Measuring the Pion Beta Decay Rate with the PIONEER Apparatus

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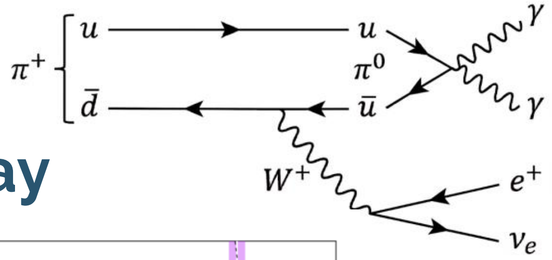
CKM Unitarity Tensions & Pion Beta Decay



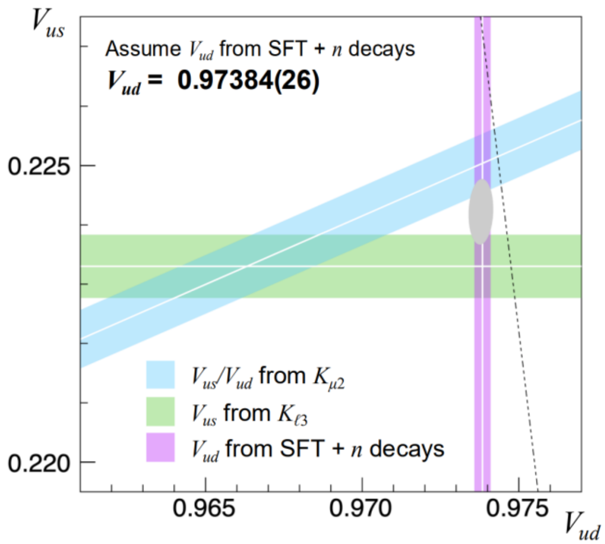
- The first row of the CKM quark-mixing matrix has a 3σ tension with unitarity
- The pion beta decay branching ratio provides a theoretically clean determination of $|V_{ud}|$

$$\Gamma_{\pi\beta} = \frac{G_\mu^2 |V_{ud}|^2}{30\pi^3}\left(1 - \frac{\Delta}{2M_+}\right)^3 \Delta^5 f(\epsilon,\Delta)(1+\delta)$$

- The PIBETA experiment measured the branching ratio to 0.64%

$$\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})} = 1.036 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.003(\pi \to e\nu) \times 10^{-8}$$

$$V_{ud}^{\pi} = 0.97386(281)_{BR}(9)_{\tau_\pi}(14)_{\Delta_R^\pi}(28)_{\Delta_f}[283]_{total}$$



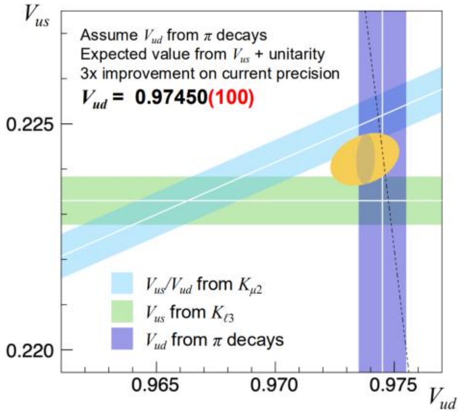
Decay Mode	Branching Ratio
$\pi^+ \to \mu^+ \nu_\mu$	$(99.98770 \pm 0.00004)\%$
$\pi^+ \to \mu^+ \nu_\mu \gamma$	$(2.00 \pm 0.25) \times 10^{-4}$
$\pi^+ \to e^+ \nu_e$	$(1.230 \pm 0.004) \times 10^{-4}$
$\pi^+ \to e^+ \nu_e \gamma$	$(7.39 \pm 0.05) \times 10^{-7}$
$\pi^+ \to \pi^0 e^+ \nu_e$	$(1.036 \pm 0.006) \times 10^{-8}$
$\pi^+ \to e^+ \nu_e e^+ e^-$	$(3.2 \pm 0.5) \times 10^{-9}$

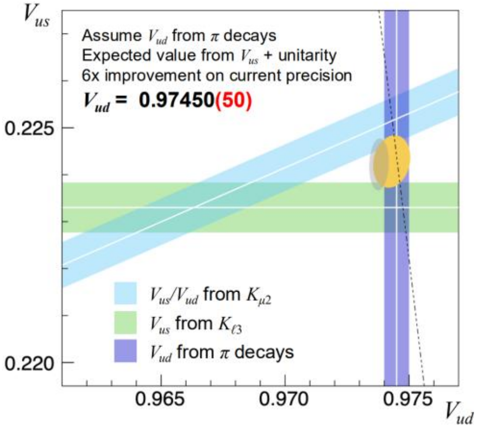
pi-e-nu & pi-beta refer to channels
PIONEER & PIBETA refer to experiments

PIONEER pi-beta goals

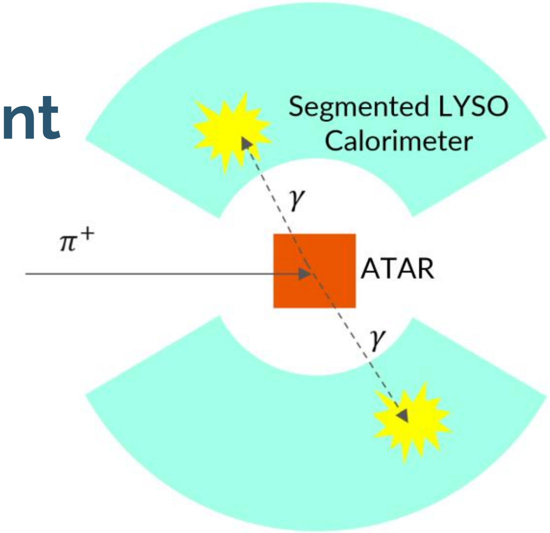
- Factor of 3 improvement: 6.25×10^5 events
  - Comparable with current uncertainty on the value from neutron decay
  - PSI πE5 beam line at 10^7 Hz
  - Higher momentum than Phase I (about 85 MeV/c) and momentum bite ($\Delta p/p = 3\%$). PIBETA ran at 115 MeV/c
- Factor of 6 improvement: 2.25×10^6 events
  - Comparable with expected uncertainty from neutron decay
  - Will need higher beam rate and/or more time

Method		Value	Uncertainty
Superallowed β Decays (SFT)	Old nuclear structure uncertainty	0.97367	± 0.00032
	New nuclear structure uncertainty		± 0.00055
Neutron Decay	With current tensions in g_A/g_V asymmetry	0.97430	± 0.00088
	With best measurements	0.97402	± 0.00042
Pion Beta Decay	Current Value	0.97386	± 0.00283
	3x Improvement		± 0.00099
	6x Improvement		± 0.00057
	10x Improvement		± 0.00043
SFT + n Decay	Best Values	0.97379	± 0.00026



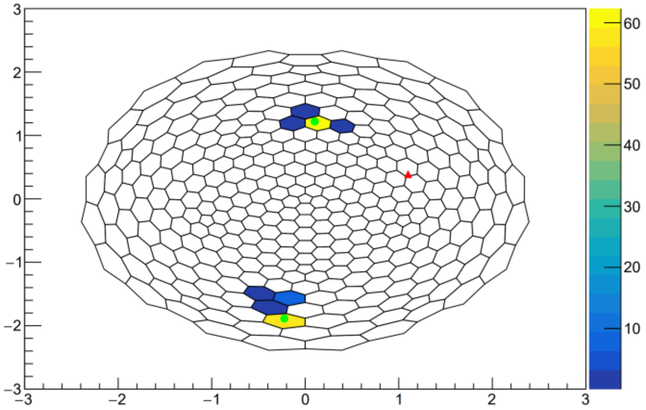


Plan for a PIONEER pi-beta Measurement



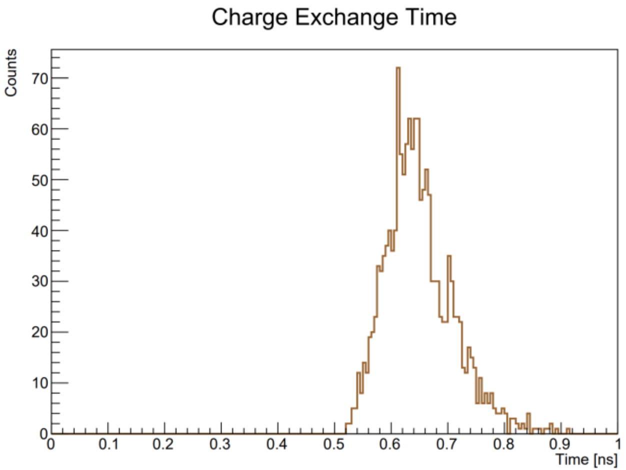
- The neutral pion from pion beta decays rapidly (8.5×10^{-17} s) to two, nearly colinear, time coincident, photons.
- They can be identified by the invariant mass $\sqrt{2E_1E_2(1 - \cos\alpha)} = 134.9769\ MeV$
- Gammas will be identified by the charge particle tracker

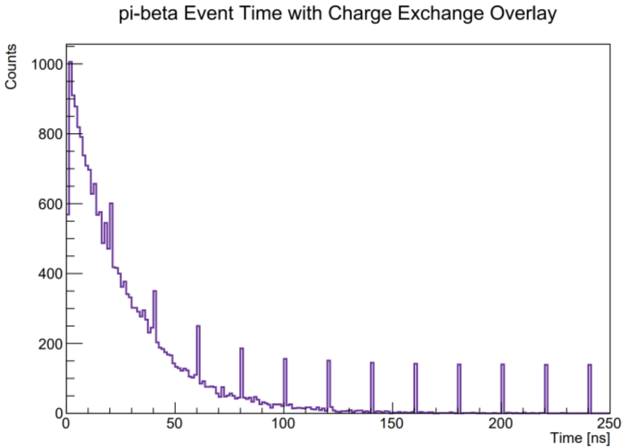
- Segmentation is necessary to distinguish gammas from each other and coincident particles
- A high density is necessary to limit pileup events that cannot be distinguished from the gammas



Charge Exchange Events

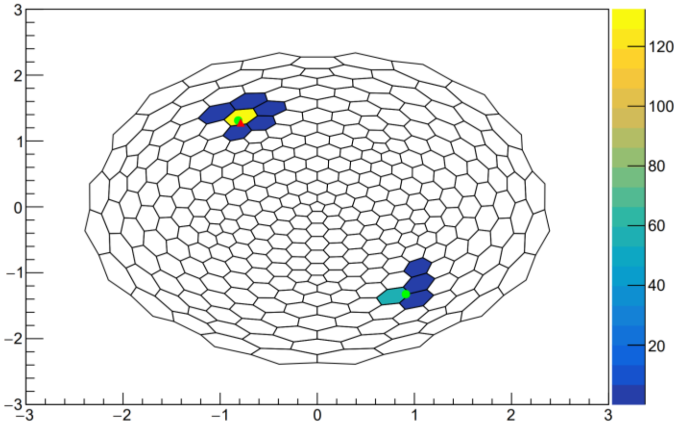
- Pion charge exchange $\pi^+ + n \rightarrow \pi^0 + p$ looks like pion beta decay in the calorimeter
- Charge exchange events occur very promptly (top)
- A 1 or 2 ns cut around RFs with upstream pion events would remove 100% of charge exchange events
- These cuts would retain 77% to 95% of the pion beta decay events, depending on the size of the cut and overall window
- Improved hardware, software and timing resolutions will essentially remove the 0.26% systematic error from the PIBETA experiment (their largest internal systematic)
- Alternatively, pion charge exchange in our system could be measured and subtracted from pi-beta time spectrum (bottom, charge exchange peaks not to scale)

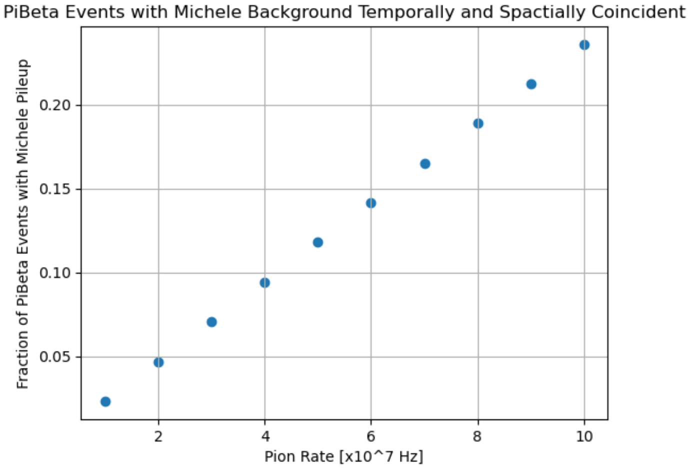




Spatially and Temporally Coincident Michels

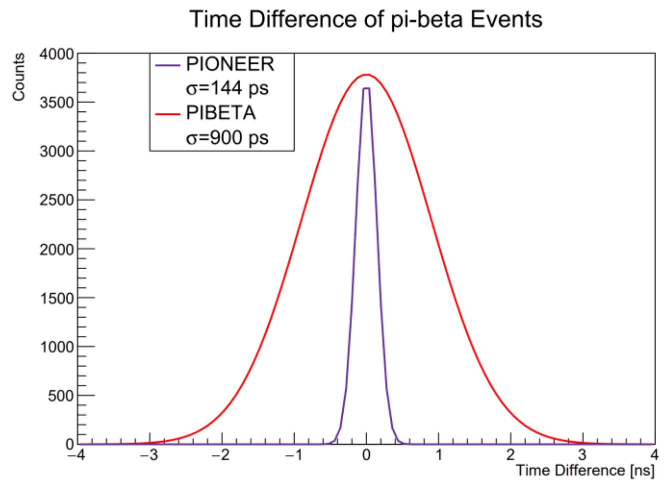
- Michels that overlap in time and space with the pi-beta gammas do hinder identification
- This results in a high energy charged particle cluster and a 65 MeV neutral cluster
- The gamma energy is higher than radiative decays and the pileup cluster can have abnormally high energy (for high-energy Michels)
- This can be measured, and a correction made
- The fraction of events with this effect is rate-dependent

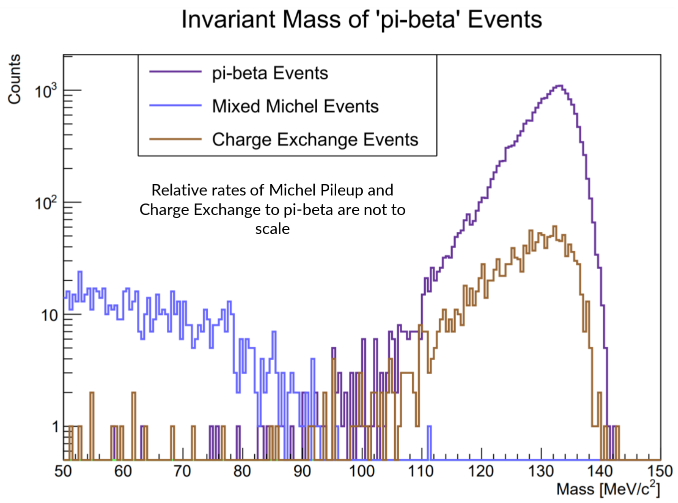




Systematic Improvements

- The timing resolution of the PIONEER calorimeter is 10 times better than in the PIBETA experiment
  - Allows for the removal of the hardware time cut PIBETA used to eliminate charge exchange events, a dominant source of uncertainty
- ATAR allows for extremely precise reconstruction of the pion stop location
  - Reduces uncertainty in angle α and geometric fiducial acceptance
- Various improvements minimize the tail of the pi-beta distribution

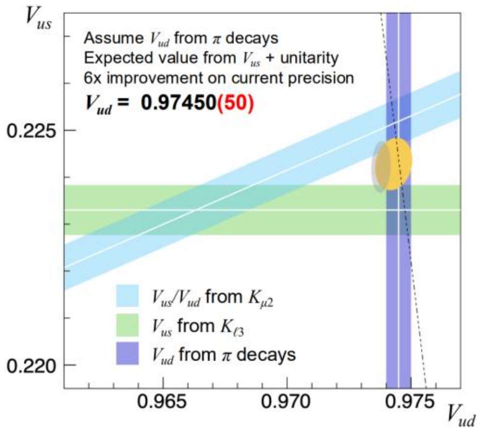


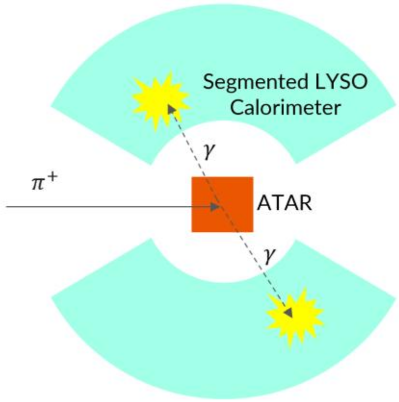


Normalization

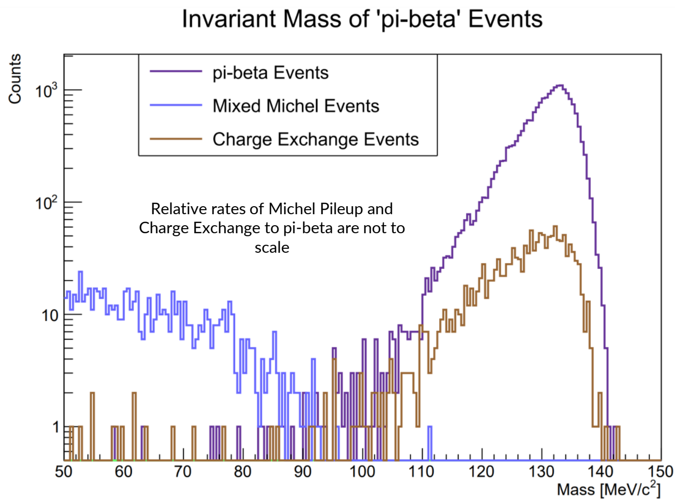
- PIBETA normalized to pi-e-nu, but the efficiency of pi-e-nu identification at a high rate has yet to be investigated
- The Phase I improvements to the pi-e-nu branching ratio removes a dominant uncertainty and our ATAR will improve the tail determination
- Normalization to total pion count has been discussed as an alternative

Conclusion & Summary





- Pion Beta Decay is the theoretically cleanest path to resolve the tension in the first row of the CKM matrix, but it is currently limited by experimental uncertainty
- PIONEER has many systematic improvements over the PIBETA design, especially the LYSO calorimeter and ATAR with 5D tracking
- More work is needed to develop and refine the normalization strategy for a pi-beta measurement



With reasonable assumptions, a 3x improvement could be achieved in 7 months of running, and a 6x improvement could be achieved in 3 years of running

References

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Backup Slides

Time Needed

- Event Goal: 6.25×10^5 pi-beta Events
    - 3 times statistical improvement
- Beam Rate: 10^7 Hz
- Uptime: 80%
- Geometric Acceptance: 50%
- Time Acceptance: about 80% (77% to 95%)

7.1 Months of Running

- The feasibility of running at higher rates is currently dependent on the normalization. If the normalization is feasible, there are no significant rate limits from the pi-beta signal. Thus 6 times improvement would be possible in under 5 years of running

Preliminary Precision Requirements

- pi-e-nu Branching Ratio Uncertainty: 0.01% (PIONEER Phase 1 Goal)
- Time and Geometric Acceptance Uncertainty: High Precision
    - These uncertainties were dominant in the PIBETA experiment, but due to improved timing resolution, software capabilities, and our ATAR to determine the pion stopping distribution, they can be greatly improved
- Dalitz Correction Uncertainty: 0.03% (Current Value)
- Photonuclear Correction Uncertainty 0.1% (Likely can be improved)
- pi-e-nu Normalization Statistical Uncertainty: 0.001%
- pi-beta Statistical Uncertainty: 0.13%
- pi-e-nu Normalization Systematic Uncertainty: 0.08% (Not yet investigated at this rate)
- pi-beta Systematic Uncertainty: 0.08% (Seems reasonable given current simulations)

PIONEER Experiment Uncertainty: 2.1×10^{-11}

PIBETA Experiment Uncertainty: 6.4×10^{-11}

Systematic uncertainties on the photonuclear correction, pi-e-nu normalization and pi-beta identification must be under 0.05% for 6x improvement

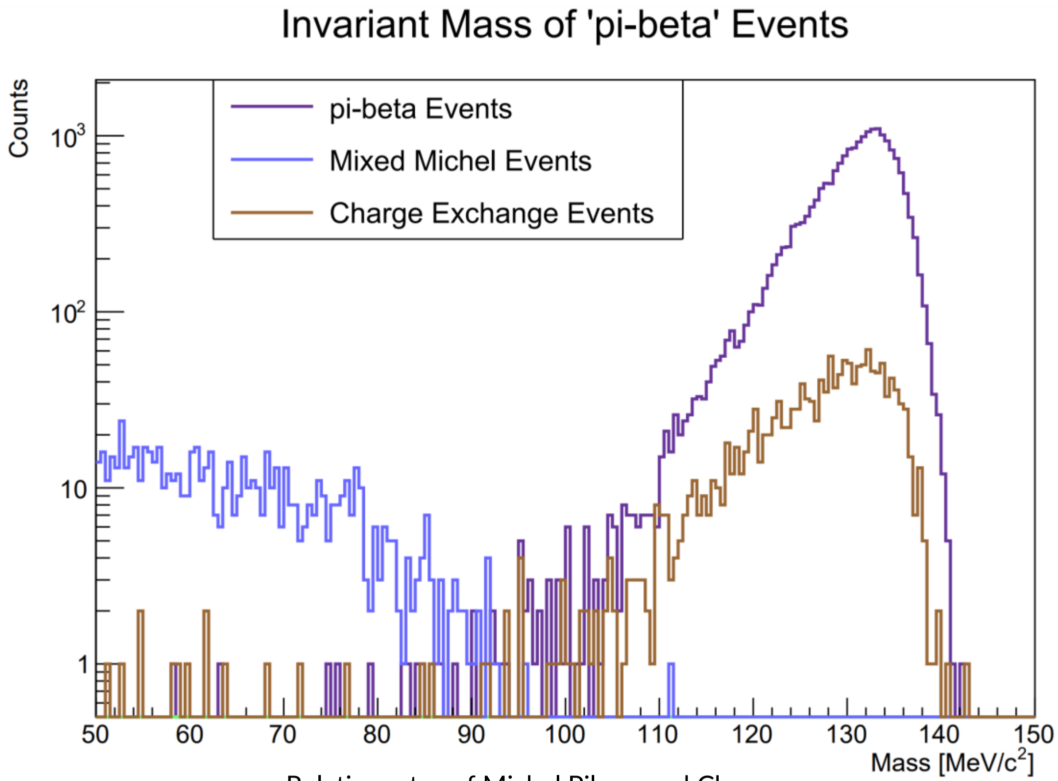
Identifying pi-beta Events

- Mass > 90 MeV
- Opening Angle > 130°
- Time Difference < 0.8 ns
- Time < 250 ns

Sensitivity: 99.94%
Specificity: 100%

The tracker will help as well

Sensitivity could be improved by making a correction for the pi-beta tail



Relative rates of Michel Pileup and Charge Exchange to pi-beta are not to scale

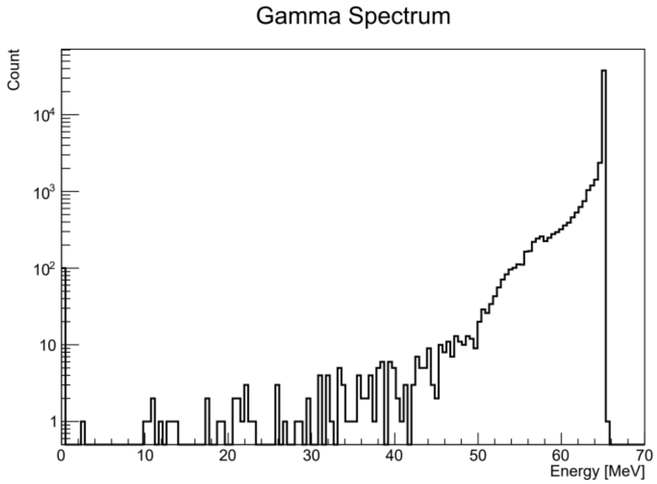
PIONEER

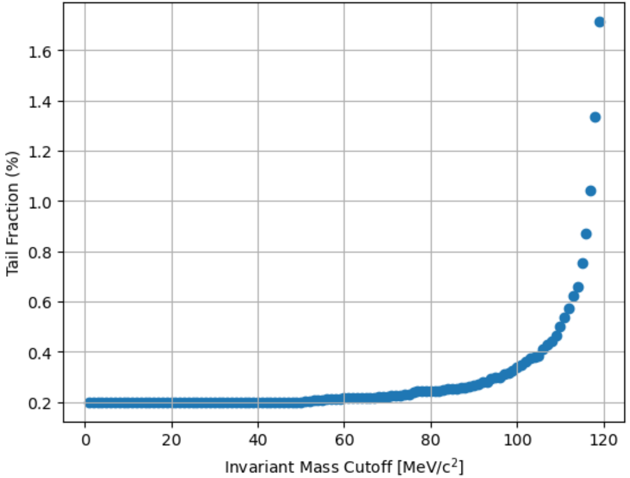
Michel Pileup

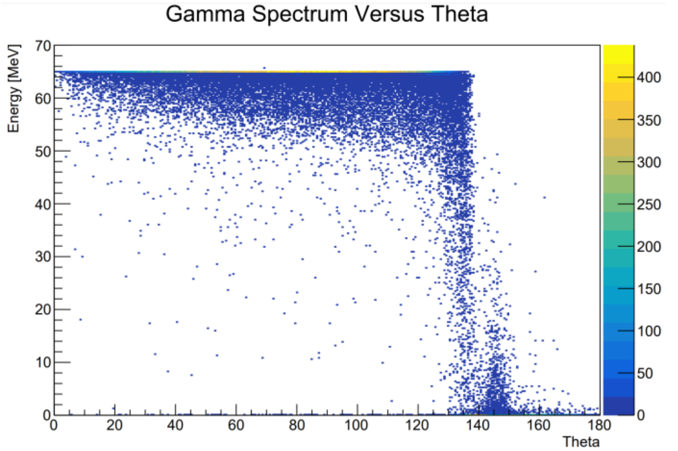
- Michel pileup events are never identified as pi-beta events because of the tracker and the invariant mass cut
- Since only one pi-beta event occurs at a time, only the combination of clusters with the closest invariant mass is counted. Thus, a Michel event in the calorimeter usually does not hinder pi-beta identification
- Since the presence of Michels does not hinder pi-beta identification, we can capture pi-beta events over the entire time range (0-250 ns)

pi-beta Tail Fraction

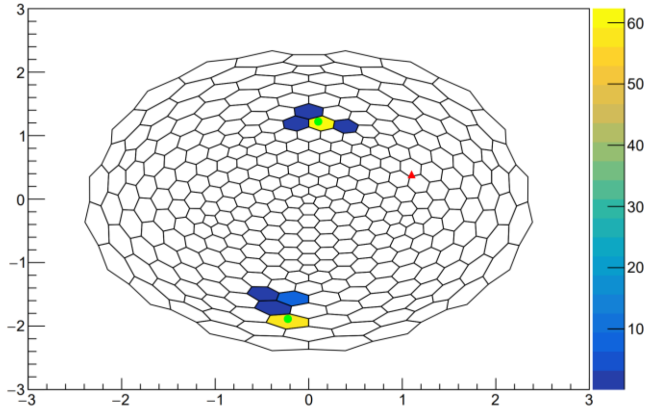
- Simulation conducted using an isotropic 65 MeV gamma source
- Invariant mass calculated assuming 180° opening angle and 65 MeV second gamma
- Spectrum and tail fraction show only fiducial events







Necessary Calorimeter Properties



- Segmentation is necessary to distinguish gammas from each other and coincident particles
- A high density is necessary to limit pileup events that cannot be distinguished from the gammas
- Given the high probability of spatial overlap, a liquid xenon calorimeter is not feasible for this measurement

Calorimeter	Inner Radius	Molière Radius	Calo Surface Area*	pi-beta Area	Overlap Probability
PIBETA CsI	26 cm	3.5 cm	8495 cm^2	308 cm^2	3.6%
PIONEER LYSO	15 cm	2.07 cm	2827 cm^2	108 cm^2	3.8%
PIONEER LXe	15 cm	5.22 cm	2827 cm^2	685 cm^2	24.2%

Preliminary Cuts

- Pion stop in ATAR
- Pion stop location is known
- No Photonuclear Interactions
- No Dalitz Decay ($\pi^0 \rightarrow e^+e^-\gamma$)
- At least two clusters with energy > 10 MeV
- All high energy clusters within fiducial volume

Angular Resolution & Pileup Suppression

- 95% of energy is contained in two Molière radii
- Angular resolution of the calorimeter is dependent on the Molière radius (R_M) of the calorimeter and the inner radius of the calorimeter (r)
- The remaining surface area can be used for pileup suppression