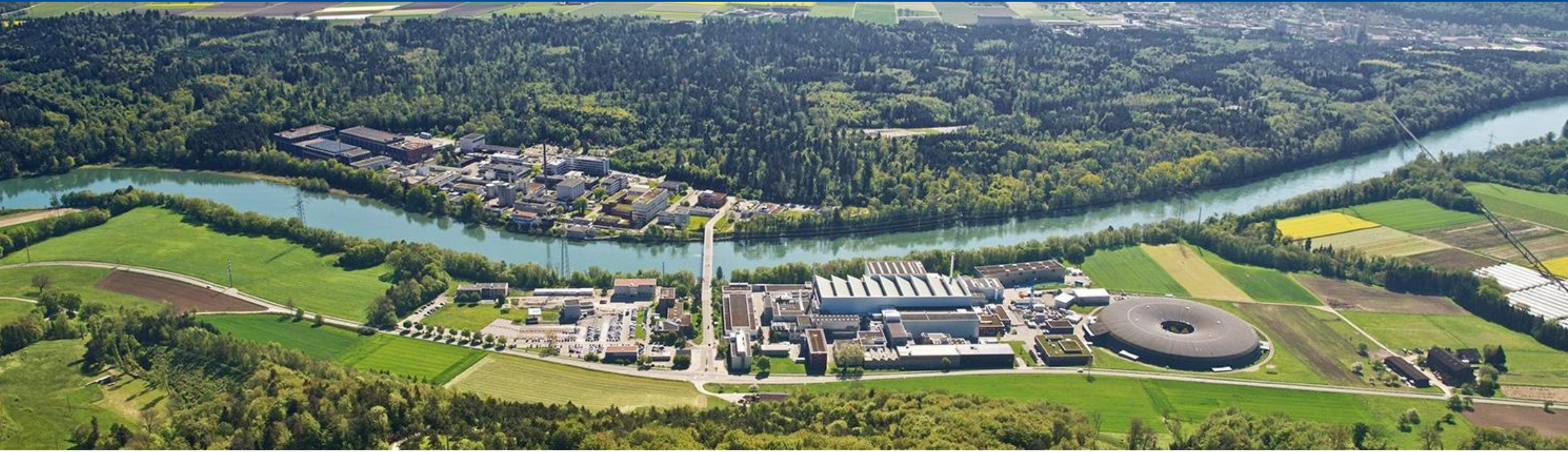


PIONEER Simulation General Results and Paths Forward

Josh LaBounty

Rare Pion Decay Workshop

10/6/2022

Analysis Technique Reminder

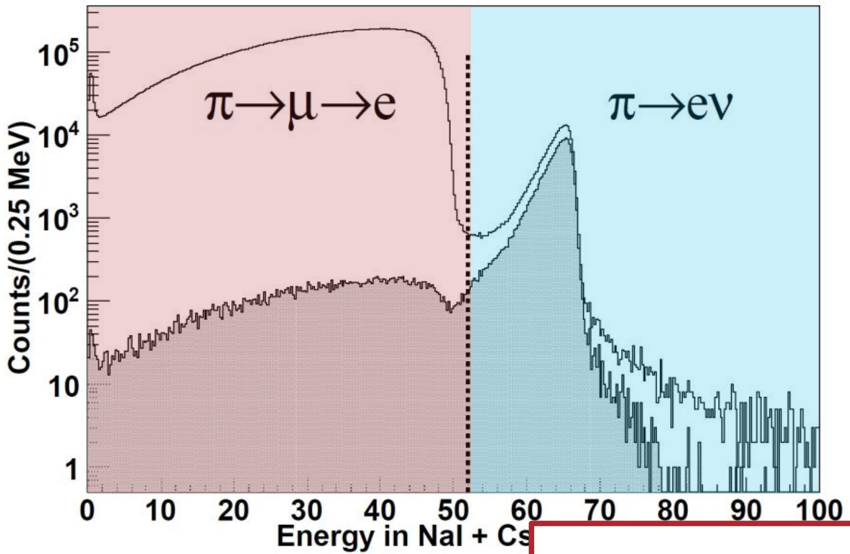
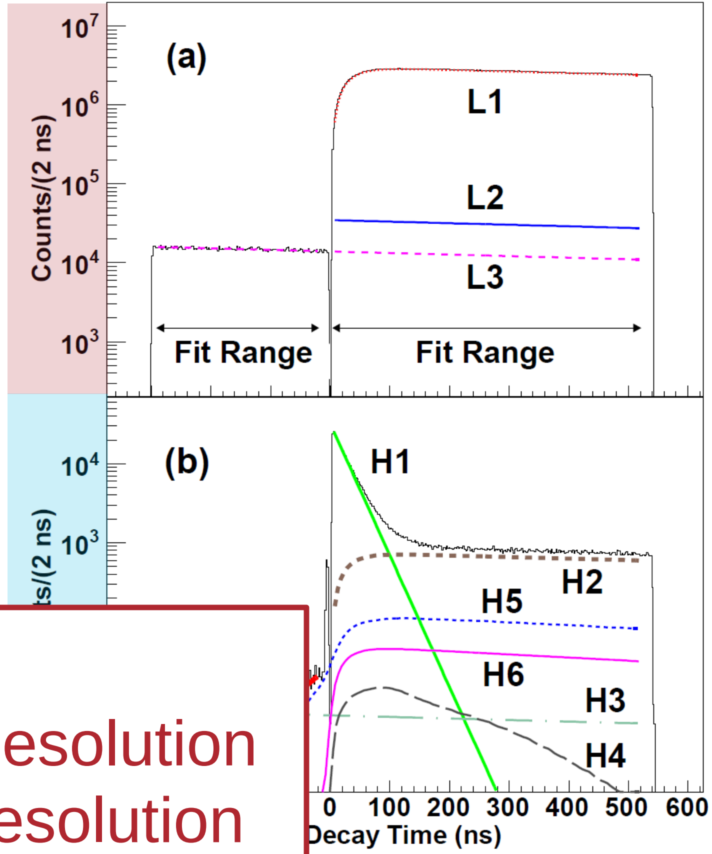


FIG. 2: Energy spectra of positrons in
ns without and with (shaded) backg
(see the text). The vertical line at 52
position.

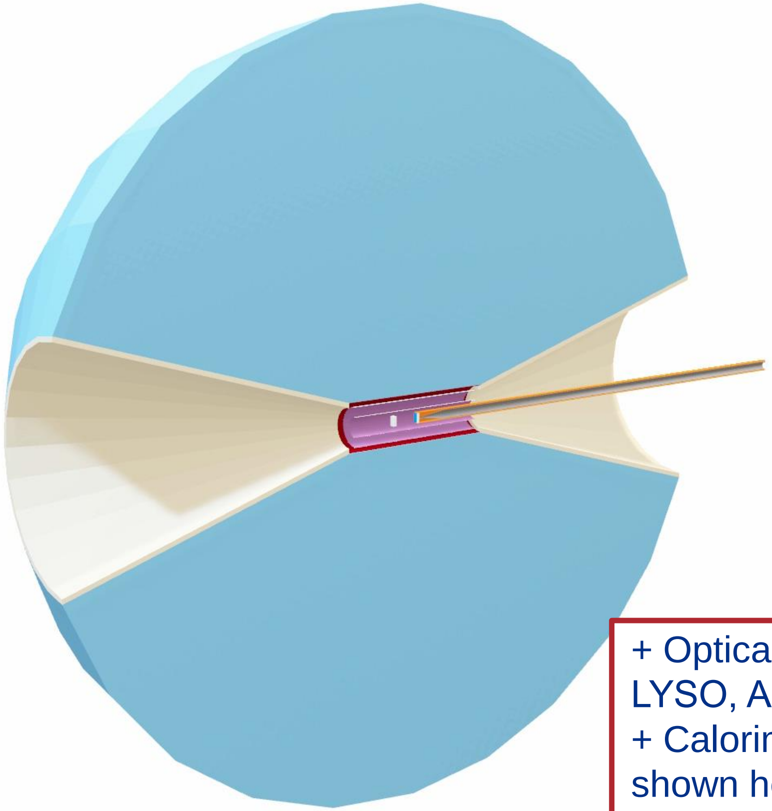


Requires:

- ✓ Energy Resolution
- ✓ Timing Resolution
- ✓ Fast Triggering

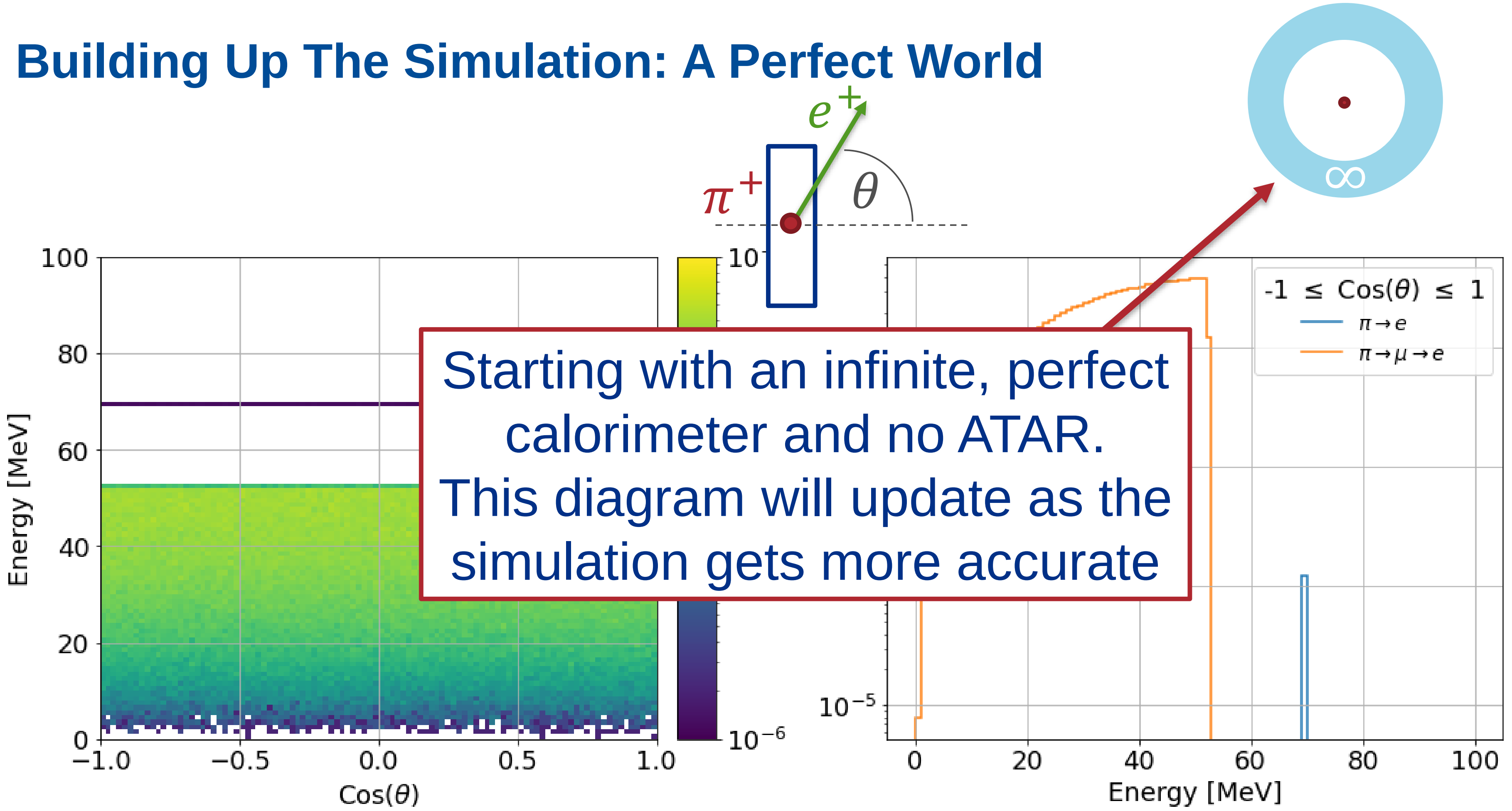
Phys. Rev. Lett. 115, 071601 (2015)

What's in the Simulation?



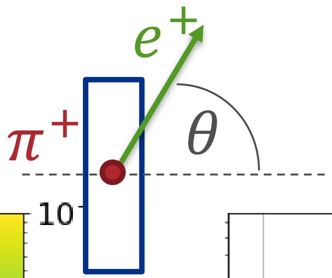
+ Optical Models for all materials (LXe, LYSO, Al, Si…)
+ Calorimeter Outer shell/readouts (not shown here)
+ reconstruction
+ …

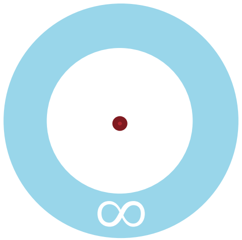
Building Up The Simulation: A Perfect World

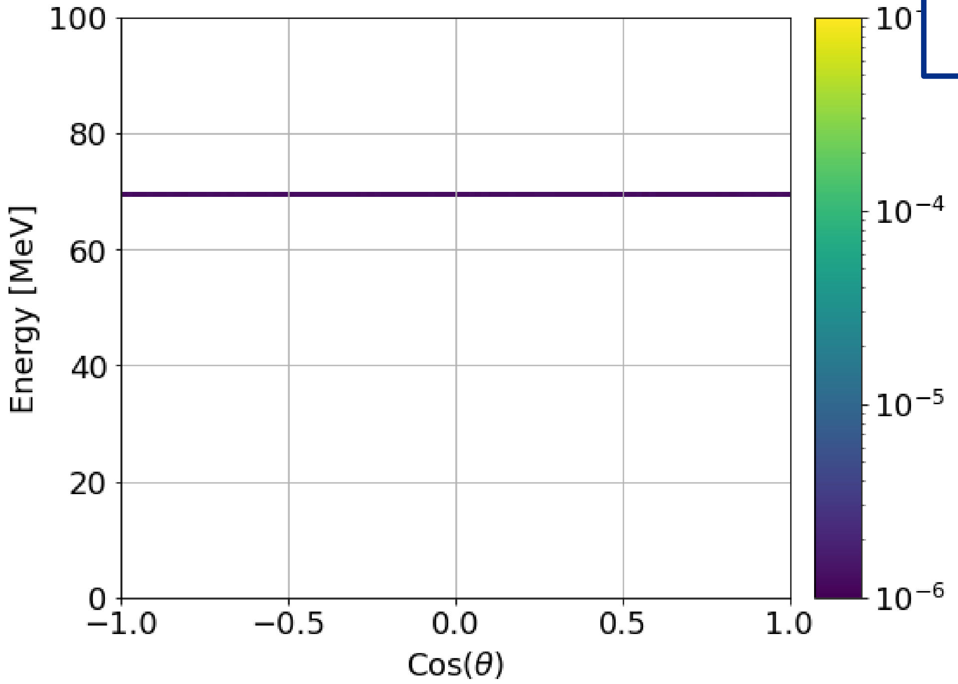


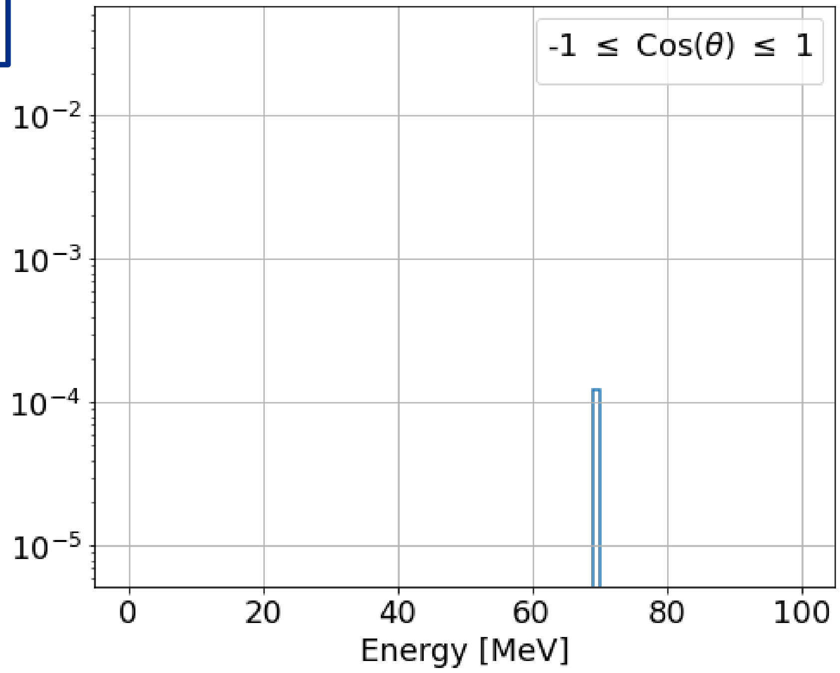
Starting with an infinite, perfect calorimeter and no ATAR.
This diagram will update as the simulation gets more accurate

Building Up The Simulation: A Perfect World
$\pi \rightarrow e$ Only, π at ATAR center







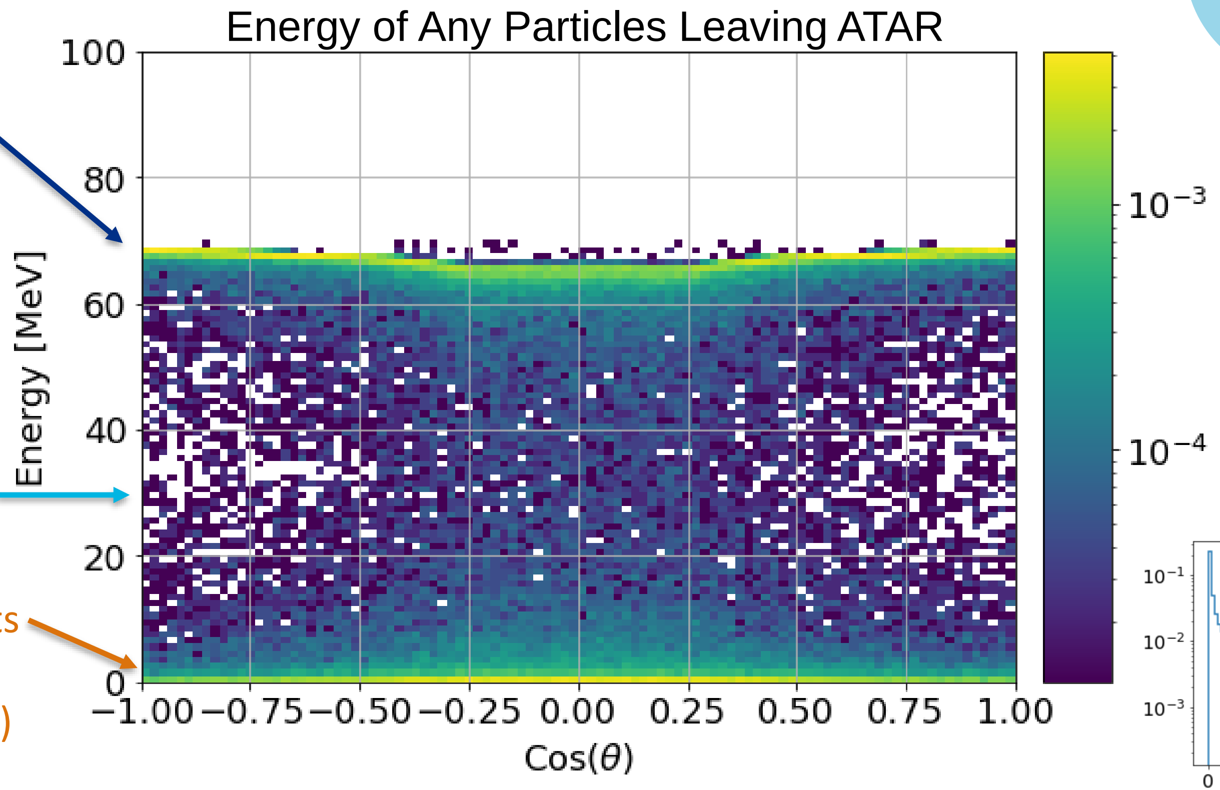


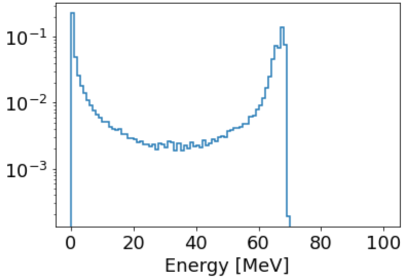
Building Up The Simulation: ATAR

"Normal" Events

Intermediate Events (Bhabha scattering, Bremsstrahlung, etc.)

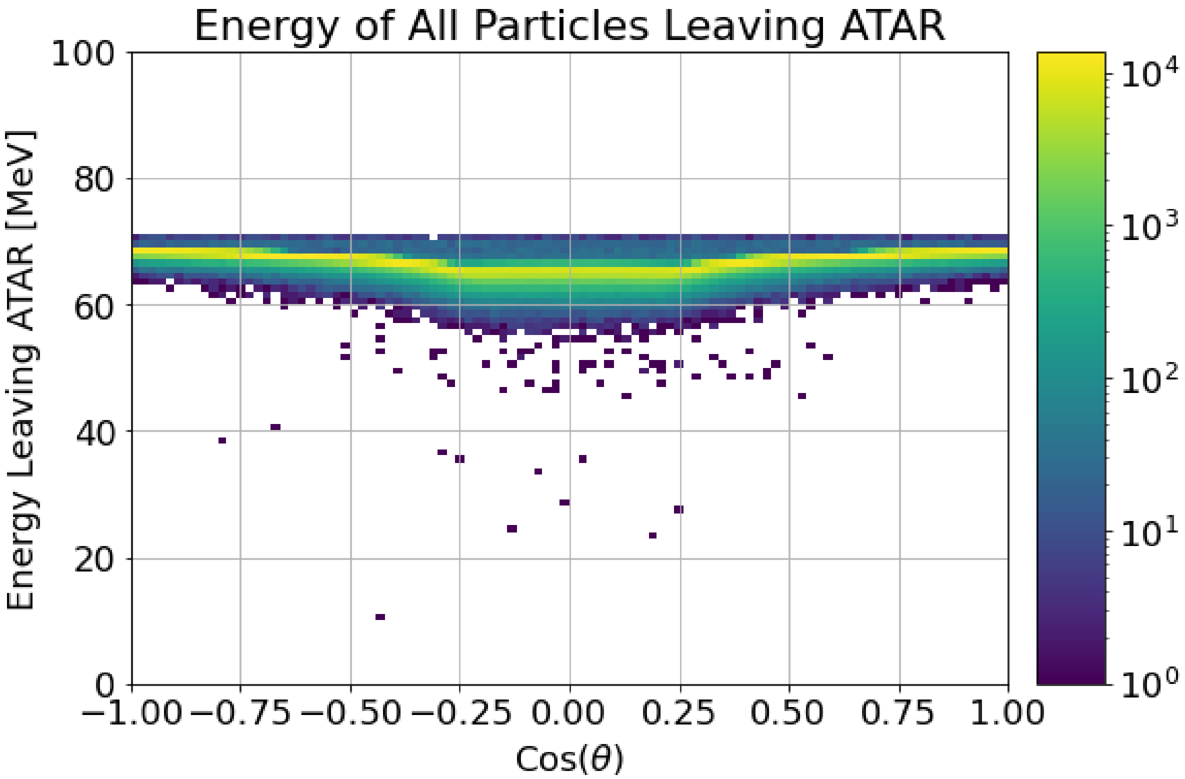
Low Energy Events (won't be able to see them anyway)

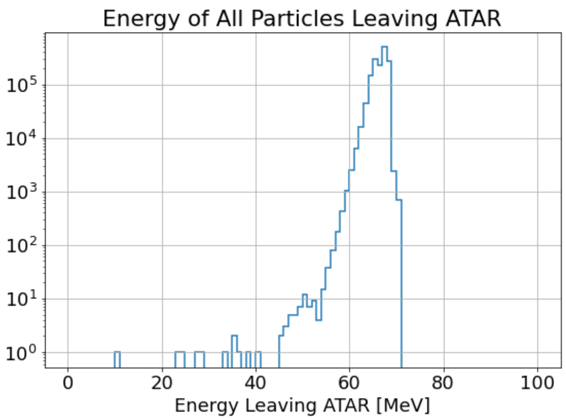




Takeaway: radiative processes matter!

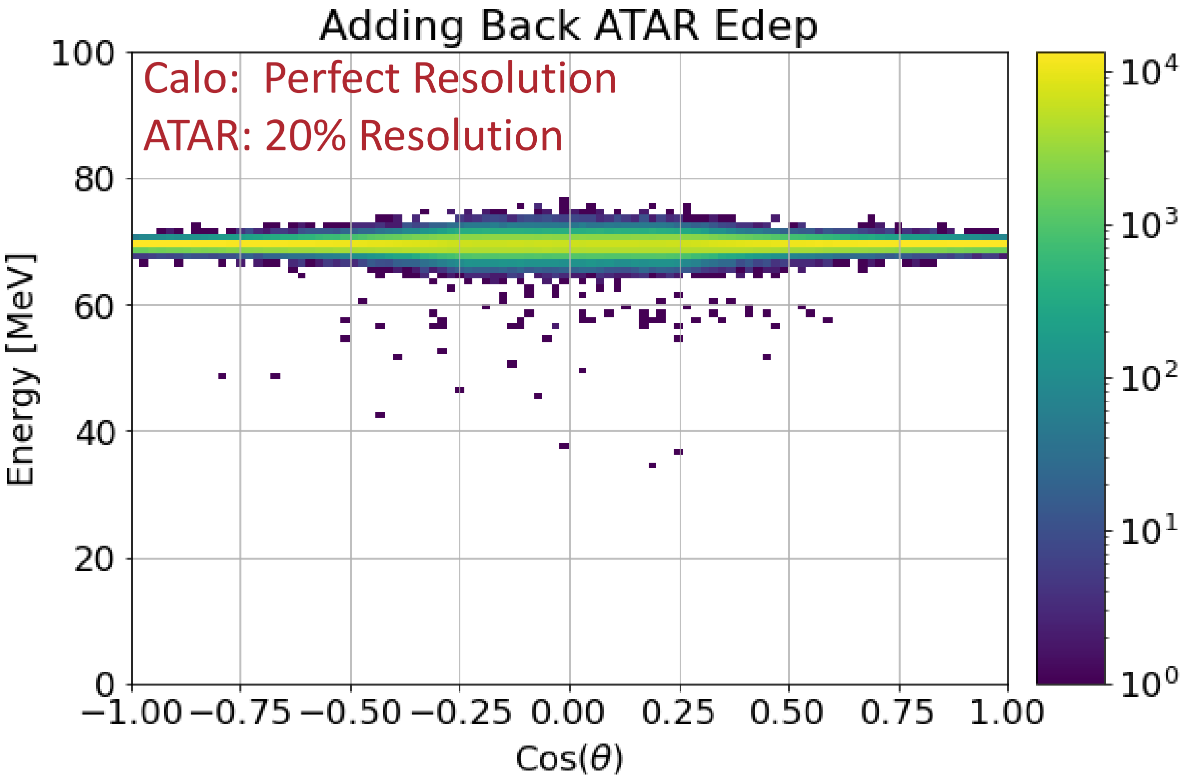
Building Up The Simulation: ATAR (Summed)

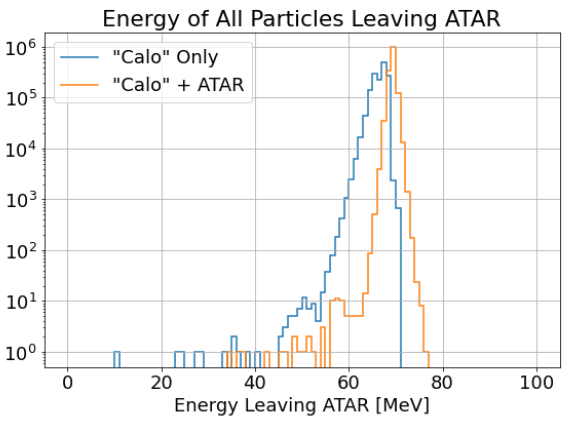




Takeaway: We need to recombine multiple tracks for some events

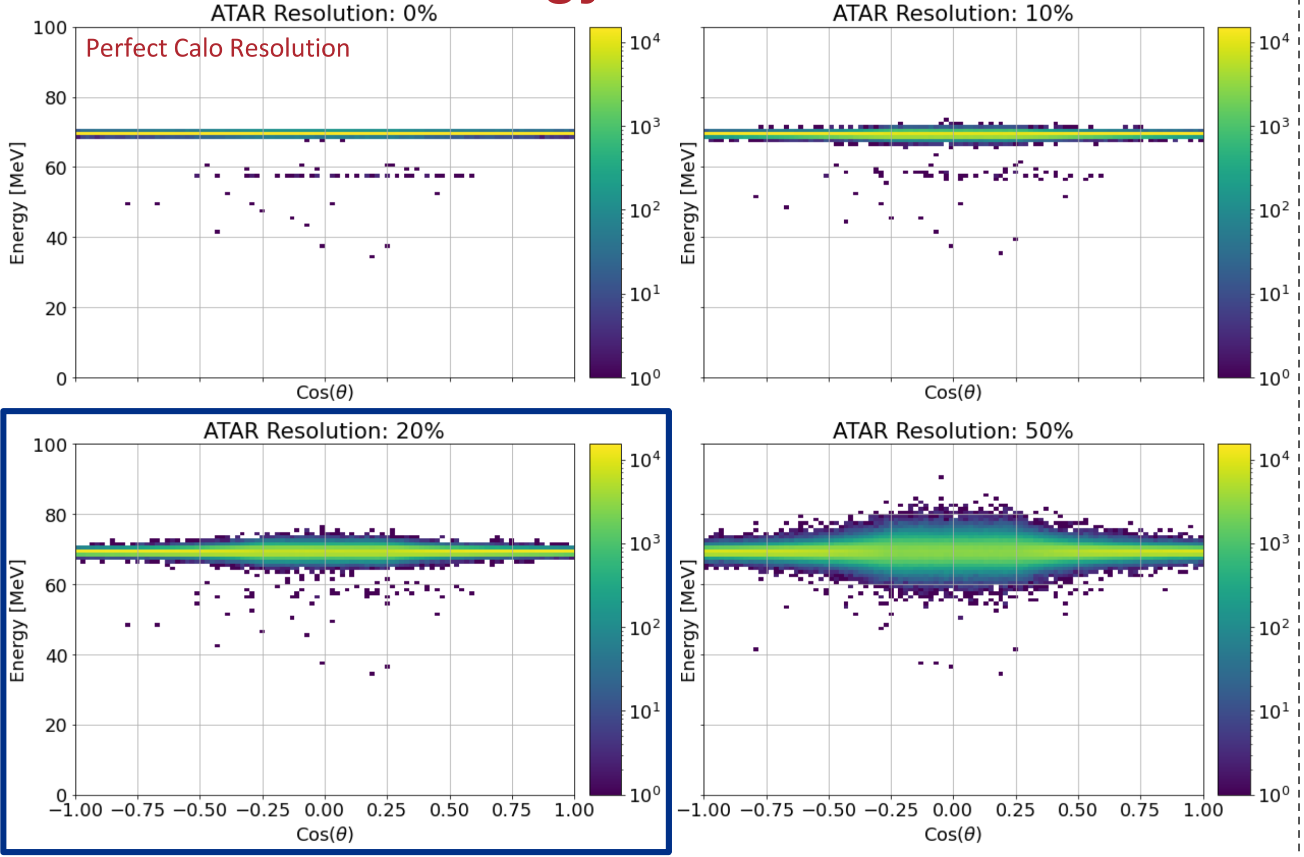
Building Up The Simulation: ATAR (Summed)

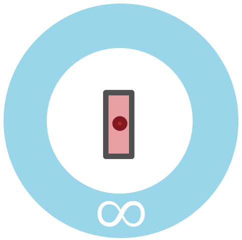


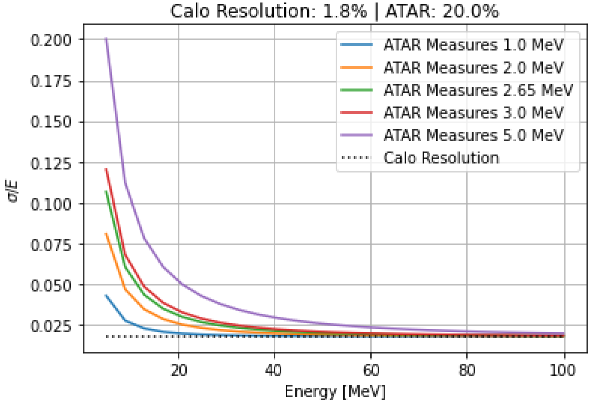


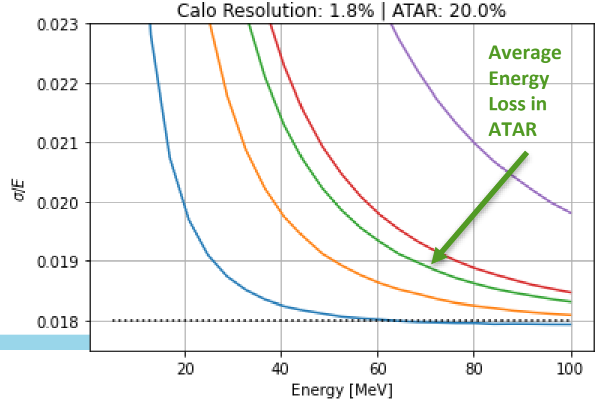
Takeaway: ATAR impact on CALO Resolution is highest ⊥ to the beam

Aside: ATAR Energy Resolution



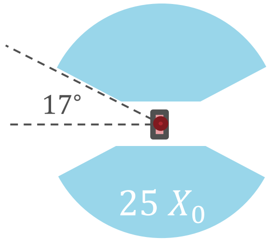




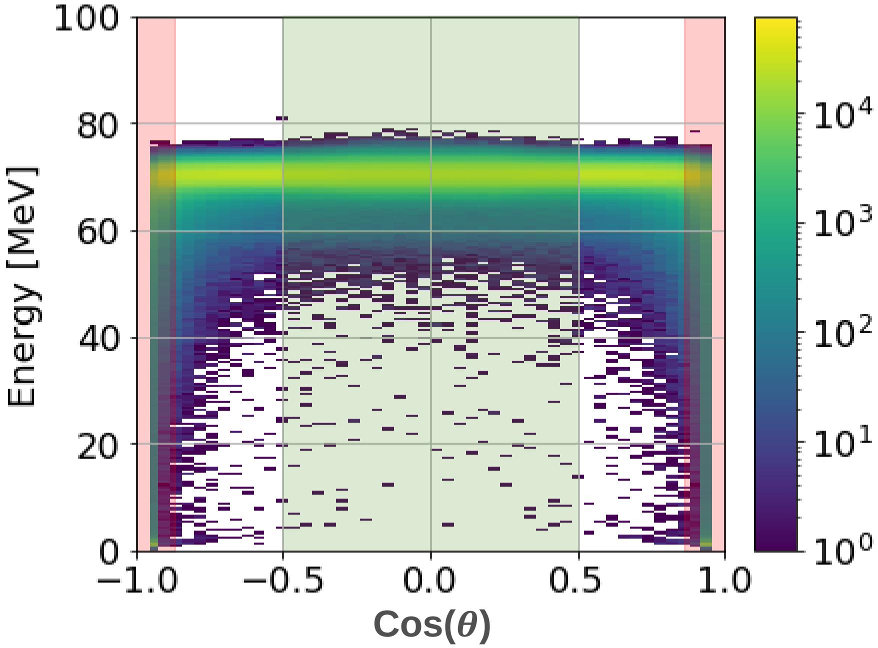


Takeaway: An ATAR with poor energy resolution can be deadly, 20% ok

With any physical detector, we don't see a "perfect" spectrum

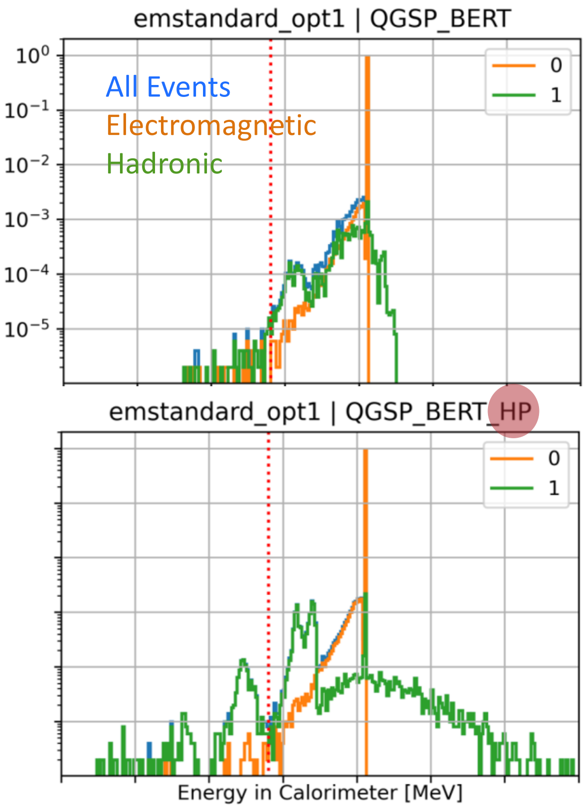


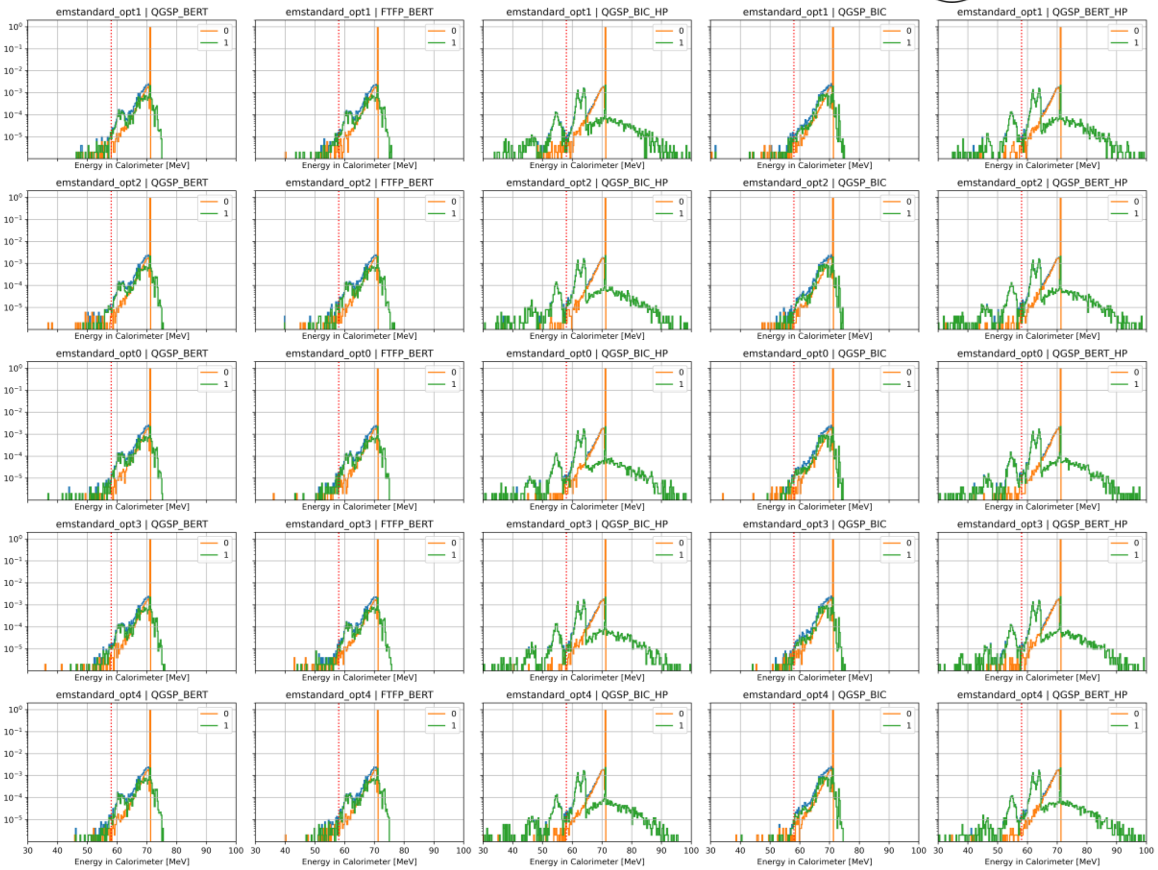
Calo Resolution: 1.8%
ATAR Resolution: 20%



Takeaway: Opening angle and finite length increase the tail fraction.

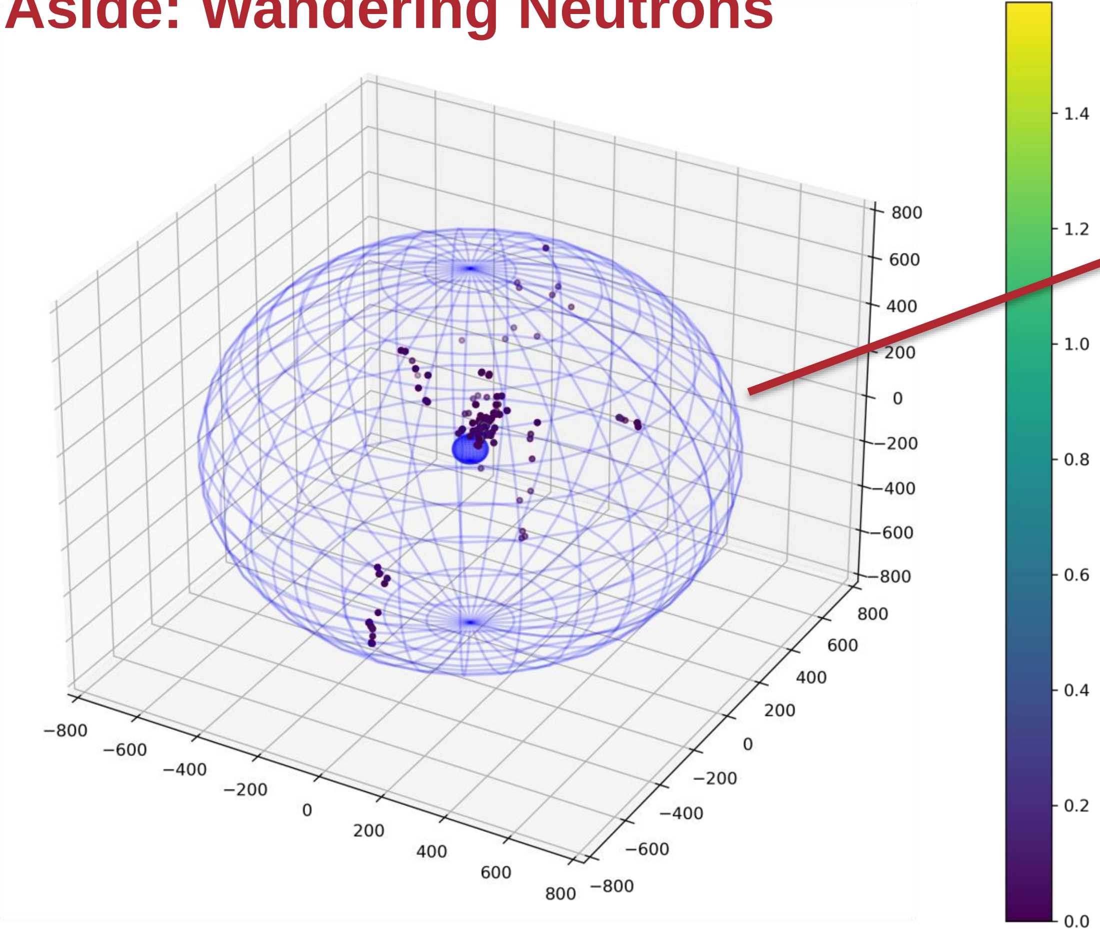
Aside: Physics Lists

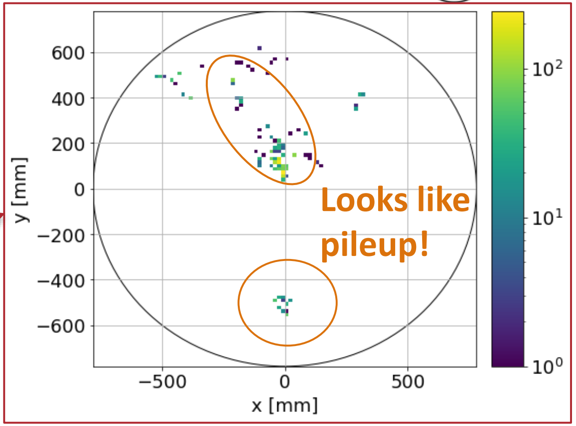


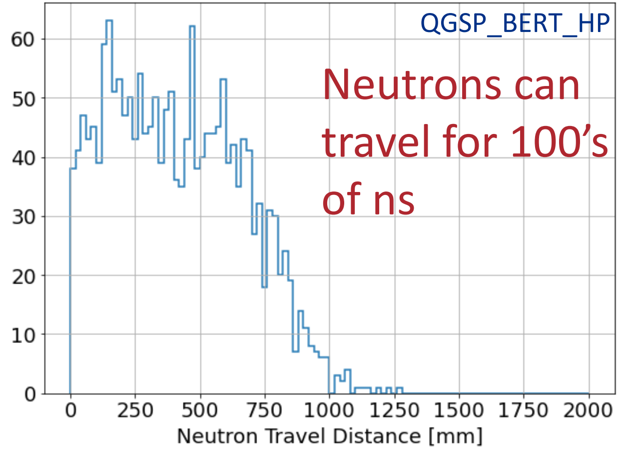


Takeaway: Geant4's physics cannot be taken as gospel

Aside: Wandering Neutrons







Neutrons can travel for 100's of ns

(more in Patrick's talk tomorrow)

Photonuclear Effects: Measurements Required

Study of a Large NaI(Tl) Crystal

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Abstract

Using a narrow band positron beam, the response of a large high-resolution NaI(Tl) crystal to an incident positron beam was measured. It was found that nuclear interactions cause the appearance of additional peaks in the low energy tail of the deposited energy spectrum.

Keywords: Calorimeter, Scintillation detectors, Photonuclear reactions

1. Motivation

The PIENU experiment at TRIUMF [1] is aiming at a measurement of the branching ratio $R = \Gamma(\pi \to e\nu + \pi \to e\nu\gamma)/\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)$ with precision <0.1%. The principal instrument used to measure positron energies from $\pi^+ \to e^+\nu$ decays ($E_{e^+} = 70$ MeV) and $\pi^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\overline{\nu}$ decays ($E_{e^+} = 0 - 53$ MeV) is a large single crystal NaI(Tl) detector [2]. Detailed knowledge of the crystal response is essential to reaching high precision, especially for determining the low energy tail response below 60 MeV [3]. In the following, results of measurements of the response of the NaI(Tl) crystal to mono-energetic positron beams are presented along with Monte Carlo (MC) simulations including photonuclear reactions.

2. Experiment Setup

The 48 cm diameter, 48 cm long NaI(Tl) crystal [2] under study was surrounded by two adjacent rings of 97 pure CsI crystals [4]. Each ring was comprised of two layers of 8.5 cm thick, 25 cm long crystals. Positrons from the M13 beamline at TRIUMF [5] were injected into the NaI(Tl) crystal to study its response. The positrons were produced by 500 MeV protons from the TRIUMF cyclotron striking a 1 cm thick beryllium target. After defining the beam momentum at the first focus, the M13 beam line is equipped with two more dipole magnets and two foci with slits before the final focus at the detector. The vacuum window was a 0.13 mm thick, 15 cm diameter Mylar foil. With this geometry, slit scattering and the effect of the vacuum window were expected to have negligible effect on the low energy tail. The incoming beam was measured with a telescope (see fig. 1) consisting of 6 planes of wire chambers arranged in the orientation of X-U-V-X-U-V, where U(V) was at 60°(−60°) to the vertical direction, a plastic scintillator (5×5 cm² area, 3.2 mm thickness), and the NaI(Tl) calorimeter. The beam momentum width and horizontal (vertical) size and divergence were 1.5% in FWHM, 2cm (1cm) and ±50mrad (±90mrad), respectively. The beam composition was 63% π^+, 11% μ^+ and 26% e^+.

3. Measurement and Results

A 70 MeV/c positron beam was injected into the center of the NaI(Tl) crystal. The beam

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Preprint submitted to Nuclear Instruments and Methods *October 30, 2018*

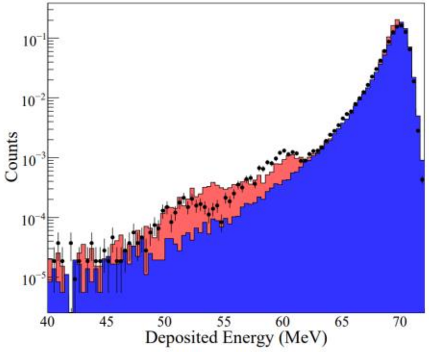


Figure 4: Comparison between data (filled circles with error bars) and simulation. The simulation was performed with (light shaded) and without (dark shaded) hadronic reaction contributions. The histograms are normalized to the same area.

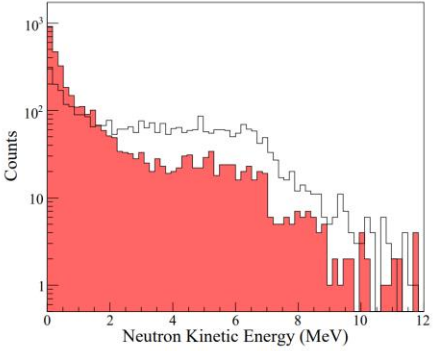
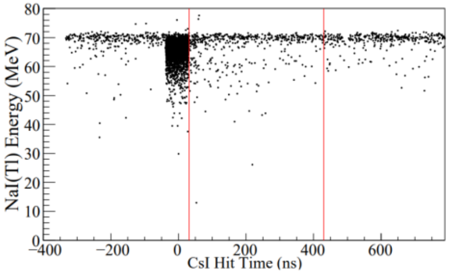


Figure 5: Simulation of the kinetic energy of the neutrons produced in (white histogram) and those that escaped from (shaded histogram) the NaI(Tl) crystal.



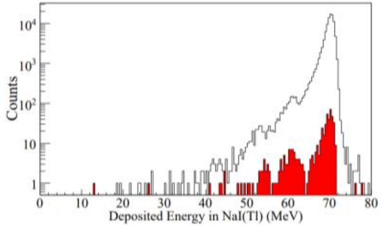
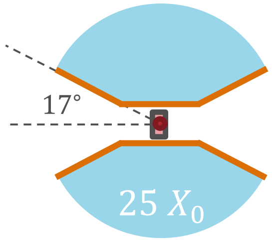


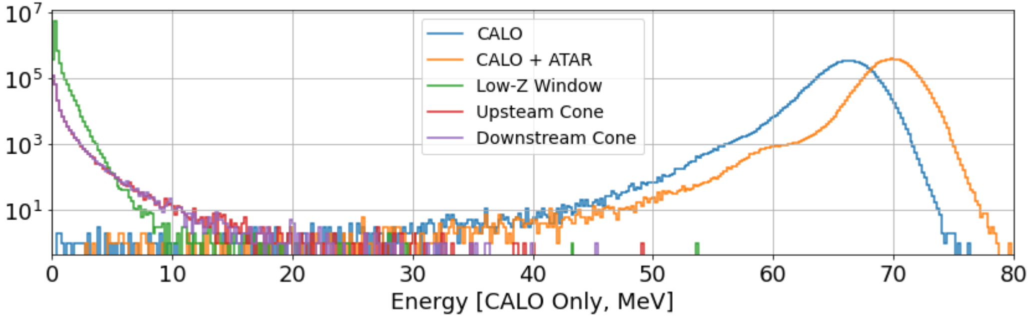
Figure 3: (Top) Deposited energy versus CsI hit timing. (Bottom) The shaded histogram represents events selected by the timing cut (between the lines) shown on the top figure.

Takeaway: A dedicated (prototype) measurement campaign is required to tune the simulation

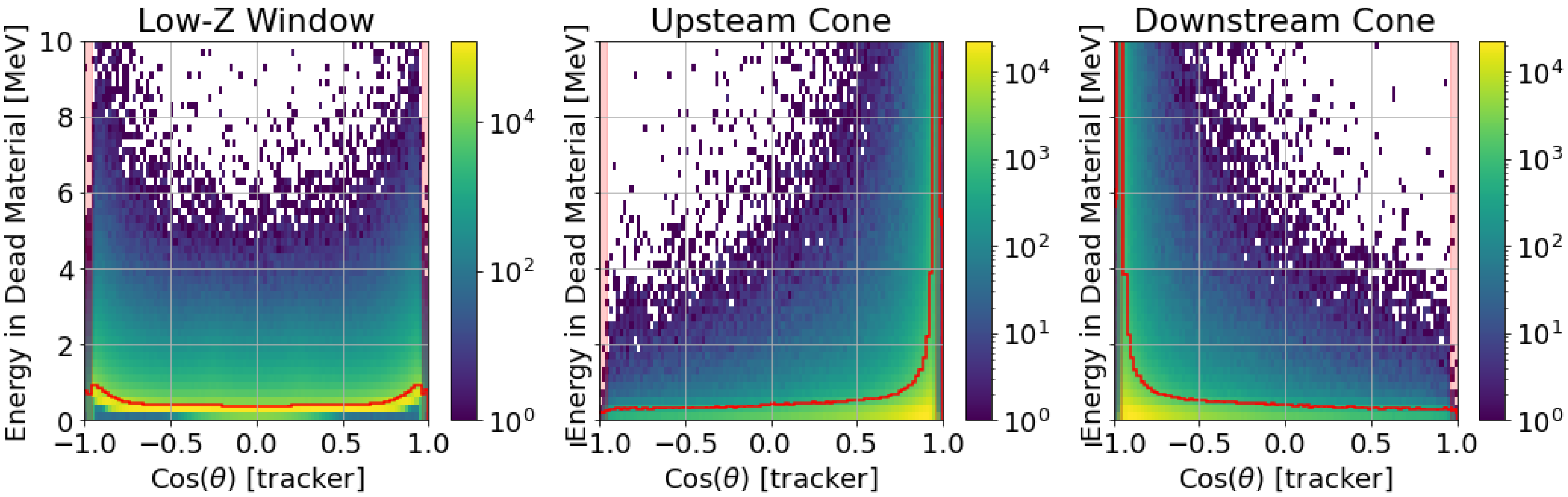
Dead Material: Beampipe

Window: 0.1 cm Be
Cones: 1 cm Al



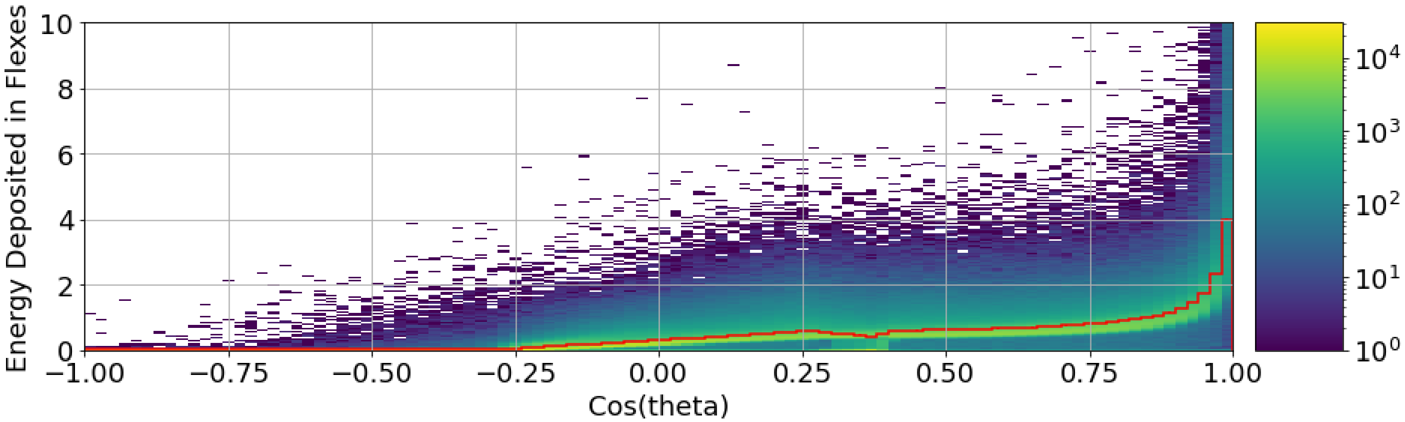


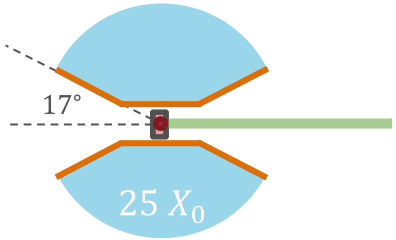
Resolution
1.8% → 2.1%

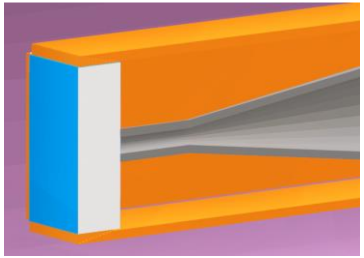


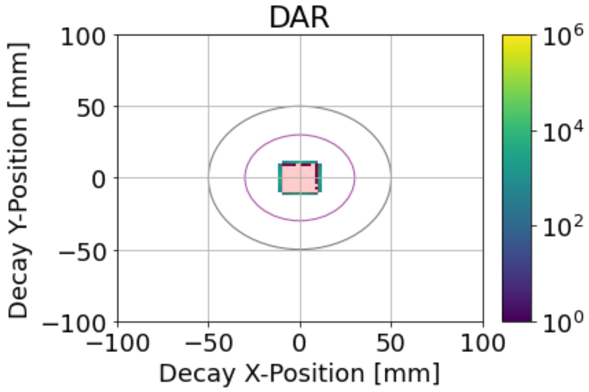
Takeaway: Immense challenge to design a multi-ton detector with as little dead material as possible

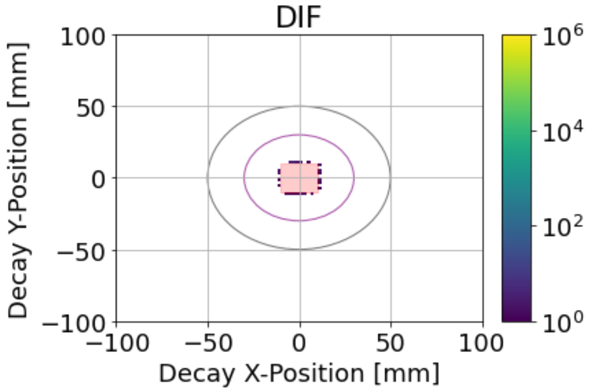
Dead Material: ATAR Readout

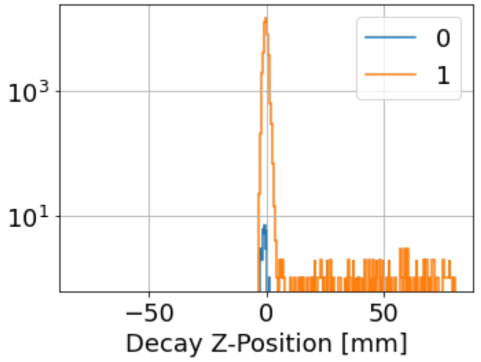












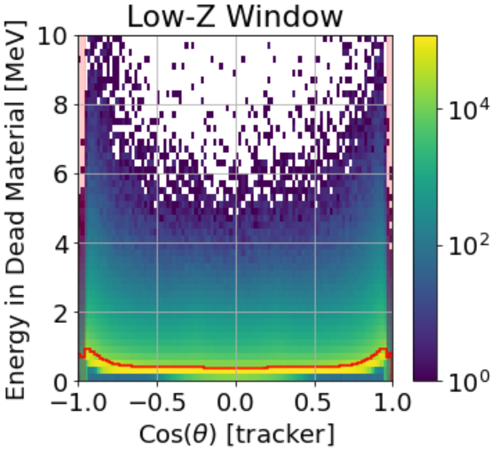
Takeaway: Readouts will affect the energy loss and will capture π^+, must be carefully engineered.

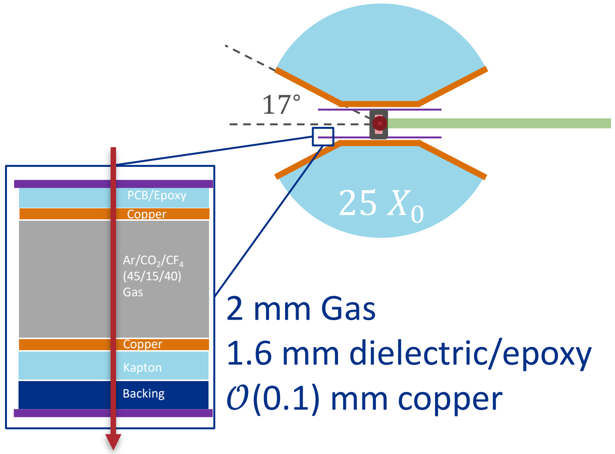
Adding A Tracker

The tracker which exists in the PIONEER simulation is a basic sketch of the μR-WELL Geometry

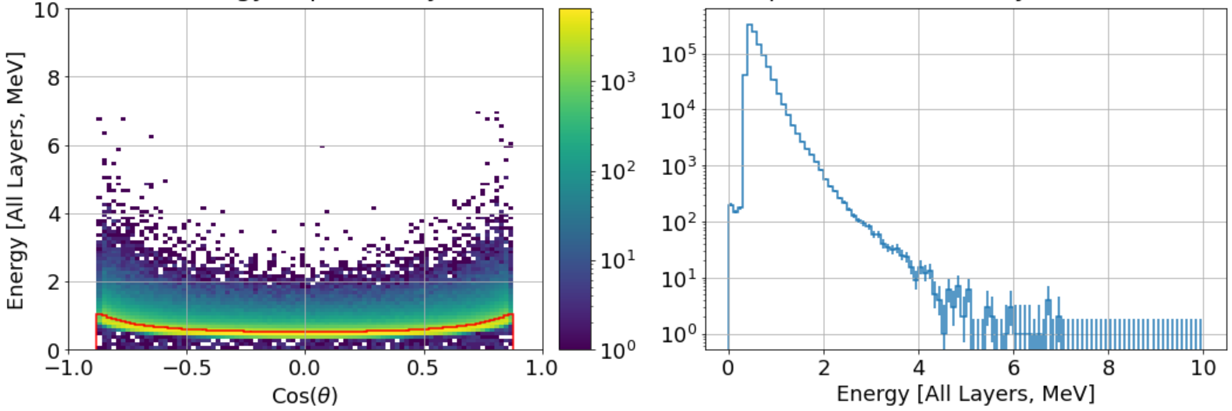
With some rough material estimates, we get an energy loss in a single Proto-μRWELL tracker layer on the same order as that of the Be LXe window.

Distortion to the calo energy spectrum must be kept to a minimum, and the thickness of the tracker should be incorporated as part of the 'dead material' budget.





Energy Deposited by a 69.2 MeV e^+ in 1 Proto-μRWELL Tracker Layer

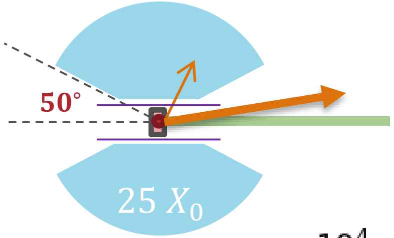


Takeaway: The tracker will contribute to the low energy tail, and so any design must be lightweight

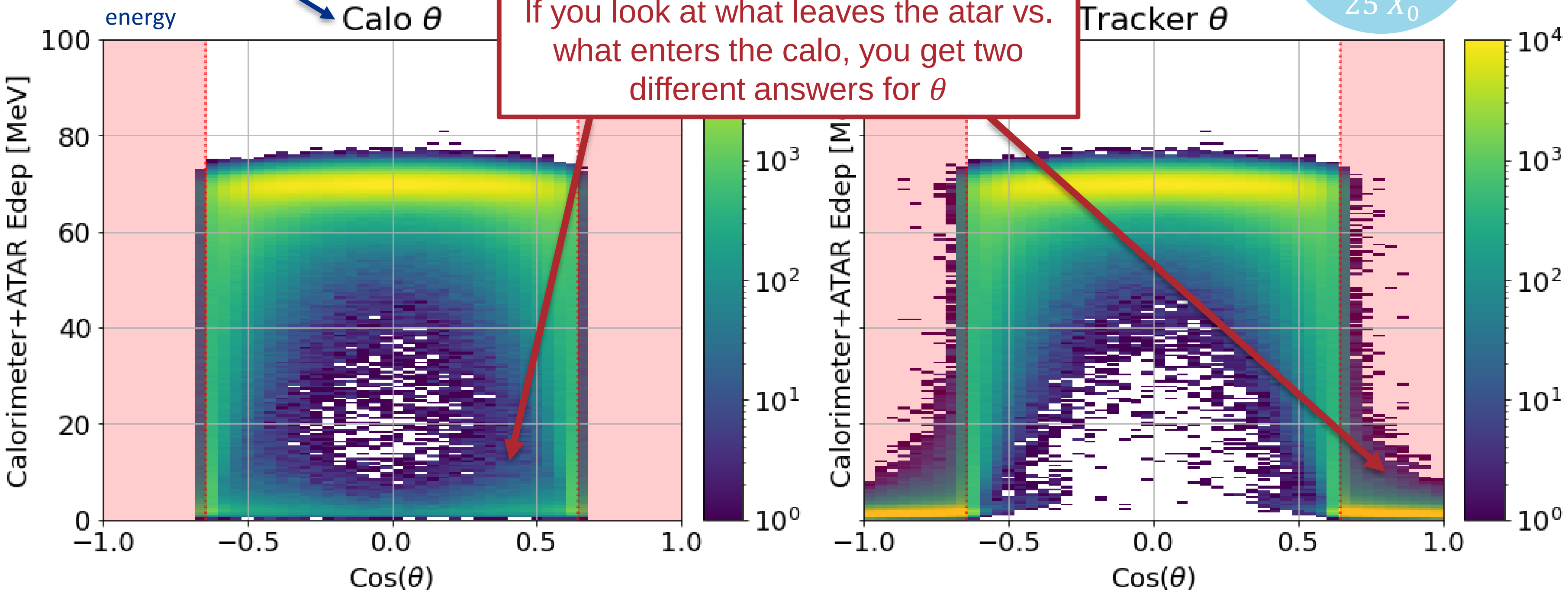
Thanks to Jaydeep for providing preliminary dimensions!

Aside: Truth vs. Calo θ

Example: 2 Particles leaving ATAR, the higher energy one misses CALO



$\bar{\theta}$ For all particles, weighted by their energy

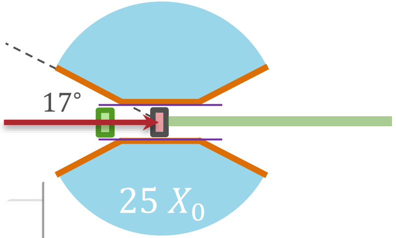


If you look at what leaves the atar vs. what enters the calo, you get two different answers for θ

Takeaway: A tracker/endcap extending beyond the Calo opening angle will help reduce tail

Note: exaggerated opening angle to illustrate effect

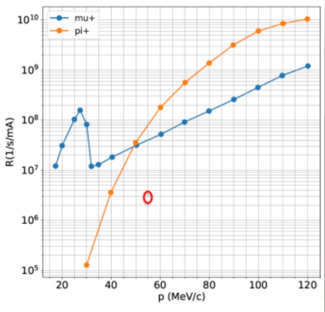
Beam: Tradeoffs of a Degrader

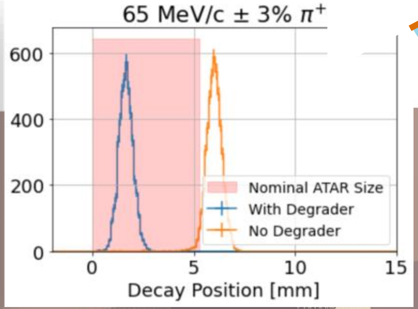


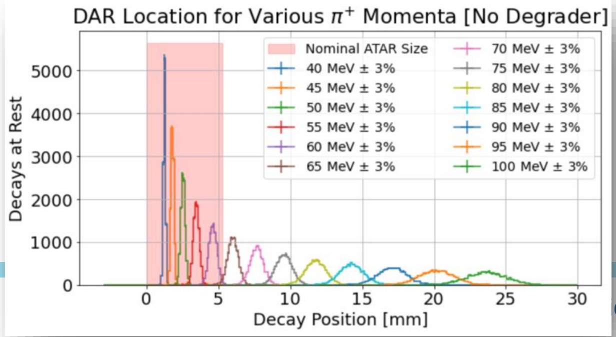
At the test beam, we were unable to achieve an acceptable rate with a 55 MeV/c π^+ beam.

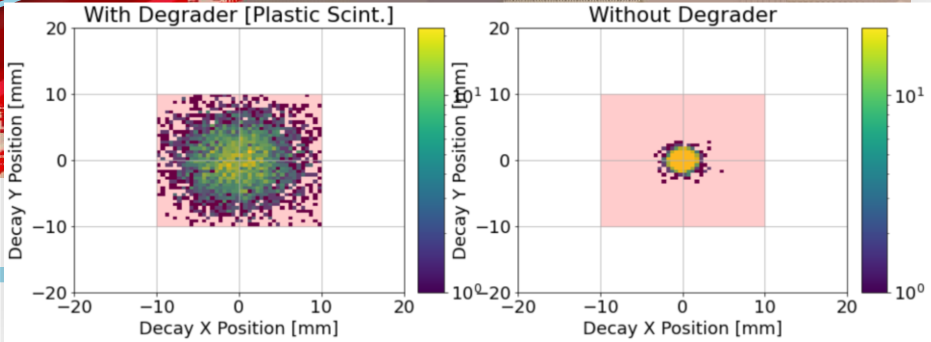
This means that we will need either:

- **An upstream degrader to stop the pions in the appropriate place within the ATAR**
  - Active (Plastic Scintillator) vs. Passive (Be, reduced scattering)
  - Location carefully chosen to not shadow the calorimeter
- **A thicker ATAR, possibly with variable thickness layers**

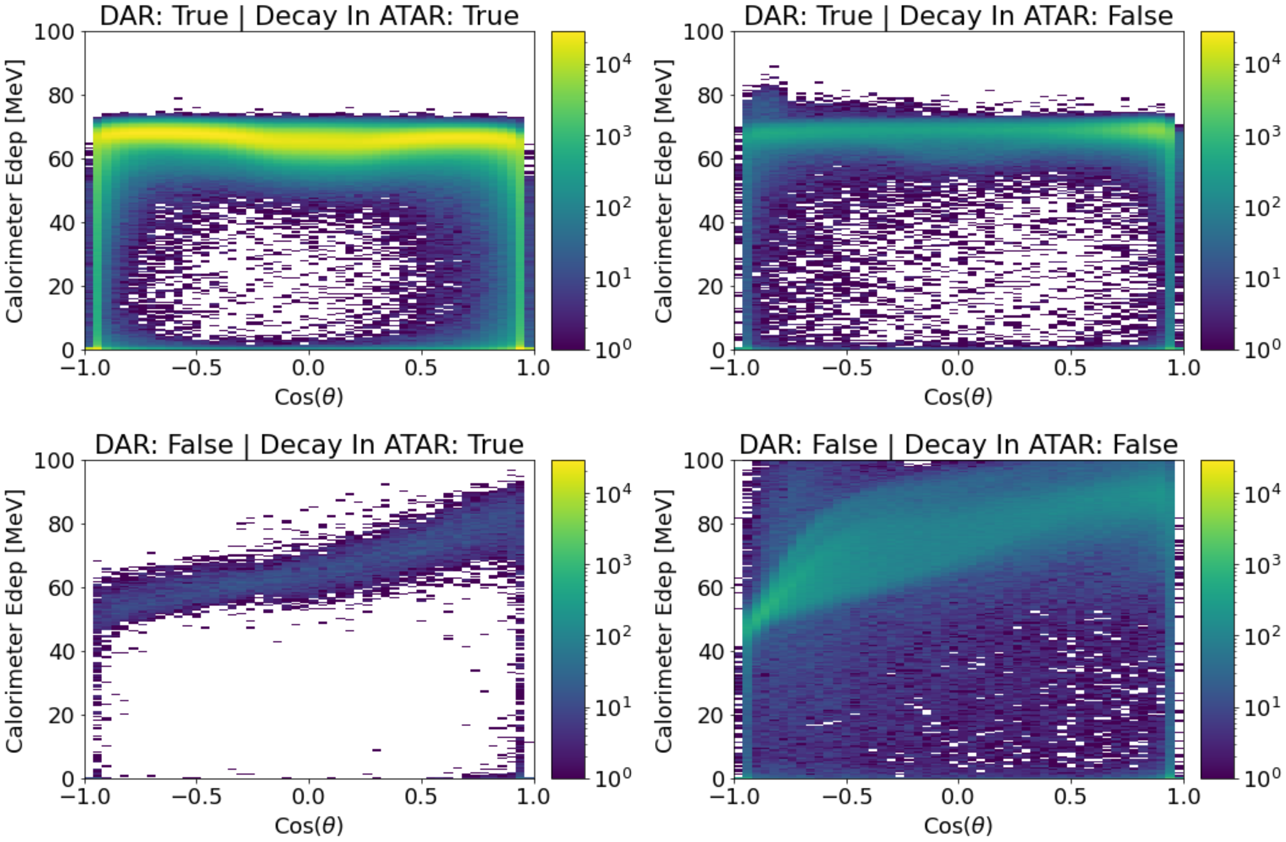


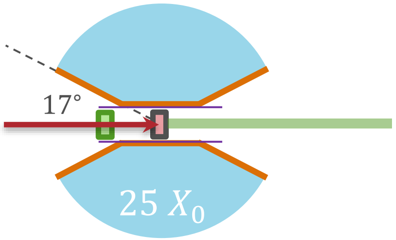


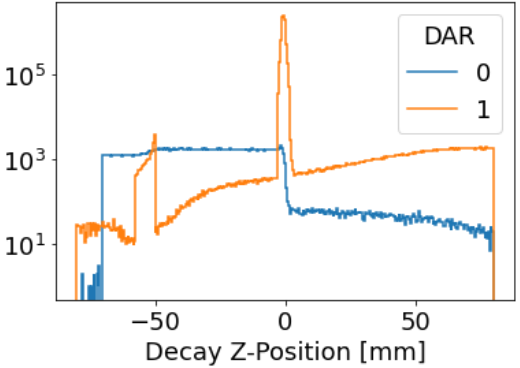


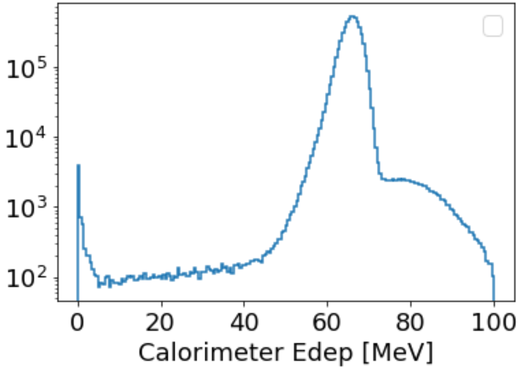


Aside: Pion Decay Locations / Decay in Flight



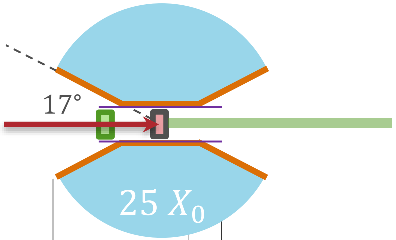






Takeaway: ATAR tagging of pions will be essential to reject background

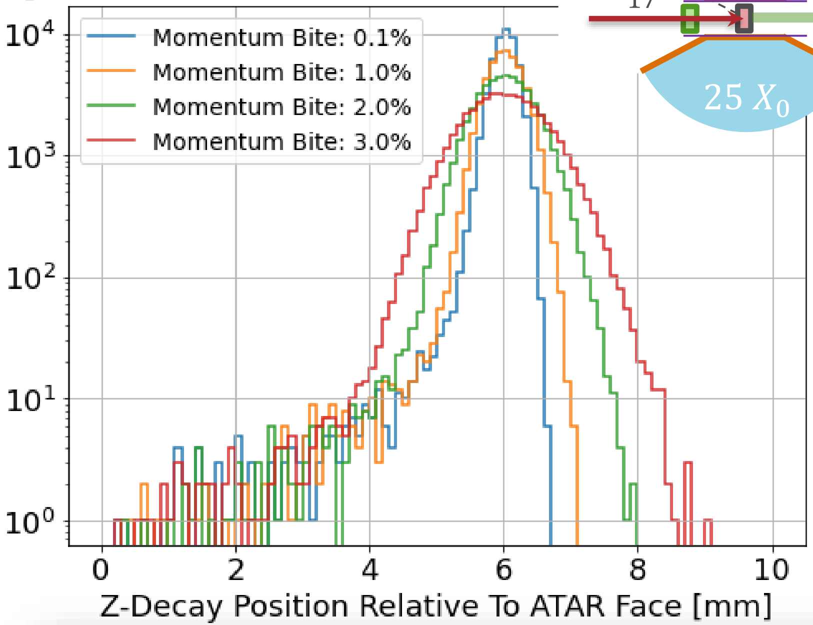
Beam Inputs: Realistic Phase Space

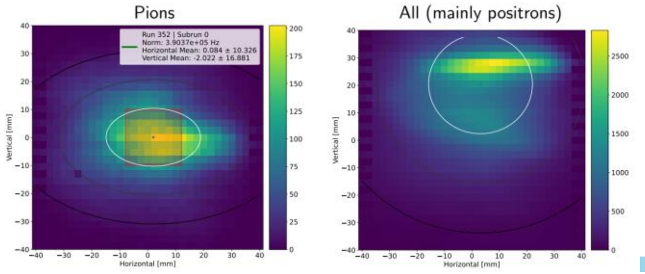


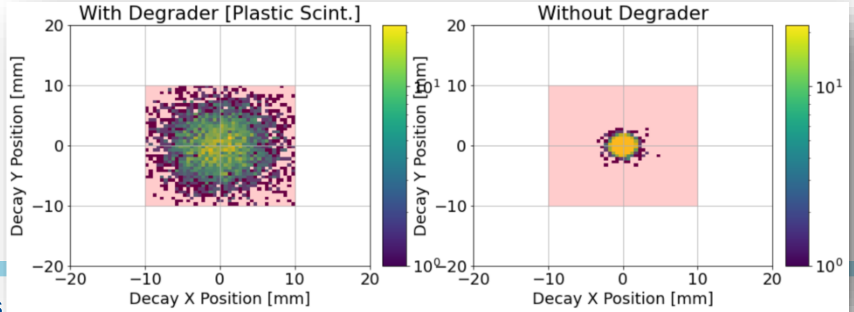
In order to finalize the design of the ATAR, we will need to know what the acceptable fiducial volume is.

This changes based on the divergence and momentum spread within the beam. Having an upstream degrader will make some requirements more stringent.

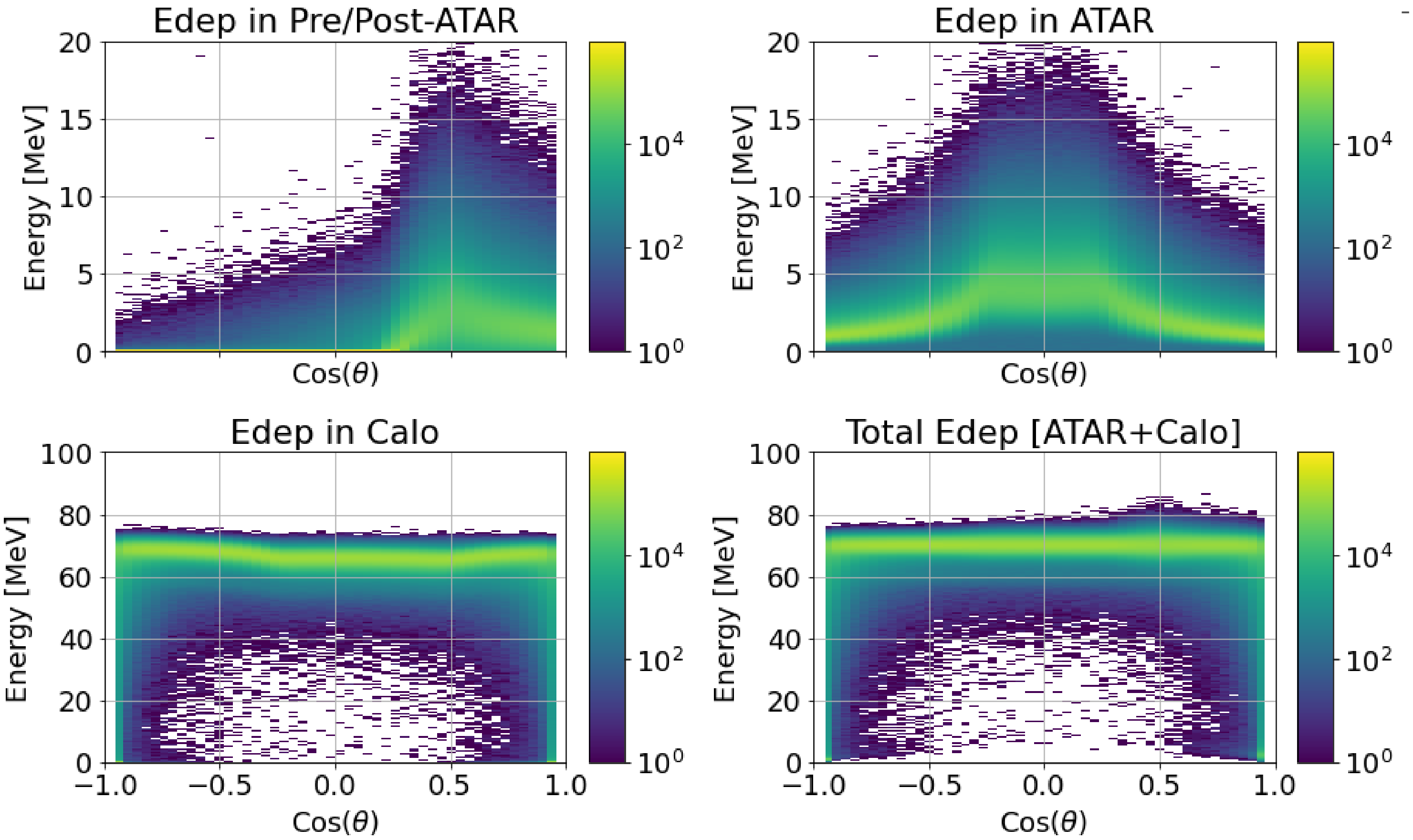
Inputs about the contamination of the beam will also be crucial for simulations of backgrounds

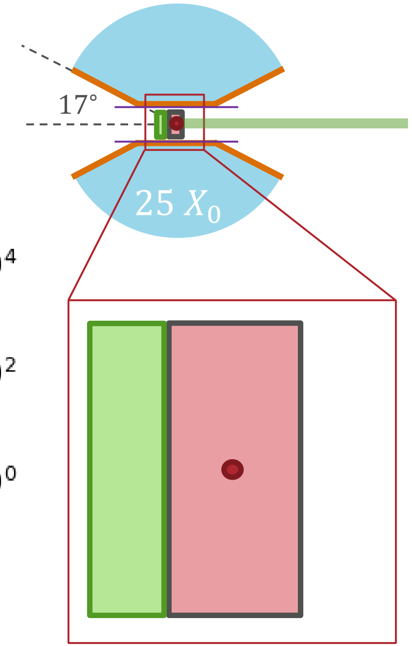






Pre-ATAR

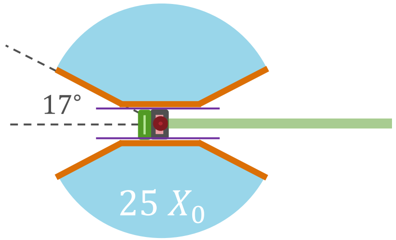




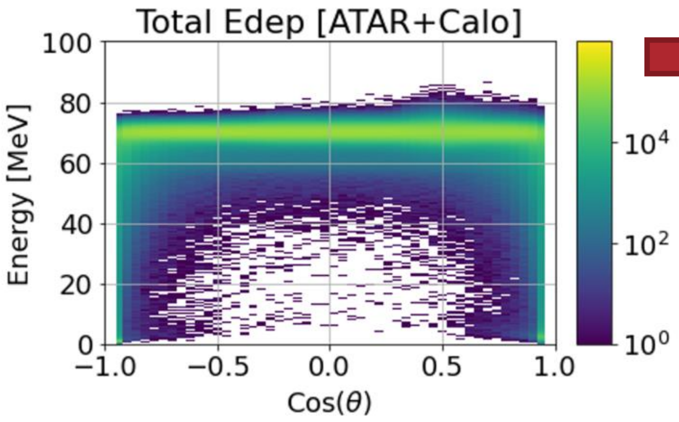
48 layer LGAD (5.76 mm) @ 20% σ/E

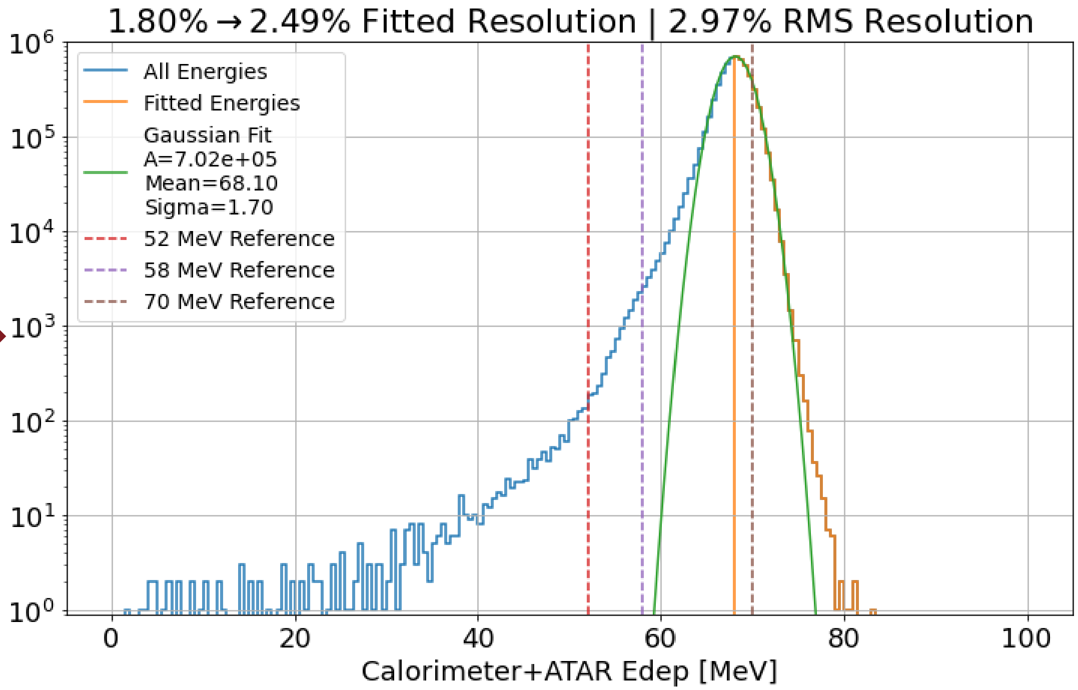
3.12 mm Si strip Pre-ATAR @ 50% σ/E

Final Resolution for π_{DAR} Positrons: 1.8% → 2.5%



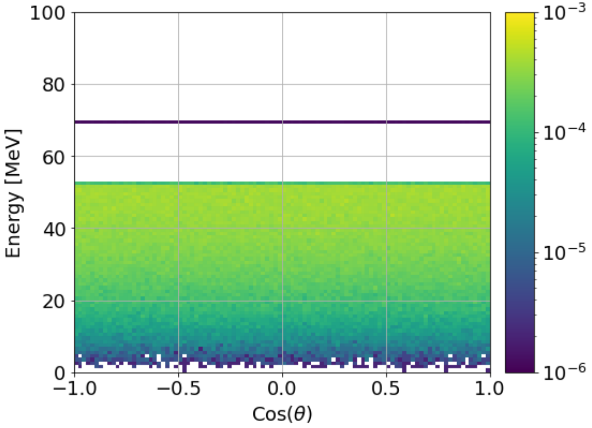
Finally:
- 0.1 cm Be window
- 2 Tracking layers
- ATAR/Calo resolution
- Readouts
- …

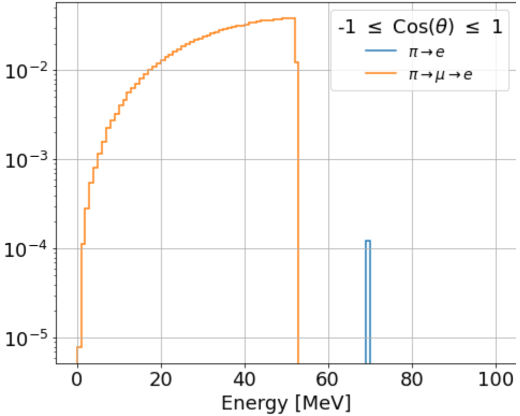


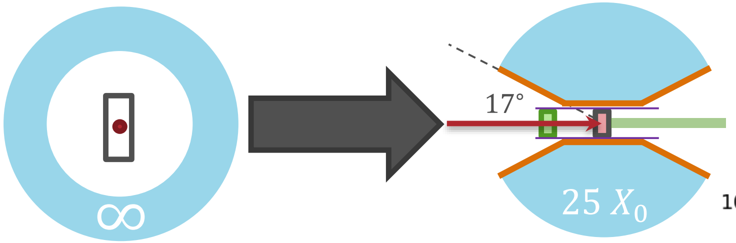


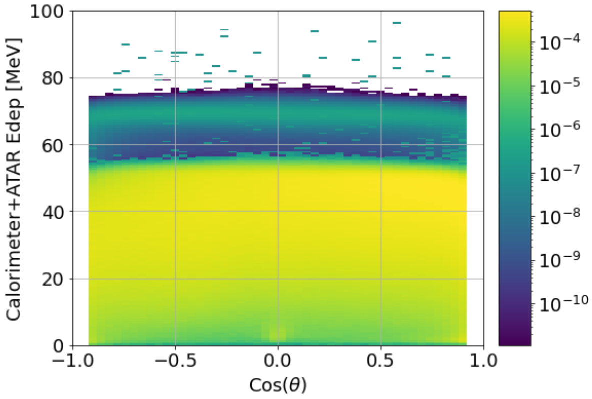
Note: Here no dead material energy 'repair' has been attempted

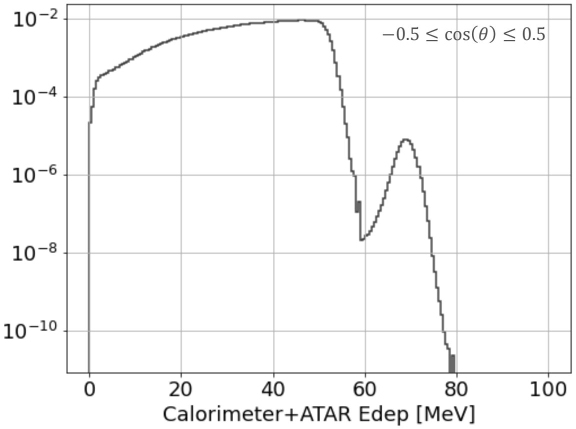
TLDR: Things Get Complicated Quickly





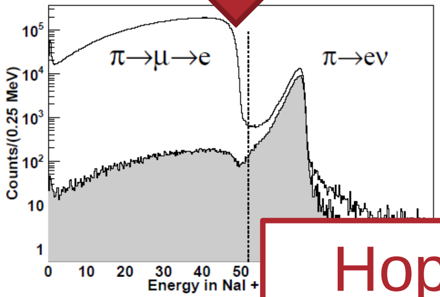






+ Pileup
+ Reconstruction effects
+ Detector response
(see later talks)

Proposal: Simulation Data Challenge



- Critical Inputs: Dec 12th
  - Best guess at all geometries
  - Event combination (pileup generation, etc.)
- External Inputs: Jan 15th
  - Detector response functions
  - Initial analysis features
- Campaign Launches: Jan 31st
  - ~2e9 unbiased π^+ decays
  - ~70 TB of raw simulation data, equivalent amount of reconstructed data
- Afterwards: Analysis Challenge (Feb-March)
  - Replicate a PIENU style analysis using the simulated data and 'realistic' detector response
  - ...ta processing

Hope to refine and push forward this idea during the workshop!

Summary

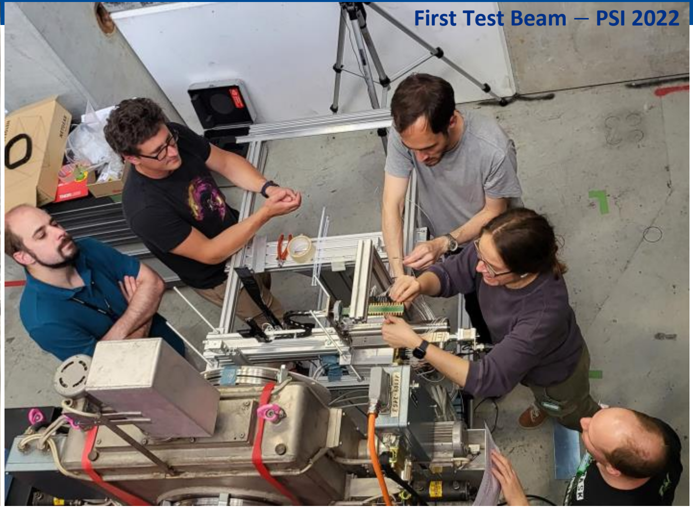
The PIONEER Simulation is helping to tackle big design choices, with many knobs to turn. Challenges are large, but not insurmountable.

Takeaways:

- Radiative/scattering processes matter!
- We may need to recombine multiple tracks/event
- ATAR impact on CALO Resolution is highest ⊥ to the beam
- An ATAR with poor energy resolution can be deadly
- ATAR should be as live as possible, but small dead layers aren’t a disaster
- Opening angle and finite length increase the tail fraction.
- Geant4’s physics cannot be taken as gospel
- A dedicated prototype measurement campaign is required to tune the simulation
- Immense (but necessary) challenge to design a multi-ton detector with as little dead material as possible
- The tracker will contribute to the low energy tail, and so any design must be lightweight
- A tracker/endcap extending beyond the Calo opening angle will help reduce tail
- ATAR tagging of pions will be essential to reject background

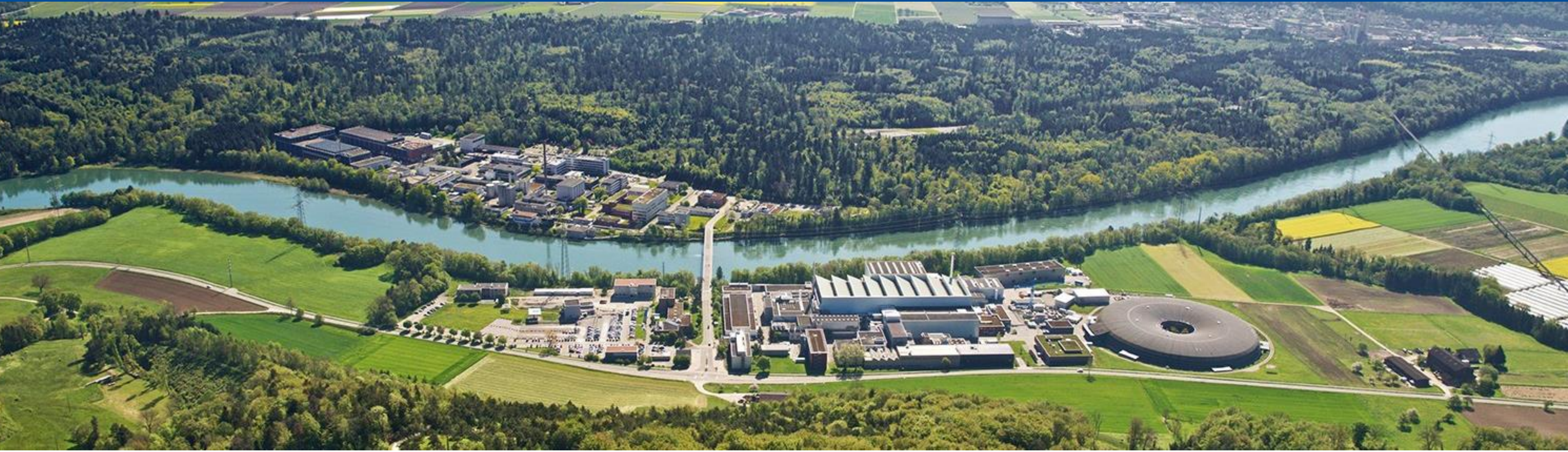
Thank you!

Some more exciting simulation results to see in the next few days!



First Test Beam – PSI 2022

Thank you!!



Backups

Works In Progress: ATAR

ATAR Group is working hard to make this detector a reality

We will see a lot of interesting talks from them on

- **Hardware design/implementation**
- **Modelling detector response**
- **Event reconstruction**

And much more!

Introduction to the ATAR project and session	*Cervantes and Velasquez Room, UC Santa Cruz*	*Simone Michele Mazza*	13:10 - 13:30
High granularity fast silicon sensors for the active target	*Cervantes and Velasquez Room, UC Santa Cruz*	*Dr Jennifer Ott*	13:30 - 14:00
Fast silicon sensor simulation with TCAD software	*Cervantes and Velasquez Room, UC Santa Cruz*	*Mohammad Nizam et al.*	14:00 - 14:30
Alternative active target design based on traditional silicon devices	*Cervantes and Velasquez Room, UC Santa Cruz*	*Xin Qian et al.*	14:30 - 14:50
Coffee	*Cervantes and Velasquez Room, UC Santa Cruz*		14:50 - 15:10
Event simulation and reconstruction in the active target	*Cervantes and Velasquez Room, UC Santa Cruz*	*Vincent Wai Sum Wong*	15:10 - 15:30
Event reconstruction experience from Lar TPC	*Cervantes and Velasquez Room, UC Santa Cruz*	*Chao Zang*	15:30 - 15:50
Front end electronics and digitization for fast silicon	*Cervantes and Velasquez Room, UC Santa Cruz*	*Abraham Seiden*	15:50 - 16:10
Overview of BNL Silicon sensor capability	*Cervantes and Velasquez Room, UC Santa Cruz*	*Dr Gabriele Giacomini et al.*	16:10 - 16:20
BNL approved LDRD related discussion and planning	*Cervantes and Velasquez Room, UC Santa Cruz*	*Volodya Tishchenko*	16:20 - 16:30

Works In Progress: LXe

Input from MEG, PANDAX, and more will be invaluable in forging a path forward.

Many talks from those sharing their experiences with LXe and those in PIONEER beginning to develop tools to understand it.

10:00	**MEG resolution and SiPM annealing update** *Cervantes and Velasquez Room, UC Santa Cruz*	*Ayaka Matsushita et al.* 10:00 - 10:30
	[redacted]	
11:00	**LXe R&D and simulation for open and segmented system** *Cervantes and Velasquez Room, UC Santa Cruz*	*Chloe Malbrunot et al.* 10:50 - 11:20
12:00	**Simulations of LXe and Hybrid crystal wrt pileup** *Cervantes and Velasquez Room, UC Santa Cruz*	*Patrick Schwendimann* 11:40 - 12:10

Works In Progress: Beam

	Results from Run1 beam tests at PSI	*Dr Anna Soter*
	Cervantes and Velasquez Room, UC Santa Cruz	16:20 - 16:50
	The beamline model and going forward	*Peter Kammel*
17:00	*Cervantes and Velasquez Room, UC Santa Cruz*	16:50 - 17:20

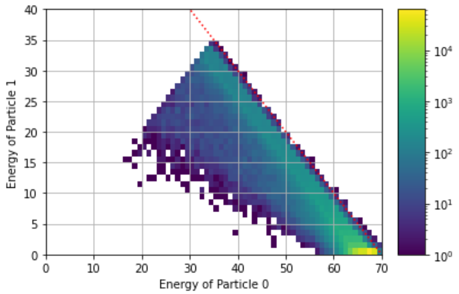
Works In Progress: Tracker

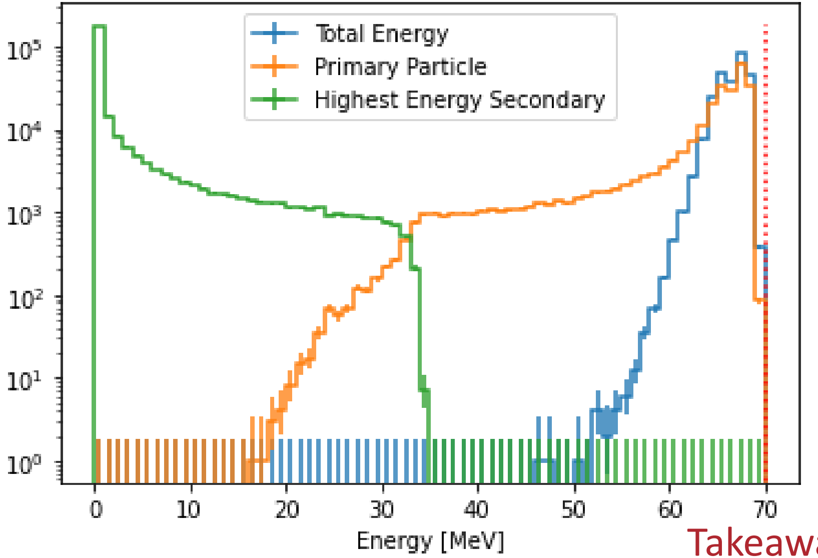
10:00

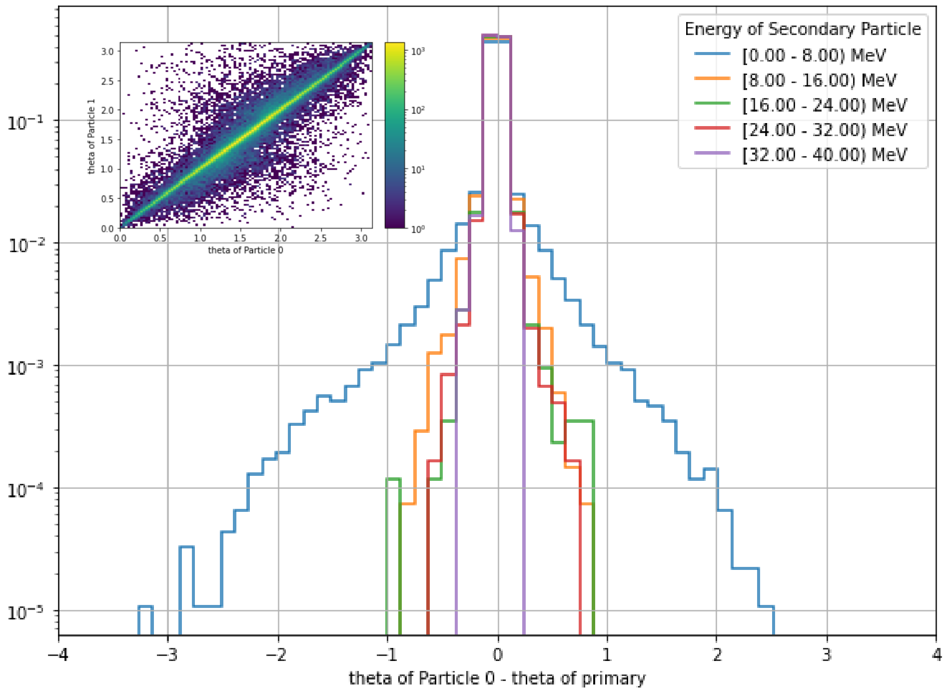
Tracker possibilities from Stony Brook *Dr Prakhar Garg et al.*

Cervantes and Velasquez Room, UC Santa Cruz 09:45 - 10:05

Aside: Angular Distribution of Energies

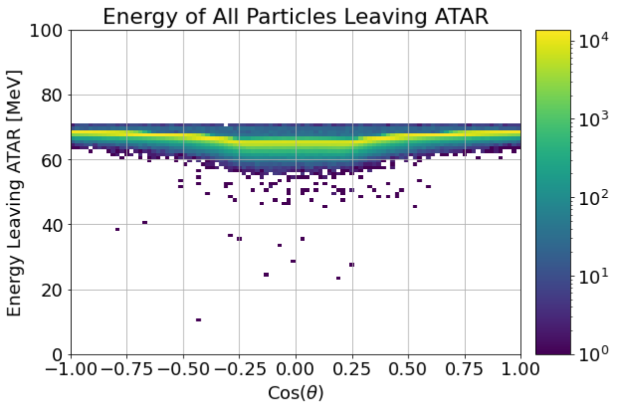


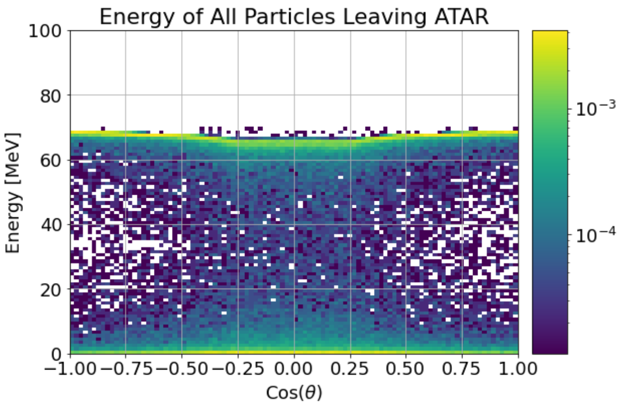


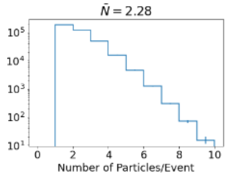


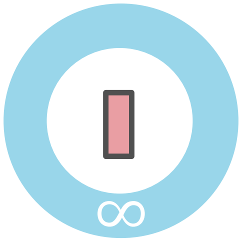
Takeaway: Multi-particle events usually appear co-linear in Calo.

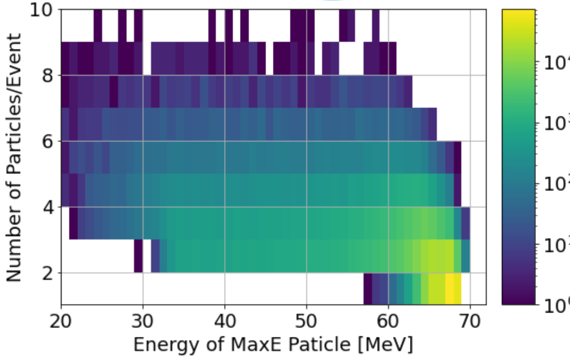
Aside: Number/Energy of Particles

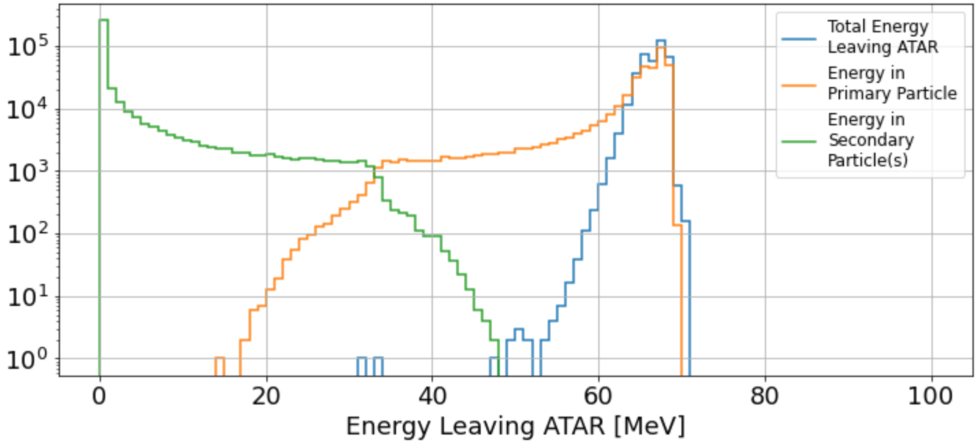


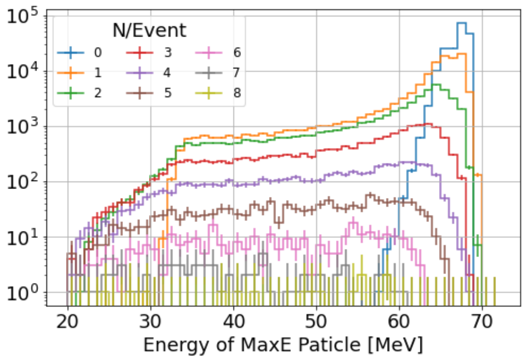




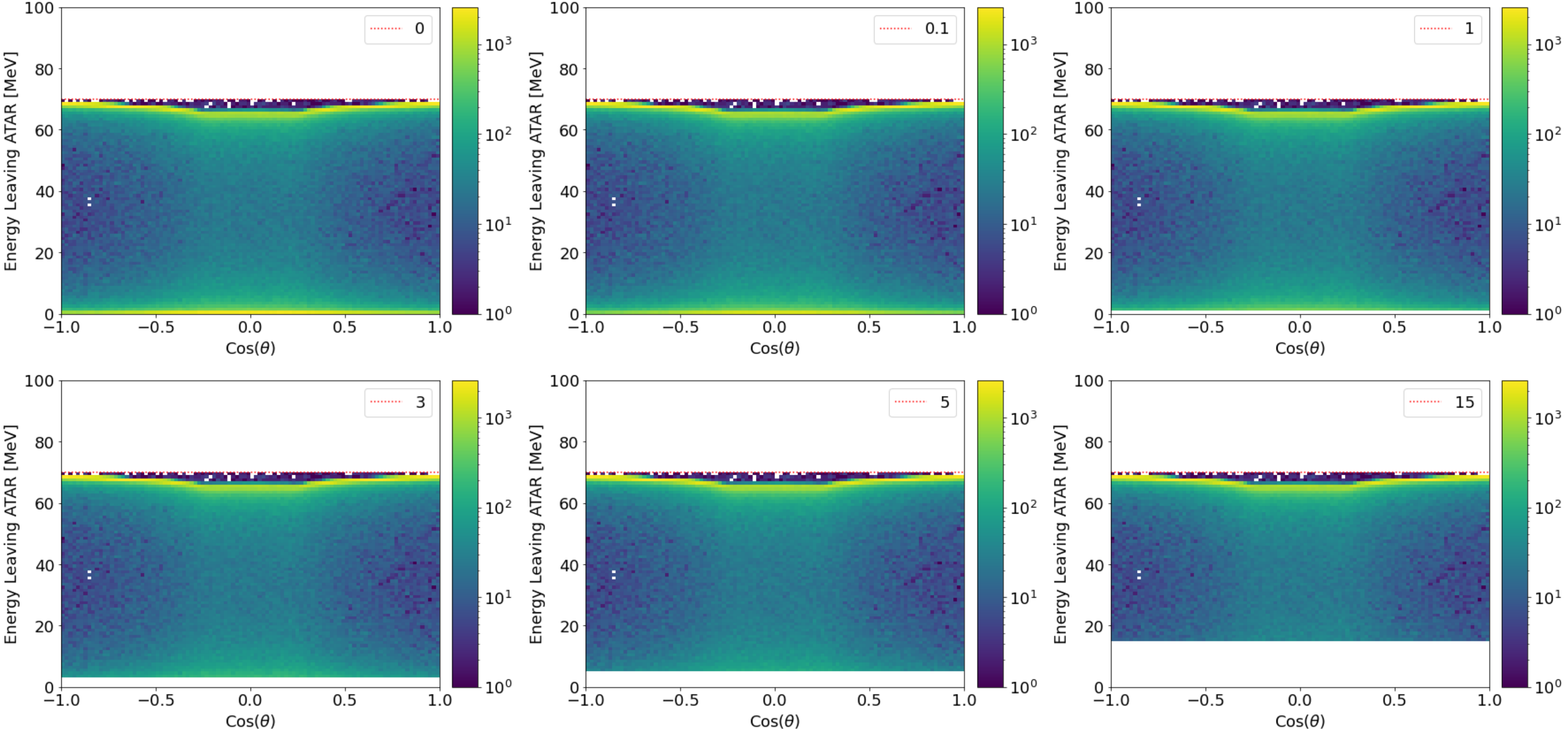




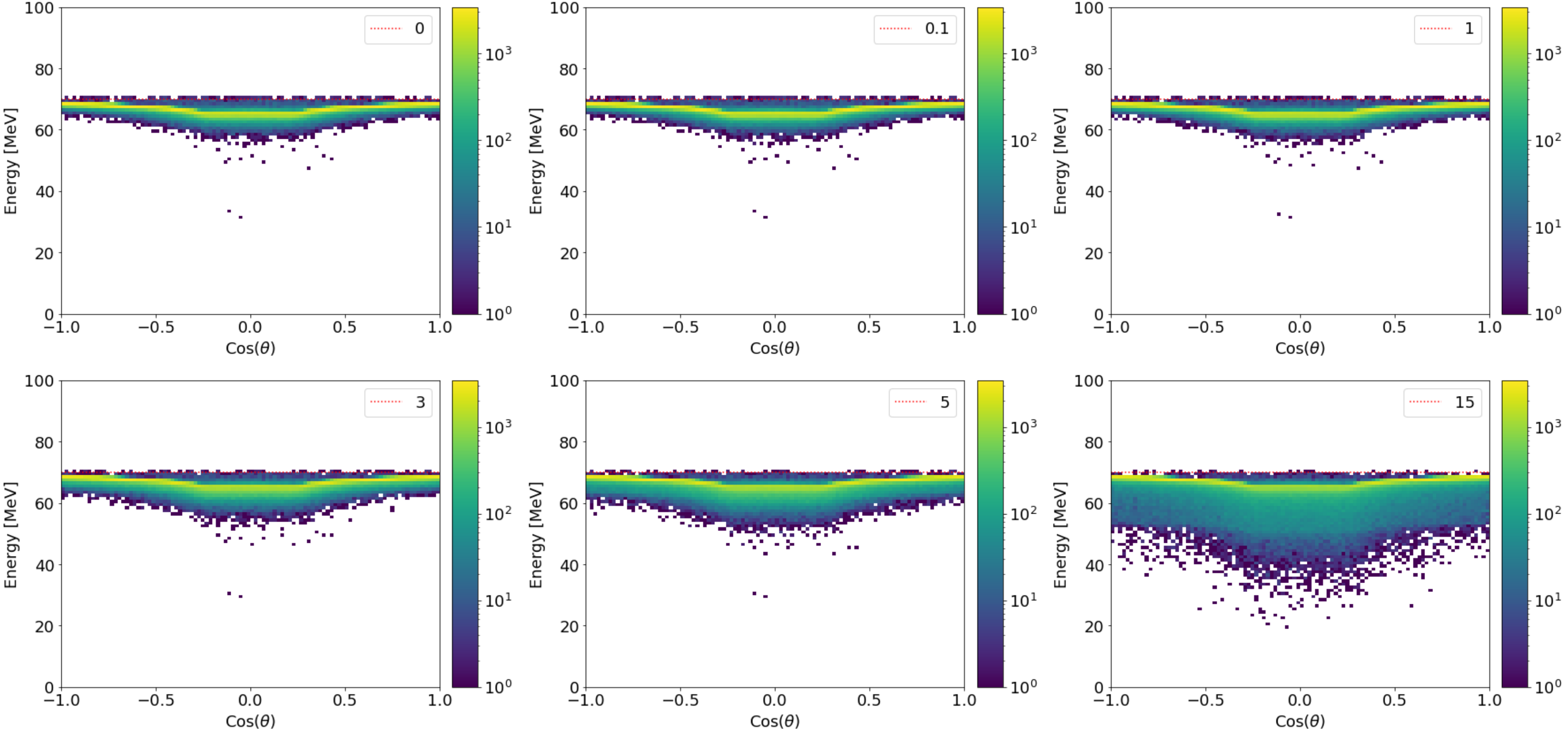




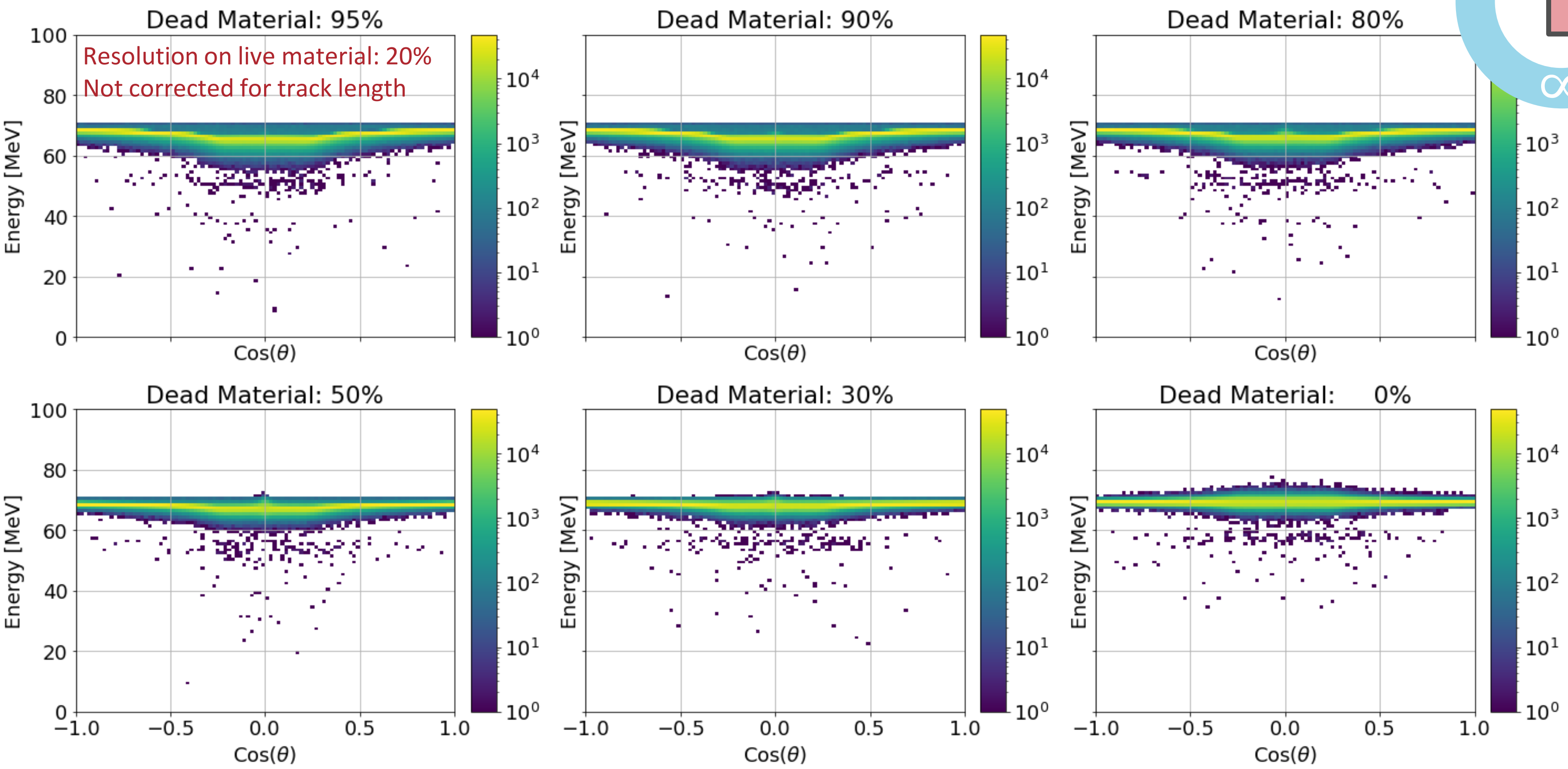
Aside: ATAR Summed with Energy Cut



Aside: ATAR Summed with Energy Cut



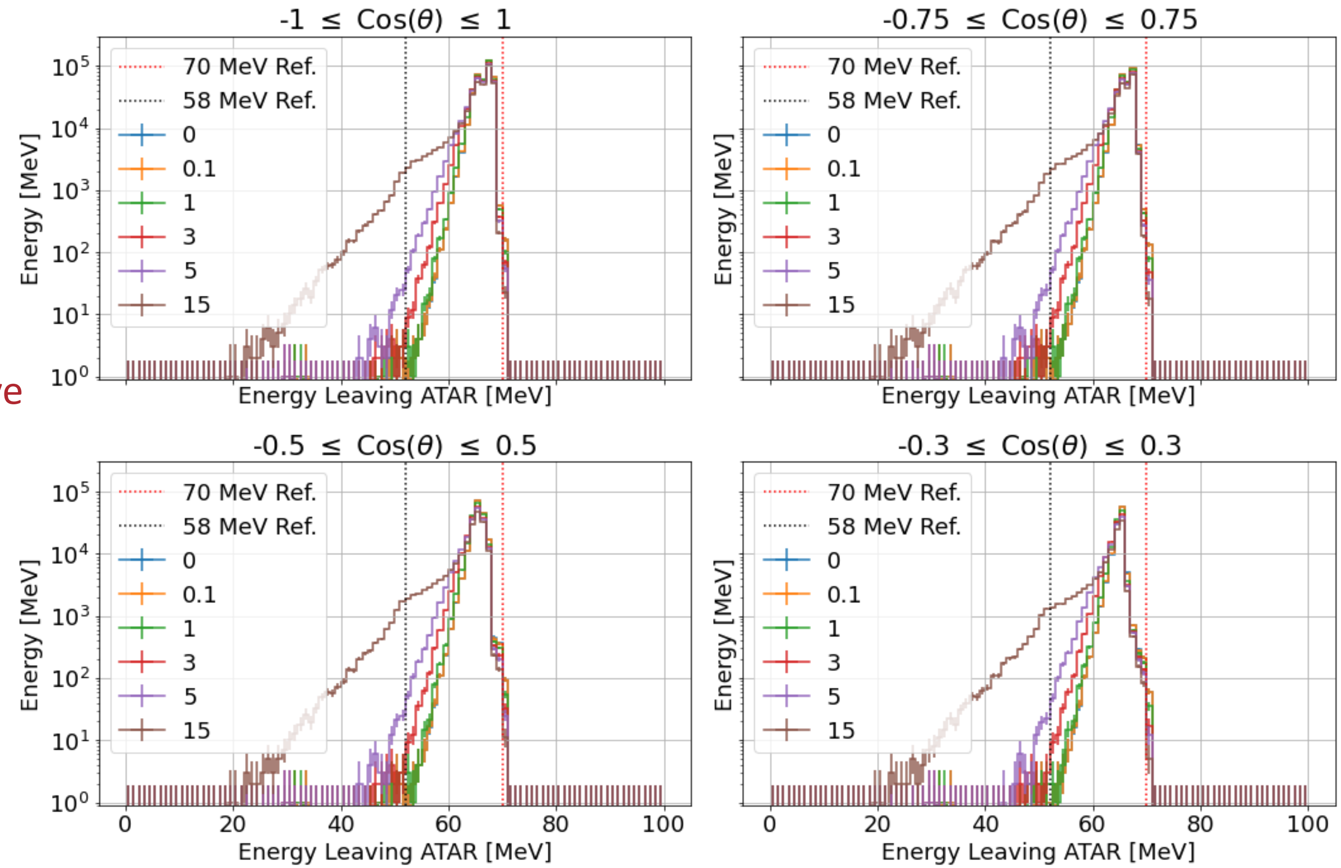
Aside: ATAR Dead Material



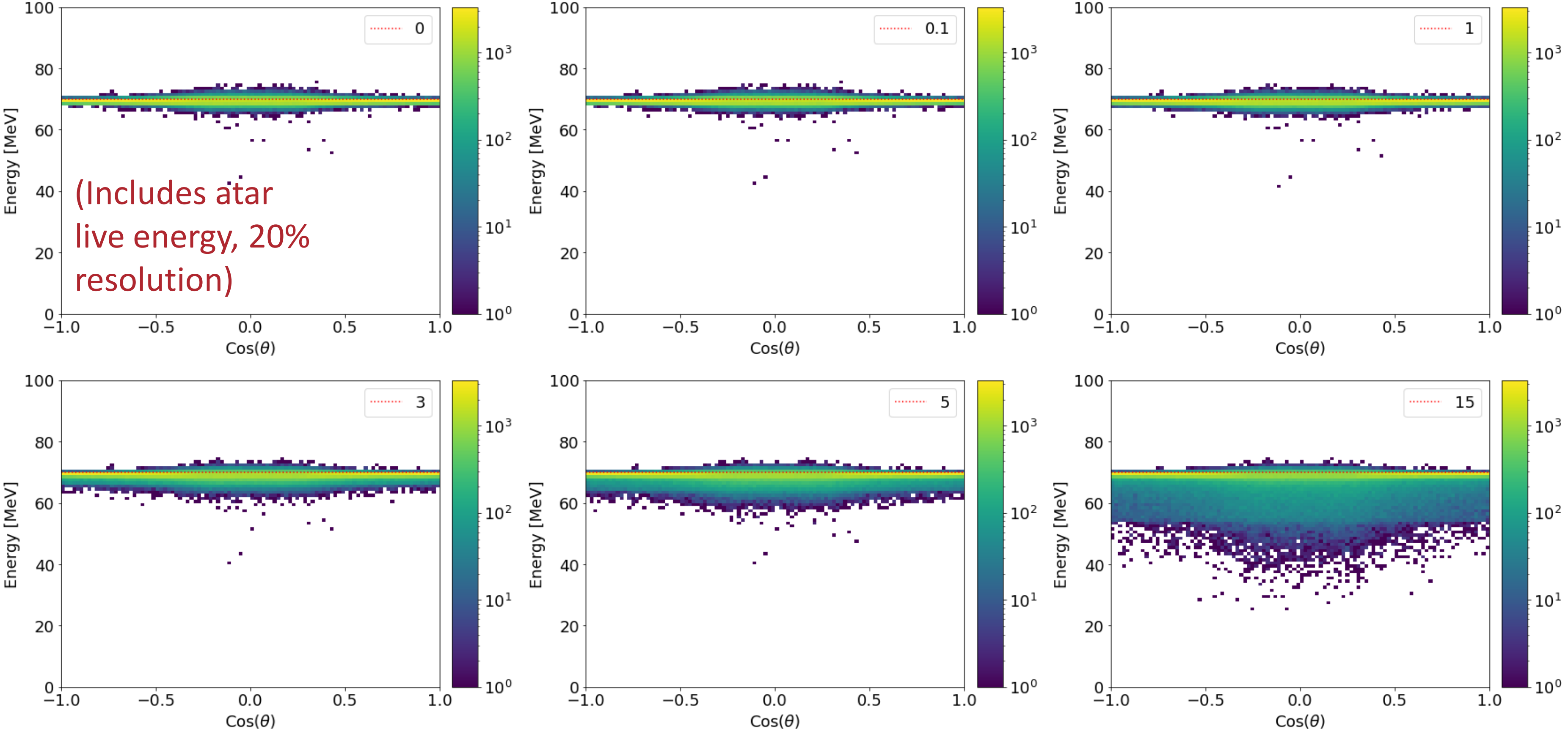
Takeaway: ATAR should be as live as possible, but small dead layers aren't a disaster

Aside: ATAR Summed with Energy Cut

(Does not include atar live energy)

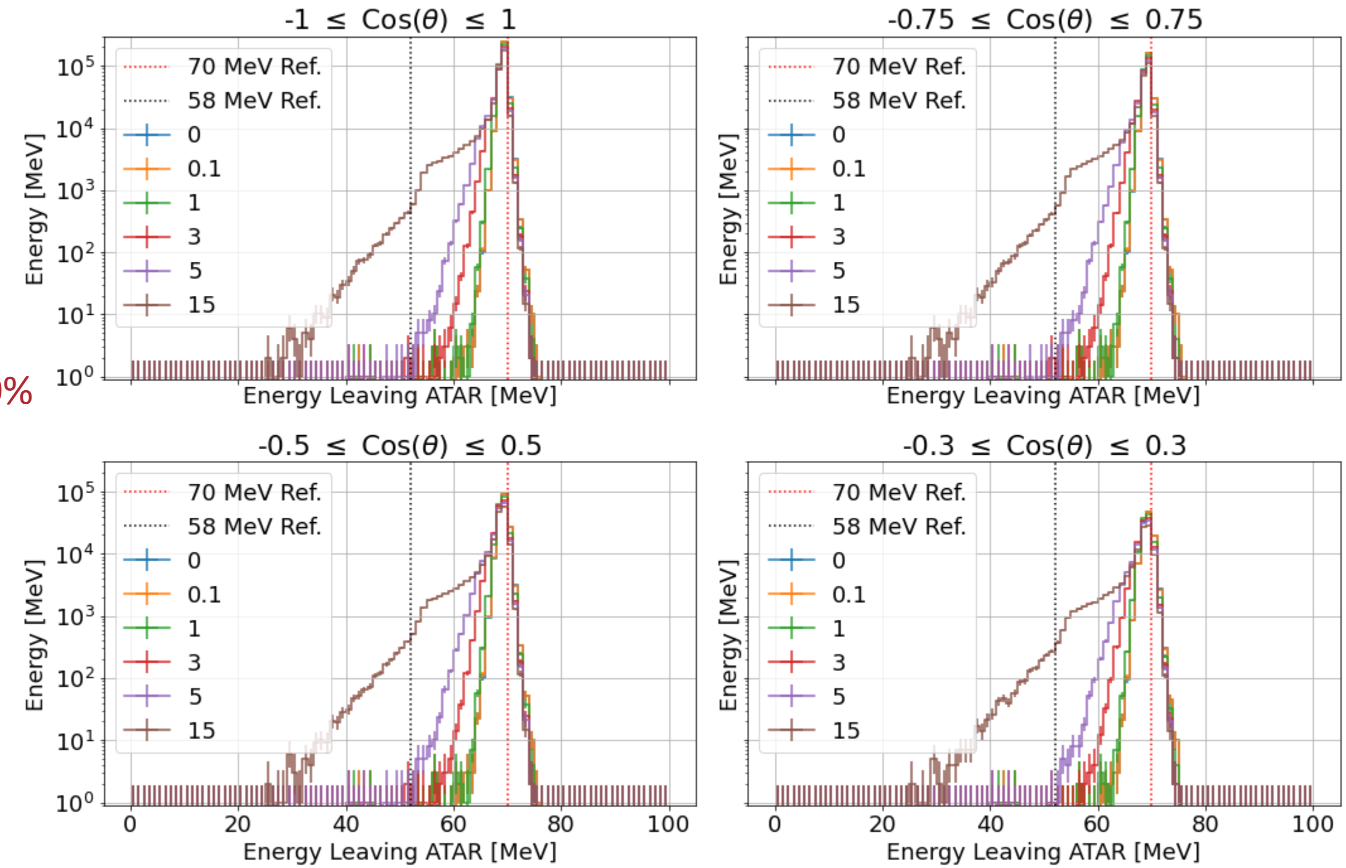


Aside: ATAR Summed with Energy Cut

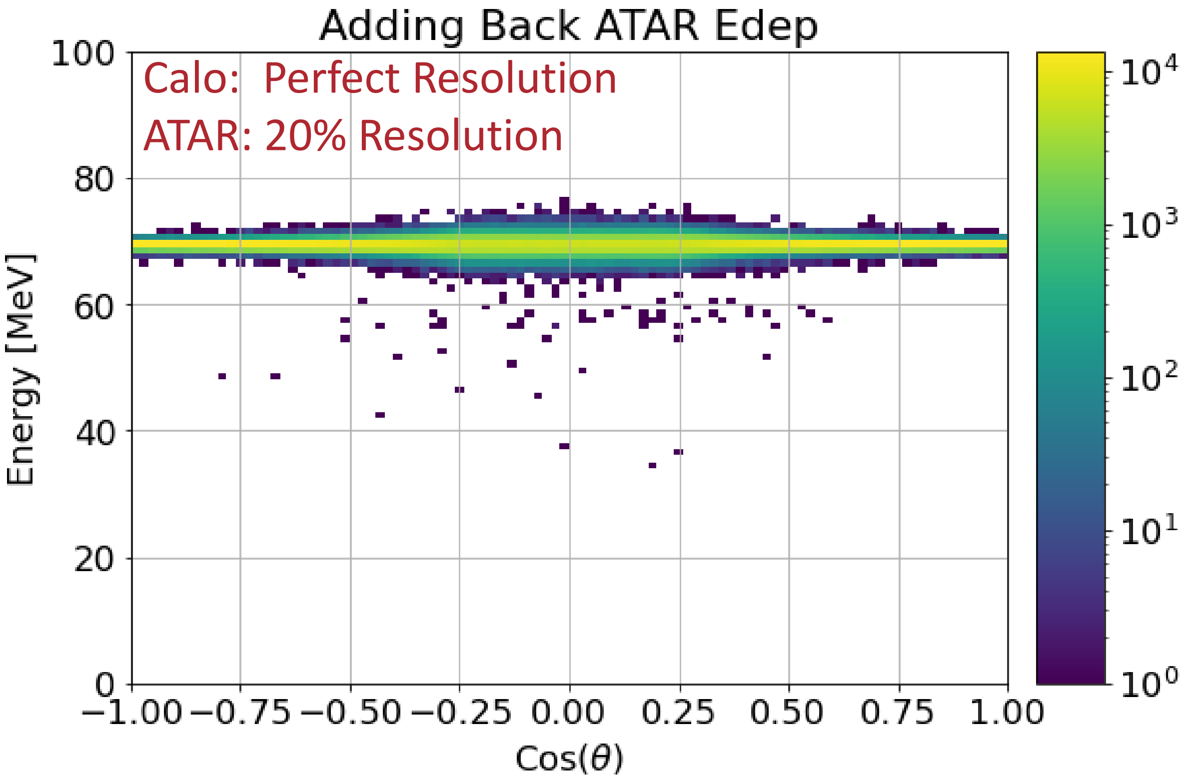


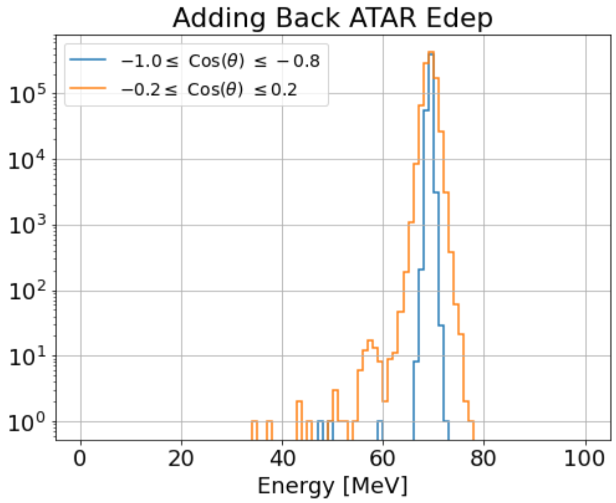
Aside: ATAR Summed with Energy Cut

(Includes atar live energy, 20% resolution)



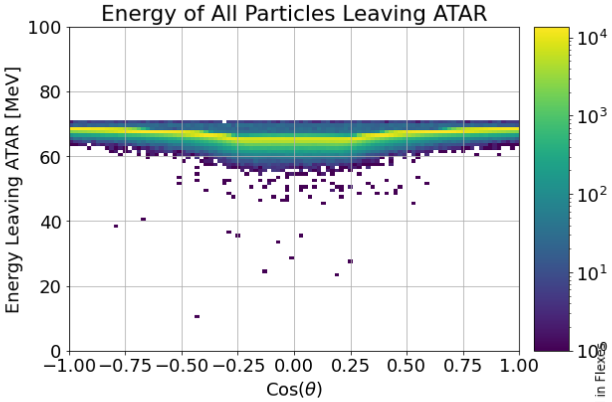
Building Up The Simulation: ATAR (Summed)

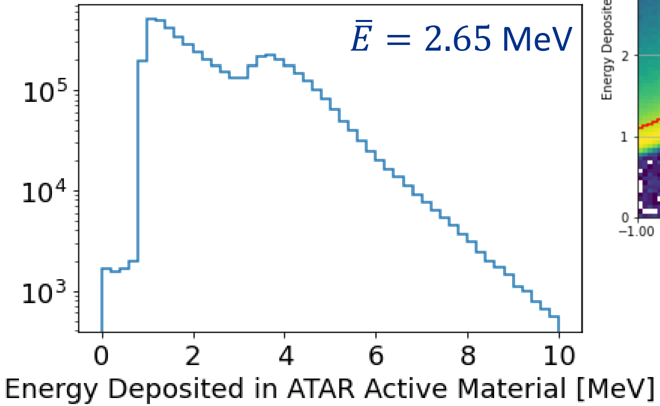


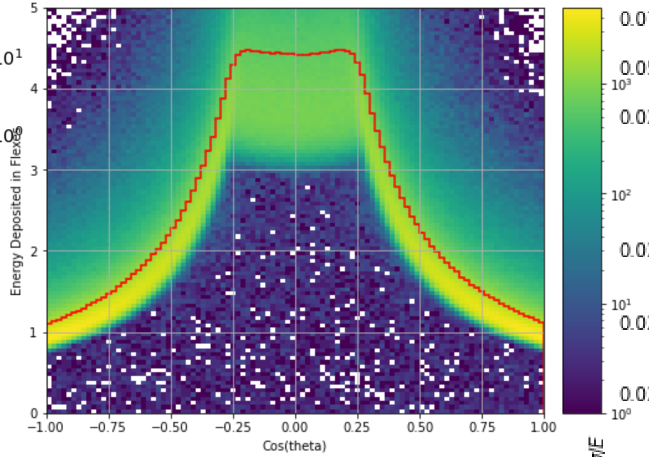


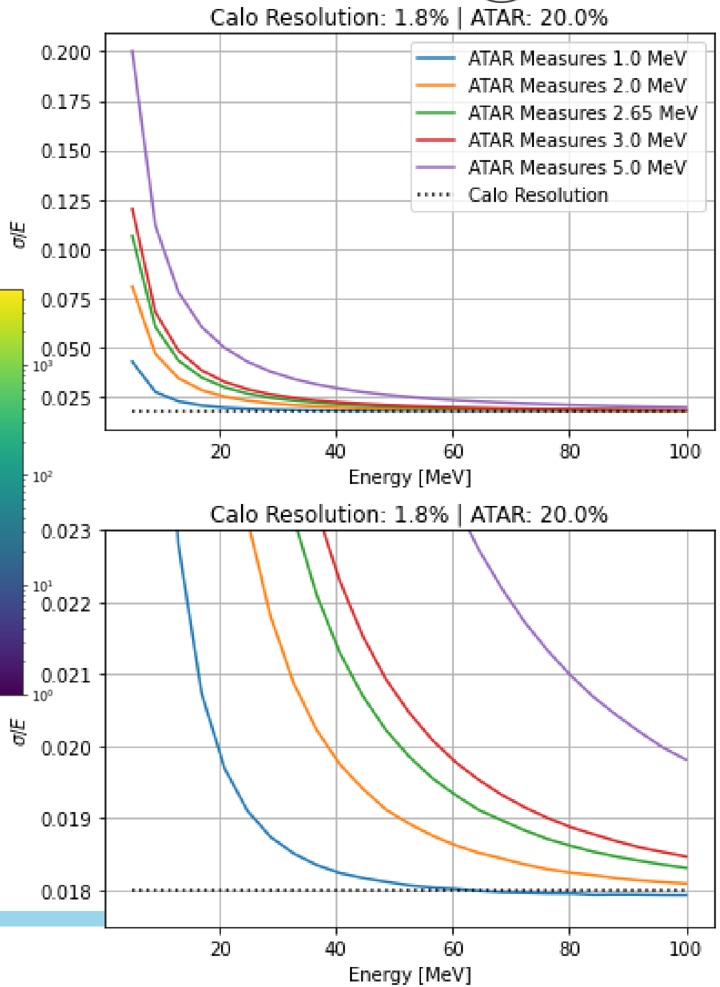
Takeaway: ATAR impact on CALO Resolution is highest ⊥ to the beam

How much energy can we put in ATAR before it hurts us?

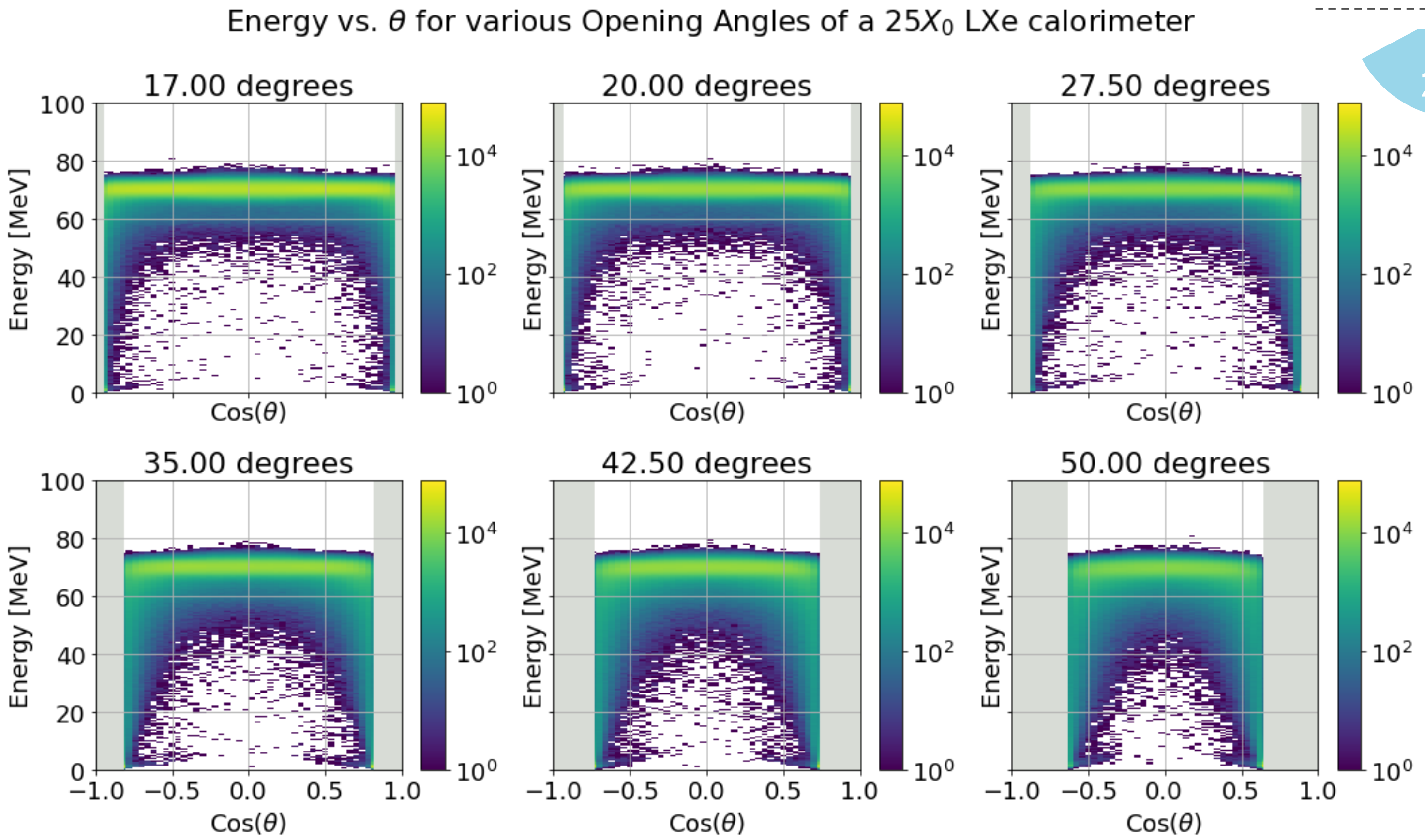


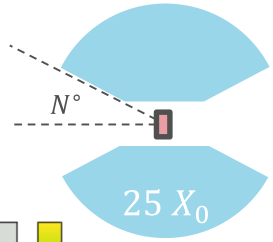






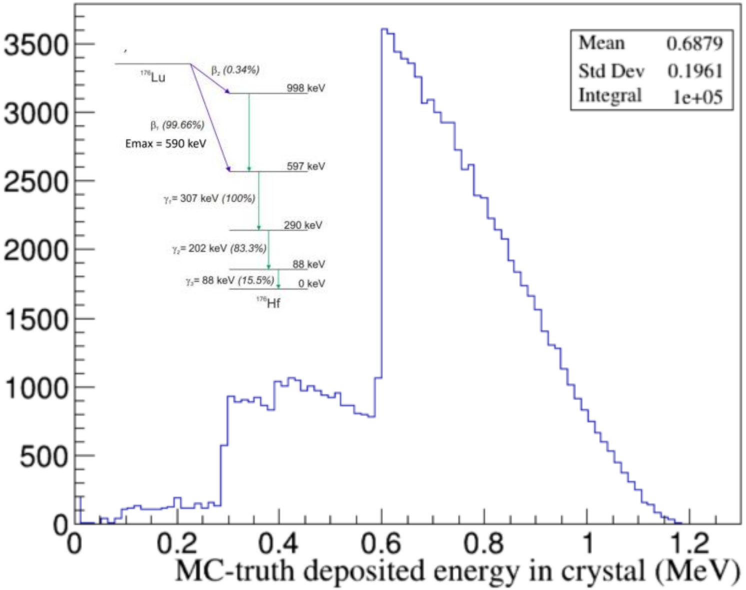
Aside: Choice of Opening Angle

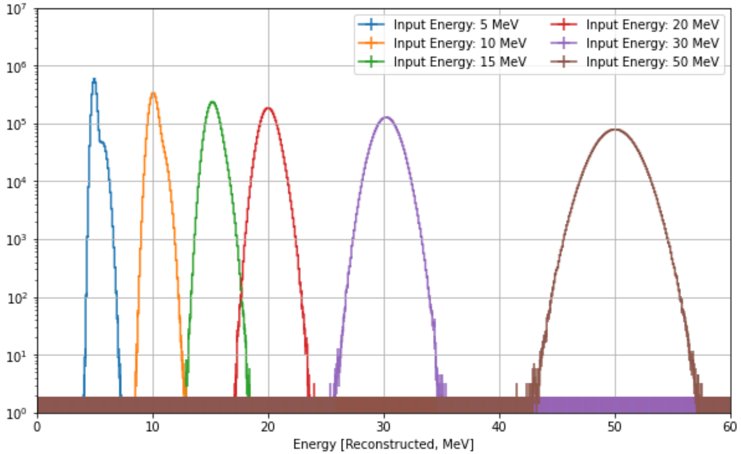


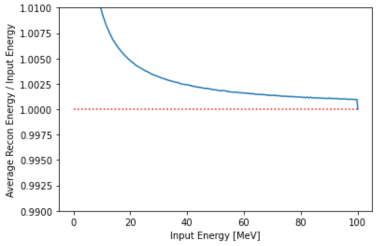


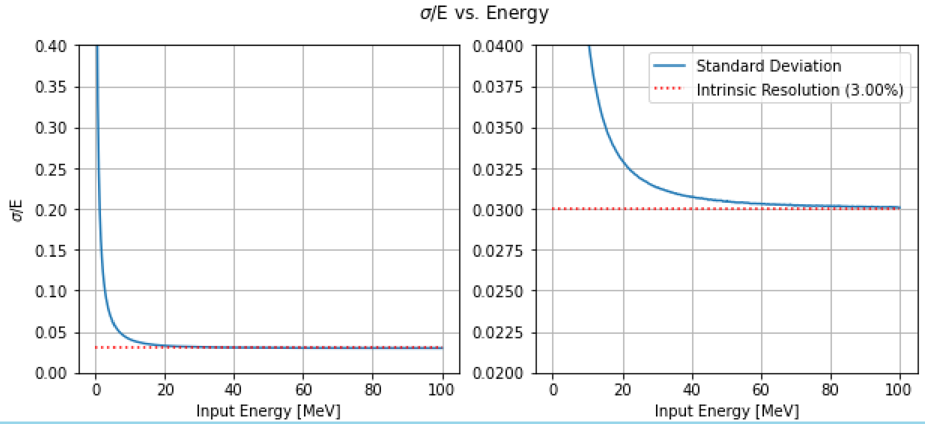
LYSO Radioactivity: Constant "Rumble" at 1 MeV

Trigger Rate = 41730 Hz



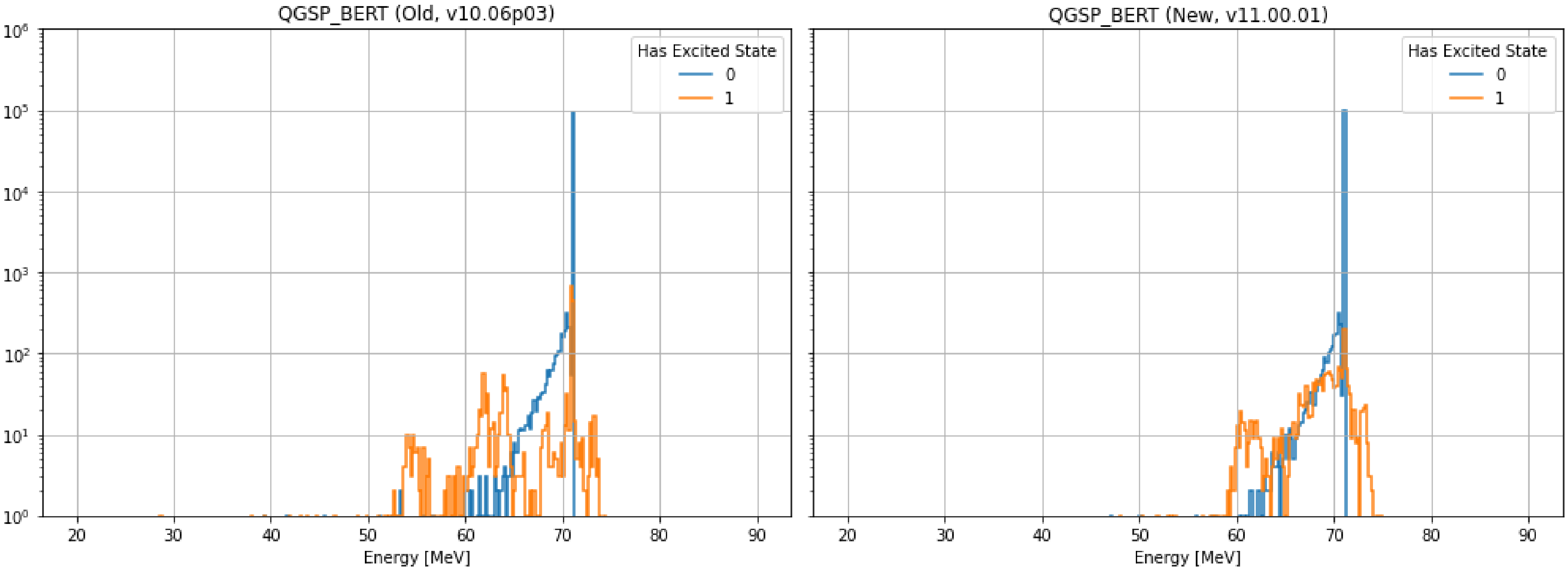






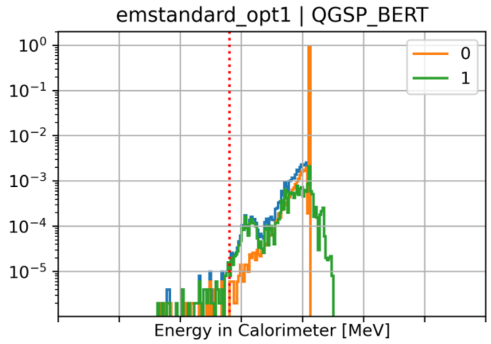
Jianglai Liu, Yong Yang, Guangping Zhang (SJTU)

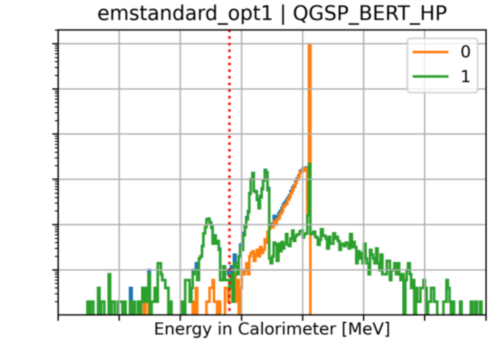
Simulation Upgrade Introduced Photonuclear Changes

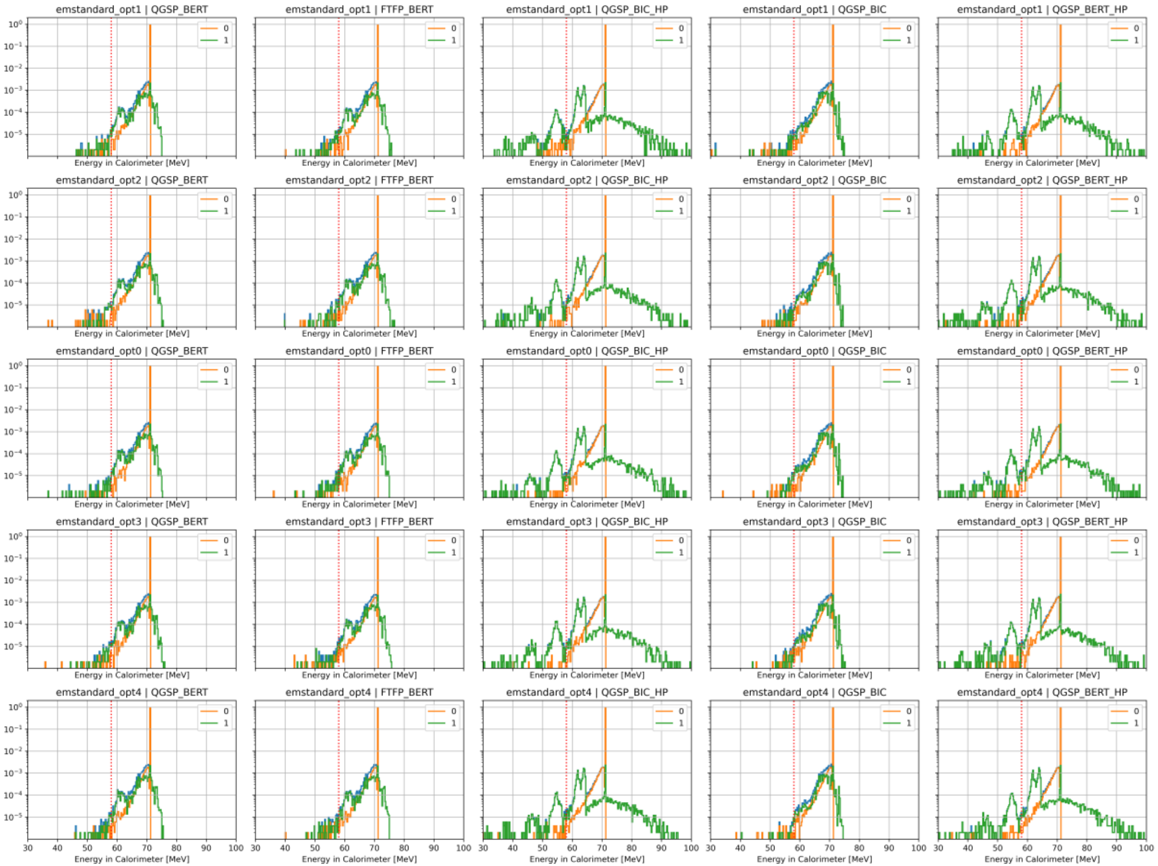


Physics List Choice is Important

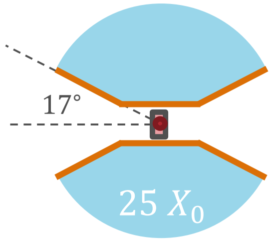
Photonuclear processes in Geant4 do not conserve energy “on an event by event basis”

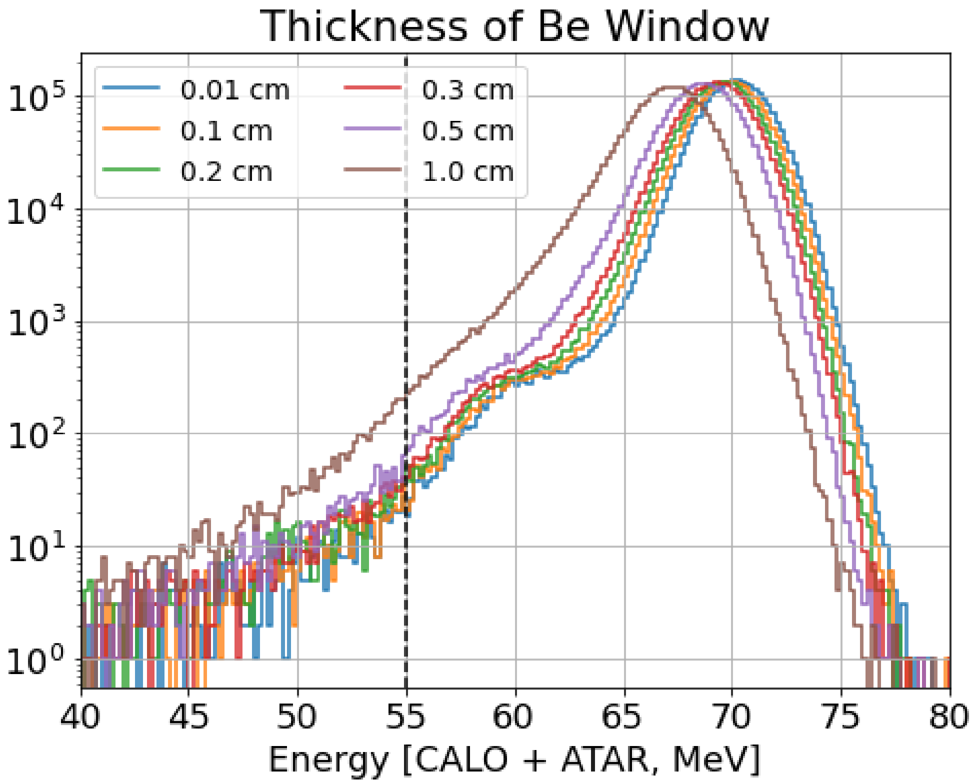


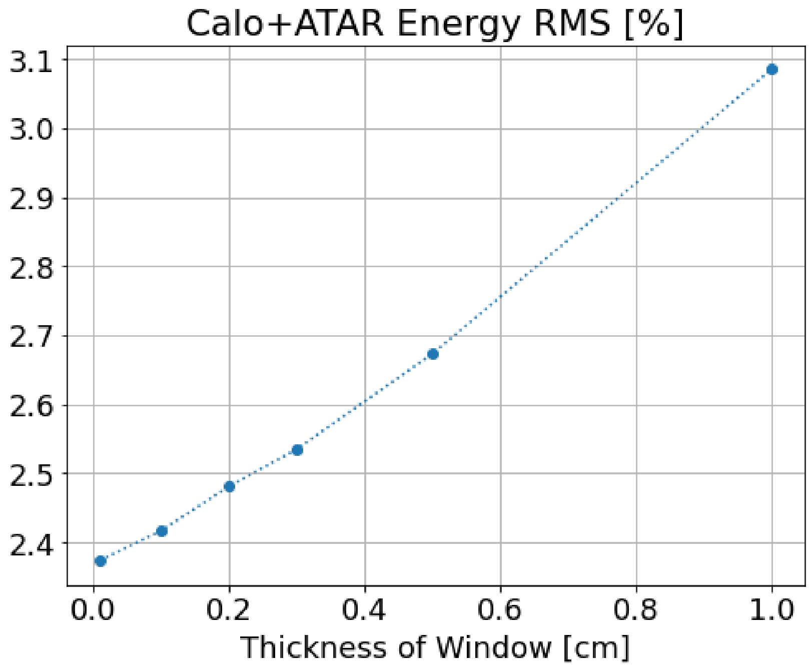




Aside: Window Thickness

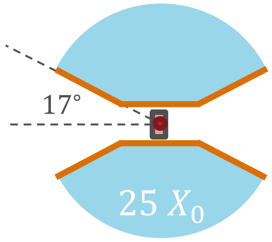


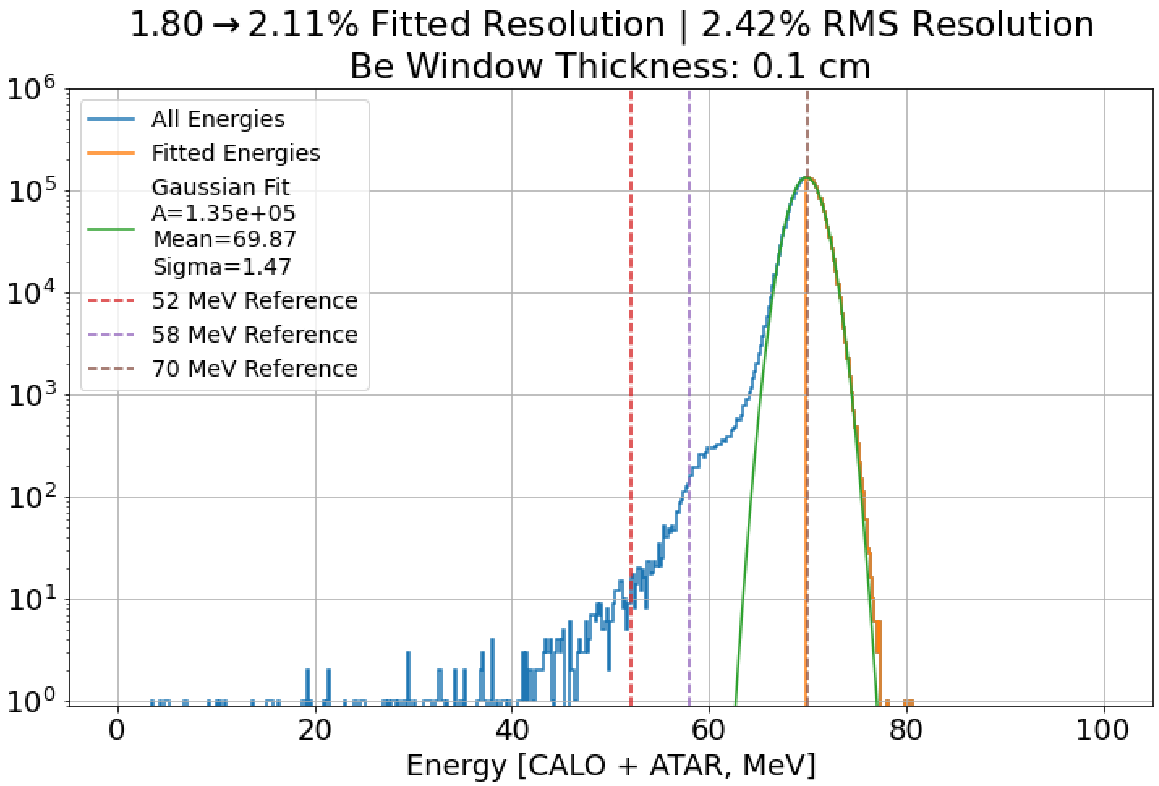




Takeaway: Immense challenge to design a multi-ton detector with as little dead material as possible

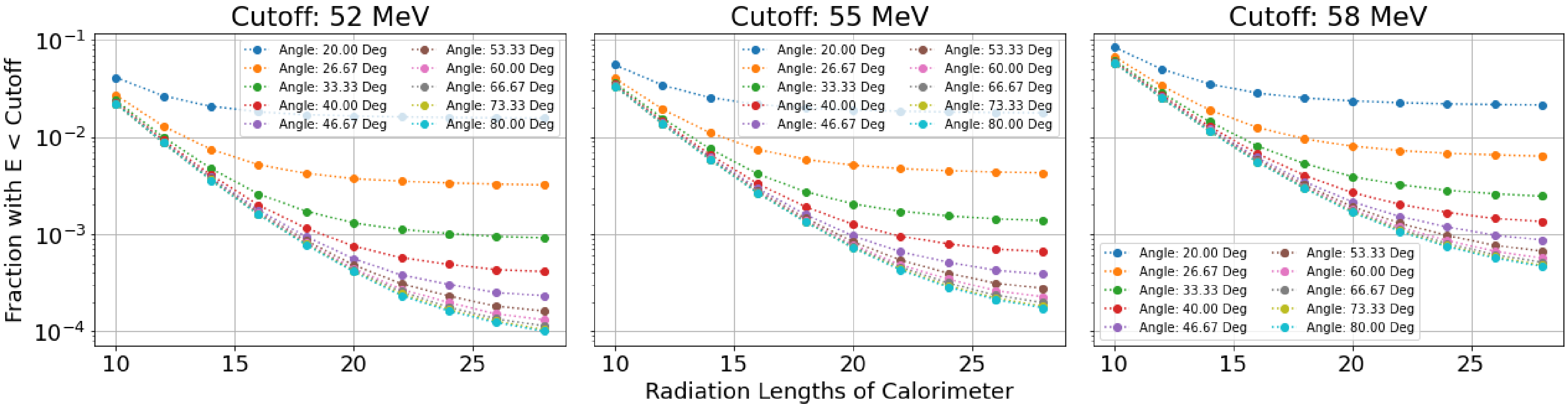
Dead Material: Beampipe

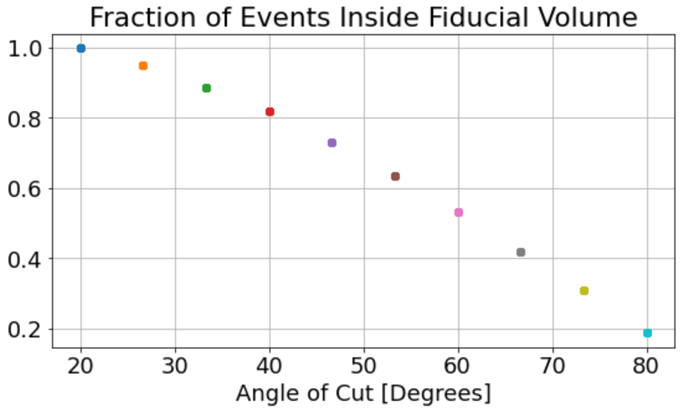


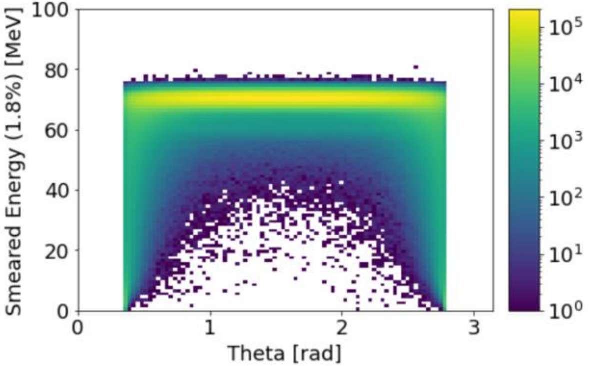


Takeaway: Immense challenge to design a multi-ton detector with as little dead material as possible

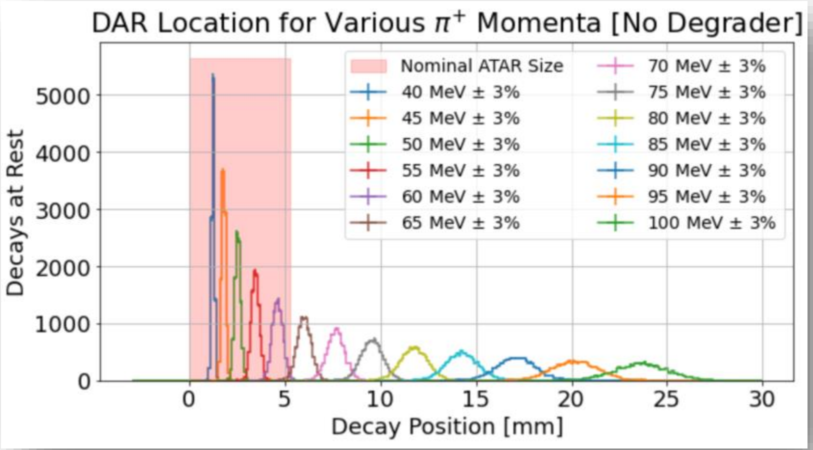
Tail Fraction vs. Angular Fiducial Volume

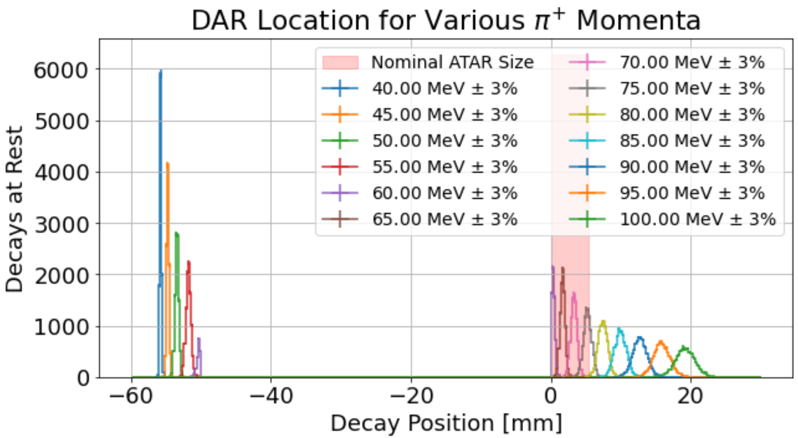


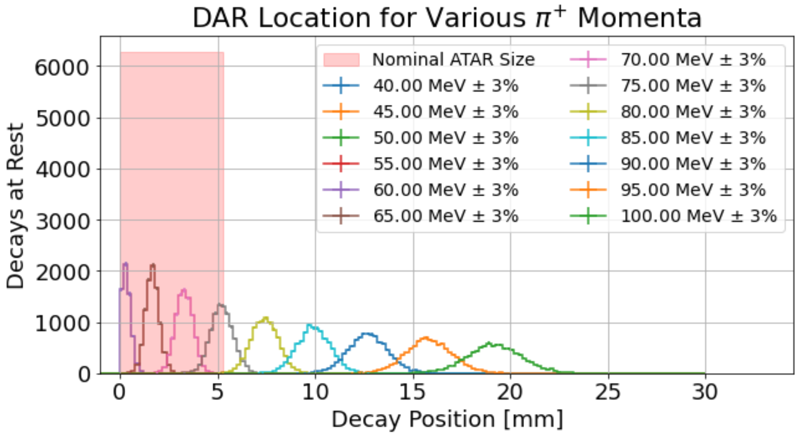




Adding A Degrader

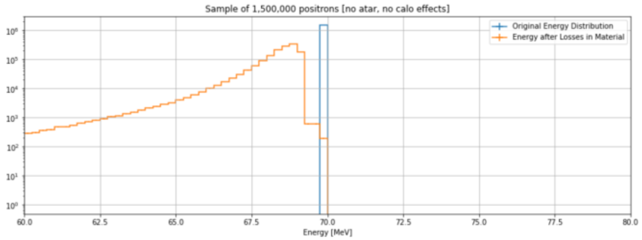




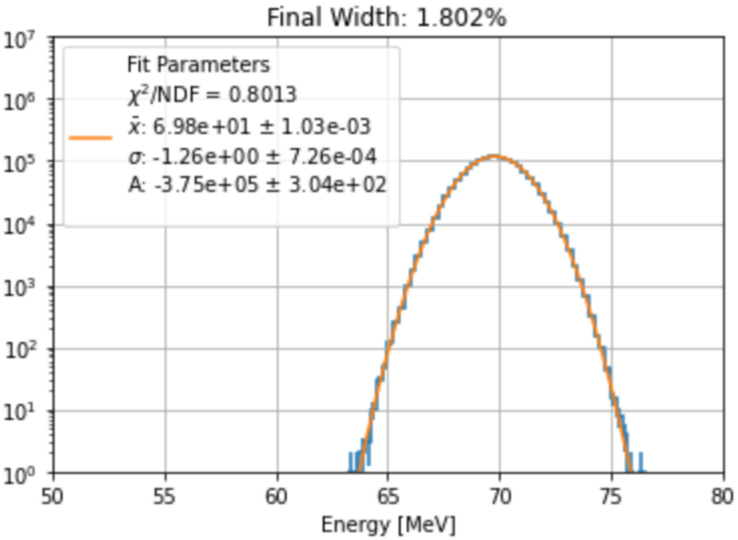


Aside: Dead Material Energy Putback

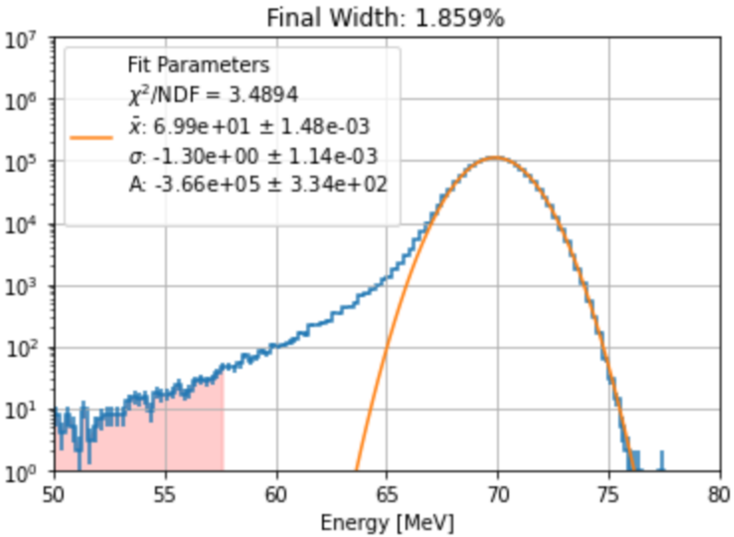
*study done with previous version of the simulation



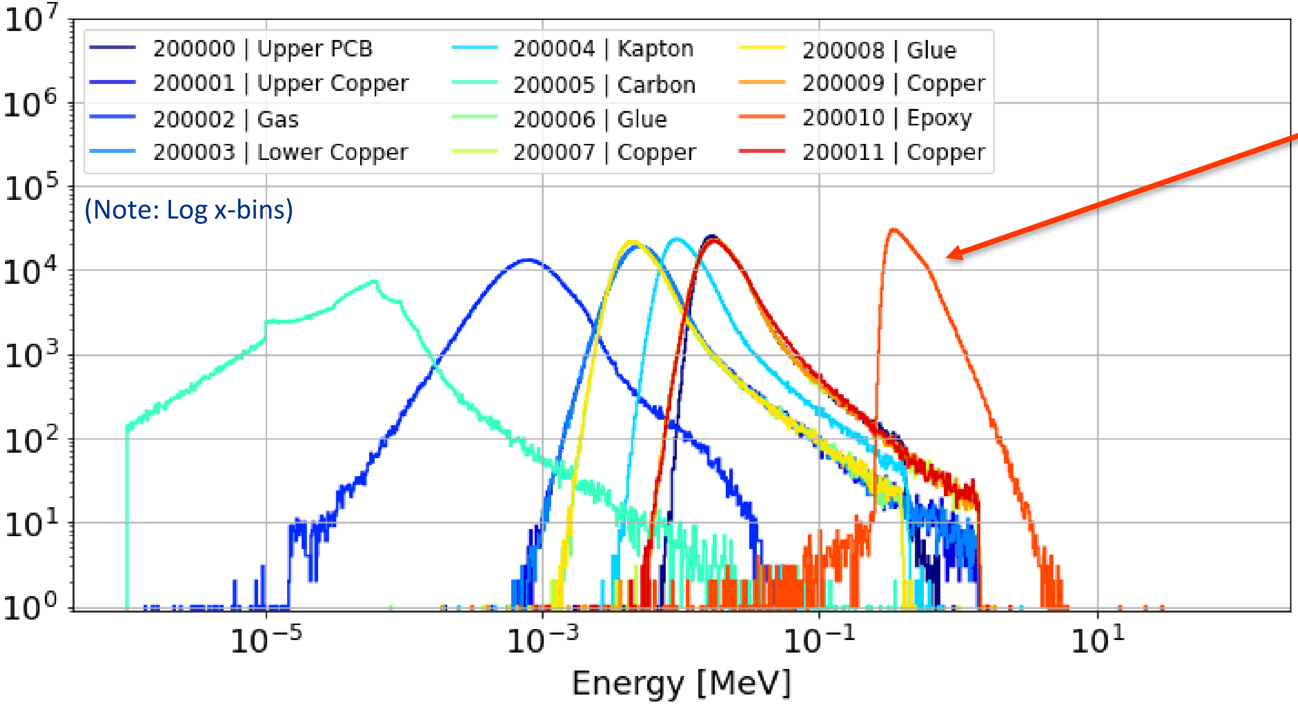
RMS (%) = 1.802



RMS (%) = 2.123
Tail Fraction (< 58 MeV) = 0.0355 %

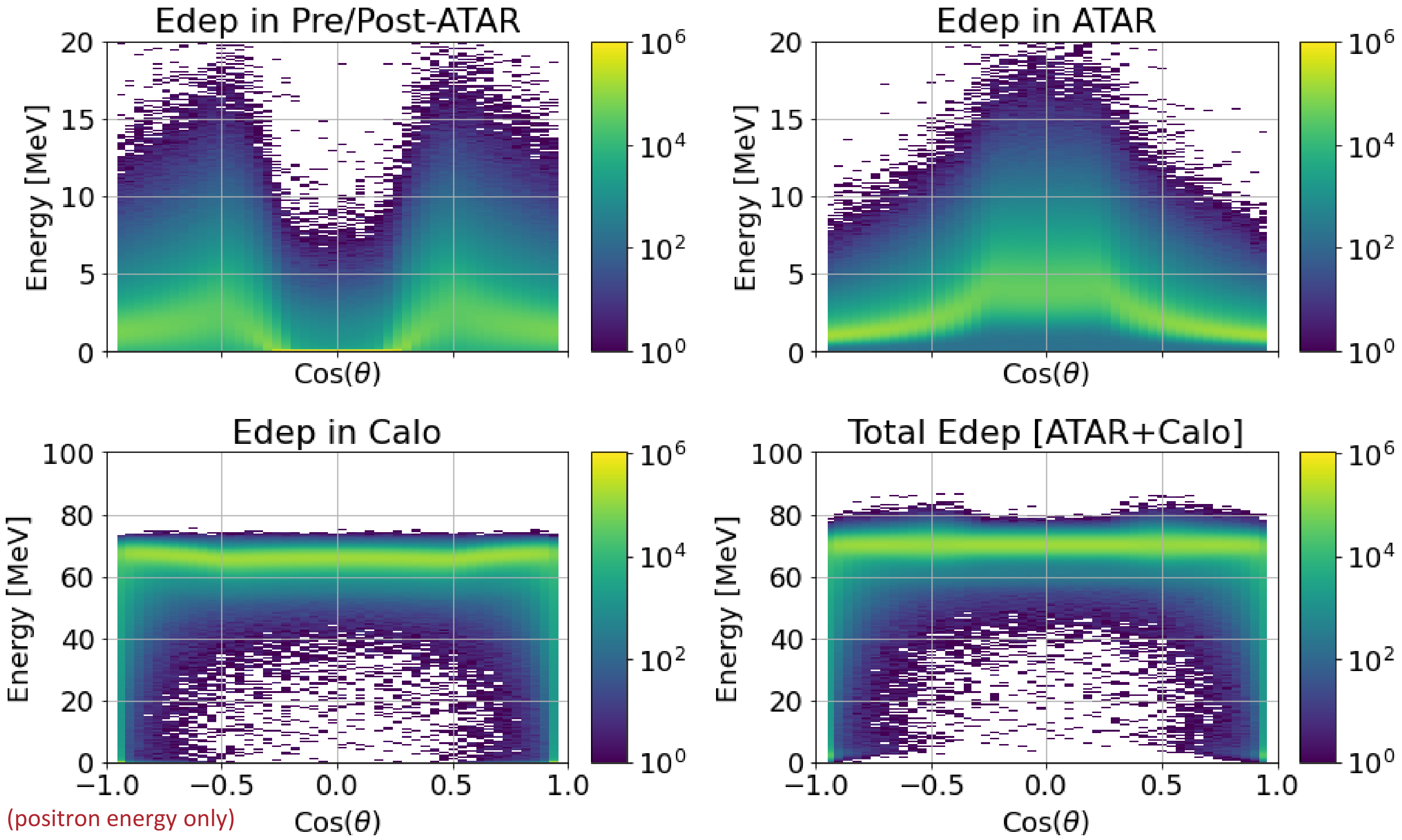


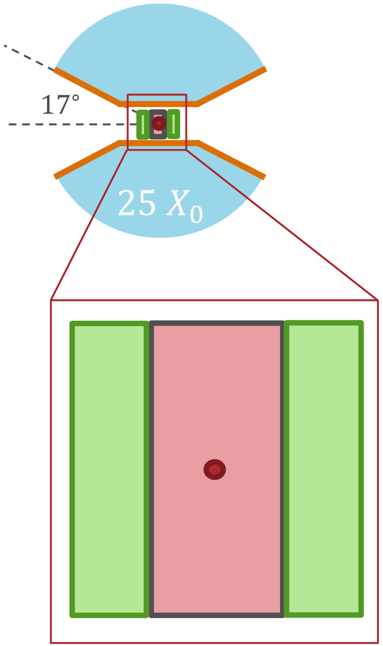
Aside: Tracker Energy Loss



Energy deposit in the tracker is driven primarily by the upper 'PCB' epoxy layer

Pre-ATAR + Post-ATAR



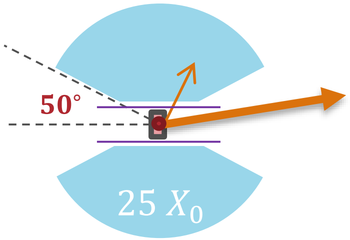


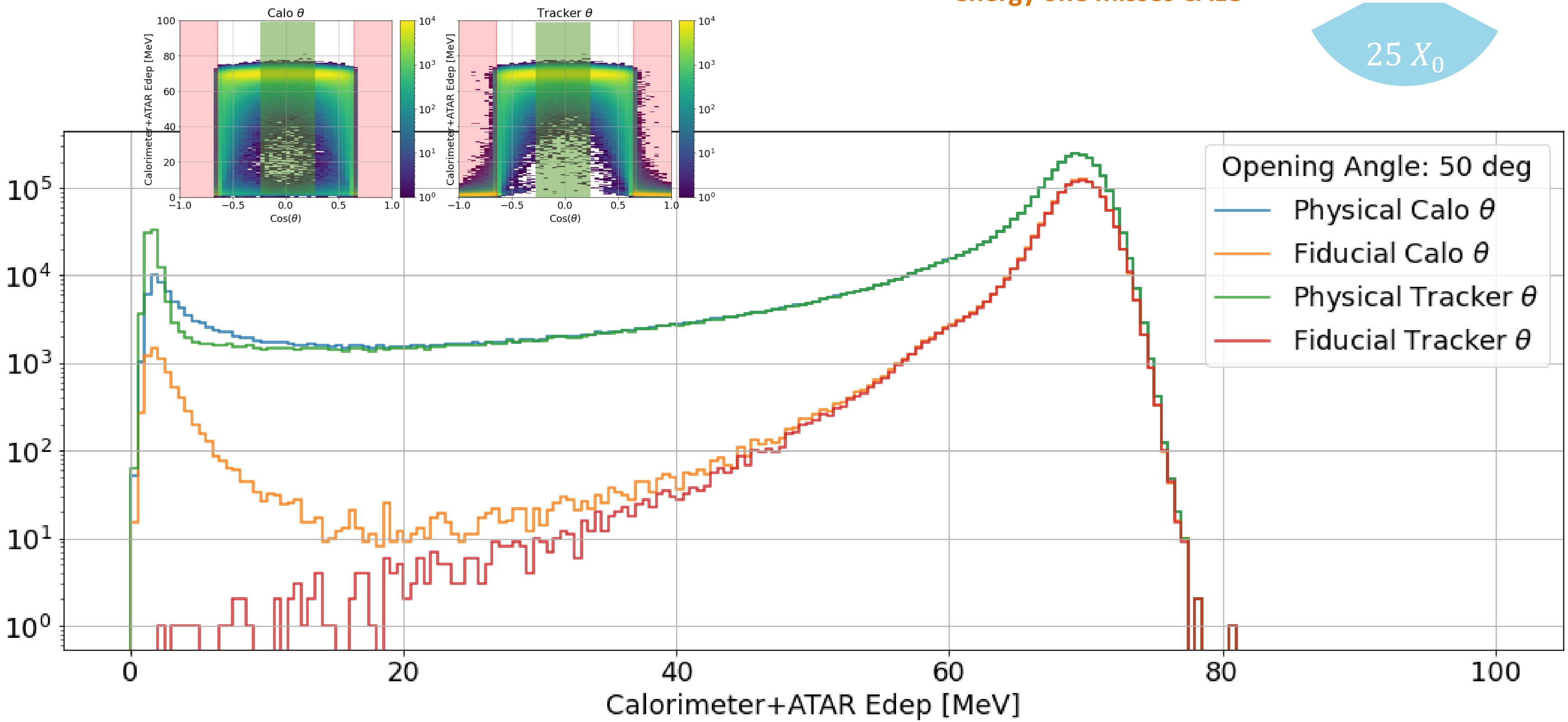
48 layer LGAD @ 20% σ/E

3.12 mm Si strip Pre/Post-ATAR @ 50% σ/E

Aside: Truth vs. Calo θ

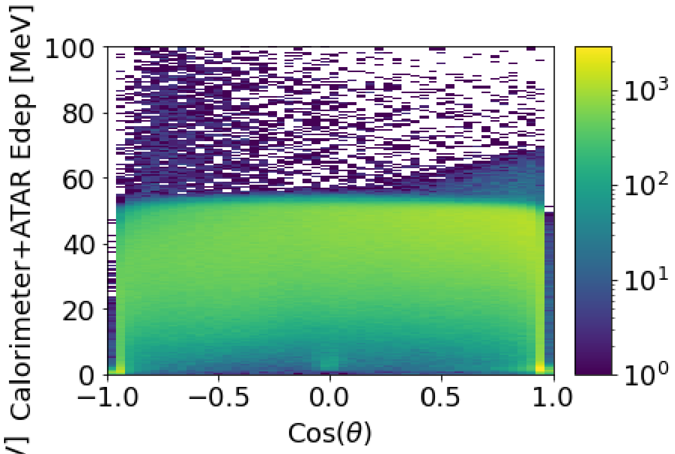
Example: 2 Particles leaving ATAR, the higher energy one misses CALO

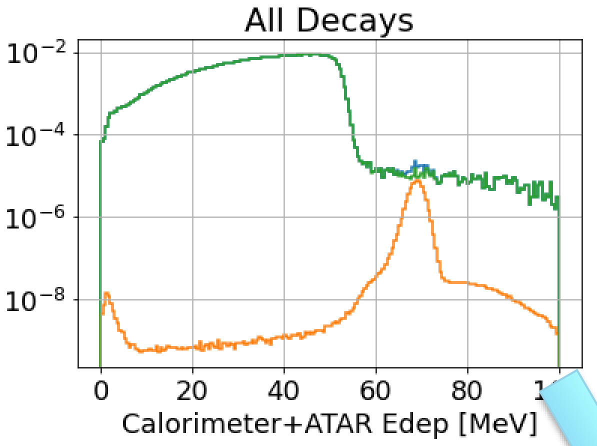


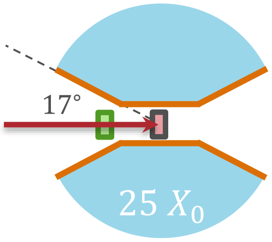


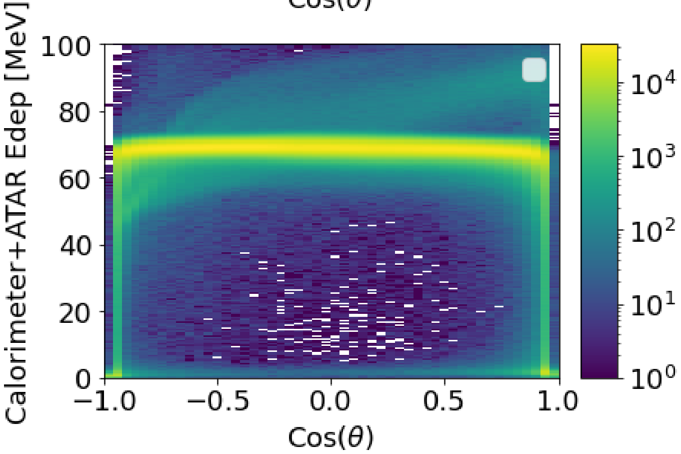
Takeaway: A tracker/endcap extending beyond the Calo opening angle will help reduce tail

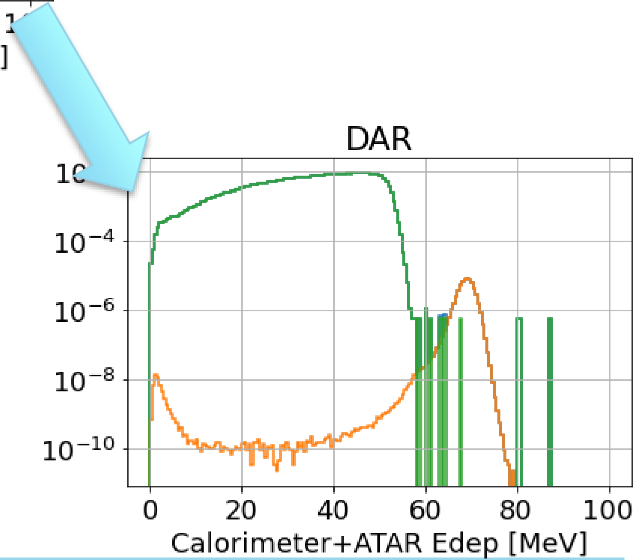
Aside: DIF Cuts



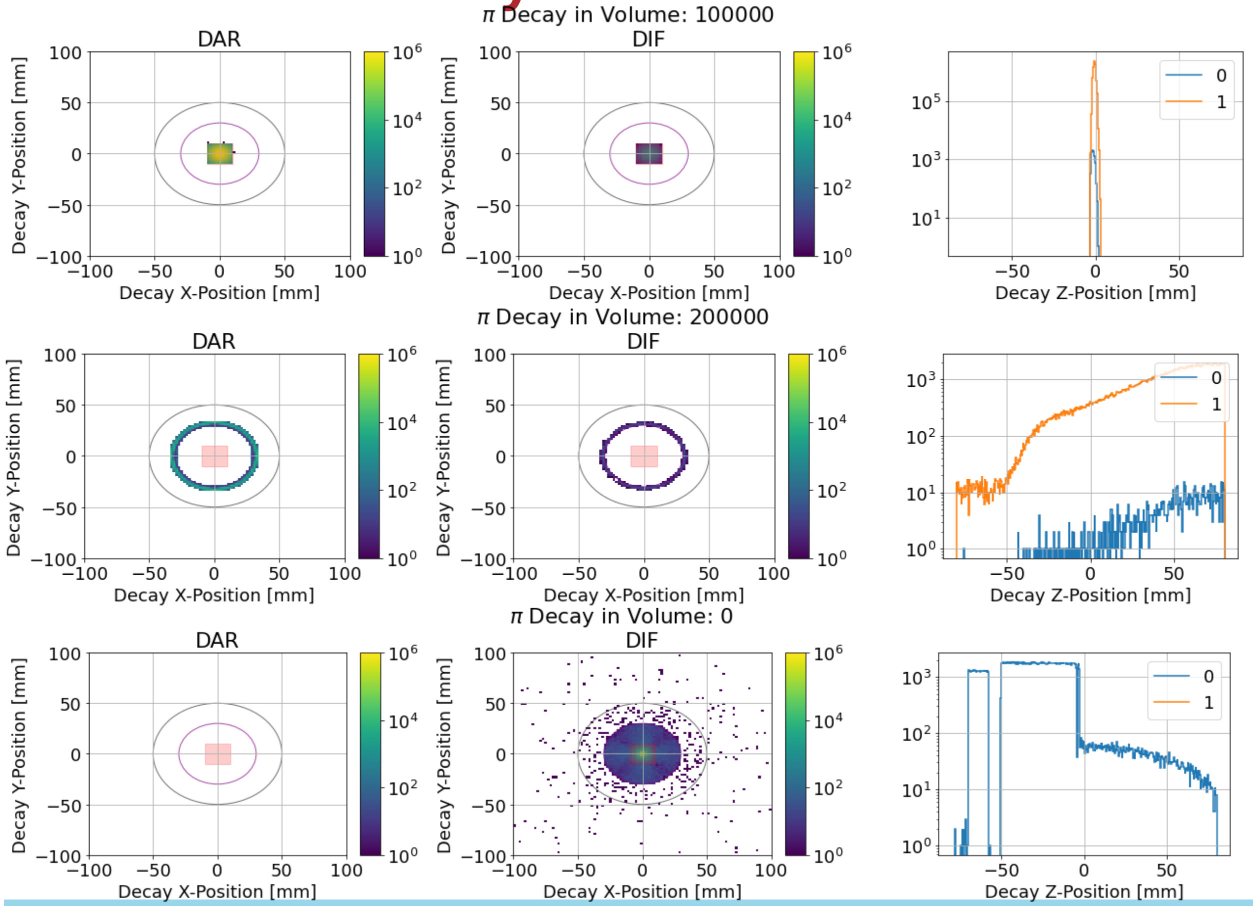


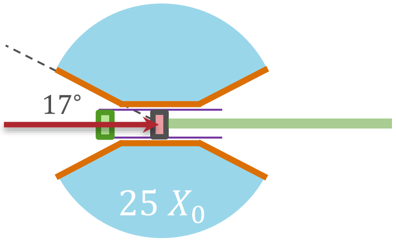






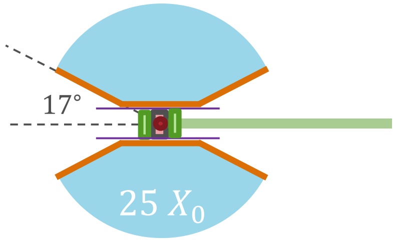
Aside: Pion Decay Locations





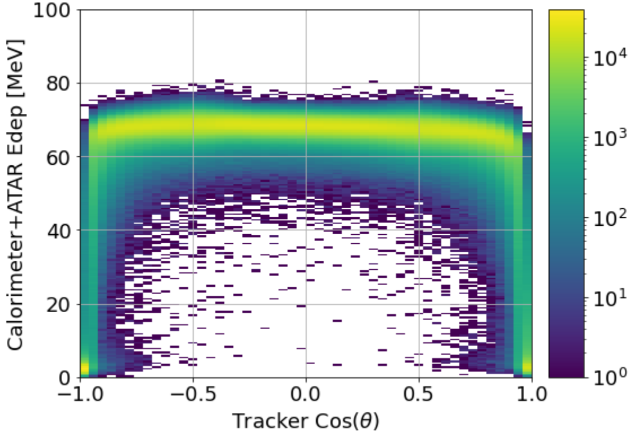
Takeaway: ATAR tagging of pions will be essential to reject background

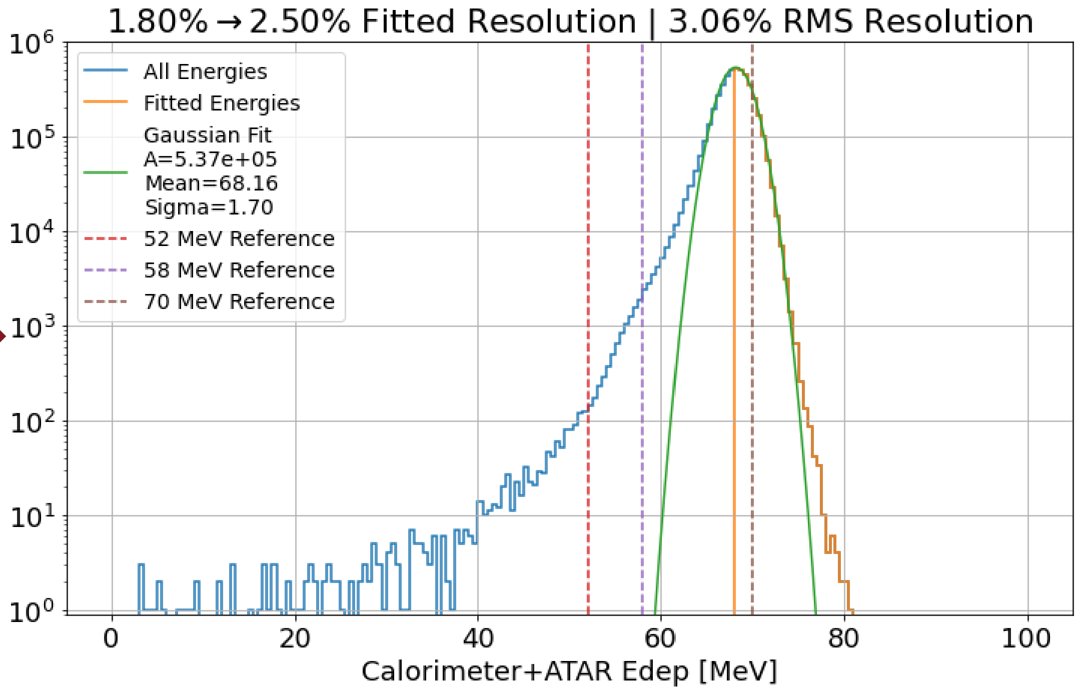
Final Resolution for π_{DAR} Positrons: 1.8% → 2.5% Pre + Post ATAR



Finally:

- 0.1 cm Be window
- 2 Tracking layers
- ATAR/Calo resolution
- Readouts
- …





Note: Here no dead material energy ‘repair’ has been attempted