TRIUMF

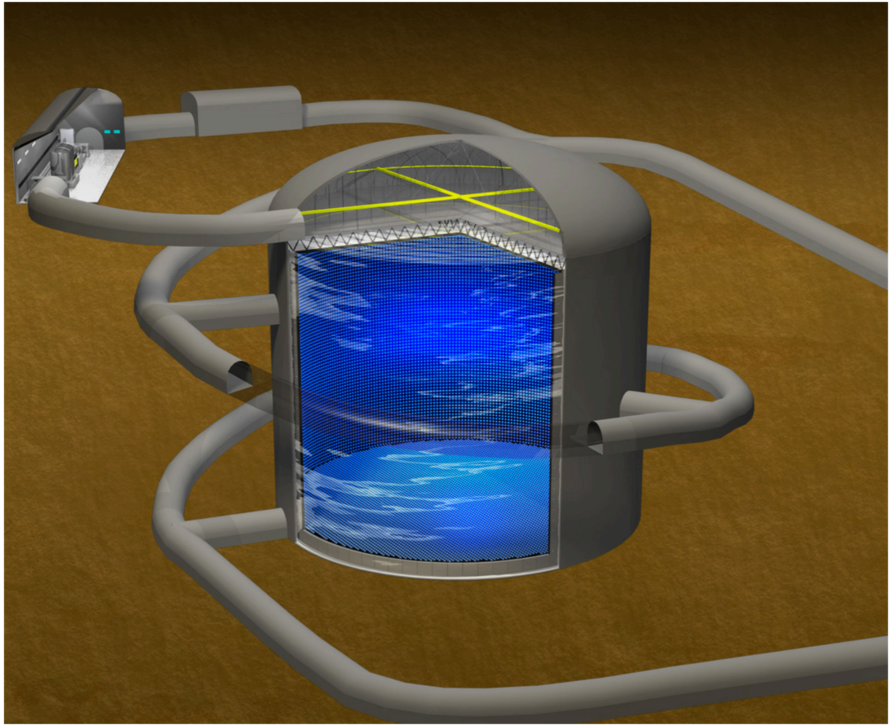
Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Precision neutrino oscillation at Hyper-Kamiokande

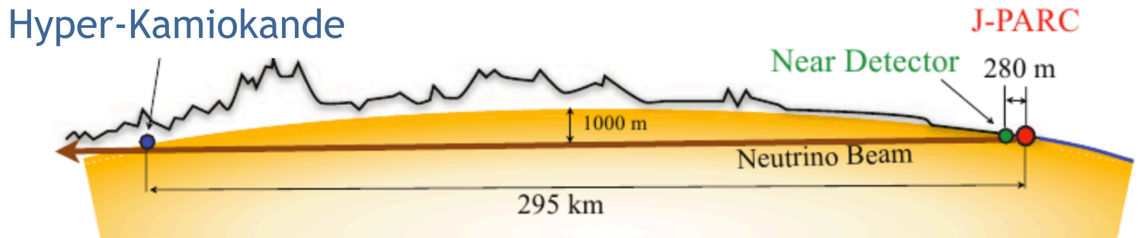
Akira Konaka (TRIUMF)

July 2019

Hyper-Kamiokande

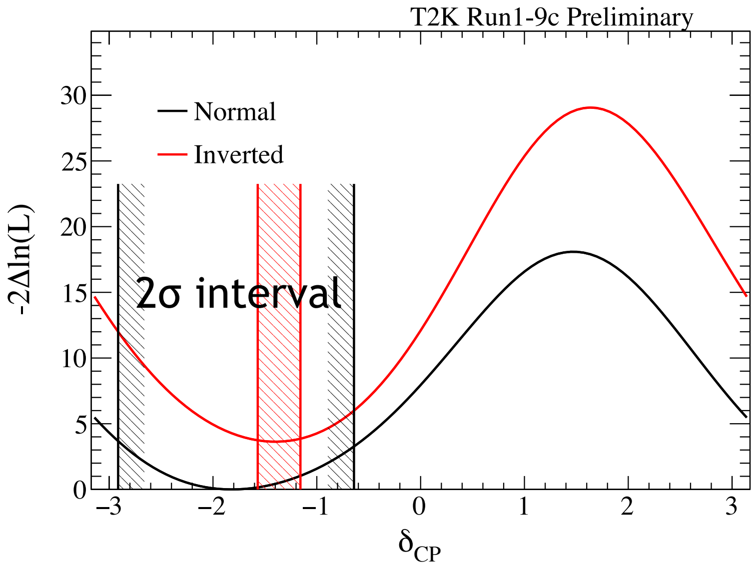


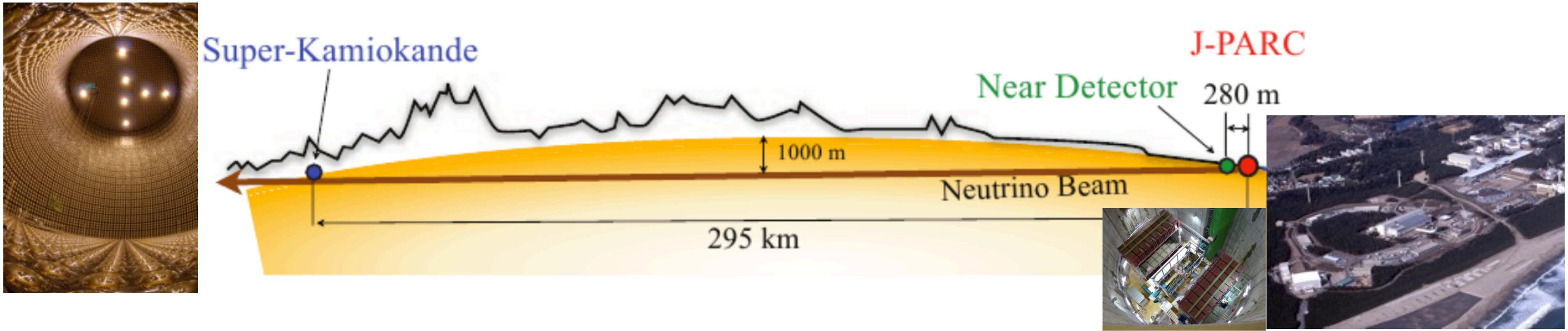
- 186kton (fid.) water Cherenkov
  - 8 times larger than SuperK
- Physics goal
  - precision ν oscillation
    - long baseline neutrinos
    - atmospheric neutrinos
  - neutrino astronomy
    - supernova & solar neutrino
  - new physics
    - nucleon decays
    - dark matter
    - non-standard ν interaction (NSI)
- Construction to start in 2020



Tokai-to-Kamioka (T2K) long baseline neutrino experiment

- 295km of neutrino travel
  - observed $\nu_\mu \rightarrow \nu_e$ oscillation
    - what is neutrino oscillation?
    - why such a long travel?
- Disfavour CP conserving $\delta_{CP}=0,\pi$ at 2σ level
    - why is CP study important?





Weak and mass eigenstates are different: Mixing

$$< \nu_l|\nu_i >= U_{li} : PMNS\ matrix$$
$$l = e, \mu, \tau : weak\ eigenstates$$
$$i = 1, 2, 3 \ : mass\ eigenstates$$

Neutrino particle (mass eigenstate) has mixed flavours e/μ/τ (weak eigenstates)!

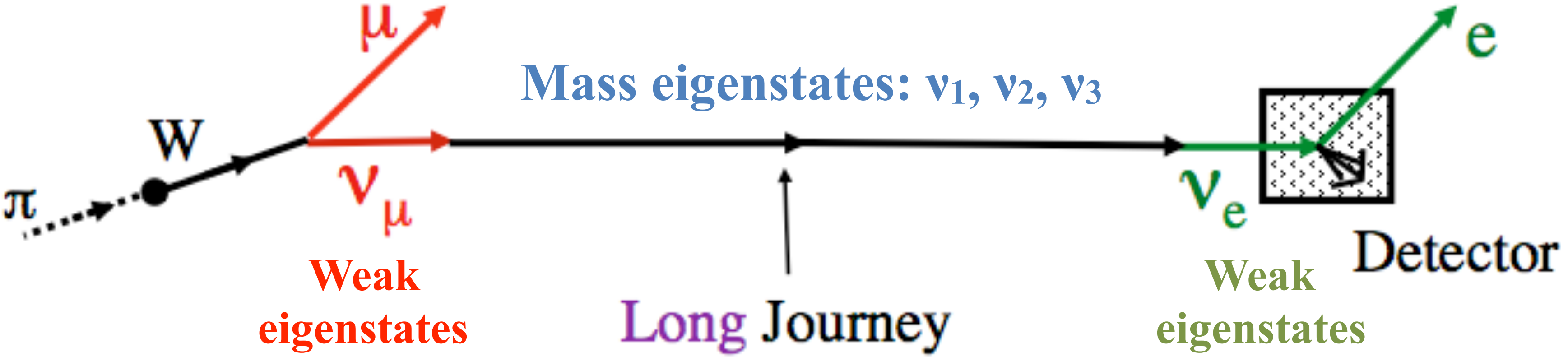


Figure: Boris Kayser

PMNS matrix (3 generation lepton mixing)

$$< \nu_l | \nu_i > = U_{li} : PMNS\ matrix$$
$$l = e, \mu, \tau : weak\ eigenstates$$
$$i = 1, 2, 3 : mass\ eigenstates$$

weak eigenstate | Pontecorvo-Maki-Nakagawa-Sakata mass mixing matrix | mass eigenstate

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

3-generation mixing allows the degree of freedom of CP violation phase δ [Kobayashi-Maskawa theory for quarks]

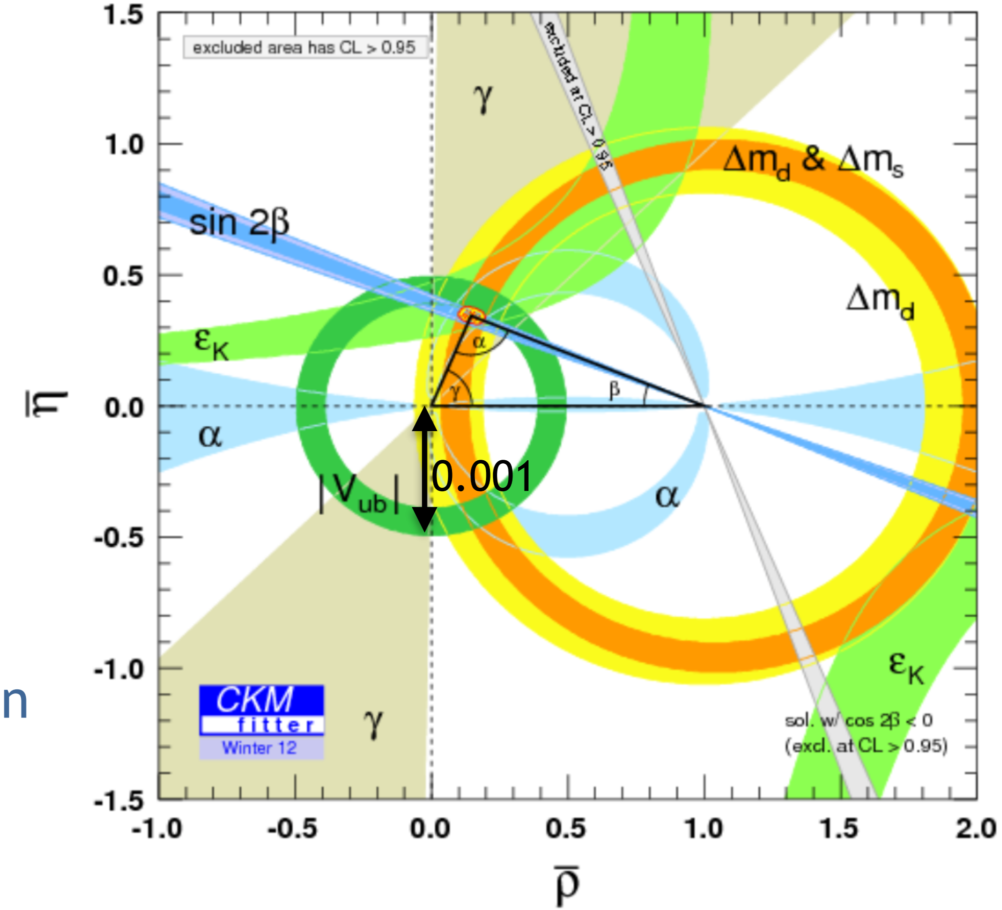
U→U* or δ→-δ for anti-neutrinos

Atm/long-baseline ν | CP violation and θ_{13} | solar/reactor ν

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \cos\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\cos\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

(Quarks)



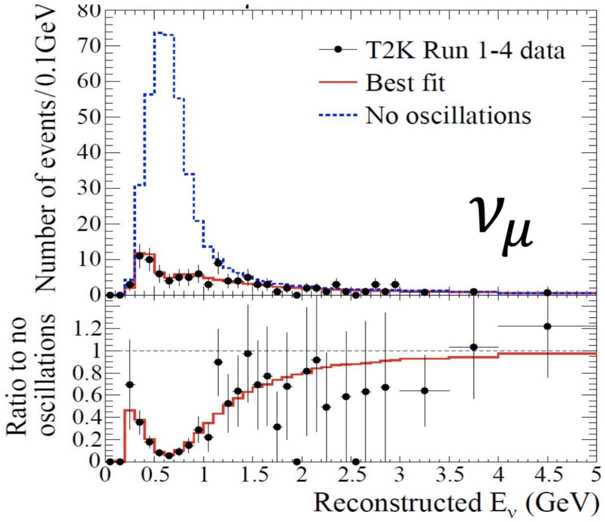
Mass eigenstates and weak eigenstates are almost the same:

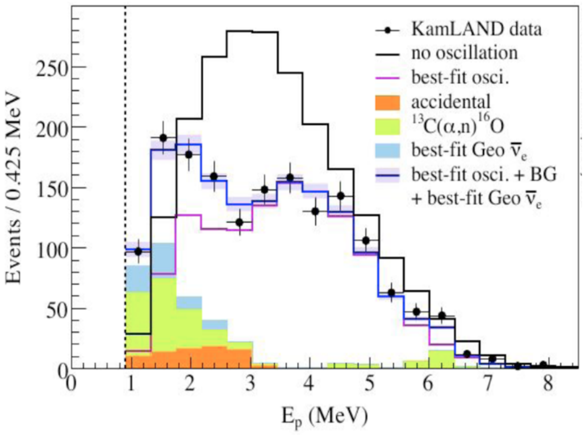
Small mixings → small CP violation

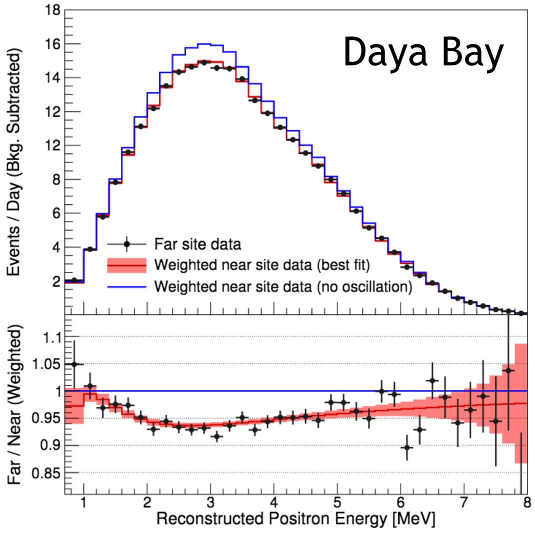
$J_{CKM} \sim 3 \times 10^{-5}$

(area of the triangle)

Neutrino mixing angles are large







- Each neutrino mixing angle are found to be suprisingly large
  - $\theta_{23} \sim 45$ degree, $\theta_{12} \sim 33$ degree, $\theta_{13} \sim 8.5$ degree
    - $J_{PMNS} = 1/8 \times \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$ ~ **$3\times10^{-2} \sin\delta$**

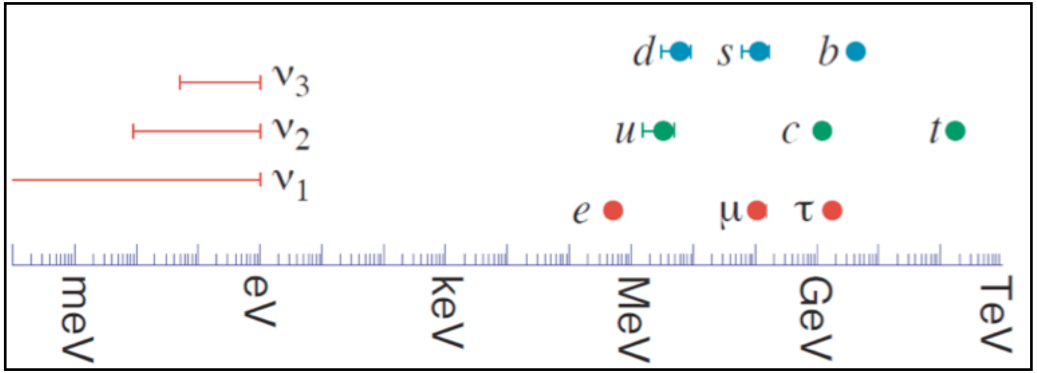
      Potentially much larger than the quark case: $J_{CKM} \sim 3 \times 10^{-5}$

      Large enough to explain the baryon asymmetry of the universe

Origin of neutrino mass?

- Neutrino mass and mixing indicates a new high energy physics scale

- Neutrino mass mixing is large
  - Different from quarks



$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$
(Quarks)

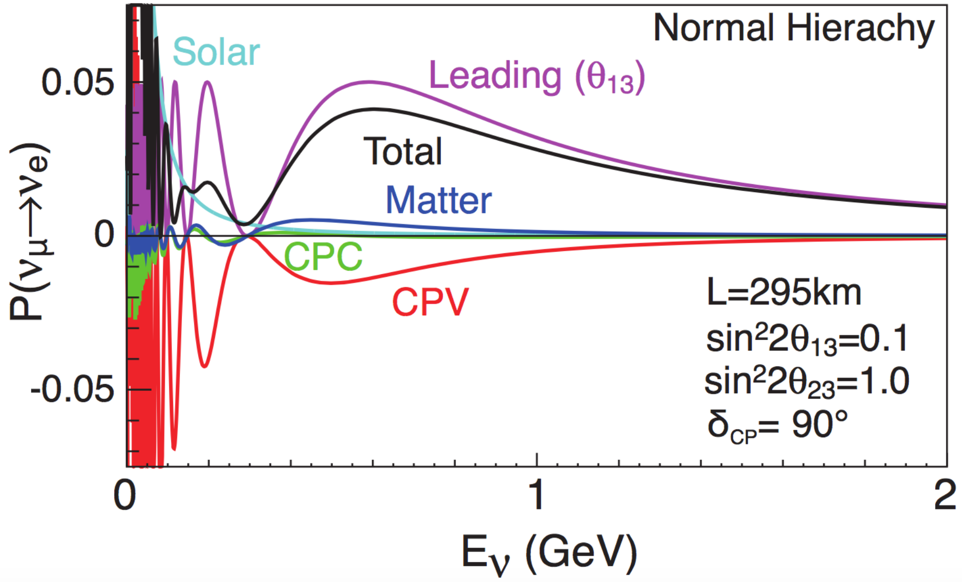
$$V_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$
(Leptons)

- ν masses are many orders of magnitude lighter
  - See-saw mechanism:
    mixing with right-handed Majorana ν, N_R
  - Mass of $N_R \sim 10^{14}$-10^{15}GeV (grand unification?)
  - Large leptonic CP violation in N_R decay can generate the Baryon asymmetry (Leptogenesis)

Large CP violation effect in neutrino oscillation expected

$$V_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

(Leptons)



T2K/HyperKamiokande) case:

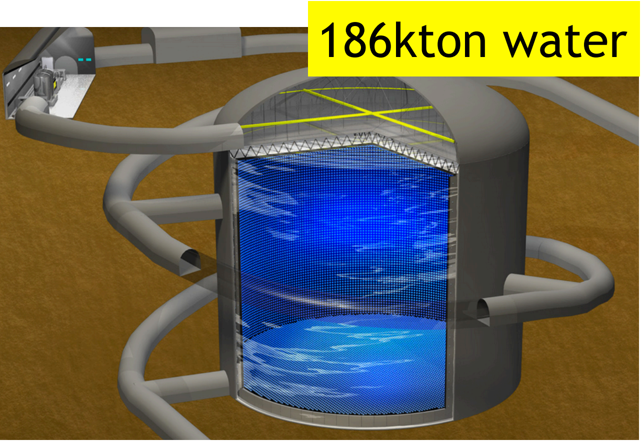
At the peak of E_ν=0.6GeV

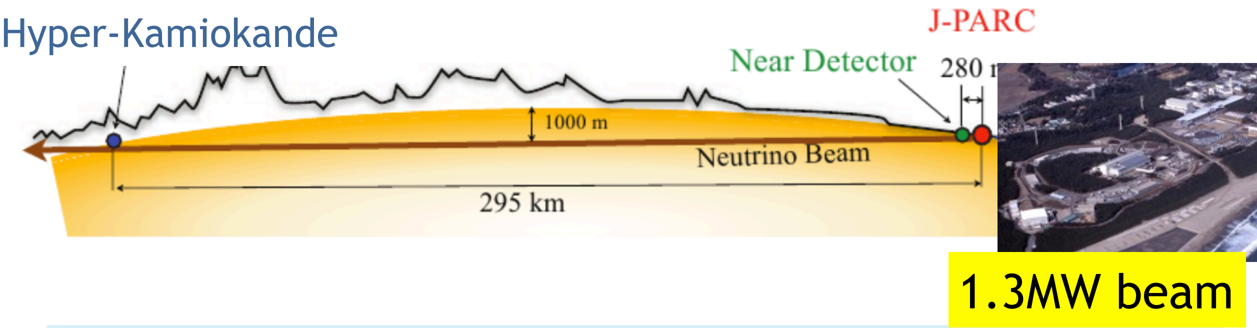
$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin\delta_{CP} + 0.07$$

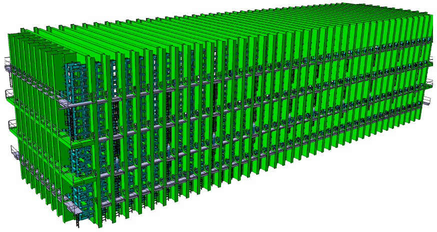
matter effect

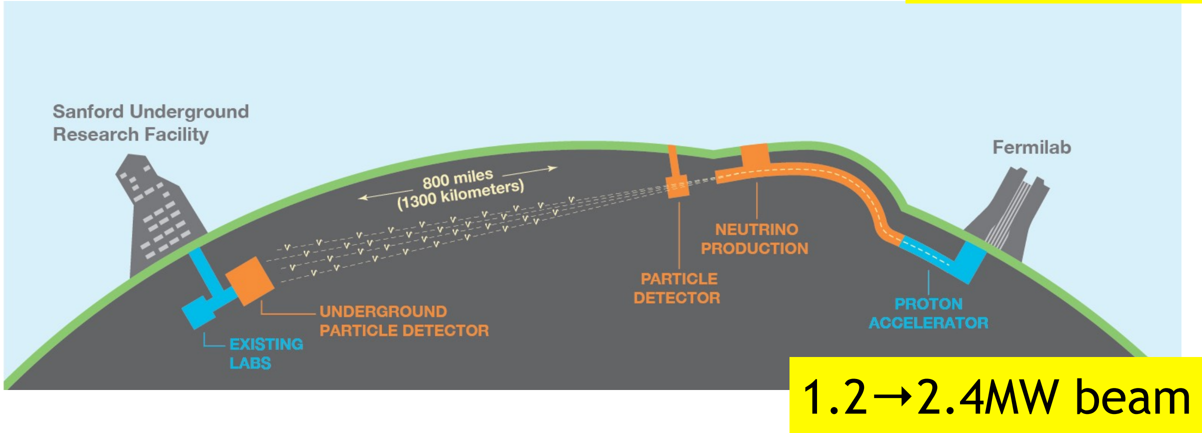
Is it easy to measure the Leptonic CP violation, then?

Large neutrino detector and high intensity beam

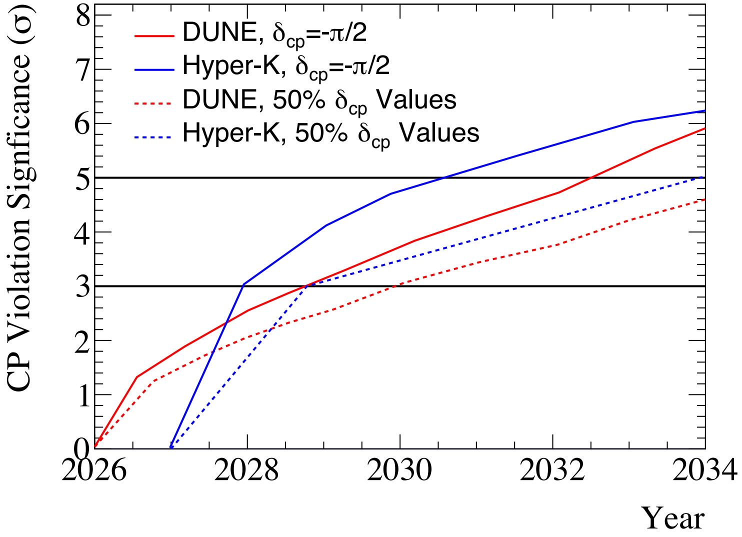


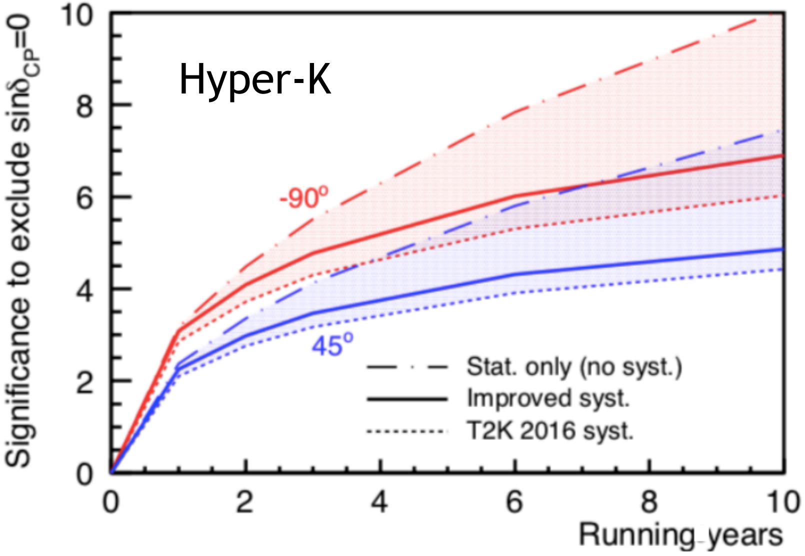






- Two experiments are in preparation: HyperK and DUNE





- HyperK and DUNE have similar sensitivities
  - Fiducial volume: HyperK 187kton DUNE 20-40kton
  - Beam power: 1.3MW 1.2-2.4MW
  - Running time: 10^7 sec/year 2×10^7 sec/year
- Systematic uncertainty limited: currently “systematic error goals” are assigned for both
  - systematic error down to significantly less than the statistical error of 3% is very challenging

Historical lessen from the discovery of neutrino oscillations

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

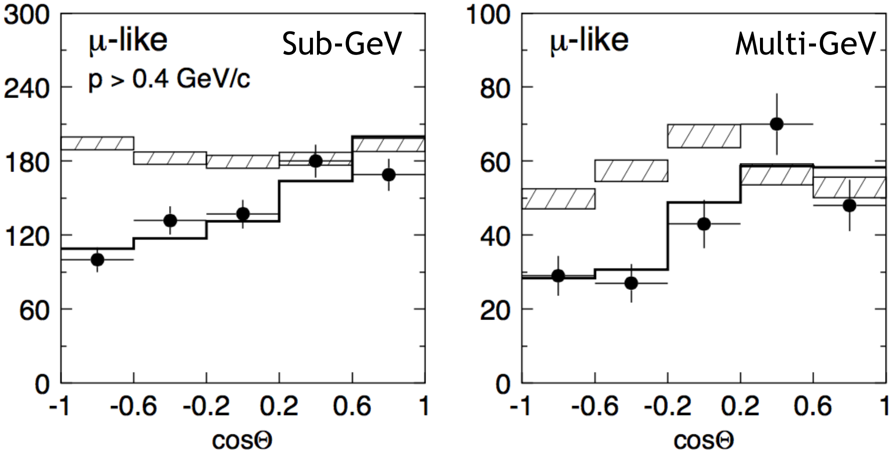
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

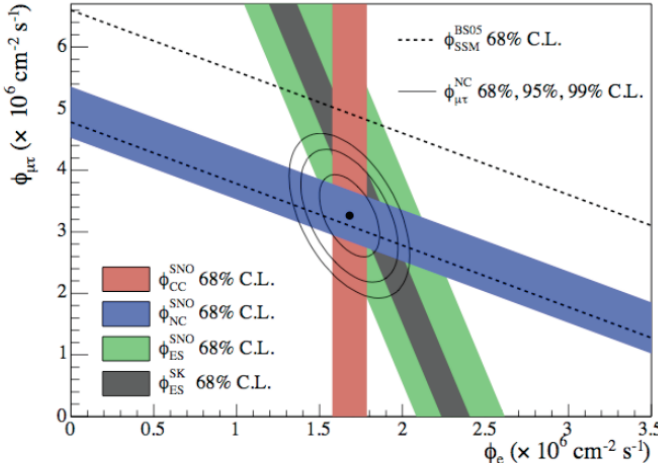
Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



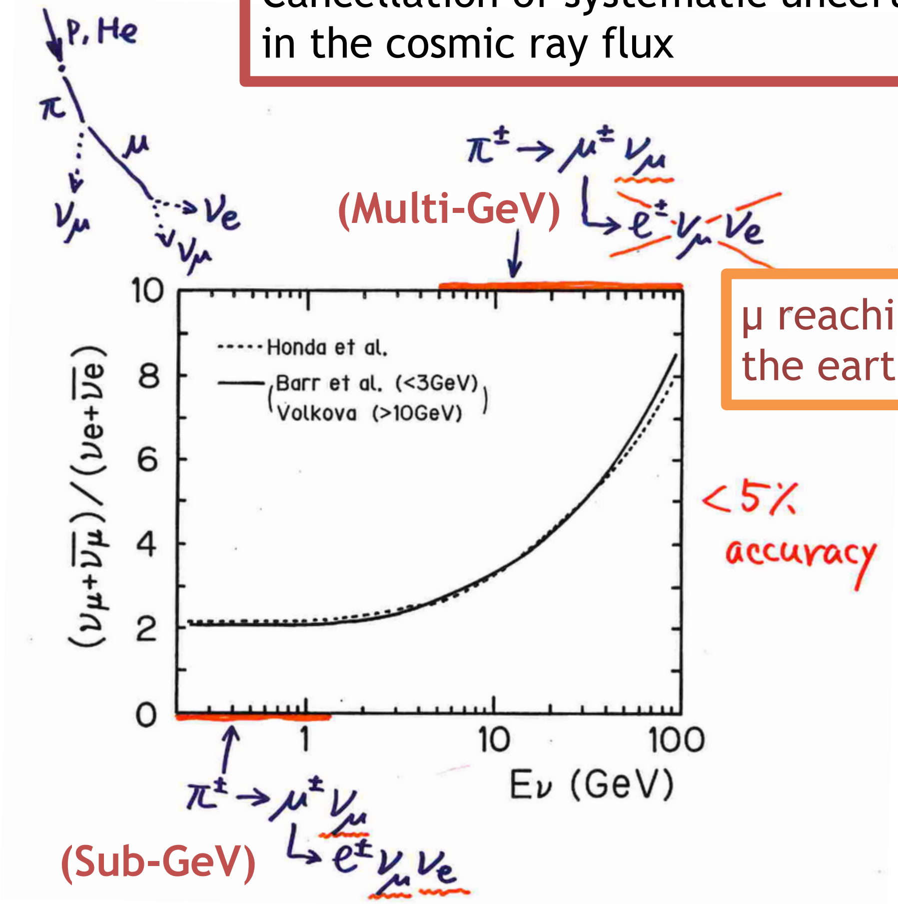
θ_{23}



θ_{12}

ν_μ/ν_e ratio in SK atmospheric neutrinos

Cancellation of systematic uncertainty in the cosmic ray flux



Neutrino oscillations :

$$\frac{\left(\nu_\mu+\bar{\nu}_\mu / \nu_e+\bar{\nu}_e\right)_{\text{Observed}}}{\left(\nu_\mu+\bar{\nu}_\mu / \nu_e+\bar{\nu}_e\right)_{\text{Calculated}}} \neq 1$$

Sub-GeV data

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.63 \pm {}^{0.026}_{0.025}\,(\text{stat}) \pm 0.05\,(\text{syst + MC stat})$$

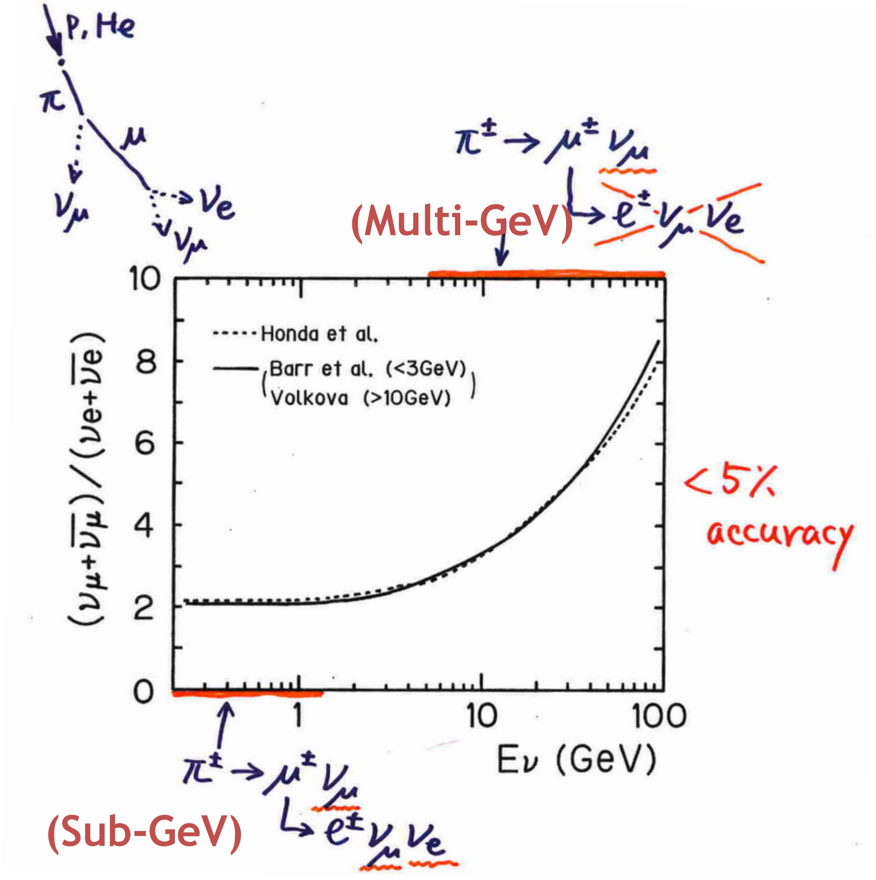
Kam. $= 0.60\,{}^{+0.06}_{-0.05} \pm 0.054$

Multi—GeV data

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.65 \pm 0.05\,(\text{stat}) \pm 0.08\,(\text{syst + MC stat})$$

Kam. $= 0.57\,{}^{+0.08}_{-0.07} \pm 0.07$

ν_μ/ν_e ratio in SK atmospheric neutrinos



Neutrino oscillations:

$$\frac{\left(\nu_\mu+\bar{\nu}_\mu / \nu_e+\bar{\nu}_e\right)_{\text{Observed}}}{\left(\nu_\mu+\bar{\nu}_\mu / \nu_e+\bar{\nu}_e\right)_{\text{Calculated}}} \neq 1$$

Sub-GeV data

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Multi—GeV data

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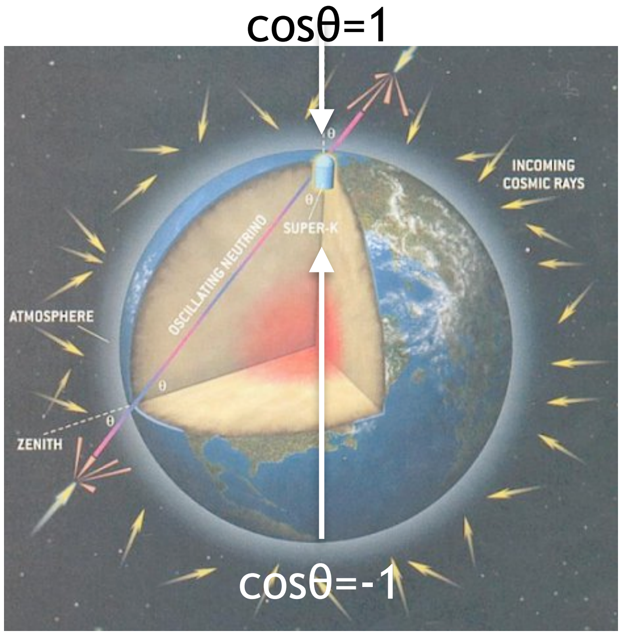
Kam. $= 0.57 ^{+0.08}_{-0.07} \pm 0.07$

$\sigma_\nu \sim 3 x \sigma_{\bar{\nu}}$, $\Phi_\mu(E)$ and $\Phi_e(E)$ shapes?

Kamiokande data already showed 5σ effect

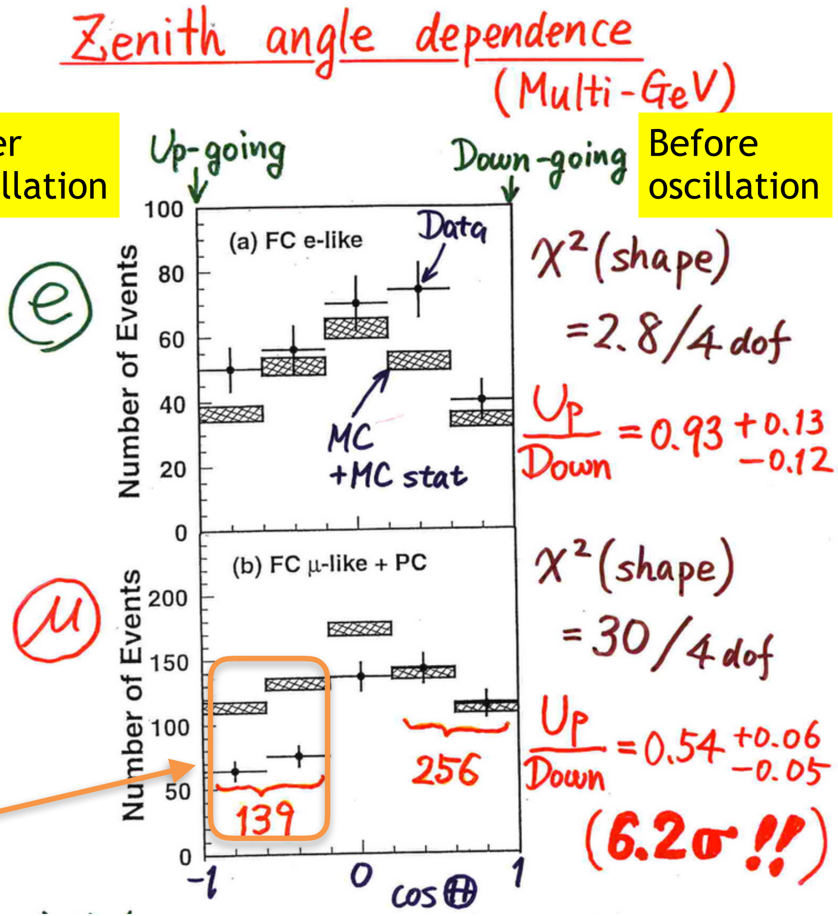
Up/Down asymmetry (direction of multi-GeV events)

SuperK is large enough to contain multi-GeV neutirnos



After oscillation

Before oscillation

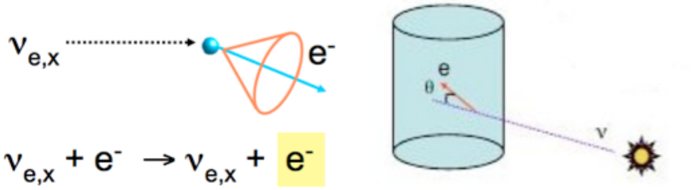


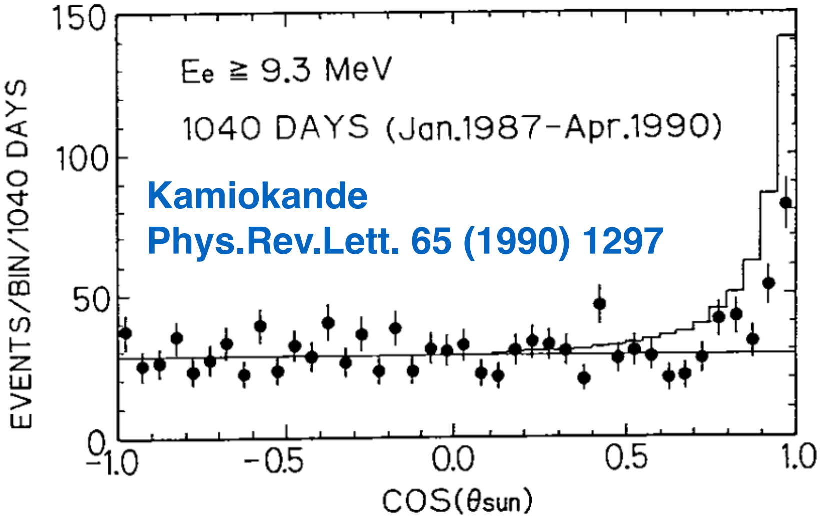
Only up-going muons have deficit:
Enough path length to oscillate!

5σ was not the discovery condition

- Kamiokande also observed solar neutrino oscillation at greater than 5σ
  - Had to wait for SNO to constrain the solar neutrino flux by neutral current

- 5σ is not the discovery condition
  - Other possibilities had to be excluded
    - Not due to models of atmospheric ν or solar ν
  - Systematic uncertainty need to be constrained by data
    - Systematics do not behave gaussian
    - **Data driven systematic error study: Data vs. MC comparison → statistical error**





$$\text{data/SSM} = 0.46 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$$

Systematic uncertainties of T2K

detector

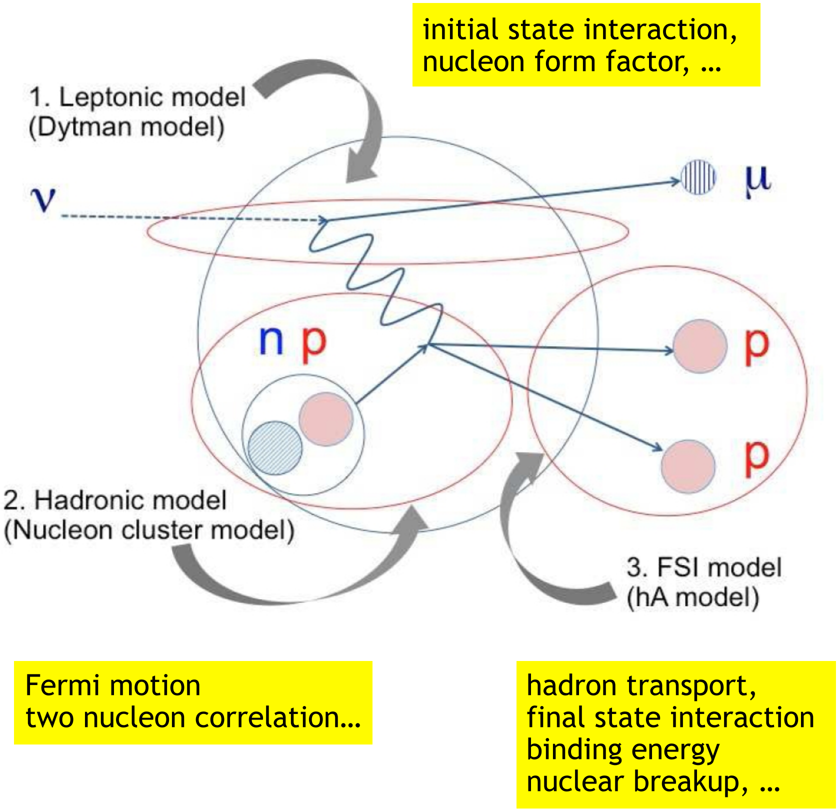
cross section

	1-Ring μ		1-Ring e			
Error source	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν mode cc1π	$\bar{\nu}$/ν ratio
SK Detector	2.40 %	2.01 %	2.83 %	3.79 %	13.16 %	1.47 %
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b "binding energy"	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- Statistical error of HyperK: 3%
  - Systematics need to be reduced well below 3%
  - current systematic uncertainty is 8.8%
    - in particular due to neutrino interactions with model uncertainties

Neutrino-nucleus interactions (CCQE-like = CC0π)

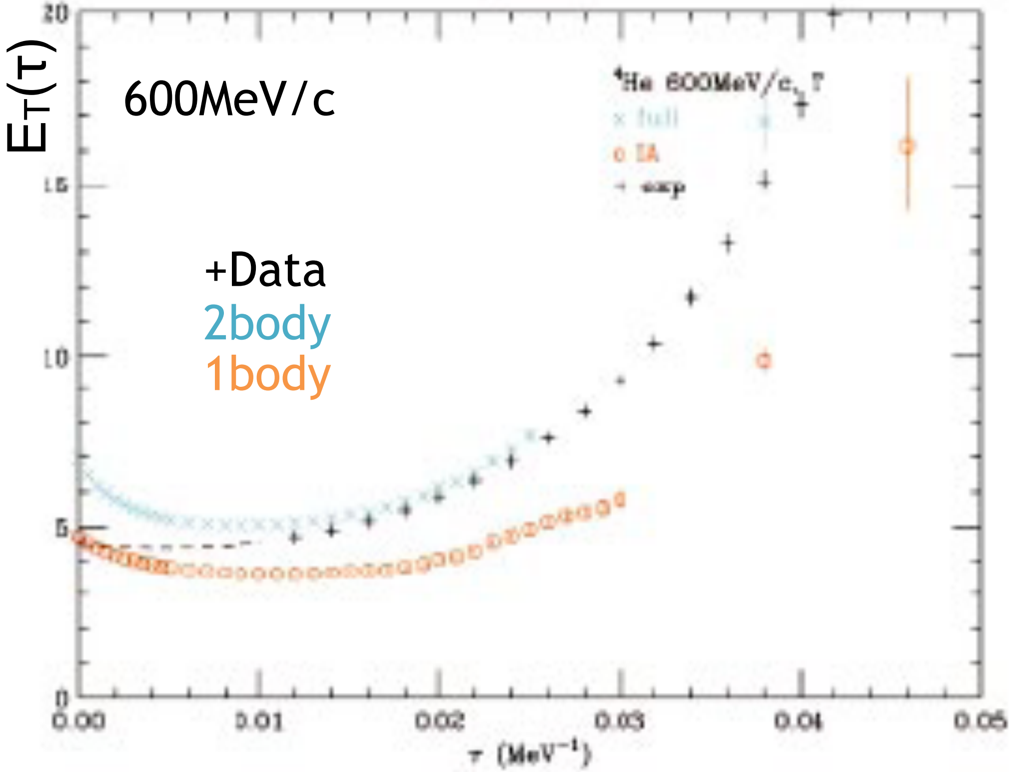
- neutrino-nucleon interaction
  - initial state interaction
  - nucleon form factor
- target nucleon inside the nucleus
  - Fermi motion, nuclear cluster (multi-nucleon) effect
- final state interaction
  - hadron transport inside the nucleus
  - excitation/break up of the nucleus, binding energy
    - how much does the outgoing lepton kinematics changes?
    - lepton is also part of the wave function: how do we model this?



e - ^{4}He Transverse $E_T(\tau)$

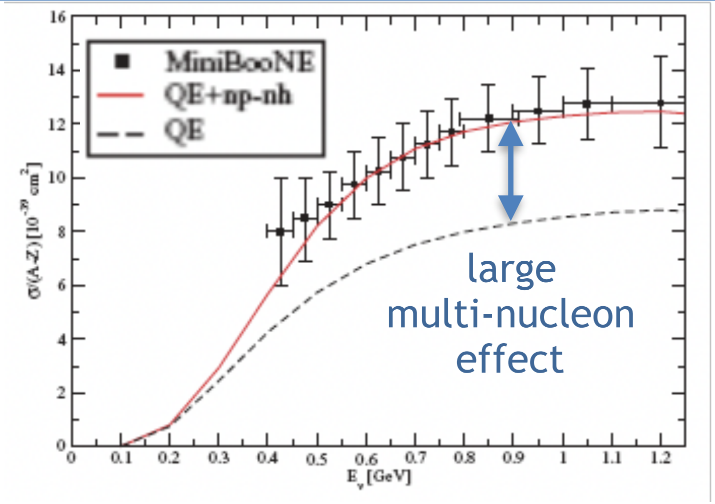
- Large 2-body effect in the transvers form factor
  - nuclear dynamics impact the lepton kinematics

J. Carlson et al, Phys.Rev.C65, 024002 (2002)



Quoted by Gerry Garvey

Significant multi-nucleon effect observed ν-C scatt.



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys (2012) 1307

"In hindsight, the increased neutrino QE cross sections and harder Q^2 distributions (high MA) observed in much of the experimental data should probably have not come as a surprise. Such effects were also measured in transverse electron-nucleus quasielastic scattering many years prior (Carlson, 2002)."

J. Carlson et al, Phys.Rev.C65, 024002 (2002)

"In contrast to earlier speculations [21] that the large enhancement from two-body currents was due to the presence of strong tensor correlations in the ground state, it is now clear that this enhancement arises from the concerted interplay of tensor interactions and correlations in both ground and scattering states. A successful prediction of the longitudinal and transverse response functions in the quasielastic region demands an accurate description of nuclear dynamics, based on realistic interactions and currents."

How can deal with the cross section systematics?

- The neutrino community faces serious challenge to overcome:
  - dynamical nuclear-hadronic effects are hard to predict
  - similar wall hit by collider, B,K decays, electron/π scatterings

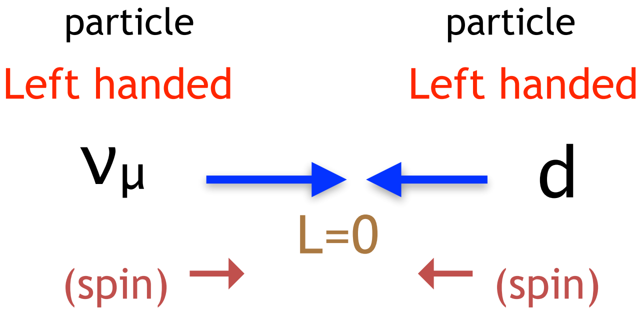
- Lessons from the past physics experiments
  - estimate it from side bands and good control sampls, and cancel them by taking ratios
  - intellectual innovations required

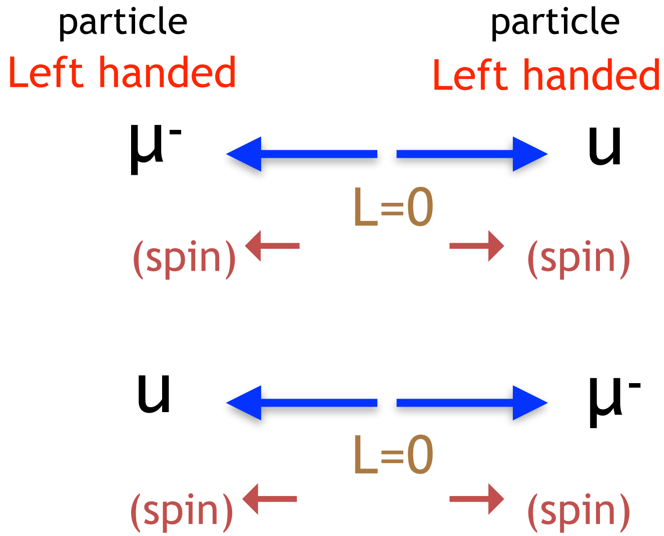
- Systematic uncertainty of 1-2% is a big challenge:
  - Standard approach: taking a ratio to cancel the systematics:
    - CP violation is the ratio between ν and $\bar{\nu}$

$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

- Do the systematic uncertainties cancel? Only partly….
  - Parity is maximally violated:
    - Only “Left-handed” particles and “Right-handed” anti-particle have weak interaction
  - Matter that neutrino hits are made of particles and NOT anti-particles
    - create difference between neutrino and anti-neutrino interactions

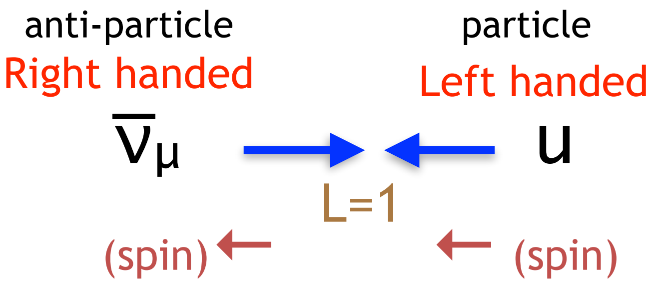
$\nu/\bar{\nu}$ cross sections: parity violation

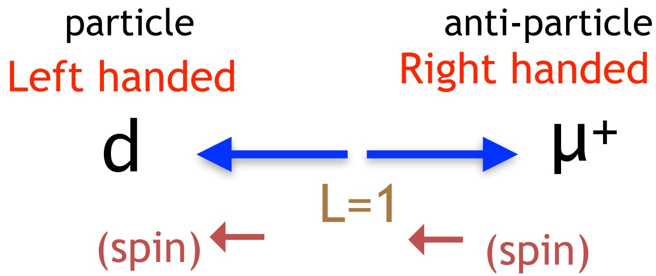




uniform μ production for ν

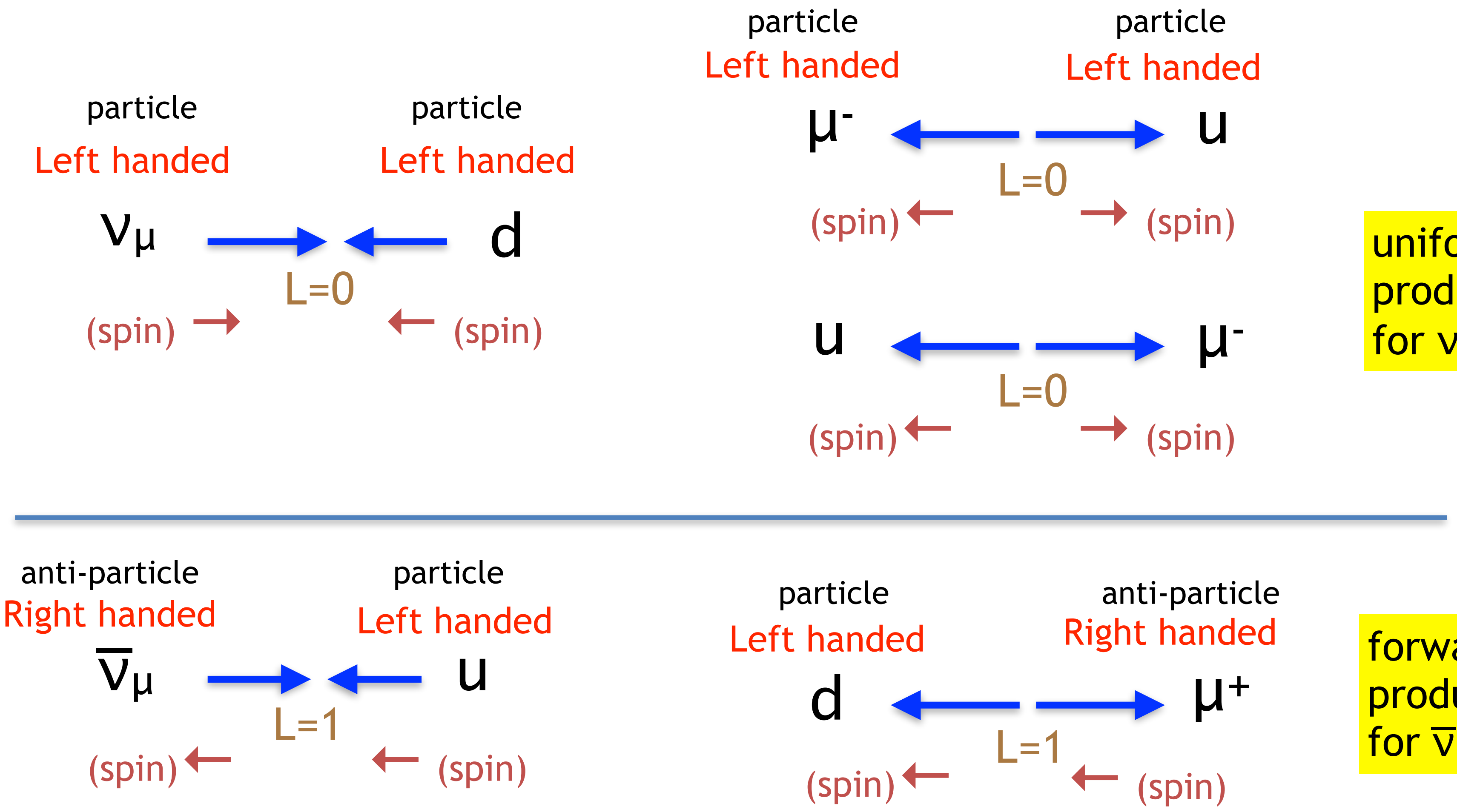
$\nu/\bar{\nu}$ cross sections: parity violation





forward μ production for $\bar{\nu}$

$\nu/\bar{\nu}$ cross sections: parity violation

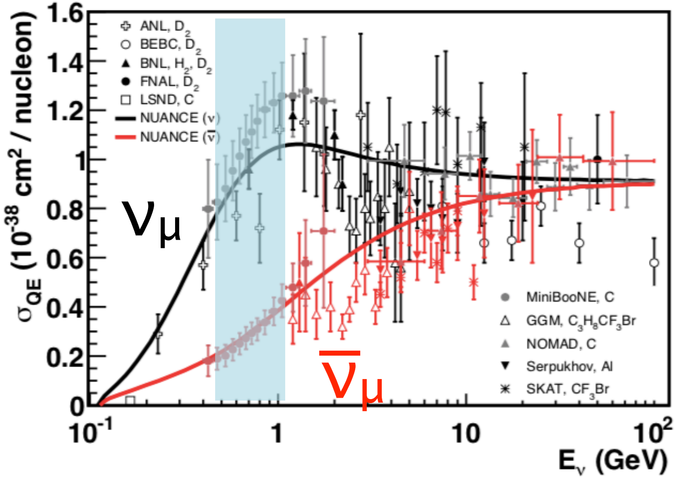


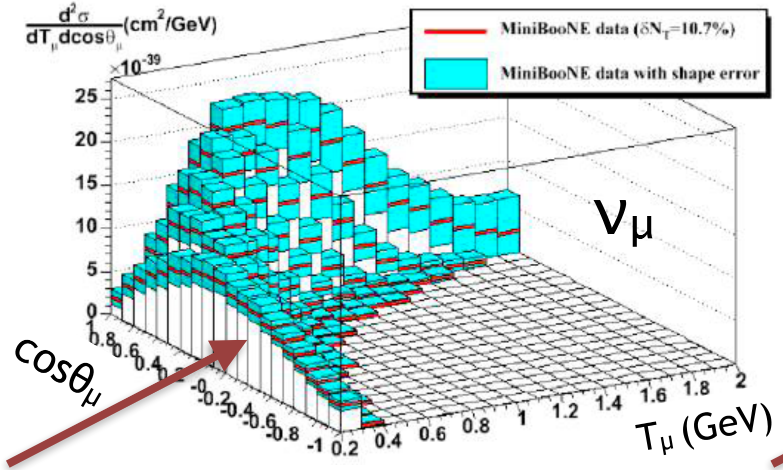
uniform μ production for ν

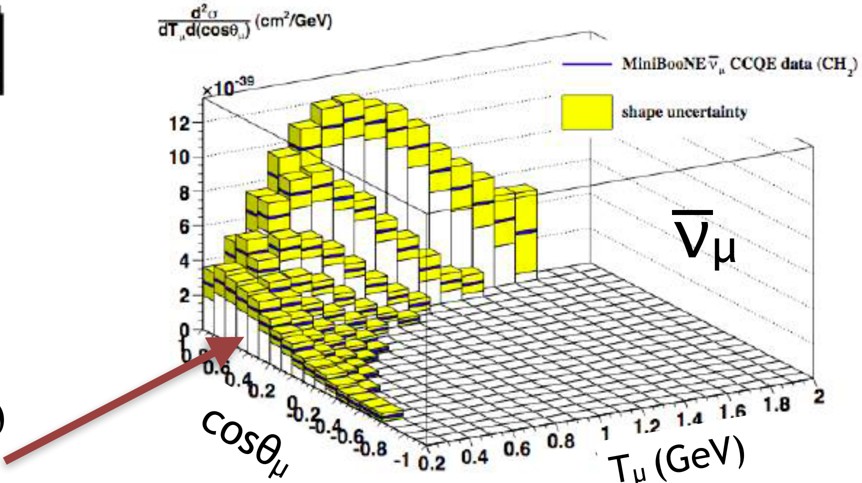
forward μ production for $\bar{\nu}$

- $\sigma_{CCQE}(\nu_\mu) > \sigma_{CCQE}(\bar{\nu}_\mu)$
  - energy dependence

- $\bar{\nu}_\mu$ cross section is forward peaked



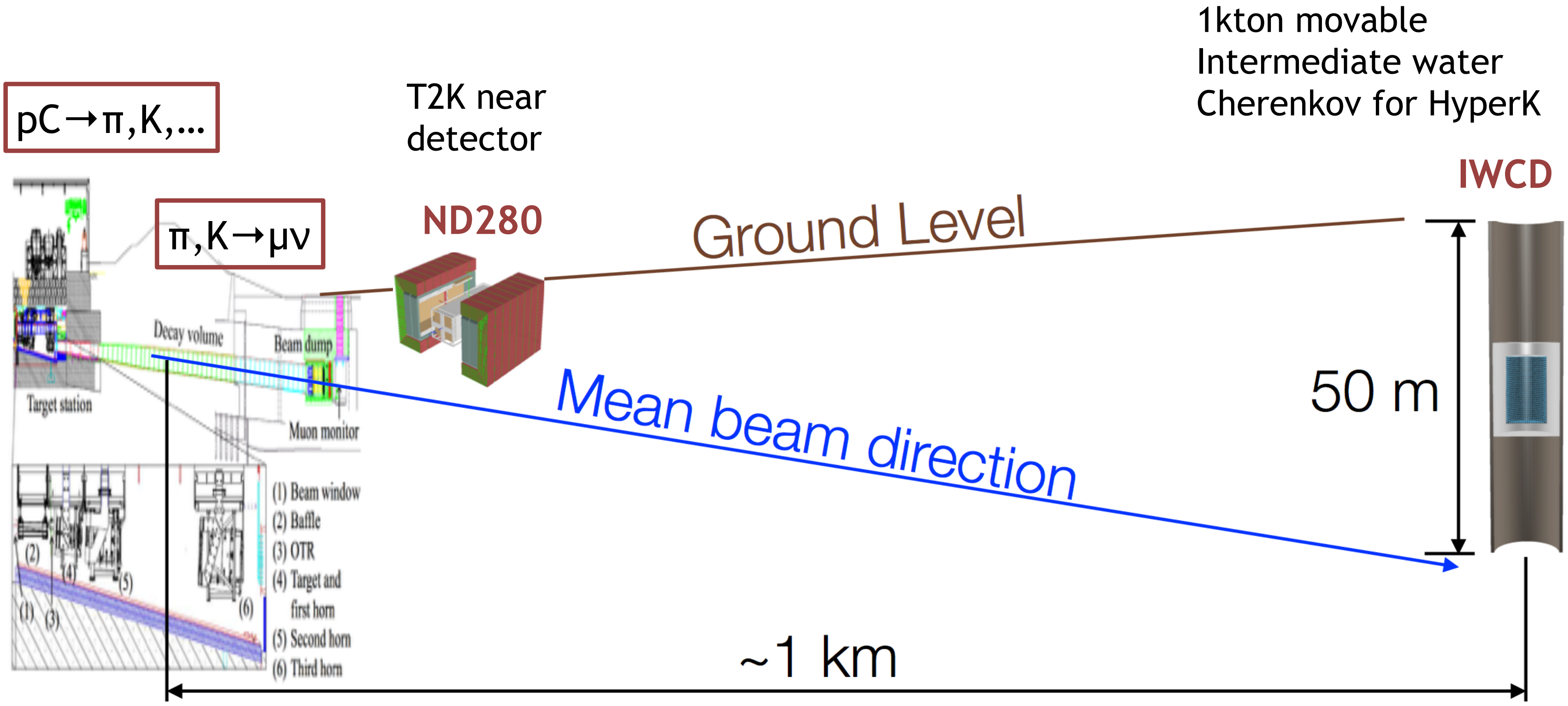




How about Far/Near ratio?

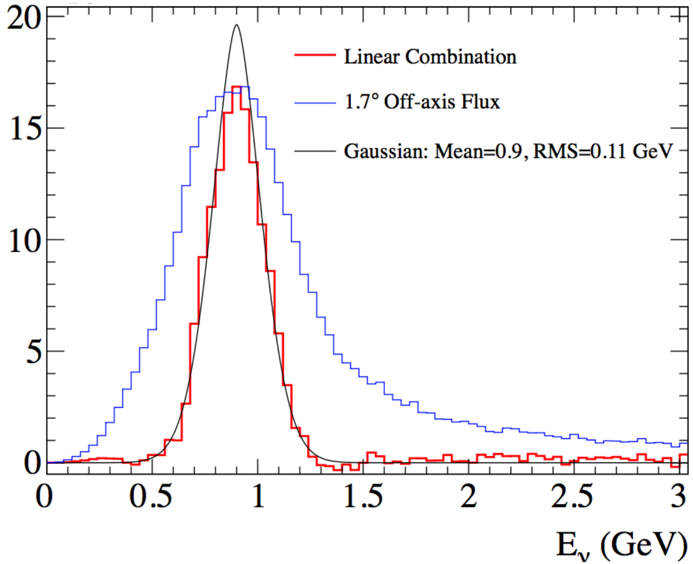
- Far/Near cancellation: same as up/down ratio in atmospheric ν
  - First order cancellation is demonstrated by T2K: 8.8% syst. error
- Sources that limit Far/Near cancellation of systematics
  - [A] Far/Near flux
    - near and far flux shapes are different in particular due to oscillation:
      - energy dependence in cross section causes difference
    - replicate the far detector flux shape by using the near detector: **IWCD**
  - [B] Near detector is ν_μ and far detector is ν_e
    - cross sections are different by15% due to m_μ vs. m_e differece
    - purely theoretical uncertainty: **IWCD $\sigma(\nu_e)/\sigma(\nu_\mu)$ measurement**
  - [C] Far/Near detector efficiencies
    - same water Cherenkov detector is needed for the near detector
    - different sizes for near and far detectors: improved **calibration** needed.

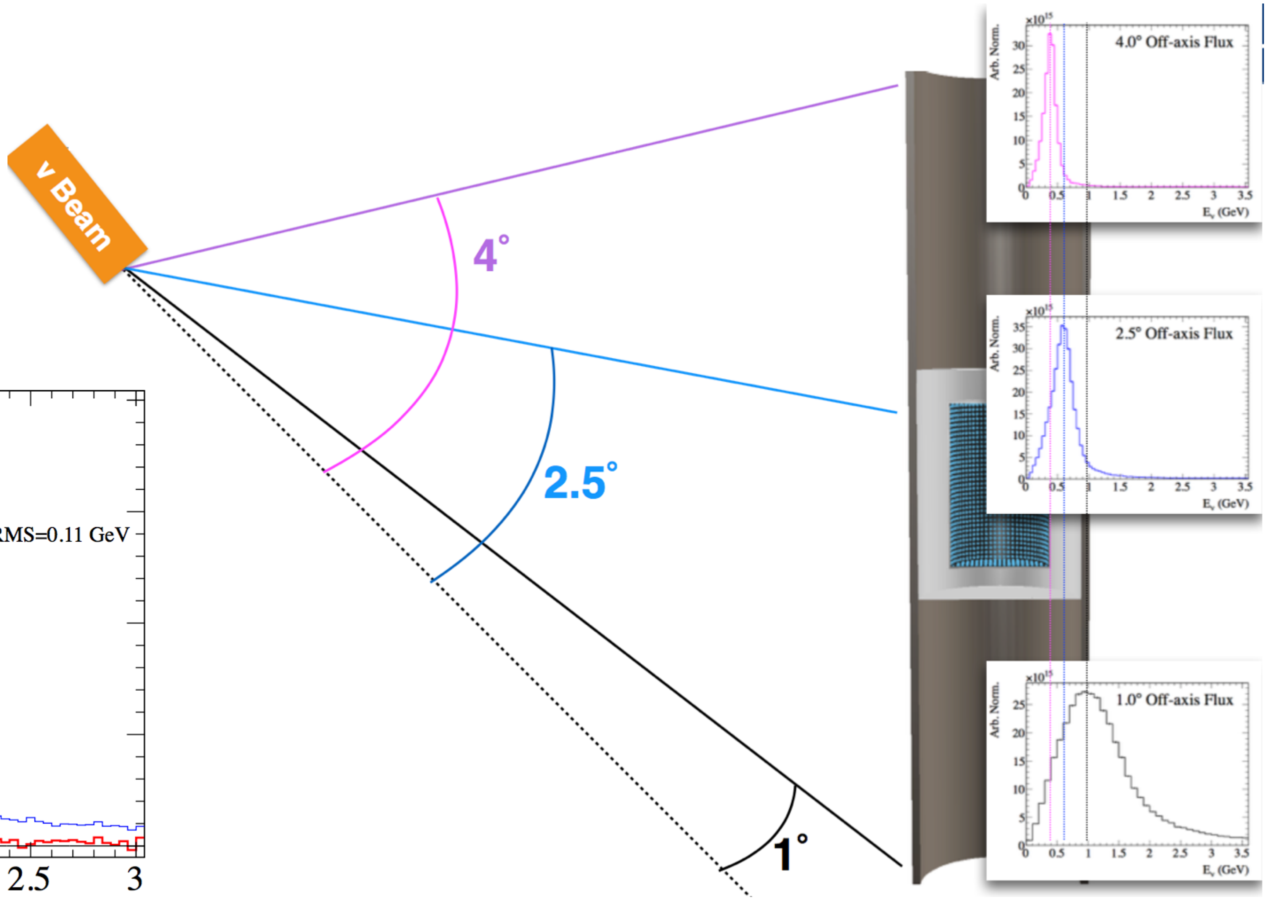
[A] Far/Near flux error cancellation with IWCD

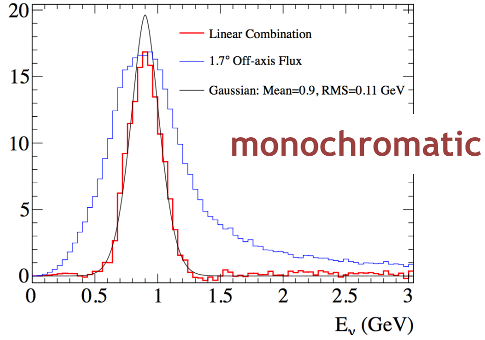


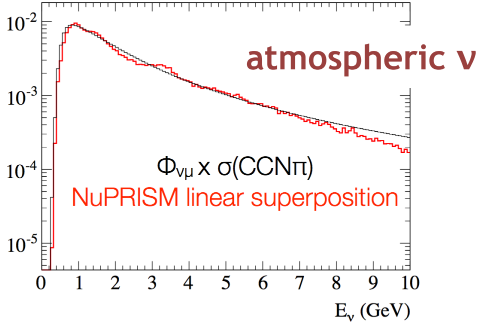
Linear combination of events at different off-axis position:

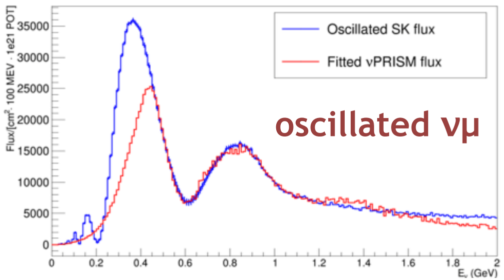
➜ Monochromatic ν beam response

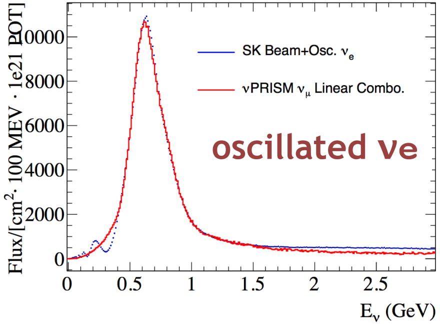




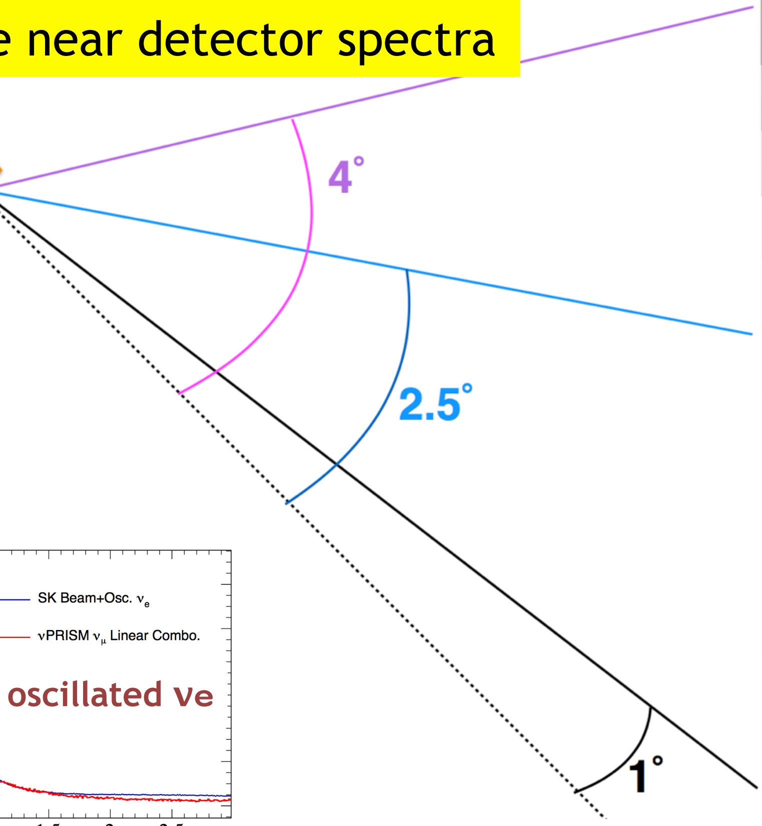


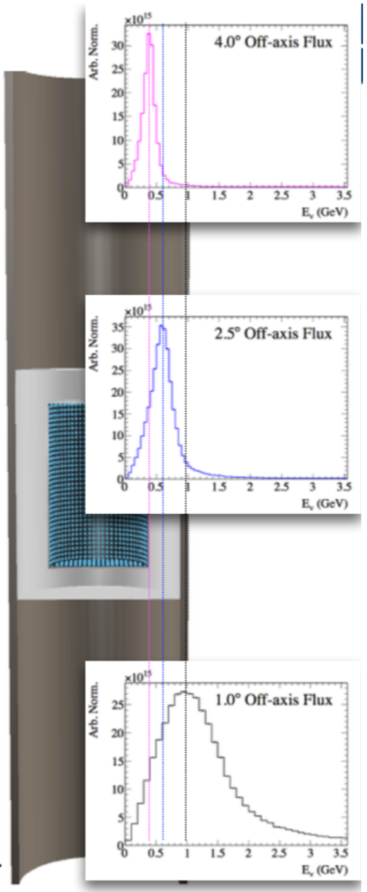






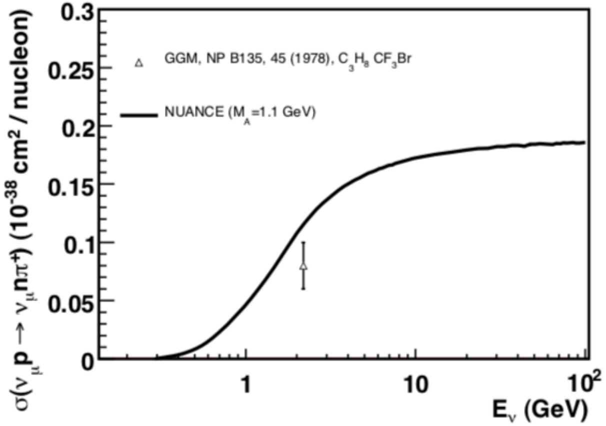
match the far spectrum
by a linear combination of
the near detector spectra

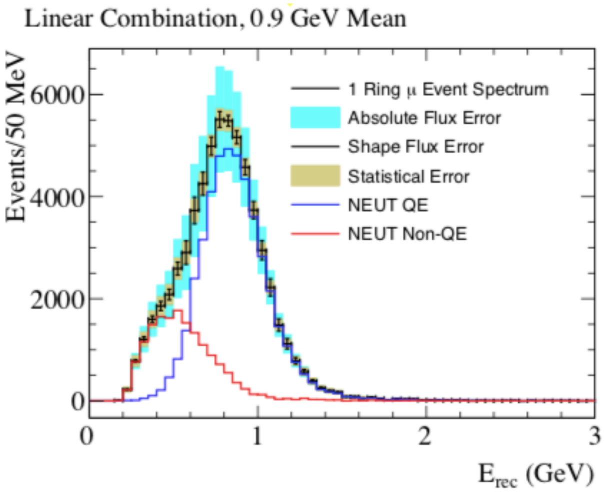


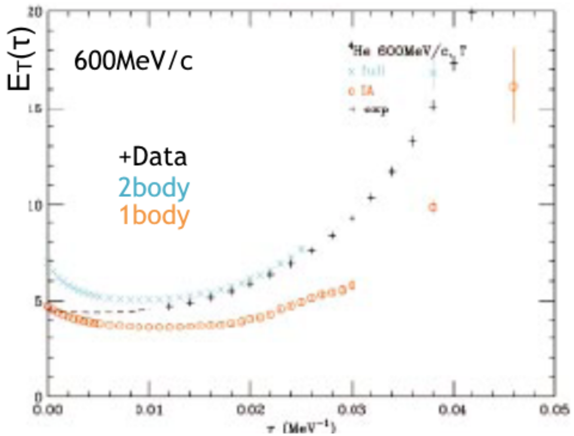


IWCD cross section study with momochromatic beam

- Monochromatic ν beam: unique first time measurements
  - NC cross section as a function of Eν
  - isolate the multi-nucleon (2p-2h) contribution
  - Study the nuclear dynamics of the neutrino interaction: S(Q,ω)
    - similar to neutron, Xray and electron scattering like J.Carlson (2002)

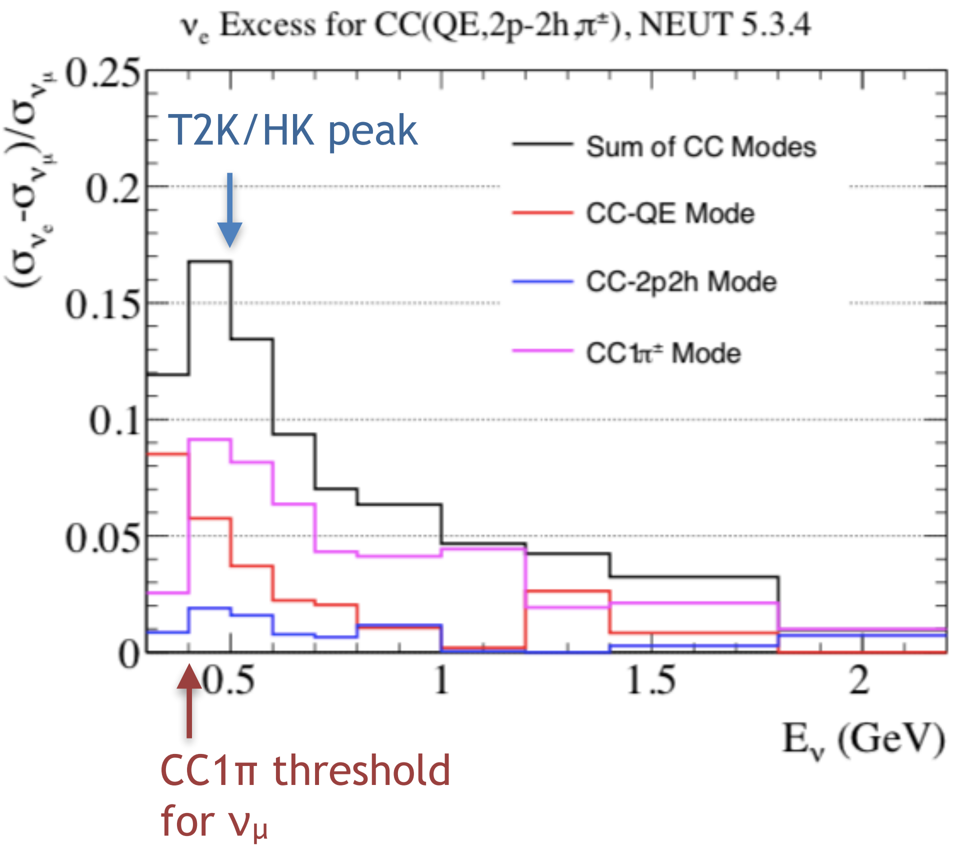




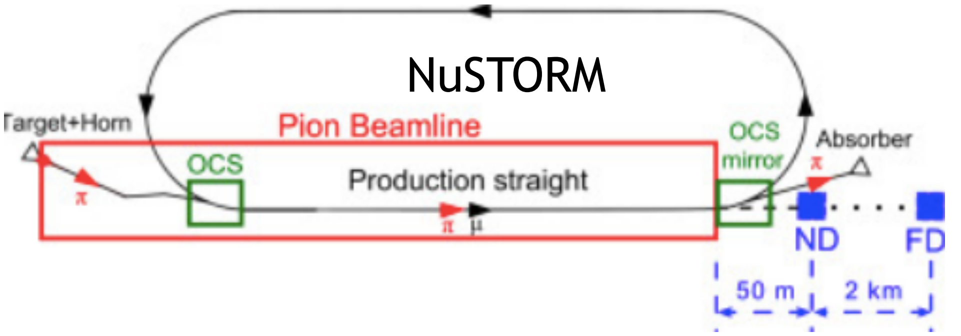


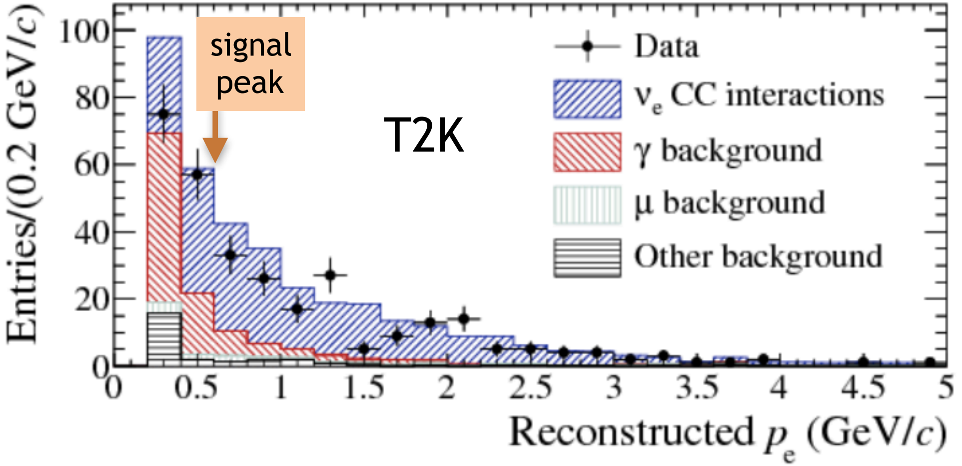
[B] $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross section difference

- Requirements:
  - better than 3% in systematic uncertainty
  - Constrain the error by data
- ~15% expected difference in $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross section ratio at the HK peak energy
  - e/μ universality (symmetry) is broken due to e/μ mass difference

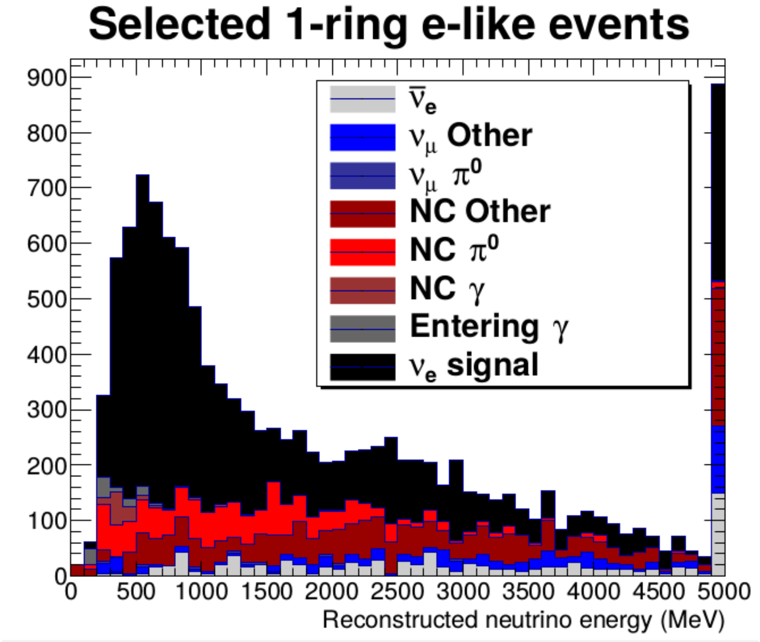


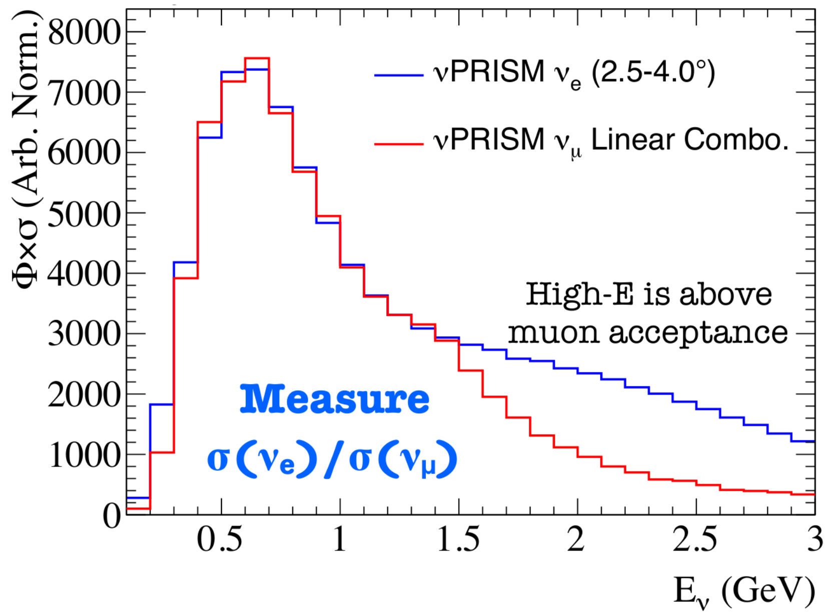
- Flux systematics is large: 5-10%
  - NuSTORM/ν-factory is proposed
    - precise flux but expensive
  - Match the ν_e/ν_μ flux in IWCD and cancel the flux systematics instead
    - relative measurement
- T2K near detector is limited by external γ backgrounds
  - fully active shielding of outer veto is essential for ν_e detection (IWCD)





$\sigma(\nu_e)/\sigma(\nu_\mu)$ by IWCD flux matching

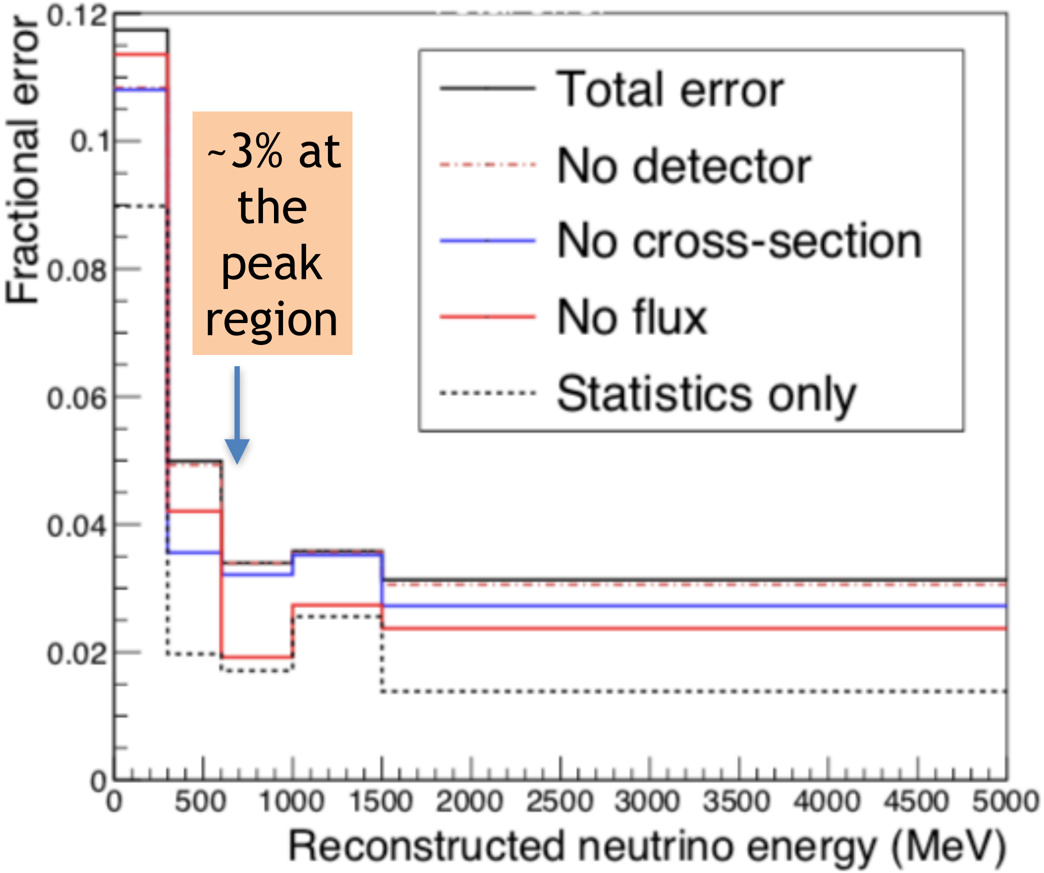




- good background suppression for IWCD
- match the IWCD ν_e flux by IWCD ν_μ flux linear combination
  - cancelling the flux systematics
    - precisely test the difference in the kinematical phase space

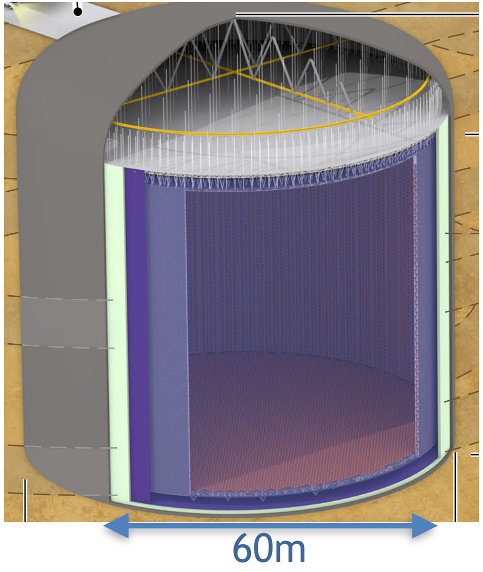
Systematic error in IWCD ν_e measurement

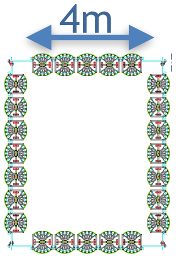
- Flux uncertainty dominates above 600-1500MeV/c
- NCγ and flux uncertainties are both significant at 300-500MeV/c
  - NA61, EMPHATIC hadron production exp.
  - e/γ separation using machine learning
    - discussed later

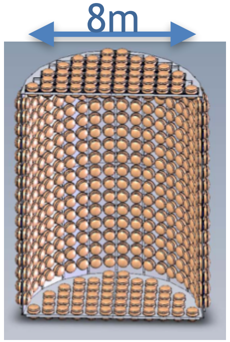


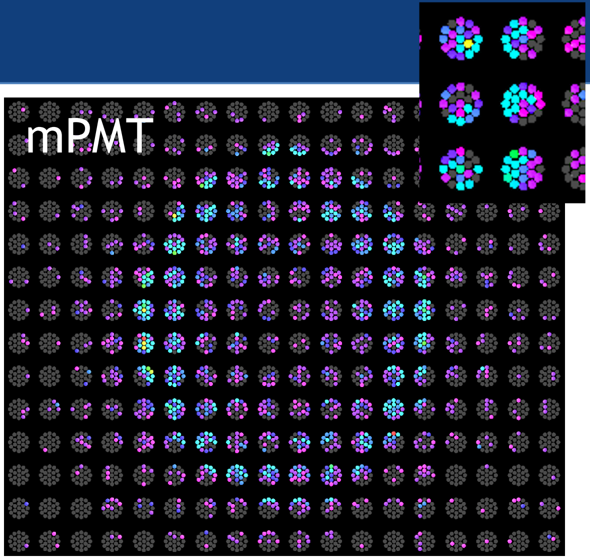
[C] IWCD detector systematics

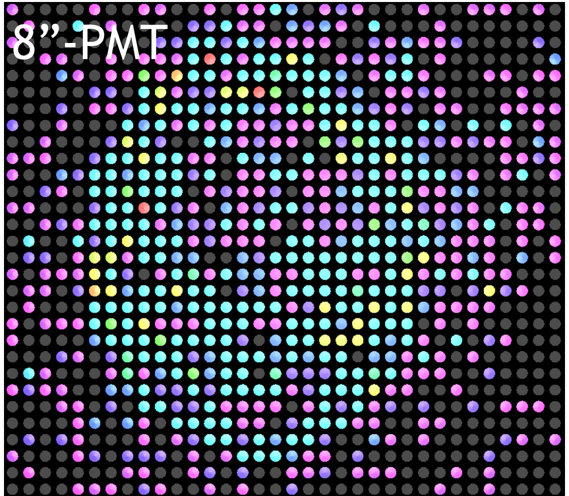
- Challenging experience of the K2K 1kton water Cherenkov
  - More stringent position requirement for small detector
  - Good understanding of the detector (calibration) needed
- Fiducial volume (vertex) systematics
  - 1% uncertainty: $2\Delta R/R=1\% \rightarrow \Delta R=0.5\%R$
    - HK:15cm, IWCD:2cm
  - Finer granularity and better timing are required:
    - HK: 50cm(PMT)/60m=0.8%, TTS(σ)=1.1nsec ~ 20cm
    - IWCD: 7.5cm(PMT)/8m=0.9%, TTS(σ)=0.6nsec ~ 12cm
- Precision calibration
  - Precise position information: Photogrammetry
  - Secondary interactions and other potential problems
    - IWCD test beam experiment

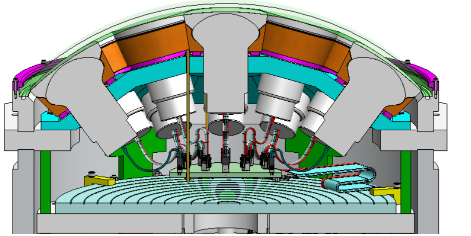




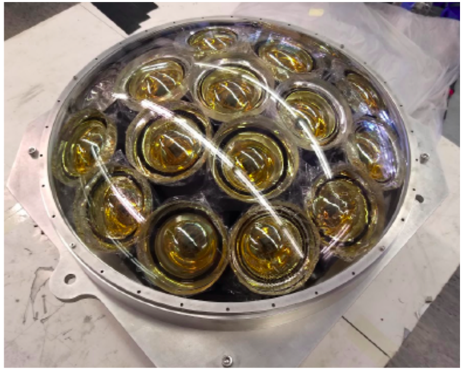


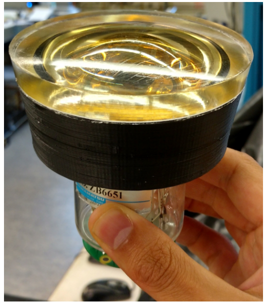


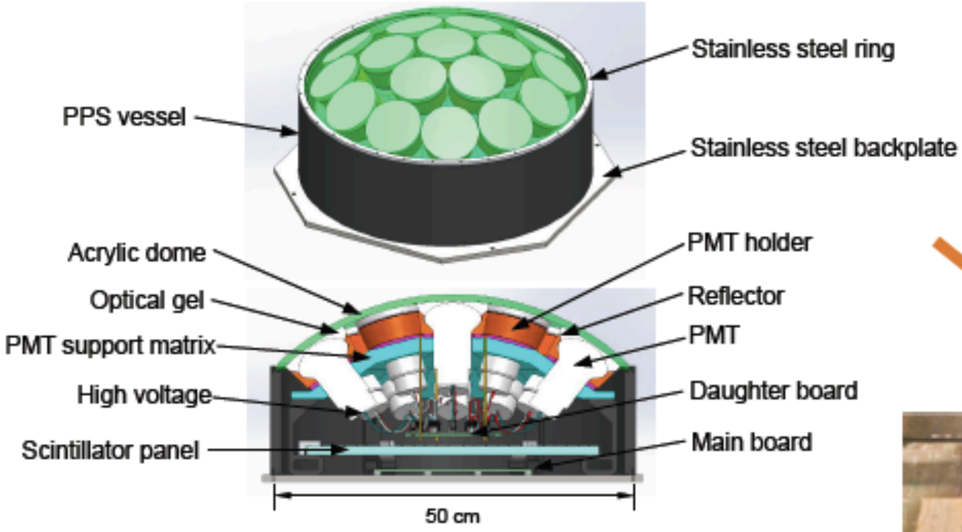




- multi-PMT (mPMT)
  - Concept from KM3NeT
  - 19 of 3" PMT's in a vessel
    - economical 3" PMT's
- mPMT for IWCD
  - finer granularity for small WC
    - also x2 better timing resolution

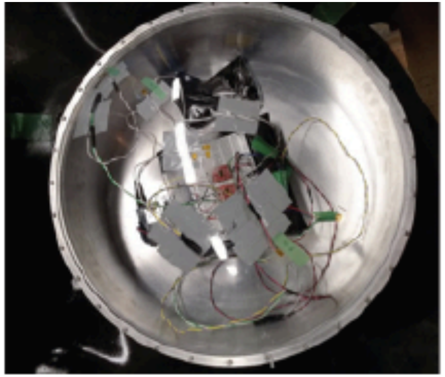




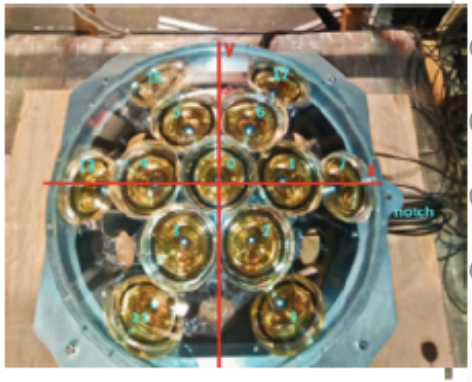


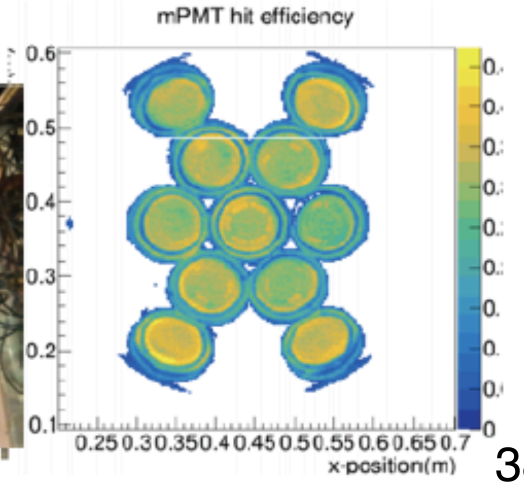
Prototypes

pressure

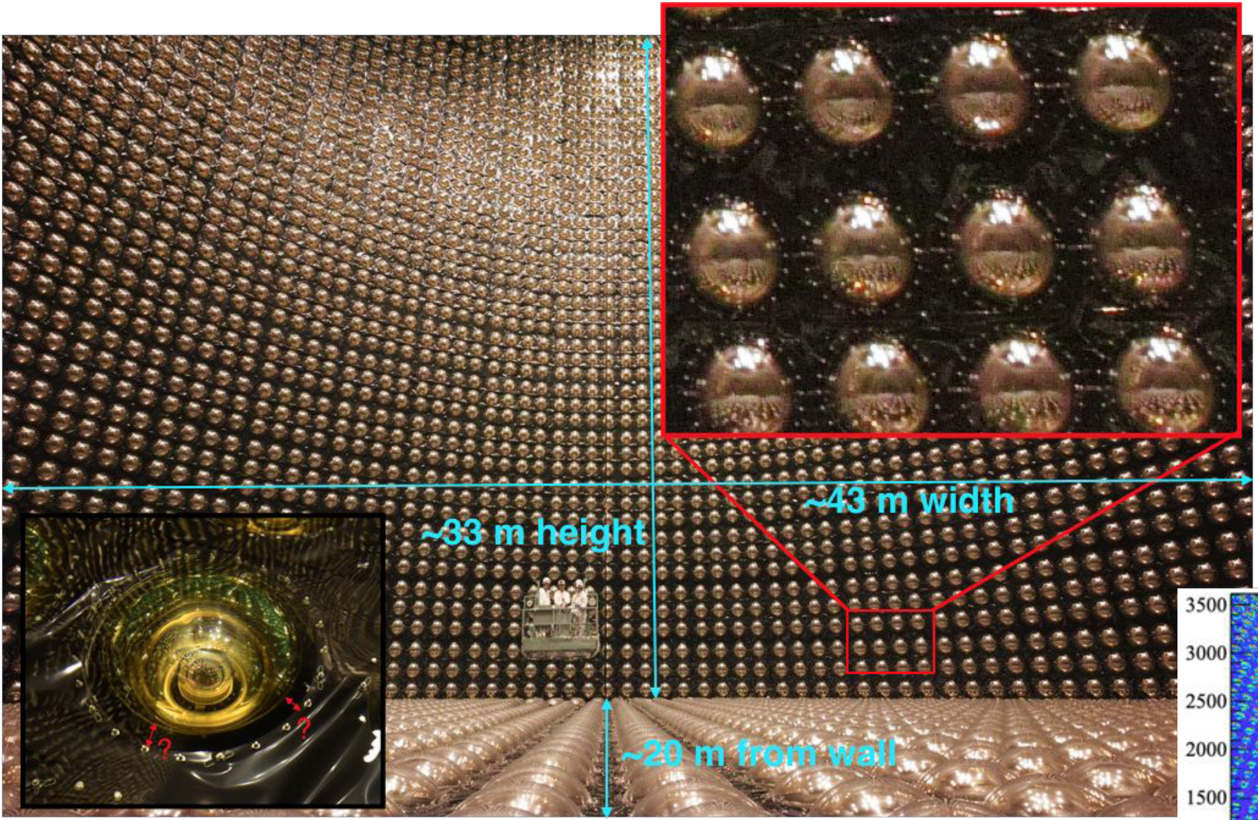


optical

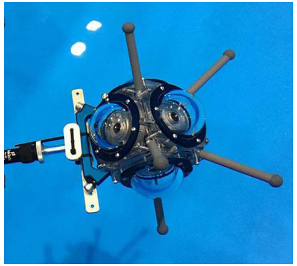


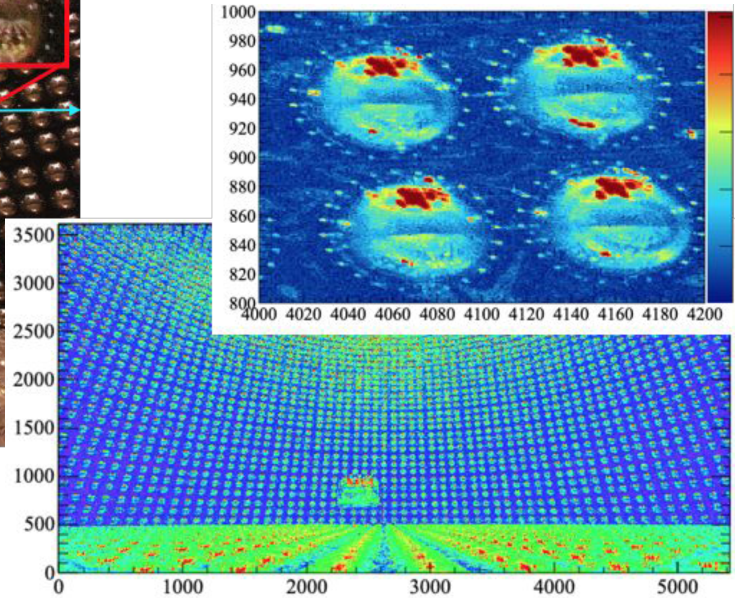


Photogrammetry being considered for SK



360Abyss underwater camera

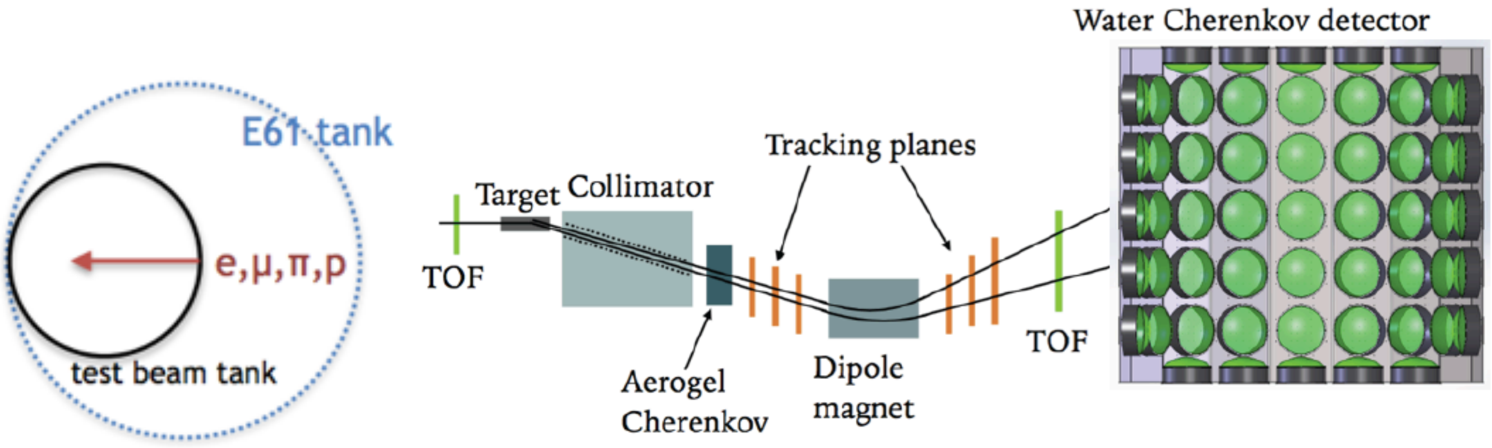


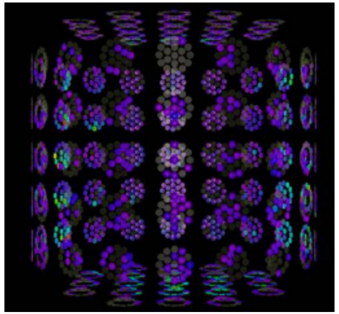


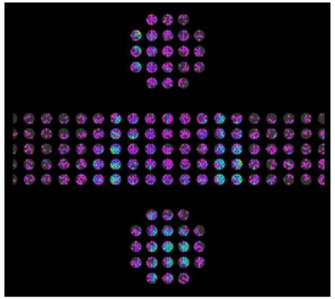
IWCD beam test

Meeting at CERN on July 18-19, 2019

- Precise response of water Cherenkov requires studies
  - backward light mismatch (~10%) in SK: impact on vertex
    - difference observed in delta ray simulation models
  - hadron interactions in water
  - stopping muons: range and charge calibration
- Prototype IWCD detector test at CERN in 2021-22
  - Expected to also Improve T2K and SK results







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HyperK - Canada

MACHINE LEARNING WORKSHOP
APRIL 15-17, 2019

Water Cherenkov Machine Learning

https://mlw.hyperk.ca

WatChMal group

Repositories 4 People 19 Teams 1 Projects 0 Settings

Experts:
K.Terao (SLAC)
W.Fedorko (TRIUMF)

HK members from Canada, Japan, Europe, and US joined

Machine learning for water Cherenkov detectors

The VISPA research centre at the University of Victoria is hosting a workshop on the application of machine learning techniques for water Cherenkov detectors. The workshop will be held on the campus of the University of Victoria from April 15-17, 2019.

The workshop will include tutorials and working sessions using GPU servers to allow participants to gain experience in machine learning techniques. The focus will be on developing techniques to analyze simulated photosensor data from the proposed intermediate and Hyper-Kamiokande water Cherekov detectors. Participation is by invitation only.

The workshop is made possible with support from the University of Victoria Office of the Vice-President Research.

University of Victoria | Victoria Subatomic Physics & Accelerator Research Centre

Pilot project of TRIUMF Data Science group

- Water Cherenkov event reconstruction
  - Machine Learning
    - Convolutional Neural Network
  - Forcing NN to be insensitive to Data/MC differences (Systematics)
    - Adversarial Neural Network
- Part of Helmholtz-TRIUMF Data Science Collaoboration

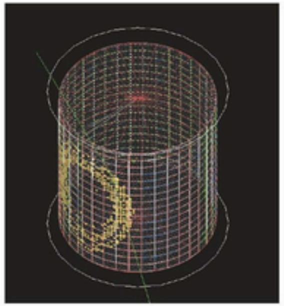
Data Science and Quantum Computing

Pilot Projects

TRIUMF has established a program in Data Science and Quantum Computing in order to enchance it's scientific impact, utilizing it's national network, international collaborations and industry contacts. Several pilot projects, where applications of Machine Learning could have a major impact have been identified to kick start this activity.

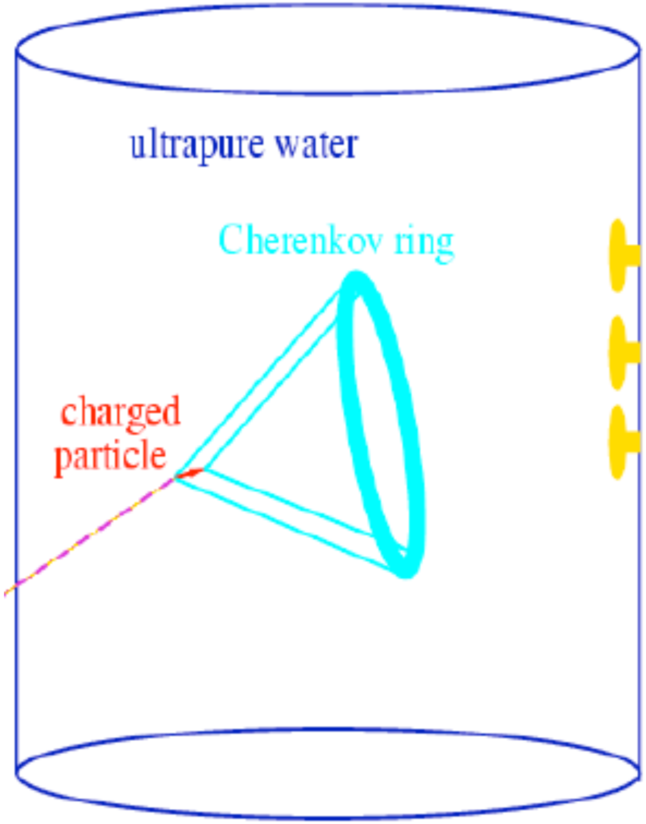
Event Reconstruction in Water Cherenkov Detectors for the Hyper-Kamiokande Project

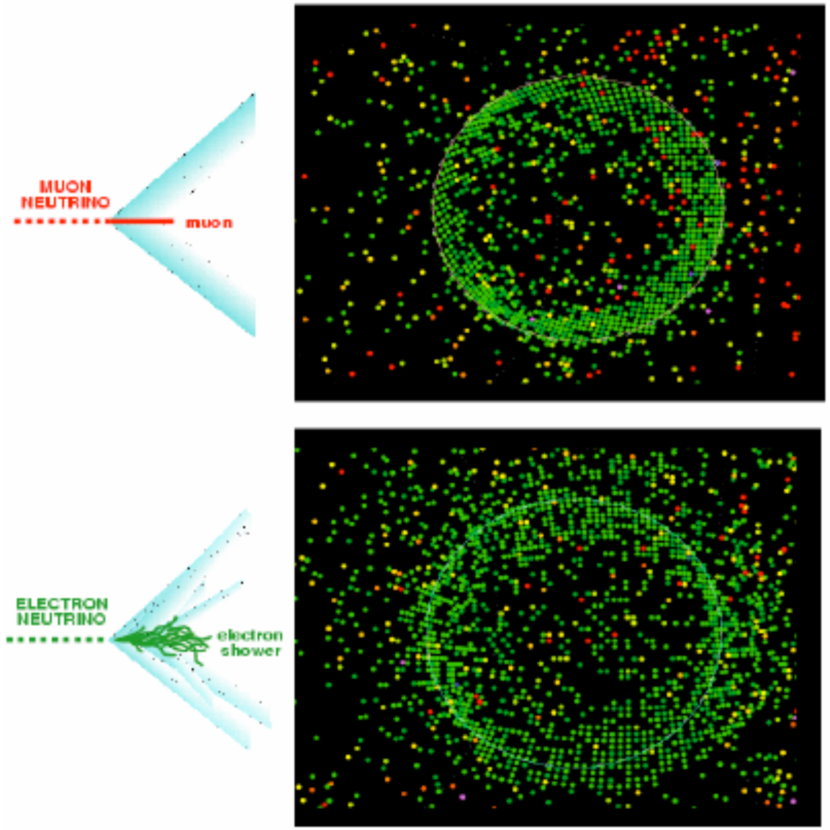
The Hyper-Kamiokande experiment is set to begin operations in the middle of next decade. One of the major science goals of this experiment is to measure the CP violating phase in the neutrino sector. Precise knowledge of this parameter can tell us if neutrinos are responsible for the matter-antimatter asymmetry observed in the Universe. One of the major systematic uncertainties limiting this measurement stems from the unknown rate of neutrino interactions producing gamma backgrounds to the main electron neutrino signal. The goal of this project is to develop deep learning techniques for particle identification and multi-ring event reconstruction in a water Cherenkov detector. It will focus on simulations of Hyper-K detectors including NuPRISM - a major TRIUMF initiative. The project will explore accepted supervised training



hyper-K event display

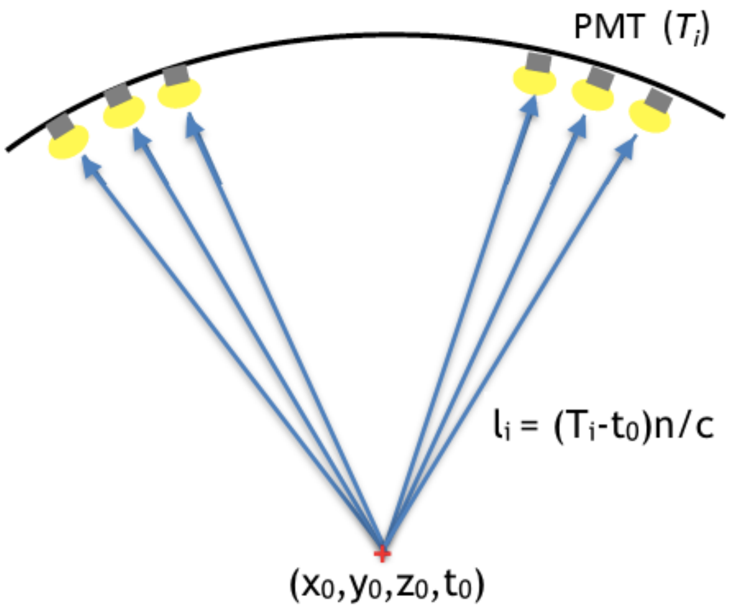
Cherenkov light detection

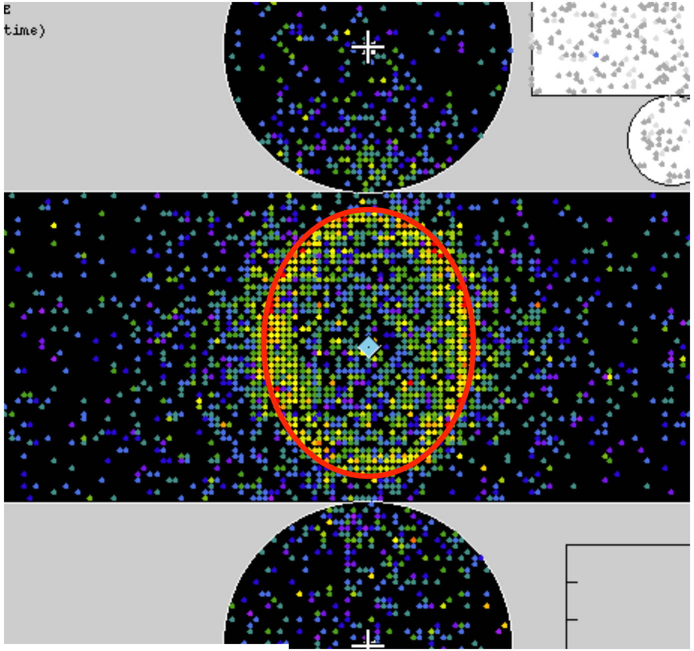


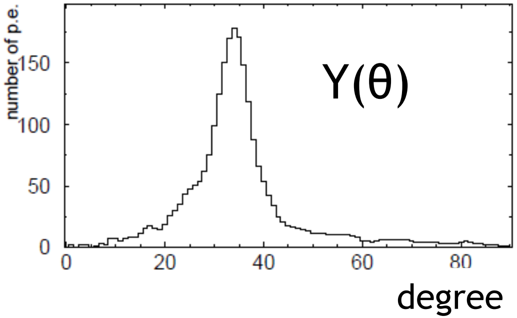


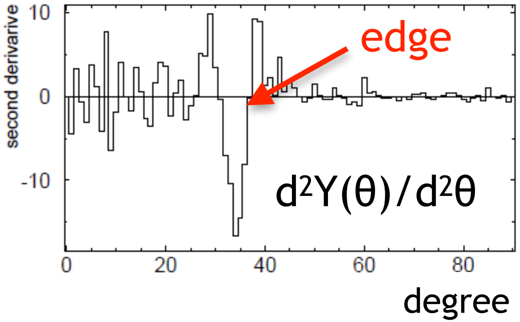
Initial event reconstruction of SuperK

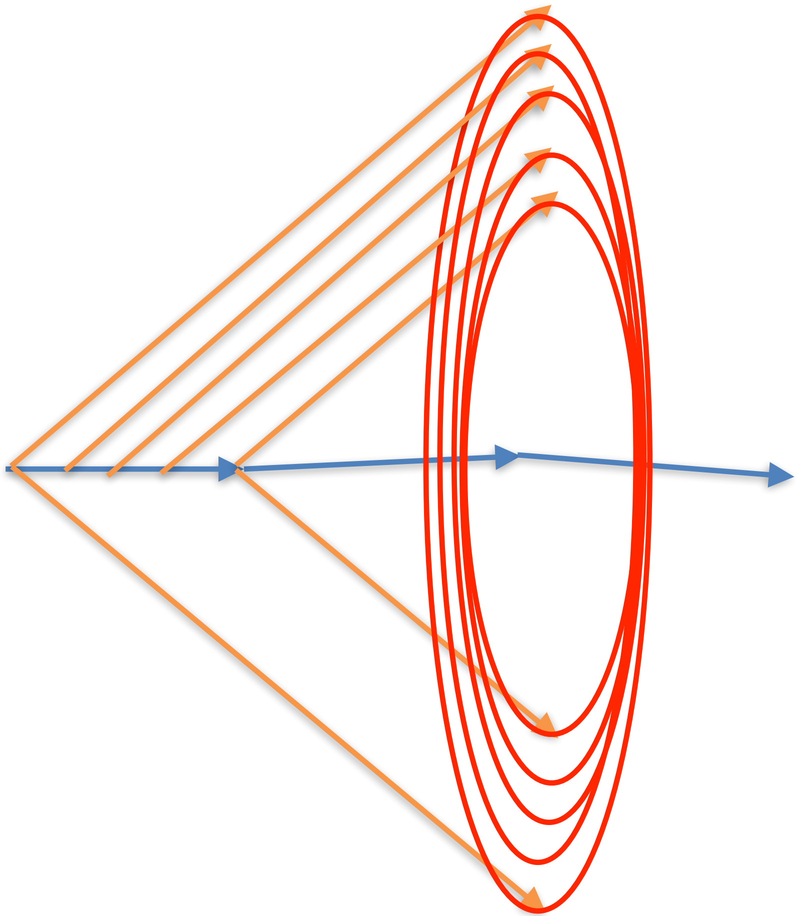
Triangulation to find the vertex

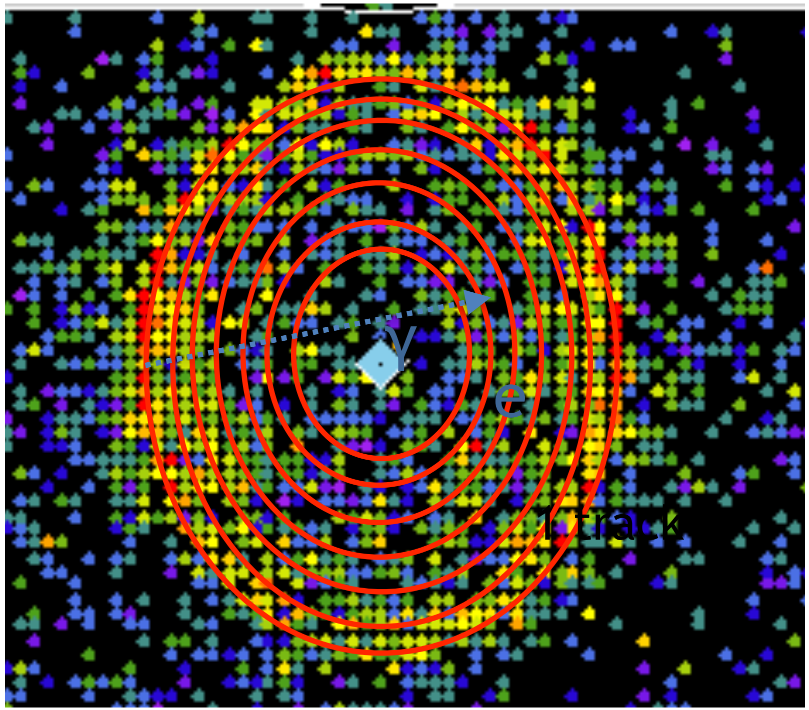






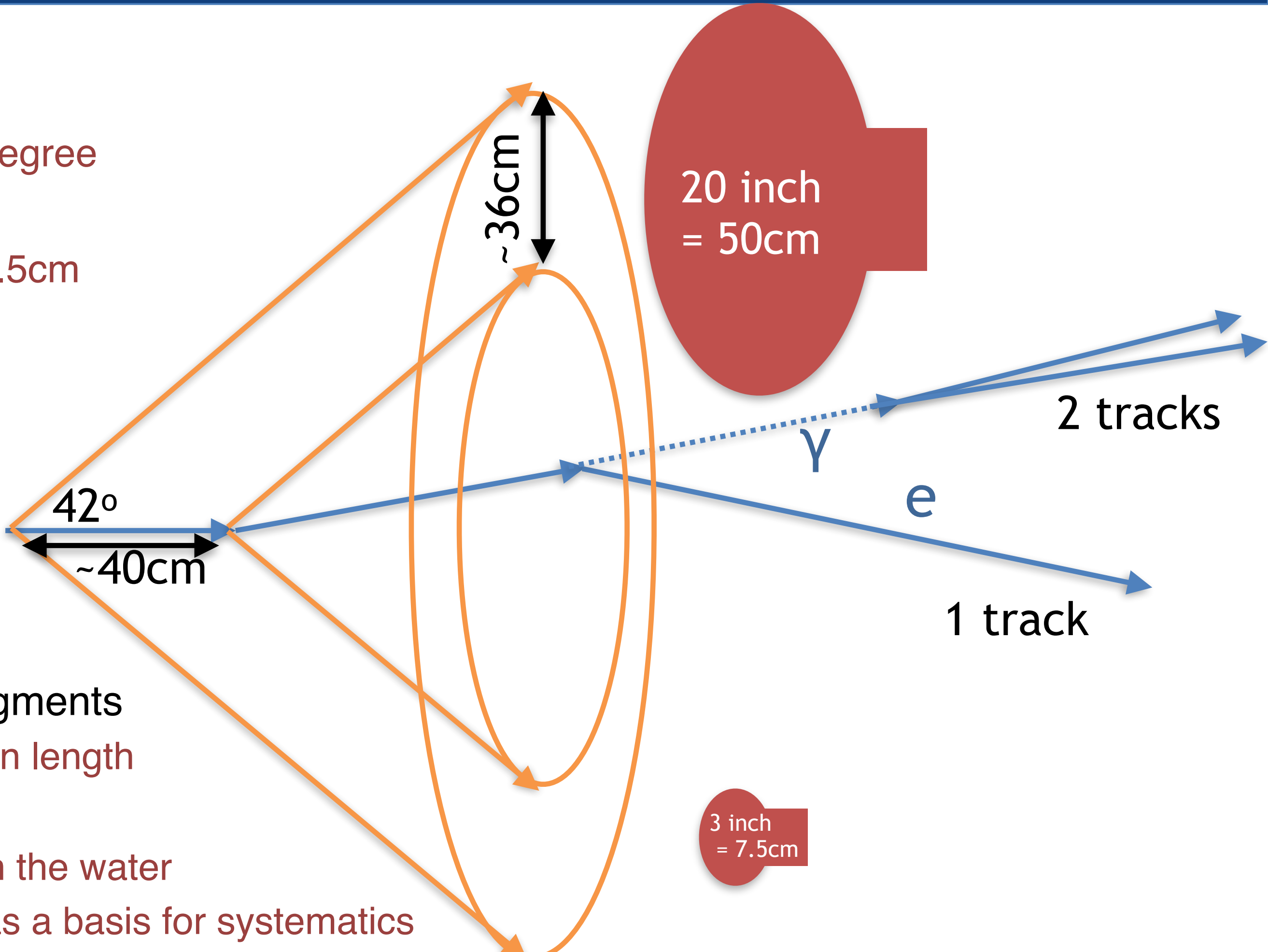





γ
e
1 track

Reconstruction of the track elements?

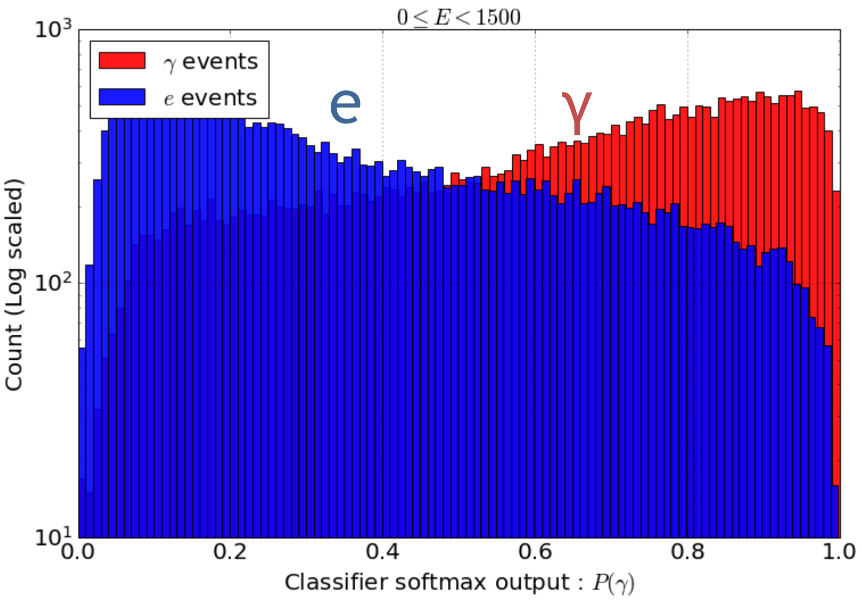
- Water
  - index: n=1.33, θ(β=1) ~ 42degree
  - radiation length ~ 36cm
  - nuclear collision length ~ 58.5cm

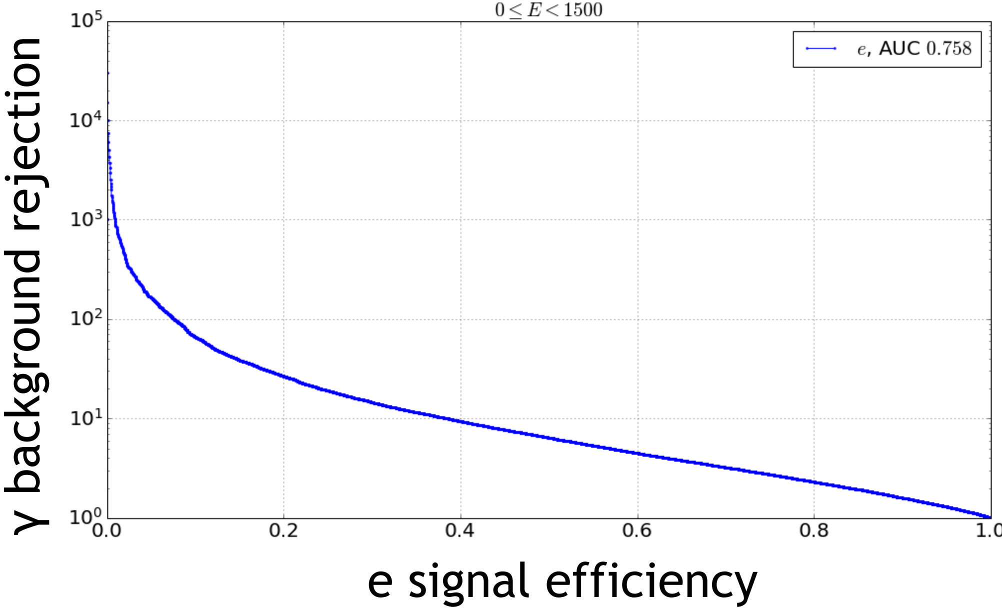


- Optical TPC:
  mPMT to catch each track segments
  - Finer granularity than radiation length
  - e/γ separation
  - identification of π scattering in the water
  - track elements can be used as a basis for systematics

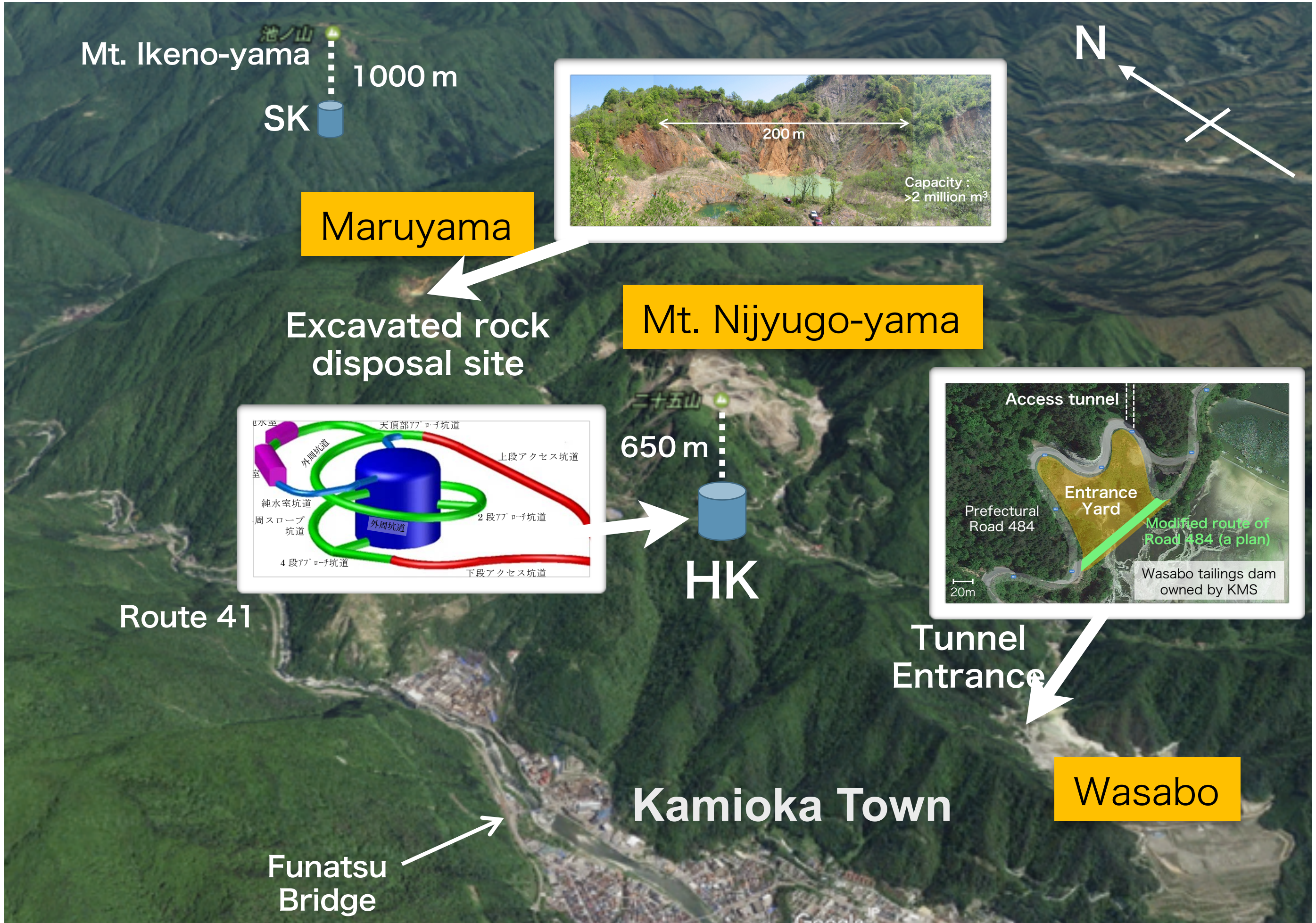
Preliminary study of electron/γ separation

- Initial look shows significant e/γ separation for IWCD MC
  - Convolutional Neural Network on e/γ/μ Monte Carlo samples





Status of Hyper-K



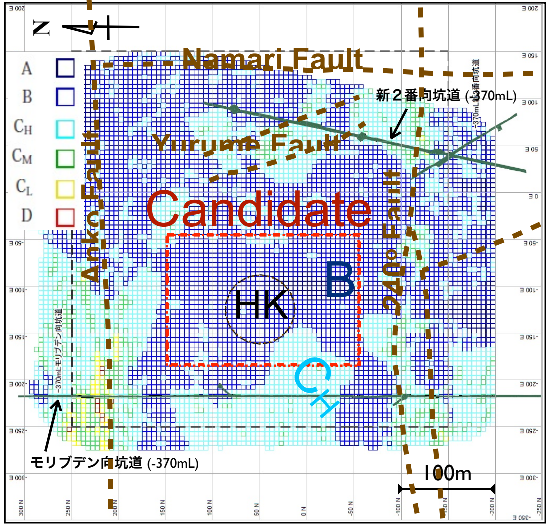
✓ Identified the candidate position with excellent rock without any discontinuities

✓By 3-dimensional seismic tomography and seismic reflection imaging

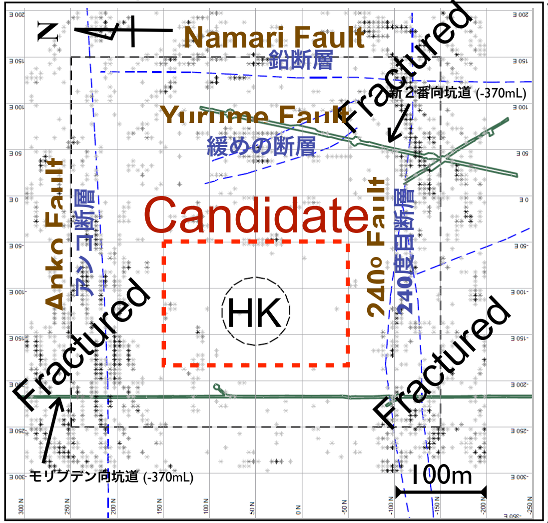
✓ Preparation for access tunnel excavation is going on

✓Environmental assess, Negotiations w/ local governments, electric company, mine company

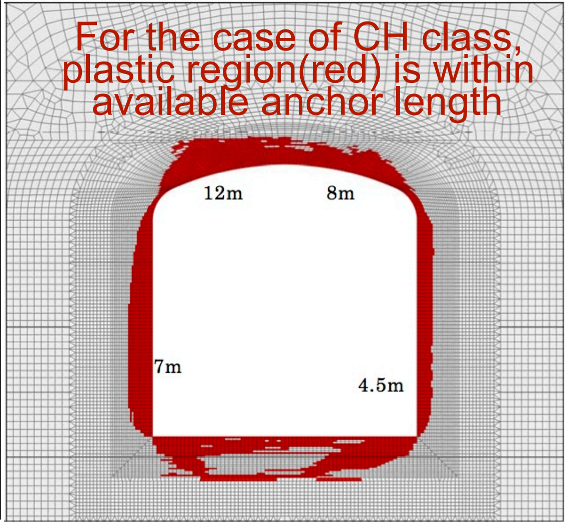
3D rock-class map



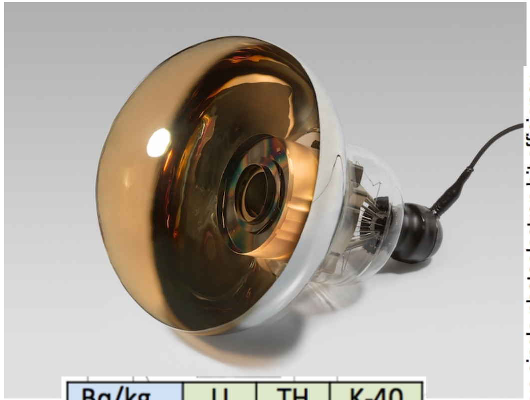
Geological discontinuities



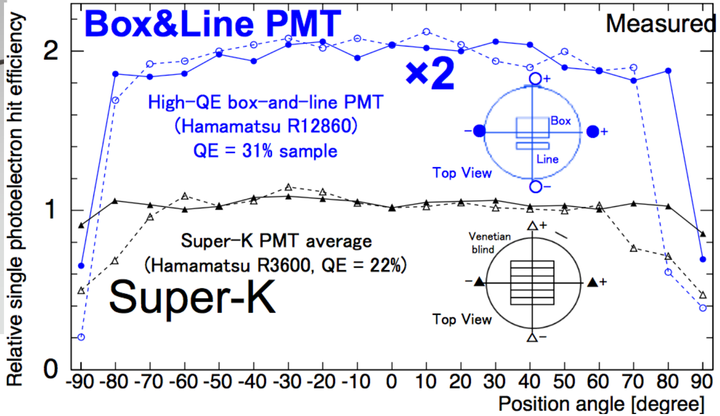
Cavern stability analysis

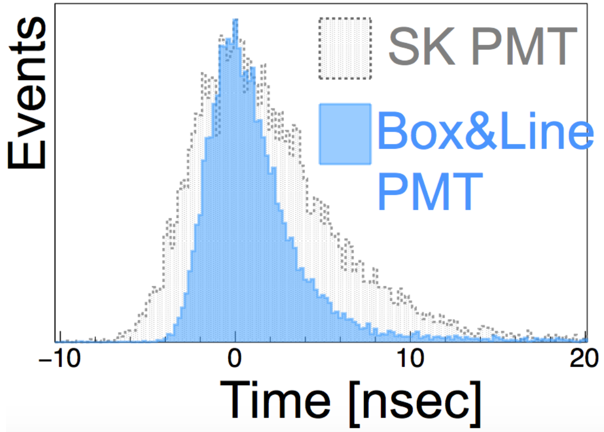


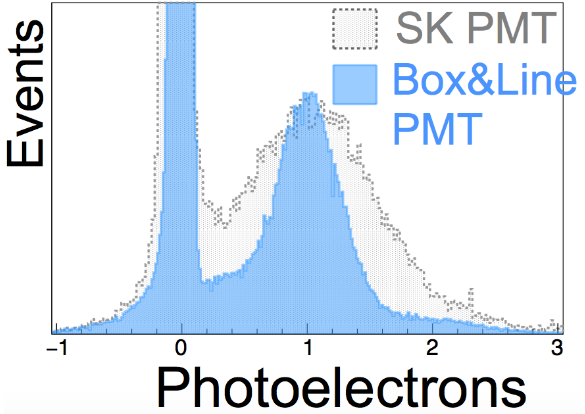
HK photosensor development



Bq/kg	U	TH	K-40
20” HK	5.4	1.8	1.6
20” SK	5.5	1.8	18.2



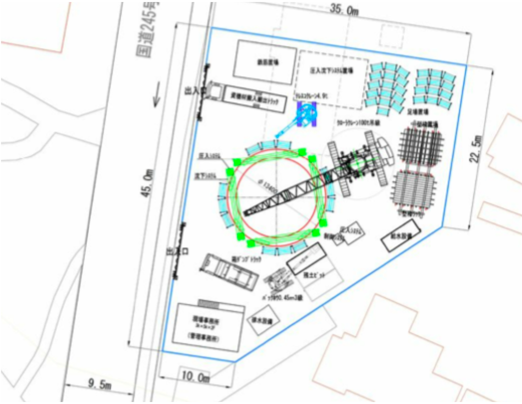


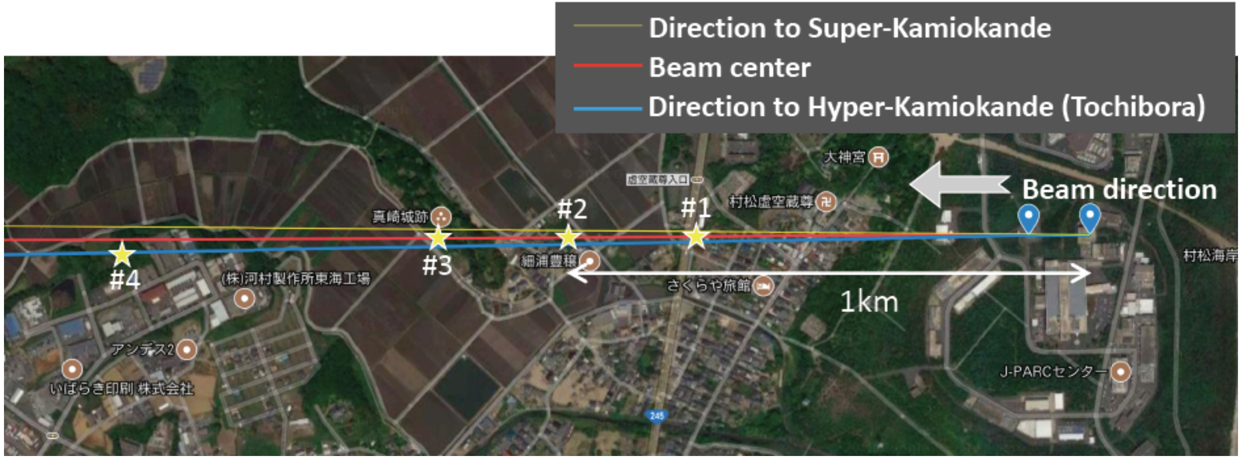


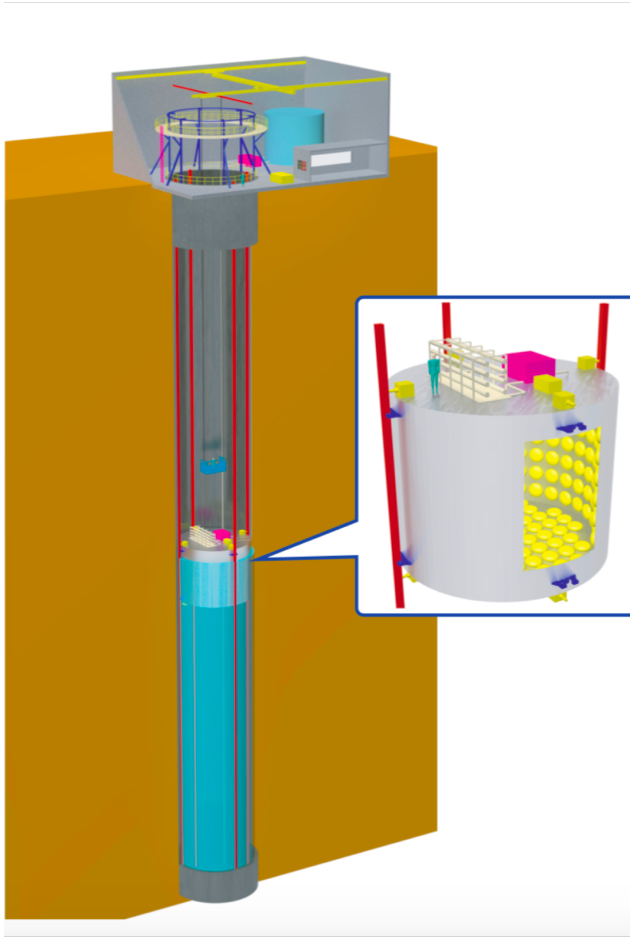
- New Hamamatsu 20” Box&Line PMT
  - x2 better photon detection efficiency
  - x2 better transit time spread
  - x2 better single photoelectron resolution
  - better pressure resistance for 80m water depth
  - Reduced radioactivities
  - Mass production on-going for JUNO project
  - Dark rate of 6kHz, and getting reduced

IWCD design

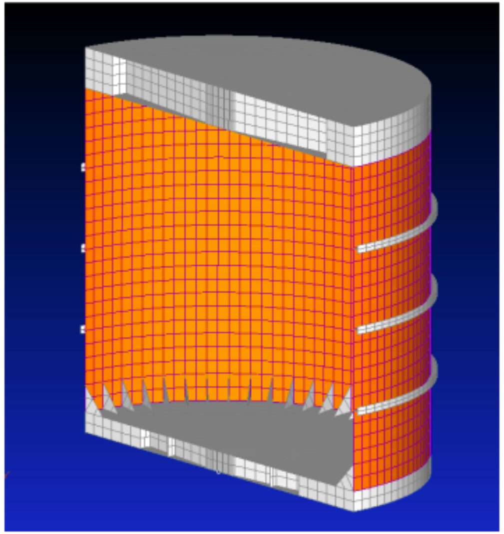
IWCD site study on-going for the FY2020 funding request by KEK

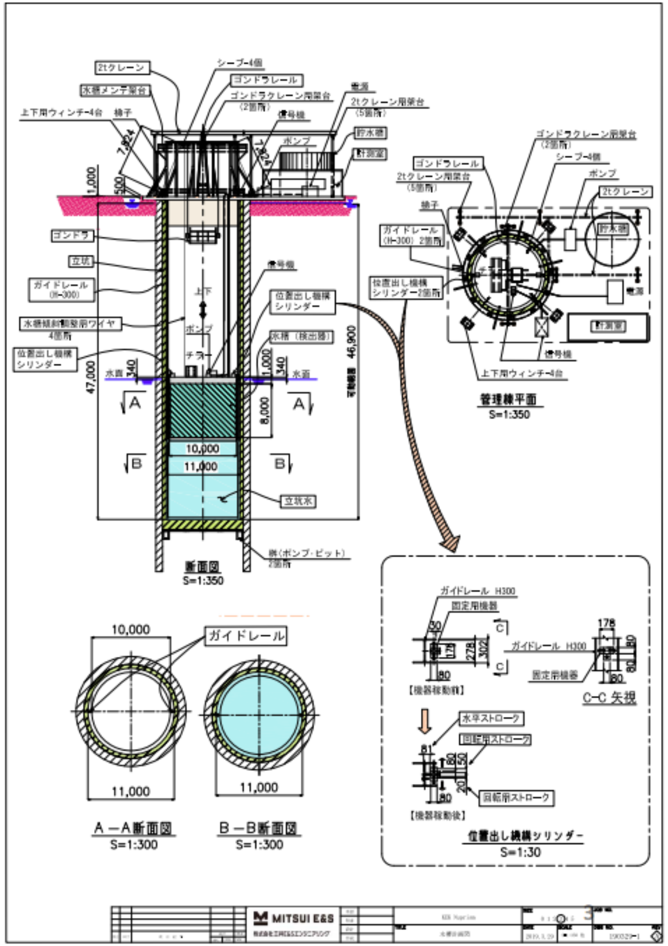






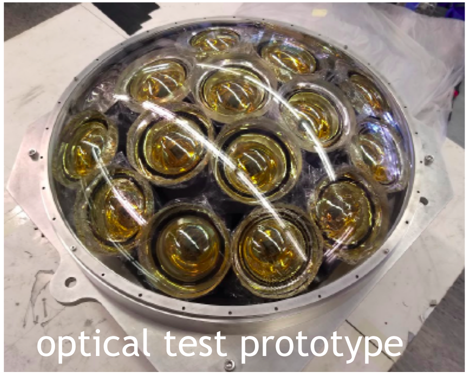
Progress in IWCD facility design

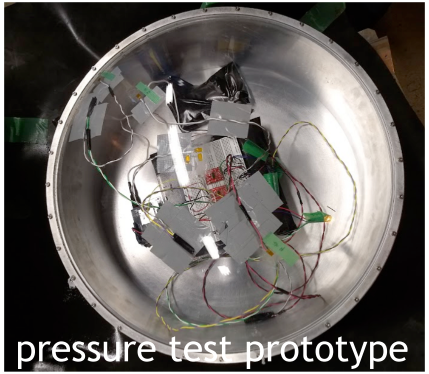




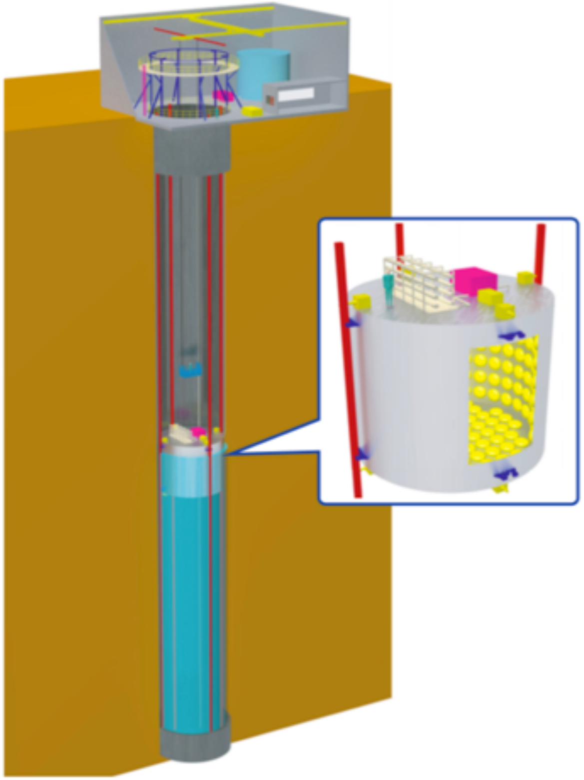
- control vertical position of tank by buoyancy
  - adjust the tilt by wires
  - fix rotation by guide rails
- IWCD facility will be requested by KEK in June

Prototype module being constructed and tested

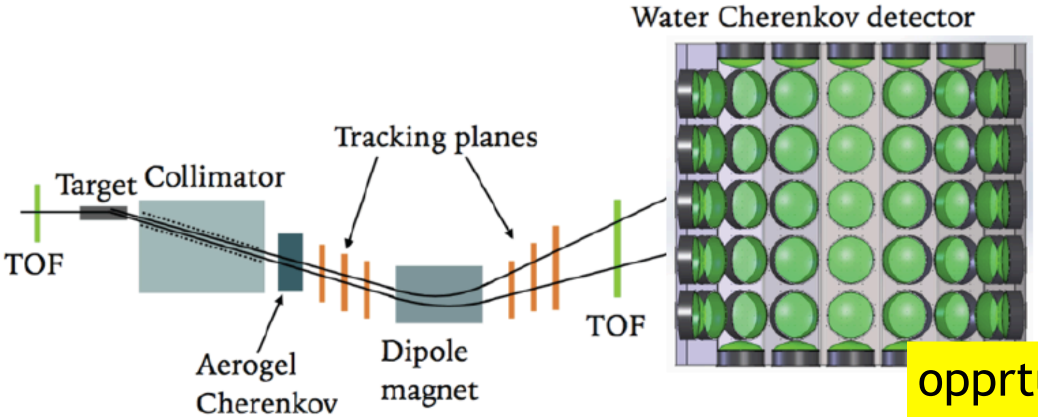




IWCD/NuPRISM run in 2026



Prototype beam test 2021-2022 (at CERN)



opprtunity for International contributions

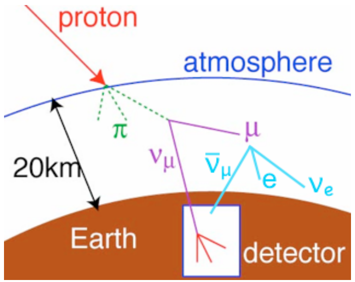
- Event reconstruction in track segements for HyperK (Optical TPC)
  - 5k-10k mPMT will provide granularity required to identify the track segments
  - Systemtic uncertaintis studies by data/MC comparison (Adversarial NN)

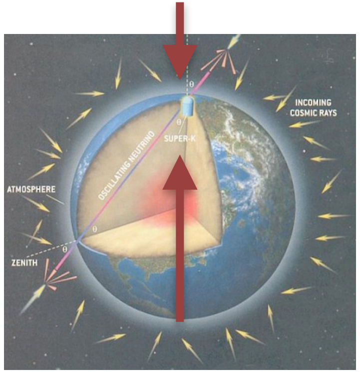
- e/γ separation
  - mPMT: fine granularity and good timing
  - directly measure NCγ to address theoretical uncertainty in ν_e appearance
    - major uncertainty of the miniBooNE anomaly

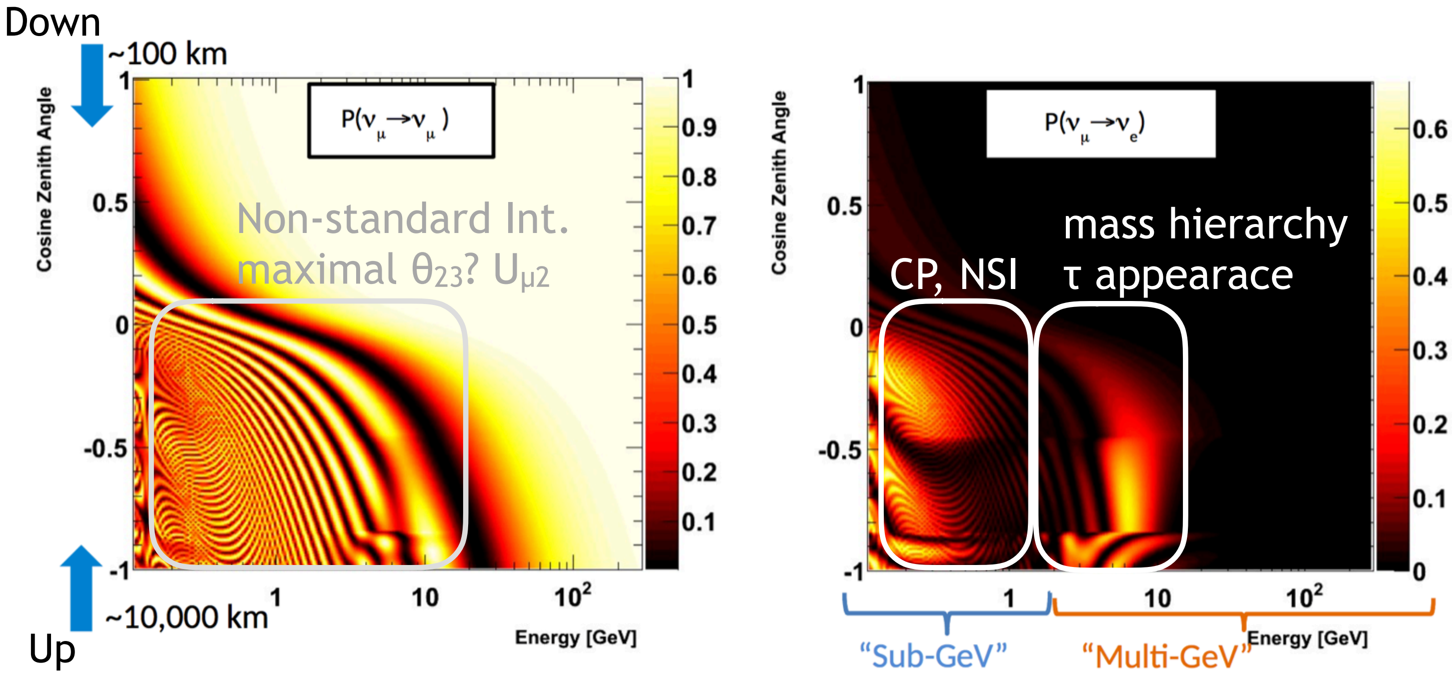
- Improvement in multi-ring event reconstruction: direction and energy
  - mPMT: finer granularity
  - CP, mass hierarchy, ν_τ appearance, ν astronomy and dark matter search
    - $CC1\pi^{+/-/0}$ samples for long baseline and atmospheric neutrinos

Opportunity for International contributions

Atmospheric neutrino oscillations

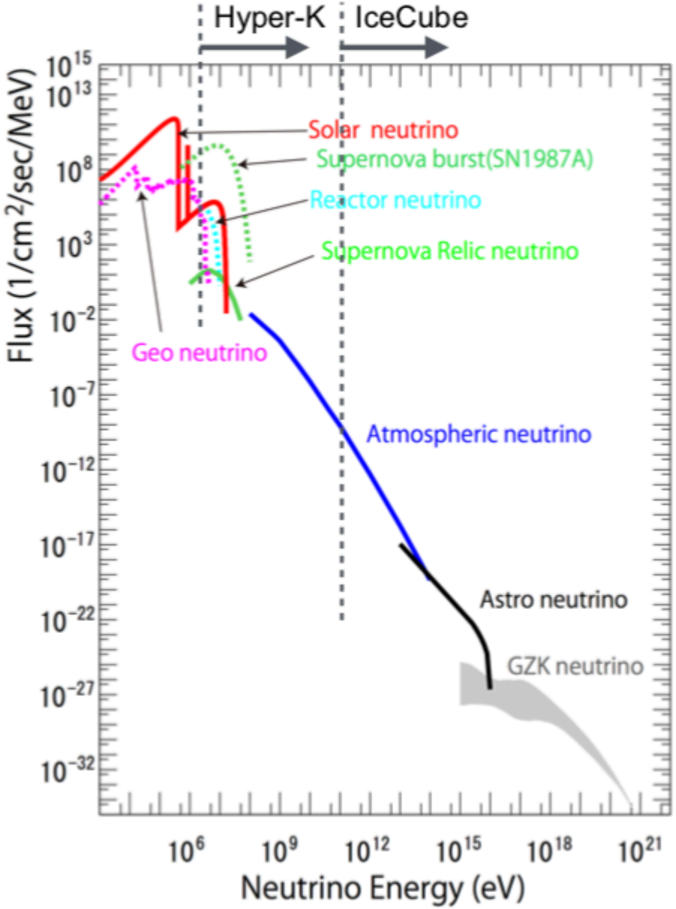




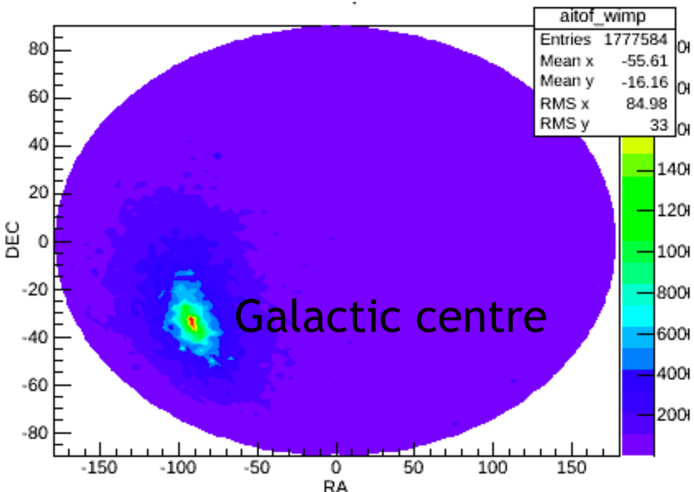


- Wide phase space of interesting neutrino oscillation patterns will be studied by HyperK
  - excellent place to search for new oscillation physics effects
    - IWCD to constrain the neutrino cross section
  - mPMT and machine learning event reconstruction to get better energy/angular reconstruction

Astrophysical neutrinos



- Astrphysical MeV-TeV ν
  - Supernova and solar neutrinos
  - WIMP annihilation in galactic centre, Sun, Earth
  - Gamma-Ray Burster Jets
- Backgrounds: atmospheric neutrinos
  - Directionality to point the source



Summary

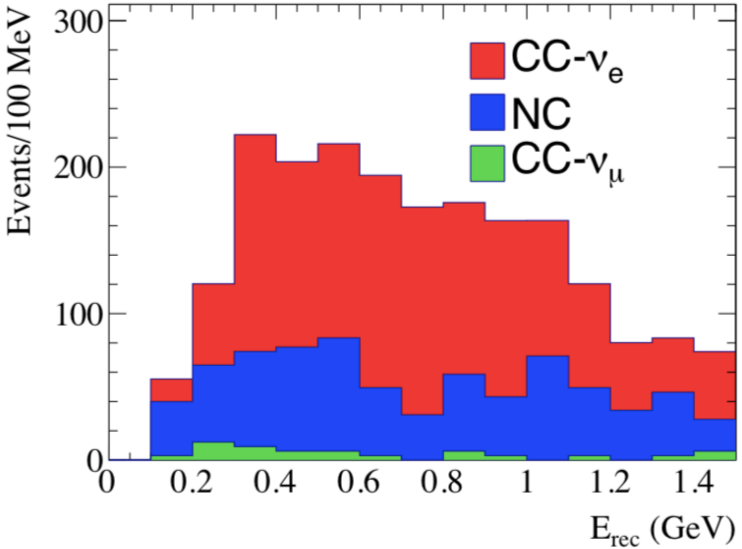
- Systematic uncertainty limits CP violation sensitivity in neutrino oscillation
  - CP effect [~$\sin\theta_{13}$] / $P(\nu_\mu \rightarrow \nu_e)$ [~$\sin^2\theta_{13}$] ~ $1/\sin\theta_{13}$
    - Large θ_{13} requires good systematic error control for CP violation discovery
  - Nuclear effects in neutrino cross sections causes serious challenge
    - interference of multi-body current and nuclear dynamics
- Far/Near cancellation provides a way to control the systematic uncertainties
  - T2K systematic uncertainty is 8.8%, larger than the HK statistical error of 3%
    - spectral difference in flux between near and far: IWCD to match the spectrum
    - cross section difference between ν_μ and ν_e : IWCD ν_e/ν_μ cross section ratio
    - detection efficiency between near and far: calibration, IWCD prototype beam test
  - Fine granularity of mPMT with Machine Learning may open the way for precise reconstruction (optical TPC) and to evaluate the systematic uncertainties
- Univ. Tokyo President pledges to start HyperK construction from April 2020
  - Full HyperK funding proposal is being evaluated by MEXT for approval this summer
  - Excellent opportunity and timing for international community to take a leading role

- Back up

Systematic uncertainty on Backgrounds

	signal		BG						Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode Events	1643	15	7	0	248	11	134	400	2058
$\bar{\nu}$ mode Events	206	1183	2	2	101	216	196	517	1906

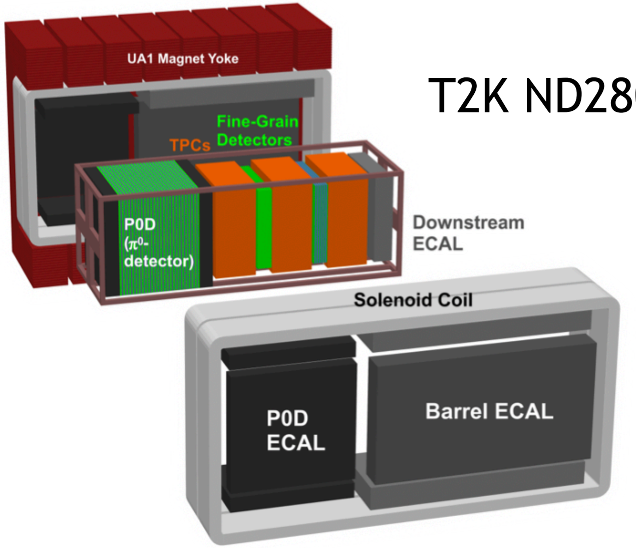
- Backgrounds measured by IWCD at 2.5 degree
  - beam ν_e and NC backgrounds are the same for HK and IWCD



Systematic uncertainty in Backgrounds

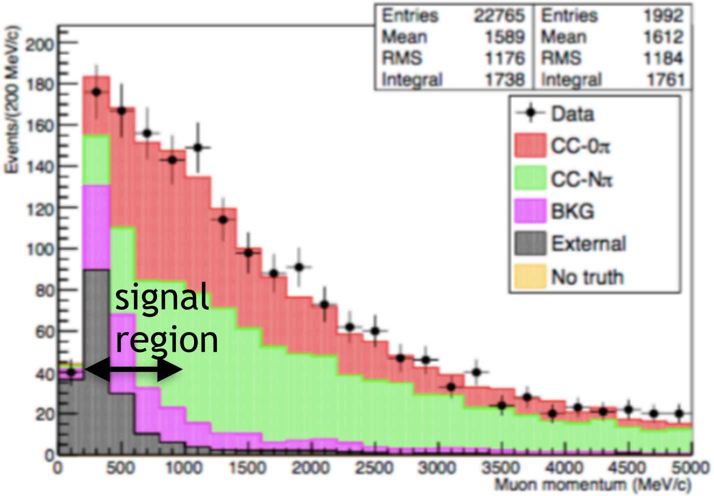
	signal		BG						Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode Events	1643	15	7	0	248	11	134	400	2058
$\bar{\nu}$ mode Events	206	1183	2	2	101	216	196	517	1906

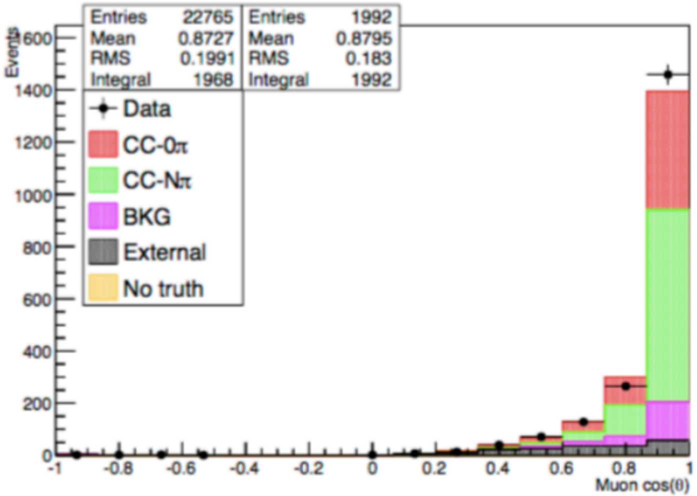
- Oscillated wrong sign background
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ in ν mode and $\nu_\mu \to \nu_e$ in $\bar{\nu}$ mode
  - Impact on $\bar{\nu}$ mode due to $\sigma(\nu) > \sigma(\bar{\nu})$
- Constraining the wrong sign BG
  - **Magnetized near detector (ND280)** needed along with the beam flux study



T2K ND280

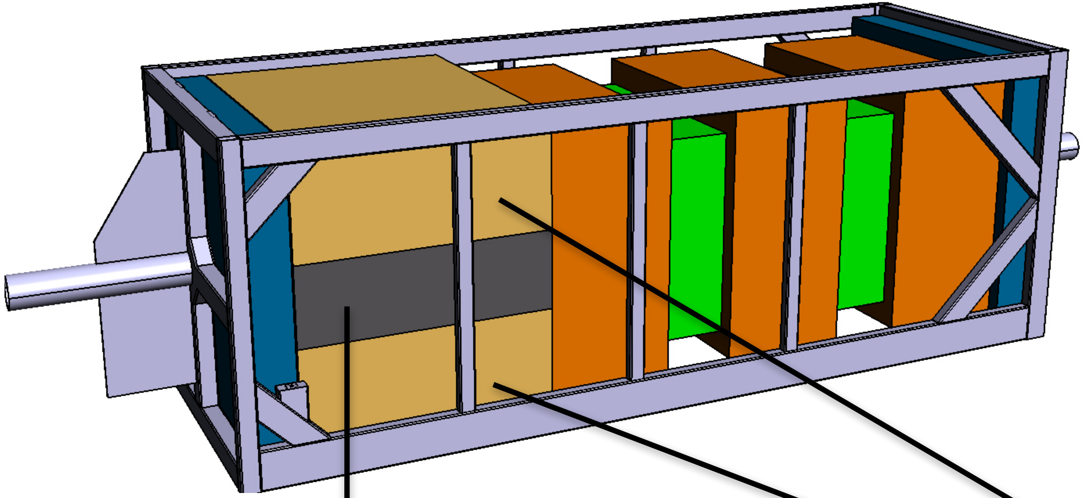
Wrong sign background study by T2K ND280

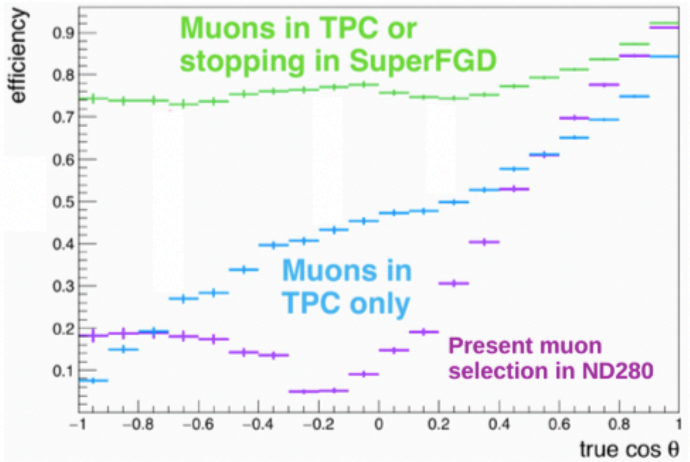


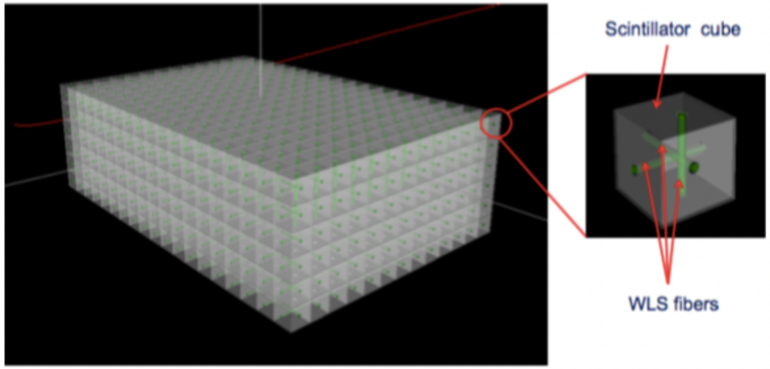


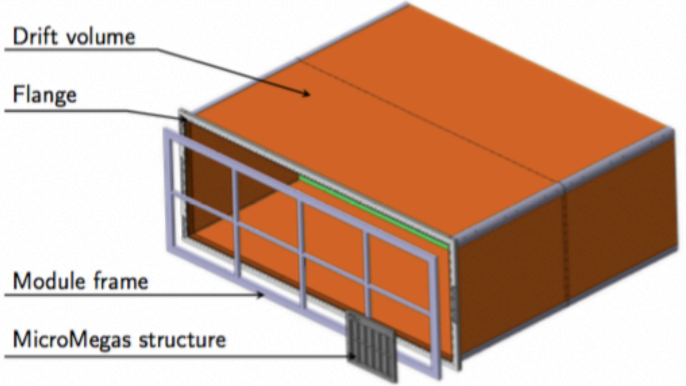
- Systematic error requirement for wrong sign component: 9% or less
- Significant background in the signal region
  - Background from π-
    - π-/μ- separation needed: active detector in the stopping region
  - External background with confusion in the μ direction
    - Time of flight detector will be added in the ND280 upgrade around TPC

T2K ND280 upgrade



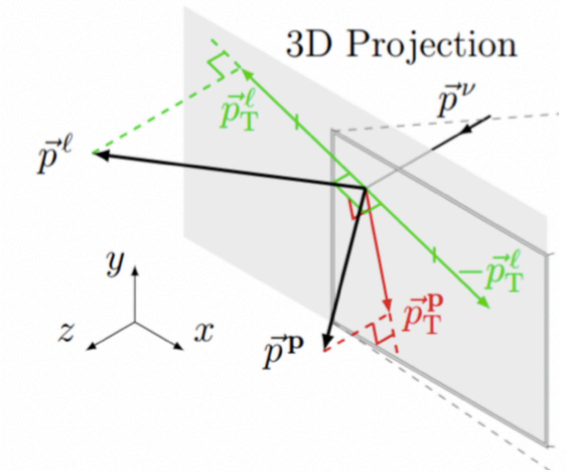


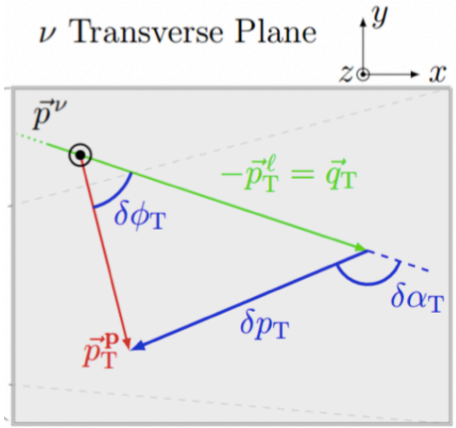




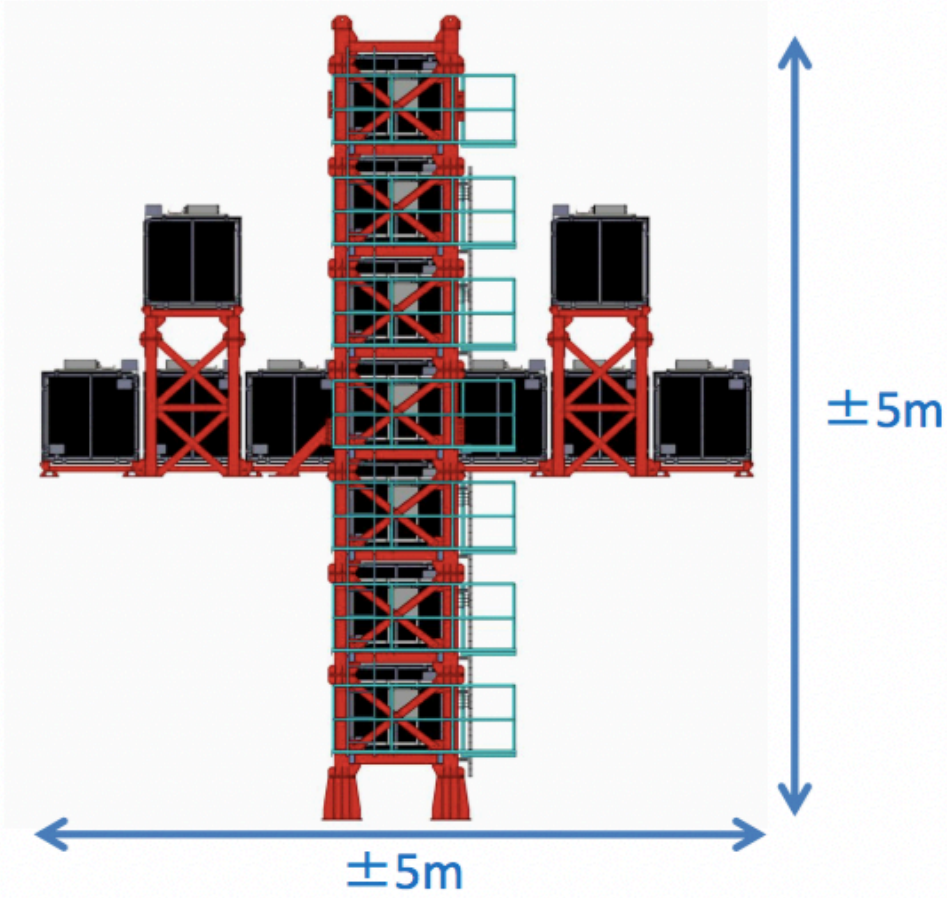
Hadronic information in ND280

- Additional ν cross section information from hadrons
  - Similar to fluorescence in X-ray/neutron scatterings
- Challenges for precision measurement
  - Convolution of dynamical effects such as FSI and 2p-2h
  - Initial ν energy is not known
- Ideas to extract information by ND280 upgrade
  - transverse variables (momentum conservation)
    - momentum balance in the transverse direction
      - momentum carried out by nucleus (p=2Mβ)?
  - calorimetric ν energy reconstruction (energy conservation)
    - total energy of CC event provides the neutrino energy
      - neutron energy measurement, in particular for $\overline{\nu}$?
  - It is important to study of this option in more detail.





INGRID detector for beam direction



- Fine grained steel and scintillator
  - higher ν energy = cross section at centre
  - higher flux at centre
- Requirement:
  - σ<0.6mrad (4MeV shift)
  - σ<0.3mrad (2MeV shift) already achieved for T2K

Summary of systematics requirements and sensitivities

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_e)/\sigma(\nu_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	3.5-5%
$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	3-5%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$, θ_{23} precision at $\sin(\theta_{23})\sim0.5$	IWCD	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	ND280	TBD (expect <9%)
Intrinsic ν_e,$\bar{\nu}_e$ and NC backgrounds	3-4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	IWCD	2.3% (neutrino)
Normalization of non-QE with E_ν>0.7 GeV	5%	θ_{23} precision at $\sin(\theta_{23})\neq0.5$	IWCD	5% (neutrino)
Normalization of non-QE with all energies	5%	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	IWCD, ND280*	5% (IWCD neutrino) <4% (N280 neutrino) <7% (ND280 antineutrino)

Summary of systematics requirements and sensitivities

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
Beam Direction	0.6 mrad (4 MeV shift)	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	INGRID	<0.3 mrad (<2 MeV)
Removal (binding) energy	4 MeV*	δ_{cp} precision at $\sin(\delta_{cp})\sim0$ Δm^2_{32} precision	IWCD, ND280	2.6 MeV (IWCD on O) ~1 MeV (ND280 on C)**
High angle measurement ($\cos\theta<0.2$)	4%	CP Violation, δ_{cp} precision at $\sin(\delta_{cp})\sim0$	IWCD, ND280	<4% statistical precision in both detectors
Beam rate monitoring	~1% per day	General monitoring of beam quality	INGRID	<0.5% per day for neutrinos and antineutrinos
Neutron Multiplicity	TBD	Atmospheric neutrino Nucleon decay	IWCD, ND280	<5% IWCD <4% ND280
$\mu\pi^0$ cross section & neutron multiplicity	TBD	$e\pi^0$ proton decay	IWCD	TBD