Calibration challenges in the MAIA calorimeters

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Outline

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2. The MAIA calorimetry system and solenoid
3. Particle behavior in the solenoid
4. Analytical calibration approach
5. 2D calibration matrix – benefits and challenges
6. Conclusion and next steps

Introduction

*What is **MAIA**?*

- ***M**uon **A**ccelerator **I**mplemented **A**pparatus*
- *One of two detector concepts proposed for a Muon Collider at $\sqrt{s}$=10 TeV*
- *Composed of shielding nozzles, trackers, a 5T solenoid, calorimeters, and a muon system*

Why are calorimeters important?

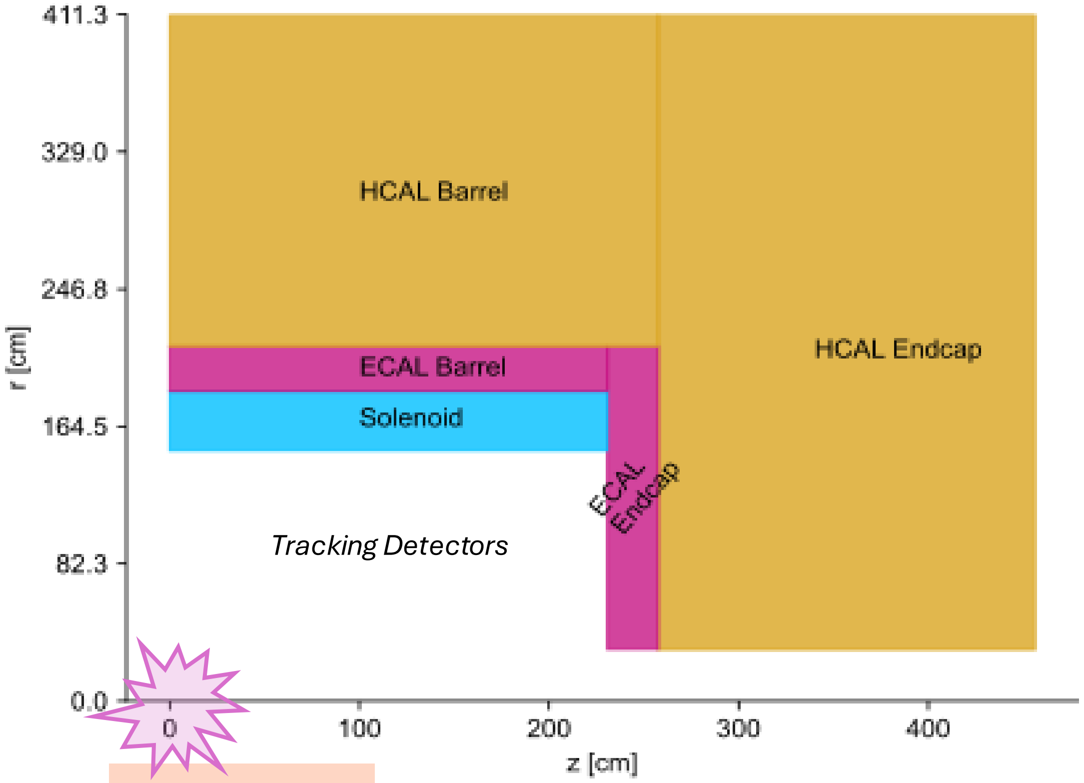
- *The electromagnetic and hadronic calorimeters are designed to **stop** EM and hadronic particles, respectively, and **measure their energy***
- ***5D calorimetry**—information about energy, timing, and position*

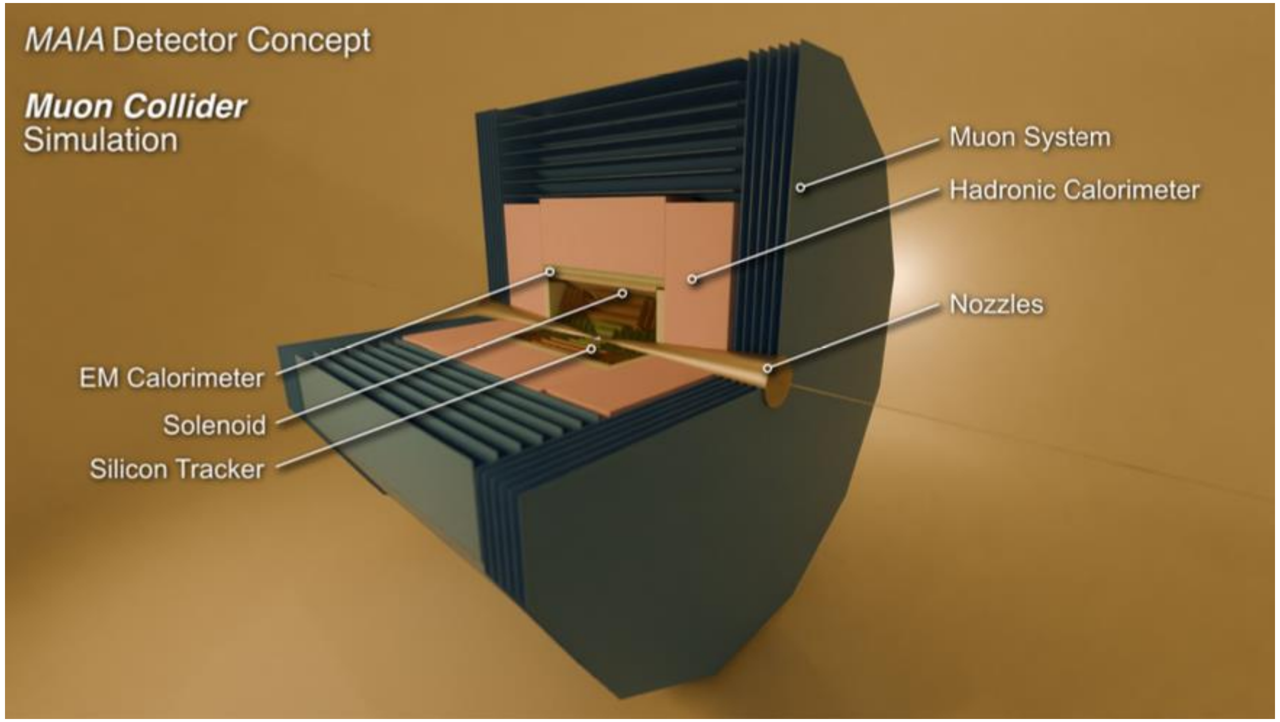
Why and how do we calibrate our calorimeters?

- *Accurate energy measurements are crucial to reconstruction*
  - ***Particle ID***
  - *Identifying **missing energy***
  - *Finding **resonances***
- *We can assess the calorimeters' performance with the simplest neutral objects (**photons and neutrons**) as **standard candles***

MAIA Calorimeters

Cross-section of the first quadrant of the MAIA detector in the RZ plane, focusing on the solenoid and calorimeters.





ECAL:
- Silicon and Tungsten
- 5x5 mm^2 cells
- 50 layers

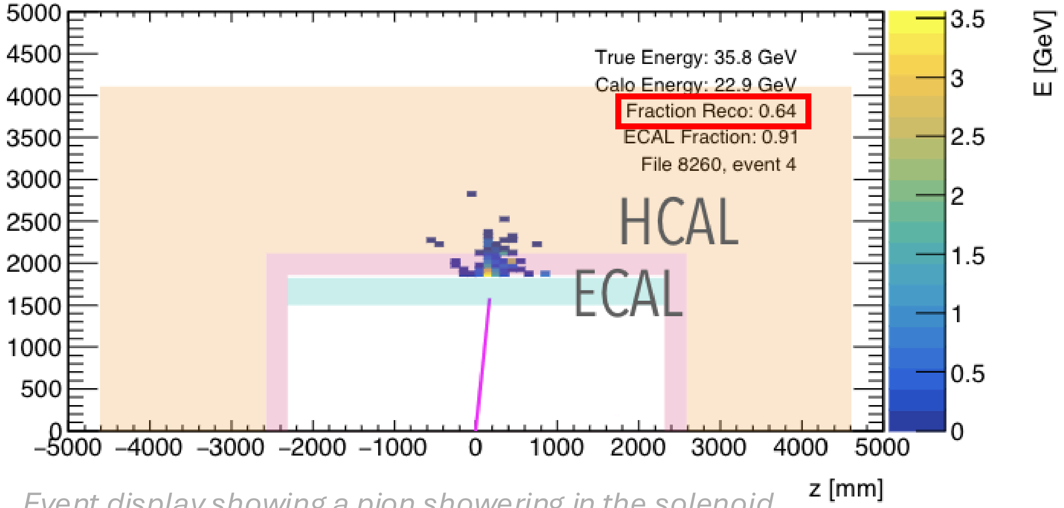
HCAL:
- Iron and scintillator
- 30x30 mm^2 cells
- 75 layers

The solenoid: BIB bodyguard or black box?

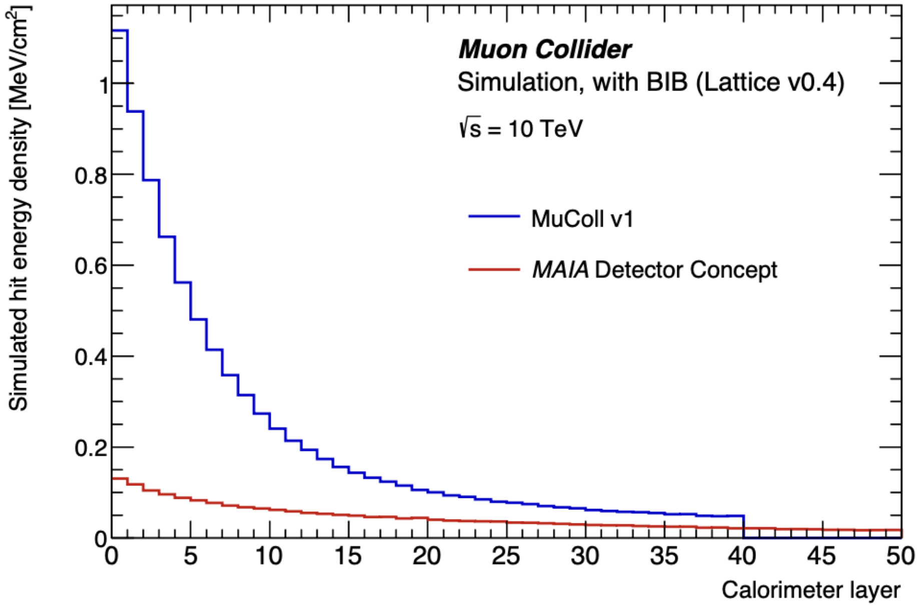
*The **solenoid** adds approximately **265 mm of aluminum** between the **trackers** and the **calorimeters.** Two interpretations…*

265 mm of **additional shielding,** drastically reducing BIB occupancy in the calorimeters!

265 mm of **detector-free material** where particles **interact** and **lose energy.**



Event display showing a pion showering in the solenoid. Plot courtesy of Tova Holmes.



Comparison of BIB energy density deposition in ECAL for different solenoid placements.

[1] arXiv:2502.00181

Material interactions in the solenoid

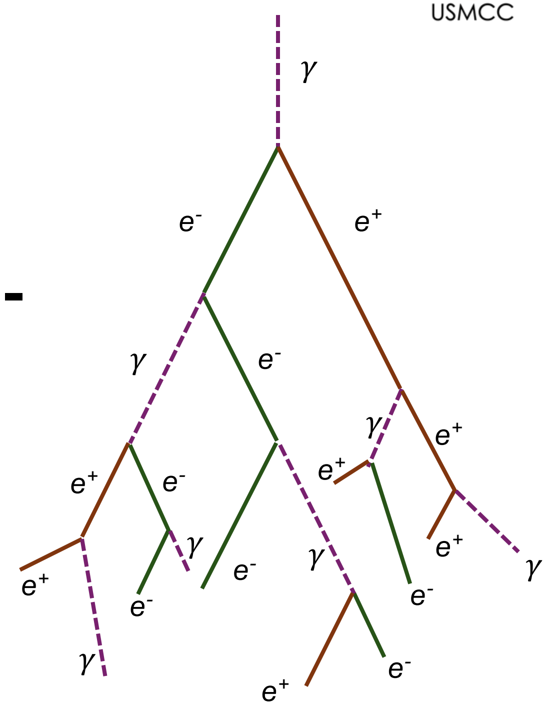
Photons lose energy via **electromagnetic showers**

- Cascade of **pair production, Bremsstrahlung,** and **e+/e- annihilation**

Neutrons lose energy via **hadronic showers**

- Cascade of nuclear processes, collisions,

and EM showers



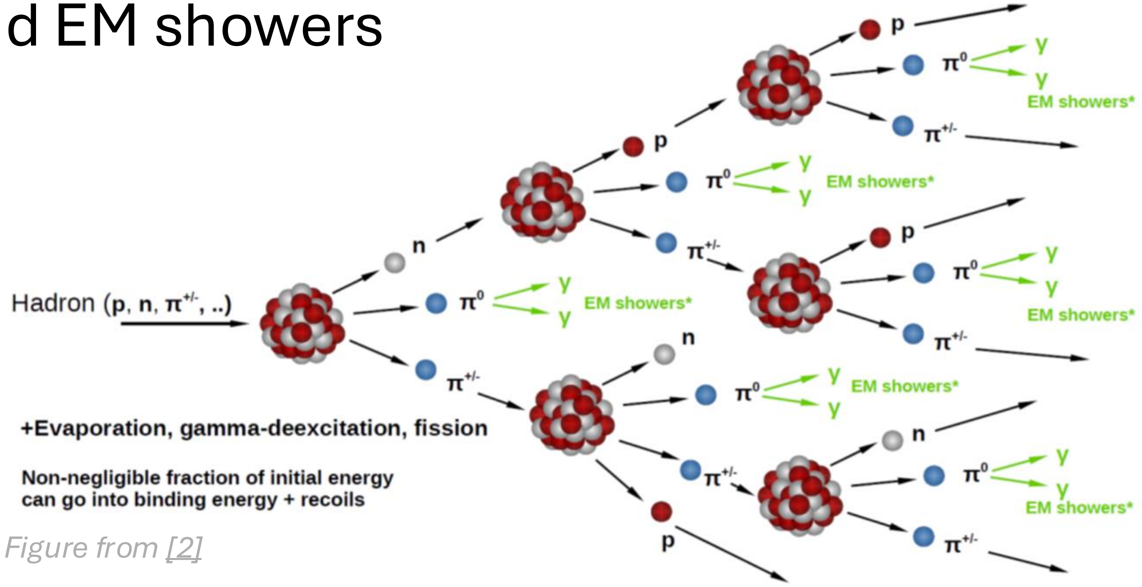


Figure from [2]

Both EM particles and hadrons can shower in aluminum, resulting in energy loss between the trackers and the calorimeters.

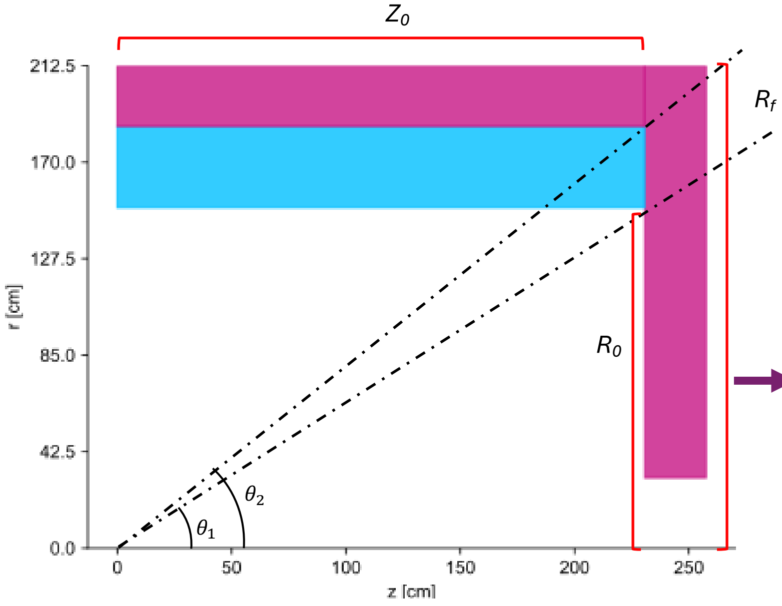
Analytical energy loss function

Let's take an analytical approach to EM showering

- Much simpler to model than hadronic showering

We derive energy response shape as a function of:

- Geometric parameters of detector
- Photon polar angle

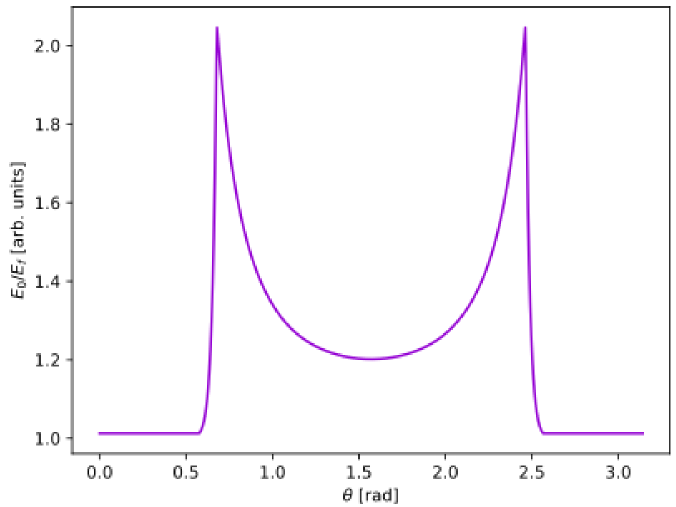


Radiation length X_0 = 8.89 cm

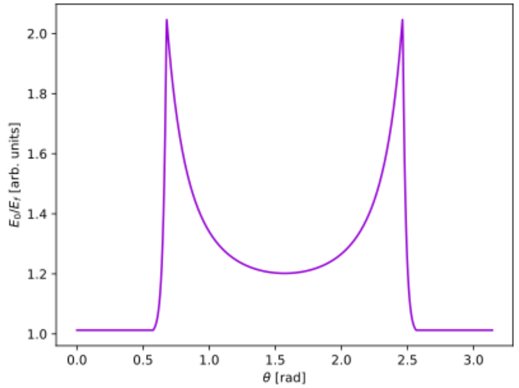
Number of Radiation Lengths in Al

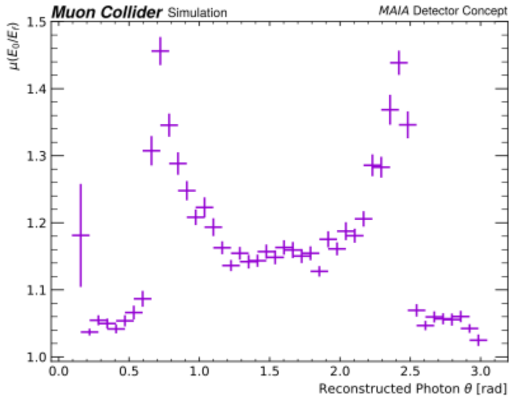
$$N(\theta) = \begin{cases} 0 & \theta < \theta_1 \\ (Z_0|\sec(\theta)| - R_0 \csc(\theta))/X_0 & \theta_1 < \theta < \theta_2 \\ \left(R_f - R_0\right)\csc(\theta)/X_0 & \theta > \theta_2 \end{cases}$$

$$E_0/E_f \propto 2^{N(\theta)}$$



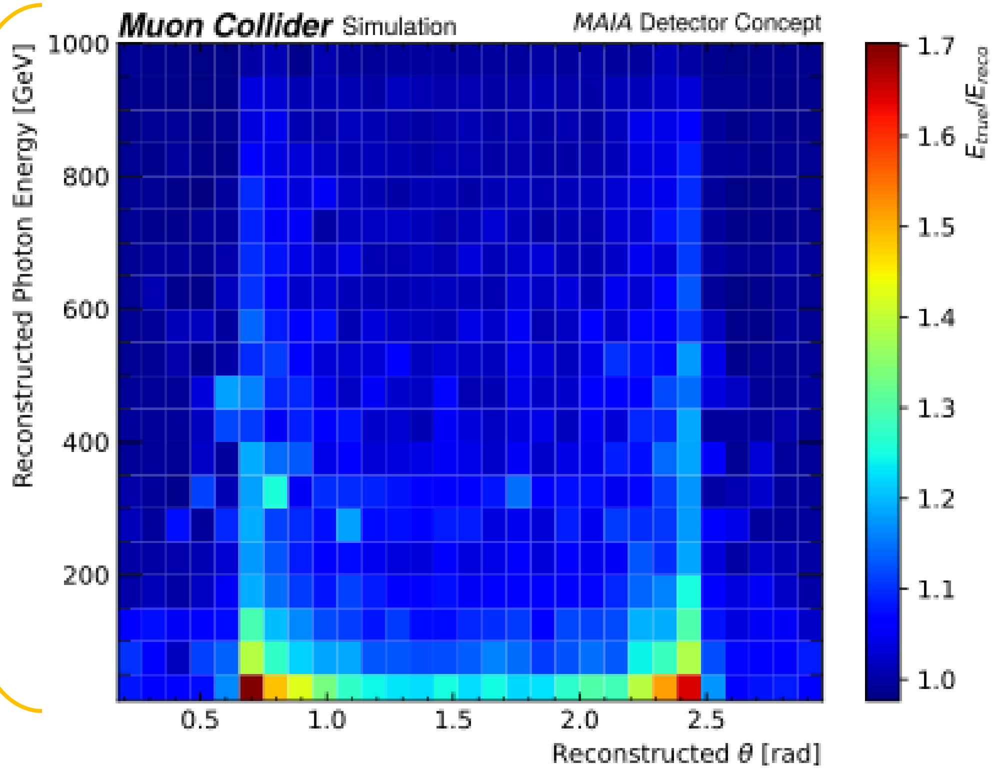
Indeed, the theta-dependence of photonic energy response follows this form…





… but theta-dependence is not the whole story.

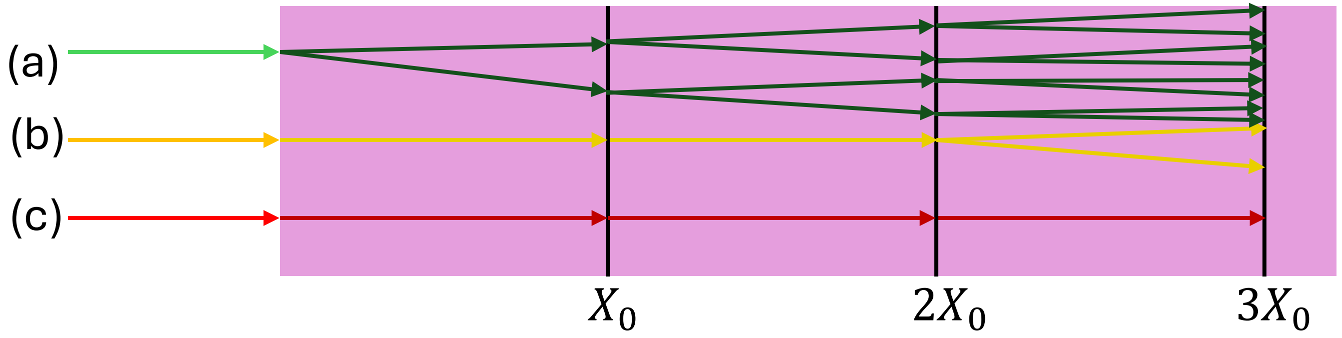
Response is also ***energy dependent—*** *higher-energy particles lose* ***fractionally less*** *energy in the material.*



Stochasticity of showering

Unlike geometric theta dependence, energy dependence of response is highly ***nontrivial*** *to model.*

- Our $2^{N(\theta)}$ functional form assumes **immediate** showering
- At high energies, may see MIP-like behavior or **stochastically delayed** showering

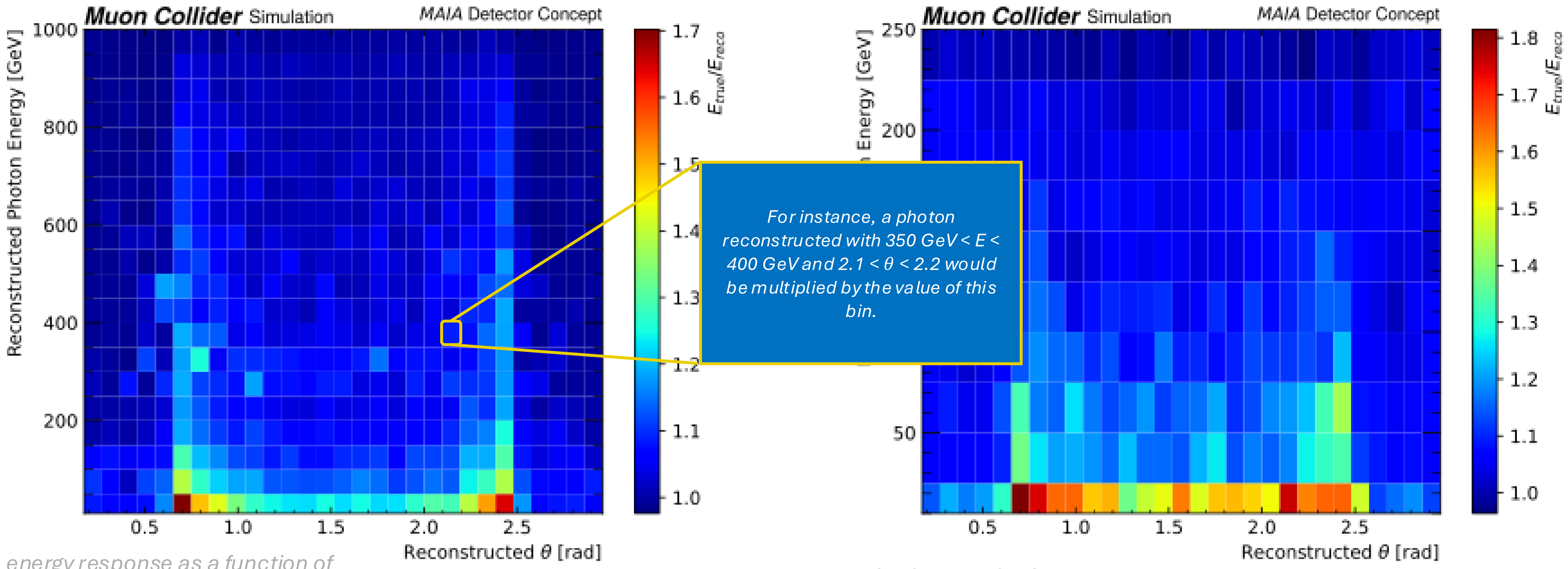


Cartoon of three particles beginning to shower at (a) the entrance to the solenoid, (b) after two interaction lengths, and (c) not at all.

Bottom line: we cannot rely on a realistic analytical calibration.

2D response as calibration function

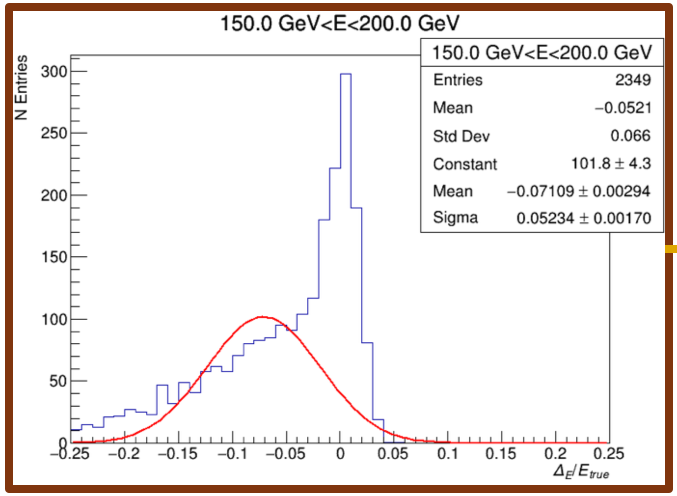
In lieu of an **analytical** calibration, we can use the response plots themselves as **calibration matrices.**

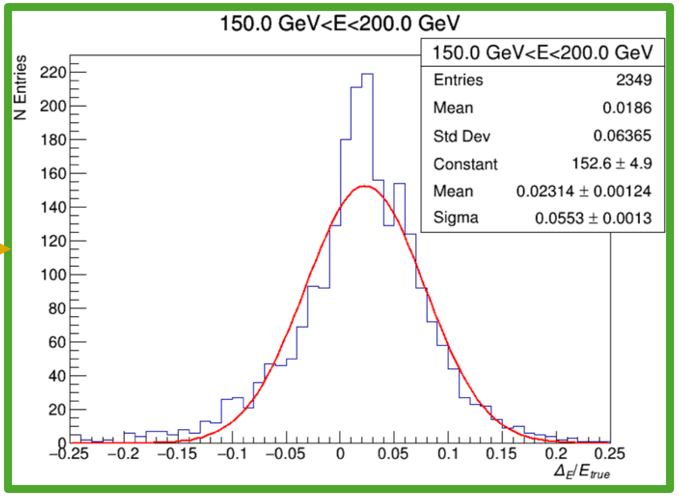


Photon energy response as a function of reconstructed energy and azimuthal angle.

Analogous plot for neutrons.

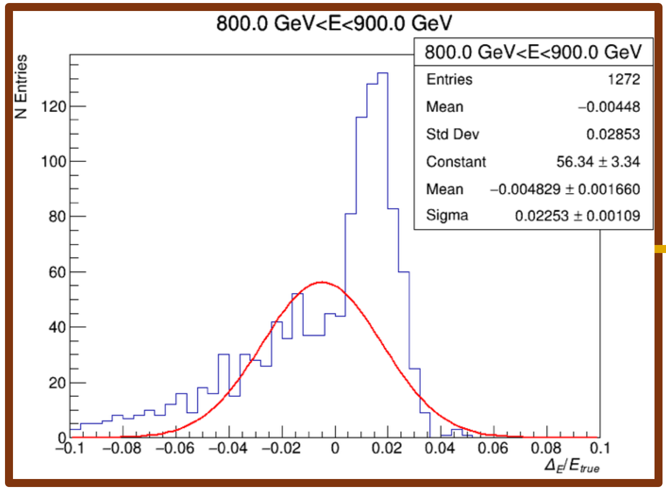
Calibrated fractional response

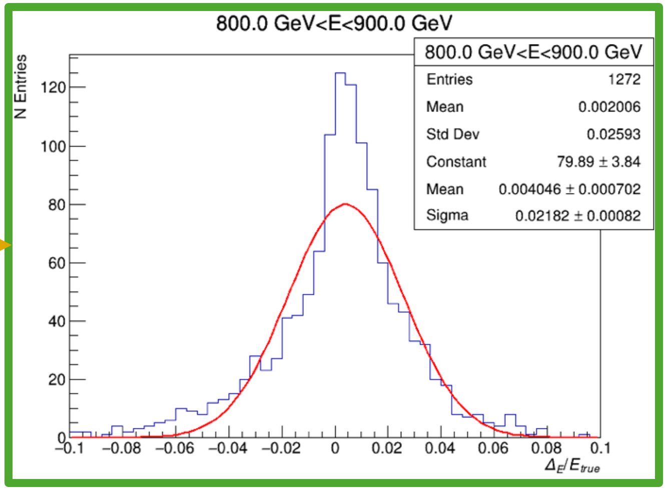




Two examples of the binned $\frac{\Delta E}{E_{true}}$ distribution for photons in an inclusive θ range, both before and after 2D response calibration is applied.

Calibration effectively ***eliminates*** *bimodality due to geometric effects.*

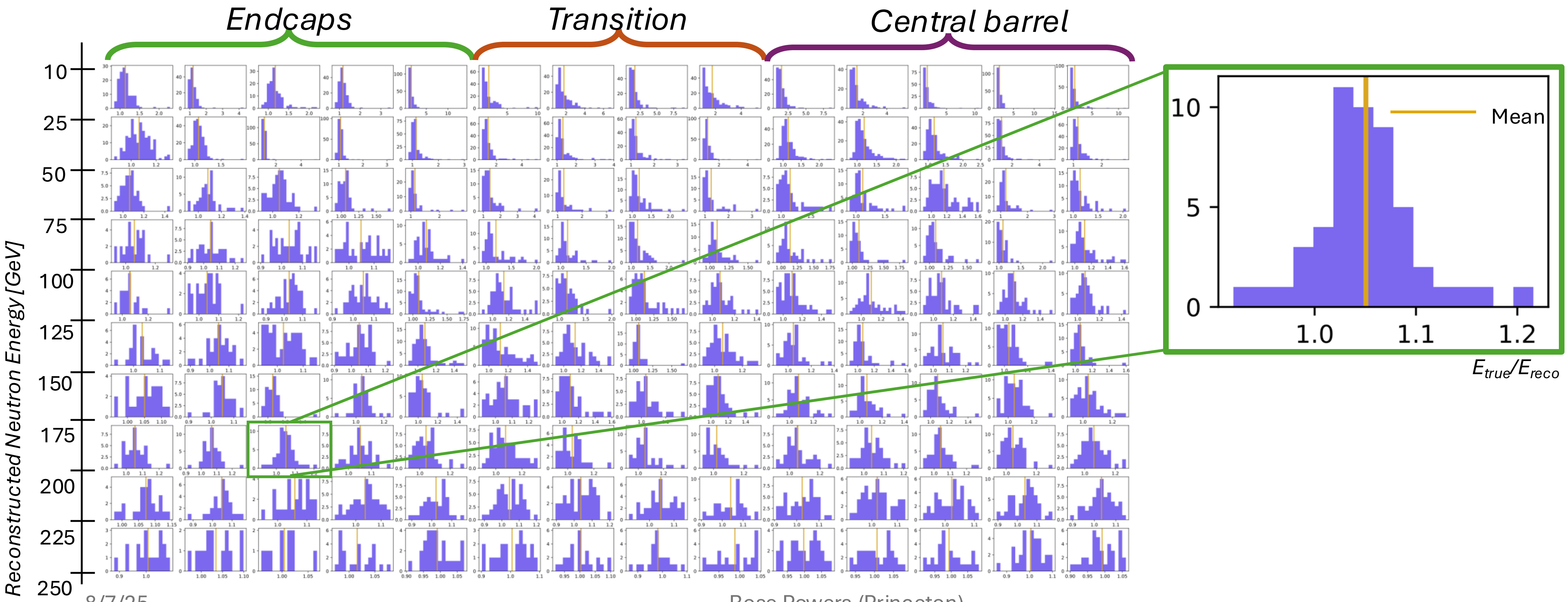




But is this really a valid approach?

These response plots take the **arithmetic mean** in each bin

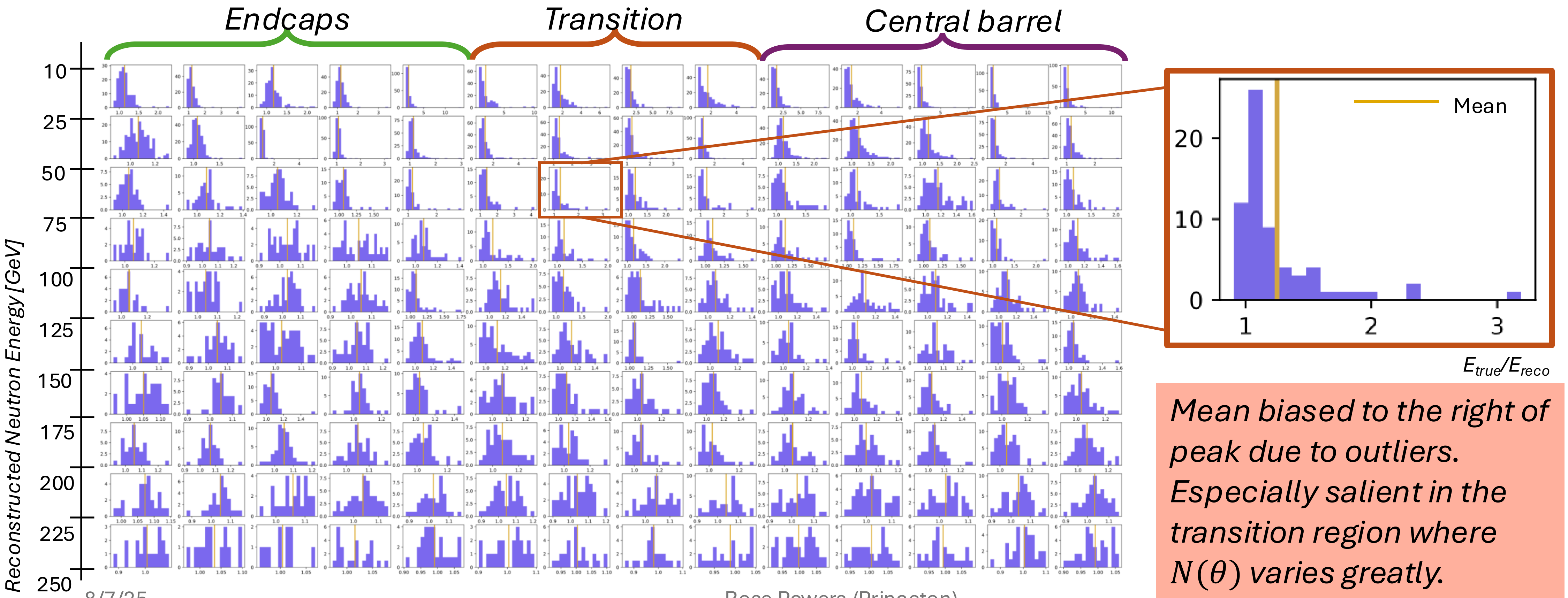
- Works well in bins with **Gaussian** distributions...



But is this really a valid approach?

These response plots take the **arithmetic mean** in each bin

- However, is susceptible to outliers
- Especially troublesome in **low-N** or **wide-range** regions



Mean biased to the right of peak due to outliers. Especially salient in the transition region where $N(\theta)$ varies greatly.

Alternative methods

A robust calibration method should not be susceptible to the influence of outliers.

- **Fitting** binned response distributions
  - Many bins exhibit near-Gaussian peaks: fitting those peaks would give a more stable mean
- A dedicated **large-statistics** calibration dataset
  - Could also stabilize and allow us to bin calibration matrix more finely
- A detailed study of particles’ interactions in the solenoid
  - Might make an interesting tangential investigation with applications in detector performance studies→opportunities here to get involved!

Conclusions and outlook

Calibration cannot completely remove stochastic broadening of energy response due to the solenoid.

- However, a 2D response-based calibration can **mitigate** the most salient geometrical and energetic dependencies
- A more **nuanced assessment** of binned response may further improve accuracy of calibration
- While the solenoid adds challenges to the calibration process, these challenges can largely be mitigated and are **far outweighed** by the solenoid's BIB reduction efficacy