Proposal for the Water Cherenkov Test Experiment (WCTE)

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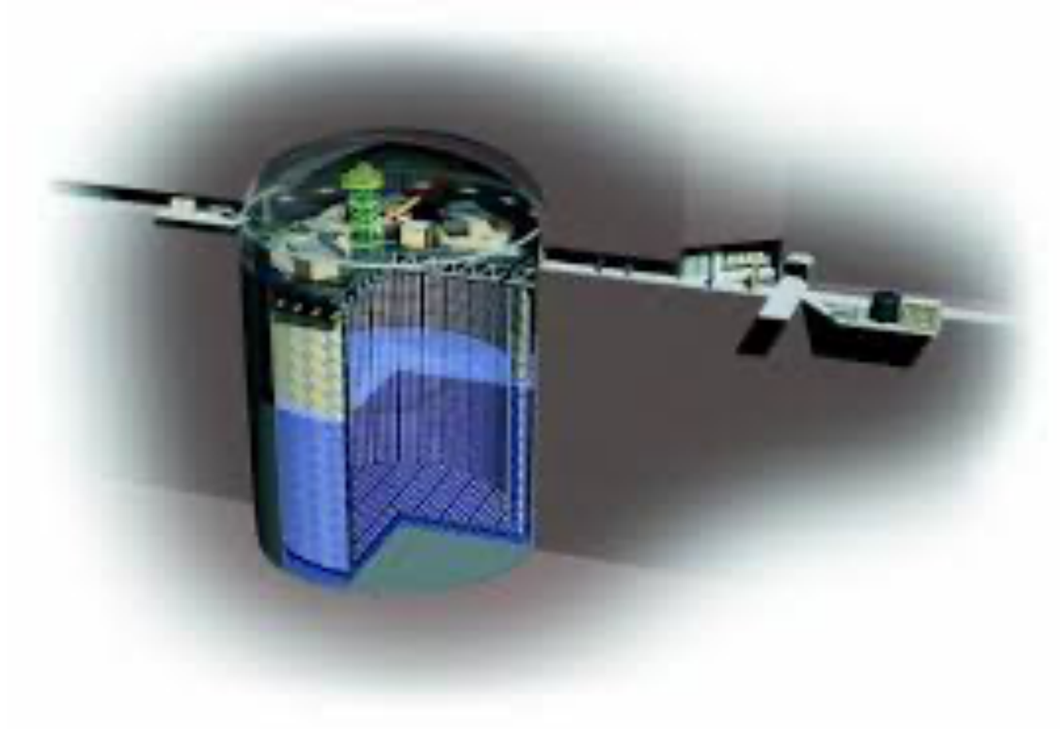
On behalf of the WCTE Collaboration

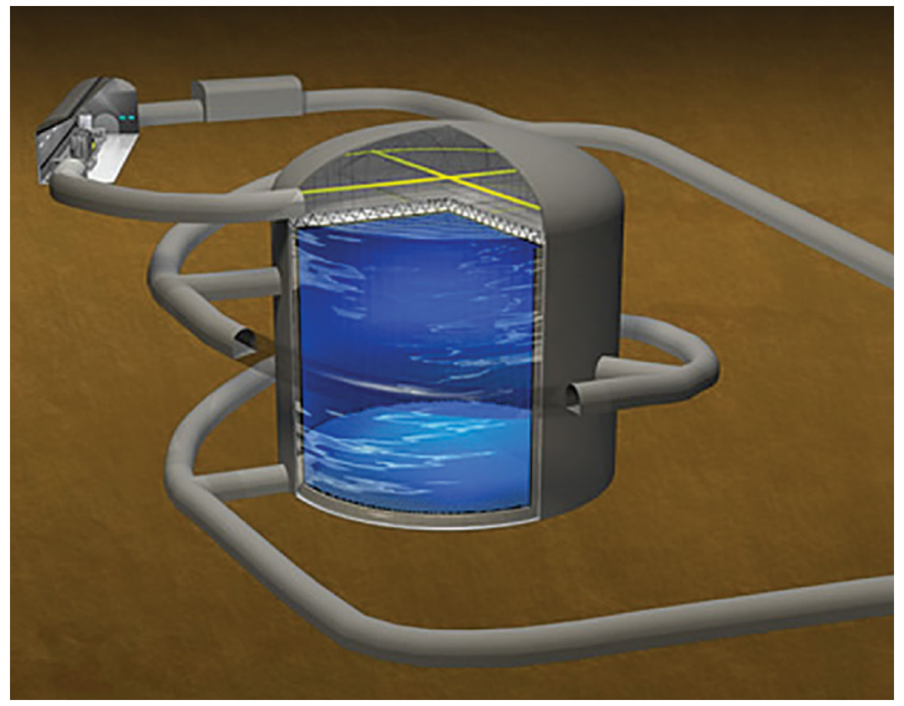
CERN SPSC Meeting - 2021/4/13

Water Cherenkov Detectors

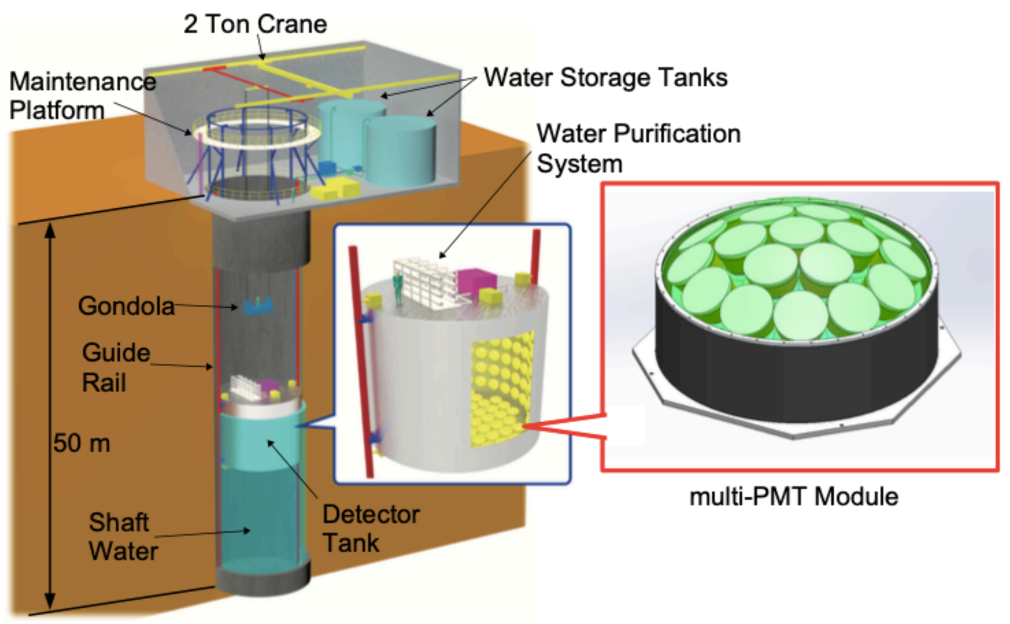
Super-Kamiokande



Hyper-Kamiokande



Intermediate Water Cherenkov Detector



ESSnuSB

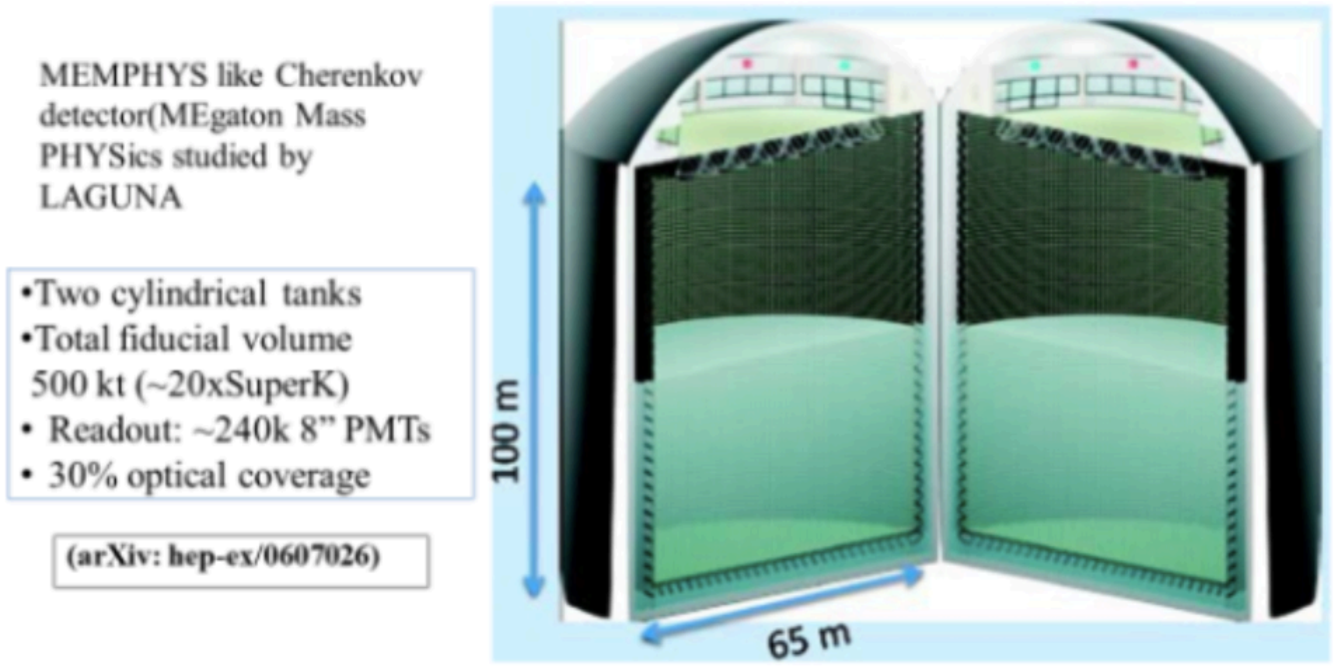
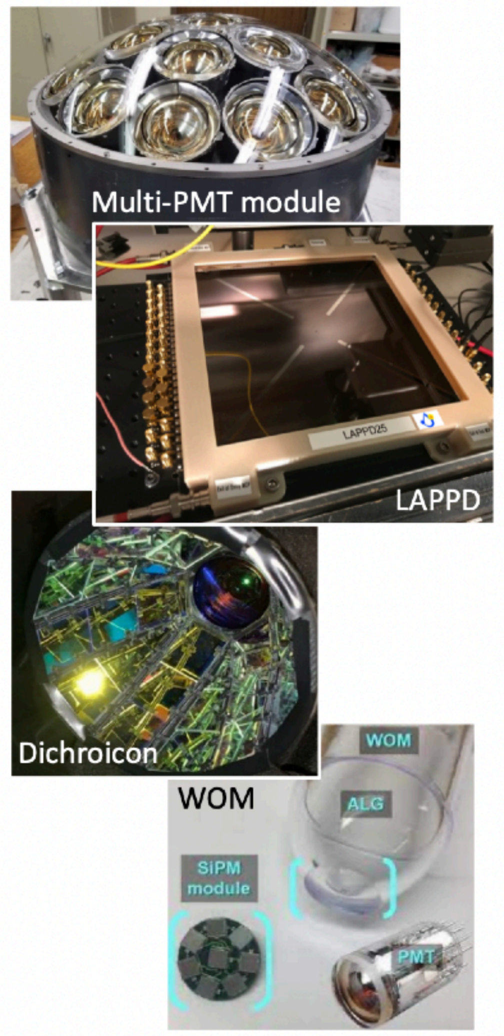


FIG. 3. Drawing of the MEMPHYS water Cherenkov detector design.

- Water Cherenkov detectors play central role in neutrino, proton decay and dark matter experiments
- Next decade will see key developments:
  - **Percent level calibration** of detectors ranging from ~1 kton to ~200 kton
  - **New photosensors** such as multi-PMTs, LAPPDs, etc.
  - **Moving detectors** in neutrino beams, such as IWCD
  - Extension of water Cherenkov technology with **$Gd_2(SO_4)_3$** doping or **water-based liquid scintillator**

R&D for Water Cherenkov Detectors

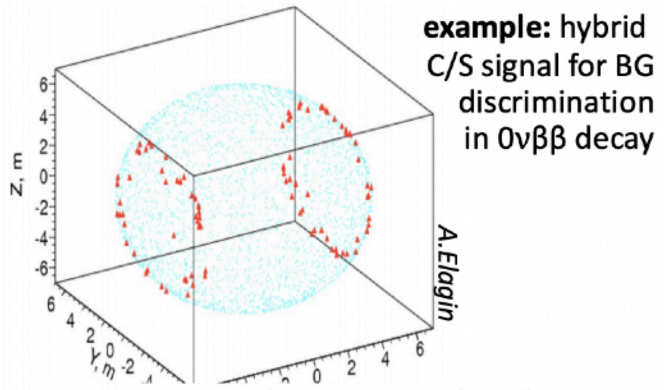
- Water and liquid scintillator detectors considered as one of the important topics for the ECFA detector R&D roadmap
- New photosensors and doping of detector media expand detection capabilities
- Take advantage of additional information with new reconstruction techniques such as machine learning
- Need a coherent R&D program to realize these developments
- A ~50 ton detector can provide a platform for testing new technologies and methods



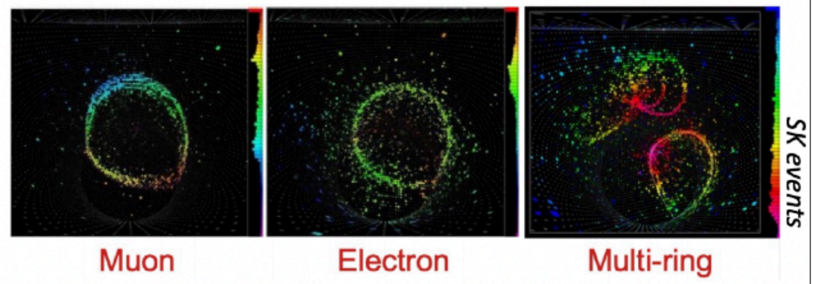
Photosensor	Features
Large-area PMTs (high-QE & MCP-PMT)	Enhanced light collection
M-DOMs, Multi-PMT modules in water	Exploit granularity for reconstruction
LAPPDs in water/WbLS	ps-timing for improved vertex reco and č/S separation
Dichroicons in WbLS	Wavelength-separation for hybrid-reconstruction
WOMs in water/LS	Large light collection area optical coupling and emission/absorption spectra
SiPMs in LS	High QE/granularity but cooling for dark noise

+ enhanced light collection:
mirrors/cones, (active) light guides, fibres, metalenses …

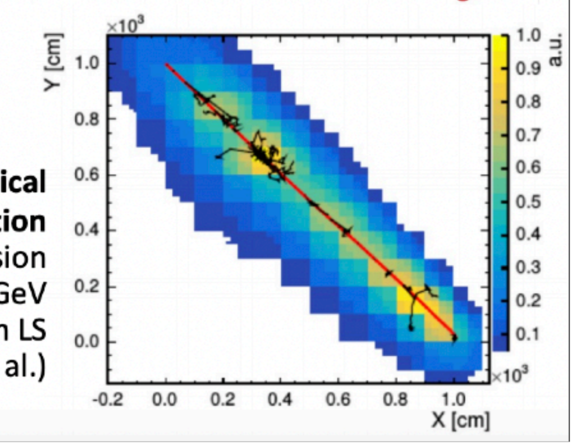
Challenges
- resolving complicated topologies
  - GeV energies: multi-π/NC events
  - MeV range: 2-track events for 0νββ
- reconstruction of hybrid signals (Cherenkov+scintillation)
- large amounts of high-resolution or wavelength-dependent data



ring topologies vs. machine learning



Approaches
- "standard" likelihood methods
- machine-learning techniques
- topological reconstruction



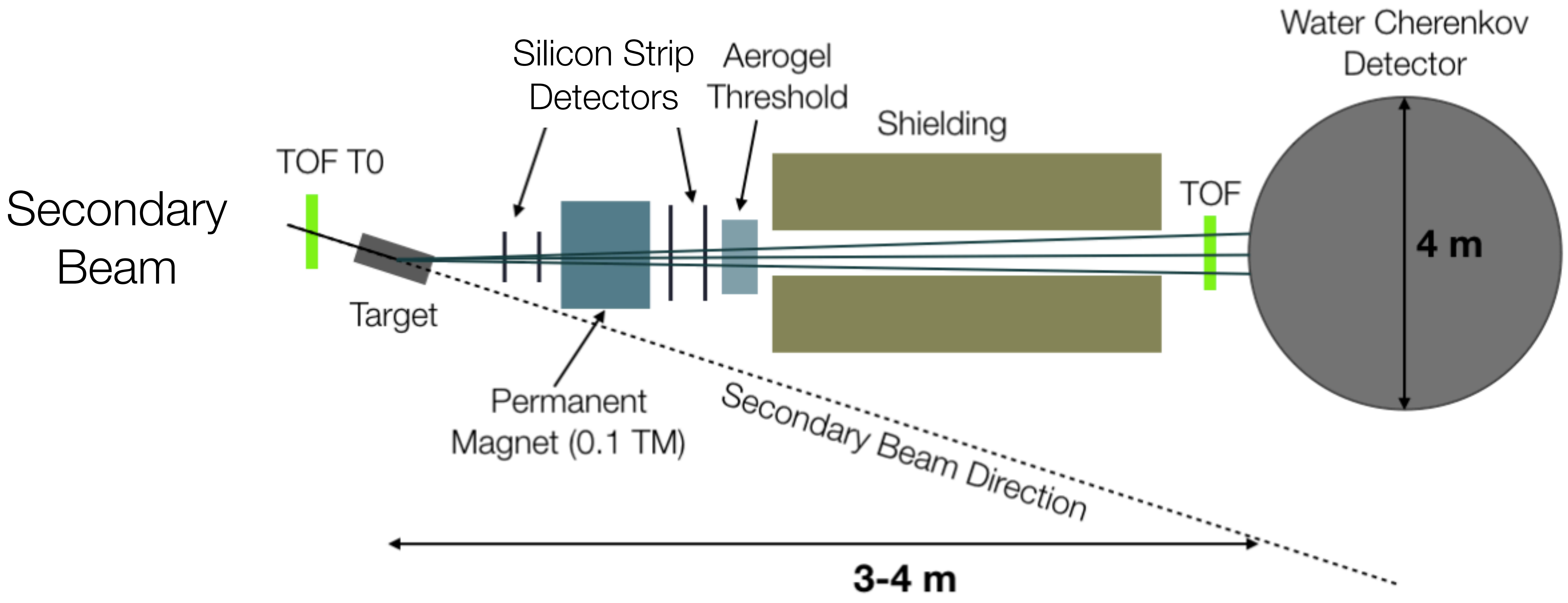
topological reconstruction of light emission along a 3-GeV muon track in LS (Wonsak et al.)

Michael Wurm (Mainz) LS & Water

ECFA Detector R&D Roadmap Symposium of Task Force 2 Liquid Detectors, M. Wurm: https://indico.cern.ch/event/999815/contributions/4260253/attachments/2223214/3765119/wurm_wls_ecfa_apr21.pdf

Proposed Water Cherenkov Test Experiment (WCTE)

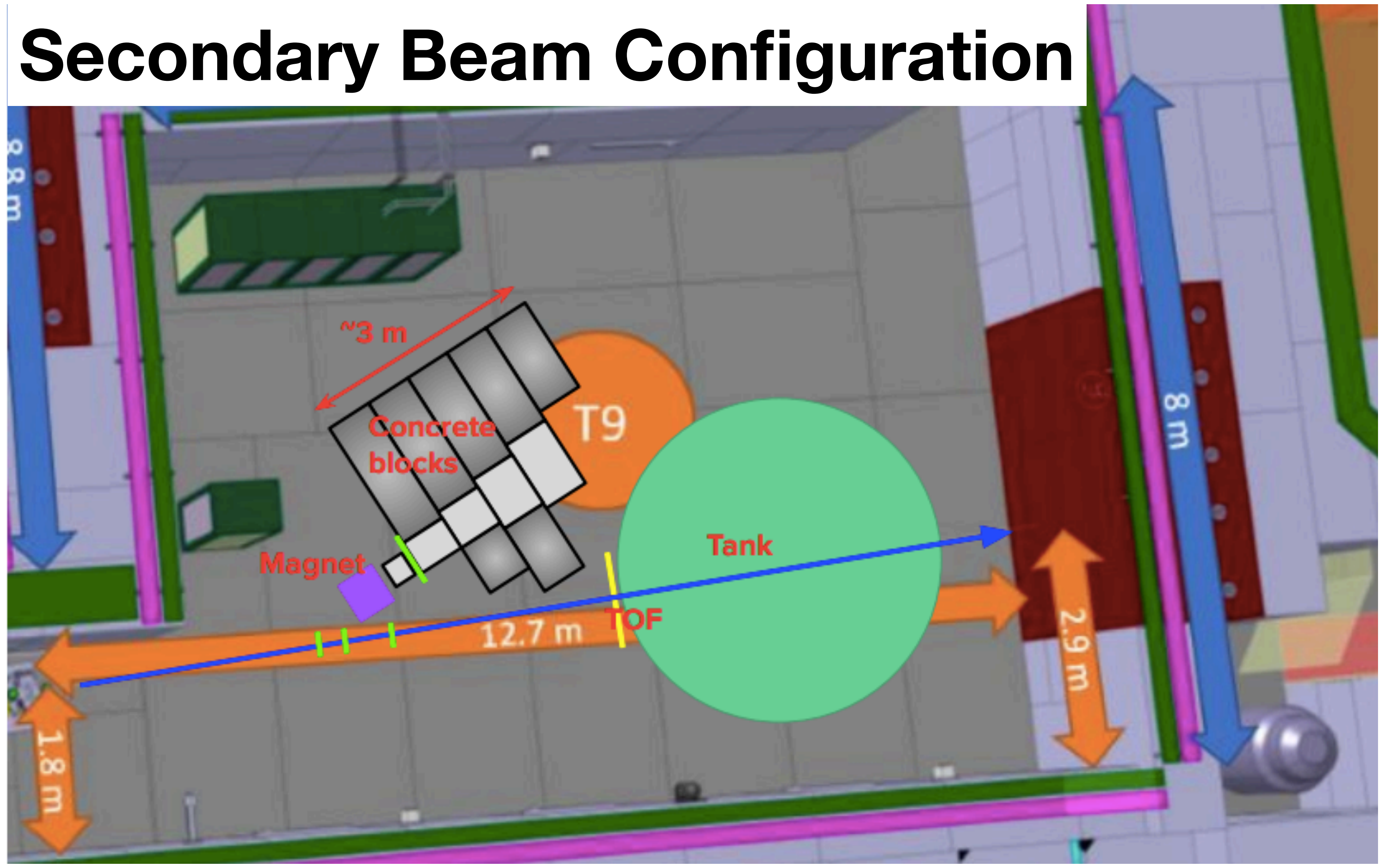
- Propose a prototype water Cherenkov detector to operate in the T9 beam line in the East Area
- Study particles directly from secondary beam and with tertiary production configuration
- We propose a test experiment that is ~4 m diameter x 4 m tall
- **Particle fluxes of $\pi^{\pm}$, p, μ, e in the 300 MeV/c-1200 MeV/c range**



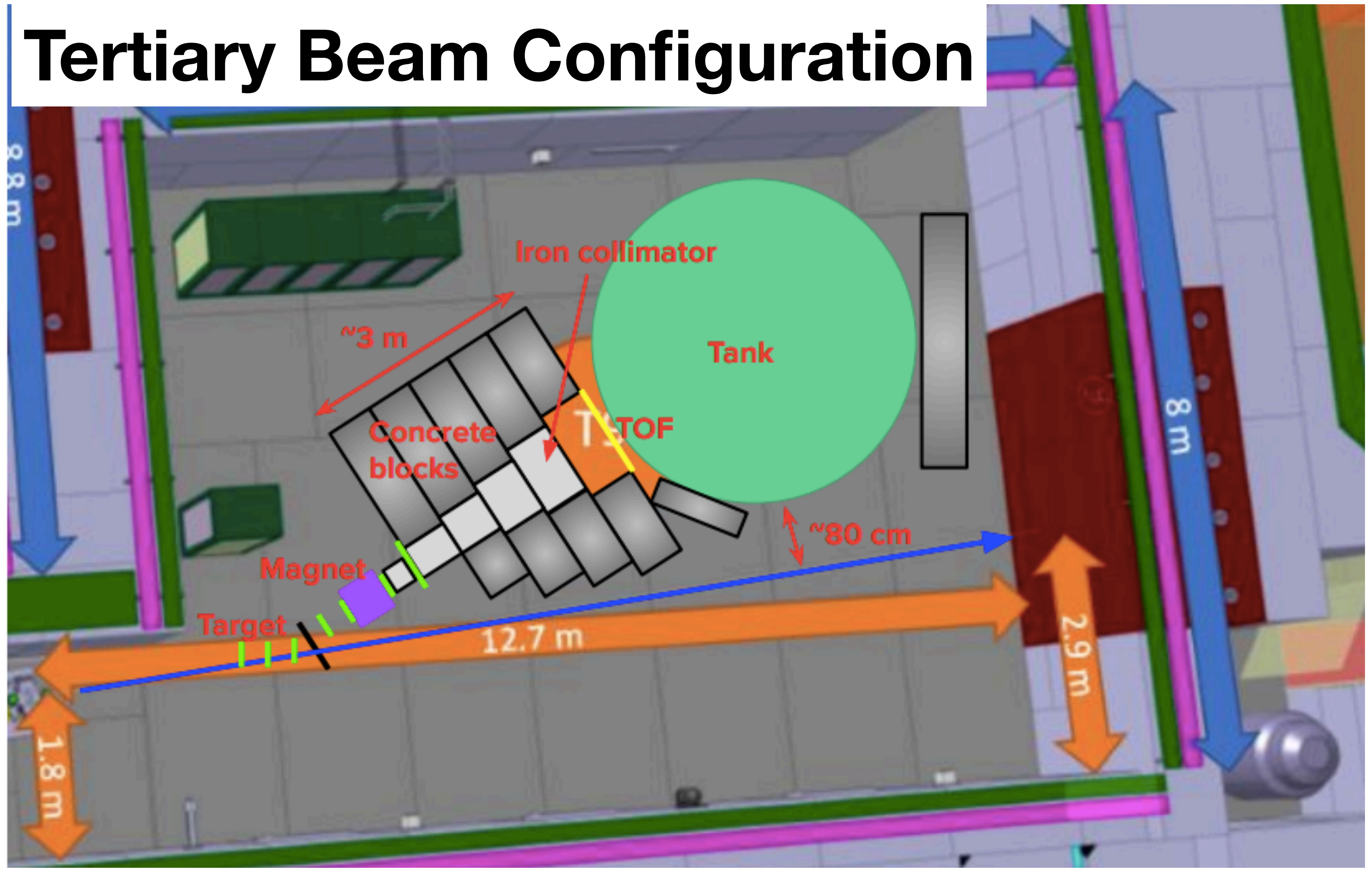
CERN-SPSC-2020-005; SPSC-P-365: http://cds.cern.ch/record/2712416?ln=en

Experimental Configurations

- We plan to operate in secondary and tertiary beam configurations:



Electron, muon and proton fluxes

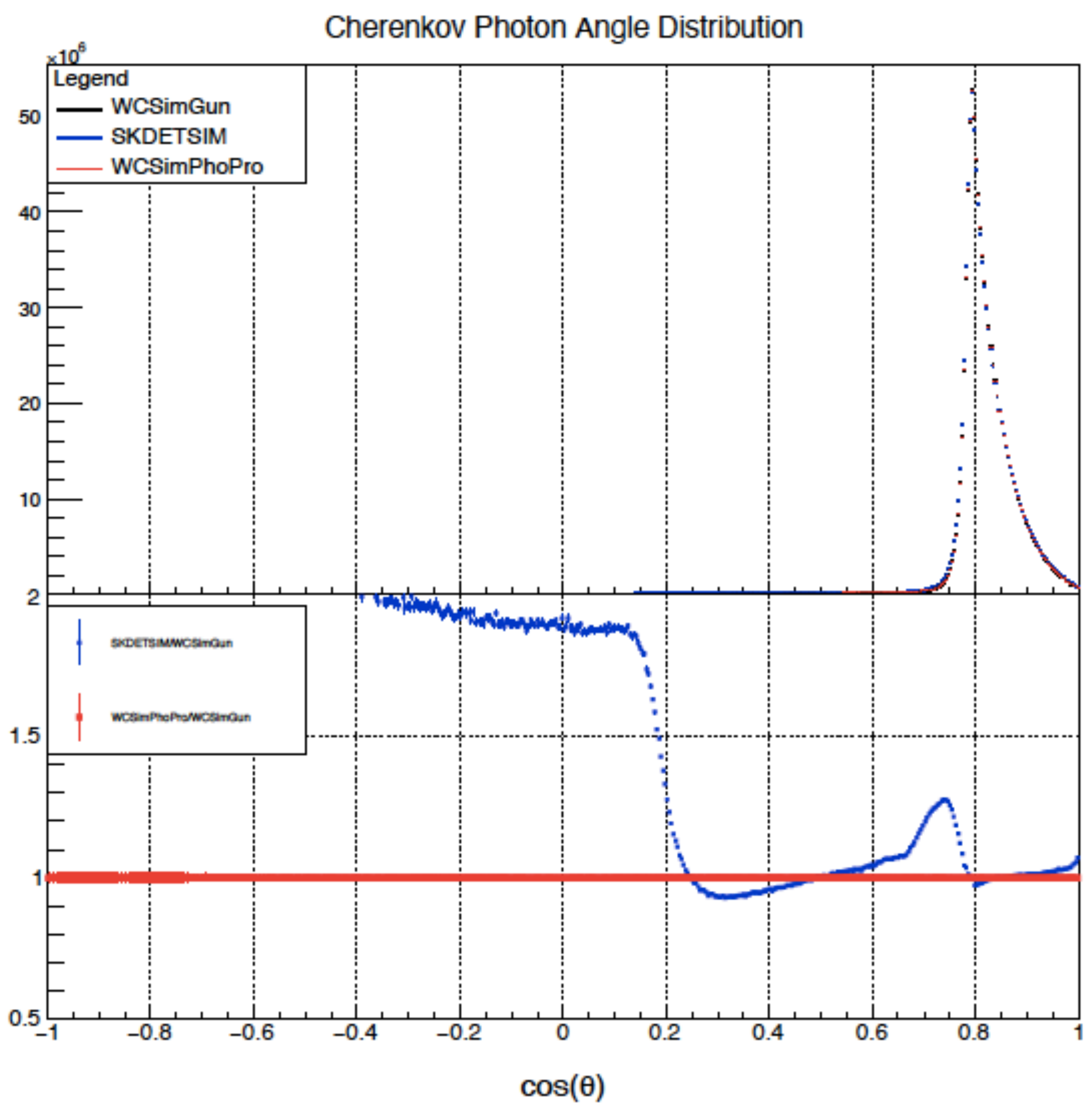


Low momentum pion and proton fluxes

- 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

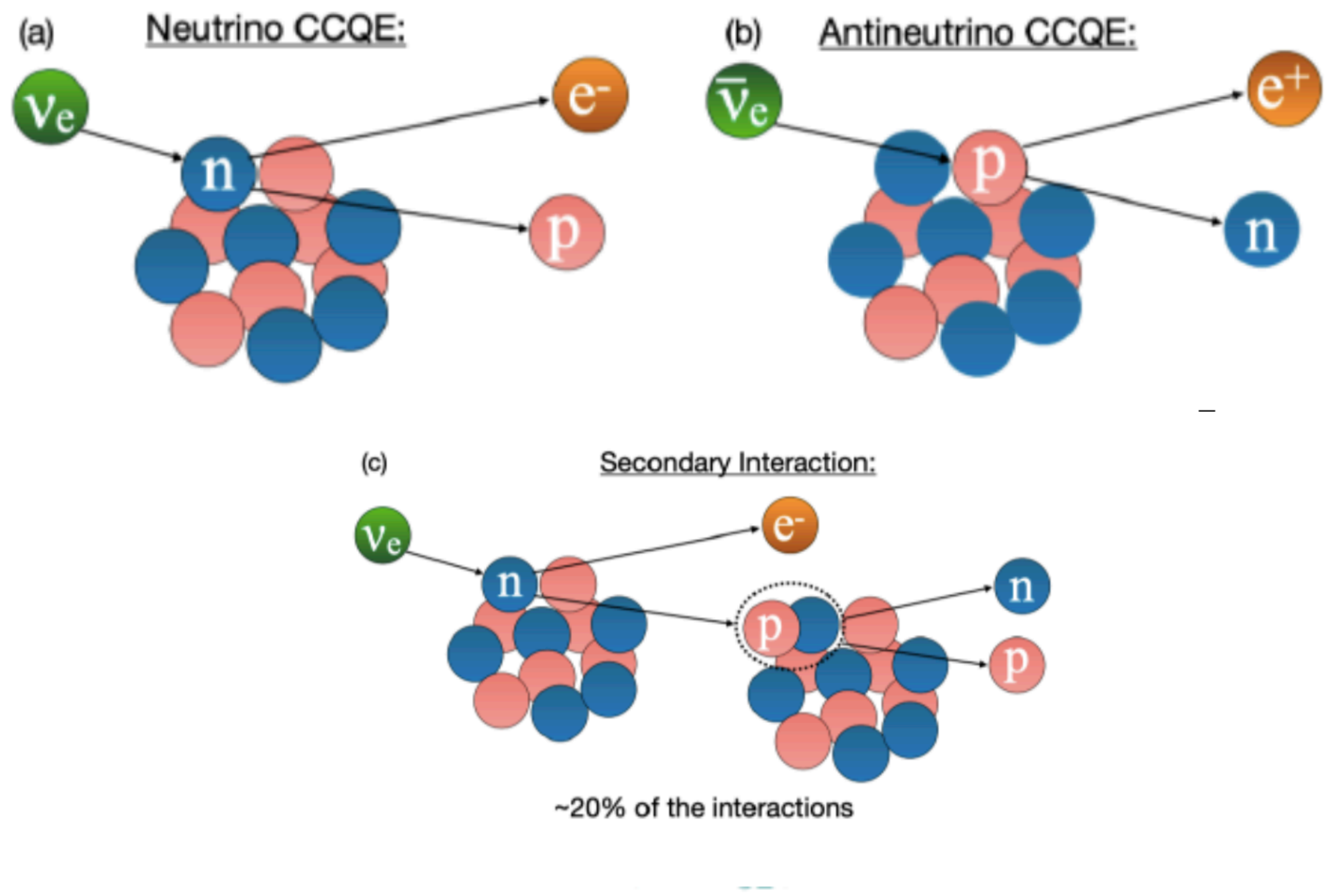
- **Measurement of Cherenkov light production**
  - Currently used simulations are not consistent
  - Introduces systematic errors in event reconstruction
  - Can be measured with well characterized beam in WCTE



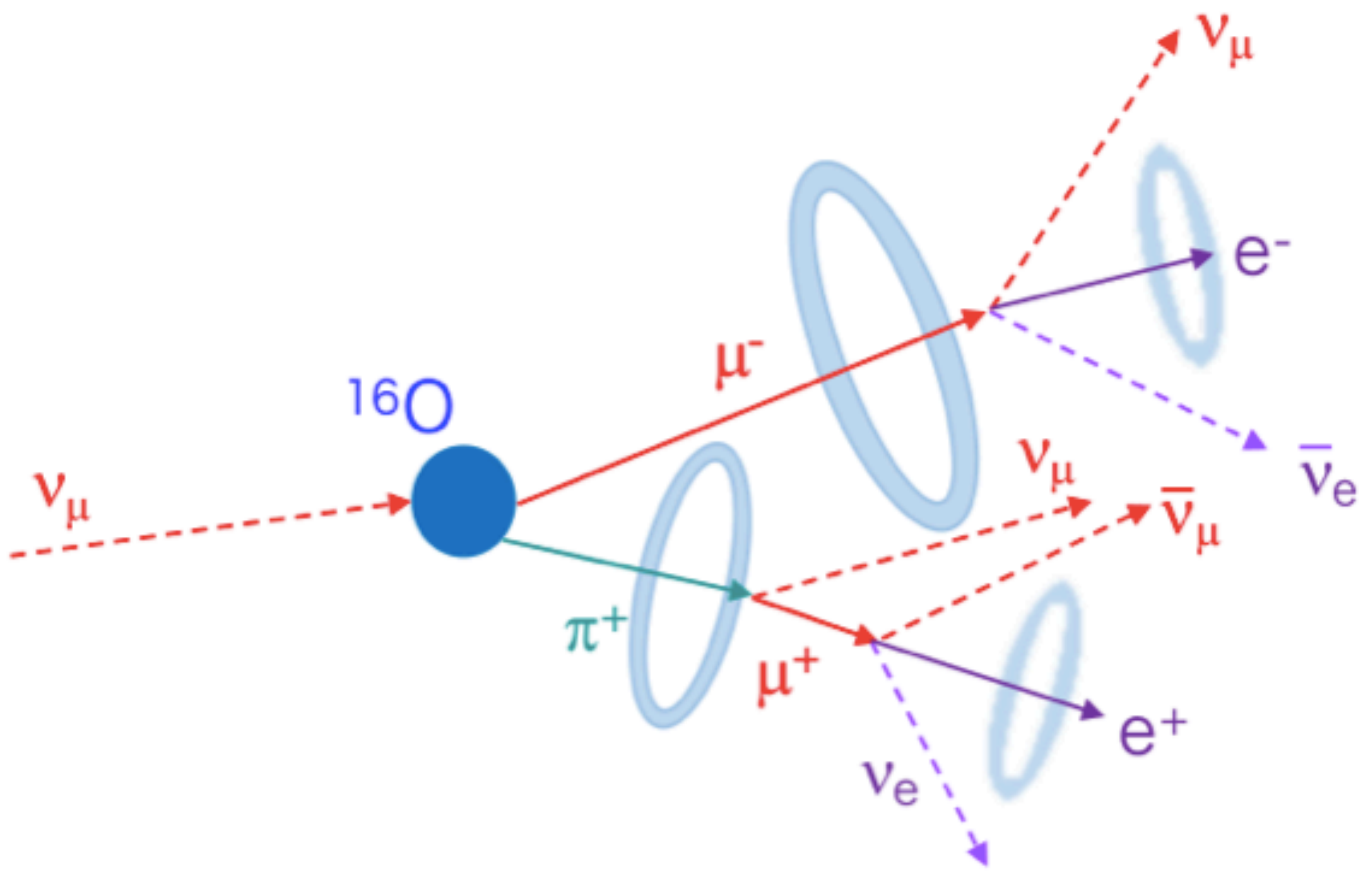
- **Study of energy scale calibration**
  - Muons crossing detectors used in Super-K to set energy scale
  - Systematic uncertainty of 2% needs to be reduced to 0.5% for Hyper-K
  - Can be studied with crossing muons of known energy in WCTE

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

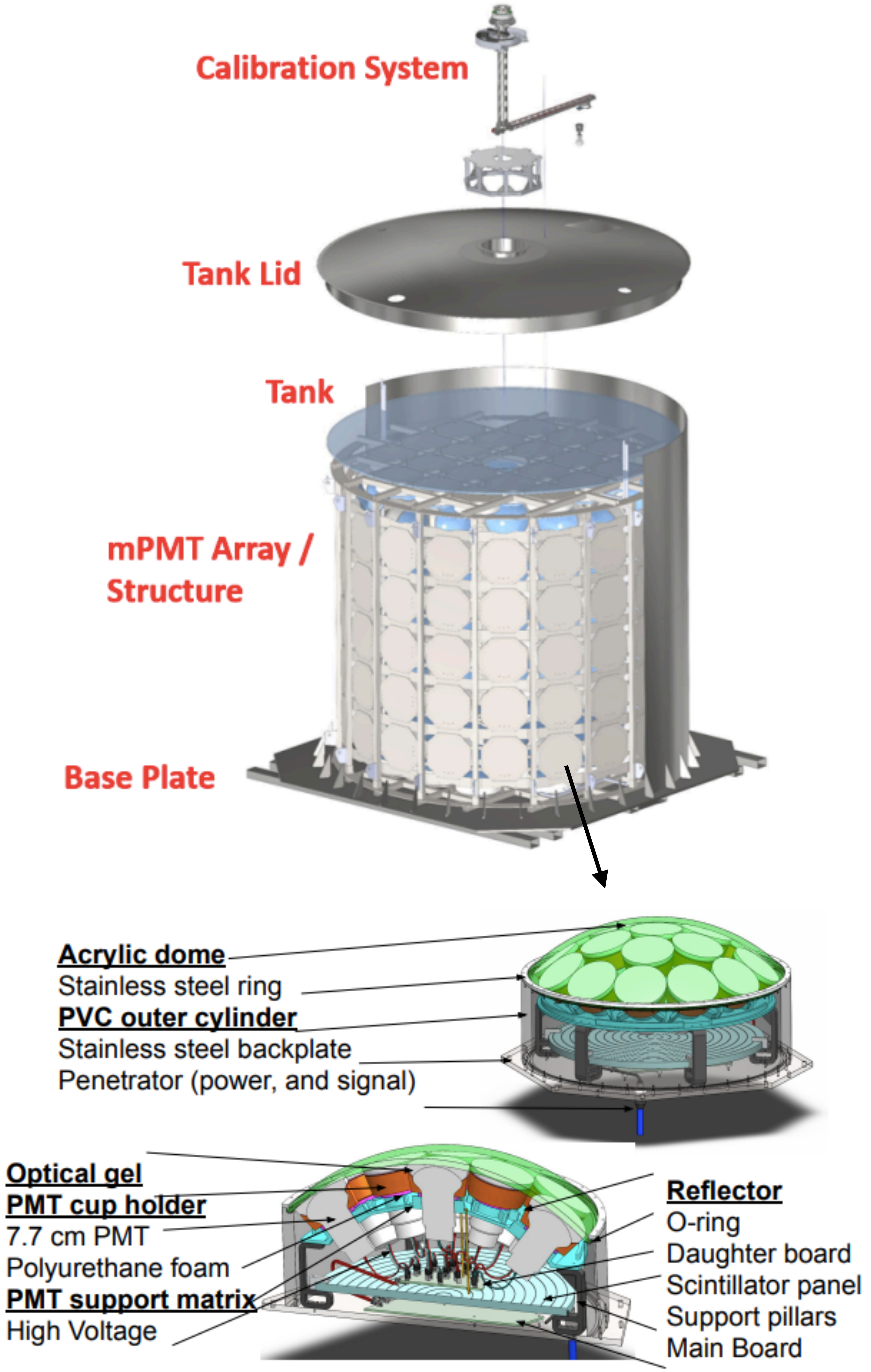


- **Study of pion scattering**
  - T2K, Super-K and Hyper-K are using samples with pions in the final state
  - Reconstruction is challenging due to modeling of hadronic scattering with limited data on oxygen
  - Can directly measure water Cherenkov detector response to pions in WCTE



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



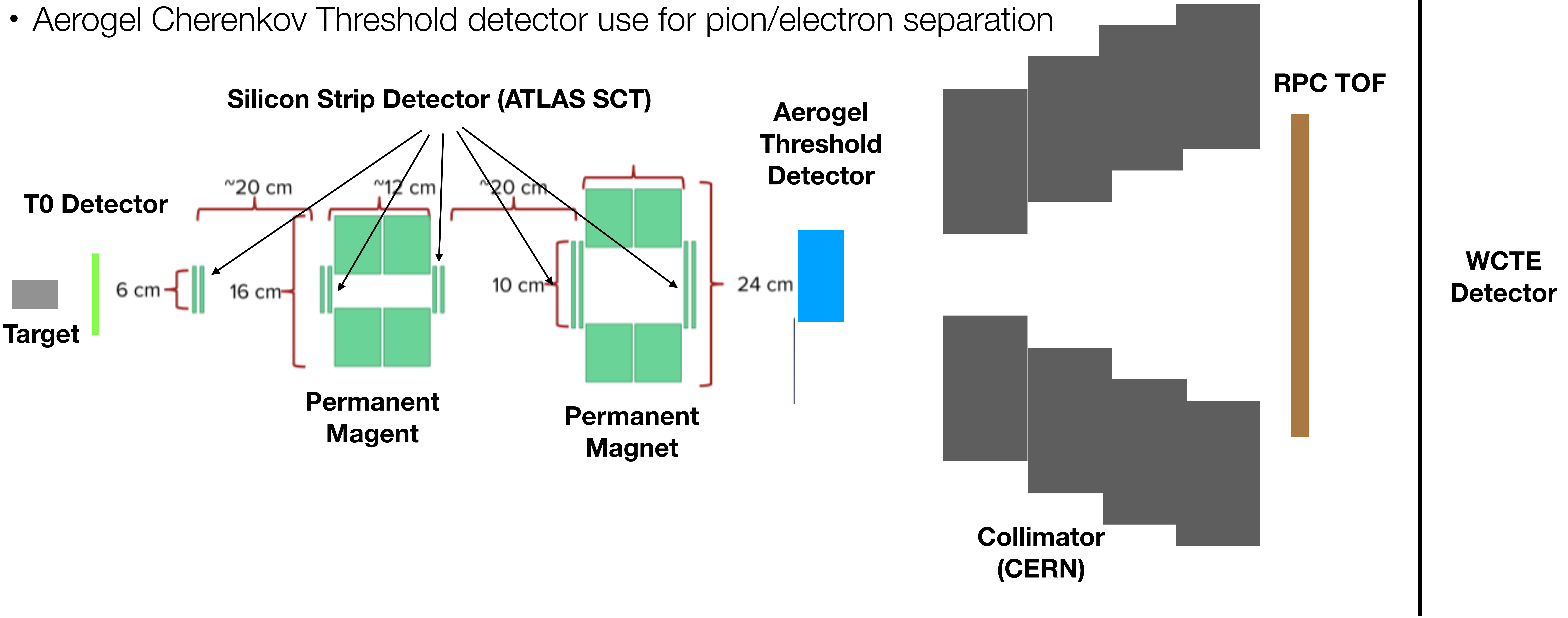
Water System

- Use standard commercial water purification system
- 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
- Consultation with EP-Safety group who will reach out to HSE about sodium sulfate solution disposal started

Commercial water system (Organo FP-2000)

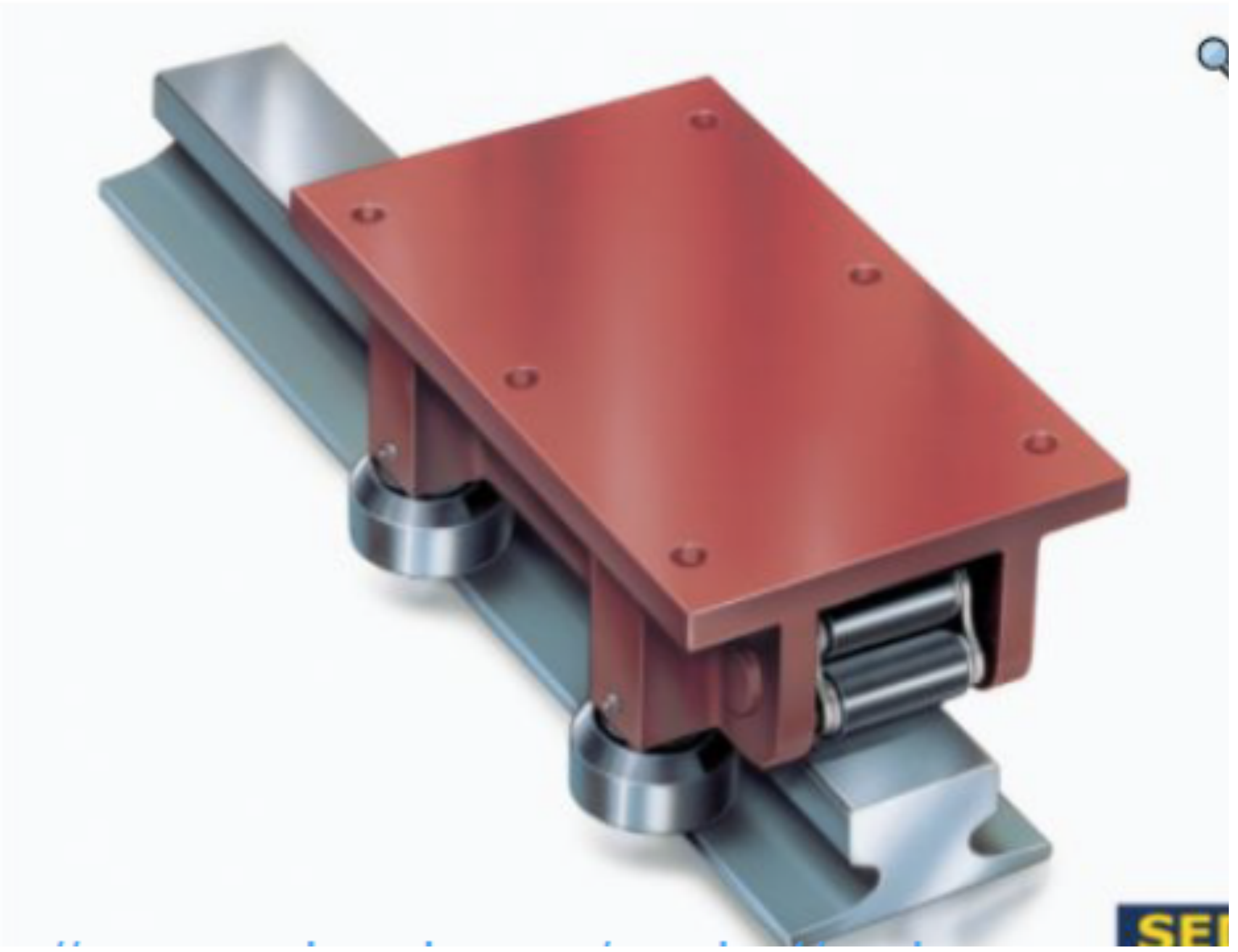
WCTE Beam Line Components

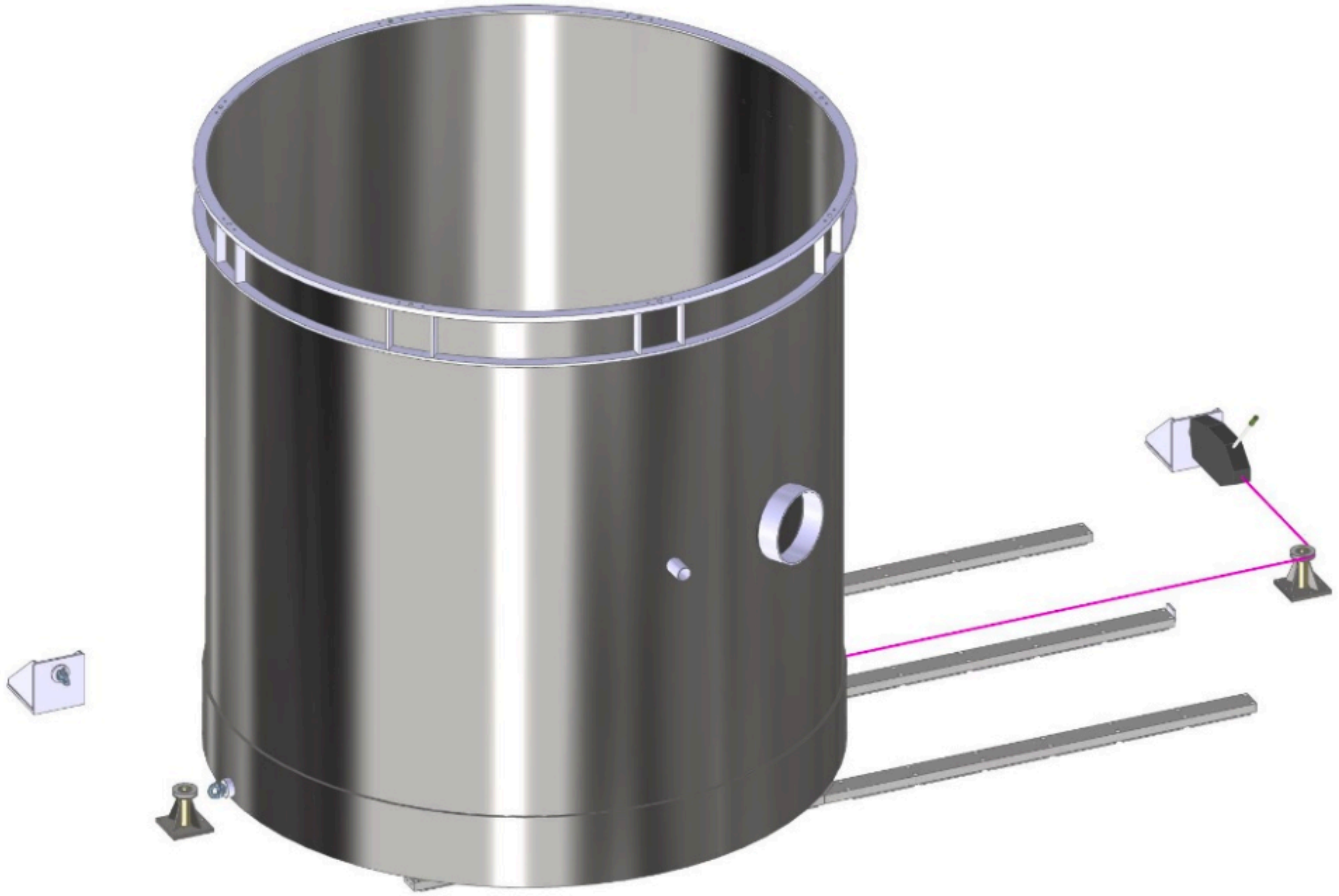
- WCTE includes tertiary production target, spectrometer and particle ID detectors
- Spectrometer: silicon strip detector for tracking and Halbach array permanent magnets
- Resistive Plate Chamber (RPC) used for time-of-flight based PID
- Aerogel Cherenkov Threshold detector use for pion/electron separation

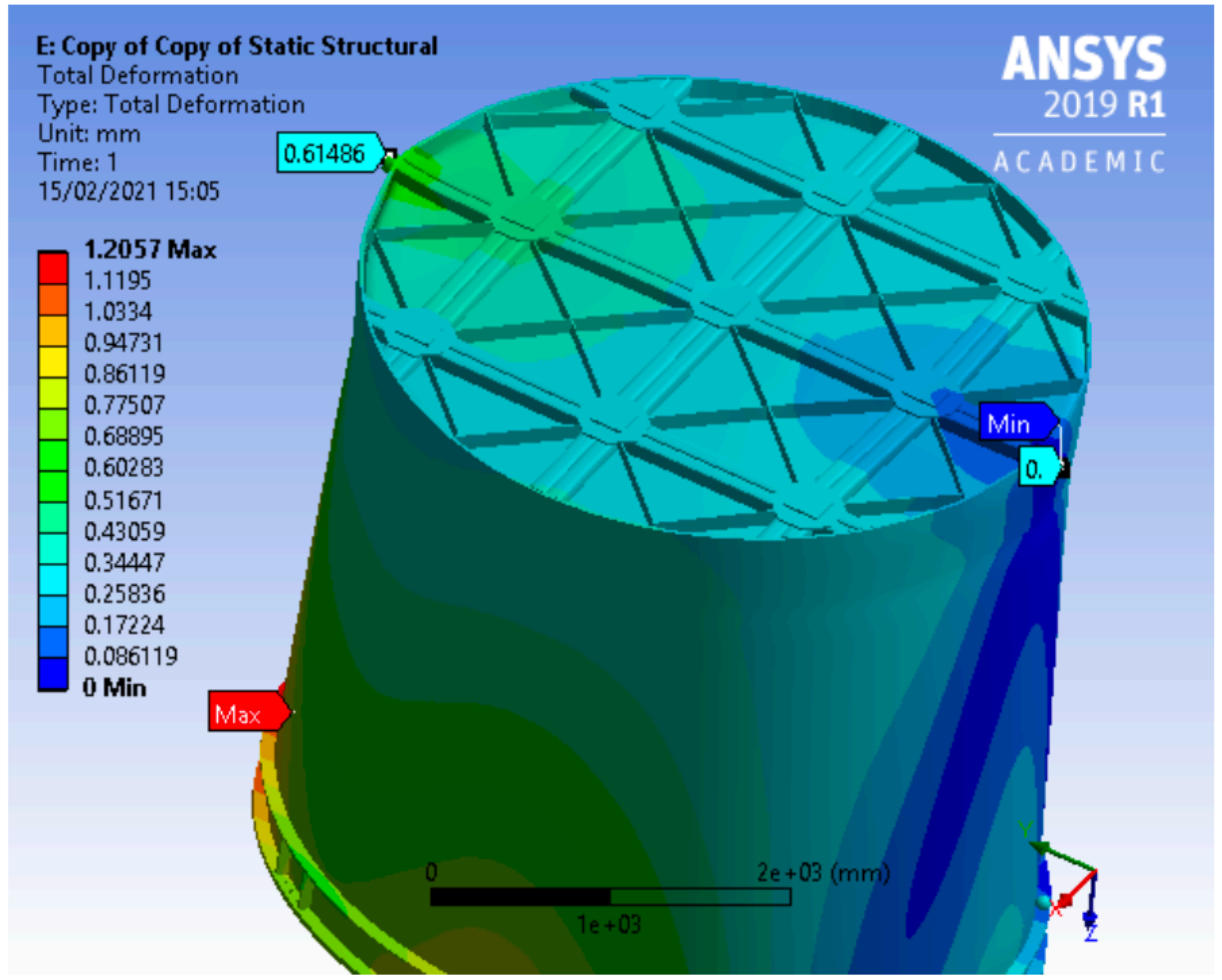


Detector Moving

- We plan to move the detector between tertiary and secondary beam configurations
- Preliminary design in prepared with help from 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







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

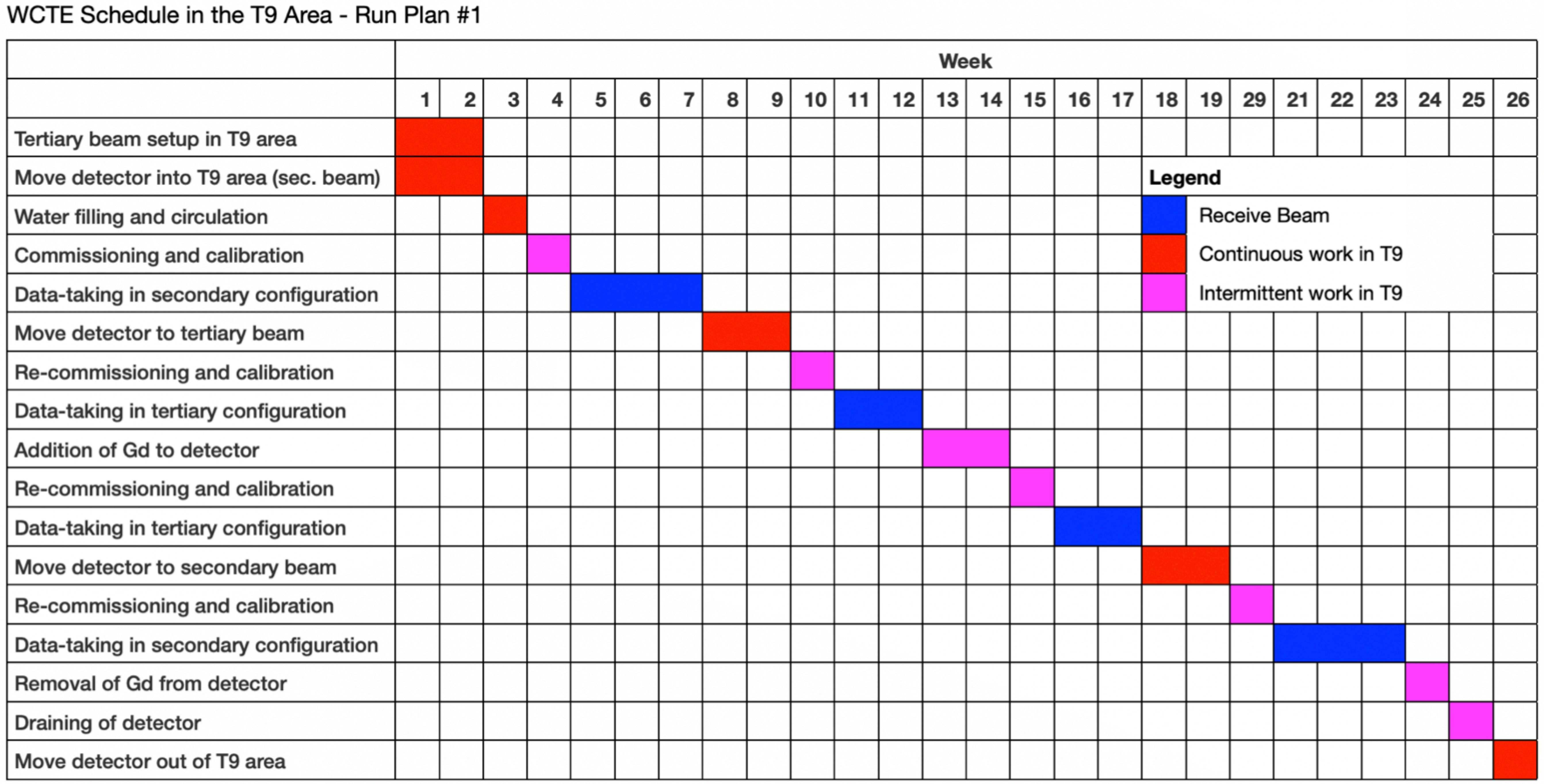
Run Plan Options

- We consider three scenarios for the WCTE Run Plan
- Run in **all four combinations of secondary/tertiary beam and pure/Gd loaded water**
  - 26 weeks in T9 beam area
  - Best understanding of detector response
- **Only take pure water data in the secondary beam configuration**, remove pure water operation in tertiary beam
  - Reduce to 20 weeks in T9 area
  - Pure water data establishes baseline for detector performance
- **Only take data with Gd loaded water in the T9 beam area**
  - Reduce to 16 weeks in T9 area
  - Cosmics data with pure water could be possible in the assembly area, otherwise no pure water baseline
  - No pure-water operation in experimental area introduces risk:
    - Ideally establish safe operation before adding Gd
    - Best to establish pure water operation of detector as baseline

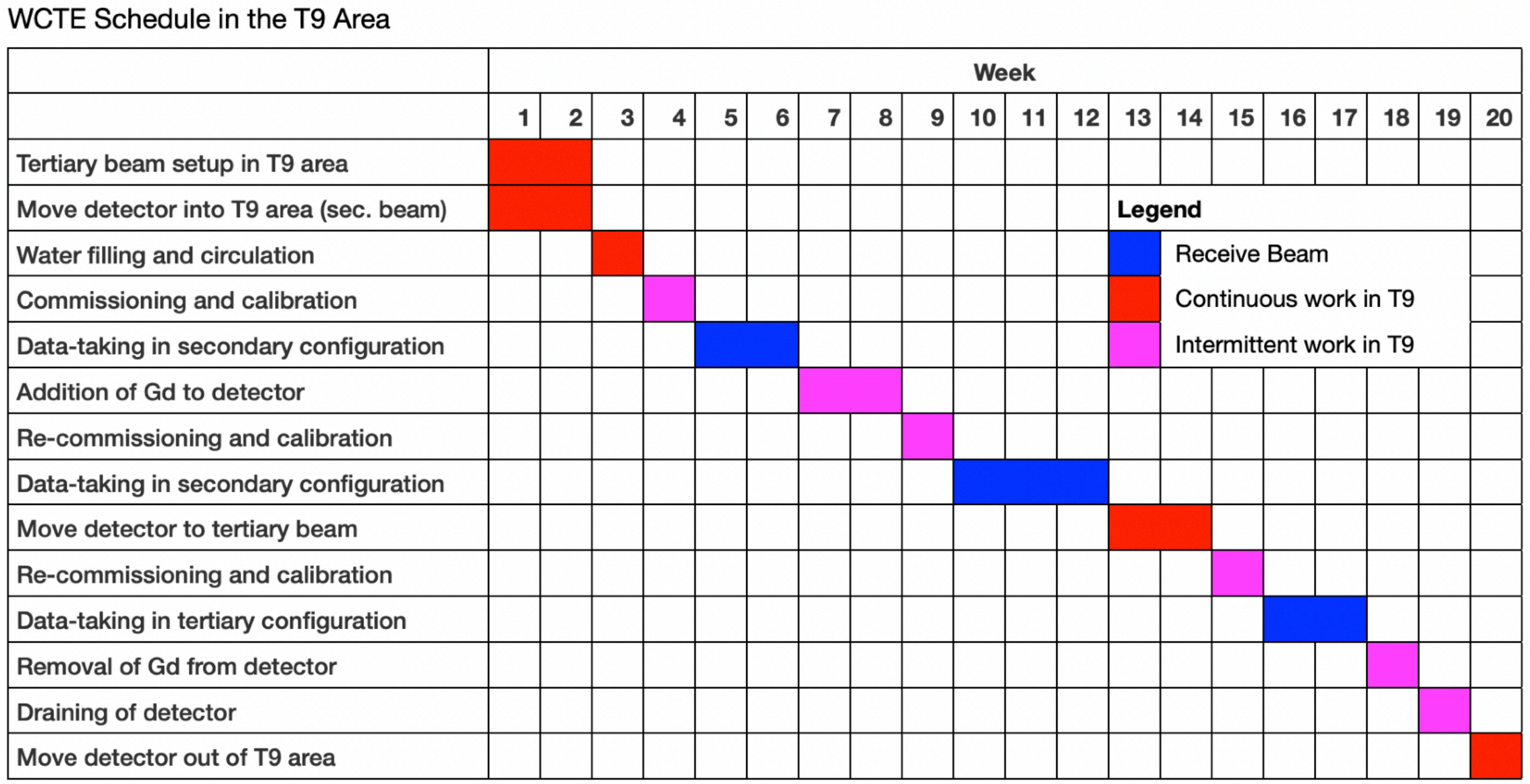
Run Plan Options 1 & 2

- Option 1 includes operation in all four configurations
- Option 2 reduces time in T9 area from 26-20 weeks by removing pure water run with tertiary beam

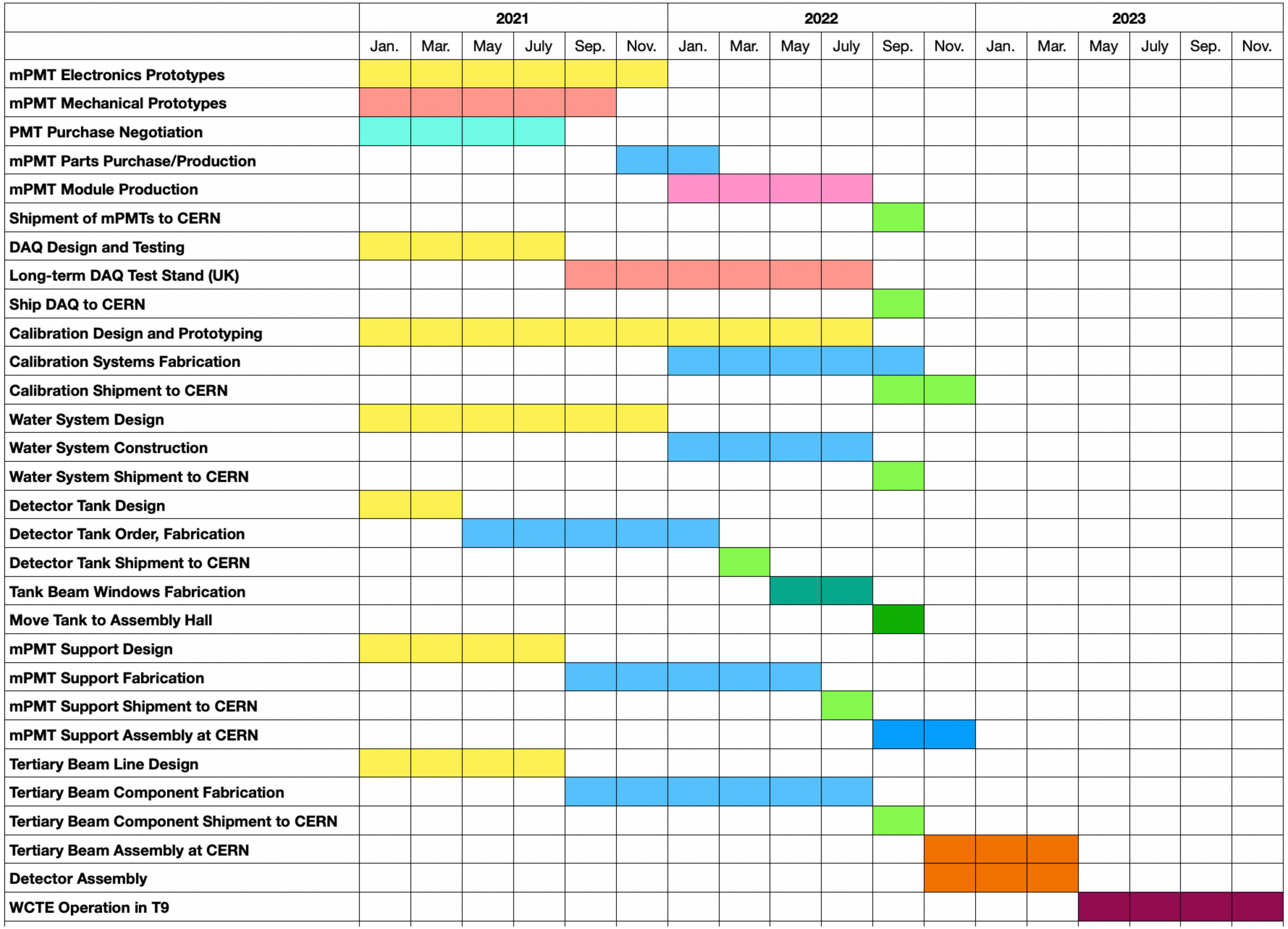
All combinations of beam and water configurations



Pure water configuration only in secondary beam configuration



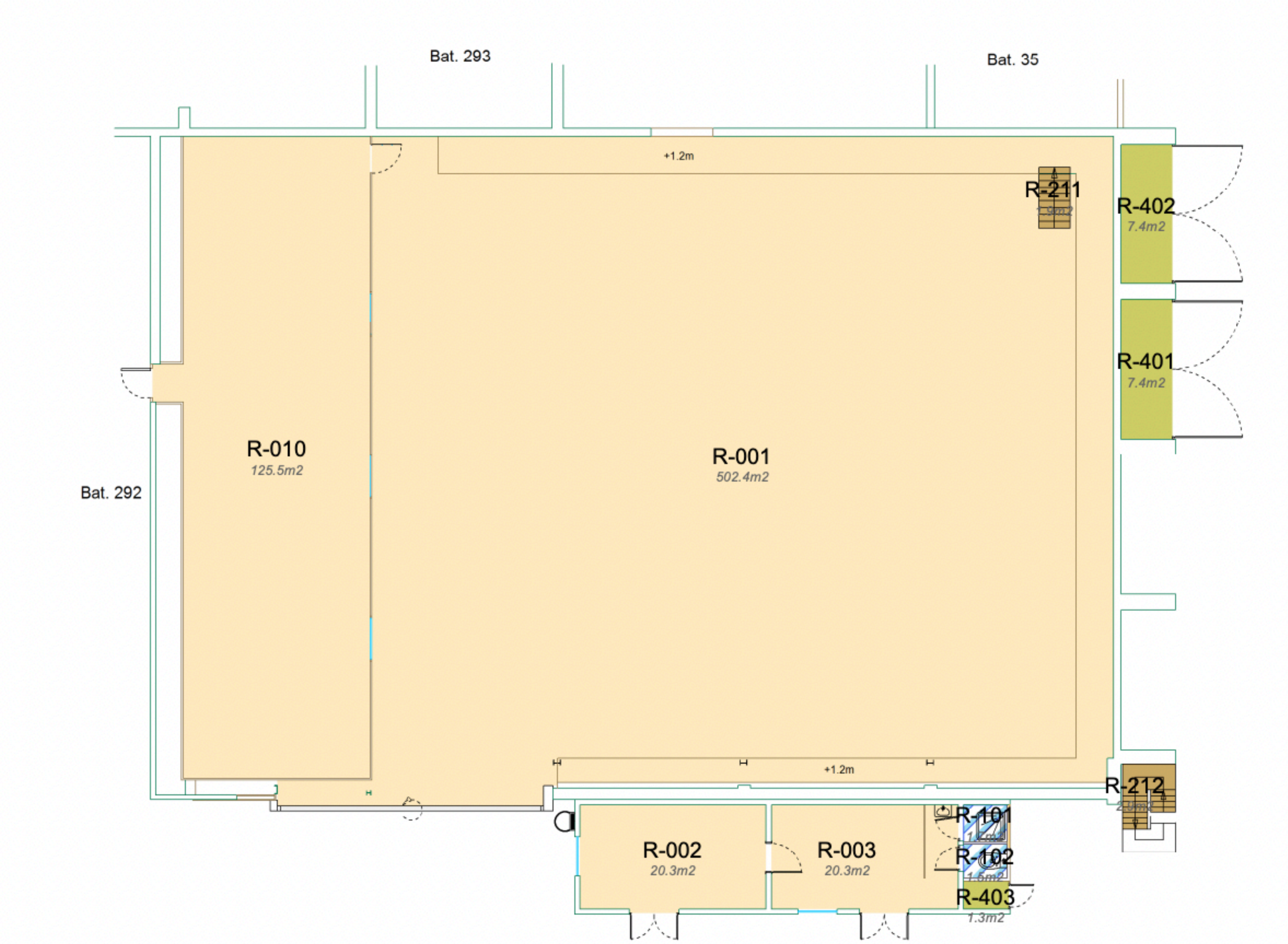
Schedule



- Start of assembly in Nov. 2022
- Start of operation in May 2023
- Schedule assumes approval around April 2021
  - Delay of approval will delay overall schedule by similar amount of time

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



Additional Requests to CERN

- Foreman from Neutrino Platform during detector assembly
- Crane operators during the detector assembly and installation
- Lifting beam for lifting the support structure and tank

- Moving of the detector from the assembly area to T9 experimental area
- 50 tons of deionized water for initial tank filling
- Shielding blocks and installation for the tertiary beam collimator
- Roller-based detector moving system and its installation and operation
- Purchasing department support for tank purchase
- Fabrication of tank windows and flanges for beam windows

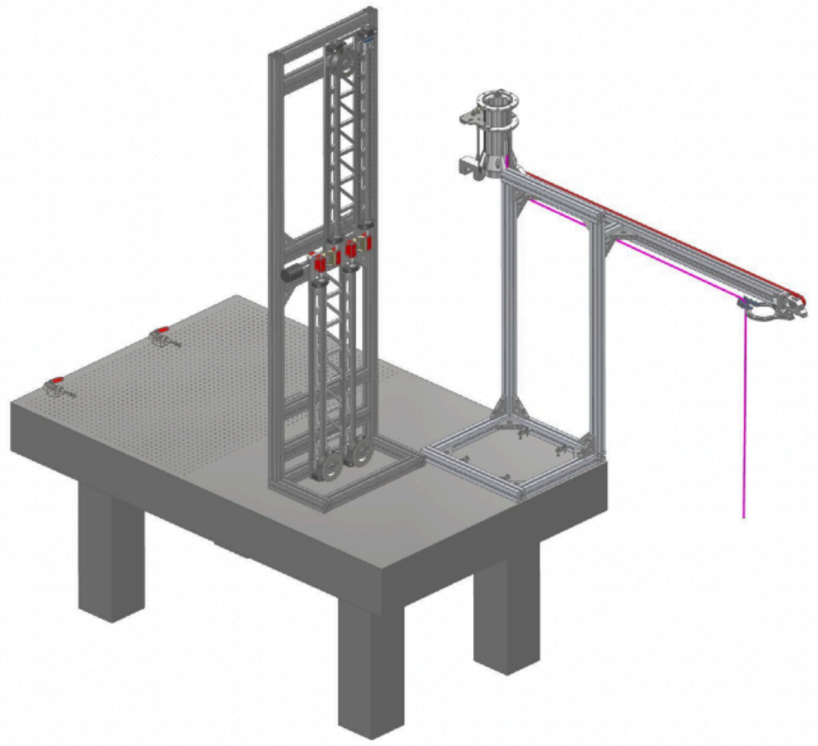
- Administrative support for shipping of parts
- Office space during construction and operation

Collaboration/Experiment Progress

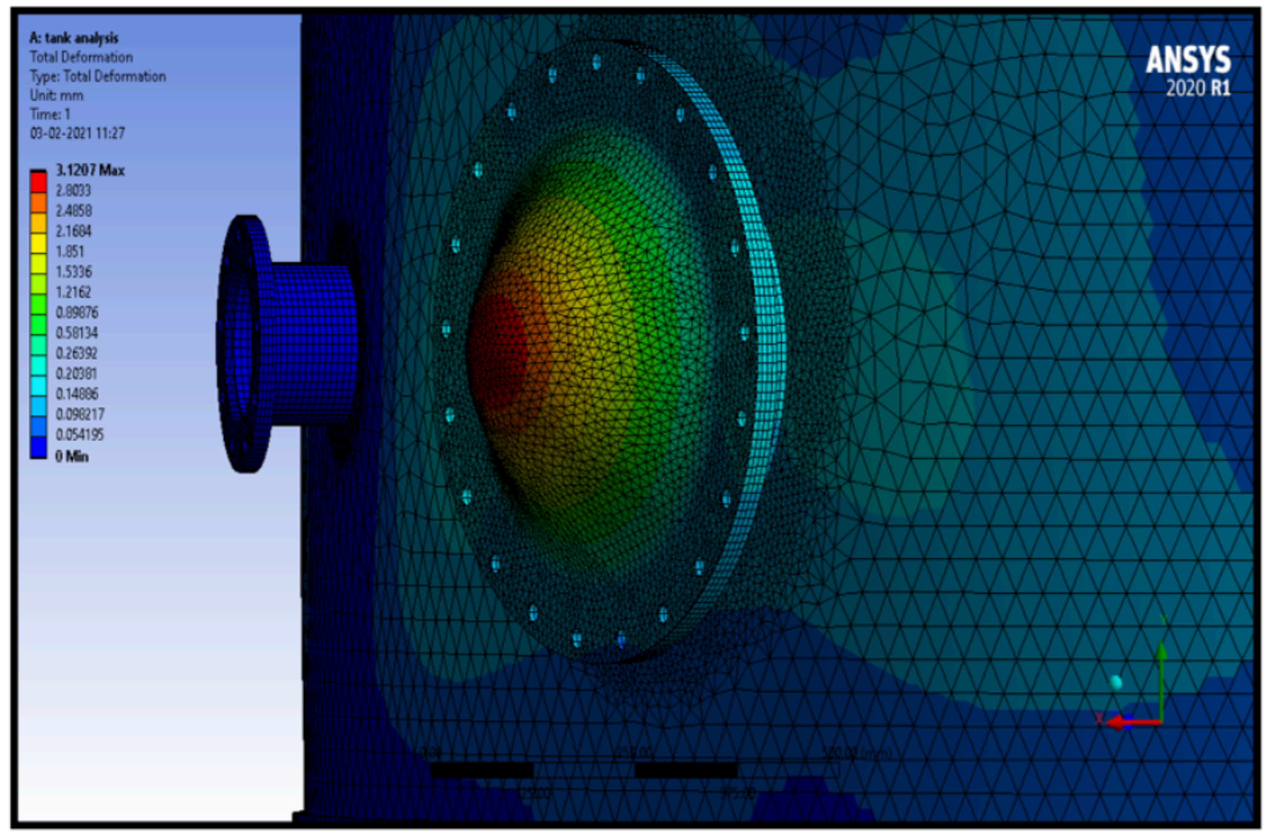
- >80 active collaborators from 38 institutes in 15 countries
- Collaborators from Hyper-K, Super-K/T2K, ESSNuSB and THEIA communities
- Almost every experimental system has responsible groups ready to contribute
  - In many cases, approval will be necessary to proceed
  - Successful funding in Canada, Poland, UK
- Many systems are at the advanced design or prototype stage:
  - multi-PMT prototypes in progress
  - Tank and support structure designs are advanced
  - Soon beginning prototype of calibration deployment system
  - Spectrometer magnet design complete

mPMT Prototype

Calibration Prototype Design



Beam Window Analysis



Summary

- Water Cherenkov Test Experiment will make measurements necessary for precision neutrino experiments at the current and next generation of water Cherenkov detectors
- New technologies such as Gd loading and multi-PMTs will be evaluated with well measured particle fluxes
- A large international collaboration from multiple projects is formed to carry out the project
- With interface to CERN groups WCTE collaboration has made significant progress on the development of the design and run plan
- With approval, many collaborators will be able to start funding requests

Extra Slides

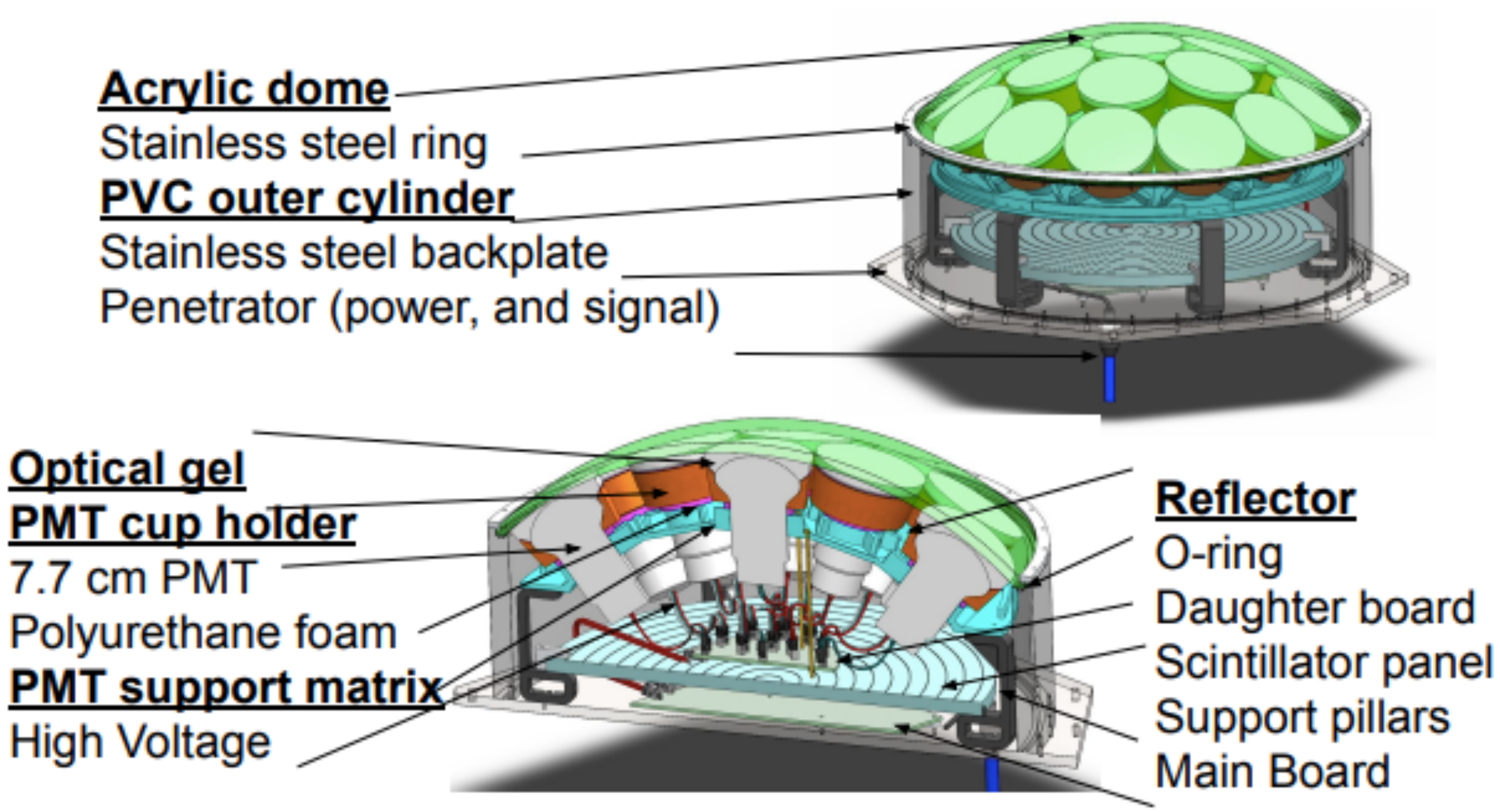
Support from CERN - Cost Estimate

Preliminary estimates prepared by Lluis Secundino Miralles Verge

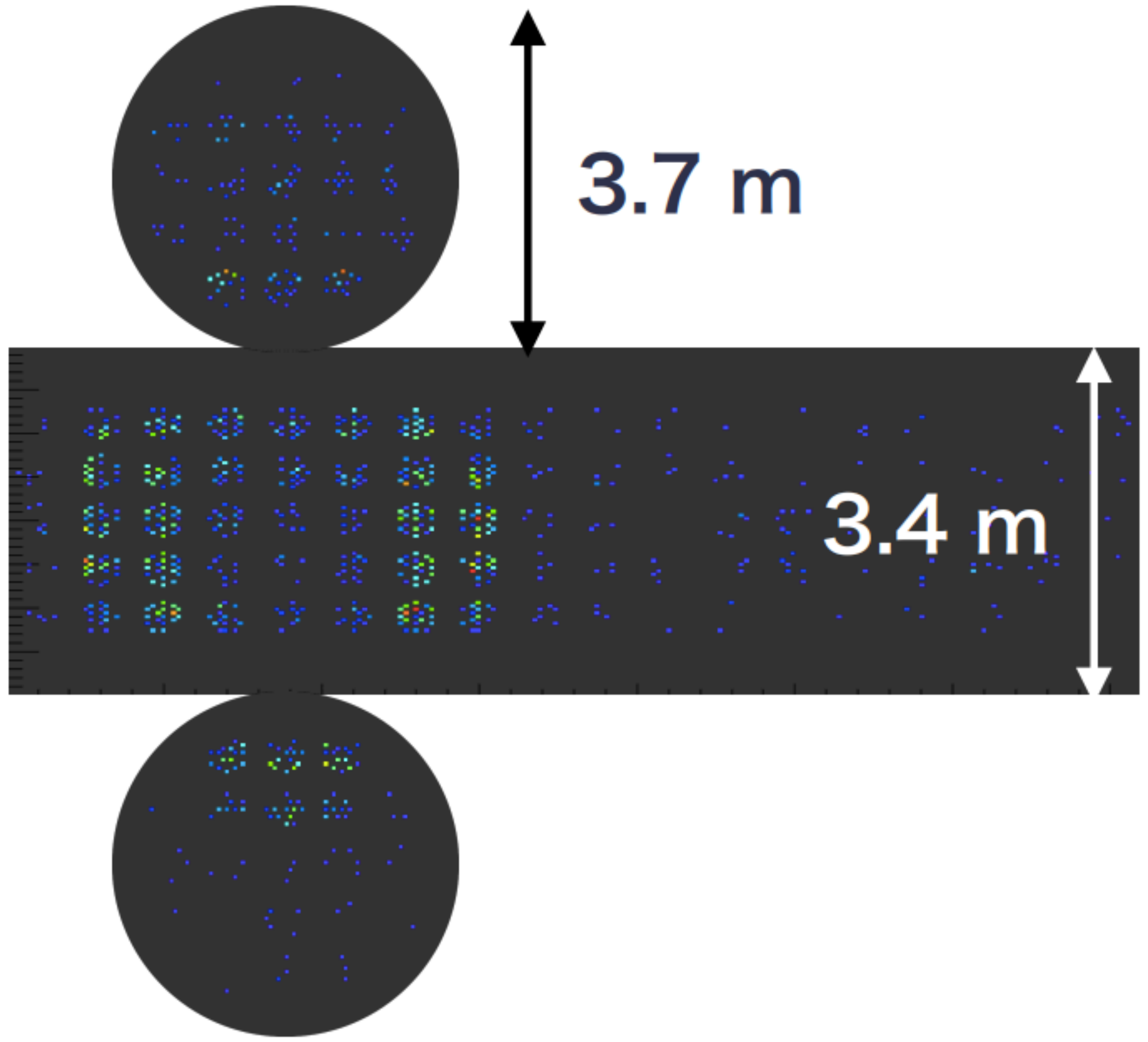
ITEM	Description	Material cost estimation (kCHF)	Personnel cost estimation (FTE)	Comments
A	Detector assembly area	50	0.1 Foreman	Foreman (Layout comissioning/ decomissioning, Logistics)
B	Support for component shipping and receiving	10	0.1 Foreman	Foreman (Logistics) . SCE-SSC Shipping/Customs service support. EN-HE transport support
C	Support during assembly	50	0.5 Foreman + 0.5 Crane operator + 0.5 Rigger technician	6 months estimated activity duration
D	Detector moving to the experimental area	25	0.1 Foreman	Foremant (Logistics) .EN-HE support. Transport (tooling, special platform)
E	Water filling	5	-	1CHF/100lt
F	Detector moving system	250	0.2 Engineer + 0.1 Draftmen + 0.4 Technician	Design, construction, installation, operation
G	Water tank procurement and ports	-	0.1 Engineer	Engineer (Technical specifications, tender follow-up) IPT support
H	Beam line setup	-	0.1 Engineer + 0.2 Technician	Engineer (Beam line setup) Technician (Installation, survey & alignment)
I	General engineering support	-	0.3 Engineer	Design review & safety compliance
J	Office Space	30	-	Office exploitation
		Material cost estimation (kCHF)	Personnel cost estimation (kCHF)	
	TOTAL	420	560	0.8 Foreman + 0.7 Engineer + 0.1 Draftmen +0.6 Technician + 0.5 Crane operator + 0.5 rigger
			Average cost estimated 175kCHF/FTE	

Photosensors & Reconstruction

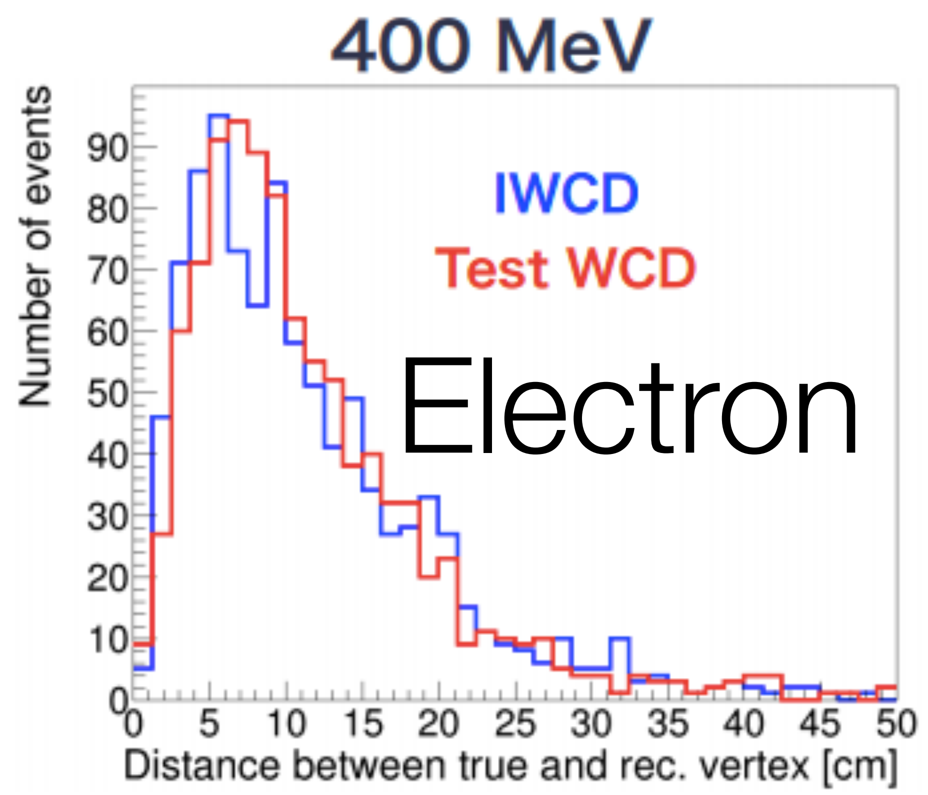
- We will use multi-PMT photo detectors in IWCD
- Very good timing resolution (1.6 ns FWHM) 3-inch diameter PMTs
- In water-tight module with FADC based readout electronics
- Power and communication to to mPMT with single cable using PoE

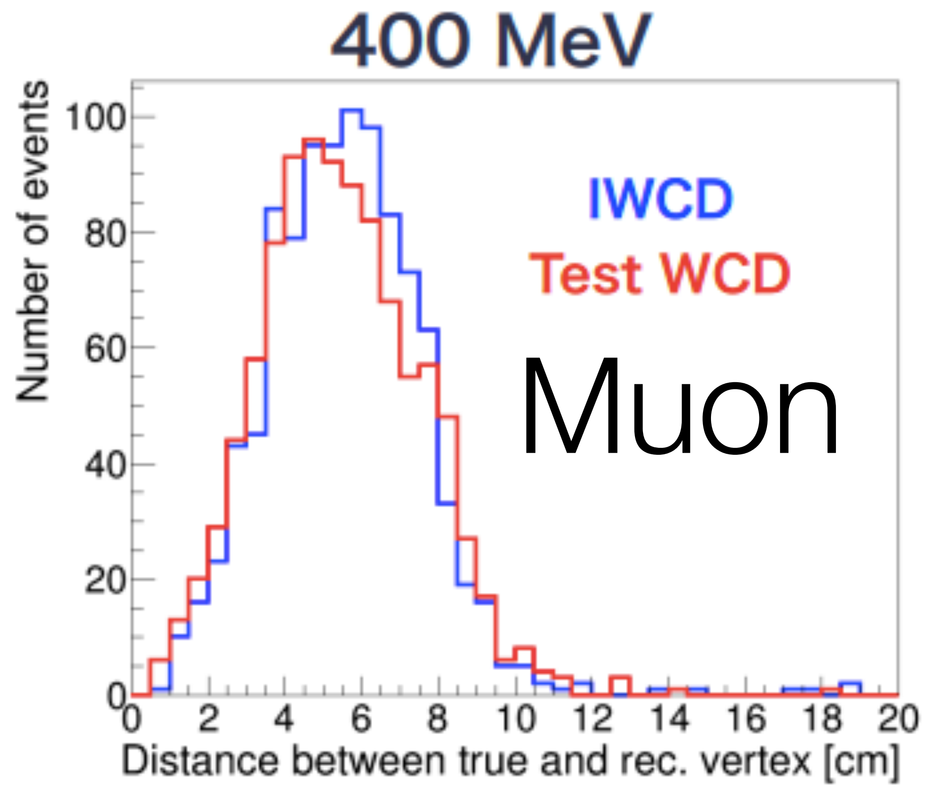


Example of simulated 400 MeV/c muon



Similar reconstruction performance to IWCD

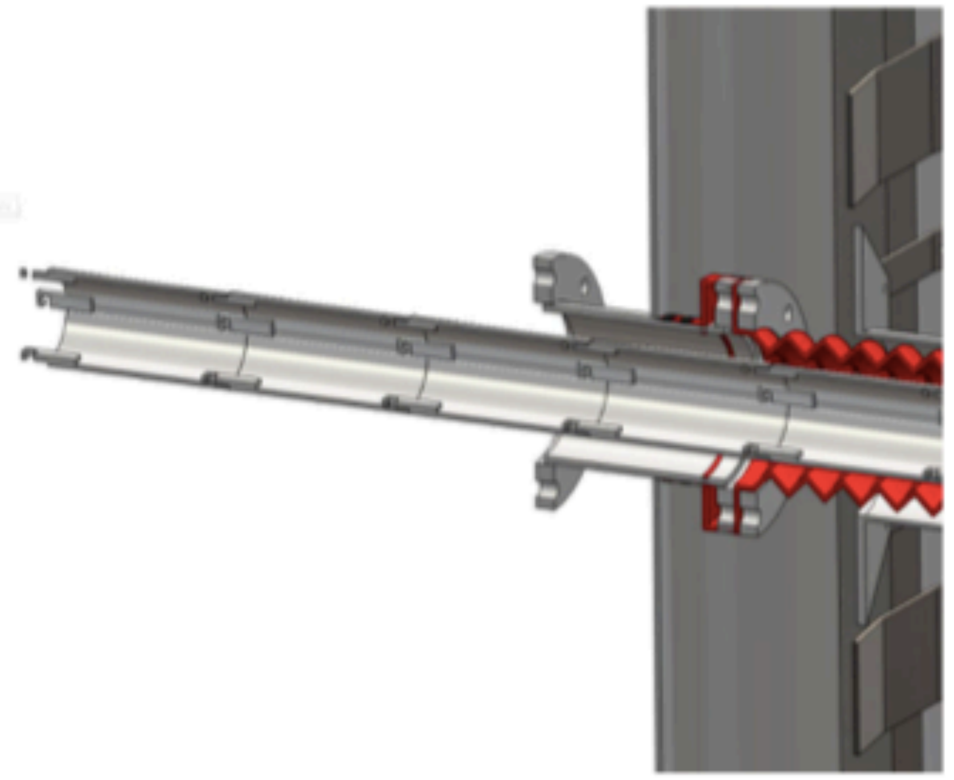


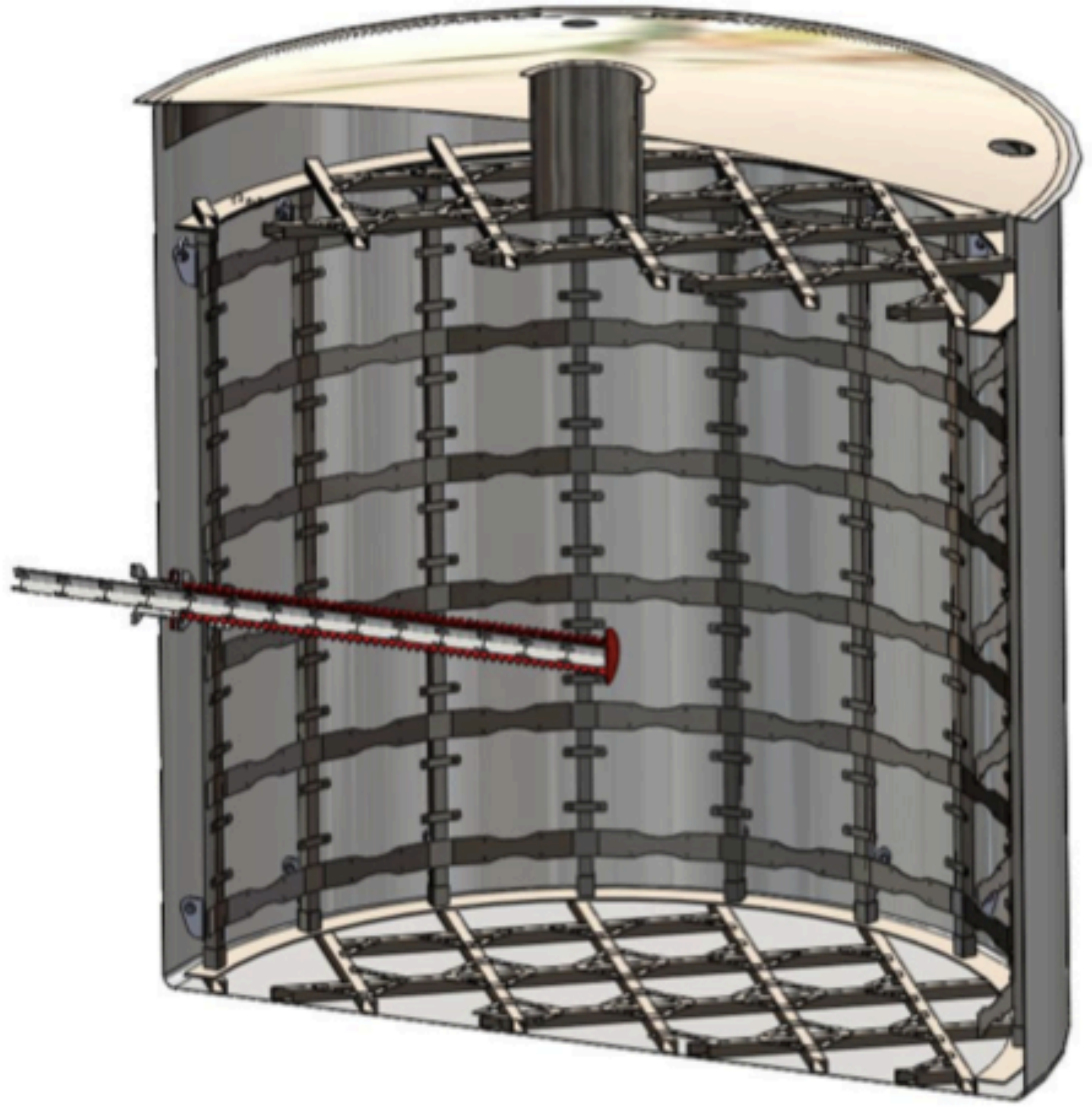


Beam Windows/Pipes

- Minimize material where beam enters detector
  - Beam pipe for secondary beam configuration
  - Beam window for tertiary beam configuration

- Developing design of extendable beam pipe to vary injection point in detector
  - Segmented pipe that can be moved into and our of detector provides structural support
  - Surrounded by flexible water-tight material



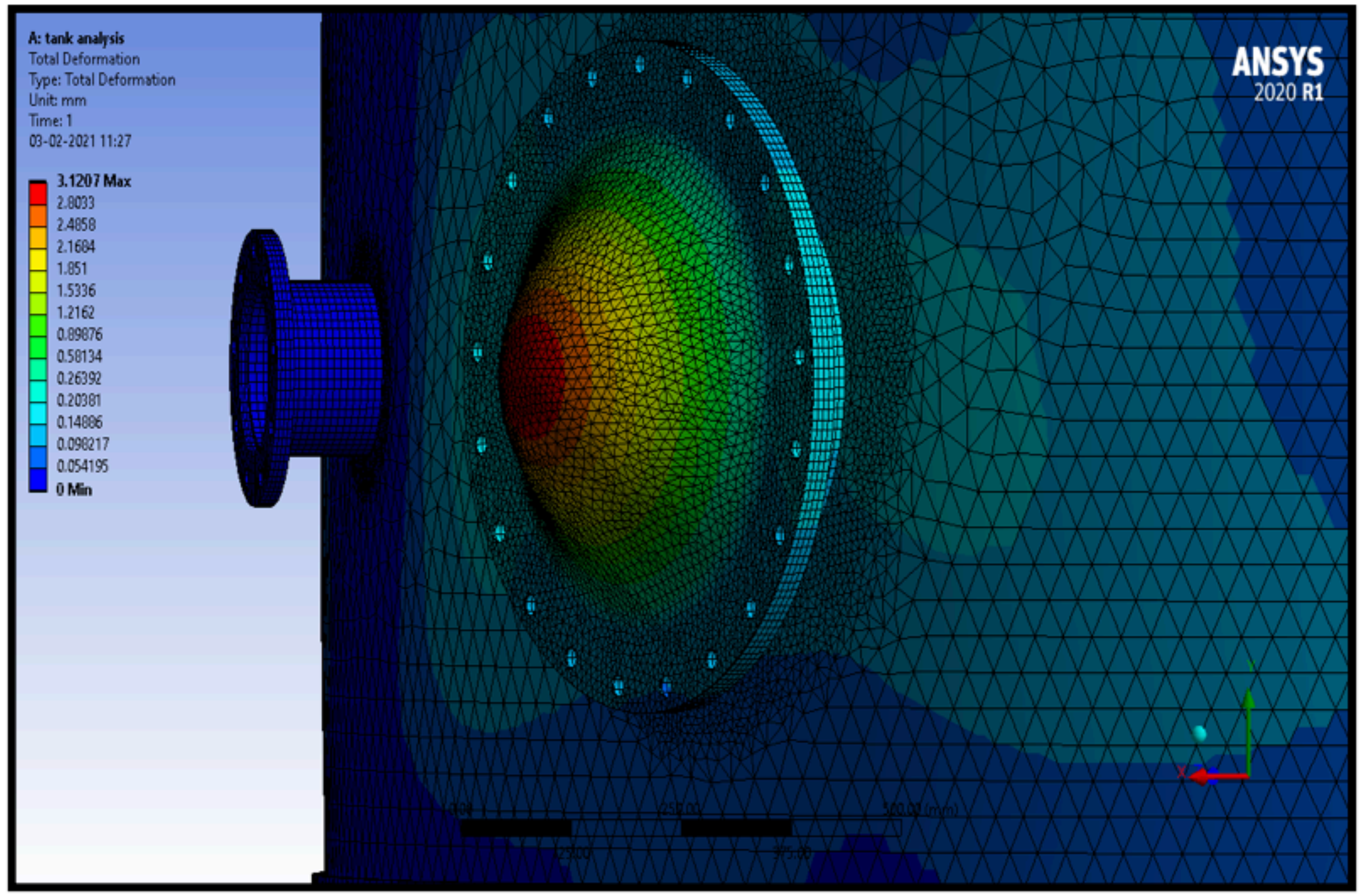


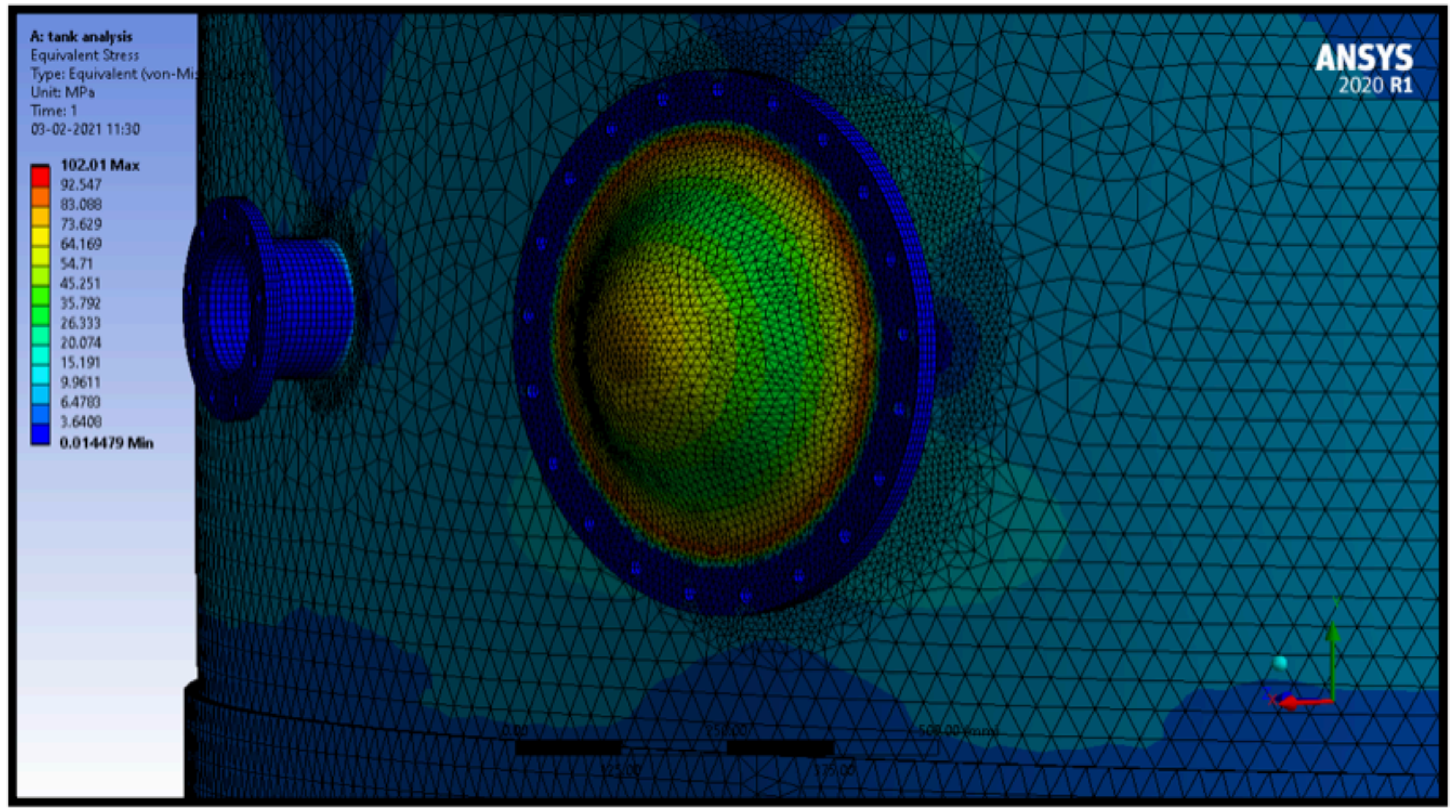
Beam Window

- Hydrostatic analysis for large beam window carried out with ANSYS
- Beam window diameter is 500 mm
- Tested cases of 2 mm and 3 mm thick SS 304

	Beam Window- 2mm	Beam Window- 3 mm
Max. X displacement of beam window	9.82 mm	3.12 mm
Max. Von Mises stress- beam window in M Pa	228.67 (Factor of Safety=0.90)	102 (Factor of Safety =2.03)

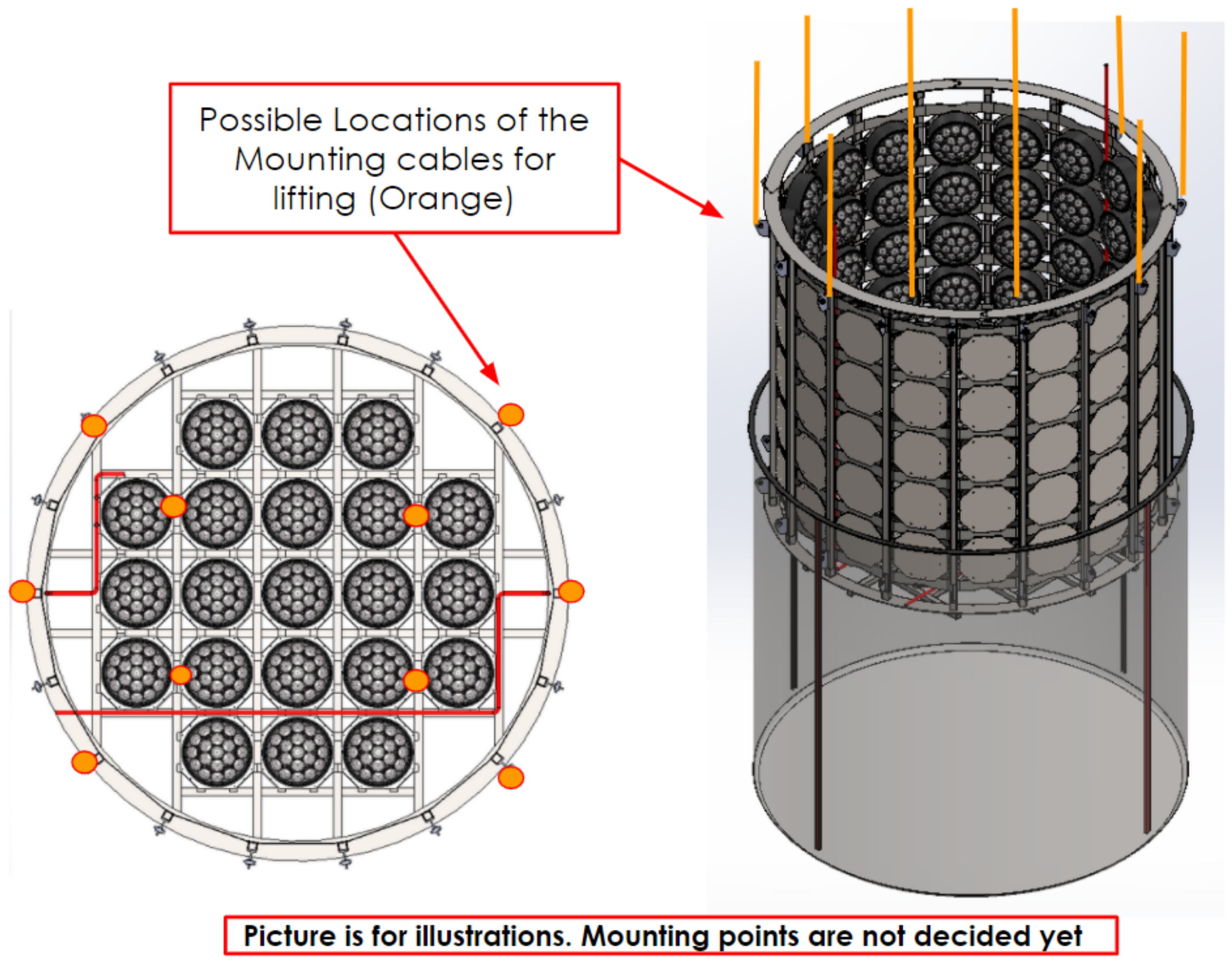
- Safety factor of 2 for 3 mm thick window in static case
- Will analyze dynamic case during detector moving

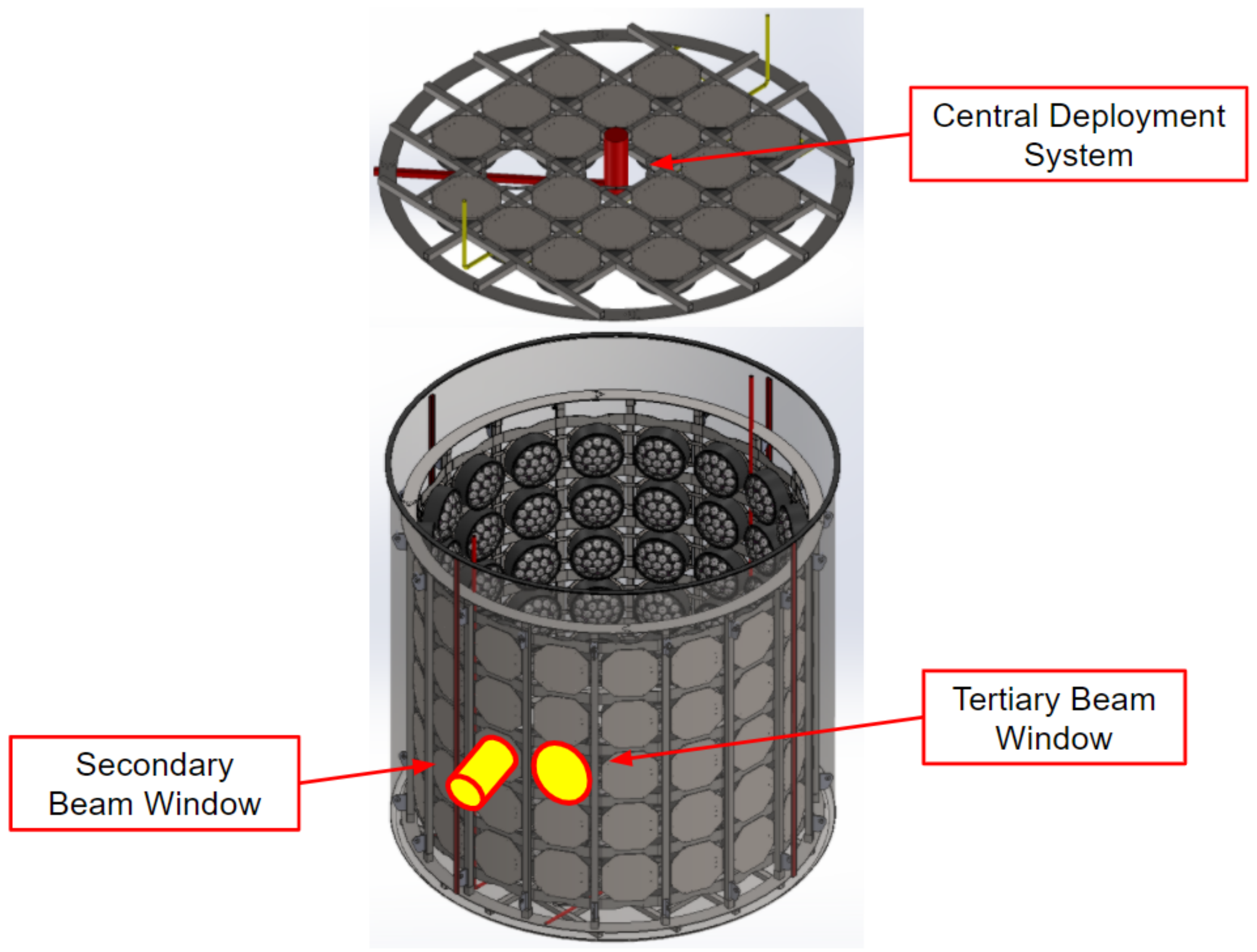


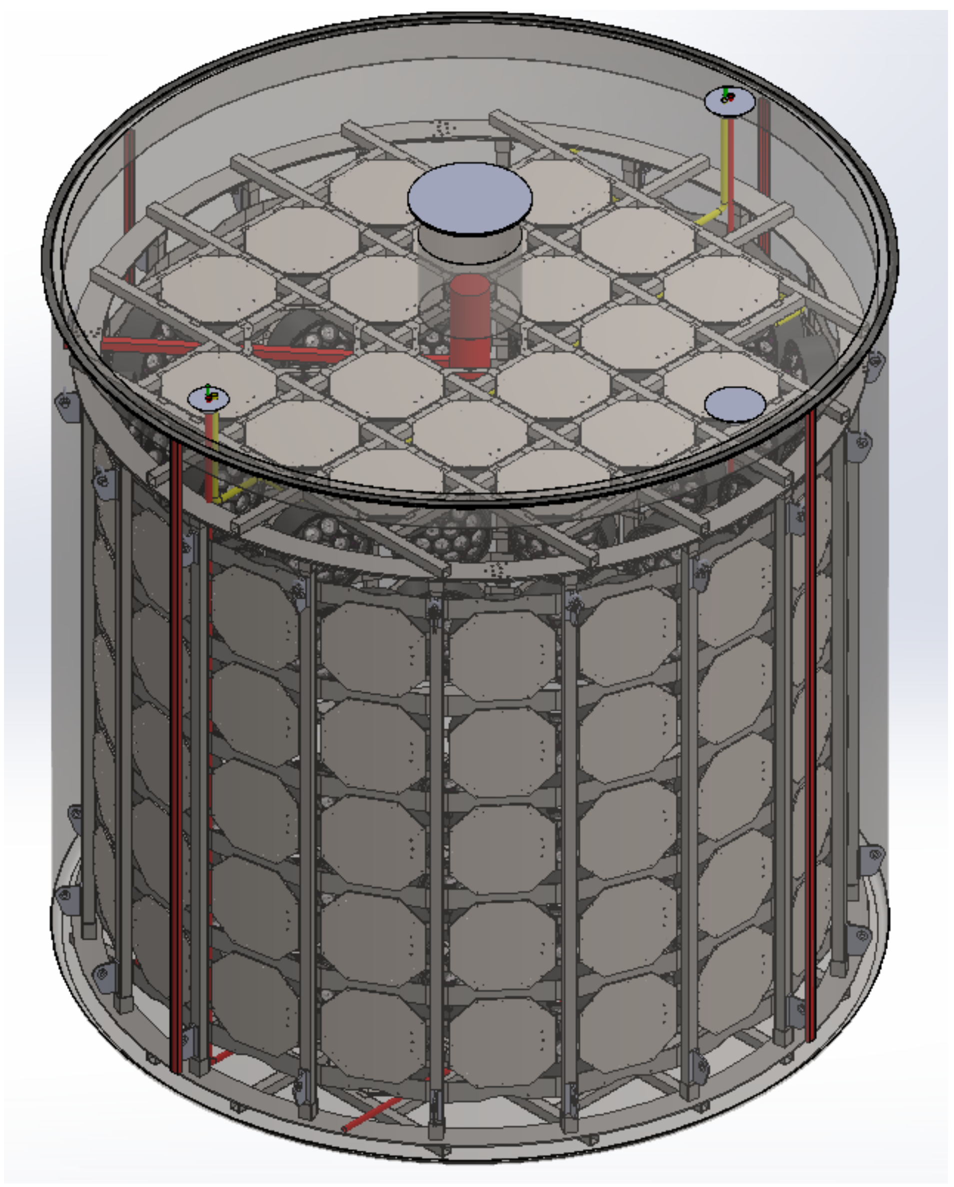


Assembly/Lifting Jig

- Assembly requires lifting the support frame into tank, lifting the top endcap and tank lid into place and then lifting the full tank+support frame for moving
- Lluis thinks that there isn't an existing lifting jig that can accommodate this
- Will need to make a new jig, so we should make sure it works for the support structure, top endcap, tank lid and full tank

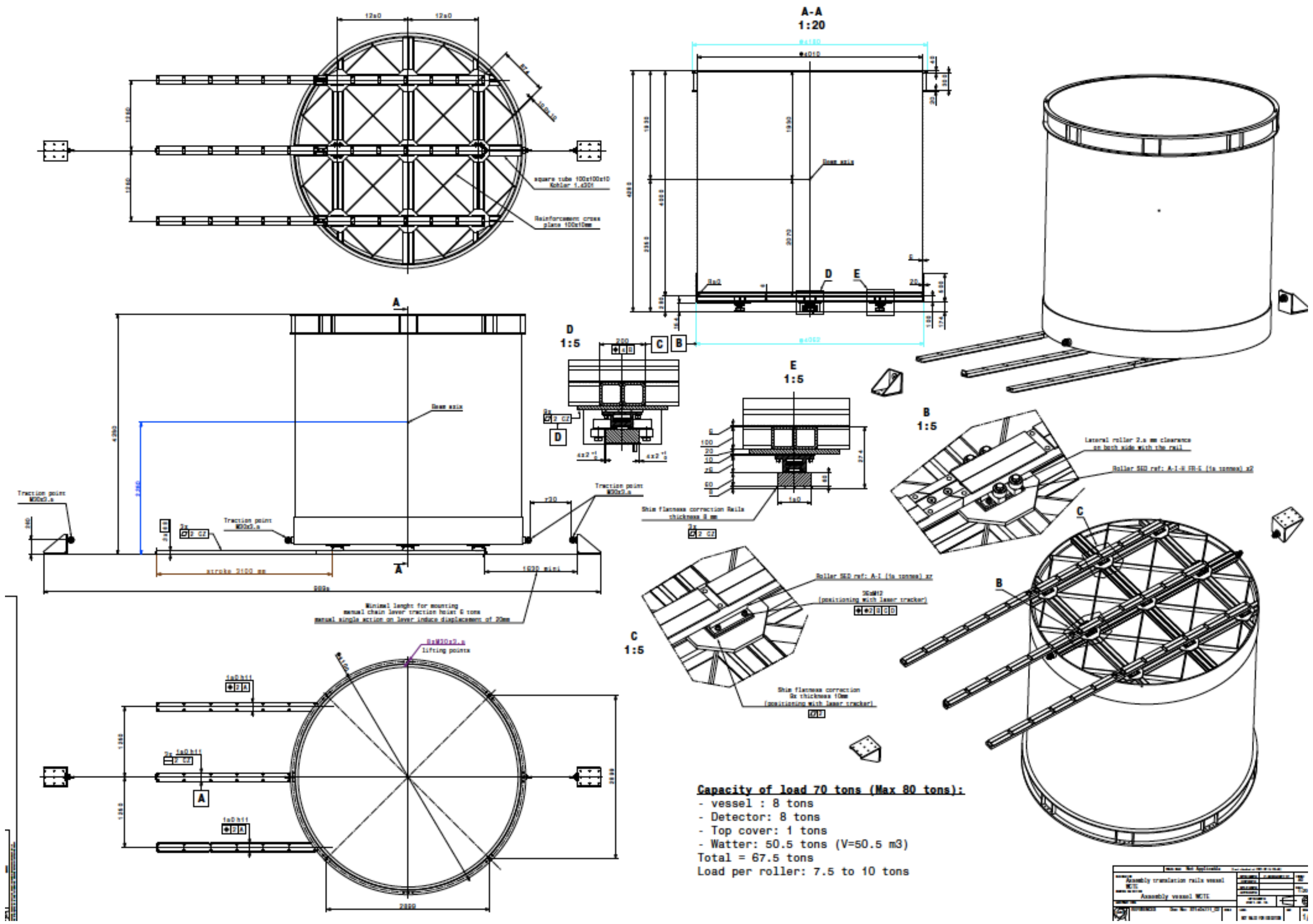






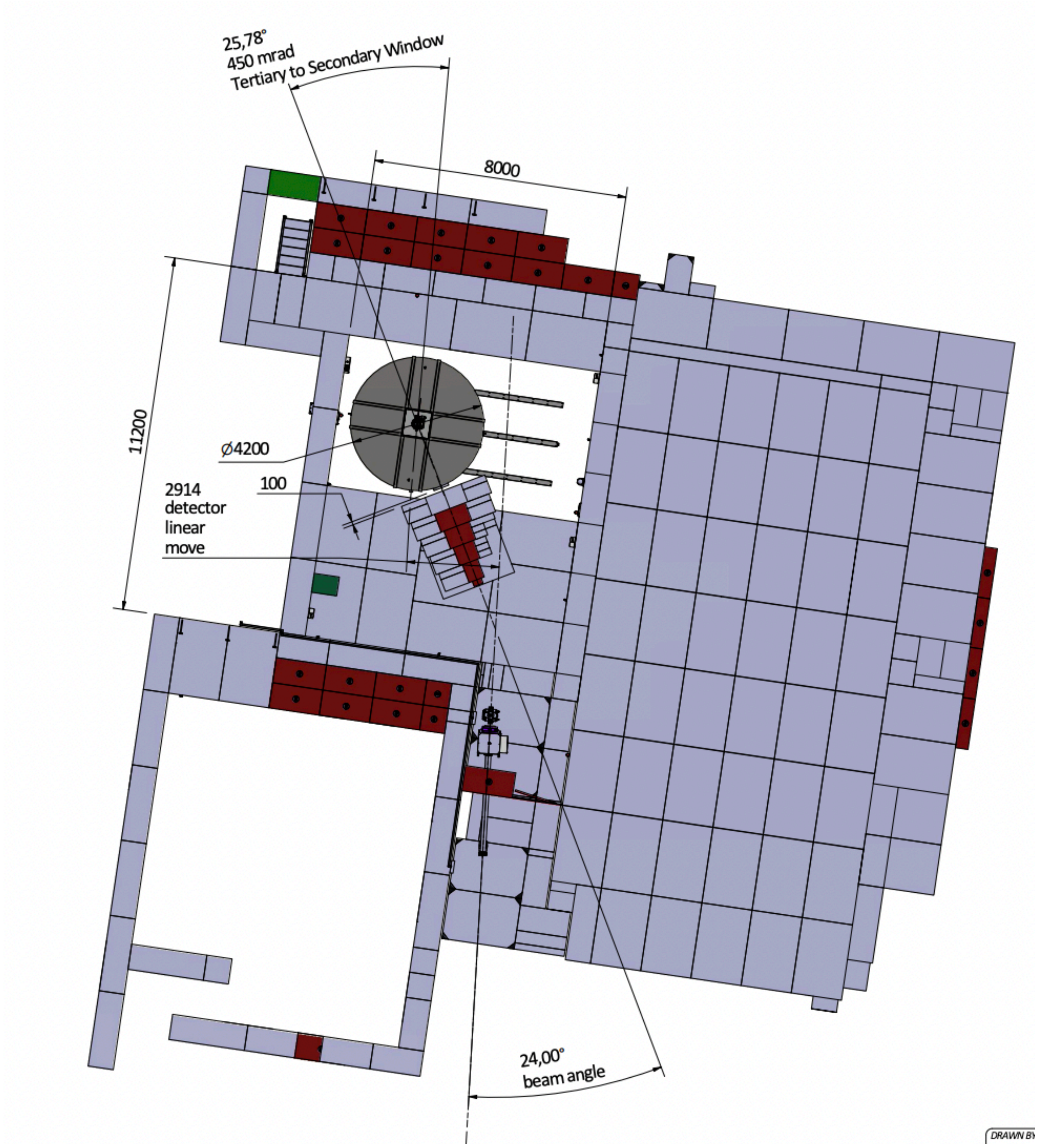
Moving in T9

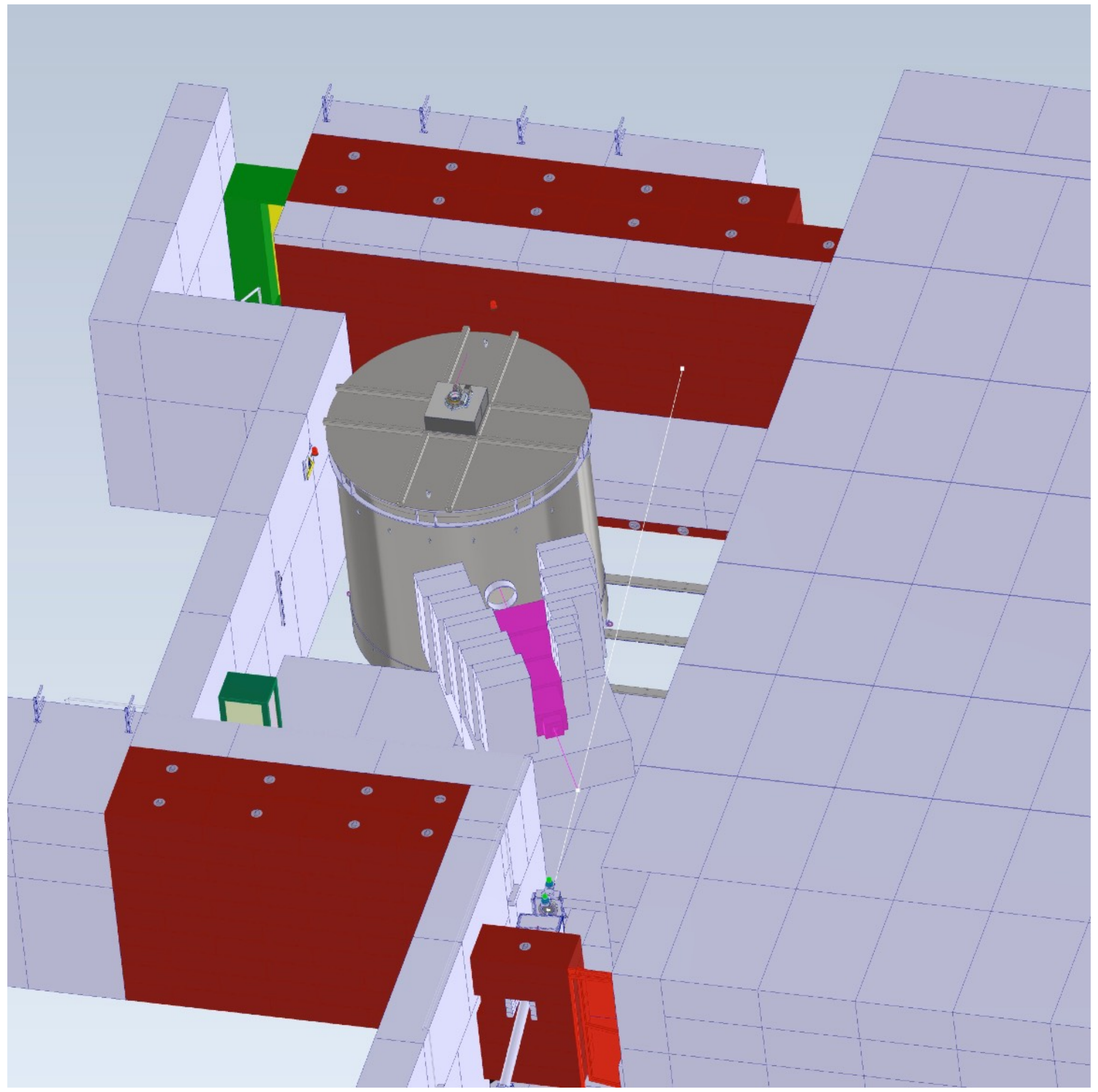
- P. Minginette has helped us prepare and initial design of the rail-based moving system
- Total length required in initial design including anchors is ~10 m

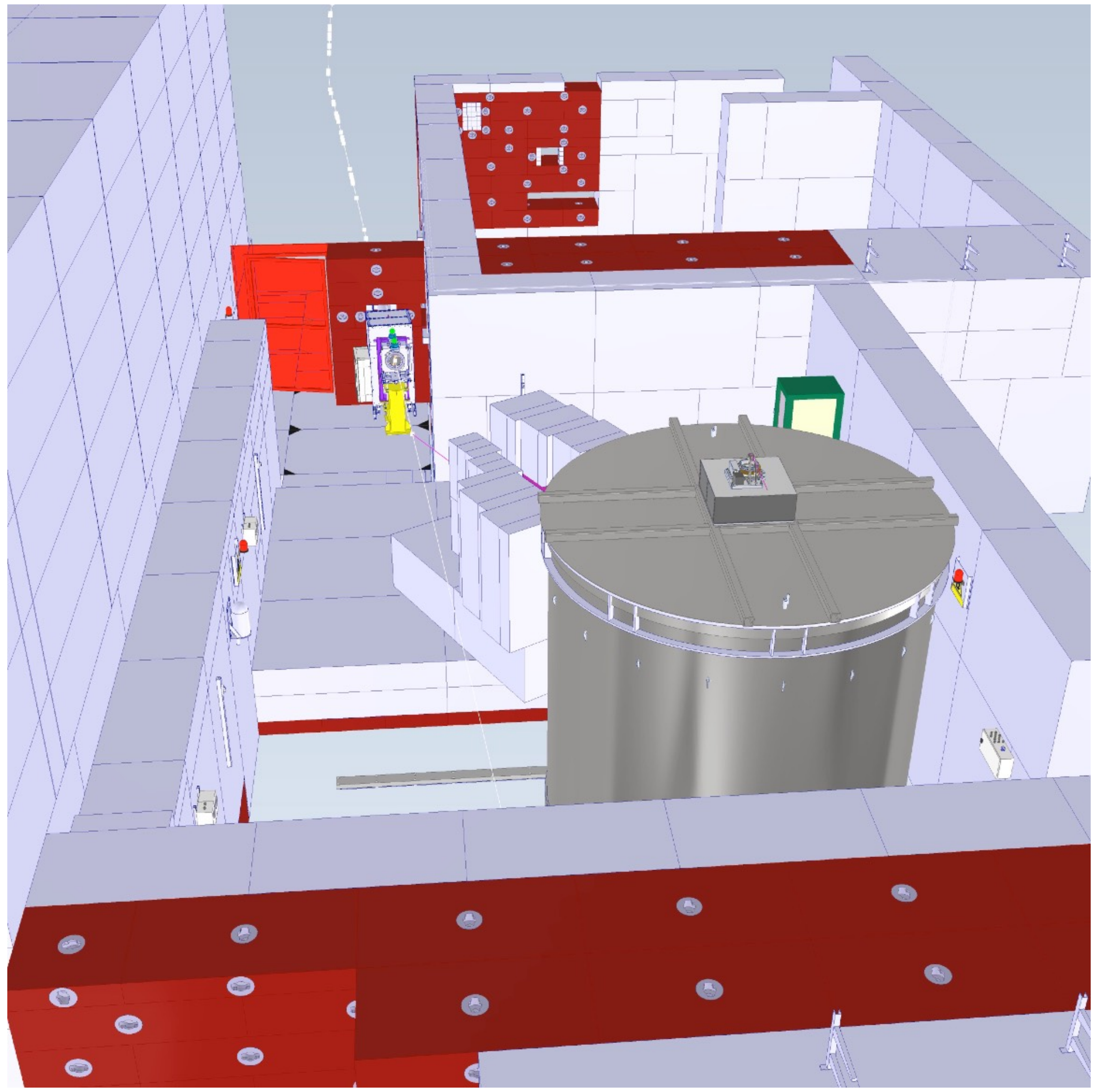


3D Model of T9 Area

- 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

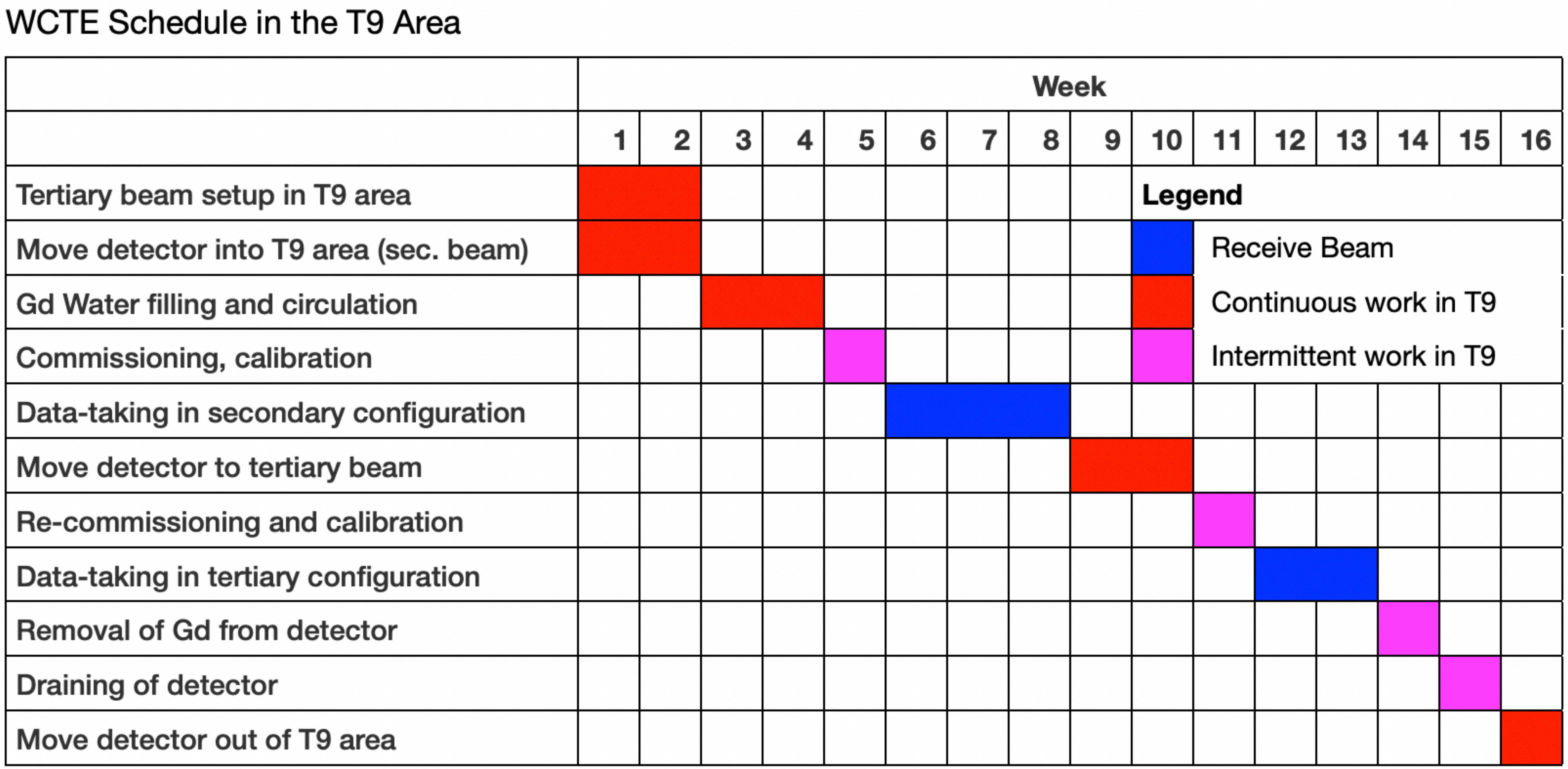




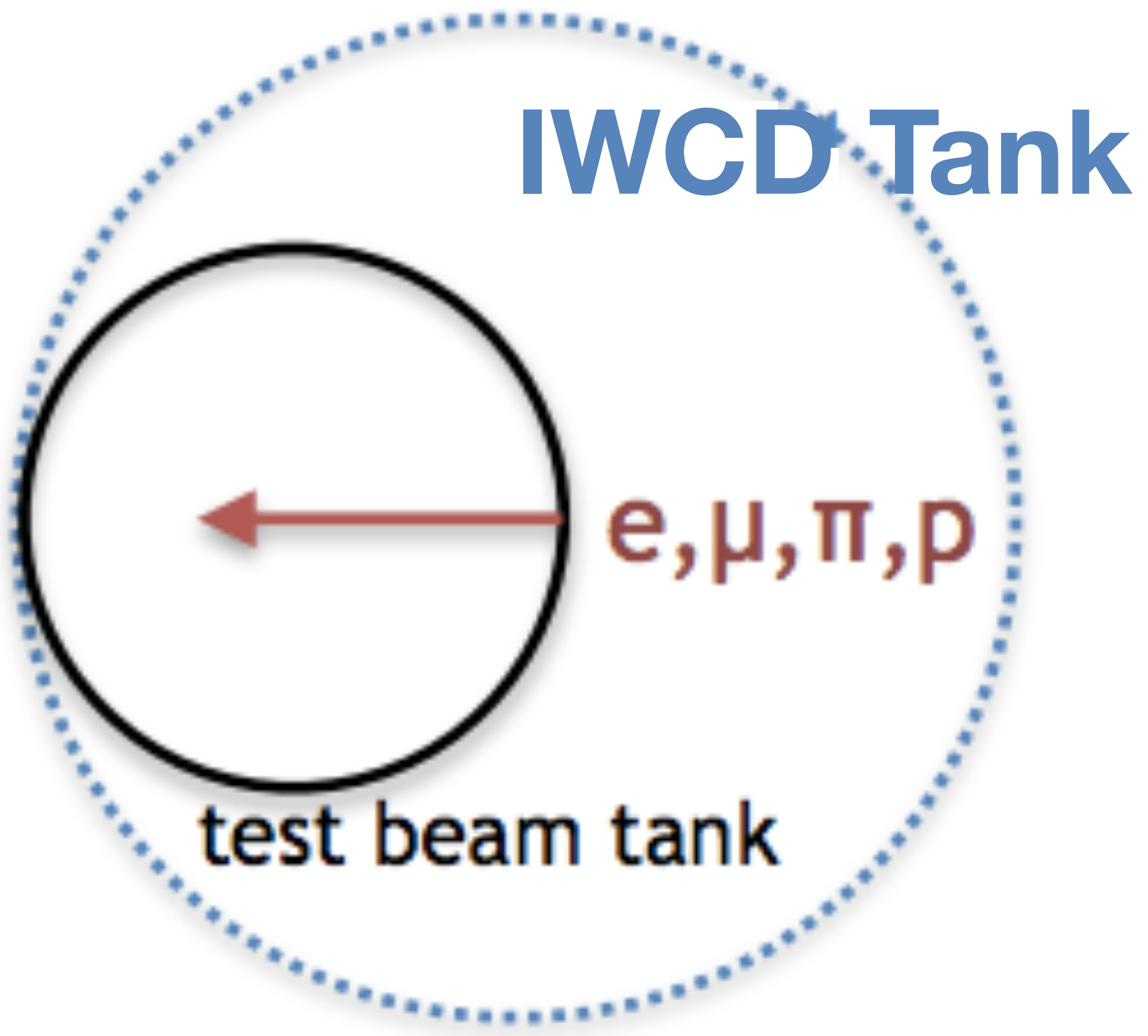


Cosmics Pure-Water Phase Only (in Assembly Area)

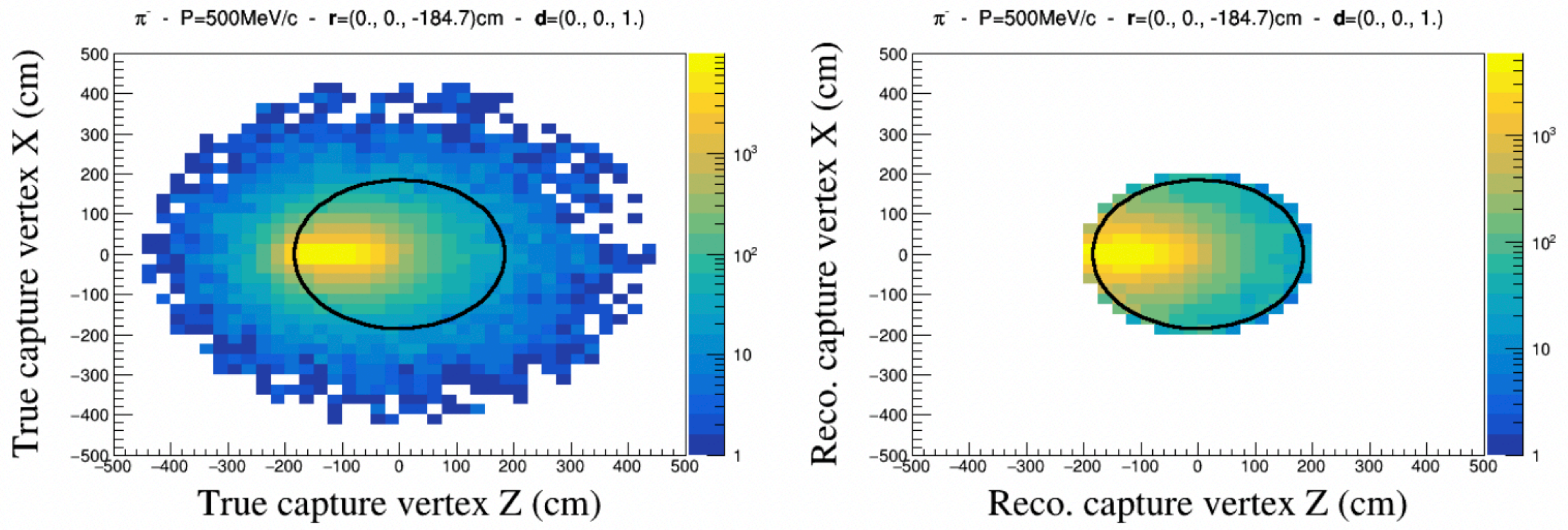
- Assume operation with pure water as baseline in T9 is not necessary
- May be due to pure water operation in assembly area or no pure water phase at all
- Total run plan is reduced to 16 weeks



Why 4 m Diameter WCTE?



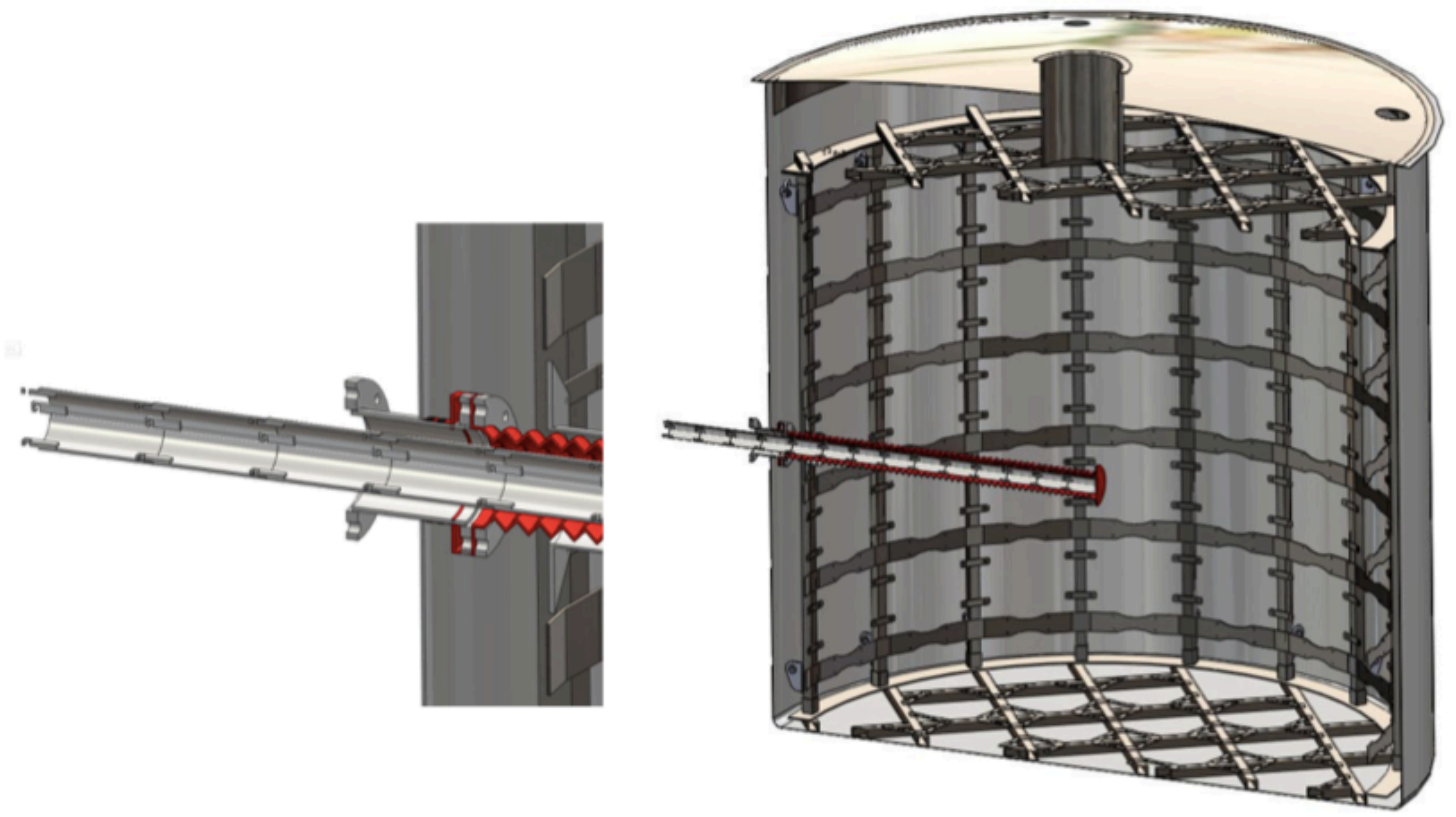
- The 4 m diameter of the WCTE detector is chosen to have particle containment and that is relevant for the IWCD
- A particle entering at the upstream edge of the WCTE has the same distance to the downstream wall as a particle produced in the center of the IWCD
- 4 m size also allows for reasonable containment of neutrons



90% of neutrons contained

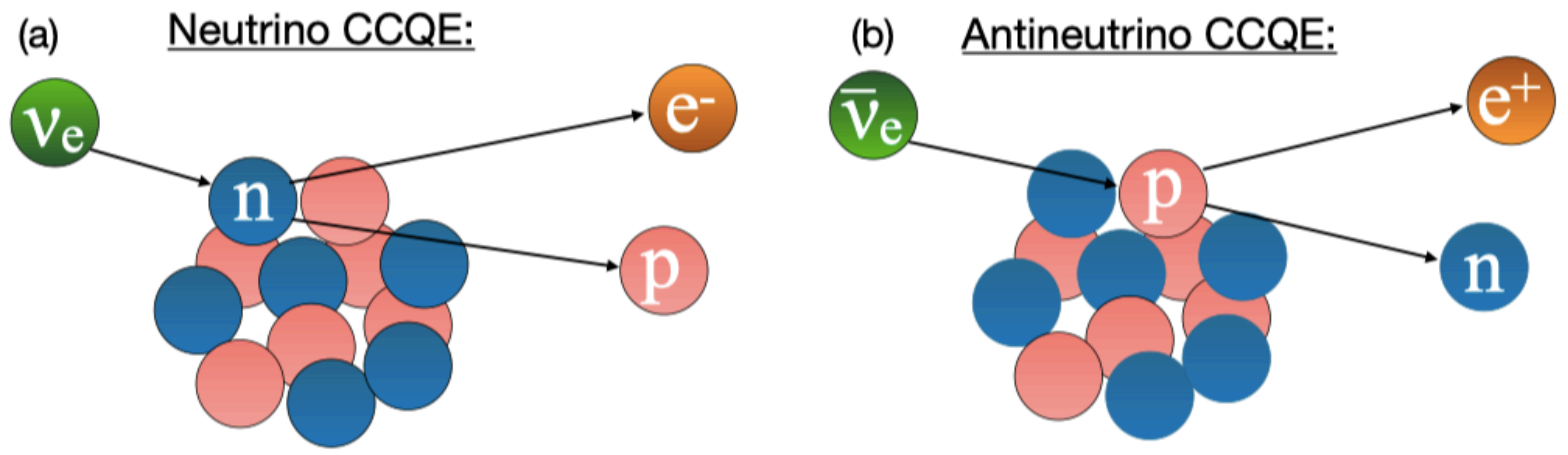
Contingency in Estimate

- For each stage, we include at least 50% contingency on top of current estimates
- Beam operation periods in tertiary configuration are based on simulation and desired integrated numbers of events
  - As described in proposal, with 1e6 secondary particles per spill and 100% efficiency, we need 3 days of operation to accumulate the necessary statistics
  - Given that we expect down time of beam and detector during data taking periods, we schedule two weeks
- We don't yet have particle rate estimates for secondary configuration from CERN experts
- We expect longer operation in secondary configuration since we run with different configurations of the beam pipe
  - We schedule 3 weeks

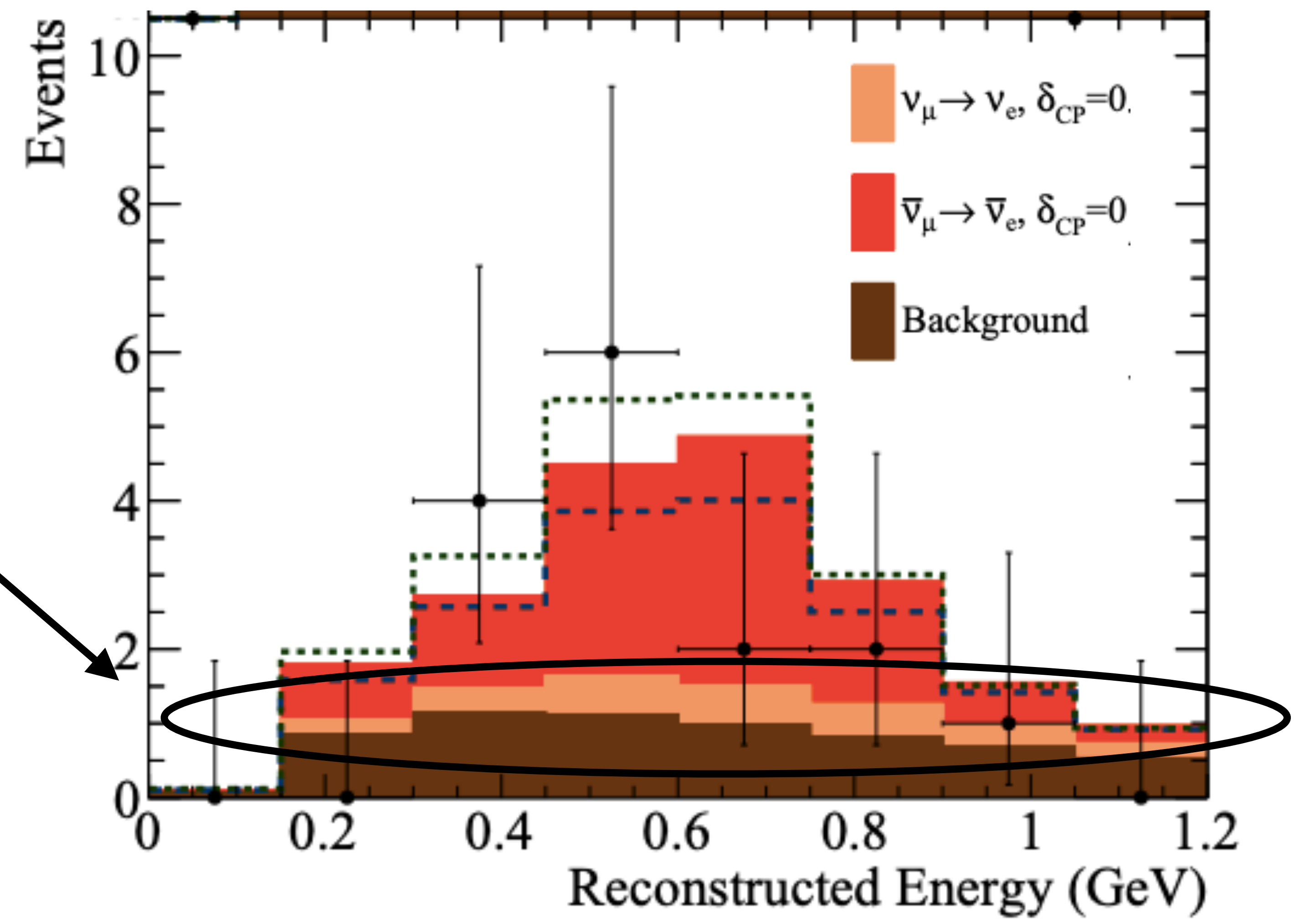


Measurements at ~5 different beam pipe positions

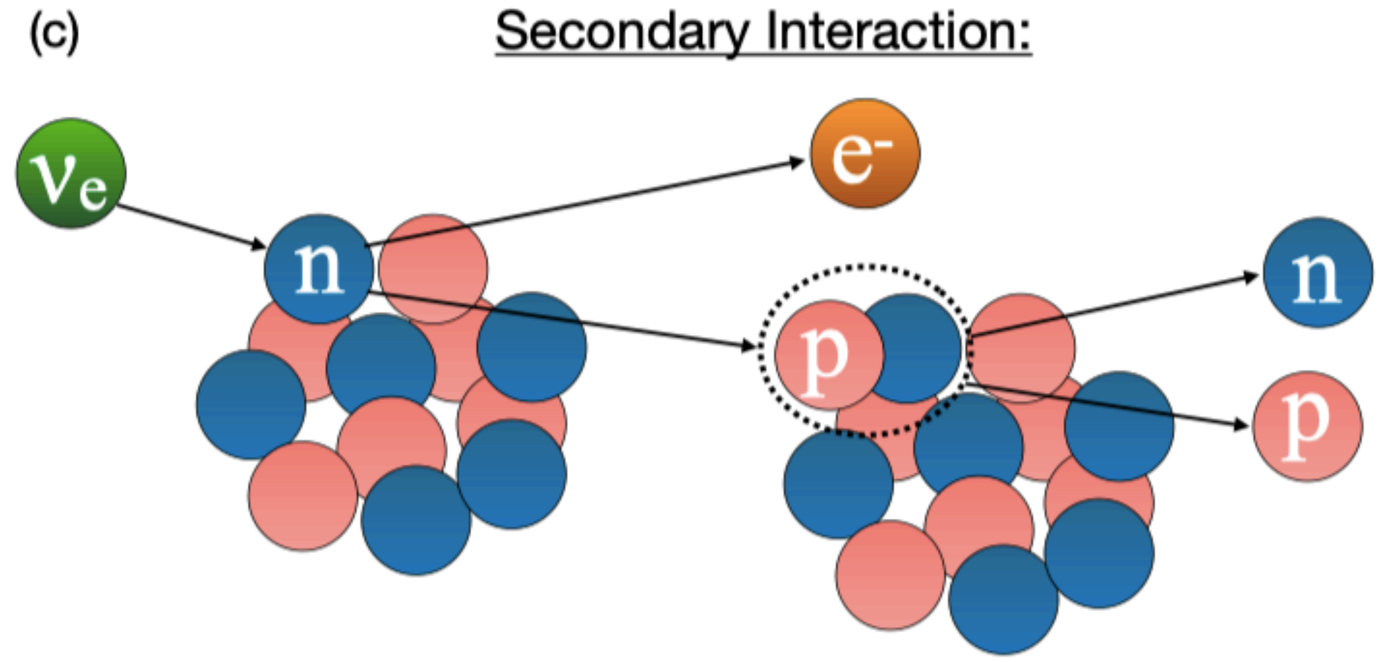
Applications of Neutron Detection in T2K



- 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

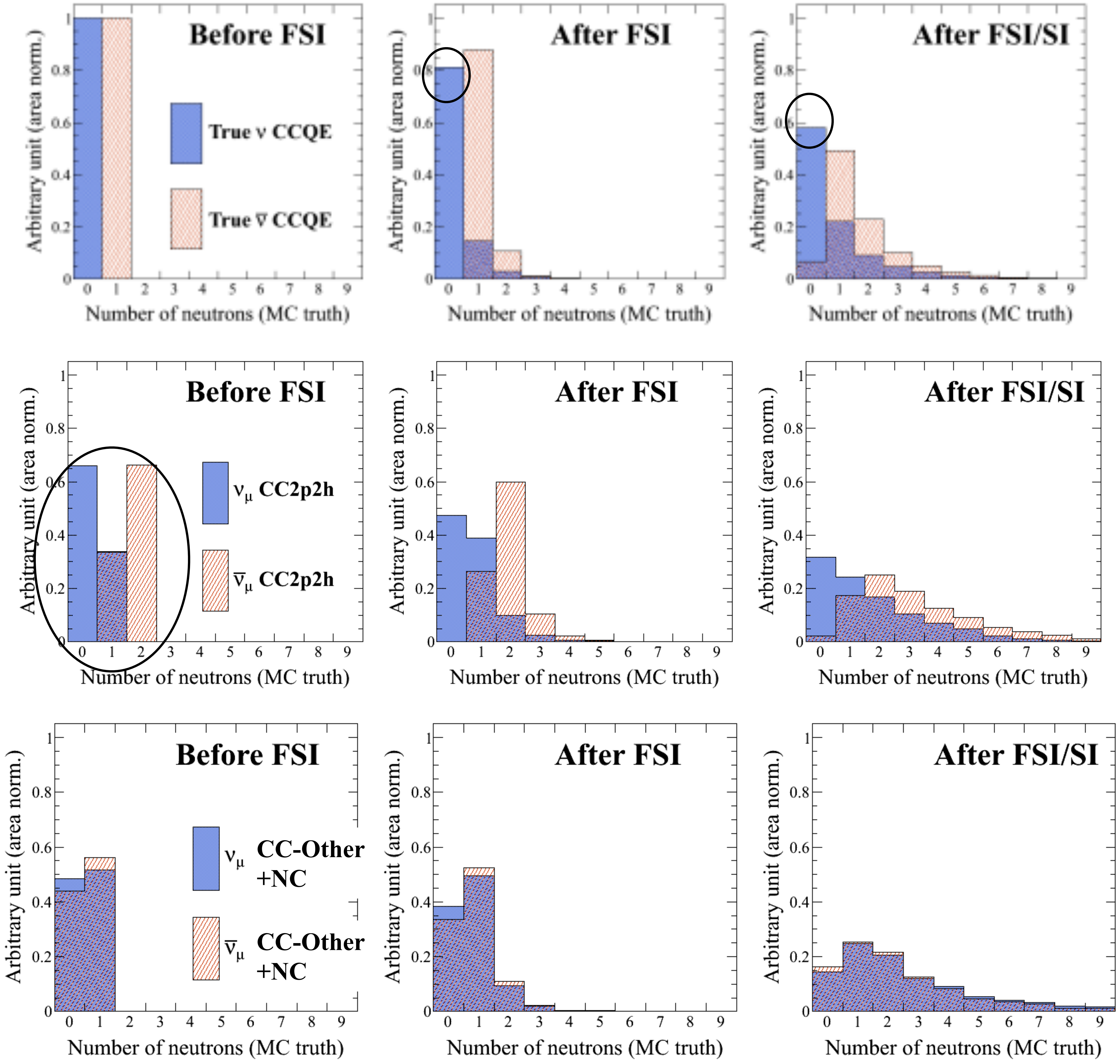


Nature 580 (2020) 7803, 339-344



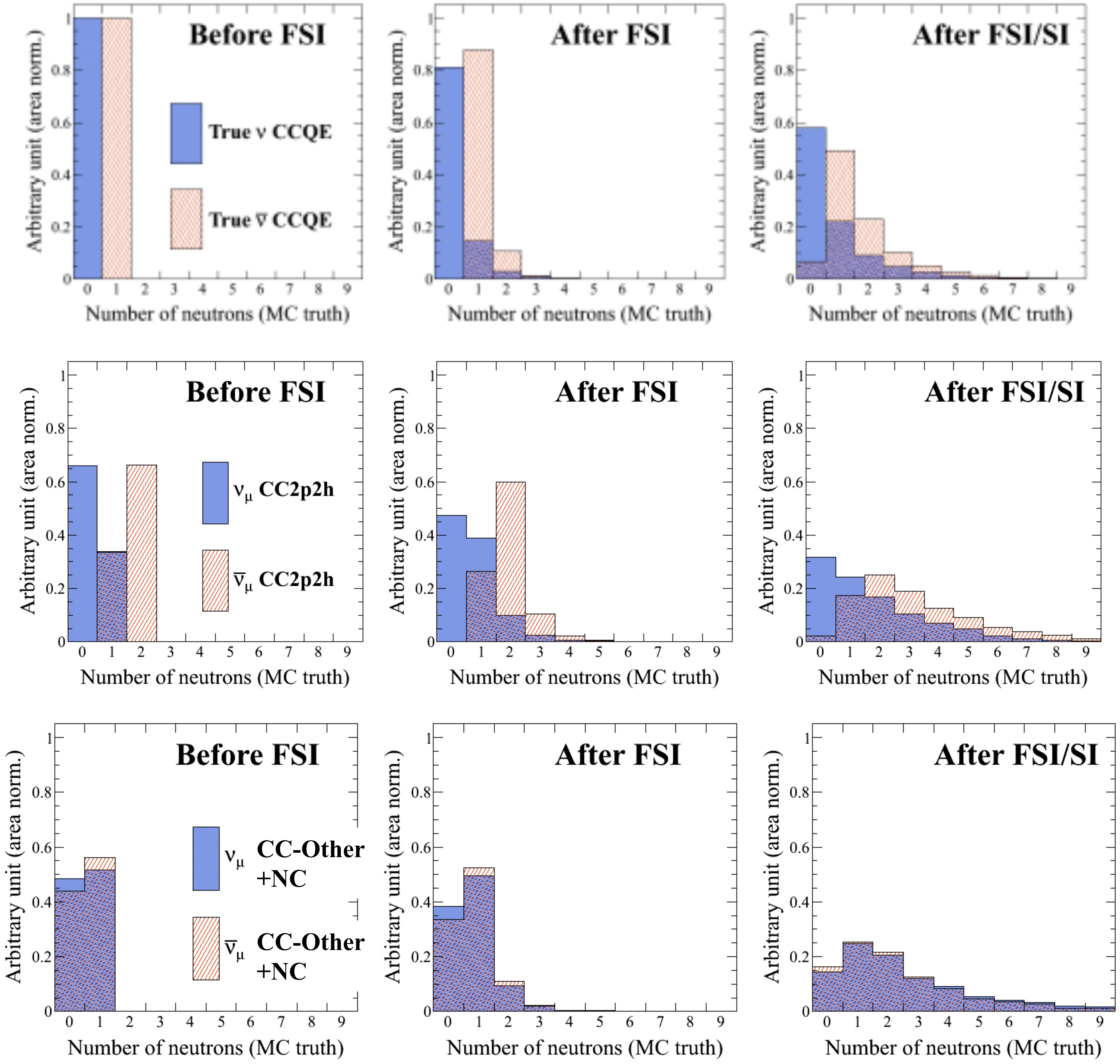
~20% of the interactions

Neutron Multiplicities (Single Ring Samples)

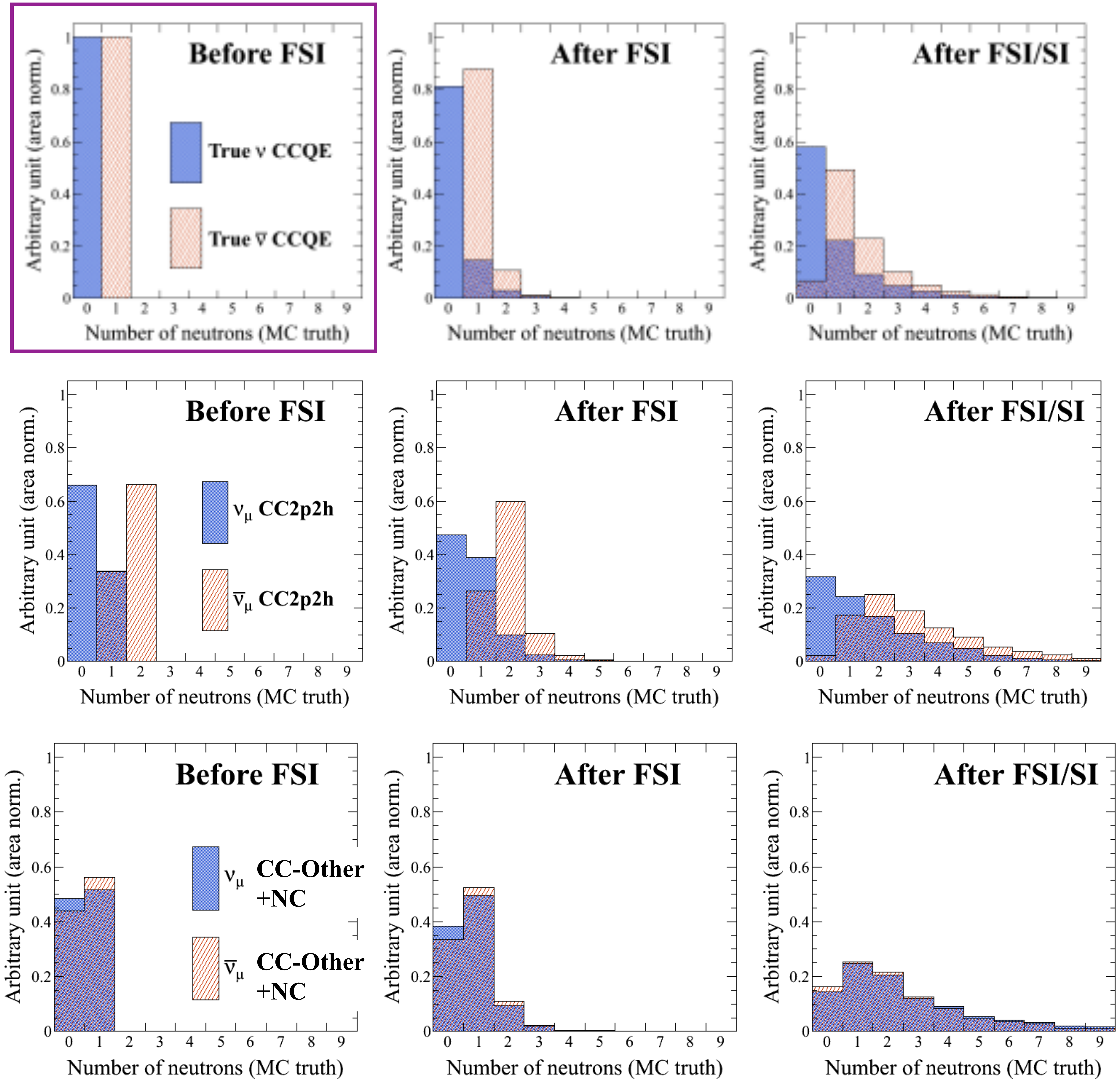


- About 20% of neutrino CCQE events pick up neutrons through final state interactions (**FSI - interactions inside target nucleus**)
- Another ~25% through secondary interactions (**SI - interactions in detector**)
- Non-quasi-elastic interactions typically have a higher rate of neutron production in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

Neutron Multiplicities Constraints

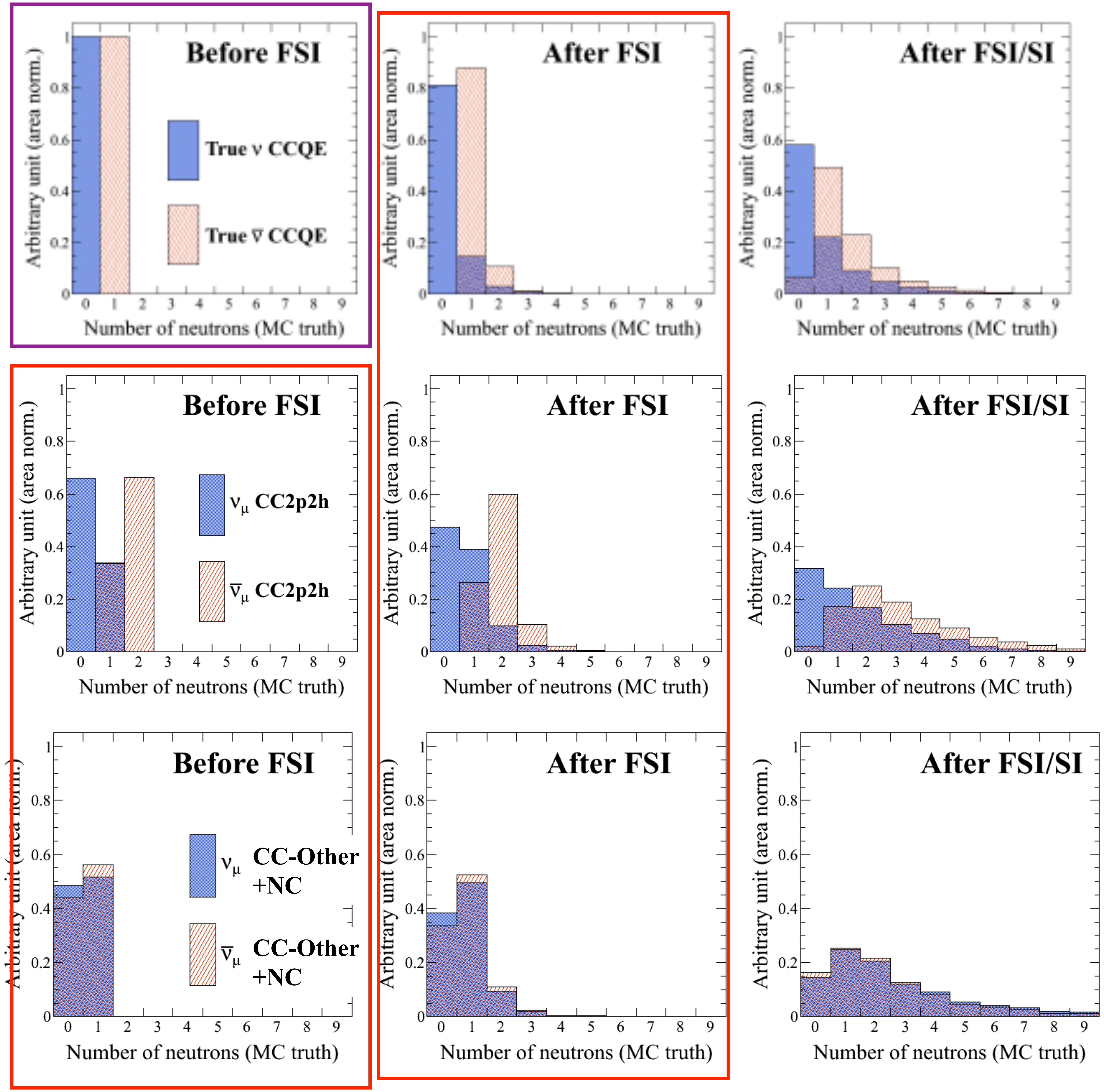


Neutron Multiplicities Constraints



Derived from model

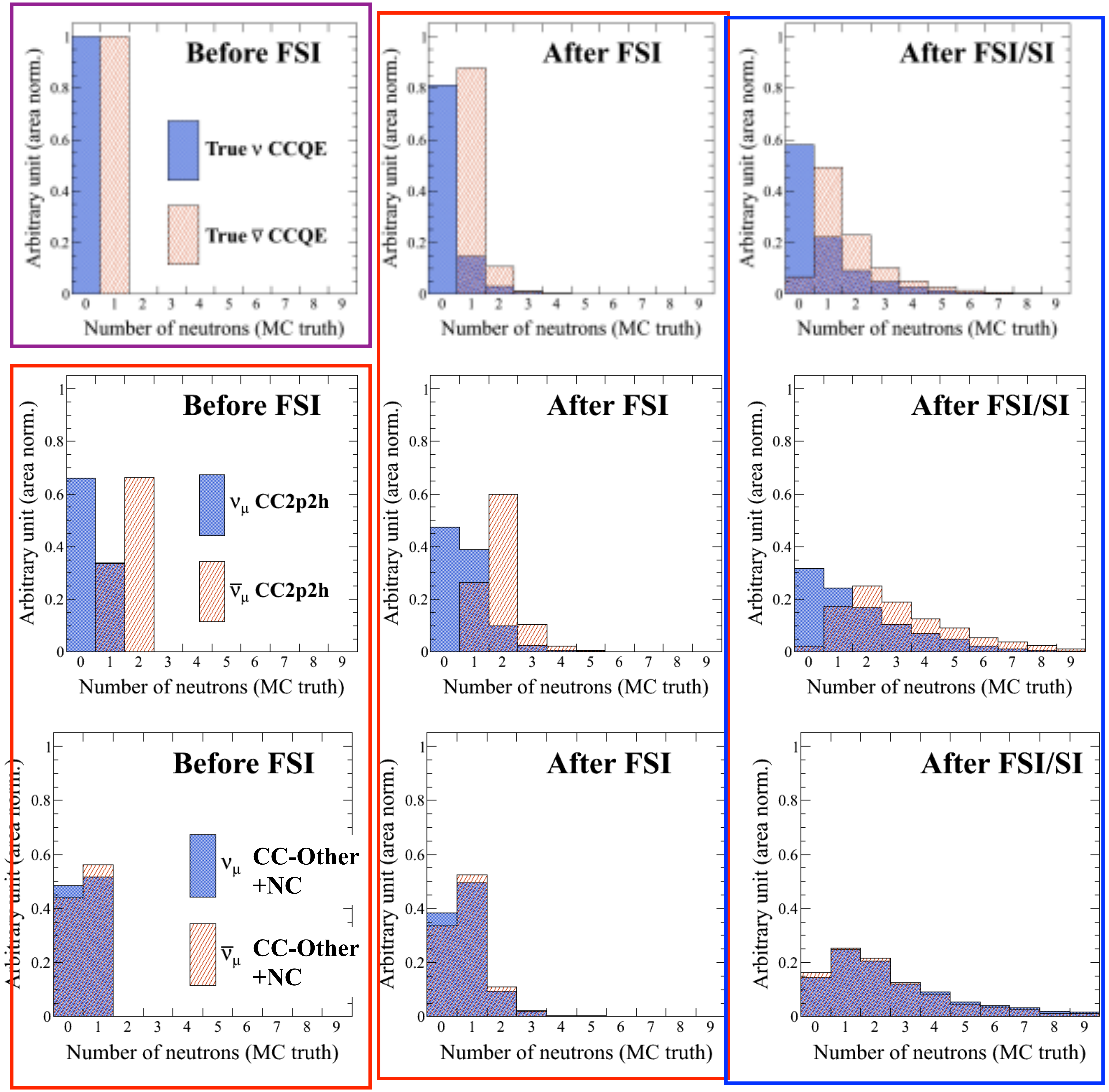
Neutron Multiplicities Constraints



Derived from model

Constrained by ND280 (upgrade) measurements

Neutron Multiplicities Constraints

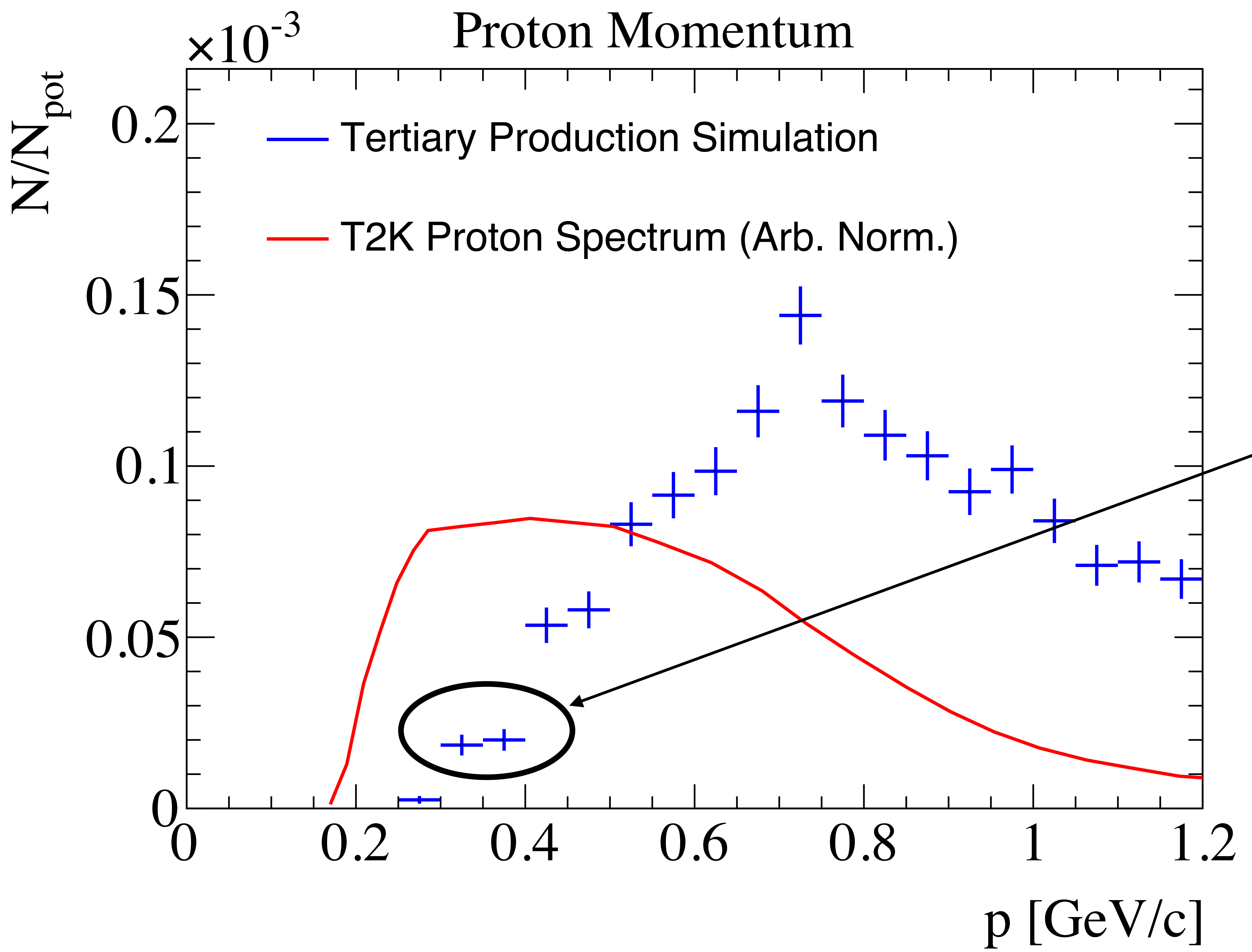


Derived from model

Constrained by ND280 (upgrade) measurements

Constrained by WCTE measurements

Proton Spectrum in WCTE



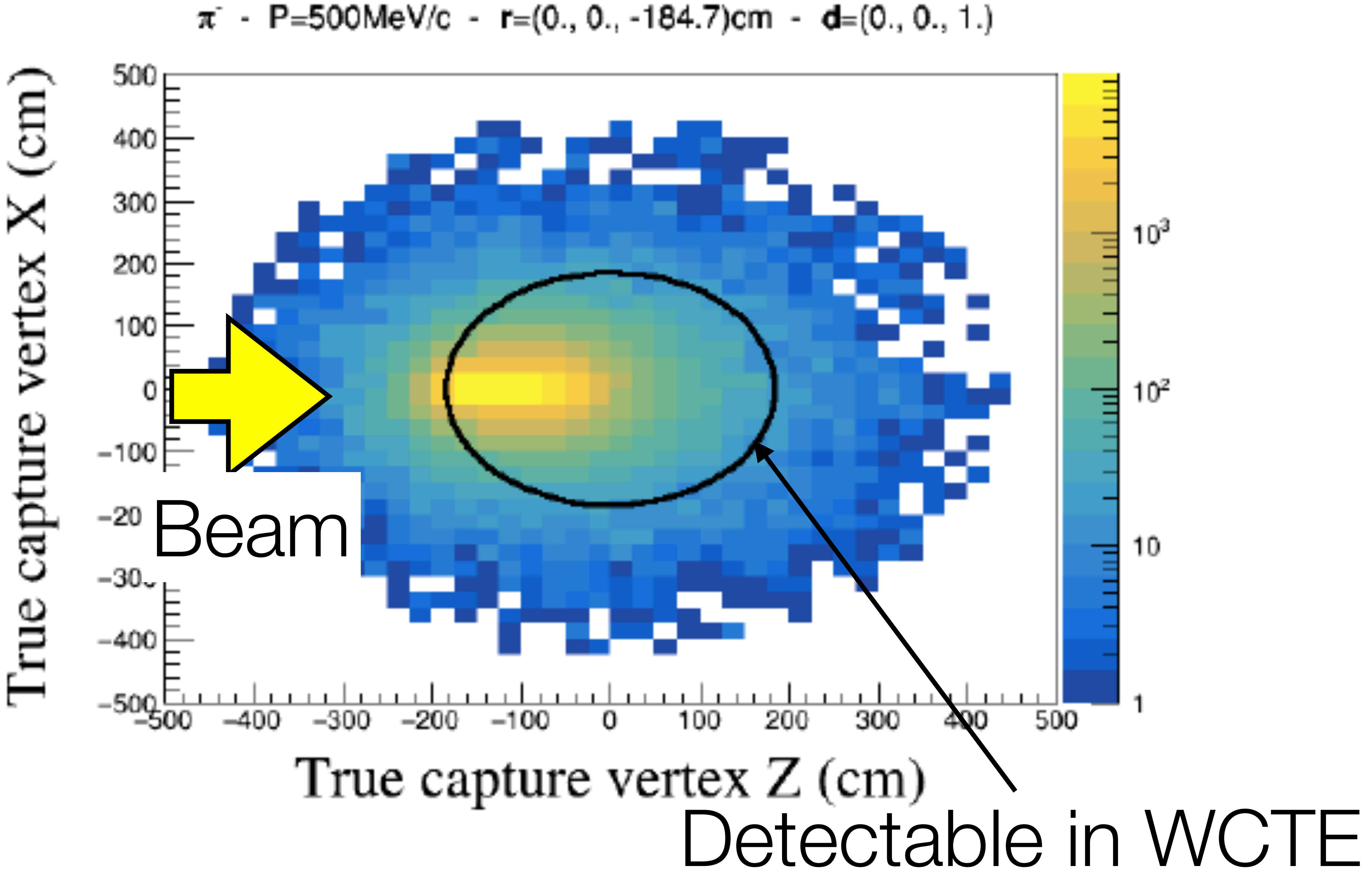
Accumulate ~20 events per spill in each of these bins

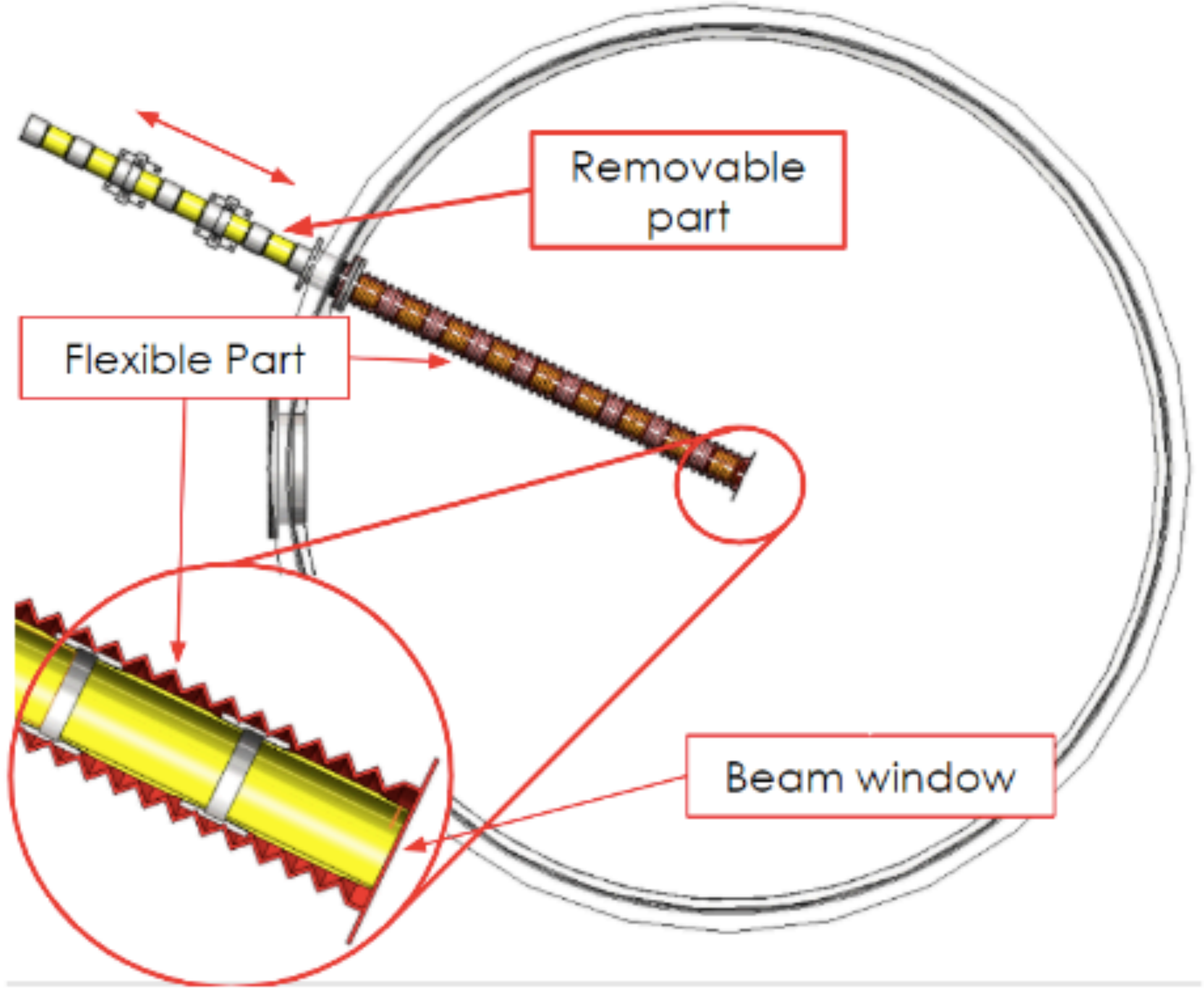
~200,000 events in planned 10,000 spills

- 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

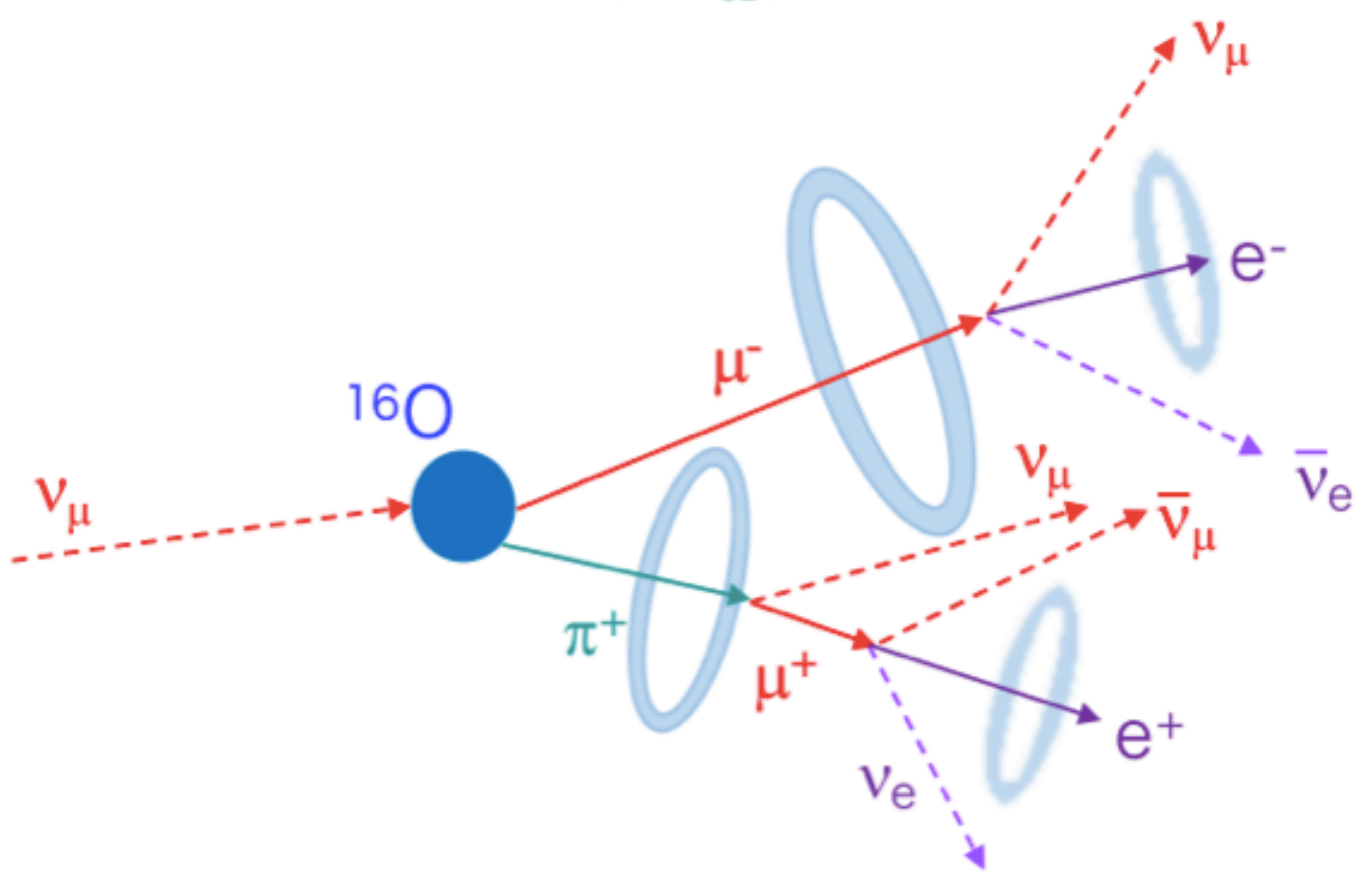




- For protons entering at edge of tank, we contain and detect ~60% of neutrons
- To increase detection of backward produced neutrons, also study protons in secondary beam configuration
  - With beam pipe, can inject protons into center of tank and detect backwards produced neutrons

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:

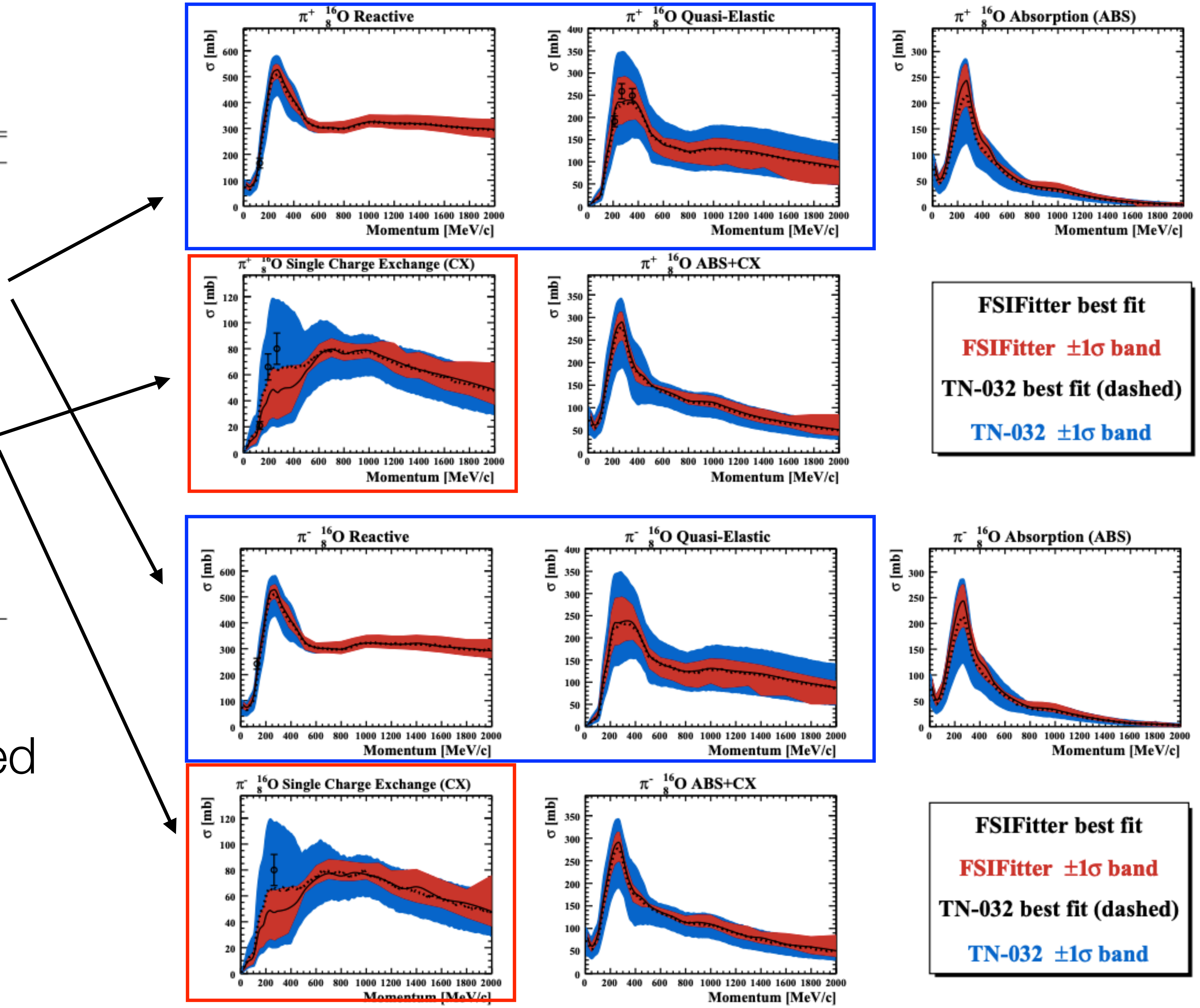
$$E_{\text{rec}}^{\nu_\mu CC\Delta^{++}} = \frac{2m_p E_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2\left(m_p - E_\mu + |\boldsymbol{p}_\mu|\cos\theta_\mu\right)},$$

- 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

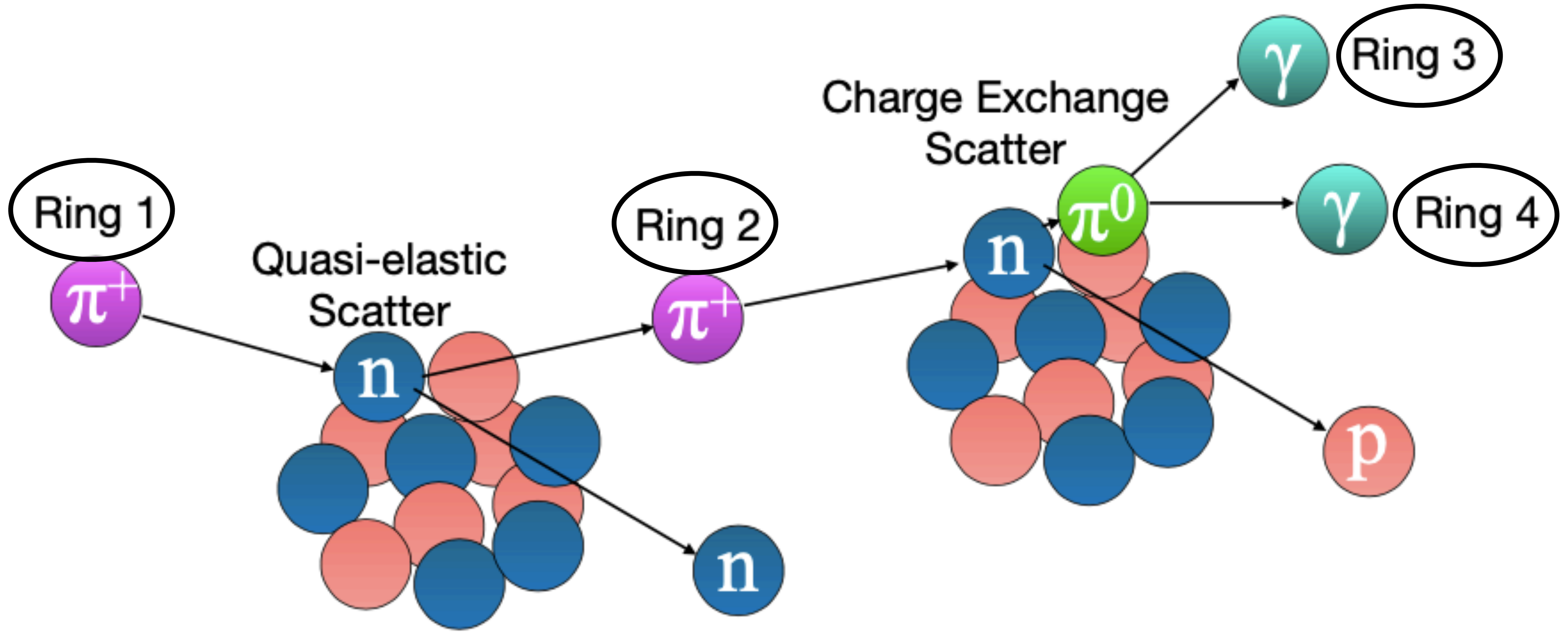
T2K Thesis, E. Pinzon

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

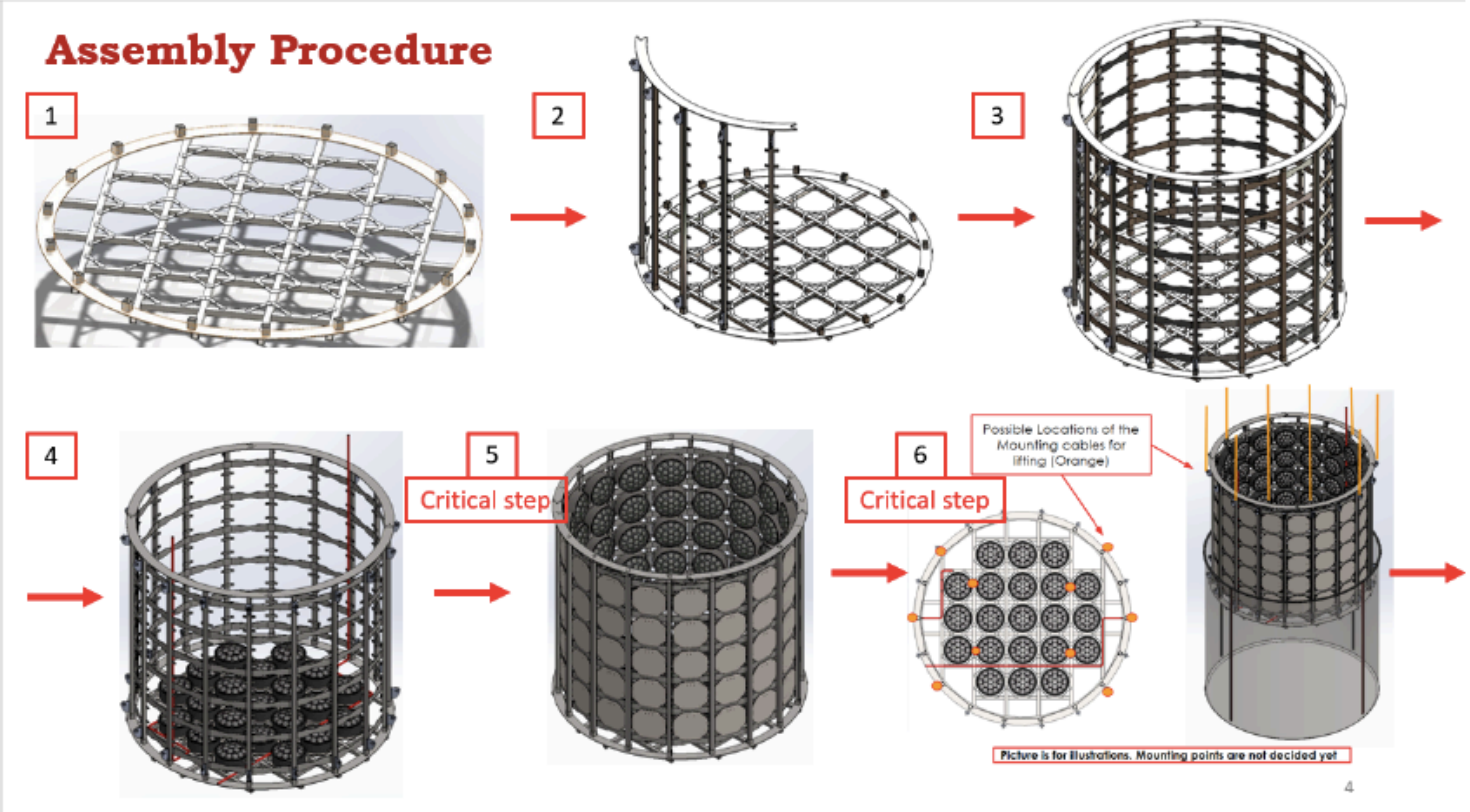
Pion Measurement in WCTE



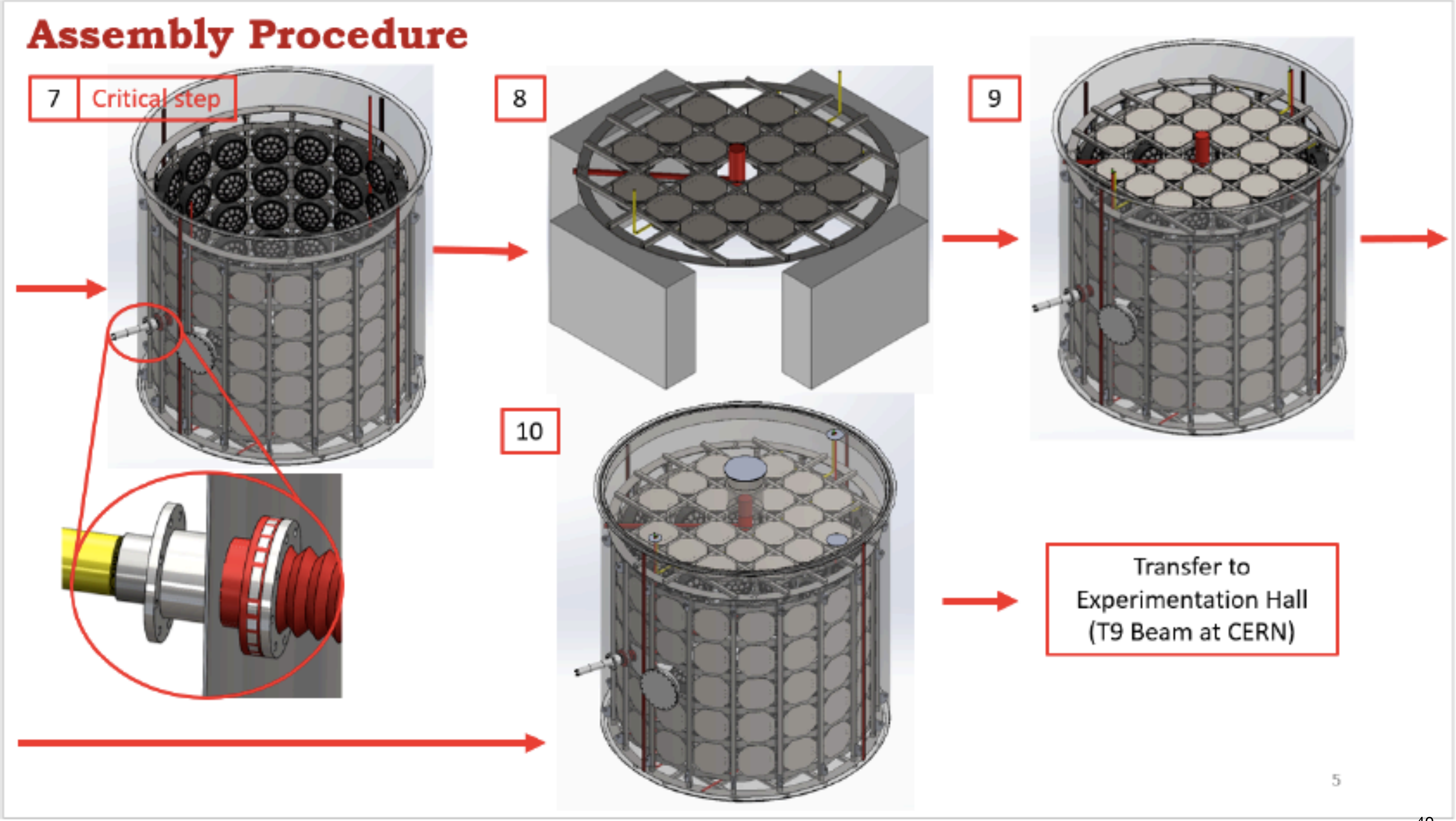
- We don't make pion interaction cross section measurements like one would do in a "thin" target experiment
- We measure impact of the full pion interaction chains on observables in detector
- For incoming pion of a given momentum measure:
  - Distribution of total visible energy
  - Distribution of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

Further Updates - Assembly Procedure

- We now include the proposed assembly procedure in the proposal
- Assemble detector outside of T9 area and then move into T9
- There is an assembly area in the same building as T9 that can be used

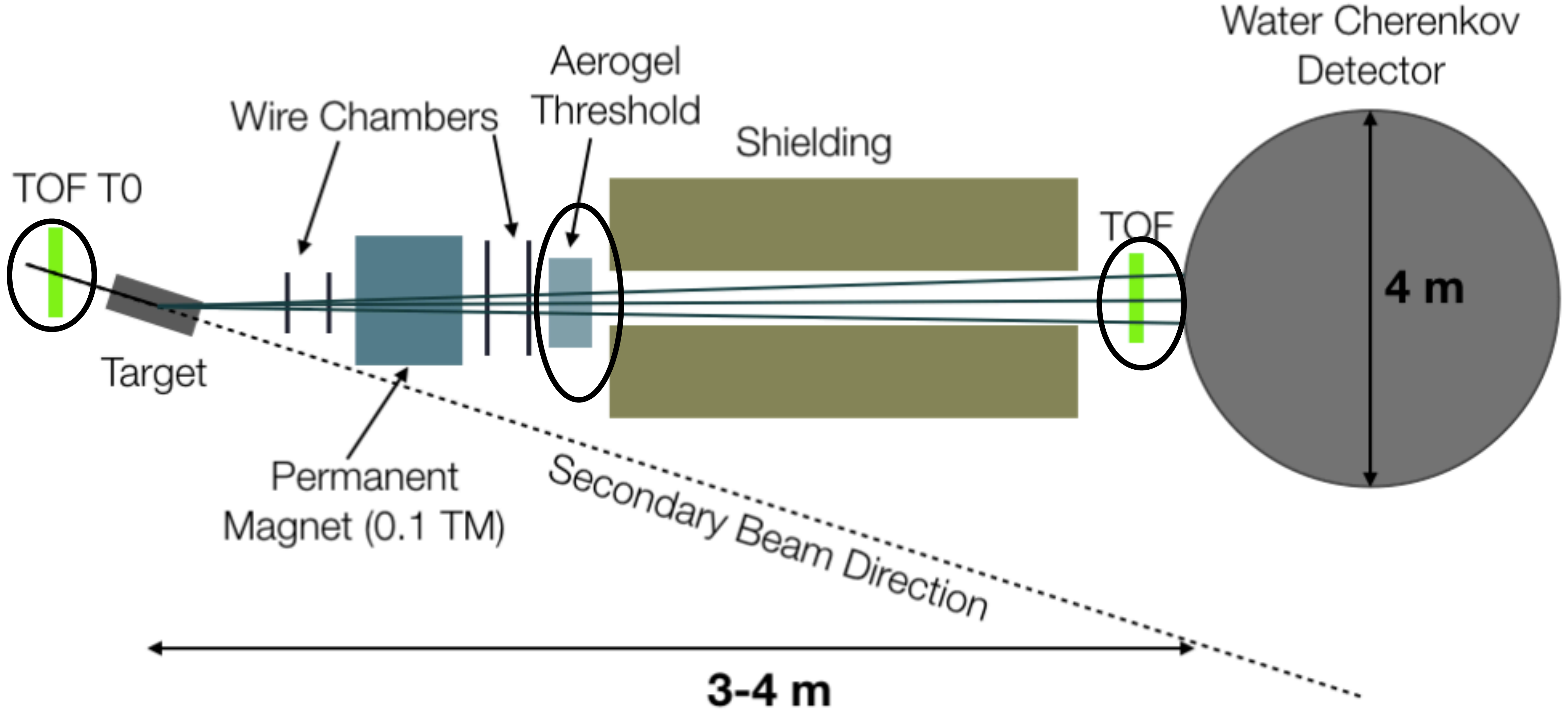


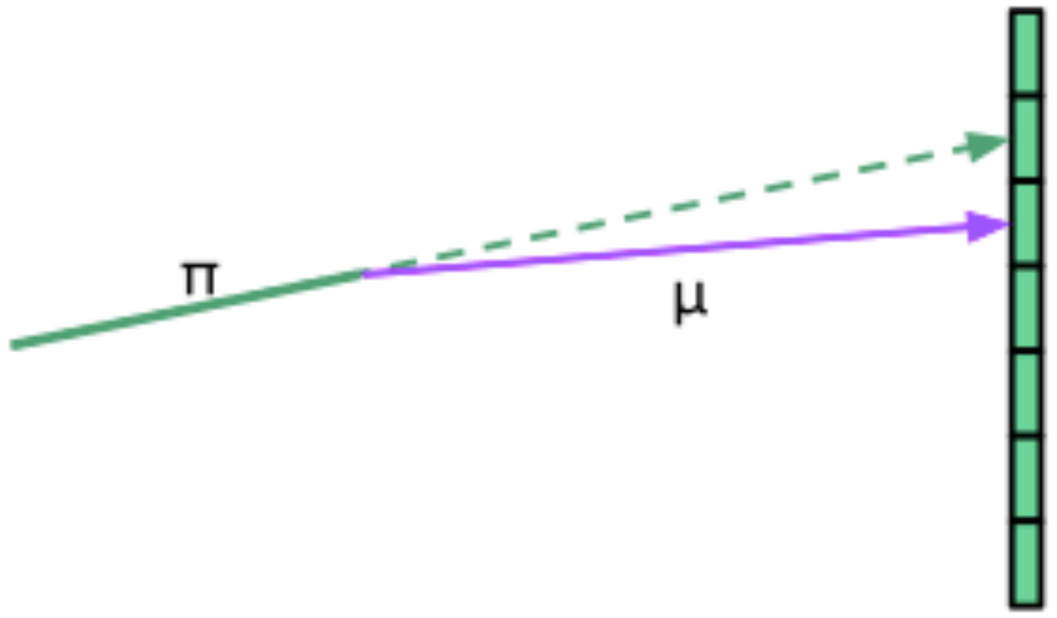
Further Updates - Assembly Procedure



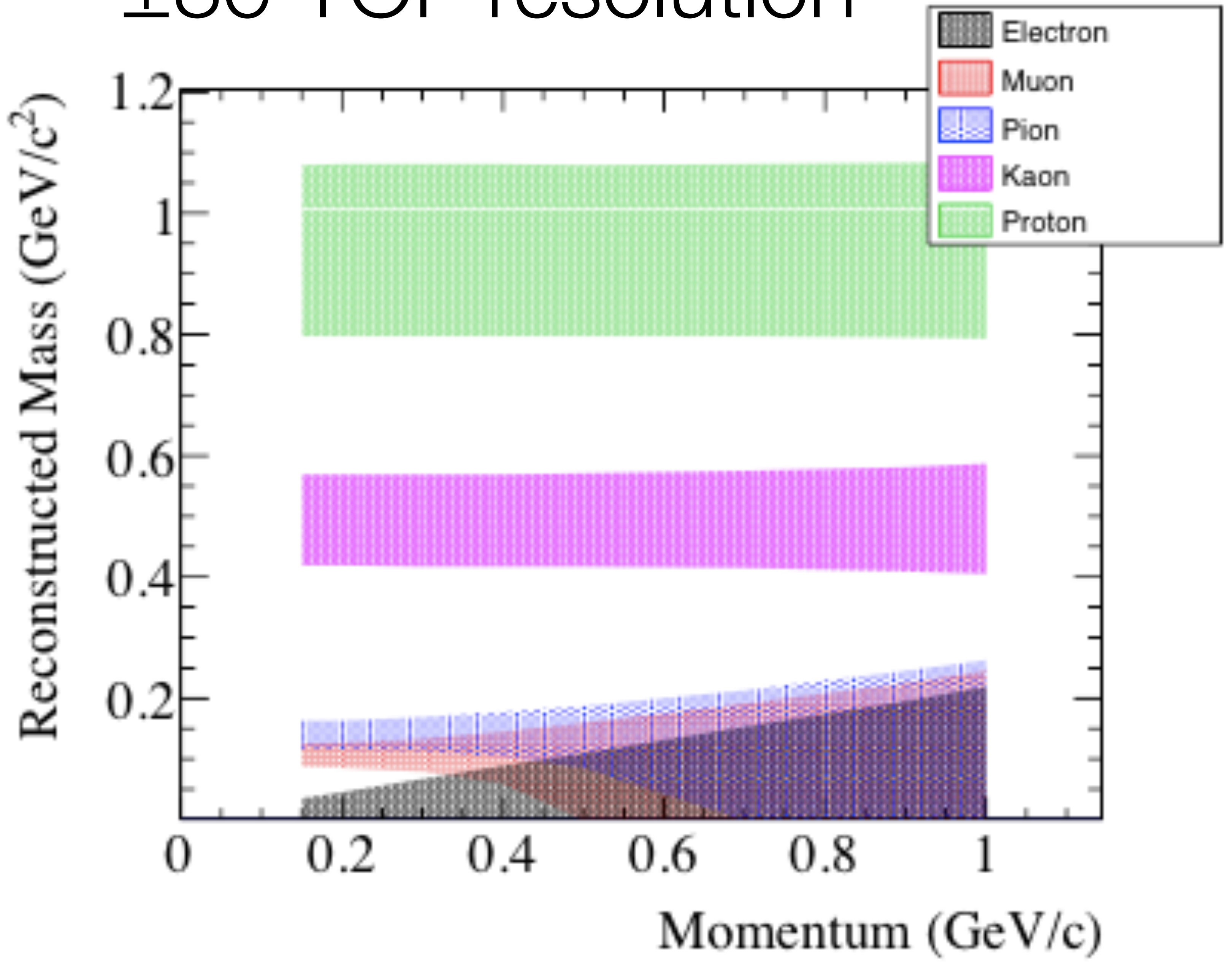
Particle Identification

- 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





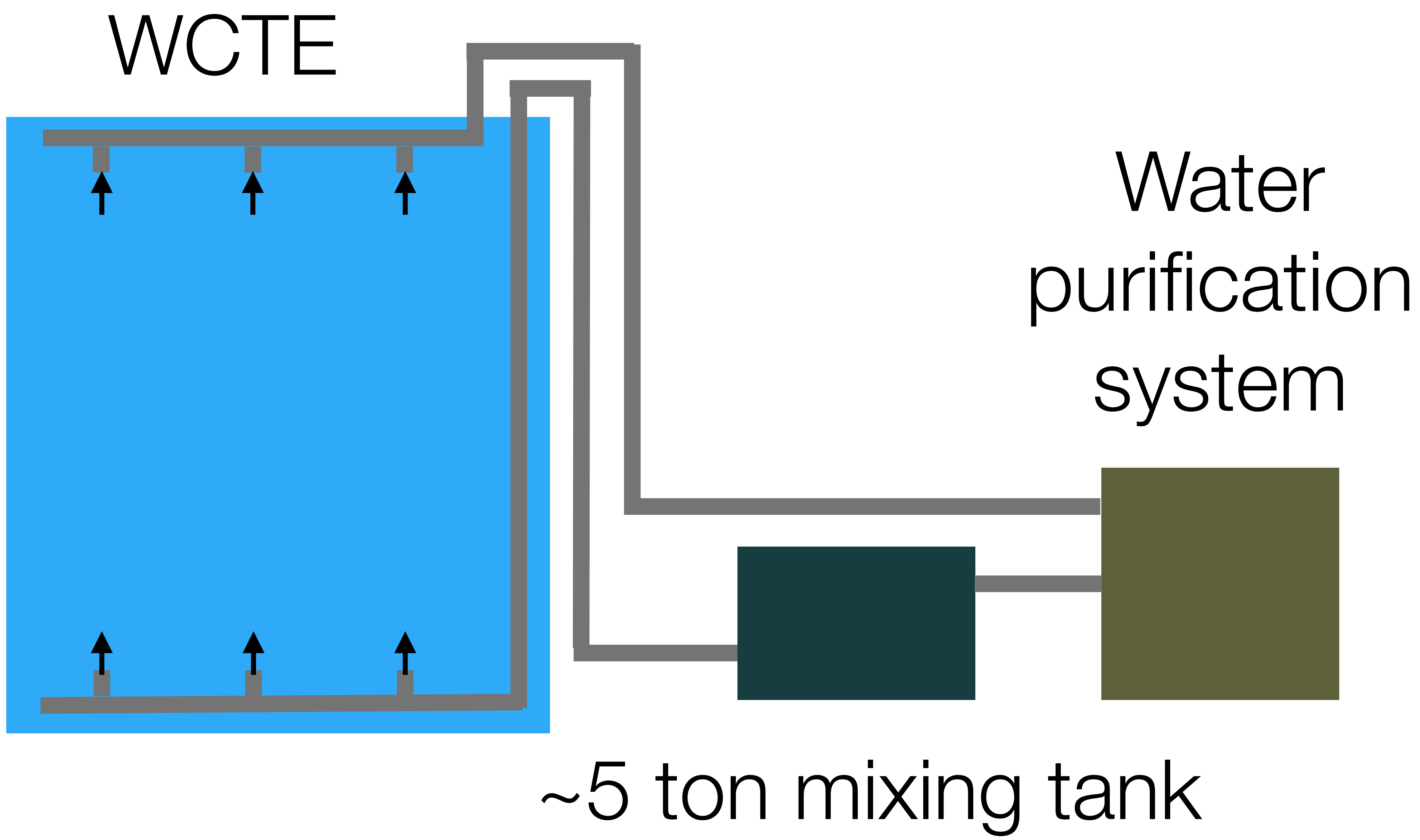
±3σ TOF resolution



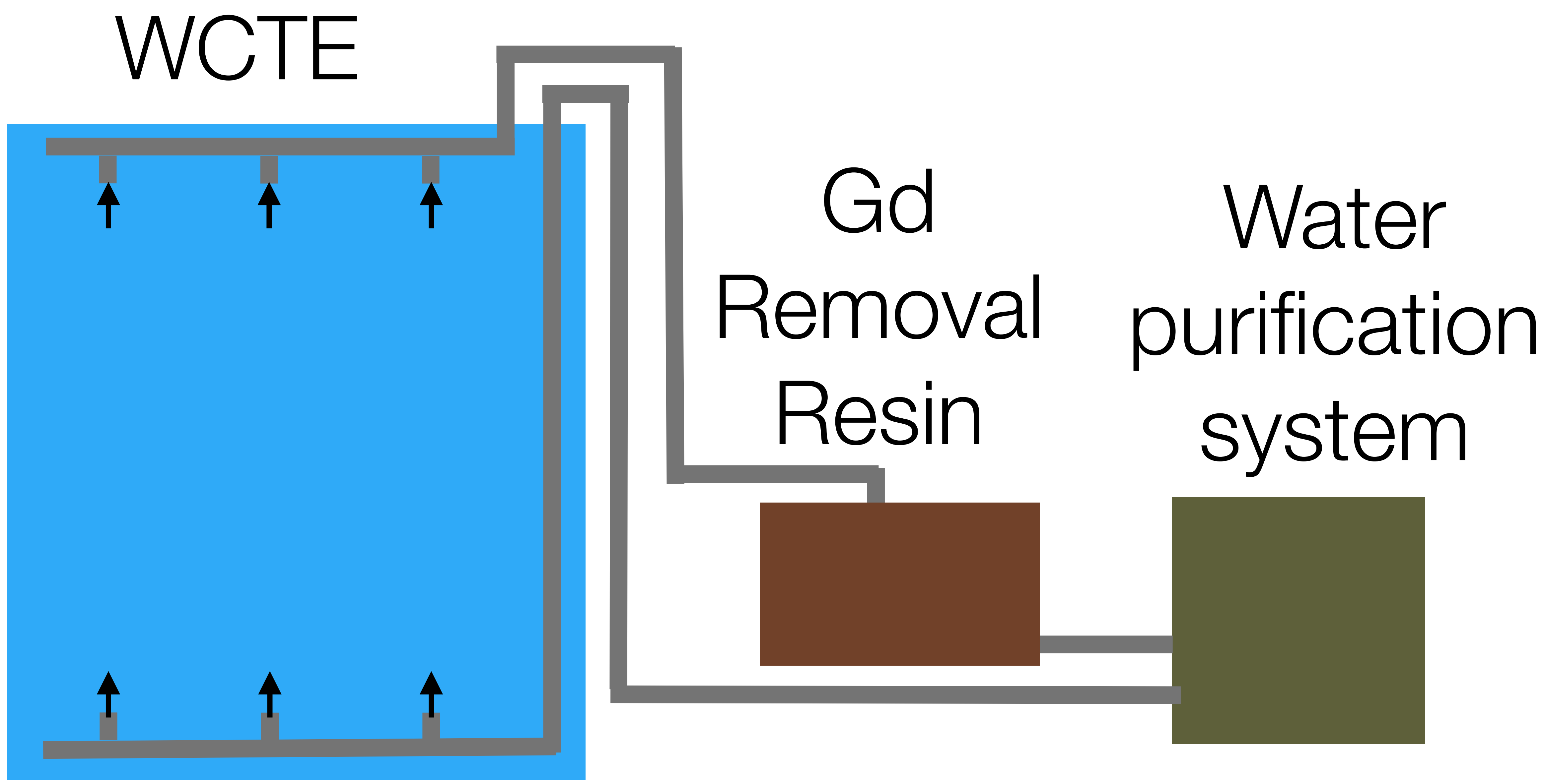
WCTE Water System - Gd Loading Phase

- 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

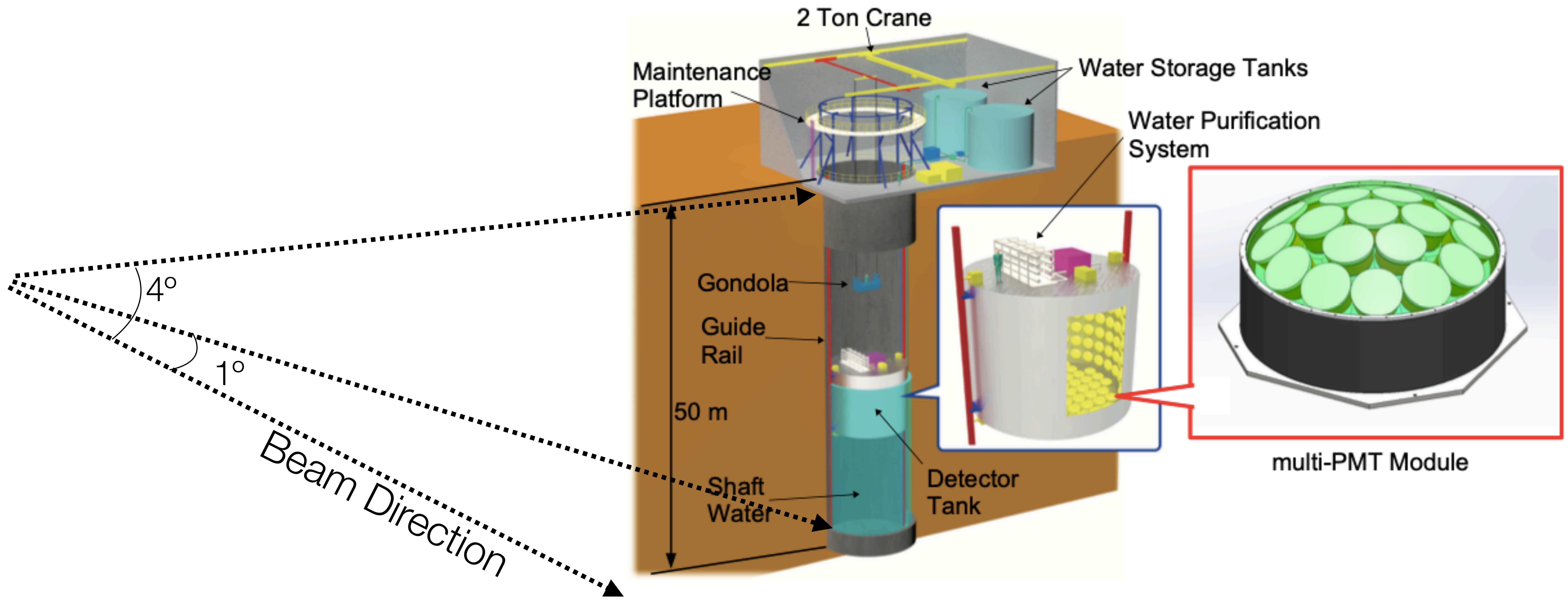


Removing Gd



WCTE Motivation

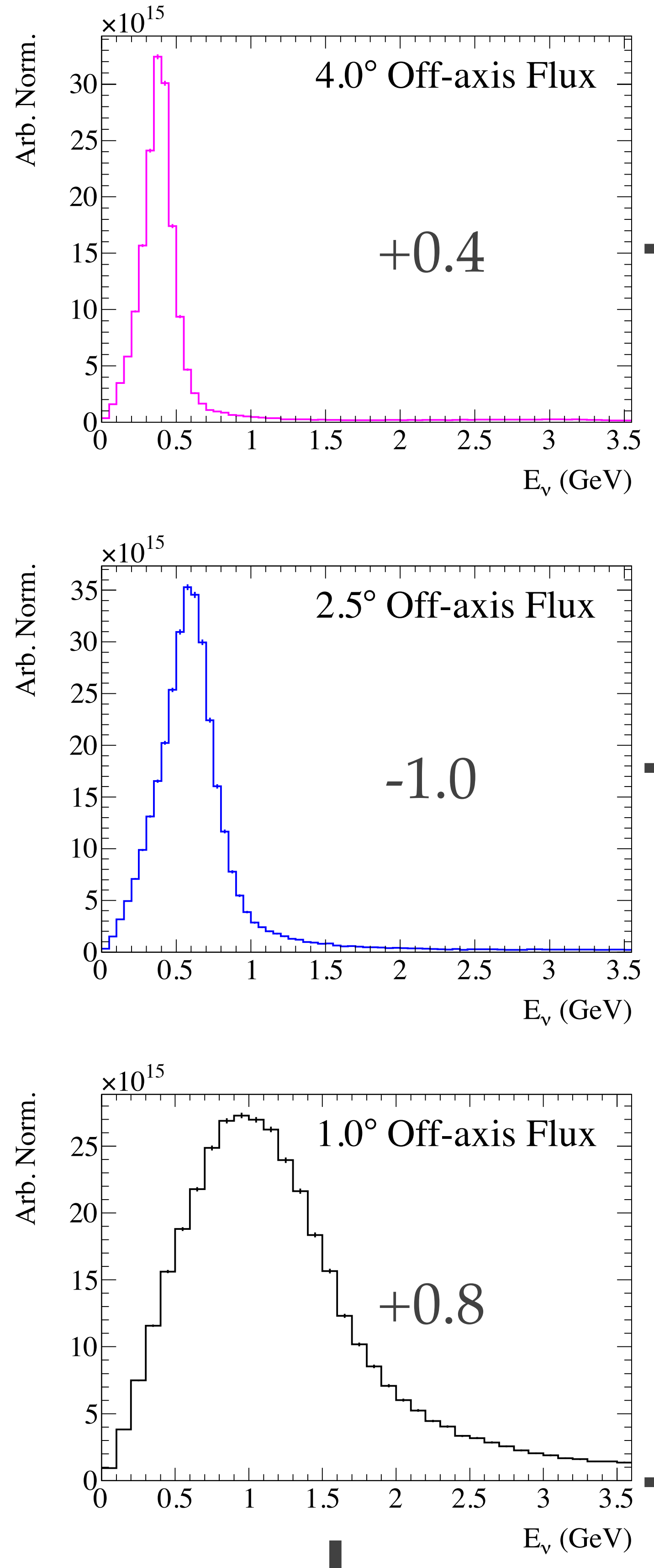
- Original motivation for water Cherenkov test experiment driven by planned Intermediate Water Cherenkov Detector (IWCD) for Hyper-K



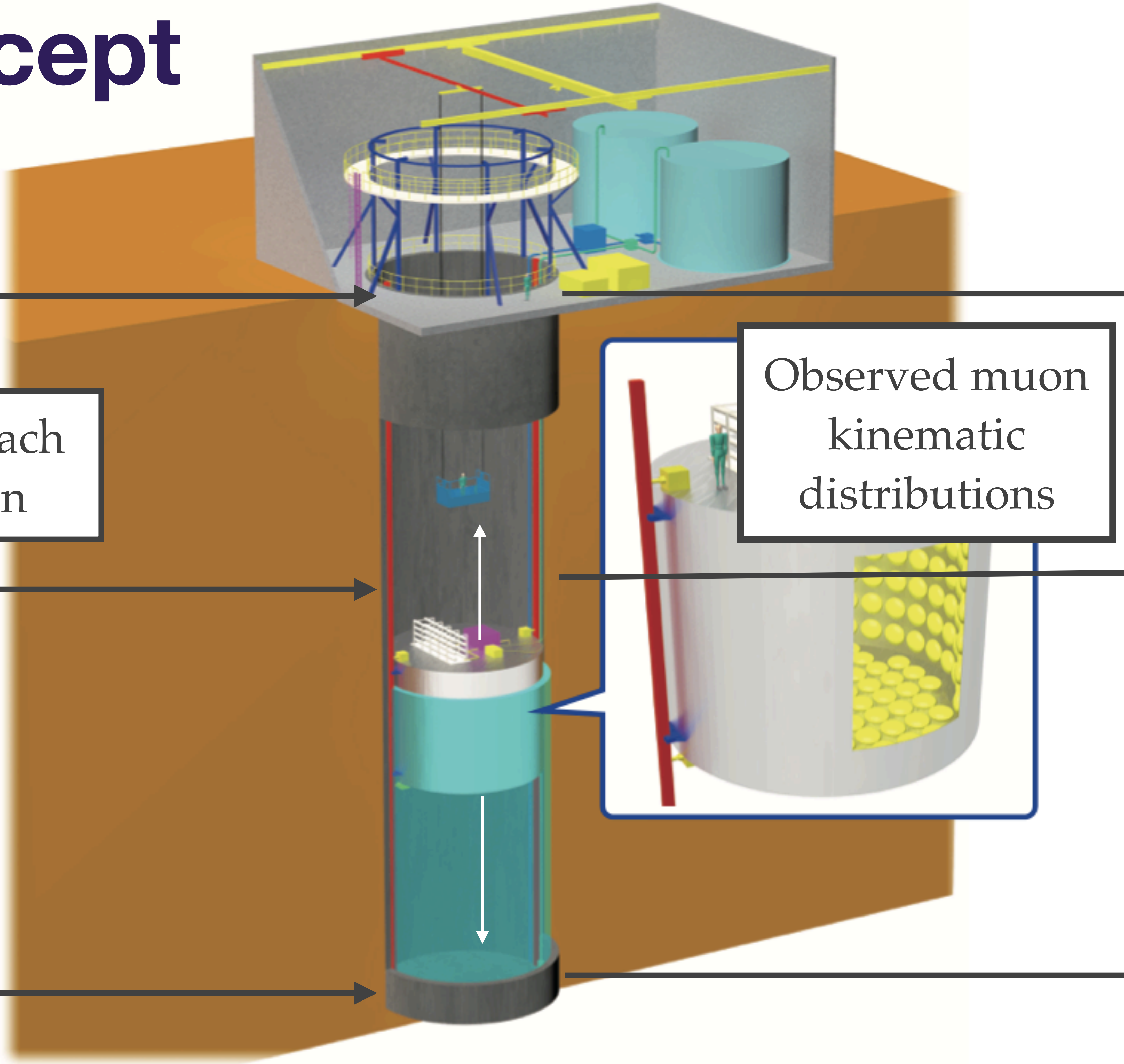
- Kilo-ton scale water Cherenkov detector
- Requires 1% level calibration
- Implement new technologies, such as the multi-PMT photosensors

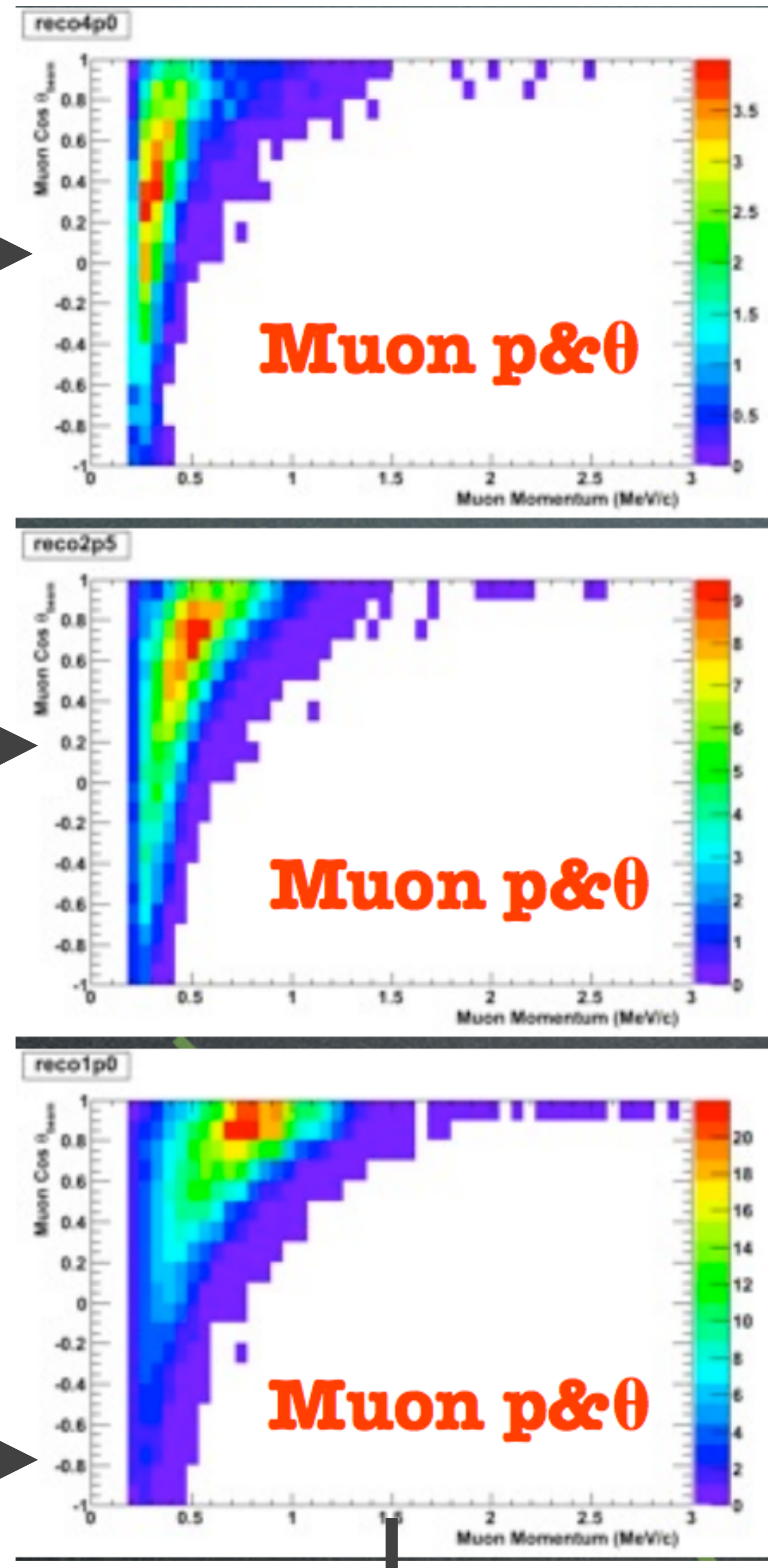
NuPRISM Concept

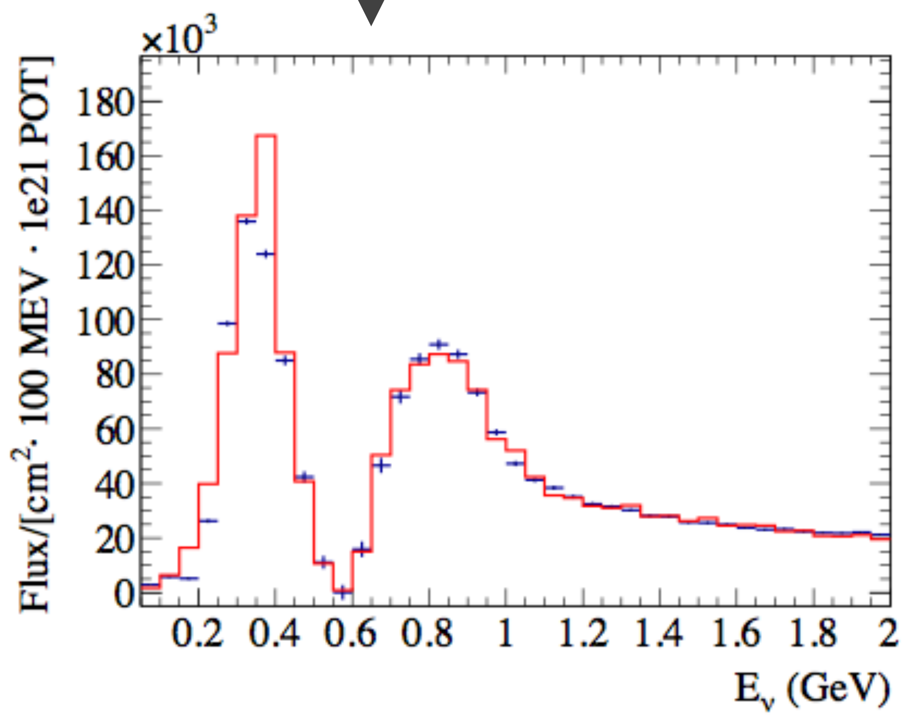
Hyper-Kamiokande



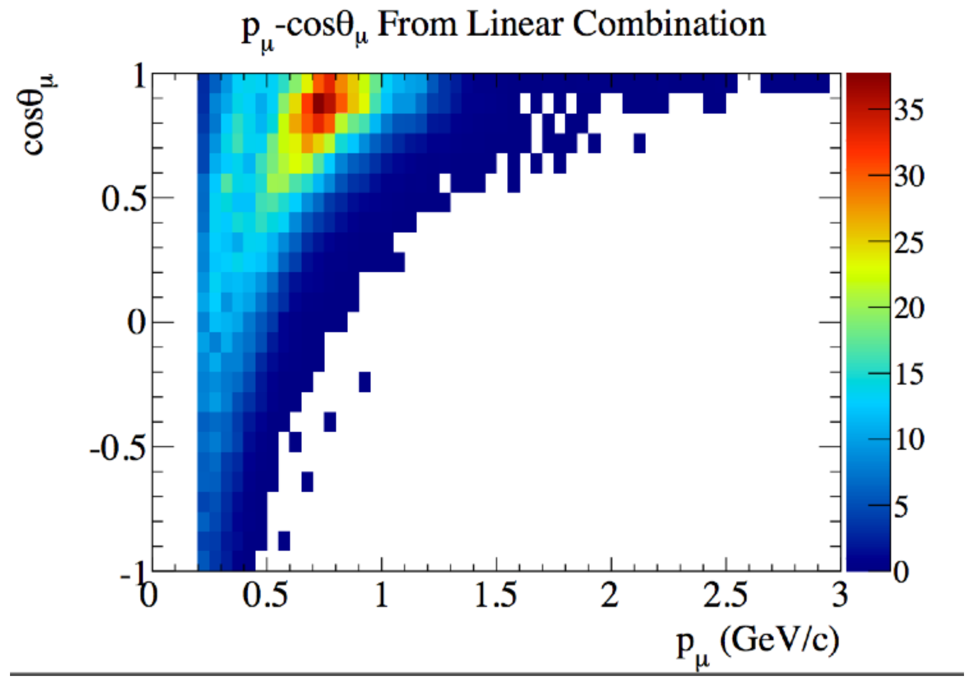
Spectra at each off-axis bin







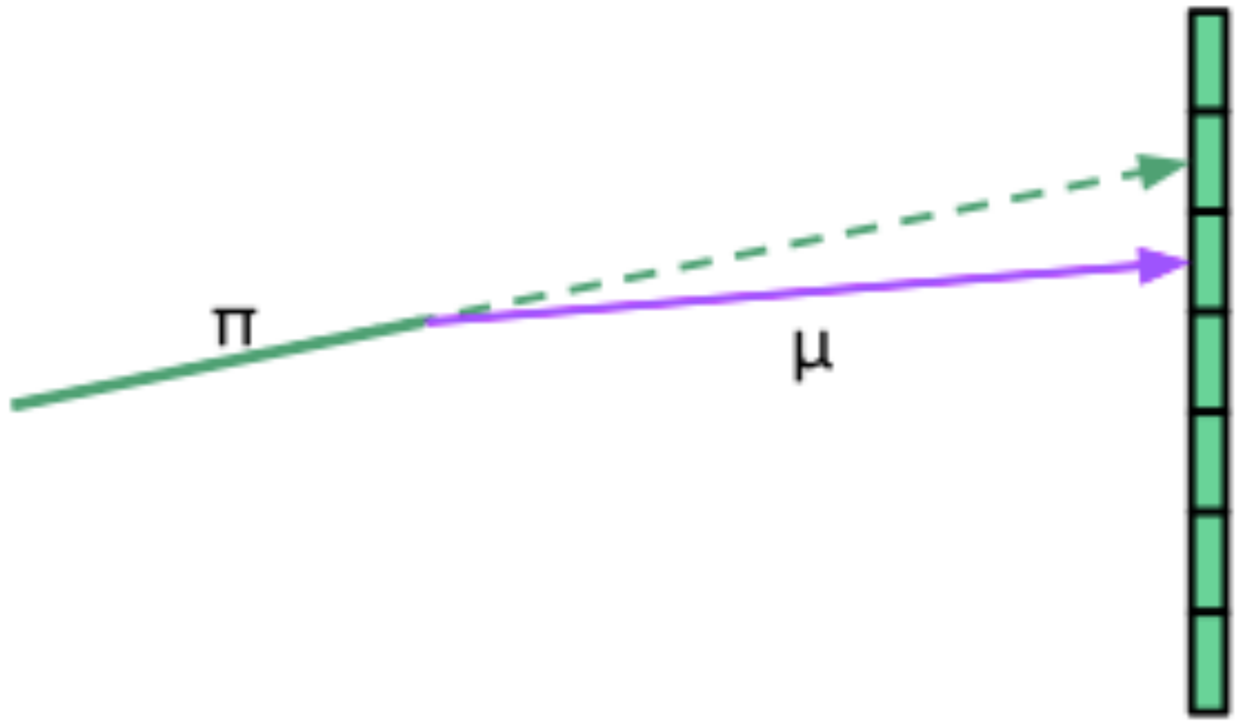
Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



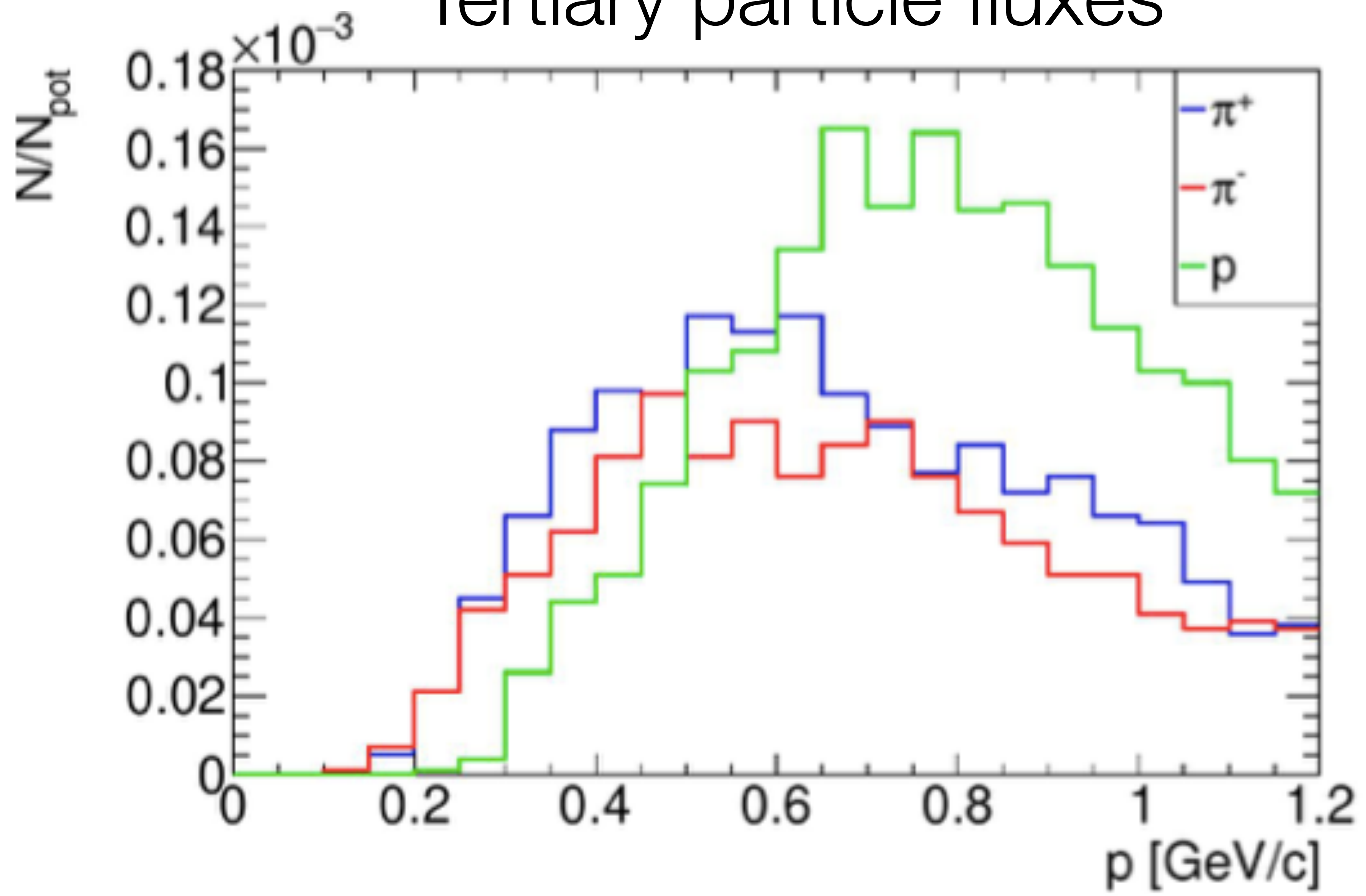
Need precise detector calibration at each position!

Particle Fluxes and PID for Tertiary beam

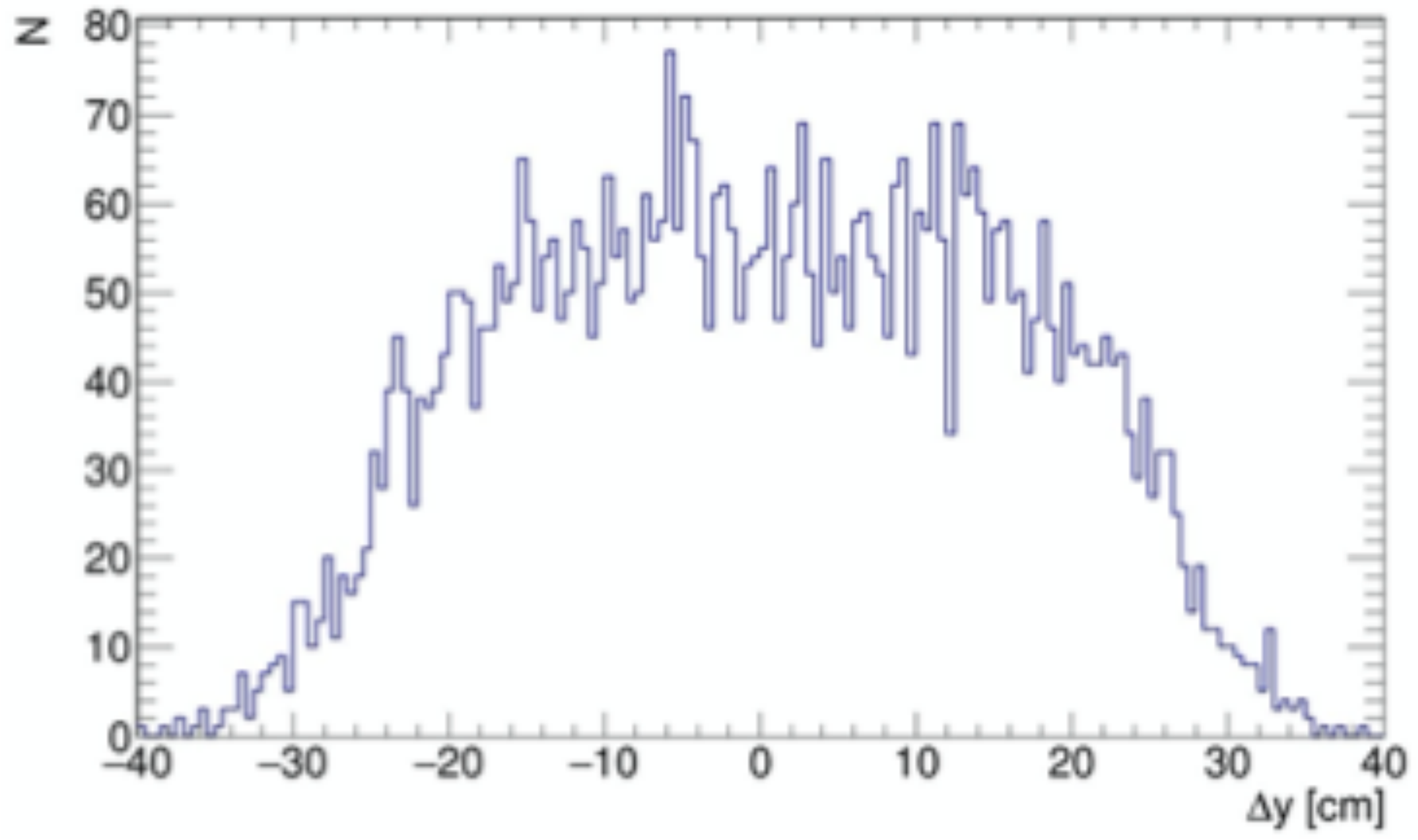
- Per 50 MeV/c bin, producing ~1e-4 particles of interest per protons on target
  - Per-spill POT can be as high as 5e6
- Significant pion fluxes down to ~200 MeV/c can be achieved
- Proton fluxes down to ~300 MeV/c
- Segmented TOF detector serves two purposes
  - Particle identification
  - Measures kinks in tracks from spectrometer to identify pion decay-in-flight



Tertiary particle fluxes

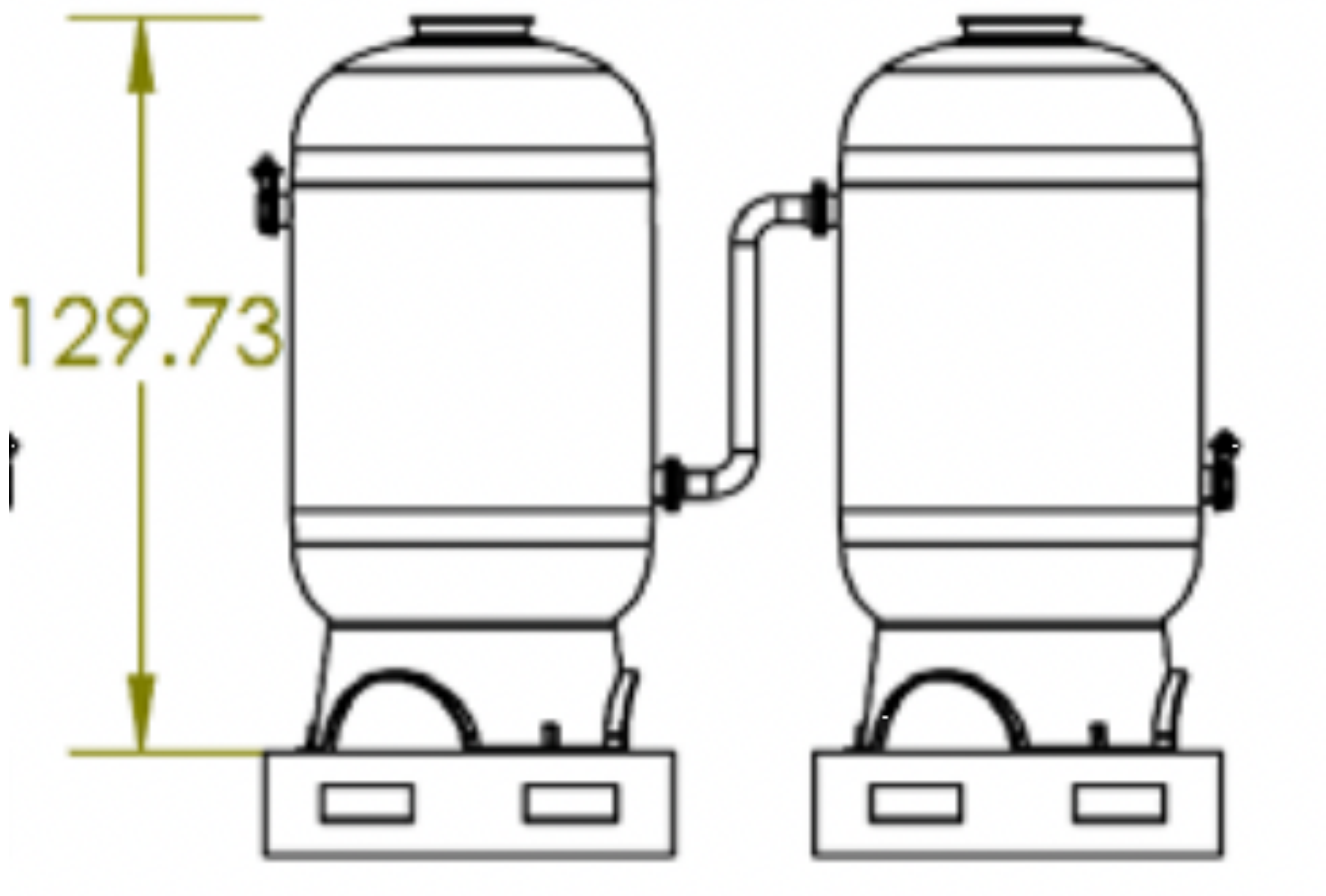


Displacement at TOF due to decay-in-flight

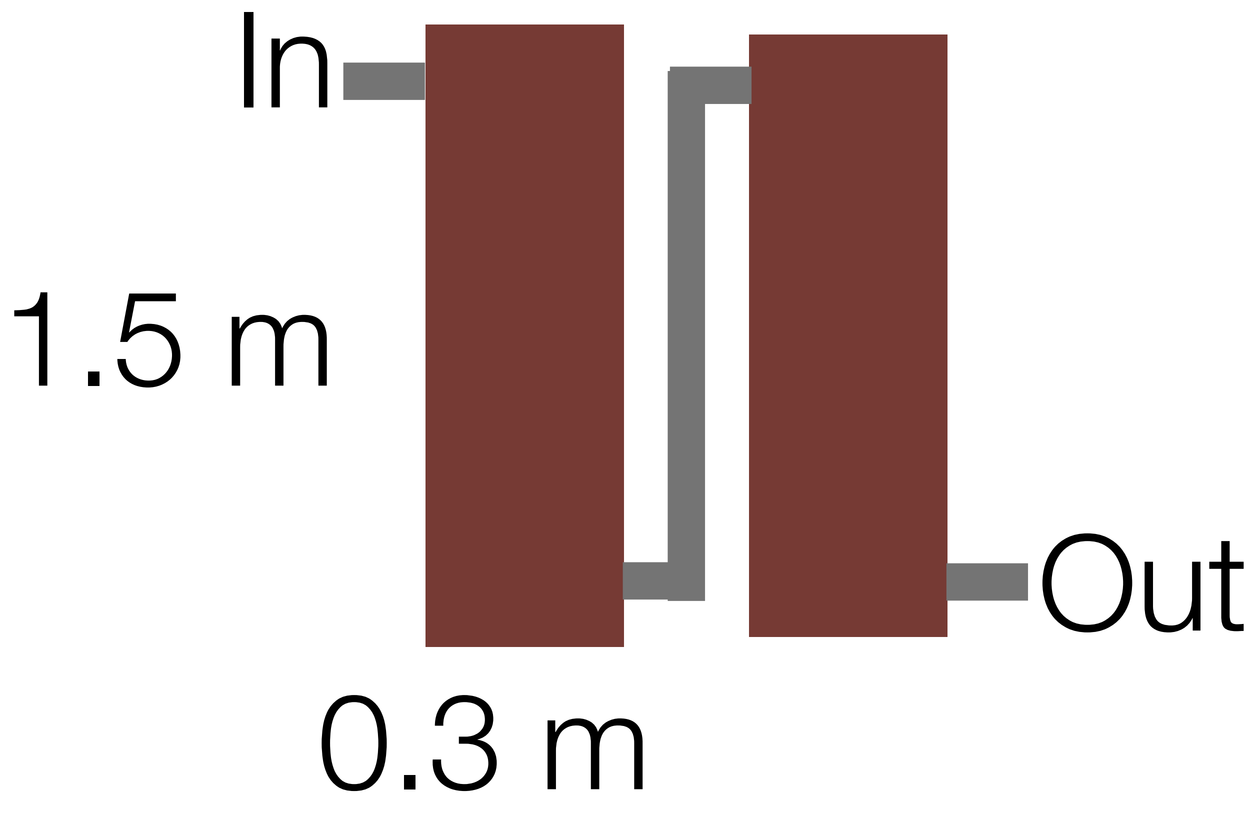


Gd Removal

- 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