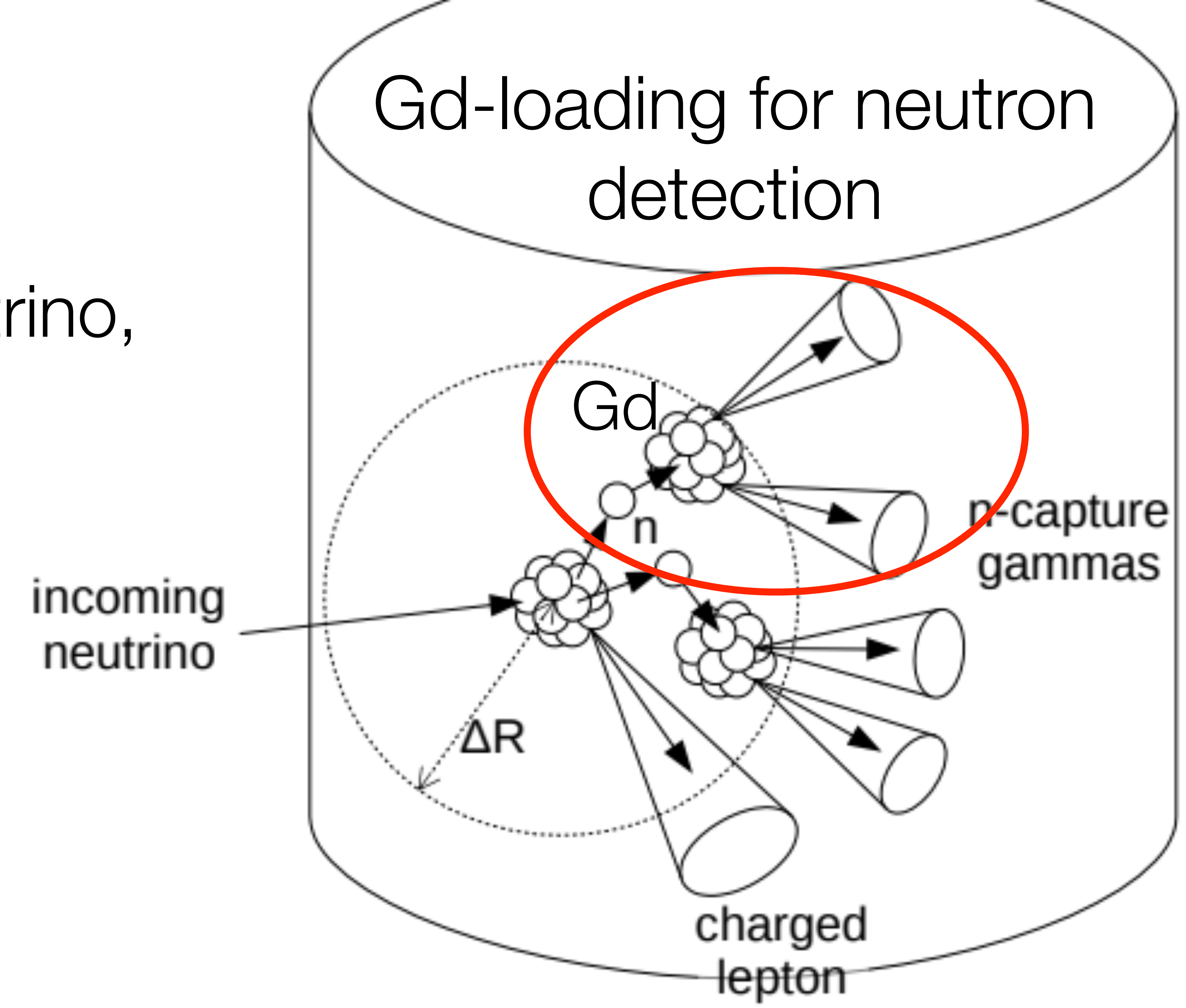
Introduction, Status of Interactions with CERN, Collaboration Status

Mark Hartz

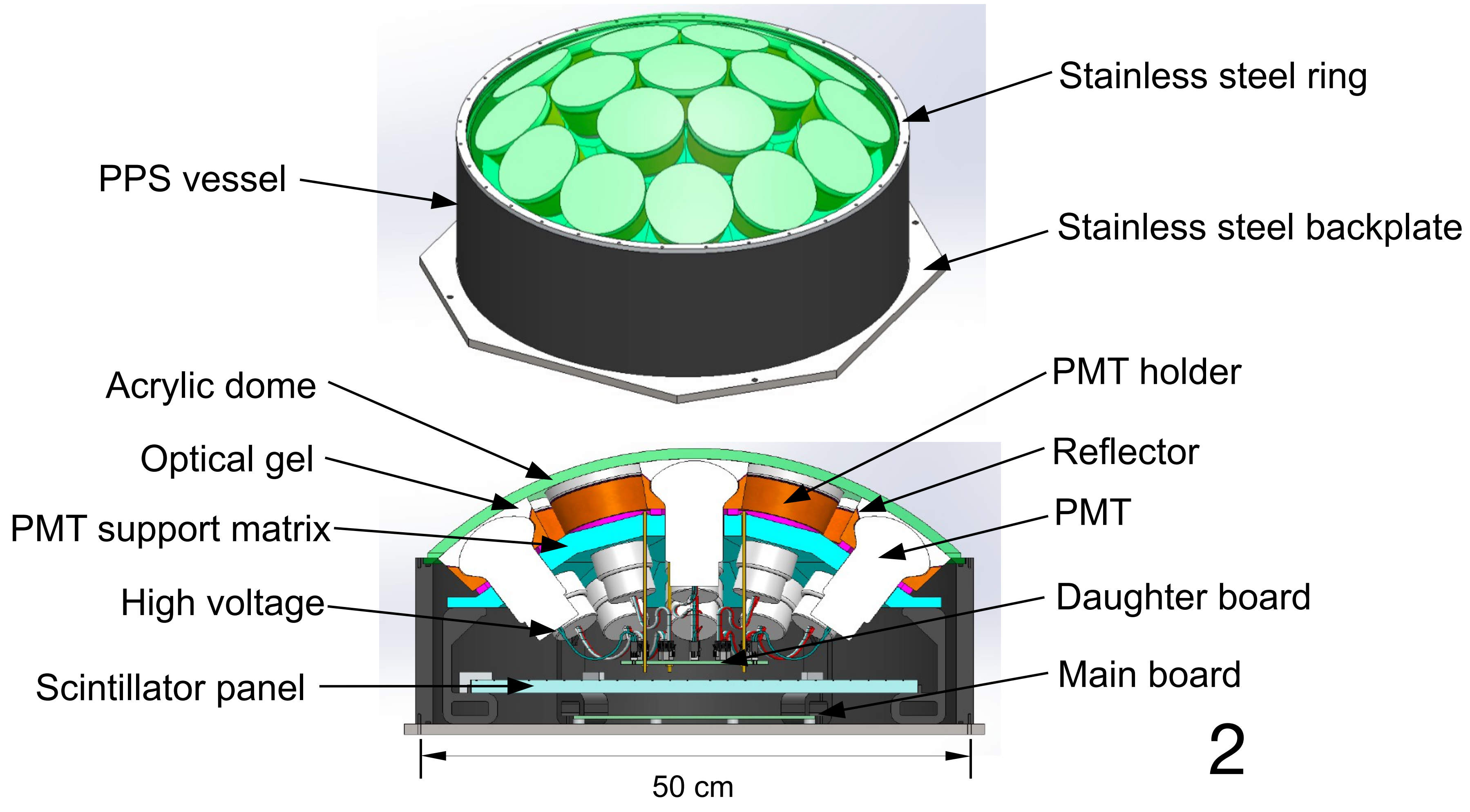
WCTE Collaboration Meeting
Monday, Nov. 29, 2021

WCTE Motivation

- Water Cherenkov detectors are used in current and future neutrino, proton decay and particle astrophysics experiments
  - Super-Kamiokande (with **$Gd_2(SO_4)_3$ loading**)
  - Hyper-Kamiokande
  - Intermediate Water Cherenkov Detector for Hyper-K (with **multi-PMT photosensors**)
  - ESSnuSB near and far detectors
  - THEIA experiment (with **water-based liquid scintillator**)
- These experiments:
  - Use new technologies
  - Require improvements in event reconstruction methods
  - Require improvements in detector calibration



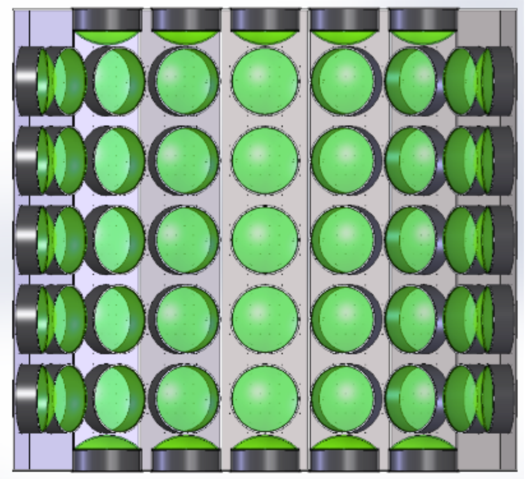
mPMT Photosensors



Building from a Test Experiment Platform

- With new applications of water Cherenkov experiments, we need a test experiment as a platform to build up to full-scale experiments
- In case of Hyper-K, test experiment is first step to IWCD and Hyper-K

Water Cherenkov Test Experiment

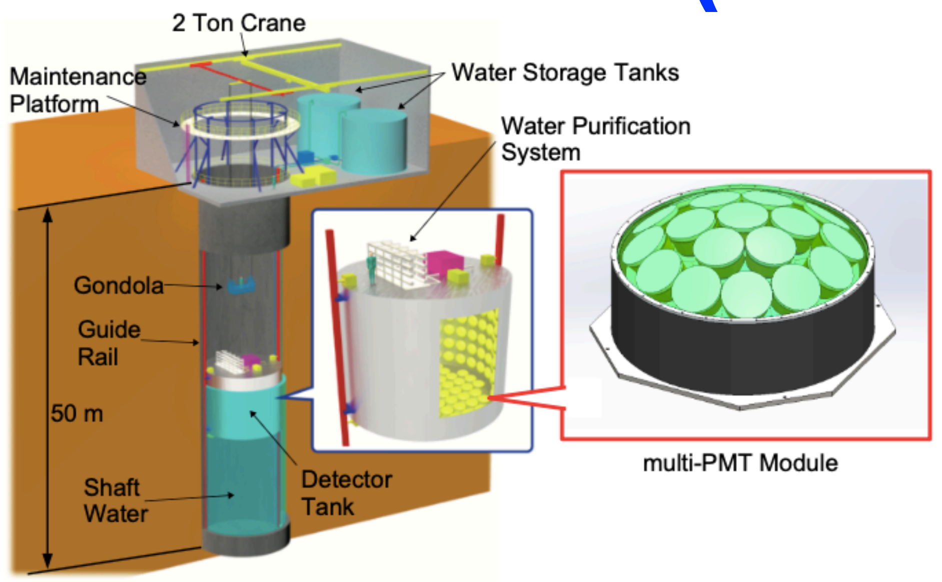


4 m tall x 4 m diameter

In charged particle test beam

~100 photosensor units

Intermediate Water Cherenkov Detector (IWCD)

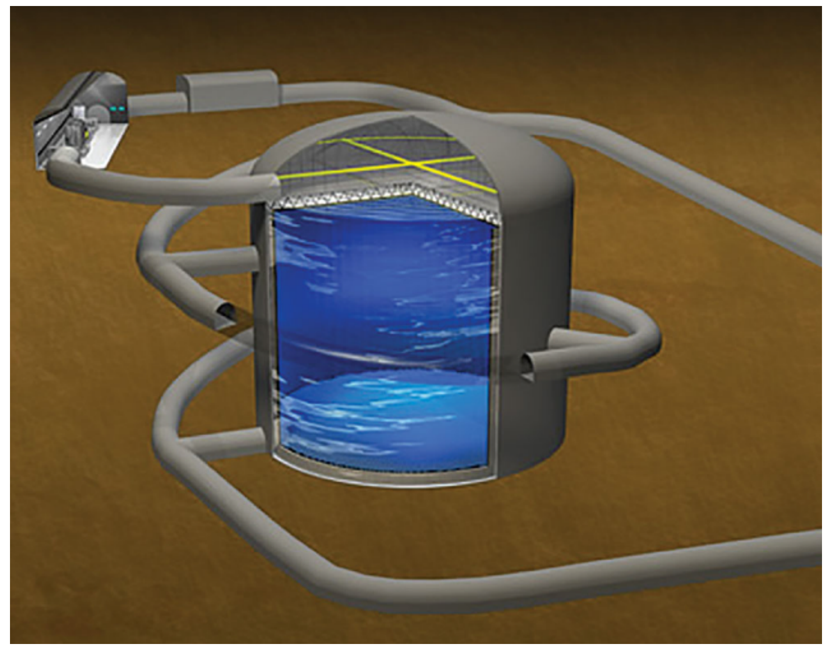


8 m tall x 10 m diameter

In J-PARC neutrino beam

~480 photosensor units

Hyper-K



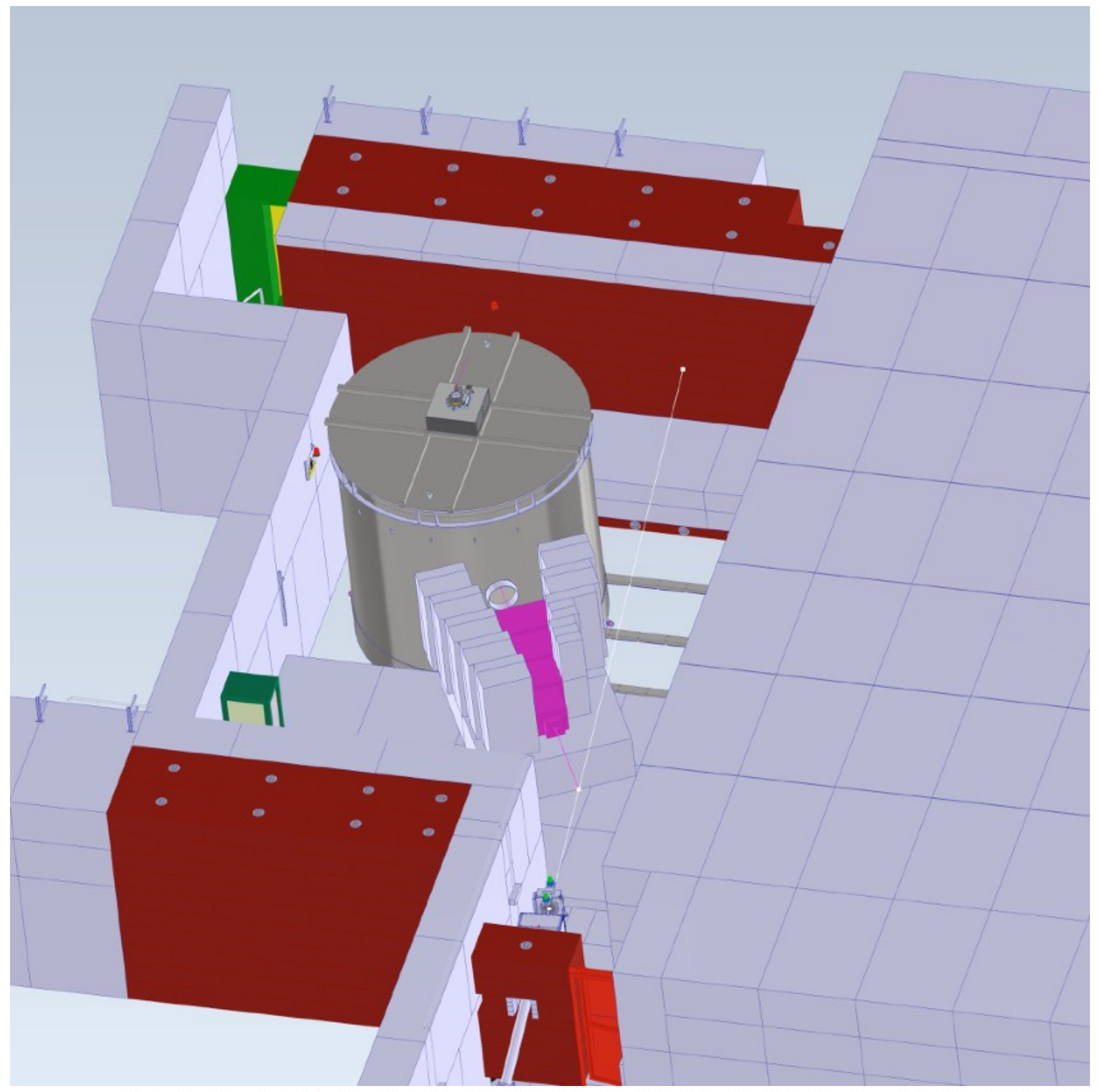
71 m tall x 68 m diameter

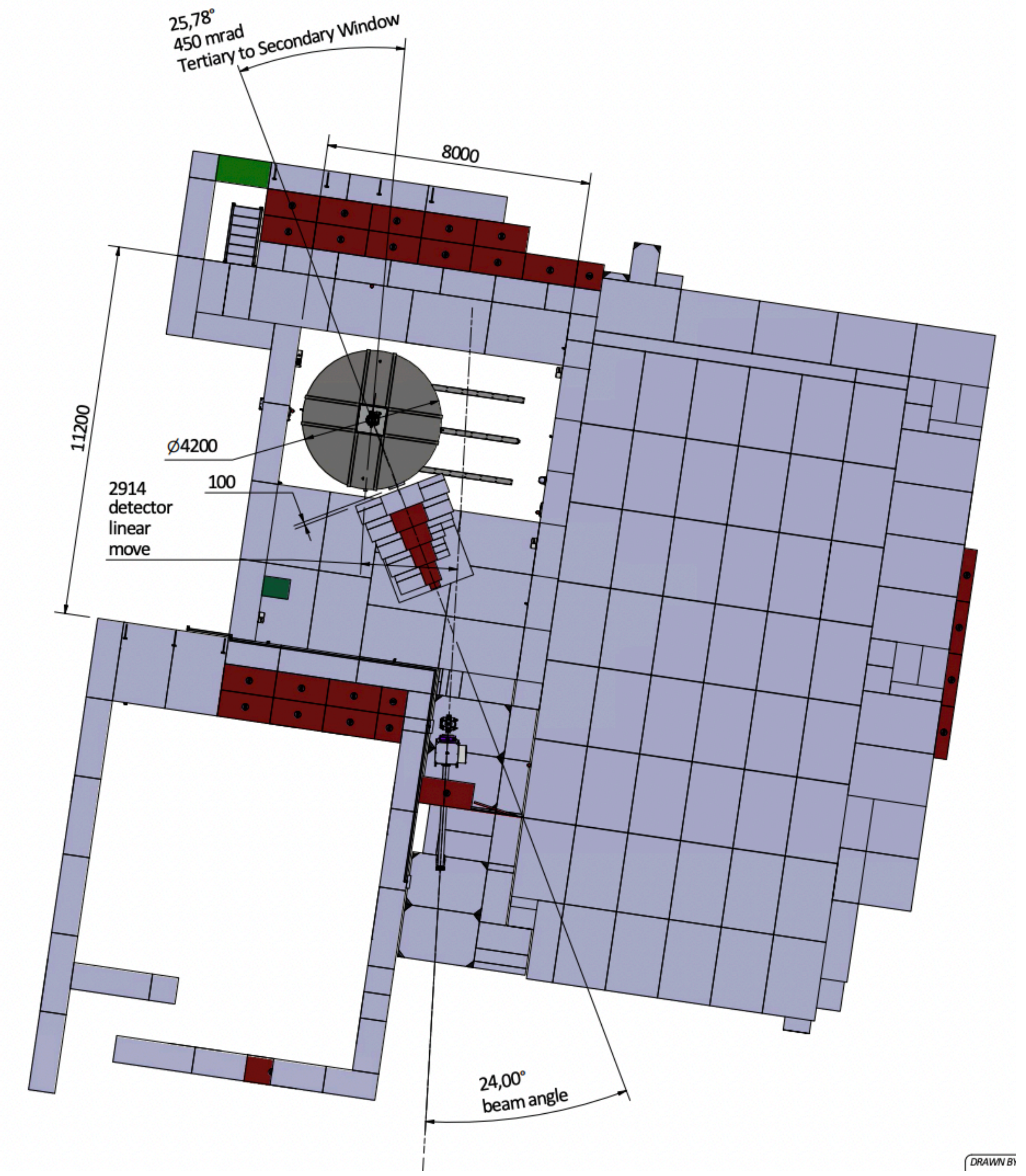
295 km from J-PARC neutrino source

>20,000 photosensor units

Proposed Water Cherenkov Test Experiment (WCTE)

- Proposed a prototype water Cherenkov detector to operate in the T9 beam line in the East Area
- Study particles directly from secondary beam and with tertiary production configuration
  - Particle fluxes of π±, p, μ, e in the 300 MeV/c-1200 MeV/c range
- Develop and deploy new technologies for water Cherenkov detectors
- Size of detector is ~3.5 m tall x 4 m diameter
  - Study event reconstruction in detector size relevant for near detectors in long baseline experiments

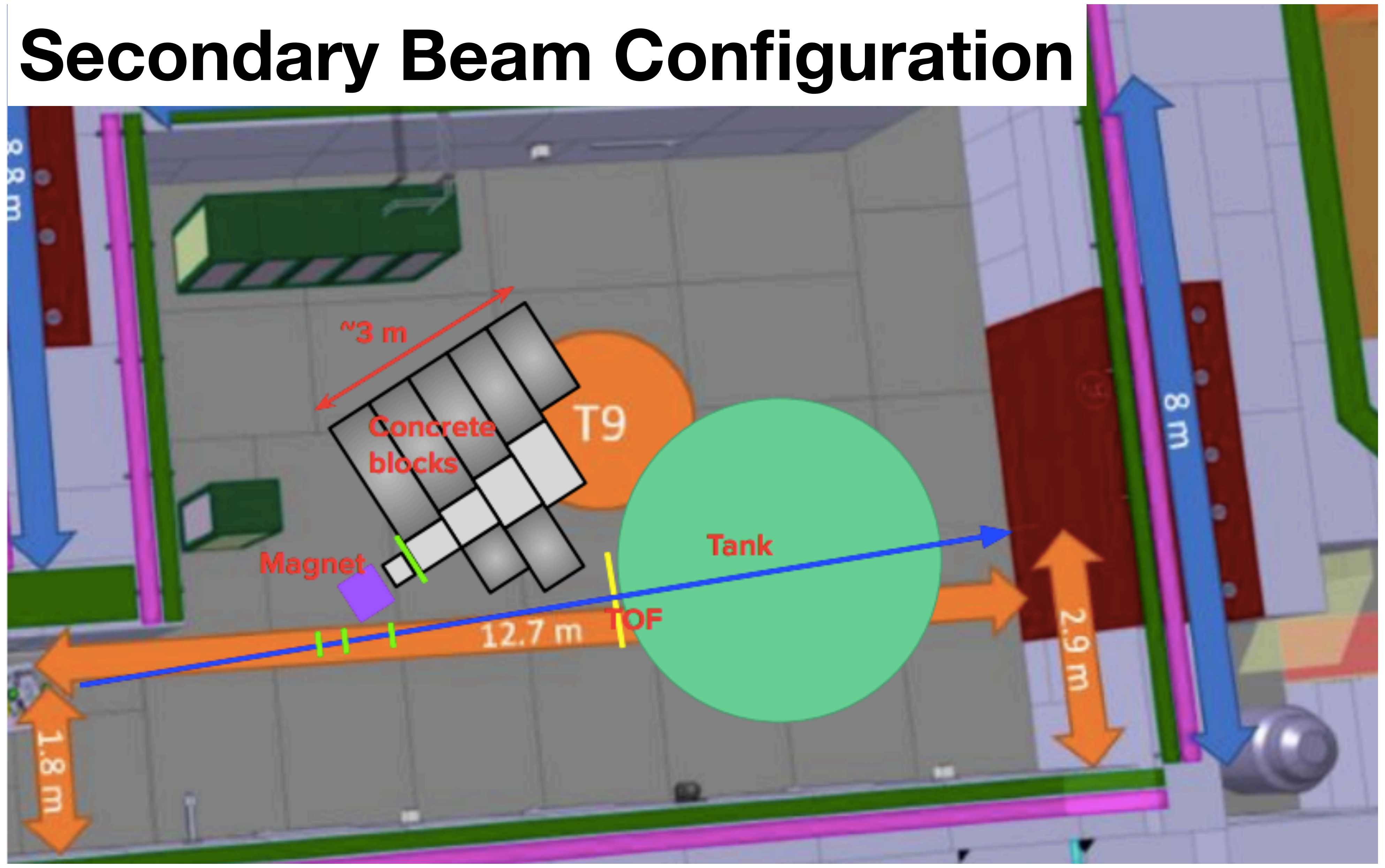


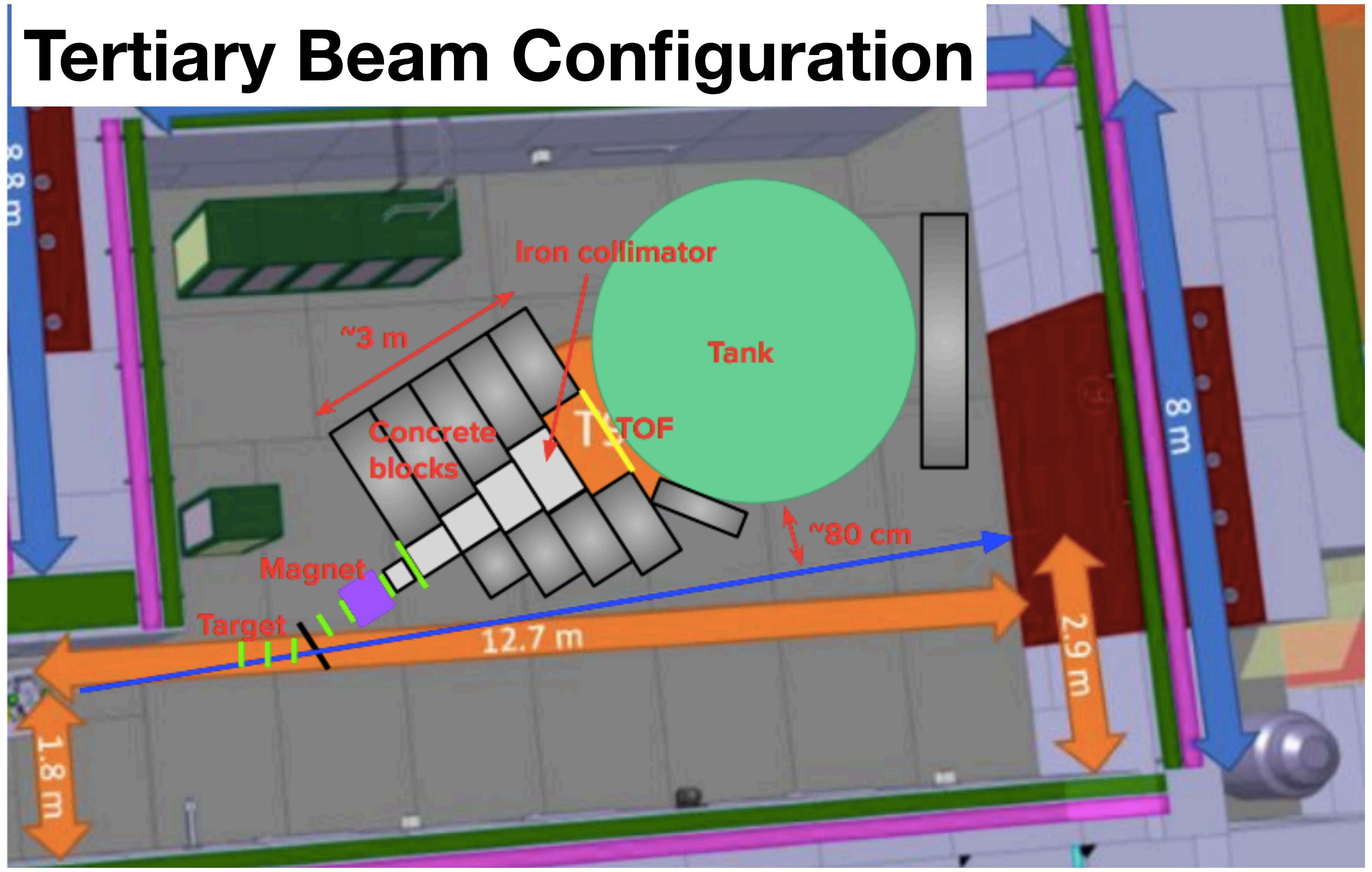


CERN-SPSC-2020-005; SPSC-P-365: http://cds.cern.ch/record/2712416?ln=en

Experimental Configurations

- Secondary and tertiary beam configuration - detector is moved on rail system





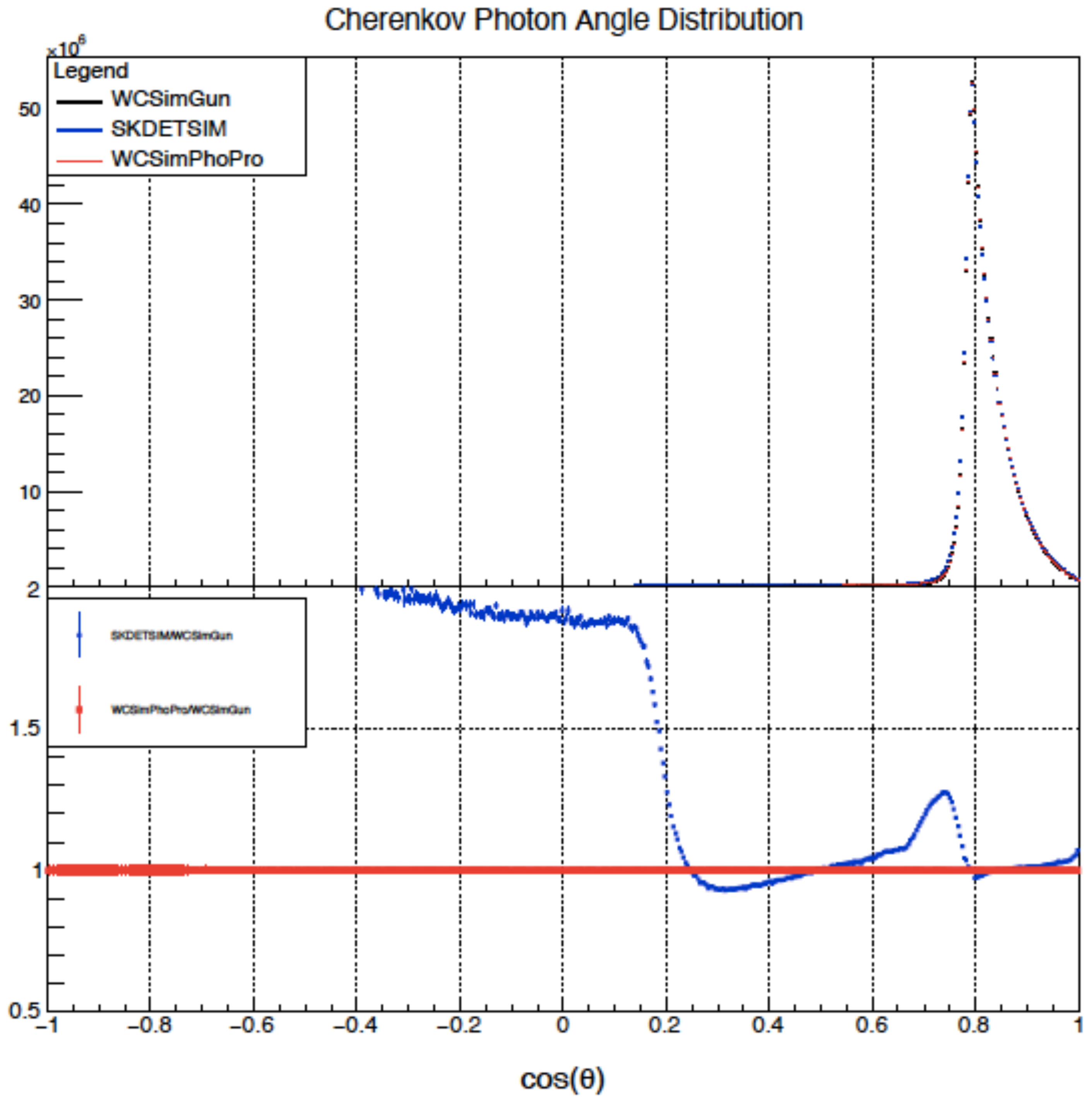
Electron, muon and proton fluxes

Low momentum pion and proton fluxes

- Configurations with pure water and **$Gd_2(SO_4)_3$** loaded water (0.2% by mass) to allow for neutron detection

Physics in WCTE - Cherenkov Angle, Muon Range

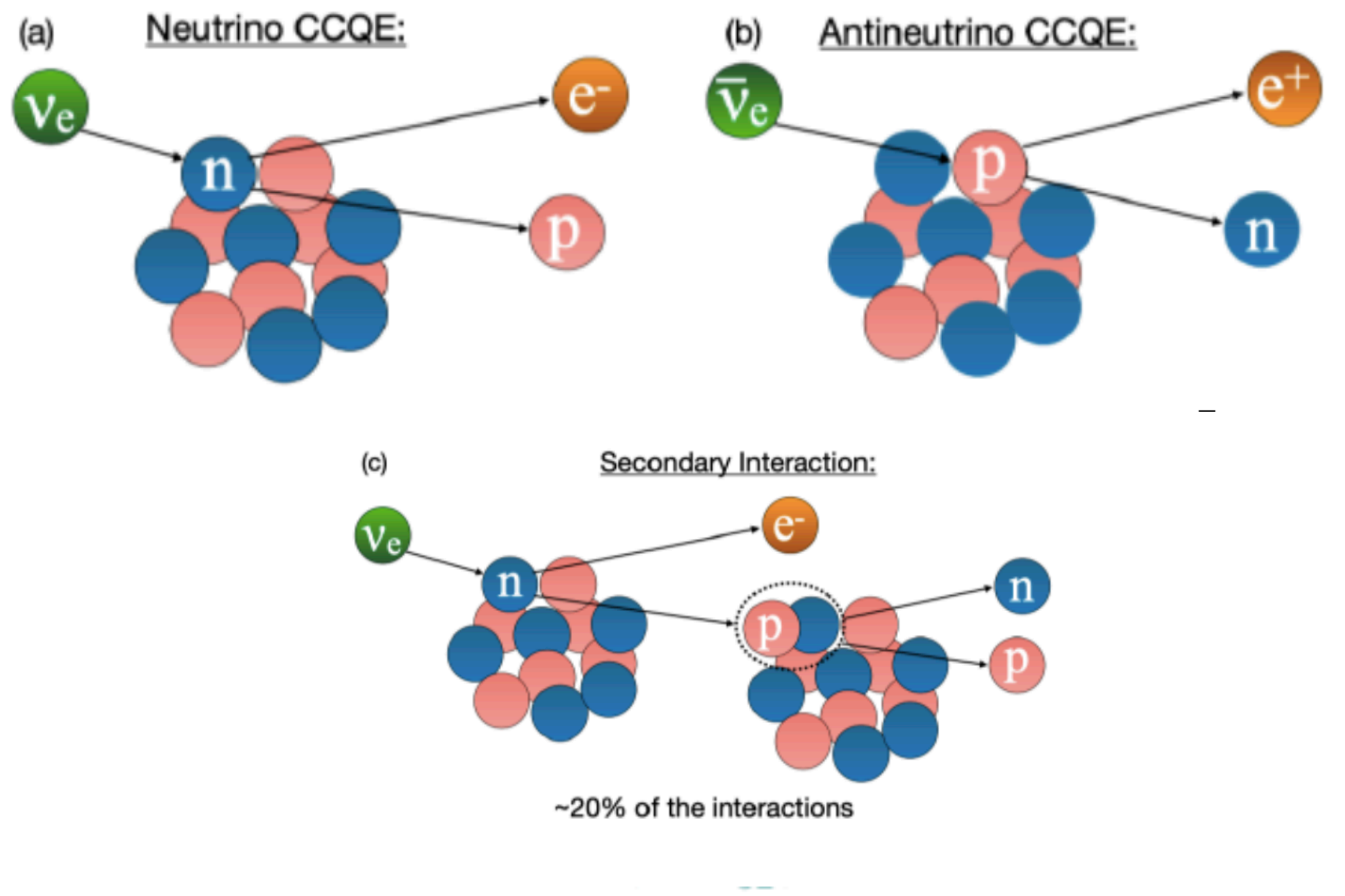
- **Measurement of Cherenkov light production**
  - Currently used simulations are not consistent
  - Introduces systematic errors in event reconstruction
  - Can be measured with well characterized beam in WCTE



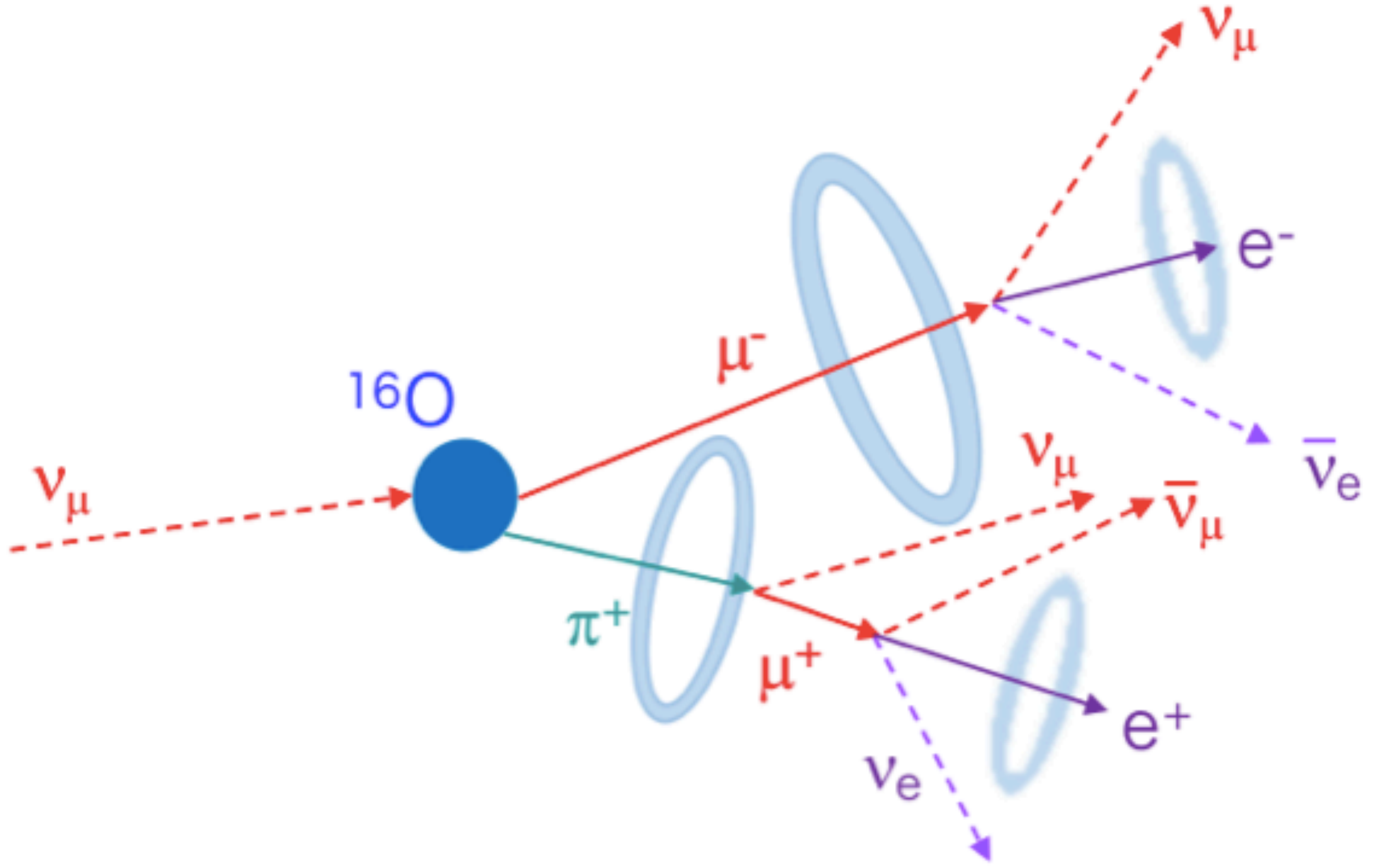
- **Study of energy scale calibration**
  - Muons crossing detectors used in Super-K to set energy scale
  - Systematic uncertainty of 2% needs to be reduced to 0.5% for Hyper-K
  - Can be studied with crossing/stopping muons of known energy in WCTE

Physics in WCTE - Neutrons and Pions

- **Measurement of secondary neutron production**
  - In SK-Gd and Hyper-K, neutrons used for neutrino/antineutrino tagging, proton decay background tagging
  - Predicted rates sensitive to secondary production by pions/protons
  - Can measure secondary production in WCTE

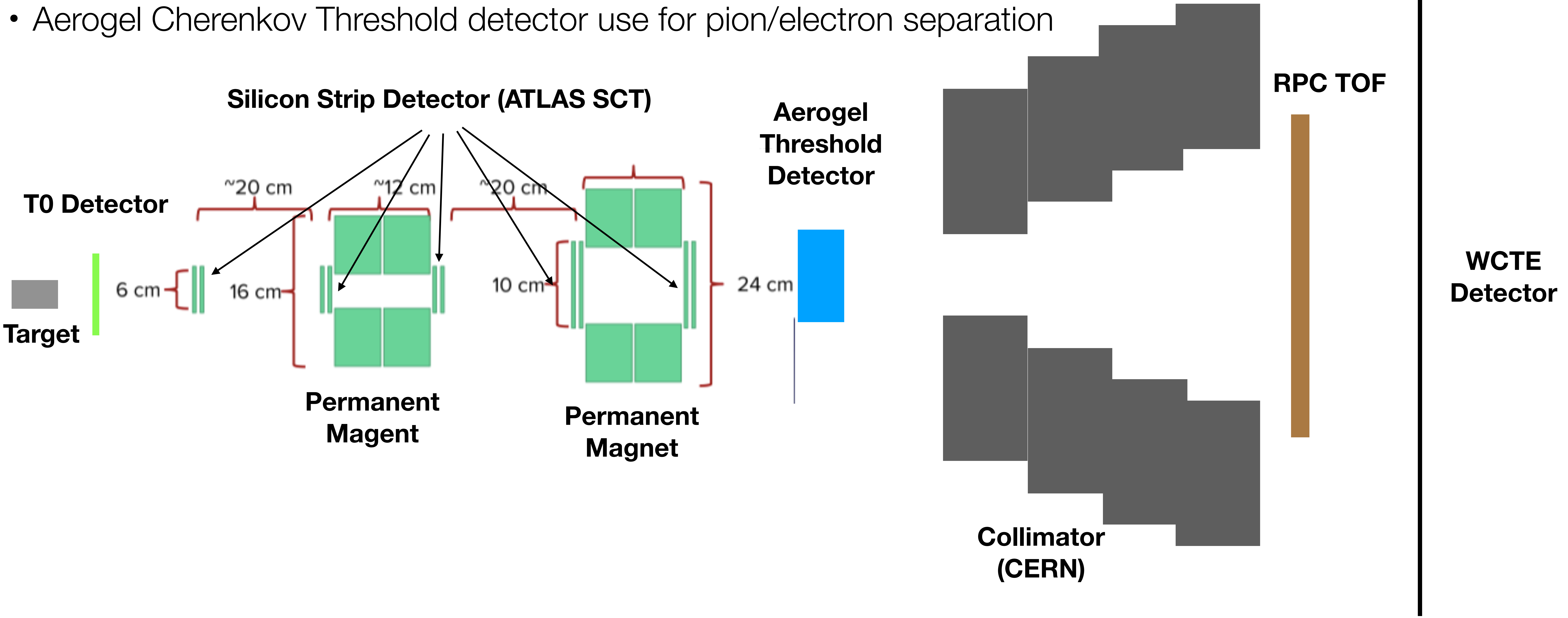


- **Study of pion scattering**
  - T2K, Super-K and Hyper-K are using samples with pions in the final state
  - Reconstruction is challenging due to modeling of hadronic scattering with limited data on oxygen
  - Can directly measure water Cherenkov detector response to pions in WCTE



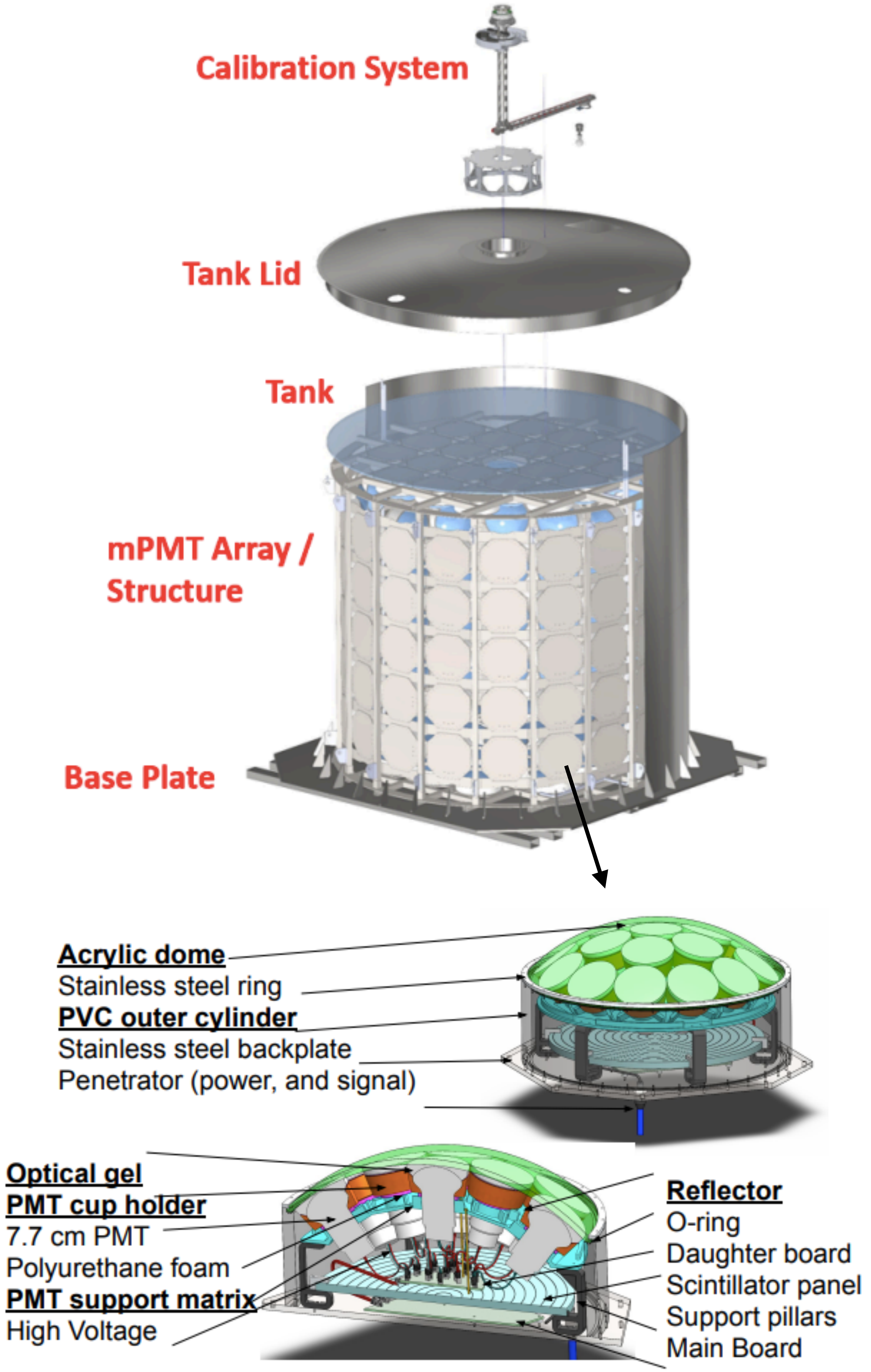
WCTE Beam Line Components

- WCTE includes tertiary production target, spectrometer and particle ID detectors
- Spectrometer: silicon strip detector for tracking and Halbach array permanent magnets
- Resistive Plate Chamber (RPC) used for time-of-flight based PID
- Aerogel Cherenkov Threshold detector use for pion/electron separation



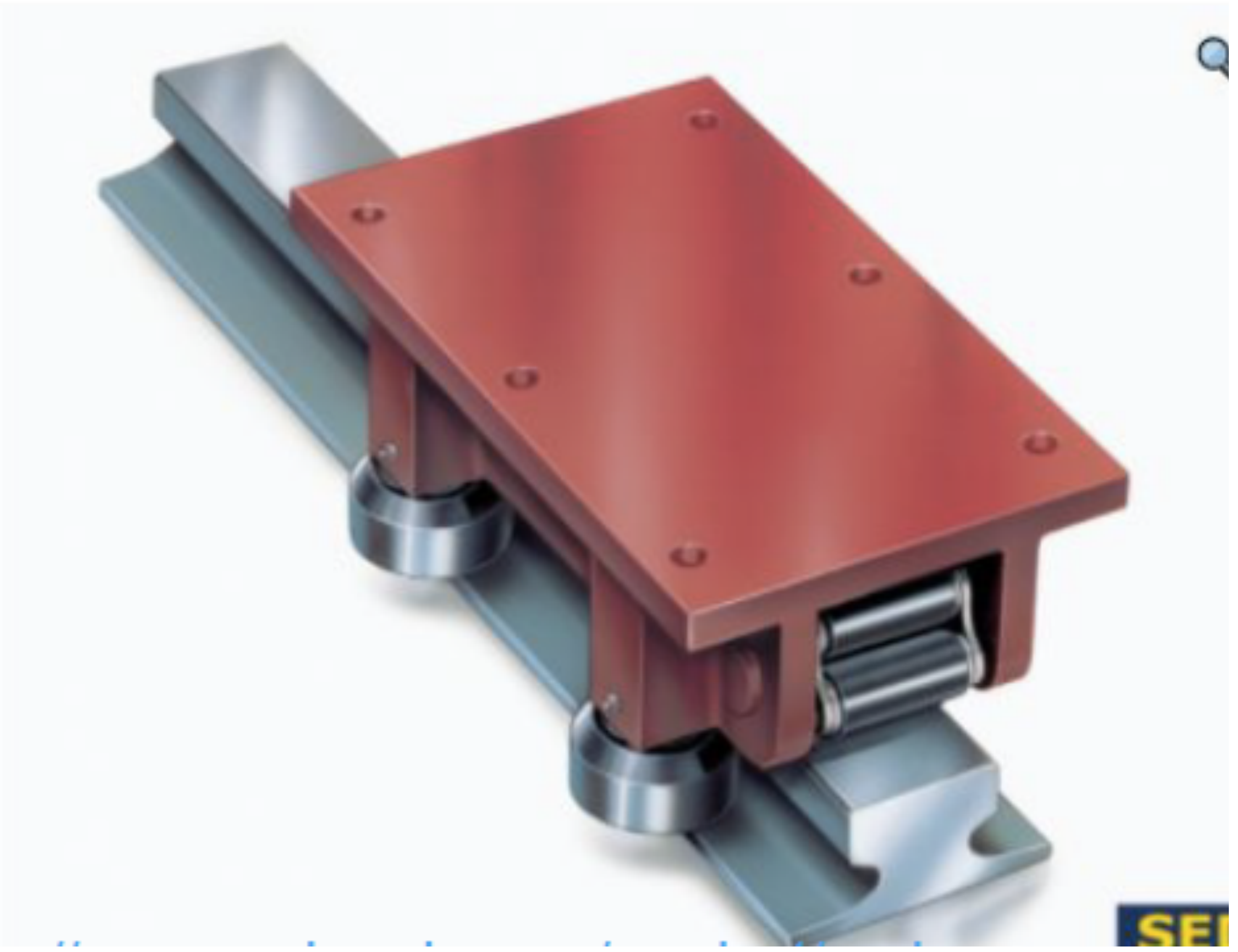
The WCTE Detector

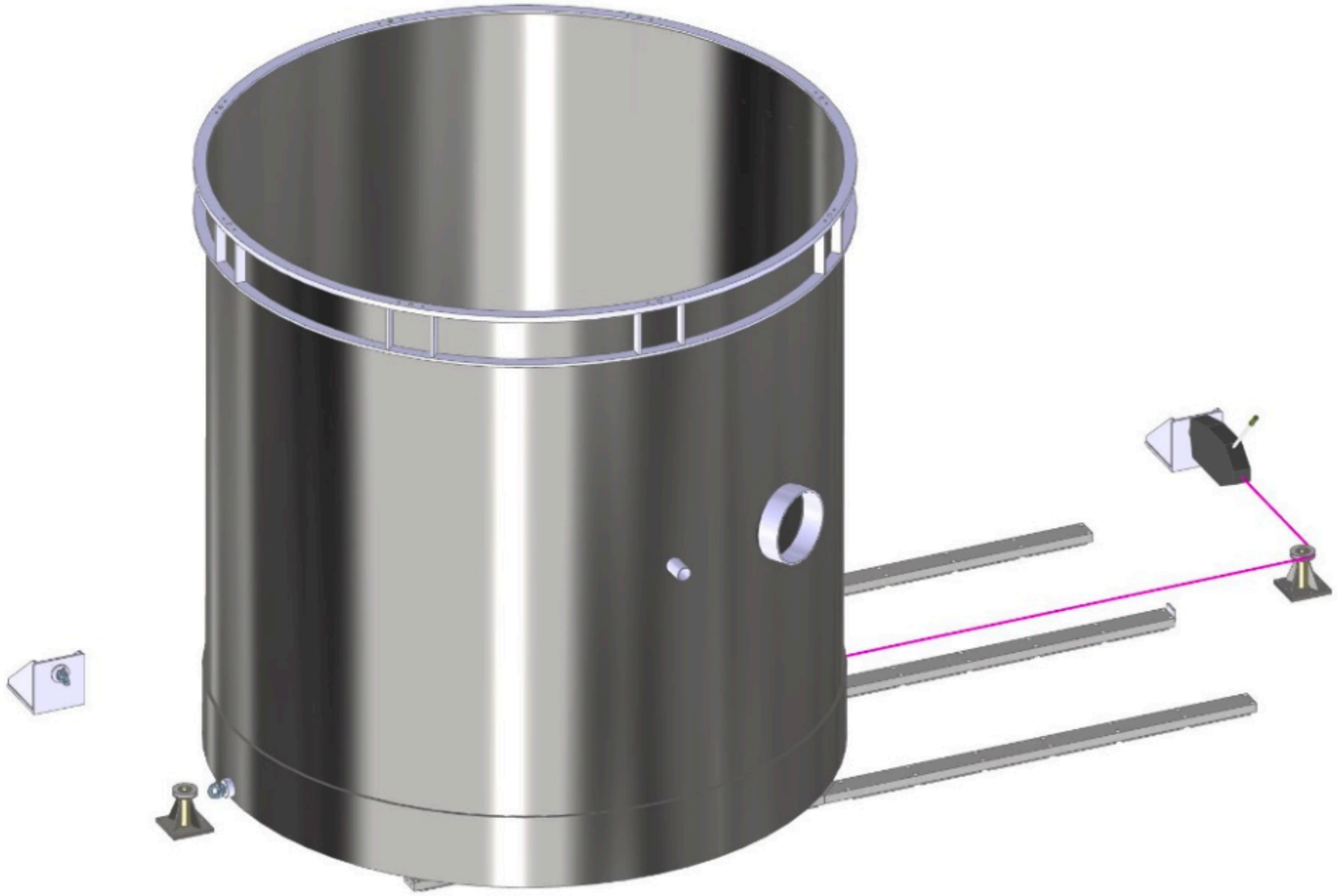
- Detector is instrumented with 130 multi-PMT modules mounted on support structure
- Multi-PMT modules each contain 19 fast 8-cm diameter PMTs, their high voltage and readout circuits
- Installed inside stainless steel 304 tank
- Calibration deployment system to deploy sources throughout detector volume
- Filled with 50 ton deionized water

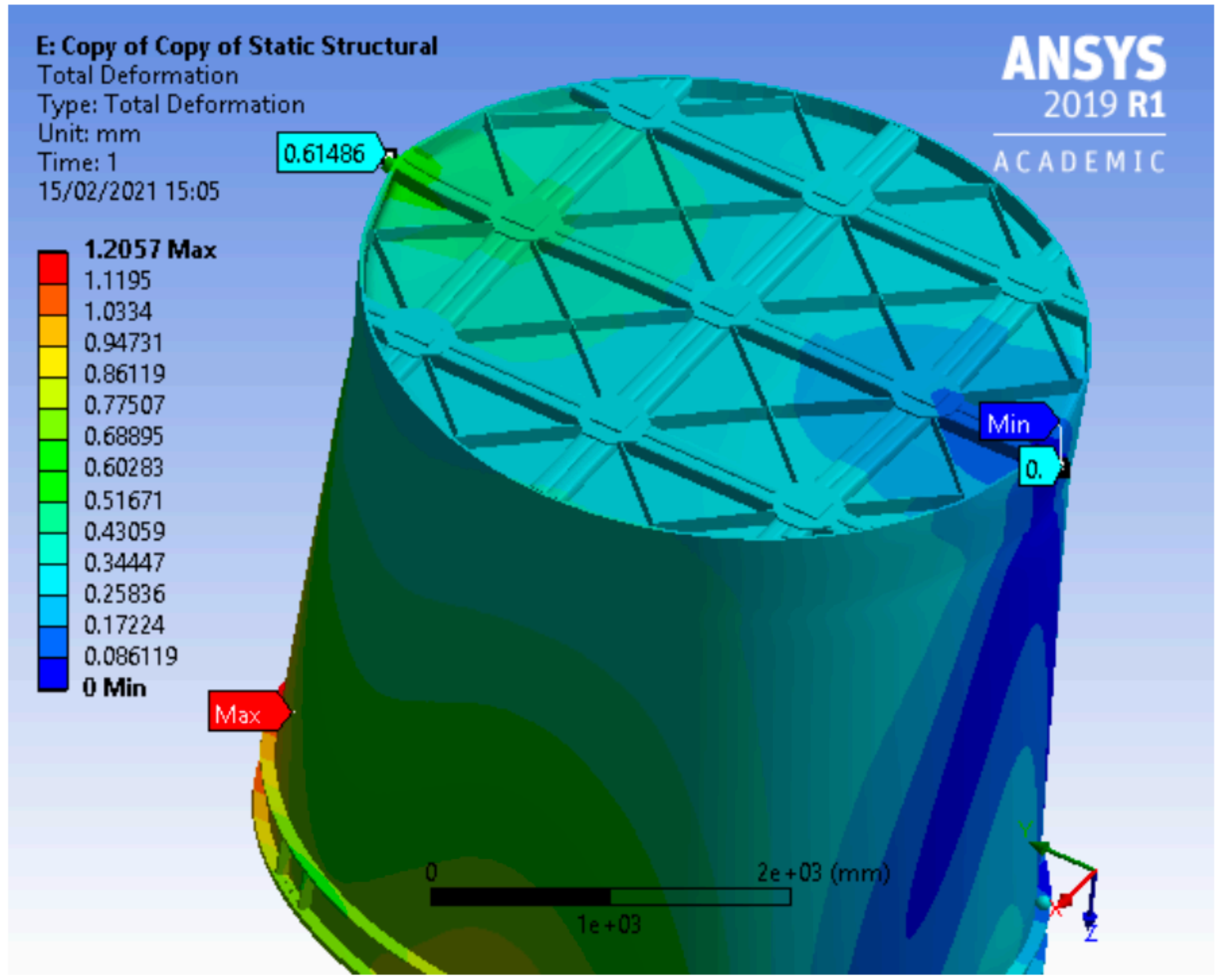


Detector Moving

- We plan to move the detector between tertiary and secondary beam configurations
- Preliminary design in prepared with help from CERN engineer P. Minginette
  - Static and dynamic analysis to establish feasibility of design
- Based on roller system with 9 skates that move along 3 rails
- Detector moved by winch and cable







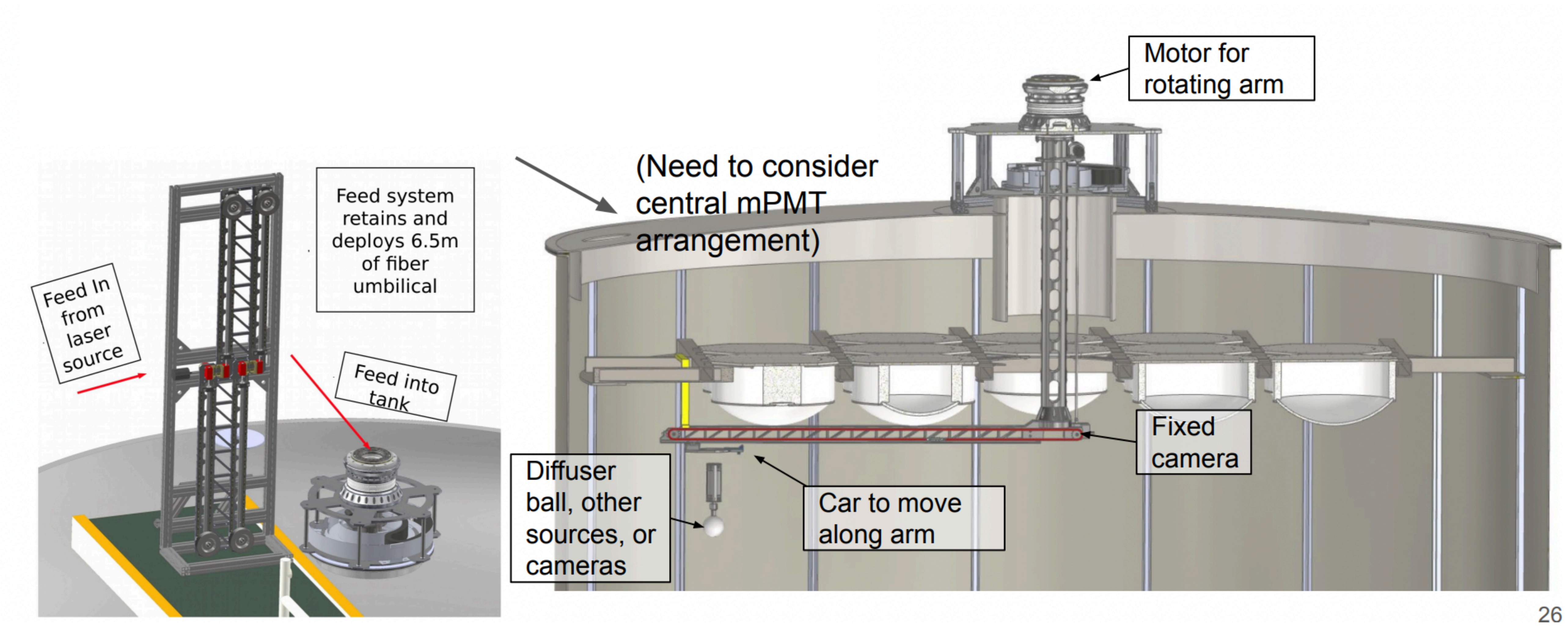
Water System

- Use standard commercial water purification system components
- Special resins used so that $Gd_2(SO_4)_3$ is not removed by water system
- Use a cation exchange resin to remove the Gd from the water
  - System tested for Super-K can remove Gd down to <0.5 ppb
  - Exchanges $3Na^+$ for Gd^{3+}
  - Output water is 0.14% sodium sulfate by mass

Commercial water system (Organo FP-2000)

Calibration Systems

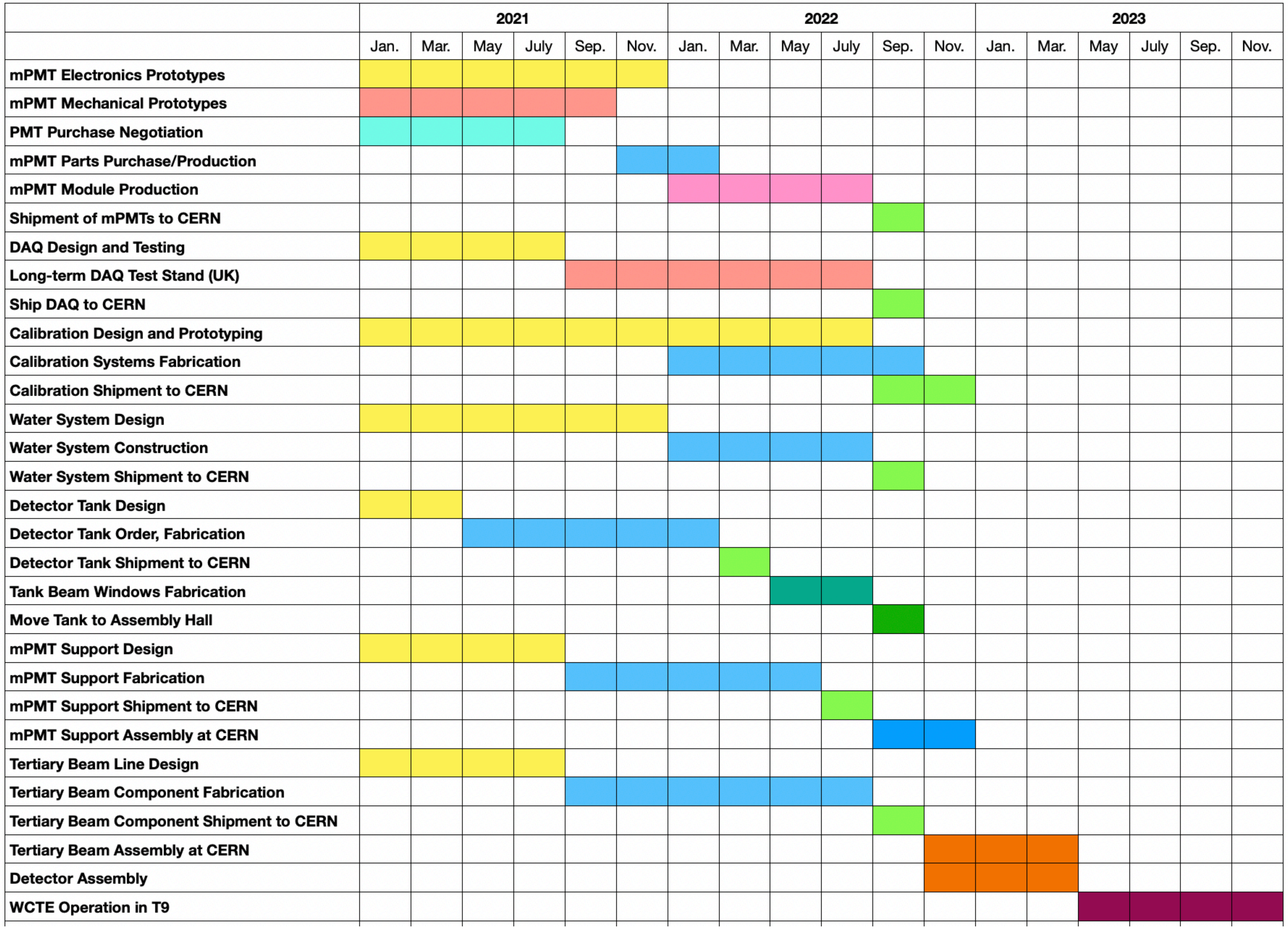
- Calibration Deployment System to move sources throughout the detector volume
  - Diffuser ball (laser)
  - NiCf gamma source
  - AmBe tagged neutron source
- Photogrammetry camera system for position calibration
- Light injection system for water/reflection calibrations



$^{252}Cf \rightarrow {}^{148}Ba + {}^{106}Mo + 4n$

$^{58}Ni + n \rightarrow {}^{59}Ni + \gamma$ (~9 MeV)

Schedule



- Start of assembly in Nov. 2022
- Start of operation in May 2023
- Schedule assumed approval around April 2021 and minimal additional impact from COVID-19
- From this meeting:
  - Funding for most WCTE components is in place/approved
  - We know better the impact of COVID-19 and supply chain issues
  - We will update the schedule

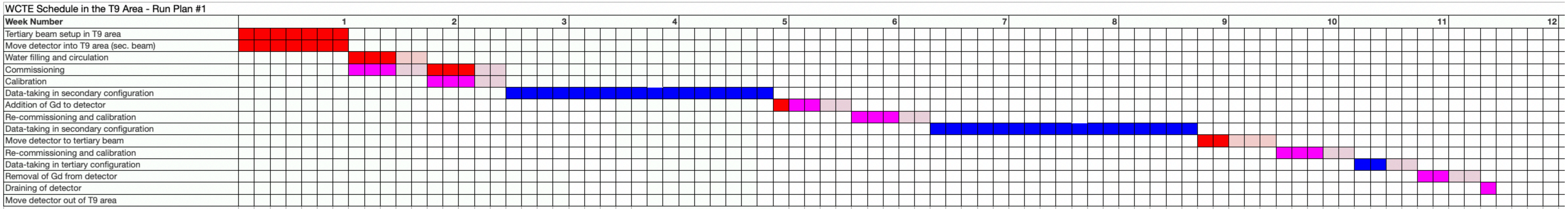
Interface to CERN

WCTE Proposal Process

- The WCTE proposal was submitted to the CERN SPSC in March 2020
- 2 Referees were assigned by the SPSC and we iterated with them to answer questions and update the proposal in March 2021
- WCTE was presented and considered at the April 2021 SPSC meeting
- The SPSC came back with two questions/suggestions
    - Asked if we proposed more than the initial pure-water and Gd-loaded runs at this time
        - If not, they suggested that we would not yet be a Neutrino platform project
        - We told them we were not proposing any additional run plan at that time
    - They asked us to consider how to reduce the time in T9 so as to minimize impact on other experiments

Example Run Plan

- Detailed planning showed that total operations in the T9 area could be as little as 12 weeks
- This was acceptable to the SPSC
- The SPSC gave the recommendation for WCTE beam time in T9



Legend	
(blue)	Receive Beam
(red)	Continuous work in T9
(magenta)	Intermittent work in T9

Tertiary beam setup in T9 area	Intend to perform before beam start
Move detector into T9 area (sec. beam)	Discussion on June 16th
Water filling and circulation	Water filling - estimate 1 day, circulation depends on initial cleanliness, 1 turnover per day. Estimate 2 days + 2 contingency
Commissioning and calibration	Initial commissioning still under discussion, 5 days for initial calibration
Data-taking in secondary configuration	Two days for data taking to collect 4e5 pions in lowest momentum bin. 2 days of contingency
Move detector to tertiary/secondary beam	Movement - 1 day, disconnect - 1 day, reconnect - 1 day, 2 day contingency (could be reduced further once connections/movement better known)
Re-commissioning and calibration	Commissioning after move - 1 day, calibration - 2 days + 2 days contingency
Data-taking in tertiary configuration	17 days of operation for 3 beam pipe configurations and 5 days of operation for 1 beam pipe configuration
Addition of Gd to detector	1 day for addition, 4 days for contingency / water turnover
Removal of Gd from detector	Need estimate - guessed at 4 days
Draining of detector	1 day
Move detector out of T9 area	Discuss on June 16th

Contingency - lighter shading

Next Steps for Approval

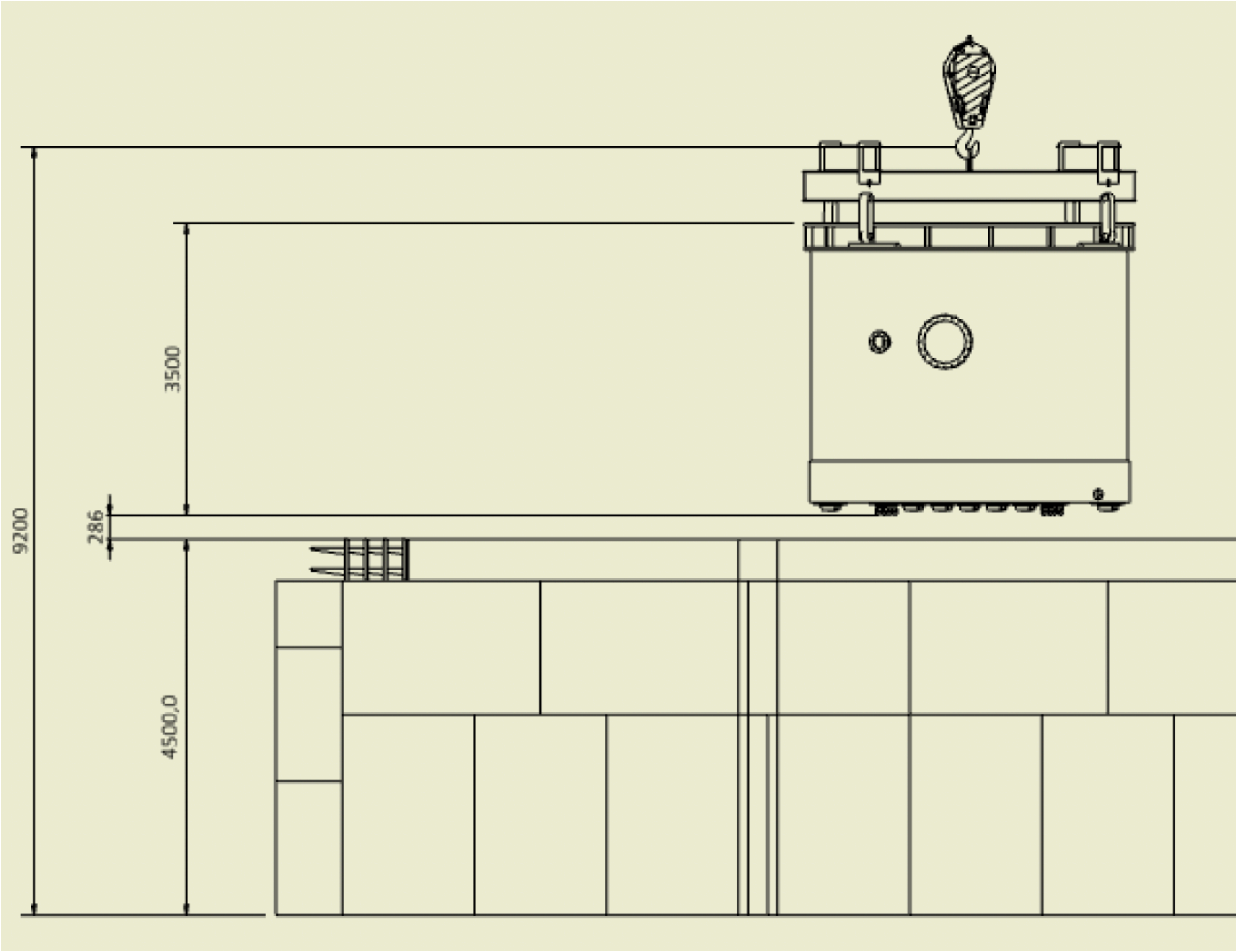
- The next and final step for approval is approval by the Research Board
- With our input D. Banerjee prepared an Engineering Change Request (ECR)
  - Includes the cost to change the experimental area to accommodate WCTE
  - Includes cost of rail moving system and lifting beam to lift detector into area
- The ECR and beam time request is considered by the Research Board
- Initial discussions in September: beam time request for T9 are only 50% of capacity
- Optimistic for approval at December 1 meeting

Safety Communications

- We submitted the Initial Safety Declaration form in order to identify potential environmental and safety hazards for WCTE
- At the beginning of November, we held the Launch Safety Discussion with CERN safety representatives
- A couple of key concerns raised
  - PVC, used in mPMT vessel, is generally not allowed at CERN due to fire/fume risk
  - SF_6 gas used in the RPC is powerful greenhouse gas and release should be kept below a certain level
- We also had some discussion of the detector transport, where the key concern is lifting the detector into the experimental area

Lifting Into Experimental Area

- WCTE will be lifted into experimental area without water - total weight is ~17,000 kg
  - For clearance issues, lid may have to be lifted in separately
- 45 t crane with hook height of 9.2 m - not enough clearance over wall
  - We are working on a reduced detector height (right) of 3.5 m
    - See report by L. Anthony
  - Need to use a low-profile lifting beam
    - See report by O. Jeremy



Collaboration Structure

- We are now moving into the phase of completing the WCTE design and soon starting construction
- Most of the WCTE systems have responsible groups leading the effort
- We want to formalize the work breakdown structure and assign leaders for each work package
- The following collaborators have agreed to be work package leaders:

  Beam - Matej Pavin (TRIUMF)
  Mechanical Systems - Chandrashekhar Garde (VIIT), Pablo Fernandez (DIPC)
  Water Systems - Patrick de Perio (TRIUMF/Kavli IPMU)
  Multi-PMTs - Marcin Ziembicki (WUT), Thomas Lindner (TRIUMF)
  DAQ & Triggering - Benjamin Richards (Warwick)
  Calibration Systems - Mark Scott (Imperial), Patrick de Perio (TRIUMF/Kavli IPMU)

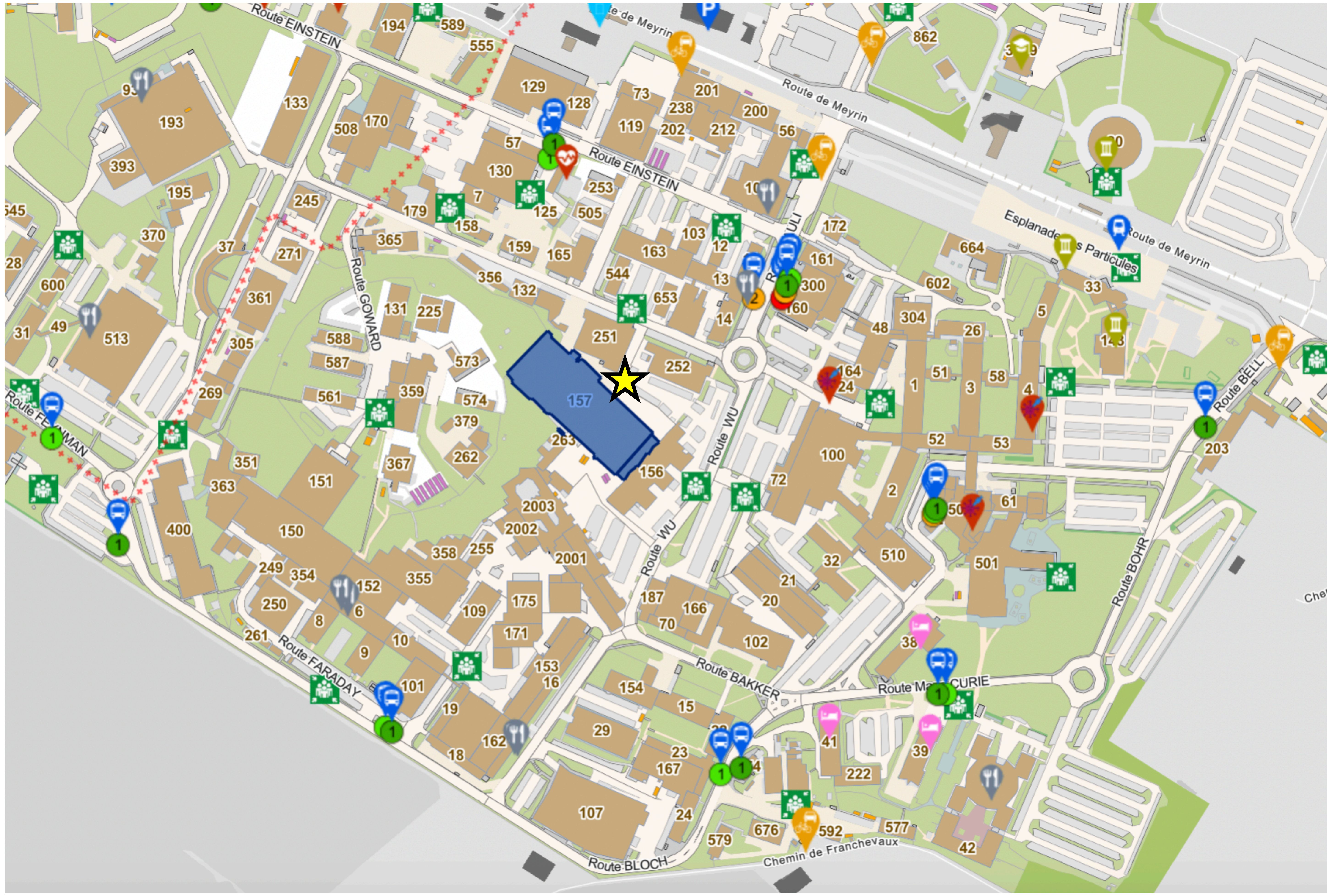
- Work package leaders are leading the preparation of Technical Design Report
- Stefania Bordoni (U. Geneva) has agreed to be the Experimental Safety Officer
- Once we have approval from CERN, we will revisit the WCTE management structure to make sure it is compatible with CERN experiments

This Collaboration Meeting

Meeting Format

- Meeting is a hybrid meeting with most joining remotely, and some present at CERN
- Those at CERN will be able to joint meetings with the CERN safety and experimental teams on Tuesday and Wednesday mornings
    - Tuesday 10:00 AM: Tour of the East Hall and T9 beam line
        - Requires dosimeter, safety shoes
    - Wednesday 9:00 AM: Fire safety meeting (to discuss use of PVC)
    - Wednesday 10:00 AM: Discussion with East Hall experimental group to follow up on an questions from the tour or otherwise

East Area Tour



Meet in front of B157 at 9:55 AM on Tuesday

Online Meeting Agenda - Monday

Introduction/Status of Interactions with CERN/Collaboration Status	*Mark Hartz*
40/S2-C01 - Salle Curie, CERN	14:30 - 15:00
Overview, Beam Simulation & Magnets	*Matej Pavin*
40/S2-C01 - Salle Curie, CERN	15:00 - 15:30
Silicon Strip Detectors	*Akira Konaka*
40/S2-C01 - Salle Curie, CERN	15:30 - 15:52
RPC TOF Detector	*Roger Wendell*
40/S2-C01 - Salle Curie, CERN	15:52 - 16:14
Detector Geometry Studies	*Lauren Anthony*
40/S2-C01 - Salle Curie, CERN	16:15 - 16:40
Beam Window Simulations	*Alj Hakim Yassine*
40/S2-C01 - Salle Curie, CERN	16:40 - 17:00

Beam Line Components

Simulation Studies

Online Meeting Agenda - Tuesday

Water Purification Techniques *40/S2-C01 - Salle Curie, CERN*	*Yasuhiro Nakajima* 14:30 - 14:50	Water System
Water System Status *40/S2-C01 - Salle Curie, CERN*	*Patrick de Perio* 14:50 - 15:05	
Overview of WCTE Mechanical Systems *40/S2-A01 - Salle Anderson, CERN*	*Akira Konaka* 15:05 - 15:20	Mechanical Systems
Design and Stability of Support Structure & Tank *40/S2-A01 - Salle Anderson, CERN*	*Saurabh Patil* 15:20 - 15:40	
Hydrostatics and Hydrodynamics of the Tank *40/S2-A01 - Salle Anderson, CERN*	*Shardul Joshi* 15:40 - 15:55	
Development of Mech. Moving Systems for WCTE *40/S2-A01 - Salle Anderson, CERN*	*Oliver Jeremy* 15:55 - 16:20	
Current Status and Future Work *40/S2-A01 - Salle Anderson, CERN*	*Chandrashekhar Garde et al.* 16:20 - 16:35	
Multi-PMT Mechanical Status *40/S2-A01 - Salle Anderson, CERN*	*Ryosuke AKUTSU* 16:35 - 17:00	Multi-PMT Photosensor
Multi-PMT Electronics *40/S2-A01 - Salle Anderson, CERN*	*Thomas Hermann Lindner* 17:00 - 17:25	

Online Meeting Agenda - Wednesday

CDS and Diffuser Ball	*Lauren Anthony*
40/S2-A01 - Salle Anderson, CERN	14:30 - 14:55
Radioactive Sources	*Josh Renner*
40/S2-A01 - Salle Anderson, CERN	14:55 - 15:20
Photogrammetry	*Michael Sekatchev*
40/S2-A01 - Salle Anderson, CERN	15:20 - 15:45
DAQ & Triggering	*Benjamin Richards*
40/S2-A01 - Salle Anderson, CERN	15:45 - 16:15
ESSnuSB near-detector reconstruction and particle-ID performance	*Alexander Burgman*
40/S2-C01 - Salle Curie, CERN	16:15 - 16:45
Closeout	
40/S2-C01 - Salle Curie, CERN	16:45 - 17:00

Calibration

DAQ and Triggering

Connection to ESSnuSB

Summary

- We have made significant progress on the WCTE proposal to the point where we expect imminent approval by the Research Board!
- Now begins the challenging work of moving the WCTE into the production/construction phase
  - New work package leaders will focus on fixing the technical design and updating the schedule
- Let's enjoy this meeting and have exciting reports and discussion on the status and future of the WCTE

Extra Slides

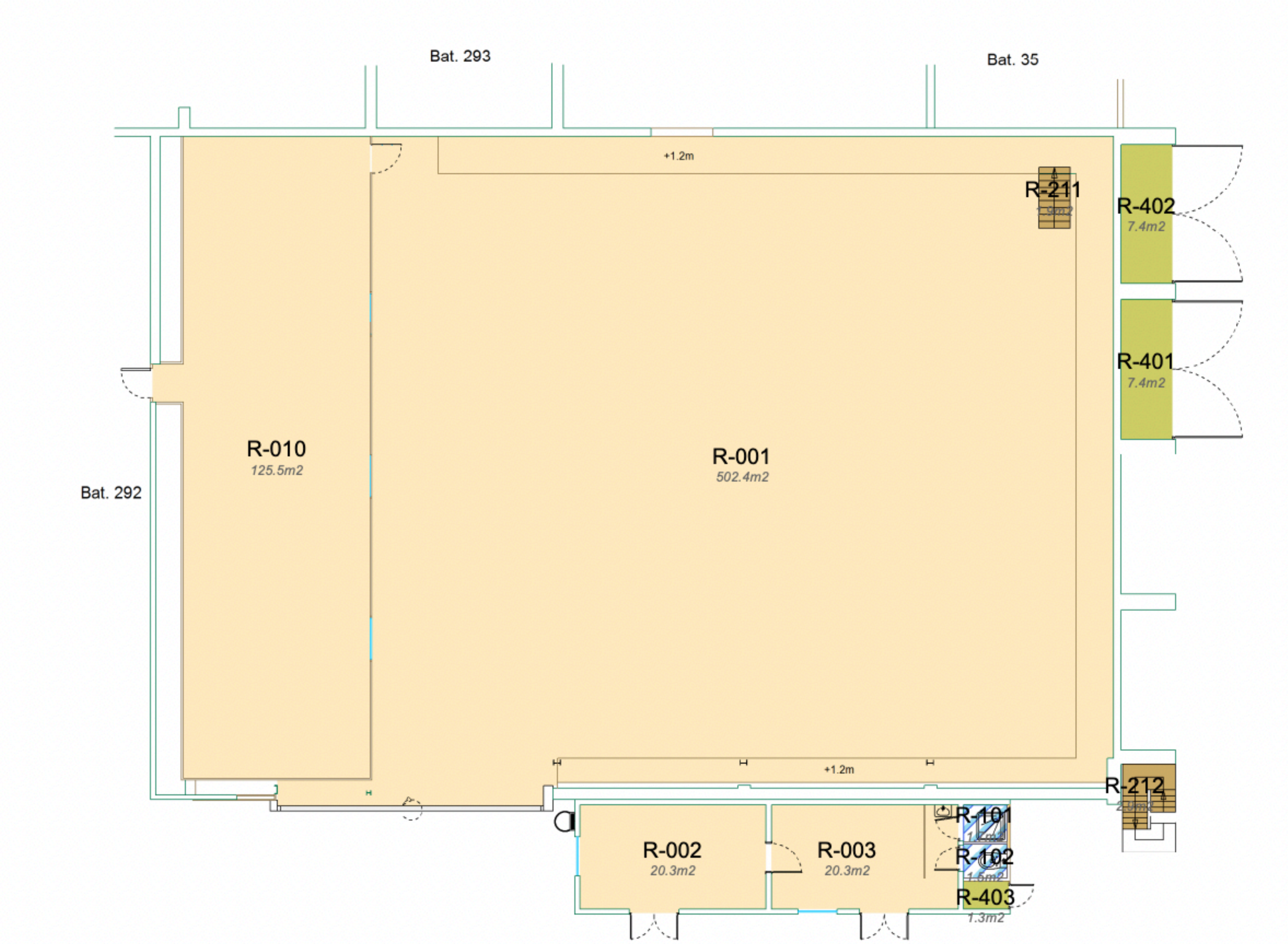
Configurations for Measurements

- We evaluate the experiment configuration required for each measurement:

Measurement	Required Beam Configuration	Required Water Configuration
Cherenkov Profile Measurement	Secondary	Pure or Gd Loaded
Secondary Neutron Production (protons)	Secondary	Gd Loaded
Secondary Neutron Production (pions)	Tertiary	Gd Loaded
Pion Scattering and Detector Response	Tertiary	Pure or Gd Loaded
Energy Scale Calibration (crossing muons)	Secondary	Pure or Gd Loaded
Reconstruction Studies (electron, muon, proton)	Secondary	Pure or Gd Loaded
Reconstruction Studies (pion)	Tertiary	Pure or Gd Loaded

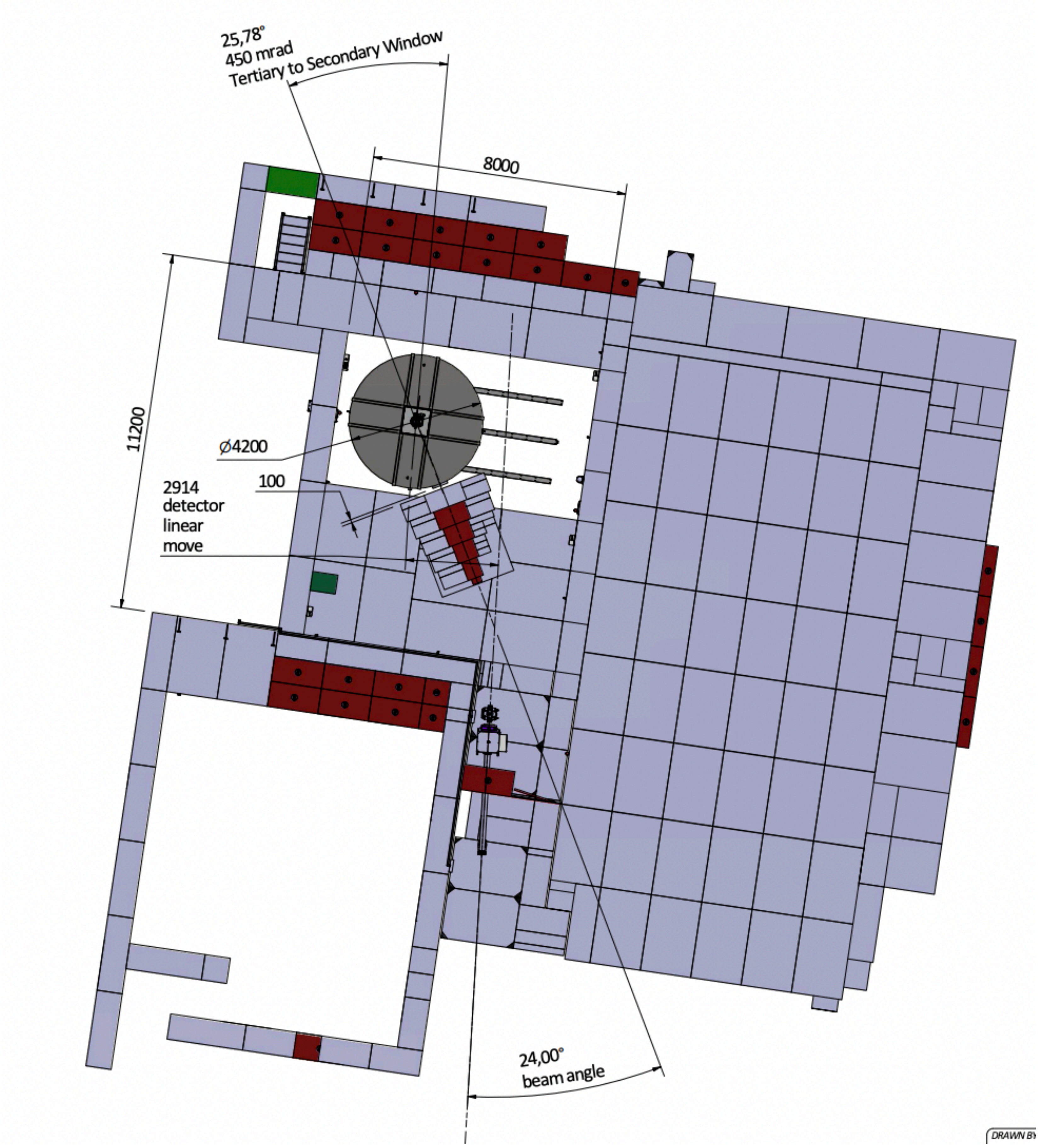
Assembly Area

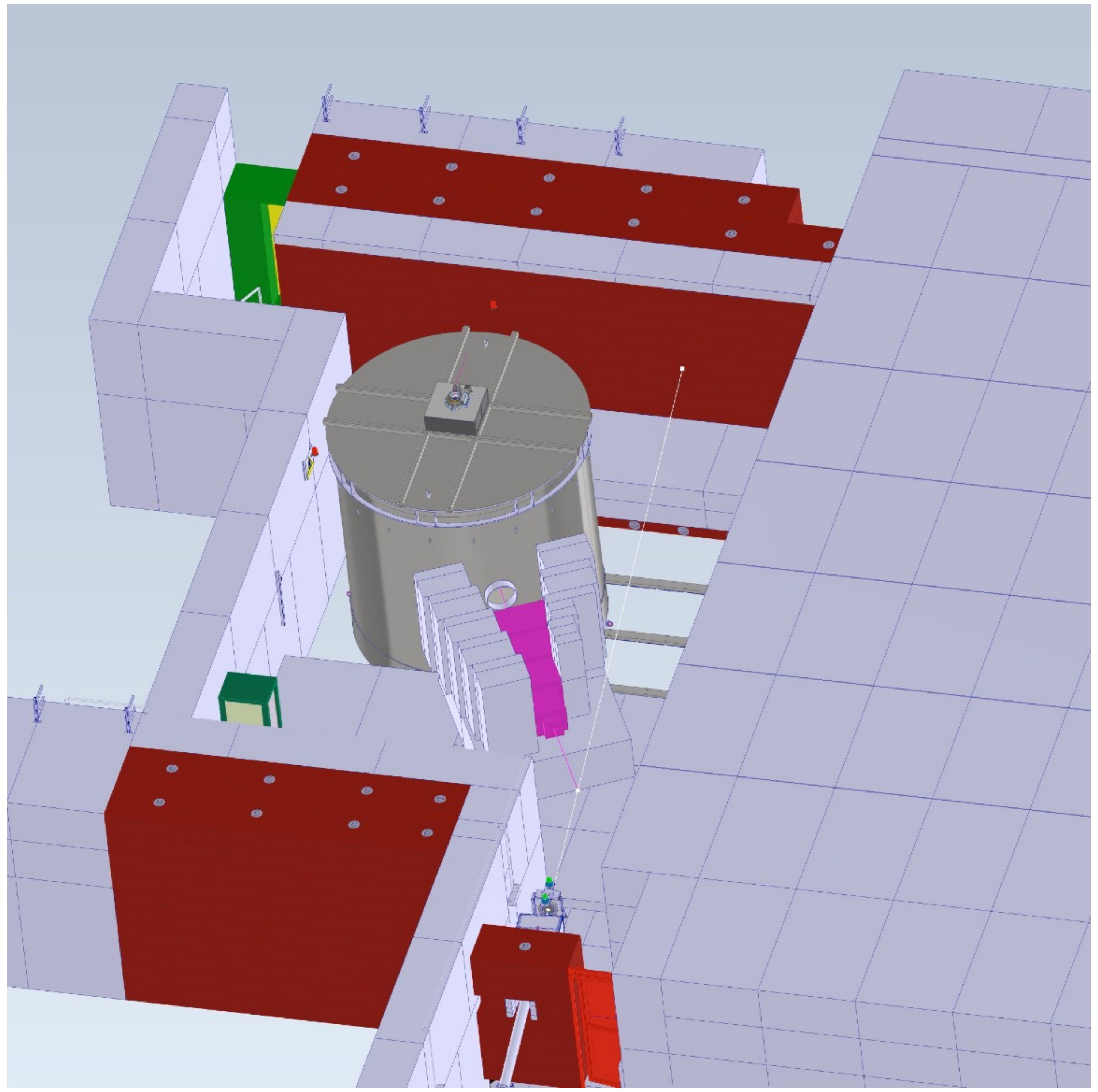
- Need area to assemble detector before installation in experimental hall
- Building 185, Gargamelle Hall has been identified and meets requirements:
  - 5.5 m x 5.5 m door
  - Crane with small hook (5 ton) and big hook (40 ton)
  - Hook height is between 15 m and 16 m
  - Floor space is 23 m x 19 m
  - ~6 months of use

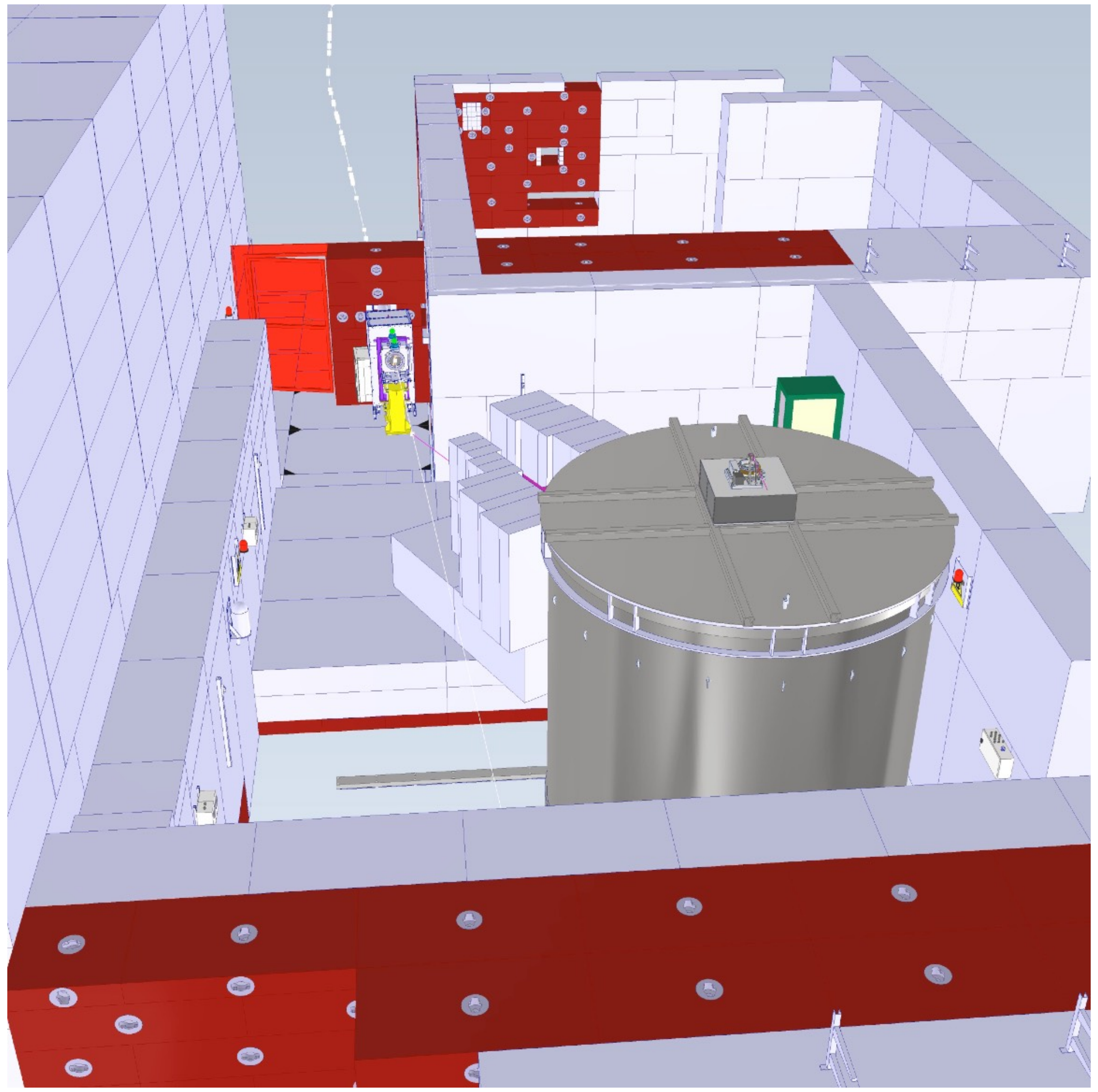


3D Model of T9 Area

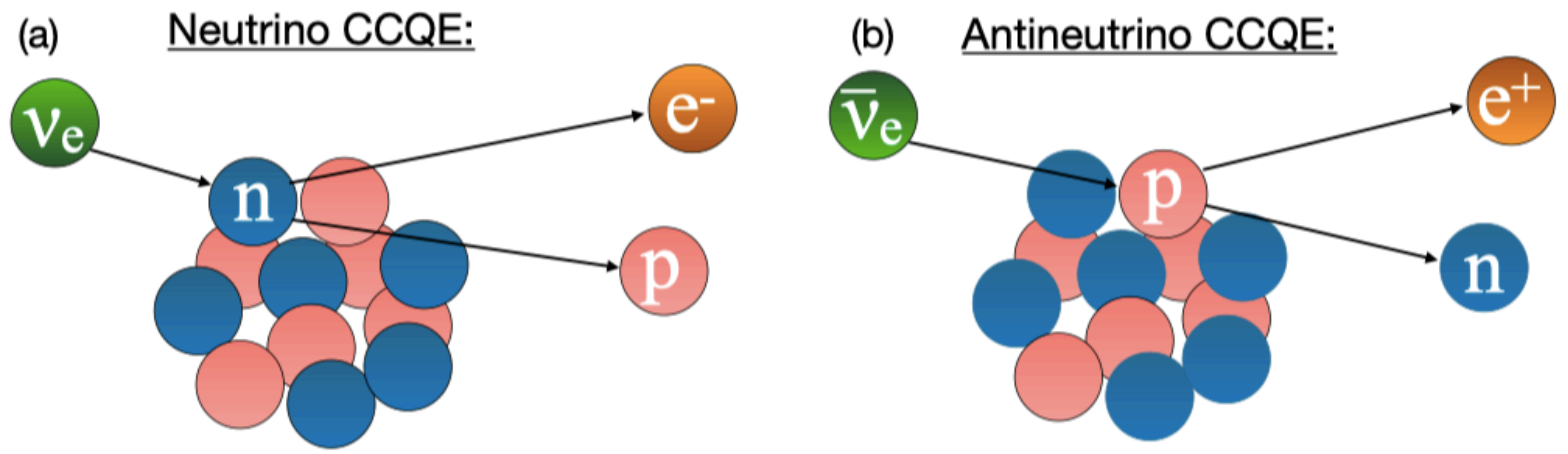
- We have received the 3D model of the T9 area, so we can start placing all components
- There is 8 m of space for the detector and moving system
  - P. Minginette confirms we can fit rail system by adjusting orientation of anchor with pulley system



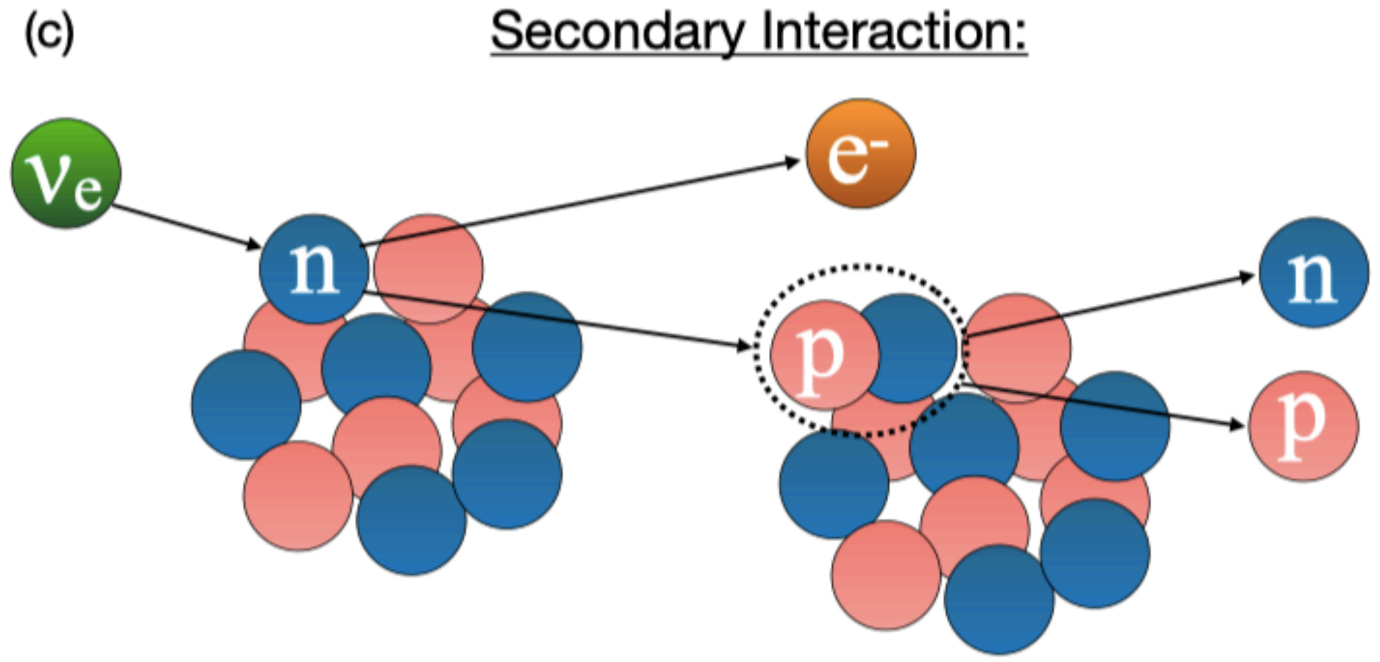




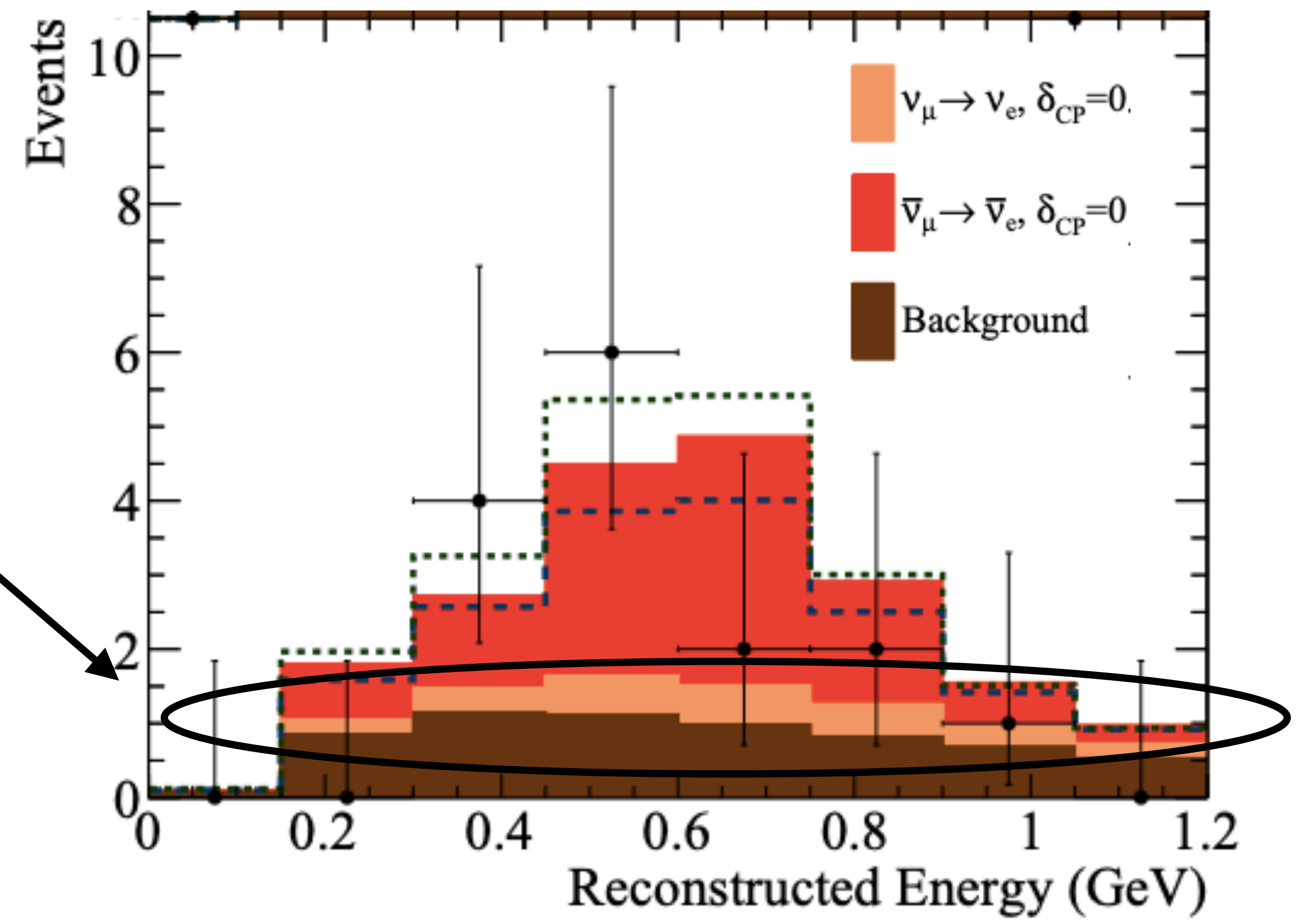
Applications of Neutron Detection in T2K



- For CCQE scattering, we expect neutrons only for antineutrino interactions in absence of FSI and SI
- Presence of neutron may be used to produce antineutrino enhanced sample (reduce wrong-sign fraction)
- Effectiveness is reduced by neutron production through FSI and SI of protons

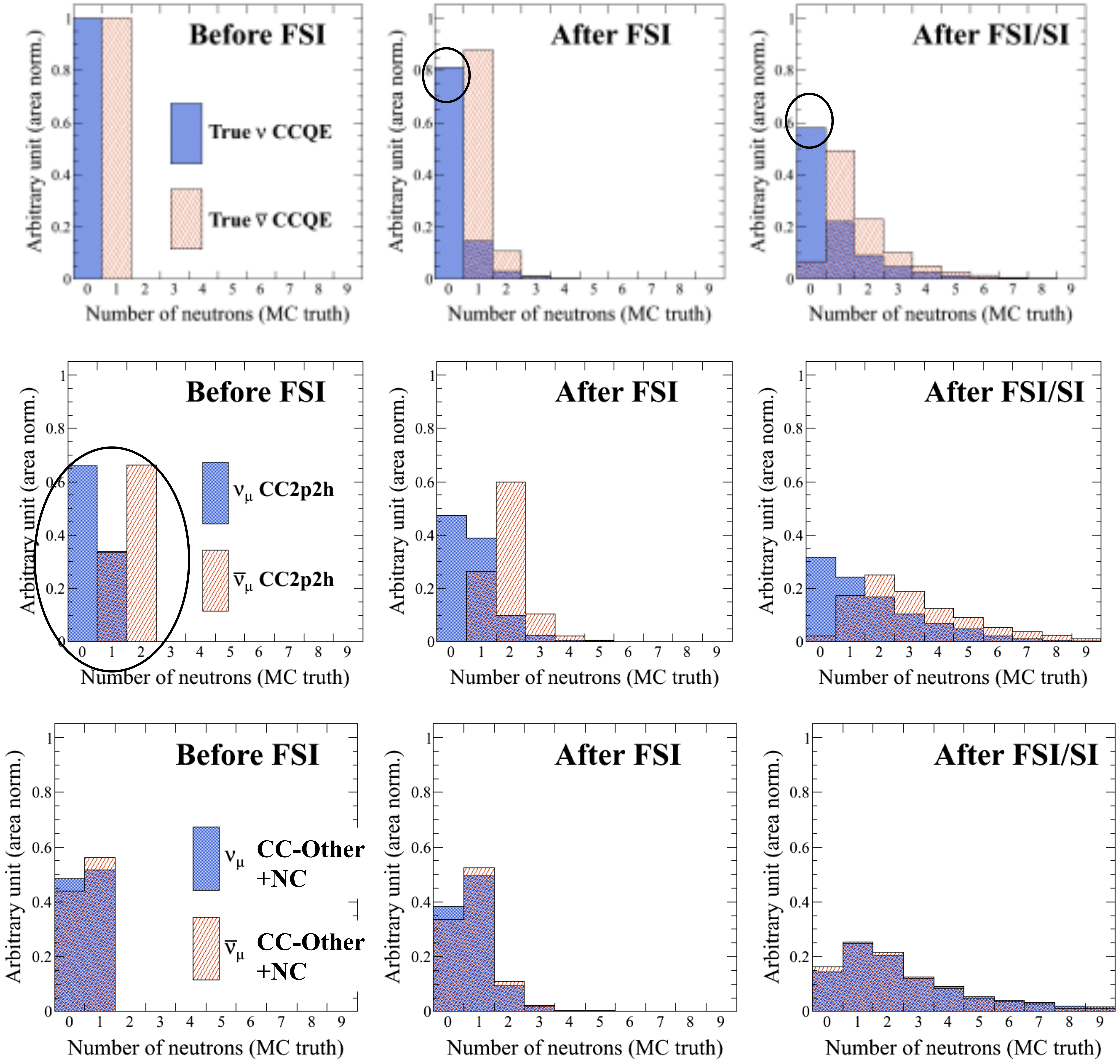


~20% of the interactions



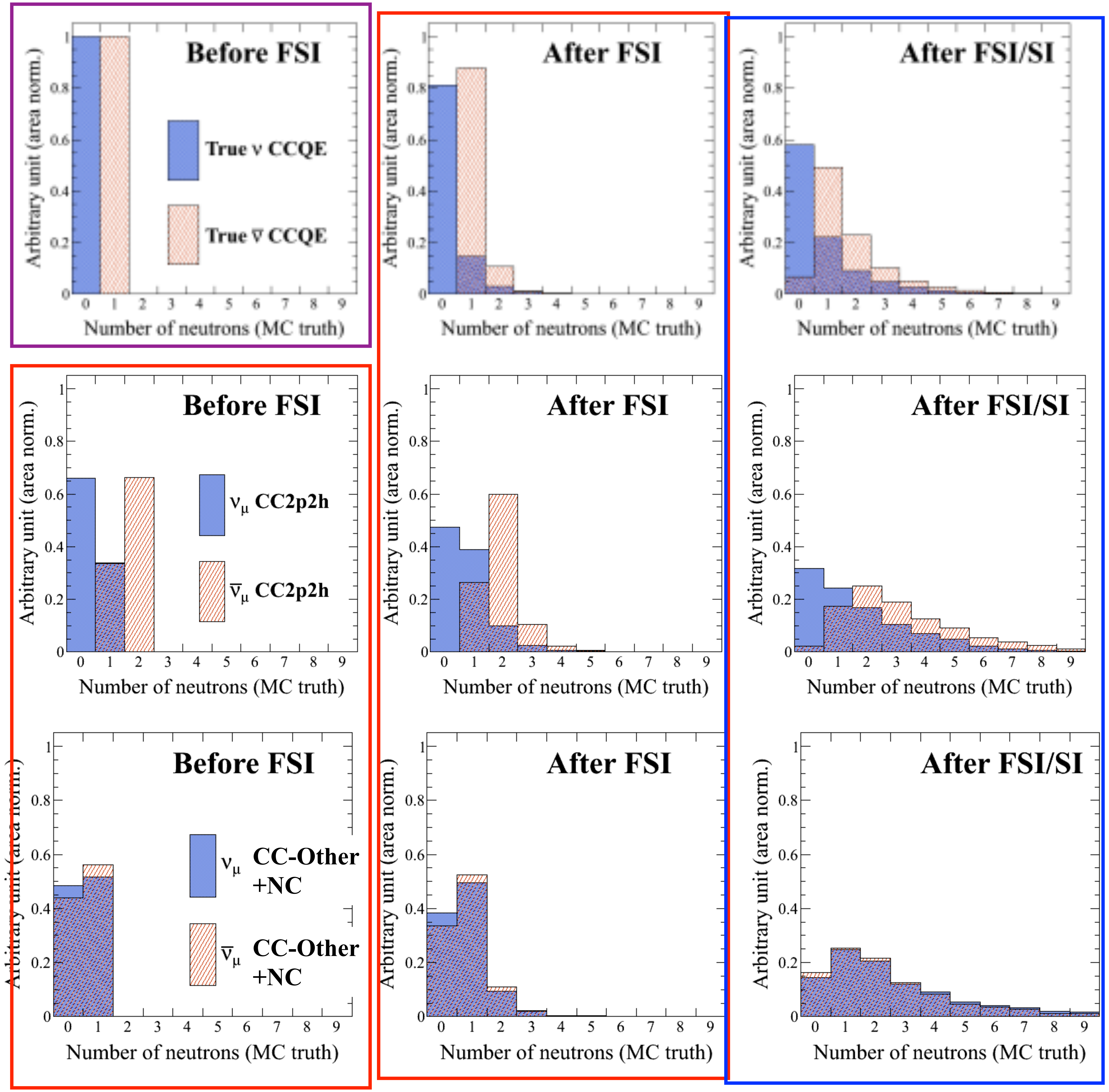
Nature 580 (2020) 7803, 339-344

Neutron Multiplicities (Single Ring Samples)



- About 20% of neutrino CCQE events pick up neutrons through final state interactions (**FSI - interactions inside target nucleus**)
- Another ~25% through secondary interactions (**SI - interactions in detector**)
- Non-quasi-elastic interactions typically have a higher rate of neutron production in the primary interaction

Neutron Multiplicities Constraints

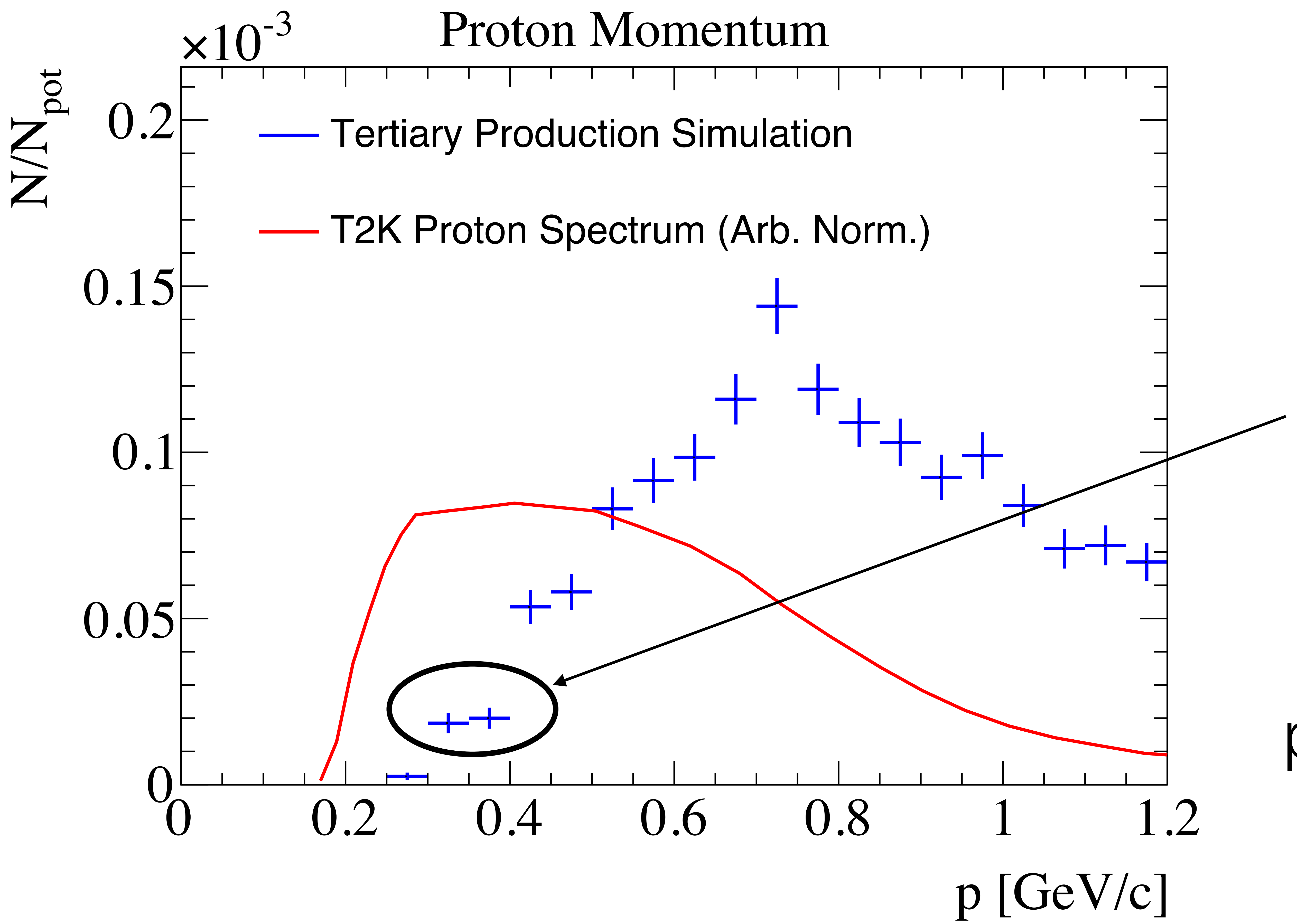


Derived from model

Constrained by ND280 (upgrade) measurements

Constrained by WCTE measurements

Proton Spectrum in WCTE



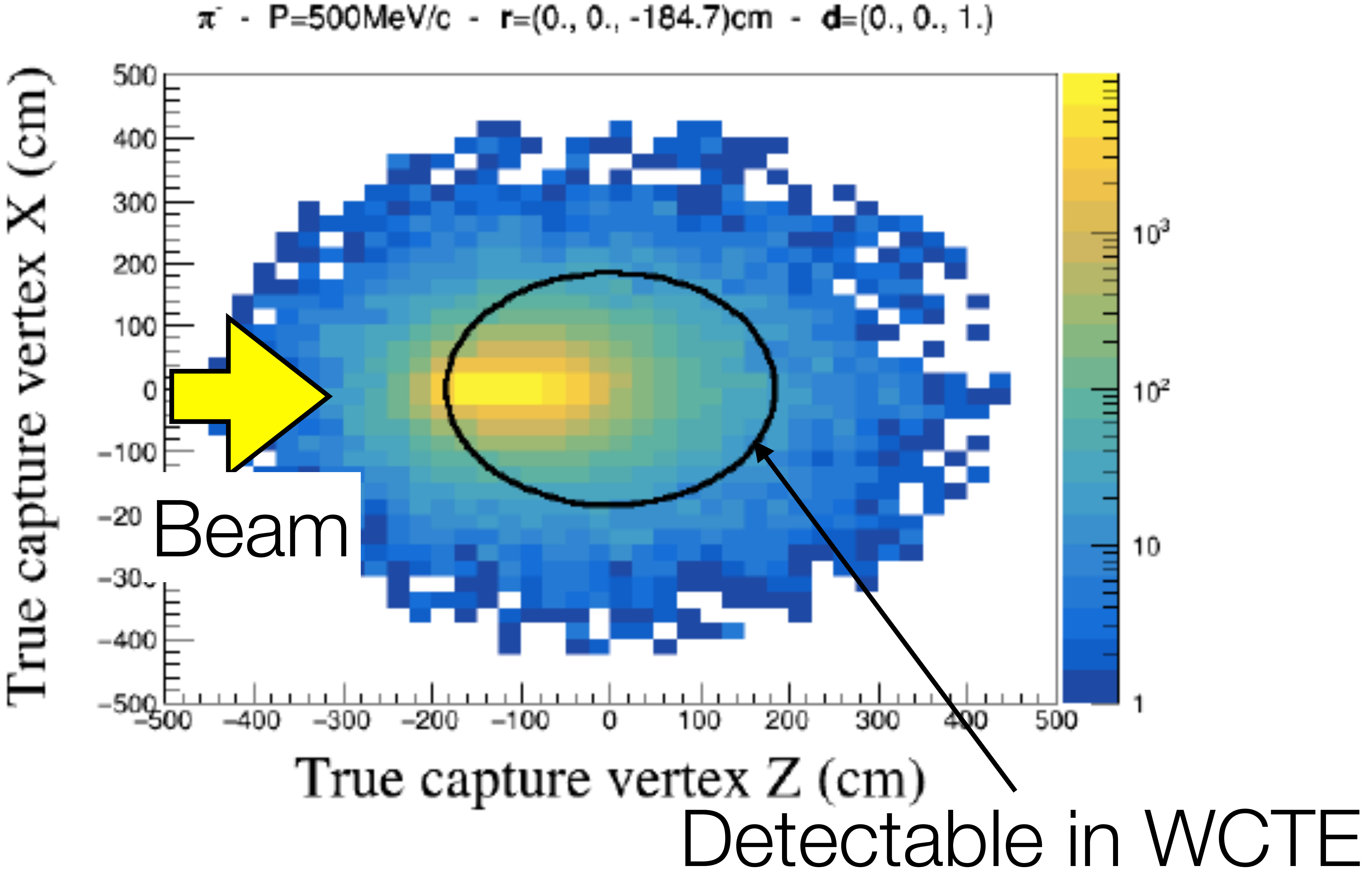
Accumulate ~20 events per spill in each of these bins

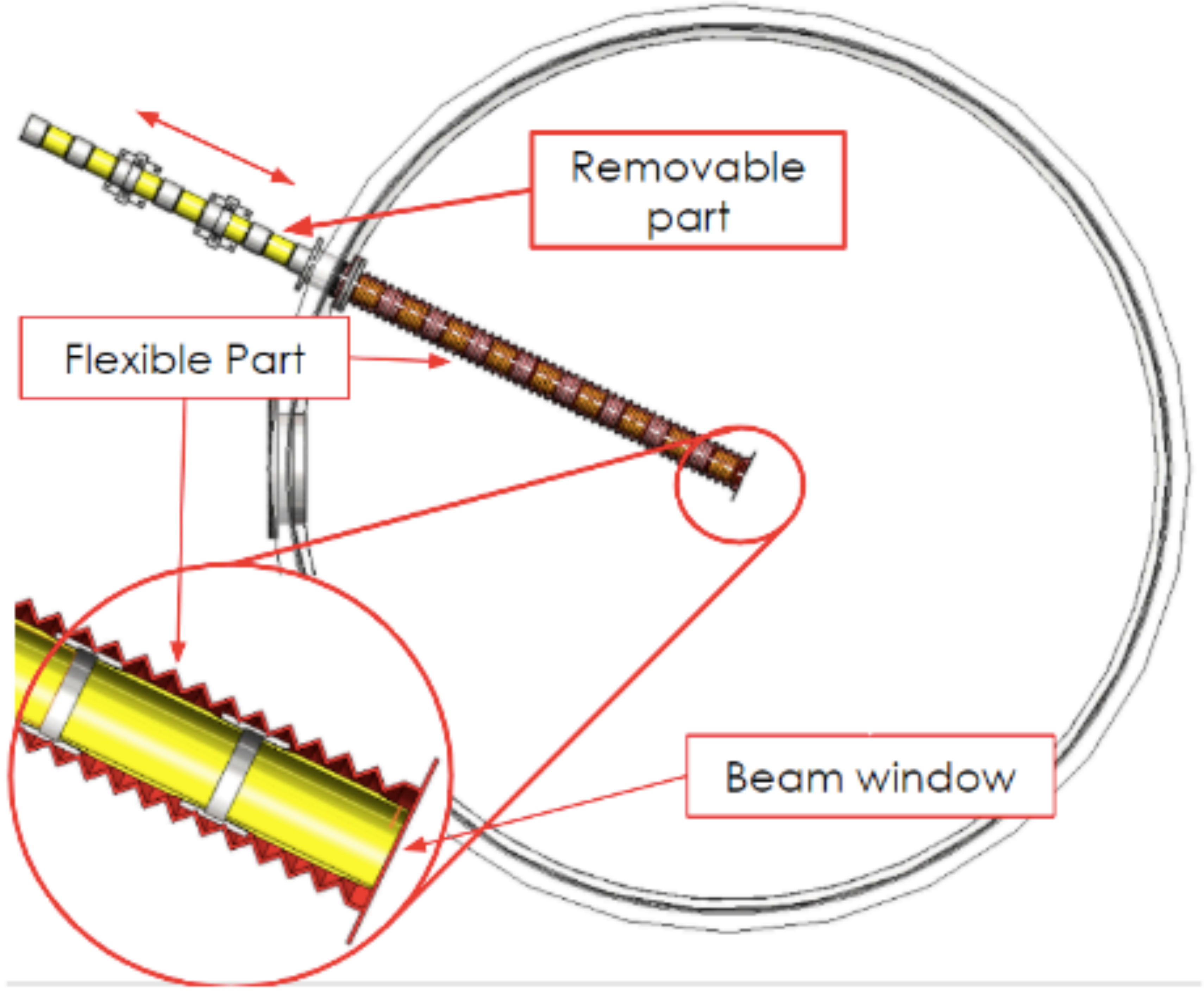
~200,000 events in planned 10,000 spills

- WCTE measures protons above 300 MeV/c with high statistics
- Covers most of relevant range for neutrino interactions in T2K and SK

Protons in Secondary Beam Configuration

Particle entering at edge of tank

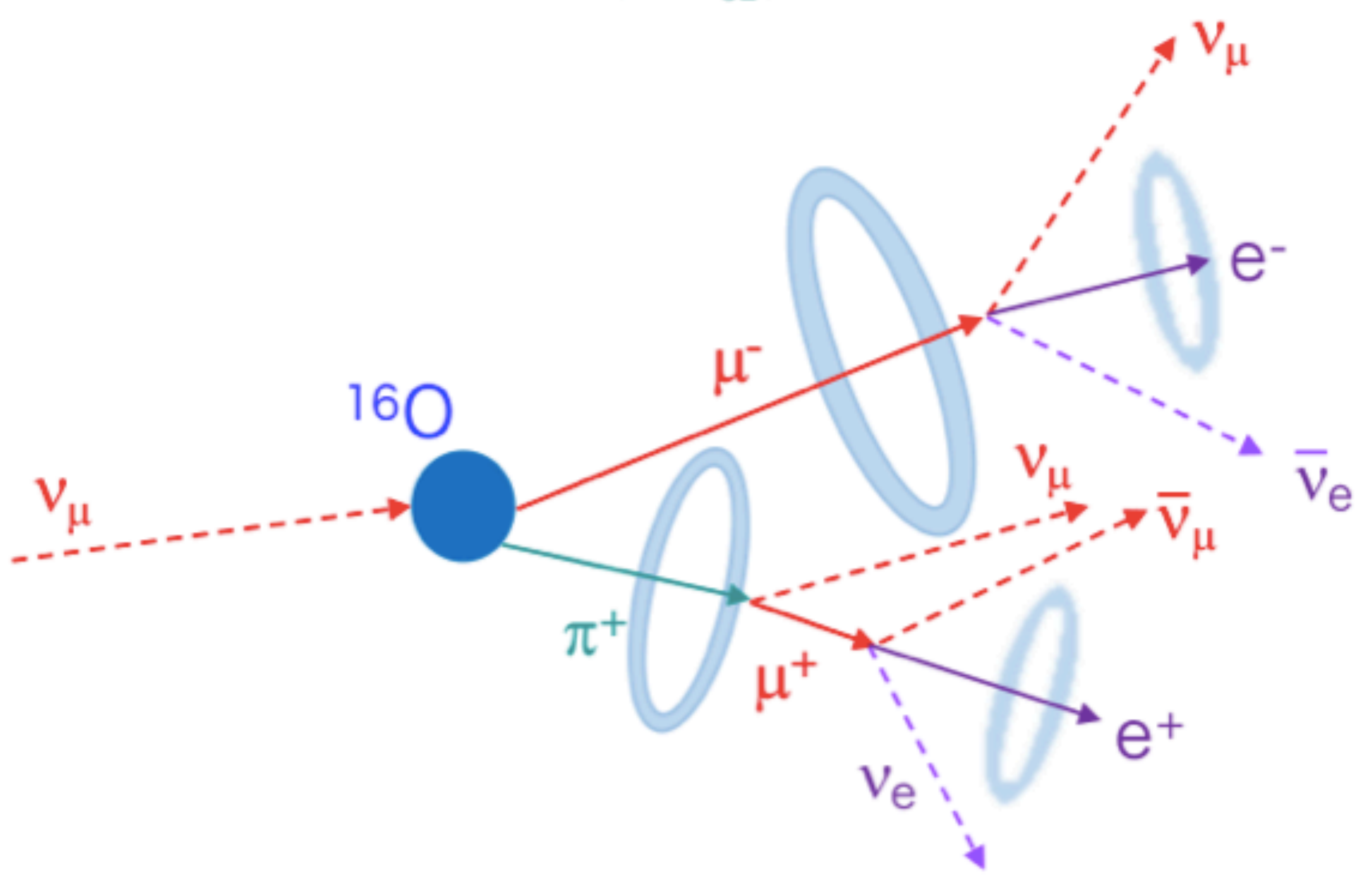




- For protons entering at edge of tank, we contain and detect ~60% of neutrons
- To increase detection of backward produced neutrons, also study protons in secondary beam configuration
    - With beam pipe, can inject protons into center of tank and detect backwards produced neutrons

Multi-Ring Samples

Pion Production
Event Topology



- Super-K atmospheric analysis already uses multi-ring samples
- T2K aims to incorporate these as well
- Super-K uses the visible energy in multi-ring samples
- T2K may use energy reconstruction with muon kinematics and assuming recoil Δ:

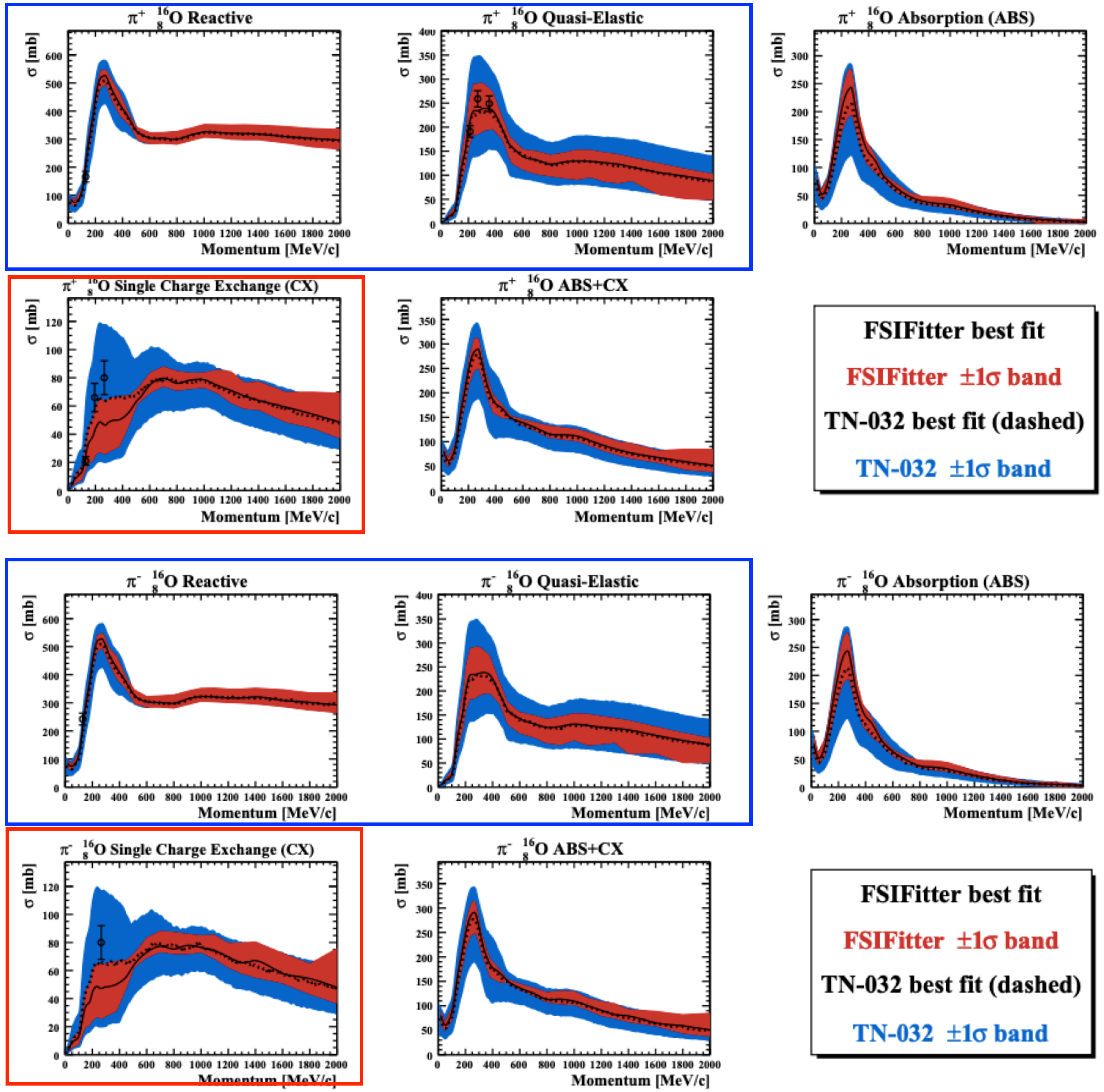
$$E_{\mathrm{rec}}^{\nu_\mu CC\Delta^{++}} = \frac{2m_p E_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2\left(m_p - E_\mu + |\boldsymbol{p}_\mu|\cos\theta_\mu\right)},$$

- Not using reconstructed pion kinematics reduces impact of uncertainties on final state and secondary interactions of pions
- Can do better if these uncertainties are reduced and reconstructed pion kinematics are included
- Pion modeling constraints can be applied to all data already collected by T2K and Super-K

Pion Scattering Data

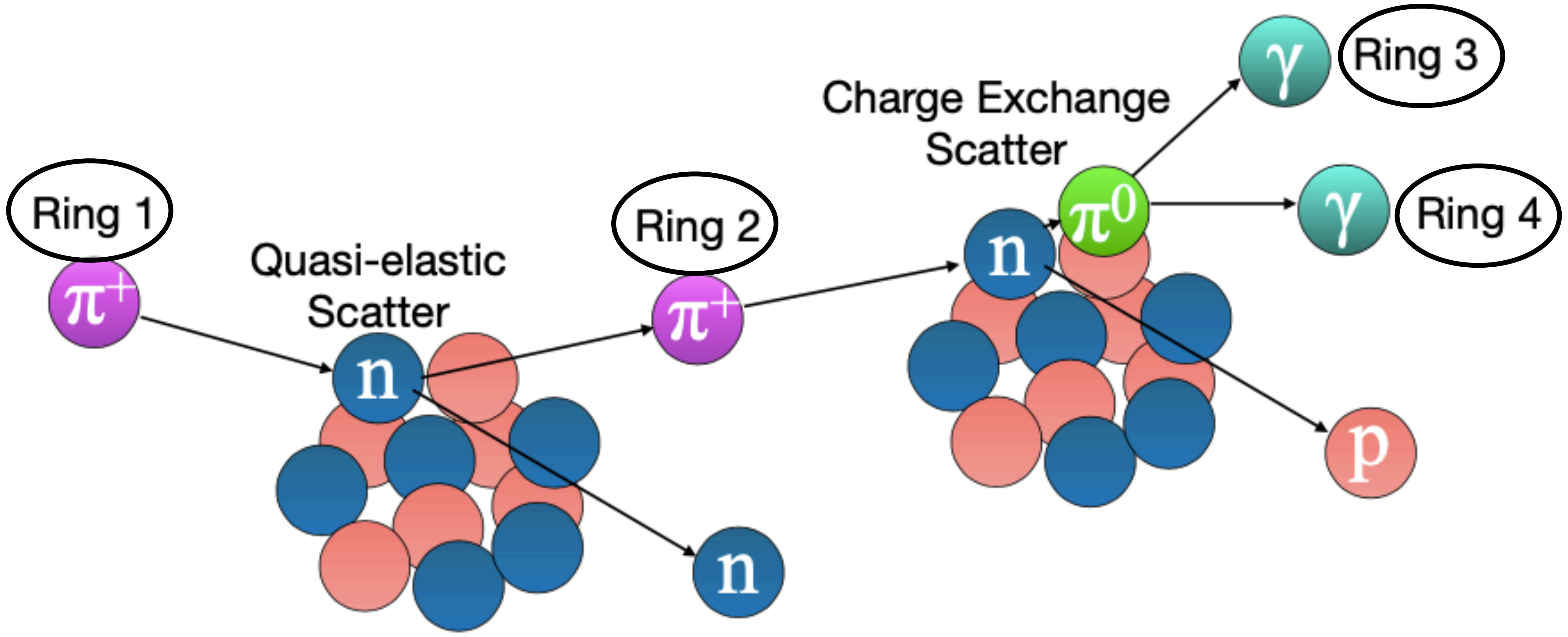
T2K Thesis, E. Pinzon

Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce et al. [11]	$\pi^\pm$	C, Al, Pb	710-2000	REAC
A. Saunders et al. [12]	$\pi^\pm$	C, Al	116-149	REAC
C. J. Gelderloos et al. [13]	π^-	C, Al, Cu, Pb	531-615	REAC
F. Binon et al. [14]	π^-	C	219-395	REAC
O. Meirav et al. [15]	π^+	C, O	128-169	REAC
C. H. Q. Ingram [16]	π^+	O	211-353	QE
S. M. Levenson et al. [17]	π^+	C	194-416	QE
M. K. Jones et al. [18]	π^+	C, Pb	363-624	QE, CX
D. Ashery et al. [19]	π^+	C, Al, Fe	175-432	QE, ABS+CX
H. Hilscher et al. [20]	π^-	C	156	CX
T. J. Bowles [21]	$\pi^\pm$	O	128-194	CX
D. Ashery et al. [22]	$\pi^\pm$	C, O, Pb	265	CX
K. Nakai et al. [23]	$\pi^\pm$	Al, Cu	83-395	ABS
E. Bellotti et al. [24]	π^+	C	230	ABS
E. Bellotti et al. [25]	π^+	C	230	ABS
I. Navon et al. [26]	π^+	C, Fe	128	ABS+CX
R. H. Miller et al. [27]	π^-	C, Pb	254	ABS+CX
E. S. Pinzon Guerra et al. [28]	π^+	C	206-295	ABS, CX



- π±+O scattering data is rather limited
- Rely on constraint of microscopic parameters within cascade model constrained by C, Al, etc. data

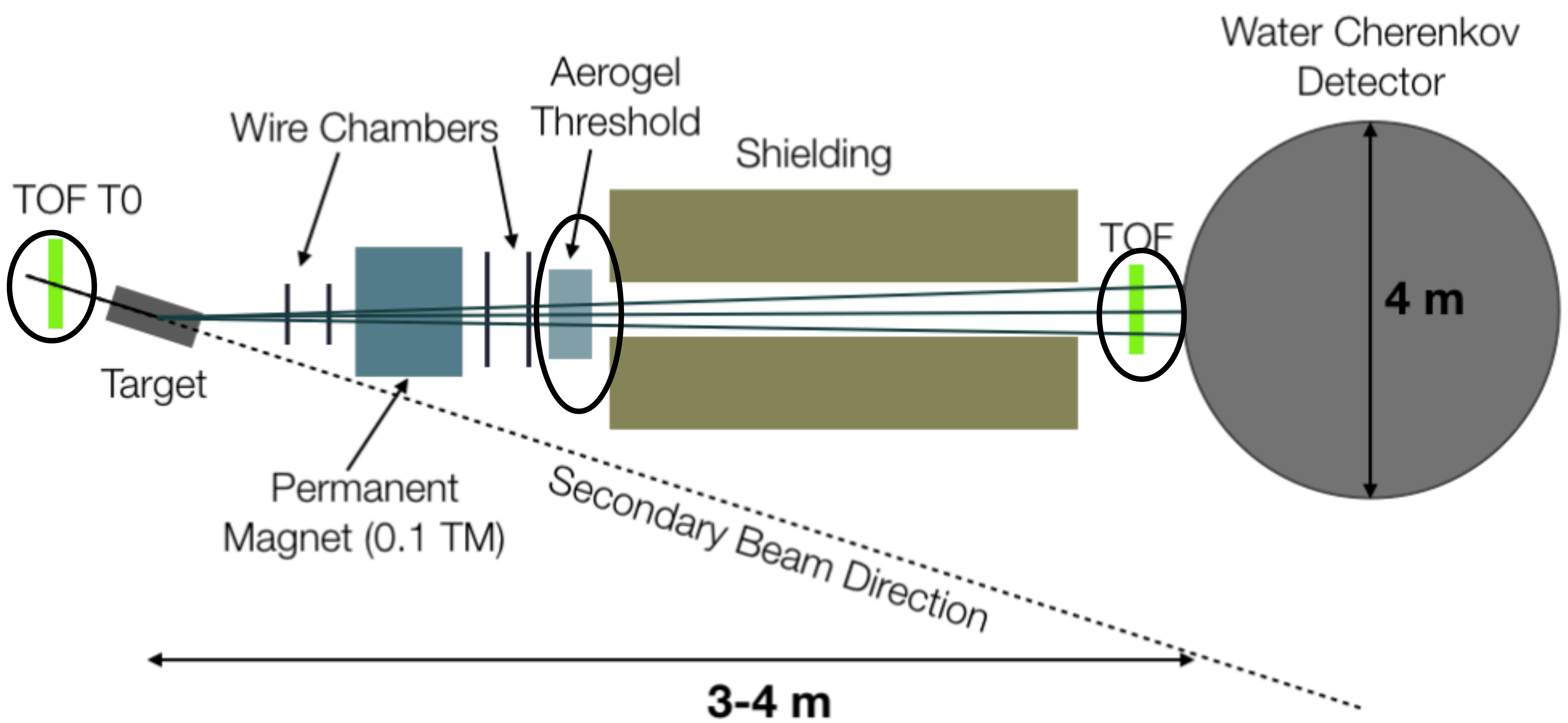
Pion Measurement in WCTE

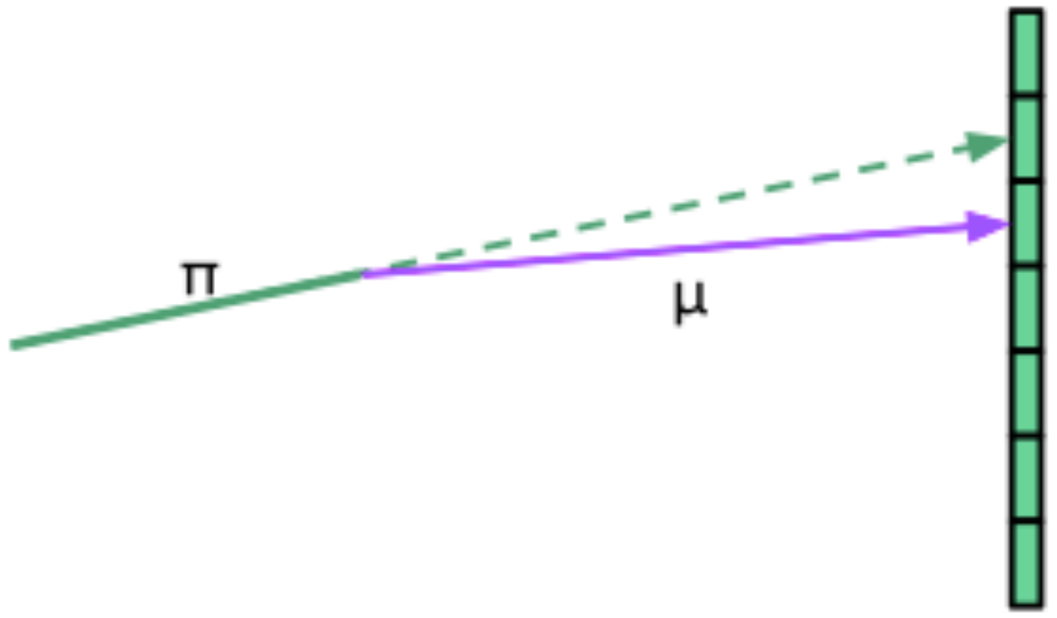


- We don't make pion interaction cross section measurements like one would do in a "thin" target experiment
- We measure impact of the full pion interaction chains on observables in detector
- For incoming pion of a given momentum measure:
  - Distribution of total visible energy
  - Distribution of number of visible rings
  - Other kinematic variables

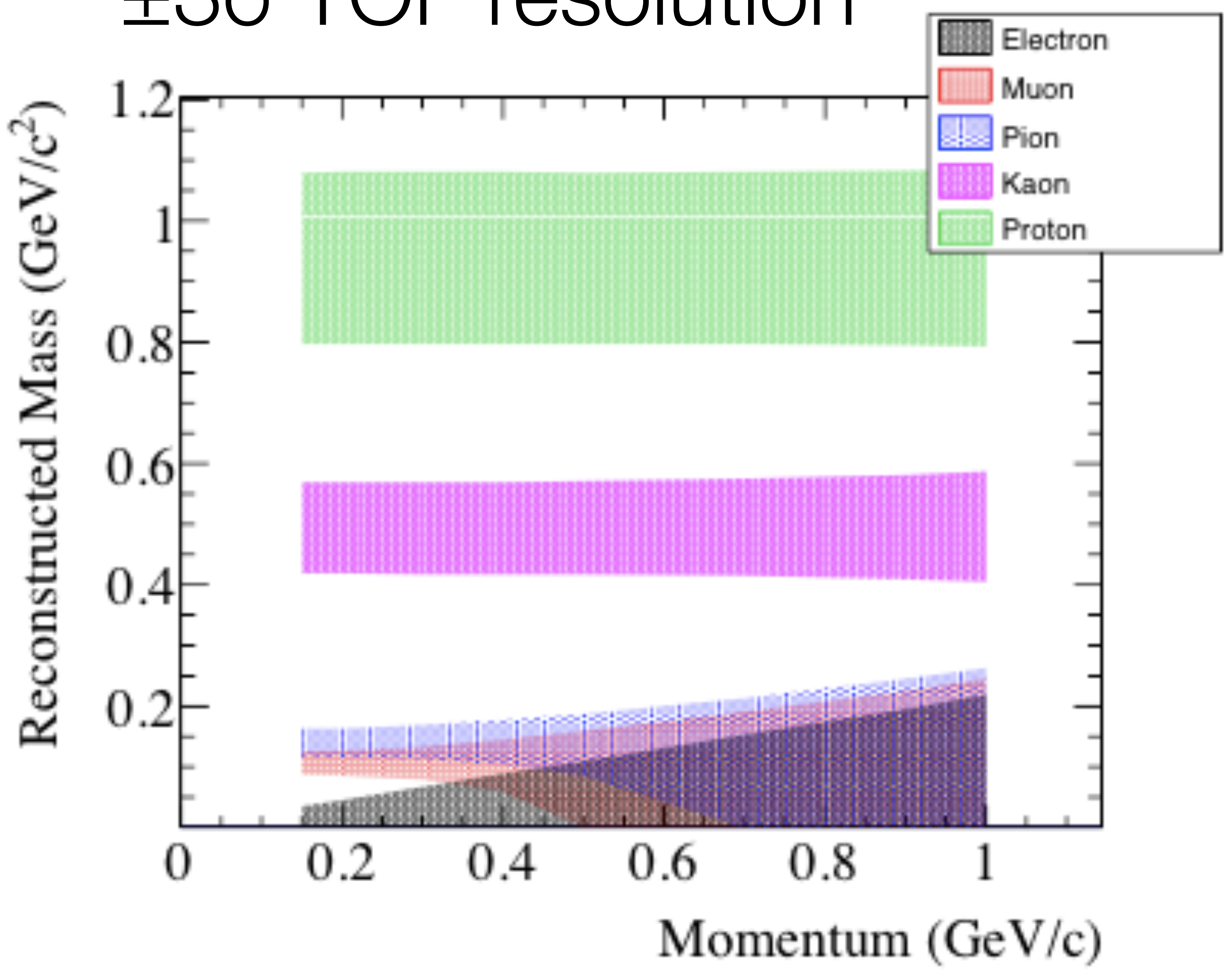
Particle Identification

- TOF detector with 100 ps resolution
  - Can use **resistive plate chambers (RPC)**
  - Sufficient resolution to separate pion, kaon and proton (lower right)
- For high-momentum pion/electron separation, we can use an aerogel Cherenkov threshold detector
- To separate muons from pion decay-in-flight, the TOF detector is segmented





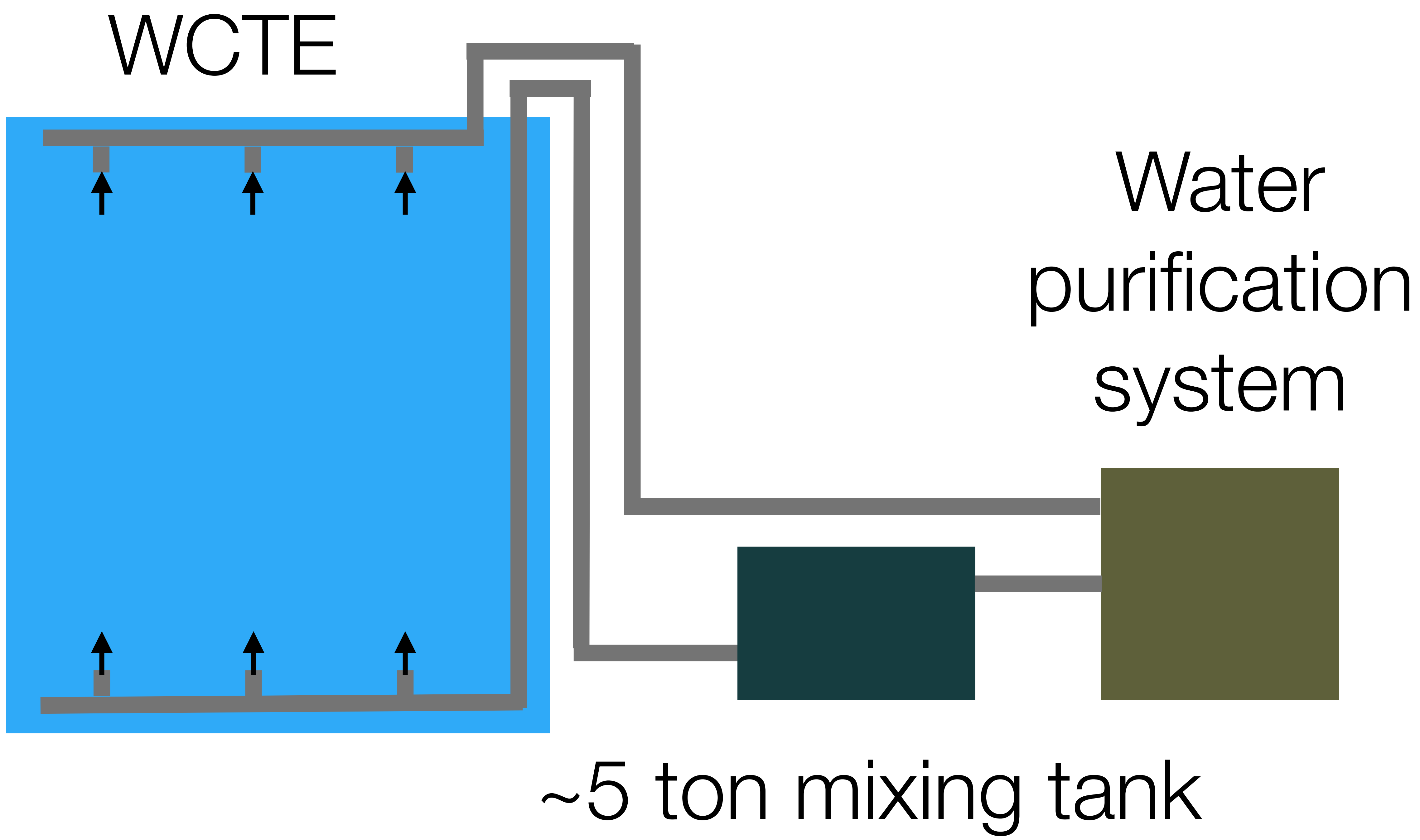
±3σ TOF resolution



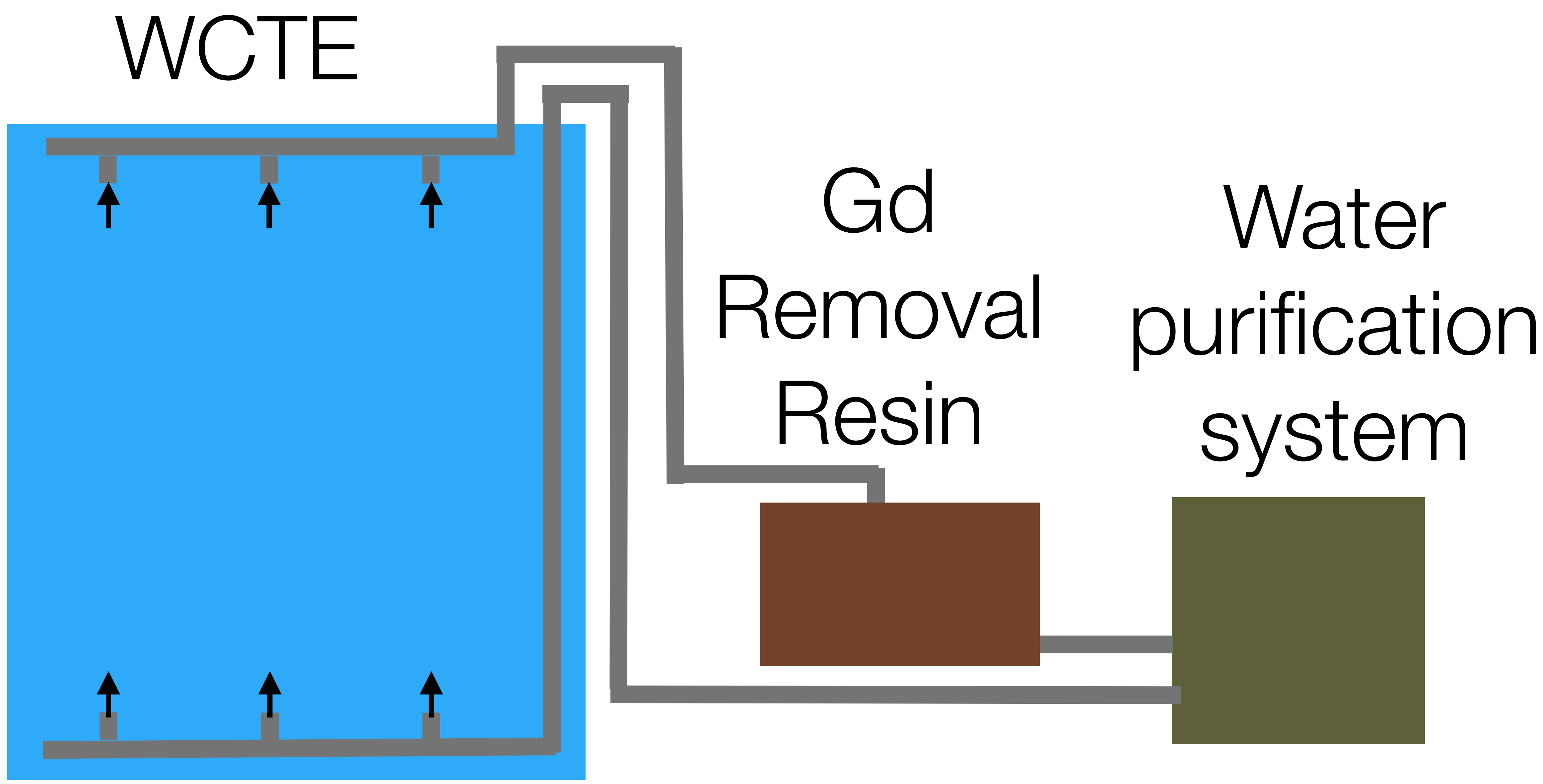
WCTE Water System - Gd Loading Phase

- Will add ~100 kg of $Gd_2(SO_4)_3$ to the water
    - During loading phase, mixing tank is added to dissolve $Gd_2(SO_4)_3$
- Ion exchange resin in water system will be removed or replaced with special resin
- Resin is used to remove $Gd_2(SO_4)_3$ when Gd loading phase is complete
    - Gd concentration measurement system will be used to monitor Gd level

Loading Gd

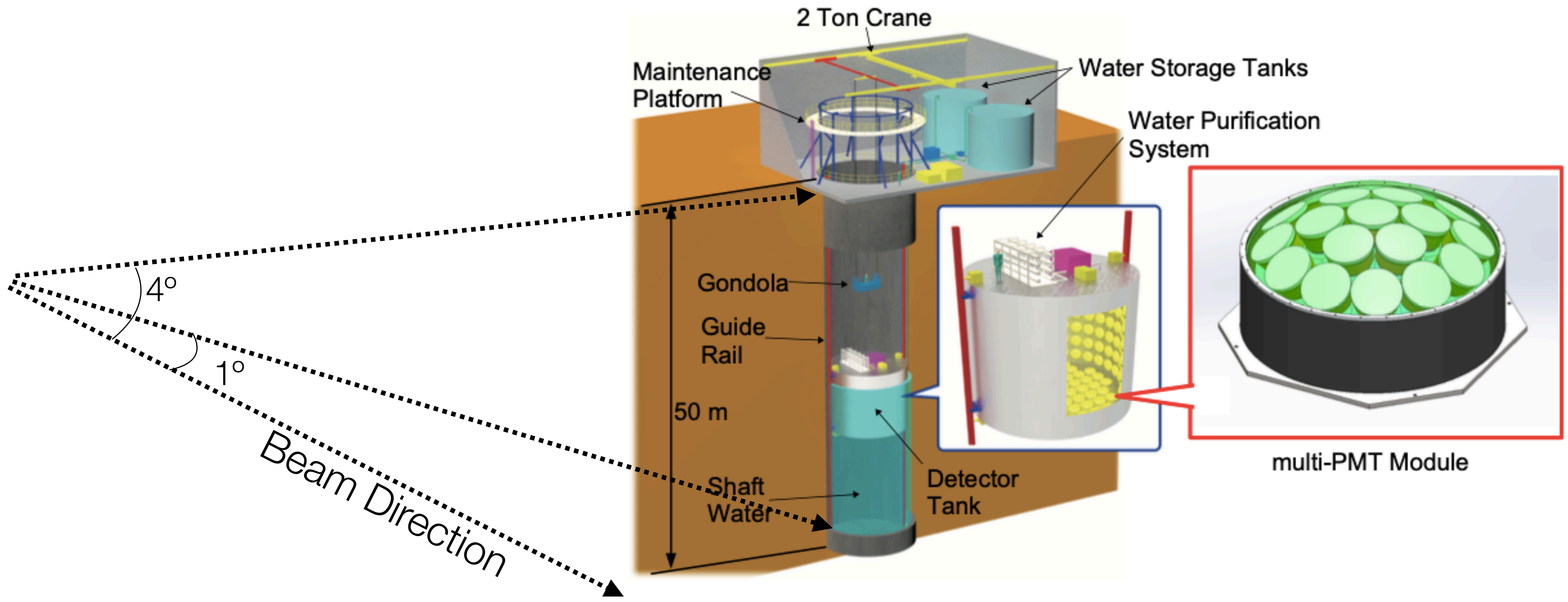


Removing Gd



WCTE Motivation

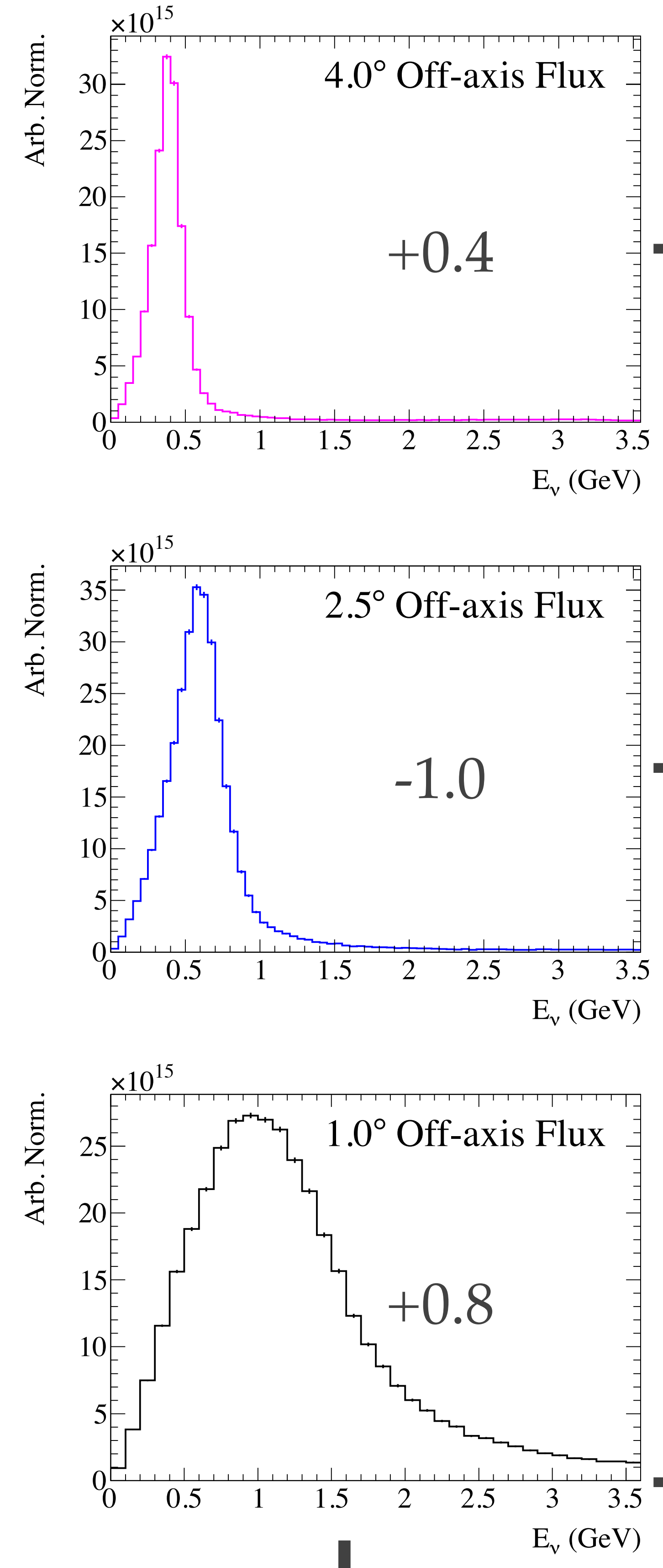
- Original motivation for water Cherenkov test experiment driven by planned Intermediate Water Cherenkov Detector (IWCD) for Hyper-K



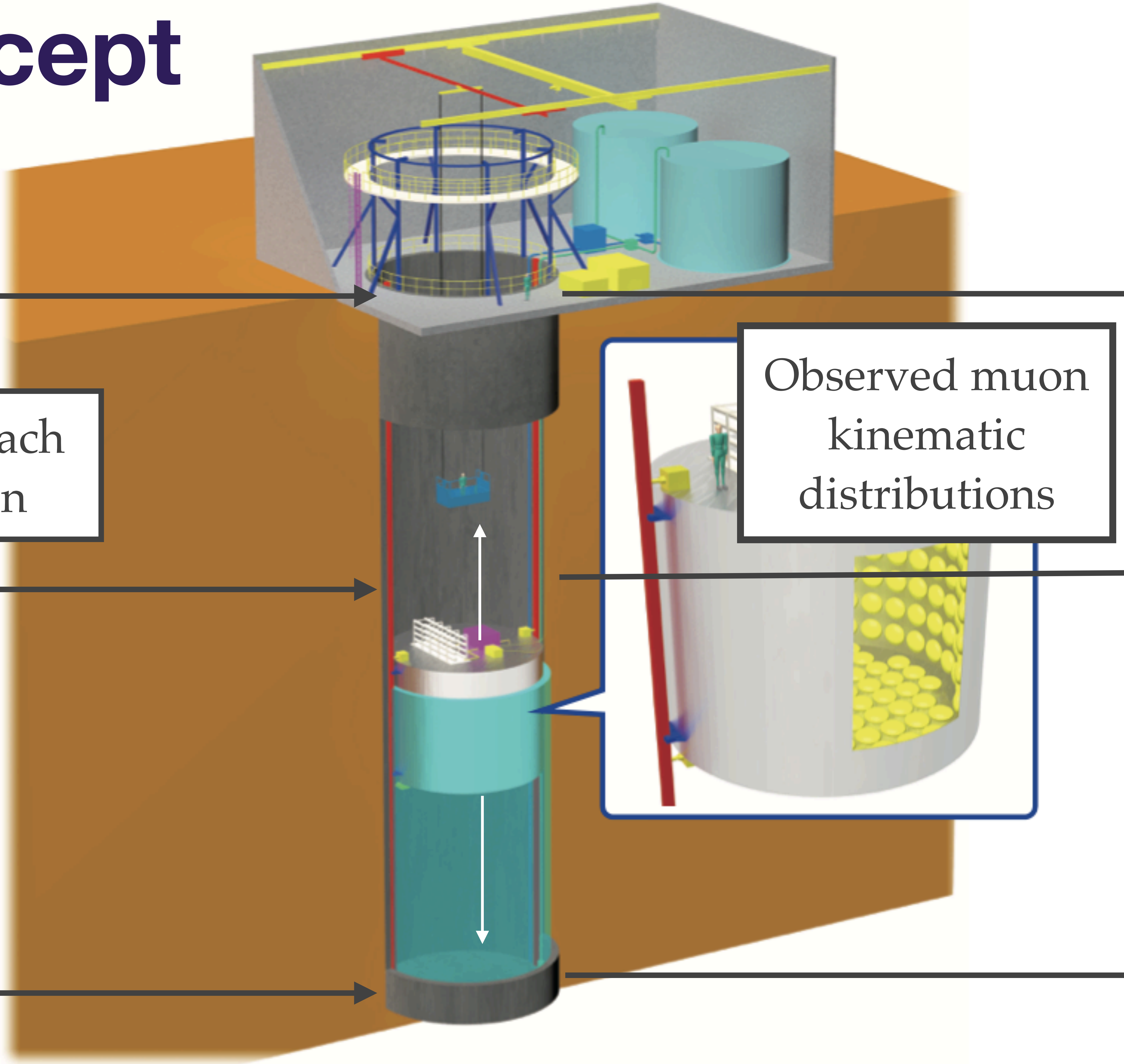
- Kilo-ton scale water Cherenkov detector
- Requires 1% level calibration
- Implement new technologies, such as the multi-PMT photosensors

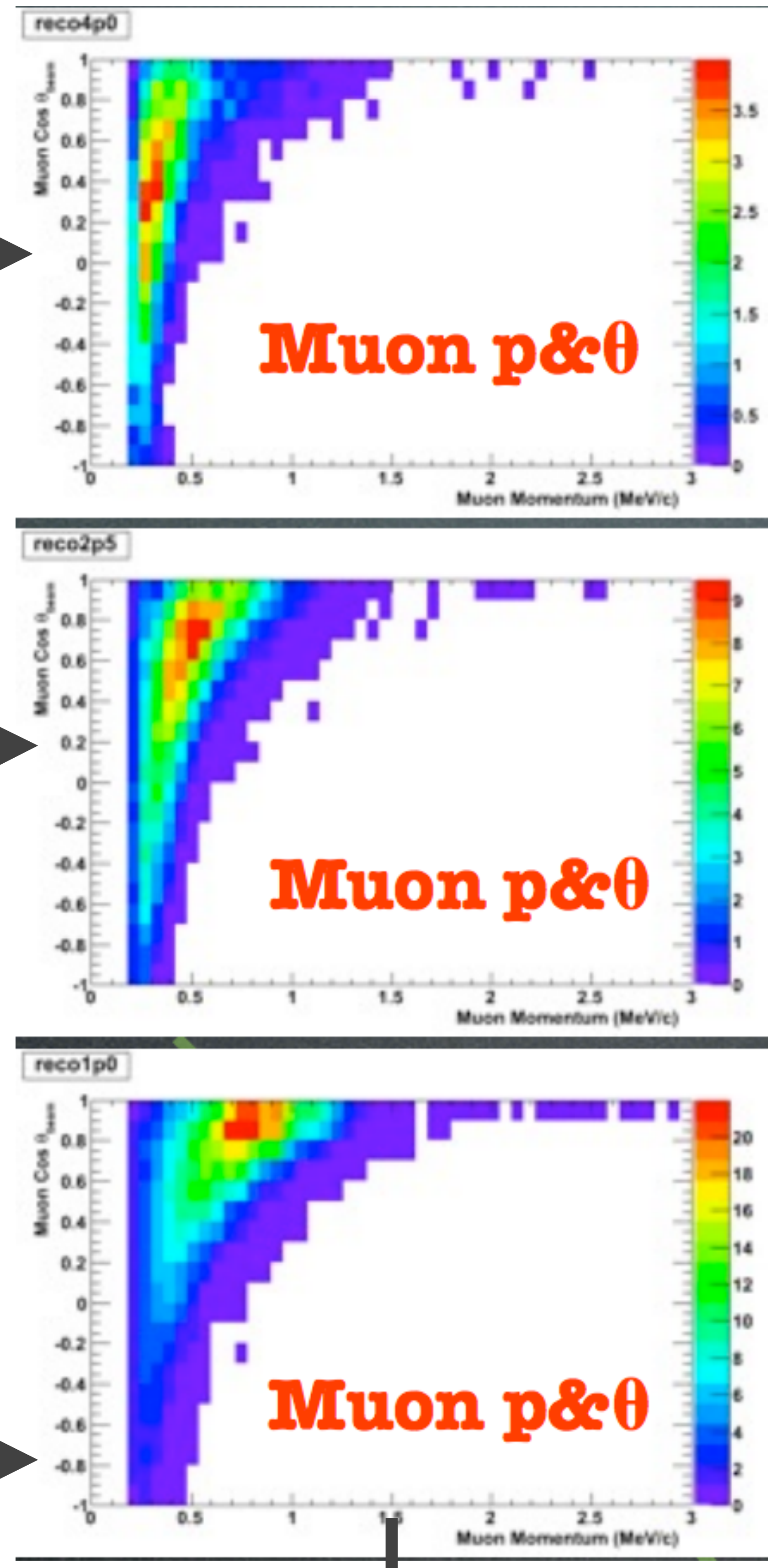
NuPRISM Concept

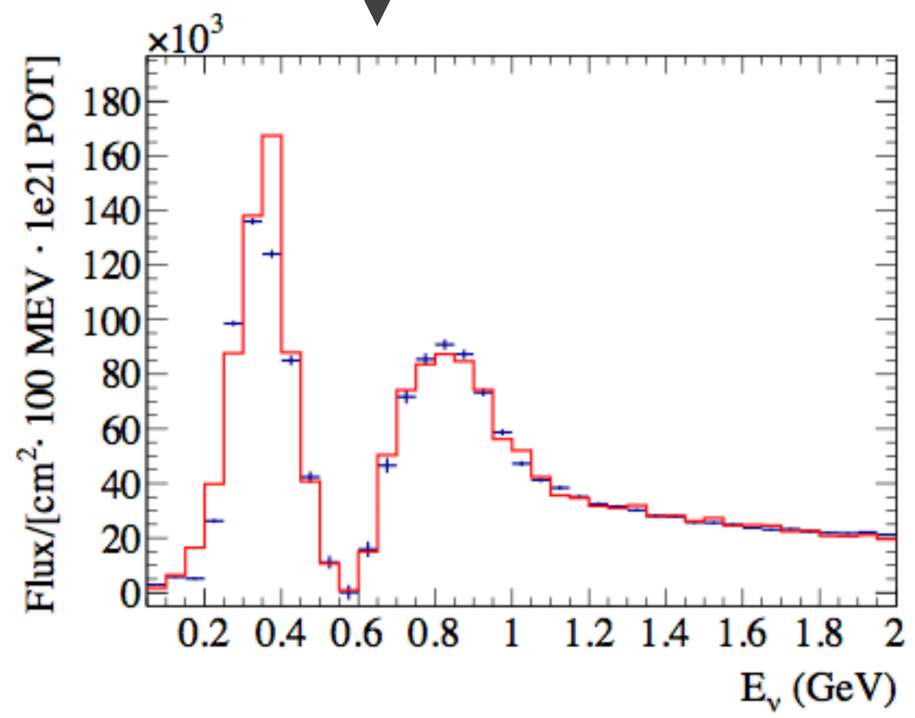
Hyper-Kamiokande



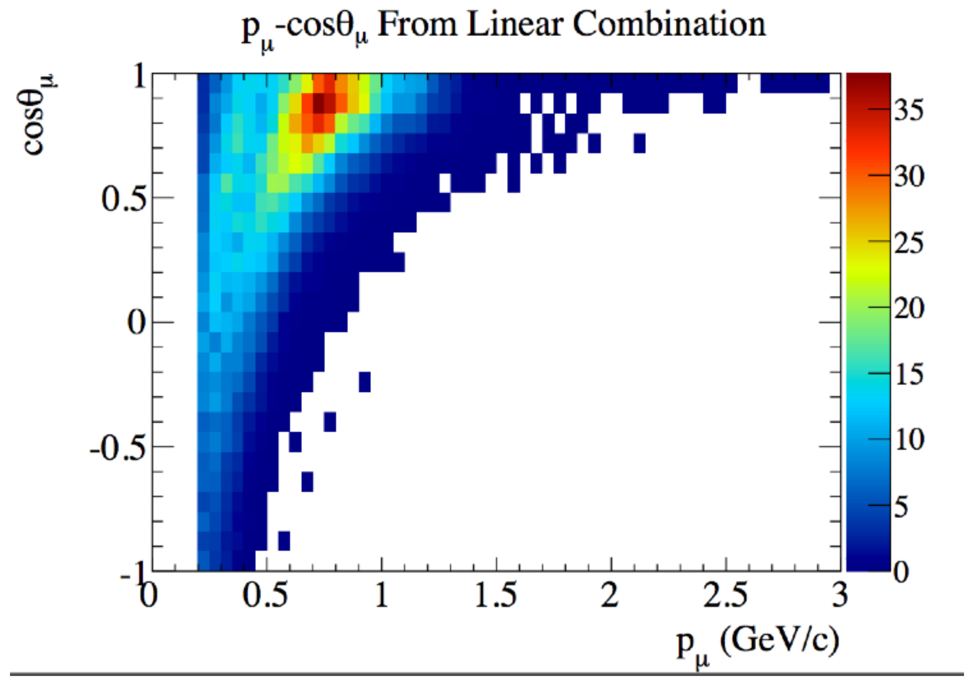
Spectra at each off-axis bin







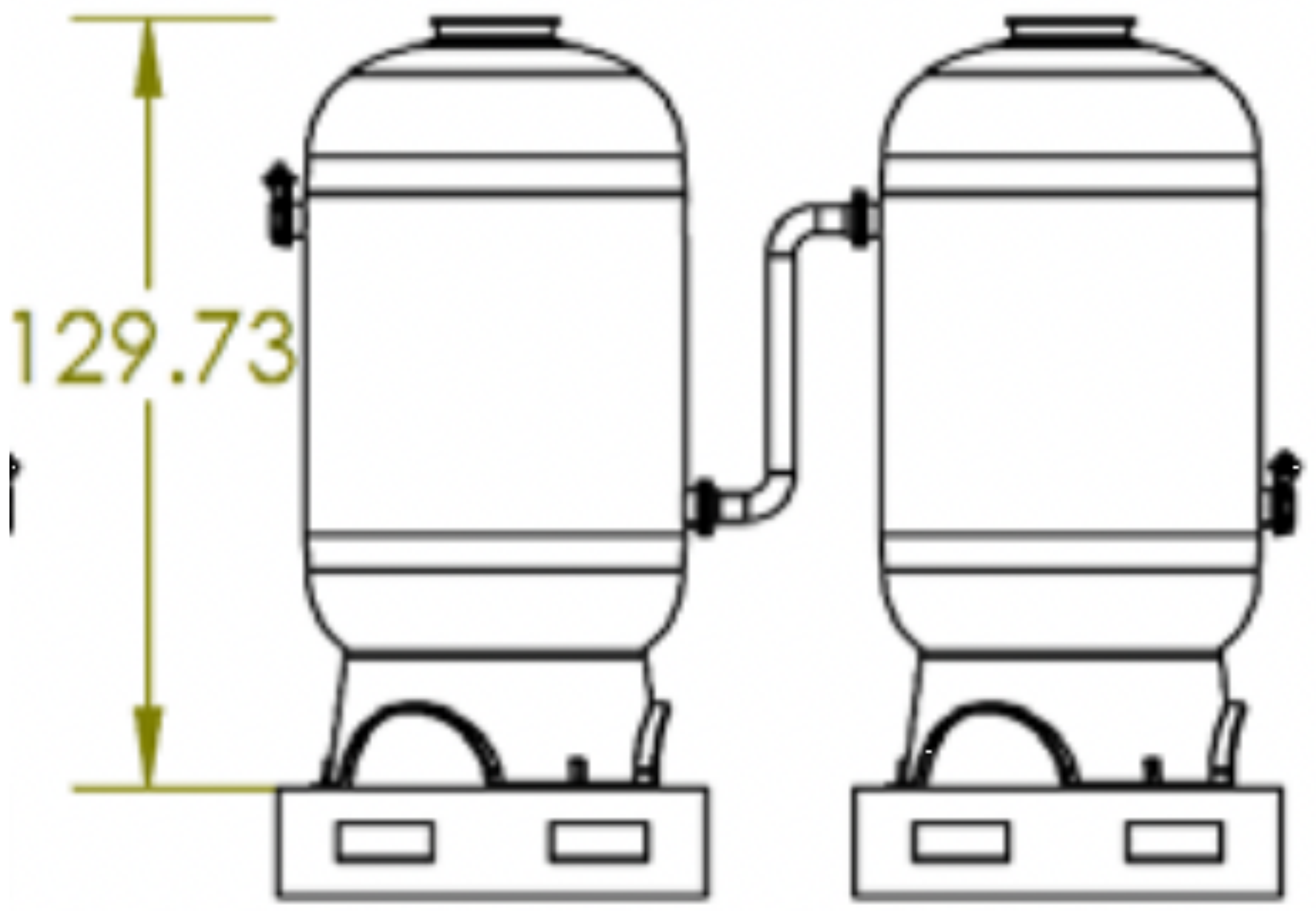
Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



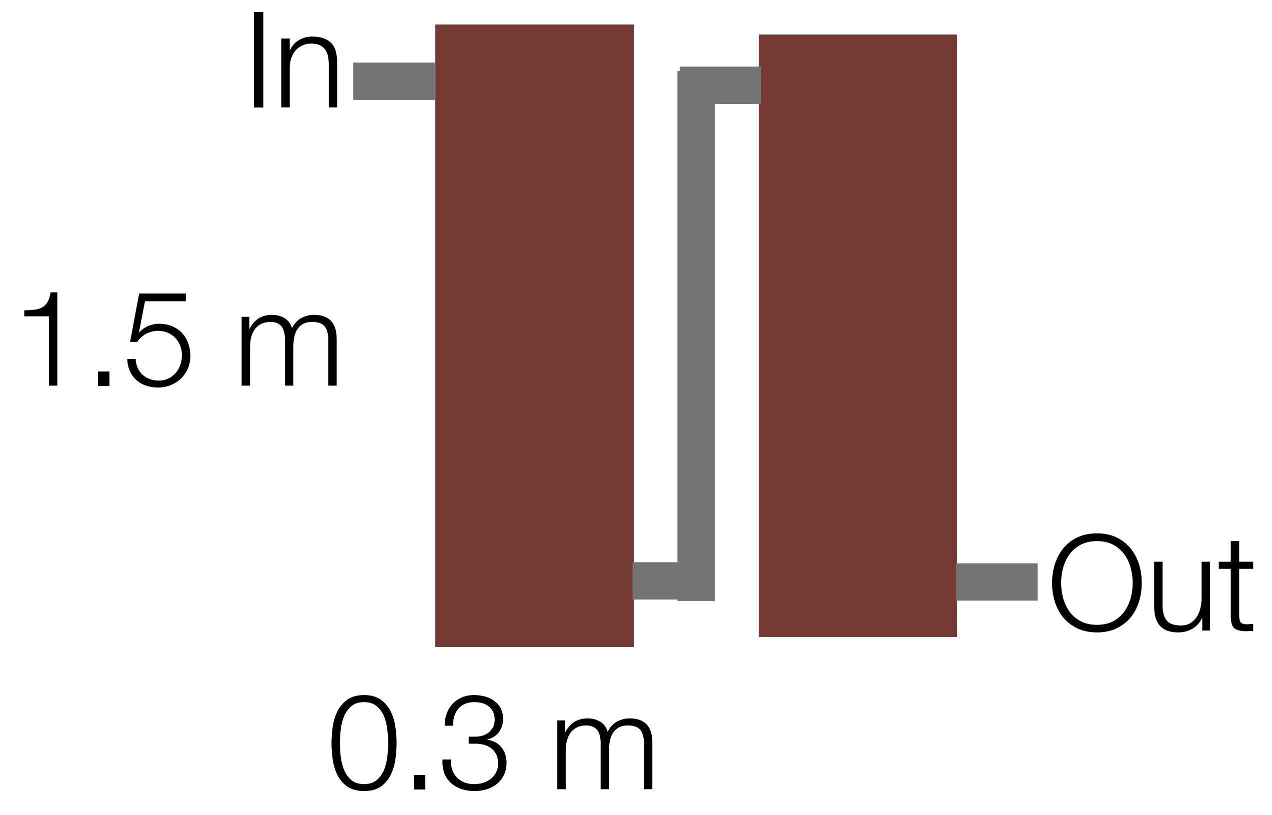
Need precise detector calibration at each position!

Gd Removal

- We use a cation exchange resin to remove the Gd from the water
- Exchanges $3Na^{+}$ for Gd^{3+}
    - Output water is 0.14% sodium sulfate by mass
- System tested for Super-K was able to remove Gd down to <0.5 ppb
- Can adapt from the Super-K design
- At Super-K, can release water with dissolved sodium sulfate into water supply



One unit from the Super-K Gd removal system



Possible WCTE configuration - 1 m^3 of resin