The Intermediate Water Cherenkov Detector for Hyper-Kamiokande

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on behalf of the Hyper-Kamiokande Collaboration

WNPPC, BANFF
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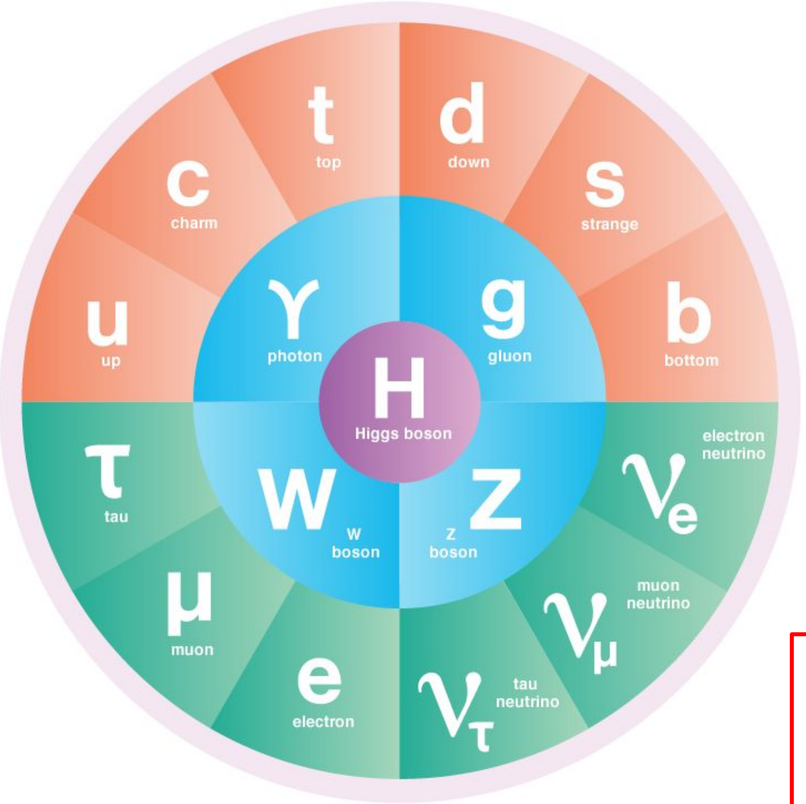
Outline

- Neutrinos
- Hyper-Kamiokande experiment
- Intermediate Water Cherenkov Detector (IWCD)

Standard model and neutrinos



$$\mathcal{L}_{mass} = \frac{g_f v}{\sqrt{2}}(\bar{f}_L f_R + \bar{f}_R f_L)$$

- Neutrinos are neutral, weakly interacting particles
- Three flavors ➔ electron, muon and tau neutrinos
- **Only left-handed neutrinos and right-handed antineutrinos are created in SM processes ➔ massless particles**

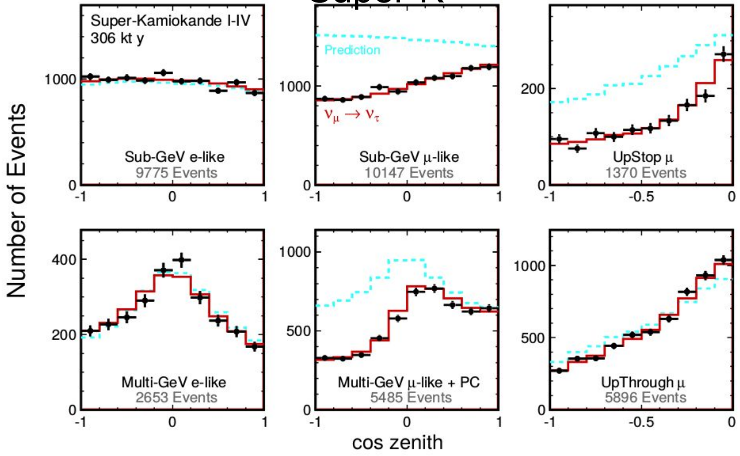
- Missing neutrinos ➔ solar neutrino puzzle and atmospheric neutrino problem

Neutrinos oscillations

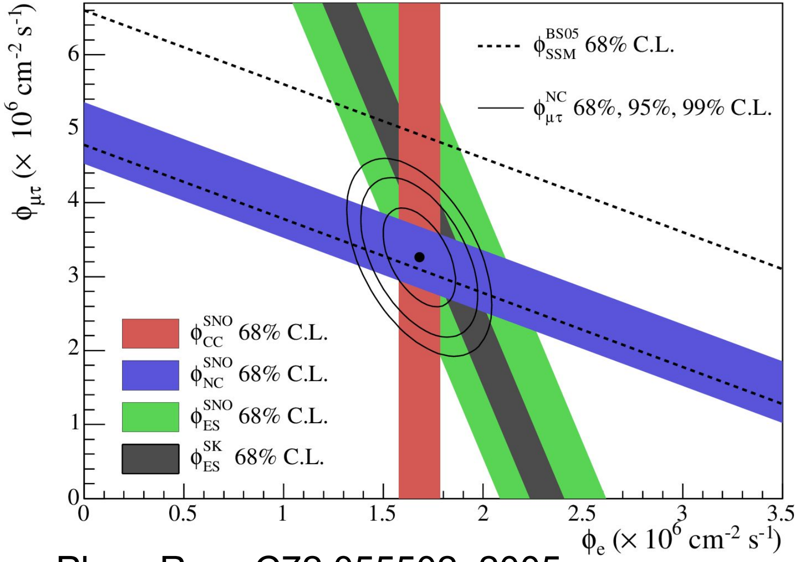
2015. T. Kajita and A.B. McDonald

- Solar neutrino puzzle and atmospheric neutrino problem (solved by SK and SNO)
- Flavor states are not mass eigenstates→ neutrinos have non-zero mass → oscillations (proposed by B. Pontecorvo)

Super-K



Phys. Rev., D71:112005, 2005



Phys. Rev., C72:055502, 2005.

Neutrino oscillations

- Flavor states are not mass eigenstates ➜ linear combination of mass states
- After propagation, relative phase between ν_i changes

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

- For 2 neutrinos

squared mass difference

$$m_2^2 - m_1^2$$

mixing angle

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \cdot \Delta m^2_{21} [eV^2] \frac{L[km]}{E[GeV]}\right)$$

Neutrino oscillations

- For 3 neutrinos ➔ Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Solar neutrinos" "Atmospheric neutrinos"

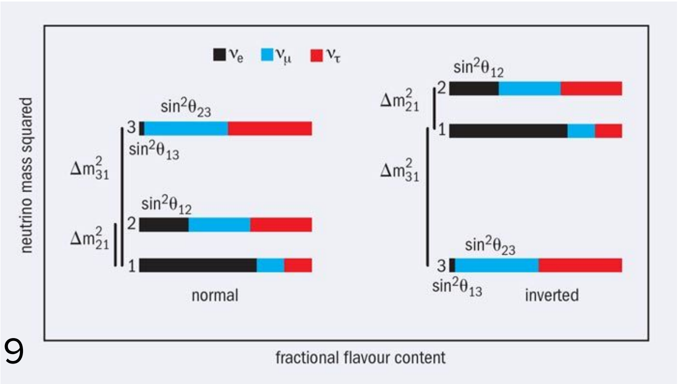
- 3 non zero mixing angles ➔ possible CP violation in the lepton sector

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$

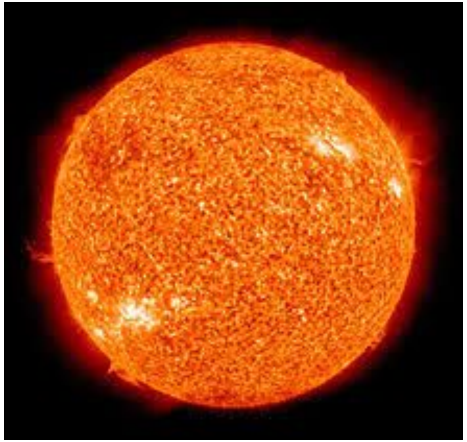
PDG 2019

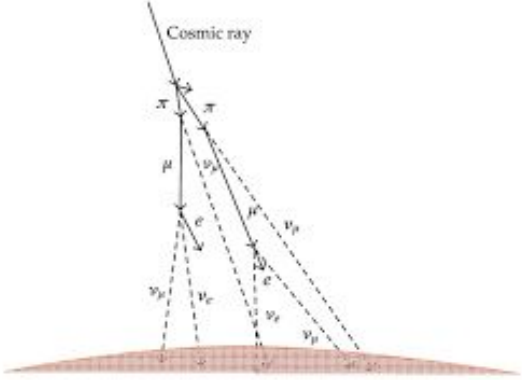
Open questions:
- CP violation
- Mass hierarchy
- θ_{23} octant

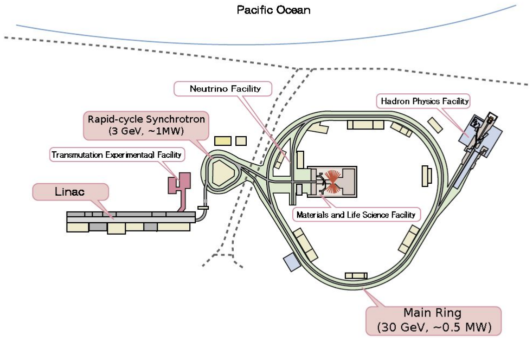


Neutrino sources

- Solar neutrinos
- Reactor neutrinos
- Atmospheric neutrinos
- **Accelerator neutrinos**







How accelerator-based long baseline experiments work?

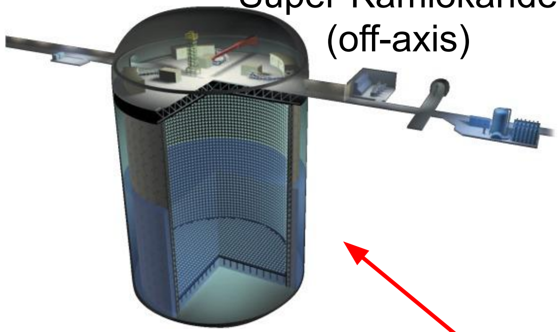
- Example: Tokai to Kamioka (T2K) in Japan

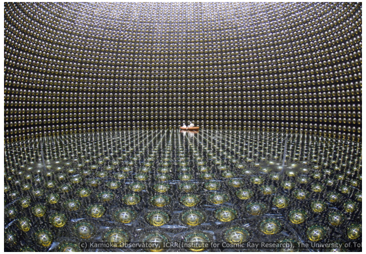
Far detector for measuring neutrinos after oscillations.

Near detectors for measuring neutrinos before oscillations.

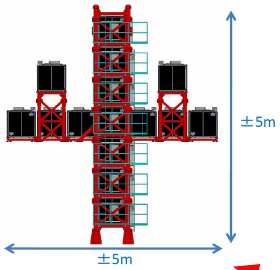
Neutrinos are decay products of pions, kaons and muons created in hadronic interactions.

Super-Kamiokande (off-axis)

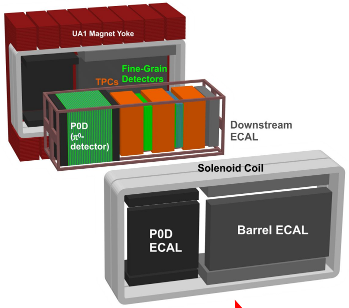




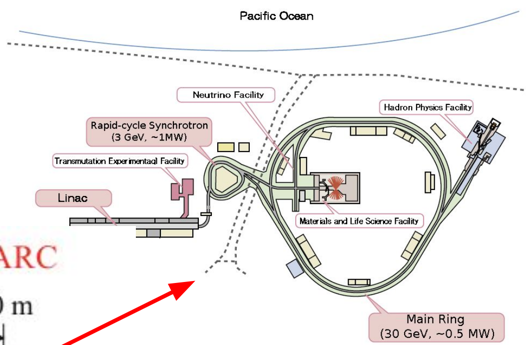
INGRID (on-axis)

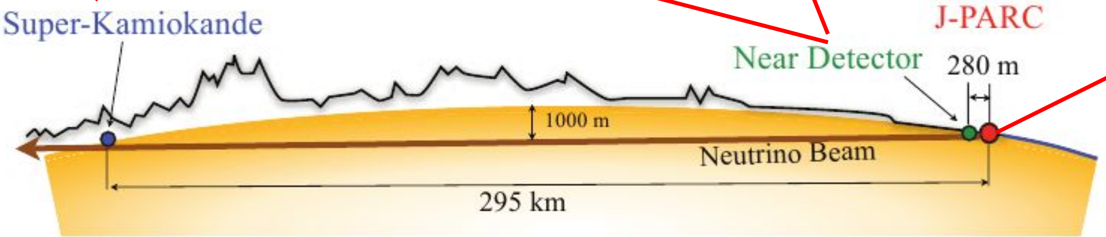


ND280 (off-axis)

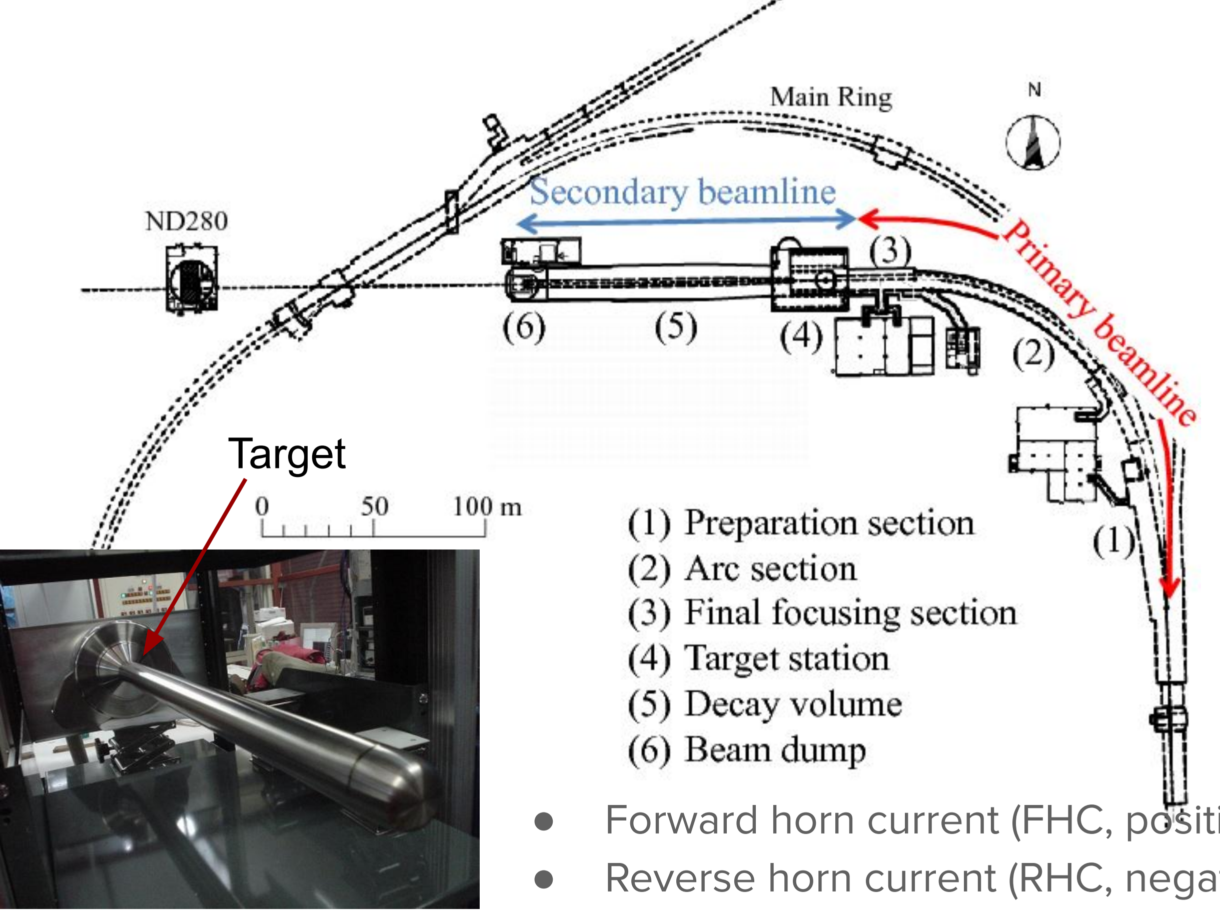


J-PARC

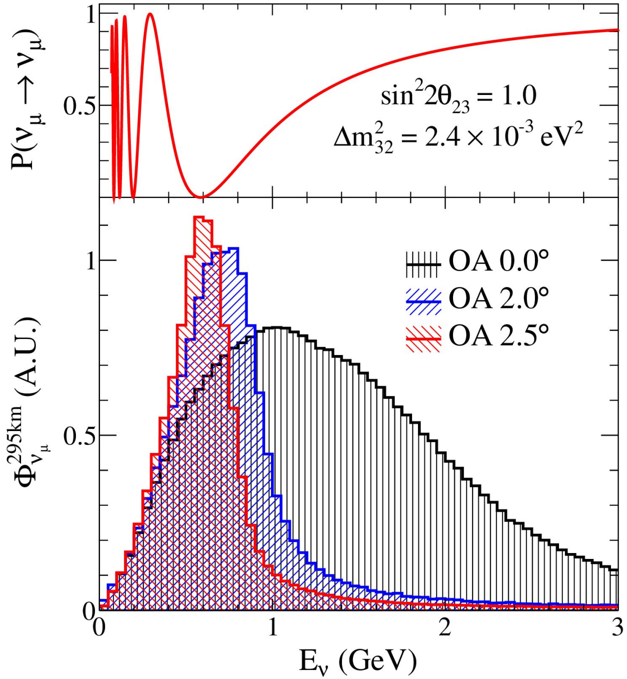




T2K neutrino beamline



Off-axis method



- Forward horn current (FHC, positive focusing) ➔ muon neutrino beam
- Reverse horn current (RHC, negative focusing) ➔ muon antineutrino beam

How accelerator-based long baseline experiments work?

Rate in the near detector

$$N_{ND}(E_\nu) \propto \Phi_{ND} * \sigma_{ND} * \epsilon_{ND}$$

Flux

Neutrino cross-section

Detector response

Rate in the far detector

$$N_{FD}(E_\nu) \propto \Phi_{FD} * \sigma_{FD} * P_{osc} * \epsilon_{FD}$$

Oscillation (survival or appearance) probability

Oscillation measurements:

1. Measure rate in the near detector
2. Extrapolate to the far detector
3. Calculate far/near ratio
4. Fit PMNS model
5. Win Nobel prize

Easy?

Not so easy :(

$$N_{ND}(E_\nu) \propto \Phi_{ND} * \sigma_{ND} * \epsilon_{ND}$$

Near detector sees line neutrino source (target + decay tunnel).
Far detector sees point neutrino source.

Target materials in near and far detectors are not necessarily the same.
Neutrino energy spectra is different in the far detector.
Nuclear effect are biassing neutrino energy reconstruction.

Detector response is different.
Final state interactions, pions re-interacting in the detector.

$$N_{FD}(E_\nu) \propto \Phi_{FD} * \sigma_{FD} * P_{osc} * \epsilon_{FD}$$

Current experiments (T2K, NOvA) are limited by statistics!

Next generation of neutrino experiments

- Hyper-Kamiokande ➜ long baseline neutrino and nucleon decay experiment
  - Atmospheric, Solar, supernova, **accelerator neutrinos**
  - Nucleon decays and BSM searches
  - **Recently funded by the Japanese government**
  - **Construction starts in April 2020**
  - **Data-taking start: 2027**
- DUNE (see slides by Nikolina Ilic)

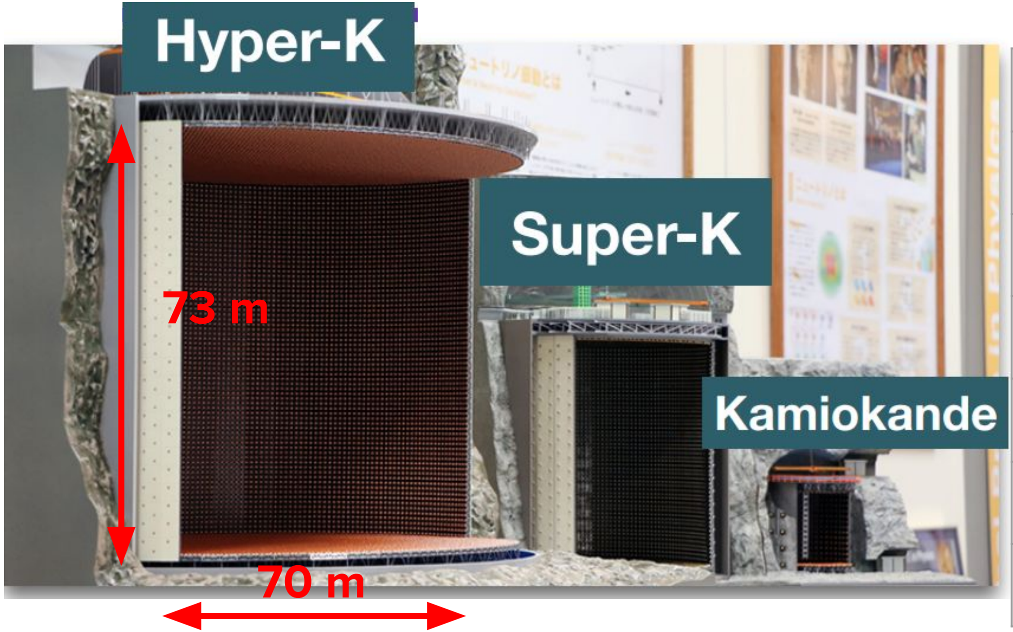
Hyper-Kamiokande project

Beam power 2.5x + 8x fiducial mass
→ 20x stat. compared to T2K

HyperK-Canada group

- **~40 collaborators (including co-op students)**
- **University of Victoria**
- **TRIUMF**
- **British Columbia Institute of Technology**
- **University of Regina**
- **University of Winnipeg**
- **York University**
- **Carleton University**

Far detector - Water Cherenkov Detector



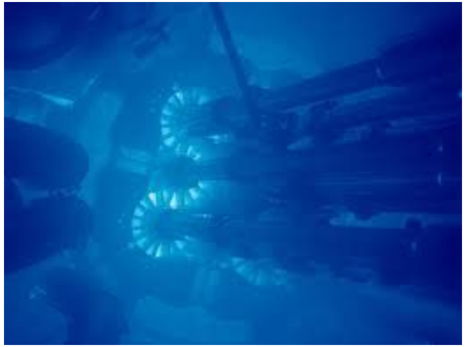
	SK	HK
Site	Mozumi	Tochibora
# PMTs (ID)	11129	40000*
# PMTs (OD)	1885	15000
Photo-coverage	40%	40%*
Mass [kton]	50	237
Fiducial mass [kton]	22.5	187

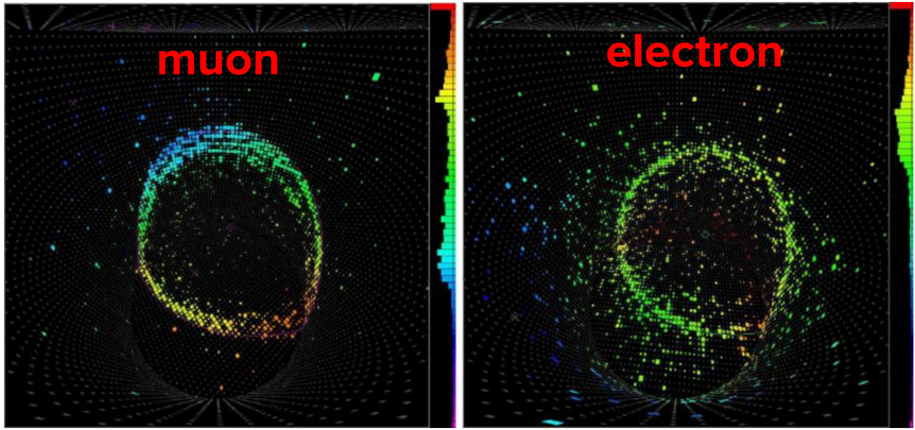
8 times larger fiducial mass than SK

*Depends on the international contribution

Water Cherenkov Detectors

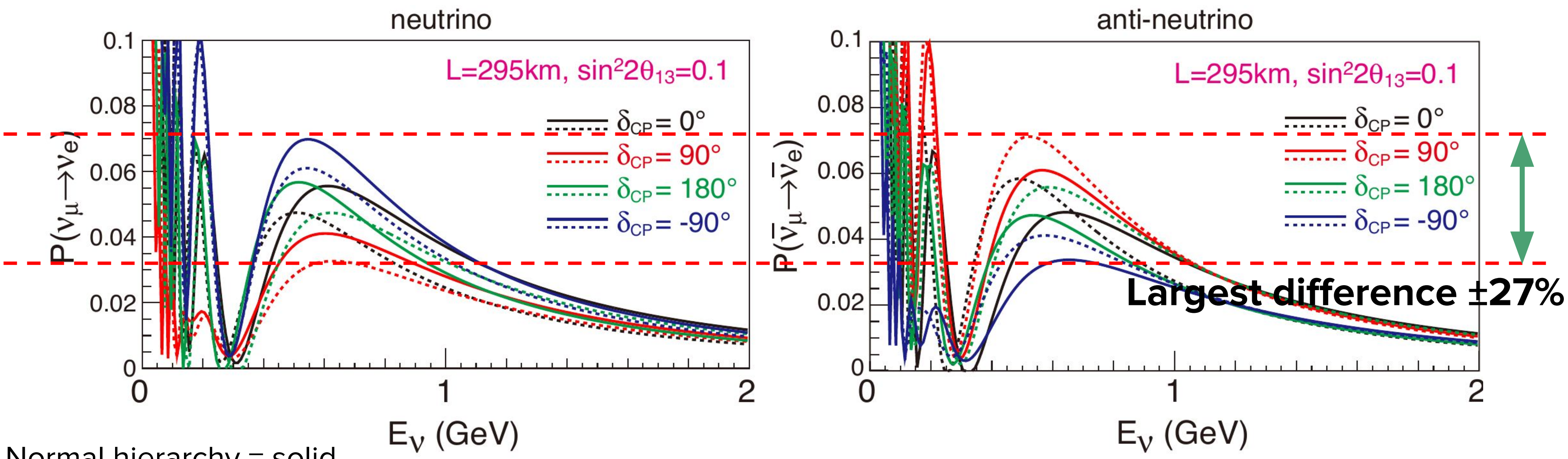
- Neutrinos interact and produce leptons (and other particles)
- If produced charged particles travel faster the the speed of light in water ➔ Cherenkov radiation
- Vertex position determined from timing
- Ring size + vertex position ➔ Cherenkov angle ➔ particle momentum
- PID (electron or muon) ➔ “fuzziness” of the ring (electron multiple scattering)





CPV measurement

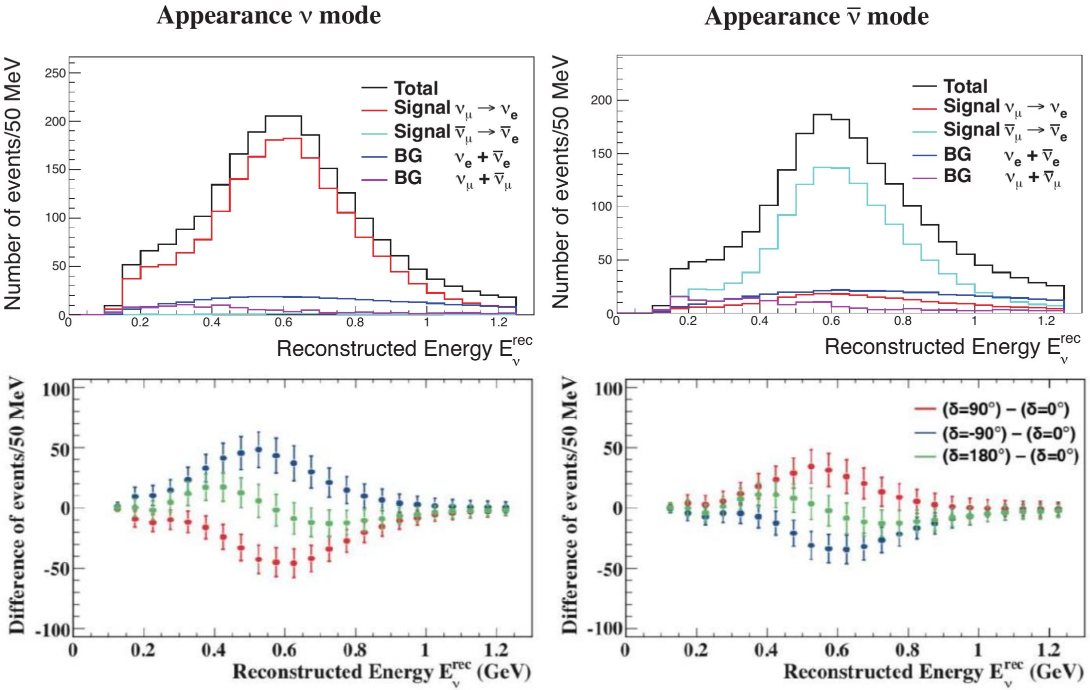
- CP violation can be measured by observing differences between ν_e and anti-ν_e appearance in the accelerator based long-baseline neutrino beam



Normal hierarchy = solid
Inverted hierarchy = dashed

Appearance probability depends on the CP phase

CPV measurement - rates



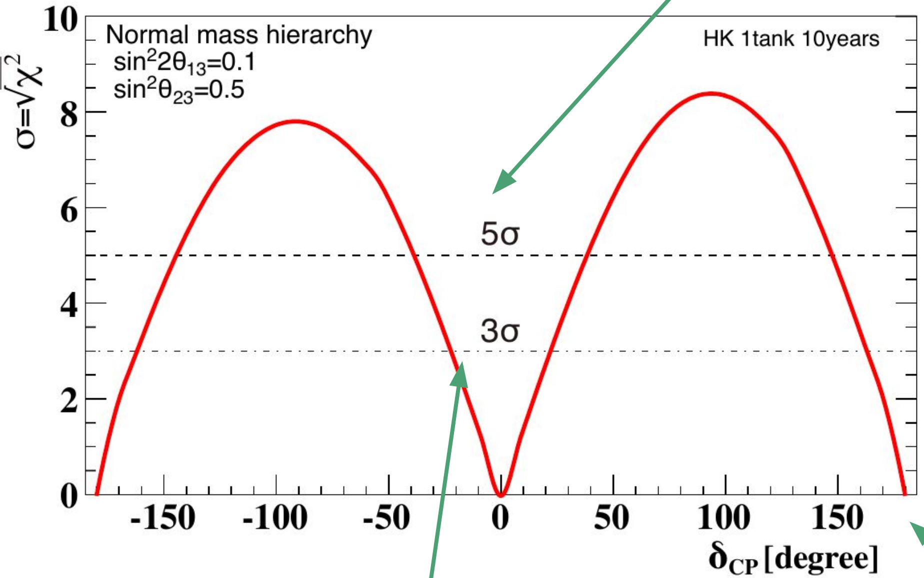
- 10 years of data-taking
- 2.7×10^{22} POT
- Fully contained events with vertex in the fiducial volume
- ν/anti-ν mode = ⅓
- Normal hierarchy, $\delta_{CP} = 0$
- **3.2% statistical uncertainty on the CPV measurement**

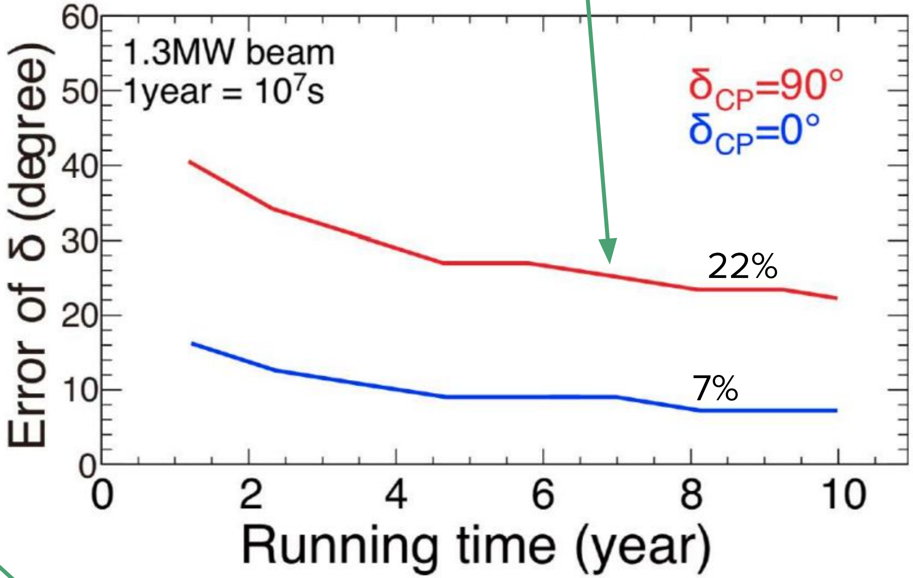
	$\nu_\mu \rightarrow \nu_e$	anti-$\nu_\mu \rightarrow$ anti-ν_e	Beam cont.	NC	ν_μ and anti-ν_μ
ν mode	**1643**	15	259	134	7
anti-ν mode	206	**1183**	317	196	4

CPV measurement - sensitivity

57% coverage of the parameter space at 5σ level

Derivative of the CPV term goes to 0 ➔ larger uncertainty





76% coverage of the parameter space at 3σ level

Assuming 3% systematic uncertainty

Systematic uncertainties

- Systematic uncertainties need to be reduced to 3% level (comparable to statistical uncertainty)
- Current uncertainty is ~6%
- Dominated by $\sigma(\nu_e)/\sigma(\text{anti-}\nu_e)$

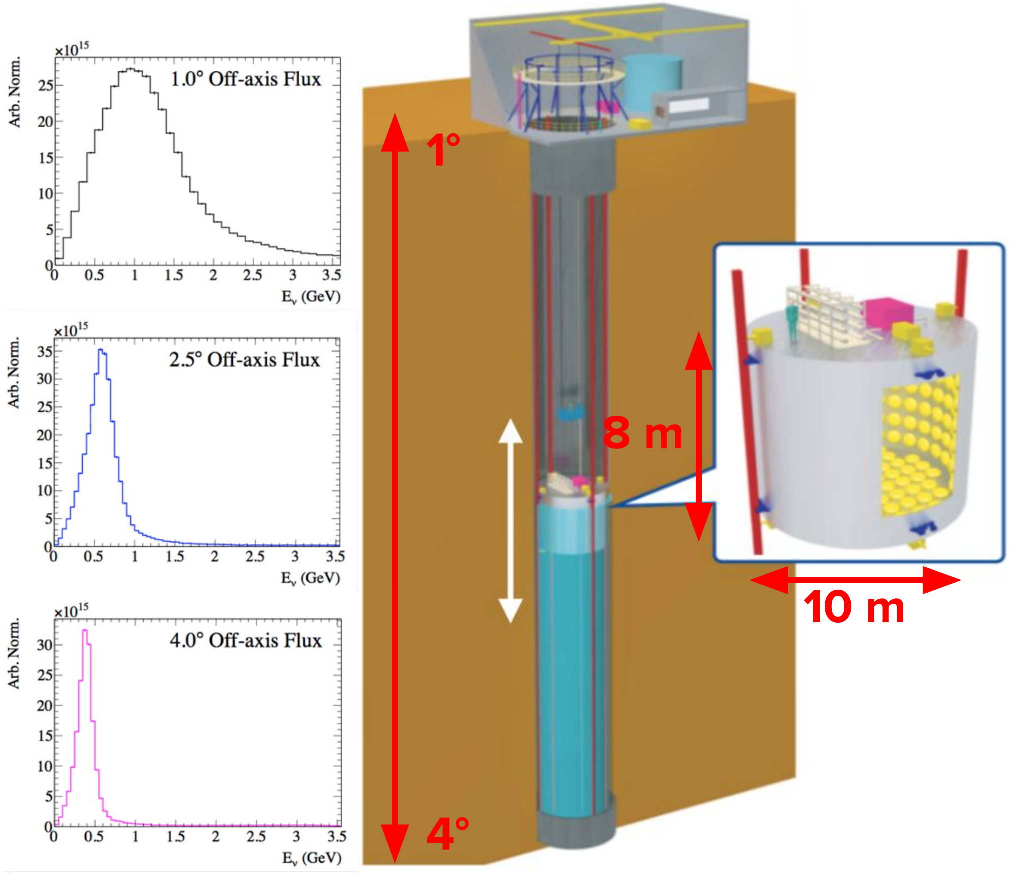
Current T2K uncertainties (for the CPV measurement)

	Uncertainty [%]
Detector (+ FSI + SI + PN)	2.16
Flux + ND280 cross-section constraint	2.31
Unconstrained cross-section	**5.21**
Total	**6.09**

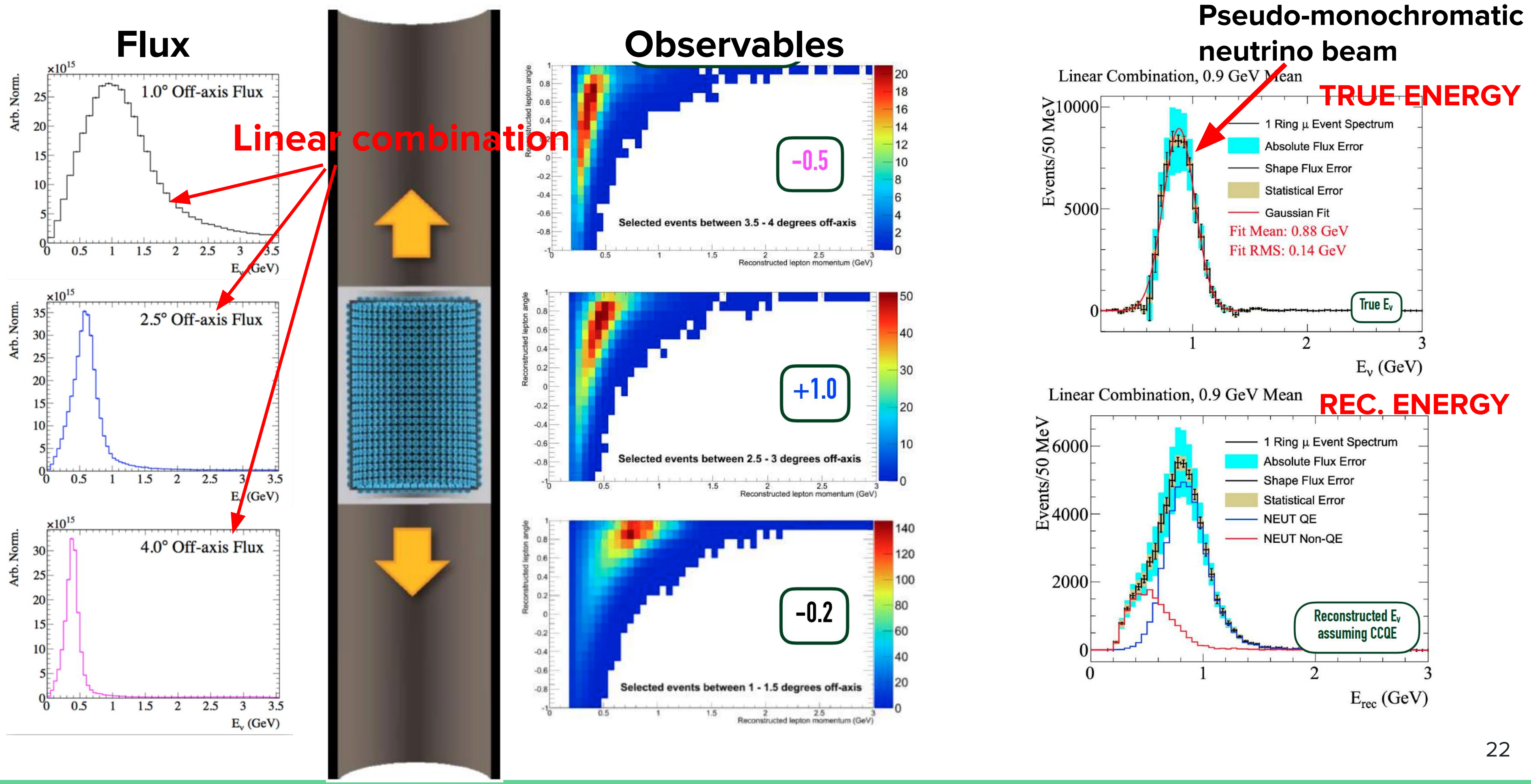
Dominated by $\sigma(\nu_e)/\sigma(\text{anti-}\nu_e)$ 3% and nucleon binding energy systematics

Intermediate Water Cherenkov detector (IWCD)

- Water Cherenkov detector in a vertical pit
- ~1 km from the neutrino source
- Different off-axis angles ➔ access to different neutrino energies
- Linear combination technique

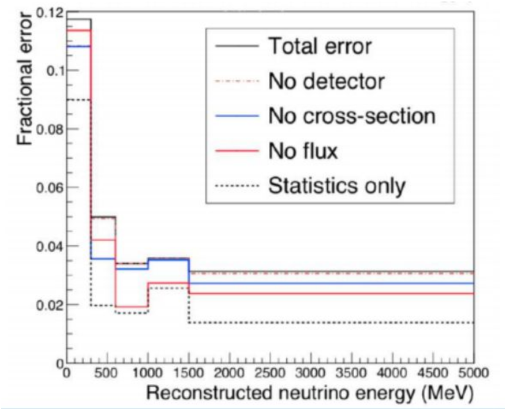


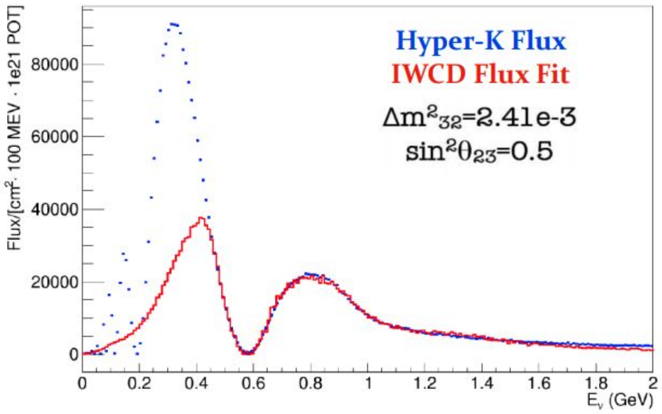
Intermediate Water Cherenkov detector (IWCD)

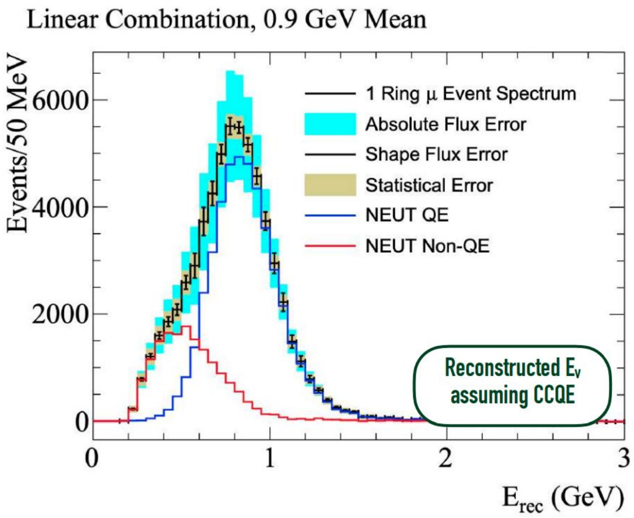


Potential IWCD measurements

- Measurement of the electron (anti)neutrino cross-section in water by using intrinsic (anti)ν_e contamination in the neutrino beam
- Constraining non-CCQE interactions
- Constraining multi-nucleon effects
- Reproduce far detector oscillated spectra

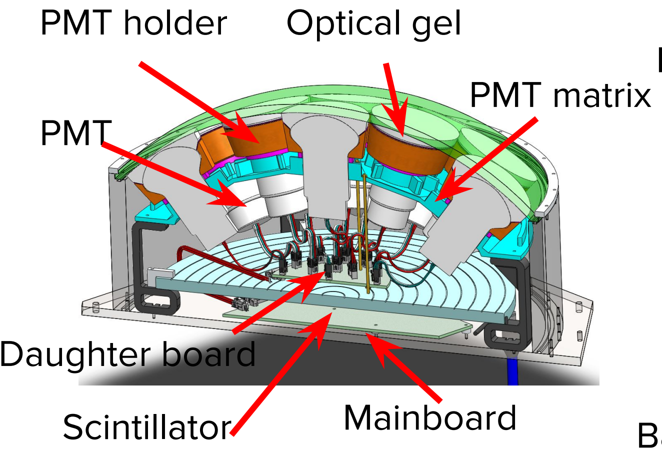


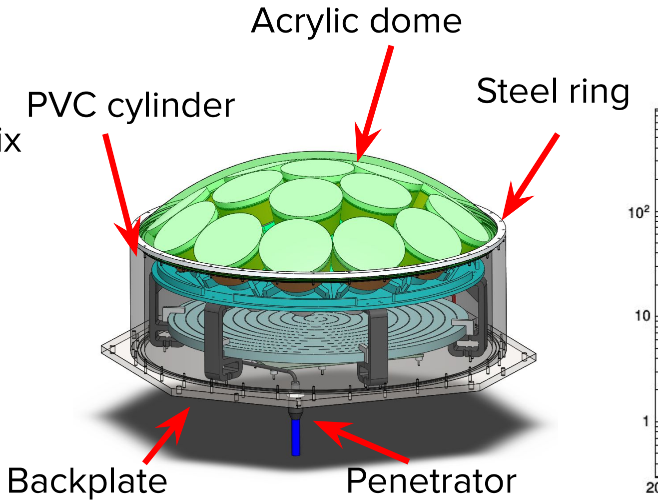


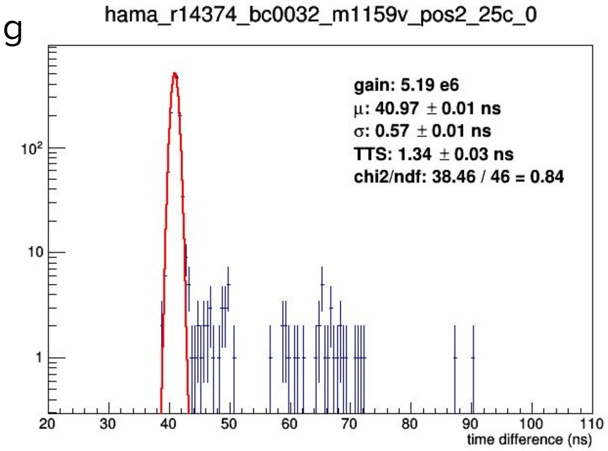


R&D for IWCD: multi-PMT

- 20'' PMTs used in SK or HK cannot be used in IWCD
- Based on KM3NeT design (optimized for water tank)
- First prototype built recently at TRIUMF
- 19 Hamamatsu R14374 8 cm PMTs
- Less photo-coverage but improved vertex resolution
- **~500 mPMTs in IWCD**

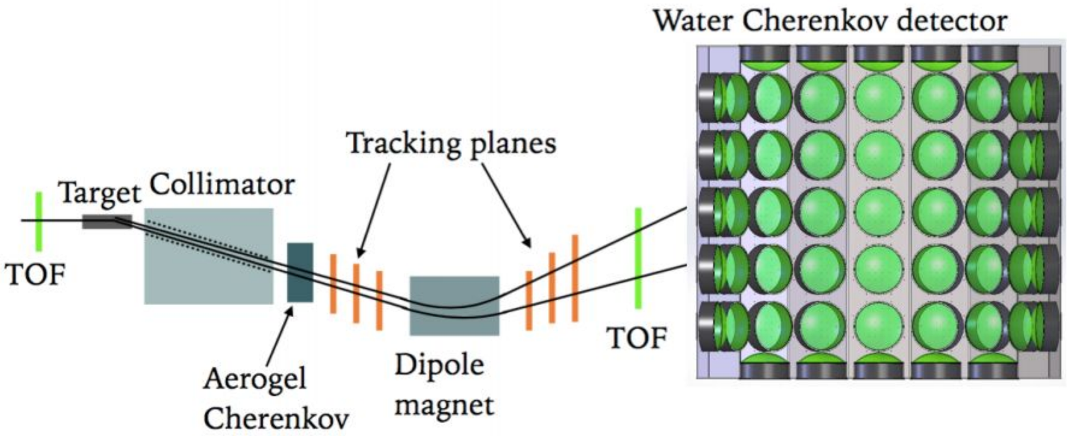






Water Cherenkov Test Experiment

- IWCD will suffer from similar systematics effects like HyperK far detector
  - Cherenkov light profile, pion interactions, electron-gamma separation, ...
- Smaller version of IWCD will be placed in the electron and hadron beam at CERN (scheduled for 2022)
- Full characterization of the detector
- This dataset can be used as a training sample in deep learning



Conclusions

- Open questions in neutrino oscillation physics ➔ CP violation, mass hierarchy, θ_{23} octant
- Next generation of experiment will be limited by systematics
- Hyper-Kamiokande ➔ next generation neutrino and nucleon decay experiment
  - Potential for CP violation discovery
- IWCD is crucial for achieving desired sensitivity in HyperK
- HyperK-Canada group is working on:
  - mPMT development
  - Water Cherenkov Test Experiment
  - Water Cherenkov calibration
  - Machine learning for water Cherenkov detectors
  - EMPHATIC hadron production experiment

BACKUP

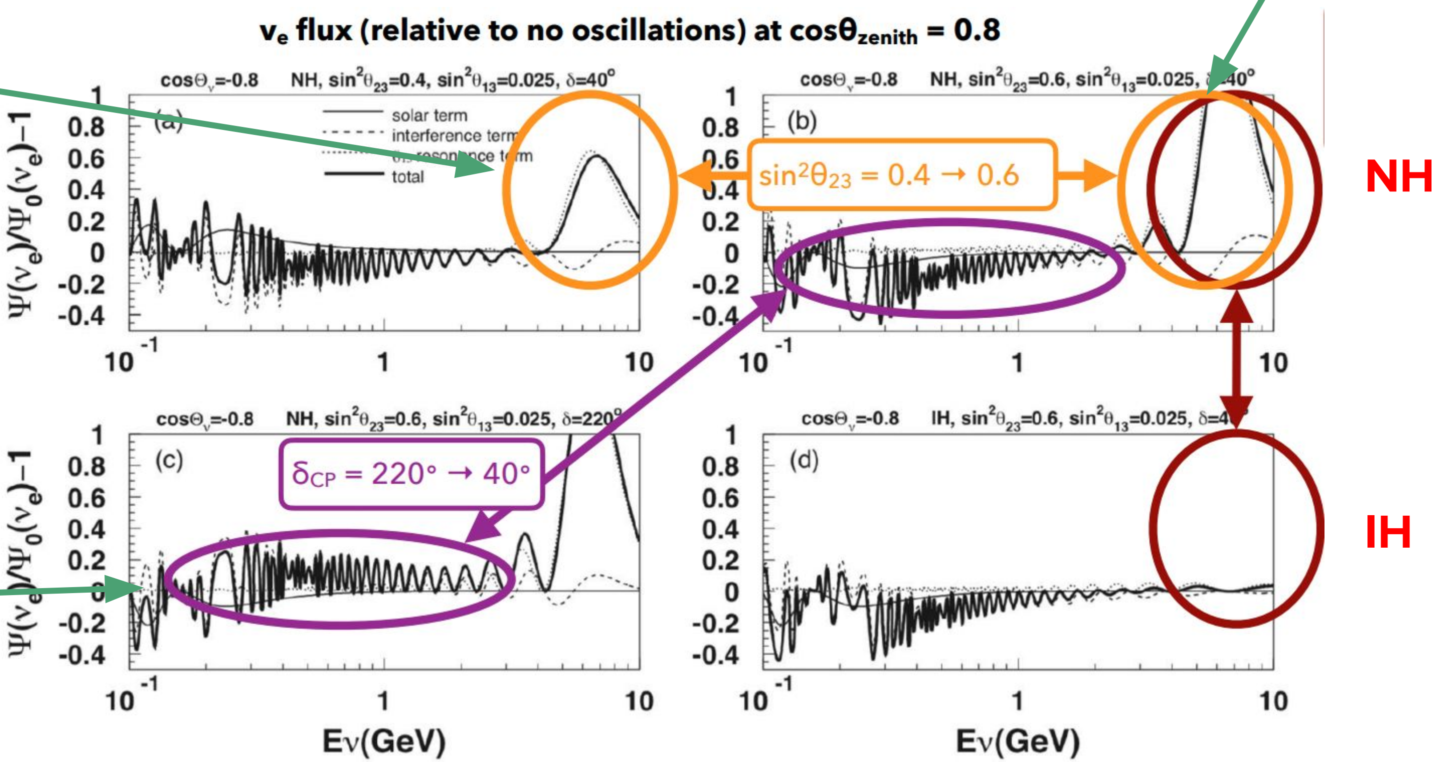
Atmospheric neutrinos

- Sensitive to CPV, mass hierarchy and θ_{23} octant

Matter effect creates resonance in multi-GeV region → present for NH

Size of the resonance is affected by $\sin^2\theta_{23}$

Sub-GeV region is sensitive to CPV

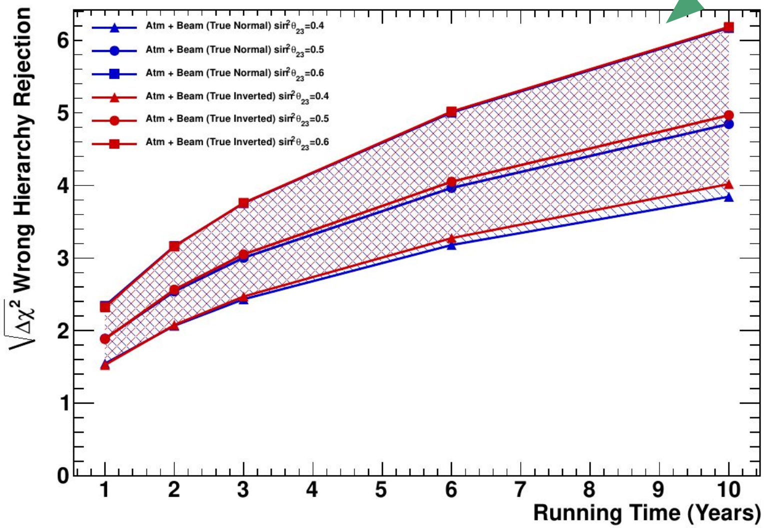


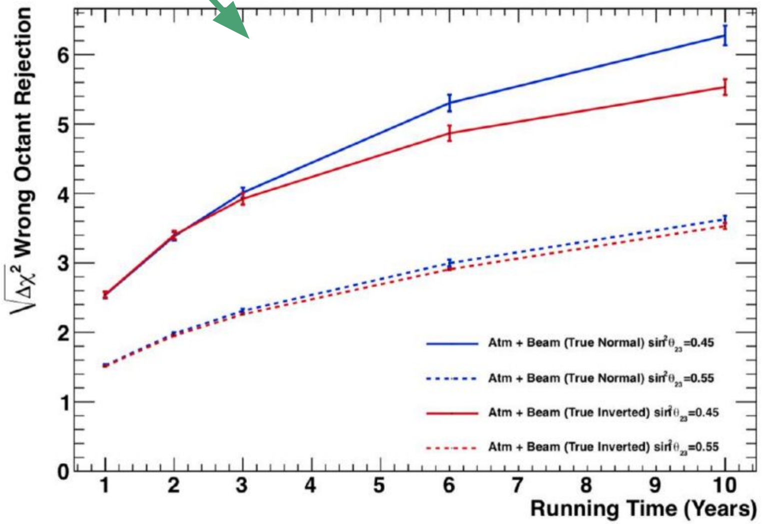
Mass hierarchy and θ_{23} octant sensitivity

Wrong hierarchy rejection at 3σ level for all θ_{23} values

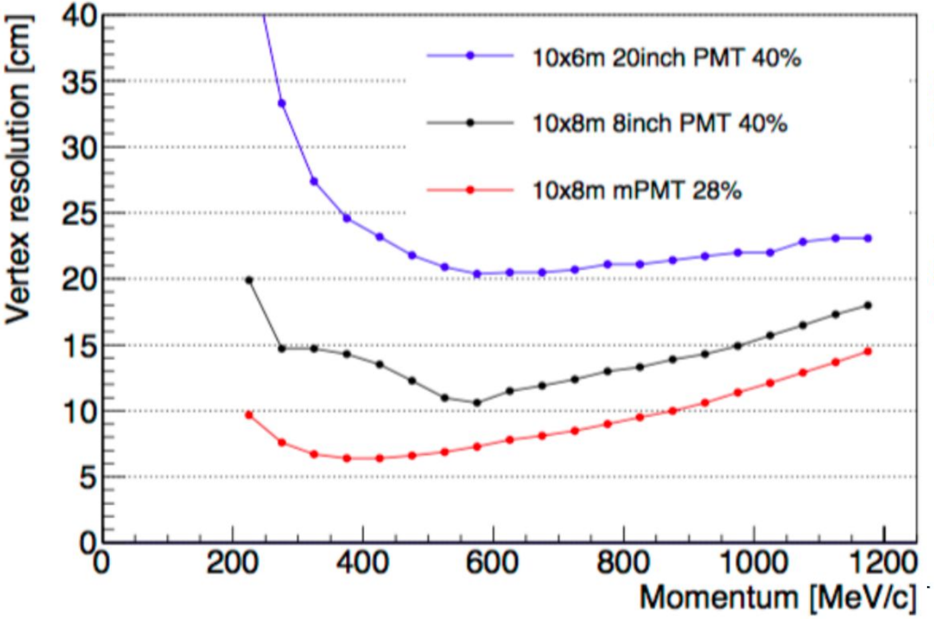
Combined beam + atmospheric neutrinos

Wrong octant rejection at 3σ level for $|\theta_{23}$-45| > 2.3°

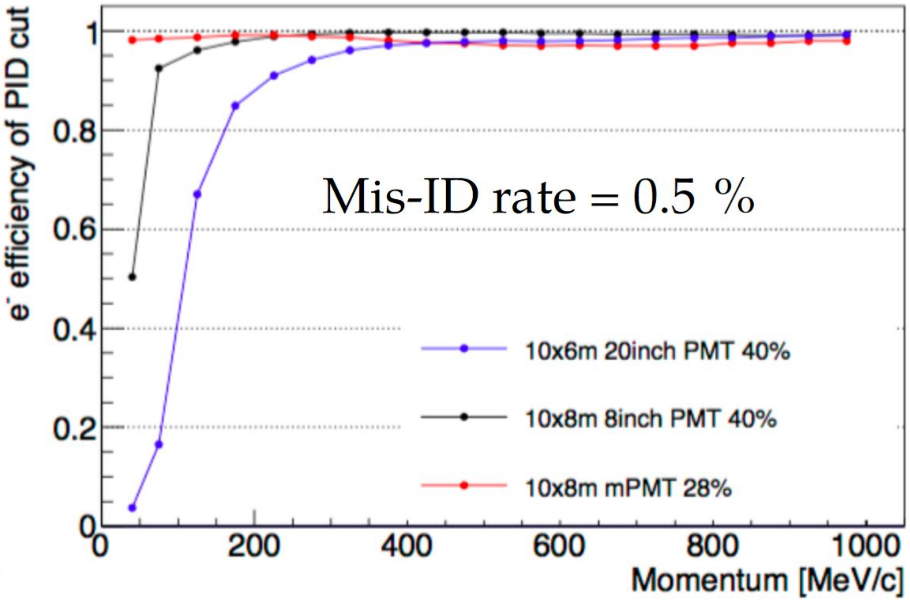




mPMT

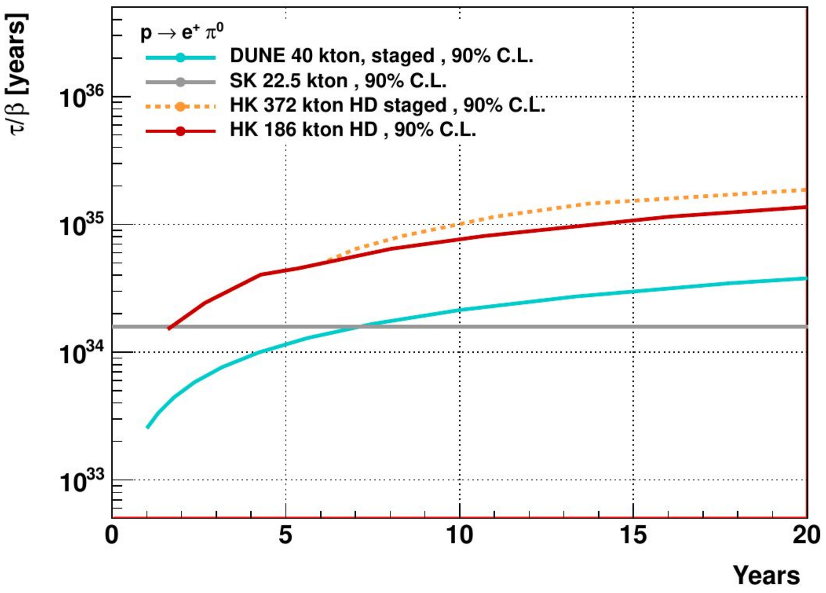


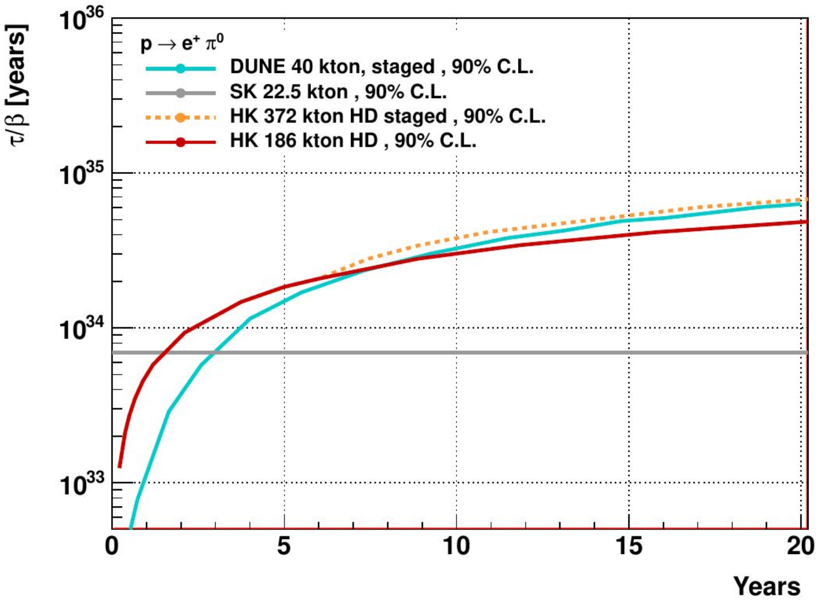
Vertex resolution [cm]
40
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
Momentum [MeV/c]
10x6m 20inch PMT 40%
10x8m 8inch PMT 40%
10x8m mPMT 28%



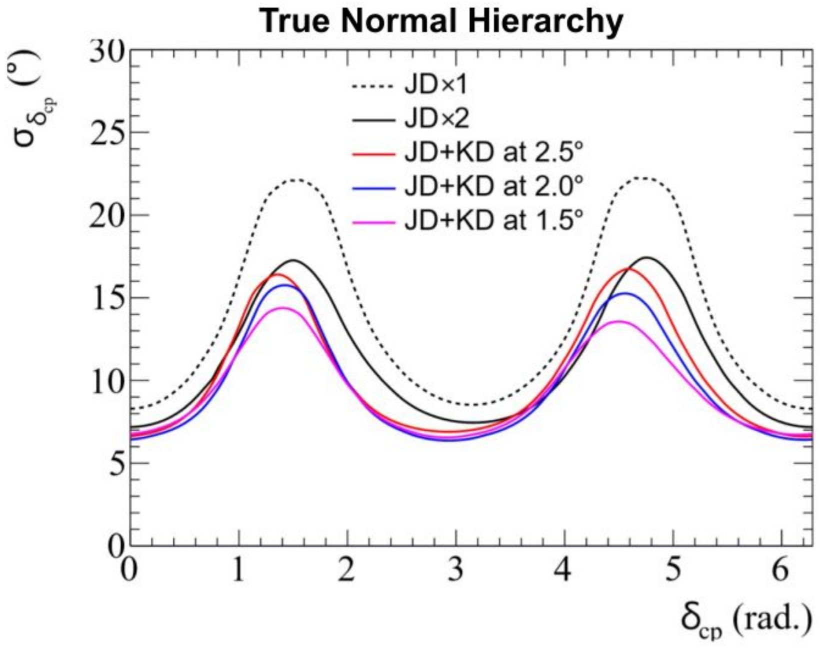
e⁻ efficiency of PID cut
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
Momentum [MeV/c]
Mis-ID rate = 0.5 %
10x6m 20inch PMT 40%
10x8m 8inch PMT 40%
10x8m mPMT 28%

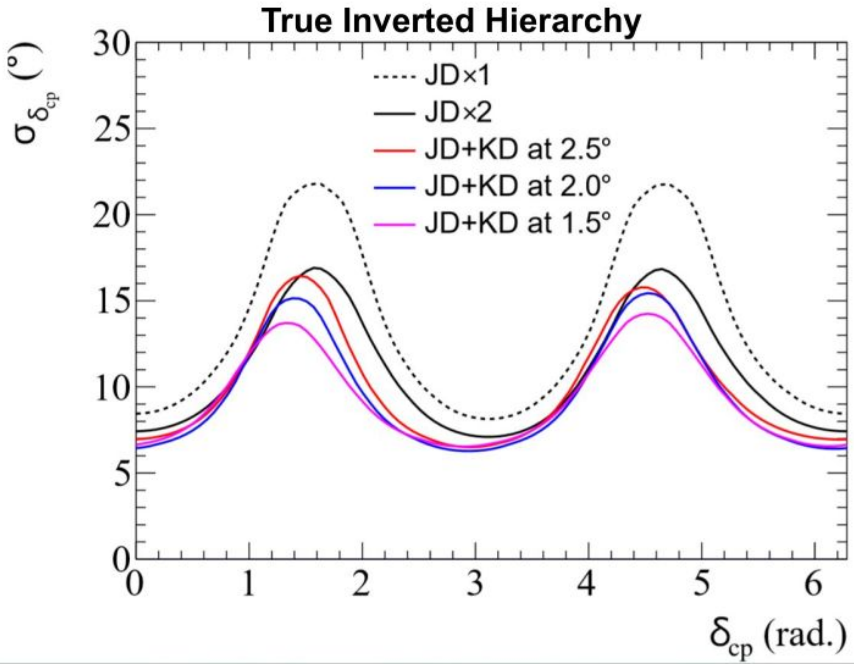
Nucleon decays





Second tank in Korea

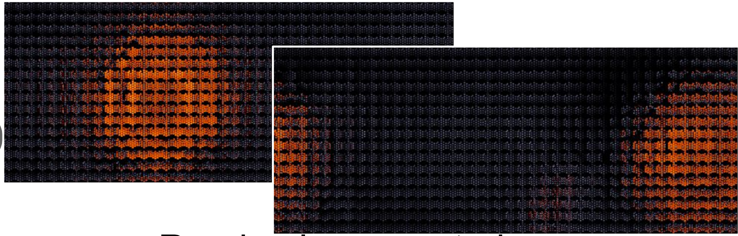




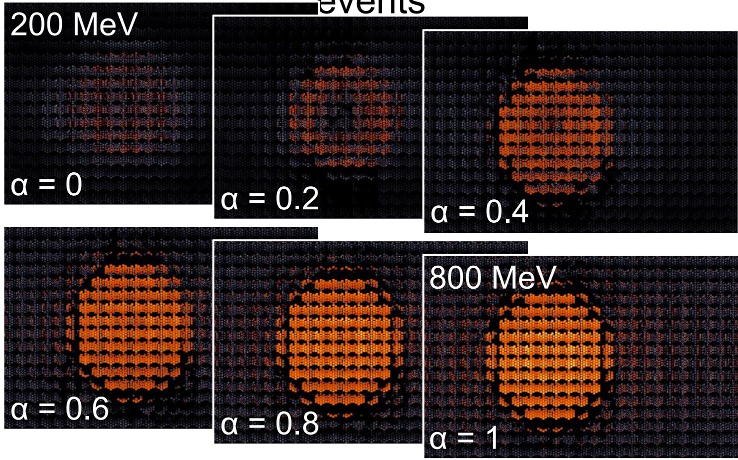
Machine Learning

WatChMaL.org

- Machine learning workshop at UVIC ➔ formation of **Wat**er **Ch**erenkov **Ma**chine **L**earning (**WatChMal**) group
    - In cooperation with Wojtek Fedorko (data scientist at TRIUMF)
- Using machine learning for PID and event reconstruction
- Convolutional Neural Networks (CNNs) for PID
    - **e-γ separation ➔ impossible with traditional methods**
    - Preliminary study with CNNs ➔ **73% γ rejection for 80% e signal efficiency**
- Variational autoencoders ➔ generative models based on data ➔ no model dependence systematics



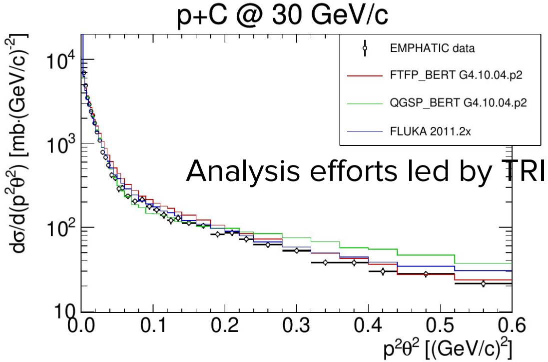
Randomly generated new events



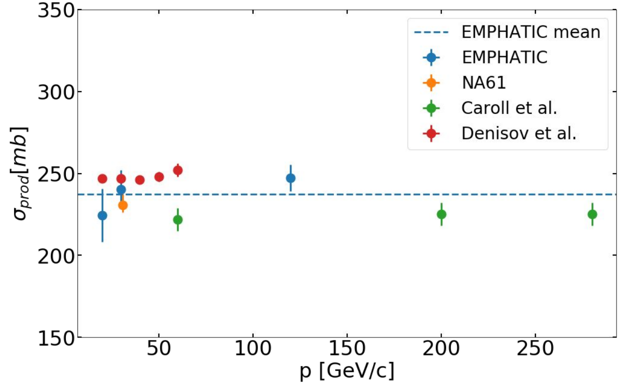
The leading author is Abhishek Abhishek, a coop student from Manitoba ➔ arXiv:1911.02369 [physics.ins-det]

EMPHATIC (**E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam in **C**hicagoland)

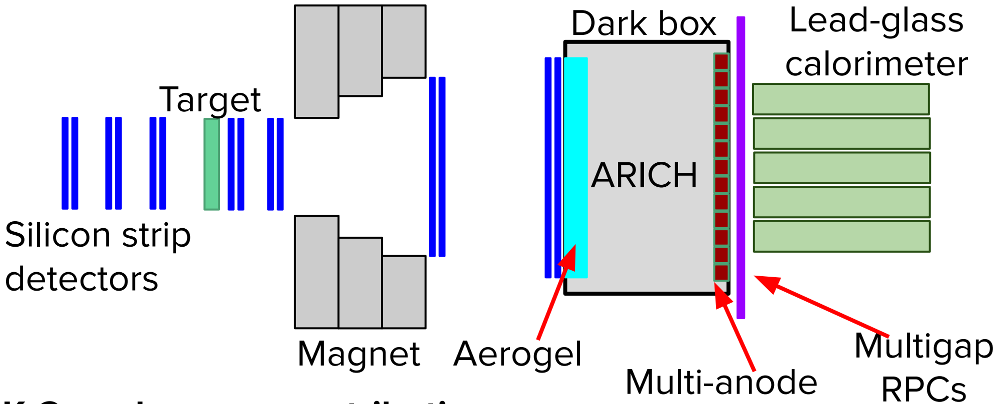
- **Approved by Fermilab PAC**
- Preliminary results from the test run in 2018 were presented in Fermilab JETP seminar



Analysis efforts led by TRIUMF



- **Next run April 1-20 2020**



HK-Canada group contributions

- Small permanent magnet (150 mrad)
- ARICH v1 (prototype currently being tested at TRIUMF)
- DAQ software, reconstruction, calibration and MC simulation