PIONEER: High Precision Measurements of Rare Pion Decay

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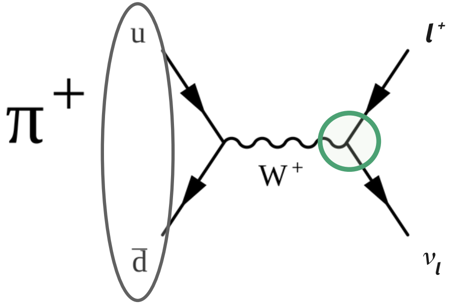
PIONEER Physics Initiative (Phase I)



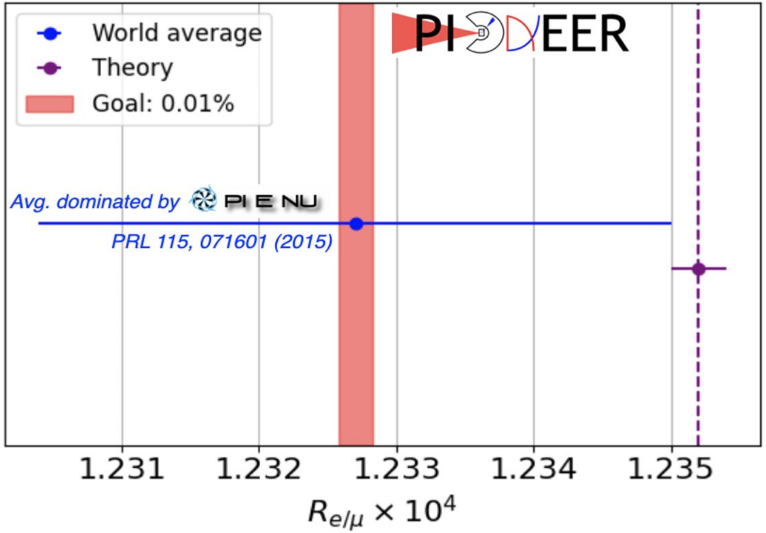
Lepton Flavor Universality (LFU):
SM assumes that all lepton flavors couple equally to the weak force.

SM predictions are ~15x more precise than the current best experimental measurements!

PIONEER will measure $R_{e/\mu}$ to 0.01%, a 10-15x improvement on the current best measurements.

Sensitive to BSM interactions:

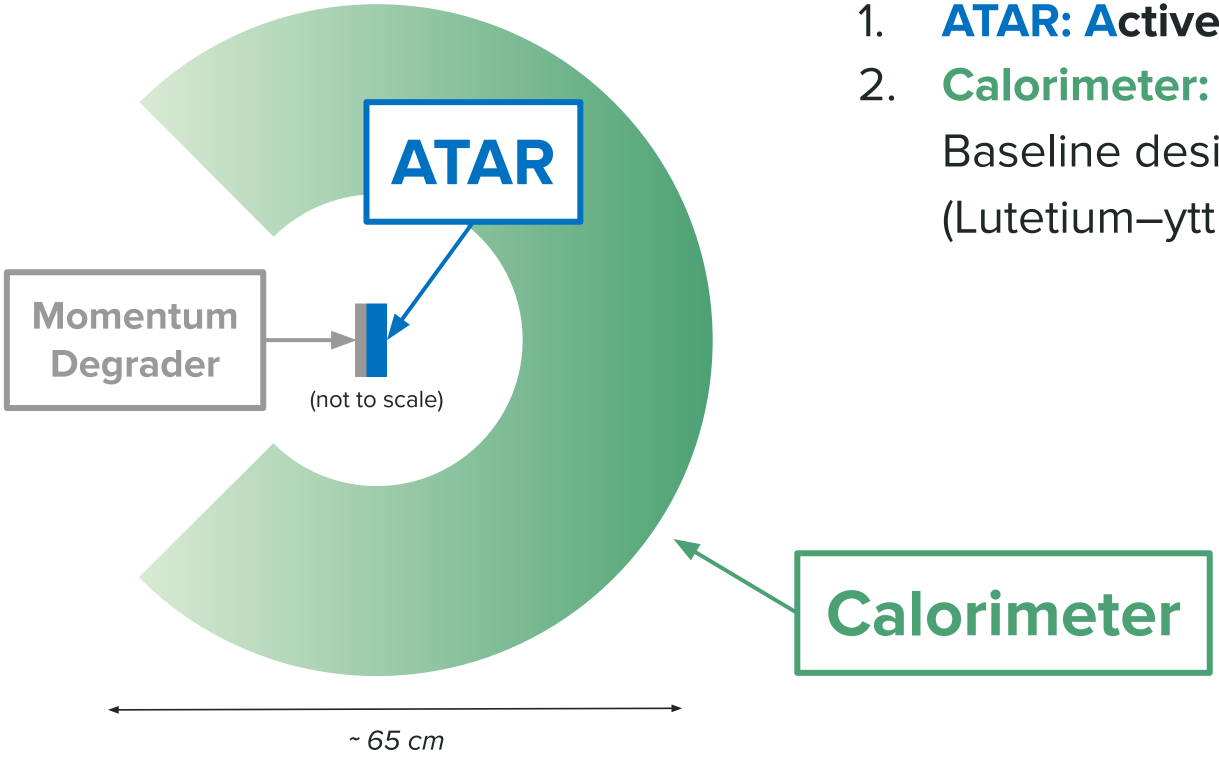
- ➔ New axial currents up to 18 TeV
- ➔ New pseudoscalar couplings up to 1100 TeV



PIONEER Collaboration, arXiv:2504.06375

V. Cirigliano et al., JHEP02(2013)046
V Cirigliano et al., NPB2009.12.020

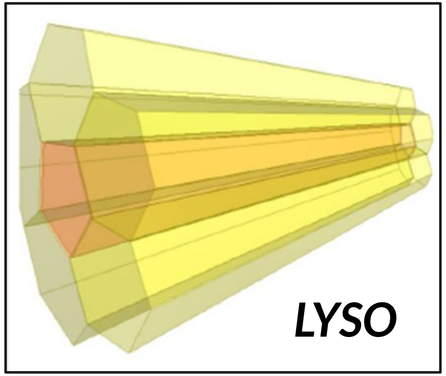
Basic Detector Geometry



Key detectors:

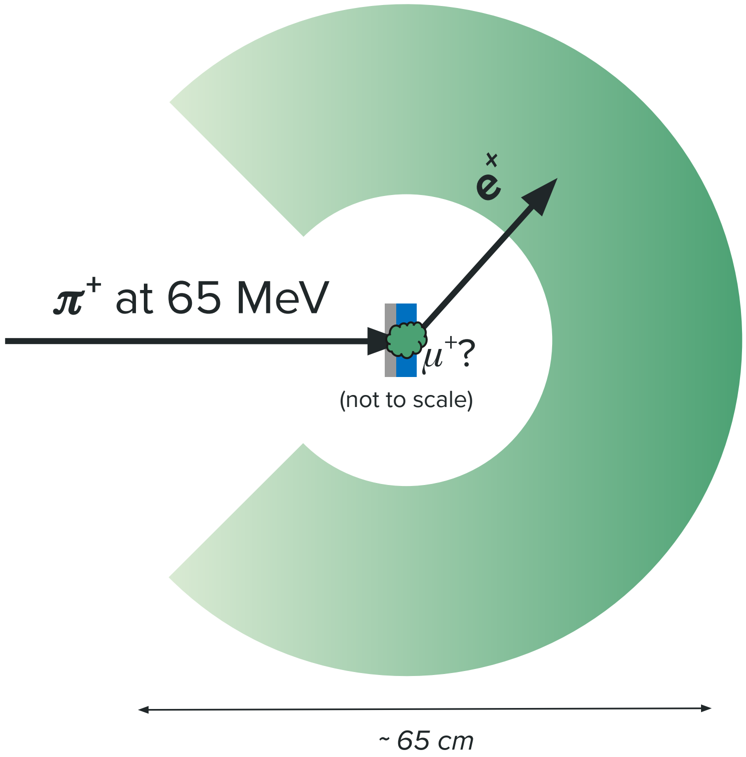
1. **ATAR: Active TARget** (20x20x6 mm)
2. **Calorimeter:**

   Baseline design uses LYSO crystals (Lutetium–yttrium oxyorthosilicate)



https://doi.org/10.1016/j.nima.2025.170320

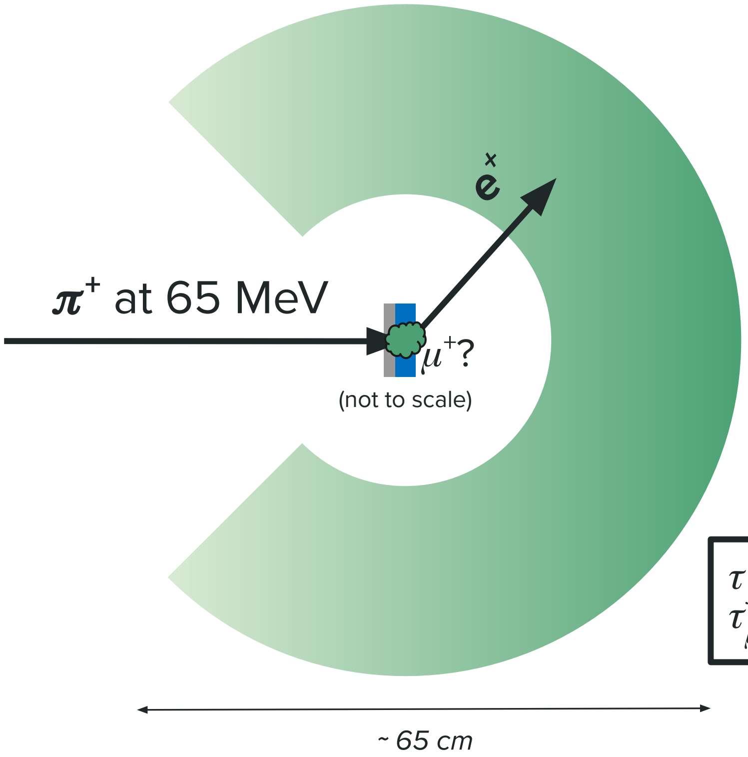
Basic Detector Geometry



Parts of each event:

1. Pion momentum degraded + stops in center of **ATAR**
2. Pion/muon decays in **ATAR**
3. Positron is emitted and deposits energy in **calorimeter**

Basic Detector Geometry



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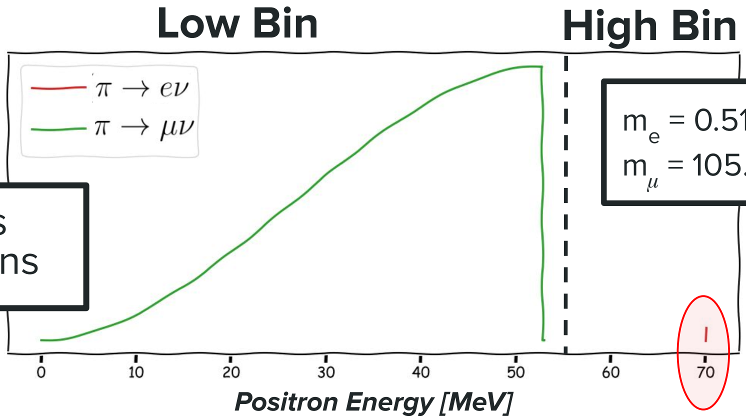
$\tau_\pi \cong$ 26 ns
$\tau_\mu \cong$ 2197 ns



m_e = 0.511 MeV
m_μ = 105.7 MeV

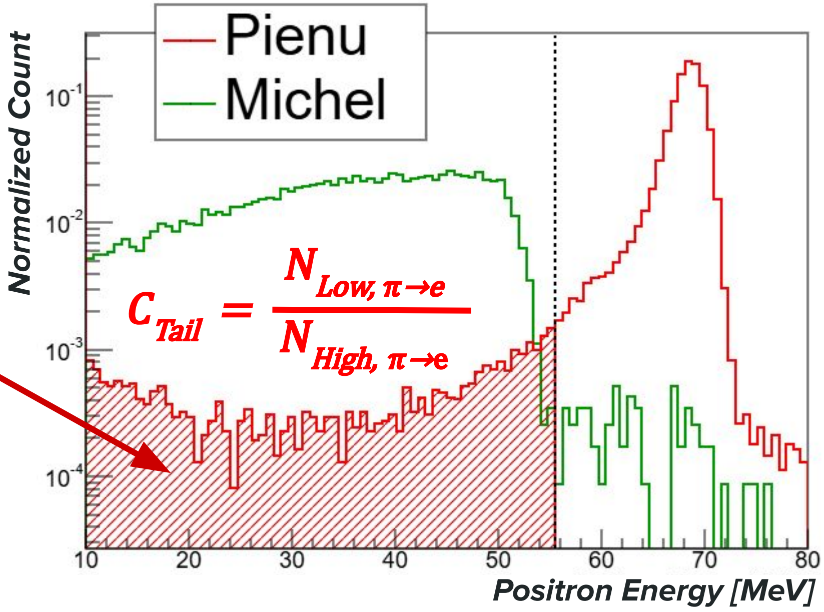
Measuring $R_{e/\mu}$ to 0.01% Precision

$$R_\epsilon = \frac{\pi\rightarrow\mu \text{ acceptance}}{\pi\rightarrow e \text{ acceptance}}$$

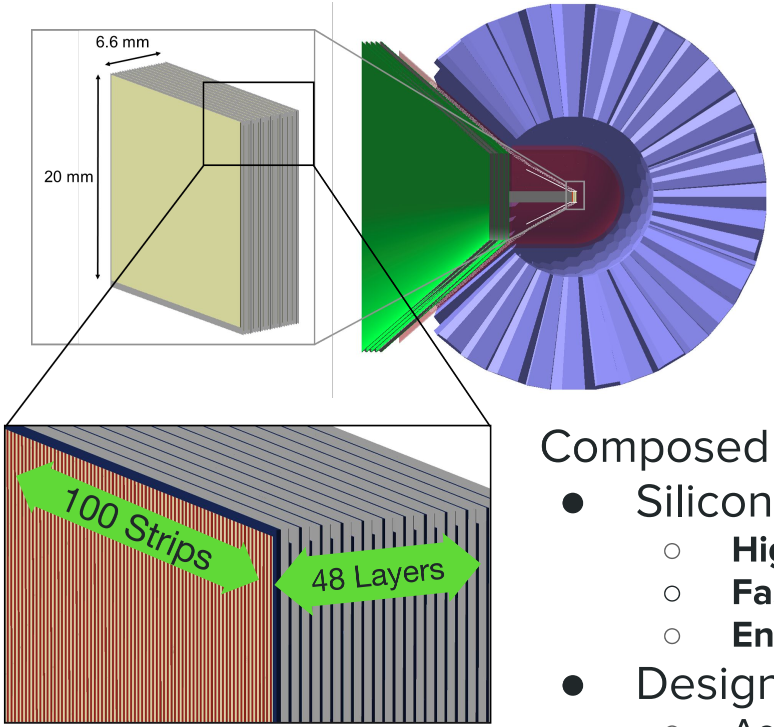
$$R_{e/\mu} = (N_{High,\,\pi\rightarrow e} / N_{Low,\,\pi\rightarrow\mu}) \times R \times [1 + C_{Tail}]$$

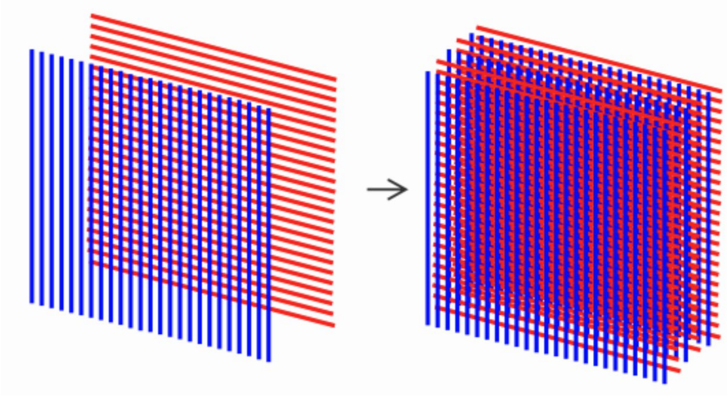
Tail fraction determined detector resolution:

- ➔ LYSO design achieves $C_{Tail} \sim 0.5\%$
- ➔ Need to measure tail with a precision around 1%



ATAR: The Heart of PIONEER



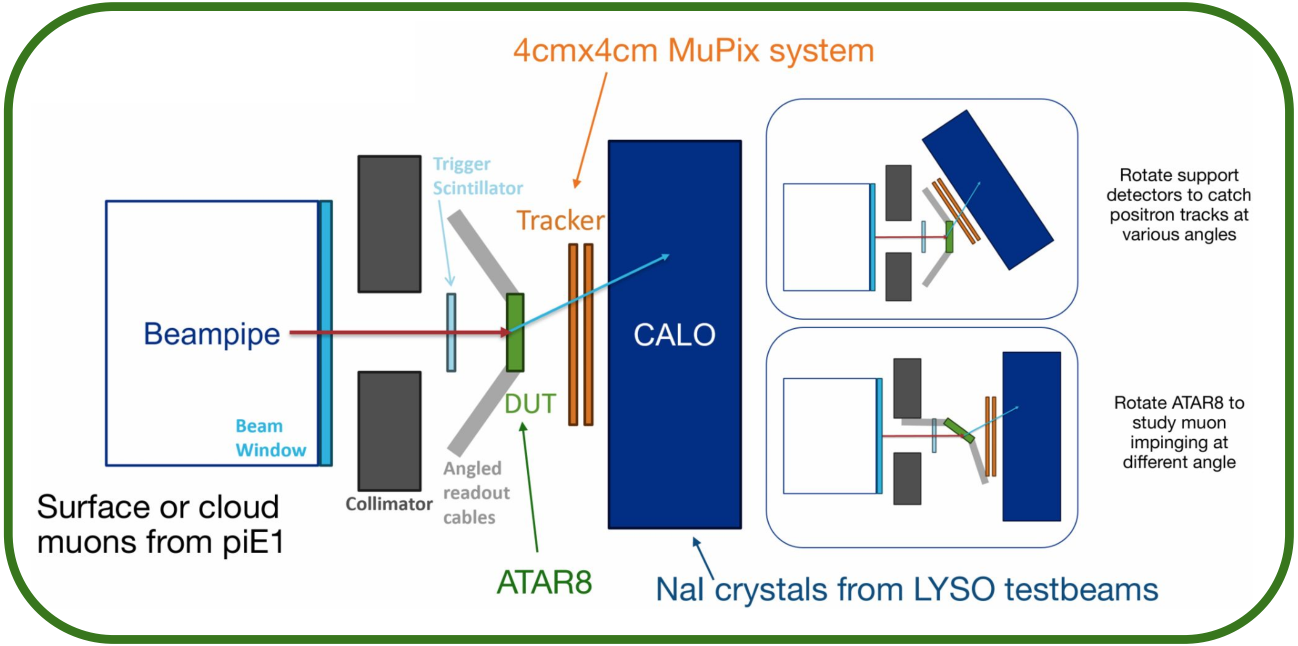


Composed of **Low-Gain Avalanche Diodes (LGADs)**

- Silicon sensors with internal gain
  - **High position granularity:** 120 μm thick, 200 μm pitch
  - **Fast timing:** ~100 ps per hit / O(ns) pulse pair resolution
  - **Energy resolution:** 10% for minimum ionizing particles (MIPs)
- Designed for detecting MIPs at the LHC
  - Actively studying saturation response to non-MIPs

J. Yang *et al* 2025 *JINST* 20 C08028

Next for PIONEER: ATAR8



ATAR8 is a prototype demonstrator scheduled to run in December at PSI. It will have 8 ATAR planes w/ 32 active channels each.

It will be used in the PiM1 beam to both demonstrate its functionality and study real stopped muon decay signals in the apparatus.

The full experiment is projected to begin in 2029.

Backup Slides

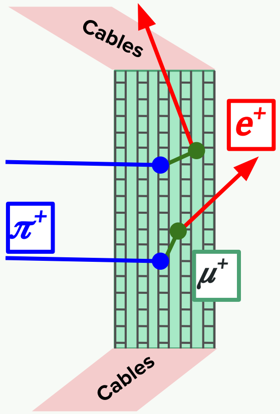
ATAR: The Heart of PIONEER

$$R_{e/\mu} = (N_{High, \pi \to e} / N_{Low, \pi \to \mu}) \times [1 + C_{Tail}] \times R_\epsilon$$

Angle Dep. Energy

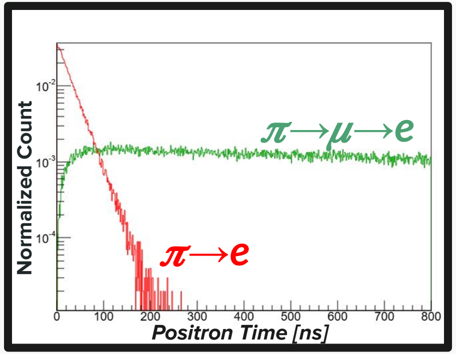
Positron energy is:

$E_{e+} = E_{Calo} + E_{ATAR} + \bar{E}_{Dead}(\theta)$

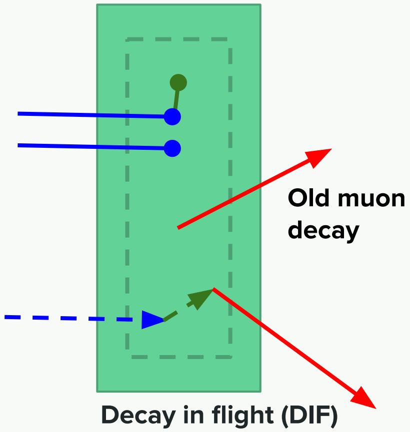


Positron Time

Counts in high/low bin will be determined by fitting time spectra w/ pion/muon lifetime

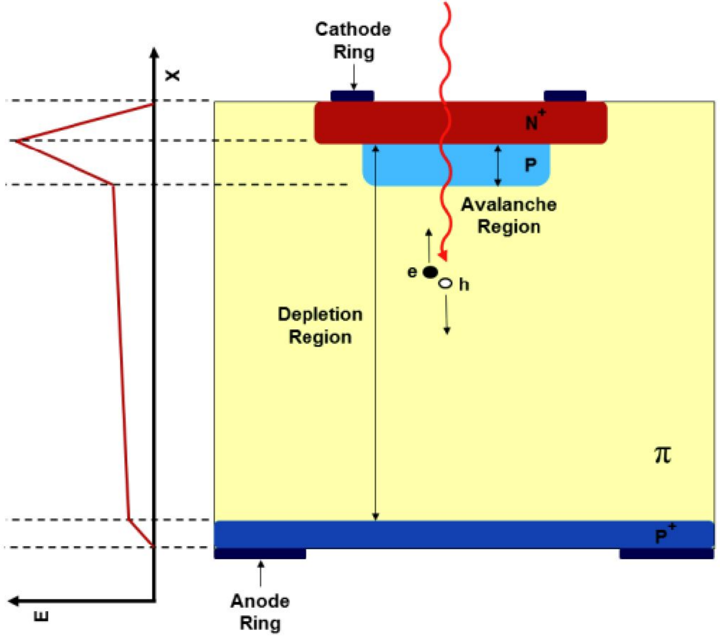


Background Rejection



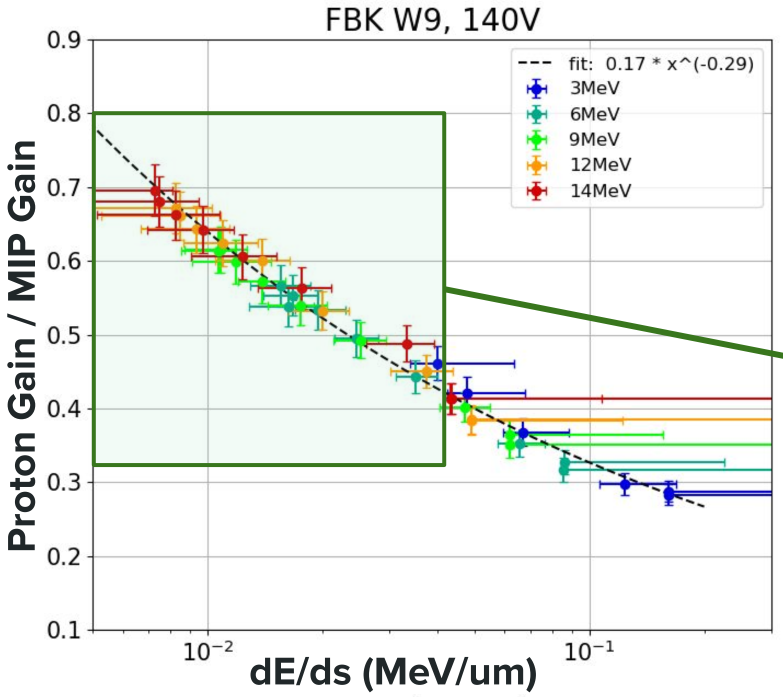
Physics of Gain Suppression

- LGADs are designed for detecting minimum ionizing particles (MIPs)
  - Based on PIN diodes with an additional p-doped layer
- Signals are amplified by an increased E-field in the avalanche region
- A highly localized energy deposit can cause screening in the gain layer
  - Reduced E-field suppresses the observed gain

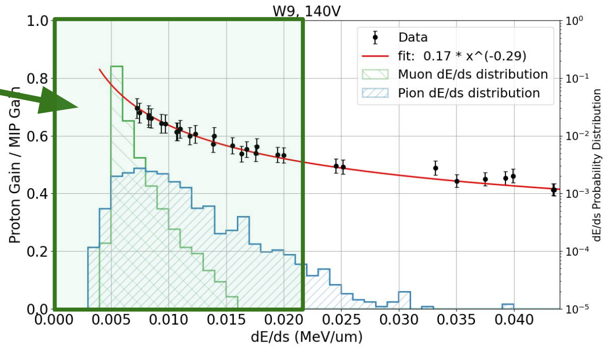


CENPA tests aim to characterize suppressed LGAD responses to non-MIPs.

Particle Species Independent Model for Gain Saturation



For **punch-through proton data**, the gain saturation can be parametrized nicely by a 1D power law function of dE/ds.



Punch-through data is concentrated in regions relevant for PIONEER