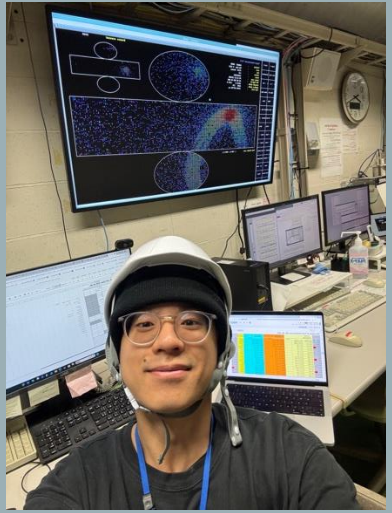
REDUCING SYSTEMATICS AT HYPER-KAMIOKANDE: CALIBRATION AND DETECTOR STUDIES



Unik Limbu

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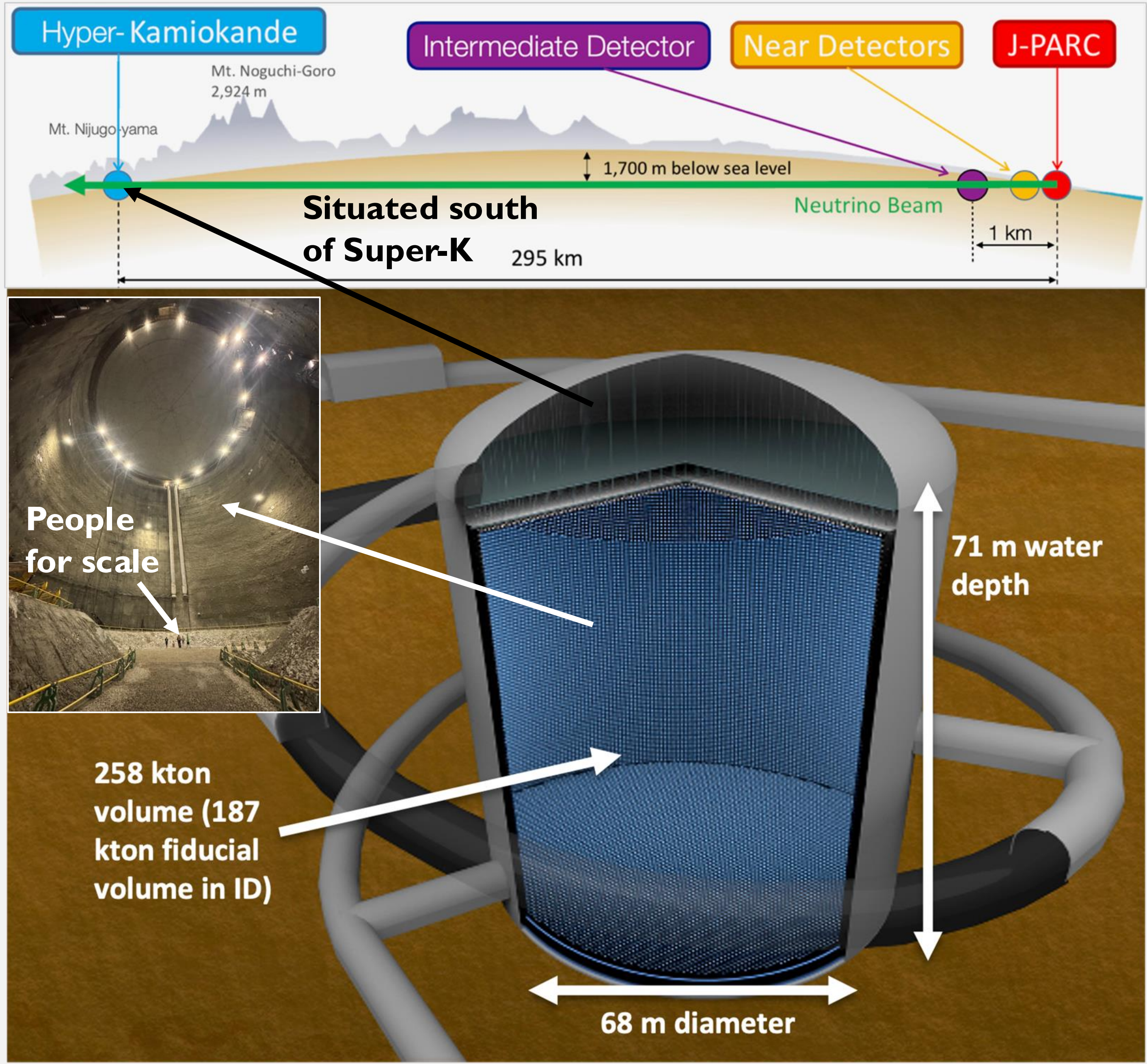
HYPER-KAMIOKANDE

- Hyper-K is the next generation water Cherenkov neutrino detector
- Located in Japan; its long-baseline (LBL) programme uses the J-PARC neutrino beam at the same off-axis angle as T2K
- Much larger and more sensitive than Super-K:
  - **8.4x** the fiducial volume
  - J-PARC beam upgraded to **1.3 MW** for the Hyper-K era

Physics goals:

- Precise **neutrino oscillation** measurements
- Search for **CP violation** in **leptonic sector**
- **Proton decay** searches
- Observation of **supernova neutrinos** and the Diffuse Supernova Neutrino Background (**DSNB**)



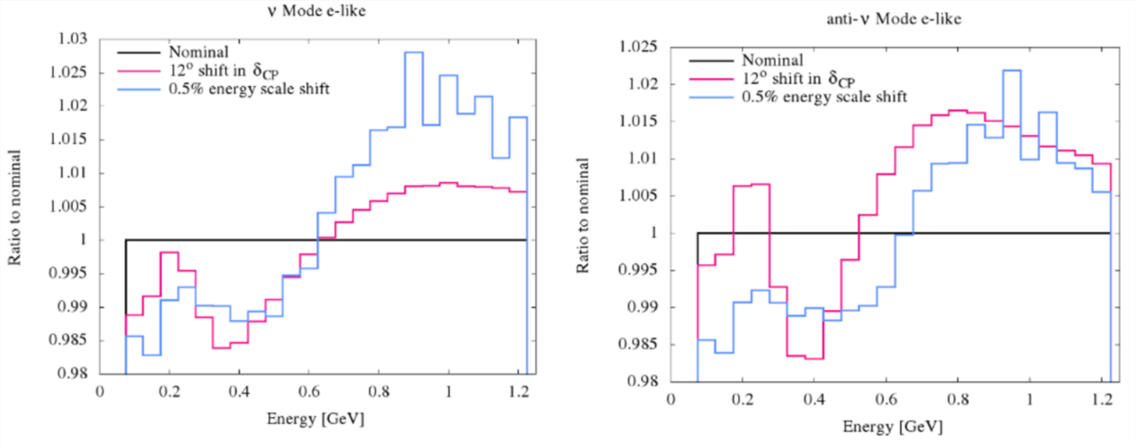
Situated south of Super-K

People for scale

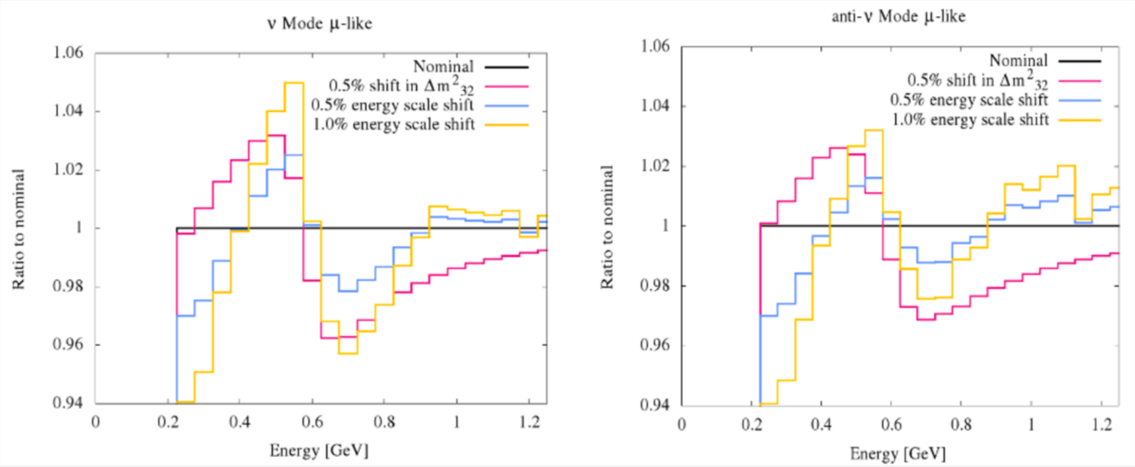
258 kton volume (187 kton fiducial volume in ID)

DETECTOR SYSTEMATICS IN HYPER-K

- Detector systematics can bias measurements and mimic oscillation signatures, limiting physics sensitivity
- Key detector systematics include:
    - Energy scale & resolution
    - Reconstruction performance (vertex, angular resolution)
    - Particle identification (PID)
    - Cherenkov ring counting efficiency
- These must be controlled to sub-percent precision → Hyper-K targets **~0.5% energy scale uncertainty**
- Motivates improved calibration strategies, e.g. bottom-up approach



Effect of 0.5% energy scale shift and 12° δ_{CP} shift on electron.



Effect of 0.5% and 1.0% energy scale shift on muon, and also the effect of 0.5% shift in Δm^2_{32}. Both top and bottom figures taken from Hyper-K technical note 21.

BOTTOM-UP CALIBRATION APPROACH

Aim**:**

Quantify uncertainties on reconstructed quantities, like **energy scale** and **particle identification (PID)**
→ using calibration-informed uncertainties in the **detector model**

Method:

- Start from known uncertainties in physical detector parameters
- Propagate these to see their effect on high-level outputs, i.e., energy, PID, etc
- Helps ensure systematics are physically motivated and data-driven

WCSim to generate detector MC + fiTQun to reconstruct events

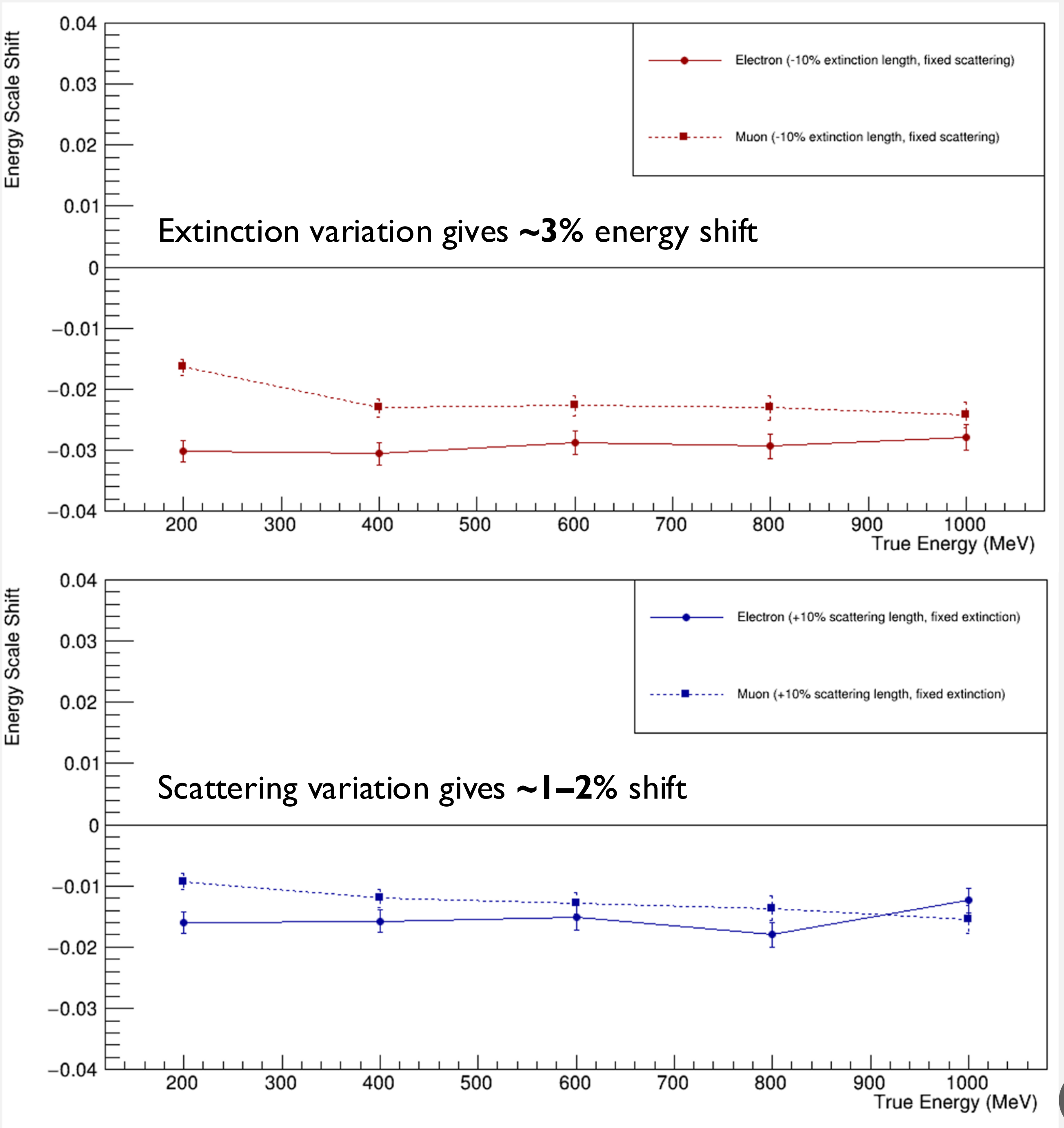
Examples of detector parameters:

- Water optical properties (light absorption and scattering)
- PMT response (angular response and efficiency)
- Reflections from PMTs, black sheet, and internal surfaces

CURRENT STUDIES I

- Studying impact of water optical parameters on reconstruction:
  - ➢ Absorption (extinction length)
  - ➢ Scattering
- Use controlled ±10% variations → Independently vary extinction and scattering
- Evaluate impact on key observables:
  - ➢ Energy scale & resolution
  - ➢ Vertex & direction
  - ➢ e/mu PID
  - ➢ Fiducial volume (FV) acceptance
- Extinction has a **bigger impact** on the energy scale than scattering

Change in Energy Scale



Extinction variation gives **~3%** energy shift

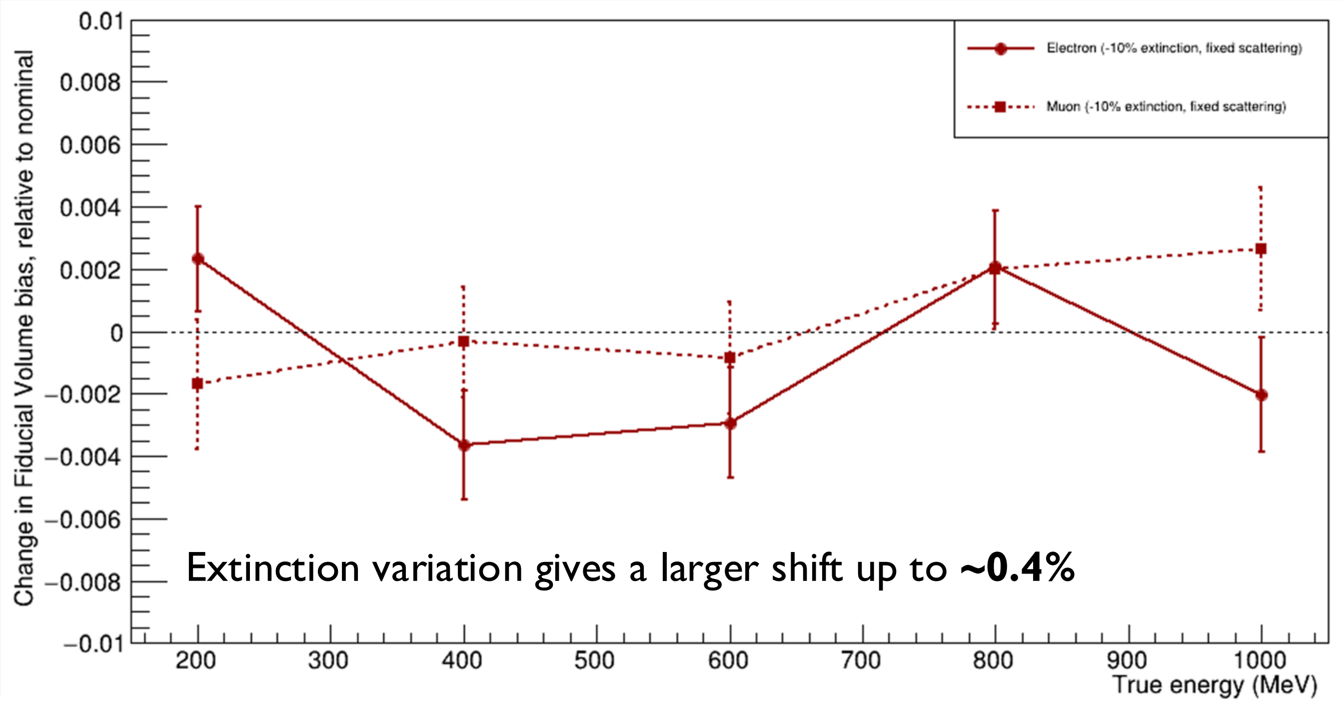
Scattering variation gives **~1–2%** shift

CURRENT STUDIES II

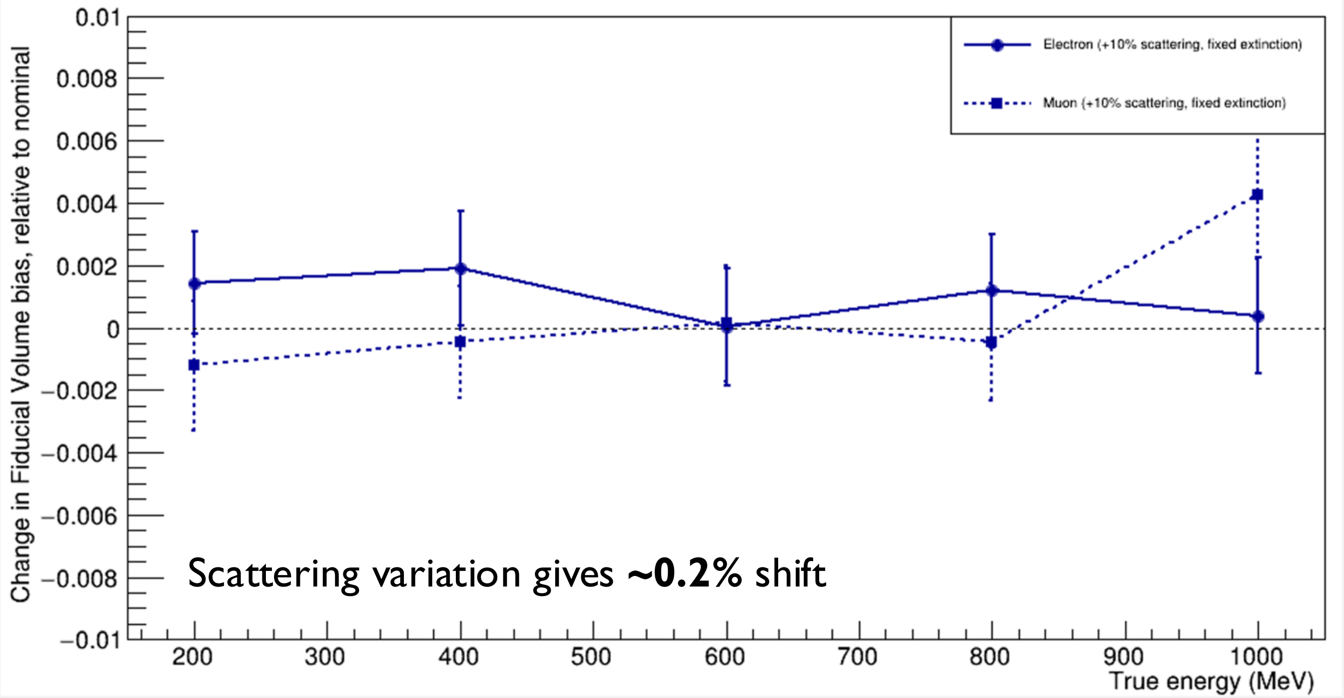
- FV acceptance (or efficiency) quantifies the fraction of events passing the cut of $D_{wall} > 200\text{cm}$
- Bias arises from vertex smearing near the FV boundary such that the bias quantified as the fractional difference:

$$b_{FV} = \frac{N^{reco}_{pass} - N^{true}_{pass}}{N^{true}_{pass}}$$

- FV selection efficiency remains stable at the **sub-percent level** under ±10% optical variations
- Within this small response, **extinction dominates** the FV-related optical systematic
- Current extension: event migration into/out of the FV boundaries



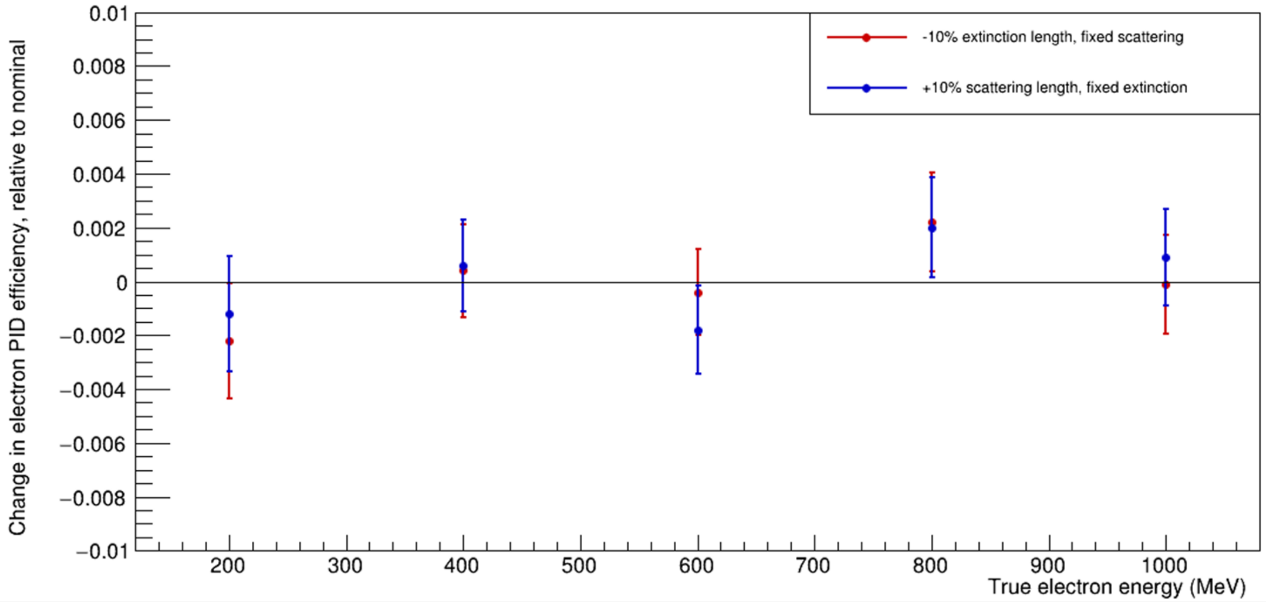
Extinction variation gives a larger shift up to **~0.4%**

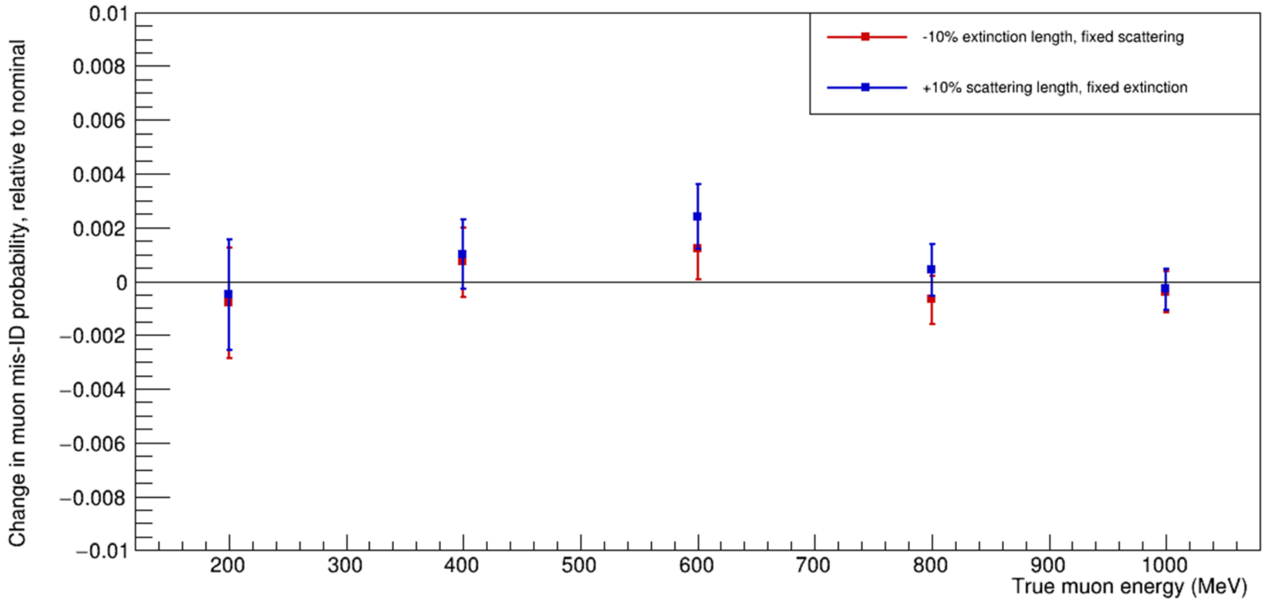


Scattering variation gives **~0.2%** shift

CURRENT STUDIES III

- Two PID observables studied:
  - Electron PID efficiency
  - Muon mis-tag rate ($\mu \rightarrow e$)
- PID observables show **weak sensitivity** to optical variations
- Muon mis-tag rate remains largely unchanged
- Optical uncertainties primarily propagate through energy and vertex reconstruction, with only **indirect impact on PID**





NEXT STEPS & FUTURE WORK FOR THE ANALYSIS

- Move from ±10% variations toward well-motivated detector systematic uncertainties
- Currently generating more statistics to reach ~0.5% precision goal → Target O(10^6-10^7 events) per configuration
- Next detector input: **PMT angular response**
  - Study global and position-dependent energy-scale shifts
  - Move beyond simple global detector shifts toward **position/angle-dependent response models**

Calibration goals:

- Use these studies to help define **uncertainty limits** on optical/PMT detector parameters
- Connect to pre-calibration and PTF (PMT-Test-Facilities) measurements of PMT response

LBL physics goals:

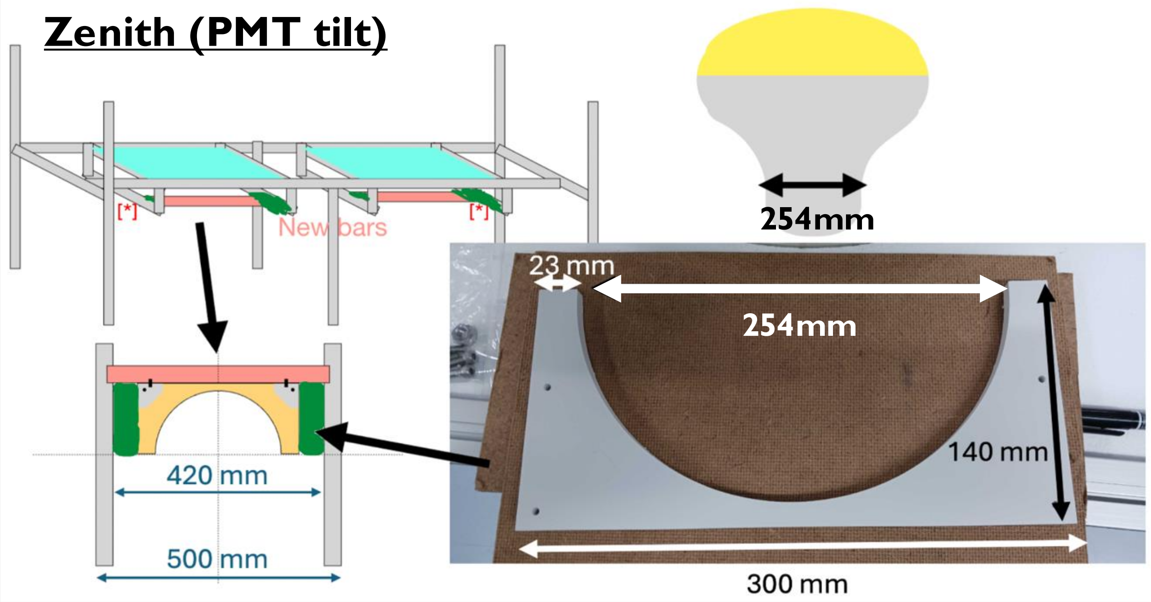
- Propagate reconstruction distortions into spectra
- Use fake-data / fit studies to estimate possible oscillation-parameter bias

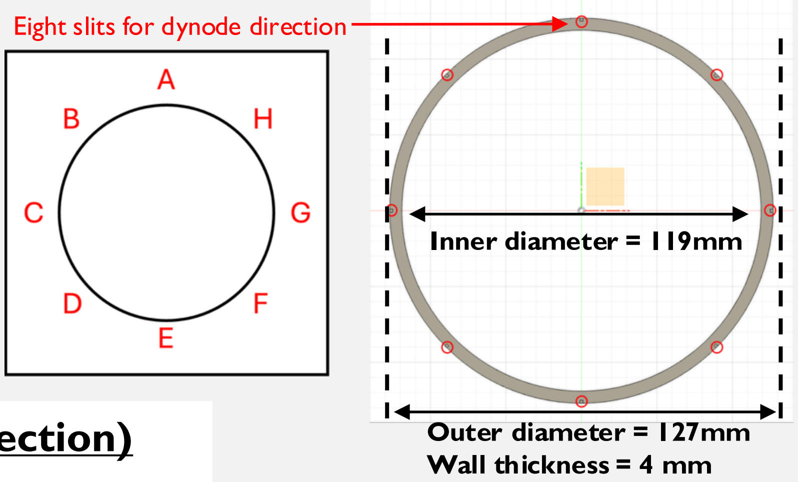
ONSITE CONTRIBUTIONS (LTA-RELATED)

PMT PRE-CALIBRATION: ALIGNMENT WORK

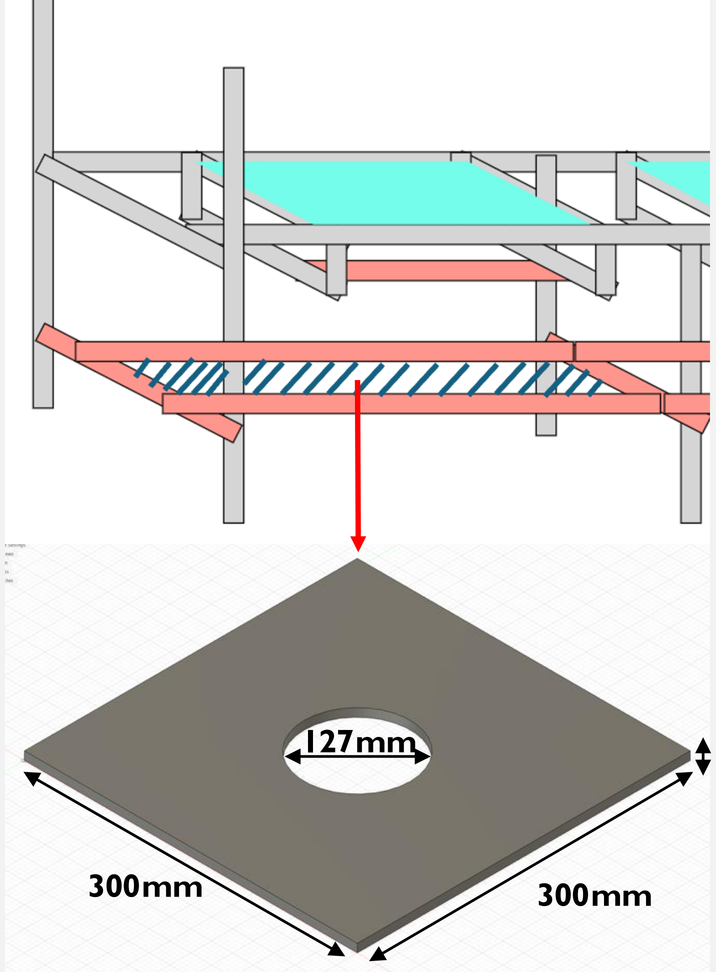
- Pre-calibration measures PMT response before installation **under controlled condition** → Characterise QE, angular response, timing, gain
- Precise PMT alignment is essential:
  - **Zenith** direction for PMT tilt
  - **Azimuth** direction for dynode direction
- Designed PMT cap (V8) and base plate (V4) in Fusion 360 for azimuth alignment

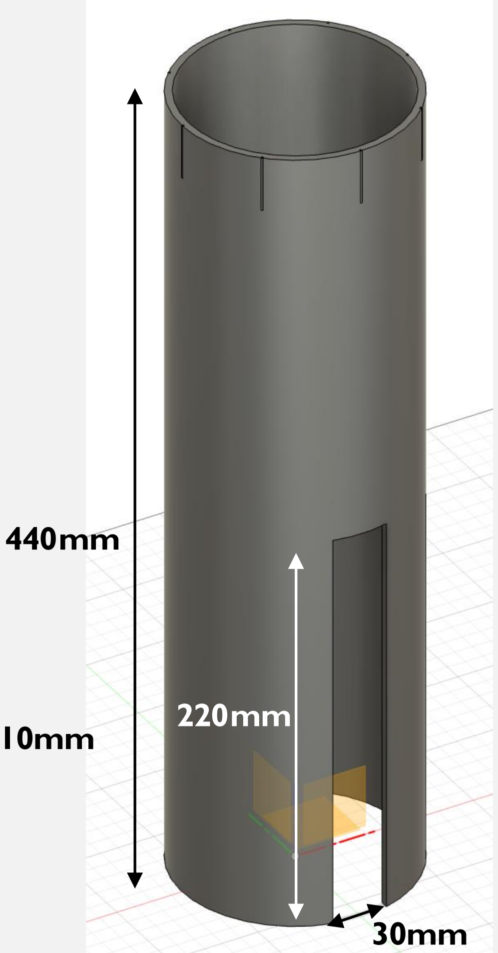
Zenith (PMT tilt)





Azimuth (dynode direction)





CURRENT STATUS

- Successfully installed top bars and zenith alignment plate → tested it and works well!
- For the azimuth direction:
  - PMT cap prototype completed → either 3D print it or find company that does it
  - Cap plate design completed
- Develop efficient PMT installation/swapping procedures for shifters
- Additional contributions:
  - Data taking for the pre-calibration light injection systems
  - Improving light-tightness (black sheets, carpets) to ensure data quality and reduce light leakage

Final version!

Newly added bars

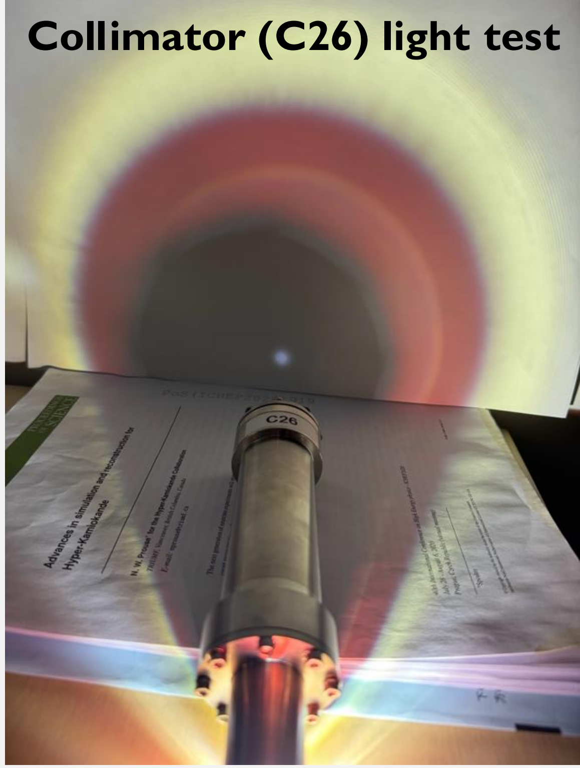
More black sheets

Carpets + boxes for better cable organisation

Testing the tilt alignment

Gloves, glasses, coat for safety!

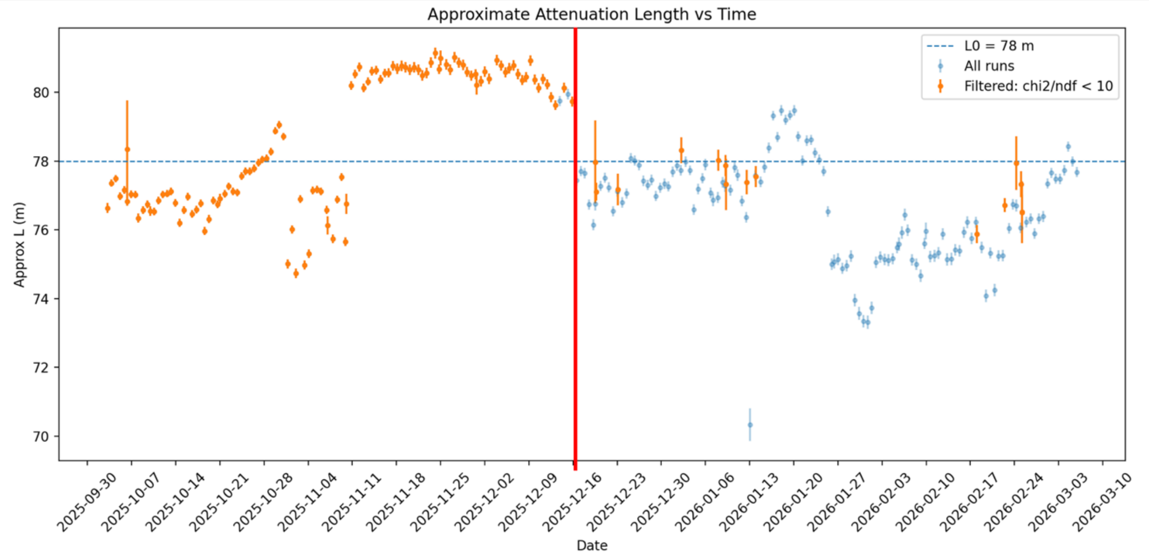
OTHER ACTIVITIES


Collimator (C26) light test

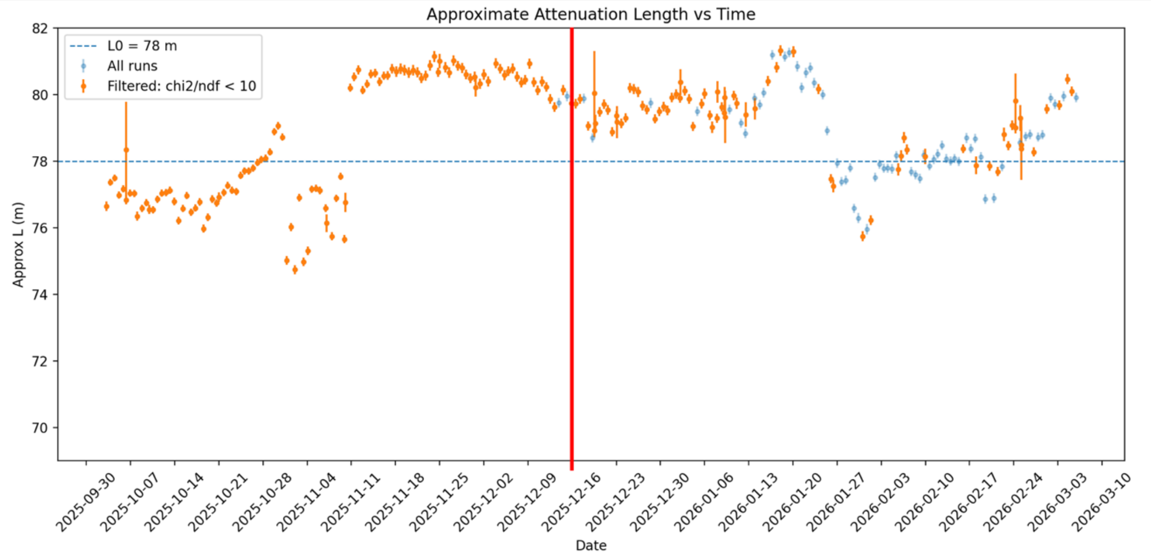
- Contributed to UKLI shipping test → Mechanical + optical validation (collimator & diffuser)
- Taken Super-K onsite shifts + upcoming T2K ND280 DAQ shift at Tokai

Super-K calibration monitoring:

- Top diffuser monitoring using real Super-K calibration data → Studied charge/occupancy stability across runs
- Investigated step-like change in mean charge around calibration/TQ-map update (red line)



Before (no correction)



After (applying correction)

CONCLUSION

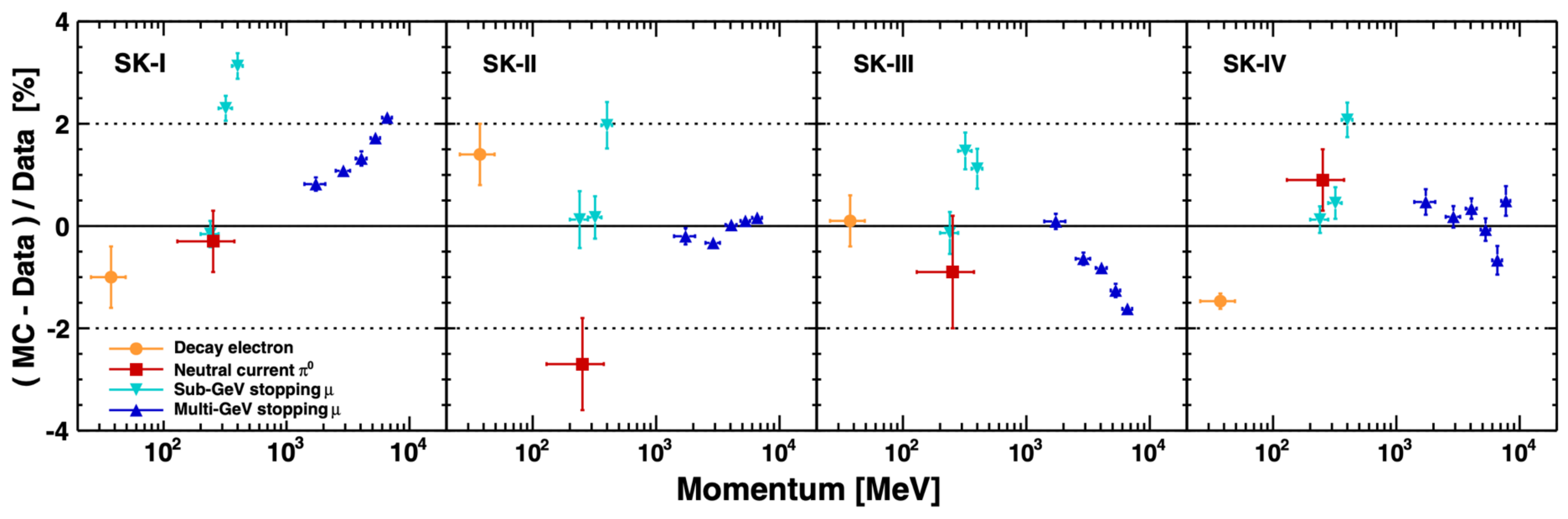
- Bottom-up calibration provides a framework to connect **physical detector parameters** to reconstructed observables and systematic uncertainties
- Optical-property studies show:
  - Absorption (extinction) dominates energy scale (~3%)
  - Scattering effects are smaller; PID shows weak sensitivity
- Next stage: study PMT angular response and position/angle-dependent detector response models → link calibration measurements to systematic uncertainty limits
- Hyper-K pre-calibration and Super-K monitoring provide practical inputs for understanding and reducing detector systematics

THANK YOU FOR LISTENING!

ANY QUESTION?

BACK UP

WHY BOTTOM-UP APPROACH?



Absolute energy scale measurements for each Super-Kamiokande period.

Top-Down Approach (used in T2K/Super-Kamiokande):

- Uses control samples (e.g. Michel electrons, π^0 mass peak, stopping muons) with known energy depositions
- Effective, but limited when **control samples don't fully cover the analysis range**
- **Assumes biases between data and MC** are covered by assigned uncertainties without identifying underlying causes

Limitations for Hyper-Kamiokande:

- **Longer photon path lengths increase sensitivity** to water absorption, scattering, and inhomogeneities
- Greater detector complexity demands more precise modelling of underlying effects → bottom-up approach will be useful!

SIMULATION & RECONSTRUCTION TOOLS

Simulation – WCSim:

- GEANT4-based simulation for water Cherenkov detectors
- Simulated particle (i.e. electrons and muons) uniformly + isotropically in the detector

Reconstruction – fiTQun:

- A **maximum likelihood** reconstruction algorithm
- Uses **PMT hit time** and **charge information** to estimate particle properties

$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_j)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

- Likelihood function includes:
    - Probability of PMT being hit or unhit
    - Expected **charge** and **time** distributions for each hit

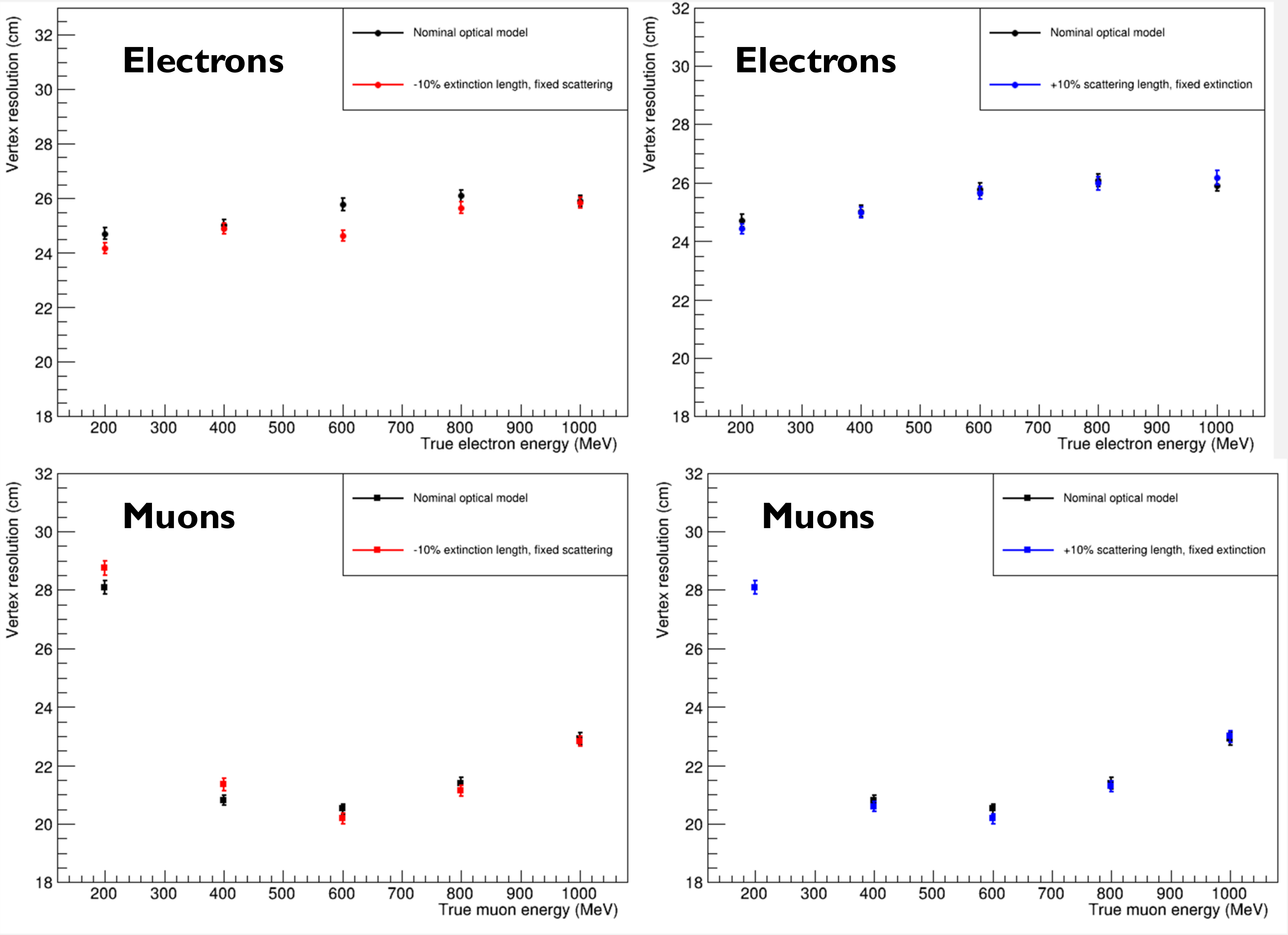
EXTINCTION LENGTH STUDIES

- Given by:

$$\frac{1}{L_{ext}} = \frac{1}{L_{abs}} + \frac{1}{L_{scat}}$$

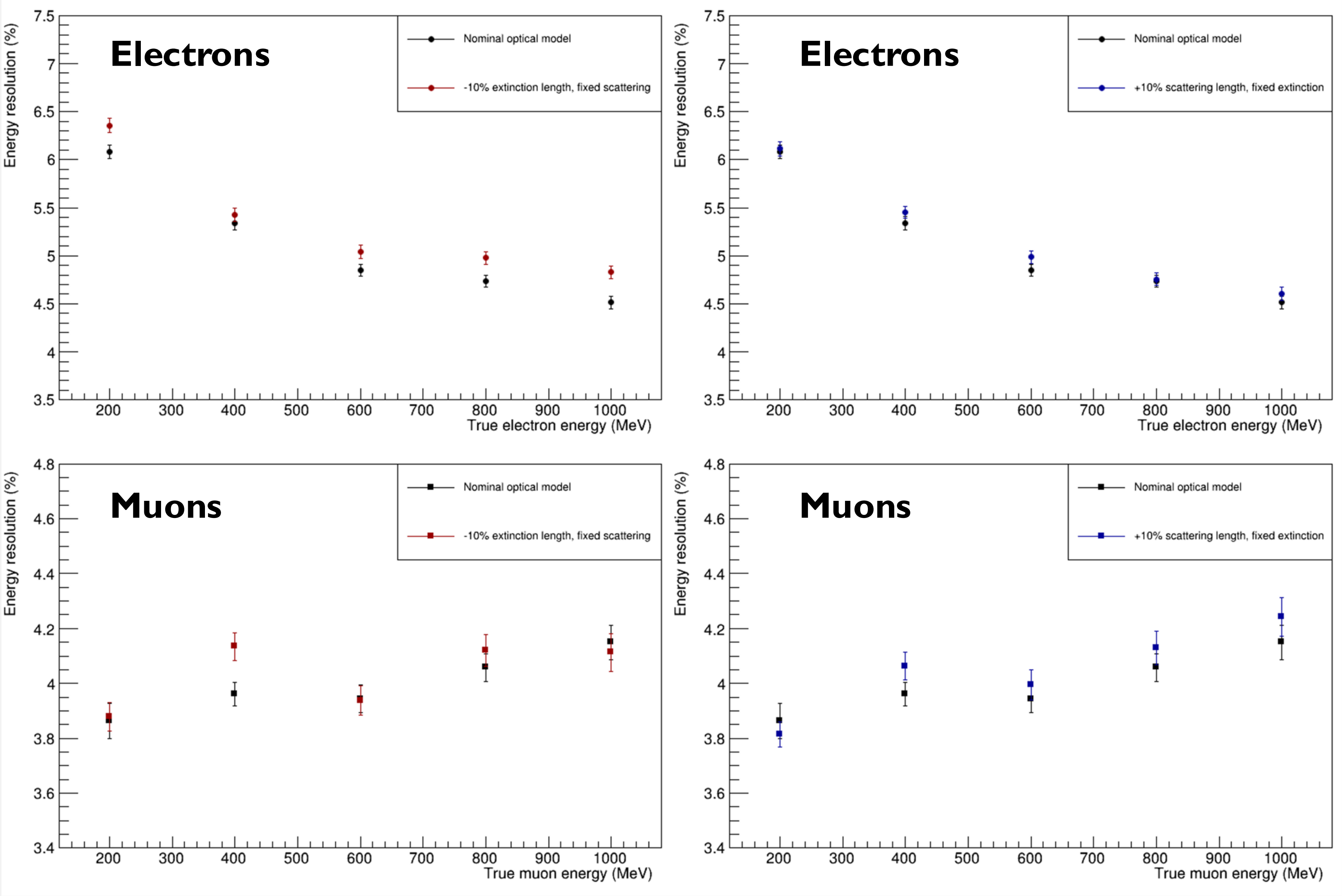
- Goal: Separate the effects of absorption and scattering on reconstructed observables
- Perform variations under two controlled conditions:
  1. **Vary extinction length** while keeping **scattering length fixed**
  2. **Vary scattering length** while keeping **extinction length fixed**
- This allows the two effects to be studied **independently and systematically**
- In this analysis, **±10% variations** are applied in each case

IMPACT ON VERTEX RESOLUTION



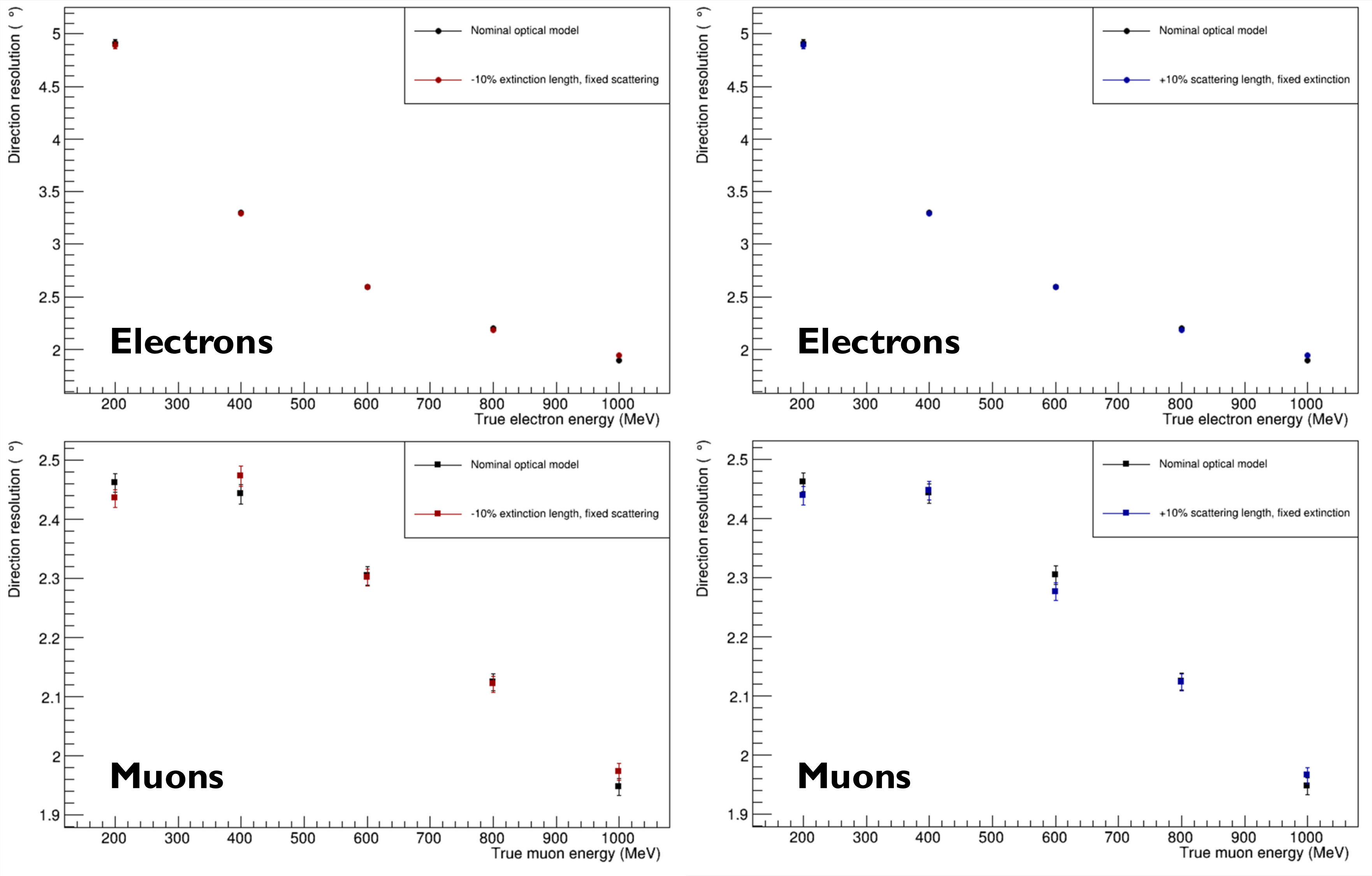
- Vertex resolution shows **measurable degradation** as extinction increases
- Scattering-only variations show **smaller changes**
- Indicating extinction (absorption-dominated) dominates vertex reconstruction response

IMPACT ON ENERGY RESOLUTION



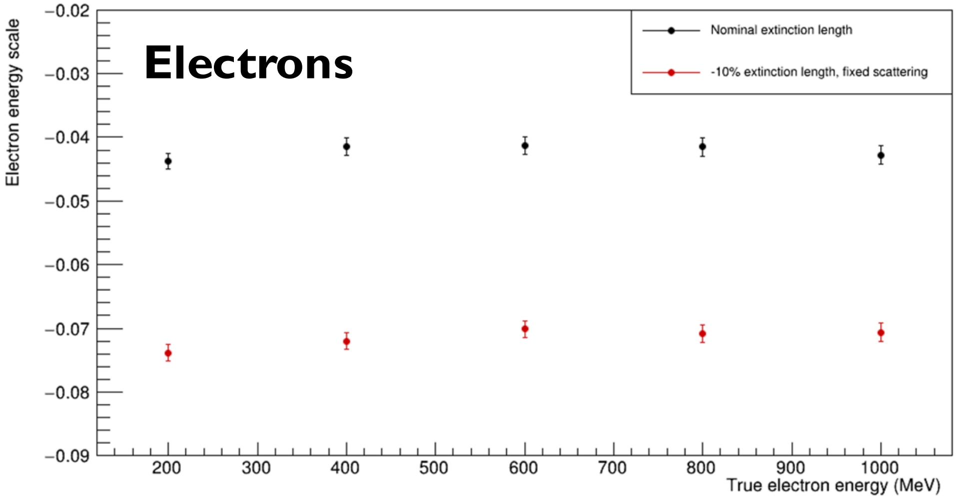
- Energy resolution is **more sensitive to extinction** (absorption-dominated) than to scattering-only variations
- This is consistent with total light yield loss being the dominant effect

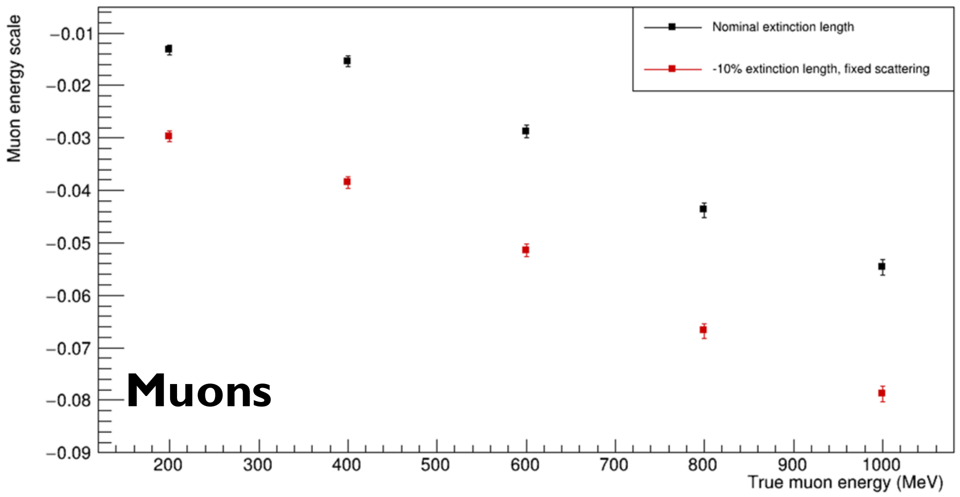
IMPACT ON DIRECTION RESOLUTION

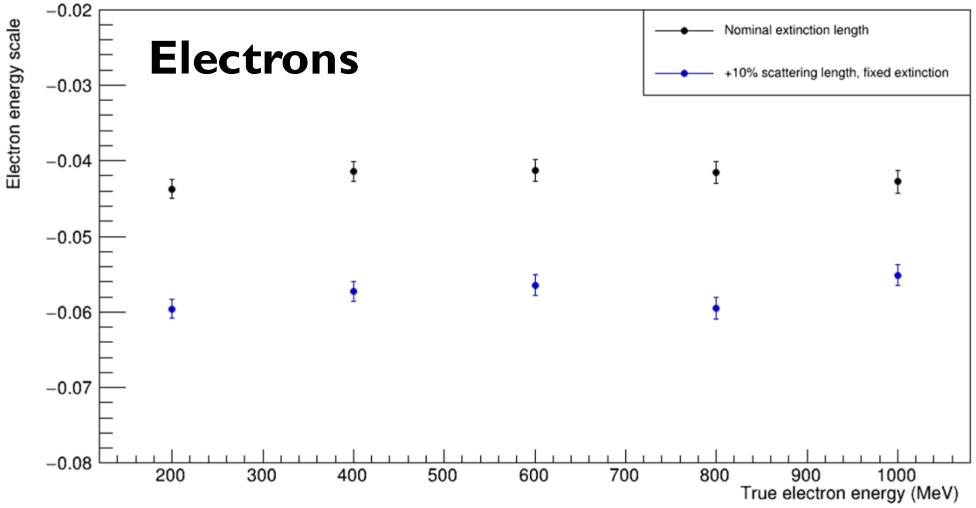


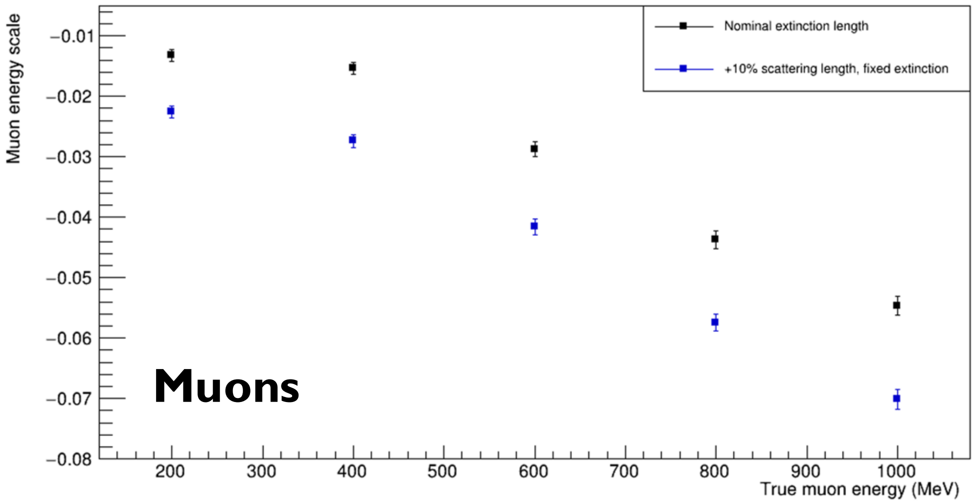
- Direction resolution (θ): 3D opening angle between reconstructed and true particle directions
- Extinction and scattering variations produce **only small changes** in direction resolution
- Similar behaviour observed for electrons and muons
- Direction reconstruction is **relatively robust** to optical uncertainties compared to vertex and energy reconstruction

ENERGY SCALE PLOTS

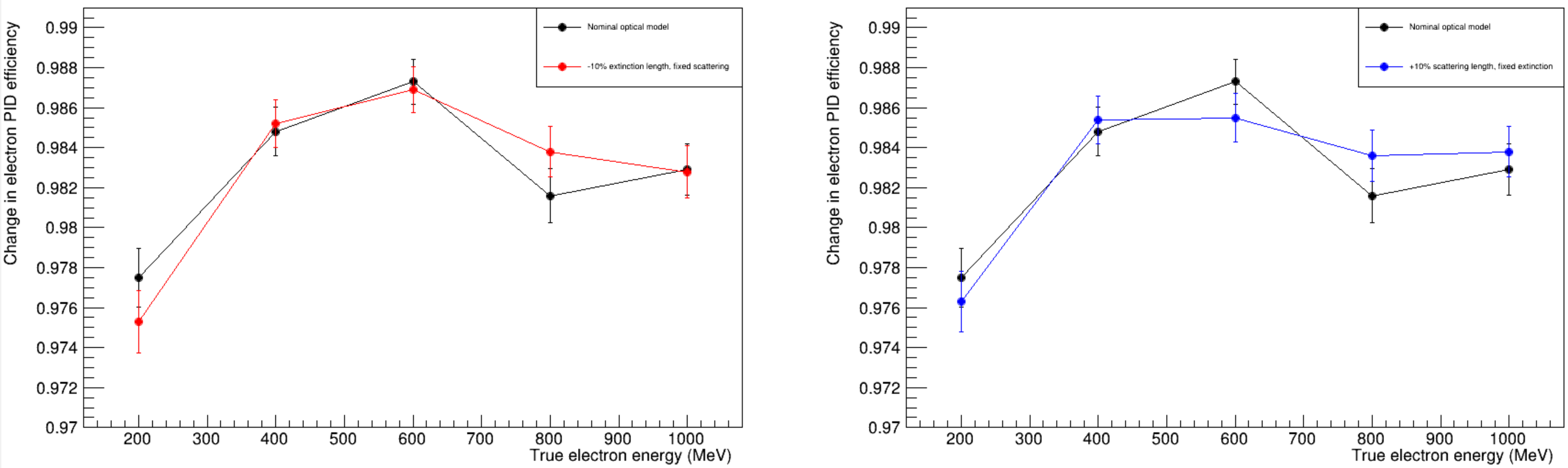




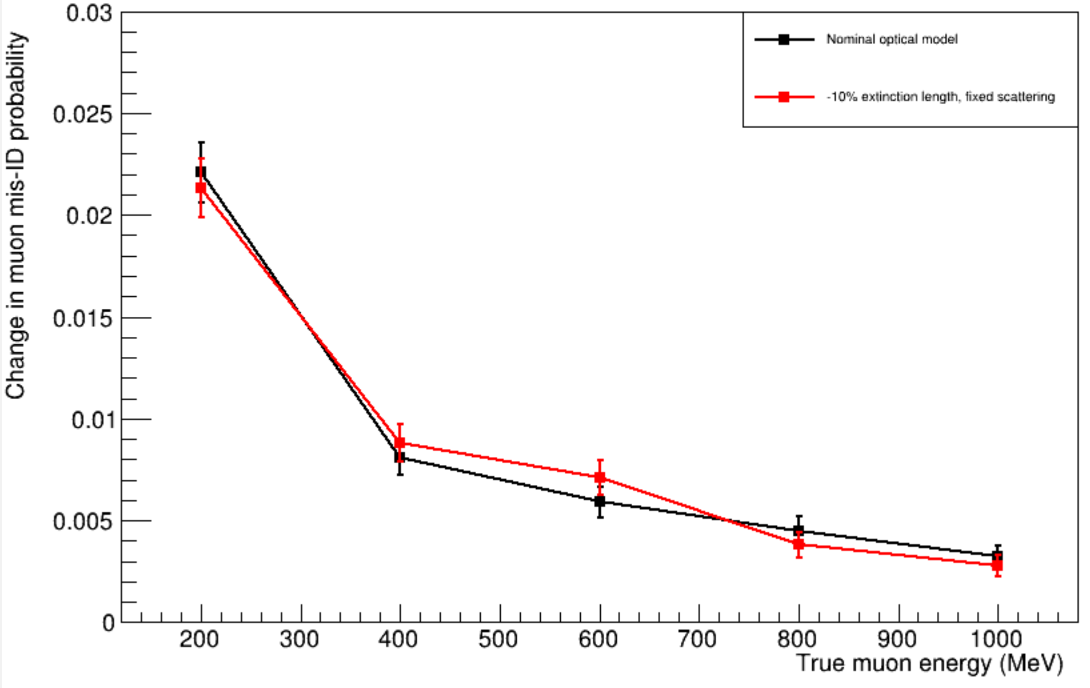


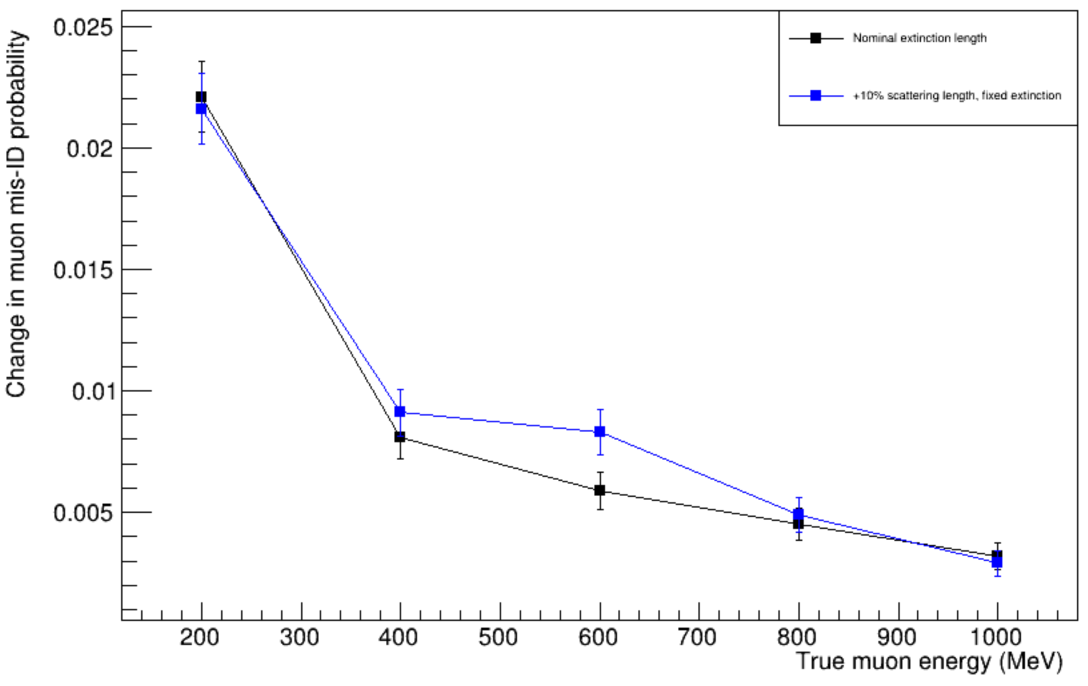


ELECTRON PID EFFICIENCY PLOTS



MUON MISTAG PLOTS





WHY STUDY FIDUCIAL VOLUME EFFECTS?

- Event rate depends on the **number of targets** inside the fiducial volume (FV)
- FV is defined using **reconstructed quantities**, not true geometry
- Optical variations in the detector model can **shift reconstructed vertices**
- This can move events **into or out of the FV**, changing the effective target mass
- FV acceptance is crucial because it directly affects:
    - Predicted event rates
    - Reconstructed energy spectra
    - Oscillation parameter measurements

PMT ANGULAR RESPONSE INITIAL STUDY - NORMALISATION CONVENTIONS

- Current WCSim B&L setup uses a flat nominal collection efficiency: $A_{\mathrm{nominal}} = 95\%$
- For a given controlled variation:

$$A_{\mathrm{varied}}(x) = A_{\mathrm{nominal}}(x) \times f(x), \qquad x = cos\theta$$

- The two normalisation conventions are:

1. Fix response at normal incidence,

$$f_1(x) = 1 + \mathrm{s}(x - 1)$$

keeps:

$$A_{\mathrm{varied}}(x = 1) = A_{\mathrm{nominal}}(x = 1)$$

2. Preserve average response (uniform $cos\theta$ integral preserved),

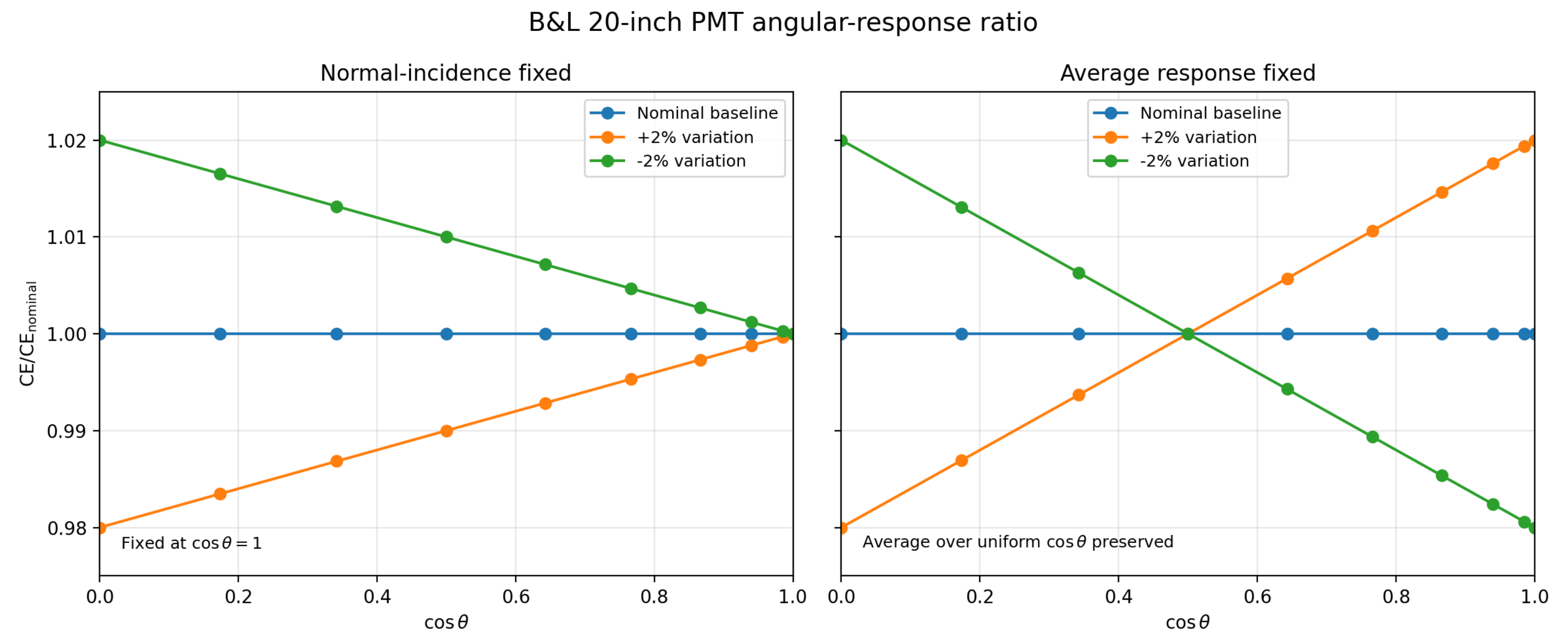
$$f_2(x) = 1 + \mathrm{s}(2x - 1)$$

keeps:

$$\int_0^1 A_{\mathrm{varied}}(x)dx = \int_0^1 A_{\mathrm{nominal}}(x)dx$$

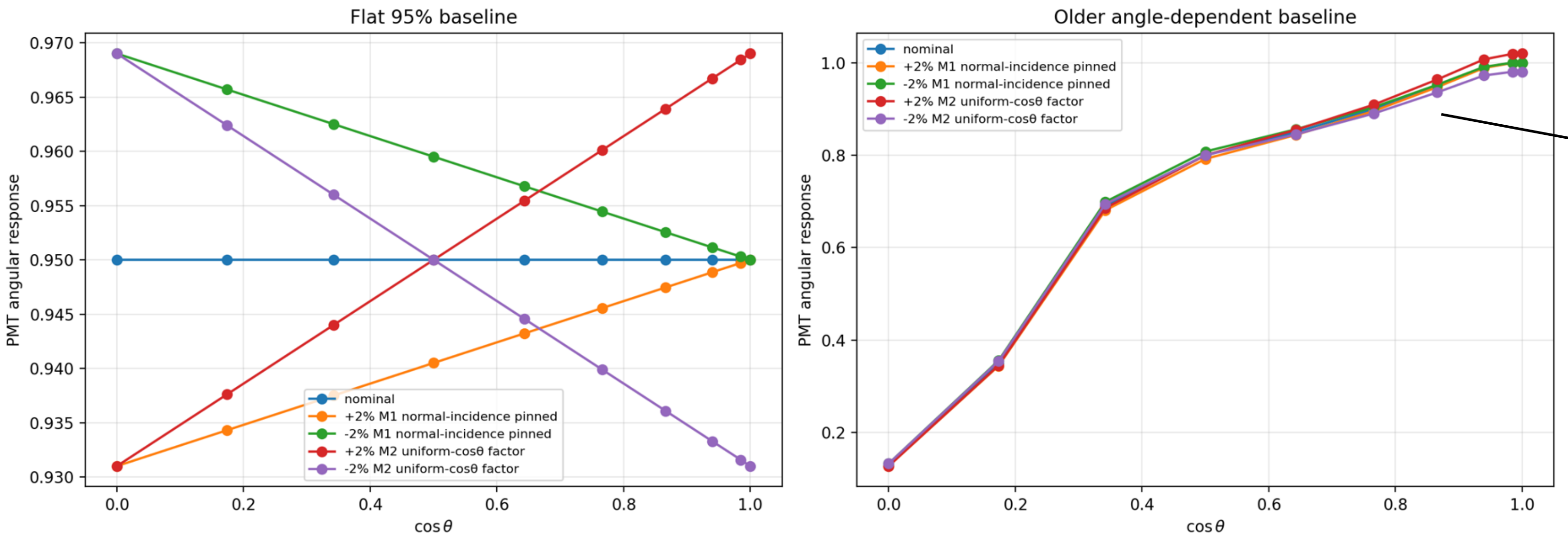
VALIDATION OF NORMALISATION CONVENTIONS

- For a given slope $s = \pm 2\%$ using both conventions, we plotted CE/CE_nominal vs cosθ
- Thus, the same ±2% slope can give different effective light yield changes



VALIDATION OF ANGULAR RESPONSE VARATIONS

- Current WCSim B&L setup uses a flat nominal collection efficiency: $A_{\mathrm{nominal}} = 95\%$
- Also checked an older angle-dependent CE curve found in WCSim as a comparison → gave more realistic-looking angular response and is (kind of) similar to FIG.16 in the Hyper-K technical note 21



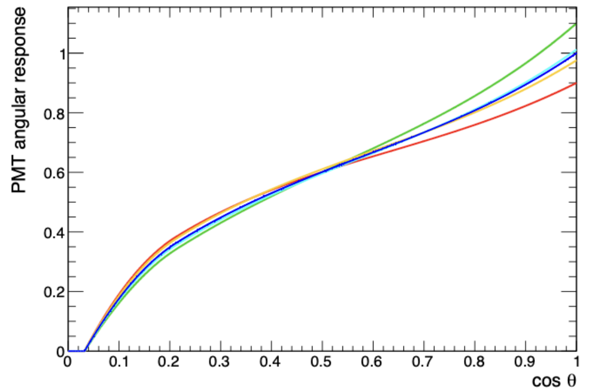


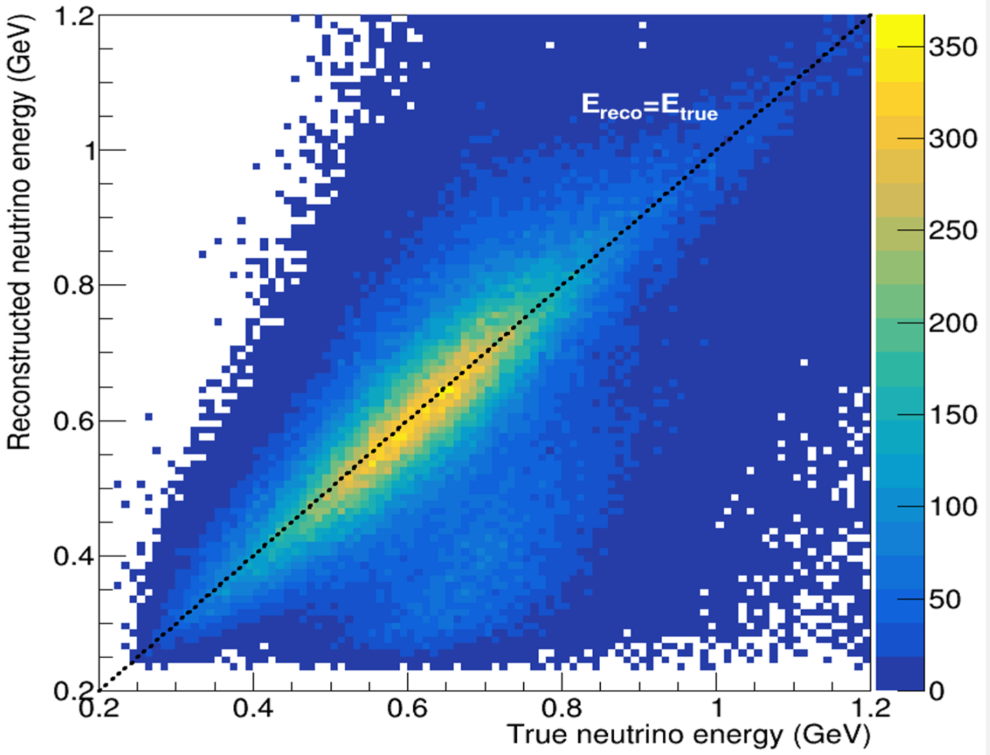
FIG. 16. The angular response variations applied to the Monte Carlo for the bottom up calibration approach. The nominal response is shown in blue, the ±2% variation is shown in yellow and cyan and the ±10% variation is shown in red and green. In the case of the ±2% variation the response has been renormalised to maintain the same overall efficiency.

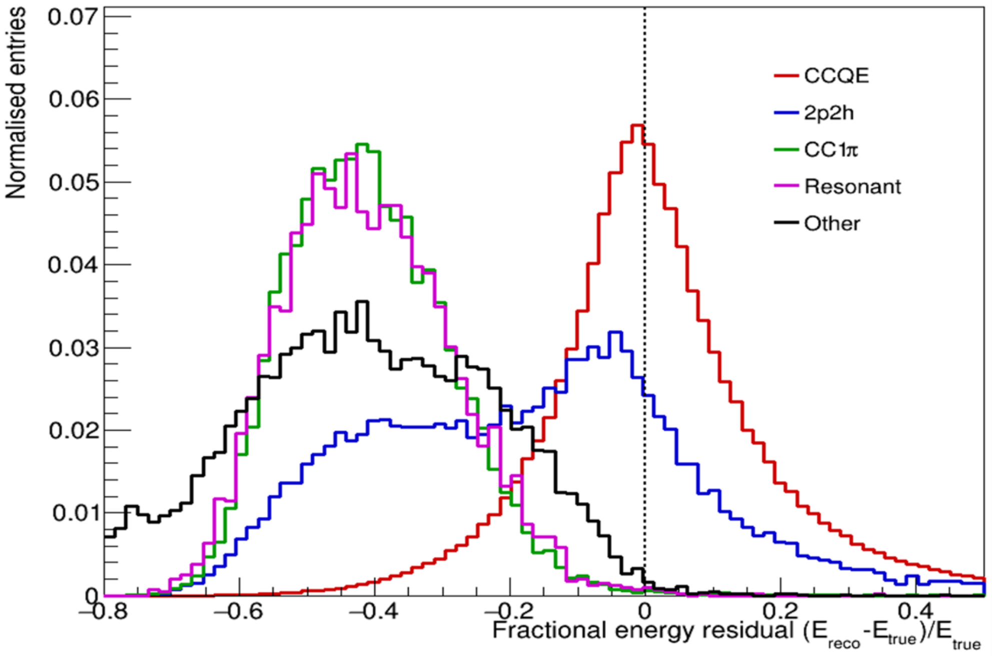
FROM BOTTOM-UP DETECTOR SYSTEMATICS TO OSCILLATION IMPACT

- Current bottom-up studies quantify impact of optical variations on:
  - Energy scale / resolution
  - PID performance
  - Vertex + FV migration
- How do detector distortions propagate into far-detector (FD) oscillation fits?
- Began exploring MaCH3-HK inputs and a possible fake-data pathway following discussions with collaborators
- Plan: Optical shifts → Reconstructions distortions → fit-level spectrum distortions → future oscillation-bias studies

INITIAL STUDY OF BENCHMARK FD SAMPLE (FHC ν_μ DISAPPEARANCE)

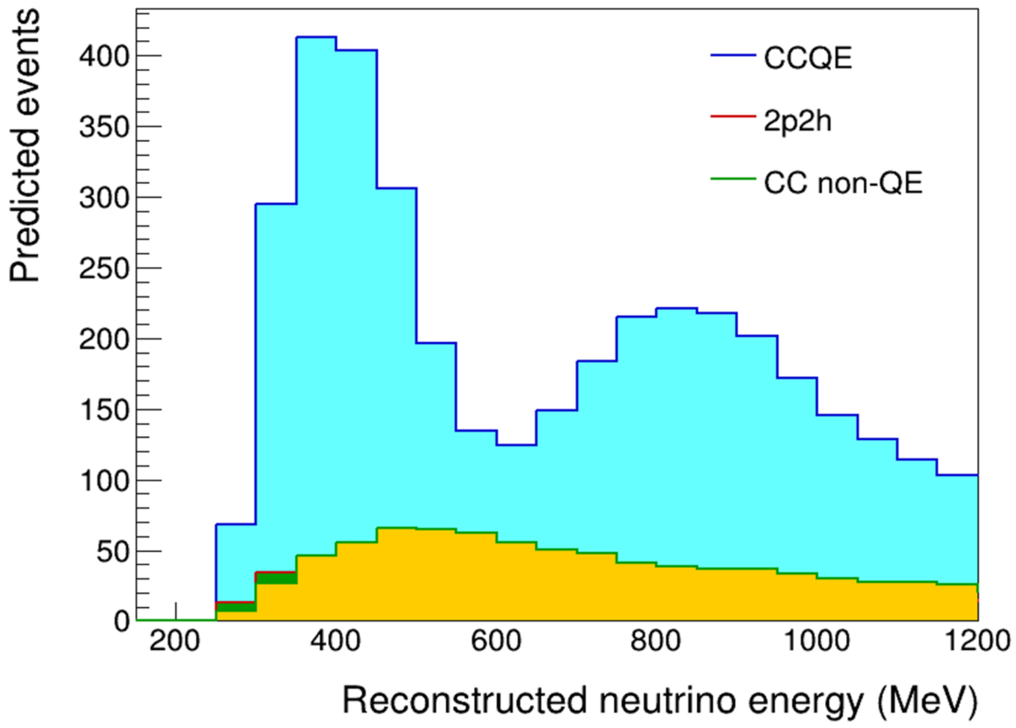
- Studied HK-scaled SK-like minituple: fhc.numu_x_numu_numuselec
- Traced three layers:
    1. Reconstruction variables such as erec, PID, fqwall, fqtowall
    2. Truth variables such as pnu, interaction mode, oscillation channel
    3. Fit-level observables such as weighted spectra (used by MaCh3)
- Useful observations:
    - ➢ Structured truth-reco event migration
    - ➢ Interaction-mode dependent residual biases
    - ➢ Natural bridge to existing bottom-up observables

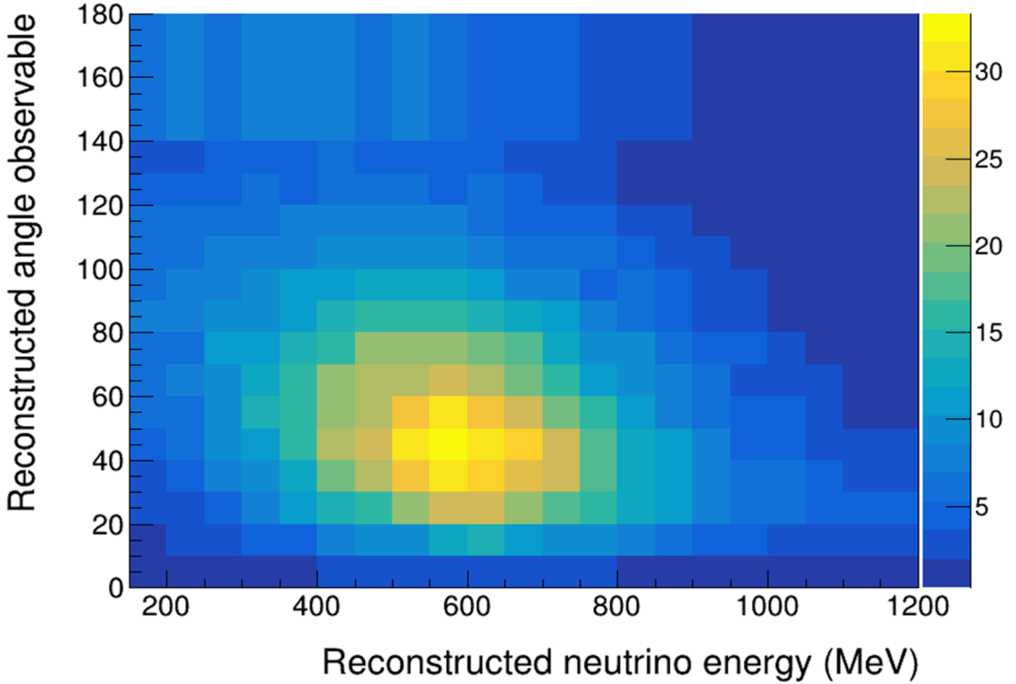




TRACING DETECTOR EFFECTS INTO FIT OBSERVABLES

- Examined fit-level spectra (SKEventRates) in MaCh3:
  - Reconstruction energy prediction
  - Mode-decomposed spectra (CCQE / 2p2h / non-QE)
  - 2D reconstructed energy-angle fit observables
- Detector systematics can be interpreted as event migration in fit space
- Possible distortion handles for fake-data studies:
  - Energy scale shifts
  - Mode-dependent distortions
  - PID/sample migration
  - FV acceptance migration
- Suggests a natural bridge from detector studies to fake-data distortions





INTRODUCTION:
PMT PRE-CALIBRATION

	In-situ calibration	Pre-calibration
Source	Ni/Cf, cosmic muons	Laser (controlled)
Direction	Limited/not controllable	Fully controllable
Environment	Full detector environment (water, B-field coupled)	Controlled environment (isolated PMT response)
Key limitation	Degeneracy between water properties and PMT response	Minimal degeneracy between effects
Role	Full detector calibration	Provides reference PMT calibration

- Hyper-K requires sub-percent energy scale precision (~0.5%) → In-situ calibration **limited by degeneracy between water properties and PMT response**
- Concept of Pre-calibration:
  - ➢ Measure PMT response before installation **under controlled condition**
  - ➢ Characterise QE, angular response, timing, gain
- Approximately 2% of PMTs are pre-calibrated and used as reference PMTs for detector calibration
- Role in calibration:
  - ➢ Decouple PMT response from water properties
  - ➢ Provide key inputs for bottom-up calibration

OVERVIEW OF THE SETUP

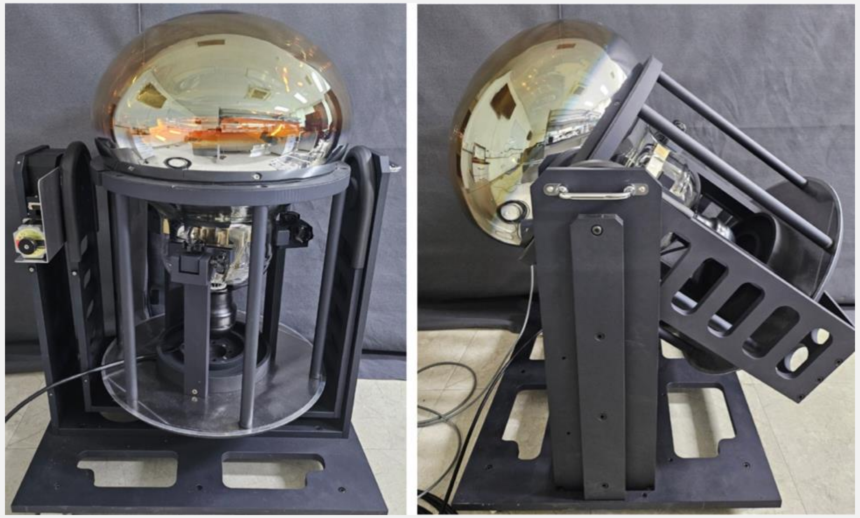
- Two complementary light injection systems with Helmholtz coils to cancel geometric field

PMT rotation system (Korean group)

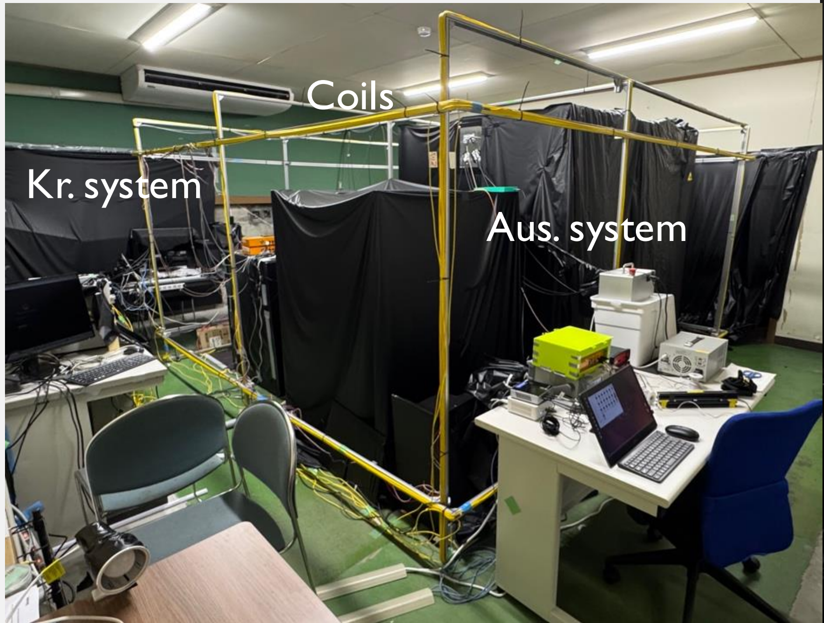
- ➢ **Fixed light source** with rotating PMT
- ➢ Advantage: Stable light intensity
- ➢ Disadvantage: Possible bias die to changing B-field

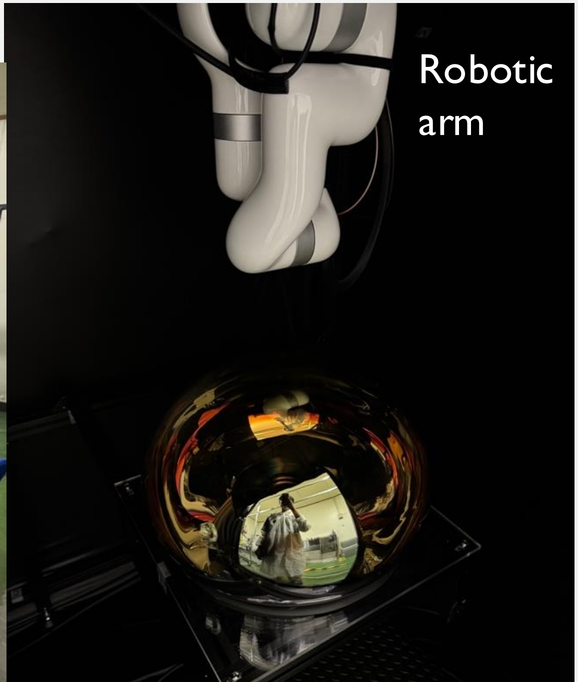
Robotic arm system (Australian group)

- ➢ Fixed PMT with **moving light source** (robotic arm)
- ➢ Advantage: More flexible change of light injection points
- ➢ Disadvantage: Possible light intensity change due to fibre bending



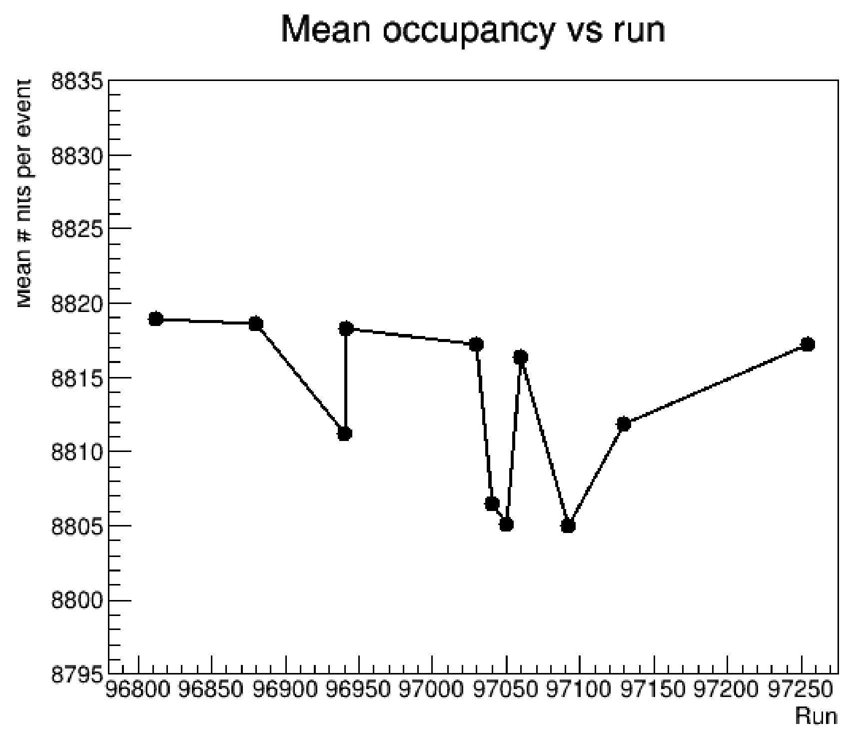
Pictures of the rotation system taken from Hyper-K technical note 108.

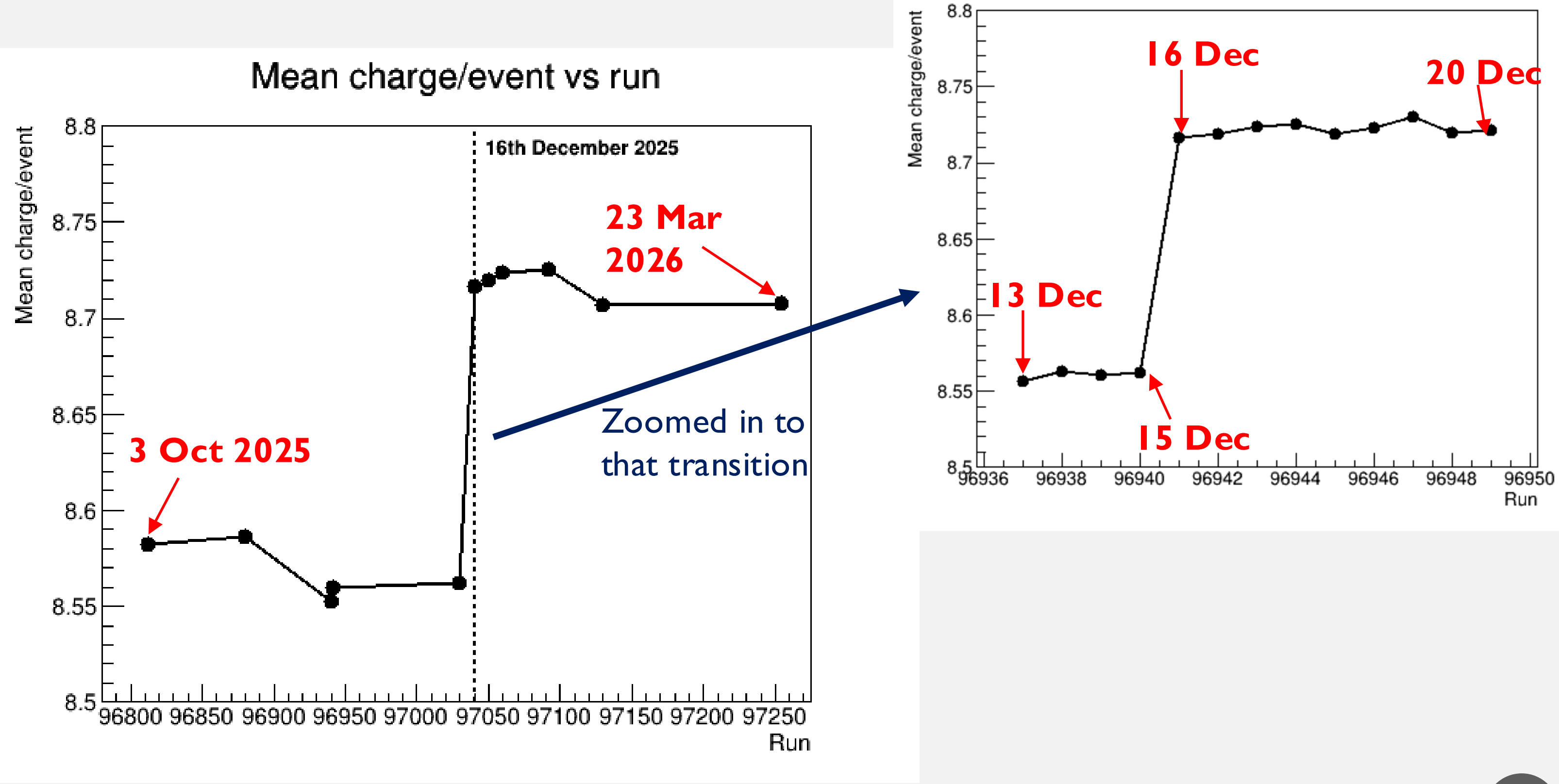




TQ MAP UPDATE - RECONSTRUCTION CONSISTENCT CHECK

- Occupancy stable → no change in event content
- Mean charge/event shows ~2% step increase between 15-16 December → so this might be likely due to skofl25b / TQ map update and not cause of detector or water effects





RADIUS-DEPENDENT CHARGE CORRECTION I

- After simple charge correction failed, we constructed a radius-dependent correction given by:

$$Q_{corr} = Q \times C(r)\,, \qquad C(r) = \frac{Q_{post}(r)}{Q_{pre}(r)}$$

- Applied:
    - Shape of radial profile
    - Only to post-transiton runs
- Implementation to integrate directly into analysis code and applied at hit level-based radius

RADIUS-DEPENDENT CHARGE CORRECTION II

BEFORE APPLYING CORRECTION