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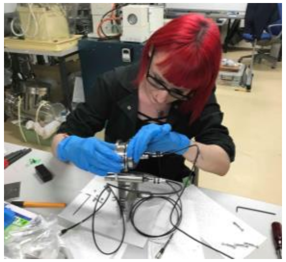

Measuring neutrino oscillations precisely:

Reducing Systematics in Water Cherenkov Detectors With the Water Cherenkov Test Experiment

09/07/2022

Dr Lauren Anthony

On behalf of the WCTE collaboration

l.anthony@imperial.ac.uk

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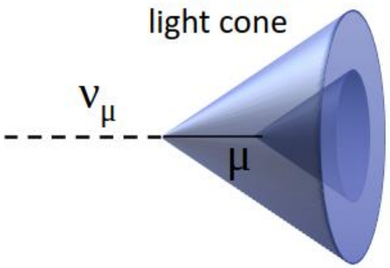
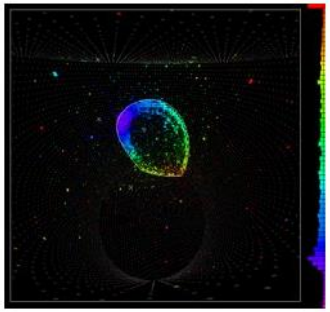
Water Cherenkov Detectors in Japan

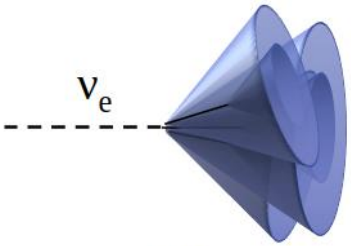
Good for neutrinos - Large mass & well understood technology

- Excellent performance
    - 99% μ/e separation
    - 2% momentum resolution
    - 1° direction resolution

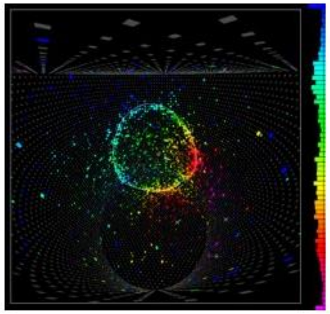
Cherenkov light cone

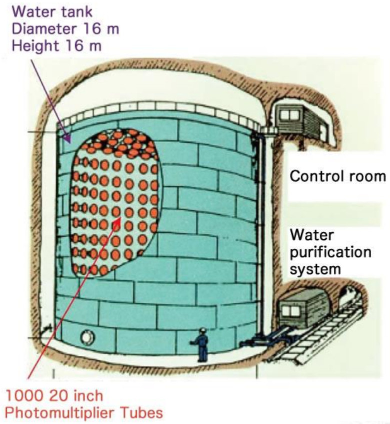






EM - shower





Past

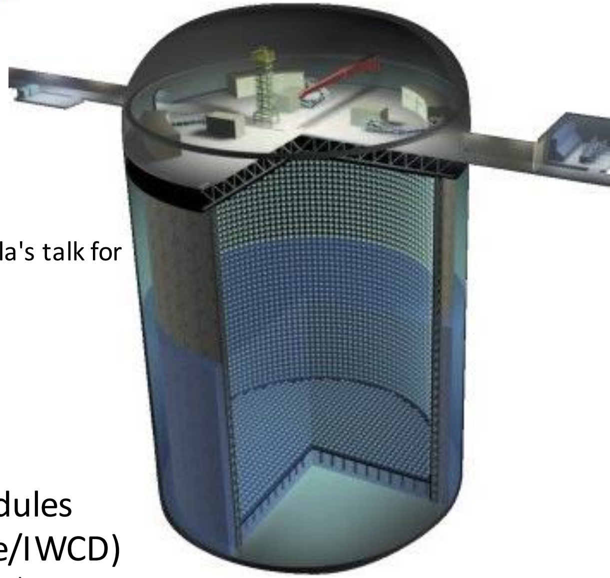
Kamiokande

0.7kt fiducial mass

Current

Super-Kamiokande

22.5kt fiducial mass



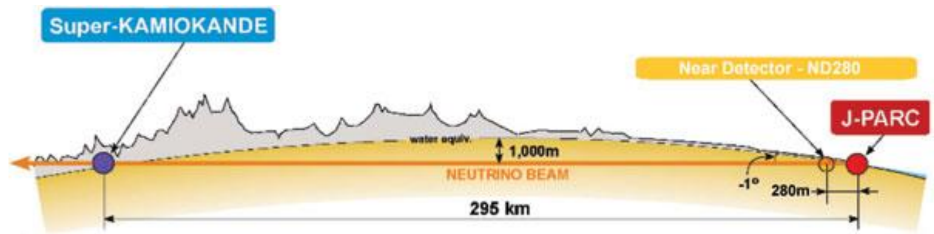
- New technologies
    - Gadolinium (Super-Kamiokande)

      (See Magdalena Posiadala-Zezula's talk for SK)
    - Water-based liquid scintillator (THEIA)
    - Photo-detector modules (Hyper-Kamiokande/IWCD)

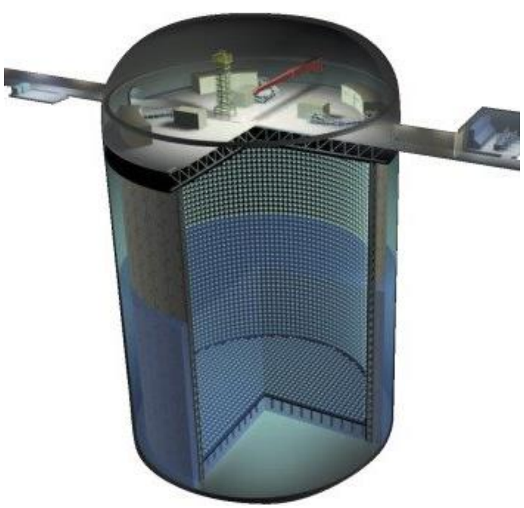
      (See Aurora Langella's talk for HK)

Neutrino Oscillation at T2K: Systematic Uncertainty

- T2K is currently limited by statistical uncertainty
- Future experiments will be systematics limited
- Largest uncertainty on electron like samples is Super-K detector uncertainty



Error source	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC CC$1\pi^+$	$1Re$ FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3



P. Dunne, Neutrino 2020, https://zenodo.org/record/4154355

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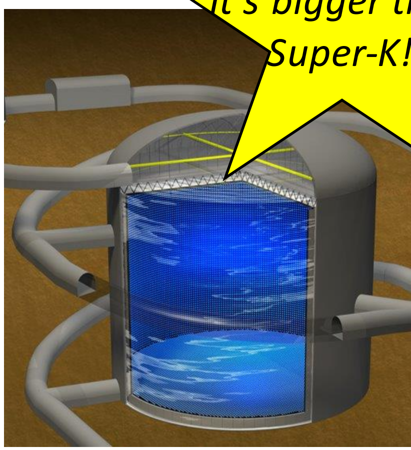
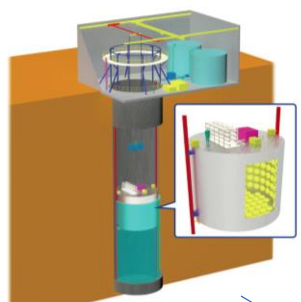
Future T2HK Experiment

Far detector

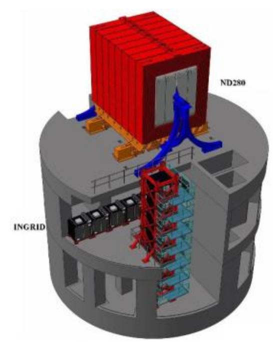
It's bigger than Super-K!



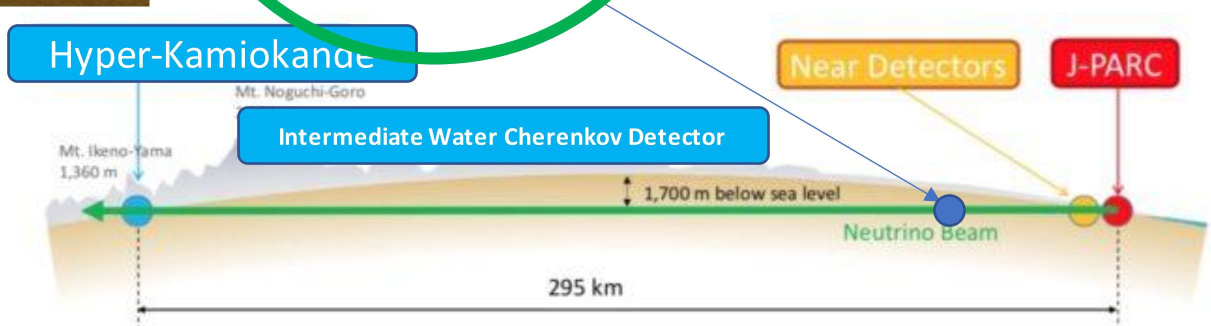
New Intermediate Detector!



Near detector complex



Beam facility



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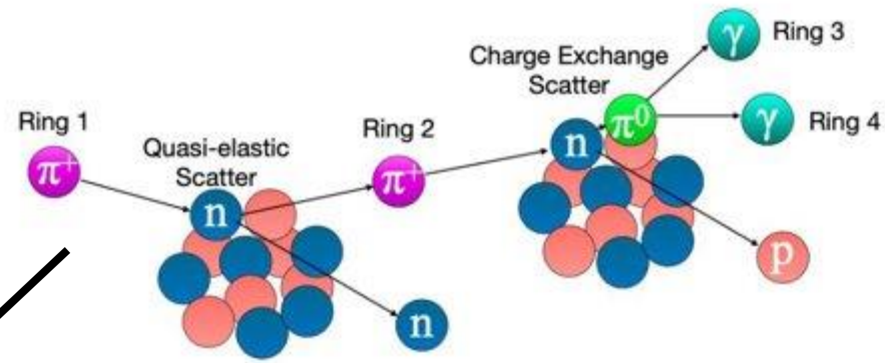
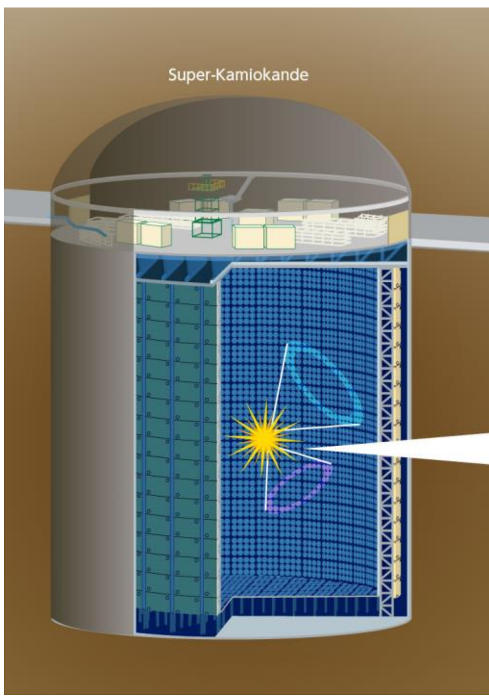
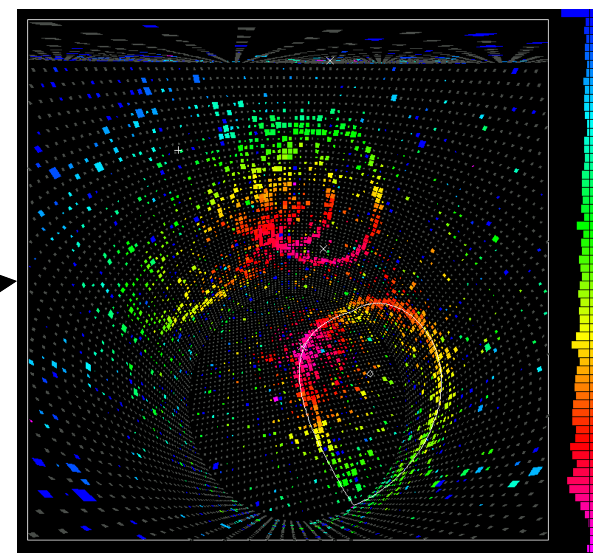
Water Cherenkov Detector Limitations: Secondary Interactions

- Super-K uncertainty includes detector effects and uncertainties in secondary interactions of pions and nucleons
    - Little data and very difficult to model

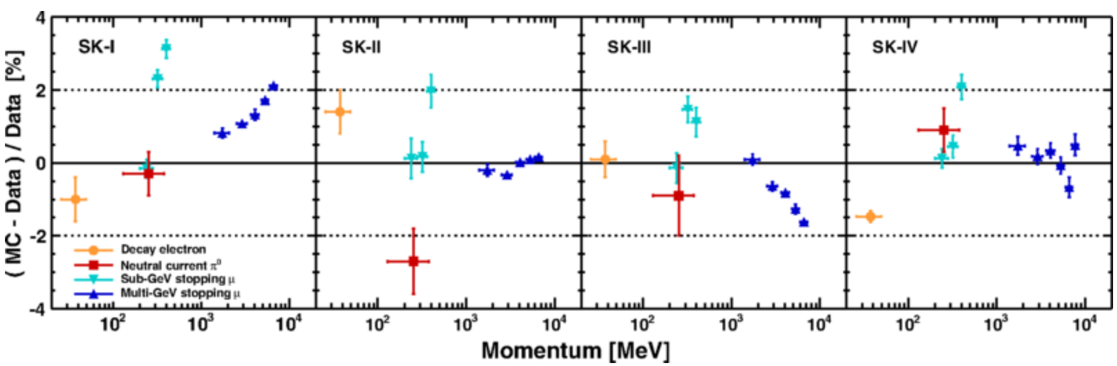






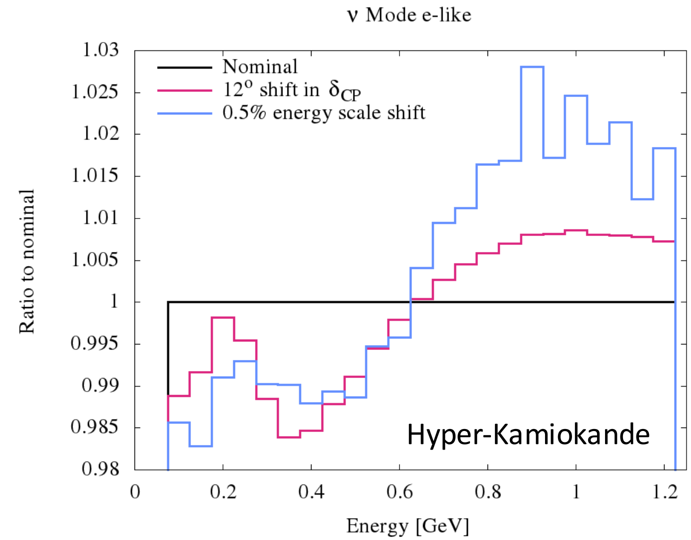
Water Cherenkov Detector Limitations: Energy scale

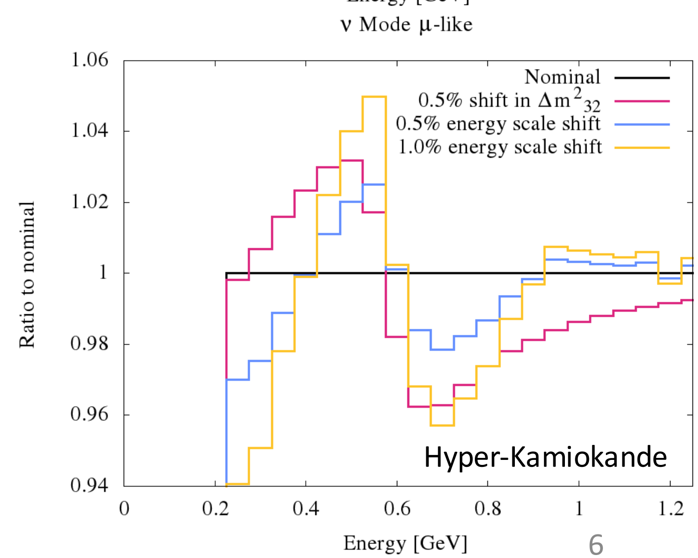
- Super-Kamiokande currently has 2% momentum resolution



DOI : 10.1103/PhysRevD.97.072001

- Detector energy scale uncertainty impacts oscillation analysis
  - Systematic errors present degeneracies in oscillation parameters
- Degenerate with δ_{CP} in e-like samples and with Δm^2_{32} in μ-like samples
- Develop calibration program to reduce uncertainty on energy scale as much as possible





L. Anthony

L. Muntenau - https://indico.cern.ch/event/855372/contributions/4441566/

Working towards reducing detector systematics:

The Water Cherenkov Test Experiment (WCTE)

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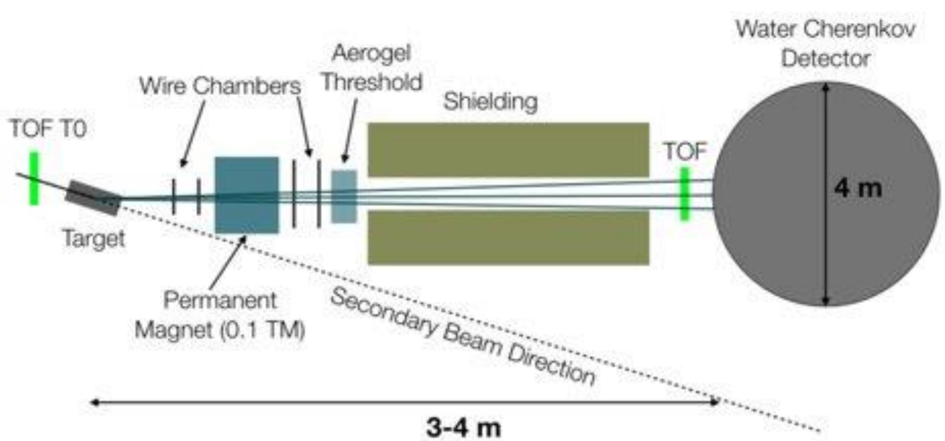
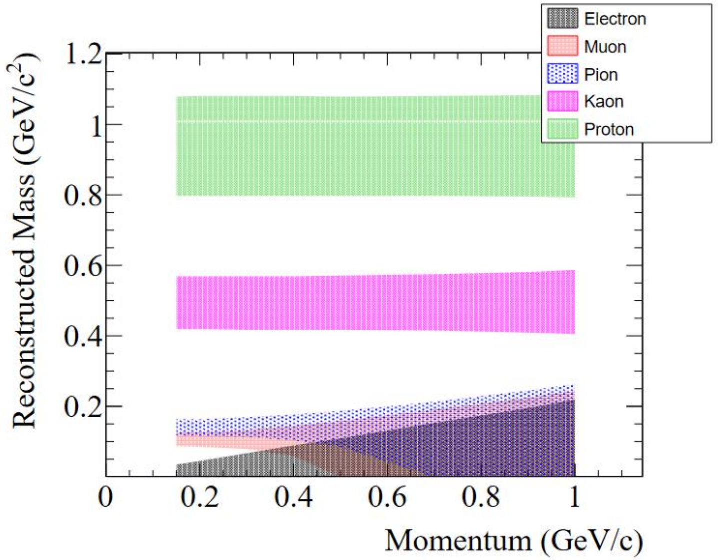
The Water Cherenkov Test Experiment (WCTE)

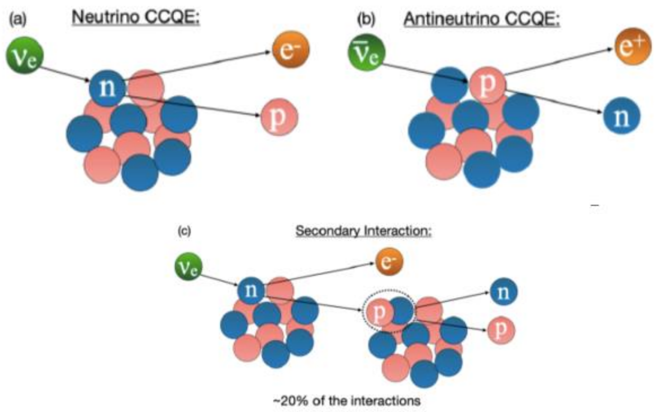
- Small scale Water Cherenkov detector to be commissioned at CERN in 2023/24
  - **Potential to become platform for neutrino measurements at CERN**
- Study detector systematics and response 200 MeV/c - 1000 MeV/c
- ~3.8 m * 3.8 m cylindrical detector
  - Proposal document can be found here: http://cds.cern.ch/record/2712416/files/?ln=en
- Gadolinium sulphate doped





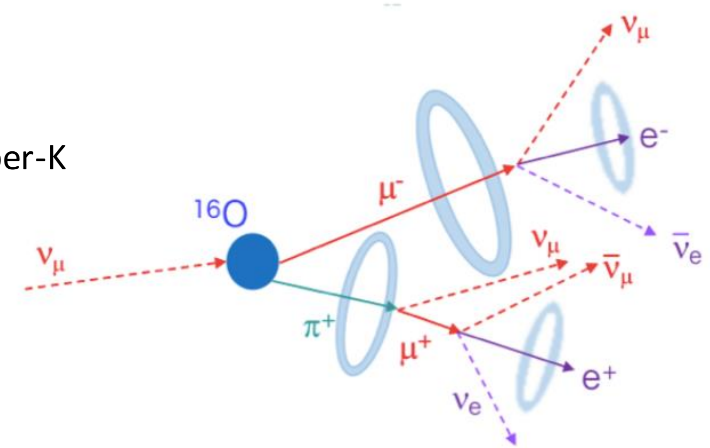
WCTE Physics Program

- **Studies of Cherenkov light production/processes**
  - Study at low momenta near Cherenkov threshold
  - Delta rays and scattering make Cherenkov angle calculations more challenging



- **Energy scale calibration**
  - At Super-K the current systematic uncertainty on overall energy scale is 2%
    - Needs to reduce to 0.5% for Hyper-K

- **Secondary neutron production**
  - Used for neutrino/anti-neutrino tagging in Super-K-Gd and Hyper-K



- **Pion scattering**
  - Reconstruction of Pions in final state is challenging
    - Limited hadronic scattering data on Oxygen and hard to model

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Experimental area @ CERN

- T9 beam line in the East Area - secondary particle beam with momenta ranging from ~400 MeV/c to ~1500 MeV/c

- 40m long secondary beamline
  - Lower energy Pions decay in flight
  - Need tertiary production target

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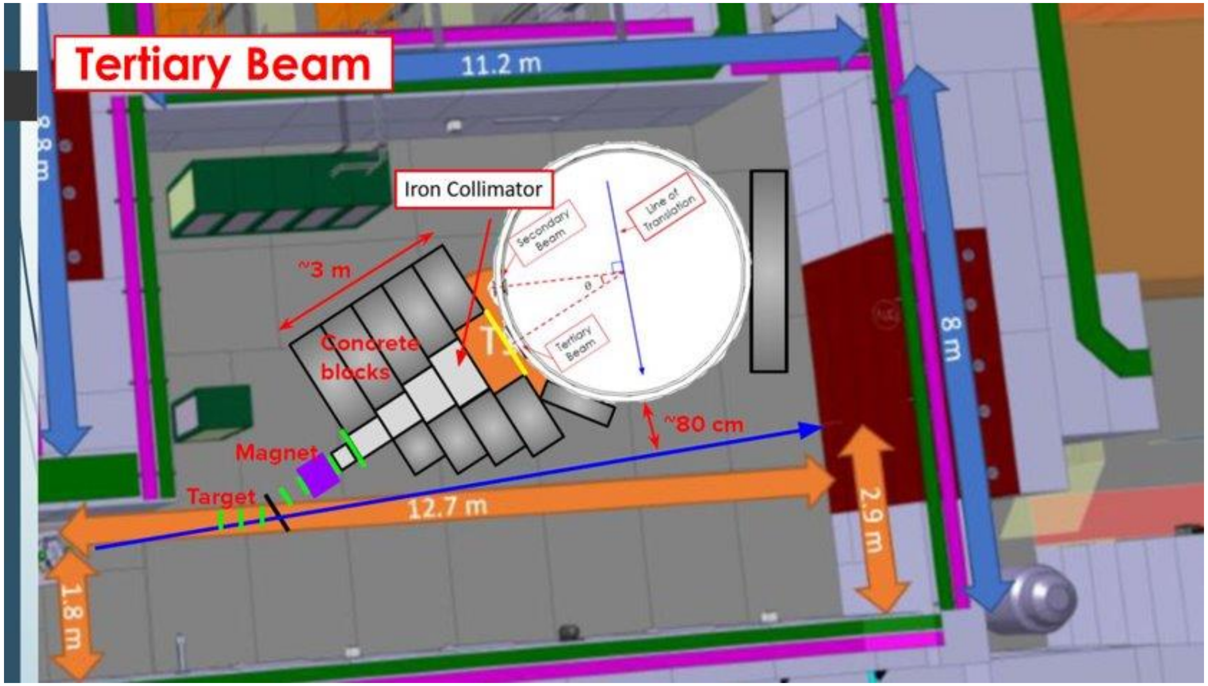
T9 Beamline @ CERN

Two beam configurations available in T9 area - Momentum range 200 – 1200 MeV/c

1. Tertiary beam position for low momentum pion and proton fluxes
   - There may be an option to use only one beam position if the low momentum beam tuning goes well later this month



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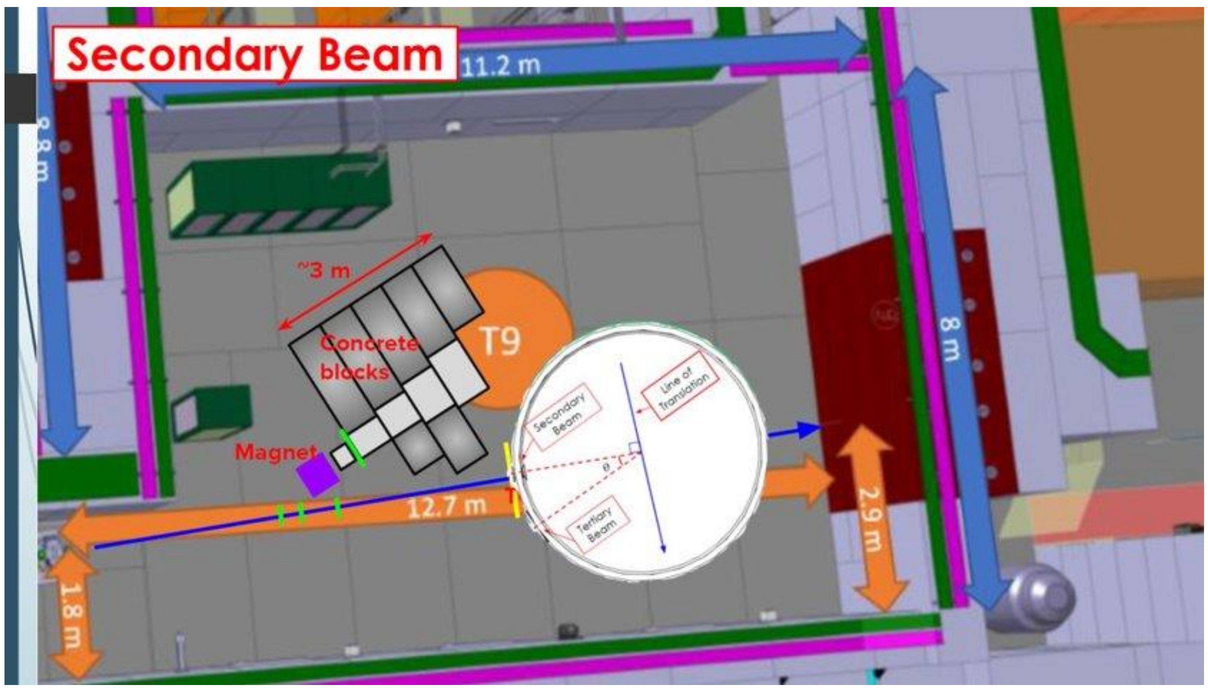
T9 Beamline @ CERN

Two beam positions available in T9 area

1. Secondary beam position for electron, muon and proton fluxes



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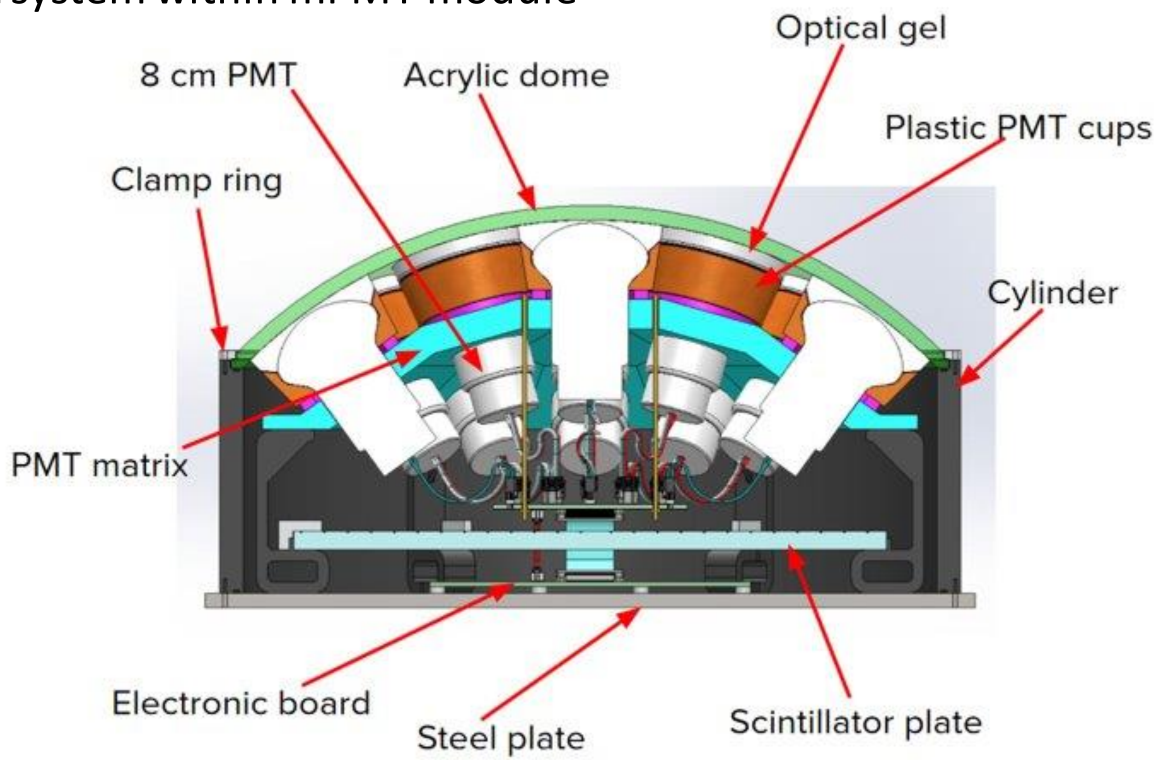
WCTE Detector Instrumentation

- Nineteen 8cm diameter PMTs (Hamamatsu R14374) - multi-PMT modules (mPMT)
- Improved granularity and timing compared to larger PMTs
- Integrated LED calibration system within mPMT module



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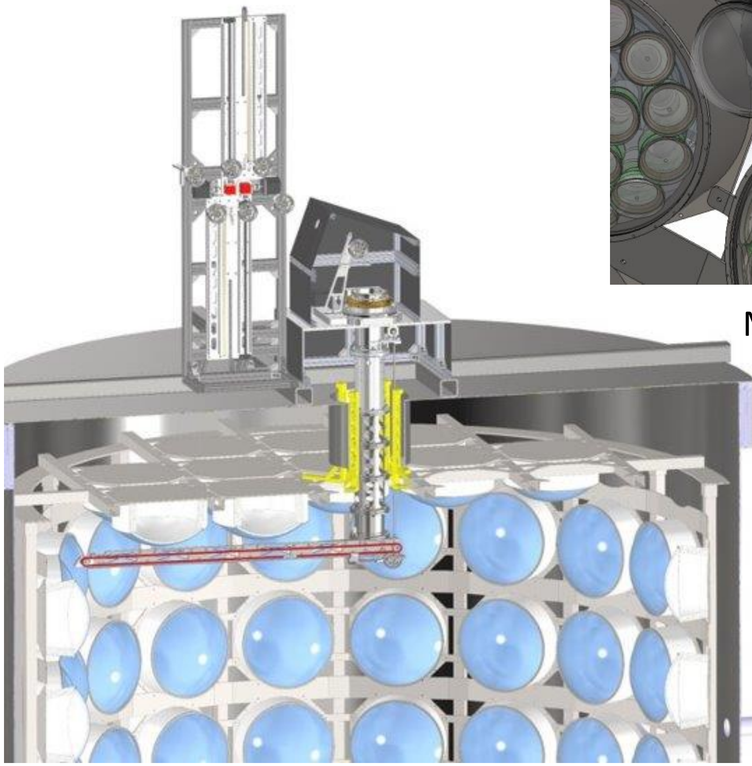
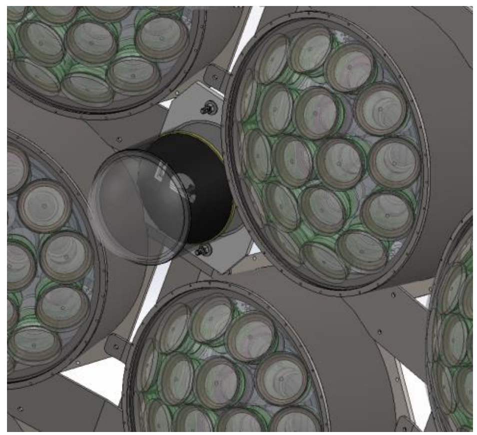
WCTE Detector Design

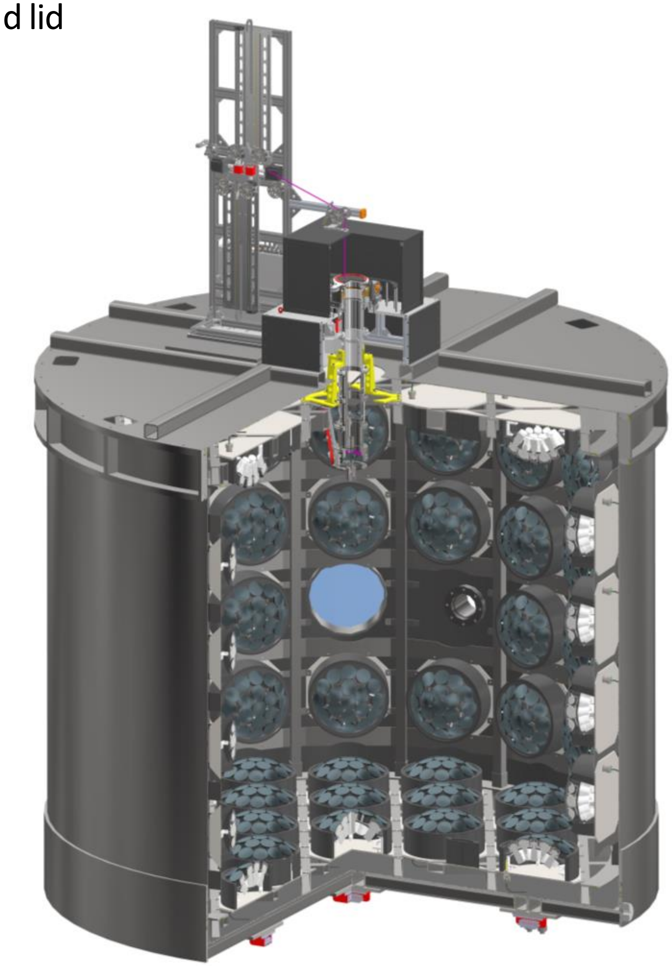
- Calibration deployment system mounted on support structure and lid
- Permanently deployed inside detector

Calibration deployment system (CDS)





Mounted cameras



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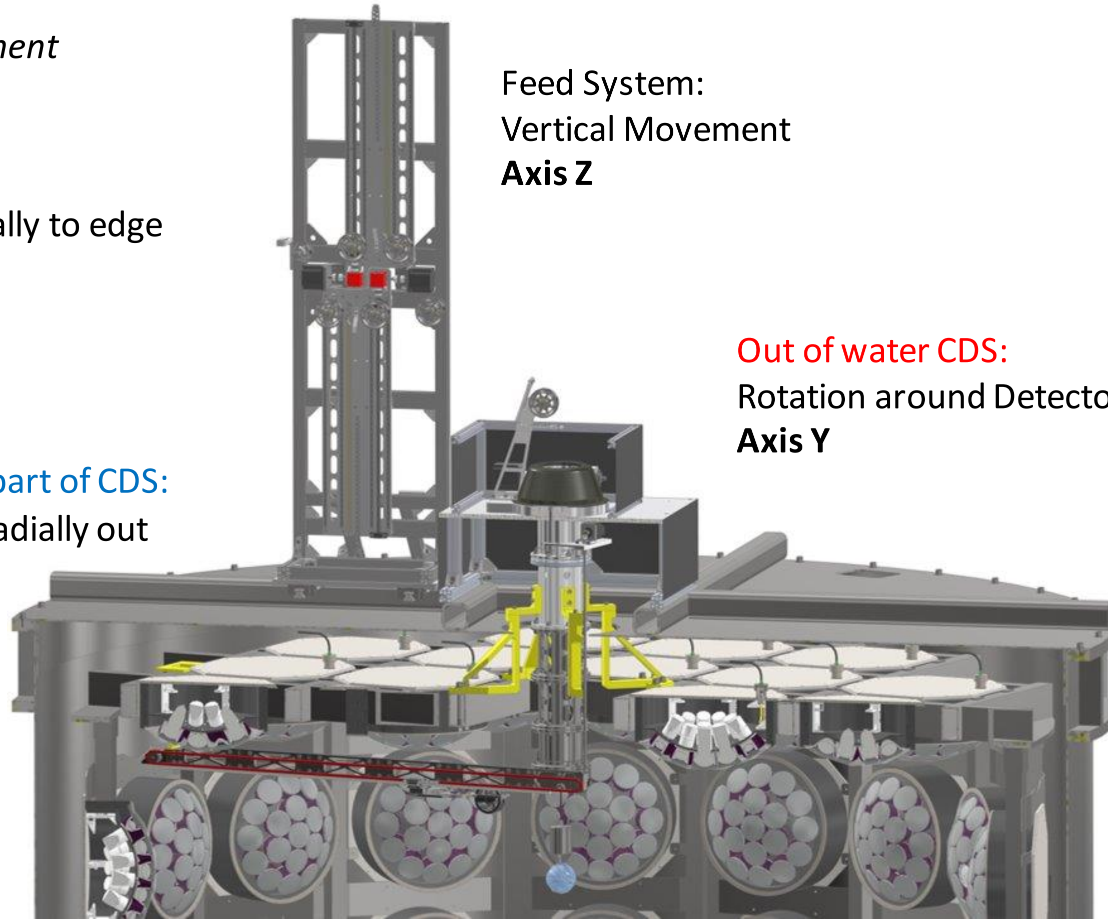
WCTE Calibration: CDS

CDS – Central Deployment System
Designed for the ***W**ater **C**herenkov **T**est **E**xperiment*

3 Axis System

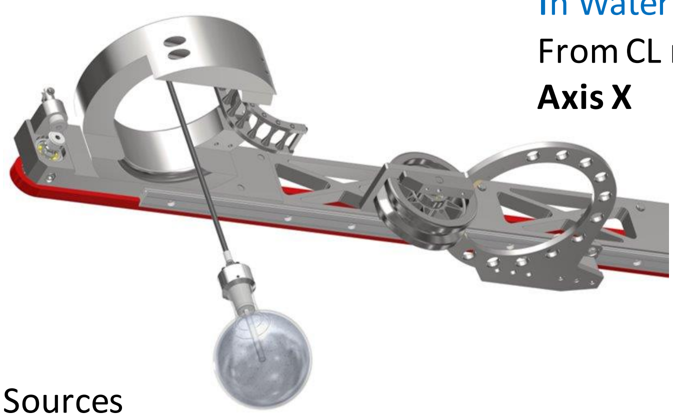
- X – Laser ball from vertical center line, radially to edge
- Y – Rotation around tank +/- 180 degree
- Z – Laser Ball vertical +/- in tank



Feed System:
Vertical Movement
Axis Z

Out of water CDS:
Rotation around Detector
Axis Y

In Water part of CDS:
From CL radially out
Axis X



- Sources
  - Isotropic light source
  - Camera for photogrammetry
  - Radioactive source

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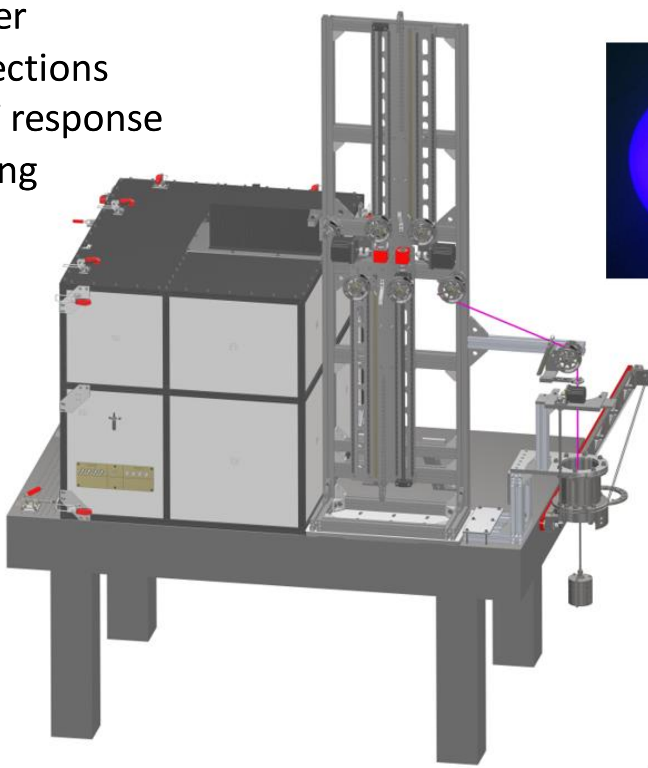
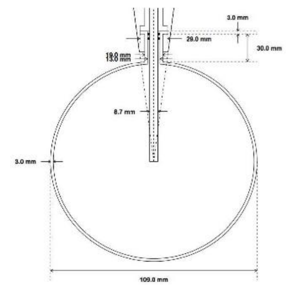
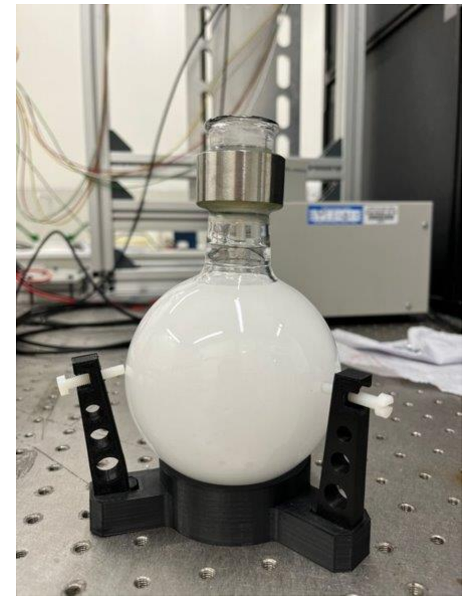
WCTE Calibration: Isotropic Light Source

- Imperial group is designing/fabricating a laser diffuser ball and associated deployment system for HK/IWCD/WCTE to measure:
  - Geometry
  - Water
  - Reflections
  - PMT response
  - Timing







- Build on SNO/SNO+/DEAP3600 design
  - Quartz flask
  - Suspended glass spheres
  - Optical gel

- Using WACKER silgel
  - 612 (softer setting)
  - 604 (harder setting)

  - 3M glass microspheres @ 0.4% by mass

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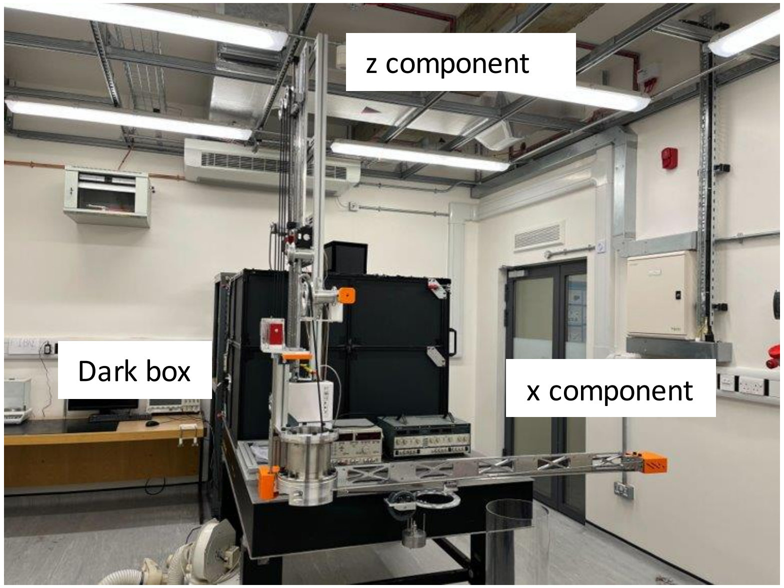
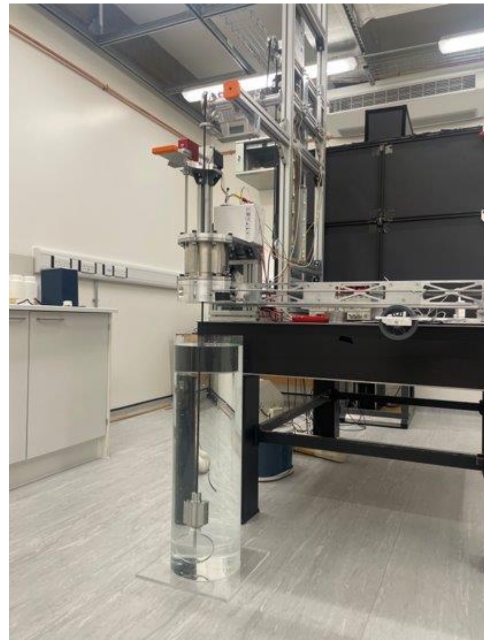
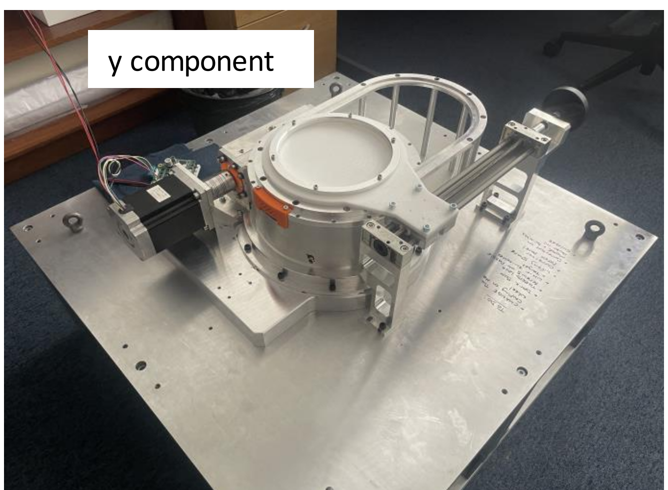
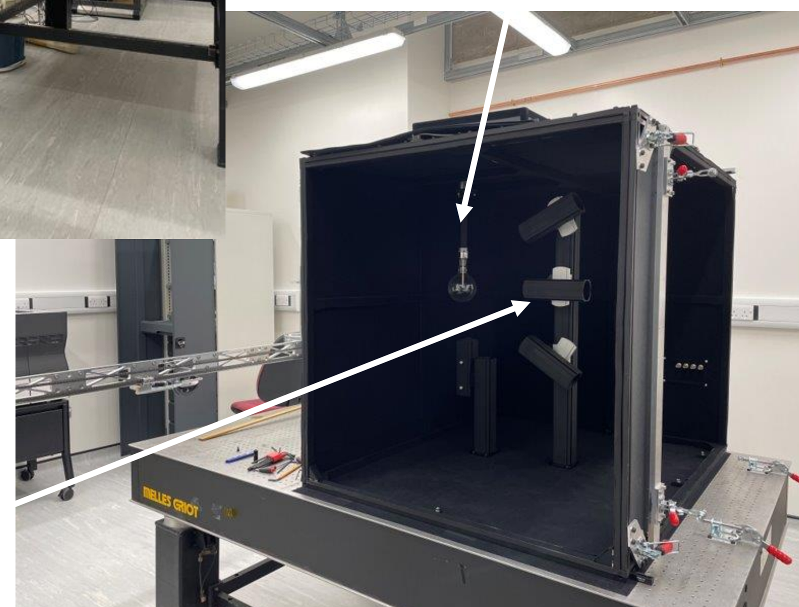
Prototype @ Imperial: CDS









Summary

- **T2K has made some of the most precise measurements of neutrino oscillation parameters**
  - Will eventually become **stats limited** -> **Build bigger detector!**
  - Even with bigger detector we will become **systematics limited**
    - **Build an intermediate detector to measure Xsec!**
    - **Build a test experiment to improve methods of reducing detector systematic errors!**

- Reduce detector systematics using a test experiment (**WCTE**) to:
  - Test new technologies
  - Measure secondary particle interactions
    - **Performing in depth simulations and reconstruction studies**
  - Demonstrate 1% level detector calibration
    - **Custom calibration systems!**
  - **Crucial for future experiments!**

- **WCTE Recommended by SPSC for beam time in 2024 – new collaborators welcome! - Feel free to get in touch if you are interested.**

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Backup

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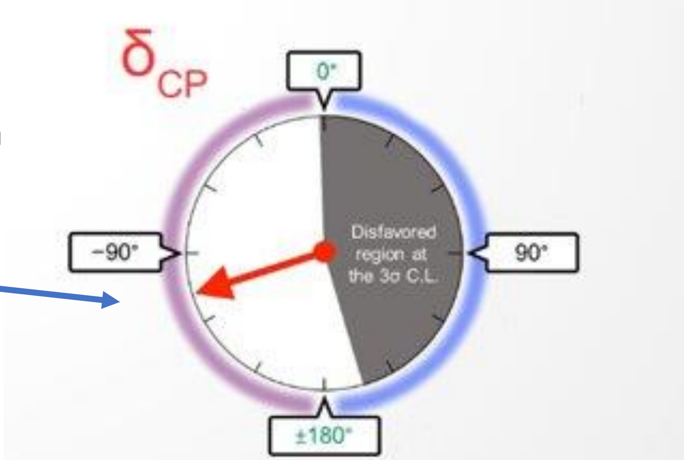
Neutrino Oscillation: Theory

- The PMNS matrix describes neutrino oscillation as a product of 3 matrices corresponding to 3 different neutrino sectors:

$$U_{\alpha i} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{(\text{Atmospheric - } \Delta m^2_{23}, \theta_{23})} \overbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}^{(\text{Reactor/Accelerator - } \Delta m^2_{31}, \theta_{13})} \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{(\text{Solar - } \Delta m^2_{12}, \theta_{12})}$$

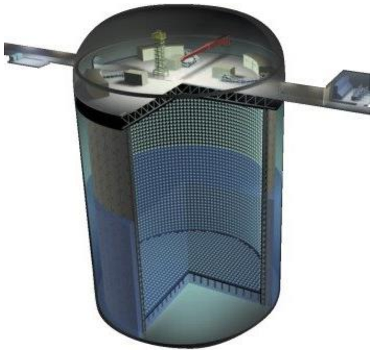
- Parameterized by 3 mixing angles and a CP violating phase delta
- Non-zero off diagonal elements implies that a neutrino of one flavour is a combination of multiple mass states
- CP violating phase has been constrained to be in this region:

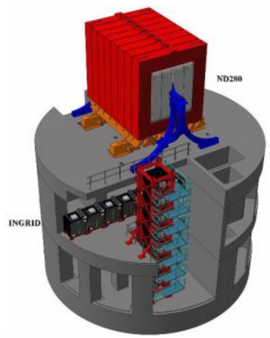


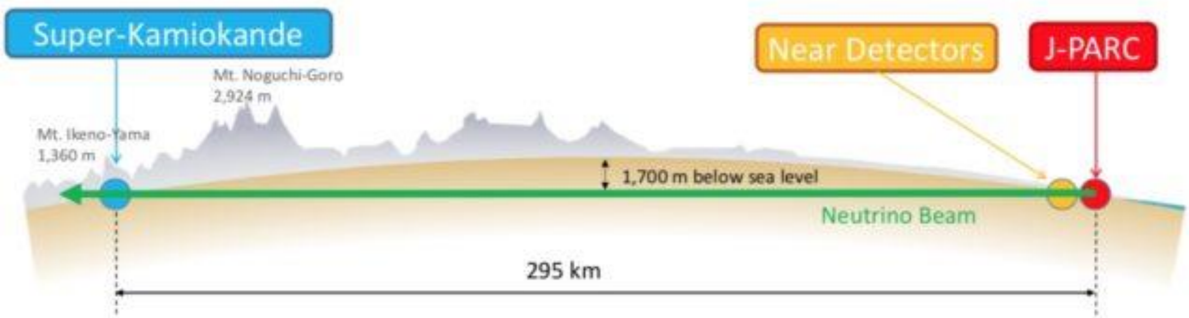
T2K Nature paper, spring 2020

α corresponds to neutrino flavour (e,μ,τ)
i corresponds to the neutrino mass eigenstate
c corresponds to cosine
s corresponds to sine
δ corresponds to the CP violating phase

The T2K Experiment







- Physics goals:
  - Measure neutrino oscillation parameters in ν_μ disappearance
  - Search for CP violation in neutrino sector
  - Neutrino X_{sec} measurements using near detectors

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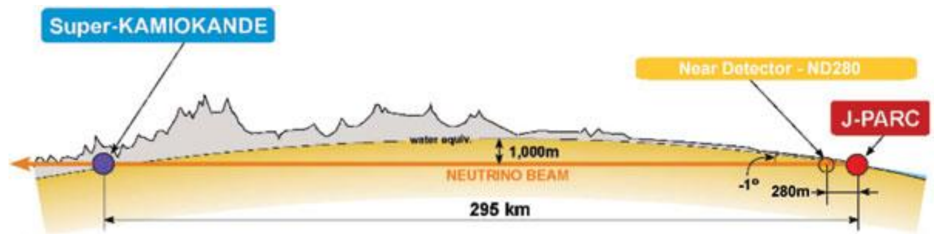
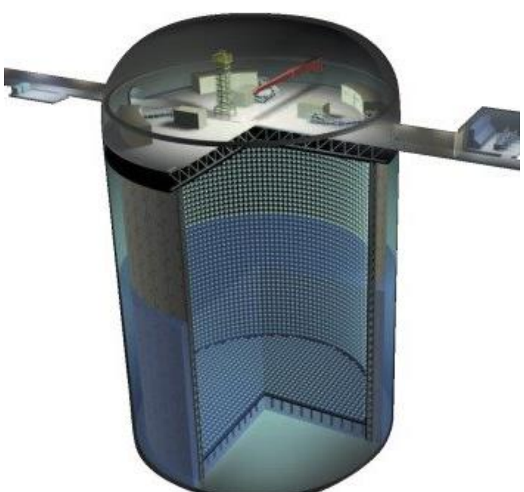
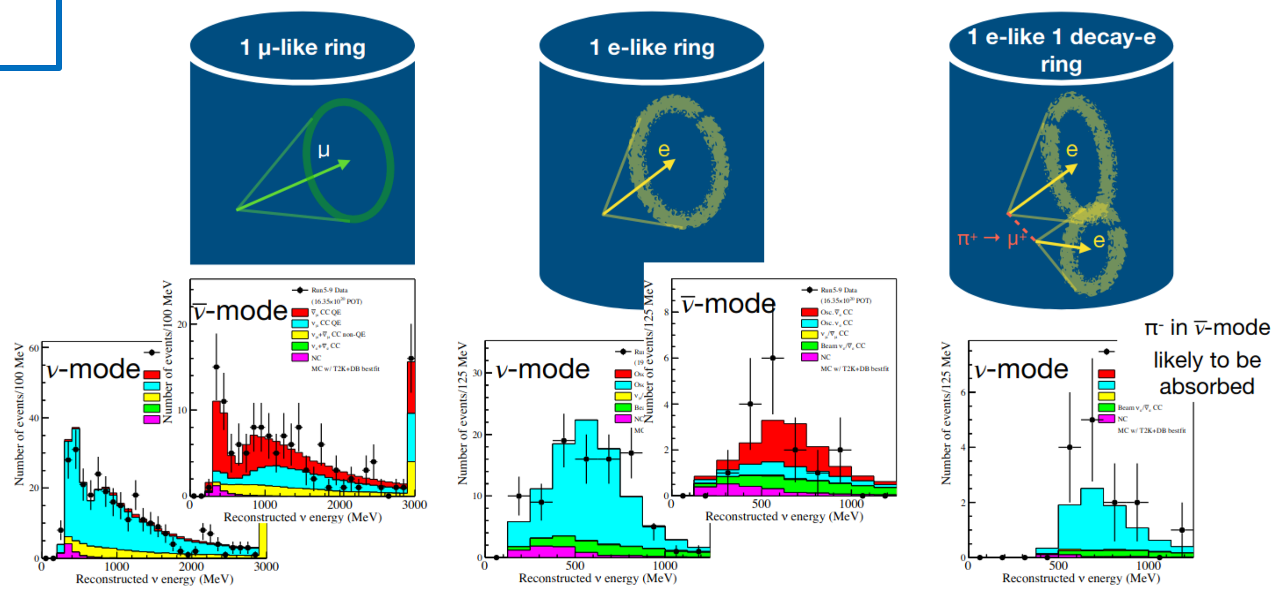
T2K Experiment: Super-Kamiokande

- 50kton water Cherenkov detector ~ 40m * 40m
- ~11000 20" Hamamatsu PMTs in the inner detector
- ~2000 8" Hamamatsu PMTs in the outer detector







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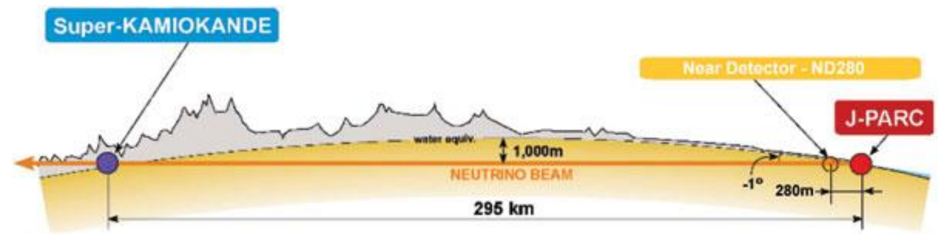
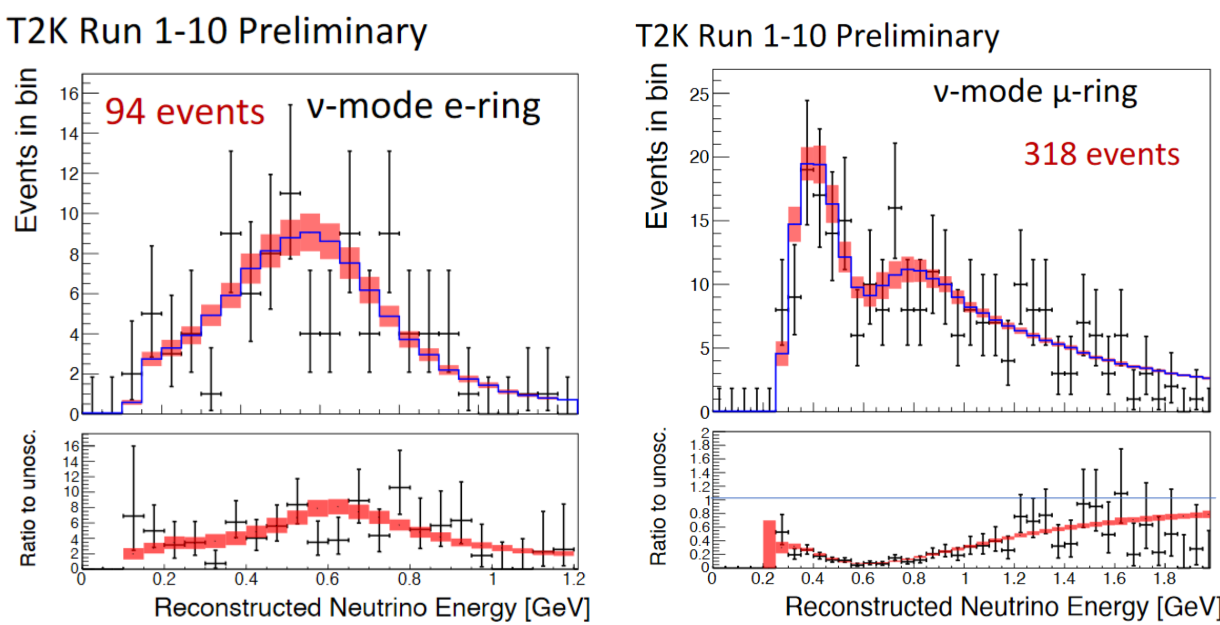
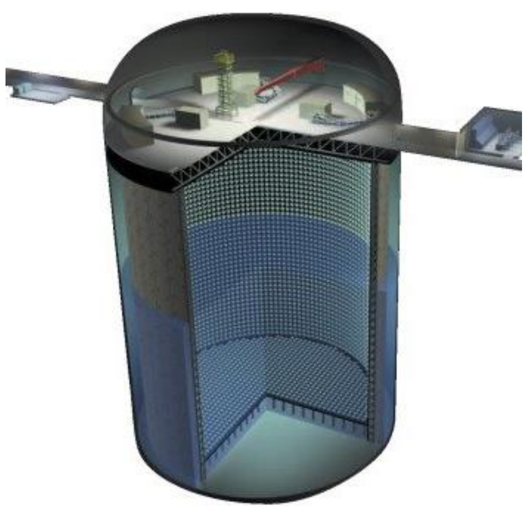
T2K Experiment: Data

- Super-Kamiokande has been in operation for ~25 years
- T2K has been taking data for ~10 years
- Made some of the most precise measurements of neutrino oscillations







P. Dunne, Neutrino 2020, https://zenodo.org/record/4154355

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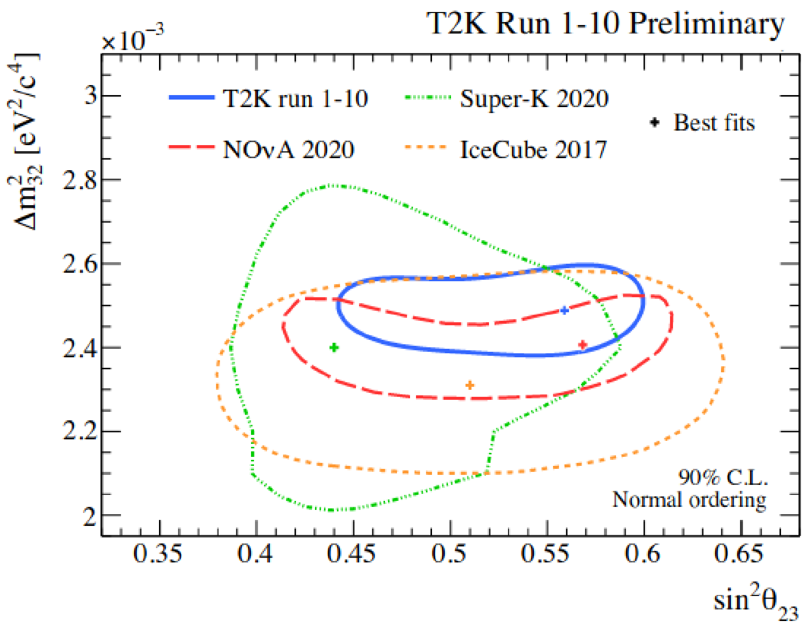
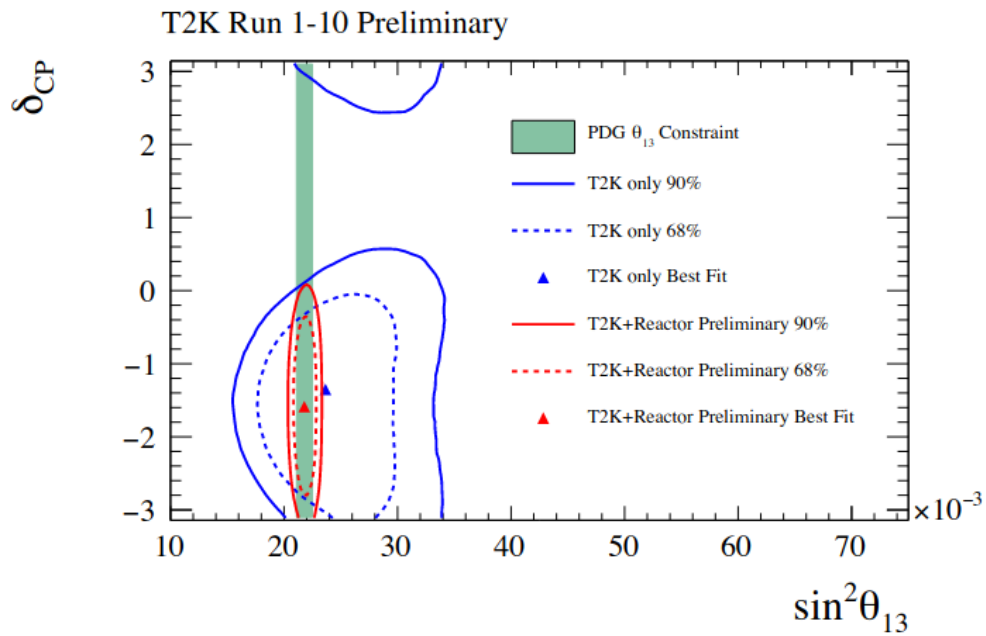
Neutrino Oscillation at T2K: Results

World leading measurements of atmospheric neutrino parameters





Small preference to non-maximal $sin^2\theta_{23}$ in upper octant

θ_{13} measurement @ T2K is consistent with constraint from reactor neutrino experiments

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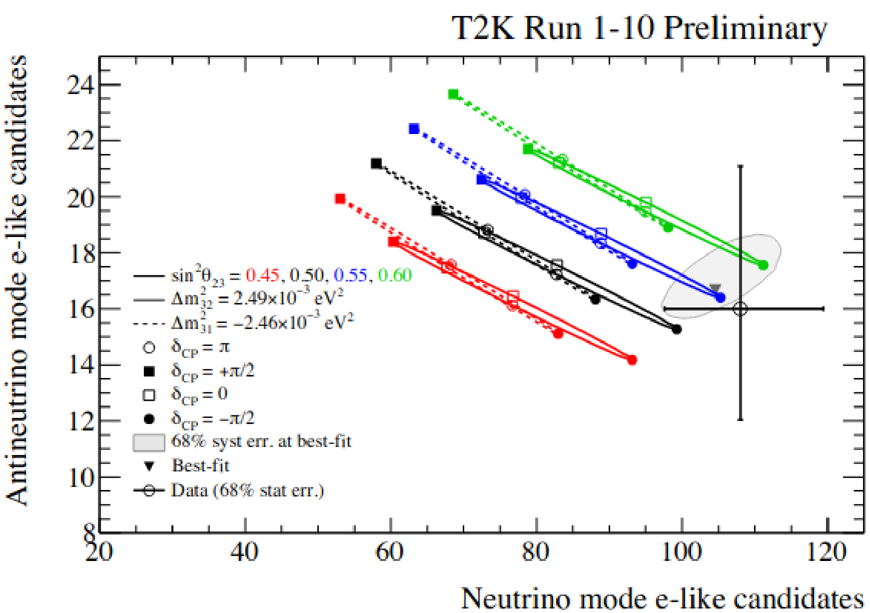
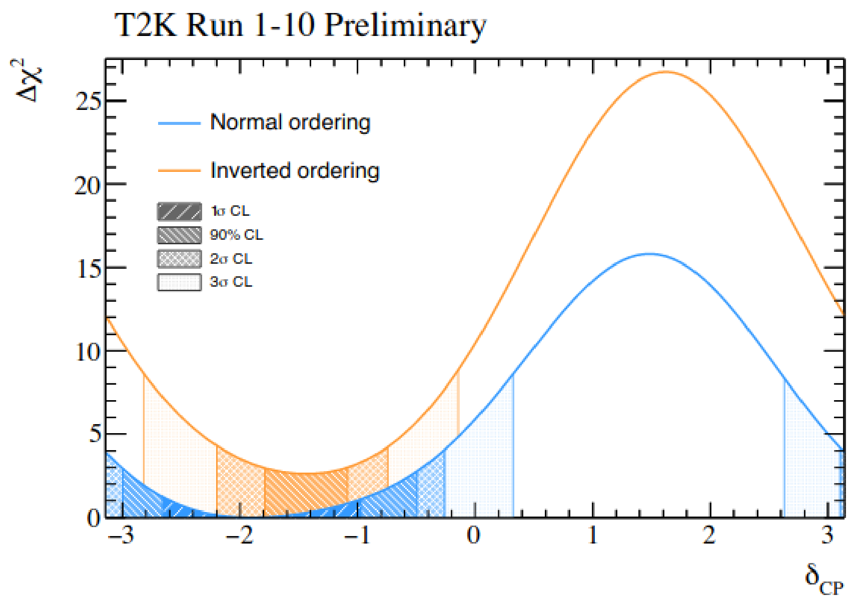
Neutrino Oscillation at T2K: Results

World leading measurements of atmospheric neutrino parameters





PMNS best fit around maximal CP-violation
Weak preference for normal ordering
Weak preference for upper octant

Large region excluded at 3σ
CP conservation at (0,π) excluded at 90% confidence level

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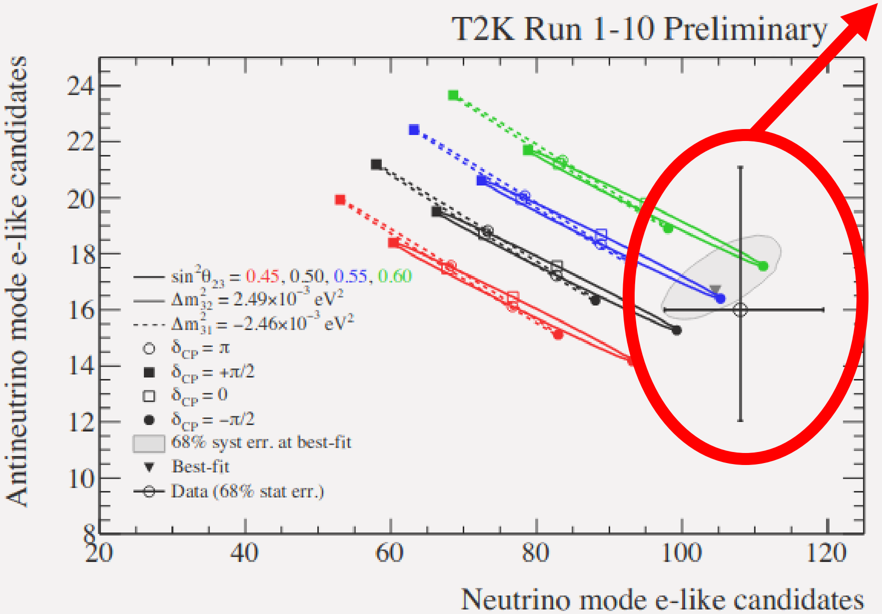
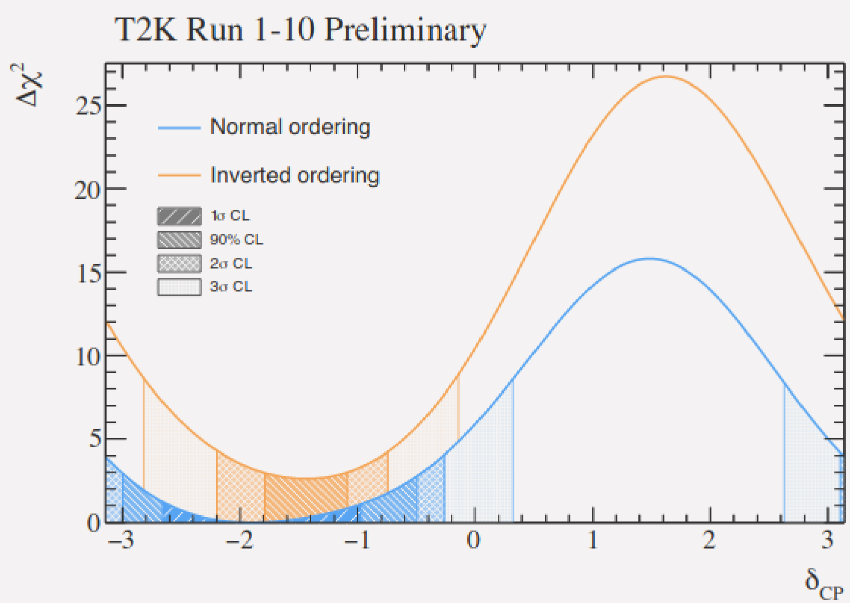
Neutrino Oscillation at T2K: Results

World leading measurements of atmospheric neutrino parameters

T2K is statistics limited!



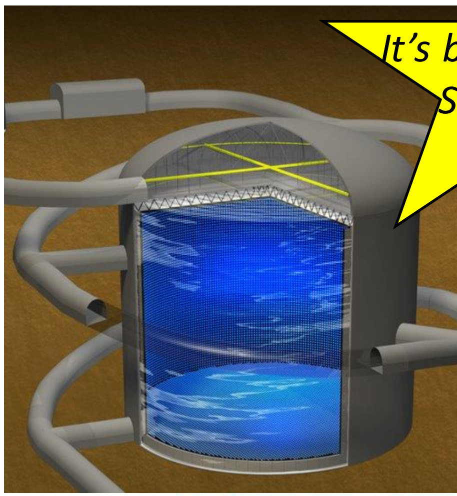


PMNS best fit around maximal CP-violation
Weak preference for normal ordering
Weak preference for upper octant

Large region excluded at 3 sigma
CP conservation at (0,pi) excluded at 90%

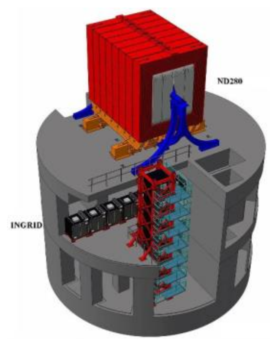
Future of the T2K Experiment

Far detector:
Hyper-Kamiokande

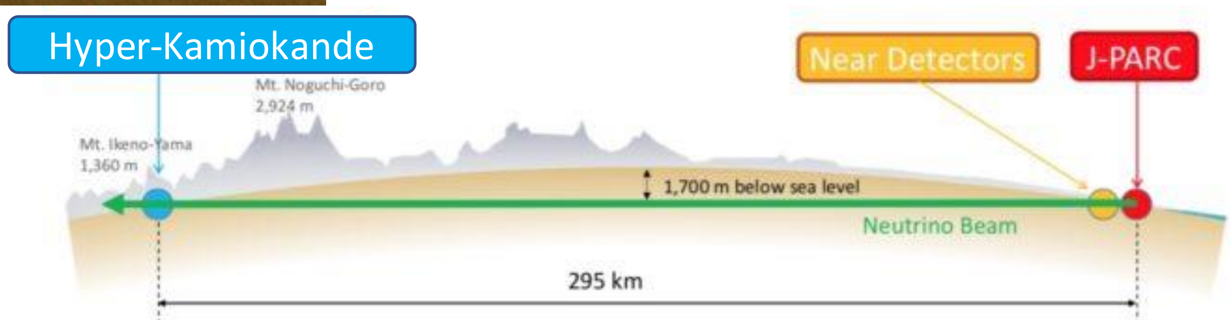


It's bigger than Super-K!

Near detector complex



Beam facility



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Hyper-Kamiokande

- Neutrino oscillation physics
  - Accelerator
  - Atmospheric
  - solar

→ Neutrino oscillation parameters
Charge Parity Violation (CPV)

- Nucleon decay

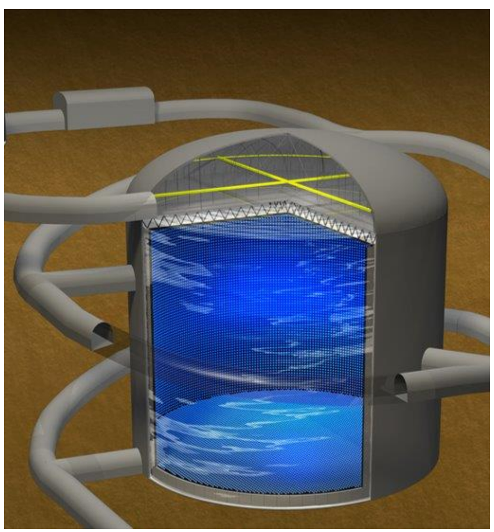
→ GUTs

- Supernova neutrinos

→ Supernova detection

- Astrophysical neutrinos

→ Dark matter searches
GRBs



- Long baseline measurements using **1.3MW bean x 6 cycles/year x 10years**
- Fiducial mass of 188 kton
  ~40000 PMTs in the inner detector
- Combination of 20" PMTs and "multi-PMT" modules
- Higher statistics than Super-K

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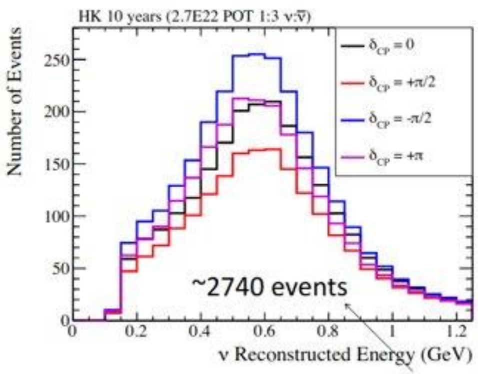
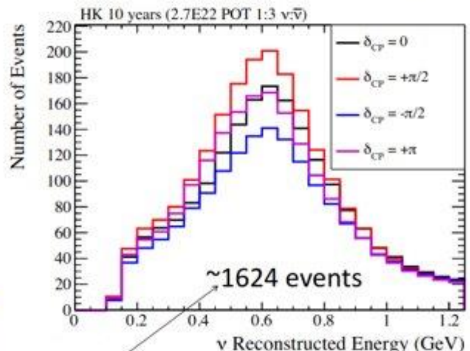
Neutrino Oscillations @ Hyper-Kamiokande

Neutrino mode : appearance



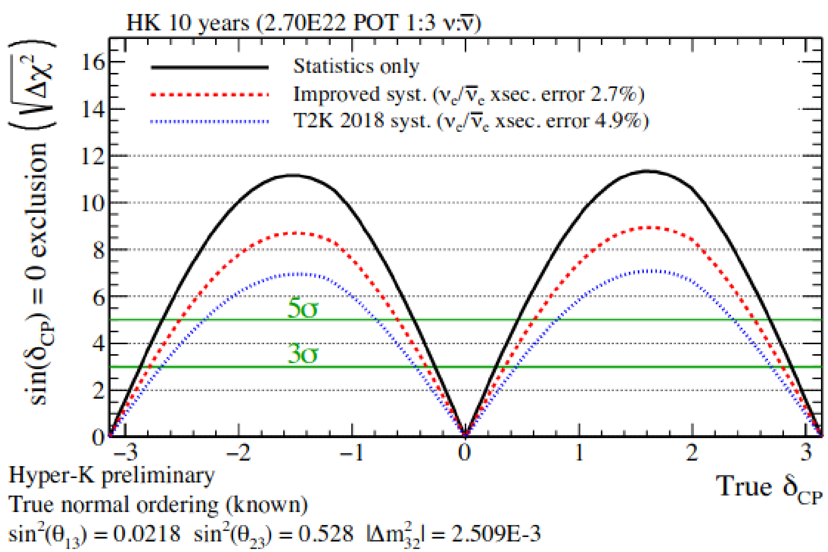
Anti-neutrino mode : appearance

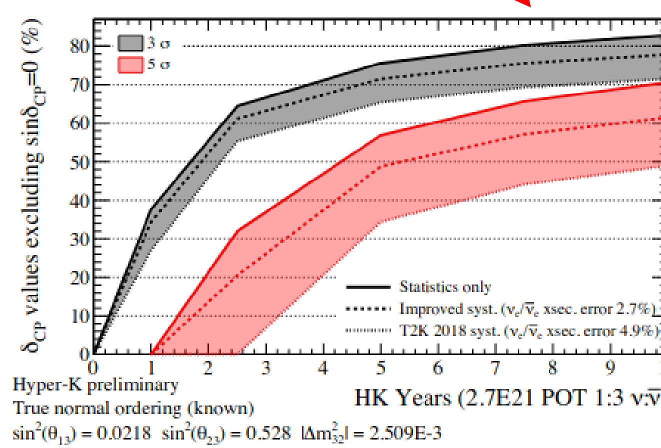


Expected @δ=-π/2

Bigger detector = more statistics!

Using current T2K ND measurements, HK becomes systematics limited





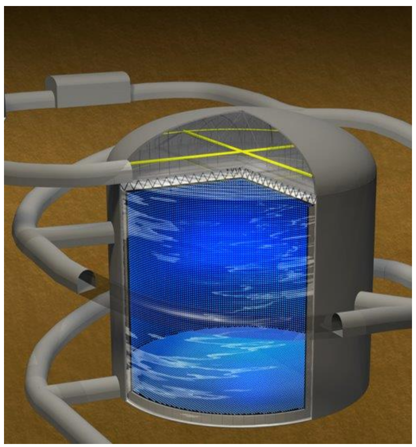
Future T2HK Experiment

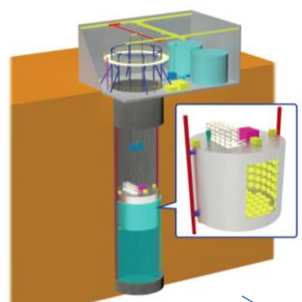
Far detector

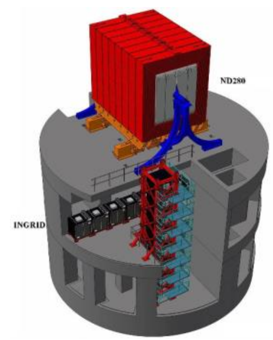
New Intermediate Detector!

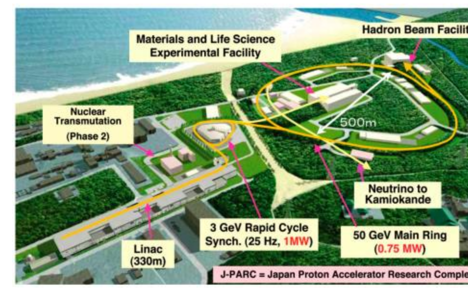
Near detector complex

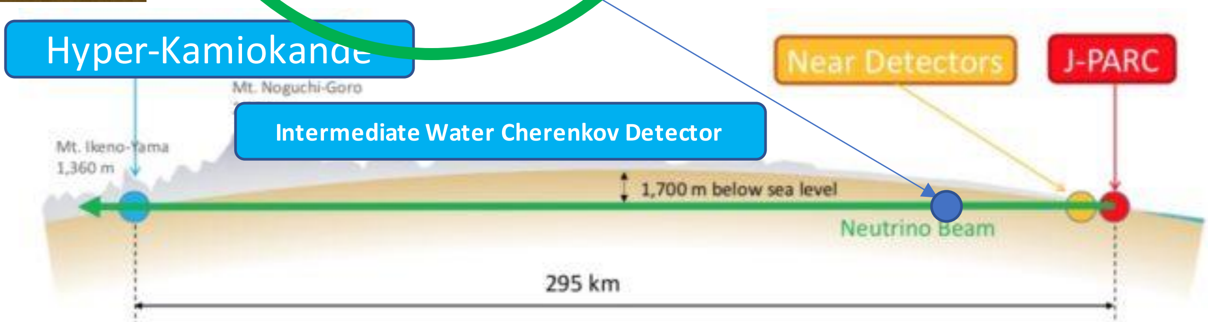
Beam facility











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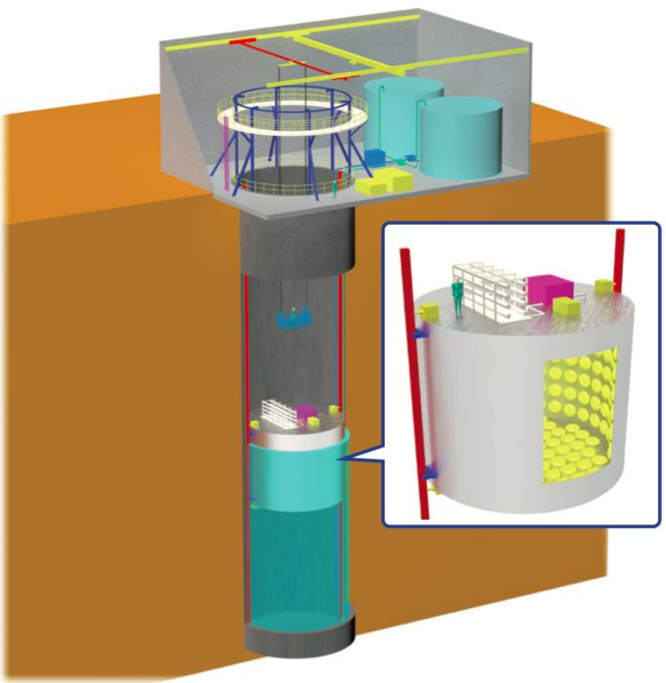
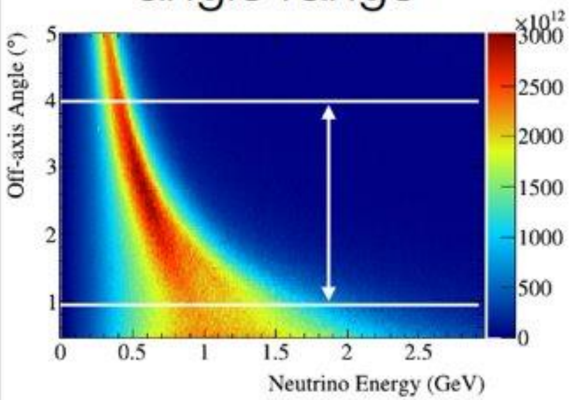
T2HK Experiment: Intermediate Water Cherenkov Detector (IWCD)

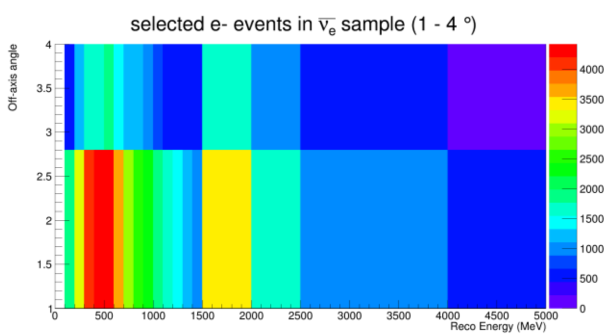
To help address the systematic uncertainty limitation in Hyper-Kamiokande, the "Intermediate Water Cherenkov Detector" (**IWCD**) has been proposed.



- 300t water Cherenkov detector
- Measure neutrino X_{sec} with same angular resolution as the far detector
- Detect small ν_e presence in the unoscillated beam

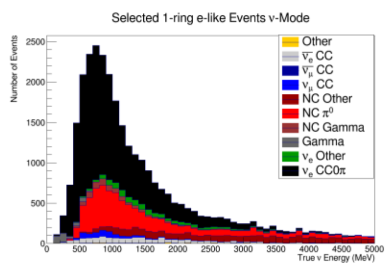
Nominal off-axis angle range

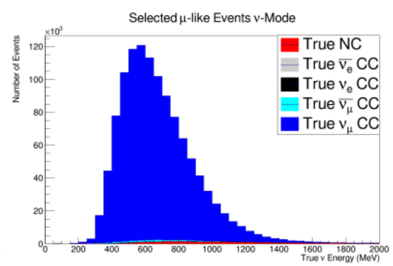


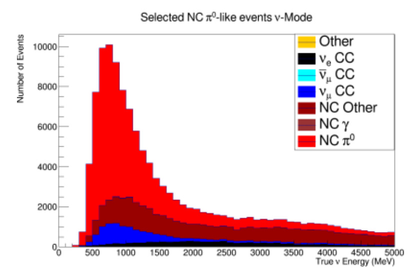


T2HK Experiment: Intermediate Water Cherenkov Detector (IWCD)

- Simultaneous fit of 3 samples
  - 1-ring e-like FHC/RHC
  - 1-ring μ-like FHC/RHC
  - $NC\pi^0$-like FHC/RHC



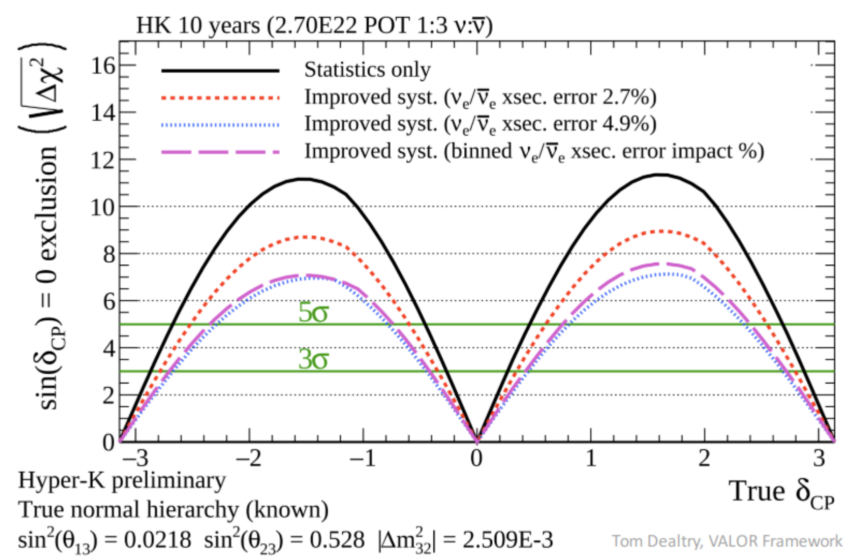




- Fit in one and two dimensions to extract ν_e and $\bar{\nu_e}$ X_{sec} errors

- Apply X_{sec} errors to HK oscillation analysis

Constraint	Error on $\nu_e/\bar{\nu_e}$ event rate ratio at HK (%)
Theory	4.92
IWCD	3.78



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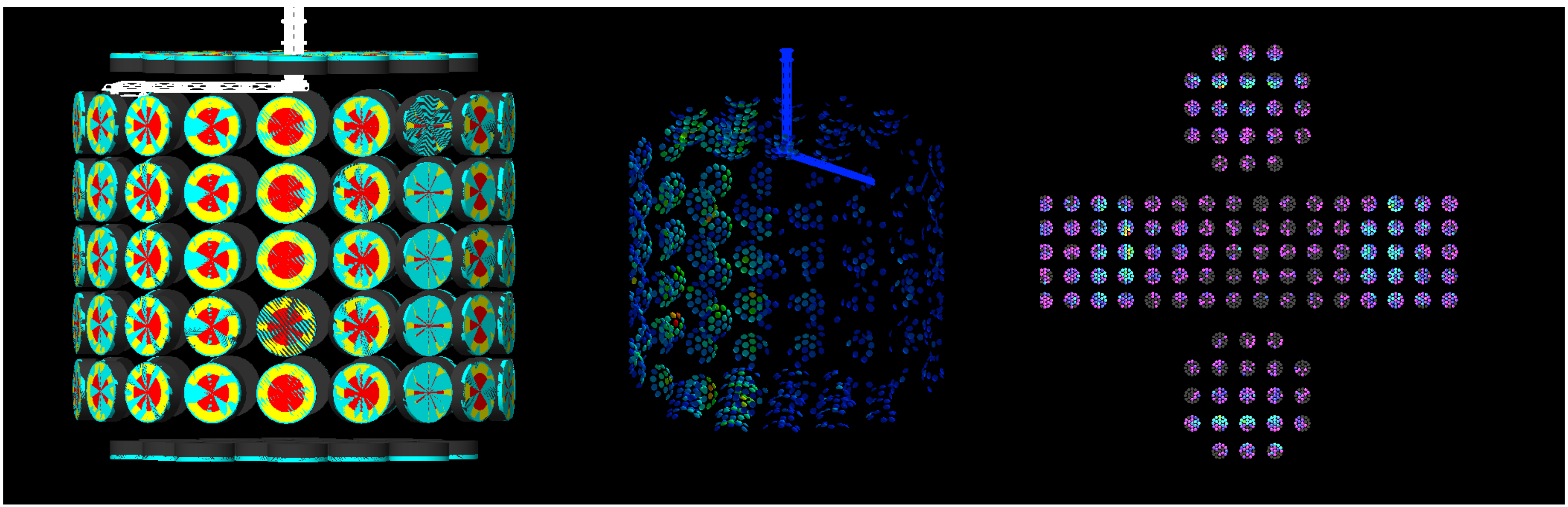
WCTE Simulation

- Using Water Cherenkov Simulation (WCSim) software to produce detector simulations
  - Open source GEANT4 based software developed for simulating large water Cherenkov detectors: https://github.com/WCSim/WCSim
  - Included mPMT modules and calibration system
    - Calibration system included by importing CAD model into GEANT4 using open source CADMesh software: https://github.com/christopherpoole/CADMesh



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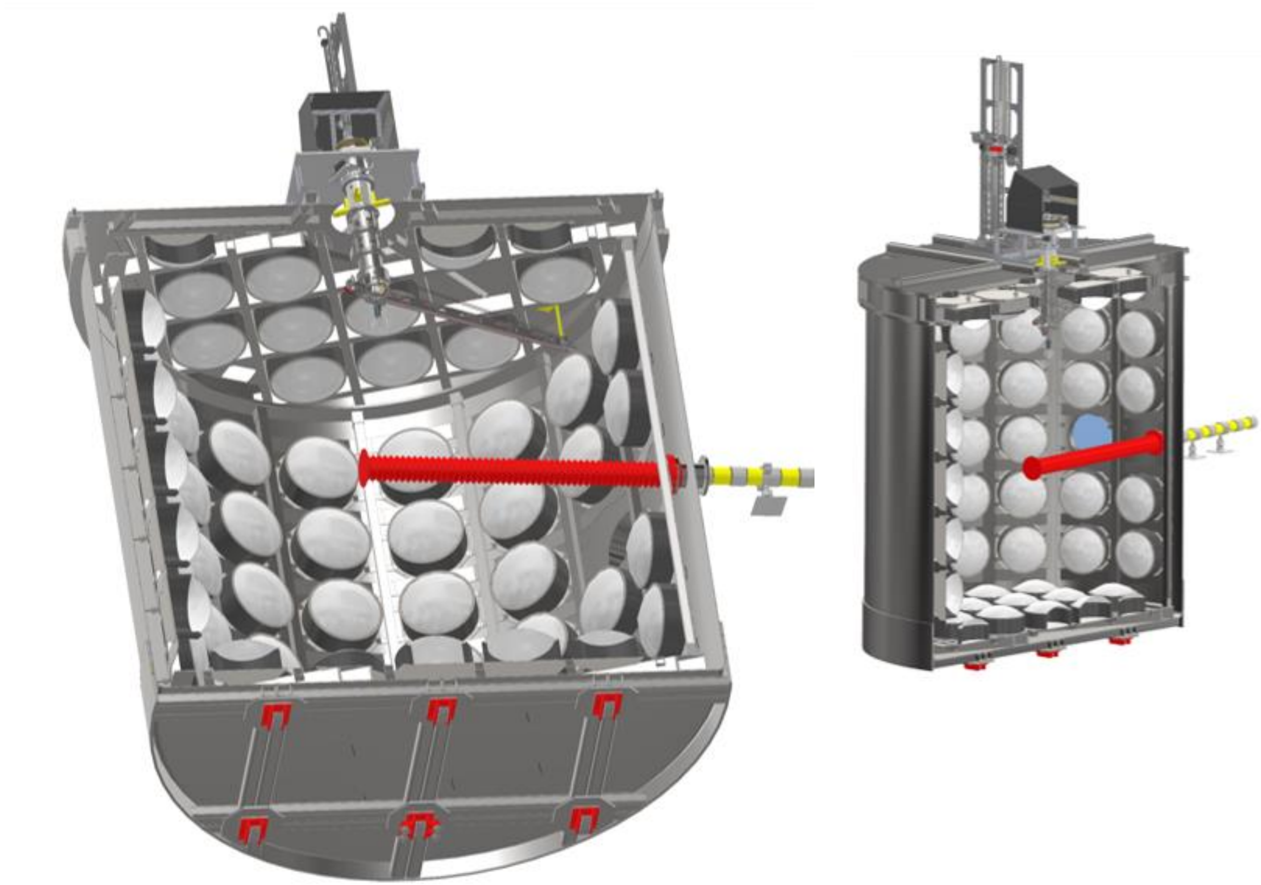
WCTE Detector Design

Detector:	Mass Kg
Vessel (inc movement sys)	4,700
mPMT Support Structure - populated	7,000 (each mPMT @ 41Kg)
Lid	1400
Water	42,000
CDS (total CDS)	200
Total Approx.	55,250



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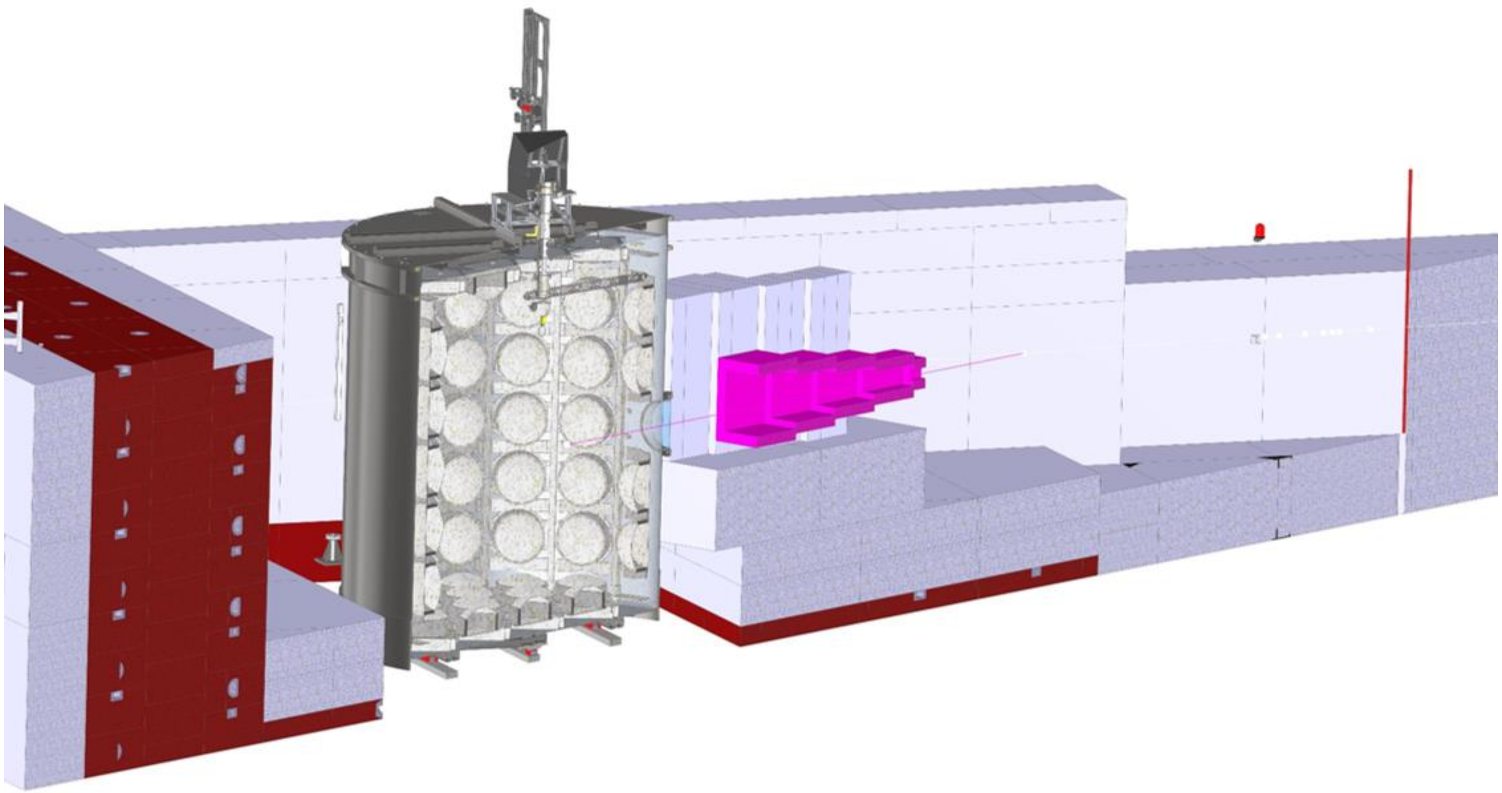
Section of Tertiary Beam into Detector



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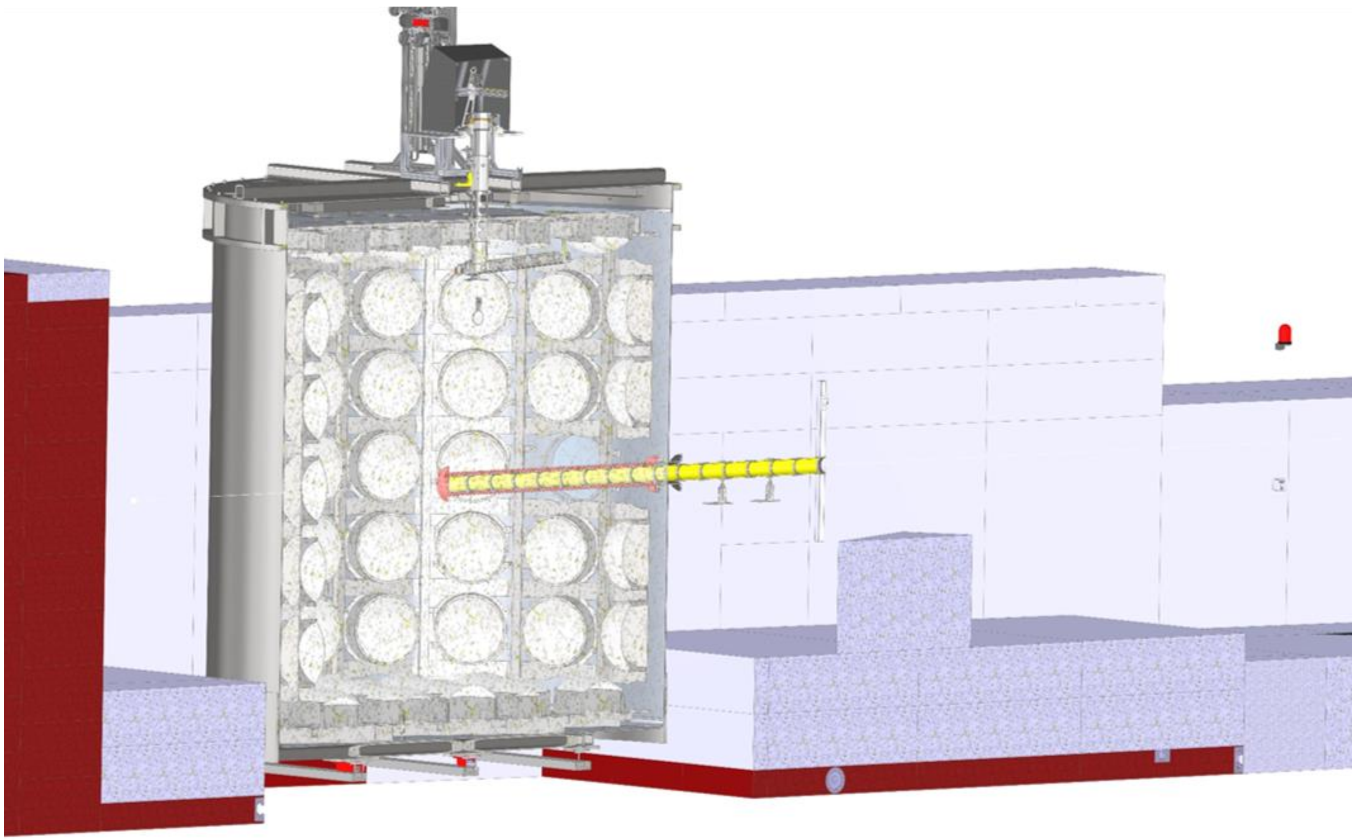
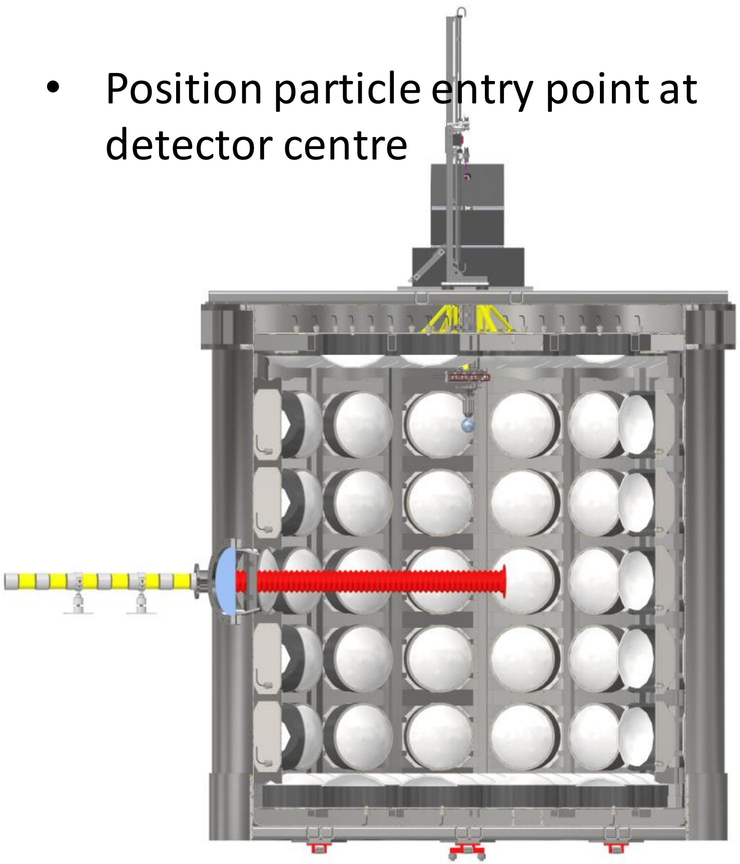
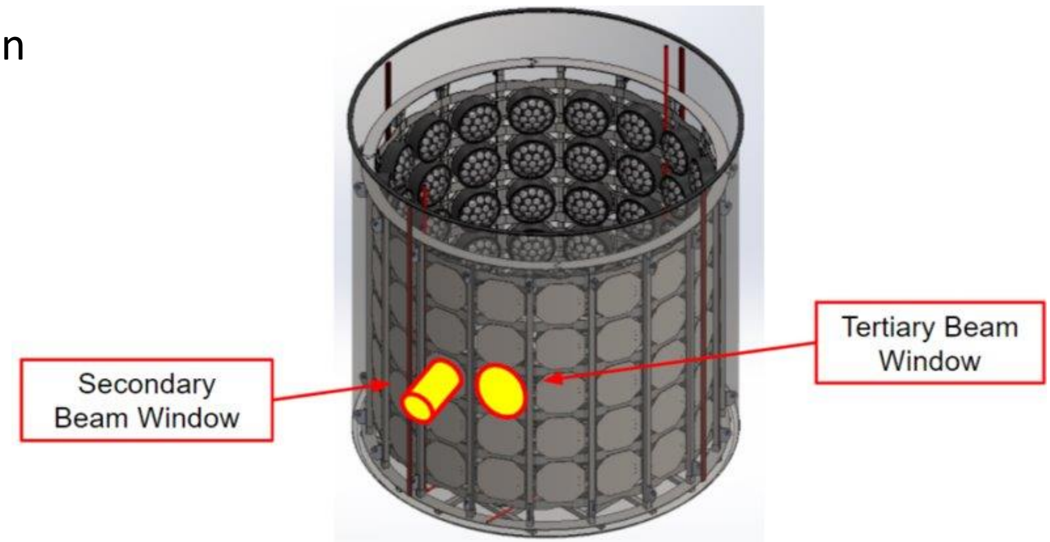
Section of Secondary Beam into Detector

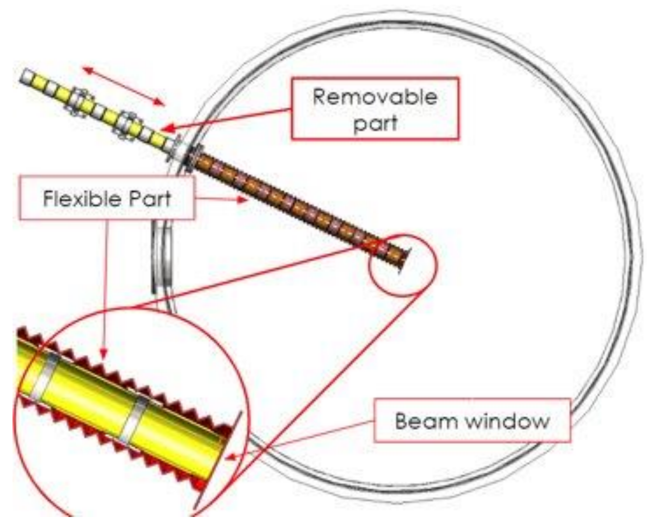


WCTE Detector Design

- Extendible beam window mounted on detector wall for use in secondary beam configuration
- Position particle entry point at detector centre







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WCTE Detector Design

Detector	Dimension mm
Diameter of Vessel OD	3800
Outermost Diameter	3960
Height*	4180

*Height from top of lid to the rollers

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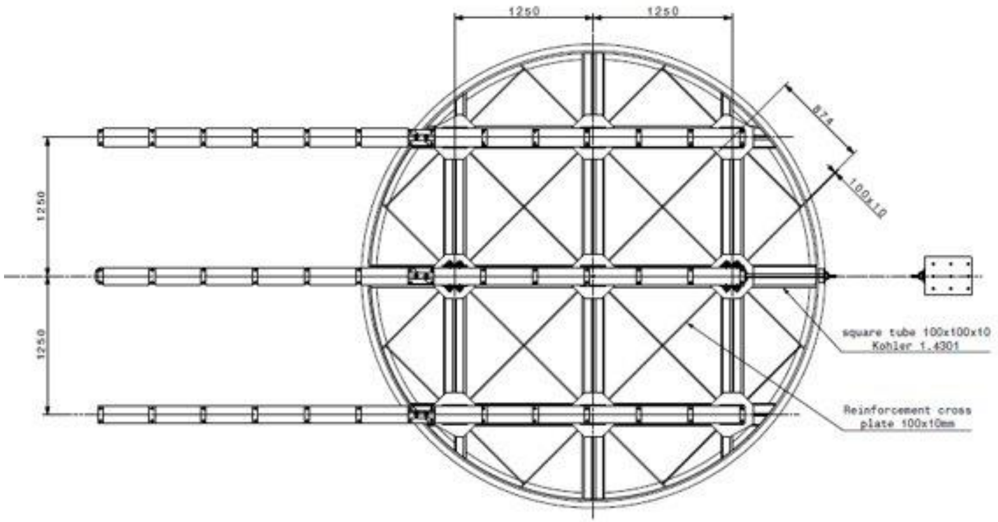
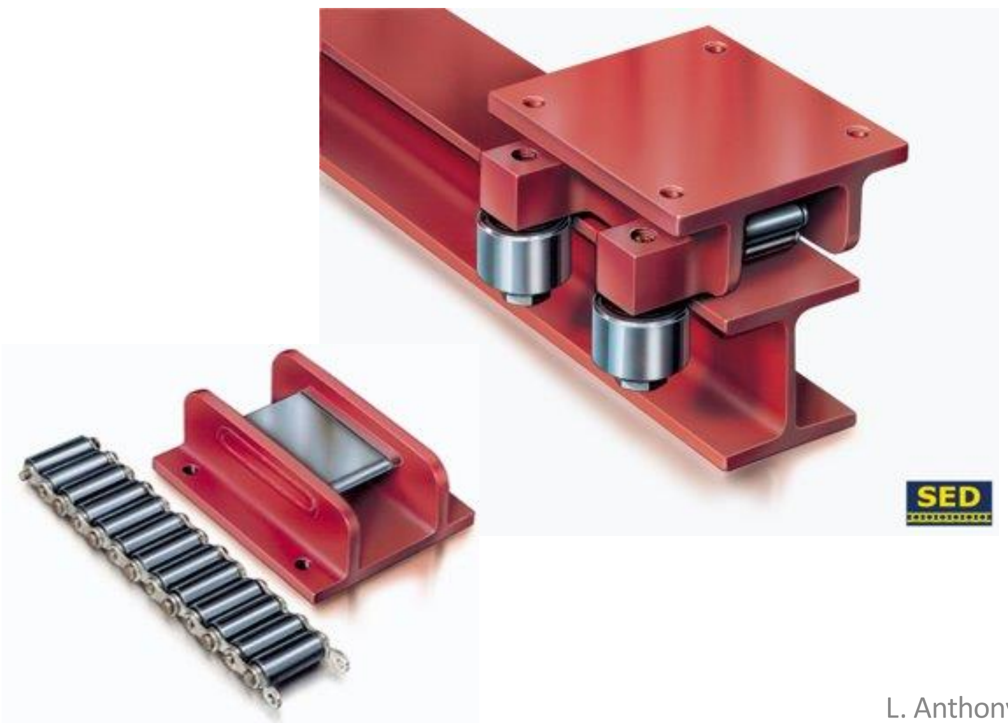
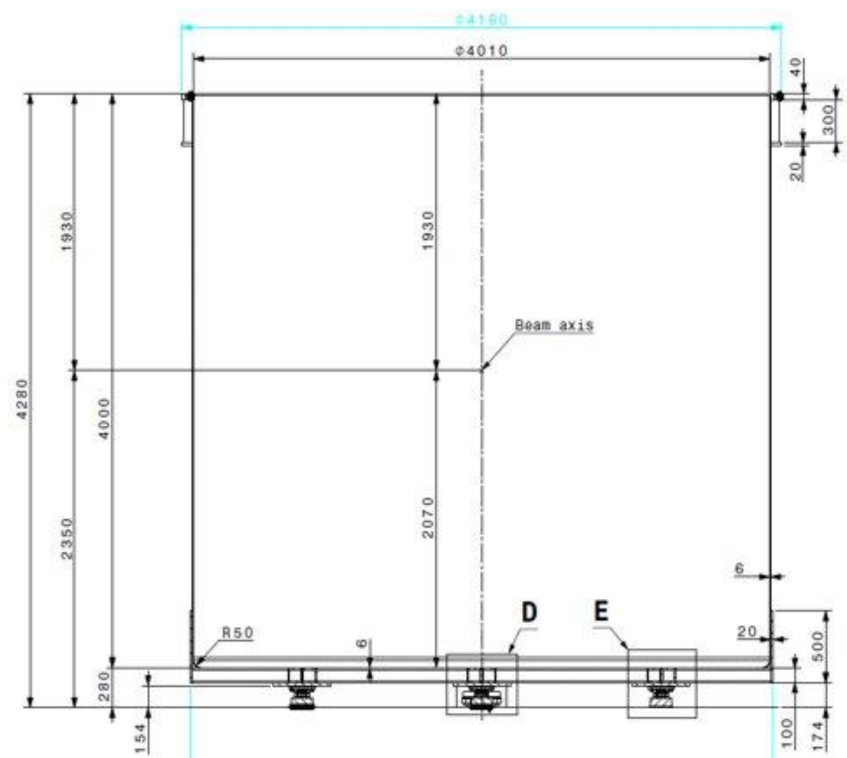
Movement System







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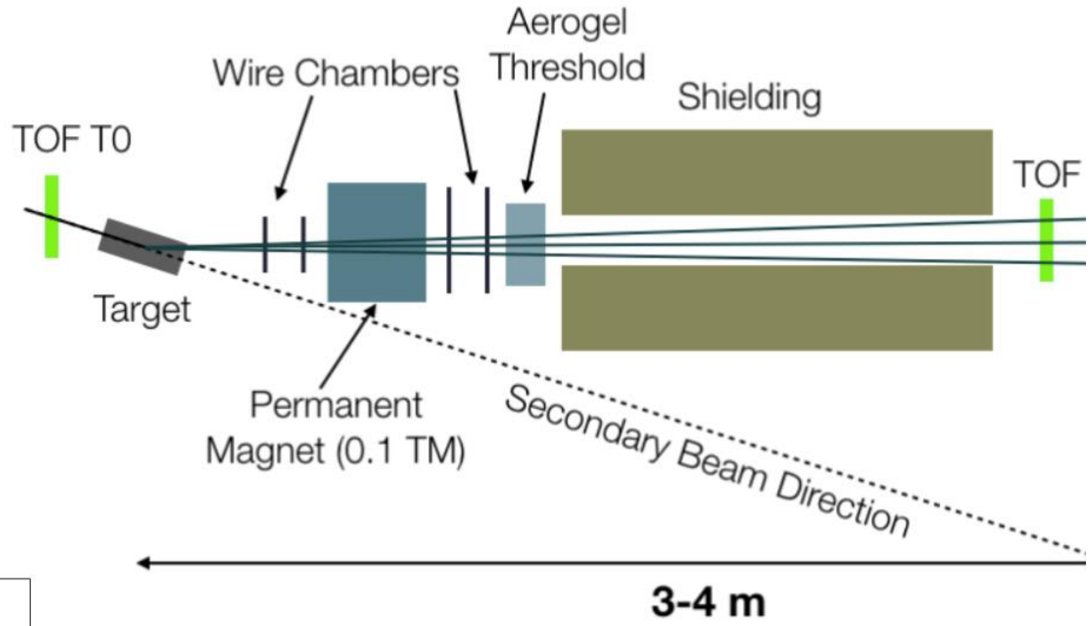
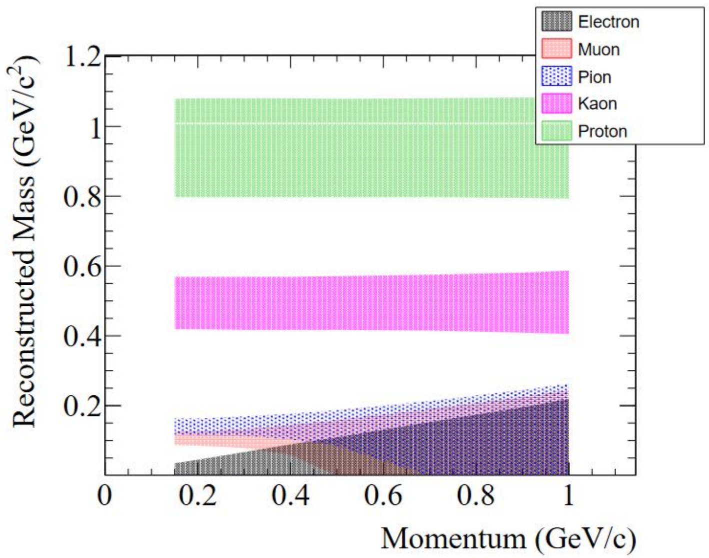
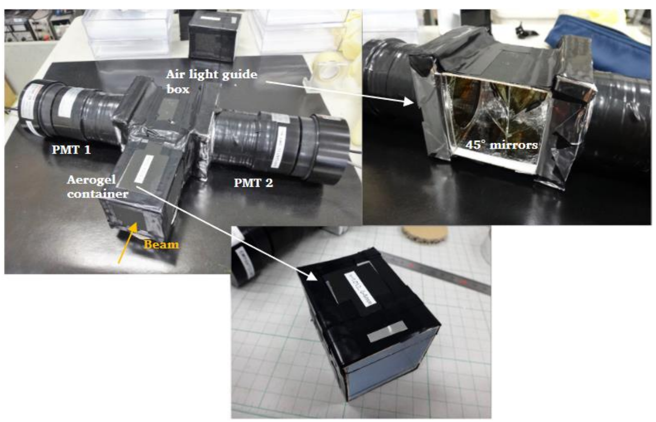
Tertiary beamline

- TOF detector with 100ps resolution RPCs
- Very good mass separation (below)



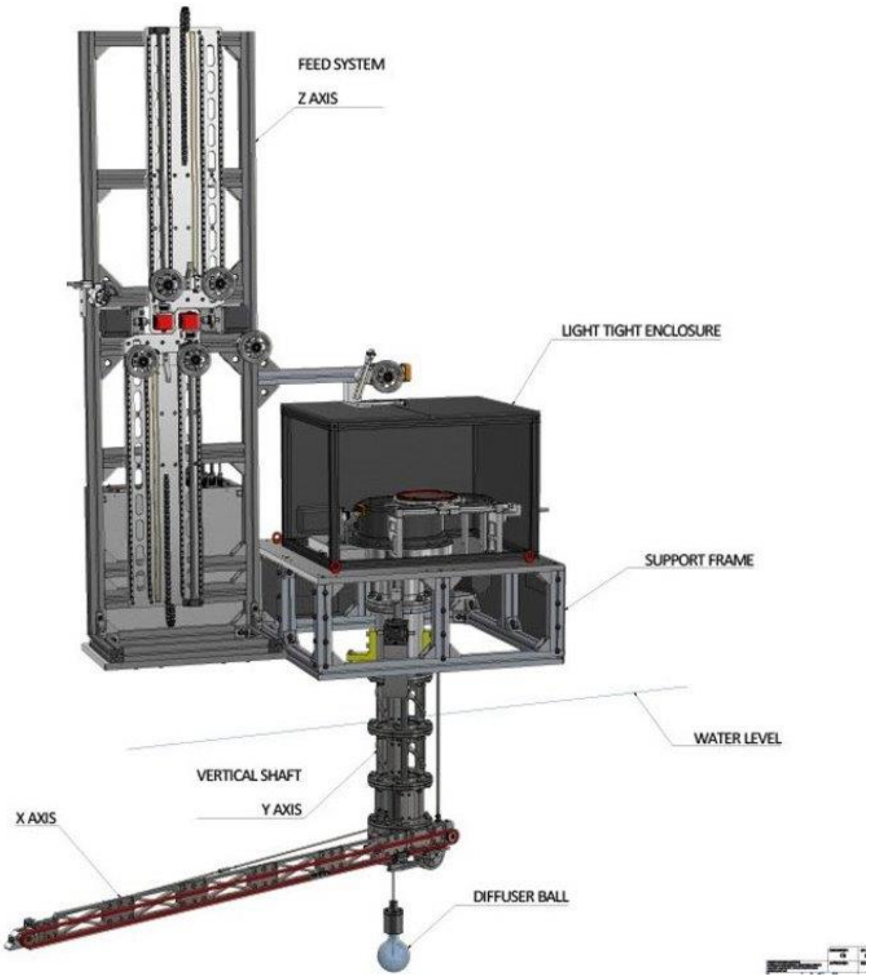


- Gas and aerogel Cherenkov detectors for higher momentum PID



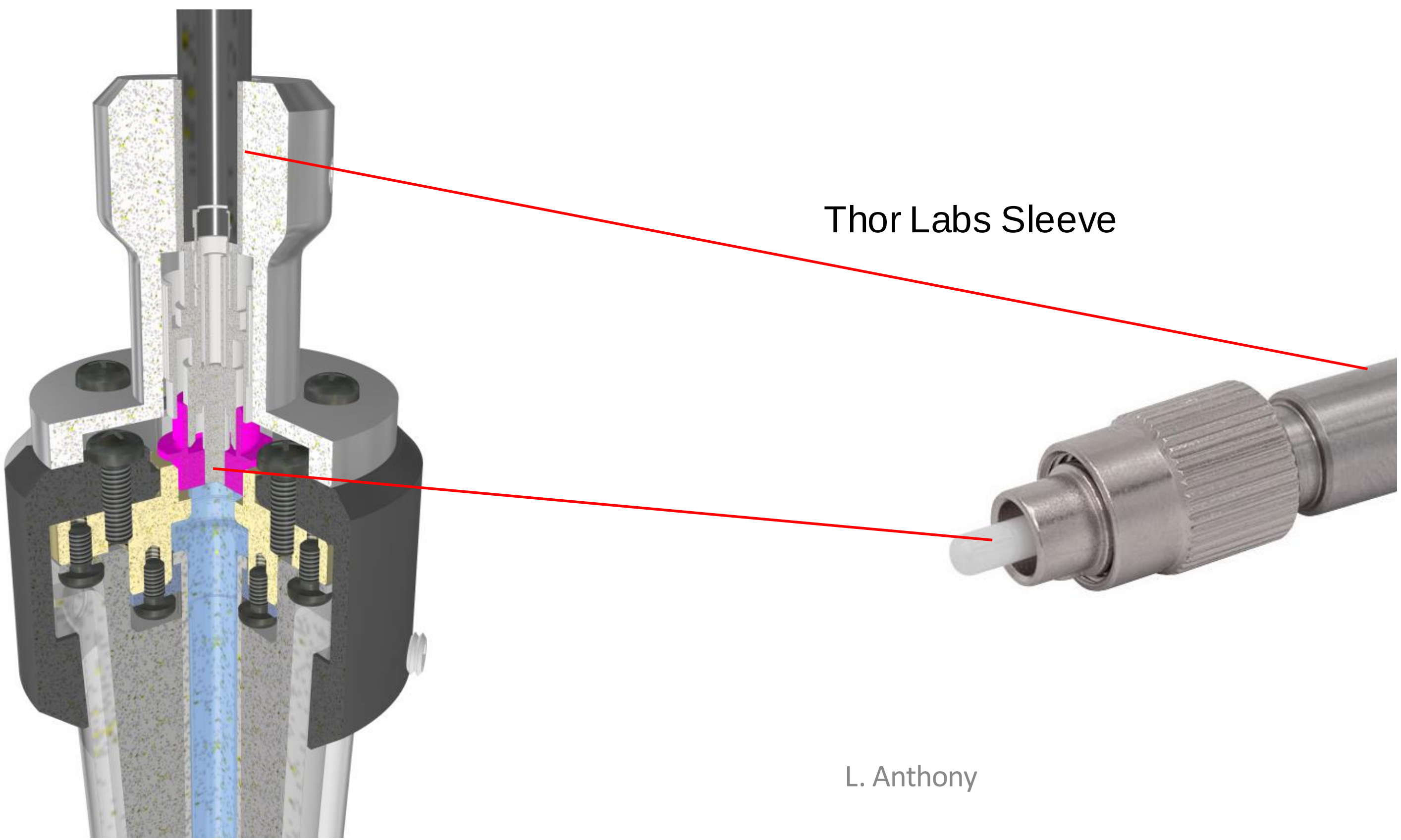
WCTE Calibration: CDS

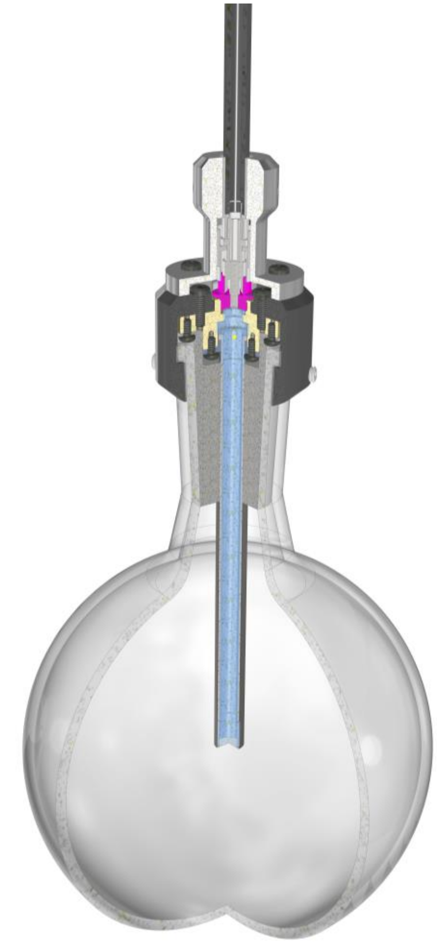
- Whole system and isotropic light source being designed and built at Imperial
- Movement in 3 axes
- Deploy sources at user defined calibration points
- Sources
  - Isotropic light source
  - Camera for photogrammetry
  - Radioactive source



Isotropic Light Source

- Umbilical Termination
  - Uses ThorLabs bulkhead HAFC connector to mate fibre with quartz rod
  - Sealed connection with optical gel to remove any air gap
  - Parts being fabricated at Imperial for prototype
- Weight will also be mounted around clamp and will use fluid seal to ensure is water tight





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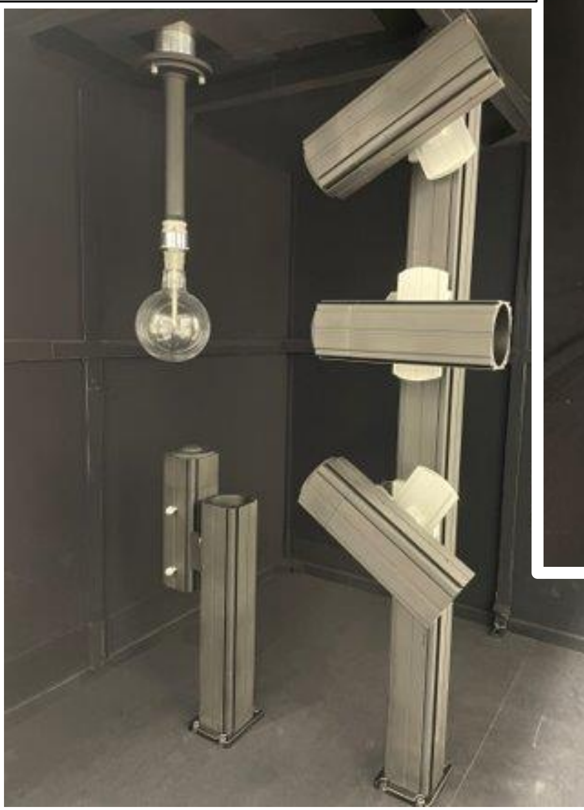
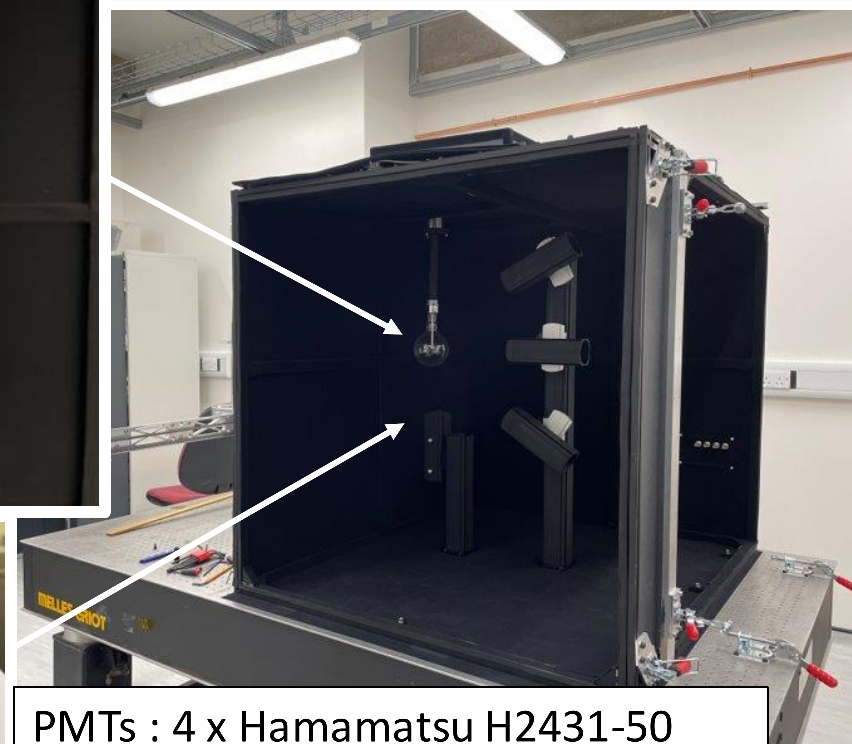
Prototype @ Imperial: Diffuse Light Source

- Developing, building and testing a laser diffuser ball based on the SNO+ design

109mm Quartz glass flask



Built a test facility to measure the uniformity of the diffuser ball



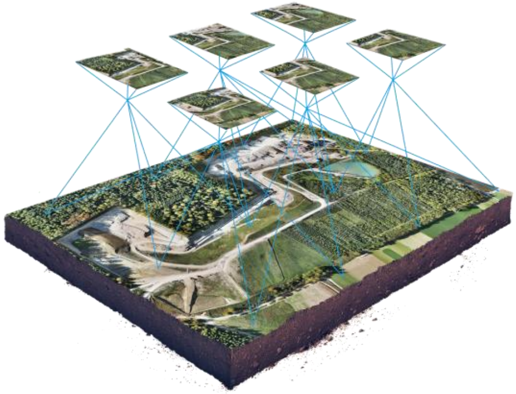
PMTs : 4 x Hamamatsu H2431-50

Photogrammetry

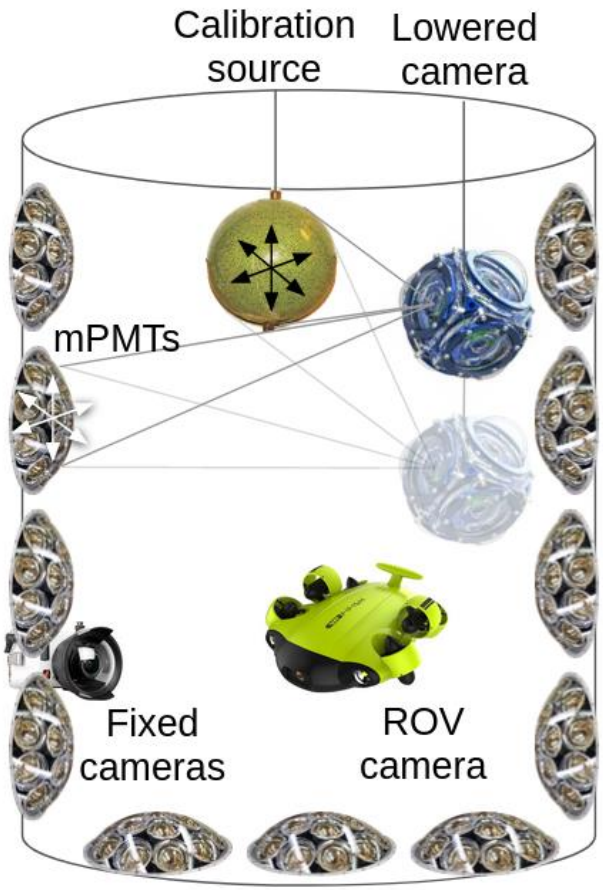
P. de Perio, N Prouse

- Detector geometry and source position measurements using stereoscopic reconstruction with photographs

- Mitigate uncertainties due to:
  - Construction tolerances / imperfections
  - Stretching / twisting of support structure due to PMT buoyancy
  - Source deployment positioning

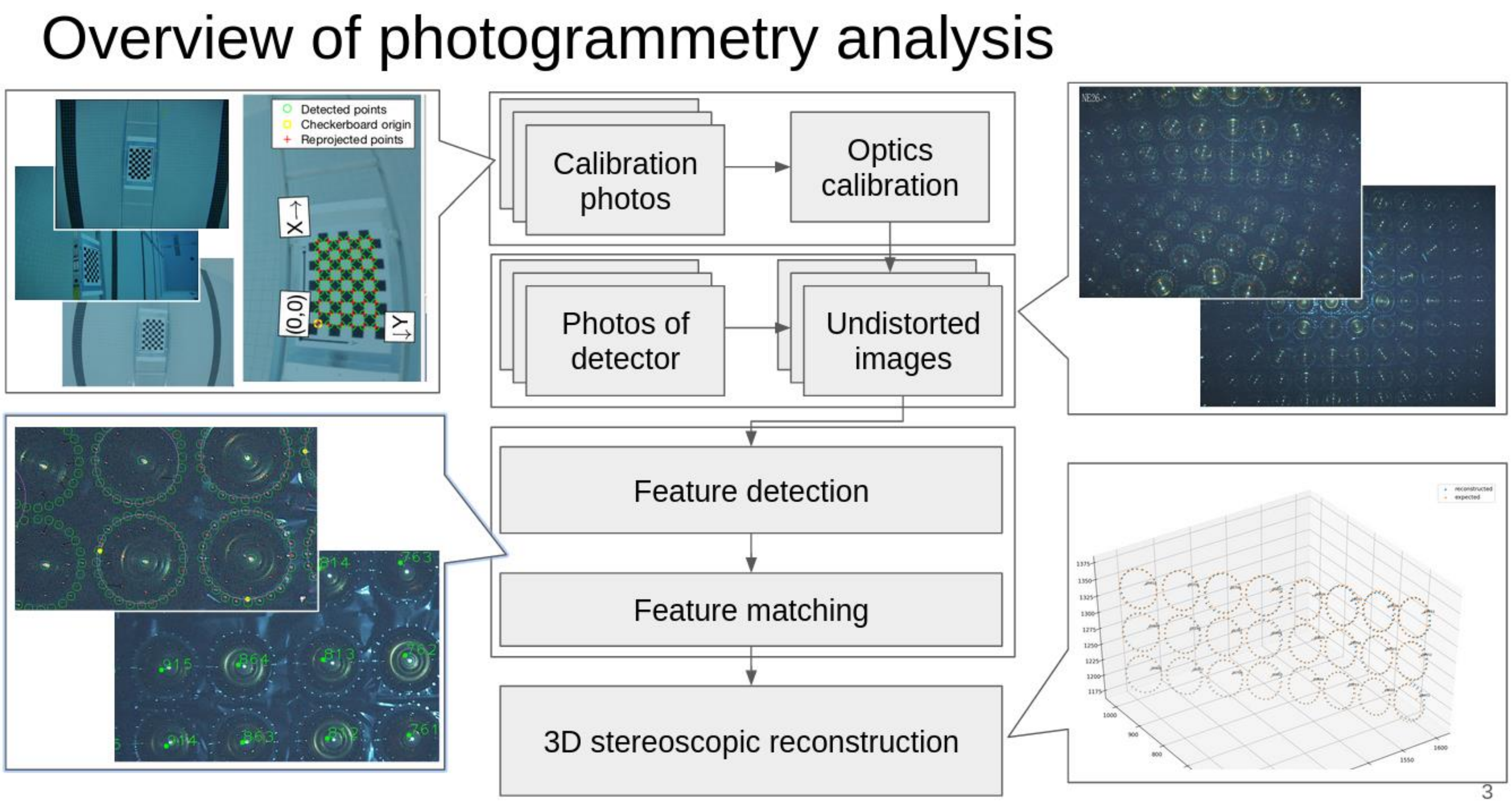


Similar to aerial topographical surveying



Photogrammetry

P. de Perio, N Prouse



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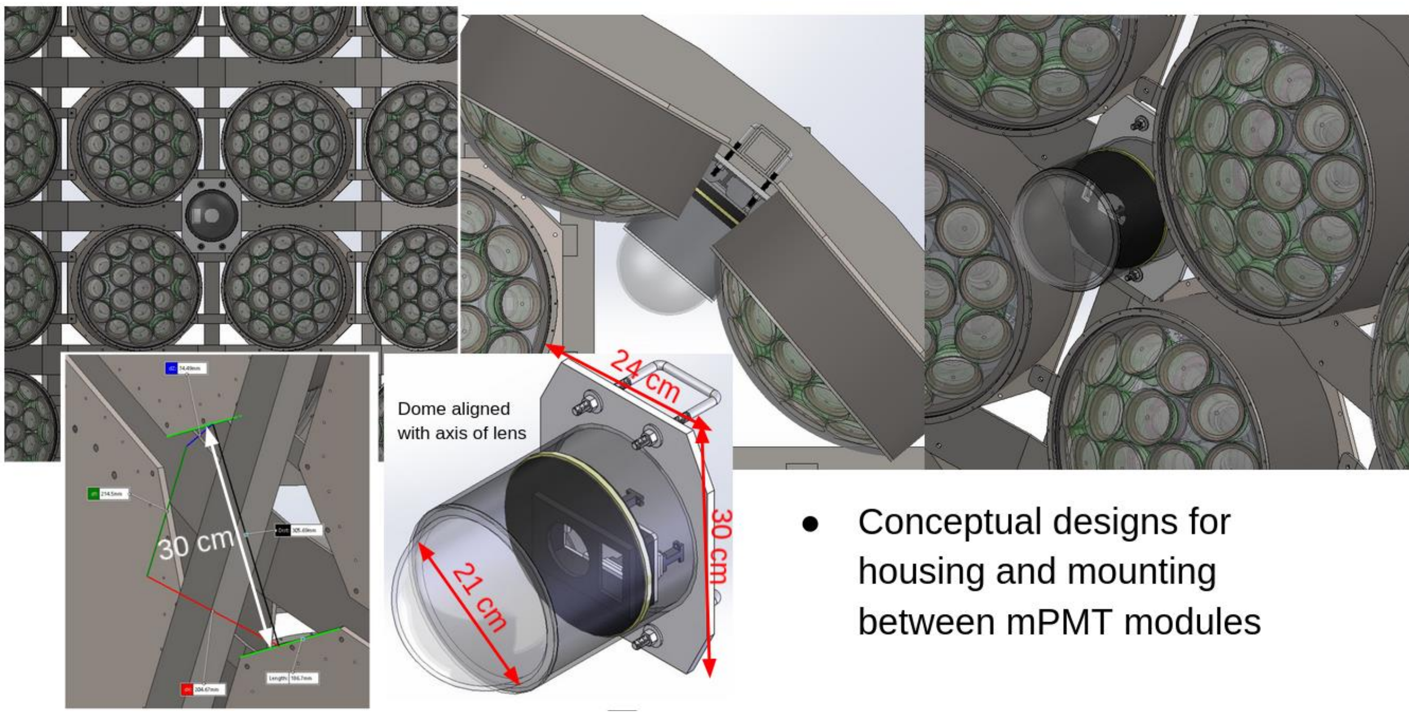
Photogrammetry

P. de Perio, N Prouse

Camera Mounting

Shubham Garode (TRIUMF)



- Conceptual designs for housing and mounting between mPMT modules

4

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Radioactive Sources

J. Renner

- NiCf – Isotropic gamma source
  - Based on Super-K calibration source
  - Used to study water quality

Nickel source used in SuperK (https://arxiv.org/abs/1307.0162)

Isotropic gamma source

  - Developing prototypes and simulations for WCTE

- AmBe – neutron source
  - Used for neutron tagging studies and Gd concentration

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

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