Considerations for the PIONEER calorimeter

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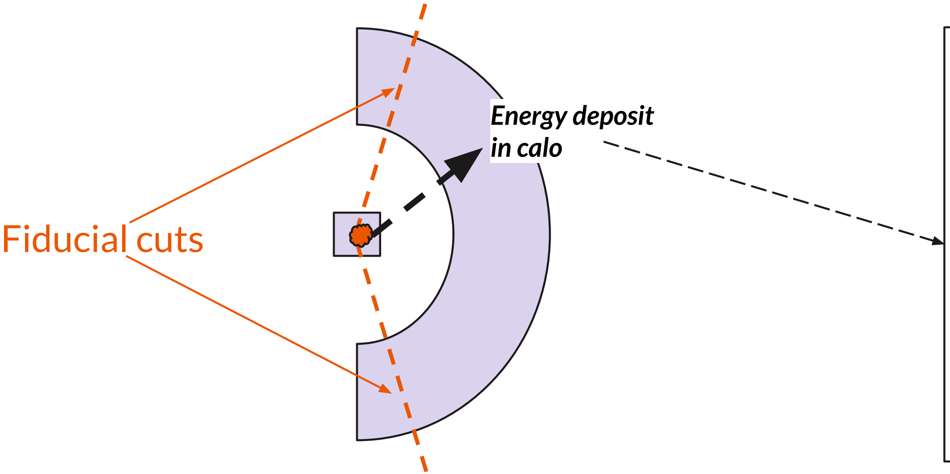
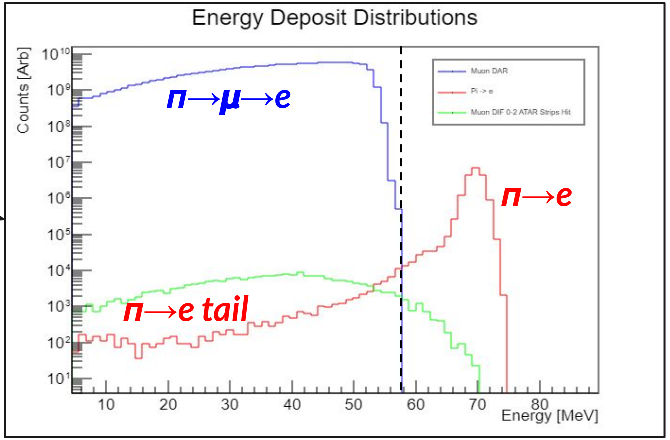
Basic function of the PIONEER calorimeter

- Process in ATAR produces a positron
- Positron from ATAR is stopped in calo and energy deposited is recorded

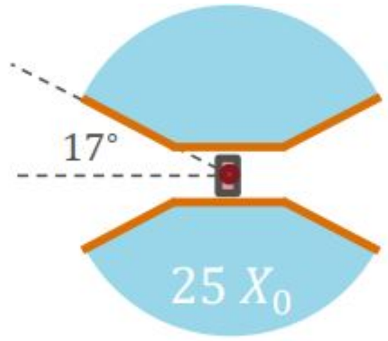




Our understanding of the PIONEER calorimeter is changing

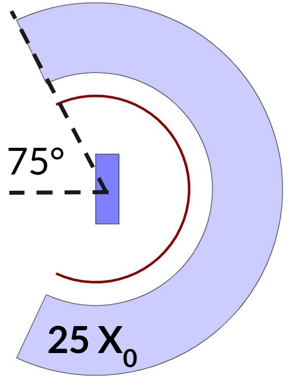
One year ago

- 1.8% energy resolution at 70 MeV
- 25 radiation lengths
- “Hamburger” calorimeter design with 17 degree opening angle

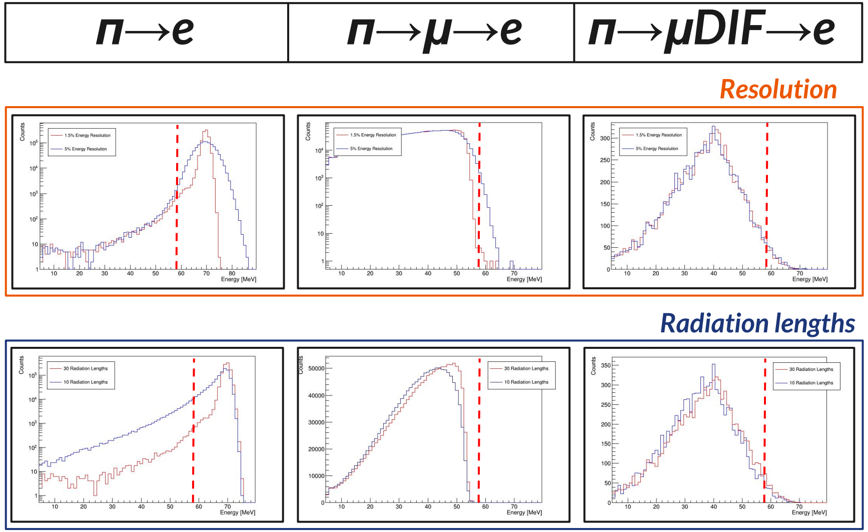


Today

- 2% energy resolution at 70 MeV
- 25 radiation lengths
- “Pacman” calorimeter design with 75 degree opening angle



Review of energy spectra distortions



Resolution smears distributions

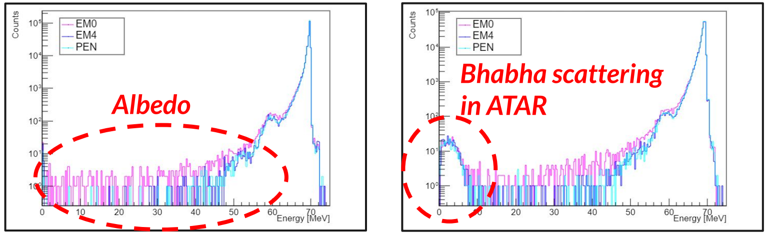
- Minor effect on ***π→e*** tail
- Increases Michel background in signal region, though ATAR should be very good at identifying this background
- Increases pileup in signal region (discussed later)

Lack of stopping power affects *π→e* tail

- Number of radiation lengths only really affects ***π→e***

Other processes such as albedo and Bhabha scattering in ATAR may affect the tail significantly (next slide)

Indirect distortions



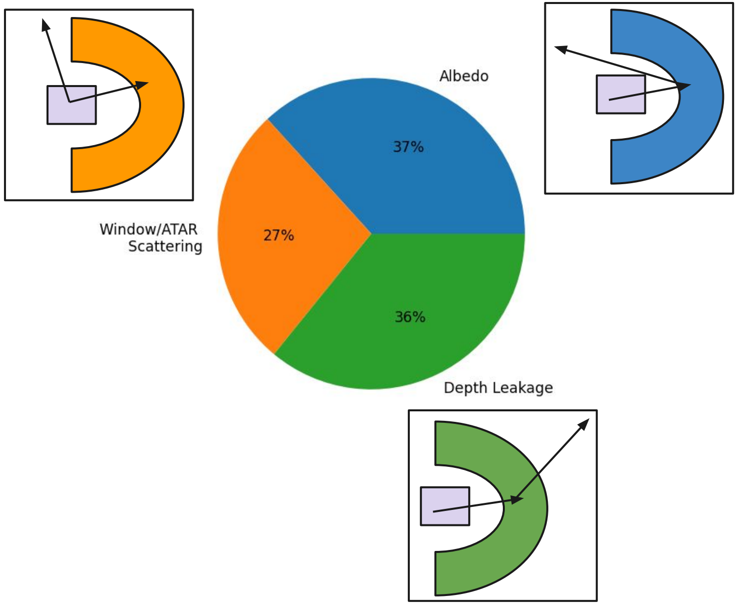
Tail composition is more than a radiation length problem

- We need a tail fraction of less than 1% to achieve the desired 10^{-4} precision
- Our nominal simulation finds tail fractions of 1.2-1.4%
- Contributions from high energy backscatter (albedo) and Bhabha scattering in the ATAR may be significantly overstated in our simulation

<u>What is the actual size of our tail? What can done to reduce it beyond building a larger calorimeter?</u>

Simulation of $\pi \rightarrow e$

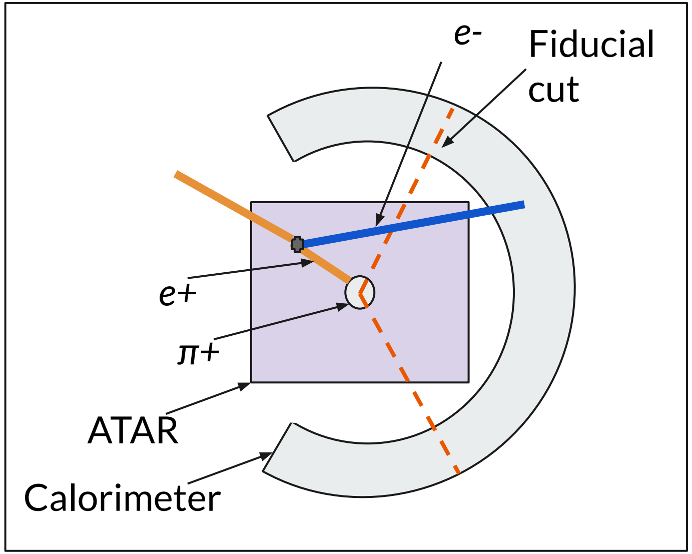
- *Pion decays from the center of the ATAR*
- *Extremely restrictive fiducial cut ~60 degrees from downstream on tracker hit*
- *Calo is 25 RL of LXe with inner radius 10 cm and angular coverage of 105 degrees in theta*
- *Energy deposits in the calo within 500 ns window are recorded*
- *EM0 electromagnetic physics list*

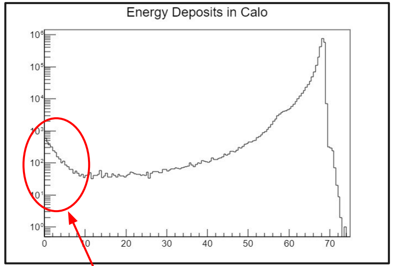


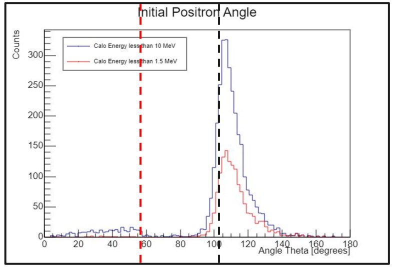
Most Bhabha scattering in ATAR shouldn't be counted in the tail

1. Pion decays to positron
2. Positron scatters off of an electron
3. Low energy electron hits fiducial volume
4. Positron scatters outside of the calo

- The angle between the e+ and e- can be large such that
  - The e+ is emitted in a direction outside the fiducial region and deposits no energy in the calo
  - This event should be rejected, but the e- registers a hit and deposits a small amount of energy in the calo
  - This event registers in the tail, but shouldn't
- The events in the resulting 'Bhabha bump' should be removed







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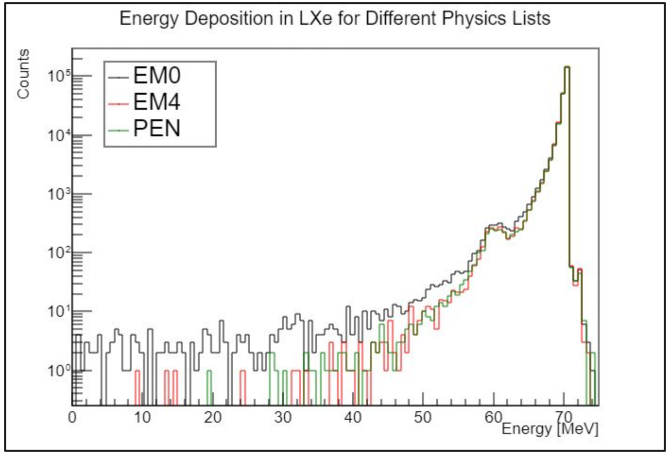
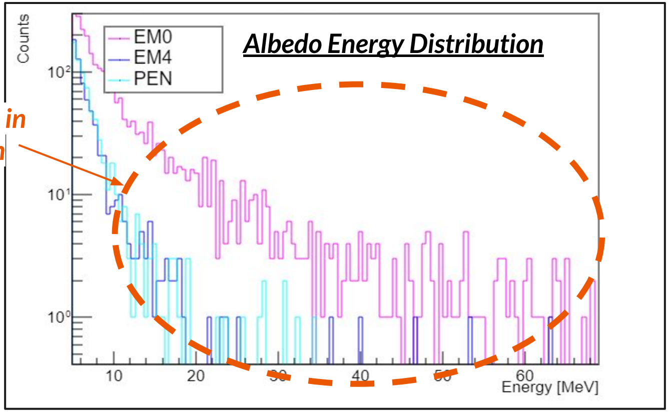
High-energy albedo may be a figment of our simulation

Albedo: The positron scatters off of the calo without depositing much energy.

- Our nominal simulation using the EM0 list predicts that this makes up more than ⅓ of tail events, but:
  - PIENU tail shape seems to better match high precision physics lists (EM4, Penelope)
  - High precision lists predict significantly fewer tail events
  - This discrepancy between lists seems to be almost entirely due to albedo
- We plan to validate our simulation and measure albedo during our LYSO beamtime at PSI

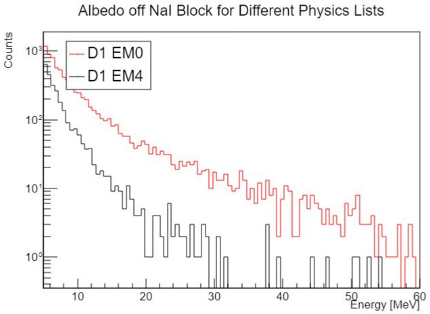


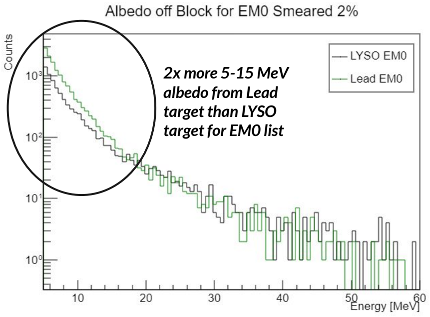
Huge difference in tail contribution

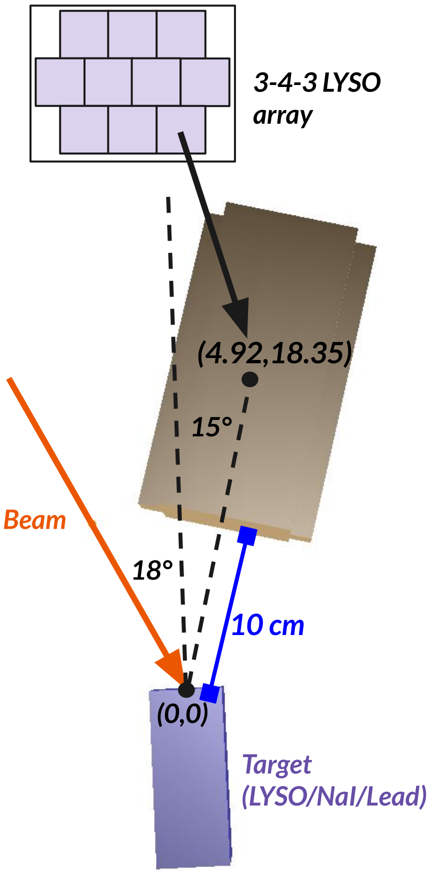


Albedo will be measured during LYSO beam tests and EM lists will be validated

- Shoot 70 MeV e+ beam at target of various materials (LYSO/NaI/Lead) and measure the albedo in our LYSO array
  - Energy deposits in LYSO array primarily from albedo
  - OR trigger on hodoscope and clock will be used to measure the background distribution
- Additional validation tests
  - Angular distribution of albedo
  - Test ~1/r^2 dependence
  - Vary beam energy

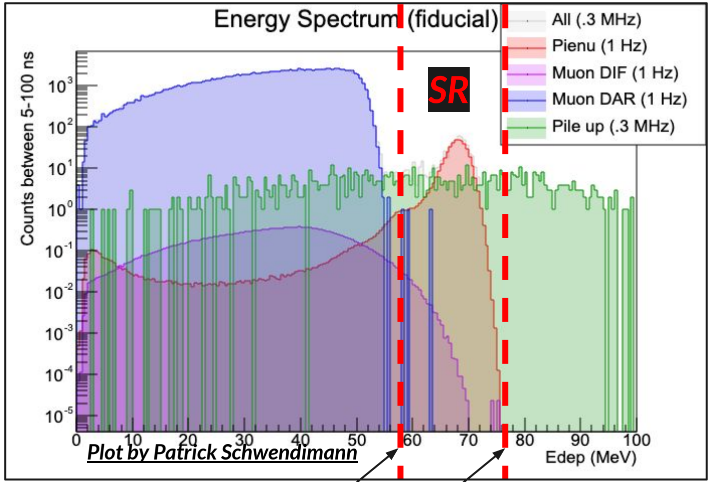






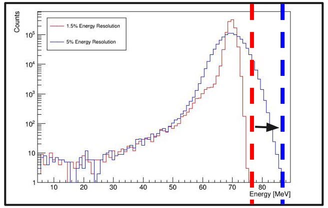
Is energy resolution as crucial as we have long assumed?

- Energy resolution largely determines the endpoints of our signal region (SR) – poor resolution causes:
  - High energy SR cut to be pushed to higher energy to include all ***π→e*** events, causing more pileup in SR
  - Increases ***π→μ→e*** background in SR, ATAR should identify these events easily due to their two Bragg peak topology
  - Energy resolution has minimal impact on the ***π→e*** tail
- Calo segmentation could provide much better pileup minimization than resolution



Separate signal from Michel

Minimize integration of pileup



Resolution increases high SR bound

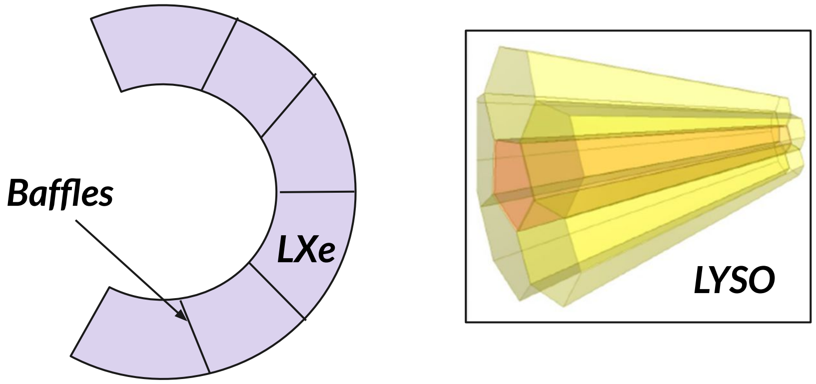
A 4% at 70 MeV resolution results in ~40% more pileup in the SR than a 2% resolution

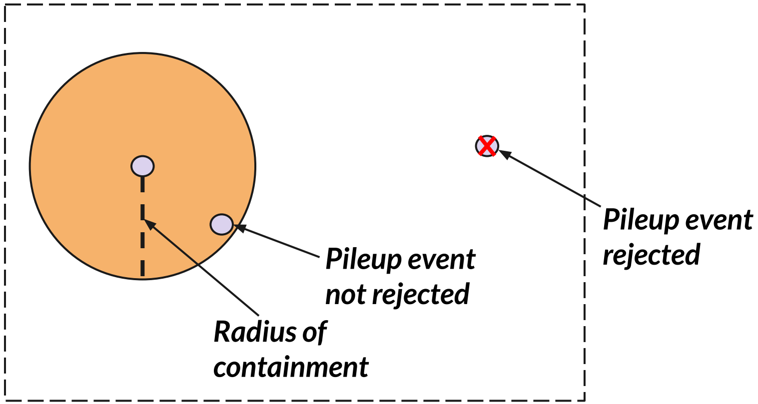
Calorimeter segmentation can be estimated through simple calculation

Segmentation of the calorimeter can be achieved using baffles for a LXe calo and is an intrinsic part of a crystal calo. A segmented calorimeter provides improved ability for the calorimeter to identify pileup.

$$\text{Pileup rejection} = \frac{\alpha \times 4\pi(\text{inner radius} + \text{shower depth})^2}{\pi(\text{containment radius})^2}$$

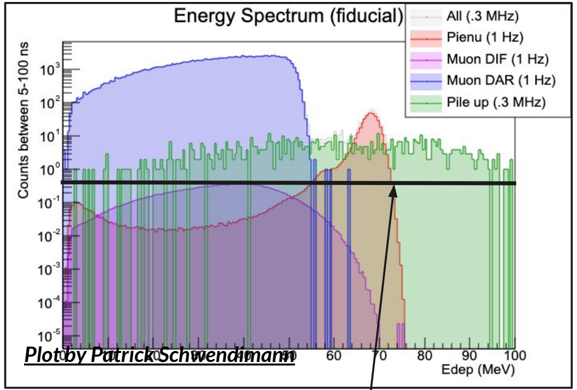
- *Pileup rejection: Factor by which pileup is reduced*
- *α = order 1 geometrical acceptance factor*
- *Inner radius: Calorimeter inner radius*
- *Shower depth: Peak position of energy weighted shower position*
- *Radius of a cylinder at which 90/95% of shower energy is contained (1-2 Moliere radii)*





Segmentation may offer huge gains in pileup rejection

- Large pileup suppression – nominal configuration has more than an order of magnitude improvement in pileup
- This is a basic calculation – we need to be careful about energy dependent shower properties, etc.
- Pileup rejection has a strong dependence on inner radius – *What if we push the calorimeter further back?*

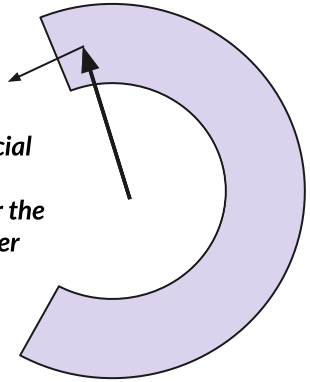


Pileup level with pileup rejection of 10

	LXe	*LYSO*
Radiation Length (cm)	2.87	1.14
Moliere Radius (cm)	5.22	2.07

Inner calo radius [cm]	LYSO Rejection [90% containment]	LYSO Rejection [95% containment]	LXe Rejection [90% containment]	LXe Rejection [95% containment]
8	30.155664	12.013828	8.273335	3.273581
9	36.192168	14.418734	9.482706	3.752103
10	42.779030	17.042898	10.774543	4.263256
11	49.916251	19.886323	12.148847	4.807038
12	57.603830	22.949006	13.605618	5.383451
13	65.841768	26.230949	15.144855	5.992494

A larger calorimeter inner radius improves tail fractions and fiducial volume too

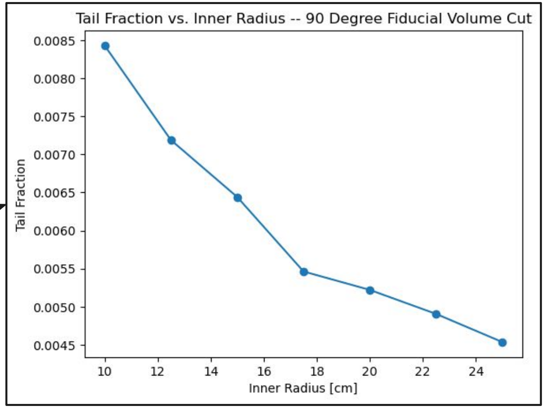


We have to make fiducial volume cuts to avoid leakage problems near the edges of the calorimeter

For a larger inner calorimeter radius:

- Better pileup rejection
- Smaller tail fraction
- Larger angular fiducial volume
- Larger volume (scales as a difference of cubes)

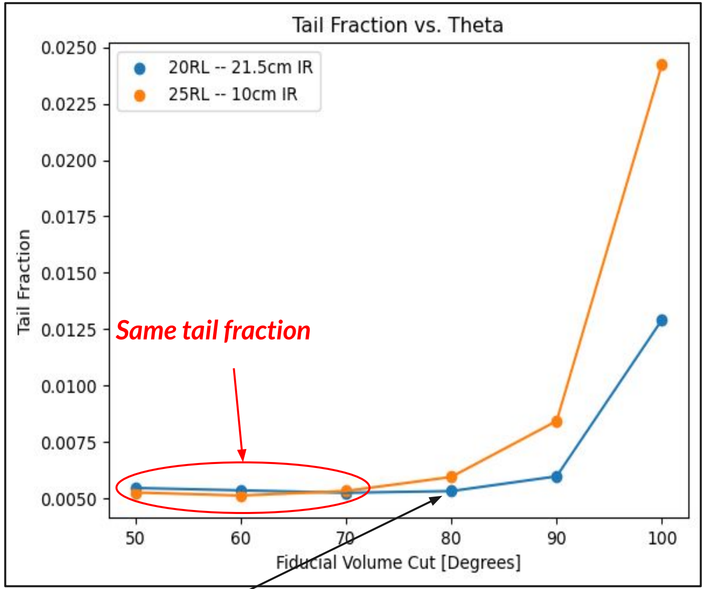
Fixed number of radiation lengths; inner radius moved back



If the calorimeter inner radius can be pushed back, there are significant advantages

For a fixed LXe volume:

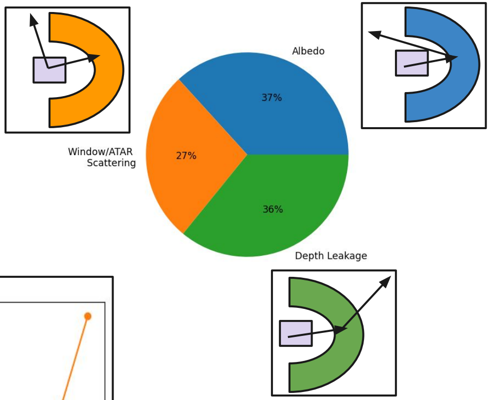
- *Radiation lengths: 25→20*
- *Inner radius: 10 cm→21.5 cm*
- **Pileup rejection increases: 11 →32**
- **Tail fraction remains constant**
- **Fiducial volume increases**

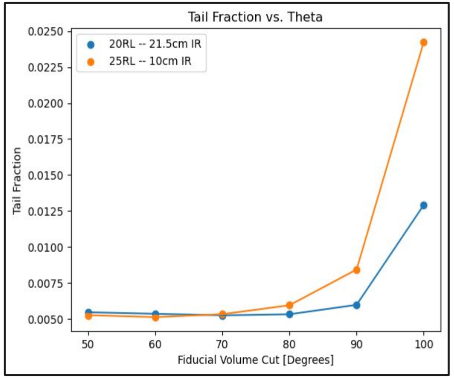


Still no change!

Discussion

- Simulation is more robust – we understand what is needed from the calo much better than a year ago
- The nominal tail fraction is only ⅓ depth leakage
- The tail fraction may be much smaller than currently claimed – Bhabha events should be removed and albedo will be verified during LYSO beam time
- Resolution may not be as important as we thought a year ago
- Segmentation provides large pileup reduction
- A larger calorimeter inner radius has huge benefits





Inner calo radius [cm]	LYSO Rejection [90% containment]	LYSO Rejection [95% containment]	LXe Rejection [90% containment]	LXe Rejection [95% containment]
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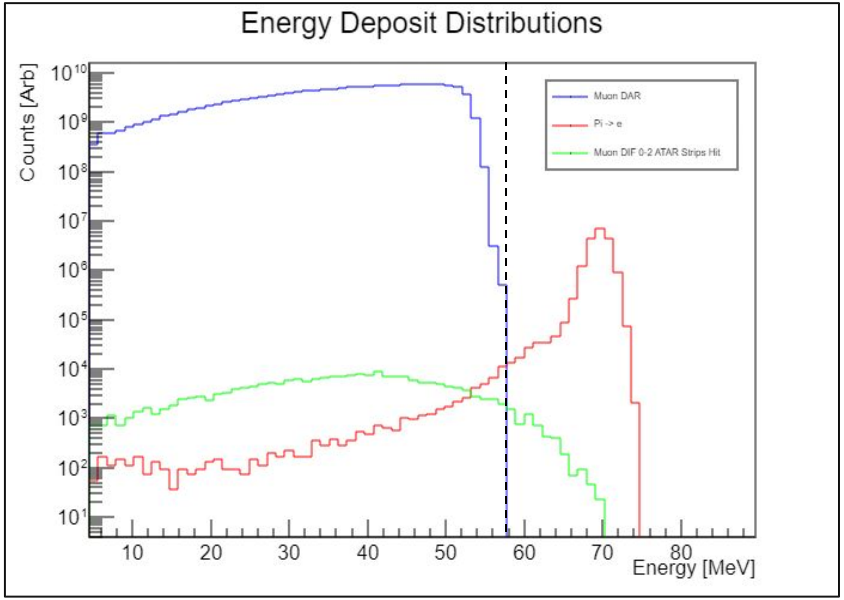
Backup slides

Energy deposit distributions

- Endpoints ***π→μ→e*** spectrum is 53 MeV whereas the e+ from ***π→e*** is sharply peaked at 69.3 MeV
    - This allows to place a cut near 58 MeV and mostly separate the two primary pion decay channels
- Real calorimeter effects distort these energy distributions from the primary pion decay channels and other events types further complicate this high/low bin strategy



What has been used? What is available?

- All non-optics PIONEER simulations have been done using the standard Geant4 physics list: BERT_QGSP
- BERT_QGSP is the standard physics list for energies up to the TeV scale with the EM0 (EM standard physics list) used for electromagnetic interactions
  - **EM0** is meant to be fast and covers a very wide range of energies
  - EM1 is the fastest EM list, but the least accurate (typically used for very high energy sim)
  - EM2/EM3 have niche applications, very similar to EM0 in the PIONEER energy range
  - **EM4/Penelope (PEN)** lists have more precise modeling of multiple scattering and more accurate stepping algorithms at the cost of increased computation time

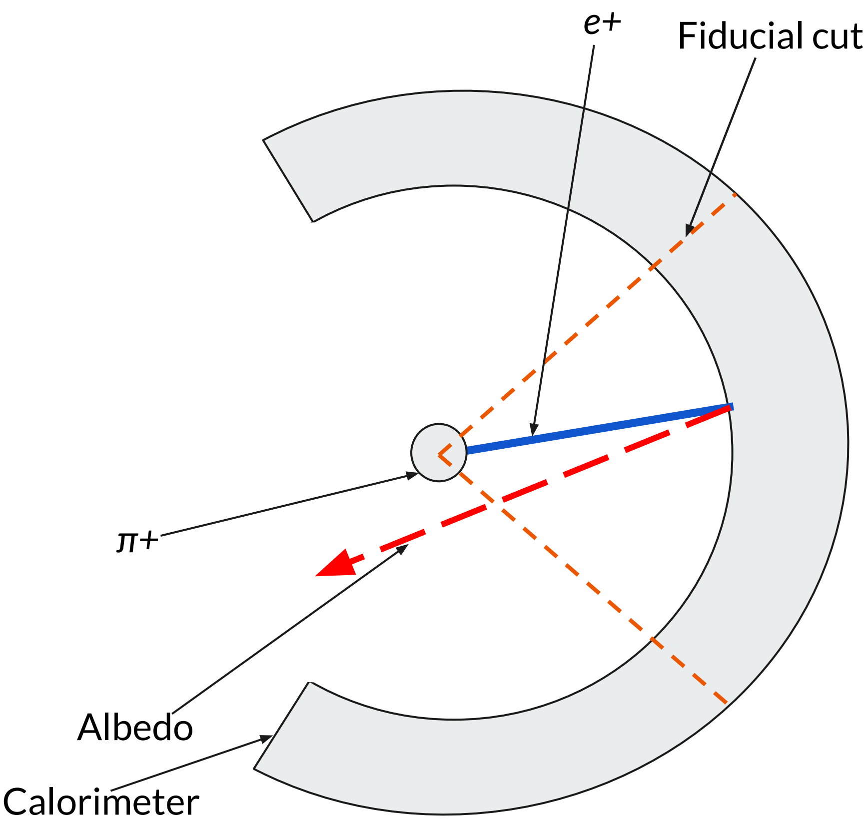
Differences in computation time

- EM0/EM1/EM2/EM3 all had similar computation times when simulating pion decays or positron beams shot into simple calorimeter volumes
- EM4/PEN took 4-5 times longer to run than less precise physics lists

Type	EM0 runtime	EM4 runtime	PEN runtime
pi+ decay	68.887 (s)	300.181 (s)	300.962 (s)
e+ beam	105.687 (s)	483.097 (s)	521.251 (s)

Toy simulation setup

- Toy simulation where pion decays to positron incident on just a calorimeter volume (and sometimes a tracker) of 25 radiation lengths
- Previously, these simulations had found very different tail fractions between different materials (i.e. LXe 2x tail compared to LYSO)
    - Ultimately, these differences were primarily attributed to different amounts of high loss albedo from different materials
- Plan: redo tests with different physics lists

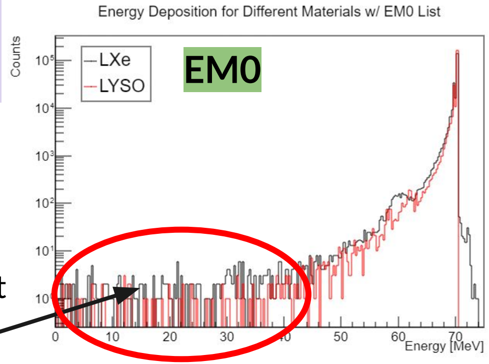


NOT TO SCALE/NO TRACKER SHOWN

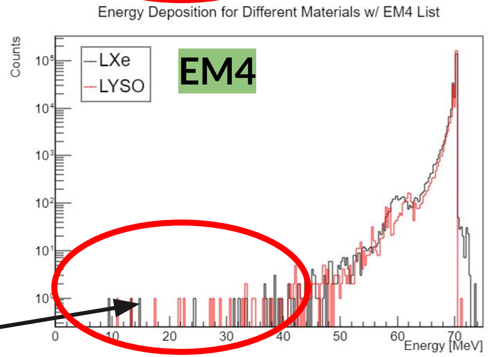
Toy simulation with different lists

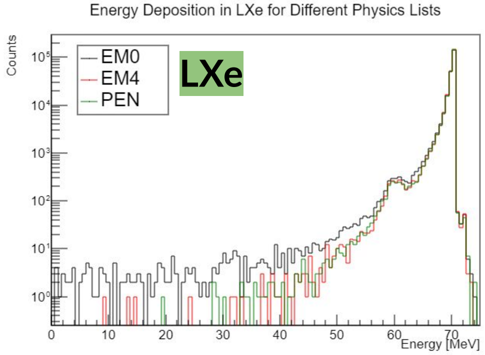
- EM0 finds a significant difference between LXe and LYSO in the tail fraction for this toy simulation with a cut at 58 MeV (0.47% for LXe and 0.26% for LYSO)
- EM4/PEN dramatically reduce the tail fraction and eliminate the difference between materials up to the difference in photonuclear bumps (tail fraction is 0.20% for LXe and 0.18% for LYSO w/ EM4). Tail fractions are nearly identical below 55 MeV between LXe and LYSO
- Within LXe, much of the difference between lists occurs in the region of the most lossy events.

Significant part of the tail is at the lowest energies. Larger tail for LXe than LYSO



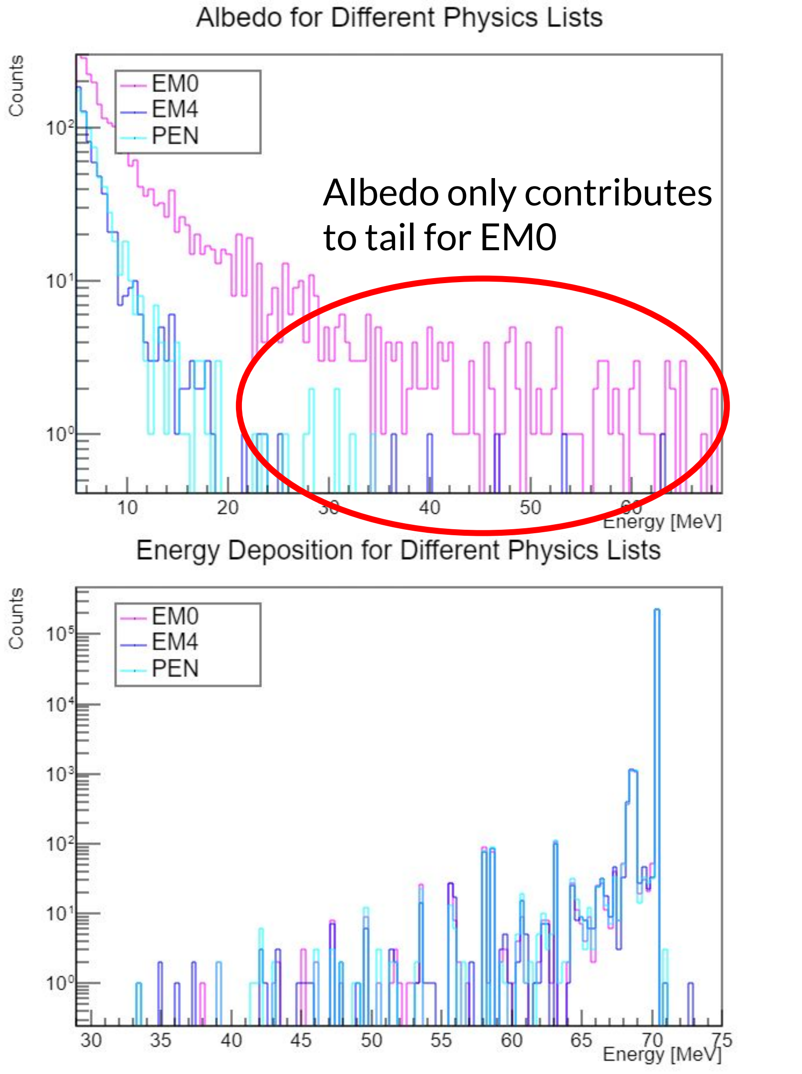
Very few events at lowest energies. Tails behave similarly for LXe and LYSO





The difference is albedo

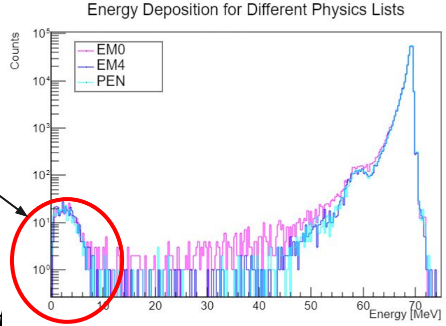
- The reduction of differences between materials and of the number of highly lossy events suggests that the physics lists might treat albedo differently
- When we track the particles exiting the front face of the calo, we find very different energy distributions between high vs. low precision lists
- There is very little difference between tail fractions from a closed calorimeter geometry (i.e. a full sphere); this suggests that albedo is the primary driver of tail fraction differences between lists

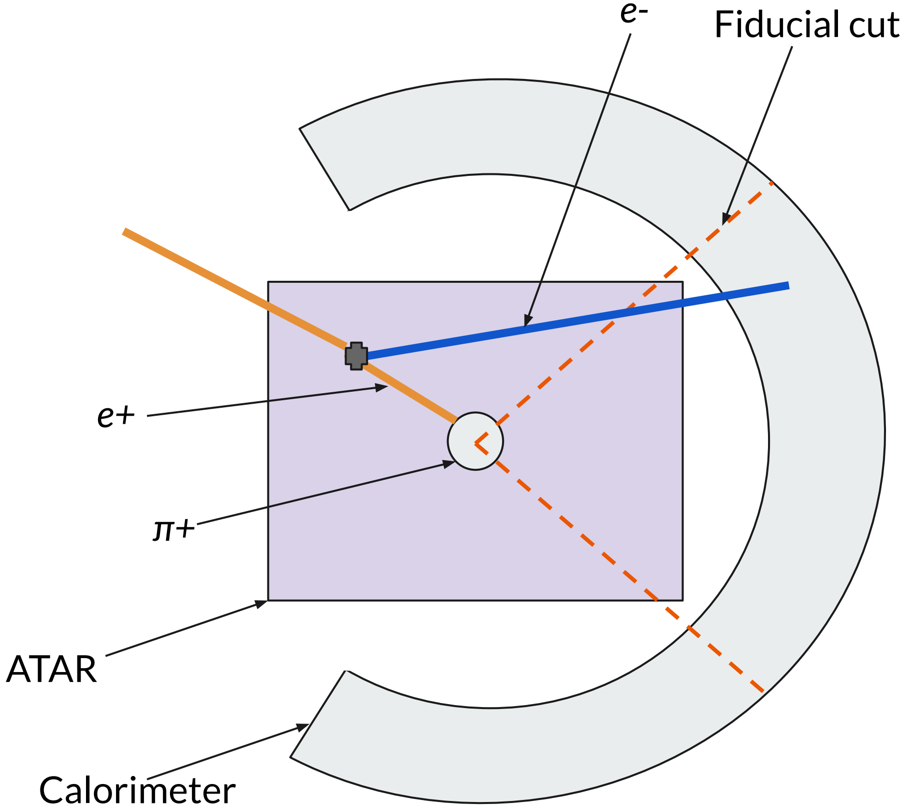


What about Bhabha scattering in the ATAR?

- Previous work using EM0 had found significant contribution to the tail fraction once the ATAR is added and a trigger is made on the first hit in the fiducial volume of the calorimeter
- We find no significant change to the bump in the tail at lowest energies assumed to be caused by Bhabha scattering in the ATAR when EM lists are varied

No difference between lists





NOT TO SCALE

Crystals with Mass Production Capability

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (°C)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
λ_{peak} [a] (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No

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