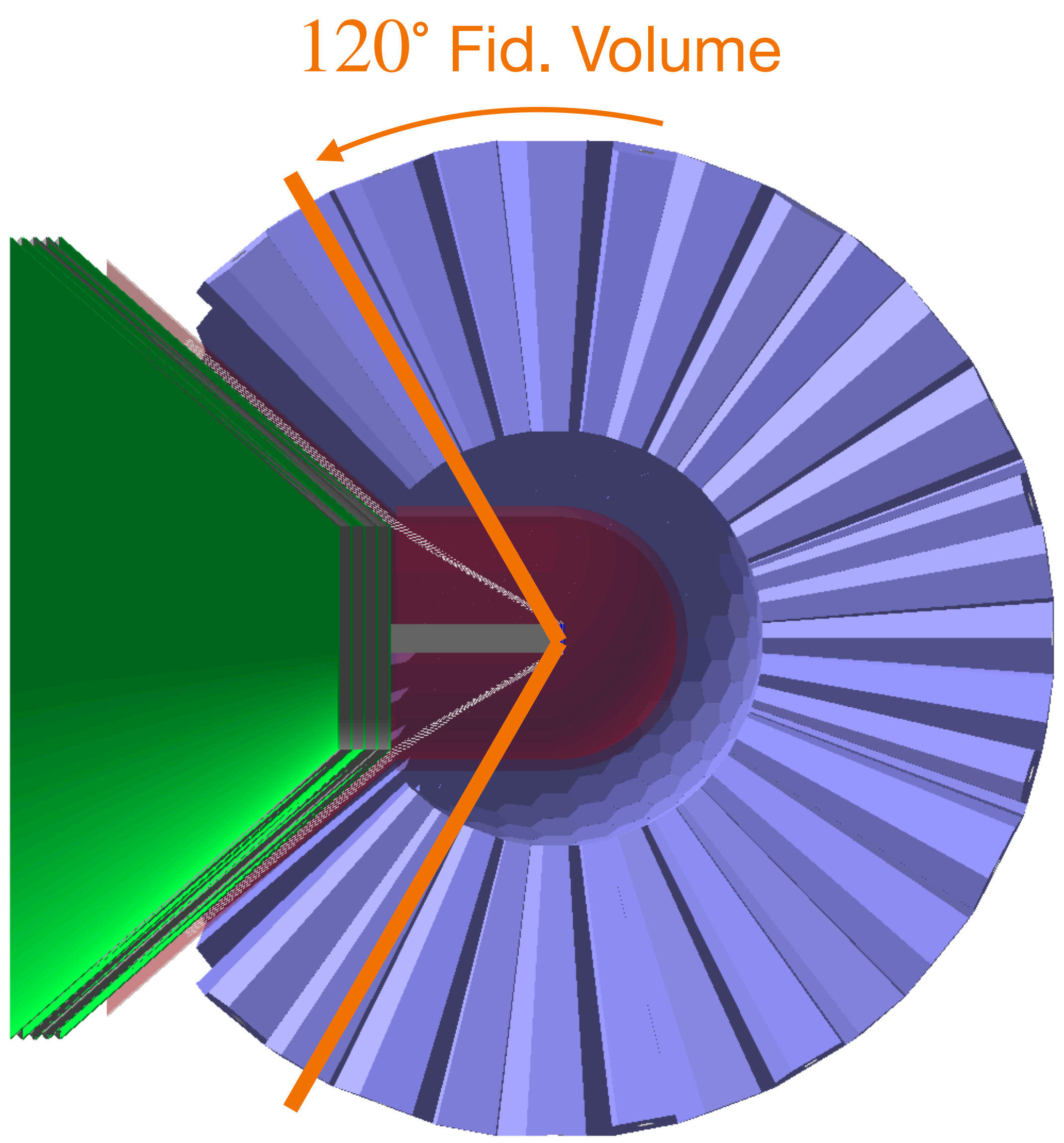
Simulation Performance

Calorimeter downselect: LXe vs LYSO

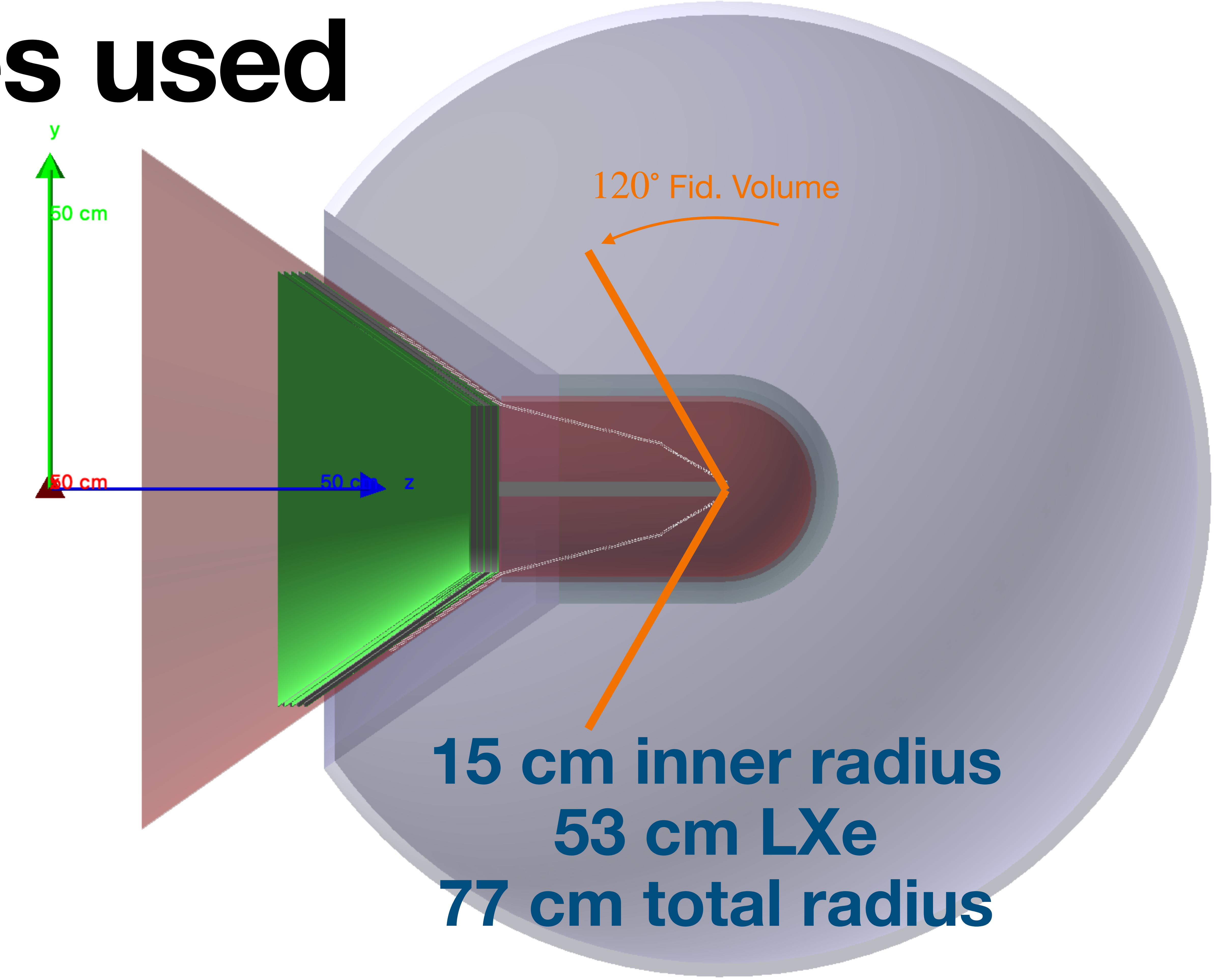
Patrick Schwendimann on behalf of the Simulation and Proto-Analysis Team, 27. Sept. 2024

Comparing the Simulation Setup

The Default Geometries used



15 cm inner radius
21 cm LYSO
42 cm total radius

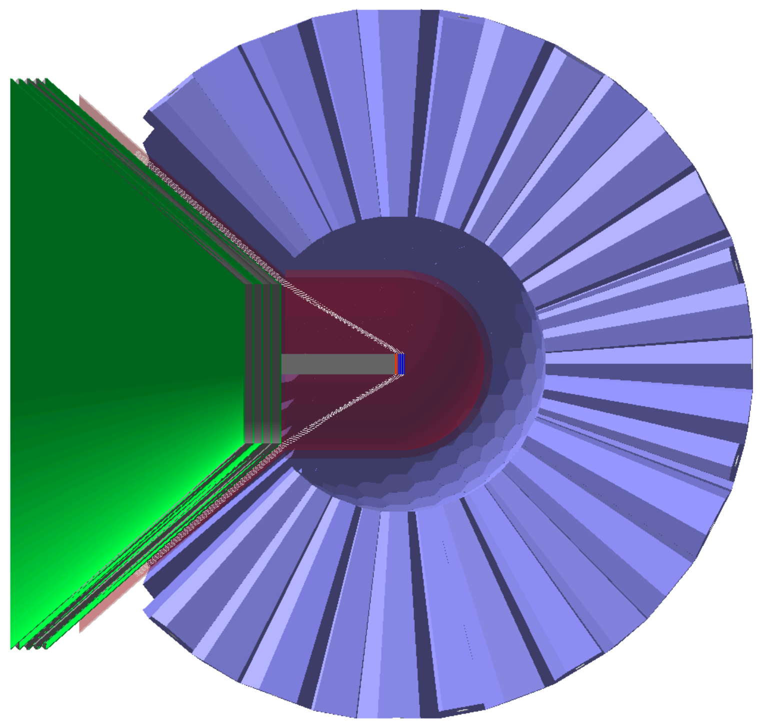


Use default ATAR, DTAR, Tracker, Halo Monitor etc.

Variation in ATAR readouts due to different spatial constraints.

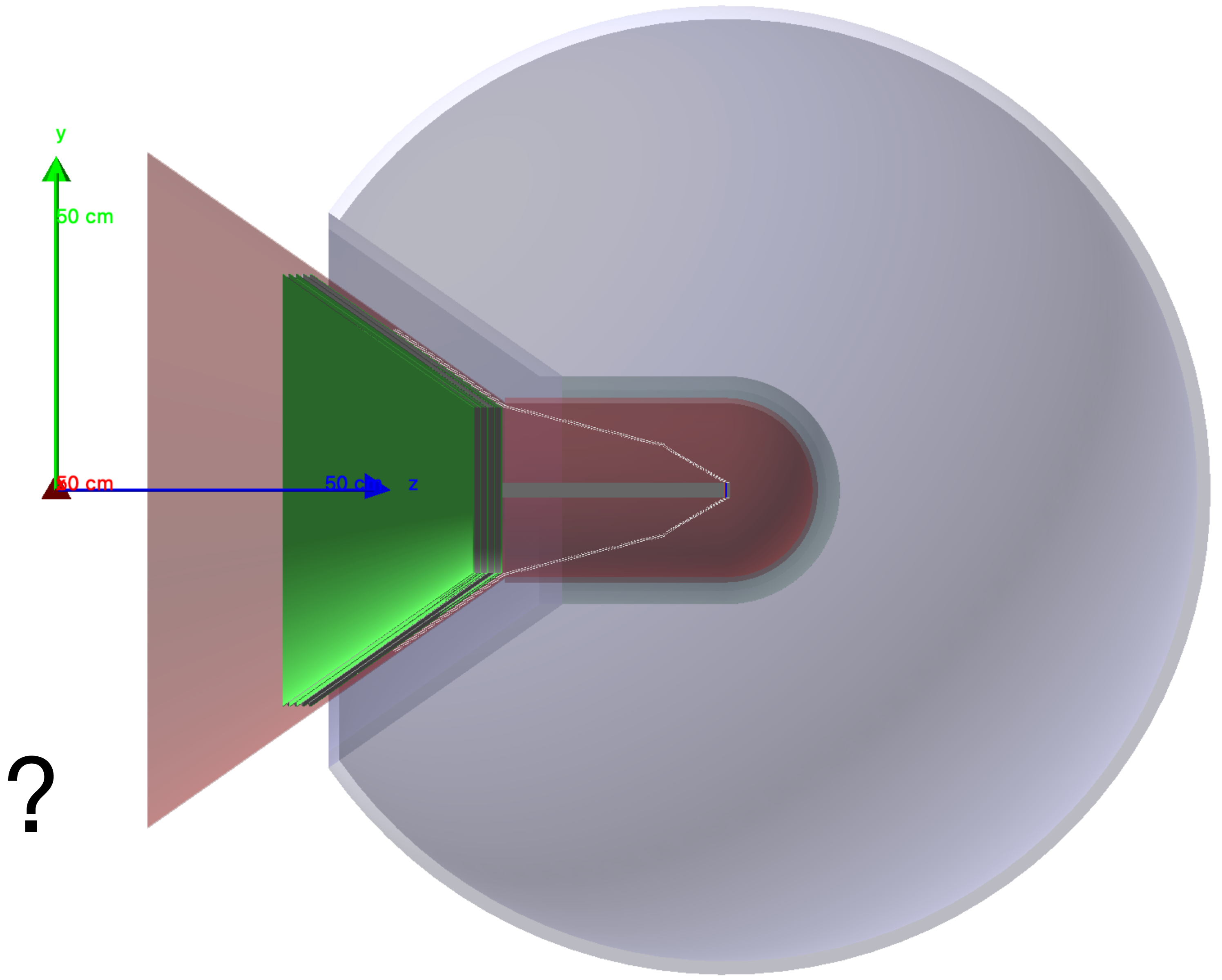
Geometry Shortcomings

… and open questions



Both

- ATAR Cable and Readout boards?



LYSO

- Entrance cone design
- Centre on Pent or Hex?

LXe

- Using tube instead of keyhole
- SiPMs plus cabling on windows

The Beam Configuration

Revisiting the proposal-based best guess beam

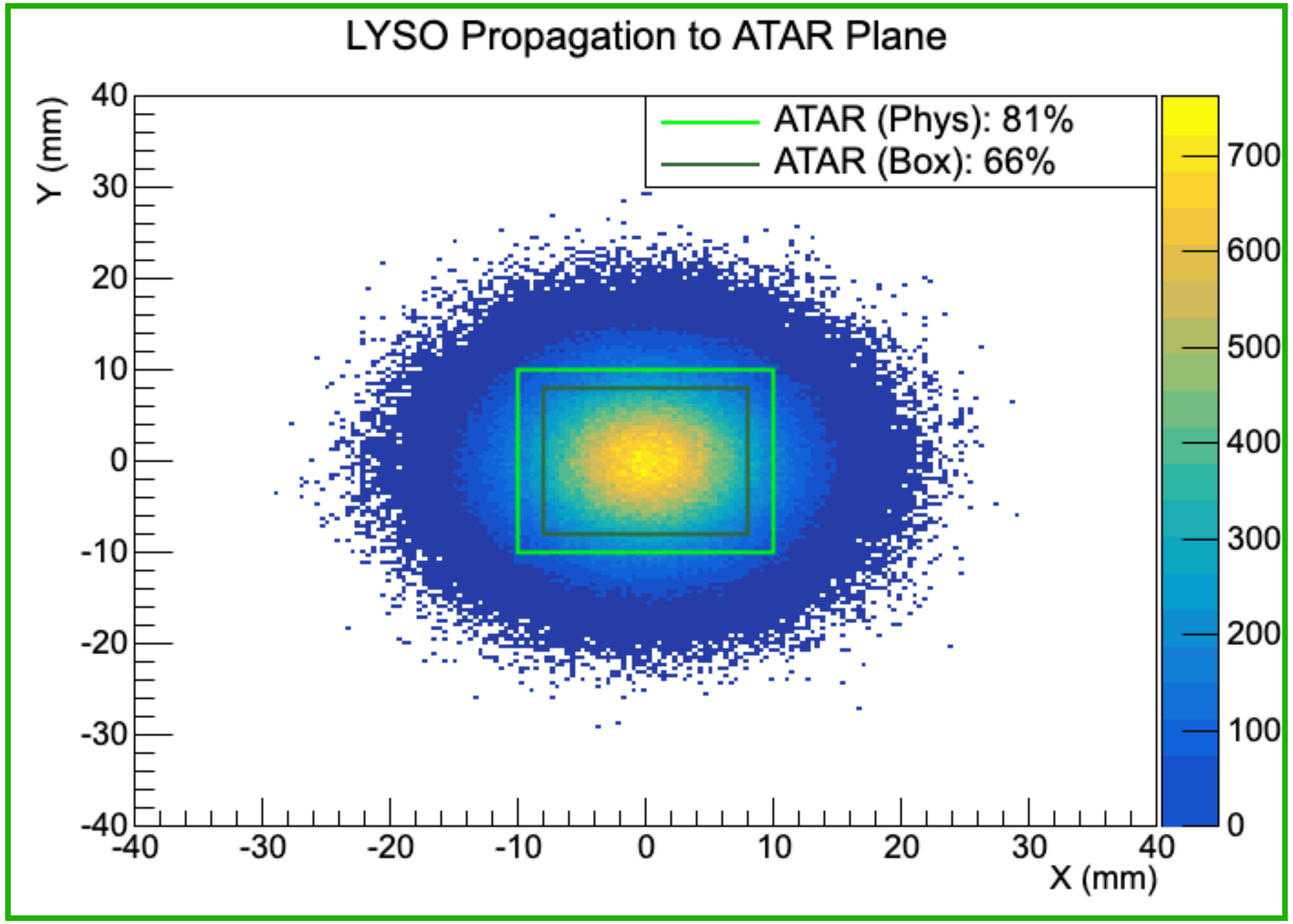
PSI info on PiE5

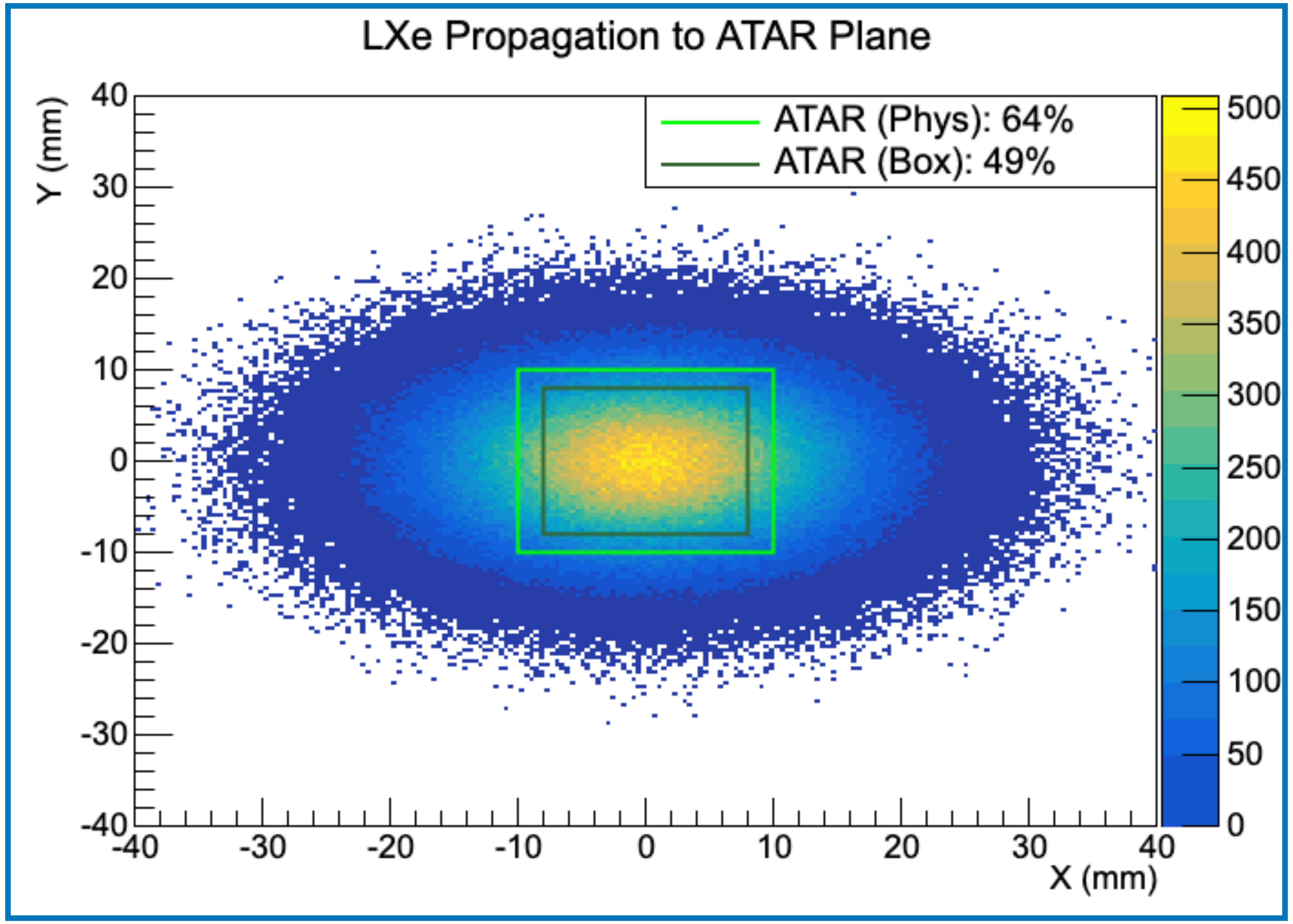
Spot size (FWHM)	15 mm horizontal
	20 mm vertical
Angular divergence (FWHM)	450 mrad horizontal
	120 mrad vertical

https://www.psi.ch/en/sbl/pie5-beamline

- Assumed Quad Aperture: 50 cm diameter
  Limits divergence to:
  - **LYSO** (at 50 cm): 460 mrad
  - **LXe** (at 85 cm): 285 mrad
- Consider argument of conserved phase space:
  - Vertical:
    (both) $\sigma_y = 6.0$ mm $\sigma_{y'} = 0.07$
  - Horizontal
    LYSO: $\sigma_x = 6.0$ mm $\sigma_{x'} = 0.17$
    LXe: $\sigma_x = 9.3$ mm $\sigma_{x'} = 0.11$

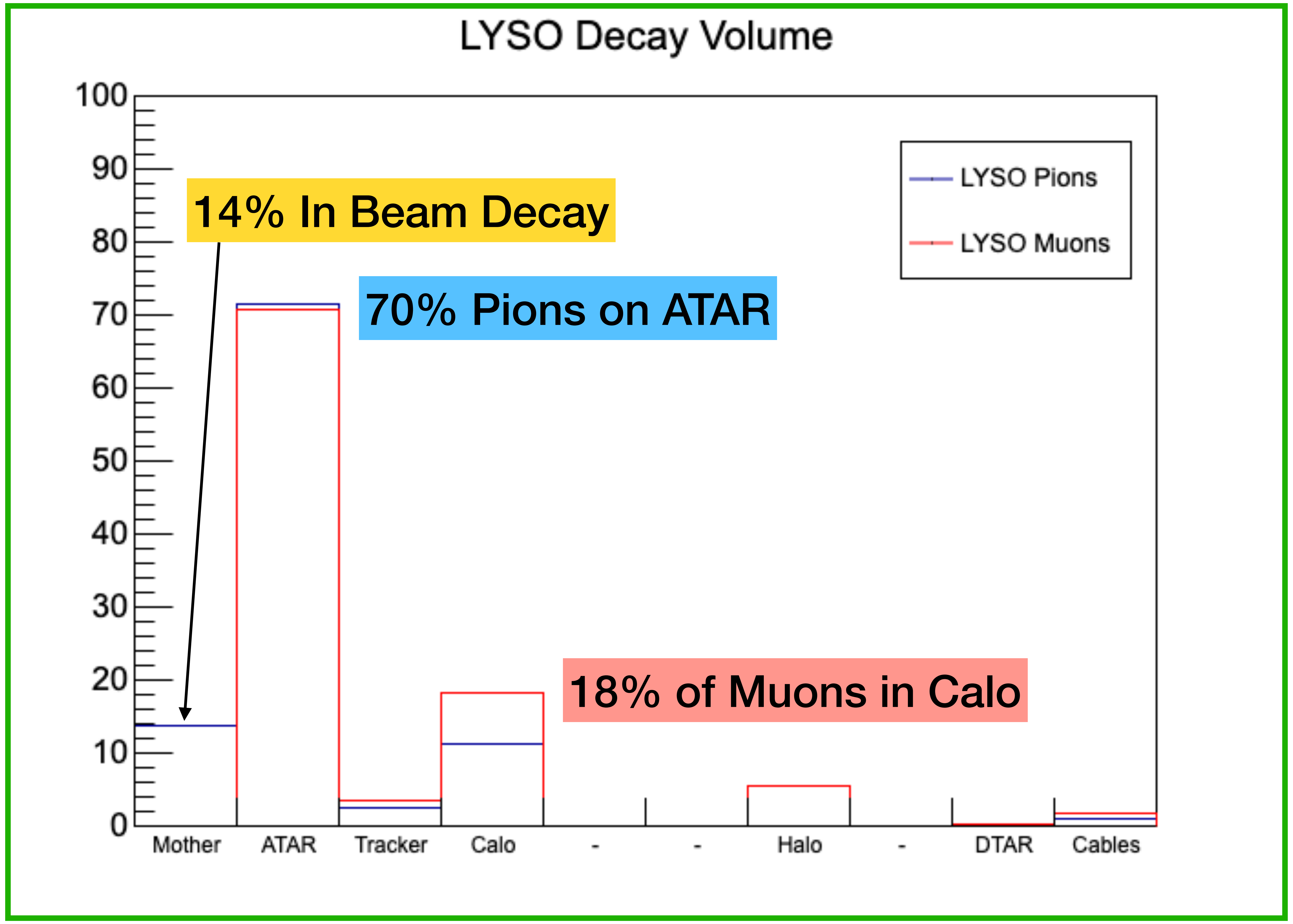
Beam propagated to target plane

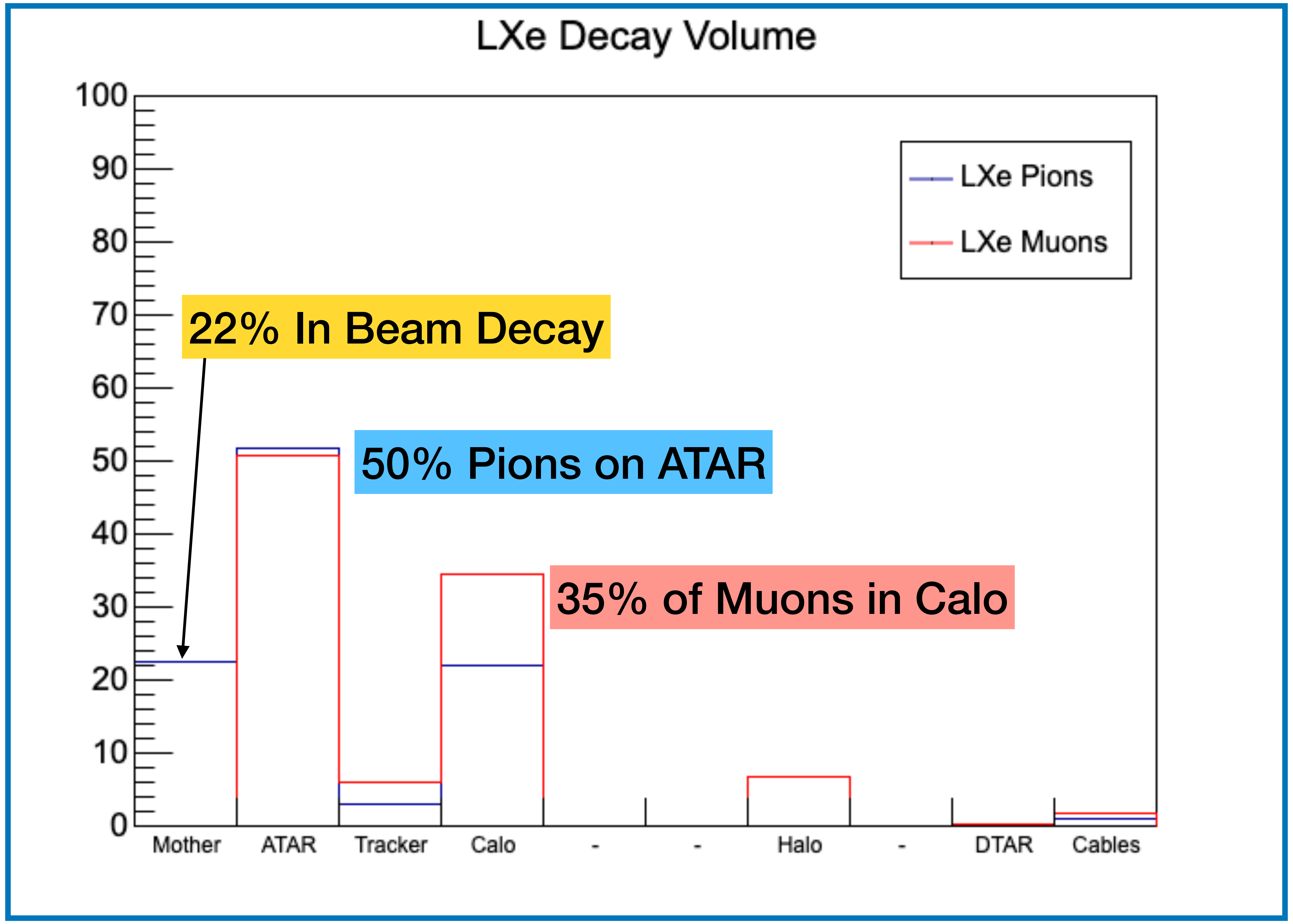




Longer focal length results in larger focus in horizontal direction.

Pion and Muon decay location





Simulated beams suggest a 47% longer run time for LXe

Require 3-Way Comparison

	LYSO (70% yield)	LXe (50% yield)
100M Pions total 419580 Pions / s	3e5 Pions / s on ATAR	2.1e5 Pions / s on ATAR
143M* Pions total 601805* Pions / s	4.3e5 Pions / s on ATAR	3e5 Pions / s on ATAR

A: Same beam rate, LXe has low statistics/longer runtime
B: Same statistics*, LXe requires a higher rate beam, increases pileup
C: High beam rate, LYSO can benefit from higher statistics

Impacts: Pileup, Statistics

*Due to a slight geometry change in LXe at the late stage of the simulation, these numbers are inaccurate by a few percent.

Detector Response Waveforms

LYSO

- Calo edep to waveform algorithm fully merged to develop branch
- Waveforms extracted from November 2023 testbeam.
- Waveform fitter tested.

Based on preliminary results with sub-optimal PMT

LXe

- Photon hits to waveform algorithm in dedicated feature branch.
- Theoretical waveform model based on anticipated PMT type. Compared to MEG II results.

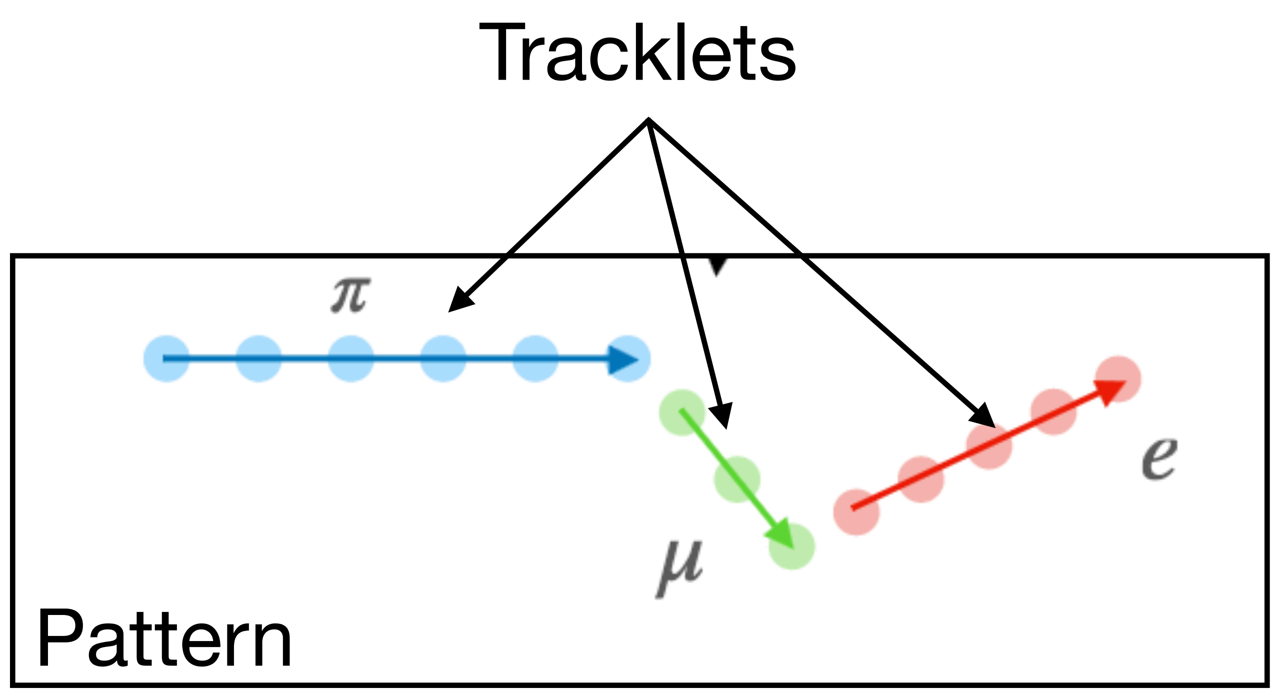
Computationally expensive photon tracking required

Waveform simulation is skipped in this study, but would be available based on reasonable approaches for both calorimeter options.

Reconstruction Strategies

Difficult to compare on even footing

- Truth based Tracklet and Pattern finding
  No updates since collab meeting.



LYSO Reconstruction (data informed)

- Calo Cluster finder in place
- ATAR-Calo matching strategy:
  1. Match based on distance-time score
  2. Match/reject based on time-score.
- Use directional info in energy reco.

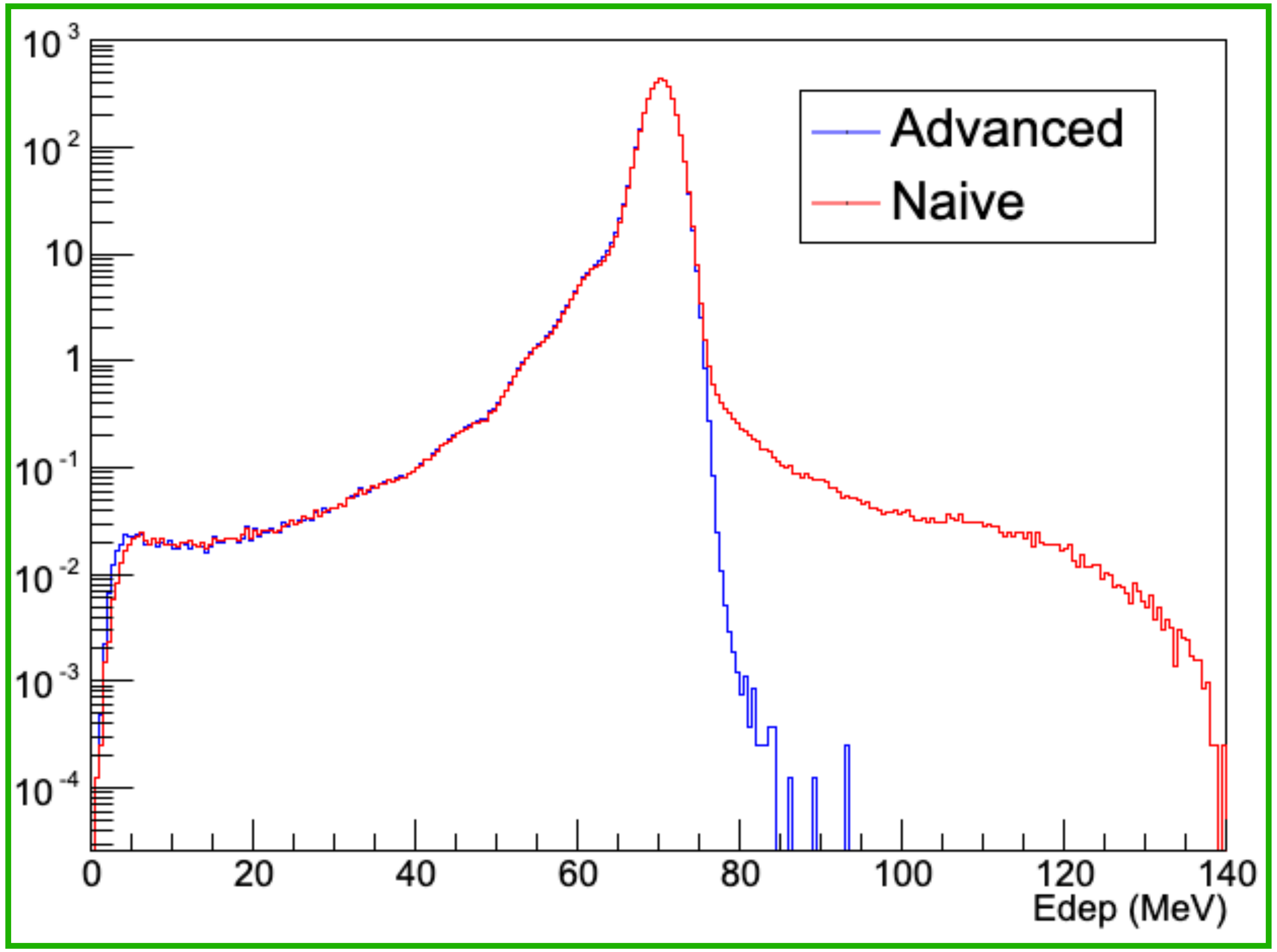
LXe Reconstruction (truth-based)

- 10 ns pileup window, otherwise naive, perfectly uniform reconstruction.
- ATAR-Calo matching based on time only

LYSO reconstruction is more advanced.

Dealing with Radiative Events

Stop in ATAR, $\theta_e < 120°$, 5 ns $< t < 55$ ns



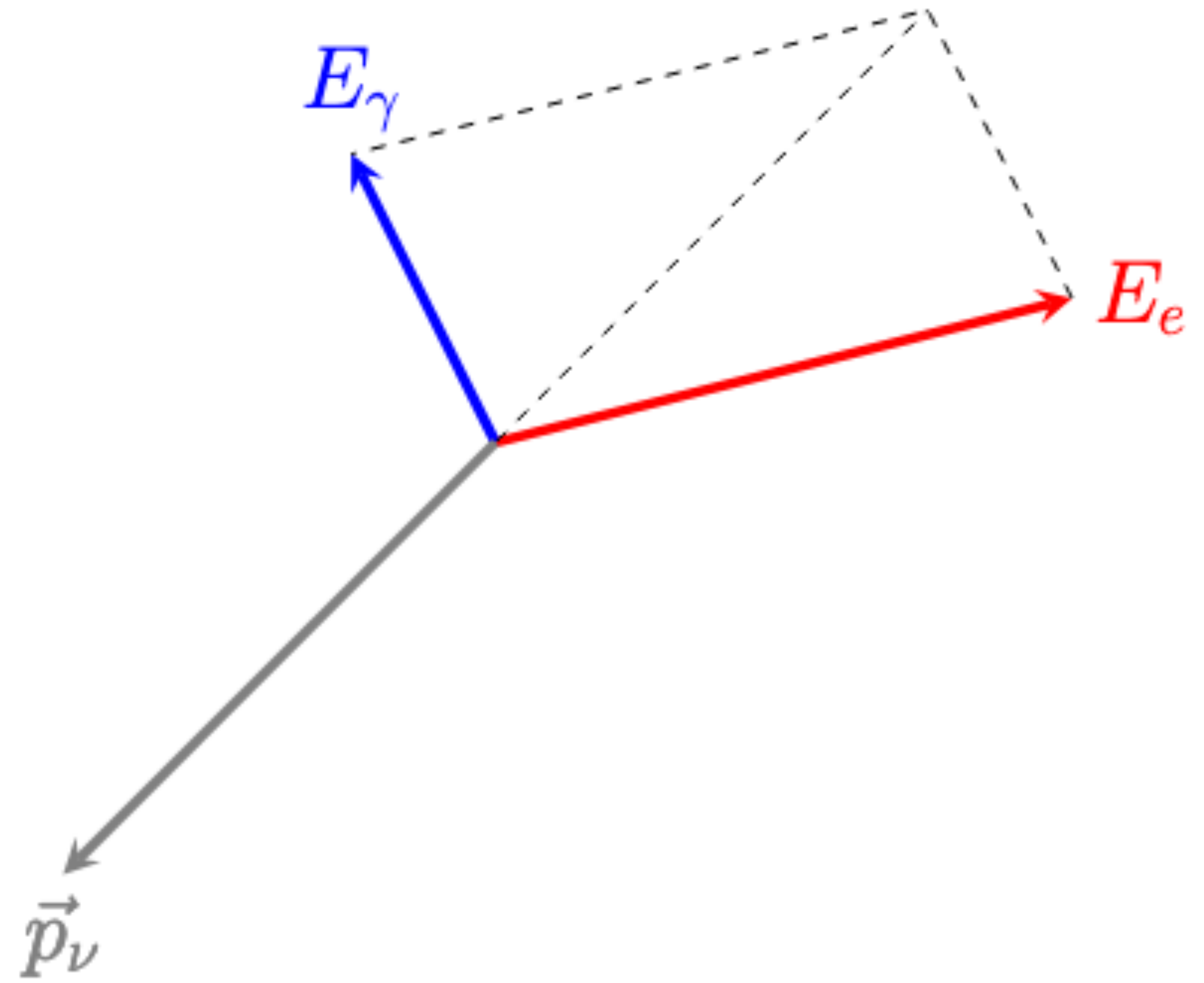
- Advanced: Invariant mass in collinear approximation
$$E = \frac{1}{2}\left(p_\nu + \sum E_i\right)$$
- Naive:
$$E = \sum E_i$$
- No significant distortion apart from radiative tail removal

Requires direction and energy measurement for two time-coincident particles.

Using segmentation

- Instead of a scalar sum of cluster energies, also consider their angles.
- Consider all particles to be high-relativistic, thus $p = E$
- Sum all momenta to find the missing $\vec{p_\nu}$
- Compute total energy divided by 2*

$$E = \frac{1}{2}\left(p_\nu + \sum E_i\right)$$



* Factor 2 to keep the same energy scale

**Single cluster events will keep the same energy.
Radiative events get mapped to lower energies.**

The Selection Cuts

… identical for both Calo Options. Most of them ATAR-based.

Main Analysis

```
time : Time Window cut: -300.00 < dt < -5.00 || 5.00 < dt < 500.00
box  : Atar Box Cut: abs(x) < 8.00 mm, abs(y) < 8.00 mm,
       1.20 mm < z < 4.80 mm
fid  : Fiducial Positron Momentum Theta Cut: theta < 120.00 deg
```

Tail Analysis

```
1p   : Single Pattern Cut
edep : Prompt/Delayed Edep cut:
       E_prompt < 10.80 MeV E_delayed < 4.50 MeV
kink : Reject events with kinks in delayed tracklet
doca : Distance of Closest Approach cut:
       doca < 0.20 mm shift < 0.12 mm
init : Minimal Stopping dE/dx for initial tracklet:
       dE/dx > 6.40 MeV/mm
dedz : Delayed dE/dz < 1.50 MeV / mm
```

The cuts are configurable and can be tuned once other input is more stable

The Selection Cuts

… identical for both Calo Options. Most of them ATAR-based.

```
time : Time Window cut: -300.00 < dt < -5.00 || 5.00 < dt < 500.00
box  : Atar Box Cut: abs(x) < 8.00 mm, abs(y) < 8.00 mm,
       1.20 mm < z < 4.80 mm
fid  : Fiducial Positron Momentum Theta Cut: theta < 120.00 deg
```

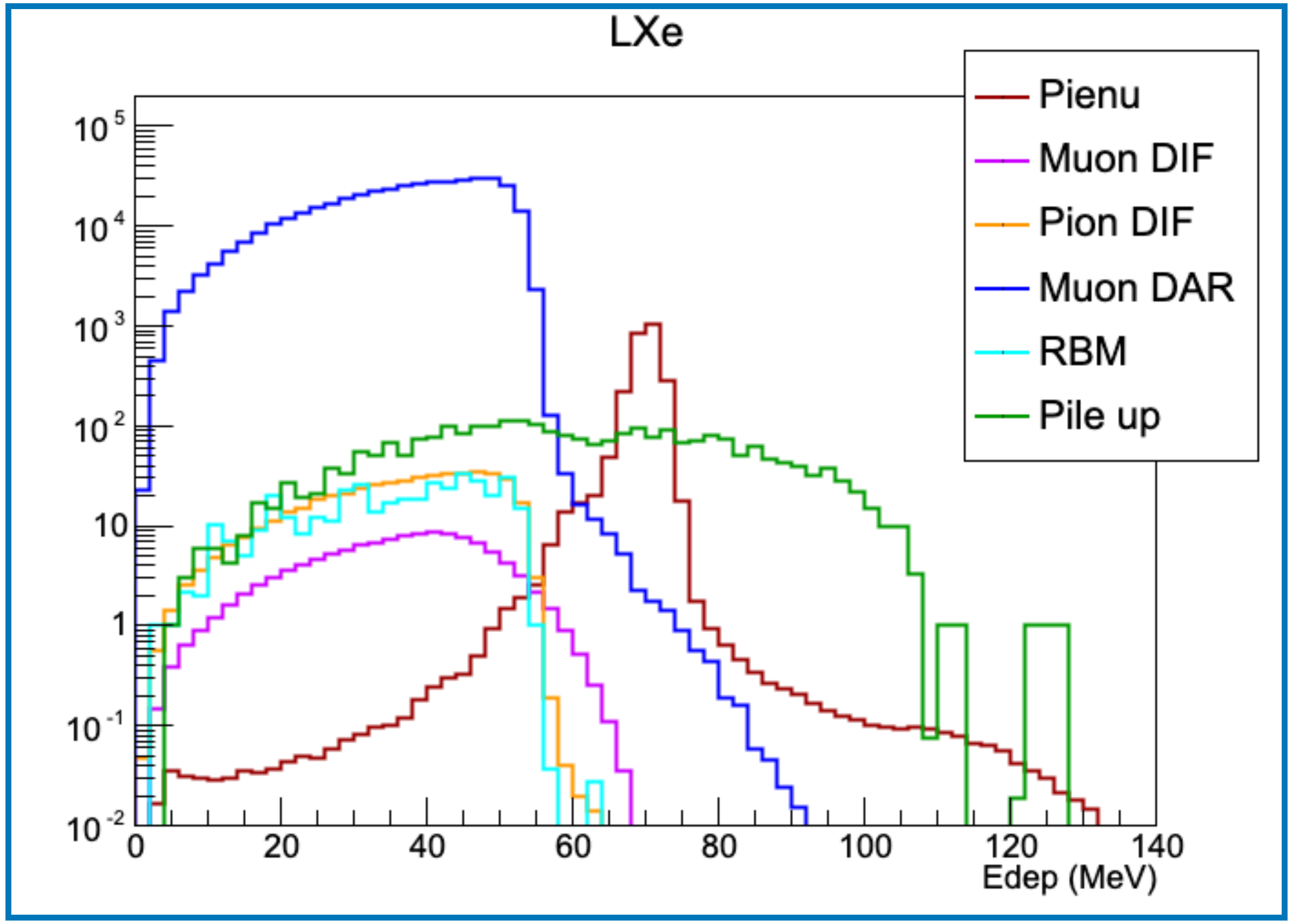
Main Analysis

`time:`	Remove beam-related background, e.g. pion interaction with silicon
`box:`	Remove pion/muon stops outside ATAR where positron can't be observed
`fid:`	Remove events where the calo is only grazed.

Comparing Simulation Results

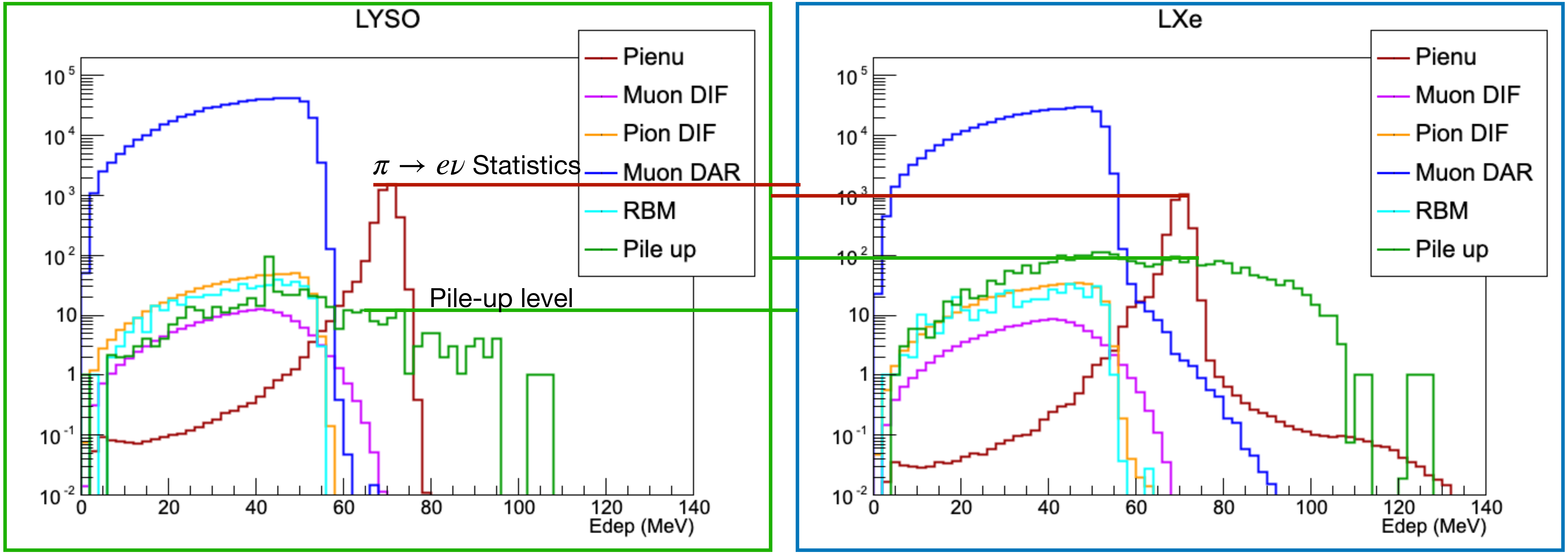
Fiducial Energy Spectra from 5 ns to 55 ns

- **Pienu**: Single $\pi \rightarrow e\nu(\gamma)$ events.
- Muon DIF: Single Muon decay in flight events in target region.
- Pion DIF: Single Pion decay in flight events in target region
- **Muon DAR**: Single pion at rest, muon at rest events. Default Michel spectrum
- RBM: Recent beam muons. Pion decays in beam such that the muon stops on target.
- **Pile up**: Hits from two different MC events got combined



Fiducial Energy Spectra

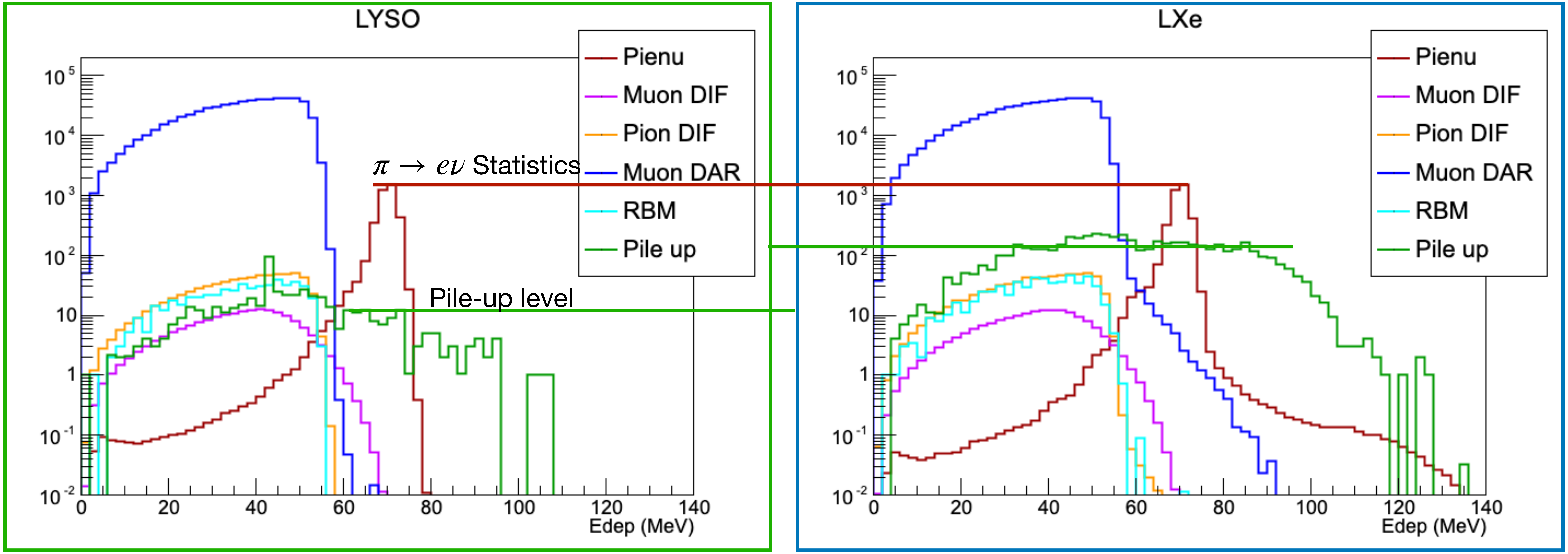
A: Same beam rate, 5-55 ns



LYSO has 47% more $\pi \rightarrow e\nu(\gamma)$ events and by an order of magnitude less pileup in the energy range between 56 MeV - 85 MeV

Fiducial Energy Spectra

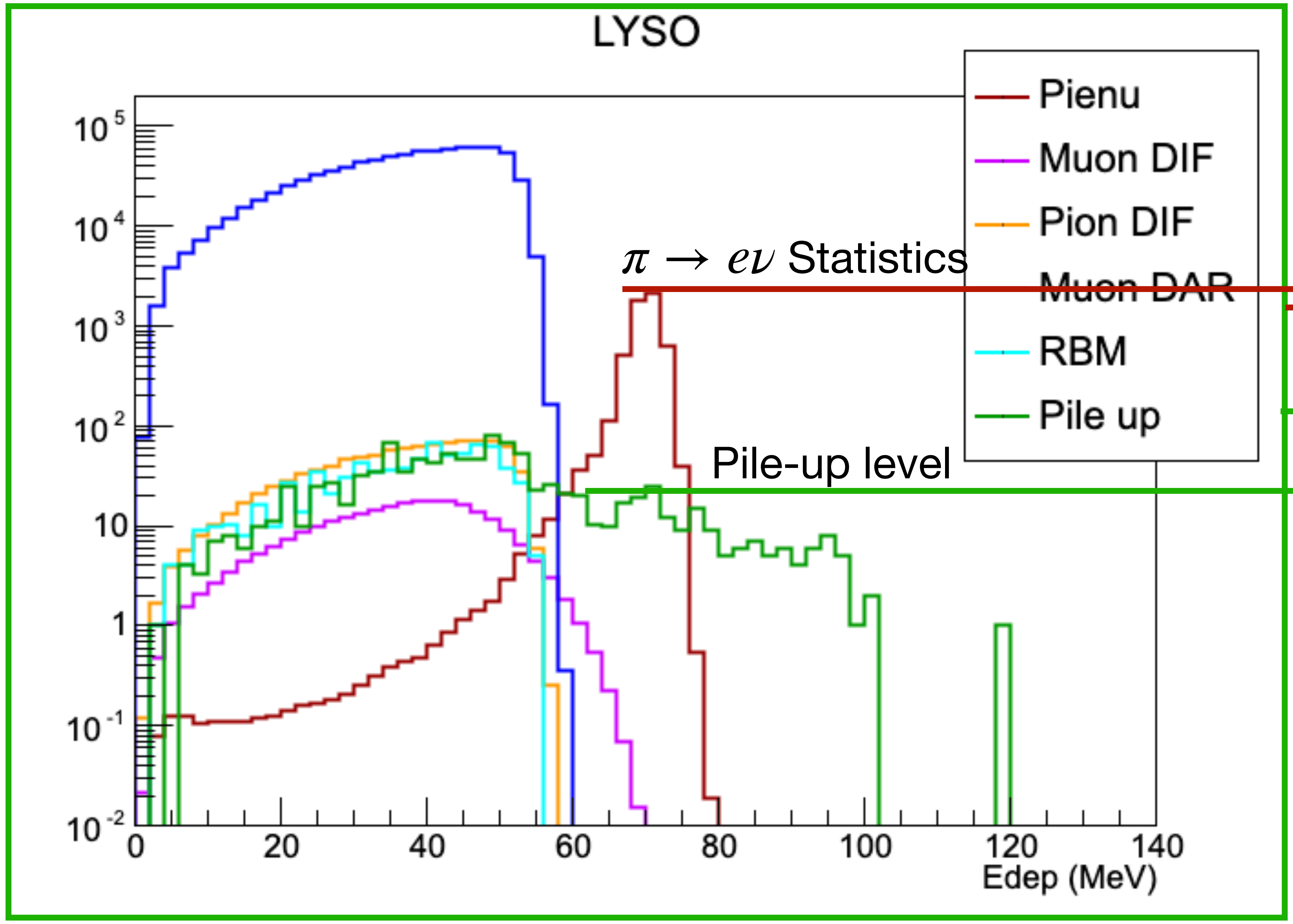
B: Same stats, 5-55 ns

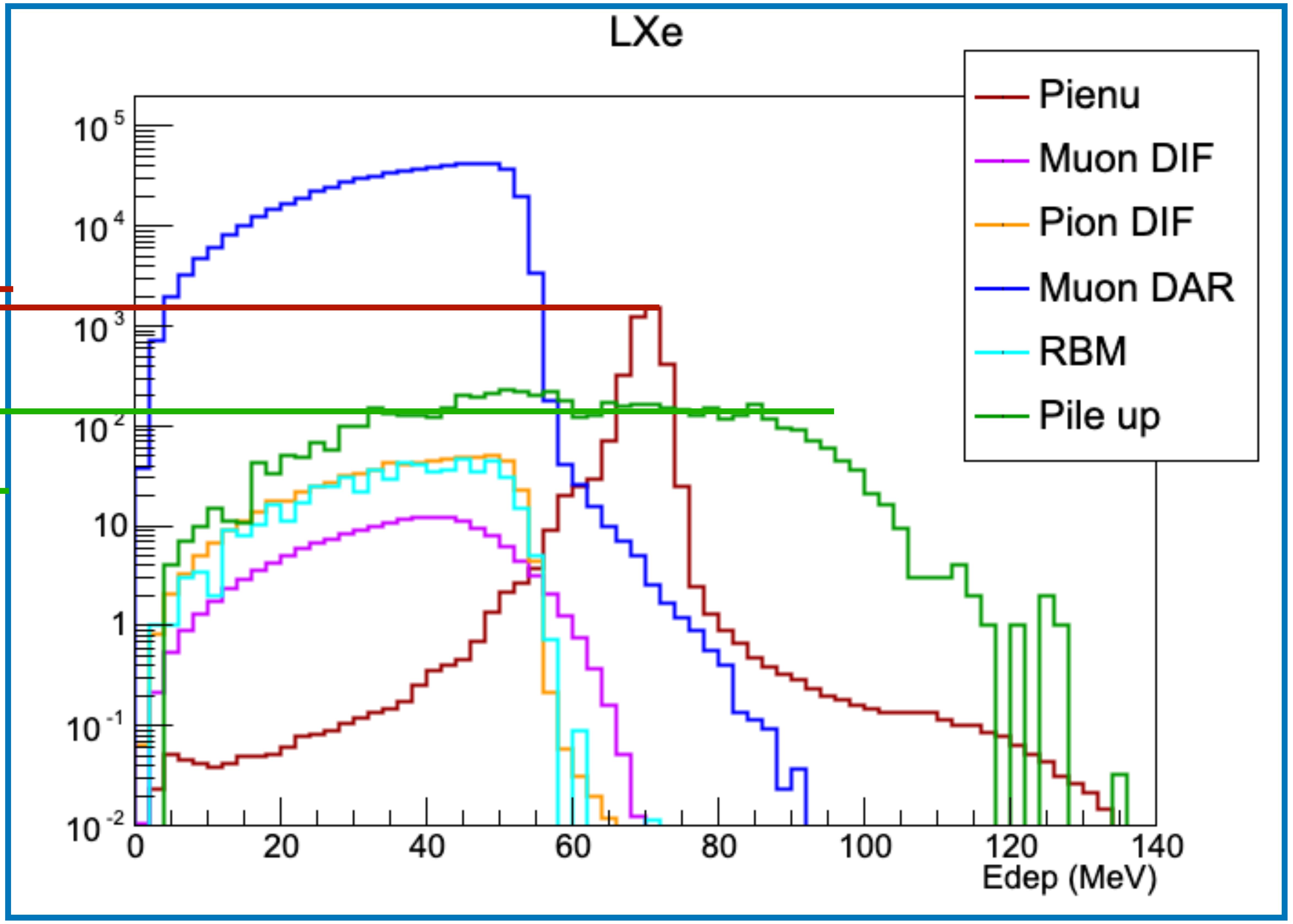


LYSO has by a factor 20 less pileup than LXe in the energy range between 56 MeV - 85 MeV

Fiducial Energy Spectra

C: High beam rate, 5-55 ns





LYSO has 47% more $\pi \to e\nu(\gamma)$ events and by an order of magnitude less pileup in the energy range between 56 MeV - 85 MeV

Fiducial Events, High and Low Bin Composition

A: Same Rate, 5 - 55 ns

	LYSO		LXe	
	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)
Pienu	3E-05	**93.5%**	2E-05	**61%**
MuDAR	99.7%	**3.2(3)%**	99.5%	**5.0(2)%**
Pile-up	**0.06(1)%**	**3.2(3)%**	**0.30(1)%**	**34(1)%**
MuDIF	0.03%	0.1%	0.03%	0.08%
PiDIF	0.1%	-	0.11%	-
RBM	0.08%	-	0.09%	-
Total	100%	100%	100%	100%

Fiducial Events, High and Low Bin Composition

B: Same Stats, 5 - 55 ns

	LYSO		LXe	
	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)
Pienu	3E-05	**93.5%**	2E-05	**53.6%**
MuDAR	99.7%	**3.2(3)%**	99.3%	**4.3(2)%**
Pile-up	**0.06(1)%**	**3.2(3)%**	**0.43(1)%**	**42(1)%**
MuDIF	0.03%	0.1%	0.03%	0.07%
PiDIF	0.1%	-	0.11%	-
RBM	0.08%	-	0.09%	-
Total	100%	100%	100%	100%

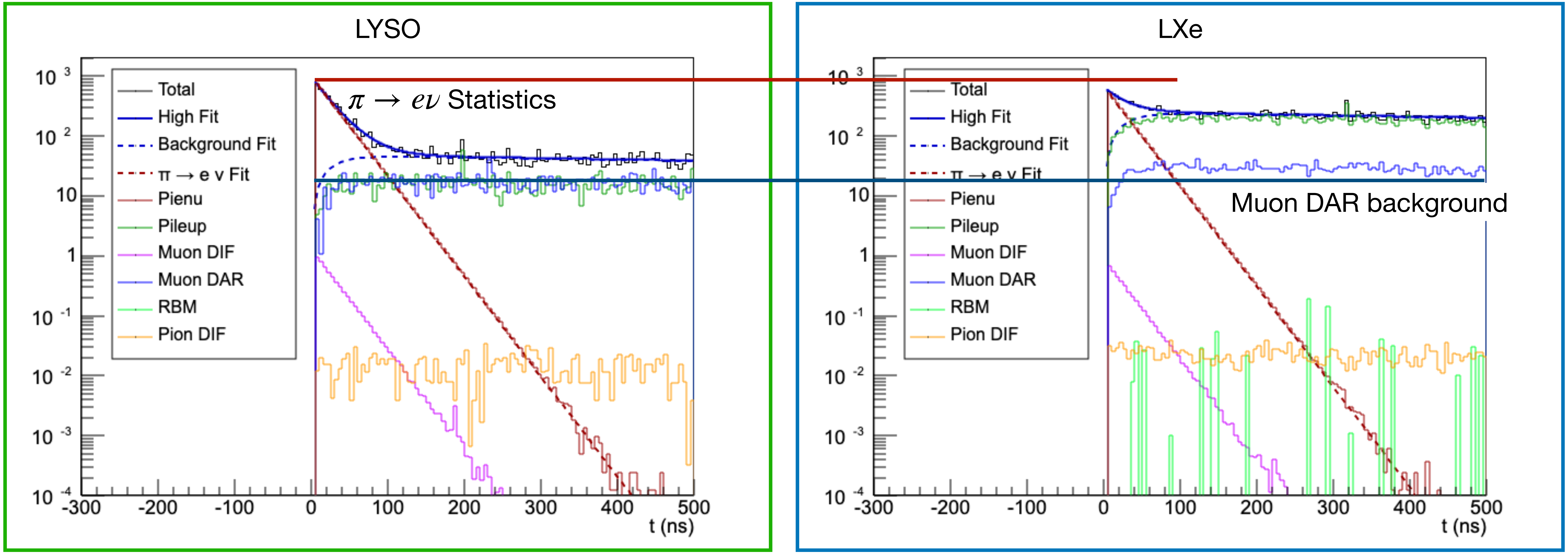
Fiducial Events, High and Low Bin Composition

C: High Beam Rate, 5 - 55 ns

	LYSO		LXe	
	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)	Low Bin (E < 56 MeV)	High Bin (E > 56 MeV)
Pienu	3E-05	**92.7%**	2E-05	**53.6%**
MuDAR	99.7%	**2.9(2)%**	99.3%	**4.3(2)%**
Pile-up	**0.09(1)%**	**4.3(3)%**	**0.43(1)%**	**42(1)%**
MuDIF	0.03%	0.1%	0.03%	0.07%
PiDIF	0.1%	-	0.11%	-
RBM	0.08%	-	0.09%	-
Total	100%	100%	100%	100%

High Energy Time Spectra

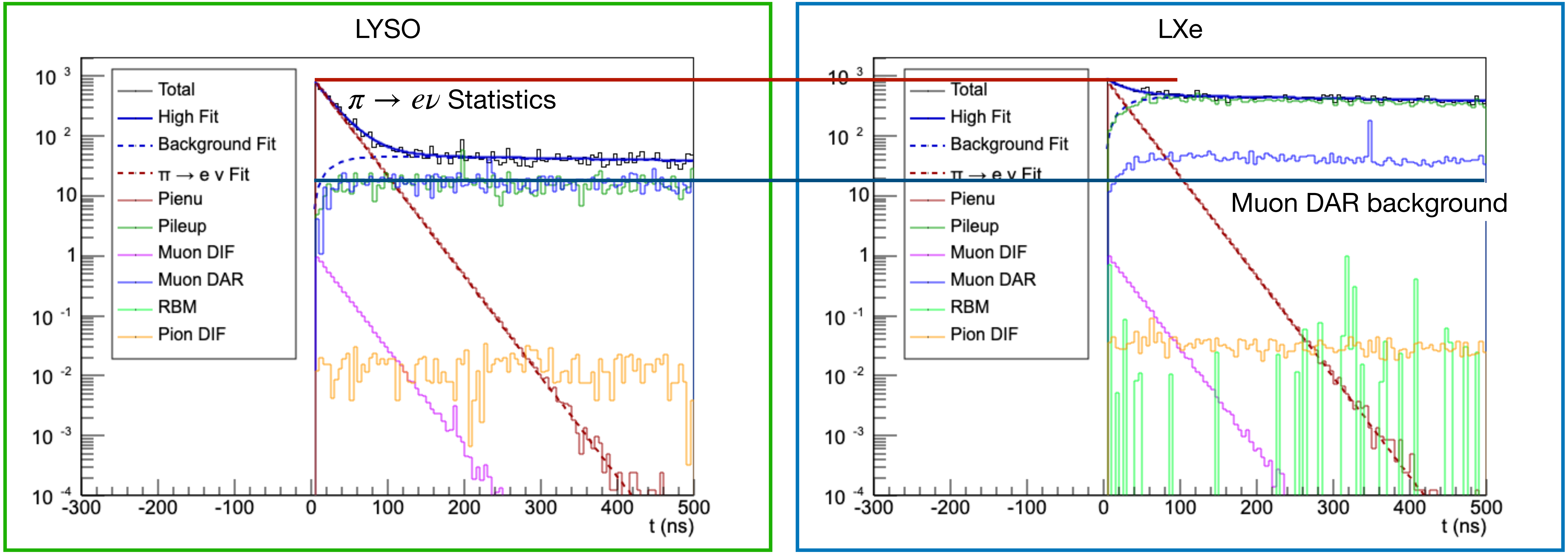
A: Same beam rate, 56 - 115 MeV



LYSO background mixture of Muon DAR leakage and pileup, LXe background dominated by pileup.

High Energy Time Spectra

B: Same stats, 56 - 115 MeV

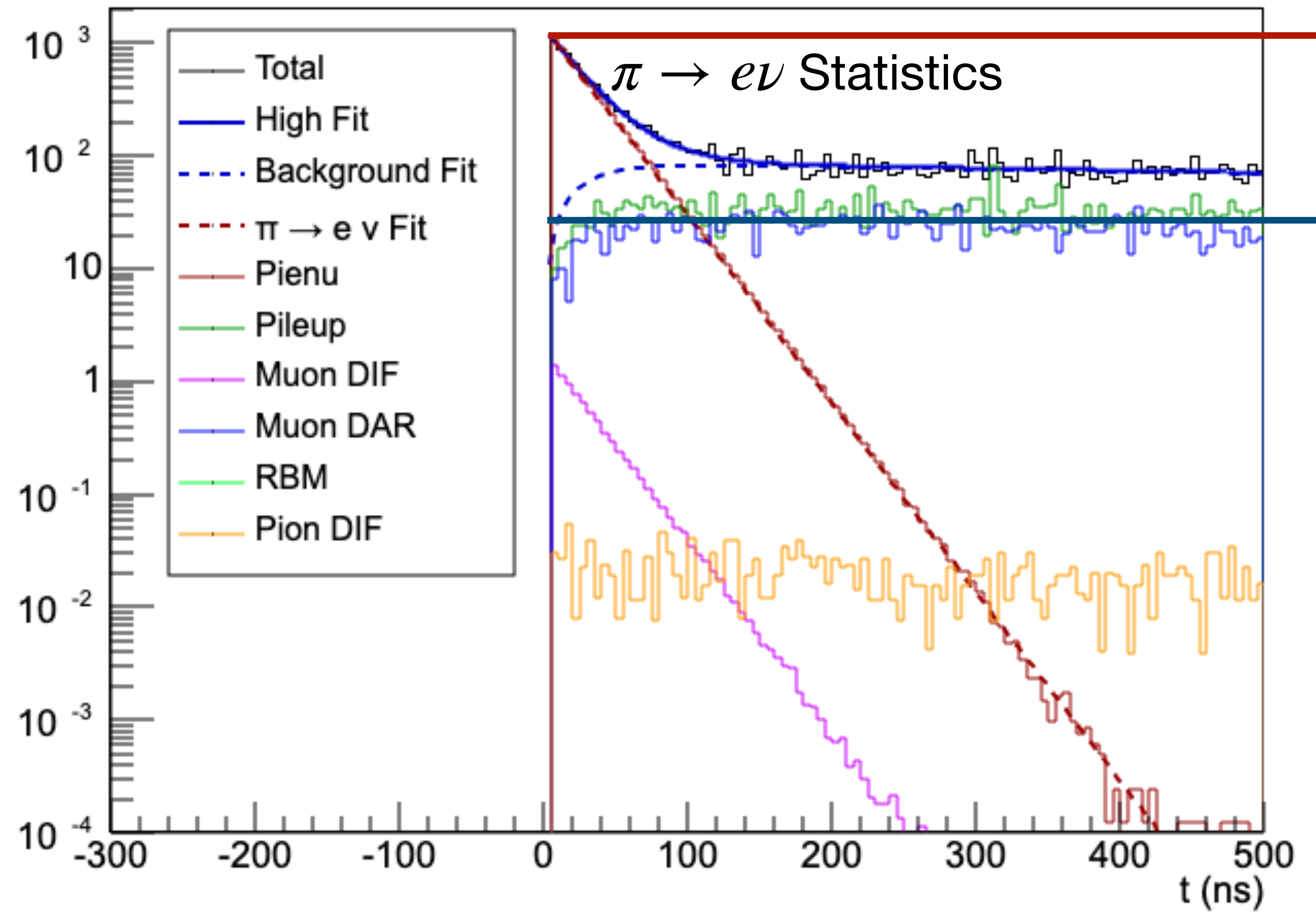


LYSO background mixture of Muon DAR leakage and pileup,
LXe background dominated by pileup.

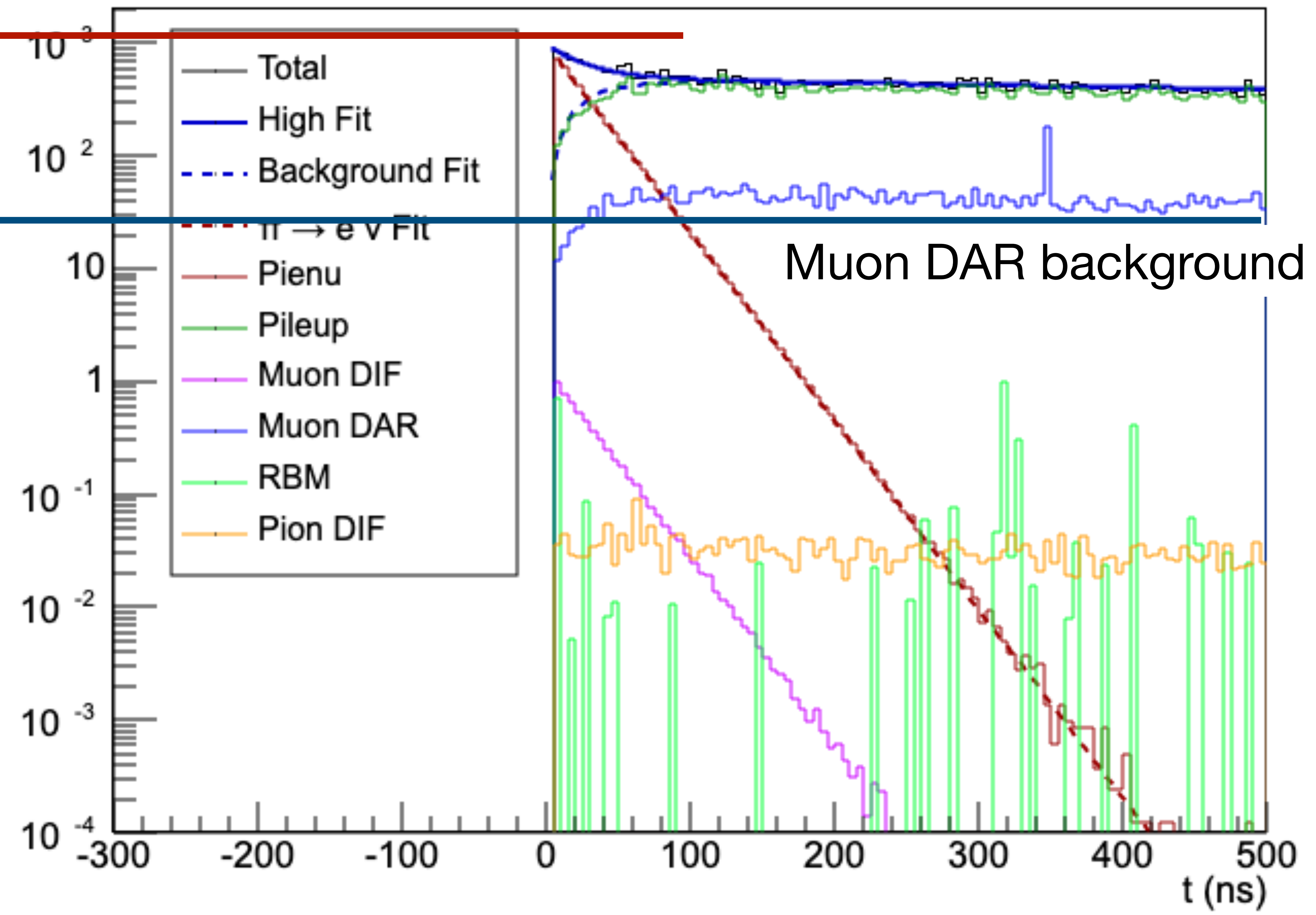
High Energy Time Spectra

C: High beam rate, 56 - 115 MeV

LYSO

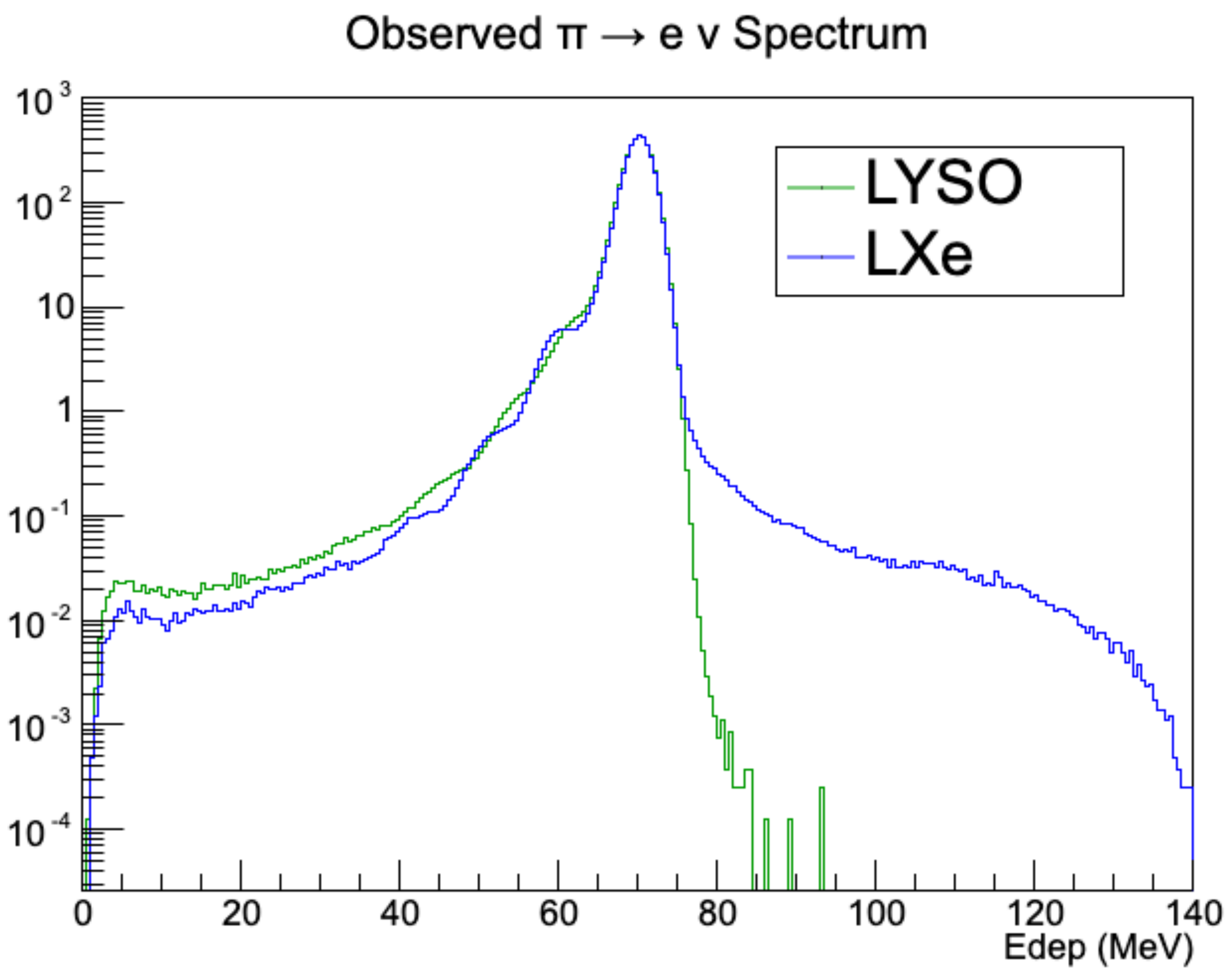


LXe



LYSO background mixture of Muon DAR leakage and pileup, LXe background dominated by pileup.

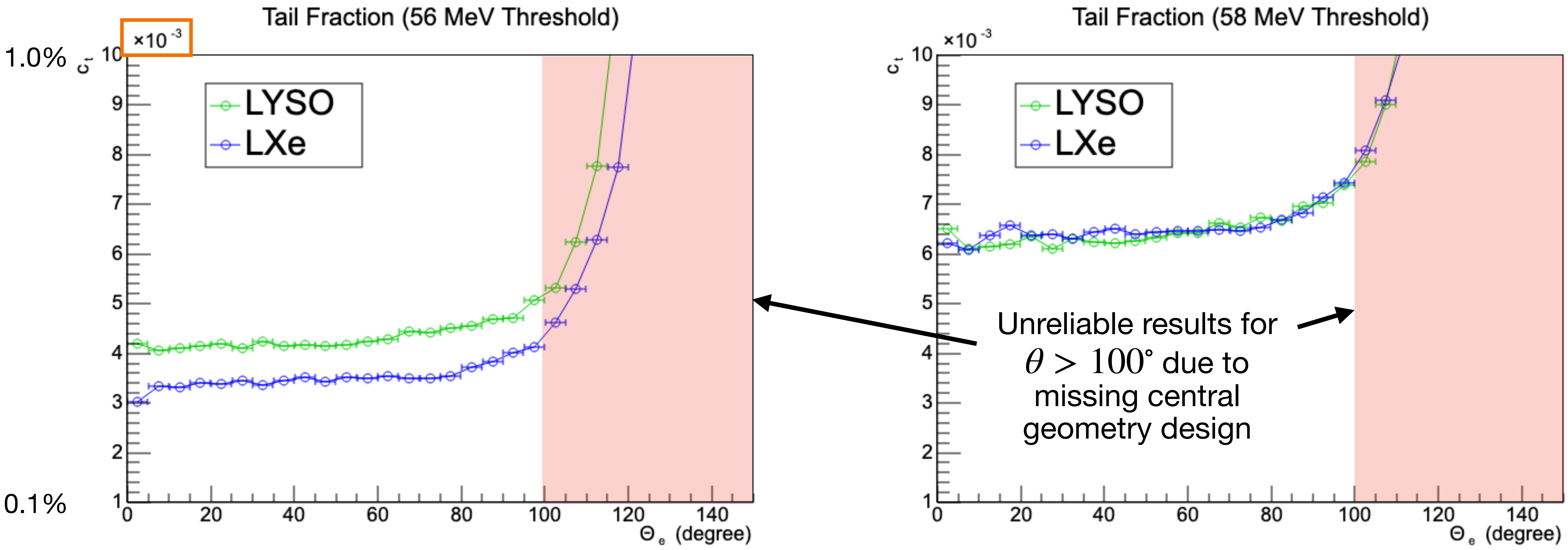
Comparing $\pi \to e\nu$ spectra



- LYSO has a larger lowest-energy tail.
- High energy radiative tail in LXe detector.
- Photonuclear peaks are shifted between LXe and LYSO
- Highest energy bins dominate tail fraction (Note the log scale)

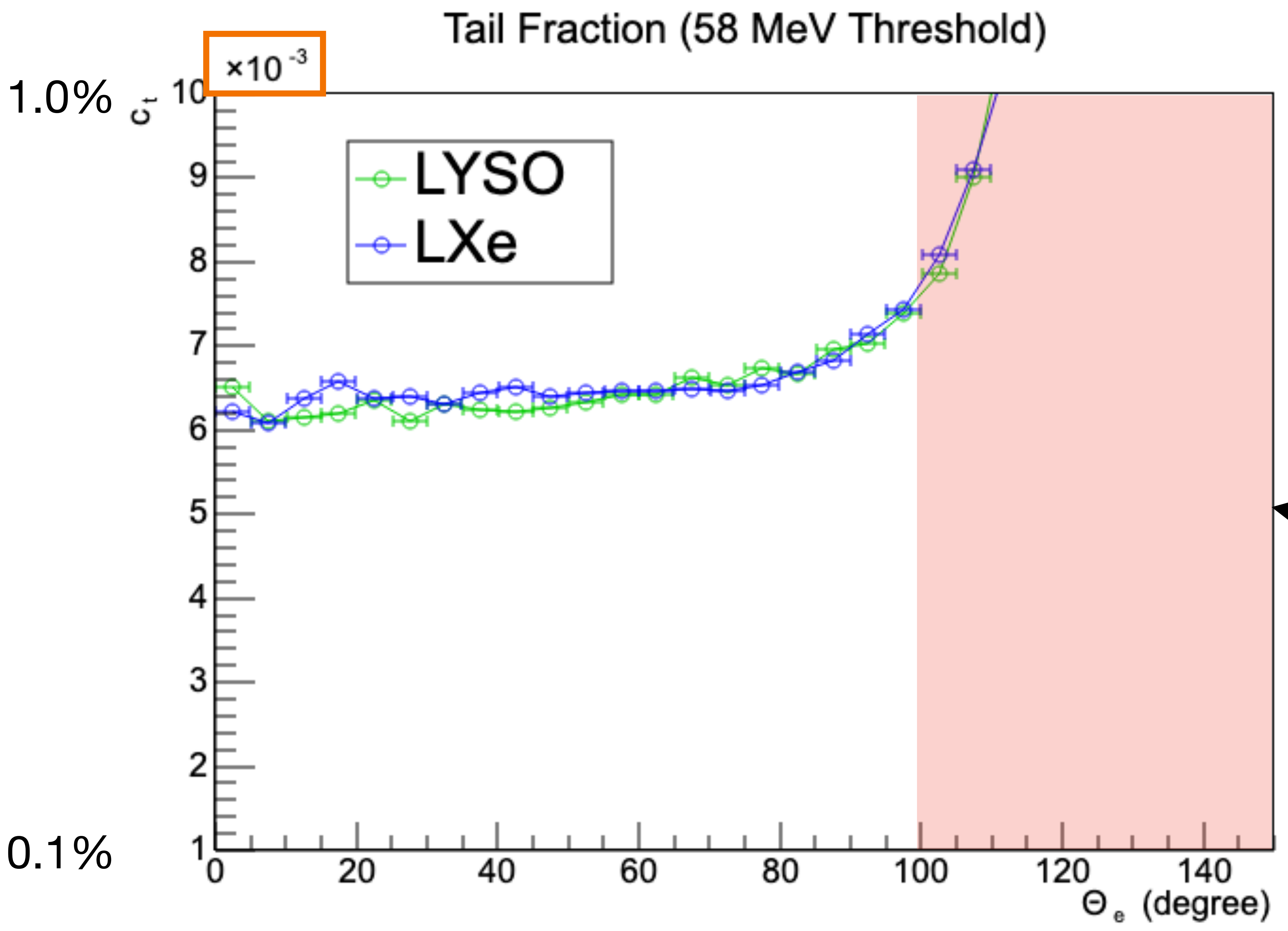
Tail fraction heavily depends on high-energy bin threshold and (photo-)nuclear cross-sections.

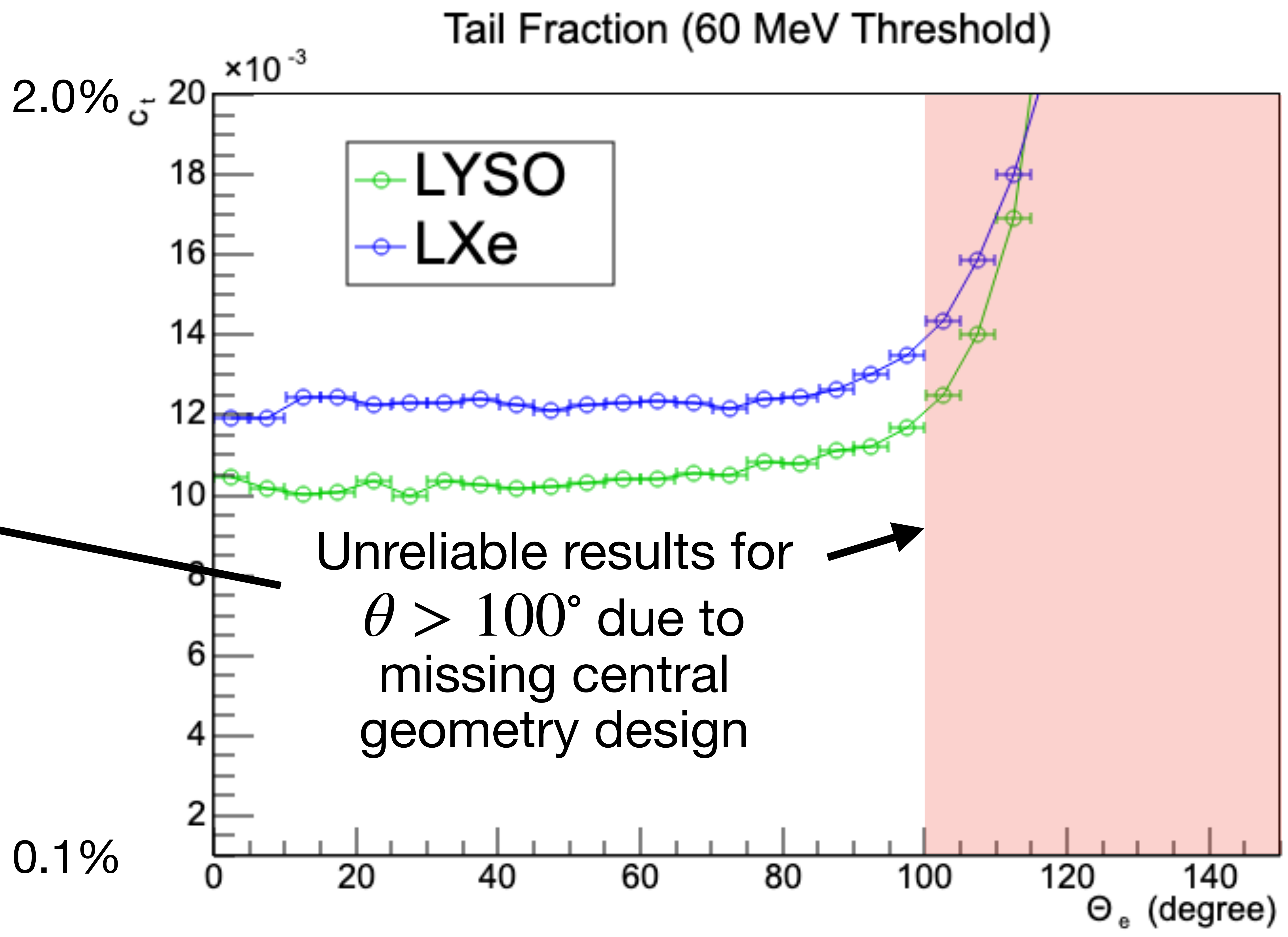
Theta-Dependence of Tail Fraction



Tail Fractions are very comparable and suffice the 1% goal for both detectors for thresholds below 58 MeV.

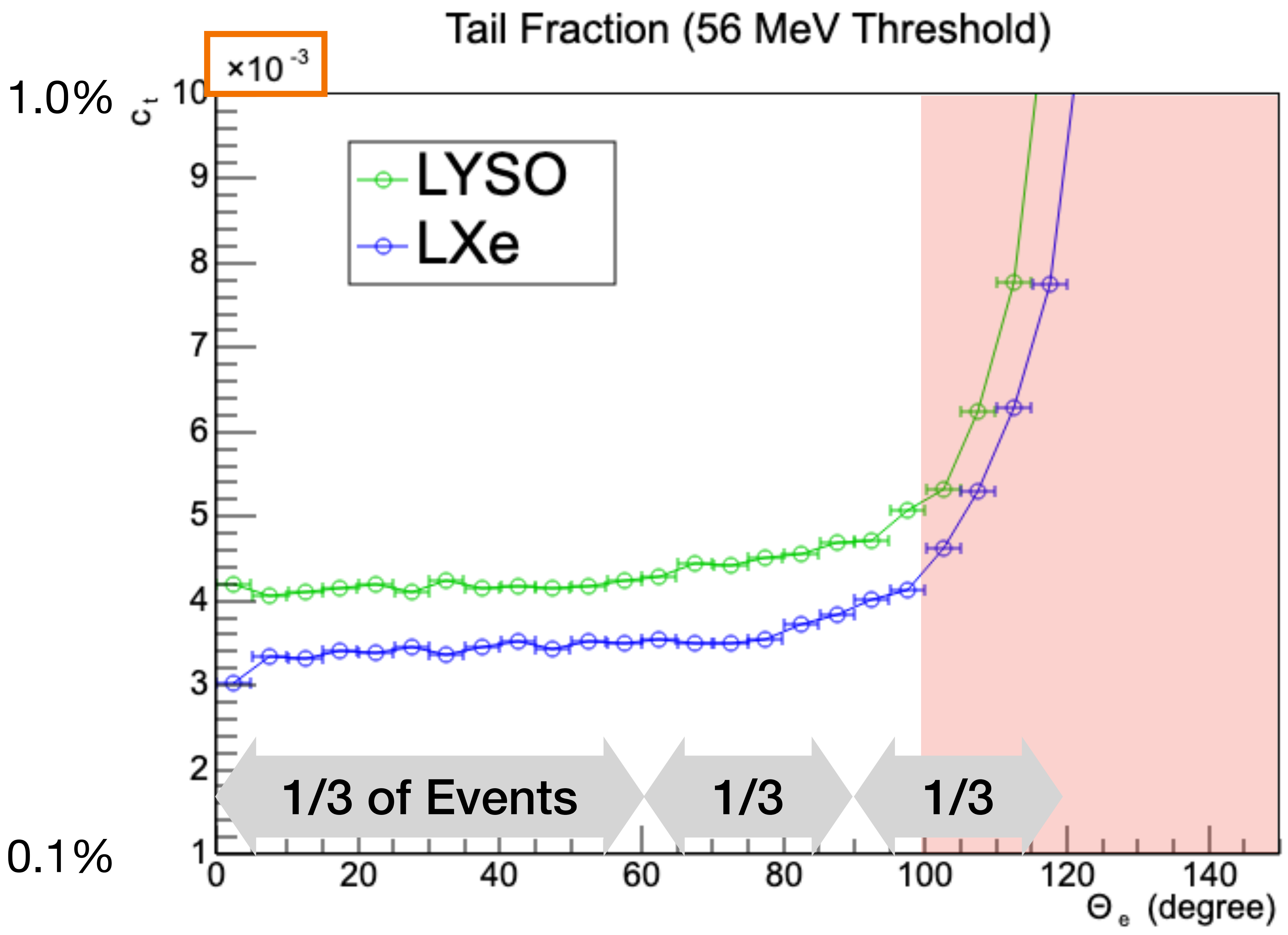
Theta-Dependence of Tail Fraction





Tail Fractions are very comparable and suffice the 1% goal for both detectors for thresholds below 58 MeV.

Comparing $\pi \rightarrow e\nu$ Tail Fraction at 56 MeV



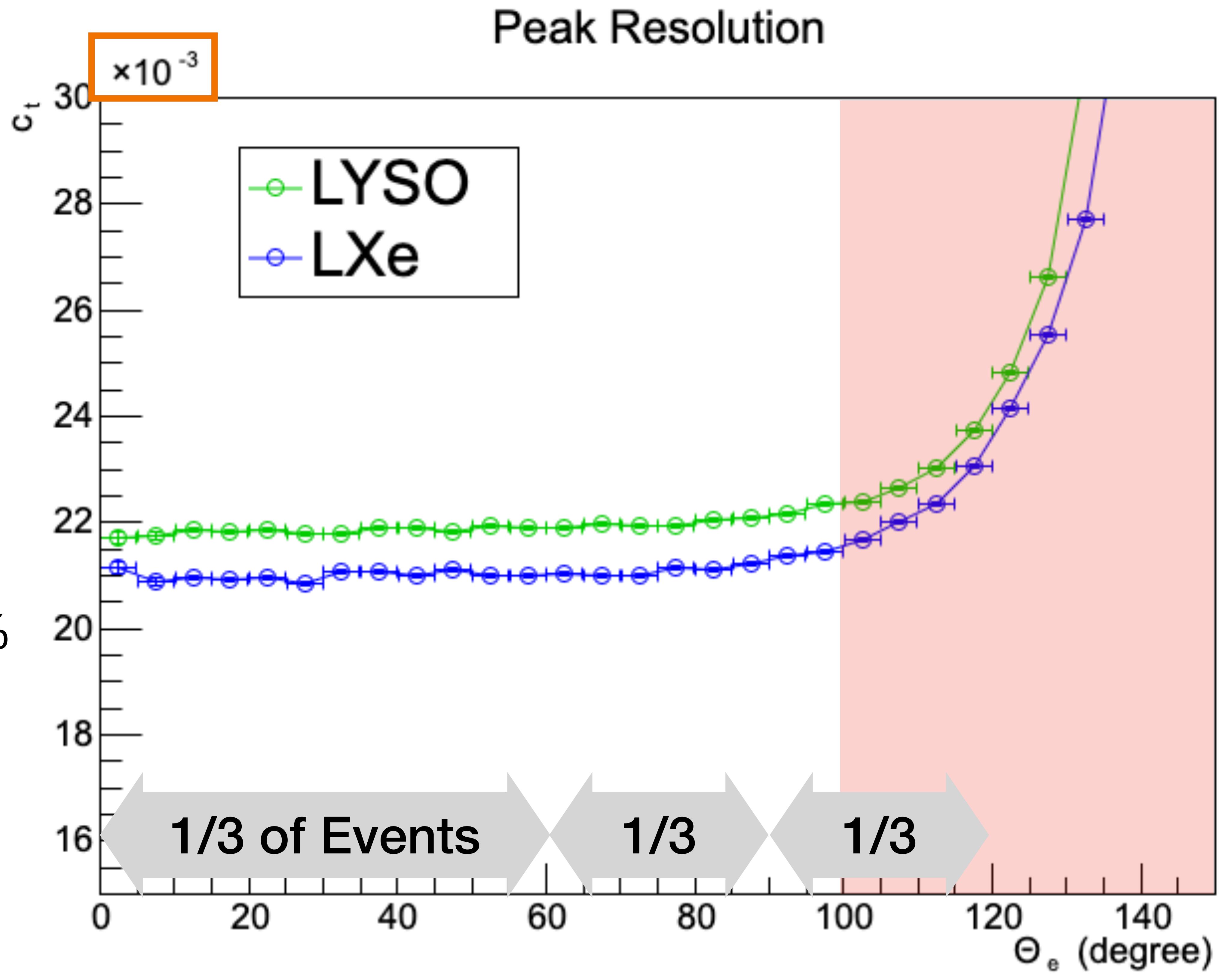
- **LYSO** (full reconstruction): **0.5%**
- **LXe** (assumed perfect): **0.4%**.
- Theta variation (max difference / mean):

	0 - 100	0 - 120
LYSO	**22%**	**94%**
LXe	**31%**	**87%**

The tail fraction simulation does not favour any of the calorimeters.
It remains one of the major concern of the ATAR reconstruction and analysis.

Comparing $\pi \rightarrow e\nu$ Peak Resolution

2.0%



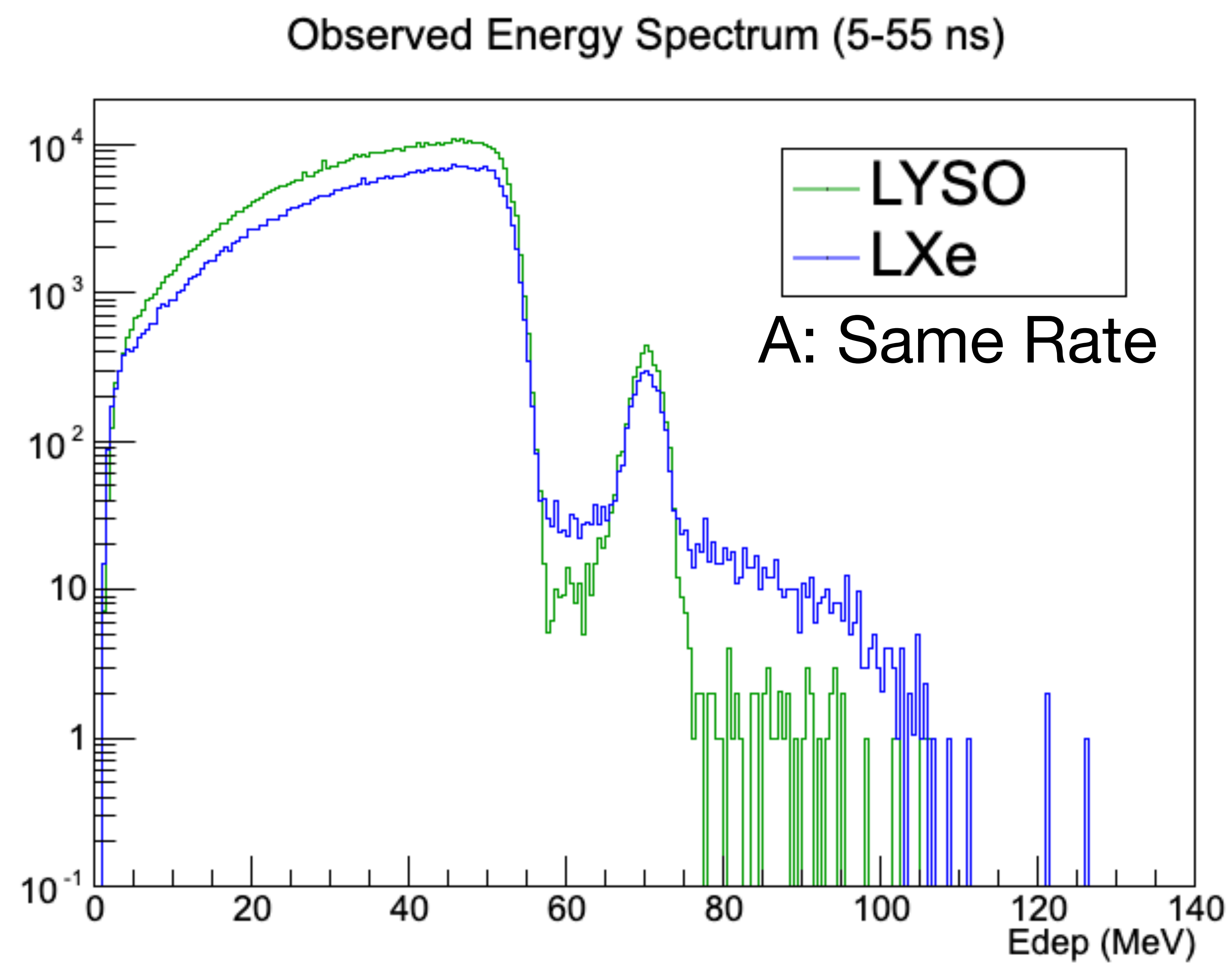
- **LYSO** (full reconstruction): **2.2%**
- **LXe** (assumed perfect): **2.1%**.
- Theta variation (max difference / mean):

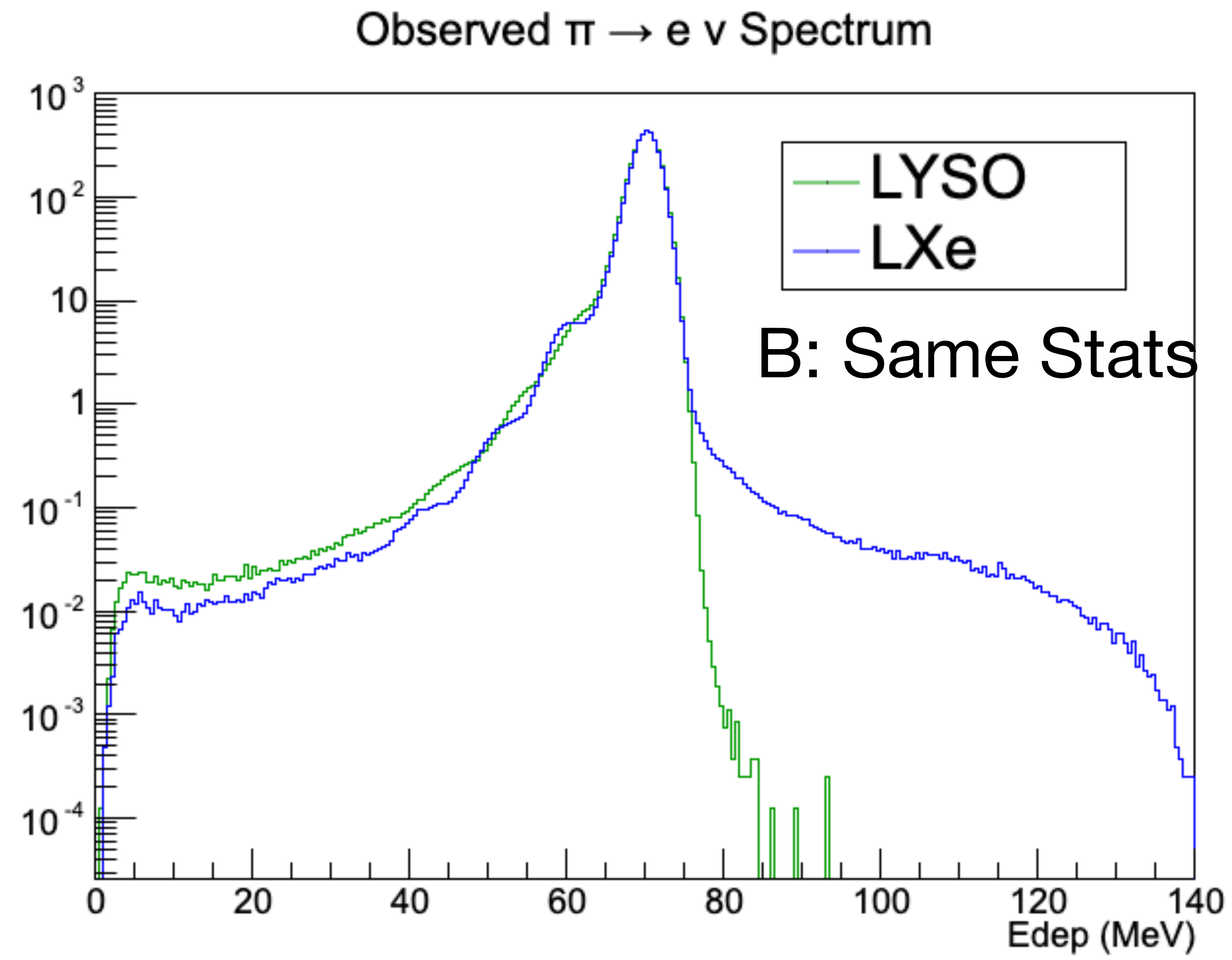
	0 - 100	0 - 120
LYSO	**2.9%**	**8.9%**
LXe	**2.9%**	**10.1%**

The simulation does not provide a significantly different resolution at 70 MeV.

Simulation Conclusion

- **LYSO** accumulates 47% more statistics in the same time, as the shorter beam focus improves the pion yield.
- **LYSO** provides a cleaner spectrum due to its intrinsic segmentation. This reduces pileup by an order of magnitude and identifies radiative decays.
- The total tail fraction is dominated by nuclear effects in the detector material. The simulation suggests a tail fraction under 1% below 58 MeV for both detectors and thus suffice the requirement laid out in the proposal.
- Both detectors show the same peak resolution.





Comparing Analysis Results

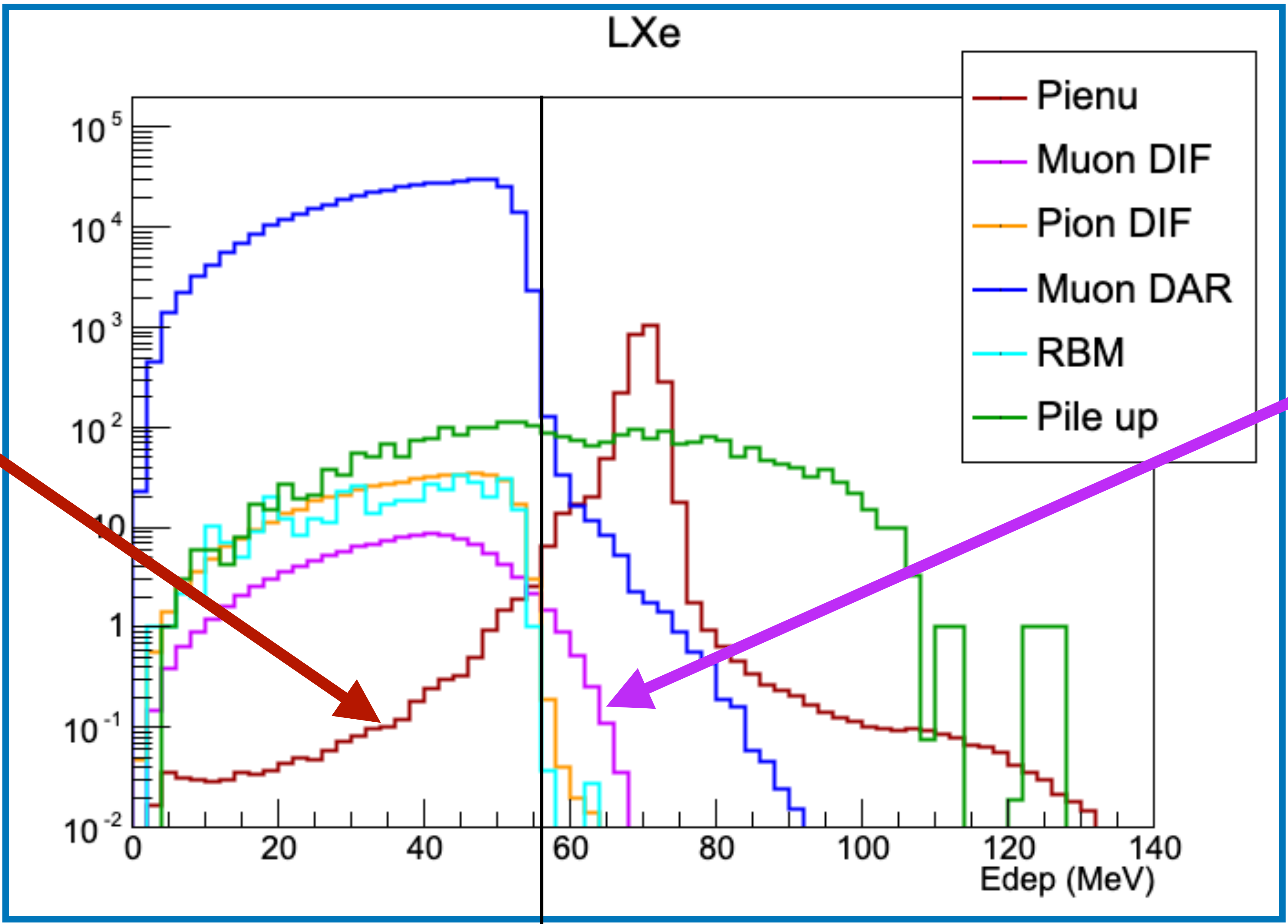
The Basic Analysis Strategy

… to be improved and fleshed out in the coming months.

Tail Analysis

Main Challenge:
- Michel
- Muon DIF
- Pion DIF
- RBM

The tail analysis is ATAR-driven. Calorimeters have minimal impact on the strategy here.



Reverse Tail

Main Challenge:
- Muon DIF

High bin time fits will pick up pile-up and muon DAR leakage, but not Muon DIF leakage. This part will likely be ATAR driven.

Low Bin	High Bin
Main Challenge: • Pileup • Acceptance	Main Challenge: • Pileup • Leakage • Acceptance

Pileup will be a 10^{-3} *to* 10^{-4} *effect. Need to understand thoroughly and assert no bias is introduced.*

The high bin is where the largest difference between calorimeters are observed. Investigate closer!

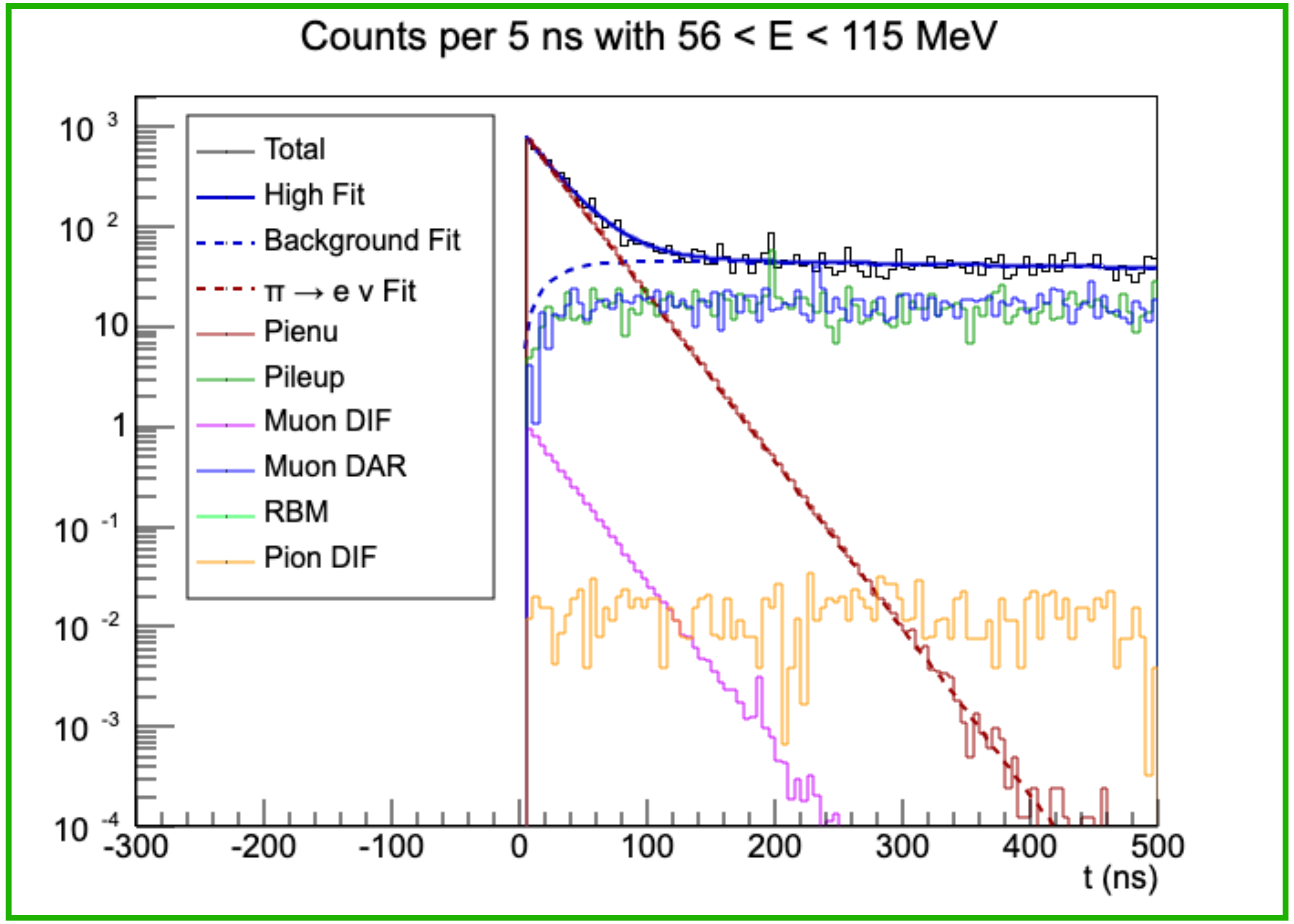
High Bin Analysis

Select events with energies above 56 MeV

- **Main Goal**:
  Get number of $\pi \to e$ events without counting pileup and mudar contamination

- **Strategy**:
  Time spectrum fit
  $$n_H(t) = Ae^{-t/\tau_\pi} + B\frac{\tau_\mu}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\pi} - e^{-t/\tau_\mu}\right)$$
  and then integrate.

- **Problems**:
  Non-trivial time spectra due to triggering on the “first” arriving pion.



High Fit Accuracy

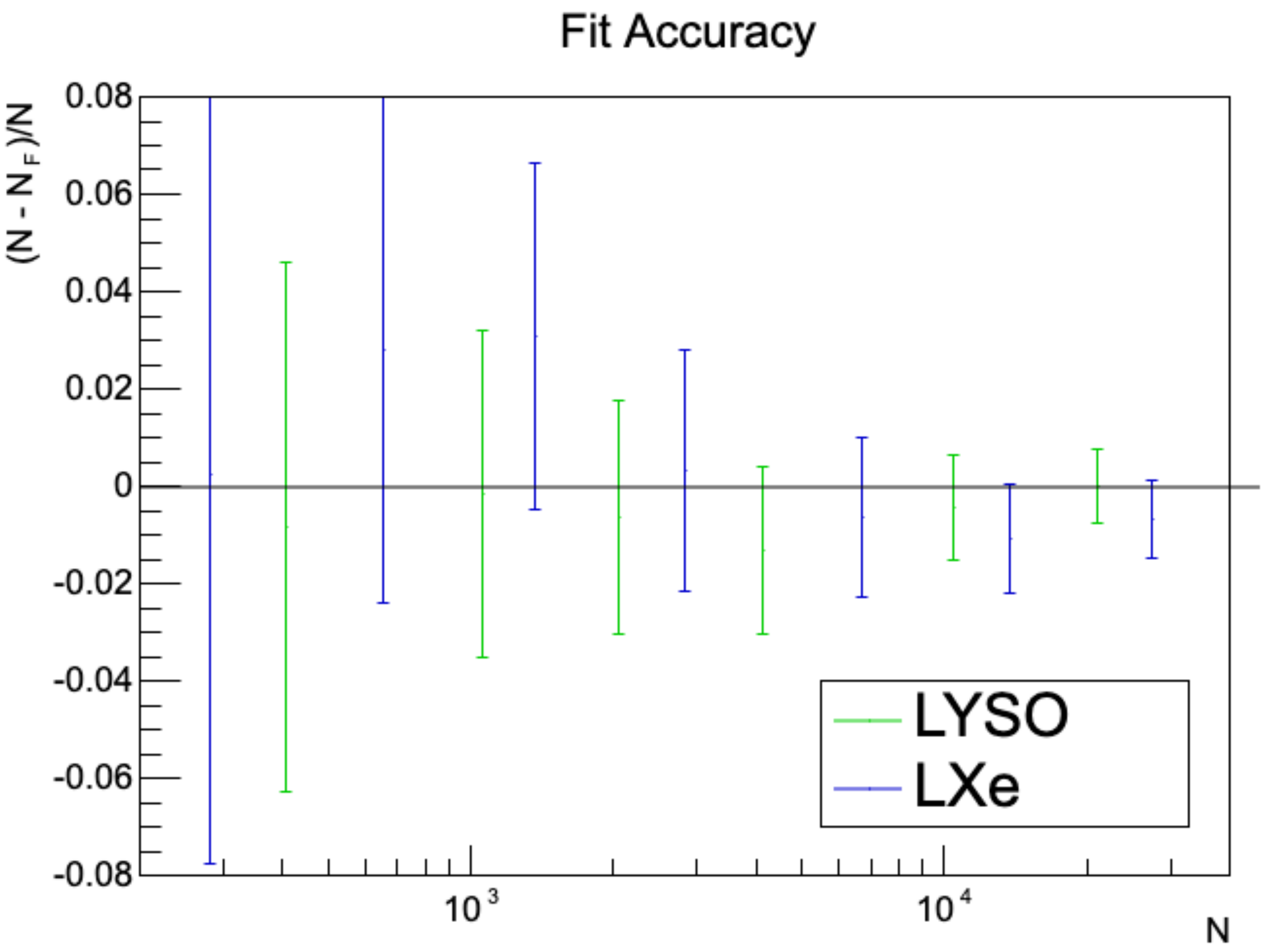
Does the fit return the right number?

- Fit Function

$$n_H(t) = Ae^{-t/\tau_\pi} + B\frac{\tau_\mu}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\pi} - e^{-t/\tau_\mu}\right)$$

- Variables:
  - N : Number of $\pi \to e\nu(\gamma)$ events counted after 5 ns (extracted from MC truth).
  - N_F: Number of $\pi \to e\nu(\gamma)$ events extracted from fit after 5 ns.

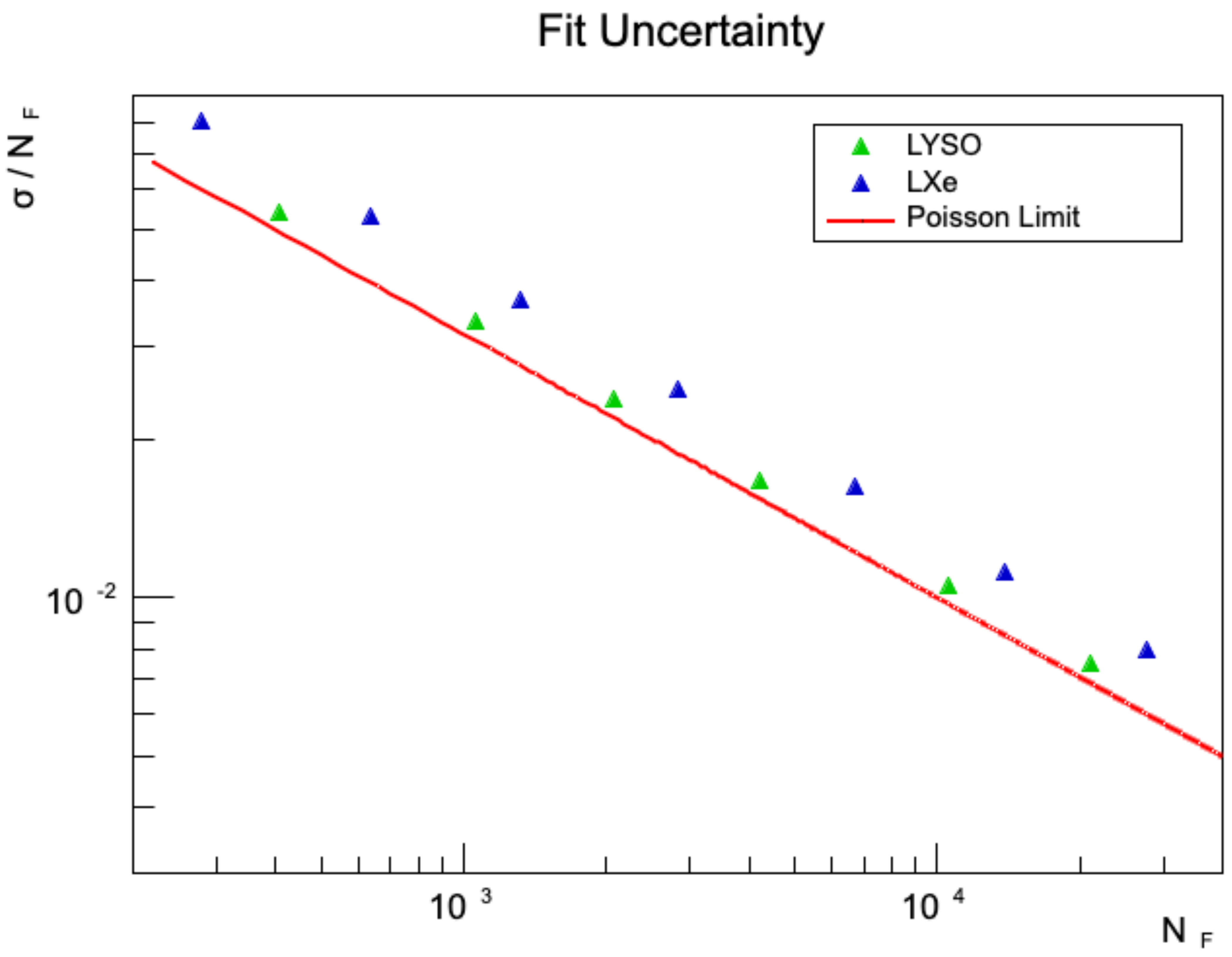
The simple analysis provides an accurate number for both detectors.

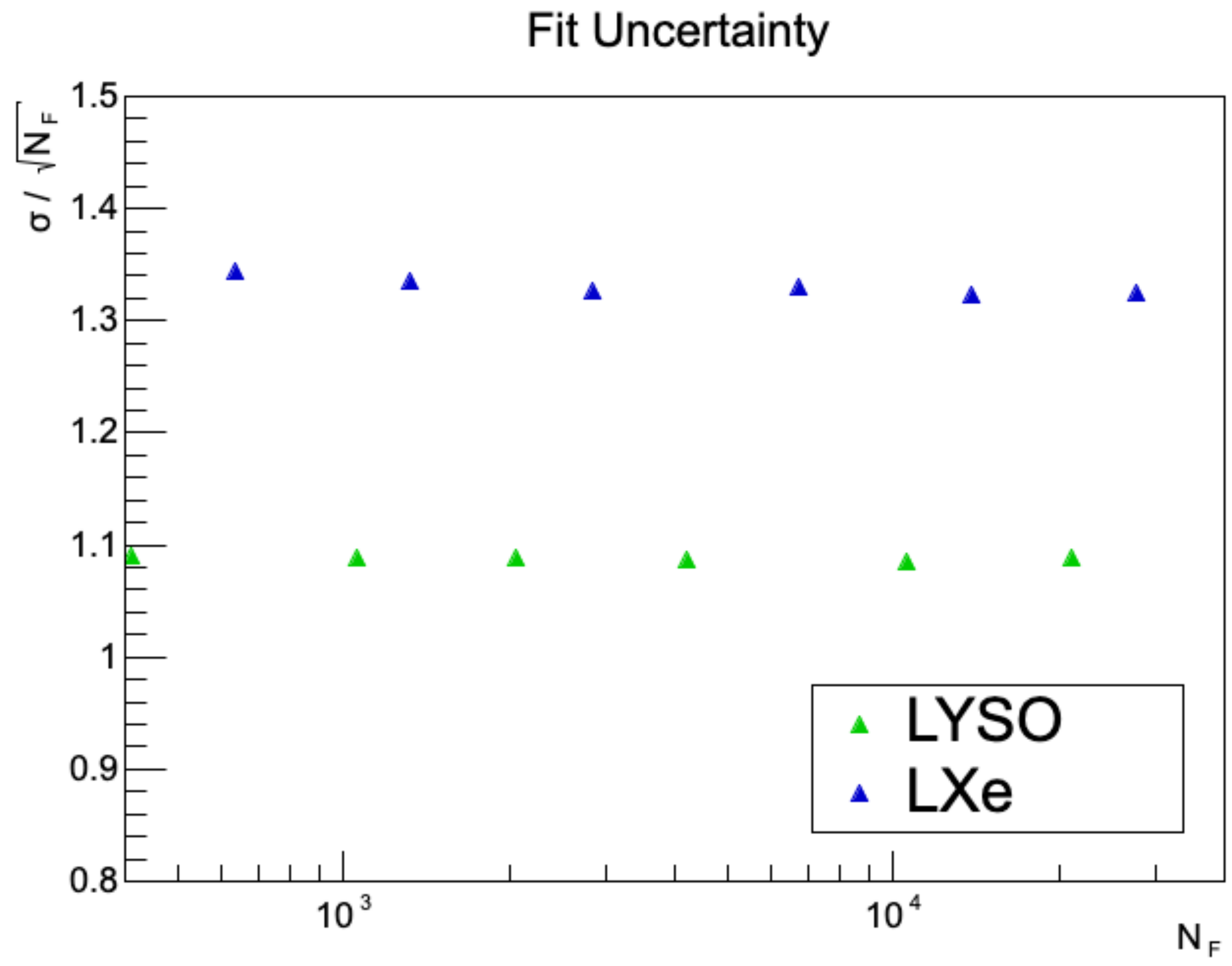


The datasets are correlated. Smaller sets are subsets of the larger ones.

High Fit Precision

N : Number of $\pi \rightarrow e\nu(\gamma)$ events counted after 5 ns (MC truth).
N_F: Number of $\pi \rightarrow e\nu(\gamma)$ events extracted from fit after 5 ns.

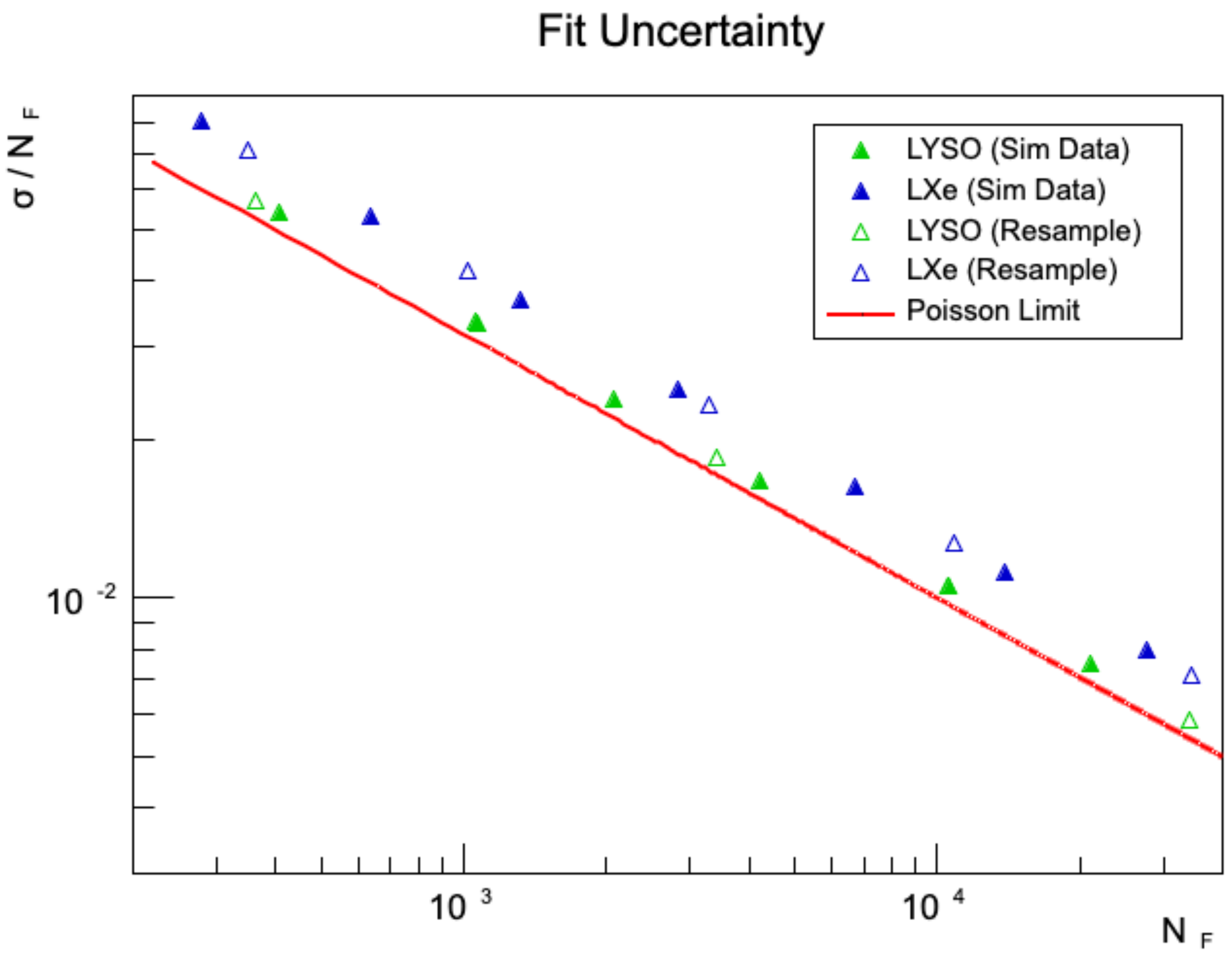




The higher pileup background for LXe results in a 22% performance degradation when it comes to fit result uncertainty.

High Fit Toy Model

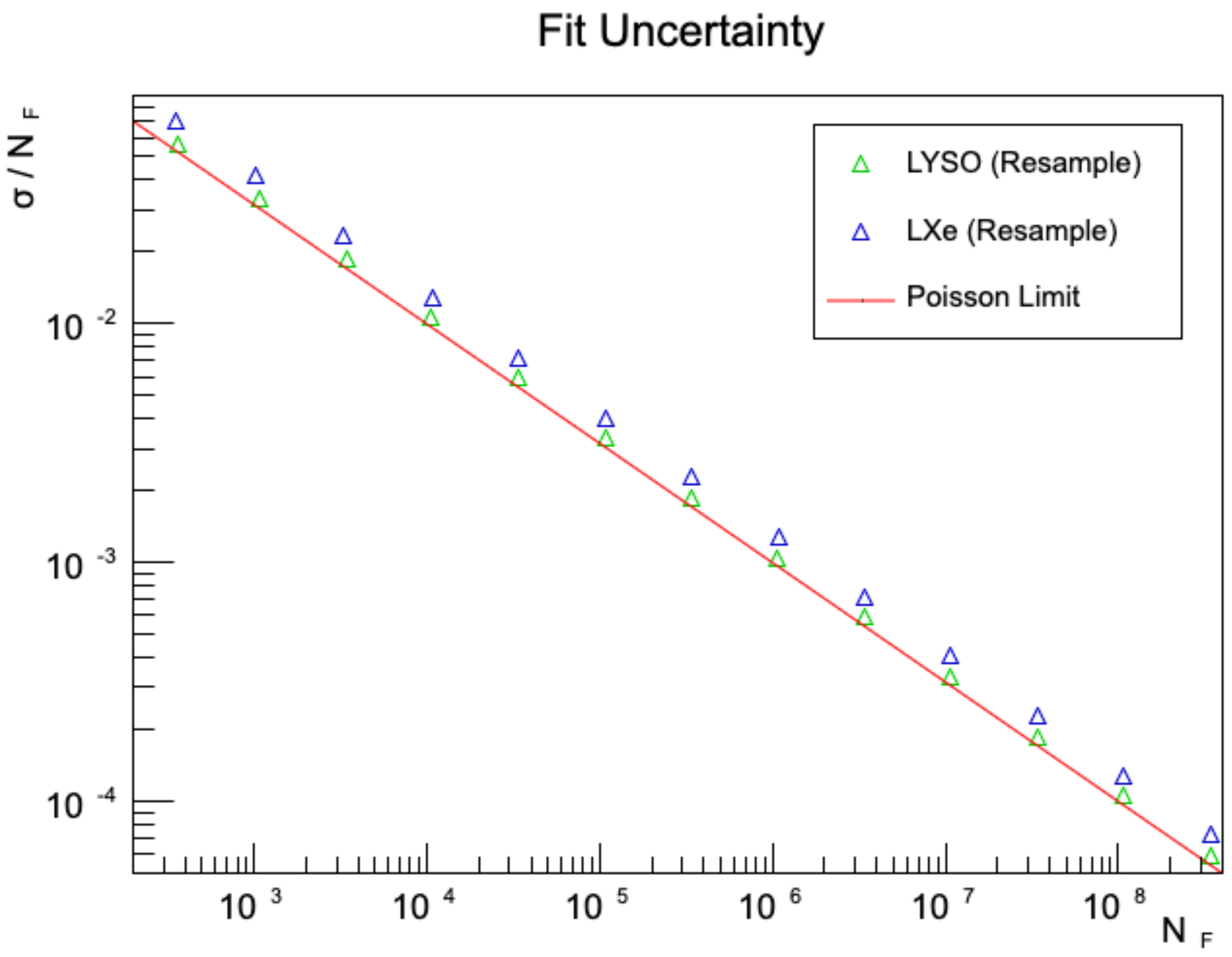
N : Number of $\pi \to e\nu(\gamma)$ events counted after 5 ns (MC truth).
N_F: Number of $\pi \to e\nu(\gamma)$ events extracted from fit after 5 ns.

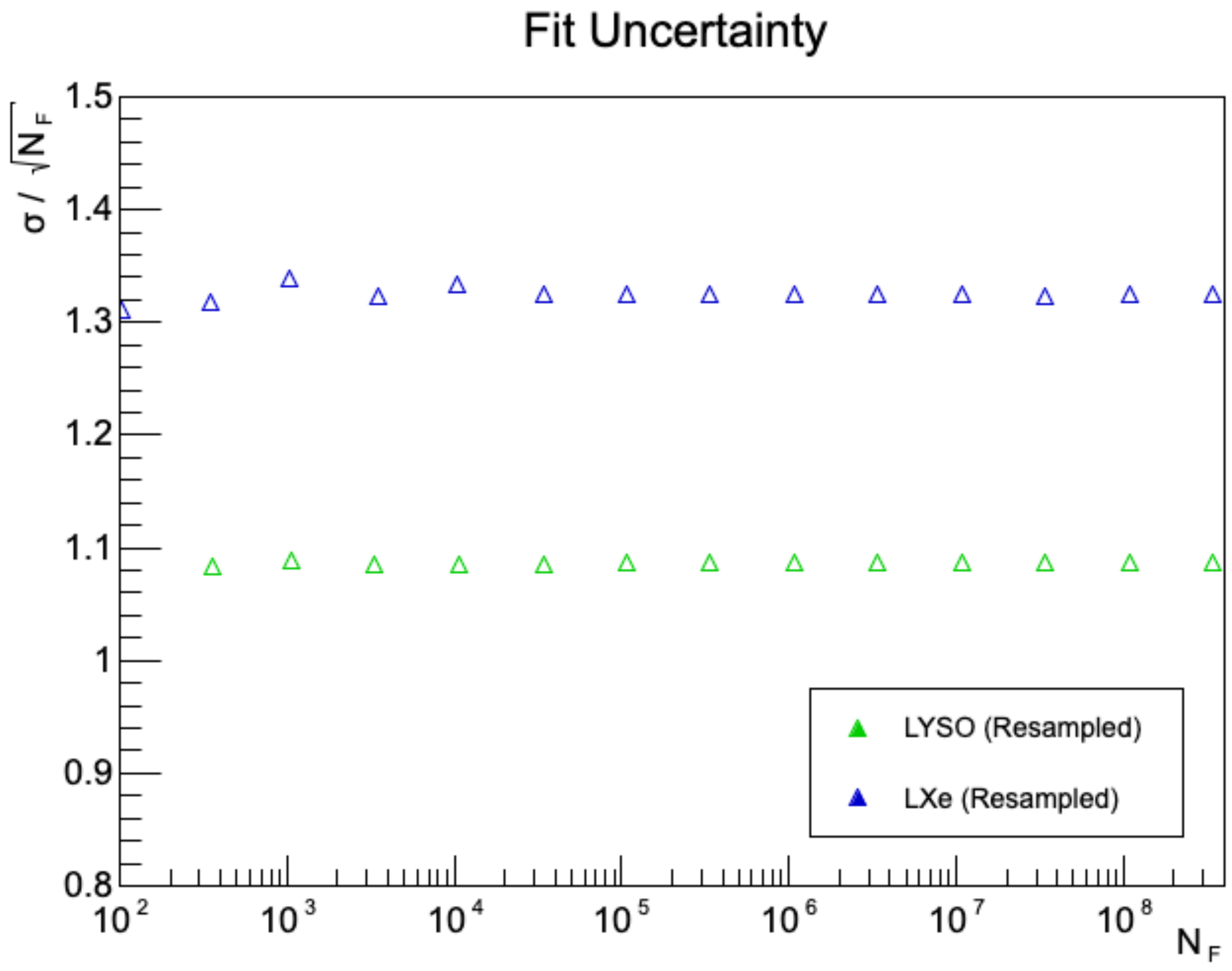


- Sample the fit function
$$n_H(t) = Ae^{-t/\tau_\pi} + B\frac{\tau_\mu}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\pi} - e^{-t/\tau_\mu}\right)$$
using obtained A and B values.
- Fit corresponding resampled histogram with the same method as real data.
- Resampled data show same behaviour as full simulation data.

High Fit Toy Model Extrapolated

N : Number of $\pi \to e\nu(\gamma)$ events counted after 5 ns (MC truth).
N_F: Number of $\pi \to e\nu(\gamma)$ events extracted from fit after 5 ns.

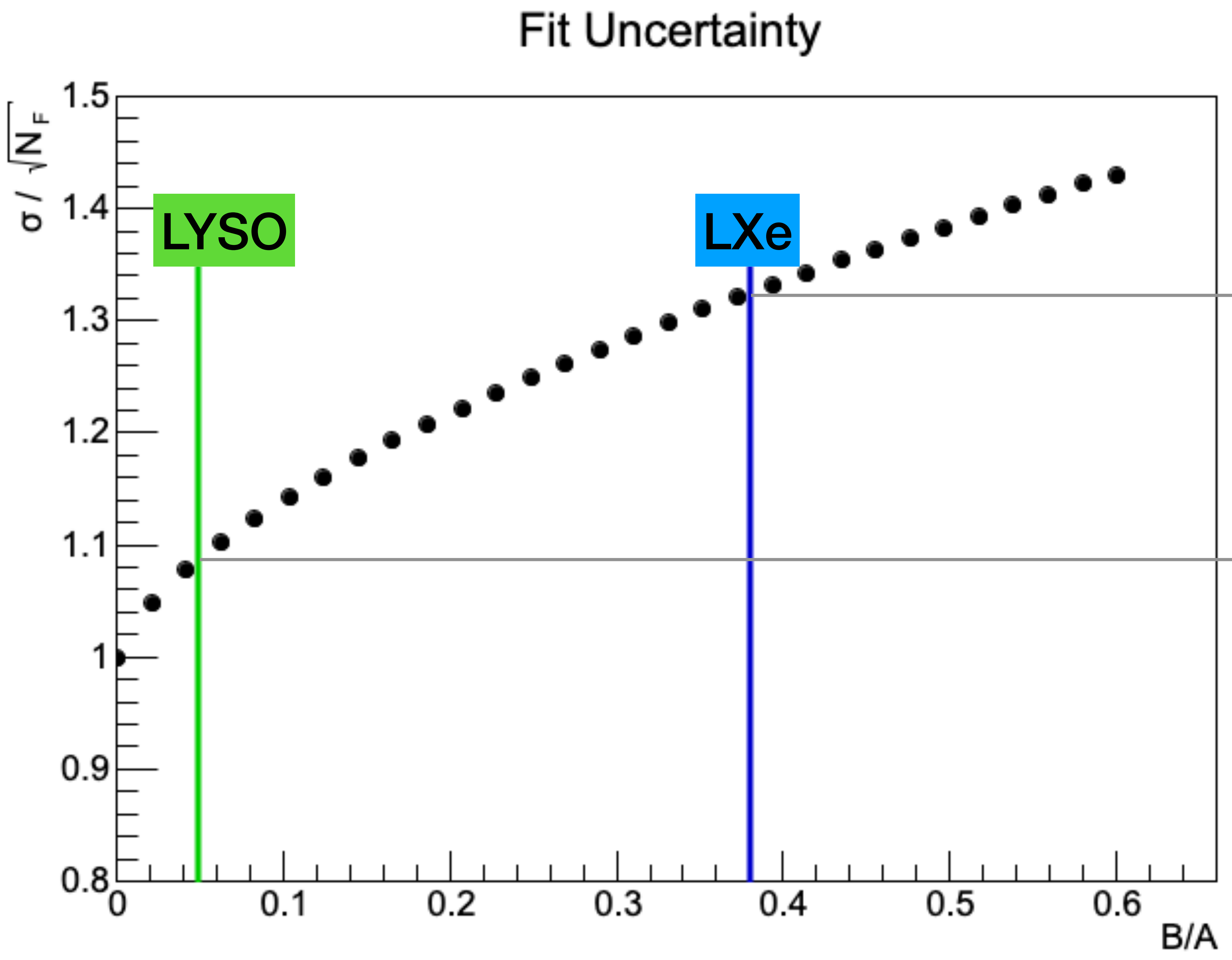


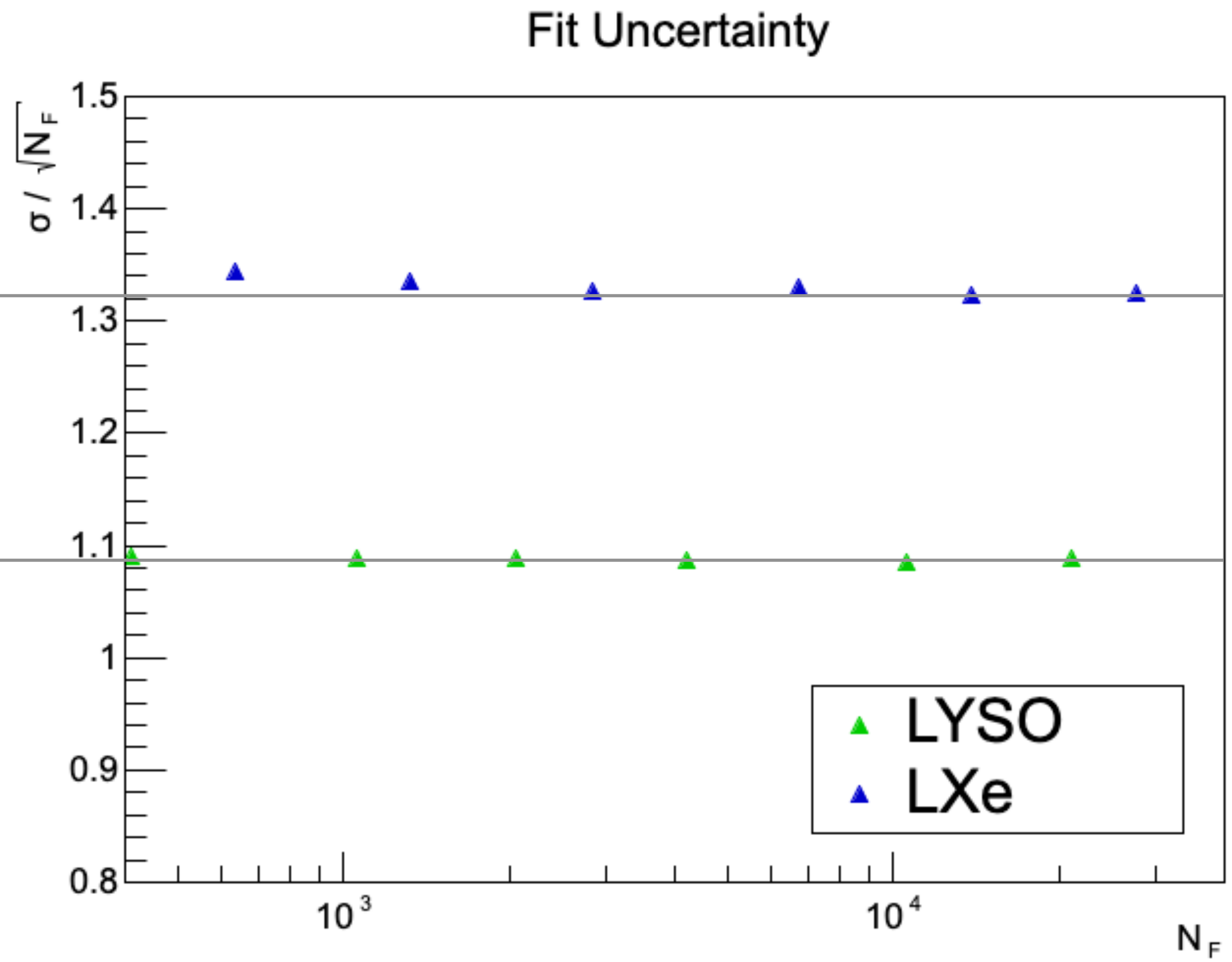


The simple fit model suggests that LXe requires about 49% more data to reach the same uncertainty in number of $\pi \to e\nu(\gamma)$ events

Effect of Background on Fit Uncertainty

Resample fit function with obtained A and variable B value





$$n_H(t) = Ae^{-t/\tau_\pi} + B\frac{\tau_\mu}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\pi} - e^{-t/\tau_\mu}\right)$$

N : Number of $\pi \to e\nu(\gamma)$ events counted after 5 ns (MC truth).

N_F: Number of $\pi \to e\nu(\gamma)$ events extracted from fit after 5 ns.

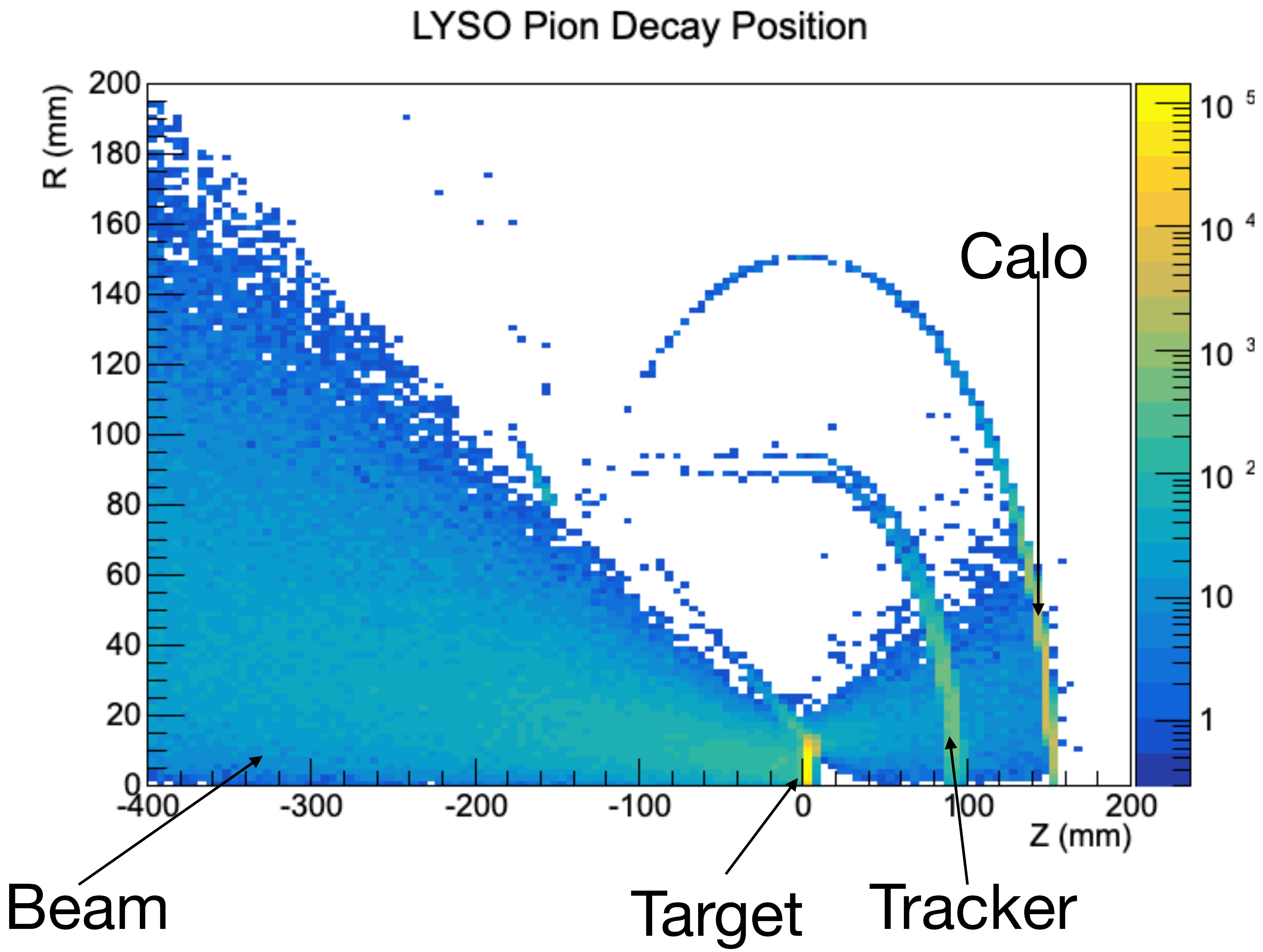
Conclusion

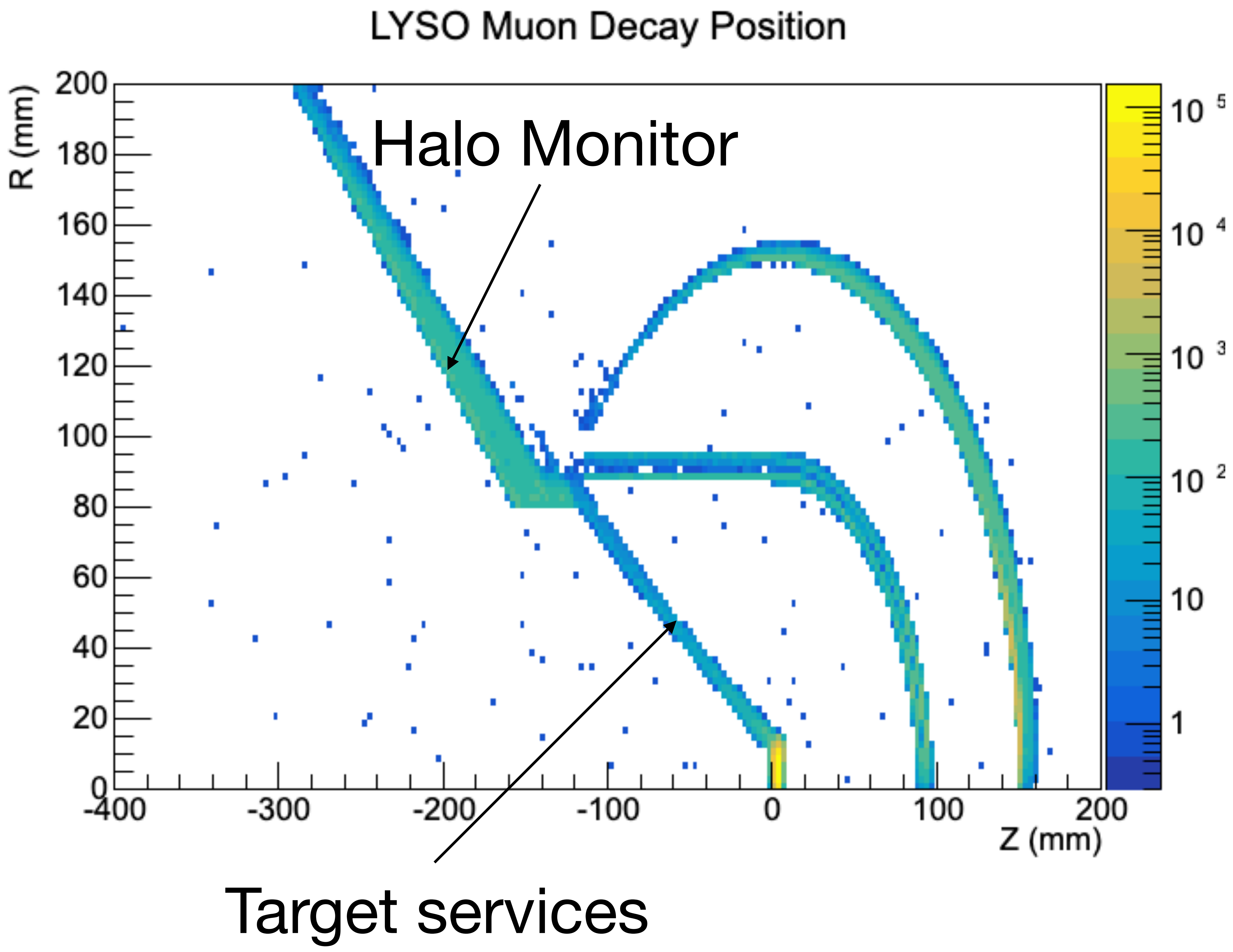
- Presented the most comprehensive comparison achievable at present time.
- Two main differences have been identified:
  - **Beam aperture**: Due to the longer distance between last quad and ATAR, a worse focus will be achieved for **LXe**. This reduces the pion on target yield and requires a 47% longer runtime to accumulate the same statistics compared to **LYSO**. It also increases background due to particle missing ATAR.
  - **Pileup contamination**: As the calorimeter reconstruction for **LXe** does currently not have any ability to mitigate pileup, it contributes significantly to the high bin, degrading the fit uncertainty. This requires 49% more statistics to obtain the same statistical uncertainty as **LYSO**.
- The simulation could not find any significant difference in terms of peak resolution or tail fraction. The latter depends on photo-nuclear effects that are currently modelled with unknown precision.

Backup slides

Resulting Pion and Muon Decay Positions

For the LYSO geometry



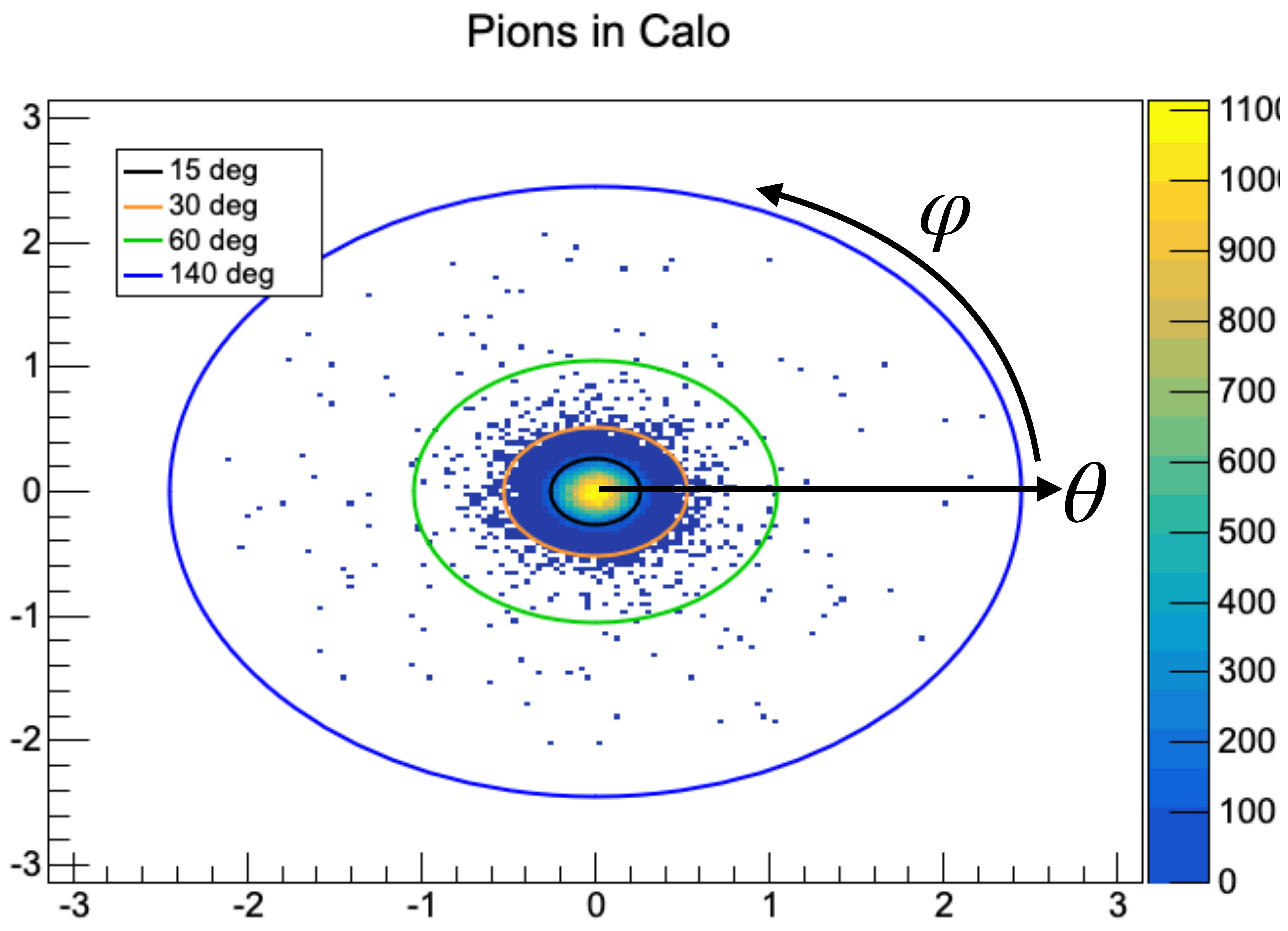


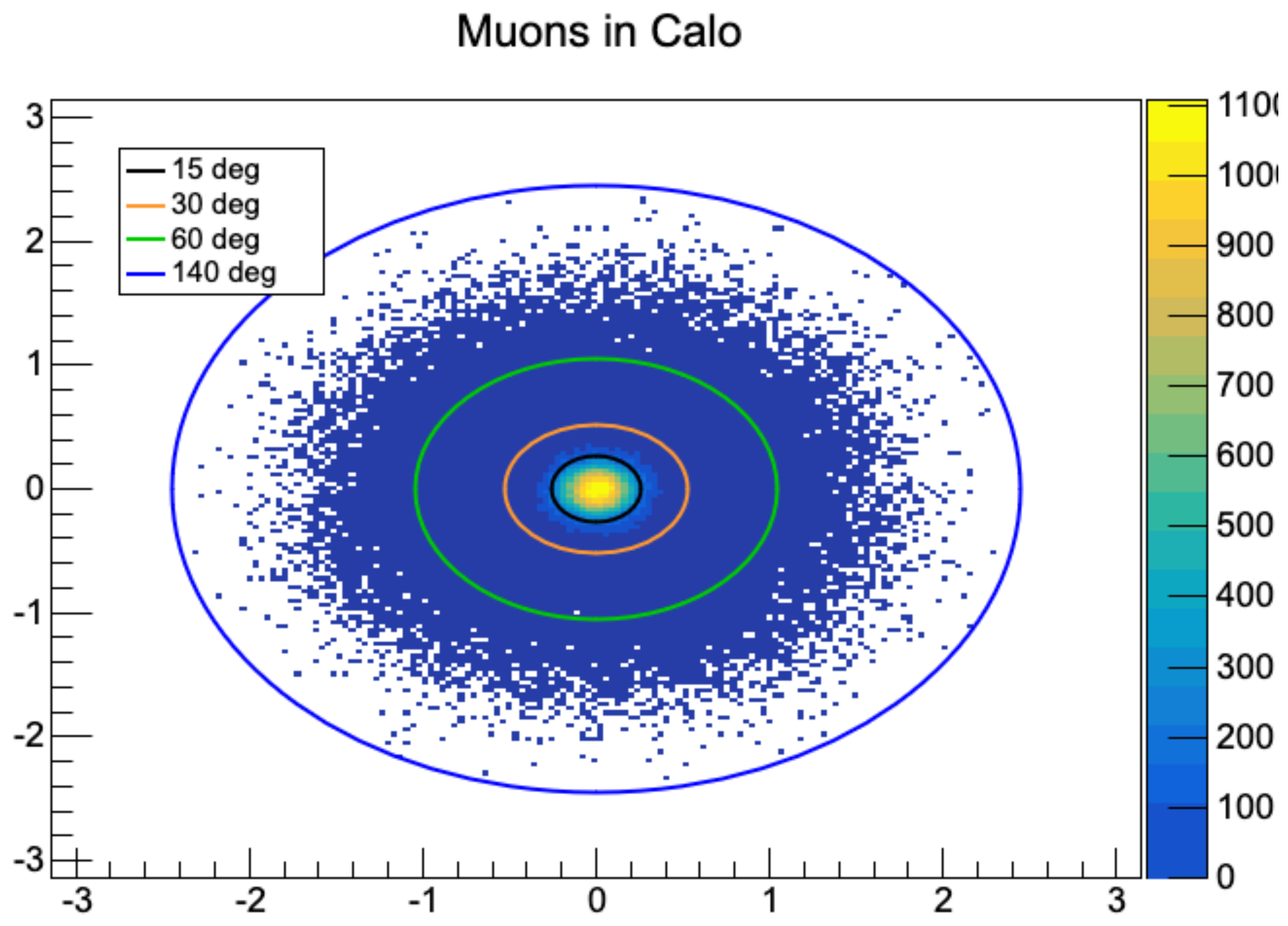
Resulting Pion and Muon Decay Positions

For the LXe geometry

Muon and Pion Distribution in Calorimeter

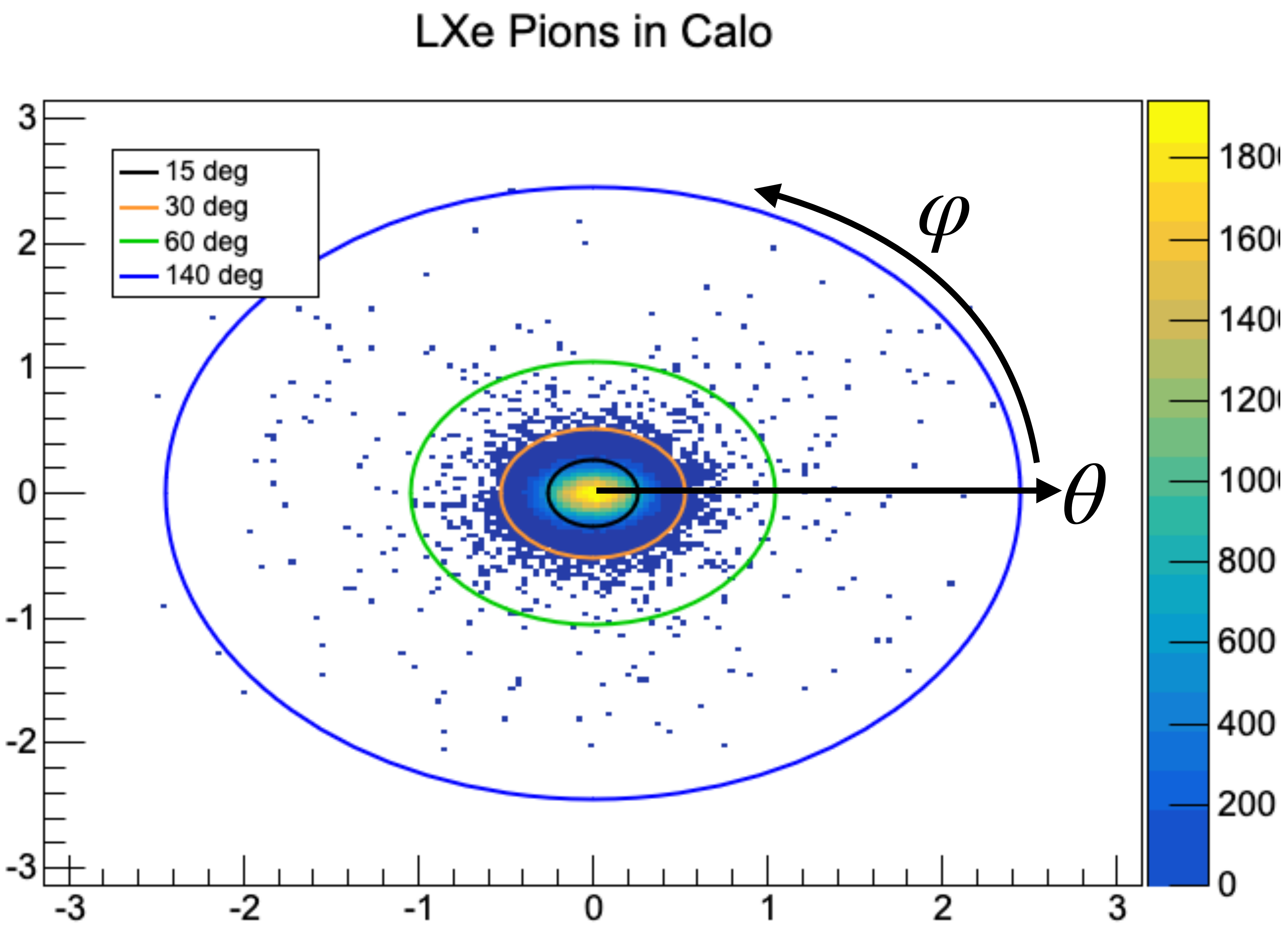
For the LYSO geometry

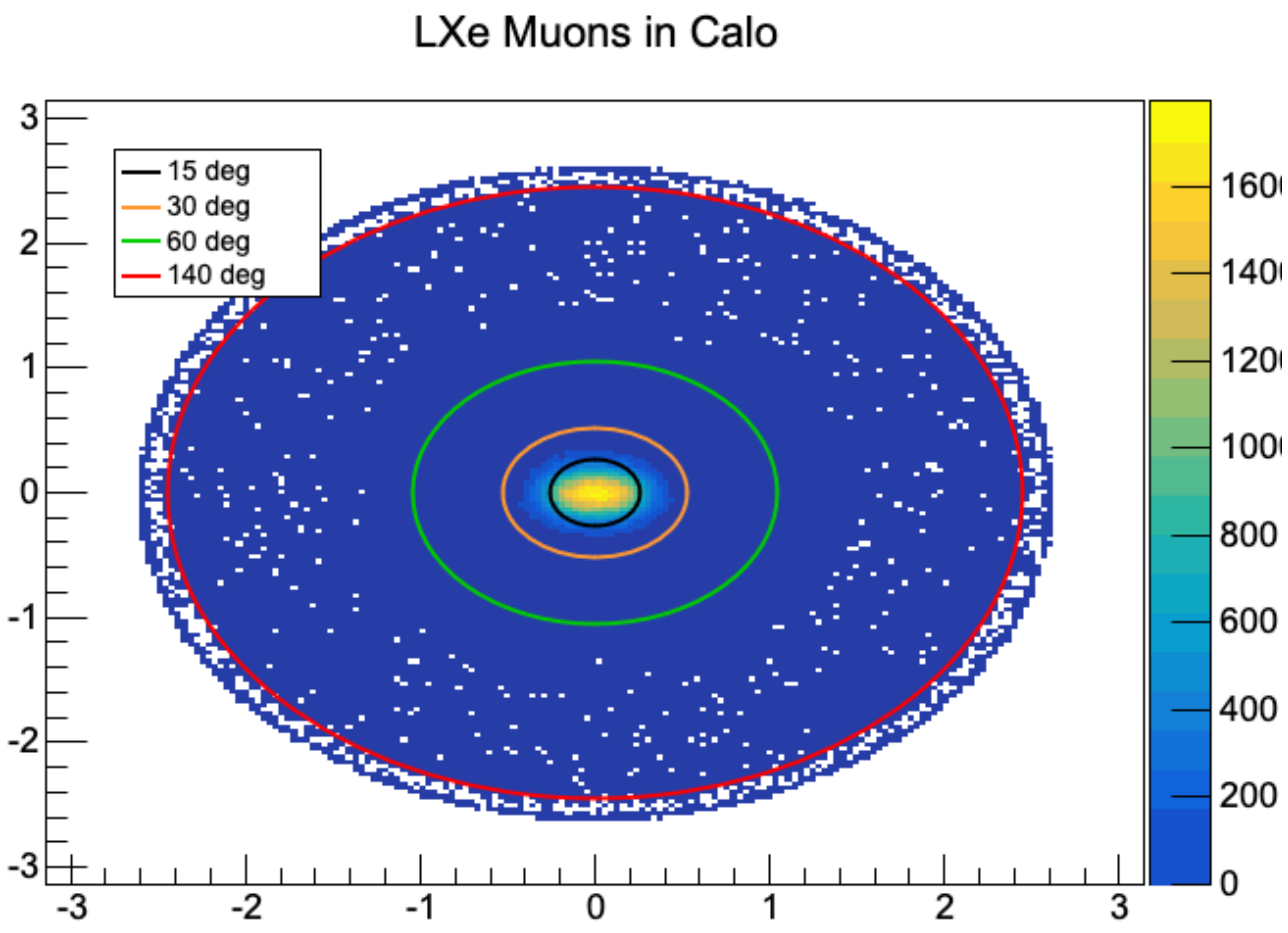




Muon and Pion Distribution in Calorimeter

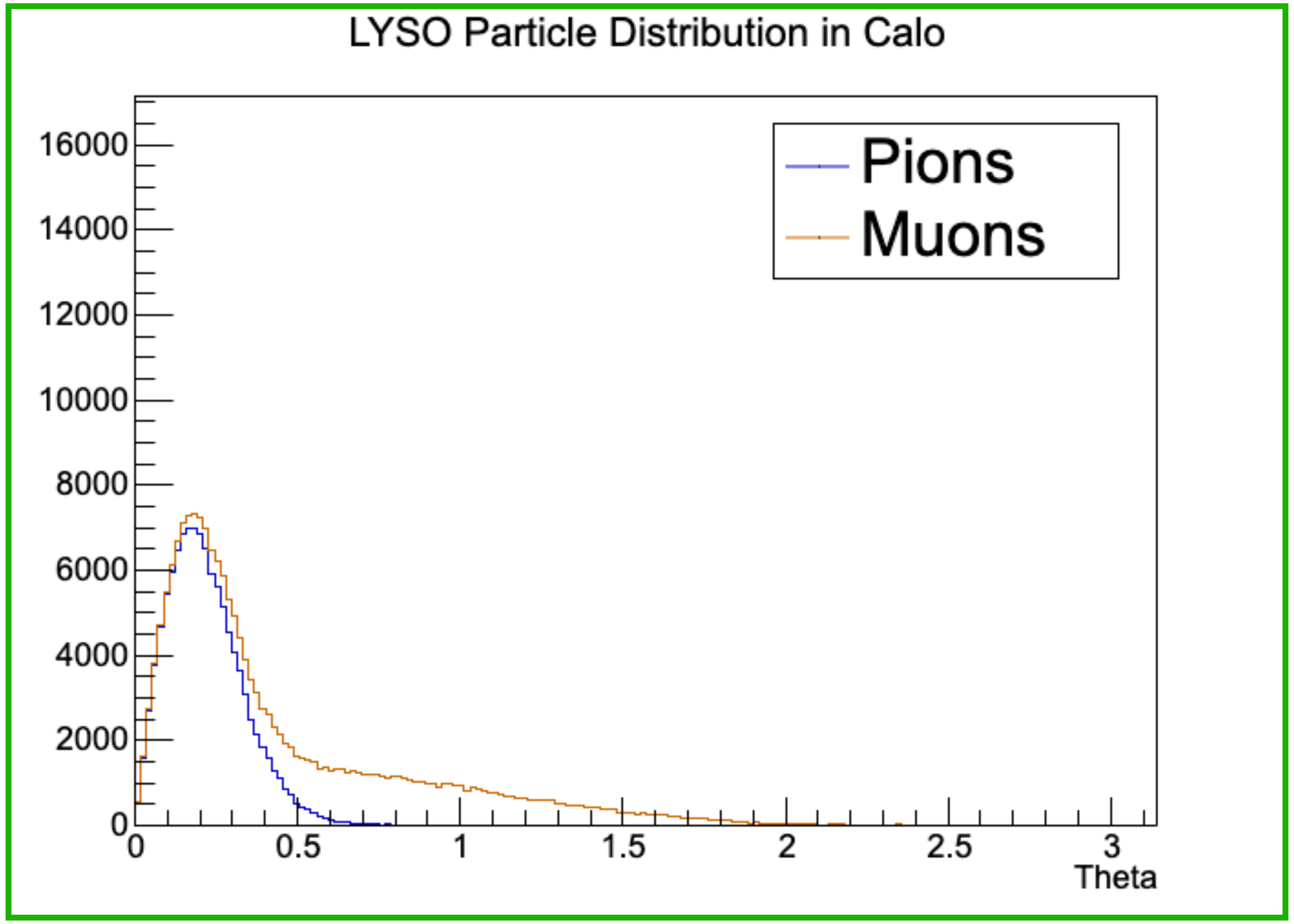
For the LXe geometry

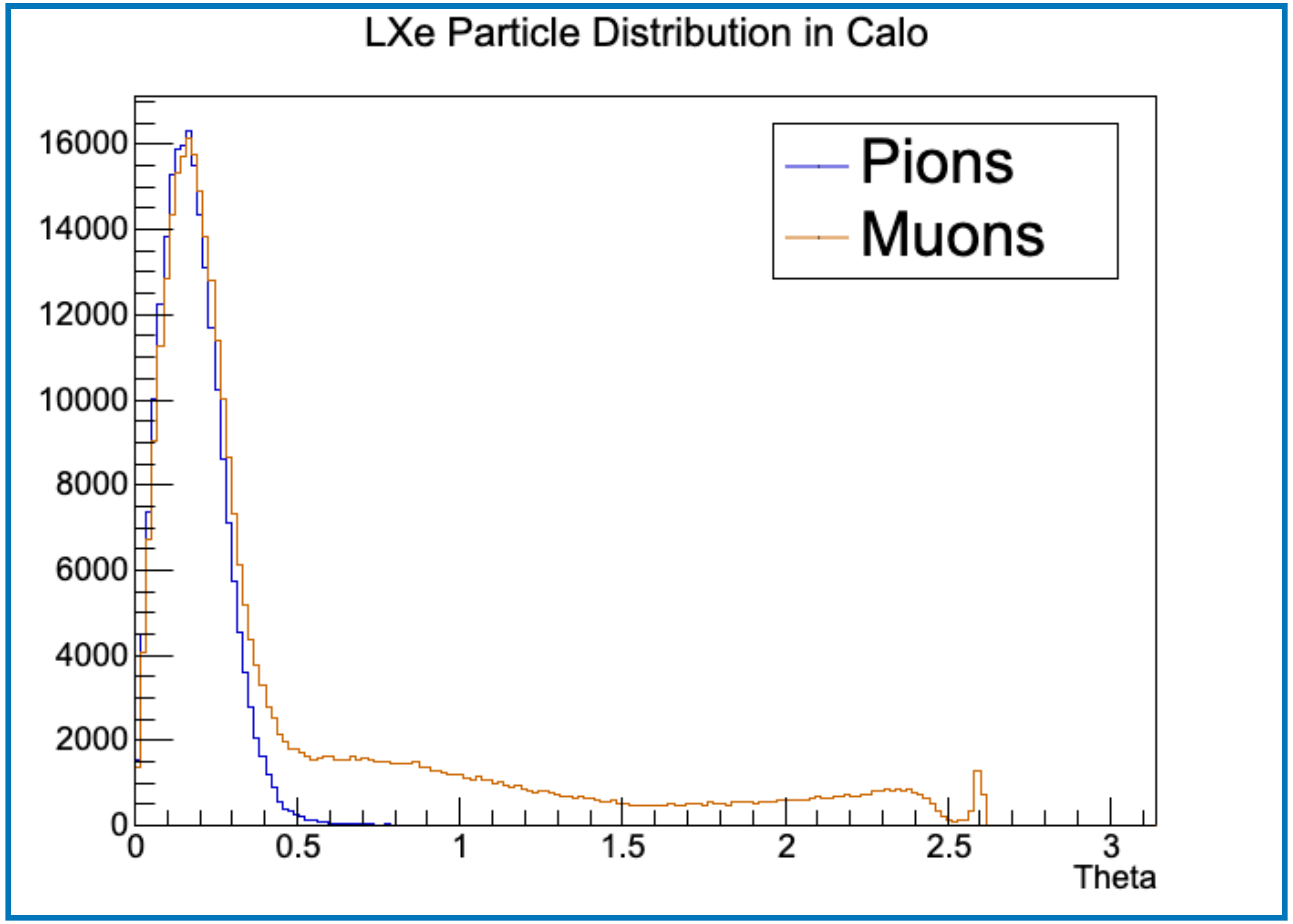




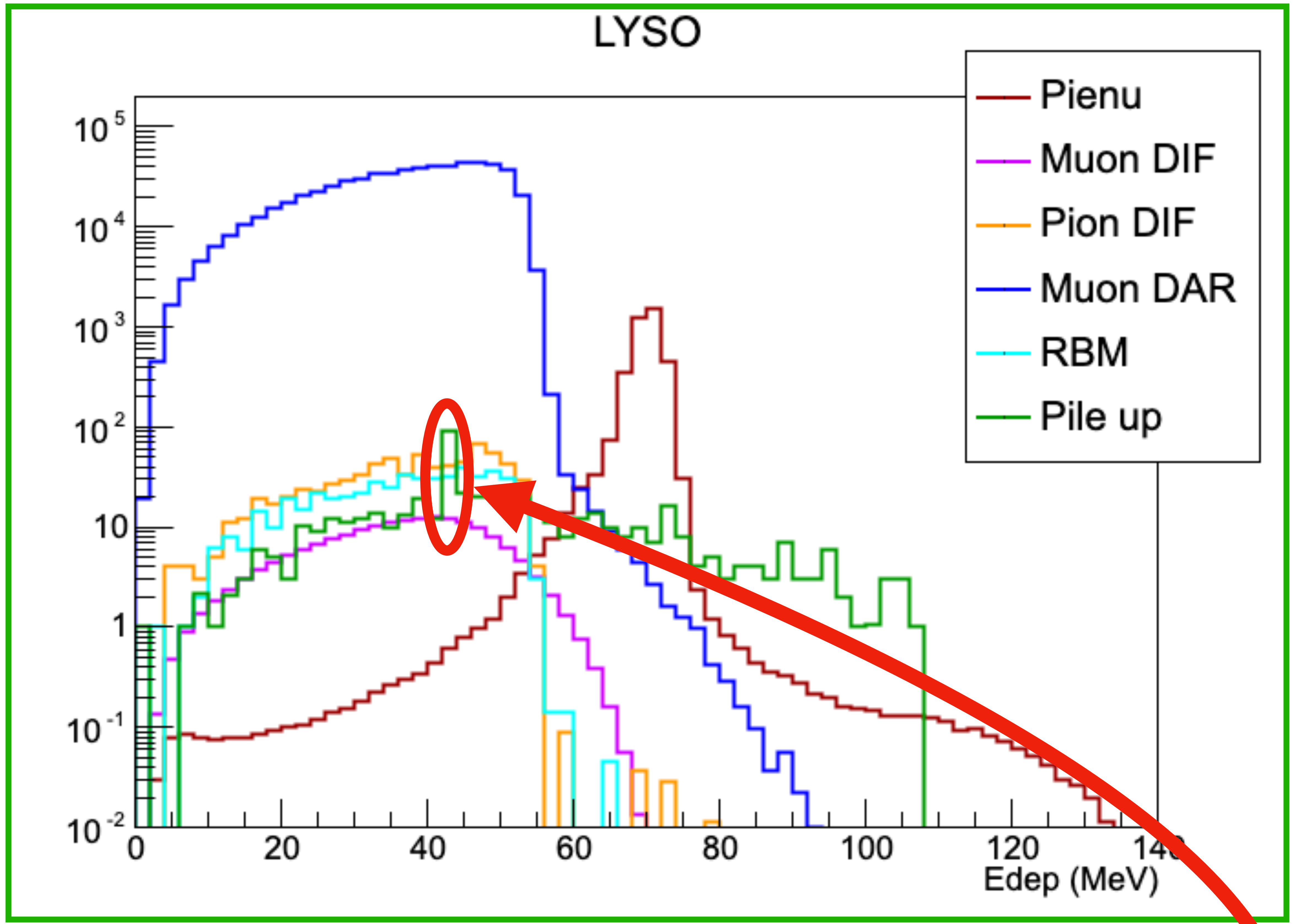
Particle Distribution in Calo

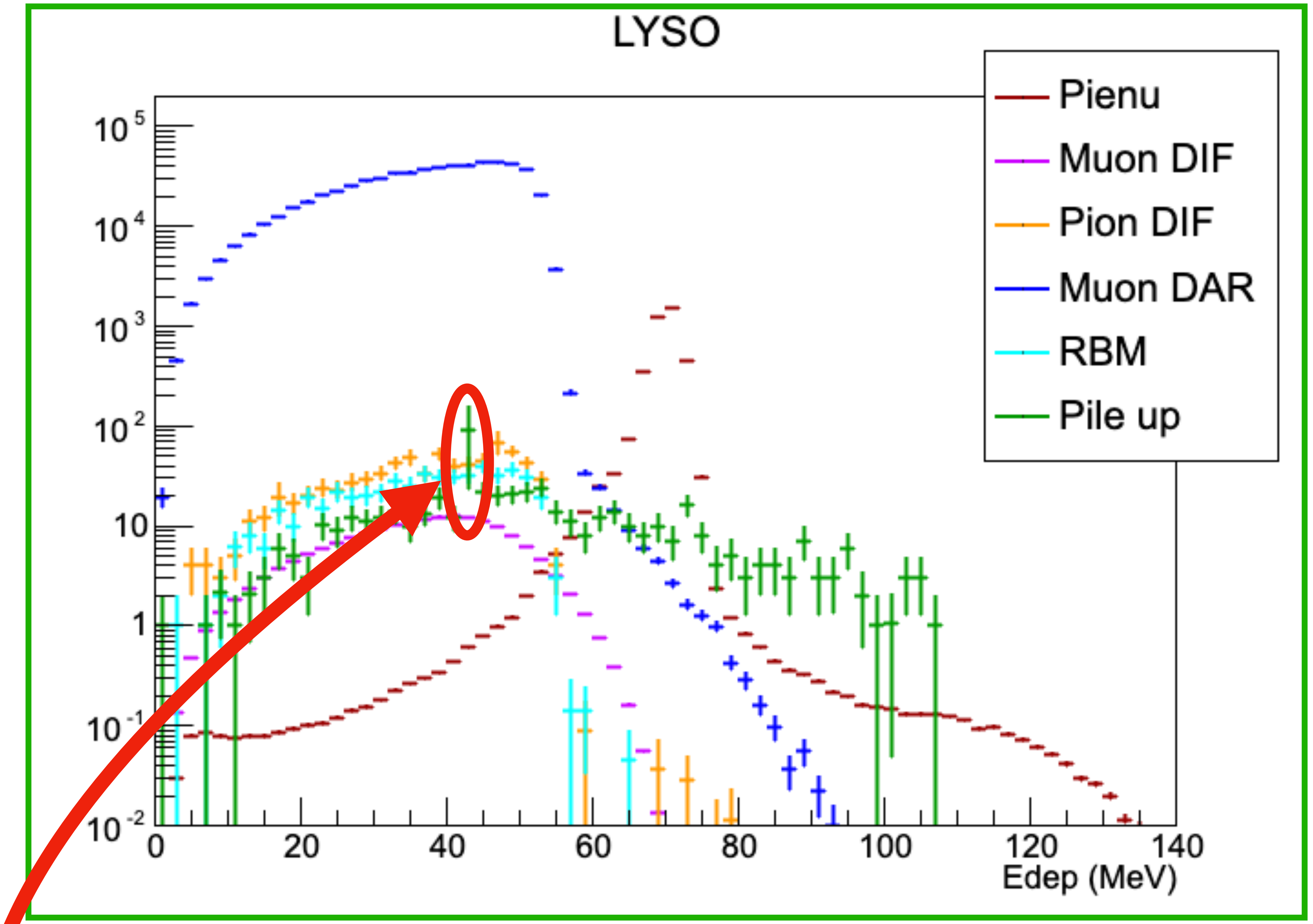
Theta Projection





Statistical fluctuations in rad muon decay

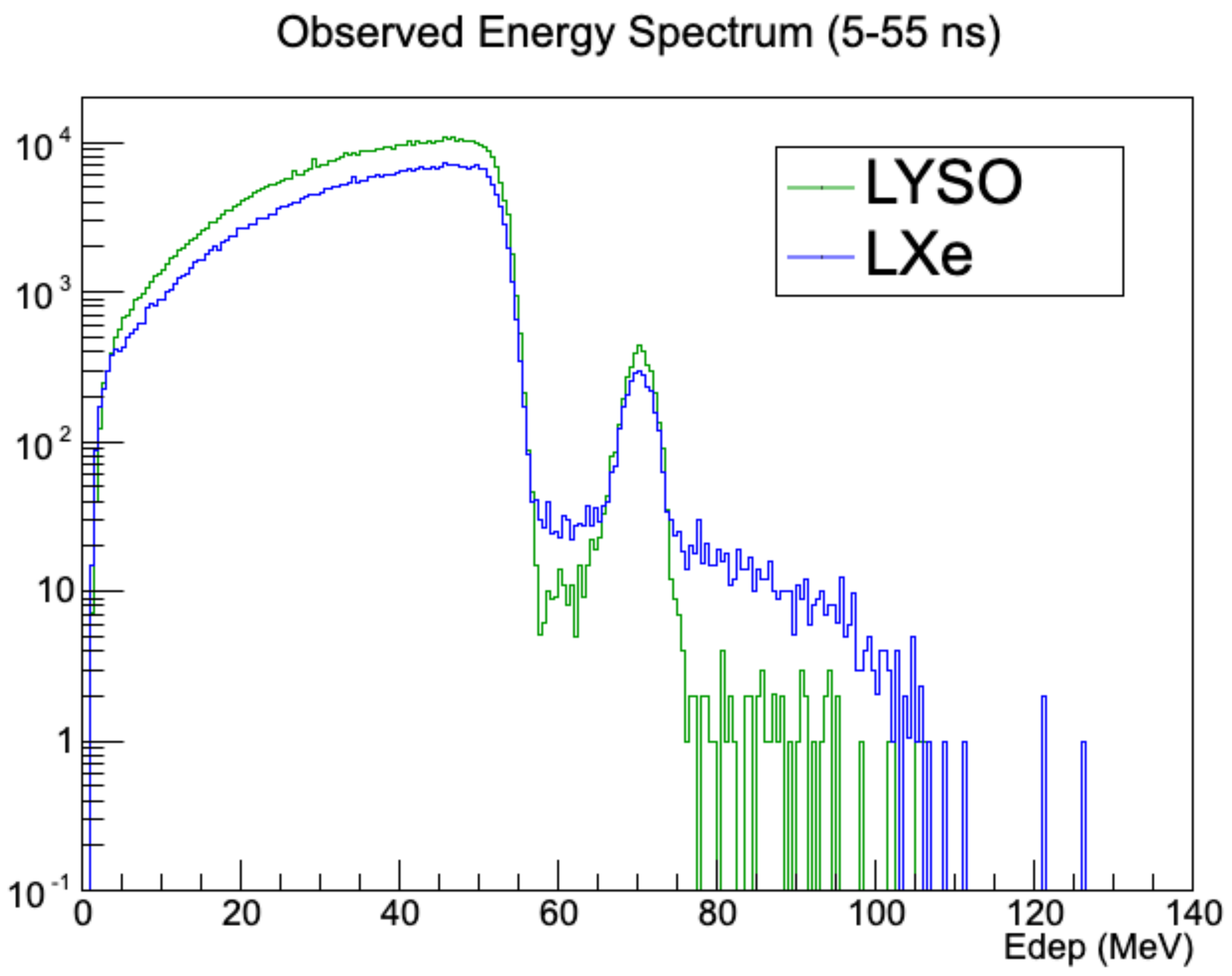


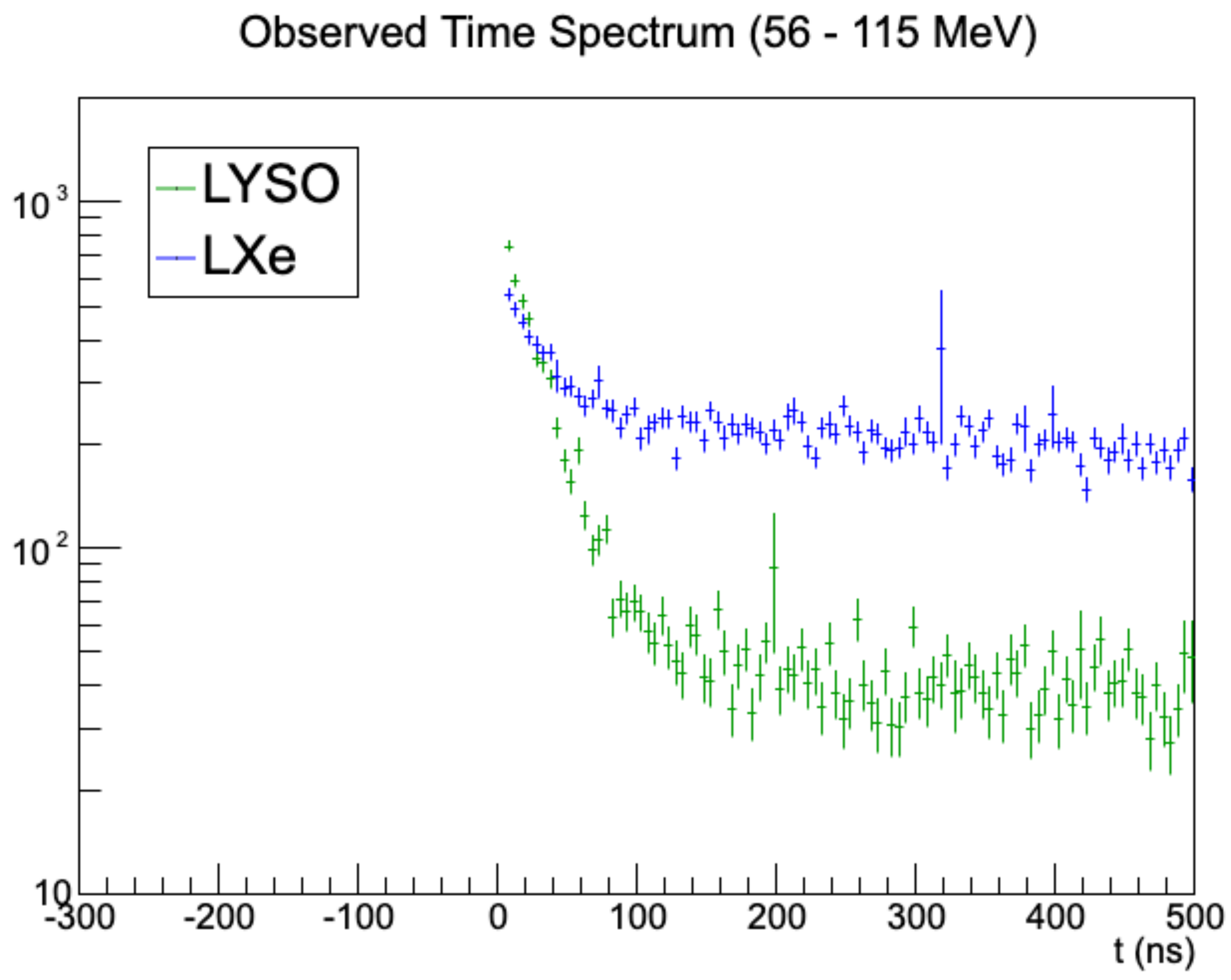


Collinear and soft singularities in $\mu \rightarrow e\nu\bar{\nu}\gamma$ differential decay rate can result in large bin values with large uncertainty for low stats bins

Observed Spectrum comparison

A: Same beam rate

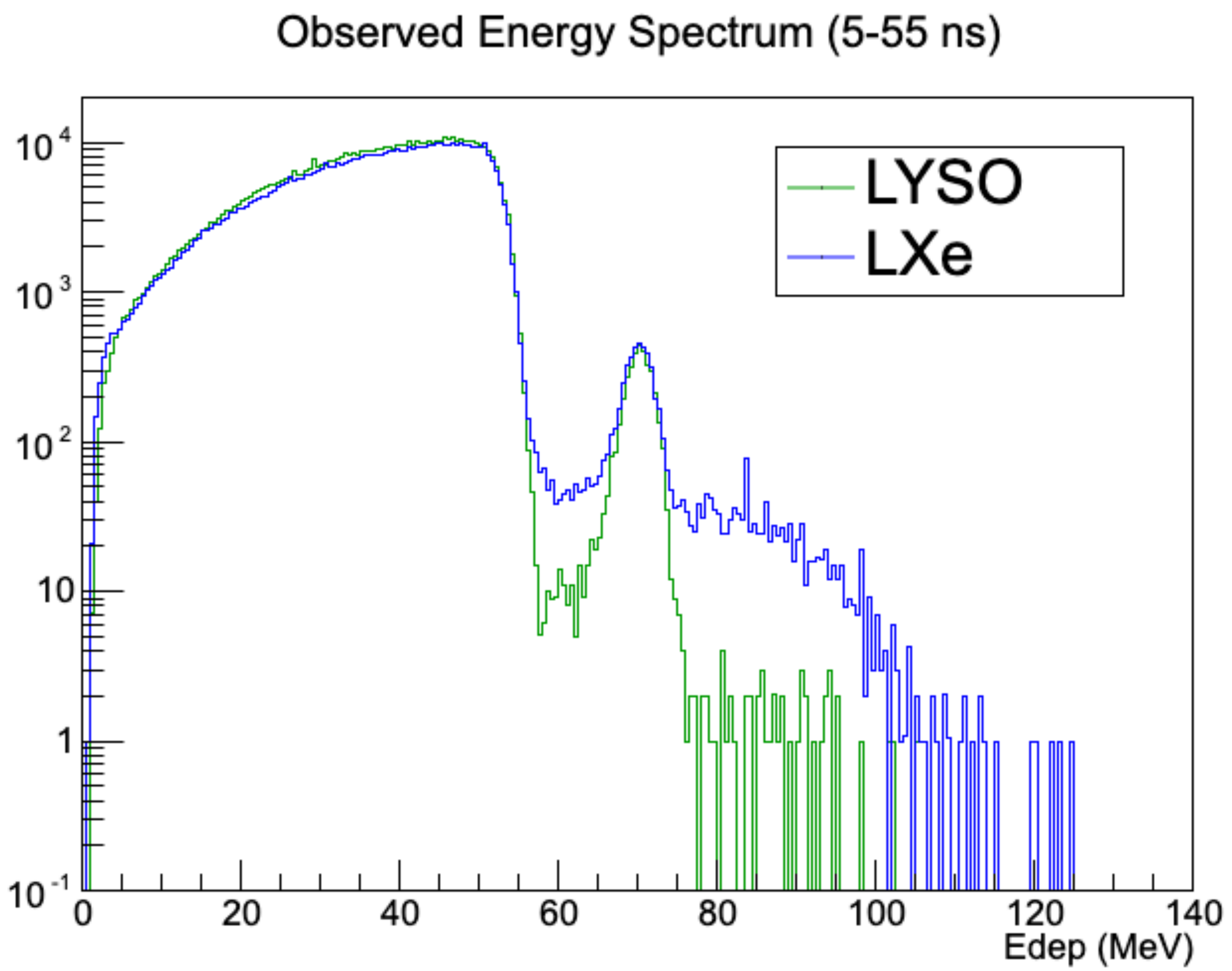


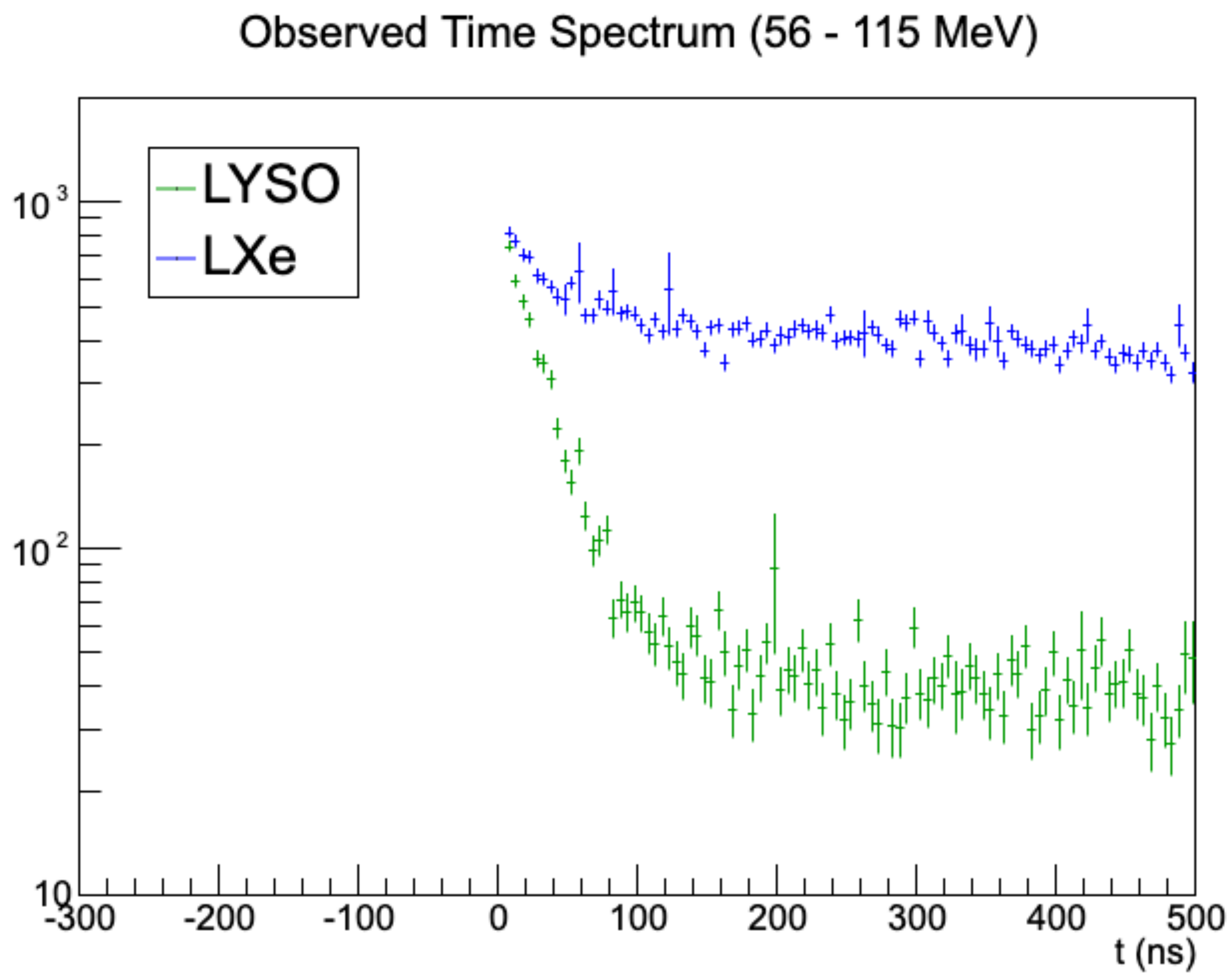


LYSO provides better statistics (beam) and cleaner spectrum (segmentation)

Observed Spectrum comparison

B: Same Stats

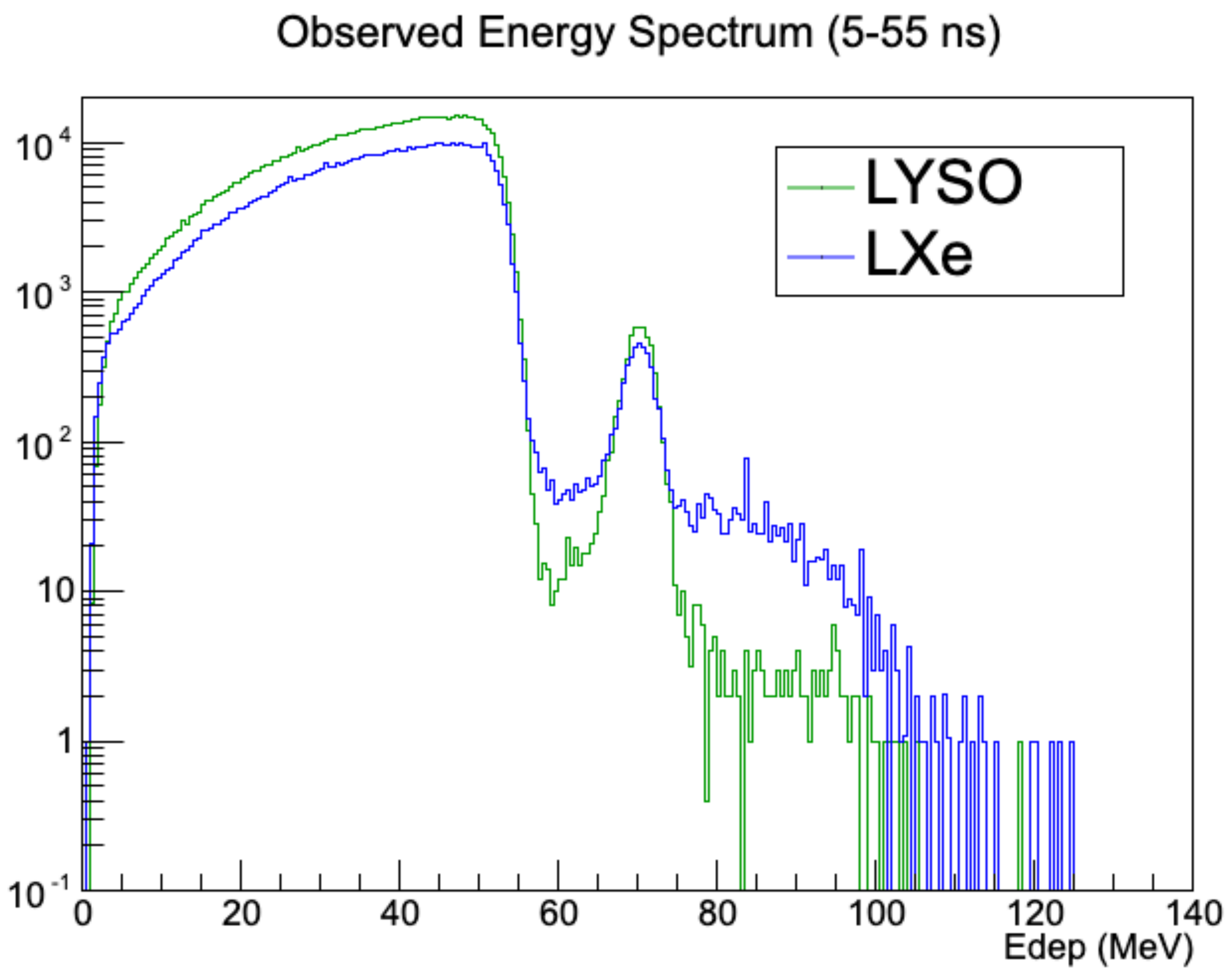


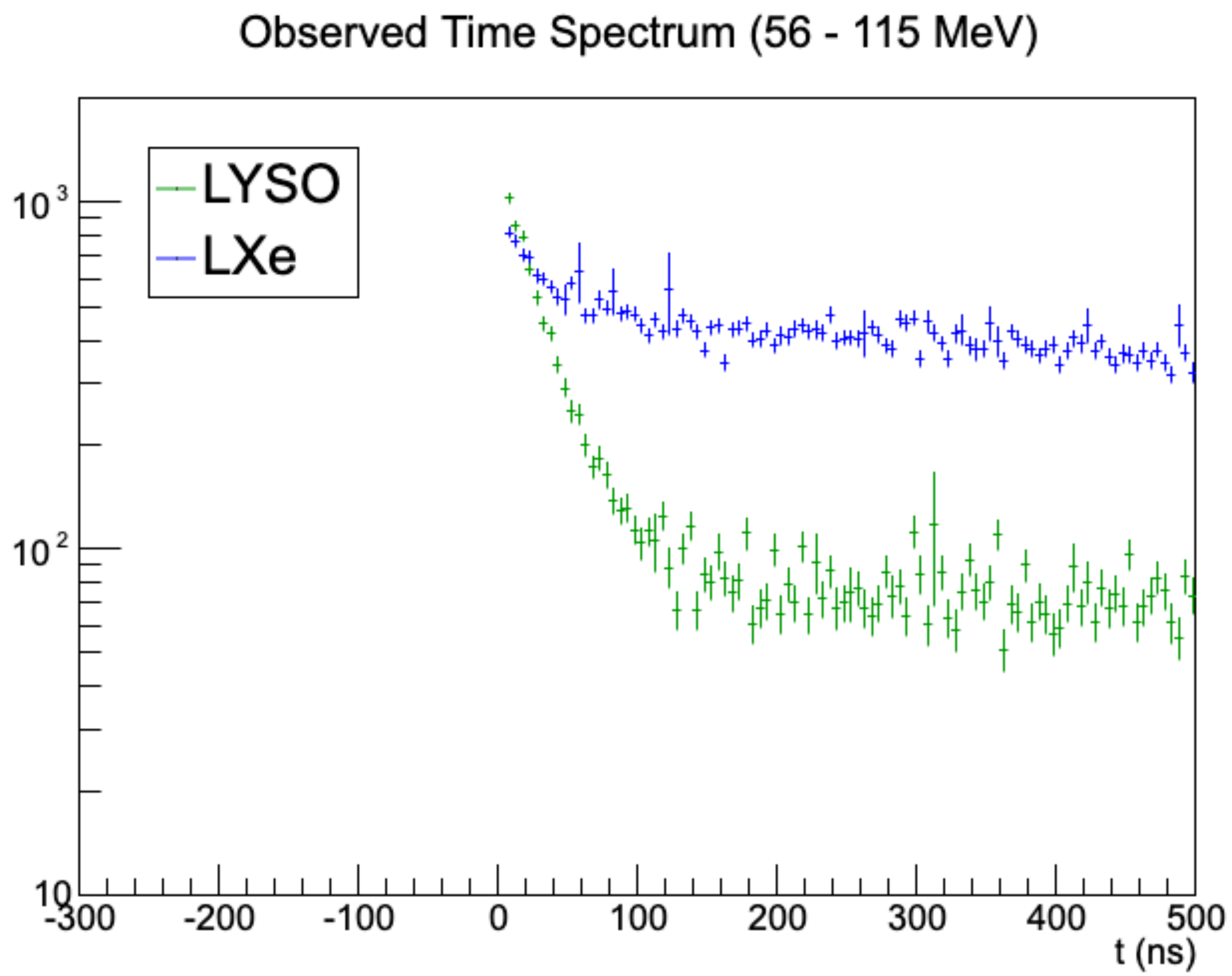


LYSO provides better statistics (beam) and cleaner spectrum (segmentation)

Observed Spectrum comparison

C: High beam rate

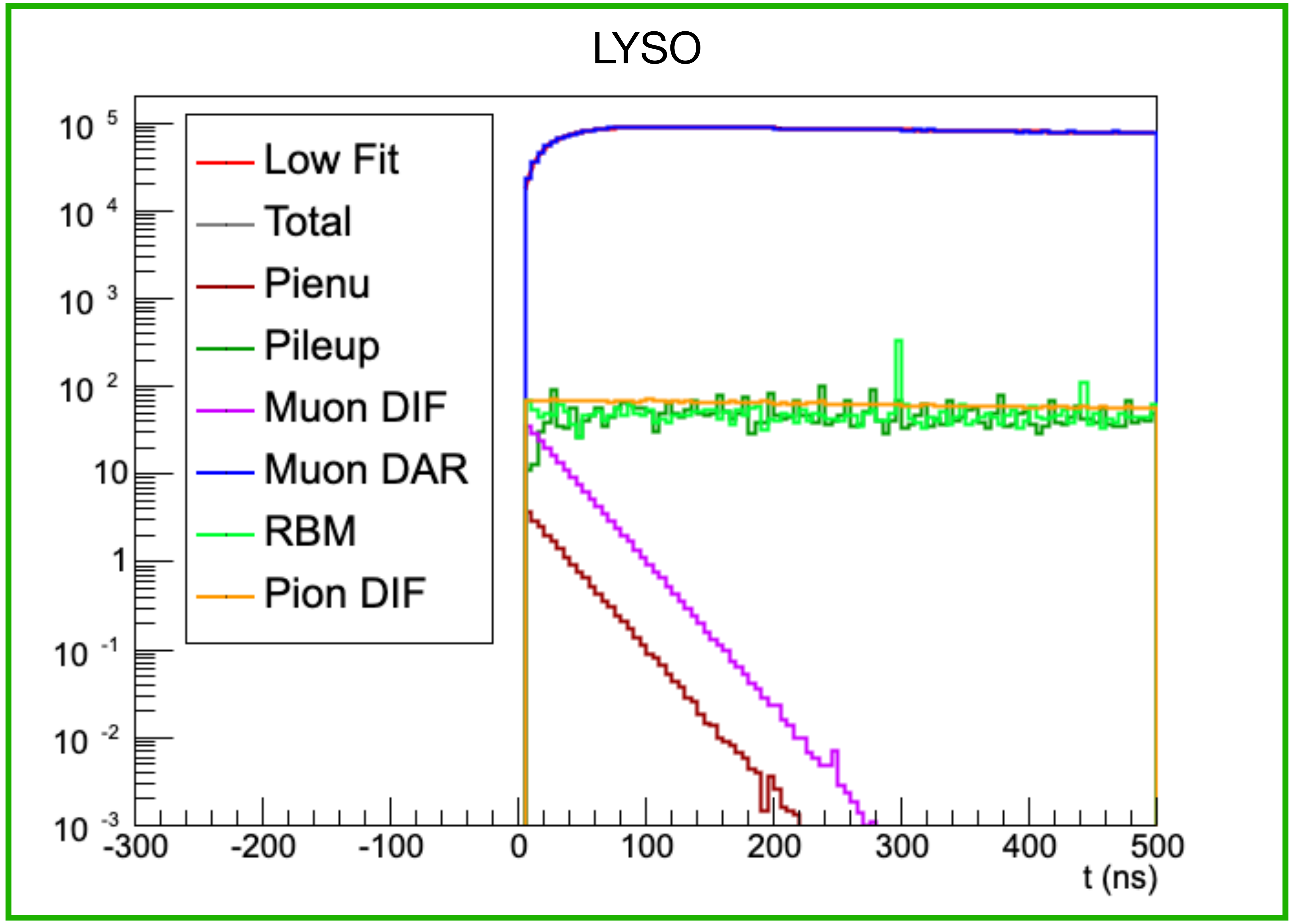


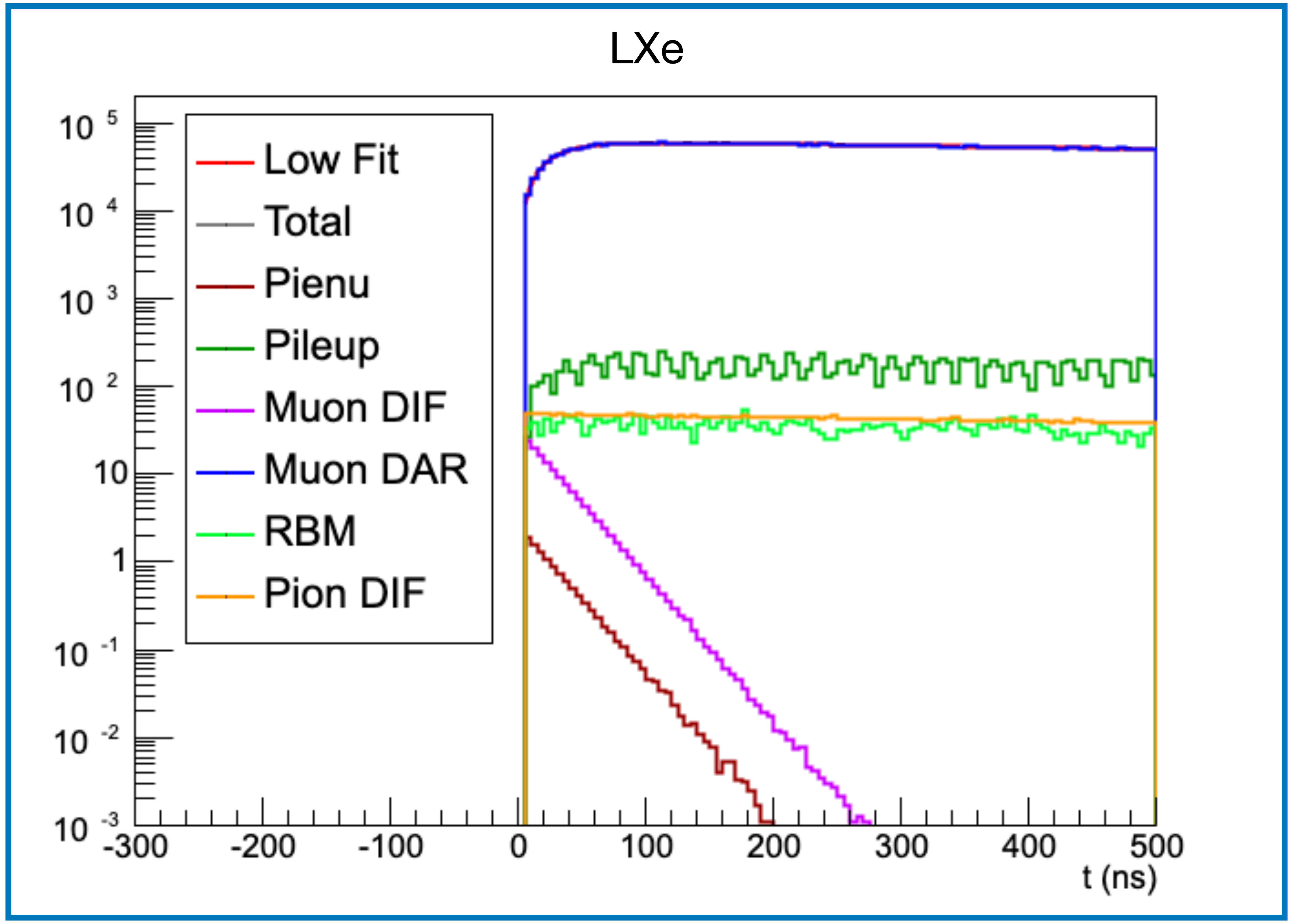


LYSO provides better statistics (beam) and cleaner spectrum (segmentation)

Low Energy Time Spectra

Same beam rate, 0 - 56 MeV





Low energy regime defined by Muon decay at rest spectrum. Beam pileup becomes a notable effect with its own distinct time spectrum (50.6 MHz).