Recent results from the T2K experiment

MARIA ANTONOVA ON BEHALF OF THE T2K COLLABORATION

INSTITUTO DE FISICA CORPUSCULAR (UV AND CSIC), VALENCIA, SPAIN

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Outline

- Neutrino oscillations
- T2K experiment
- Oscillation analysis
- Recent results
- Future plans
- Summary

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Neutrino oscillations

Atmospheric and accelerator | Accelerator and reactor | Reactor and solar

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

Flavor eigenstates

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) – neutrino mixing matrix

Mass eigenstates

Neutrino oscillations parameterized with:

- Three mixing angles:

  $\theta_{23} \sim 45^o$, $\theta_{13} \sim 9^o$, $\theta_{12} \sim 34^o$
- Two squared mass differences

  $\Delta m^2_{21} \approx 7.5\times10^{-5} eV^2$,

  $|\Delta m^2_{32}| \approx 2.5\times10^{-3} eV^2$,

  $\Delta m^2_{ij} = m^2_i - m^2_j$
- CP violating phase δ_{cp}

*PDG 2016

Current efforts:

- Precise measurement of the oscillation parameters (θ_{23}octant, θ_{13})
- Neutrino mass hierarchy
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$
- Presence of CP violation and value of δ_{cp}
- “Sterile neutrino”? Exotics?

- Neutrino oscillations
- **T2K experiment**
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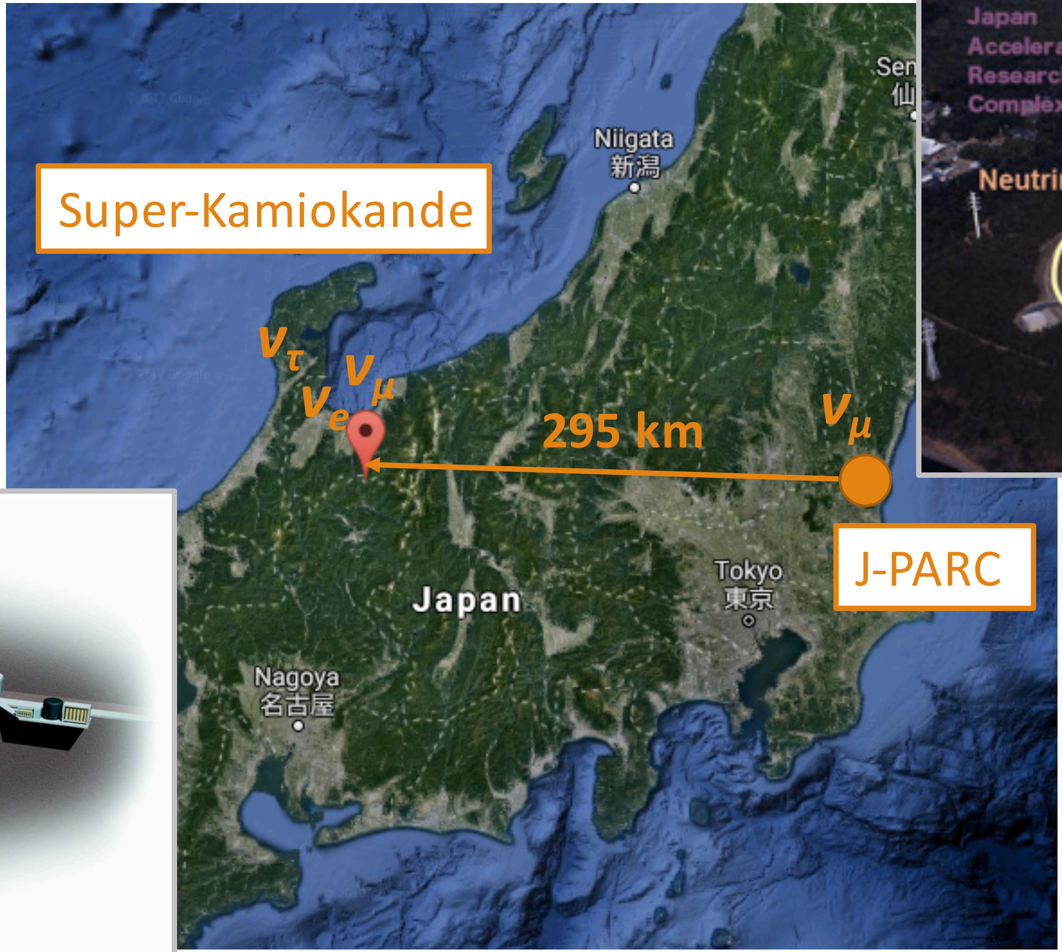
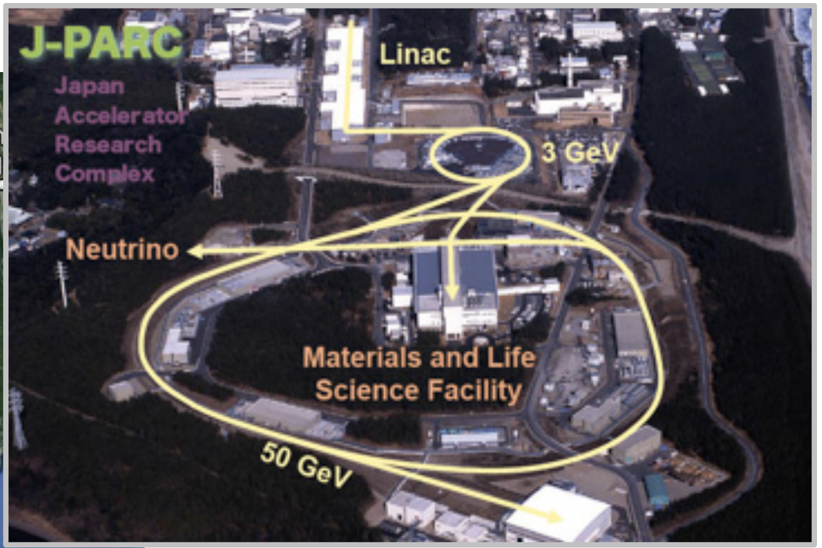
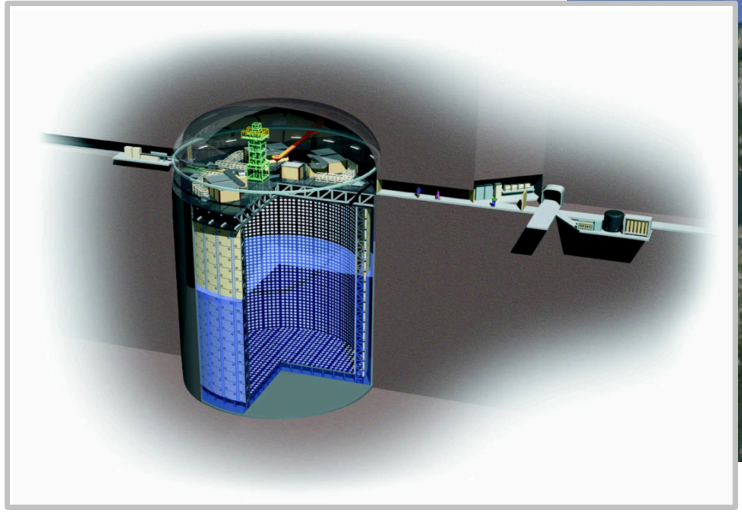
T2K experiment







Neutrino oscillations in T2K

- T2K studies neutrino and antineutrino oscillations
  - $\nu_\mu \to \nu_\mu, \nu_\mu \to \nu_e$
  - $\bar{\nu}_\mu \to \bar{\nu}_\mu, \bar{\nu}_\mu \to \bar{\nu}_e$
- Appearance channel: θ_{13}, CP violation, θ_{23} octant, mass hierarchy

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2\theta_{23}}\,\underline{\sin^2 2\theta_{13}}\,\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

Leading term

$$-\underline{\sin 2\theta_{12}}\,\underline{\sin 2\theta_{23}}\,\underline{\sin 2\theta_{13}}\cos\theta_{13}\,\underline{\sin\delta}\,\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violating

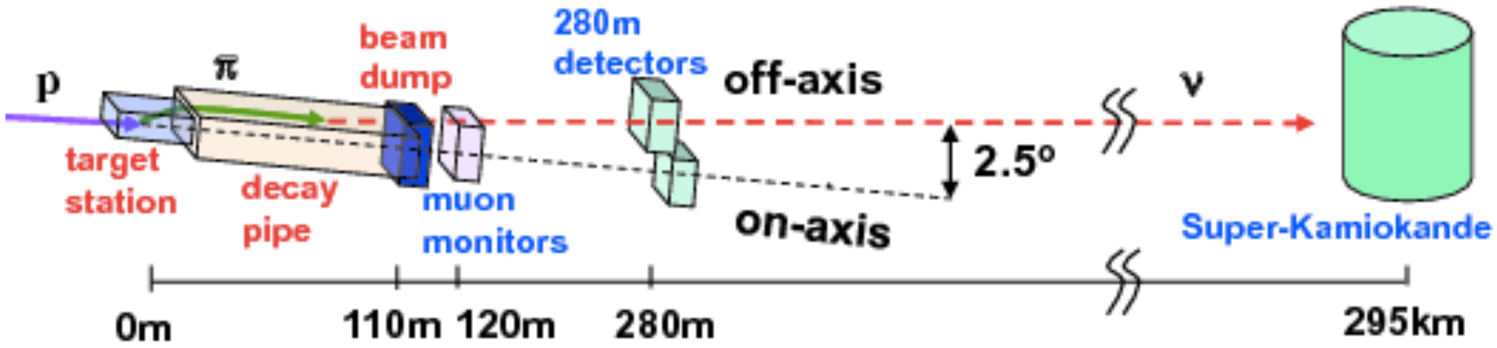
$a \equiv 2\sqrt{2}G_F n_e E$
Matter effect

- For antineutrino oscillations (P($\bar{\nu}_\mu \to \bar{\nu}_e$)) δ turns into – δ and a to - a
- Disappearance channel: measure θ_{23} and $|\Delta m^2_{32/1}|$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^2\underline{\theta_{13}}\sin^2 \underline{2\theta_{23}})\sin^2(\Delta m^2_{32}\frac{L}{4E})$$

T2K design

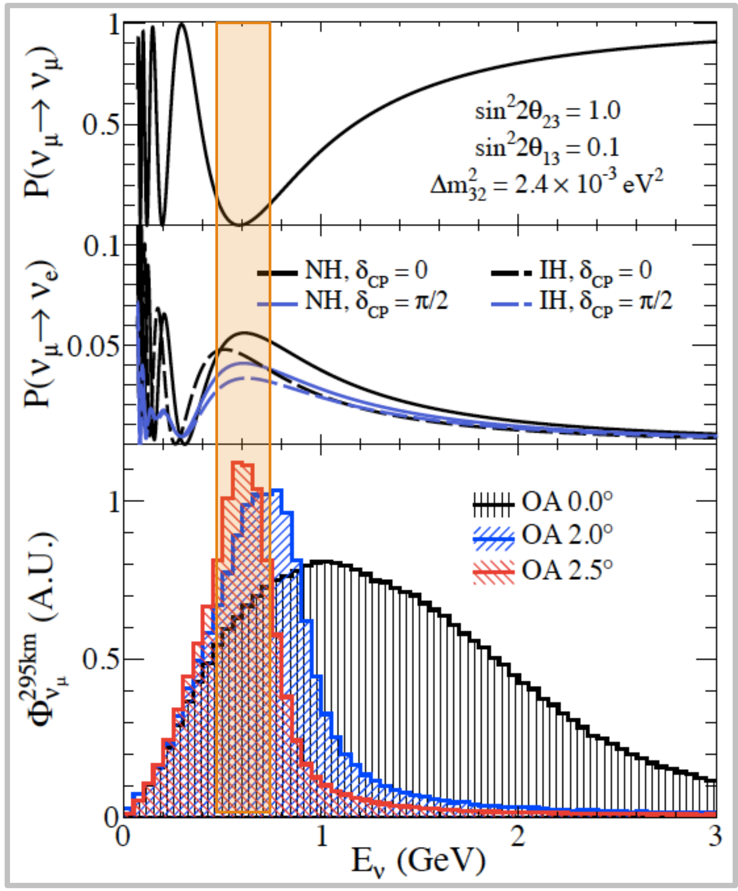
Protons from J-PARC accelerator



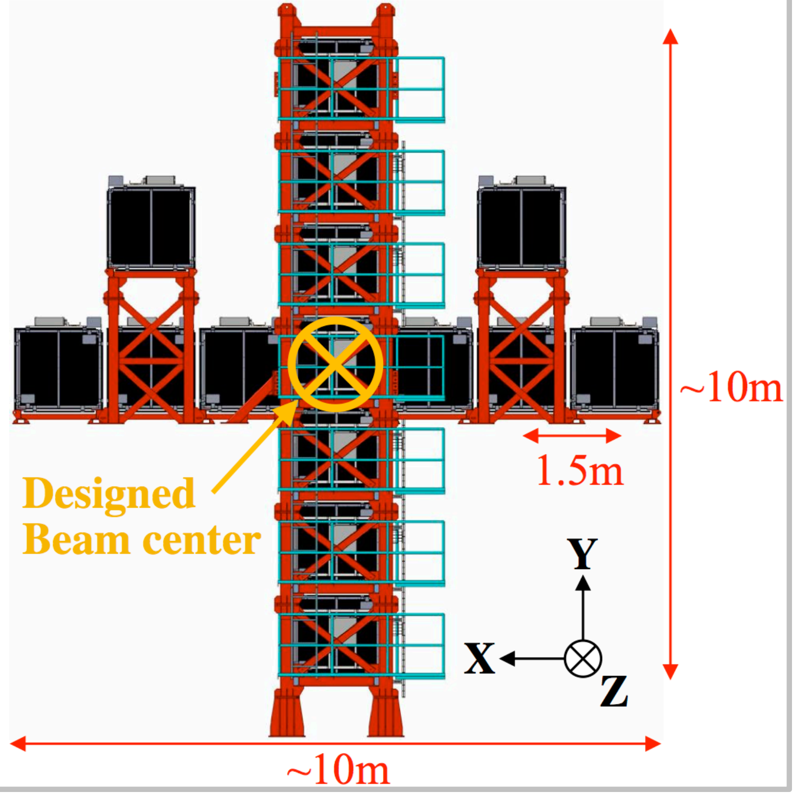
$$N_{ND} \approx \Phi_{ND} \times \sigma_{ND} \times \epsilon_{ND}$$

$$N_{FD} \approx \Phi_{FD} \times \sigma_{FD} \times \epsilon_{FD} \times P_{osc}$$

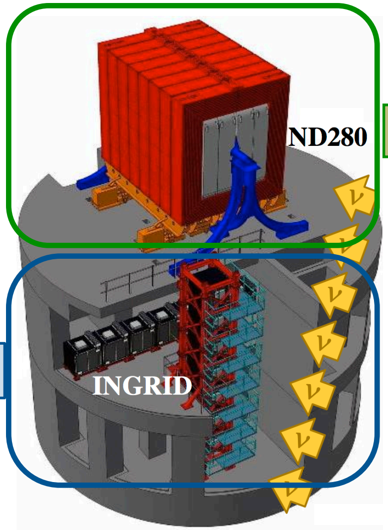
flux | cross section | detector efficiency | oscillation probability

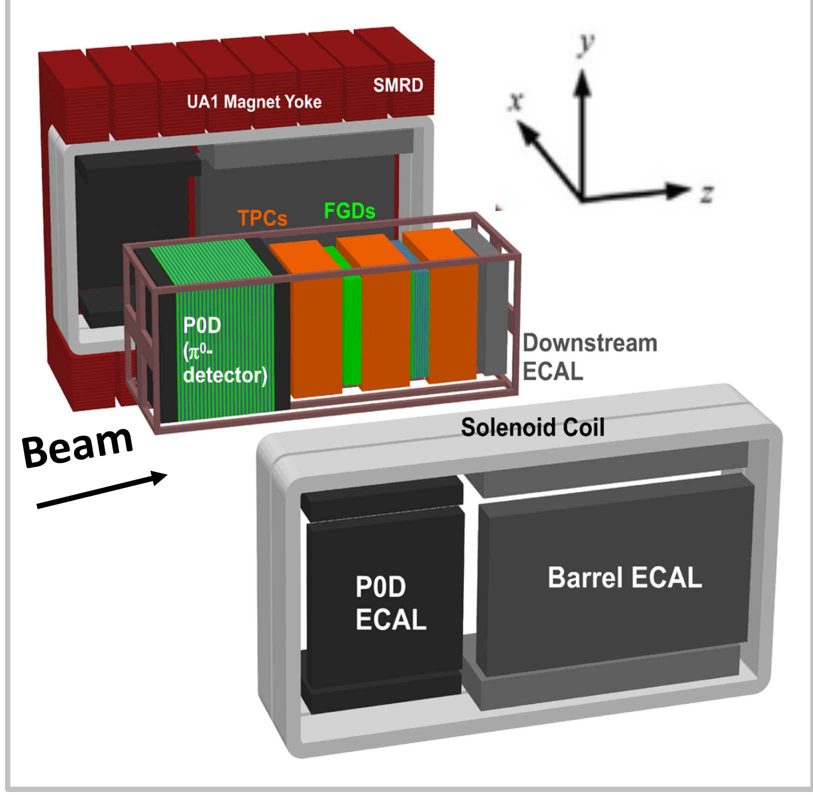


- Off-axis beam
- Far detector and complex of near detectors
- Neutrino energy peak at ~ 0.6 GeV
  (L = 295 km, tuned for 1st osc. maximum)
- High-purity intense neutrino (antineutrino) beam
  - $\nu/\bar{\nu}$ beam production by reversing current in magnetic horns
- Reduced background from intrinsic ν_e and high energy tail



Near detectors





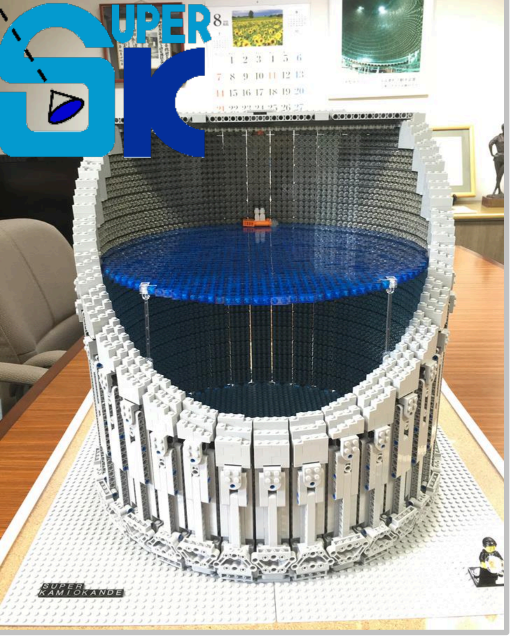
INGRID:

- On-axis detector
- Iron\scintillator modules
- Beam direction and rate stability monitor
- Day-by-day measurements

ND280:

- Off-axis detector
- Sub-detectors in 0.2 T magnetic field:
  - Fine-Grained detectors (FGD)
  - Time-Projection Chambers (TPC)

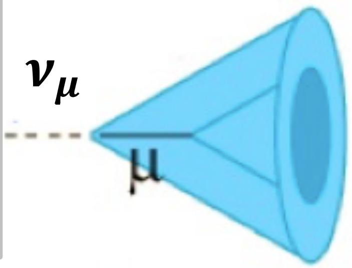
  tracker
- Used to constrain flux and cross-section uncertainty

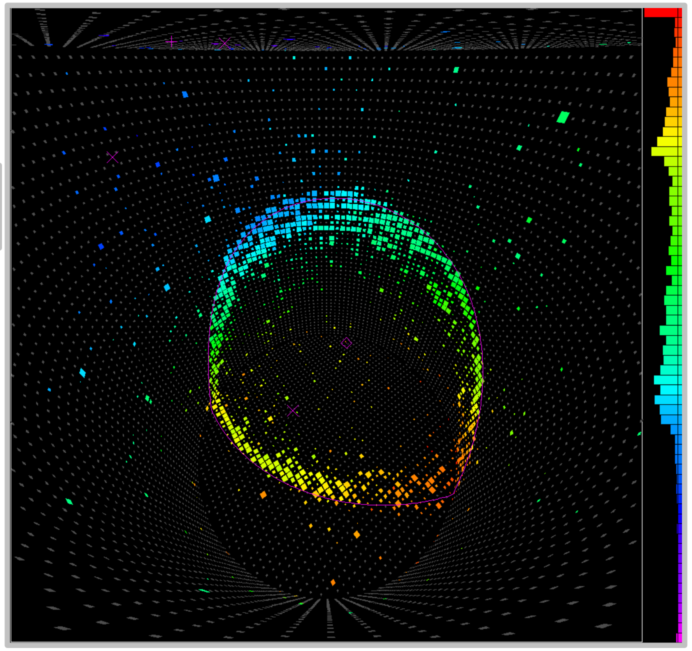


Far detector

- 50 kt water-Cherenkov detector
- 1 km underground
  (~2700 m of water equivalent)
- No magnetic field

μ – like event



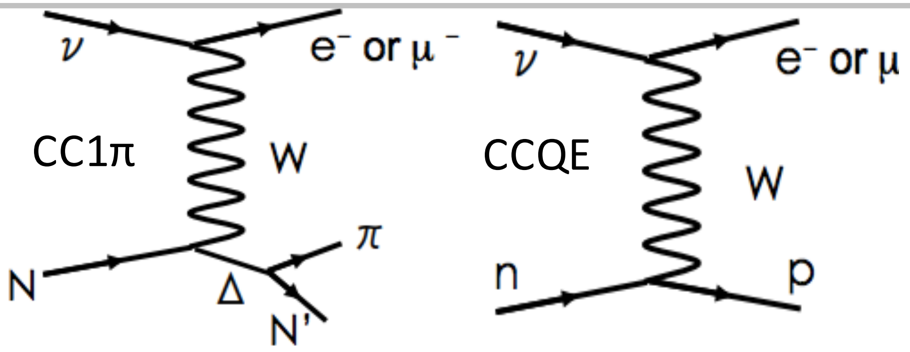


- Analysis samples: **TOTAL: 5 samples!**

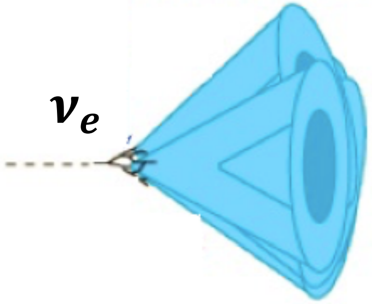
CCQE – μ – like and e – like events for ν and $\bar{\nu}$ mode

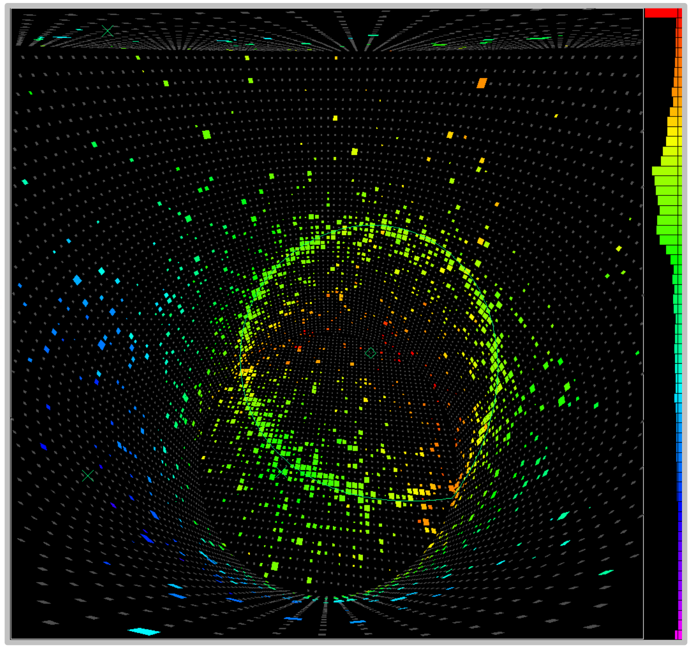
CC1π – 1 e-like ring and 1 delayed decay electron (~ 10% of events)

Good separation between ***e*** and ***μ*** events



e – like event





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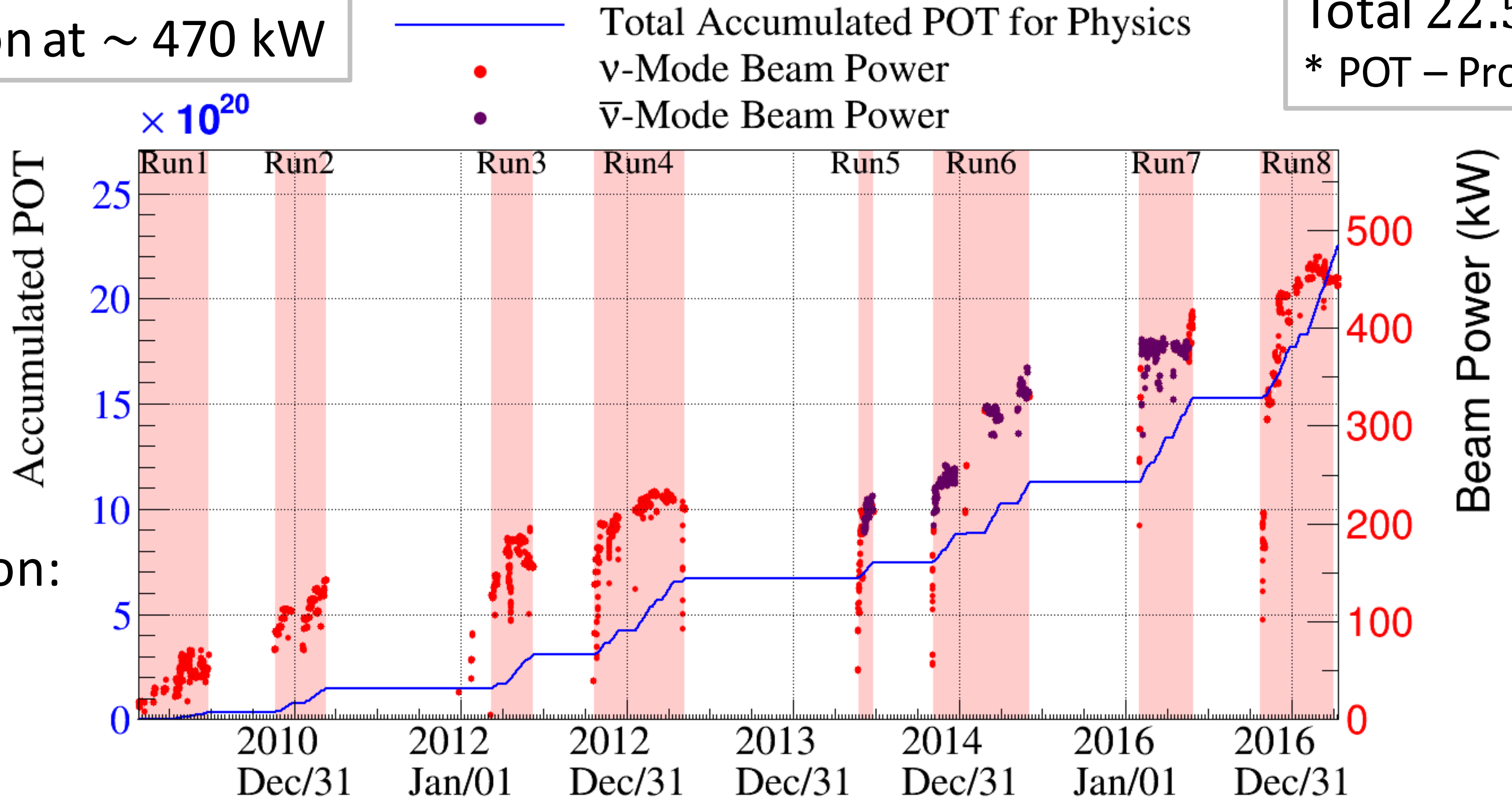
Data taking

Stable operation at ~ 470 kW

Total 22.54×10^{20} POT
* POT – Protons On Target

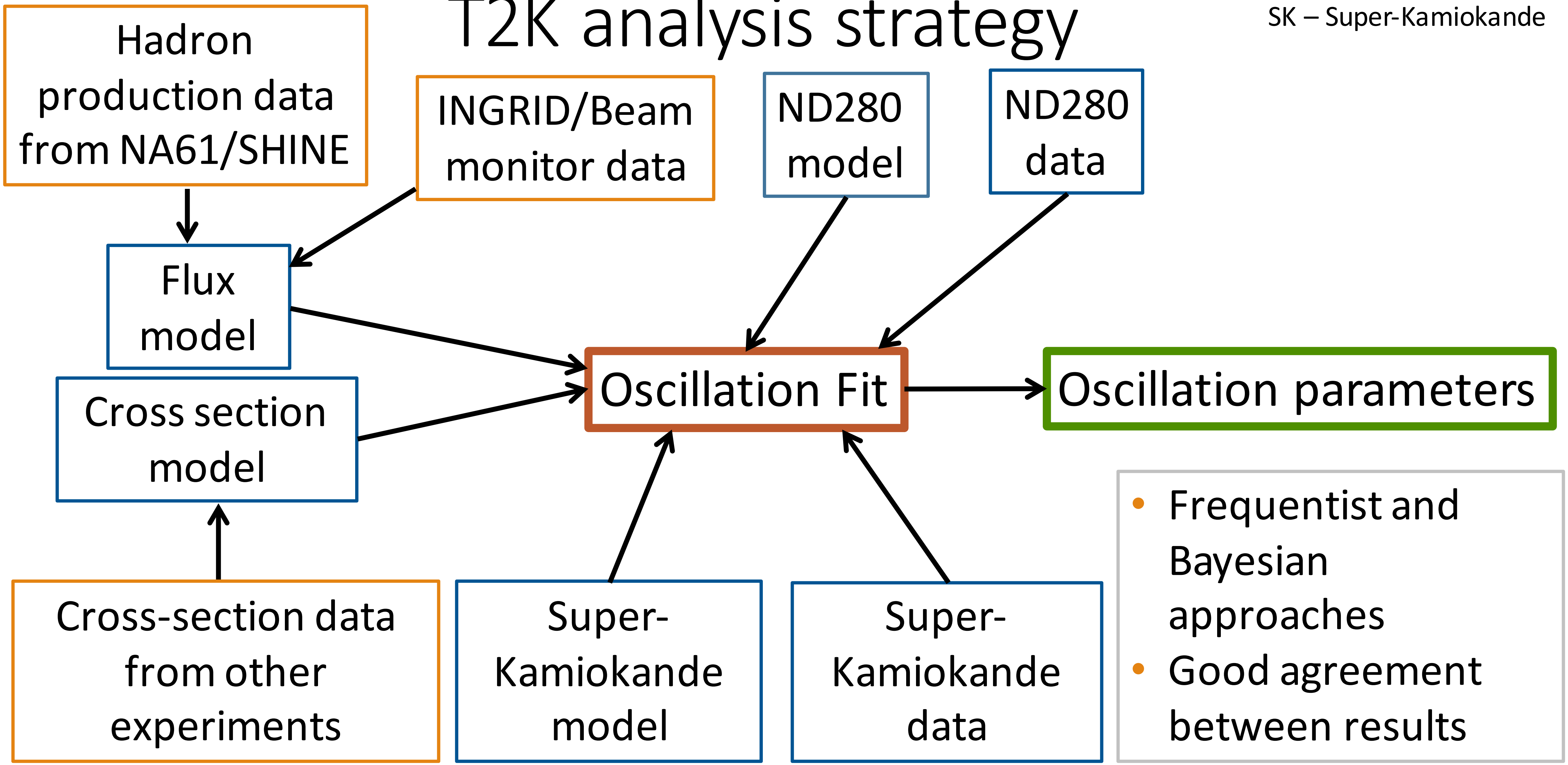


Start of operation: 2010

- 14.93×10^{20} POT in neutrino mode and 7.62×10^{20} POT in antineutrino mode
- Neutrino statistics doubled during 2016-2017 data taking period

T2K analysis strategy

SK – Super-Kamiokande



- Frequentist and Bayesian approaches
- Good agreement between results

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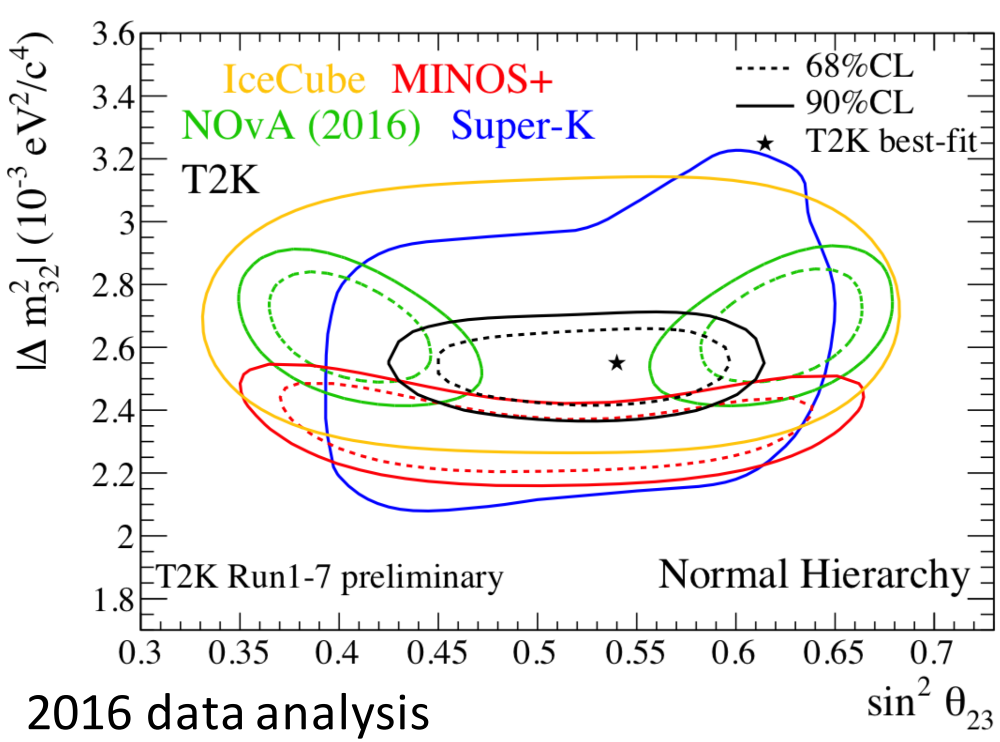
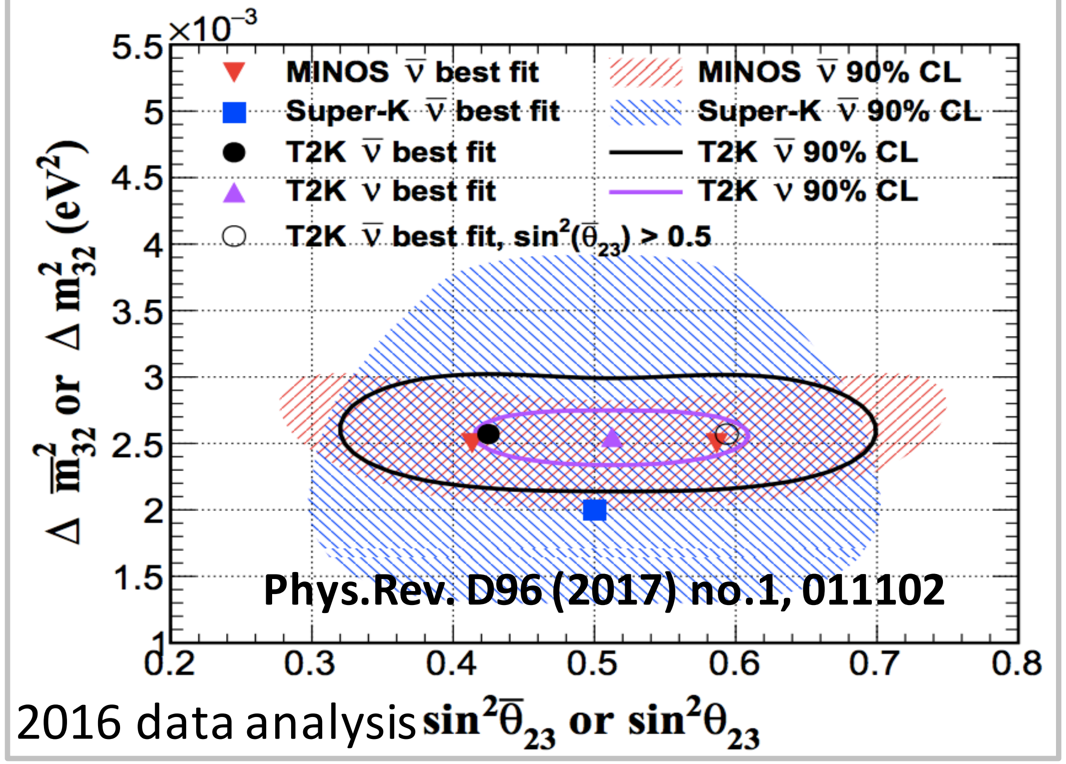
Analysis results: $|\Delta m^2_{32}|$ and θ_{23}



2016 data analysis

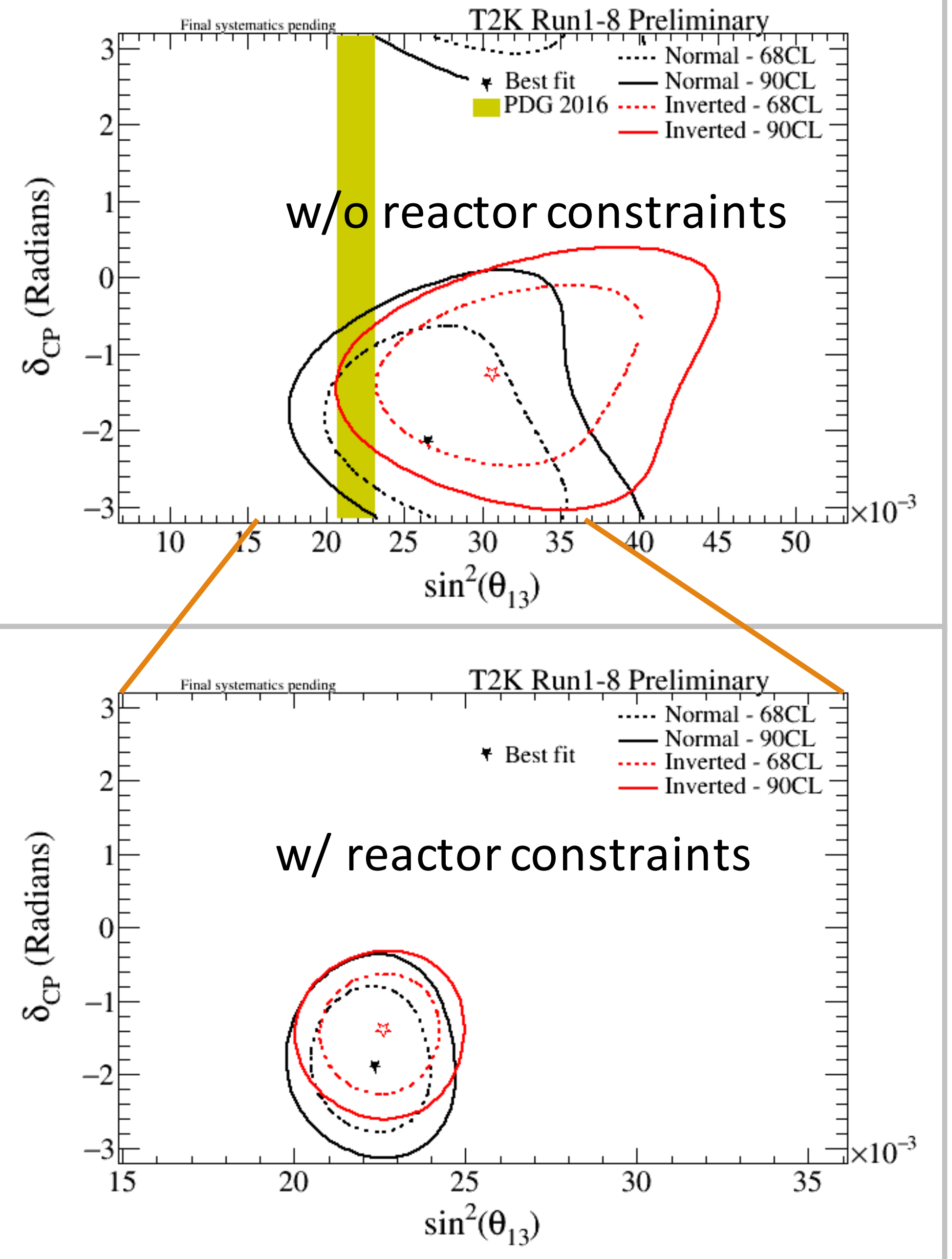


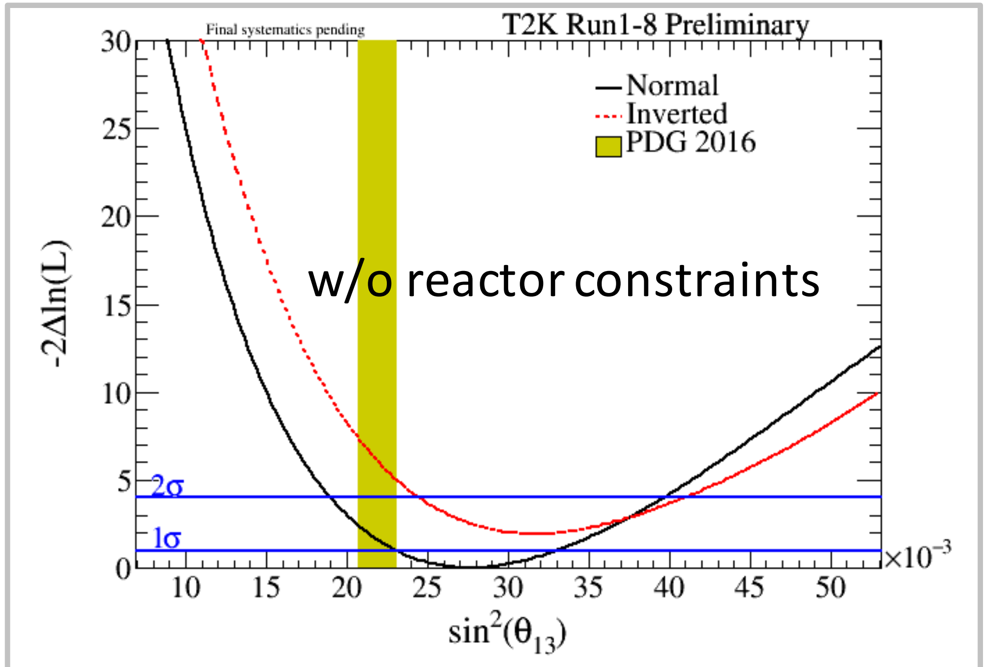
2016 data analysis

- 2016 analysis:
  - results comparable with other experiments
  - consistent results in neutrino and antineutrino modes → CPT conservation
- 2017 analysis:
  - pending final systematics

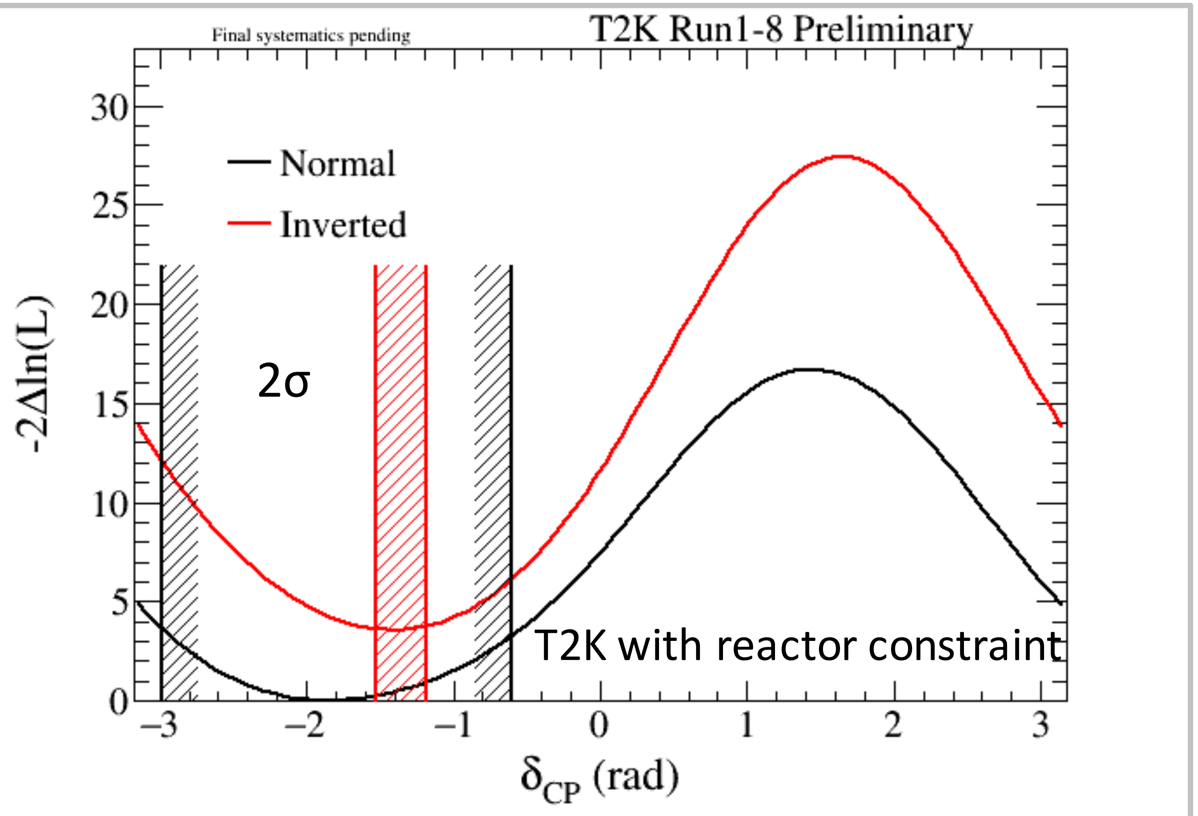
Analysis results: θ_{13}

- T2K results consistent with reactor experiments' data
  - PDG'16: $\sin^2\theta_{13} \approx 0.0210 \pm 0.0011$
- T2K data favor normal mass hierarchy
- Result may be used to put constrain on δ_{cp}





Analysis results: CP violation



- Joint analysis with reactor constrain applied
  - ***Best fit: δ_{cp}* = -1.833**
  - **Normal mass hierarchy preferred**
- CP conservation excluded at the 2σ level
- δ_{cp} (at 2σ) :
  - [-2.981; -0.600] normal mass hierarchy
  - [-1.531; -1.184] inverted mass hierarchy

Reactor constraint $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

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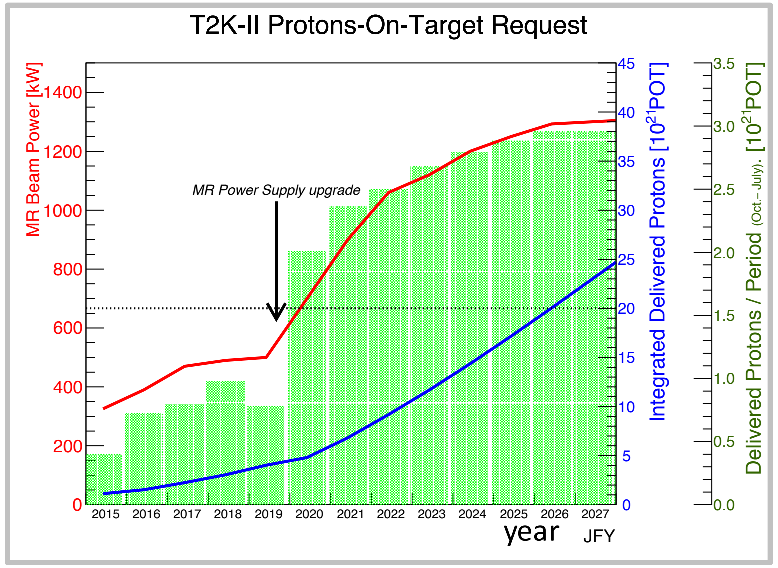
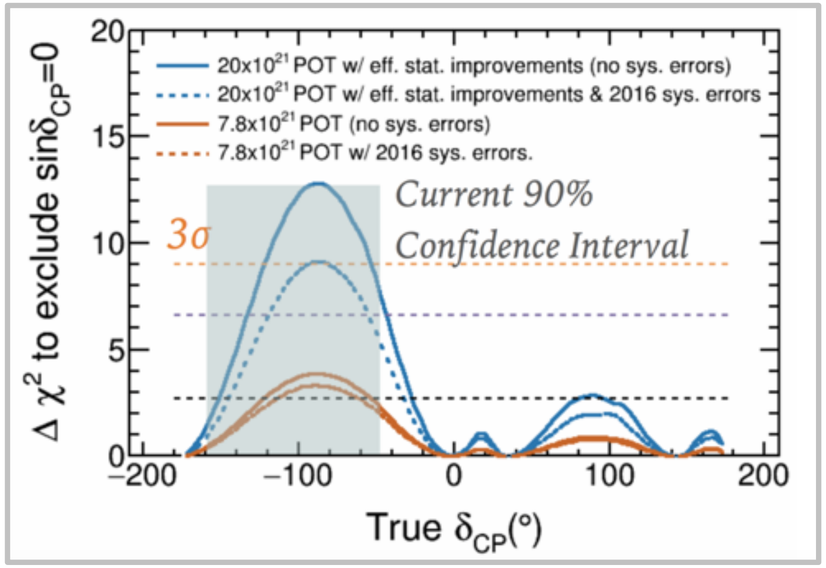
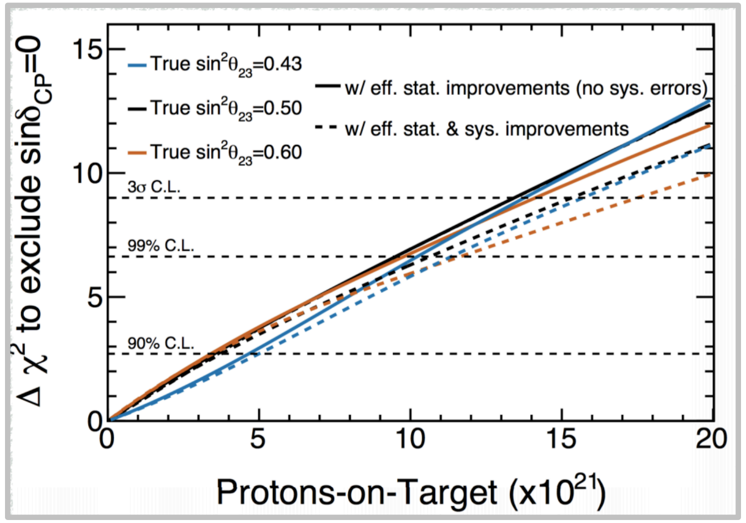


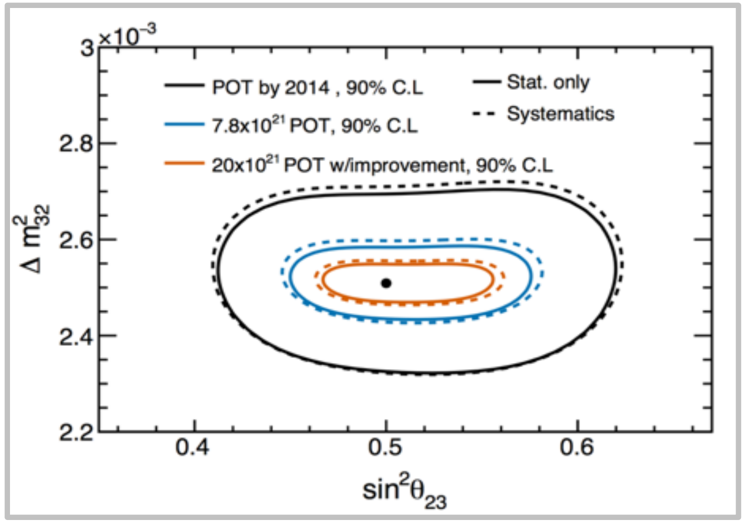
T2K II Proposal: 20×10^{21} POT



Future plans

- Increase $\nu_\mu/\bar{\nu}_\mu$ statistics
  - 7.8×10^{21} POT by ~ 2021
  - T2K II proposal to operate until 2026
- Possibly exclude CP conservation at 3σ level
- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 9% (2014) → 6% (2016) → 4%(2020..)?
- Near detector upgrade
- Improve precision for atmospheric parameters





Summary

- By summer 2017 accumulated $22.54{\times}10^{20}$ POT
- θ_{13} and θ_{23} measurements are consistent with other experiments' data
- Excluded CP conservation @2σ level
  - Data favor normal mass hierarchy and the best fit is close to δ_{cp} = -π/2

Plans:

- Continue data taking
- T2K II proposal: run until 2026
  - Beam line upgrade to reach power ~ 1MW
  - Near detector upgrade to further improve understanding of neutrino interactions

Backup

T2K Collaboration

～500 members, 63 institutes, 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
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. Edu.
Okayama U.
Osaka City U.
Tokyo Institute of 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
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

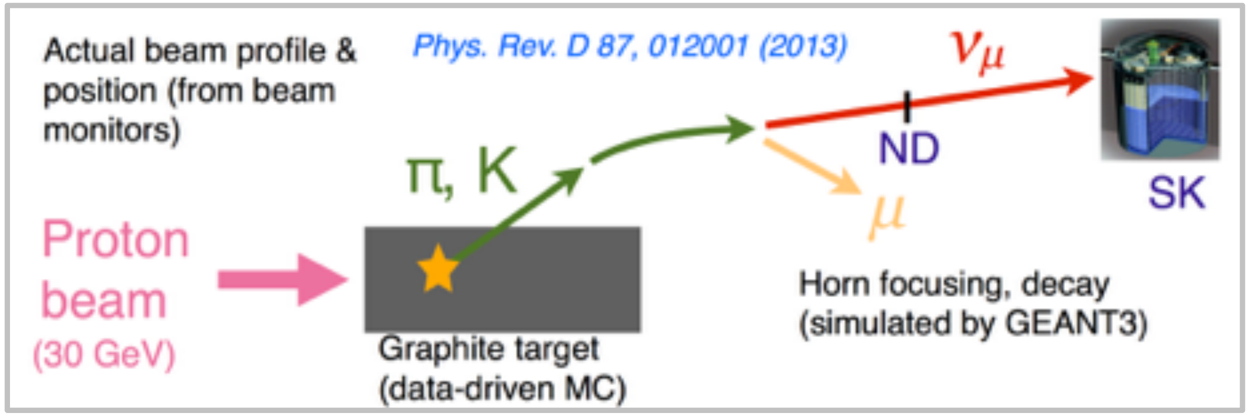
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

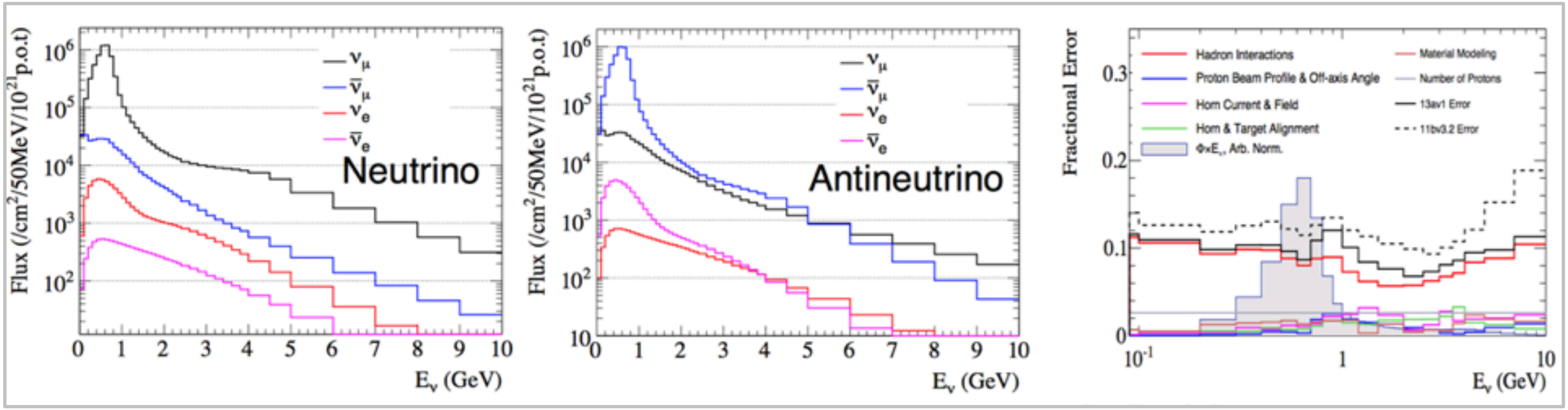
Recent publications

- First measurement of the ν_μ charged-current cross section without pions in the final state on a water target (arXiv:1708.06771)
- Measurement of neutrino and antineutrino oscillations by the T2K experiment including a new additional sample of ν_e interactions at the far detector (arXiv:1707.0148)
- Measurement of $\bar{\nu}_\mu$ and ν_μ charged current inclusive cross sections and their ratio with the T2K off-axis near detector (Phys.Rev. D96 (2017) no.5, 052001)
- Measurement of the single π^0 production rate in neutral current neutrino interactions on water (arXiv:1704.07467)
- Updated T2K measurements of muon neutrino and antineutrino disappearance using 1.5×10^{21} protons on target (Phys.Rev. D96 (2017) no.1, 011102)
- Search for Lorentz and CPT violation using sidereal time dependence of neutrino flavor transitions over a short baseline (Phys.Rev. D95 (2017) no.11, 111101)
- Combined Analysis of Neutrino and Antineutrino Oscillations at T2K (Phys.Rev.Lett. 118 (2017) no.15, 151801)

T2K Neutrino flux prediction

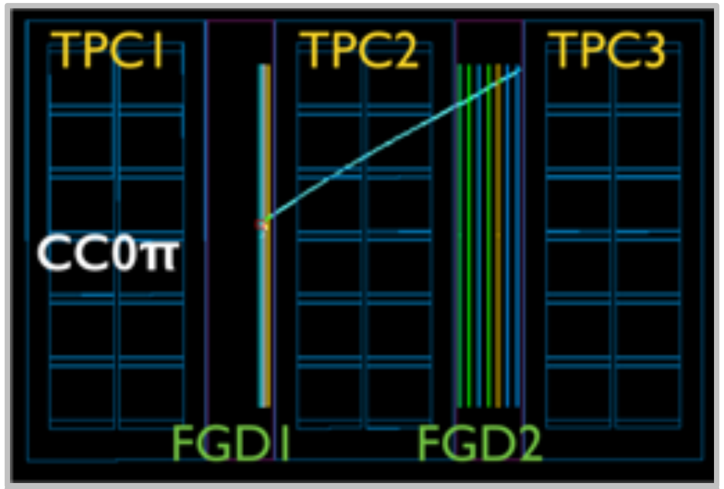
- Simulation: FLUKA, GCALOR and GEANT3
- External data: hadron production from NA61/SHINE (CERN)
  - Reduction of uncertainties: ~30% to ~10%
- Background from ν_e fraction at ~0.5% level

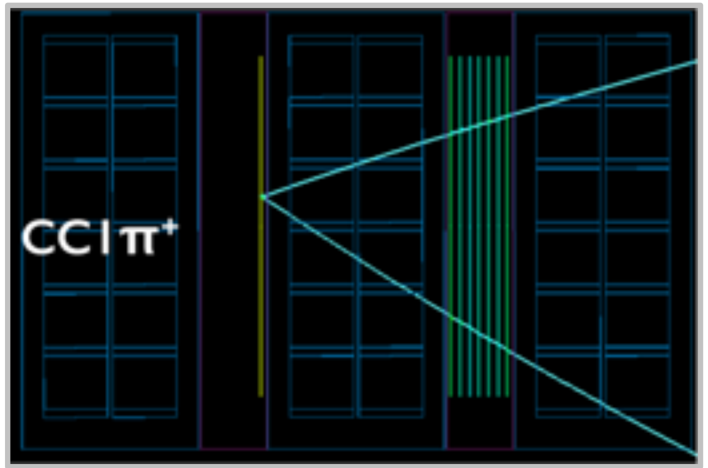


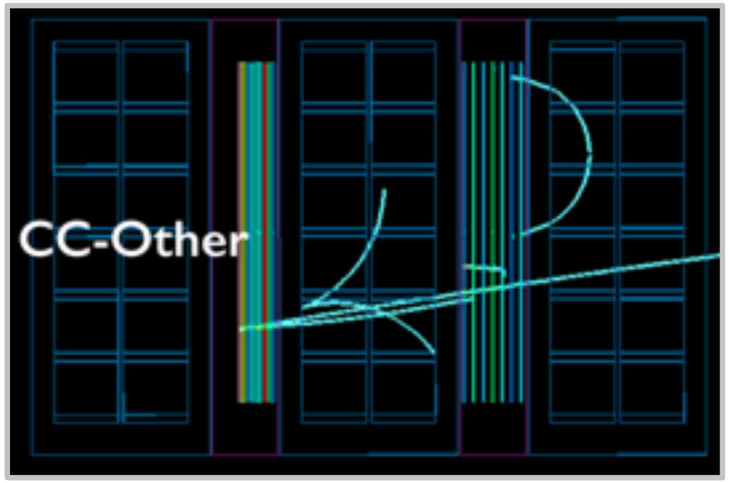


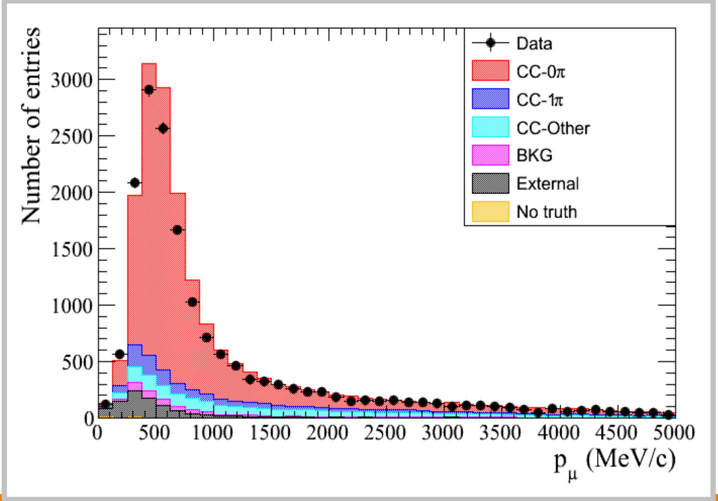
ND280 analysis samples: ν_μ-mode

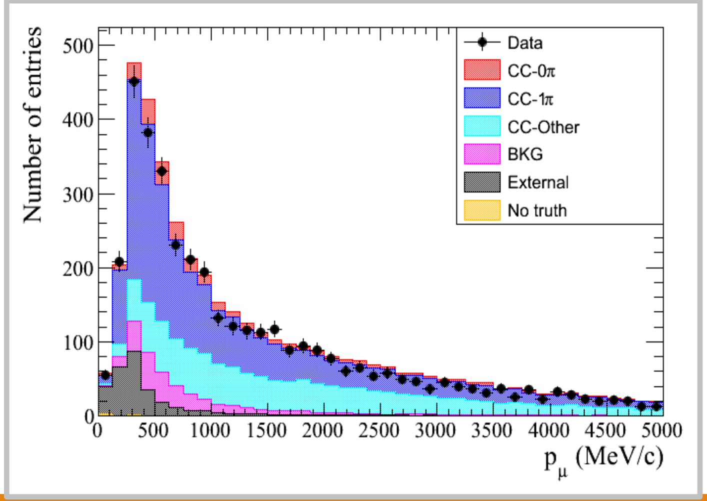
- CC0π – muon 0 pions in final state
- CC1π – 1 pion and muon in final state
- CC-Other – all other CC interactions

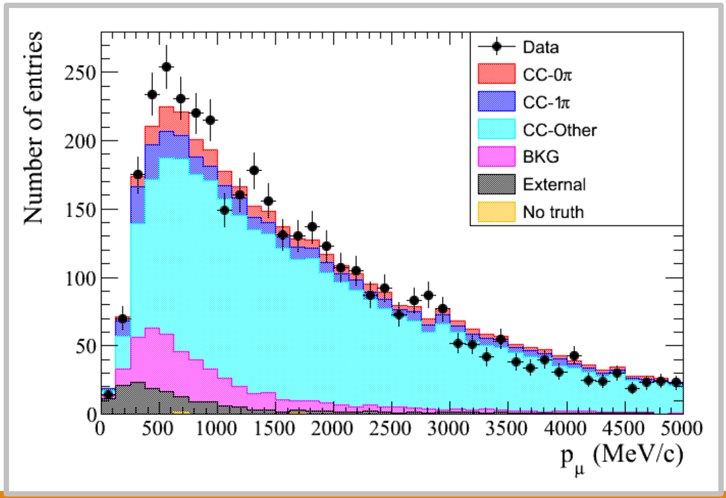






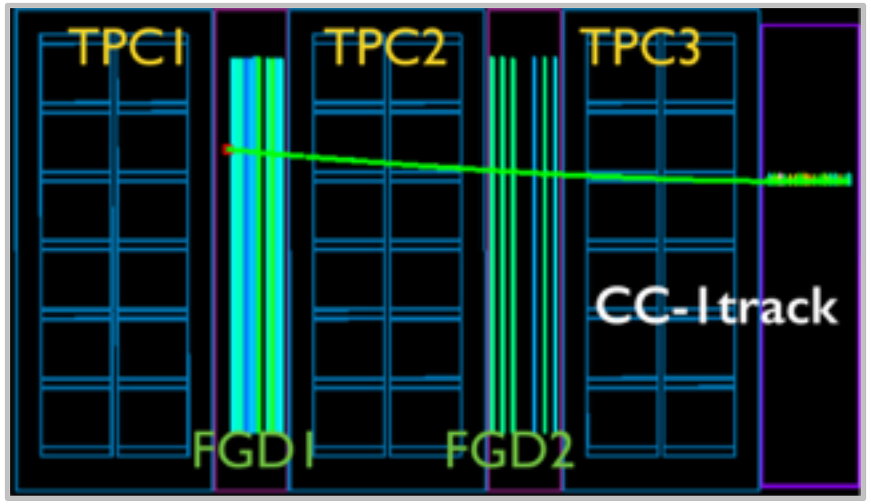


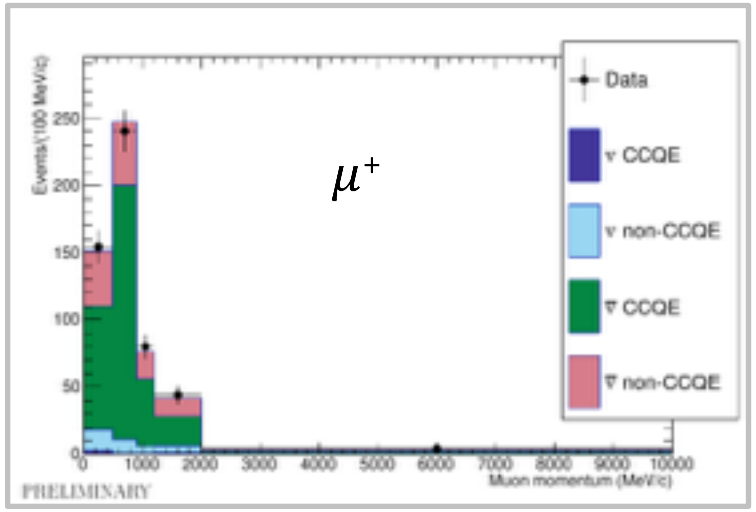


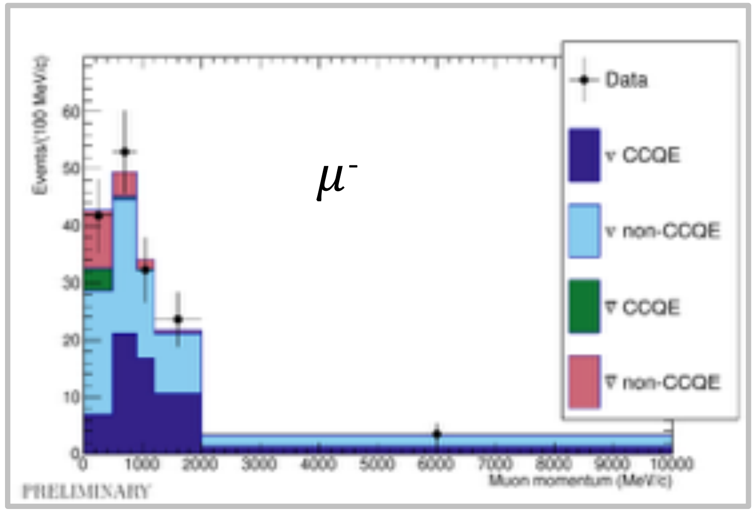


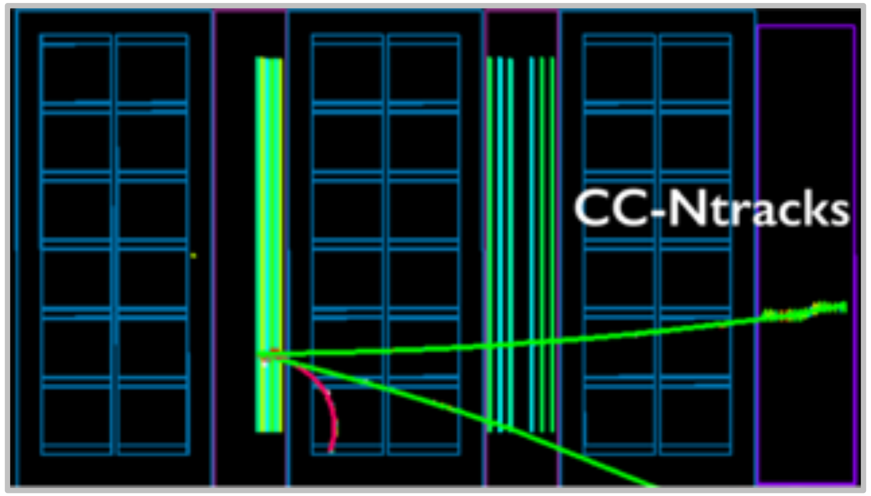
ND280 analysis samples: $\bar{\nu}_\mu$-mode

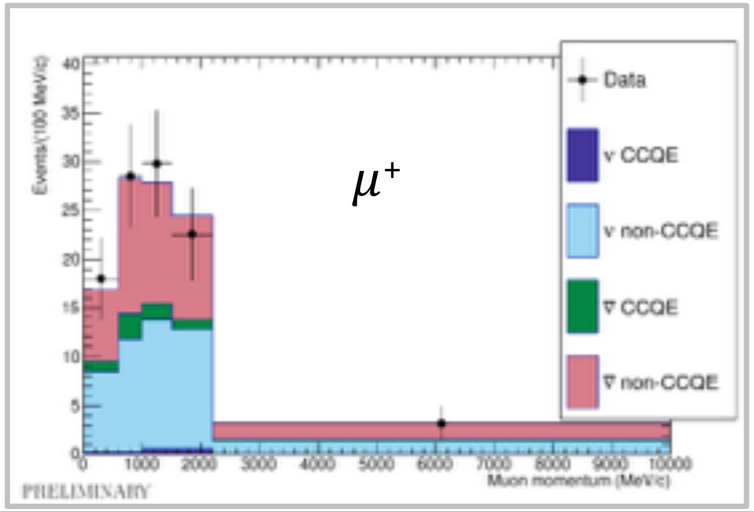
- CC-1-track and CC-N-tracks samples

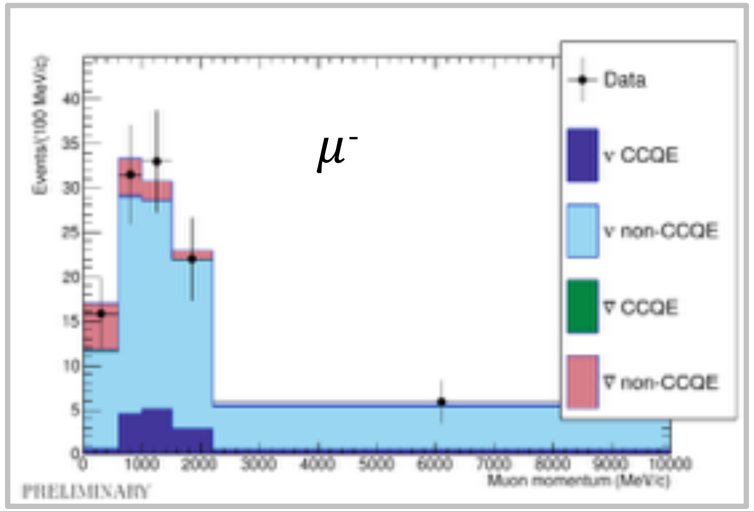






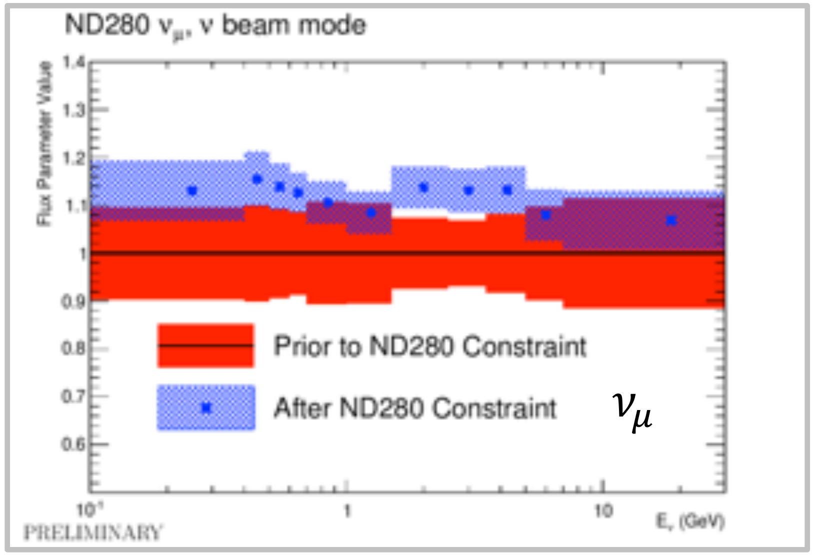


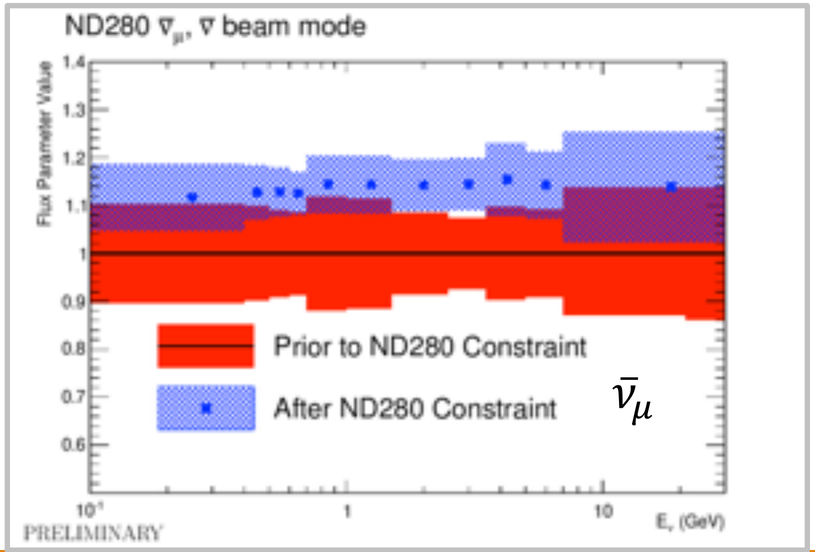




ND280 in oscillation analysis

T2K Preliminary
(2017 analysis)





Total N_{SK} Fraction Uncertainty, %		ν_μ	ν_e	anti-ν_μ	anti-ν_e
Flux	W/O ND280	7.6	8.9	7.1	8.0
Cross section	W/O ND280	7.7	7.2	9.3	10.1
Flux and cross section	W/ ND280	2.9	4.2	3.4	4.6
Final/sec. hadronic interactions	-	1.5	2.5	2.1	2.5
Far detector	-	3.9	2.4	3.3	3.1
Total	W/O ND280	12.0	11.9	12.5	13.7
Total	W/ ND280	5.0	5.4	5.2	6.2

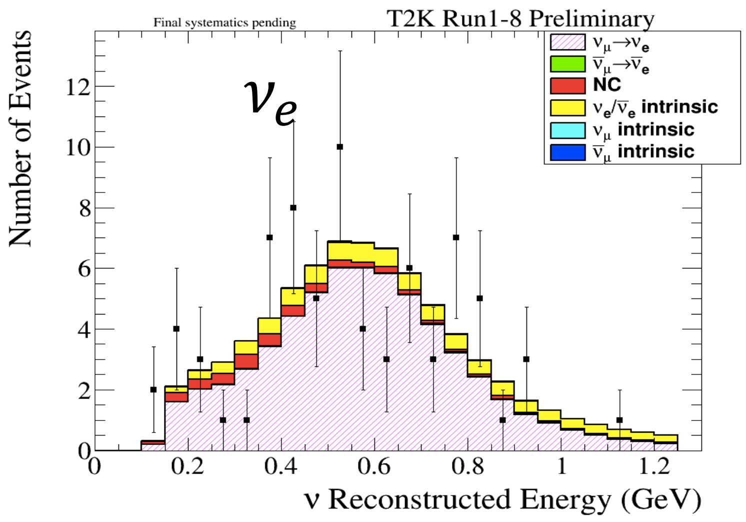
- Fit to ND280 data constrains flux and cross section model
- Significant reduction of systematic uncertainties for oscillation analysis
  - ≈12%→≈6%

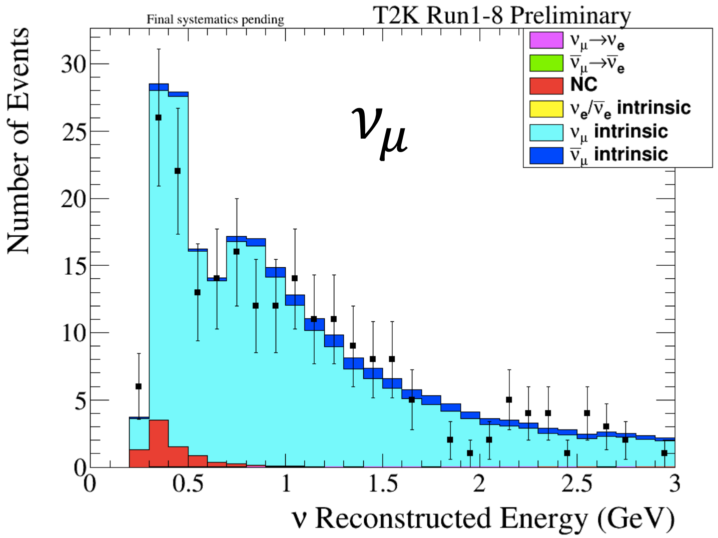
Total systematics uncertainties

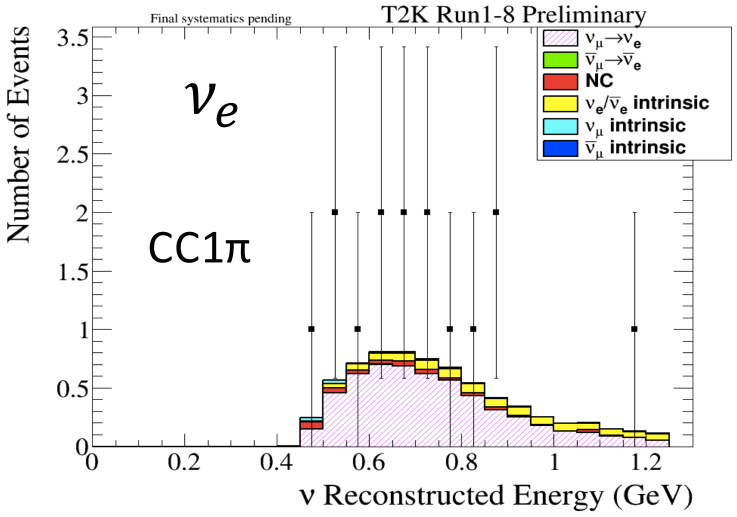
Systematic uncertainties (%) used in 2017 analysis

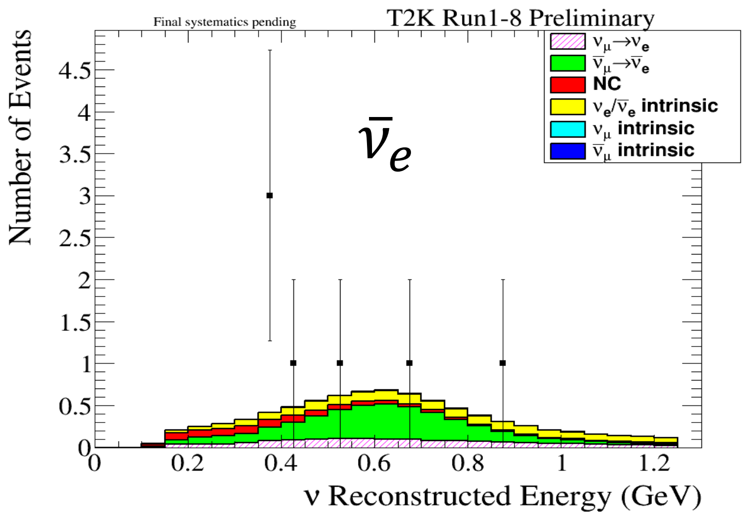
	1Rmu		1Re			
Error Source	FHC	RHC	FHC	RHC	FHC 1 d. e.	FHC/RHC
SK Detector	1.9	1.6	3.0	4.2	16.5	1.6
SK FSI+SI+PN	2.2	2.0	2.9	2.5	11.3	1.6
SK Detector+FSI+SI+PN	2.9	2.5	4.2	4.8	19.2	2.1
ND280 const. flux & xsec	3.3	2.7	3.2	2.9	4.1	2.5
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	0.0	2.6	1.5	2.6	3.1
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.1	0.3	1.0	0.2
Syst. Total	4.4	3.8	6.3	6.4	19.6	4.7

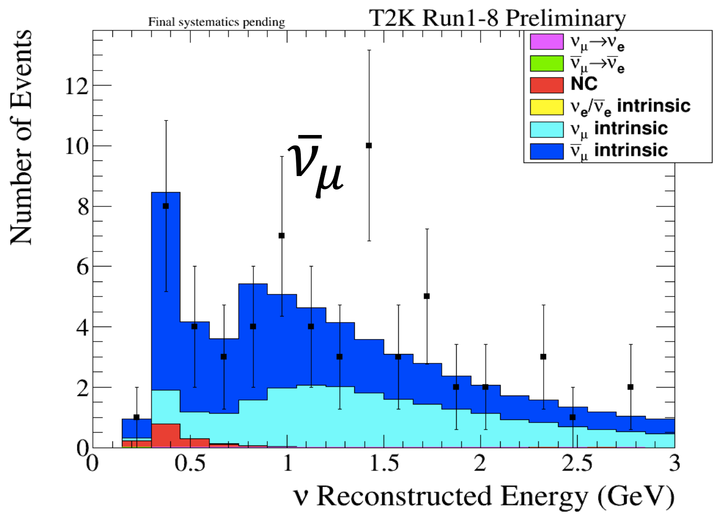
SK analysis samples





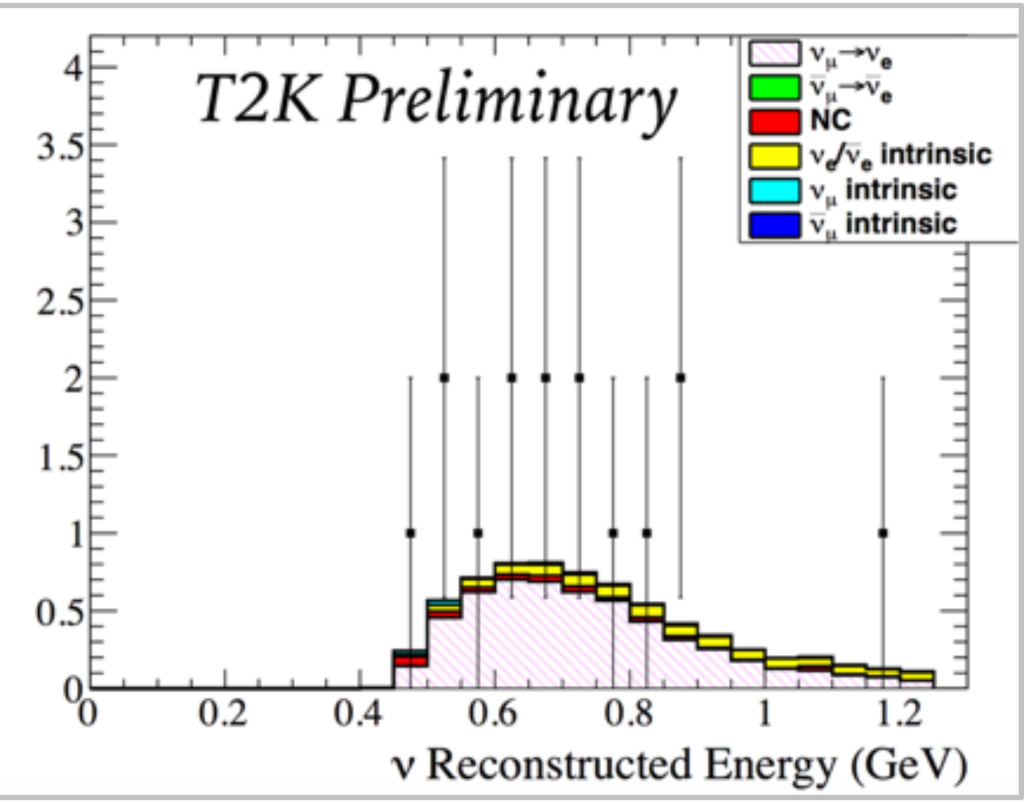


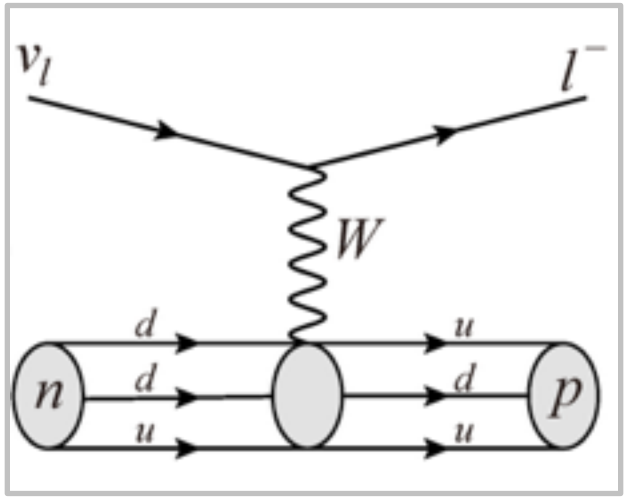


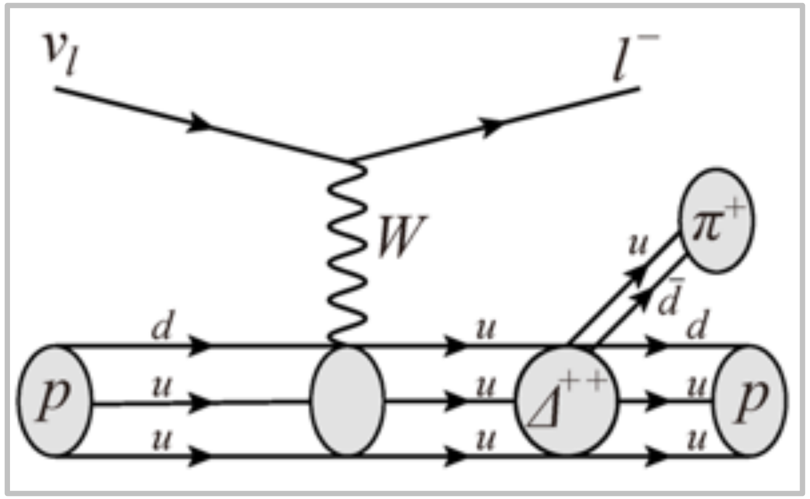


New analysis sample in SK: CC1π

- 1 e-like ring and 1 decay electron
- Applied only for ν-mode running
  - Gain ~10% more statistics (MC)
  - 15 events observed
- Five samples available for T2K analysis







Event rates

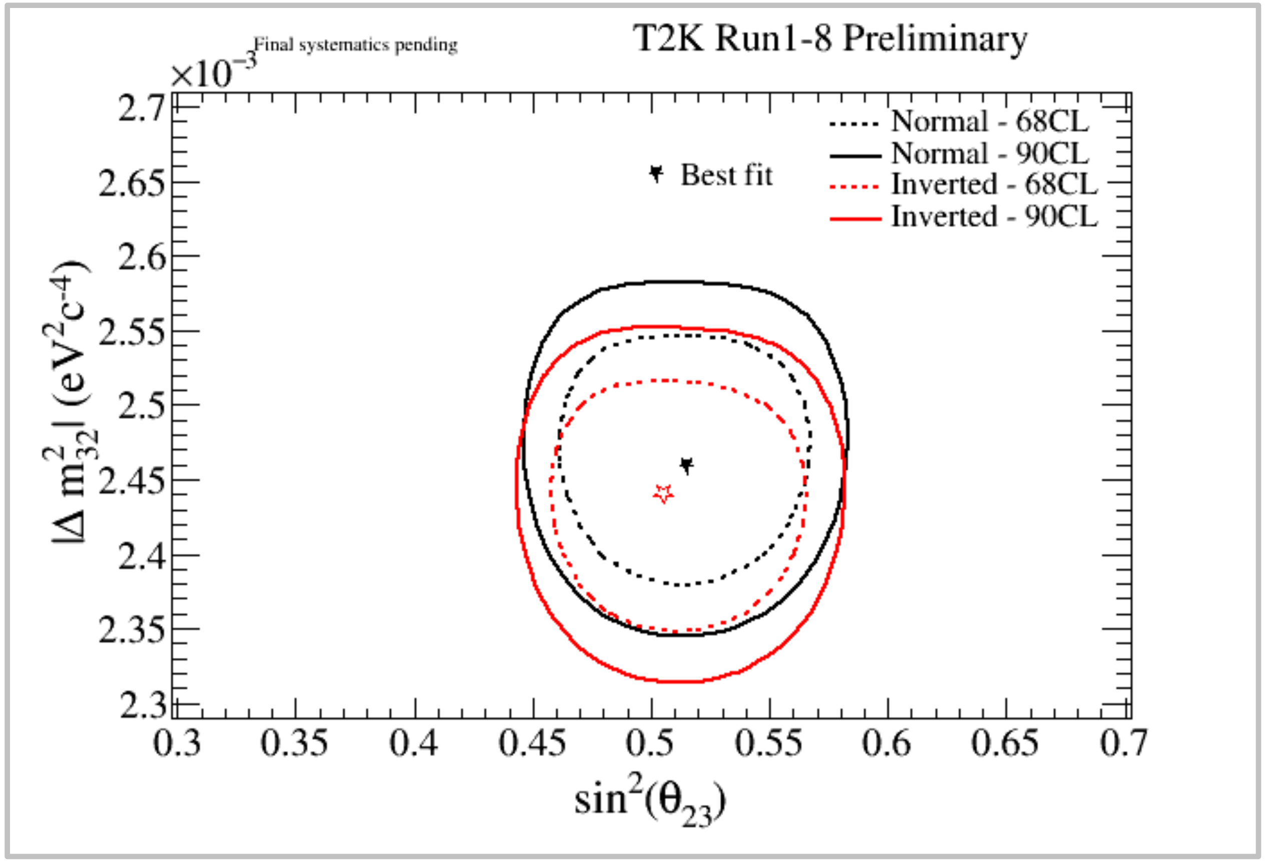
	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	$\boxed{6.92}$	6.01	4.87	5.78	$\boxed{15}$
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8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

- Largely in line with the prediction for $\delta_{CP} = -\pi/2$
- More observed e-like CC1π events **15** than maximum expectation **6.92**

Robustness of T2K analysis results

- Neutrino interaction modelling is a rapidly developing media
  - Study potential bias in the T2K oscillation analysis due to the choice of neutrino interaction model and investigate variations that are not yet implemented in the fit model
  - Produce fake data studies by varying parts of the interaction model
  - Fit using the model without the variations
  - Evaluate biases in the fitted oscillation parameters
- Use different data sets:
  - Discrepancies between models and data that may indicate deficiencies in models
  - Planned improvements to models not yet available in oscillation fitting framework

Analysis results: $|\Delta m_{32}^2|$ and θ_{23}



Posterior Bayesian probability

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
Normal mass hierarchy	0.193	0.674	0.868
Inverse mass hierarchy	0.026	0.106	0.132
Sum	0.219	0.781	1

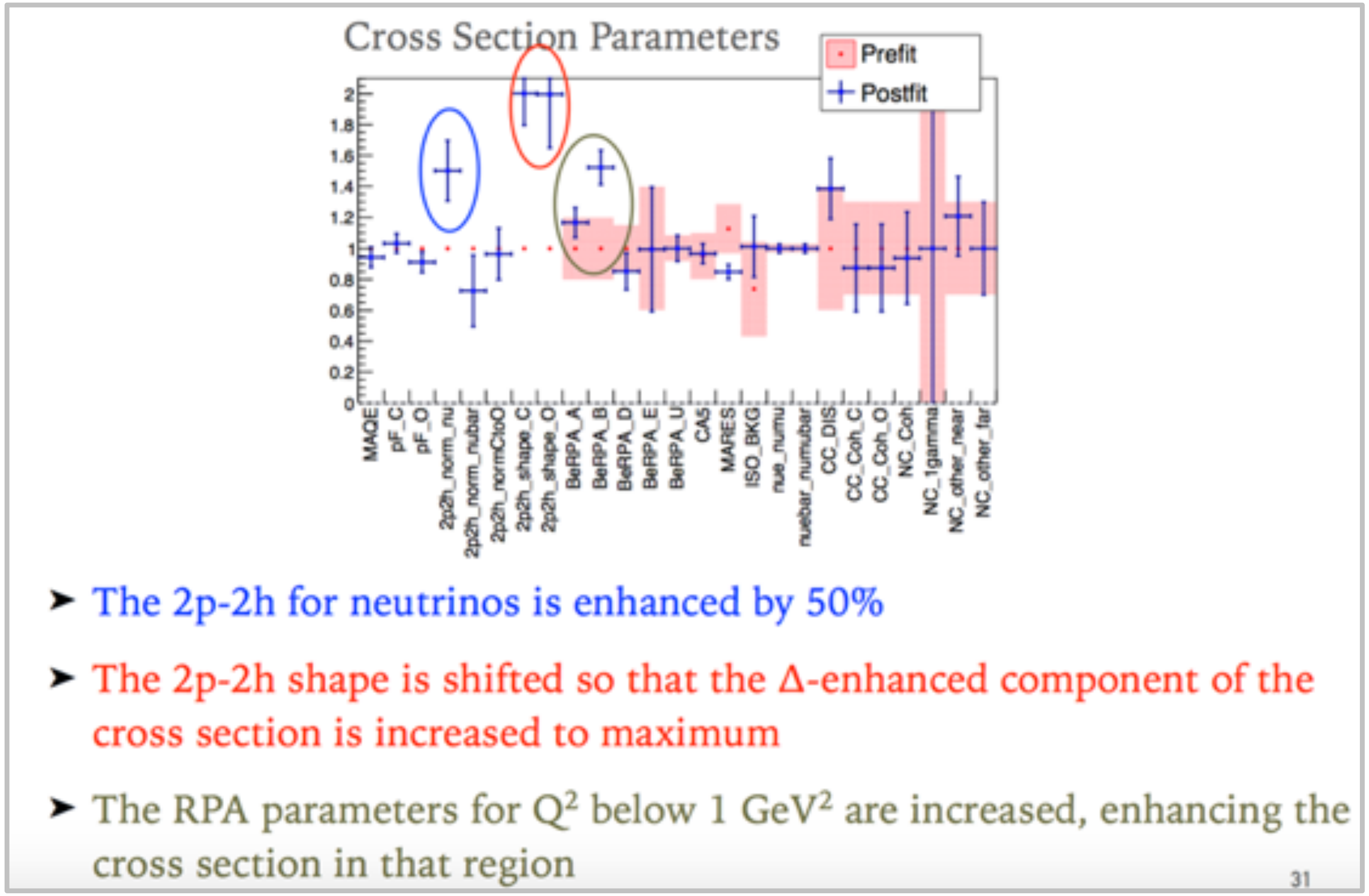
*Pending final systematics

- Best fit for normal mass hierarchy:
  - $|\Delta m_{32}^2| \approx 2.462^{+0.081}_{-0.084} \times 10^{-3}\ eV^2/c^4$
  - $\sin^2\theta_{23} = 0.532^{+0.046}_{-0.068}$
- Best fit for inverted mass hierarchy:
  - $|\Delta m_{32}^2| \approx 2.51^{+0.081}_{-0.083} \times 10^{-3}\ eV^2/c^4$
  - $\sin^2\theta_{23} = 0.534^{+0.043}_{-0.07}$

Fake data studies in T2K

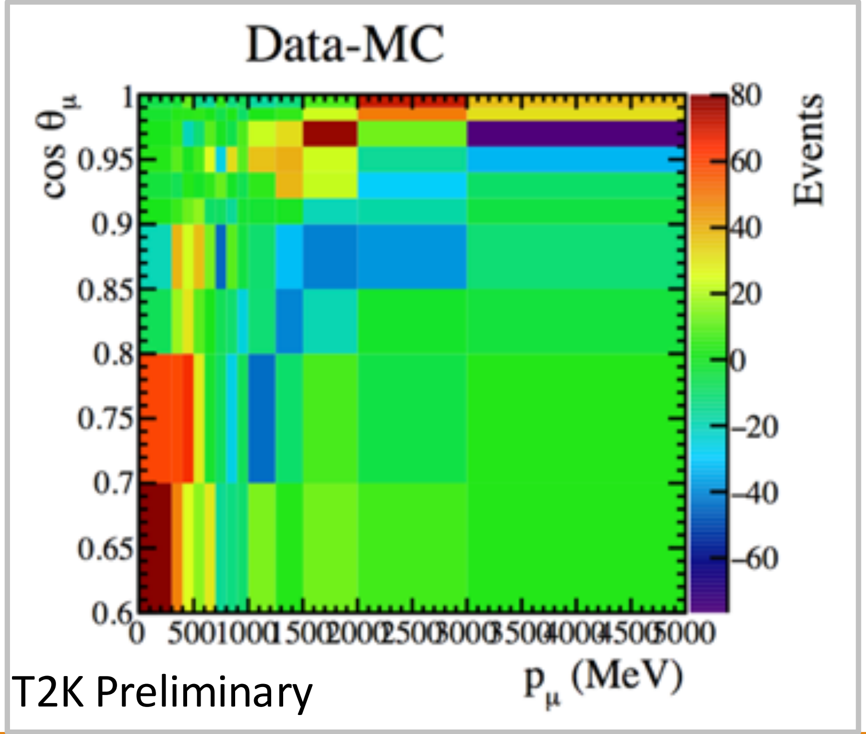
- Use different data sets:
- Data-driven variation generated based on the pre-fit data/prediction discrepancy in ND280 (and external data, e.g. Minerva)
- Variations produced with different assumptions of the axial form factor
- Variations that cover discrepancies in pion spectrum observed in ND280
- Variations to probe new pion production model

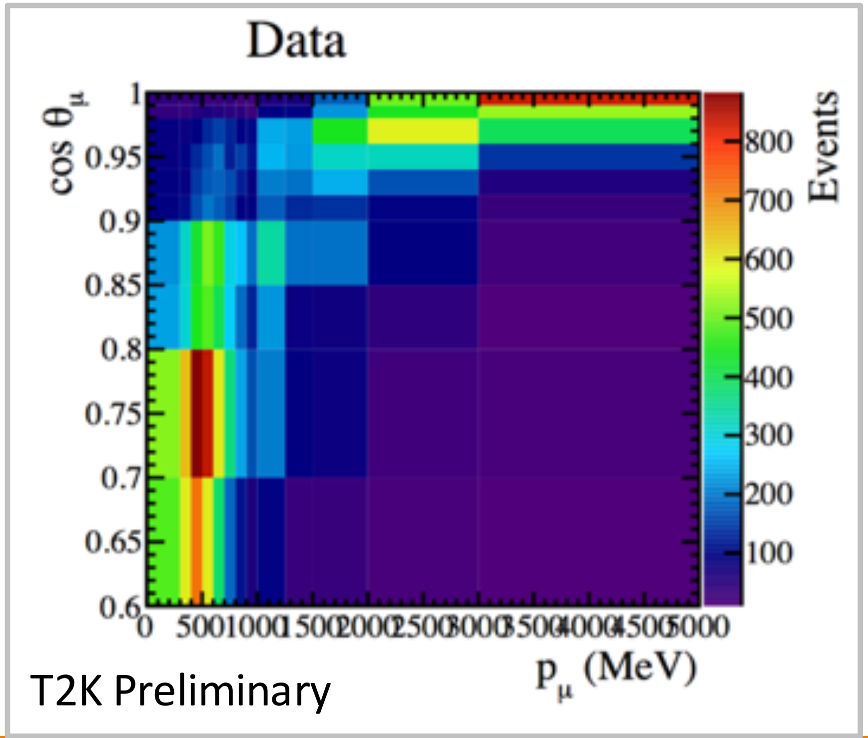
ND280 fit result



Example of ND280 data-driven fake data studies

- Use excess of data over prediction prior to ND280 fitting
- Assign observed access to three different interactions
  - CCQE enhanced
  - 2p2h with intermediate Δ resonate (2p2h-Δ)
  - Pure nucleon-nucleon correlations (2p2h-nonΔ)
- Use excess to predict event rates in ND280 and Super-Kamiokande





Example of ND280 data-driven fake data studies

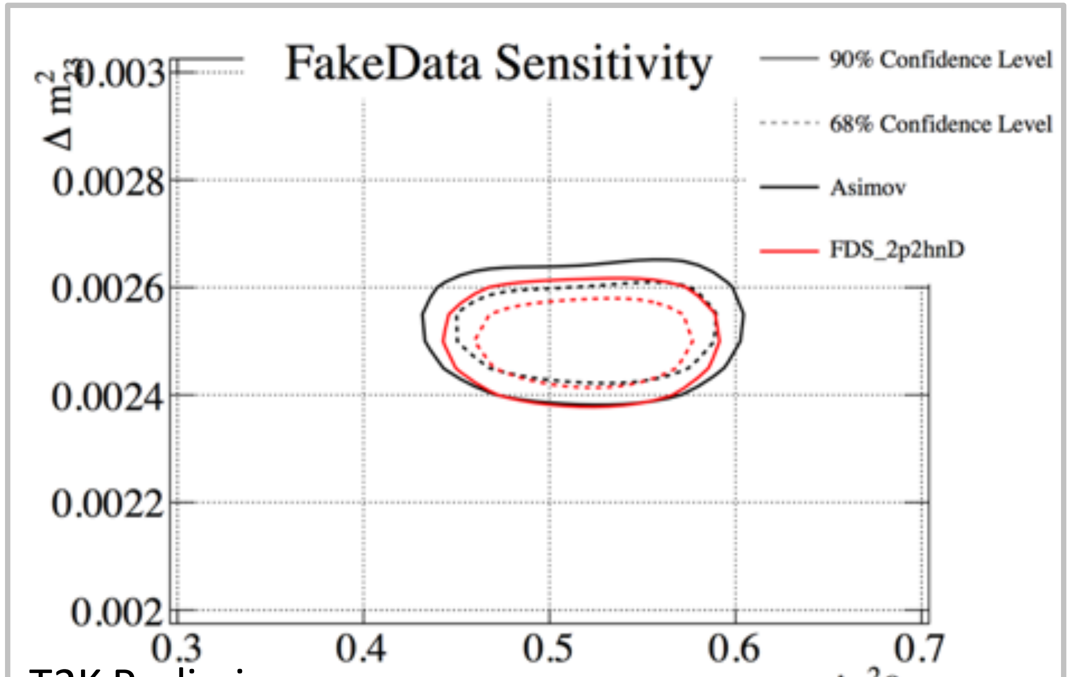
- Example studies for the fake-data studies produced for Asimov data sample

Parameter(s)	Asimov A
$\sin^2\theta_{23}$	0.528
$\sin^2\theta_{13}$ reactors	0.0219
$\sin^2\theta_{12}$	0.304
$\|\Delta m^2_{32}\|$ (NH) / $\|\Delta m^2_{31}\|$ (IH)	2.509×10^{-3} eV^2/c^4
Δm^2_{21}	7.53×10^{-5} eV^2/c^4
δ_{CP}	-1.601
Mass Hierarchy	Normal

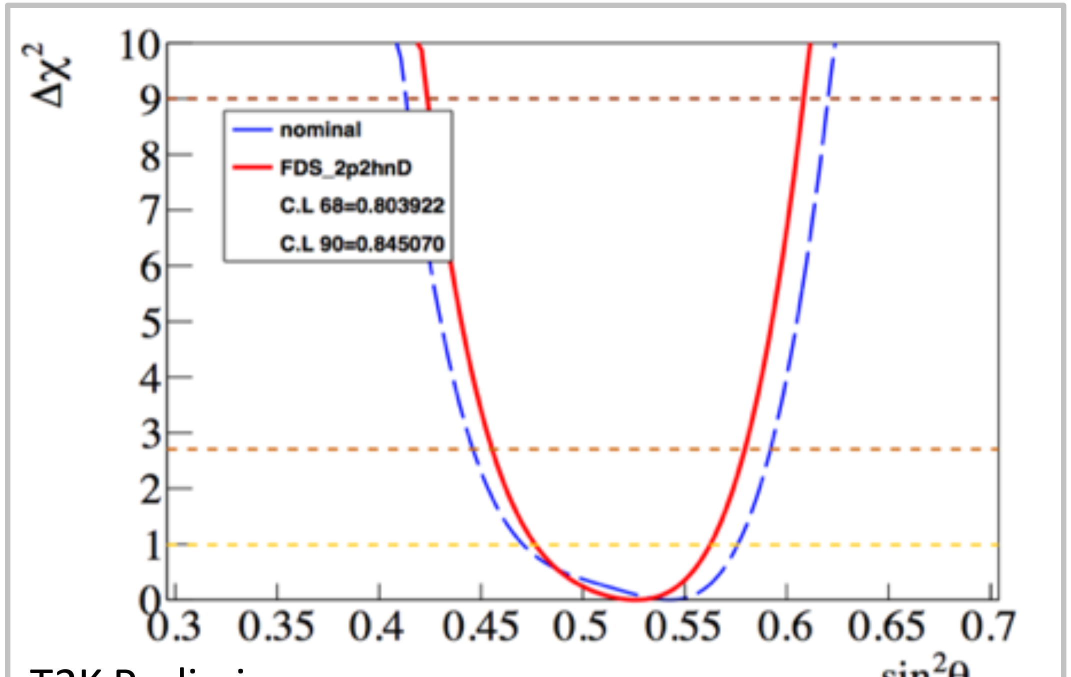
- Used in analysis to get sensitivity values
- Values set to PDG-2016 data and best fit values from the previous T2K analysis

Fake data studies
Effect on "atmospheric" parameters

- Bias of Δm^2_{23} to lower values and $\sin^2\theta_{23}$ to max mixing
- Narrow contour obtained for fake data studies
- Studying whether should incorporate these effects of variations as an additional systematic uncertainty
- No conclusive statement yet



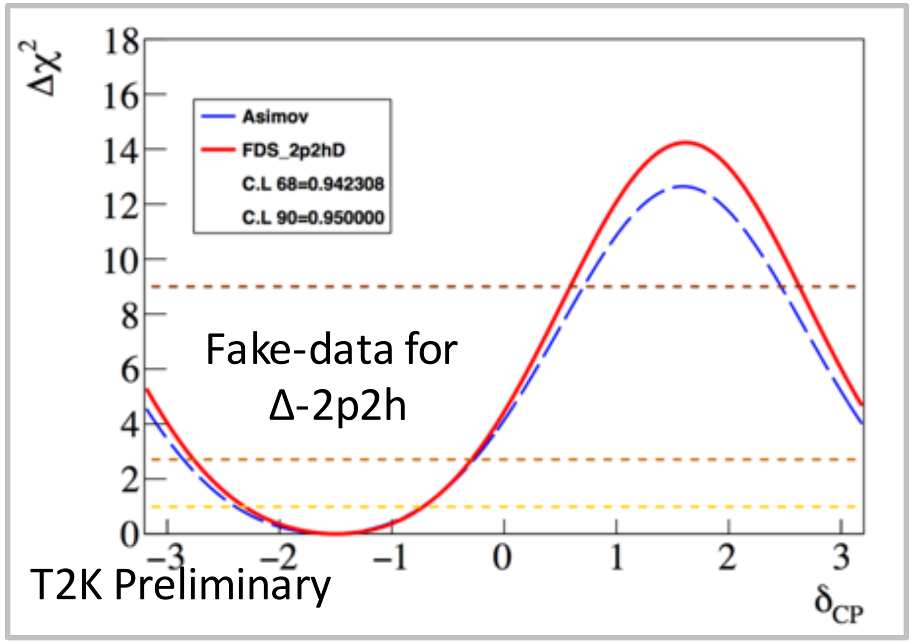
T2K Preliminary

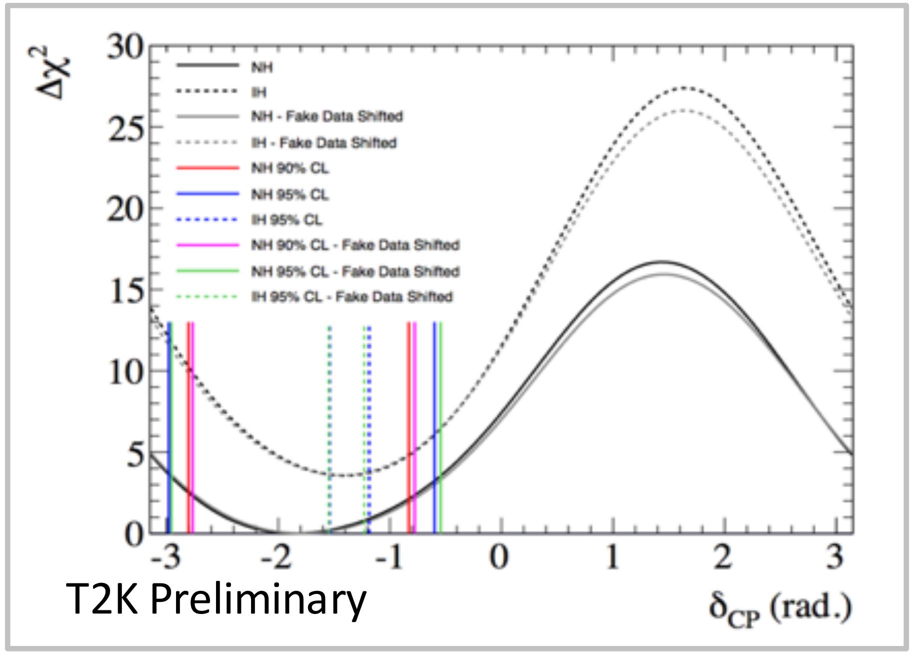


T2K Preliminary

Fake data-studies
Effect on δ_{CP}

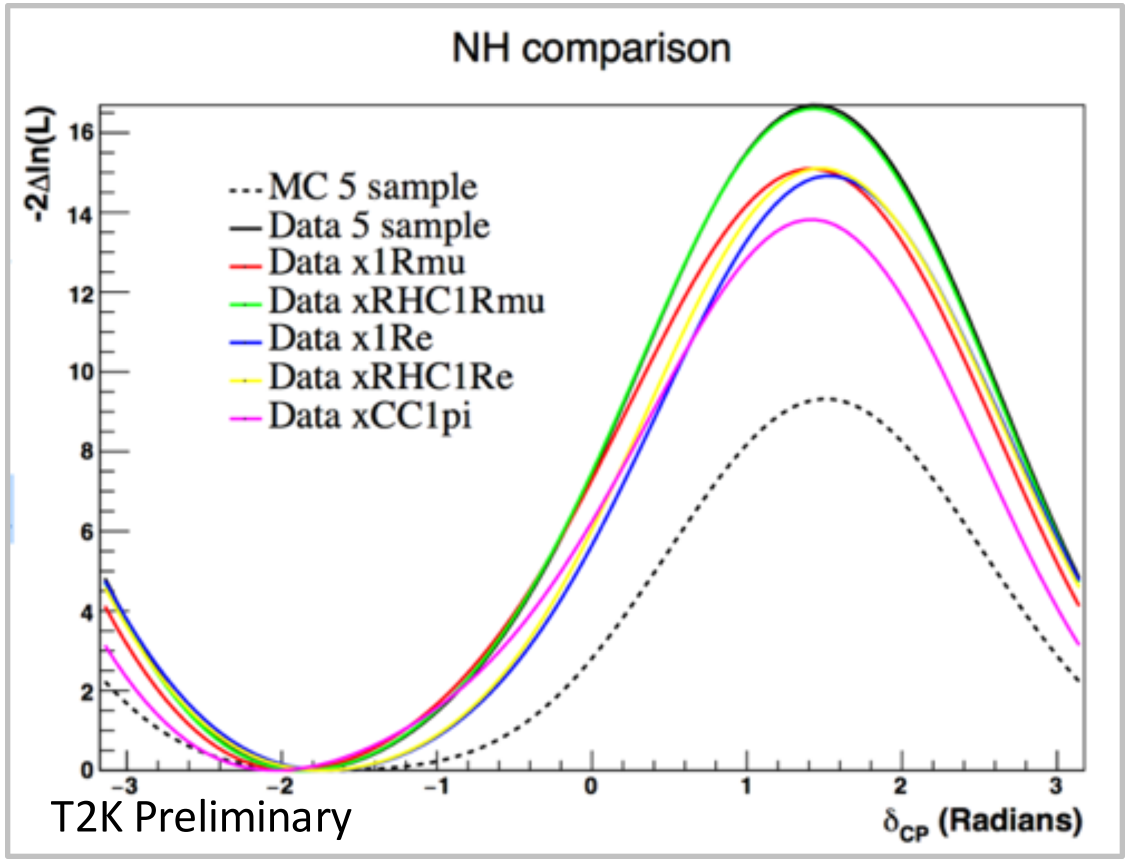
- Right: Compare nominal MC and the fake data
- Left: shift data $\Delta\chi^2$ according to difference observed in fake data study
- Max change/shift to the confidence interval/mean point: $\simeq$ 2%
  - Small effect on δ_{CP} limits



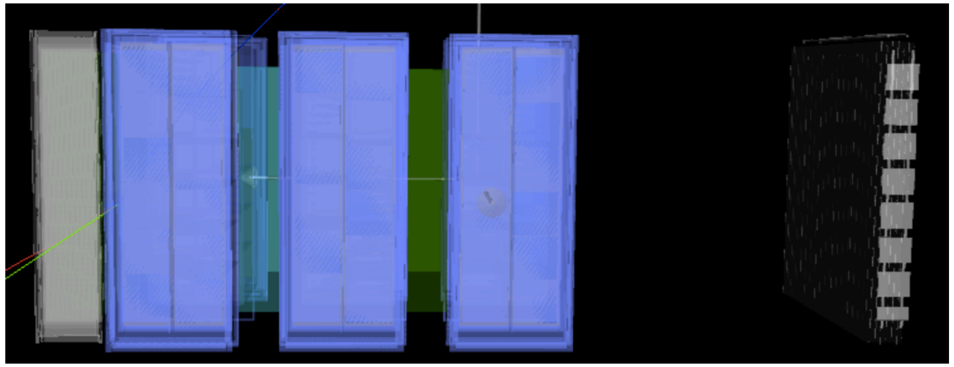


Impact of data samples on δ_{CP}

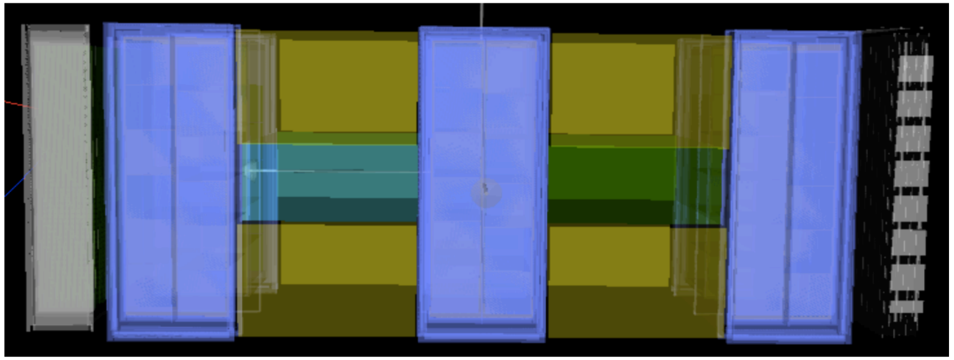
- Take data samples out 1 at a time and replace with nominal Monte Carlo prediction → check the change on limits
- Largest effect from e-like CC1π sample



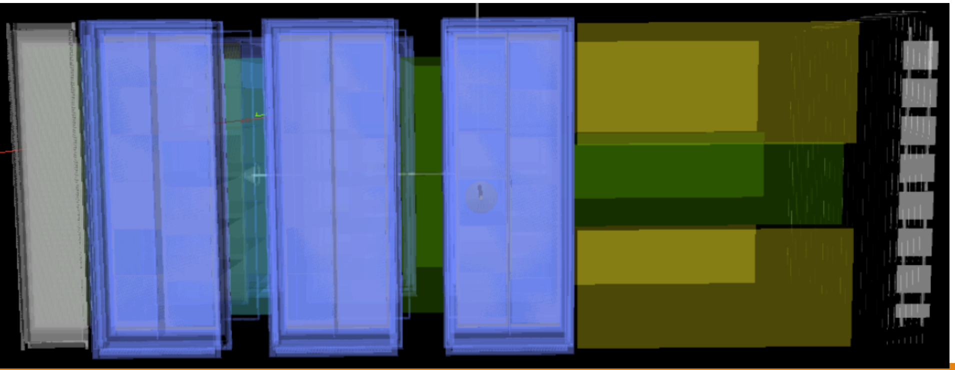
ND280 Upgrade



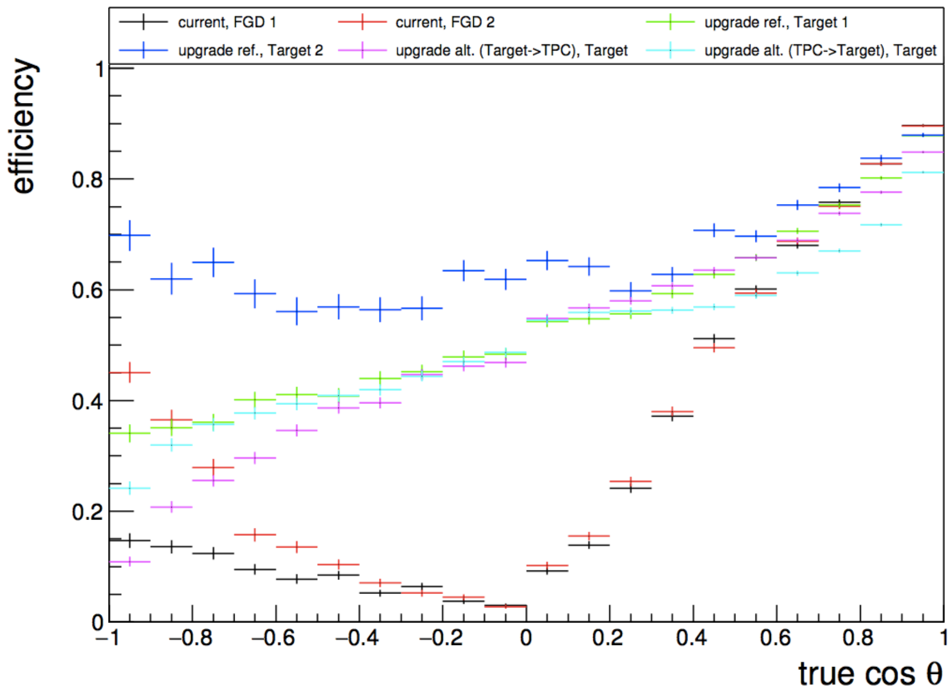
Current
ND280 configuration



Reference
ND280 configuration



Alternative
ND280 configuration



Angle reconstruction efficiency