Results from T2K and Prospects with T2K-II

2019/4/9, Prospects of Neutrino Physics

K.Sakashita (KEK/J-PARC) for T2K collaboration

Contents

- Introduction
- T2K latest results
- T2K-II prospects
- Summary

T2K(Tokai-to-Kamioka) experiment

Long base-line neutrino oscillation experiment

some of T2K results so far :

- Discovery of ν_e appearance in 2013

  Phys.Rev.Lett. 107, 041801 (2011)
  Phys.Rev.Lett. 112, 061802 (2014)

- Search for CP violation in neutrino oscillation

  Phys.Rev.Lett. 121, 171802 (2018)

T2K collaboration

International collaboration

(as of 2019 Jan. : ~500 members, 68 institutes, 12 countries)

Recently, CERN neutrino group has joined !

Physics motivation

After $\nu_\mu \to \nu_e$ discovery by T2K, and precise θ_{13} meas. by Reactor experiments

- **CP violation parameter δ_{CP}**

hint for the origin of matter dominate universe

[Nucl. Phys. B774 (2007) 1 etc.]

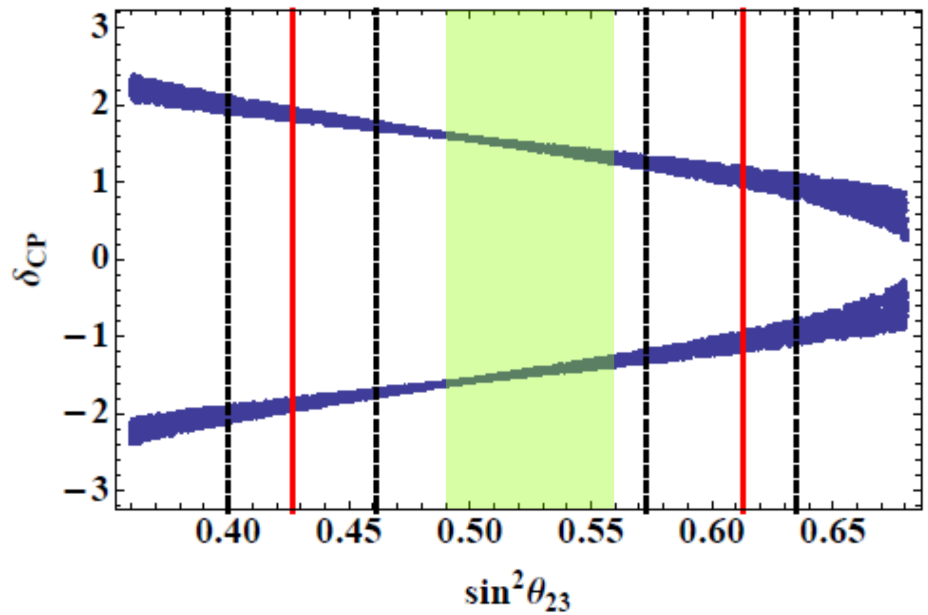
- **Is θ_{23} maximal ?**
- **mass ordering**
- **3-flavor structure**

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

large difference to quark mixing matrix

$$|V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

Shimizu, Tanimoto, Yamamoto, arXiv:1405.1521



maximal θ_{23} and a large CP violation ($|\delta| \sim \pi/2$) may indicate a flavor symmetry?

[arXiv:1405.1521]

ν_e appearance probability

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{E}\right)$$

$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP} \sin^2 \left(\frac{\Delta m^2_{31} L}{E}\right) \sin \left(\frac{\Delta m^2_{21} L}{E}\right)$$

$\delta_{CP} \to -\delta_{CP}$ if $\bar{\nu}_\mu \to \bar{\nu}_e$

$$+ (\text{matter eff. term}) + ..$$

sensitive to mass hierarchy

proportional to L : small at T2K(L=295km)

$$P(\nu_\mu \to \nu_e) \Leftrightarrow P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

→explore CP violation

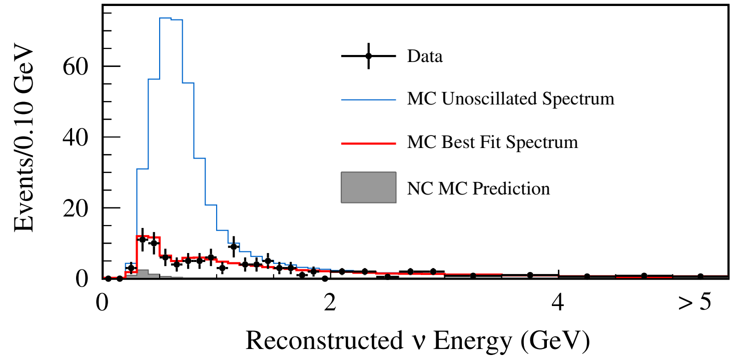
ν_μ disappearance probability

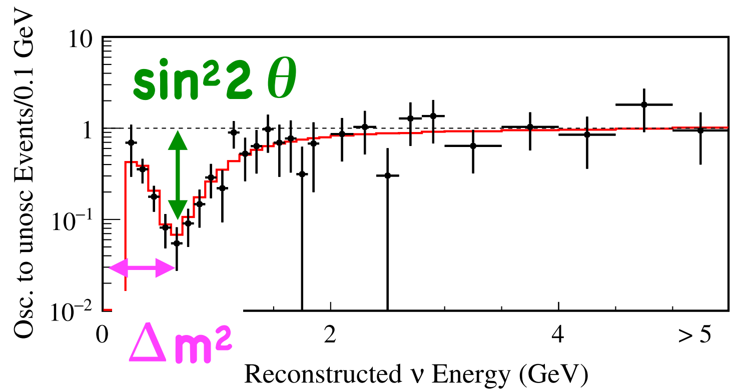
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23}$$

Leading Term

$$+ \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Next-to-Leading

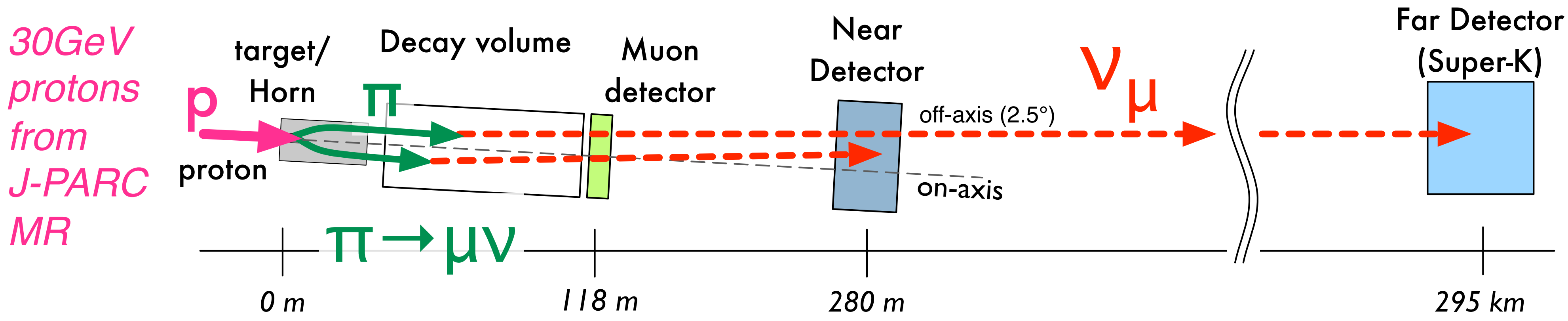




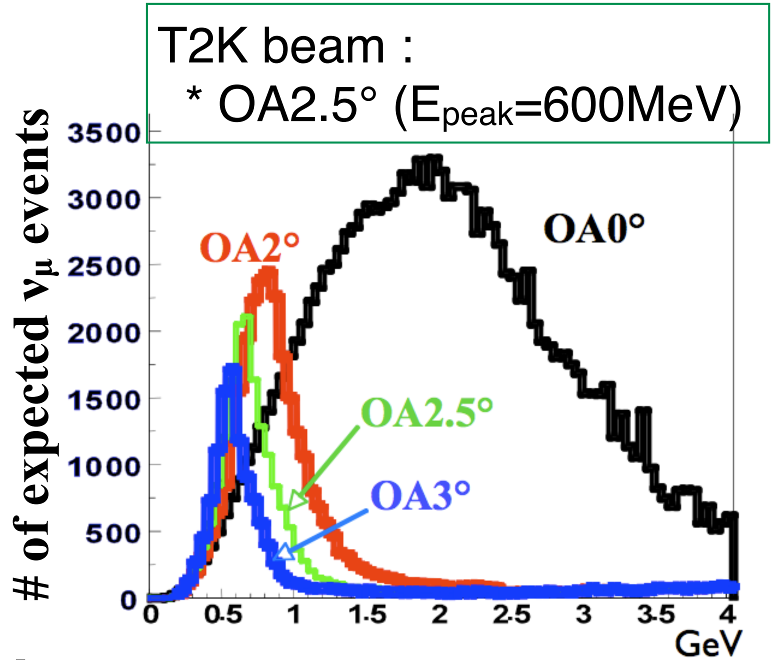
→precise measurement of

θ_{23}, Δm^2

T2K neutrino beam



- Accelerator-based ν beam
- ν energy is narrow with off-axis method
  L = 295km → oscillation peak at 0.6GeV
- ν / $\bar{\nu}$ can be switched by flipping horn polarity

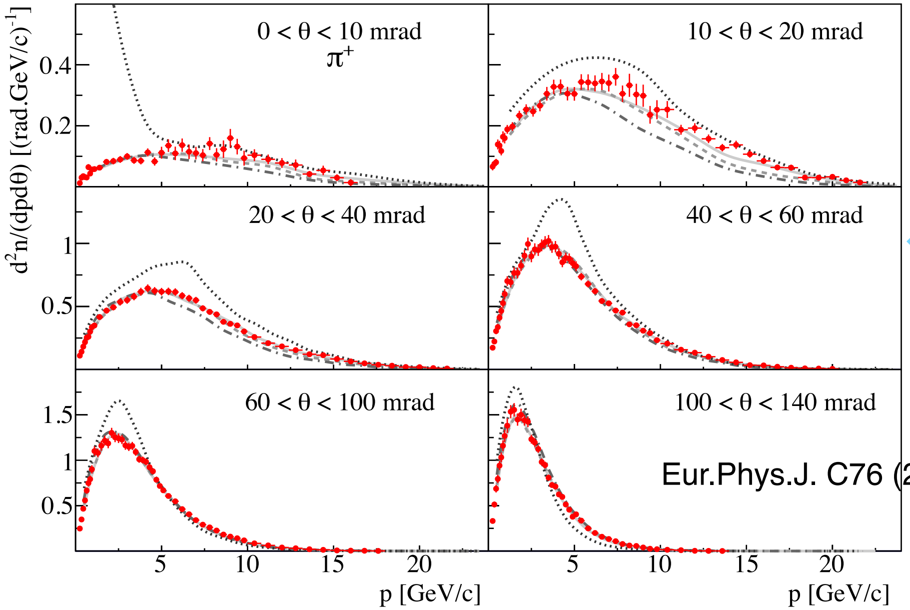


- **<1% of intrinsic ν_e at peak energy**
- **~5% of wrong sign component in $\bar{\nu}$ beam mode**

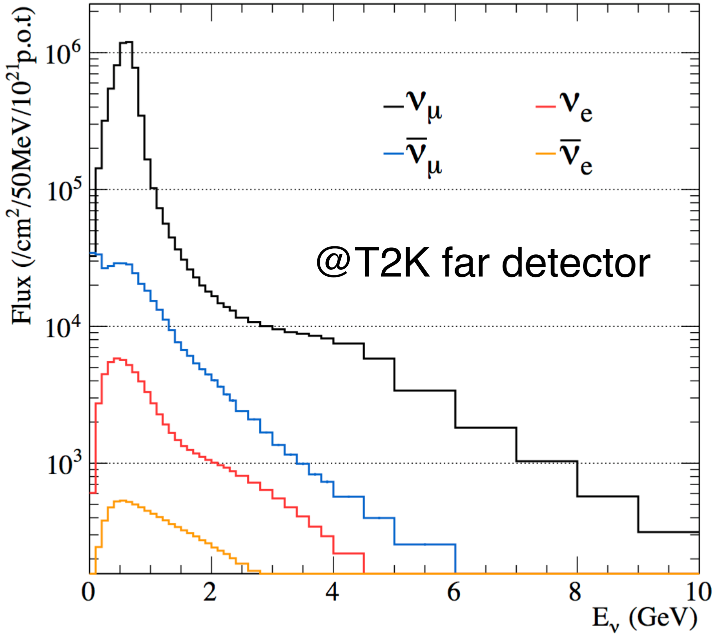
Neutrino flux and its error

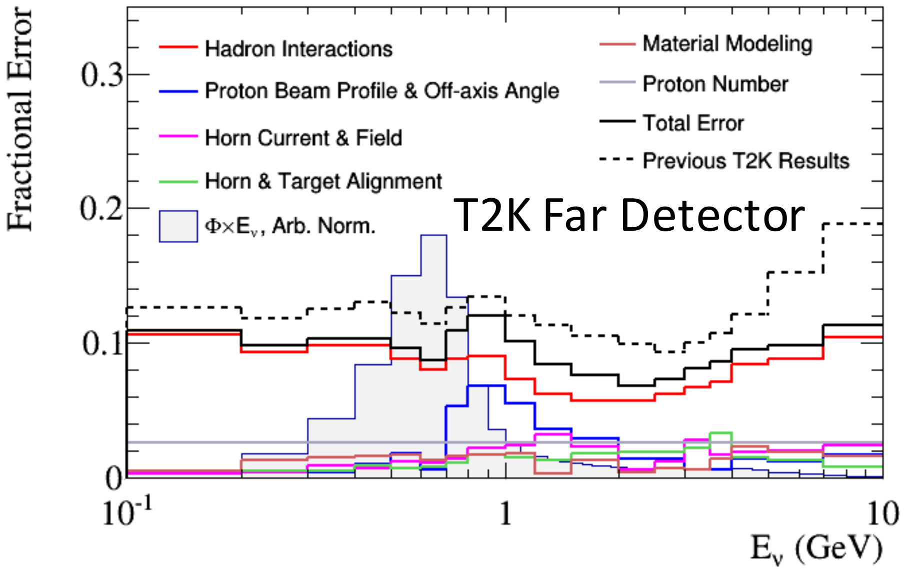
- ν flux is calculated based on
  - measurement of proton beam profile
  - π, K yield measurements by CERN NA61/SHINE experiment

<u>π+ yield from 30GeV p+C interaction</u>



Eur.Phys.J. C76 (2016) no.2, 84





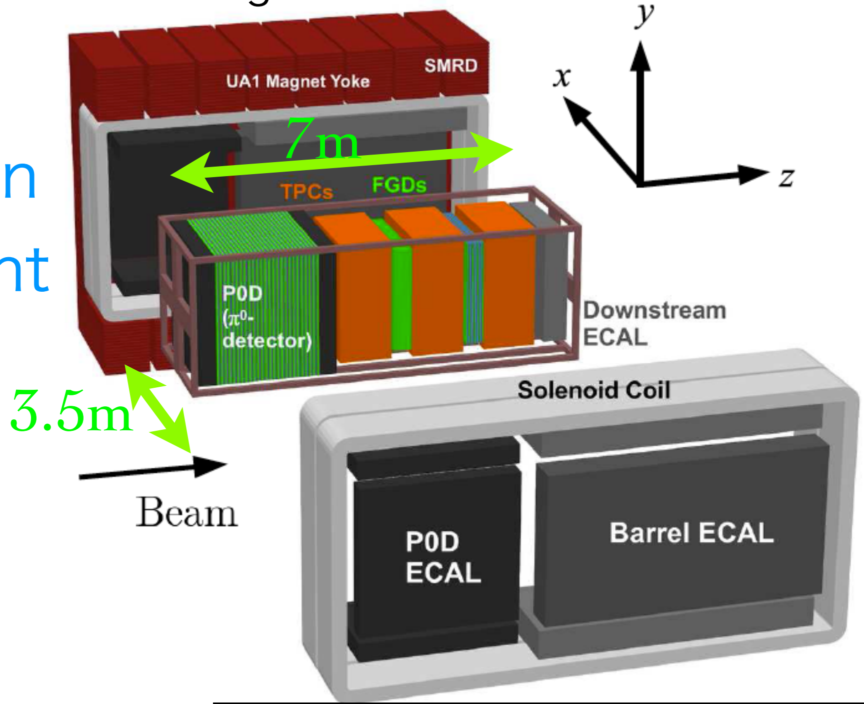
w/o Near detector constraint

- Total absolute flux uncertainty is ~10% (similar size for anti-nu beam)
- Near-to-far extrapolation is also calculated

Near Detectors

ND280 @ Off-axis

0.2T UA1 magnet

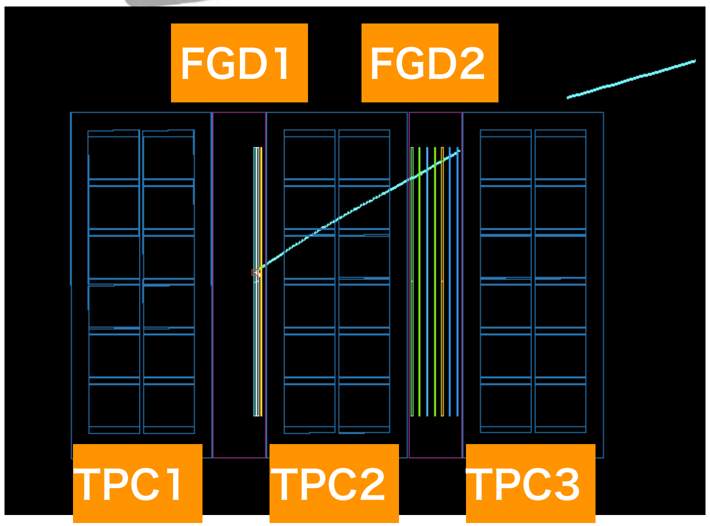


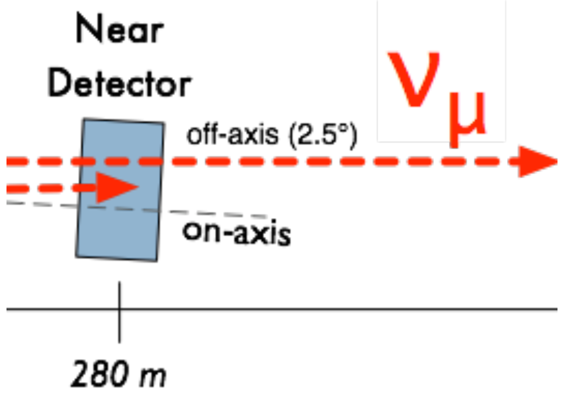
ν flux、

ν interaction

measurement

- FGD
  - scintillator bars target (water target in FGD2)
- TPC
  - momentum, dE/dx measurement

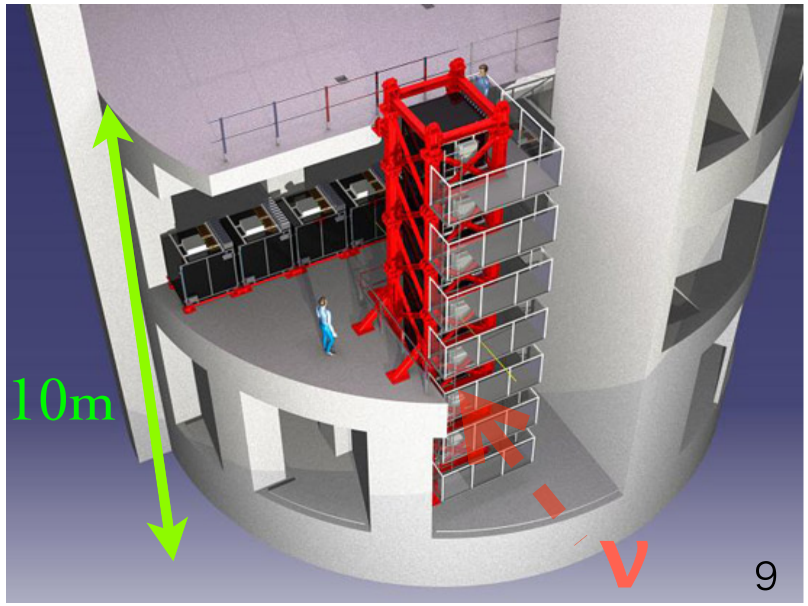




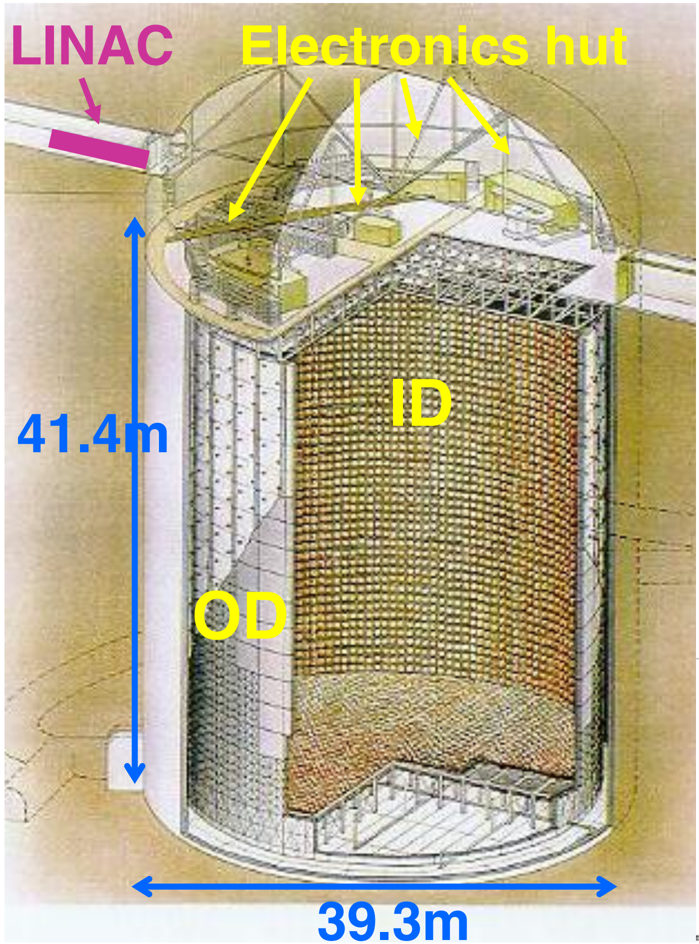
INGRID @ On-axis

ν beam direction,

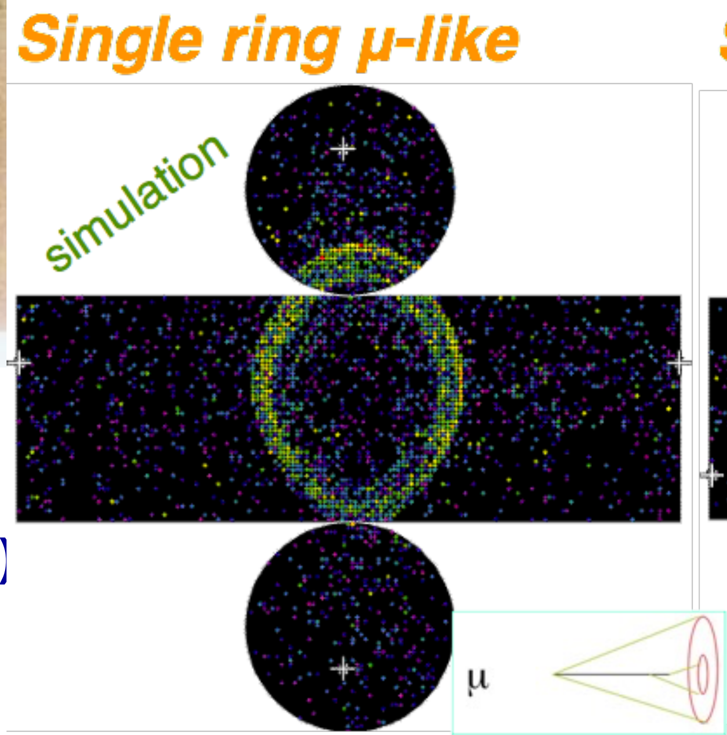
intensity measurement

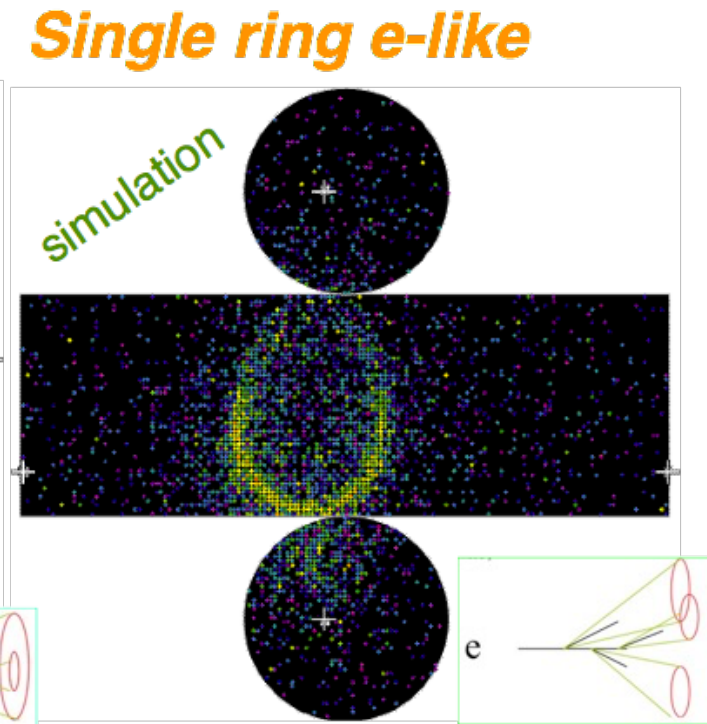


Far detector (Super-K)

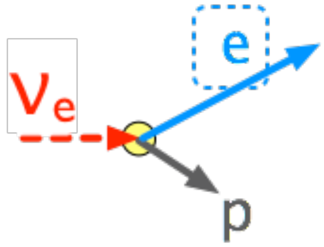
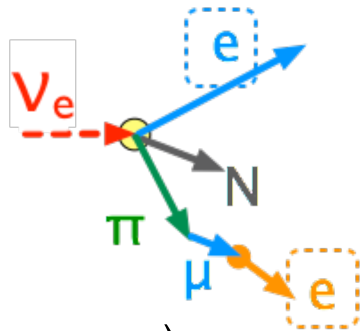
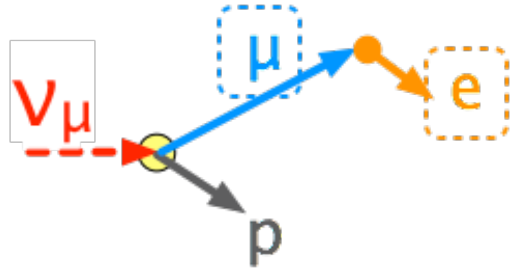


- 50kton water Cherenkov detector
- ID: ~11,000 x20inch PMTs
- Good e-like/μ-like separation
- 4π acceptance
- Refurbishment in summer 2018 for Gd loading (planned in 2019-2020)





Signal and Background at Far detector

a single ring μ-like or e-like at FD	ν_e ($\bar{\nu}_e$) appearance	ν_μ ($\bar{\nu}_\mu$) disappearance
Signal (5 signal categories)	• CCQE e-like  • CC1π e-like (*)  (* only for ν_e app.)	• CCQE μ-like 
Major backgrounds	• intrinsic ν_e in beam • NCπ^0 • wrong sign ν in beam	• CC nonQE • wrong sign ν in beam

T2K oscillation analysis method

$$N_{FD}(E_{rec}) = \sum_{E_t} \Phi(E_t) P_{osc}(E_t) \sigma(E_t) \epsilon(E_t, E_{rec})$$

E_t:true ν energy, ε:efficiency

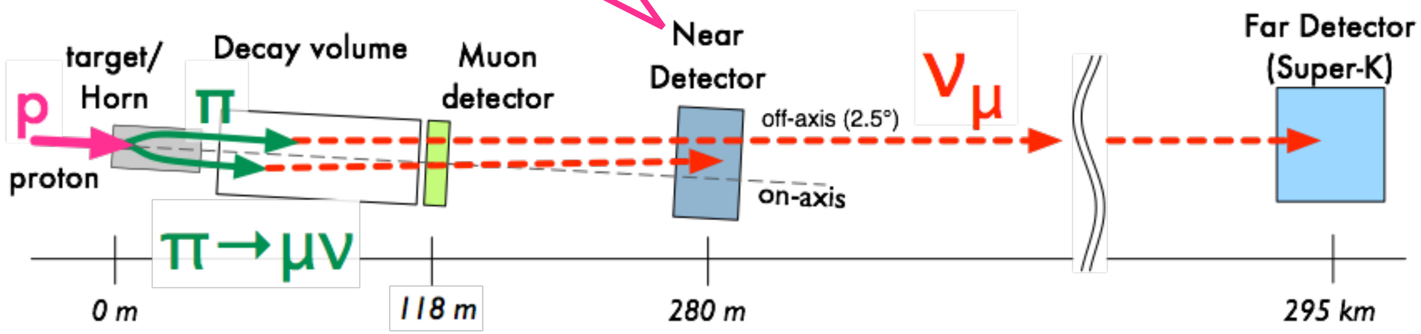
extracting oscillation parameters
by comparing observation and prediction at FD.
But, uncertainties from ν flux and ν-N cross section

$$N_{ND}(E_{rec}) = \sum_{E_t} \Phi(E_t) \sigma(E_t) \epsilon(E_t, E_{rec})$$

Modeling ν flux and ν-N cross section and constraint those models by ND data

Target N. : C,O
Acceptance : Forward dir.

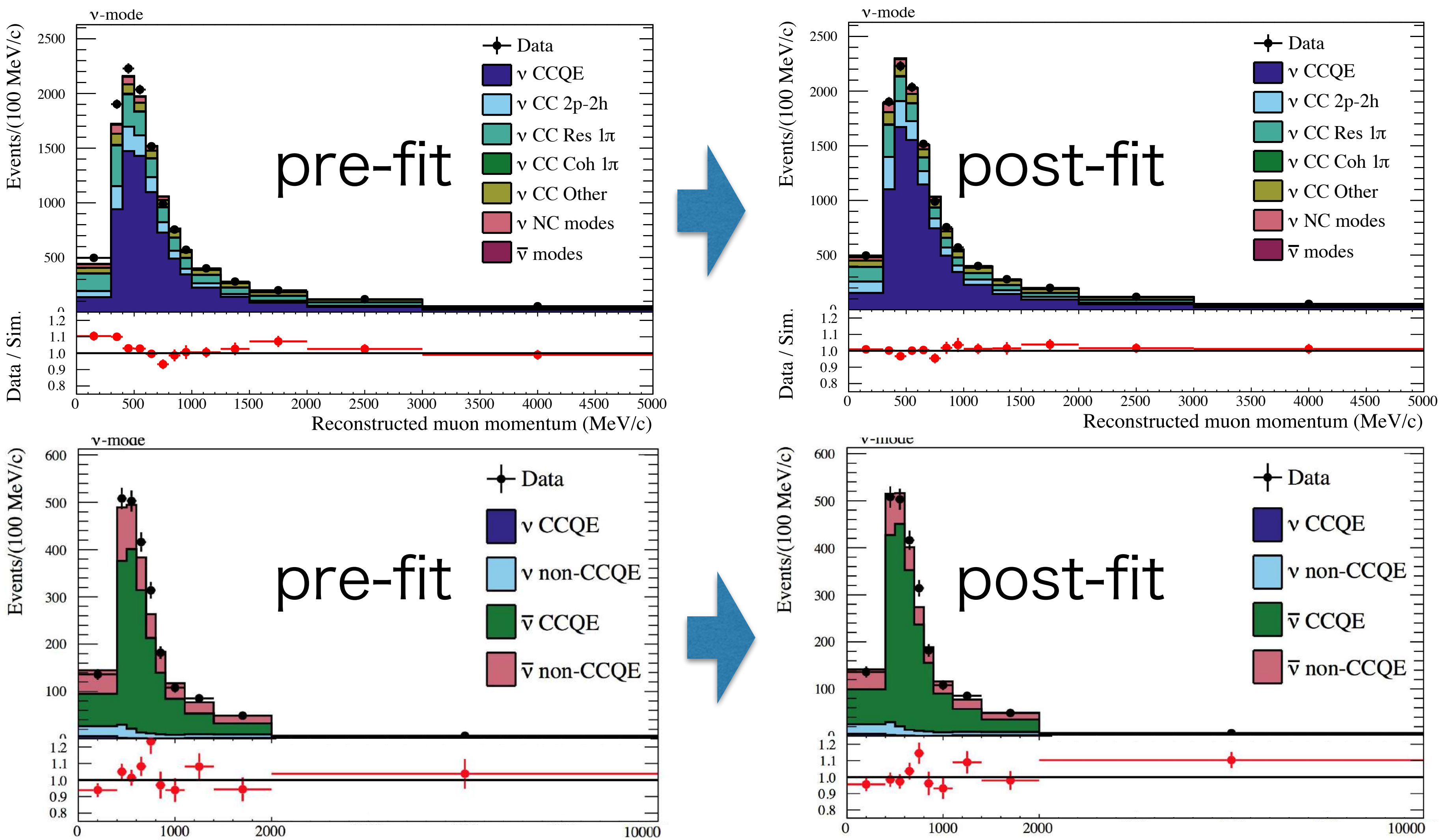
Target N. : O
Acceptance : 4π



taking into account difference of target nucleus and acceptance btw ND and FD

Constraint flux, xsec model with ND280 data

top : ν-mode FDG2 CC-0π　bottom : $\bar{\nu}$-mode FGD2 CC-1track



Systematic uncertainty for # of FD events

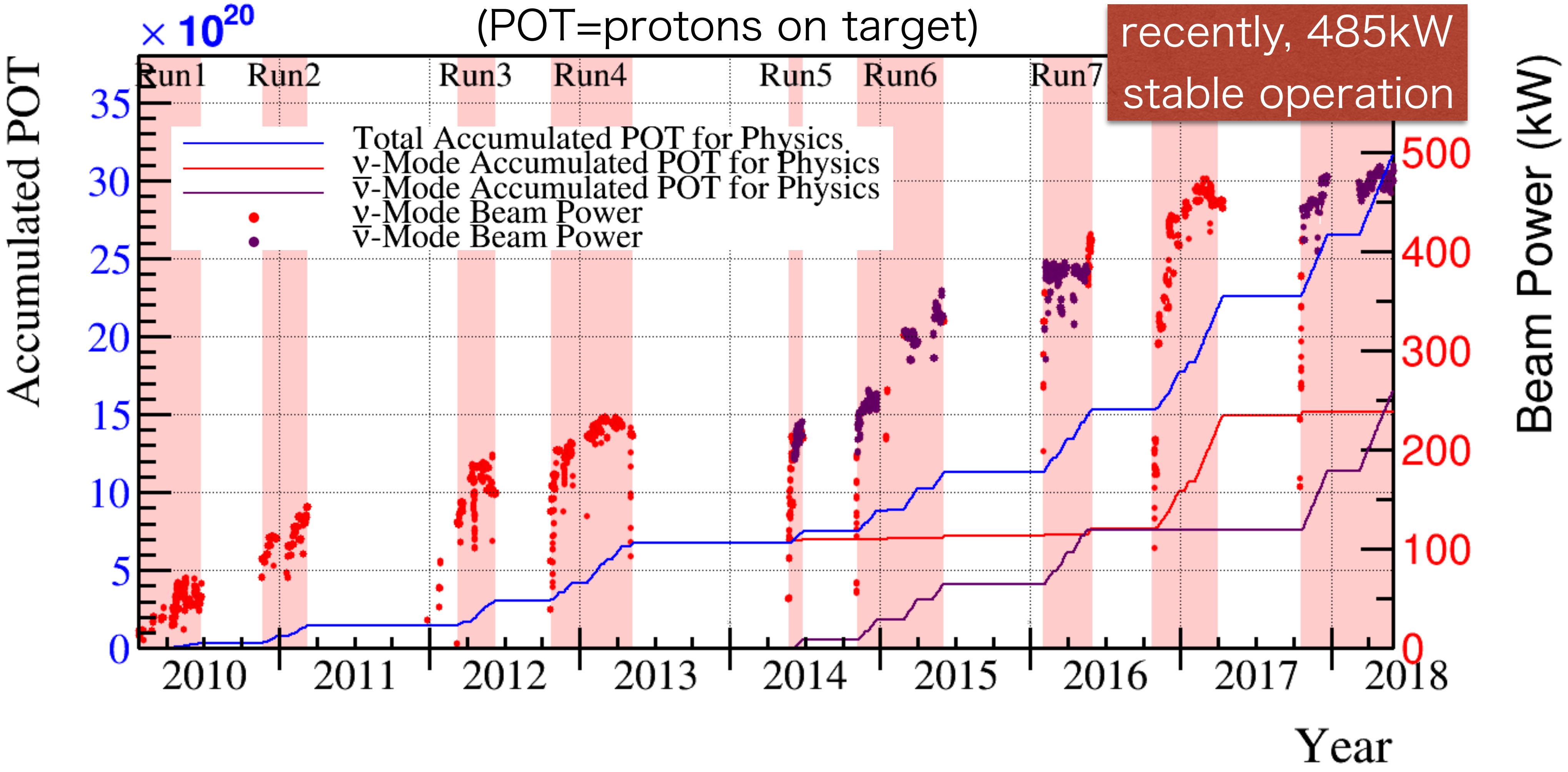
FHC : ν-mode beam, RHC : $\bar{\nu}$-mode beam

(%)

	Single ring μ-like		Single ring e-like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
Final state, Secondary int.	2.21	1.98	3.00	2.31	11.43	1.57
Flux+Xsec after ND constraint	3.27	2.94	3.24	3.10	4.09	2.67
Binding energy(E_b)	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc.	0.03	0.03	2.69	2.49	2.63	0.77
Total	**5.12**	**4.45**	**9.19**	**7.57**	**18.51**	**6.03**

- Error on FHC/RHC ratio which contributes to CPV study is ~6%

Accumulated POT and beam power



Accumulated 15.1x10^20 POT for neutrino mode and

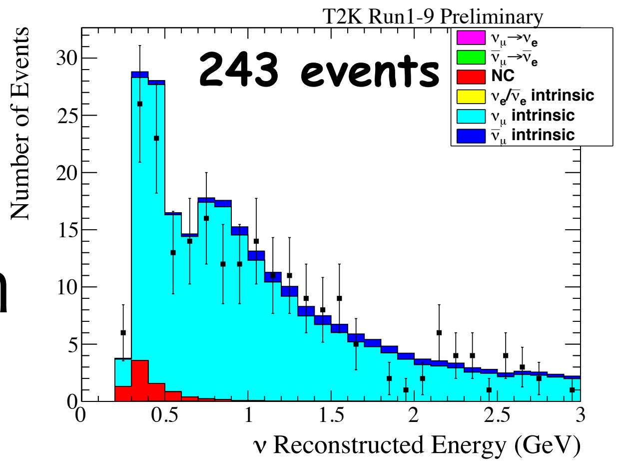
16.5 x 10^20 POT for ant-neutrino mode

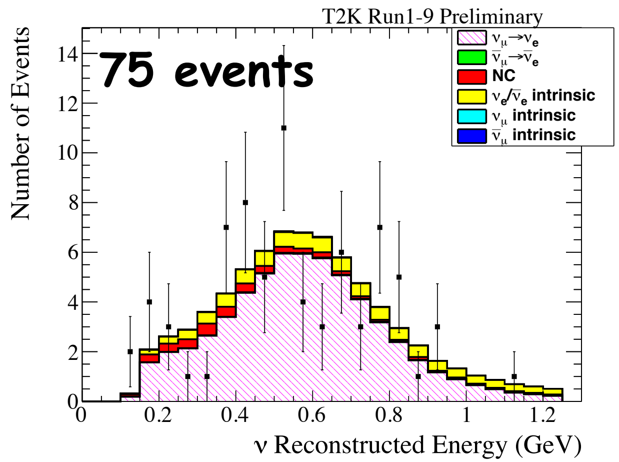
(total POT corresponds to 40% of the T2K approved POT)

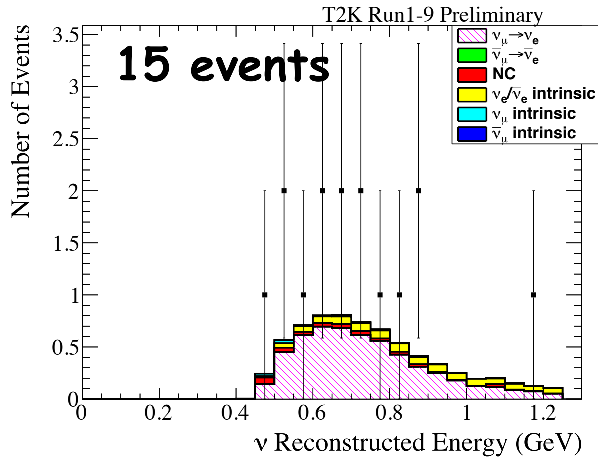
FD observed event

CCQE μ-like | CCQE e-like | CC1π e-like

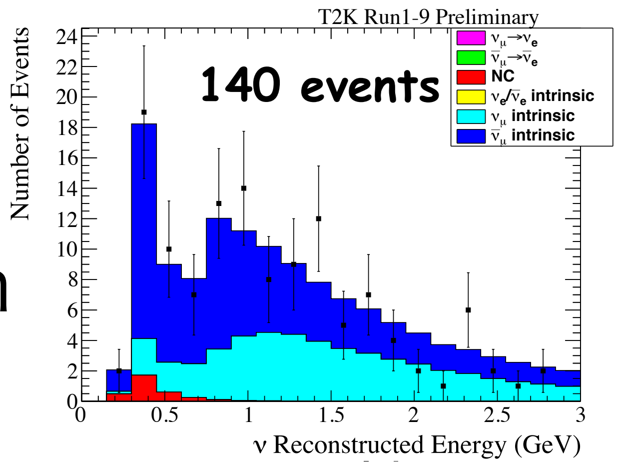
ν beam

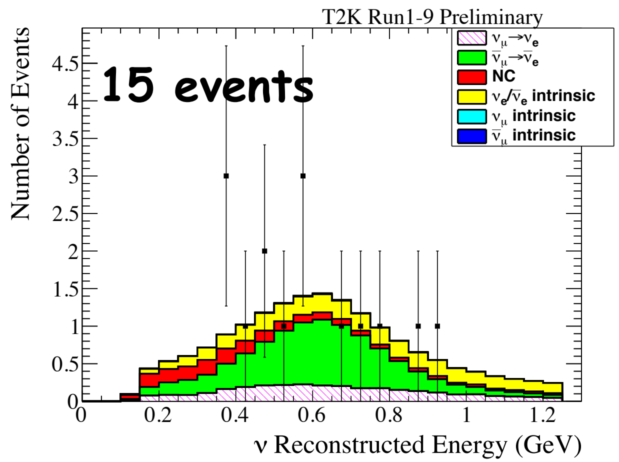






$\overline{\nu}$ beam





MC assumption :

$\delta_{CP} = -\pi/2$

Normal Hierarchy

$\sin^2\theta_{23} = 0.528$

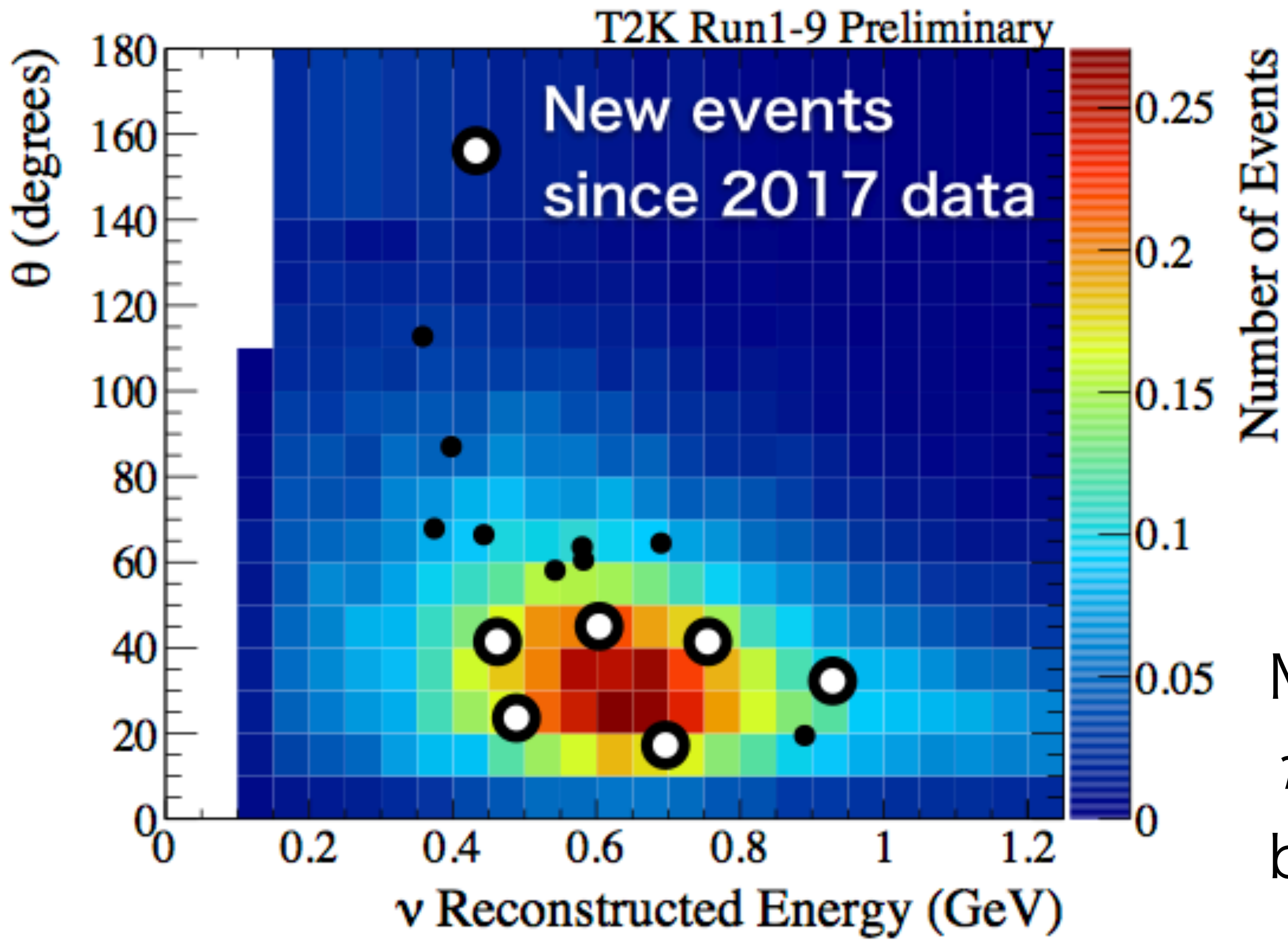
$\sin^2\theta_{13} = 0.0212$

ν-mode : 14.9×10^{20} POT , $\overline{\nu}$-mode : 16.3×10^{20} POT

$\overline{\nu}_e$ appearance search

15 of CCQE e-like events observed in $\overline{\nu}$-mode data

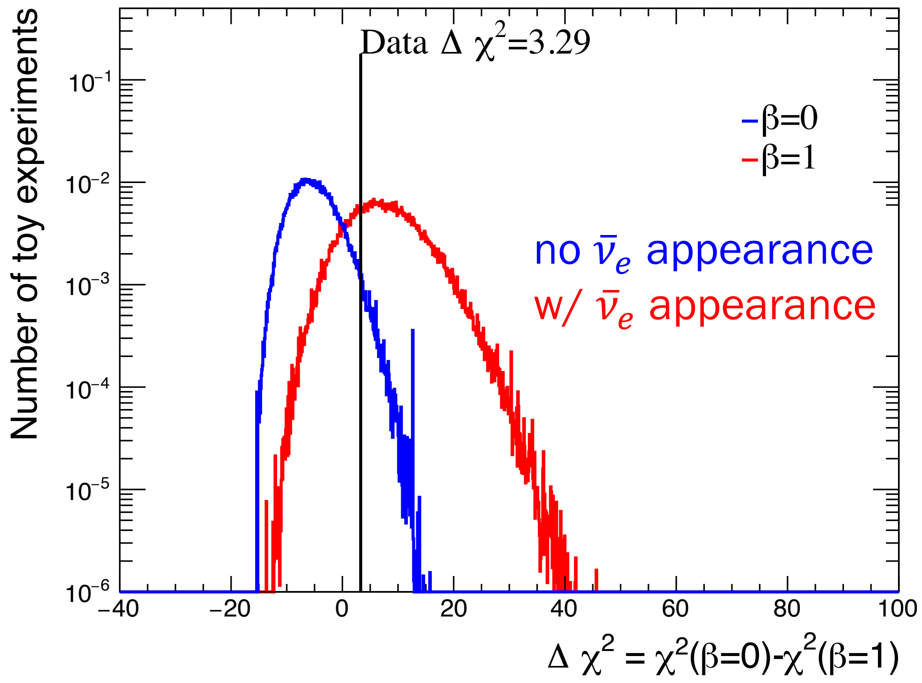
T2K : 16.3×10^{20} POT



Main backgrounds are $\nu_\mu \rightarrow \nu_e$ (wrong sign), beam intrinsic $\overline{\nu}_e + \nu_e$

$\overline{\nu}_e$ appearance search

15 of CCQE e-like events observed in $\overline{\nu}$-mode data



Expectation

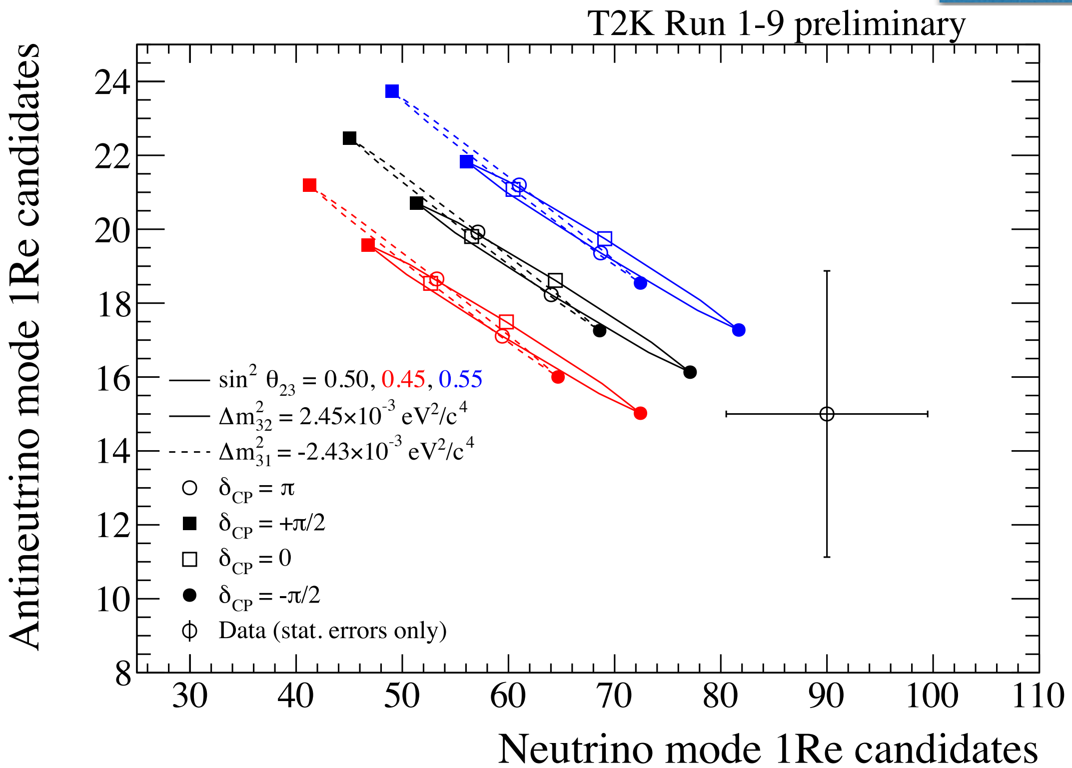
9.4 events w/o $\overline{\nu}_e$ appearance
17.2 events w/ $\overline{\nu}_e$ appearance

No $\overline{\nu}_e$ appearance hypothesis is excluded by 2.25σ significance w/ rate+shape information

ν_e vs $\bar{\nu}_e$ appearance

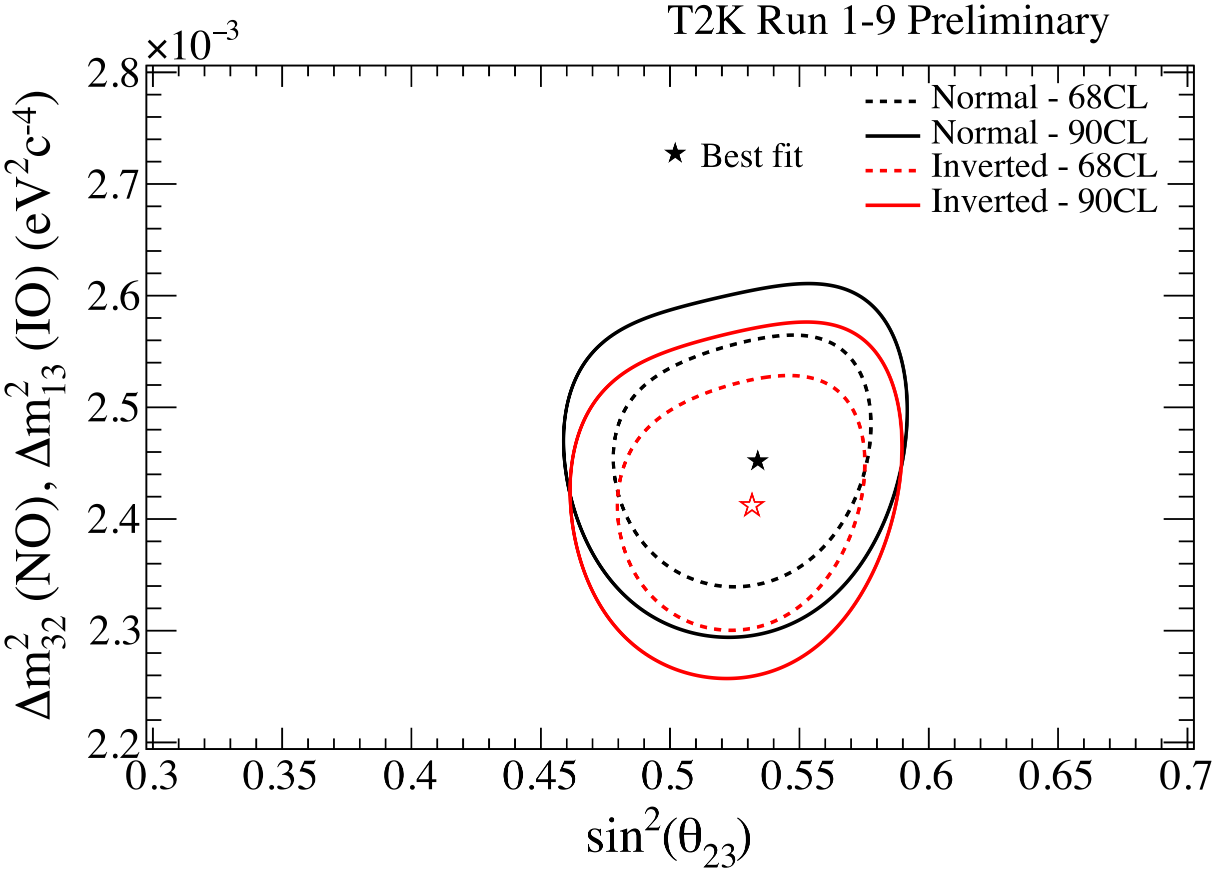
- Comparison of # of ν_e and $\bar{\nu}_e$ appearance candidates

	Obs.	Expectation δ=-π/2 (CPV)	Expectation δ=π (CPC)	Expectation δ=π/2 (CPV)	Expectation δ=0 (CPC)
$\nu_\mu \to \nu_e$ candidates	90	81.4	68.6	55.5	68.3
$\bar{\nu}_\mu \to \bar{\nu}_e$ candidates	15	17.1	19.3	21.7	19.4



→ *oscillation parameters are extracted using all event samples (not only ν_e samples but also ν_μ samples)*

ν_μ disappearance



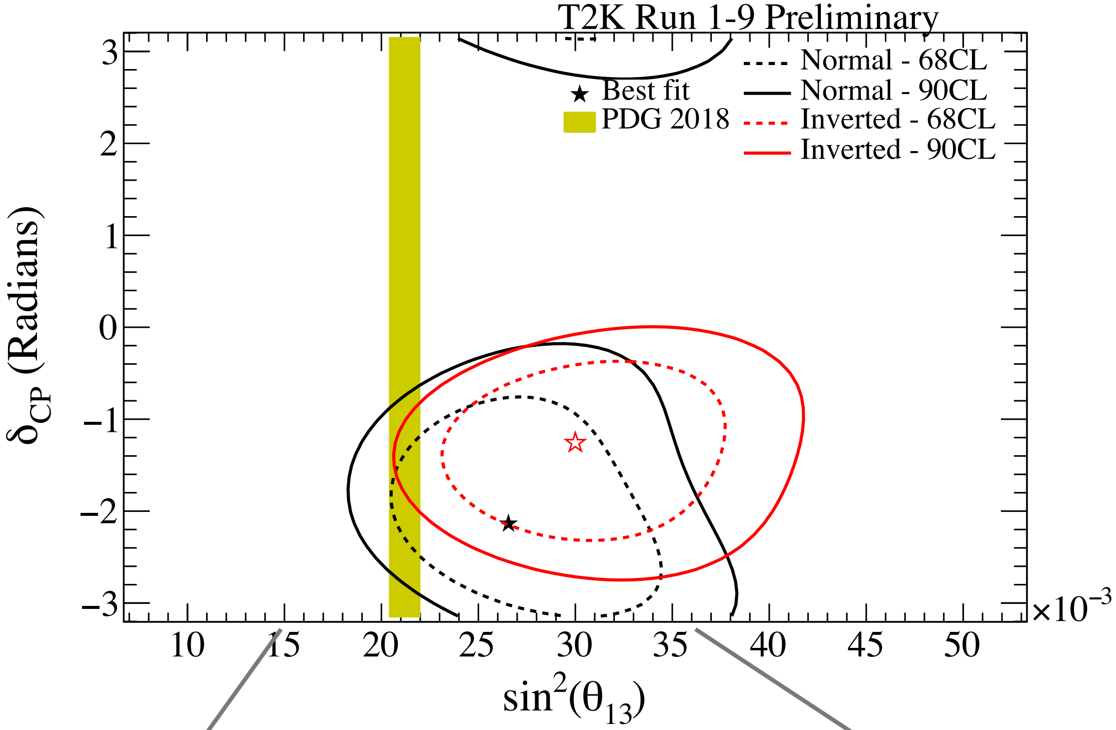
posterior probability

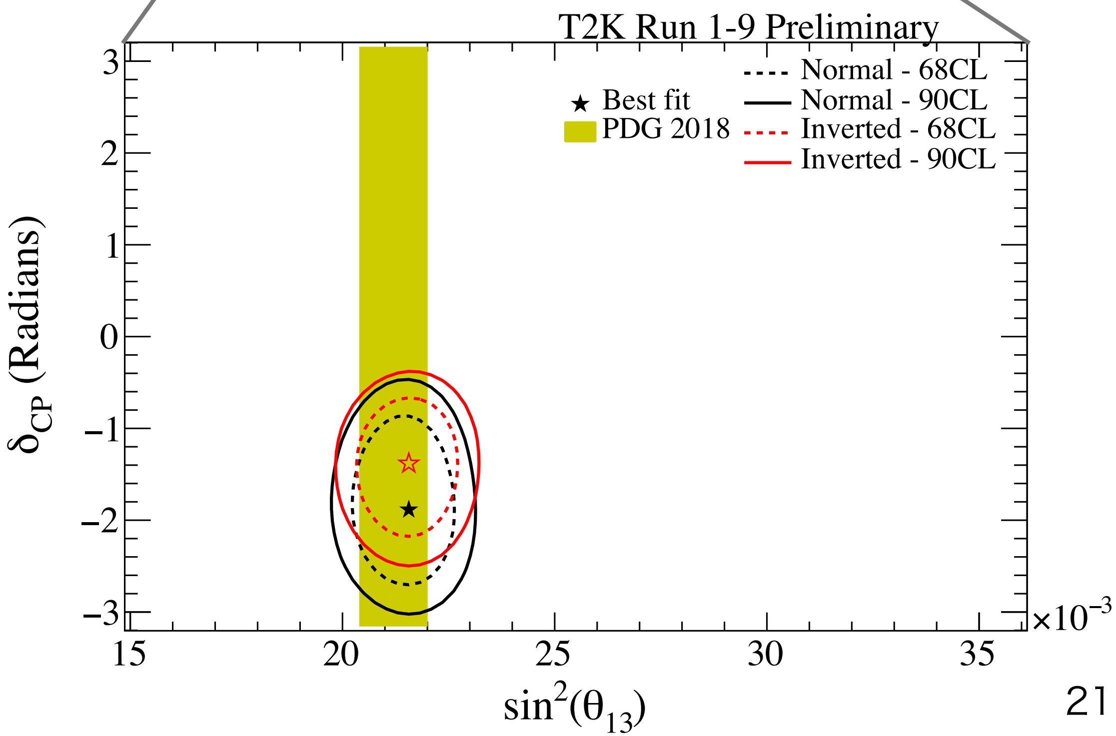
	$\sin^2\theta_{23}$<0.5	$\sin^2\theta_{23}$>0.5	Sum
Normal	0.184	0.705	0.889
Inverted	0.021	0.090	0.111
Sum	0.205	0.795	1

- Contours for ν_μ disappearance parameters $\sin^2\theta_{23}$, Δm^2_{32} (w/ reactor constraint on $\sin^2\theta_{13}$)
- Consistent with maximal mixing
- Data prefers normal mass ordering

δ_{CP} vs $\sin^2\theta_{13}$

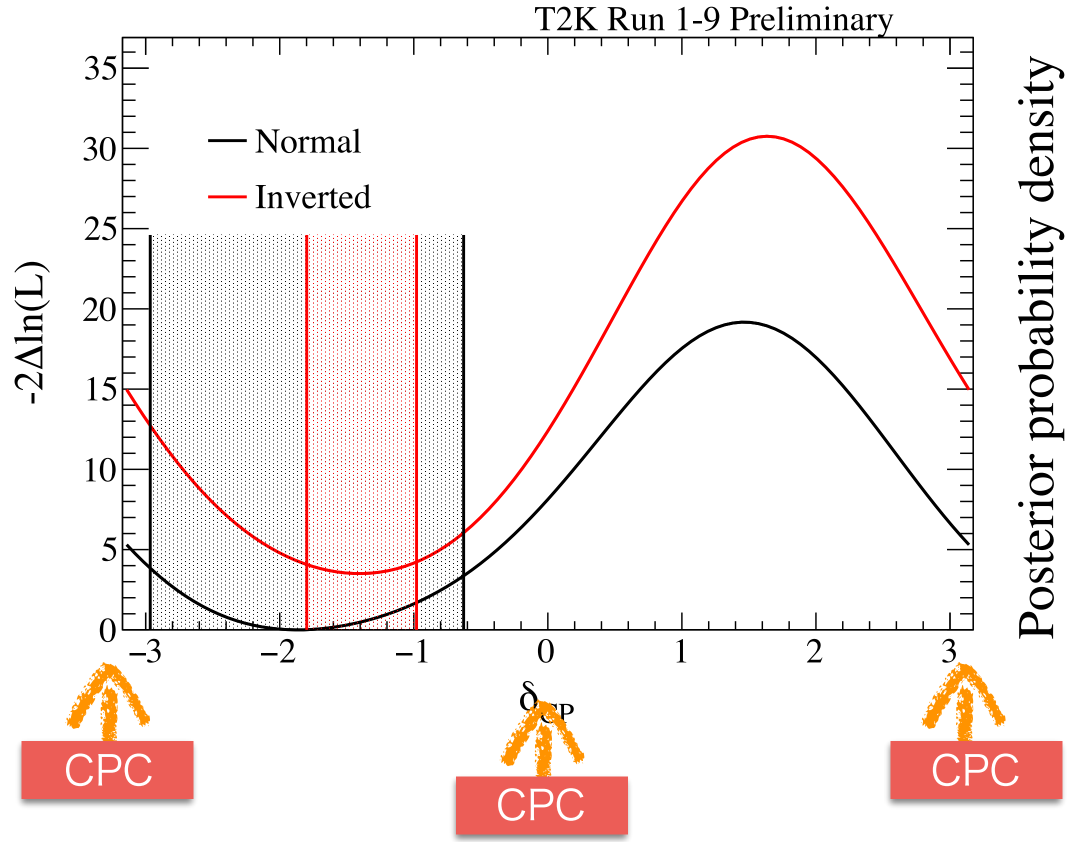
- Contours for δ_{CP} and $\sin^2(\theta_{13})$ w/ all the data samples
- Top plot shows only T2K allowed region
- Bottom plot shows with reactor constraints on $\sin^2(\theta_{13})$ (PDG2018)

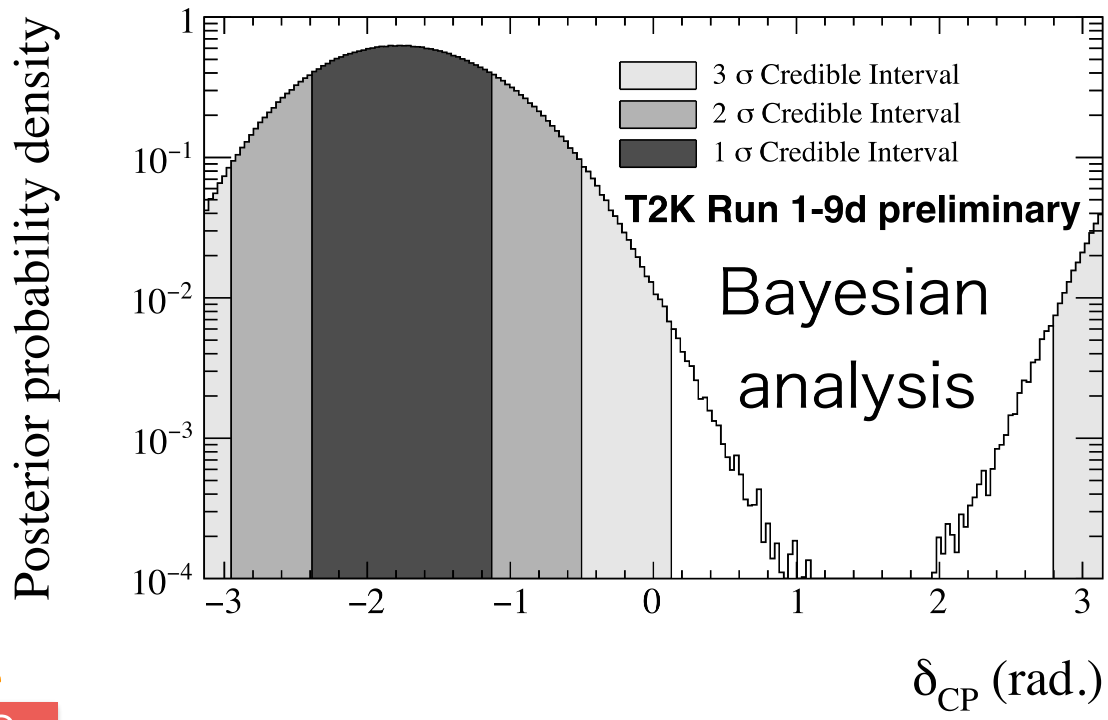




Constraints on δ_{CP}

ν-mode : 14.9×10^{20} POT , $\bar{\nu}$-mode : 16.3×10^{20} POT





2σ C.L. interval

Normal hierarchy [-2.966, -0.628] rad.

Inverted hierarchy [-1.799, -1.979] rad.

CP conserving values (δ=0, $\pm\pi$) are excluded with 2σ level

→ **Need more data for confirmation of CPV**

Prospects of analysis improvement

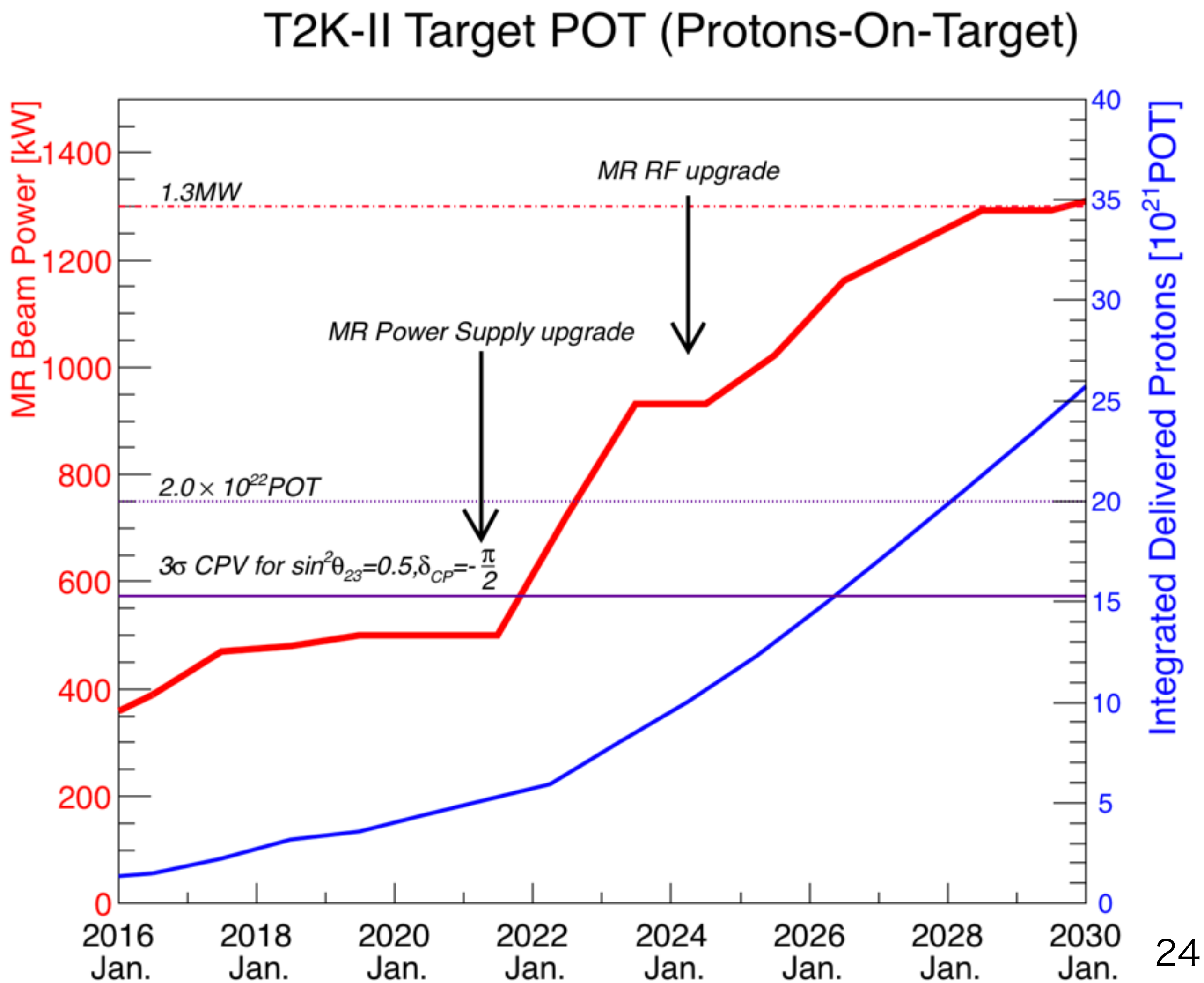
- Systematic error improvements
  - Flux error will be reduced to ~6% by using replica target data of NA61/SHINE hadron production measurement
  - Neutrino interaction modeling will be upgraded based on latest experimental results
- T2K+NOvA, T2K+SK joint analysis are under discussion between collaborators
  - Aim to do T2K+NOvA analysis around 2021

T2K-II

We plan to accumulate more data up to 2×10^{22} POT by 2027 (J-PARC E65 [T2K-II])

J-PARC PAC stage-1 status

- Beam power upgrade to 1.3MW
- Near detector upgrade to reduce the total systematic error down to ~4%



Beam power upgrade plan

	Achieved	Target
Beam power [MW]	0.5	1.3
# of protons per pulse	2.6×10^{14}	3.2×10^{14}
Rep. Time [sec]	2.48	1.16

Power ∝ 30GeV x # of protons x $1/T_{rep.}$

- **Upgrade of MR main power supply, RF and collimators**
- **Upgrade of neutrino beamline**

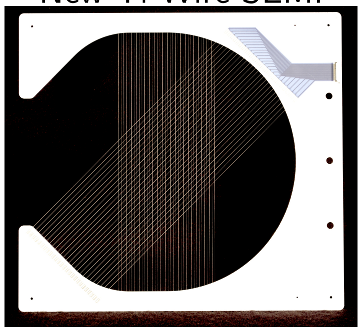
Upgrade for 1Hz rep.

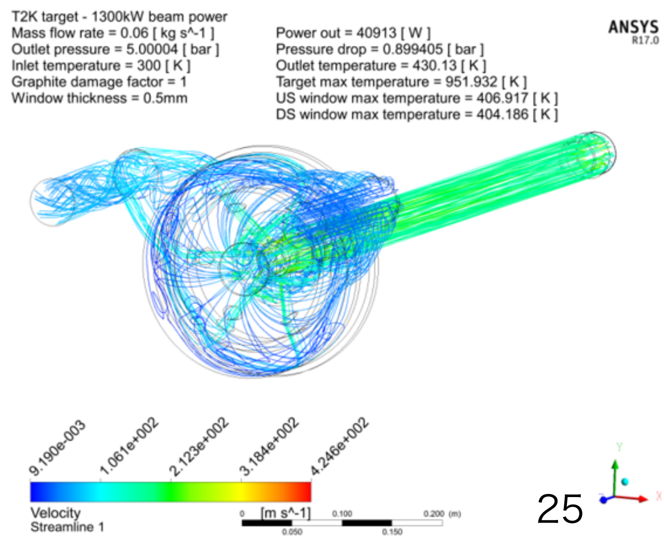
Reinforcing cooling capability (target, horn etc.)

R&D w/ international and domestic cooperation

New beam monitors

New Ti Wire SEM:



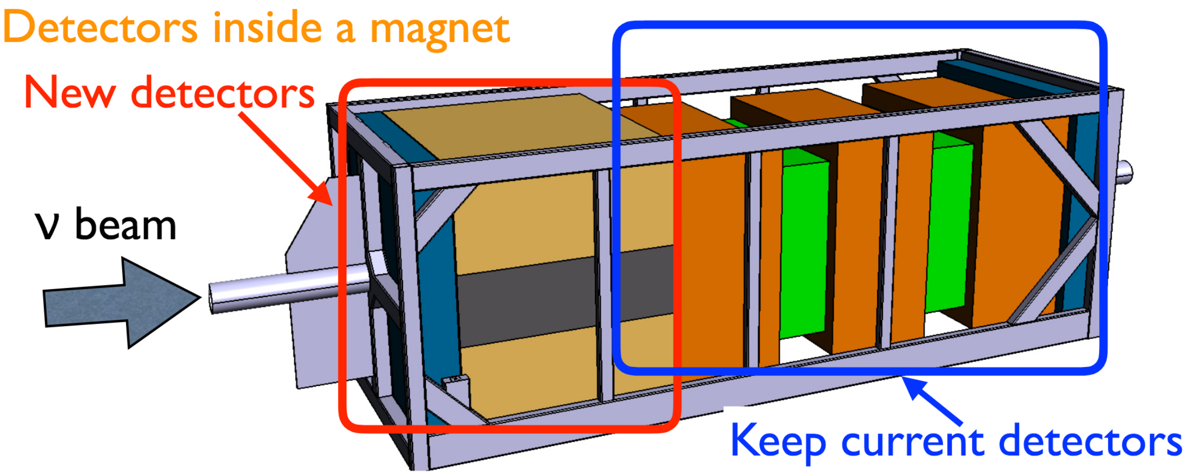


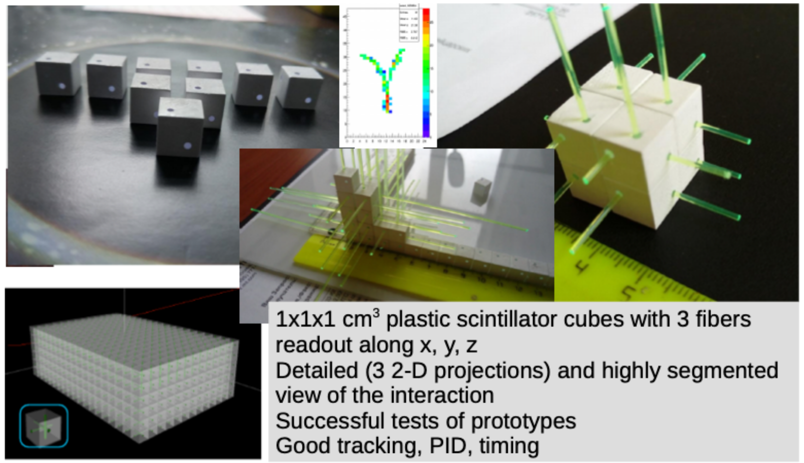
Near Detector upgrade

Replacing part of ND280 with new detectors to enhance capability

arXiv:1707.01785

Super-FGD

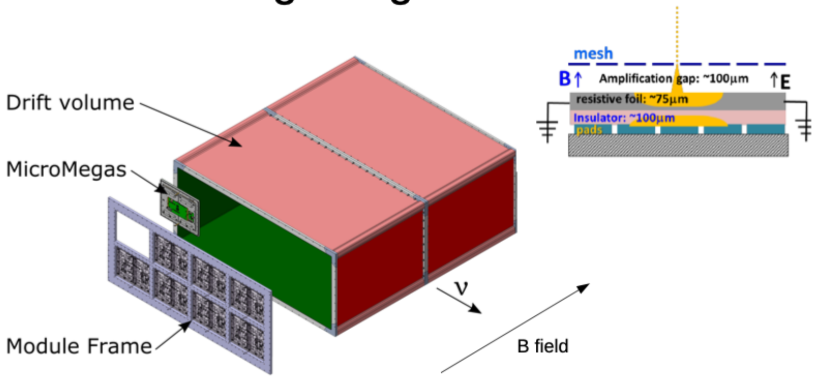




- *TDR submitted to PAC and reviewed (J-PARC & CERN)*
- *Strong collaboration of experts from Europe (incl. CERN), Japan and USA*
- *will be approved as CERN NP06*

Aiming installation in 2021

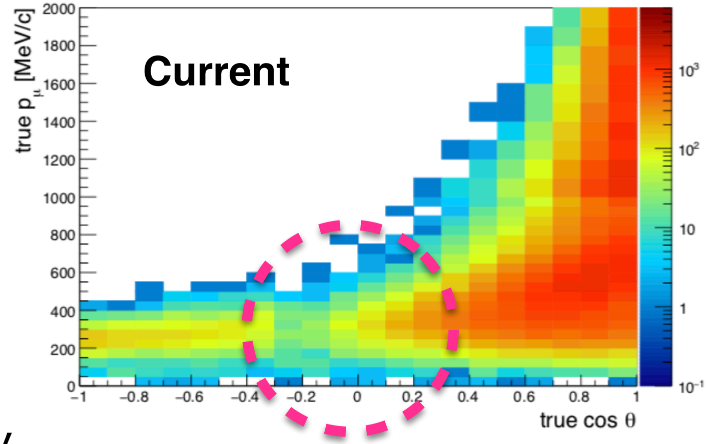
High Angle-TPCs

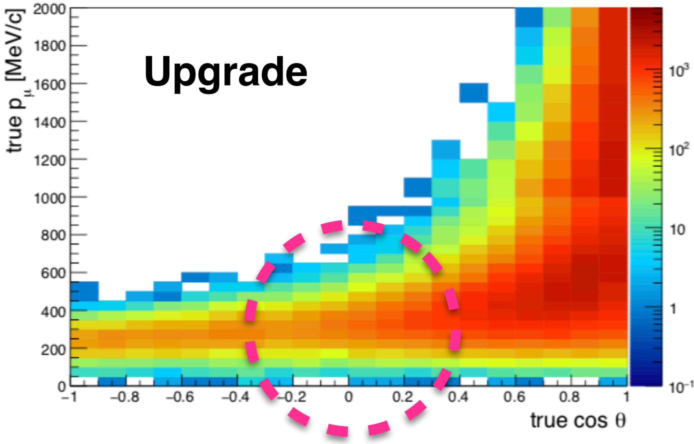


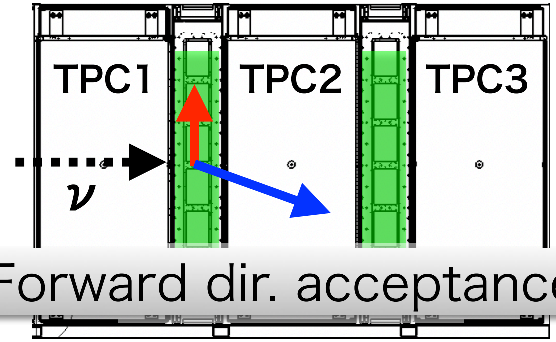
- Atmospheric pressure TPC using the same gas mixture as the present TPC
- Main difference with the existing TPC: thin field cage, resistive Micromegas
- Large overlap with the TPC group
- Benefiting from ILC TPC developments and RD51

Near Detector upgrade

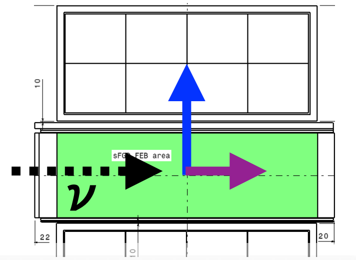
- Large angle acceptance will be improved
- High granularity can improve vertex reconstruction efficiency



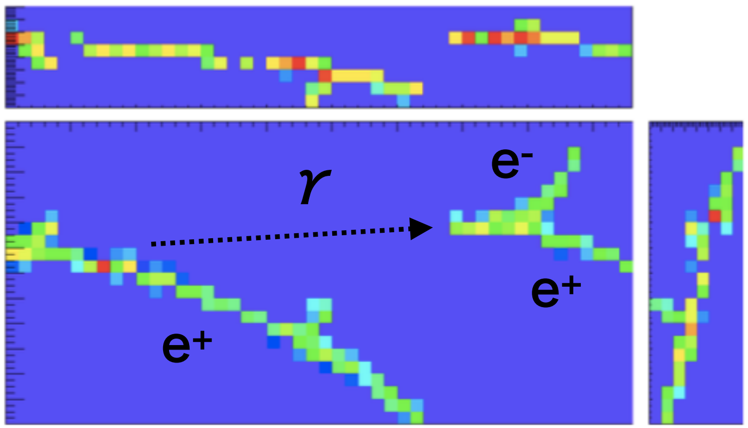




Forward dir. acceptance

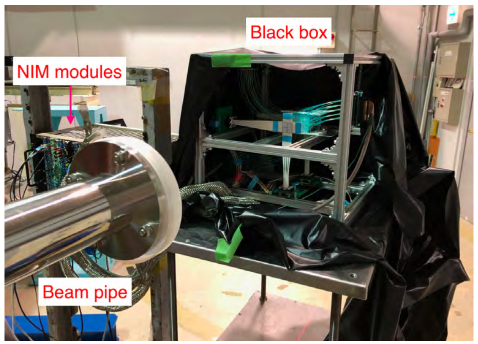


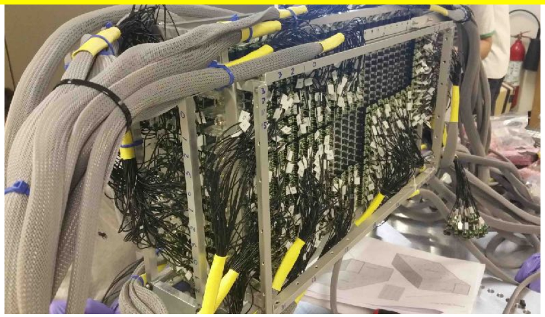
Larger angle acceptance

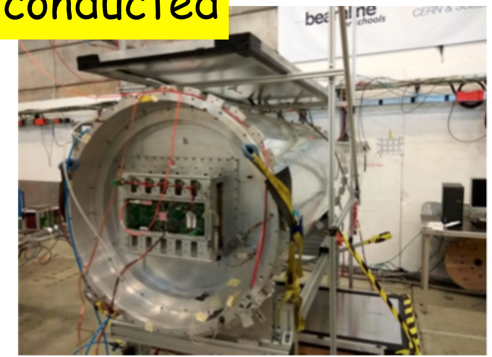


Positron, 1 GeV, B = 0.2T

Test beams for prototypes of SuperFGD, TPC, TOF are conducted



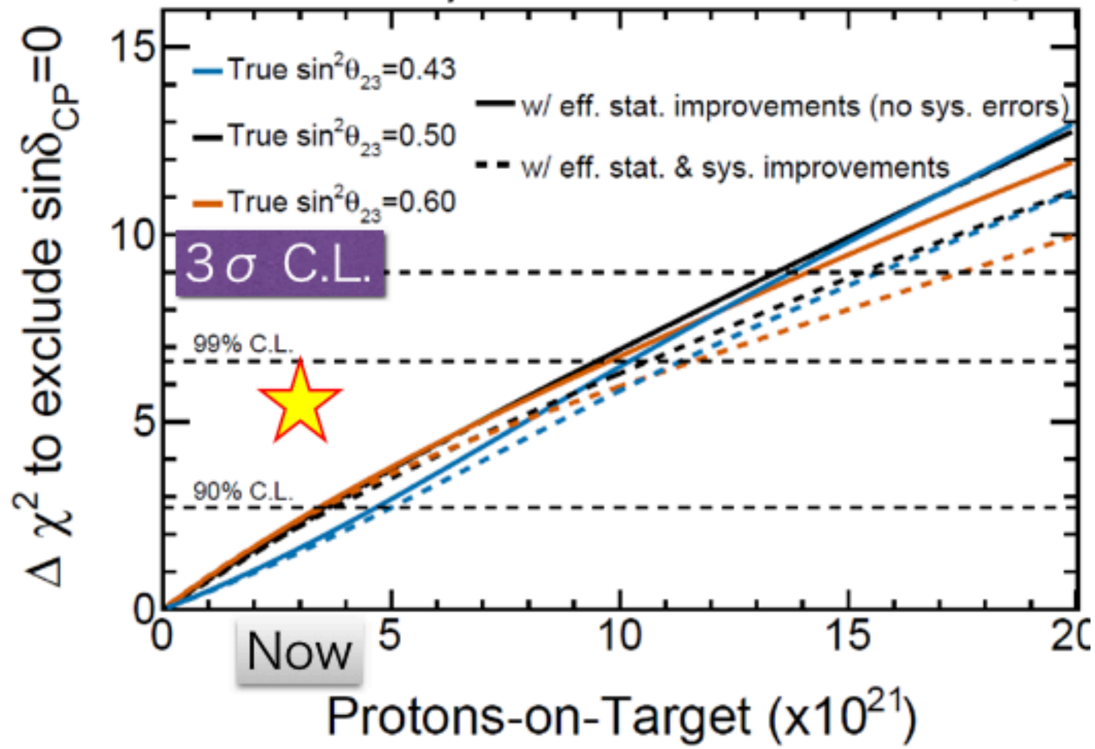




T2K-II Physics Prospects

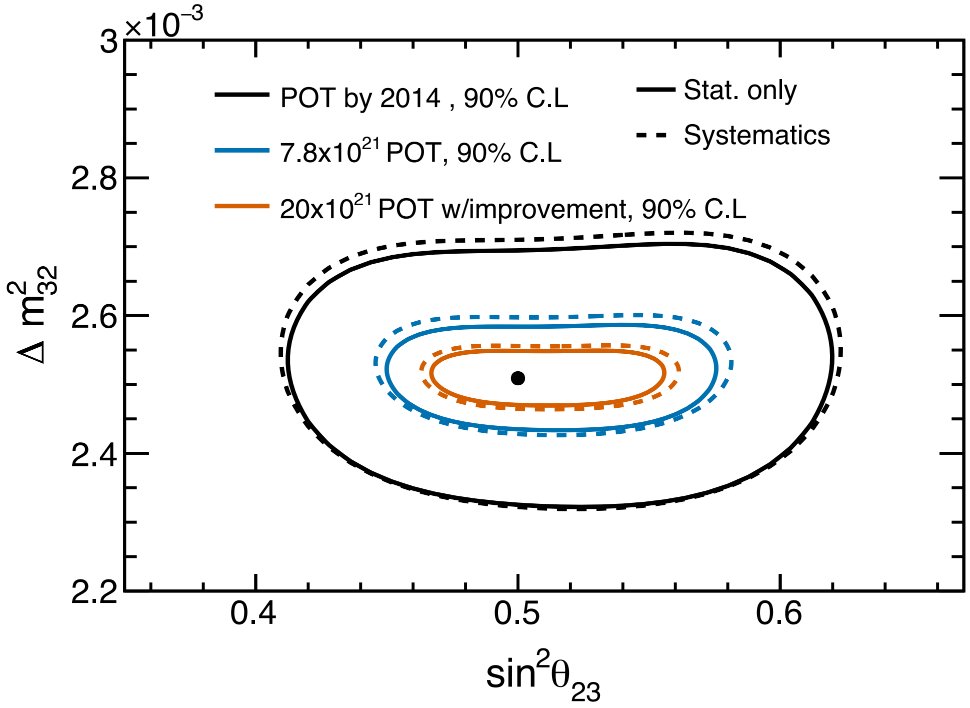
Sensitivity to exclude $\sin\delta_{CP}=0$

$\delta_{CP}= -\pi/2$



>3σ CPV sensitivity

Sensitivity of $\sin^2\theta_{23}$, Δm^2_{32}



~1% precision of Δm^2,

0.5°-1.7° precision of θ_{23}

(depends on true value)

Summary

- Recently, stable operation with 485kW beam power
- T2K collected 3.16 x 10^{21} POT up to now and it indicates a large CPV in neutrino oscillation
- We plan to upgrade beam power and near detector and collect more data up to 20 x 10^{21} POT [T2K-II]
- We aim to detect neutrino CPV with 3σ sensitivity at T2K-II