INSTITUTE OF PARTICLE PHYSICS

H. A. TANAKA (UBC/IPP)

T2K IN CANADA: STATUS AND PROSPECTS

T2K

ND280
"near" detector

J-PARC

Super Kamiokande
"far" detector

~500 collaborators from
58 institutions, 11 nations

Intense ~600 MeV ν_μ beams for neutrino oscillations studies

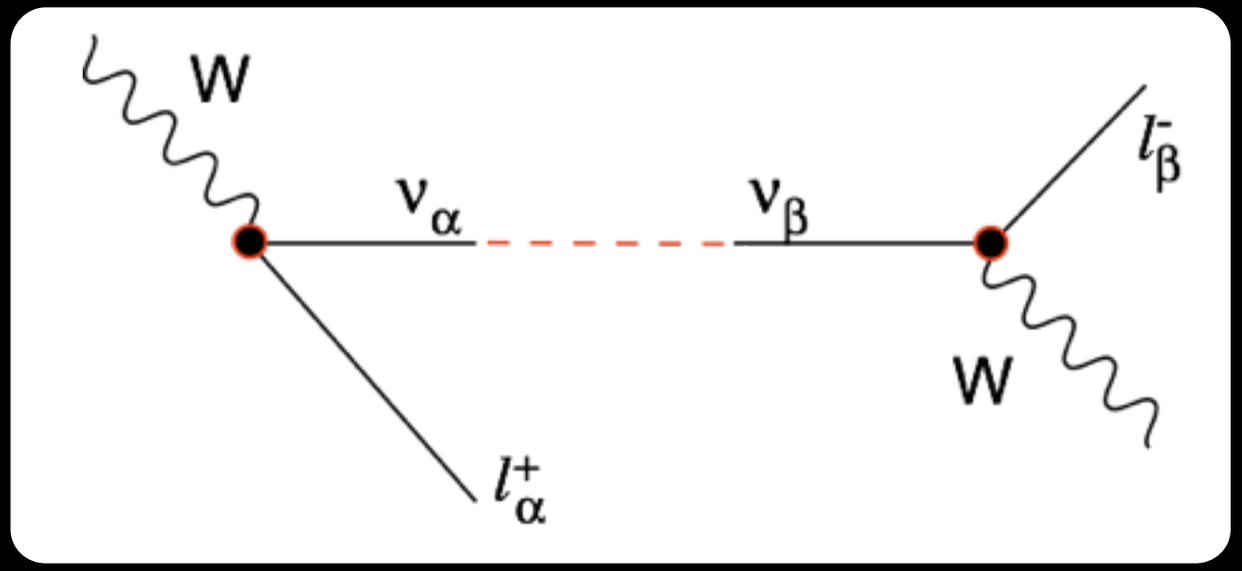
- $\nu_\mu \rightarrow \nu_e$ oscillations to probe three flavor mixing
- ν_μ disappearance: precision measurement of θ_{23} and Δm^2_{32}

see "T2K Experiment"
Nucl.Instrum.Meth. A659 (2011) 106-135

NEUTRINO OSCILLATIONS

- Neutrinos produced in weak decays are linear combinations of mass/energy eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$



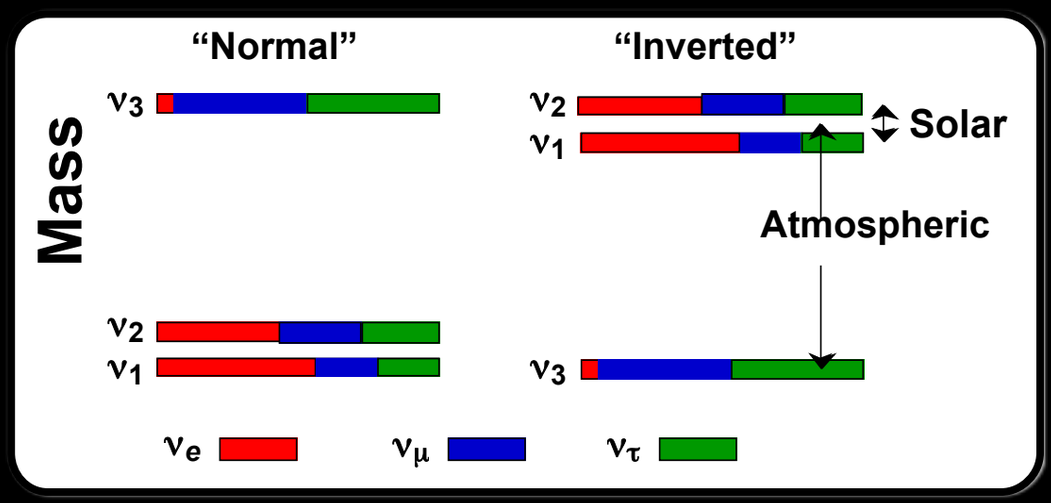
- Time evolution: component of another flavor may be acquired

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin[2.54\Delta m^2_{ij}(L/E)]$$

L (km), E(GeV)

in vacuum

- For three flavors:
  - U = U(θ_{12}, θ_{13}, θ_{23}, δ; α_1, α_2)
  - 3 mass splittings: Δm^2_{21}, Δm^2_{31}, Δm^2_{32}



OSCILLATIONS AT T2K

- $\nu_\mu \rightarrow \nu_e$ appearance

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \sim \quad & \sin^2 2\theta_{13} && \times \sin^2\theta_{23} && \times \frac{\sin^2(1-x)\Delta}{(1-x)^2} \\
& -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} && \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} && \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha^2 && \times \sin^2 2\theta_{12} \cos 2\theta_{23} && \times \sin\Delta \frac{\sin^2[x\Delta]}{x^2}
\end{aligned}
$$

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

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

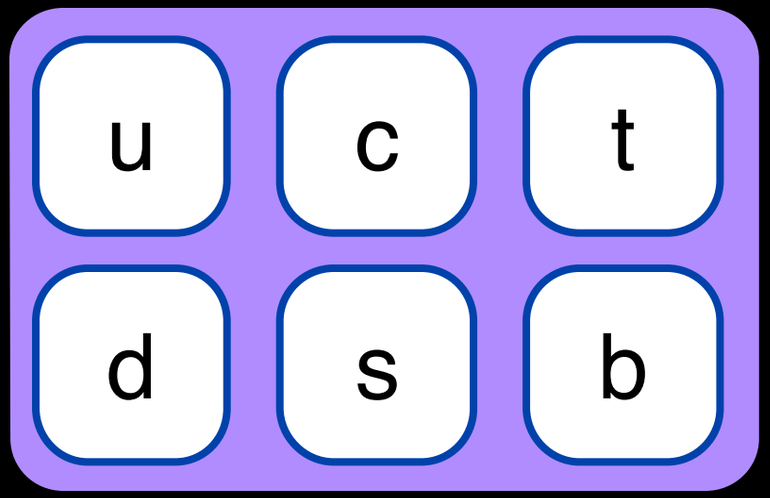
oscillation with "wavelength" set by Δm^2_{31} require $\theta_{13} \neq 0$

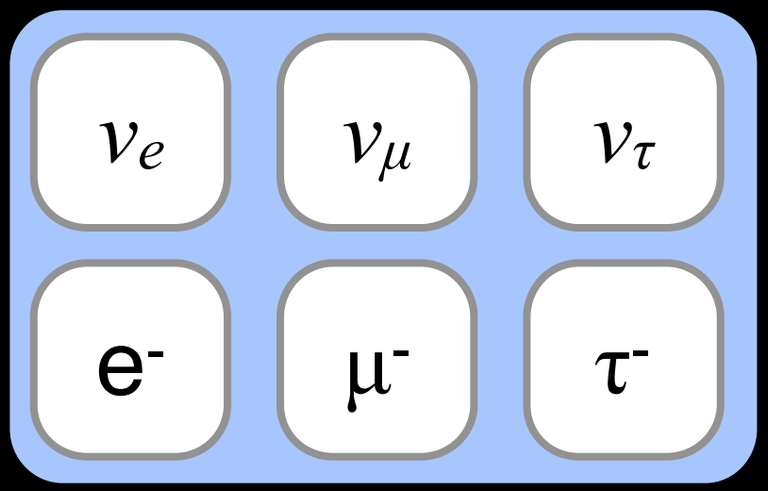
- ν_μ disappearance

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

$\theta_{13} \neq 0$ leads to full 3-flavor mixing structure

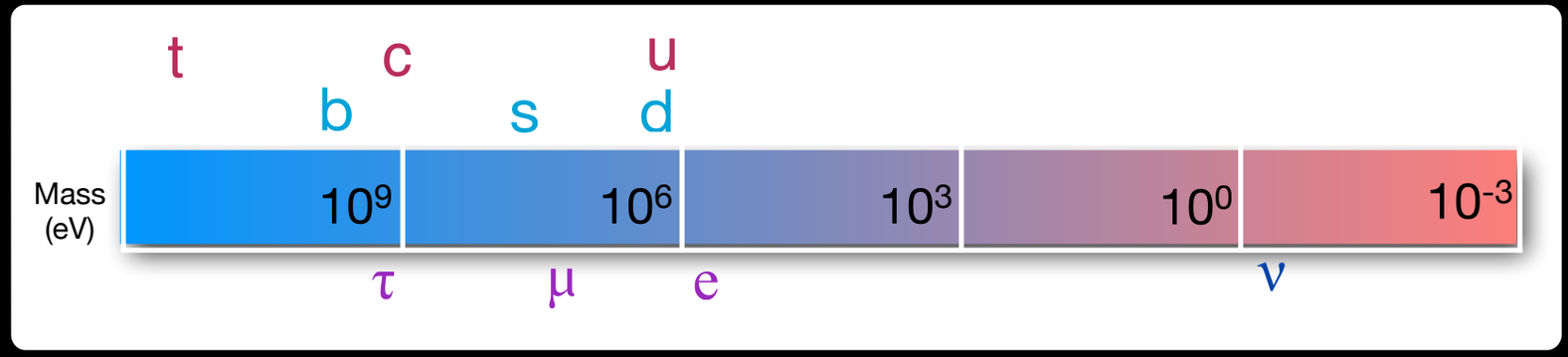
BIGGER PICTURE





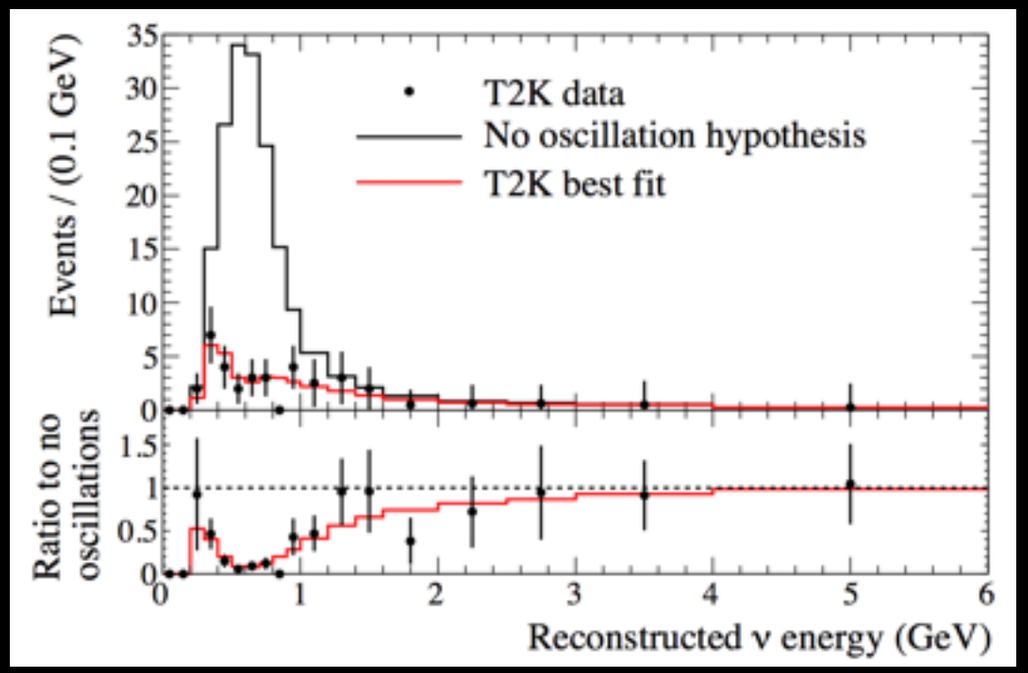
$$|V_{\rm CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

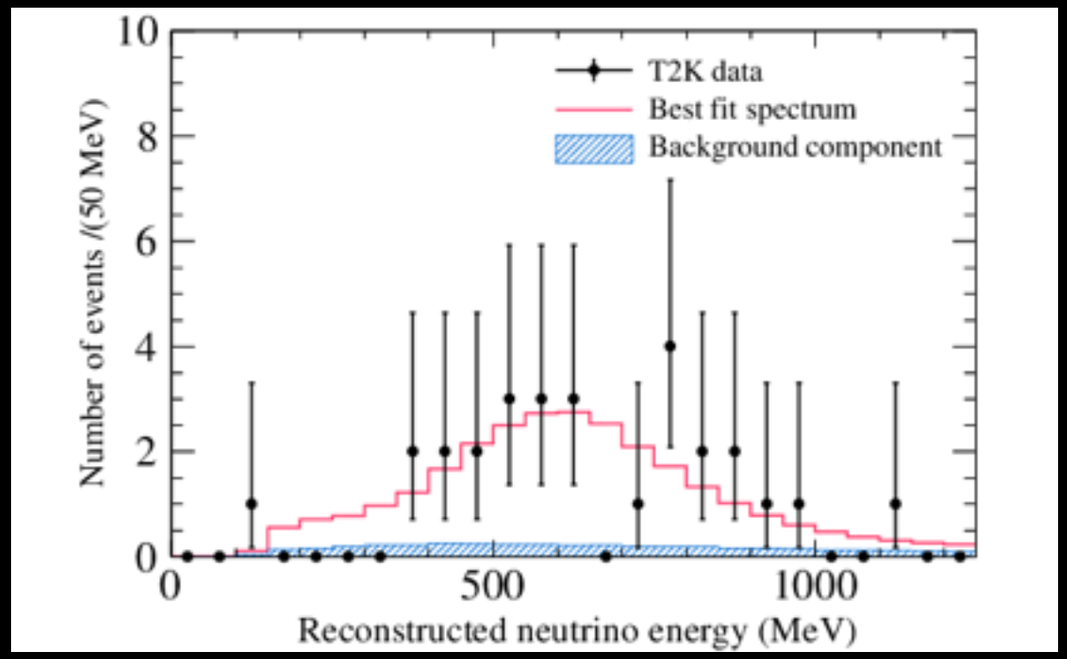
$$|U_{\rm MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & \overset{\sim 0.15}{\cancel{0}} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

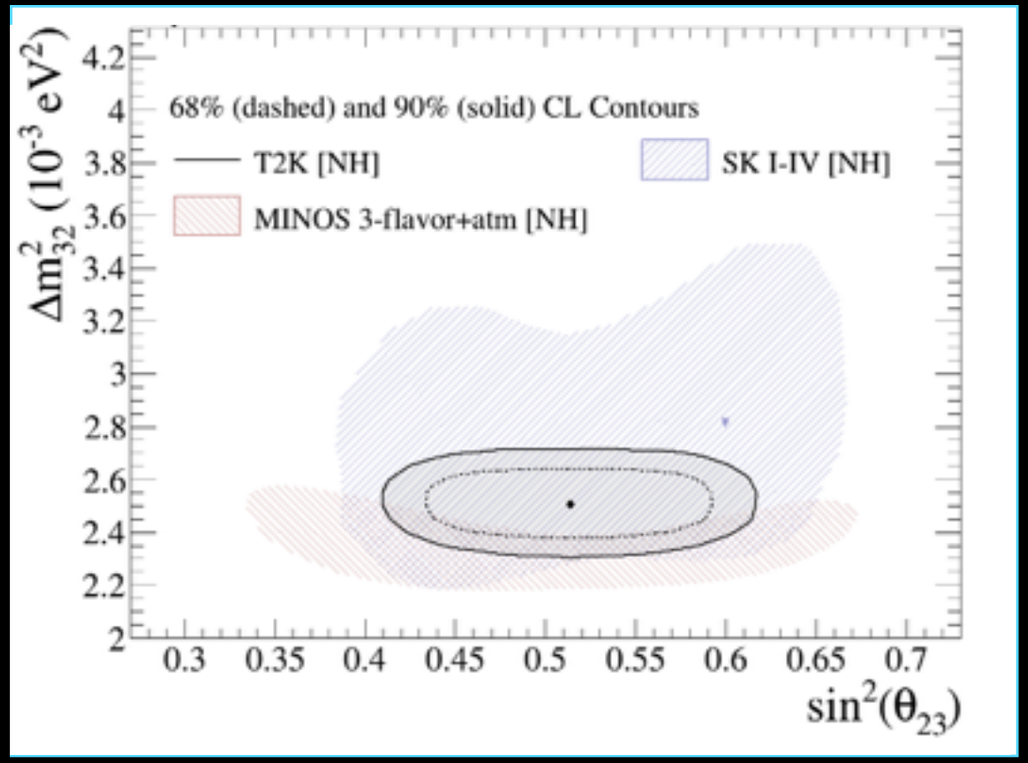


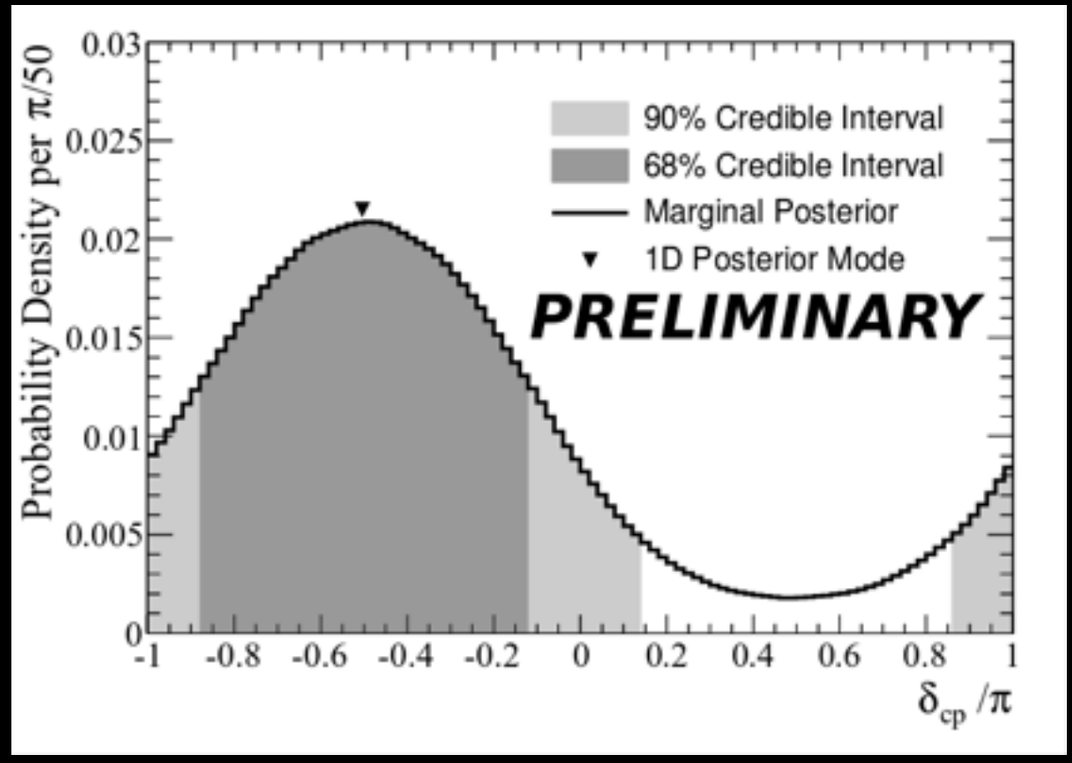
- Whence mass? mixing? generations?
- Intimately connected to:
  - Quark flavor programme at BELLE2
  - Role of the Higgs Boson in providing mass . . . .
  - Neutrinoless double beta decay at SNO+, EXO
  - Cosmology in understanding the role of neutrinos in shaping the universe

RECENT HIGHLIGHTS:









- World-leading results with 8% of expected data! (see talk by K. Mahn)
- 2011-2013: indication→observation of $\nu_\mu \rightarrow \nu_e$: defining moment for the field

T2K TALKS AT CAP CONGRESS

SPEAKER	TITLE	SESSION
K. MAHN	RECENT RESULTS FROM LBL EXPERIMENTS	M2-4
M. SCOTT	NEUTRINO CROSS SECTION MEASUREMENTS AT THE T2K NEAR DETECTOR	M2-4
S. BERKMAN	IDENTIFYING SINGLE PION PRODUCTION IN NEUTRINO INTERACTIONS AT SK	M2-4
A. HILLAIRET	THE MEASUREMENTS IN THE T2K NEAR DETECTOR	M2-4
J. MYSLIK	USING THE T2K NEAR DETECTOR IN NEUTRINO OSCILLATION MEASUREMENTS	M2-4
E. PINZON	MEASUREMENTS OF PION ABSORPTION AND CHARGE EXCHANGE FOR T2K	T2-10
C. NANTAIS	A SEARCH AT SK FOR LOW MASS DARK MATTER CANDIDATES IN THE T2K BEAM	W1-7

T2K IN CANADA

The JHF-Kamioka neutrino project

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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],
A. Konaka[6]

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[2] Inst. of Particle and Nuclear Studies, High Energy Accelerator Research Org. (KEK), Tsukuba, Ibaraki 305-0801, Japan

[3] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

[4] Department of Physics, Kyoto University, Kyoto 606-8502, Japan

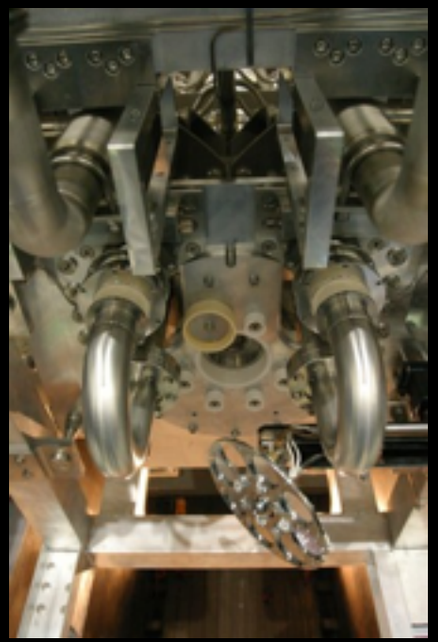
[5] Department of Physics, Tohoku University, Sendai, Miyagi, 980-8578, Japan

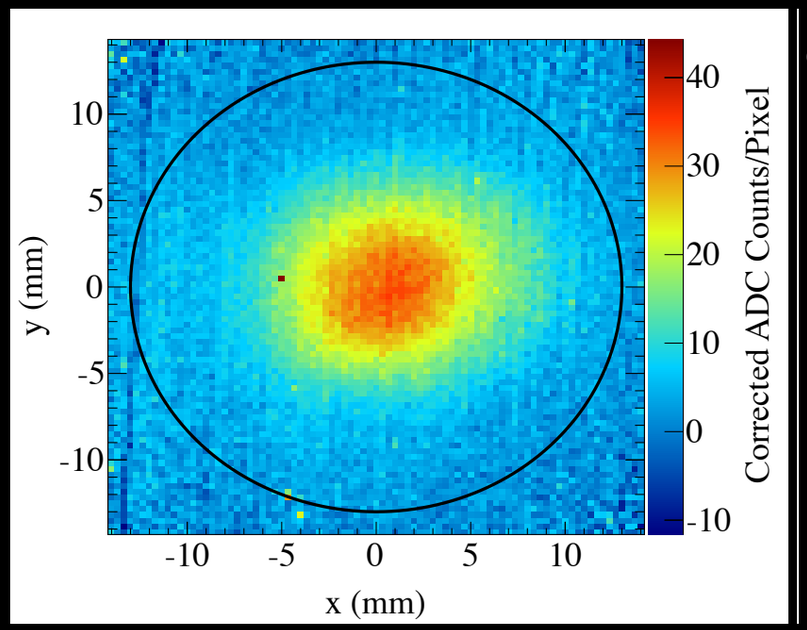
[6] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada, V6T 2A3

- From Canada:
  - 17 Faculty/Staff (12 FTE)
  - 6 postdocs
  - 14 graduate students
    - 7 PhDs awarded so far
  - continuous stream of undergrads (USRA, coop, etc.)
  - 6 universities + TRIUMF

- Canada is a founding member of the T2K collaboration
- Key defining features introduced by Canadians:
  - off-axis beam concept (from earlier BNL proposal)
  - design of near detector

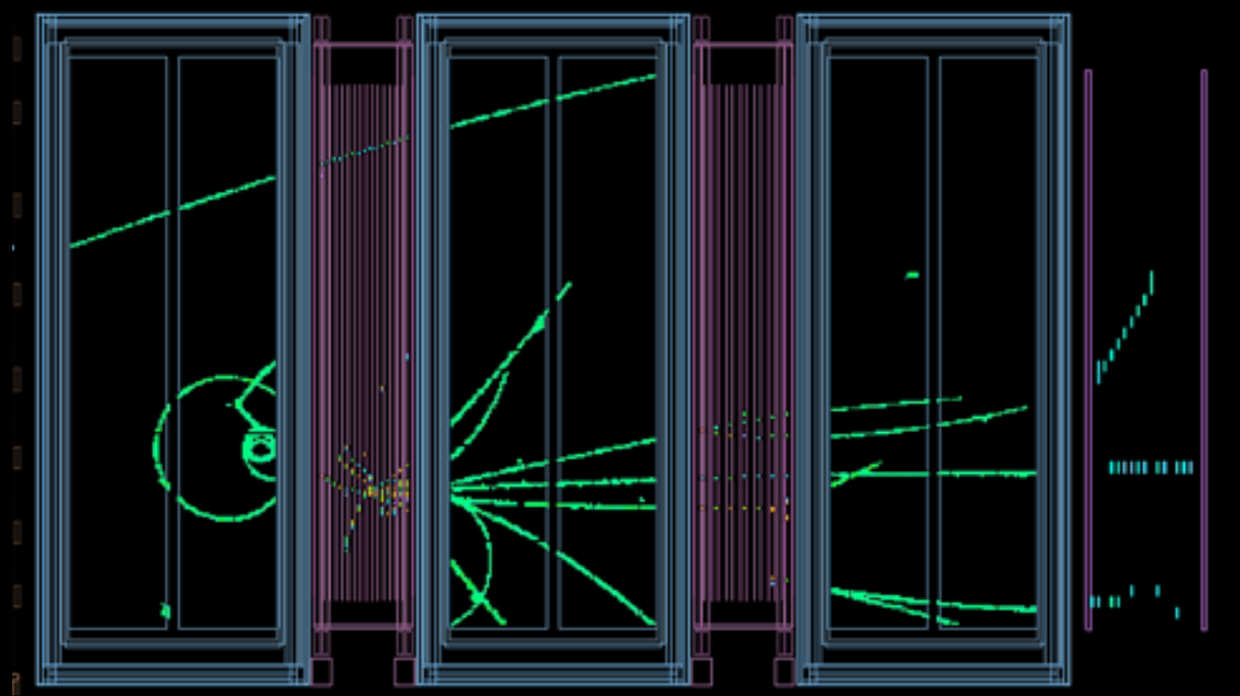
CANADIAN CONTRIBUTIONS





- Near Detector (ND280)
  - Fine-grained detectors (Oser)
    - electronics/MPPCs (Retiere)
  - Time projection chambers (Karlen)
    - electronics upgrade (Jamieson)
  - Detector-wide services (Miller)
  - Data acquisition, slow control, network (R. Poutissou)

- Beamline:
  - OTR Monitor (Bhadra/Martin)
  - Monitor stack (TRIUMF)
  - target remote handling (TRIUMF)



- Computing:
  - ComputeCanada provide ~1/2 CPU for entire collaboration
  - CFI-funded “Tier 1” storage at TRIUMF

LEADERSHIP:

BEAM	*M.P. HARTZ**		
NEAR DETECTOR	H.A. TANAKA	S. OSER	
FAR DETECTOR	A. KONAKA	H.A. TANAKA	*M. WILKING**
OSCILLATION	*K. MAHN**		
ND MUON	S. OSER	*M. WILKING**	*A. HILLAIRET*
ND ELECTRON	*B. JAMIESON**		
ND RECON	*A. HILLAIRET*		
ND CALIBRATION	F. RETIERE	*Y. PETROV*	
ND COMP/SOFT	*T. LINDNER**		
XSEC	*K. MAHN**		
BANFF (NEAR/FAR)	*M.P. HARTZ**	*M. SCOTT*	
RUN COORD.	D. KARLEN	*N. HASTINGS*	
ANALYSIS CHAIR	*H.A. TANAKA*		
EXECUTIVE	J-M POUTISSOU	J.F. MARTIN	*D. KARLEN*
SPEAKERS	*S. BHADRA*		
PUBLICATION	S. OSER	*A. KONAKA*	

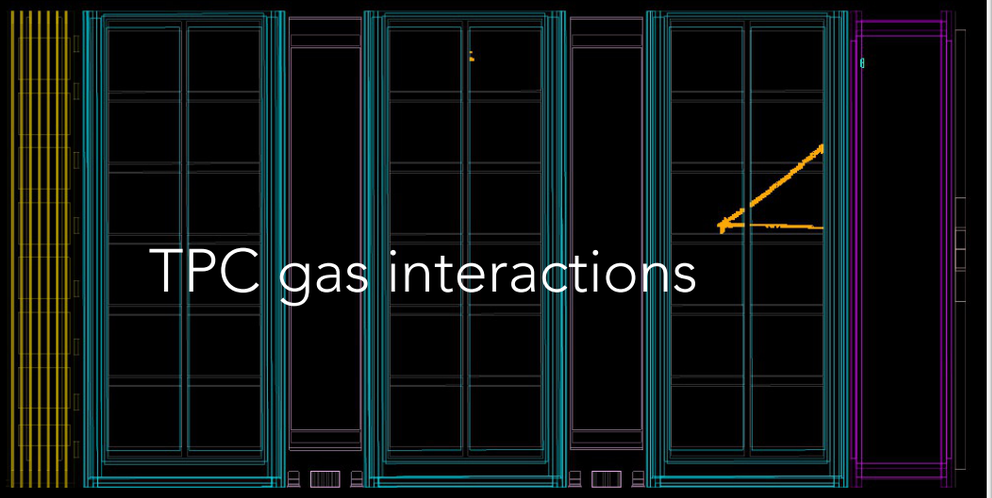
- Leadership across entire effort (beam, near detector, far detector, etc.)
  - T2K-Canada postdocs taking many prominent leadership roles
  - and transitioning to faculty/staff positions (*)

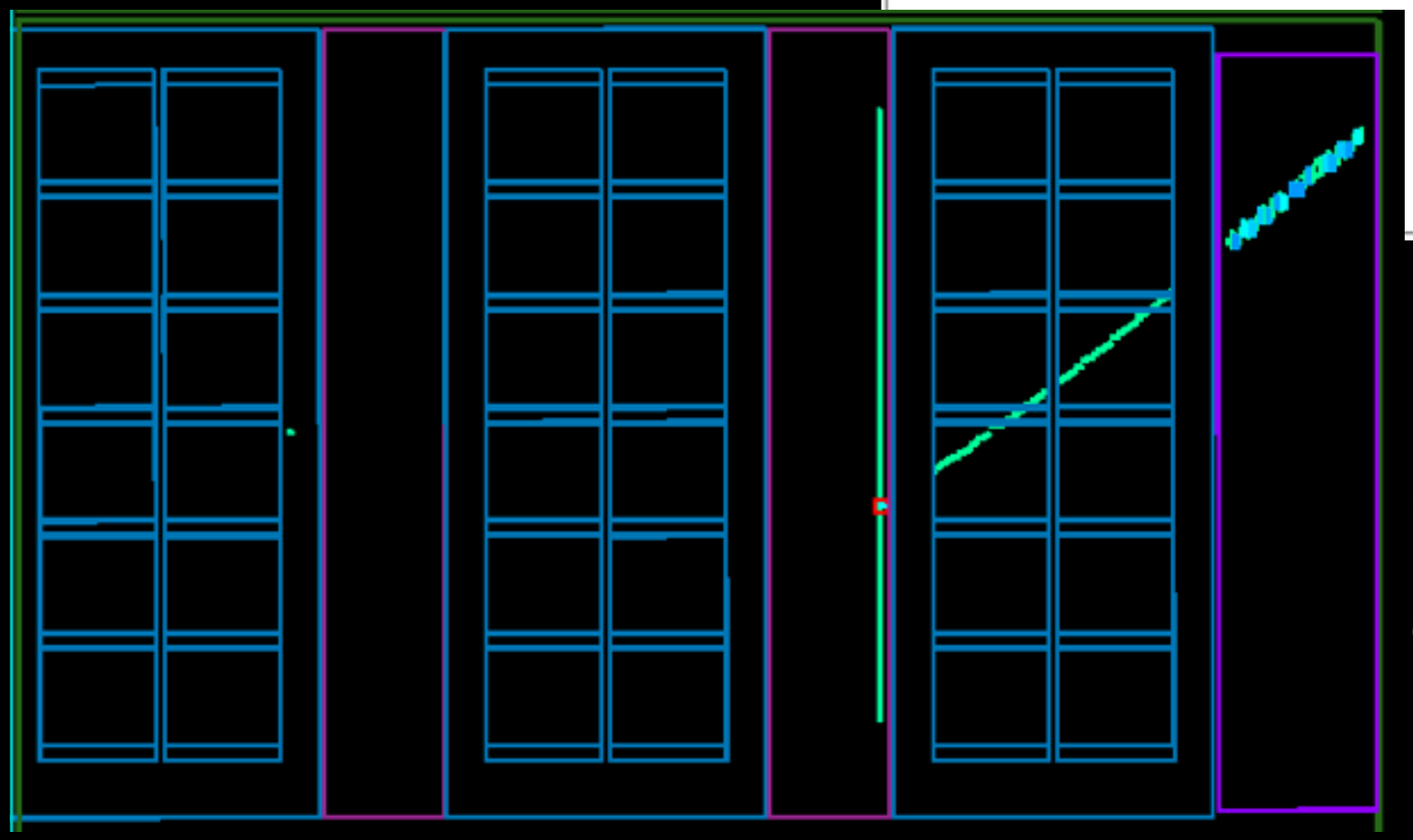
ANALYSIS CONTRIBUTIONS

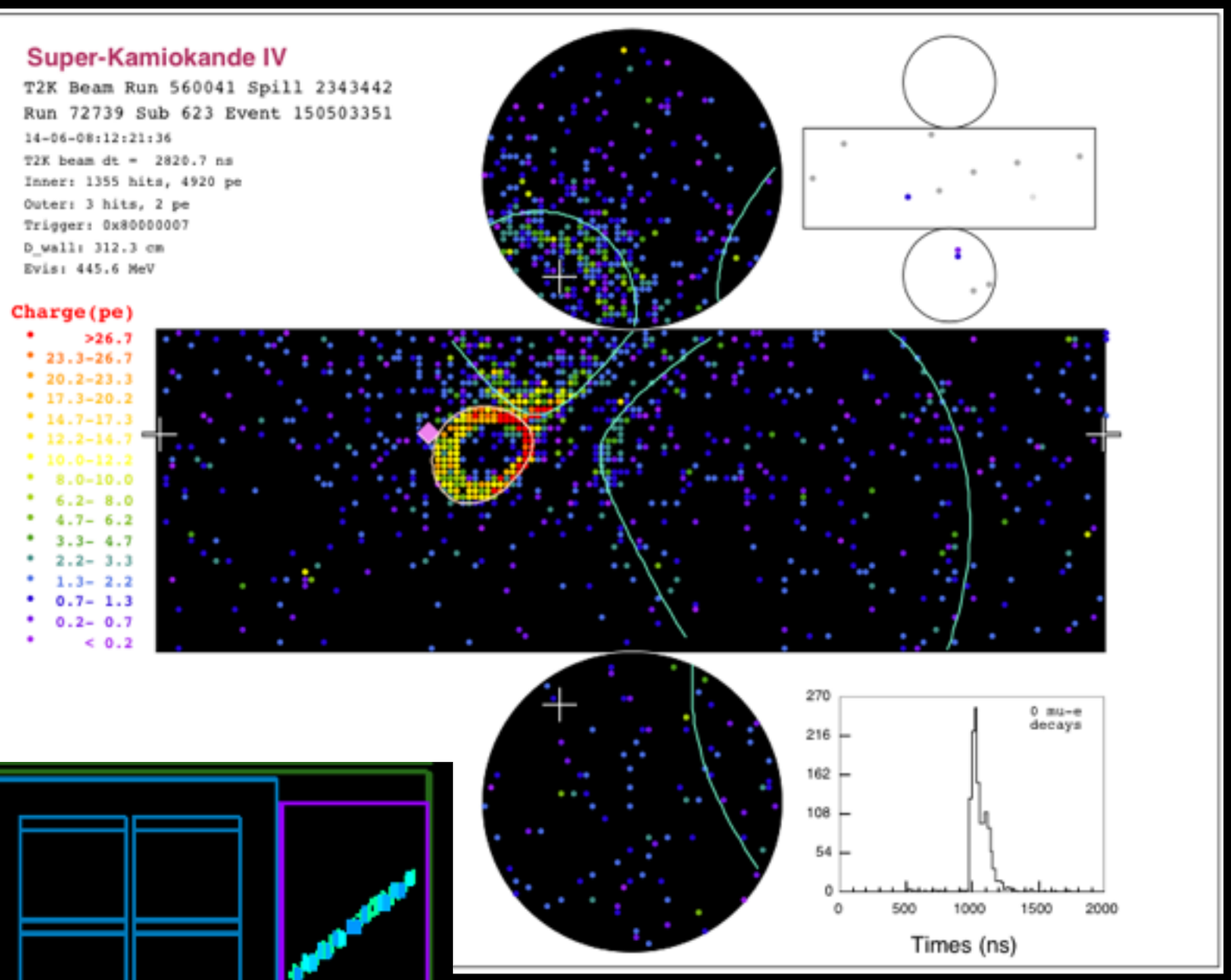
- Neutrino Flux prediction:
  - reweighting formalism for propagating all systematic uncertainties
- Near detector ν_μ analysis:
  - Main contribution to oscillation analysis to reduce uncertainties from 30% →10%
  - continuous improvements towards improved systematic uncertainty
- Near/Far extrapolation (BANFF)
  - Primary formalism for incorporating near detector data constraints
- Far detector reconstruction:
  - new framework (fiTQun) reduces key backgrounds by 70%
  - additional benefits for SK (proton decay, etc.) in the works
- Neutrino interaction modeling
  - advancements in neutrino interaction models (final state interactions, etc.)
  - formalism for propagating uncertainties into analyses
  - measurements of pion interactions at TRIUMF (DUET)
- Oscillation analysis
  - Markov Chain MC/Bayesian methods to explore complex space of physics and nuisance parameters

"Uncommon scientific vision and leadership" (NSERC Review)

T2K is back in operation



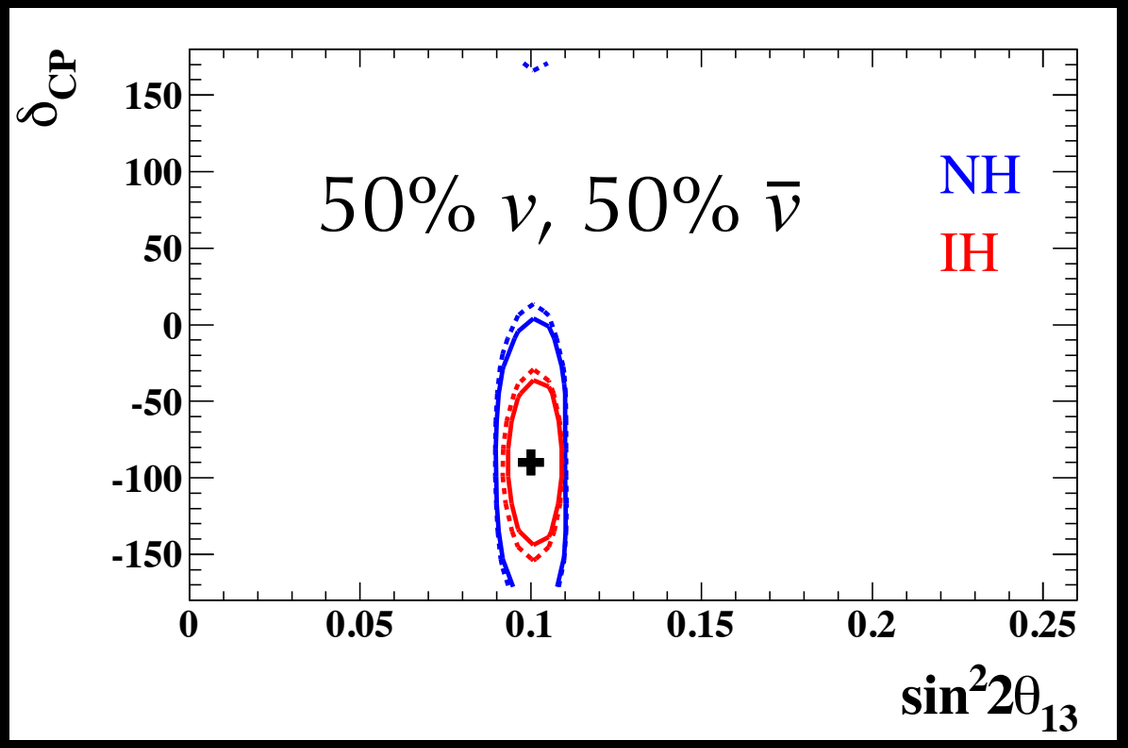


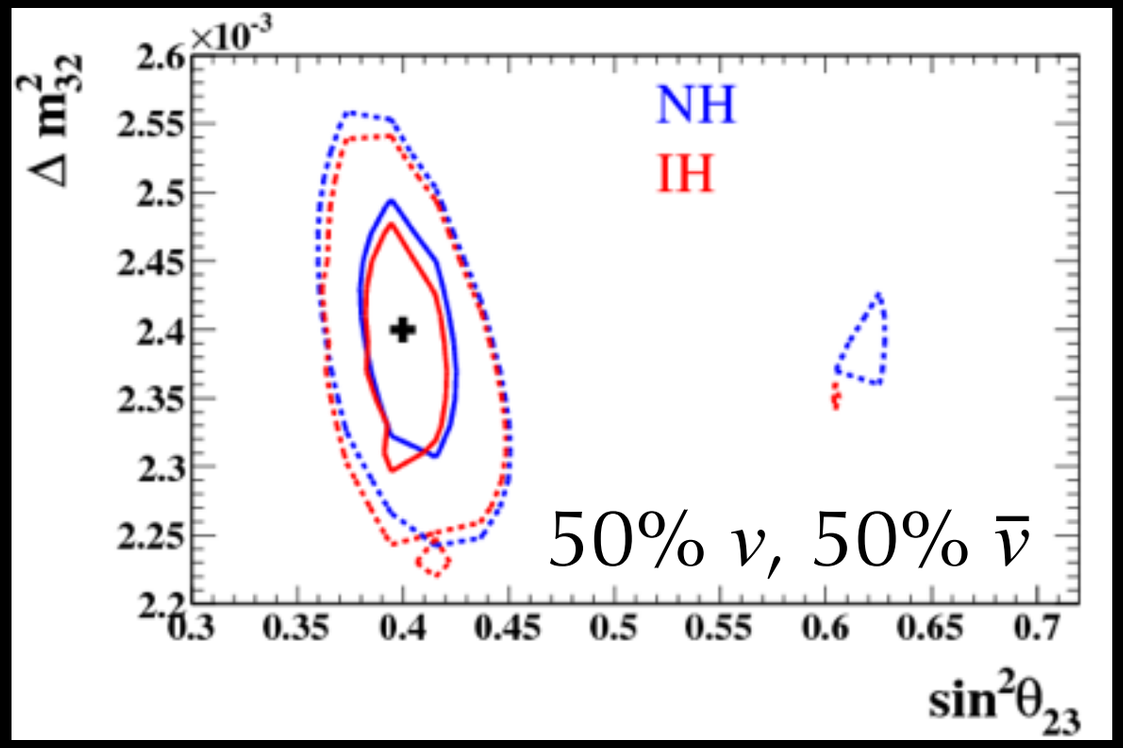


First events from antineutrino-mode operation

OUTLOOK FOR T2K

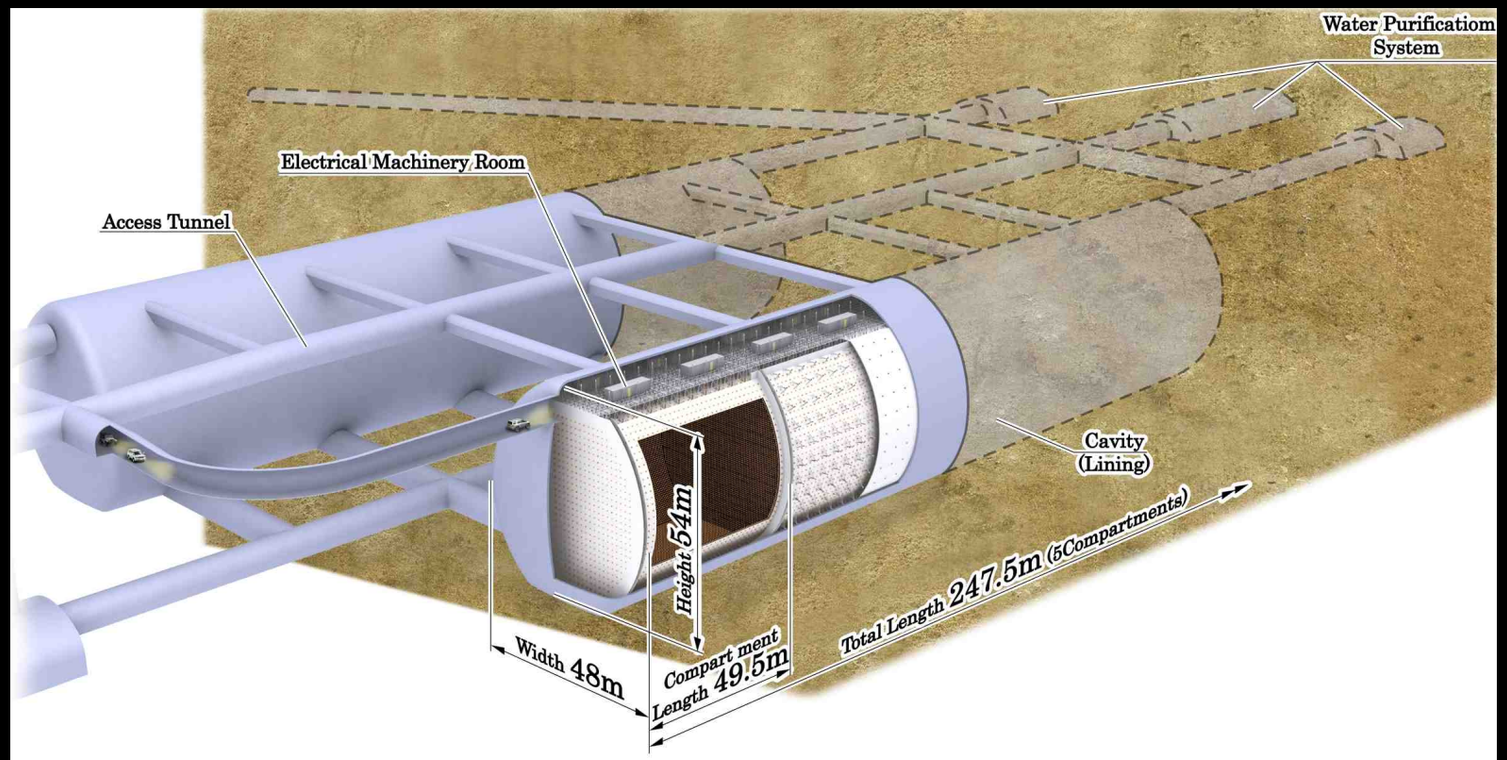
90% CL sensitivities with 7.8×10^{21} POT
reactor θ_{13} constraint

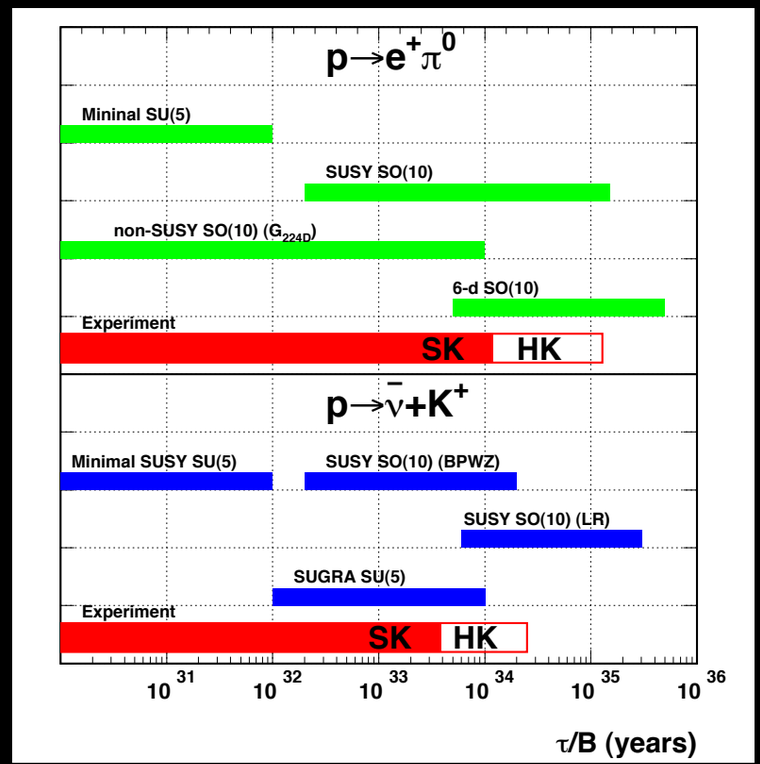


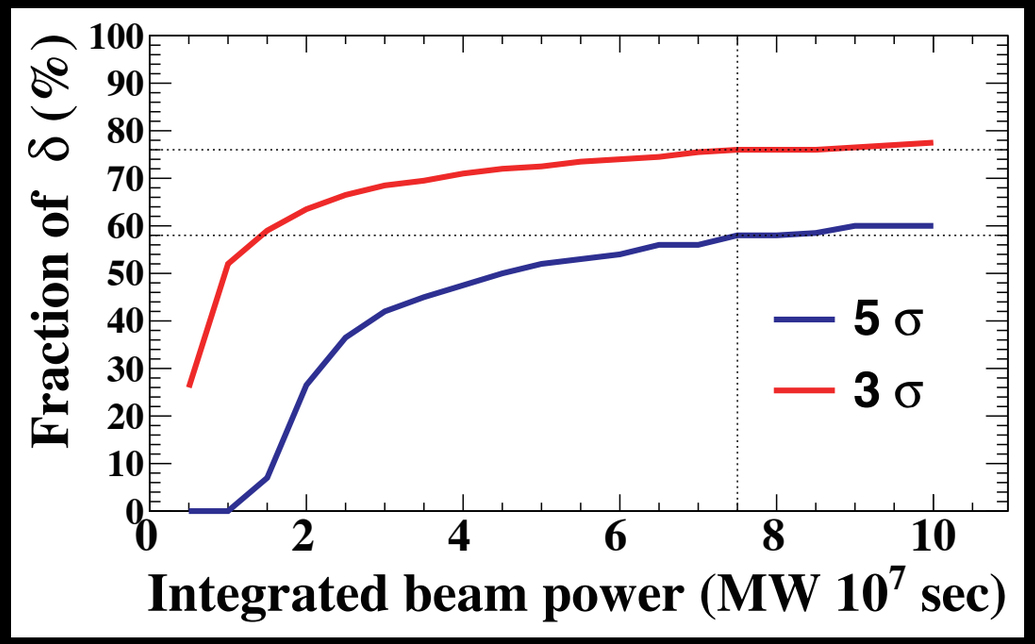


- In general, physics sensitivities improved with antineutrino running
  - T2K will start running significant exposures of antineutrino running
  - 1 month "pilot" run in progress
- Looking forward to:
  - observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance, $\bar{\nu}_\mu$ disappearance measurements
    - word-leading measurements can be achieved with mid-term exposures
  - Near detector antineutrino interactions studies
    - unique capability from sign-selection in magnetic field

HYPER-KAMIOKANDE





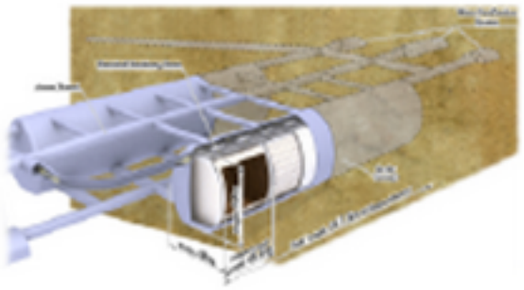


Projected sensitivities based on extensive experience at T2K and SK

- 20x upgrade of SK
  - 1 MT water volume with 99k PMTs
  - Wide ranging program of:
    - neutrino oscillations (CPV, etc.)
    - proton decay
    - neutrino astrophysics (SN, etc.)
- One of top 27 (out of 192) projects in the Science Council of Japan's "Master Plan"

5th Open Meeting for the Hyper-Kamiokande Project

19-22 July 2014
Canada/Pacific timezone



Overview

The Hyper-Kamiokande project is being designed to be the next decade's flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos.

Following the successful format of the previous meetings, we will hold the 5th International Open Working Group Meeting for Hyper-Kamiokande **in Vancouver, Canada, on the campus of the University of British Columbia and TRIUMF.**

The meeting will be open to all interested scientists and community members.

The outline of the meeting is:

- **19 July (Sat.):** Preemeetings and IBR (International Board of Representatives) Meeting
- **20 July (Sun.):** Plenary Sessions, Workshop Dinner
- **21 July (Mon.):** Plenary Sessions
- **22 July (Tue.):** Plenary Session till noon, followed by tour of TRIUMF.

- We will host a meeting for Hyper-Kamiokande in Vancouver 19-21 July
  - Meetings at TRIUMF and UBC
- It is an “Open” meeting:
  - we welcome anyone who is interested to attend the meeting
  - please register at:

http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=34

SUMMARY

- T2K is the leading long baseline experiment
  - discovery of $\nu_\mu \rightarrow \nu_e$ sets the stage for the next era of neutrino studies
    - search for leptonic CP violation
  - Most precise measurement of θ_{23}
- We are now expanding the programme with antineutrino-mode running
  - with full data set, we may see our first hints of ν-CPV, θ_{23} octant
  - with NOvA, we may provide first indications on the mass hierarchy
- Canada is a leading player in T2K with fundamental roles in
  - defining the experiment from the start, current/future goals
  - delivering on/exceeding expectations in physics output
- We are planning to play an equally important role on Hyper-Kamiokande
  - towards discovery of ν-CPV and proton decay
  - observatory for astrophysical sources of neutrinos
  - CFI (2015 IF) proposal for photosensor and electronics development
  - Already establishing leadership in detector, physics, calibration, management.

BEAM/ACCELERATOR

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 - 300 (400)			750
SX power [kW]	3 (10)	10 (20)	25 (30)	20 - 50	→		100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s	2.48 s	2.40 s			1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9					
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW)				
Injection system FX system	Inj. kicker						

R&D

Manufacture installation/test

R&D

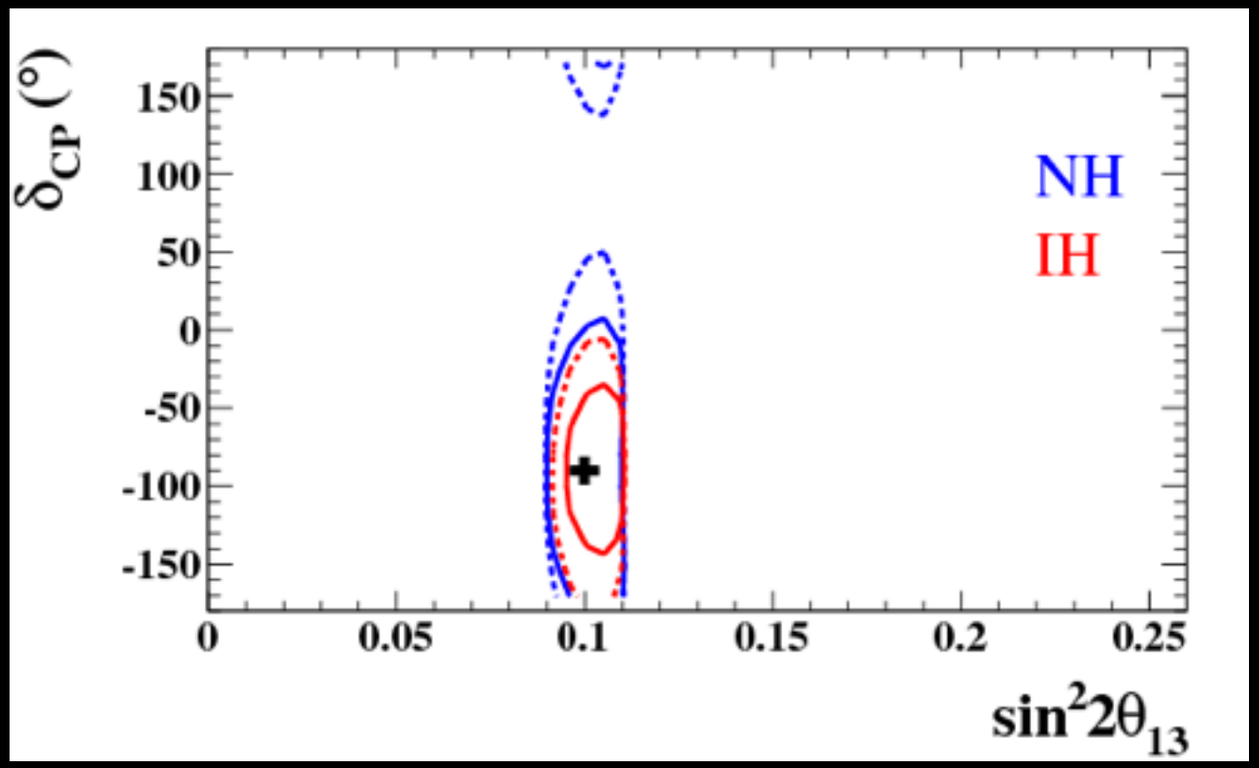
Manufacture installation/test

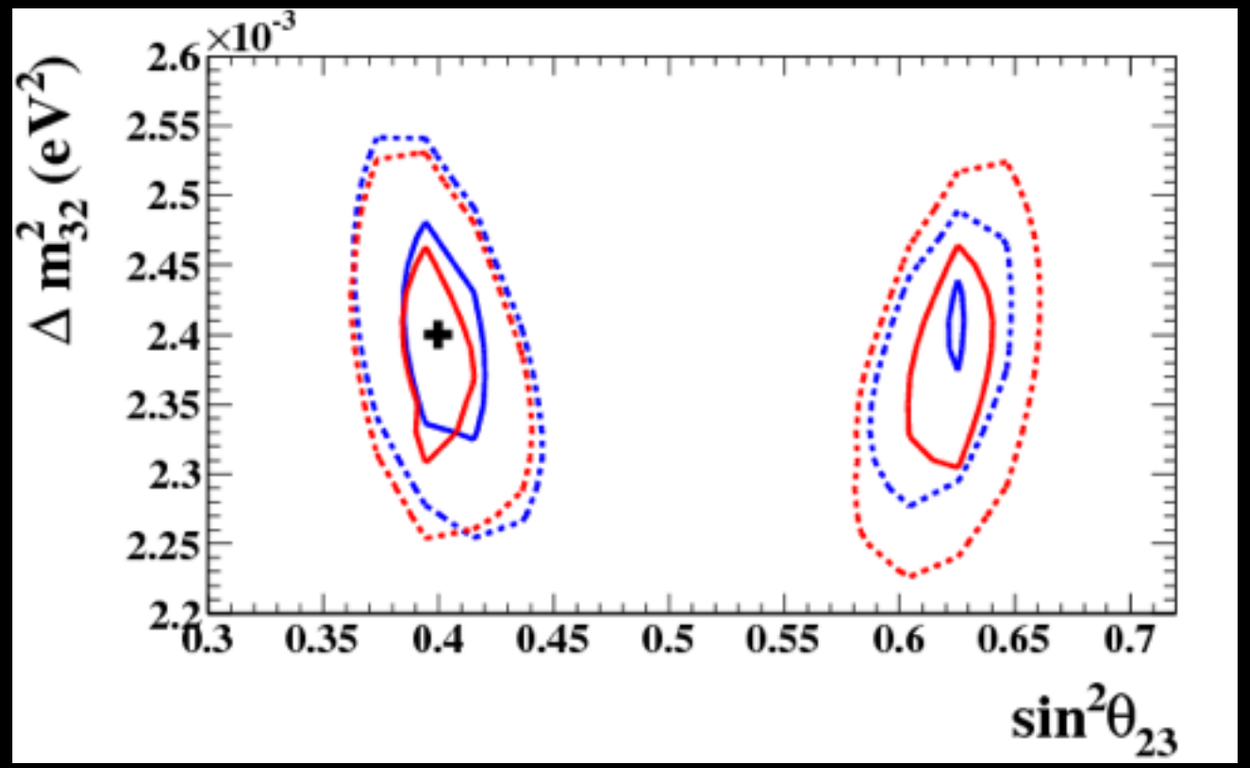
Kicker PS improvement, Septa manufacture /test

Kicker PS improvement, LF septum, HF septa manufacture /test

- 400 MeV LINAC upgrade completed in FY2013

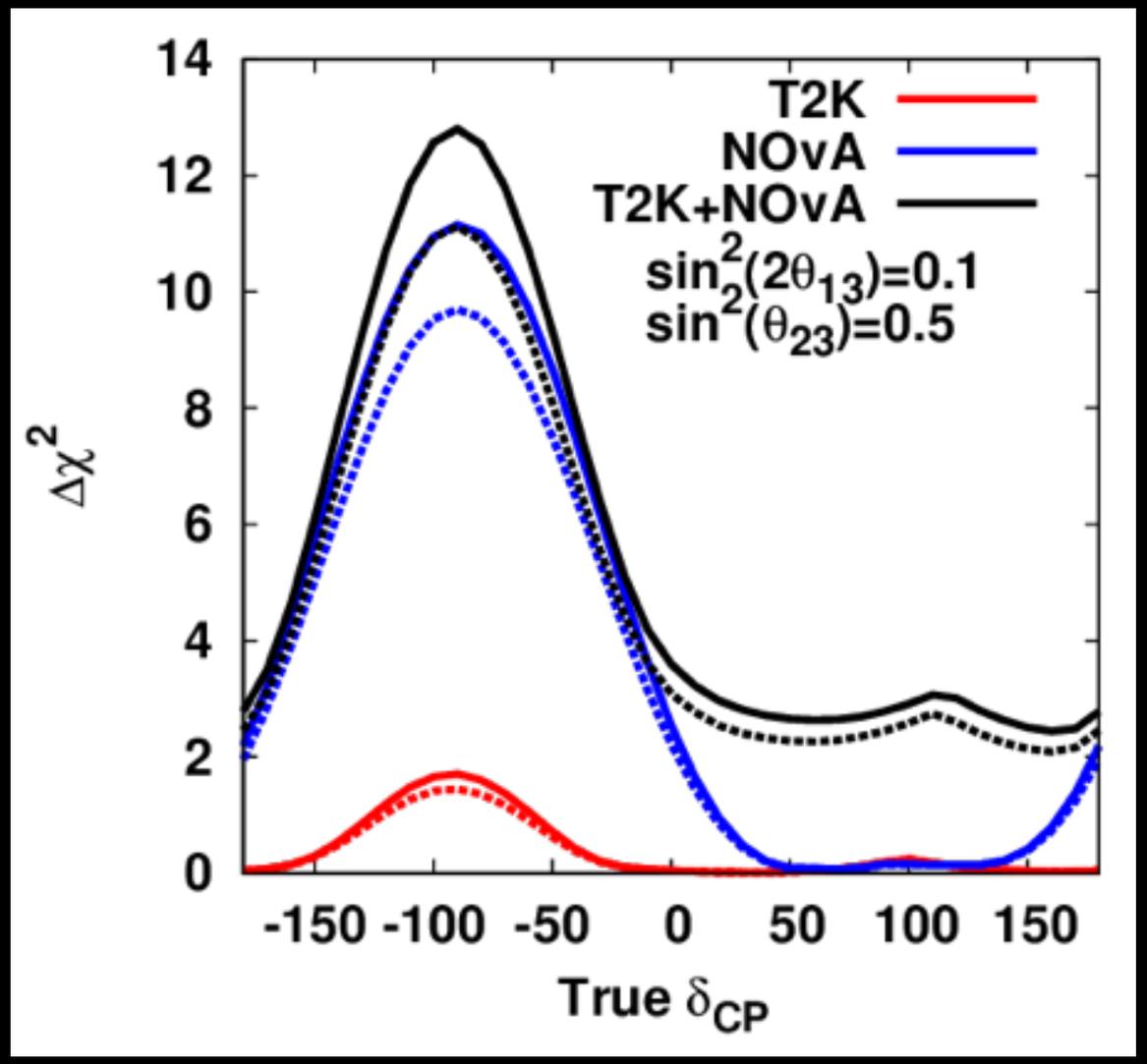
ALL NEUTRINOS, ALL THE TIME

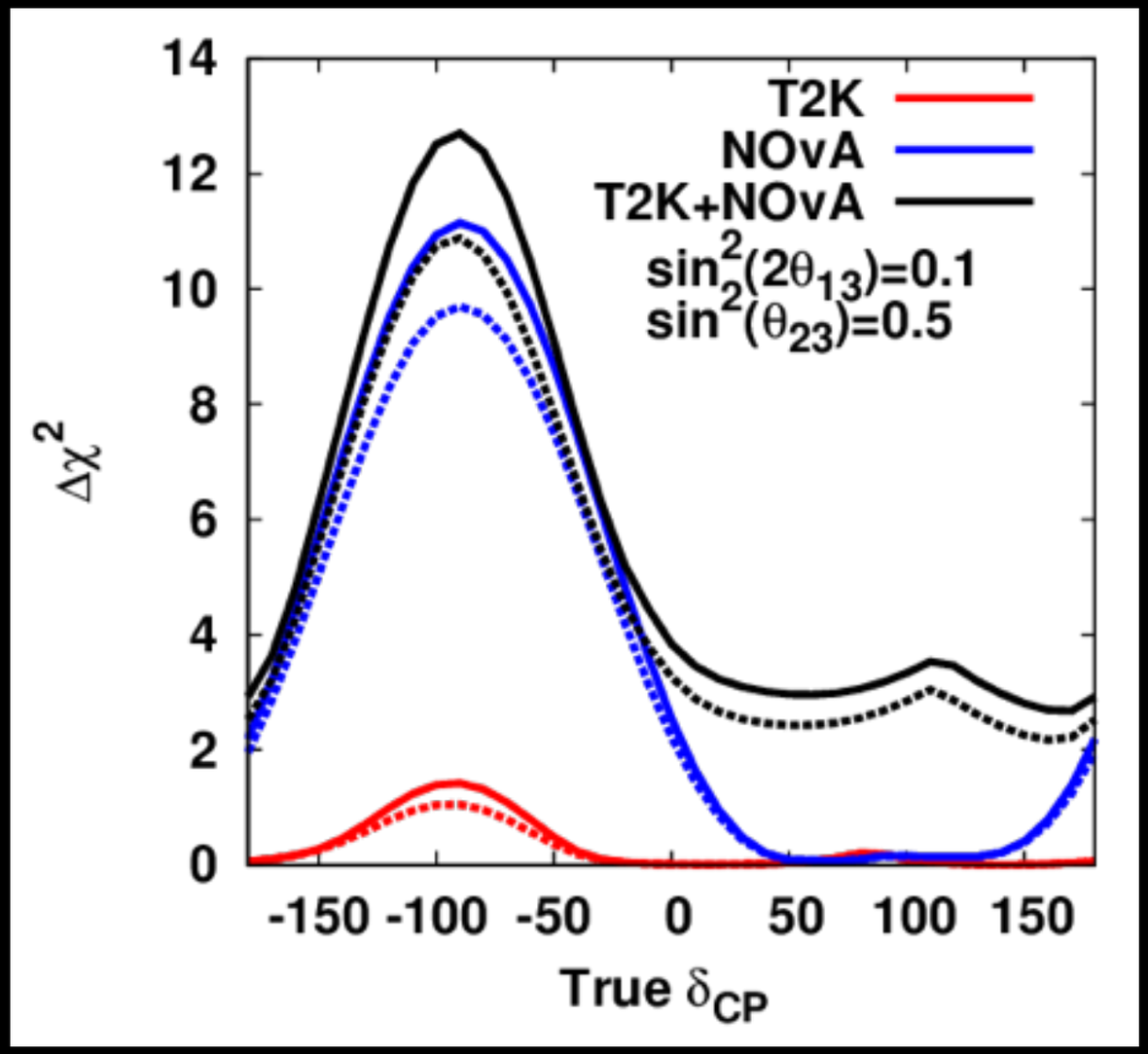




- Sensitivity worsened significantly by systematics

MASS HIERARCHY SENSITIVITY





- Left: 50/50 in T2K and NOvA
- Right: 100% neutrino in T2K, 50/50 in NOvA