T2K

Yoshinari Hayato

(Kamioka obs., ICRR)

The T2K Collaboration

~470 collaborators from 12 countries and 67 institutes

Host institutes KEK (beam facility and near detectors)
ICRR (Super-Kamiokande)

Canada
Univ. of Regina
TRIUMF
Univ. of Toronto
Univ. of Winnipeg
York Univ.

France
CEA/DAPNIA Saclay
LLR Ecole Polytechnique (IN2P3)
LPNHE-Paris

Germany
RWTH Aachen Univ.

Italy
INFN Sezione di Bari
INFN Sezione di Roma
Napoli Univ.
Padova Univ.

Russia
INR

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
Univ. of Silesia, Katowice
Technical Univ., Warsaw
Warsaw Univ.
Wroclaw Univ.

Spain
IFAE, Barcelona
IFIC, Valencia
UAM, Madrid

Switzerland
Bern
CERN
ETHZ
Univ. of Geneva

United Kingdom
Univ. of Glasgow
Imperial College London
Lancaster Univ.
Univ. of Liverpool
Queen Mary, Univ. of London
Royal Holloway, Univ. of London
Oxford Univ.
Univ. of Sheffield
STFC/RAL/Daresbury Lab.
Univ. of Warwick

Japan
Keio Univ.
Kobe Univ.
Miyagi Univ. of Education
Osaka city Univ.
Kavli IPMU, U-Tokyo
Tokyo Inst. of Tech.
Tokyo Univ. of Science
KEK
Kyoto Univ.
Okayama Univ.
ICRR, U-Tokyo
Univ. of Tokyo
Tokyo Metropolitan Univ.
Yokohama National Univ.

United Sates of America
Boston Univ.
Univ. of California, Irvine
Colorado State Univ.
Univ. of Colorado
Duke Univ.
Univ. of Houston
Louisiana State Univ.
Michigan State Univ.
Univ. of Pennsylvania
Univ. of Pittsburgh
Univ. of Rochester
SLAC
Stony Brook Univ.
Univ. of Washington

Vietnam
IFIRSE, Quy Nhon
IOP, Hanoi

Neutrino oscillation and properties of neutrinos

Neutrino oscillations

- Non-zero neutrino mass states

$$(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3)$$

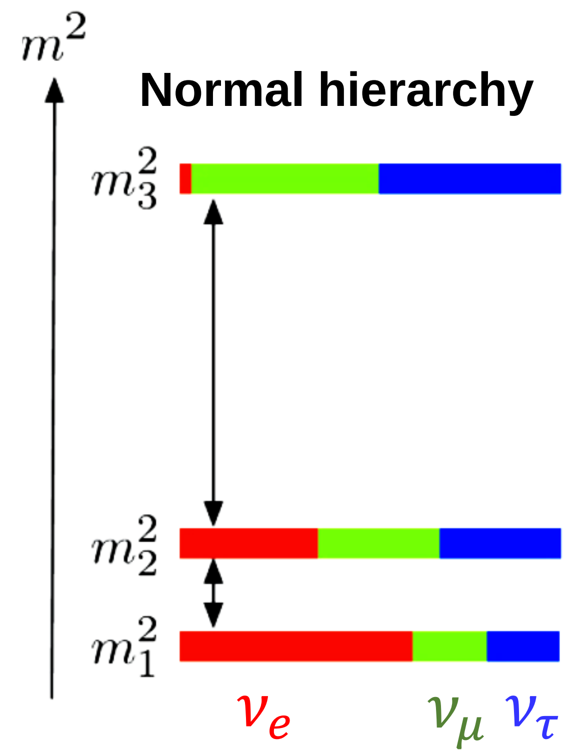
- Flavor mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$

2 mass differences $(\Delta\mathrm{m}^2_{32}, \Delta\mathrm{m}^2_{21})$

1 CP phase (δ_{CP})



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \cdot \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \cdot \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

1) Measurements of θ_{13} and study of CP violation

ν_e and $\overline{\nu_e}$ appearance probabilities and their difference

2) Precise measurements of $(\Delta m^2_{32}, \theta_{23})$

ν_μ and $\overline{\nu_\mu}$ disappearance probabilities

Using the intense ν_μ and $\overline{\nu_\mu}$ beams from J-PARC neutrino beam facility.

T2K neutrino beam ~ Off axis beam ~

Maximize sensitivity in oscillation studies

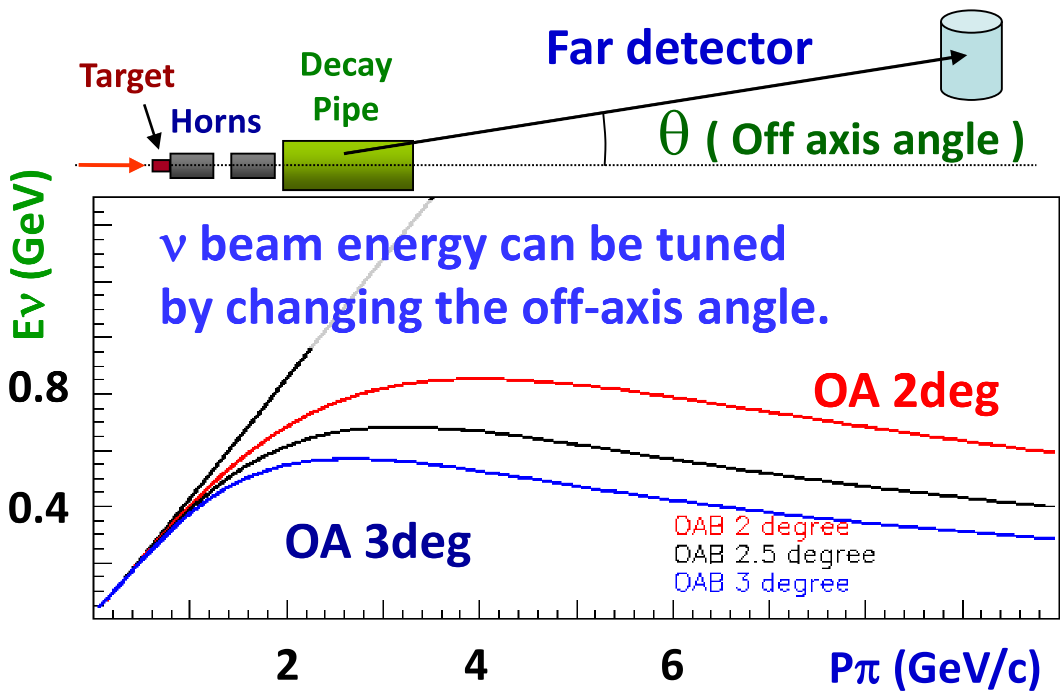
→ ***Use narrow band beam with peak energy at the oscillation maximum***

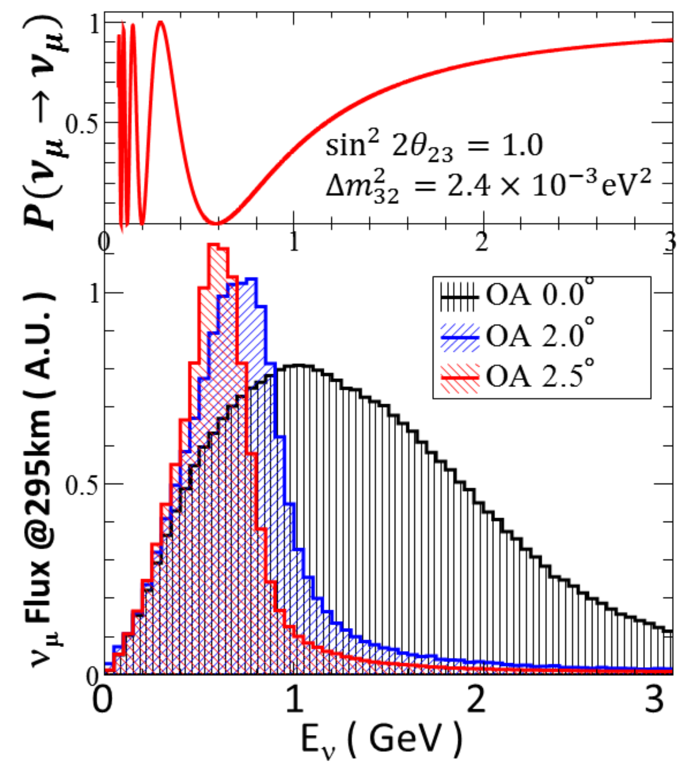
→ ***Off axis beam*** (ref.: BNL-E889 Proposal)

- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is tunable (Change off axis angle)

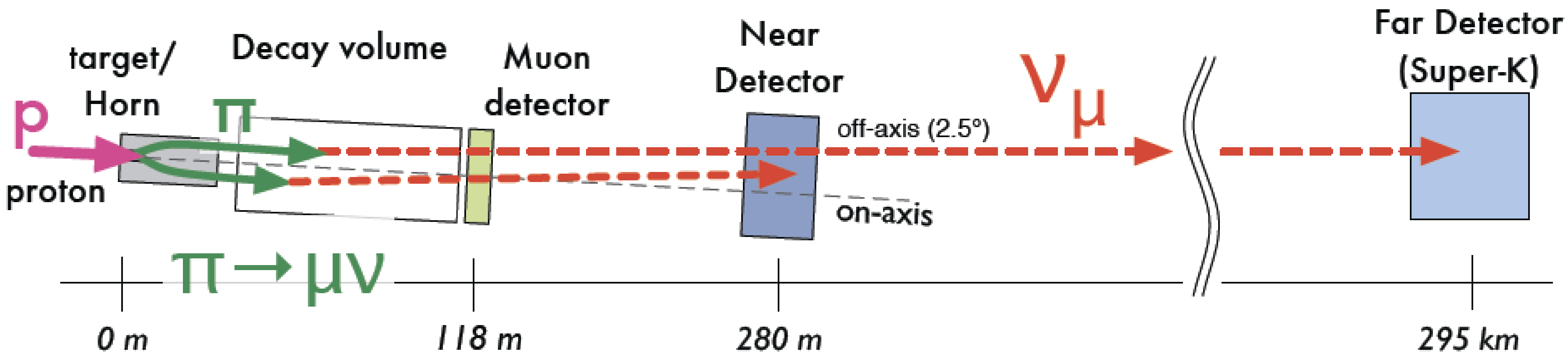
Important to monitor beam direction!

(1mrad ~ peak E_ν shifts by ~15 MeV)





T2K ~ Schematic diagram of the experiment



3 major components

1. Accelerator, neutrino beam line & beam monitors

   Produce neutrino beam
   and monitor primary and secondary particles

2. Neutrino detectors in the near site

   Measure produced neutrino beam before oscillation
   ~ measure yield, energy spectrum, flavor ratio
   ~ study neutrino interactions

} Tokai

3. Neutrino detector (SK) at far site ~ Kamioka

   Measure oscillated neutrino beam
   and determine neutrino oscillation parameters

T2K far detector ~ Super-Kamiokande

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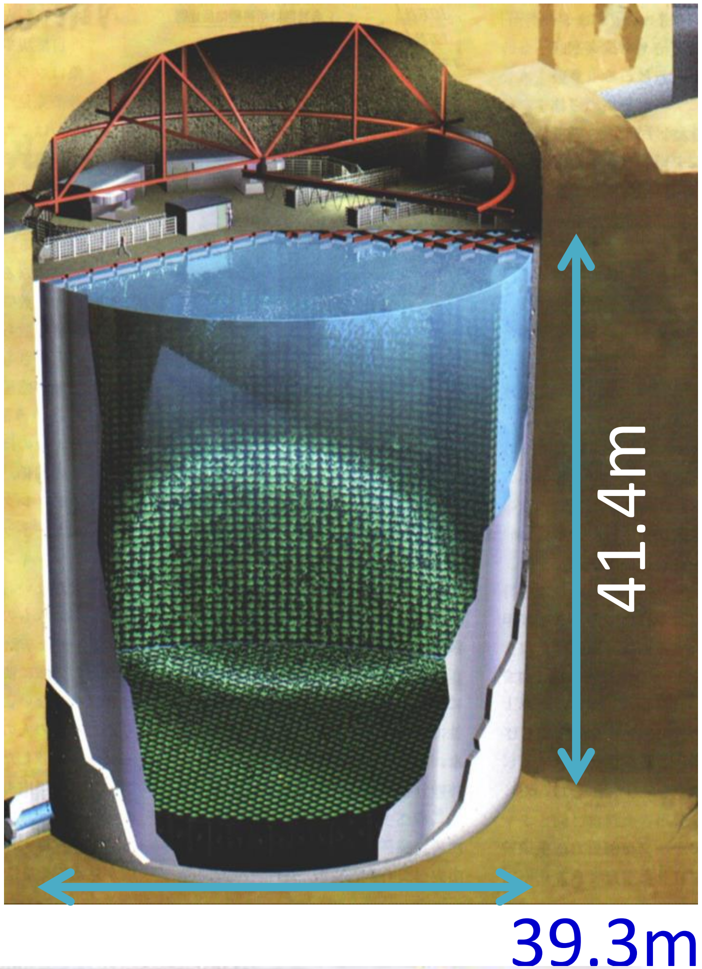
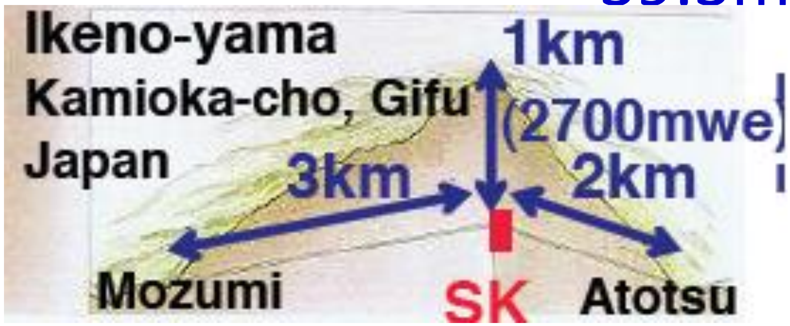
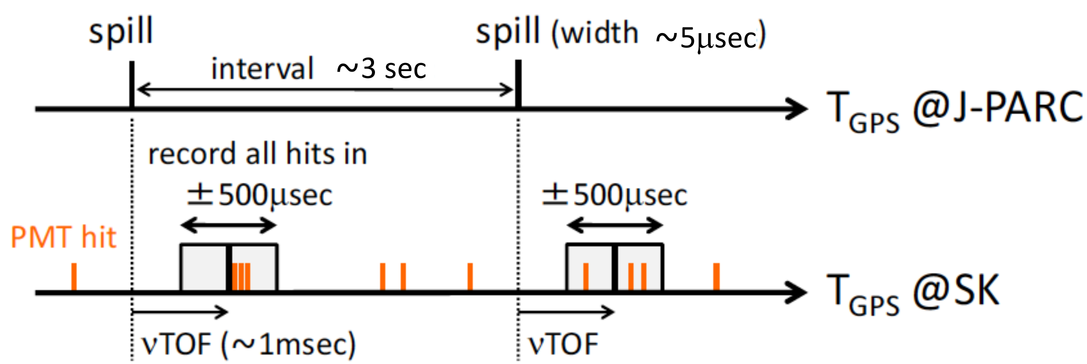


- New DAQ system installed in 2008
- Recording of all PMT hits within ±500μsec of each ν beam arrival timing in SK using GPS.
- 2 independent GPS system
- Additional special GPS receiver

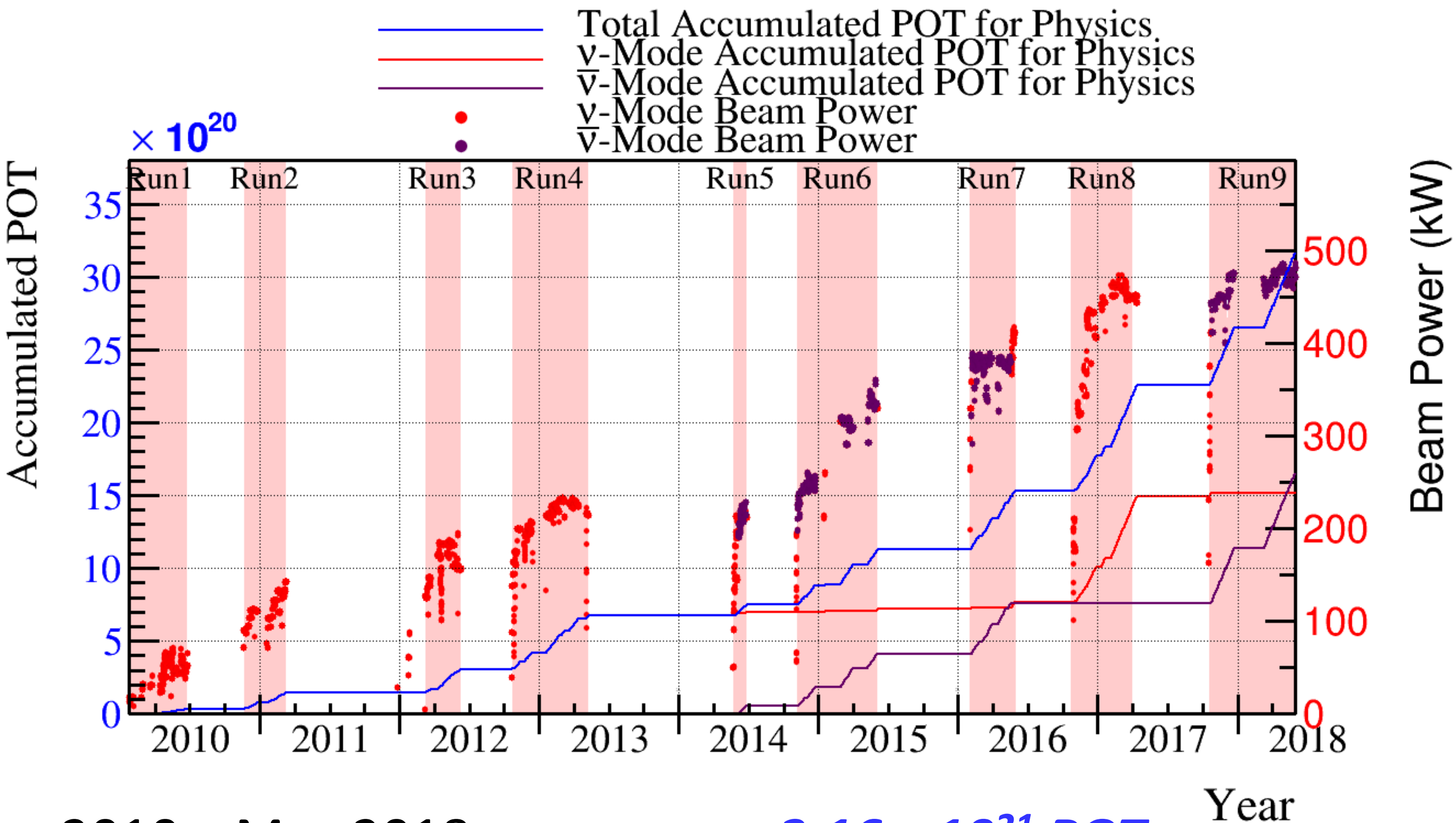
  To monitor the "GPS time" difference between Tokai and Kamioka.





T2K neutrino beam history and status

The T2K experiment started physics data taking in Jan. 2010.



Jan. 2010 ~ May 2018 : ***3.16 x 10^21 POT***

1.51×10^{21} POT ν-mode + 1.65×10^{21} POT $\bar{\nu}$ mode

Latest oscillation analyses used : ***3.12 x 10^21 POT***

1.49×10^{21} POT ν mode & 1.63×10^{21} POT $\bar{\nu}$ mode data

Important T2K results

2010 Start taking ν-mode data

2011 First indication of ν_e appearance from a ν_μ beam (2.5σ)

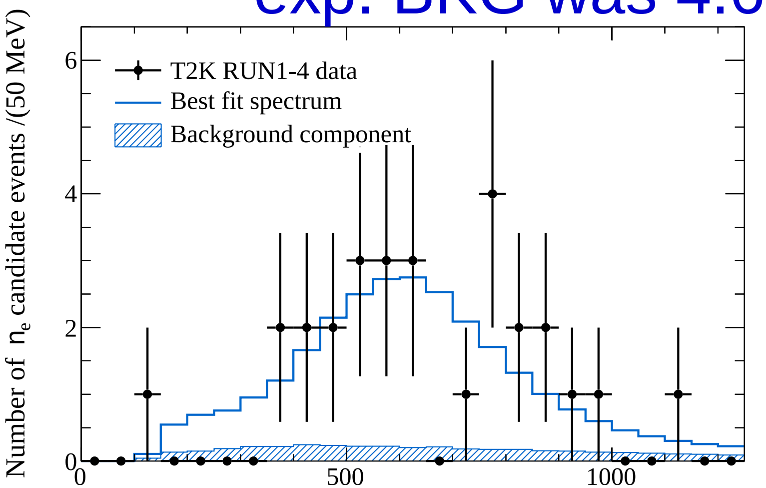
2013 First observation of ν_e appearance from a ν_μ beam (7.3σ)

2014 First 90% C.L. hint of $\delta_{CP} \neq 0$

2014 Started taking $\bar{\nu}$-mode data

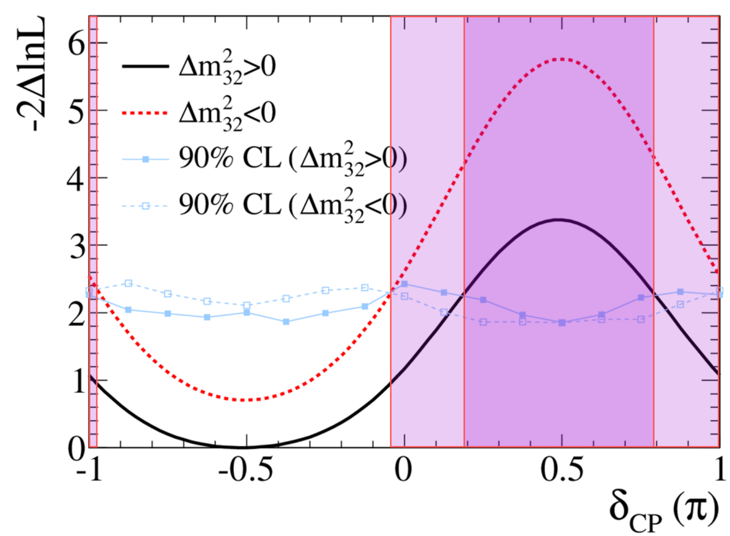
2017 Increased SK fiducial volume with new event reconstruction.
Add new ν_e CC 1π sample → ***Stronger hint of CP violation***

2013: 28 ν_e candidates
exp. BKG was 4.6



Reconstructed ν energy (MeV)

2014: δ_{CP} negative log likelihood



Contributions from SK (ICRR)

1) Collect T2K neutrino beam data using SK

2) Provide T2K neutrino beam event data

- Define "T2K beam neutrino event" selection criteria
  (kind of higher-level software trigger)
- Monitor the quality of the data
  Using atmospheric ν events, calibration data etc..
- Make DST applying the T2K ν event selection criteria

3) Provide reconstruction tools

- Based on the event reconstruction tools
  developed for the atmospheric neutrino analyses.
- Optimize for the T2K neutrino oscillation analyses

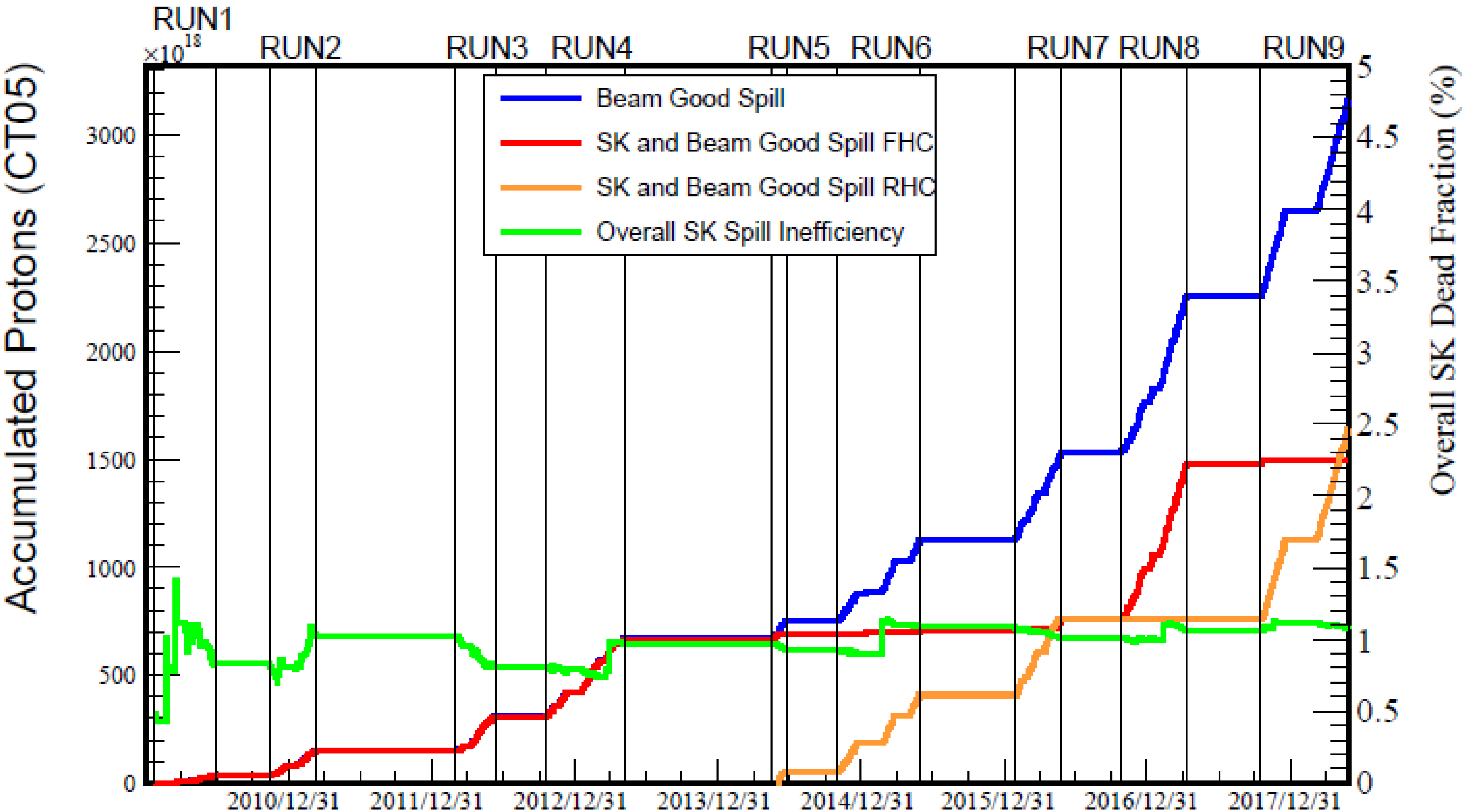
4) Provide relevant calibration / reference data

5) Provide neutrino interaction simulation library / programs,
detector simulation programs
and also SK simulation data for T2K.

6) Evaluate / provide systematic uncertainties in SK

Contributions from SK (ICRR)

Overall spill inefficiency @ SK is ~ 1%

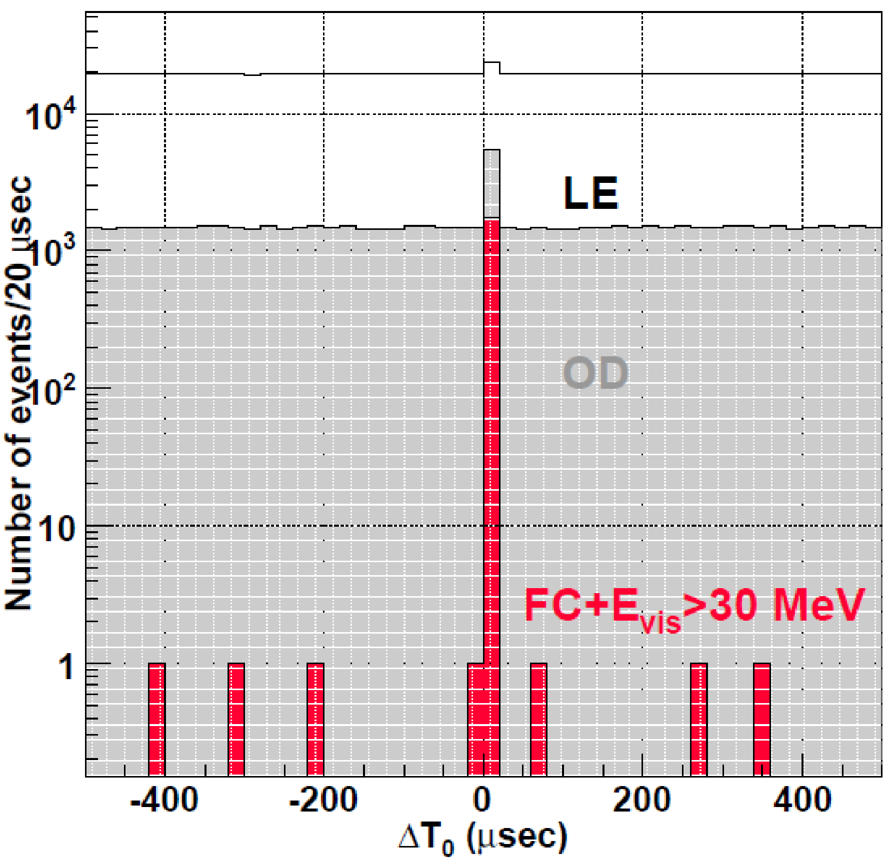


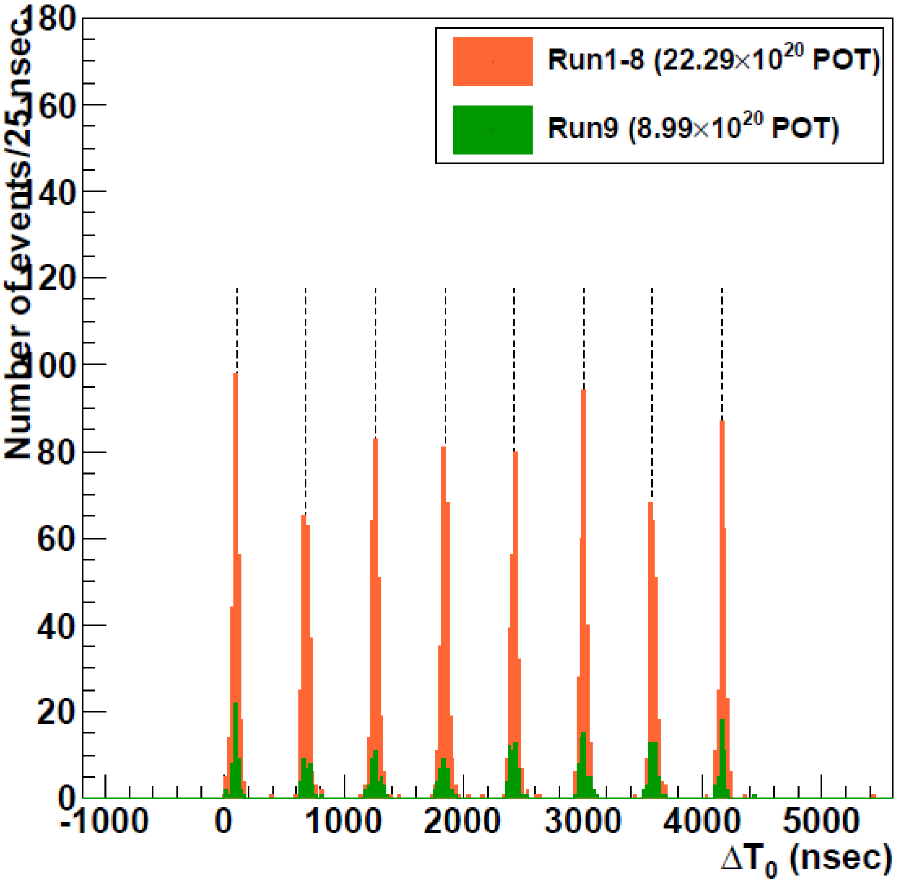
Contributions from SK (ICRR)

Observed candidate neutrino event timing distribution

Number of the accidental background events of atmospheric neutrino are consistent with expectation.

Beam bunch time structure is clearly observed.



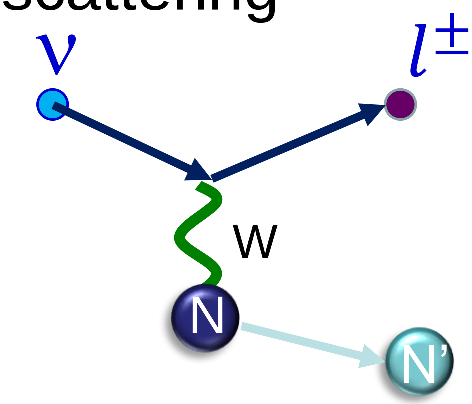


Event samples in SK ~ 1 ring events

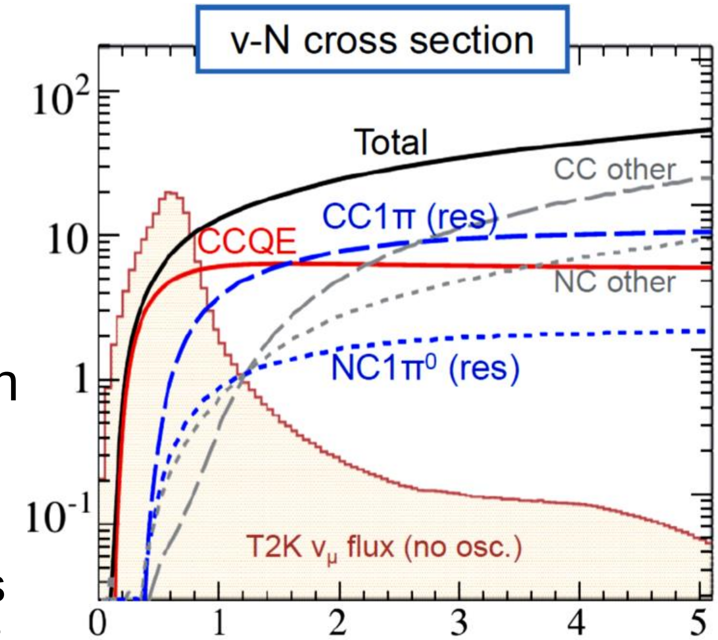
Signal events

~ Induced by charged current quasi-elastic scattering

$$\boldsymbol{\nu + n \to l^- + p} \text{ or } \boldsymbol{\bar{\nu} + p \to l^+ + n}$$

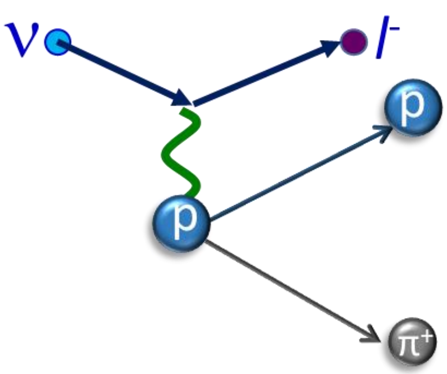


Dominant interaction in the T2K energy region.
Simple kinematics
→ Reconstruct neutrino energy
using observed lepton



New event category for neutrino run
~ Charged current 1 pion production ~

$$\boldsymbol{\nu + p \to l^- + \pi^+ + p}$$



Second dominant interaction
in T2K.

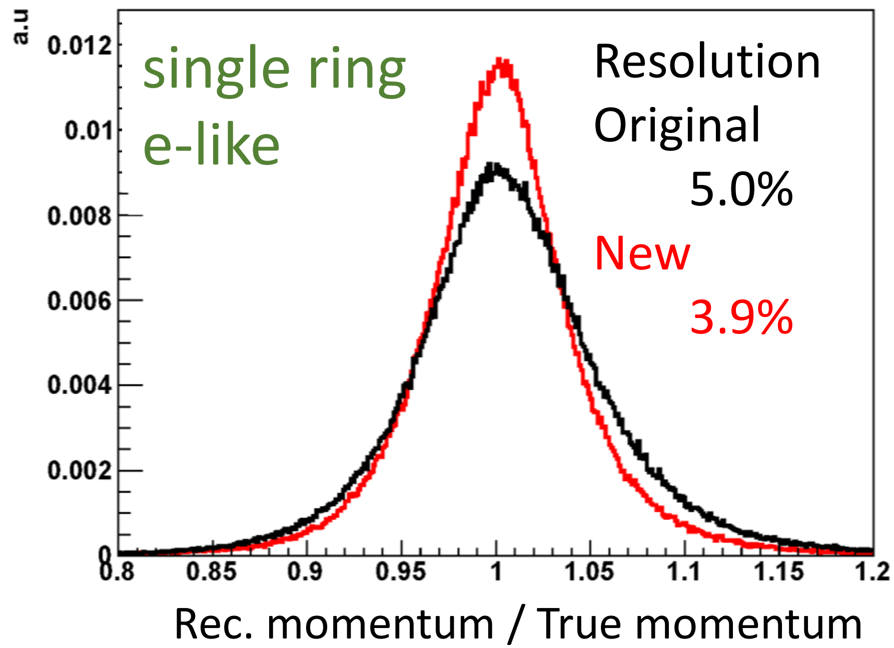
Identify the events
with two decay electrons
from l^- and π^+.

Recent improvements ~ New event reconstruction

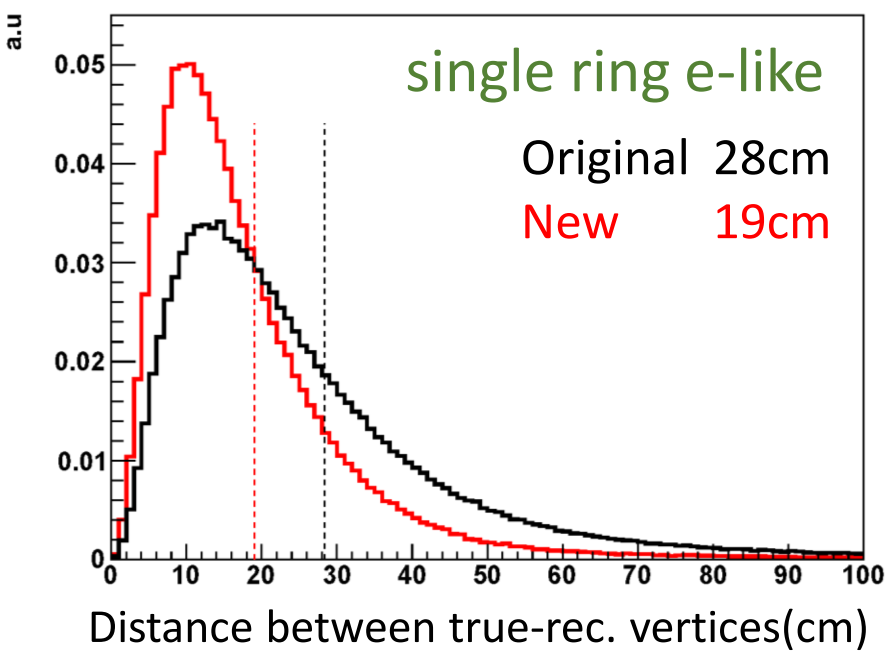
New event reconstruction
~ Improved performances

Fiducial volume has been
expanded by ~20%.

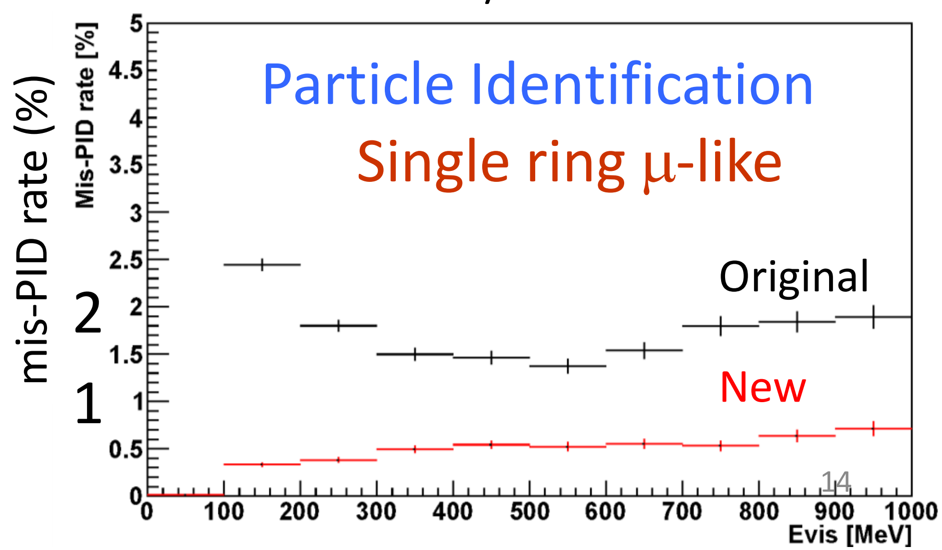
Momentum reconstruction



Vertex reconstruction



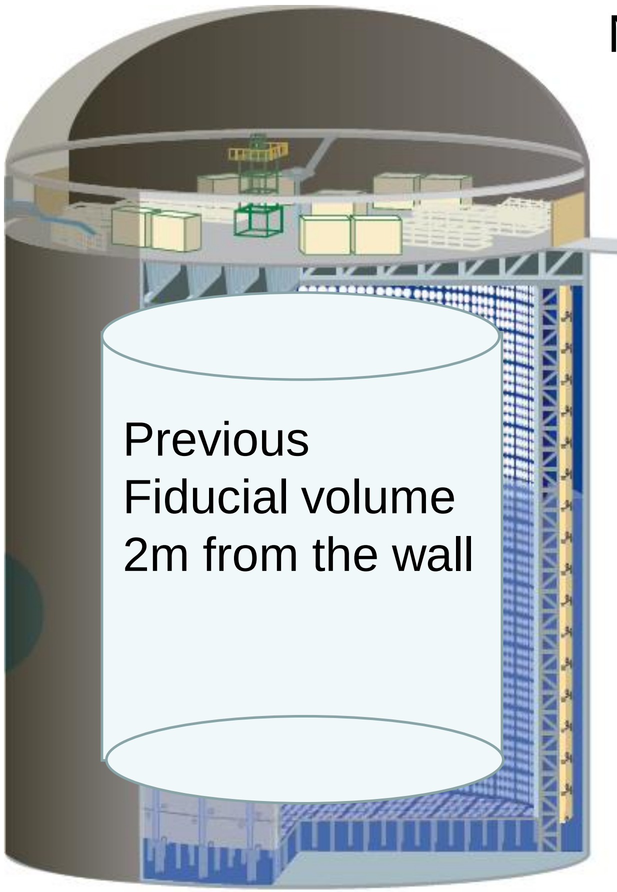
Particle Identification



Recent improvements ~ New fiducial volume criteria

Previously

Neutrino interaction vertex is at least 200cm from the detector wall.
(= dwall > 200cm.)



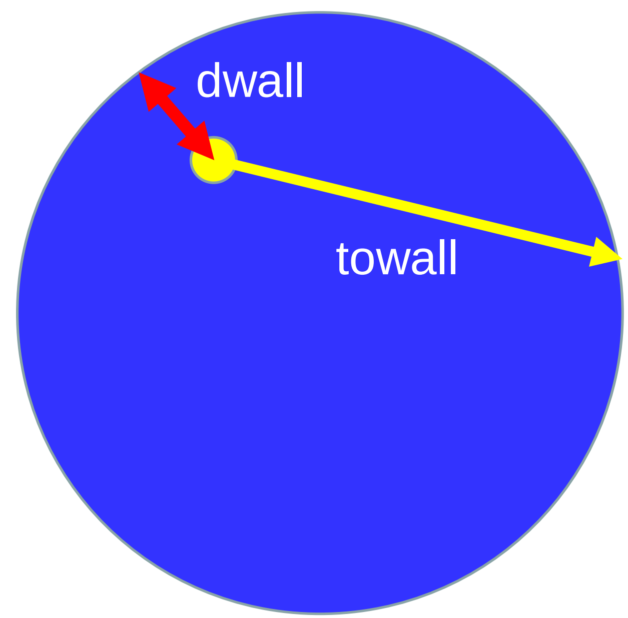
New fiducial volume definition.

μ-like events

Interaction vertex is at least 50cm from the wall (dwall > 50cm) and distance to the wall in the particle direction is at least 250cm (towall > 250cm).

e-like events

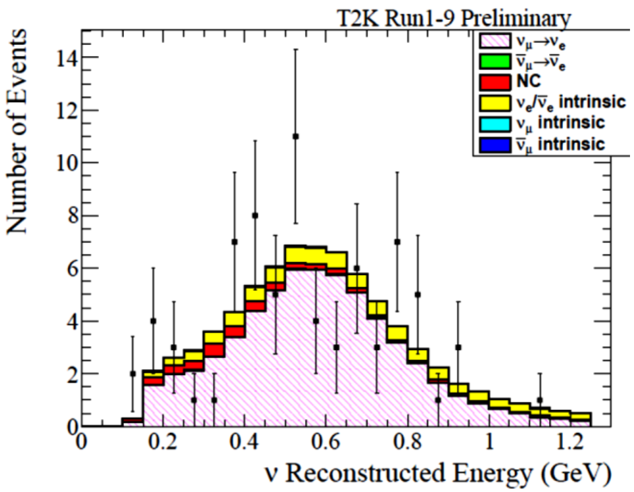
dwall > 80cm and towall > 170cm.



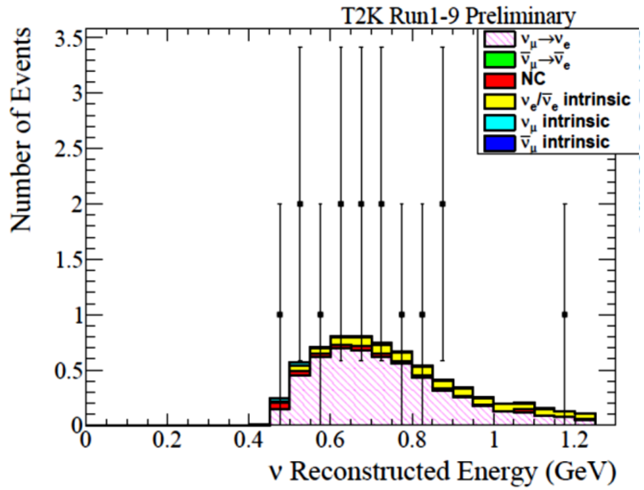
Latest T2K Dataset (Jan. 2010 ~ May 2018)

ν mode 1.49×10^{21} POT & $\bar{\nu}$ mode 1.63×10^{21} POT

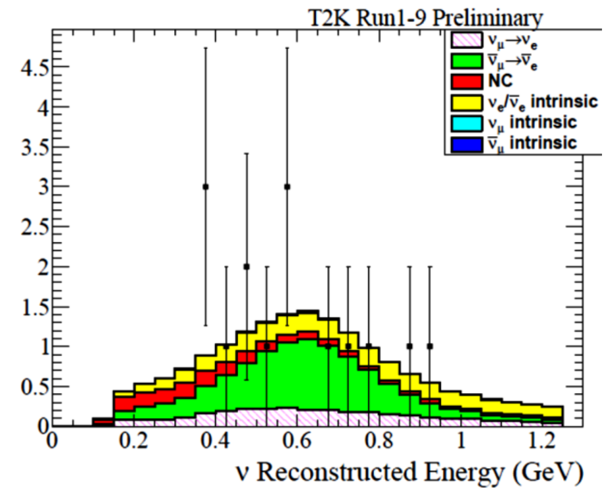
ν_e sample 75 events



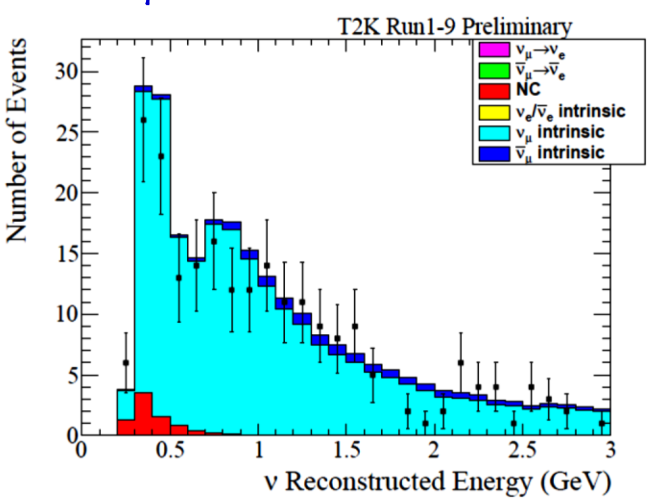
ν_e (e^- + π^+) sample **15 events**



$\bar{\nu}_e$ sample 15 events



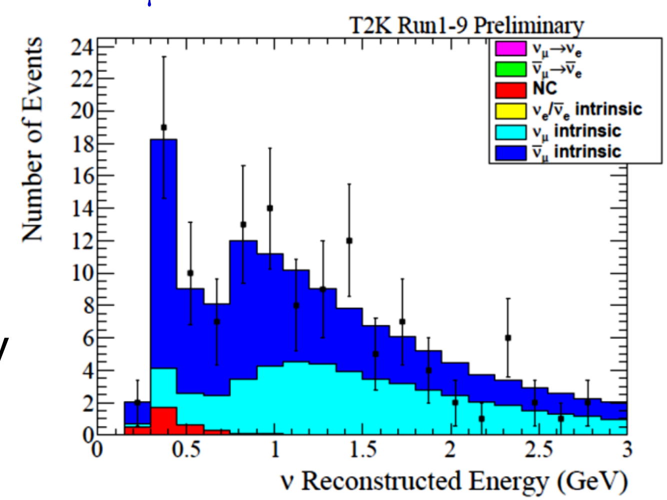
ν_μ sample 243 events



MC assumption

- $\sin^2\theta_{23}$=0.528
- $\sin^2\theta_{13}$=0.0219
- δ=-1.601
- Normal mass hierarchy

$\bar{\nu}_\mu$ sample 102 events



T2K experiment ~ Analysis strategy

Extracting the "oscillation parameters" from observables

~ ***compare the data and the prediction with oscillations***.

Prediction

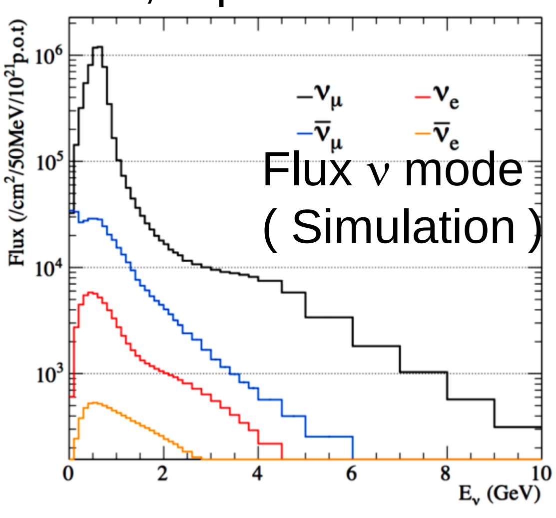
Based on Monte-Carlo simulation

with various constraints from the measurements

ν flux

ν cross sections

Beam simulation program
(FLUKA + GEANT3 w/ GCALOR)
+ π, K production data (NA61 etc.)

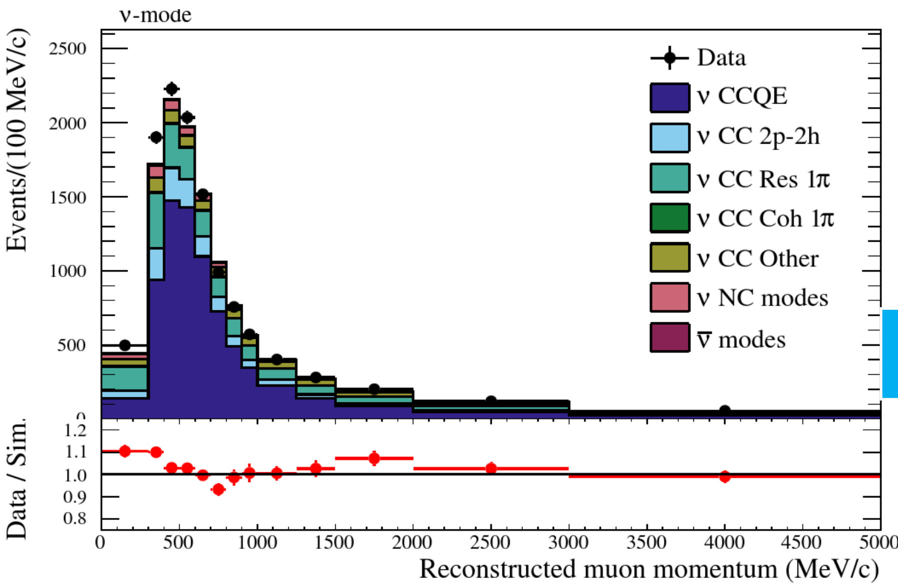


ν interaction simulation program
(NEUT)
+ External constraints (data)

Near detector measurements
to constrain uncertainties
of neutrino flux and
neutrino interaction models

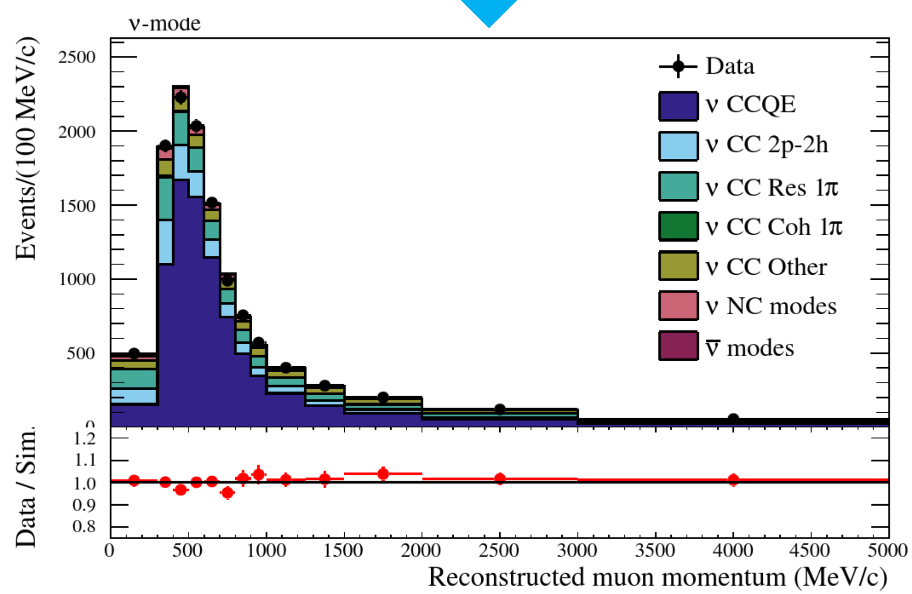
prediction in SK

Latest T2K neutrino oscillation analyses



Systematic uncertainties

Fit neutrino flux and
neutrino interaction model parameters
using the data from near detectors.



Systematic errors are reduced.

Examples : SK event rates

ν mode 1-ring CCQE μ-like
14.6% → 5.1%

ν mode 1-ring CCQE e-like
16.9% → 8.8%

$\bar{\nu}$ mode 1-ring CCQE μ-like
12.5% → 4.5%

$\bar{\nu}$ mode 1-ring CCQE e-like
14.4% → 7.1%

Latest T2K neutrino oscillation analyses

Systematic uncertainties

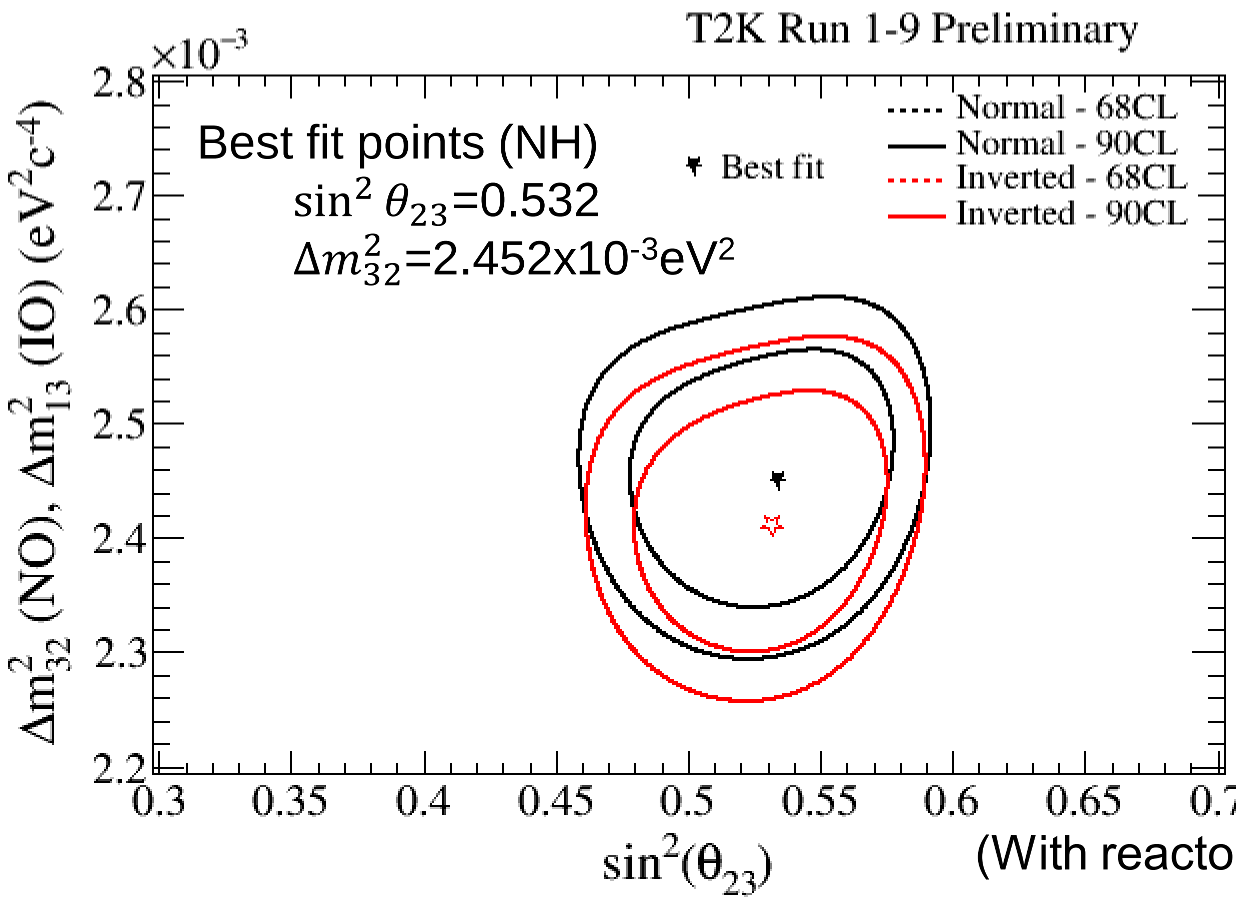
% errors on predicted event rates of each data sample

	1-ring μ-like		1-ring e-like		
Error source	ν mode	$\bar{\nu}$ mode	ν mode (CCQE)	ν mode (CC 1π)	$\bar{\nu}$ mode
SK detector	2.40	2.01	2.83	13.15	3.80
SK FSI+SI+PN	2.21	1.98	3.00	11.43	2.31
Flux + X-sec. ND constrained	3.27	2.94	3.24	4.09	3.10
Nuclear binding energy	2.38	1.72	7.13	2.95	3.66
$\sigma(\nu_e)/\sigma(\overline{\nu_e})$	0.00	0.00	2.63	2.61	1.46
NC 1γ production	0.00	0.00	1.09	0.33	2.60
NC other interactions	0.25	0.25	0.15	0.99	0.33
Oscillation parameters	0.03	0.03	2.69	2.63	2.49
All systematics	5.12	4.45	8.81	18.38	7.13
All with oscillation	5.12	4.45	9.19	18.51	7.57

Total systematic errors are ***4 to 9 %*** for ***4 dominant samples***.

Latest T2K Results (Jan. 2010 ~ May 2018)

ν_μ disappearance

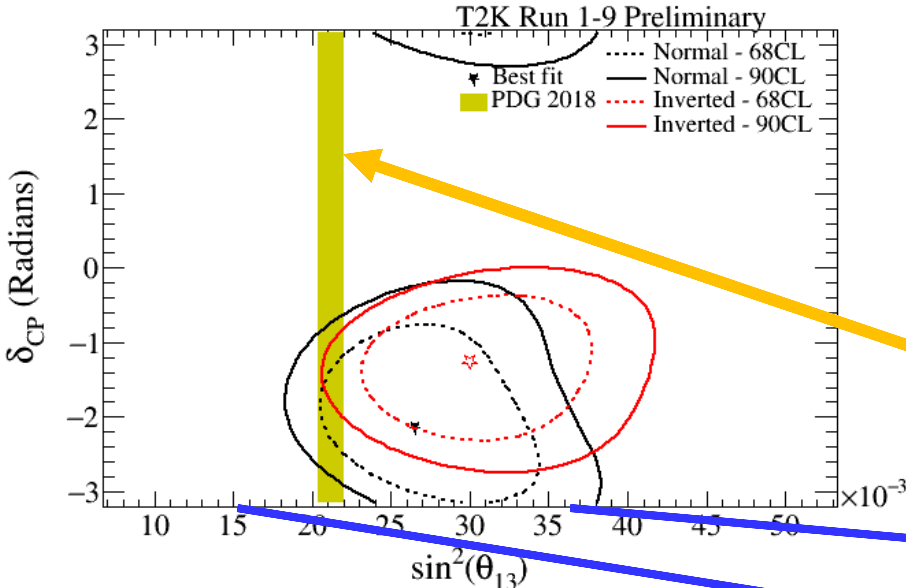


(With reactor constraints)

T2K data are compatible with maximal mixing ($\sin^2\theta_{23}$=0.5).
Slightly stronger constraint on $\sin^2\theta_{23}$
than expected from sensitivity study.

Latest T2K Results (Jan. 2010 ~ May 2018)

ν_e appearance

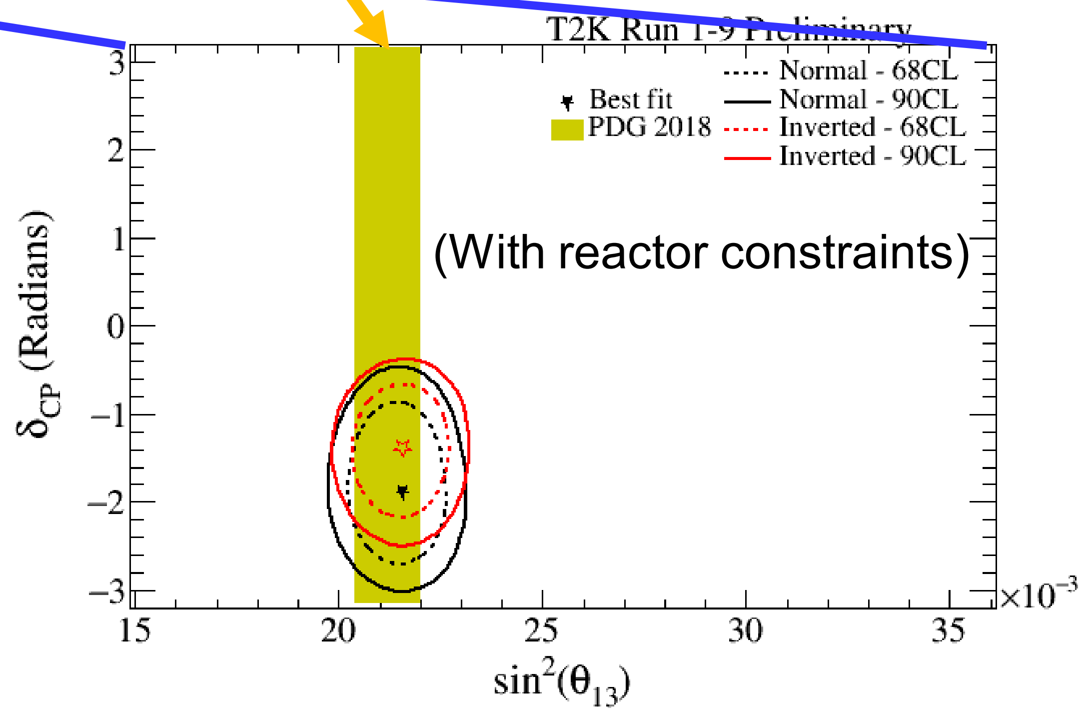


T2K-only
(without reactor constraints)

Yellow bands
θ_{13} from reactor experiments

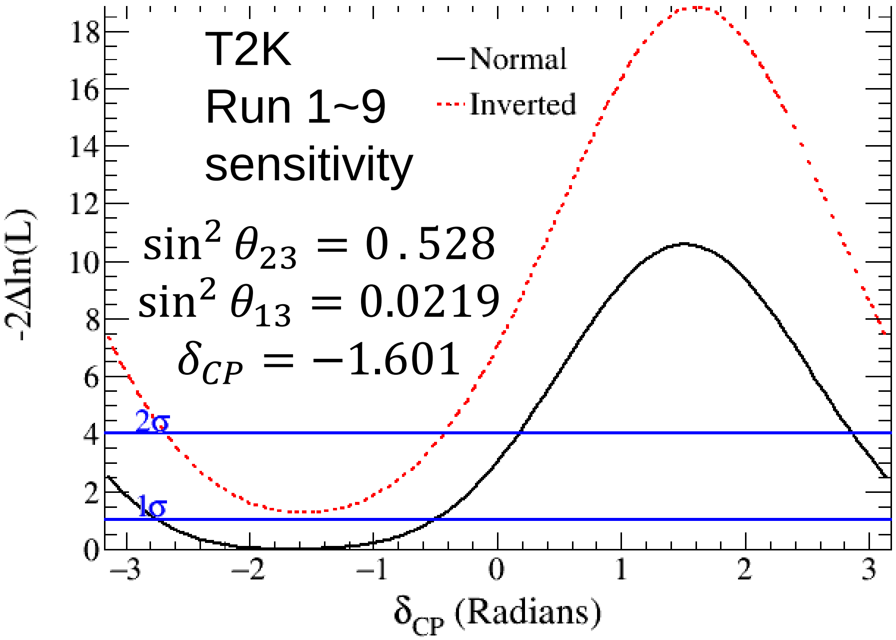
T2K + reactor constraints

Preference for values
of $\delta_{CP} \sim -\pi/2$.

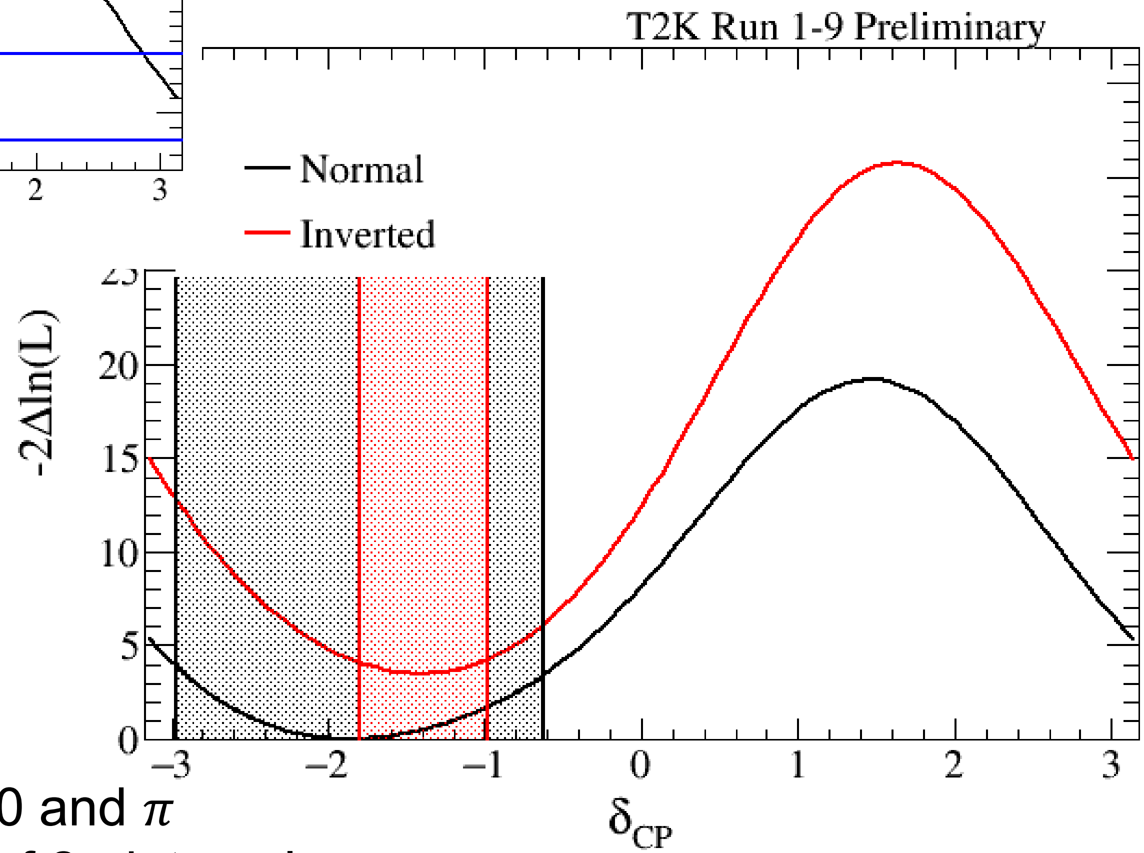


Latest T2K Results (Jan. 2010 ~ May 2018)

ν_e appearance



T2K Run 1 ~ 9 data fit
with reactor constraint on $\sin^2\theta_{13}$



Best fit point
δ_{CP}=-1.885 rad.
(Normal H.)

δ_{CP} 2σ confidence interval
NH [-2.966, -0.628]
IH [-1.799, -0.979]

CP conserving values δ_{CP}= 0 and π
fall outsize of 2σ intervals

Summary and future outlook

T2K has collected ~40% of the initial target POT.

T2K has been publishing world-leading important results since 2011.

- First signature of ν_e appearance θ_{13}.
- Precise measurements of Δm^2_{32} and θ_{23}.

Recent results indicates CP violation in the lepton sector.

- CP conserving $\delta_{CP} = 0$ and π fall out of 2σ confidence intervals.

Still, statistically limited and we will continue taking data.

- Data from SK-Gd are expected to help the analyses.

Extension of the T2K experiment has been proposed and we have received the stage-1 approval.

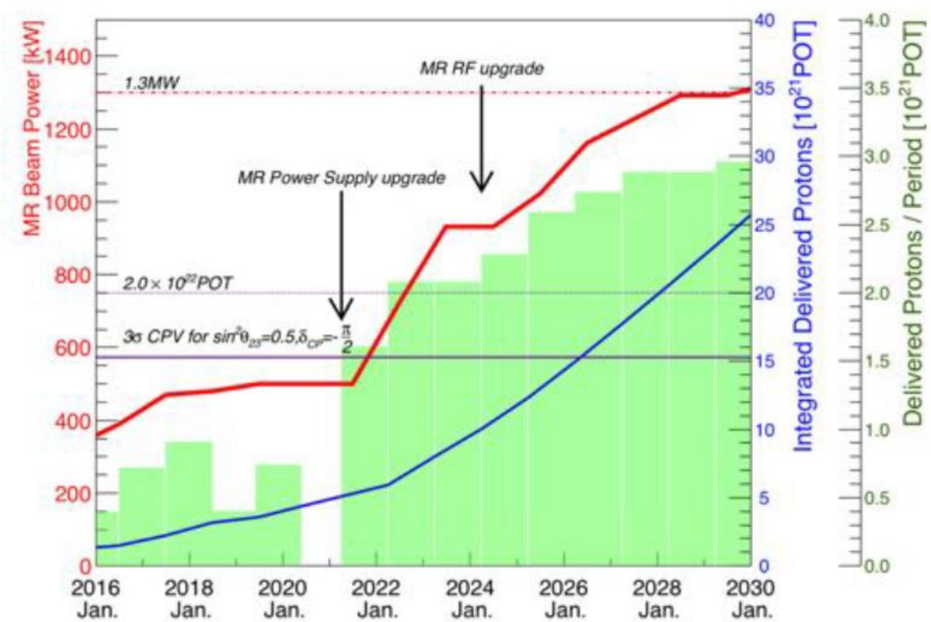
Summary and future outlook

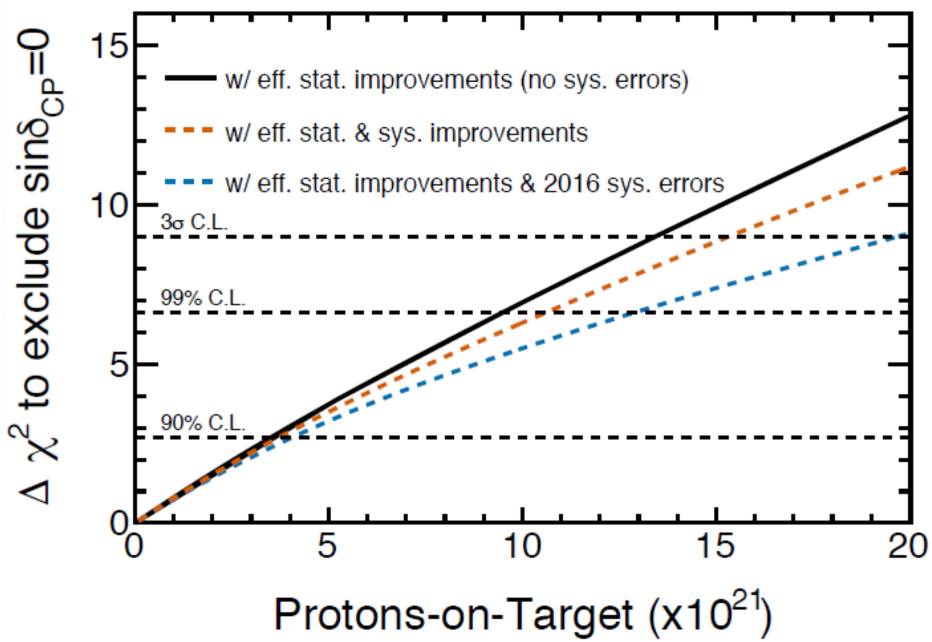
T2K-II

- 20 x 10^{21} POT by 2027~2028 (= before HK starts.)
- Target beam power : 1.3MW
- Increase horn current (320kA)
- Reduce systematic errors
  ~ esp. neutrino-nucleus interactions

The beam intensity and the near detector upgrade works are in progress.

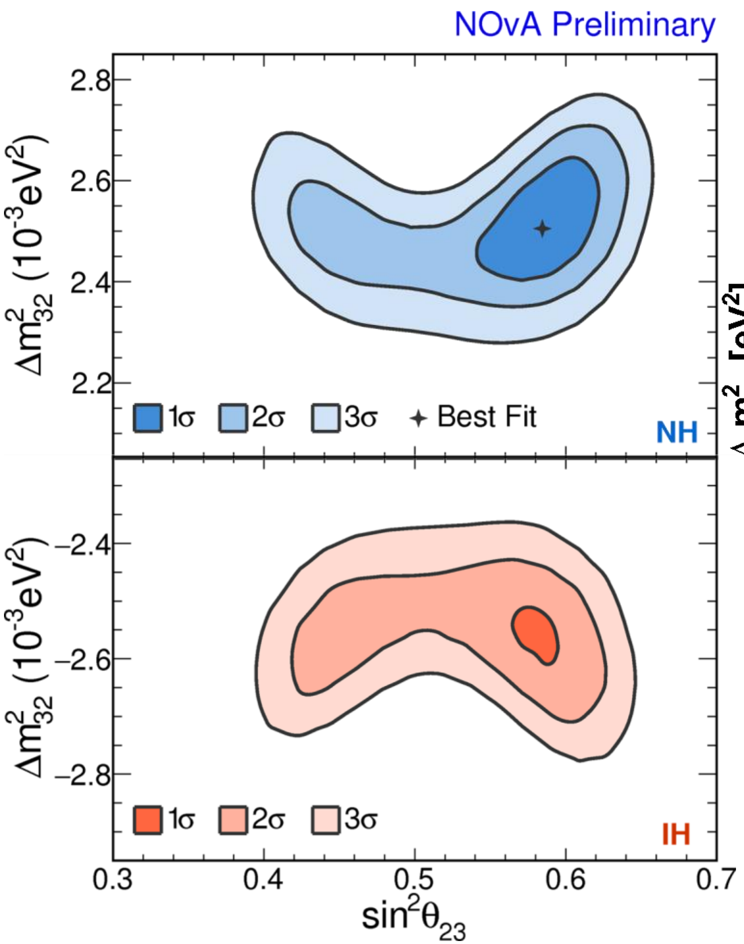
T2K-II Target POT (Protons-On-Target)

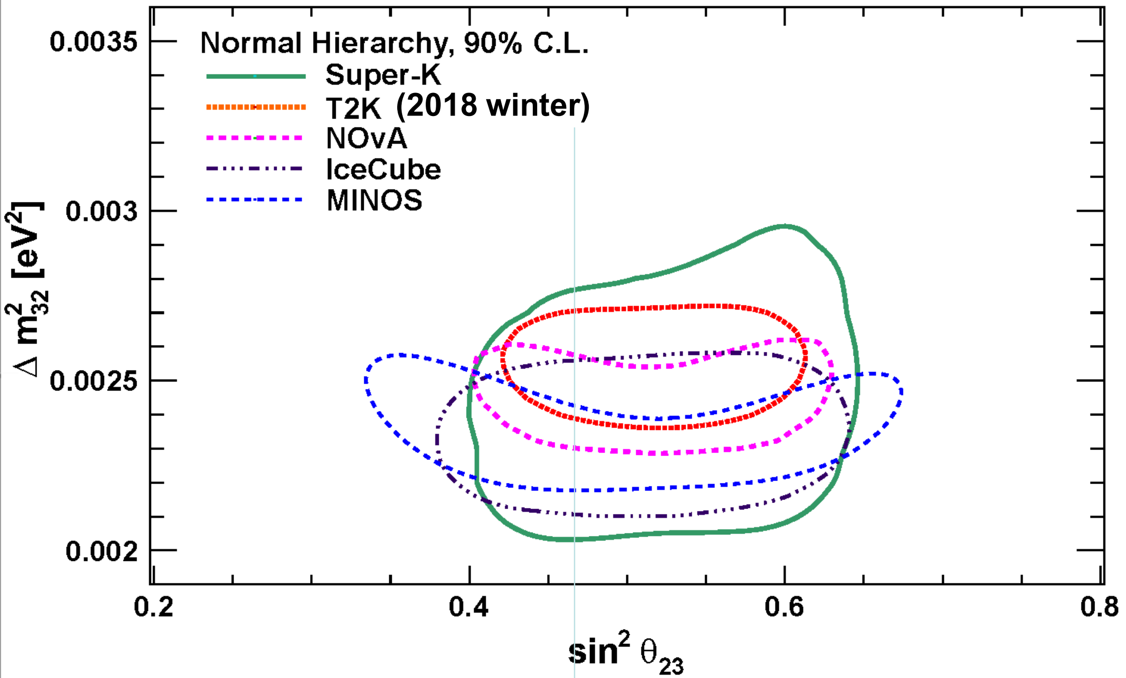




Fin.

Δm^2_{32} and θ_{23} allowed regions





Taken from the talk by A. Himmel
(June 15, 2018)

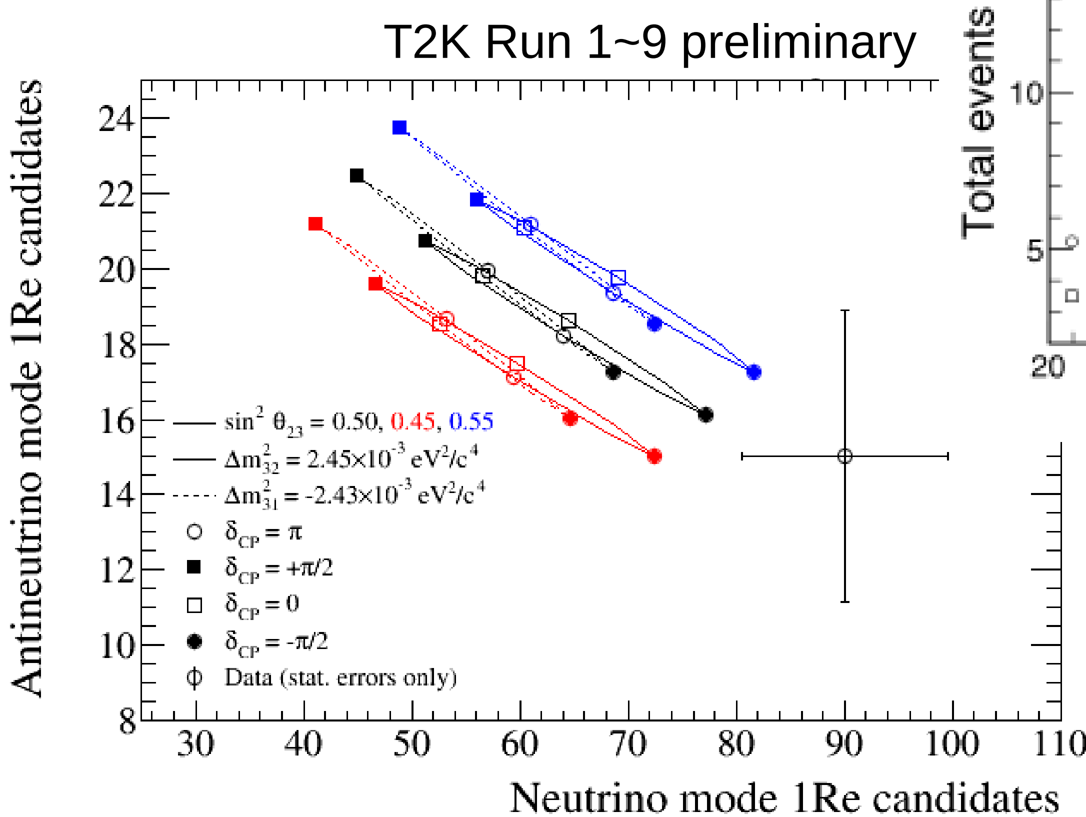
Numbers of ν_e and $\overline{\nu_e}$ candidates

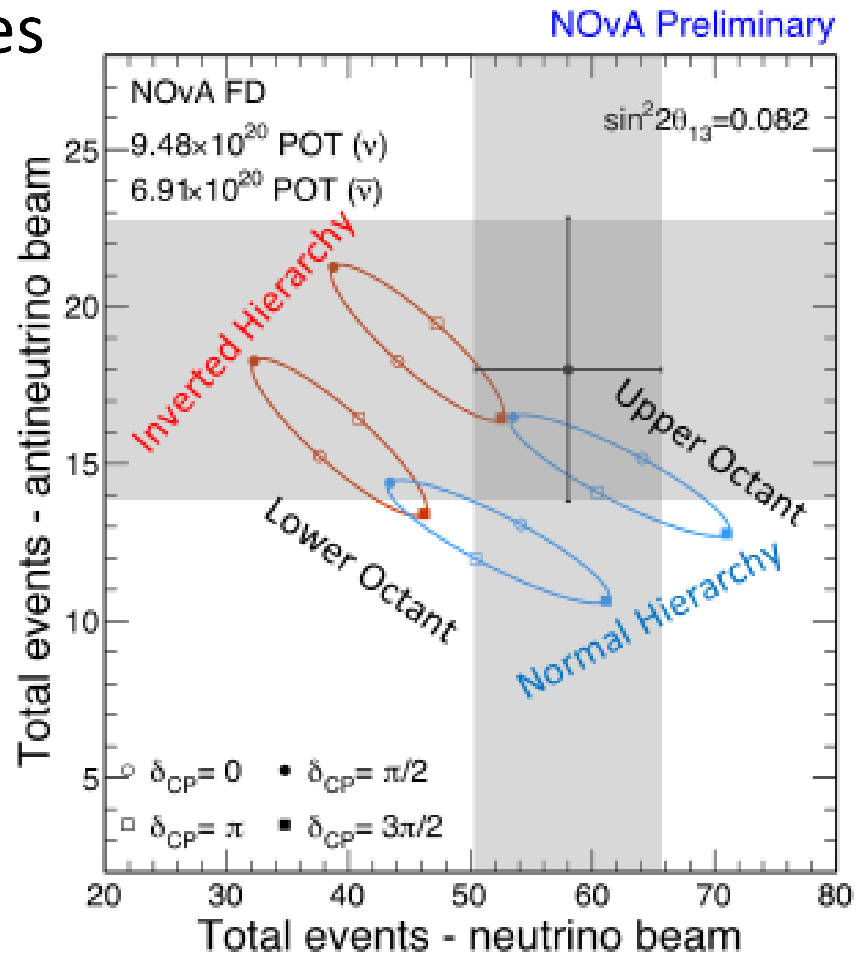
T2K

15 $\overline{\nu_e}$ candidates

90 ν_e candidates

(75 CCQE + 15 CC1π)





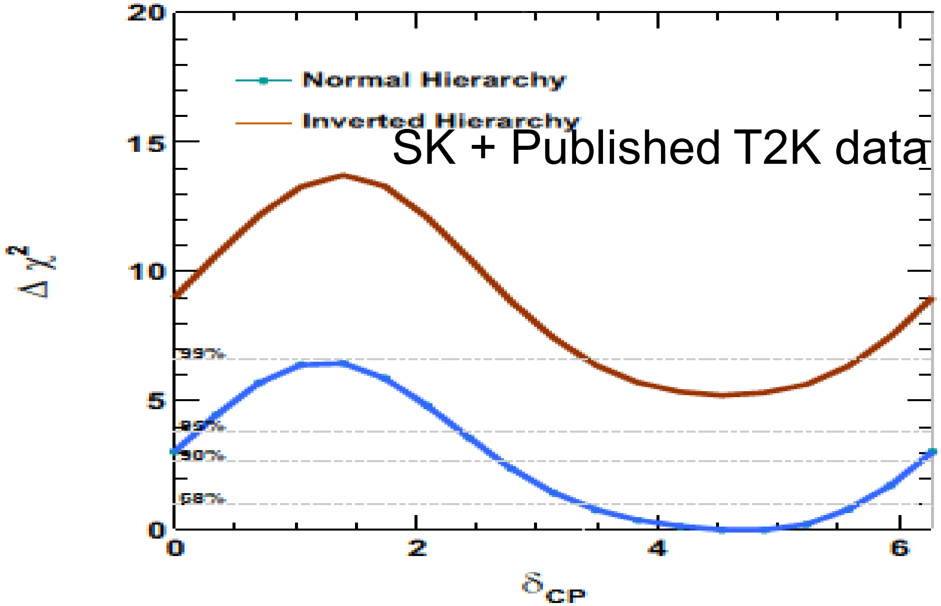
NOvA

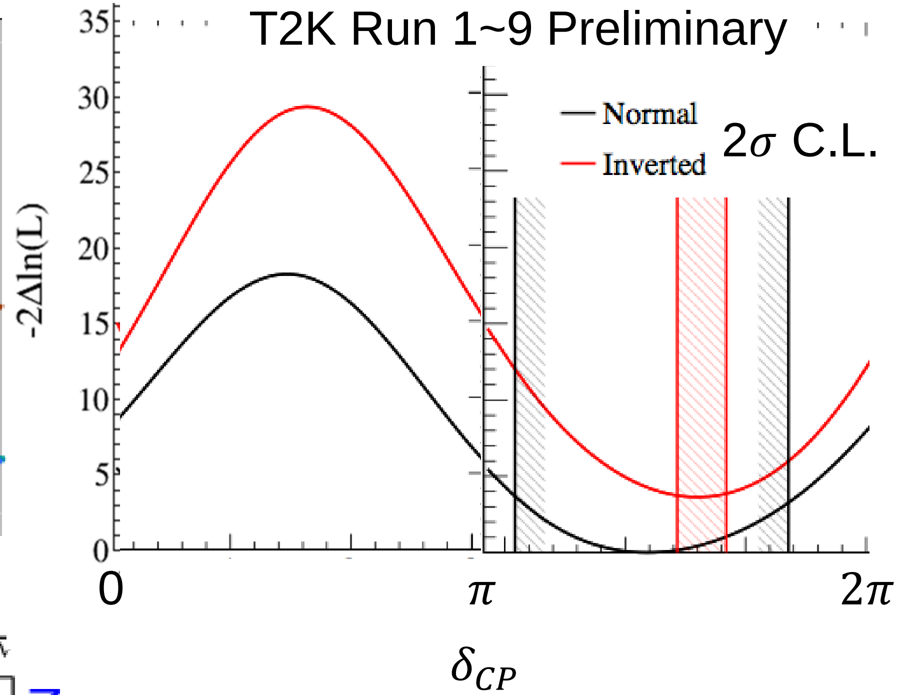
18 $\overline{\nu_e}$ candidates

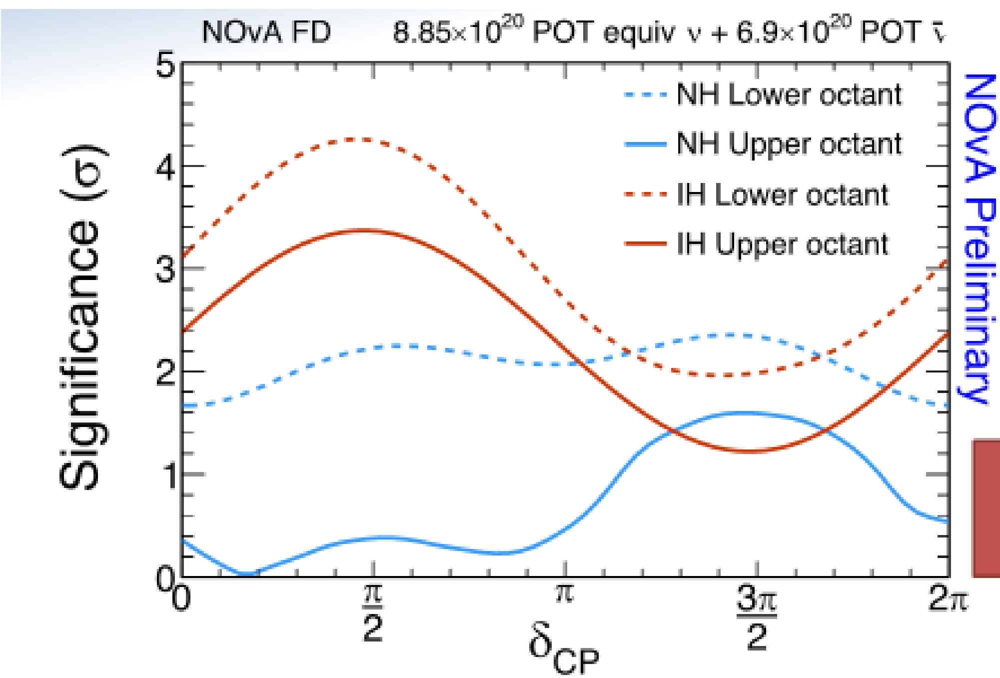
58 ν_e candidates

Taken from the talk by A. Himmel (June 15, 2018)

δ_{CP} allowed regions







Consistent with all δ_{CP} values in NH at < 1.6σ.

Taken from the talk by A. Himmel (June 15, 2018)