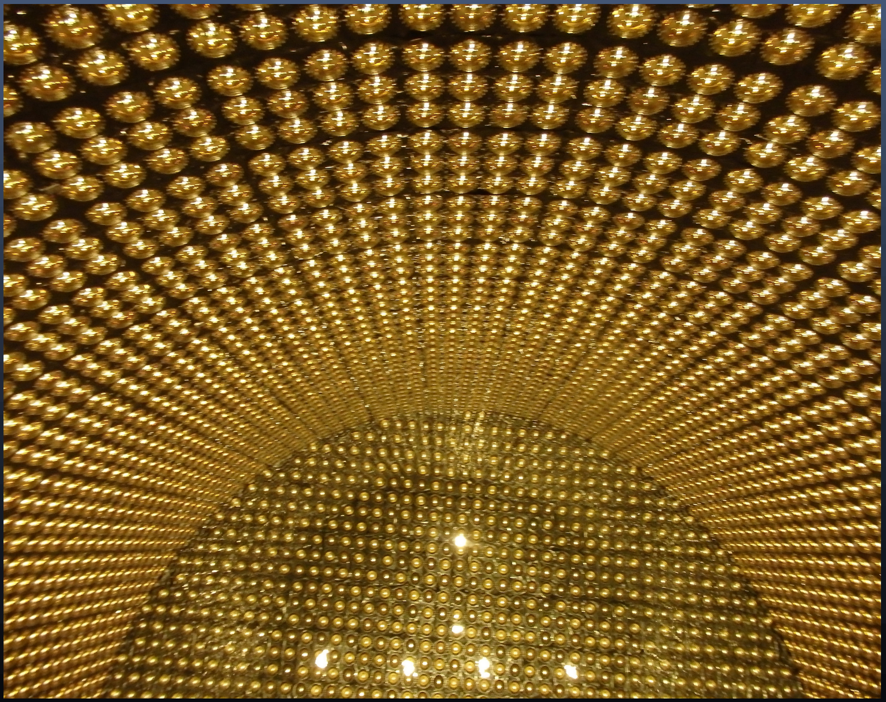
Recent T2K neutrino oscillation results

Dr Laura Kormos
on behalf of
the T2K Collaboration

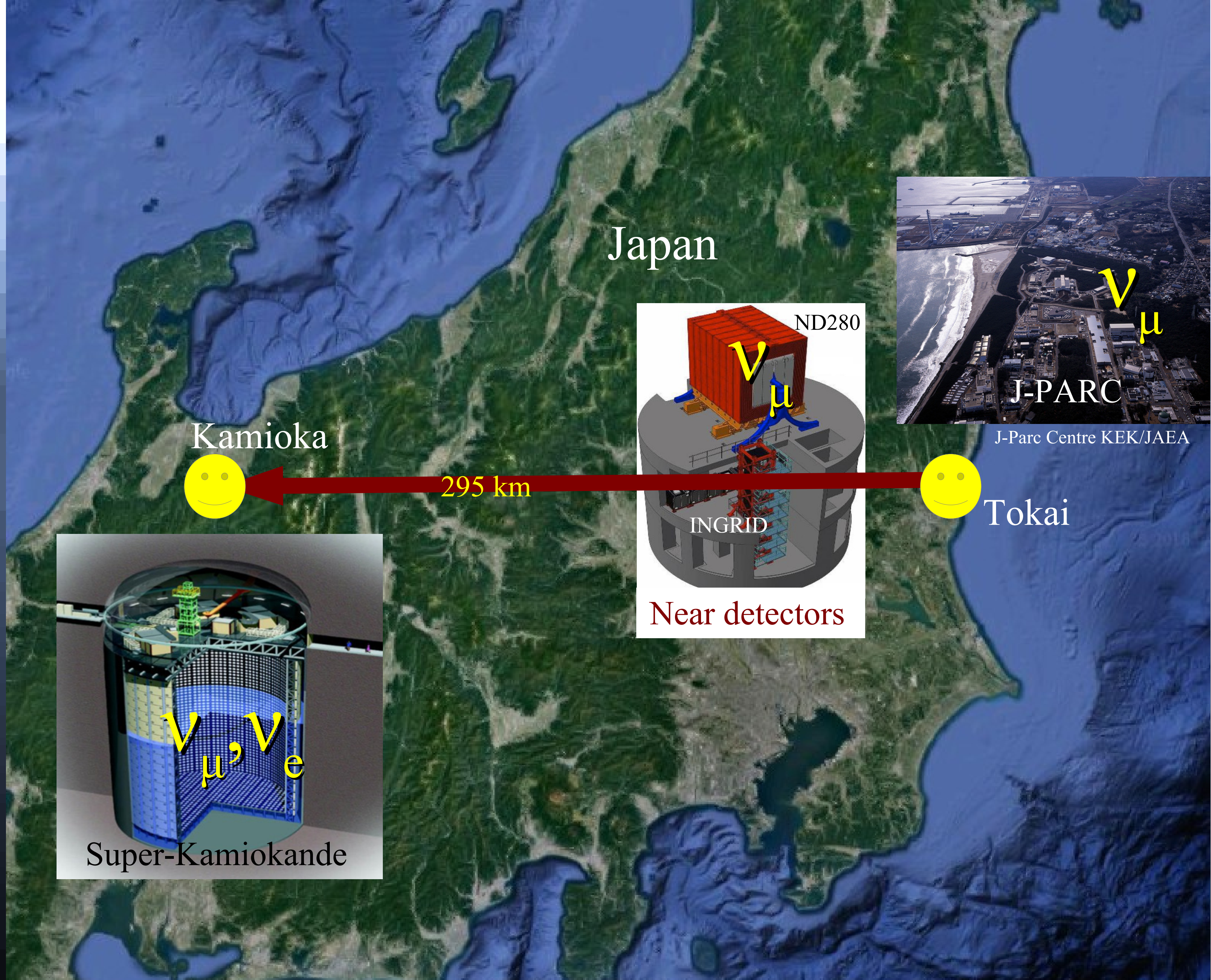
- T2K (Tokai to Kamioka)
- ν_μ and $\bar{\nu}_\mu$ disappearance
- $\bar{\nu}_e$ appearance
- ν_e appearance and δ_{CP}
- T2K-II
- The future



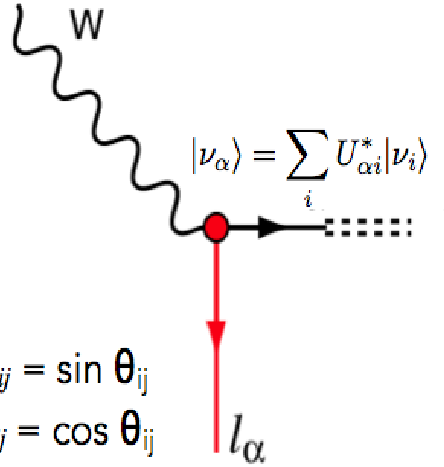
- PRL Editor's Choice paper with the 2017 analysis PRL **121,** 171802 (2018)
- Results also available from Neutrino 2018: "T2K Status, Results, and Plans", Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018, Heidelberg, Germany, DOI: 10.5281/zenodo.1286751, URL: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

T2K
(Tokai to Kamioka)

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



Mixing of three neutrinos



$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS mixing matrix

"standard" parametrization

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

Current knowledge

$\theta_{12} \sim 33^\circ$

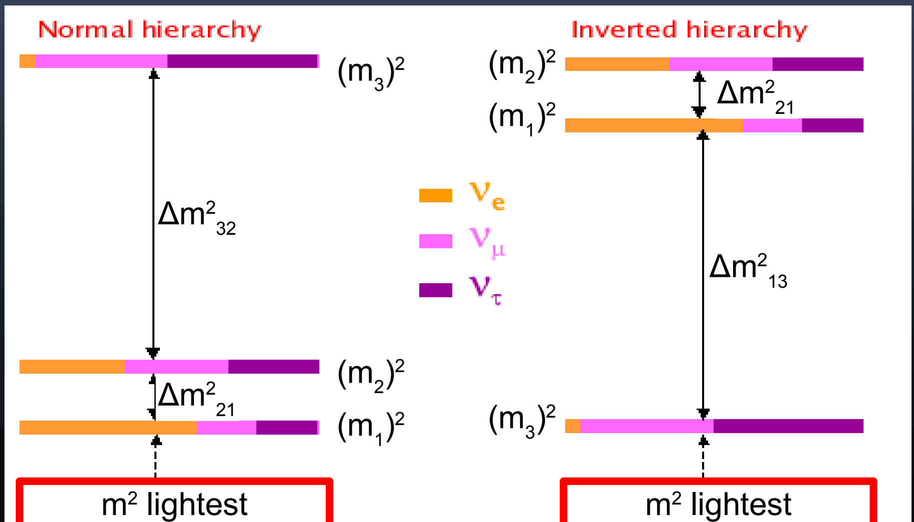
$\theta_{23} \sim 45^\circ$

$\theta_{13} \sim 9^\circ$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

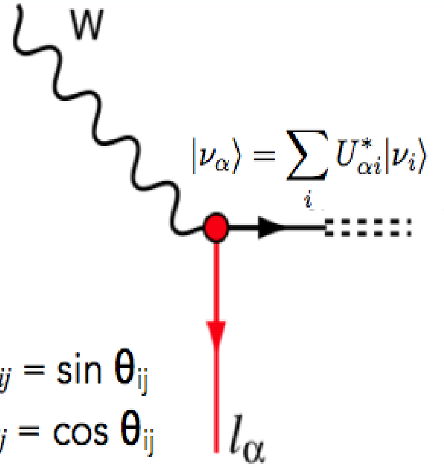
$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{ij} = m_i^2 - m_j^2$



Mass Hierarchy

Mixing of three neutrinos



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3}\\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS mixing matrix

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

"standard" parametrization

$$U = \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix}$$

Current knowledge

$\theta_{12} \sim 33^\circ$

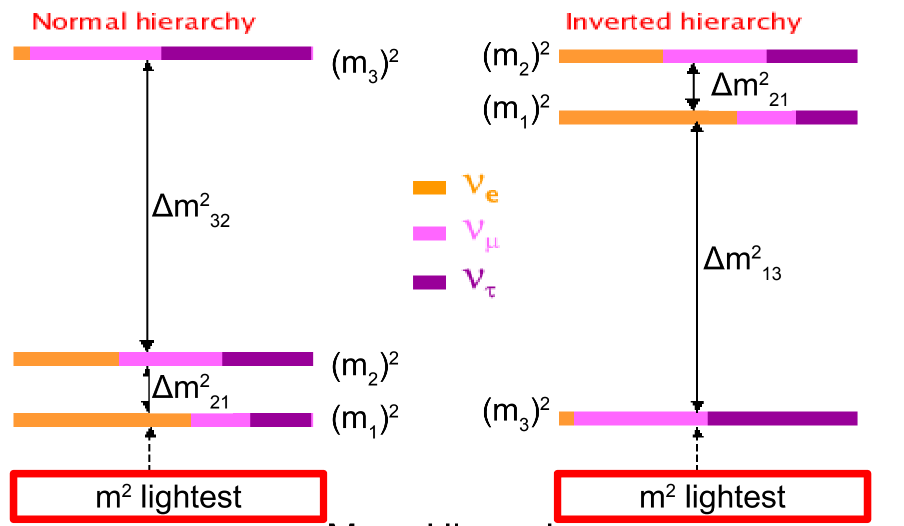
$\theta_{23} \sim 45^\circ$

$\theta_{13} \sim 9^\circ$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{ij} = m_i^2 - m_j^2$



Mass Hierarchy

Oscillations at T2K

Appearance

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

$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\underline{\sin\delta}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ — 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} dependence — Octant sensitivity — CP-odd phase

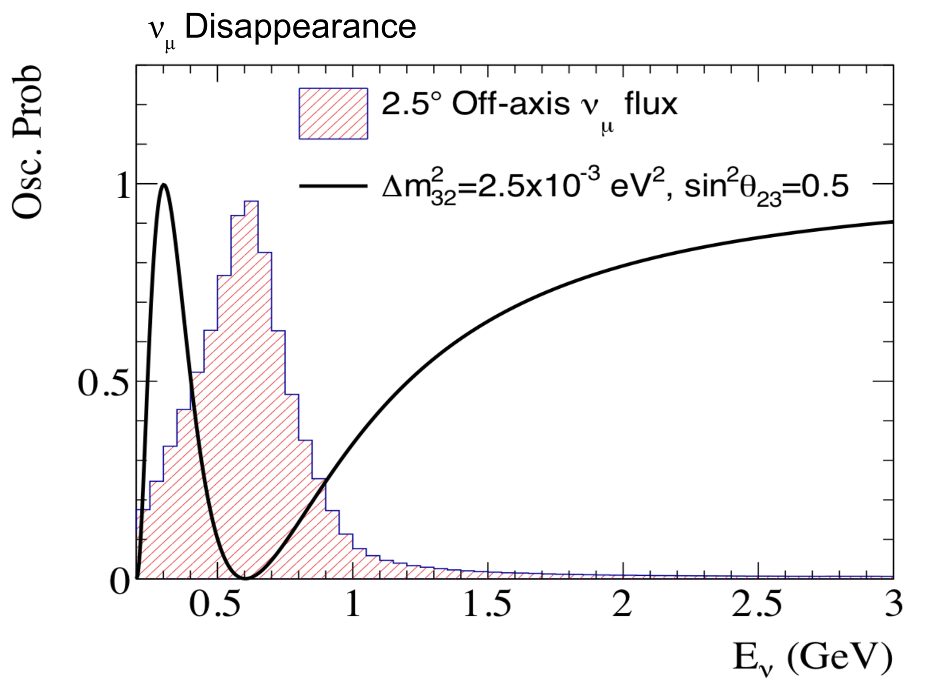
Disappearance

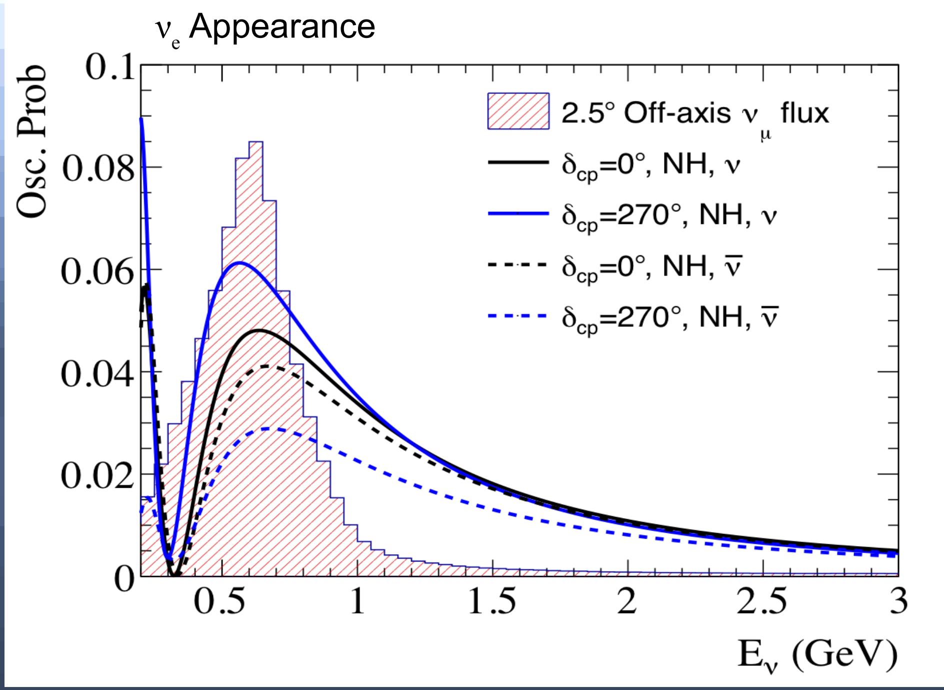
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4\theta_{13}\cdot\underline{\sin^2 2\theta_{23}} + \sin^2 2\theta_{13}\cdot\underline{\sin^2\theta_{23}}\right)\cdot\sin^2\frac{\Delta m_{32}^2\cdot L}{4E_\nu}$$

(Leading and next terms only)

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

Oscillations at T2K



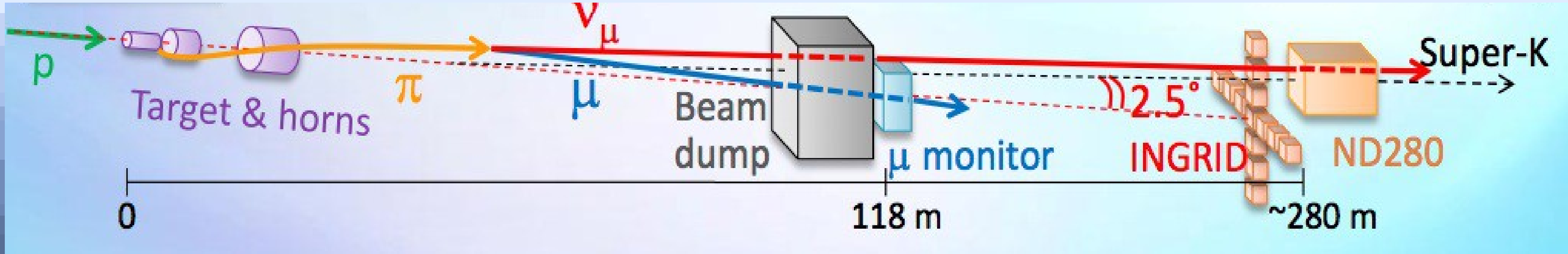


- Tests CPT symmetry
- LO* dependence on $\sin^2 2\theta_{23}$
  - hard to distinguish $\theta_{23}>45^o$ from $\theta_{23}<45^o$
- LO dependence on $|\Delta m^2_{32}|$
  - doesn't depend on sign of mass splitting

(* Leading Order)

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

The T2K beam

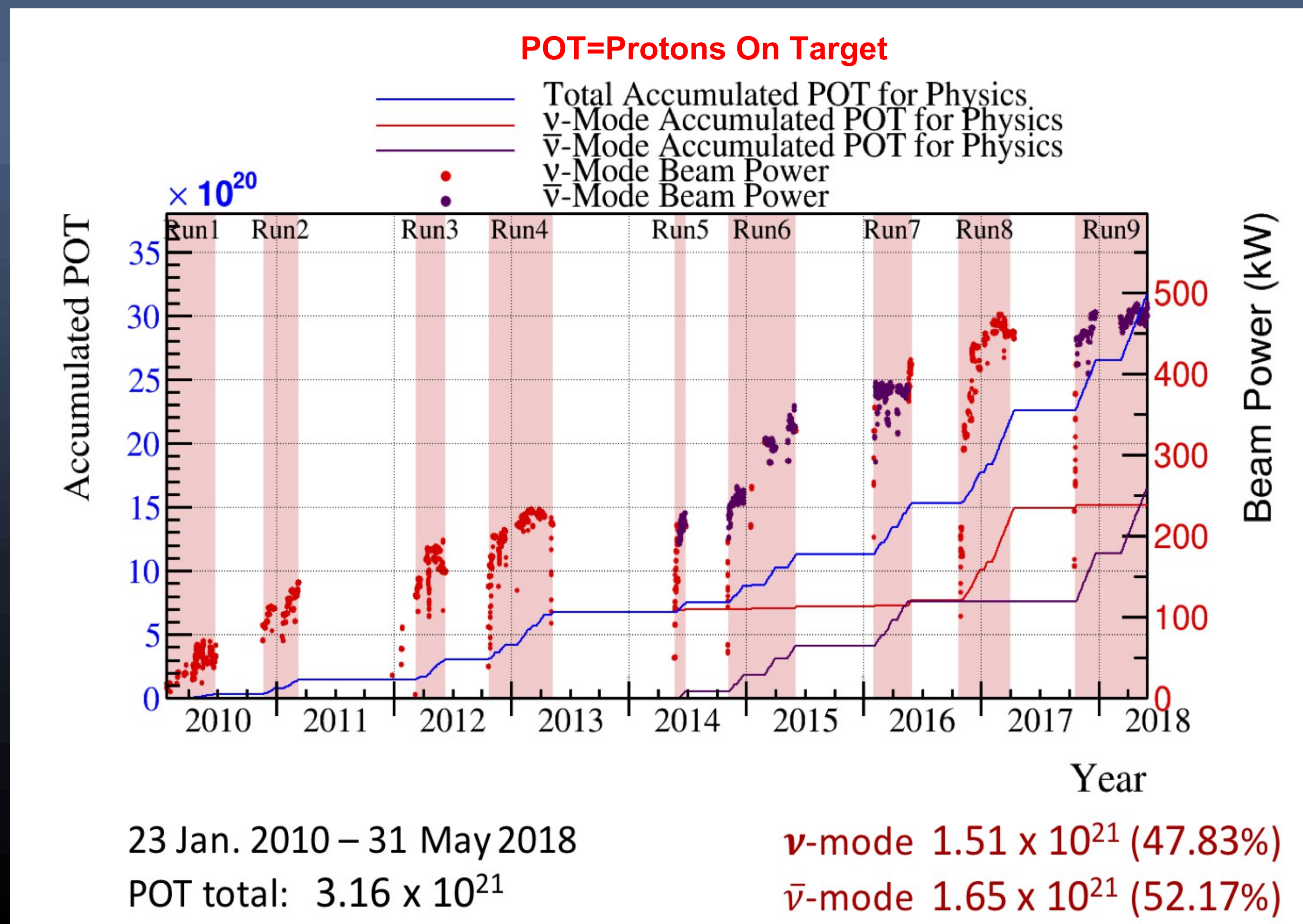


- Primarily ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  (forward horn current, FHC, or neutrino mode)

- Reverse polarity for $\bar{\nu}_\mu$ beam:

  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

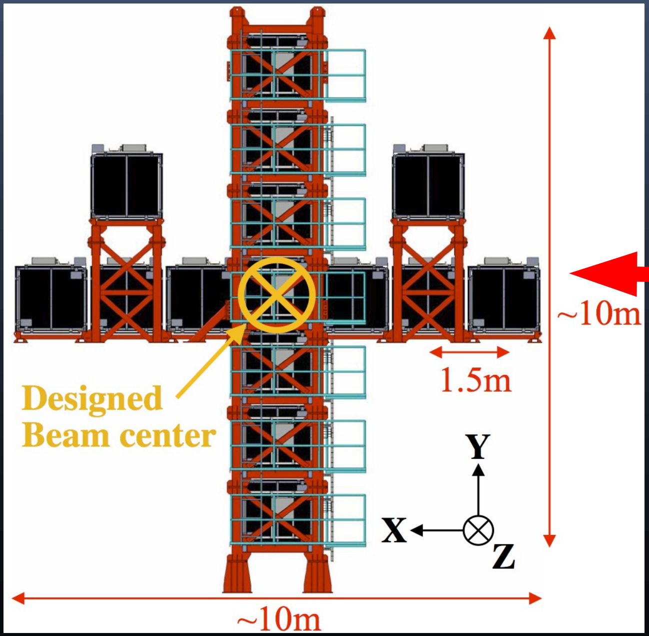
  (reverse horn current, RHC, or antineutrino-mode)

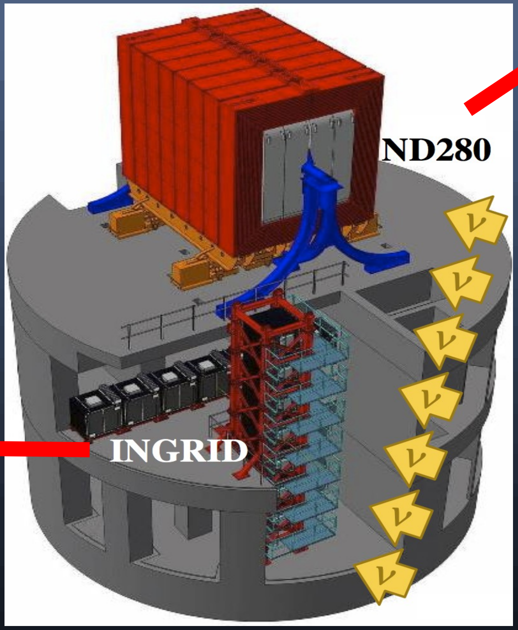


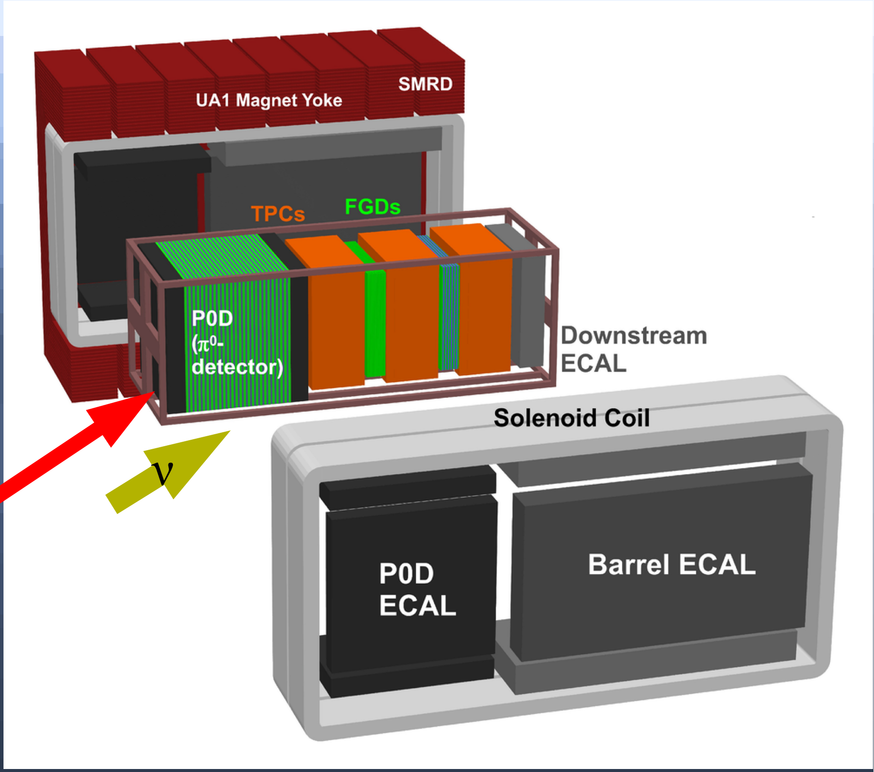
Near detectors

INGRID

- Identical modules in cross
- Iron and plastic scintillator tracking calorimeter
- Monitors ν, $\bar{\nu}$ beam direction and stability





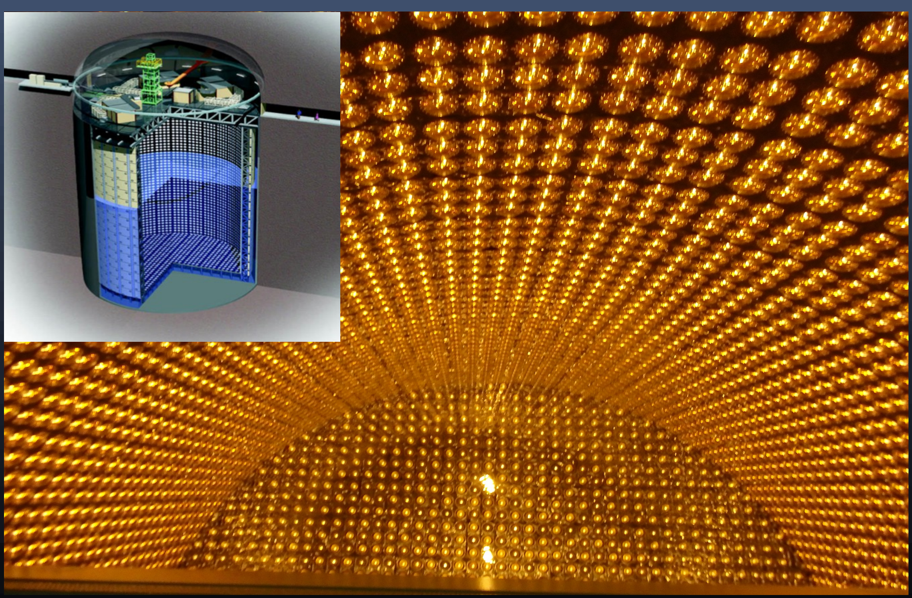


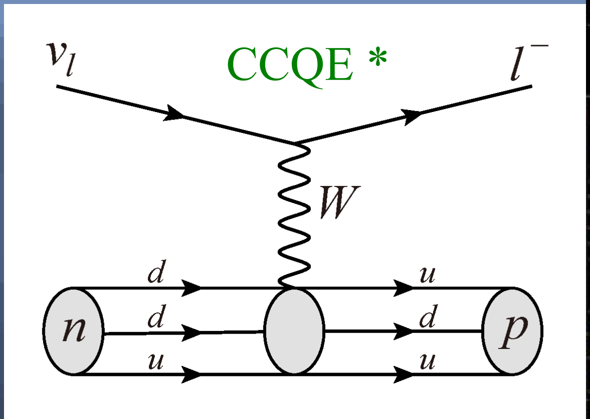
ND280

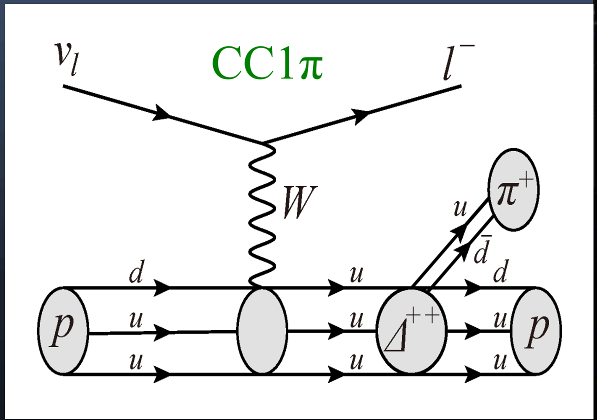
- **Off-axis (2.5°) detector**
- 0.2 T magnet
- Trackers, calorimeters, muon range detectors
- Water, carbon, lead, targets.
- Beam ν_e , flux, cross sections, exotics

Far detector: Super-Kamiokande

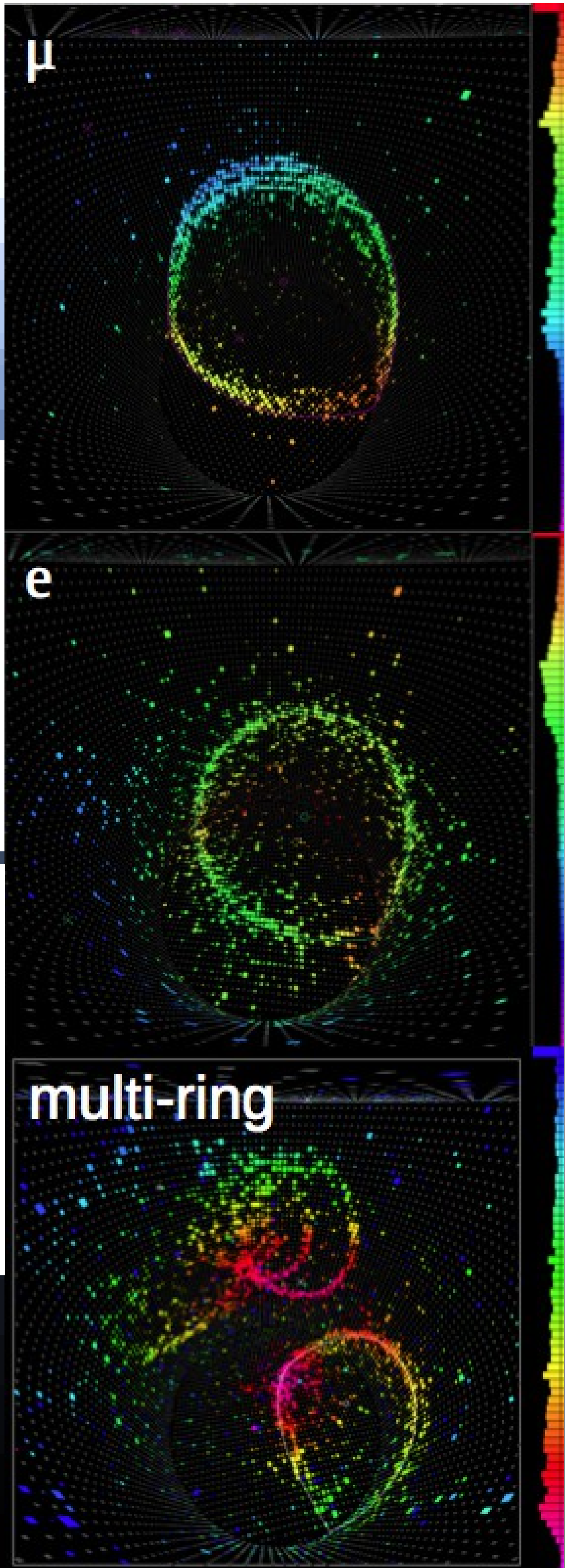
- 50 kton Water-Cherenkov detector
- 2.5^{o} off axis (same as ND280)
- Excellent e/μ separation, π^0 rejection
- Select 1-ring, CCQE-enriched sample
- Select CC1π^+ sample (ν_e appearance)
- ν kinematics derived from lepton





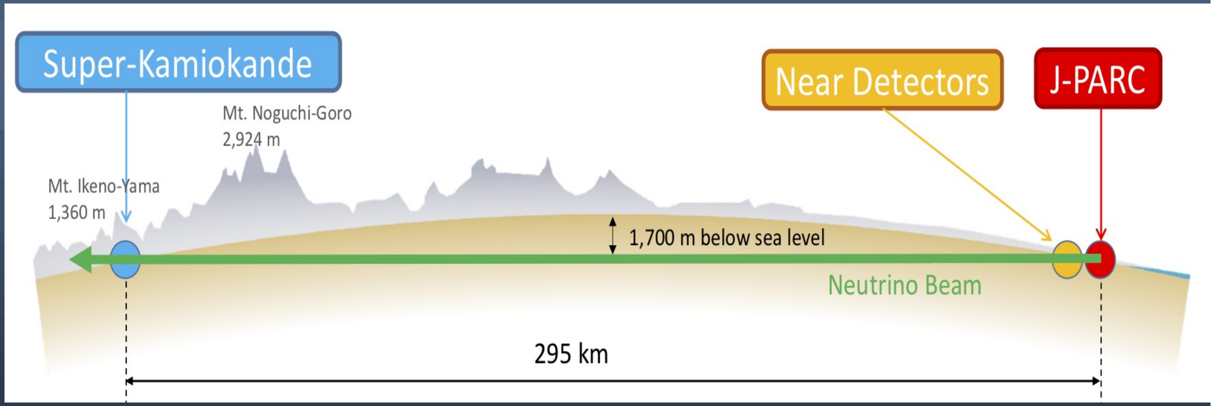


* Charged-current quasi-elastic



T2K oscillation analysis overview

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

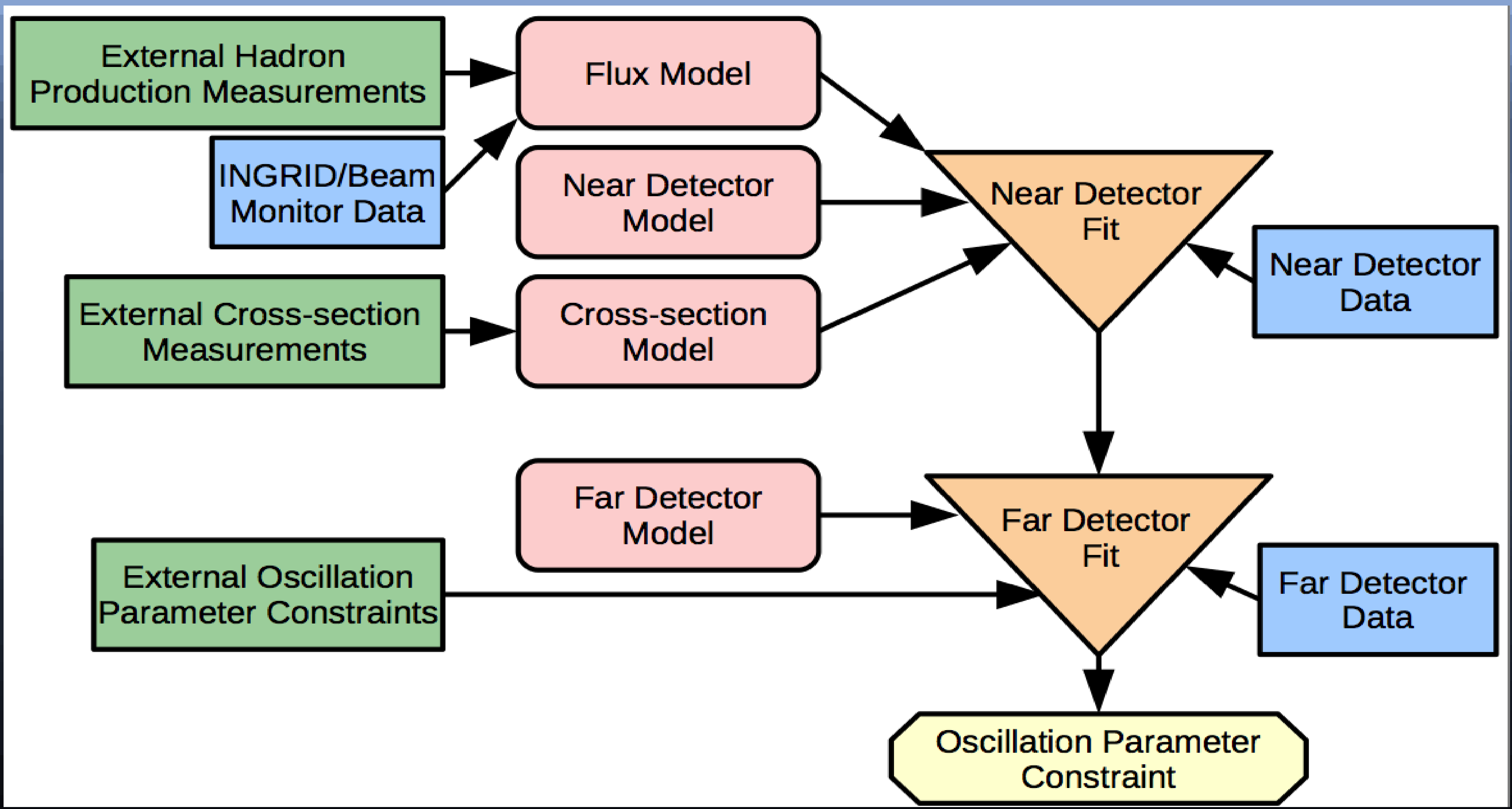


- $N_{ND} \sim \Phi_{ND} \bullet \sigma_{ND} \bullet \varepsilon_{ND}$

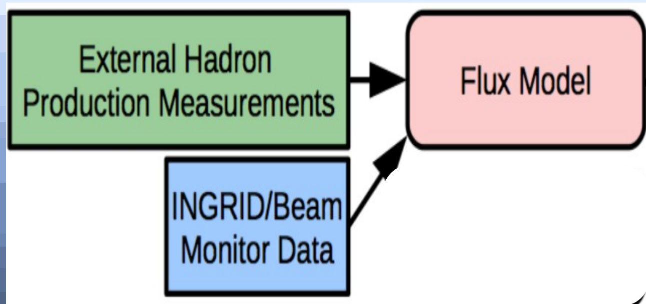
  Observable Flux Cross section Detector response

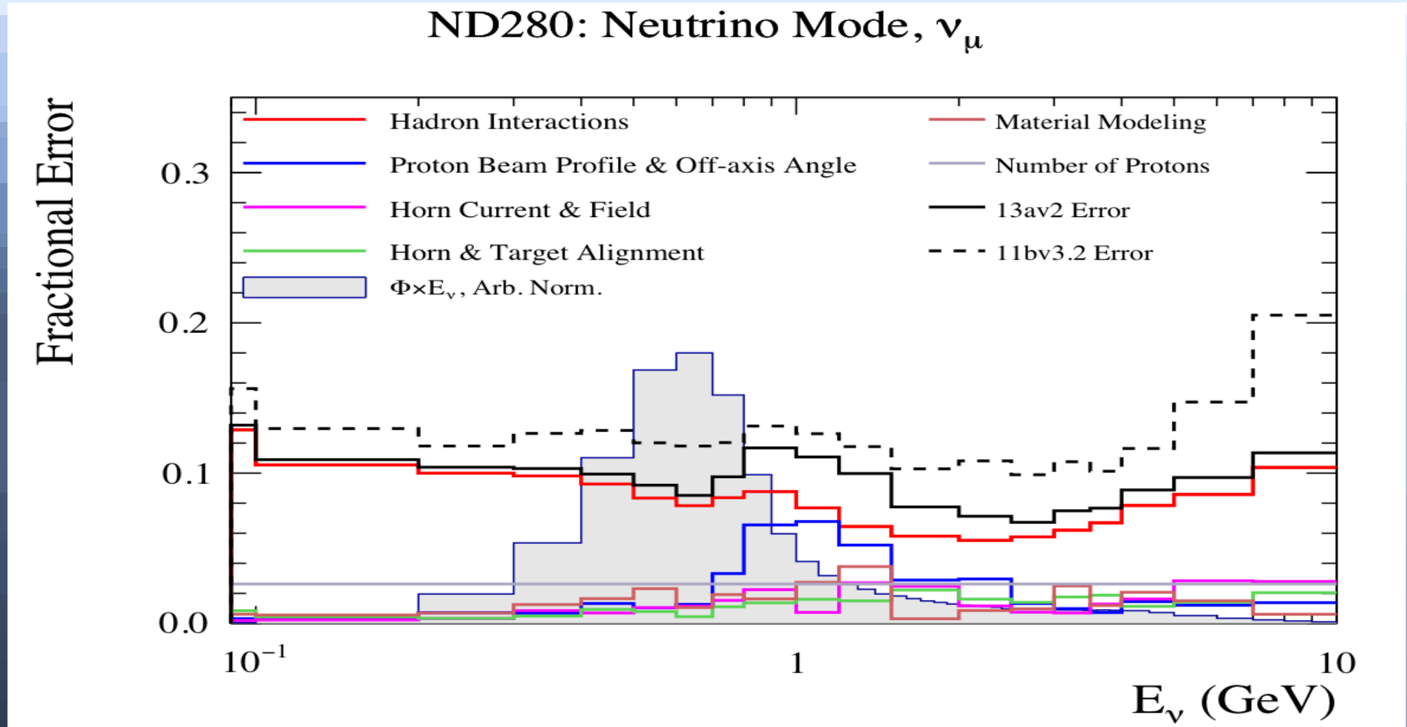
- $N_{FD} \sim \Phi_{FD} \bullet \sigma_{FD} \bullet \varepsilon_{FD} \bullet P_{Osc}$

T2K oscillation analysis overview

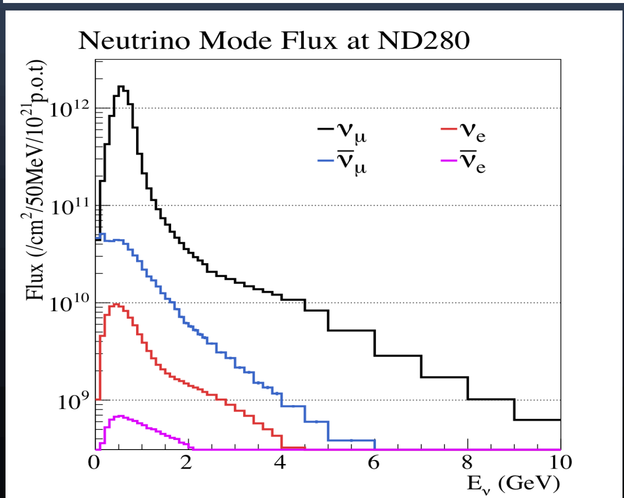


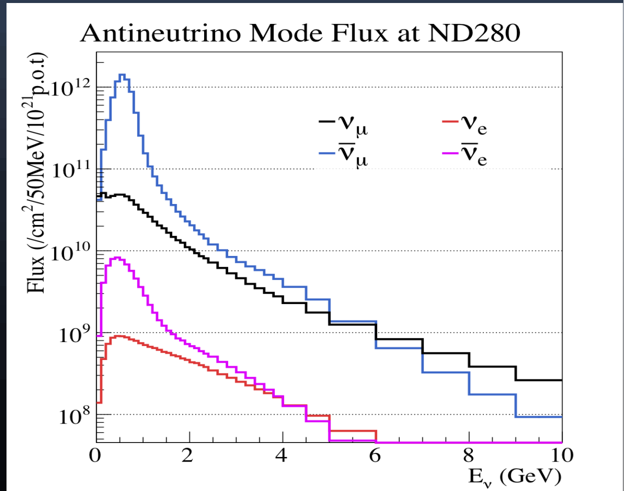
Flux prediction and uncertainties





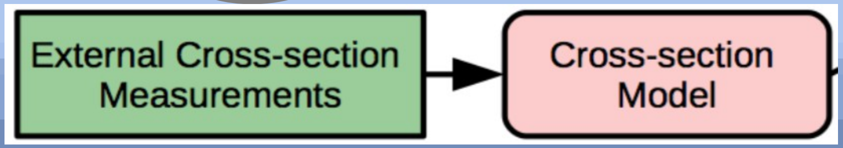
- Flux simulation (FLUKA/GEANT3/ GCALOR)
- Tuned using external data (NA61/SHINE hadron production measurements)
- Intrinsic ν_e component ~0.5% at flux peak



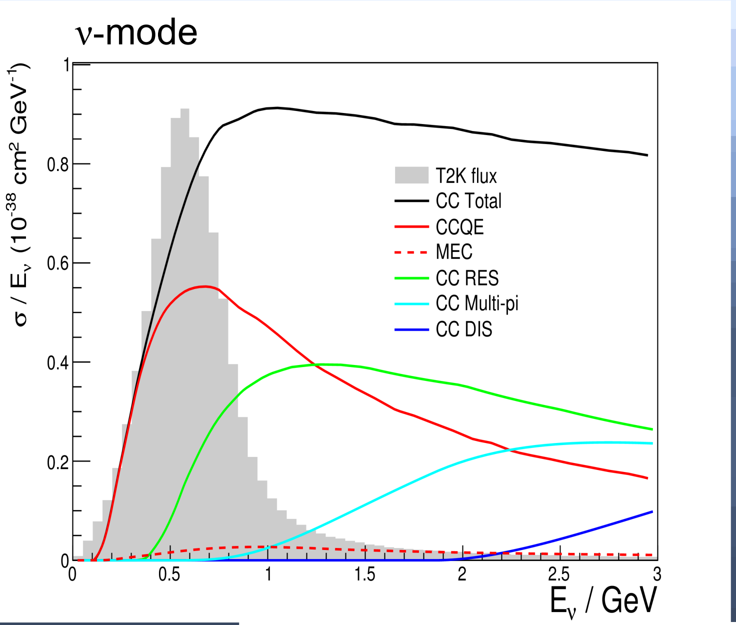


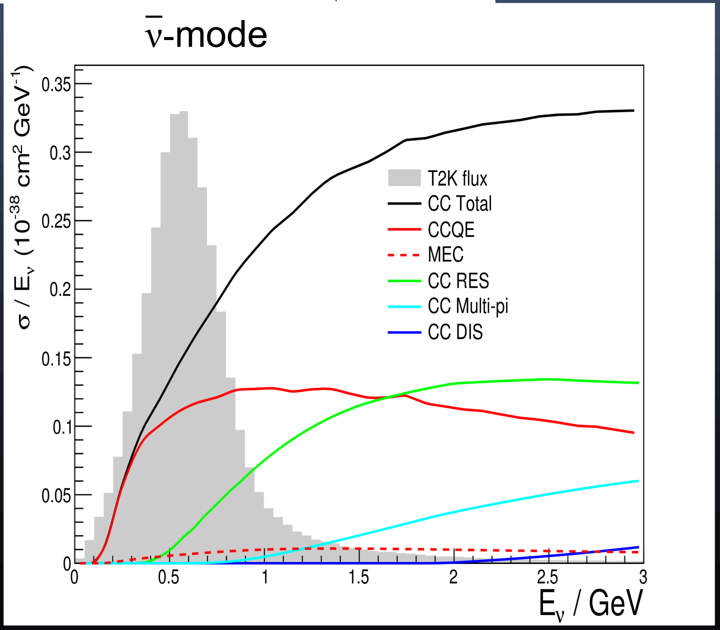
Cross-section model

Talk by
Georgios Christodoulou
Saturday morning

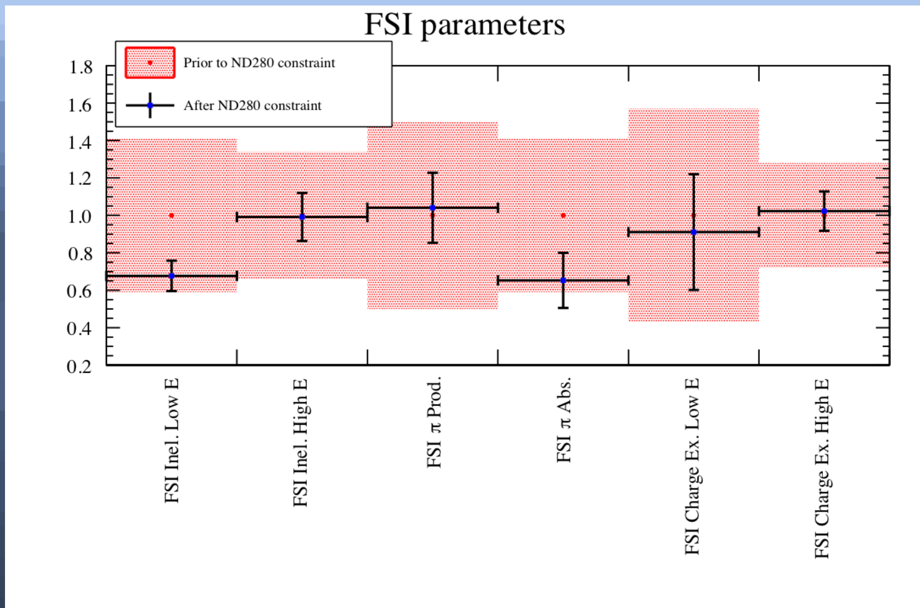


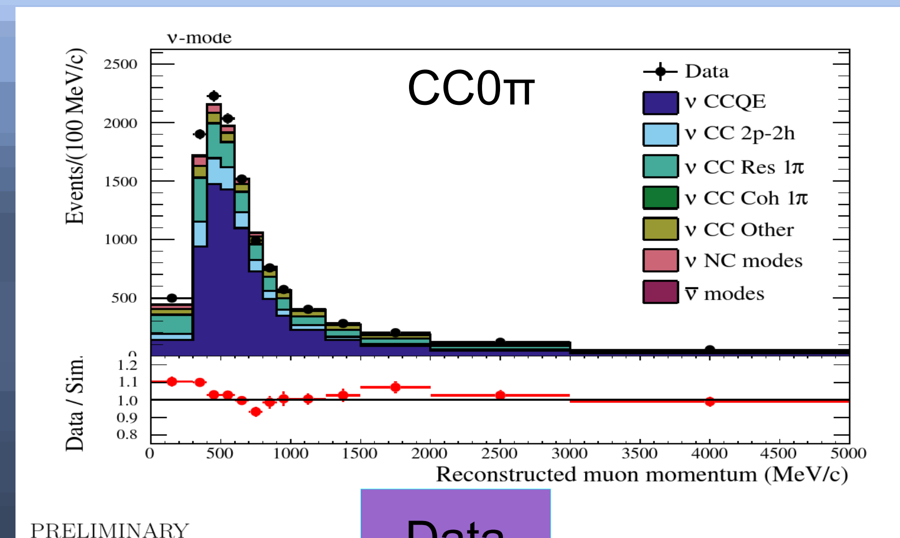
- NEUT generator tuned to external data from MiniBooNE, MINERνA, bubble chambers, etc
- Examples:
  - CCQE:
    - Relativistic Fermi Gas (RFG)
    - Random Phase Approximation (RPA)
  - CC-RES:
    - pion reinteractions inside the nucleus



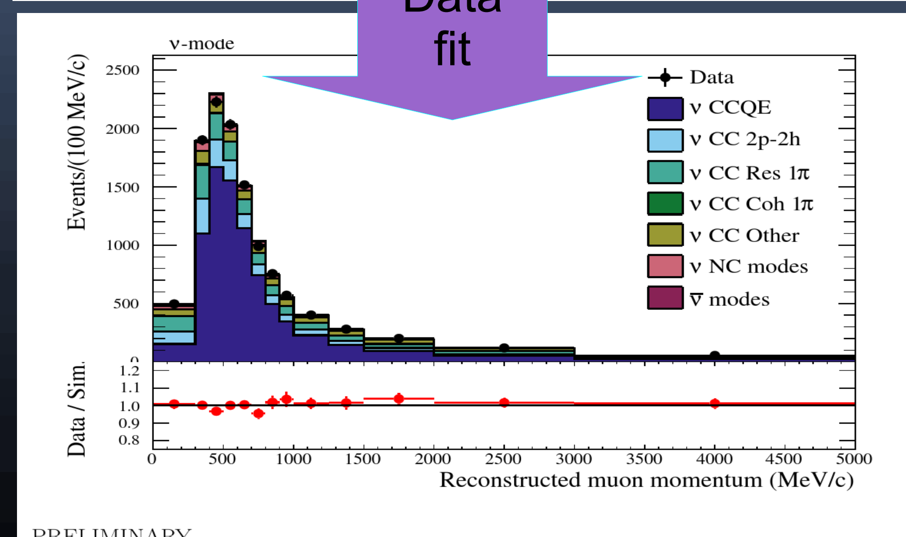


ND280 data fitting and constraints





Data fit



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

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

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
ν-mode μ CCQE	272.34	271.97	272.30	272.74	243
$\bar{\nu}$-mode μ CCQE	139.47	139.12	139.47	139.82	140
ν-mode e CCQE	74.46	62.26	50.59	62.78	75
ν-mode e CC1π	7.02	6.10	4.94	5.87	15
$\bar{\nu}$-mode e CCQE	17.15	19.57	21.75	19.33	15

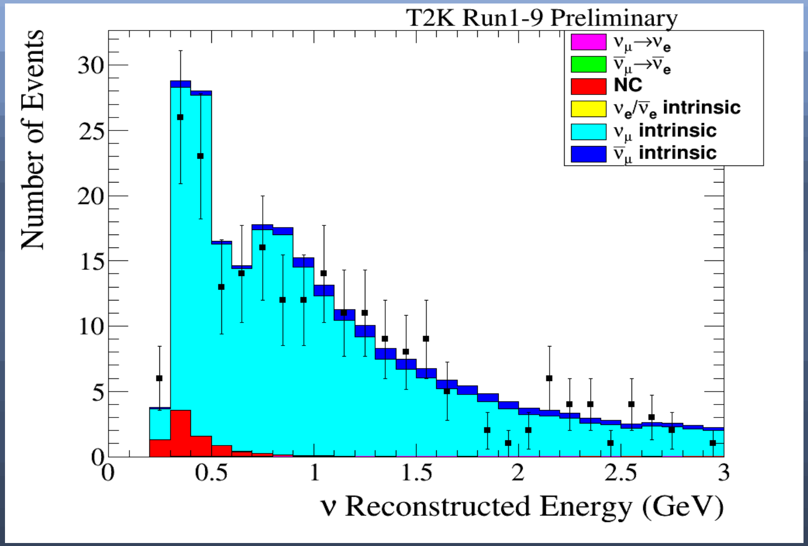
Analysis frameworks

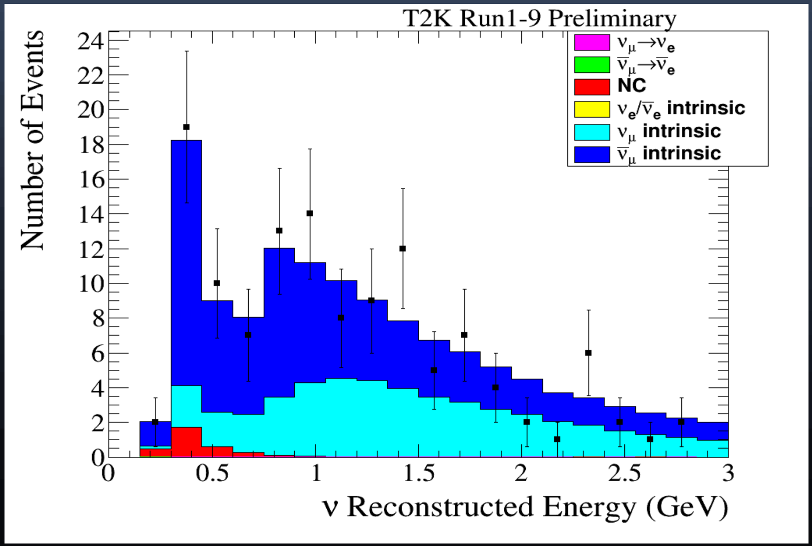
- Frequentist with likelihood fit to
  - E_{rec}/θ_{lep} for ν_e/ $\bar{\nu}_e$
  - E_{rec} for ν_μ/ $\bar{\nu}_\mu$
- Frequentist with likelihood fit to
  - p_{lep}/θ_{lep} for ν_e/ $\bar{\nu}_e$
  - E_{rec} for ν_μ/ $\bar{\nu}_\mu$
- Bayesian with Markov Chain MC
  - E_{rec} for all samples
  - simultaneous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

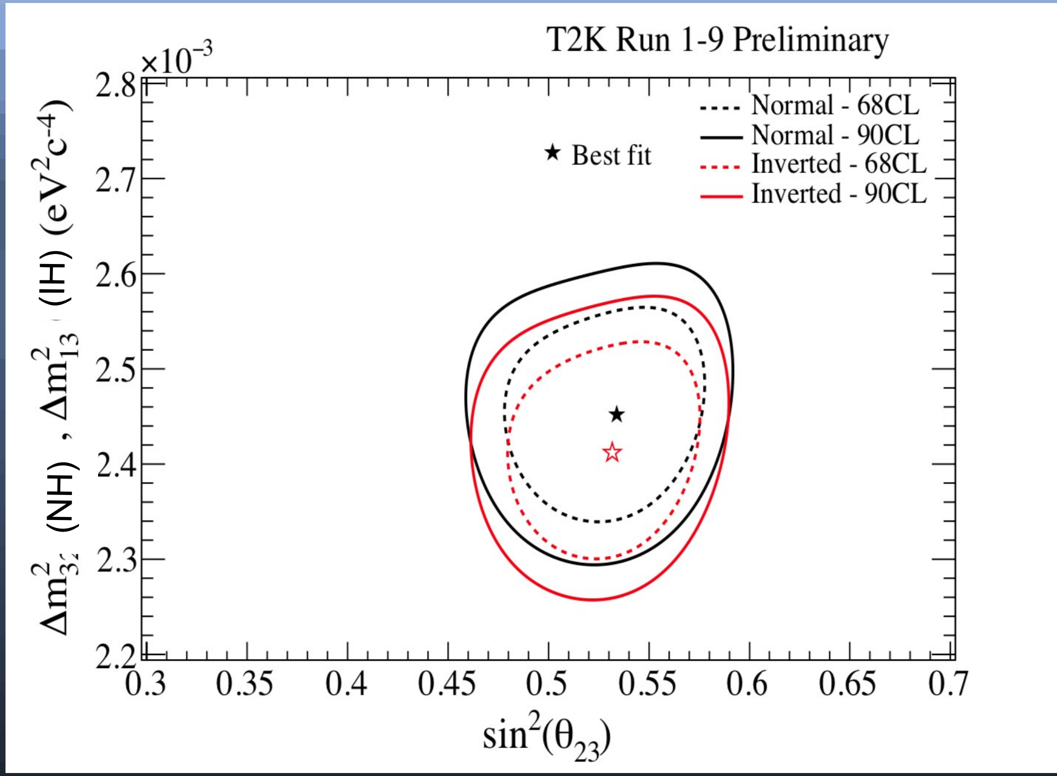
Events observed at SK vs ND data-tuned predictions under oscillation hypothesis using NH, 2018 PDG θ_{13}, $\sin^2\theta_{23}$= 0.528.

15 events observed in CC1π$^+$ sample, with prediction of 7.02 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}







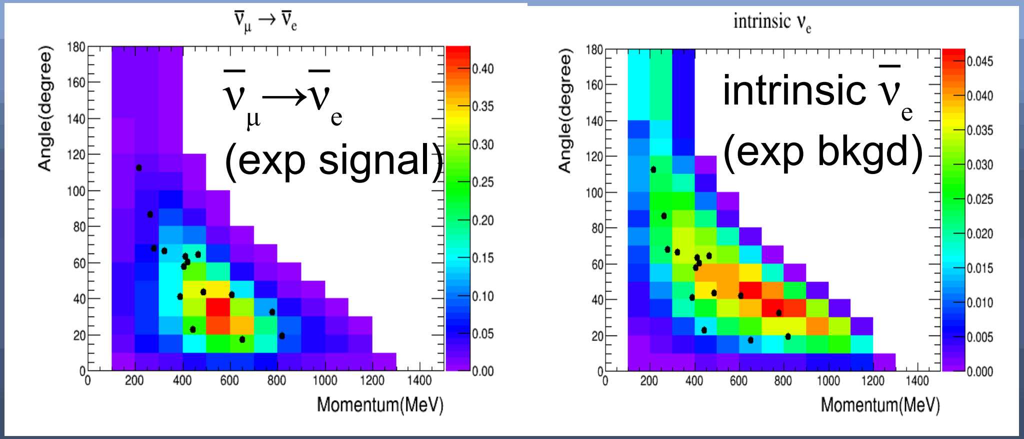
	NH (best fit)	IH (best fit)
$\sin^2\theta_{23}$	$0.532^{+0.030}_{-0.037}$	$0.532^{+0.029}_{-0.035}$
$\lvert\Delta m^2\rvert$ (x 10^{-3} eV^2)	$2.452^{+0.071}_{-0.070}$	$2.432^{+0.069}_{-0.071}$

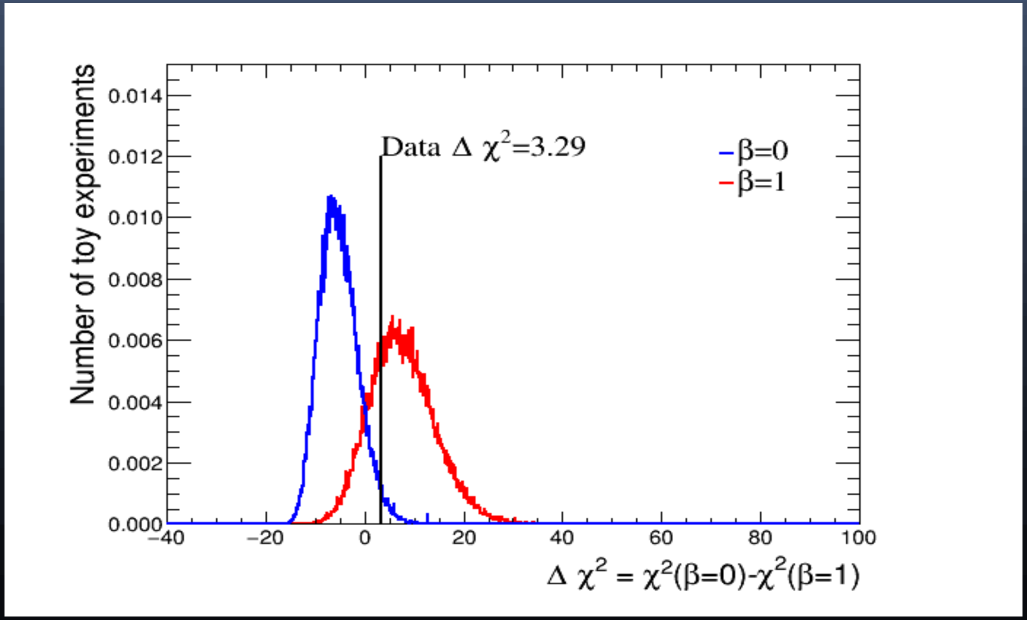
$\bar{\nu}_e$ appearance search

- Compare consistency with PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0)
  - if β=0 expect 9.4 events
  - if β=1 expect 17.1 events
  - Data = 15 events
- Use rate+shape analyses:

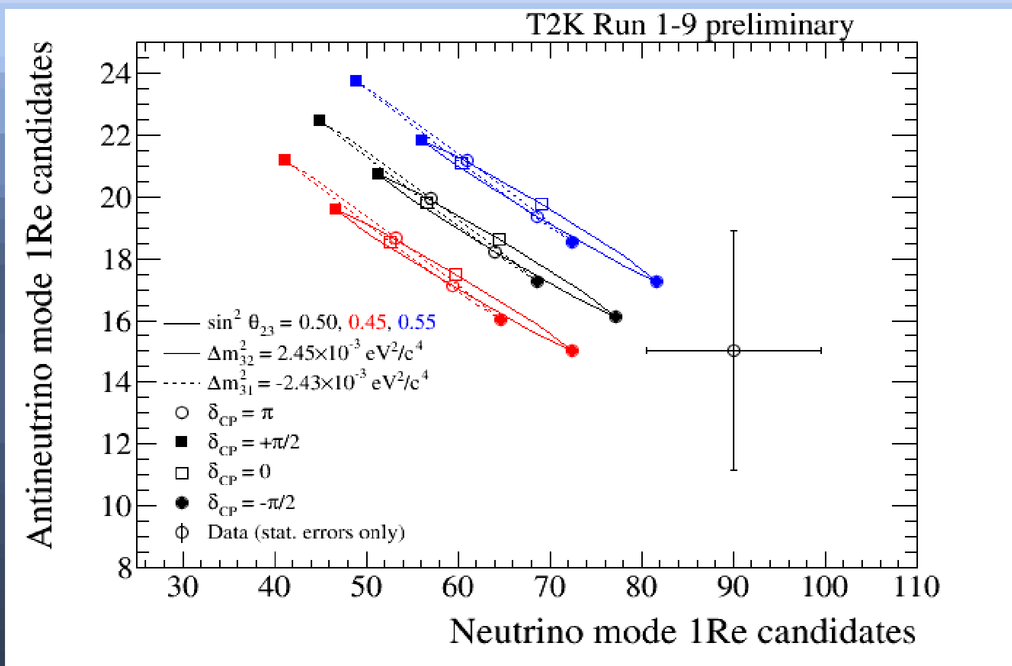
β	Hypothesis	P-value
β=0	NO appearance	p=0.024
β=1	PMNS appearance	p=0.261

- **β=0 excluded at 2σ → NO appearance is excluded at 2σ.**

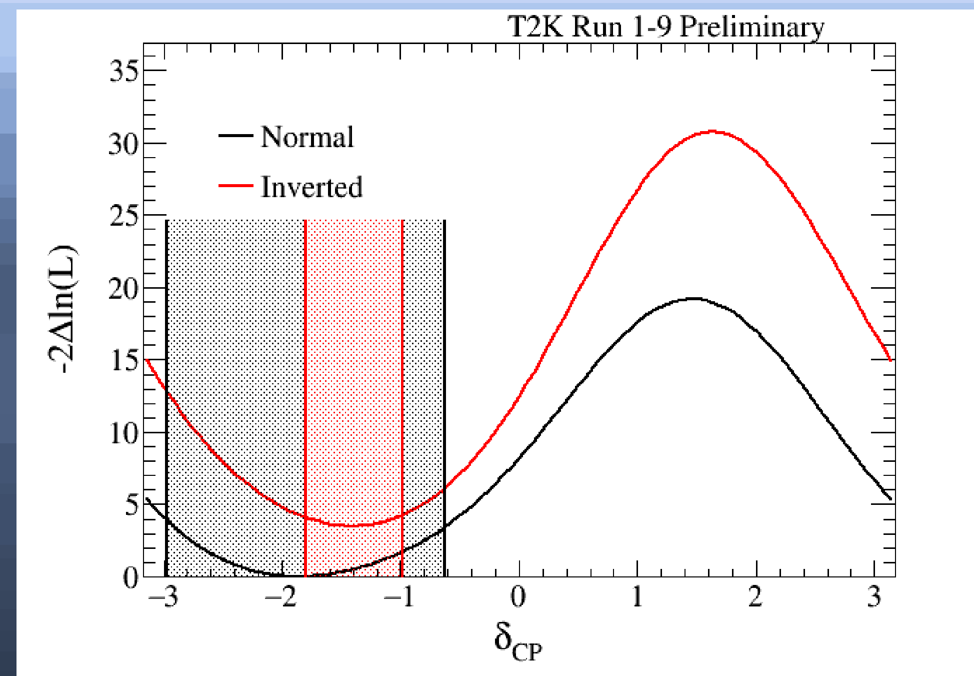




ν_e and $\bar{\nu}_e$ sample: δ_{CP}



With reactor θ_{13}



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

- T2K result with reactor constraint:

δ_{CP} = [-2.509, -1.260] NH (no IH at 1σ)

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

ν_e appearance: θ_{13}

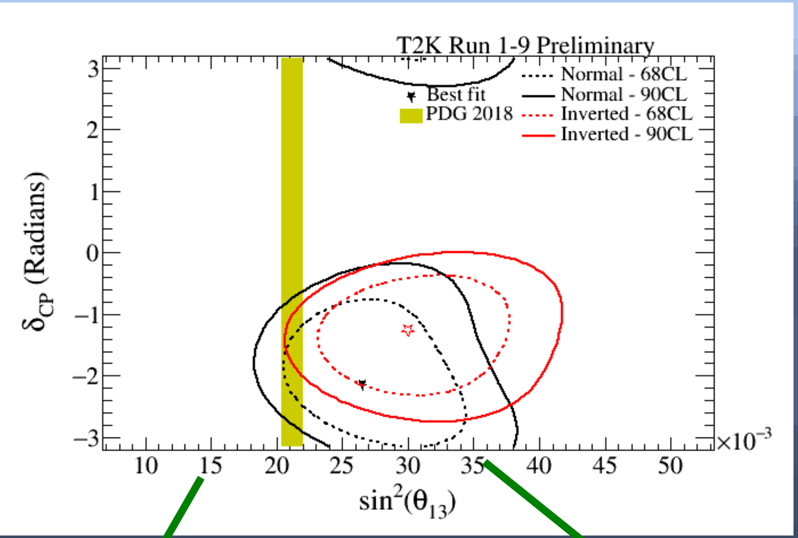
T2K only

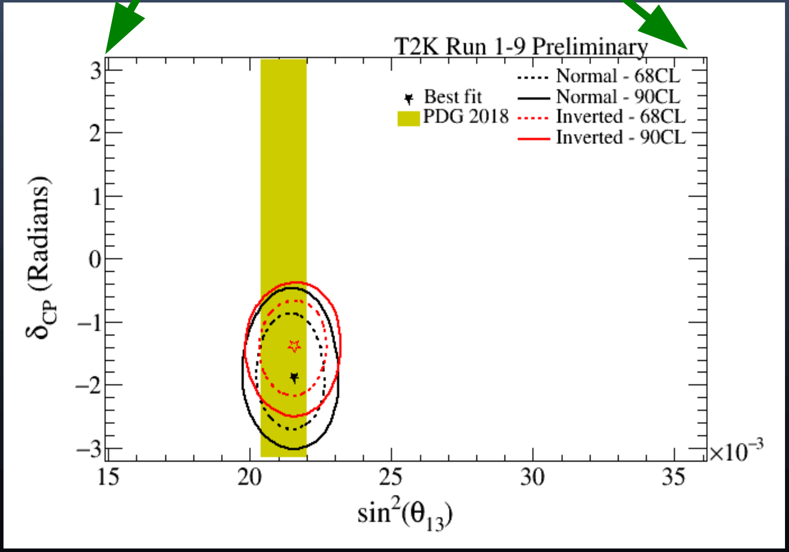
	NH (best fit)	IH (best fit)
$\sin^2\theta_{13}$	$0.0268^{+0.0055}_{-0.0043}$	$0.0300^{+0.0059}_{-0.0050}$

Bayesian posterior probabilities (with reactor)

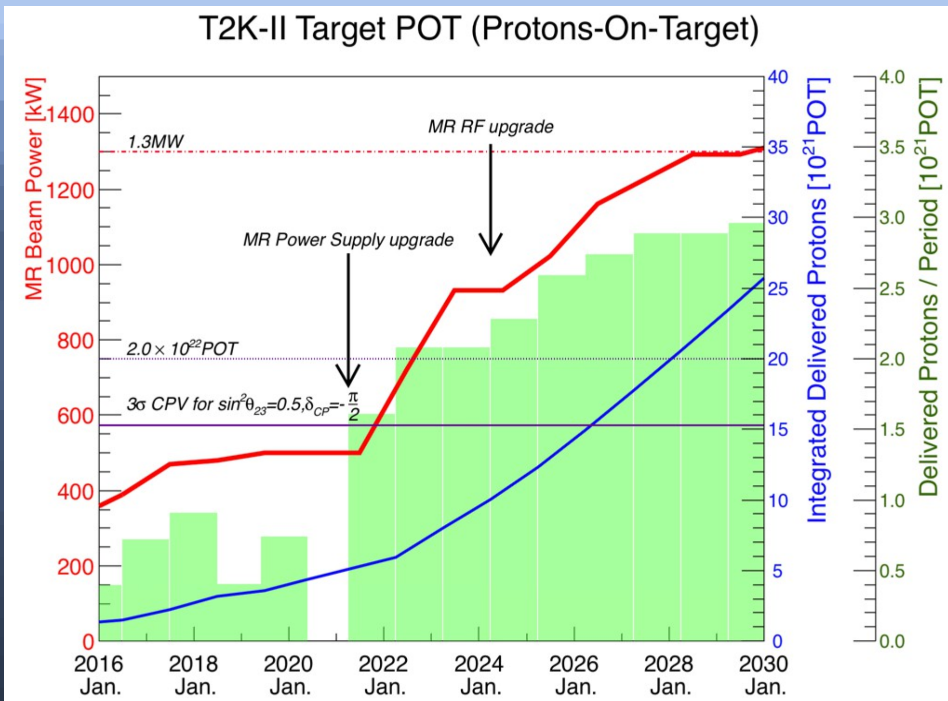
	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.184	0.705	0.889
IH ($\Delta m^2_{31} < 0$)	0.021	0.090	0.111
SUM	0.205	0.795	1

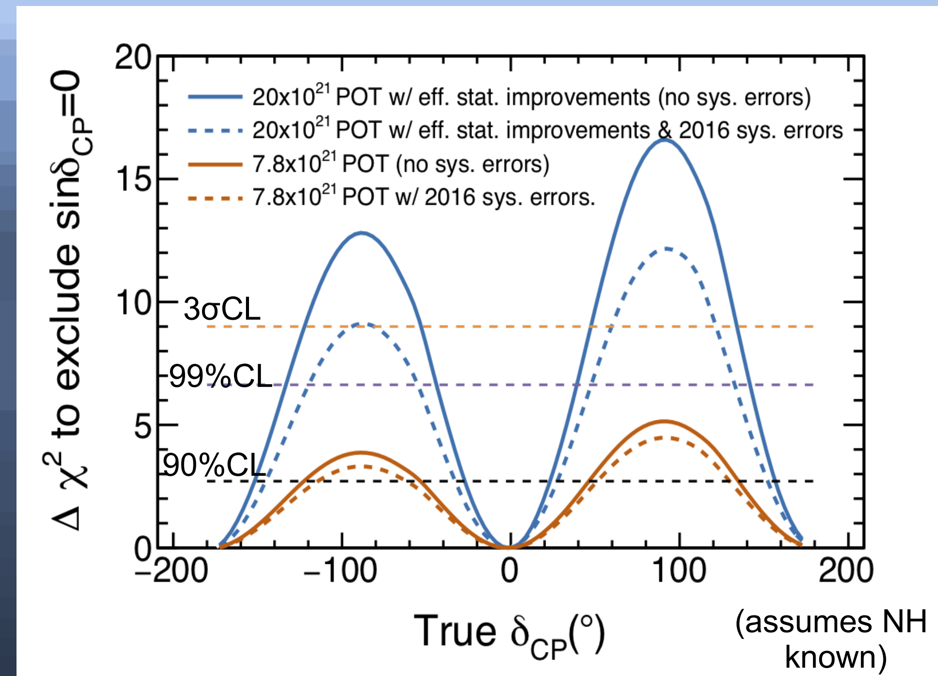
Bayes factor for NH/IH is 8.0





T2K-II: upgrade beam and detectors



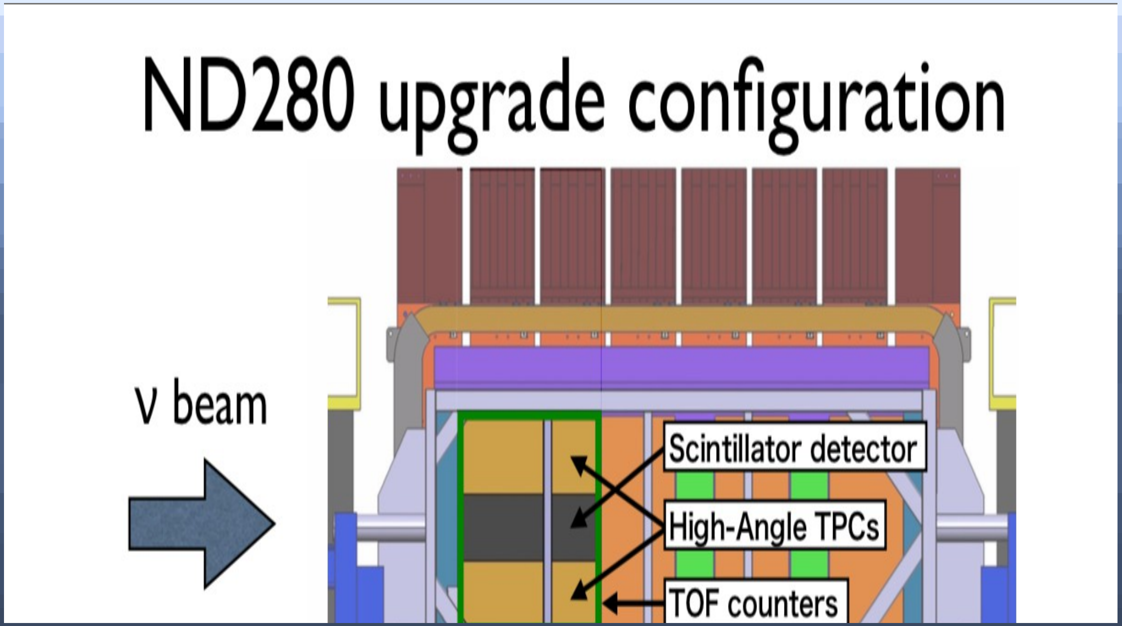


- *1st stage* of J-PARC main ring power supply upgrade approved
    - *Near future*: Aiming for 750 kW beam power (currently 485 kW)
- *T2K-II* extends T2K run to 20 x 10^{21} POT (stops ~ 2027 when HK starts)
- *Long term:* beamline upgrade to reach 1.3 MW

Talk by Benjamin Quilain after coffee

ND280 upgrade

See slides from previous talk.



- 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.

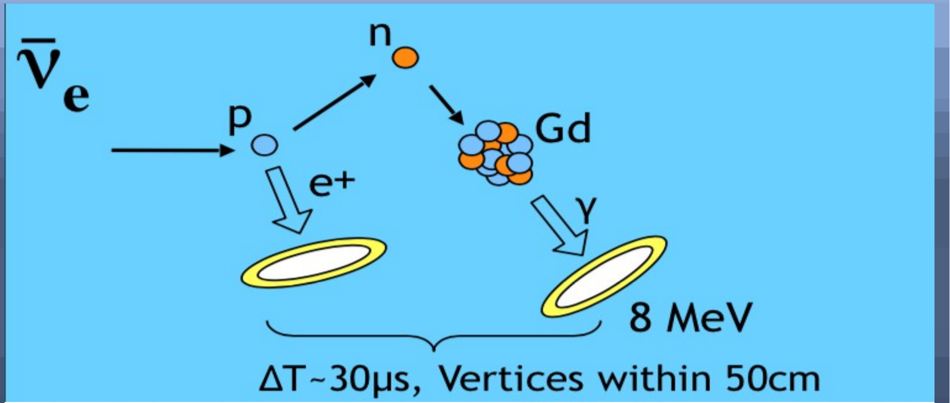
- T2K-II goal: reduce detector systematics to ~4%
  - improve acceptance, timing, efficiency for short tracks.
- WAGASCI/BabyMIND collaboration has become part of T2K.
  - (3D scintillator detector)

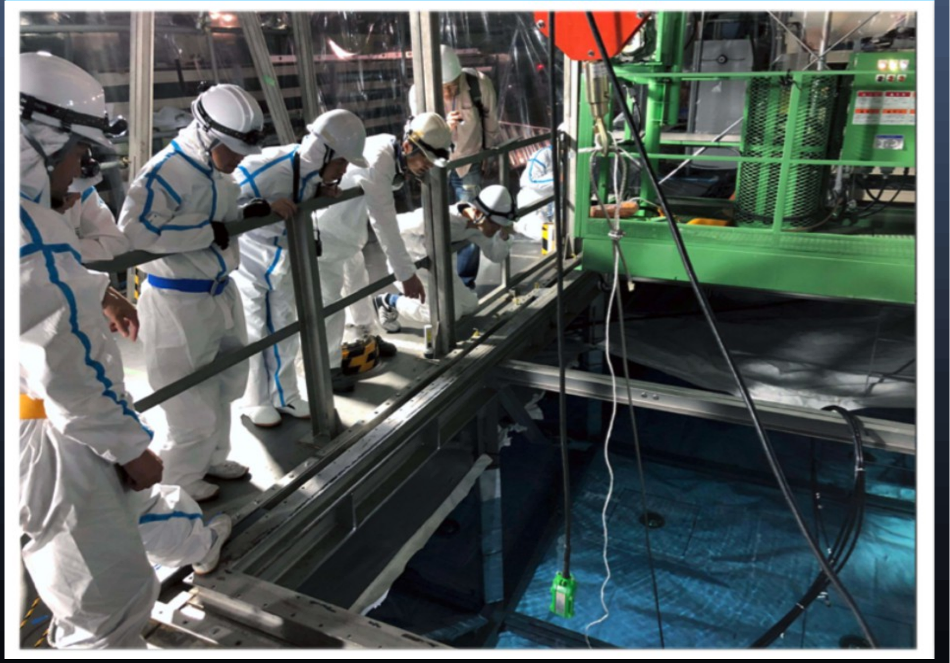
Talk by Etam Noah Saturday

- CERN support, test beam was last summer.
- TDR: T2K Collaboration. T2K ND280 Upgrade - Technical Design Report. arXiv. 2019 Jan 11.
- Aim to install upgraded ND280 in 2021.

SK upgrade

- Additional SK data samples under study
  - $CC1\pi^+$, $NC\pi^0$ in both ν- and $\bar{\nu}$-mode
- 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.
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.

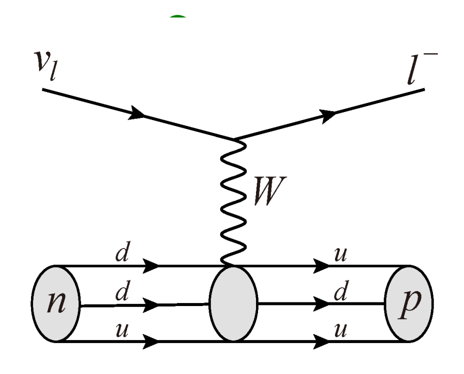




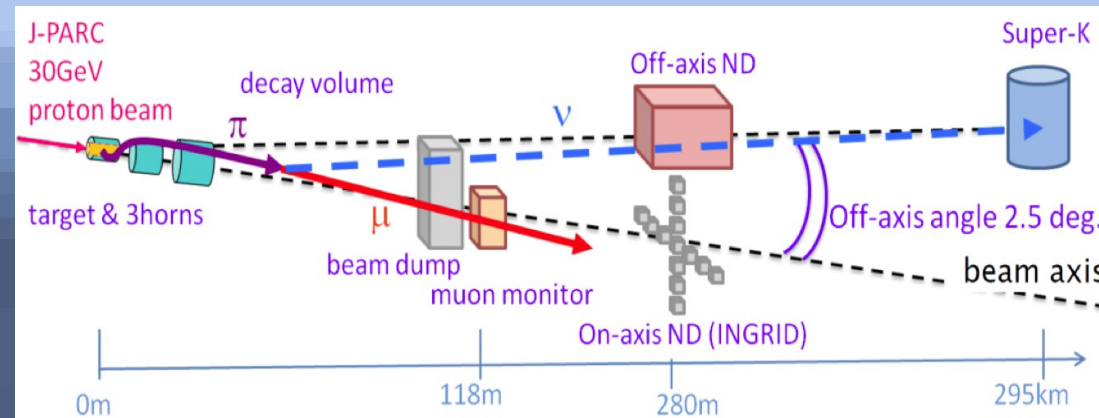
Summary

- 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
- Hints of direct $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ observation
- First (mild) indications of neutrino mass hierarchy
- Competitive (sometimes the only) neutrino cross-section measurements (talk by Georgios Christodoulou on Saturday)
- 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! (previous talk)

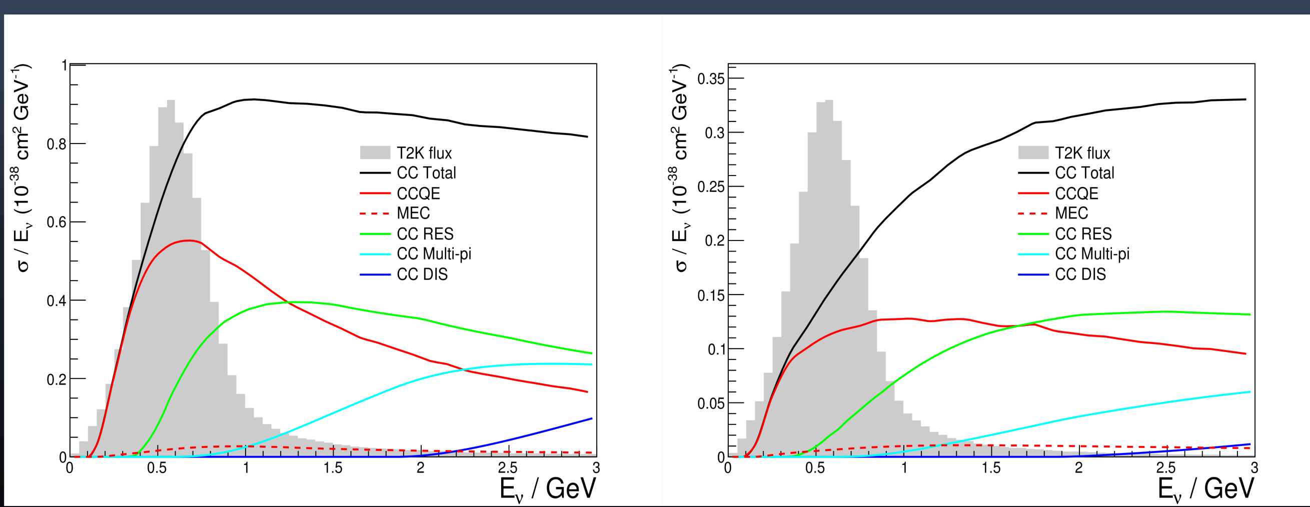
Extras

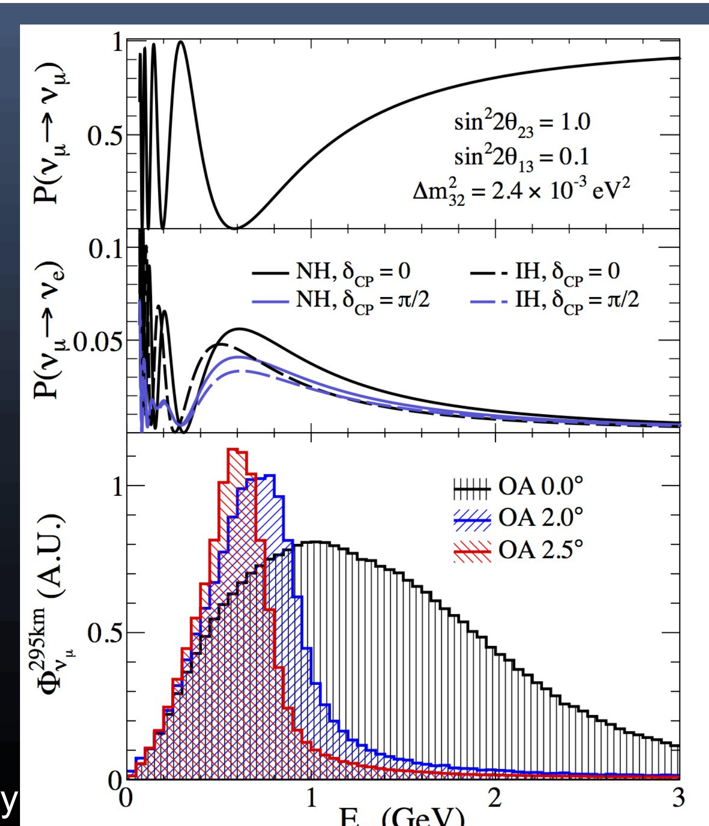


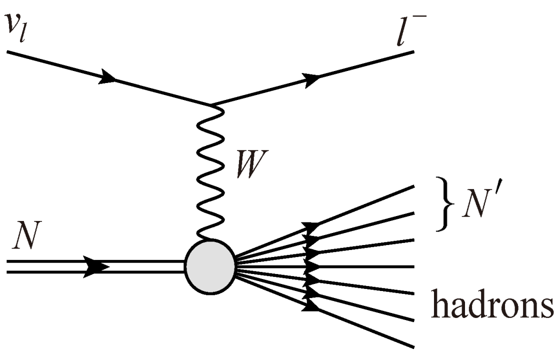
Off-axis technique



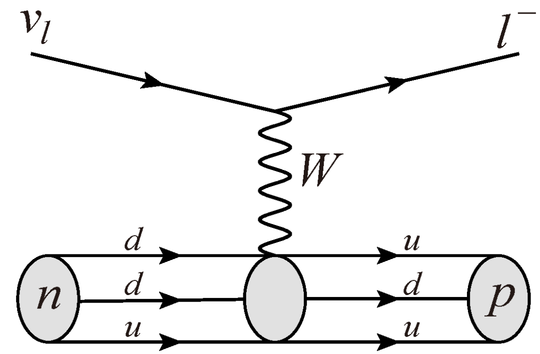
- Enhanced oscillation – beam energy tuned to oscillation max
- Enhanced CCQE fraction
- Less intrinsic ν_e contamination
- Less Neutral Current background

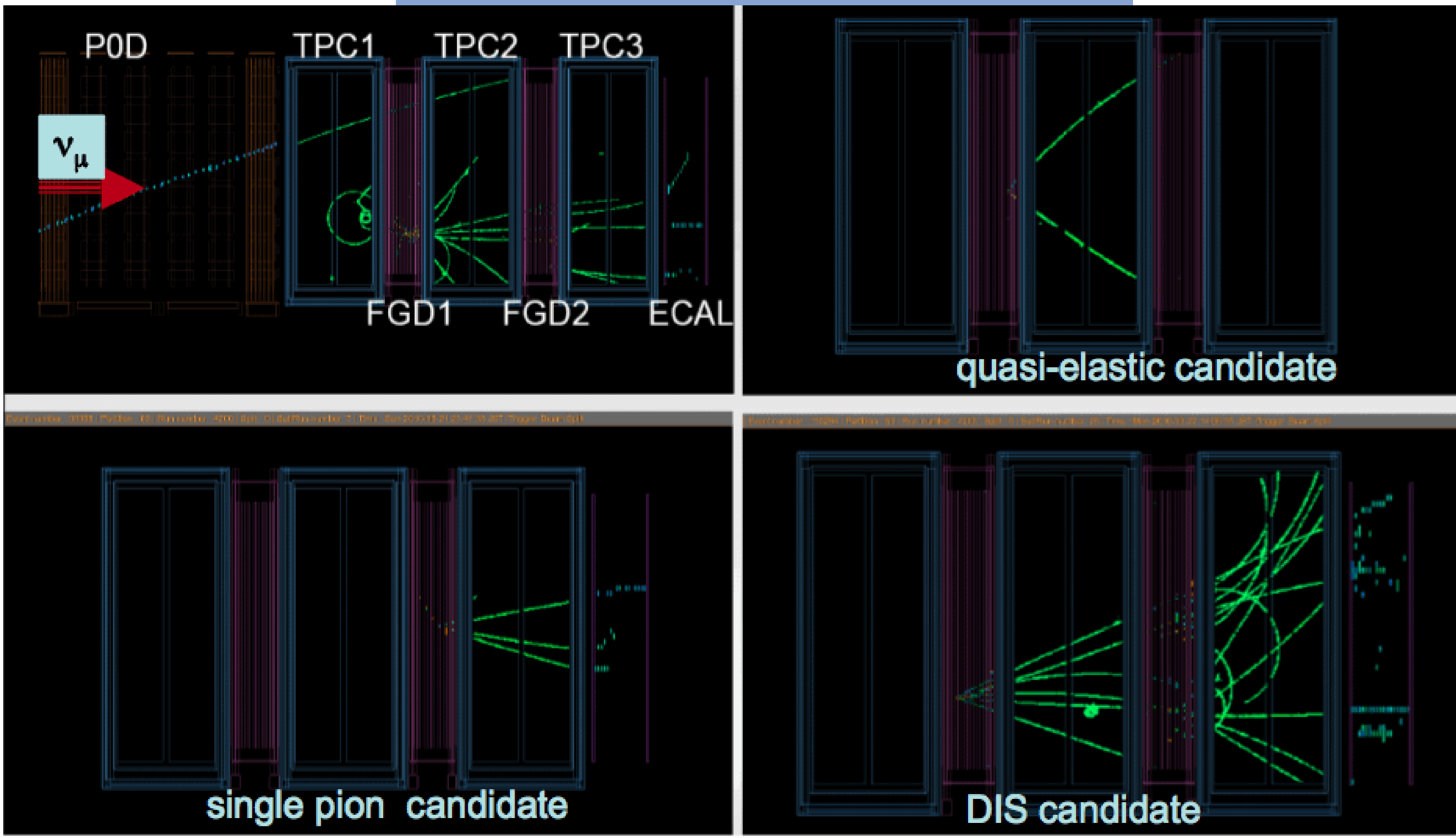






ND280 events

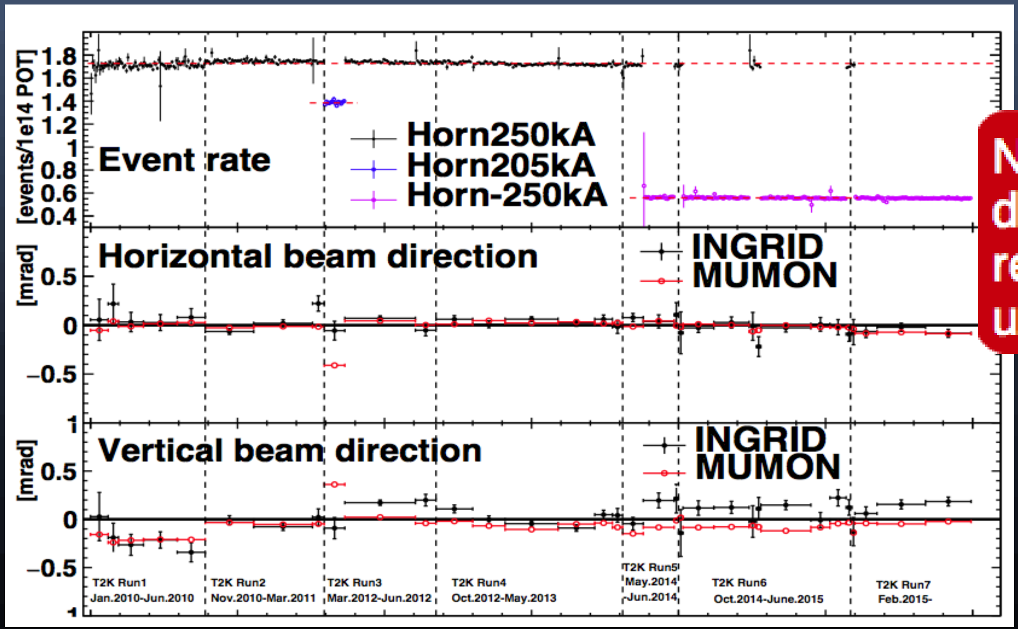




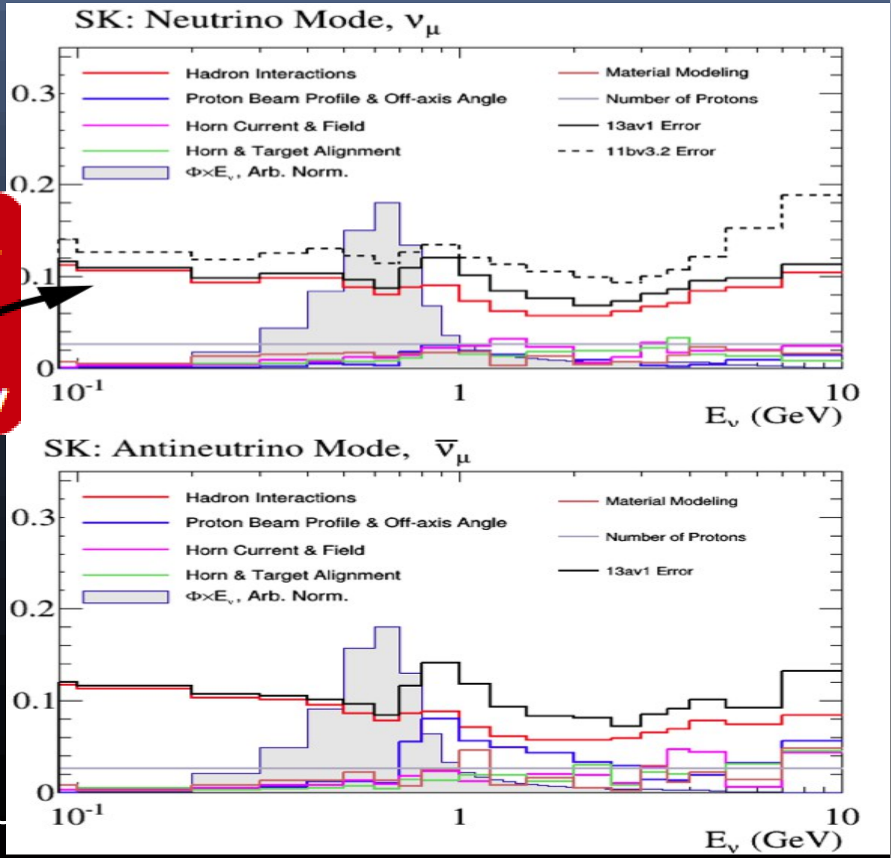
Flux uncertainties

- Beamline uncertainties
  - Proton beam parameters
  - Focusing horns
  - Component alignment

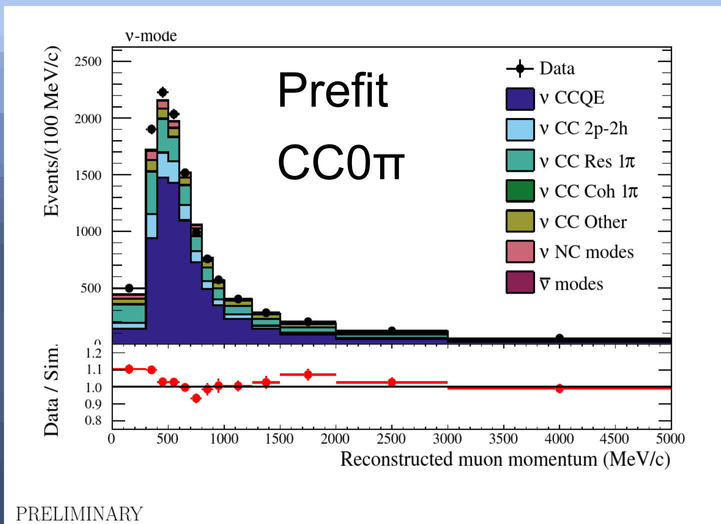
- Hadron production uncertainties
  - NA61/SHINE uncerts
  - Re-interactions, Secondary production

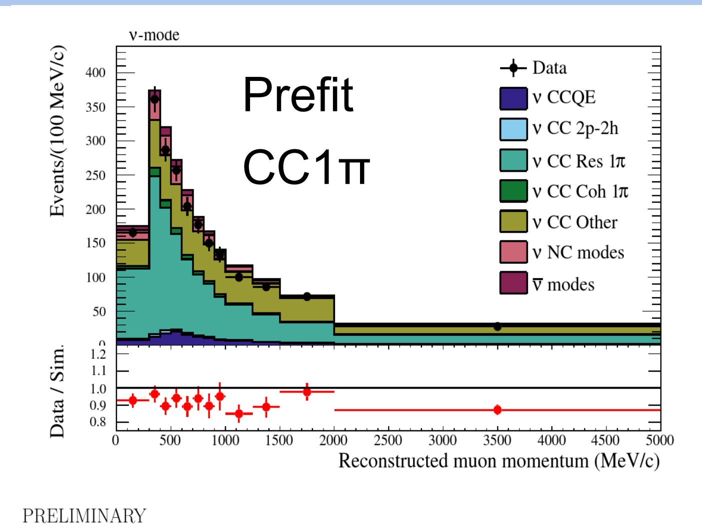


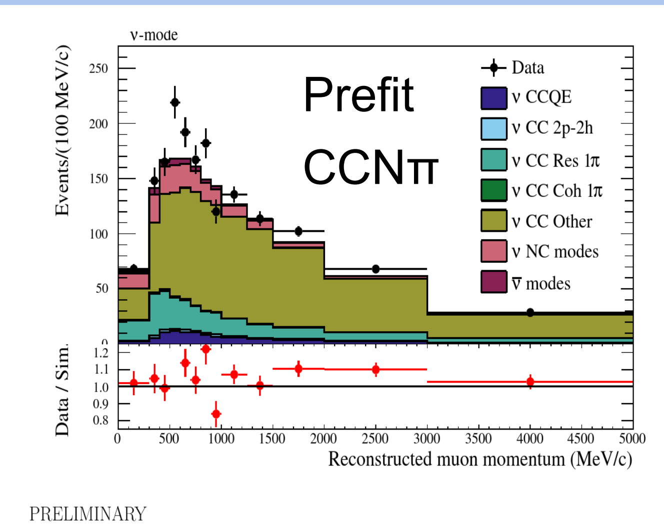
New NA61 data has reduced uncertainty

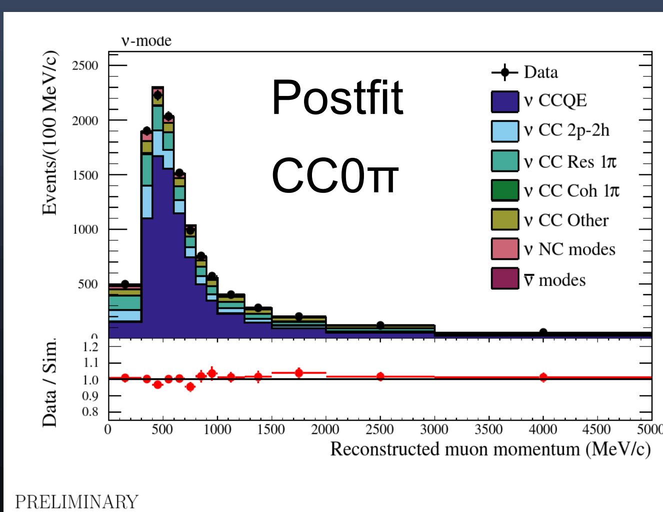


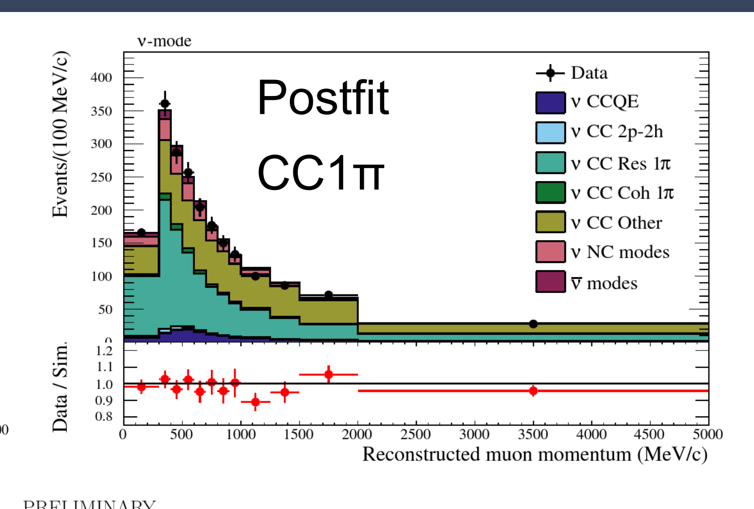
ND280 samples, ν-mode (FGD1)

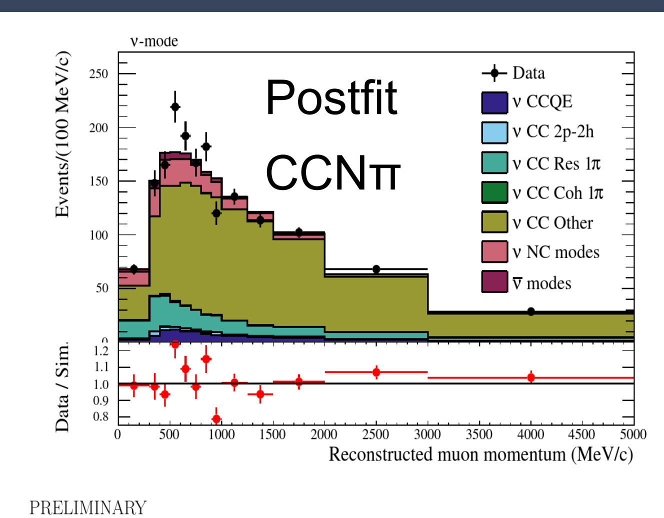






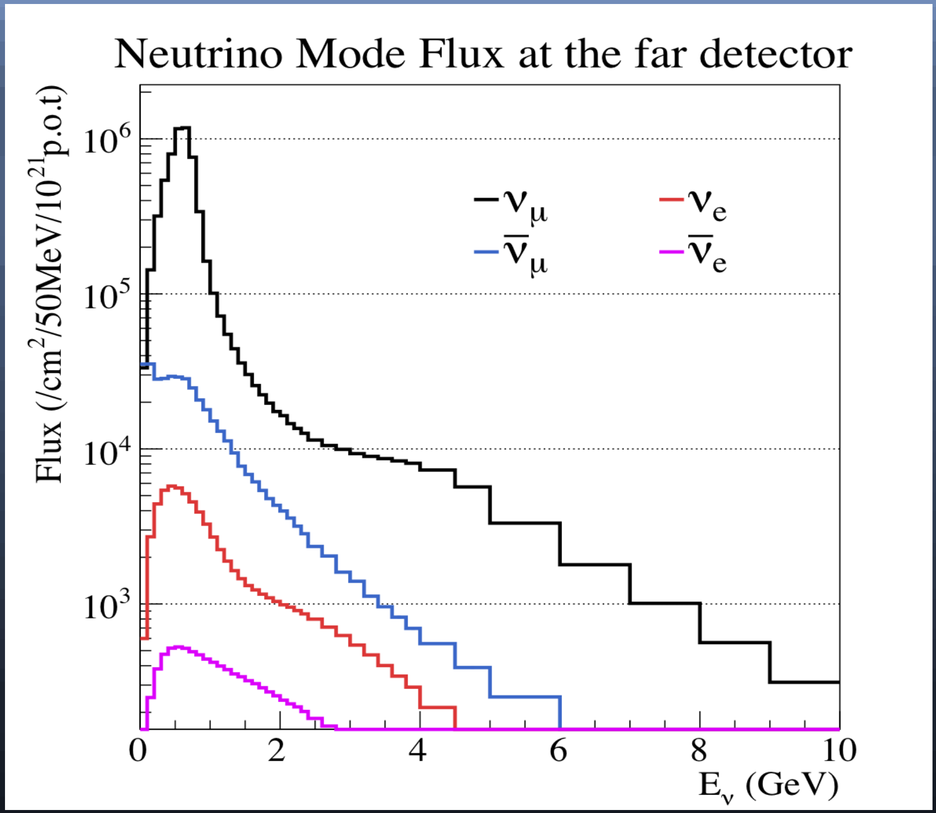


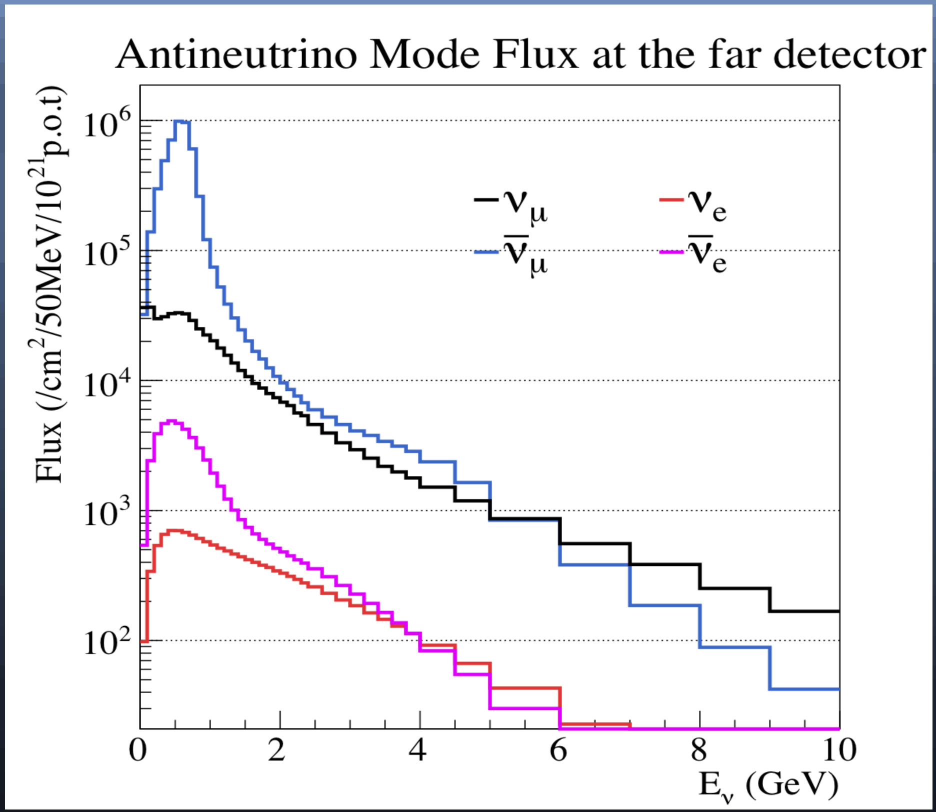




ND280 samples, $\bar{\nu}$-mode (FGD1)

Flux predictions at SK





from Mark Hartz, KEK Aug 2017

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

from Mark Hartz, KEK Aug 2017

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

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

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

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

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

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

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

$\bigcirc$ = *detected particles*