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Canada's national laboratory
for particle and nuclear physics
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Status and Prospects of the T2K Experiment

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TRIUMF and University of Winnipeg

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- Neutrino Oscillations
- Description of T2K experiment
- Most recent T2K oscillation results
- Plans for future:
  - T2K-II
  - NuPRISM
  - Hyper-K

- Neutrino flavour eigenstates are not the same as mass eigenstates
- Neutrinos can oscillate between flavour eigenstates.

Flavor (weak) eigenstate

Mass eigenstate

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

$$\left(\begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"atmospheric ν" (Super-K, T2K, NOVA) θ_{23} ~ 45°

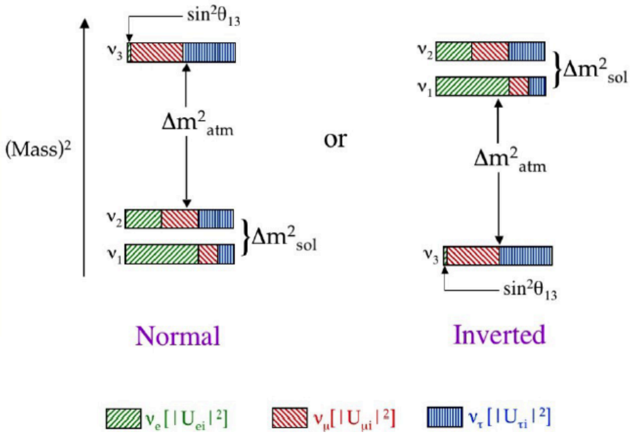
Recently observed (Daya Bay, RENO, T2K) θ_{13} ~ 8.5°

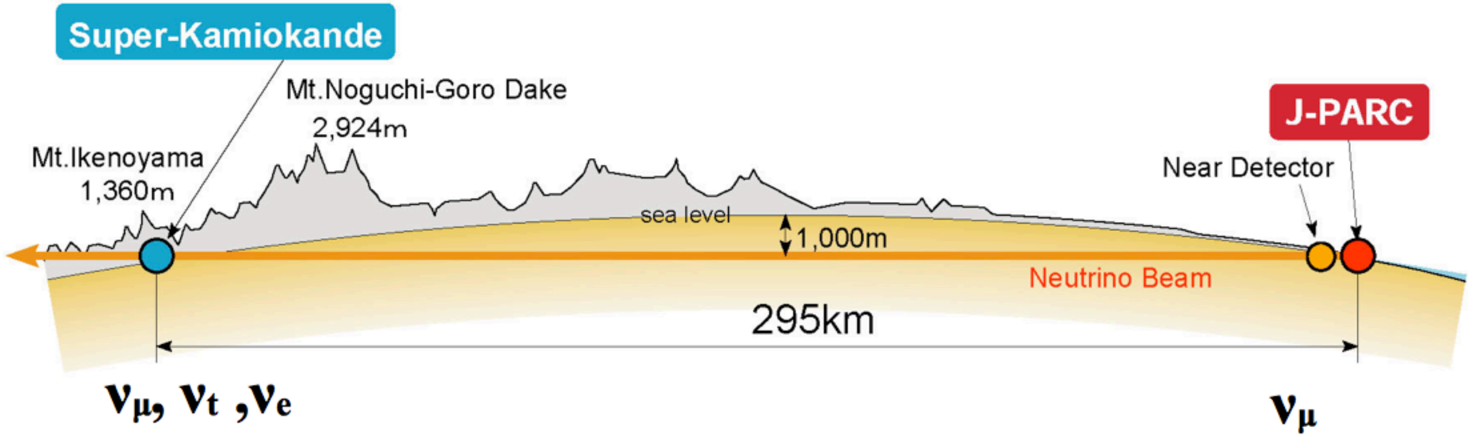
"solar ν" (SNO, Kamland) θ_{23} ~ 34°

- Several different techniques for probing oscillations, including:
  - Accel long baseline: look for ν_μ -> ν_μ , ν_e
  - Reactor short baseline: look for ν_e -> ν_e

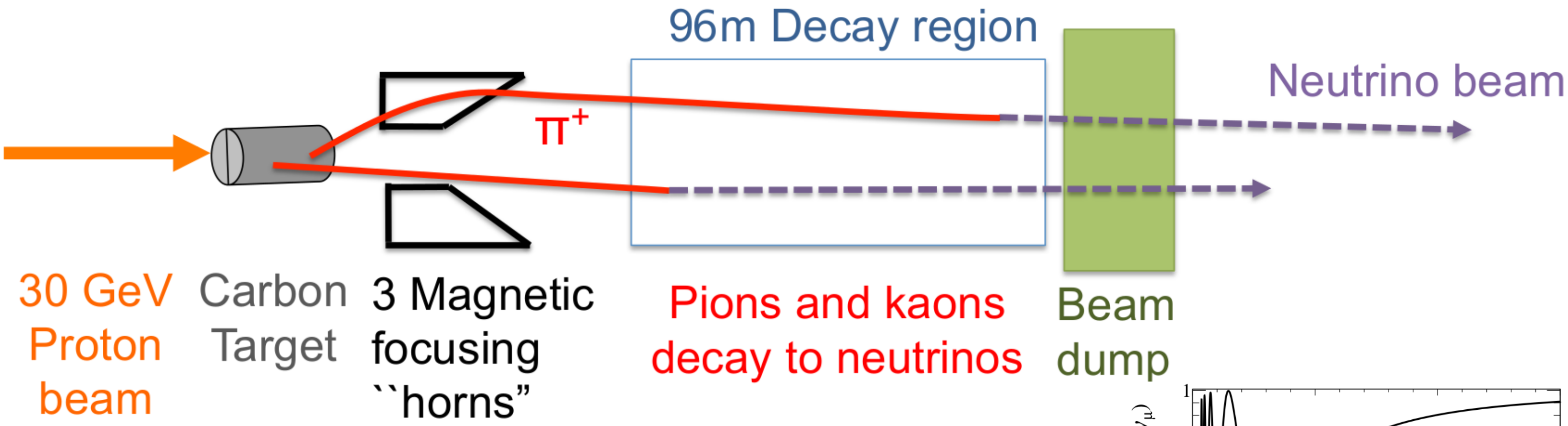
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Key goal for future long baseline neutrino experiments:
  search for leptonic CP violation.
  - There are various theories which explain cosmological matter/antimatter asymmetry through leptonic CP violation
- Other physics: precision measurements of mixing angles, mass hierarchy



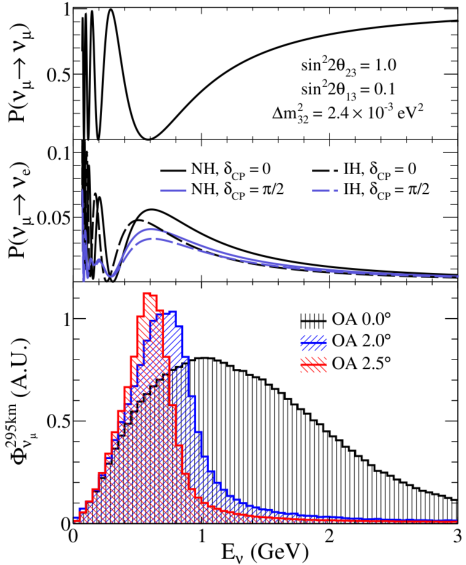


- Produce a beam of ν_μ neutrinos using the JPARC proton beam.
- Measure the neutrino flux, flavour content and interaction dynamics at the near detector (ND280), before any oscillations have occurred.
- Measure flux and flavour content at far detector Super-K (SK).
- Baseline and angle chosen to maximize oscillations. $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{32} \frac{L}{4E})$
- Combining together this information we can derive measurements of neutrino oscillation parameters.

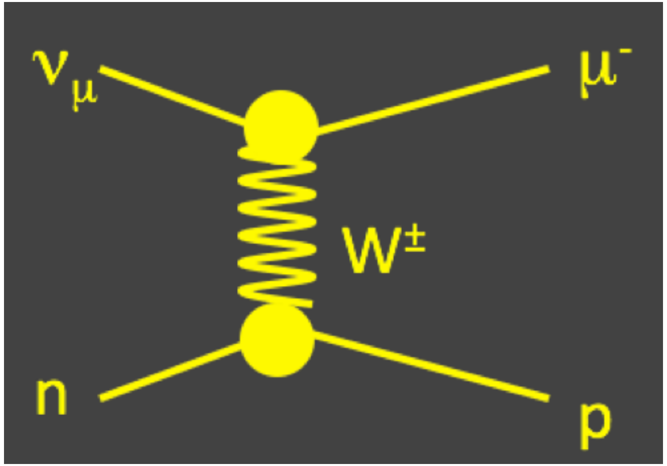


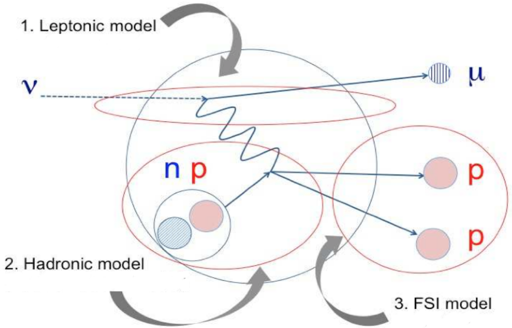
Note:

- Can produce beam of neutrinos or anti-neutrinos by changing horn polarity.
- T2K uses “off-axis” effect
  - Narrower, lower energy neutrino beam
  - Tuned to match oscillation probability

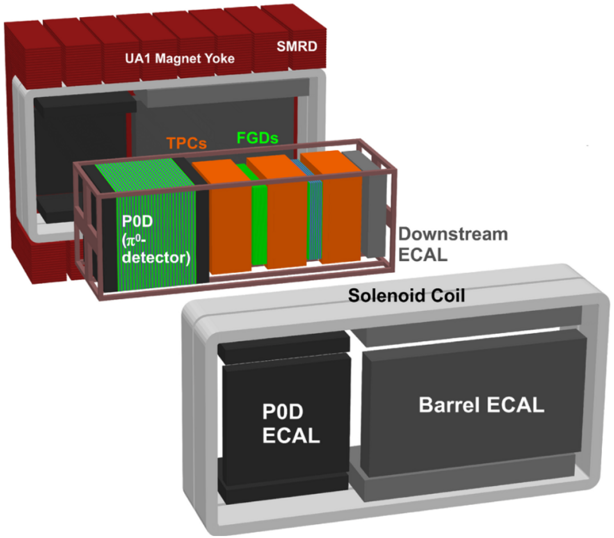


- One challenge of neutrino physics: need to infer all information about neutrino from the outgoing particles (including neutrino energy).
- Charge Current Quasi Elastic (CCQE) interactions is preferred selection channel.
- The neutrino energy and flavour is determined from the final state particles.
- Can determine neutrino energy based only on outgoing muon 4-momentum.
- But…
  - *Other interaction modes can mimic CCQE, ie if pion is missed.*
  - *Neutrino can scatter off correlated nucleon pair*
  - *Target nucleon is not at rest in the nucleus; difficult to model velocity distribution.*

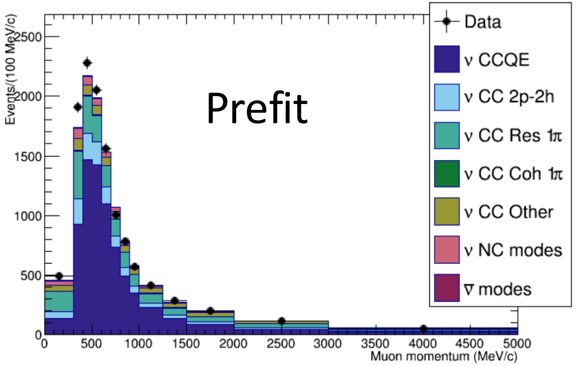


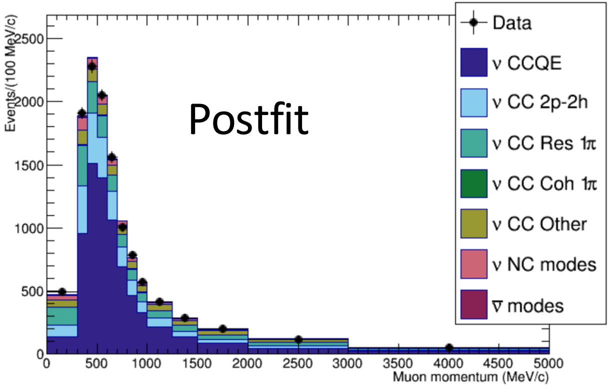


Near Detector: ND280



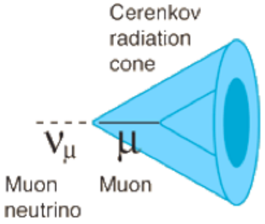
- 2 FGDs (Fine Grained Detectors):
  - Thin, wide scintillator planes.
  - Provides active target mass (one FGD is half water).
- 3 TPCs (Time Projection Chambers):
  - Excellent measurements of charged particles from FGDs.

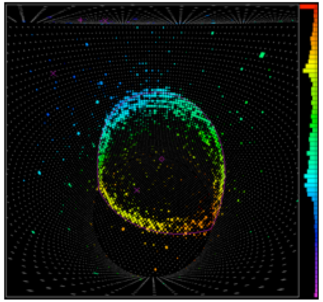


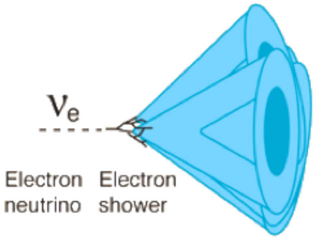


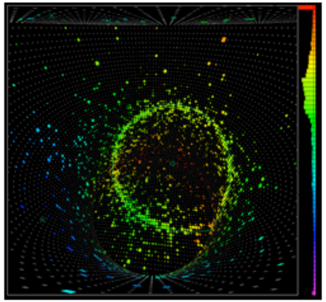
Measurements in ND280 constrain flux and cross-section models.

- Ring-imaging water Cherenkov detector
- 22.5 kT fiducial volume
- 11,000 photo-multiplier tubes (PMTs)





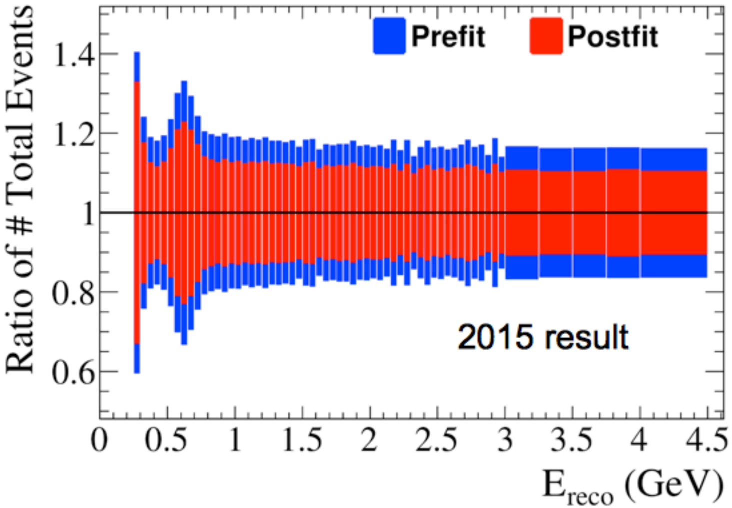


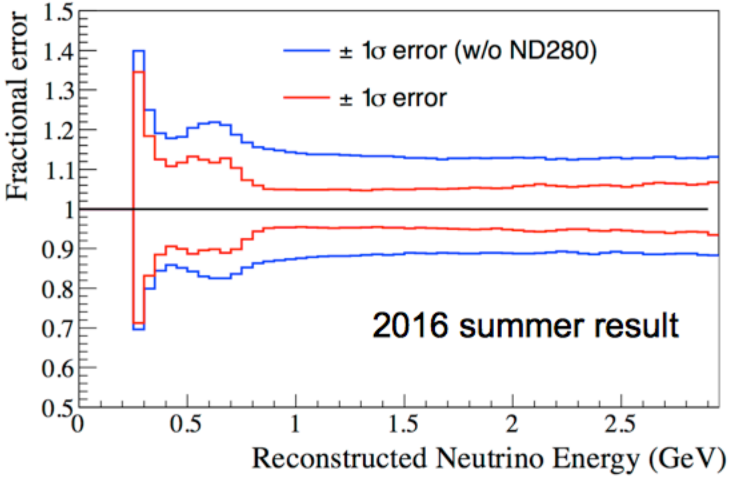


- Raw data produced in Japan.
- ND280 raw data replicated to main storage elements at TRIUMF and RAL.
- Processing of raw data and associated simulations done at computing sites throughout Canada, UK and USA.
- Processed data and MC files copied back to TRIUMF and RAL. All files are fully replicated between TRIUMF and RAL.

- New Compute Canada allocation
  - 460 core-years at cedar-compute
  - 50TB nearline storage at NDC-SFU
  - 1000TB of dcache storage at NDC-SFU

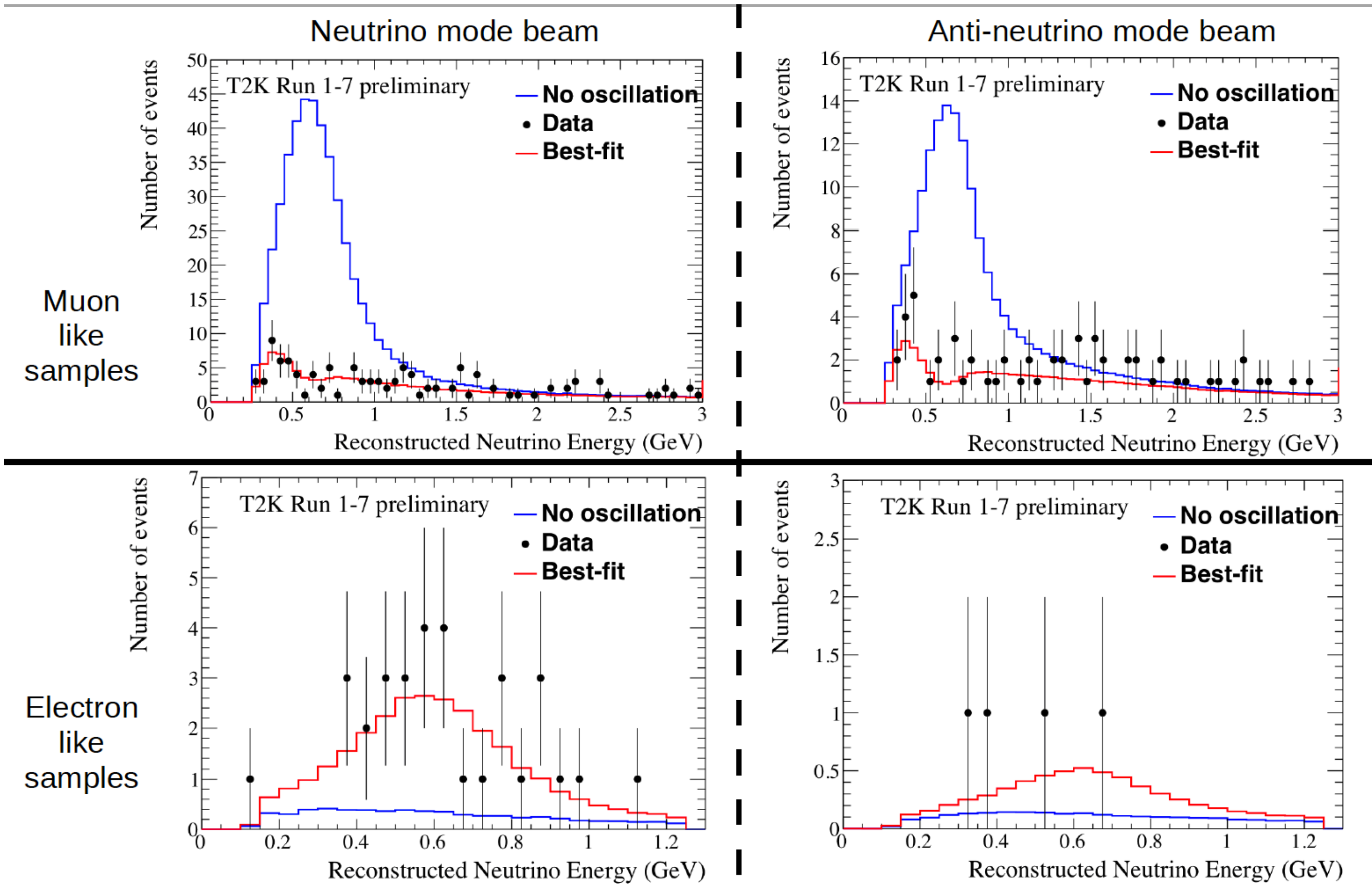
- Flagship analysis - PRL 118, 151801, Editor's Suggestion
- First combined neutrino + anti-neutrino data
- Use both neutrino appearance and disappearance
- Near detector constraint using both carbon and water targets
  - Reduced error in region of interest (600MeV) from ~20% to ~10%



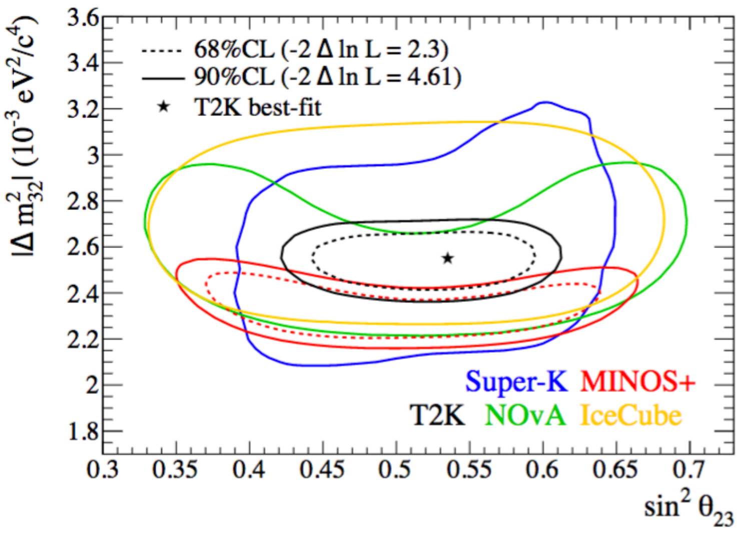


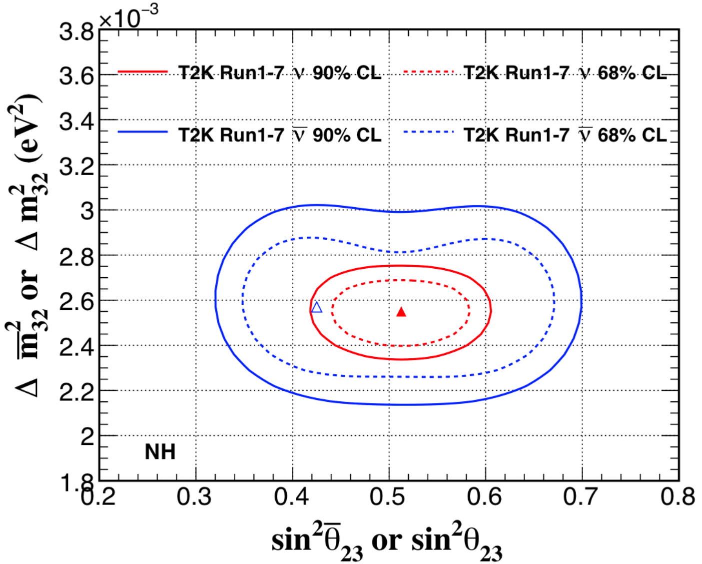
Super-K Observations

- 7.482×10^{20} protons on target in neutrino mode.
- 7.471×10^{20} protons on target in anti-neutrino mode.

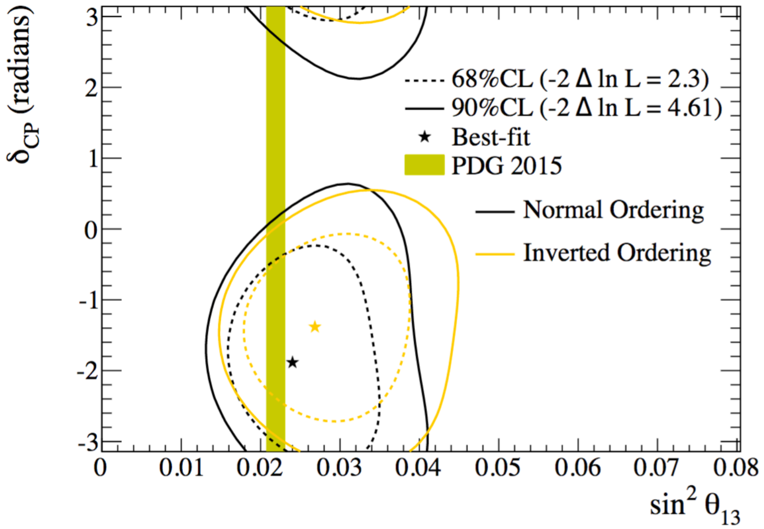


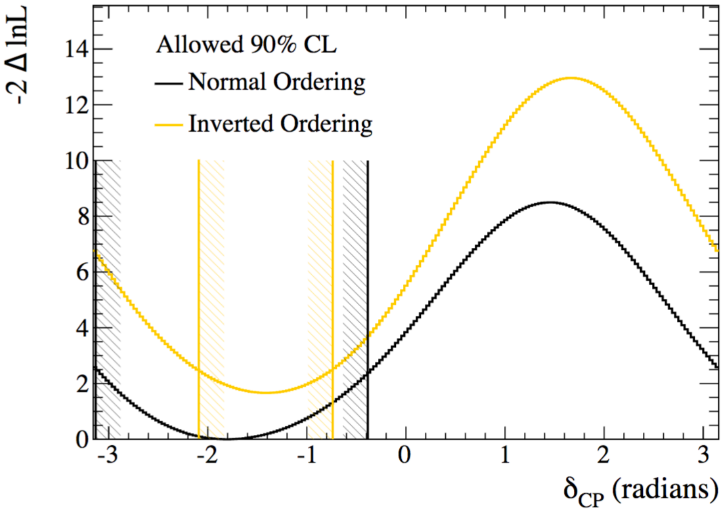
Muon Neutrino Disappearance





- T2K data prefers maximal muon neutrino disappearance (left)
  - Weak tension (2.4σ) with NOvA result
- Neutrino and anti-neutrino data at T2K agree (right)
  - Test CPT symmetry

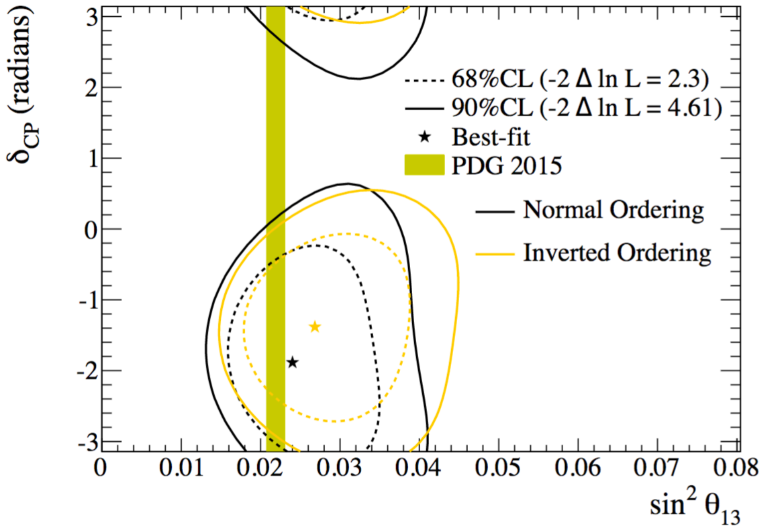


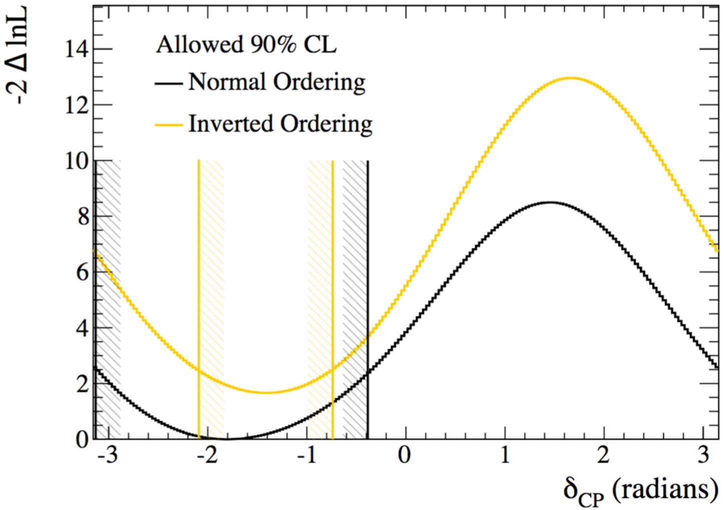


- Fit to T2K data alone
  - First exclusion in δ_{CP} space from a single experiment

- T2K data combined with reactor measurements
  - Exclude CP conservation ($\sin(\delta_{CP}) = 0$) at 90%
  - Allowed region: [-2.98 to -0.47]
  - Weak preference for 'normal' neutrino mass hierarchy

CP Violation Results



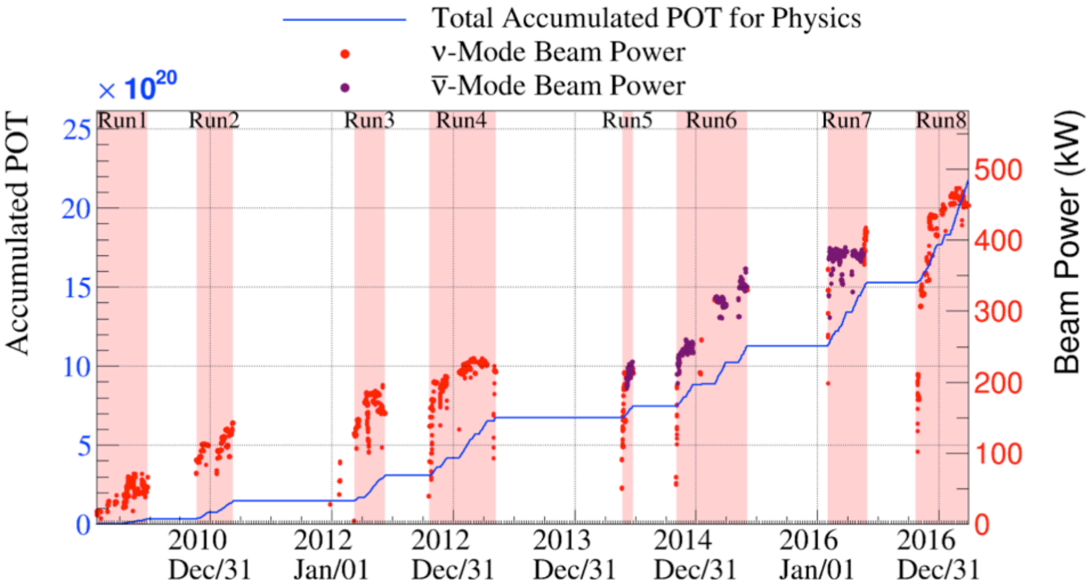


- Fit to T2K data alone
  - First exclusion in δ_{CP} space from a single experiment

Many other T2K results on neutrino cross-section and other exotic physics!

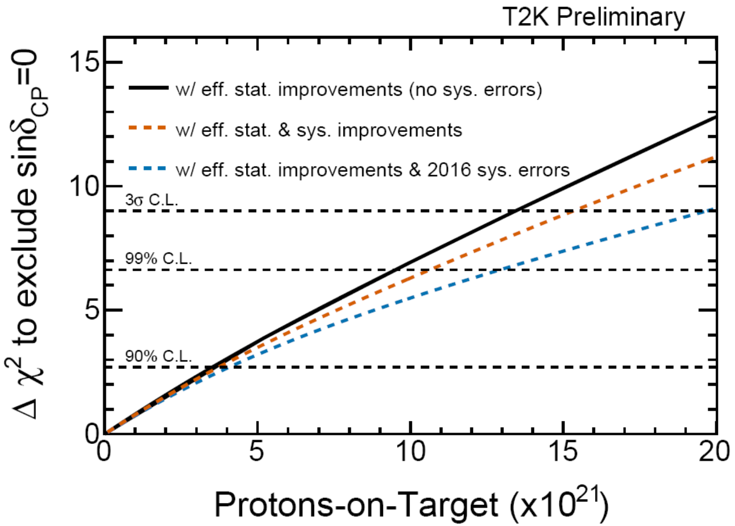
- T2K data combined with reactor measurements
  - Exclude CP conservation ($\sin(\delta_{CP}) = 0$) at 90%
  - Allowed region: [-3.13 to -0.39]
  - Weak preference for 'normal' neutrino mass hierarchy

More T2K data



- JPARC neutrinos beam power continues to increase – 470kW reached
- Run 8 finished – T2K doubled neutrino beam statistics
  - Data accumulated: **14×10^{20}** protons-on-target (POT) in neutrino beam mode and 7.6×10^{20} POT in anti-neutrino beam mode
  - Oscillation results later this year.

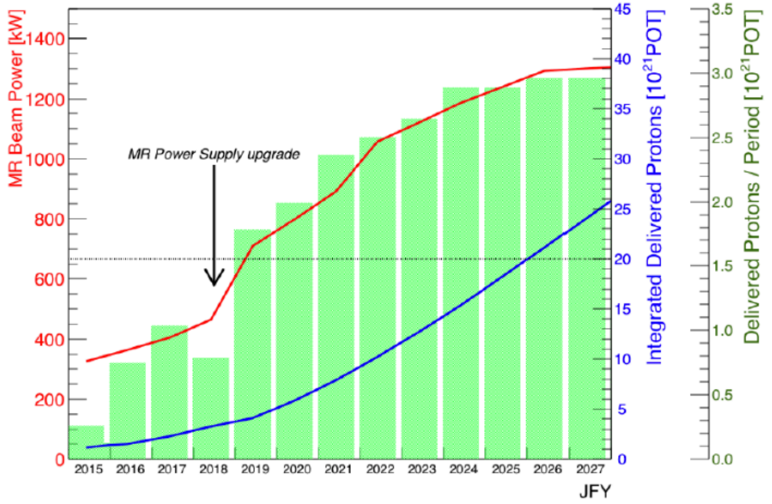
- Proposal to add x3 more statistics to T2K dataset (total of 20 x 10^{21} POT)
  - 3σ sensitivity to CP violation
  - Limited by systematics (particularly cross-section uncertainties)



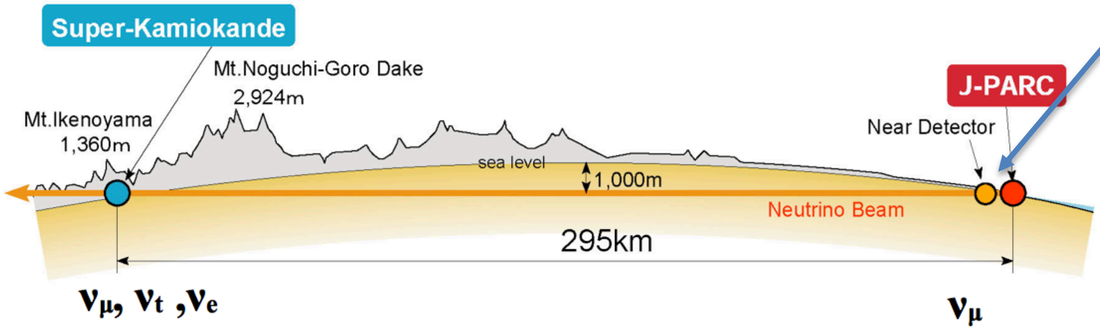
	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

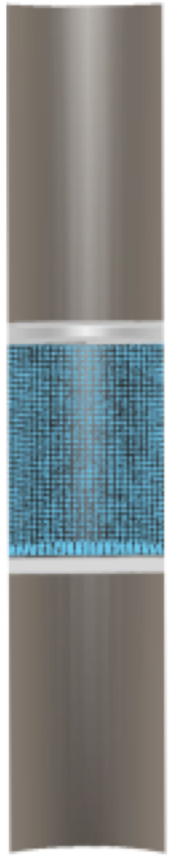
T2K-II Progress

- Stage-1 approval from J-PARC PAC
- First stage of MR power supply upgrade approved
  - Reduce MR acceleration cycle from 2.48 → 1.3 sec
  - with currently achieved power of 430 kW → 800 kW
- Looking beyond 1 MW to 1.3 MW beam
  - Highest priority in Recent KEK Project Implementation Plan
  - Prepare for Hyper-Kamiokande and explore T2K run to ~2026
- Need plan for further controlling systematic errors…



- New water Cherenkov detector spanning 1° – 4° from the neutrino beam axis
  - 52.5m tall, 1km from T2K neutrino production target
- Movable cylinder:
  - Inner Detector (ID): 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall
- Measure neutrino interaction spectra at different off-axis angles.





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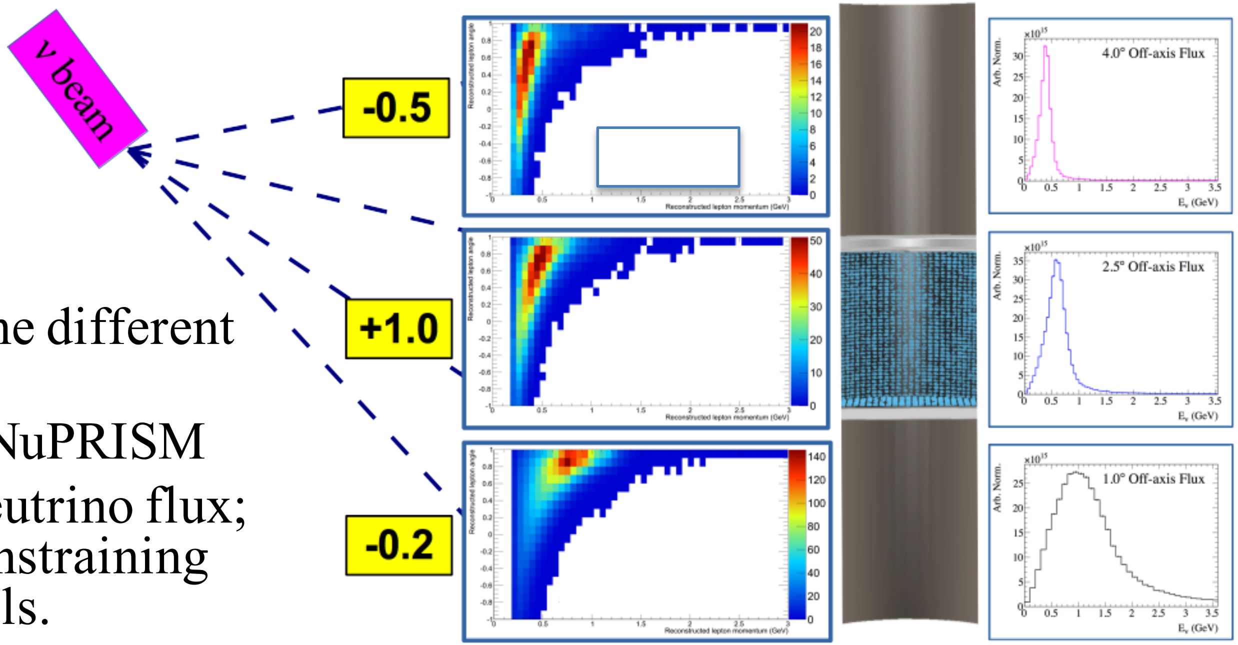
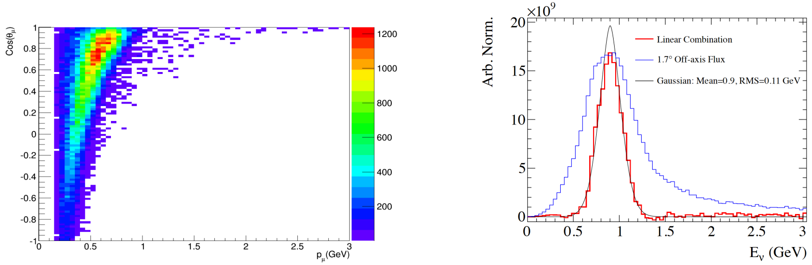
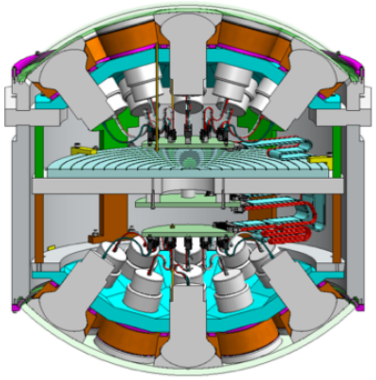
NuPRISM Concept

- Weight and combine different off-axis fluxes
- Apply to slices of NuPRISM
- Create Gaussian neutrino flux; very helpful for constraining cross section models.
- Can also use technique to create more complicated spectrums.
  - John Walker talk for details…

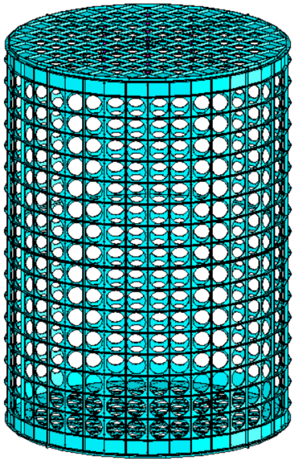




- Design involves multi-PMT modules (mPMT) that have array of 3" PMTs.
- Advanced design of mPMT support structure
- Start with phase-0, with detector on surface.

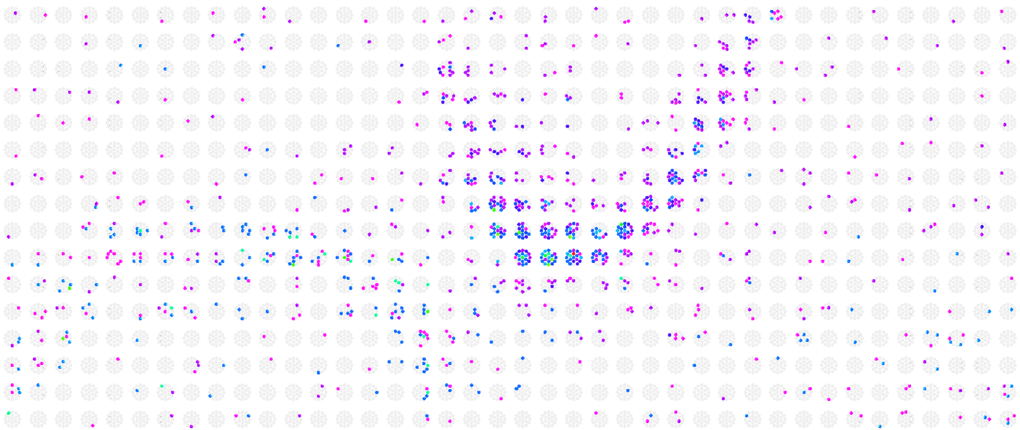


mPMT conceptual design

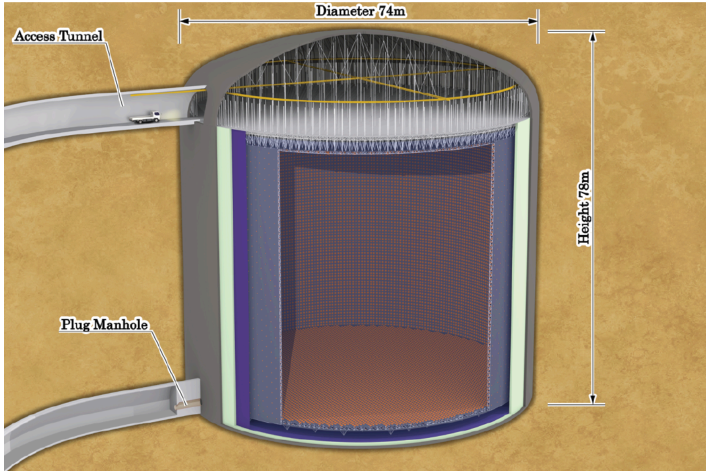


mPMT support structure

Unrolled NuPRISM event display with mPMT

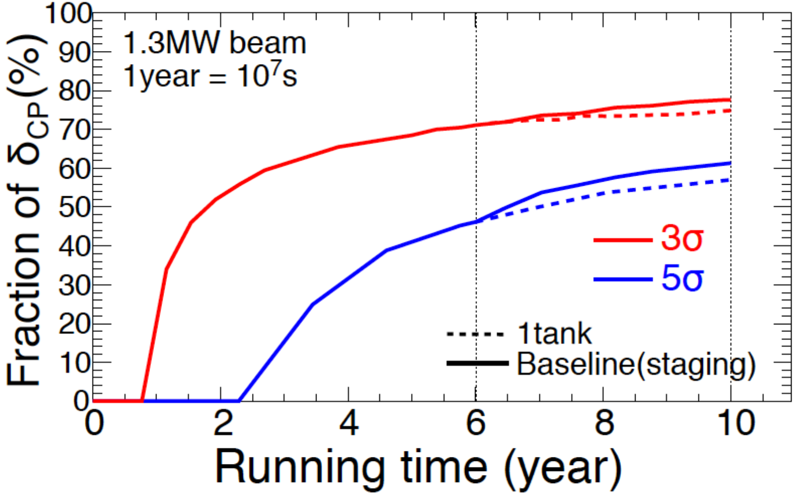


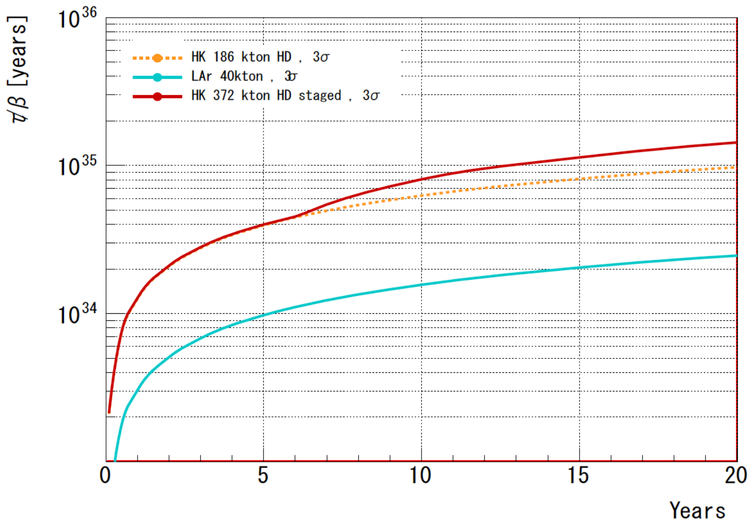
- Proposed Successor to Super-Kamiokande.
- Key parameters:
  - 2 tanks (second tank coming online 6 years later).
  - Tank size: 74m diameter, 60m height.
  - Fiducial mass per tank: 187kton.
    - x10 Super-K fiducial mass.
  - Instrumented with 40,000 high-QE, high resolution 20” PMTs.



- Search for Leptonic CP violation, using J-PARC neutrinos.
- NuPRISM key for reducing systematics.

Fraction of possible CP values for which HK can find CP violation





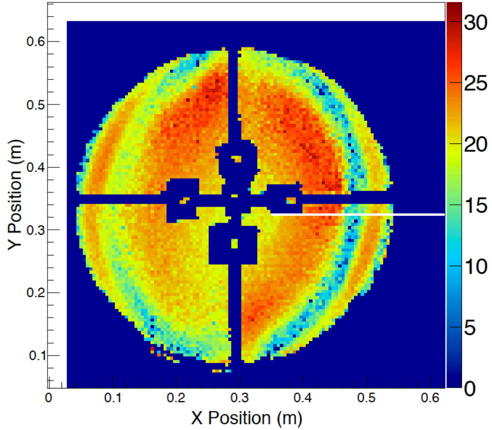
3σ discovery potential for $p \to e^+\pi^0$ decay

- Dramatic improvements in sensitivity to many channels of nucleon decay.

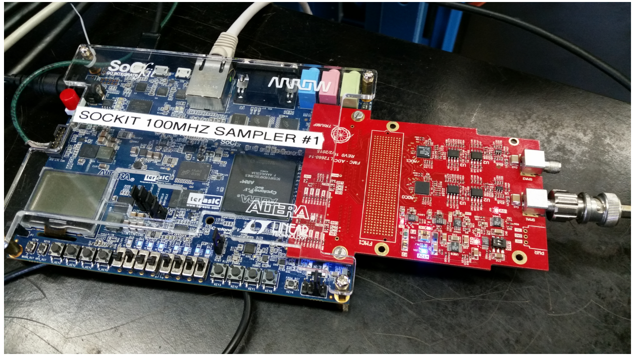
Plus many other exciting physics topics…

- Development of new 20” PMTs with higher QE and better timing resolution.
- Development of new mPMT modules, with better angular information.
- Improvements to calibration systems, including better understanding of PMT response.
- New electronics for 20” PMTs.

Hamamatsu box/line dynode PMT



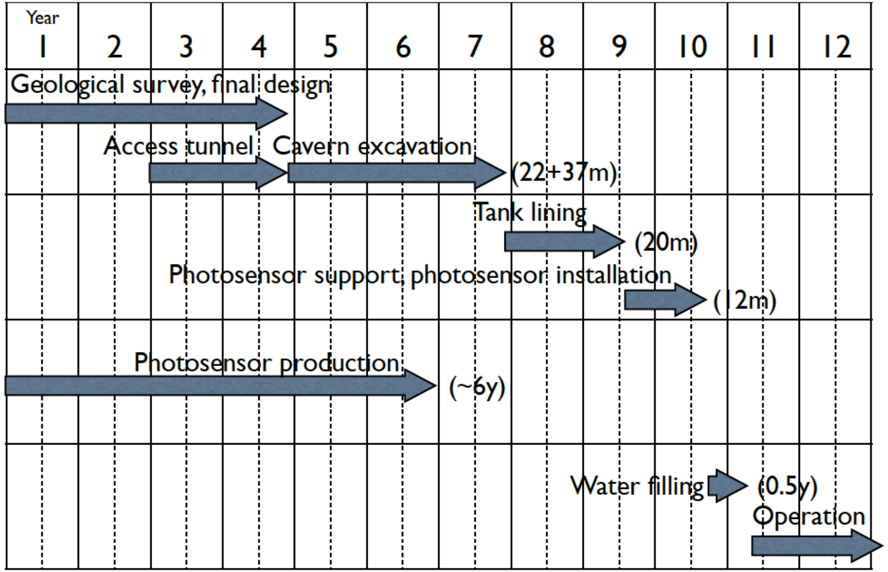
20” Gain scan at TRIUMF Photosensor Test Facility



100 MSPS ADC Prototype

- Hyper-Kamiokande selected as a high priority large project by the Science Council of Japan
- Budget request lead by the president of University of Tokyo (PI: Takaaki Kajita)
- MEXT road map selection by July and the funding result to be announced in December

Construction Timeline



- Latest T2K results fully utilize neutrino and antineutrino data to constrain δ_{CP}.
- Continue to accumulate more statistics with T2K and T2K-II.
- NuPRISM is important project for constraining cross-section systematics for CP violation measurement.
- Hyper-Kamiokande design is well advanced and significant progress on funding/approval.

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