T2K NEUTRINO OSCILLATION RESULTS AND HYPER-K FUTURE PROSPECTS

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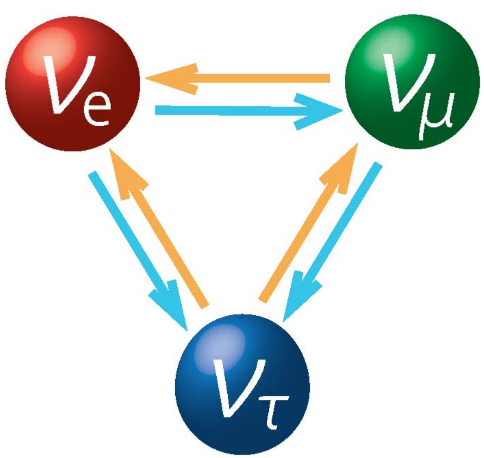
Outline

- Introduction to neutrino oscillations
- The T2K experiment
  - Result from neutrino running
  - New results from anti-neutrino running
- The Hyper-Kamiokande experiment
  - Neutrino oscillation parameter sensitivities

Neutrino mixing and oscillations

- Neutrino production and detection is determined by flavor eigenstates
- They propagate in mass eigenstates so flavor can change with time and position
- Neutrinos can therefore oscillate between flavor eigenstates



Flavor eigenstates

Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakawa matrix

Neutrino oscillation parameters

The PMNS matrix

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

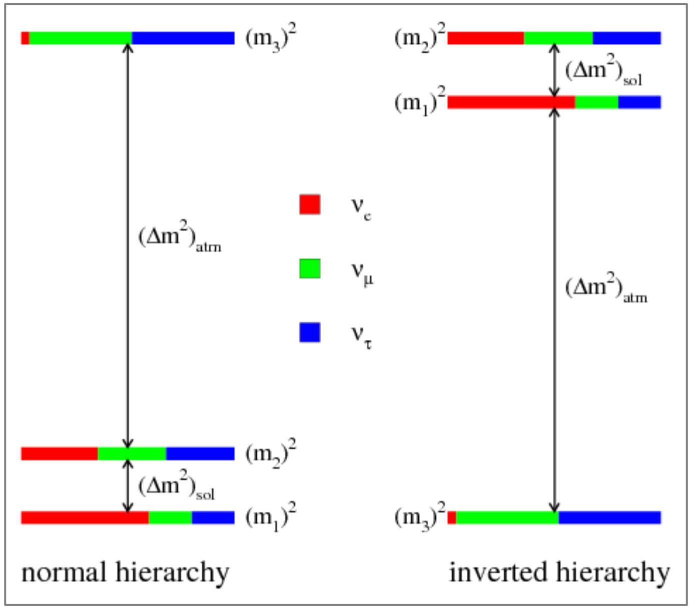
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/ Accelerator
$\Theta_{23} \approx 45° \pm 6°$ (T2K)

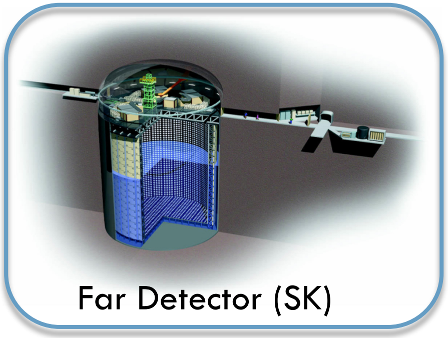
Reactor/ Accelerator
$\Theta_{13} \approx 9.1° \pm 0.6°$ (T2K)

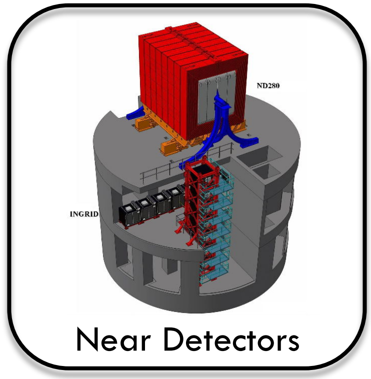
Solar/ Reactor
$\Theta_{12} \approx 34° \pm 1°$

- Three mixing angles Θ_{12}, Θ_{23} and Θ_{13}
  - $\Theta_{23}=45°$ (maximal mixing)?
  - $\Theta_{23}<45°$ or $\Theta_{23}>45°$ (octant)?
- One CP violation phase δ_{CP}
  - Non-zero δ_{CP}?
- Two mass splittings (Δm^2_{12} and Δm^2_{23})
  - Mass hierarchy?

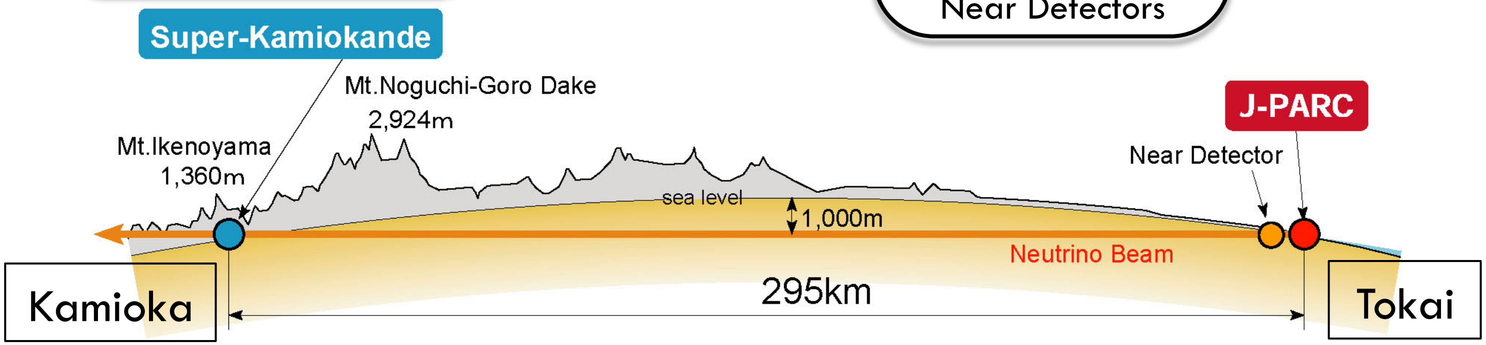


The T2K (Tokai to Kamioka) experiment



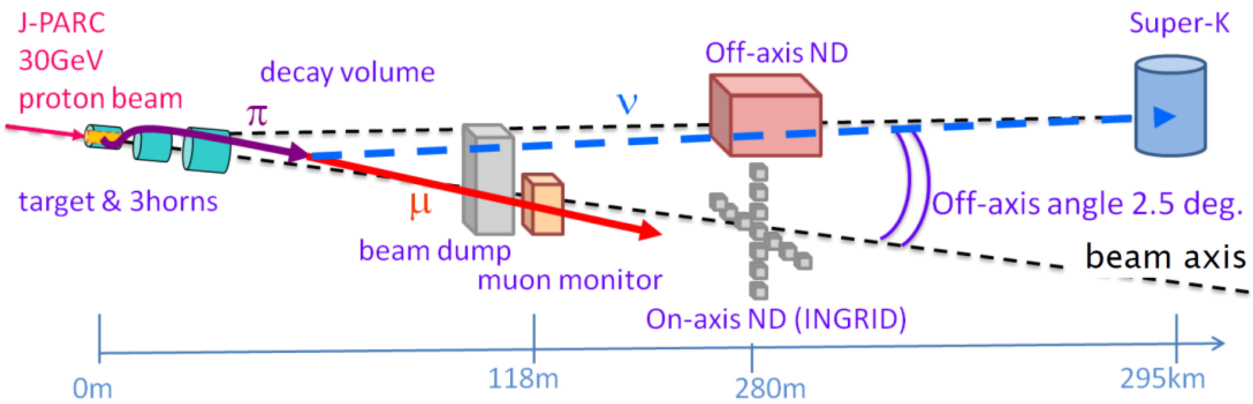


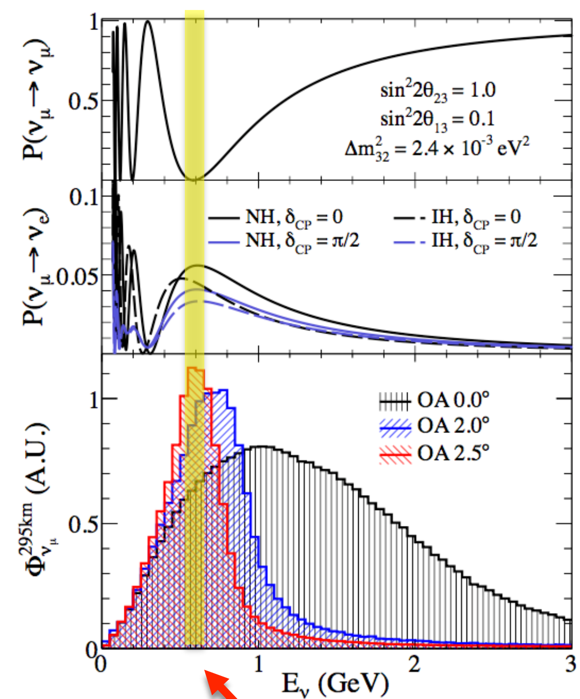
J-PARC
(KEK-JAEA, Tokai)



- Long-baseline neutrino oscillation experiment using a ν_μ beam produced at J-PARC
- Designed to measure ν_e appearance and ν_μ disappearance
  - Θ_{23} , Θ_{13} , Δm^2_{32} and sensitivity to δ_{CP}

Neutrino production & off-axis beam





- Proton beam on graphite target produces hadrons (mostly $\pi^{\pm}$)
- Positive (negative) π's are focused by 3 magnetic horns and decay to produce ν_μ ($\bar{\nu}_\mu$)
- T2K uses a 2.5° off-axis angle beam
  - Narrow band beam
  - Matches oscillation maximum by design
  - Reduces high energy background

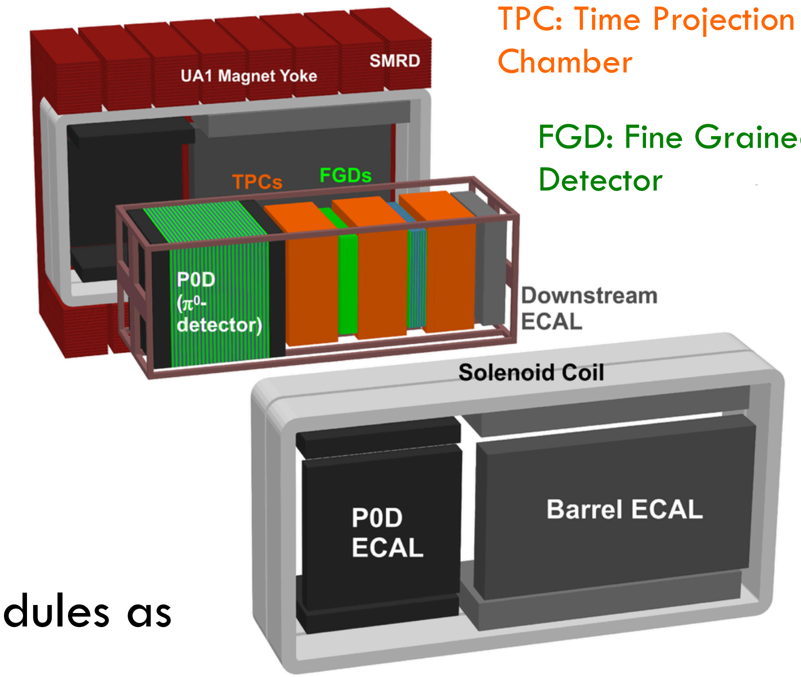
Energy peak at ~0.6 GeV

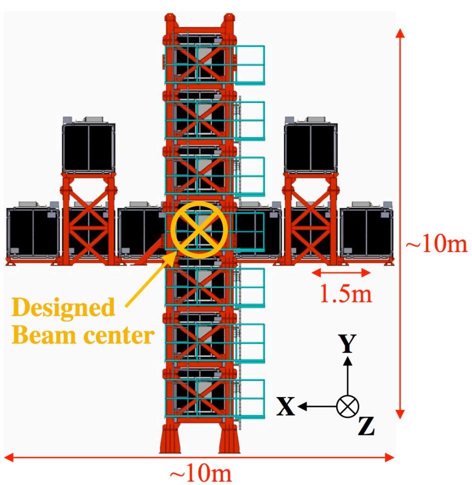
Near detectors at 280 m

- ND280 (off-axis)
- Several sub-detectors in 0.2 T magnetic field
  - 2 FGDs: Scintillator (C) and water (O) targets
  - 3 TPCs: Particle identification (μ/e misidentification < 0.2%)
- Neutrino interaction rates before oscillations
- Intrinsic ν_e contamination in beam
- Neutrino cross sections

TPC: Time Projection Chamber

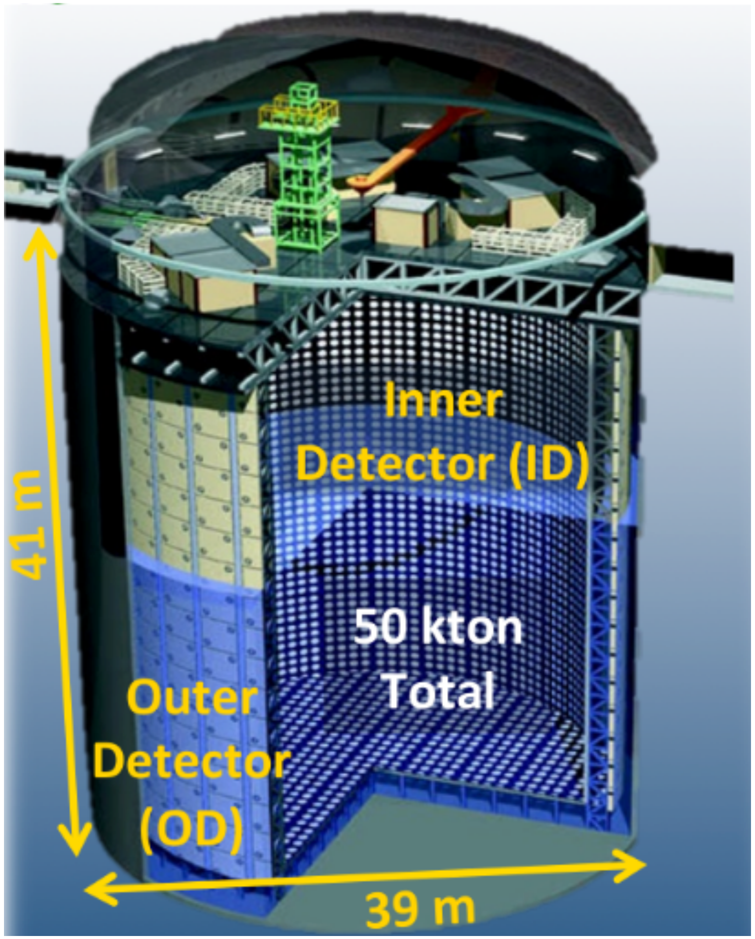
FGD: Fine Grained Detector



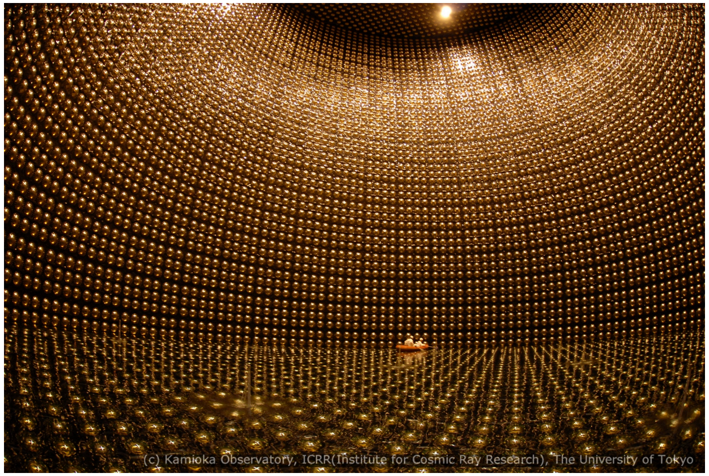


- INGRID (on-axis)
- 16 iron/scintillator modules as tracking calorimeters
- 1 scintillator-only module as active target
- Monitors beam intensity, direction, profile and stability
- Neutrino cross sections

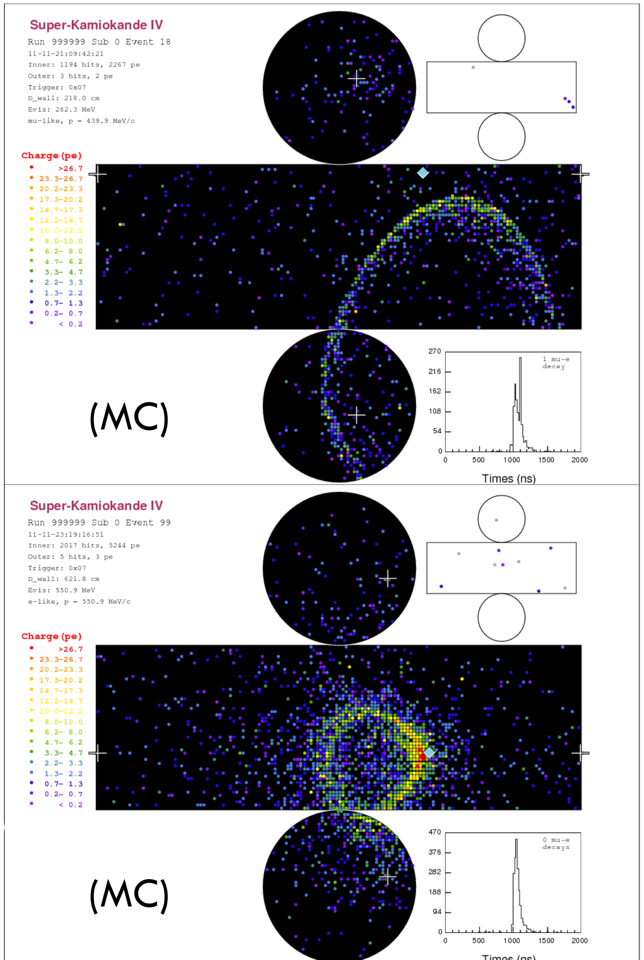
Far detector: Super-Kamiokande (SK)



- 50 kton water Cherenkov detector
  - 22.5 kton fiducial mass
- ~11k 20-inches PMTs in inner detector
- ~2k 8-inches PMTs outer detector
  - Veto entering background (cosmic rays, radioactivity) and rejects exiting events



SK detection principle



$\nu_\mu \rightarrow \mu$

sharp rings

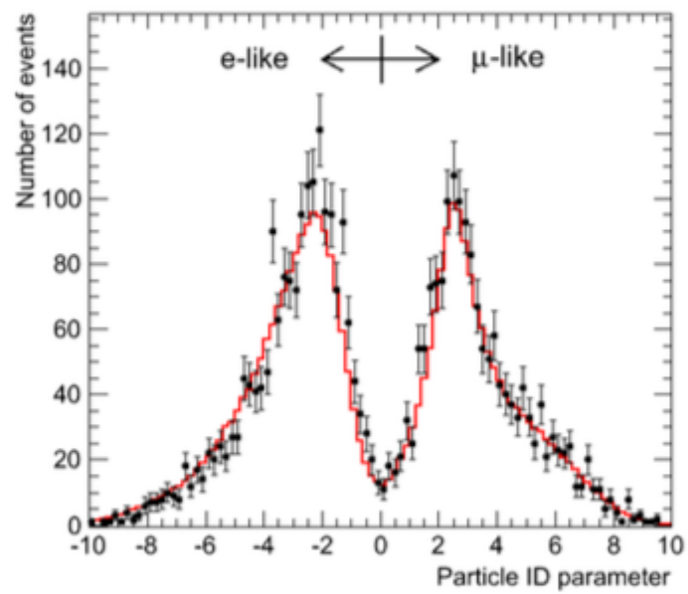
μ-like

$\nu_e \rightarrow e$

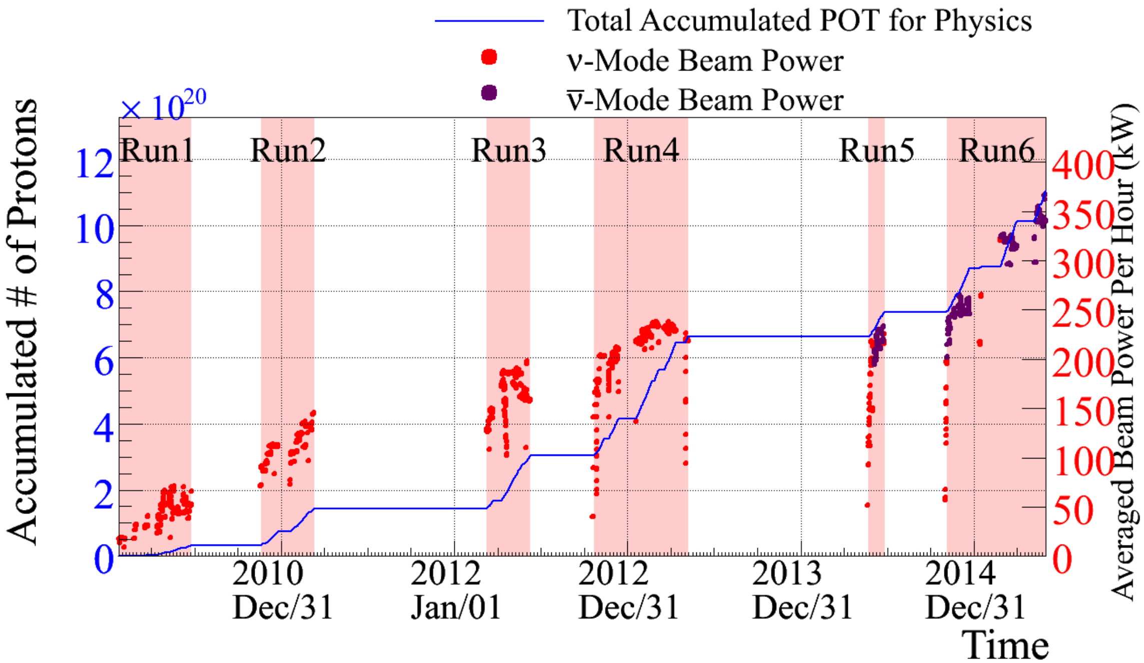
"fuzzy" rings

e-like

- SK uses Cherenkov ring shape to identify charged current ν_μ or ν_e interactions
- μ/e misidentification is < 1%



Beam delivered to T2K



T2K goal is 78×10^{20} PoT

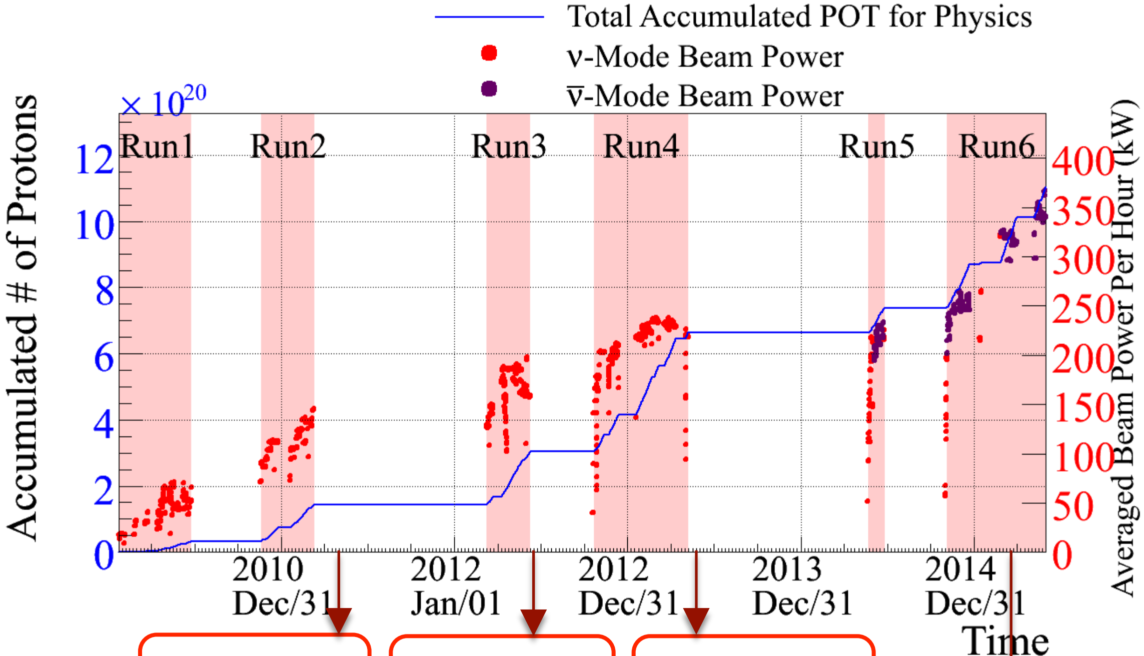
Maximum beam power achieved so far 371 kW

T2K started to take $\bar{\nu}$-mode beam data in summer 2014

Results presented in this talk use data up to March 12th, 2015

- Accumulated Proton on target (PoT) up to June 1st 2015: 11.0×10^{20} (total) = 7.0×10^{20} (ν) + 4.0×10^{20} ($\bar{\nu}$)
- Data analyzed so far:
  ND280: 5.8×10^{20} (ν) + 4.3×10^{19} ($\bar{\nu}$)
  SK: 5.8×10^{20} (ν) + 2.3×10^{20} ($\bar{\nu}$)

Released T2K oscillation results



ν_e app. 2.5σ

ν_μ disapp. first release

ν_e app. 3.1σ

ν_e app. 7.3σ

ν_μ disapp. highest Θ_{23} precision

Joint ν_e / ν_μ analysis
First hints on δ_{CP}

$\bar{\nu}_\mu$ disapp. first release (NEW)

T2K goal is 7.8×10^{20} PoT

Maximum beam power achieved so far 371 kW

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ν-mode analyses results (2010-2013 data)

ν_e appearance measurement

<u>Phys.Rev.Lett. 112, 061802 (2014)</u>

- 28 ν_e events were detected at SK
  - 4.9±0.6 expected without oscillation
- Maximum likelihood fit in (p_e,Θ_e) to obtain the oscillation parameters
- Result is consistent with the independent analysis using reconstructed neutrino energy

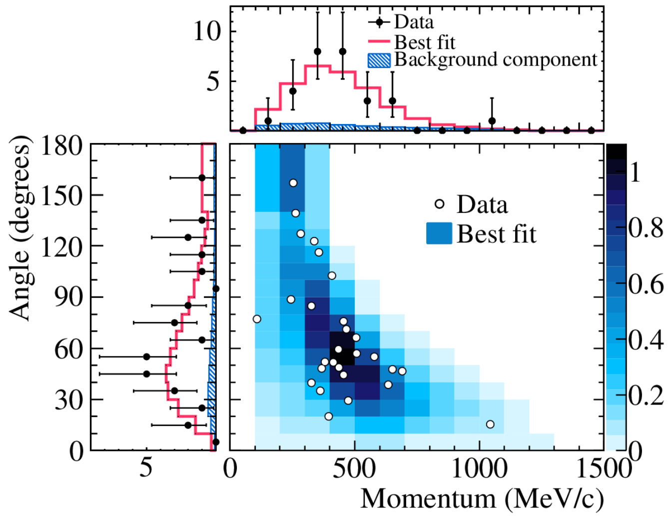
$$\sin^2 2\vartheta_{13} = 0.140^{+0.038}_{-0.032} \quad \text{(NH)}$$

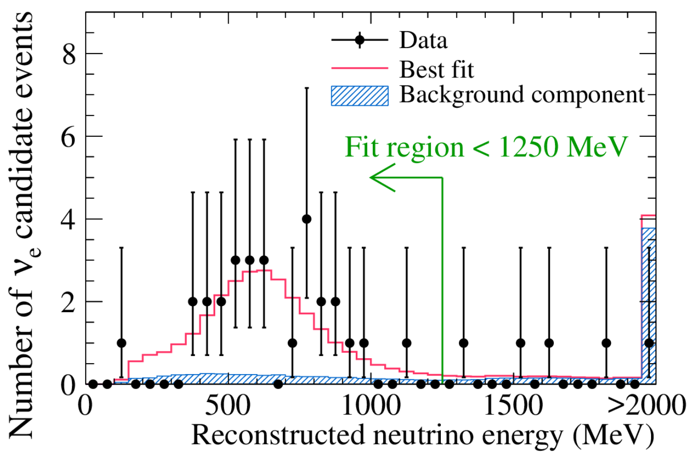
$$\sin^2 2\vartheta_{13} = 0.170^{+0.045}_{-0.037} \quad \text{(IH)}$$

68% C.L.

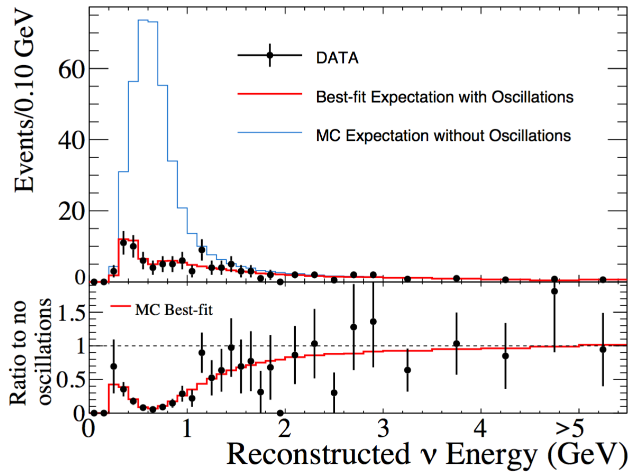
7.3σ significance for non-zero θ_{13}

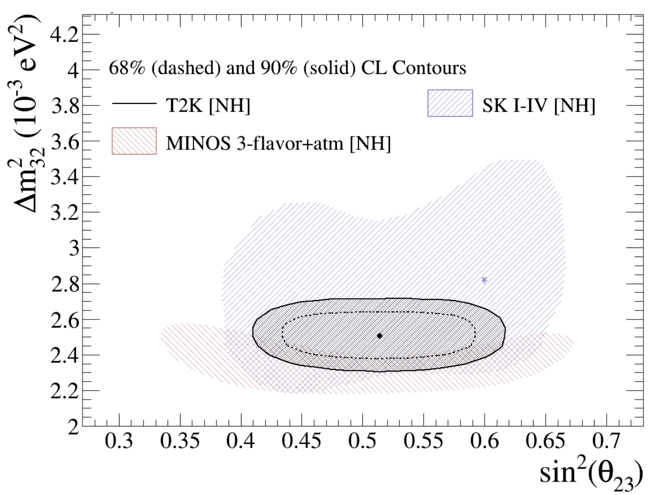
Discovery of ν_e appearance!





ν_μ disappearance measurement





<u>Phys.Rev.Lett. 112, 181801 (2014)</u>

- Disappearance of ν_μ events was observed
  - 120 candidates
  - 446.0±22.5 expected without oscillation
- Fit to the reconstructed energy spectrum to determine oscillation parameters

$$\sin^2\vartheta_{23} = 0.514^{+0.055}_{-0.056}$$

$$\Delta m^2_{32} = (2.51 \pm 0.10)\times 10^{-3}\, eV^2/c^4$$

(NH)

$$\sin^2\vartheta_{23} = 0.511^{+0.055}_{-0.055}$$

$$\Delta m^2_{32} = (2.48 \pm 0.10)\times 10^{-3}\, eV^2/c^4$$

(IH)

68% C.L.

Most precise measurement of $\sin^2\Theta_{23}$!

Joint ν_μ/ν_e analysis

Phys.Rev.D 91, 072010 (2014)

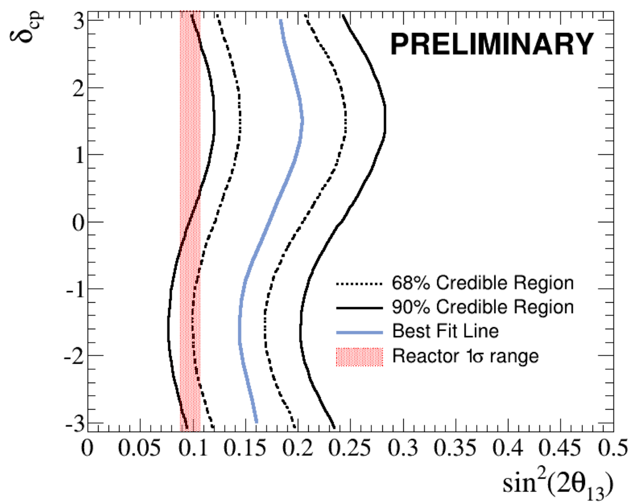
- Simultaneous fit to ν_μ and ν_e spectra in far detector
  - Correlations between oscillation parameters properly taken into account
- Included constraint from reactor experiments

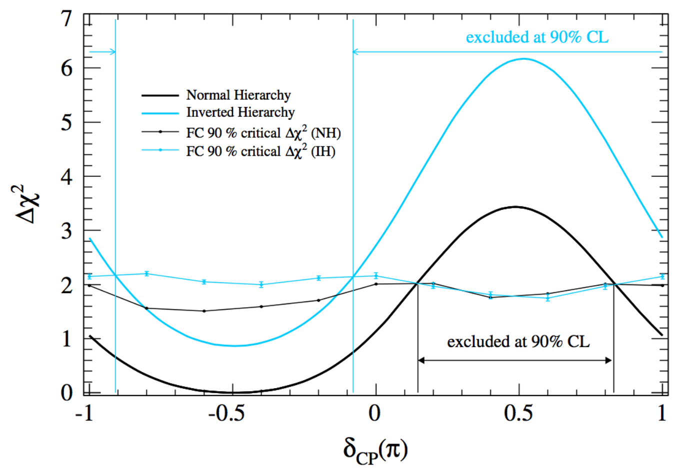
$$\delta_{CP} \in [0.15, 0.83]\pi \quad \text{NH}$$

$$\delta_{CP} \in [-0.08, 1.09]\pi \quad \text{IH}$$

Excluded at 90% C.L.

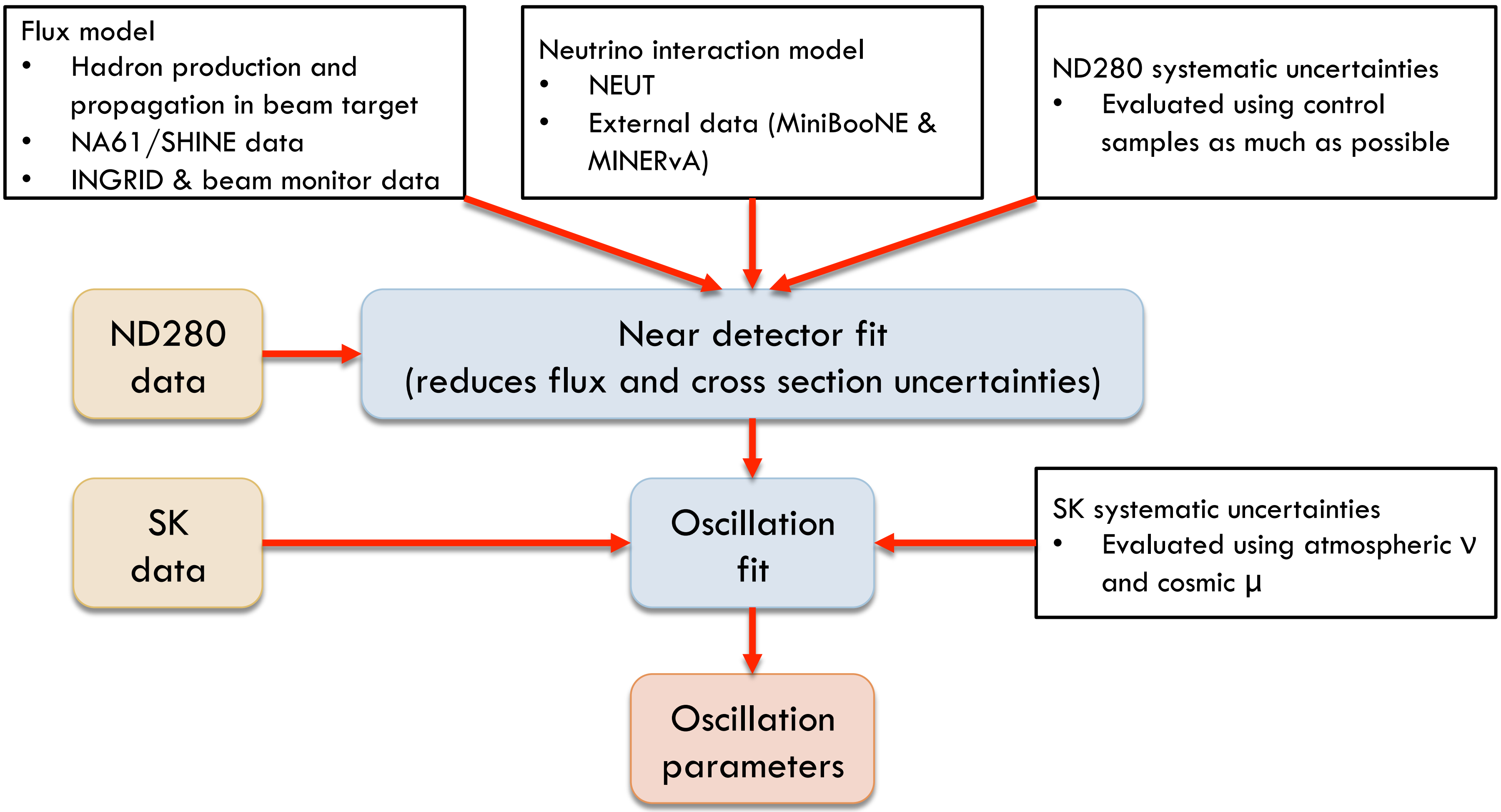
Hints to a value of δ_{CP} of $-\pi/2$





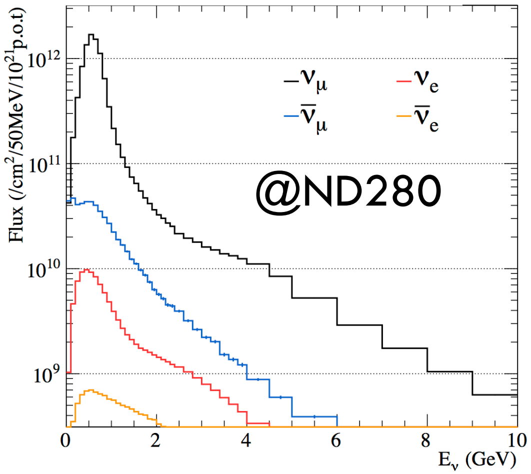
First $\bar{\nu}$-mode analysis result (NEW)

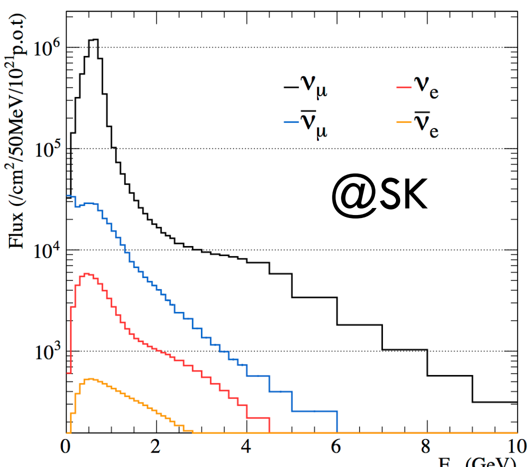
Oscillation analysis overview



Flux model predictions

ν-mode beam





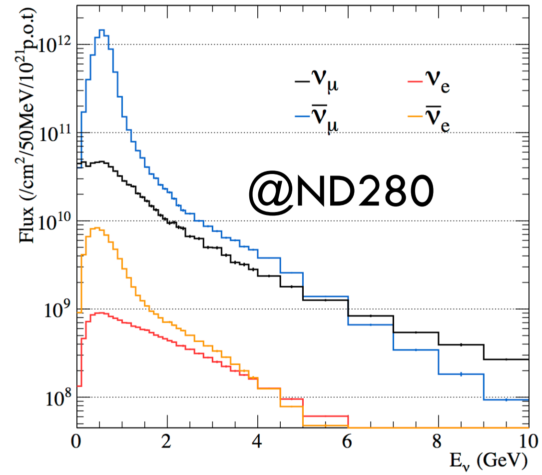
Beam simulation is tuned with NA61/SHINE hadron production data

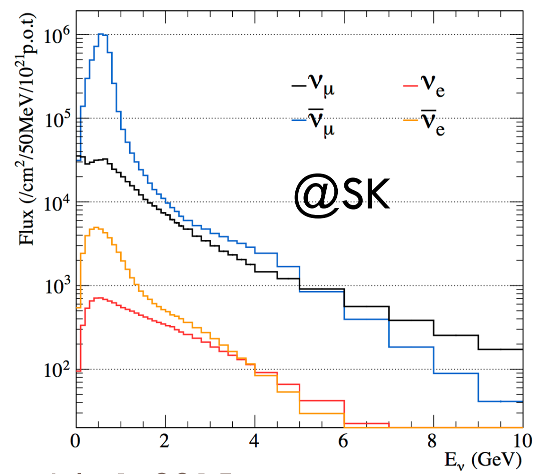
Flux is predicted at ND280 and SK in ν and ν̄ modes

"Wrong sign" background is much higher in ν̄ mode

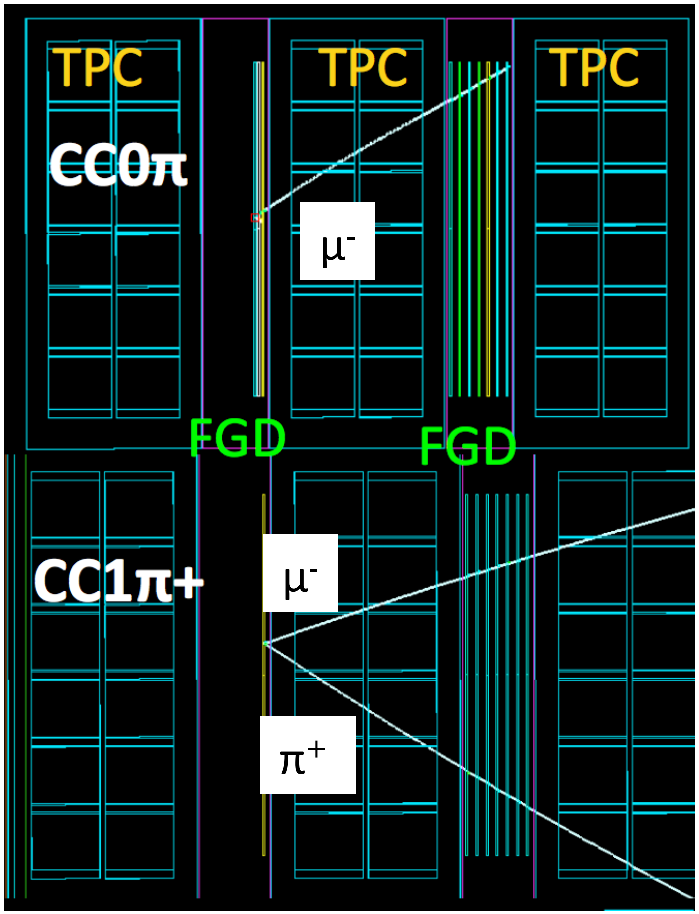
Small intrinsic ν_e background

ν̄-mode beam

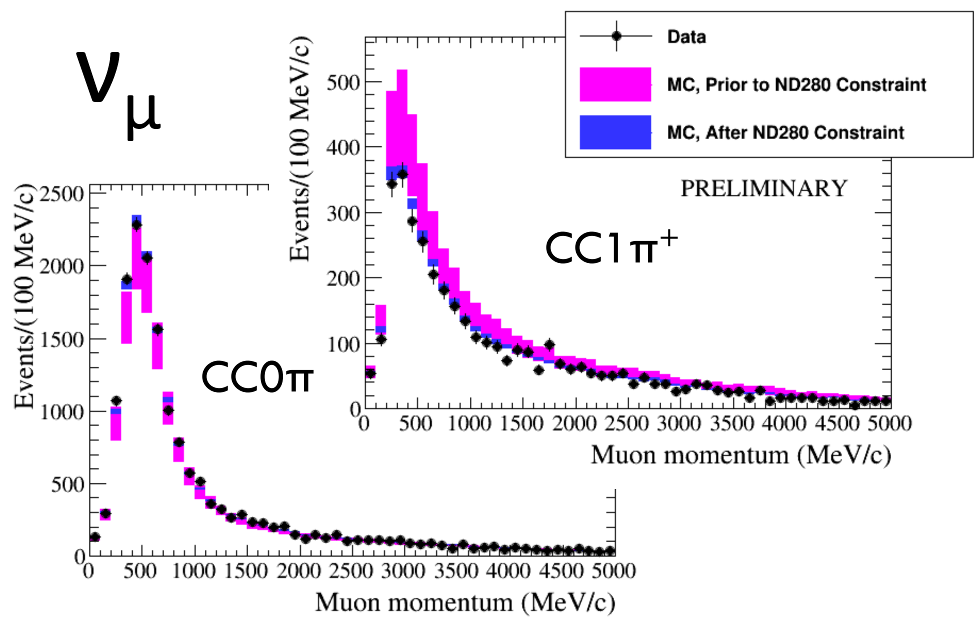




Near detector fit (ν-mode beam)



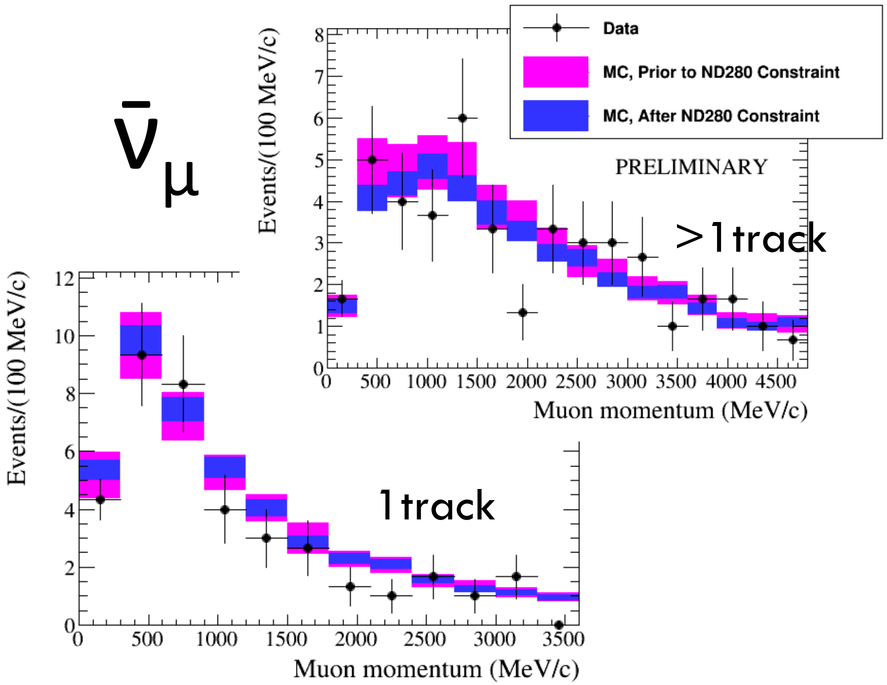
- Select CC ν_μ events and classify them based on π content
  - Each sample is sensitive to different ν energy ranges and interactions
- Fit the reconstructed (p_μ, $\cos\Theta_\mu$) distributions
  - Flux and cross section model parameters are adjusted and uncertainties reduced



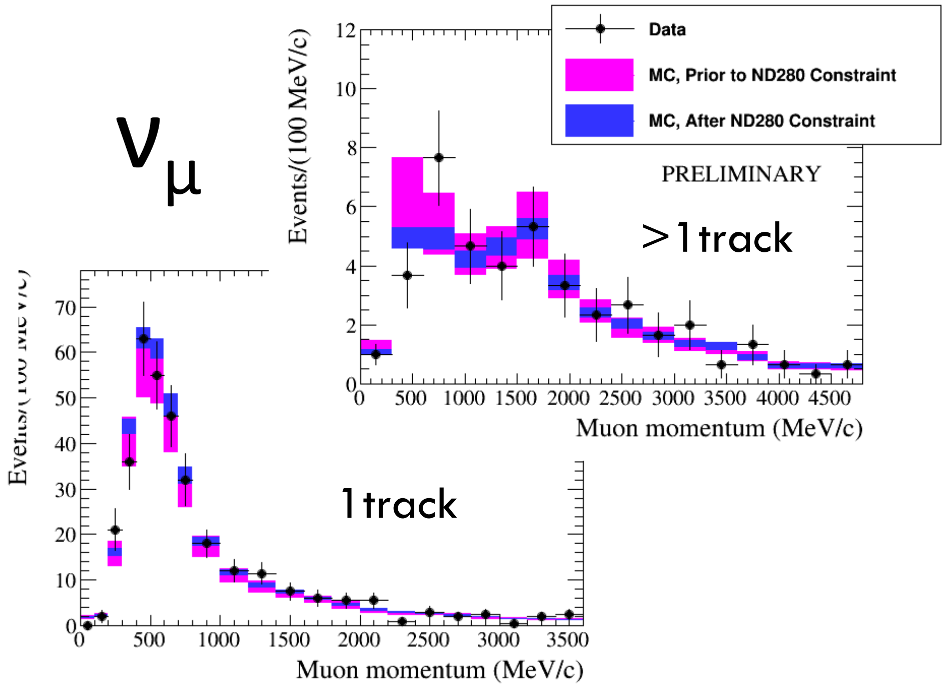
Near detector fit ($\bar{\nu}$-mode beam)

- Select $\bar{\nu}_\mu$ and ν_μ candidates and classify them based on number of tracks
  - Large ν_μ contamination
  - Statistics is lower than ν-mode beam

$\bar{\nu}_\mu$

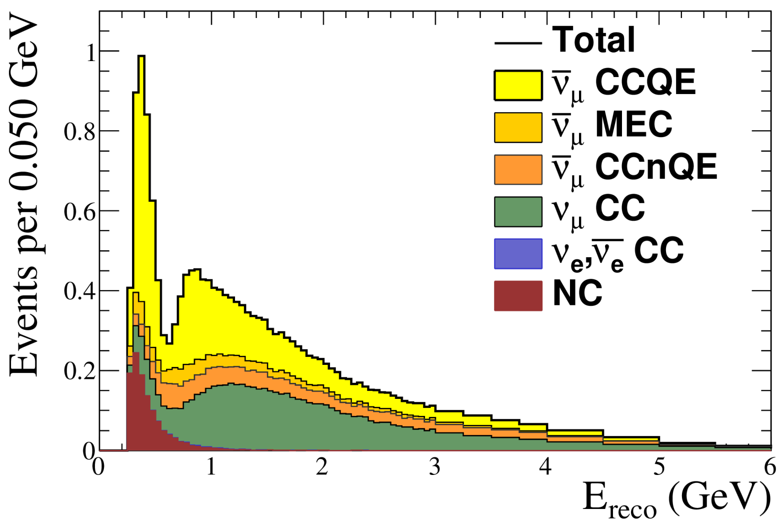


ν_μ

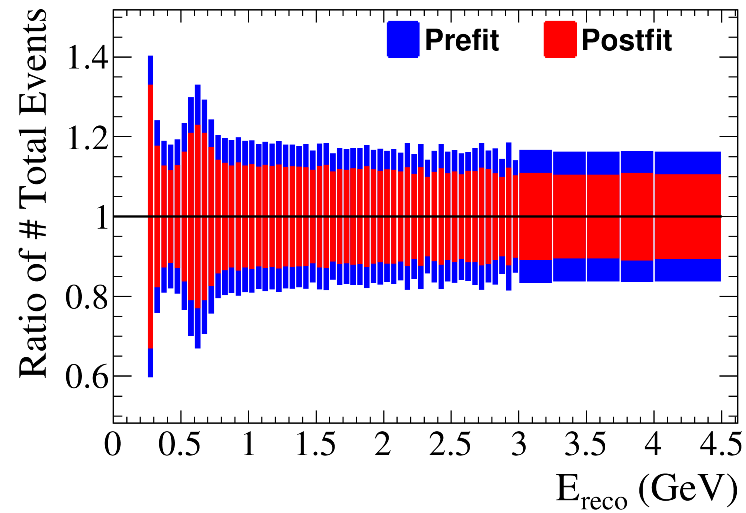


SK expectation and uncertainties ($\bar{\nu}$-mode beam)

Expected spectrum at SK



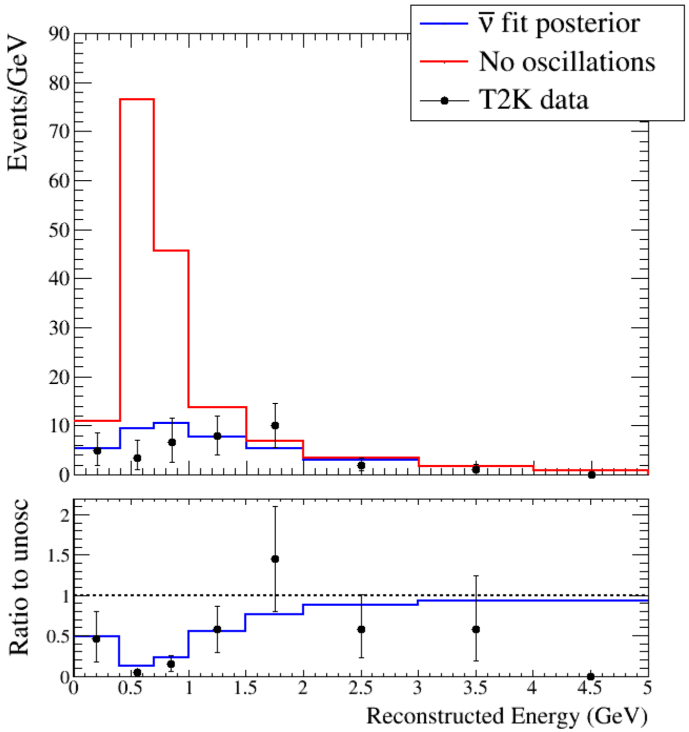
Fractional uncertainties



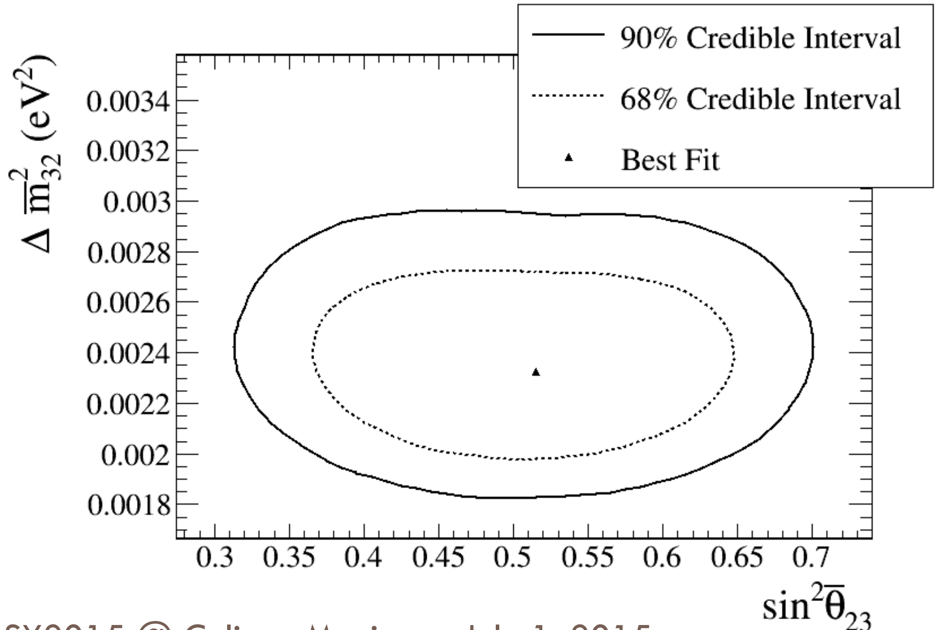
		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK specific)	10.0 %	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

- SK prediction assuming neutrino oscillation parameters
  - 19.9 $\bar{\nu}_\mu$ events with oscillation
  - 59.8 $\bar{\nu}_\mu$ events without oscillation
- The ND280 constraint reduces systematics uncertainties in expected events at SK

$\bar{\nu}_\mu$ disappearance measurement



- Data shows clear evidence for oscillation
  - 17 $\bar{\nu}_\mu$ events detected in SK
  - 59.8 expected without oscillation
- This analysis is statistically dominated



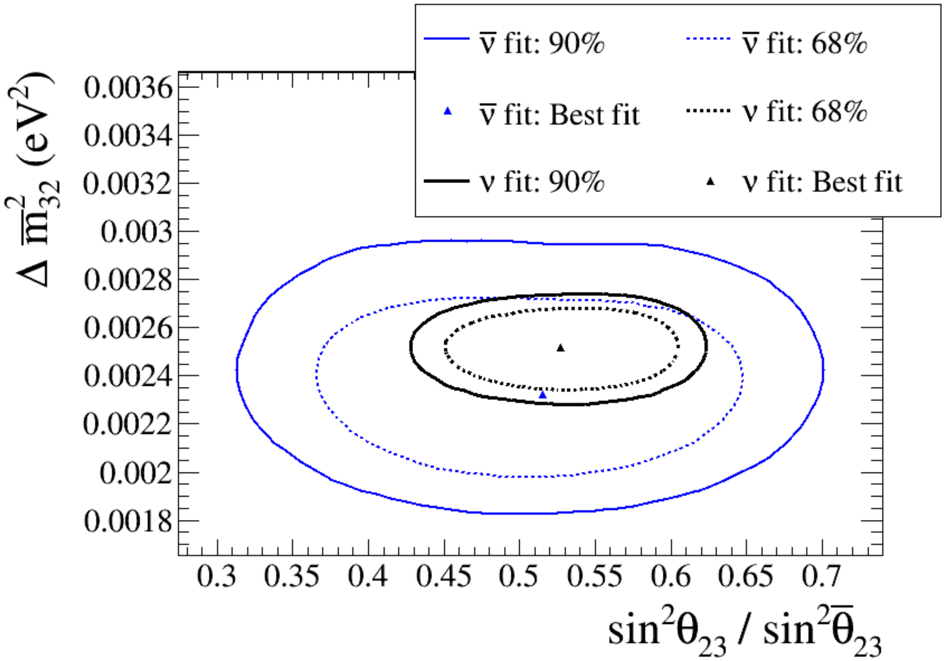
$$\sin^2 \bar{\vartheta}_{23} = 0.515^{+0.085}_{-0.095}$$

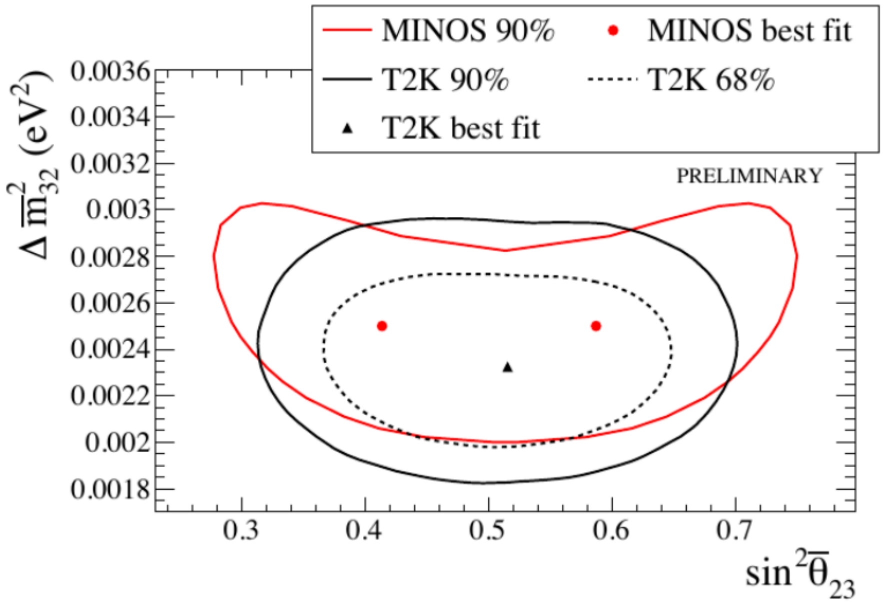
$$\Delta \bar{m}^2_{32} = (2.33^{+0.27}_{-0.23}) \times 10^{-3}\, eV^2/c^4$$

Comparison to other results

- No difference between ν_μ and $\bar{\nu}_\mu$ oscillation parameters
- The $\bar{\nu}_\mu$ has much larger contours than ν_μ analysis due to current limited statistics

- T2K and MINOS are compatible
- T2K contour already smaller than MINOS in $\sin^2\Theta_{23}$





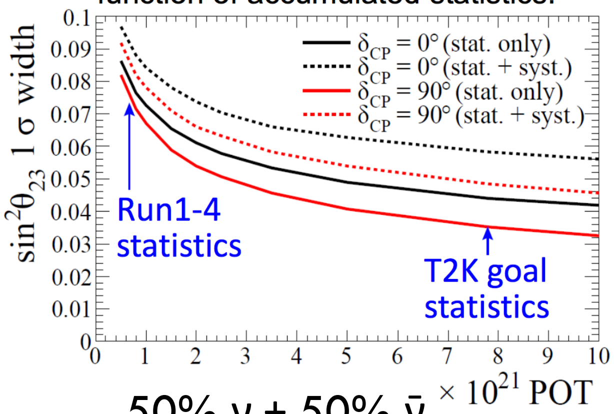
MINOS data is beam and cosmic combined

P. Adamson et al., Phys. Rev. Lett. 110 (2013) 25, 251801

T2K future prospects

- T2K goal is 7.8×10^{21} POT
  - 14% already achieved
- 50% ν and 50% ν̄ gives best sensitivity for a wider region of oscillation parameter space

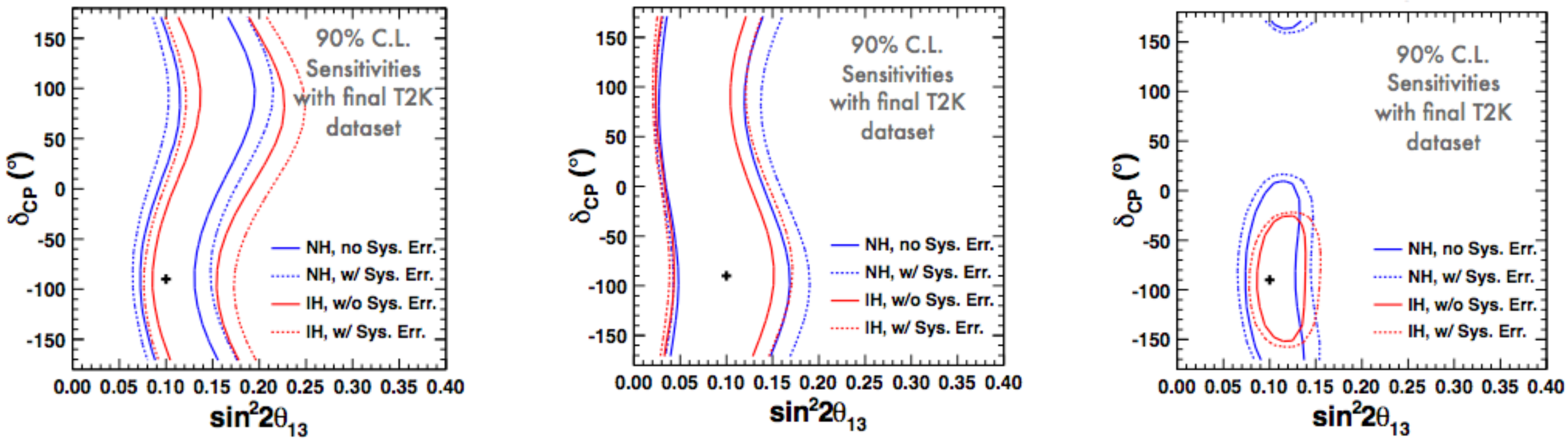
Expected precision on $\sin^2\theta_{23}$ as a function of accumulated statistics.



100 % ν

100 % ν̄

50% ν + 50% ν̄



T2K near-future prospects

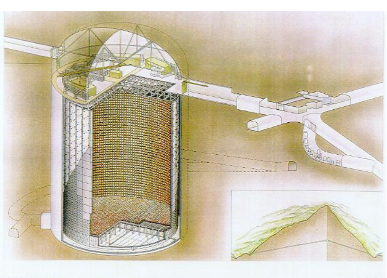
- T2K will continue to collect more data in $\bar{\nu}$- mode and it already has twice the data presented in this talk
  - $\bar{\nu}_\mu$ disappearance will be updated
  - $\bar{\nu}_e$ appearance analysis is underway
  - Stay tuned for these results to come soon at 2015 summer conferences

The Hyper-Kamiokande experiment

Hyper-Kamiokande

Letter of Intent
arXiv:1412.4673v2[hep-ex]

- Next generation Mega-ton water Cherenkov detector
  - Proposed successor to Super-Kamiokande
  - x25 larger fiducial volume than Super-K



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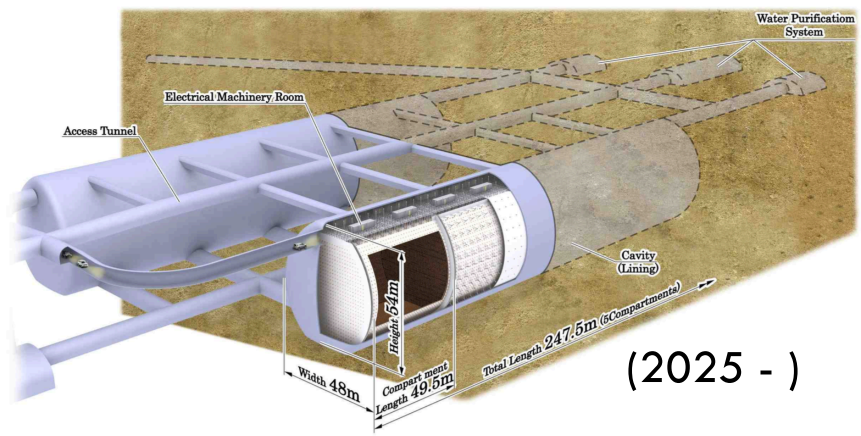


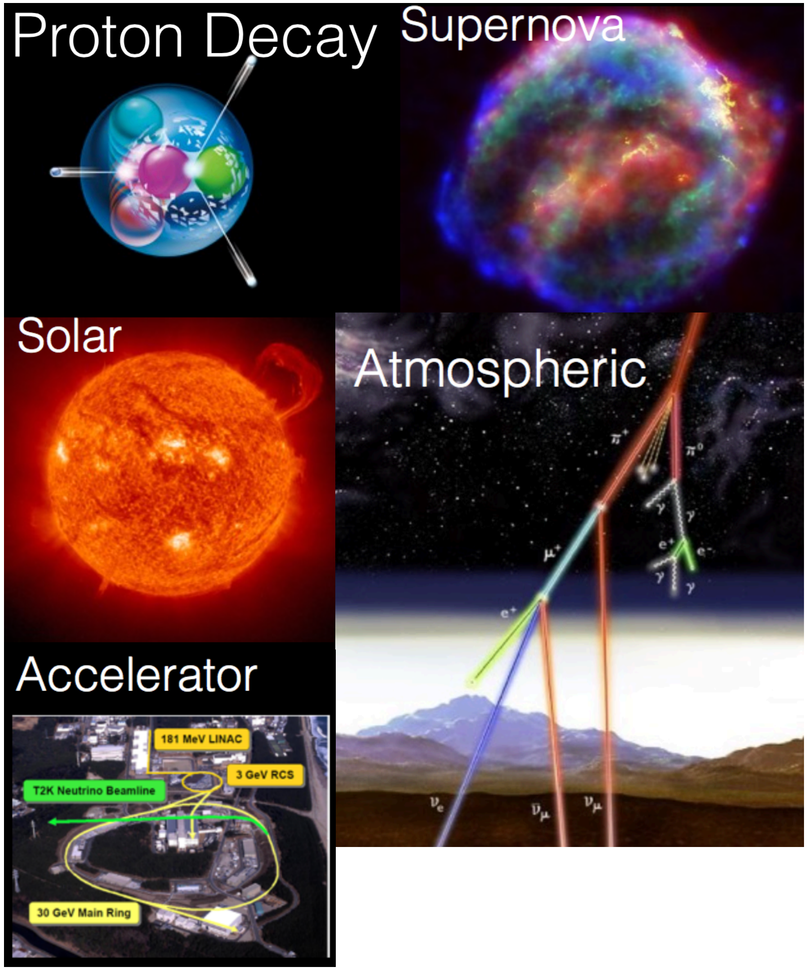
(2025 -)

50 (22.5) kton total (fiducial) volume
11k 20-inch PMTs

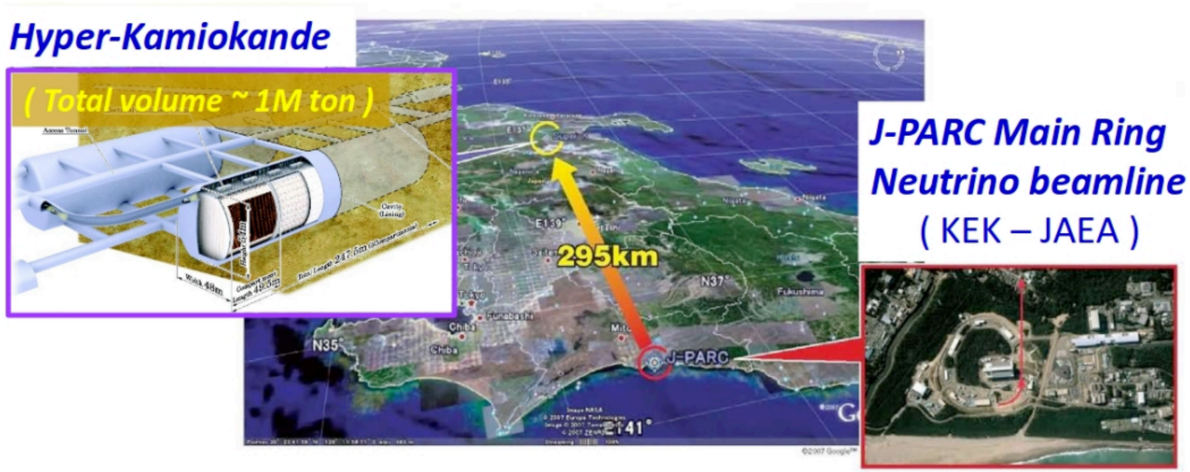
990 (560) kton total (fiducial) volume
99k 20-inch photosensors

Physics potential of Hyper-K

- Hyper-K has various physics objectives:
  - Long-baseline neutrino oscillation
    - 76% coverage of δ_{CP} at 3σ
  - Atmospheric neutrino oscillation
    - Opportunity to resolve mass hierarchy and Θ_{23} octant
  - Proton decay sensitivity extended by a factor 10
    - p ➔ $e^+ + \pi^0$: 5.7×10^{34} years (3σ)
    - p ➔ $\nu + K^+$: 1.2×10^{34} years (3σ)
  - Astrophysics observations
    - Supernova bursts, supernova relic neutrinos, indirect dark matter
- Focus of this talk is on long-baseline neutrino oscillation

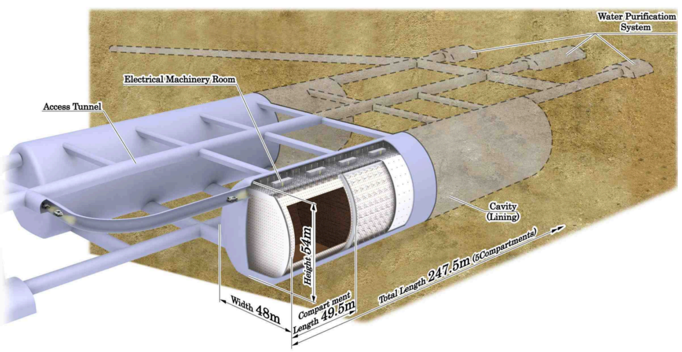


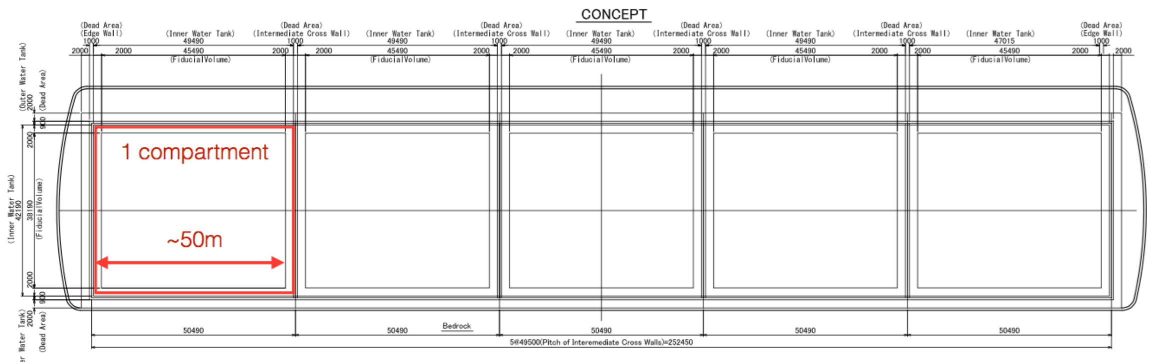
Tokai to Hyper-Kamiokande



- Hyper-K candidate site is Tochibora mine in Kamioka
  - 8km south of Super-K
- Hyper-K will operate with same beam (J-PARC) and same off-axis angle (2.5°) as Super-K
- Current J-PARC beam power is ~350 kW (May 2015) but it will be upgraded to 750 kW in a few years

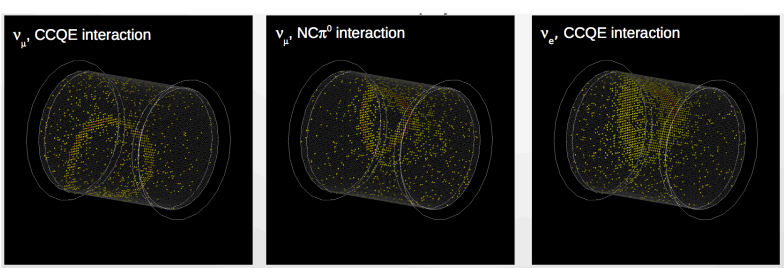
Hyper-Kamiokande detector



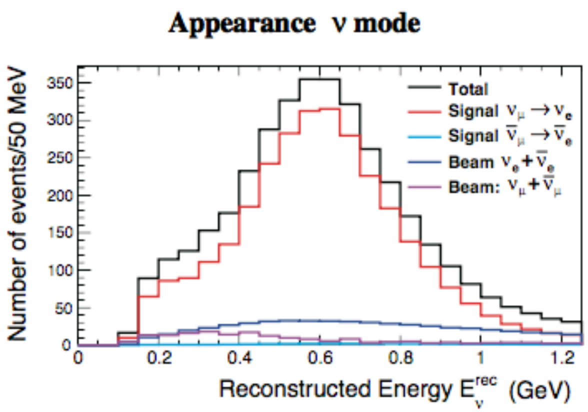


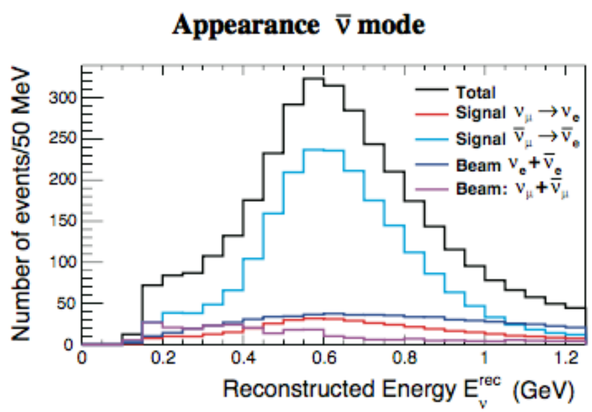
- Detector composed of 2 separated tanks
- 2x5 optically separated compartments comparable with Super-K
  - Detector performance of Hyper-K should be effectively the same as Super-K
- Uses well proven water Cherenkov detector technology
  - Many years of experience from Super-K

GEANT4 event displays



Oscillation measurements with Hyper-K





- Assumed 7.5MW x 10^7s (1.56×10^{22} PoT) exposure
- Equivalent to10 years with 750 kW beam

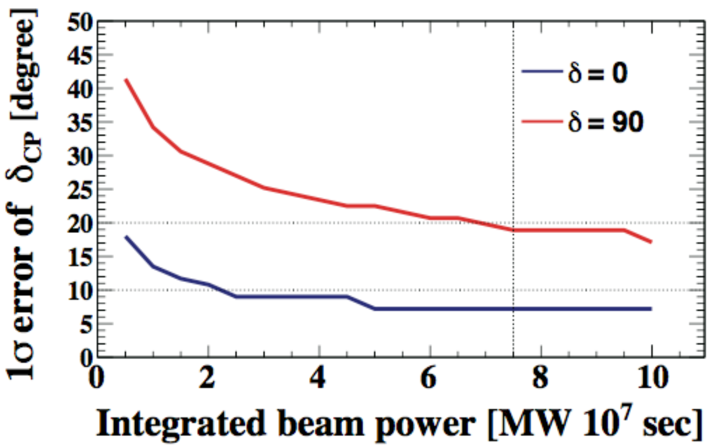
- High statistics of neutrino events thanks to:
  - large fiducial mass
  - high power J-PARC neutrino beam
- Systematics errors are already well understood based on Super-K and T2K
- Hyper-K will be one of the most sensitive experiment to probe neutrino CP violation

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode	
	νe	νμ	ν̄e	ν̄μ
Flux&ND	3.0	2.8	5.6	4.2
XSEC model	1.2	1.5	2.0	1.4
Far Det. +FSI	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

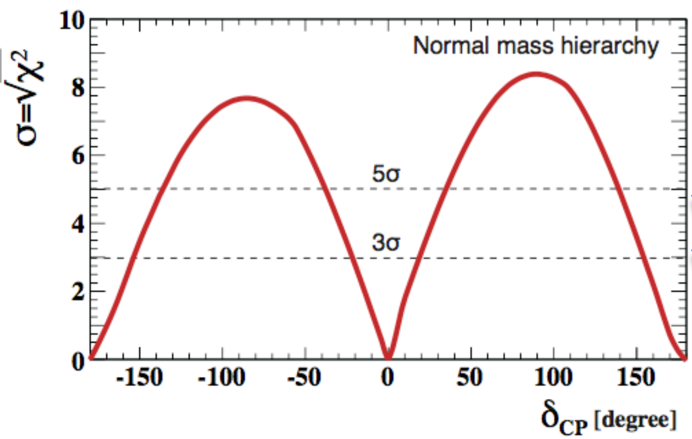
(T2K 2014)	
νe	νμ
3.1	2.7
4.7	5.0
3.7	5.0
6.8	7.6

Hyper-K sensitivity to δ_{CP}

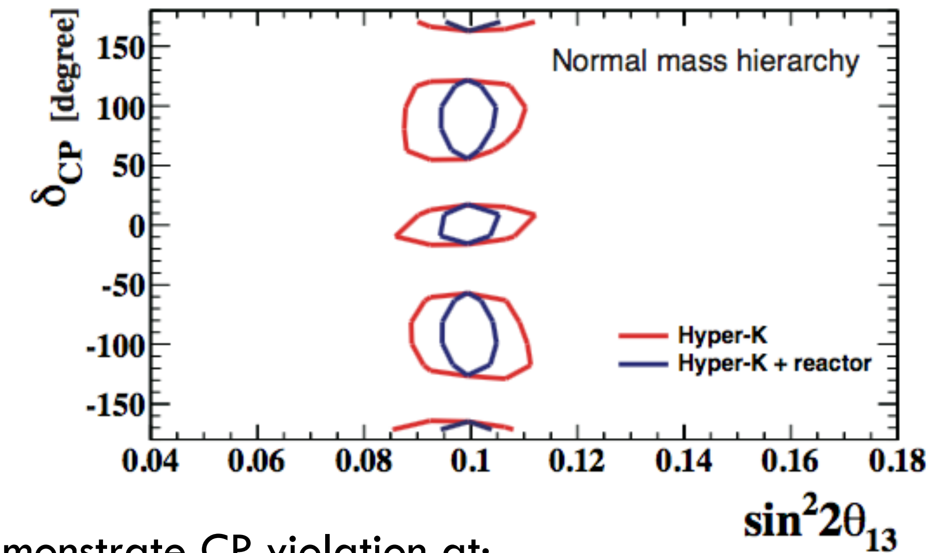


δ_{CP} resolution at 7.5MWx10^7 sec (10 year exposure):
6° (19°) for δ=0° (90°)

sin$\delta \neq 0$ exclusion



90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)

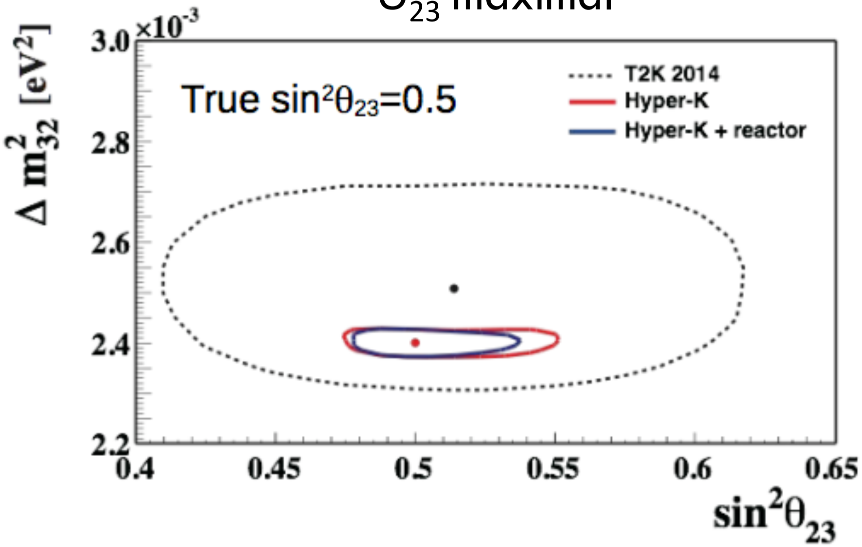


Can demonstrate CP violation at:
- 5σ for 58% of δ_{CP} values
- 3σ for 76% of δ_{CP} values

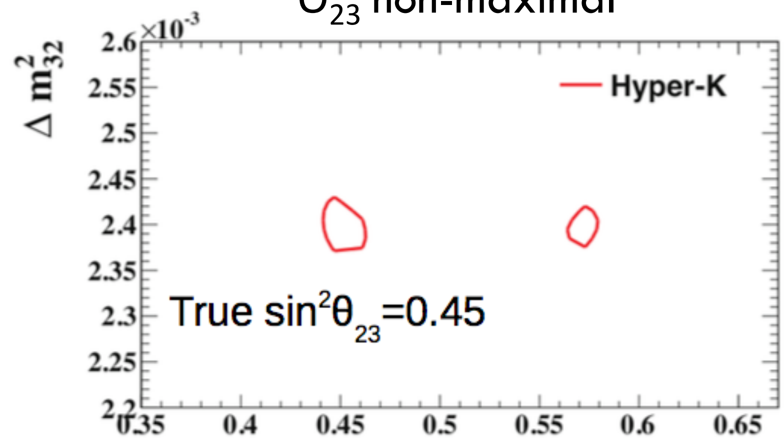
Sensitivity to Θ_{23}

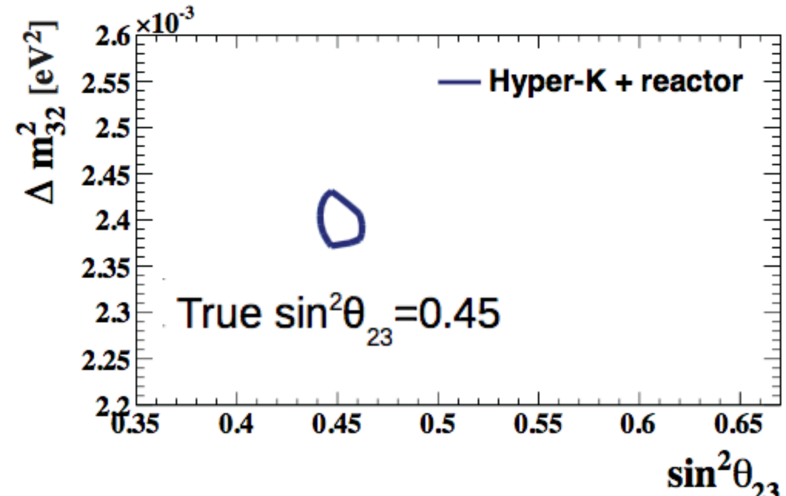
- Huge improvements in Θ_{23} measurements with nominal 10 year exposure
- For non-maximal Θ_{23}, reactor constraint breaks octant degeneracy

Θ_{23} maximal



Θ_{23} non-maximal





Conclusions

- T2K results in neutrino mode has been presented
  - 7.3 σ discovery of ν_e appearance
  - most precise measurement of Θ_{23} through ν_μ disappearance
  - Hints of δ_{CP} =-π/2 through the joint ν_{e}/ν_μ analysis with reactor constraint

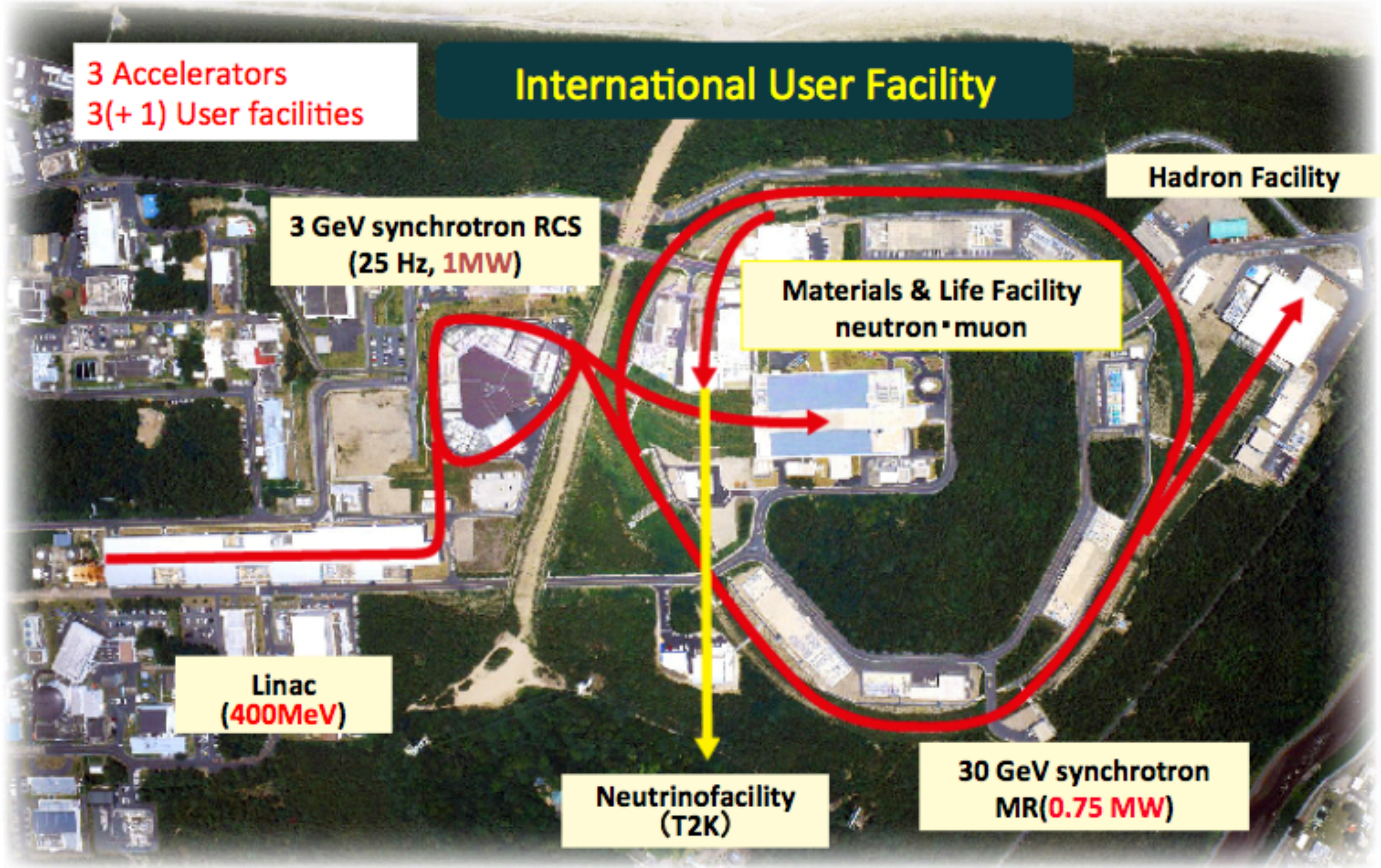
- Also, T2K's first analysis of $\bar{\nu}_\mu$ disappearance
  - Limited by statistics
  - T2K already has more anti-neutrino data that will be released during the summer – stay tuned

- Hyper-Kamiokande is the proposed successor of Super-Kamiokande

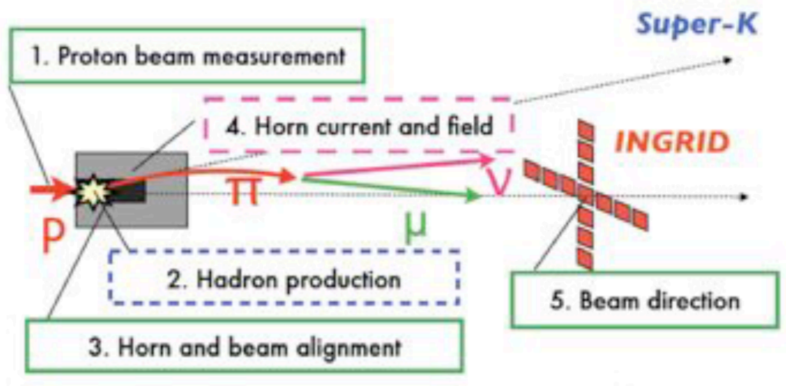
- Together with the expected upgrade of the J-PARC neutrino beam can make world-leading measurements of CP violation and other neutrino oscillation parameters

Backups

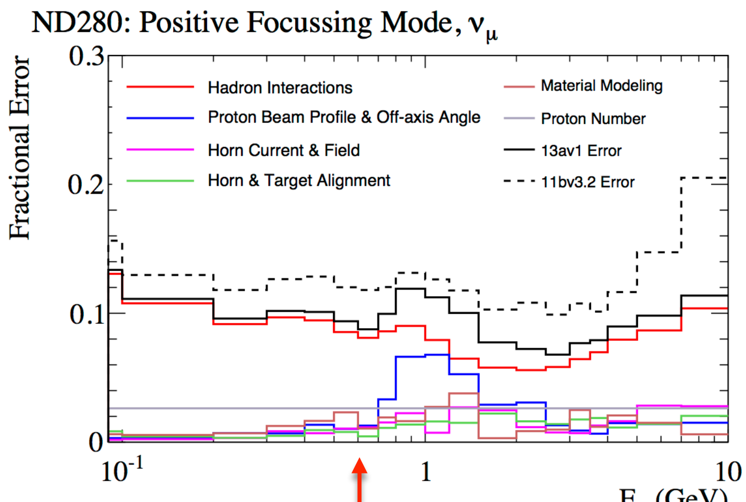
Japan Proton Accelerator Research Complex

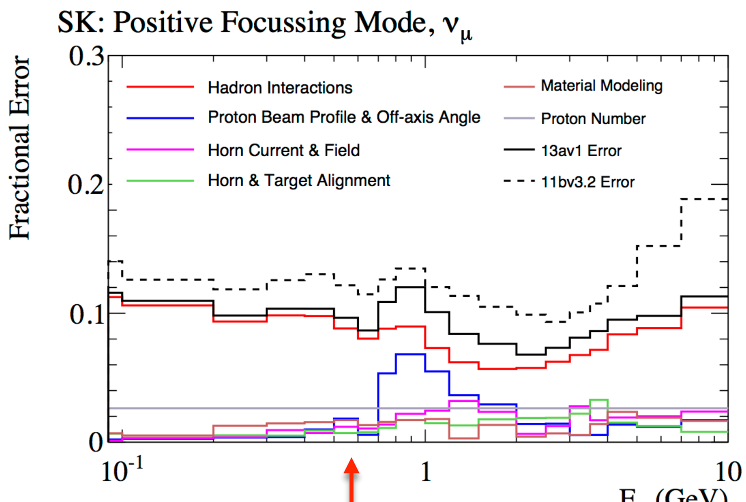


Flux model uncertainties



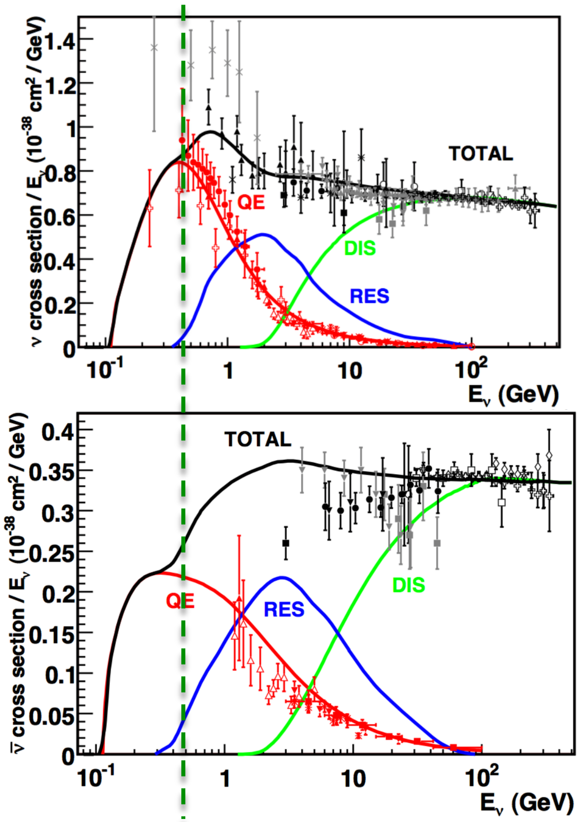
- Total uncertainty on T2K flux is ~10%
  - Main component comes from hadron interactions model
- SK and ND280 fluxes are highly correlated
  - ND280 analysis can reduce systematic errors in SK



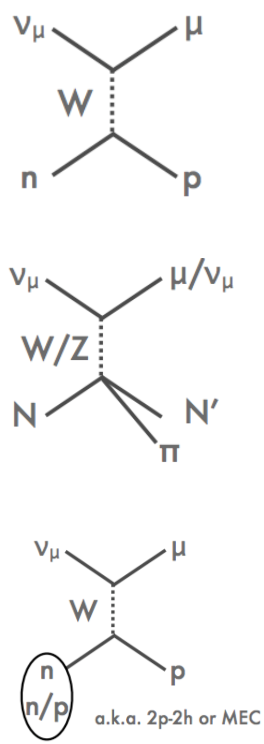


Interaction models

T2K uses NEUT to generate neutrino interactions in ND280 and SK



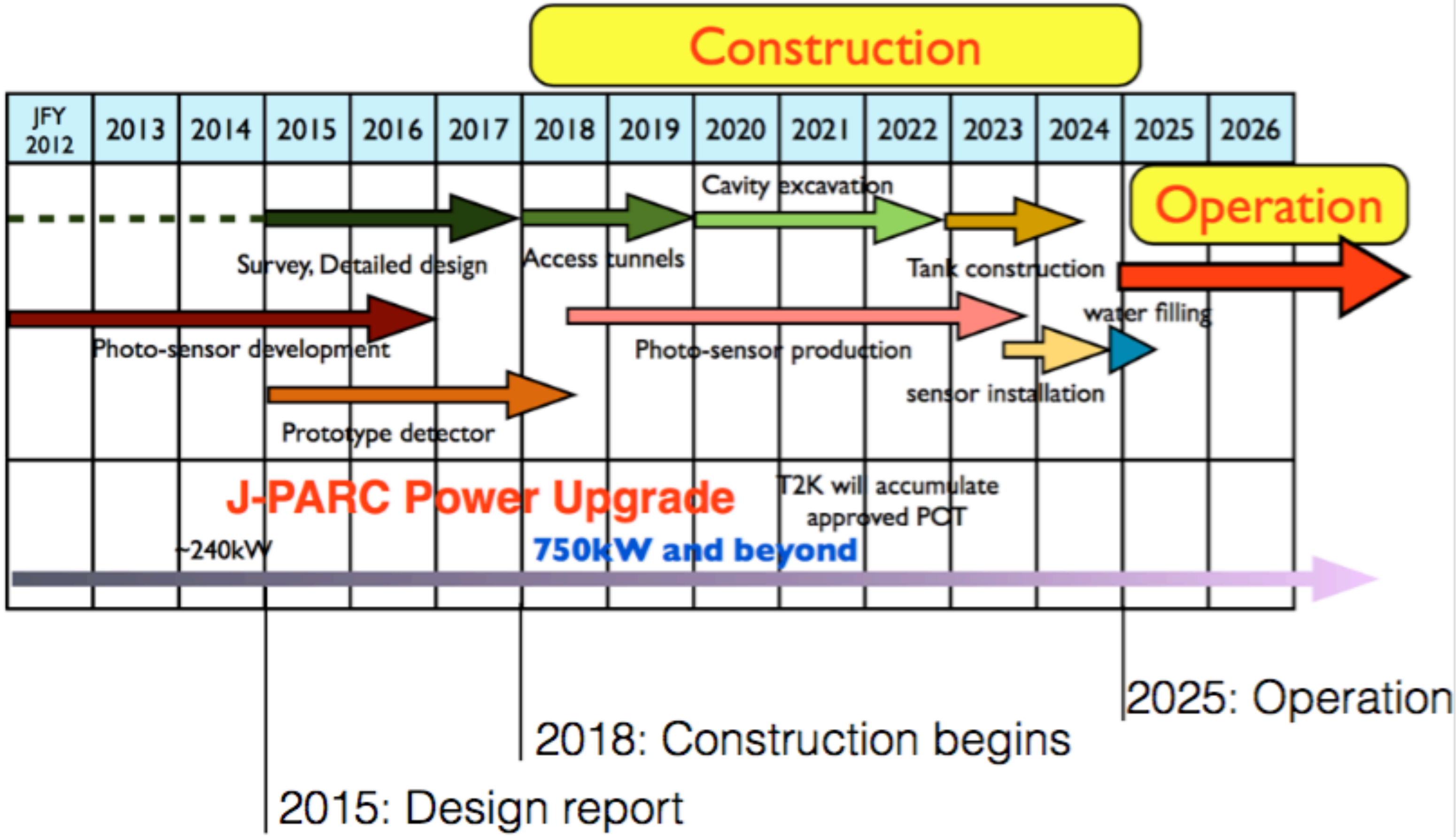
T2K peak energy
~0.6 GeV



- CC-QE
  - $\nu_\mu^- + n \rightarrow \mu^- + p$
  - Dominant at T2K energies
  - Neutrino energy reconstruction from muon kinematics only
- CC-RES
  - $\nu_\mu^- + p \rightarrow \mu^- + p + \pi^+$
  - Pion could be missing due to intra-nuclear interactions and misidentified as CC-QE
- Multi-nucleon (2p-2h) interactions
  - $\nu_\mu^- + [np] \rightarrow \mu^- + p + p$
  - CCQE-like but different kinematics

Models are tuned to external data (MiniBoone and MINERvA)

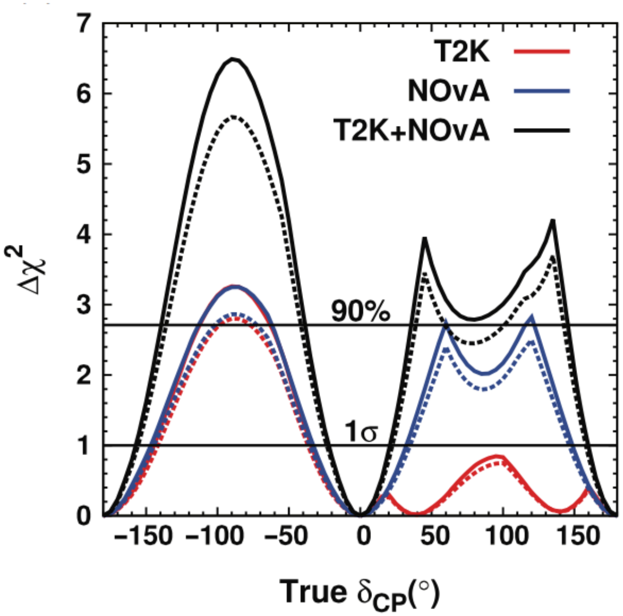
Hyper-K timeline



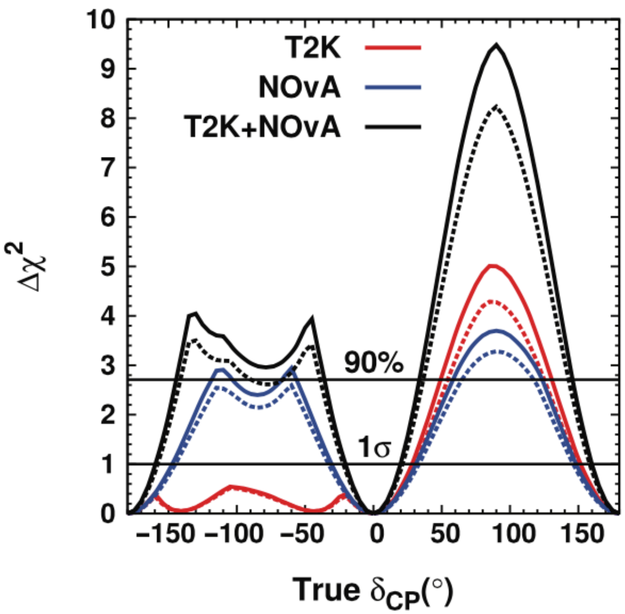
T2K + Nova

- Ability to measure delta CP is greatly enhanced by incorporating data from Nova
  - Mainly because Nova's greater sensitivity to the mass hierarchy through matter effects

Normal hierarchy

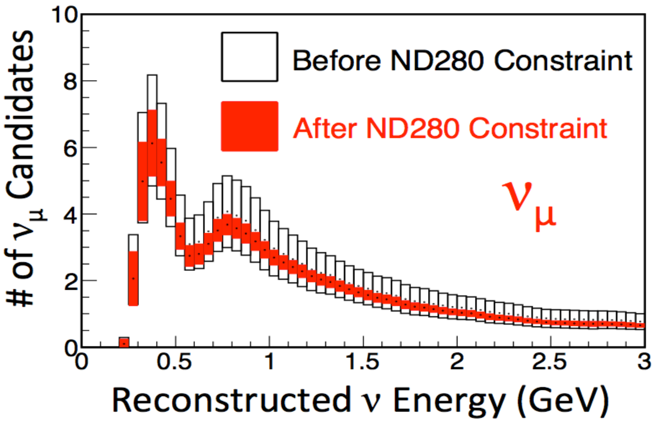


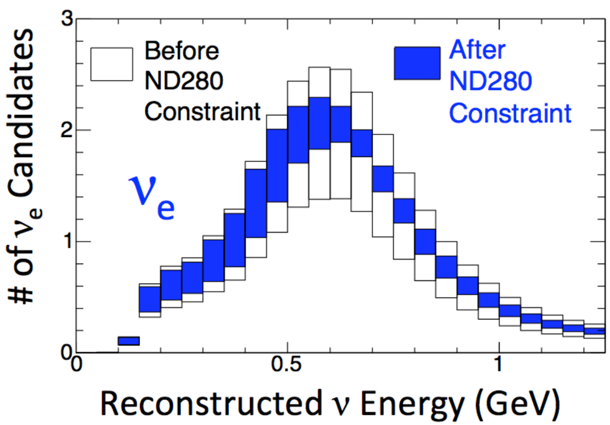
Inverted hierarchy



SK prediction systematics (ν-mode)

		ν_μ events	ν_e events
Neutrino flux and cross section	without ND280 comparison	21.8%	26.0%
	with ND280 comparison	2.7%	3.1%
Difference of target material between near and far		5.0%	4.7%
Final or Secondary Hadronic Interaction		3.0%	2.4%
Super-Kamiokande detector		4.0%	2.7%
total	without ND280 extrapolation	23.5%	26.8%
	with ND280 extrapolation	7.7%	6.8%





ν_e appearance formula

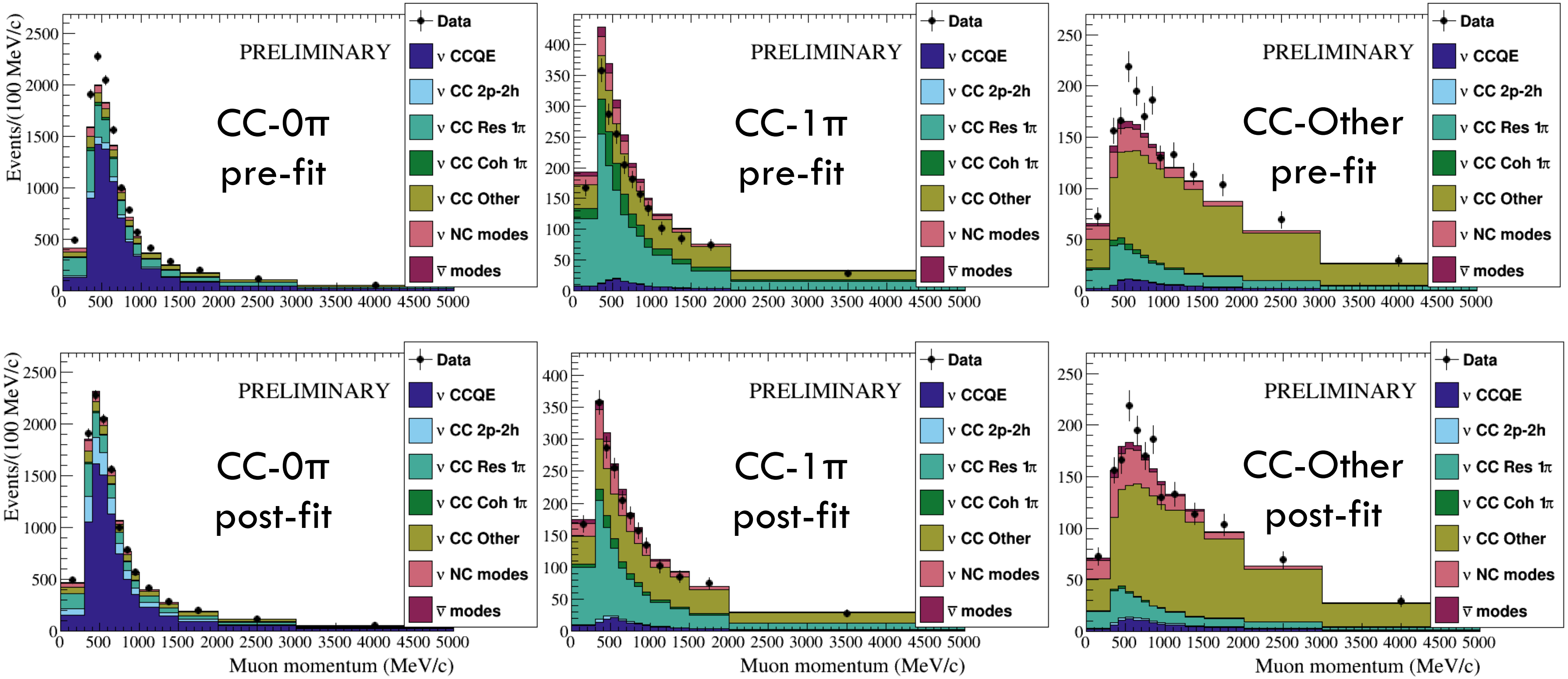
$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right)$$
$$+ 8C_{13}^2 S_{12} S_{13} S_{23} \left(C_{12} C_{23} \cos \delta_{\mathrm{CP}} - S_{12} S_{13} S_{23}\right) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21}$$
$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta_{\mathrm{CP}} \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21}$$
$$+ 4S_{12}^2 C_{13}^2 \left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta_{\mathrm{CP}}\right) \sin^2 \Phi_{21}$$
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 \left(1 - 2S_{13}^2\right) \frac{aL}{4E_\nu} \cos \Phi_{32} \sin \Phi_{31},$$

where $\Phi_{ji} = \Delta m_{ji}^2 L / 4E_\nu$. The terms that include

$$a \equiv 2\sqrt{2} G_{\mathrm{F}} n_e E_\nu = 7.56 \times 10^{-5}\,[\mathrm{eV}^2] \left(\frac{\rho}{[\mathrm{g\,cm^{-3}}]}\right) \left(\frac{E_\nu}{[\mathrm{GeV}]}\right)$$

Near detector fit (ν-mode beam)

- Select ν_μ candidates and classify them based on π content
  - Each sample is sensitive to different ν energy ranges and interactions
- Fit the reconstructed (p_μ, $\cos\Theta_\mu$) distributions
  - Flux and cross section model parameters are adjusted and uncertainties reduced



Near detector fit ($\bar{\nu}$-mode beam)

- Select $\bar{\nu}_\mu$ and ν_μ candidates and classify them based on number of tracks
  - Large ν_μ contamination
  - Statistics is lower than ν-mode beam
- Fit the reconstructed (p_μ, $\cos\Theta_\mu$) distribution
  - Flux and cross section model parameters are adjusted and uncertainties reduced