T2K neutrino and anti-neutrino oscillation results

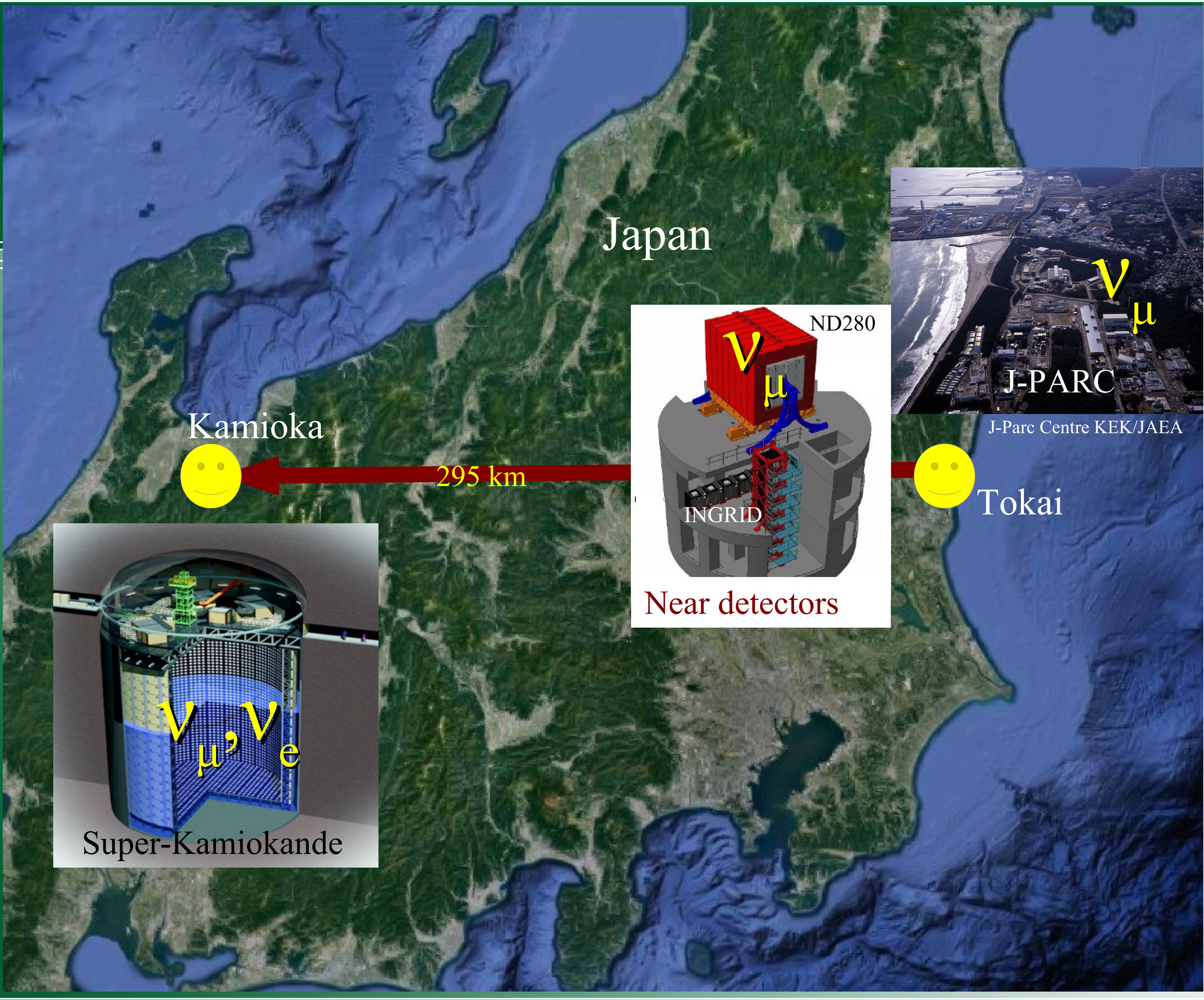
- T2K (Tokai to Kamioka)
- ν_μ and $\bar{\nu}_\mu$ disappearance
- $\bar{\nu}_e$ appearance search
- ν_e appearance and δ_{CP}
- T2K-II
- The future

- PRL Editor's Choice paper with the 2017 analysis PRL **121,** 171802 (2018)
- Results also available from Neutrino 2018: "T2K Status, Results, and Plans", Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018, Heidelberg, Germany, DOI: 10.5281/zenodo.1286751, URL: https://doi.org/10.5281/zenodo.1286751

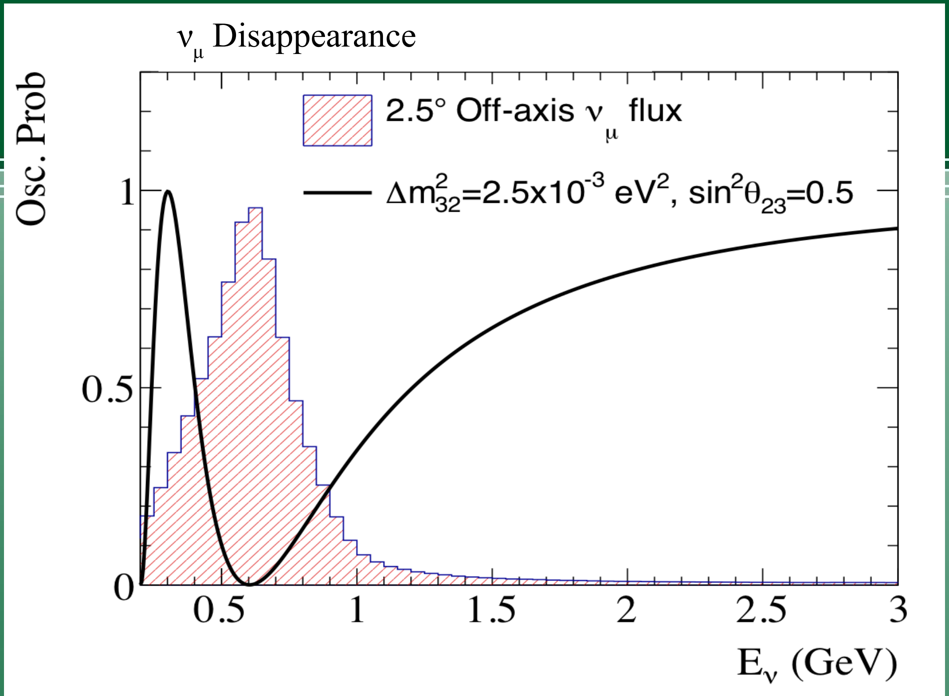
- Dr Laura Kormos,
on behalf of the T2K Collaboration

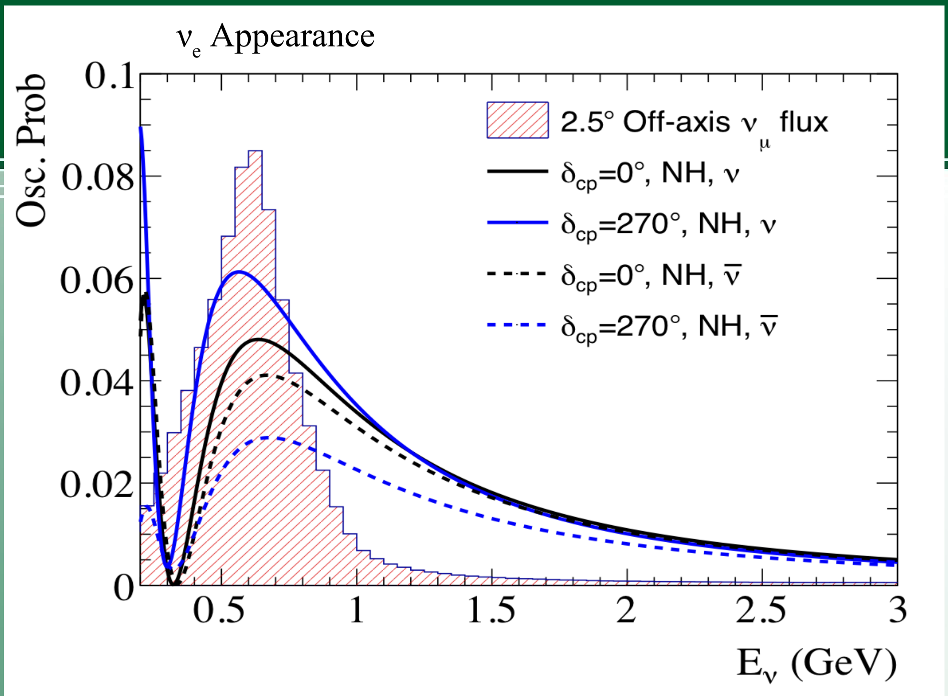
T2K
(Tokai to Kamioka)

- J-PARC beam
  - ν_μ
- Near detectors:
  - INGRID on-axis
  - ND280 off-axis
- Far detector:
  - SK off-axis



Oscillations at T2K

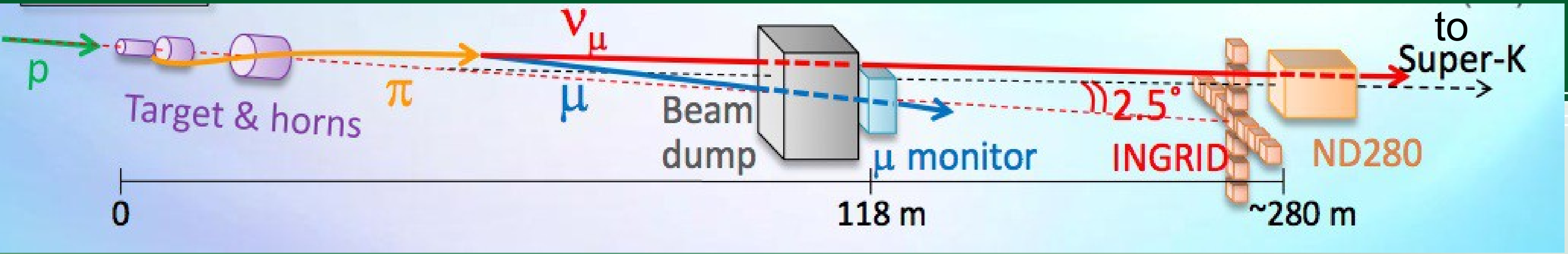




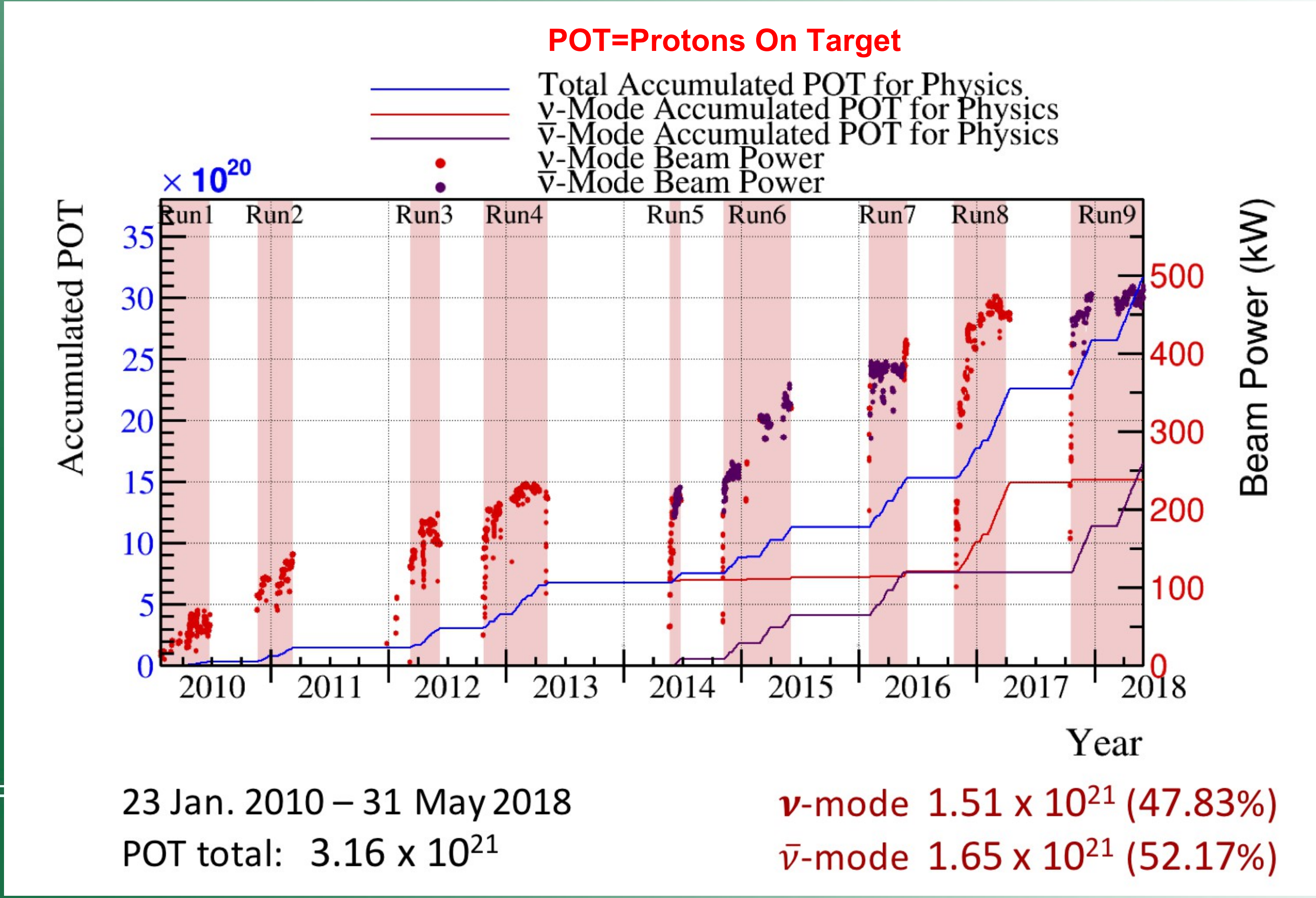
- **Tests CPT symmetry**
- Leading order dependence on $\mathbf{\sin^2 2\theta_{23}}$
  - **hard to distinguish $\theta_{23}>45^o$ from $\theta_{23}<45^o$**
- Leading order dependence on $|\mathbf{\Delta m^2_{32}}|$
  - doesn't depend on sign of mass splitting

- **Tests CP symmetry**
- Leading order dependence on $\mathbf{\sin^2 2\theta_{13}}$, $\mathbf{\sin^2\theta_{23}}$
  - **can separate $\theta_{23}>45^o$ from $\theta_{23}<45^o$**
- Sub-leading dependence on $\mathbf{\sin(\delta_{CP})}$
  - **can detect CP violation (~27% effect)**
- Sub-leading dependence on $\pm\mathbf{\Delta m^2_{32}}$
  - **~10% matter effect**

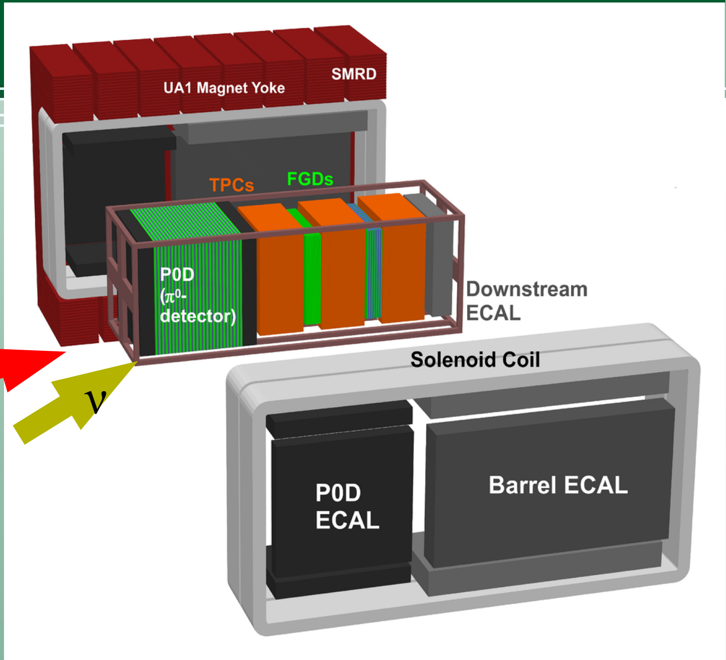
The T2K beam



- Primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (forward horn current, FHC, or neutrino-mode)
- Reverse polarity for $\bar{\nu}_\mu$ beam: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ (reverse horn current, RHC, or antineutrino-mode)

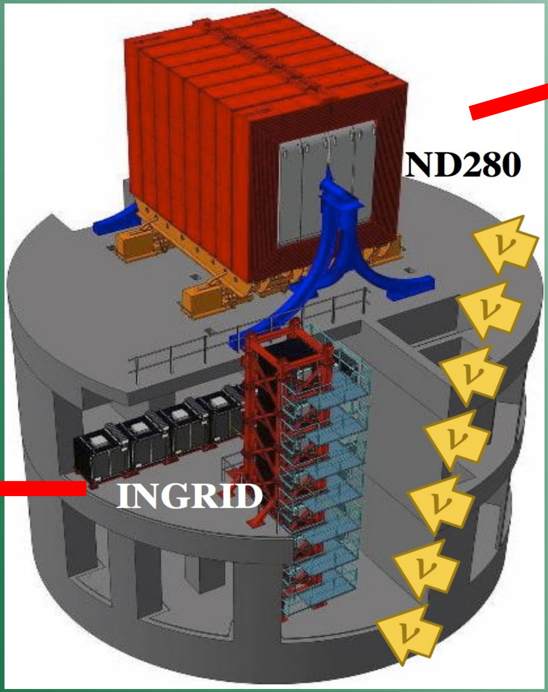


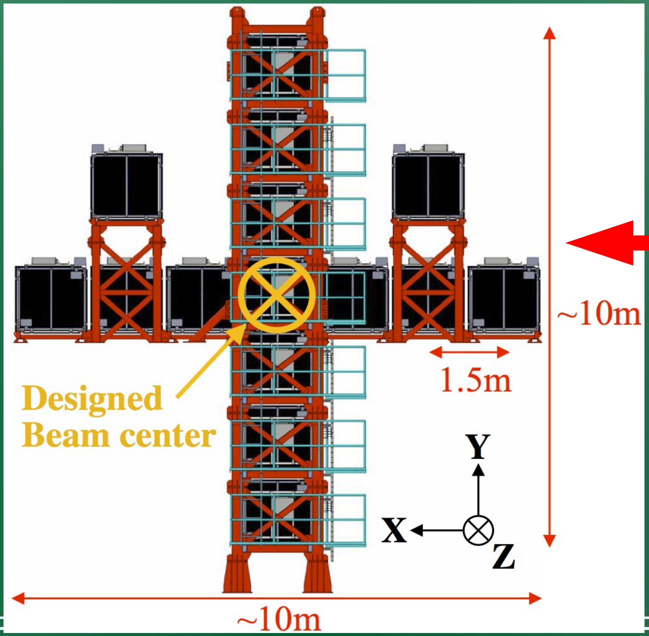
Near detectors



INGRID

- 7x7 (+2) identical modules
- Iron and plastic scintillator tracking calorimeter
- Monitors ν, $\bar{\nu}$ beam direction and stability



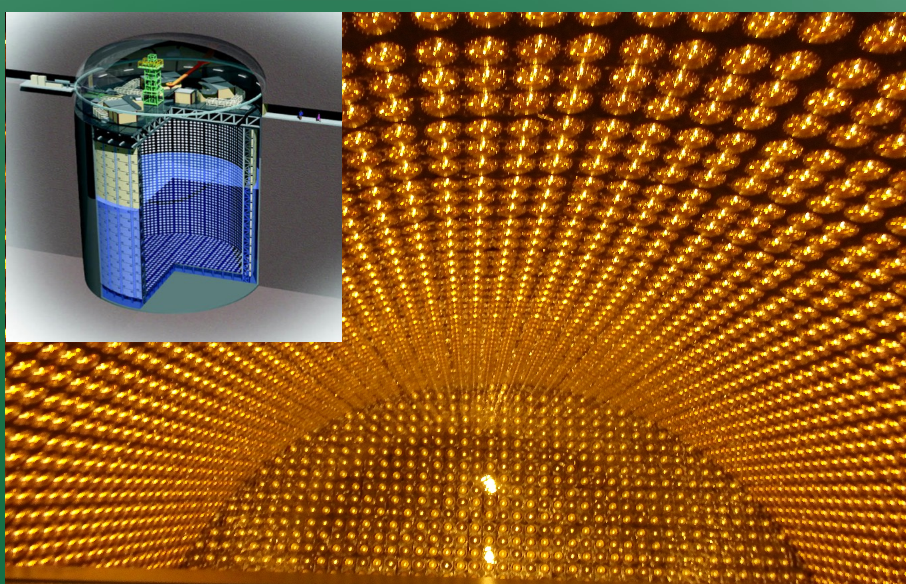


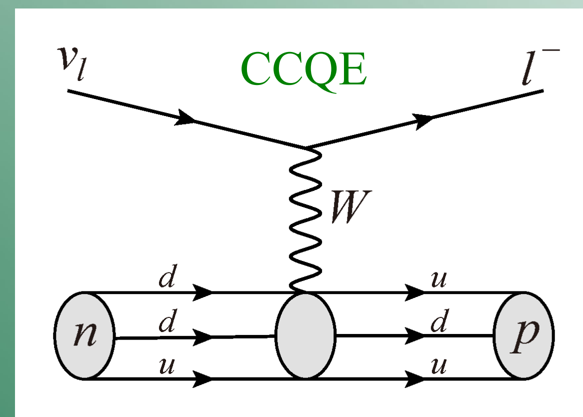
ND280

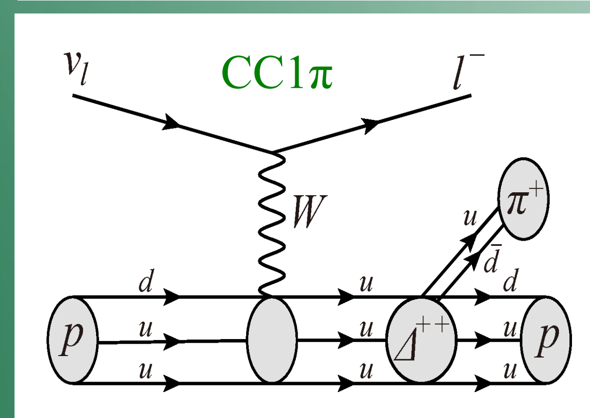
- Off-axis (2.5°) detector
- 0.2 T magnet
- Trackers, calorimeters, muon range detectors
- Water, carbon, lead, targets.
- Beam ν_e, flux, cross sections, exotics

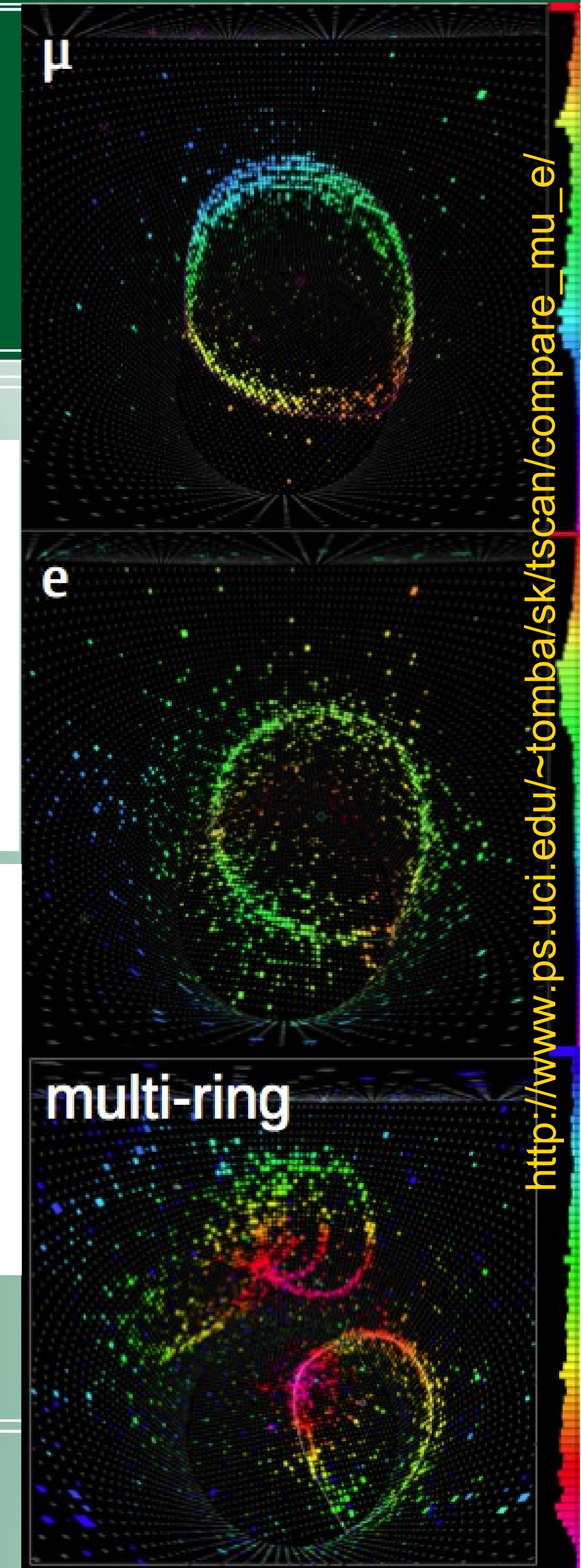
Far detector: Super-Kamiokande

- 50 kton Water-Cherenkov detector
- 2.5^{o} off axis (same as ND280)
- Excellent e/μ separation, π^0 rejection
- Select 1-ring, CCQE-enriched sample
- Select CC1π^+ sample (ν_e appearance)
- ν kinematics derived from lepton



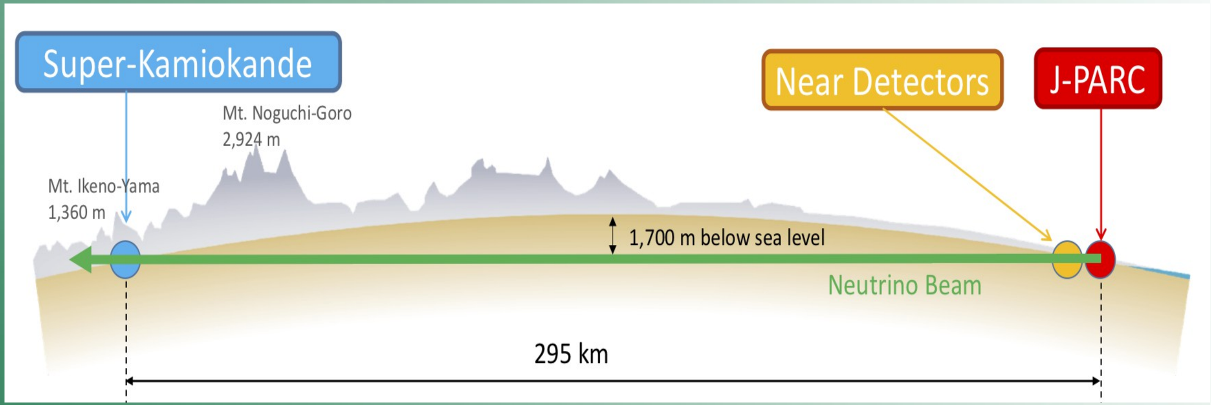






T2K oscillation analysis overview

- Measure N events
- Compare events observed at near and far detectors
- Extract oscillation probability

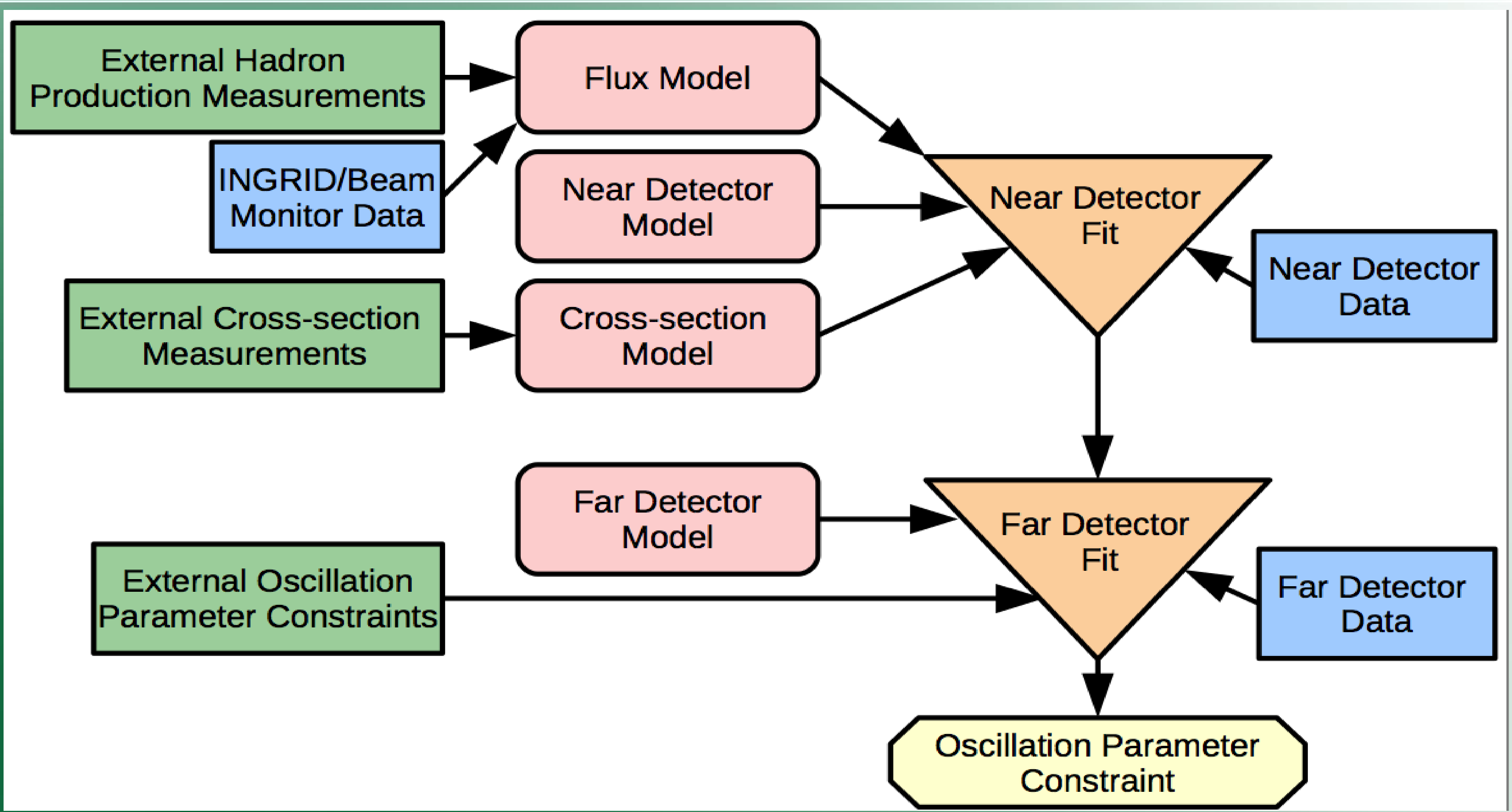


- $N_{ND} \sim \Phi_{ND} \bullet \sigma_{ND} \bullet \varepsilon_{ND}$

  Observable Flux Cross section Detector response

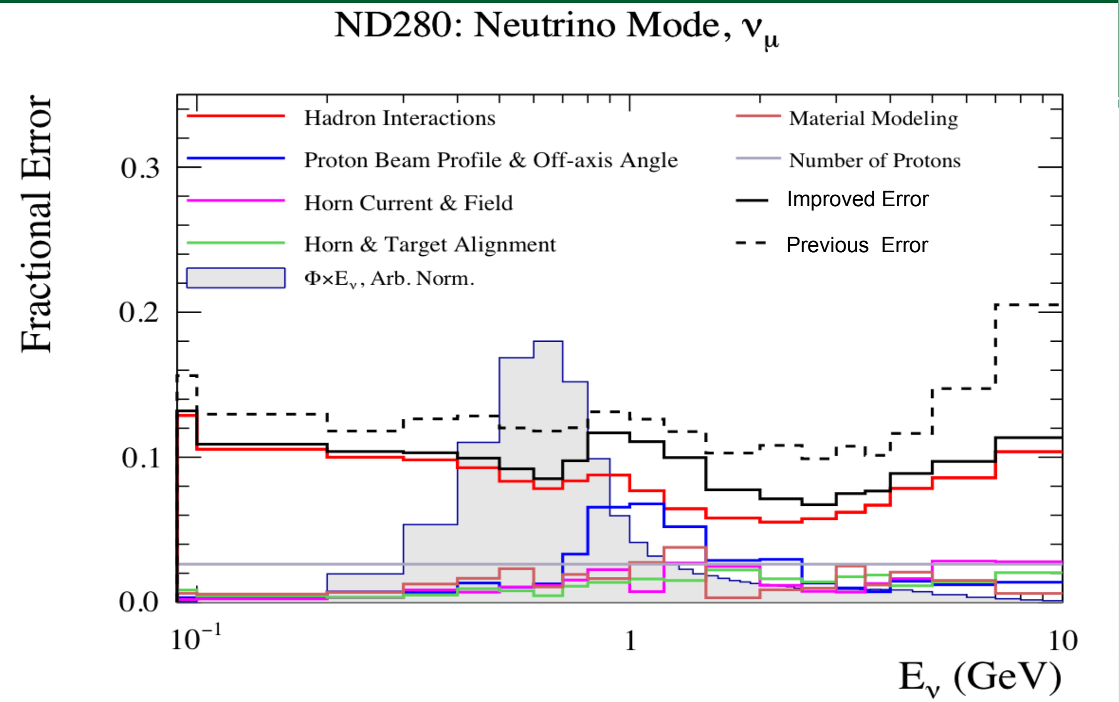
- $N_{FD} \sim \Phi_{FD} \bullet \sigma_{FD} \bullet \varepsilon_{FD} \bullet P_{Osc}$

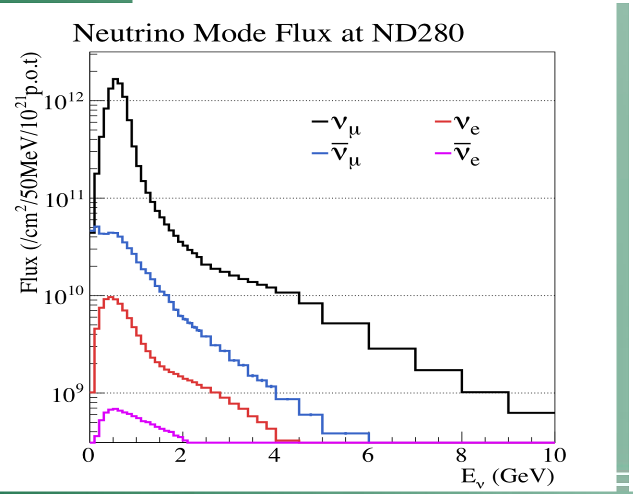
T2K oscillation analysis overview

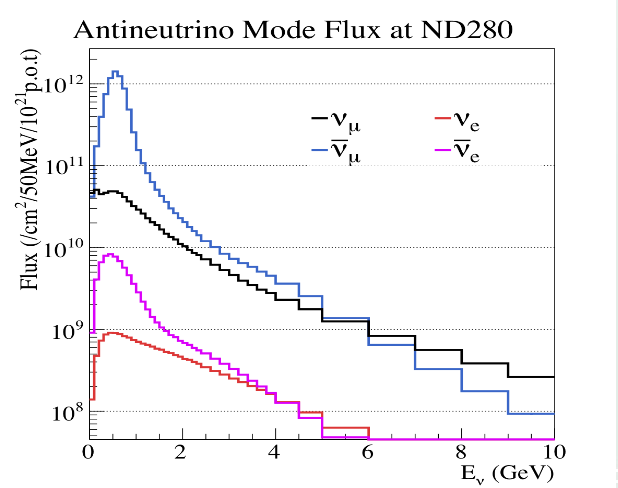


Flux prediction and uncertainties

- Flux simulation (FLUKA/GEANT3/ GCALOR)
- Tuned using external data (NA61/SHINE hadron production measurements)
- Intrinsic ν_e component ~0.5% at flux peak

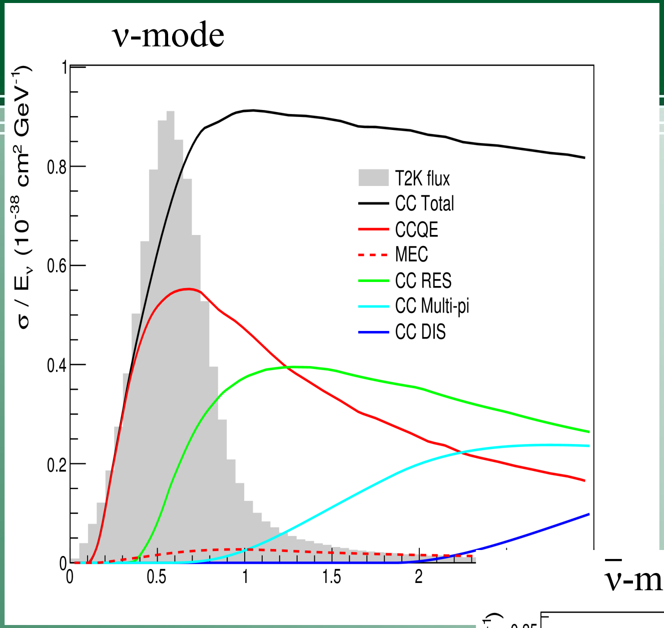


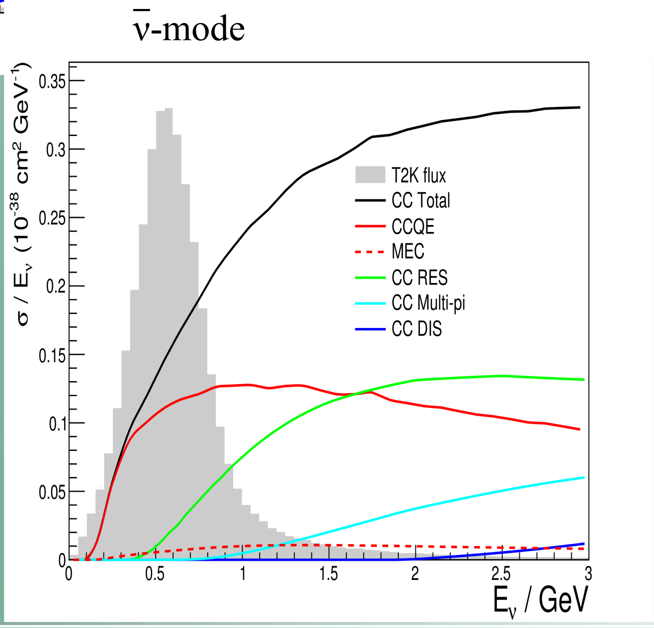




Cross-section model

- NEUT generator tuned to external data from MiniBooNE, MINERνA, bubble chambers, etc
- Examples:
  - CCQE: Relativistic Fermi Gas (RFG) + rel. Random Phase Approximation (RPA)
  - CC-RES: pion reinteractions inside the nucleus





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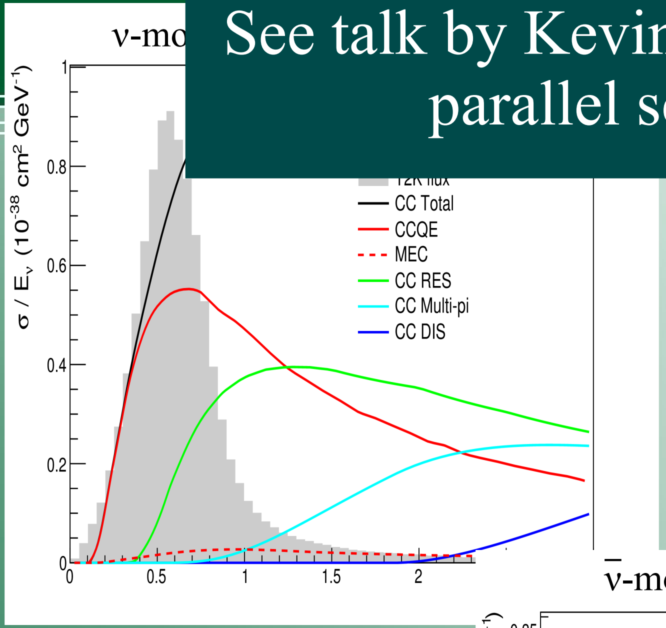
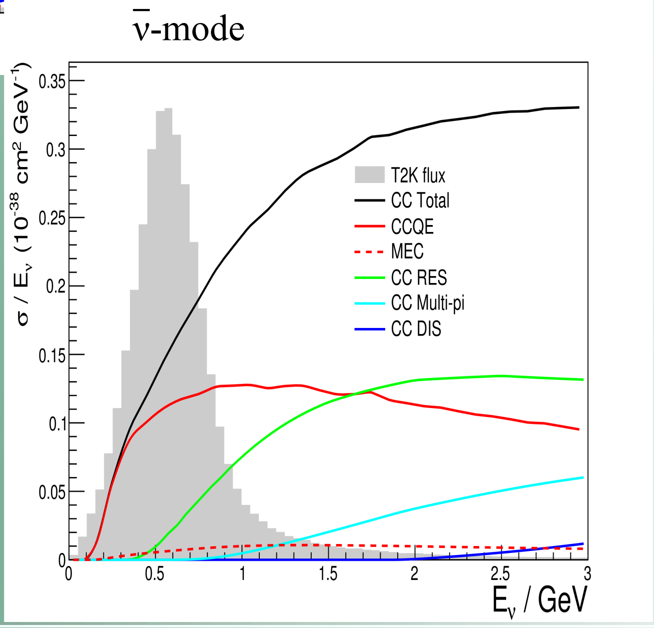
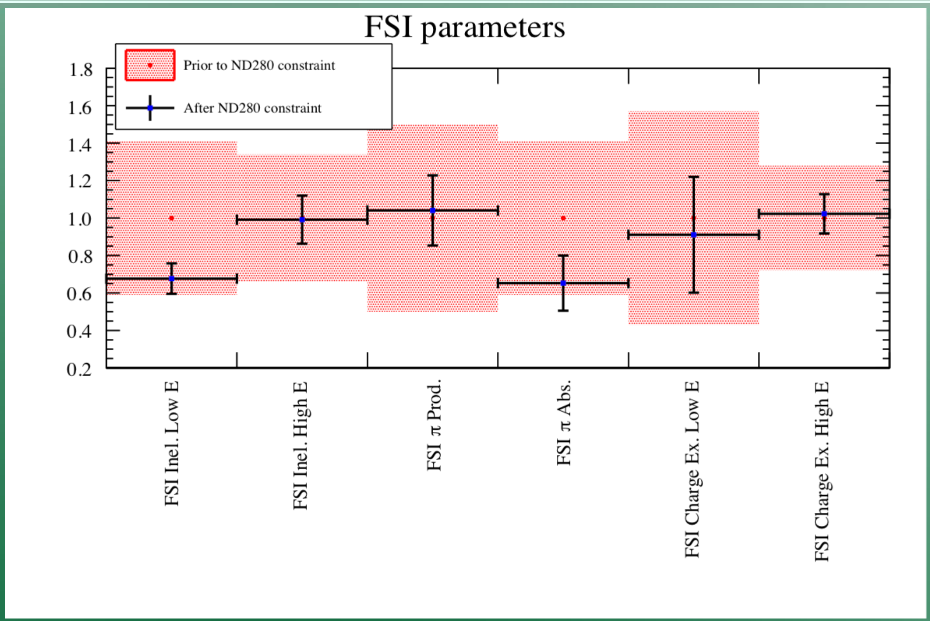
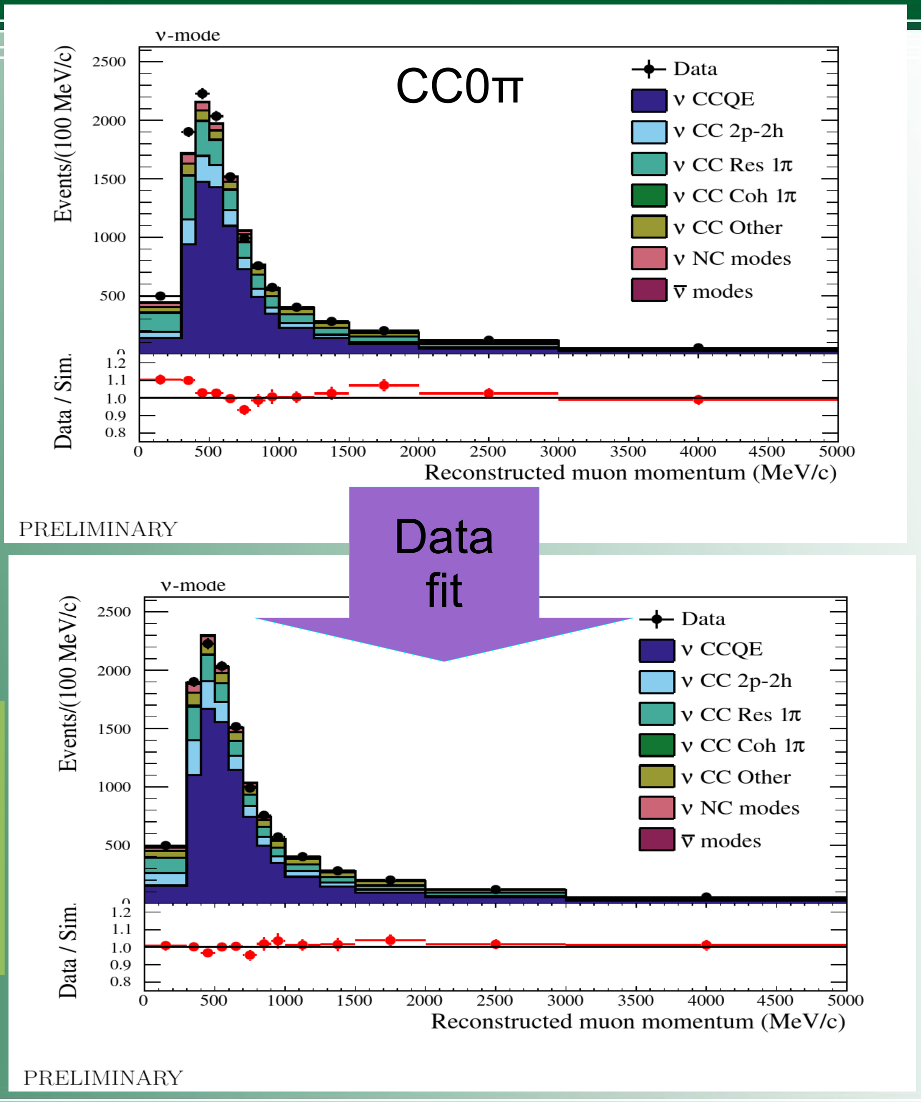


See talk by Kevin McFarland in parallel session.



ND280 data fitting and constraints





- Showing only 1 (CC0π) of 14 ND280 data samples: 6 samples in ν-mode and 8 in ν̄-mode
- Fit tunes ~780 parameters (showing only FSI cross-section parameters)

Joint analysis with ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$

Analysis frameworks

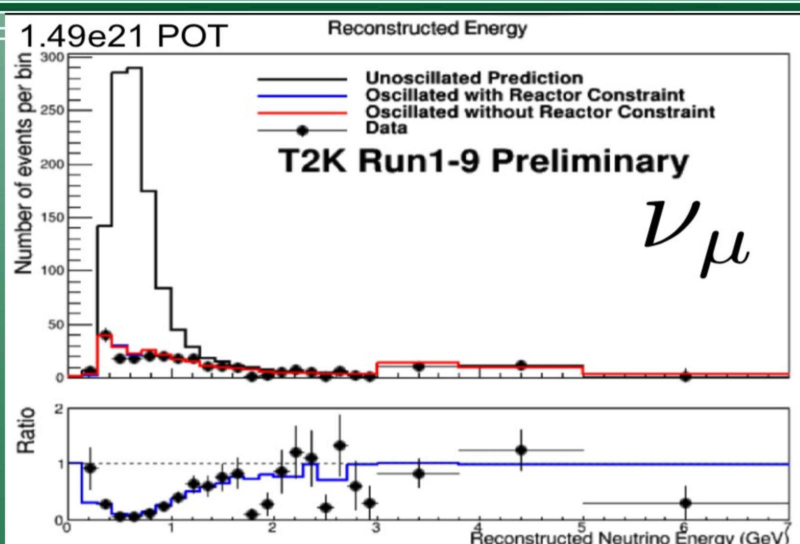
- Frequentist with likelihood fit to
  - E_{rec}/θ_{lep} for $\nu_e/\bar{\nu}_e$
  - E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- Frequentist with likelihood fit to
  - p_{lep}/θ_{lep} for $\nu_e/\bar{\nu}_e$
  - E_{rec} for $\nu_\mu/\bar{\nu}_\mu$
- Bayesian with Markov Chain MC
  - E_{rec} for all samples
  - simultaneous fit with near detector

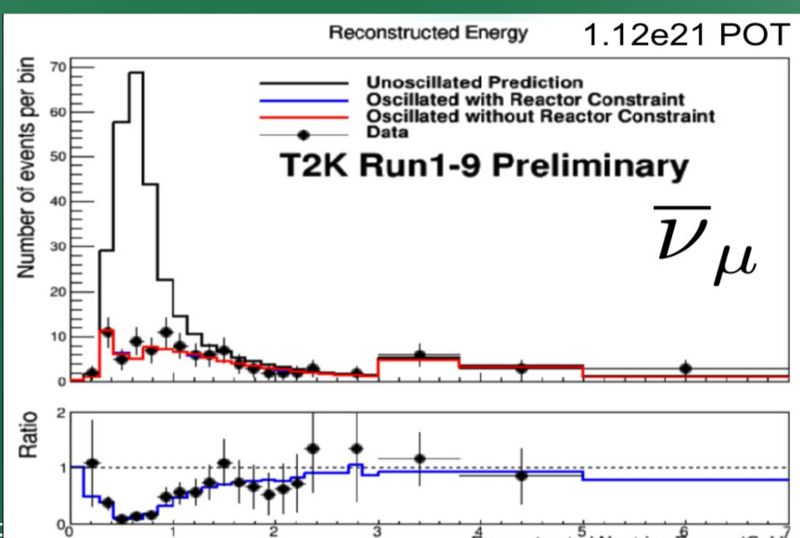
SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
ν-mode μ CCQE	268.5	268.2	268.5	268.9	243
$\bar{\nu}$-mode μ CCQE	95.5	95.3	95.5	95.8	102
ν-mode e CCQE	73.8	61.6	50.0	62.2	75
ν-mode e CC1π	6.9	6.0	4.9	5.8	15
$\bar{\nu}$-mode e CCQE	11.8	13.4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

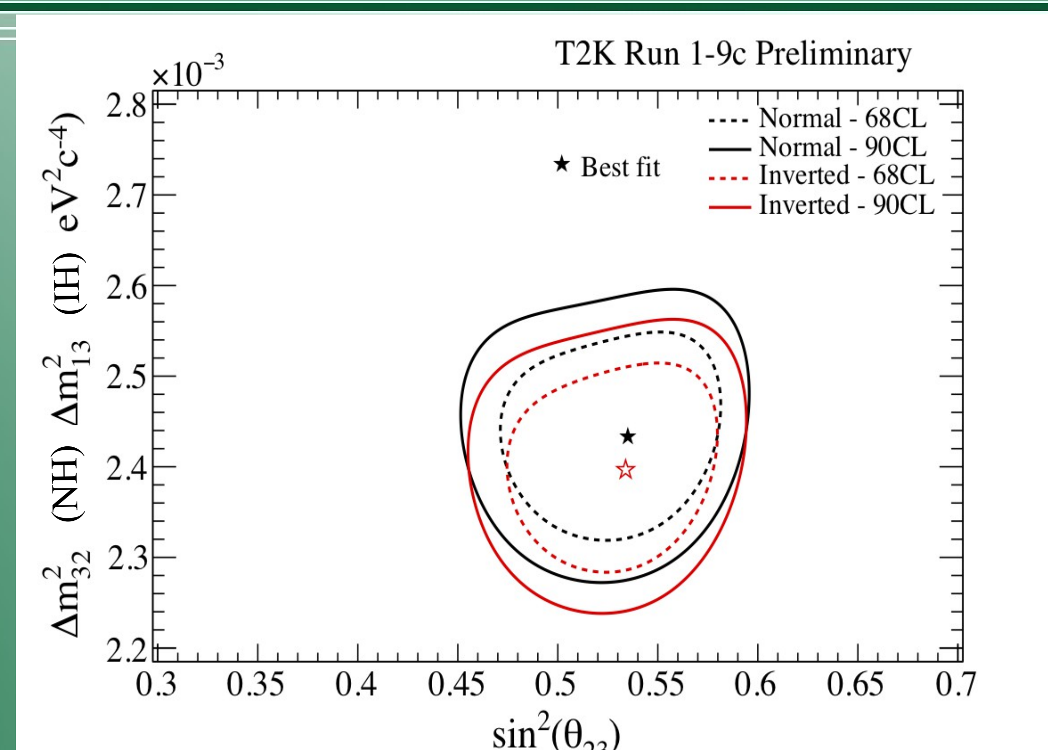
Events observed at SK vs ND data-tuned predictions under oscillation hypothesis using NH, 2016 PDG θ_{13}, and $\theta_{23}= 45^o$.

15 events observed in CC1π^+ sample, with prediction of 6.9 max. p-value for fluctuation this significant in any one of the five samples is 12%.

ν_μ and $\bar{\nu}_\mu$ disappearance: Precision era of θ_{23} and Δm^2_{atm}





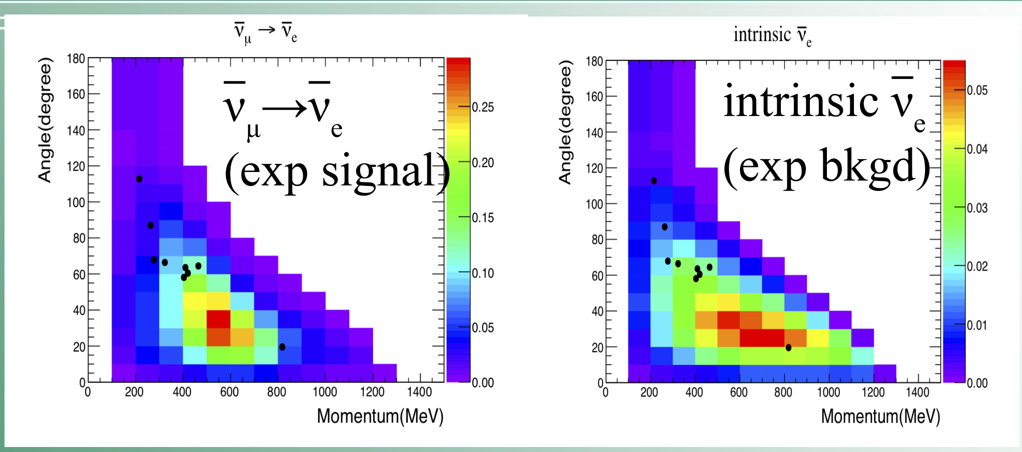


Constant $\Delta\chi^2$, Gauss approx , fixed hierarchy, reactor constraint applied

	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2\rvert$ (x 10^{-3} eV^2)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

$\bar{\nu}_e$ appearance search

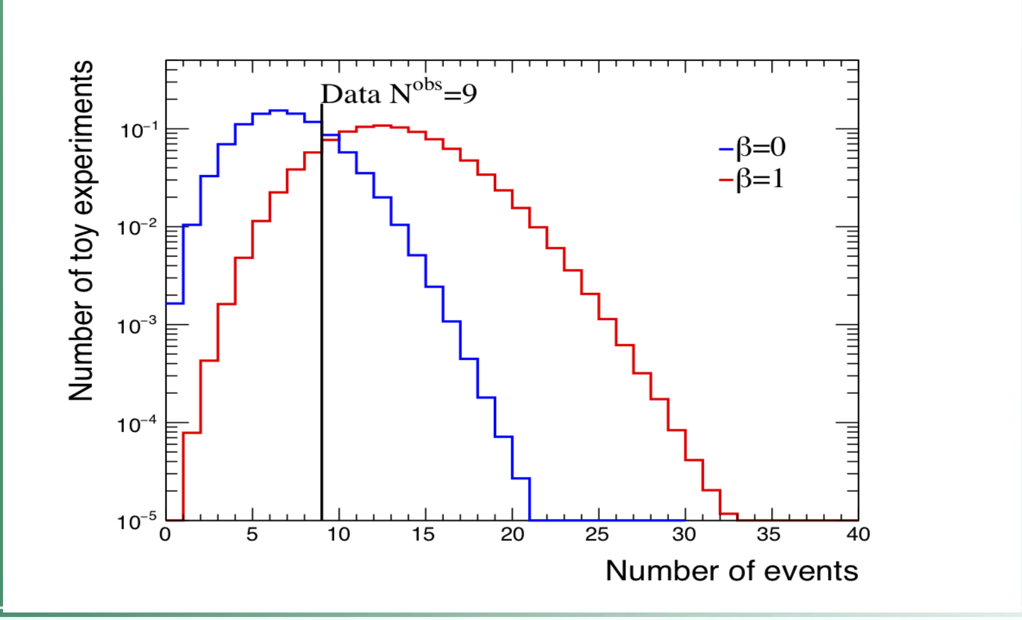
- Compare consistency with PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0)
  - if β=0 expect 6.5 events
  - if β=1 expect 11.8 events
- The data shapes look more consistent with background spectra than $\bar{\nu}_e$ signal.



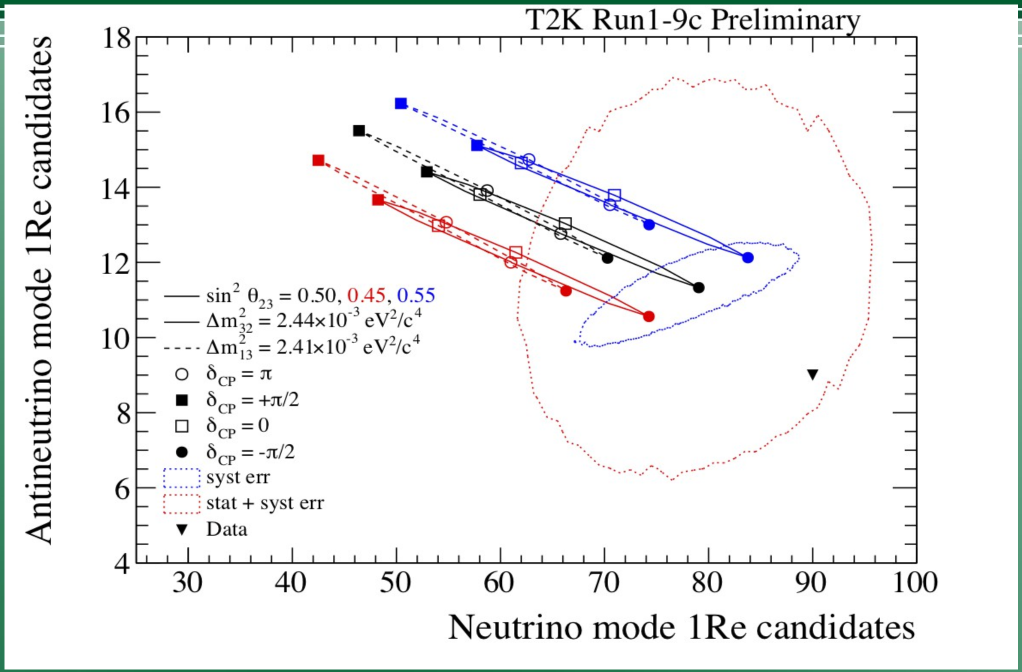
- Use rate+shape analyses:

β	Hypothesis	P-value
β=0	NO appearance	p=0.233
β=1	PMNS appearance	p=0.0867

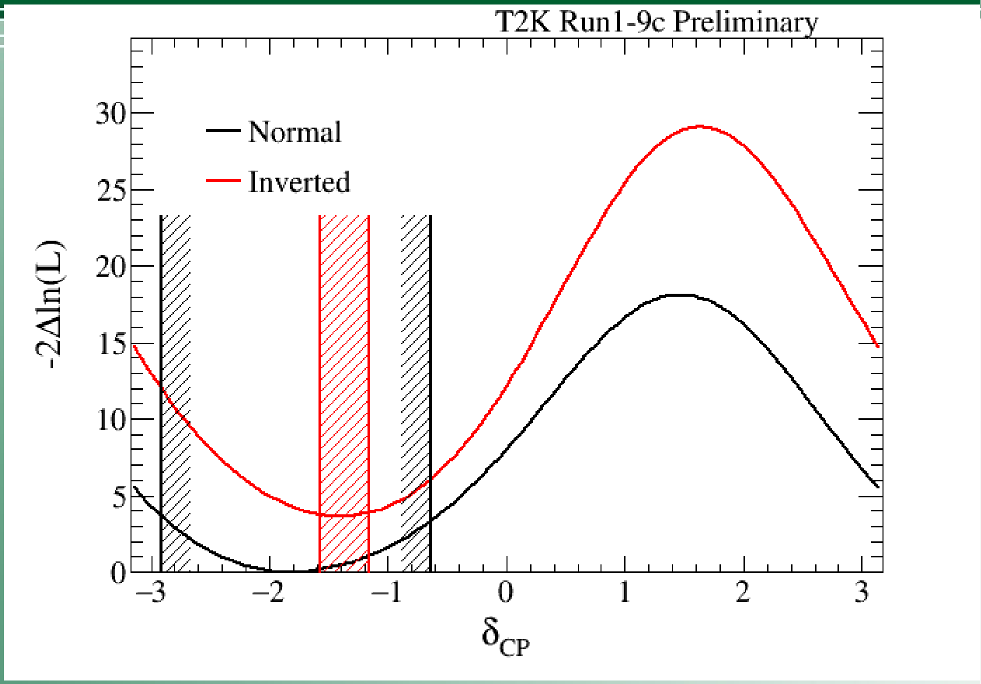
- **No strong conclusion yet.**



ν_e and $\bar{\nu}_e$ sample: δ_{CP}



Contours: 1σ, δ_{CP} = -π/2, $\sin^2\theta_{23}$ = 0.5, NH, reactor θ_{13} for 300k toys



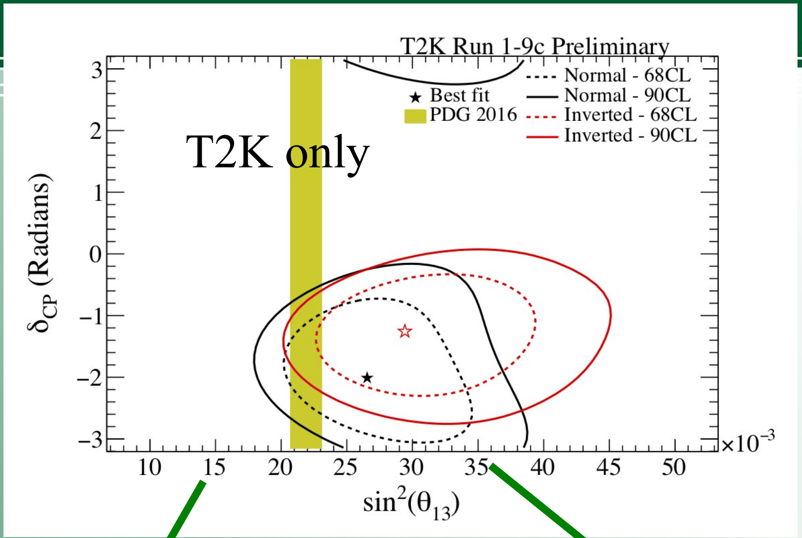
δ_{CP} with Feldman-Cousins 2σ critical values and reactor θ_{13}

- T2K result with reactor contraint:

δ_{CP} = [-2.437, -1.228] NH (no IH at 1σ)

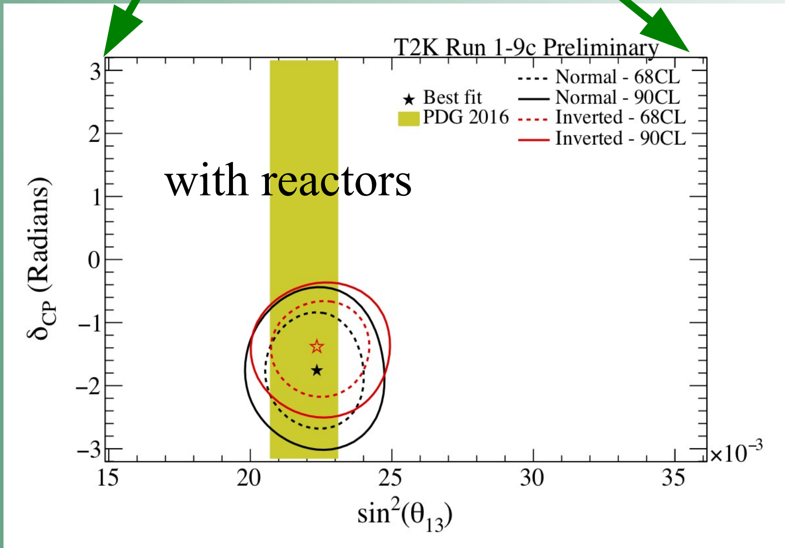
CP conservation (δ_{CP} = 0, π) disfavoured at 2σ for both MH.

ν_e appearance: θ_{13}



T2K only

	NH	IH
$\sin^2\theta_{13}$	$0.0268^{+0.0051}_{-0.0046}$	$0.0305^{+0.0064}_{-0.0052}$

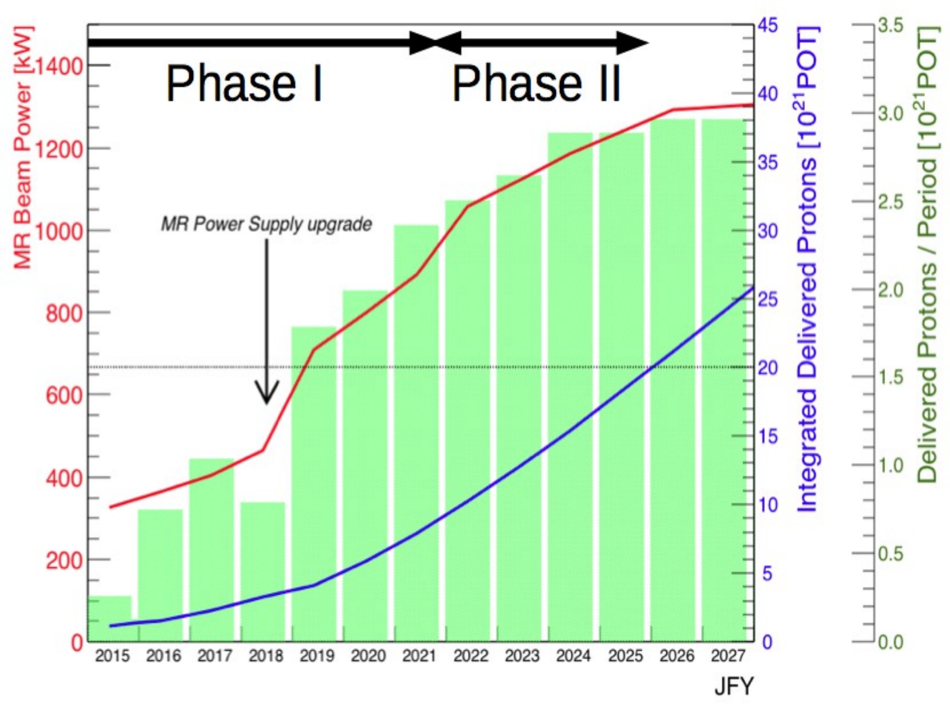


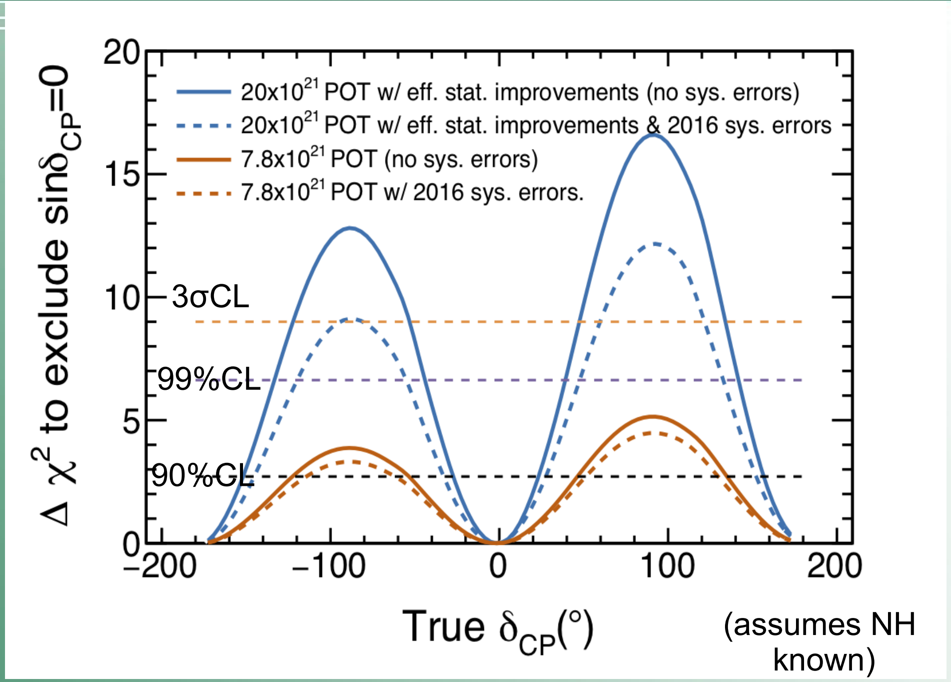
Bayesian posterior probabilities (with reactor)

	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

Bayes factor for NH/IH is 7.9

T2K-II: upgrade beam and detectors

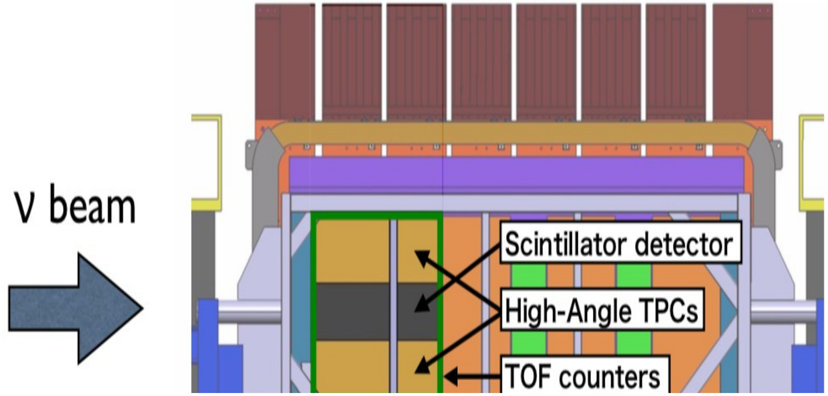




- 1st stage of J-PARC main ring power supply upgrade approved
  - Near future: Aiming for 750 kW beam power (currently 485 kW)
- T2K-II extends T2K run to 20 x 10^{21} POT (stops ~ 2026 when HK starts)
- Long term: beamline upgrade to reach 1.3 MW

ND280 upgrade

ND280 upgrade configuration



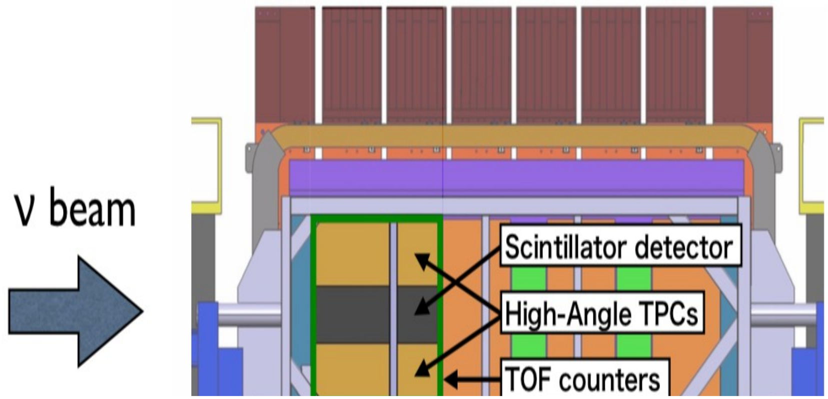
- Replace (most of) P0D with scintillator detector + 2 high-angle TPCs and TOF.
  - improve acceptance for large-angle tracks.
- Keep current "tracker" (2 FGDs + 3 TPCs) & upstream part of P0D, as well as ECal, magnet & SMRD.
  - keeps continuity and forward acceptance.

- T2K-II goal: reduce detector systematics to ~4%
  - improve acceptance, timing, efficiency for short tracks.
- WAGASCI/BabyMIND collaboration has become part of T2K.
  - (3D scintillator detector)
- CERN support, test beam was this summer.
- TDR by end 2018.
- Aim to install upgraded ND280 in 2021.

ND280 upgrade

See talk by Etam Noah Messomo in the Detector parallel session.

ND280 upgrade configuration



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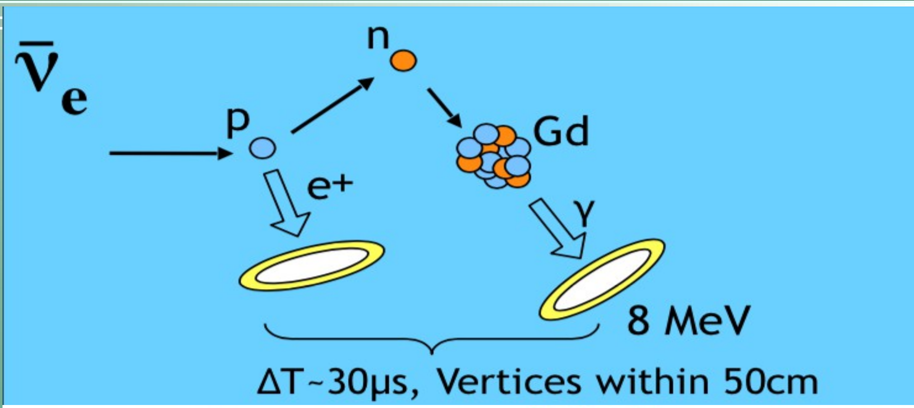
- T2K-II goal: reduce detector systematics to ~4%
  - improve acceptance, timing, efficiency for short tracks.
- WAGASCI/BabyMIND collaboration has become part of T2K.
  - (3D scintillator/water detector)
- CERN support, test beam was this summer.
- TDR by end 2018.
- Aim to install upgraded ND280 in 2021.

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%.



Summary

- T2K has a rich and varied neutrino physics programme
- Precise measurement of θ_{23} , Δm^2_{32}
- First suggestions of CPV in the lepton sector
- First (mild) indications of neutrino mass hierarchy
- Competitive (sometimes the only) neutrino cross-section measurements (see talk by Kevin McFarland in parallel session)
- Constraints on neutrino interaction models, nuclear models
- Limits on ν_s , Lorentz Violation, etc are in progress or published (not covered)
- T2K-II: beam, ND280, SK upgrades – until HK! (see talk by Etam Noah Messomo in parallel session)

Extras

Oscillations at T2K

Appearance

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

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

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

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

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

ν vs. $\bar{\nu}$ sign change

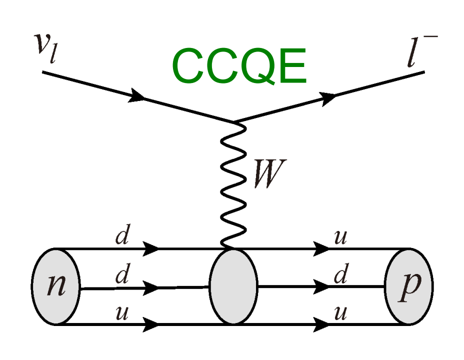
$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2} G_F n_e E$

θ_{13} dependence — Octant sensitivity — CP-odd phase

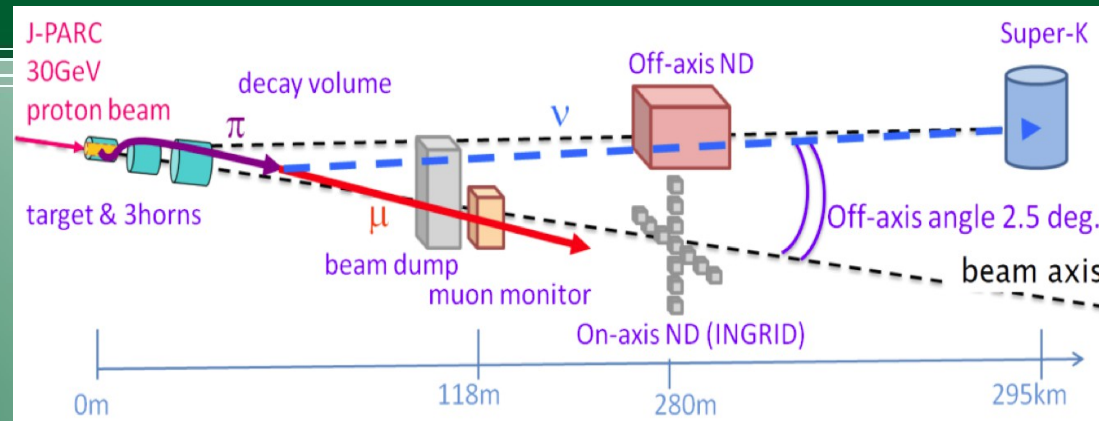
Disappearance

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

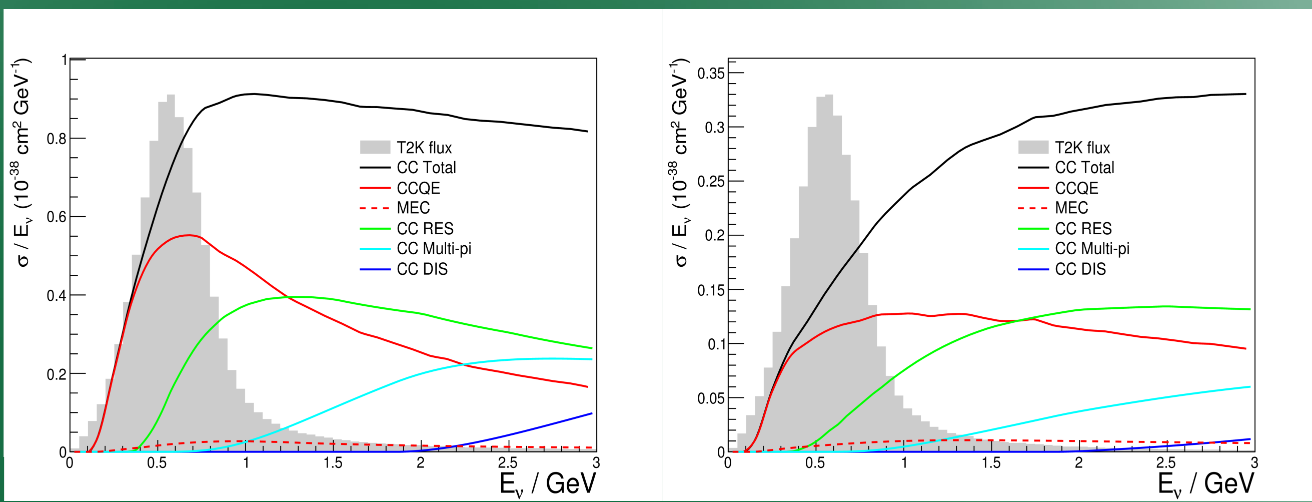
θ_{23} dependence — Octant sensitivity — $P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = P_{PMNS}(\nu_\mu \rightarrow \nu_\mu)$ Test of CPT

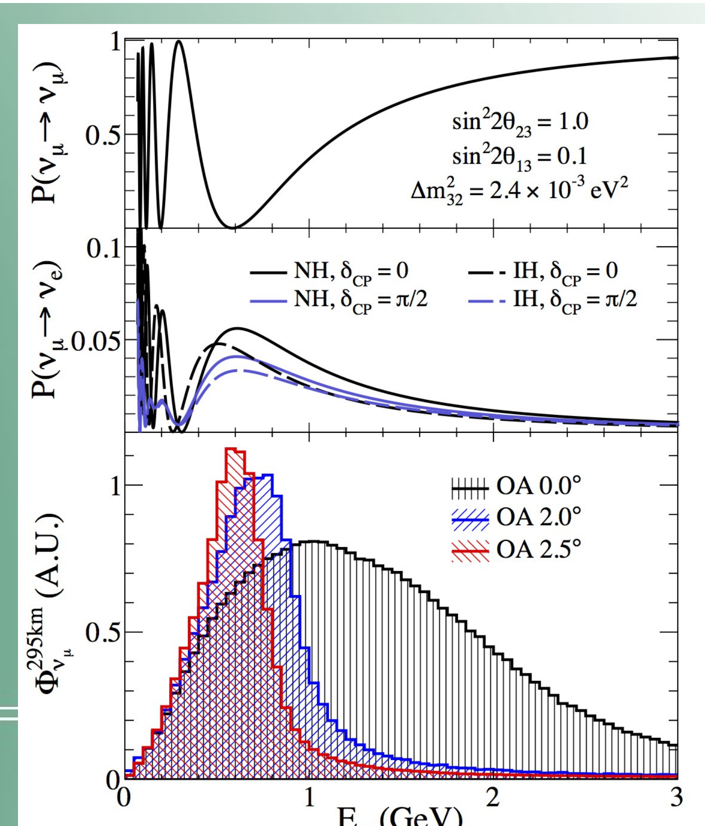


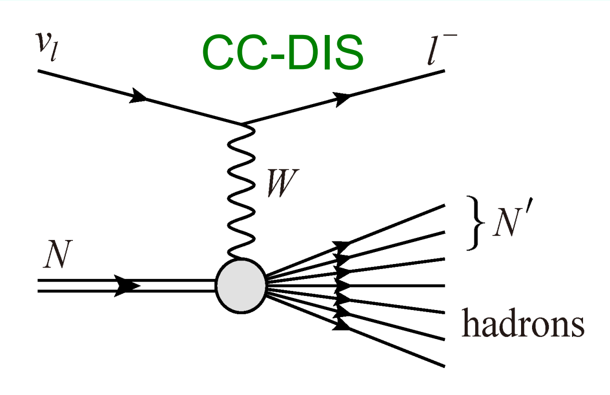
Off-axis technique



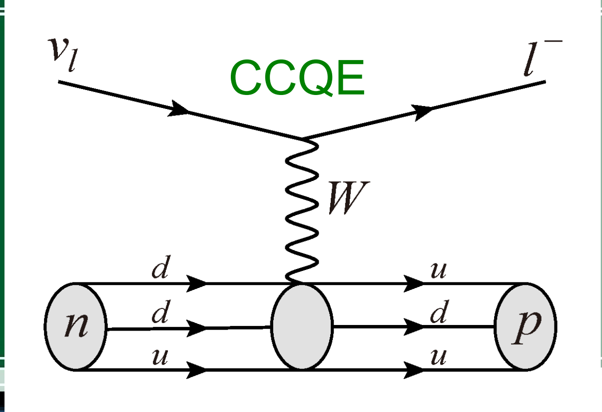
- Enhanced oscillation – beam energy tuned to oscillation max
- Enhanced CCQE fraction
- Less intrinsic ν_e contamination
- Less Neutral Current background

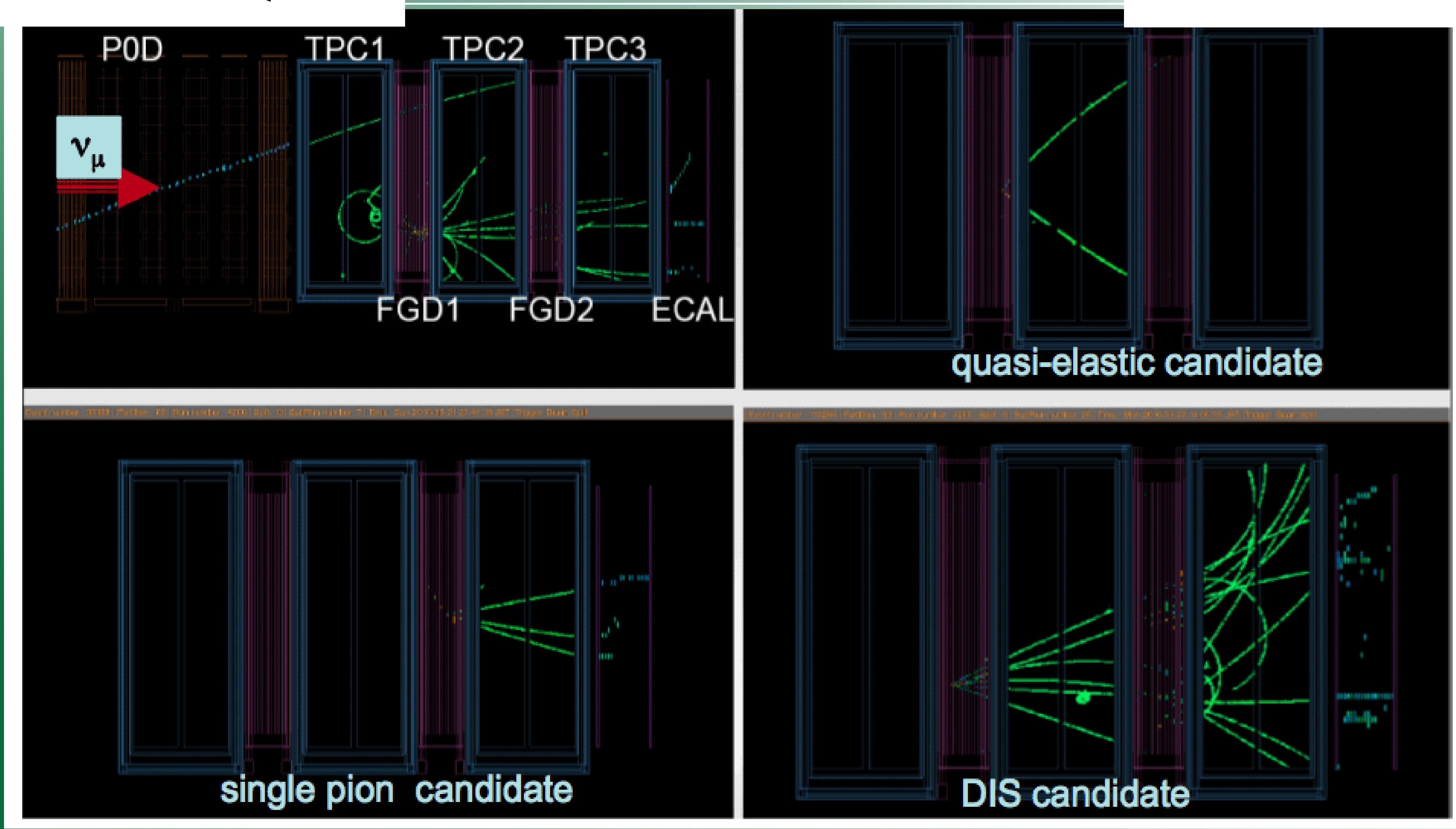






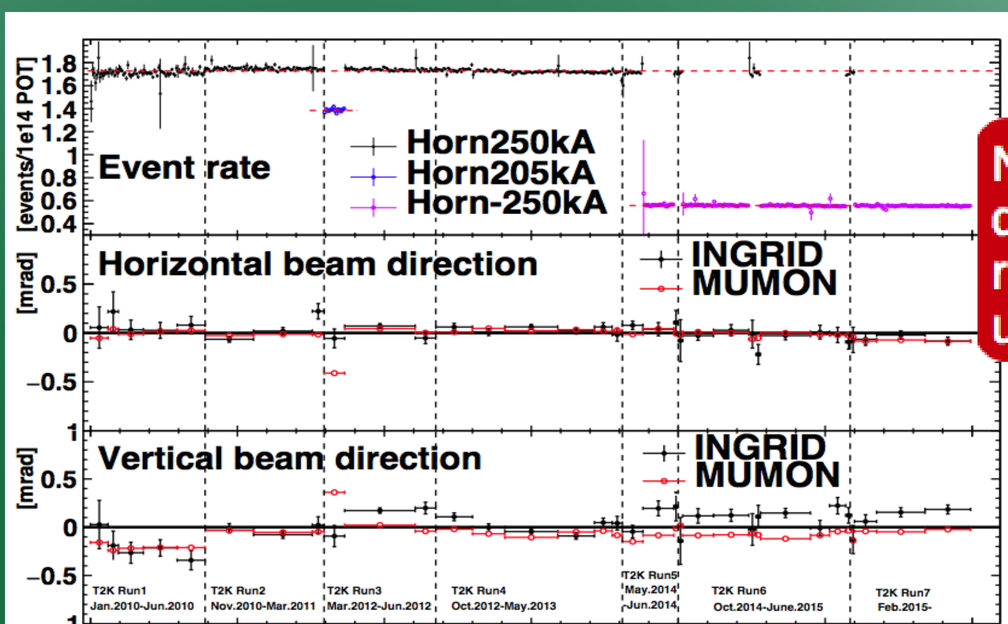
ND280 events



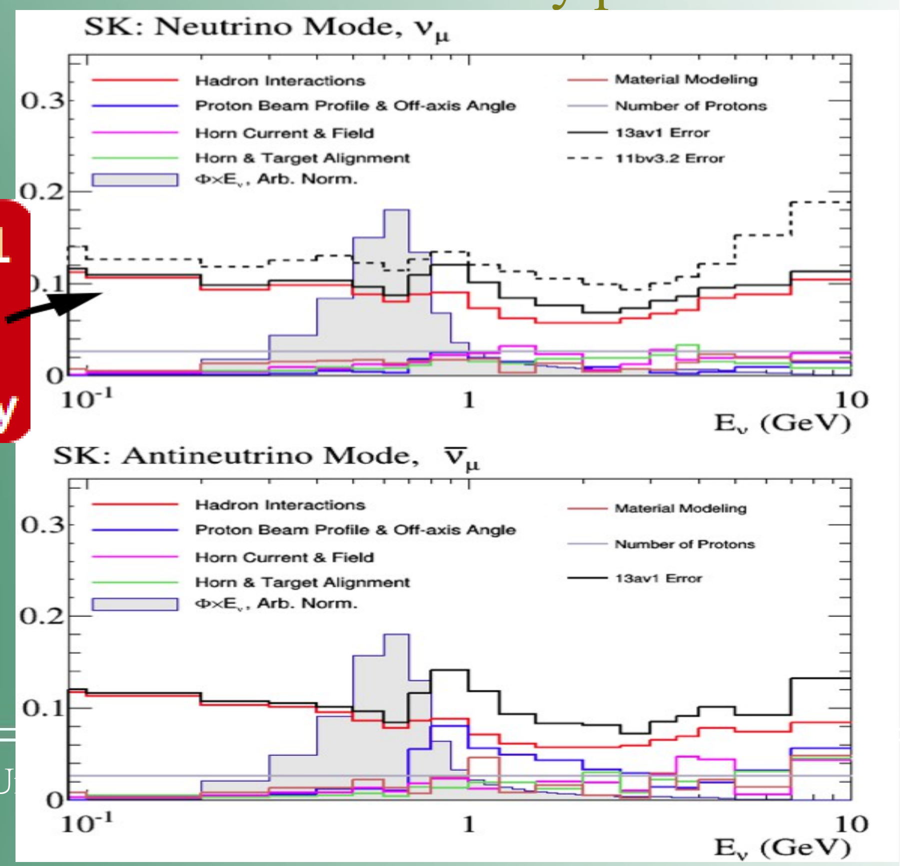


Flux uncertainties

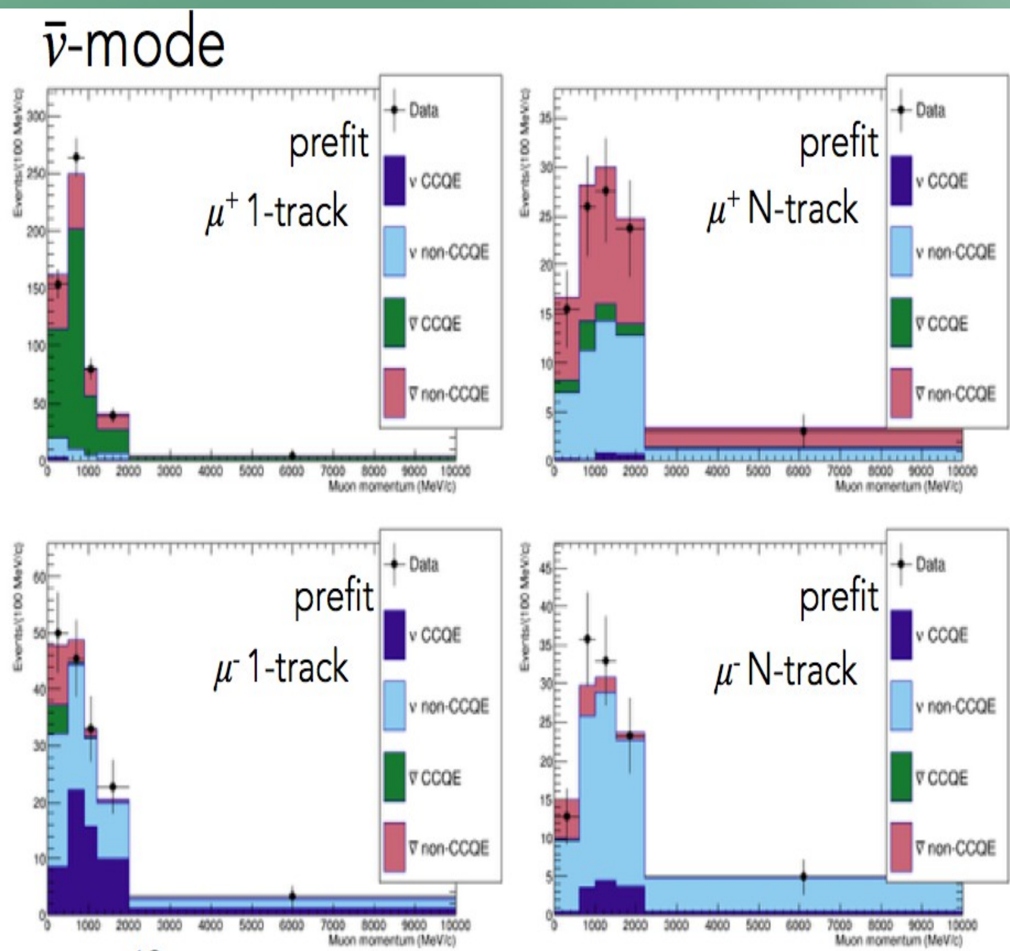
- Beamline uncertainties
  - Proton beam parameters
  - Focusing horns
  - Component alignment
- Hadron production uncertainties
  - NA61/SHINE uncerts
  - Re-interactions, Secondary production

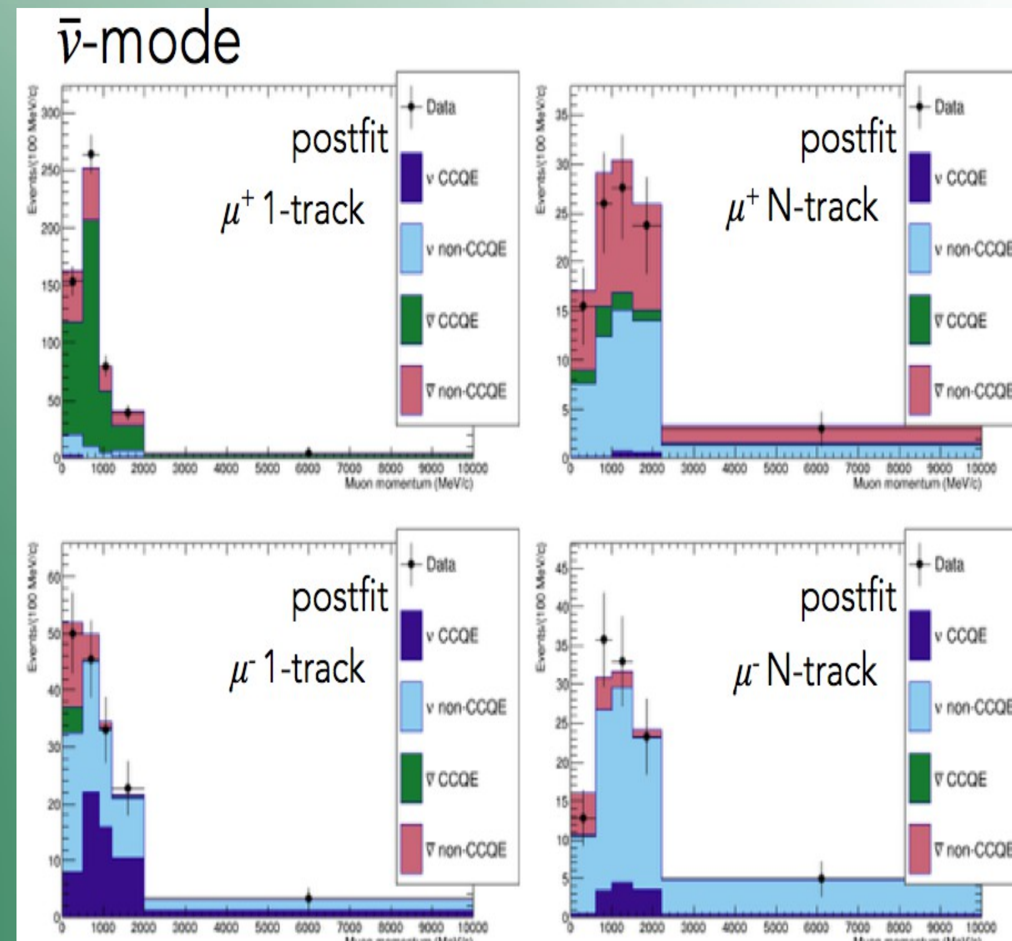


New NA61 data has reduced uncertainty

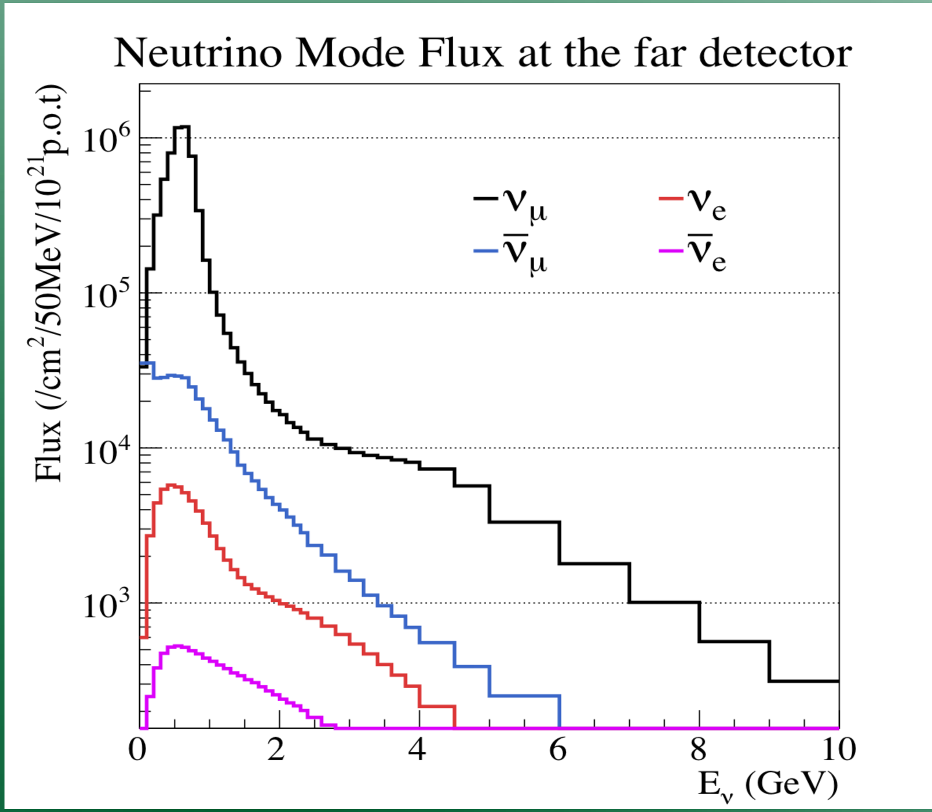


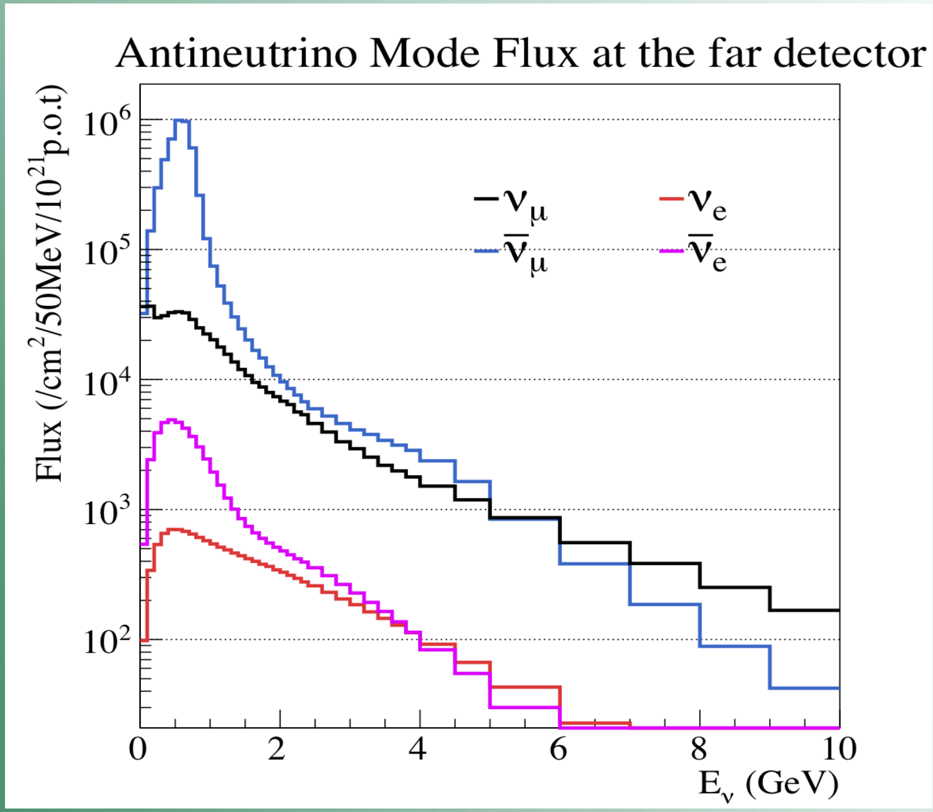
ND280 samples, $\bar{\nu}$-mode





Flux predictions at SK





FITQUN RECONSTRUCTION ALGORITHM

- 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

THE FIVE SAMPLES

- 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

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

$$\downarrow$$

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

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

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$

$$\downarrow$$

$$\mu^+ + \nu_\mu$$

$$\downarrow$$

$$e^+ + \nu_e + \bar{\nu}_\mu$$

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*