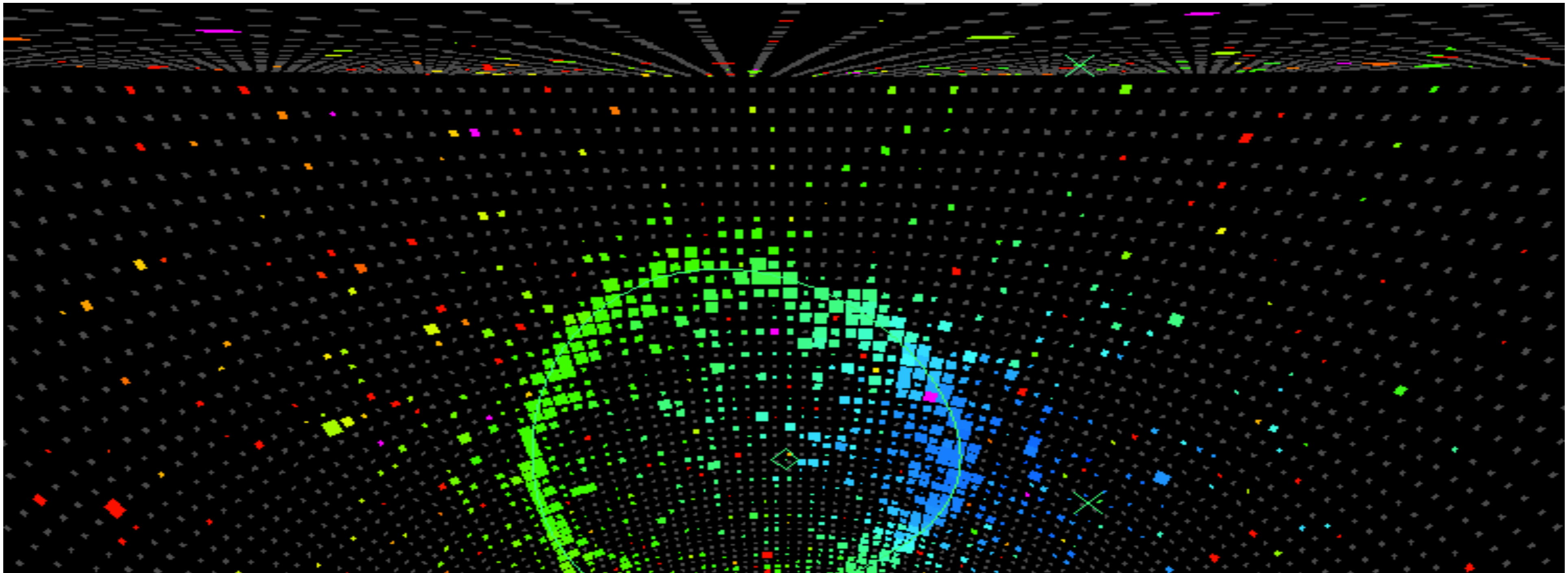


T2K

New T2K Neutrino Oscillations Results

Chang Kee Jung

Stony Brook University

for the T2K Collaboration

DPF Meeting

Fermilab

August 4, 2017

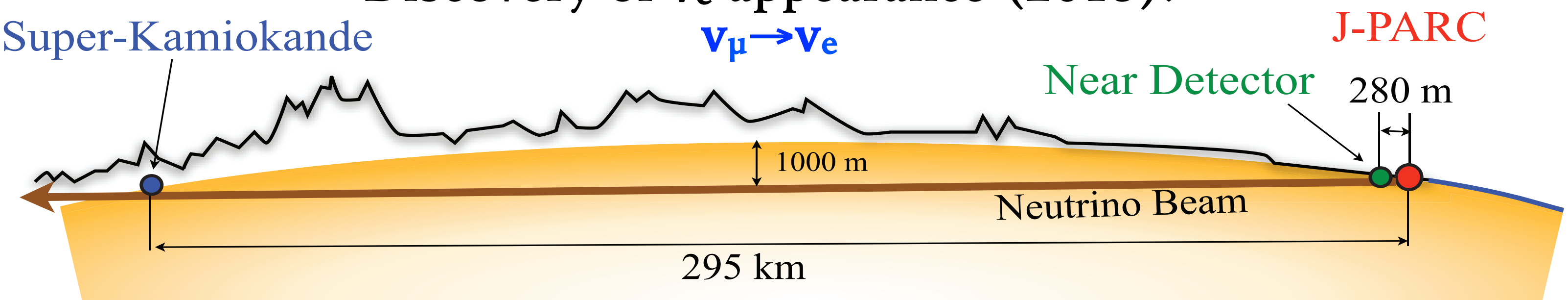
This presentation is a digest version.
It will focus on the changes and improvements since summer 2016

For a full presentation, see:
https://kds.kek.jp/indico/event/25337/ or
https://www.t2k.org/docs/talk/282

And for the corresponding press release, see:
http://t2k-experiment.org/2017/08/t2k-2017-cpv/

The T2K Experiment

Discovery of ν_e appearance (2013):



"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

The T2K Collaboration
(~500 members, 63 institutions, 11 countries)

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

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

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. Education
Okayama U.
Osaka City U.
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.

Poland
IFJPAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
U. Wroklaw

Russia
INR

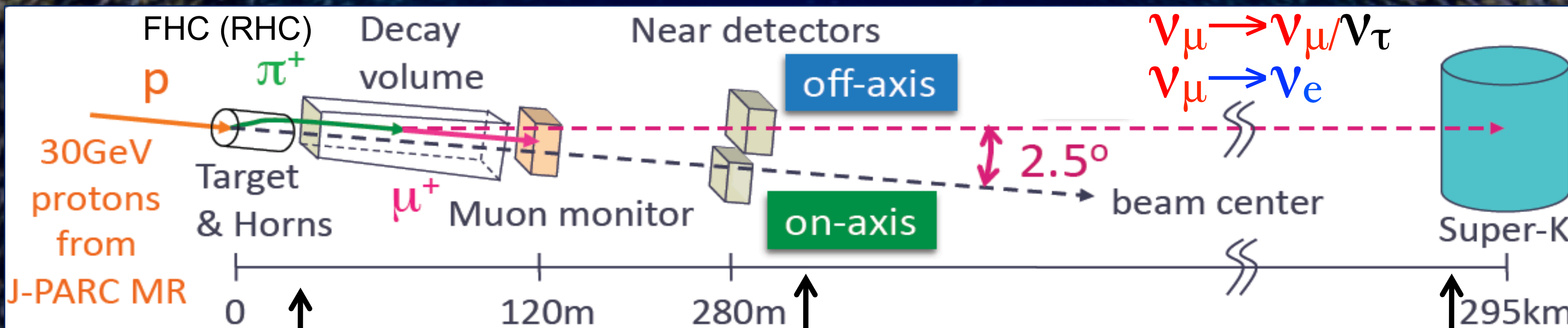
Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma, Madrid

Switzerland
U. Bern
U. Geneva
ETH Zurich

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 S. U.
Michigan S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester

T2K Experimental Setup and Oscillation Analysis Strategy



Tracking inside horns and He vessel

GEANT3+GCALOR

Proton beam interaction in the target

→Hadron production

FLUKA, NA61, etc.

Φ

Near detector data

Fit

Constrained Φ σ

σ

Neutrino-nucleus interaction models

External data

SK data and uncertainties (detector and uncorrelated σ)

Fit

Measured oscillation parameters

Predicted Φ and correlated σ at SK

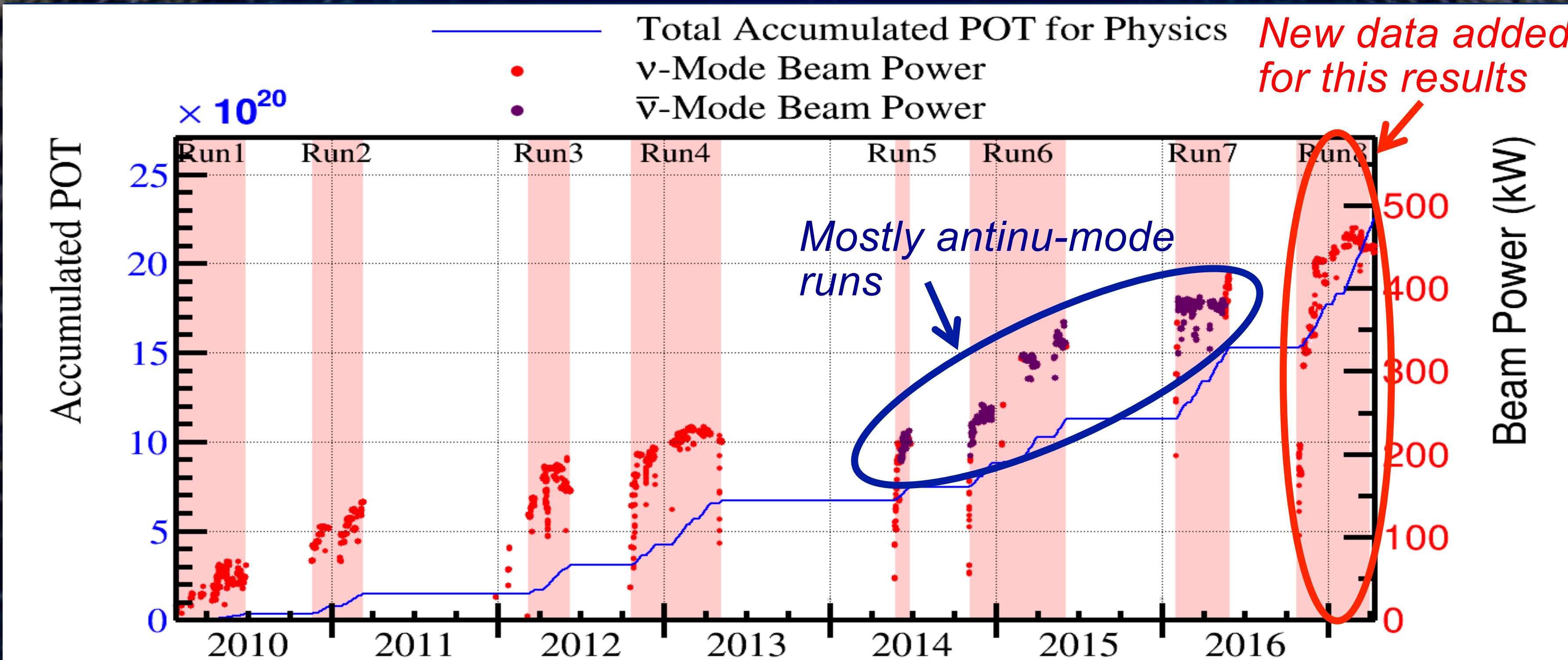
$$\Phi^{SK} \cdot \sigma^{H2O}_{reaction} \cdot \varepsilon_{SK} \cdot P_{osc} dE_\nu$$

Progresses amd Improvements since Summer 2016 (ICHEP16)

- New Data
  - Double the neutrino-mode data in 1 year!
- Improved event reconstruction and optimized selection
  - A new class of event sample for Oscillation Analysis (OA)
    - ν_e CC1π^+
  - Full implementation of new event reconstruction algorithm (fiTQun) in the far detector (SuperK) analysis
    - fiTQun was used for NCπ^0 background rejection only in the T2K 2013 "Observation of ν_e appearance" OA
    - Newly optimized event selection including expansion of the fiducial volume for OA

  → ***Effective Increase in the data efficiency/statistic by ~30%***
- Improved neutrino-nucleus interactions modeling

T2K Data Taking in Neutrino and Antineutrino Beam Modes



- Stable operation at ~470 kW achieved (design power: 750 kW)
- Mostly antineutrino-mode run from June 2014 – May 2016
- Total POT for physics: 14.7×10^{20} (nu-mode), 7.6×10^{20} (antinu-mode) → ~ 29% of the total approved POT (7.8×10^{21})

New Class of Event Sample for OA

- 4 classes of event samples for the 2016 OA
  - (ν_μ CCQE) 1 Muon-like Ring, ≤1 decay electron
  - (ν_e CCQE) 1 Electron-like Ring, 0 decay electrons
  - For both nu-mode (FHC) and antinu-mode (RHC)
- New sample added for the 2017 OA
  - (ν_e CC1π^+) 1 Electron-like Ring, 1 decay electron
  - Only for nu-mode
    - No antinu-mode CC1π^- due to π^- absorption

→ A total of 5 event samples for the summer 2017 OA

Below Cherenkov threshold

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$

$$\pi^+ \downarrow \mu^+ + \nu_\mu$$

$$\mu^+ \downarrow e^+ + \nu_e + \bar{\nu}_\mu$$

detected particles

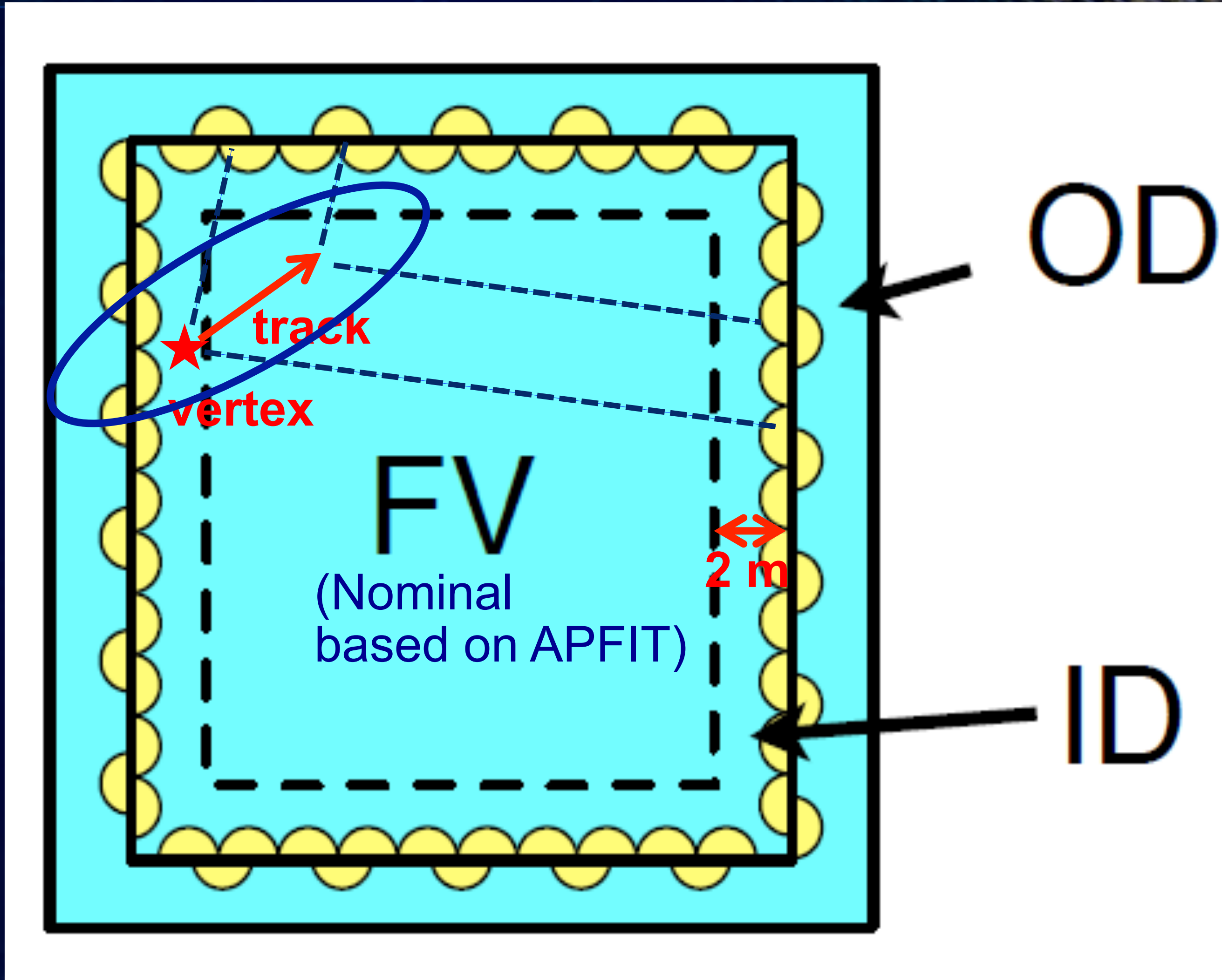
Super-Kamiokande (T2K Far Detector) Fiducial Volume Expansion/Optimization

Save this type of events!

Q: This looks obvious. Why was not done earlier?

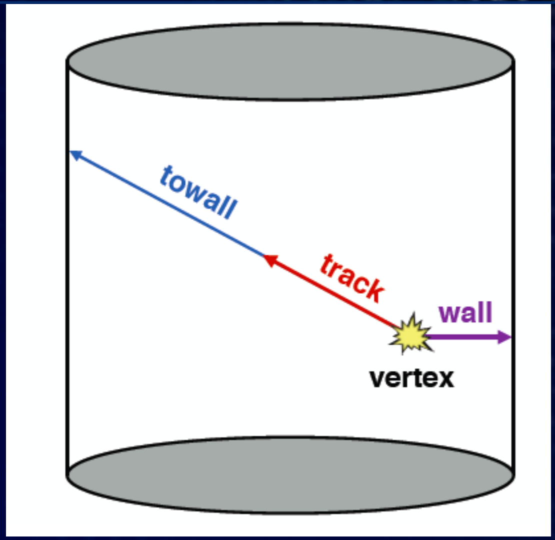
A: Already tried at K2K. But, the benefit of increased in stat can be compromised w/ increased syst. errors

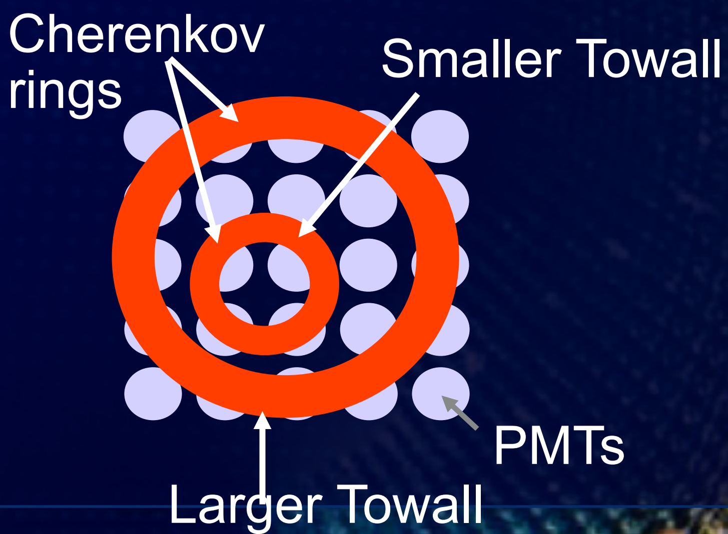
→ Needs an advanced tool and methodology



Fiducial Volume Optimization

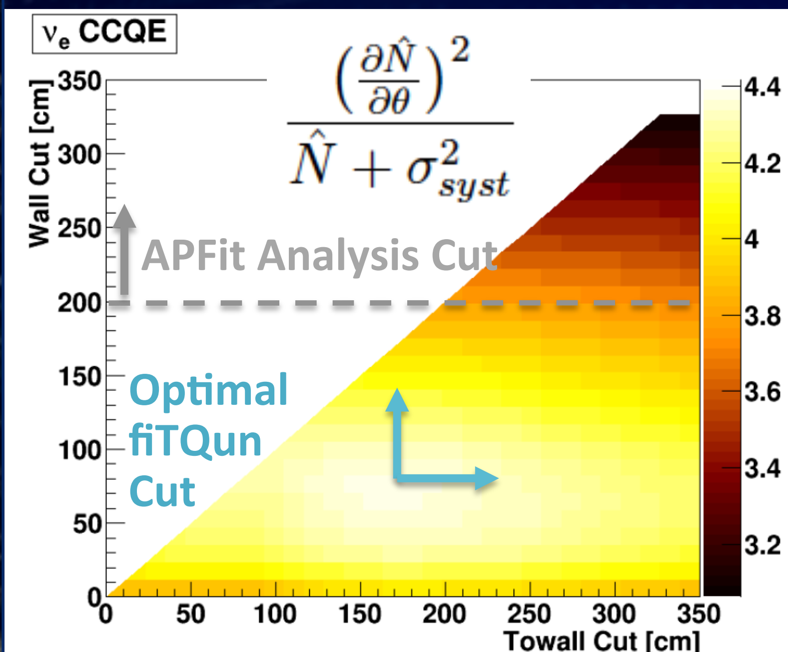
- Select events based on the two variables
  - "wall": distance of event vertex from the wall
    - require minimum distance to exclude external backgrounds
  - "towall": distance to the wall along the particle trajectory
    - larger towall → larger # of PMT hits → better reconstruction
- Optimize selection accounting for both statistical and systematic errors



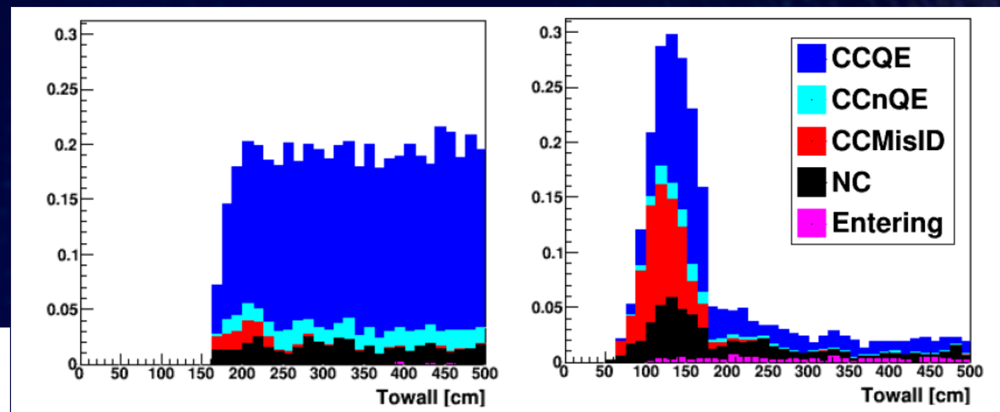


Fiducial Volume Optimization w/ fiTQun

- For each of the 5 samples, optimal [wall, towall] values are determined by maximizing the sensitivity metric



Accepted Events   Rejected Events



Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ-like FHC	250 cm	50 cm
CC1π 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ-like RHC	250 cm	50 cm
All samples w/ APFIT	200 cm	200 cm

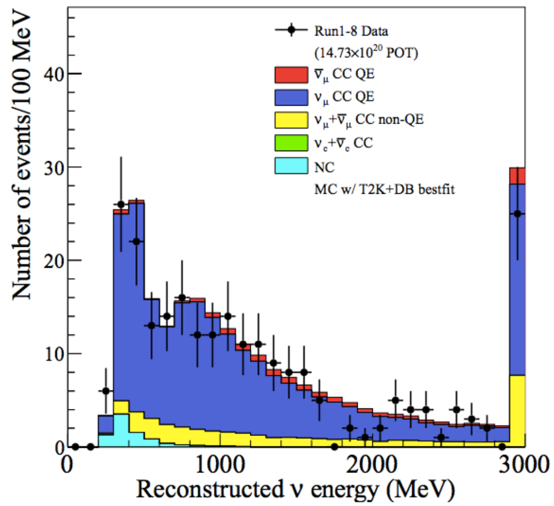
Improvements in the Neutrino-Nucleus Interaction Models

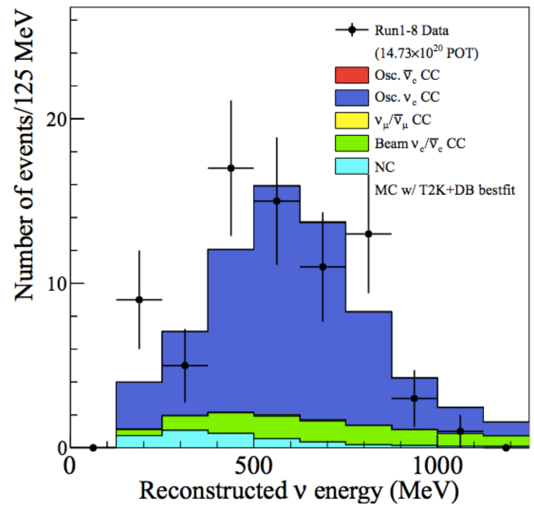
- Significantly improved neutrino interaction models in NEUT (primary neutrino interaction generator used in T2K):
  - Improved pion production model
    - tuning to data on hydrogen and deuterium
  - Inclusion of a model for multi-nucleon scattering processes
    - "Valencia 2p-2h model" *Phys. Rev. C83 (2011) 045501*
  - Improved CCQE model
    - Inclusion of the effect of long-range correlations in the nucleus, using "Random Phase Approximation" (RPA) calculation method

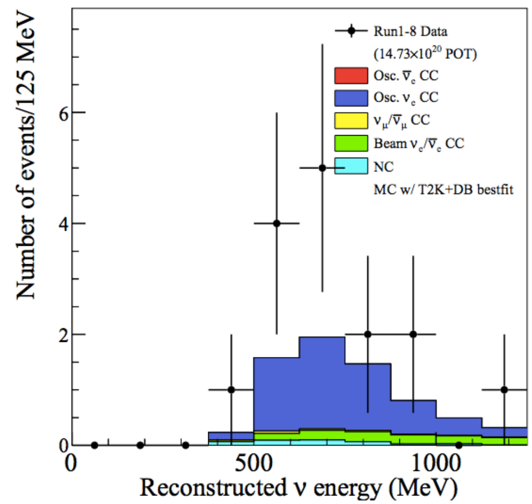
→ This analysis: developed new parameterizations of the uncertainties in multi-nucleon and RPA modeling

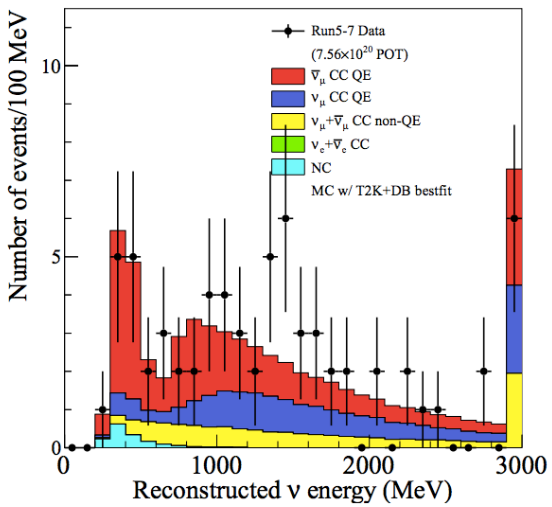
Observed Energy Spectra of 5 Samples

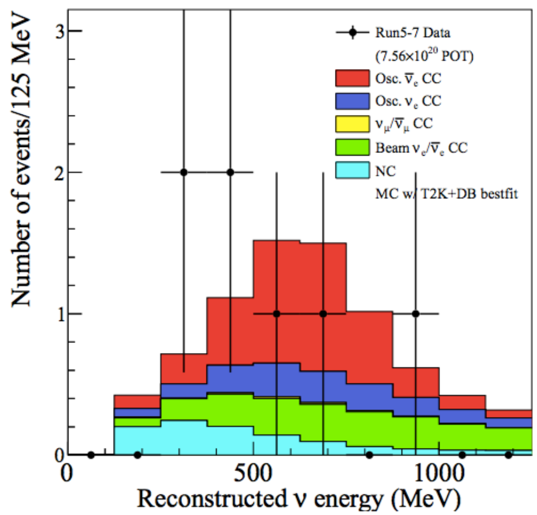
CCQE 1 μ-like ring	CCQE 1 e-like ring	CC1π 1 e-like ring











Upper panels: nu-mode
Lower panels: antinu-mode

T2K Preliminary

T2K Predicted and Observed Event Rates

Sample	Predicted Rates				Observed Rates
	δ_{cp}=-π/2	δ_{cp}=0	δ_{cp}=π/2	δ_{cp}=π	
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

- e-like sample: observed rates consistent with the $\delta_{cp} = -\pi/2$ hypothesis
- CC1π sample: observed rate is 15 while the maximum predicted rate is 6.92
  - p-value for upward/downward fluctuation in one sample: 2.5%
  - p-value for upward/downward fluctuation at least 1 of 5 samples is: 11.9%

Systematic Errors

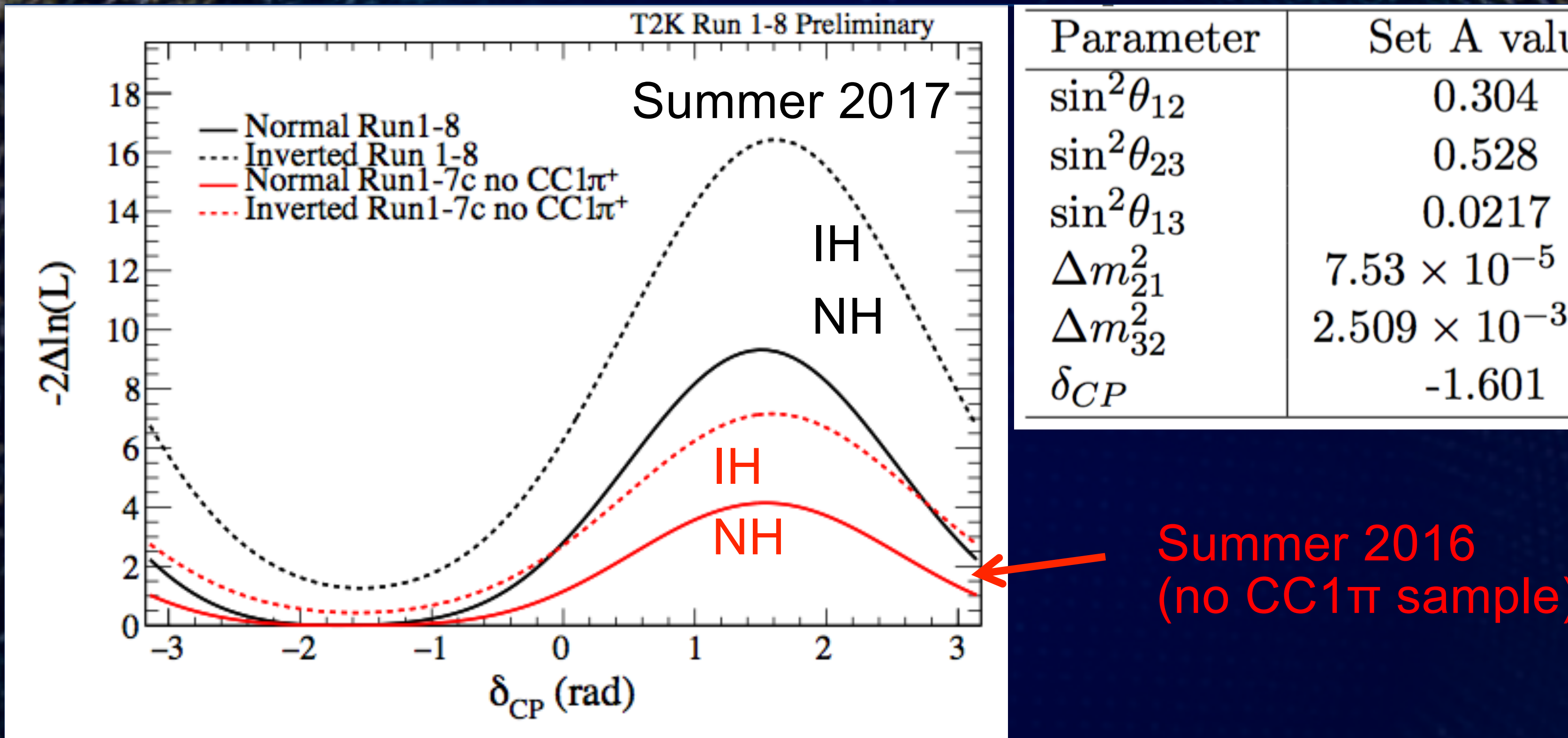
	% Errors on Predicted Event Rates, Osc. Parameter Set A					
	1R μ-Like		1R e-Like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	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

4 – 7%

largest

most relevant for extracting CPV effect

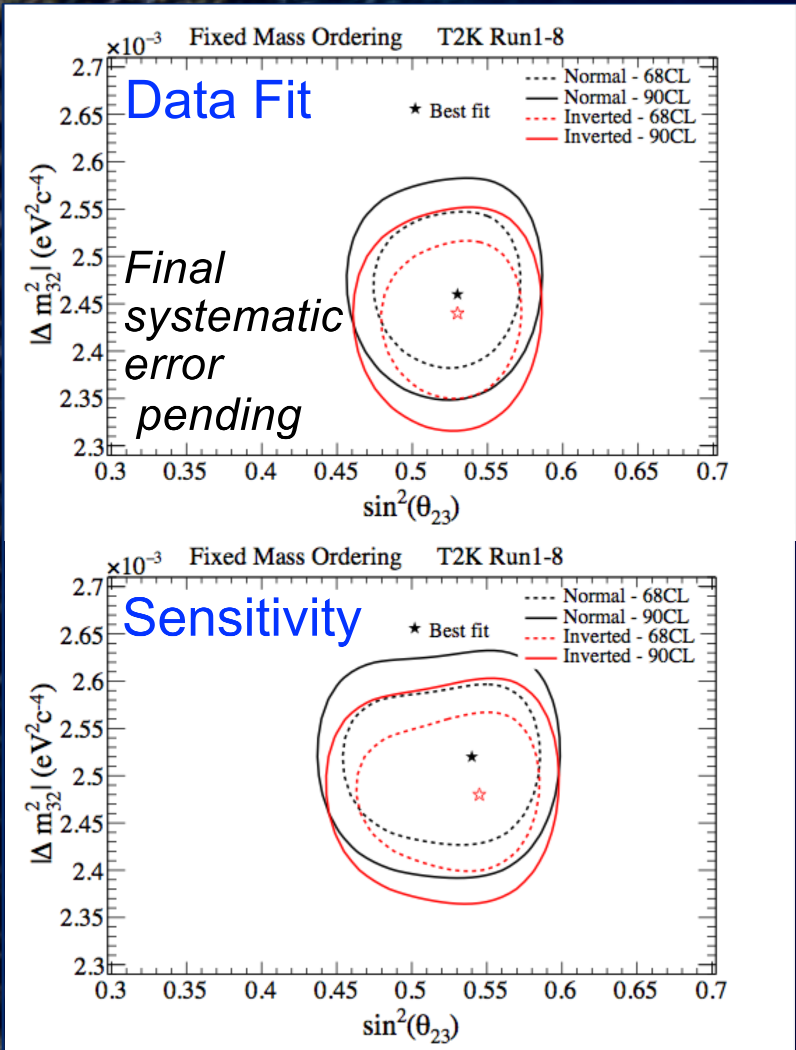
T2K Summer 2017 Sensitivity on δ_{CP}



Parameter	Set A value
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{23}$	0.528
$\sin^2\theta_{13}$	0.0217
Δm^2_{21}	7.53×10^{-5} eV^2
Δm^2_{32}	2.509×10^{-3} eV^2
δ_{CP}	-1.601

- Sensitivity for excluding CP conserving values in parameter set A has more than doubled since last year

"Full" Joint Fit for θ_{23} & Δm^2_{32}



- Fit the normal and inverted hierarchies separately
- Results with the reactor constraint on $\sin^2 2\theta_{13}$ shown
- Constraint on $\sin^2\theta_{23}$ is slightly stronger than the sensitivity
- The final systematic error evaluation is still pending
  - Extensive studies show impact on the δ_{CP} measurement is minor
    - Maximum change to the NH 2σ confidence interval was 2.3%

Full Joint Fit for θ_{13} & δ_{CP}

- T2K only fit without the reactor constraint: closed contours in δ_{cp} at 90% CL
- The T2K value for $\sin^2\theta_{13}$ is consistent with the PDG 2016 average:

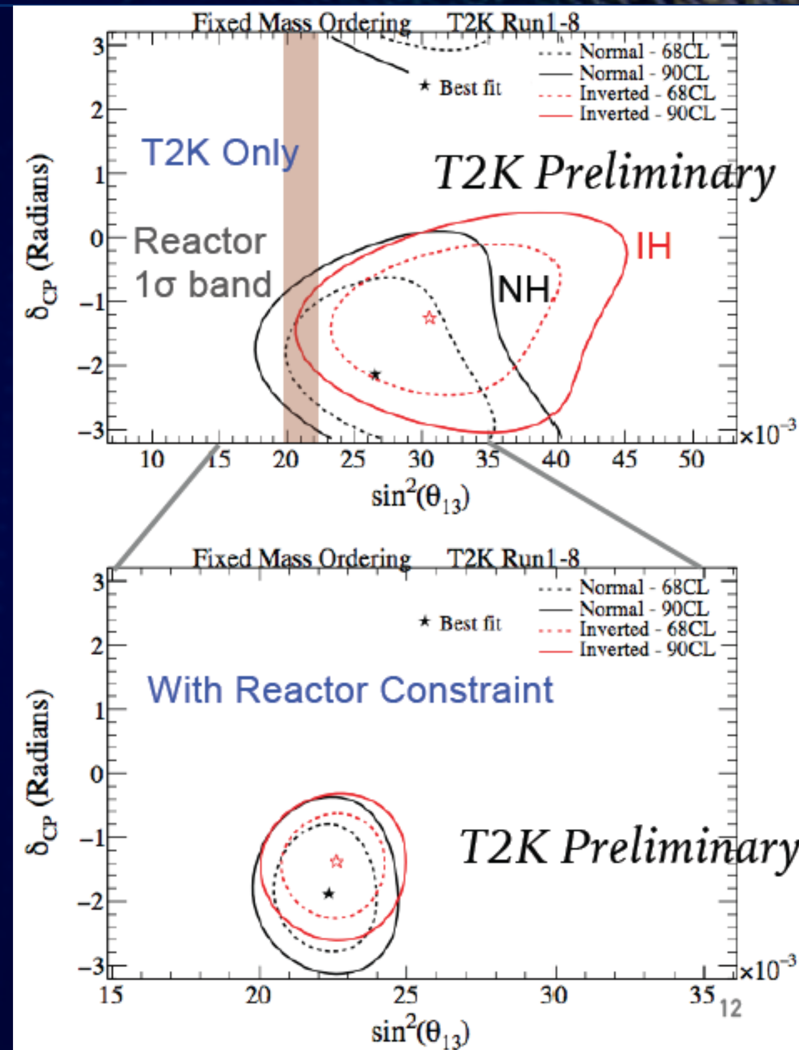
T2K Best Fit

$$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047} \text{ (NH)}$$

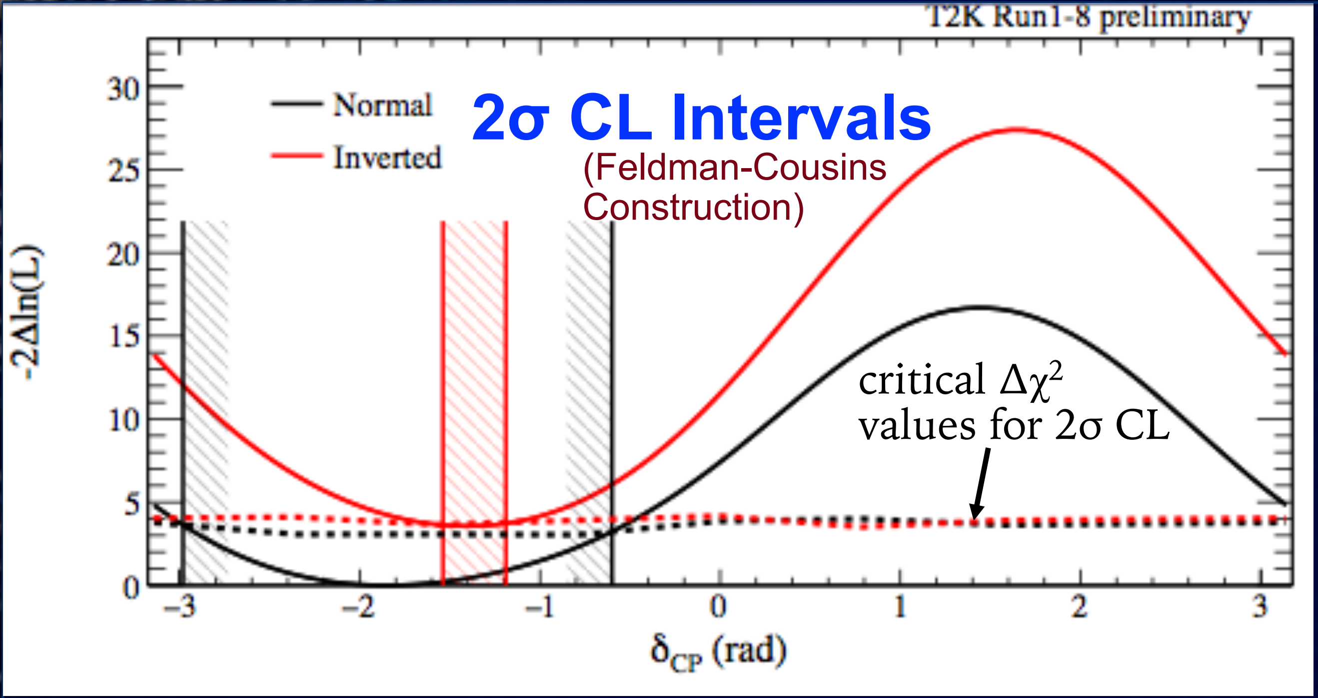
PDG 2016

$$\sin^2\theta_{13} = 0.0210 \pm 0.0011$$

- Adding the reactor constraint improves the constraint on δ_{cp}



"Full" Joint Analysis Results on δ_{CP} (with Reactors' Measurement of $\sin^2\theta_{13}$ as a Constraint)



- $\sin^2\theta_{13}$ is marginalized using the reactors' measurement as prior probability

- Best fit: $\delta_{CP} = -1.83$ rads in NH
- 1σ CL interval:
  - NH: [−2.49, −1.23] rads
- 2σ CL intervals:
  - NH: [−2.98, −0.60] rads
  - IH: [−1.54, −1.19] rads

→ CP conserving values (0, ±π) fall outside of the 2σ intervals

Summary and Future Plans

- T2K has made a great stride towards CPV in lepton sector
  - Thanks to increased beam power and beam delivery efficiency
  - Improved event construction and optimized event selection

→ CP conserving values of δ_{cp} are excluded at 2σ!

  → Great news for the community and the future experiments

- Accumulate ~8x10^{20} POT in antinu-mode (fall 17 – spring 18)
- Aim to achieve sensitivity for CPV @ ~3σ level by ~2026
  - **"T2K-II" phase**: proposed to extend T2K run to 20x10^{21} POT
    - Obtained Stage-I status approval
  - Reduce systematic uncertainties → 4% level
    - ND280 Upgrade (~2021)

The End

Supplements

For additional detailed information, see:
https://kds.kek.jp/indico/event/25337/ or
https://www.t2k.org/docs/talk/282