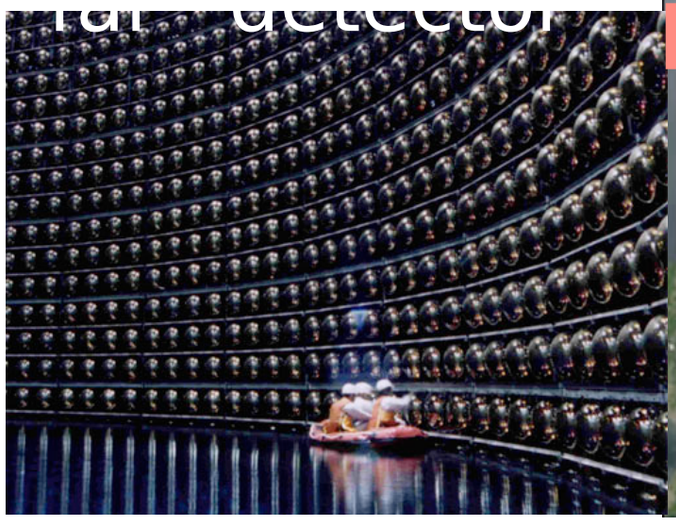
OVERVIEW OF T2K-CANADA ACTIVITIES

B. Jamieson (University of Winnipeg)
presented on behalf of T2K-Canada

IPP AGM
28 May 2017, Kingston, ON

T2K

Super Kamiokande



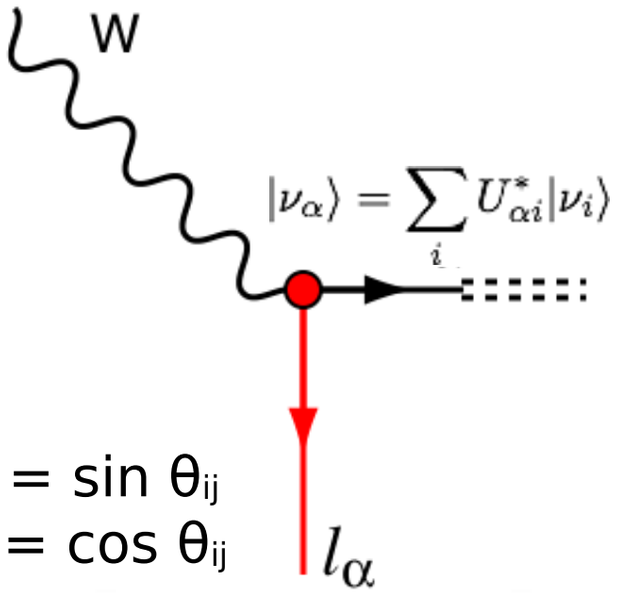
ND280
"near" detector

J-PARC

~400 collaborators from 58 institutions, 11 nations

Intense $\nu_\mu/\overline{\nu}_\mu$ beam sent 295 km across Japan and detected with the Super-Kamiokande detector to study neutrino oscillations

MIXING OF THREE NEUTRINOS



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

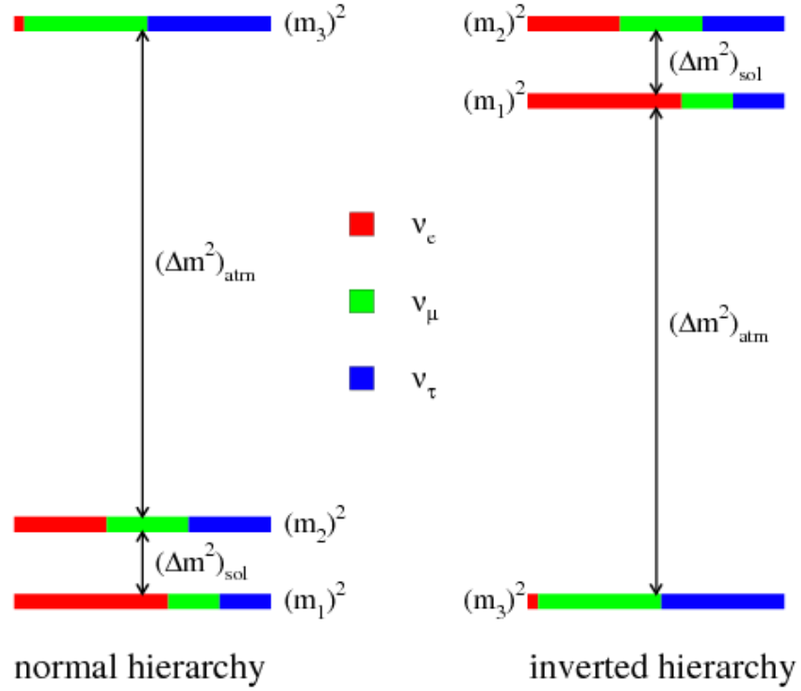
s_{ij} = sin θ_{ij}

c_{ij} = cos θ_{ij}

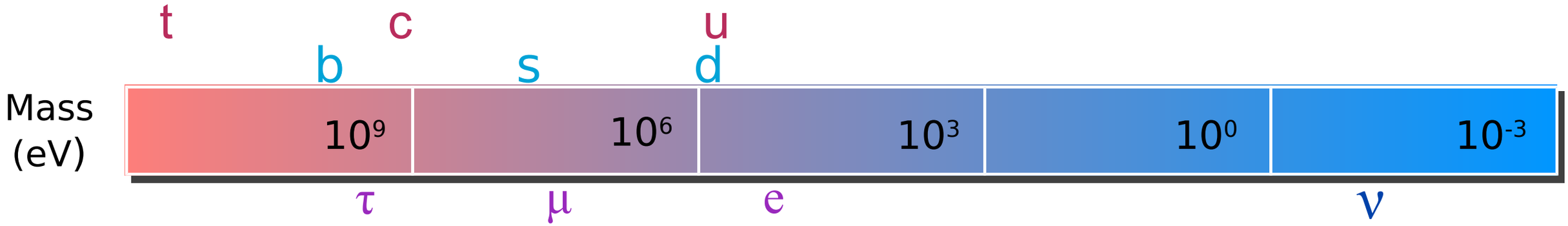
"standard" parametrization

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- Two mass splittings known
  - "ordering" still unknown
- One complex Dirac phase δ



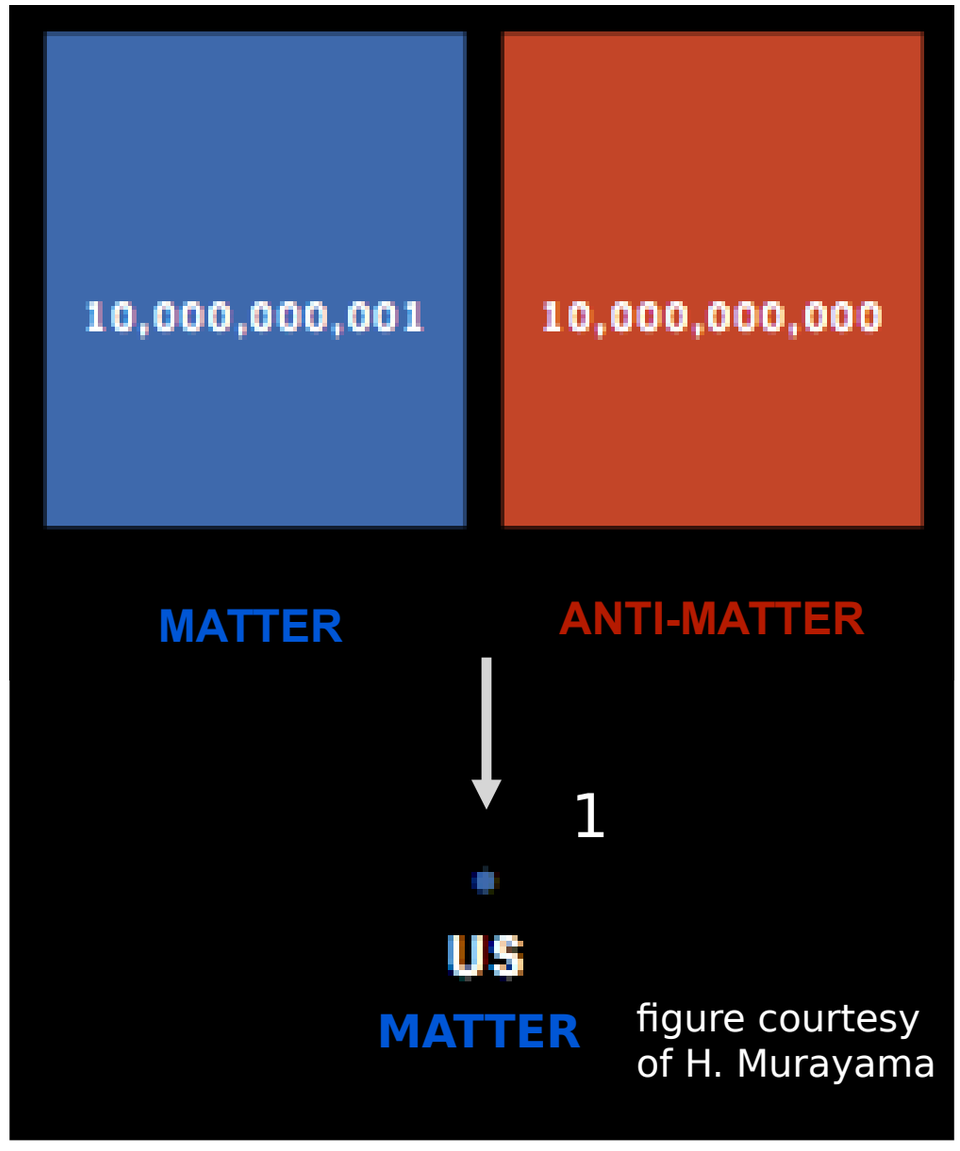
BIG PICTURE



$$|U_{quark}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

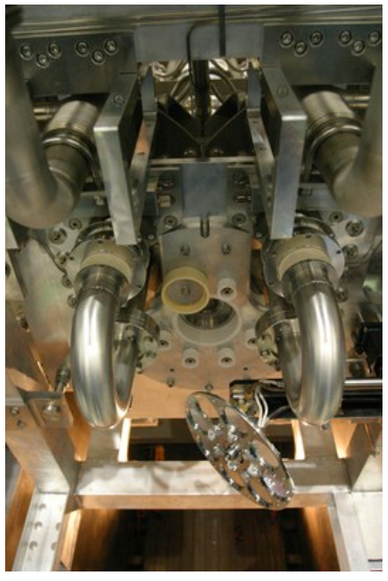
$$|U_{lepton}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

- What is the underlying physics behind
  - mixing?
  - quark, lepton, neutrino mass?
- What role does it have in shaping the universe?
- Seeking hints and answers through neutrinos is recognized globally as among the highest priorities in particle physics



CANADIAN INVOLVEMENT

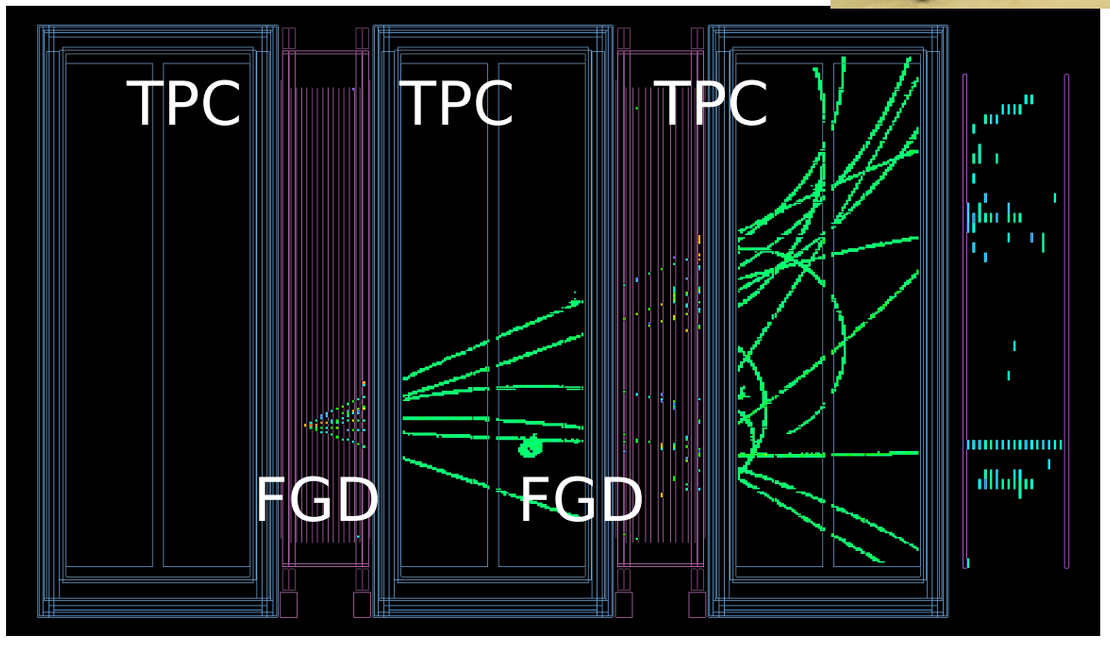
- Founding members of collaboration in 2001
  - introduced “off-axis” beam concept
  - major impact on near detector concept



OTR

TPC

FGD



The JHF-Kamioka neutrino project

Y. Itow[1], T. Kajita[1], K. Kaneyuki[1], M. Shiozawa[1], Y. Totsuka[1],
Y. Hayato[2], T. Ishida[2], T. Ishii[2], T. Kobayashi[2], T. Maruyama[2],
K. Nakamura[2], Y. Obayashi[2], Y. Oyama[2], M. Sakuda[2], M. Yoshida[2],
S. Aoki[3], T. Hara[3], A. Suzuki[3],
A. Ichikawa[4], T. Nakaya[4], K. Nishikawa[4],
T. Hasegawa[5], K. Ishihara[5], A. Suzuki[5],
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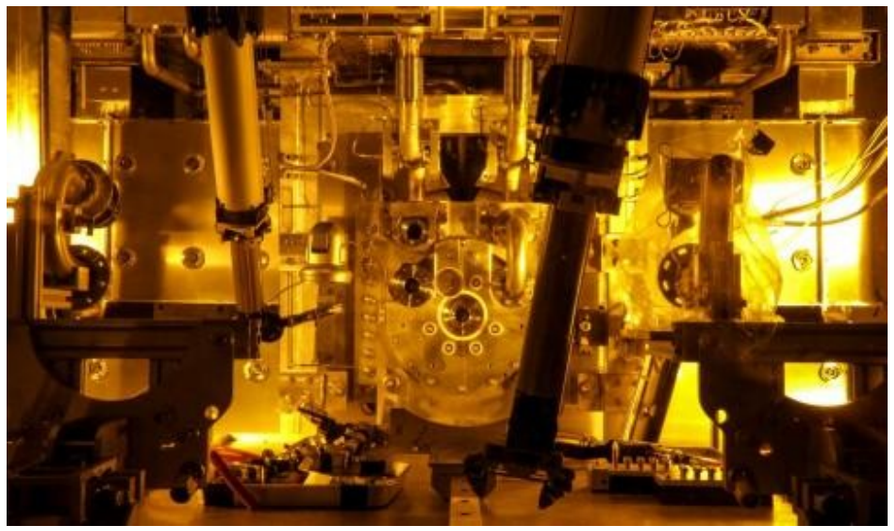
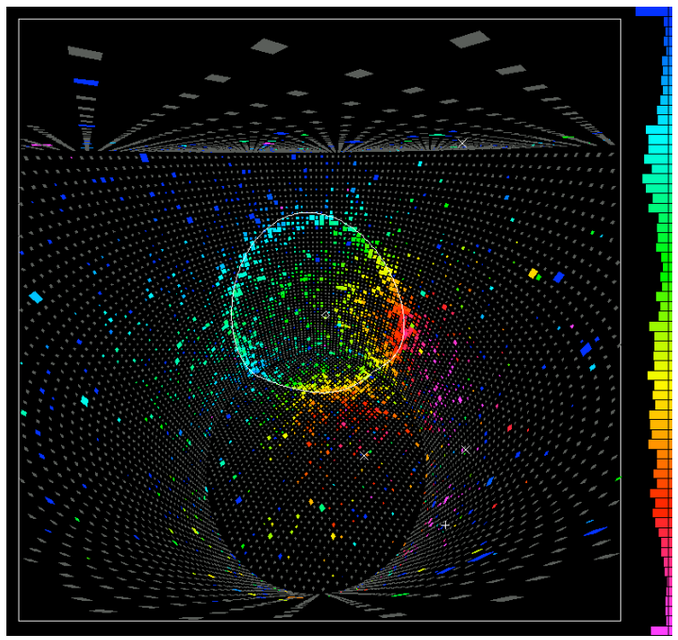
- 2004-2009 Construction phase
  - Near detector tracker
    - 2 fine-grained scintillating tracking detectors
    - 3 time projection chambers
    - core of ND280 off-axis detector
  - Optical Transition Radiation monitor
    - proton beam profile measurement immediately upstream of target
    - critical element of beam operations
- 2010- data-taking begins

SUPPORT

- TRIUMF: strong support for
  - design, construction, operation of detectors
  - overall ND280 network, cooling, slow control
  - critical beam line design, monitoring, and maintenance
  - computing:
    - main software repositories, databases
    - t2k.org website
    - collaboration-wide data distribution
  - test beam for pion interaction studies (DUET)





- Compute Canada
  - >5 million core-hours of CPU/year
    - roughly 1/2 of collaboration-wide capacity for data/MC production
  - Catalyst for Canadian analysis contributions
    - ND280 calibration and reconstruction
    - Improved Super-K reconstruction (fiTQun)
    - near/far extrapolation and Markov Chain-based analysis
- CFI Support at the Universities
  - PMT test facility, main elements of DUET experiment, Tier-1 data storage at TRIUMF

Complements and enhances NSERC operation and research support

T2K CANADA CURRENT HQP

Postdocs and RA's

- John Walker – TPC Operations and nuPRISM design studies, PID for improved nue selections in nd280
- Mark Scott – Near/far extrapolation convener, NuMu analysis, nuPRISM &HK
- Tom Feusels – FSI convener, CC0pi cross-sections, HK photosensor convener, nuPRISM &HK
- Arturo Fiorentini – Beam convenor, Beam OTR, beam MC, pion FSI studies
- Nick Hastings – run coordination, data quality convener, data and monte-carlo productions

- Excellent record of seven previous postdocs moving into faculty positions
  - becoming leaders of new experimental efforts (nuPRISM) , oscillation analysis, and neutrino interactions

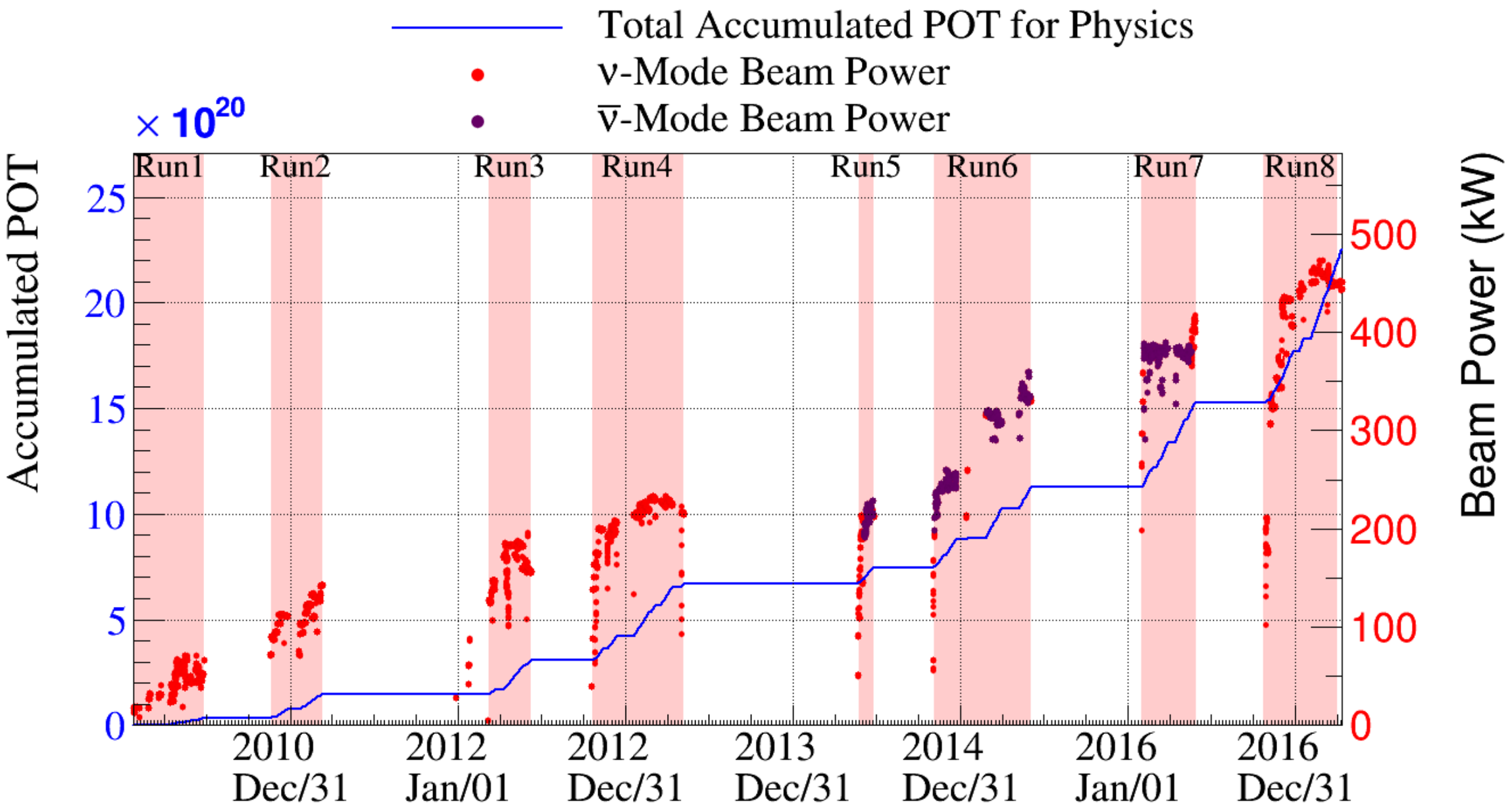
+ Several Undergraduate co-op or NSERC USRA students

Graduate Students

- Fady Shaker – nd280 anti-nue cross-section measurement
- Jashanjot Brar – optical calibration for nuPRISM
- Sophie Berkman – Numu CC1pi analysis at SK
- Elder Pinzon – Harpsicord TRIUMF measurement of pion interactions
- Trevor Towstego – Nue CC1pi analysis at SK, nuPRISM design studies
- Khalid Gameil – FNAL hadron production measurements
- Mitchell Yu – nd280 CC1pi analysis and beam OTR
- Corina Nantais – NCgamma dark-matter search in SuperK
- Jiae Kim – CC0pi analysis looking for 2p2h
- Marcello La Posta – new Regina grad student

- additional 14 graduate students graduated
  - good record of students going on to post-docs and successful careers in industry

NEUTRINO DATA COLLECTED

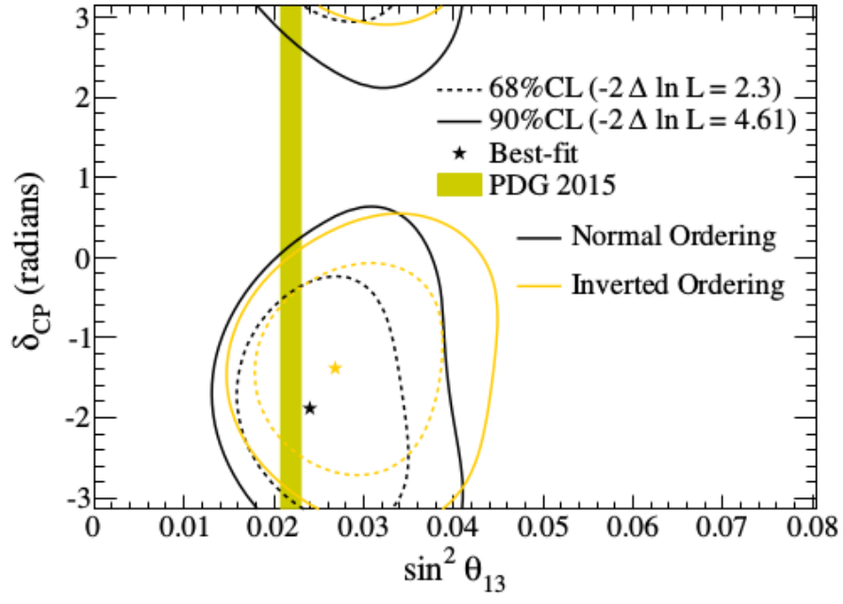


- Steady increase in beam power
  - ~240 kW in 2014 → 420 kW in 2016 → 470 kW in 2017
- Antineutrino beam
  - reverse polarity of focussing to collect and decay π^- ($\rightarrow \mu^- + \bar{\nu}_\mu$)

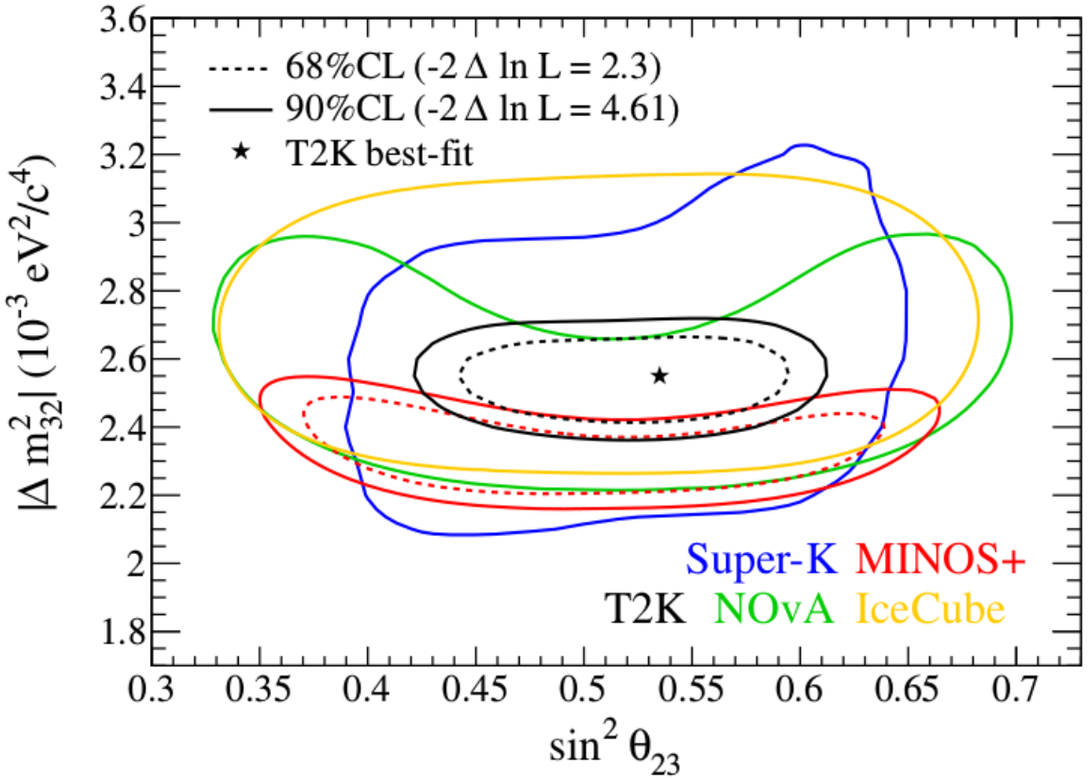
T2K OSCILLATION PARAMETERS

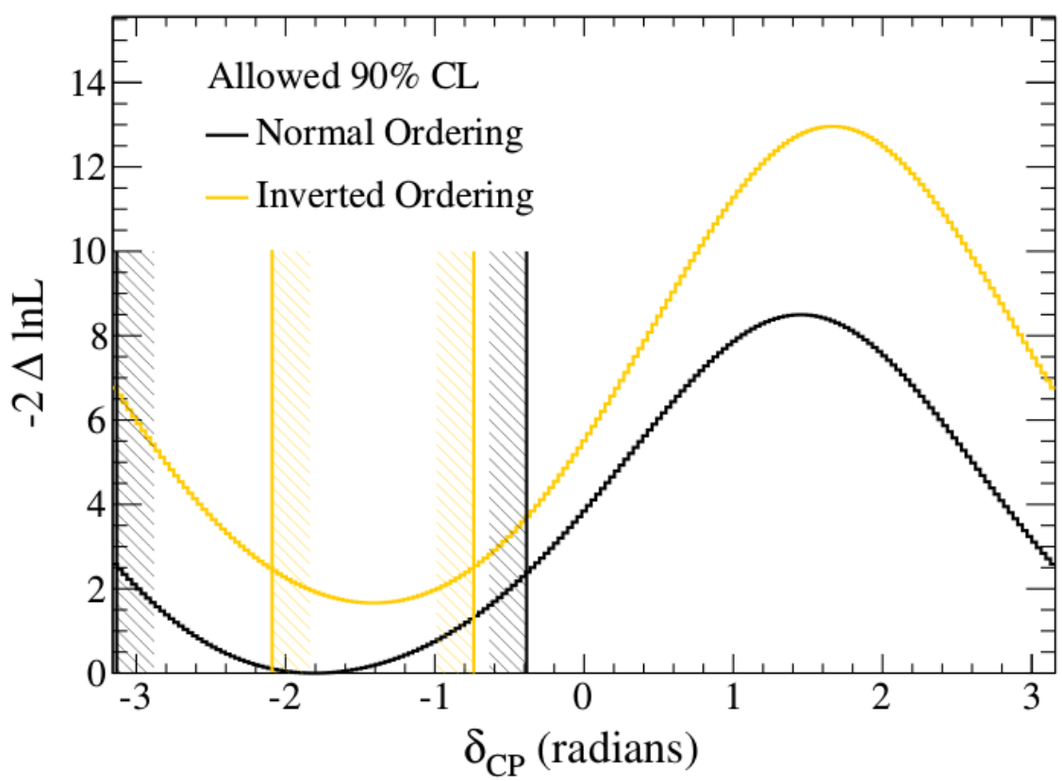
CAP talk of Thomas Lindner (TRIUMF) – June 1 at 08:30 Botterell B139

Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4



- Data favors: maximal θ_{23} (~π/4), large ν_e appearance, δ_{CP} ~-π/2, normal hierarchy
- Significant milestone: first fully joint analysis across four oscillation modes
  - important analysis improvements including FGD2 water target data

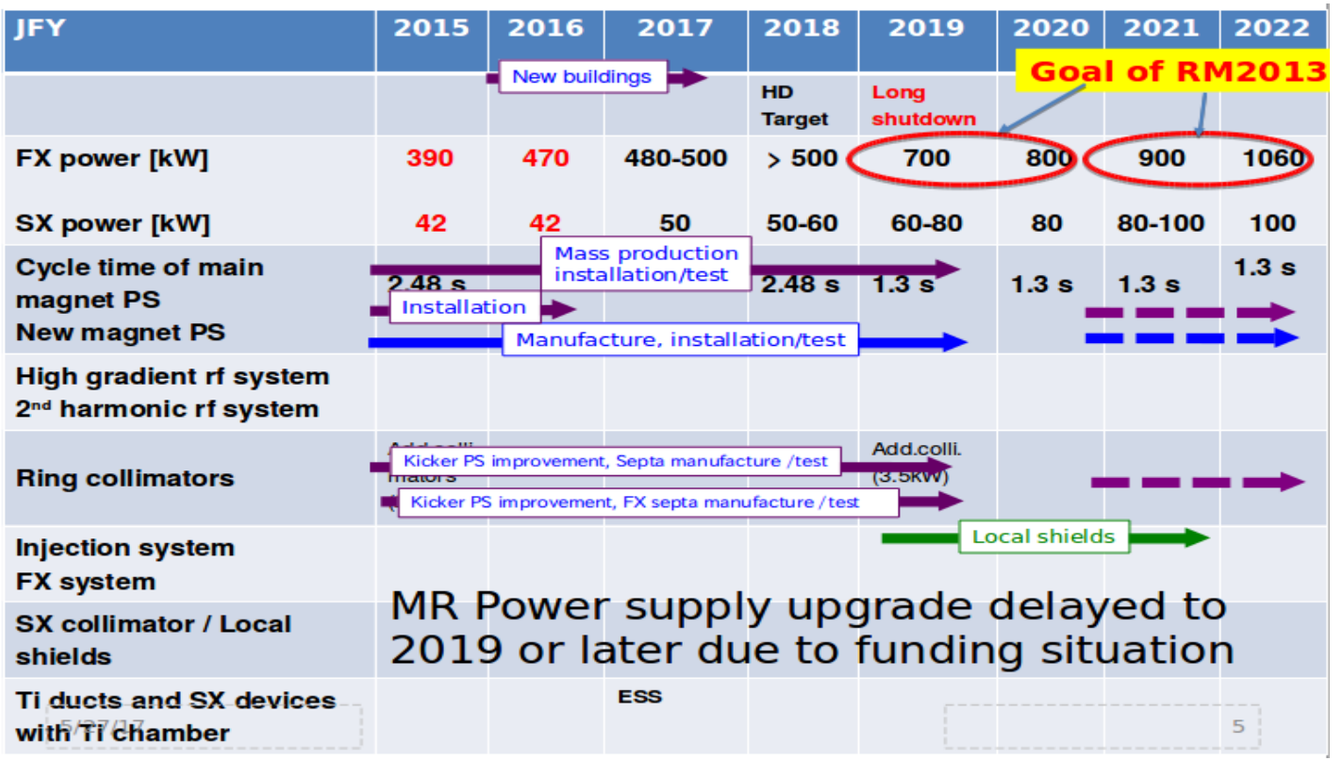


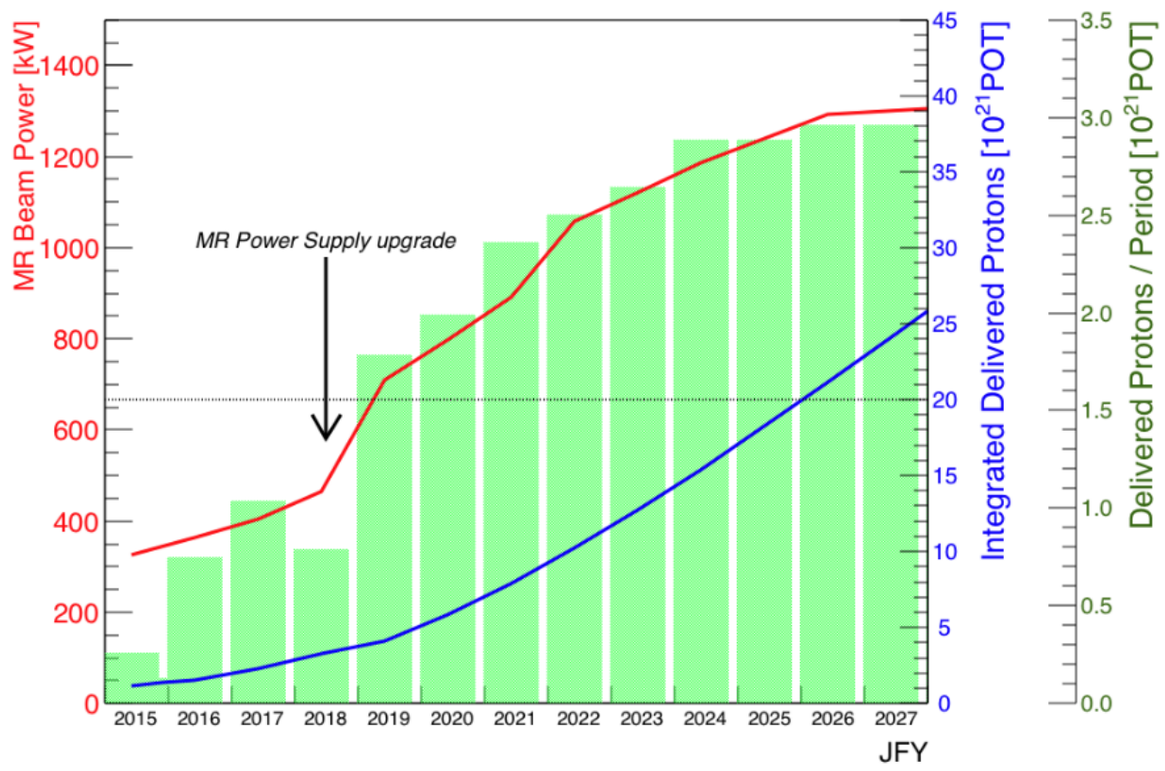


PRL 118 (2017) 151801

editor's choice

J-PARC MAIN RING UPGRADE





- MR power upgrade approved
  - MR cycle 2.48 → 1.3 sec
  - power of 470 kW → 900 kW
- looking beyond 1 MW to 1.3 MW beam
  - Highest priority in KEK Project Implementation Plan
  - Hyper-Kamiokande and T2K run to ~2026

POT totals today

	FHC (10^{20} POT)	RHC (10^{20} POT)	TOTAL (10^{20} POT)
T2K	14.9	7.6	22.5
NOvA	~9.5	~2.1	~11.6

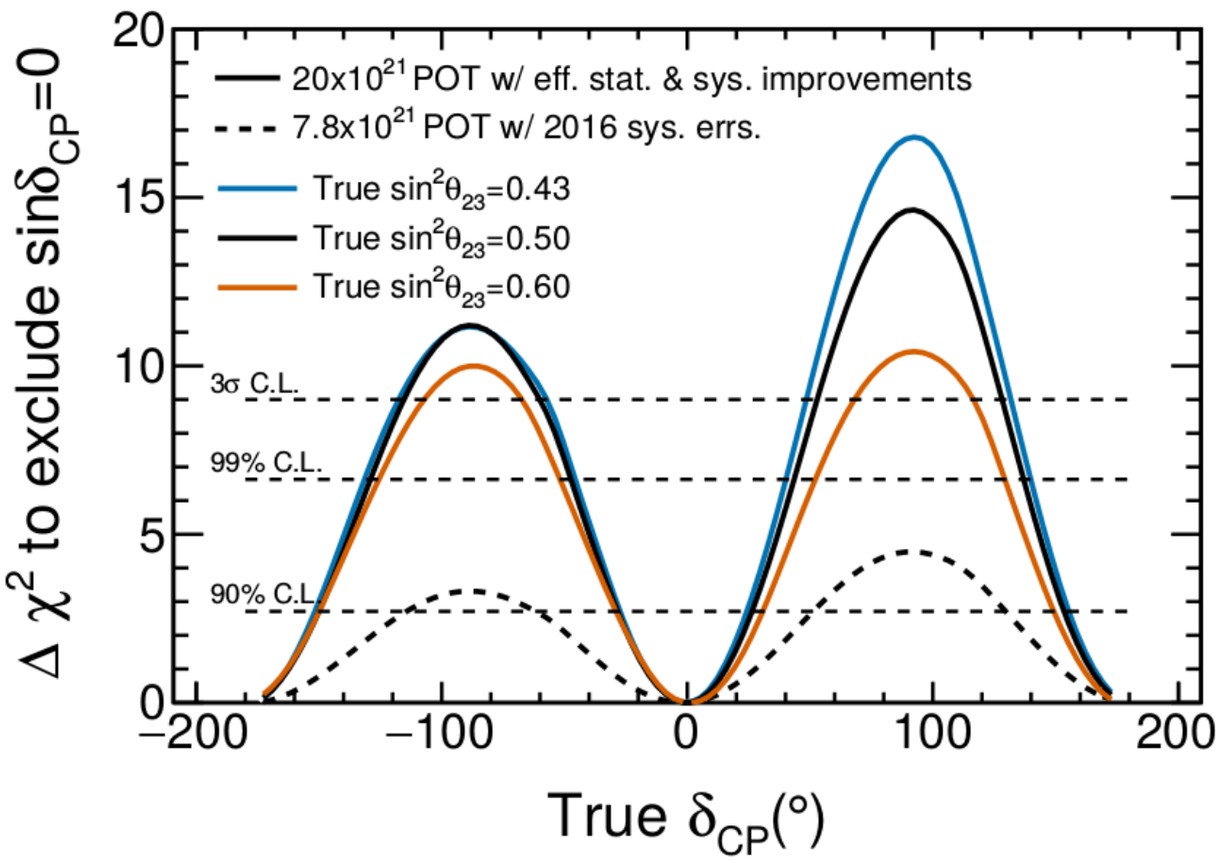
NOvA expects to have about **13e20 POT** by Sep 2017.

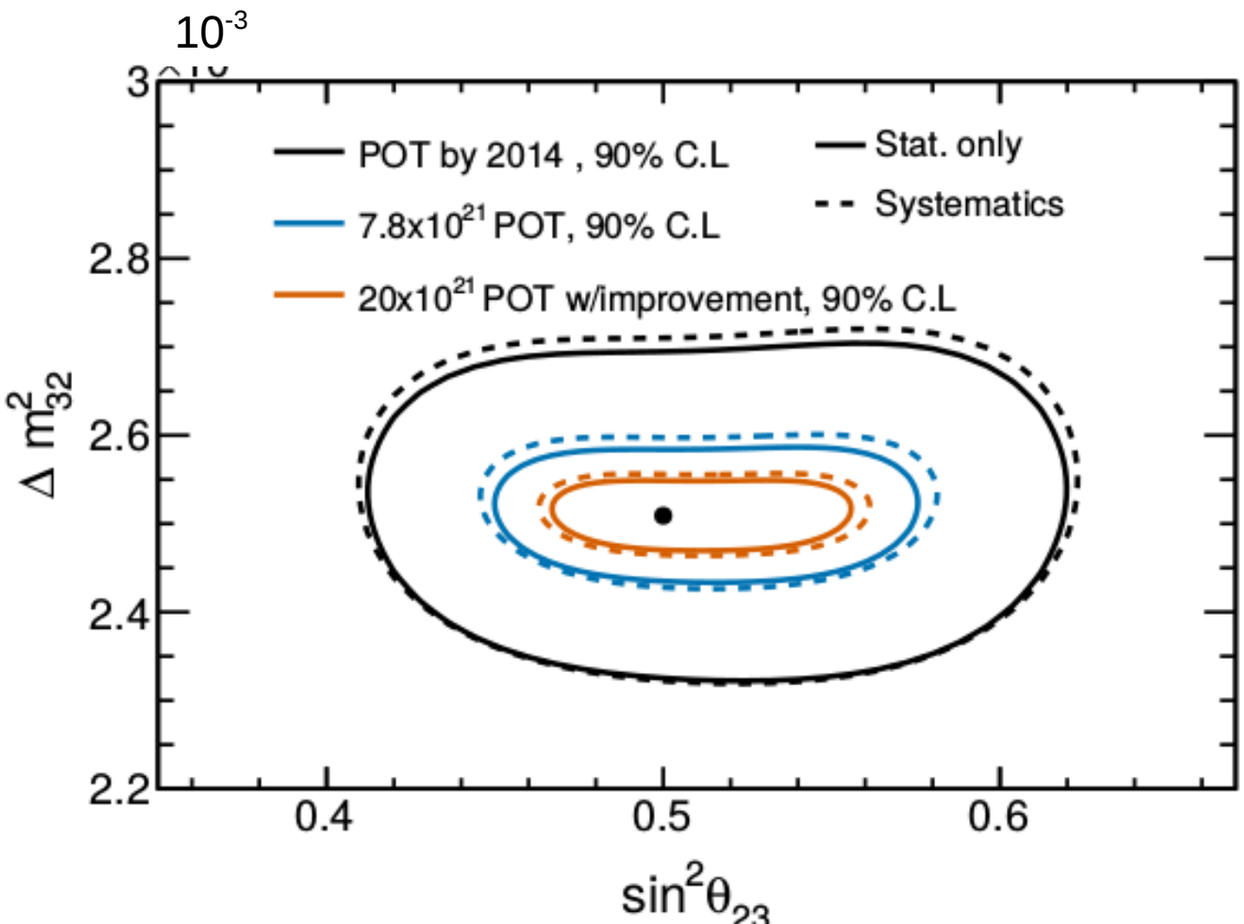
“T2K-II” GOALS

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	467.6	356.3	4.0	73.3	1.8	32.3
ν_e sample	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode	0	133.9	16.7	73.6	29.2	0.4	14.1
$\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

- Accumulate 20x10^{21} POT by 2026
  - ~3x approved POT
  - in advance of next generation
- ~3 σ significance for CPV in (currently) favorable cases
- θ_{23} precision of better than 1.7º

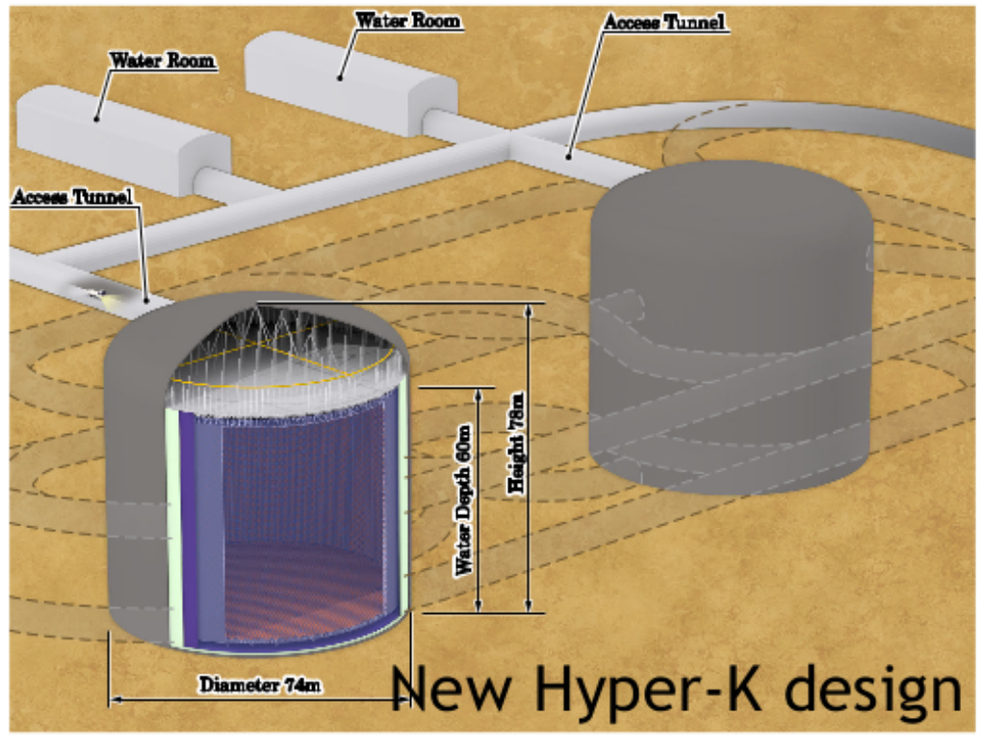
assumes MH known





Hyper-Kamokande Prospects

- HK technical design report in Dec.2015
  - New vertical tank geometry with staging
    - Fiducial volume is reduced to 187kton:
      fit in the Japanese budget constraint
    - x2 enhanced photo-sensor coverage by international contributions
      unique design with additional info: multi-PMT
  - Reviewed by International Advisory Committee
    - Strong support for the new baseline design
    - Proposal submitted to Science Council of Japan (SCJ)
      SCJ (2017) -> MEXT Roadmap (2017) -> Funding
    - HK funding request from ICRR (Kajita) for FY2018
      Funding request for the far detector
      Funding for accelerator/NuPRISM from KEK (KPIP)



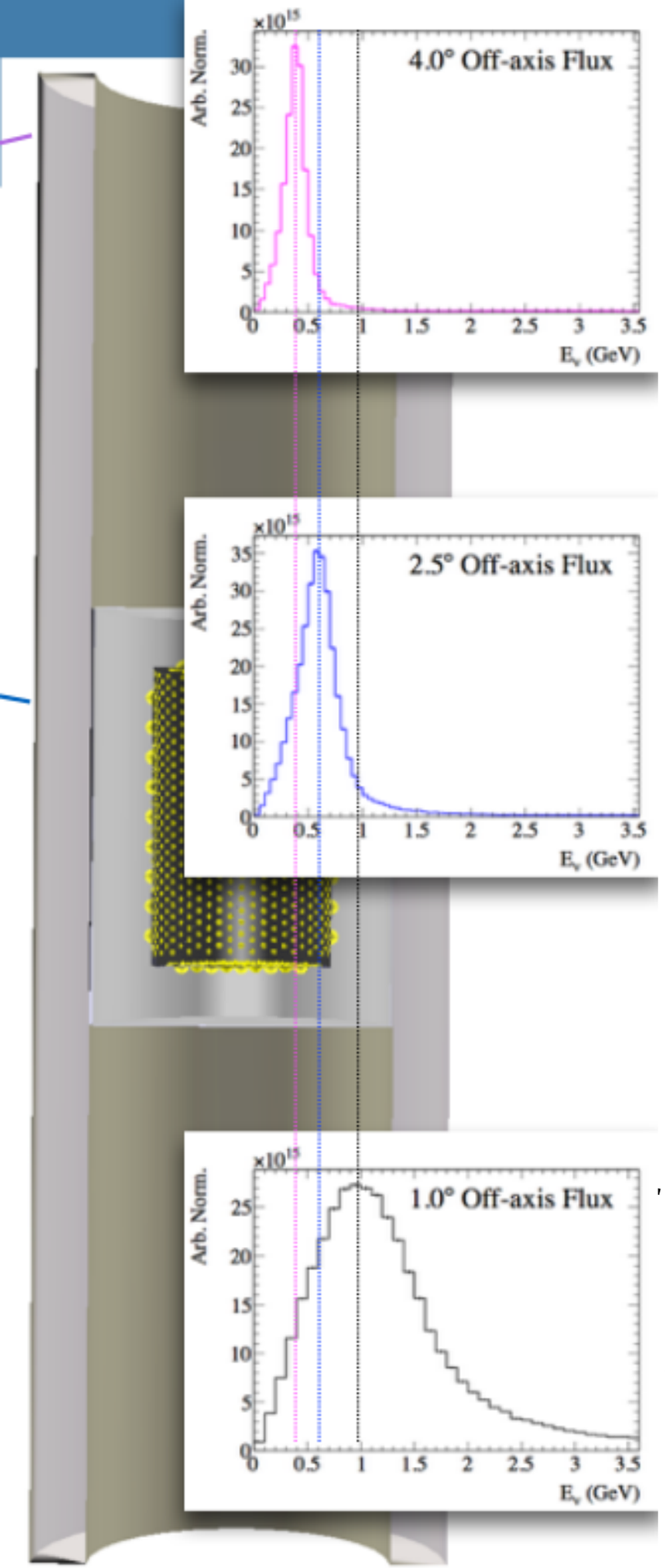
New Hyper-K design

Leadership roles:

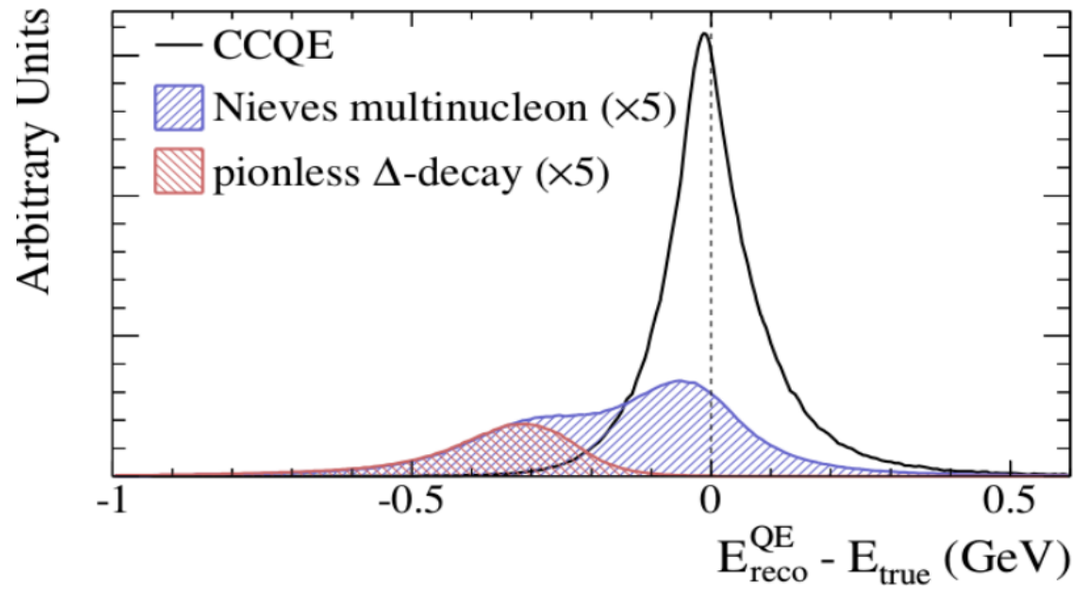
- Thomas Lindner – DAQ/electronics convener
- Tom Feusels – photosensor convener

NuPRISM

CAP talk of John Walker (Winnipeg) – June 1 at 09:00 Botterell B139



- New concept to exploit the variation of neutrino energy with off-axis angle
- Data taken at different angles can directly predict neutrino interactions with arbitrary neutrino fluxes including effects from oscillation

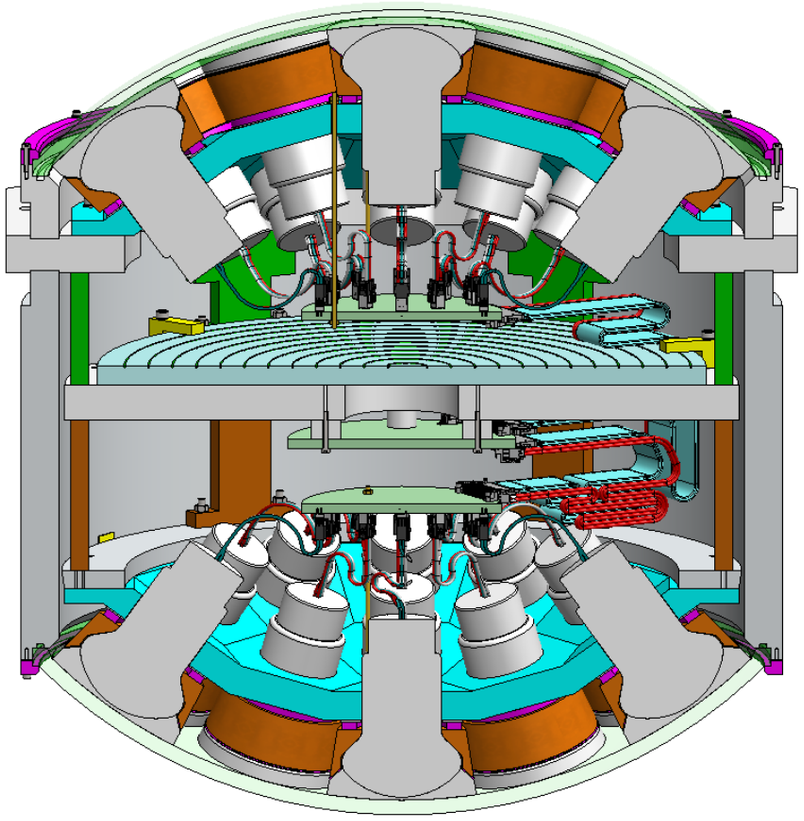


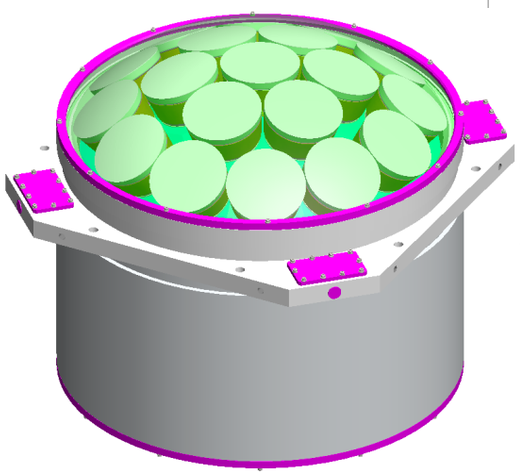
- addresses critical ν interaction modeling systematics
- Initial phase on surface with large off-axis angle for precision ν_e/ν_μ measurements granted Stage 1 status at J-PARC

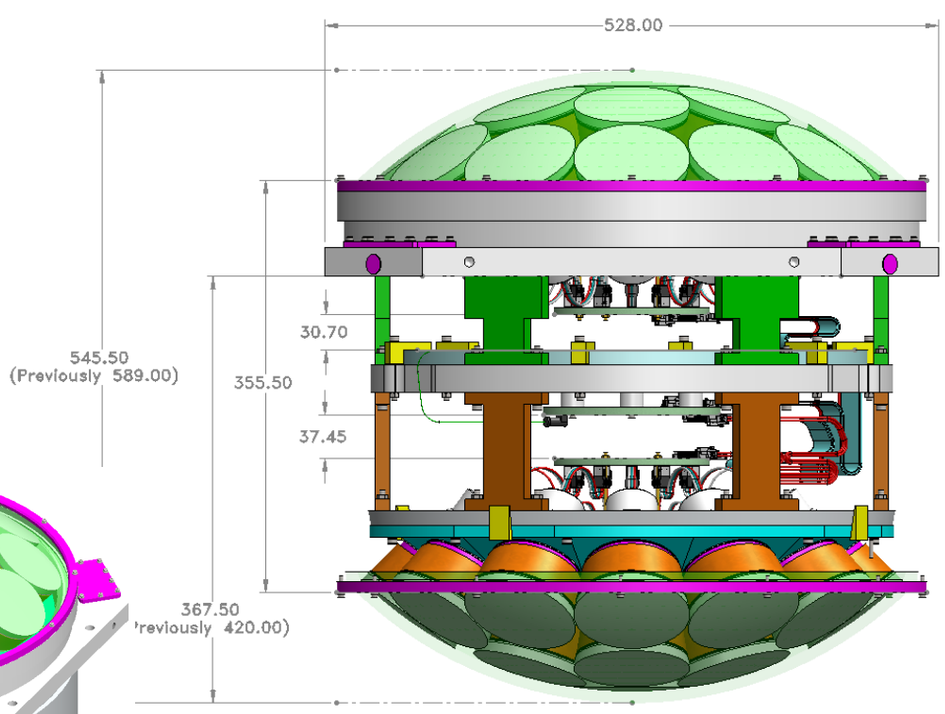
$$N(\nu_\mu \rightarrow \nu_e) = \Phi_\nu(E_\nu) \times \sigma_\nu(E_\nu) \times \varepsilon(E_\nu) \times P(\nu_\mu \rightarrow \nu_e; E_\nu)$$

CAPSTONE:

- Large CFI Innovation Fund Proposal pending
  - “Canadian Advanced PhotoSensor Technology for Neutrino Experiments”
  - Alberta (lead), Regina, Toronto, York
  - SNOLAB, TRIUMF, Winnipeg as partners
  - design/build multi-PMT modules for IceCube, KM3NET, NuPRISM
- Funding would:
  - complete design of mPMT design for NuPRISM
  - establish production and testing facilities for mPMTs
  - produce mPMTs for IceCube, KM3NET and NuPRISM
- UA members (D. Grant, C. Kopper) join this grant for NuPRISM
- Funding outcome in June 2017

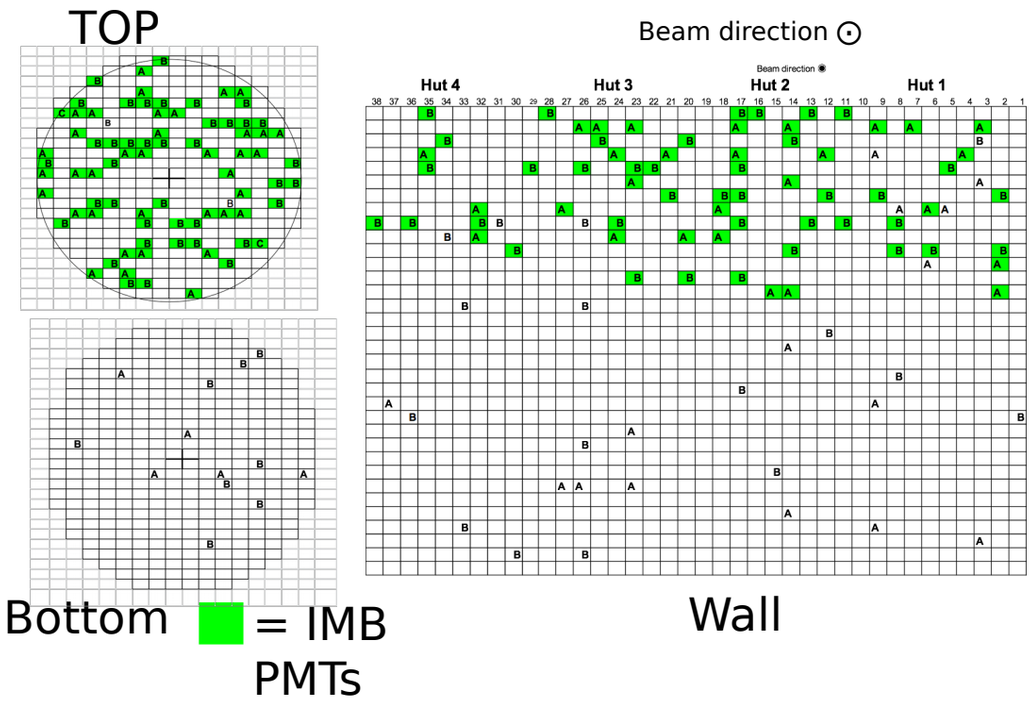






SK-OD REFURBISHMENT

- In 2015, the Super-K decided to proceed with “SK-Gd”
  - Load water with $GdSO_4$: enhanced neutron detection capabilities with n-Gd capture
  - Eventually aim for 100 ton loading (0.2%) results in 90% capture rate
- First stage expected in summer 2018
  - expected to last ~6 months to repair SK tank and replace OD PMTs
  - long shutdown for MR PS upgrade at JPARC in 2019
  - KEK and JPARC will schedule neutrino schedule to maximize neutrino data for T2K through this period



- Nearly 200 out of 1885 OD PMTs are now dead
  - mortality is especially high among old IMB PMTs
  - rate of 1 PMT every 11 days
- Participate in OD replacement work
  - student participation + travel
  - NSERC RTI for replacement 8” PMTs may be submitted
- Canada has become a key partner in the collaboration
  - member of Executive Committee (A. Konaka)

NSERC CRSNG

People. Discovery. Innovation.

NSERC DISCOVERY GRANT TO T2K

- Awarded two year grant
  - 1,150,000 in year FY2017
  - 1,300,000 in year FY2018
- Two years award to see results of CFI competition and progress on J-PARC beam intensity upgrade for T2K-II and funding of Hyper-K

“The Evaluation Section recognizes the excellence of the applicants and the quality of their record in training Highly Qualified Personnel. The scientific contributions of the applicants are rated as outstanding. The objectives of the proposal are clearly stated; however, the Evaluation Section has identified several uncertainties associated with the proposed research program. These include the outcome and timeline of the J-PARC Program Advisory Committee approval process for T2K-II, Hyper-K and NuPRISM, as well as the outcome from the current CFI competition. Taking this into account, the Evaluation Section recommends funding for a period of two years. On this timescale, some of these uncertainties should be resolved making it possible for the applicants to prepare a focused and detailed proposal. The recommended level of funding takes into account the significant pressure on the Subatomic Physics Envelope, the findings from the Expert Review Committee, as well as expected carry-over from the current fiscal year. The Evaluation Section believes that the recommended level of funding will allow the applicants to successfully carry out the proposed scientific program.”

Conclusion and Outlook for T2K-Canada

- T2K-II aims at the discovery of CP violation at 3σ level before 2026
  - Statistics:
    - J-PARC upgrades: accelerator upgrades, horn current
      - highest priority in the KEK Project Implementation Plan
    - Analysis improvements with FiTQun: fiducial volume, CC1π
      - FiTQun developed by the Canadian group
  - Systematic uncertainties: new innovative approaches
    - Cross section (most challenging): NuPRISM
    - Flux: hybrid emulsion hadron production experiment at Fermilab
    - Detector efficiency: PTF, NuPRISM-0
  - Both T2K-II and NuPRISM received stage-1 by J-PARC PAC
    - Laboratory support towards TDR and funding requests
    - Both T2K-II and NuPRISM are initiated by the Canadian group
- Funding request to start HyperK construction from FY2018 from ICRR (PI:Kajita)
  - HyperK operation from 2026

The End.

ν OSCILLATIONS AT TOKAI→KAMIOKA

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Precision measurement of $\sin^2 2\theta_{23}$.
- CPT tests with antineutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

~30% max. effect

$$-\alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+\alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+\mathcal{O}(\alpha^2)$$

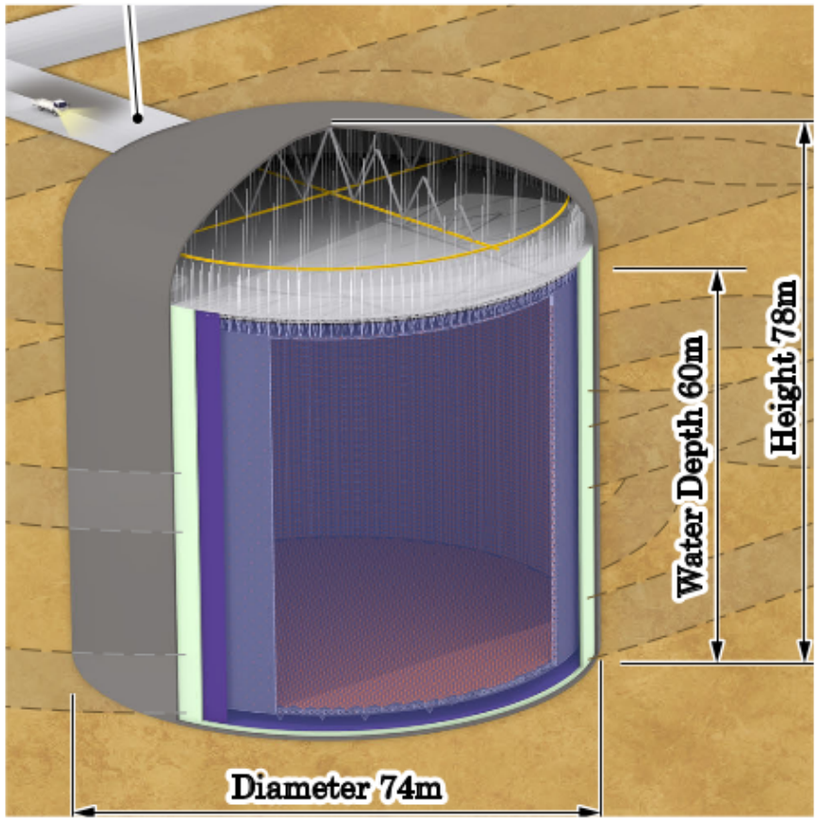
~±10%

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

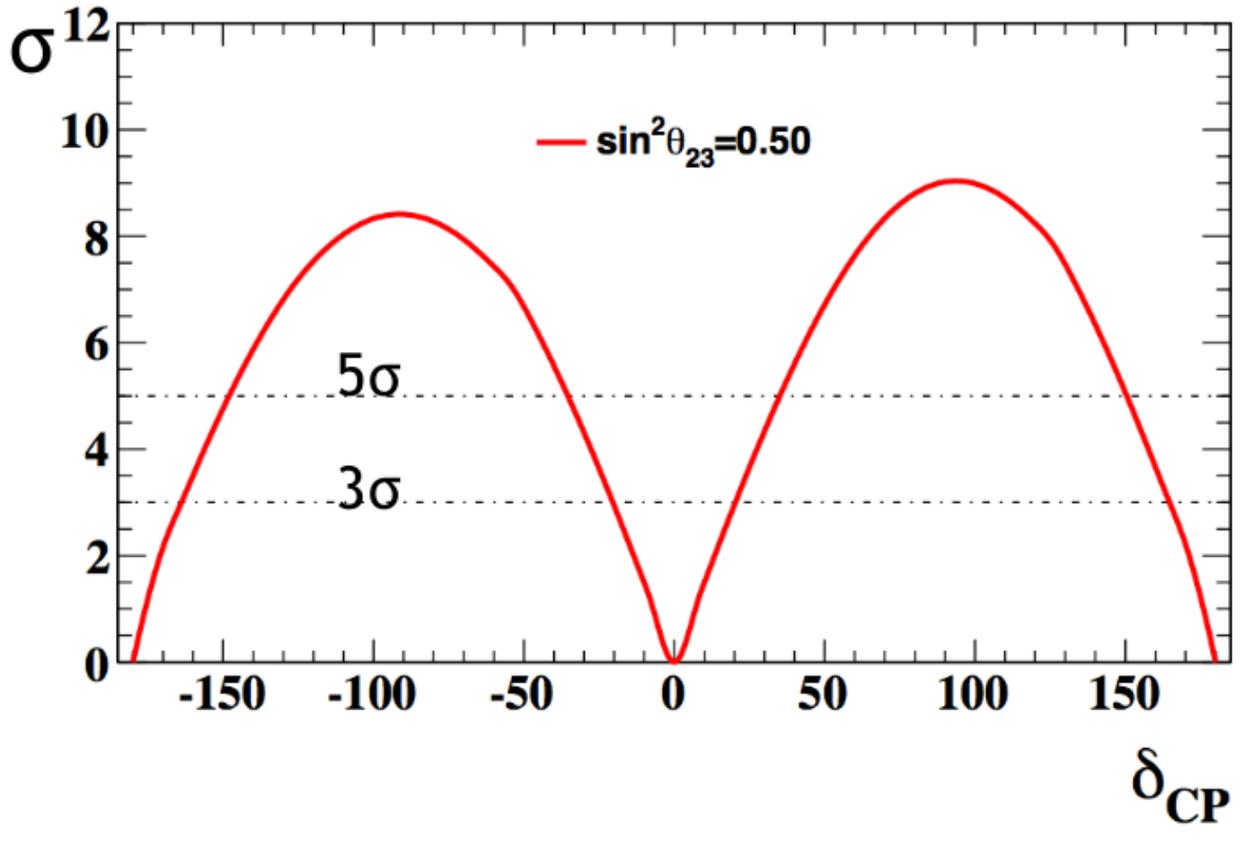
M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted)

Hyper-Kamiokande Physics Goals



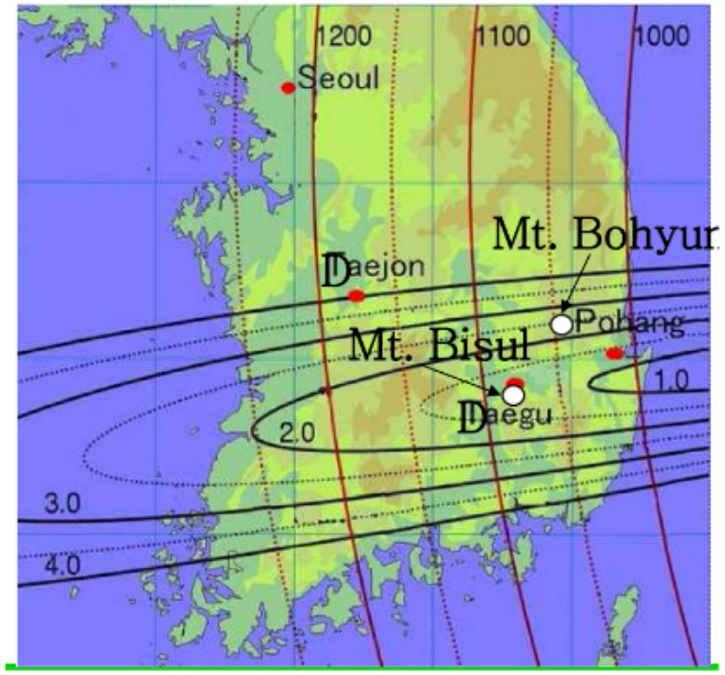
Physics goals:
- Precision neutrino oscillation, CP violation
- Nucleon decays, dark matter search
- Particle astrophysics: solar/supernova ν

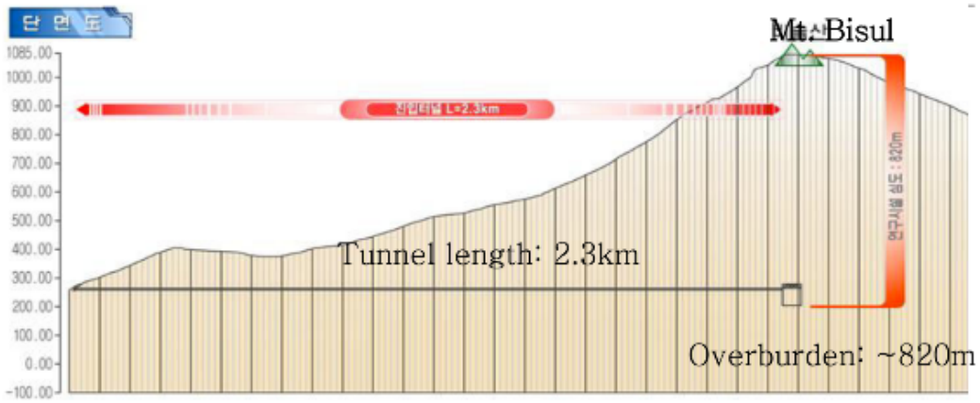


Hyper-Kamiokande:
~10 times larger detector than SuperK

2018-2025 Construction
2026 Physics data taking

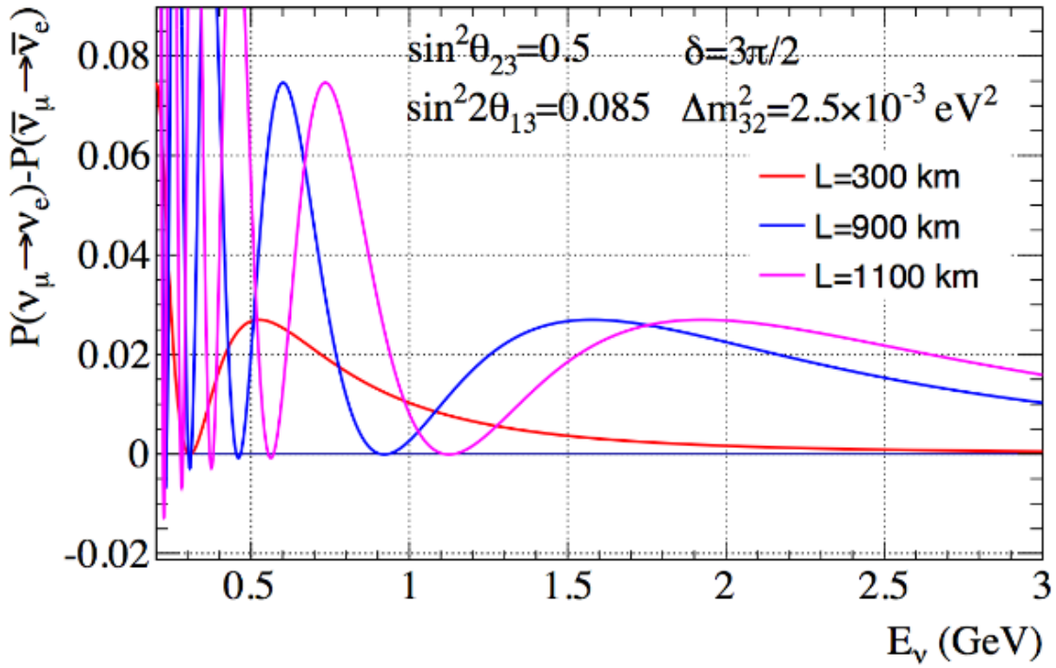
Second Hyper-Kamiokande in Korea





A white paper (ArXiv:0611.06118)

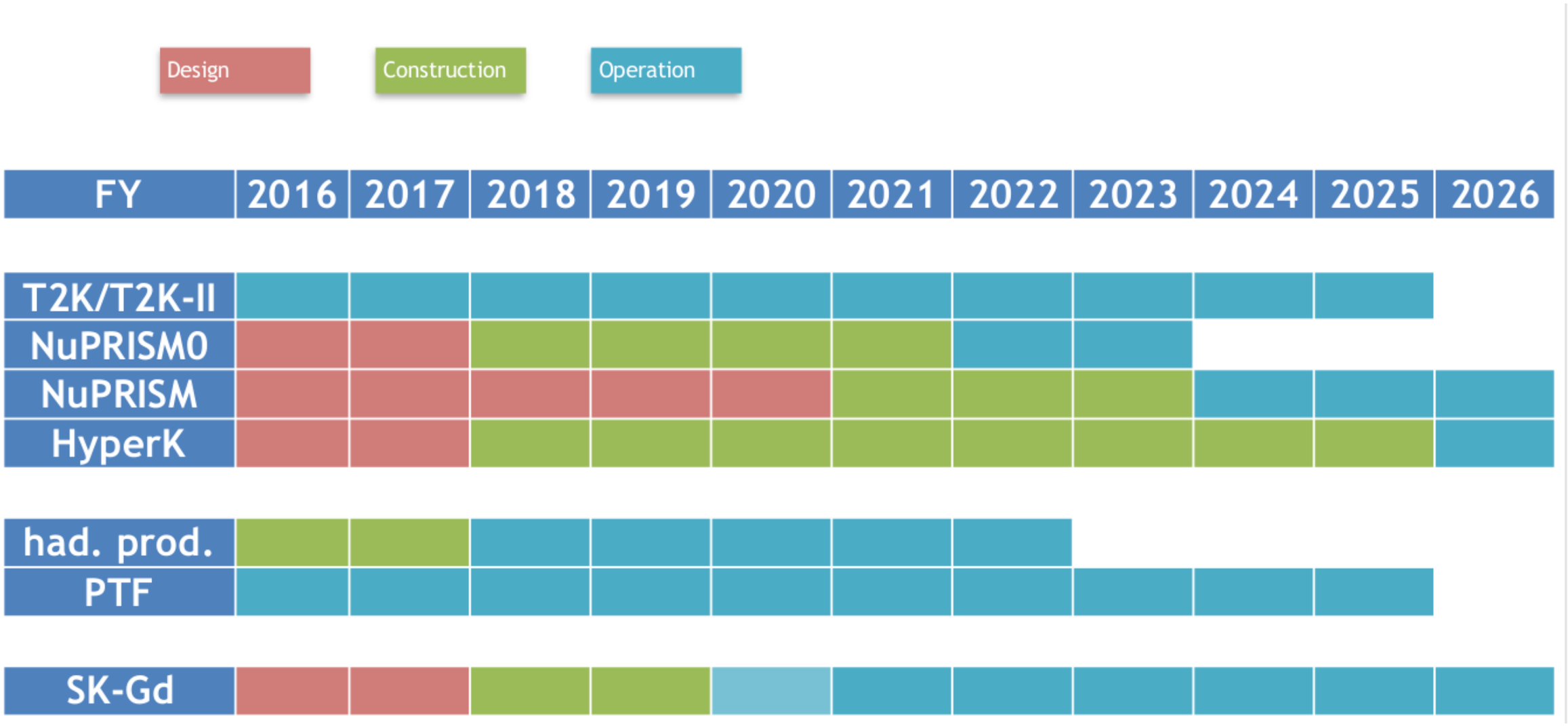
x3 CPV enhancement at the 2nd oscillation maximum



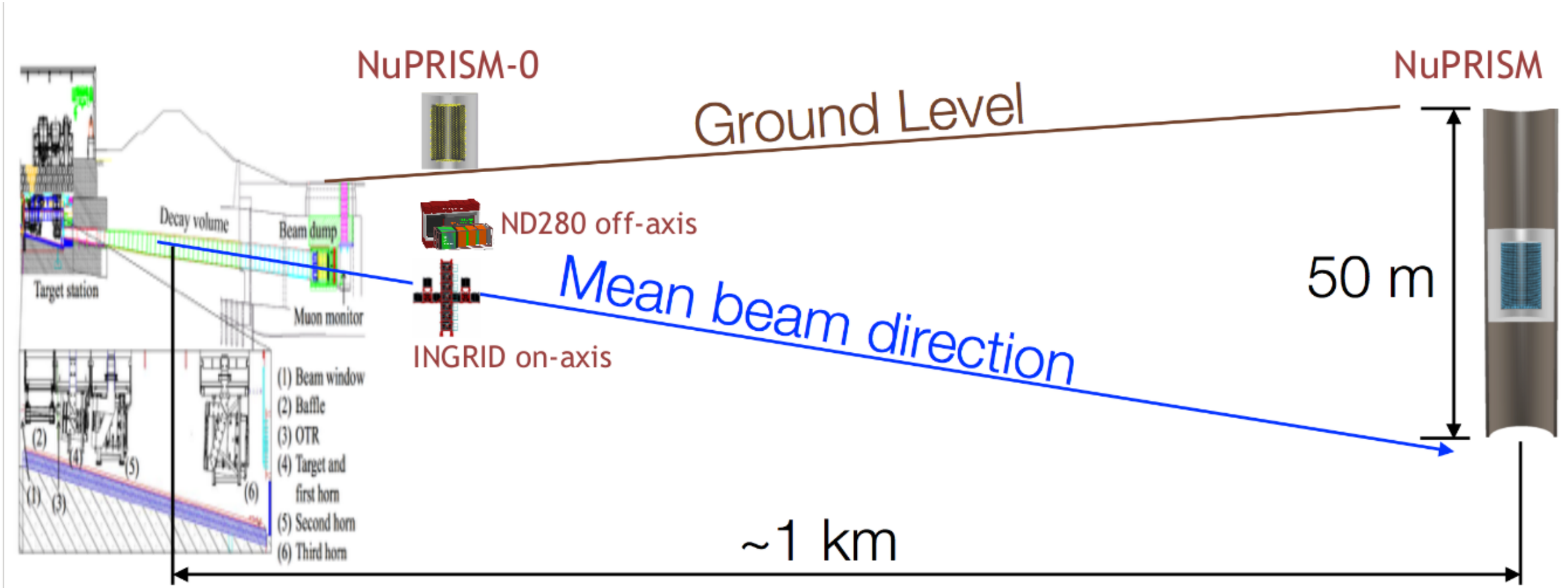
Revival of T2HKK idea initiated by Canada

RENO-50 → T2HKK

Timeline to Hyper-Kamiokande



NuPRISM Experiment Setup



Start with the surface detector: NuPRISM0

- Demonstrate the detector calibration at 1-2% level
- ν_e cross section study @8-12° off-axis

SUPPORT IN CANADA AND BEYOND

INSTITUTE OF PARTICLE PHYSICS
INSTITUT DE PHYSIQUES DES PARTICULES

Institute of Particle Physics 2015 Brief
- “Essential” to the Canadian particle physics community

Institute of Particle Physics Brief to 2017-2021 NSERC Subatomic Physics Long Range Planning Committee

2017 NSERC Subatomic Physics Long Range Plan
- One of four “Flagship” facilities/experiments
- Recommendation:“Ensure they fully realize their potential”

Canadian Subatomic Physics Long Range Plan

2017-2021

TRIUMF

Five-Year Plan
2015–2020
REALIZING THE VISION

TRIUMF Five Year Plan (2015-2020)
- One of three “selected high profile international experiments”

ICFA Neutrino Panel

2.1: The present accelerator-based long-baseline neutrino-oscillation programme is vibrant and has substantial discovery potential.

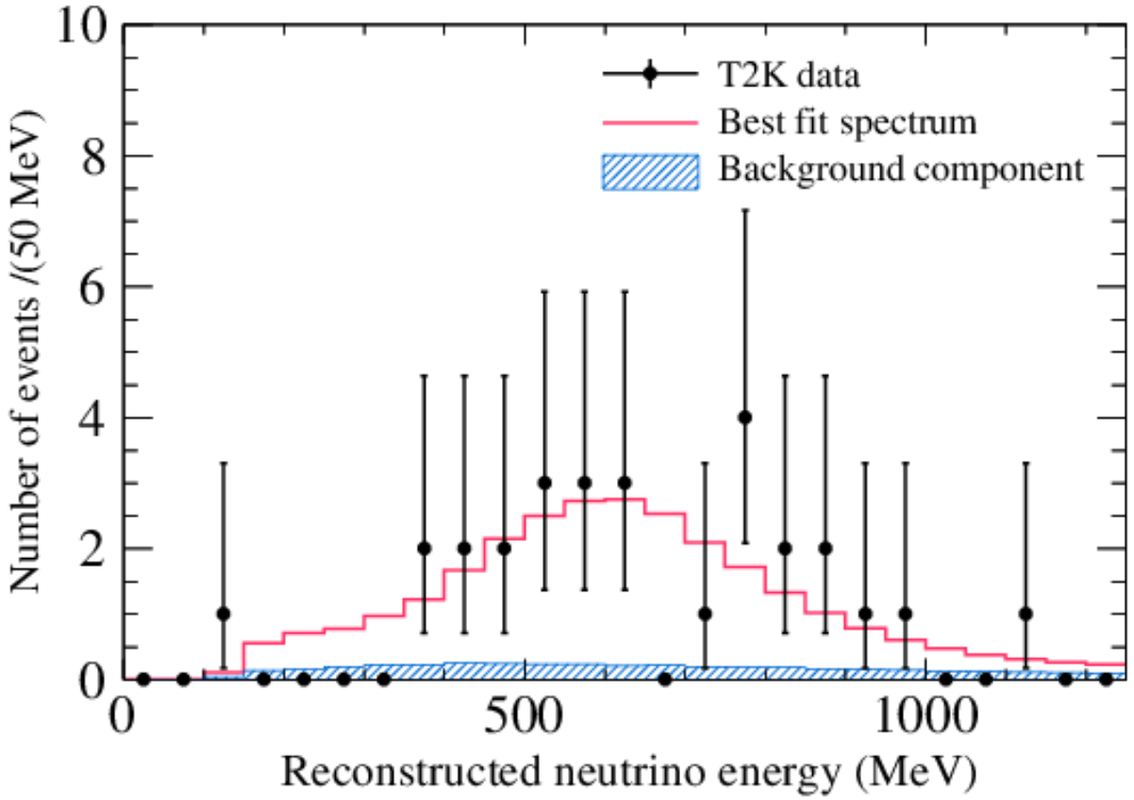
Recommendation 2.1: Full exploitation of the present generation of experiments should continue thereby maximising their discovery potential and the scientific return on historical investment.

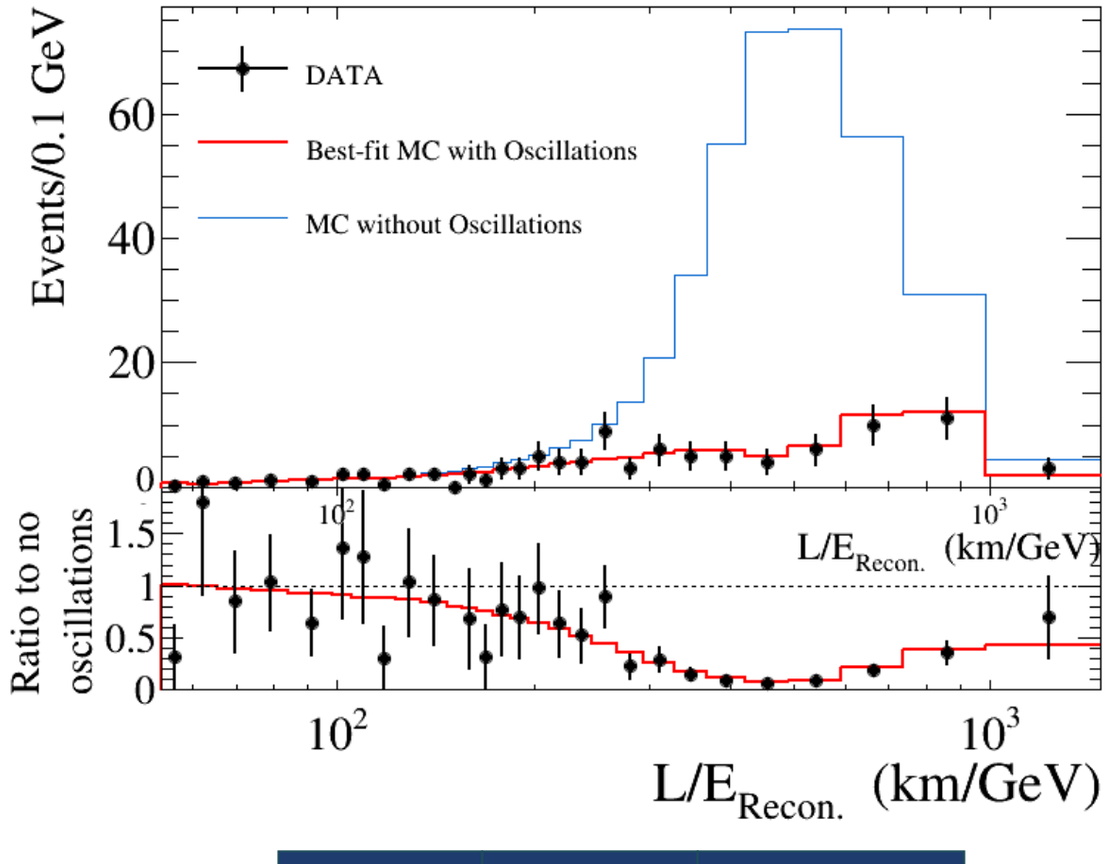
Roadmap for the international, accelerator-based neutrino programme

Discussion document

The ICFA Neutrino Panel

NEUTRINO MODE DATA (2013)





- 28 ν_e candidates observed
  - 5.0 expected in absence of osc. effects
  - definitive observation of $\nu_\mu \rightarrow \nu_e$ oscillations
- 120 ν_μ candidates observed
  - 446 expected in absence of osc. effects
  - Most precise determination of ν_μ disappearance

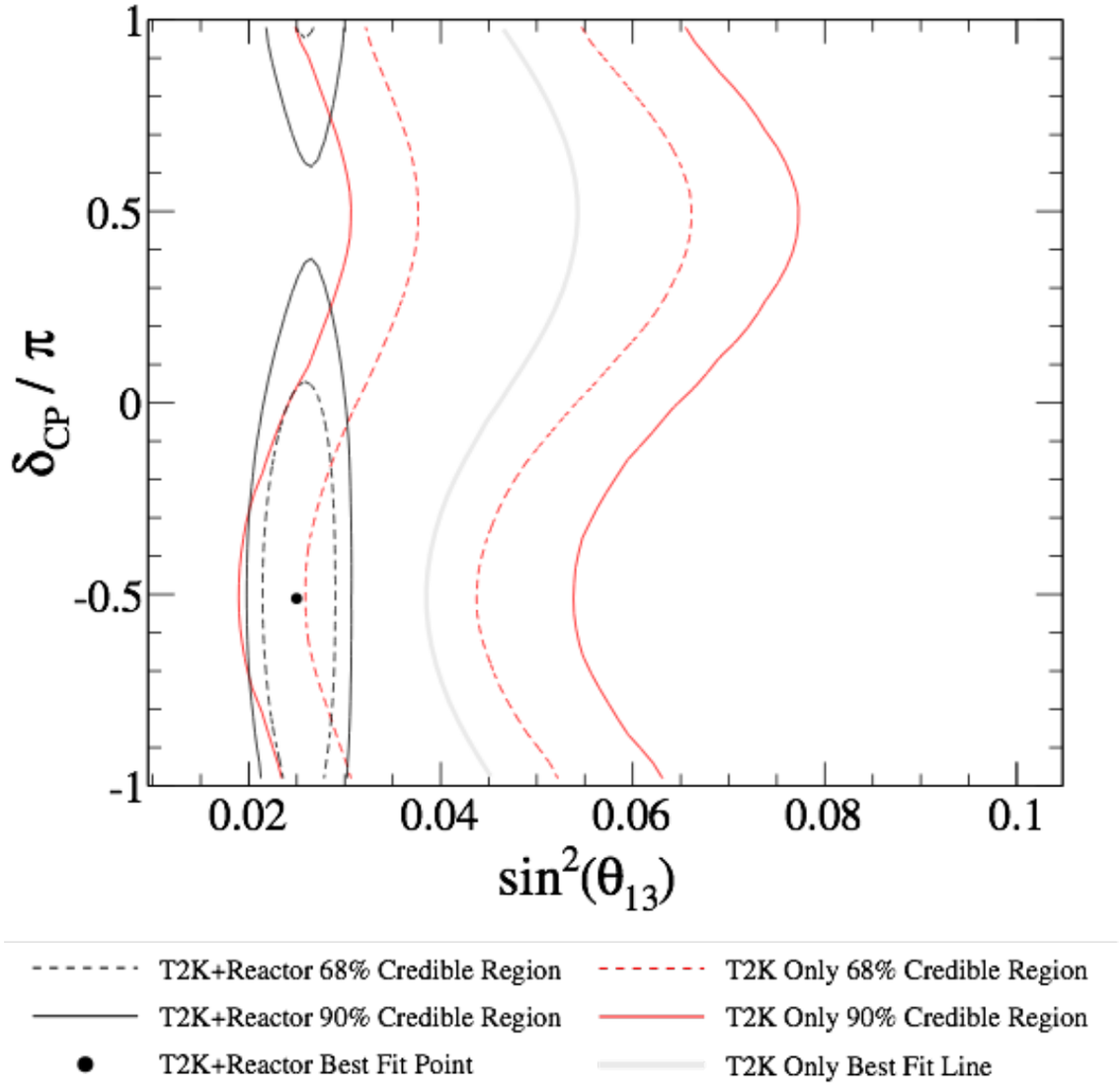
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$
$$\Delta m^2_{32} = (2.51 \pm 0.51) \times 10^{-3}\ \mathrm{eV}^2/c^4$$

	Osc.	No osc.
ν_μ	0.9	1.4
$\bar{\nu}_\mu$	0.1	0.1
$\nu_e/\bar{\nu}_e$	3.3	3.5
$\nu_\mu \rightarrow \nu_e$	16.6	0.0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.2	0.0
Total	21.1	5.0

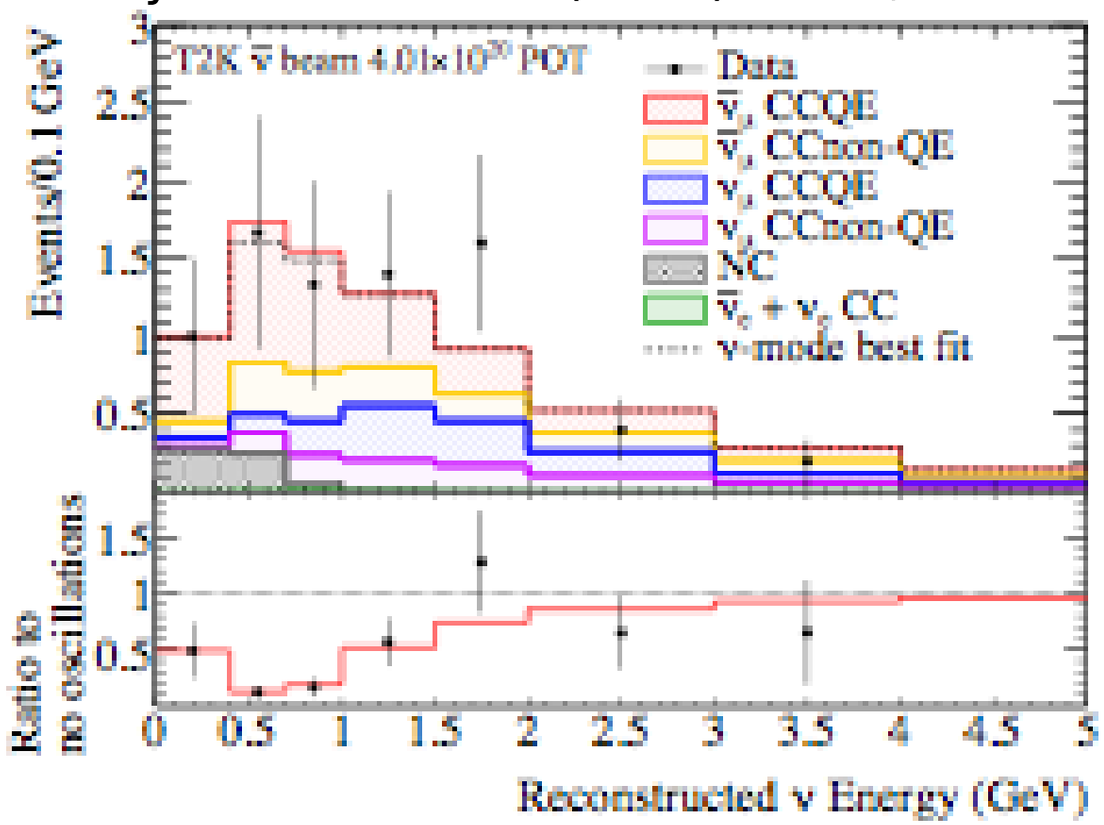
expected number of ν_e candidates
for $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, NH

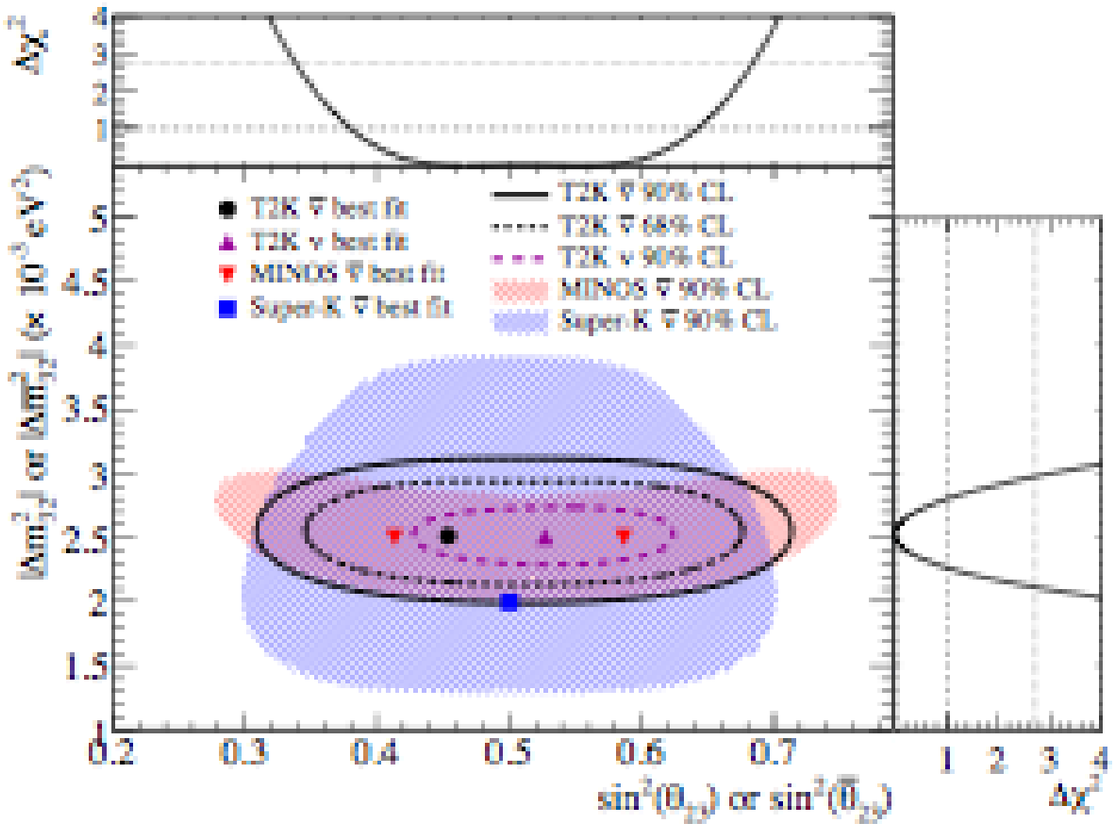
2014-2015

Phys.Rev. D91 (2015) no.7, 072010



Phys.Rev.Lett. 116 (2016) no.18, 181801

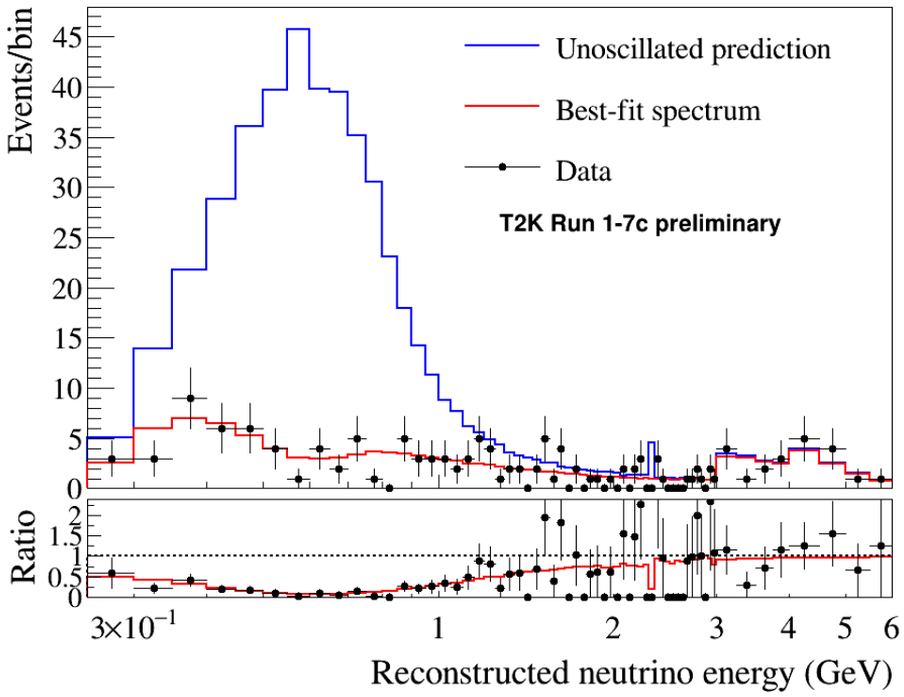




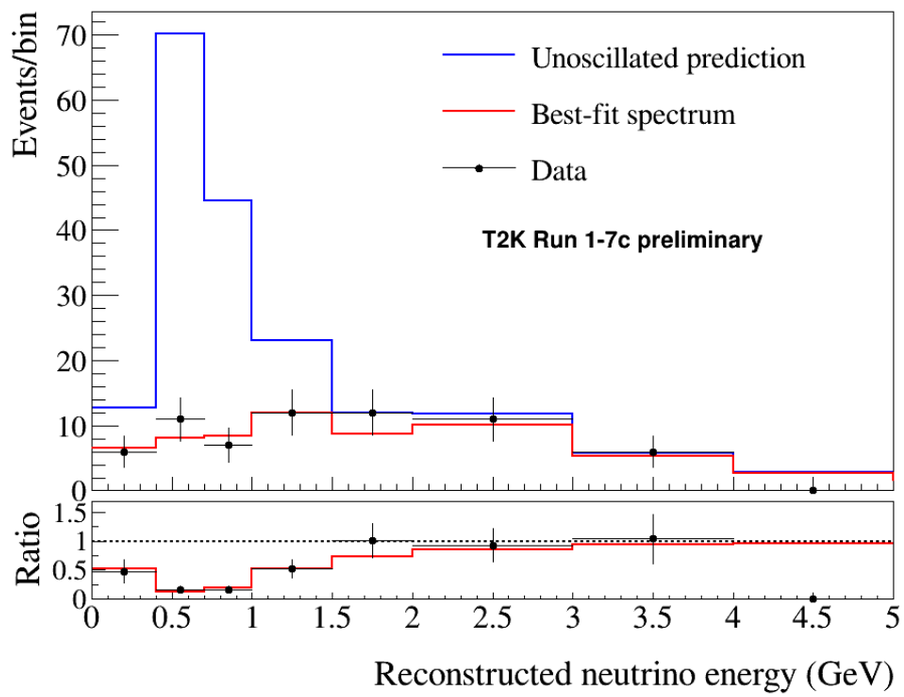
- Top: Joint analysis of ν_μ disappearance and ν_e appearance in neutrino mode
  - Key analysis contributions from Canadian members
  - Paper committee chair: D. Karlen
- Right: First $\bar{\nu}_\mu$ disappearance results with antineutrino data

2016: $\nu/\bar{\nu}$-MODE DATA

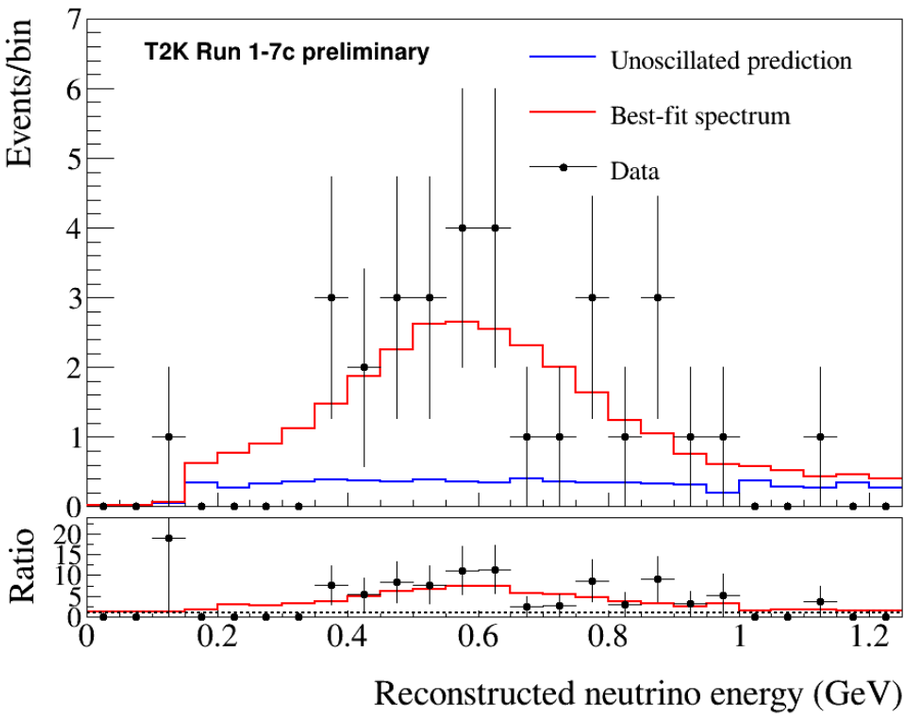
ν_μ candidates



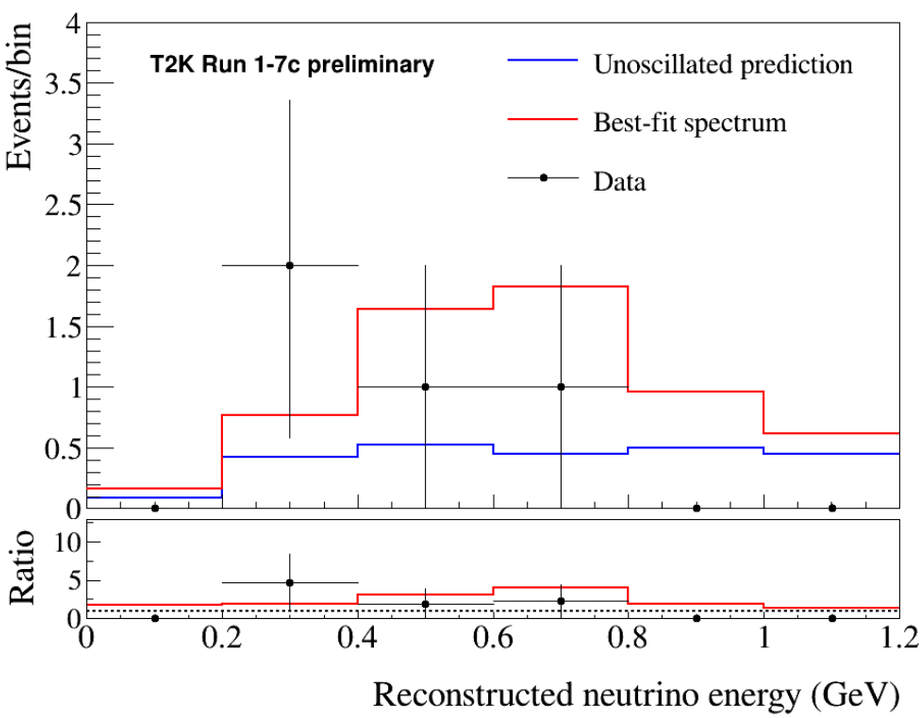
$\bar{\nu}_\mu$ candidates



ν_e candidates

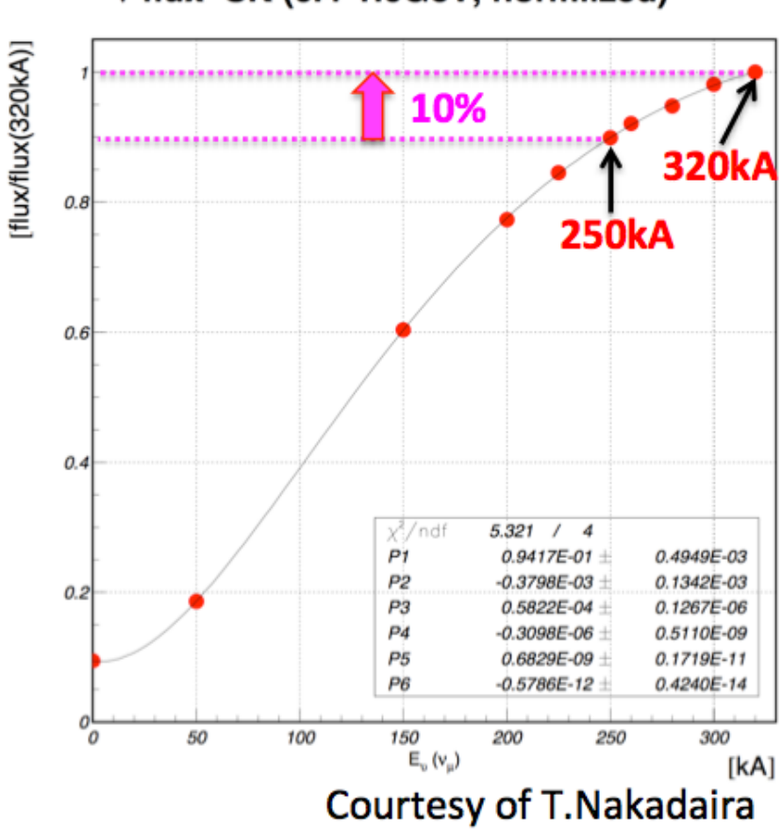


$\bar{\nu}_e$ candidates



- ν_μ candidates:
  - 481 expected in the absence of oscillations
  - 135 observed
- $\bar{\nu}_\mu$ candidates:
  - 177 expected in the absence of oscillations
  - 166 observed
- ν_e candidates
  - 6 expected in absence of $\nu_\mu \rightarrow \nu_e$ oscillations
  - 32 events observed
- $\bar{\nu}_e$ candidates
  - 2.4 expected in absence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
  - 4 events observed

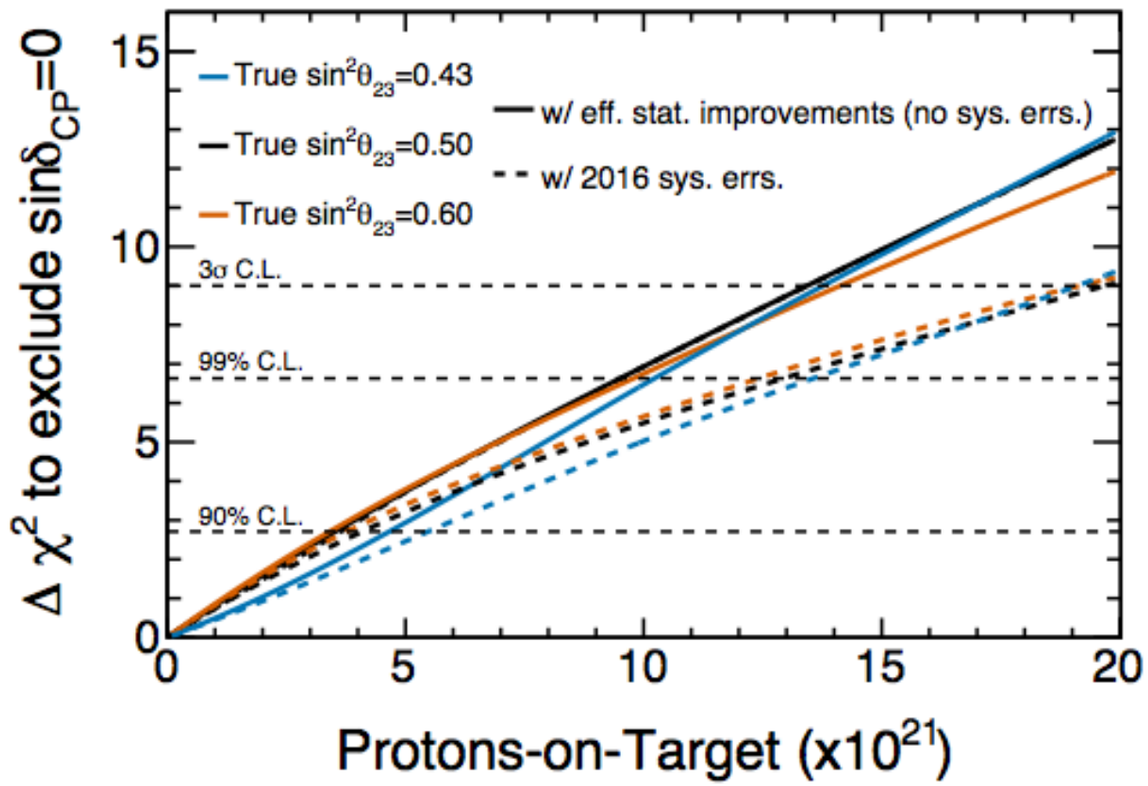
T2K-II NEEDS:



Courtesy of T.Nakadaira

- Goals require several significant developments
  - Increase horn current from 250 →325 kA, ~10% increase
    - power supply upgrade underway
- Increase effective efficiency of SK ν_e selection by 40%
  - increase fiducial volume
  - include additional inelastic channels into ν_e signal

- Sensitivity significantly impacted by systematic errors
  - new near detector (NuPRISM) and other improvements to reduce impact of systematic errors



- T2K-Canada plays leading role in necessary efficiency and systematic improvements

DEMOGRAPHICS

- Current membership
  - 11 graduate students
  - 6 postdocs
  - 1 programmer
  - 13 faculty/staff
- Steady stream of undergraduates through co-op, USRA, 3rd/4th year project courses
- Membership in T2K steady since 2009 when major construction completed
  - includes ~18 technical/engineering staff who continue to be associated with the collaboration