Simulation of Pileup in the Liquid Xenon Calorimeter

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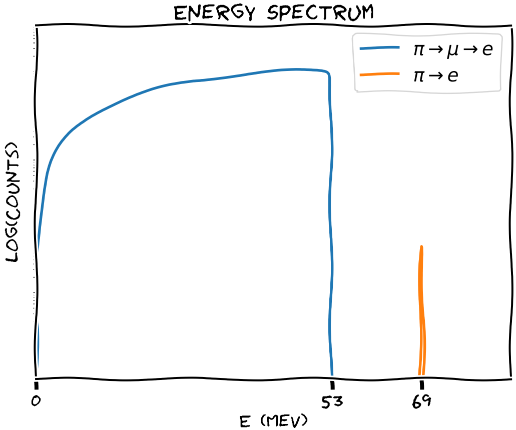
Rare Pion Decay Workshop

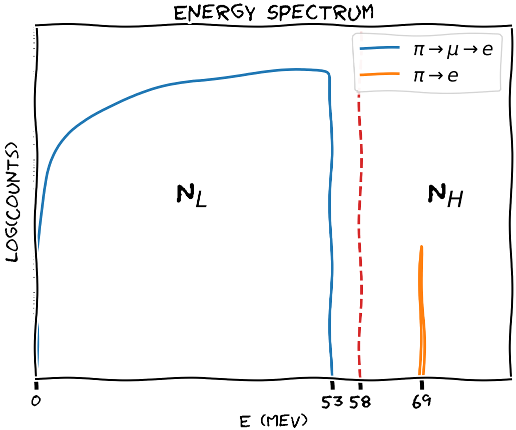
Overview

The Goal



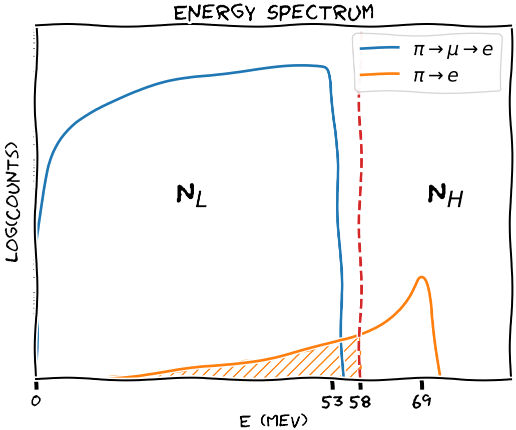
$$R_{e/\mu} = \frac{\Gamma(\pi \to e(\gamma))}{\Gamma(\pi \to \mu(\gamma))}$$

How to Reach our Goal



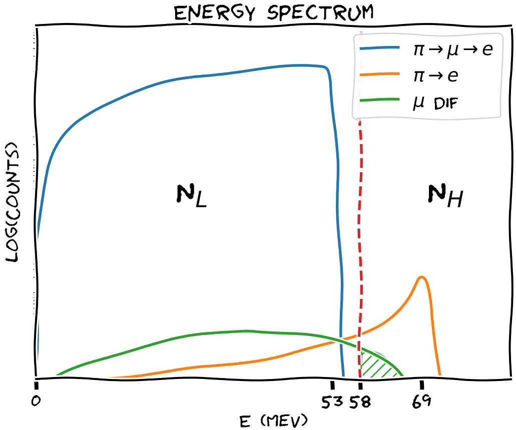
$$R_{e/\mu} = \frac{N_H}{N_L}$$

The Devil in the (de)Tail



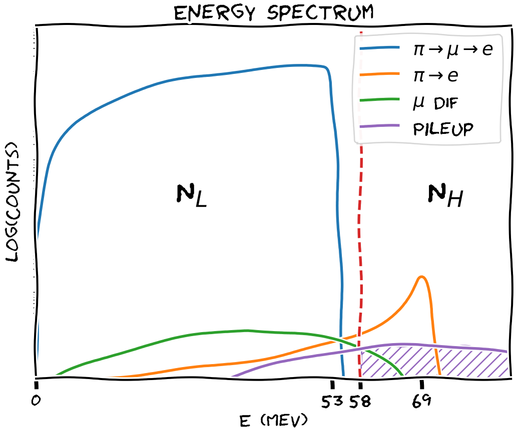
$$R_{e/\mu} = \frac{N_H}{N_L}(1 + c_T)$$

Another known Devil: Muon Decay in Flight



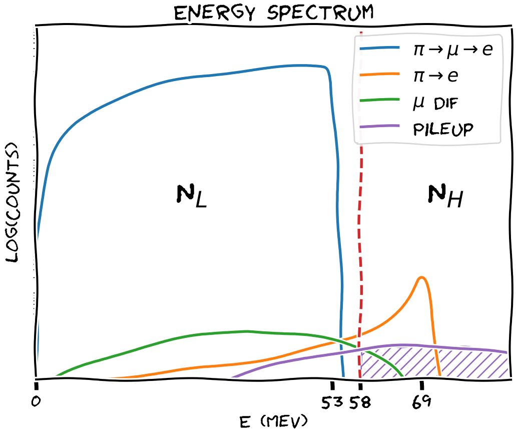
$$R_{e/\mu} = \frac{N_H}{N_L} \frac{1 + c_T}{1 + \boldsymbol{c_{DIF}}}$$

Devils Piling Up



$$R_{e/\mu} = \frac{N_H}{N_L} \frac{1 + c_T}{1 + c_{DIF} + \boldsymbol{c_{PU}}}$$

Keeping the Corrections under Control

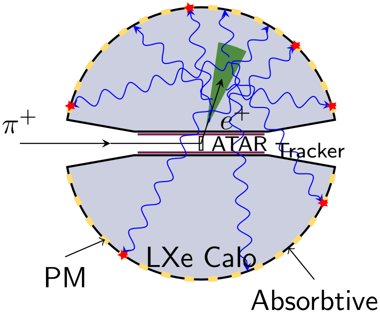


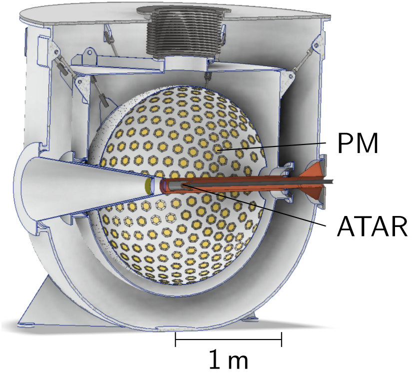
$$R_{e/\mu} = \frac{N_H}{N_L} \frac{1 + c_T}{1 + c_{DIF} + c_{PU}}$$

To Reach our Sensitivity Goal

	Value	Precision
$R_{e/\mu}$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-8})$
N_L	$\mathcal{O}(1)$	$\mathcal{O}(10^{-4})$
N_H	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-8})$
c_T	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-4})$
c_{DIF}	???	$\mathcal{O}(10^{-4})$
c_{PU}	???	$\mathcal{O}(10^{-4})$

From Pion Decay to Photon Detection



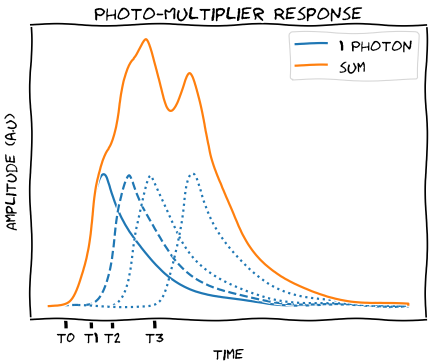


Track optical photons from creation to absorption. Register times of photo-multiplier hits for post-processing.

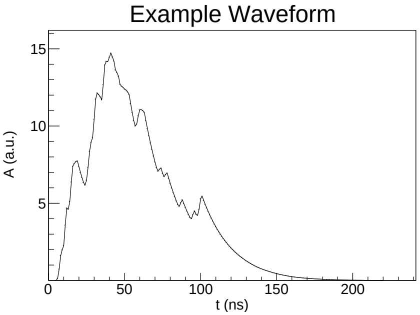
From Photon Counting to Electronic Signal

For each Photomultiplier

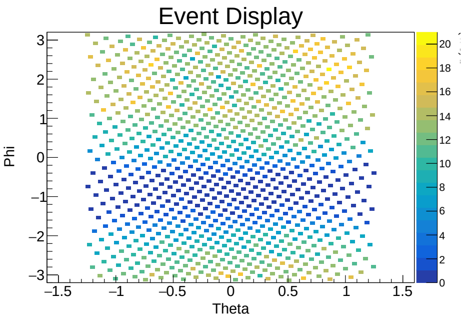
- Estimate the single photon response
- Consider Photon Detection Efficiency
- Convolve hit times with single photon response



A Possible Event



Charge Distribution

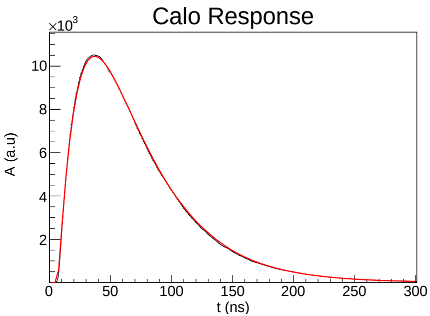


Position reconstruction will be extremely hard

From Electronic Signal to Reconstructed Event

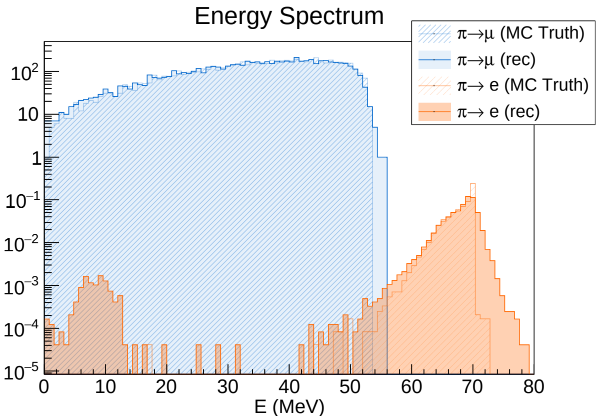
Event Reconstruction

- Sum all PM Waveforms
- Fit 1 Hit Template
  Parameters: Q, t
- Fit satisfying?
  yes finish
  no try additional hit



$t = 0$ $Q = 901.4$

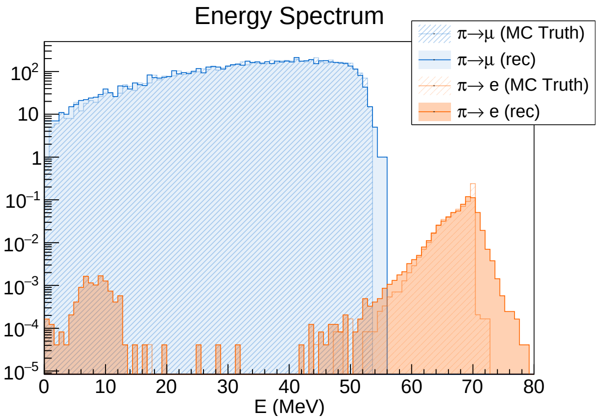
Reconstructed Spectrum



Tail Fraction (< 58 MeV)

MC Truth:	0.7 %
Rec. Energy:	3.1 %

Reconstructed Spectrum



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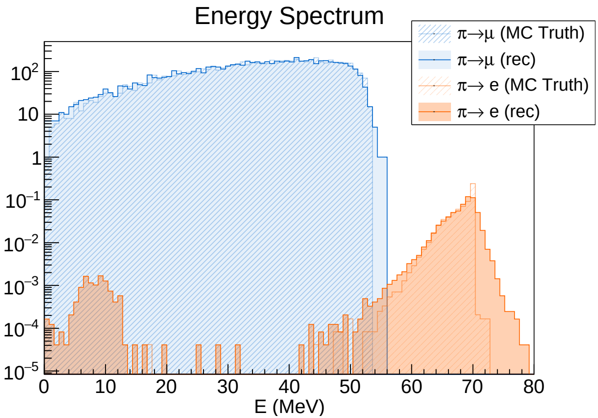
What went wrong?

- 4.5 times increased tail

Reconstructed Spectrum



Tail Fraction (< 58 MeV)

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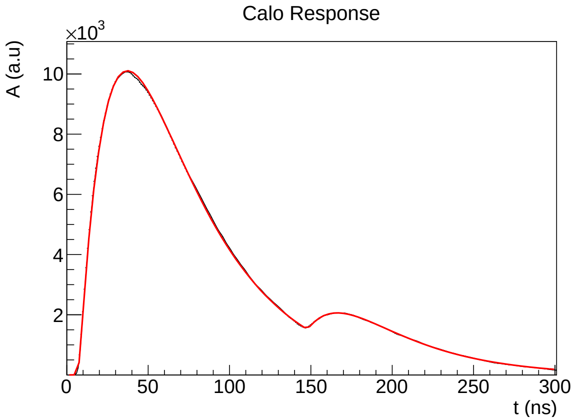
Rec. Energy:	3.1 %

What went wrong?

- 4.5 times increased tail
- What are those 10 MeV events?!

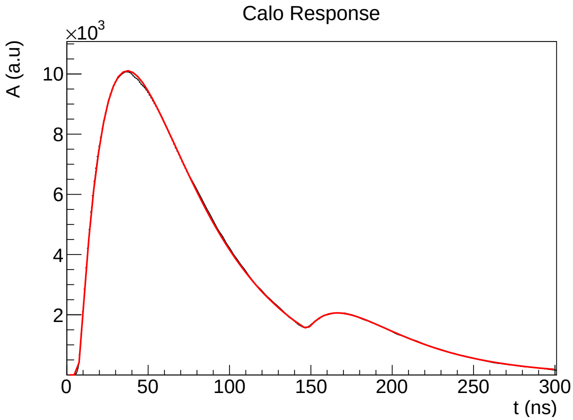
How many Events do your Analyser Eyes See?



Fit Result

1. $t_0 = 0.1, E_0 = 60\,\text{MeV}$
2. $t_1 = 140, E_1 = 7\,\text{MeV}$

How many Events do your Analyser Eyes See?



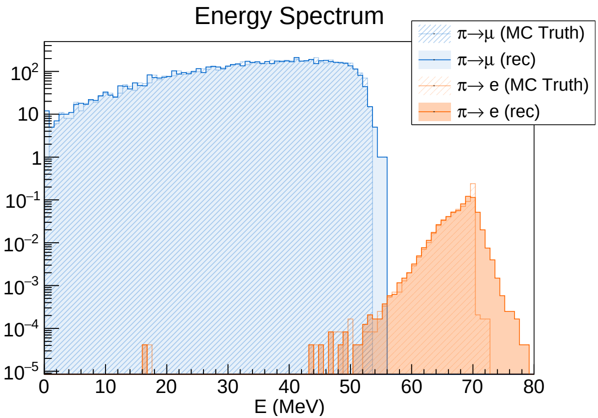
Fit Result

1. $t_0 = 0.1, E_0 = 60\,\text{MeV}$
2. $t_1 = 140, E_1 = 7\,\text{MeV}$

Truth is

Nuclear Effects can result in neutron emission and delayed energy deposit.

Reassembling the partial deposits



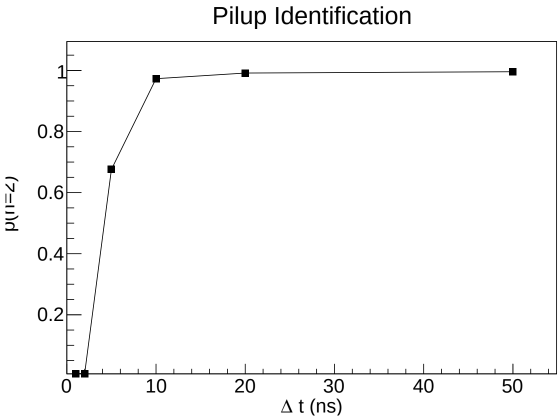
Assumption

Identify all such events and reconstruct them as one.

Tail Fraction (< 58 MeV)

MC Truth:	0.7 %
Rec. Energy:	0.8 %

What if there are really two events?



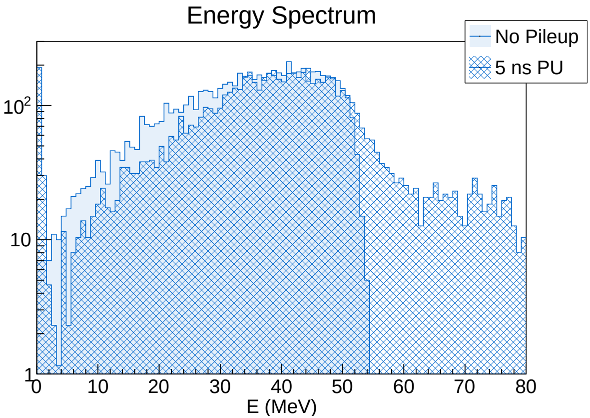
Method

Sum the detector response of two events with given delay

Efficiencies

$\sim 0\,\%$	for $\Delta t < 2$ ns
$\sim 66\,\%$	for $\Delta t \approx 5$ ns
$> 95\,\%$	for $\Delta t > 10$ ns

Distorting the Energy Spectrum



Unidentified Pileup

Reconstruct two particles with E_1 and E_2 as one with energy $E = E_1 + E_2$

Contamination

About a quarter of the unidentified PU events end up with a reconstructed energy similar to a $\pi \rightarrow e\nu$ event.

Educated Guesses on Pileup

Reminders

- Beam Rate: $R_B = 3 \times 10^5 \pi/\mathrm{s}$
- Pileup window: $T = 10\,\mathrm{ns}$

Geometrical Acceptance

- Fiducial Volume covers $\approx 3\pi$
- Calo Rate: $R_C = R_B \cdot \frac{3}{4} \approx 2.25 \times 10^5$

Poisson Statistics

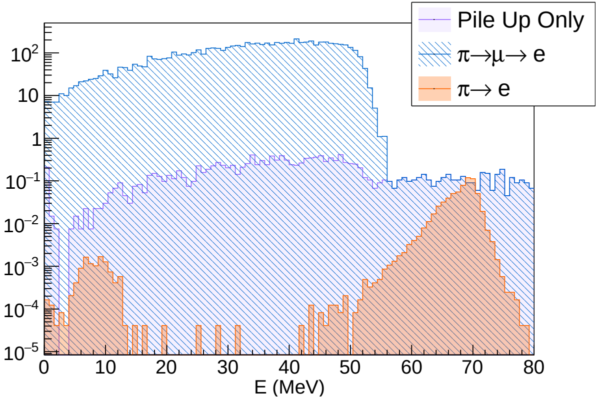
$$p(n) = \frac{(R_C \cdot T)^n e^{-R_C \cdot T}}{n!}$$

Pileup Probability

- Trigger on first decay
- Chance for a second one

$$p_{PU} \approx R_C \cdot T \approx 2.25 \times 10^{-3}$$

The Unadorned View



Contamination

Events in $\pi \to e\nu$ Region

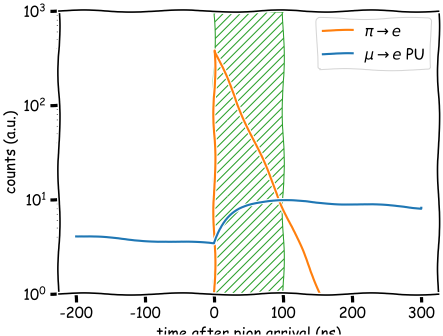
58 MeV $< E <$ 80 MeV

20 %	$\pi \to e\nu$
80 %	Pileup

Remember

Require $N_{\pi \to e\nu}$ to 10^{-4}

Selecting the Time Window



Reminder

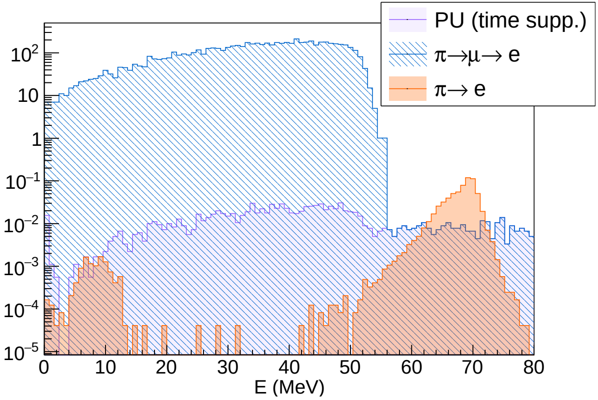
π^+ Lifetime: 26 ns
μ^+ Lifetime: 2197 ns
Expected Rate: 3×10^5 π per second

Select 100 ns After π Arrival

- 98 % of π decay
- 7 % of PU events

$\mathcal{O}(10)$ Suppression

Remaining Contamination



Slowly Getting There

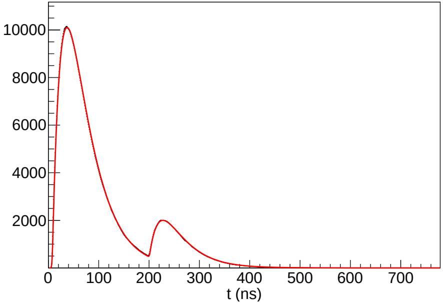
Events in $\pi \to e\nu$ Region
58 MeV $< E <$ 80 MeV

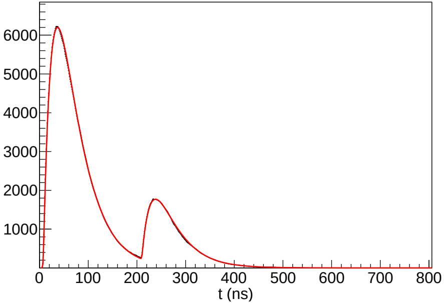
75 %	$\pi \to e\nu$
25 %	Pileup

To get to 10^{-4} uncertainty

- estimate from sidebands
- suppression from tracker

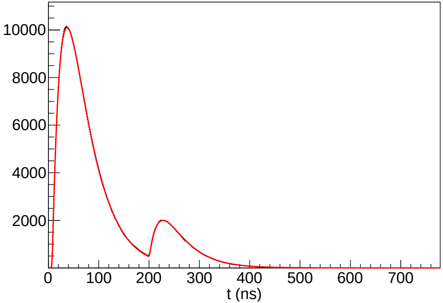
Two Kind of Reconstructed Calo Events





Two Kind of Reconstructed Calo Events

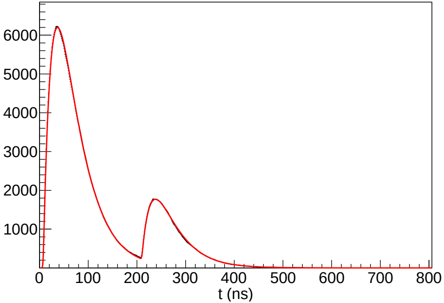
Nuclear Effects



False Identification as PU

Produce two tail events

Pile Up Effects

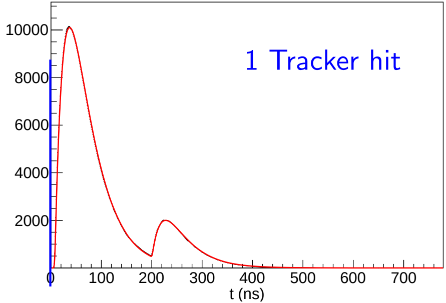


For $\Delta t < 10$ ns

Potentially identified $\pi \to e$ events

Two Kind of Reconstructed Calo Events

Nuclear Effects



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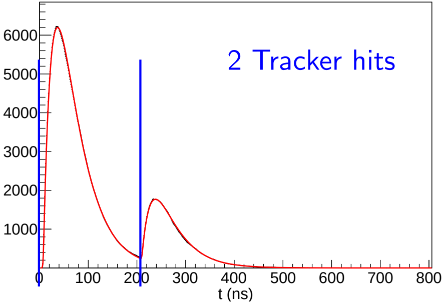


For $\Delta t < 10\,\text{ns}$

Potentially identified $\pi \rightarrow e$ events

Pileup identification

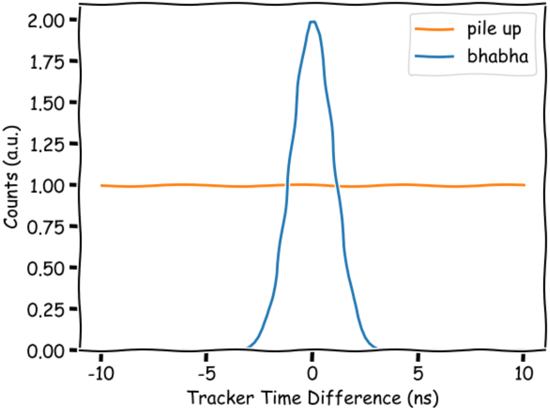
Calo on its own

- Separate pulses with time separation larger than 10 ns
- $\pi \to e\nu$ events with nuclear effects can look like two $\mu \to e\nu\nu$ events piling up
- Separation fails for shorter time differences entirely. Two Michel events can fake a signal event.

Using Tracker Information

- Most of the time, pileup will come with two tracks
- $\pi \to e\nu(\gamma)$ events will typically come with one charged track.

Dealing With Bhabha-Events



One Event, Two Tracks

Caused by interaction inside ATAR (e.g. Bhabha scattering)

- coinciding in time
- geometrical correlation?

Tracker with good resolution improves pileup suppression.

Required going forward

Event Identification

- Calo may not be able to separate Nuclear Effects from Pileup
- Require to know corrections to 10^{-4}
  - Sideband Fits
  - Suppression based on ATAR and Tracker input

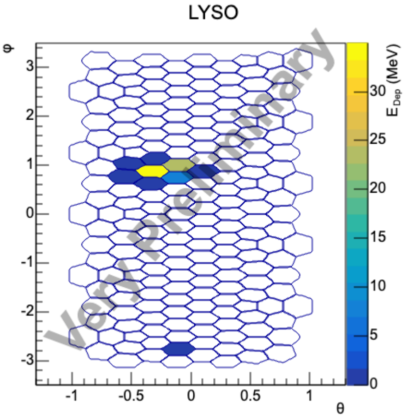
Extensive Studies of Detector Performance Needed

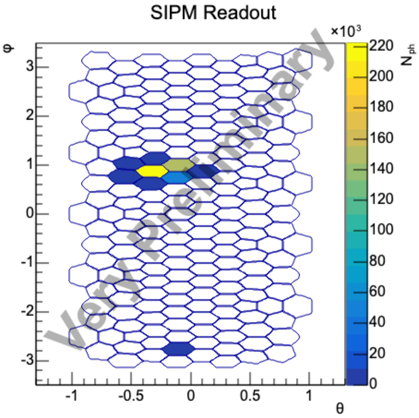
Require estimates of

- detector responses as well as background noise
- reconstruction performance and identification efficiencies

The Simulation Challenge is a good point to start

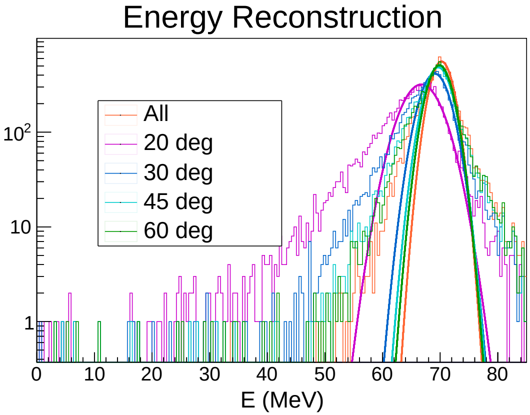
LYSO + CsI Hybrid





Shower mostly local with few escapes

LYSO Resolution



Performance

ψ	Res.	Acc.
20°	4.9 %	3 %
30°	3.4 %	7 %
45°	3.1 %	15 %
60°	2.9 %	25 %
180°	2.6 %	100 %

LXe Comparison

- Single Volume
- Resolution: 1.8 %