PIONEER: A Next Generation Rare Pion Decay Experiment

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Background

In the past decade, a number of anomalies which hint at Lepton Flavor Universality Violation (LFUV) have been discovered. Some notable examples are shown in Fig. 1. In addition to this, there exists a $\approx 3\sigma$ tension between experimentally determined values of the CKM matrix and unitarity.

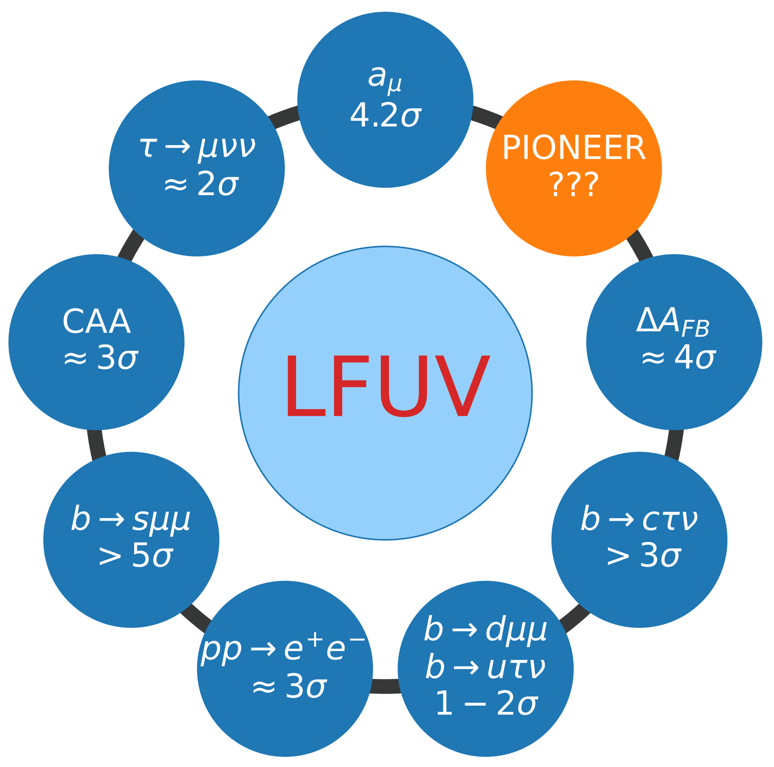

Figure 1: Assorted LFUV anomalies and their significance. PIONEER Phase-I will be able to significantly contribute to this space. Image concept: Andreas Crivellin.

PIONEER Goals

$$\text{Phase-I: } R_{e/\mu} = \frac{\Gamma_{e\nu_e(\gamma)}}{\Gamma_{\mu\nu_\mu(\gamma)}} \to 0.01\% \quad (1)$$

$$\text{Phase-II/III: } R_{\pi\beta} = \frac{\Gamma_{\pi^0 e\nu_e}}{\Gamma_{all}} \to 0.06\%. \quad (2)$$

$$\to R_{\pi\beta} = \frac{G_\mu^2 |V_{ud}|^2}{30\pi^3}(...) \to |V_{ud}| \text{ to } 0.02\% \quad (3)$$

Measuring the π^+ branching ratios above will provide an excellent test of LFUV (Eq. 1, Fig. 2 Left) and CKM Unitarity (Eq. 2-3, Fig. 2 Right).

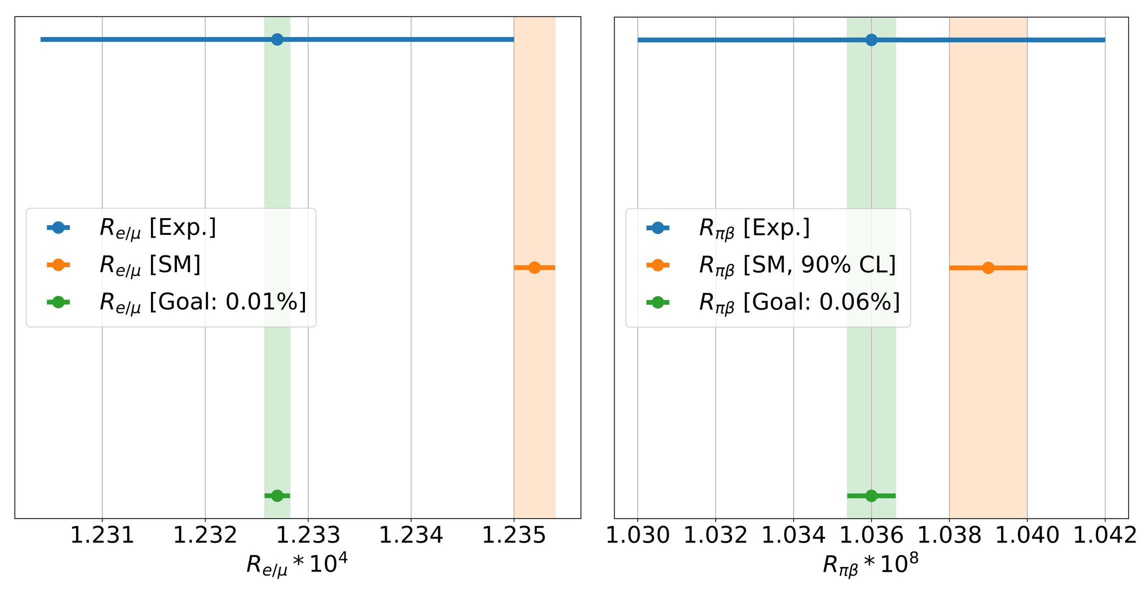

Figure 2: Goals of the PIONEER Experiment

Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**$\leq$ 0.01**

Table 1: $R_{e/\mu}$ precision for PIENU 2015 (left) and estimated precision for PIONEER (right). Reproduced from [4].

PIONEER

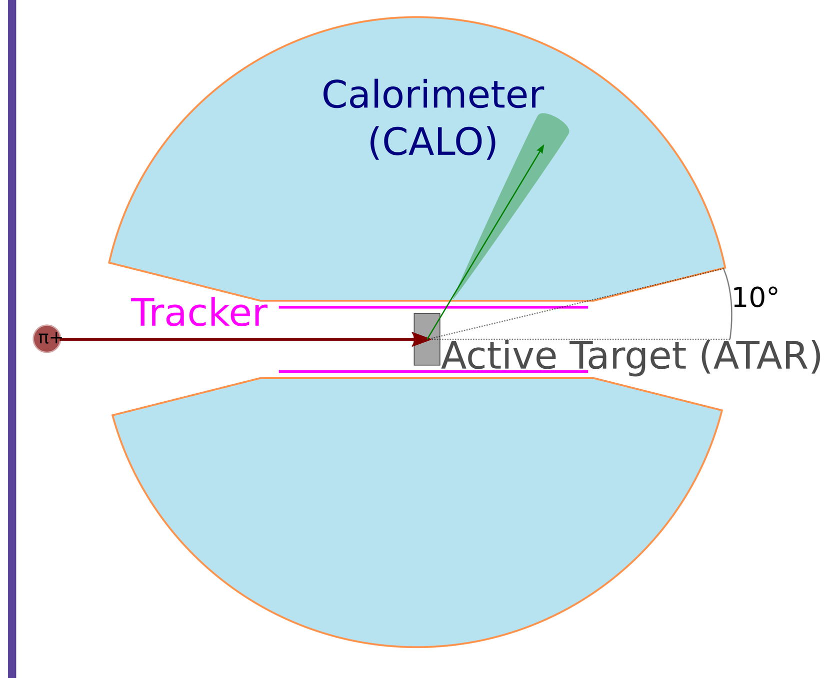

Figure 3: Diagram of PIONEER showing the main subsystems. This will be situated at the end of the $\pi E5$ beamline (Fig. 10) at PSI.

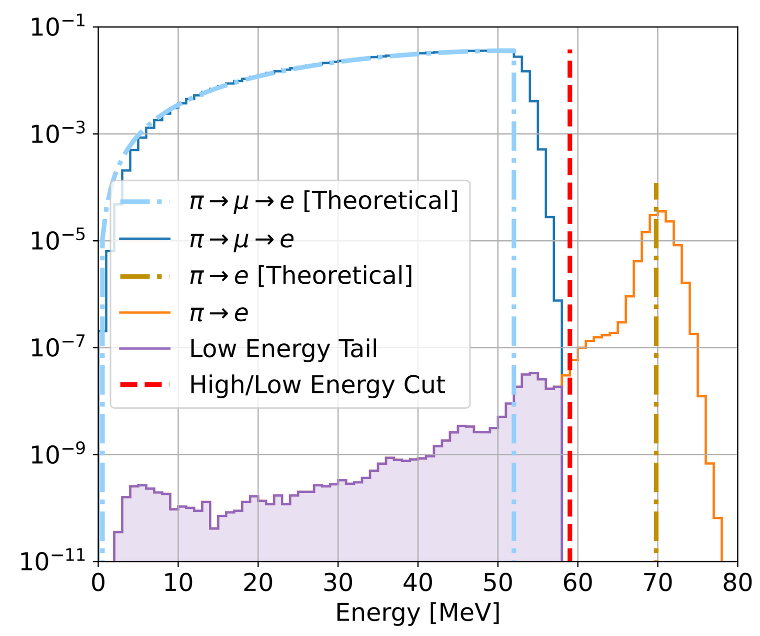

Figure 4: Simulated energy spectrum in a $25X_0$ CALO. The low-energy $\pi \to e$ tail (Purple) was particularly damaging to previous generation experiments.

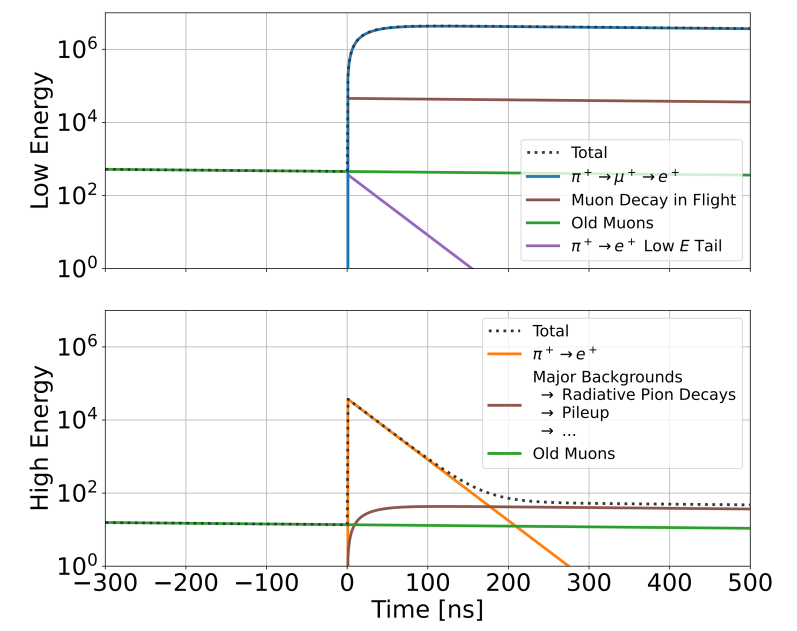

Figure 5: Simplified time spectrum showing the main decay channels as well as some backgrounds. A fit to this spectrum is used to extract the branching ratio $R_{e/\mu}$.

Calorimeter: CALO

Two calorimeter designs are in consideration for the PIONEER experiment. The first (Fig. 6c) is a sphere of Liquid Xenon (LXe) approximately 80cm ($25X_0$) in radius. The second (Fig. 6a,b) is a tessellated sphere consisting of an inner layer of $16X_0$ LYSO scintillator, with a $12X_0$ "tail catcher" of CsI behind (reusing the existing calorimeter from the previous-generation PEN experiment). Each of these designs presents unique challenges (Table 2), but both are optimized to address the primary limiting factor in previous generation experiments: the low-energy "tail" of $\pi \to e$ decays which appear below the endpoint of the Michel ($\pi \to \mu \to e$) spectrum (Fig. 4, Purple).

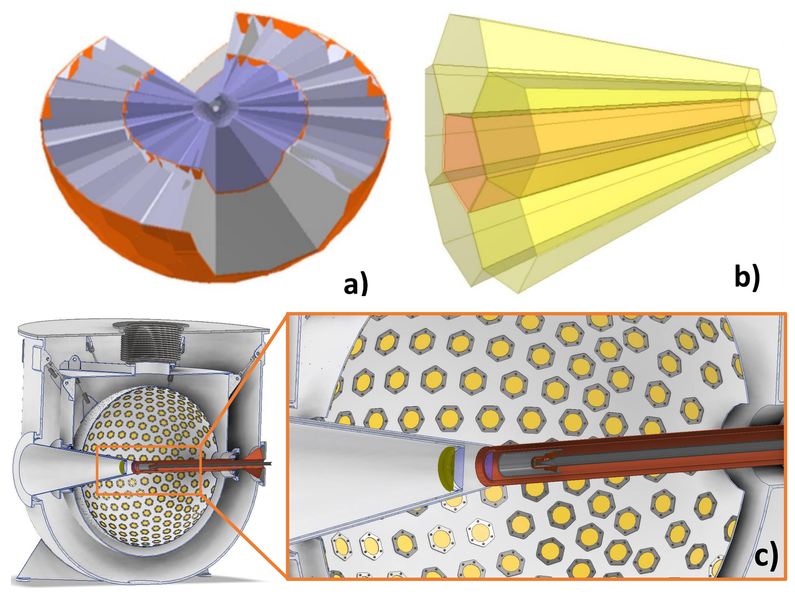

Figure 6: Competing calorimeter concepts: A LXe based design (c) vs. highly segmented LYSO+CsI (a,b).

Property	LXe	LYSO+CsI
Timing	45ns	36ns (LYSO)
X_0	25	28
Resolution	2.10%	4%
Segmentation	Requires innovation	Intrinsic, known
Experience	MEG, DM Searches, $0\nu\beta\beta$	Shorter crystals, PET
Photosensors	VUV SiPM issues	Standard SiPMs
Cost	Larger, Ongoing	One time

Table 2: LXe vs. LYSO+CsI

Active Target: ATAR

The ATAR (Fig. 8) is the heart of PIONEER. It consists of 48 AC-LGAD[3] planes with 100 active silicon strips each. The highly segmented ATAR will provide 4D tracking information for all incident particles, allowing us to distinguish different particle species, tag different types of decays (Fig. 7), and remove the Michel spectrum from systematic datasets (Fig. 9). This will provide a unique tool for a direct measurement of the tail.

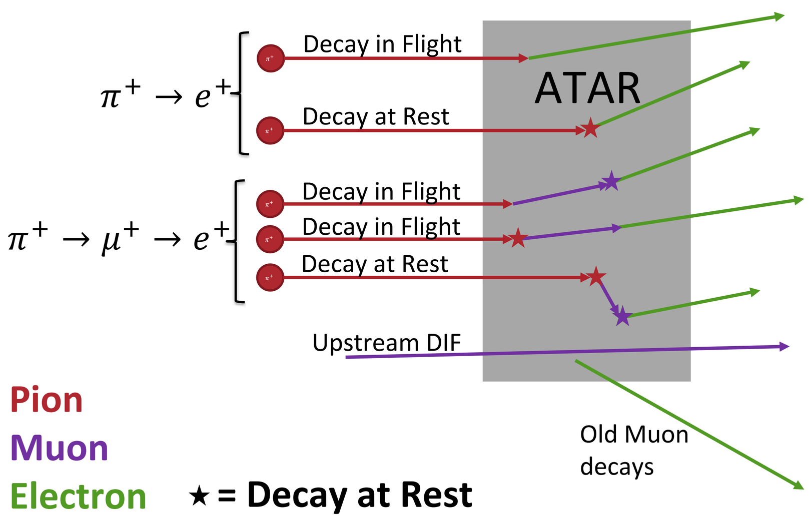

Figure 7: Possible decay chains in the ATAR

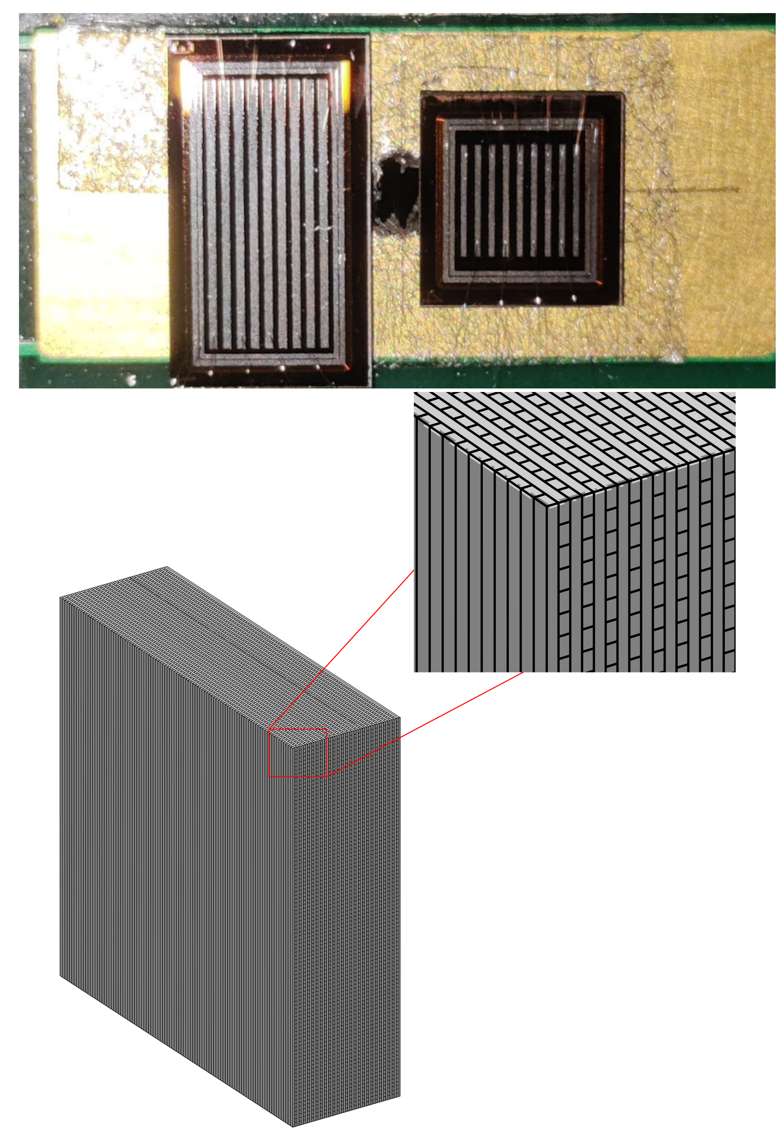

Figure 8: Top: Prototype LGAD tested at PSI. Bottom: Simulation view showing ATAR strip layout

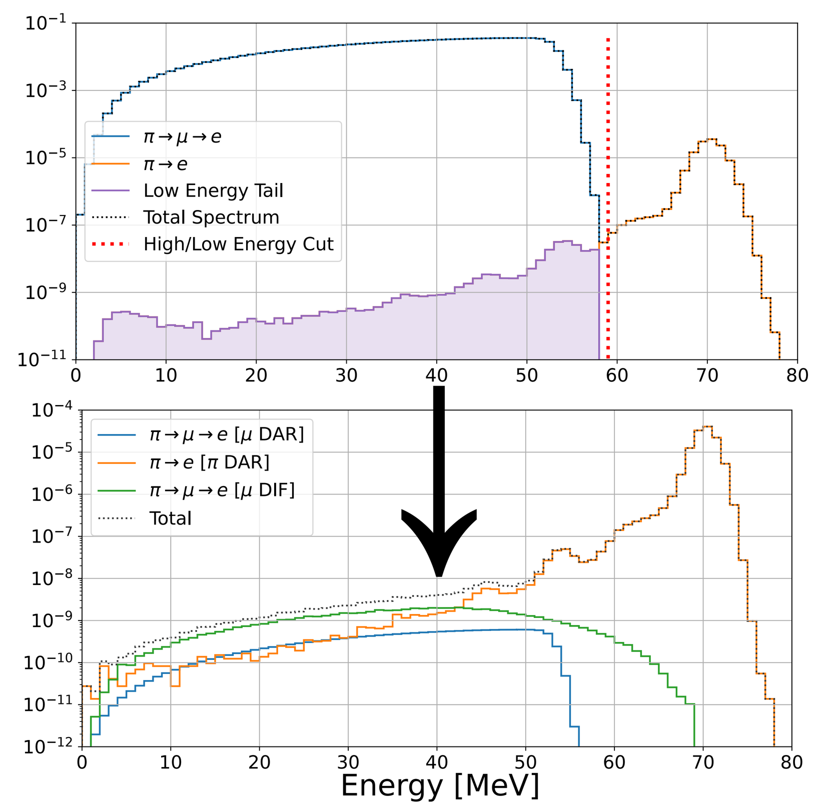

Figure 9: Simulated suppression of the Michel background using ATAR information.

Application of Machine Learning algorithms to these preliminary simulations have shown that realistic position and timing resolution from the ATAR will allow the experiment to achieve its systematic goals (Table 1) and improve on the uncertainty associated with the tail by a factor of 10.

First Beam Tests

The PIONEER experiment will be located at Paul Scherrer Institutes (PSI) $\pi E5$ beamline (Fig. 10). Initial measurements of the phase space of the beam were conducted in May 2022 to confirm that it meets the experimental requirements for PIONEER:

- ☑ π^+ Rate > 300kHz (Phase-I)
- ☑ $\sigma_x, \sigma_y < 10$ mm
- $\delta p/p < 2\%$
- $< 10\%$ μ^+, e^+ contamination

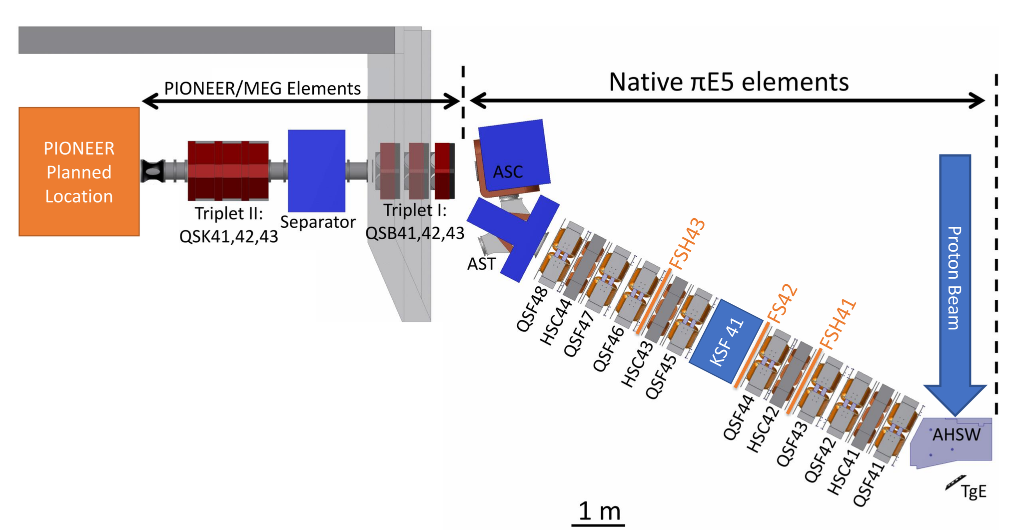

Figure 10: The $\pi E5$ beamline at PSI. π^+ travel from right to left.

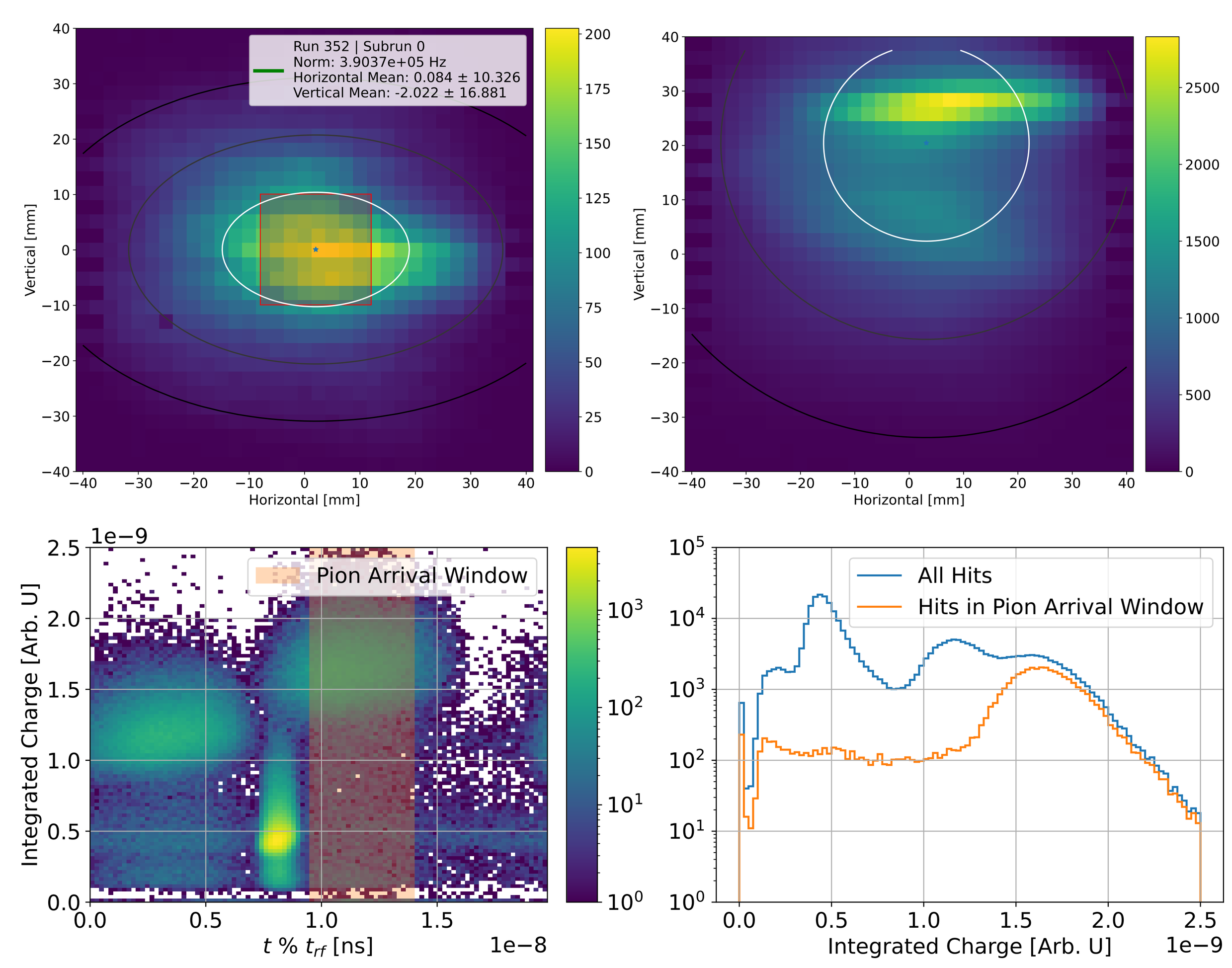

Figure 11: Top Left: Spatial beam profile with a π^+ detector threshold showing a Phase-I rate and acceptable σ_y. Top Right: Lower detector threshold, showing e^+/μ^+ contamination. Bottom Left: Time of particle arrival vs. Energy. The width of the pion "cloud" is $\propto \delta p/p \approx 3.5\%$. Bottom Right: Total energy spectrum and energy of selected π^+ (corresponding to the right and left beamspots above respectively).

During this testbeam, we were able to successfully tune the beam to achieve a good rate and adequate vertical focus (Fig. 11 Left). However, the lack of a secondary focus after the separator meant that significant e^+ and μ^+ contamination of the beam remained when achieving an acceptable π^+ focus. These beam tests will be used to verify the `G4Beamline` and `TRANSPORT` simulations, and help inform design changes to the beamline.

References

[1] Vincenzo Cirigliano and Ignasi Rosell. "Two-Loop Effective Theory Analysis of $\pi\ (K) \to e\bar{\nu}_e[\gamma]$ Branching Ratios". In: *Phys. Rev. Lett.* 99 (23 Dec. 2007), p. 231801. DOI: 10.1103/PhysRevLett.99.231801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.99.231801.

[2] Andreas Crivellin and Joaquim Matias. *Beyond the Standard Model with Lepton Flavor Universality Violation*. 2022. DOI: 10.48550/ARXIV.2204.12175. URL: https://arxiv.org/abs/2204.12175.

[3] Simone Michele Mazza. *An LGAD-based full active target for the PIONEER experiment*. 2021. DOI: 10.48550/ARXIV.2111.05375. URL: https://arxiv.org/abs/2111.05375.

[4] PIONEER Collaboration et al. *PIONEER: Studies of Rare Pion Decays*. 2022. DOI: 10.48550/ARXIV.2203.01981. URL: https://arxiv.org/abs/2203.01981.