T2K: RECENTS RESULTS AND PROSPECTIVE

Gabriella Catanesi
Istituto Nazionale di Fisica Nucleare (INFN) Bari –Italy

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Neutrino Oscillations

If mass and weak eigenstates are different:

- Neutrino is produced in weak eigenstate
- It travels a distance L as a mass eigenstate
- It will be detected in a (possibly) different weak eigenstate

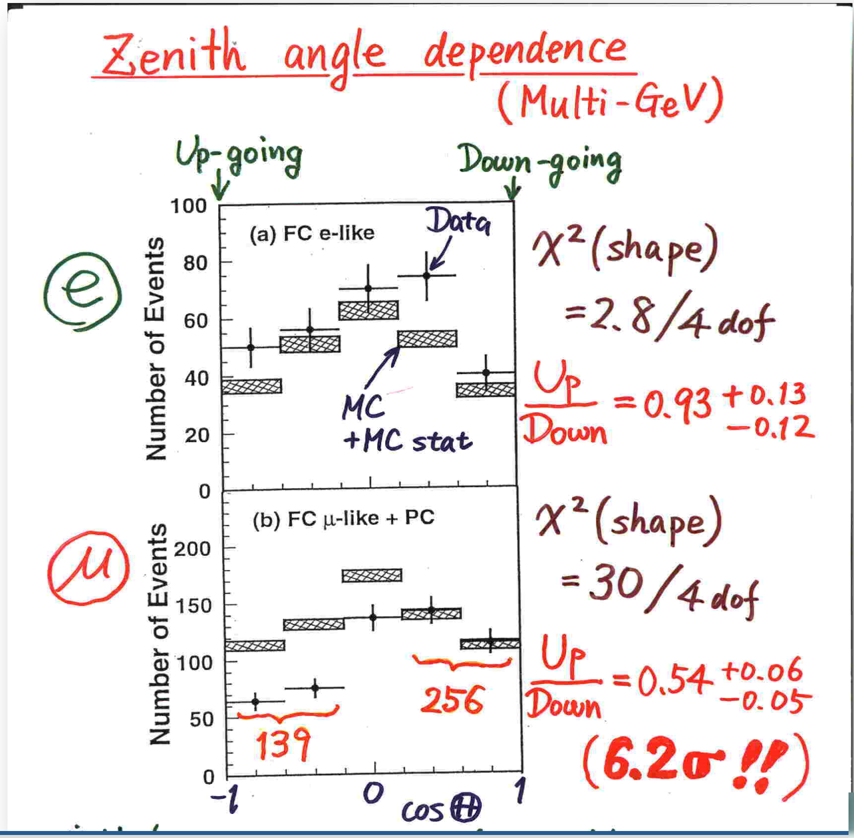
Bruno Pontecorvo
1969

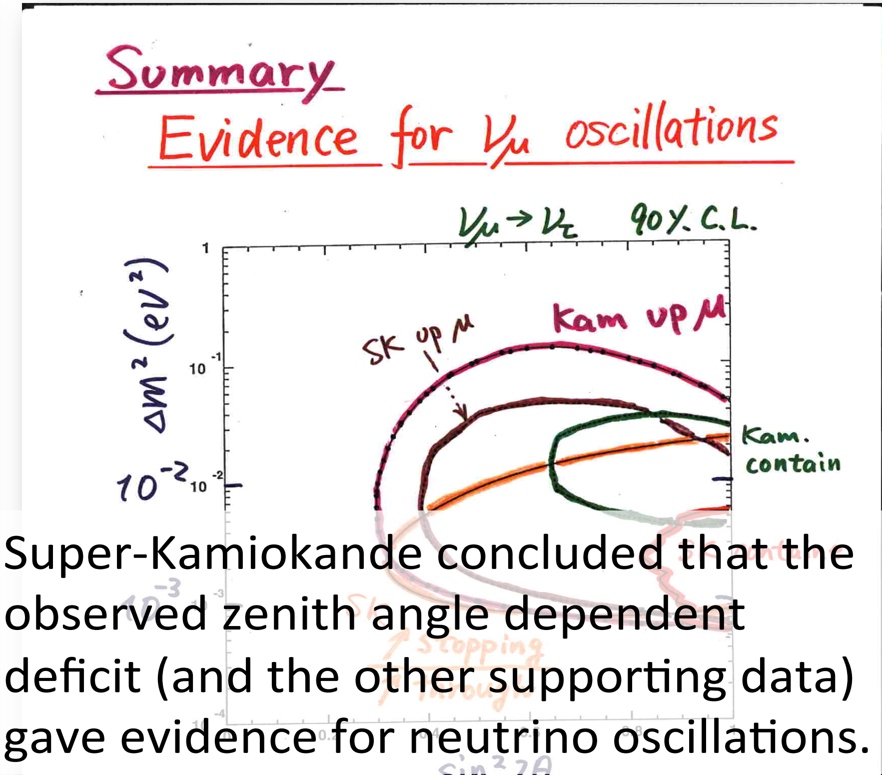
ν_μ → ν_1, ν_2, ν_3 → $\nu_\mu,\ \nu_e$ or ν_τ

$$\begin{pmatrix} \nu_\mu \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_x) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Y. Fukuda et al., PRL 81 (1998) 1562





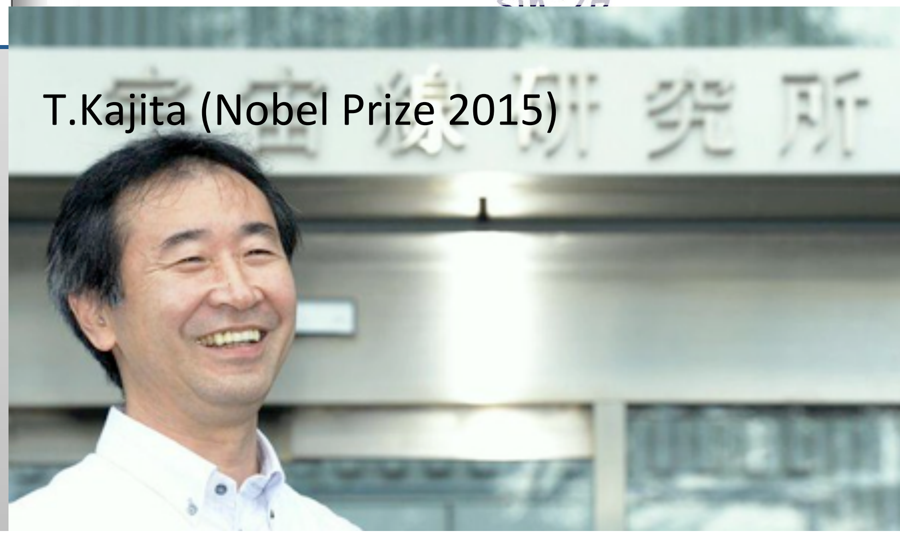
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

$\Delta m^2 \sim 3\times10^{-3}\ eV^2$

L/E ≈ 1000 (KM/GeV)

Long-Baseline

T.Kajita (Nobel Prize 2015)



The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix (before 2011)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \times \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix} \times \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

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

atmosferic ν
accelerator ν

$\sin^2\theta_{23} \sim 1/2$

$\Delta m^2 \sim 3\times10^{-3}\ eV^2$

SBL reactor ν
accelerator ν

Interference

$\sin^2\theta_{13} \sim 0$?

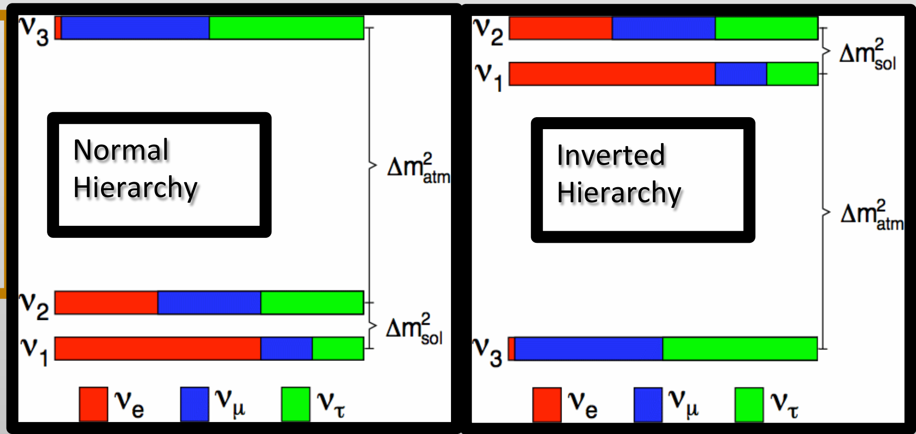
solar ν
LBL reactor ν

$\sin^2\theta_{12} \sim 1/3$

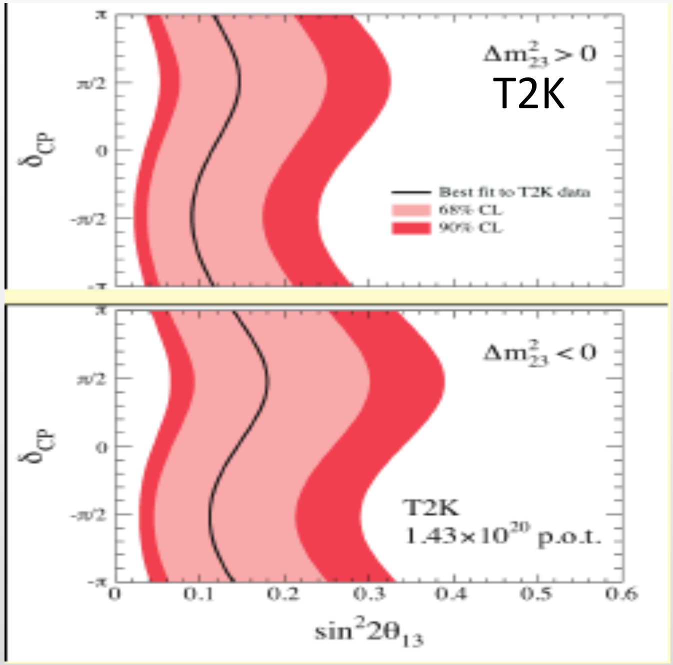
$\delta m^2 \sim 8\times10^{-5}\ eV^2$

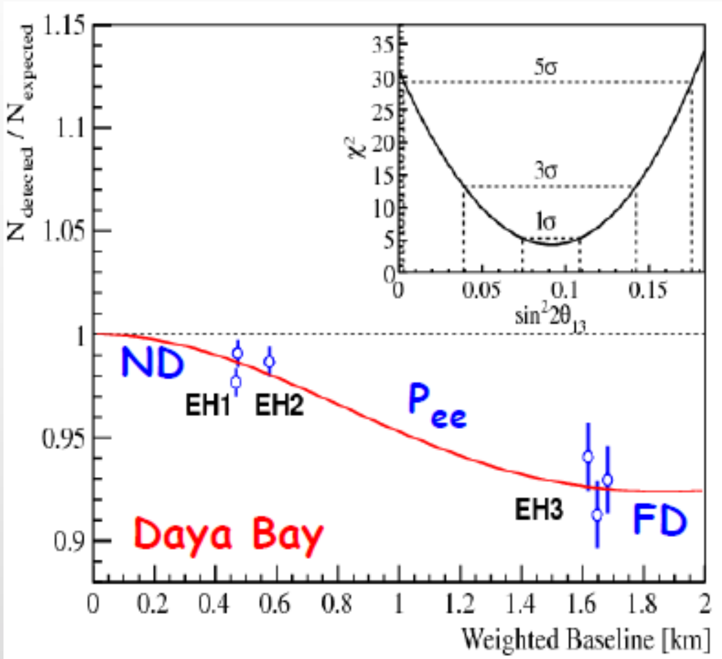
Neutrino sources

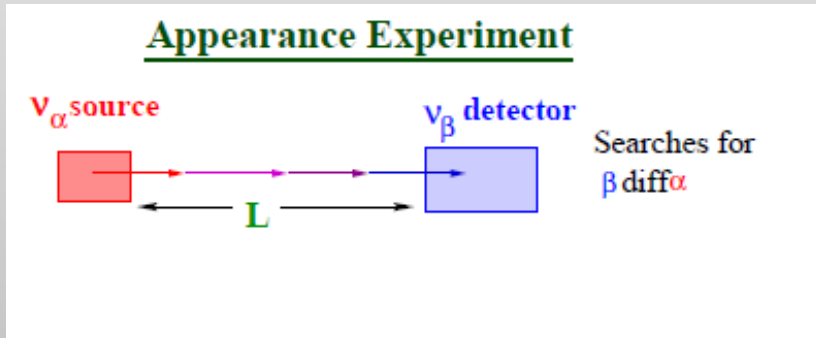
- Natural sources (solar and atmosferic)
- Reactor ν
- Accelerator ν («Long Baseline»)

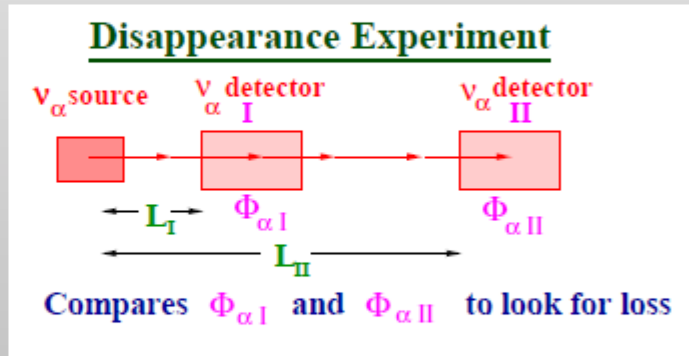


Everything changed in 2011/2012

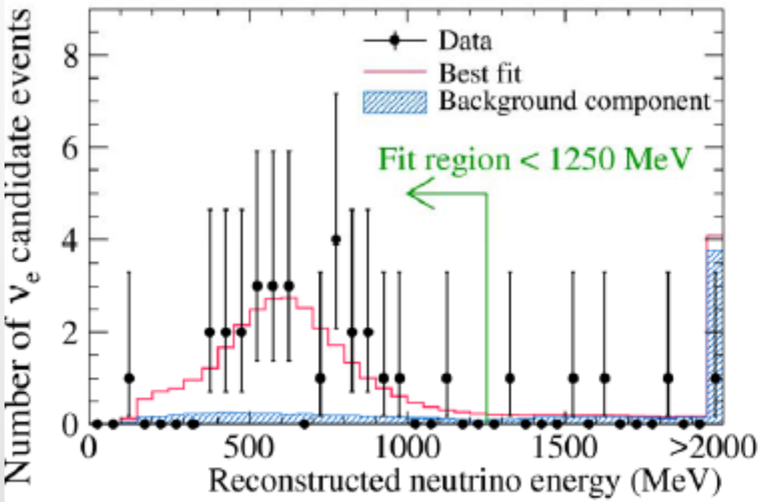




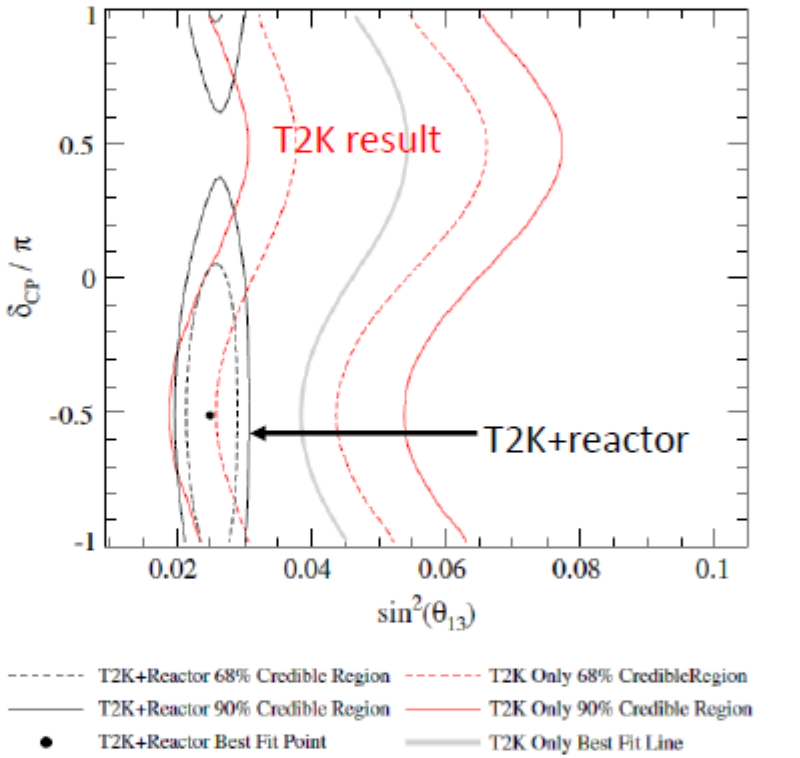




ν_e appearance by T2K



PhysRevLett.112.061802 (2014)



28 events observed over 4.92±0.55 bkgs → 7.3σ excess

First Confirmation of 'Appearance phenomenon' w/ > 5σ significance.

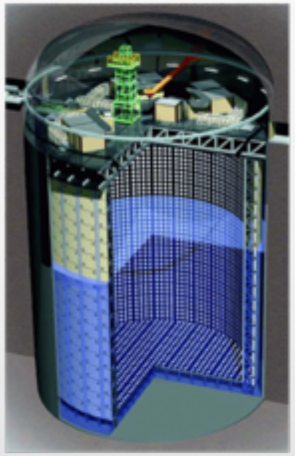
Word's bigger LBL neutrino experiment

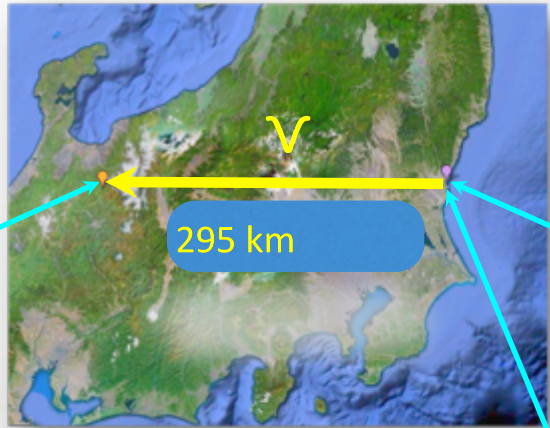
~400 physicists, 58 institutions, 11 nations, 3 continents

Breakthrough prize 2015 **(Nishikawa-san +T2K collaboration)**
for their role in the discovery and study of neutrino oscillation.

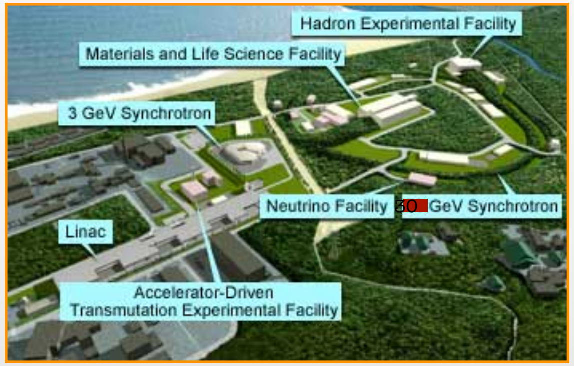
The Tokai to Kamioka (T2K) Experiment

Super-K Detector



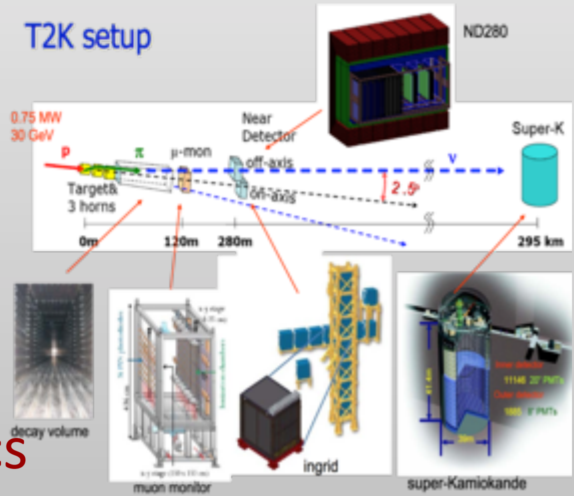


J-PARC Accelerator



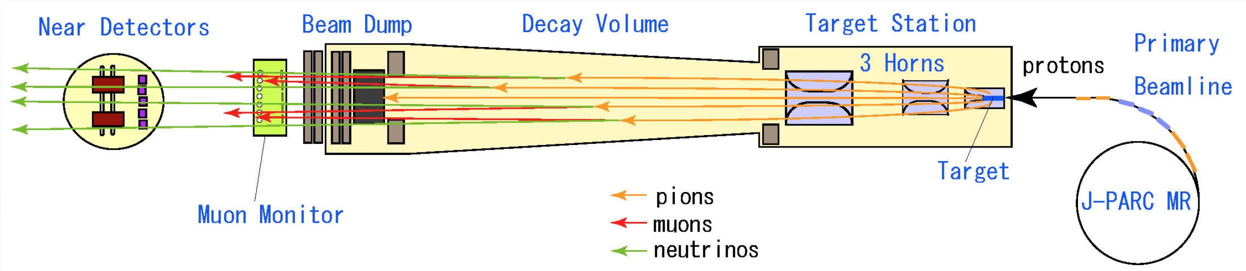
- The T2K experiment searches for neutrino oscillations in a **high purity ν_μ beam**
- A near detector located 280 m downstream of the target measures the un-oscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector

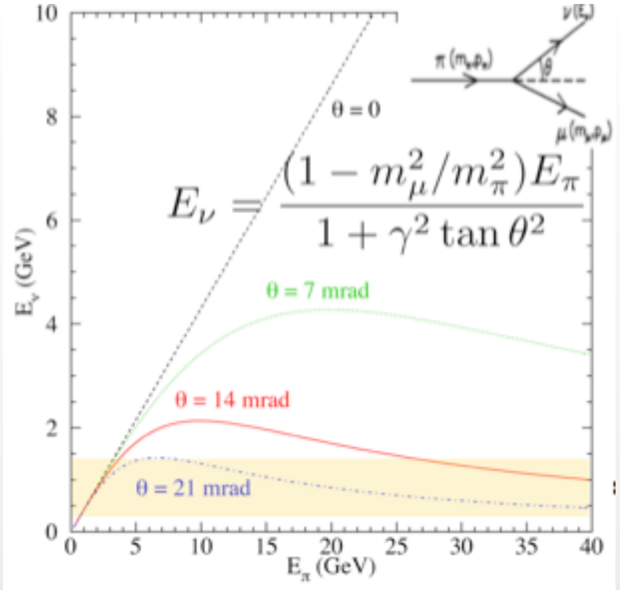
Near Detector



- ν_e appearance
- ν_μ disappearance
- δ_{cp}
- X-section + exotics

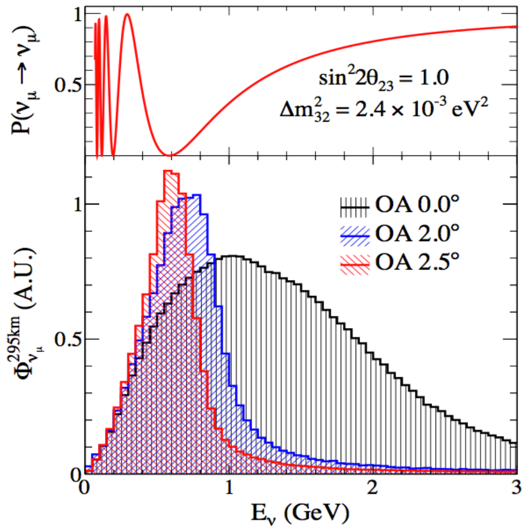
Off-Axis Beam



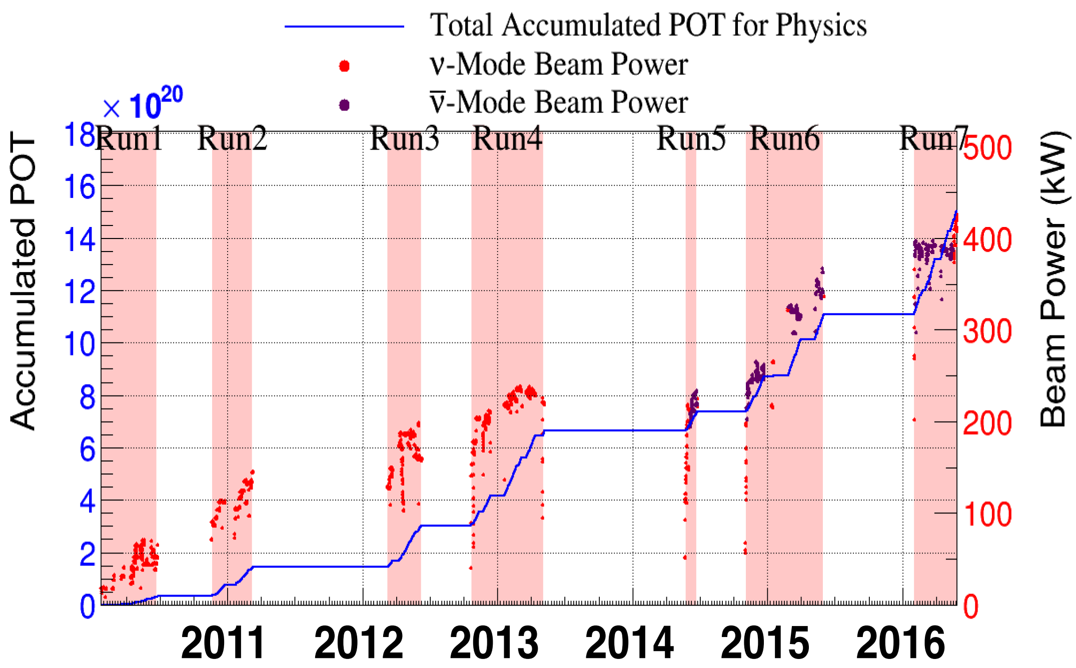


- 30 GeV proton beam generated by J-PARC Main Ring (MR) directed to the graphite target
- Secondary pions collected and focused by the magnetic horns
  - ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (Forward horn current)
  - $\overline{\nu}$ beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$ (Reverse horn current)

- Uses off-axis method to make the spectrum peak at 600 MeV
  - Expected oscillation maximum at L=295 km



Data Taking



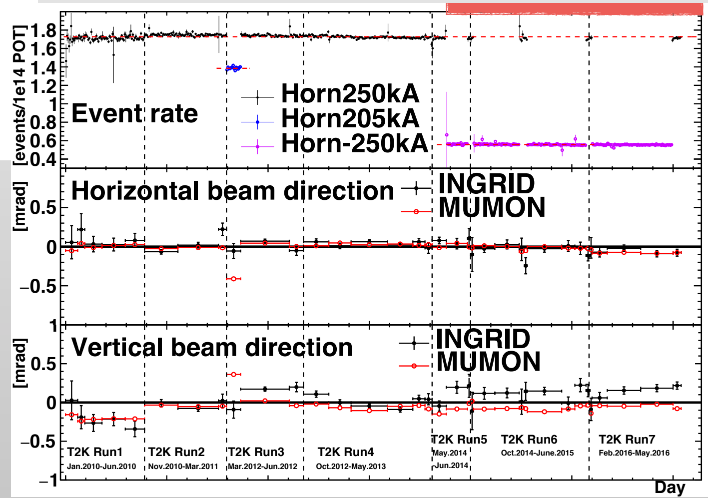
27 May 2016

POT total: 1.510×10^{21}

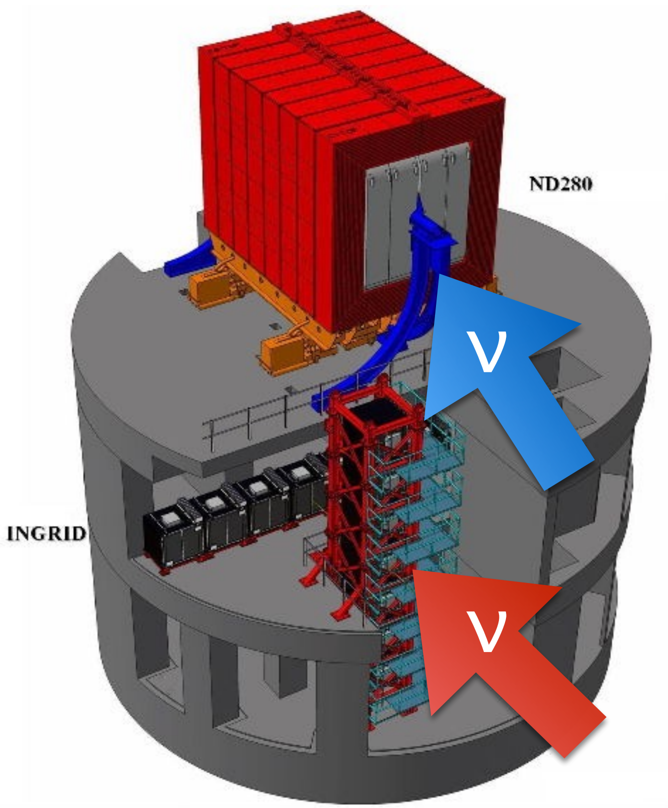
(POT = Proton on target)

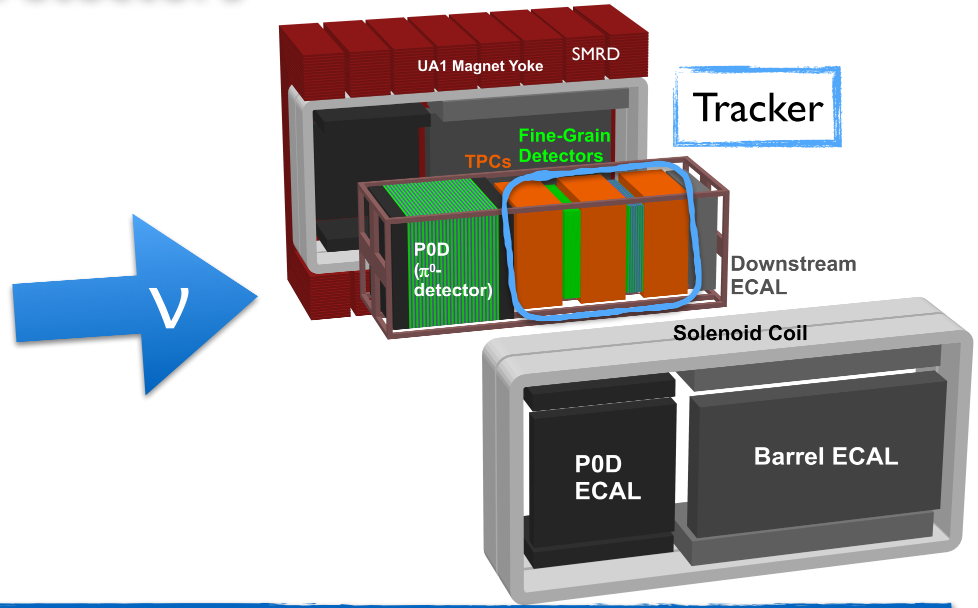
ν-mode POT: 7.57×10^{20} (50.14%)

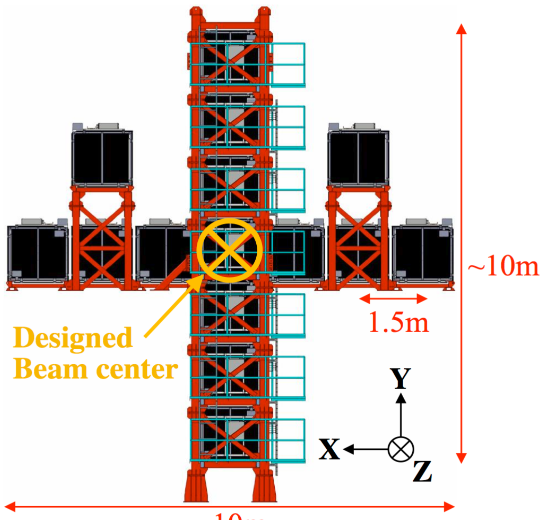
ν̄-mode POT: 7.53×10^{20} (49.86%)



Near Detectors







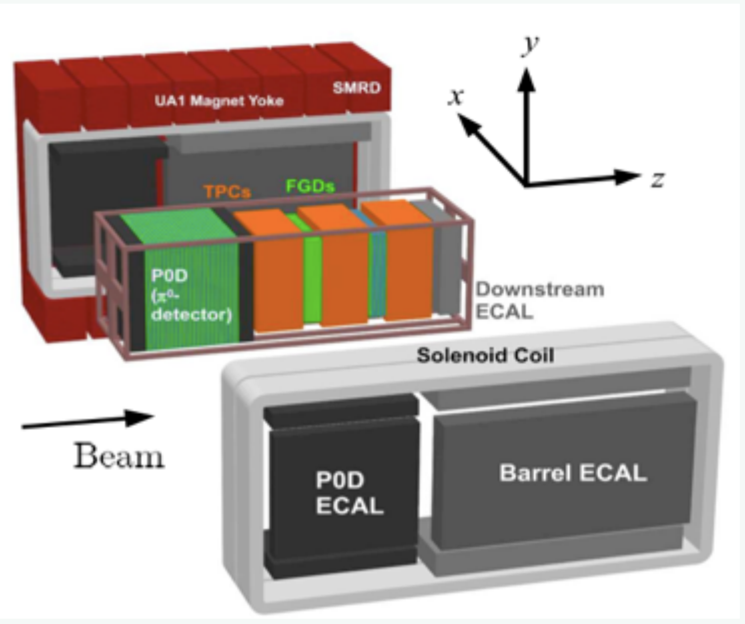
ND280 (off-axis)

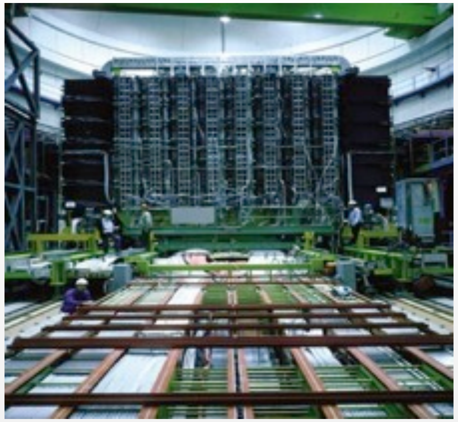
- **Magnet:** B = 0.2 T
- **TPC:** p measurement + particle-ID with dE/dx
- **FGD:** Fine-grained detectors (2 x 0.8 t) → FGD1 (C), FGD2 (C+H_2O)
- **SMRD:** magnetized muon range detector
- **P0D:** pi-zero detector (Pb/brass-H_2O-scintillator)
- **ECal:** electromagnetic calorimeter

INGRID (on-axis)

- **ν_μ CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (16 Fe/Scint modules + 1 central one made of scintillator only)

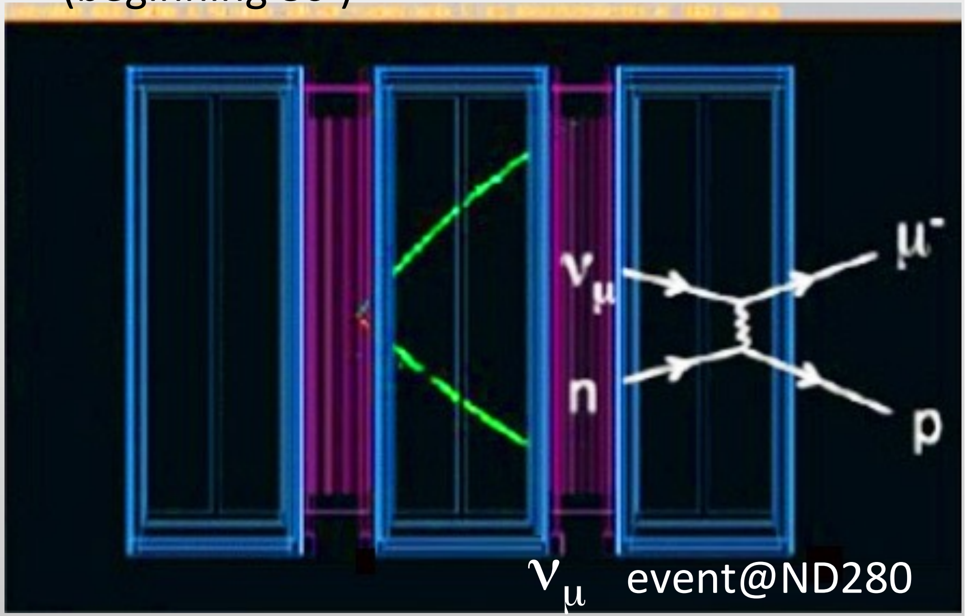
ND280



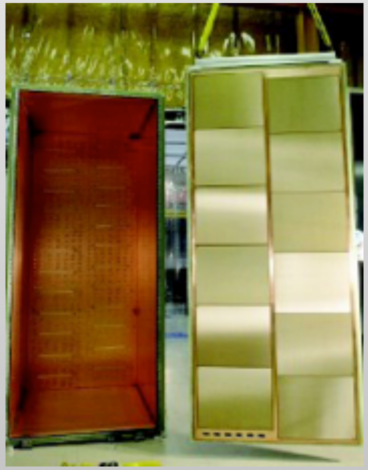


UA1 Magnet@CERN
(beginning 80')

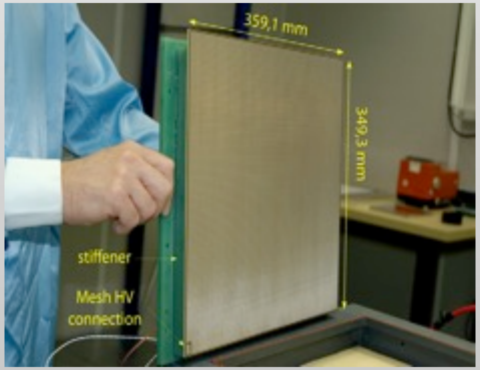
ND280 Installation



ν_μ event@ND280

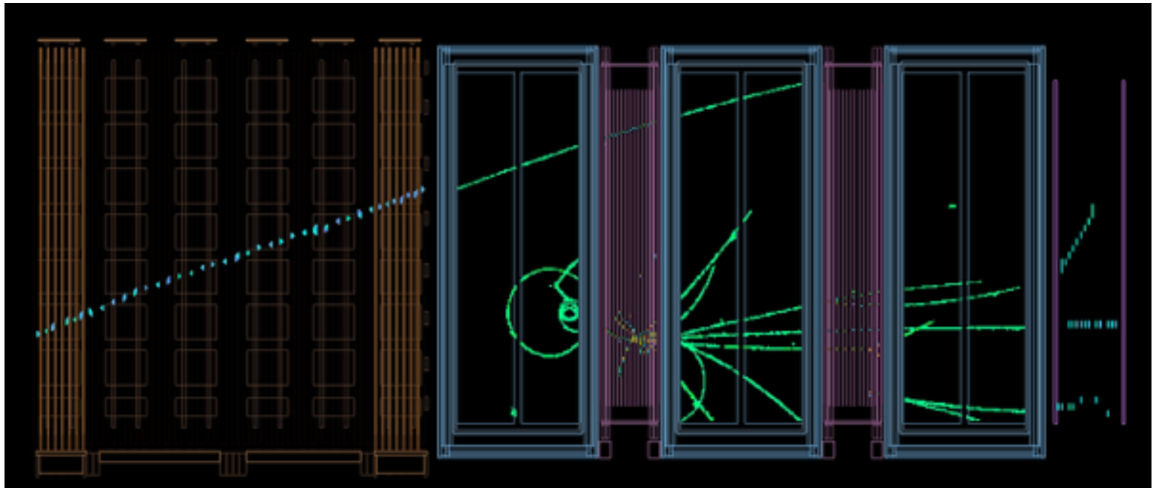


TPC assembling



TPC design with advanced
detectors (MPGD)

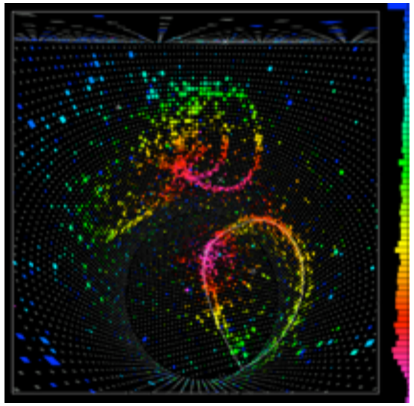
ANALYSIS STRATEGY



Near detectors observe the neutrinos prior to oscillations

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{NEAR}$

ε_{FAR}

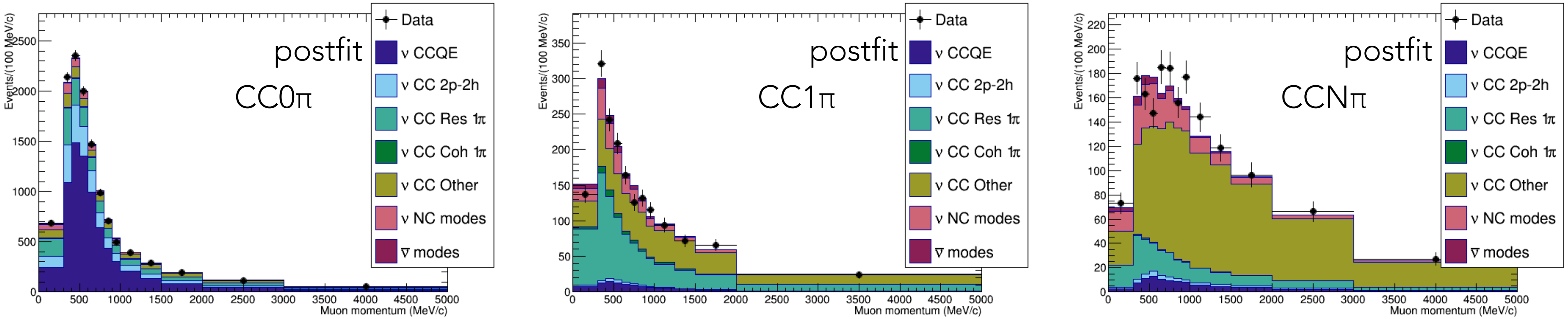


$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot \mathbf{P_{osc}}$

- Use near detector neutrino interactions to constrain flux x **σ** uncertainty across
  - different topologies
  - carbon and water targets (FGD1/FGD2)
  - "wrong sign" ν_μ-CC in $\bar{\nu}$-mode beam

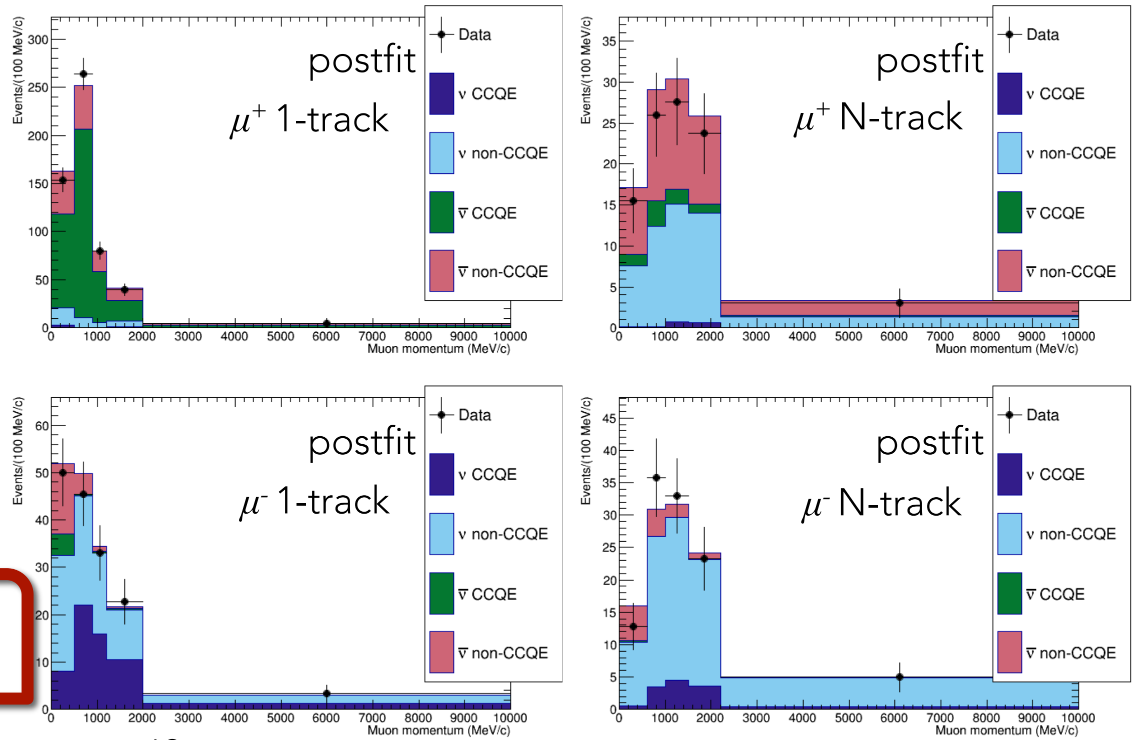
	FHC		RHC	
	ν_μ	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_e$
φ	3.6	3.7	3.7	3.8
σ	4.1	5.2	4.1	5.4
SK	4.2	3.5	3.9	4.0
PREFIT	11.9	12.6	12.7	14.3
TOTAL	5.1	6.8	5.1	7.4

Neutrino Flux @ Nd280



ν-mode

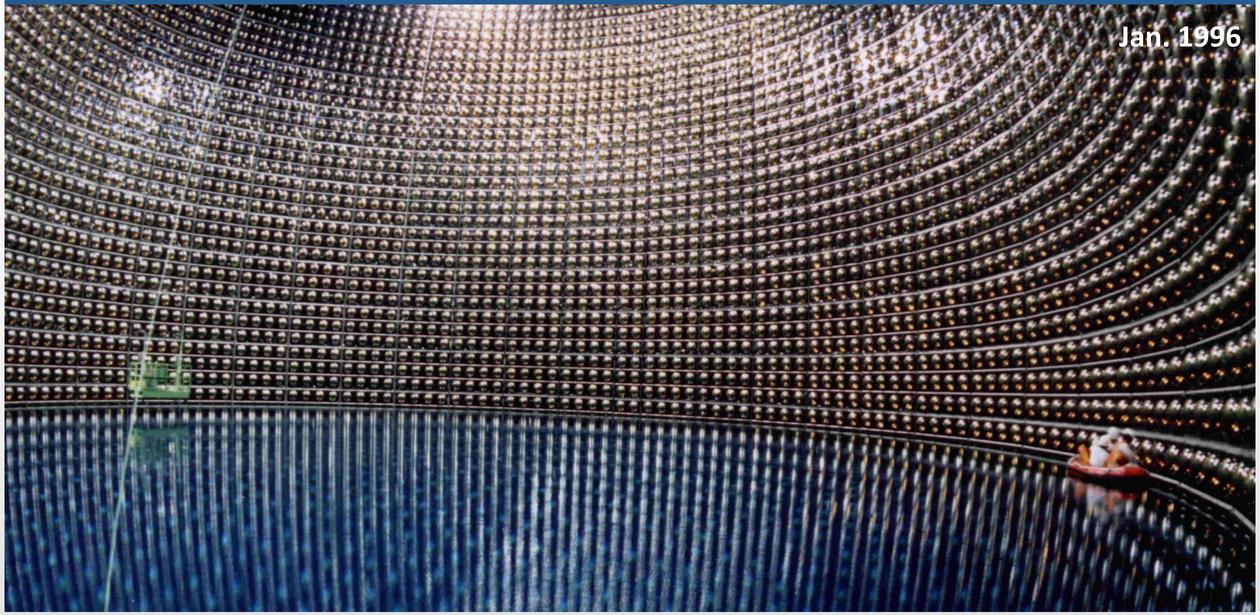
$\bar{\nu}$-mode

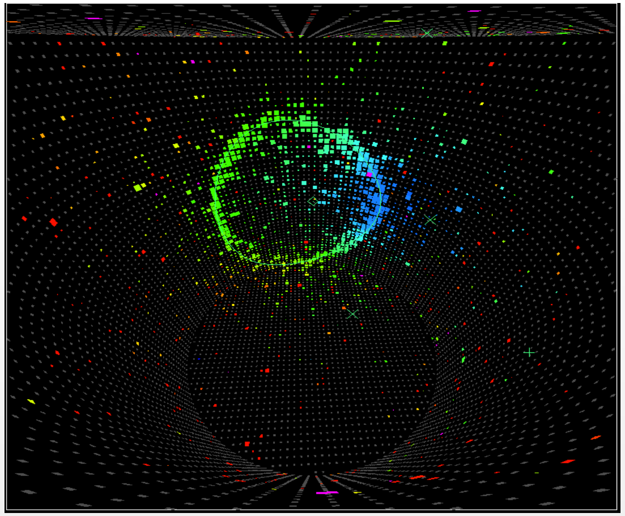


- 6 ν-mode samples (FGD1,2) 5.8x10^{20} POT
  - ν_μ CC0π, CC1π, CCnπ
- 8 ν-mode samples (FGD1,2) 2.8x10^{20} POT
  - $\bar{\nu}_\mu$ CC 1-track, CC N-track + ν_μ "wrong sign"
- simultaneous fit of μ momentum/angle:
  - FGD1 (all plastic) and FGD2 (water+plastic)
  - Flux parameters increase by ~15%
  - Cross sections ~consistent with input
- P-value = 8.6%
- Reduce uncertainties from 12-15% to 5-8%

Super-Kamiokande

Filling water in Super-Kamiokande

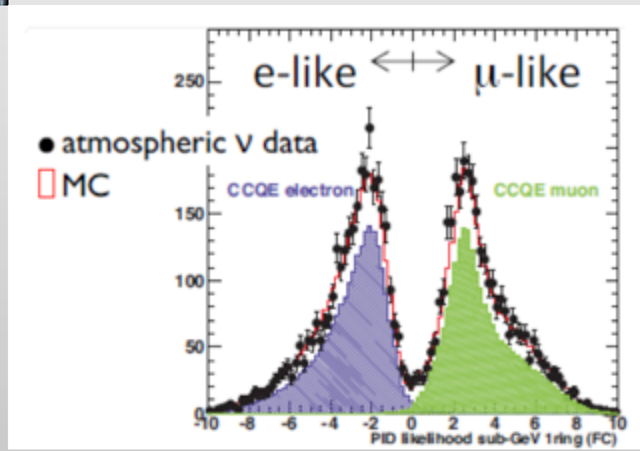




Neutrino interaction
in Super-Kamiokande

One of the 10.000 photosensors of SK

$\varepsilon > 80\%$

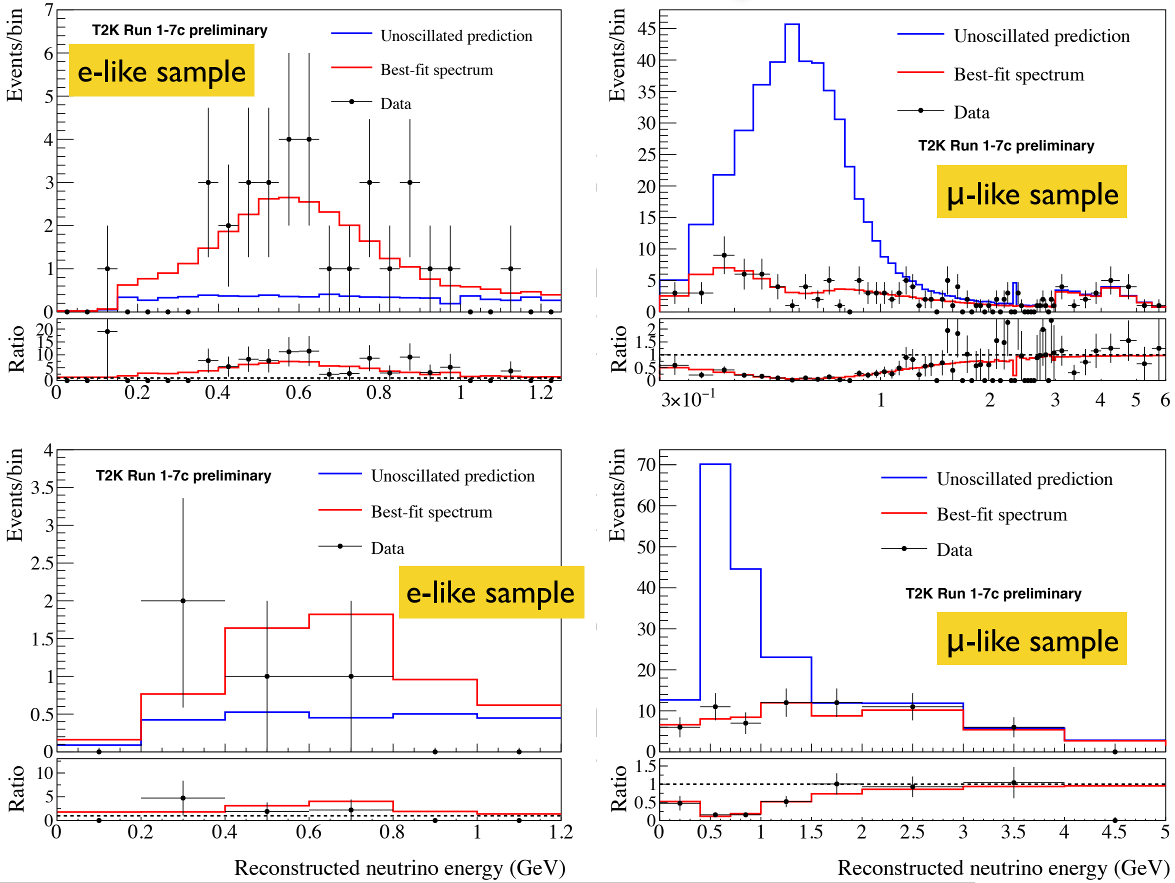


Probability that a muon is identified
as an electron is < 1%

Events at Super-Kamiokande

ν beam mode

ν̄ beam mode



Normal hierarchy						
Beam mode	Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	Observed
neutrino	μ-like	135.8	135.5	135.7	136.0	135
neutrino	e-like	28.7	24.2	19.6	24.1	32
antineutrino	μ-like	64.2	64.1	64.2	64.4	66
antineutrino	e-like	6.0	6.9	7.7	6.8	4

Inverted hierarchy						
Beam mode	Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	Observed
neutrino	μ-like	135.1	135.3	135.0	134.8	135
neutrino	e-like	25.4	21.3	17.1	21.3	32
antineutrino	μ-like	63.8	64.0	63.8	63.7	66
antineutrino	e-like	6.5	7.4	8.4	7.4	4

Larger than expected ν_e appearance

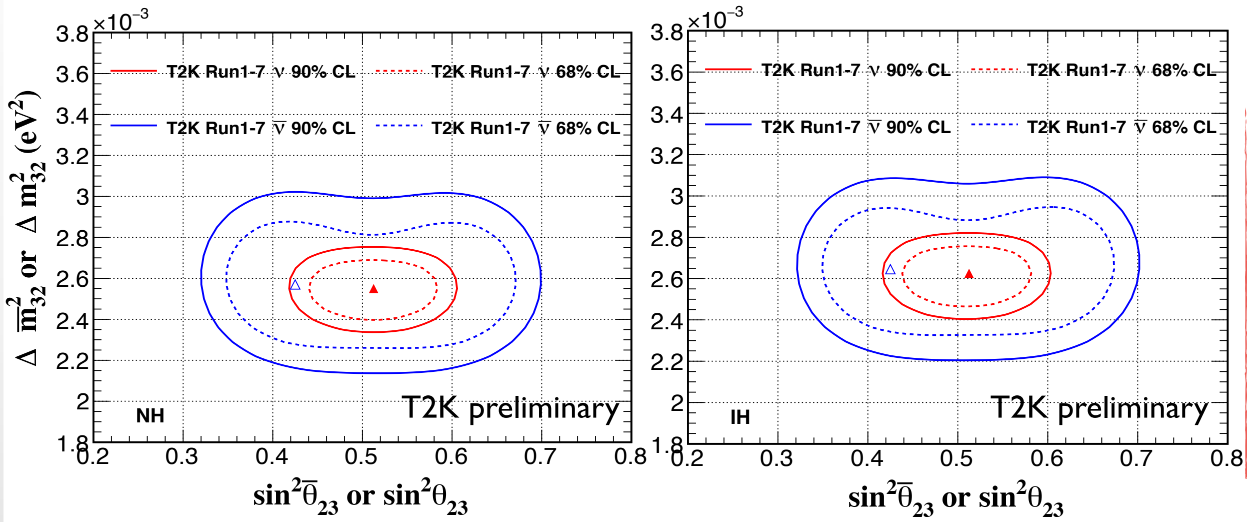
Smaller than expected $\bar{\nu}_e$ appearance

Data prefer the value of δ_{CP} inducing the largest ν-ν̄ asymmetry: -π/2

- Oscillation and systematic parameters are shared between the 4 samples
- Fit simultaneously the 4 samples to maximize the sensitivity to the oscillation parameters

ν_μ and $\bar{\nu}_\mu$ disappearance results

Constraints on the atmospheric parameters: θ_{23} and Δm^2_{31}

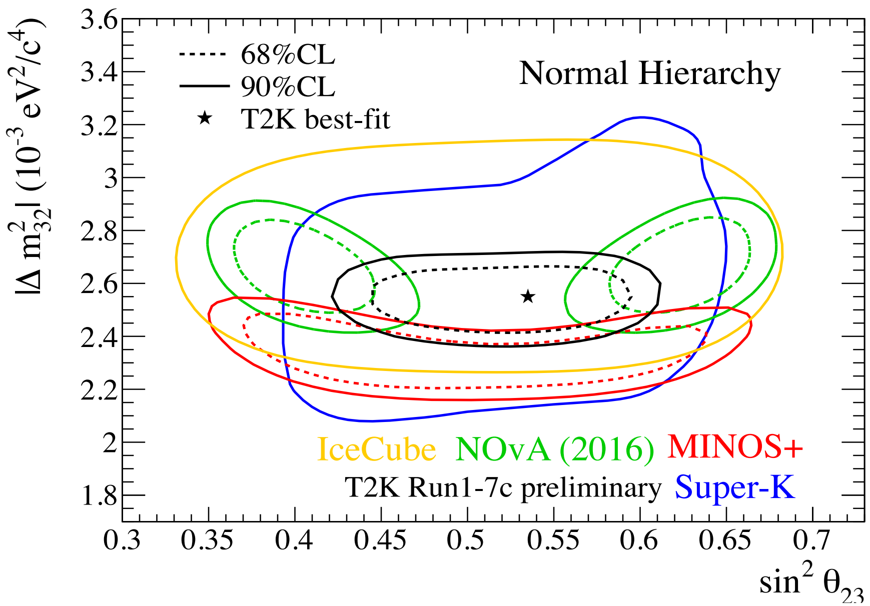


- CPT theorem:

$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

if $P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow$

CPT theorem is violated



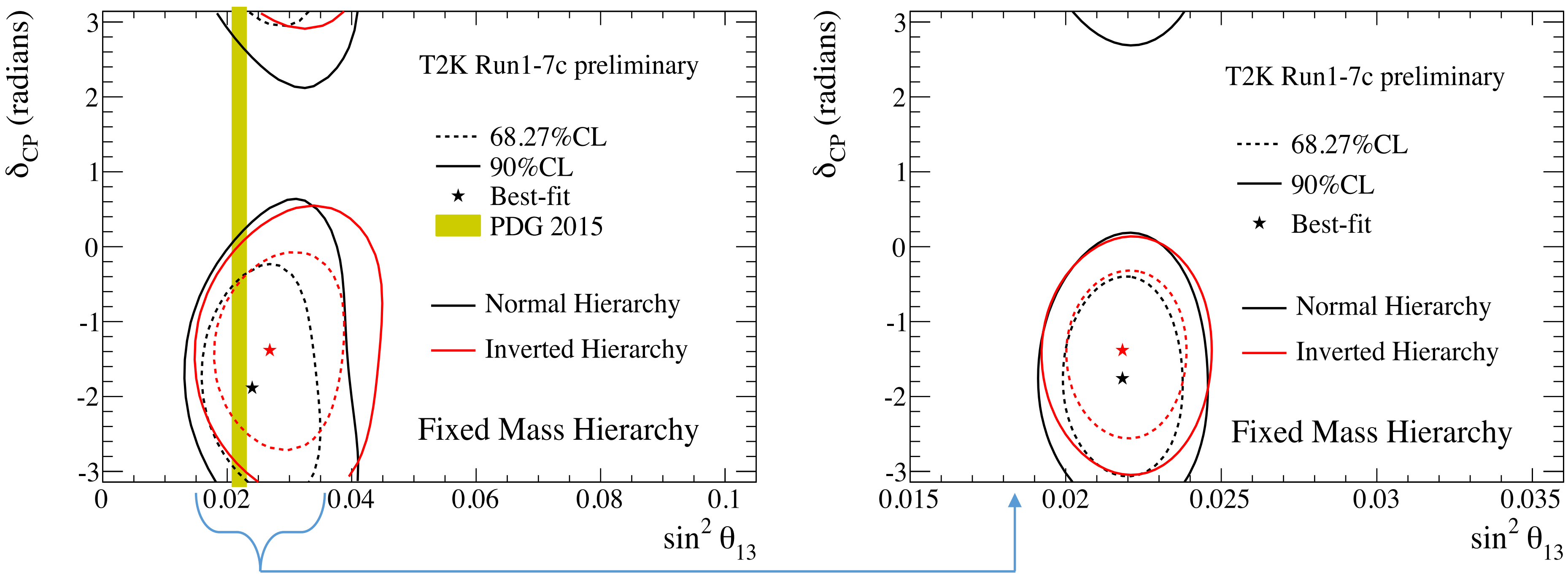
- World-leading measurement of $\sin^2\theta_{23}$
- Results continue to be consistent with maximal mixing/oscillation
- No significant differences between ν and $\bar{\nu}$

	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.007}$
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-5}$ eV^2/c^4)	$254.5^{+8.1}_{-8.4}$	$251.0^{+8.1}_{-8.3}$

θ_{13} and δ_{cp}

T2K-Only

T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



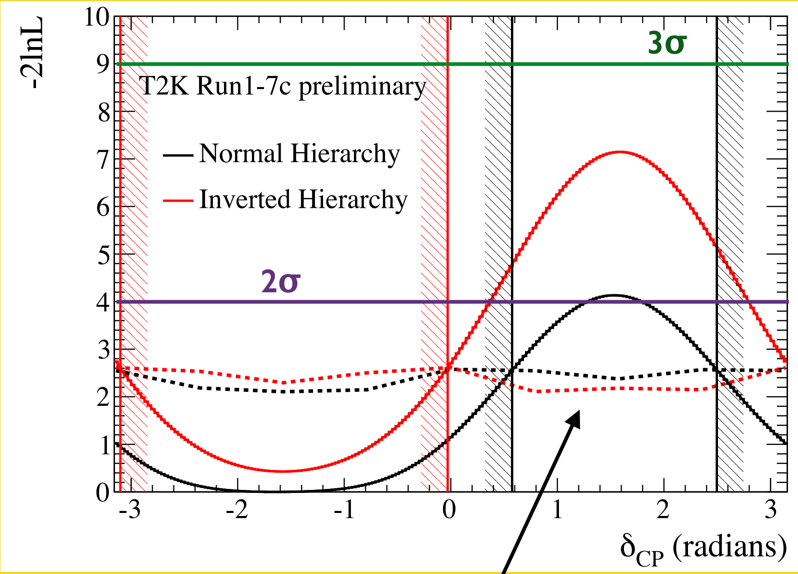
- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

Results: δ_{CP} confidence regions

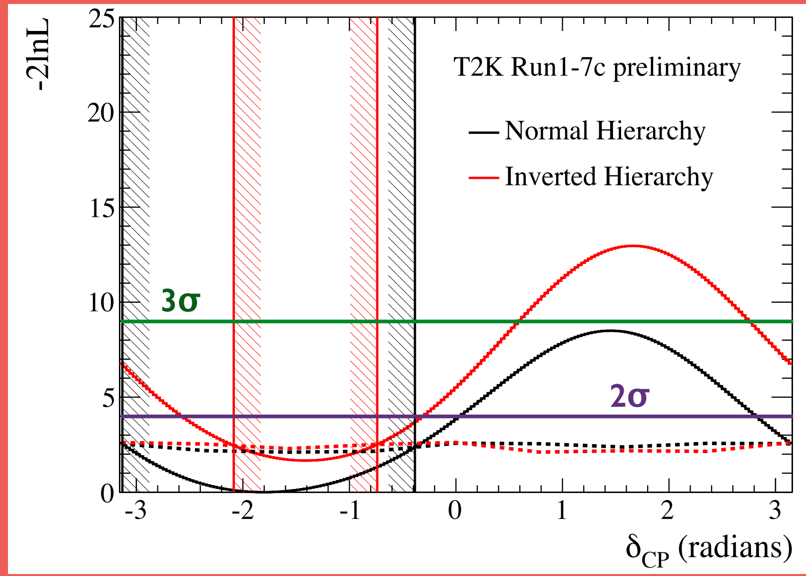
T2K + Reactor θ_{13} (PDG 2015)

$\sin^2\theta_{13}=0.022$, $\sin^2\theta_{23}=0.528$, NH, $\delta_{CP}=-1.601$

Run 1-7 sensitivity



Run 1-7 observed



Feldman-Cousins critical $\Delta\chi^2$ values for 90% C.L.

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

Toy MC: for NH and true $\delta_{CP} = -\pi/2$ the probability for excluding δ_{CP} = 0 or π at 90% C.L. is19.6% and 17.3% respectively

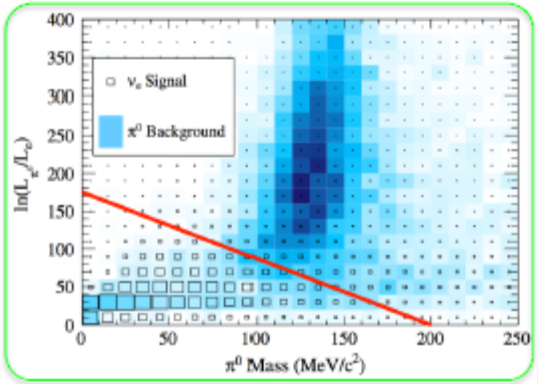
90% Confidence Interval:

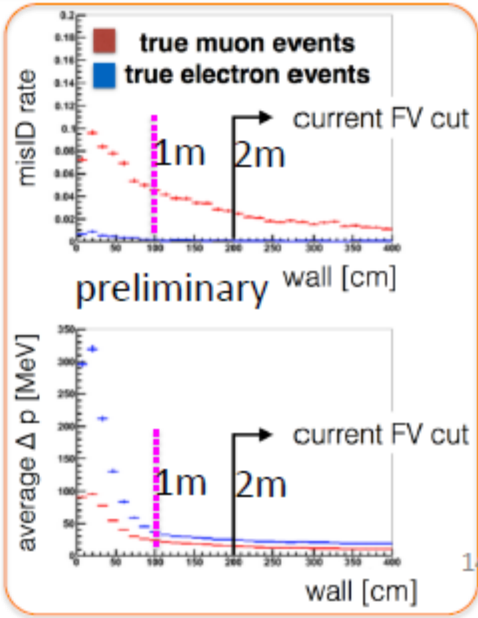
- δ_{CP} = [-3.13, -0.39] assuming NH
- δ_{CP} = [-2.09, -0.74] assuming IH

Analysis Improvements

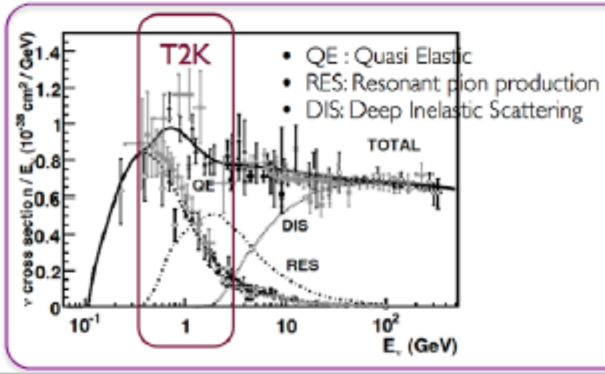
Development of new event reconstruction algorithm for SK

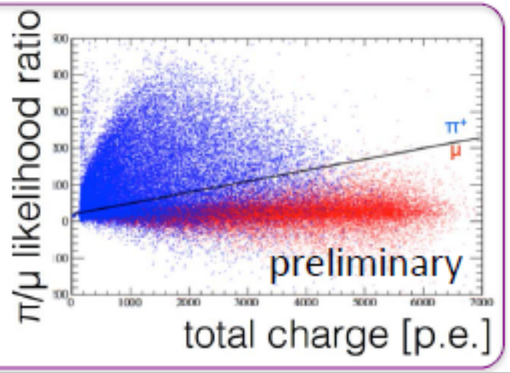
- Better π^0 rejection (done)
- Better vertex resolution:
    - Fid. vol. cut from ID wall
        – 2m → 1m (being studied)
        – ~20% gain
- Better PID → π/μ separation in SK.
    - Exclusive CC1π sample (~~being studied~~)
        – ~10% gain by using the sample.



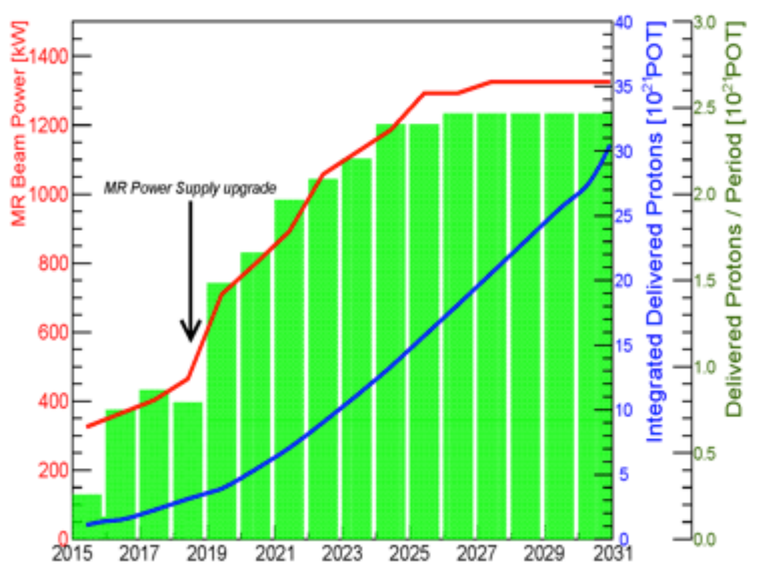


ICHEP 2016

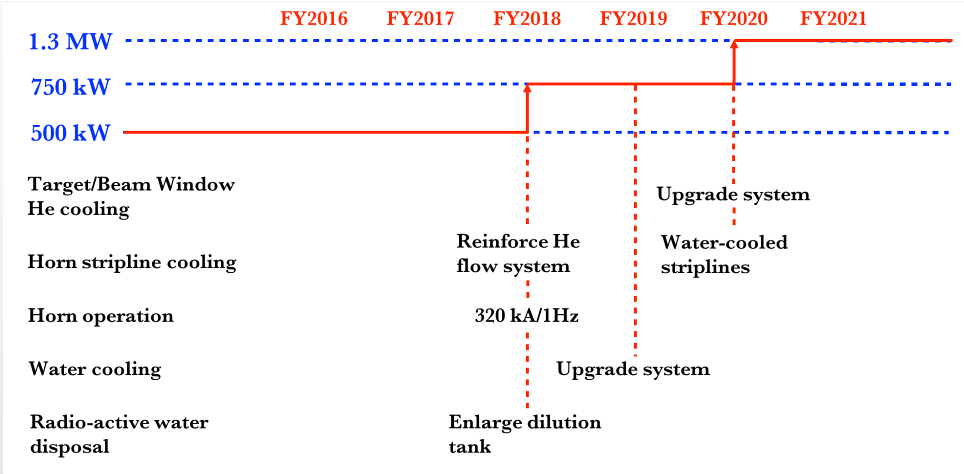




Beam Upgrade



Secondary Beamline Upgrade Schedule

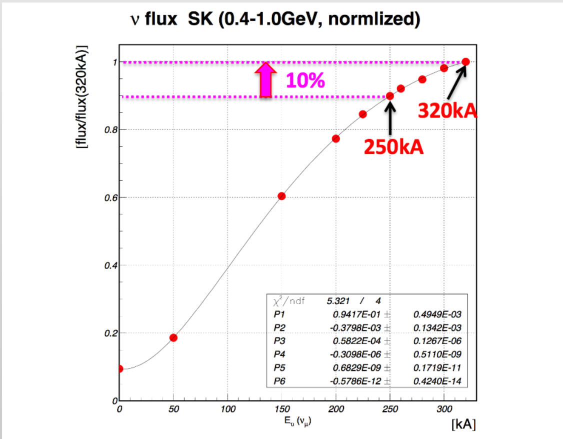


T2K aim to reach the number of approved POT (7.8×10^{21}) in ~2021.

Begin phase II in ~2021 up to 2026, before expected start of Hyper-K (~2026)

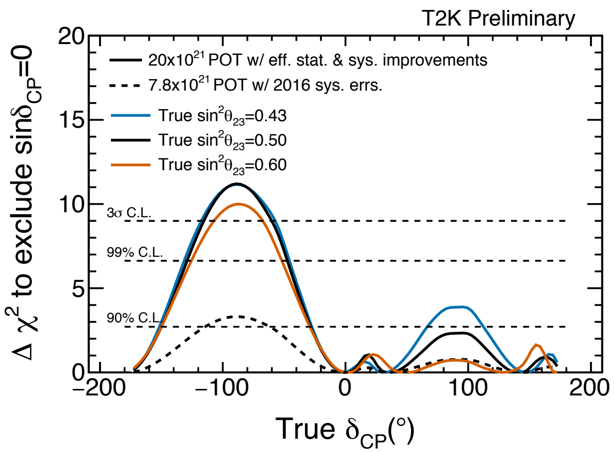
Beam performance upgrades:

- Approved main ring power supply upgrade & horn current increase (250 kA → 320 kA) in 2018 → 750 kW
- Accelerator & beamline upgrade (double the spill frequency) in 2021 → 1.3 MW

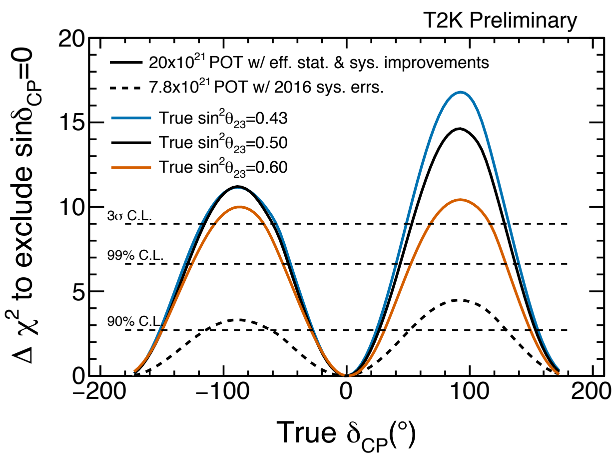


Flux Improvement @ 320 kA

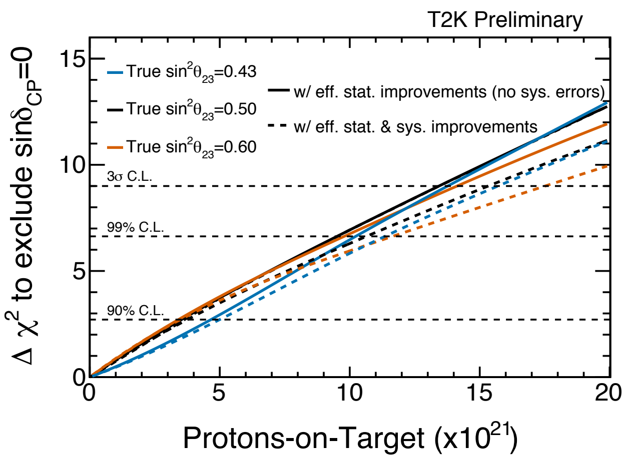
T2K phase II (T2K-II)   Data Taking : 2020-2025



hierarchy unknown



external hierarchy input

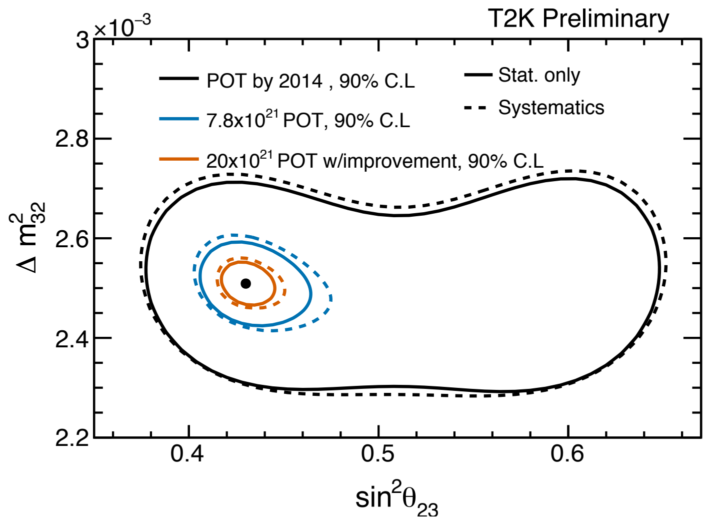


- ~3 σ sensitivity to CP violation for favourable (and currently favoured) parameters

Statistic x 3 = 20 x 10^{21} p.o.t

Sys. Errors 2/3 reduction (6% -> 4%)

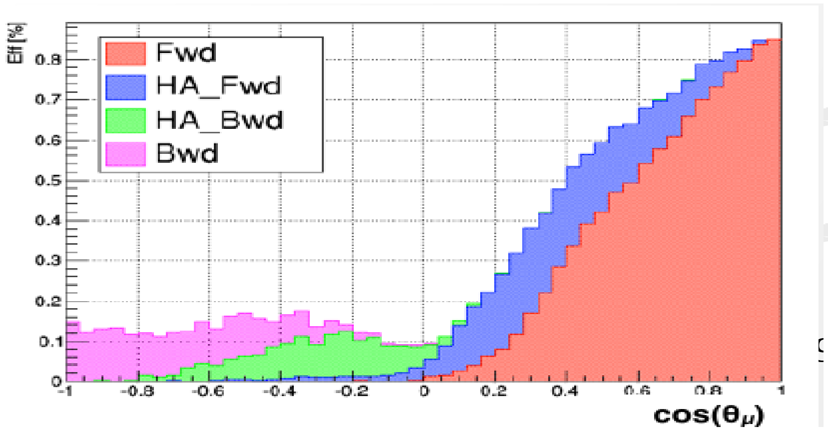
LOI: 01/2016, Proposal 06/2016



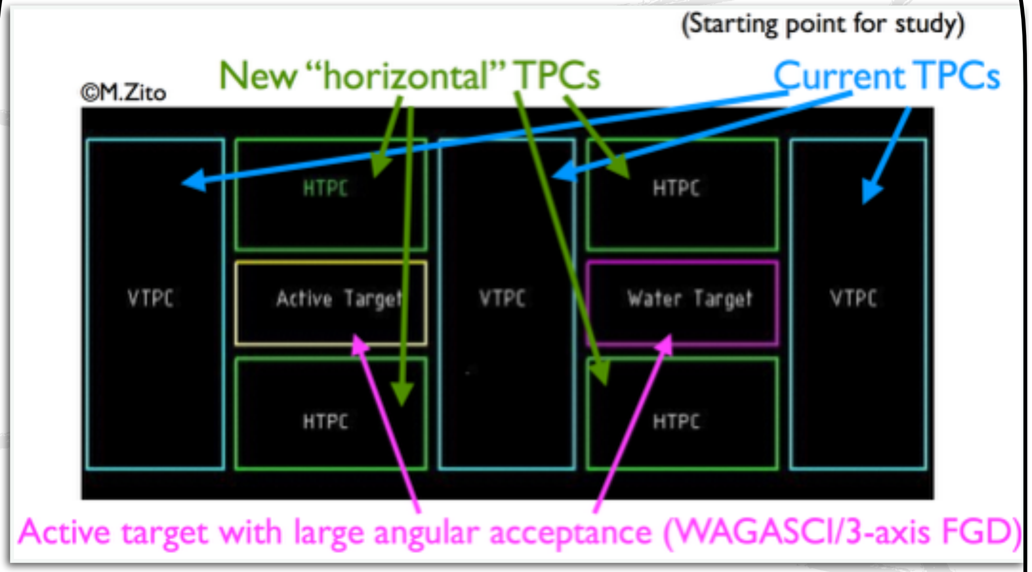
- Precise measurement of θ_{23}:
  - octant resolution if θ_{23} at edge of currently allowed values
  - otherwise, measure θ_{23} to ~1.7° or better

Upgrading T2K: near detectors

- High stats of T2K-II motivate reduction of systematics
- T2K Task Force formed to improve existing ND280 detector
  - Active water detector elements
  - Expand phase space (high zenith-angle tracks)
  - Lower momentum thresholds
  - Third view of vertex detector



T2K ND280 Upgrade Task Force



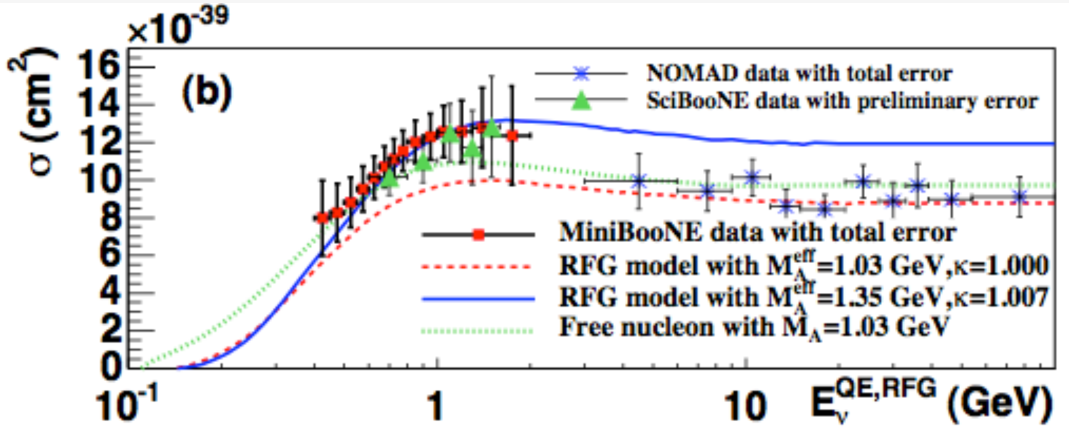
- Goal : CDR-like document describing the preferred configuration for an ND280 upgrade to be delivered Fall 2016
  - Based on a quantitative evaluation of the performance
- Boundaries : to be installed around 2020, within the ND280 pit, reusing the magnet facility

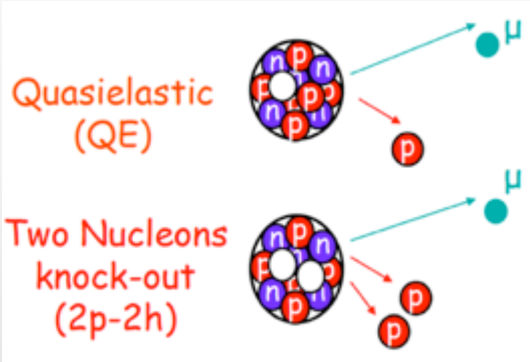
Near Detectors (High Pressure TPC)

2) Add new detectors in the 280m pit: High pressure TPC to study low momentum final state particles and in particular resolve vertex

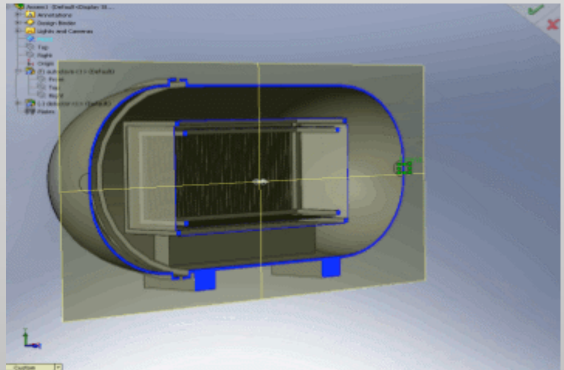
HPTPC detector design to reduce xsec systematics

arXiv:1002.2680 [hep-ex]





- Significant discrepancies on proton multiplicity and momentum distributions
- Need low momentum thresholds to reduce xsec systematics
- Important difference lie below threshold for liquid detectors



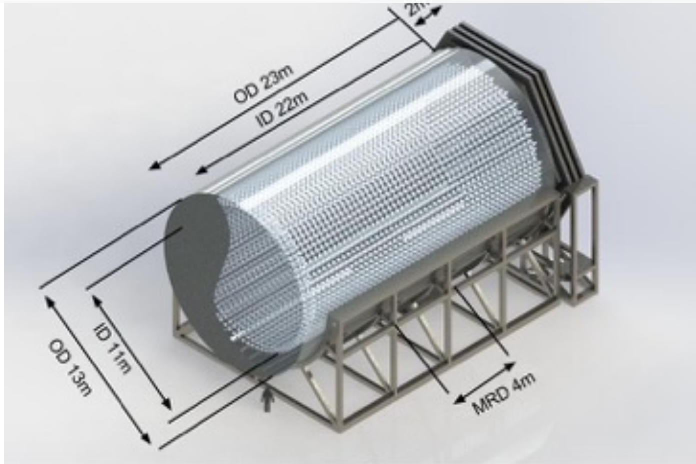
- T2K has pioneered (~1 bar) gas TPCs for accelerator neutrinos
- Need a path to high pressures for sufficient statistics
- Generic to next generation LBL experiments

* Federico Sanchez talk

Intermediate Detector (* WP4)

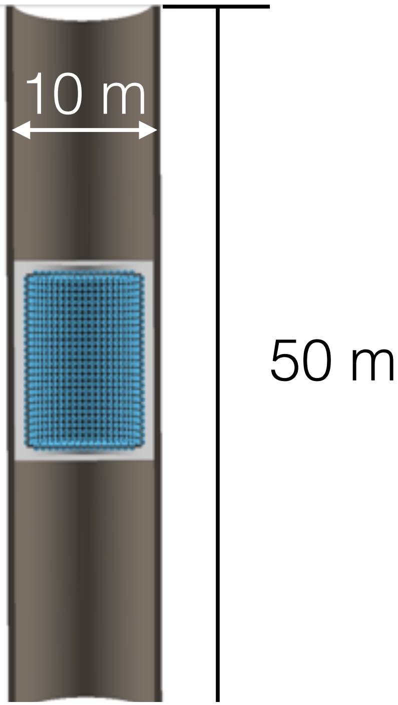
TITUS

- Located 2.5° off-axis in same direction as Tochibora at 1.8 km
- Gd-loading for neutron detection
- Magnetized muon range detector
- Long geometry for high momentum muon containments



NuPRISM

- Tall detector covers 1.0°-4.0° off-axis angles for studying energy dependence of neutrino interactions
- Located at 1-1.2 km baseline

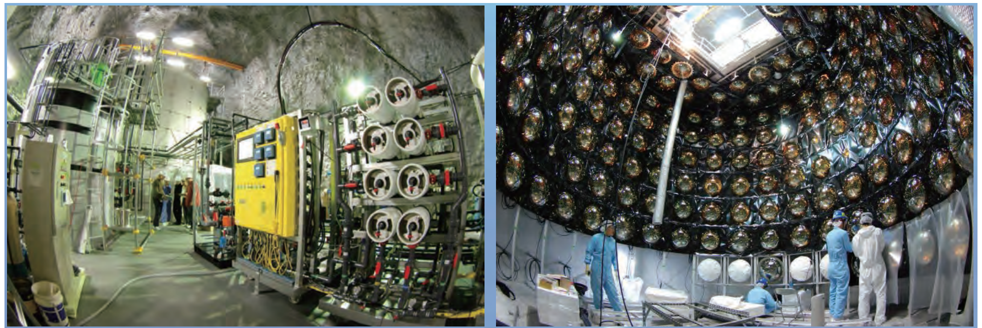


Process for a single detector design with off-axis spanning coverage and Gd-loading is started

Far Detector Upgrade

- The reconstruction performance of Super-K is steadily improved.
  - The FitQun program to reconstruct the Cherenkov rings. The π^0 background in T2K was reduced to 1/3.
- The upgrade of Super-K (called SK-Gd) is under development to improve the neutron detection capability that is used to identify anti-neutrino events. A 0.2% concentration of a gadolinium will be dissolved in a Super-K tank if all the requirements are cleared.
- Physics Target
  - Relic Supernova Neutrinos
  - Neutrino versus Anti-neutrino Separation

SK-Gd test facility



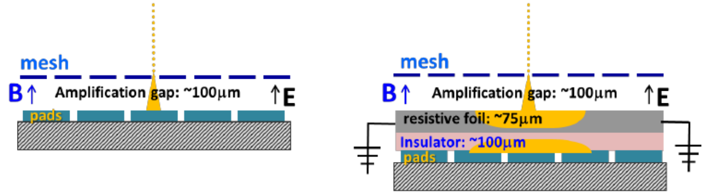
Thank you !

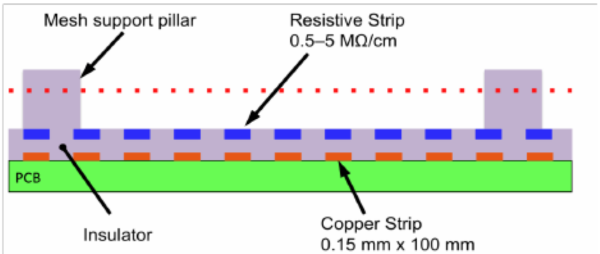
backup

New Horizontal TPCs

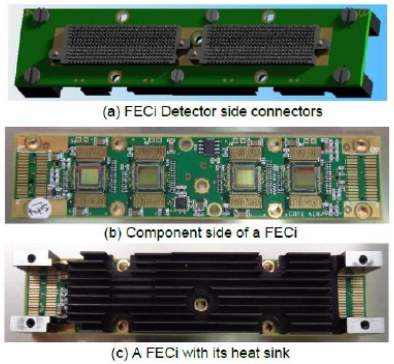
Resistive Bulk Micromegas

- Several advantages (charge spread, intrinsic spark protection)
-





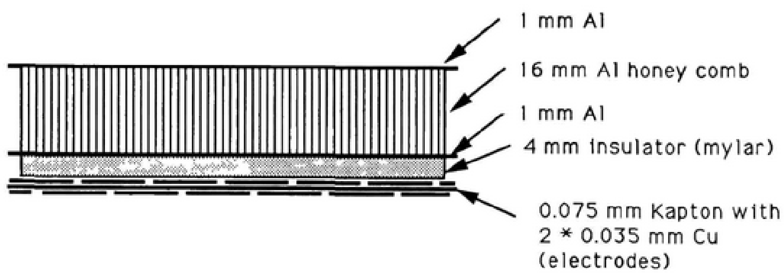
ILC TPC R/O electronics



NEXT STEPS

- ✓ Design Report of the ND280 upgrade by the end of the year
- ✓ 2017: detailed design of the detectors/setting up the project and funding
- ✓ 2017-18 Neutrino Platform tests (with HPTPC)
- ✓ 2018-2020 construction/installation

Very thin FieldCage

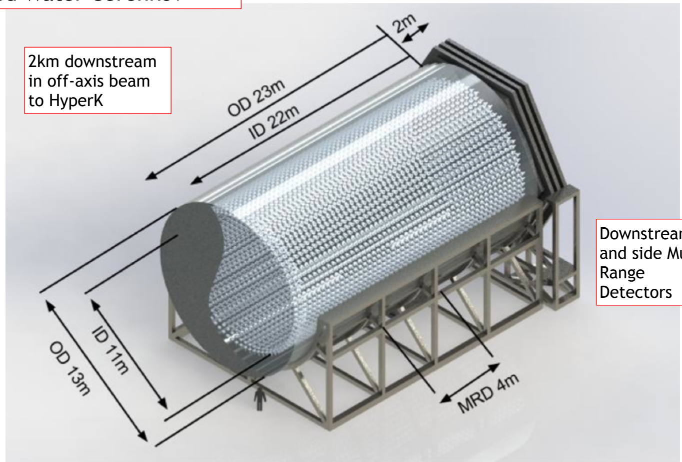


TITUS Detector

11m diameter
22m length
40% photo-coverage (~3k 12” PMTs)
2kt Gd-loaded Water Cerenkov

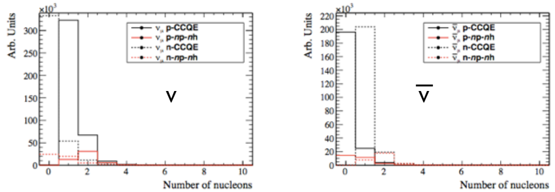
TITUS

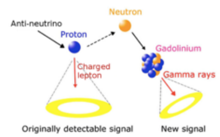
Tokai Intermediate Tank for the Unoscillated Spectrum



Gd Doping

- 0.1% $Gd_2(SO_4)_3$ allows tagging of final state nucleons
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons 74% → 83%
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron 61% → 73%

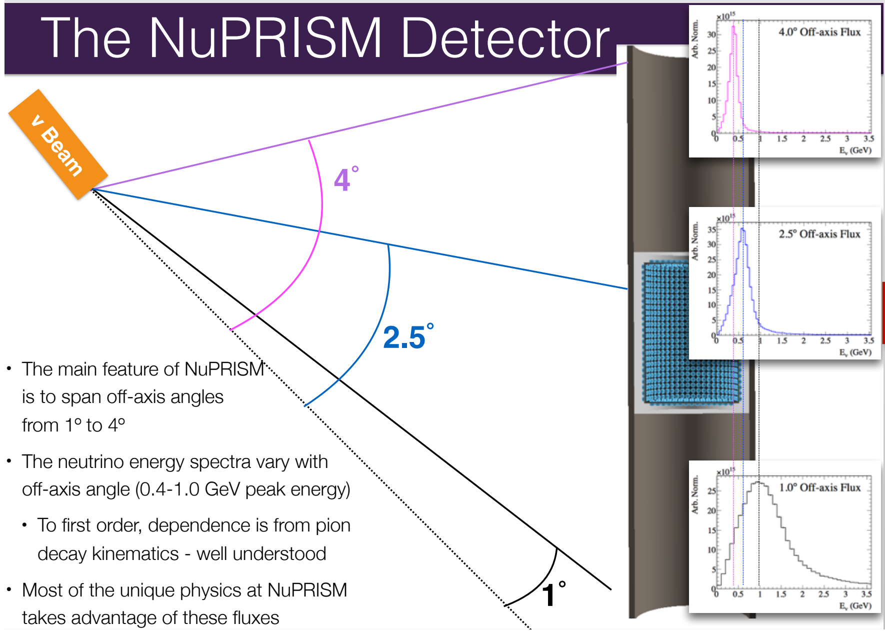




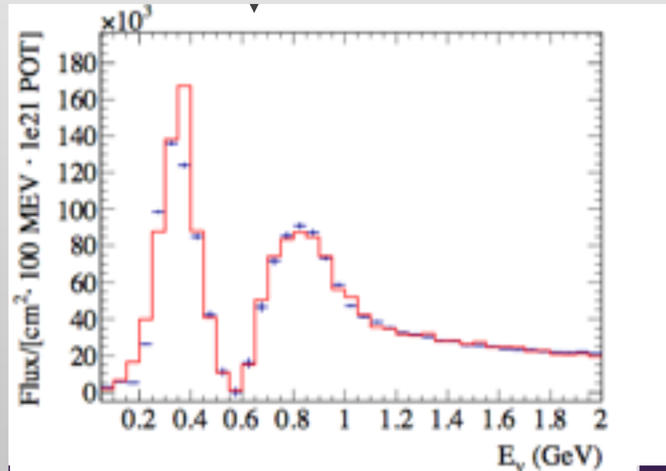
GENIE v2.8.0 simulations of neutrino/antineutrino interactions with C target

- Clear n signals can be modified by nuclear effects: re-scattering, charge exchange, and absorption in the nuclear media
- Statistical information remains - powerful approach for H_2O
- Cross section measurements

The NuPRISM Detector

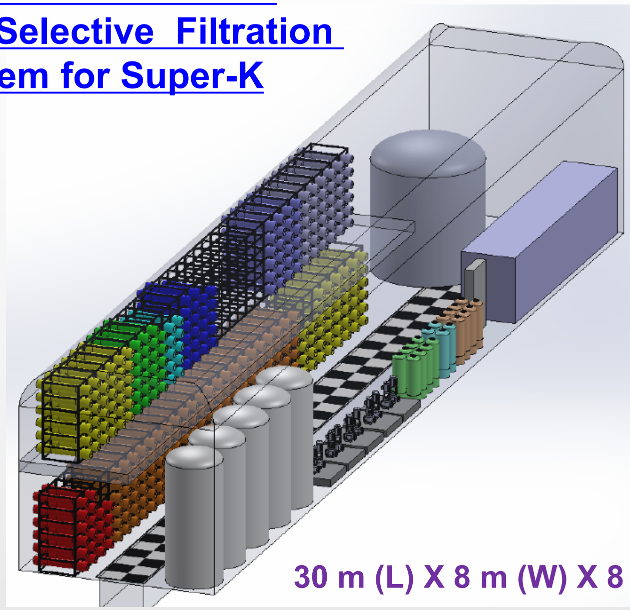


- The main feature of NuPRISM is to span off-axis angles from 1° to 4°
- The neutrino energy spectra vary with off-axis angle (0.4-1.0 GeV peak energy)
  - To first order, dependence is from pion decay kinematics - well understood
- Most of the unique physics at NuPRISM takes advantage of these fluxes



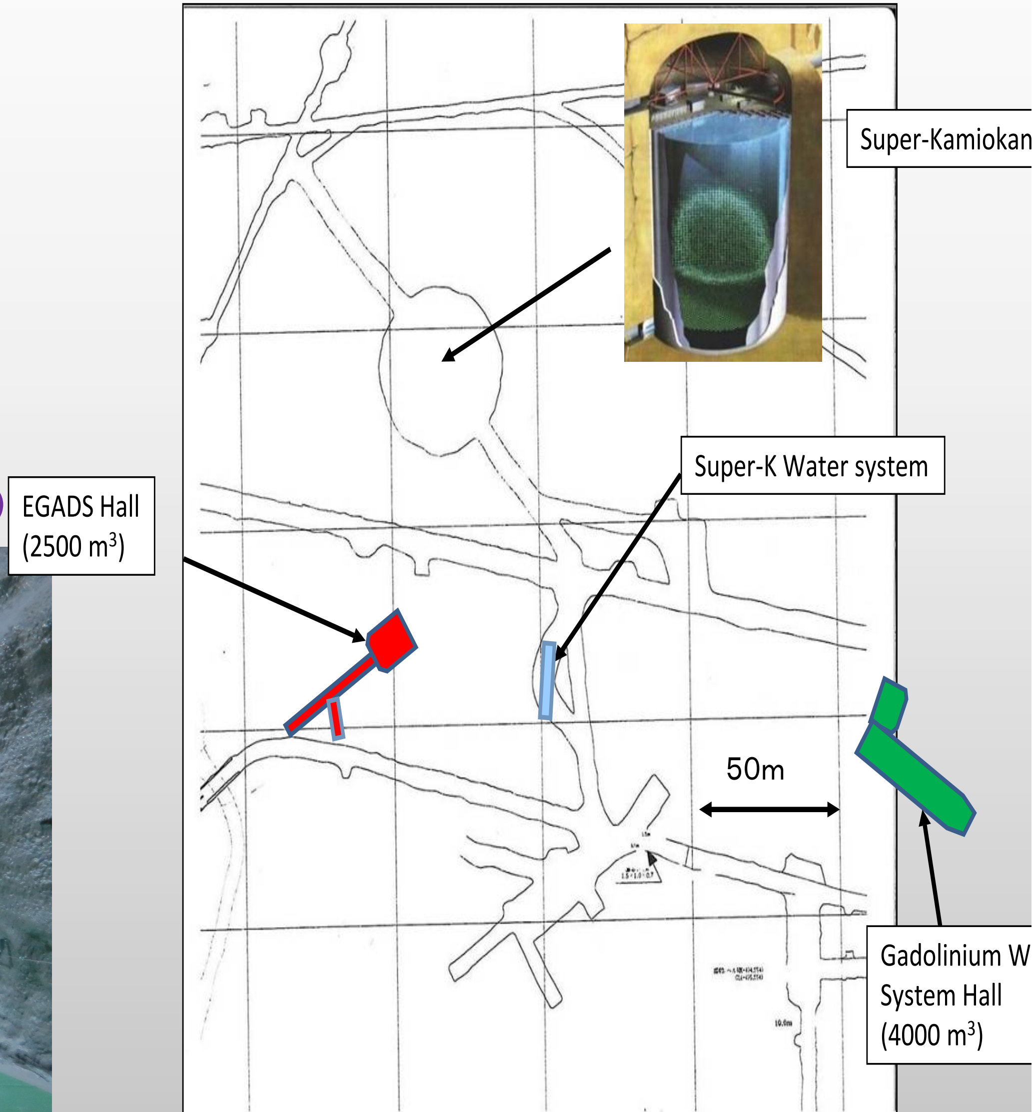
HK Intermediate WC Detect

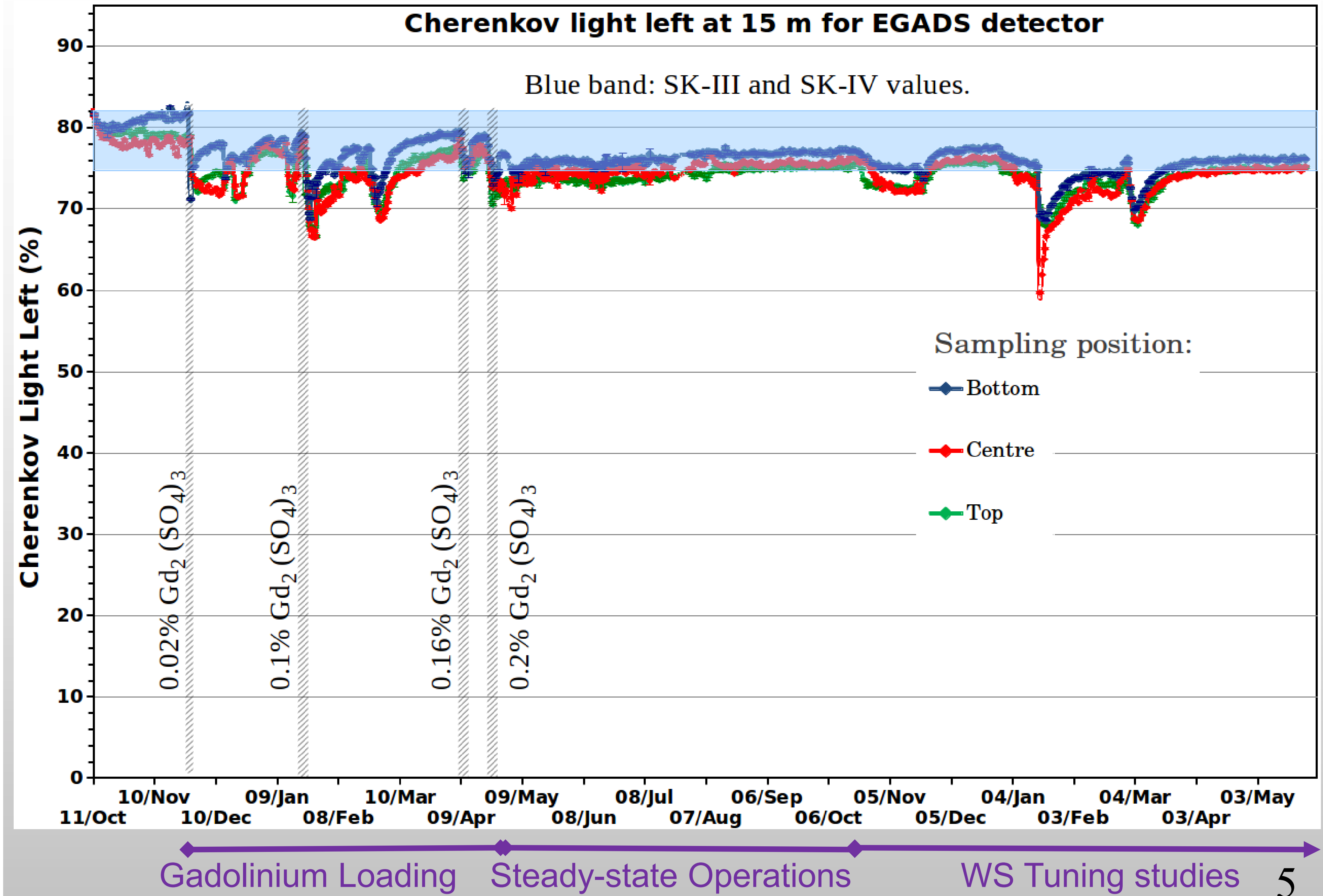
South Coast Water's 60 m^3/hr Selective Filtration System for Super-K



30 m (L) X 8 m (W) X 8 m (H)

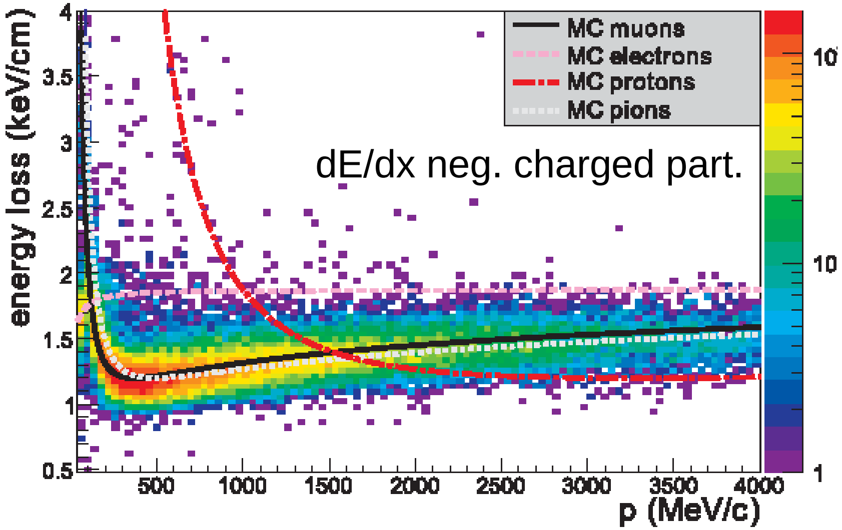
Hall G ready for occupancy; April 22nd, 2016 [photo by M. Ikeda]

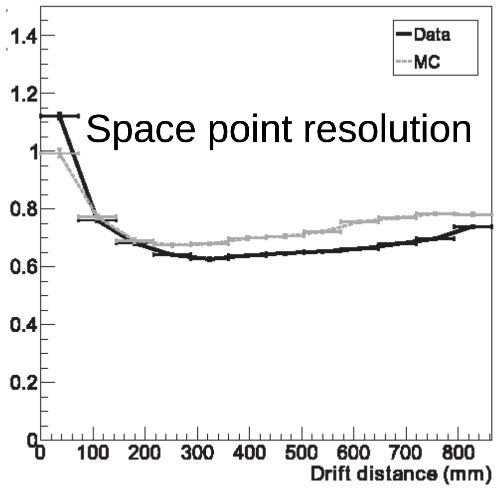


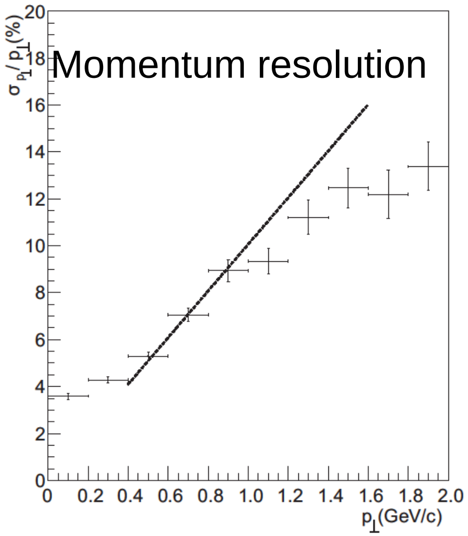

Cherenkov light left at 15 m for EGADS detector
Blue band: SK-III and SK-IV values.
Cherenkov Light Left (%)
90
80
70
60
50
40
30
20
10
0
0.02% $Gd_2(SO_4)_3$
0.1% $Gd_2(SO_4)_3$
0.16% $Gd_2(SO_4)_3$
0.2% $Gd_2(SO_4)_3$
Sampling position:
Bottom
Centre
Top
10/Nov
09/Jan
10/Mar
09/May
08/Jul
06/Sep
05/Nov
04/Jan
04/Mar
03/May
11/Oct
10/Dec
08/Feb
09/Apr
08/Jun
07/Aug
06/Oct
05/Dec
03/Feb
03/Apr
Gadolinium Loading
Steady-state Operations
WS Tuning studies

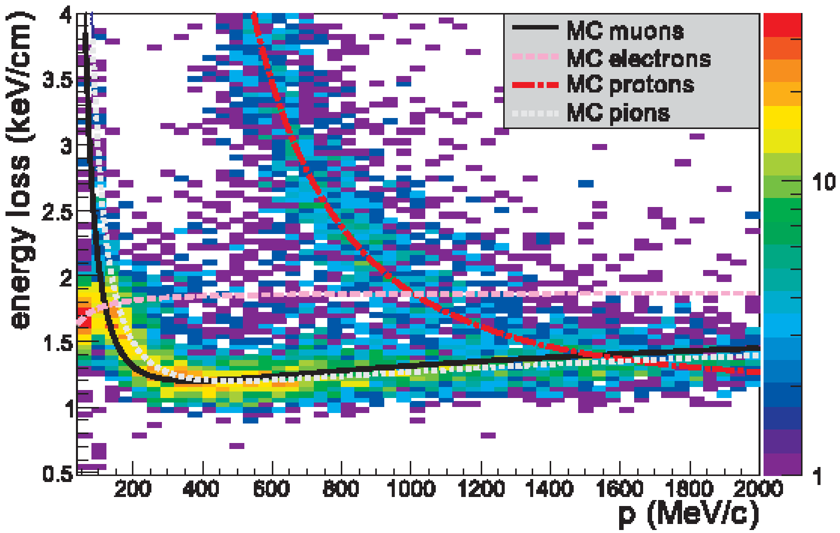
TPC performances

- Three large TPC for the T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detect
- Playing a key role in the study of the neutrino fl interactions (charge, momentum and dE/dx PID
- Space resolution : 0.6 mm
- Momentum res. 9% at 1 GeV
- dE/dx: 7.8 % (MIP)









dE/dx pos. charged part.