The prospects of the Water Cherenkov Experiment and the status of the calibration sources for the Hyper-K detectors

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"
AGENCIA ESTATAL DE INVESTIGACIÓN
IPC
WCTE
Hyper-K

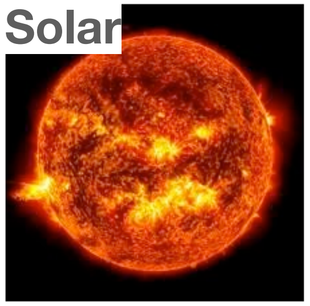
Introduction

- Success of Kamiokande and Super-Kamiokande proving **water-Cherenkov detector technology**
- **Hyper-Kamiokande** (HK) leading neutrino experiment scheduled for 2028:
  - **Huge target mass**
  - Excellent **particle reconstruction** to expand **physics** reach
- Broad and ambitious physics programme covering studies from many neutrino sources and the search for proton decay.

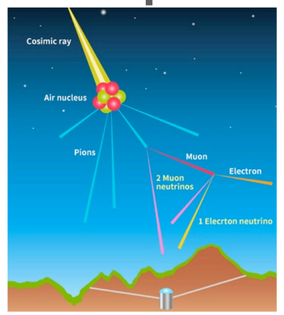
Best limits for proton decay
T2K far detector
Nobel Prize: discovery of neutrino oscillations

Atmospheric and solar neutrino ‘anomaly’
SN1987A
Nobel Prize: detection of cosmic neutrinos

Solar



Atmospheric



Supernova

SUPER-K

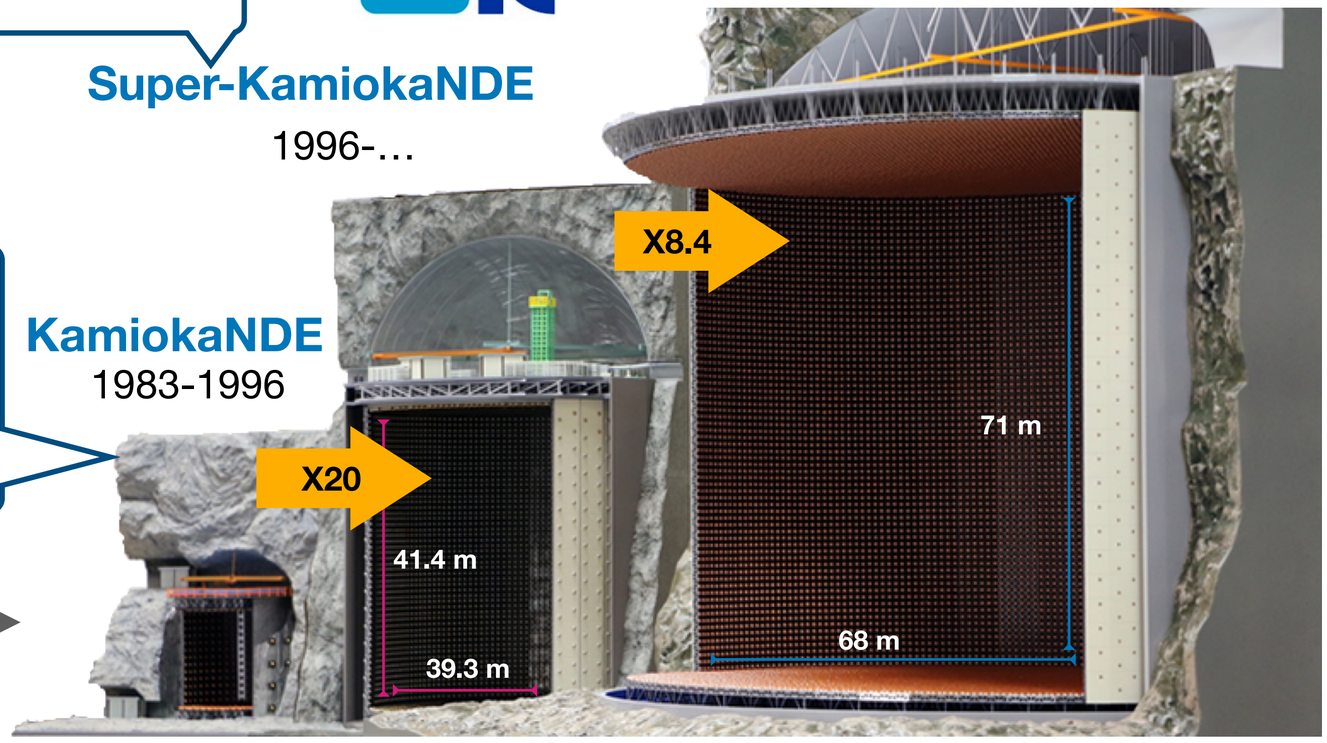
Hyper-KamiokaNDE
~2028

Hyper-K

Super-KamiokaNDE
1996-…

KamiokaNDE
1983-1996

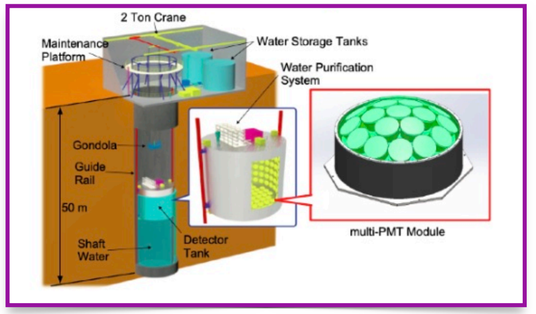
Accelerator



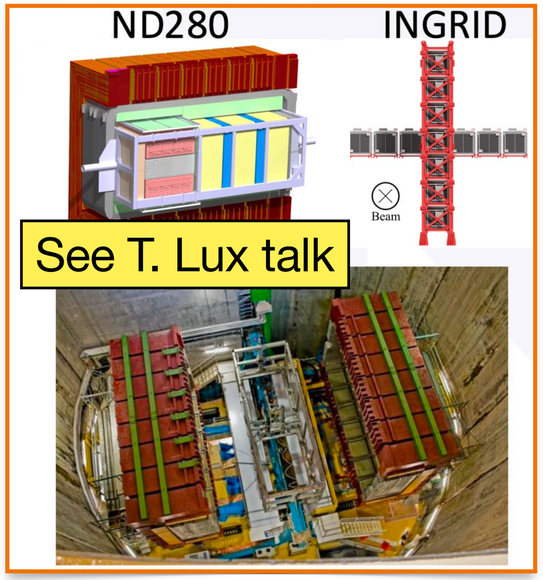
The Hyper-Kamiokande Detectors

- Neutrinos produced at **J-PARC** (Tokai) sent 295km across Japan to the **HK Far** detector (Kamioka).
- **Near** and **Intermediate** help to measure the beam before oscillation.

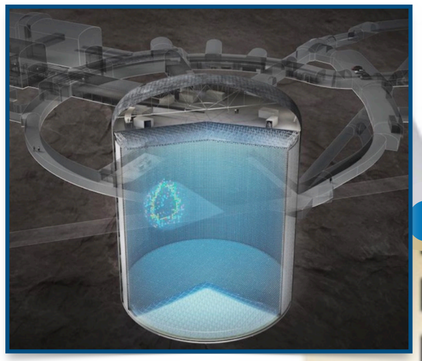
INTERMEDIATE DET.

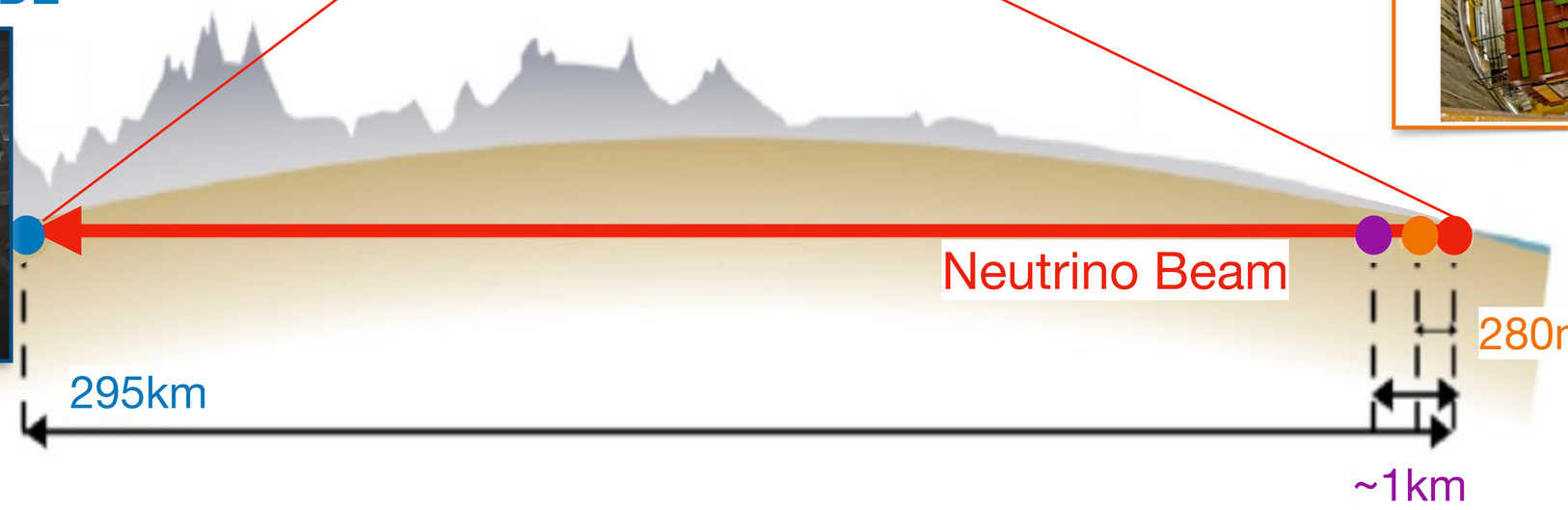


NEAR DET. FACILITY



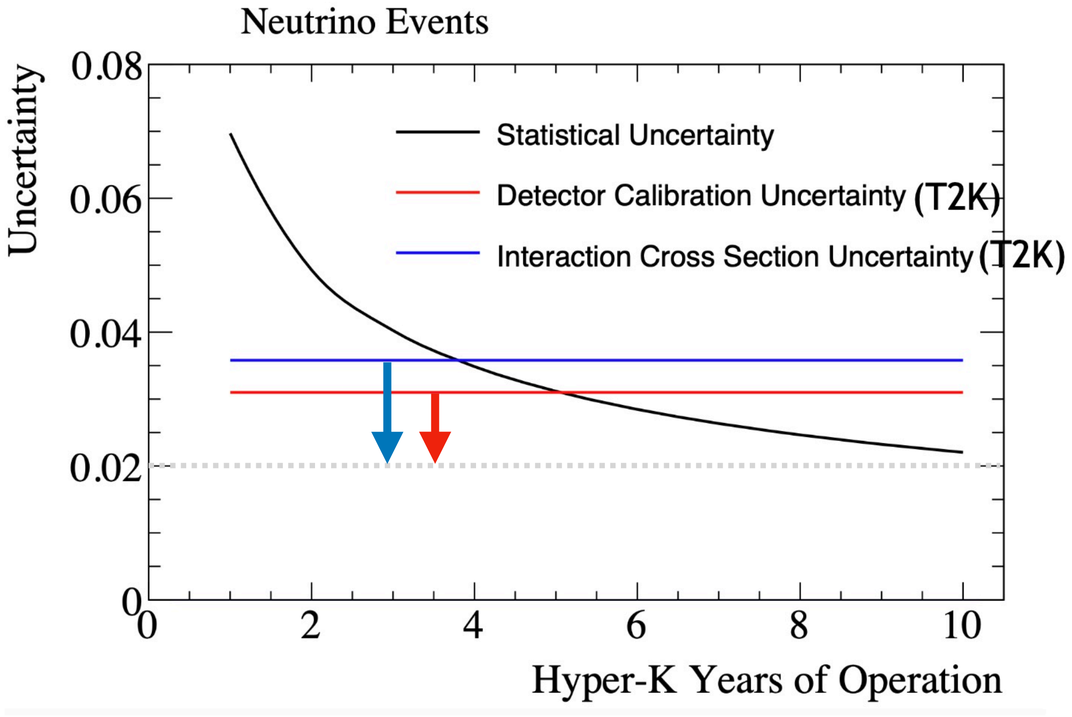
HYPER-KAMIOKANDE





J-PARC

Hyper-K Systematic Uncertainties

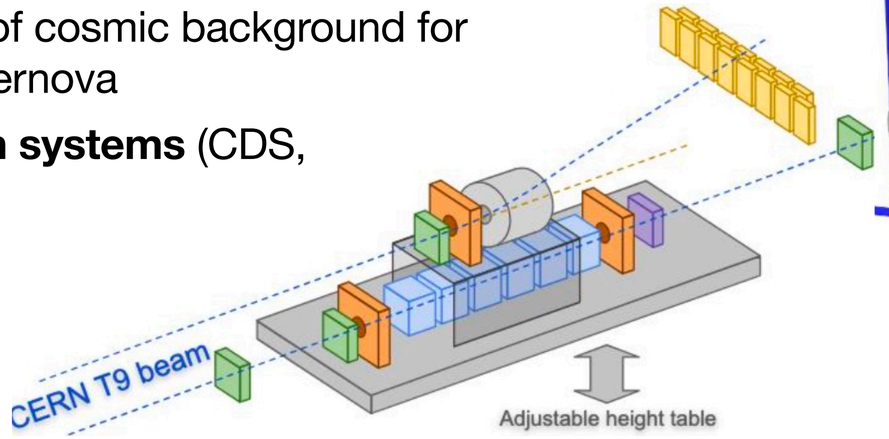


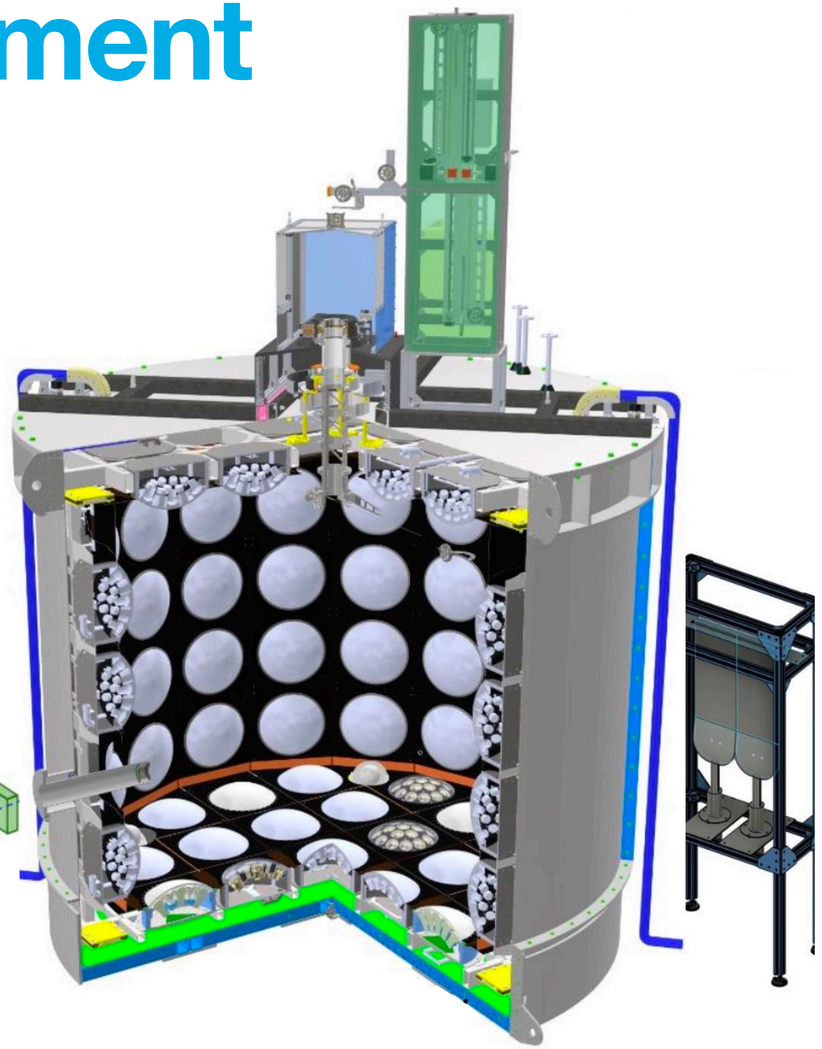
Total systematic uncertainties should be reduced to below 2%

- **Neutrino interaction model uncertainties → Critical to CP violation measurement**
  - ν and $\bar{\nu}$ production to understand ν_μ beam flux, ν_e contamination and 'wrong sign' background
  - ν interaction cross-sections on water for CCQE signal, other CC signal channels and wide array of backgrounds
- **Detector model uncertainties**. Precision understanding is required of
  - Interactions of particles propagating in water.
  - Cherenkov light production of charged particles.
  - Propagation of light through water.
  - Photosensors response to light.
  - Reconstruction of event topologies.

The Water Cherenkov Experiment

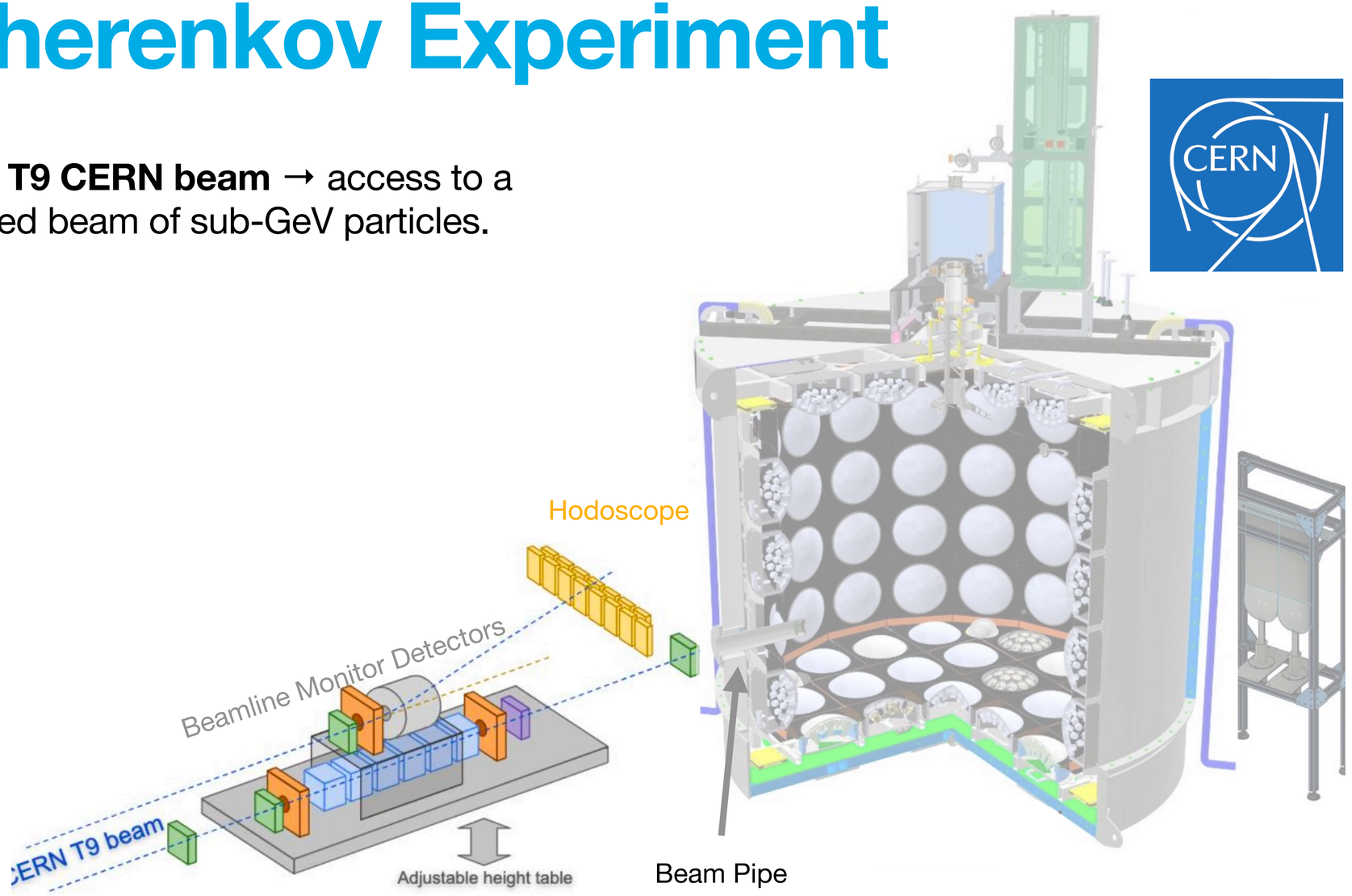
- Proof of concept and demonstration of technologies being developed for **IWCD** and **Hyper-K** and other future detectors.
  - ➡Controlled particle (e, μ, π) samples for precise experimental study of **water Cherenkov responses** and **hadronic/nuclear effects.**
  - ➡Neutron production and interaction in water
    - $\nu/\bar{\nu}$ **tagging by neutrons** → effects of matter in oscillation probabilities
    - e, μ, π **quasi-elastic scattering** → 2p-2h background
    - **9Li production** → study of cosmic background for measurement of relic supernova
  - ➡Test mPMT and **calibration systems** (CDS, sources, photogrammetry).





The Water Cherenkov Experiment

- Water tank located at the end of **T9 CERN beam** → access to a well understood and characterized beam of sub-GeV particles.



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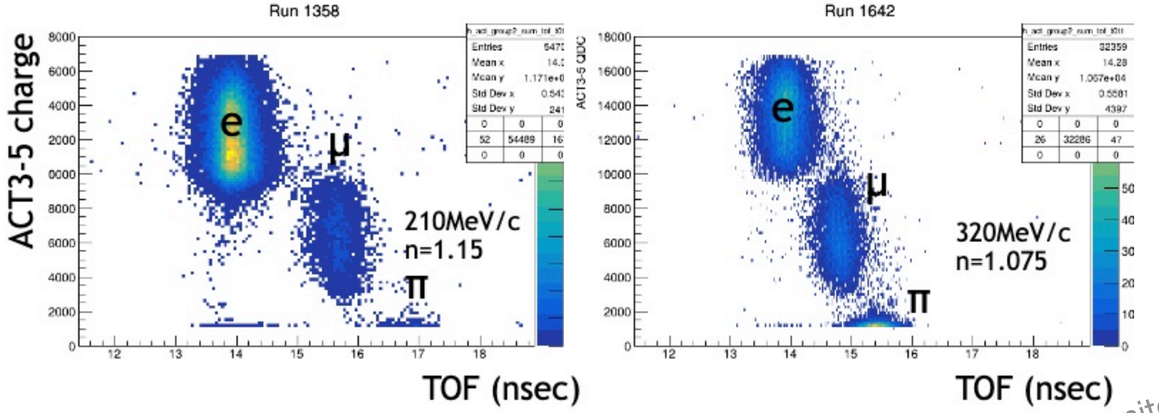

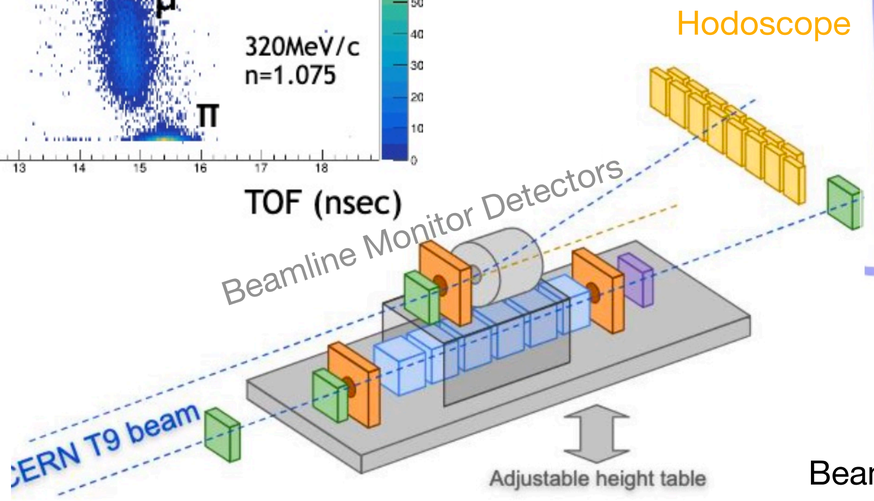

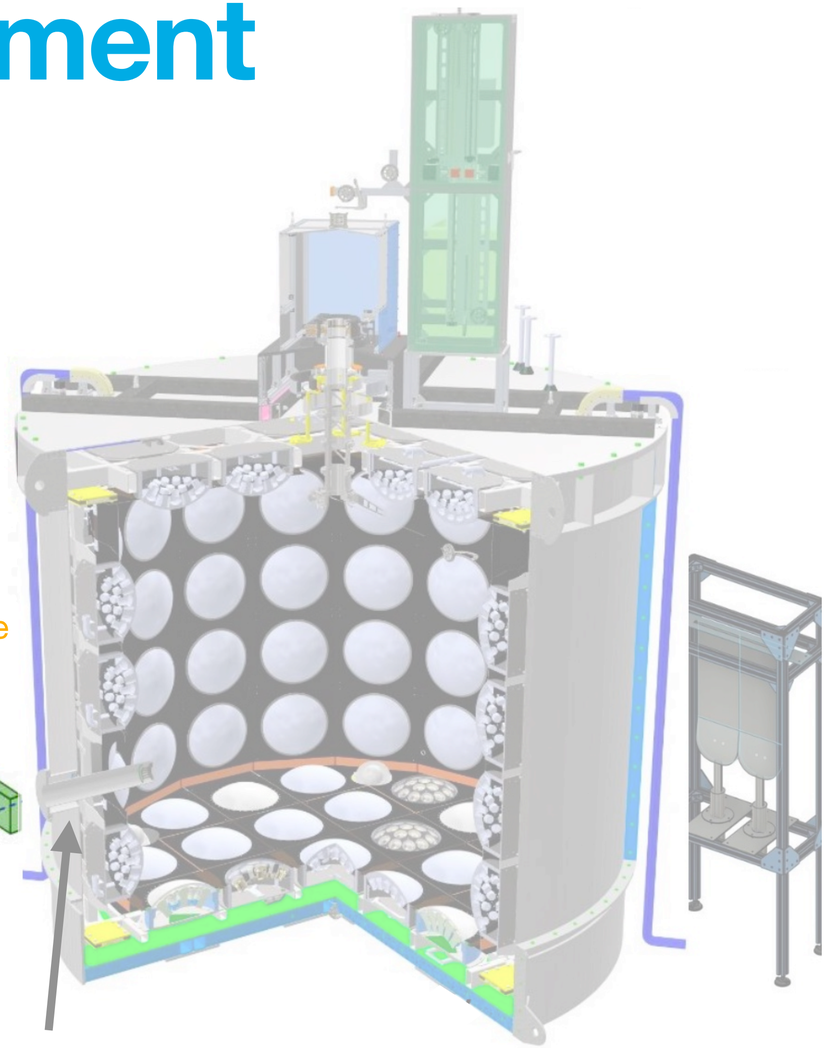

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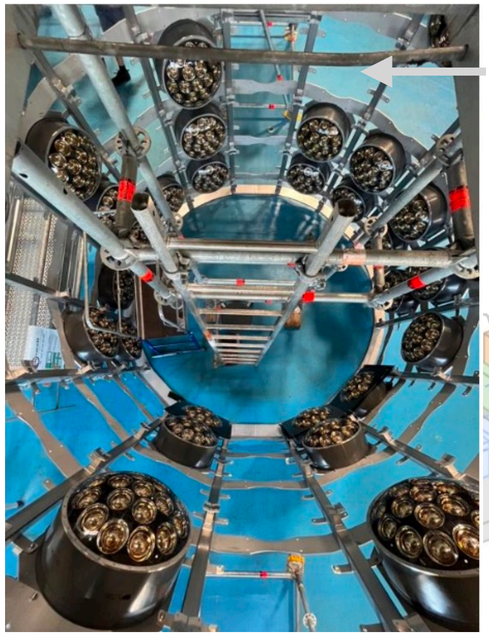

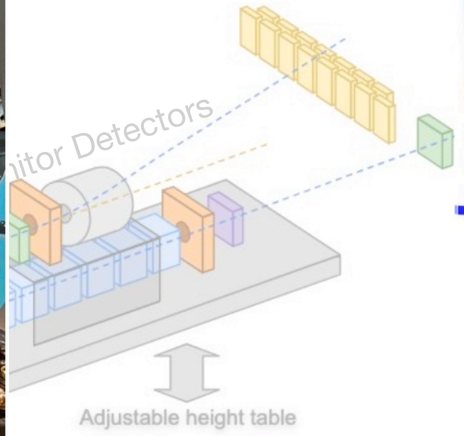

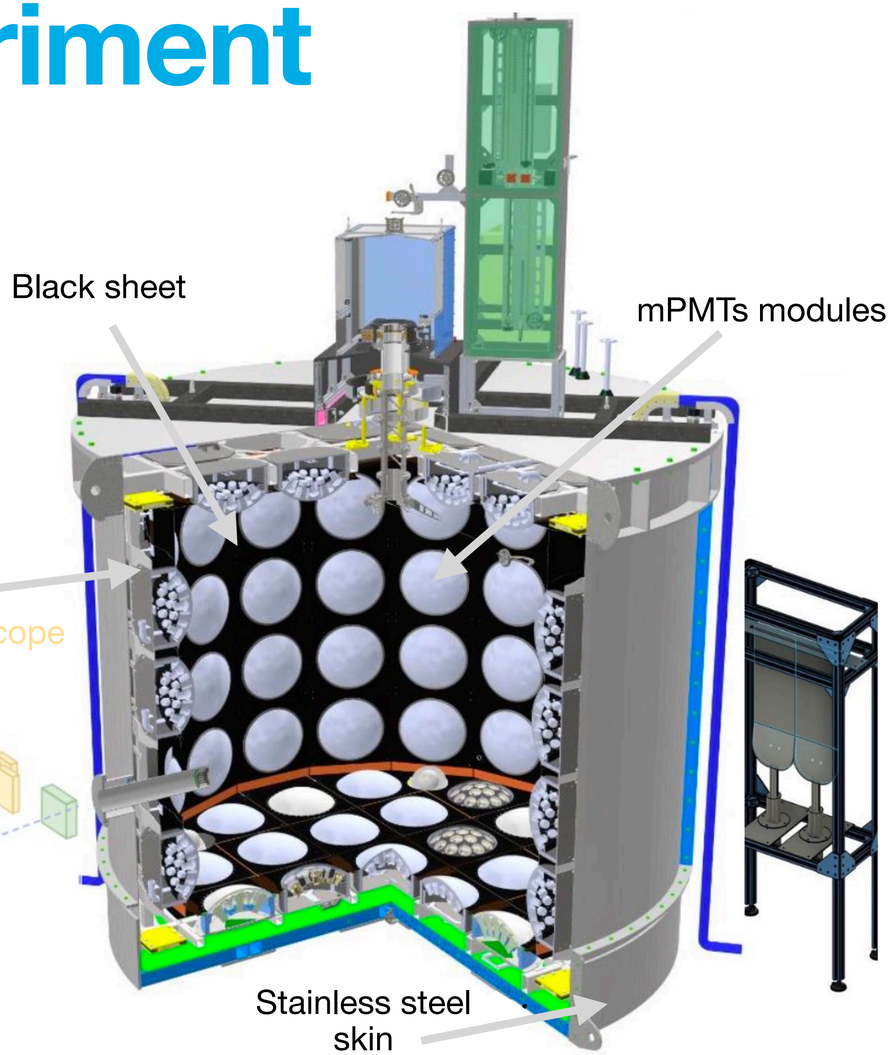

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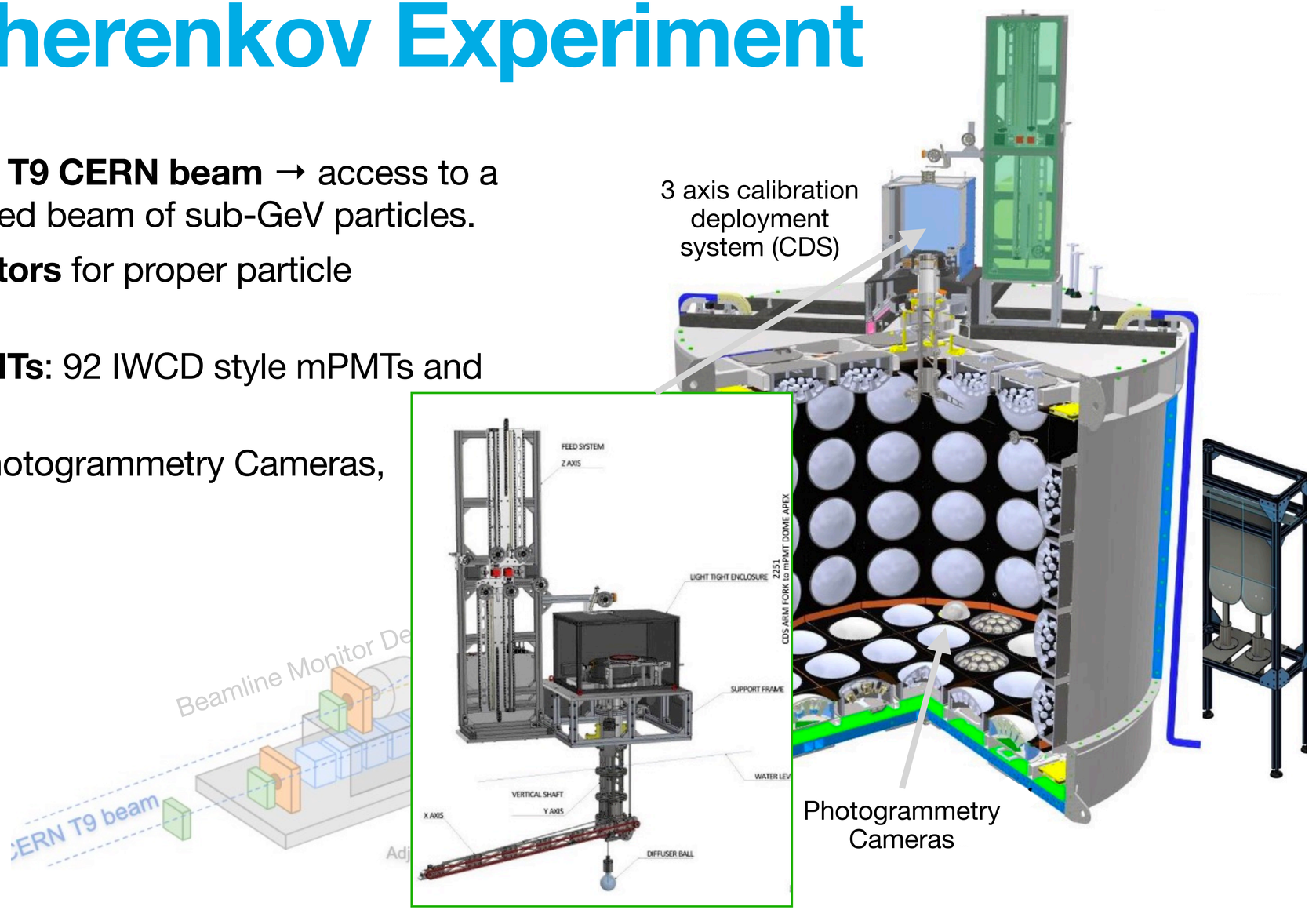

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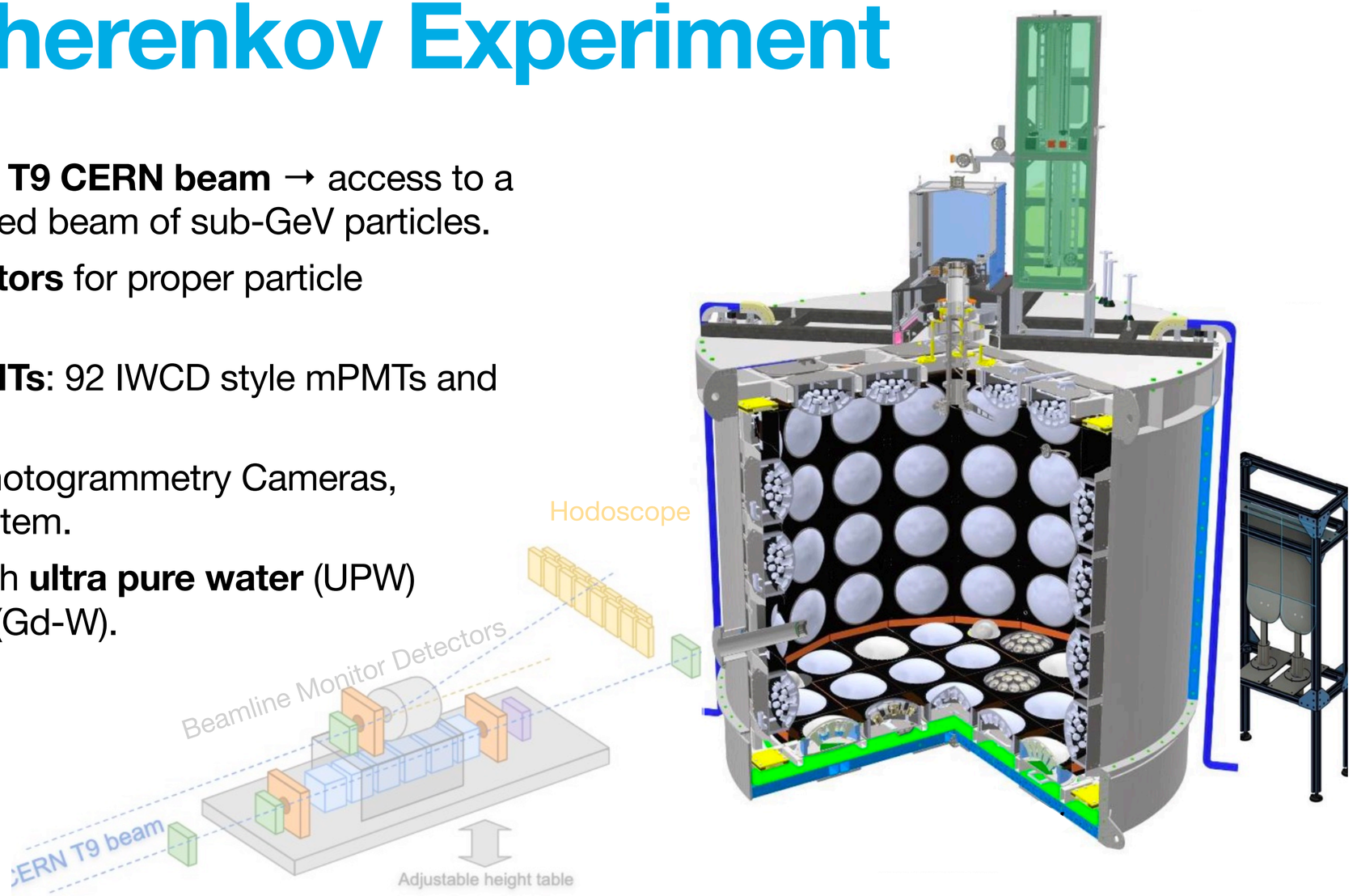
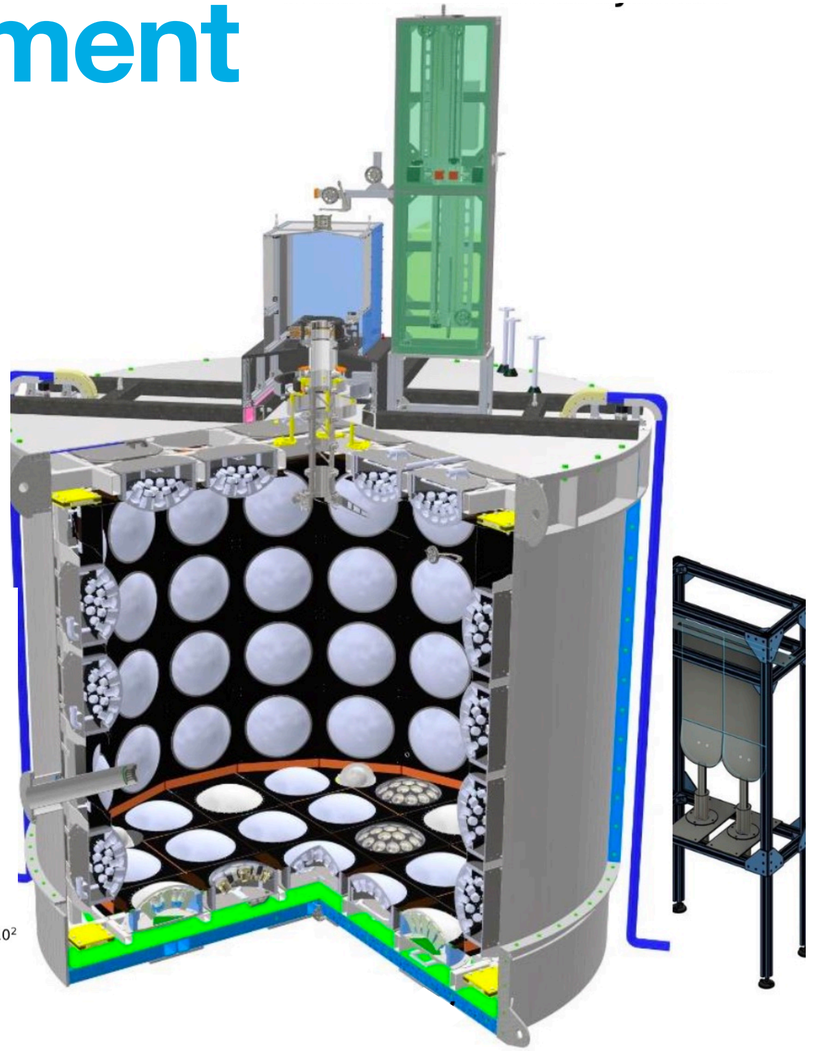
- Detailed **calibration system**: Photogrammetry Cameras, LED, calibration deployment system.
- Two data taking phases: one with **ultra pure water** (UPW) and one with **Gd loaded water** (Gd-W).

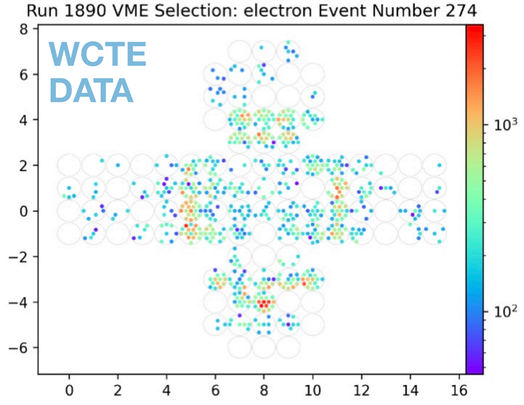


The Water Cherenkov Experiment

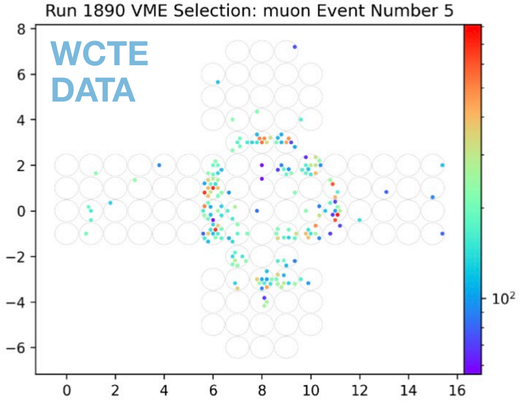
- Detector finished **assembly Sep 2024**, took **beam data** during **fall 2024** and **spring 2025**.
- Predominantly, runs with **UPW mode**. Gd-W data was taken for 1.5 weeks.
- Runs with **beam momentum [200, 1200] MeV/c** with different charged particles. Calibration data taken along data taking campaigns.



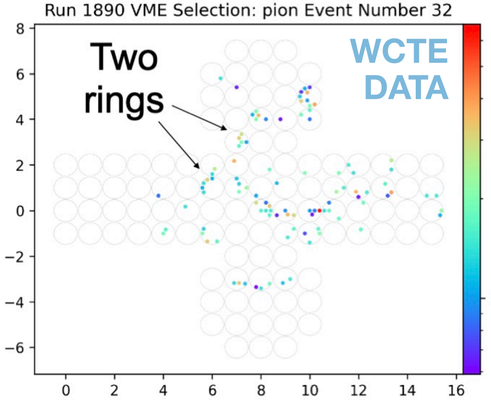
Electron 250 MeV/c



Muon 250 MeV/c

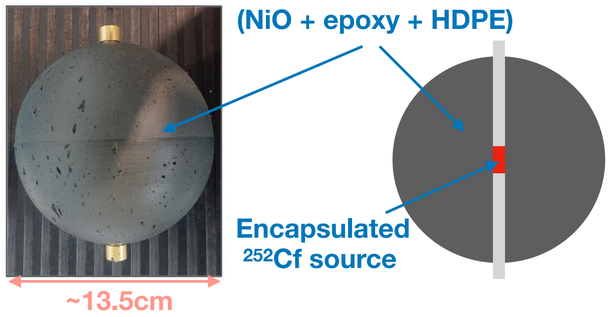


Pion 250 MeV/c



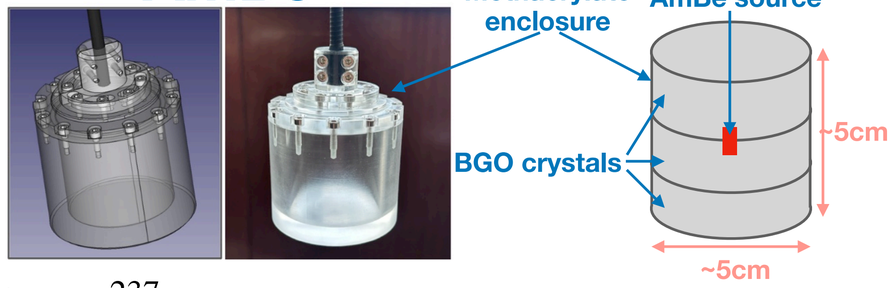
Calibration Radioactive Sources

NiCf



Both sources were produced by USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA, IGFAE, IPC

AmBe



$$n + {}^{58}Ni \rightarrow {}^{59}Ni^{*} \rightarrow {}^{59}Ni + \gamma$$

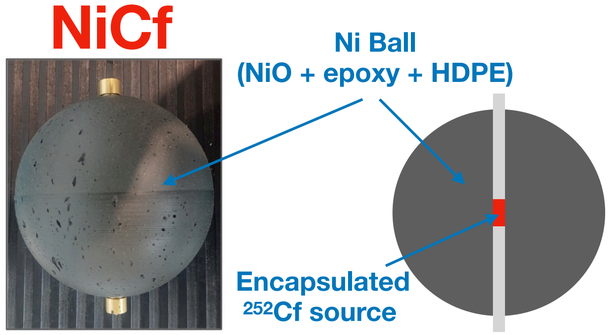
$${}^{241}Am \rightarrow {}^{237}Np + \alpha + \gamma$$

$$\alpha + {}^{9}Be \rightarrow {}^{13}C^{*} \rightarrow {}^{12}C + n + \gamma$$

- Neutrons from ^{252}Cf source thermalised and captured on nickel.
- Gammas of ~9MeV emitted.
- Source designed for **PMT calibration**: isotropic source for SPEs, calibrate relative Quantum Efficiency (QE) and study PMT angular responses.

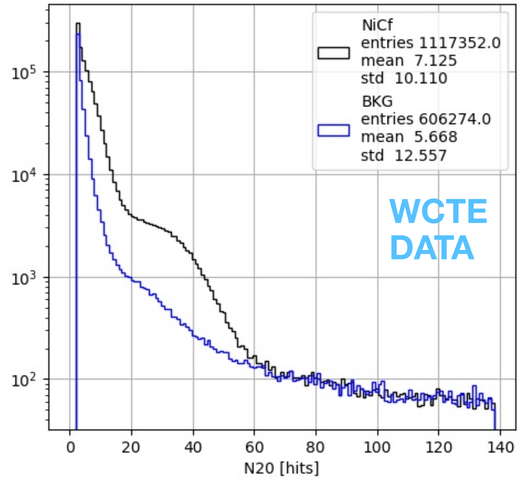
- Gamma + Neutron emitter.
- **Gammas** produce **scintillation light** in every direction thanks to the BGO crystals.
- **Neutrons** are thermalised and **captured** (either H or Gd isotopes).
- Allow to study **neutron captures** and **evaluate neutron capture efficiency.**

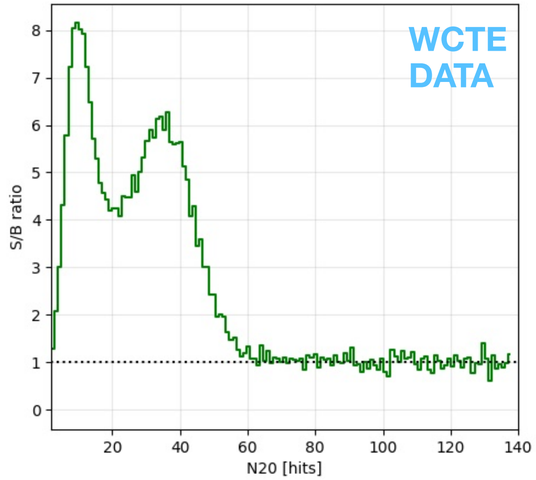
Calibration Radioactive Sources: NiCf

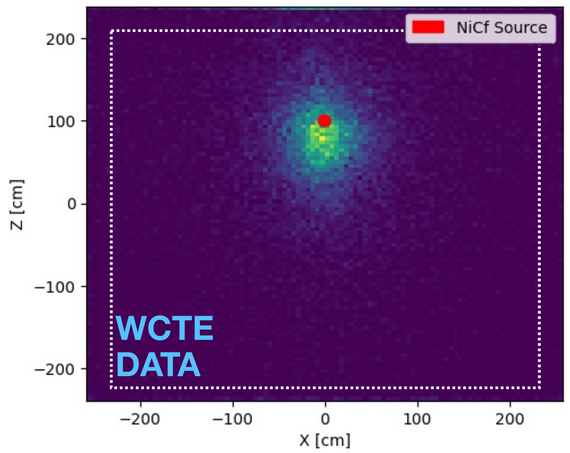


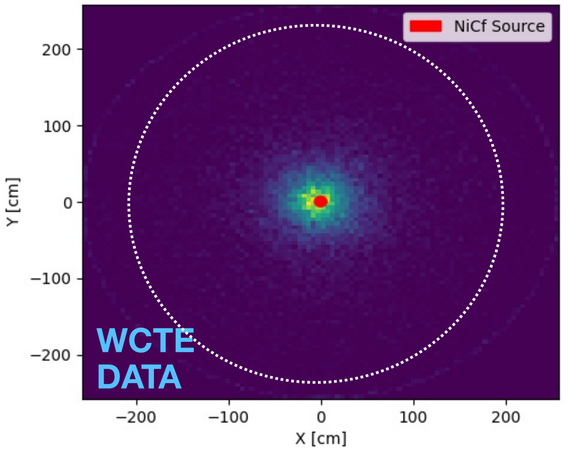
$$n + {}^{58}Ni \rightarrow {}^{59}Ni* \rightarrow {}^{59}Ni + \sum_i \gamma_i$$

- Signal and background runs sampled in time clusters. Number of PMT hits observed in those time clusters allow to **separate** between **candidate events** and **background**.
- Candidate **signal** well **reconstructed** in the **position** of the **detector.**
- Studies of **relative QE** currently **ongoing.**



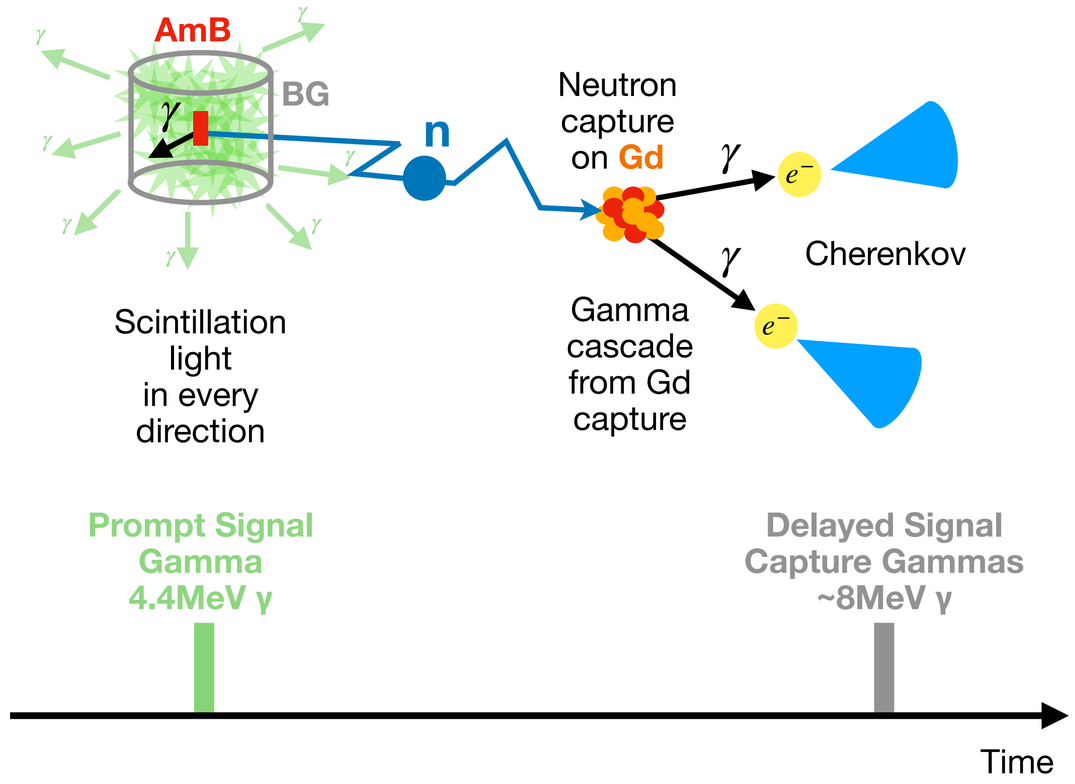


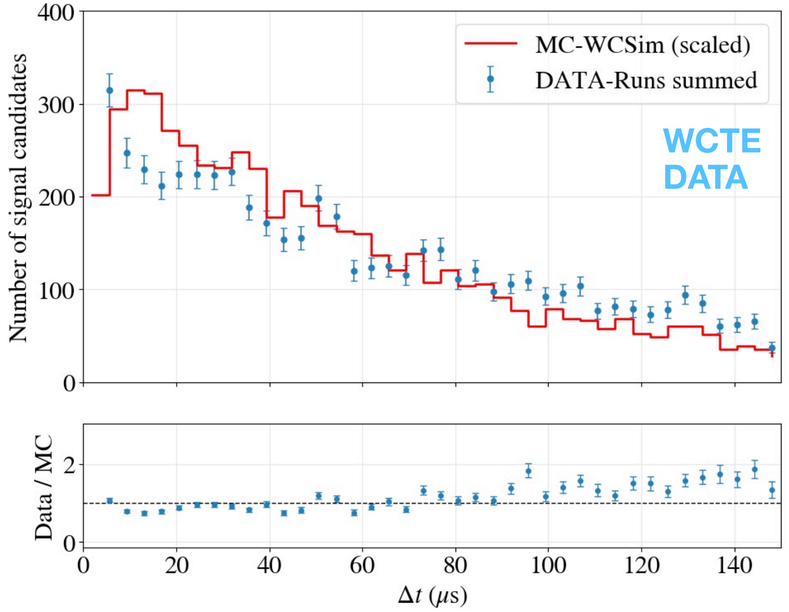


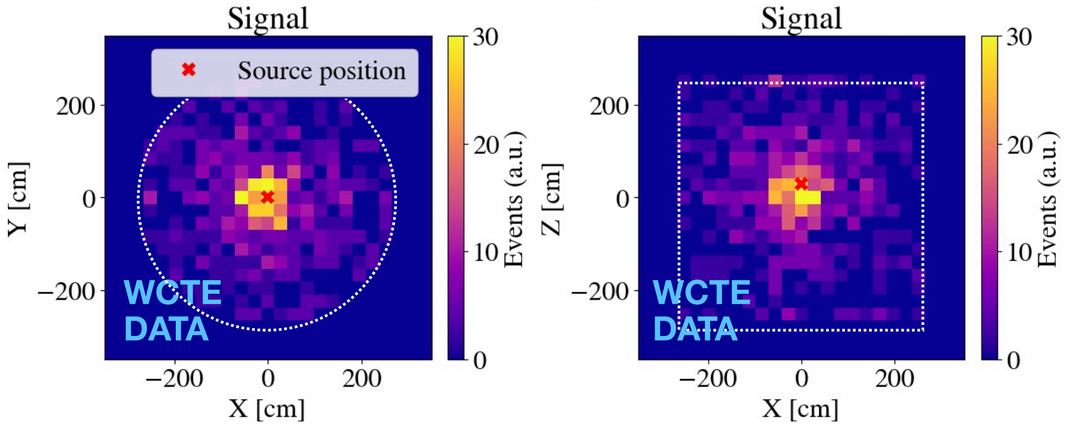


Calibration Radioactive Sources: AmBe

- **Coincidence** code used to search for scintillation **signal** + **neutron** captures in Gd-W.
- Vertex **reconstruction** of the capture events on the tank.

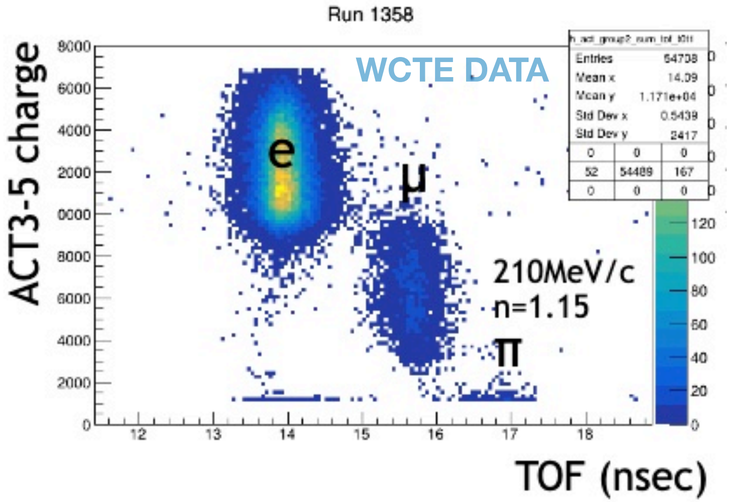


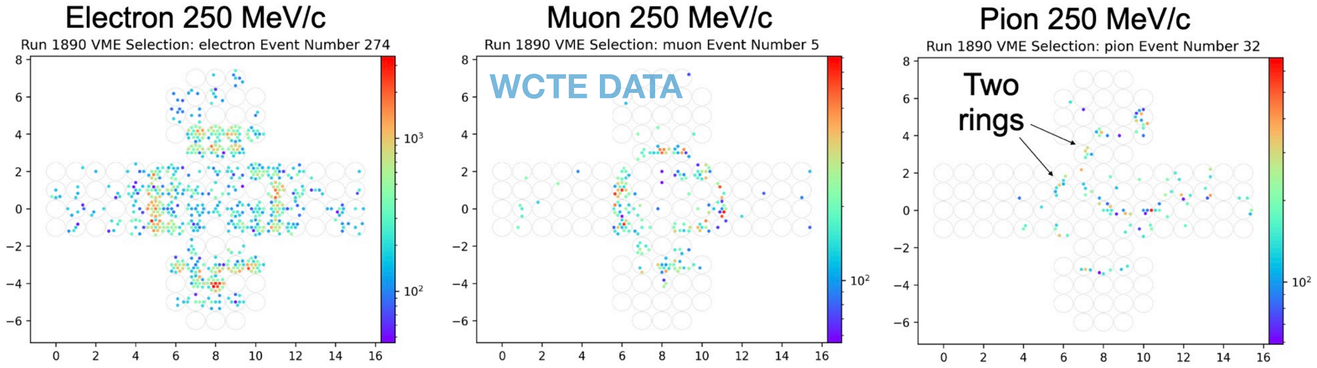


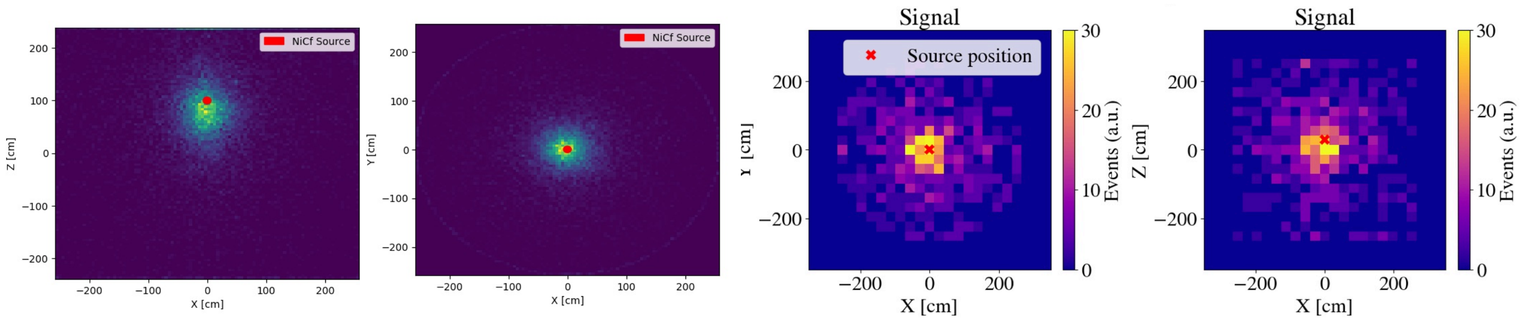


Summary

- WCTE is the **first water Cherenkov detector** to be placed in a **fully characterized bea**m of sub-GeV tagged e, μ, π, p, γ
- It successfully took **data** along this year with UPW and Gd-W, using **different beam/detector configurations.**
- Beam paper ready for publication.
- **Calibration sources** produced by Spanish collaborators: promising **results** and good **prospects** towards their production for Hyper-K intermediate and far detectors.







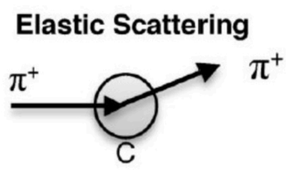

Thanks for your
attention!

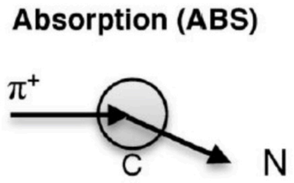
Back-up

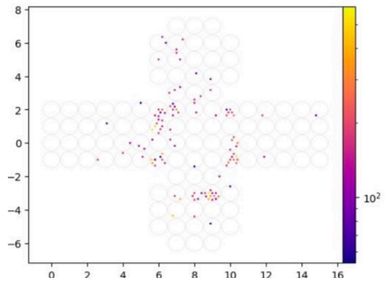
WCTE Physics Goals

➡Controlled particle (e, μ, π) samples for precise experimental study of **water Cherenkov responses** and **hadronic/nuclear effects**

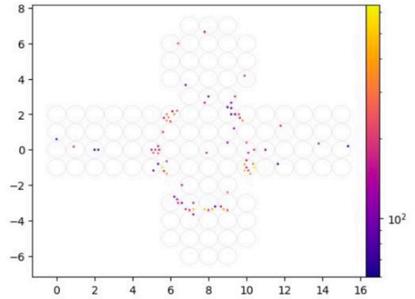
- e/μ **identification** $\rightarrow \mu$ background from ν_μ CC interactions
- e/γ **identification** $\rightarrow \pi^0$ background from NC interactions
- π **cross section** $\rightarrow \pi^\pm$ background from interactions, pion absorption



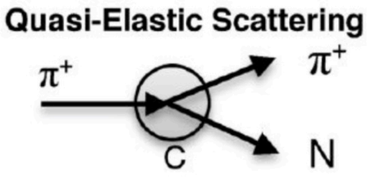


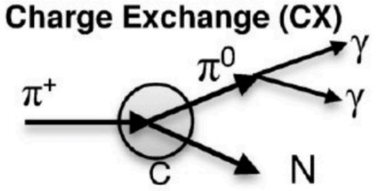


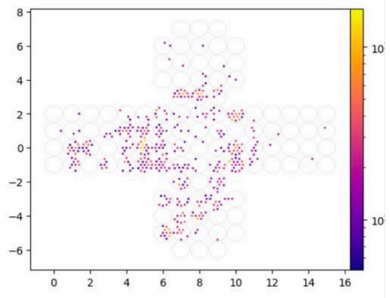
Forward scattering



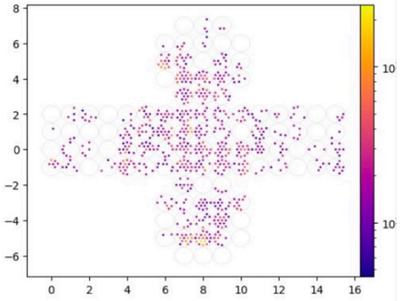
Thin Ring





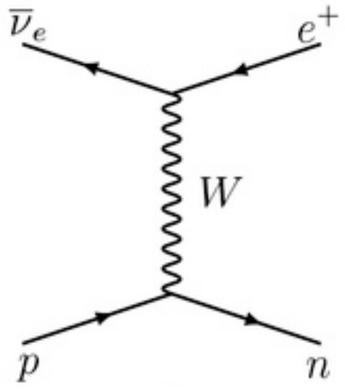


Large Angle Scattering



Shower

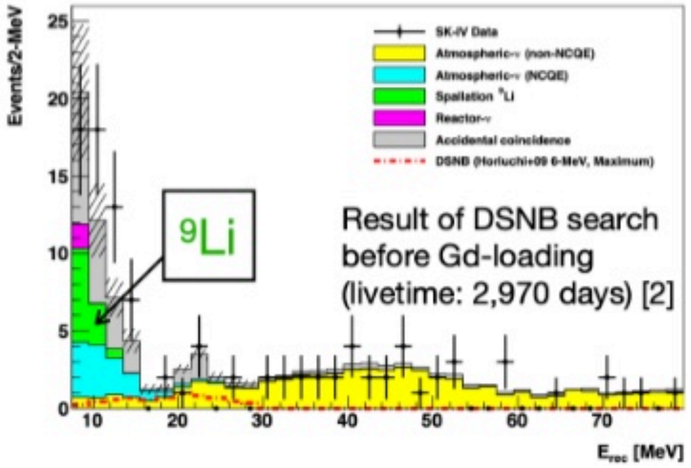
WCTE Physics Goals

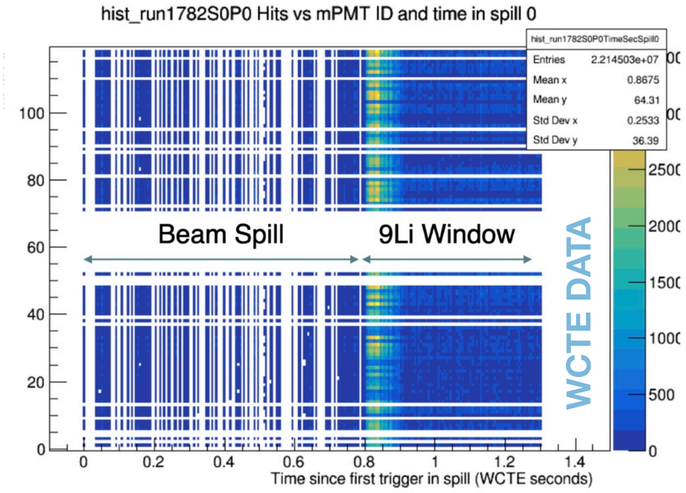


$$\mu + {}^{12}C \rightarrow {}^{9}Li + X$$
$$\downarrow$$
$${}^{9}Be* \rightarrow {}^{9}Be + n$$

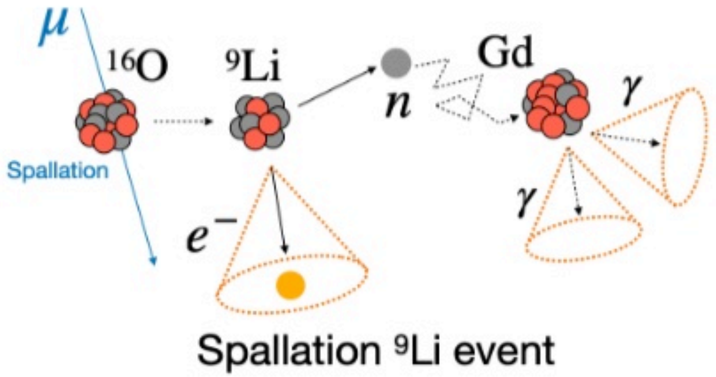
➡Neutron production and interaction in water

- $\nu/\bar{\nu}$ **tagging by neutrons** → effects of matter in oscillation probabilities
- e, μ, π **quasi-elastic scattering** → 2p-2h background
- **9Li production** → study of cosmic background for measurement of relic supernova

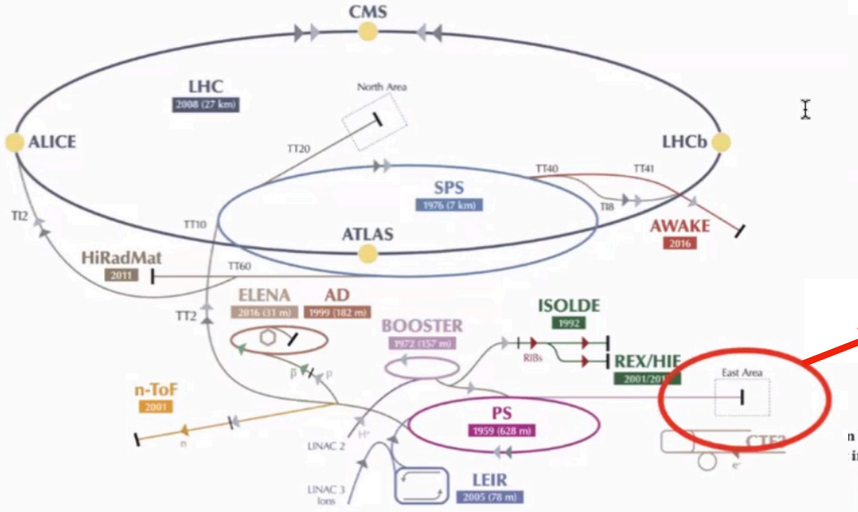


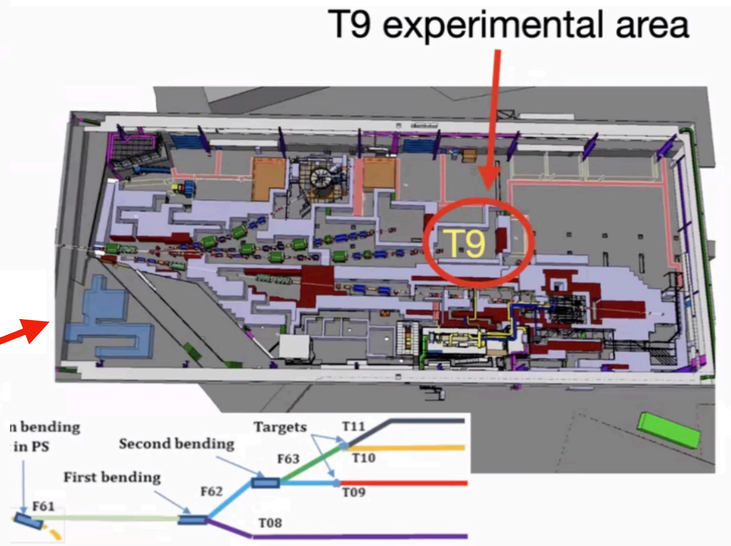


Search for 9Li after 0.4s spill

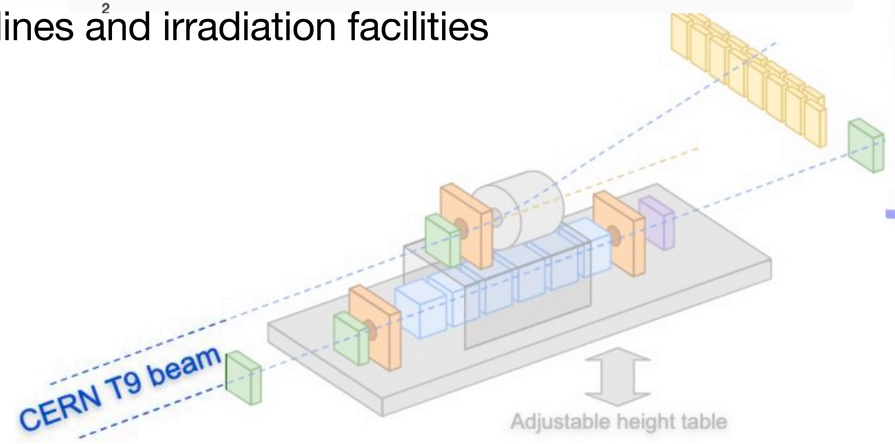


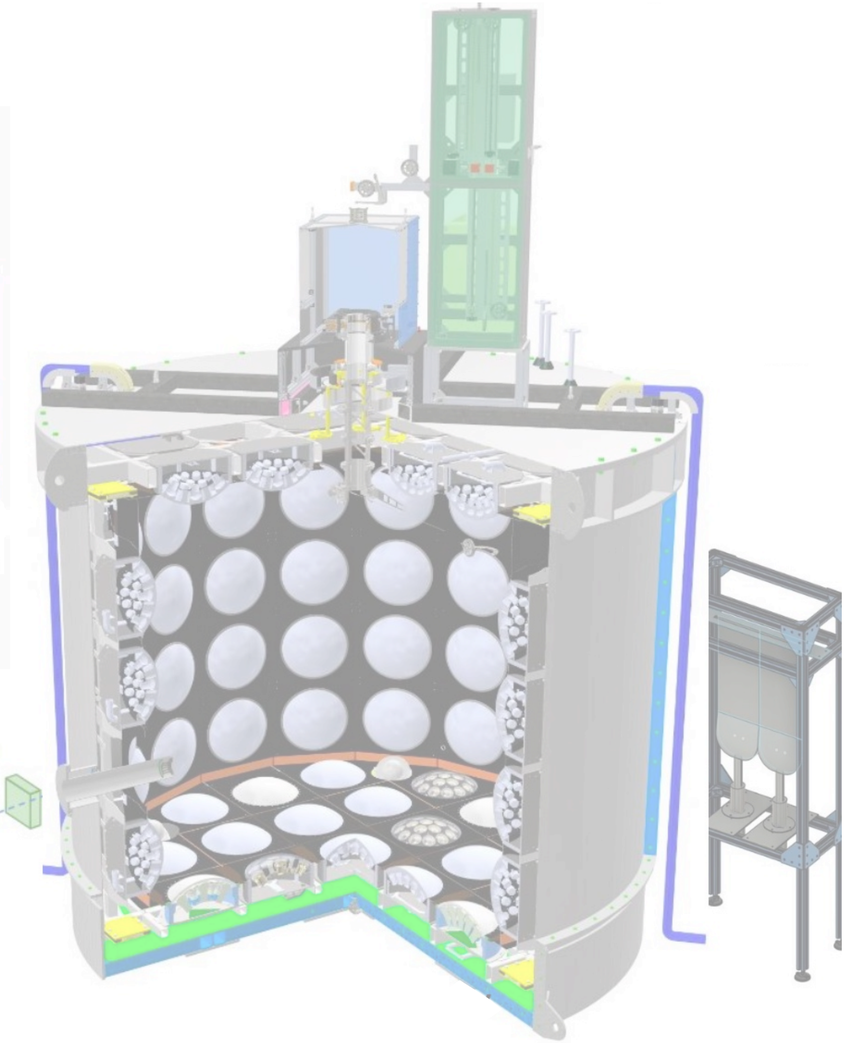
T9 Beam Line





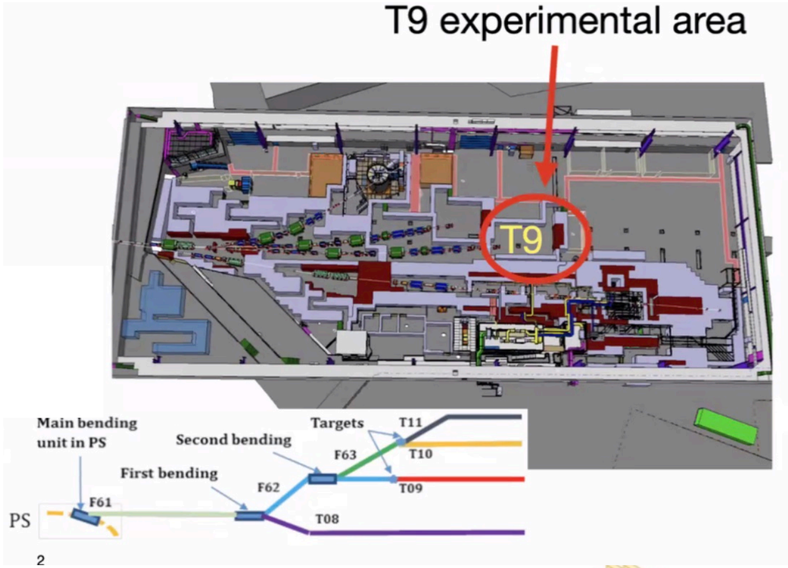
- East area hall → secondary beam lines and irradiation facilities share primary beam from the PS (24 GeV/c protons)

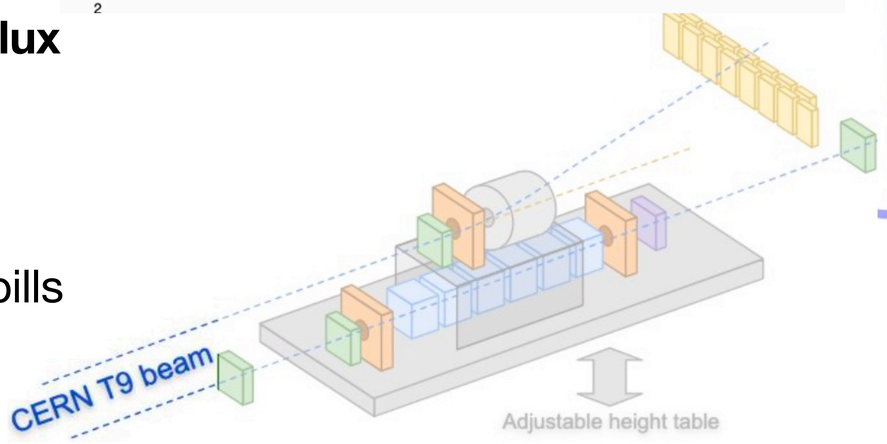


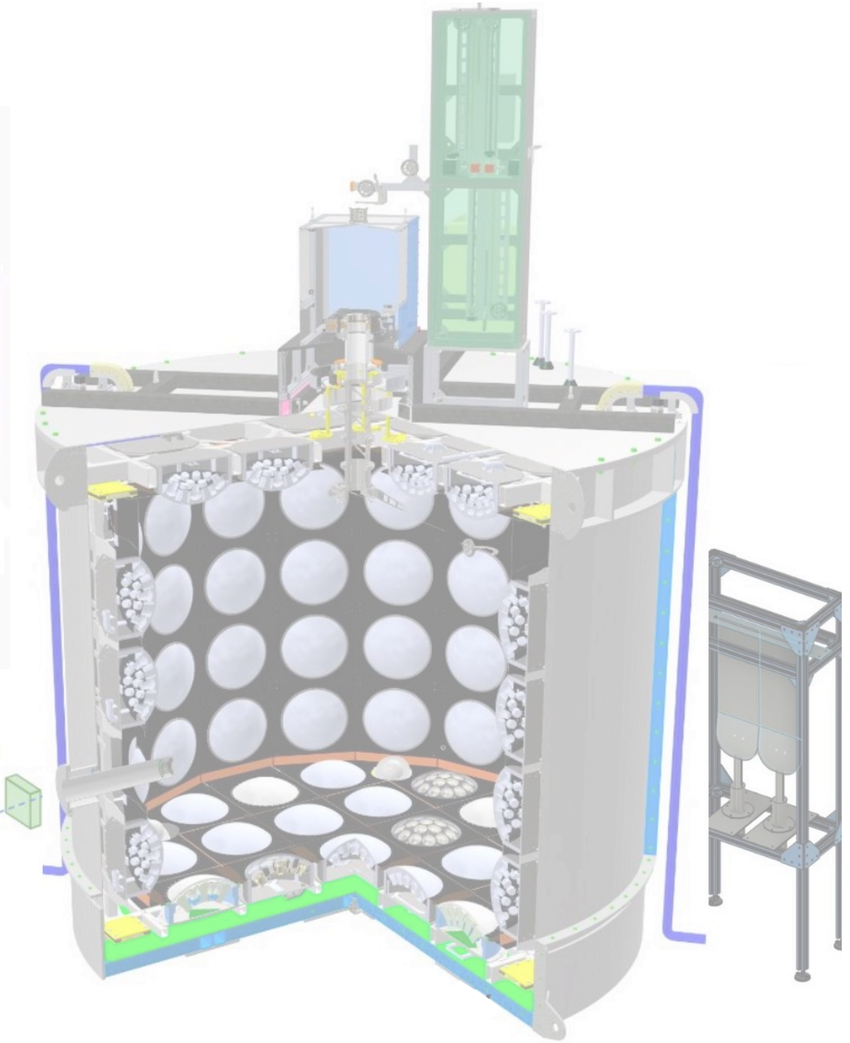


T9 Beam Line

- **Beam Target:**
  - Multi-target system that allows **changing the target** remotely depending on the users requirements.
- **Beam Line**:
  - Several **collimators** to define horizontal and vertical **acceptance**, control **beam flux** and define the central **momentum spread**
- **Beam spills:**
  - within 2.4s gate → up to 3 spills in 47s cycles for T9



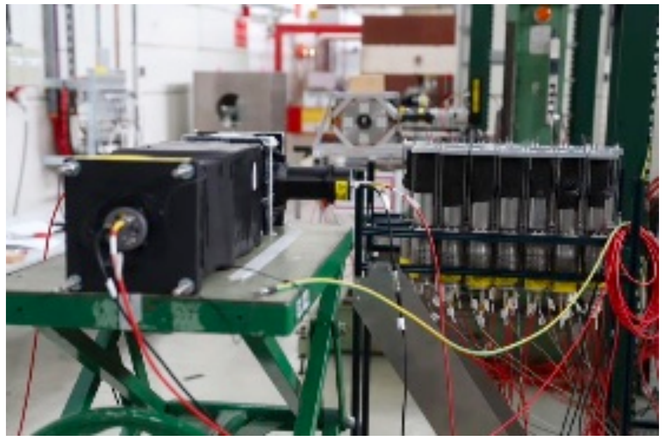


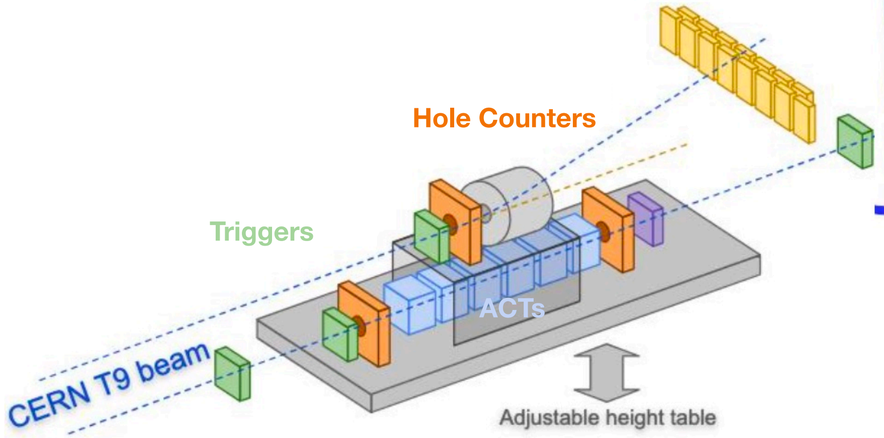


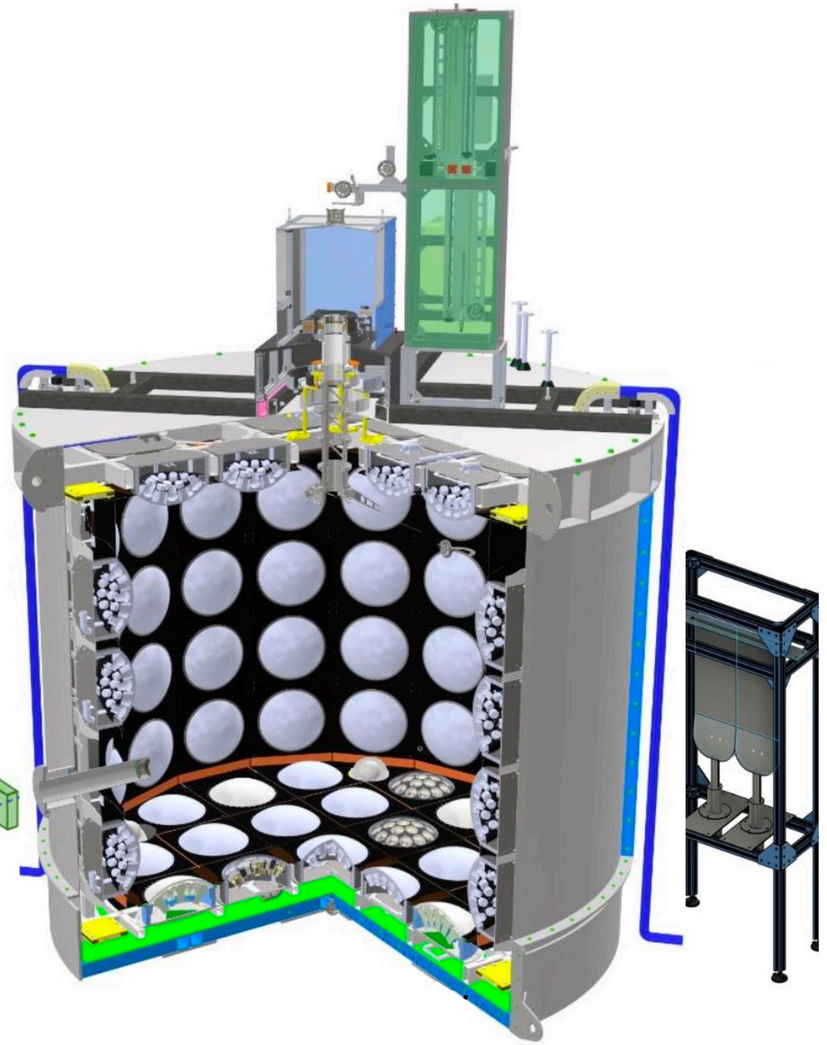
24

Beam Monitors

- Once **T9 beam** is selected
  - **Triggers** identify particles in beam line
  - **Hole counters** veto particles that shower before reaching WCTE
  - **Aerogel Cherenkov Threshold (ACT)** detectors use aerogel produced at Chiba university with n between [1.006, 1.150]
    - Low index aerogel used to **identify** e^+/e^-
    - Higher index aerogels are matched to beam momentum for π/μ **separation**







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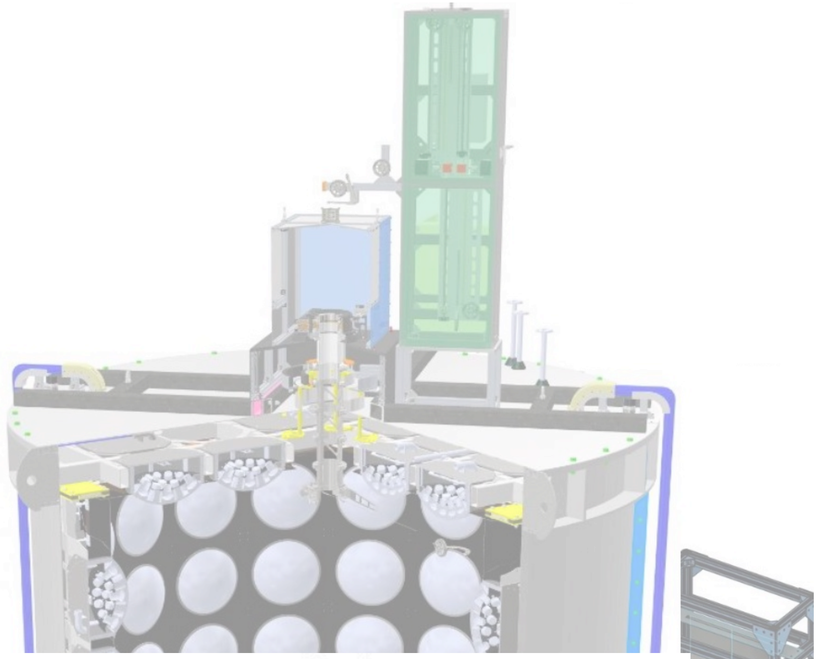

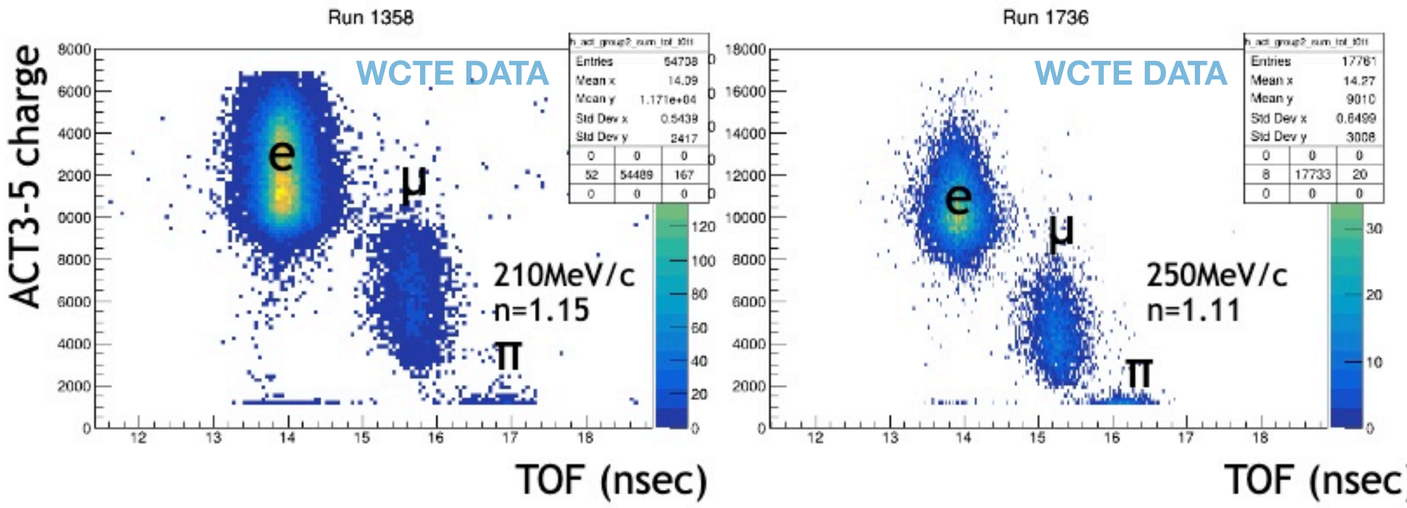

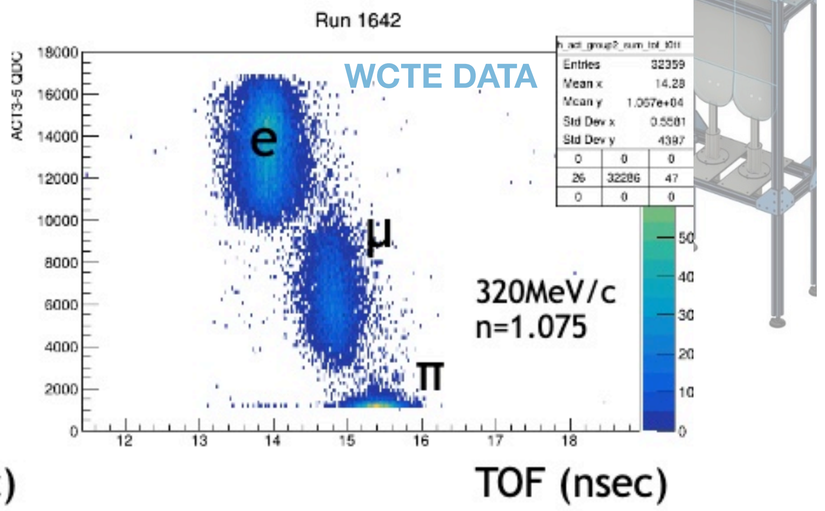

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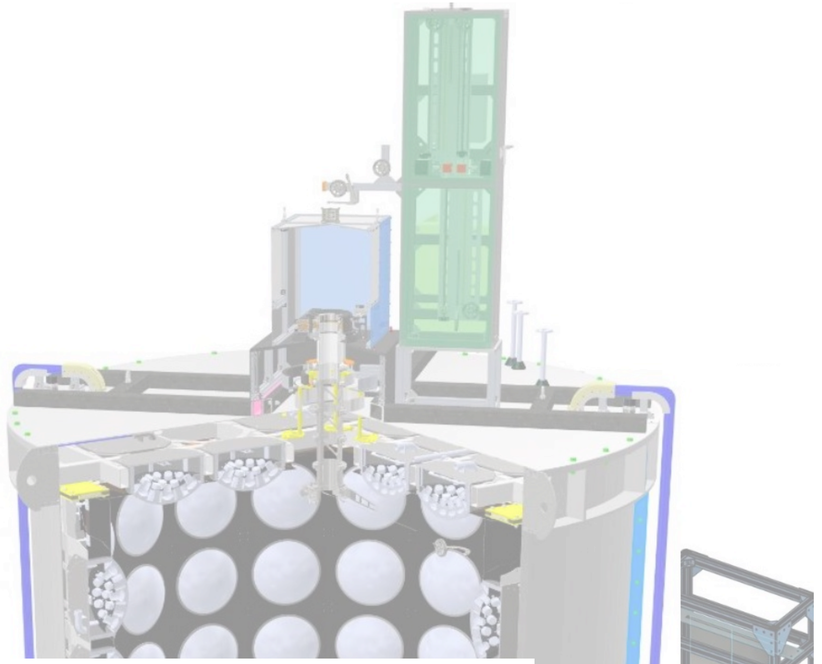
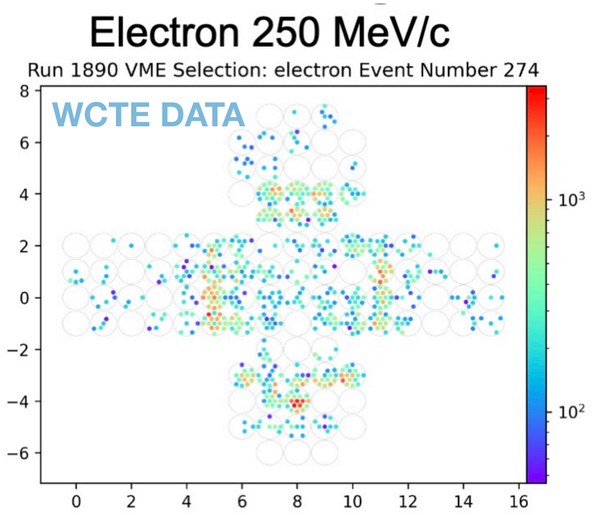
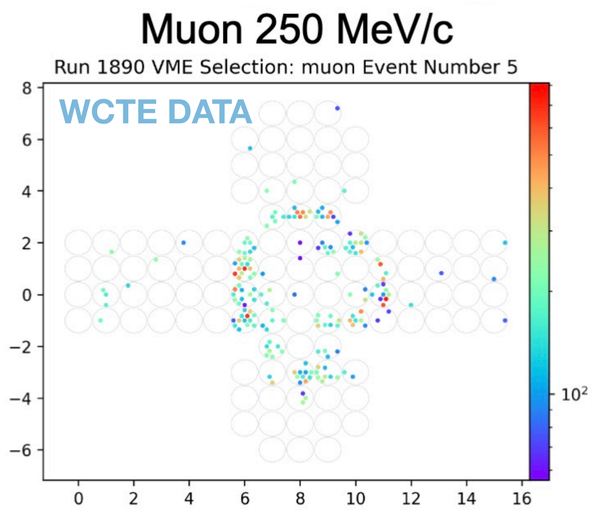
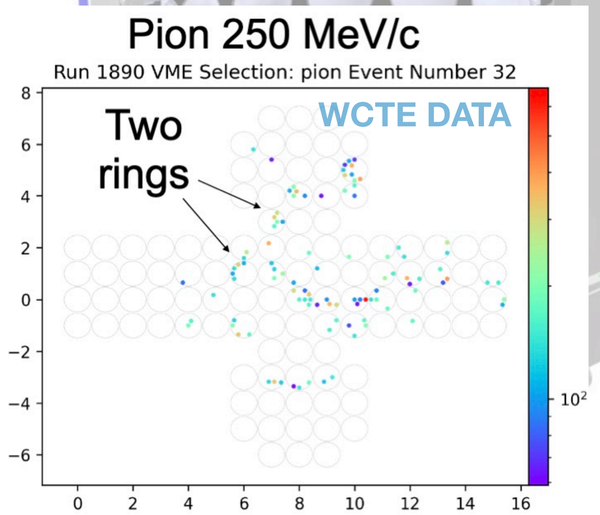








WCTE Physics Goals

➡Controlled particle (e, μ, π) samples for precise experimental study of **water Cherenkov responses** and **hadronic/nuclear effects**

- e/μ **identification** →μ background from ν_μ CC interactions
- e/γ **identification** → π^0 background from NC interactions
- π **cross section** →$\pi^\pm$ background from NC interactions, pion absorption

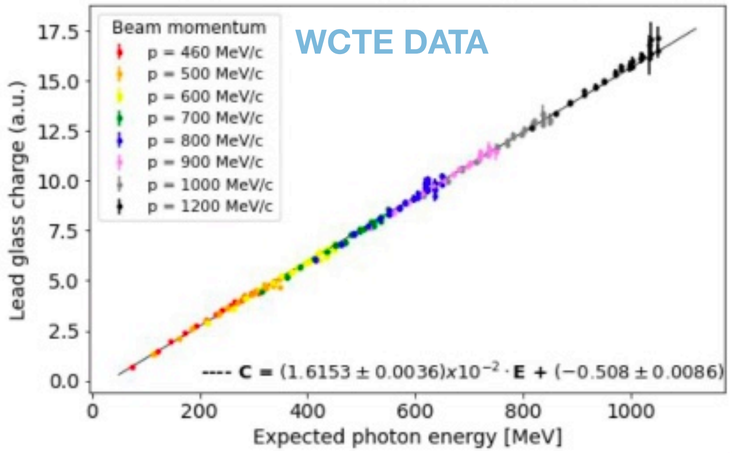
➡Neutron production and interaction in water

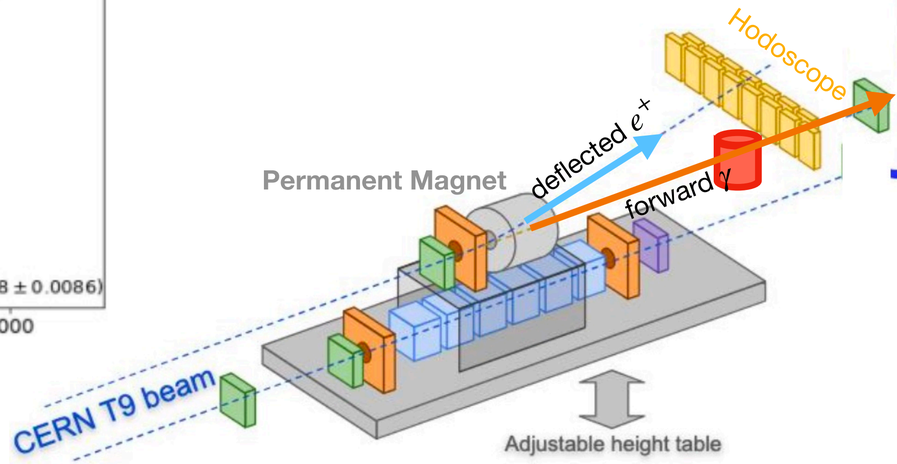
- $\nu/\bar{\nu}$ **tagging by neutrons** → effects of matter in oscillation probabilities
- e, μ, π **quasi-elastic scattering** → 2p-2h background
- **9Li production** → study of cosmic background for measurement of relic supernova

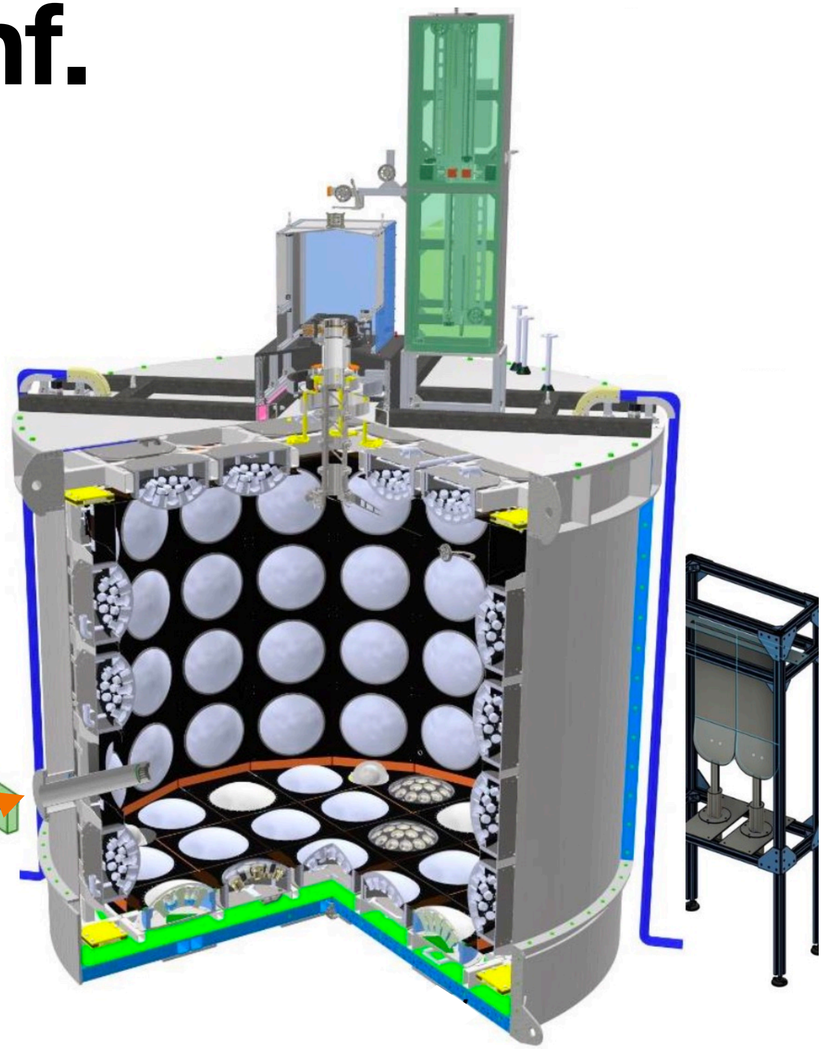
WCTE will provide input on neutrino energy reconstruction and data-driven systematic error evaluations

Beam Monitors: tagged γ conf.

- e^+ produces γ by bremsstrahlung
- Permanent magnet **deflects** $e^{\pm}$
- **Hodoscope** measures deflection angle to infer γ energy from beam momentum
- Validated γ energy measurement using **lead glass calorimeter**



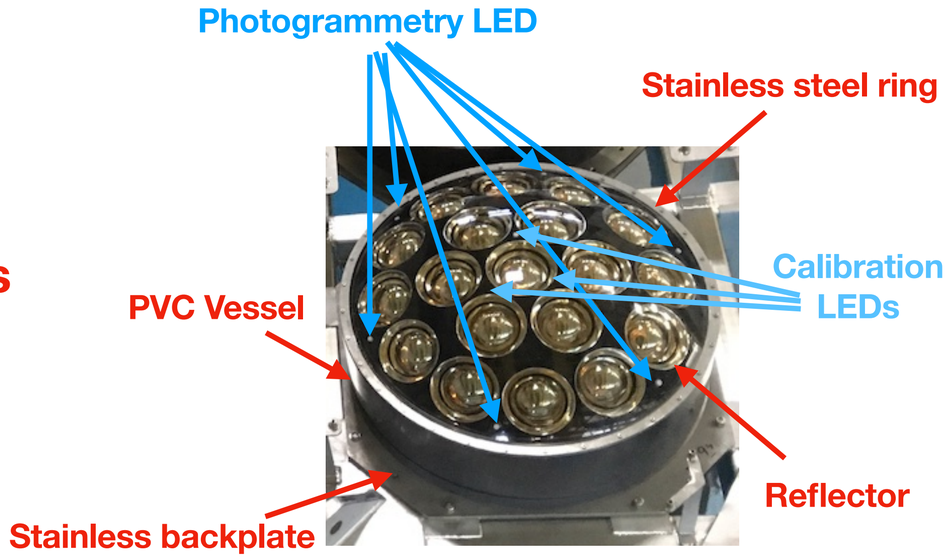




24

mPMTs

- modules with 19x8cm diameter **PMTs** (Hamamatsu R14374)
  - **93 'IWCD style' mPMTs** (ex-situ)
  - **4 'Hyper-K' style mPMTs** (in-situ)
- Improve granularity and timing compared to larger PMTs
- <1ns timing resolution
- Additional directionality information
- Integrated **LED calibrations systems**:
  - 6 slow LED fibres for photogrammetry
  - 3 fast LED fibers used for timing calibrations



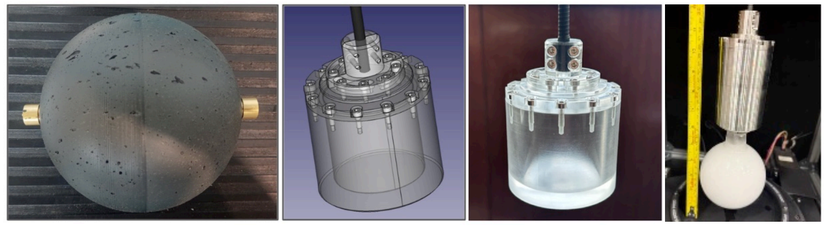
Ex-situ

In-situ

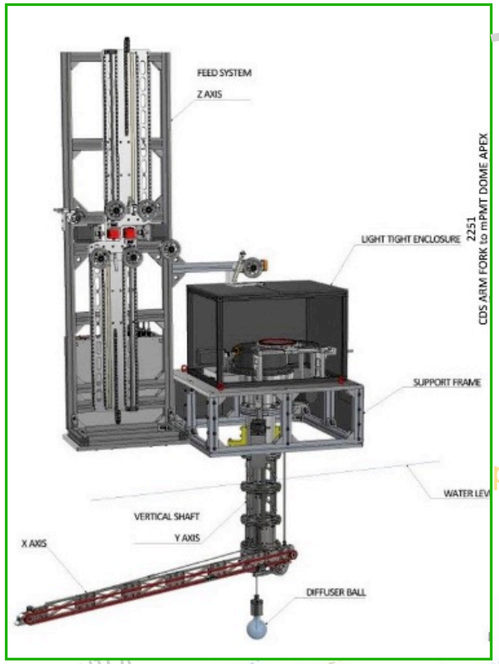
Calibration Deployment System

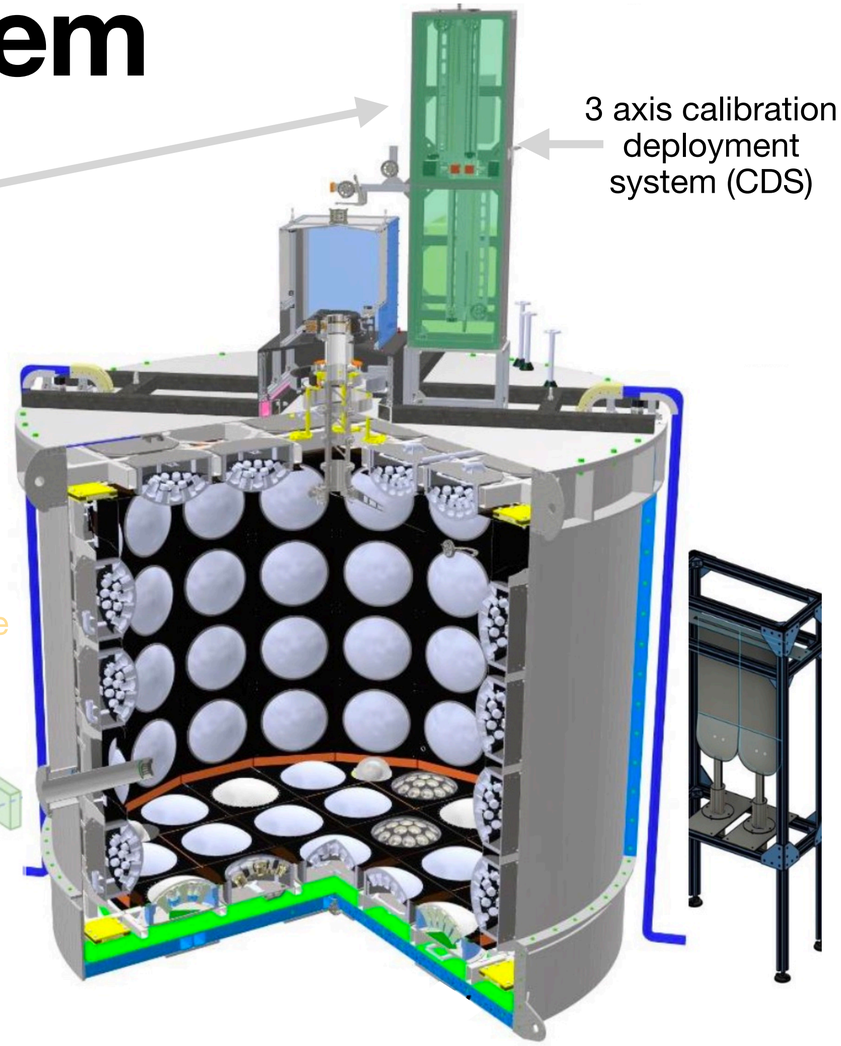
- Axis **CDS** → prototype for IWCD
  - Allows deployement of sources along the water tank
- Interchangeable sources (prototypes for IWCD and Hyper-K)
  - **NiCf** source for low energy gamma
  - **AmBe** for neutron multiplicity
  - **Diffuser ball** for gain and timing calibration

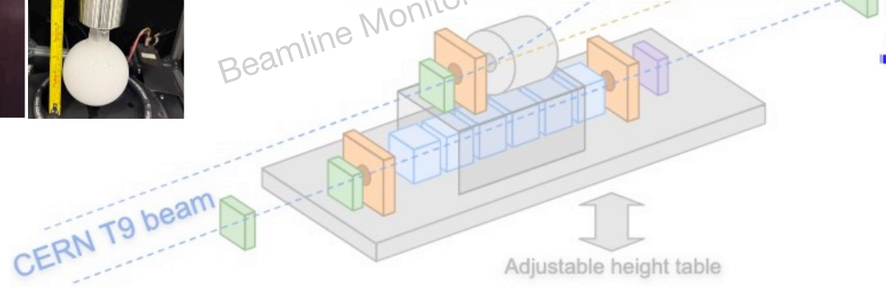
NiCf AmBe Diffuser Ball



Talk from Diego



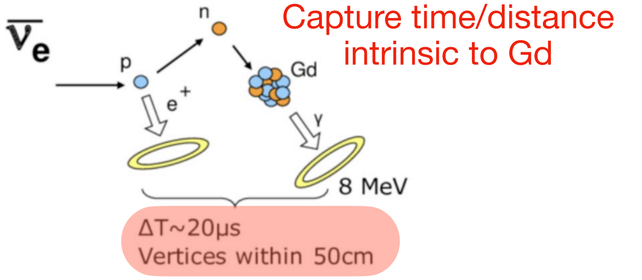




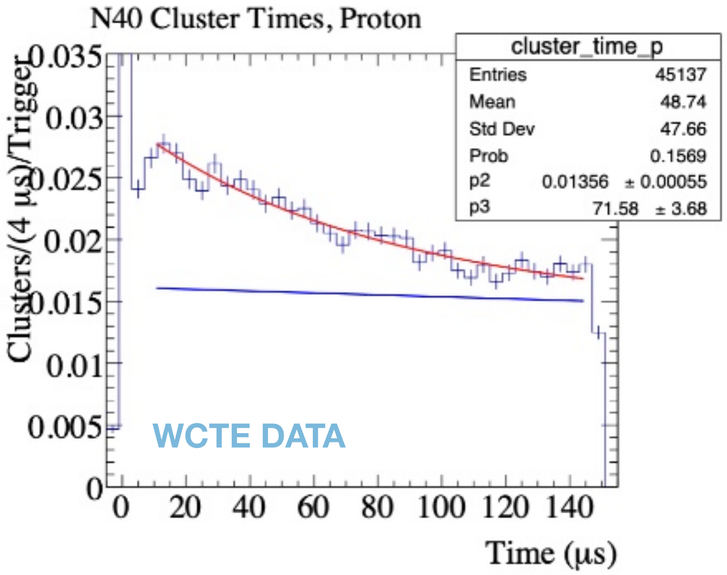
24

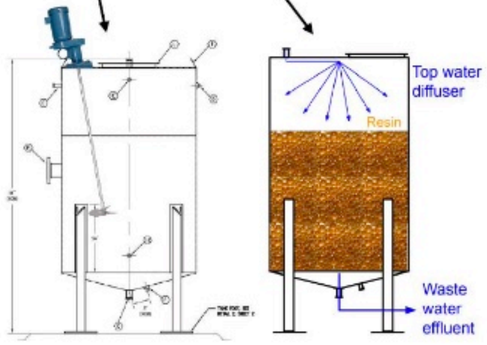
Gd loaded

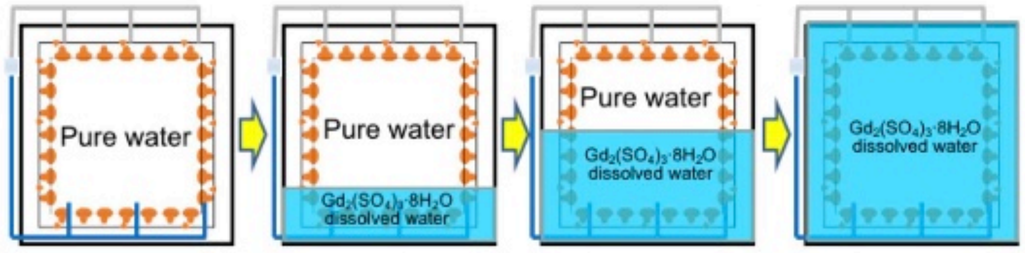
- Neutron tagging beneficial for $\nu/\bar{\nu}$ discrimination and further studies
- Super-K loaded to a ~0.1% Gd in the detector (90% neutron capture efficiency)
- WCTE accommodated Gd loading, loaded to a 0.03%

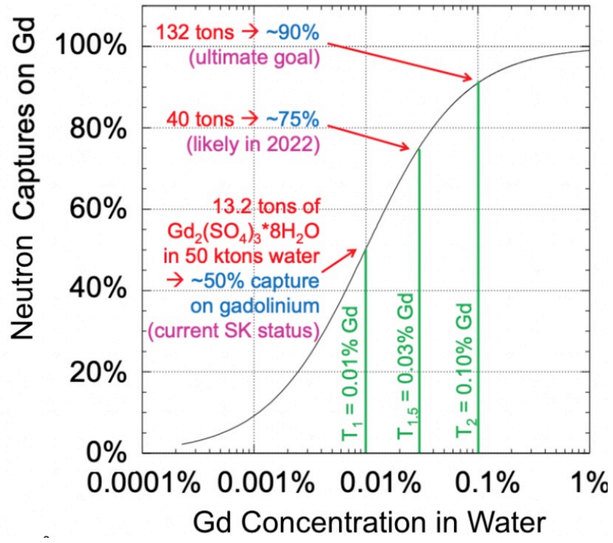


Capture time/distance intrinsic to Gd









WCTE Timeline

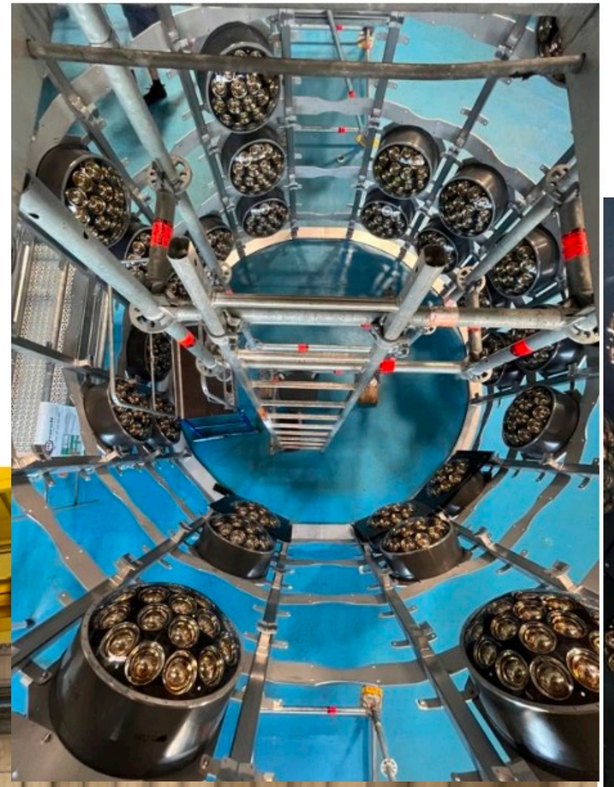
2024

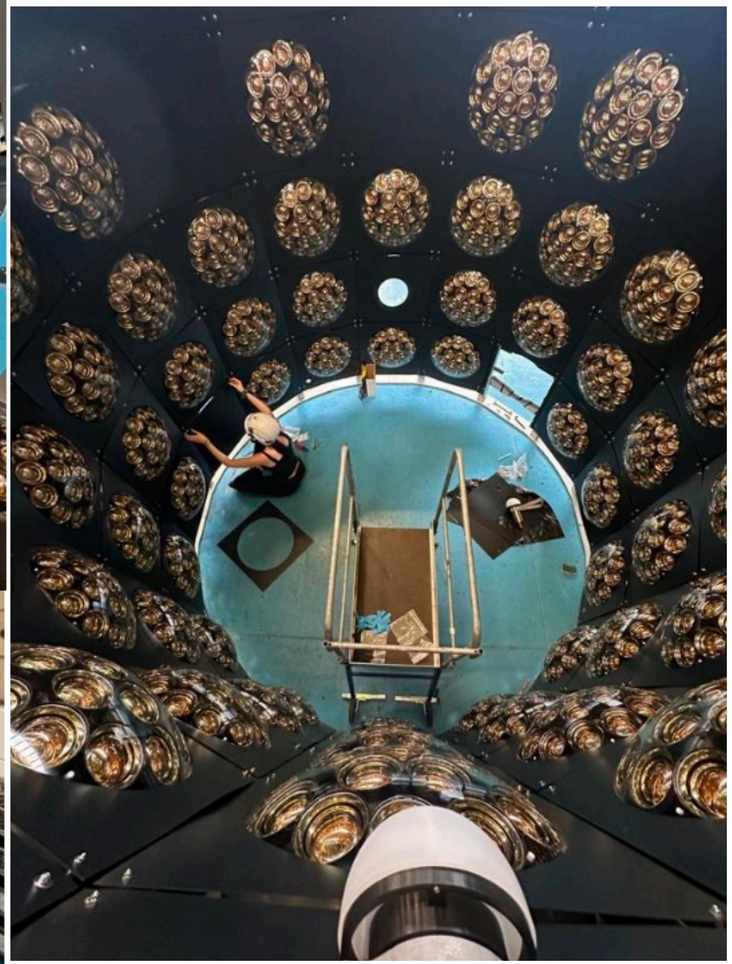
Assembly

Commissioning and First Data

2025

Full Data Taking





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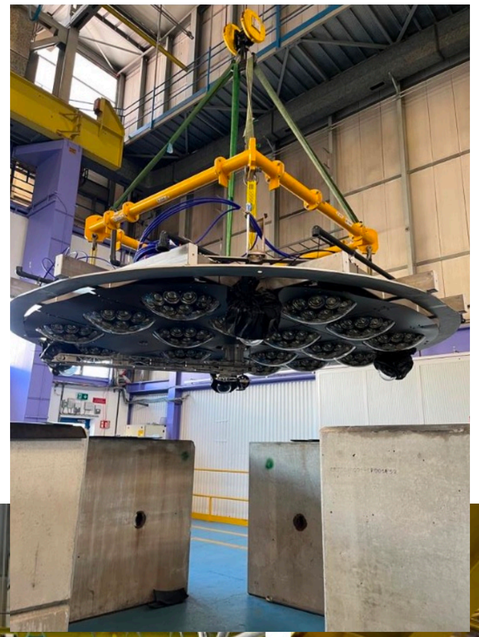

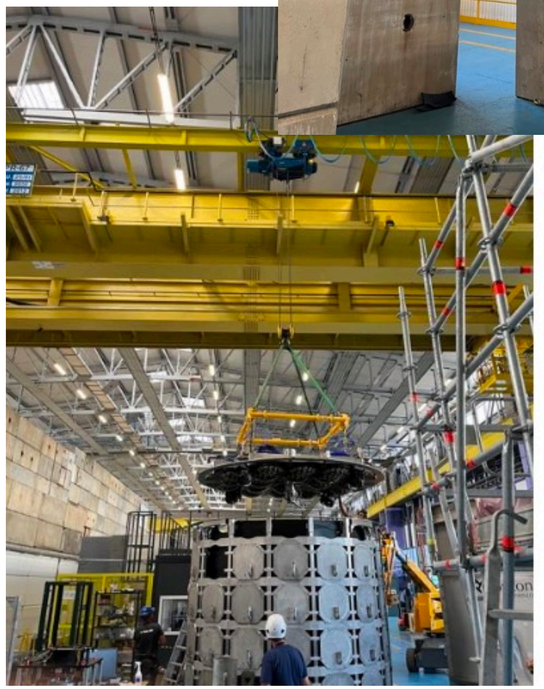

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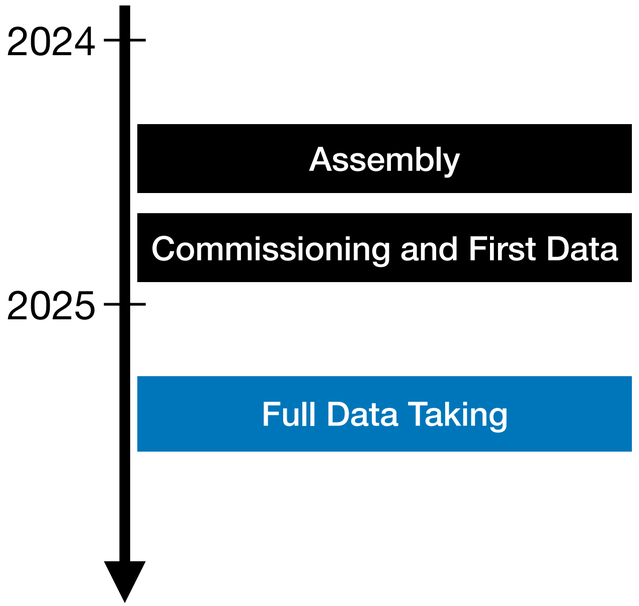
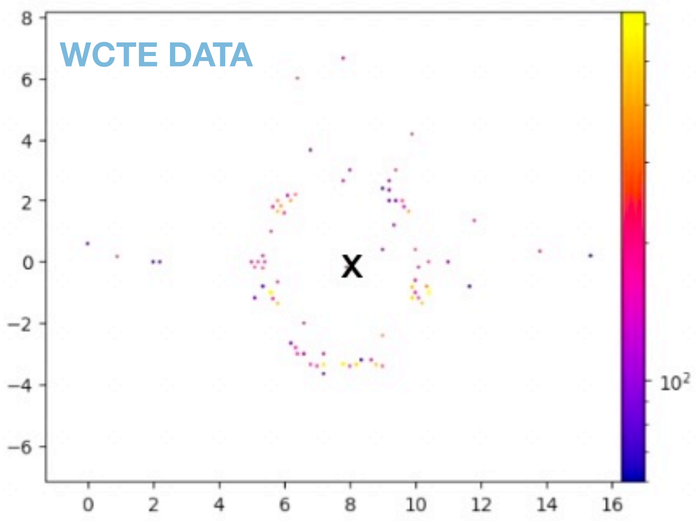


- **April 2 - May 31:** Successful second data taking campaign. Predominantly, runs with UPW mode. Gd-W data was taken for 1.5 weeks. Data taking summary:

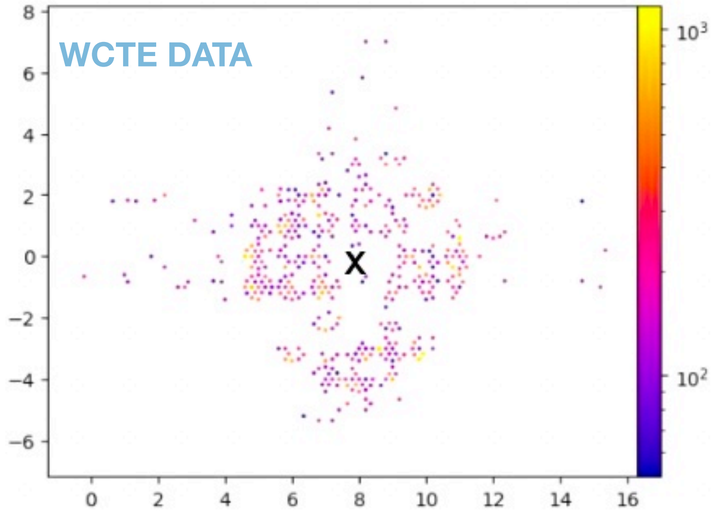
Beam Mode	Beam Momentum	Water Mode	Measurements
Charged Particle (+, -)	200 -1200 MeV/c	UPW	Reco. Capabilities, pion scattering
Charged Particle (+, -)	800 MeV/c		Muon/electron scattering
Tagged Gamma	500-1000 MeV/c		Gamma Identification
Charged Particle (+, -)	200 -1200 MeV/c	Gd-W	Neutron Production
Tagged Gamma	500 - 1000 MeV/c		Photonuclear with n tagging

WCTE Physics Goals

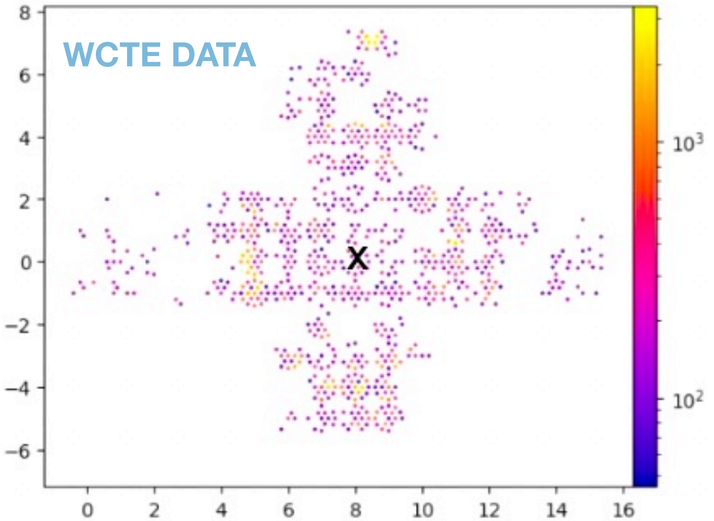
➡Controlled particle (e, μ, π) samples for precise experimental study of **water Cherenkov responses** and **hadronic/nuclear effects**



Pion



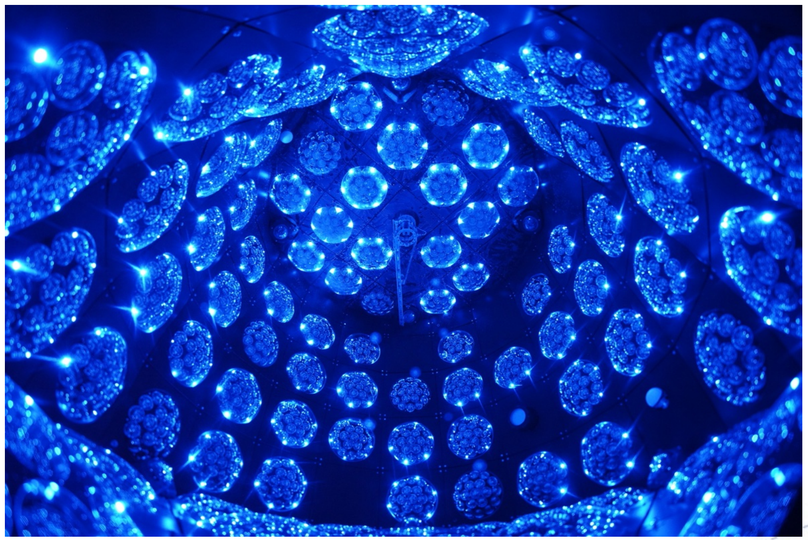
Muon

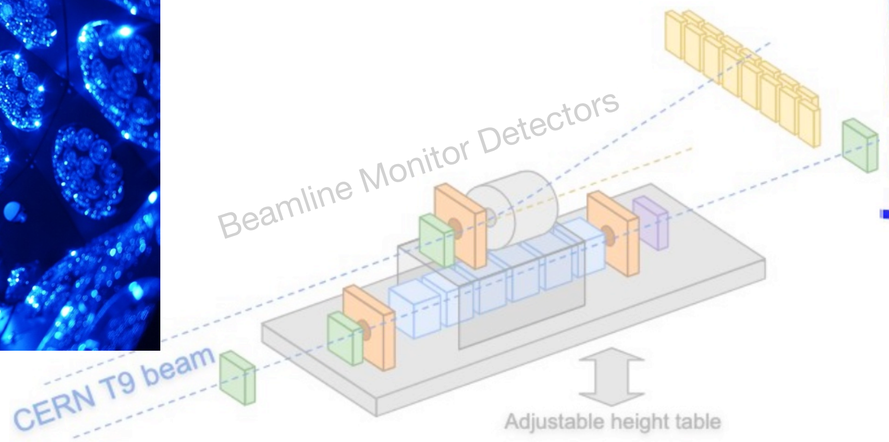


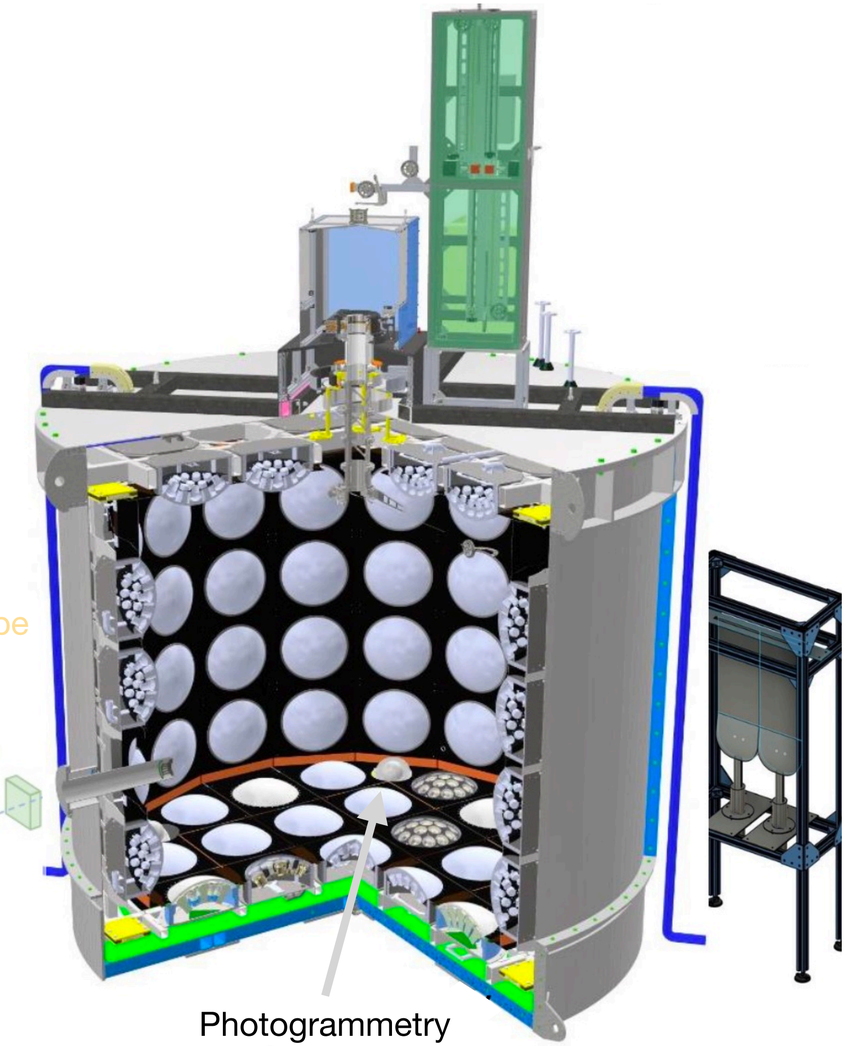
Electron

Photogrammetry

- Cameras mounted inside of the detector →3D detector geometry reconstruction
- < 1cm position reconstruction expected to observer any deformation of mPMT support structure after filling







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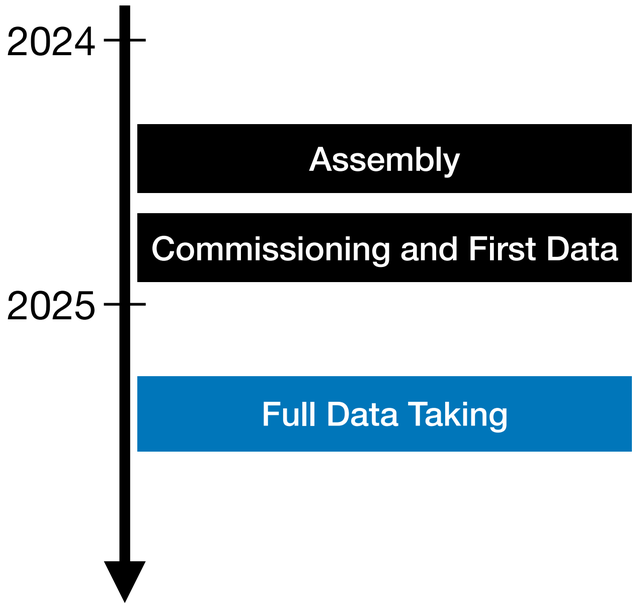
WCTE Assembly



- **April 2 - May 31:** Successful second data taking campaign.
  Data taking summary:

Data Type	Water Type	Beam Configuration	Beam Momenta (MeV/c)	Benchmark
Pion scatter, particle identification, energy scale, 9Li	Pure	Charged particle (+,-)	200-500 (33 points)	20k muons, 10k at most momenta
Lepton Scattering	Pure	Charged particle (+,-)	780-900	0.5M muons, 30M electrons
Gamma Particle Identification	Pure	Tagged Photon	500, 650, 800 1000	100k gammas at each momentum
Proton Reconstruction	Pure	Charged particle (+)	1100-1500	100k protons at each momentum
Trigger minimum bias data	Pure	Charged particle (+)	80-500	100k positrons
Kaon Reconstruction	Pure	Charged particle (+,-)	1100-1150	Few thousand kaons
9Li and 2p-2h in π quasi-elastic scattering	Gd	Charged particle (+,-)	260-360	5k pions at each momentum (may be less)
Secondary neutron production	Gd	Charged particle (+,-)	400-1200	100k protons at each momentum
Lepton Scattering	Gd	Charged particle (+,-)	800,1000	10M electrons/positrons (may be less)
Photonuclear Scattering	Gd	Tagged Photon	500, 650, 800 1000	500k gammas total (may be less)