Recent Results from T2K

DBD16 – Osaka
9th Nov

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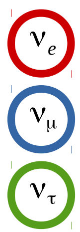
LLR – Ecole Polytechnique

On behalf of the T2K collaboration

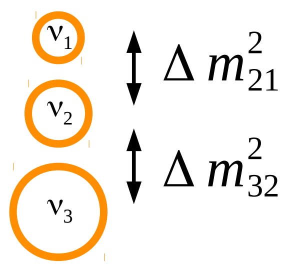
Three neutrino mixing

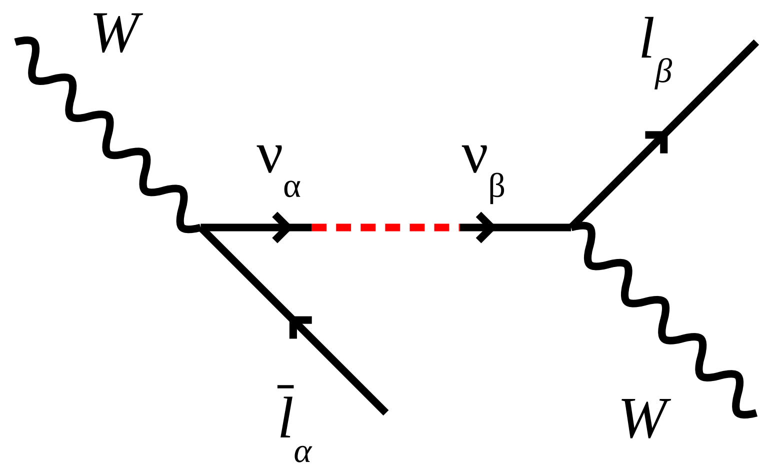
- PMNS framework

Interact as weak process eigenstates
Propagate as mass eigenstates



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





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

Current knowledge:

$\theta_{12} \approx 33°$
$\theta_{23} \approx 45°$
$\theta_{13} \approx 9°$

$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2$
$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}\ eV^2$

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

$\Delta m^2_{ij} = m^2_i - m^2_j$

Oscillations

Appearance

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

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

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

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

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

ν vs. $\bar{\nu}$ sign change

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

θ_{13} dependence — Octant Sensitivity — CP odd phase

Disappearance

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

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

Questions

- θ_{23} Octant? (θ_{23} <, > or = 45°)
  - Sensitivity to $\sin^2\theta_{23}$ (same for ν and $\bar{\nu}$)

- CP violation?

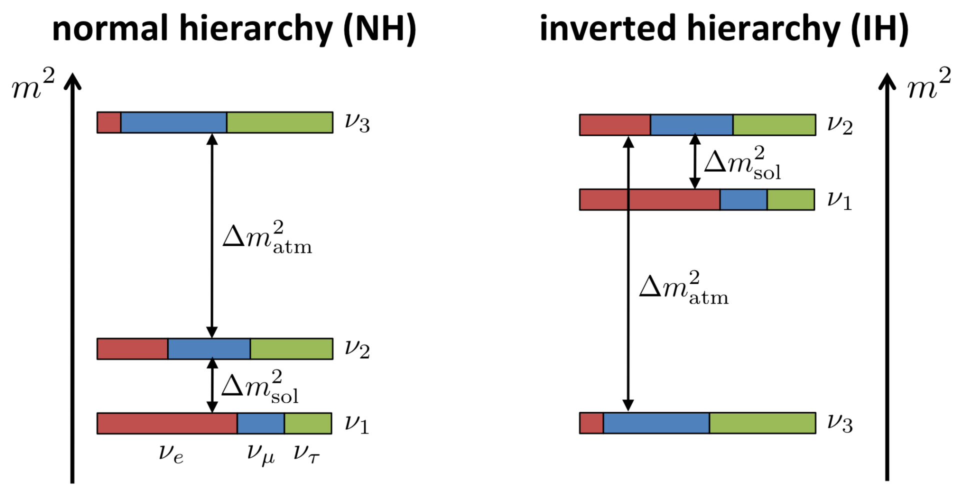
±30% effect at T2K

  - $\delta_{CP}=0,\pi$ → no CP violation
  - $\delta_{CP}=-\pi/2$ → enhance ($\nu_\mu \to \nu_e$), suppress ($\bar{\nu}_\mu \to \bar{\nu}_e$)
  - $\delta_{CP}=\pi/2$ → ($\bar{\nu}_\mu \to \bar{\nu}_e$) enhance , suppress ($\nu_\mu \to \nu_e$)

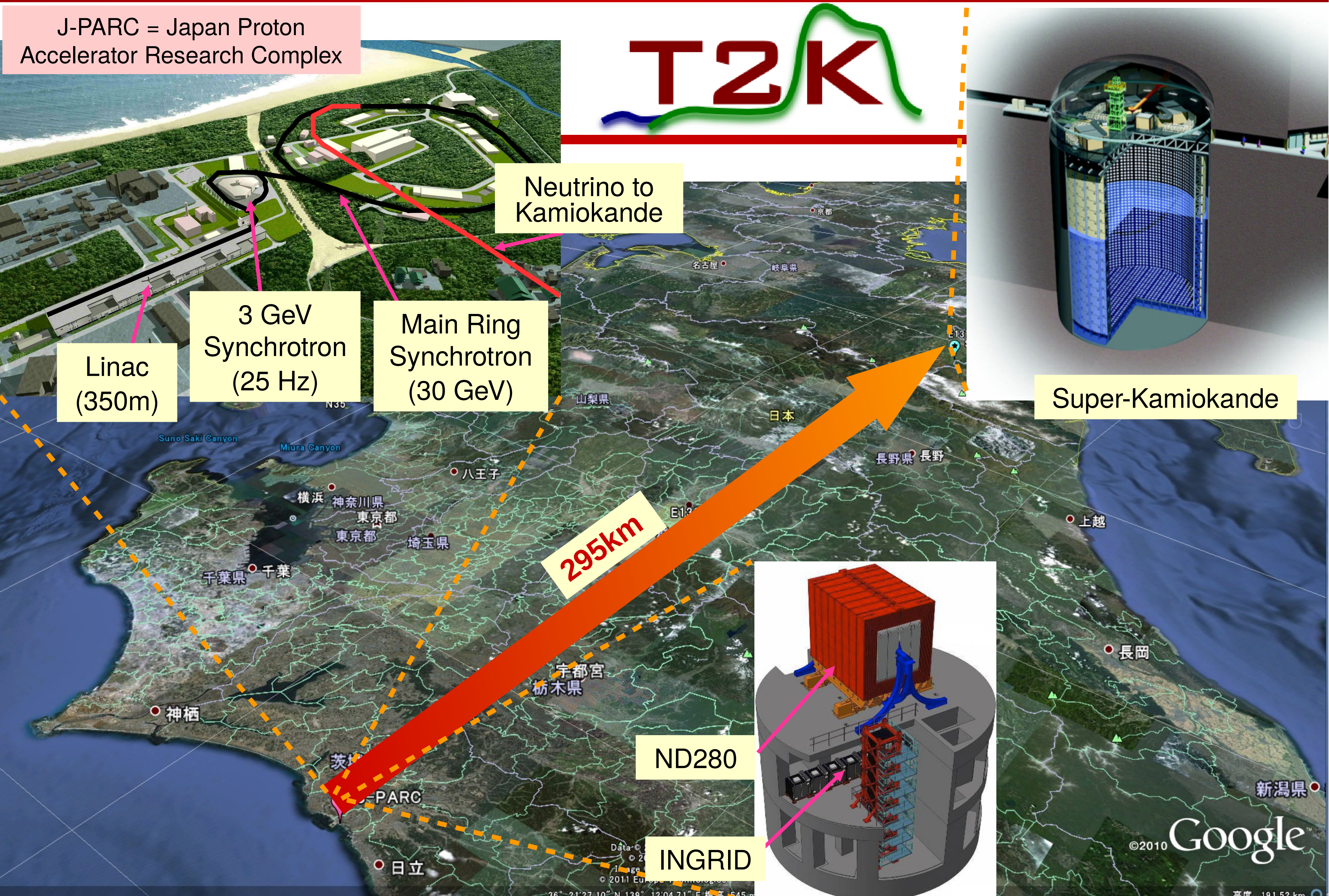
- Mass hierarchy?

±10% effect at T2K

  - enhance ($\nu_\mu \to \nu_e$)
  - suppress ($\bar{\nu}_\mu \to \bar{\nu}_e$)



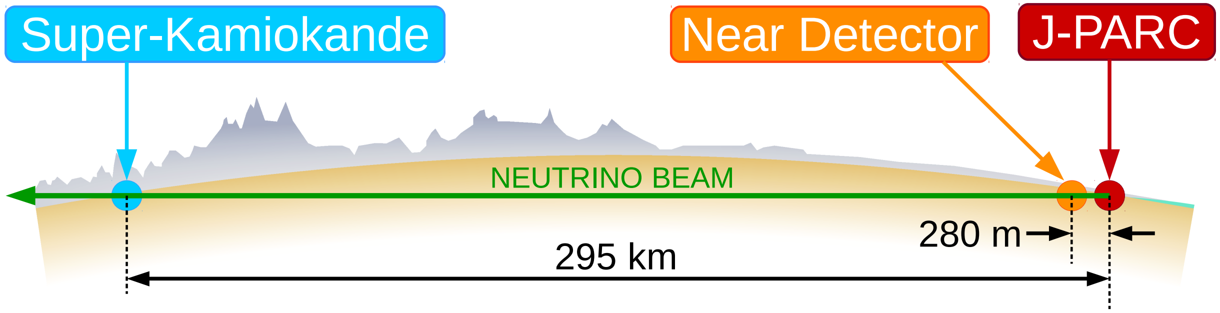
  - enhance ($\bar{\nu}_\mu \to \bar{\nu}_e$)
  - suppress ($\nu_\mu \to \nu_e$)



K. Abe et al., The T2K Experiment. NIM A 694(0):211 – 223, 2012

T2K Experiment

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



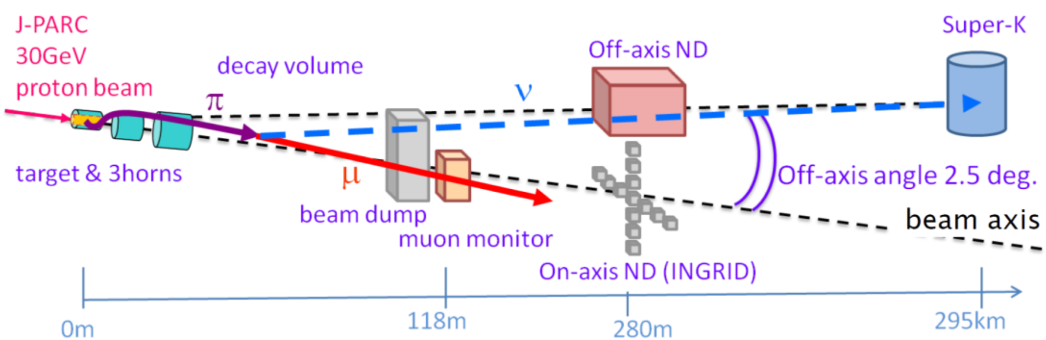
$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Observable　　Flux　　Cross section　　Detector response

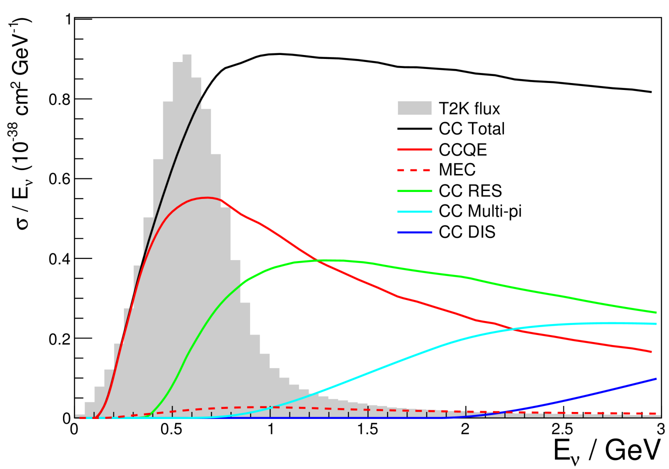
$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc.}$$

Off-axis Beam

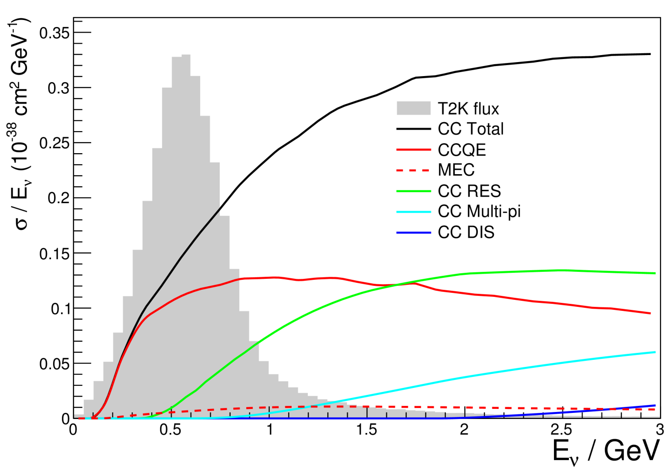
- High purity ν_μ beam
- Enhanced oscillation – Lower energy beam tuned to maximise oscillations at baseline
- Enhanced CCQE fraction – Energy reconstruction at Super-Kamiokande
- Reduced intrinsic ν_e contamination
- Reduced Neutral Current event feed down

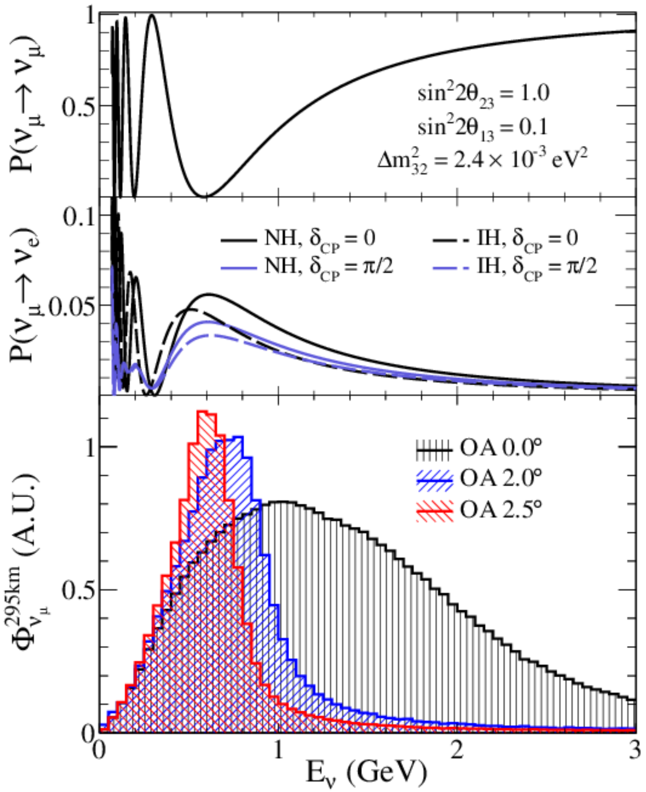


Neutrino Cross section



Antineutrino Cross section

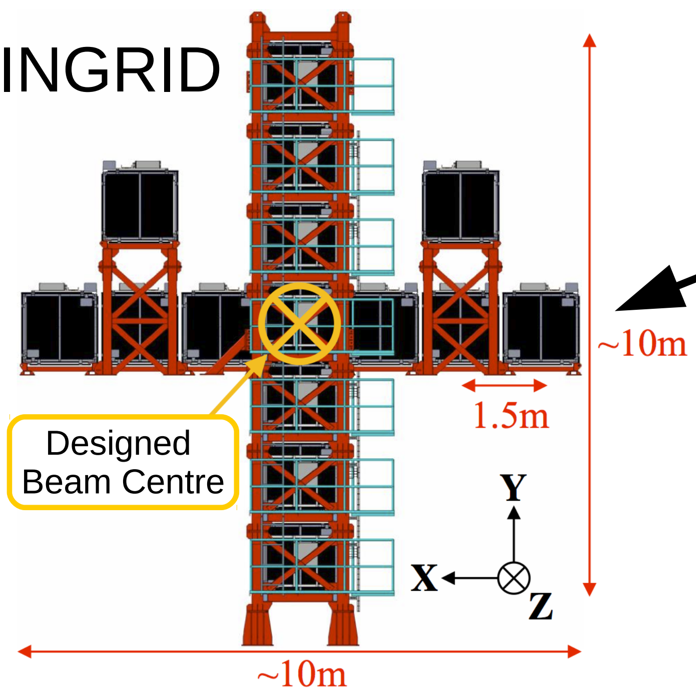


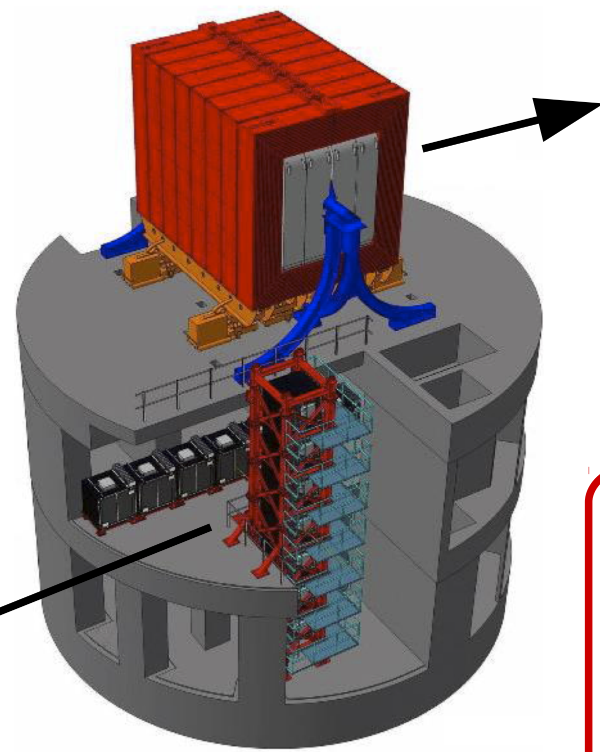


Near Detectors

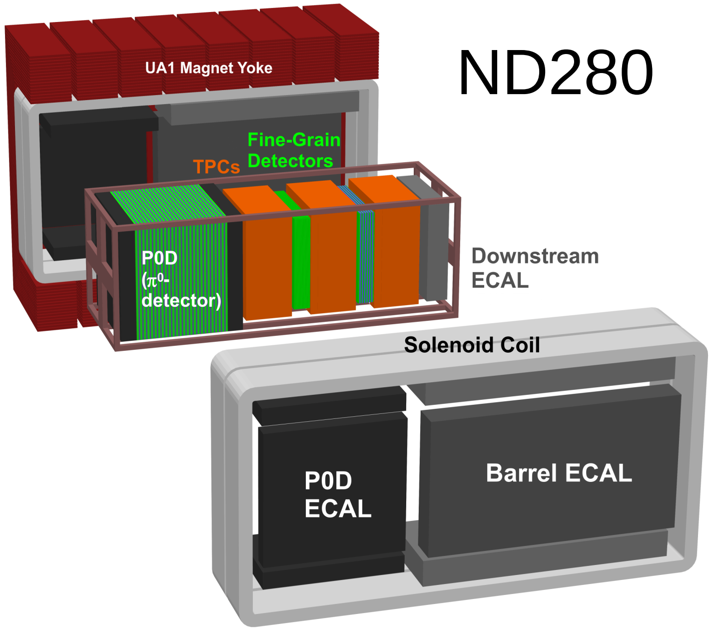
- 7+7 (+2) identical modules
- Iron and scintillator tracking calorimeter
- Beam direction and stability monitoring

INGRID





ND280

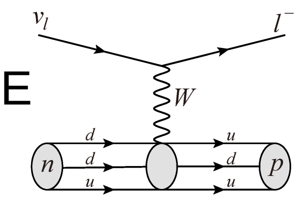


- Off-axis detector
- Magnet 0.2 T
- Trackers, Calorimeters and muon range detectors
- Active (scintillator) and passive (water) targets

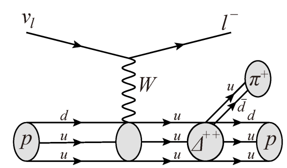
Super-Kamiokande Detector

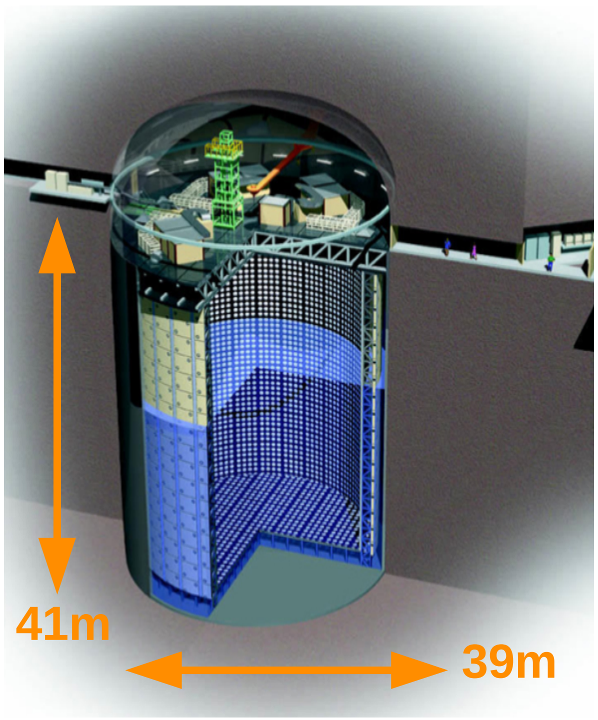
- 50kton Water Cherenkov detector
- Optically separate inner and outer (veto) volumes
- Excellent e/μ separation, π^0 rejection
- Select single ring, CCQE enriched samples
- E_ν(CCQE) determined from lepton kinematics

CCQE



CC1π





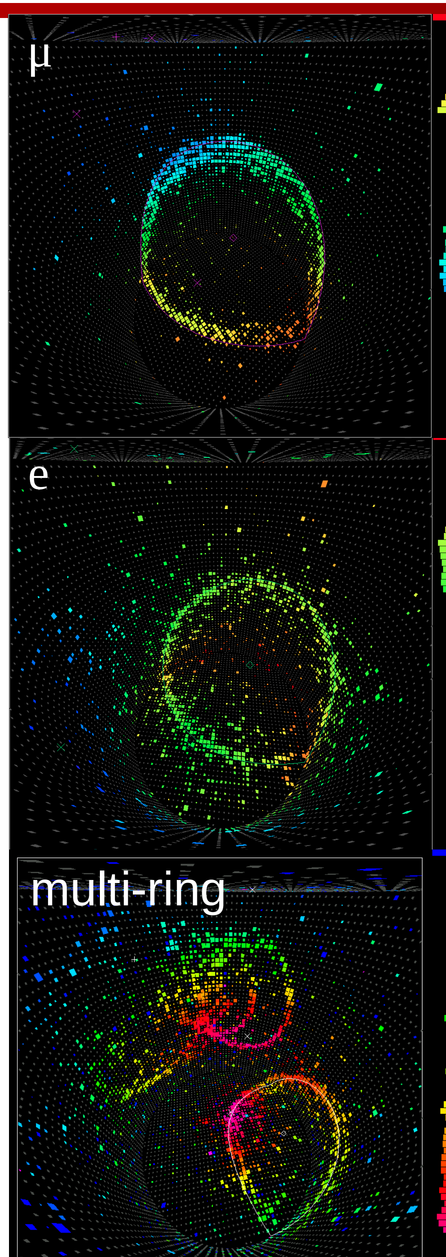
- Signal

$$\nu_\alpha + n \rightarrow l_\alpha^- + p \qquad \bar{\nu}_\alpha + p \rightarrow l_\alpha^+ + n$$

- Background

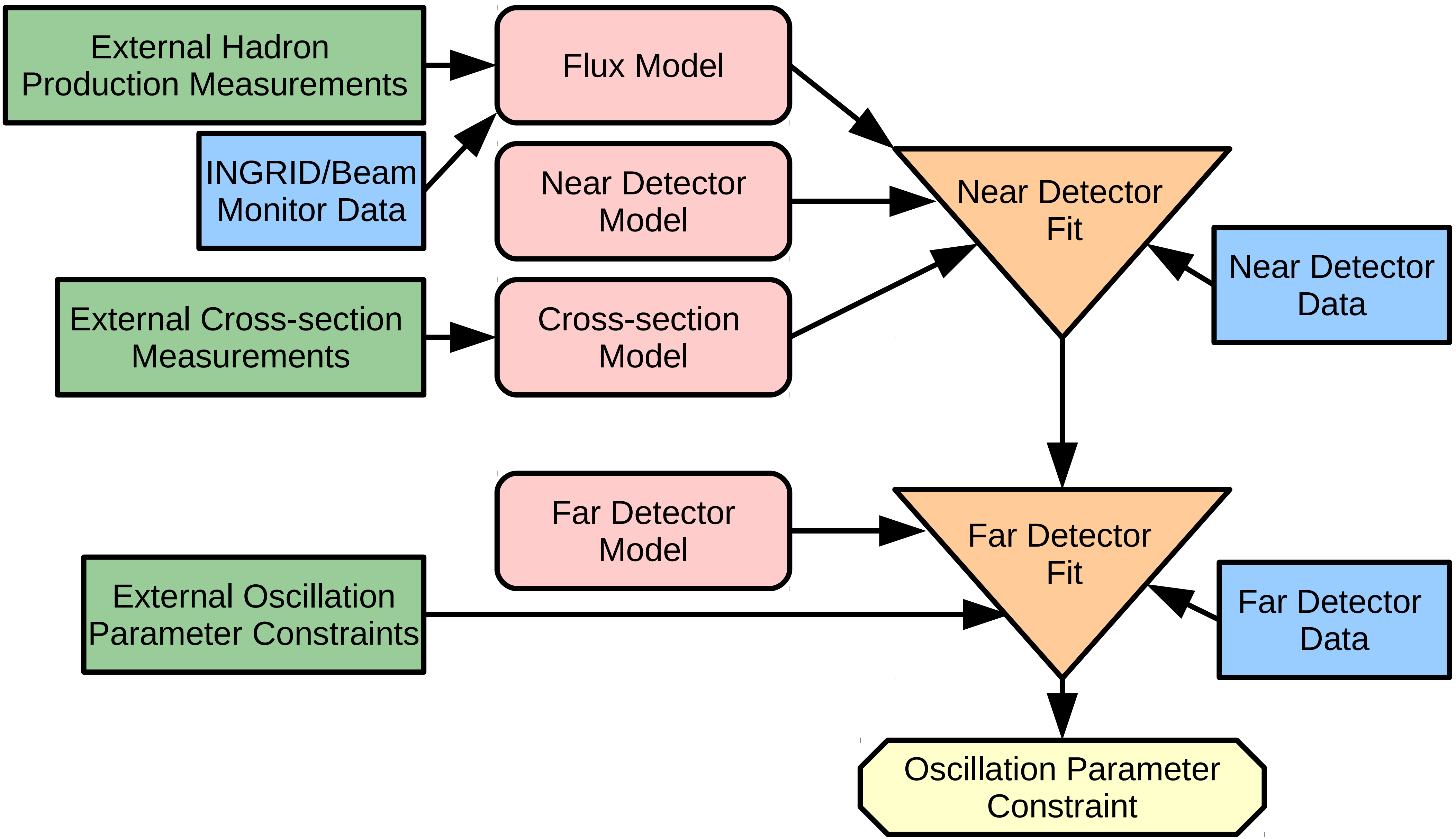
$$\nu_\alpha + n(p) \rightarrow l_\alpha^- + n(p) + \pi^+$$

$$\nu_\alpha + n(p) \rightarrow \nu_\alpha + n(p) + \pi^0$$



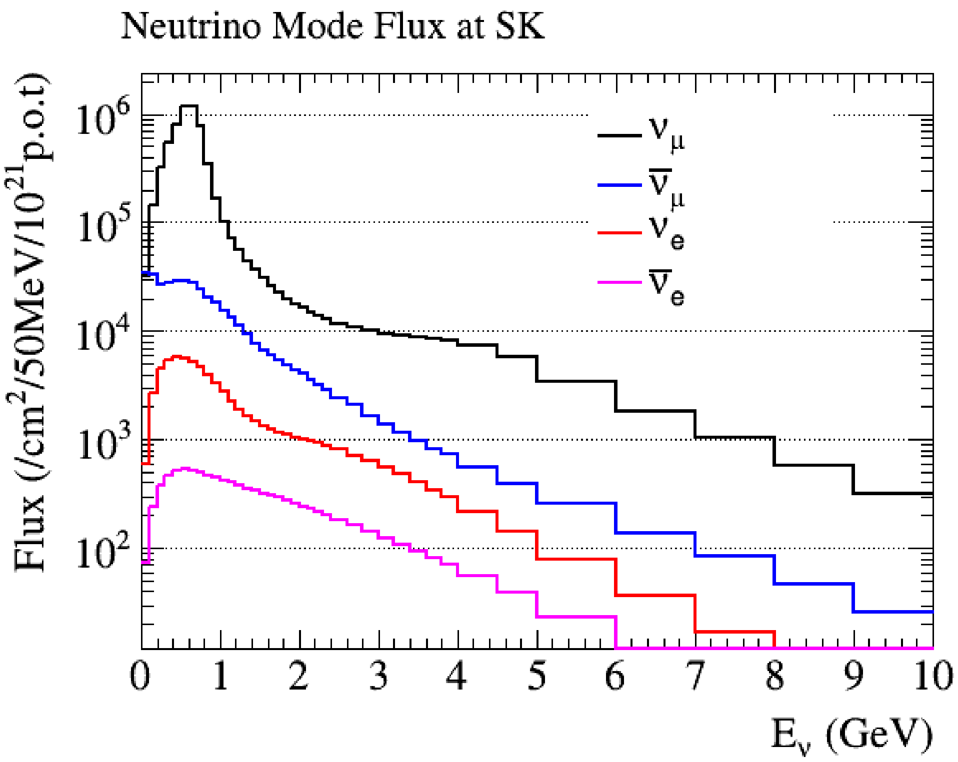
http://www.ps.uci.edu/~tomba/sk/tscan/compare_mu_e/

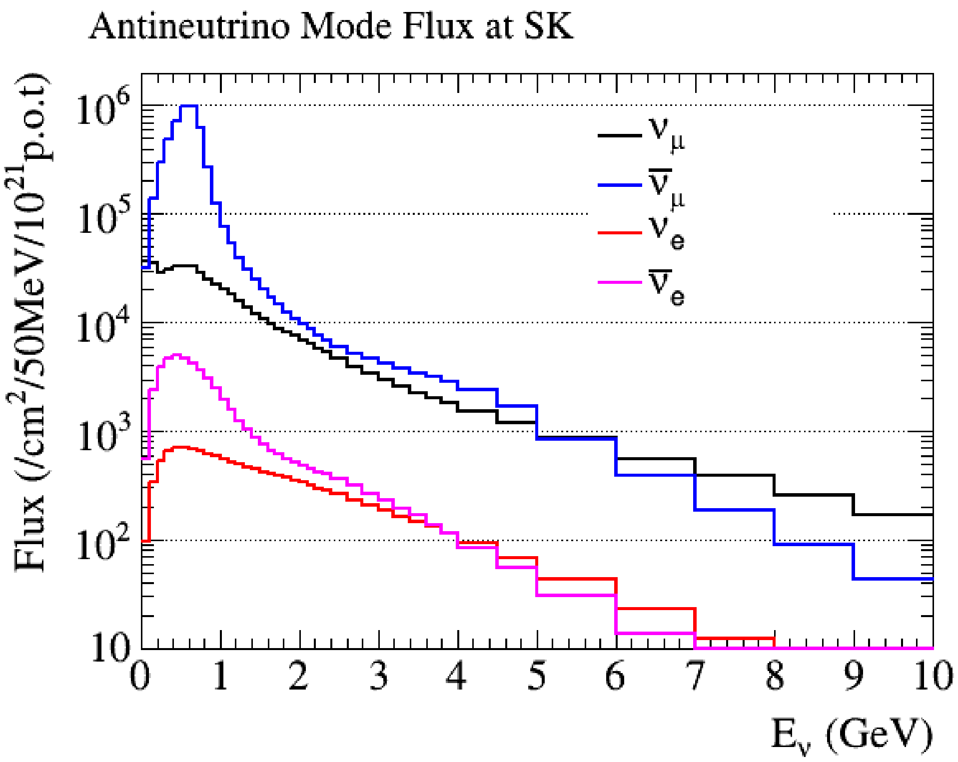
T2K Oscillation Analysis Overview



Flux Prediction

- Flux simulation (FLUKA/GEANT3/GCALOR)
- Tuned using external data →NA61/SHINE experiment measures hadron production from thin carbon target and T2K replica target
- Large neutrino component in antineutrino flux
- Intrinsic ν_e component ~0.5% at flux peak

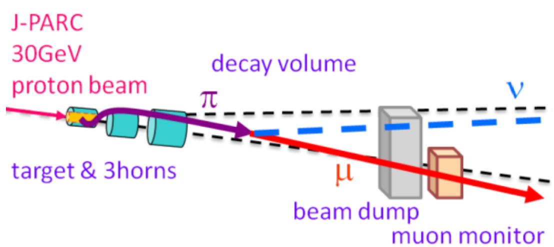




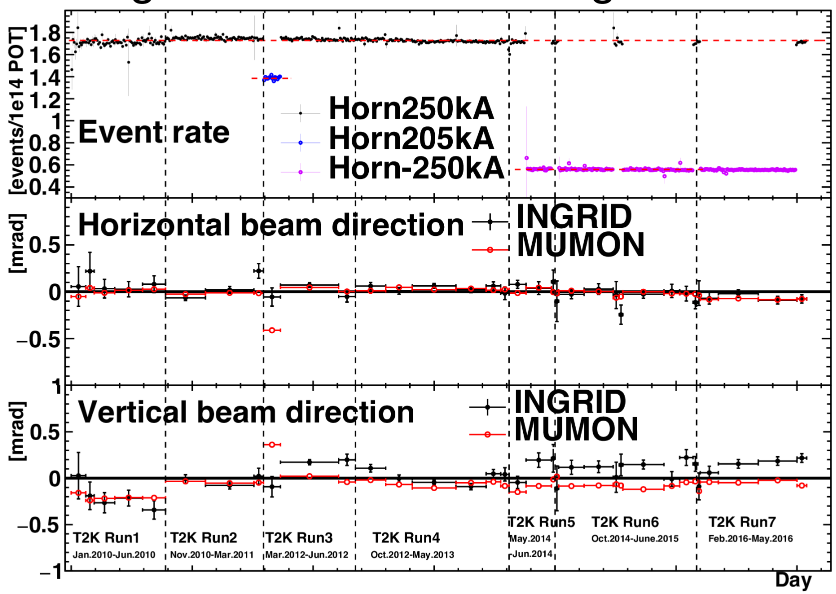
Flux Uncertainties

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

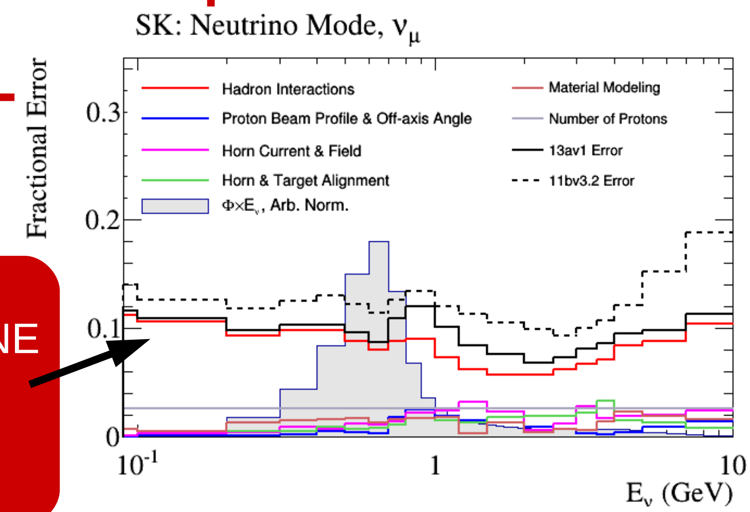
Frac. error on N_{SK} ≈ 7.7-8.8% (pre-fit)

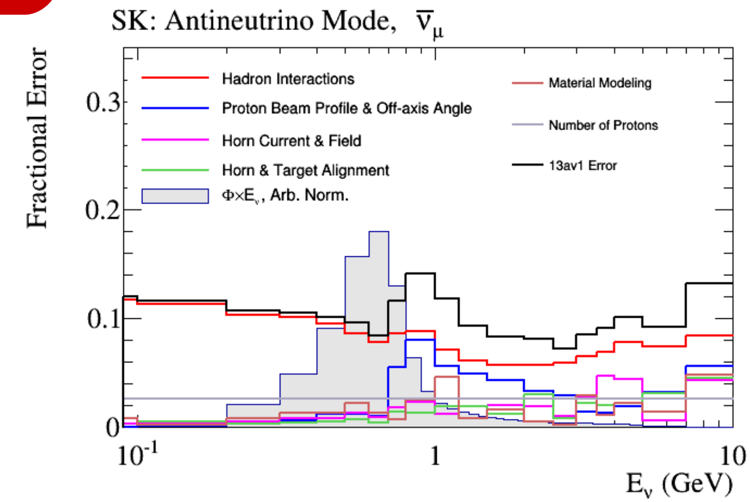


High statistics monitoring of beam



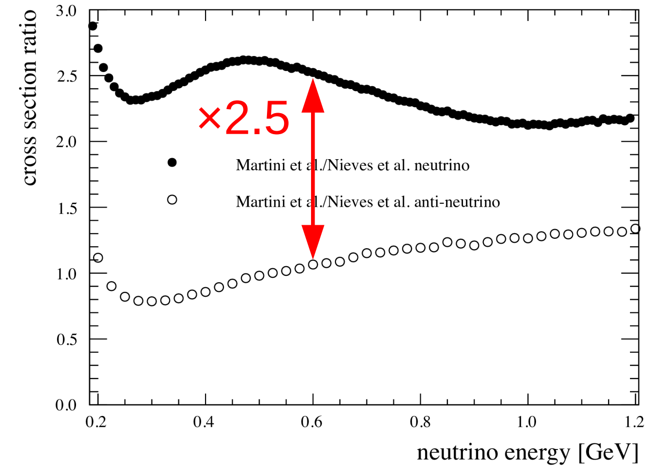
New NA61/SHINE data has reduced uncertainty





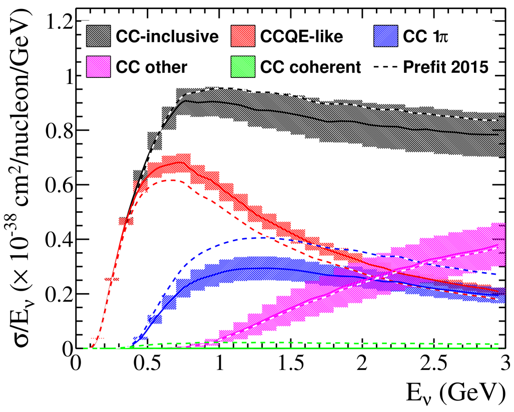
Cross-section Model

- NEUT* generator tuned to external data from MiniBooNE, MINERνA and Bubble Chambers
- CCQE: Relativistic Fermi Gas (RFG) + rel. Random Phase Approximation (RPA)
- Multinucleon interactions implemented
  - ~10% relative to CCQE
  - 2p2h model by Nieves et al.†
- Additional freedom for antineutrinos
  - 2p-2h normalisation (see right)
  - $\bar{\nu}_e/\bar{\nu}_\mu$ cross-section ratio ($\nu_e/\bar{\nu}_e$ cross sections not yet explicitly constrained by the near detector fit)
- Fractional error on N_{SK} ≈ 7.1-7.7% (pre-fit)

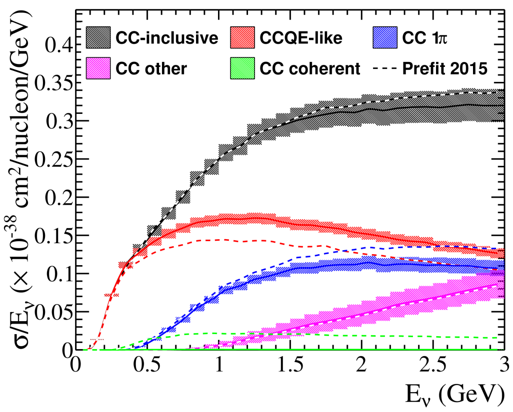


Large difference in ratio of 2p-2h cross-section models between neutrinos and antineutrinos

neutrino



antineutrino

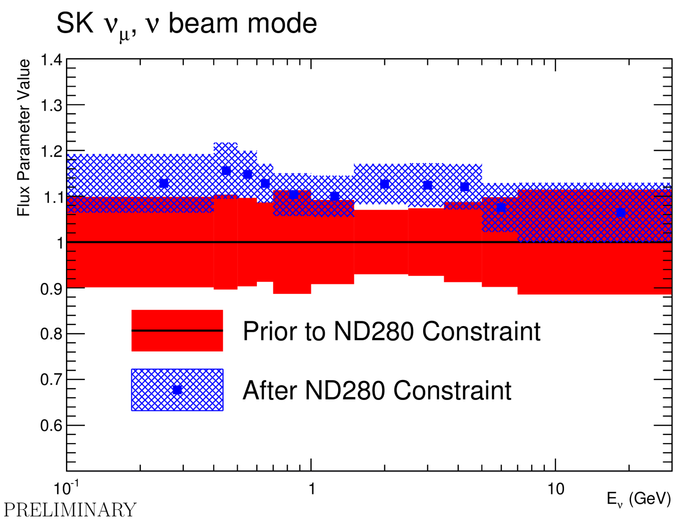


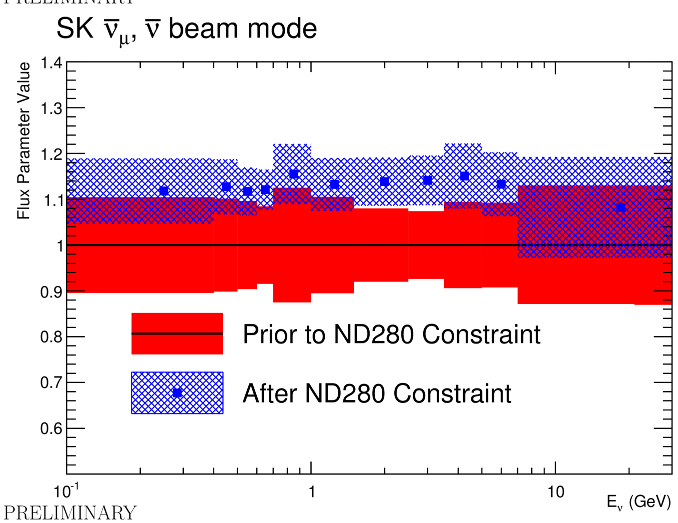
*Y. Hayato, A neutrino interaction simulation program library NEUT, Acta Phys. Pol. B 40, 2477 (2009)

†J. Nieves, I. R. Simo, and M. J. V. Vacas, The nucleon axial mass and the miniboone quasielastic neutrino-nucleus scattering problem, Phys. Lett. B 707, 72 (2012).

Near Detector Fit

Flux Parameter Fit



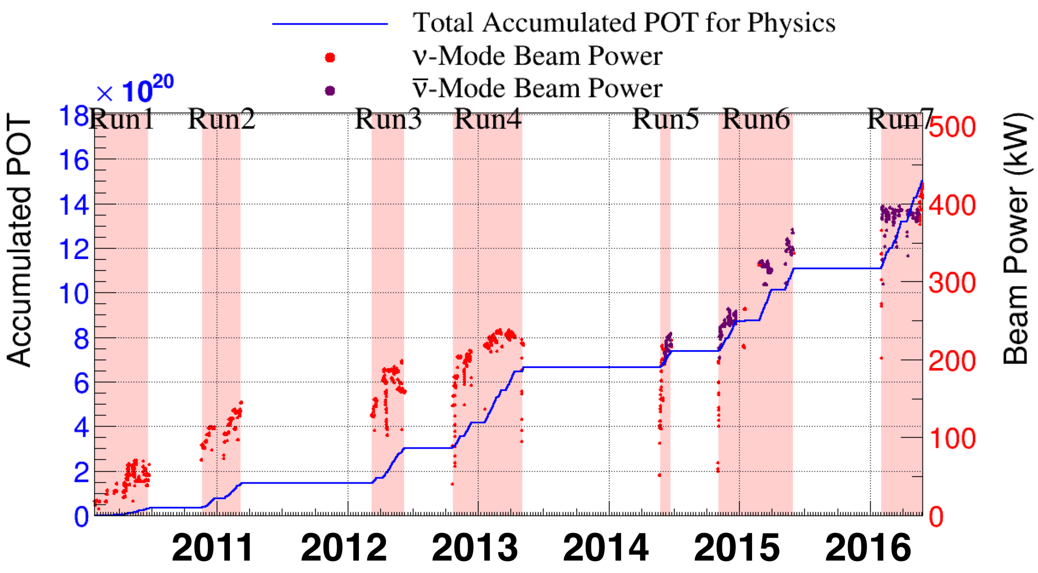


- Each model parameter in the analysis has associated systematic uncertainty
- Near detector fit constrains flux and cross-section uncertainty propagated to far detector as covariance
- Separate "on-water" constraint from ND280 for the first time
- ND280 "wrong sign" constraint in $\bar{\nu}$-mode

Total N_{SK} Fractional Uncertainty			
Beam mode	**Sample type**	**w/o ND280**	**w/ ND280**
neutrino	**μ-like**	**12.0%**	**5.03%**
neutrino	**e-like**	**11.9%**	**5.41%**
anti-neutrino	**μ-like**	**12.5%**	**5.22%**
anti-neutrino	**e-like**	**13.7%**	**6.19%**

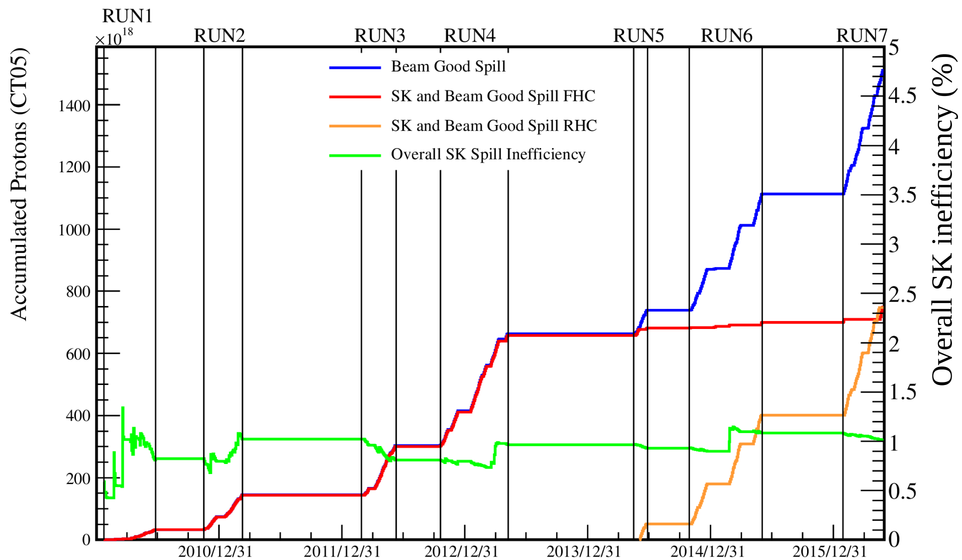
Accumulation of Data

- Antineutrino exposure doubled in Run7



27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)



- Beam power reached 420 kW

POT = Protons On Target

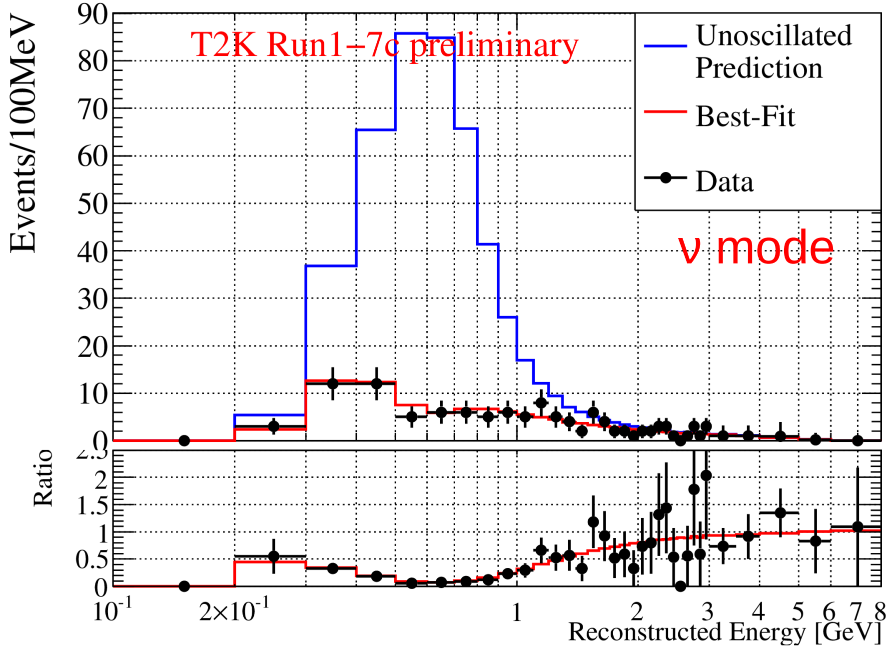
Results presented today use:
12,831,370 beam spills
ν-mode: 7.482×10^{20} POT
ν̄-mode: 7.471×10^{20} POT

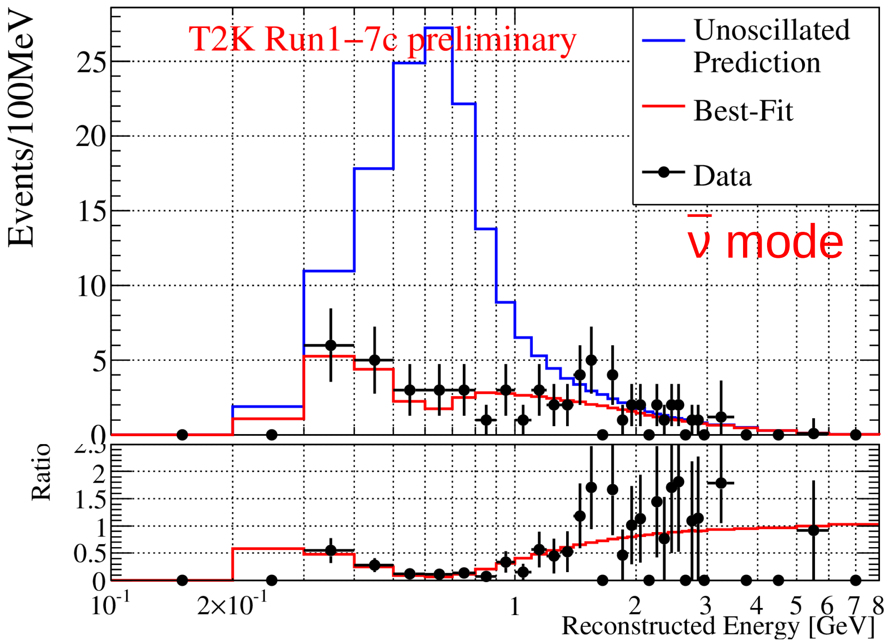
Far Detector ν_μ and $\bar{\nu}_\mu$ Samples

- ν mode: 135 events
- $\bar{\nu}$ mode: 66 events

Single ring μ-like selection

1. Fully contained, Fiducial volume
2. Single ring
3. Muon-like
4. Momentum > 200 MeV
5. Zero or one decay electrons



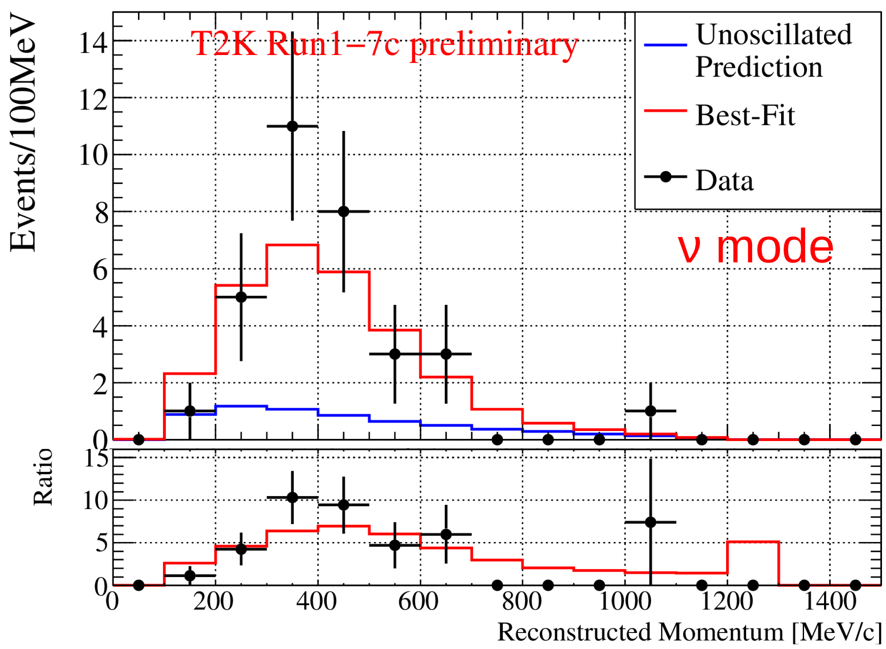


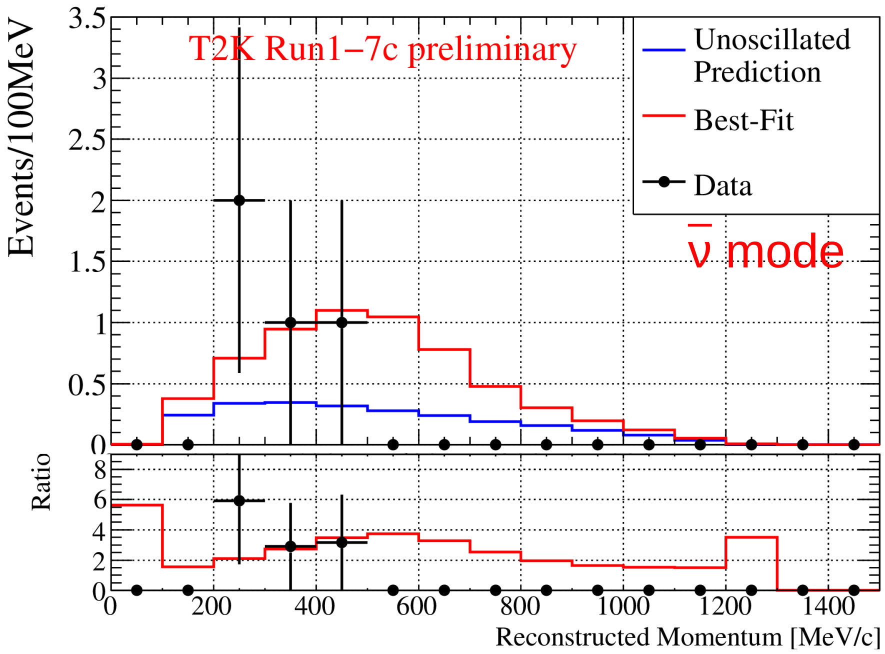
Far Detector ν_e and $\bar{\nu}_e$ Samples

- ν mode: 32 events
- $\bar{\nu}$ mode: 4 events

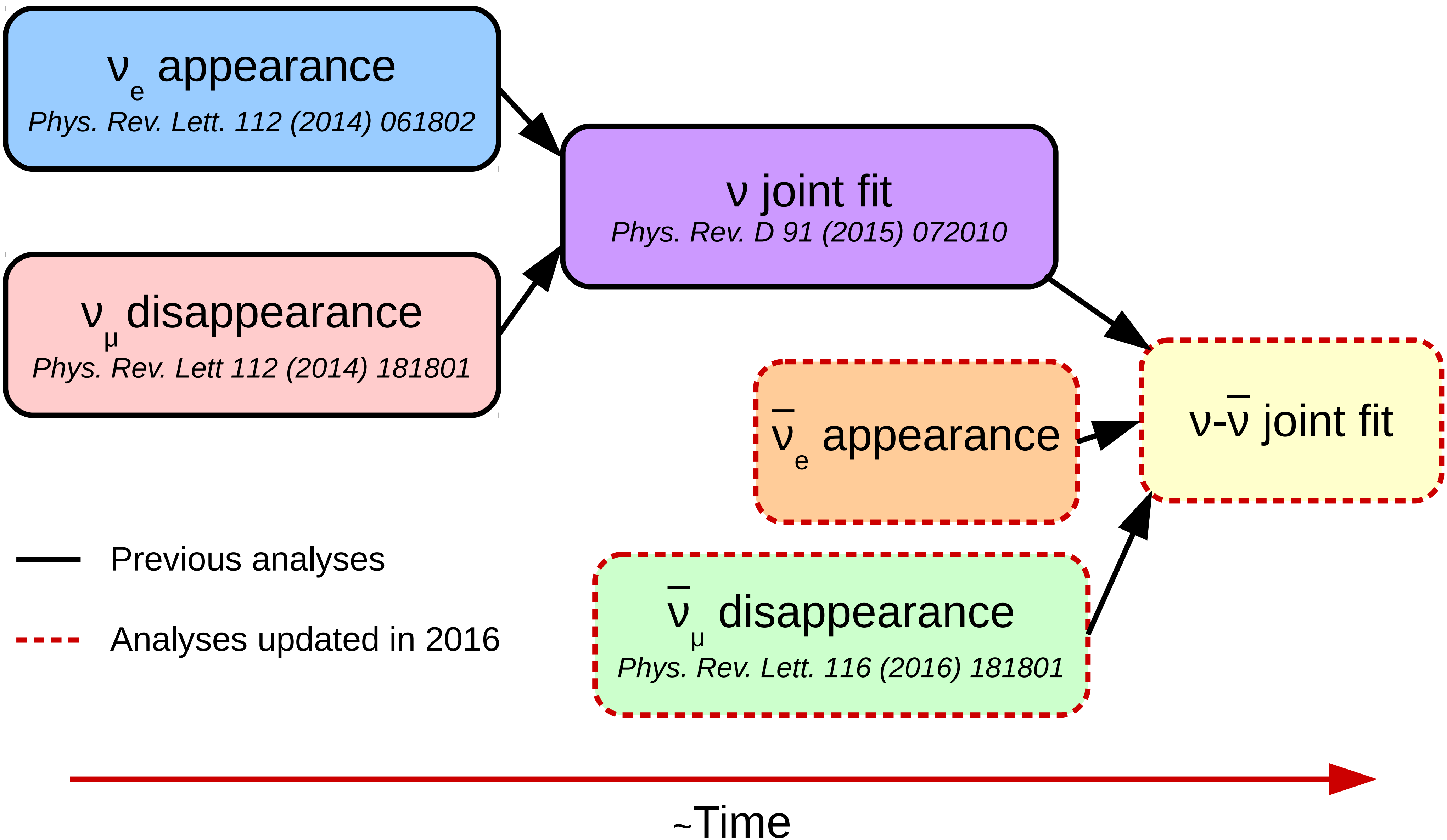
Single ring e-like selection

1. Fully contained, Fiducial volume
2. Single ring
3. Electron-like
4. Visible energy >100 MeV
5. Zero decay electrons
6. Reconstructed energy < 1.25 GeV
7. Not pi0-like



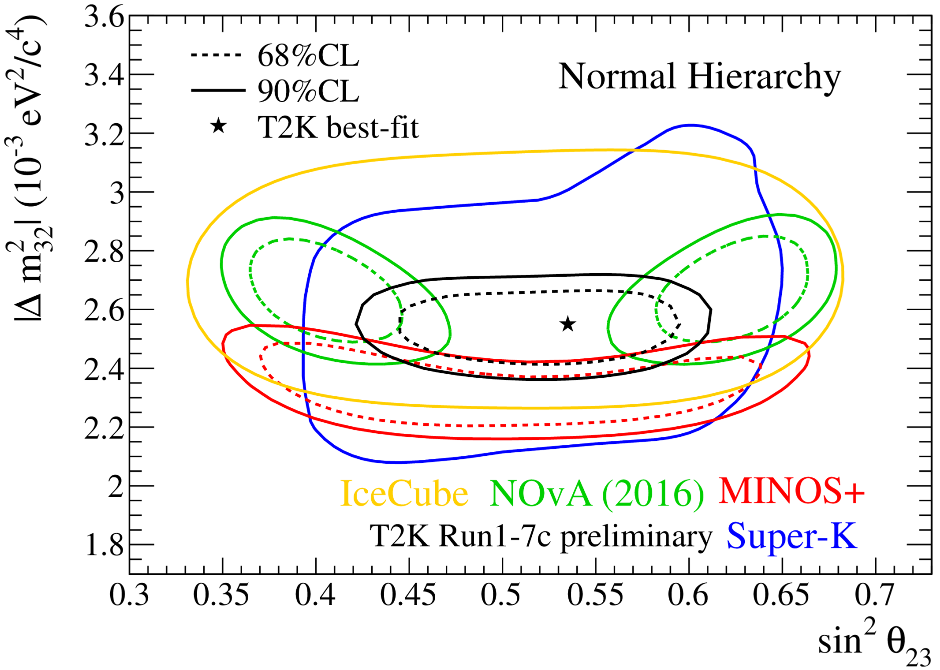


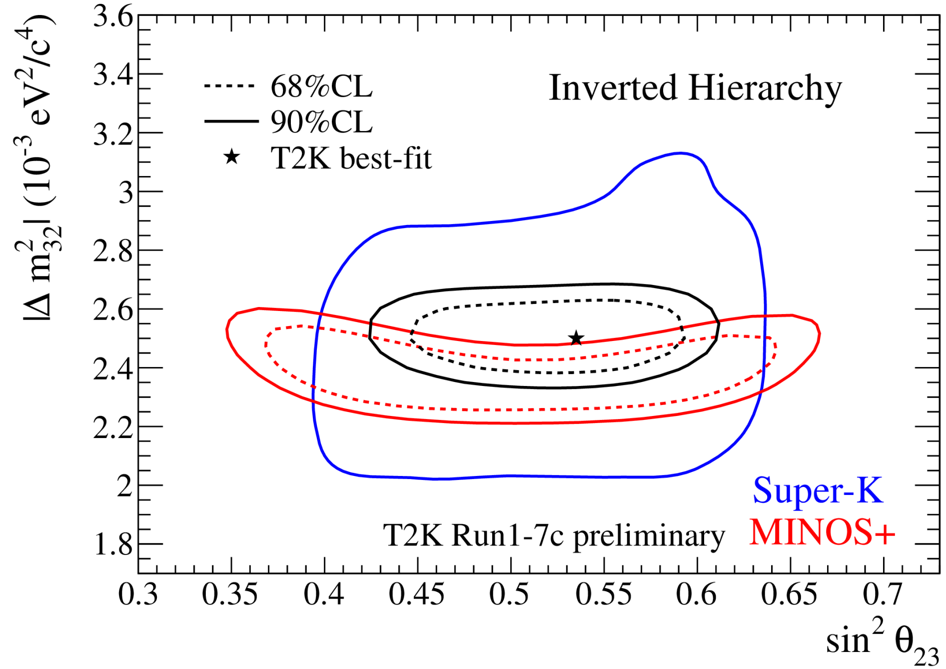
T2K Osc. Analysis History



Joint Analysis Results – θ_{23} & Δm^2_{32}

T2K + reactor
($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)



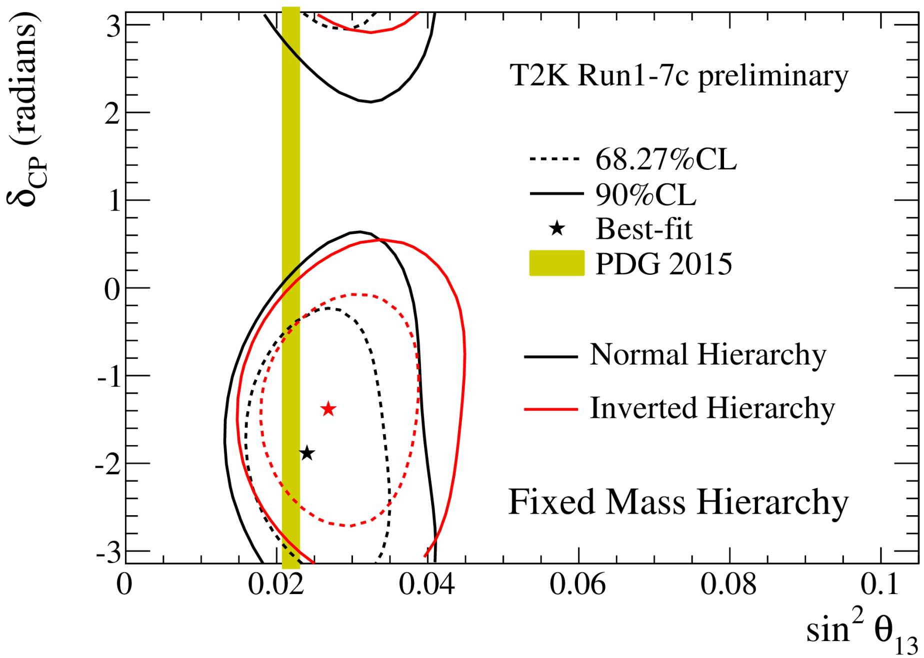


- Data consistent with maximal mixing
- Compatible with other experimental results

1D Parameter Constraints		
	NH.	IH.
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

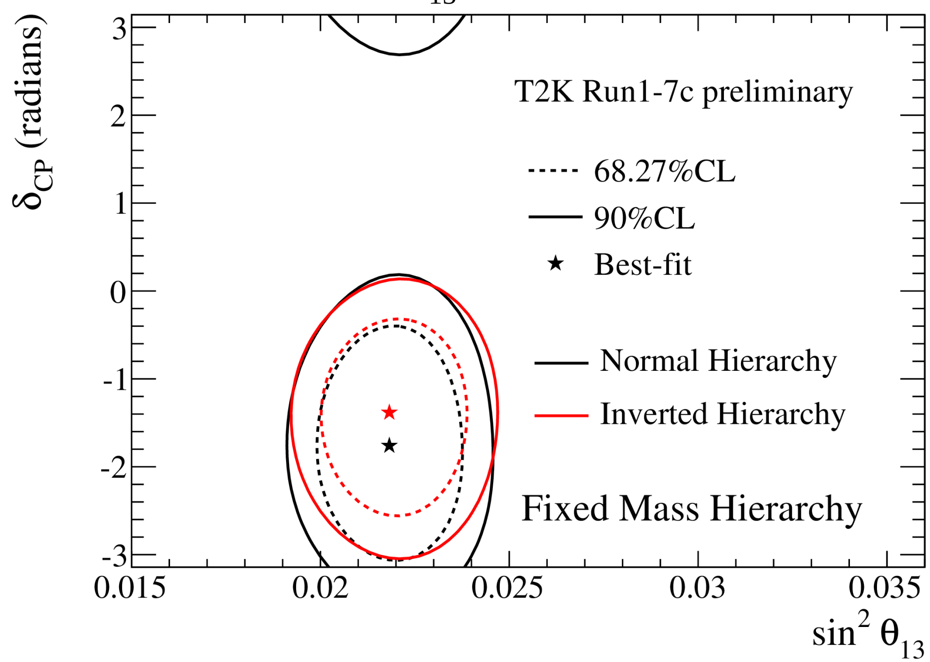
Joint Analysis Results – θ_{13}

T2K-only



T2K + reactor

($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)



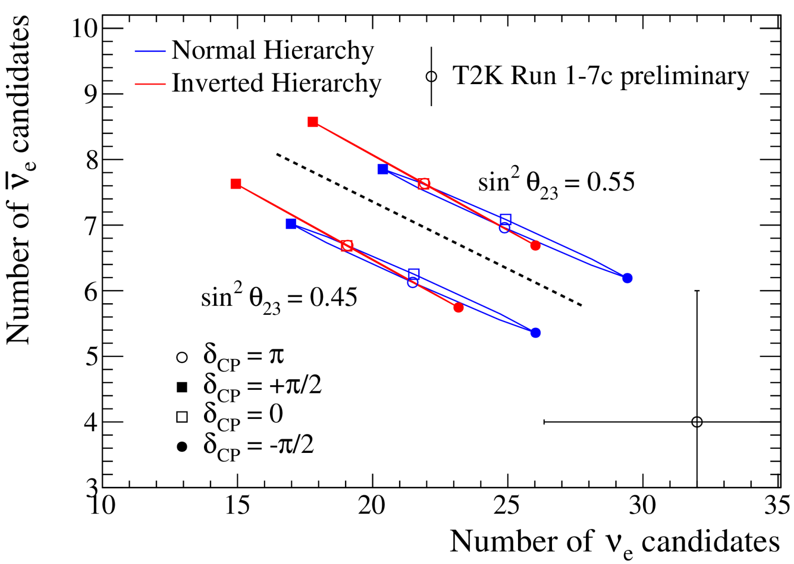
- T2K-only measurement consistent with reactor results
- Favours “small” $\sin^2\theta_{13}$ and large CPV

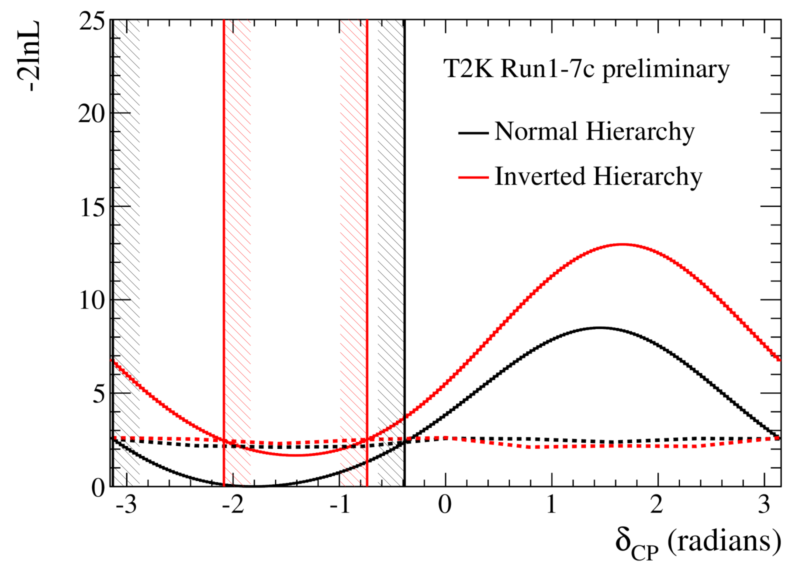
Joint Analysis Results – δ_{CP}

	Expected Number of Events (NH)				Observed
	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π	
ν_e-like	28.7	24.2	19.6	24.2	32
$\bar{\nu}_e$-like	6.0	6.9	7.7	6.8	4

- More ν_e appearance events than expected + fewer $\bar{\nu}_e$ appearance events than expected
- Data prefers largest CP asymmetry $\delta_{CP} \approx -\pi/2$, normal hierarchy

CP conservation (δ_{CP} = 0,π) disfavoured at 90% C.L.





Normal hierarchy: CP= [-3.13, -0.39] [-179°, -22°] at 90% CL
Inverted hierarchy: CP= [-2.09, -0.74] [-120°, -42°] at 90% CL

Joint Analysis Results - MH

- T2K Bayesian Analysis
  - Integrate over posterior likelihood to compare hypotheses

Bayesian Posterior Probabilities			
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} < 0.5$	**Line Total**
Inverted Hierarchy	**0.10**	**0.14**	**0.25**
Normal Hierarchy	**0.29**	**0.46**	**0.75**
Column Total	**0.39**	**0.61**	**1**

Weak preference for Normal Hierarchy

Antineutrino Fits

- Methodology
  - Allow antineutrinos to oscillate differently to current PMNS description for neutrinos
  - Use neutrino samples to constrain wrong sign background parameters

$\bar{\nu}_\mu$ disappearance test of CPT

$$\bar{\theta}_{23} \neq \theta_{23}, \Delta \bar{m}^2_{32} \neq \Delta m^2_{32}$$

Test of $\bar{\nu}_e$ appearance

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

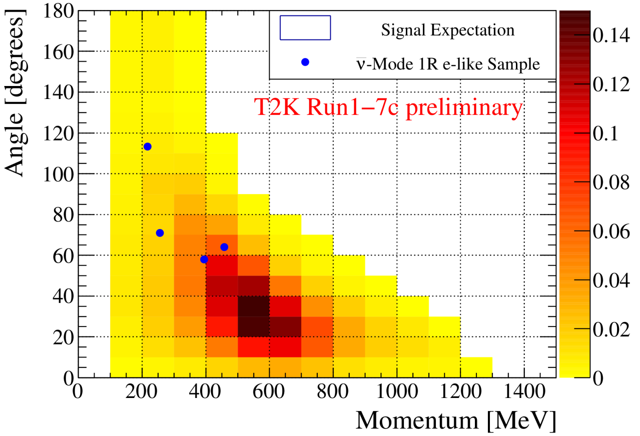
$\bar{\nu}_e$ appearance

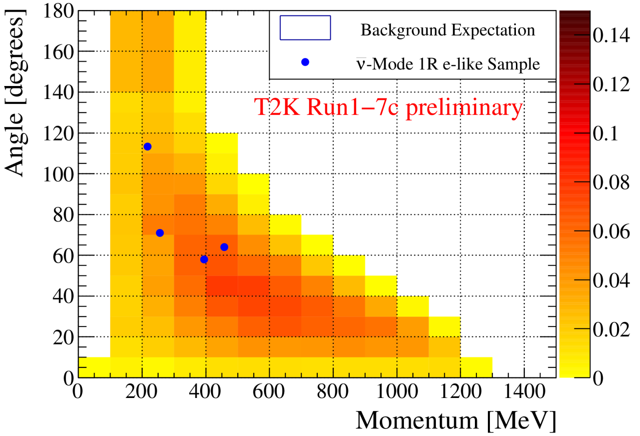
- $\bar{\nu}_e$ appearance not yet observed
- Test the hypothesis

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- Consider cases β=0, β=1
- Rate only and Rate+Shape
- Data preference inconclusive

- Two events more background-like





Results Summary		
	P-value (β=0)	P-value (β=1)
Rate Only	0.41	0.21
Rate+shape	0.46	0.07

Sensitivity:
65% of β=1 toy experiments return P-value(β=0) ≤ 0.05 in rate+shape analysis

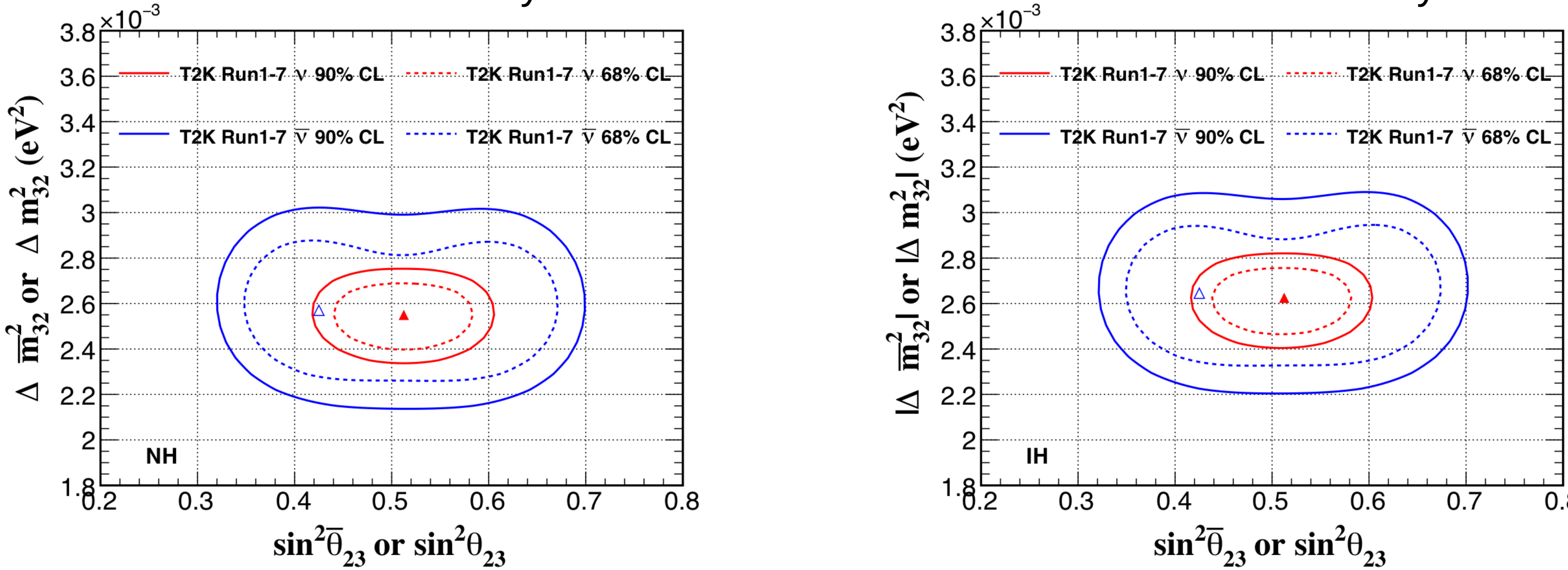
$\bar{\nu}_\mu$ disappearance

- Test CPT invariance $\bar{\theta}_{23} \neq \theta_{23}, \Delta \bar{m}^2_{32} \neq \Delta m^2_{32}$

- Good agreement between $P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ and $P_{PMNS}(\nu_\mu \rightarrow \nu_\mu)$

Normal Hierarchy

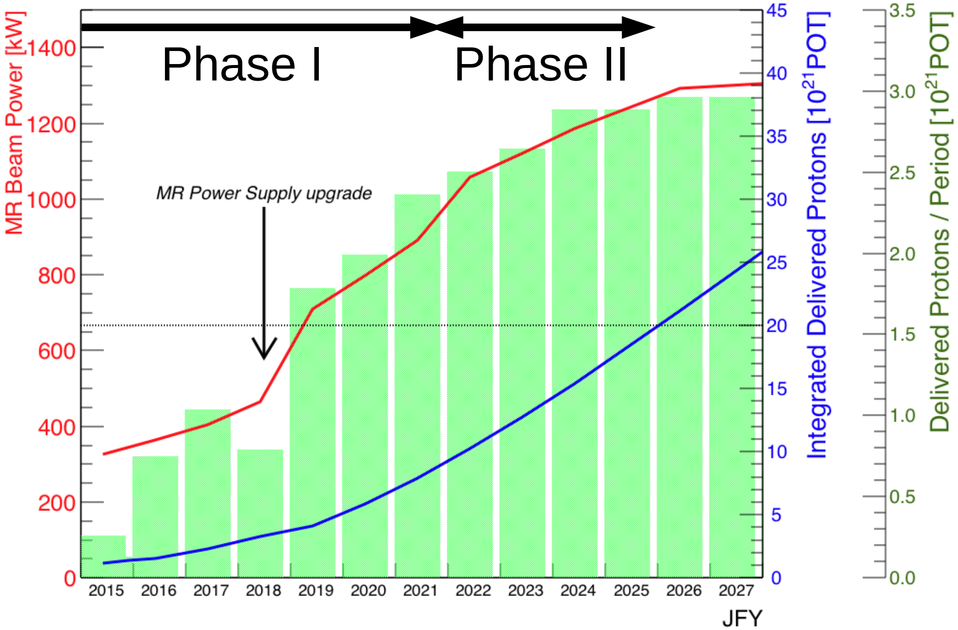
Inverted Hierarchy



Future of T2K

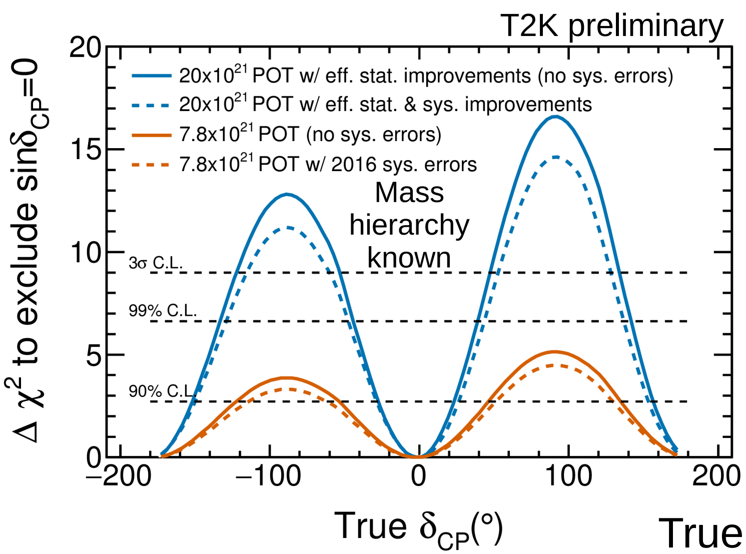
- Staged beam upgrade to increase intensity
  - 420 kW → 750 kW → 1.3 MW
- Sample selection development to increase statistics
  - Fiducial volume expansion, CC nonQE event samples, multi-ring (~+40%)
- Analysis improvements to reduce sys. Uncertainties 6% → 4%
- Proposal for extension of T2K with phase II
  - Increase POT collected $7.8 \times 10^{21} \rightarrow 20.0 \times 10^{21}$

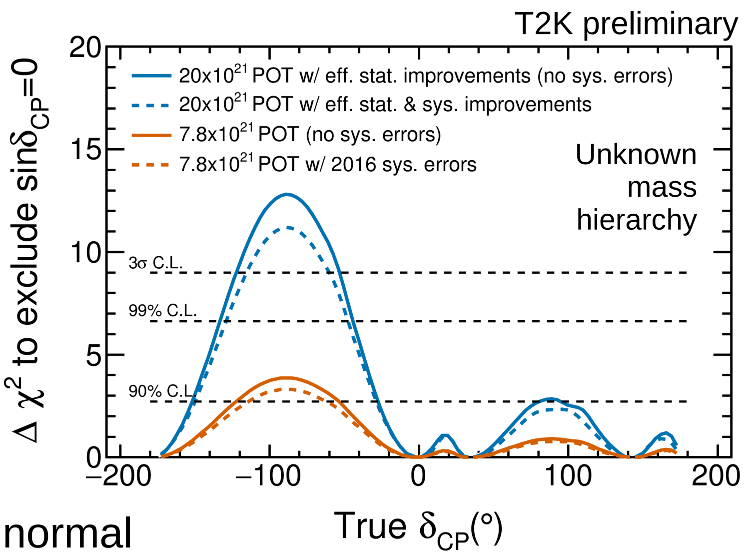
- Beam Upgrade
  - To 750 kW – Decrease bunch interval (2.48 sec → 1.3 sec)
    - Replace Main Ring Power Supply
    - Upgrade MR RF
  - To 1.3 MW Further decrease in bunch interval (1.3 sec → 1.16 sec) and Increase protons per bunch $2.7 \times 10^{14} \rightarrow 3.2 \times 10^{14}$
  - Increase horn current 250 kA → 320 kA (~+10% stats)



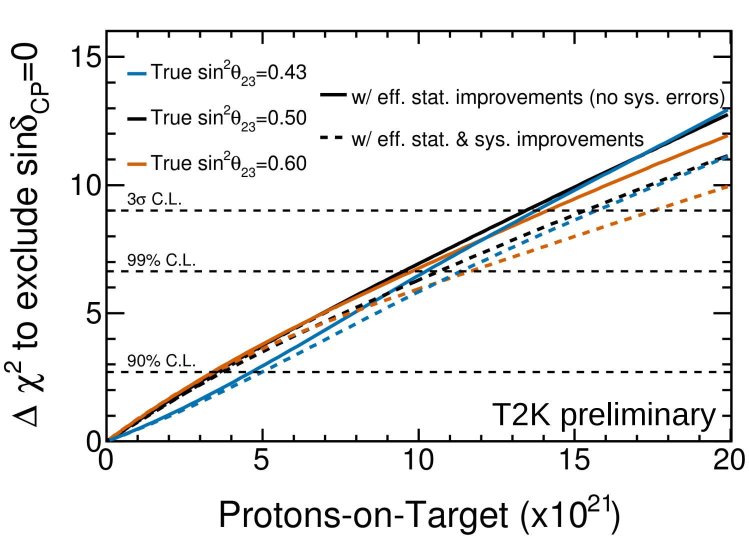
Oscillation Analysis Prospects

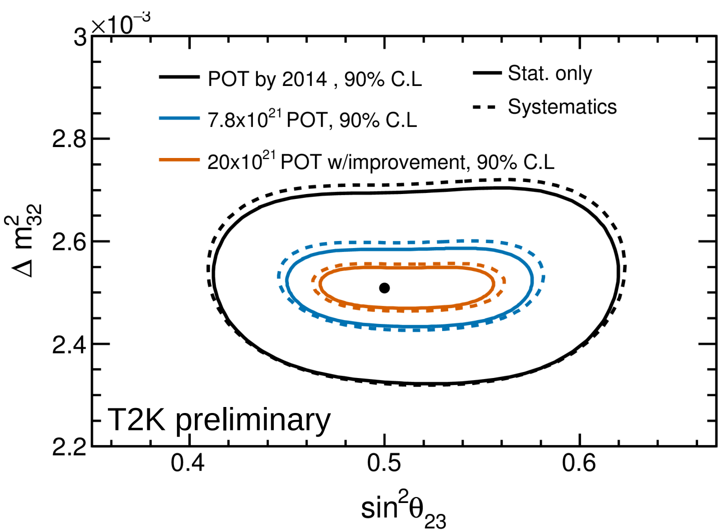
- With +50% effective statistics/POT and reduced uncertainties





True hierarchy is normal





Summary

- Accumulated 15×10^{20} POT (~20% of total)
  - Data taking has resumed following the Summer break
- First fully-joint oscillation analysis completed
  - $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance joint fit
  - Water target and “wrong sign” constraints from near detector
  - Data consistent with θ_{23} at maximal mixing, $\delta_{CP}\sim-\pi/2$, normal hierarchy
  - CP conservation $\delta_{CP}=(0,\pi)$ disfavoured at 90% C.L.
- Beam power continues to increase – anticipate 750kW in near future, first stage approved
- T2K-phase II
  - Accelerator and beamline upgrades → 1.3MW
  - Run to 2026, accumulate 20×10^{21} POT

The T2K Collaboration

~ 500 members, 61 Institutes, 11 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metropolitan U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

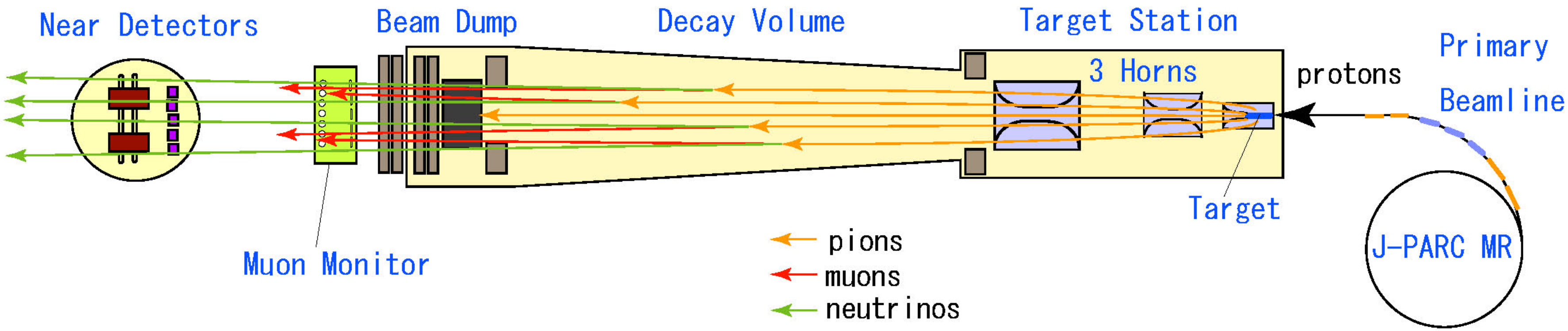
Switzerland
ETH Zurich
U. Bern
U. Geneva

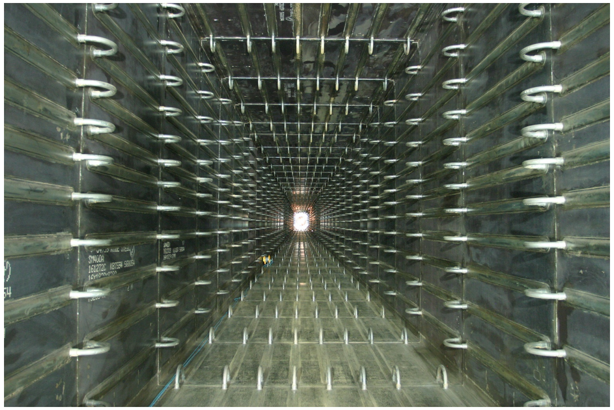
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

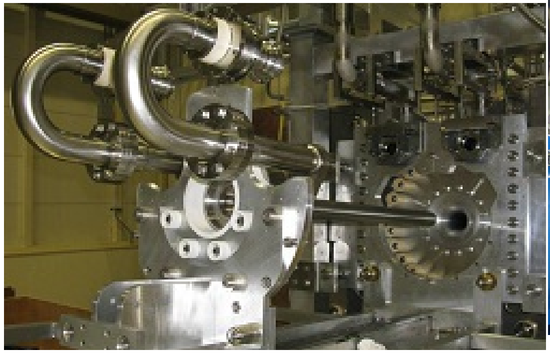
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Supplemental

Neutrino Beamline



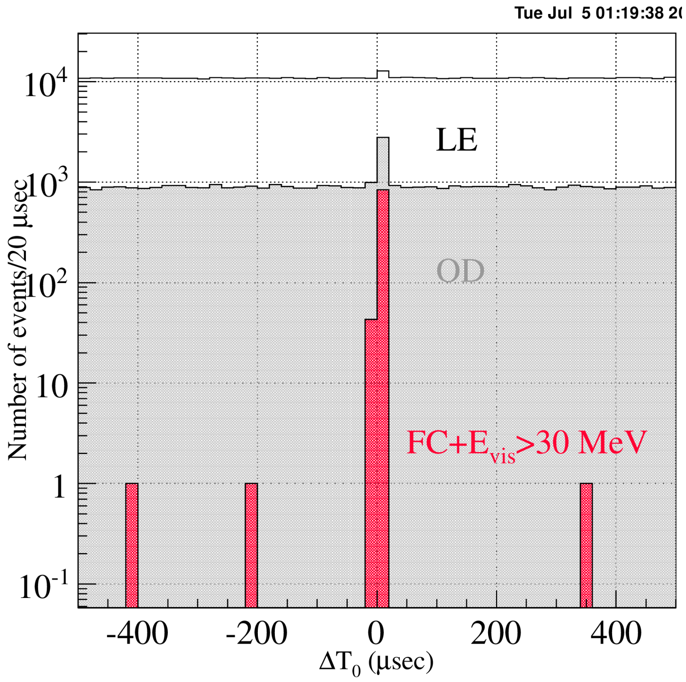




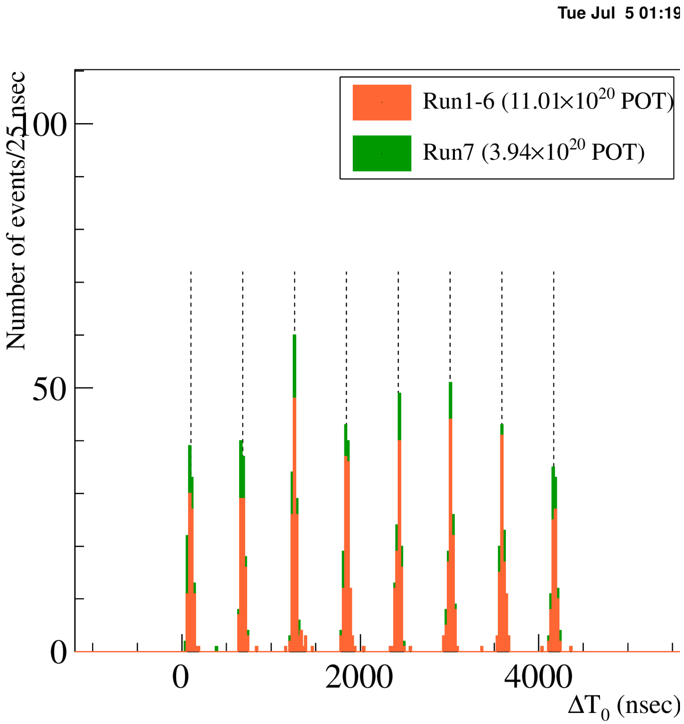
T2K Event Timing

- Extraction of T2K events

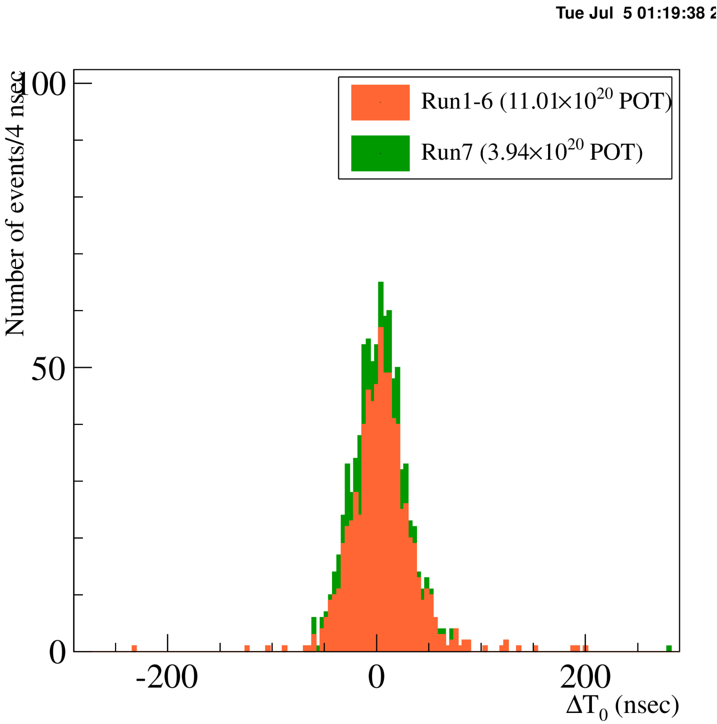
All data extracted



Fully-contained && ΔT_0 -2–10μs



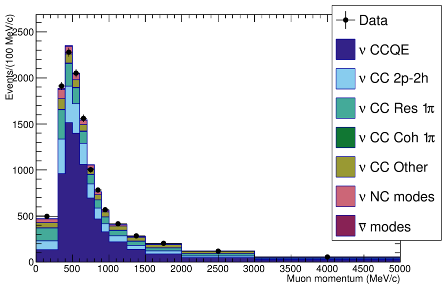
w.r.t. bunch centre



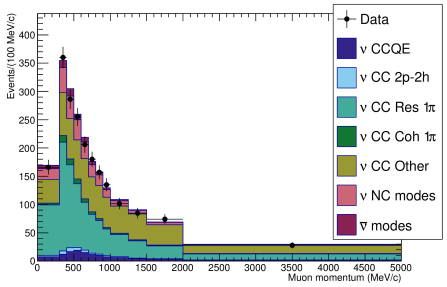
ND280 Fit

- FGD1 – post-fit

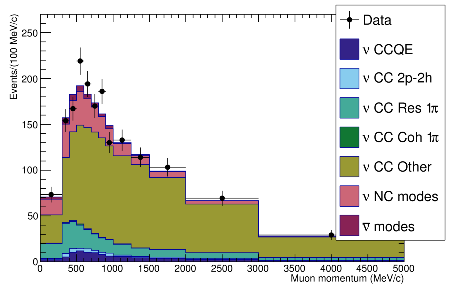
ν beam mode



CC 0pi

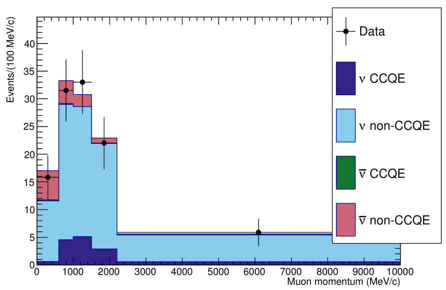


CC 1pi

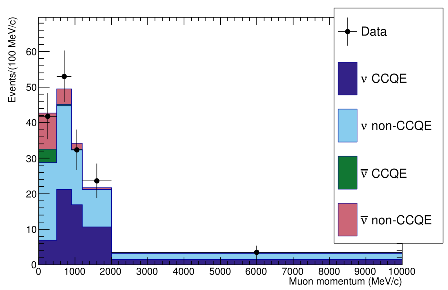


CC other

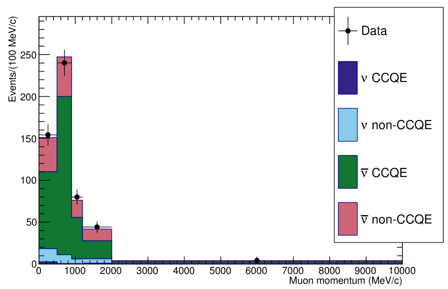
ν̄ beam mode



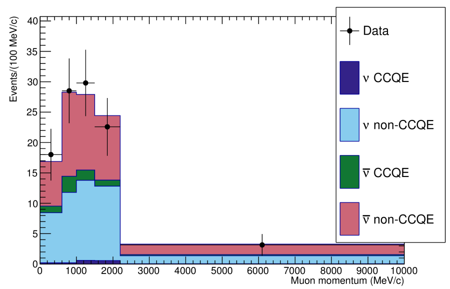
Nu CC 1trck



Nu CC 2trck



Nubar CC 1trck

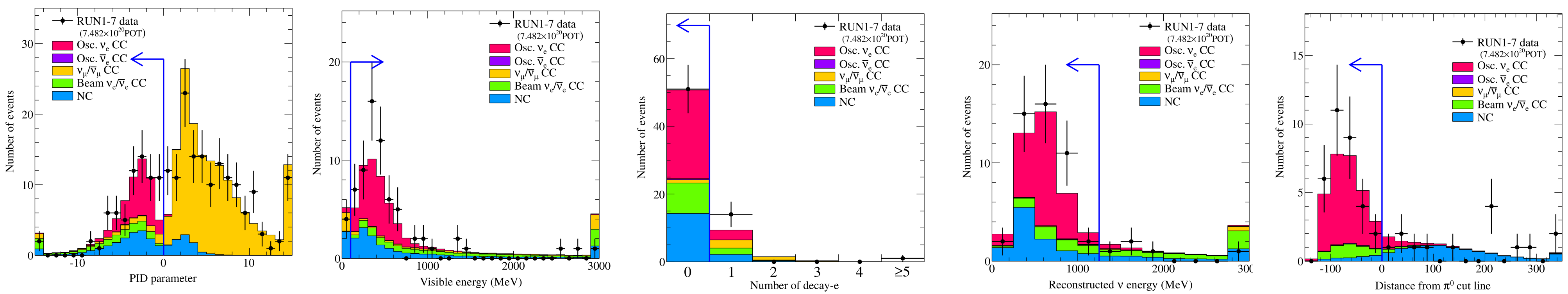


Nubar CC 2trck

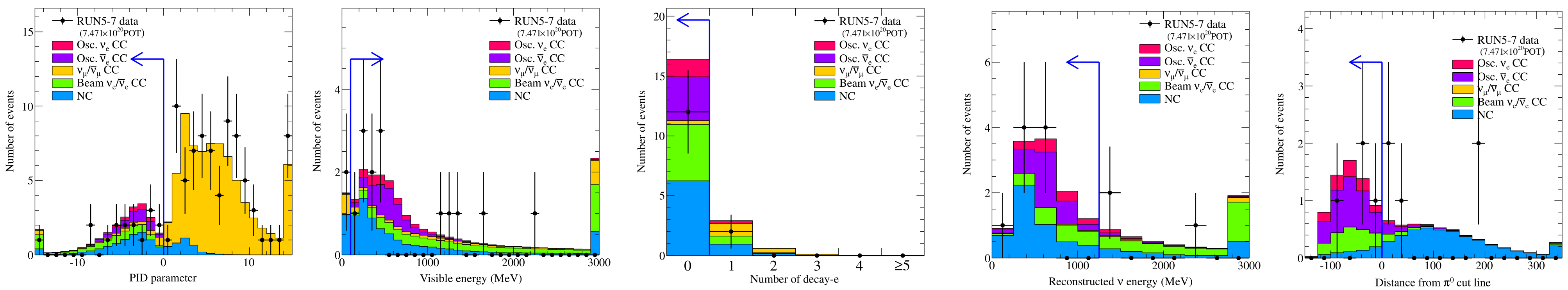
Event Selection at Super-K

- e-like sample selection

ν beam mode



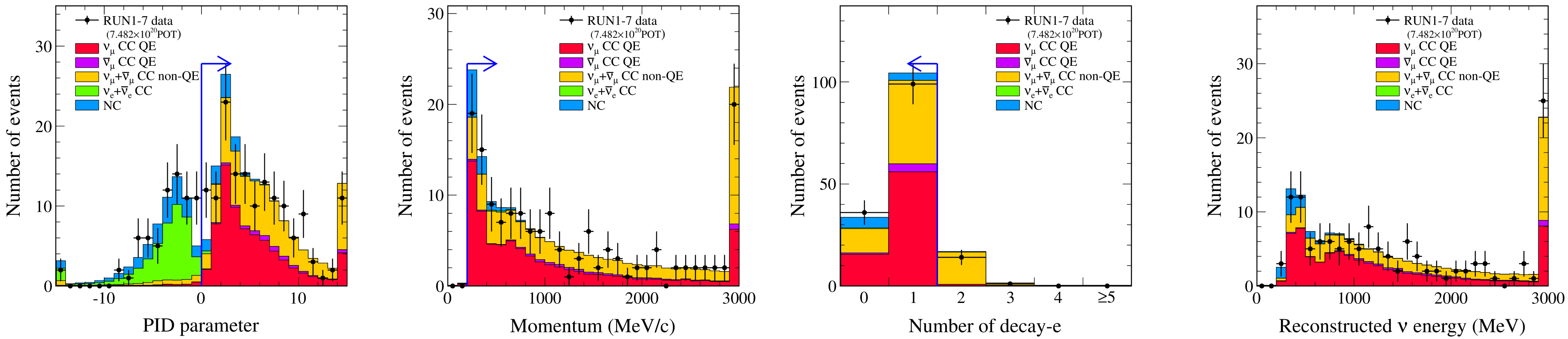
$\bar{\nu}$ beam mode



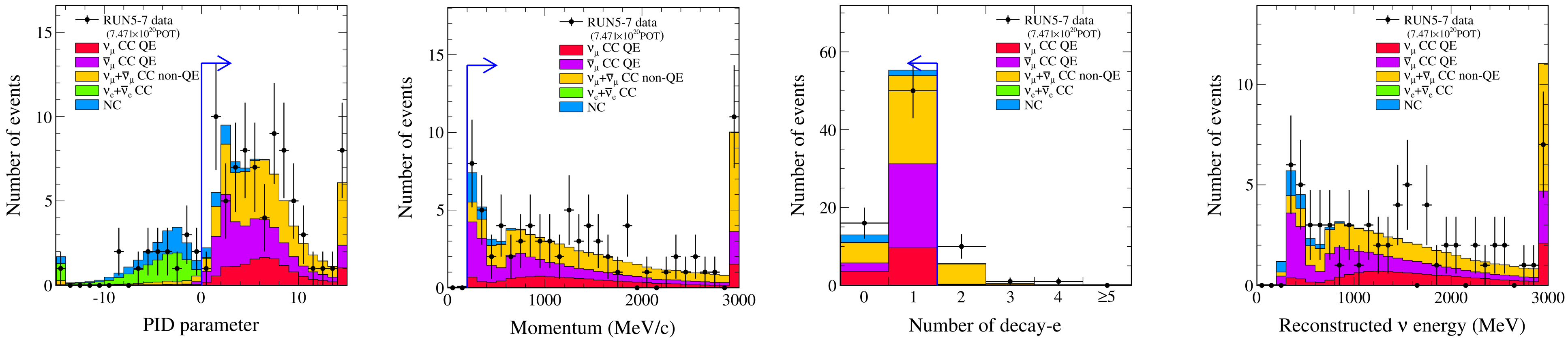
Event Selection at Super-K

- μ-like sample selection

ν beam mode

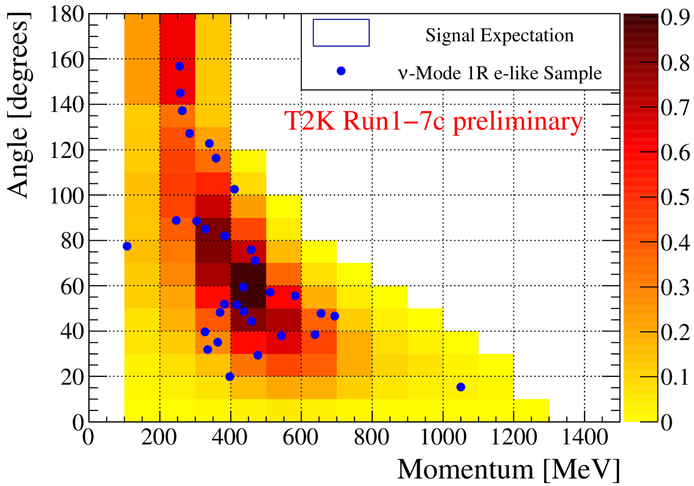


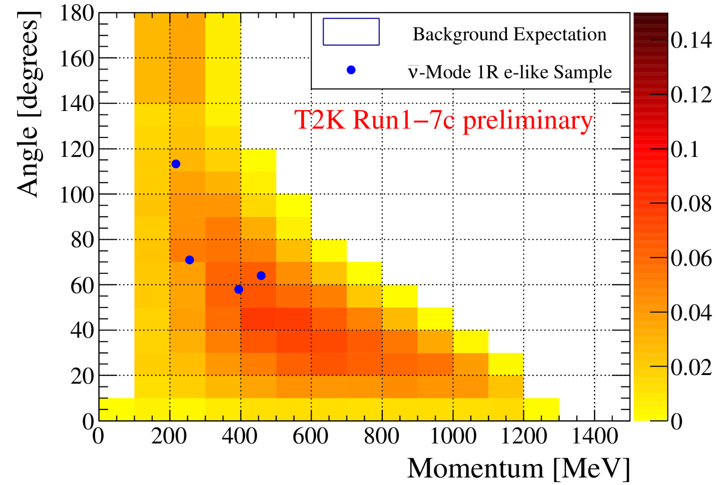
$\bar{\nu}$ beam mode

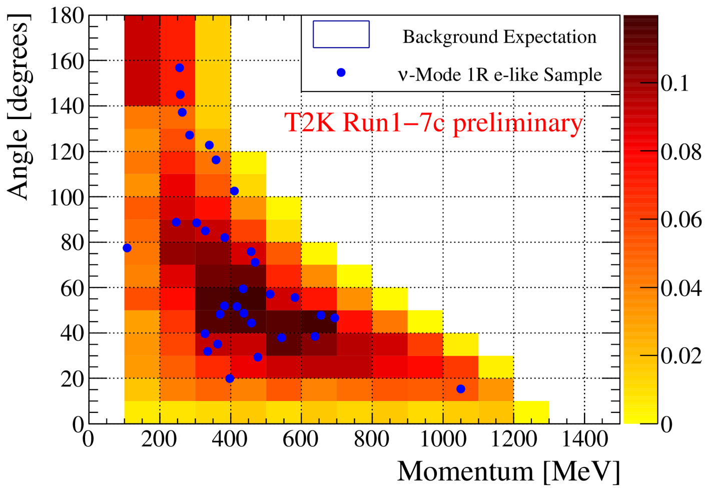


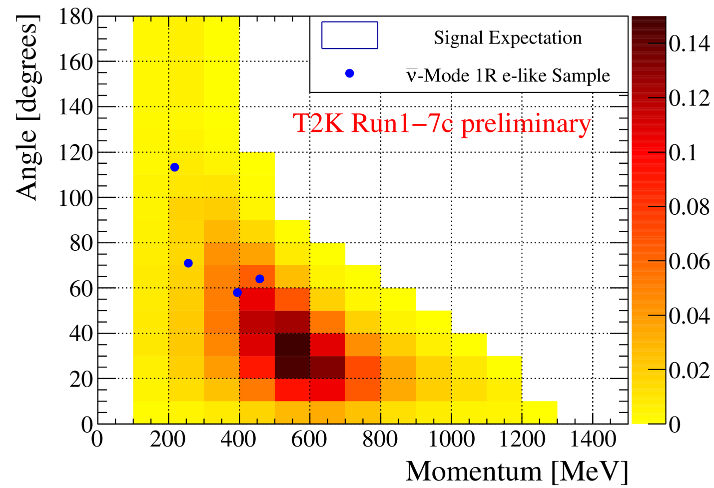
P-theta distributions

- Nue and Nuebar samples



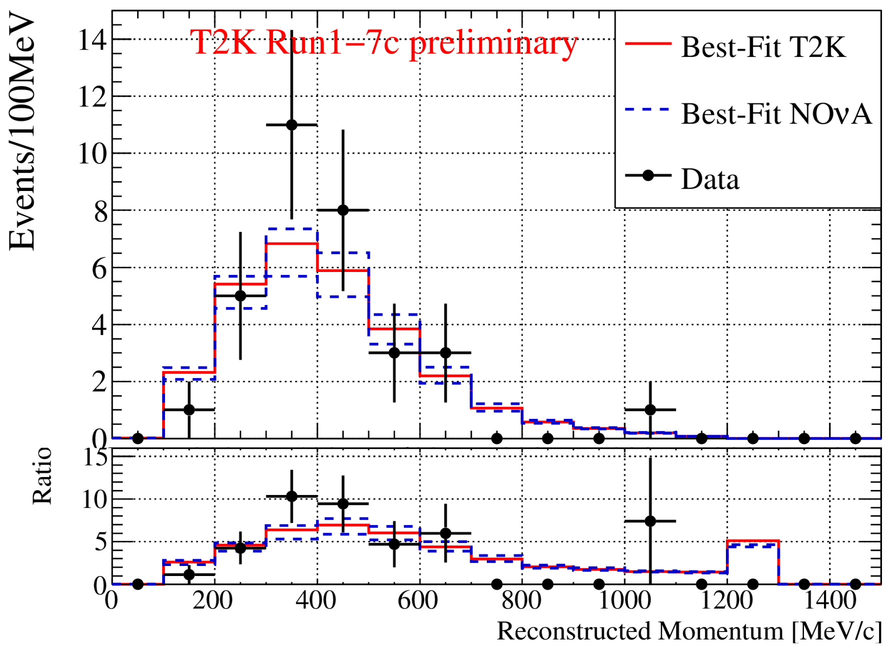


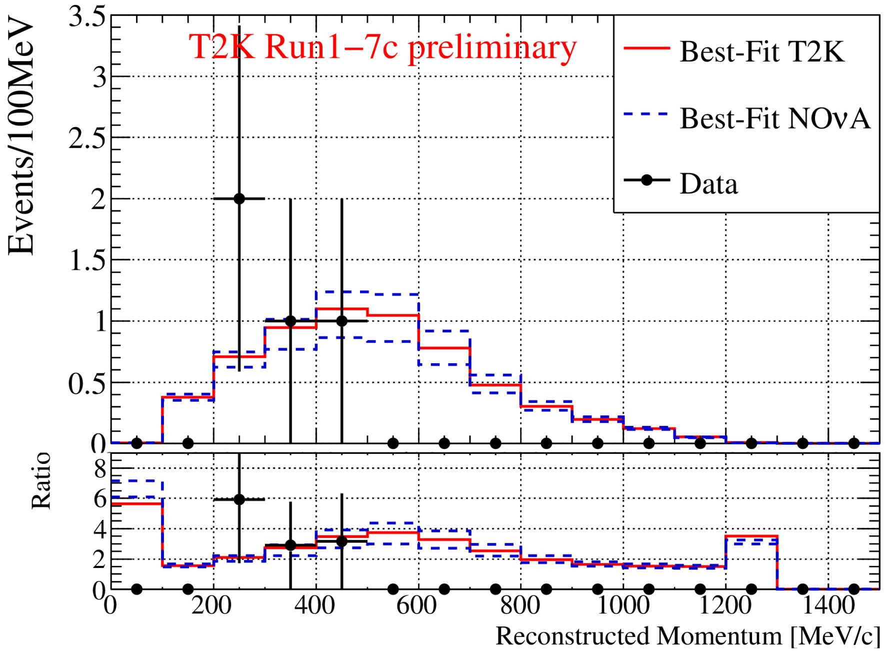




Joint Analysis Results - ν_e and $\bar{\nu}_e$

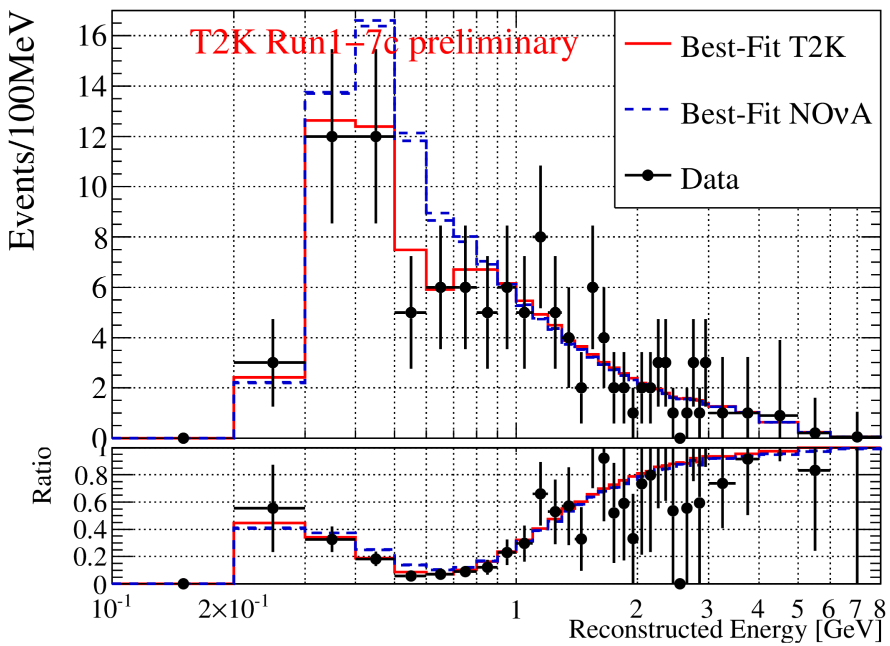
- Comparison to NOvA Best-Fit Spectra

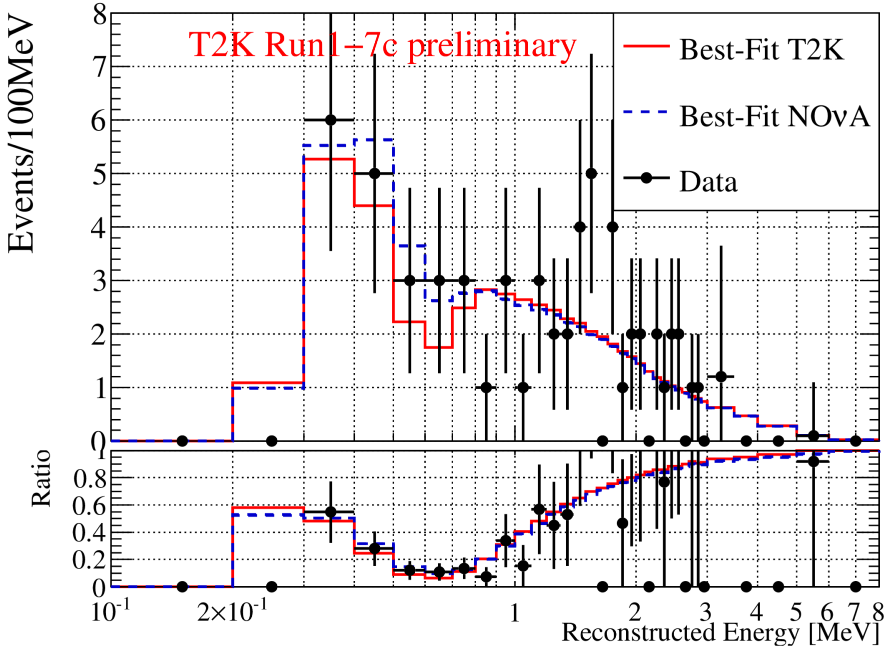




Joint Analysis Results - ν_μ and $\bar{\nu}_\mu$

- Comparison to NOvA Best-Fit Spectra





Vacuum Oscillations

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$
$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$
$$-8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$
$$+4 s_{12}^2 c_{13}^2 (c_{12} c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta) \sin^2\Delta_{21}$$

Leading term

CP Conserving

CP Violating

Solar

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

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