Hyper-Kamiokande

Hyper-K IWCD

- Intermediate Water Cherenkov Detector -

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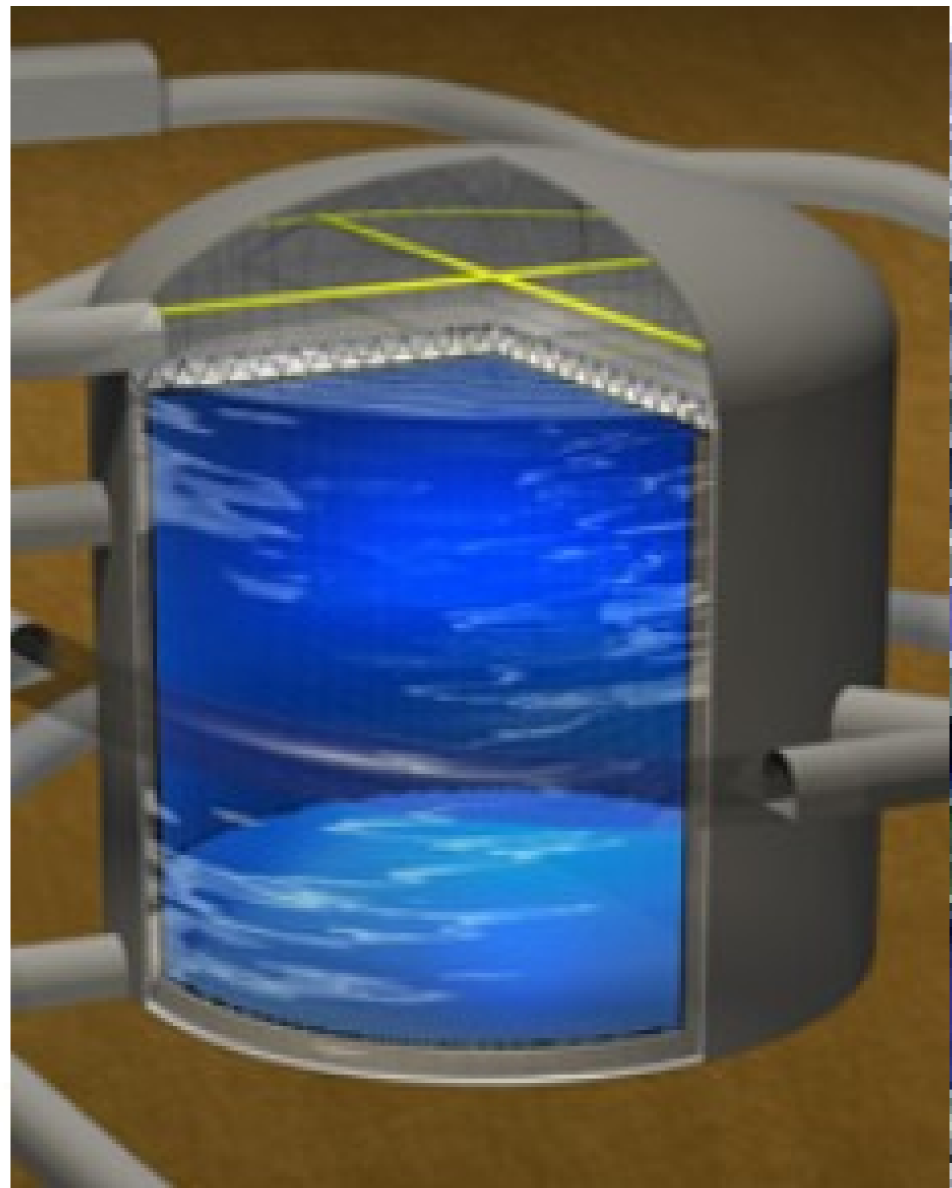
TRIUMF

The Hyper-K long-baseline program



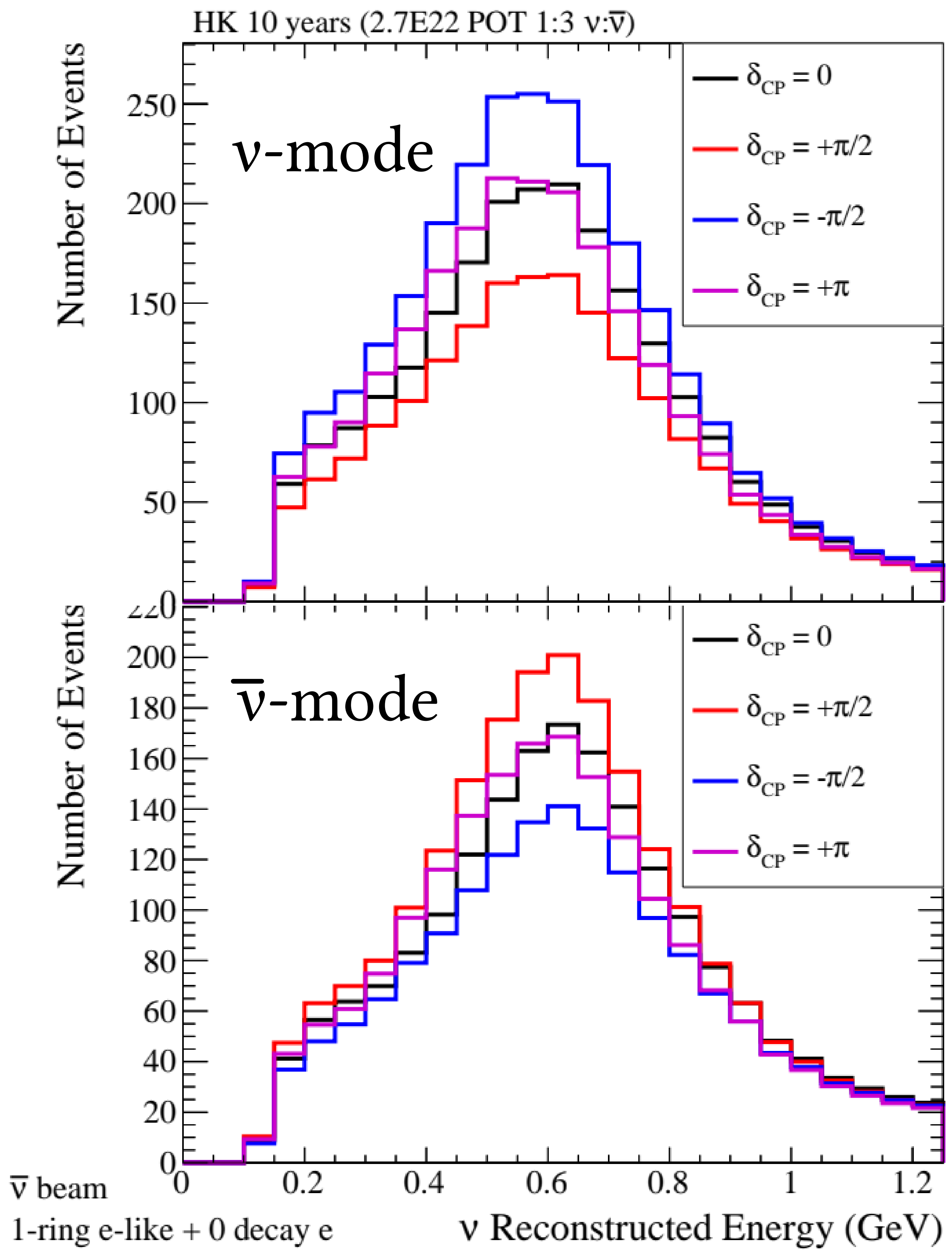
The Hyper-K detector

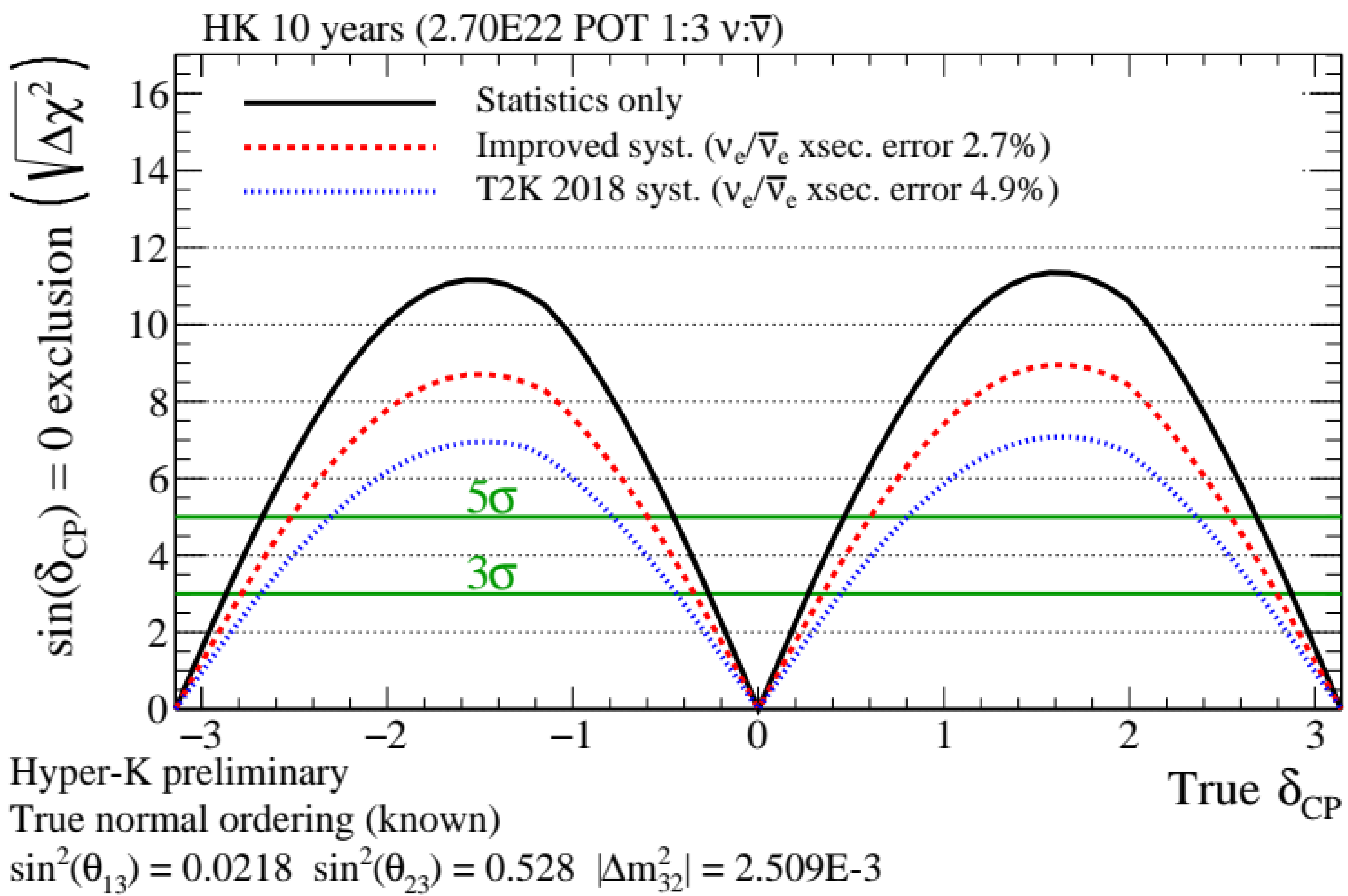
◆ Will study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations to search for CP violation, following the successful T2K experiment

◆ Will have 2.5 x more intense beam and 8 x higher fiducial mass of the far detector

◆ Interaction rates will be 20 x higher than the T2K's one $\Longrightarrow$ Measurements will be systematically limited

ν_e and $\overline{\nu}_e$ cross-section uncertainties

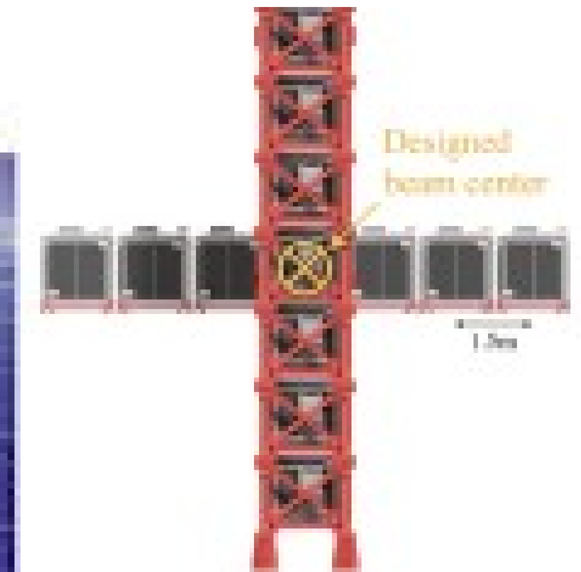


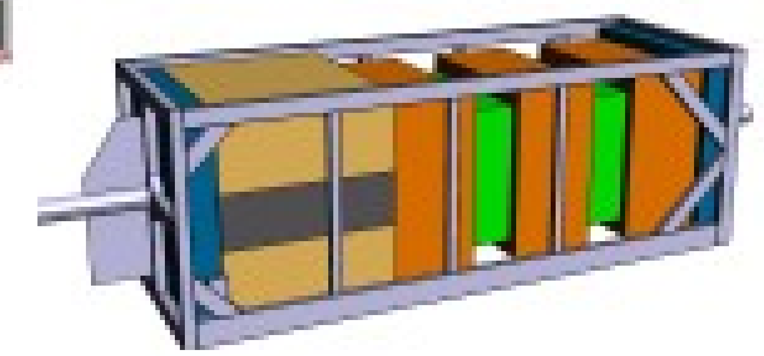


- The CP violation will be studied by essentially comparing observed ν_e and $\overline{\nu}_e$ event rates
- ν_e and $\overline{\nu}_e$ cross-section uncertainties will be dominant

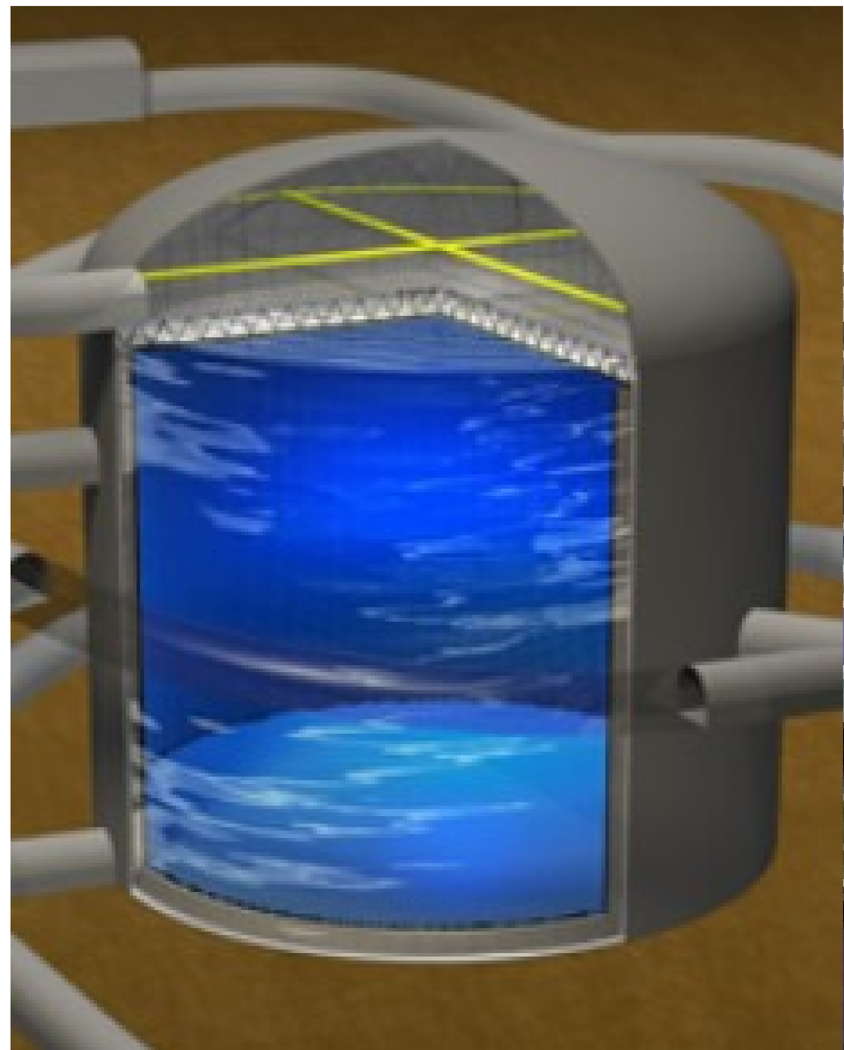
Intermediate Water Cherenkov Detector

Other near detectors @ 280m
- INGRID
- Upgraded ND280

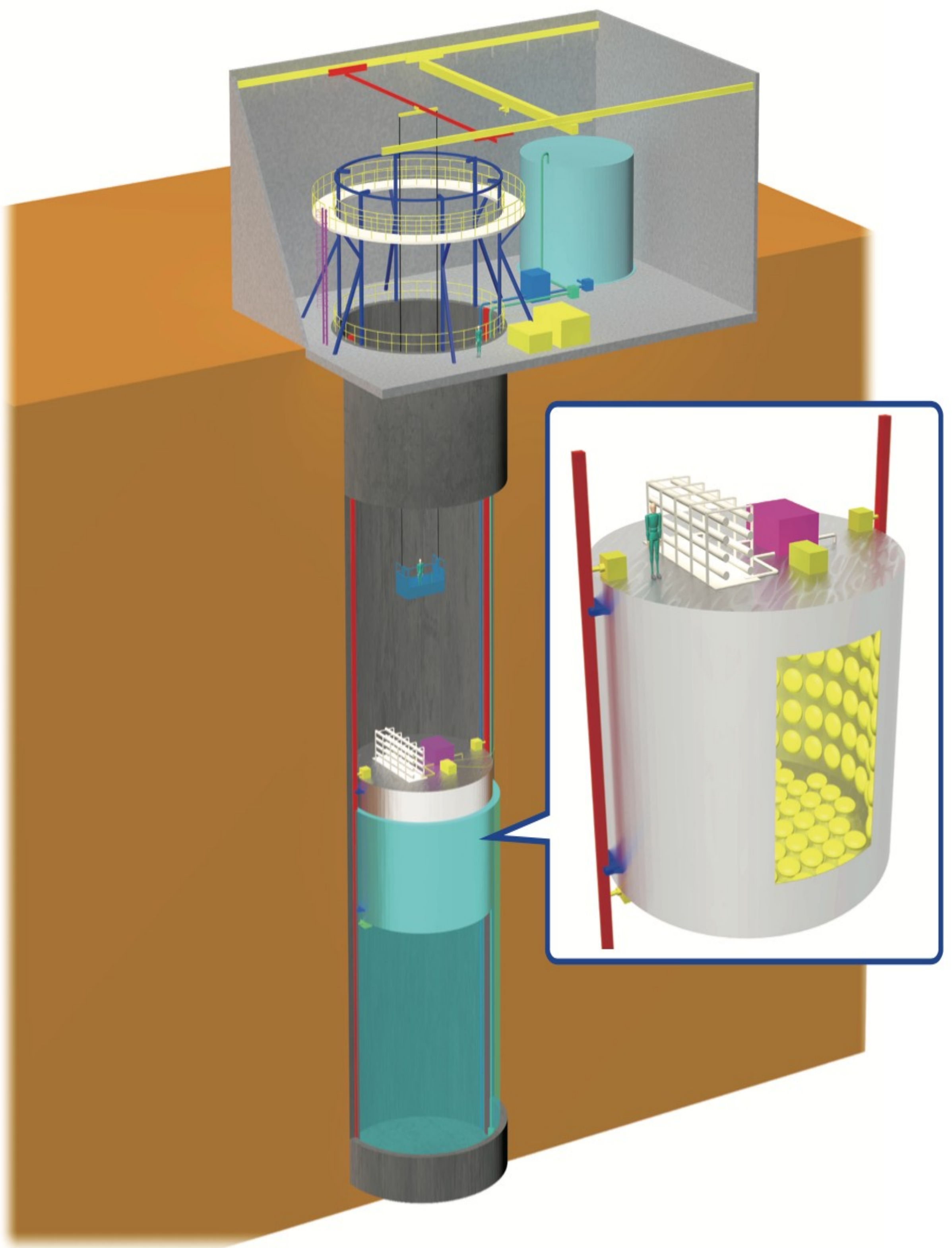




The Hyper-K detector



IWCD



@ ~1km

◆ Sub-kiloton scale water Cherenkov detector (Φ8m x 6m)

⟹ 480 photosensor modules inside the tank

⟹ 60 ton of fiducial volume

◆ Gadolinium loading option to add neutron detection capability

The vertically movable detector

◆ Neutrino energy spectrum depends on off-axis angle

◆ Taking data at different vertical positions provides true energy information

Active water shielding

◆ T2K results are suffering from large background events induced by external high energy γs

⟹ Reduction of this background is important

◆ IWCD has two regions that can serve as active shield for protecting the γ background

⟹ water volume in the pit

⟹ non-fiducial volume inside the detector

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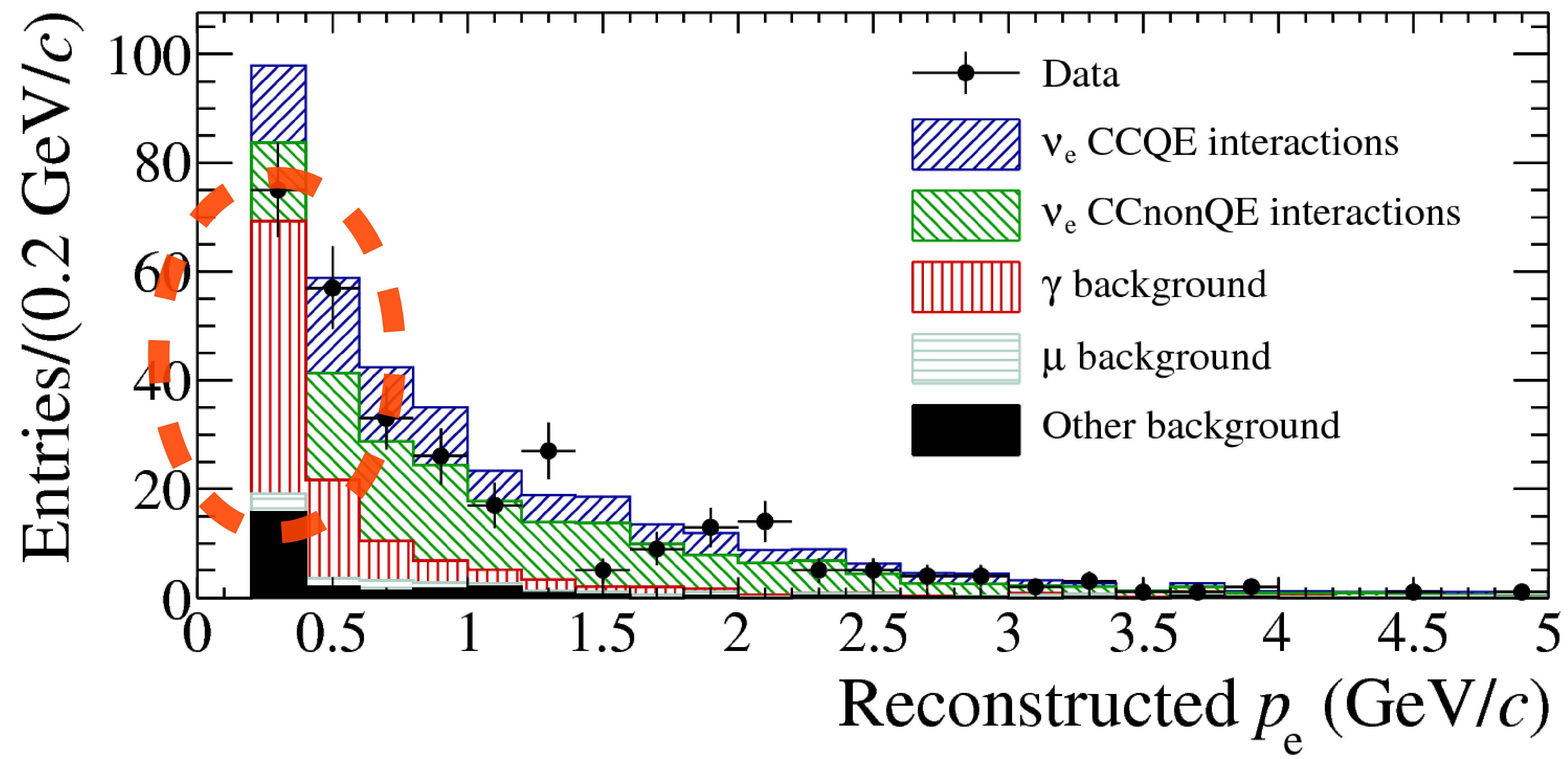
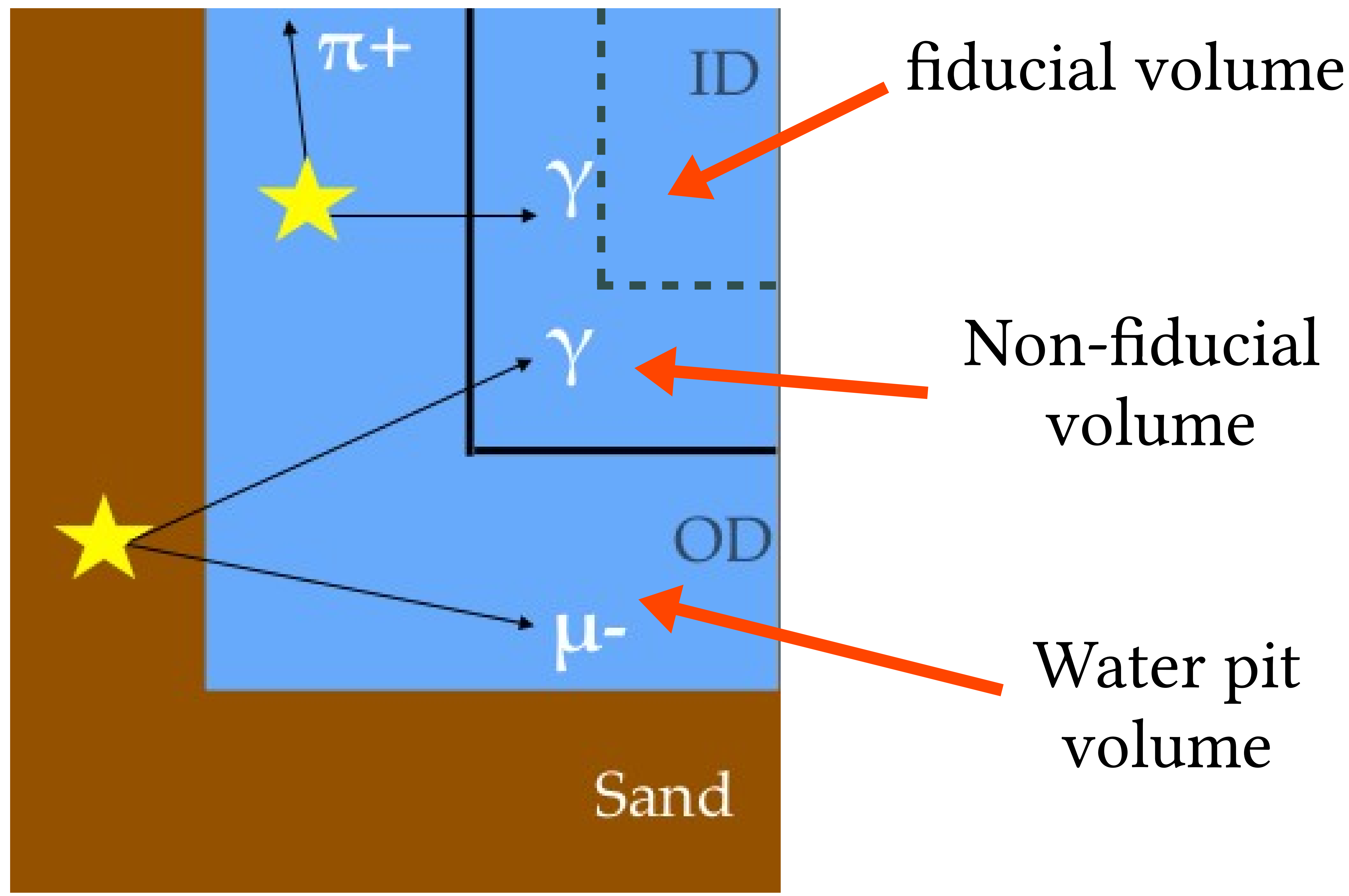




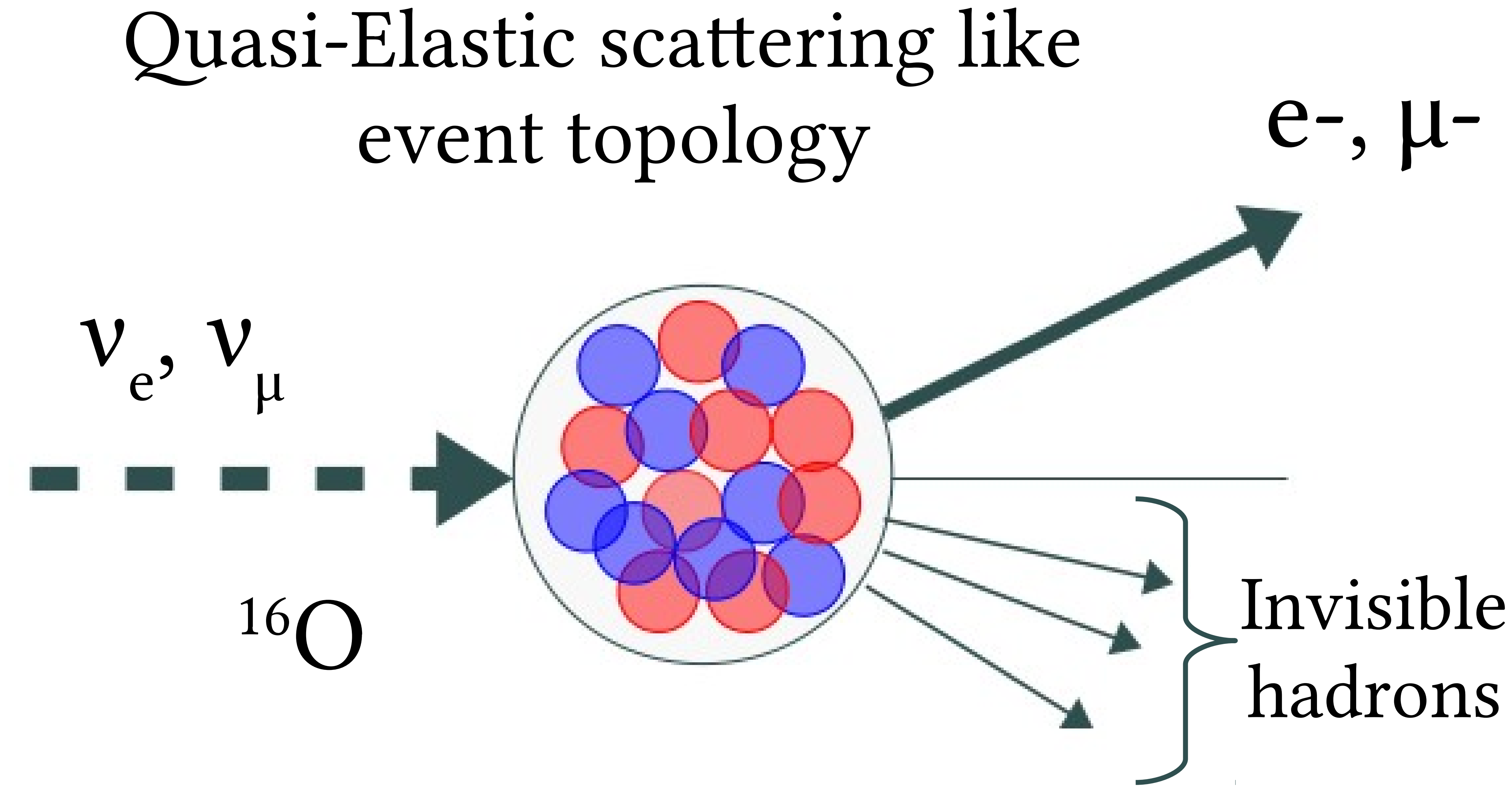
ν_e and $\bar{\nu}_e$ cross-section measurements

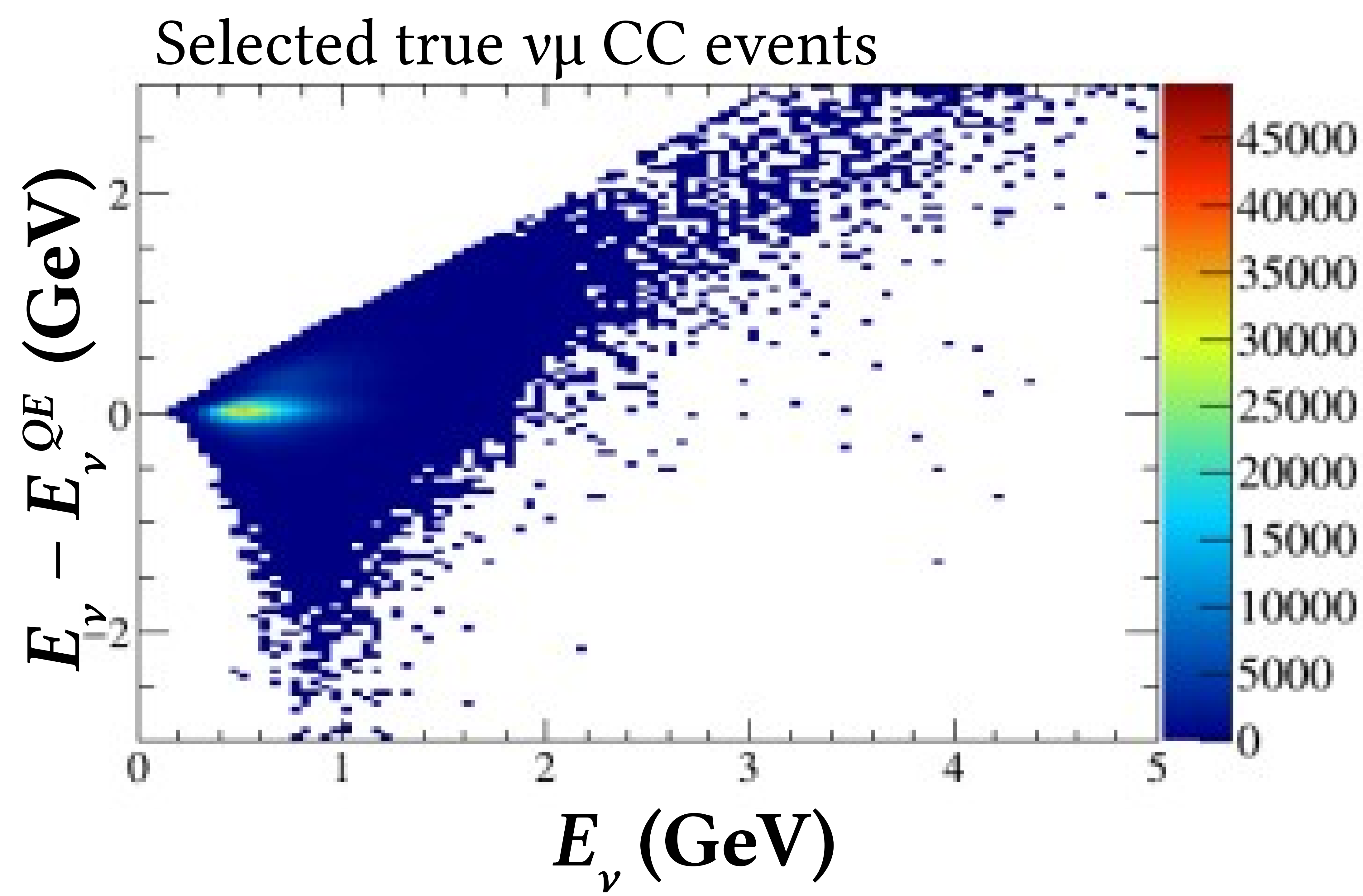
- About 1% of ν_e and $\bar{\nu}_e$ components in the beam can be identified
- Over 18,000 ν_e CC events enable a cross-section measurement binned in true energy
- Improved error on the ratio between the ν_e and $\bar{\nu}_e$ event rates at the far detector
  - ⇒ The true energy dependent constraints: **3.7%**
  - ⇒ T2K's theory based constraints: **5.0%**
  - ⇔ Statistical error: **1.4%**

Improving the constraints

- ν oscillations depend on true neutrino energy (E_ν)
- Water Cherenkov detector infers neutrino energy from lepton momentum and scattering angle, assuming QE interaction (E_ν^{QE})
- Want to constraint ν_e and $\bar{\nu}_e$ cross sections in terms of the relationship between E_ν and E_ν^{QE}, for the oscillation measurements
- In theory, ν_e and ν_μ have same cross section, except for the effects of the charged lepton mass difference

  $\Rightarrow$ Utilize the very high ν_μ event statistics to constraint the relationship

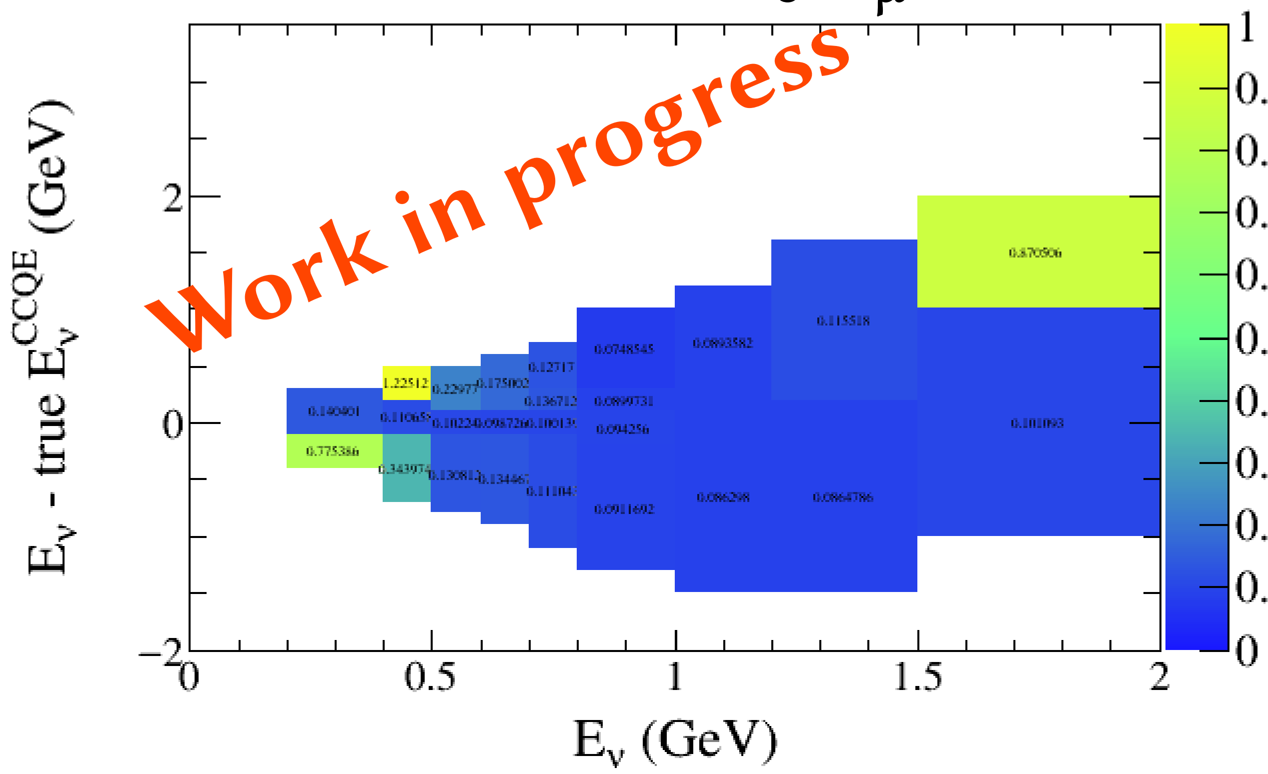




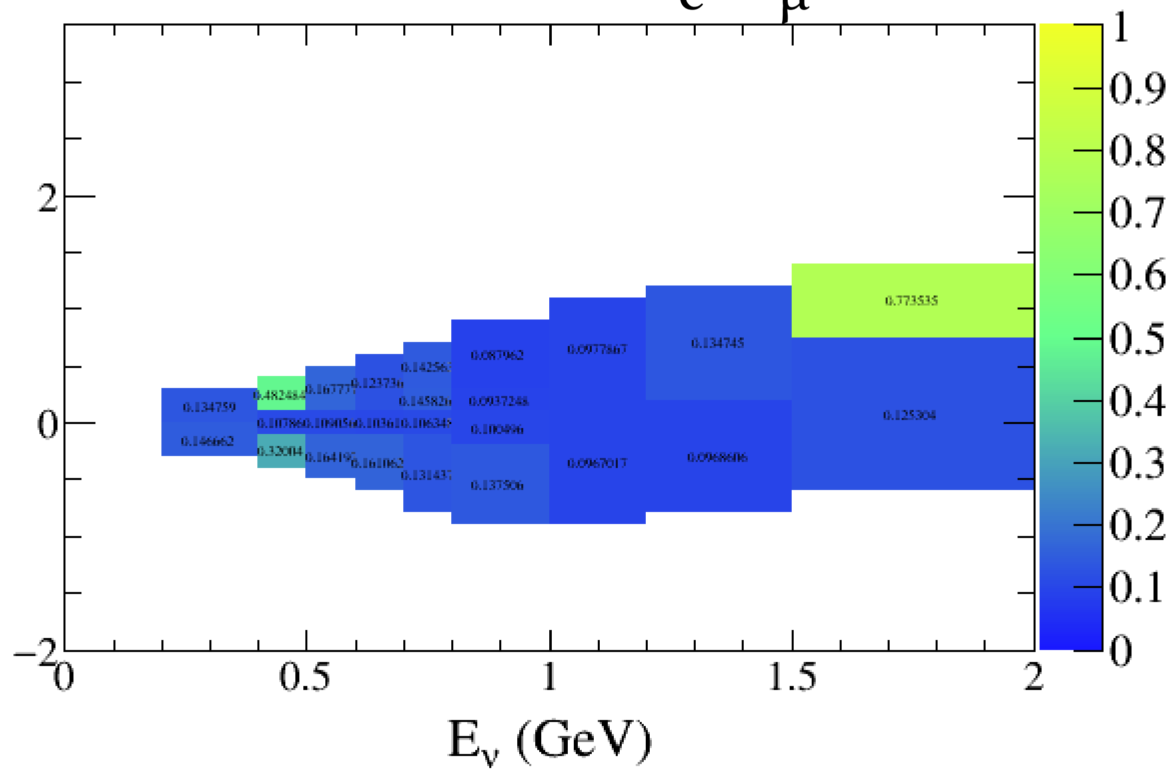
Constraints on E_ν and E_ν^{QE} space

- Common cross-section parameters are applied to both ν_μ and ν_e interactions.
- Additional parameters are applied to ν_e interaction only to account for the ν_e/ν_μ difference
- These parameters are fitted to IWCD events together with flux and T2K interaction model uncertainties and propagated to the far detector with the correlations

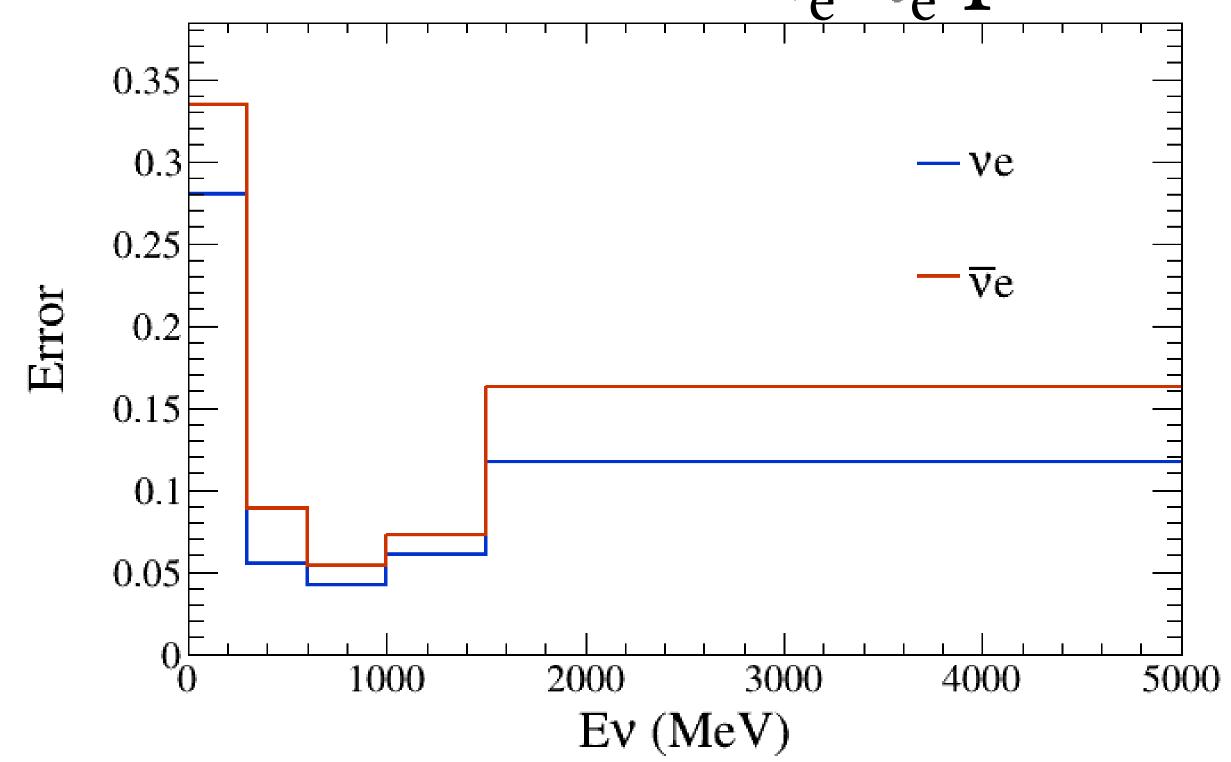
Common ν_e,ν_μ pars



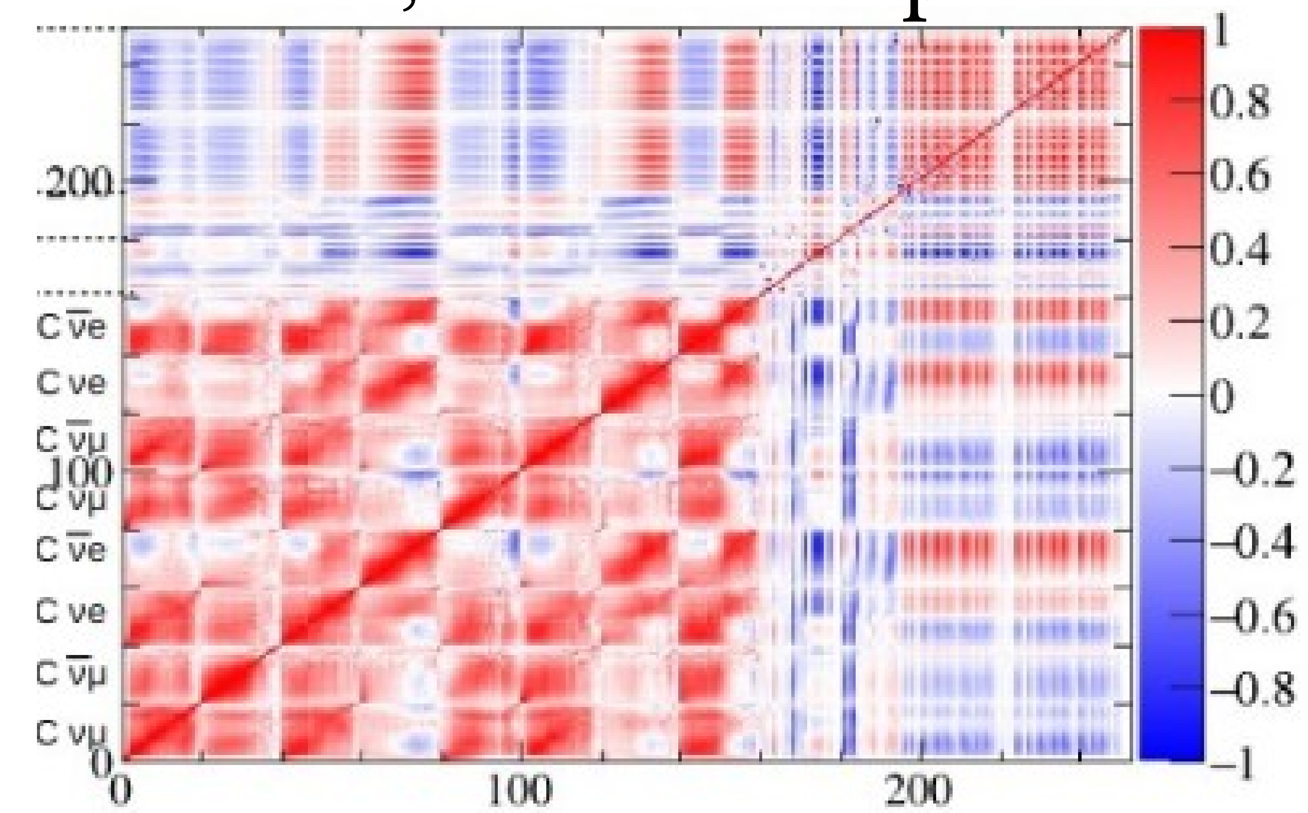
Common $\bar{\nu}_e,\bar{\nu}_\mu$ pars



Additional $\nu_e,\bar{\nu}_e$ pars



Correlations btw flux, int., and IWCD. pars



- The resultant error at the far detector: **4.1%** $\Longleftrightarrow$ the theory constraint: **5.0%**

Photosensor module

- The detector size is much smaller than the far detector

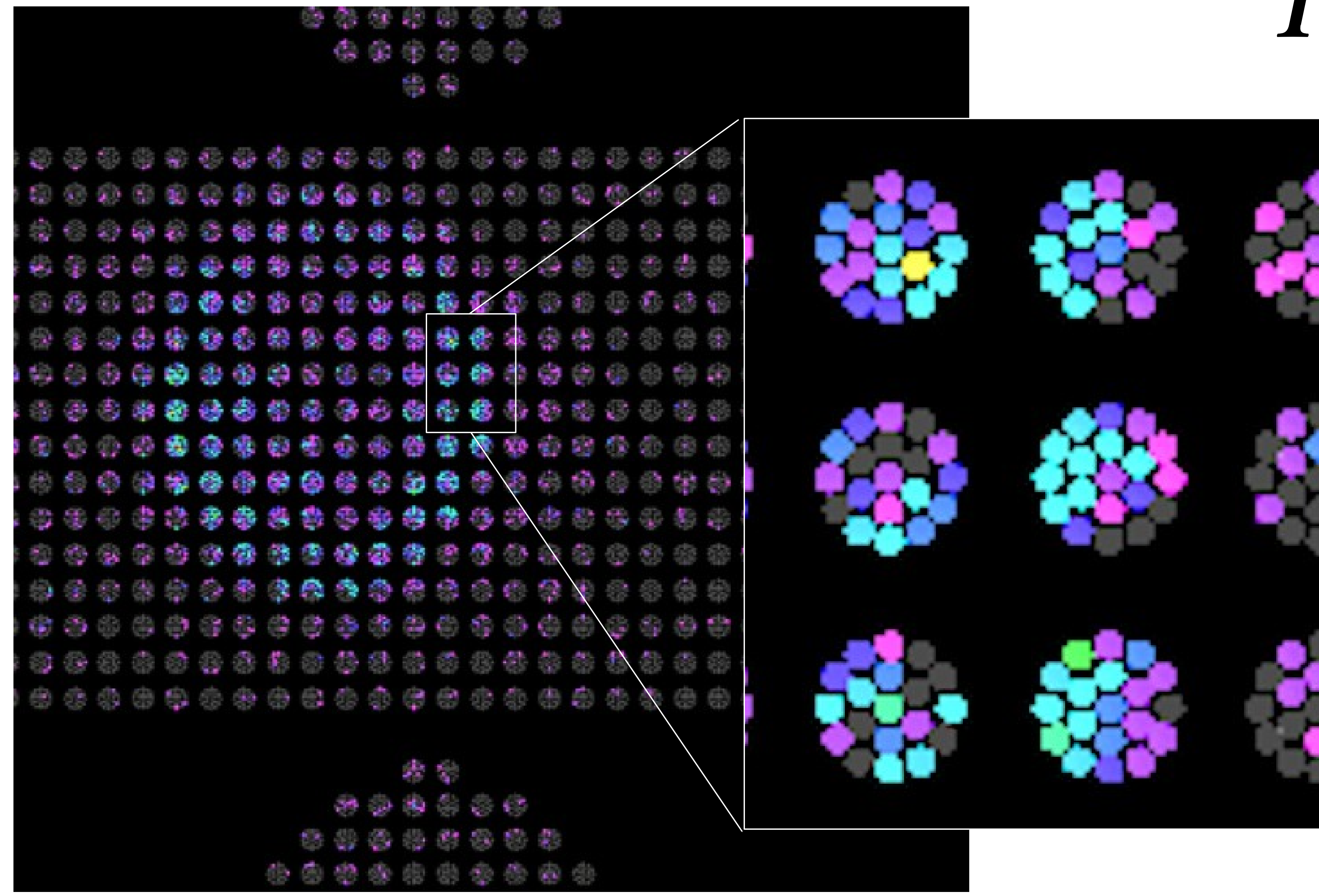
  ⟹ Higher granularity and better timing resolution needed to utilize off-axis angle information

- 19 3-inch diameter photomultiplier tubes integrated in a water-tight module

  ⟹ Acrylic dome, PVC cylinder, and stainless steal backplate used

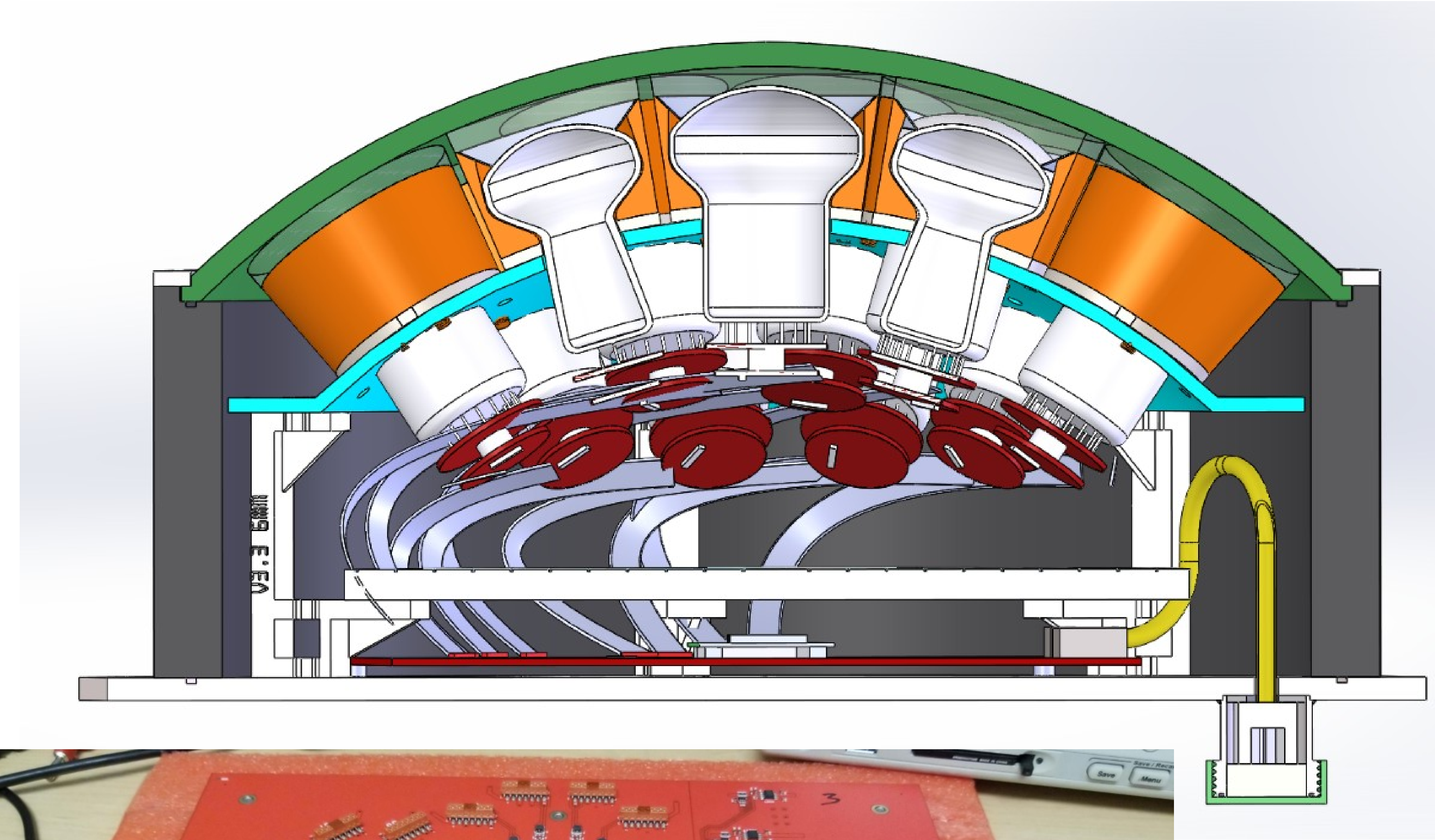
  ⟹ Each tube optically coupled to the acrylic dome by a gel, in order to enhance light collection

  ⟹ Tube placement being able to gain directional information



Electronics and photosensor

◆ High voltage circuits and readout electronics mainboard are inside

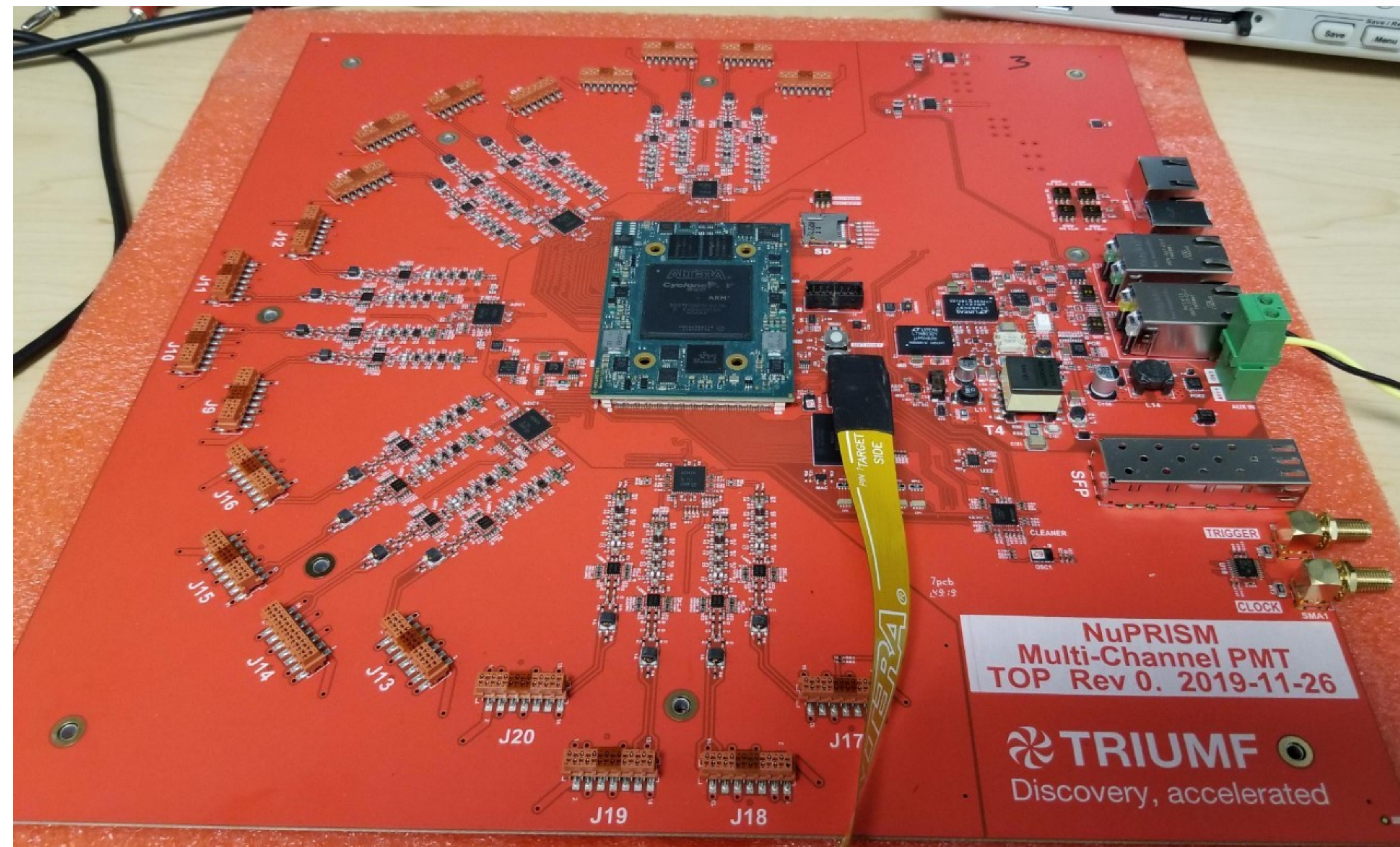


◆ 20-channel 125 MSPS FADC mainboard developed

⟹ Full waveform can be readout, allowing better pile-up event identification

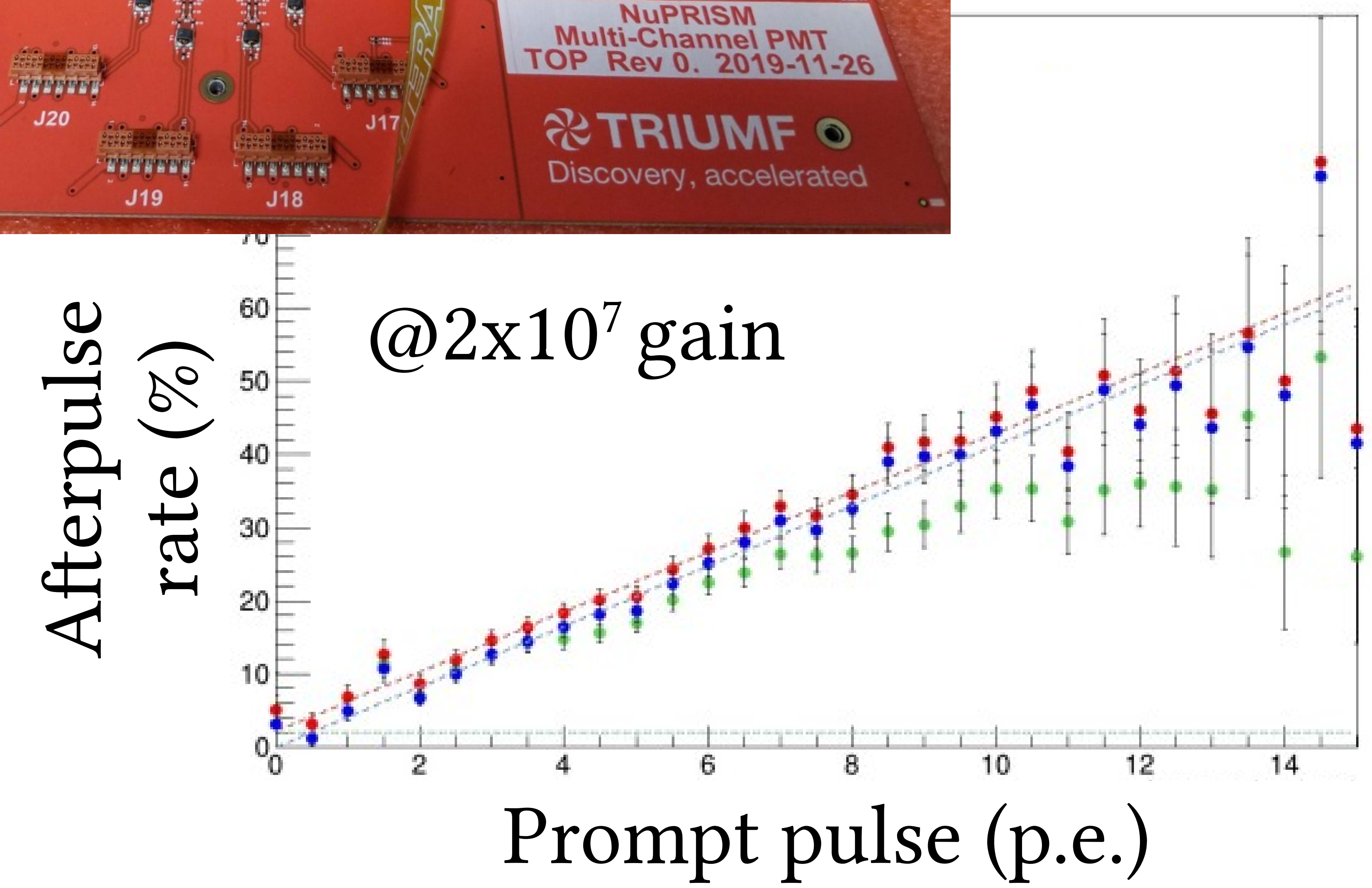
⟹ Digitization and pulse-finding are done

⟹ LEDs mounted for detector calibration



◆ Characteristics of Hamamatsu R14374 3-inch PMT measured with the mainboard

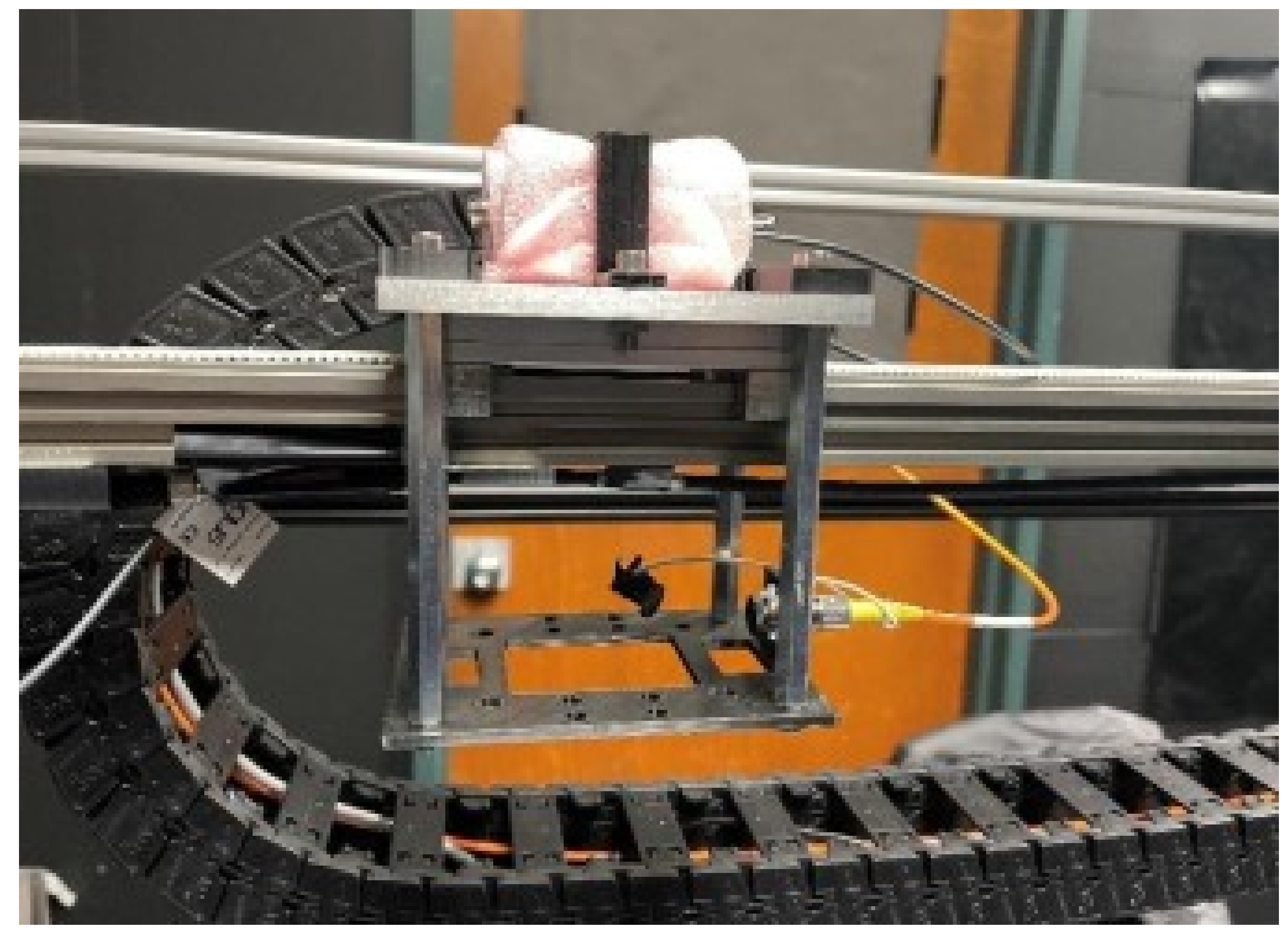
⟹ TTS: ~1.5ns, Dark rate: <1kHz, Afterpulse rate: <5%/P.E.



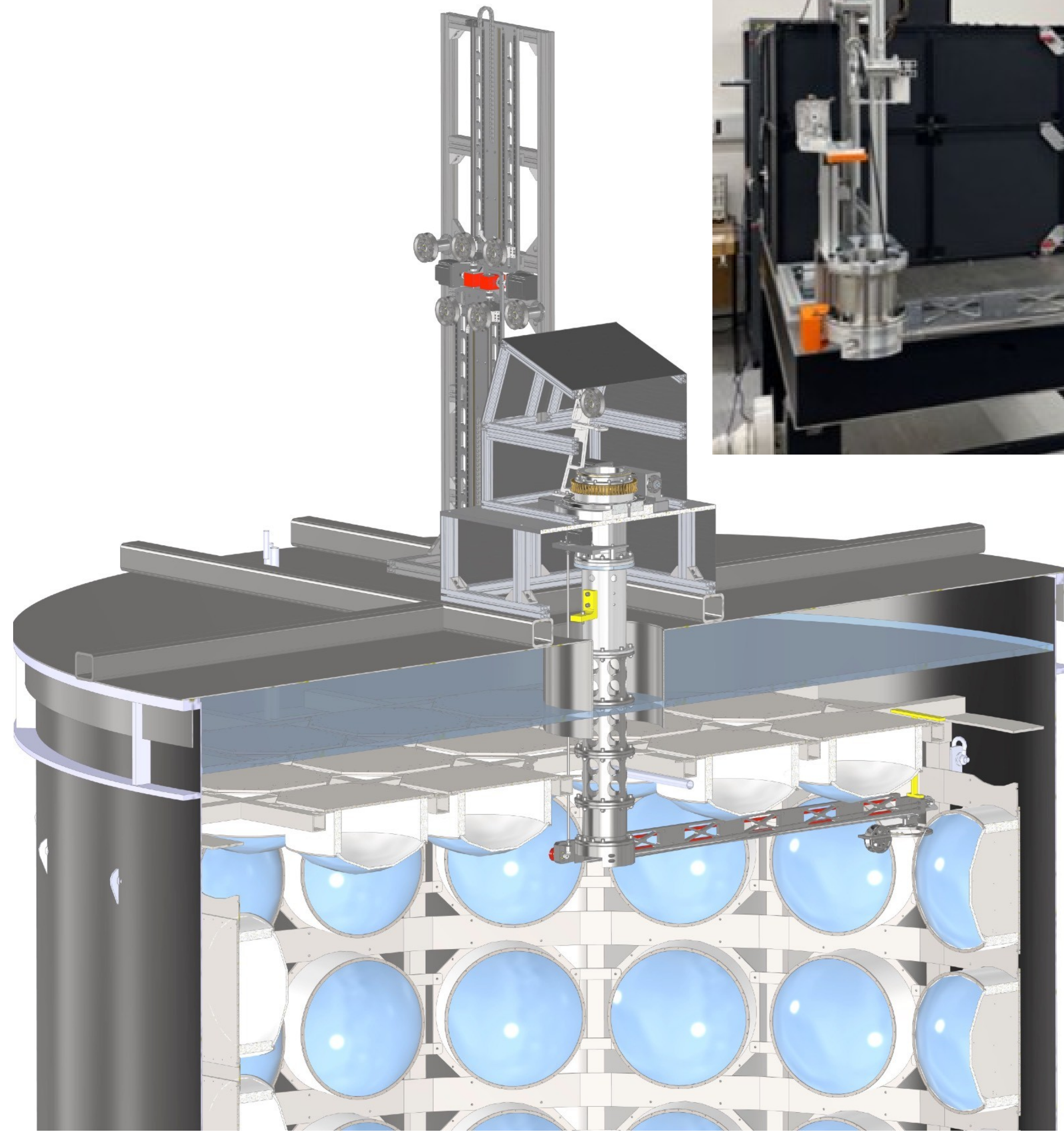
Pre-calibration

- Will characterize the response of the module by an ex-situ calibration
  - ⟹ Single photo-electron distribution
  - ⟹ Detection efficiency
  - ⟹ Timing resolution

- A test stand being developed
  - ⟹ Use both uniform and collimated light sources, allowing position dependence measurements
  - ⟹ Temperature controlled



Detector calibrations



- The moving detector needs to be precisely calibrated at each vertical position

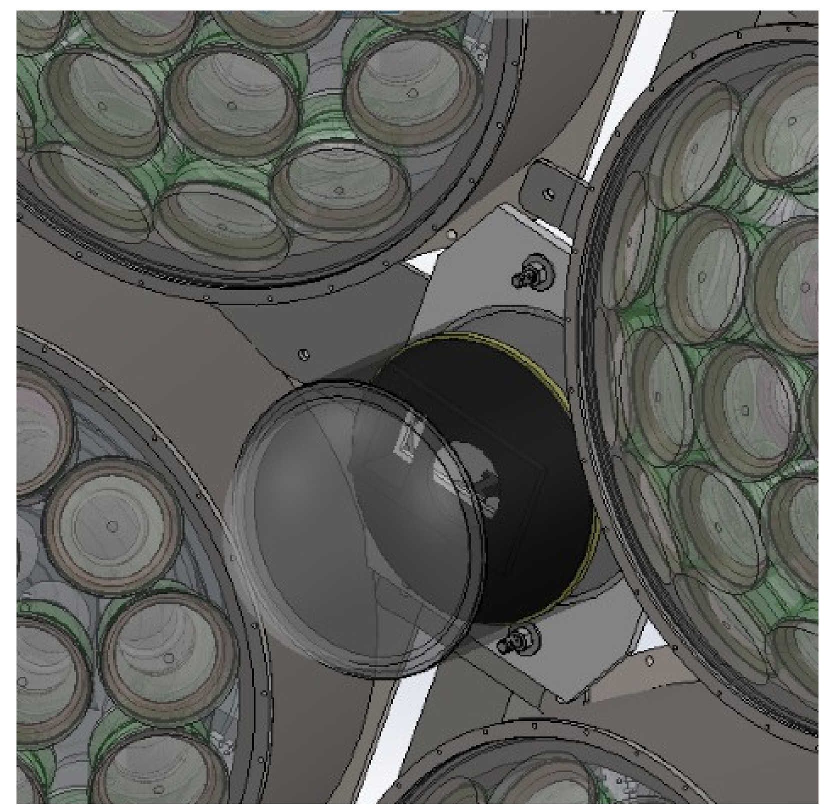
- An accurate calibration source deployment is essential to understand the position dependent detector response

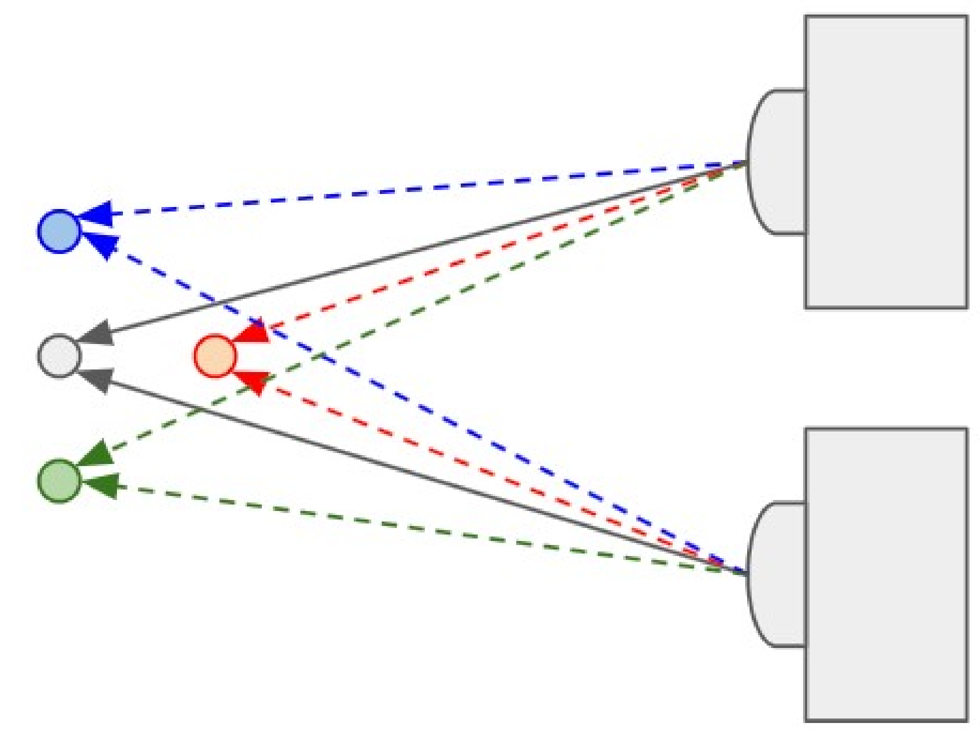
  ⟹ Auto 3D-depolyment system being developed

- For the small detector size, the positions of photosensor modules need to be understood precisely

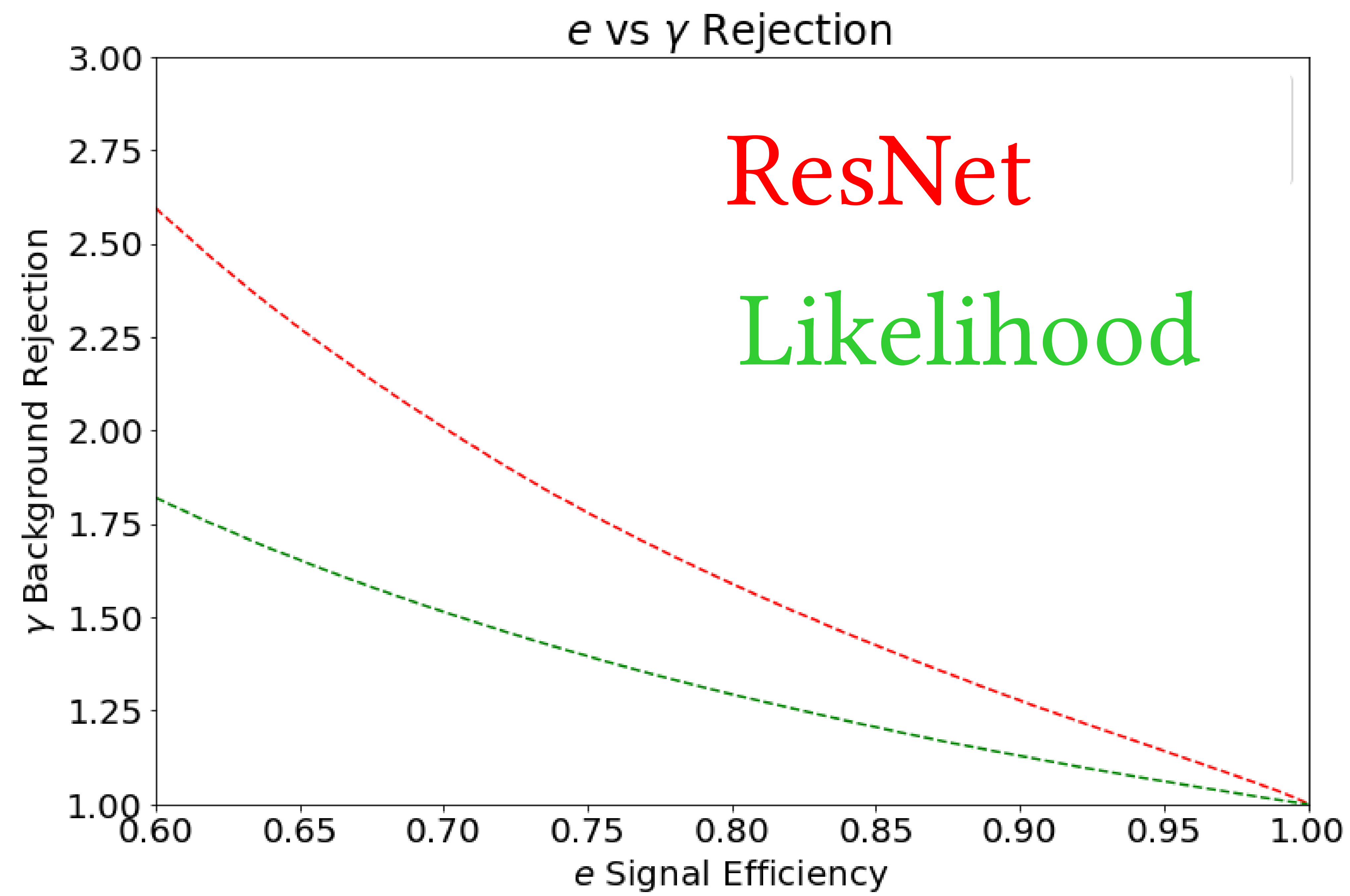
  ⟹ Taking photos of the modules by cameras inside the detector

  ⟹ Using photogrammetry technique used for measuring the positions from the photos

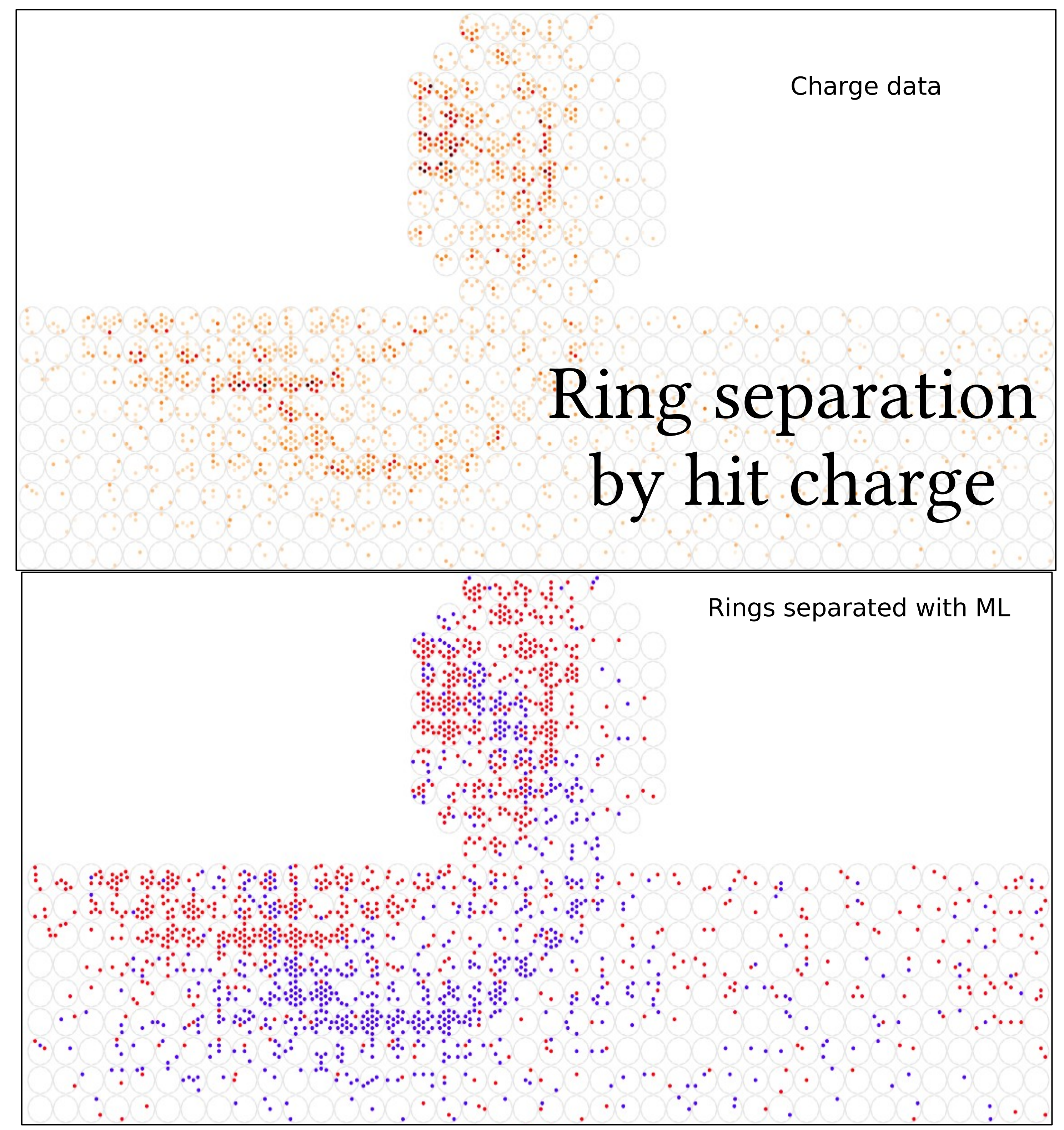




Machine learning



- Currently a maximum likelihood event reconstruction algorithm is used
  - ⟹ Want to improve e-γ sepration
  - ⟹ Want to increase processing speed



- Machine learning based reconstruction being developed
  - ⟹ Significantly faster processing speed and improved particle identification confirmed with particle gun simulation
  - ⟹ Application to the IWCD physics sample is ongoing

Summary

- Controlling systematic uncertainties are essential to make full use of the high beam data statistics at the Hyper-K far detector

- The Intermediate Water Cherenkov Detector is planed to control the critical systematic uncertainty for the CP violation study

- We are working toward the finalization of the IWCD design

Backup slides

Event pile-up

◆ Neutrino interaction timing will follow the T2K's eight bunched beam structure

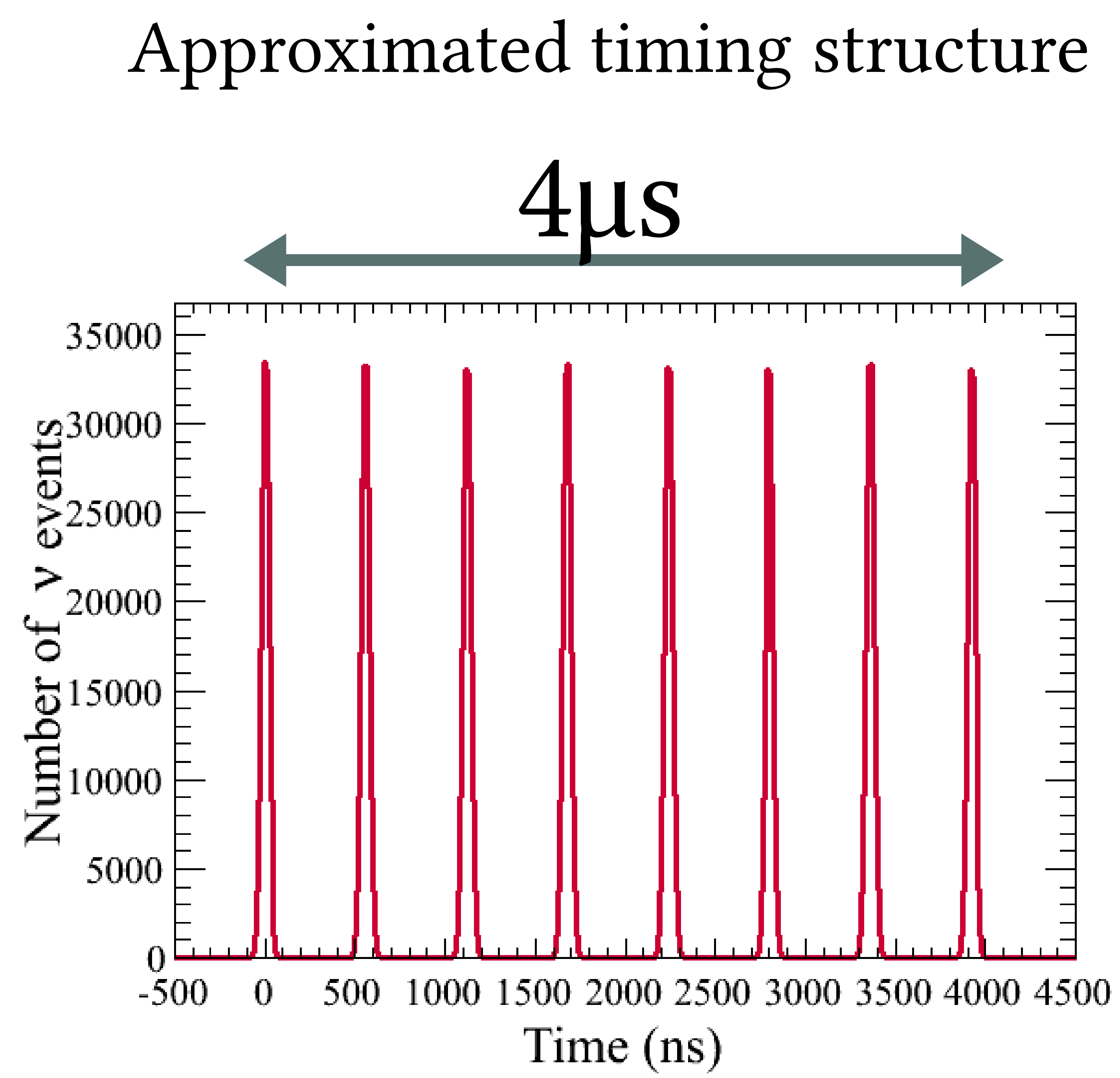
◆ Multiple neutrino interactions can take place within 50 ns due to the intense bunched beam and the detector size

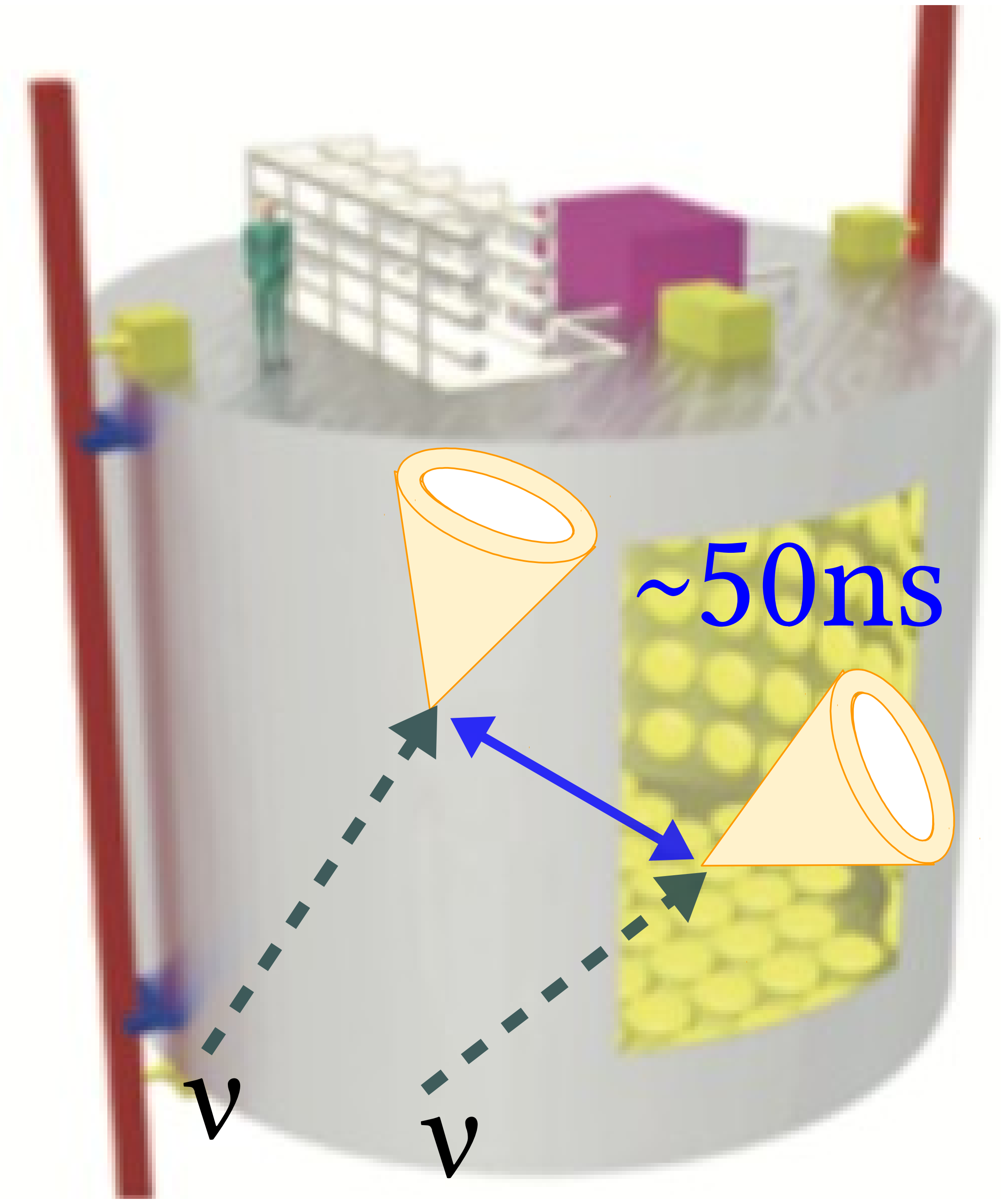
◆ These interactions may not be reconstructed well

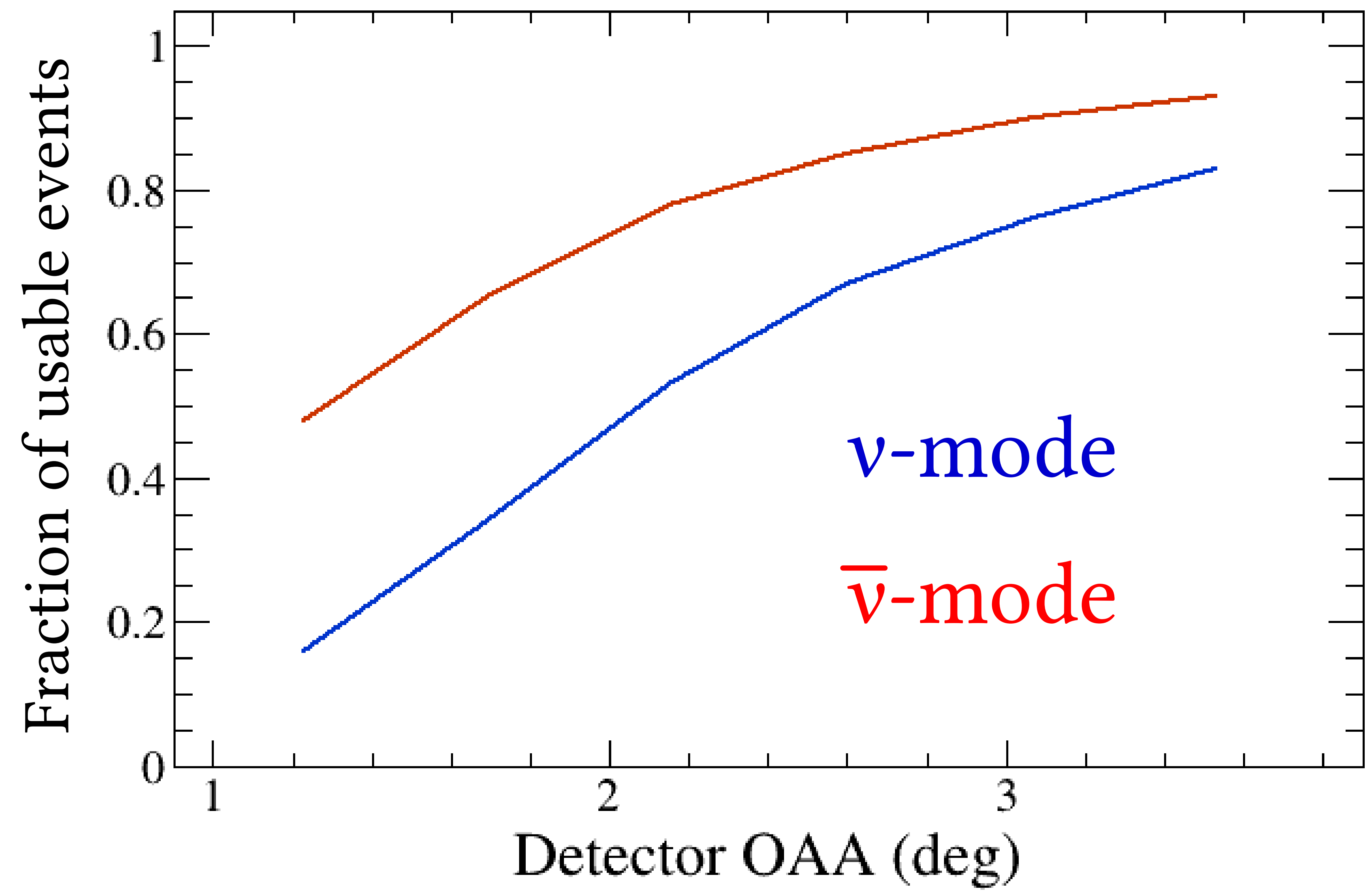
⟹ Use single interaction events only

◆ Interaction rates increase at more on-axis positions

⟹ The loss of events becomes larger

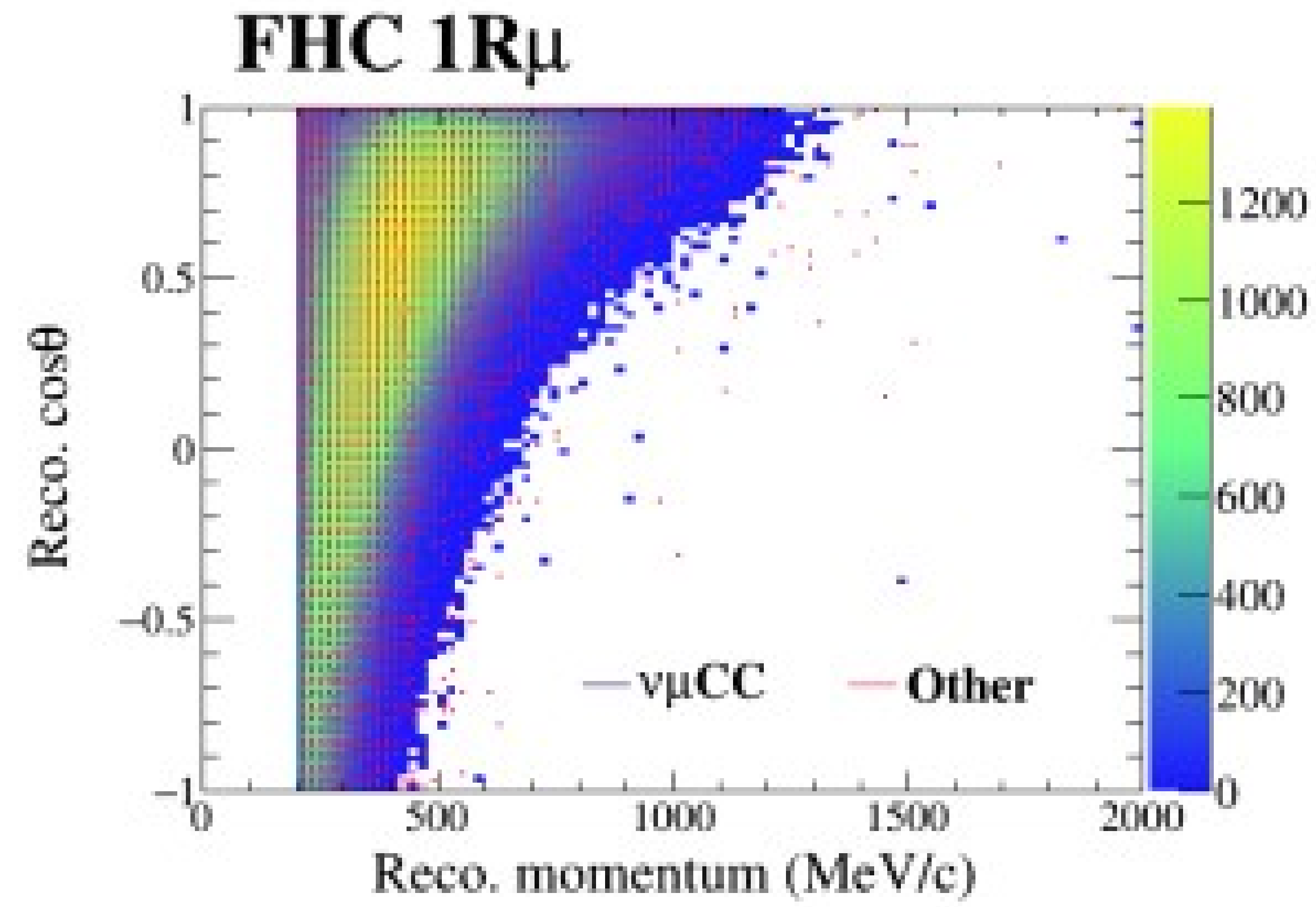


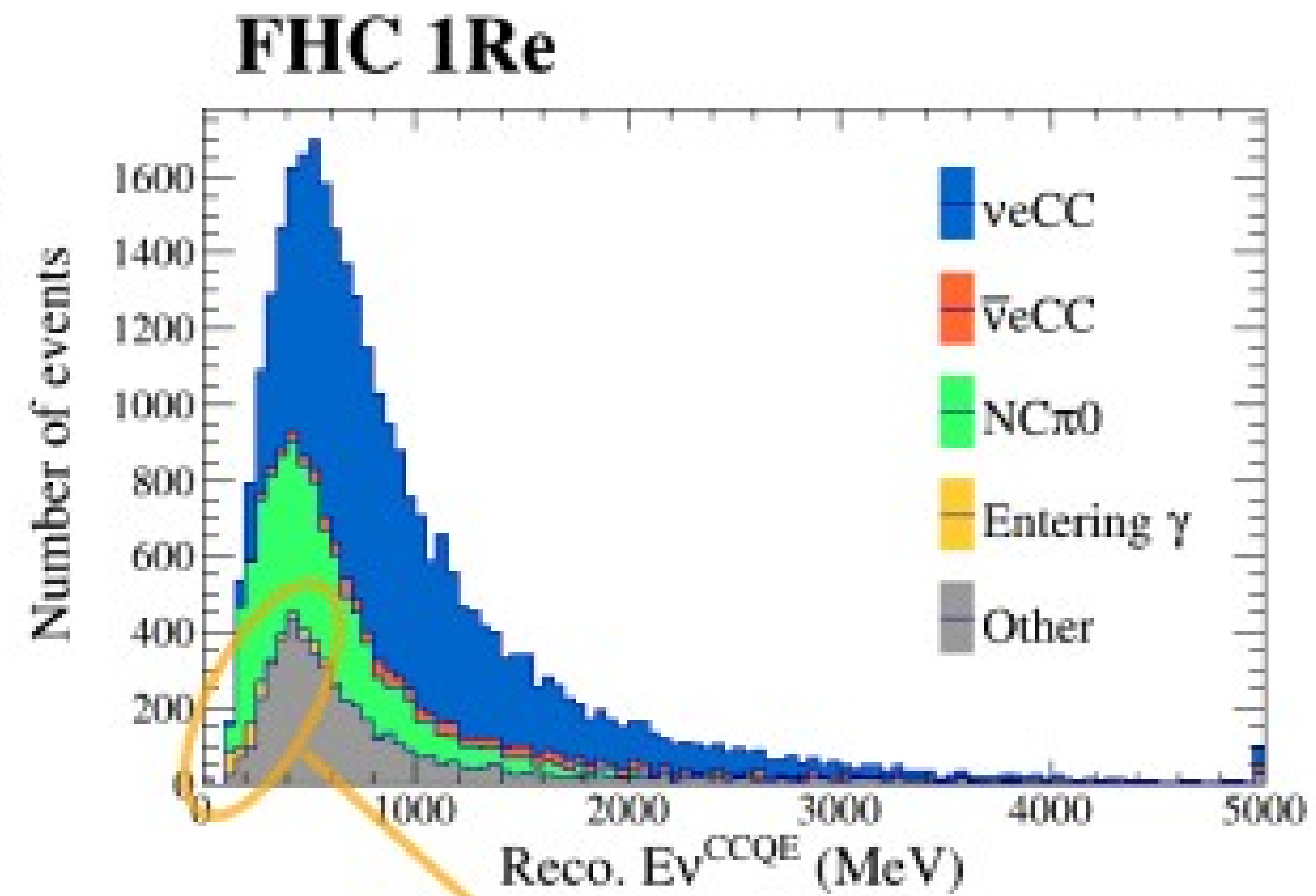


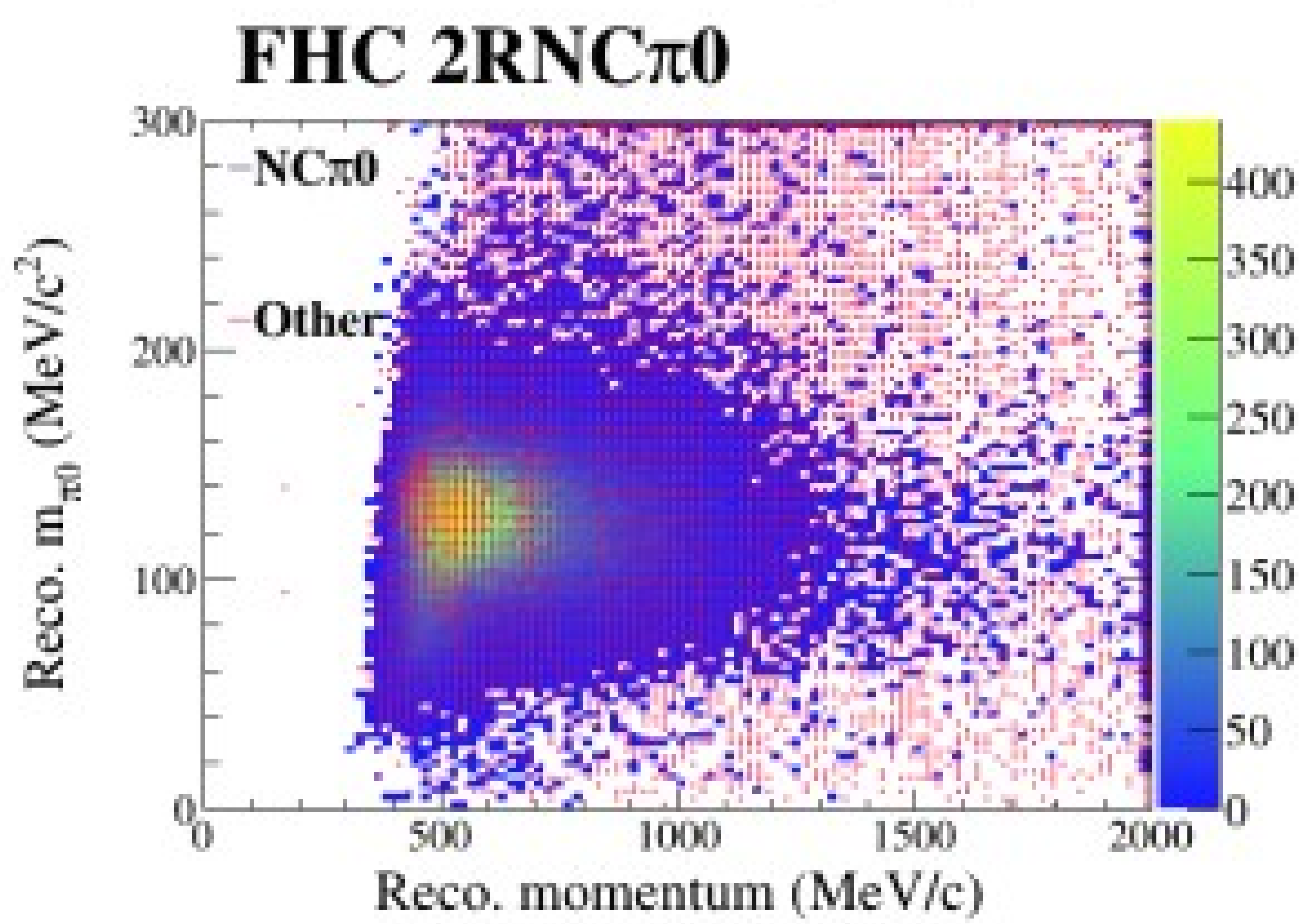


Analysis samples

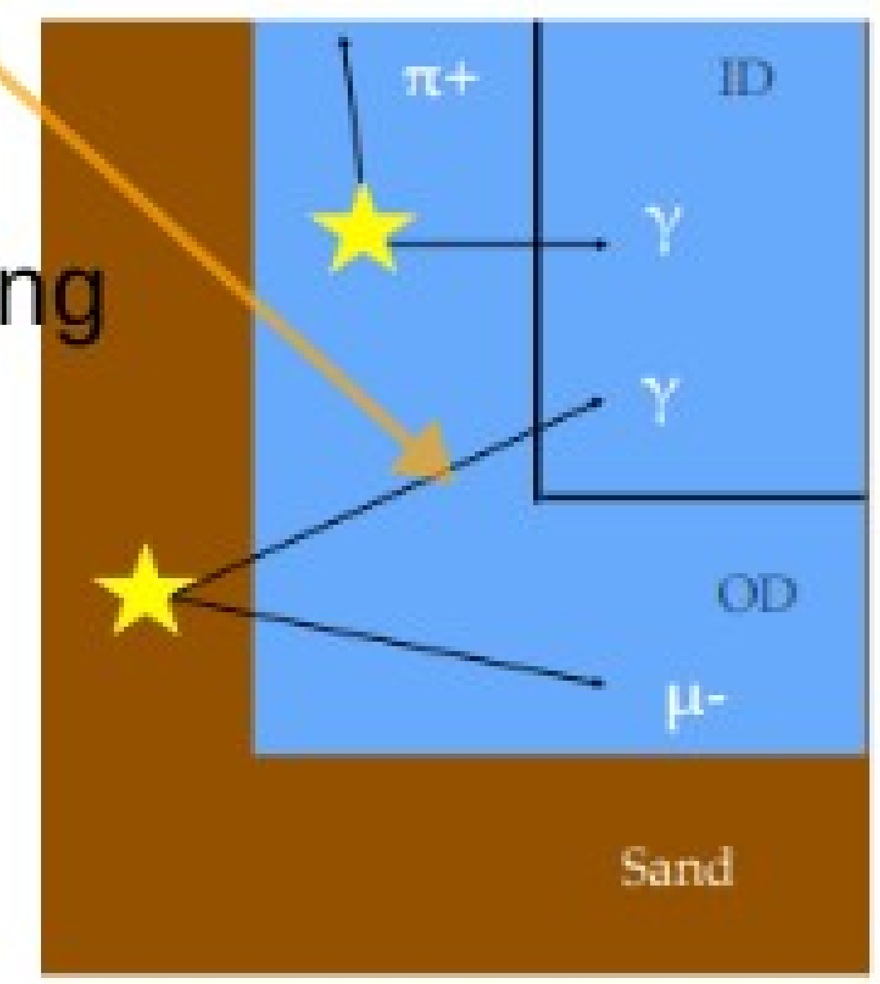
- 6 samples in total
    - (FHC, RHC) $\times$ (1Re, 1Rμ, 2Rπ0)
- RHC samples are basically the same as FHC, but have non negligible wrong sign components
- All the samples are further binned in reco. off-axis angle







Small entering γ thanks to OD active shield



Analysis binning

- FHC/RHC 1Rμ
  - P: 0, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0 GeV (8 bins)
  - $\cos\theta_\mu$: -1, 0.5, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1.0 (10 bins)
  - θ_{OA}: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 degree (6 bins)

- FHC/RHC 1Re
  - E_ν^{CCQE}: 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 (20 bins)
  - θ_{OA}: 1.0, 2.8, 4.0 degree (3 bins)

- FHC/RHC NCπ0
  - P: 0, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 1.0, 1.25, 1.5, 2.0 GeV (11 bins)
  - m_{π^0}: 0, 0.1, 0.125, 0.15, 0.175, 0.2, 0.25, 0.3 GeV (7 bins)
  - θ_{OA}: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 degree (6 bins)

- θ_{OA}: off-axis angle calculated using ave. π decay position and reco. position by fiTQun

Likelihood function

- Define the negative log-likelihood to evaluate errors on IWCD parameters for given configuration (OAA, POT, etc.)
  - Predicted event rate, $\mathcal{E}$, depends on both IWCD normalization ($\boldsymbol{f}$) and systematic ($\boldsymbol{p}$) parameters

$$-2\ln\mathcal{L} = \sum^{\text{samples}} \sum^{\text{bins}} 2\left(\mathcal{E} - \mathcal{O} + \mathcal{O}\ln\left(\frac{\mathcal{O}}{\mathcal{E}}\right)\right) + \sum_{i}^{\text{pars}} \sum_{j}^{\text{pars}} (p_i - p_i^{\text{prior}})(V_{cov}^{-1})_{ij}(p_j - p_j^{\text{prior}})$$

- Calculate Hessian matrix w.r.t $\boldsymbol{f}$ and $\boldsymbol{p}$ at their true value $\rightarrow$ median sensitivity
  - $\boldsymbol{p}$: flux, T2K 2018 XSec, IWCD det systematics considered (details in backup)