UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Status of nu-mu nu-e combined analysis

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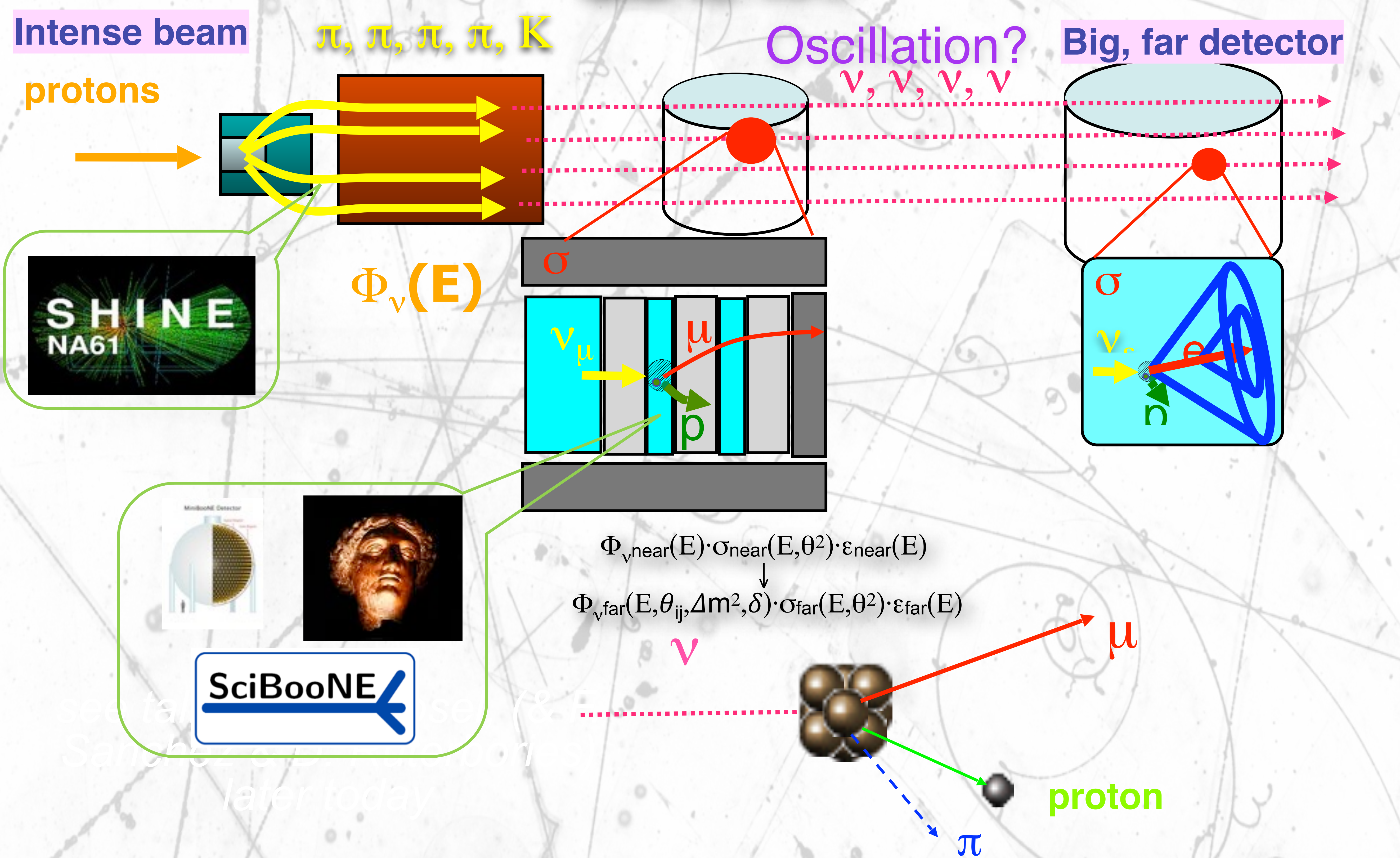
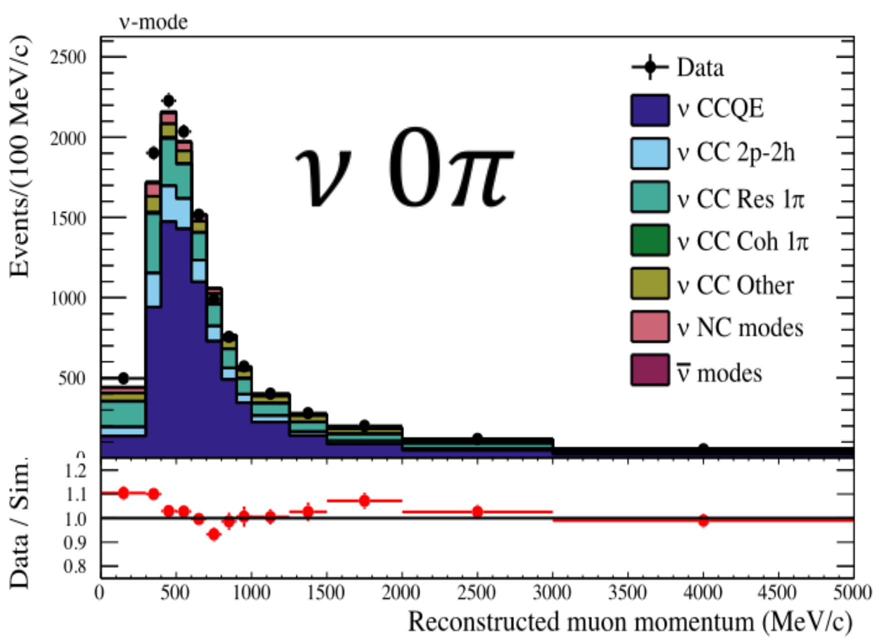
T2K experimental strategy

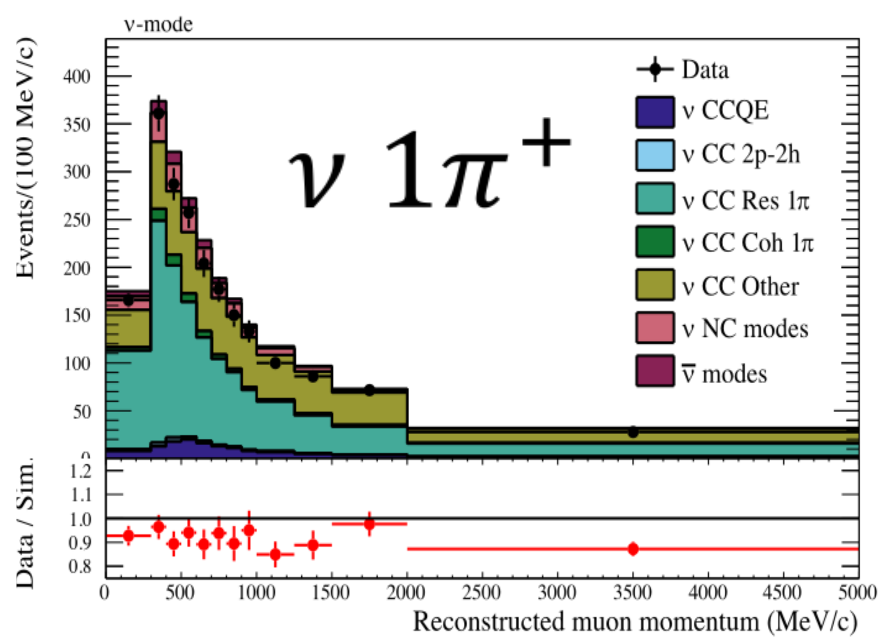
Search for CPV by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

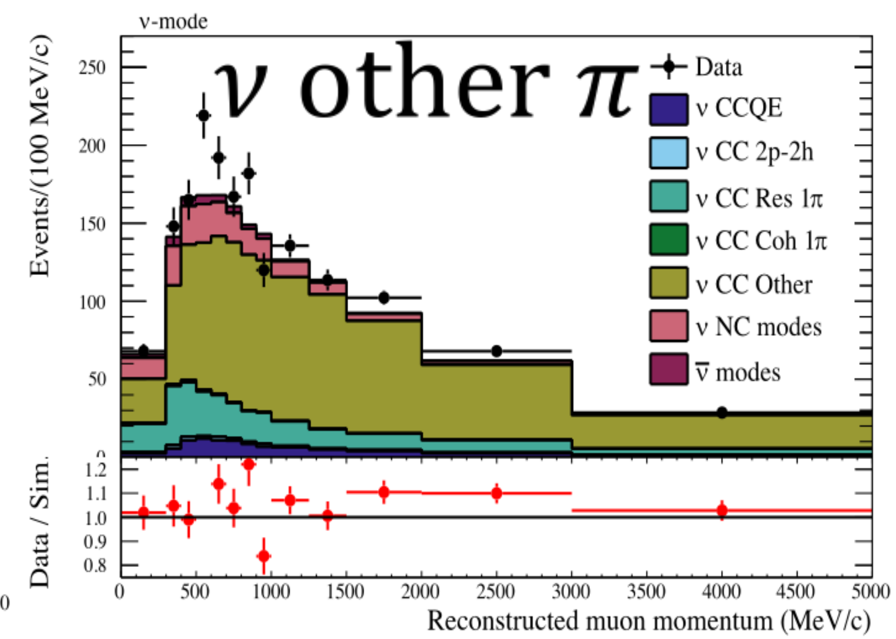


Samples: Near and Far

- Off-axis near detector samples divided by visible pion content, beam focusing

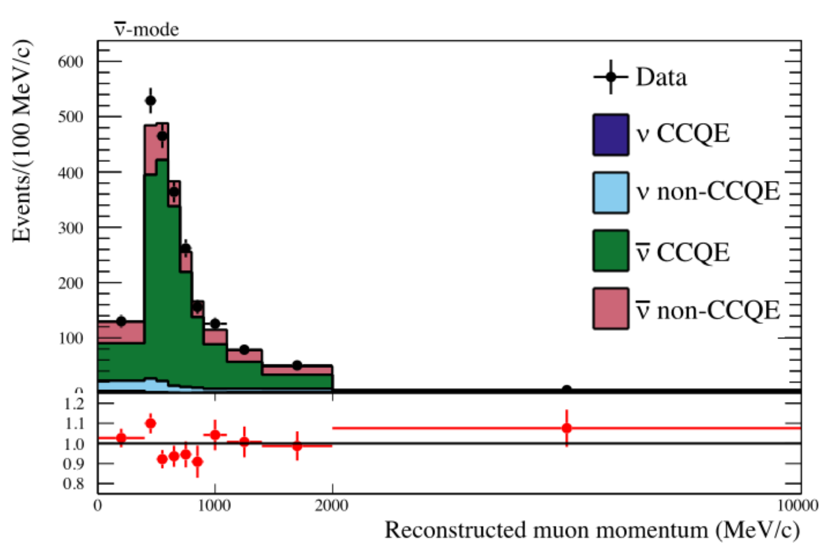






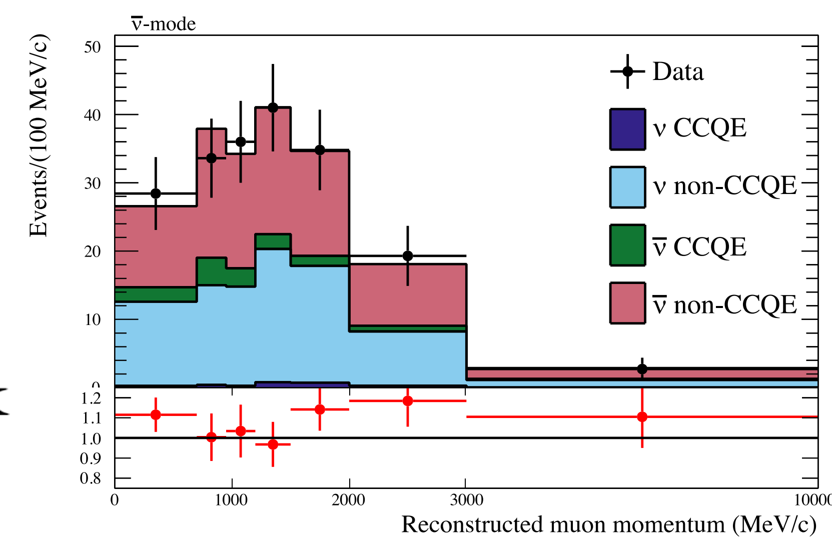
Reconstructed muon momentum (and angle)

for both CH target and CH+H_2O targets, separately.



$\bar{\nu}$ 1 track

$\bar{\nu}$ >1 track



Oscillation @ T2K

Appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2(c_{12}c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\quad \Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $\quad a = 2\sqrt{2}G_F n_e E$

θ_{13} dependency — Octant dependency — CP-odd phase

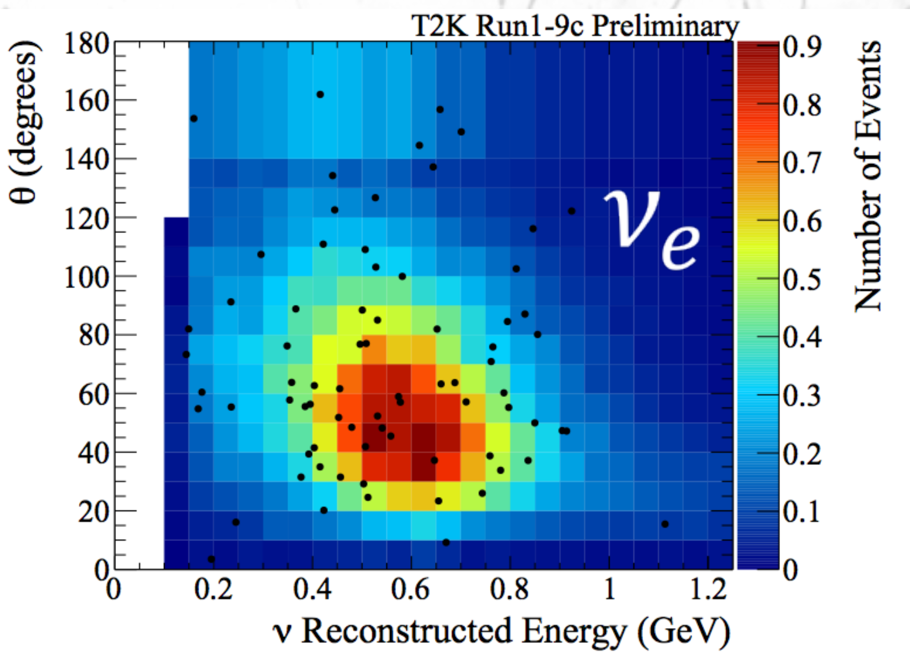
Disappearance

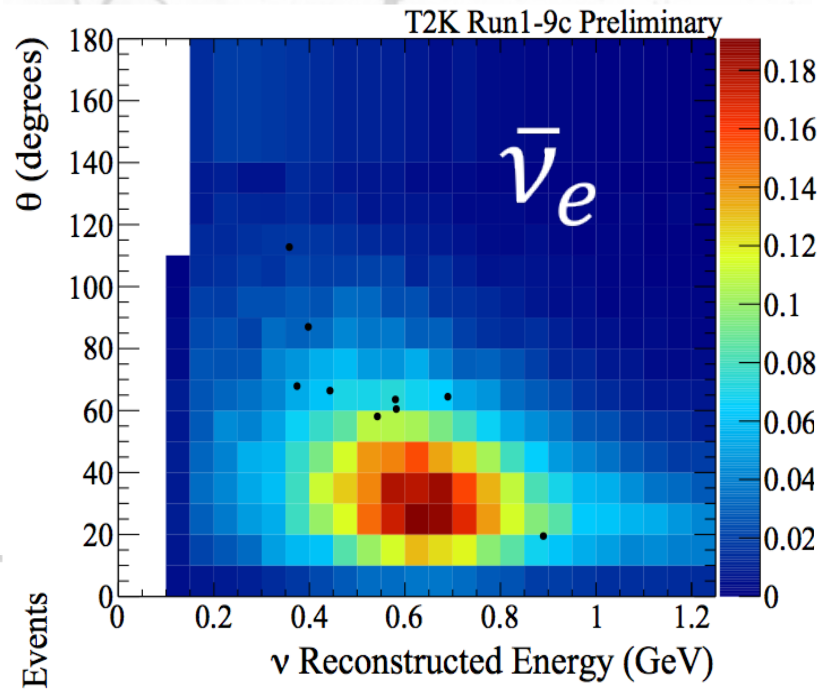
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

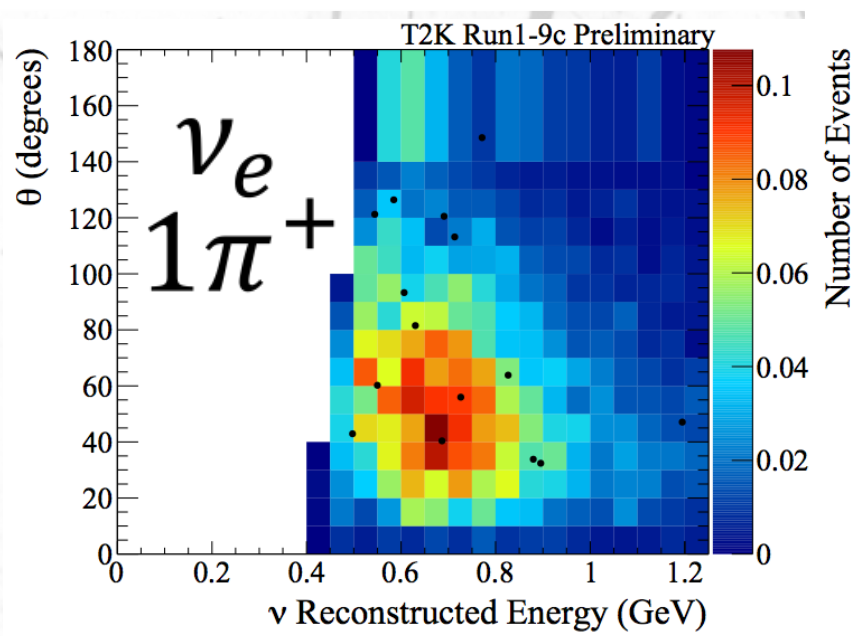
Samples: Near and Far

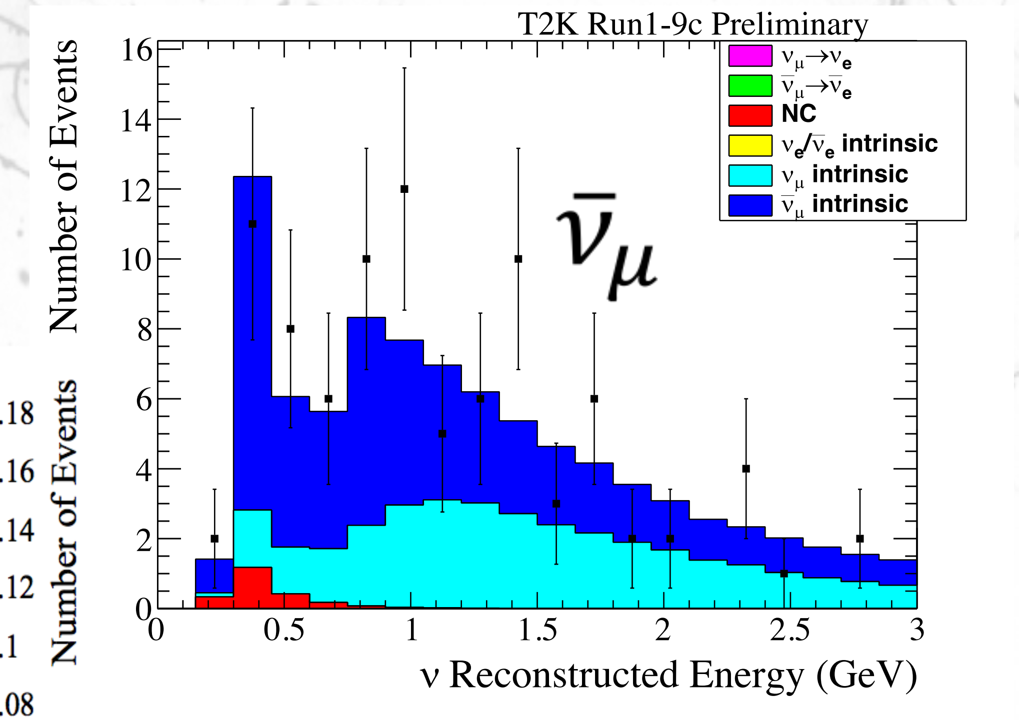
- Select events with no pions (& $\nu_e 1\pi^+$ sample).
- E_ν from lepton:

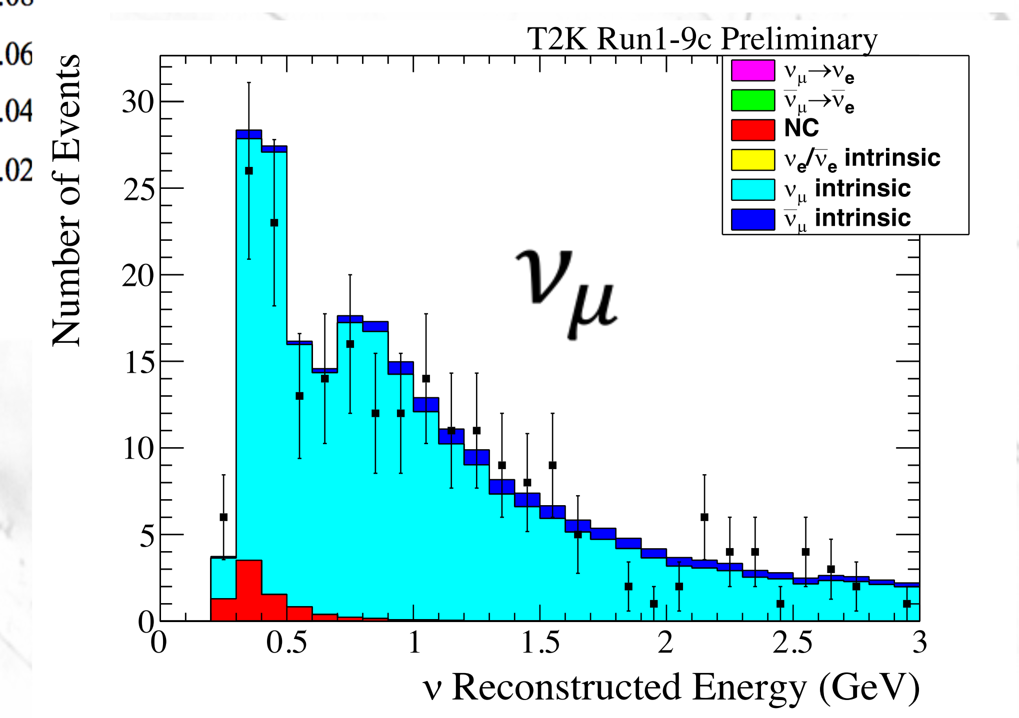
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$











The Far samples

THE FIVE SAMPLES

T2K

- Using the reconstructed fiTQun quantities, five samples are selected:

Neutrino Mode (forward horn current FHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

(CC1π) 1 Electron-like Ring, 1 decay electron

$$\nu_\mu(\bar{\nu}_\mu)+N\rightarrow\mu^-(\mu^+)+X$$
$$\downarrow$$
$$e^-(e^+)+\bar{\nu}_e(\nu_e)+\nu_\mu(\bar{\nu}_\mu)$$

$$\nu_e(\bar{\nu}_e)+N\rightarrow e^-(e^+)+X$$

$$\nu_e+N\rightarrow e^-+\pi^++X$$
$$\downarrow$$
$$\mu^++\nu_\mu$$
$$\downarrow$$
$$e^++\nu_e+\bar{\nu}_\mu$$

NEW!

Antineutrino Mode (reverse horn current RHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

No antineutrino mode CC1π sample due to π^- absorption

◯ = *detected particles*

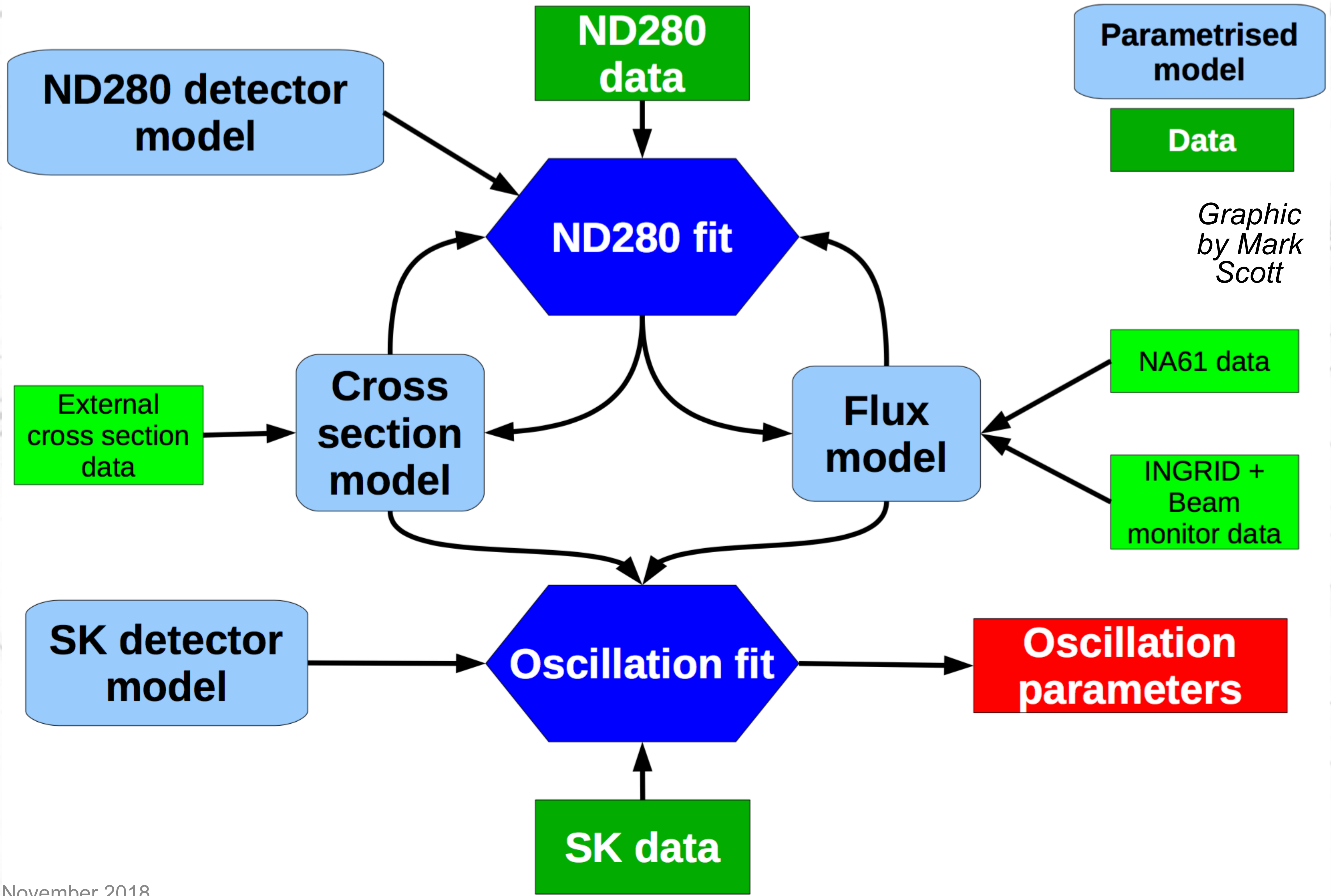
New reconstruction algorithm

FITQUN RECONSTRUCTION ALGORITHM

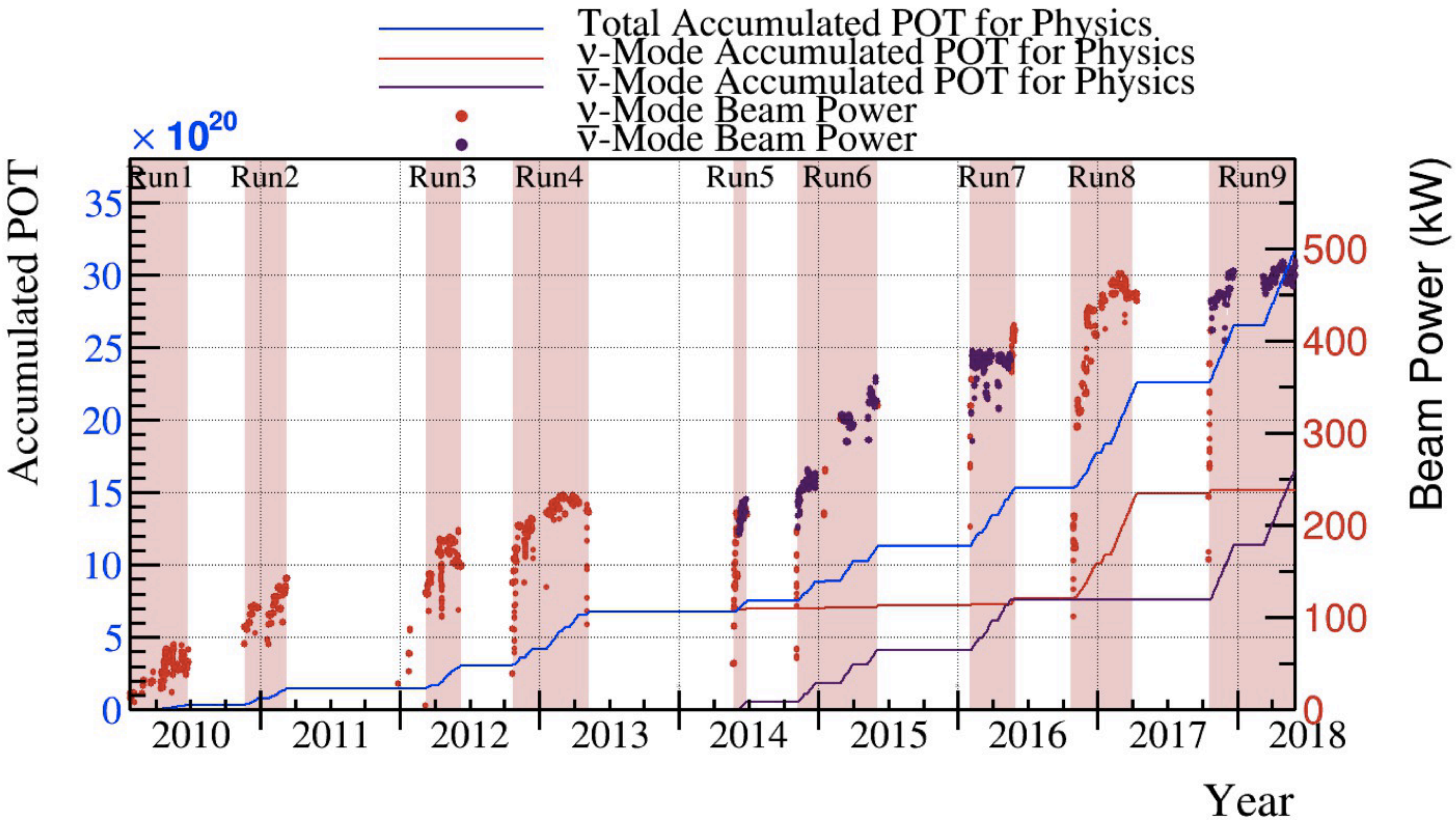
T2K

- Previous T2K analyses have used the event reconstruction algorithm **APFit**
- For this result, event reconstruction at Super-K updated to use the **fiTQun** algorithm
- **fiTQun** uses a charge and time likelihood for a given ring(s) hypotheses
  - Maximizes likelihood for each event
  - Complete charge and time information in the likelihood leads to improved event reconstruction
- **fiTQun** previously used in T2K analyses for the rejection of π^0 from electron neutrino candidates

Schematic of Osc. Analysis



Beam!



23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

ν-mode 1.51×10^{21} (47.83%)

$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

Strategy is to get 50%/50% FHC and RHC

Events

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC μ CCQE	268.5	268.2	268.5	268.9	243
RHC μ CCQE	95.5	95.3	95.5	95.8	102
FHC e CCQE	73.8	61.6	50.0	62.2	75
FHC e CC1π^+	6.9	6.0	4.9	5.8	15
RHC e CCQE	11.8	13.4	14.9	13.2	9

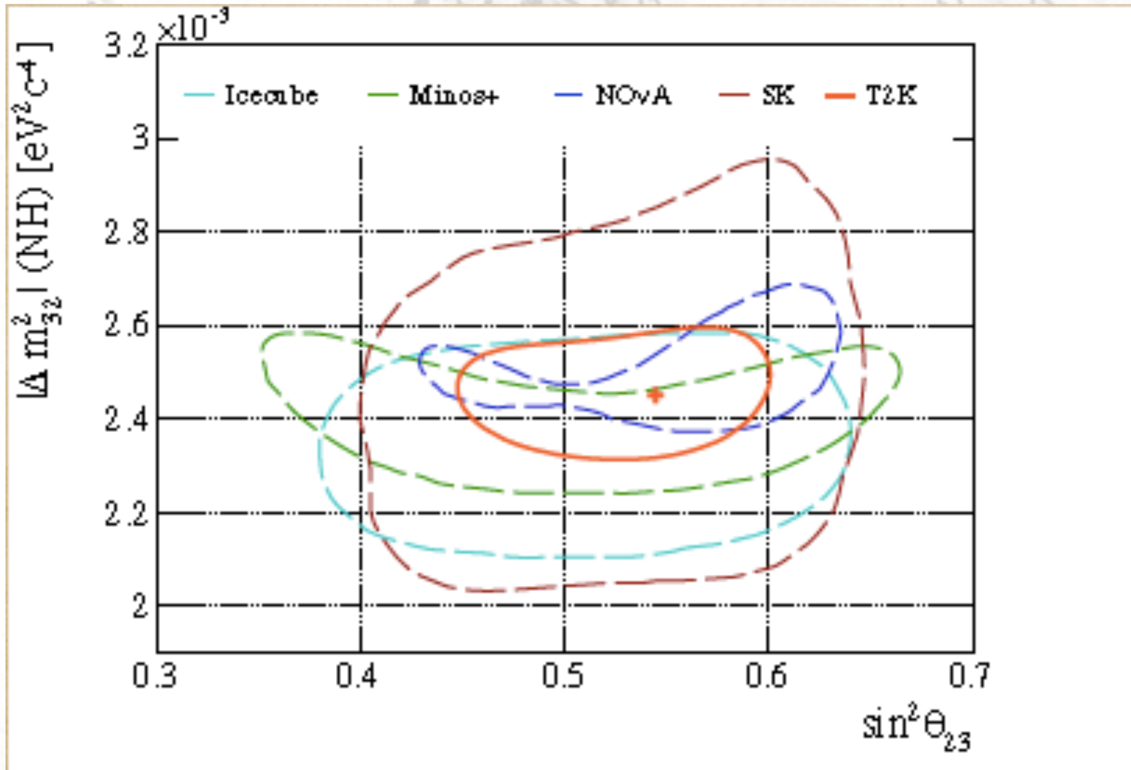
Analyses

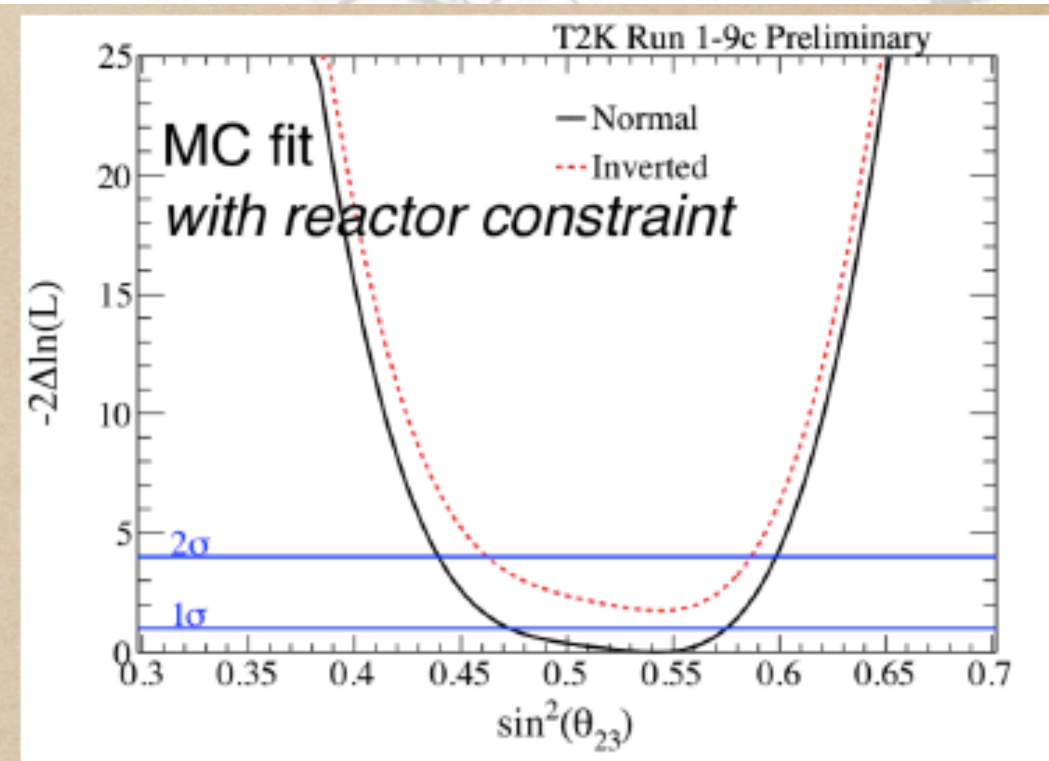
Frequentist with likelihood fit to
E_{rec}/θ_{lep} for ν_e/ ν_e
E_{rec} for ν_μ/ ν_μ

Frequentist with likelihood fit to
p_{lep}/θ_{lep} for ν_e/ ν_e
E_{rec} for ν_μ/ ν_μ

Bayesian with Markov Chain MC
E_{rec} for all samples
simultaneous fit with near detector

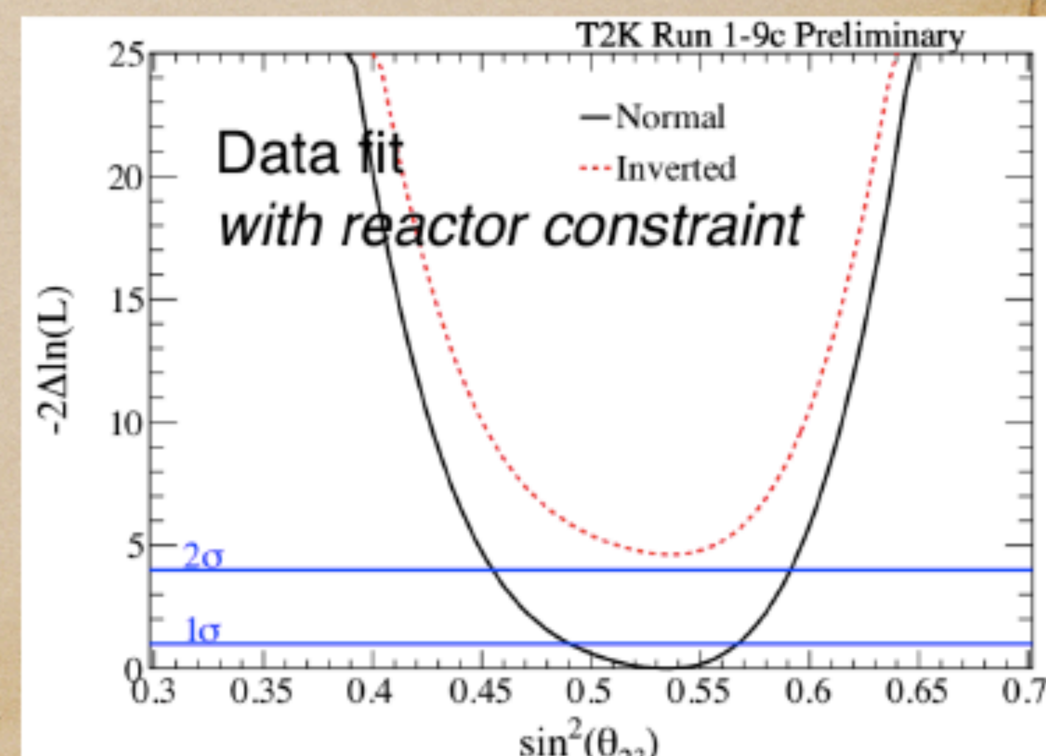
Oscillation results





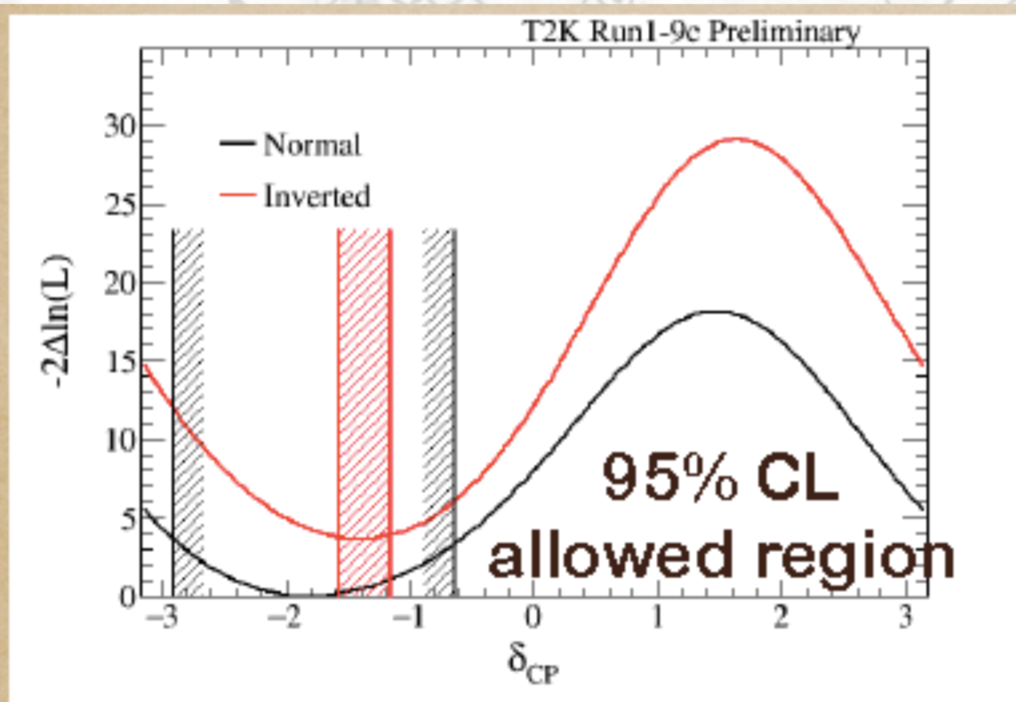
- World best measurement of $\sin^2(\theta_{23})$→ compatible with maximal mixing

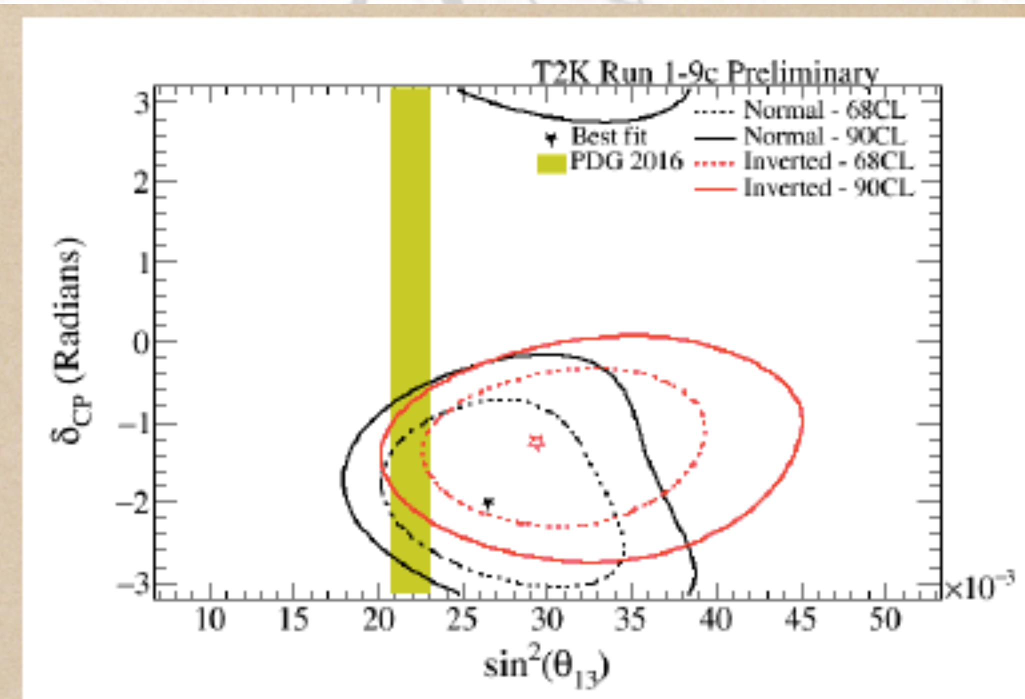
	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2\rvert$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$



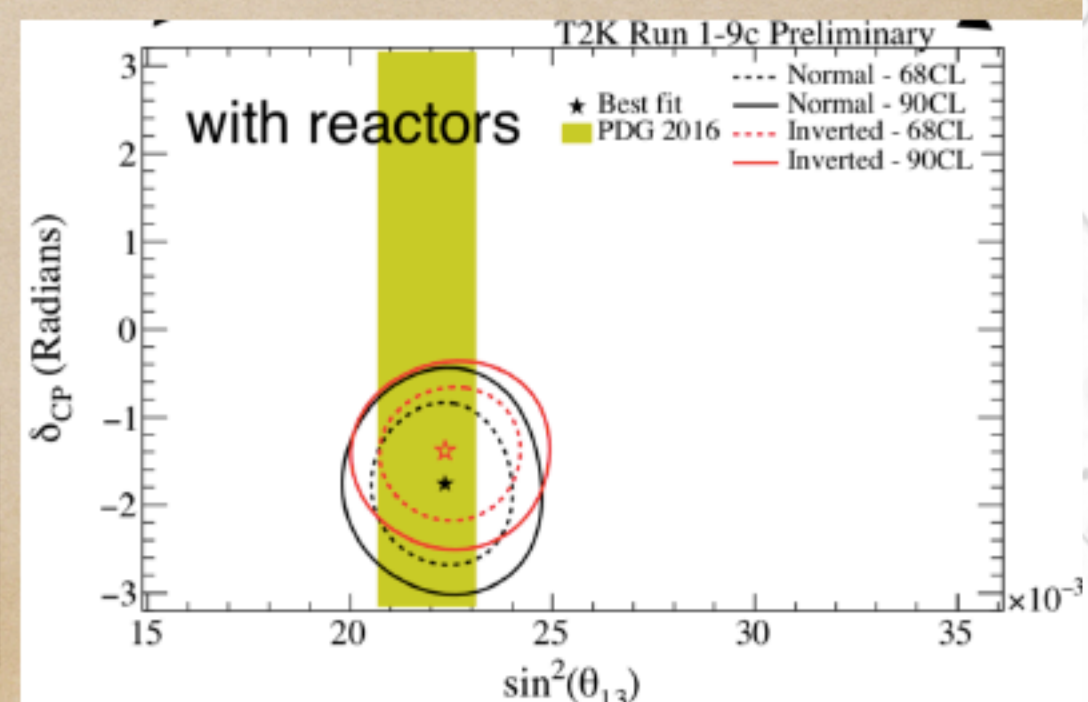
From Claudio

Oscillation results





- Precise measurement of $\sin^2(\theta_{23})$ → compatible with maximal mixing
- T2K alone and T2K+reactor both prefer values of δ_{CP}~$-\pi/2$
- Normal ordering is also favoured

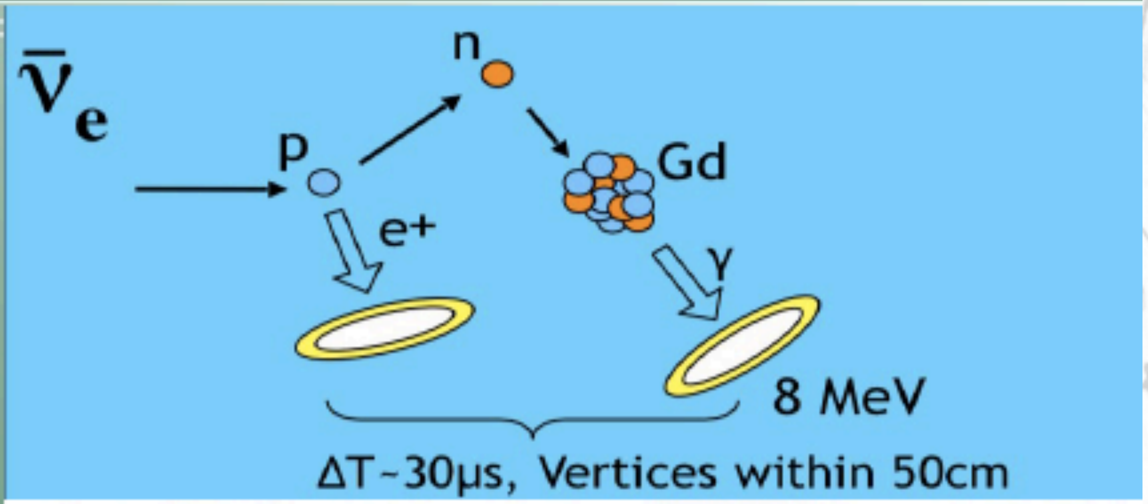


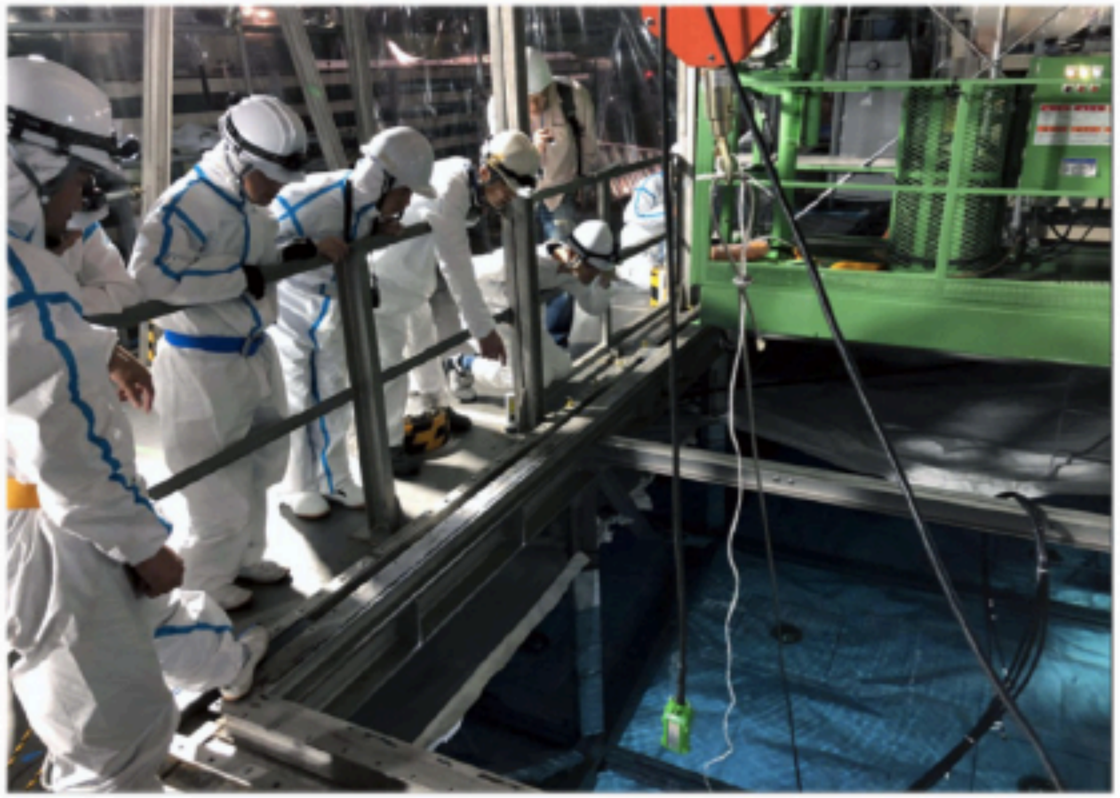
	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	SUM
NO ($\Delta m^2_{32}>0$)	20,4 %	68,4 %	88,8 %
IO ($\Delta m^2_{31}<0$)	2,3 %	8,9 %	11,2 %
SUM	22,7 %	77,3 %	100 %

From Claudio

SK upgrade

- Additional SK data samples under study
  - $CC1\pi^+$, $NC\pi^0$ in both FHC, RHC
- SK-Gd project
  - enhance neutron detection
  - improve low-energy $\bar{\nu}_e$ detection
  - may provide wrong-sign background constraint in $\bar{\nu}_e$ -mode data.
- Repairs to SK tank finished, filling with water and ready in Jan 2019.
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.





The Gd might help us to improve the far detector samples via the detection of neutrons in the final state: neutrino vs. antineutrino

Conclusions & next steps

- T2K has moved from simple oscillation fits to a full data fit during the Jennifer period.
- This is the first time this combined analysis is done offering many advantages:
    - Consistent treatment of errors and correlations.
    - 3ν oscillation fits.
- Next steps:
    - Improve the samples at ND using more final states and better detector acceptance.
    - Improve ND with the ND280 upgrade program.
    - Improve on final state events samples.
    - Larger statistics will also open new possibilities at the Far detector with more bins, 2D fits, etc…