Recent Results from T2K

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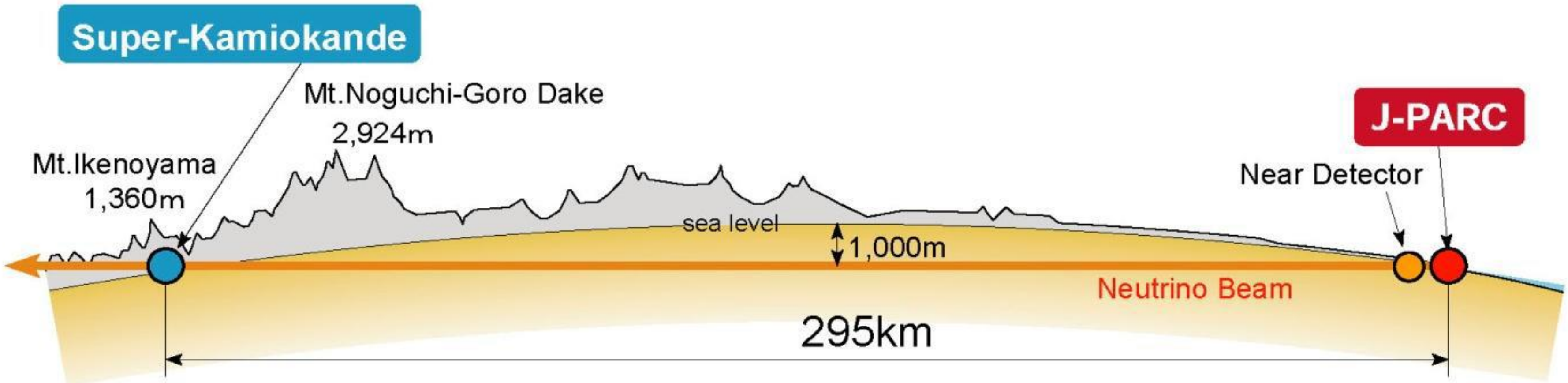
on behalf of the T2K Collaboration

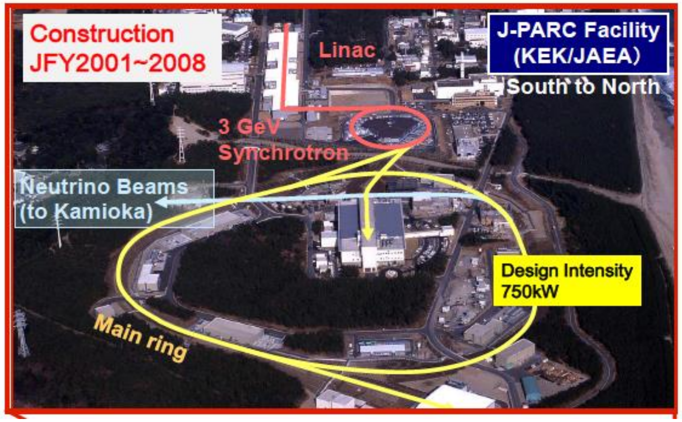
TAU 2016
Beijing
Sept. 22, ‘16

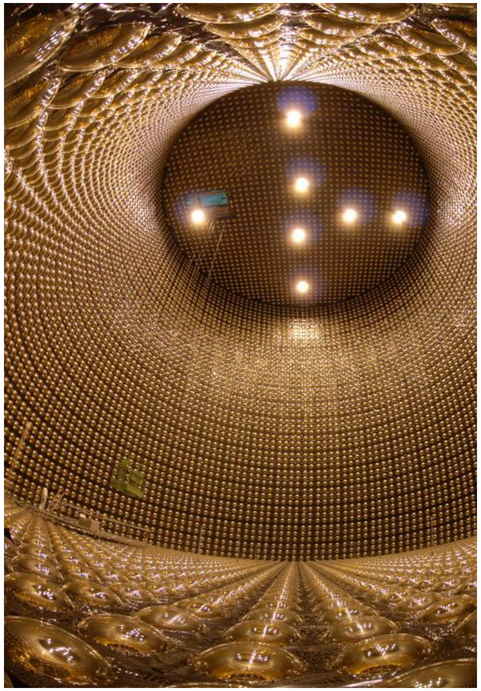
The T2K Experiment

11 countries
~500 members

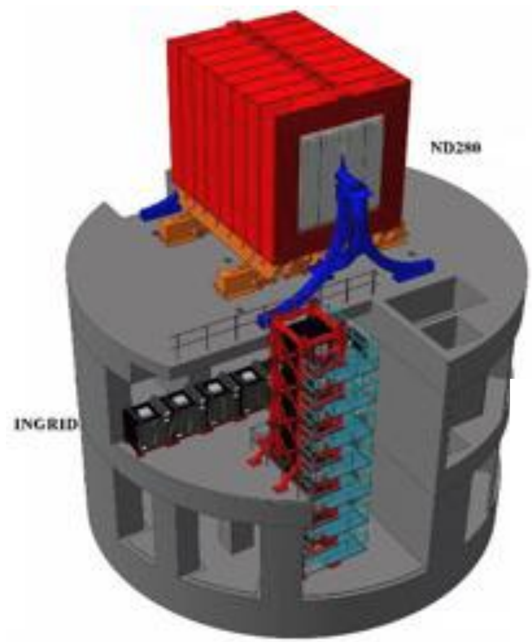


JPARC - accelerator complex



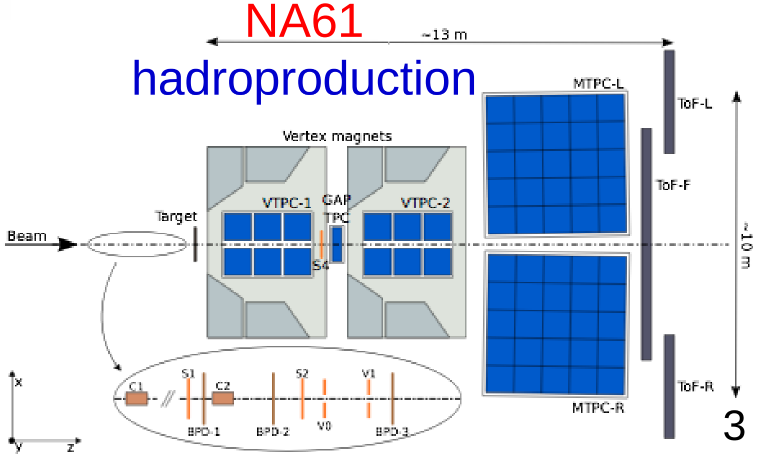


far detector
Super–Kamiokande

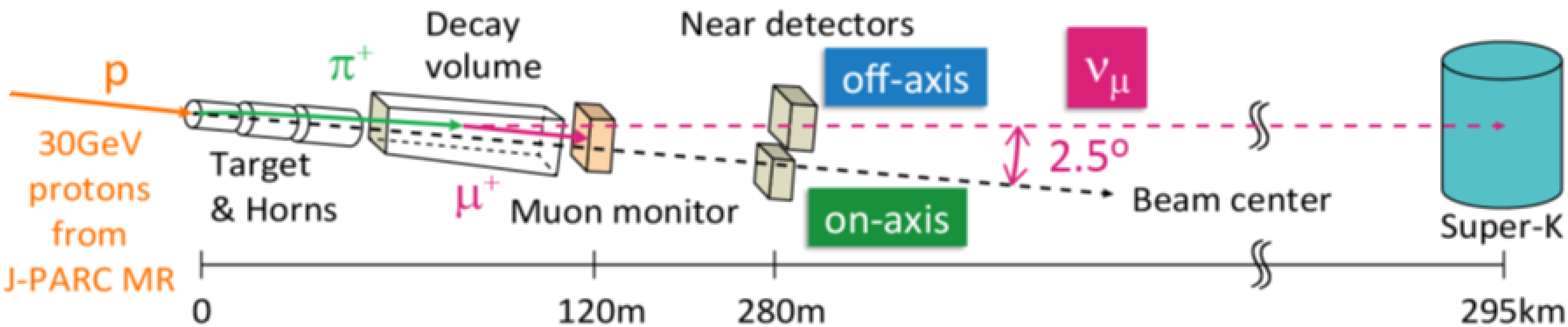


near detectors
Off-axis: ND280
On-axis: INGRID

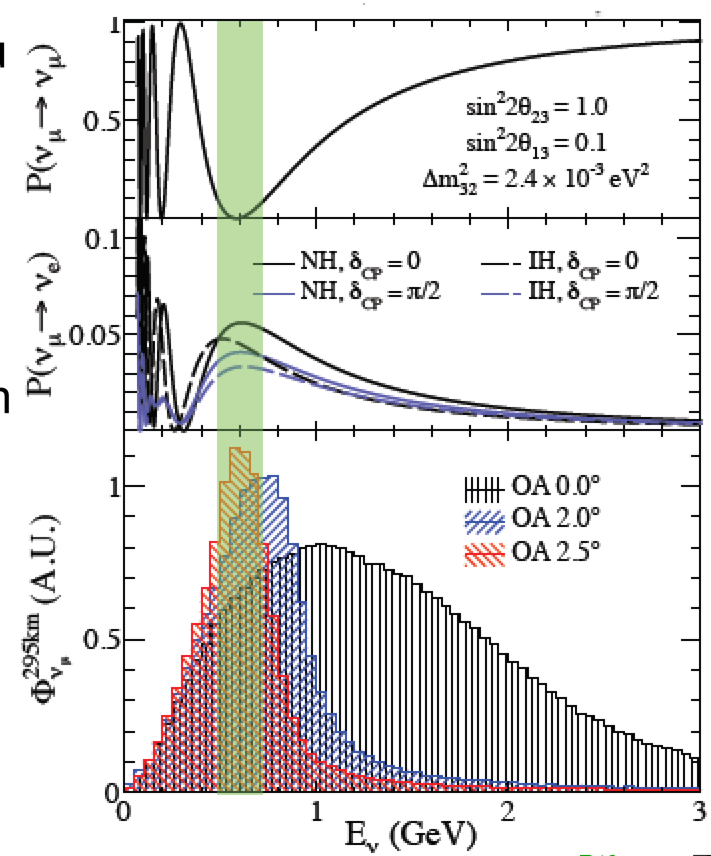
NA61
hadroproduction



Neutrino Source at J-PARC



(anti-)ν beam is created in the decay in flight of π / K / μ produced by interactions of 30-GeV protons on a 90-cm long graphite rod



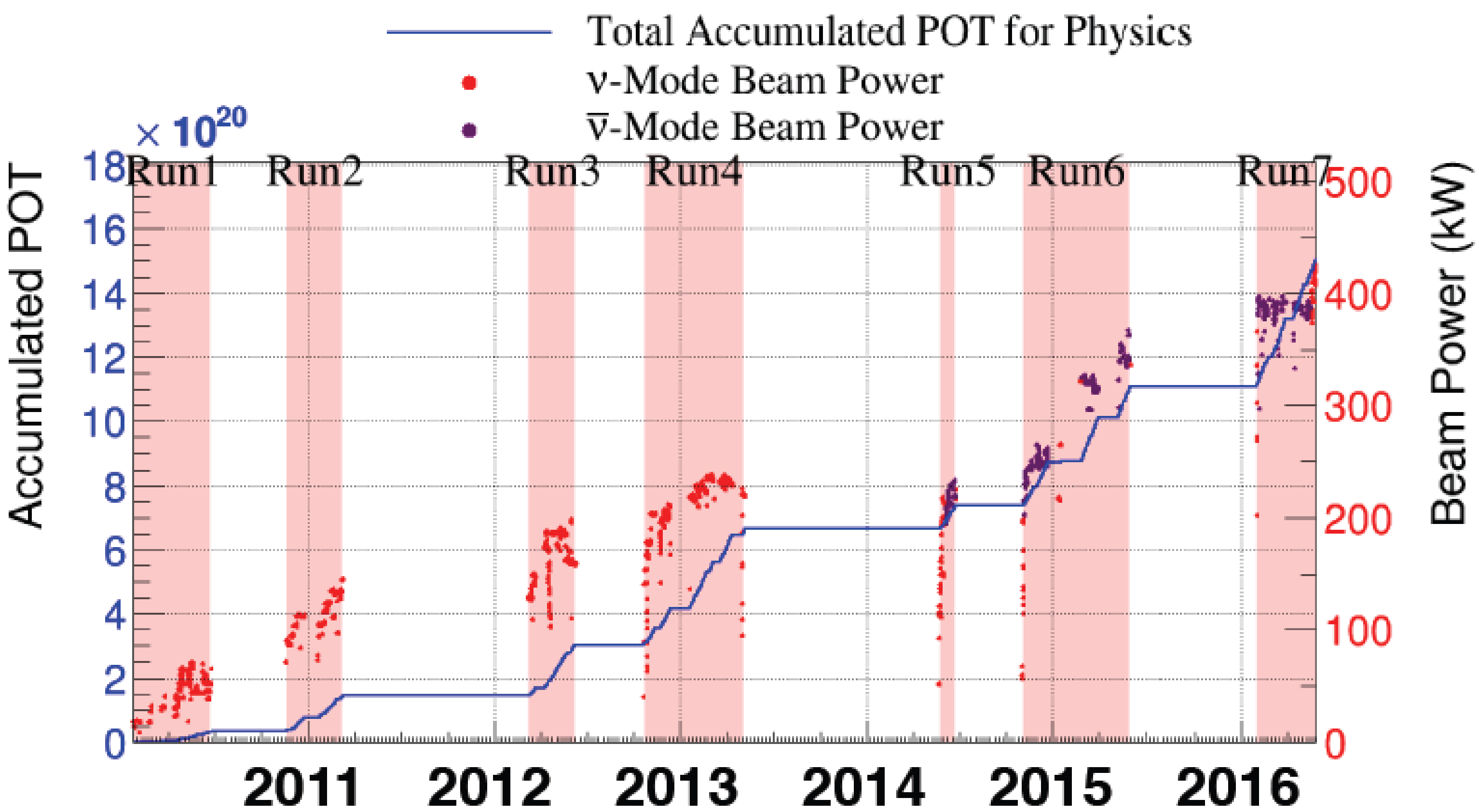
2.5⁰ off-axis neutrino beam

- Very narrow energy spectrum
- Neutrino beam energy “tuned” to oscillation maximum
- Reduced high-energy tails
- E_ν almost independent of parent pion energy

Neutrino beam predictions rely on experimental hadro-production data (NA61) for modeling the primary proton beam interactions in the T2K target

Horn focusing cancels partially the p_T dependence of the parent meson

Data Collected



Reached beam power of 420 kW

Accumulated POT - protons on target (May 27, 2016)

15.10 $\times 10^{20}$ in total

7.57 $\times 10^{20}$ in ν mode

7.53 $\times 10^{20}$ in $\bar{\nu}$ mode

3 Flavor Neutrino Mixing

Flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}\left(\vartheta_{12}, \vartheta_{23}, \vartheta_{13}, \delta_{CP}\right) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Matrix (CKM matrix of lepton sector)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

$\theta_{23} = 45^0$
SuperK (atm. ν)
K2K / Minos
T2K

$\theta_{13} \sim 8^0$
Daya Bay
Reno
T2K

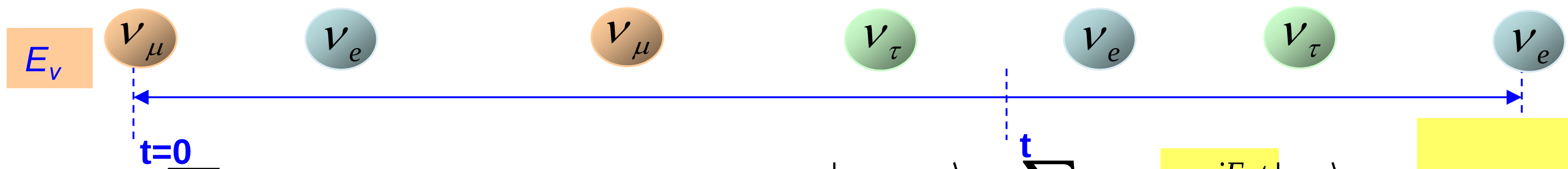
$\theta_{12} \sim 34^0$
solar ν
KamLAND

neutrinoless double beta decay

$$|U|_{3\sigma}^{\rm LID} = \begin{pmatrix} 0.798 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\ 0.232 \to 0.520 & 0.445 \to 0.697 & 0.617 \to 0.789 \\ 0.249 \to 0.529 & 0.462 \to 0.708 & 0.597 \to 0.773 \end{pmatrix}$$

NuFIT 2016

Neutrino Oscillations and Time Evolution



$$|\nu_\alpha(t=0)\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \quad \dashrightarrow \quad |\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}\, e^{-iE_i t}|\nu_i\rangle$$

$$E_i \approx p + \frac{m_i^2}{2p}$$

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta(t)|\nu_\alpha(t=0)\rangle\right|^2 = \sum_i \left|U_{\alpha i}\, U_{\beta i}\right|^2 + \sum_{i\neq j} U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha i}\, U_{\beta i}\, e^{-i(E_i - E_j)t}$$

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

$$P_{\mu\to e} = 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2\frac{\Delta m^2_{31}L}{4E}\left(1+\frac{2a}{\Delta m^2_{31}}(1-2S^2_{13})\right)$$ leading, θ_{13} driven

$$+8C_{13}{}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$ CPC

$$-8C_{13}{}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{21}L}{4E}$$ CPV

$$+4S_{12}{}^2 C_{13}{}^2(C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\frac{\Delta m^2_{21}L}{4E}$$ solar

$$-8C_{13}{}^2 S_{13}{}^2 S_{23}{}^2(1-2S_{13}{}^2)\frac{aL}{4E}\cos\frac{\Delta m^2_{32}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}$$ matter effects

6 independent parameters govern oscillation

θ_{12}, θ_{23}, θ_{13}, δ_{cp}, Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

ν_e Appearance and Oscillation Parameters

$\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$

leading terms

"octant" dependence, whether $\theta_{23} > 45^0$, $\theta_{23} = 45^0$, or $\theta_{23} < 45^0$

δ_{CP}: +- 27% effect at T2K for $\theta_{23} = 45^0$

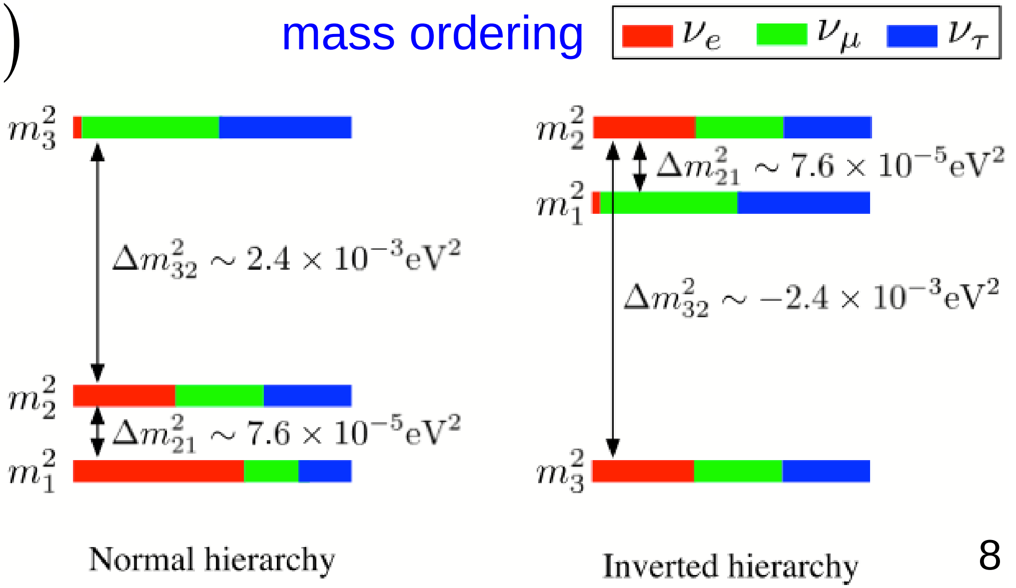
δ_{CP} = ~–π/2: enhances $P(\nu_\mu \rightarrow \nu_e)$

suppresses $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

δ_{CP} = ~+π/2: suppresses $P(\nu_\mu \rightarrow \nu_e)$

enhances $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

mass ordering



mass hierarchy: +-10% effect at T2K

normal: enhances $P(\nu_\mu \rightarrow \nu_e)$

suppresses $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

inverted: suppresses $P(\nu_\mu \rightarrow \nu_e)$

enhances $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Neutrino Oscillation Analysis Overview

$$N_{FD} \sim \Phi_{FD}(E_\nu)\cdot\sigma_{FD}(E_\nu)\cdot\varepsilon_{FD}\cdot P(\nu_\mu \rightarrow \nu_e)$$

Observed rate of ν_μ and ν_e constrains the oscillation probability P.
Depends on:

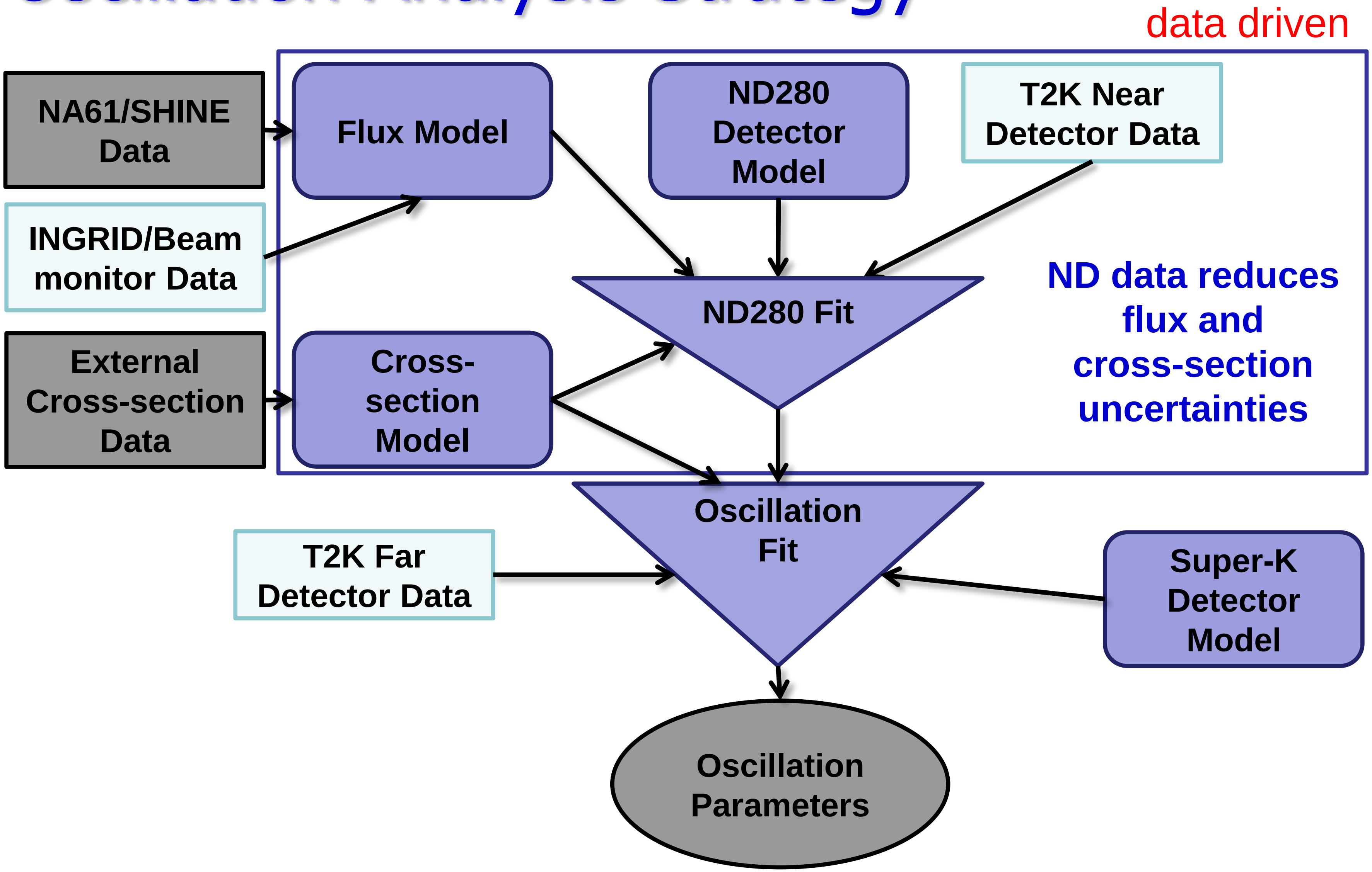
Neutrino flux prediction	Neutrino cross-section model	Far Detector selection & efficiency

Reduce the error on the rate of ν_μ with the near detector measurements.

$$N_{ND} \sim \Phi_{ND}(E_\nu)\cdot\sigma_{ND}(E_\nu)\cdot\varepsilon_{ND}$$

Neutrino flux prediction	Neutrino cross-section model	Near Detector selection & efficiency

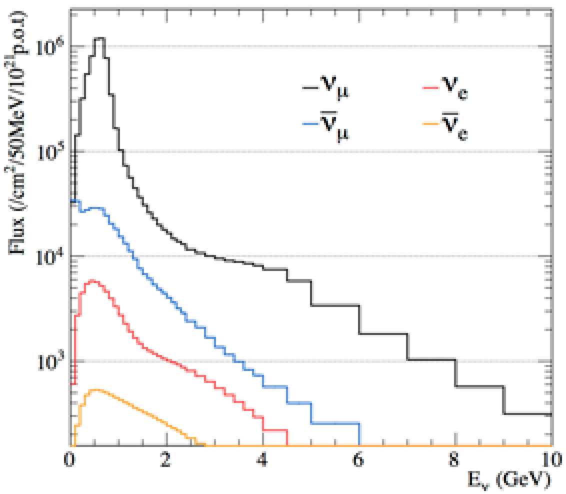
Oscillation Analysis Strategy



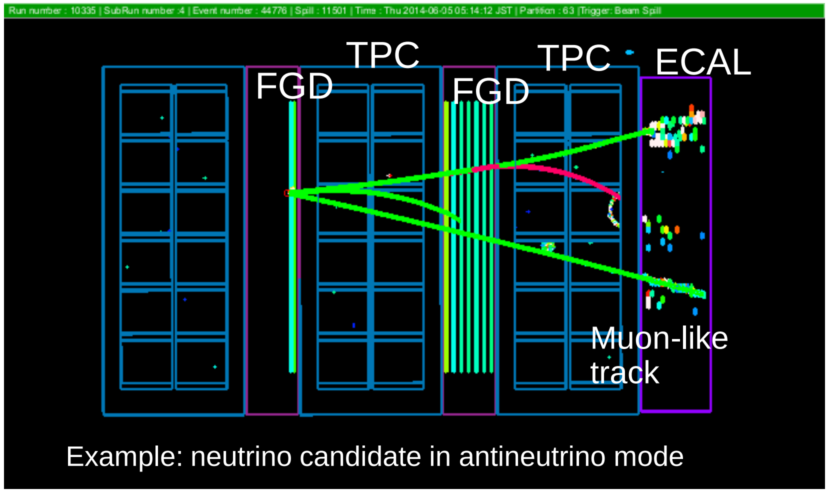
In the latest analysis, the ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$ samples are fit simultaneously to maximize the sensitivity to the oscillation parameters

Sources of Systematic Uncertainties

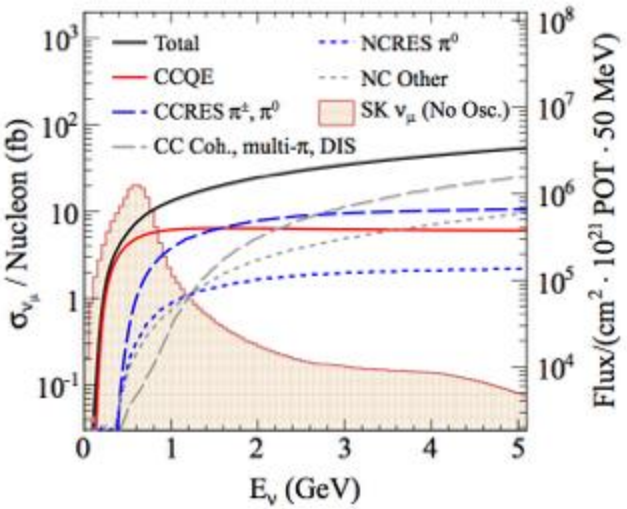
Neutrino flux



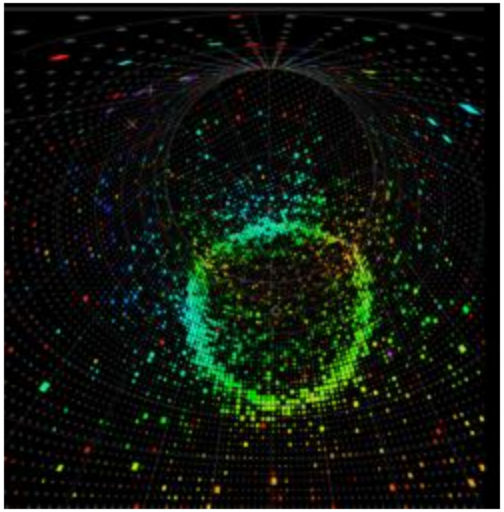
Near Detector response



Neutrino interactions



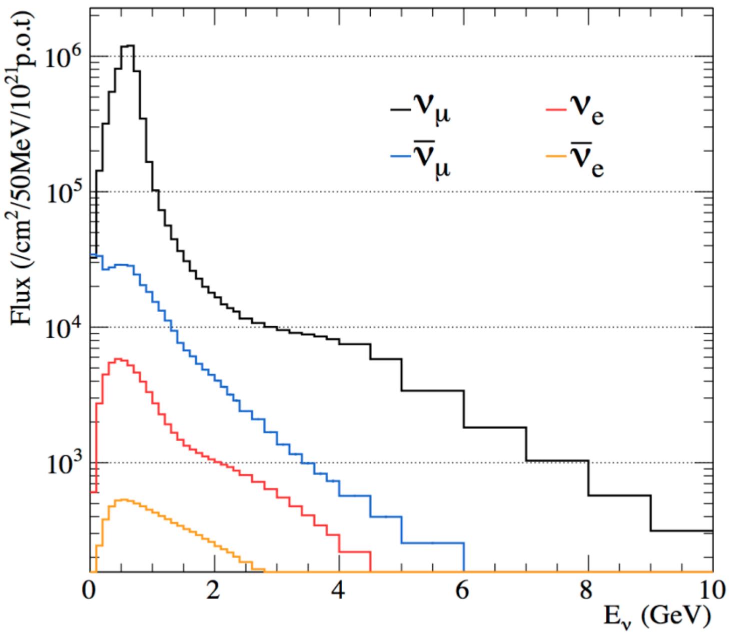
Far Detector response

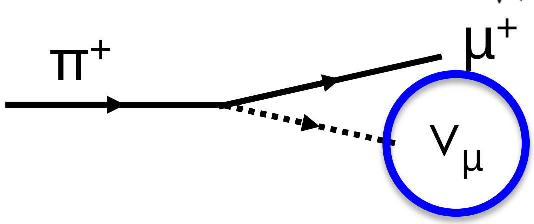


Neutrino Flux Predictions

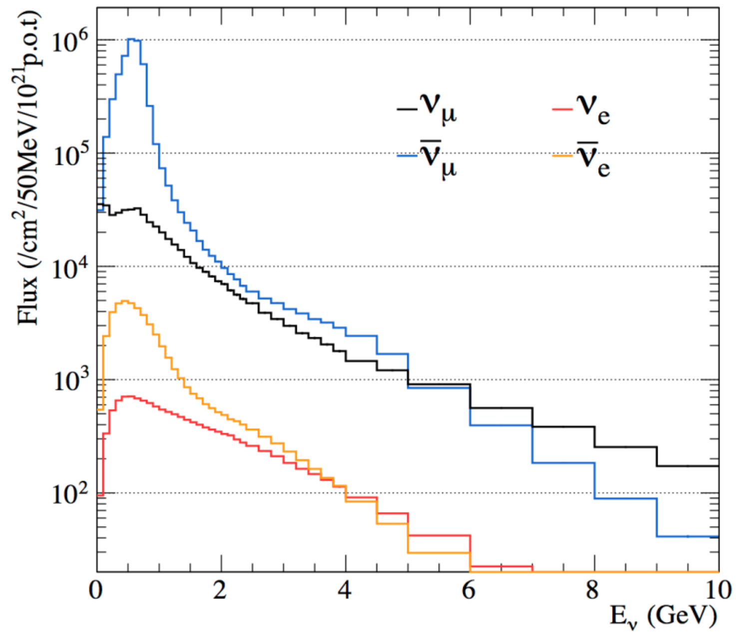
T2K, PRD87 (2013) 012001

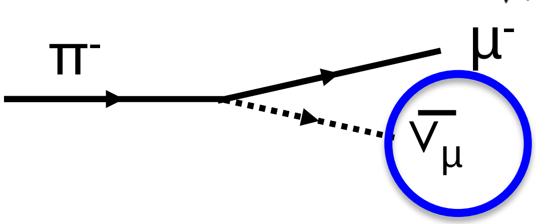
Neutrino mode operation





Antineutrino mode operation





Data driven (NA61) FLUKA/Geant3 based neutrino beam simulation

Significant wrong sign component in antineutrino mode
increases in event rate due to lower antineutrino cross section

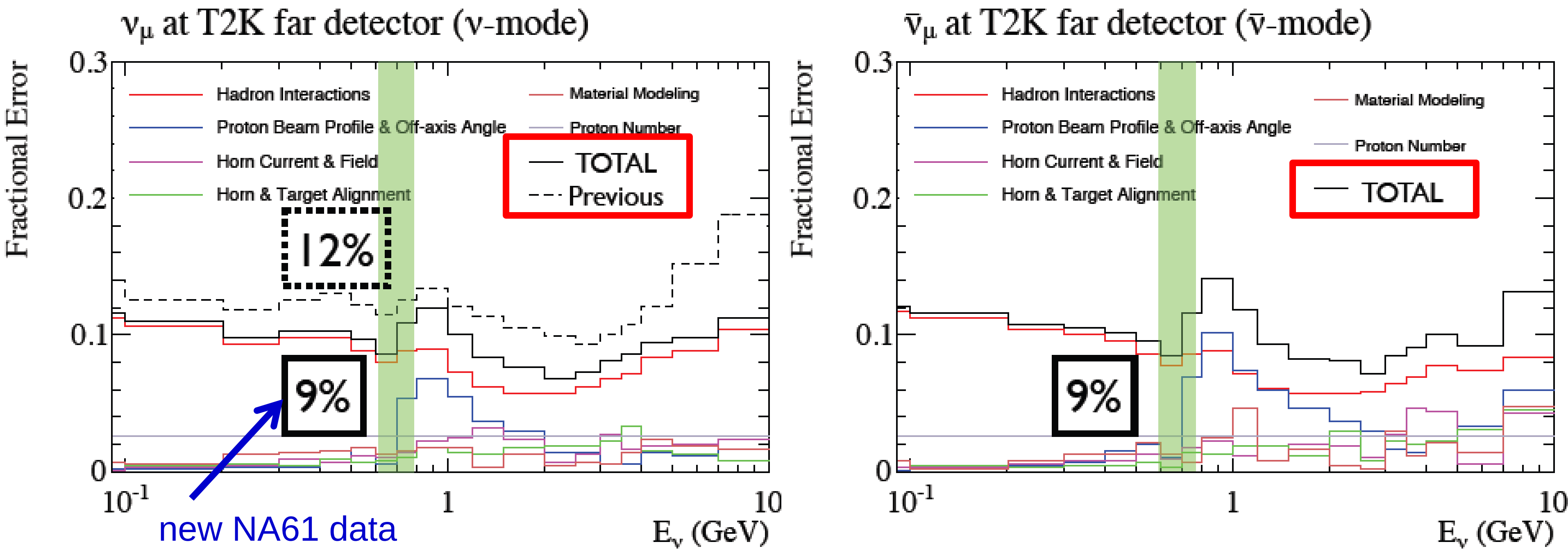
Intrinsic electron neutrino component ~0.5% near the peak

Absolute Neutrino Flux Uncertainties

Beamline related uncertainties
- proton beam profile
- off-axis angle
- horn current and field

Hadron interaction model uncertainties
- NA61 uncertainties
- re-interactions
- secondary hadron production

At T2K peak energy, flux uncertainty has decreased to ~10%

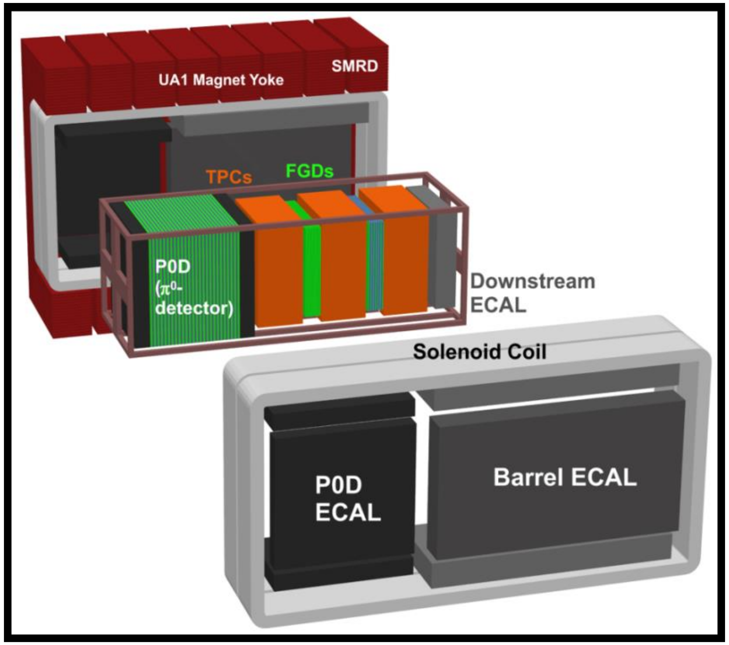


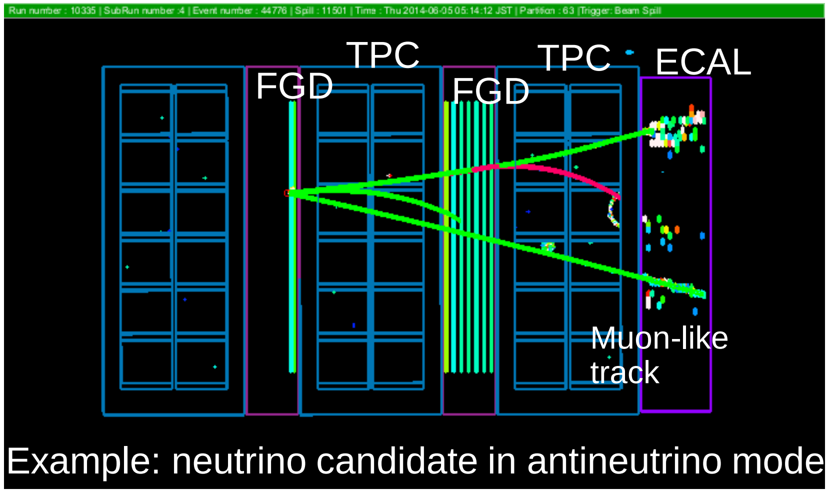
Dominant flux uncertainties stem from hadron interactions

Uncertainties are comparable for neutrino mode and antineutrino mode operation

Replica target data from NA61/SHINE is being incorporated in the T2K flux prediction
→ reduce further systematics

The ND280 Near Detector





Constrains neutrino flux before oscillations
(CC ν_μ and $\bar{\nu}_\mu$ data)

Measures neutrino interactions
on scintillator (CH) and water targets

0.2 T magnetic field

Plastic scintillator detectors
(FGD, POD, ECALs, SMRD)

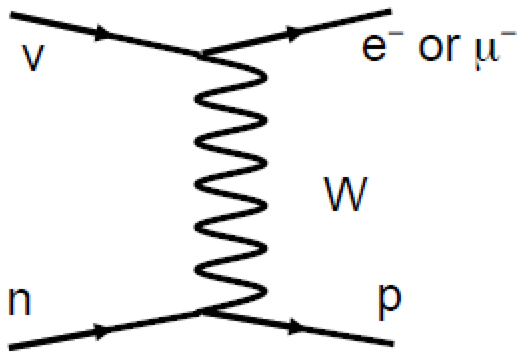
Time Projection Chambers
better than 10% dE/dx resolution

Muon momentum, sign from curvature in magnetic field
10% momentum resolution at 1 GeV/c

Neutrino Interactions

Oscillation probability depends on neutrino energy.
In T2K energy range, dominant process is Charged-Current Quasi-Elastic

CCQE



Neutrino energy from measured lepton momentum and angle

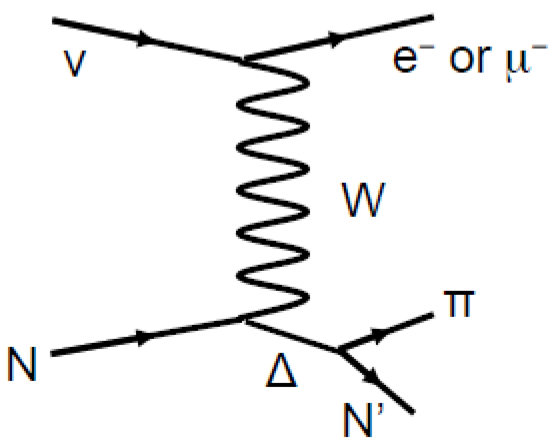
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2-body kinematics and assumes the target nucleon is at rest

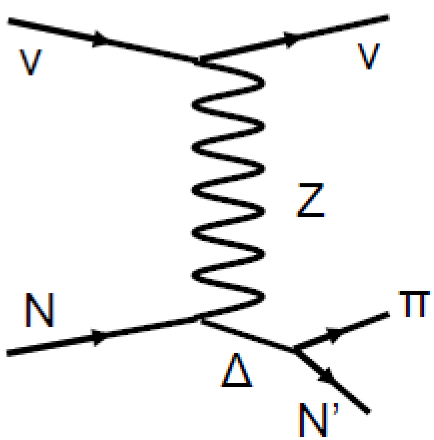
Additional significant processes:

- CCQE-like multi-nucleon interaction
- Charged-current single pion production (CC1π)
- Neutral-current single pion production (NC1π)

CC1π



NC1π



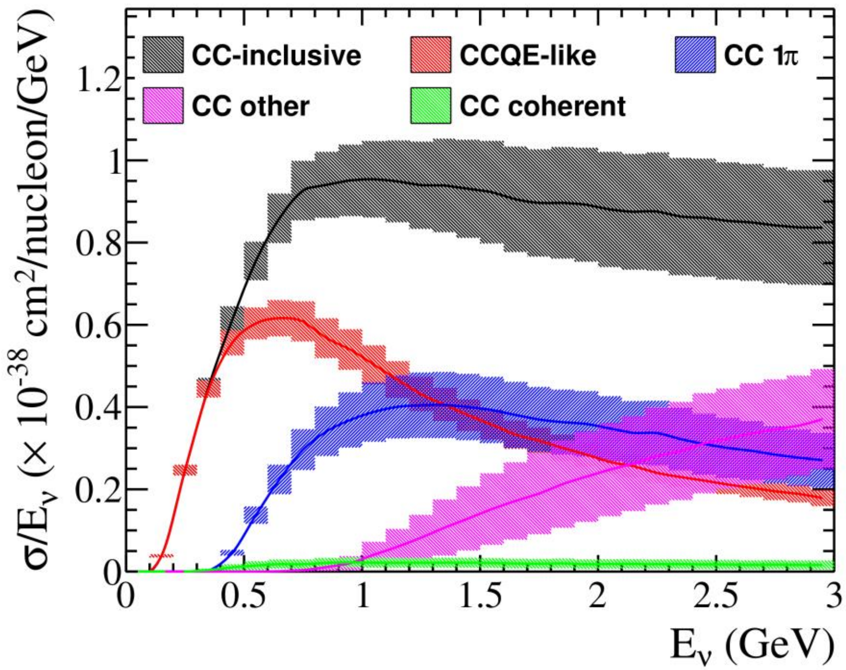
Improved Neutrino Interaction Model

Most recent NEUT generator tuned to external data (MiniBooNE and MINERνA)

Improved CCQE description:
- nuclear effects (Fermi Gas + RPA)
- nuclear correlations (MEC – 2p2h)
- final state interactions (FSI)

Resonant π production retuned

Tensions with some data sets remain.
Cross-section model uncertainties come from underlying model parameters and normalization.

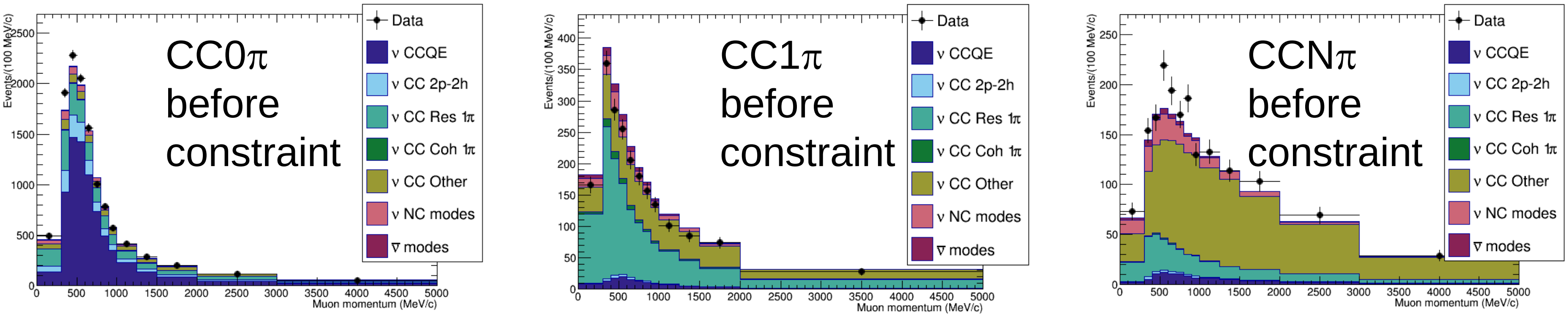


Expected number of events at the far detector is tuned using a binned likelihood fit to the ND280 data (in bins of p_μ and θ_μ) taking into account
- variations in the flux model parameters
- cross-section model parameters
- ND280 detector uncertainties

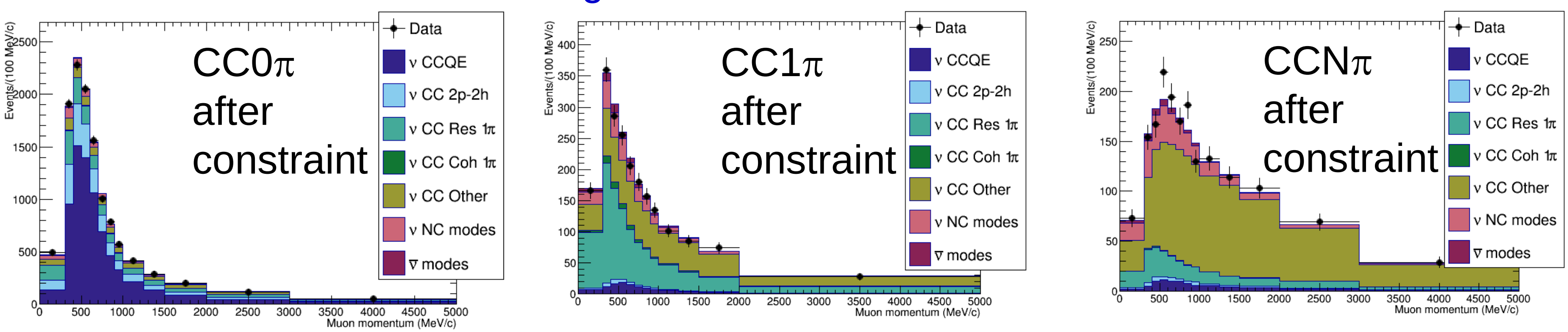
Neutrino interactions separated in CC0π, CC1π, CCNπ (# of outgoing πs)
NEW interactions in ND280 $H_2 0$ target included

ND280 Constraints for Far Detector

neutrino mode example

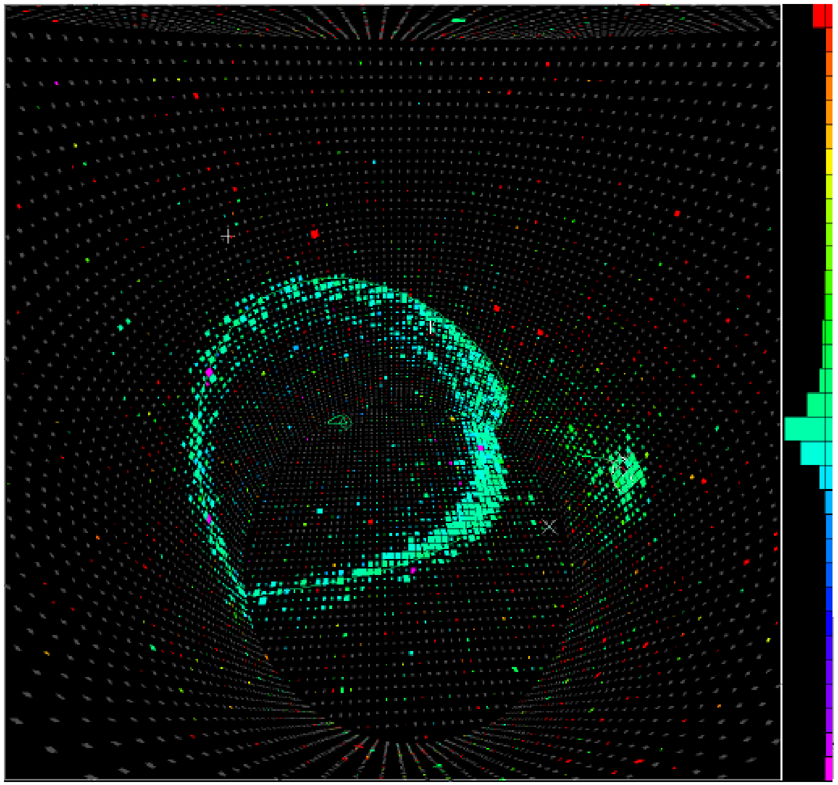


The data is in better agreement after the flux and ND280 constraints

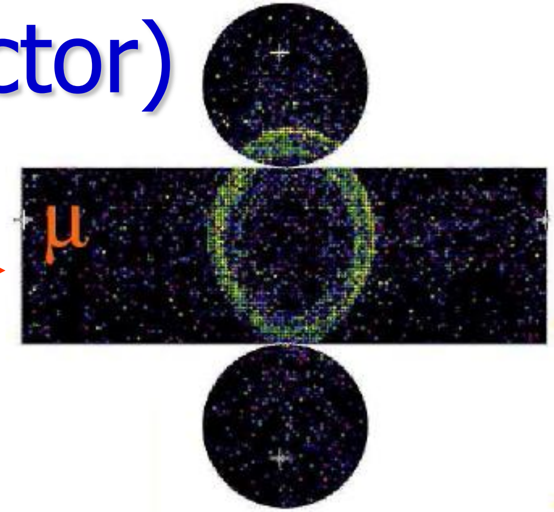


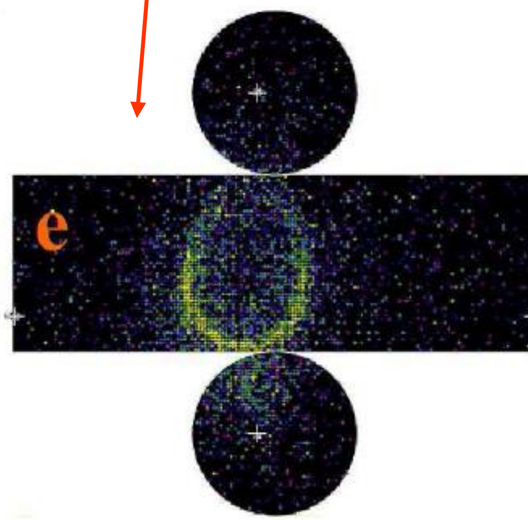
	single ring μ-like $\Delta N_{SK}/N_{SK}$		single ring e-like $\Delta N_{SK}/N_{SK}$	
Systematic uncertainty	pre-fit	**post-fit**	pre-fit	**post-fit**
flux and cross section	10.9 %	**2.5 %**	11.4 %	**2.7 %**
Total	12.1 %	**4.9 %**	11.9 %	**5.2 %**

T2K Typical Events (Far Detector)

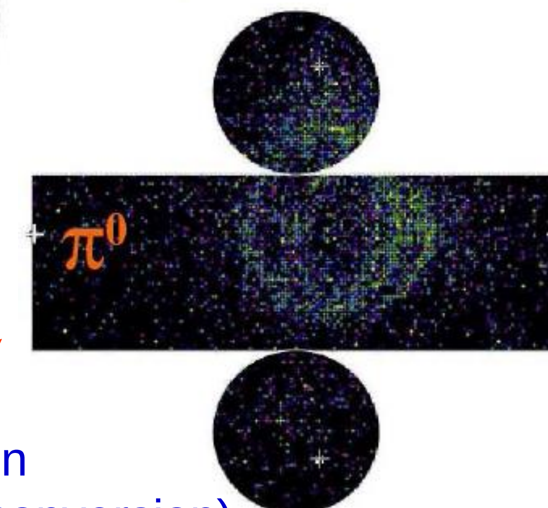


good $\mu - e$ separation





simulated event display (FD response)



background for ν_e appearance:

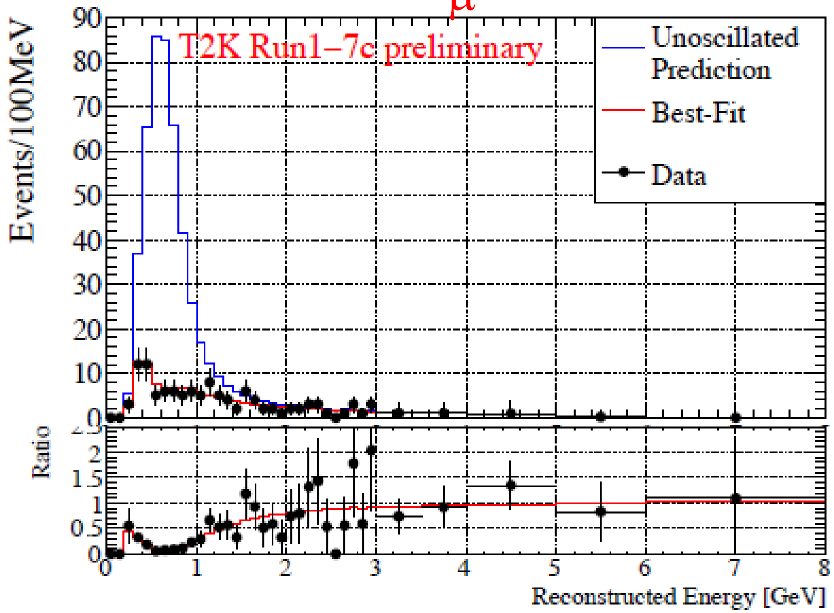
- intrinsic ν_e component in initial beam
- merged π^0 rings from NC interactions

good π^0 rejection
(2 rings from γ conversion)

ν_μ / $\overline{\nu}_\mu$ Disappearance

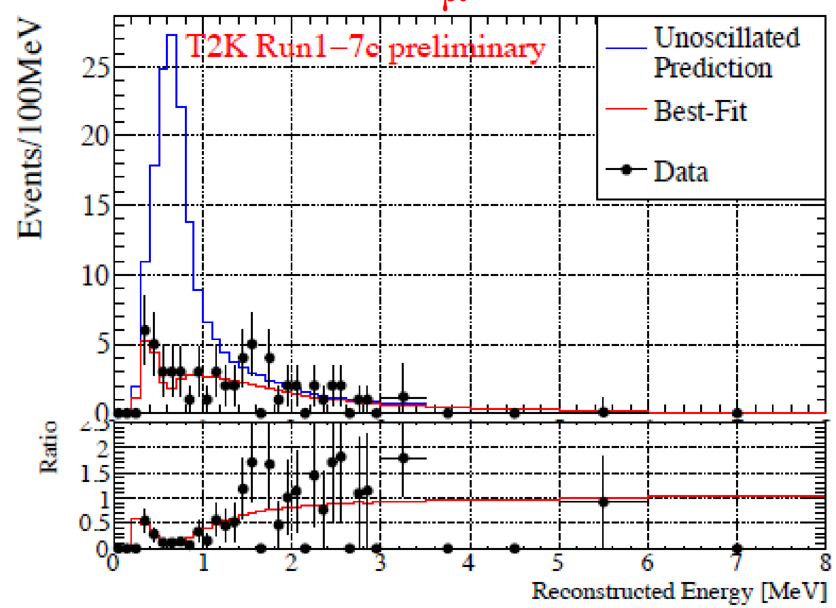
$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

ν_μ



135 events observed
(135.8 ev. expected*)

$\overline{\nu}_\mu$

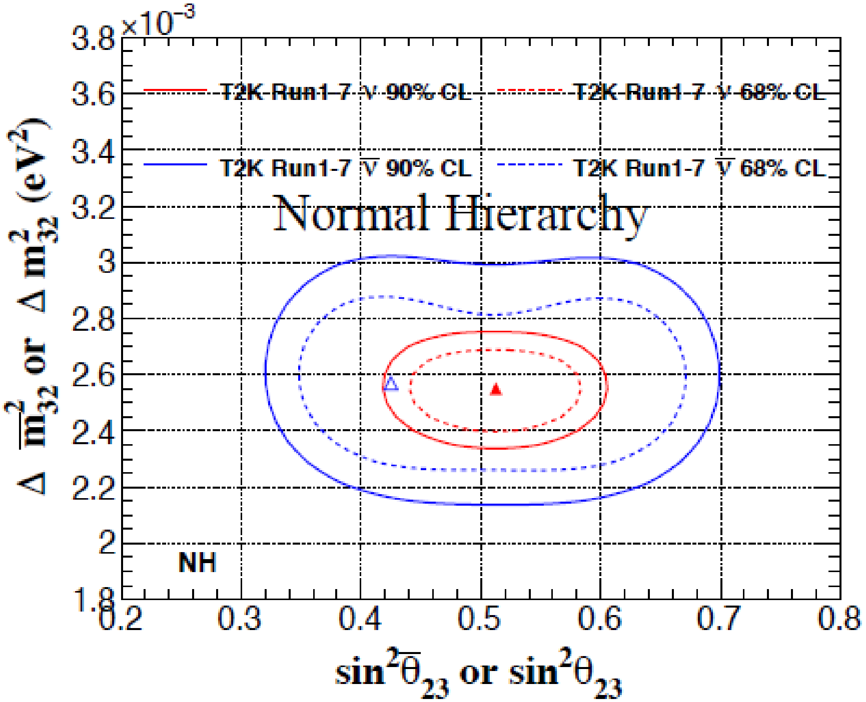


66 events observed
(64.2 ev. expected*)

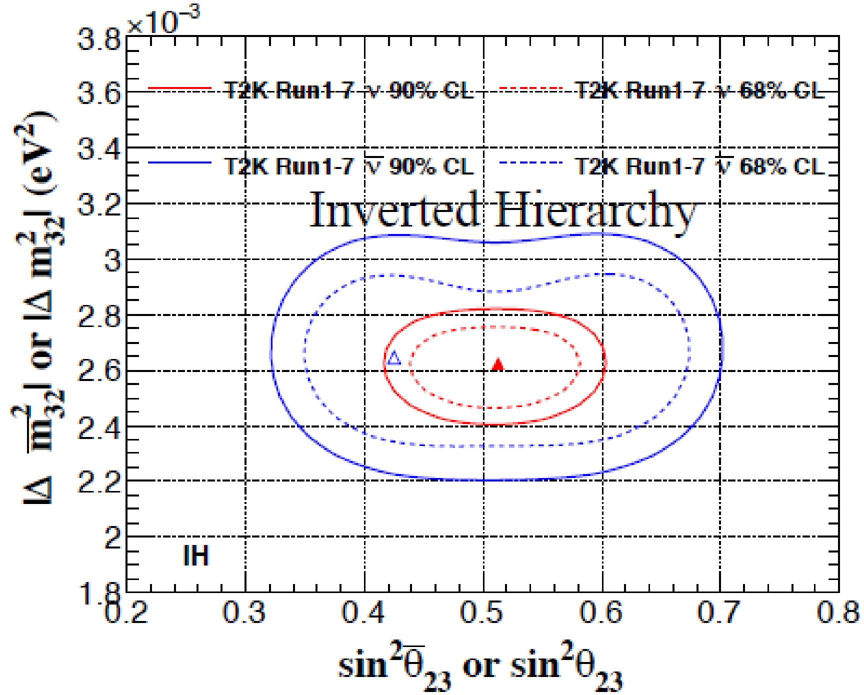
*with $\sin^2\theta_{23}$ = 0.528, $|\Delta m^2_{32}|$ = 2.509 $10^{-3} \times$ eV^2, δ_{CP} = -1.601
from the fit to the ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$ samples
and $\sin^2\theta_{13}$ = 0.0217 from PDG2015

θ_{23} and $|\Delta m^2_{32}|$

Normal Hierarchy



Inverted Hierarchy



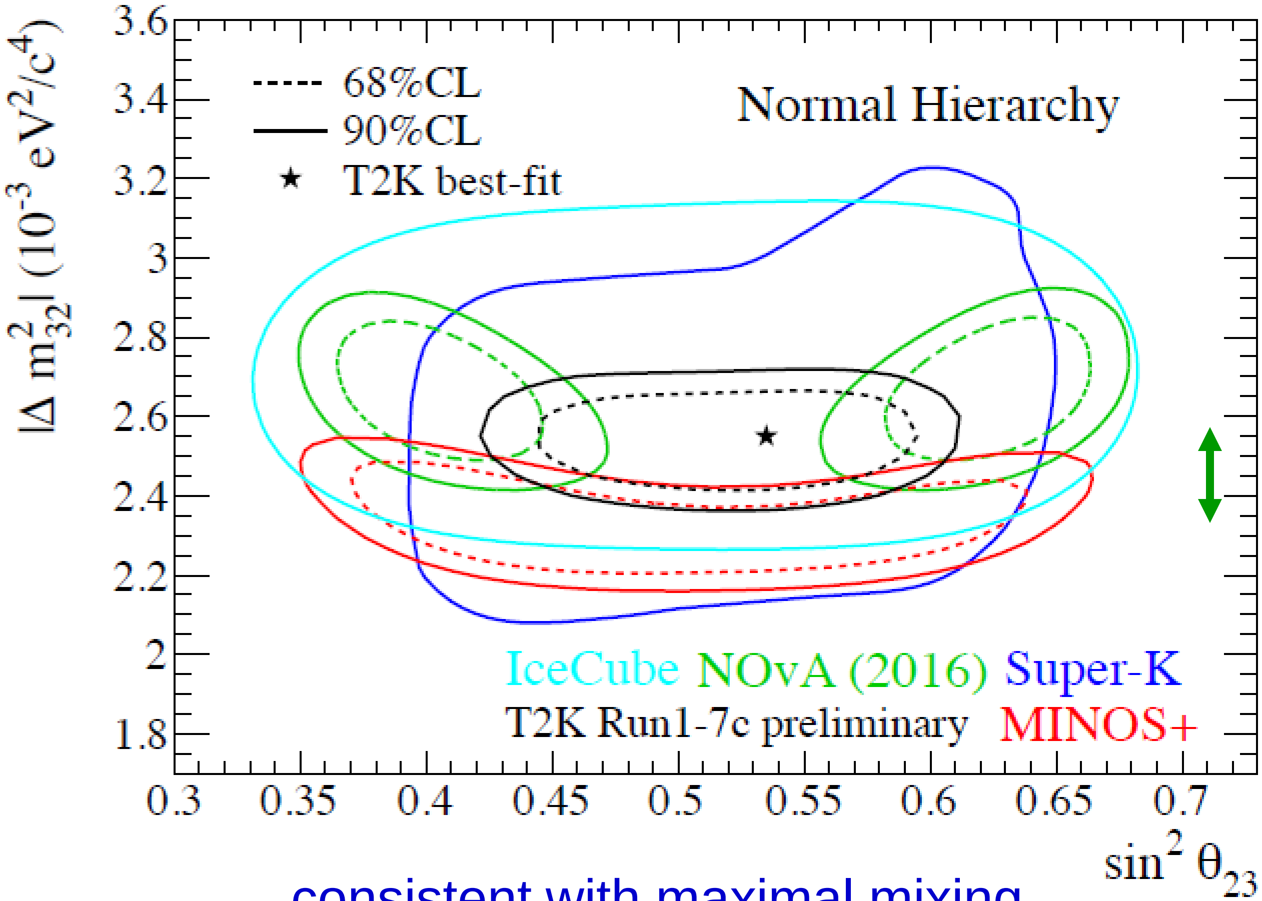
$$\left|\Delta m^2_{32}\right| = [2.34, 2.75]\times 10^{-3}\,\mathrm{eV}^2 \text{ at 90\% CL}$$

$$\sin^2\theta_{23} = [0.42, 0.61] \text{ at 90\% CL}$$

$$\left|\Delta \bar{m}^2_{32}\right| = [2.34, 2.75]\times 10^{-3}\,\mathrm{eV}^2 \text{ at 90\% CL}$$

$$\sin^2\bar{\theta}_{23} = [0.32, 0.70] \text{ at 90\% CL}$$

θ_{23} and $|\Delta m^2_{32}|$



DayaBay

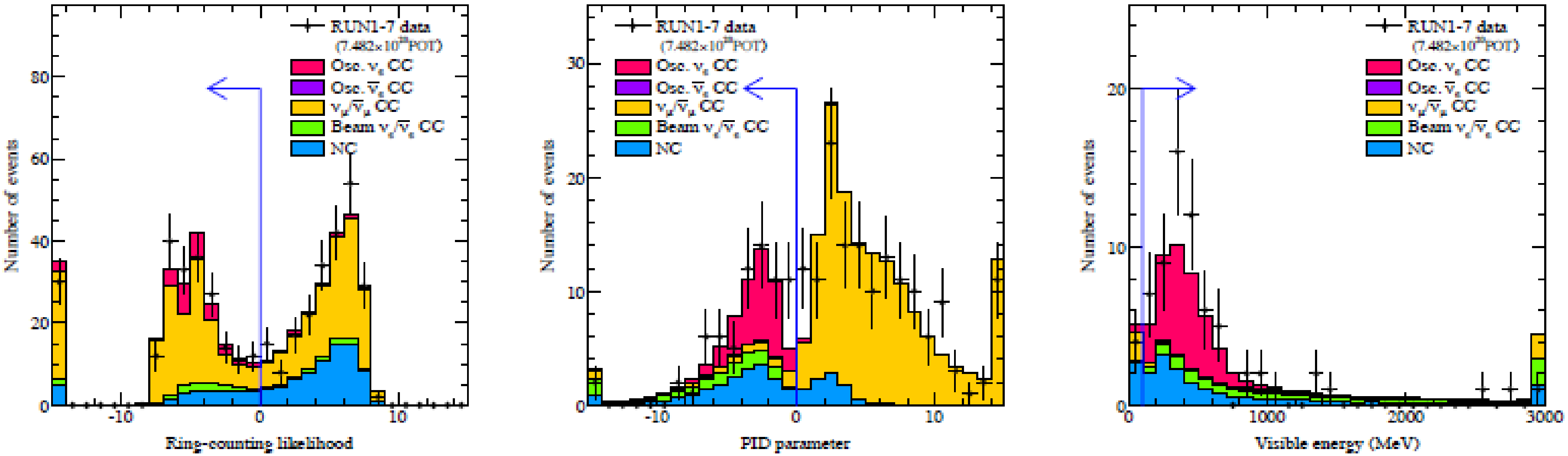
$$\left|\Delta m^2_{ee}\right| = \left(2.45 \pm 0.08\right) \times 10^{-3}\,\mathrm{eV}^2$$

at 90% CL (NH)

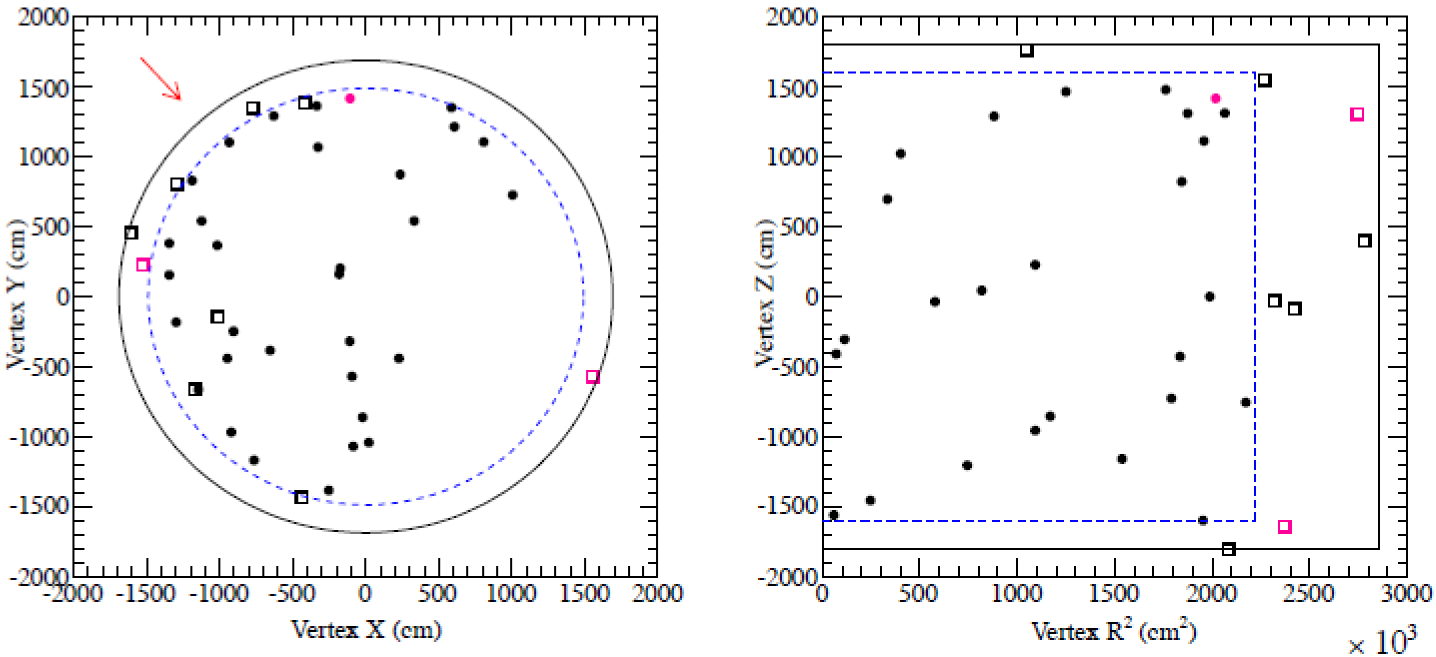
consistent with maximal mixing

	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

ν_e Far Detector Selection

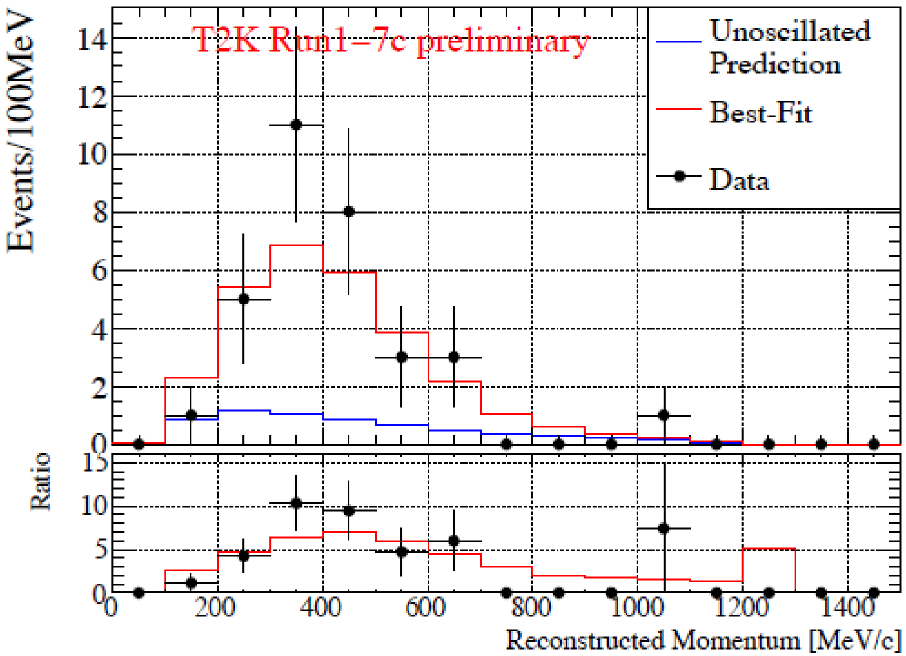


distribution of ν_e interaction vertices in SK



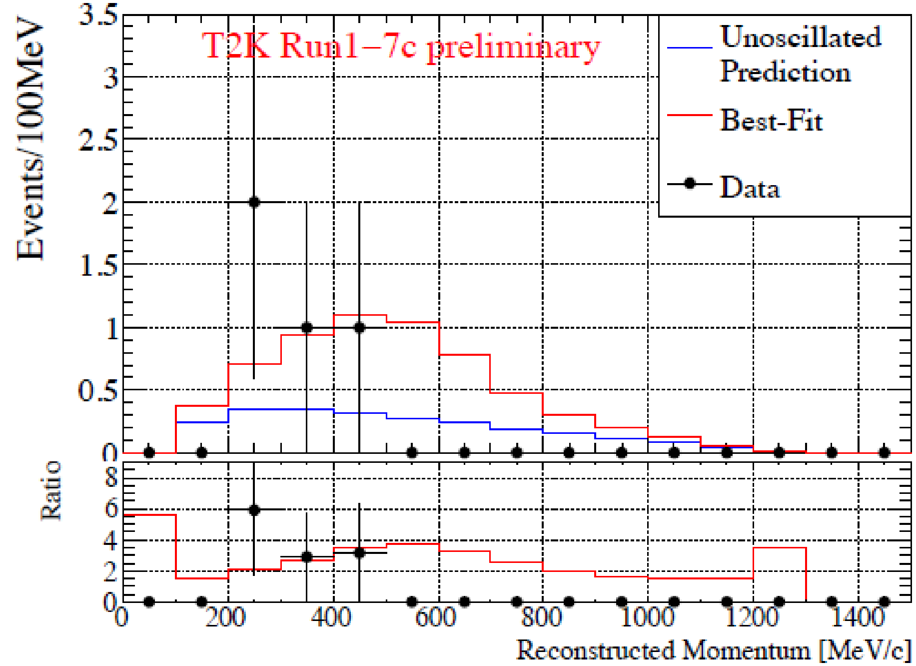
ν_e / $\overline{\nu}_e$ Appearance

ν_e



32 events observed

$\overline{\nu}_e$

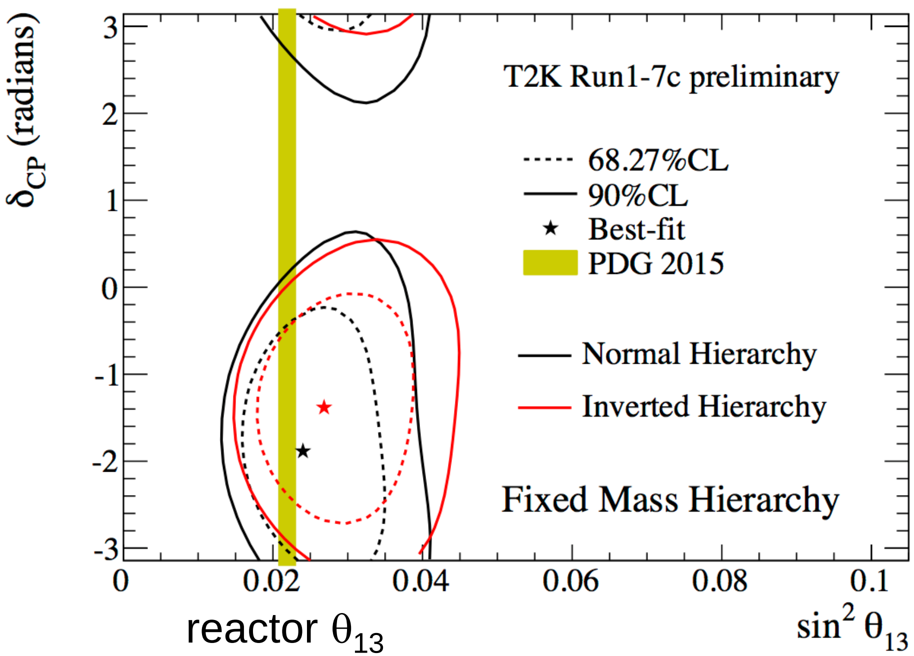


4 events observed

	expected number of events (NH, $\sin^2\theta_{23}$= 0.53)				observed
	δ_{CP} = -π/2	δ_{CP} = 0	δ_{CP} = +π/2	δ_{CP} = π	
ν_e	28.7	24.2	19.6	24.1	32
$\overline{\nu}_e$	6.0	6.9	7.8	6.8	4

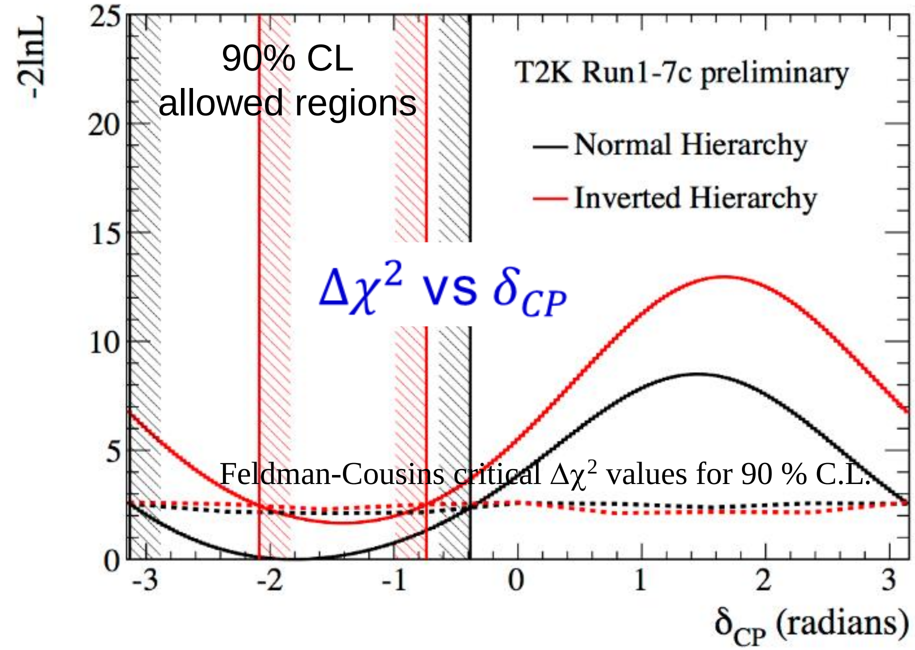
θ_{13} vs δ_{CP}

T2K only



with reactor constraint

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



T2K-only result consistent with reactor measurements

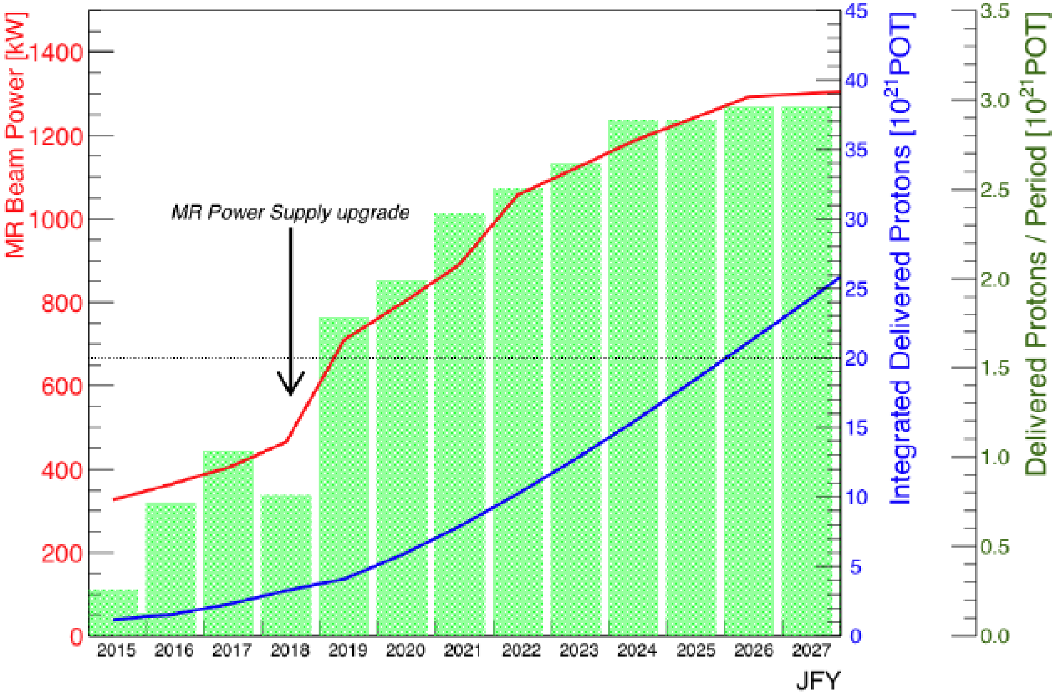
Favors the δ_{CP} ~ - $\pi/2$ region

normal hierarchy: δ_{CP} = [-3.13, -0.39] [-179^0, -22^0] at 90% CL

inverted hierarchy: δ_{CP} = [-2.09, -0.74] [-120^0, -42^0] at 90% CL

T2K to T2K-II

Proposal to extend T2K run to 20×10^{21} POT
Currently approved to 7.8×10^{21} POT



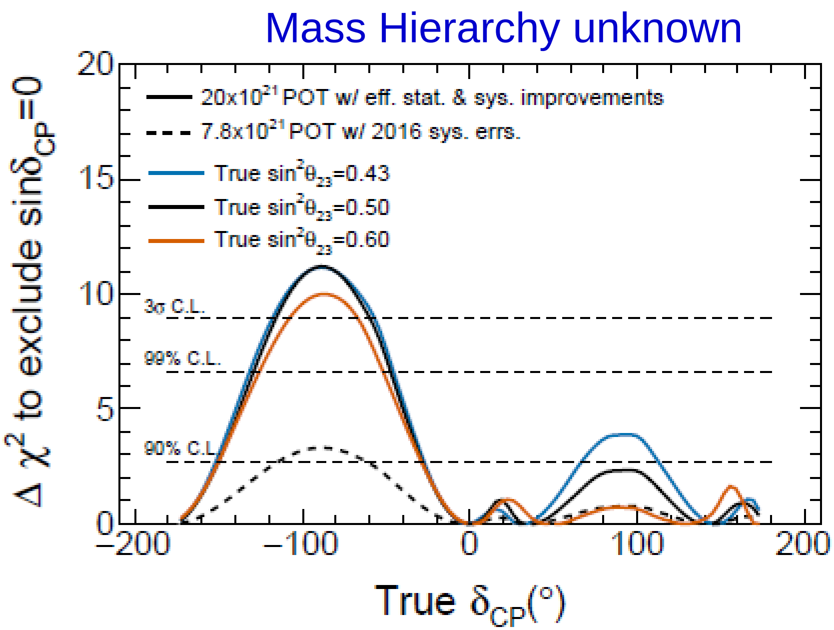
J-PARC main ring power supply upgrade is approved
(reduce cycle from 2.48 sec to 1.3 sec)

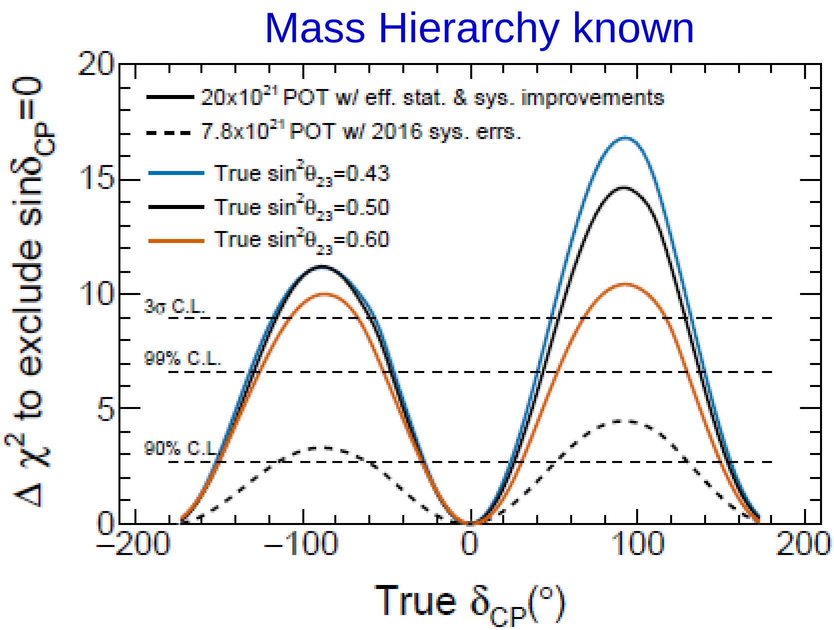
Accelerator and beam line upgrade aiming at > 700 kW operation

ND280 upgrades under discussion

Physics Potential of T2K-II

arXiv:1607.08004



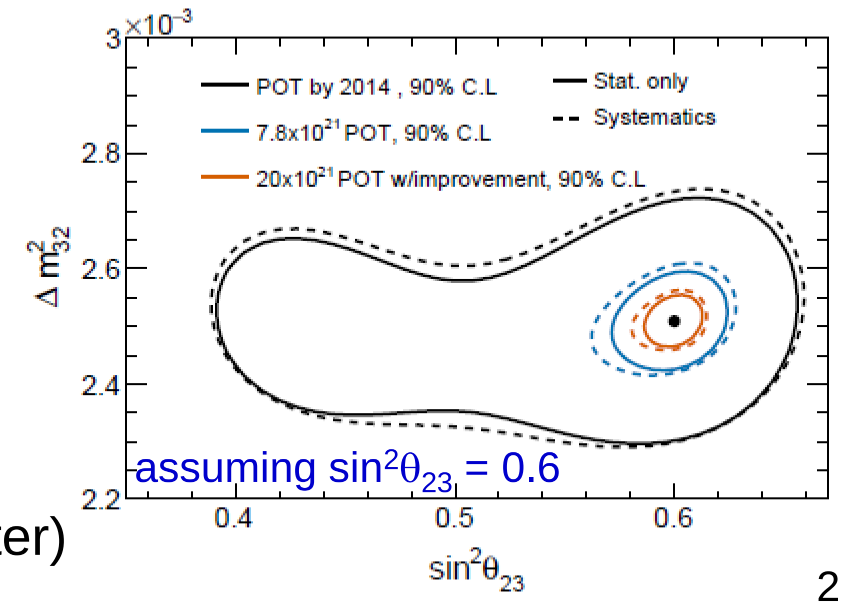


50% increase in effective POT

reduction of systematic errors

3 σ sensitivity to CP violation for favorable (and currently favored) parameters

precise measurement of θ_{23} (to 1.7^0 or better)



Conclusions

Accumulated ~ 15 × 10^{20} protons on target (POT)
equally split in ν-mode and $\bar{\nu}$-mode
Beam power continuously increasing (420 kW at the end of run 7)

Fully joint analysis across all modes of oscillation
ν_μ / $\bar{\nu}_\mu$ disappearance and ν_e / $\bar{\nu}_e$ appearance

Near detector and NA61 hadroproduction data used to constrain rate at far det.
water target and “wrong sign” from ND280

Data prefer maximal θ_{23} mixing, δ_{CP} ~ $-\pi/2$, normal hierarchy

“maximal” ν_μ / $\bar{\nu}_\mu$ disappearance, “large” ν_e appearance, “small” $\bar{\nu}_e$ appearance
δ_{CP} = [-3.13, -0.39] at 90% CL (NH)
δ_{CP} = [-2.09, -0.74] at 90% CL (IH)

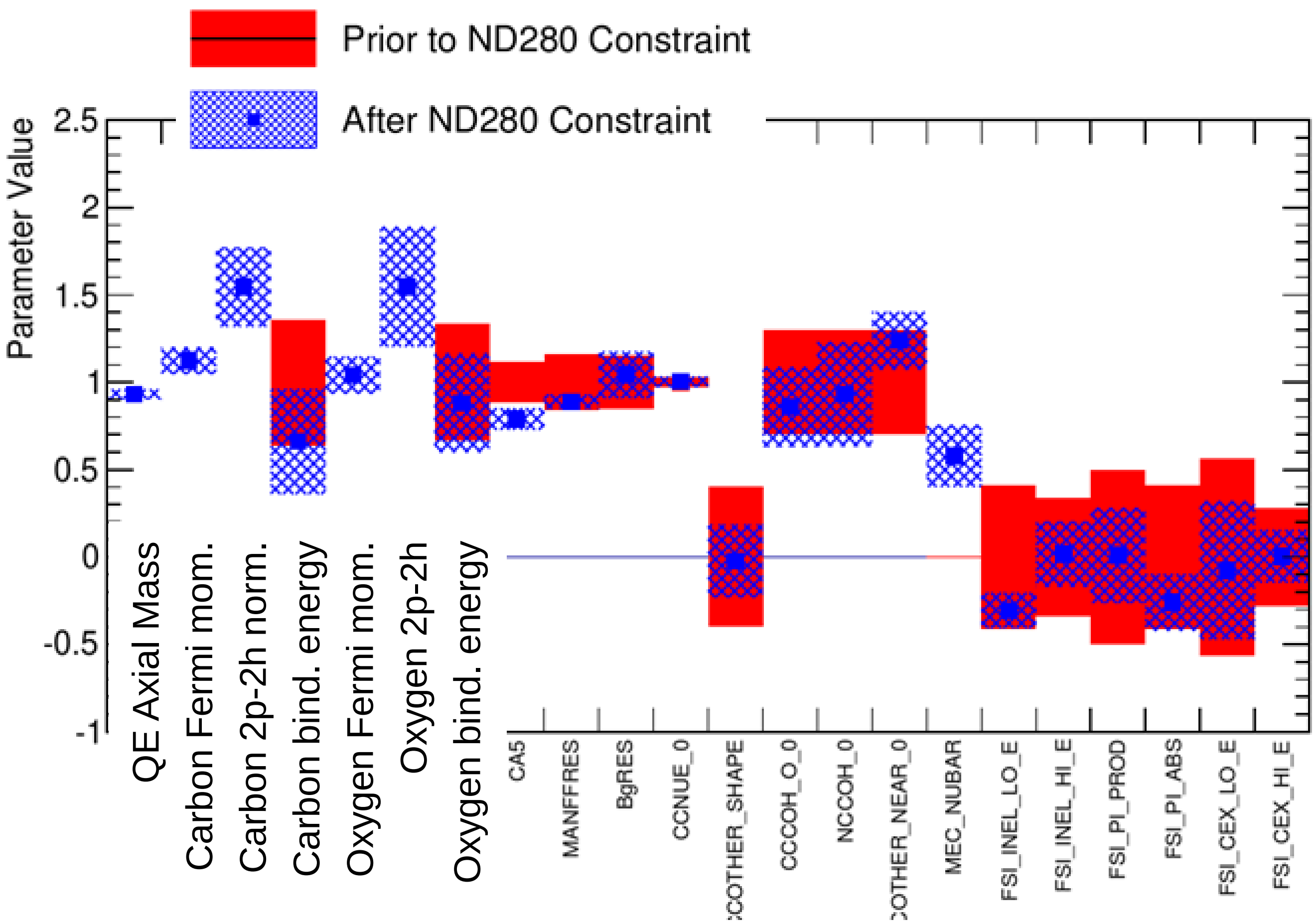
Accelerator upgrade approved, aiming for > 700 kW operation

Proposal to extend T2K (T2K-II)

additional material

Cross-Section Tuning

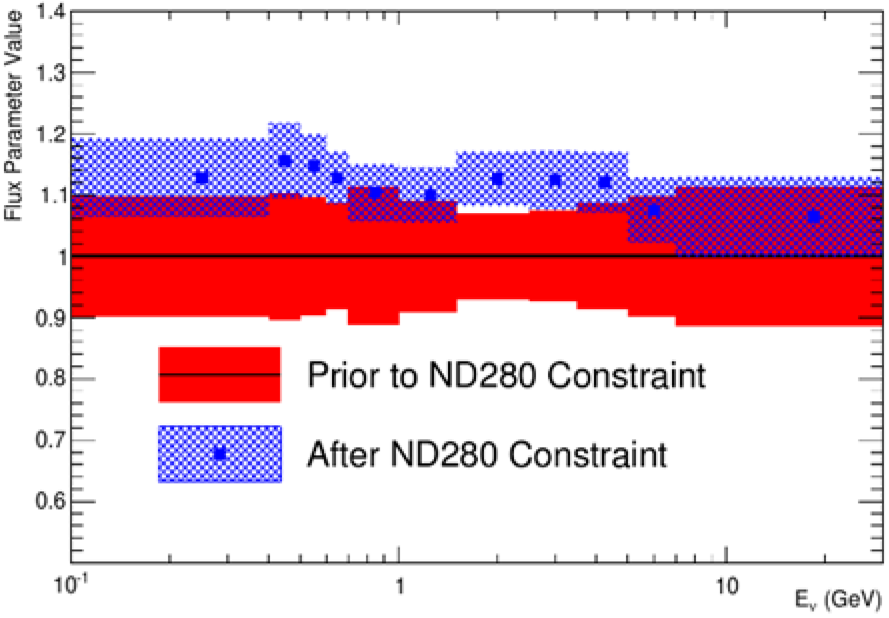
Cross-section model is propagated to far detector rate



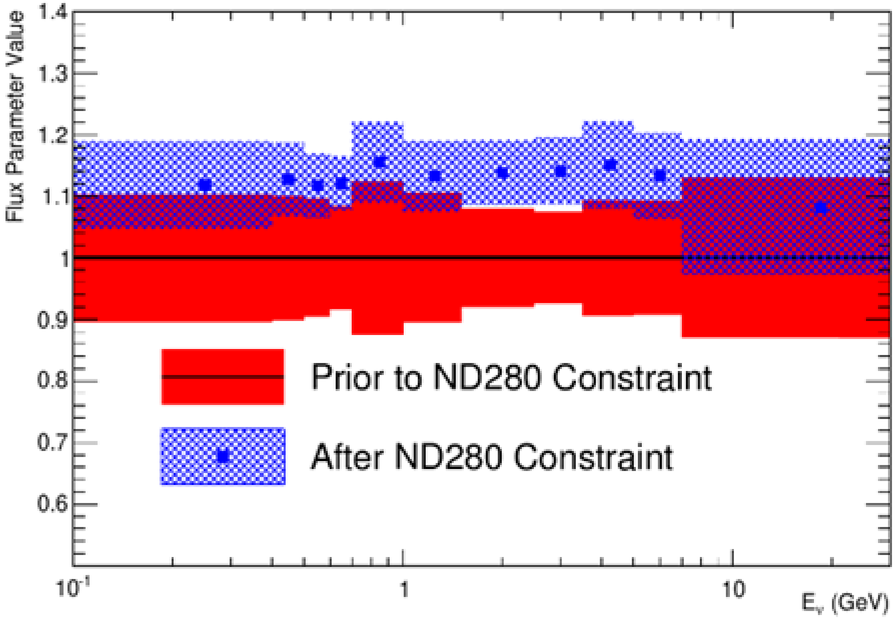
Parameters control CCQE model, multi-nucleon and resonance model
Some cross-section parameters (2p2h on C and O, M_A^{RES}) changed significantly compared to external prior values
In general error on parameters is decreased

Flux Tuning

ν-mode ν_μ flux normalization



$\bar{\nu}$-mode $\bar{\nu}_\mu$ flux normalization



Muon neutrino / antineutrino flux correlates to electron neutrino / antineutrino flux

Increased flux preferred with new cross-section model
$\rightarrow$ predicted flux at far detector is generally increased