Lessons Learned From PIENU

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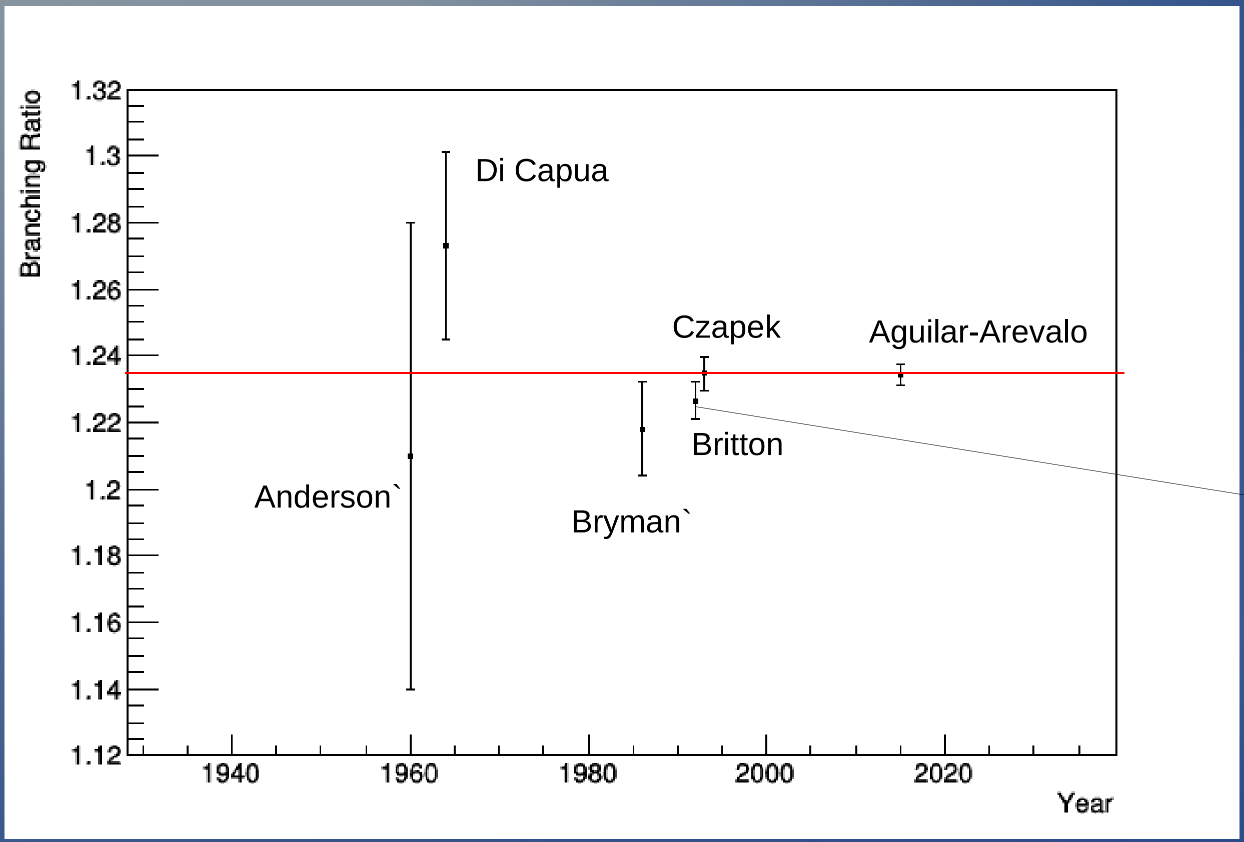
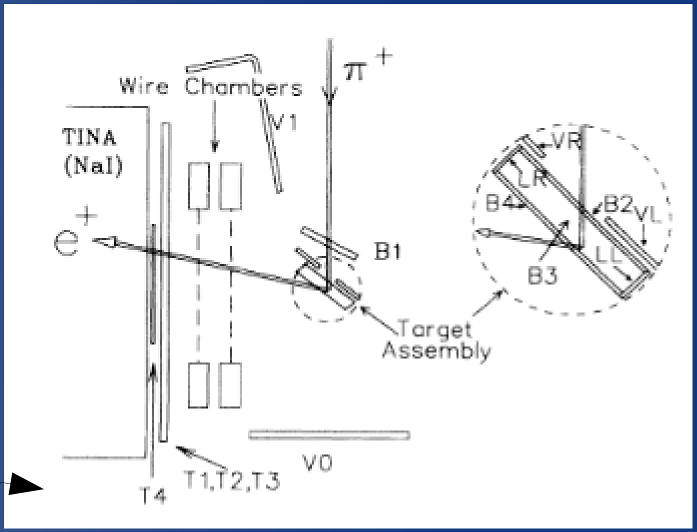
on behalf of the PIENU collaboration

History of Experimental Measurements





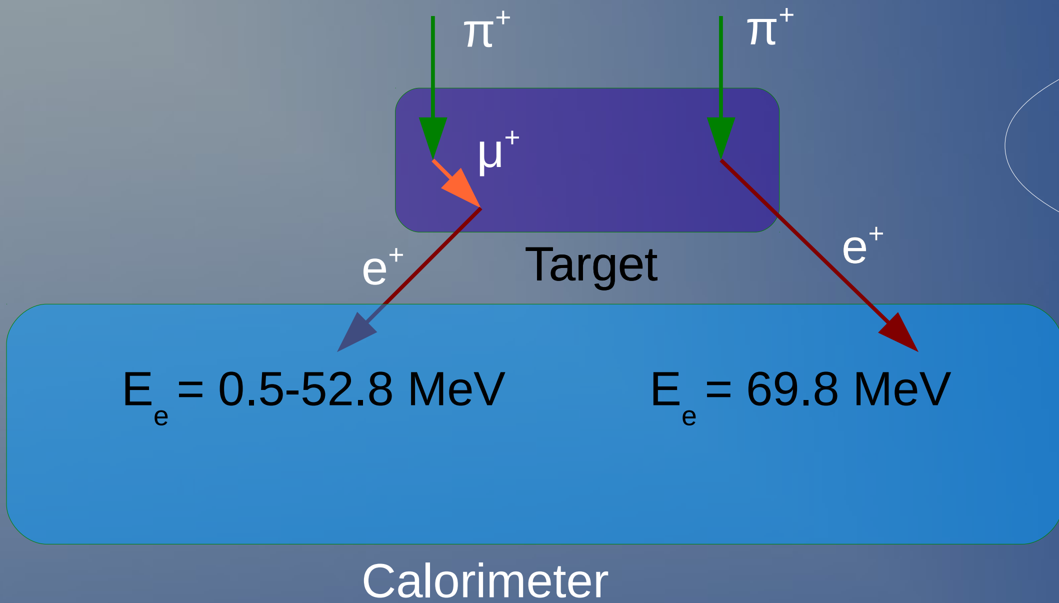
Previous PIENU Setup

2.9% acceptance

Red line shows theoretical value

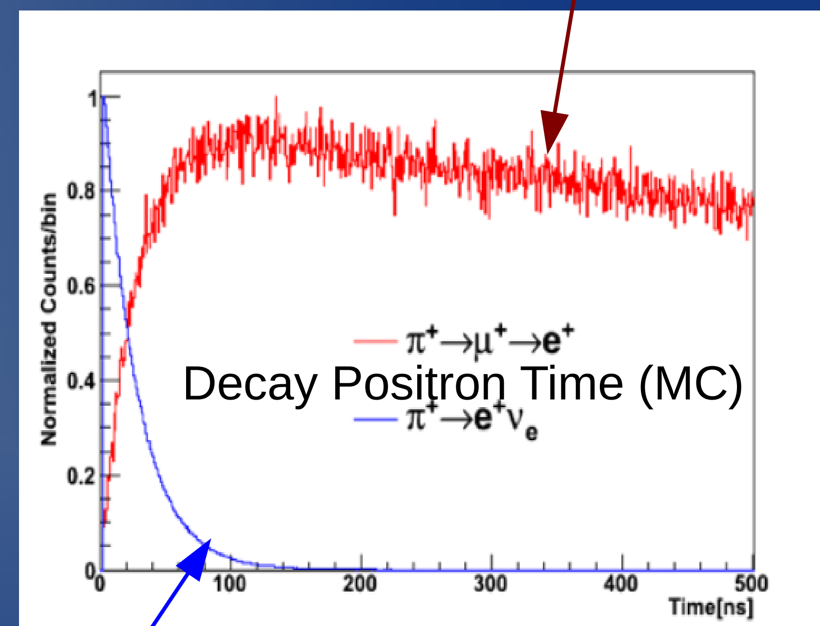
PDG average: ~0.2% experimental precision

Experimental Technique



$\pi^+ \longrightarrow \mu^+ \longrightarrow e^+$

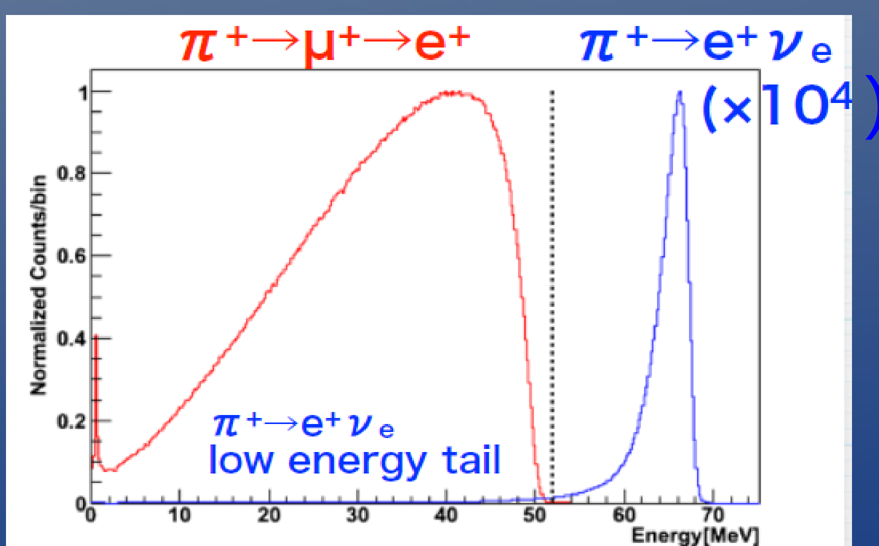
$N_{PIMU} / (\tau_\mu - \tau_\pi) \times (e^{-t/\tau_\mu} - e^{-t/\tau_\pi})$



Decay Positron Time (MC)

$\pi^+ \longrightarrow e^+$

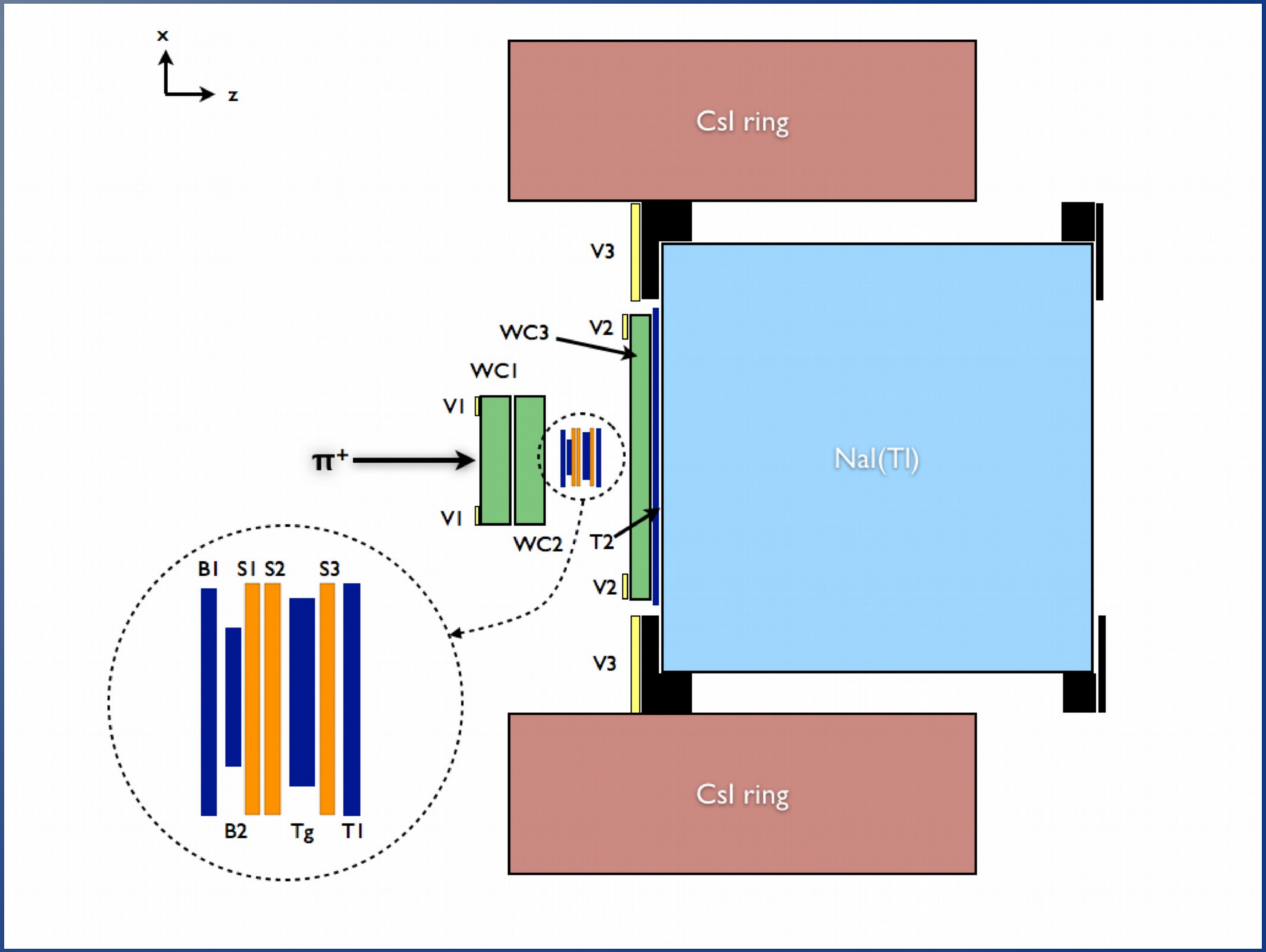
$(N_{PIE} / \tau_\pi)\, e^{-t/\tau_\pi}$



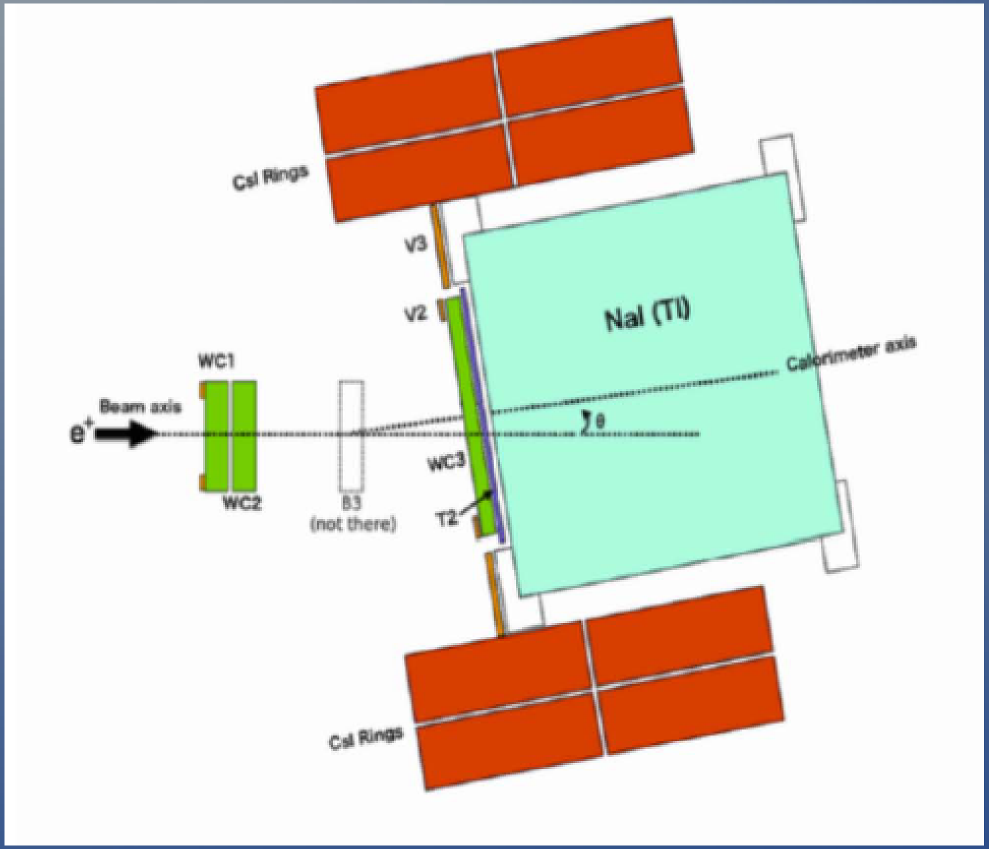
Decay Positron Energy (MC)

Detector

- B1 rate 50-60 kHz
- Acceptance ~ 20%
- Energy Resolution 2.2% (FWHM) at 70 MeV
- 19 radiation lengths of NaI, 9 of CsI
- One NaI crystal, 97 CsI crystals
- Sub-ns time resolution from waveform fits of plastic scintillator PMTs
- Pileup rejected in ~8 μs window around the pion, due to ~1 μs NaI waveform



Tail correction



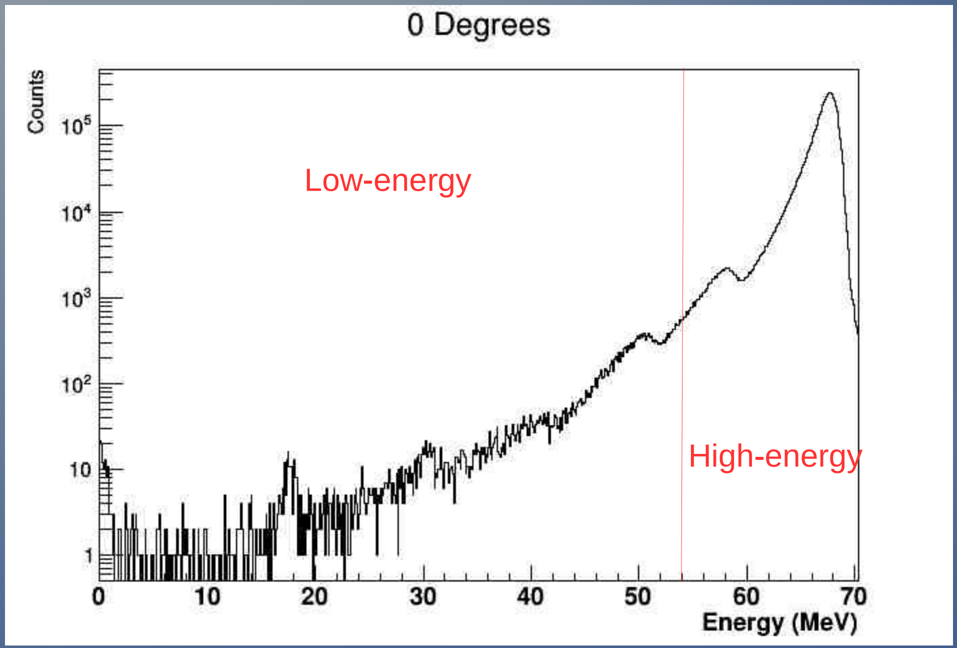
Largest source of systematic uncertainty; required special data to be taken

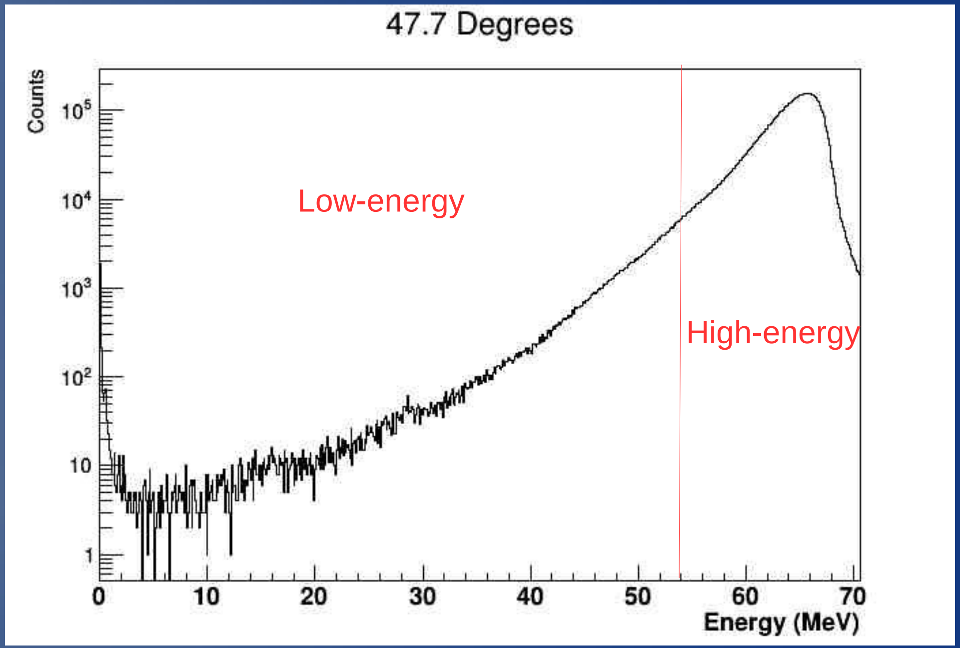
B1, B2, Tg, T1, S1, S2, S3 removed from the detector

Beamline tuned for 70 MeV/c positrons

Measurements were done at 10 different angles between the beam and the crystal axis

Positron Beam





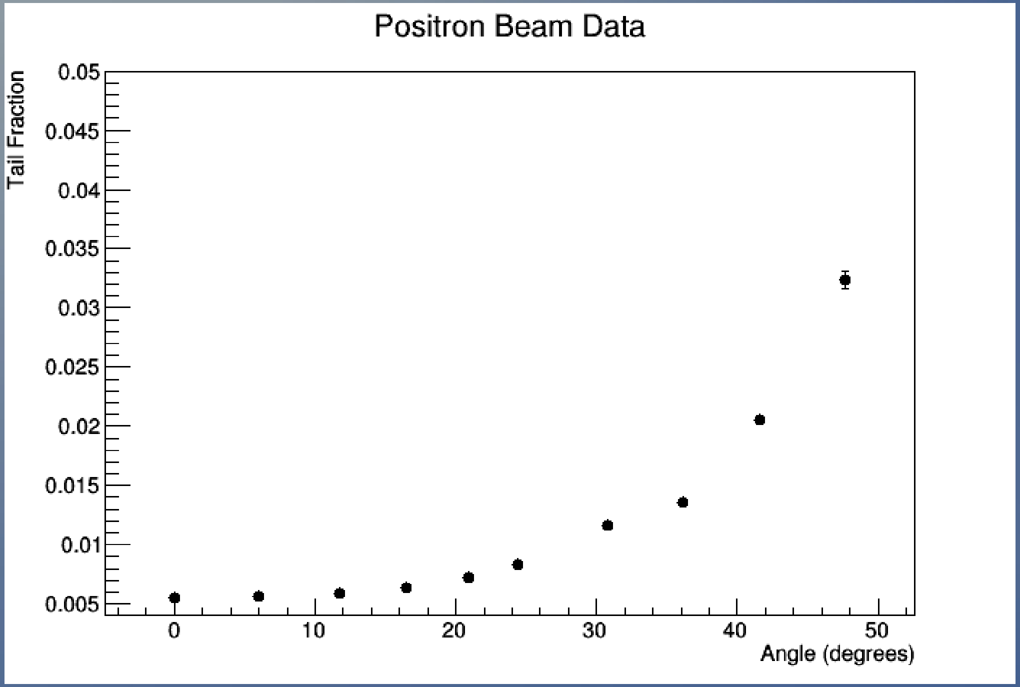
0.55% ± 0.01% of the spectrum below cutoff

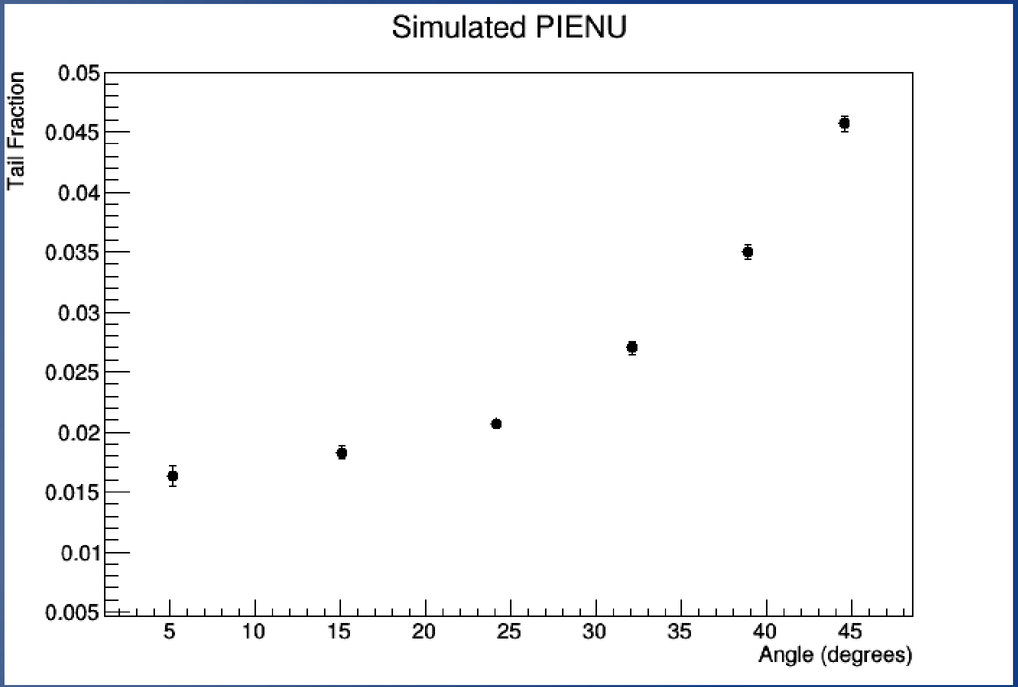
Extra peaks at 50 MeV and 58 MeV due to photonuclear reactions in ^{127}I

3.23% ± 0.07% of the spectrum below cutoff

Extra peaks still present, but invisible underneath tail due to shower leakage

Tail fraction as a function of angle





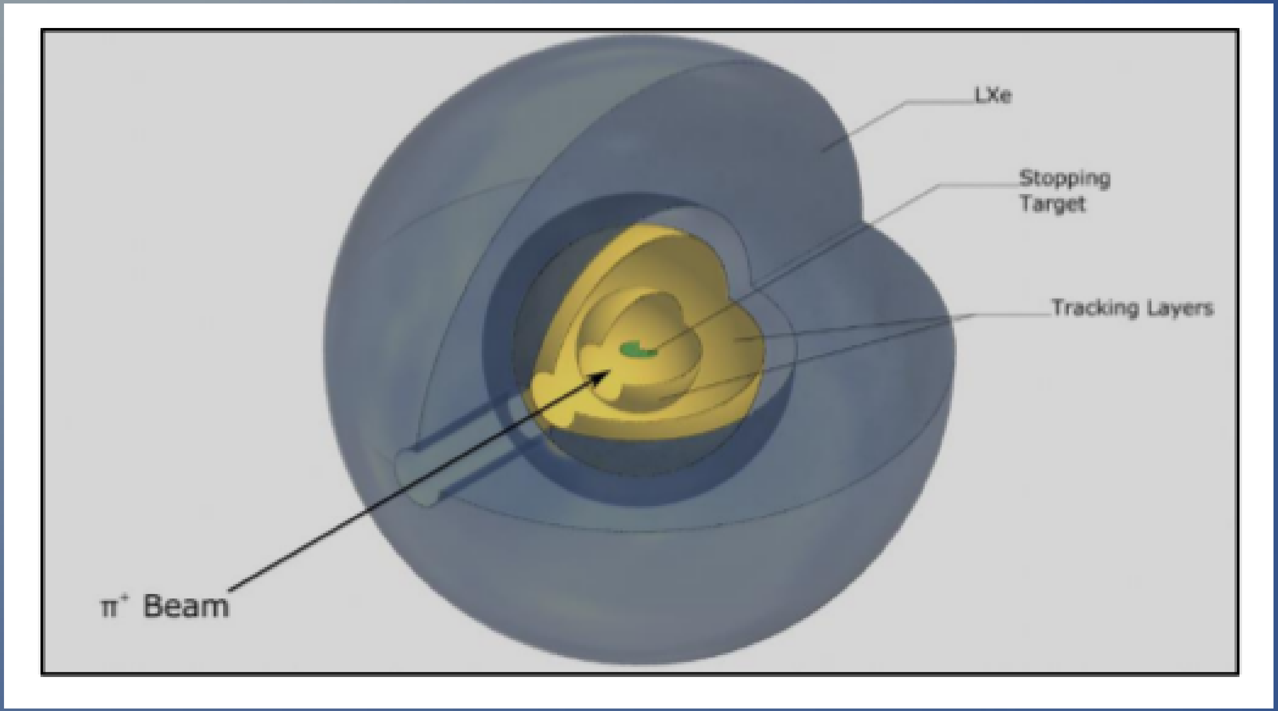
Errors on the right are MC statistics, errors on the left are stat + syst (mostly syst)

Plateau at small angles for PIENU events due to Bhabha scaterring upstream of calorimeter: positron flies away into the void and low-energy electron triggers. Another small acceptance problem!

PIENU/PEN Comparison

- PIENU had more radiation lengths of calorimeter, very good energy resolution
- PEN had much higher acceptance
- PIENU doesn’t use stopping target information

PIENUXe



60 cm radius liquid xenon is about the same number of radiation lengths in every direction as PIENU had for on-axis decays

Exception is decays along the beam-pipe; can use tracking around target to cut away those events

Combines advantages of PIENU and PEN:
Deep, uniform calorimeter

High acceptance

Silicon stopping target?

Fast detector response

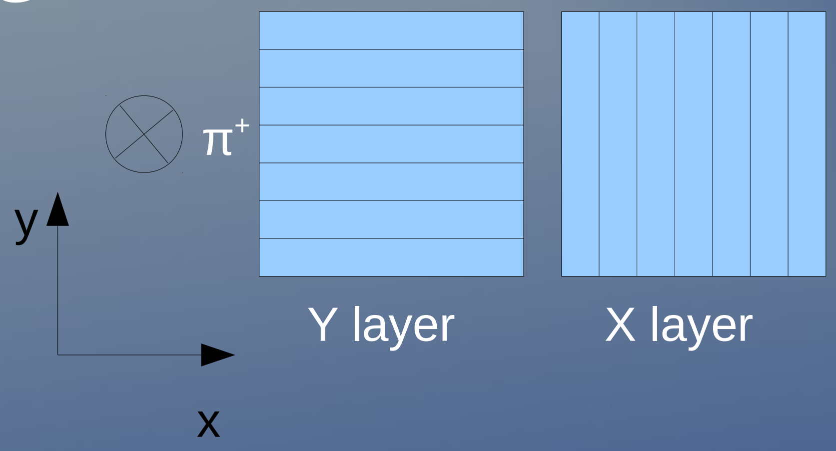
Challenges:
Expensive (relative to PIENU)

Hard to design and operate

Need to keep material around target to a minimum while maintaining good tracking performance

Stopping Target Concept: LGAD

Incident beam
~15 MeV pions
@ ~1 MHz



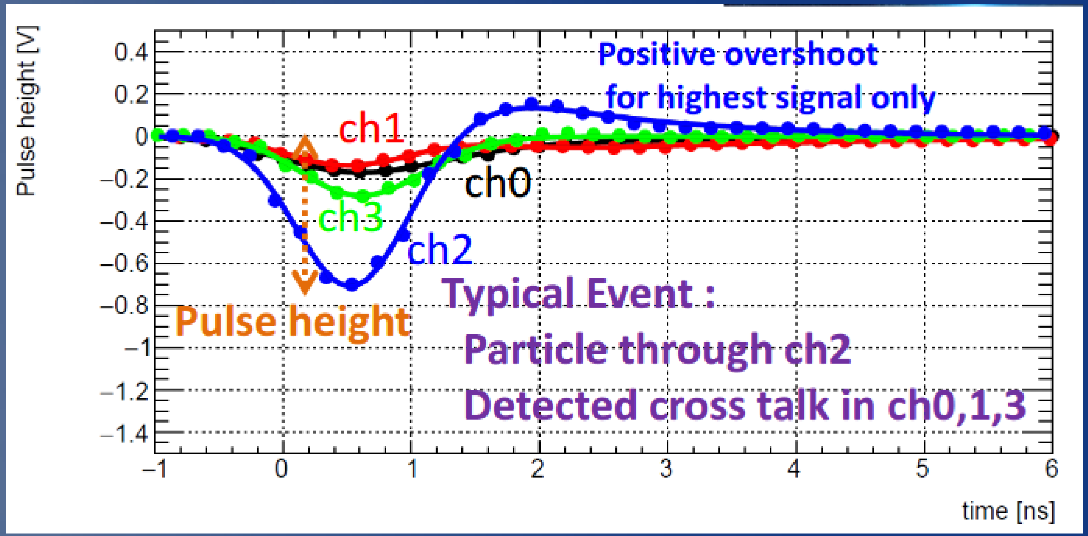


Image from "First Prototype of Finely Segmented HPK AC-LGAD Detectors" by Koji Nakamura, Vertex2020

Pion range ~ 5 mm
Muon range ~ 0.5 mm
Positron exits target
and enters calorimeter

- LGADs: 50 μm thick strips
  - Time Resolution down to 30 ps
  - Very fast pulses (pictured)
  - Can be 100 μm wide, giving good position resolution
  - With suitable electronics, provides dE/dx

Obstacles

- Physical design of detector, including cryo and cabling
- Very accurate knowledge of real detector geometry
- Pion beam with low contamination from other particles, narrow momentum bite, high flux
- Proper characterization of beamline
- Thorough measurement of detector response, both initially and ongoing
- Proper characterization of electronic noise, both initially and ongoing
- Version-controlled, unit-tested software, for both DAQ and analysis
- Robust checks of incoming physics data
- Other than that it’s easy

Projected Improvements

- Statistics
  - At least 10x higher beam rate
  - Acceptance higher than PIENU by factor of 7-8
  - Fast detector response will allow reconstruction of pileup events. This will give an improvement by a factor of ~5
- Systematics
  - Low-energy tail reduced by factor of 5-10
  - Reconstruction of decay verteces gives additional handle; study required to determine separation power

Summary

- PIENU was an incremental improvement on the previous PIENU experiment
- PIENUXe represents a great leap forward
- Medium-scale investment for significant physics reach