Summary of Task 2.4 for WP2 – Neutrino oscillation analysis

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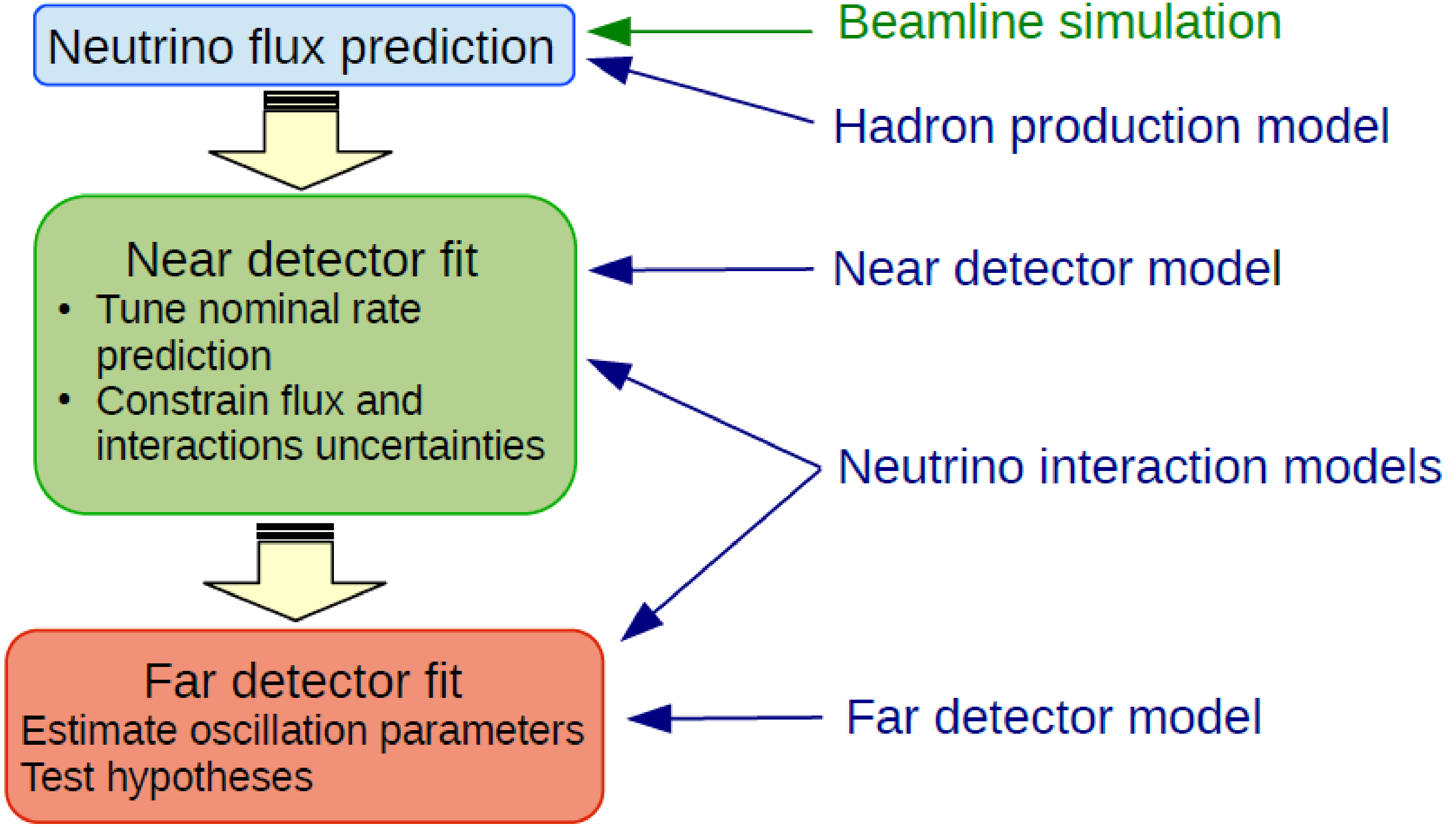
Oscillation analysis

- 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

Proton selection in ND280

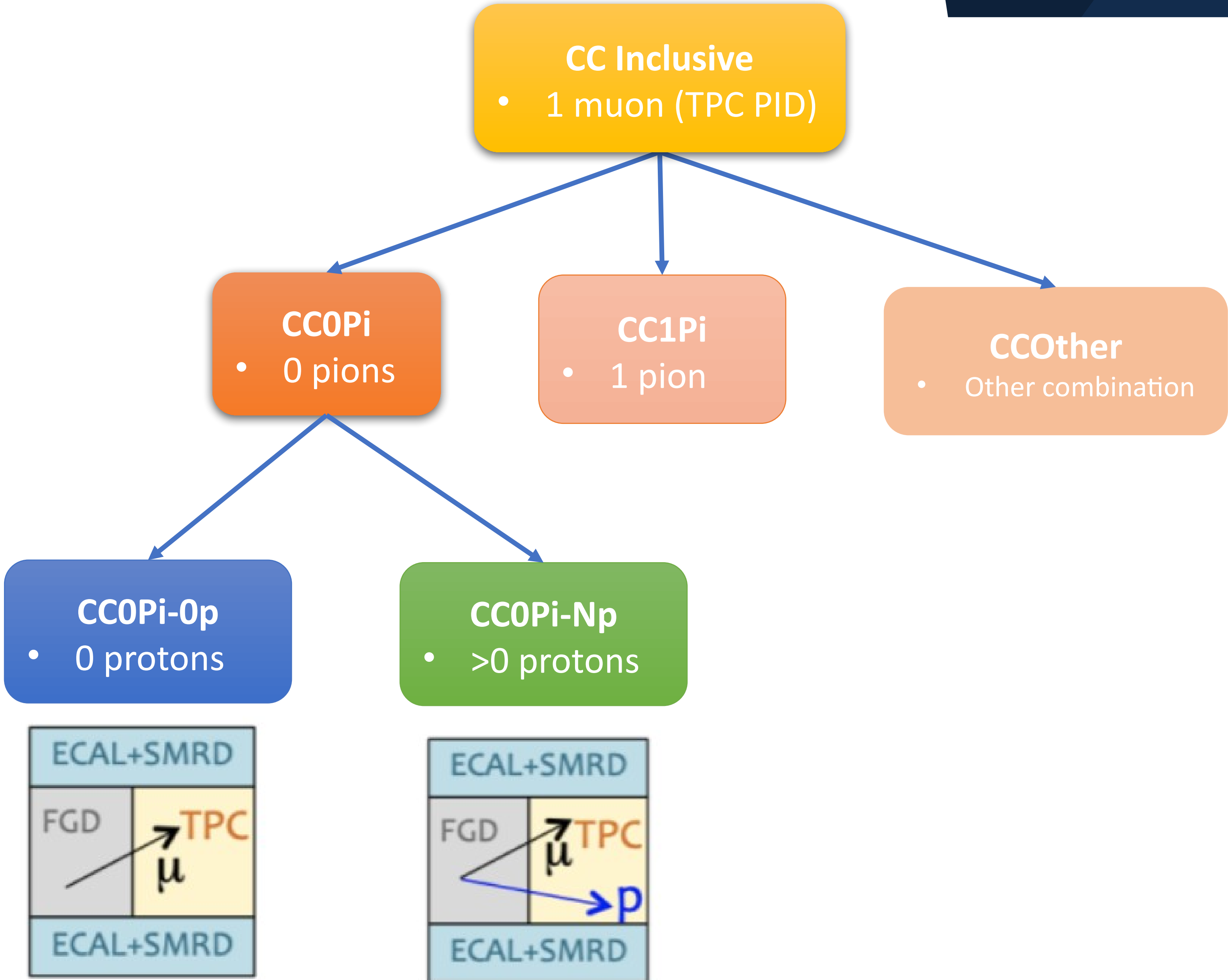
ND280 fit is important part of **T2K** oscillation analysis.

ND280 fit uses various samples (from FGD1 and FGD2), based on pion multiplicity.

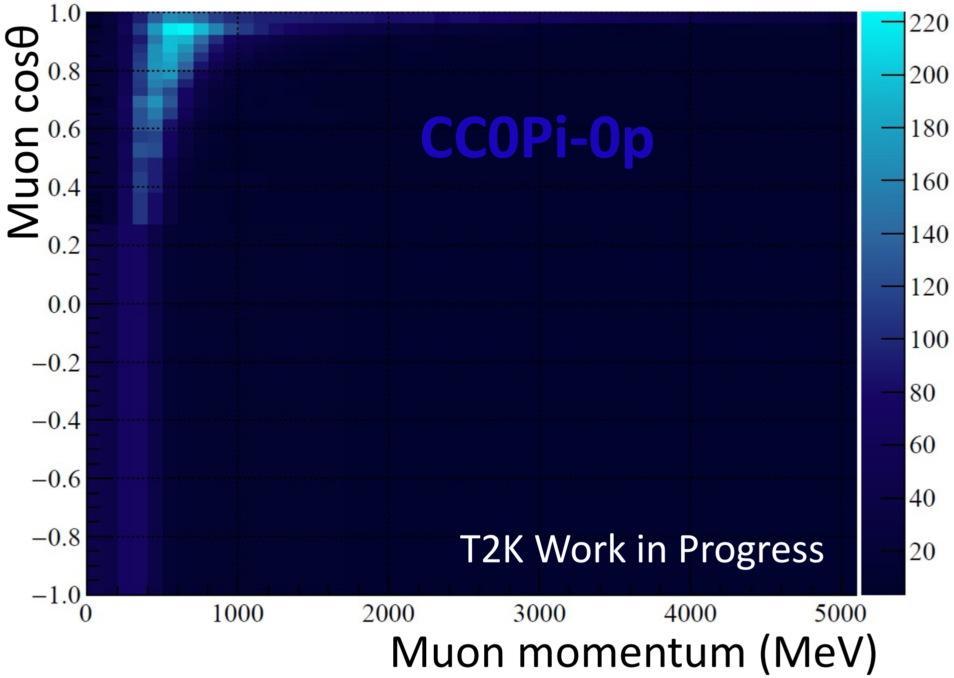
Each sample has different physical properties and allows to probe different neutrino interactions.

Muon kinematics (momentum and emission angle) is used for fitting MC to data.

Proton samples: **CC0Pi-0p** and **CC0Pi-Np** originate from split of **CC0Pi** based on proton multiplicity (TPC and FGD PID).



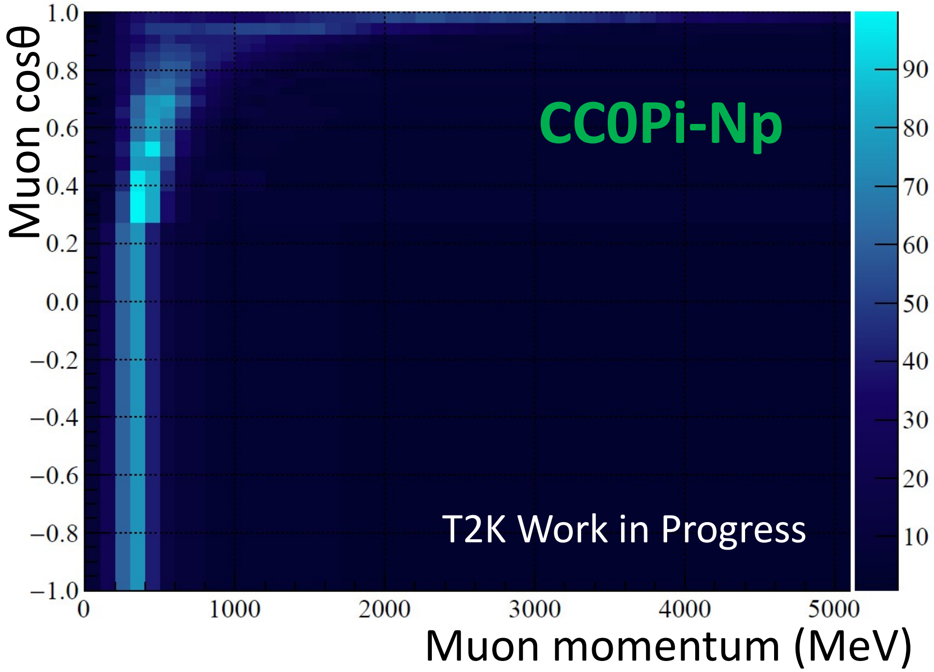
Properties of proton sample



Both samples have different phase space of muon kinematics.

ND280 proton tracking threshold is about 450-500 MeV/c.

Different fraction of reactions.



CC0Pi-0p - lower muon momentum, mostly forward going muons.

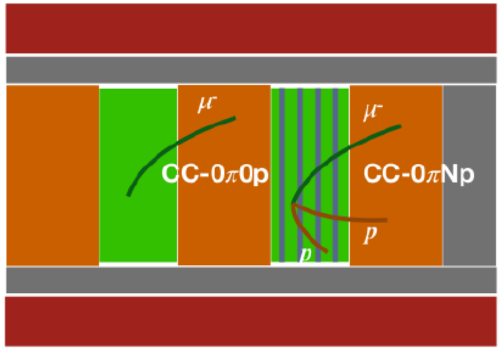
Better purity for CCQE.

	CC0Pi	CC0Pi-0p	CC0Pi-Np
	Fraction %	Fraction %	Fraction %
CCQE	51	58	38
2p2h	11	10	11
RES	23	19	30
Other	15	13	21

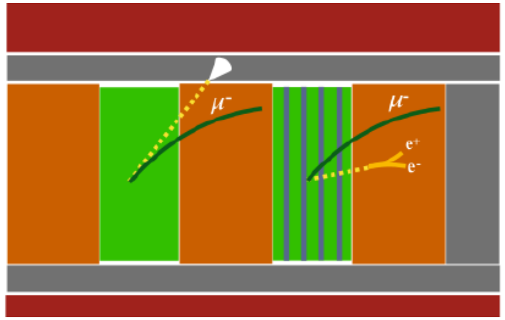
CC0Pi-Np - higher muon momentum, more muons going at higher angle.

Better purity for non-CCQE contributions.

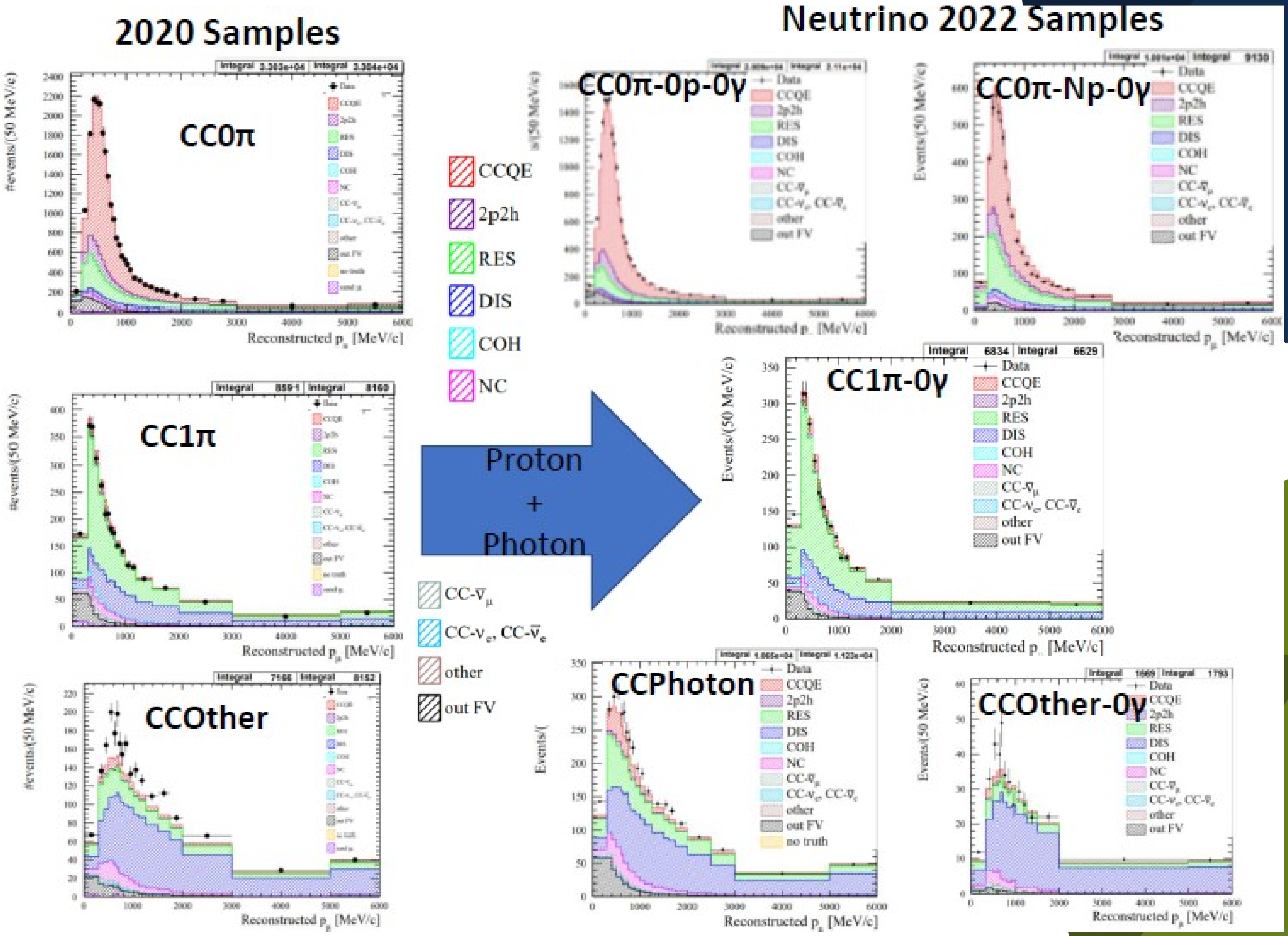
New selection in Near Detector



Increase ability to constrain CCQE and 2p2h in selected samples

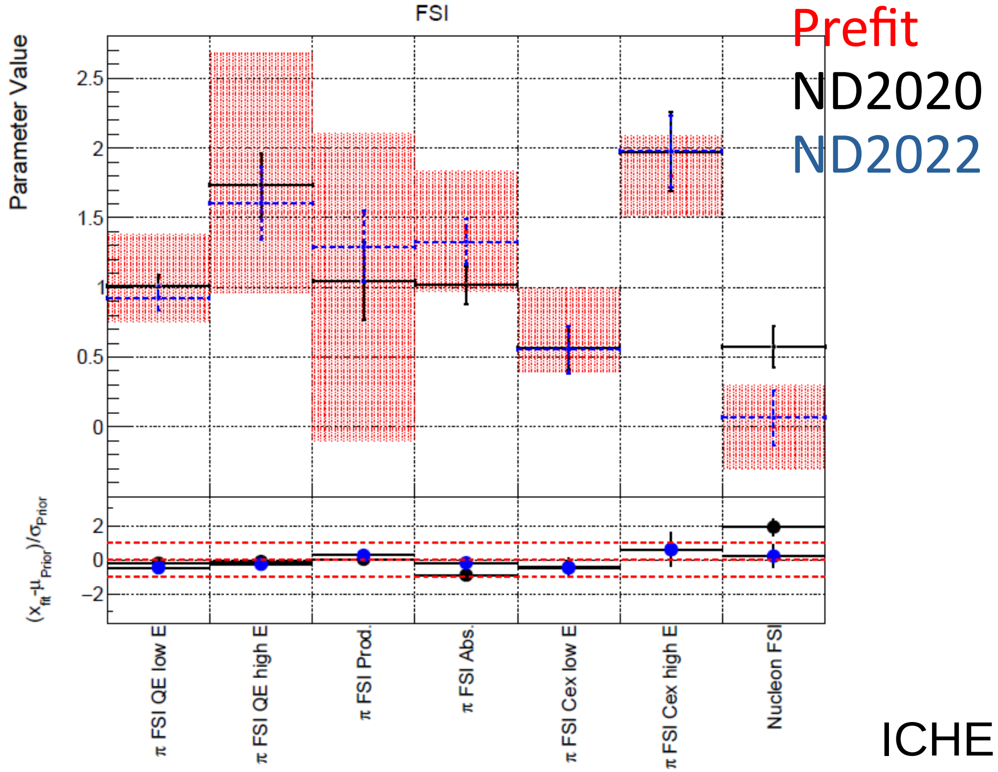


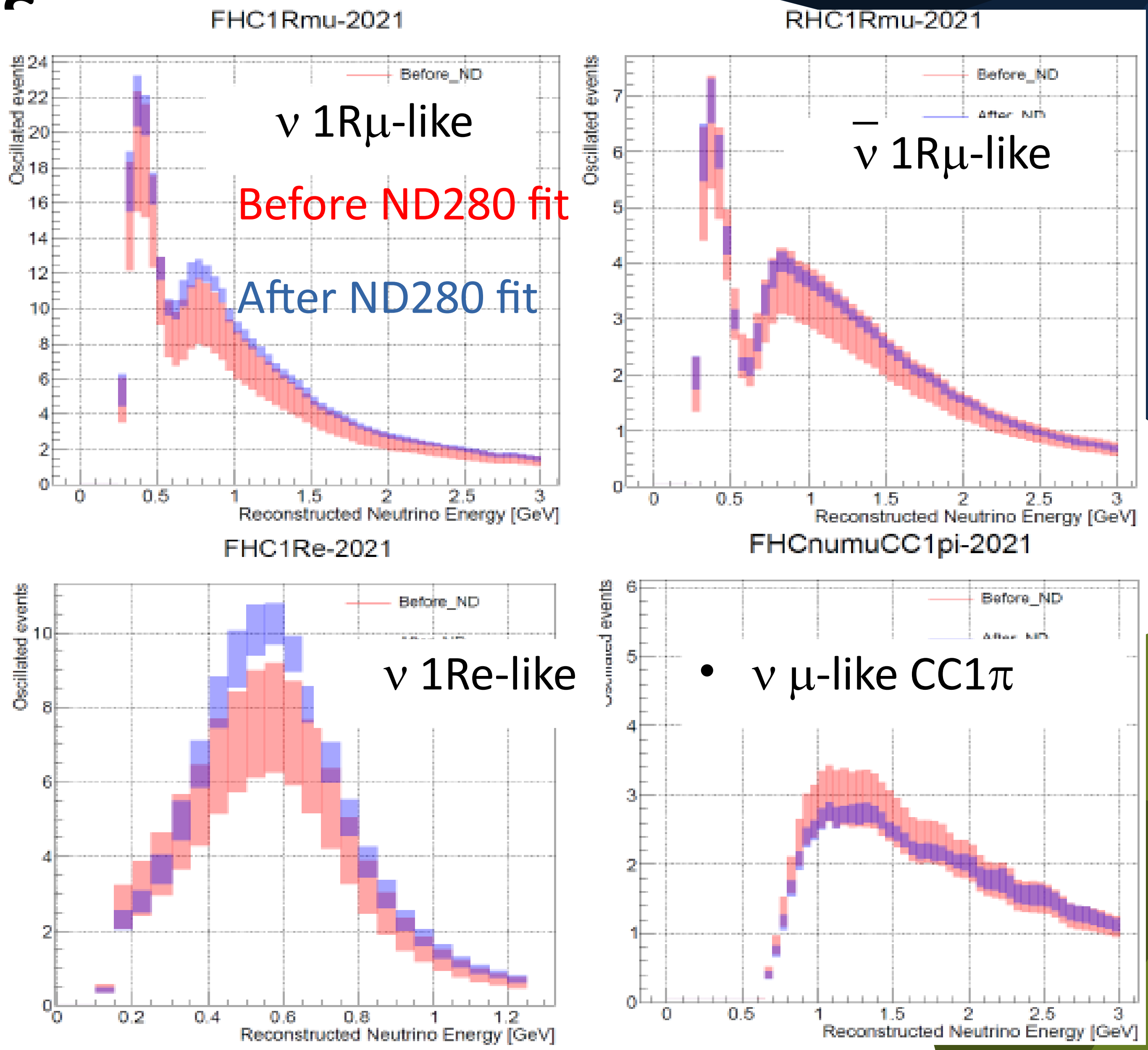
Creates new samples dominated by DIS and $CC\pi^0$



Near Detector fit results

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





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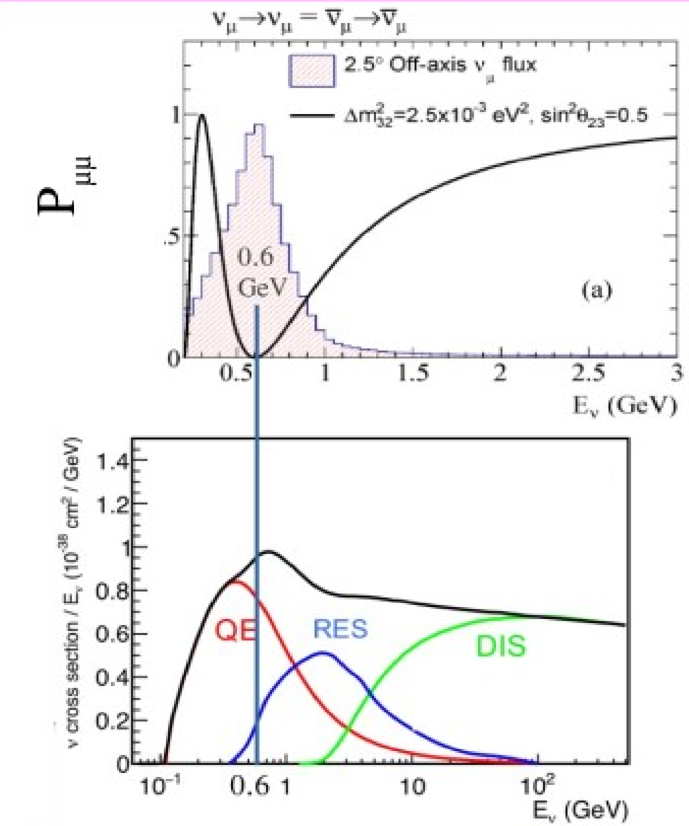
Multi-ring ν_μ charged current $1\pi^+$ events

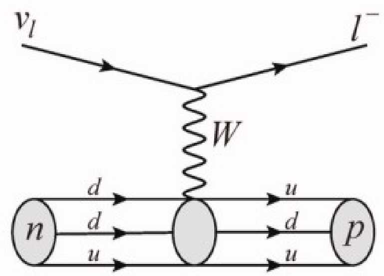
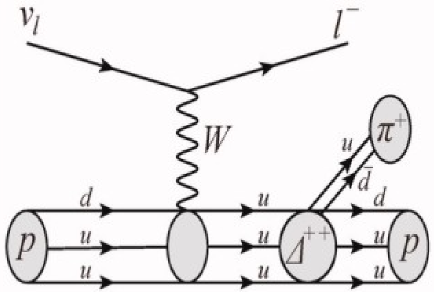


- Most dominant interaction at T2K flux peak: Charged Current Quasi Elastic (CCQE) interaction of ν and $\bar{\nu}$:
  $\nu_l + n \to l^- + p$; $\bar{\nu}_l + p \to l^+ + n$.

- 2[nd] dominant interaction: Resonant single pion production

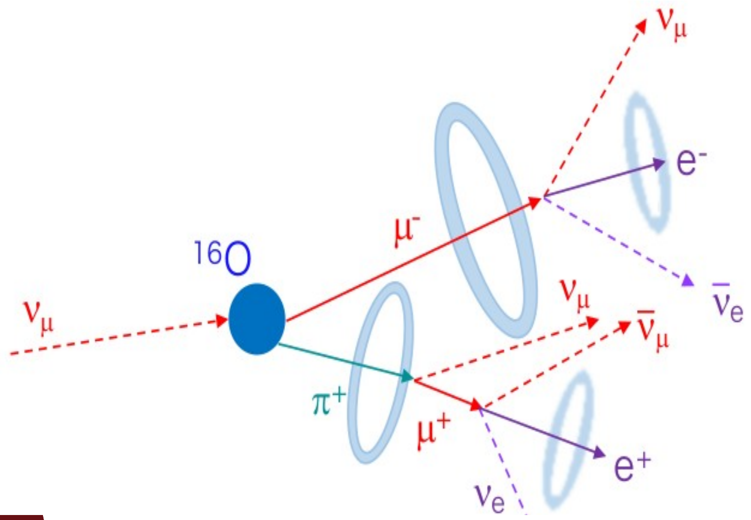
$$\nu_l\, p \to l^-\, p\, \pi^+ \;;\; \bar{\nu}_l\, p \to l^+\, p\, \pi^-$$
$$\nu_l\, n \to l^-\, n\, \pi^+ \;;\; \bar{\nu}_l\, n \to l^+\, n\, \pi^-$$
$$\nu_l\, n \to l^-\, p\, \pi^0 \;;\; \bar{\nu}_l\, p \to l^+\, n\, \pi^0$$

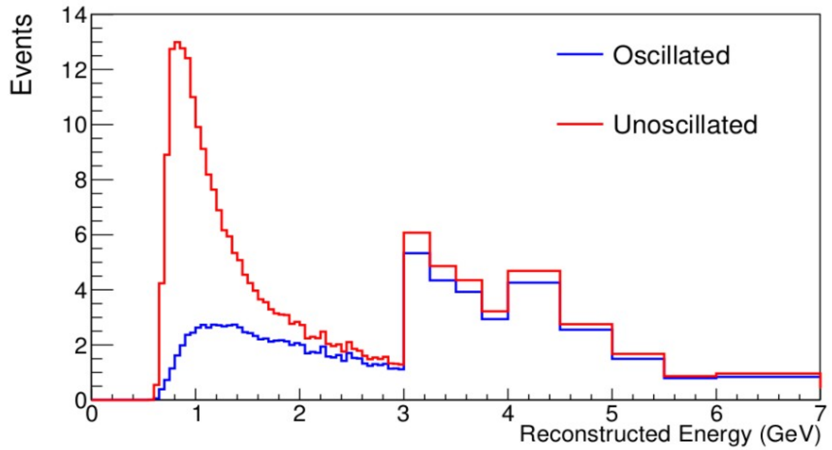
6 Far detector samples at SK

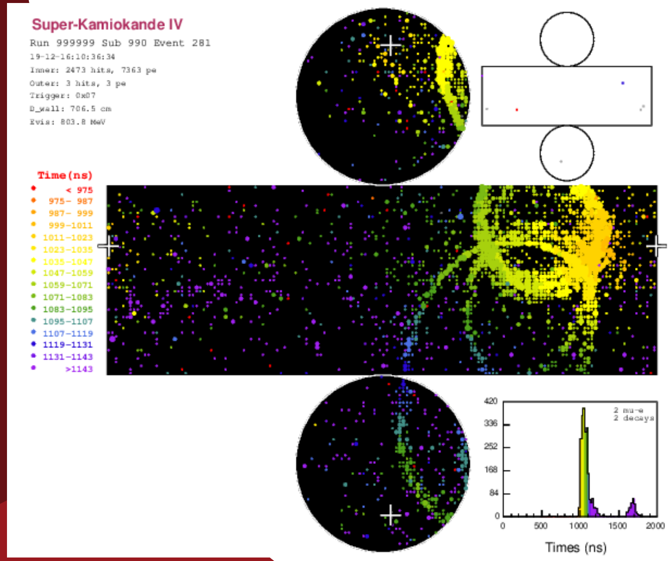
Interaction	Visible Topology	Mode
$\nu_l, \bar{\nu}_l$ CCQE, $l = \mu, e$ 	1 ring μ–like 1 ring e–like	ν and $\bar{\nu}$
ν_l CC RES $1\pi^+$, $l = e, \mu$ 	1 ring e–like + 1 decay electron (π^+ is below the Cherenkov threshold) Multi-ring ν_μ charged current $1\pi^+$ events: 1 ring each from μ^- and π^+ (above cherenkov threshold) + 1 or 2 decay electrons; 1 ring from μ- only (π^+ is below cherenkov threshold) + 2 decay electrons	ν only

Multi-ring ν_μ charged current $1\pi^+$ events in SK

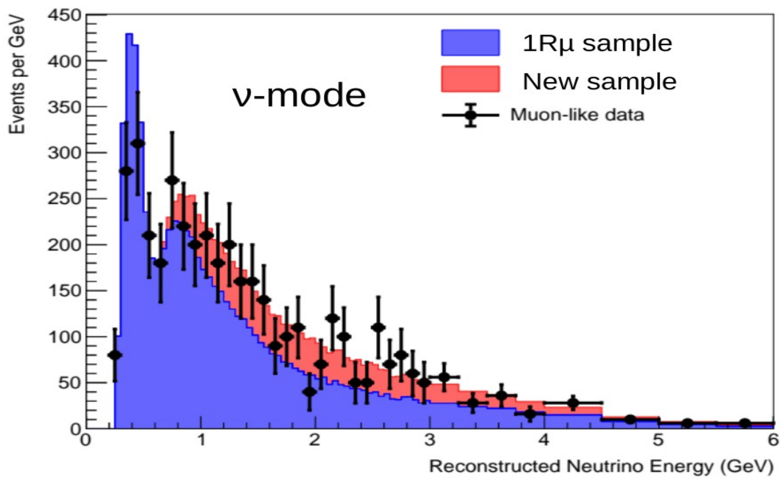
- NEW! Included from T2K run 1-10 ν mode data for the first time in T2K oscillation analysis.
- Parent E_ν ~1.2 GeV → oscillation effect is still present.



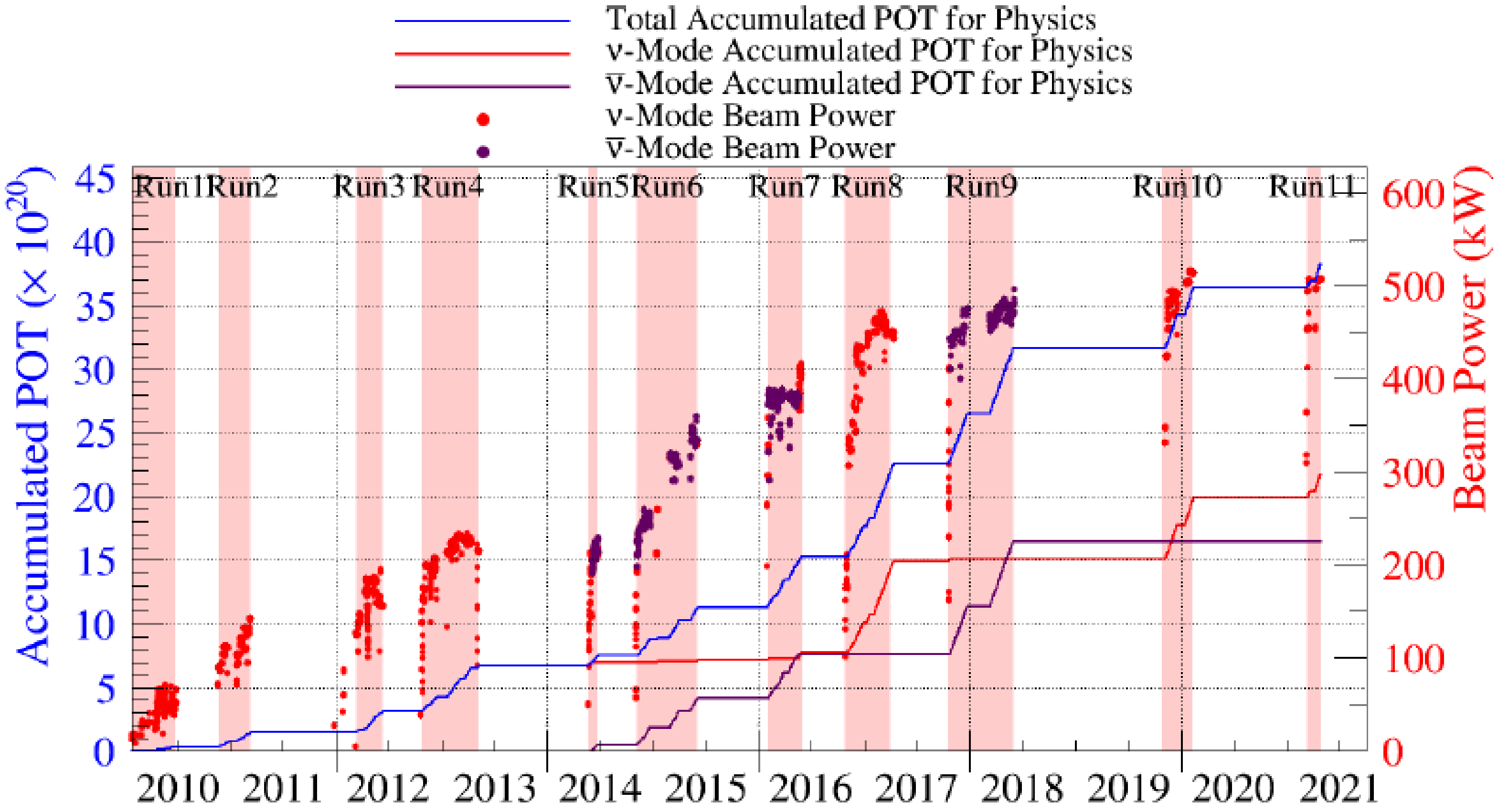




~30% increase in total ν_μ-like events: Sensitive to θ_{23} & $|\Delta m^2_{32}|$.



Same data set as in 2020 analysis



Used here:

Near detectors

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

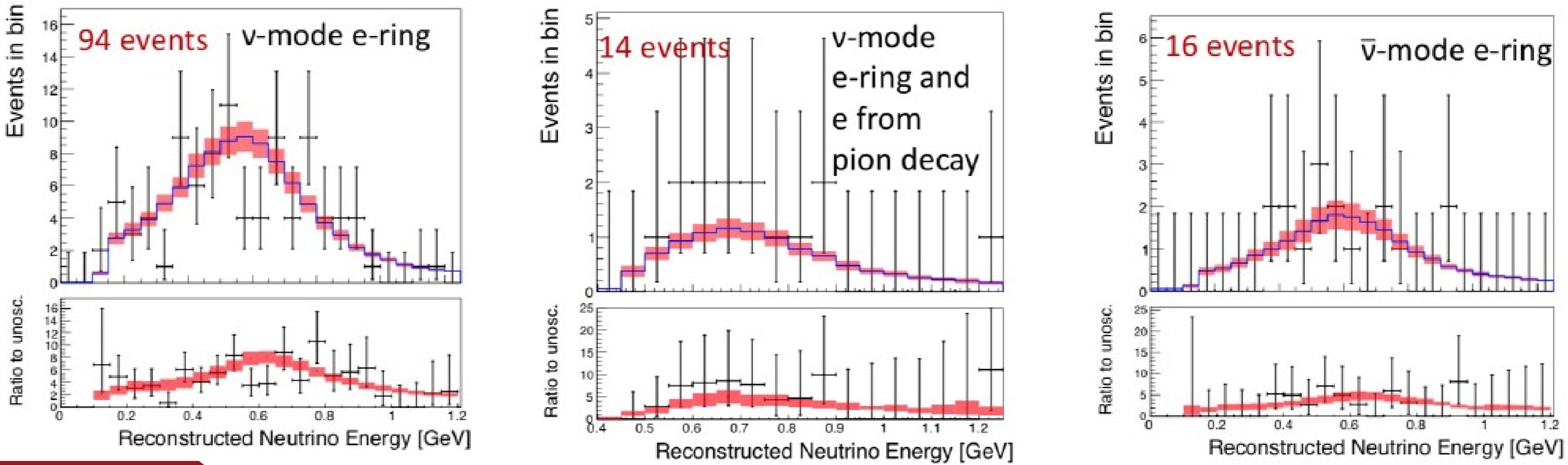
Far detector

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

Far Detector samples

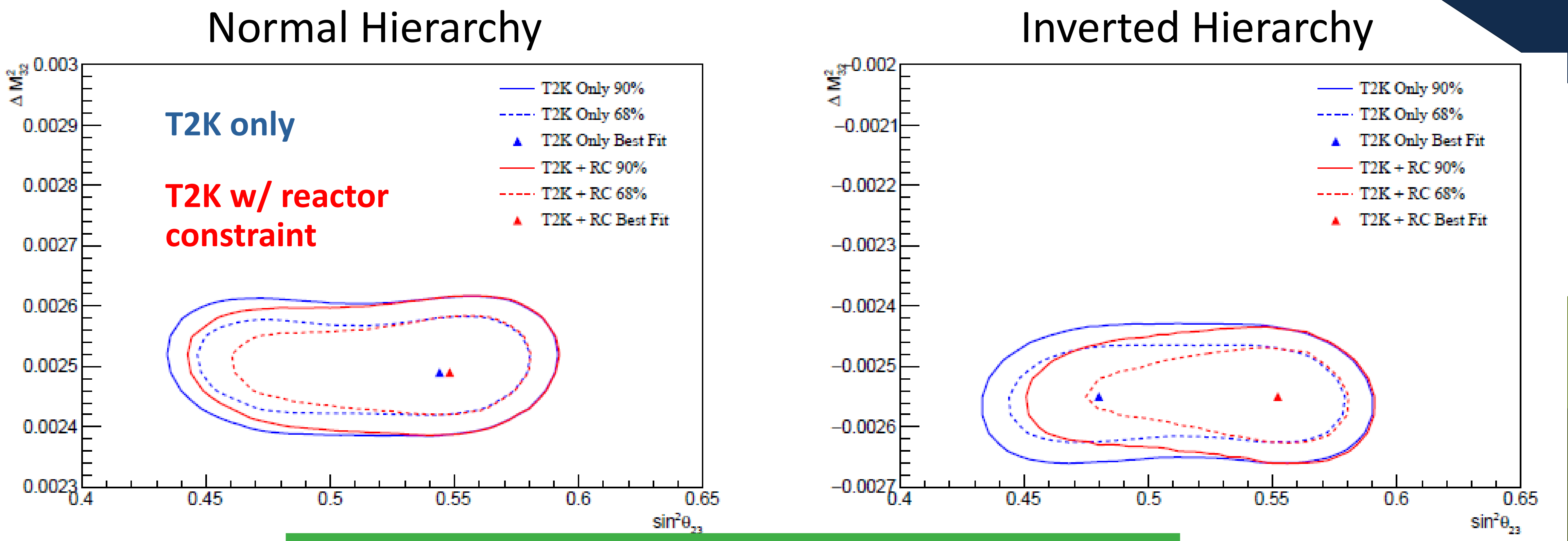
- Detected number of ν_e events consistent with $\delta_{CP}=-\pi/2$
- New sample of ν_μ CCπ increase statistics of about 30%

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)

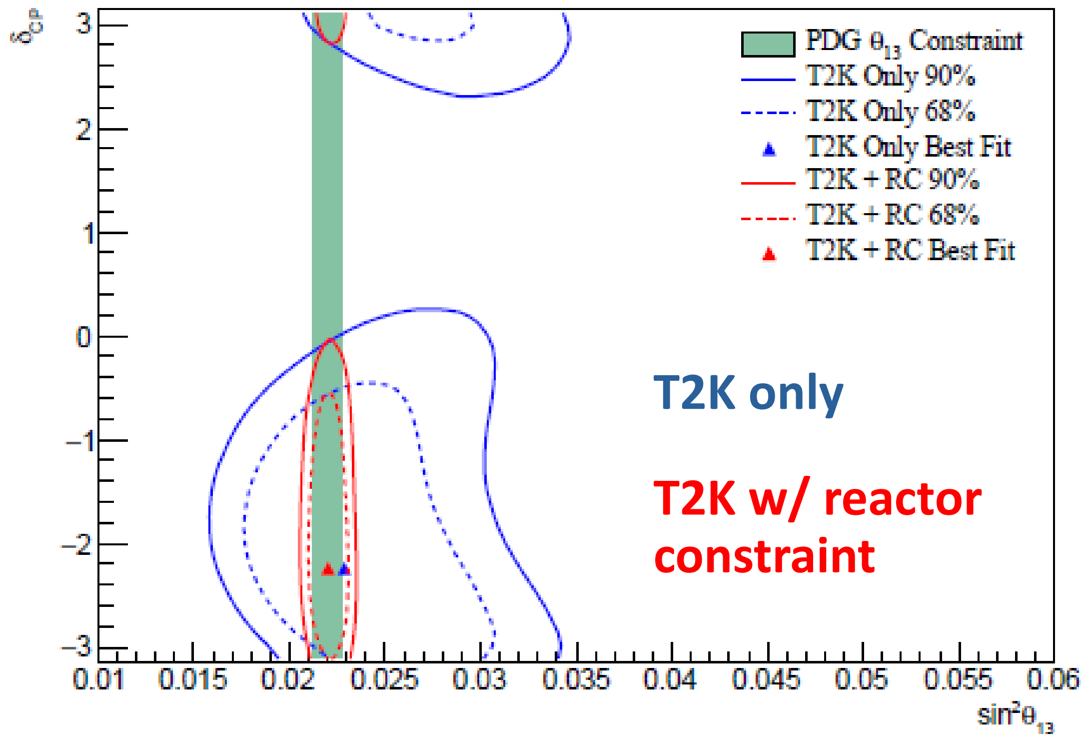


Best fit in the upper octant, lower octant still allowed in 68% CL

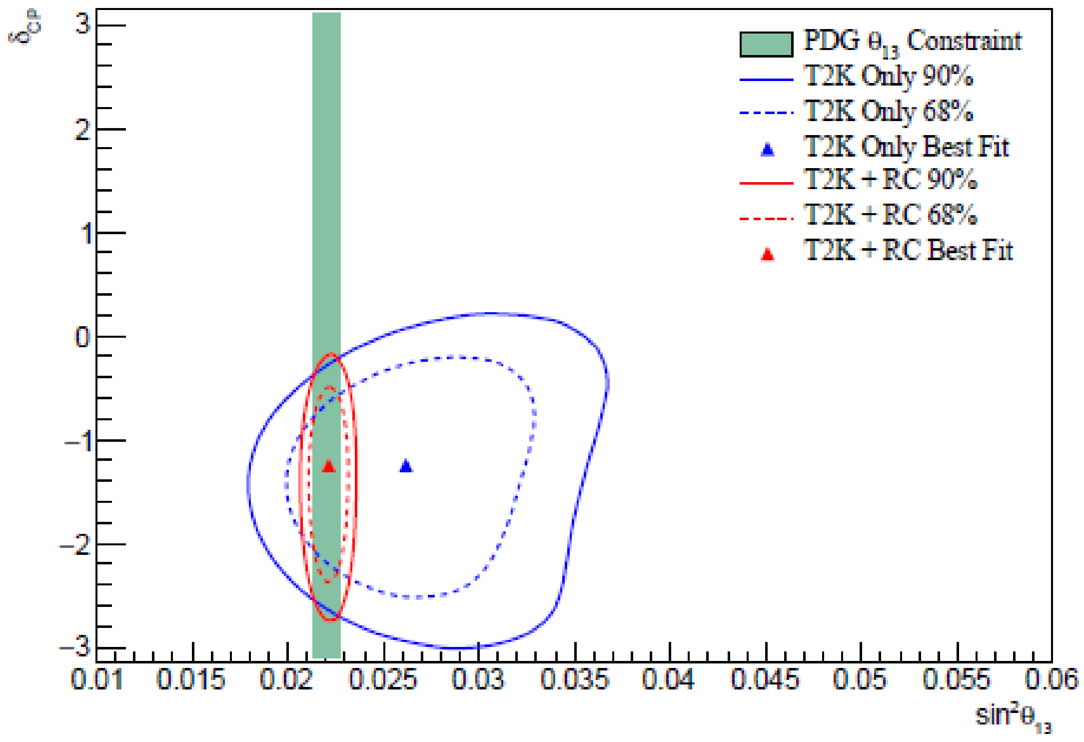
Results on δ_{CP} and θ_{13}

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

Normal Hierarchy

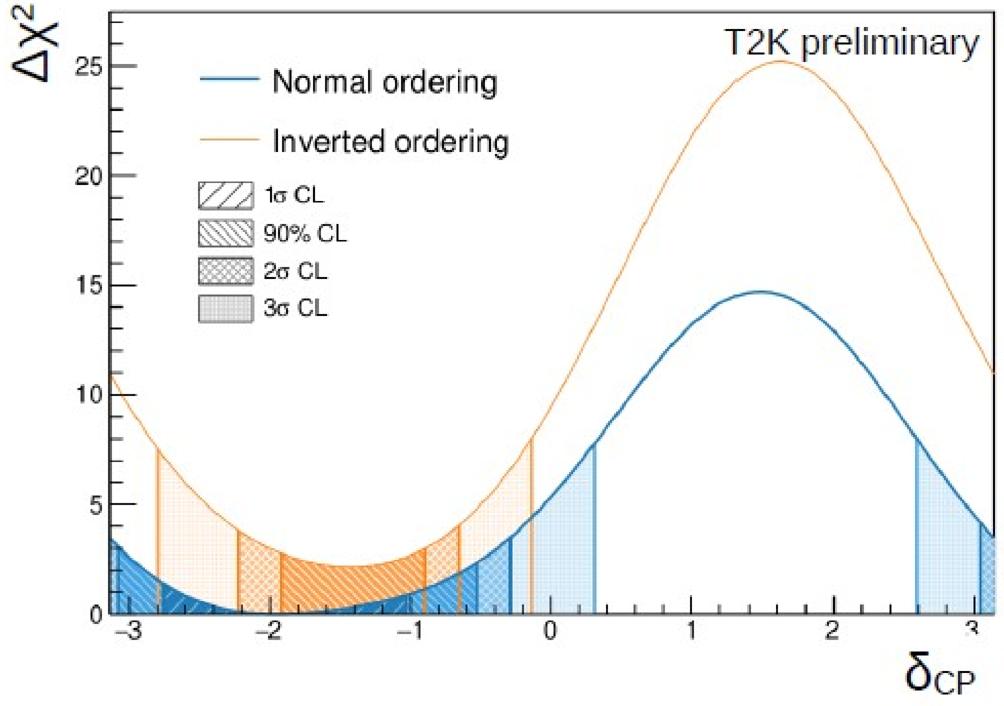


Inverted Hierarchy

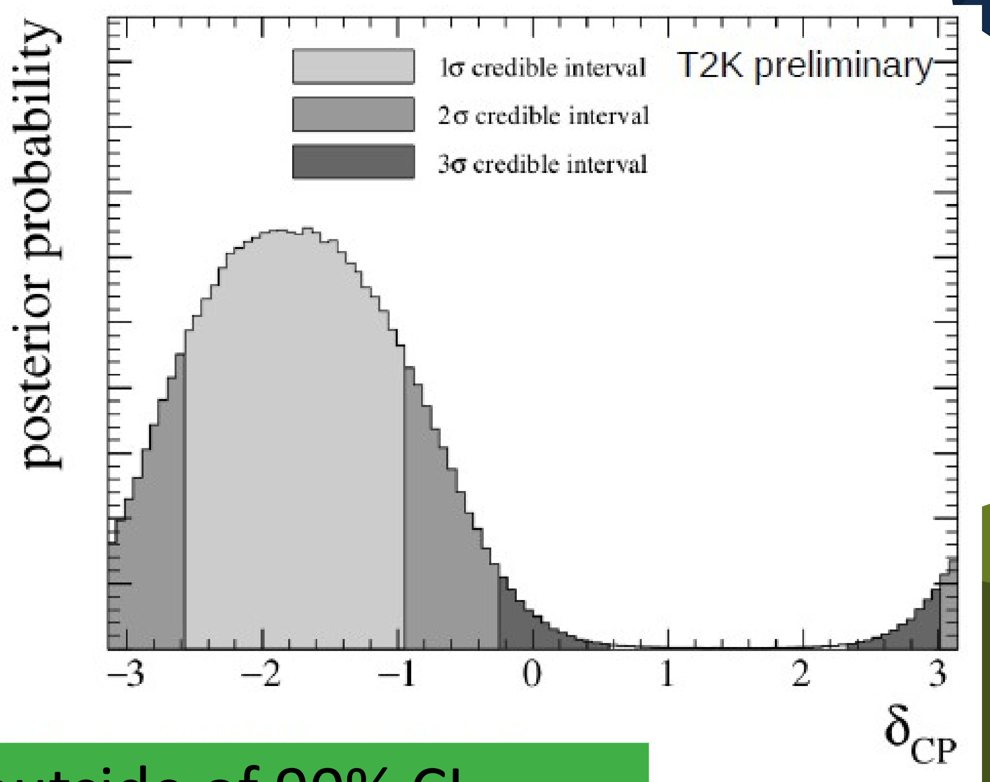


Results on δ_{CP} phase

Frequentists approach (Feldman-Cousin method)



Bayesian approach (marginelized 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
NH ($\Delta m^2_{32} > 0$)	0.24	0.39	0.63
IH ($\Delta m^2_{32} < 0$)	0.15	0.22	0.37
Sum	0.39	0.61	1.000

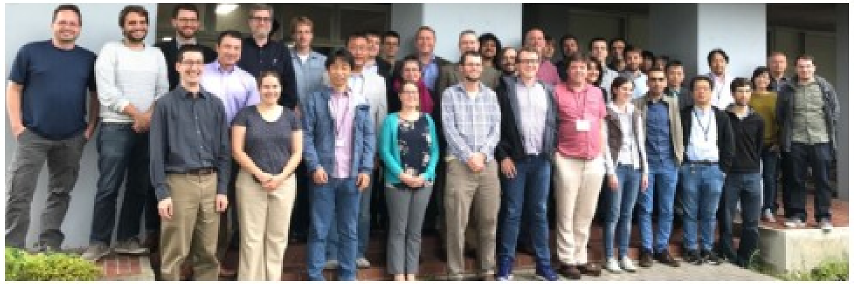
T2K+reactor

T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IH ($\Delta m^2_{32} < 0$)	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 – 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