Simulations to optimize the PIONEER liquid xenon calorimeter

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Introduction : PIONEER physics

Lepton flavour universality (LFU) is a symmetry of the standard model (SM). This symmetry means that the weak charged coupling constant, g, is equal for the three lepton flavours: $g_e = g_\mu = g_\tau$. However, some recent results hint at a potential LFU discrepancy between theory and experiment. One portal to improve the theory to experiment comparison is rare pion decays. The goal of the PIONEER Experiment is a precision measurement of the rare pion decay as indicated in Figure 1.

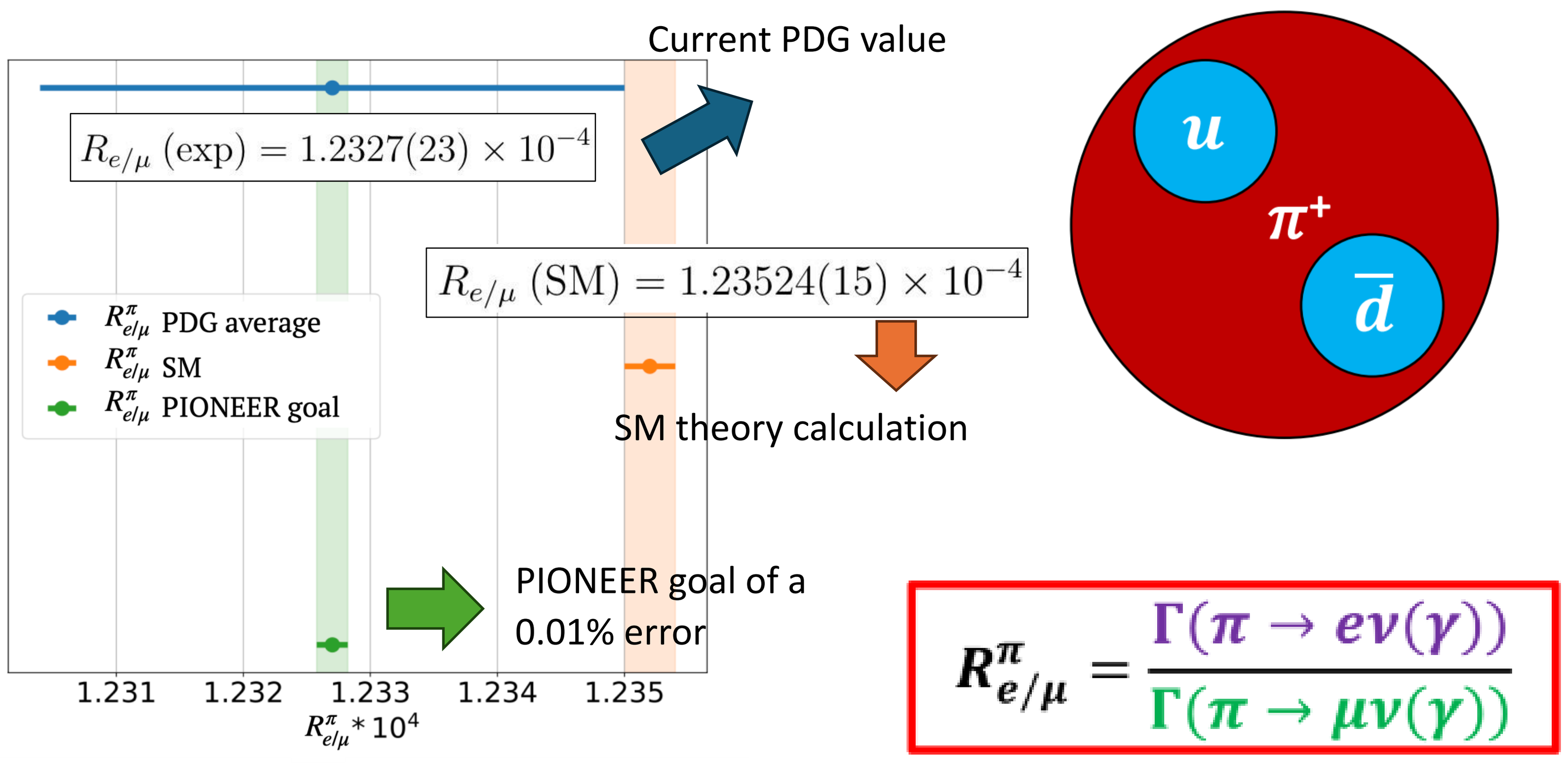

Figure 1: Current measurement of pion branching ratio, the SM prediction, and the PIONEER goal.

Rare pion decay

LFU is tested using the branching ratio for pion decay to positrons over muons, where $\Gamma(\pi^+ \to e^+\nu(\gamma))$ is the decay rate of the pion to positron, and similarly for the pion to muon as shown in Figure 2. The pion decay to muons is much more likely than to positrons, the measured energy spectrum of the decays is used to discriminate between them [1].

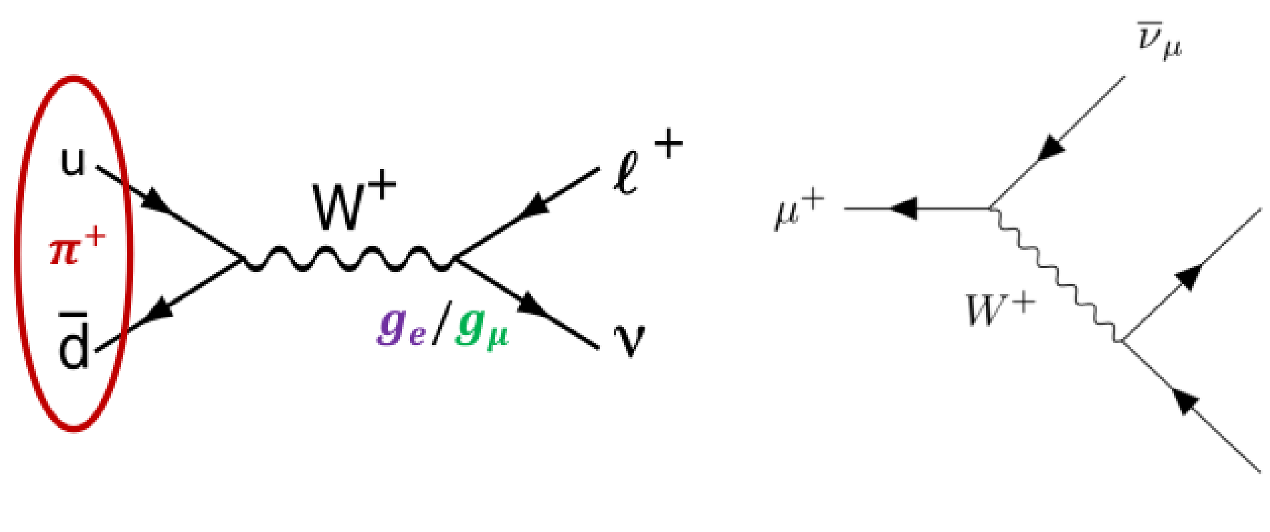

Figure 2: Feynman diagrams of pion decay where $l = e/\mu$ (left) and muon decay (right)

Liquid xenon calorimeter

PIONEER will use a calorimeter to measure the energy of the positrons, before this a GEANT-4 simulation was built to study and optimize the energy resolution. This is important to be able to understand the detector, and to determine the low energy tail fraction for $\pi^+ \to e^+\nu(\gamma)$ events, to discriminate between e^+, and e^+ from μ^+. Two key questions emerge:

1. What is the effect of dead material?
2. What is the effect of the amount of liquid xenon?
   (1 of the 2 calorimeter material options)

Dead material refers to detector objects that cannot be measured directly, leading to energy loss. Figure 3 shows a schematic of the objects studied in the calorimeter simulations.

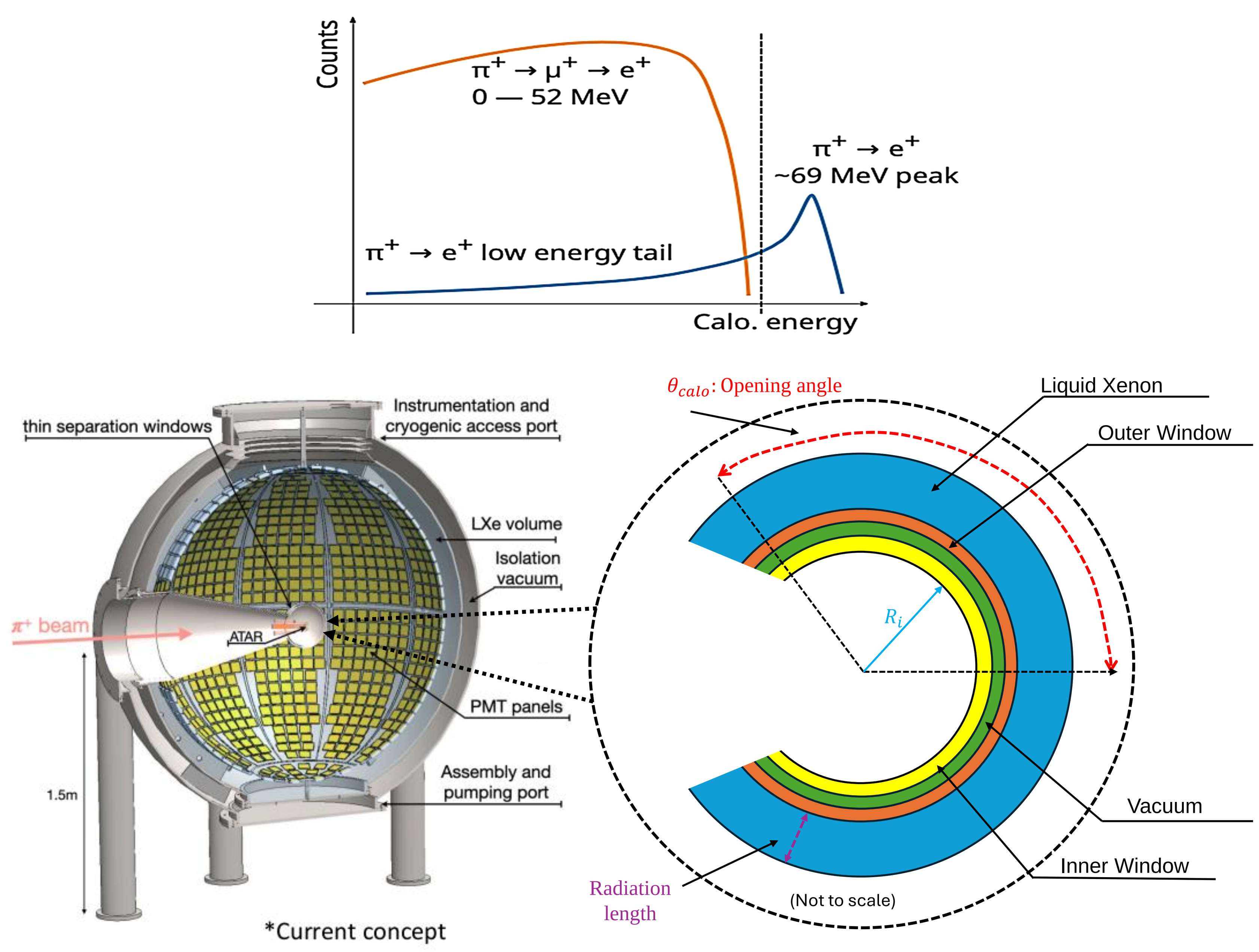

Figure 3: Pion decay event signatures (top), PIONEER current liquid xenon calorimeter concept (bottom)

Effect of dead material : windows

The energy lost in a given amount of dead material follows a Landau distribution. This is used to extract an estimate of the energy lost in the dead material, such as the energy lost in the dead material of the special windows that are needed for the cryogenic LXe system.

- Window consists of three layers: inner, vacuum, and outer.
- This study looks at the impact of different outer window thicknesses.
- Dependence on the opening angle is explored.

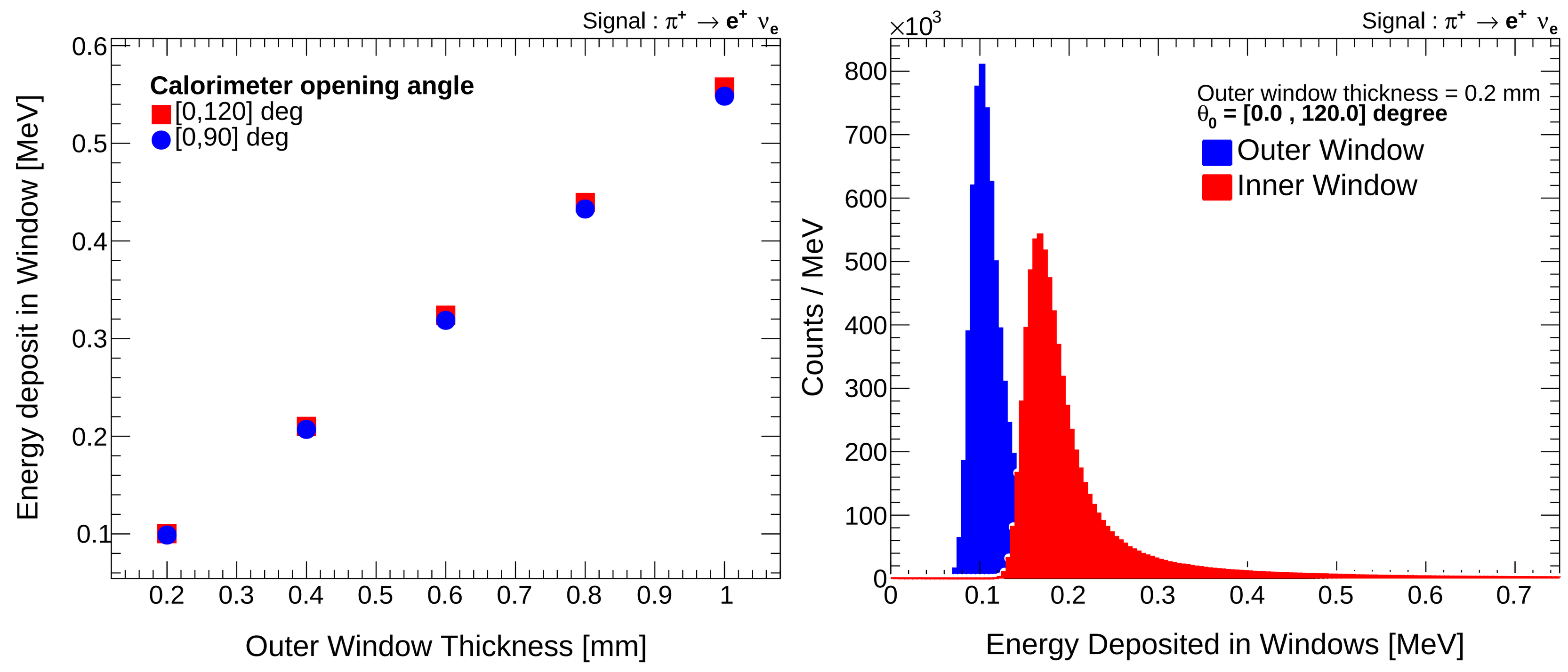

Figure 4: The energy deposit in the window as a function of thickness by opening angle (left).The energy deposit distribution of window layers for the nominal outer window thickness(right)

Effect of the liquid xenon depth

The positron energy deposit in the LXe calorimeter from pions decaying at rest can be fit to measure energy resolution.

- Energy resolution can be extracted from the fit as σ/E_{peak}
- The goal is $\sim 1\%$ energy resolution / tail fraction.
- The resolution depends on the amount of LXe, referred to as radiation length.

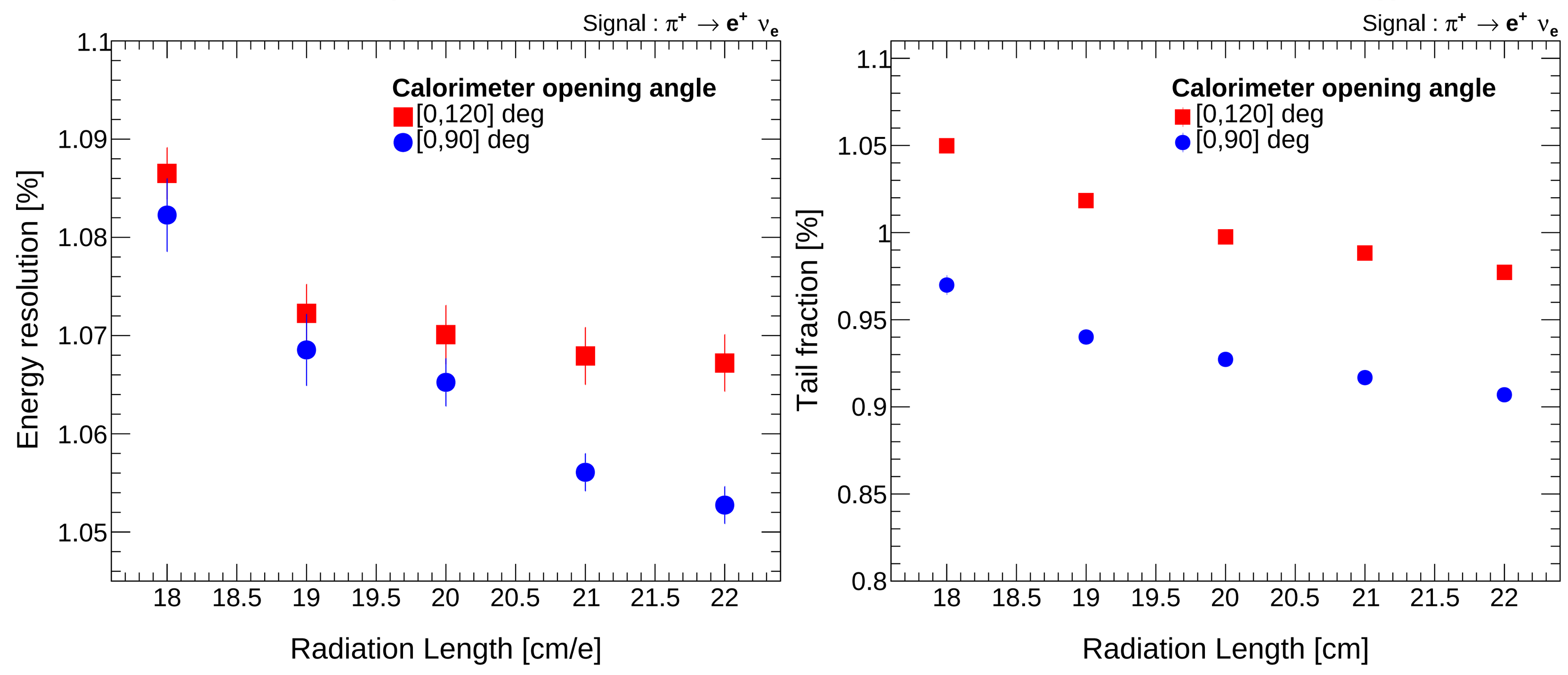

Figure 5: The energy resolution in the LXe (left), the shower tail fraction below 53 MeV vs the calorimeter depth in radiation lengths for $\pi^+ \to e^+\nu$ events (right).

Sensitivity of tail fraction and energy resolution

Positrons (e^+) from the rare two body pion decay show a characteristic energy. The resulting $\pi^+ \to e^+\nu$ positron energy spectrum is shown below.These studies show key aspects:

- The energy lost in the LXe windows is minimal.
- A good energy resolution can be achieved with a 20 radiation length LXe calorimeter.

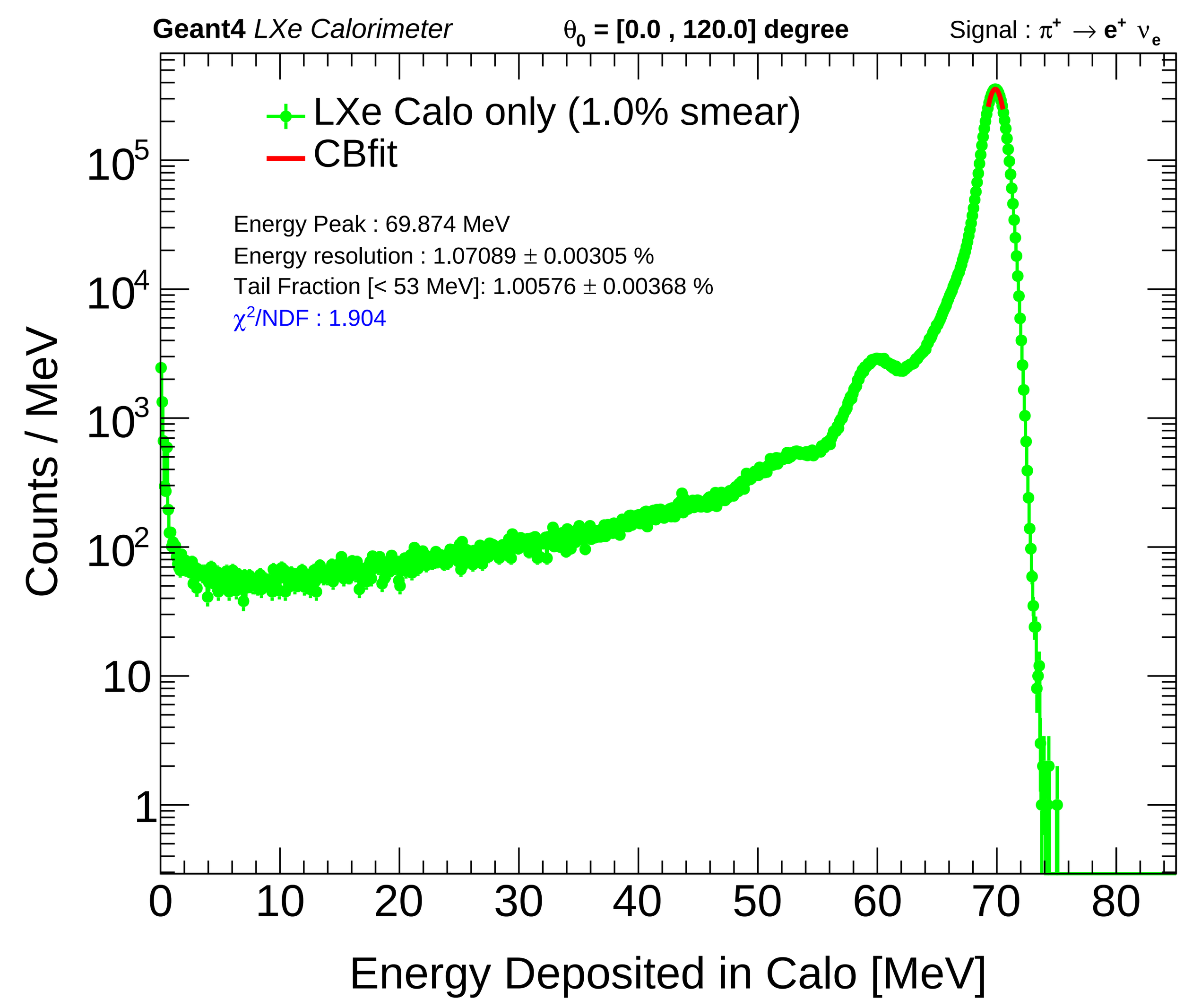

Figure 6: e^+ spectra from the energy deposit in the calorimeter

References

[1] PIONEER Collaboration, "Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment" arXiv.2203.05505.