Latest results of T2K

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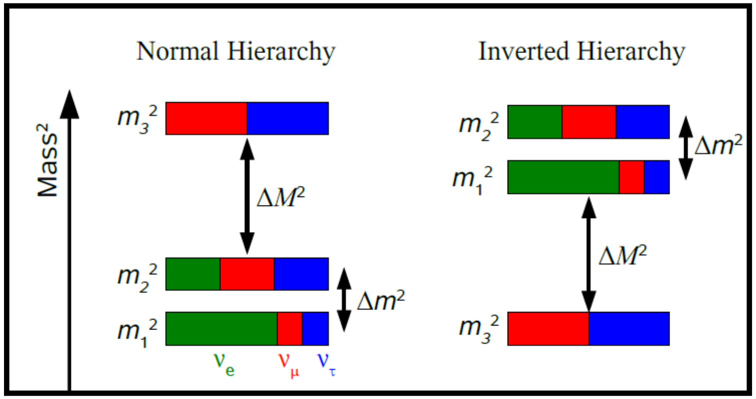
on behalf of the T2K collaboration

Outline

- Physics overview:
  - Introduction to mixing and parameter space.
  - Long-baseline (LBL) measurement principle.
  - Processes relevant for detection.
- T2K:
  - Experiment.
  - Selection/analysis.
  - Results.
- Future – T2K-II.
- Conclusion.

Neutrino sector mixing



- Neutrinos are massive(!) – 3 mass states i with masses m_i.
  - Oscillation phenomenology depends on **mass splittings**:

$\Delta m^2_{21}=m^2_2-m^2_1$, $\Delta m^2_{32}=|m^2_3-m^2_2|$.

- Neutrino mass states ν_i related to flavour states ν_α by **PMNS Matrix**: $|\nu_i\rangle = \sum_{\alpha=1}^{3} U_{\alpha i}|\nu_\alpha\rangle$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

X Majorana phases

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

Atmospherics, **LBL accelerators** | SBL reactors, **LBL accelerators** | LBL reactors, Solar

PDG16

$$\sin^2(\theta_{12}) = 0.304 \pm 0.014$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.51 \pm 0.05$$
$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{13}) = (2.19 \pm 0.12) \times 10^{-2}$$

Outstanding questions

- Mass ordering (“hierarchy”): **Normal** ($m_3>m_2$) or **inverted** ($m_3<m_2$).
- $\theta_{23}>45^\circ,<45^\circ,=45^\circ$?
  - Underlying symmetry??
- CP phase δ_{CP}.
- Absolute masses, Majorana neutrinos… Not accessible with oscillations.

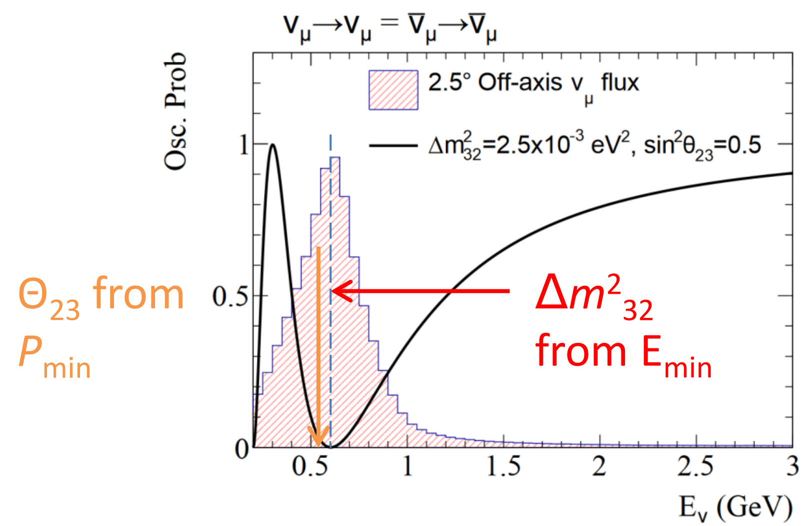
Principle of LBL oscillation measurements

- Mass/flavour state mixing => oscillation of definite flavour beam into different flavour components.
  - Probability a function of L/E_ν. Baseline L fixed for a given experiment.

- For muon neutrino beam, $\nu_\mu \rightarrow \nu_\tau$ dominant ($\theta_{23} \gg \theta_{13}$)
  - To first order:

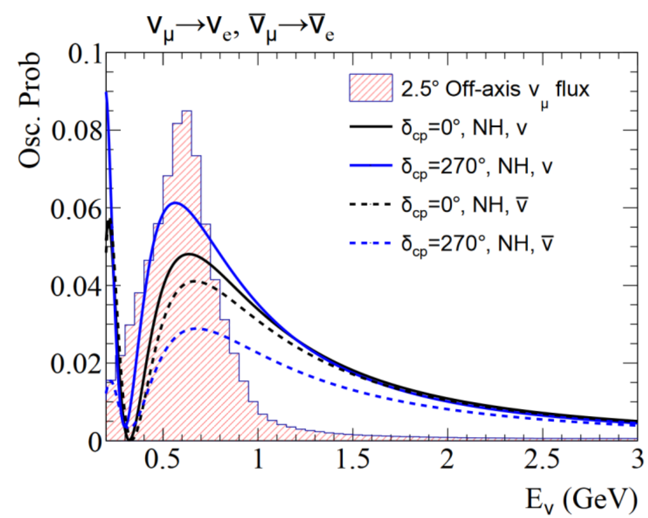
$$P_{\mu \rightarrow x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right)$$

  - Measure θ_{23}, Δm^2_{32} this way.



- Subdominant mode $\nu_\mu \rightarrow \nu_e$ used to measure θ_{13}.
  - To first order:

$$P_{\mu \rightarrow e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



δ_{CP} determination

- Full picture:

$$P(\nu_\mu \to \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}(1-2s_{13}^2)\right)$$

Leading including matter effect

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

CP conserving

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

CP violating

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

Solar

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

Matter effect (small)

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

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

replace δ by −δ and a by $-a$ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

- **Measure δ_{CP}** using difference between ν and $\bar{\nu}$ oscillation probabilities!
- Complication – matter effects may increase or diminish asymmetry in probabilities => ambiguity.
  - For NH, matter and CP effects move asymmetry in same direction. At T2K CP effect is larger (~25% vs 10% for matter effects).

Interaction Processes

- Neutrino-nucleus interactions dominate over neutrino-electron at these energies.

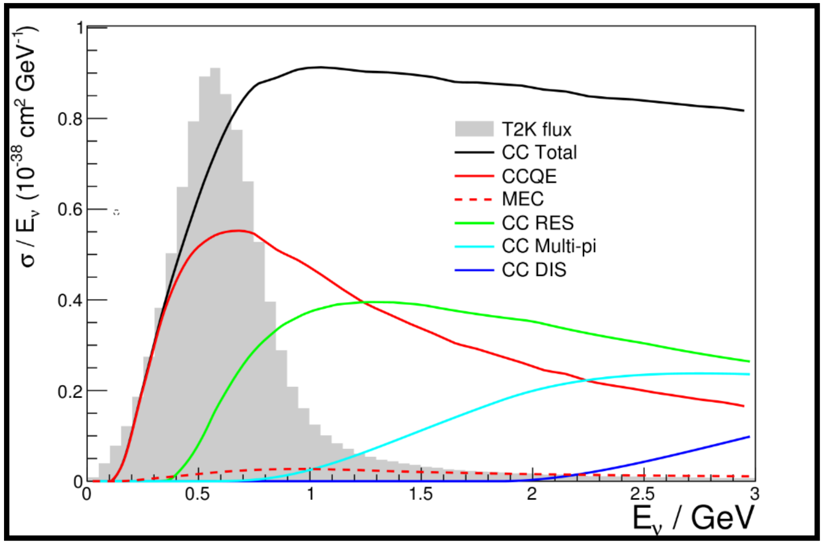
- **Charged-current quasi-elastic** (CCQE)
  - $\boldsymbol{\nu + n \rightarrow l^{-} + p}$
  - Dominant at T2K energies.
  - Heavy nucleus => deduce E_ν from lepton energy and angle (in principle)

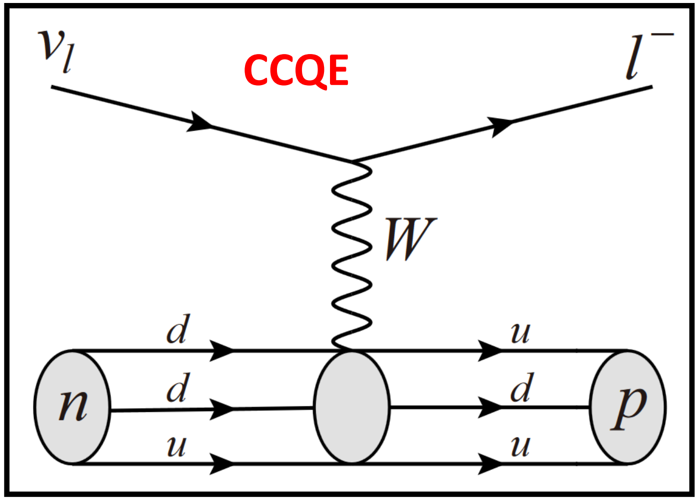
- **Charged-current resonant pion production** (CC-RES)
  - $\boldsymbol{\nu + n \rightarrow l^{-} + p + \pi^{+}}$
  - Also non-resonant single pion production.

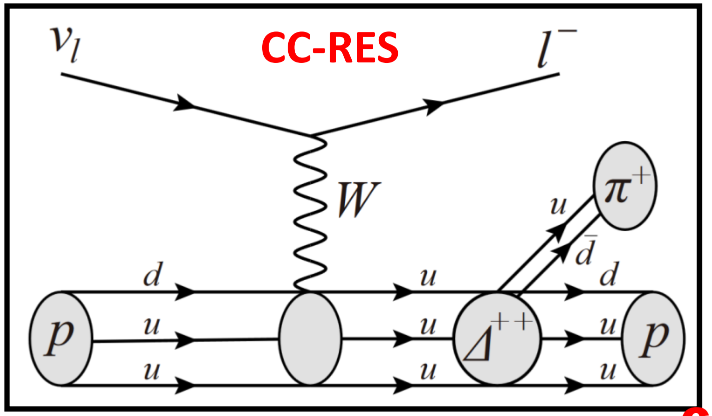
- **Deep inelastic scattering** (DIS) – less common at T2K energies:
  - Typically many outgoing hadrons.
  - may look like lower E_ν CCQE => background.

- **NC interactions** (outgoing neutrino, no charged lepton)
  - NC-$\pi^0 \rightarrow \gamma + \gamma$ important background for ν_e-CCQE.

- Nuclear effects in initial/final state complicate the picture…







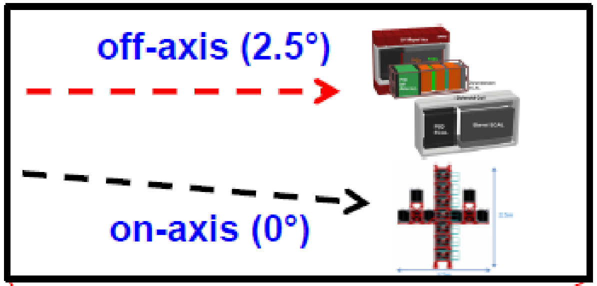
T2K experiment

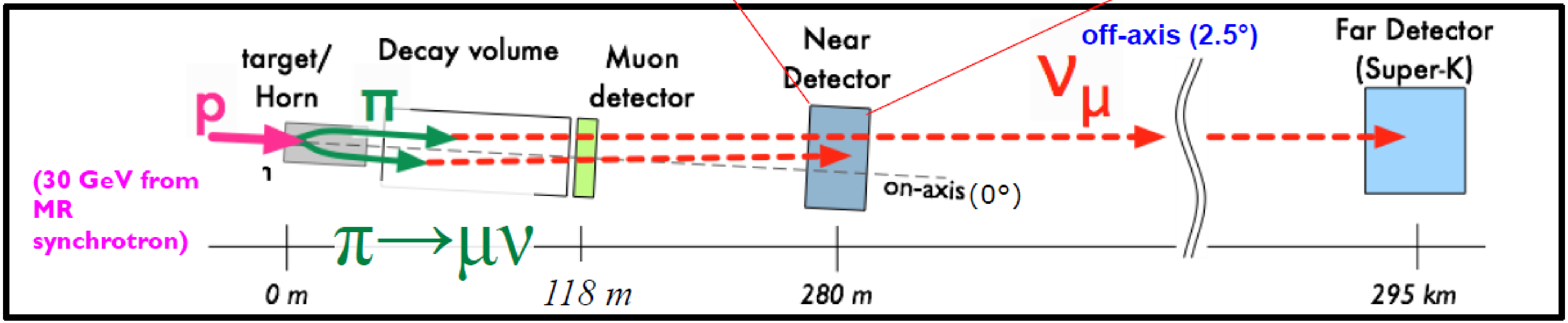
- ν_μ beam from J-PARC MR accelerator in Tokai on East Coast of Japan.
  - Produce $\nu, \bar{\nu}$ by changing focusing horn polarity.
- Far detector is the Super-K water-Cherenkov detector at Kamioka mine.
- Suite of near detectors at J-PARC.

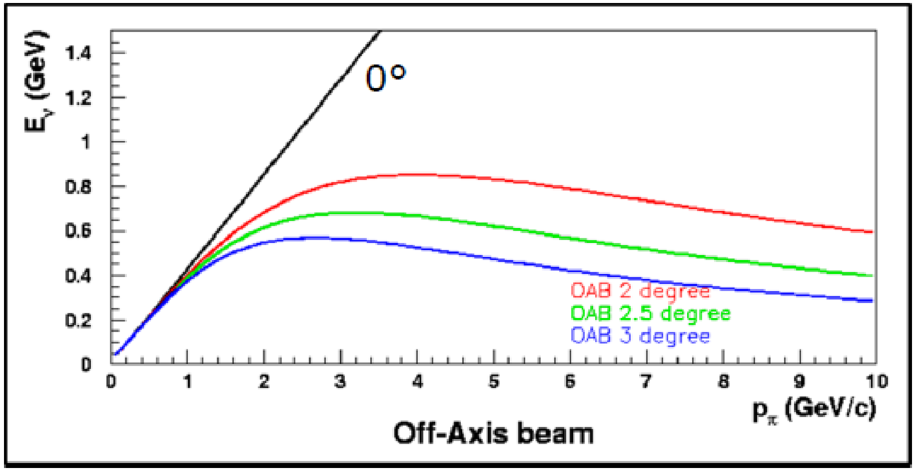
T2K experiment

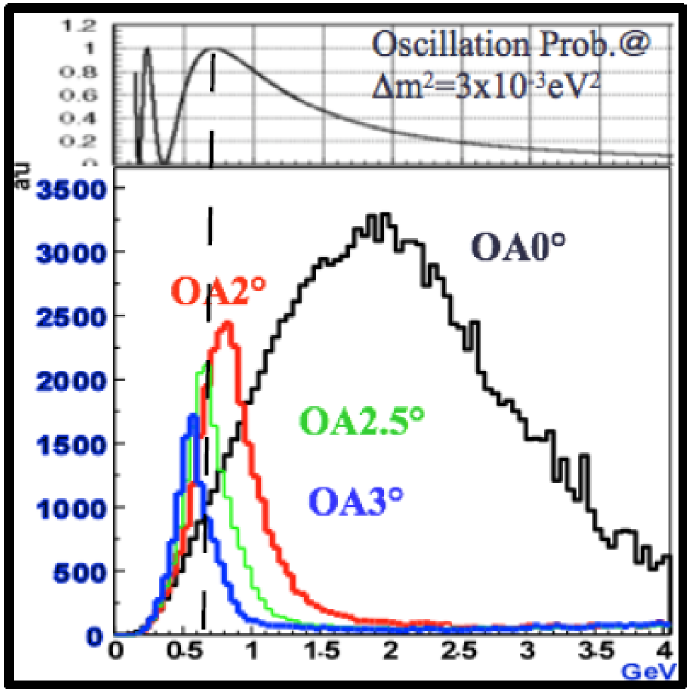
- 11 countries, 63 institutes, ~500 collaborators!
- We won the Breakthrough Prize for Fundamental Physics in 2016 (shared with Daya Bay, KEK, Super-K, SNO, KamLAND).
- Public webpage: http://t2k-experiment.org

Design principle





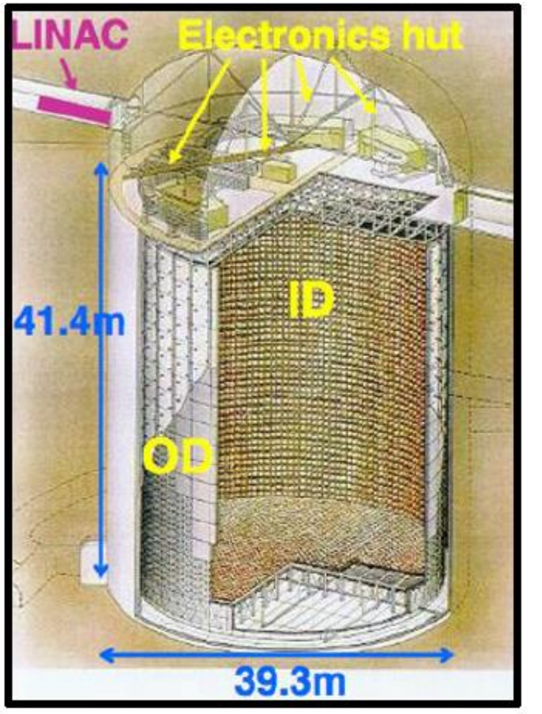


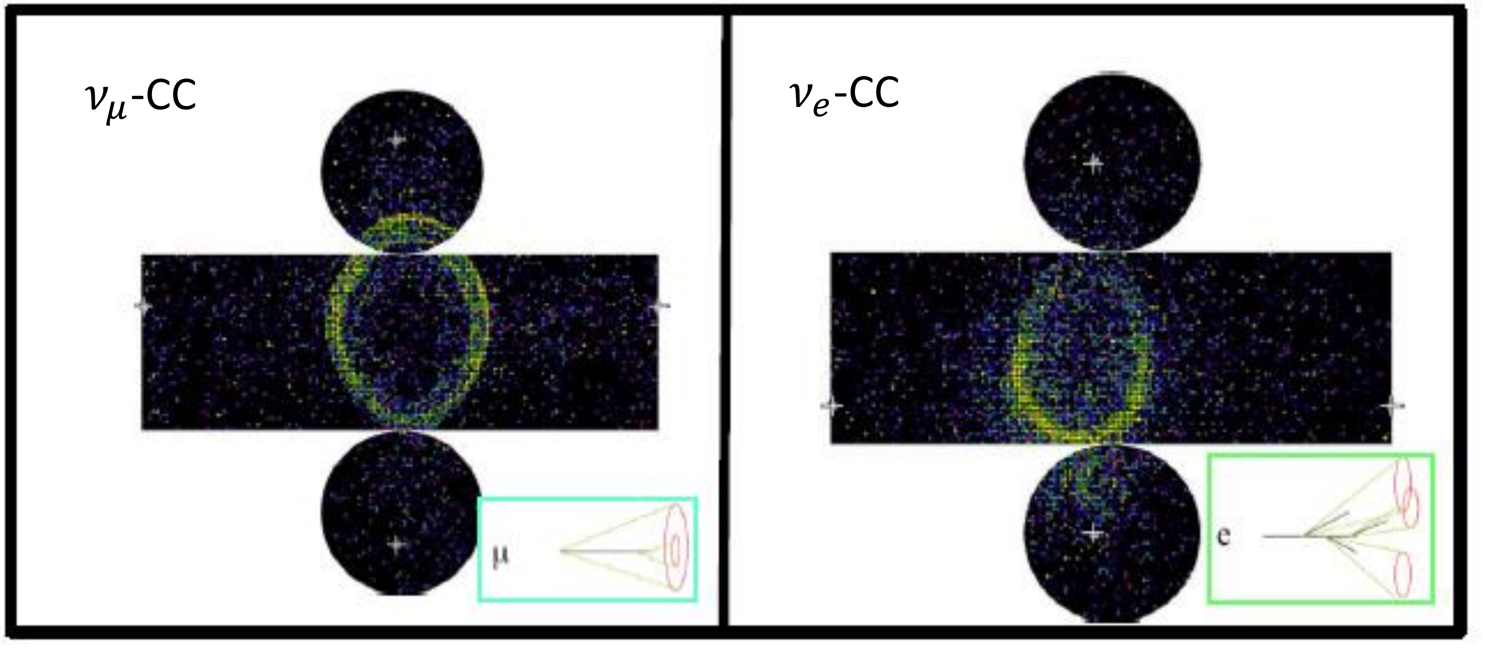


- Novel feature - off-axis beam to reduce high-energy tail
  - Narrow-band beam around oscillation maximum
  - Feed-down from mis-reconstructed DIS/resonance events at SK into analysis region reduced.

Far detector - Super-K

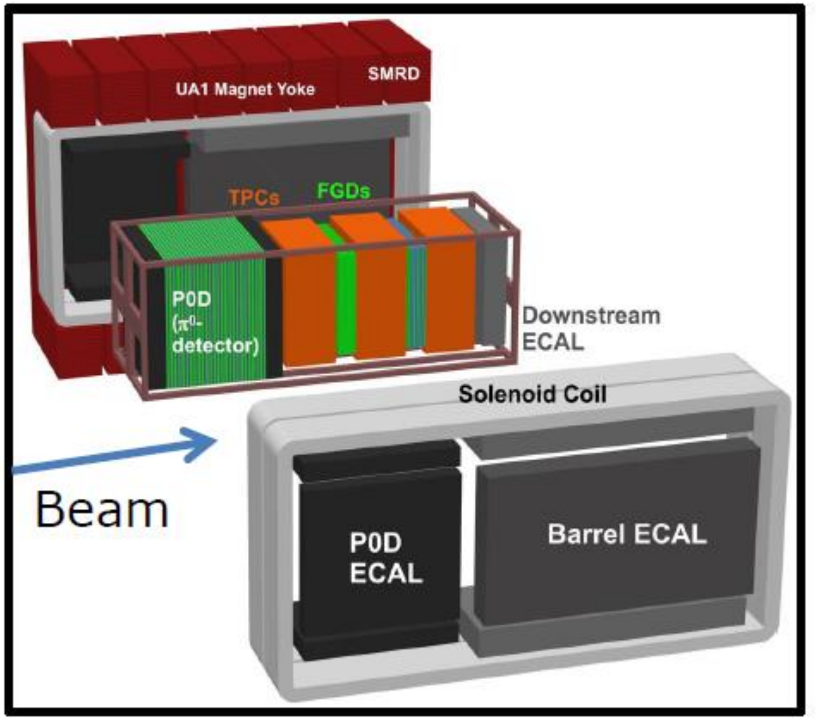
- In Kamioka mine, 1 km rock overburden (equivalent to 2700 m water).
- 22.5 kt fiducial volume water Cherenkov.
  - Inner detector with ~11000 20-inch PMTs.
  - Outer veto with ~1900 8-inch PMTs.
- Particle energy from Cherenkov opening angle.
- μ /e PID from ring shape.
  - Clean muon rings.
  - “Fuzzy” electron rings from multiple scattering/showering.
- Protons/low-energy pions invisible.



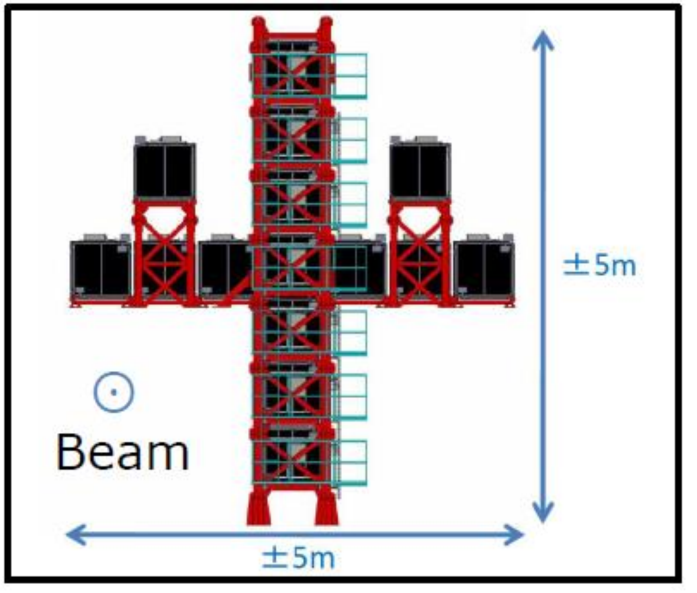


Near detector complex

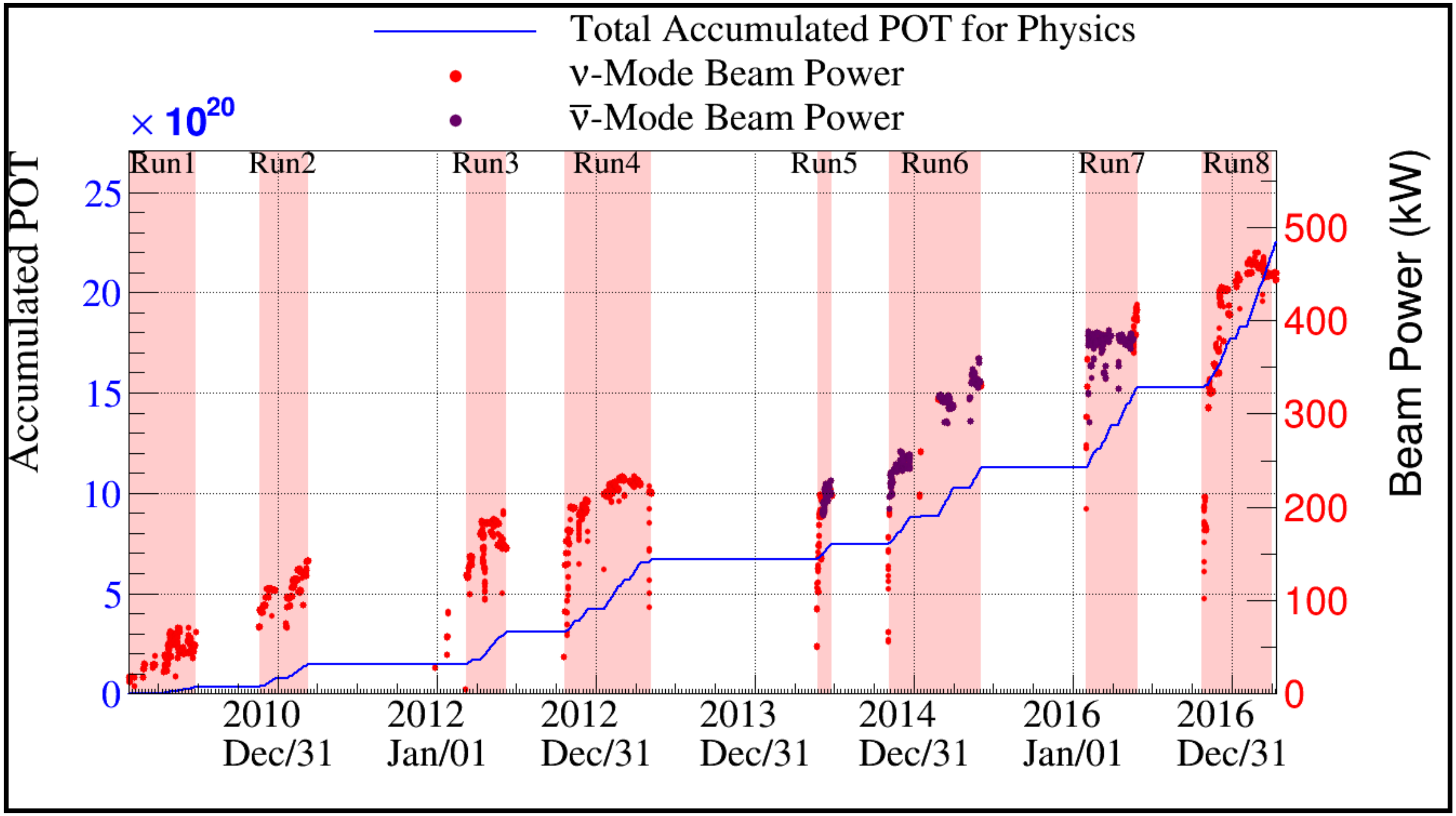
- "ND280" detector
  - Same off-axis angle as Super-K => many shared systematics cancel between near and far detectors
  - FGD – plastic scintillator neutrino targets, one fully active and one with water layers
  - Gas TPCs for momentum measurement and PID
  - Subdetector optimised for π^0 detection at upstream end of detector
  - Surrounded by ECAL and MRDs, with 0.2T magnet



- "INGRID" detector
  - On-axis beam monitor – measure flux and beam profile
  - 14 modules in a "plus" configuration centred on beam axis, with two diagonal modules
  - Each module is a $1m^3$ iron-plastic scintillator sampling calorimeter

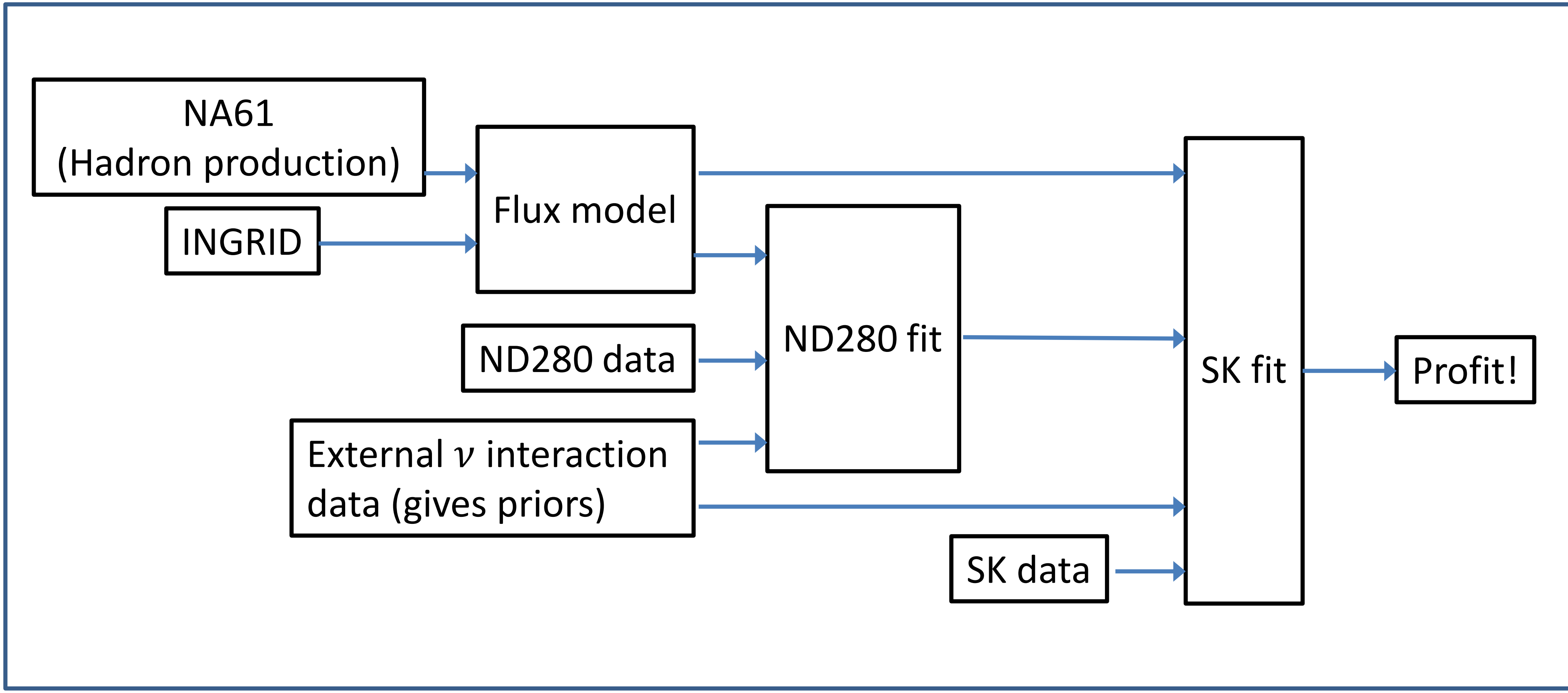


Flux delivery



- Beam power now at ~450 kW.
- Total 30 GeV Protons On Target (POT) = 2.25 x 10^{21}
  - With forward horn current (ν): 1.49 x 10^{21}
  - With backward horn current ($\bar{\nu}$): 0.76 x 10^{21}
- Analyses presented are based on samples of 0.75 x 10^{21} POT in each beam mode (Runs 1-7).
  - ~250 selected events at far detector.

Analysis strategy

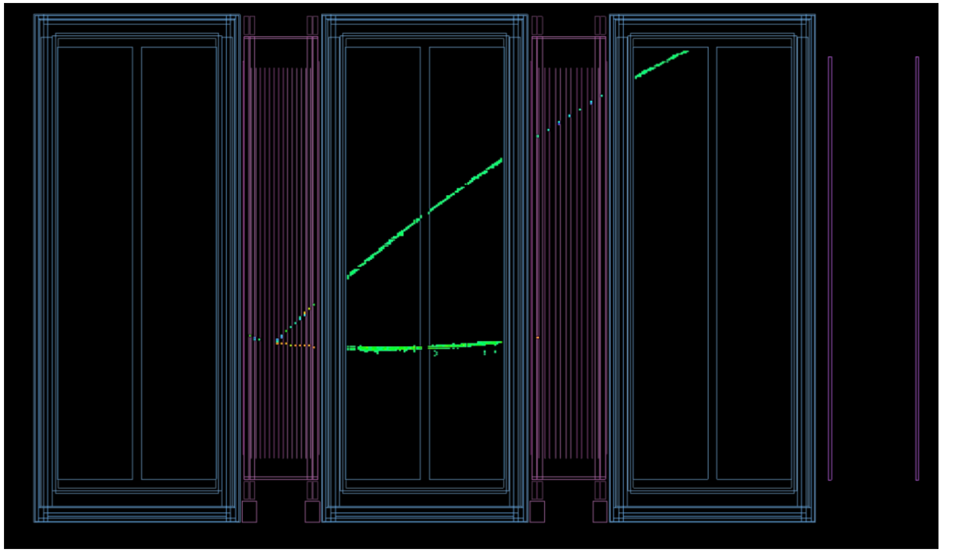


- External constraints:
  - hadron production in target from NA61 experiment at CERN.
  - Neutrino interaction data.
- 2-step fit: use everything else to constrain systematic errors and use this in fit to SK data. **Joint fit** of Δm^2_{32}, θ_{23}, θ_{13}, δ_{CP} to all SK data.

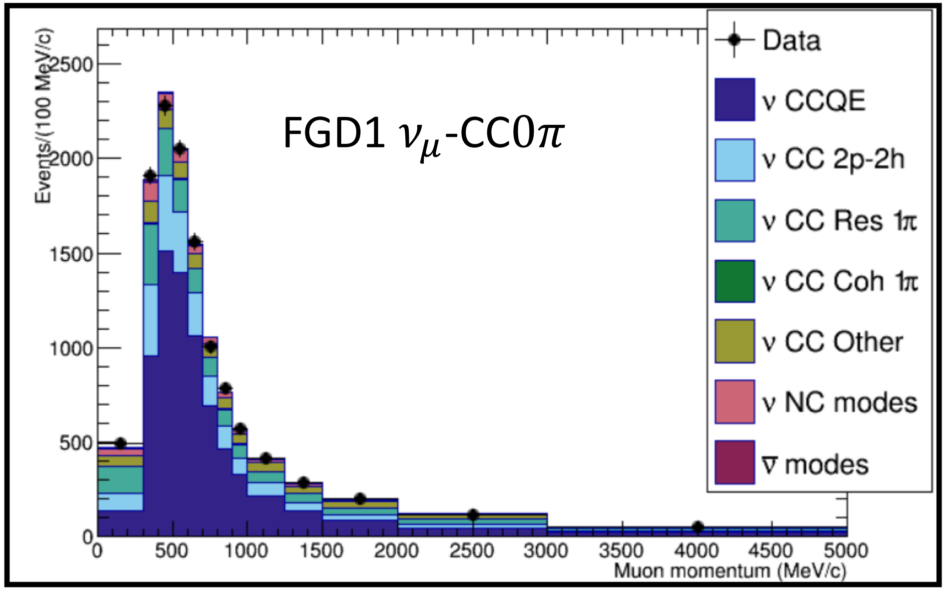
ND280 samples

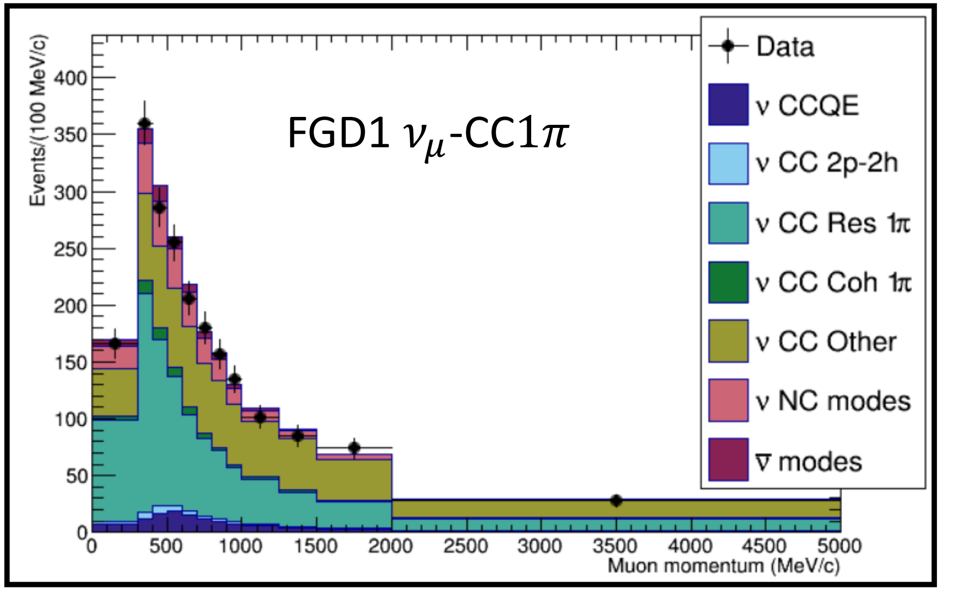
- Fit flux/cross-section parameters to several samples in near detector.
  - FGD1/FGD2.
  - Pion multiplicities.
  - Neutrino/antineutrino mode.

- Example samples below.



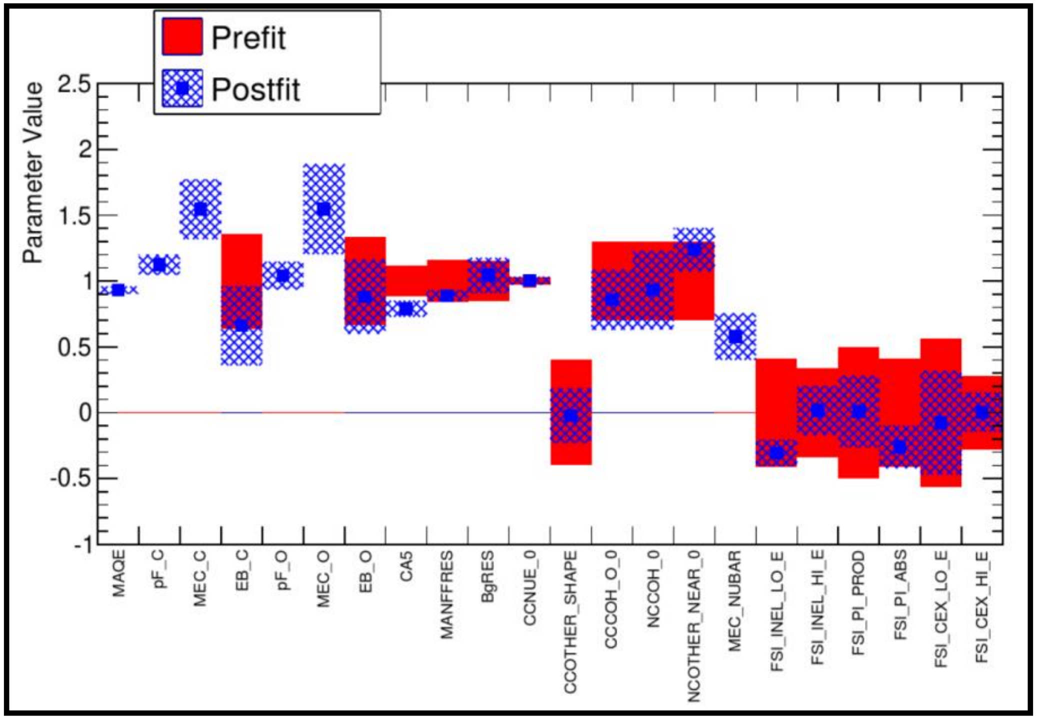
ν_μ-CC event in FGD1

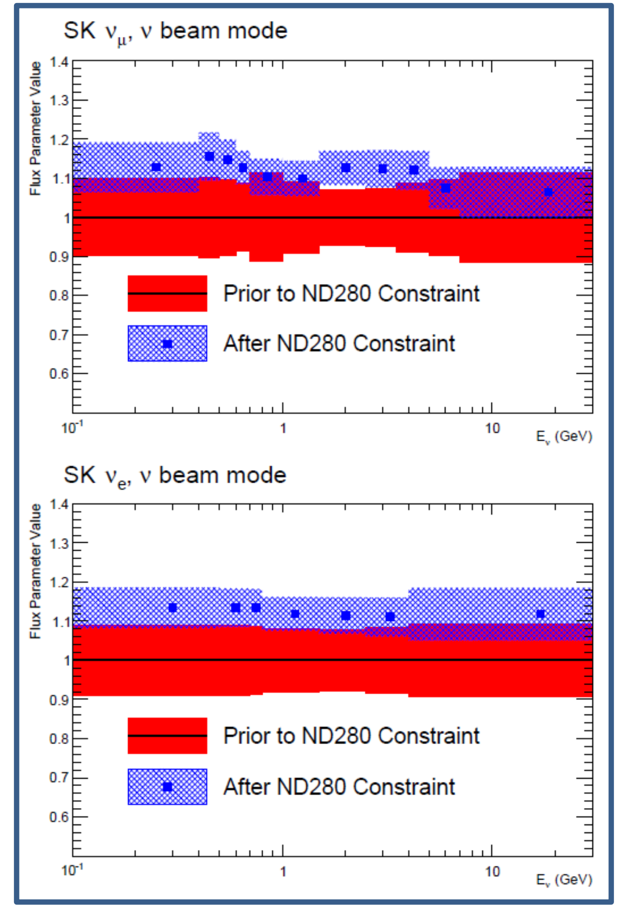




Systematic uncertainties pre/post ND280+INGRID fit

- Large improvement in systematic uncertainties from near detector data!





	single ring μ-like $\Delta N_{SK}/N_{SK}$		single ring e-like $\Delta N_{SK}/N_{SK}$	
Systematic uncertainty	pre-fit	**post-fit**	pre-fit	**post-fit**
flux and cross section	10.9 %	**2.5 %**	11.4 %	**2.7 %**
Total	12.1 %	**4.9 %**	11.9 %	**5.2 %**

For neutrino mode

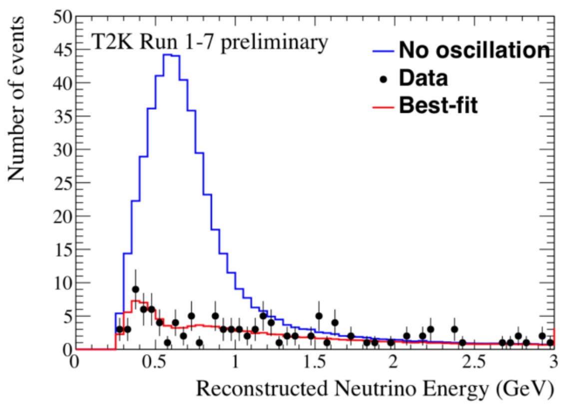
Super-K selections

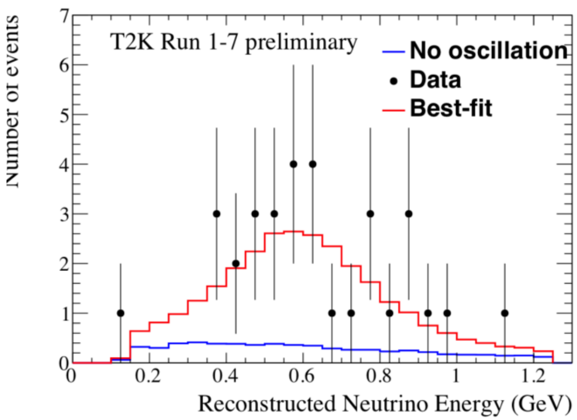
- 2 primary samples – ν_μ-CCQE-like, ν_e -CCQE-like.
  - Separate samples for ν and $\bar{\nu}$ running.

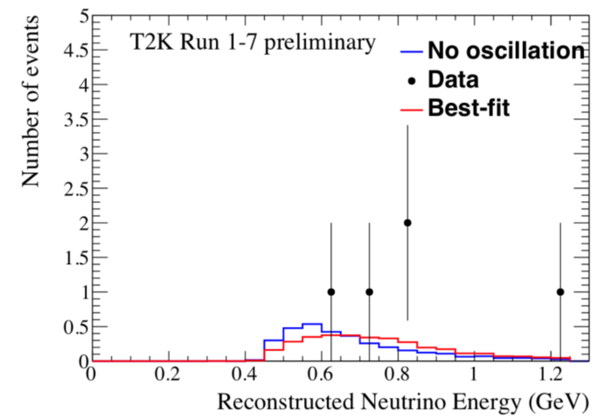
- New extra sample – ν_e-CC1π-like (only for ν mode) – increase ν_e statistics.

1 ring μ-like (ν_μ-CCQE) | 1 ring e-like (ν_e-CCQE) | CC1π^+-like

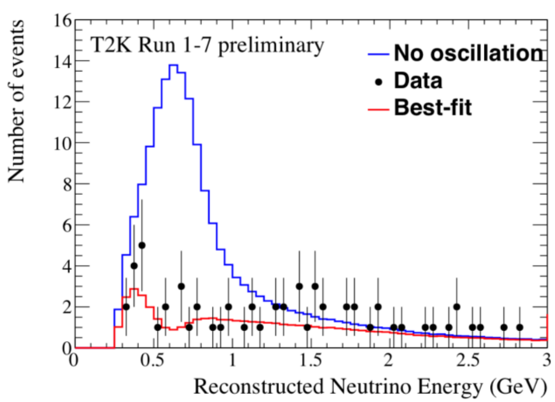
ν mode

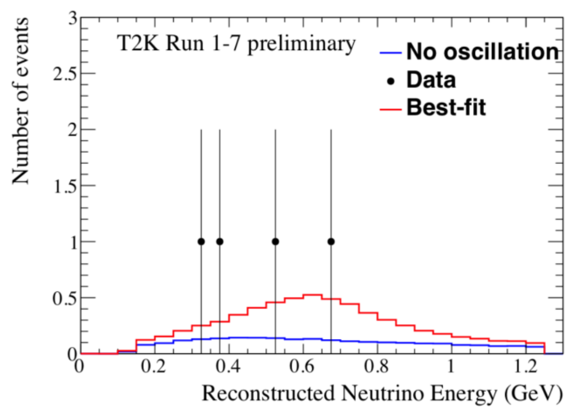






$\bar{\nu}$ mode

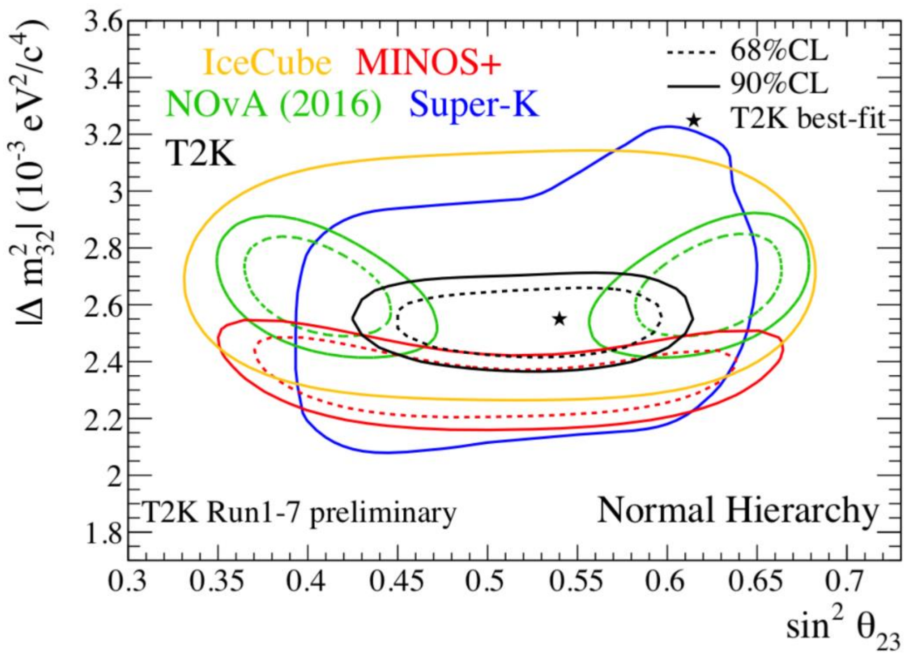


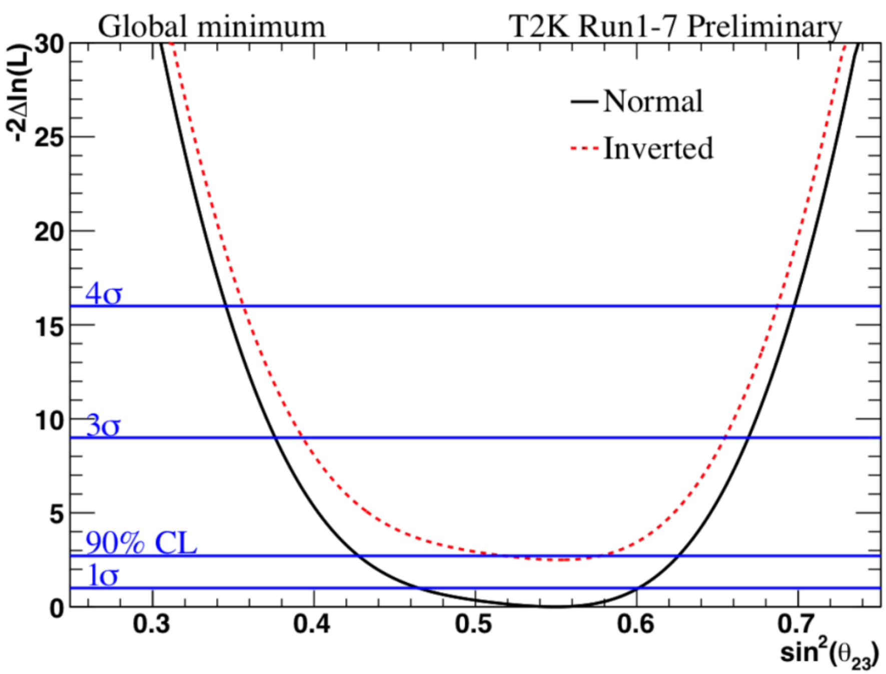


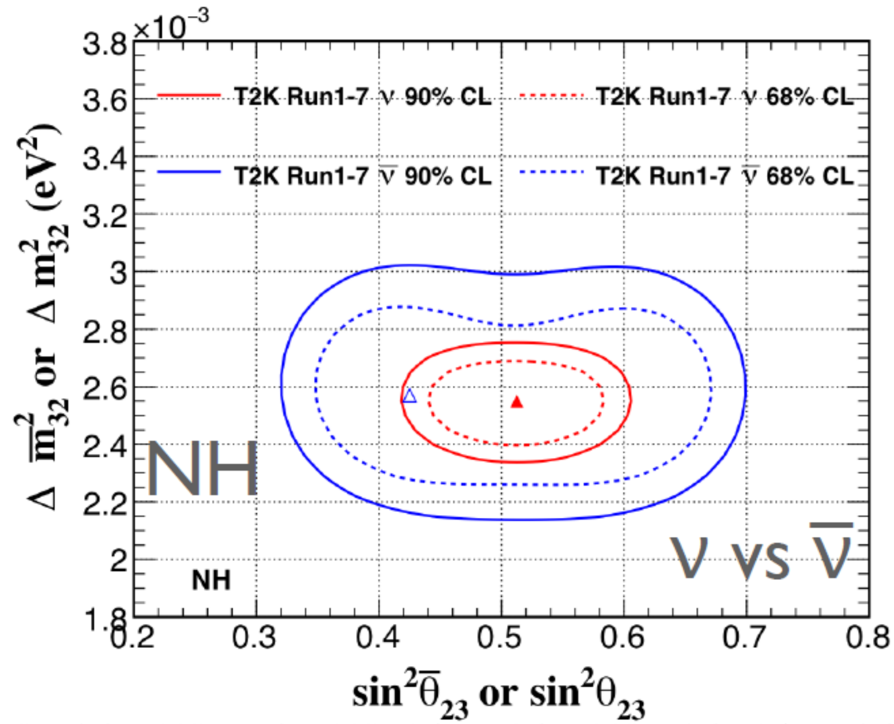
Channel	Number of events
ν mode 1 ring μ-like	135
ν mode 1 ring e-like	32
$\bar{\nu}$ mode 1 ring μ-like	66
$\bar{\nu}$ mode 1 ring e-like	4
CC1π^+-like	5

Results – Δm^2_{32}, θ_{23}

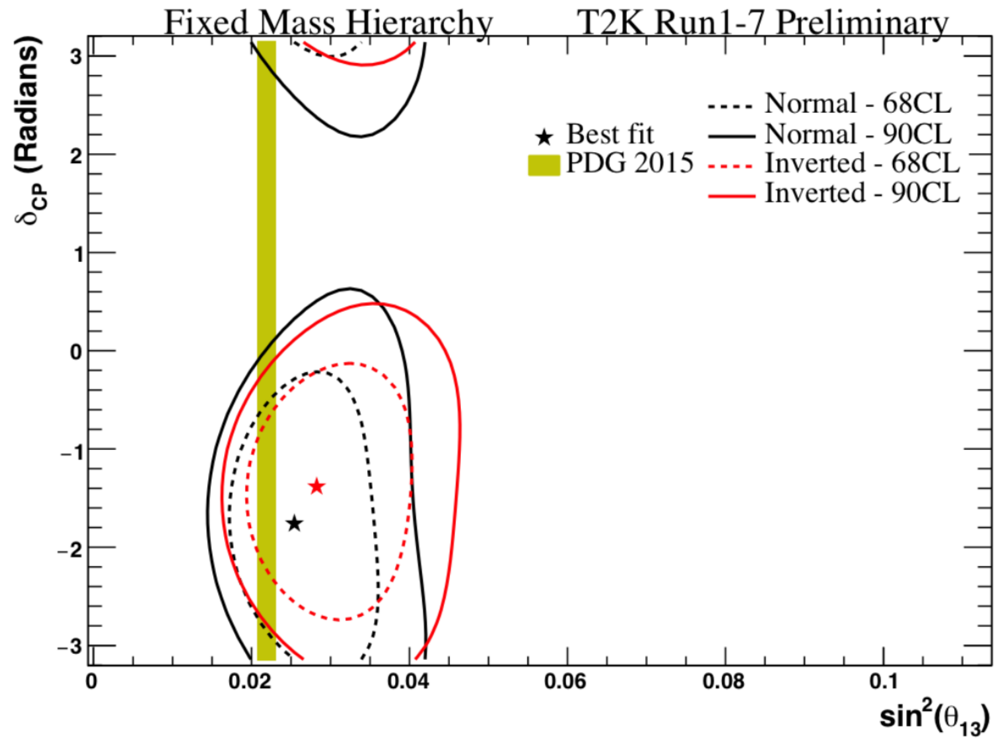
- T2K has world-leading results for θ_{23}, Δm^2_{32}. No tension with other results.
- Agreement between ν and $\bar{\nu}$ data.
  - CPT appears to be conserved!
- No clear indication of octant or $\theta_{23}\neq45^\circ$ from T2K data.



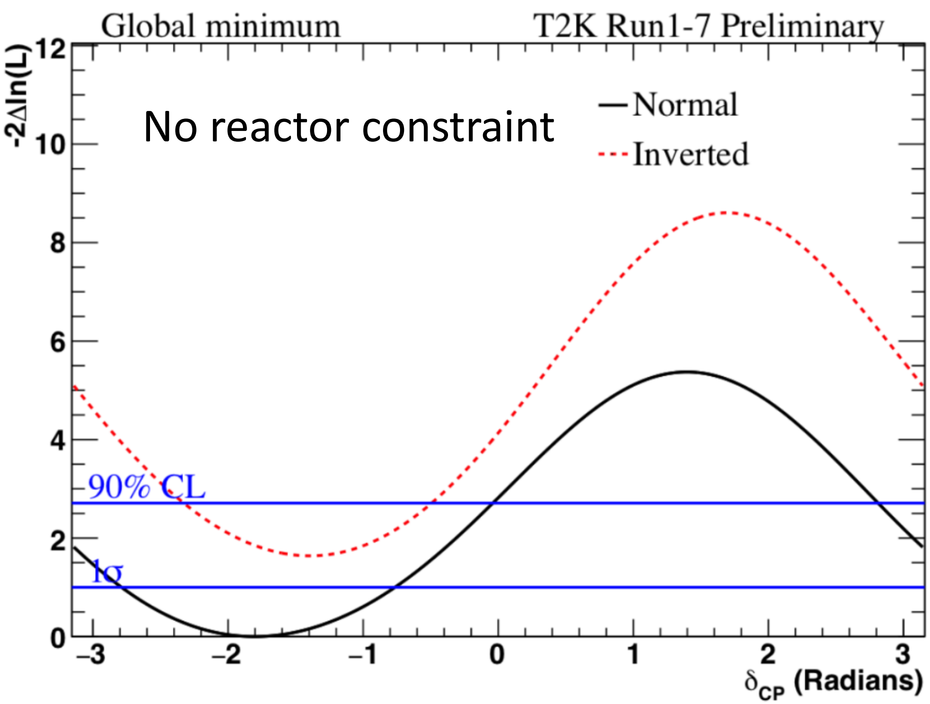


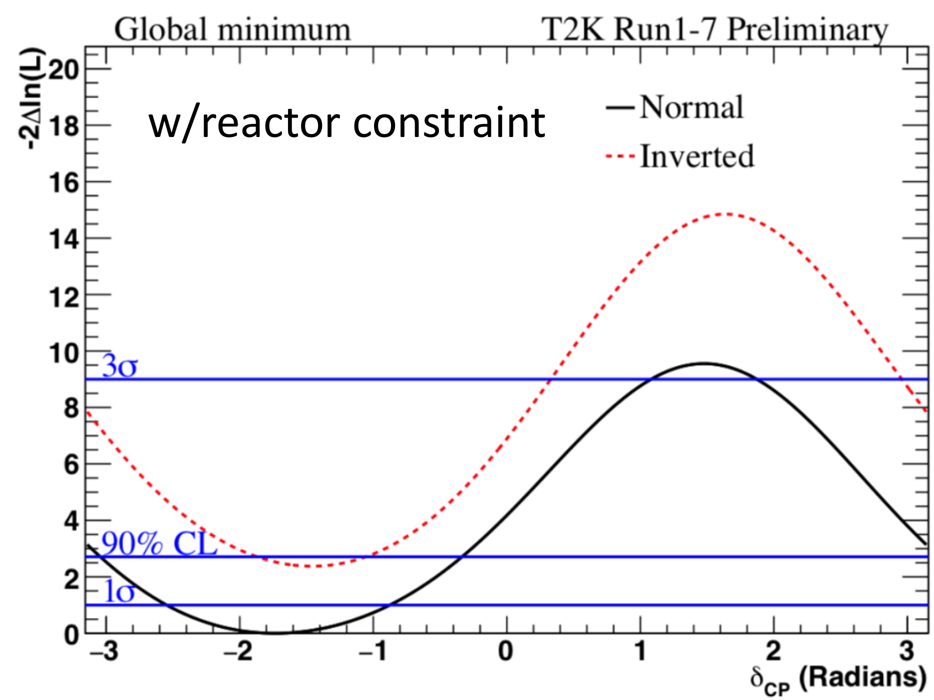


Results – θ_{13}, δ_{CP}



- θ_{13} measurement compatible with PDG (driven by reactors).
- Normal hierarchy, large CP violation favoured.
  - δ_{CP} = 0 excluded at 90% CL.
- Significant improvement in results from inclusion of reactor constraint.
  - δ_{CP} = 0 excluded at 2σ.

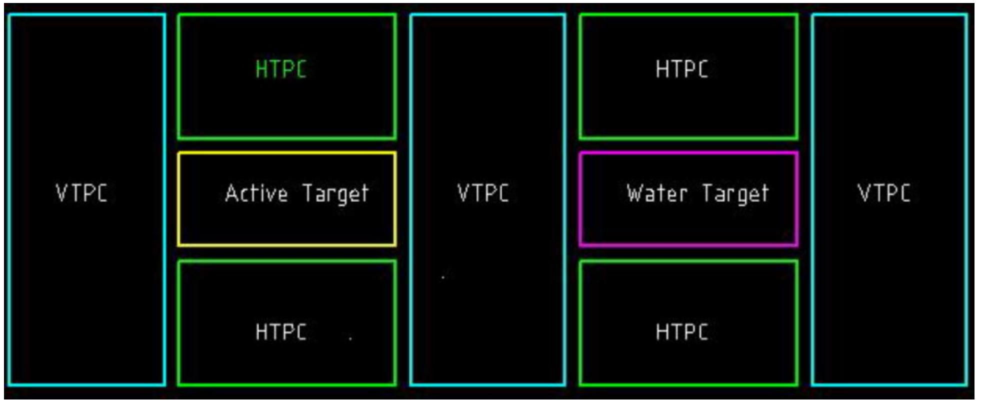




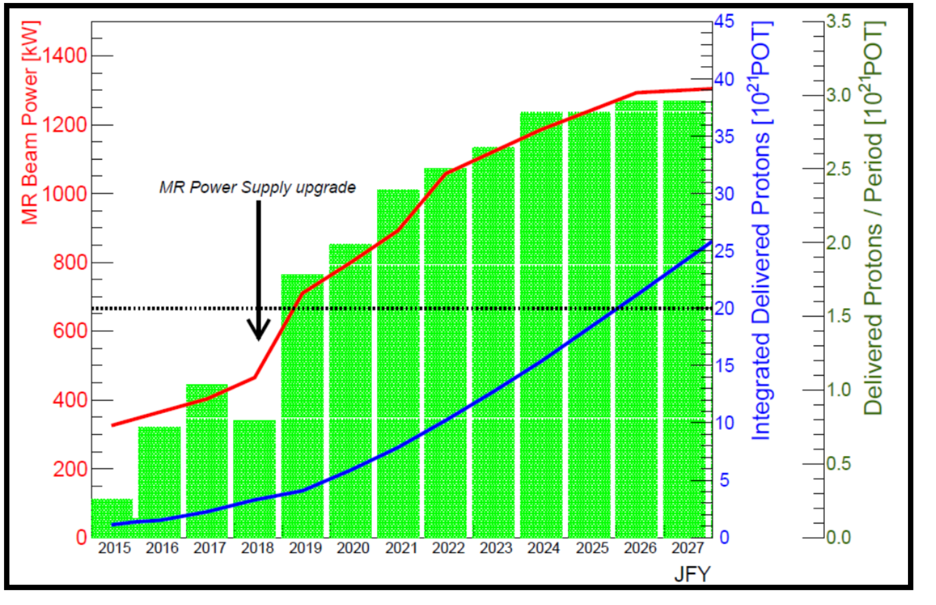
T2K – the future

- 7.8 x 10^{21} POT approved; expected ~2021.
  - Beamline upgrades => beam power increase to 750kW.

- T2K-II proposal:
  - Start ~2021.
  - 20 x 10^{21} POT by 2026. Beam upgrades – focusing horn currents 250->320 kA, beam power 750 kW->1.3 MW.
  - Near detector upgrades+analysis improvements (inc. Super-K fiducial volume increase) => improved systematics.

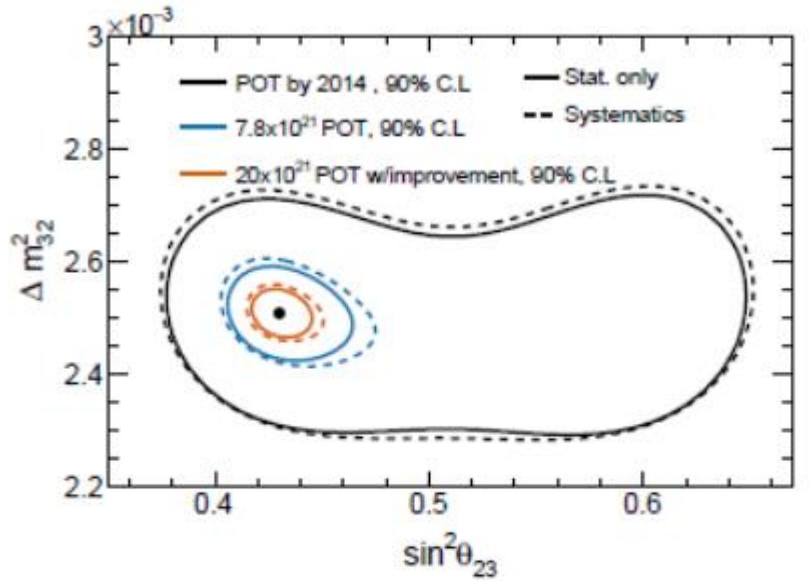


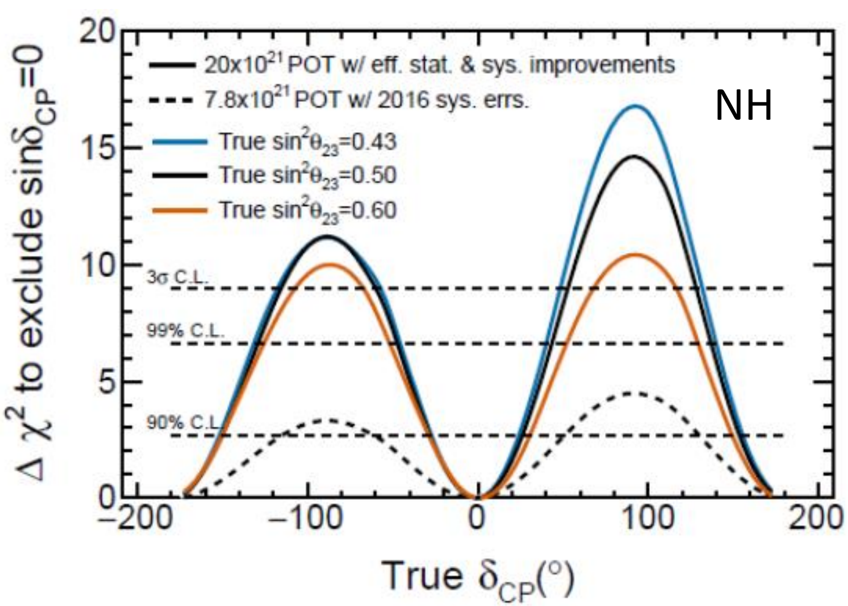
New near detector design under review!

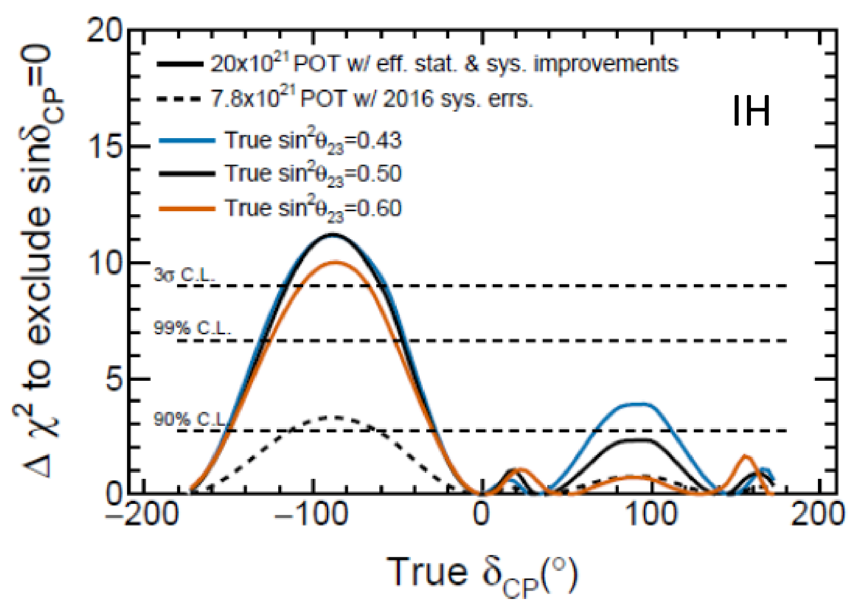


T2K – the future

- 3σ exclusion of $\delta_{CP} = 0$ if true δ_{CP} is $\pm\pi/2$ and hierarchy is known to be NH.
  - Better if mass hierarchy is externally constrained.
  - Assume 1/3 reduction in systematic errors c.f. 2016 analysis.
- Highly precise θ_{23} determination.







Conclusion

- T2K experiment running well and producing world-leading results:
  - Beam power ~450kW, 2 $\times 10^{21}$ POT milestone reached!
  - $\sin^2(\theta_{13})$ measurement compatible with reactors.
  - Precise measurements of $\sin^2(2\theta_{23})$, Δm^2_{32}.
  - CP conservation excluded at 90% CL!

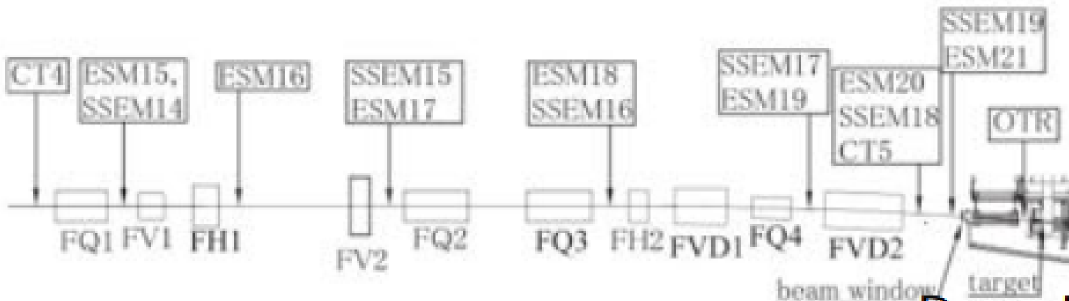
- Exciting developments to come:
  - x4 increase in POT for remainder of T2K phase 1.
  - T2K-II:
    - Near detector upgrades and 20 x 10^{21} POT statistics.
    - 3σ exclusion of $\delta_{CP} = 0$ for NH if true δ_{CP} is $\pm\pi/2$.
    - Potential to determine θ_{23} octant if Nature gives us luck!

Backup

Beam monitors

T2K Primary Proton Beam Monitors

Beamline Final Focusing Section



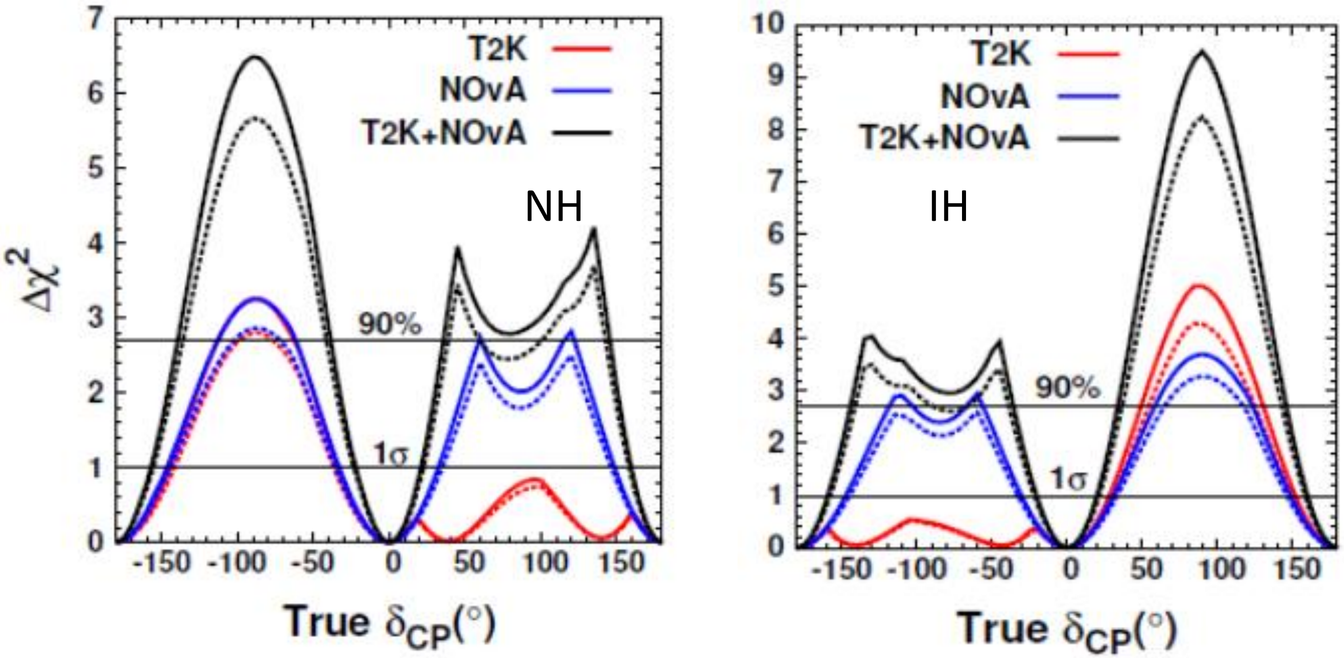
Beam Direction $\longrightarrow$

- Beam monitors are essential for protecting beamline equipment and understanding proton beam parameters for neutrino flux MC
- 5 CTs (Current Transformers) – monitor beam intensity
- 50 BLMs (Beam Loss Monitors)
- 21 ESMs (Electrostatic Monitors) – monitor beam position
- 19 SSEMs (Segmented Secondary Emission Monitors) – non-continuously monitor beam profile
- 1 OTR (Optical Transition Radiation) Monitor – continuously monitors beam at target
- MUMON (Muon Monitor) – continuously monitors secondary muon beam position and profile (not a primary proton beam monitor)

T2K+NOvA

- Combination with NOvA assuming 1:1 v:vbar running for both experiments (dashed lines are without normalisation systematics)
- Fit in top plots does not constrain MH to be the true value.
- Considerable improvement in MH determination and delta=0 rejection compared to individual measurements.
- *Neutrino Oscillation Physics Potential of the T2K Experiment, Prog. Theor. Exp. Phys. (2015) 043C01*

Delta=0 rejection



MH determination