Neutrino oscillations in T2K and prospects of Hyper-Kamiokande experiment

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Layout of the presentation

- Introduction to the T2K experiment

  - which oscillations we probe

  - experiment layout

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- Measurement of neutrino oscillations

  - what's new in the analysis in 2022

  - neutrino oscillation results, $\sin^2\theta_{23}$, Δm^2_{23}, $\sin^2\theta_{13}$, δ_{CP}

- Future of the T2K experiment

- Hyper-Kamiokande experiment – physics programme and timescale

Introduction to T2K

- International collaboration of 470 members from 13 countries
- Long-baseline neutrino oscillation experiment located in Japan
- Started its operation in January of 2010
- Provides world leading measurements of θ_{23} and δ_{CP} … also measures cross-sections of neutrino interactions

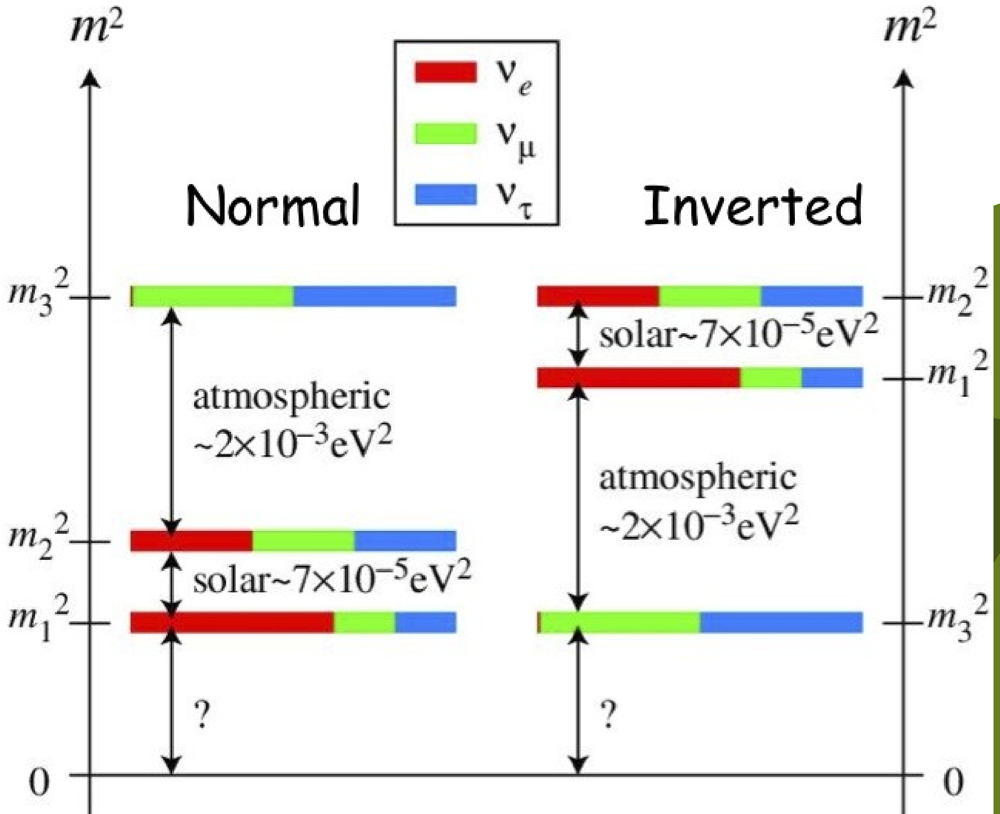
Where we are?

Neutrino mixing matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{-i\delta_{CP}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

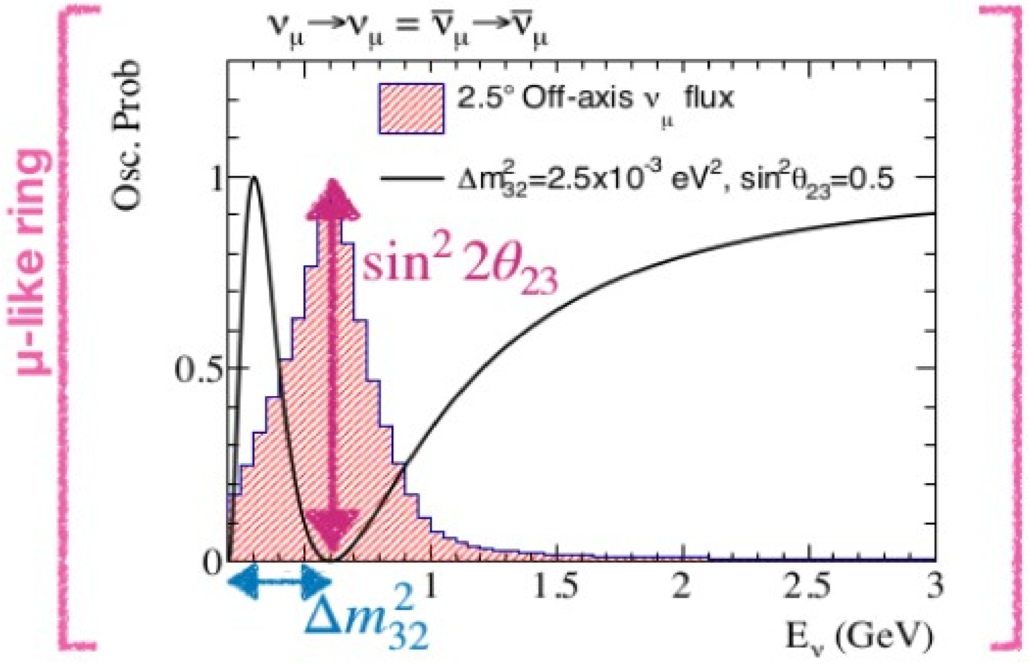
- What is value of δ_{CP}, *0*, π, or in between?
- What is mass ordering, $\Delta m^2_{32}>0$?
- Which octant of θ_{23}, $\sin^2\theta_{23}>0.5$?
- Precise measurement of mixing parameters



What we measure in T2K?

ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}$$
$$\times(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$



ν_e appearance

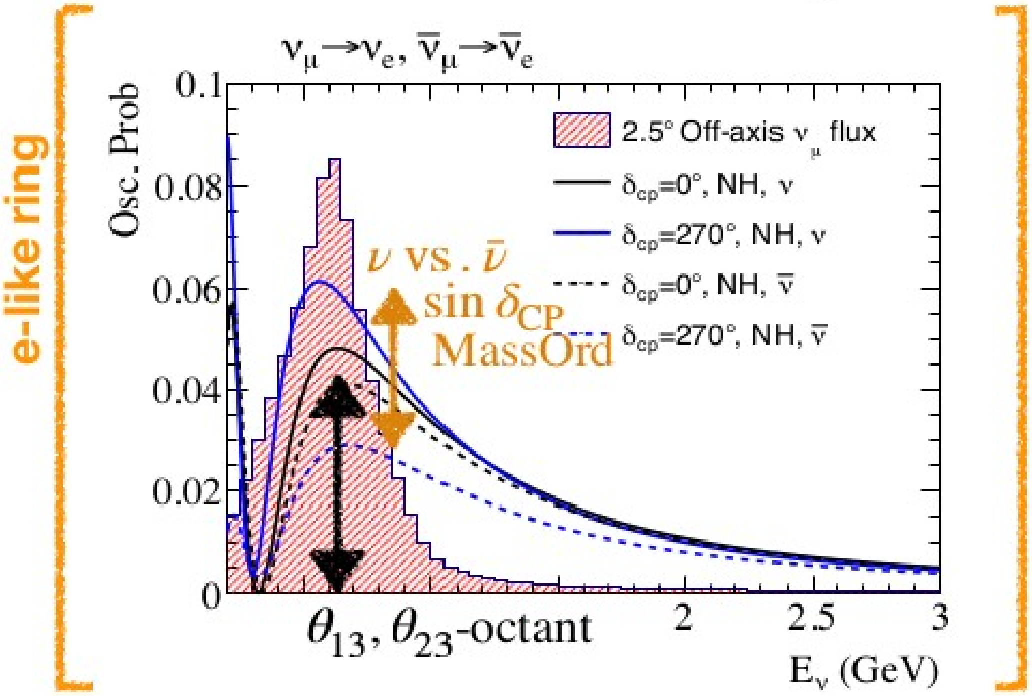
$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

"-" for ν

"+" for $\bar{\nu}$

$$\mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

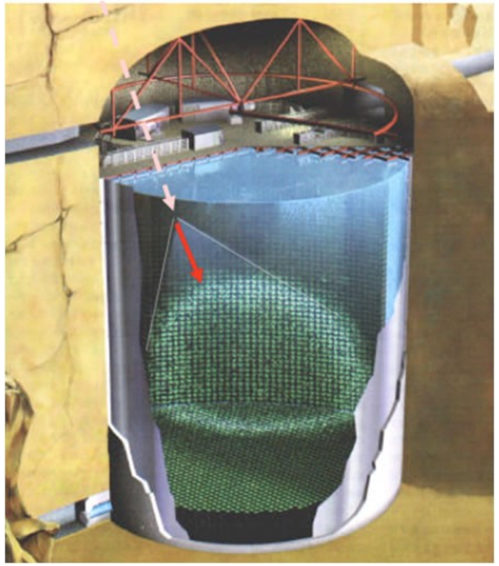
$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} = 0.033\sin\delta_{CP}$$



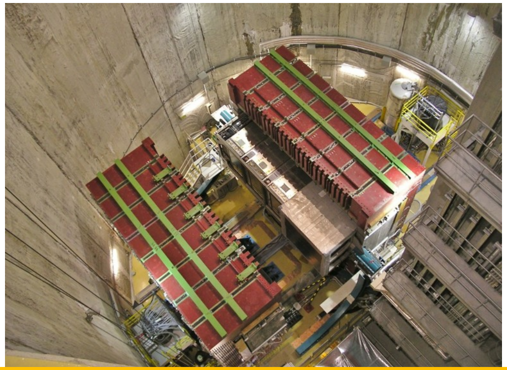
Equations w/o matter effect

The T2K experiment

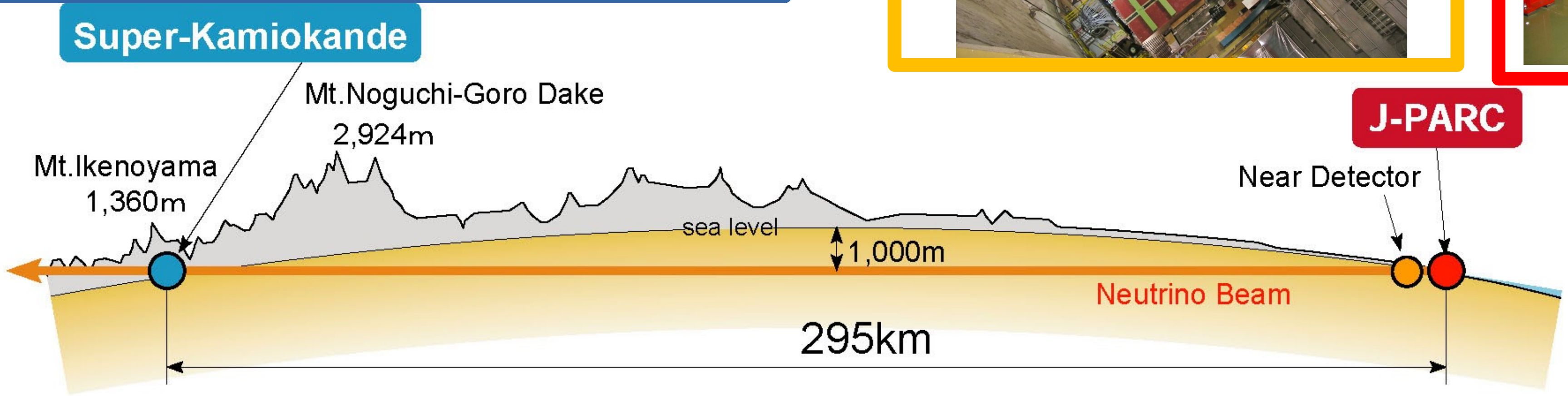
Far Detector Super-Kamiokande – 50kt ultra pure water using Cherenkov technique – can distinguish interactions of ν_μ from ν_e – study oscillations



Near Detector ND280 – scintillator trackers and TPCs – constrain unoscillated neutrino flux, measures cross-sections of neutrino interactions

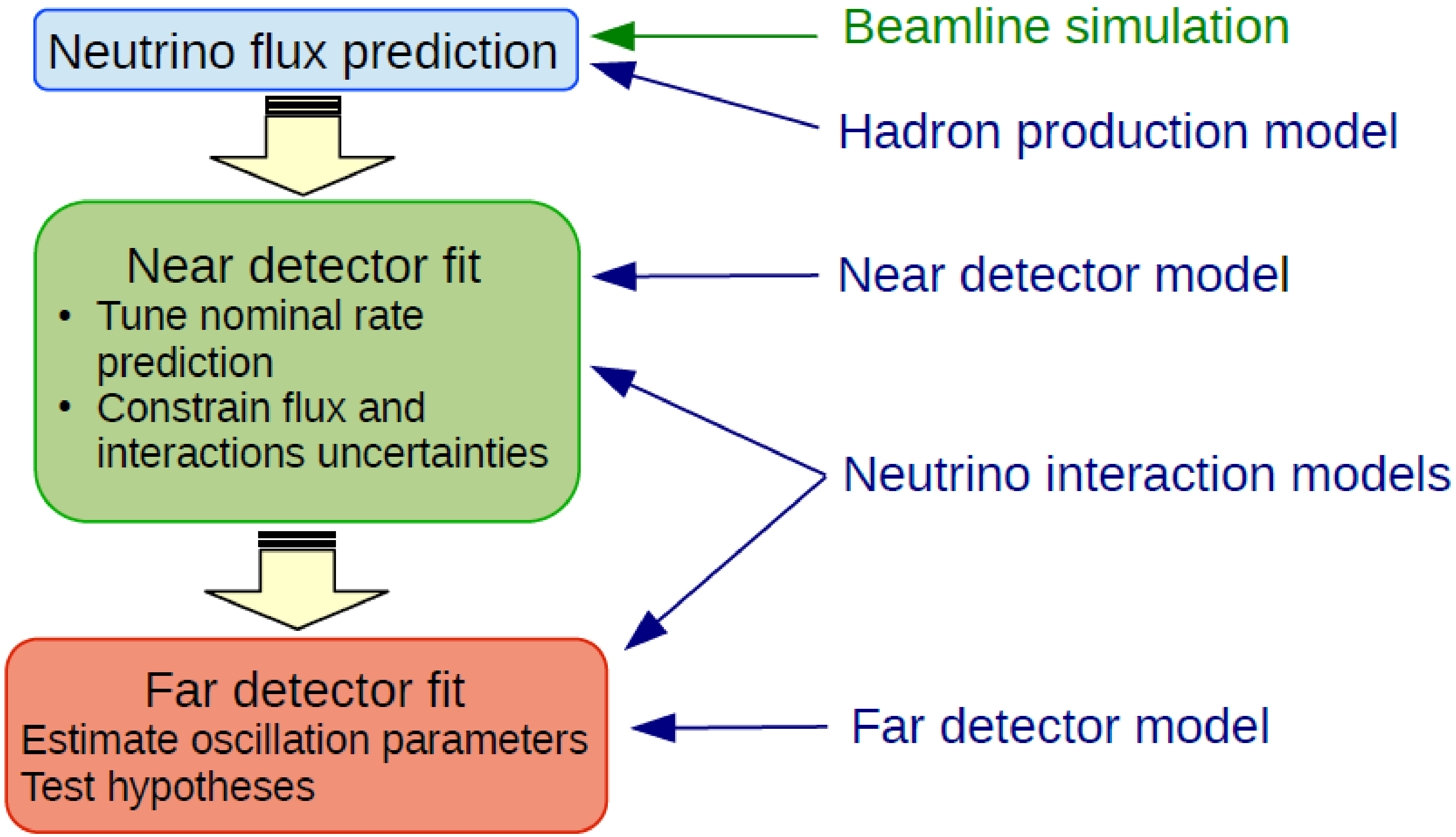


JPARC accelerator centre – sends 30GeV proton beam on graphite target producing hadrons π, K – ν and $\bar{\nu}$ beam can be produced



Oscillation analysis

- Likelihood analysis: compare observed data at the far detector to predictions based on a model of the experiment to make measurements
- Produce both frequentist and Bayesian results
- Model of the experiment built based on different simulations and models



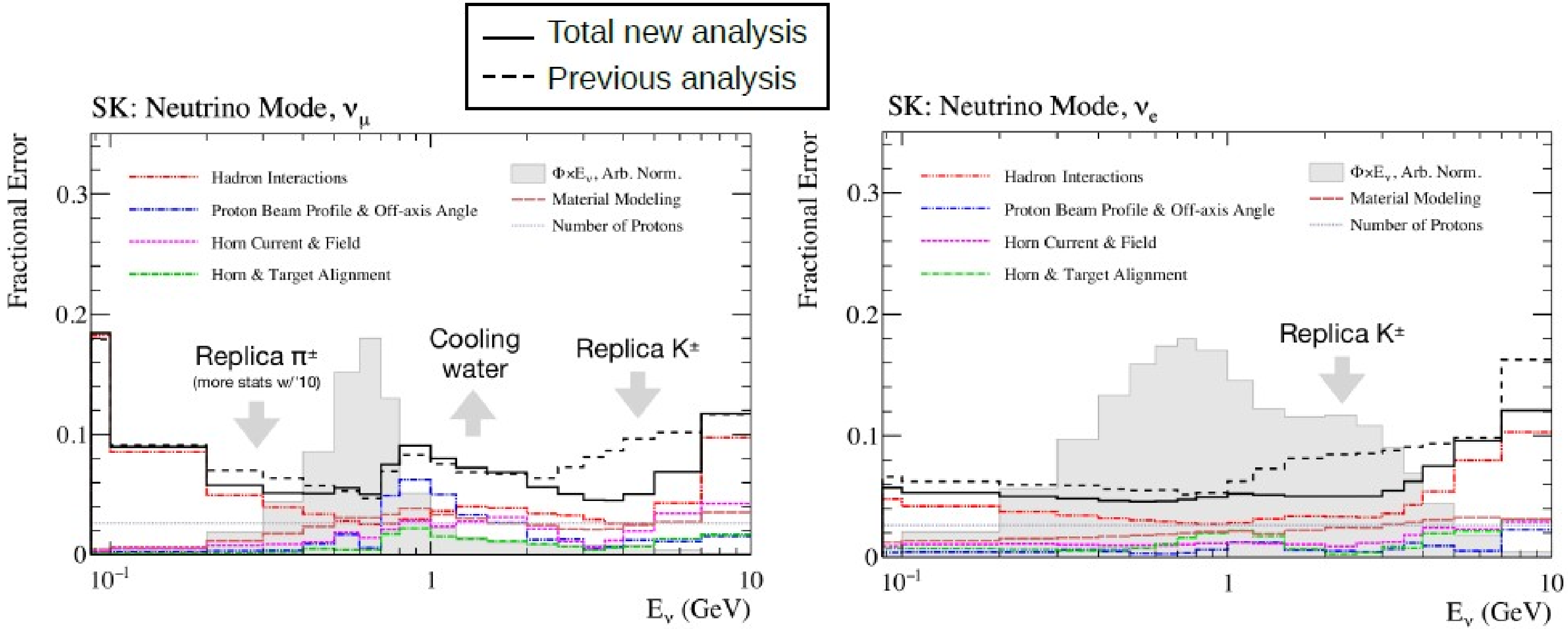
Near and far detector fits done sequentially or simultaneously depending on analysis

What's new in 2022 analysis?

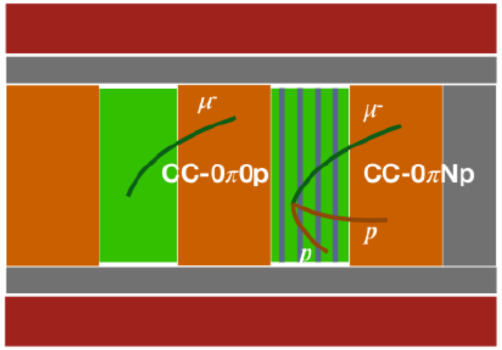
- Updated flux prediction based on analysis of the NA61/SHINE 2010 replica target data for hadron production
- Updated neutrino interaction model – improved uncertainties for spectral function model and additional uncertainties for resonant and multi-pion events as well as FSI
- New proton and photon tagging selection for the near detector ND280
- In far detector analysis introduce new μ-like CC1π sample selection

New flux prediction

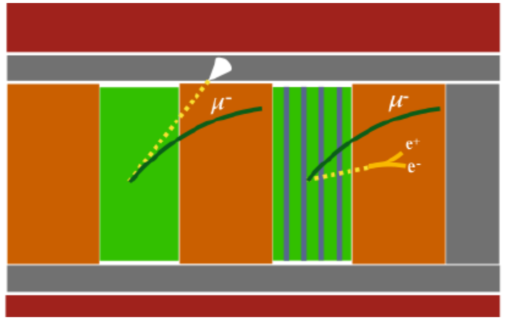
- Hadron production measured by dedicated NA61/SHINE experiment at CERN
- New hadron production data taken at 2010 (before use data from 2009)
  - more statistics for π^{+-} production
  - adds K^{+-} and proton production data
- Additional updates on the part of the models (as cooling water in horns)



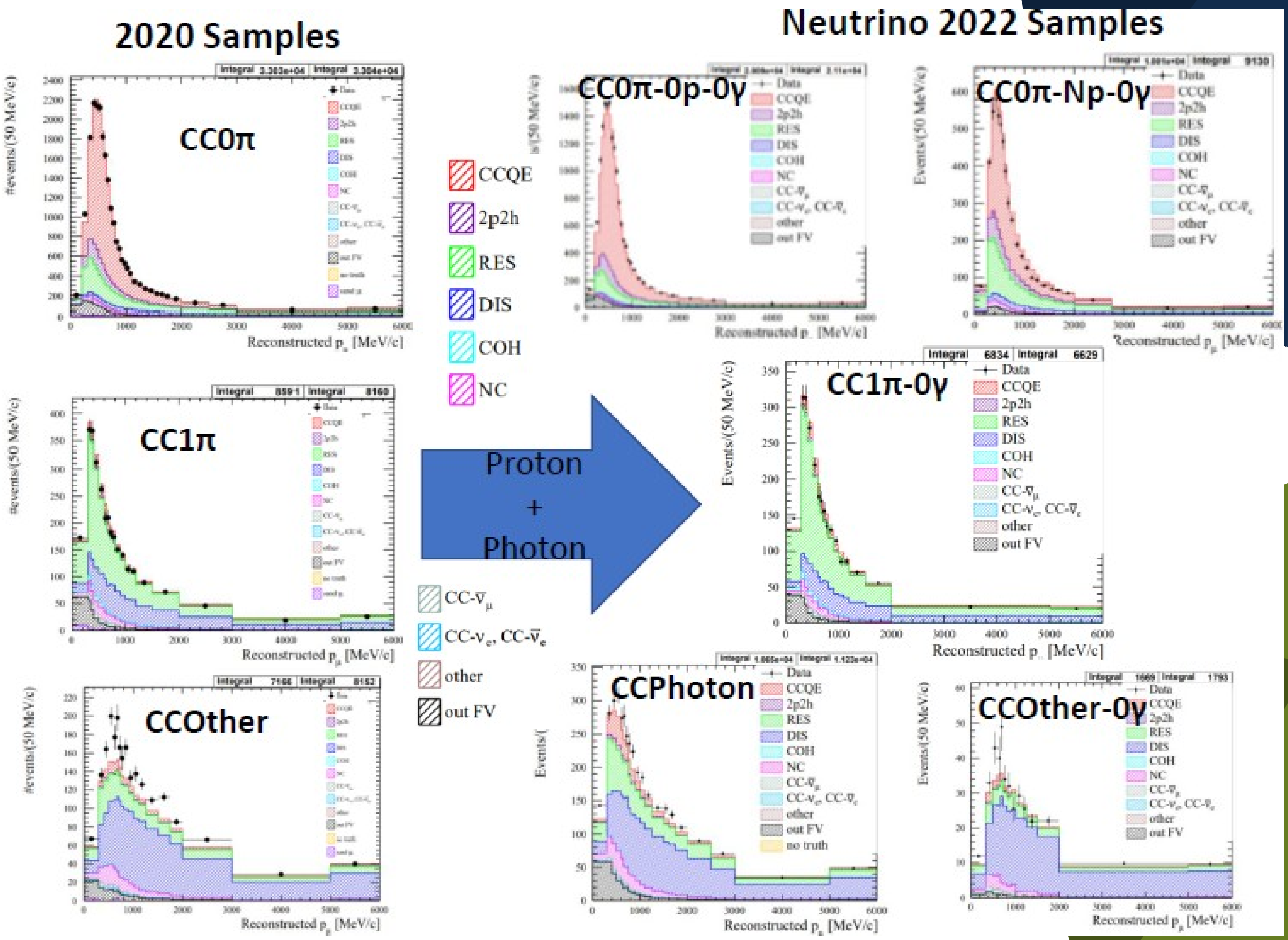
New selection in Near Detector



Increase ability to constrain CCQE and 2p2h in selected samples

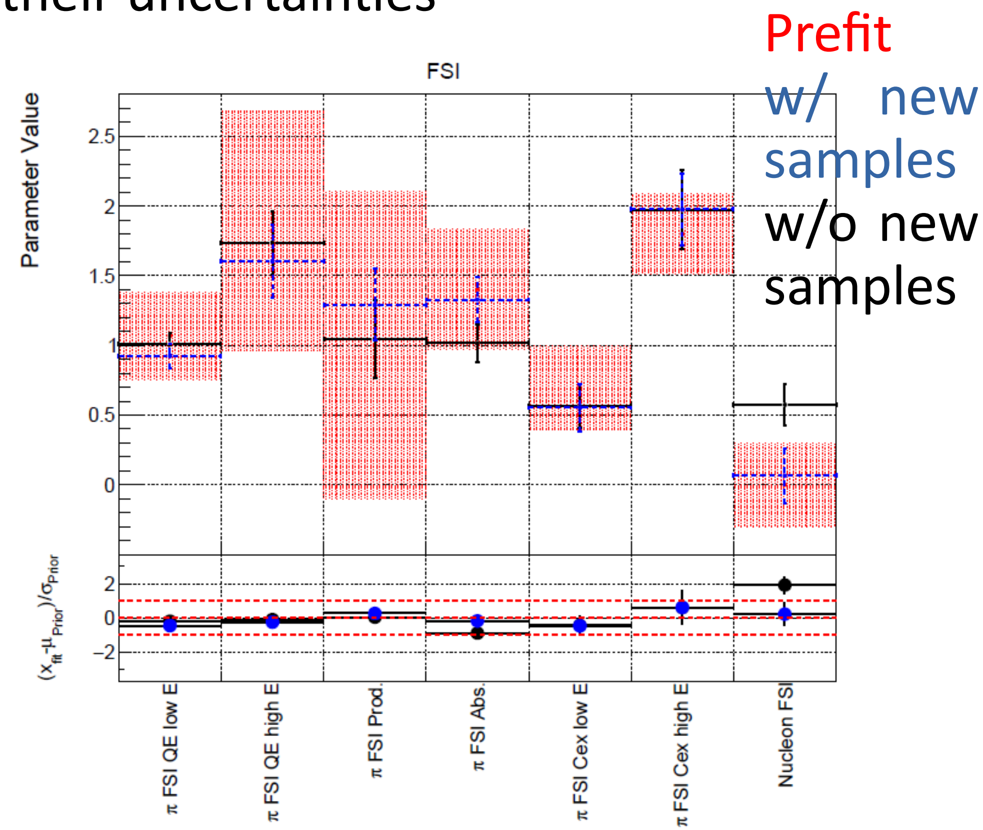


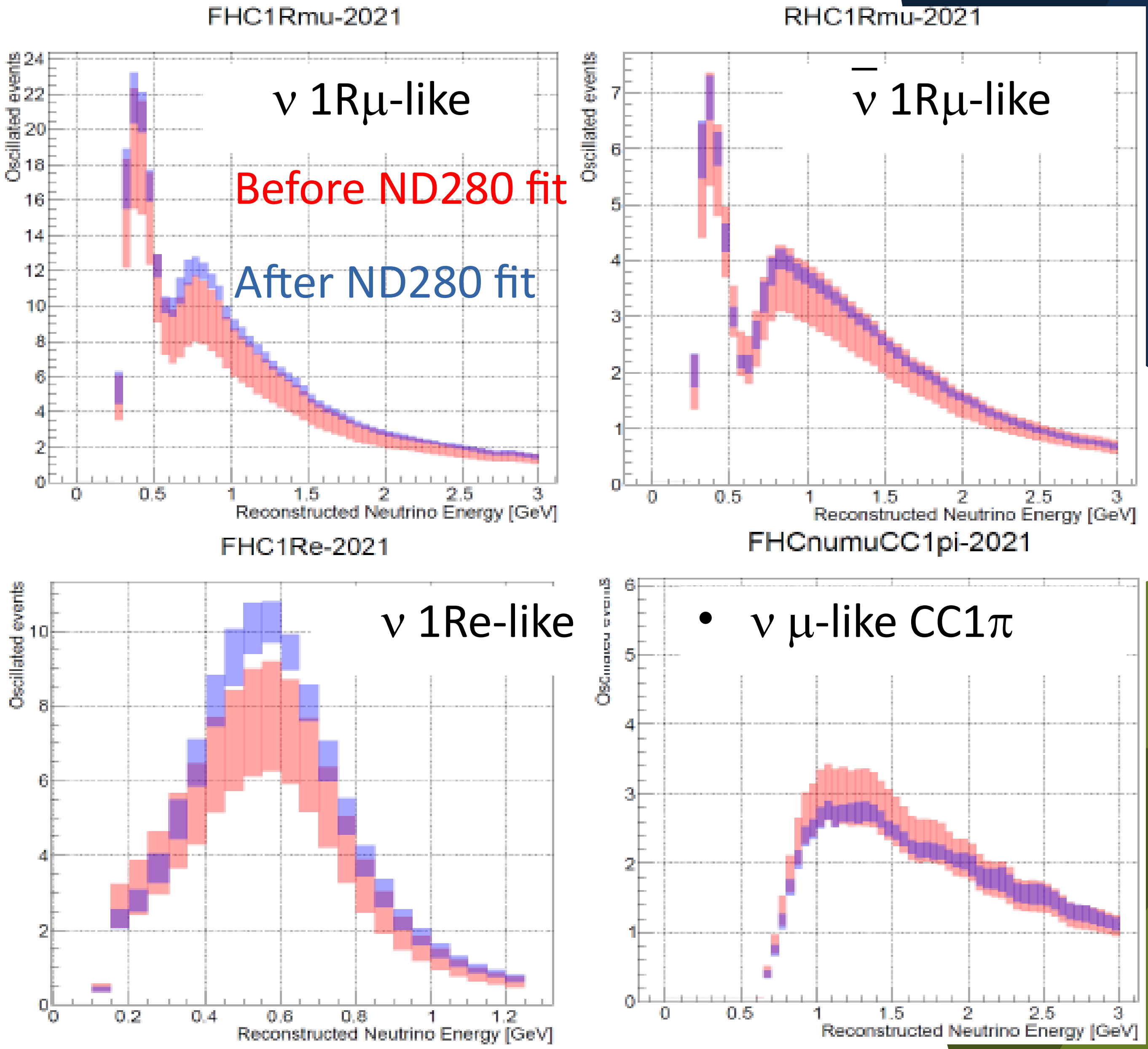
Creates new samples dominated by DIS and $CC\pi^0$



Near Detector fit results

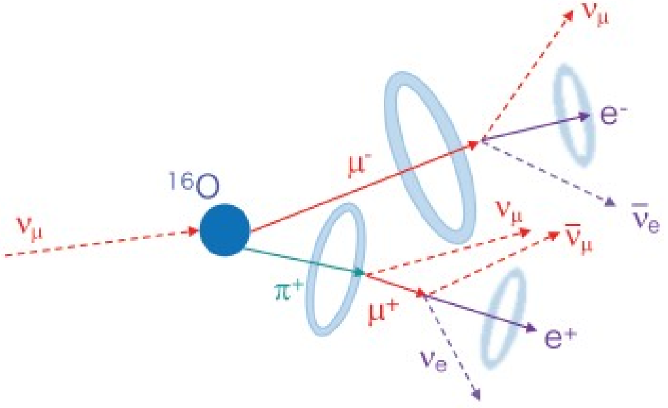
- Constraint neutrino flux and provides prediction of flux for Far Detector including CC1π sample
- Constrain interaction parameters and their uncertainties





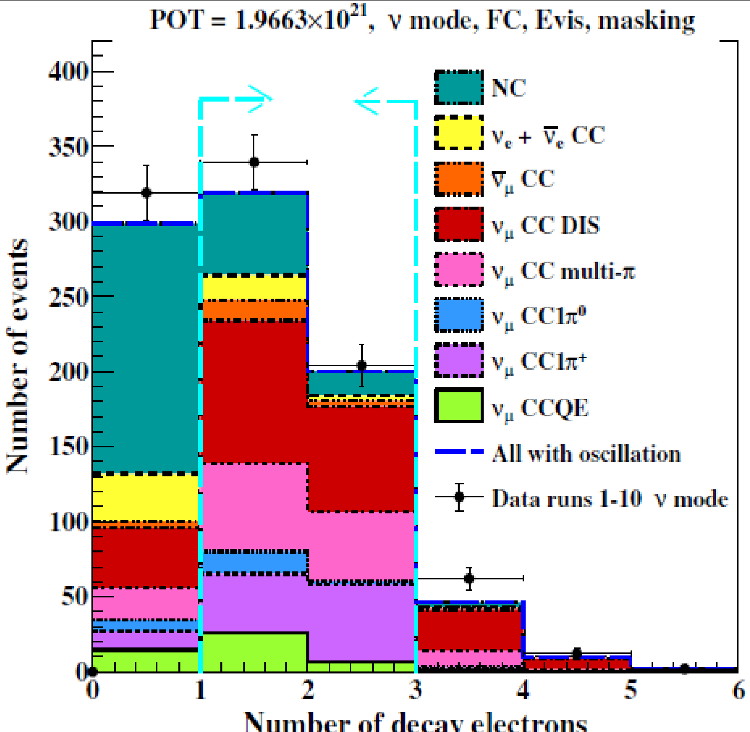
New multi-ring sample for SK

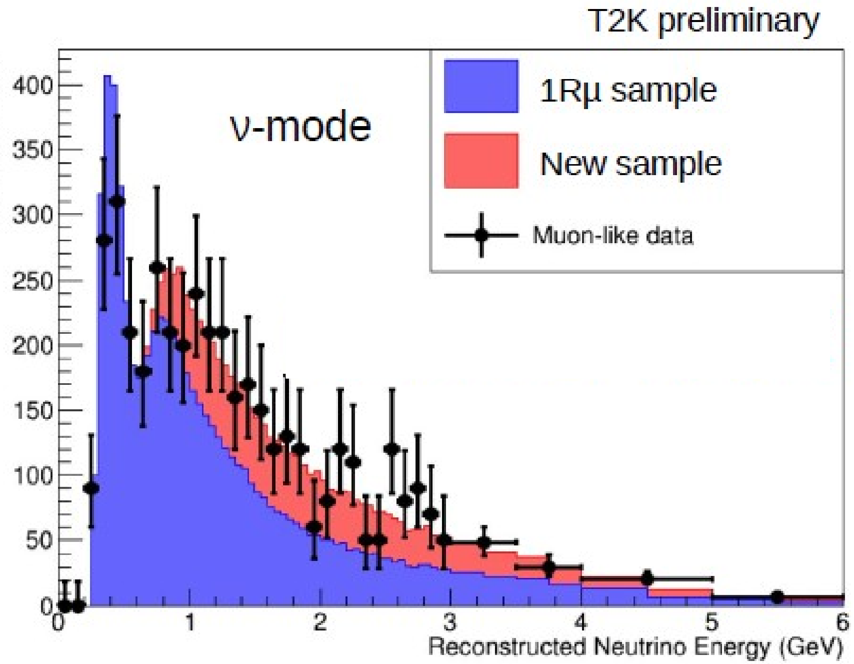
- New analysis adds a far detector sample targeting ν_μ CC1π^+ interactions in ν-mode
- Combination of 1Rμ + 2 M.e and 2 rings events
- Increase ν-mode μ-like statistics by ~30%
- Sensitive to oscillations, but higher energy than nominal μ-like sample
- Dominated by different interaction mode



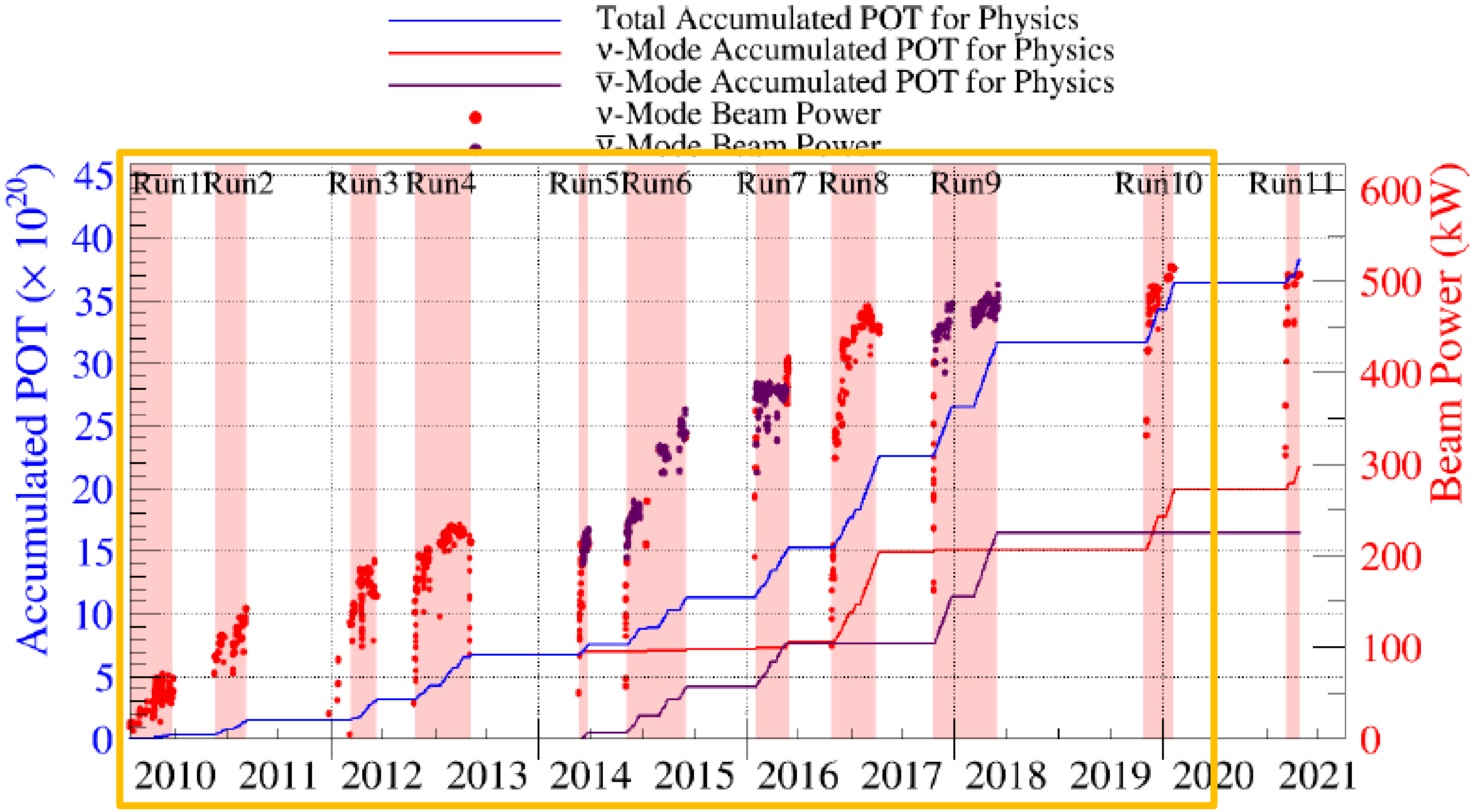
Signal: CCDIS, CCmπ, CC1π^+

CC1π^0
CCQE
CC$\nu_e\nu_e$
CCν_μ
NC





Same data set as in 2020 analysis



Used here:

Near detectors

ν-mode: 1.3905×10^{21} POT
$\bar{\nu}$-mode: 0.6307×10^{21} POT

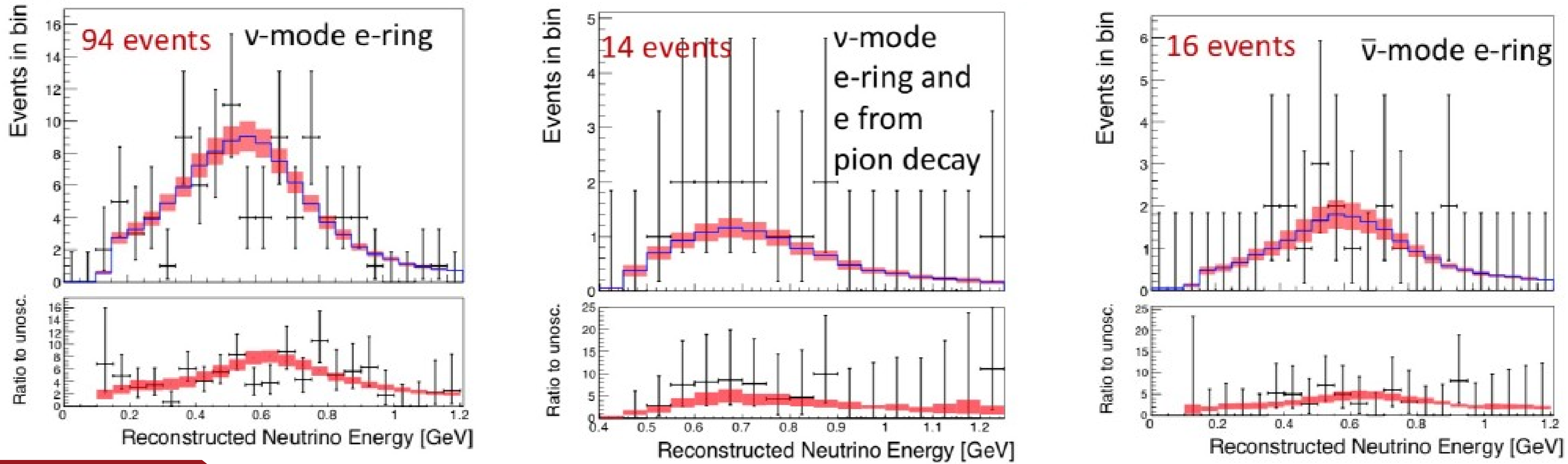
Far detector

ν-mode: 1.9664×10^{21} POT
$\bar{\nu}$-mode: 1.6346×10^{21} POT

Far Detector samples

- Detected number of ν_e events consistent with $\delta_{CP}=-\pi/2$
- New sample of ν_μ CCπ increase statistics of about 30%

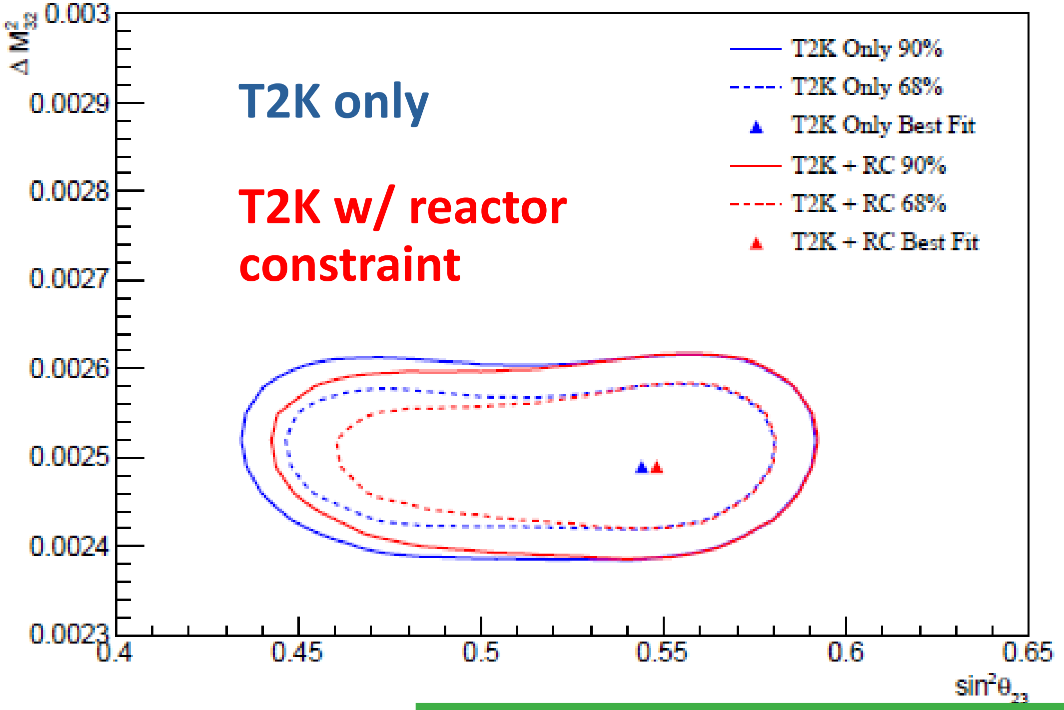
Mode	Sample	δ=-π/2 MC	δ=0 MC	δ=π/2 MC	δ=π MC	Data
ν	1Re	102.7	86.7	71.1	87.1	**94**
	1Re CC1π⁺	10.0	8.7	7.1	8.4	**14**
	1Rμ	379.1	378.3	379.1	380.0	**318**
	MRμ CC1π⁺	116.5	116.0	116.5	117.0	**134**
$\bar{\nu}$	1Re	17.3	19.7	21.8	19.4	**16**
	1Rμ	144.9	144.5	144.9	145.3	**137**



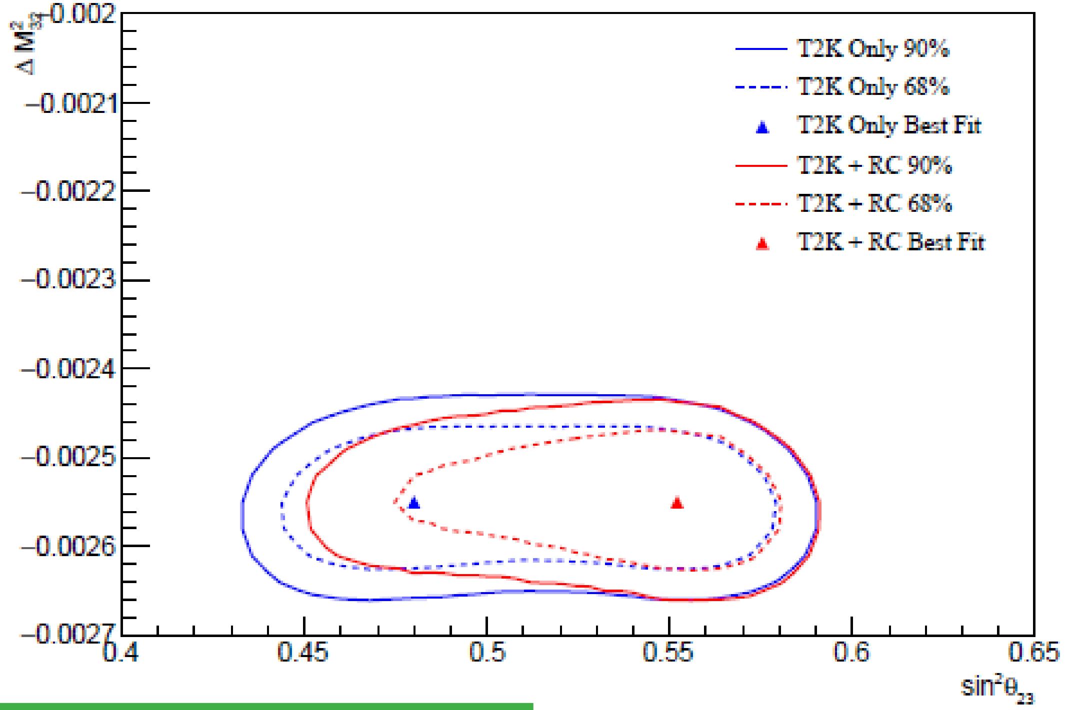
Results in Atmospheric region

2D contours for Bayesian analysis with simultaneous fit of the Near and Far Detectors data (joint fit of ν_μ and ν_e)

Normal Ordering



Inverted Ordering

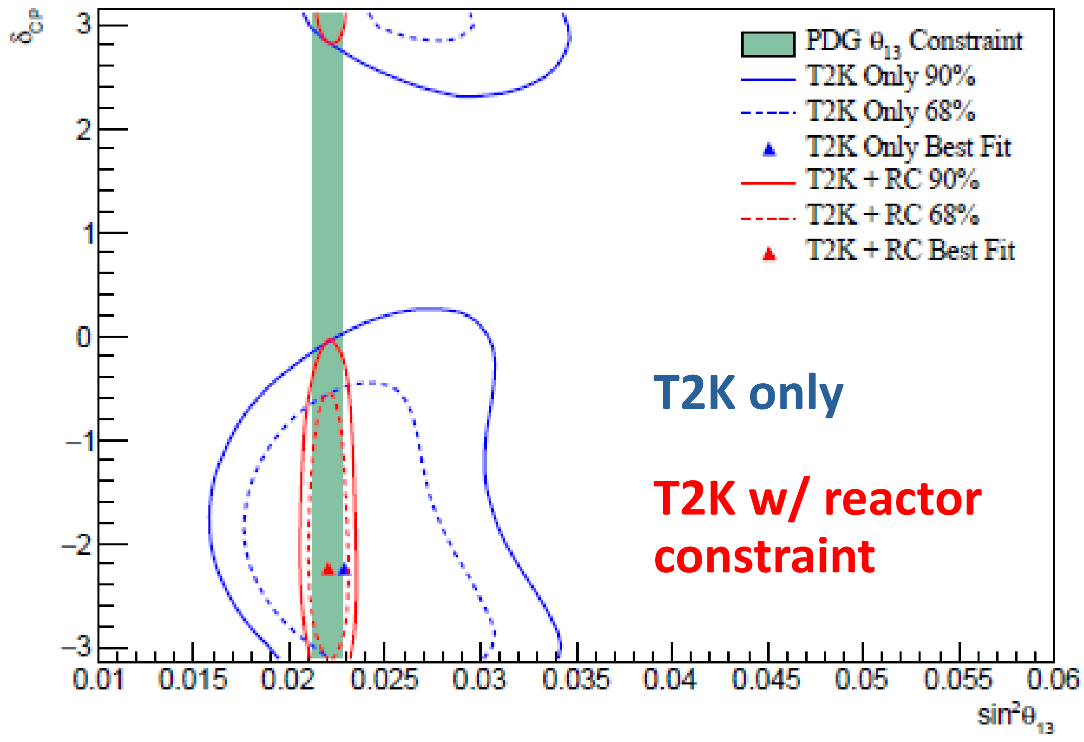


Best fit in the upper octant, lower octant still allowed in 68% CL

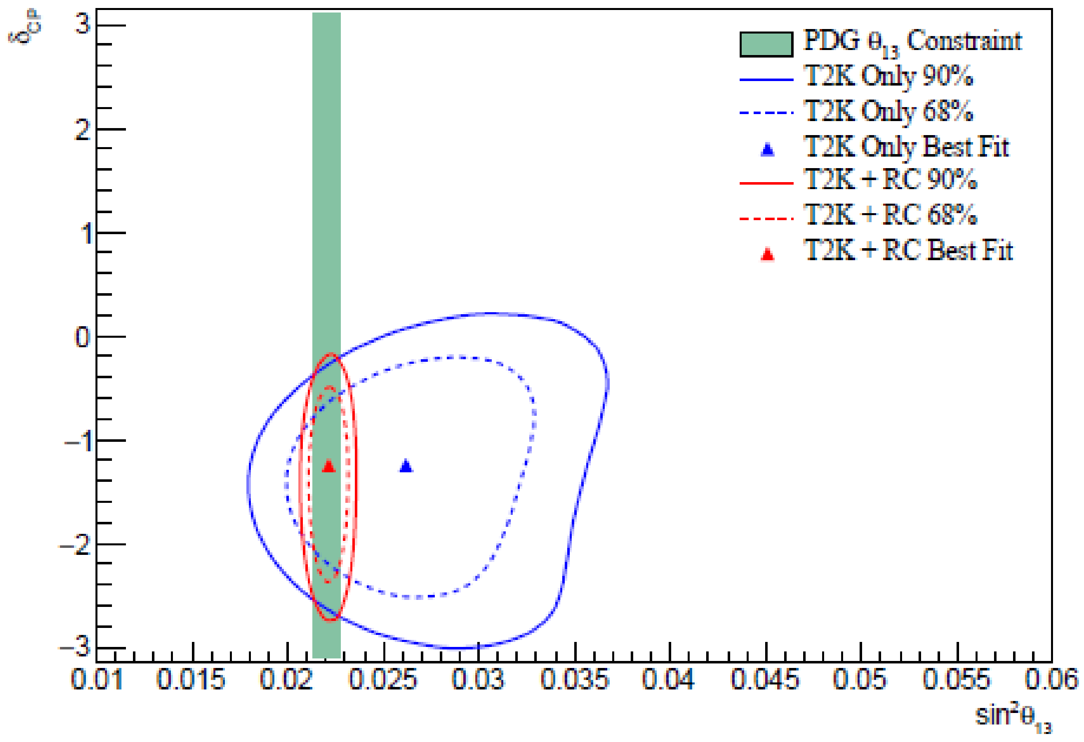
Results on δ_{CP} and θ_{13}

2D contours for Bayesian analysis with simultaneous fit of the Near and Far Detectors data (joint fit of ν_μ and ν_e)

Normal Ordering

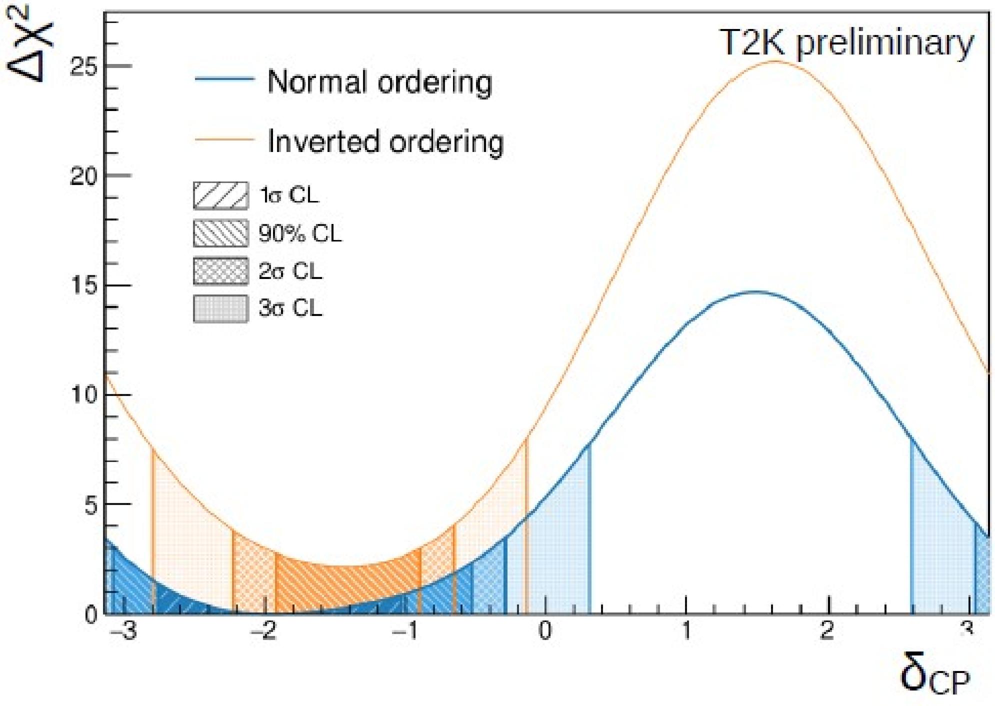


Inverted Ordering

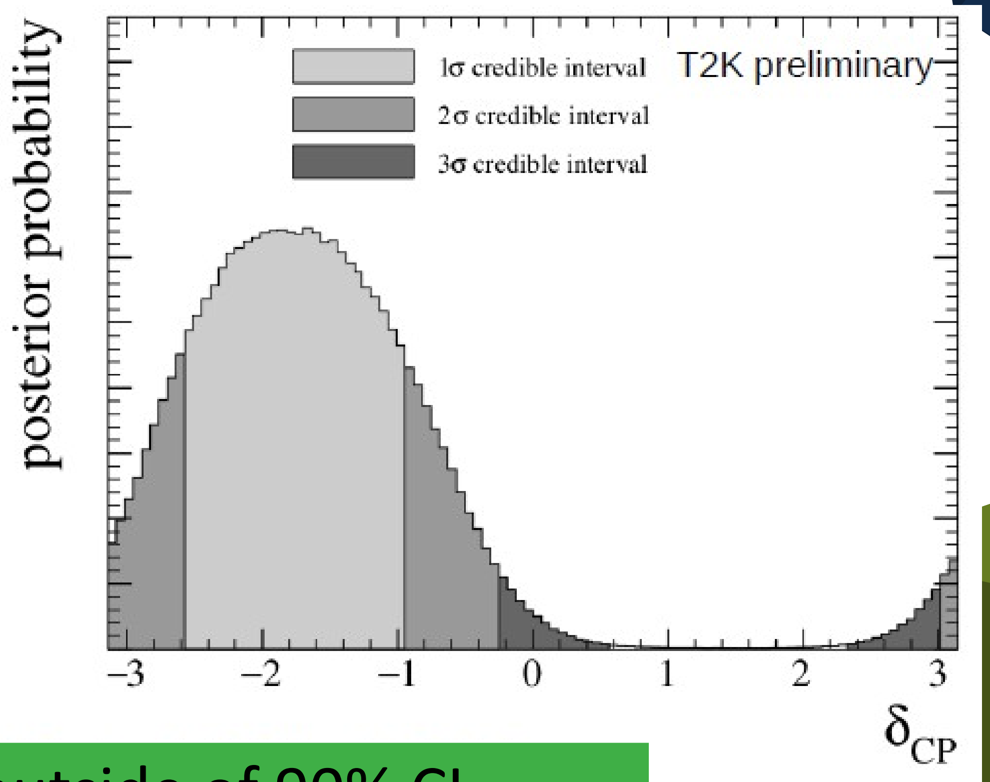


Results on δ_{CP} phase

Frequentists approach
(Feldman-Cousin method)



Bayesian approach
(marginalized over MO)



CP conserving values outside of 90% CL
Best fit close to maximal CP violation near $-\pi/2$

Results model preference

- Looking at posterior probabilities for the different combinations of octant and mass ordering hypotheses
- Mild preference for normal ordering and upper octant, stronger when using constraint from reactor experiments for θ_{13}, but still limited significance

T2K only

T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO $(\Delta m^2_{32} > 0)$	0.24	0.39	0.63
IO $(\Delta m^2_{32} < 0)$	0.15	0.22	0.37
Sum	0.39	0.61	1.000

T2K+reactor

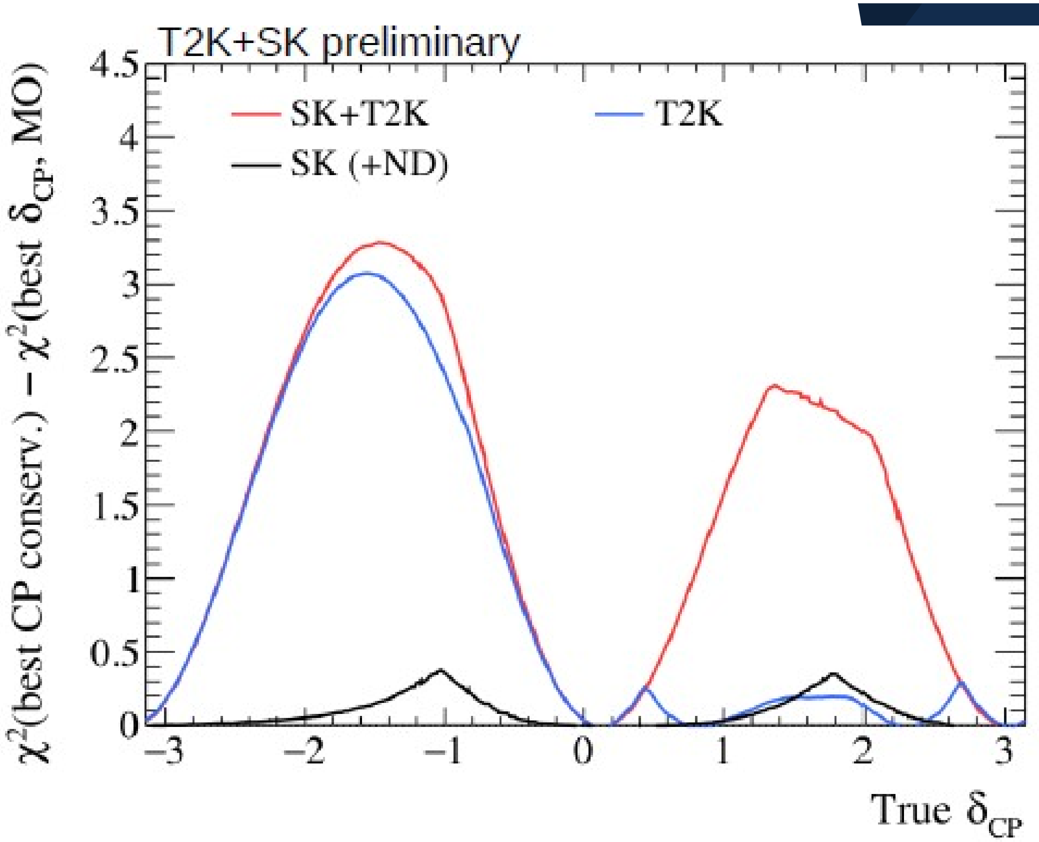
T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO $(\Delta m^2_{32} > 0)$	0.20	0.54	0.74
IO $(\Delta m^2_{32} < 0)$	0.05	0.21	0.26
Sum	0.25	0.75	1.000

θ_{13} constraint from reactor experiments is $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

T2K-SK atmo. joint analysis- Sensitivity

- Common fit for T2K beam data and SK atmospheric data
- SK covers wide range of energies and baseline then T2K, with particular sensitivity to MO from high energy neutrinos
- Unified interaction model for T2K and low E SK atmospheric samples (Sub-GeV)
- High energy atmospheric neutrinos use mainly model of neutrino interactions from SK analysis
- Flux and detector models from each experiment uncorrelated

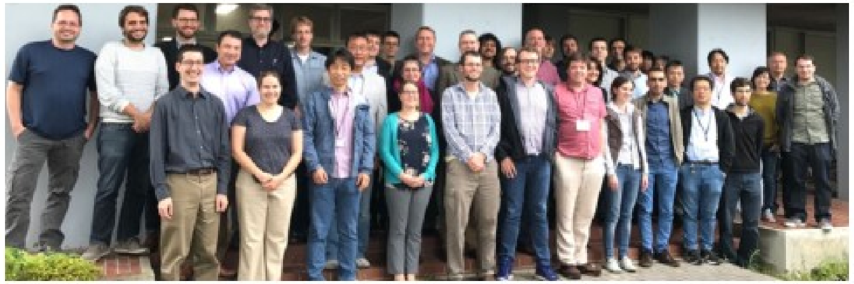
Ability to exclude CP conservation as a function of δ_{CP}



T2K-SK constraint on interaction uncertainties used for low E atmo sample, assume $\sin^2\theta_{23}=0.528$, $\sin^2\theta_{13}=0.0218$ (NO)

T2K – NOνA joint fit

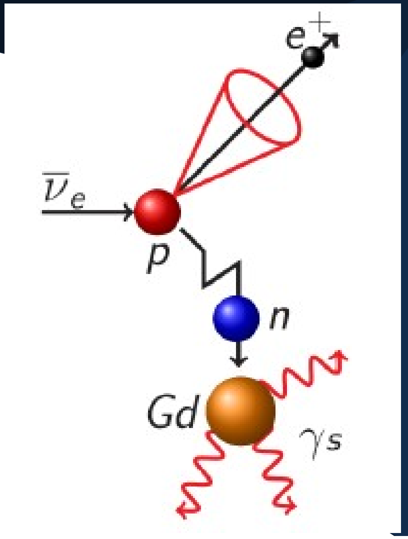
- 2 long baseline experiments with different baselines, energy ranges and detector technologies: complementarity to study oscillations
- The two collaborations have started work on a joint analysis of their data
  - → increased sensitivity
  - → ability to break degeneracy between mass ordering and δ_{CP}



Experimental Property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection Technology	Water Cherenkov	Segmented liquid sintillator bars
CP Effect*	32%	22%
Matter Effect	9%	29%

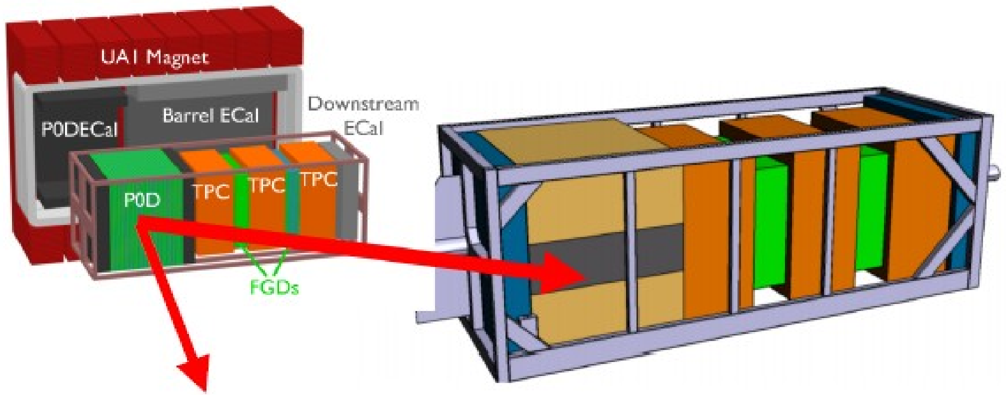
*Minimum difference of $\sin(\delta_{cp})=0$ and $\sin(\delta_{cp})=\pm1$, neutrinos and antineutrinos

Future of T2K

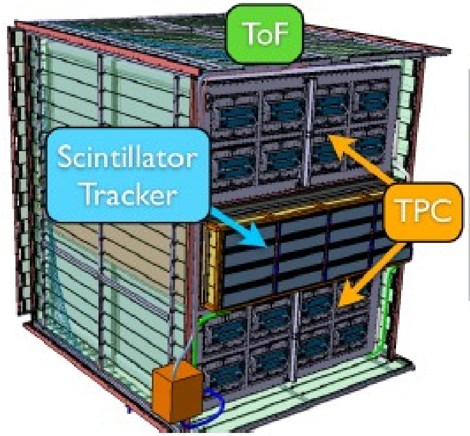


- **SK is loaded with Gd sulfate** since summer 2020 (now adding more Gd to water) This helps with neutron tagging and discrimination between ν and ν interactions. T2K already recorded beam data in SK-Gd phase, but they are not yet analysed. We can see neutron capture signal in the data.

- **Upgrade of main ring magnets and horn current supplies –** ongoing. Will allow operation at higher current 250 → 320 kA and provide higher intensity beam. Expected to be ready in 2023.



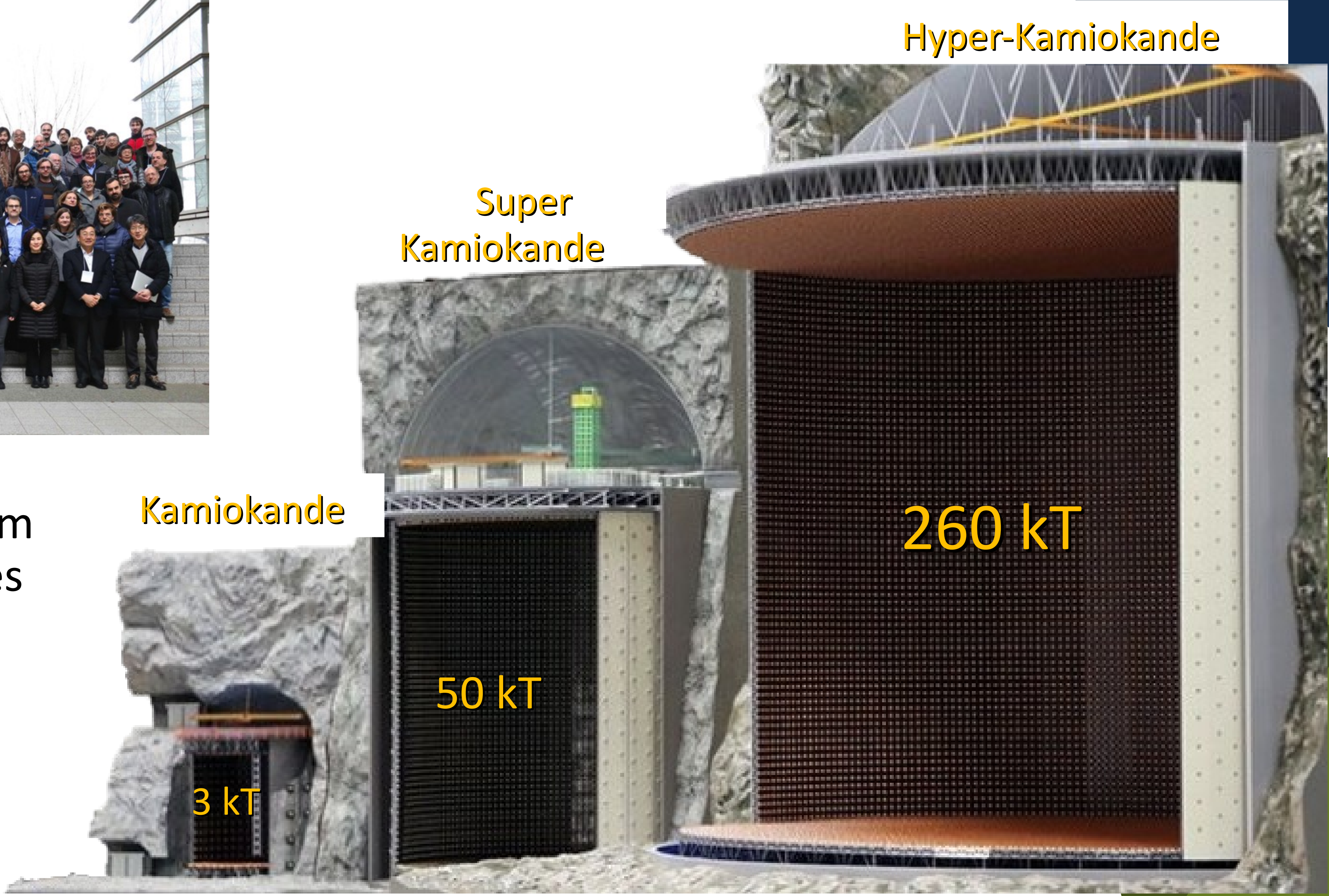
- **Near Detector upgrade –** Pi0 detector replaced by 2 million 1cm^3 cubes scintillator detector SuperFGD surrounded by the TPCs. Will help to measure cross-sections of neutrino interactions and constraint uncertainties in oscillation analysis. Expected to operate in 2023.



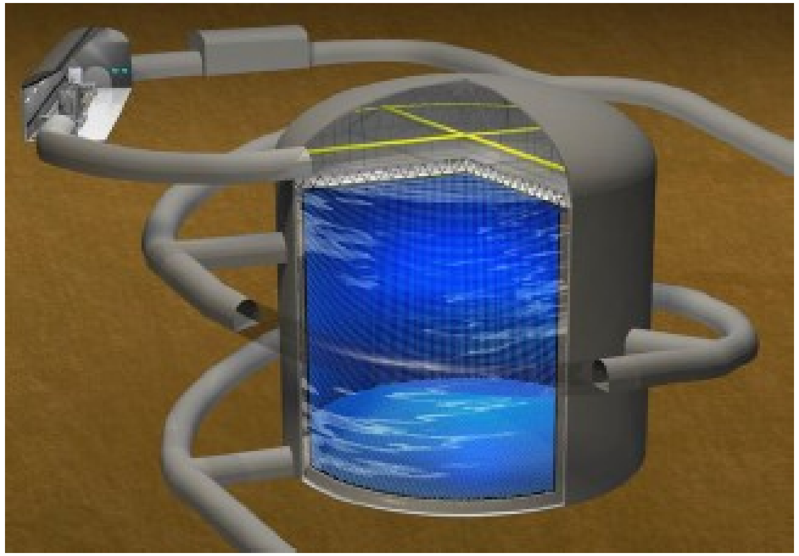
- Lower thresholds
- Improved efficiency for high angle tracks
- Improved determination of track directions

Hyper-Kamiokande

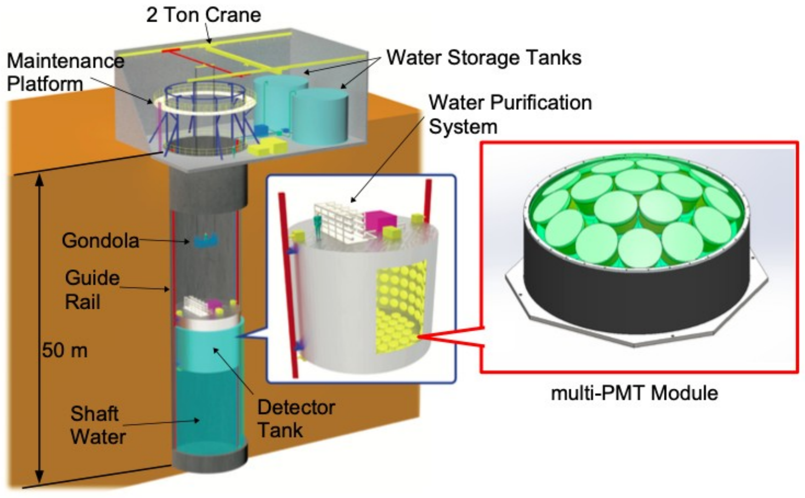
>400 physicists from
20 different countries



Hyper-Kamiokande – new detectors



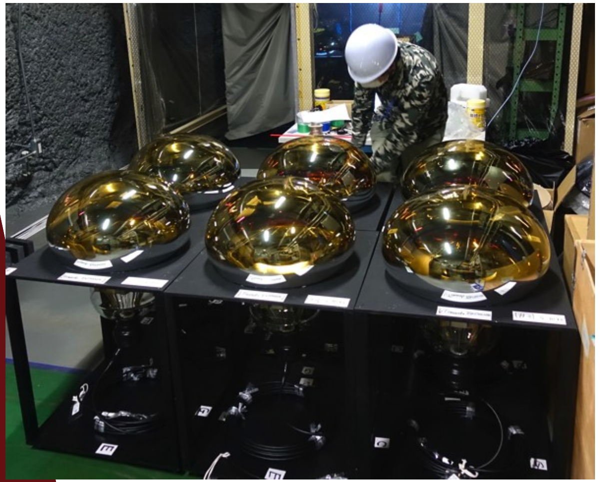
- 260 kT of ultra pure water
- Tank diameter 68m, height 71m
- 20% photocathode coverage
- Tunnel construction almost done, cavern excavation will start soon
- Tank will be built in 2024/2025



Intermediate Water Cherenkov Detector

- 1kT scale doped with Gd water Cherenkov detector with minimum overburden
- Diameter 8m, height 6m
- Moving detector that allows measurement of unoscillated neutrino spectrum at different off-axis angels

New photomultiplier tubes



New 20'' inner detector PMTs

- Single photon efficiency 24%, twice more then for current PMTs in Super-K
- Dark noise 4kHz, Time resolution 1.5ns (is 3ns for SK)
- PMT production has started and will be finished by 2026 (20 000 new PMTs)

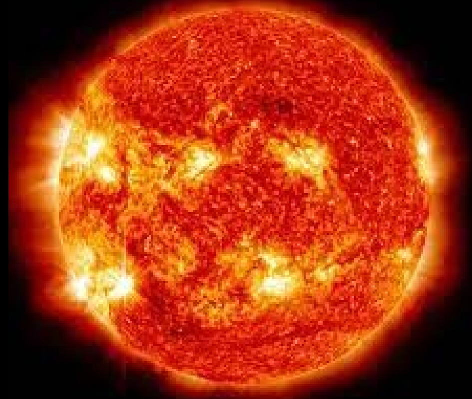
New Multi-PMT units

- Array of 19 3'' PMTs
- Dark noise 19x200-300Hz, transit time spread 1.3ns
- Directional information, improved spatial and timing resolution
- To be used in inner Hyper-K detector together with new 20'' PMTs and in Intermediate Water Cherenkov detector

Physics Programme

Proton decay

Solar neutrinos



Supernovae neutrinos

- Neutrino oscillations

  - using atmospheric neutrinos and JPARC $\nu/\bar{\nu}$ beam

  - CP violation and precise measurement of oscillation parameters

  - mass hierarchy determination

- Search for nucleon decay

- Astrophysics

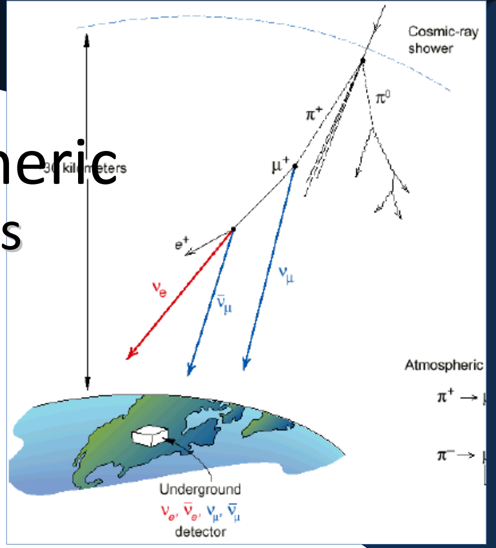
  - solar neutrinos

  - Supernovae burst, diffuse Supernovae Background Neutrinos

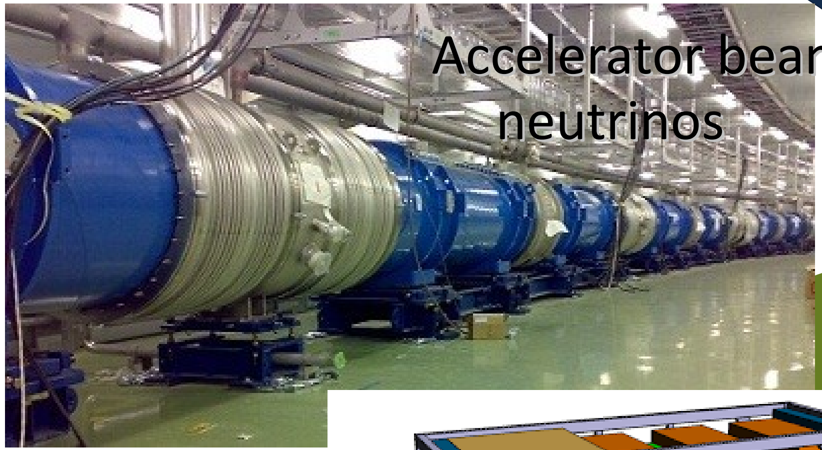
  - Dark Matter search

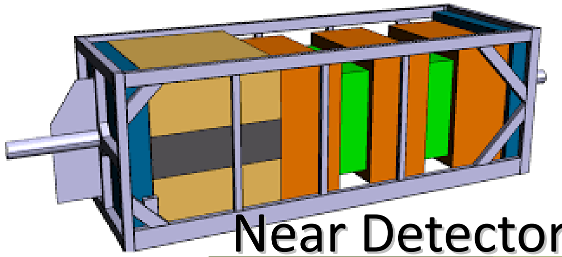
Not covered in this talk

Atmospheric neutrinos



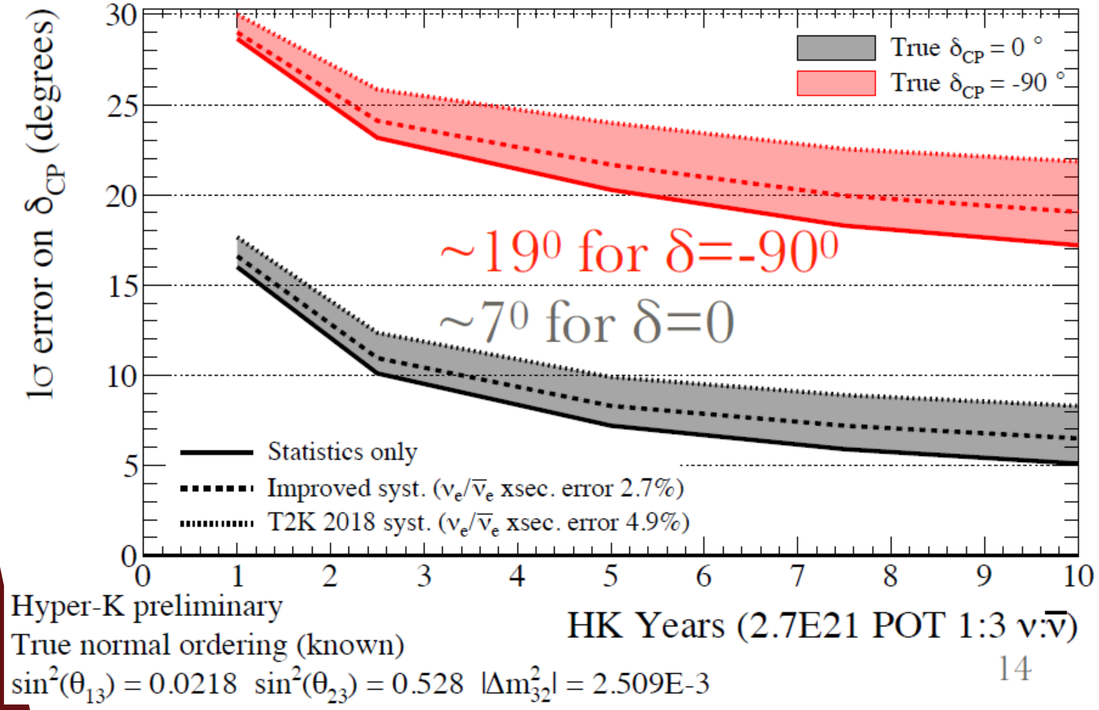
Accelerator beam neutrinos

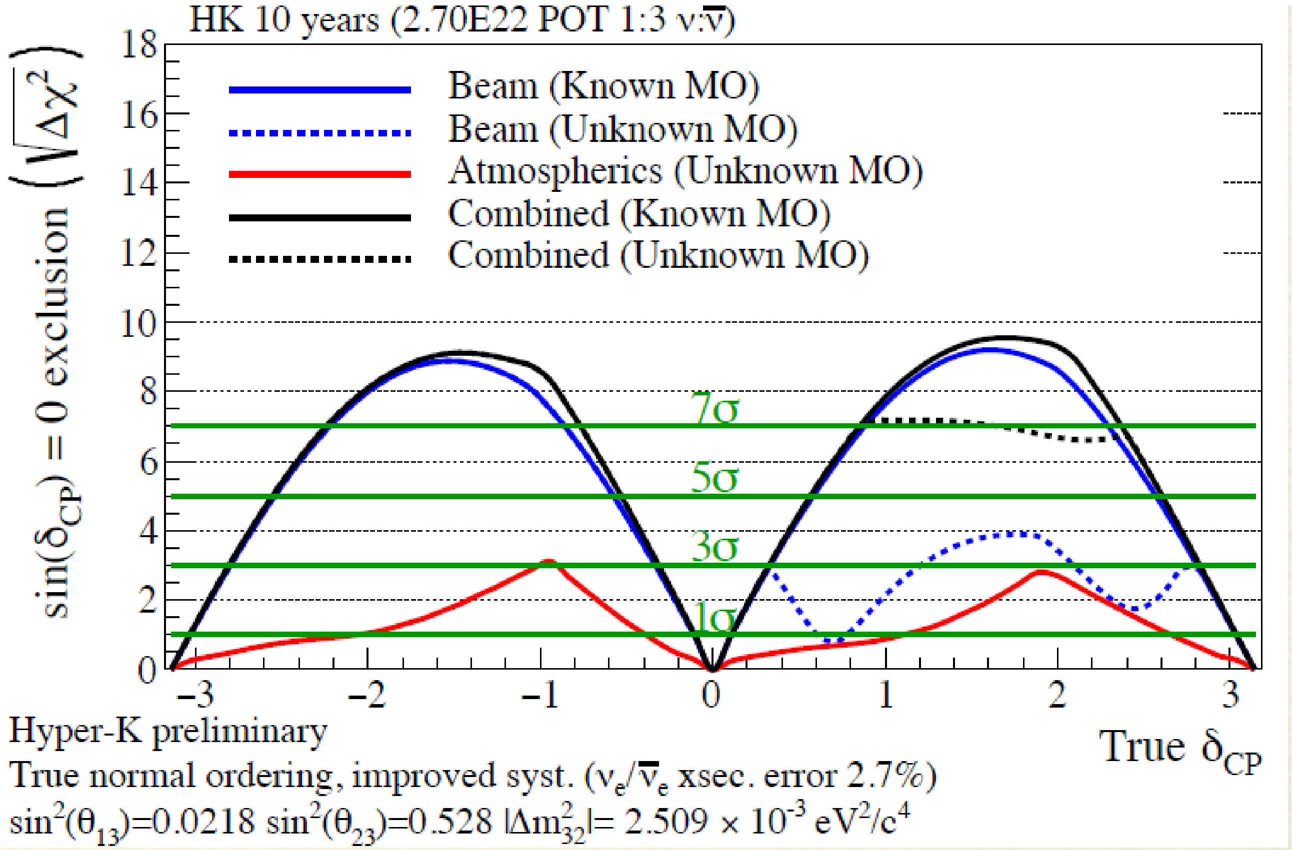




Near Detector

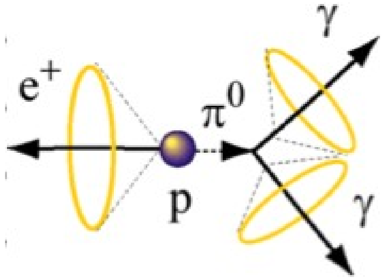
CP violation sensitivity





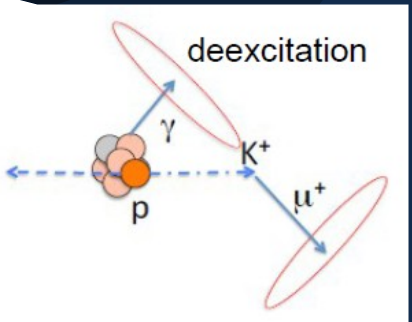
- Assume 10 years of data taking, 1:3 $\nu:\bar{\nu}$
- Good chance to discover leptonic CP violation
- Use atmospheric neutrinos to help remove mass ordering ambiguity

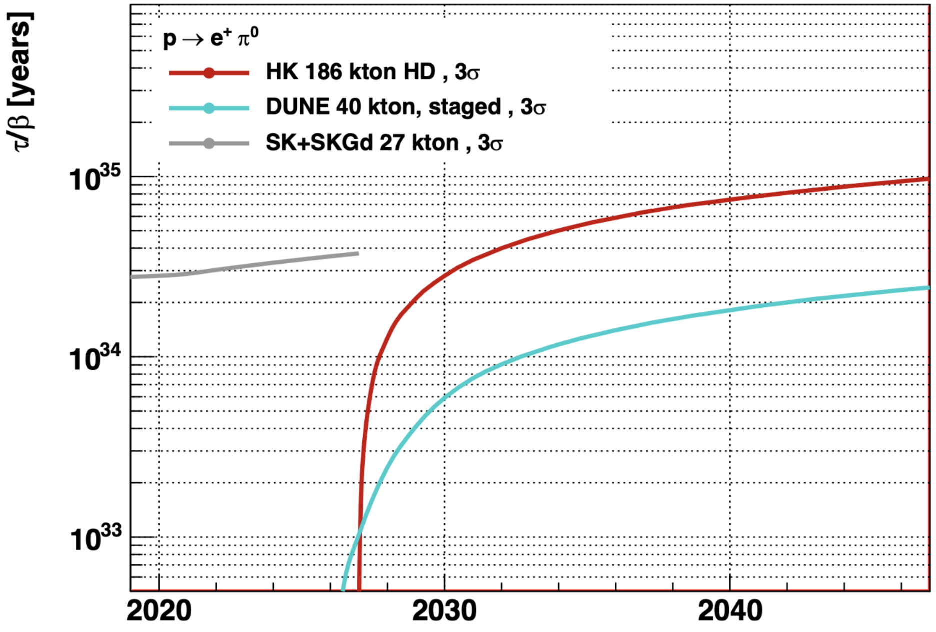
Search for proton decay

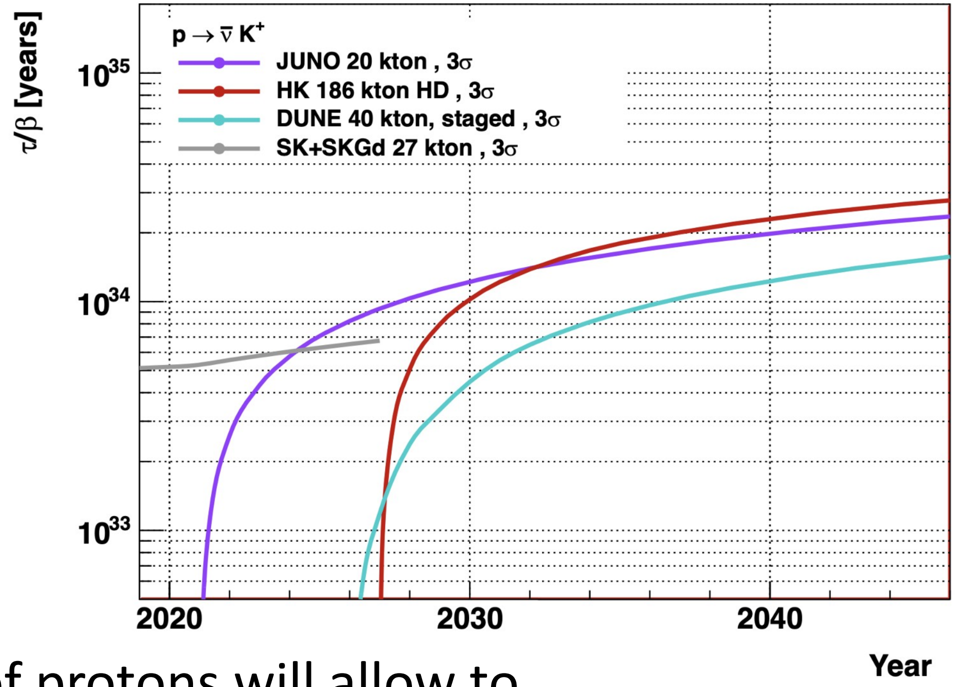


- Positron and photons are reconstructed as e-like rings
- Neutron capture on water, 2.2MeV γ, efficient tagging of prompt γ from residual nuclei deexcitation

- Kaon is not visible in water Cherenkov detector, but it's reconstructed from the decay products: monochromatic muon (236MeV) and prompt photon (6.3MeV)

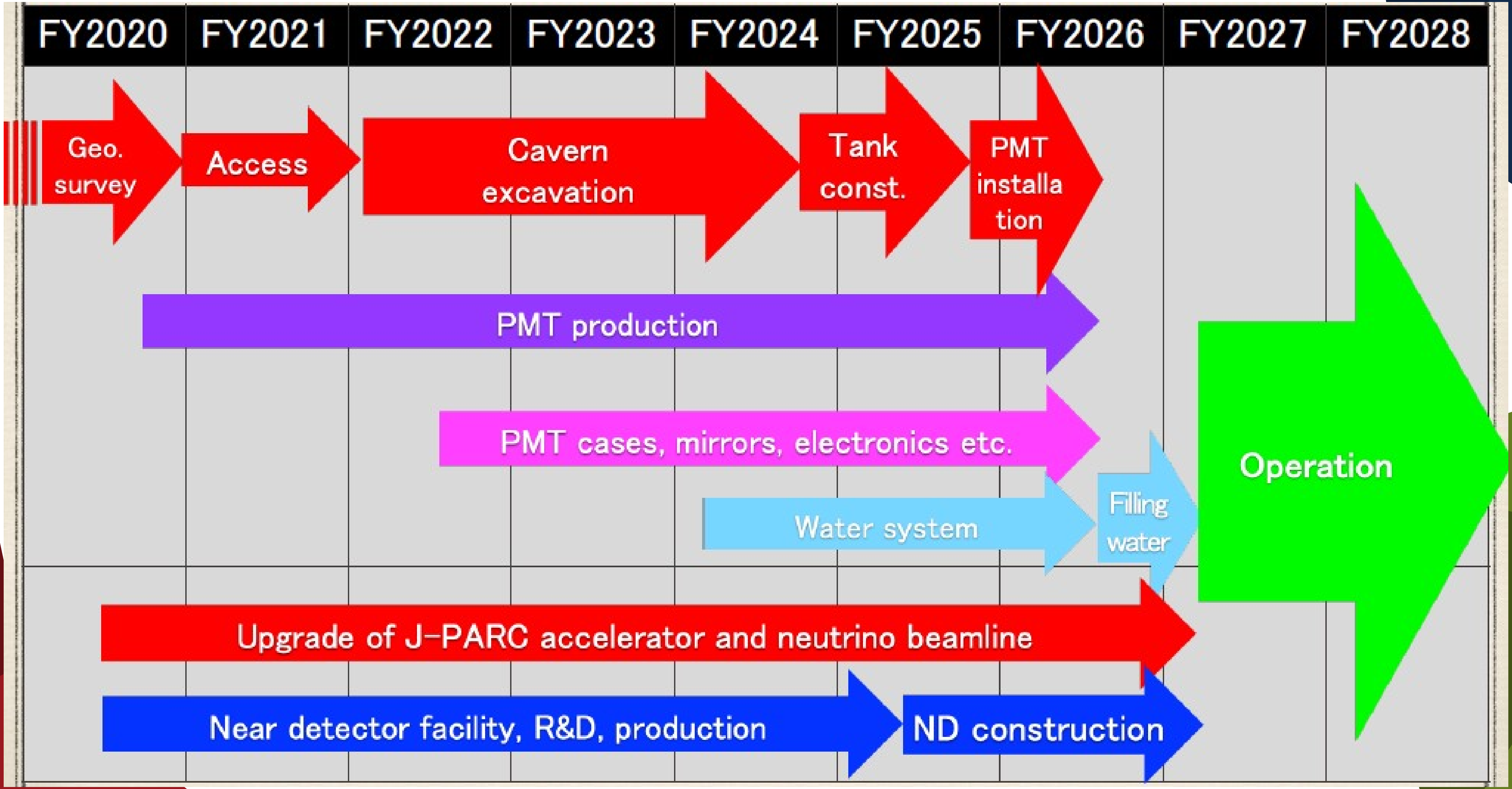






Huge water tank containing a lot of protons will allow to extend current limits by one order of magnitude

Hyper-Kamiokande schedule



Summary

- **T2K** is performing precise measurements of θ_{23} and Δm^2_{23} and looking for CP violation and determination of mass ordering. Its program will be continued by the Hyper-Kamiokande experiment.

- New analysis has been enhanced with new samples allowing:

  - exclude at 90%CL conservation of CP symmetry

  - obtain mild preference for normal ordering and upper octant

- Future will use SK-Gd data, perform joint analysis of T2K-SK atmo, T2K-NOνA and upgrades of the ν beam and the Near Detector

- **Hyper-Kamiokande** planned to operate in 2027

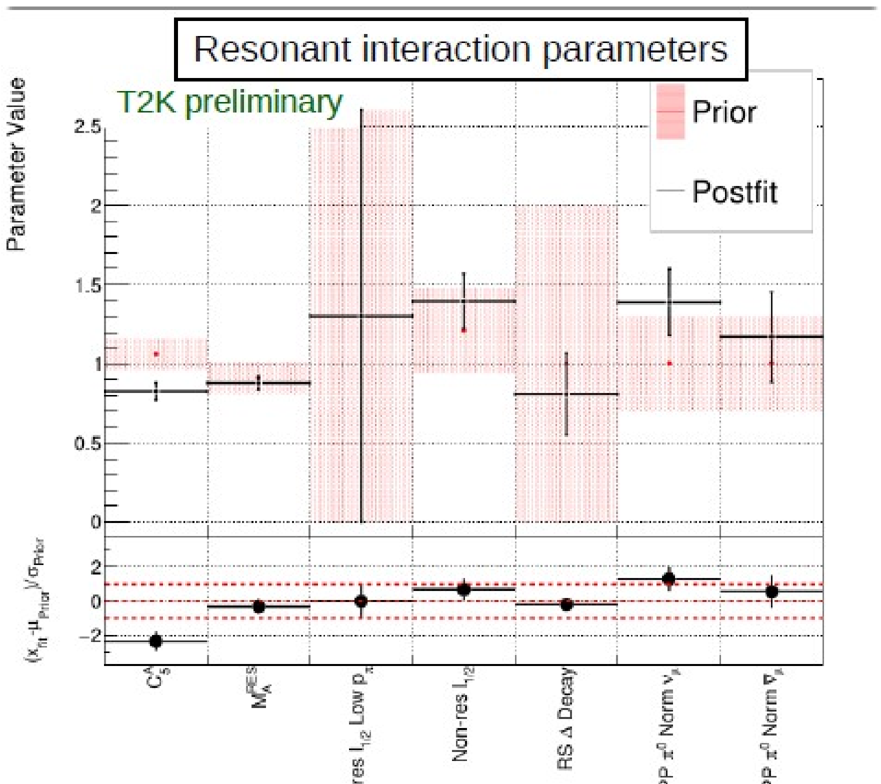
  - wide physics program including ν oscillations, proton decay, solar and atmospheric ν, Supernovae burst and dark matter search

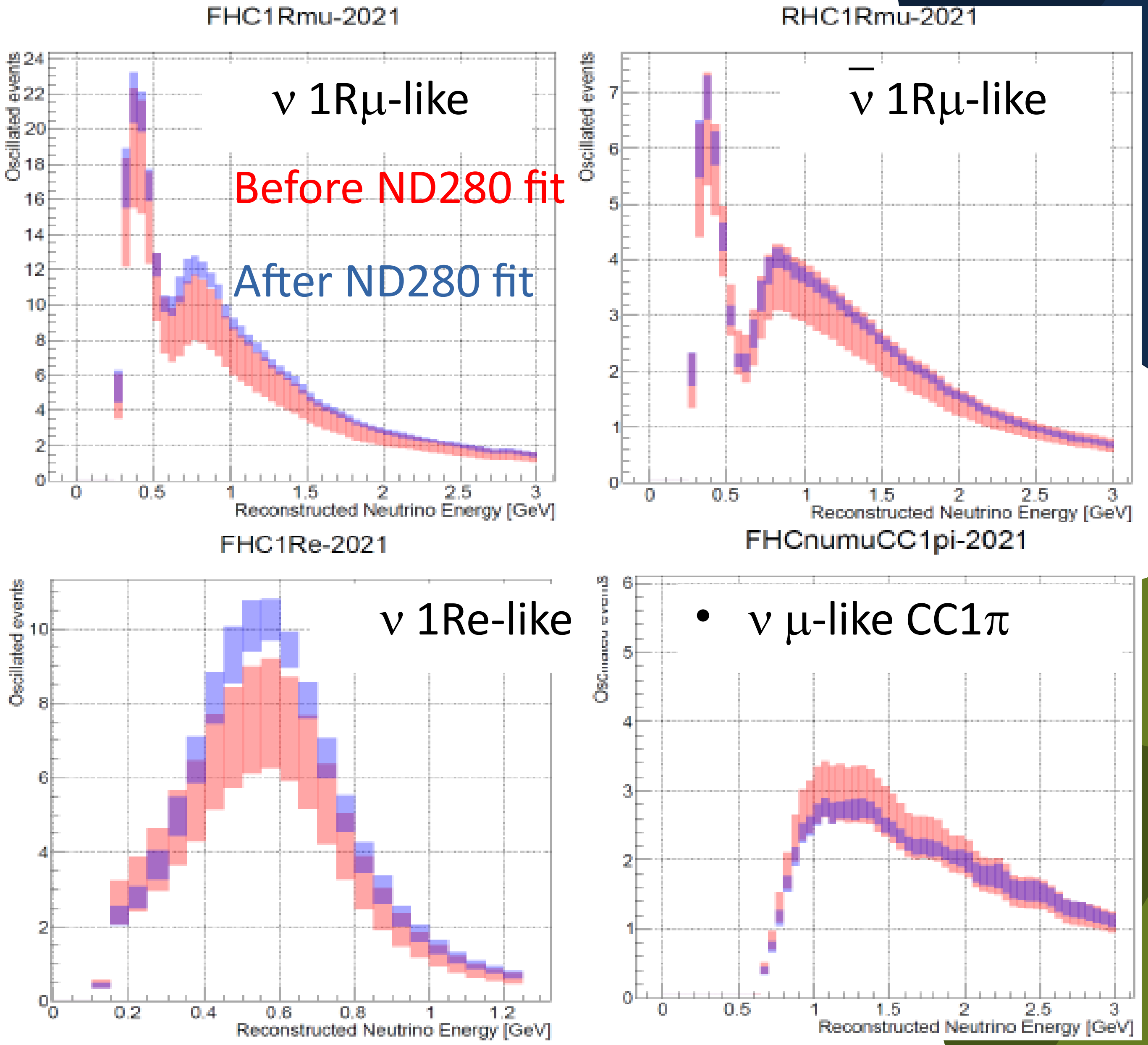
- Ongoing R&D of new photomultipliers

Backup Slides

Near Detector fit results

- Constraint neutrino flux and provides prediction of flux for Far Detector including CC1π sample
- Constrain interaction parameters and their uncertainties





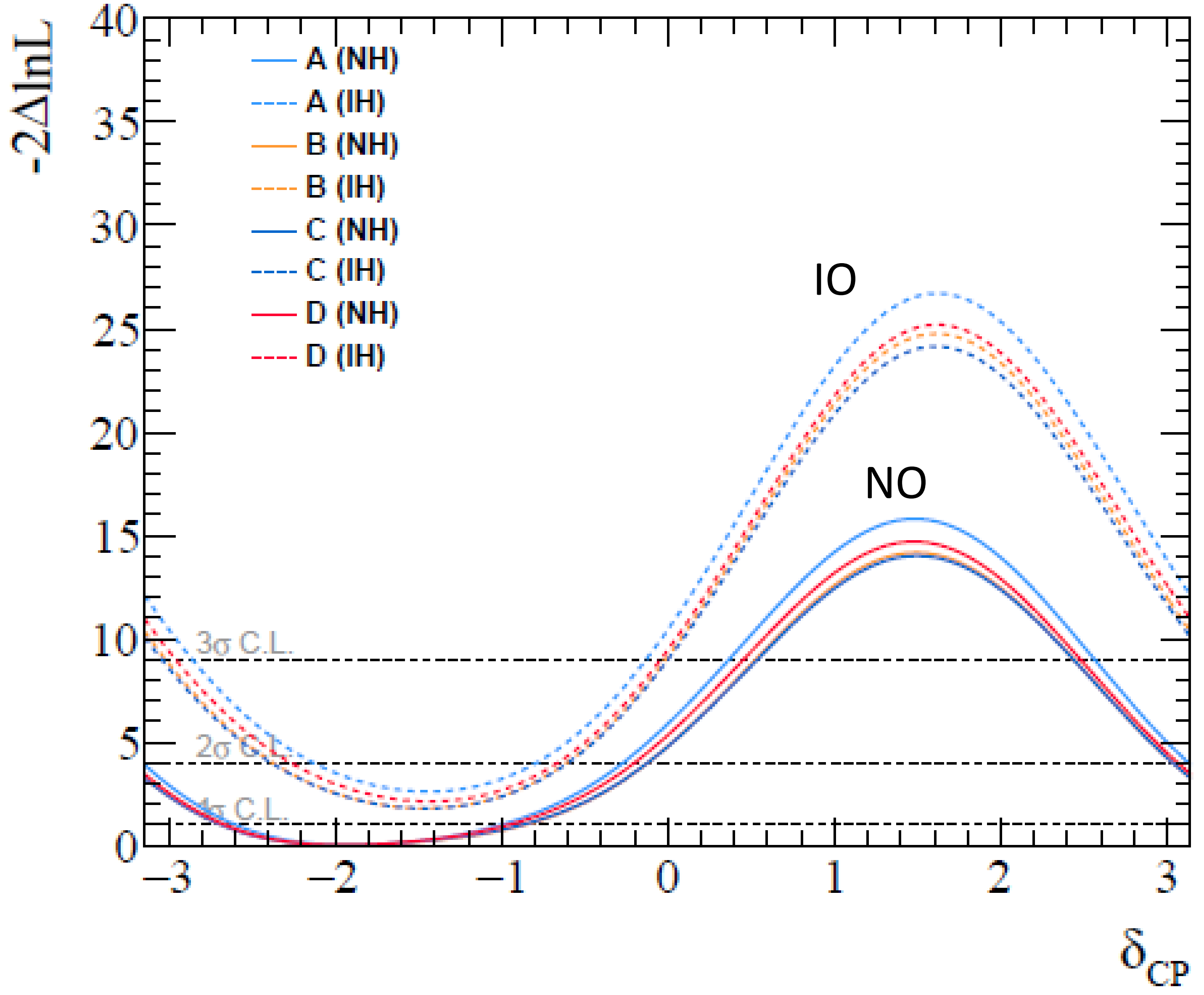
Effect of changes in the oscillation analysis

A – Neutrino 2020

B – A + new Interaction model and new proton and photon samples in Near Detector

C – B + modification of reactor constraint from PDG2019 to PDG2021

D – C + multi ring ν_μ CC1π



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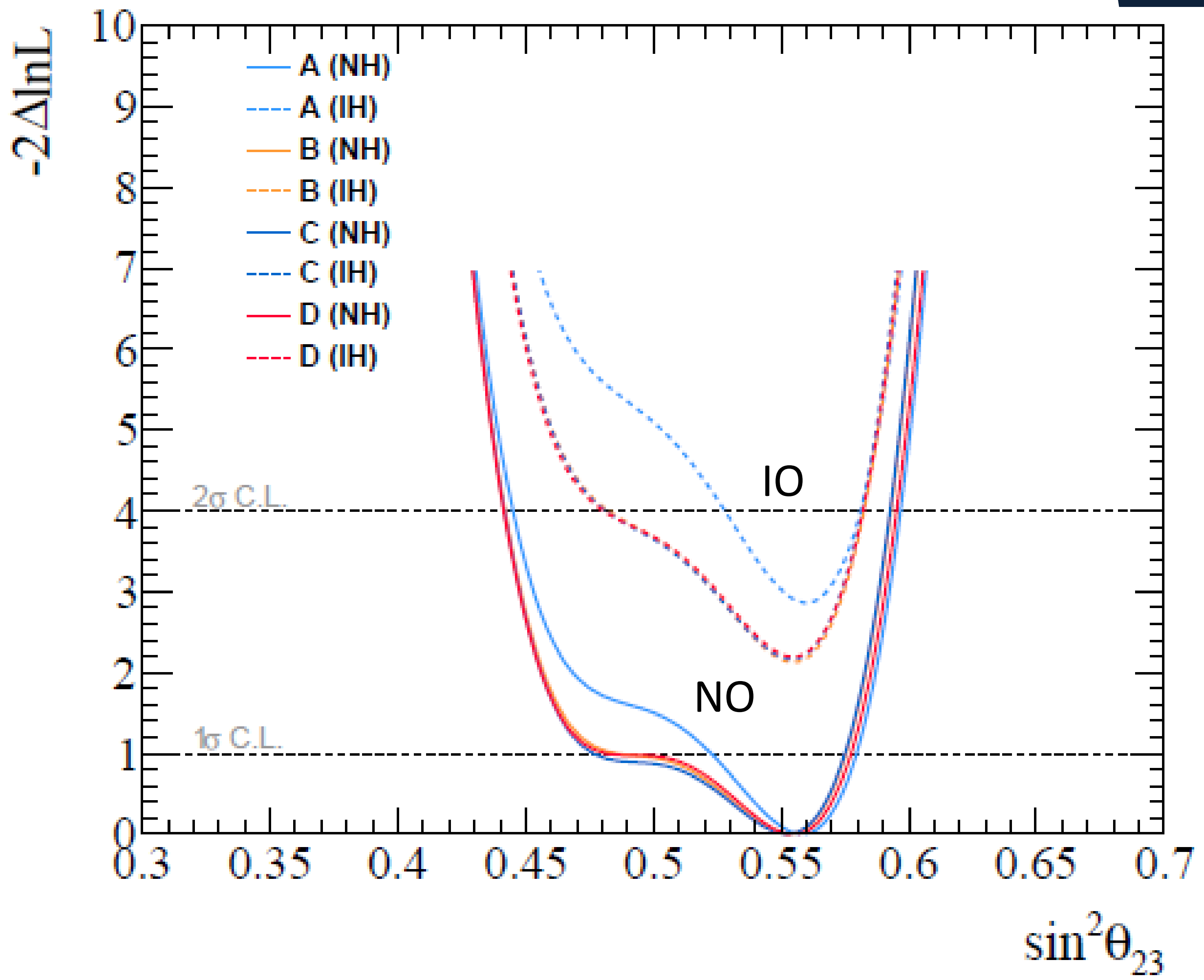
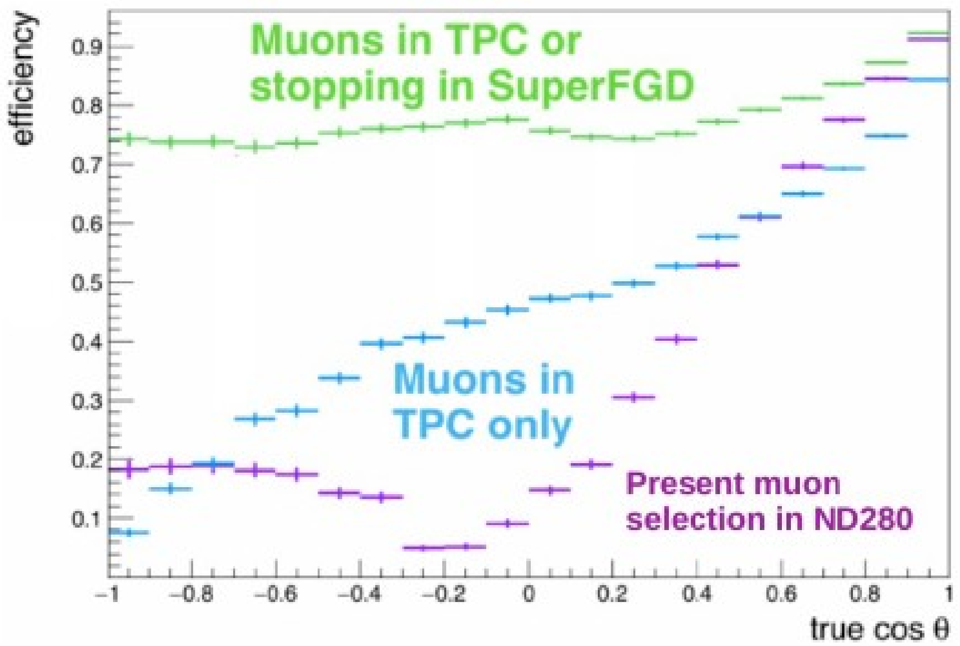
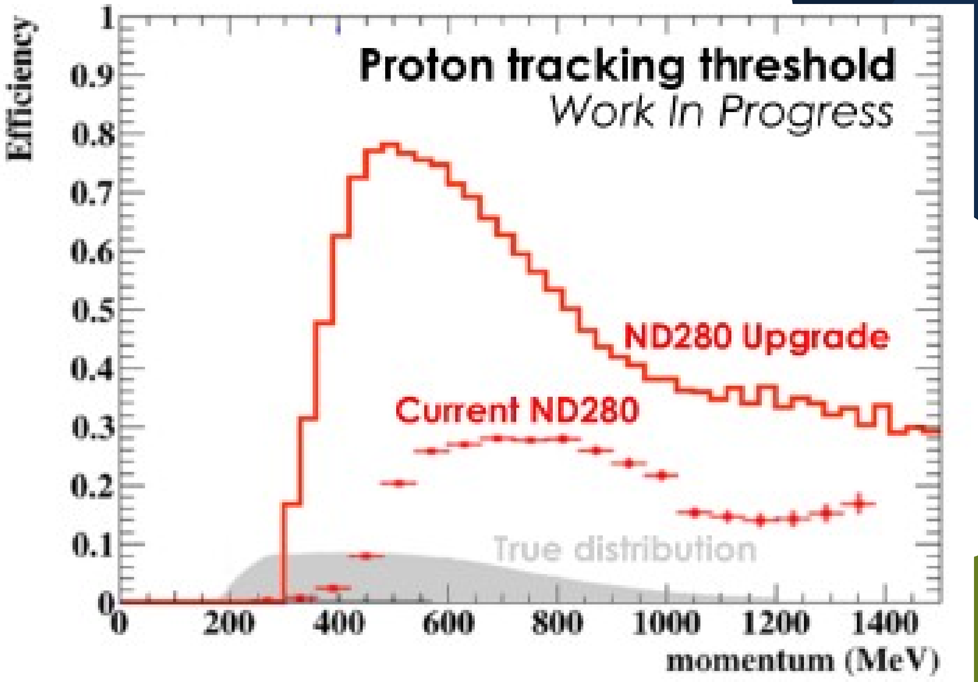
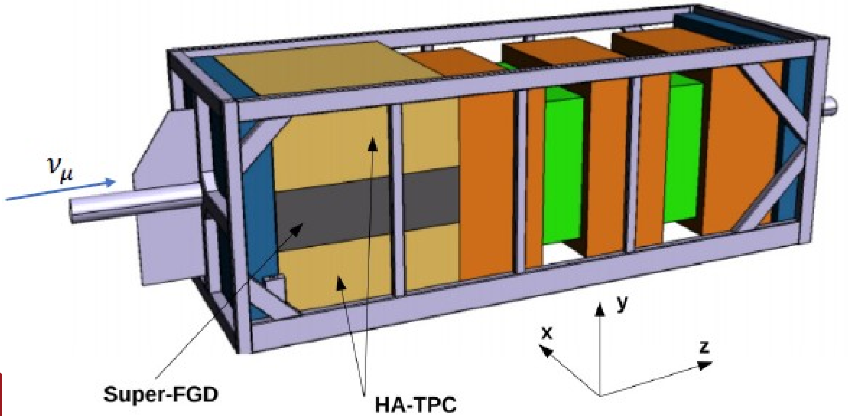


Near Detector upgrade- performance







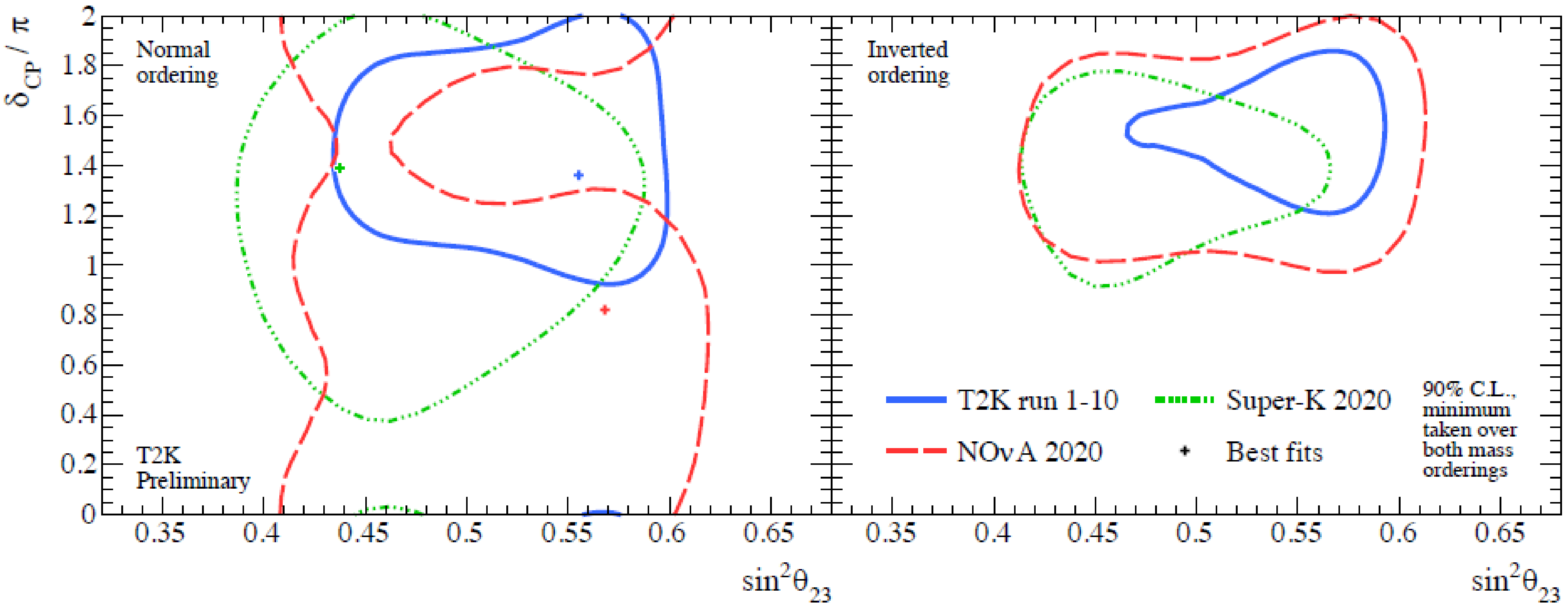
- SuperFGD – 2million of 1cm^3 cubes – high granularity
- High angle TPC
- Time of Flight detector

T2K and NOνA comparison

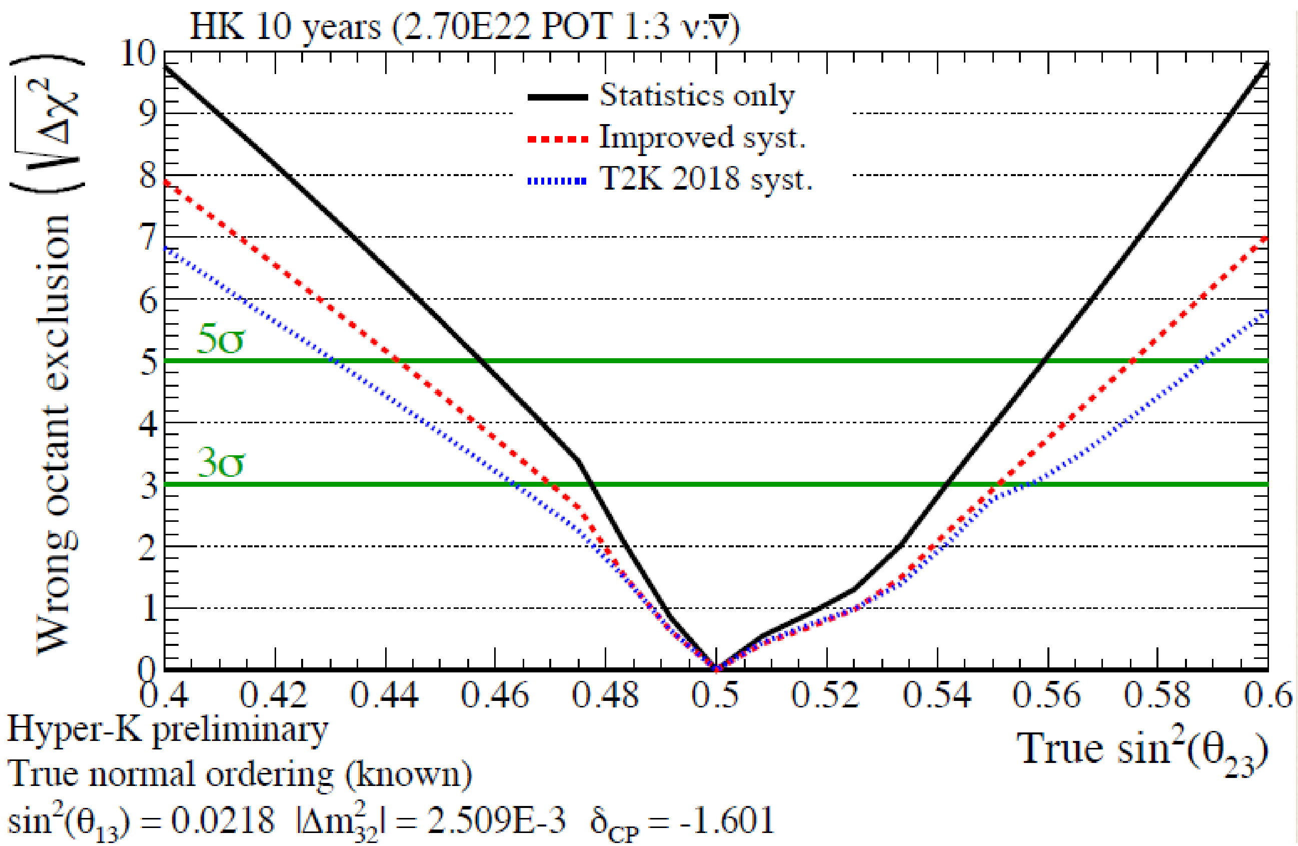
Oscillation Analysis Neutrino 2020

T2K and NOvA 90% contours overlap with best fit δ_{CP}- θ_{23} points just outside of 90% contours and similar θ_{23} best fit values

Consistent δ_{CP} with Super-K, but prefer different θ_{23} octant



Octant sensitivity from beam neutrinos



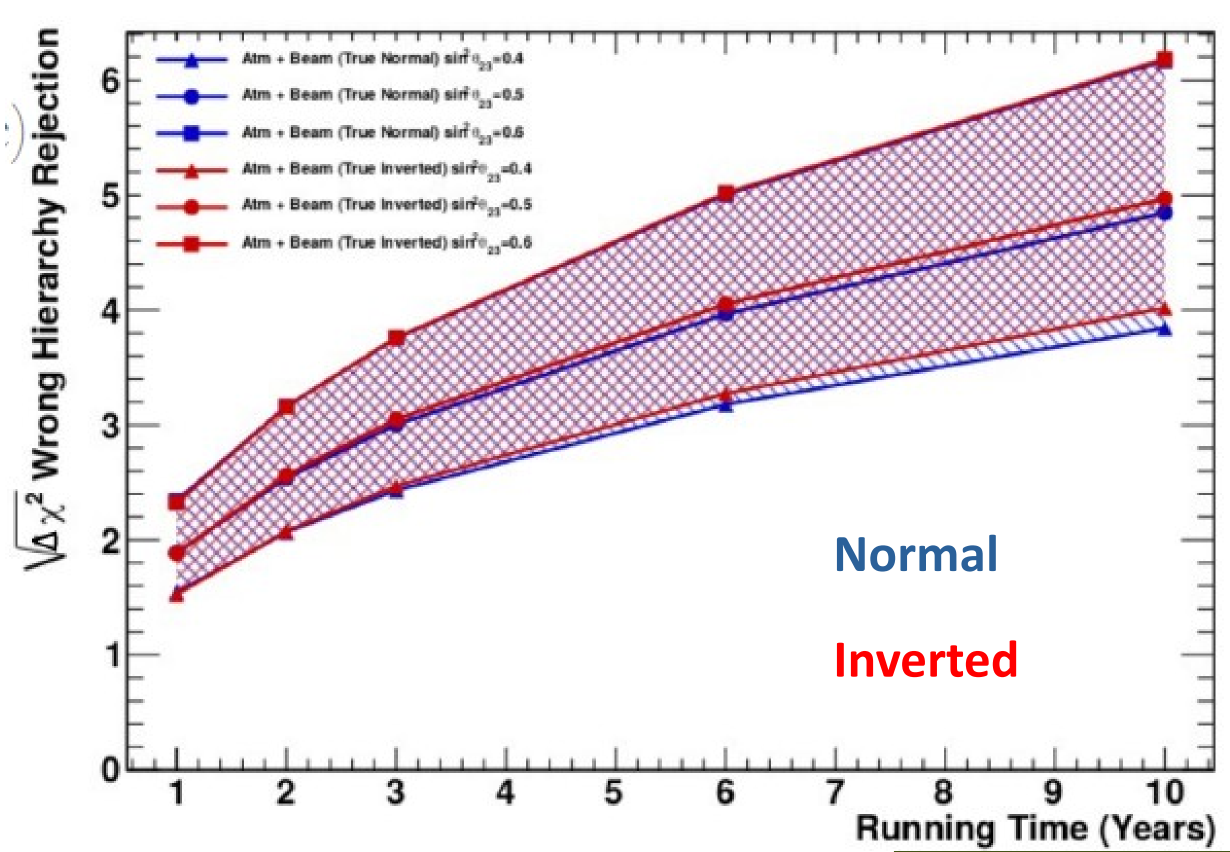
- For known normal ordering and improved systematics exclude wrong octant >5σ unless $0.47<\sin^2\theta_{23}<0.55$

Atmospheric neutrinos

- Strong matter effects for neutrinos passing through the Earth (up to 12 000 km)

  - for normal ordering
    $\nu_\mu \rightarrow \nu_e$ is enhanced

  - for inverted ordering
    $\nu_\mu \rightarrow \nu_e$ is enhanced



- Joint analysis of beam and atmospheric data can exclude wrong mass ordering of 4-6σ depending on $\sin^2\theta_{23}$