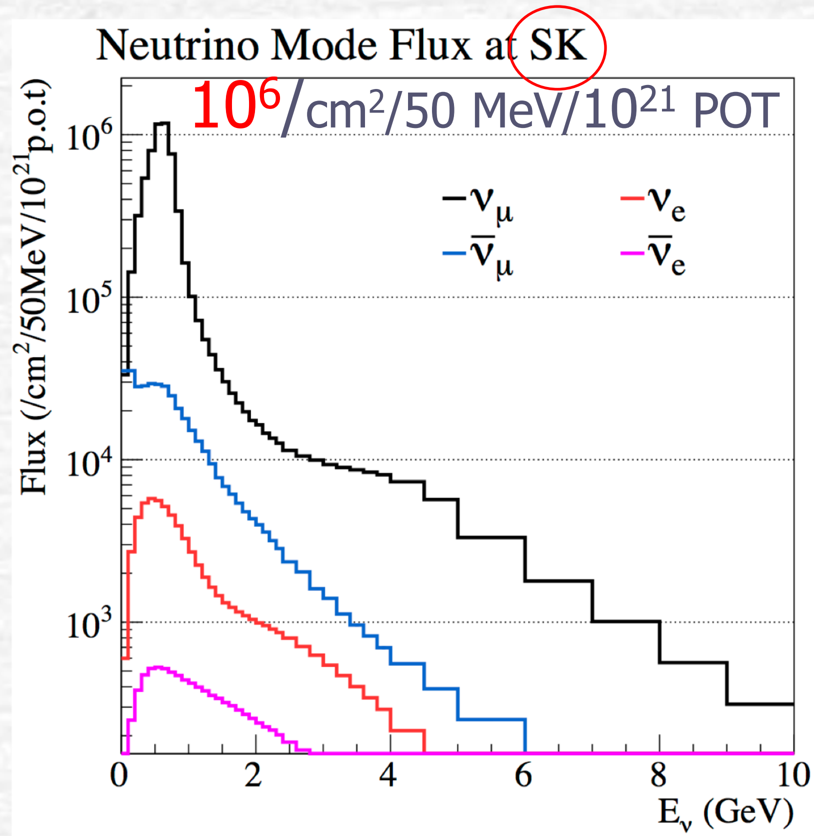
- ✓ Input from the proton **beam monitors** (beam profiles and current)
- ✓ **FLUKA2011** simulation: hadron production in the graphite target
  - ✓ this is tuned with **NA61/SHINE** *thin* (2 cm) target **data**
- ✓ **GEANT3**: propagation through magnetic horns and decay into neutrinos



Neutrino flux predictions

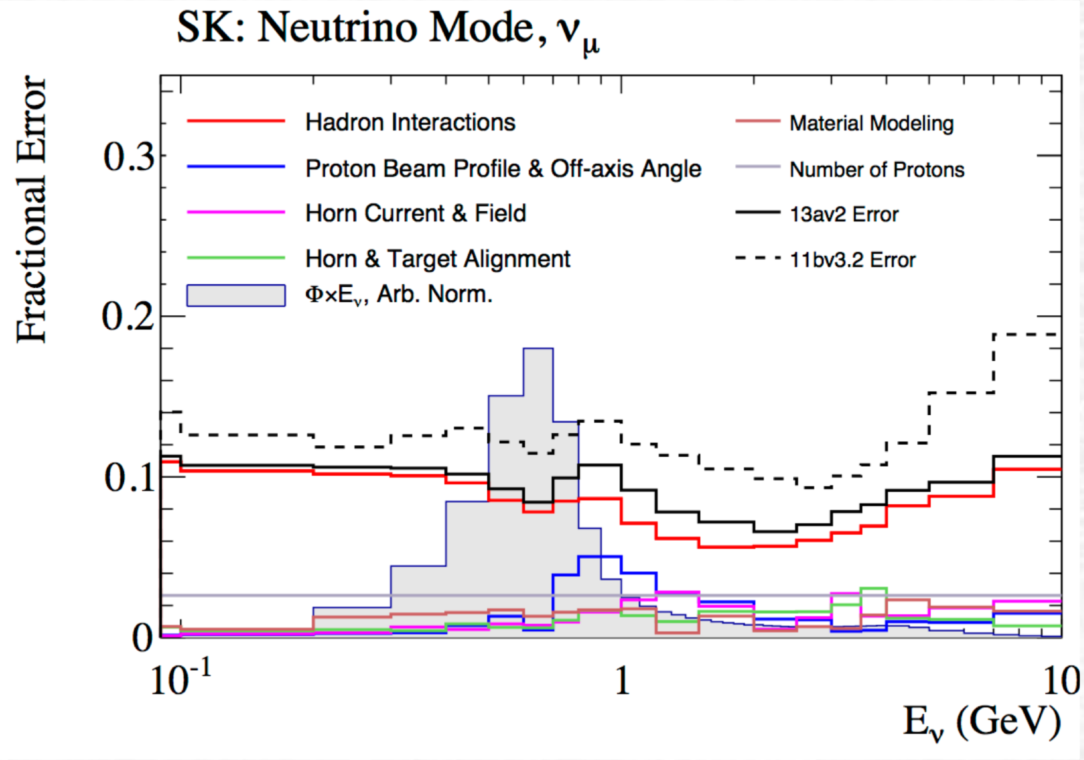
(without oscillation)





Uncertainties of the neutrino flux

- ✓ Flux prediction uncertainty is **8-12%**
- ✓ Uncertainties on **hadronic interaction** modeling are largest
- ✓ **NA61/SHINE** data taken with **replica T2K target** is being incorporated for future analyses -> reduce flux uncertainty



Neutrino interactions

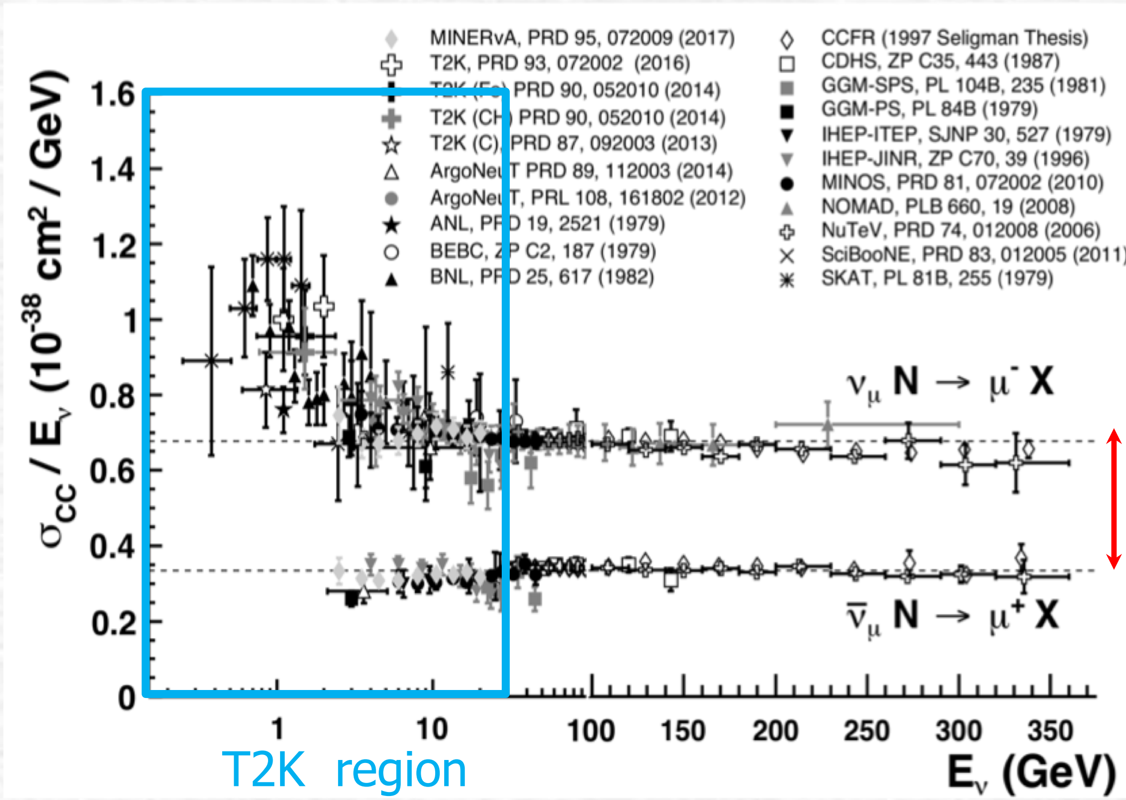
Charged-current (CC) *inclusive* $\nu_\mu/\bar{\nu}_\mu$ cross sections

C. Patrignani et al. (**PDG**), Chin. Phys. C, **40**, 100001 (**2016**) and 2017 update:

10^{-38} cm^2/GeV

per nucleon

10^{-39} cm^2/GeV



ν_μ N

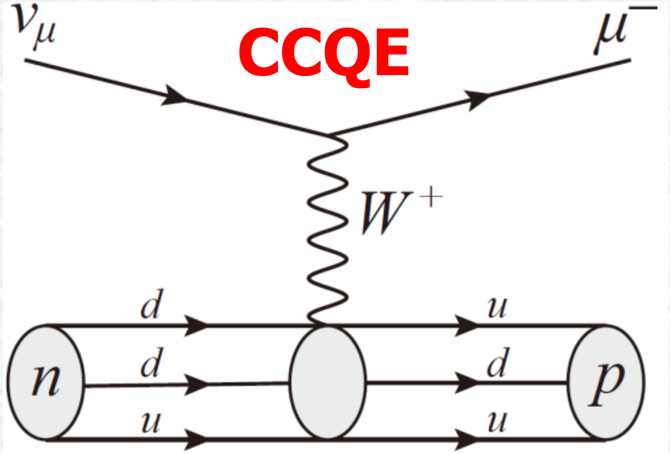
$\simeq 2\times$

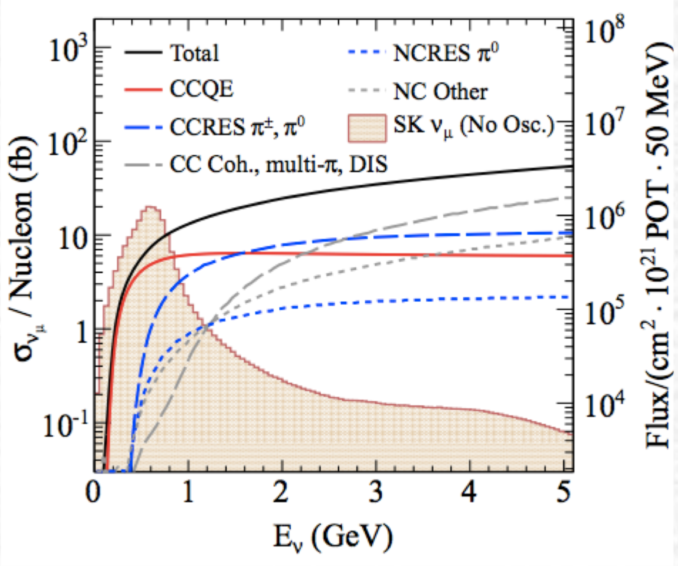
$\bar{\nu}_\mu$ N

Neutrino interaction modeling

<u>Interactions at T2K energies:</u>

- ✓ **Dominant** contribution: **CCQE** (charged-current quasi-elastic)
- ✓ Interactions **with 1 or more pions** in the final state
- ✓ Nuclear effects can **mimic** CCQE interactions:
  - a) neutrino scatters on a correlated pair of nucleons ("2p2h" = "2 particle-2 hole", "multi-nucleon");
  - b) produced pion is re-absorbed in the *nucleus*;
  - c) produced pion is absorbed in the *detector*

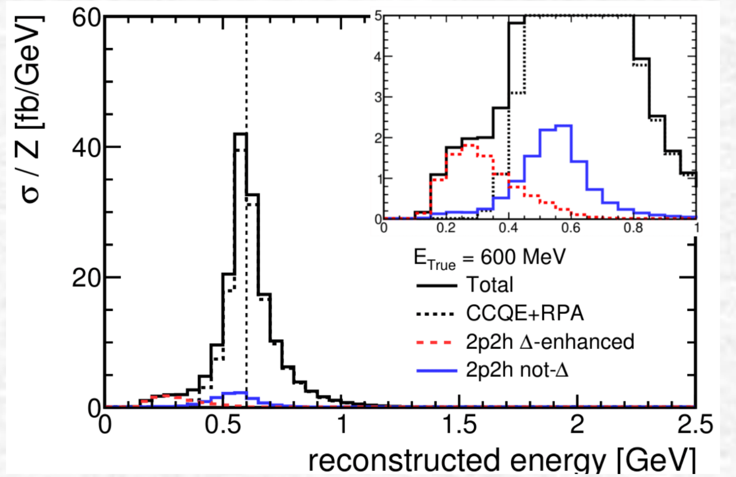


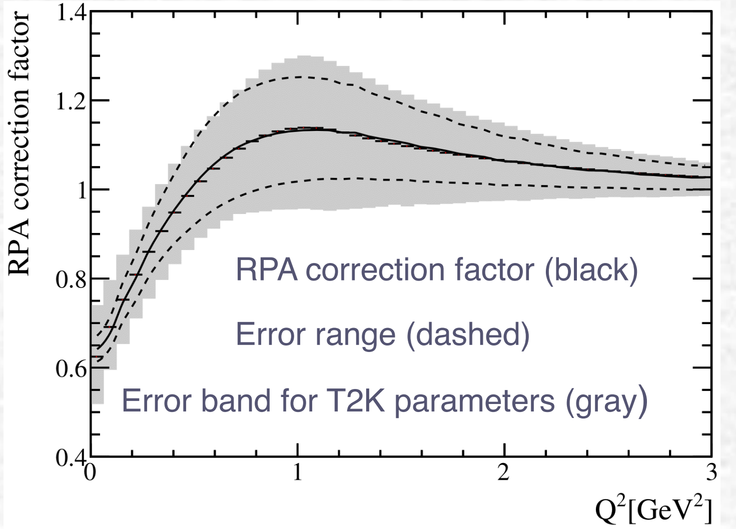


Interaction model improvements

Modifications of the main T2K neutrino generator (NEUT):

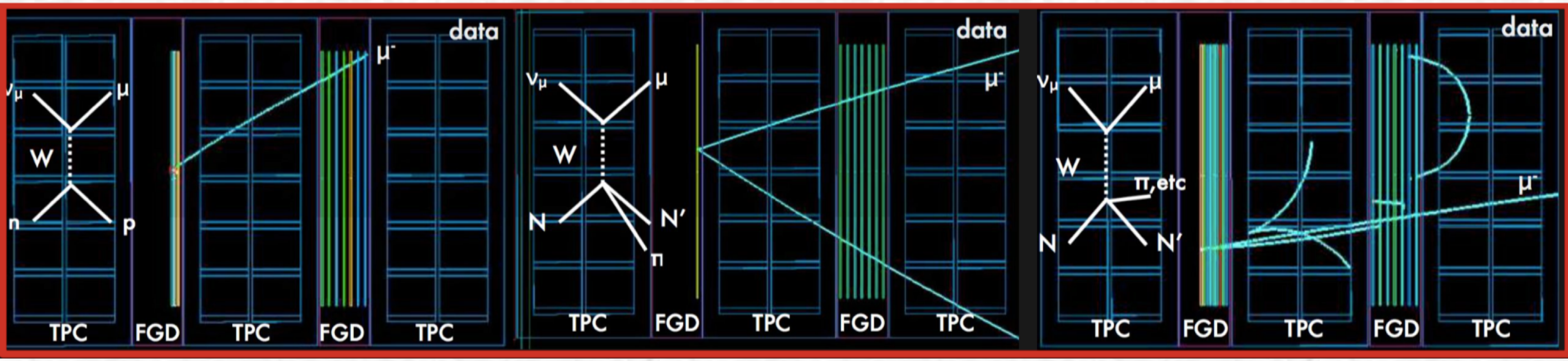
- ✓ A model for **multi-nucleon** scattering processes (Valencia 2p-2h model) was included in NEUT
- ✓ CCQE model was improved by including the **RPA correction factor** (RPA = random phase approximation)
- ✓ Pion production model was tuned to data on hydrogen and deuterium



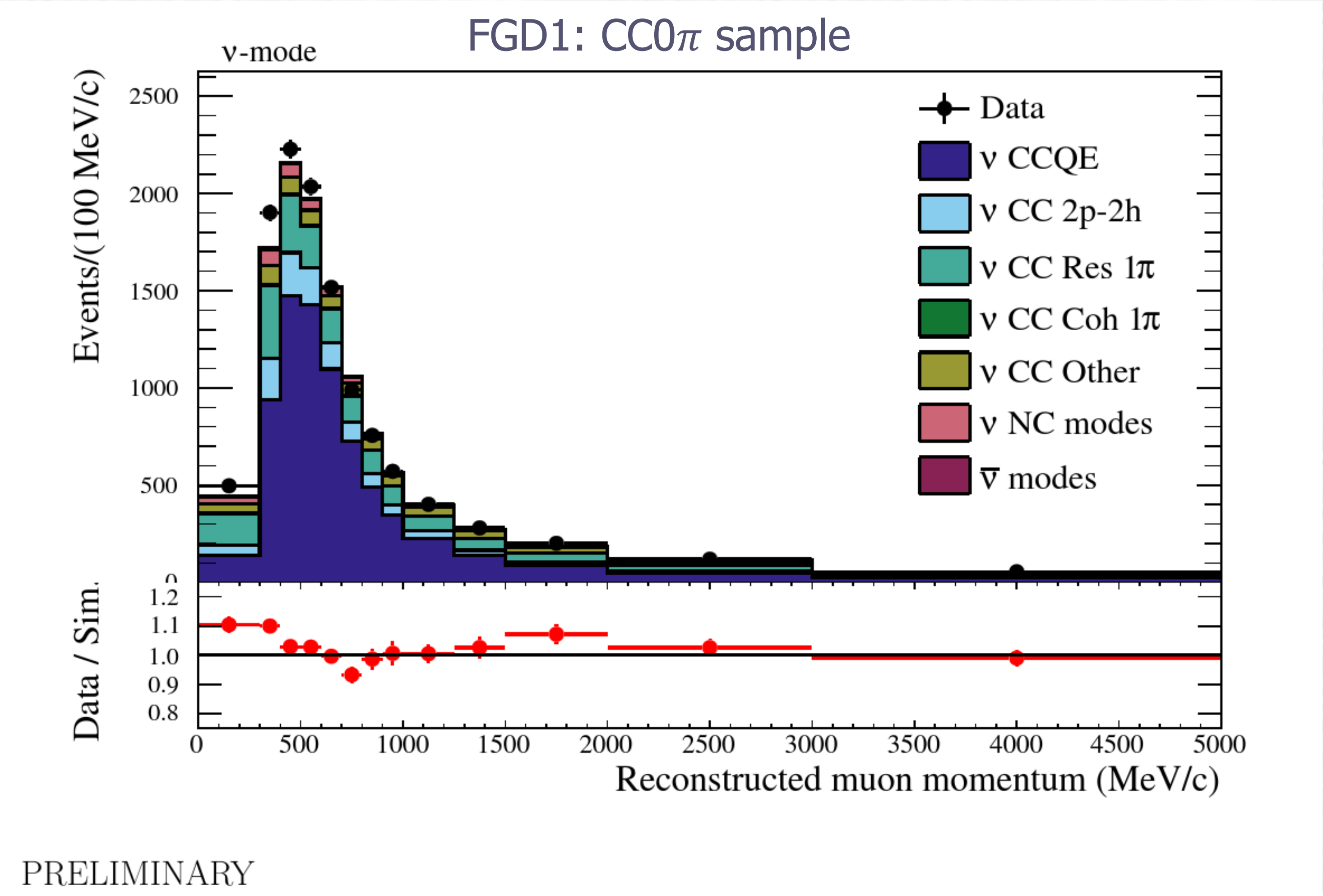


Near Detector constraint

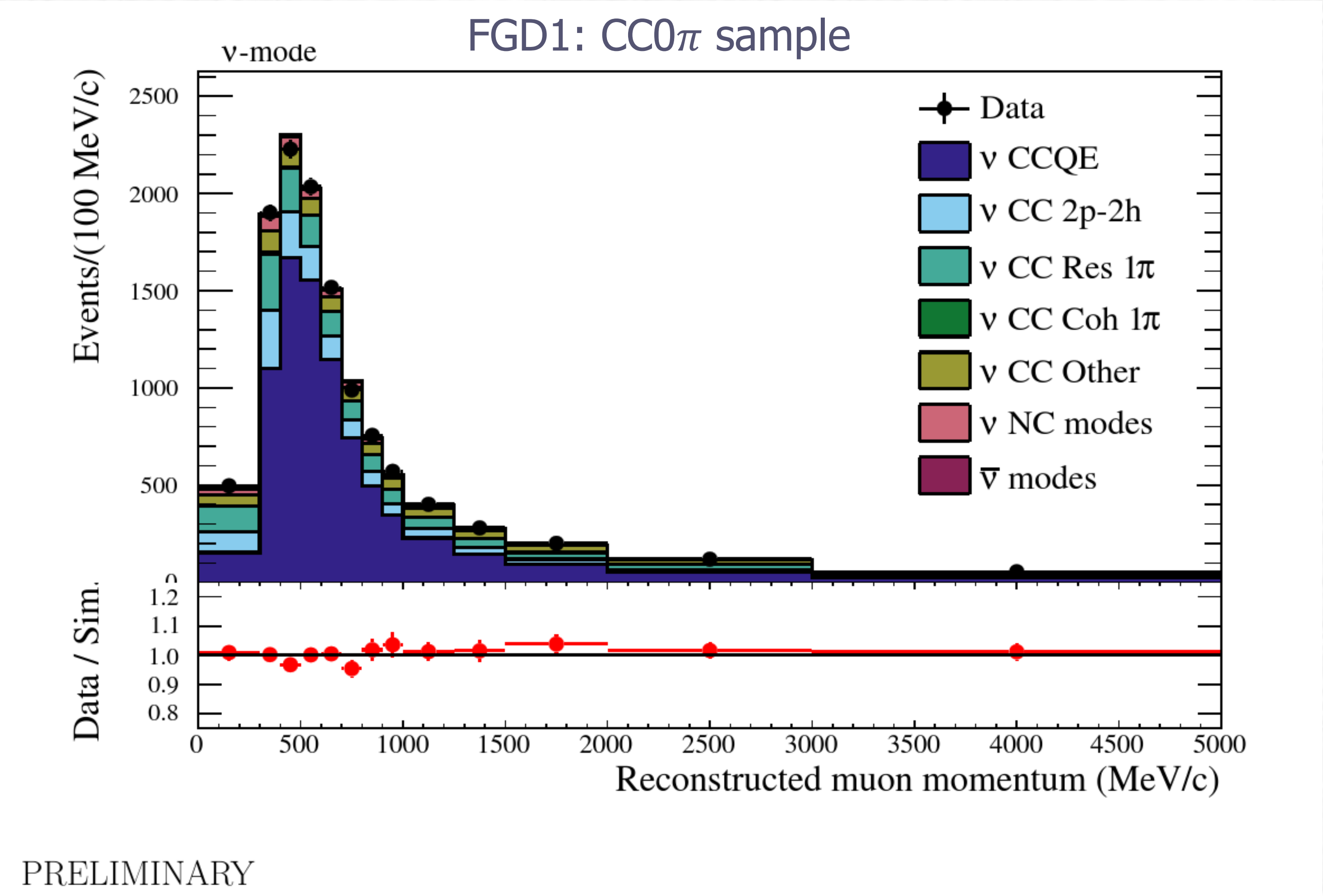
- Neutrino flux parameters (**f**) and neutrino interaction model parameters (**x**) for the SK can be constrained by ND280
- A binned likelihood **L**(**f**, **x**, d) is maximized for 14 ND280 data samples (6 for ν_μ-mode and 8 for $\bar{\nu}_\mu$-mode) [d=detector systematic parameters]
- MAX{**L**(**f**, **x**, d)} -> get central values and systematic uncertainties of parameters (**f**, **x**) for the oscillation analysis



Near detector constraint: pre-fit

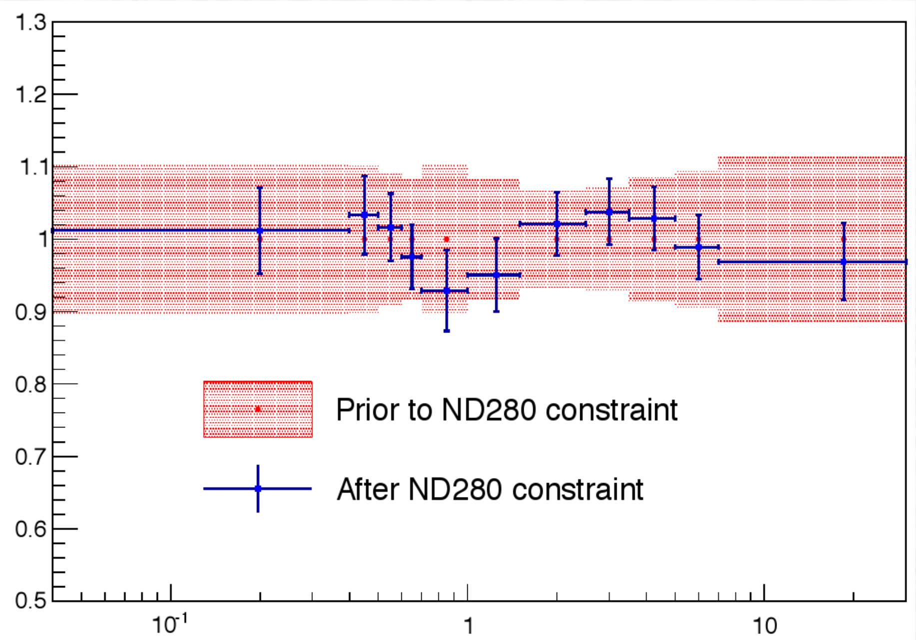


Near detector constraint: post-fit



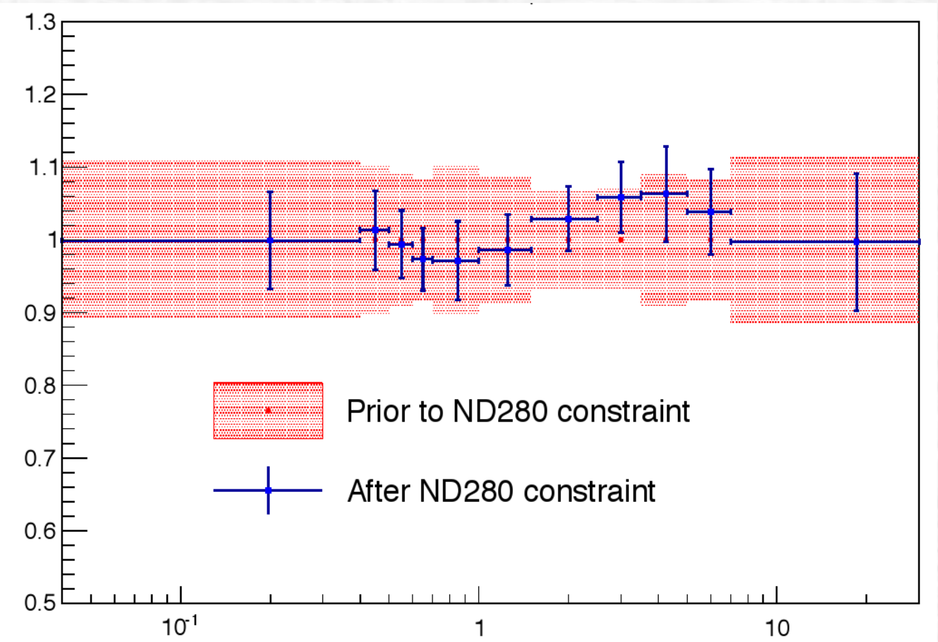
Fitted flux parameters

Super-K **neutrino**-mode flux



Neutrino Energy (GeV)

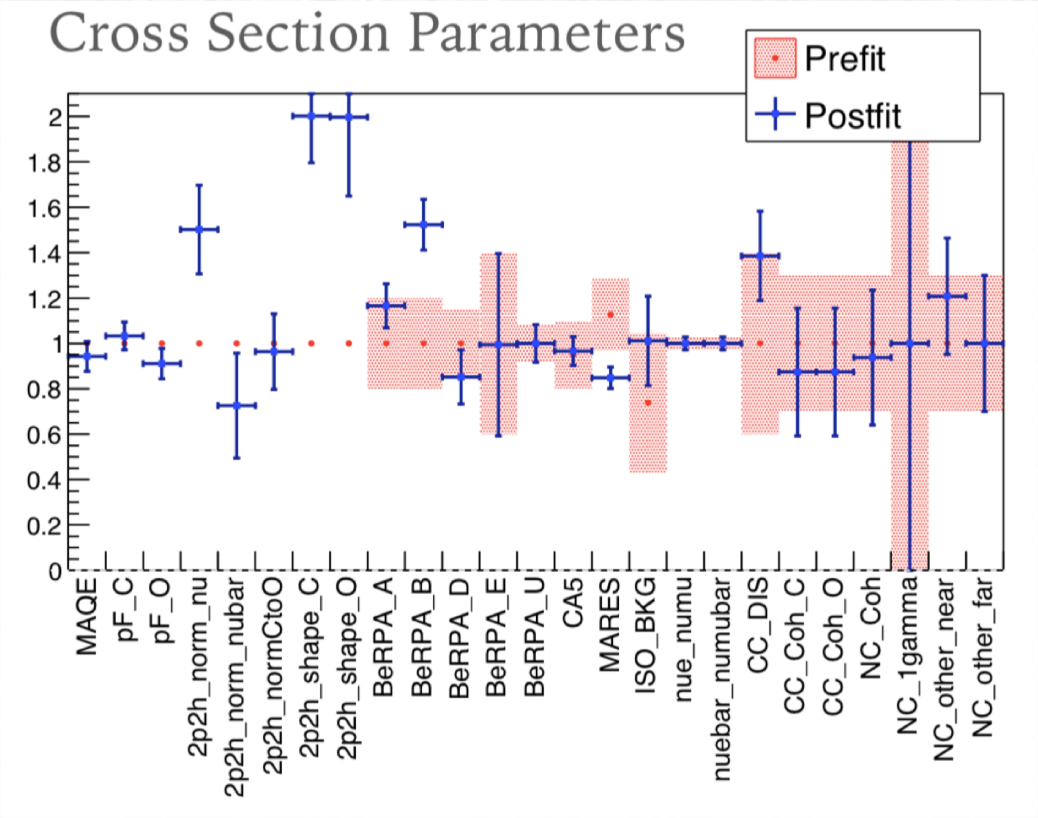
Super-K **antineutrino**-mode flux



Neutrino Energy (GeV)

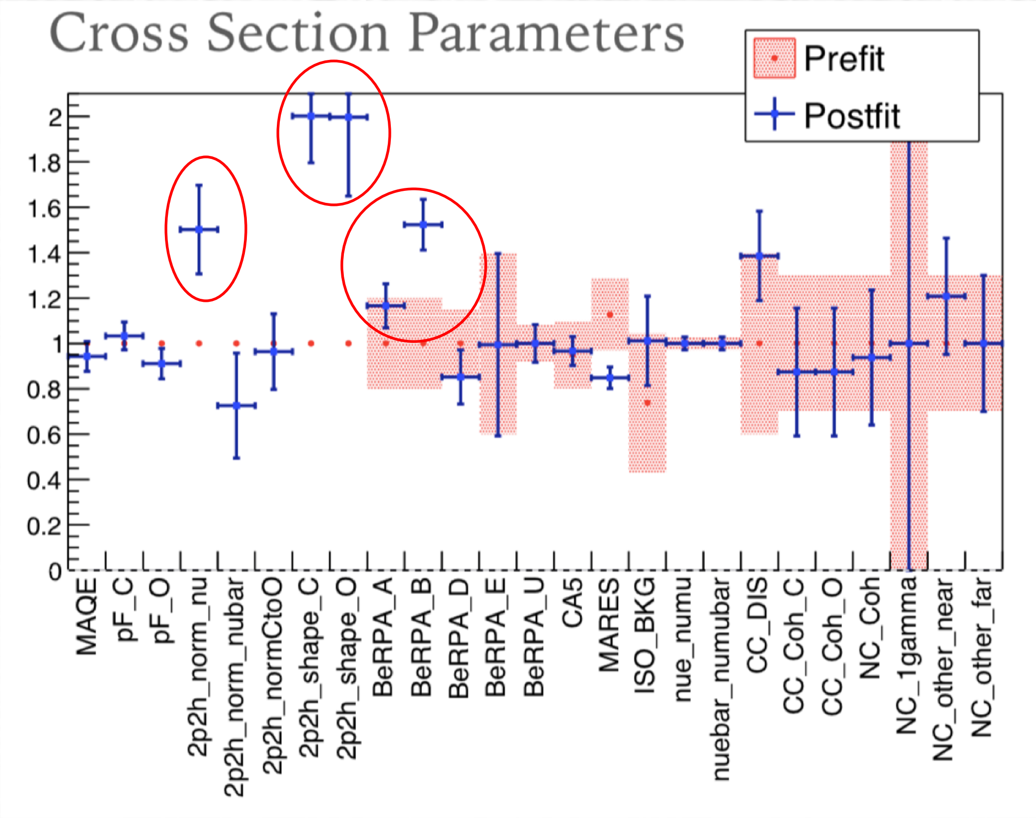
- ✓ Fitted flux parameters are near their nominal values (Post/Pre-fit $\simeq$1)
- ✓ Most of the fitted flux parameters are within 1σ prior uncertainty

Fitted interaction model parameters



The cross-section parameters include normalizations and Fermi momenta for C and O, parameters of nuclear effects (2p-2h, RPA), etc.

Fitted interaction model parameters



The fit enhanced some of cross-section parameters (related to 2p-2h and RPA)

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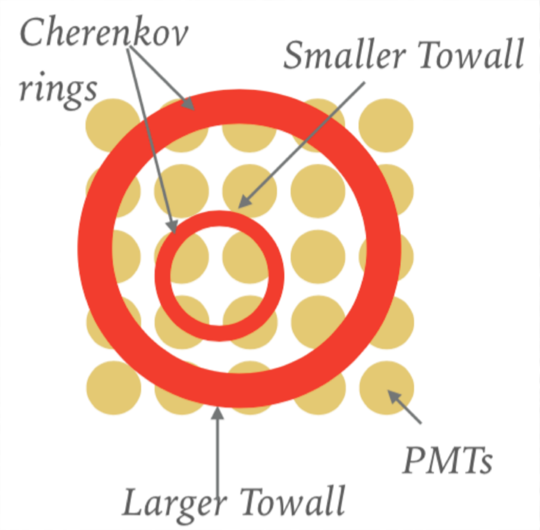
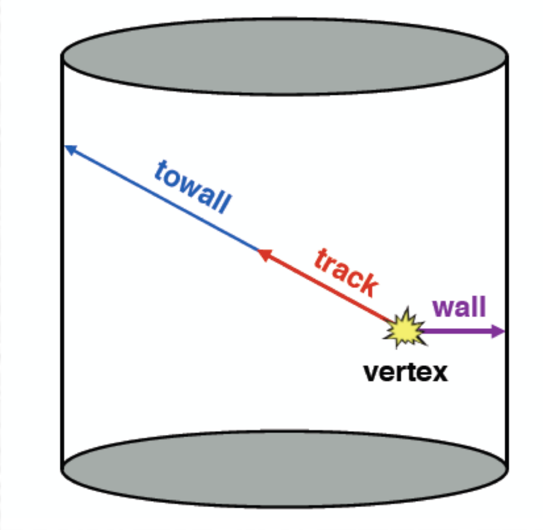
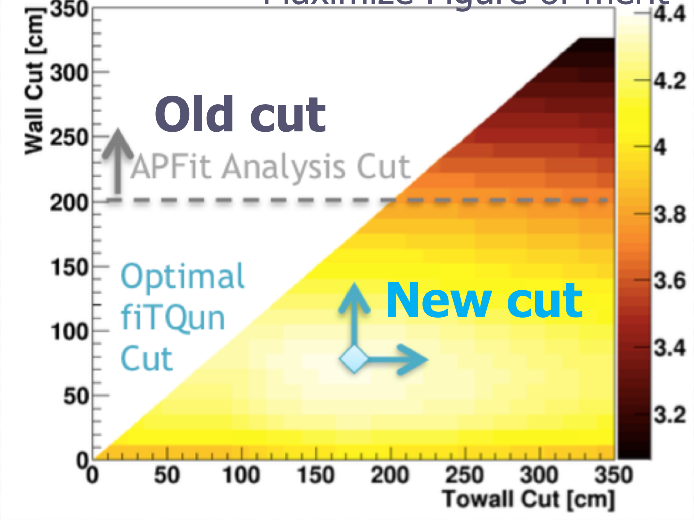
Super-K event reconstruction

- ✓ New reconstruction algorithm: fiTQun (uses a charge and time likelihood) instead of previous algorithm APFit
- ✓ Re-optimizing fiducial volume (FV) cut: expansion of the FV by ≃20-30% leads to ~30% increase in effective statistics





Maximize Figure of merit

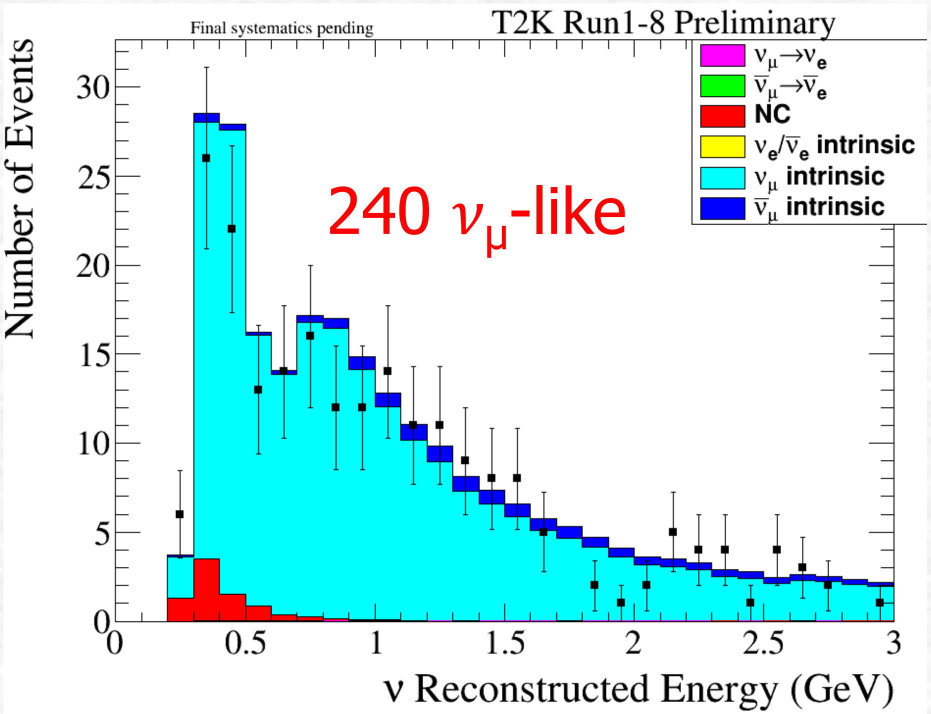


Two variables to constrain Fiducial Volume in the fitQun:

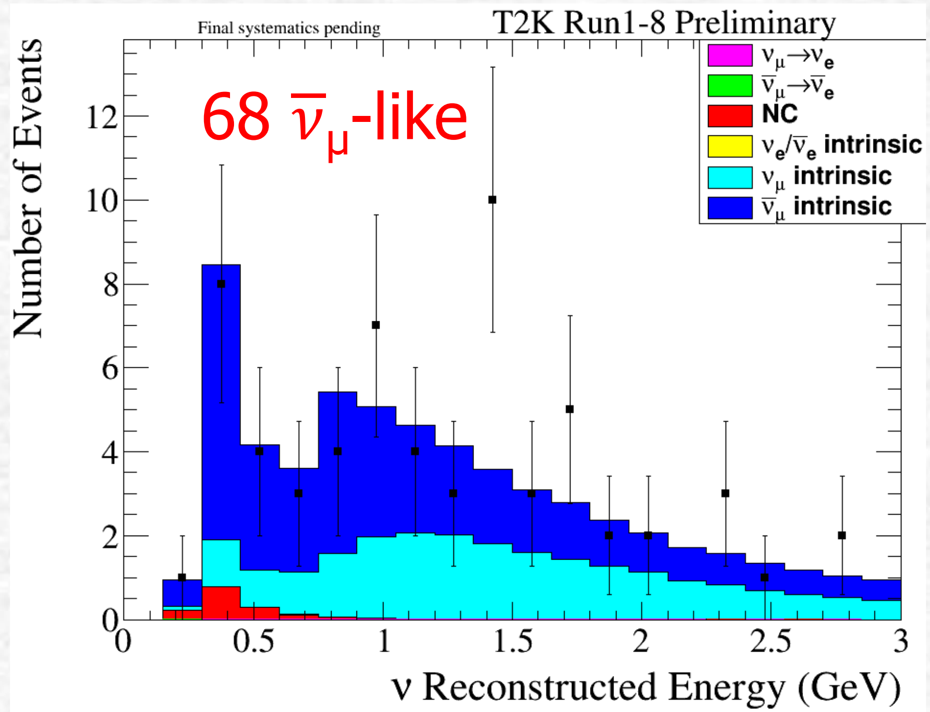
- wall = distance of vertex from wall (to exclude external background)
- towall = distance to the wall along the particle trajectory
  - Larger towall = better reconstruction (finer sampling of ring)

Super-K spectra: disappearance

Neutrino mode (14.7×10^{20} POT)



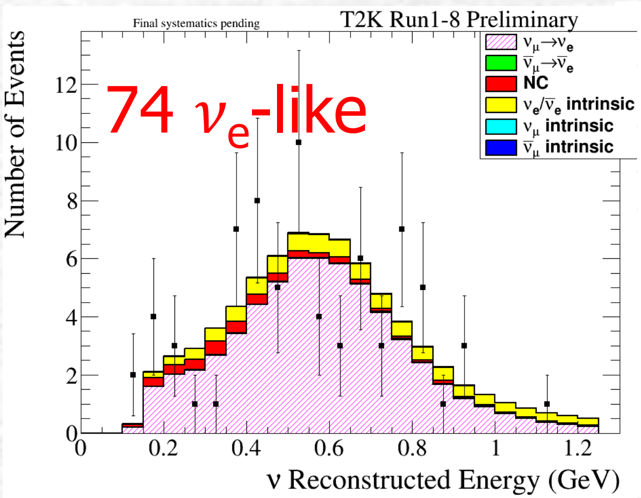
Antineutrino mode (7.6×10^{20} POT)

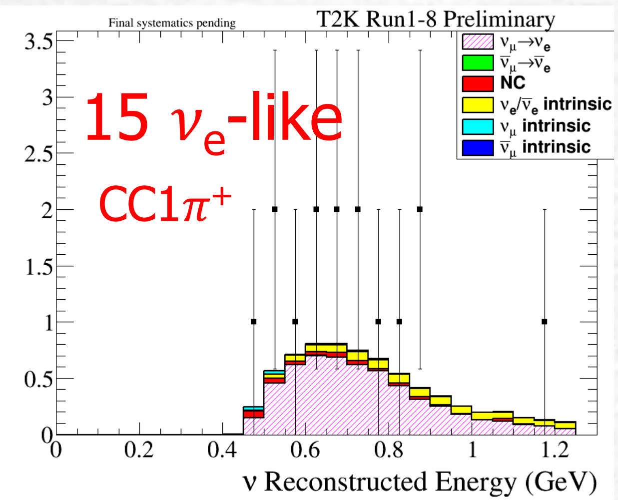


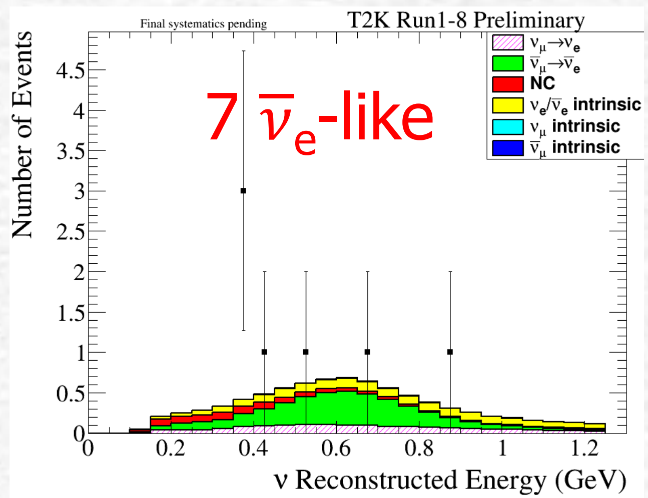
Data ν_μ-like	Expected			
	$\delta = -\pi/2$	$\delta = 0$	$\delta = \pi/2$	$\delta = \pi$
240	267.8	267.4	267.7	268.2

Data $\bar{\nu}_\mu$-like	Expected			
	$\delta = -\pi/2$	$\delta = 0$	$\delta = \pi/2$	$\delta = \pi$
68	63.1	62.9	63.1	63.1

Super-K spectra: appearance







Neutrino mode (14.7x10^{20} POT)

Data ν_e-like	Expected			
	δ = -$\pi/2$	δ = 0	δ = $\pi/2$	δ = π
74	73.5	61.5	49.9	62.0

CC1π^+ sample in **neutrino** mode: 1 e-like ring + 1 decay electron

Data ν_e-like CC1π^+	Expected			
	δ = -$\pi/2$	δ = 0	δ = $\pi/2$	δ = π
15	6.9	6.0	4.9	5.8

Antineutrino mode (7.6x10^{20} POT)

Data $\bar{\nu}_e$-like	Expected			
	δ = -$\pi/2$	δ = 0	δ = $\pi/2$	δ = π
7	7.9	9.0	10.0	8.9

Systematic errors at SK (%)

	1-Ring **μ-like**		1-Ring **e-like**			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode $CC1\pi^+$	ν-/$\bar{\nu}$-modes
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI + SI + PN	2.20	1.98	3.01	2.31	11.43	1.57
Flux+Cross sect. constrained	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
$NC1\gamma$	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic error	4.40	3.76	6.10	6.51	20.94	4.77

FSI = Final State Interaction
SI = Secondary interactions
PN = Photo-nuclear interactions
NC = Neutral Current

Total error is in 4-7% range (except for ν-mode $CC1\pi$ sample)

Systematic errors at SK (%)

	1-Ring **μ-like**		1-Ring **e-like**			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	ν-/$\bar{\nu}$-modes
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI + SI + PN	2.20	1.98	3.01	2.31	11.43	1.57
Flux+Cross sect. constrained	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic error	4.40	3.76	6.10	6.51	20.94	4.77

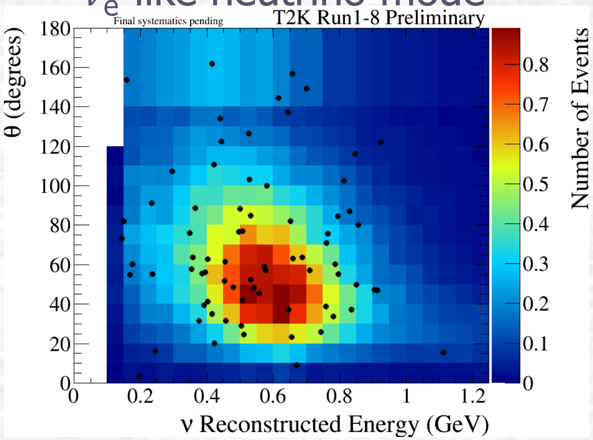
FSI = Final State Interaction
SI = Secondary interactions
PN = Photo-nuclear interactions
NC = Neutral Current

Errors for ratio of ν-/$\bar{\nu}$-modes e-like (appearance) samples are relevant for extraction of CP violation effect

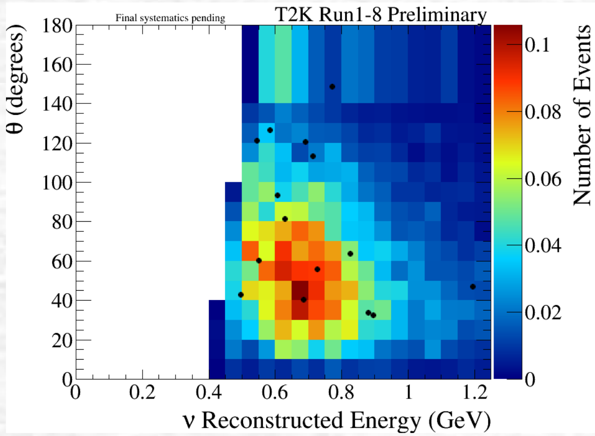
Joint fit of $(\nu + \bar{\nu})$-data

- ✓ 5 SK data samples in neutrino and antineutrino modes
- ✓ A binned likelihood **L**(**o**, **p**) is built for these data samples (**o** – oscillation; **p** – other parameters)
- ✓ Marginalize the likelihood (integrate over **p** and some of **o** parameters) and find a maximum (minimum of -2ln**L**)
- ✓ 3 analyses: Frequentist and Bayesian approaches -> *confidence* intervals and *credible* intervals of the oscillation parameters

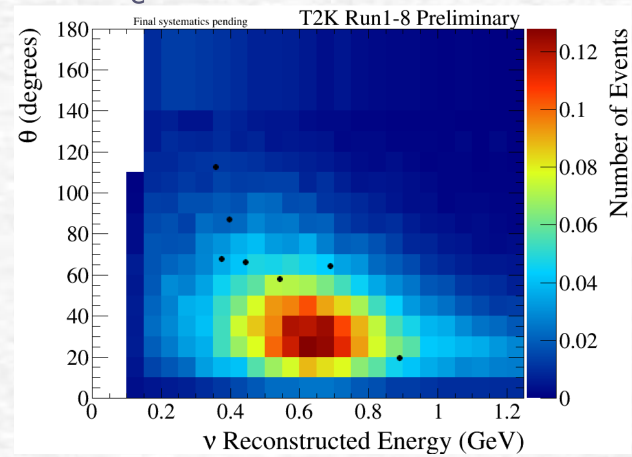
ν_e-like neutrino mode



ν_e-like CC1π^+ neutrino mode

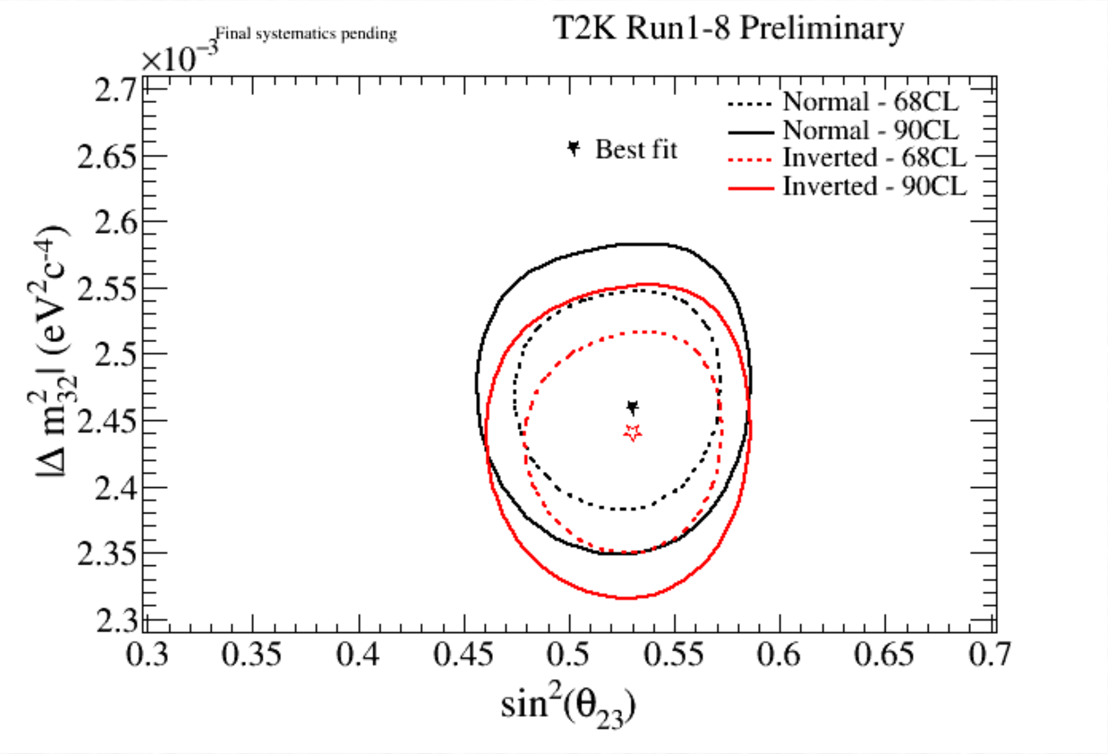


$\bar{\nu}_e$-like antineutrino mode

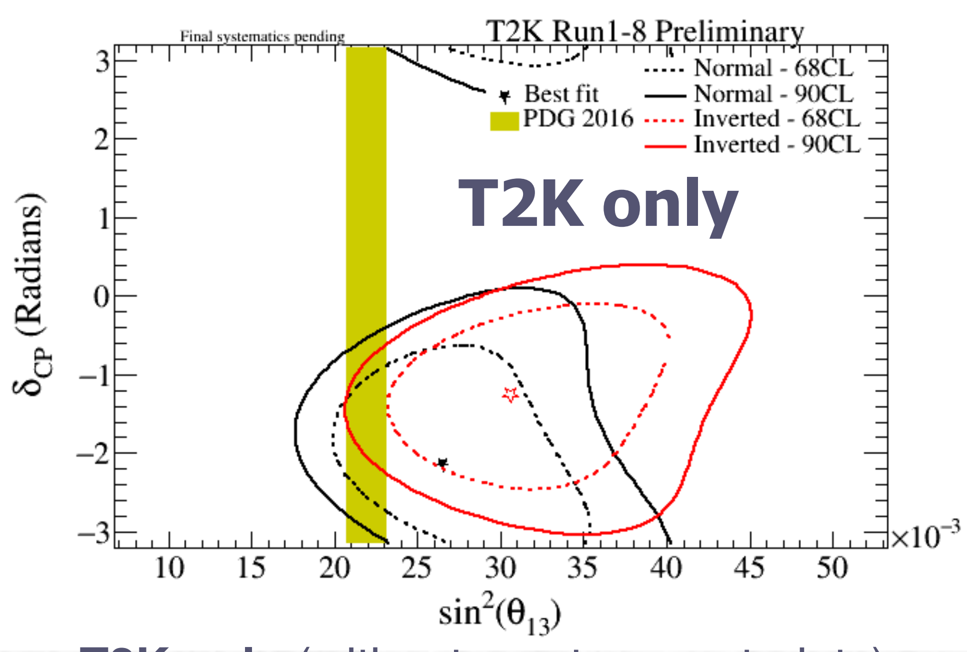


Atmospheric parameter constraint

- Fit the normal and inverted hierarchies separately
- θ_{13} is reactor constrained
- Final systematics pending

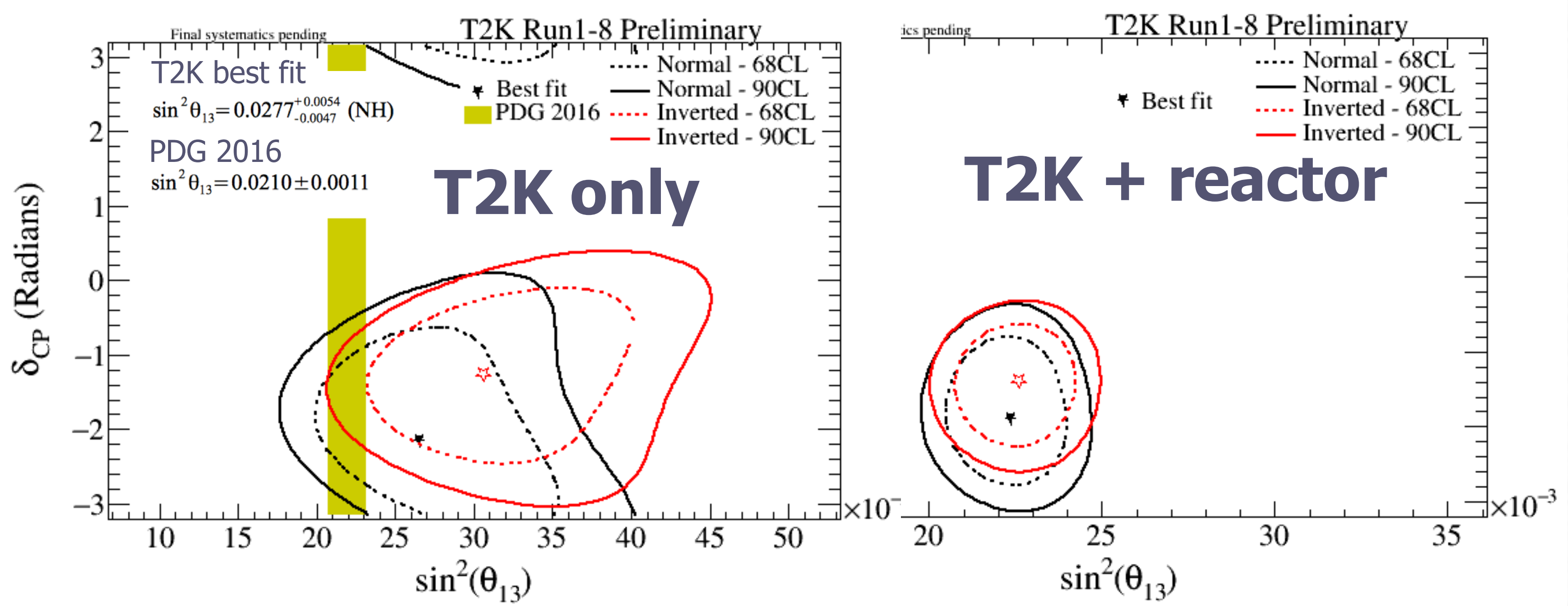


T2K (θ_{13}, δ_{CP}) constraints



- **T2K only** (without reactor constraints): $\sin^2\theta_{13}$ is compatible with results of the reactor experiments.
- Preferable values of δ_{CP} around $-\pi/2$

T2K (θ_{13}, δ_{CP}) constraints



- **T2K only** (without reactor constraints): $\sin^2\theta_{13}$ is compatible with results of the reactor experiments.
- Preferable values of δ_{CP} around $-\pi/2$

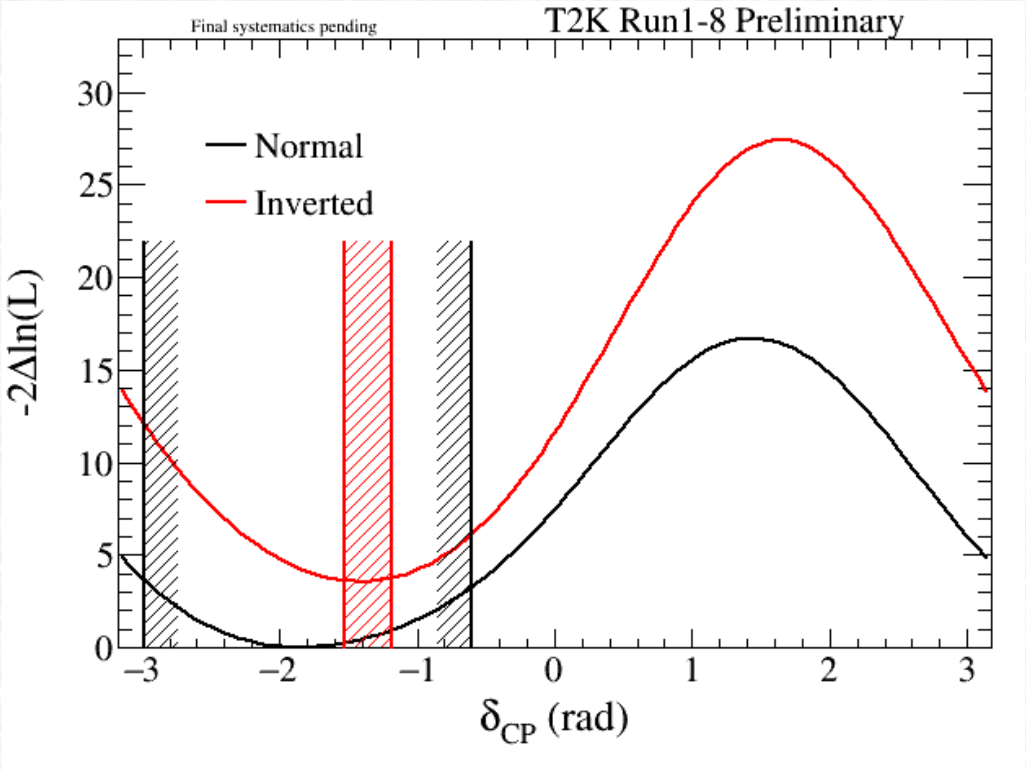
- **T2K + reactor** constraints: clear preference of δ_{CP} around $-\pi/2$

T2K δ_{CP} results

Best fit point: **-1.83** radians in Normal Hierarchy

<u>**2σ CL intervals**</u>:

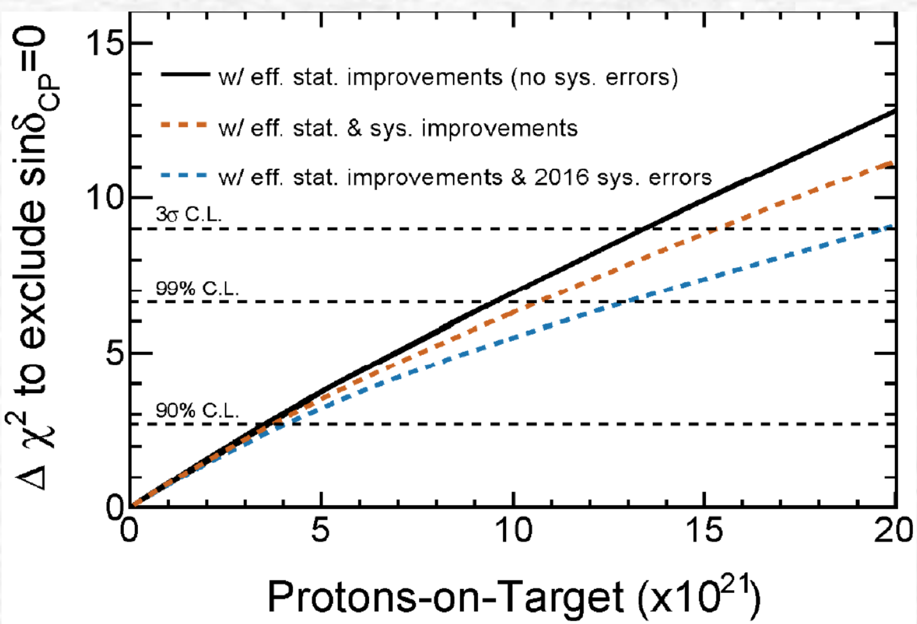
- *Normal* Hierarchy: [**-2.98**, **-0.60**] radians
- *Inverted* Hierarchy: [-1.54, -1.19] radians
- CP conserving values 0, π both fall outside 2σ CL intervals

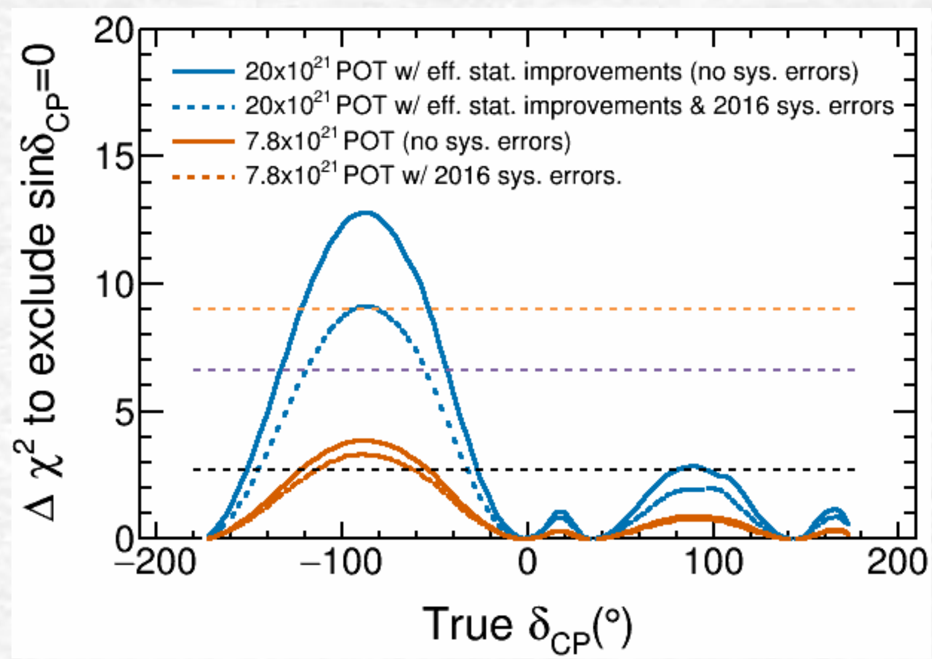


The Future (2021-2026): T2K-II

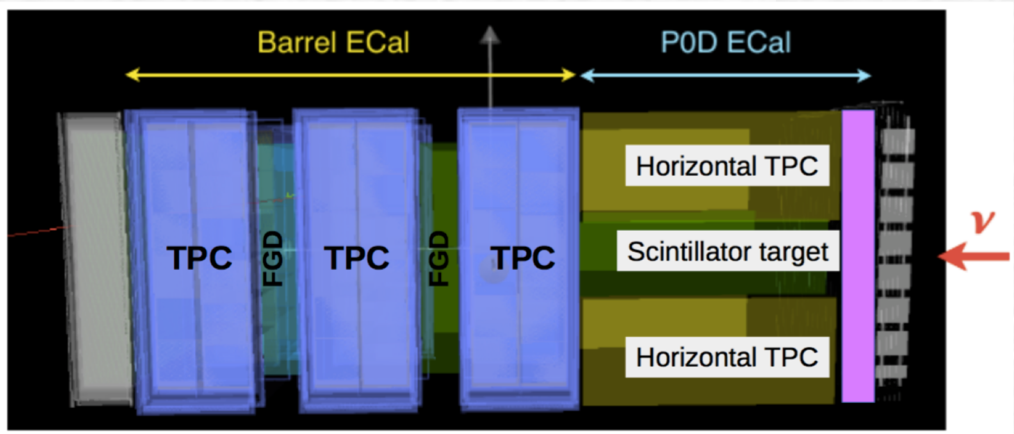
- T2K's primary goal (7.8×10^{21} POT) could be reached by 2021
- Next proposal: to reach 20×10^{21} POT by 2026
- Search for CPV: if δ_{CP} is near current best fit, then 3σ discovery of CP violation is possible in T2K-II (need to improve systematic uncertainties)

arXiv:1609.04111



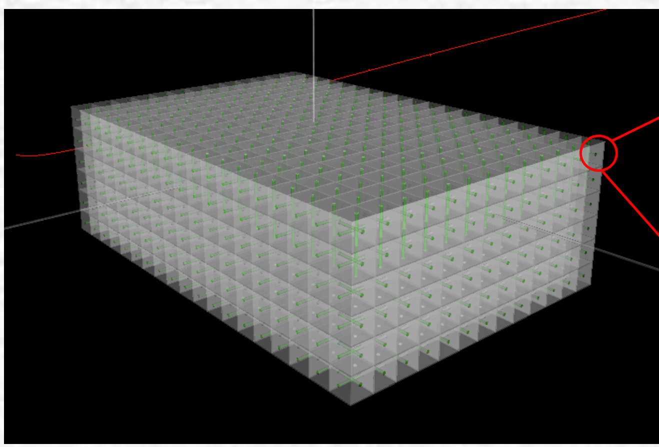


T2K-II: Near Detector upgrade

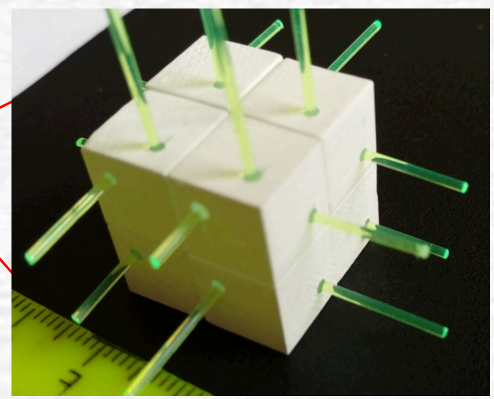


Current P0D will be replaced by
- a fully active scintillator neutrino target (Super-FGD) and
- 2 Horizontal TPCs

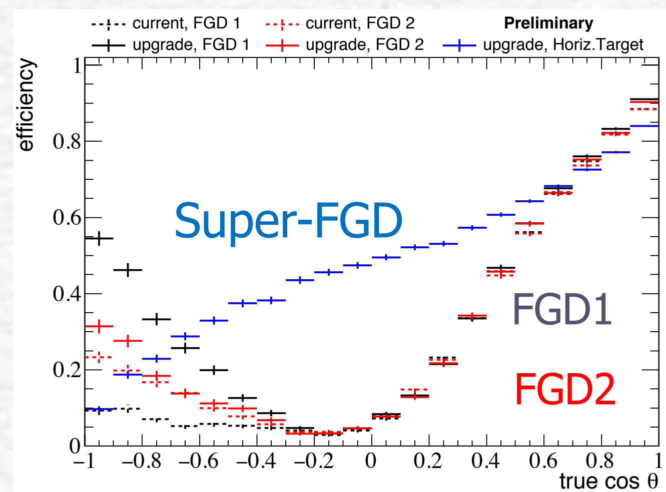
CC incl selection efficiency VS cosθ



Scintillator target (Super-FGD): over 2 million cubes



1 cm^3 cubes
3 fibers per cube



Muon angle (True cosθ)

Summary

- Since summer 2016 T2K has doubled neutrino- and antineutrino-mode data (current total ~3.1×10^{21} POT)
- Updates to the T2K oscillation analysis:
  - Improvements to neutrino interaction model (added nuclear effects)
  - New reconstruction and event selection at Super-K: effective improvement in statistics by ~30%
- T2K oscillation study results (for 14.7×10^{20} POT in neutrino mode and 7.6×10^{20} POT in antineutrino mode):
  - CP conserving values of δ_{CP} are excluded at 2σ
- Proposal of T2K-II: to collect 20×10^{21} POT in 2021-2026
  - R&D for Upgrade of the Near Detector is ongoing

Backup slides

T2K Collaboration

~500 members, 64 Institutes, 12 countries

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

France
CEA Saclay
LLR E. Poly.
LPNHE 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.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

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

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

Probability of $\nu_\mu \rightarrow \nu_e$ (appearance) with 1st order matter effect

$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

Leading term including matter effect

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP conserving

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\boxed{\sin\delta}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP violating

$$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

Solar

$$-8c_{13}^2 s_{13}^2 s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

Matter effect (small)

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

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

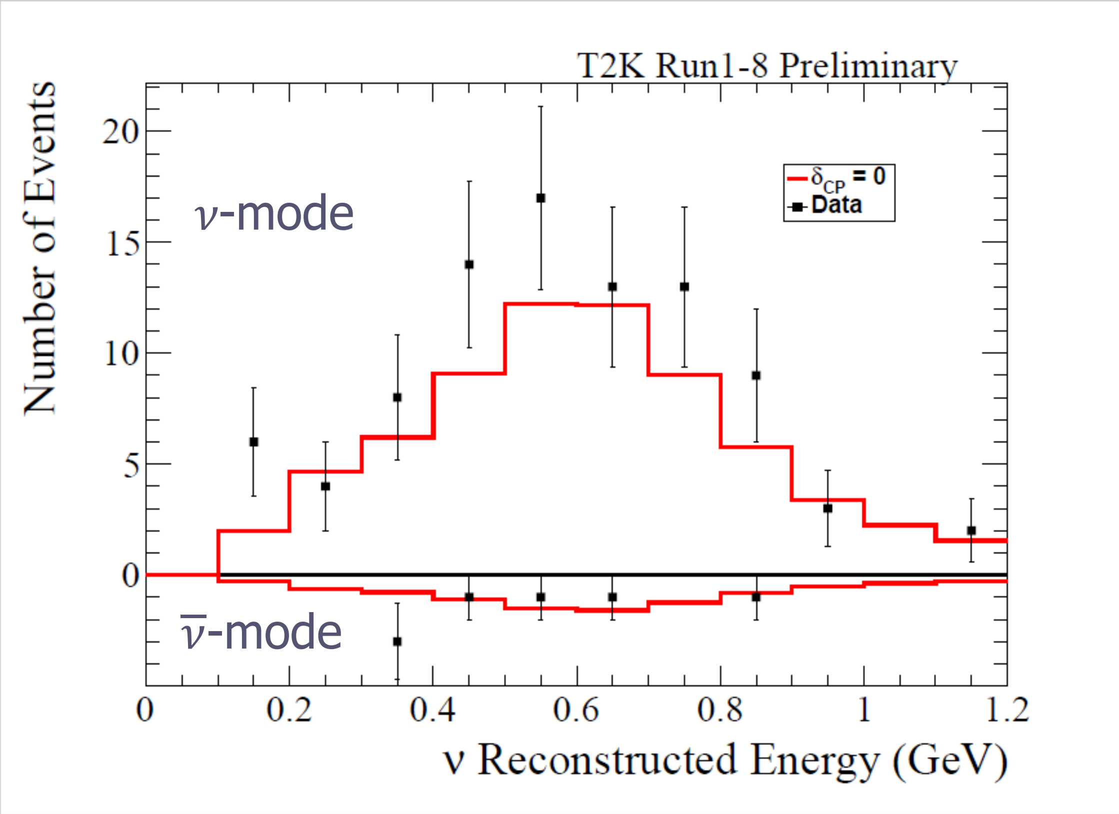
$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

replace δ by $-\delta$ and a by $-a$ for $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

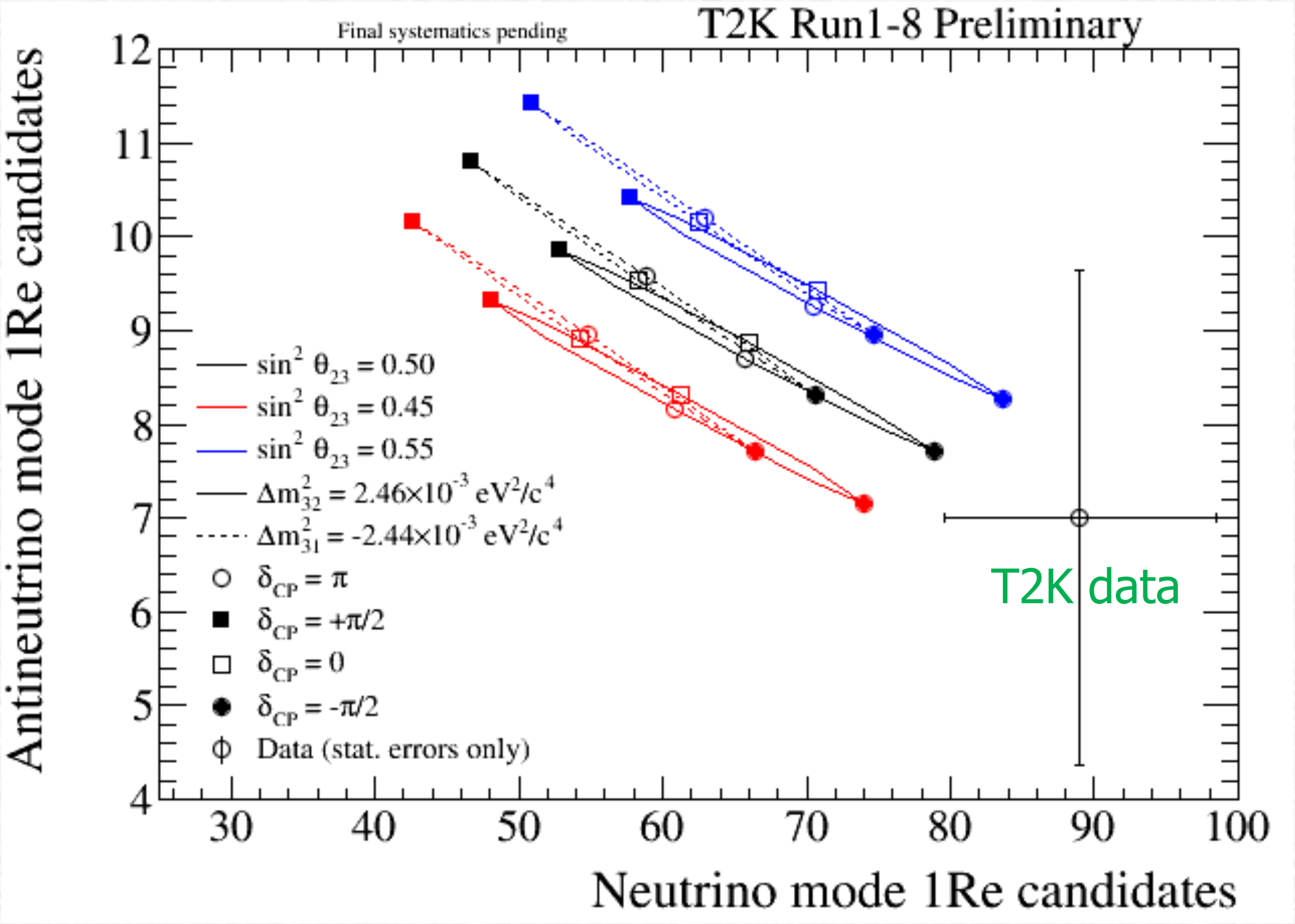
$\nu_e/\bar{\nu}_e$ appearance: data and prediction

Compared to $\boldsymbol{\delta_{CP} = 0}$ prediction:

- data excess in ν-mode
- data deficit in $\bar{\nu}$-mode



$\nu_e/\overline{\nu}_e$ appearance: data and prediction



Far future (2026-2036): Hyper-Kamiokande

- J-PARC MR power: ~1.3 MW
  - 2.7×10^{22} POT (10 years)
- Upgraded Near Detector
- New Far Detector in Tochibora mine
  - same baseline, 295 km,
  - same off-axis angle, 2.5°
  - 60 m (height), 74 m (diameter)
  - total volume 258 kton
  - 40% photocoverage
- Better sensitivity (3-5σ of CPV discovery)
- Rich (astro)physics program