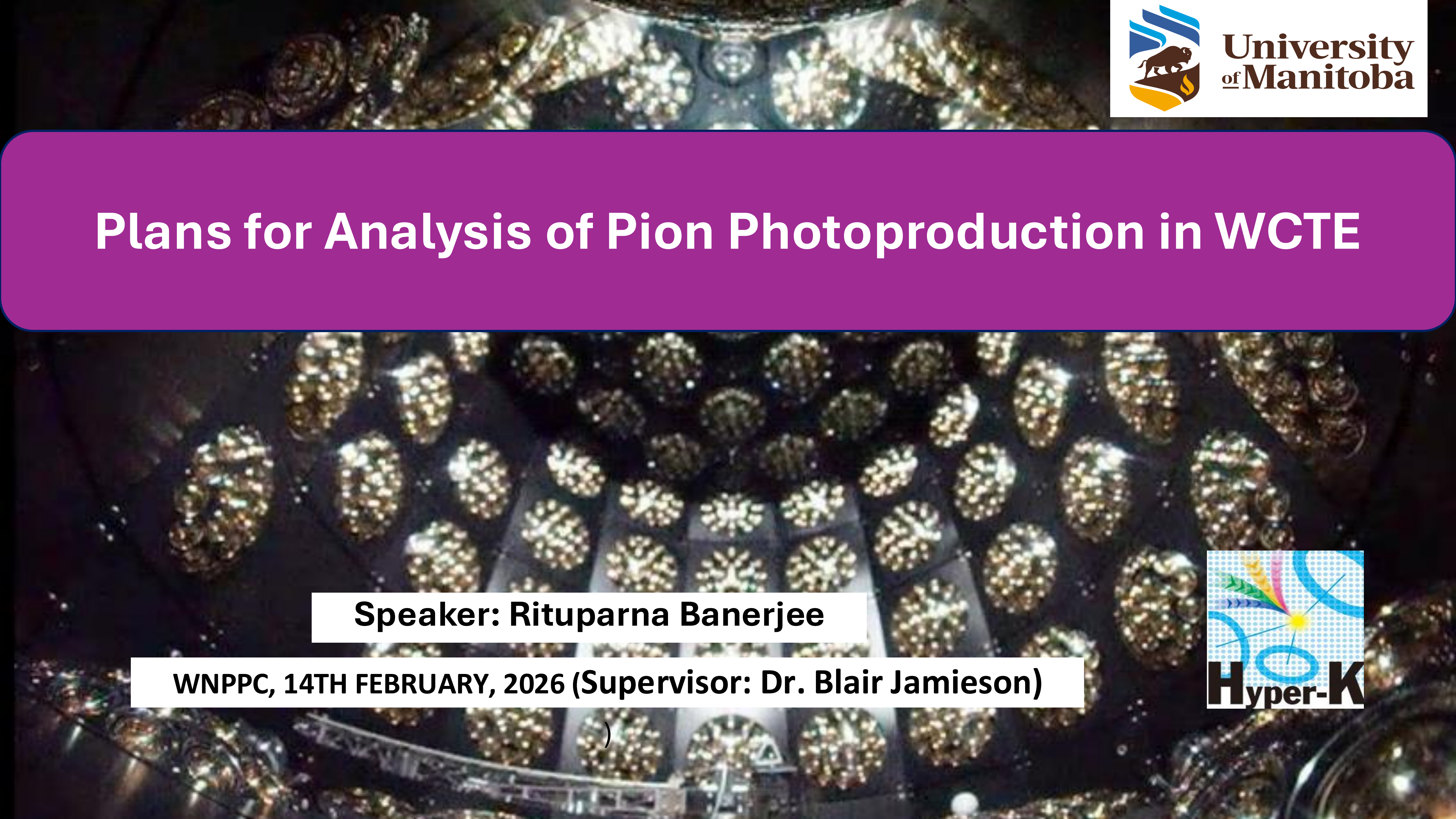


Plans for Analysis of Pion Photoproduction in WCTE

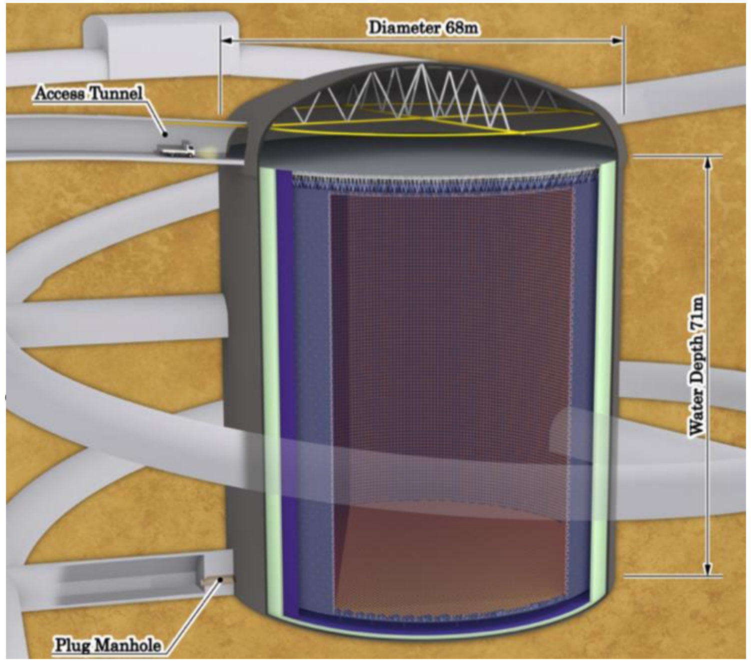
Speaker: Rituparna Banerjee

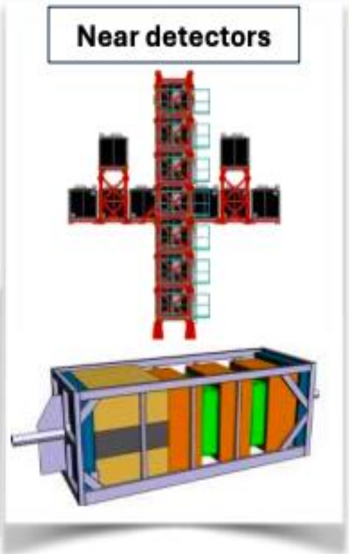
WNPPC, 14TH FEBRUARY, 2026 (Supervisor: Dr. Blair Jamieson)

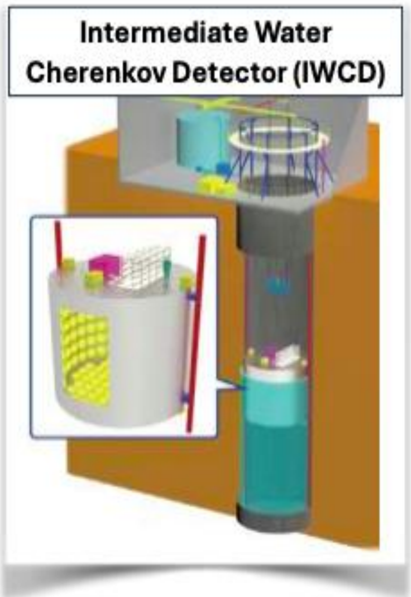
)

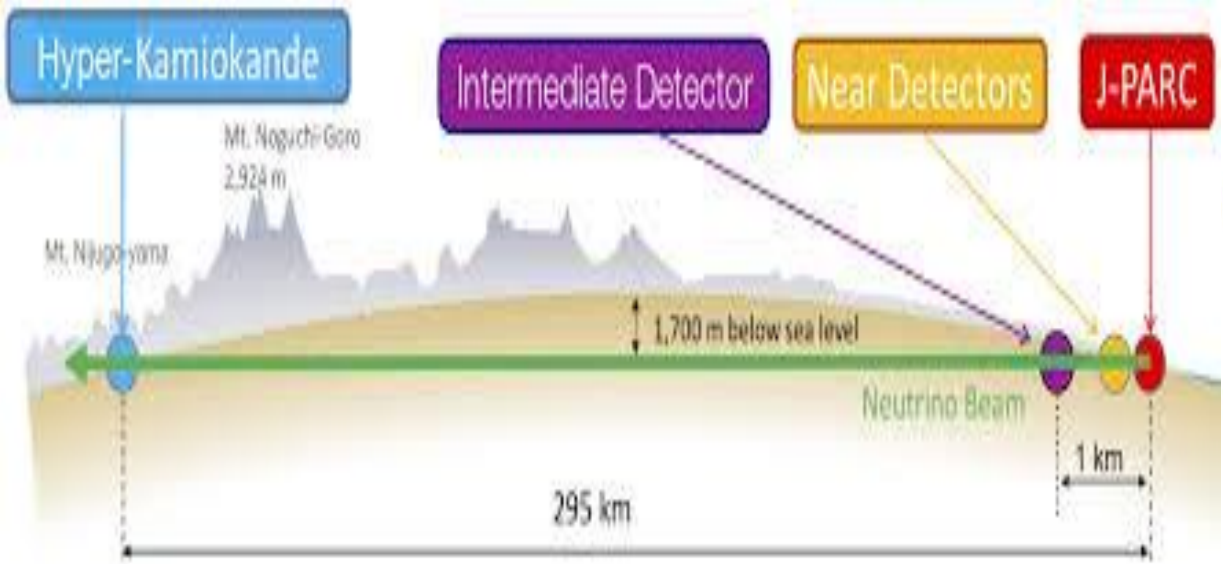
The Hyper-Kamiokande Experiment

- **Hyper-Kamiokande (Hyper-K)** is a world leading next-generation neutrino experiment, building on success of Super-Kamiokande & T2K.
- It consists of a set of **near** and **intermediate** detectors (IWCD) and **far detector** (also called as Hyper-Kamiokande).
- Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities.

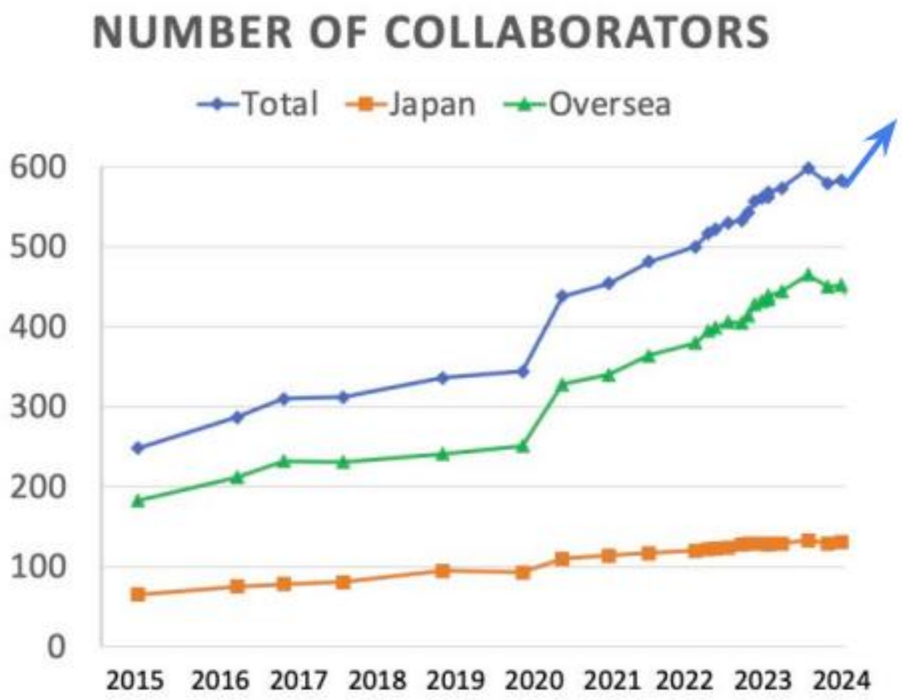



Near detectors


Intermediate Water Cherenkov Detector (IWCD)

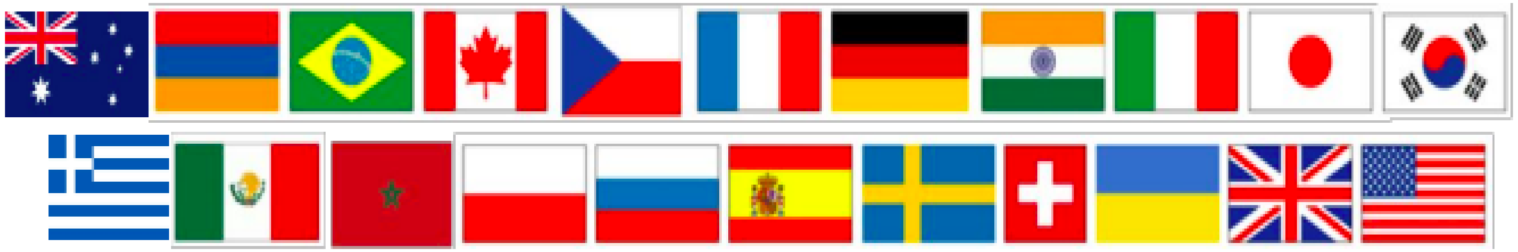


Hyper-K Collaboration



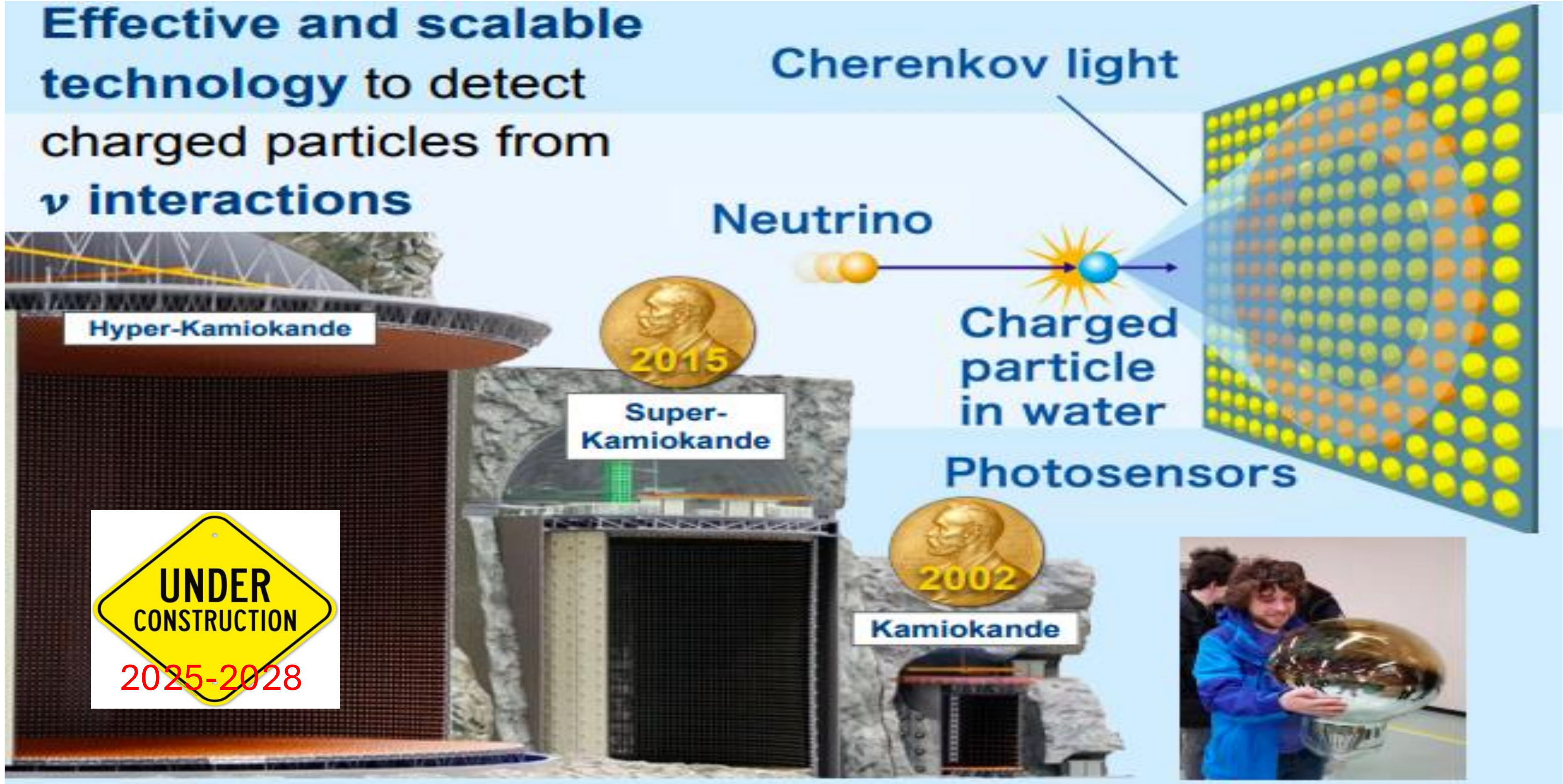

Hyper-K Collaboration Meeting, TRUIMF, Vancouver (August 2025)

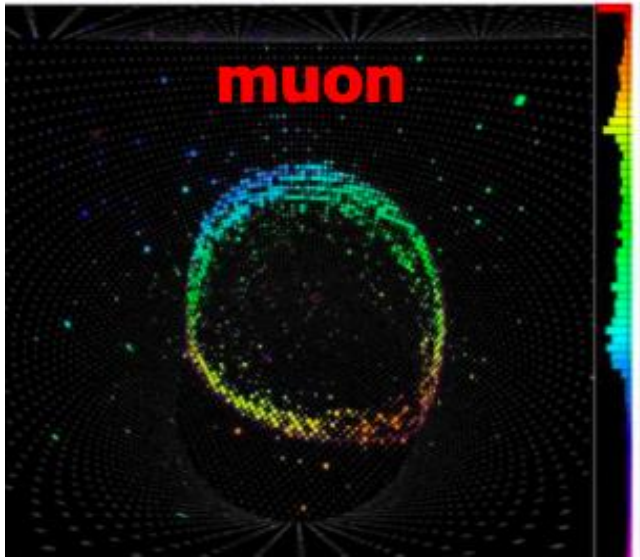
- **22 countries**
- 106 institutes
- 650 members
- As of now, this number keeps on growing!

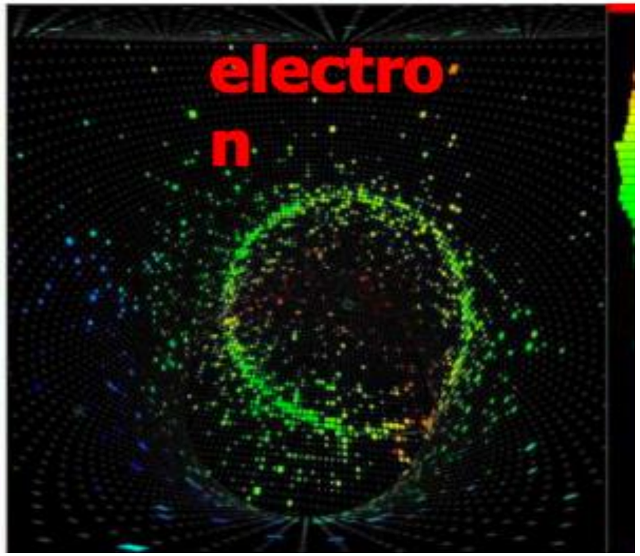


Principle of Operation: How Water Cherenkov Detectors Work?

- Neutrinos interact and produce leptons (and other particles).
- Charged particles travelling faster than the speed of light in water will produce **Cherenkov radiation**.
- Cherenkov radiation will be measured by PMTs and manifests on the detector wall in the **shape of rings**.

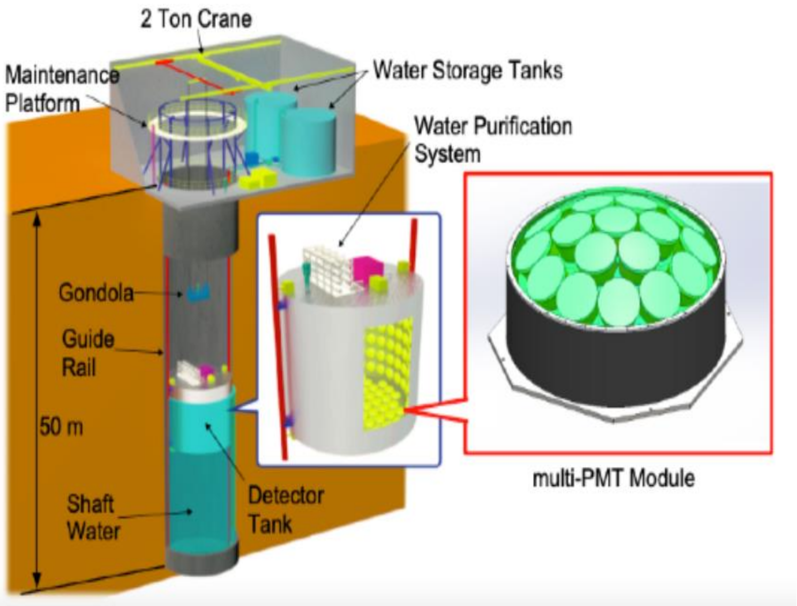


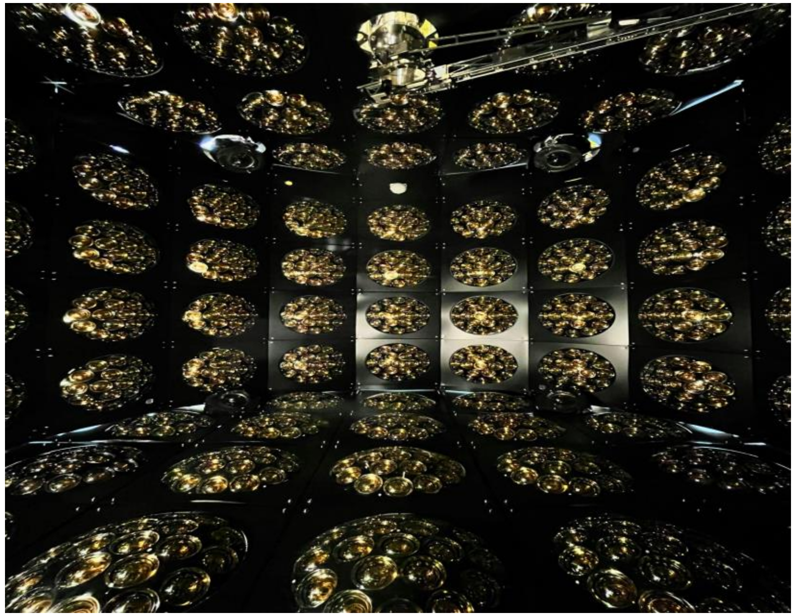




Water Cherenkov Test Experiment (WCTE)

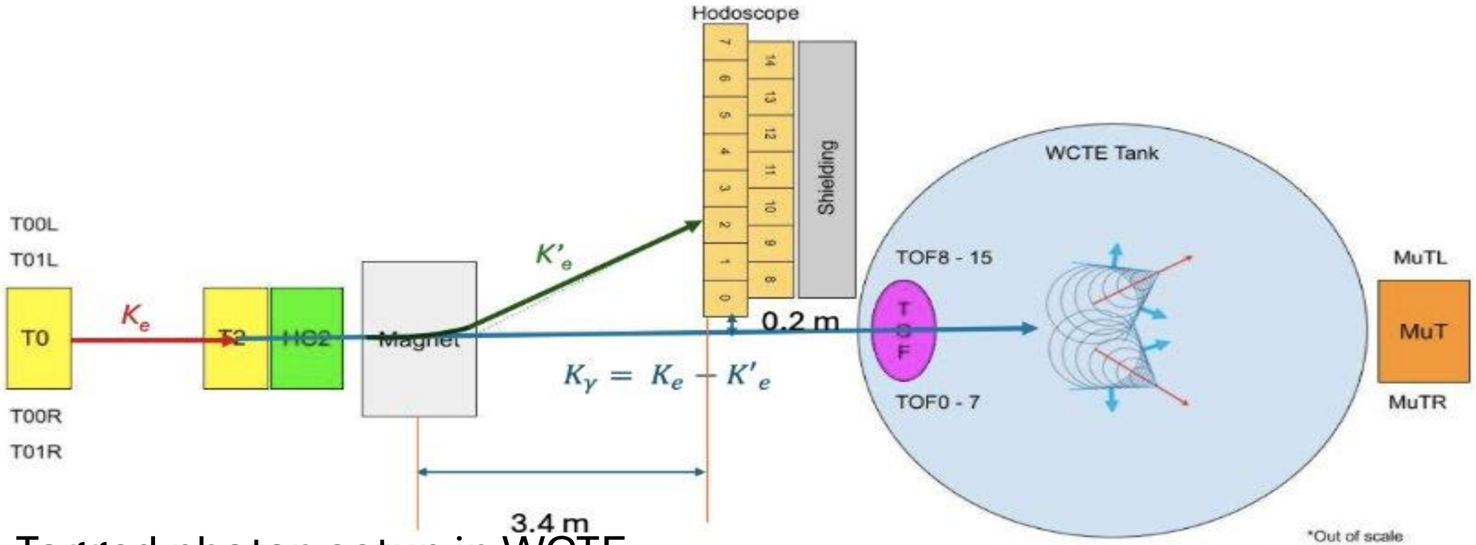
- The **Water Cherenkov Test Experiment (WCTE)** is a technology prototype of the **Intermediate Water Cherenkov Detector (IWCD)** of the Hyper-Kamiokande (Hyper-K) experiment.
- It is a **40-ton** water Cherenkov detector and consists of **~130 mPMTs** and 19 3-inch diameter PMTs inside each mPMT unit.
- Operated in the T9 beamline of the East Area at CERN from October 2024 to June 2025 using both pure **water** and **gadolinium-loaded** configurations.



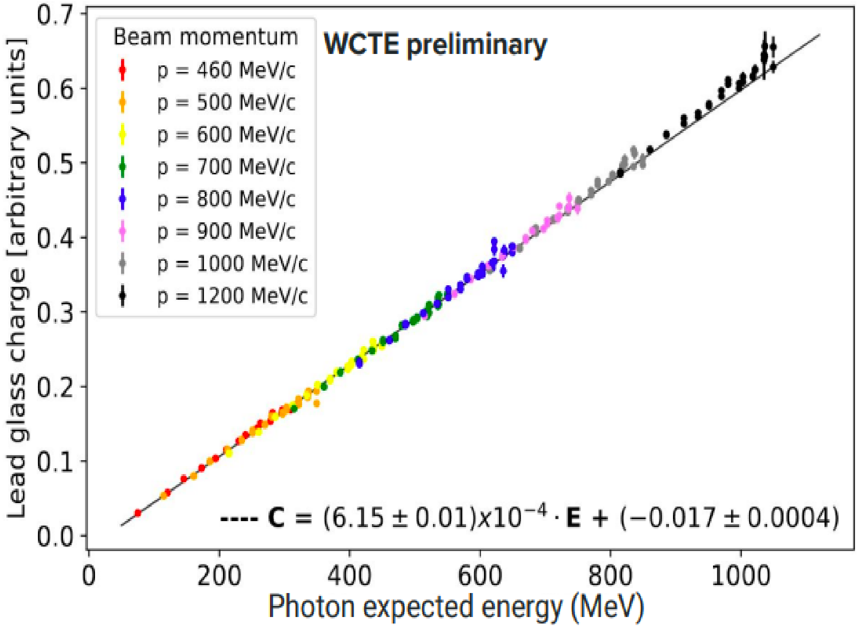


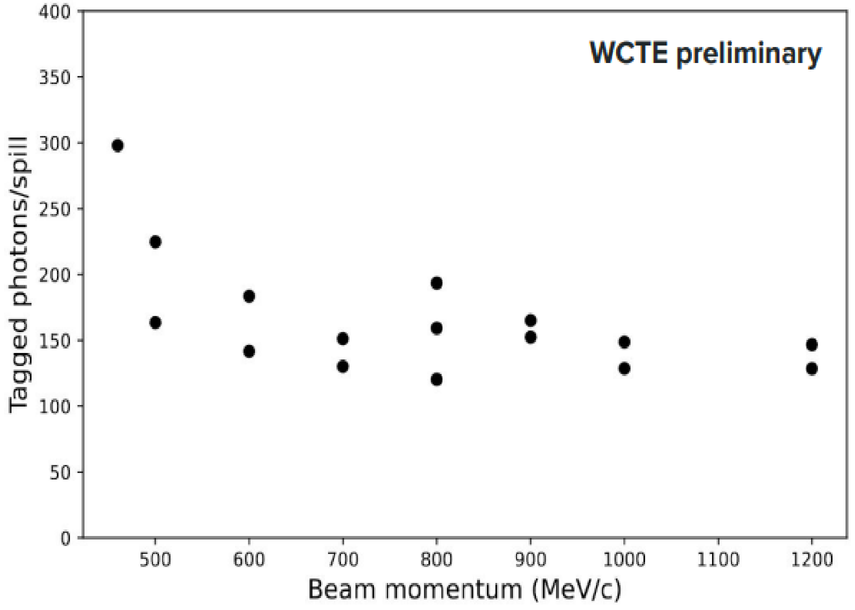
Tagged Photon Setup in WCTE

- As electrons go through matter, they can **lose energy** in the form of **Bremsstrahlung photons**.
- Electrons are **deflected** by the permanent magnet after emission, depending on their energy.
- Deflected electrons pass through a segmented hodoscope positioned after a magnet.
- Electron beam of momentum **460 MeV/c to 1.2 GeV/c** produces photons with energy from **100 MeV/c to 1 GeV/c.**

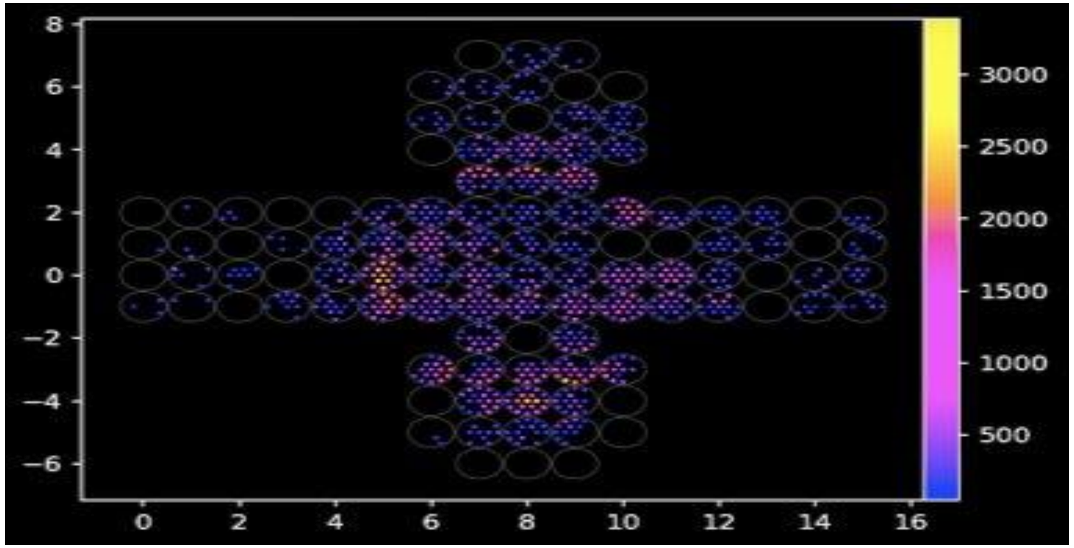


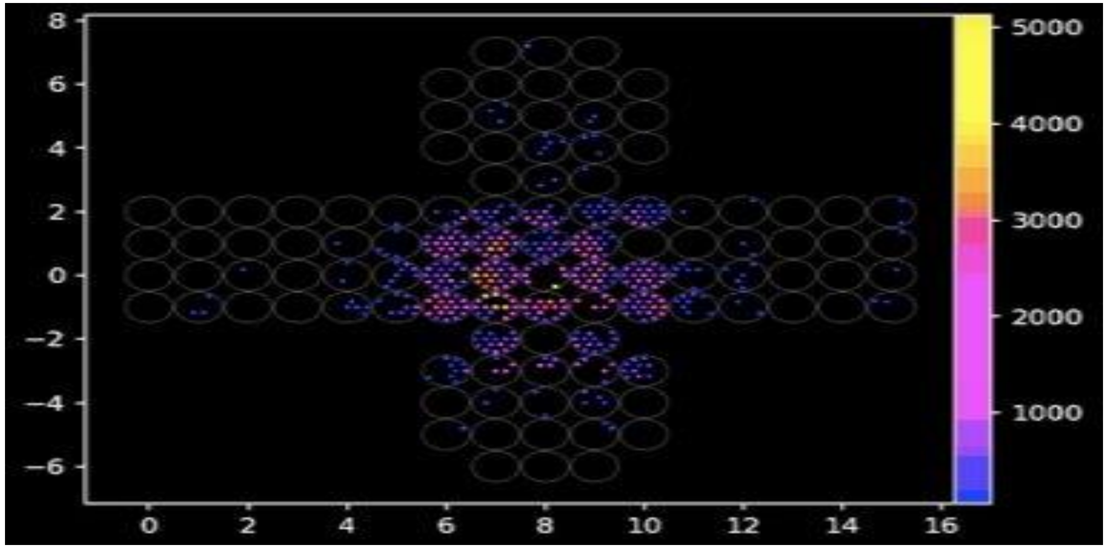
Tagged photon setup in WCTE

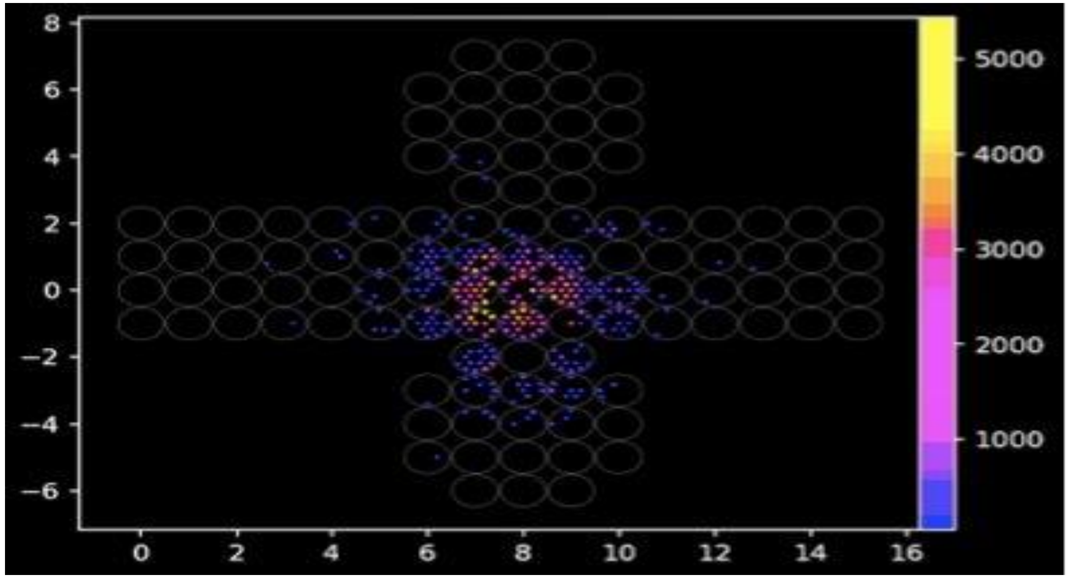


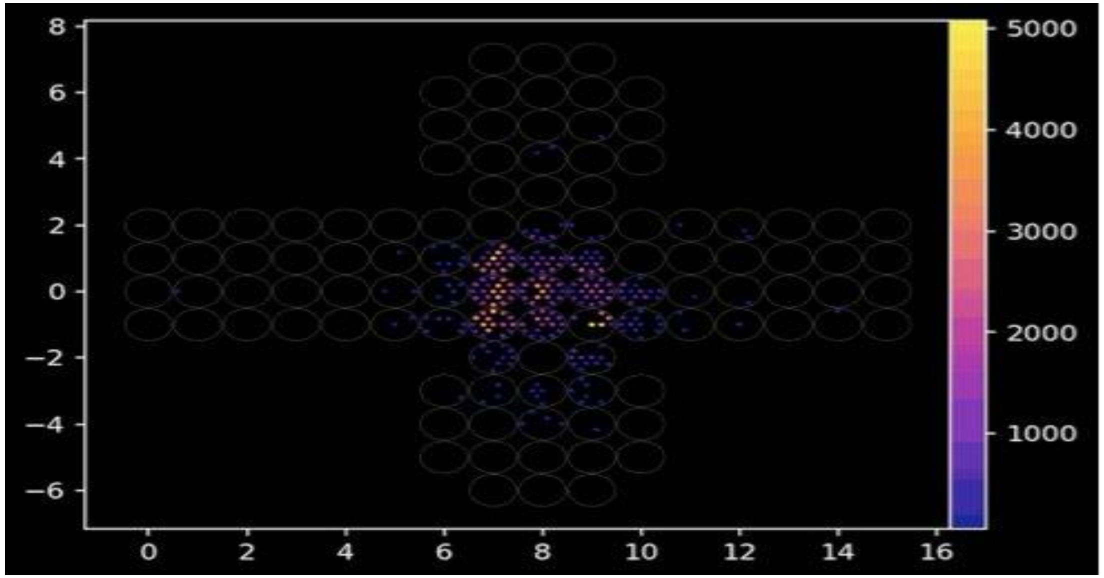


Event Display for Tagged Photon Beam (using 1 GeV/c Data)



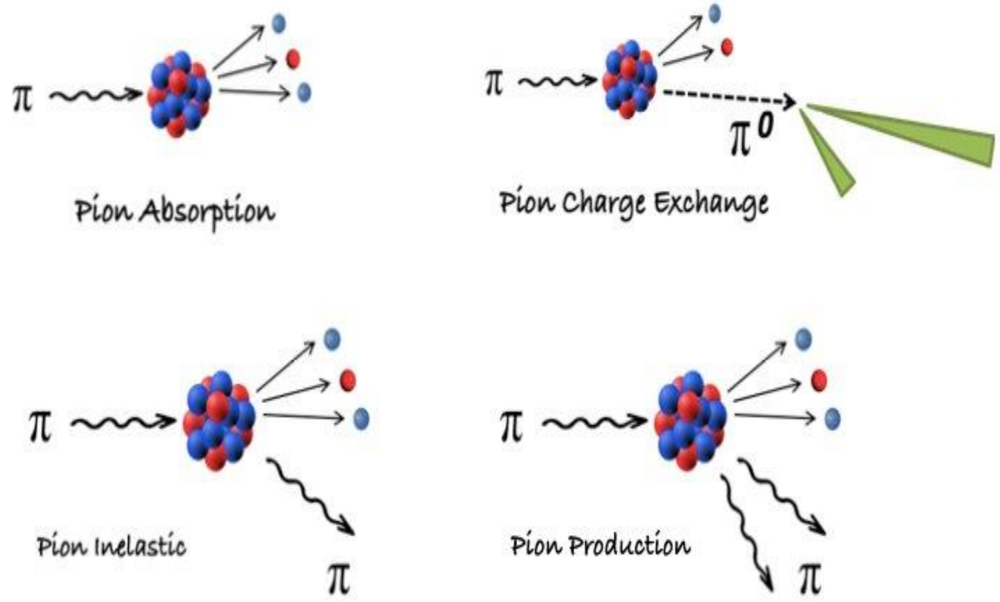






Motivation: Why Study Pion Photoproduction?

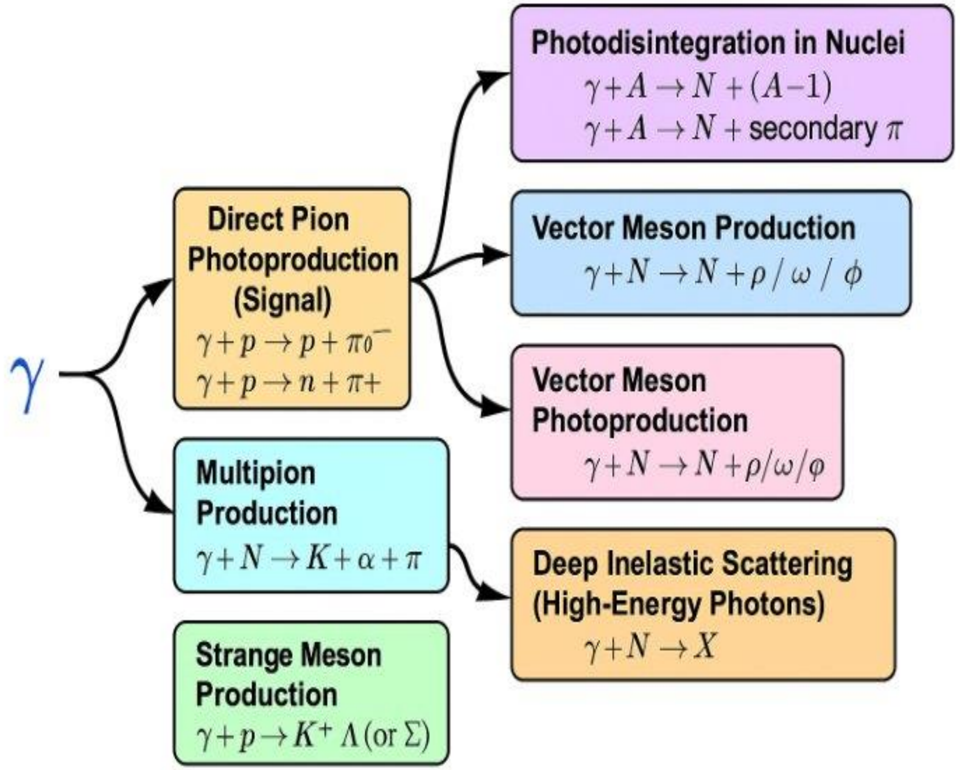
- Probe nucleon structure and test **Quantum Chromodynamics (QCD)** in the **low energy regime**.
- Central Importance in understanding **neutrino-nucleus interactions.**
- Understanding **nuclear effects** in water Cherenkov detectors.
- Provide critical input for testing models of hadronic structure.
- Essential for **controlling systematics** in future neutrino oscillation experiments.



Some Possible Pion interactions in water

Pion Photoproduction Channels

- Below are the possible **pion photoproduction** channels:
  - ☐ **$\gamma + p \rightarrow p + \pi^0$,**
  - ☐ **$\gamma + p \rightarrow n + \pi^+$,**
  - ☐ **$\gamma + n \rightarrow n + \pi^0$,**
  - ☐ **$\gamma + n \rightarrow p + \pi^-$**
- Incident photon interacts with a proton or neutron producing charged or neutral pions.



Gamma interactions in water

Cross-Section Calculation for Pion Photoproduction

- For a tagged photon beam, the **cross section** for the pion photoproduction process can be estimated using: $\boxed{d\Omega/d\sigma = N_{signal}/\mathcal{L}\cdot\Delta\Omega\cdot\epsilon}$

- Where, **N_{signal}** is the **number of signal events** after background subtraction.

- **L** is the **integrated luminosity** and can be determined as follows:

$$\boxed{\mathcal{L} = N\_\gamma \times n\_t}$$

Number of incident tagged photons **Target density**

- **ΔΩ** is the **solid angle** bin size.

- Overall **detection efficiency** can be computed as follows:

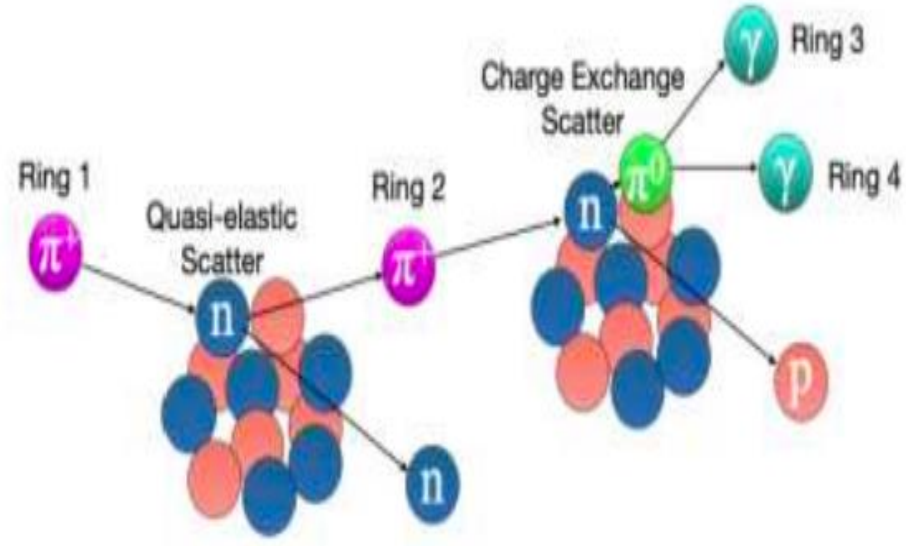
$$\boxed{\varepsilon = A \times \varepsilon\_rec \times \varepsilon\_PID}$$

selection efficiency

Detector acceptance **Reconstruction efficiency**

Pion Photoproduction Cross-Section Measurement Steps

- ☆ Event Selection Strategy
- Methodology: Particle Identification Ring Reconstruction Technique
- Background Estimation
- Systematic Uncertainties



Event Signatures for Pion Photoproduction

1. Π^0 photoproduction signature: **γ + p → p + π^0; π^0 → γ + γ**

- Two **electromagnetic showers** from the γ → e^+e^- conversions.
- This produces **two e-like Cherenkov rings**.
- **Key signature**: purely e-like topology, no delayed Michel electron.

2. Π^+ photoproduction signature: **γ + p → n + π^+; π^+ → μ^+ + v_μ, then μ^+ → e^+ + v_e + v̄_μ**

- π^+ itself can produce a **sharp, well-defined μ-like ring** if it's above Cherenkov threshold.
- **If it slows down and stops:** π^+ → μ^+ + v_μ (lifetime ~26 ns).
- **Key signature**: μ-like ring, delayed e^+, sometimes hadronic activity

3. Π^- photoproduction signature: **γ + n → p + π^-**

- π^- above Cherenkov threshold: sharp **μ-like ring.**
- **When it stops:** it is captured by a nucleus instead of decaying.
- **Key signature**: μ-like ring **without** delayed Michel e^-, often **nuclear capture signature**(gammas/neutrons).

Distinction between π^0,π^+ and π^- events in the detector

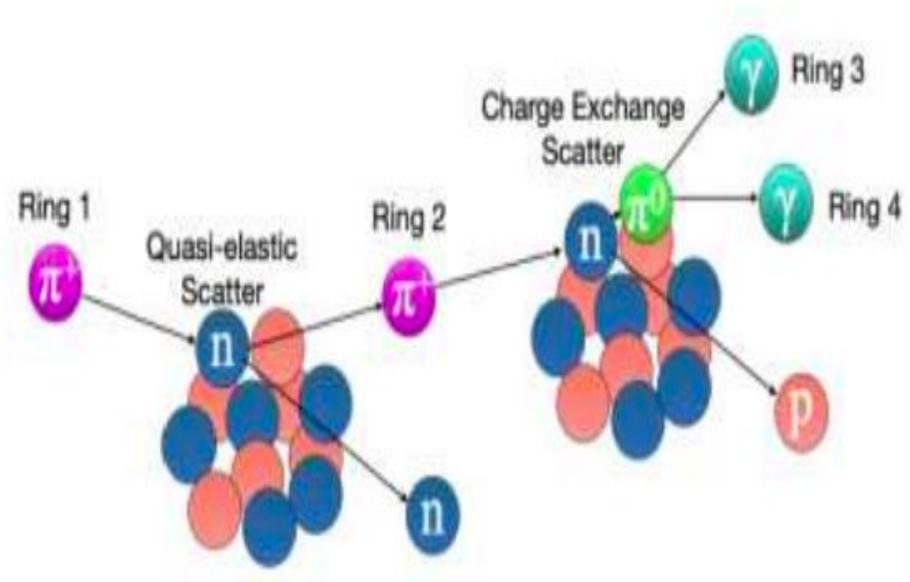
- Table below shows the **final state signature** and **detector observables** for neutral/charged pion production:

Event Type	**Final State Signature**	**Detector Observables**
Π^0 production	2 fuzzy e-like rings	Two EM showers
Π^+ production	μ-like ring	Michel electron
Π^- production	μ-like ring (if fast)	No michel electron but possible neutron capture

Summary Table showing distinction between Π^0,Π^+ and Π^- events in the detector

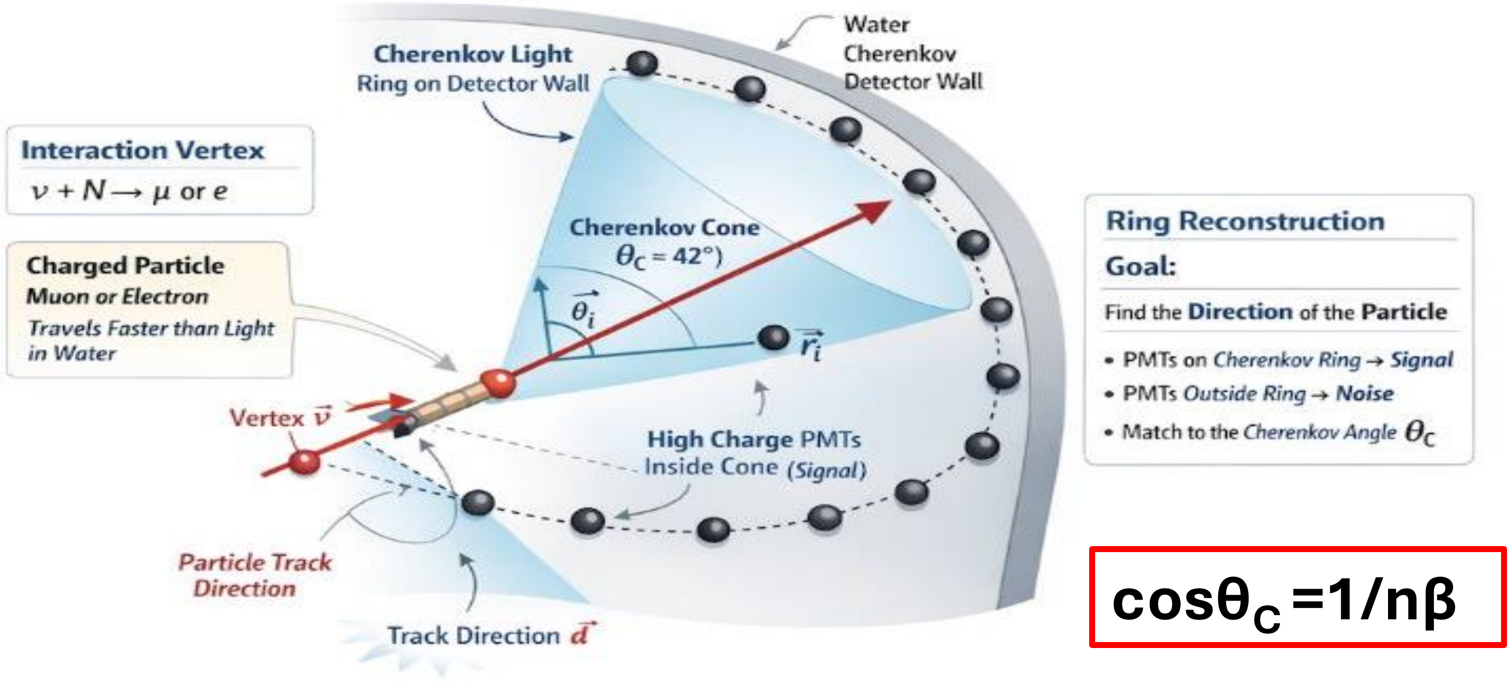
Pion Photoproduction Cross-Section Measurement Steps

- Event Selection Strategy
- Methodology: Particle Identification Ring Reconstruction Technique
- Background Estimation
- Systematic Uncertainties

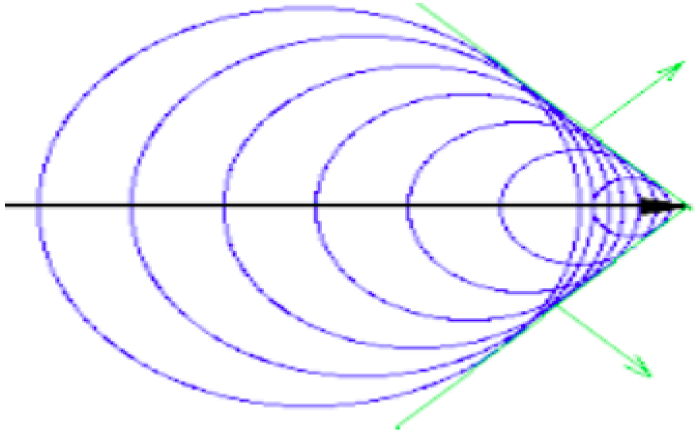


Methodology: Preliminary Ring Reconstruction Technique

- Charged particles in a Water Cherenkov Detector originate at **random positions** in the detector volume.
- The vertex of these particles will correspond to the **centre** of the largest circle.
- Shape of Cherenkov ring produced would identify **particle type** (eg, electron, muon or pion).
- Electron rings are **fuzzier** (due to showers) compared to muon or pion rings.



$$\boxed{\cos\theta_C = 1/n\beta}$$



Cherenkov Ring Reconstruction in Water Cherenkov Detectors

Cherenkov Radiation Wavefront

Preliminary Ring Reconstruction Algorithm

Preliminary Ring Reconstruction Algorithm

Step 1:

Select PMT hits **above** charge threshold

Preliminary Ring Reconstruction Algorithm

Step 1:

Select PMT hits **above** charge threshold

Step 2:

Estimate **Event Vertex** (using timing fit)

Preliminary Ring Reconstruction Algorithm

Step 1:

Select PMT hits **above** charge threshold

Step 2:

Estimate **Event Vertex** (using timimg fit)

Step 3:

Project **PMT hit positions** into angular space

Preliminary Ring Reconstruction Algorithm

Step 1:

Select PMT hits **above** charge threshold

Step 2:

Estimate **Event Vertex** (using timing fit)

Step 3:

Project **PMT hit positions** into angular space

Step 4:

Search for **Ring Like Structures**

Preliminary Ring Reconstruction Algorithm

Step 1:

Select PMT hits **above** charge threshold

Step 2:

Estimate **Event Vertex** (using timing fit)

Step 3:

Project **PMT hit positions** into angular space

Step 4:

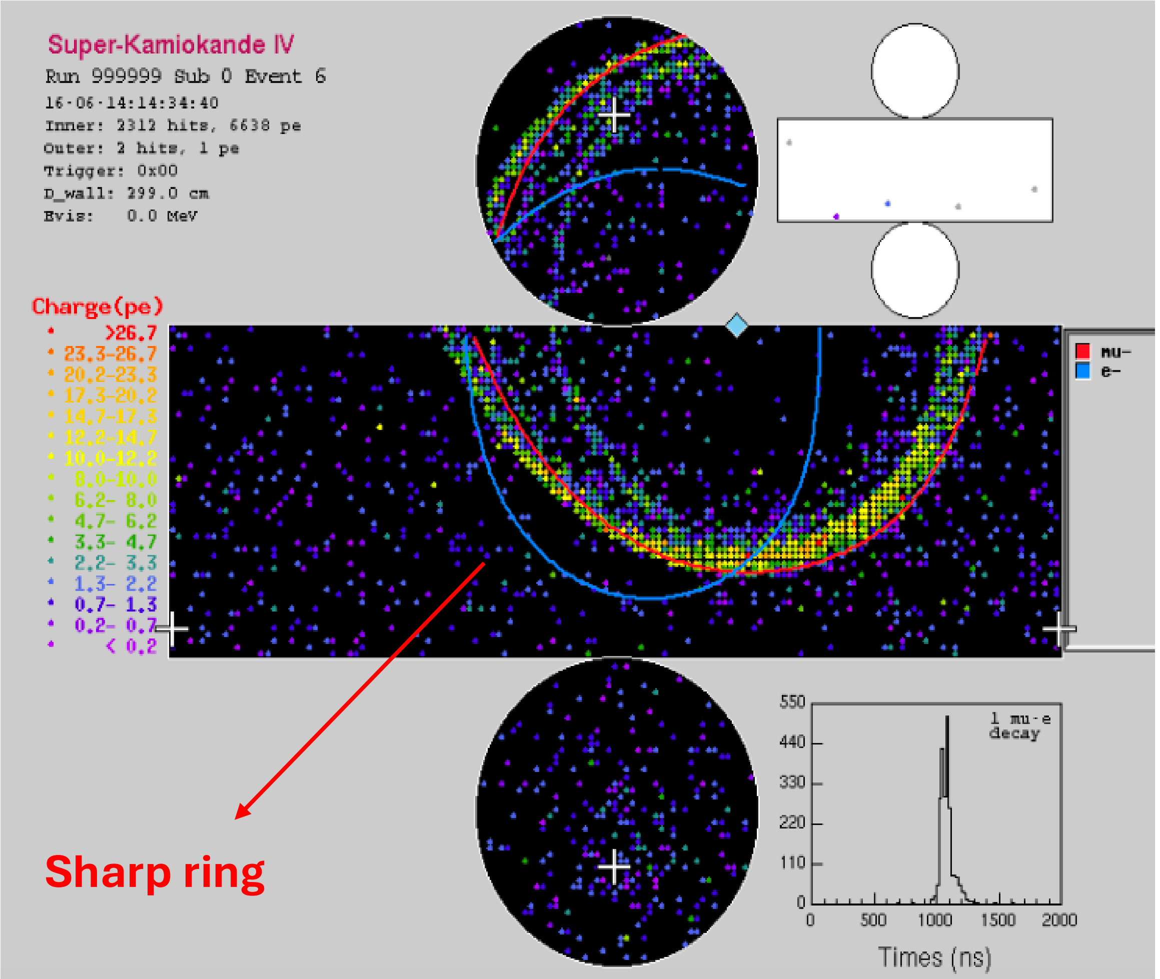
Search for **Ring Like** Structures

Step 5:

Particle Identification using Ring Structure

Super-Kamiokande Event Display

Single Muon display

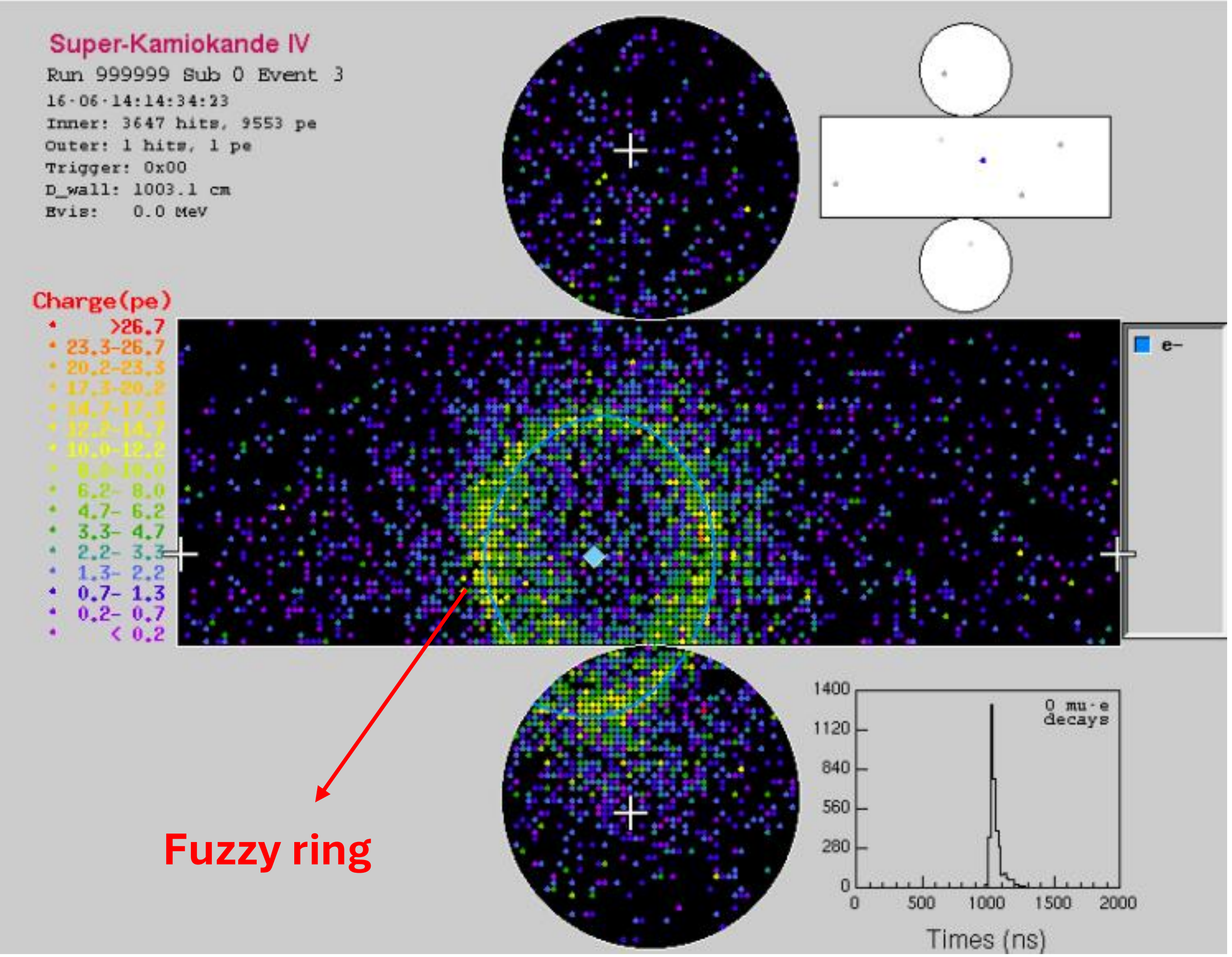


Super-Kamiokande IV

```
Run 999999 Sub 0 Event 6
16-06-14:14:34:40
Inner: 2312 hits, 6638 pe
Outer: 2 hits, 1 pe
Trigger: 0x00
D_wall: 299.0 cm
Evis:   0.0 MeV
```

Sharp ring

Single Electron display



Super-Kamiokande IV

```
Run 999999 Sub 0 Event 3
16-06-14:14:34:23
Inner: 3647 hits, 9553 pe
Outer: 1 hits, 1 pe
Trigger: 0x00
D_wall: 1003.1 cm
Evis:   0.0 MeV
```

Fuzzy ring

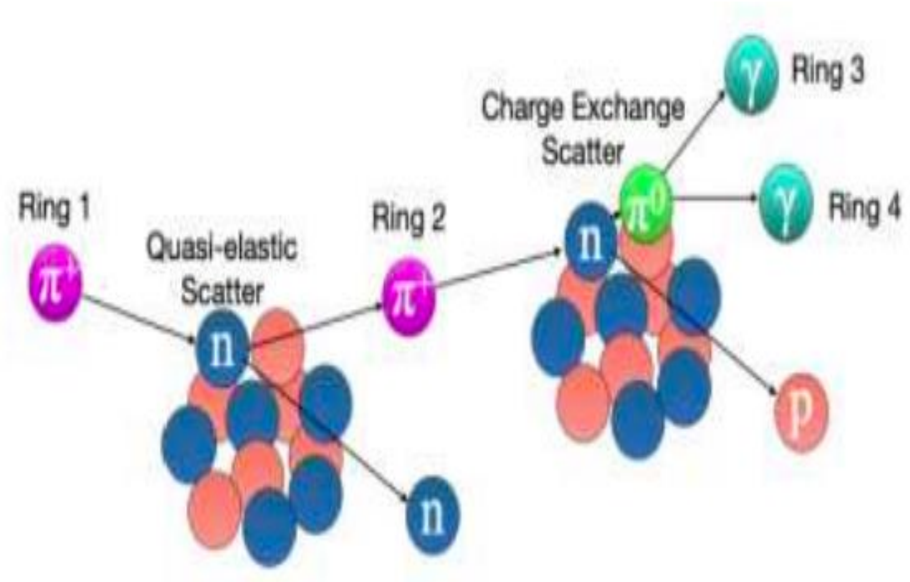
Pion Photoproduction Cross-Section Measurement Steps

Event Selection Strategy

Methodology: Particle Identification Ring Reconstruction Technique

★ Background Estimation

★ Systematic Uncertainties



Possible Backgrounds and Sources of Systematic Uncertainties

1. Possible Backgrounds

- **Neutral Current (NC) interactions or Charged Current (CC) Non-Pion Events** (NC Π^0 production can be misidentified as e-like ring due to $\gamma \rightarrow e^+e^-$ conversion)
- **Pion Absorption(**π^+ or π^- produced but absorbed before exiting nucleus → mimics no-pion events.)
- **Atmospheric Neutrino Backgrounds(**Cosmic ray muons producing pions in the detector)
- **Detector Misidentification(**Ring overlap, i.e., multi-ring events reconstructed as a single ring)

2. Detector-related

- **Energy scale calibration** (PMT gain, water transparency,electronics response)
- **Vertex reconstruction accuracy** (geometry alignment, timingoffsets)
- **Cherenkov light modeling** (photon scattering/absorption, Gd effects)
- **Detection efficiency** (uncertainties from simulation)

3. Physics modeling

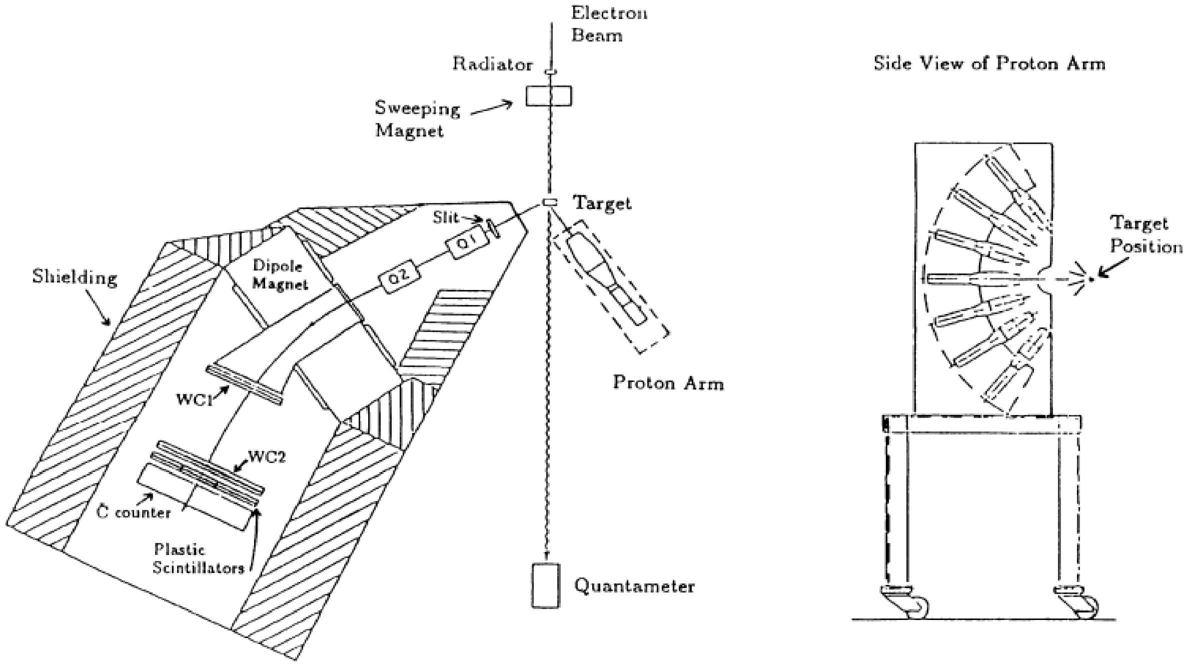
- **Neutrino interaction cross-sections** (QE, RES, DIS,coherent production)
- **Final-state interactions (FSI)** in nucleus (pion absorption,charge exchange)
- **Decay modeling** (Michel electron spectrum, π^0 decayphoton distributions)

4. Simulation & Analysis

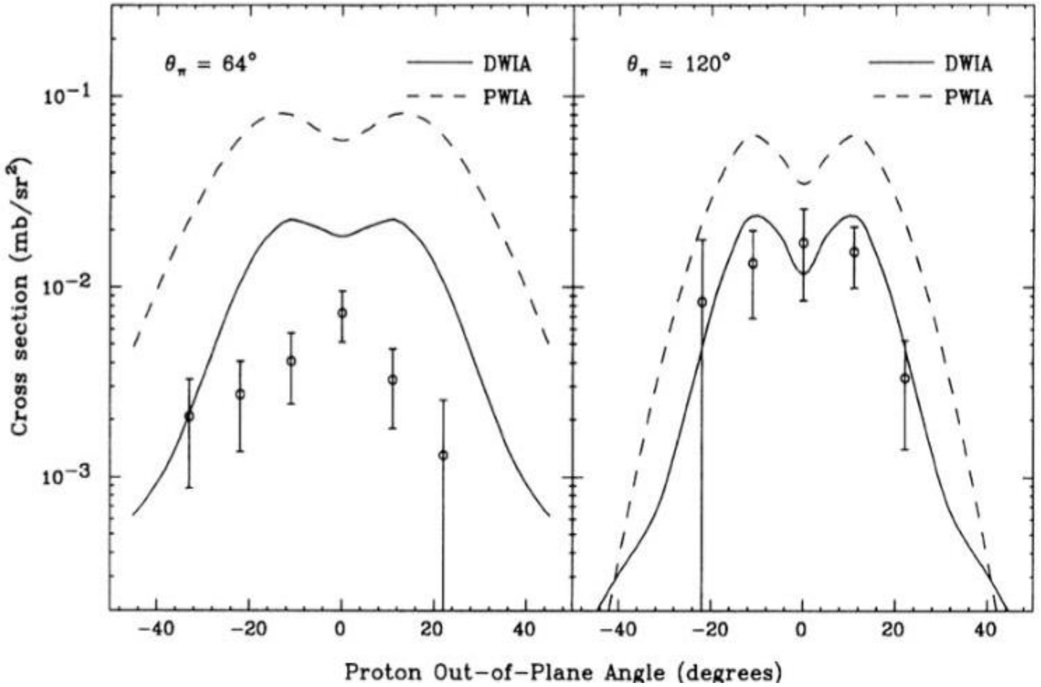
- **GEANT4 simulation**
- **Selection cuts** (PID thresholds, topology classification)

Previous Pion Photoproduction Data on ^{16}O (Phys Rev C, 1992)

- The **Bates Linear Accelerator** measured the **(γ, π$^-$p)** reaction on ^{16}O.
- An **electron beam** passed through a 1.5-mm Al radiator and a 0.13-mm Be viewing screen located upstream of the experimental target.
- End-point energy of the produced **bremsstrahlung photon beam** was about 360 MeV.



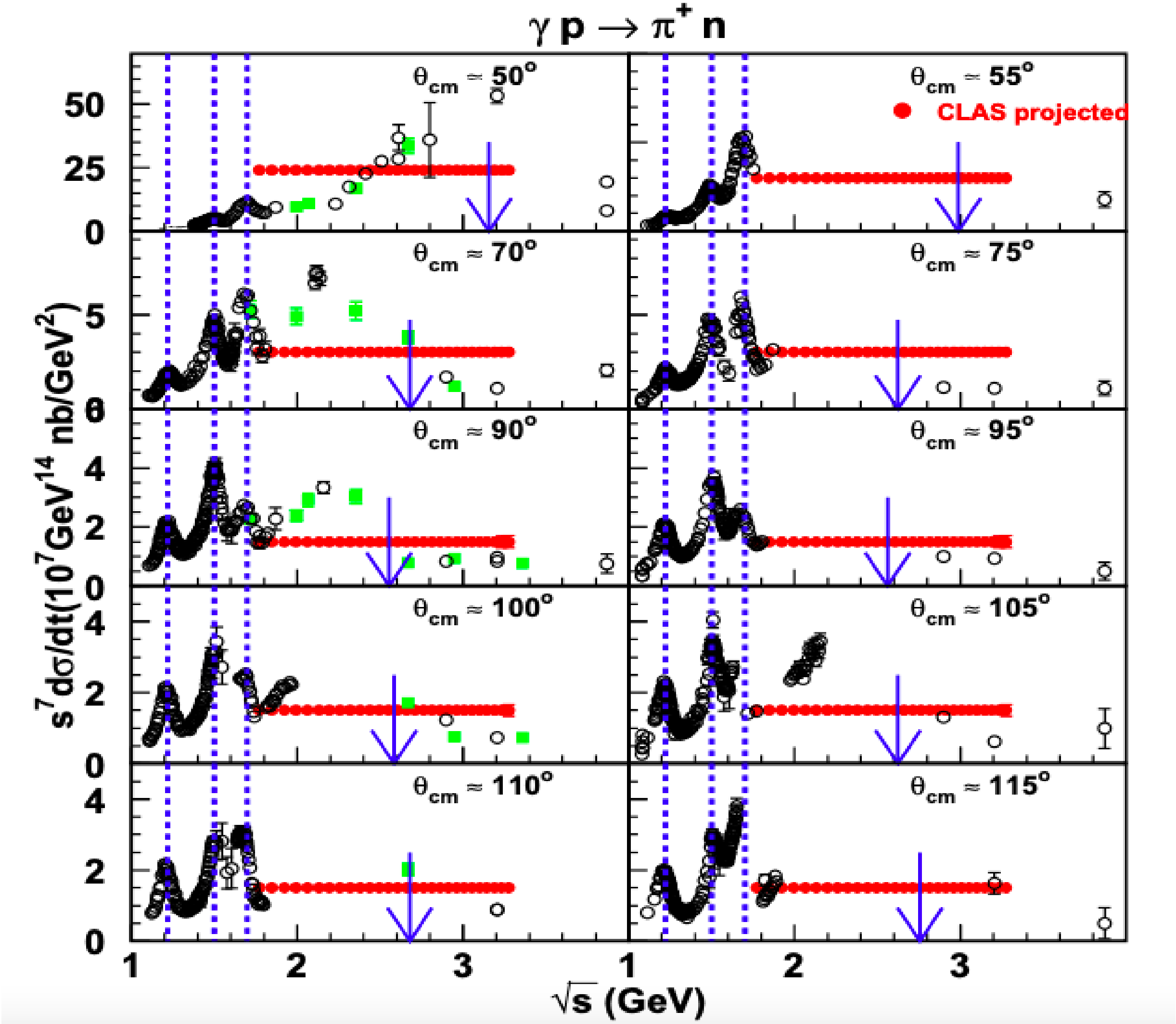
Layout of the ^{16}0(γ, π-p) experiment at the Bates Linear Accelerator Center.



Out-of-plane angular correlations for the 160(y,~-p) reaction at E, = 360 MeV

Previous Pion Photoproduction Data on H (Phys Rev C, 2011)

- The **γp → π^+n** process was studied in **CLAS** using a tagged photon beam.
- The measurement was done on a 40 cm **liquid hydrogen target.**
- This experiment needed **100 hours** (~4 days) of electron beam at **E_0 = 5.7 GeV** with 25 nA current.



Projected results for the γp → π +n process as a function of √ s for different pion centerof-mass angle.

Current and Future Work

Current Work

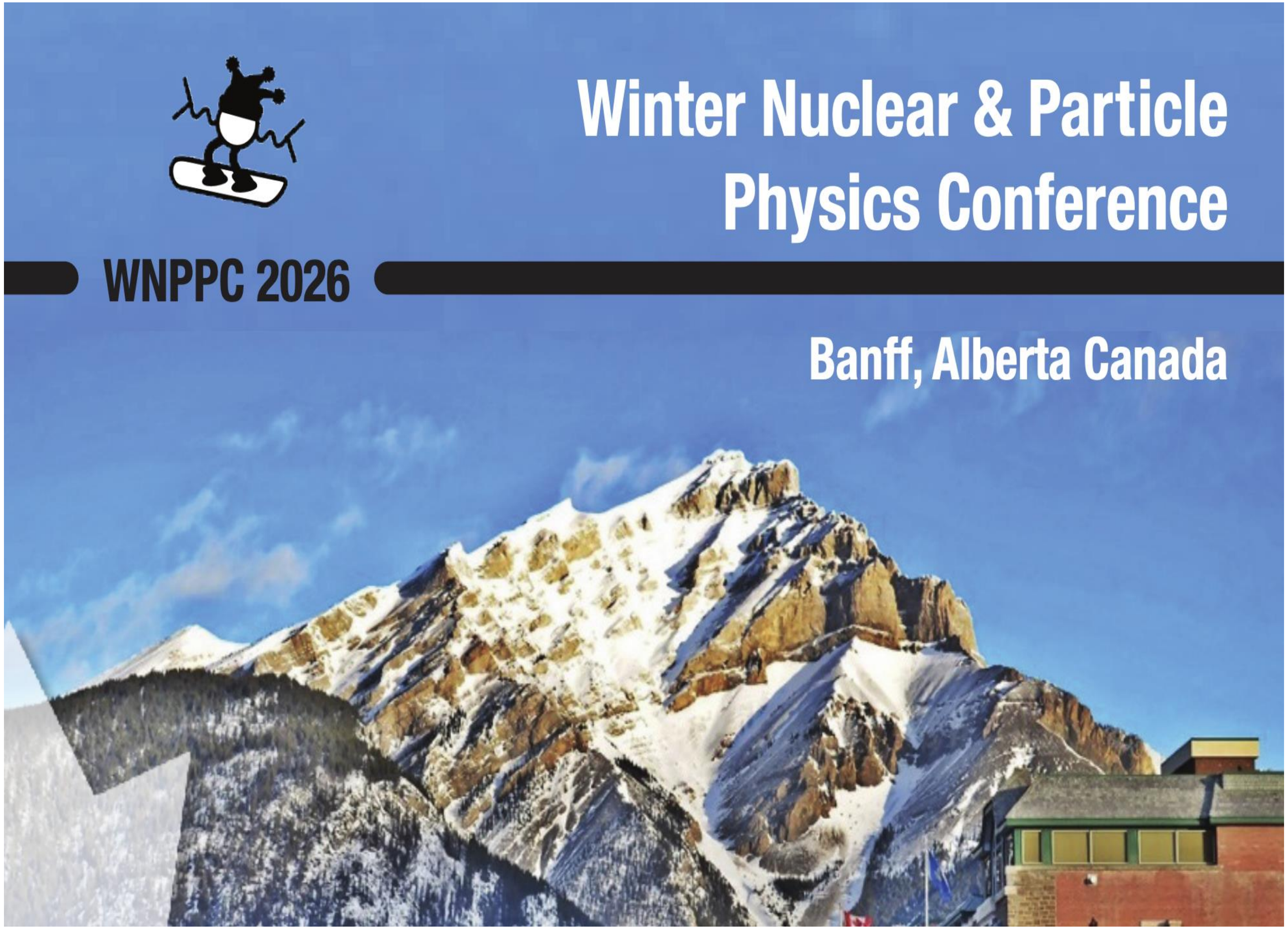
- Analyzing **300 MeV photon events** generated using **WCSim**.
- Studying **detector observables** such as:
  - PMT hit distributions
  - Charge and timing information
  - Ring reconstruction performance
- **Validating reconstruction performance** using **truth-level** Monte Carlo information.

Future Work

- Implement a **vertex reconstruction algorithm** using a **Markov Chain Monte Carlo (MCMC)** approach.
- Develop and test a **likelihood-based** framework for:
  - Reconstructing interaction vertex position
  - Improving angular resolution
  - Optimizing energy reconstruction
- Compare **MCMC-based reconstruction results** with existing fitting methods.
- Extend **analysis framework** to pion photoproduction channels.

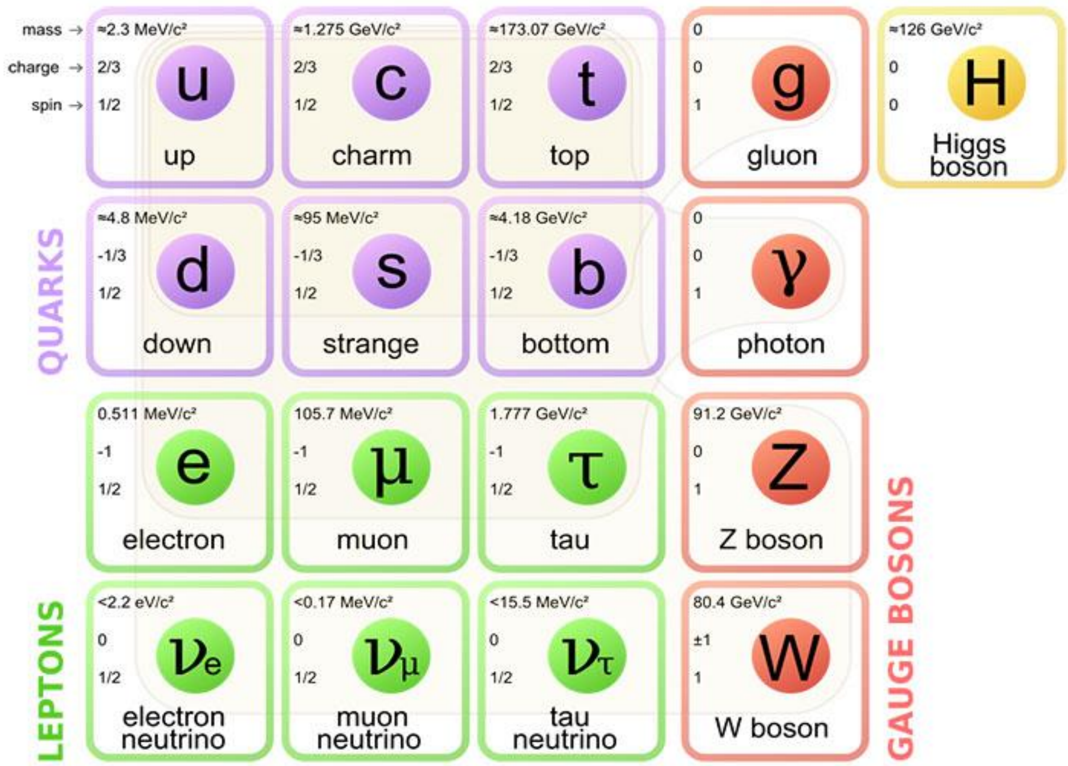
Thank You!

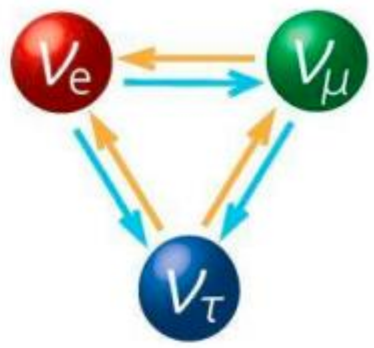
Questions or comments?

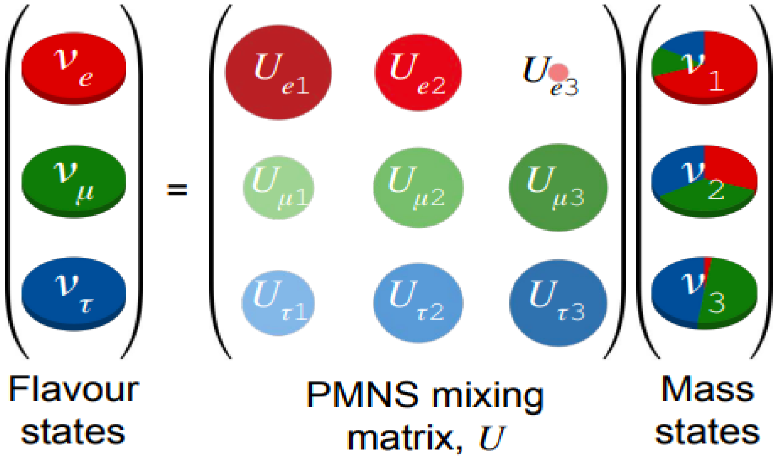


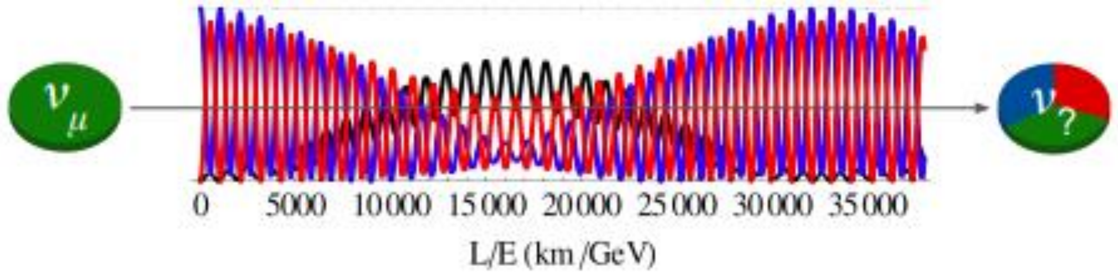
Back Up Slides

Neutrino and Oscillations







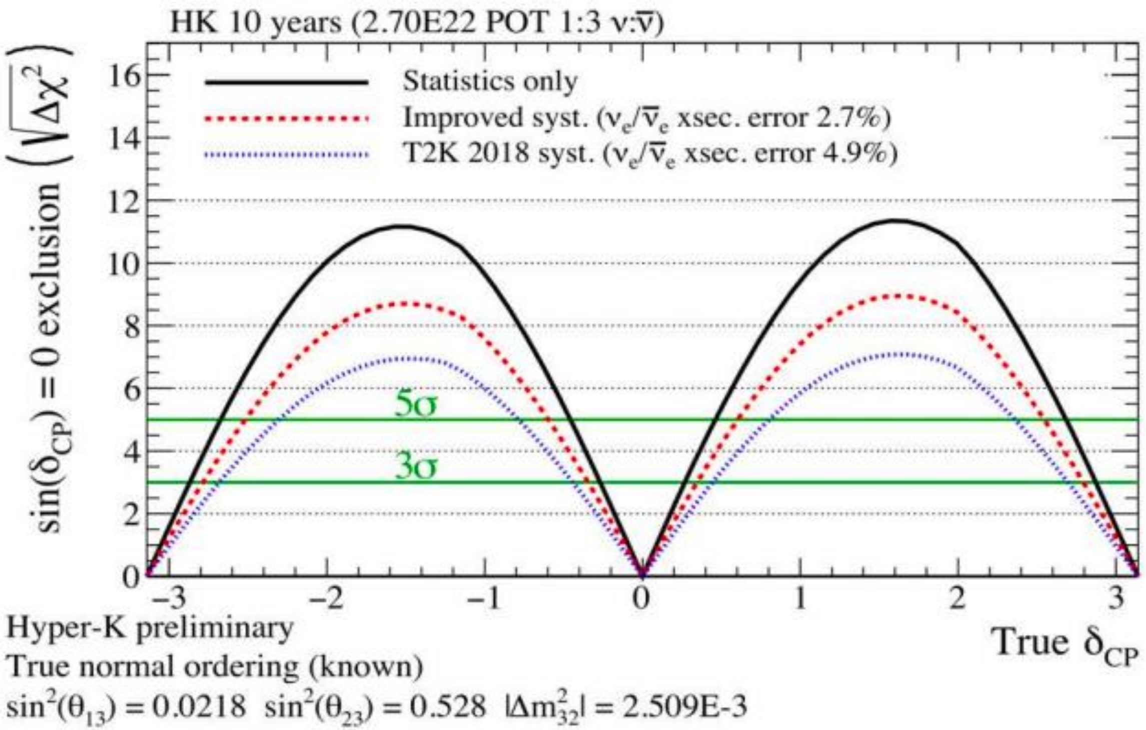


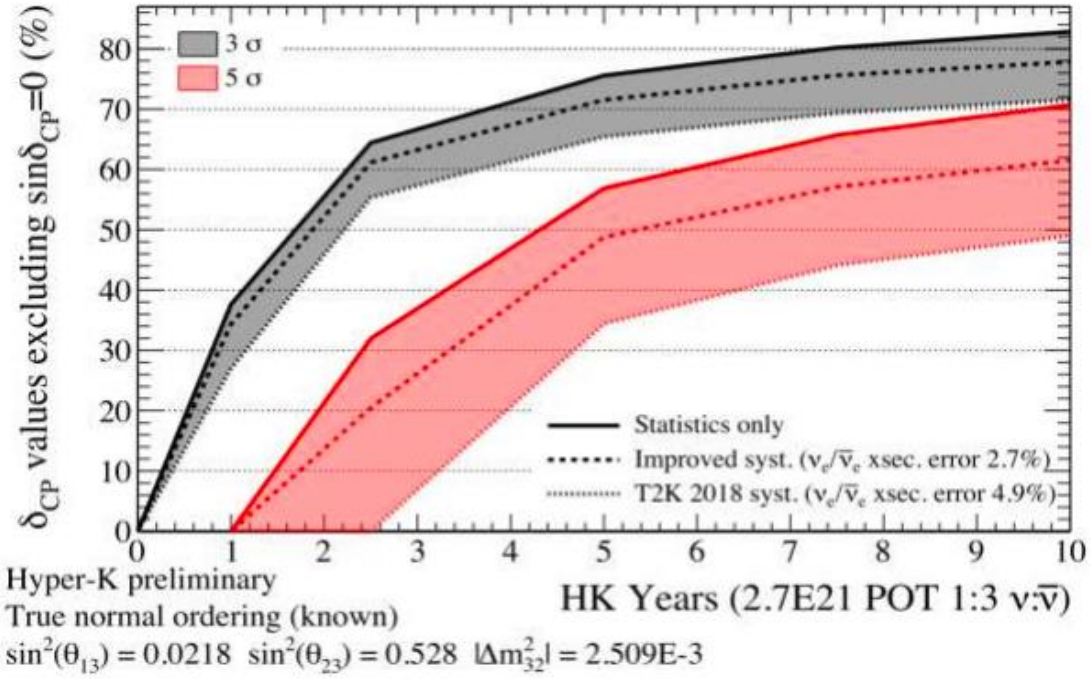
- Neutrino oscillations are a **quantum mechanical phenomenon** in which neutrinos change their flavour.
- Standard Model ν are massless, but their flavours oscillate if
- neutrinos have nonzero mass
- with multiple different mass states
- where each flavour state is a mixture of mass-states

$$P_{\alpha\rightarrow\beta}(L) = \left| \sum_{i=1}^{3} U_{\alpha i}^{*} U_{\beta i} e^{-i\frac{Lm_i^2}{2E_\nu}} \right|^2$$

Neutrino Oscillation Measurements

- Reduction of systematic errors has large impact on potential to discover CP violation
- >5σ discovery after 10 years for 60% of δCP values
- ~8σ around δCP = -π/2 (favoured by T2K measurements)





Intermediate Water Cherenkov Detector (IWCD)

UNDER CONSTRUCTION
2025-2028

- 1 kton water Cherenkov detector, Diameter ~8 m, height ~6 m at 750 m from neutrino target.
- Use mPMTs for readout:
  - -~400 19x8 cm PMTs in a 50 cm PMT housing.
  - - High granularity and timing resolution.