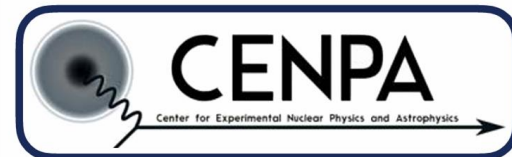
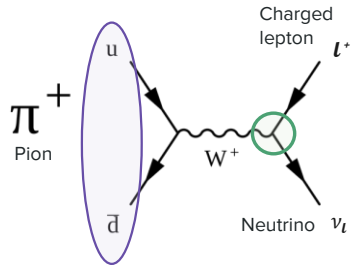


LGAD Gain saturation characterization with highly ionizing particles

Jessie Yang
University of Washington
October 22, 2026



LGAD Based Active Target for PIONEER



Will measure pion branching ratio to 0.01% precision

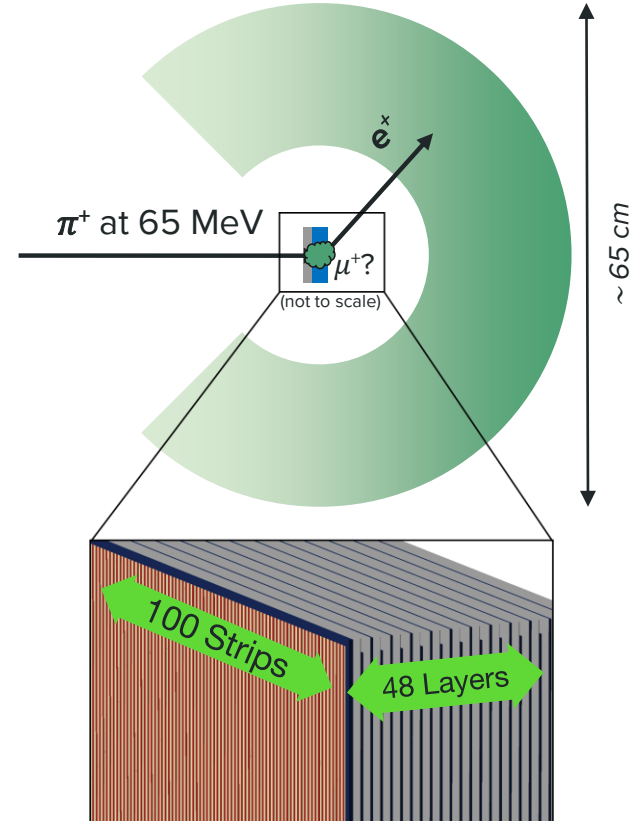
- 15x improvement of world's best experimental measurements
- The most sensitive probe of Lepton Flavor Universality Violation (LFUV)

$$R_{e/\mu}^{Exp} = \frac{\Gamma(\pi \rightarrow e\nu)}{\Gamma(\pi \rightarrow \mu\nu)} = 1.23270(230) \times 10^{-4}$$

LGADs provide 5D tracking (x,y,z,t,E) in the target region.

We need to understand LGAD response for a large range of energy deposits

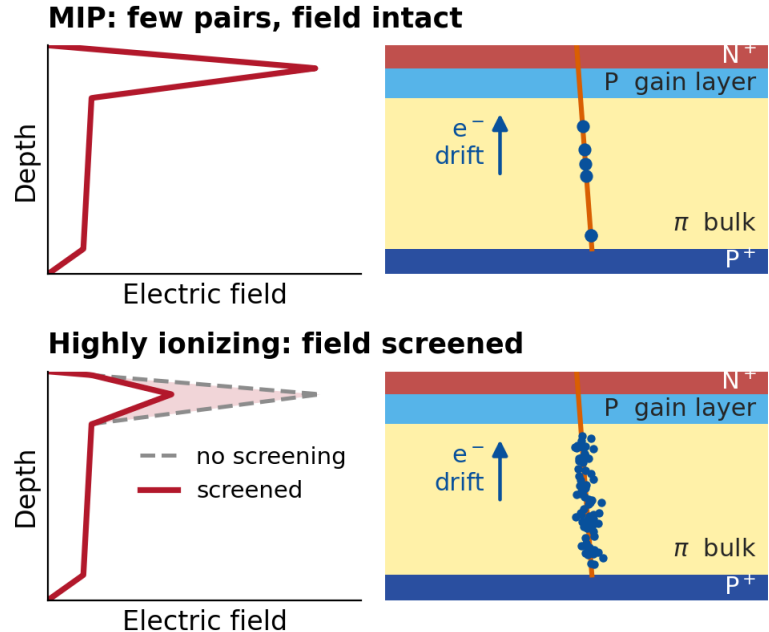
- Bragg peak from pion and muon stops equals O(100) MIPs



Physics of Gain Suppression

- LGADs are designed for detecting minimum ionizing particles (MIPs)
 - Extension of PIN diode design 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

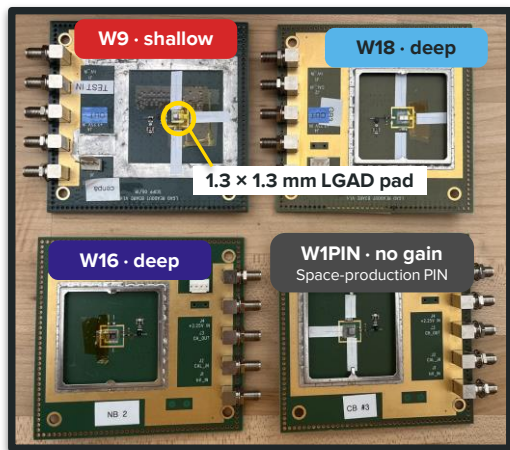
We aim to characterize and model dependencies of gain saturation in LGADs for highly ionizing particles.



schematic, not to scale

Devices Under Test (DUTs)

- All DUTs are single-pad LGADs
- Two vendors: FBK and HPK
 - Focus on FBK due to ability to reliably produce Ti-LGADs for minimal cross-talk in PIONEER



Readout chain

Amplifier board

2 GHz bandwidth
single-channel board, UCSC SCIPP

Second stage

gain 10
GALI-52+, Mini-Circuits

Waveform digitizer

6.4 GS/s, 11 bit, self-triggering
SAMPIC, CEA-IRFU and IJCLab

SAMPIC: D. Breton et al., Nuovo Cim. C 43 (2020) 7

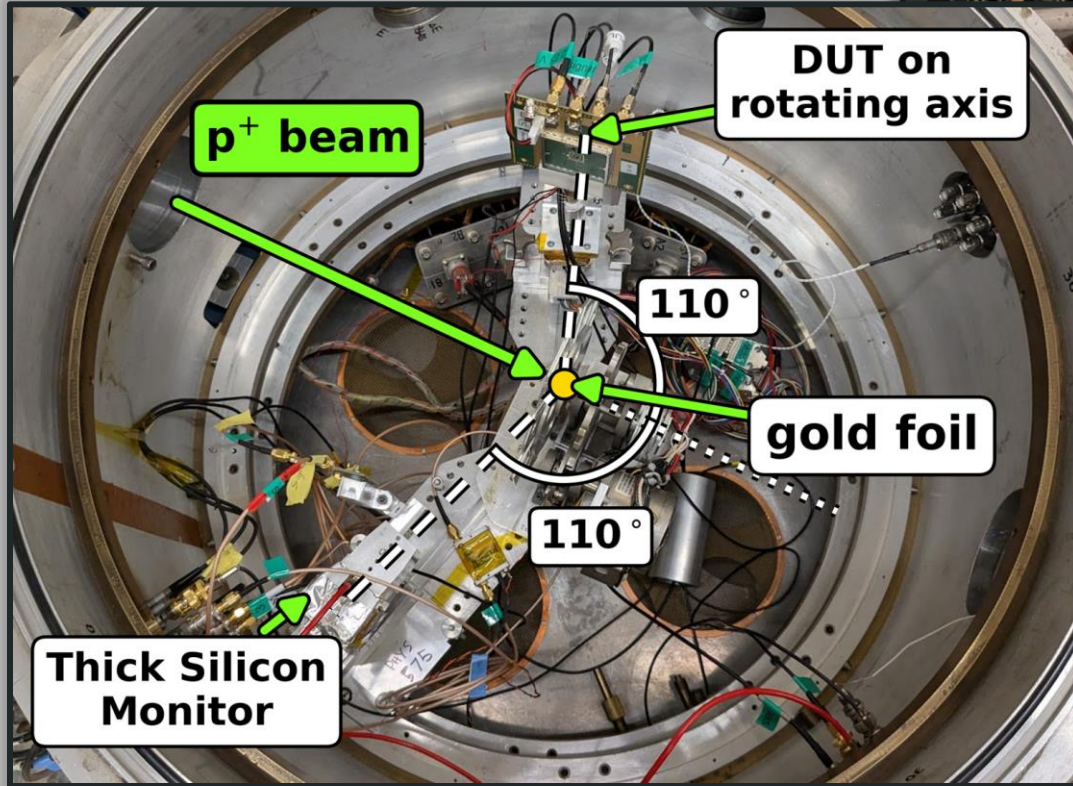
Wafer	Vendor	Thickness	Gain layer
2023 · HPK			
3.1	HPK	50 μm	Deep
3.2	HPK	50 μm	Deep
2024 · FBK Space			
W1	FBK	50 μm	Shallow
W8	FBK	100 μm	Shallow
W11	FBK	150 μm	Shallow
2025 · FBK UFSD4, this paper			
W9	FBK	50 μm	Shallow
W16	FBK	50 μm	Deep
W18	FBK	50 μm	Deep

Two papers published, third one in preparation

S. Braun *et al* *NIM A* 1064 (2024) 169395

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

Experimental Setup



- DUTs placed in a **Rutherford Backscattering (RBS)** chamber to reduce intensity to O(kHz) rate
- Silicon monitor (SiMon) positioned opposite DUT to measure post-RBS spectrum
- Scan parameters per sensor:
 - Operating bias voltage
 - Incident angle (1° to 71°)
 - Incident proton energy
- Control measurements performed with PIN diodes and with Sr-90 and Am-241 sources

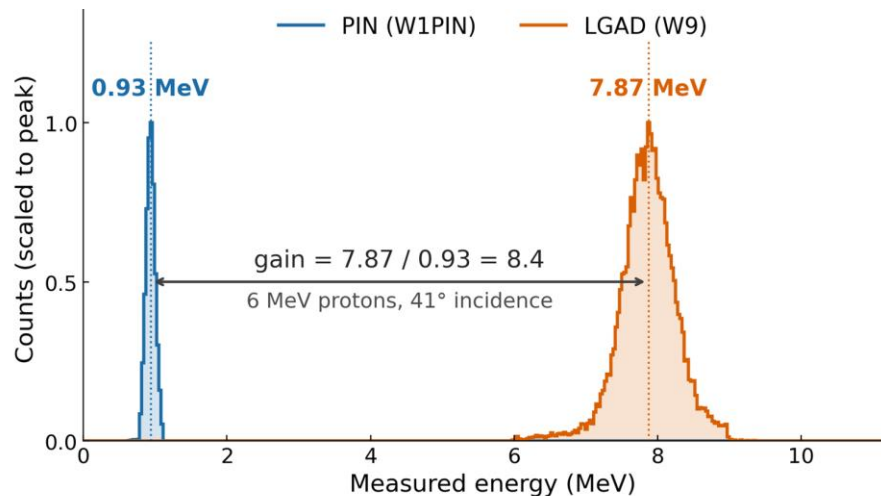
Measuring Proton Gain

- Energy spectra are populated by the integral of each waveform
- Peak of energy spectra is fit with a Gaussian and defines the measured run energy E

$$G = E_{\text{LGAD}} / E_{\text{PIN}}$$

- Reference: the W1PIN peak, checked against Geant4
- PIN reference uncertainty: 3.3% to 6.6%, the same for every sensor

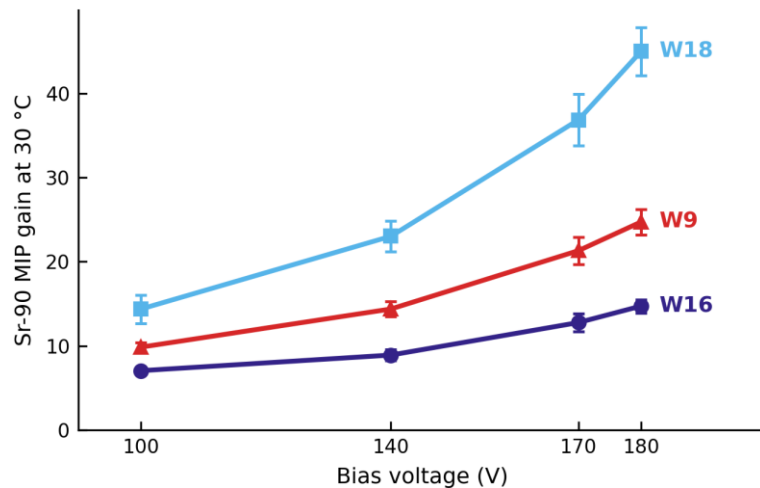
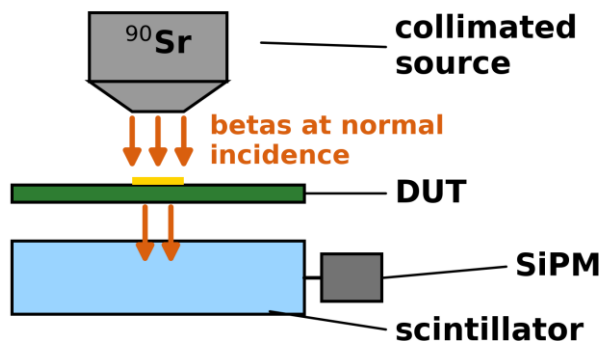
To study suppression, we need to compare the measured proton gain with the unsaturated MIP gain.



LGAD: W9 at 180 V. PIN: W1PIN at 100 V.

Measuring MIP Gain

- Sr-90 betas serve as the MIP reference (gain at low charge density, before saturation sets in)
- A coincident hit in a scintillator behind the LGAD selects the high-energy betas that pass through it, so each deposits close to a MIP.
- Absolute deposit simulated with Geant4.



Sensor	Thickness	Doping depth	Relative doping
FBK W9	50 um	Shallow	1.06
FBK W16	50 um	Deep	0.83
FBK W18	50 um	Deep	0.81

Sensors obtained from an old ATLAS production

Measured Relative Gain Depends Strongly on the Density of Charges Deposited

$$G_{\text{rel}} = G_{\text{proton}} / G_{\text{MIP}}$$

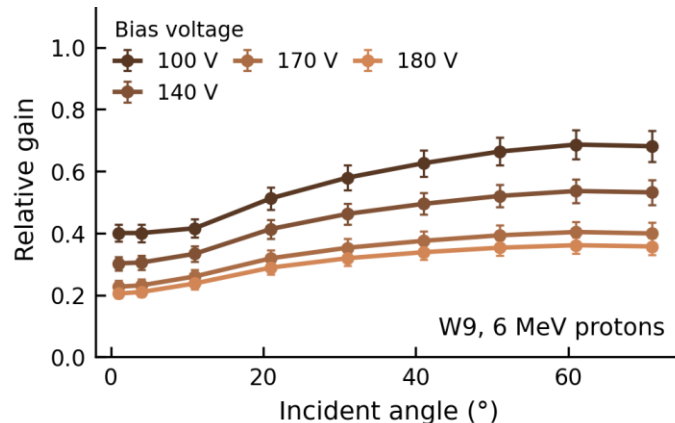
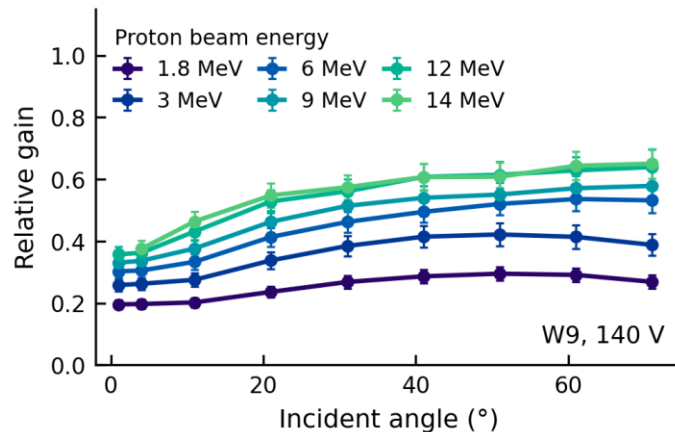
$G_{\text{rel}} = 1$ means no suppression.

Temperature corrections add up to 3% uncertainty.

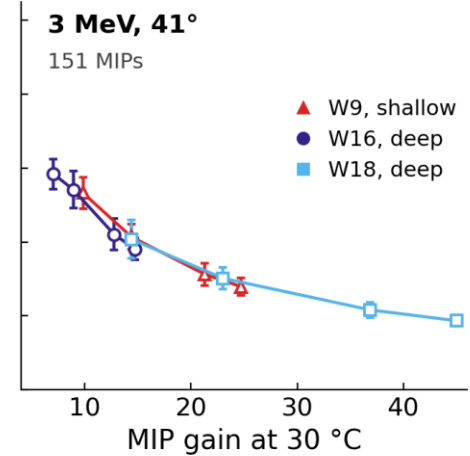
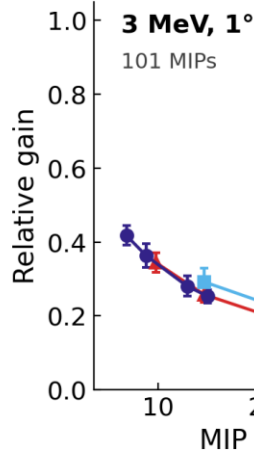
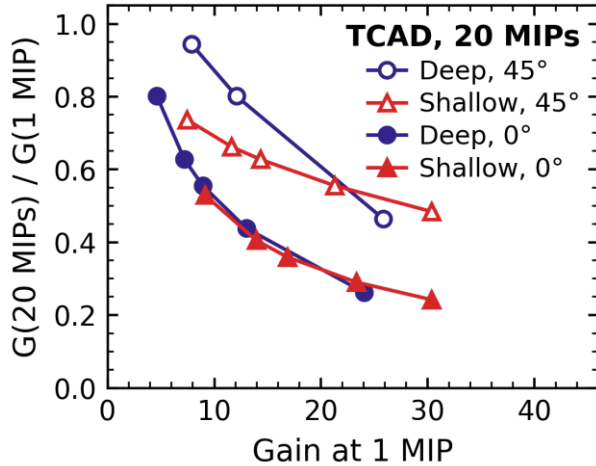
Greater gain suppression is observed for deposits with greater charge densities

- Lower incident angles
- Lower incident energy (i.e. greater dE/dx)
- Higher bias voltages

Higher beam energies bring the deposits down toward those of PIONEER's stopping pions and muons.



Gain-Layer Depth Makes Little Difference



- In 2023–24, the deep HPK 3.1 was suppressed less than the shallow FBK W1, but the vendors differ
- TCAD at 20 MIPs predicts no difference at normal incidence and less suppression for a deep layer at 45°
- In 2025, the shallow W9 and the deep W16 and W18, all FBK, show no significant difference at 1° or 41°
- These protons deposit 100 MIPs or more, so a difference may only appear at lower charge densities

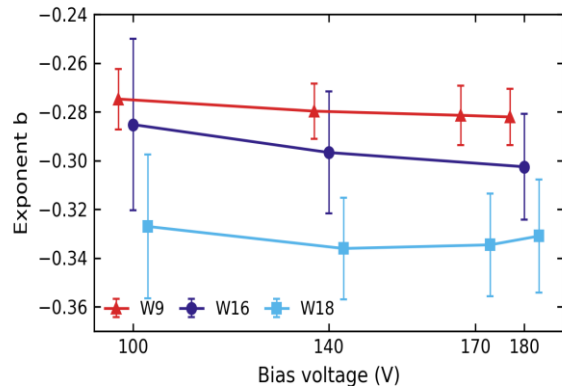
Modeling Gain Suppression

Suppression is local screening in the gain layer, so it depends on the charge per unit area, dE/ds

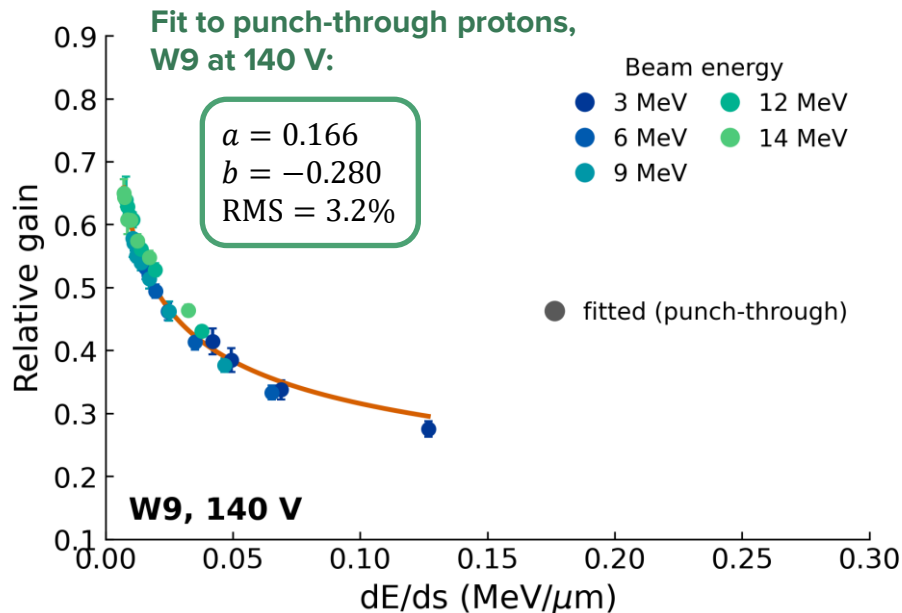
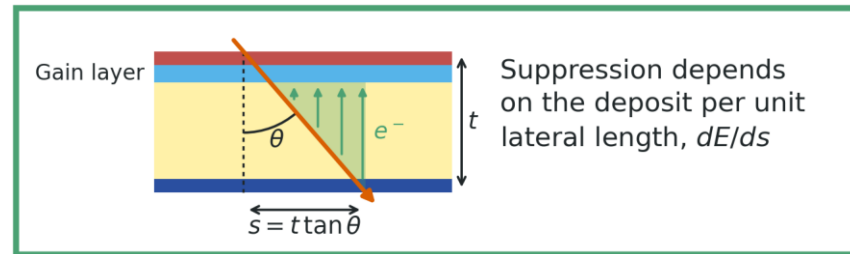
$$G_{\text{rel}} = a (dE/ds)^b$$

$$ds = t \tan \theta$$

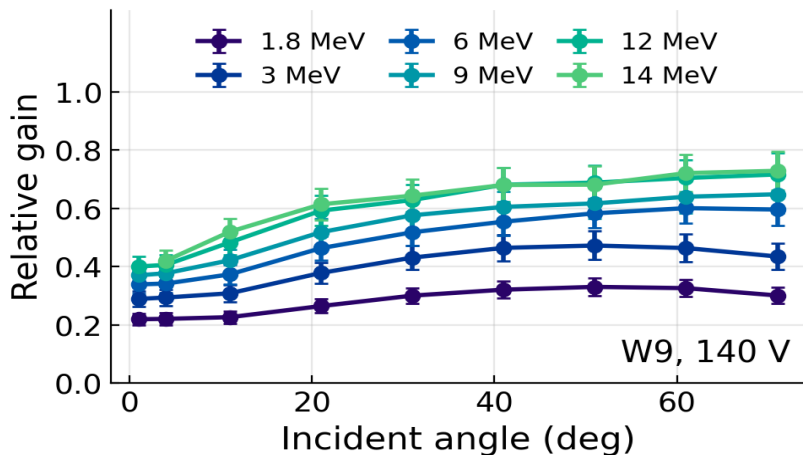
$t = 55 \mu\text{m}$; ds is the track's projection on the gain layer



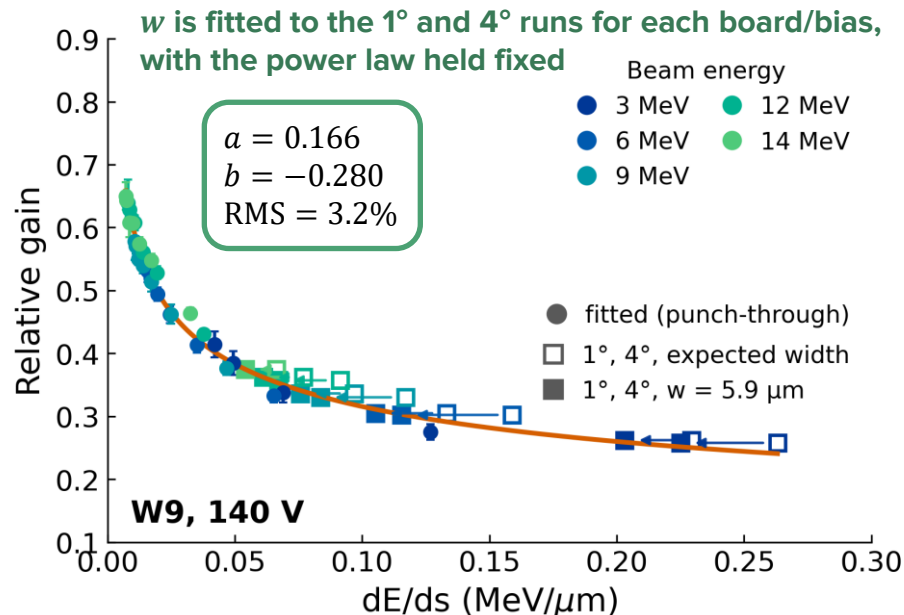
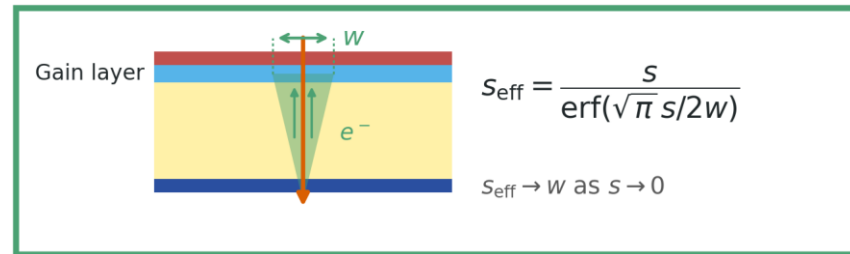
Each board maintains the same b across each bias.



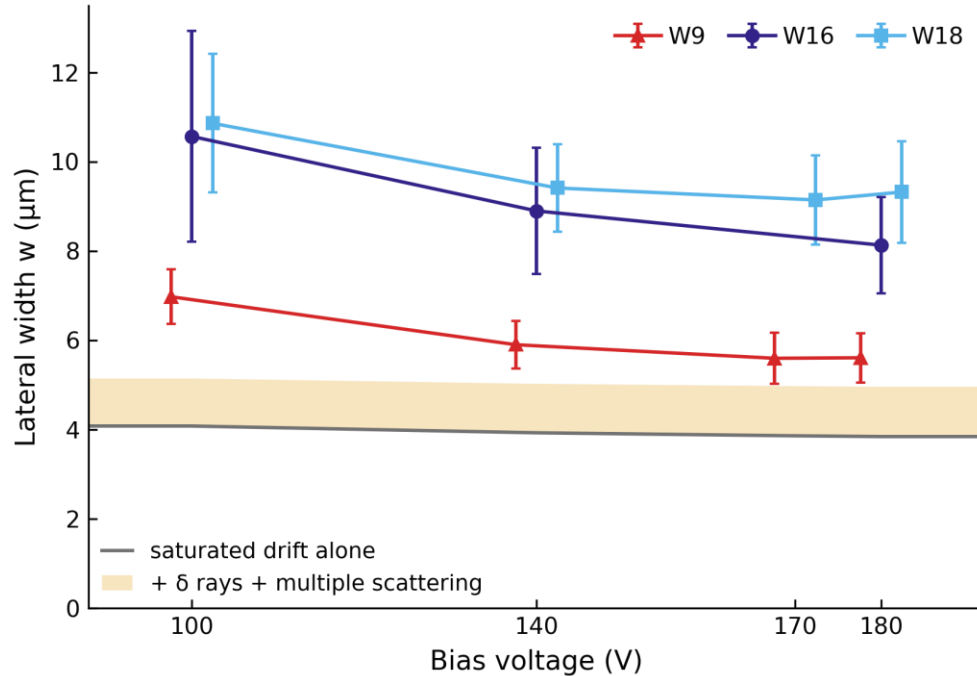
Lateral Width w



At normal incidence the track projects onto a point, so dE/ds would diverge. The data suggests a minimal angular resolution around 5° to 10° , corresponding a finite width w of the charge column.



Lateral Width by Sensor



All three sensors are wider than expected

The estimate is at most $5.2 \mu\text{m}$, from drift, δ rays and scattering

W16 and W18, deep gain layers

8.1 to $10.9 \mu\text{m}$, which is 1.6 to 2.1 times the estimate

W9, shallow gain layer

5.6 to $7.0 \mu\text{m}$, which is 1.1 to 1.4 times the estimate

Other models are being considered.

Systematics and Open Questions

Primary systematics

MIP gain **4–12%**

W1PIN reference **3.3–6.6%**

Added in quadrature:

Simulation vs. data 1.8–5.8%

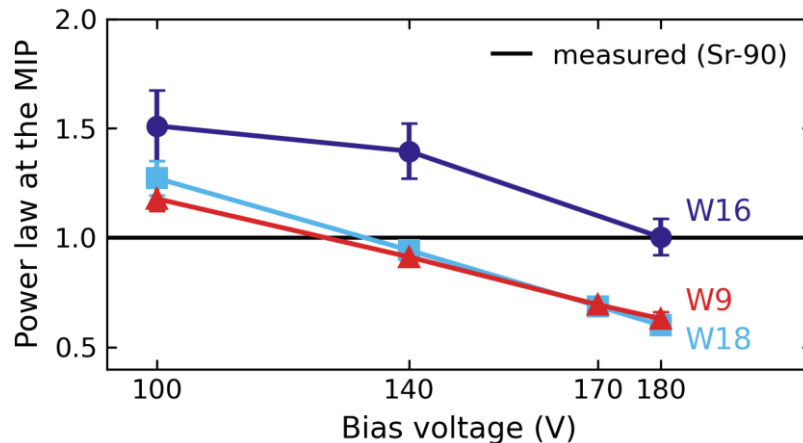
Board transimpedance 2.8%

Beam energy offset up to 2.9%

Proton-run temperature **0.9–2.9%**

Open questions

- The law misses the MIP gain, 1.2–1.5 at 100 V and 0.6–1.0 at 180 V
- Fitted widths are 1.5–2.7 times the saturated-drift width

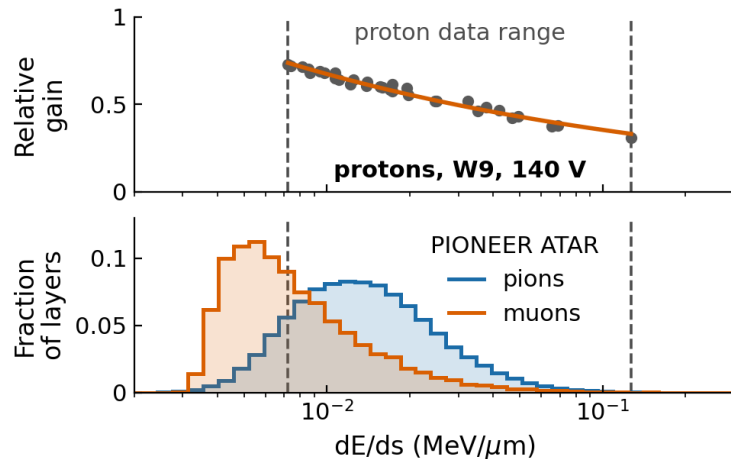


Summary and Outlook

Measured the gain suppression of LGADs with protons:

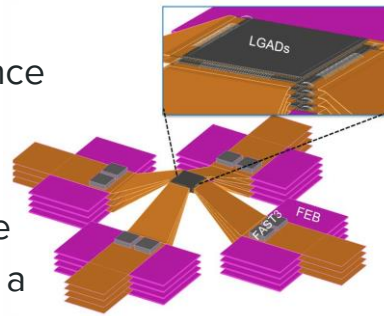
- FBK W9, W16 and W18 at 1.8–14 MeV and up to 71°
- Stronger at higher bias and for lower-energy protons; the gain-layer depth matters little
- Punch-through data follow a power law in dE/ds

$$G_{\text{rel}} = a (dE/ds)^b$$

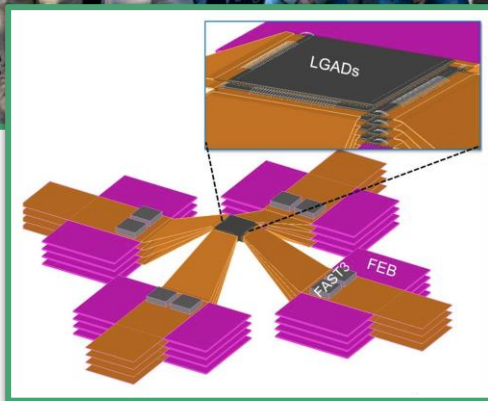
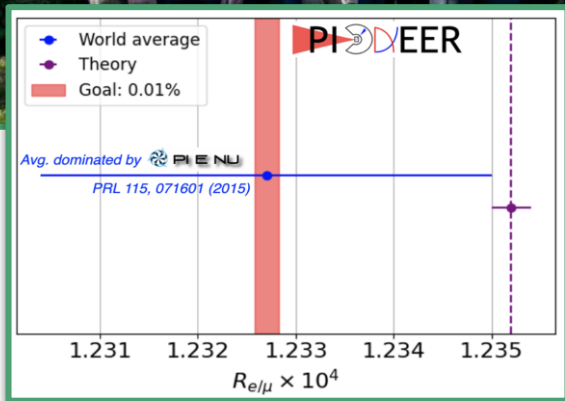
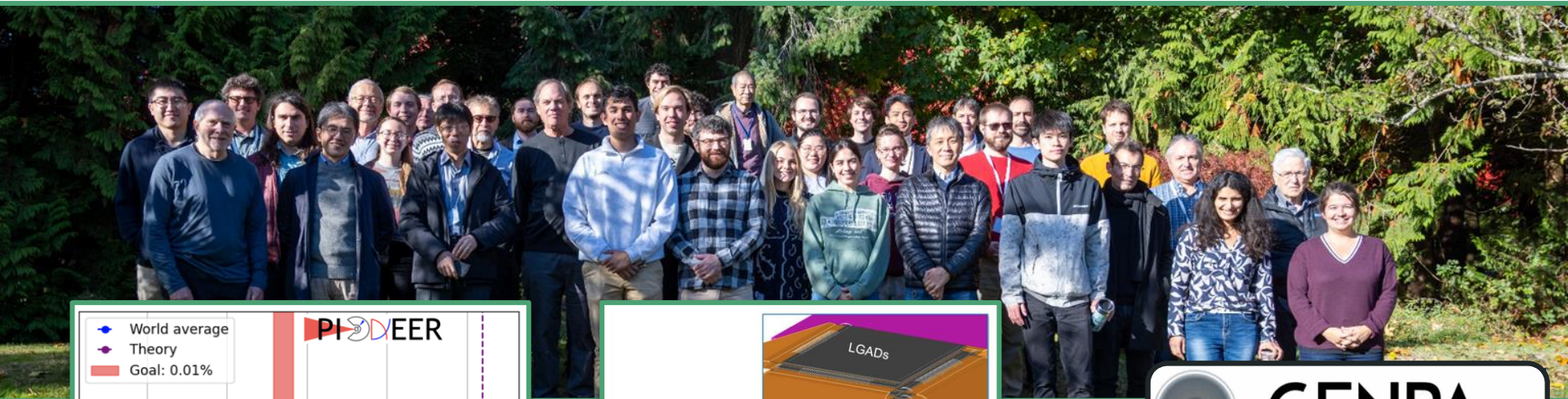
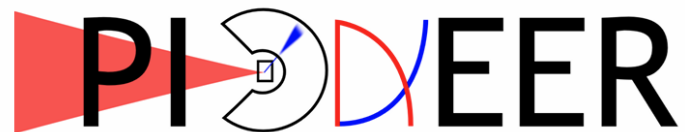


Beamtime for the PIONEER demonstrator at the end of 2026!

- Validate species independence with muons (and pions)
- Test below our data range, where 55% of muon layers lie
- Run incident angle scan with a MIP-like positron beam



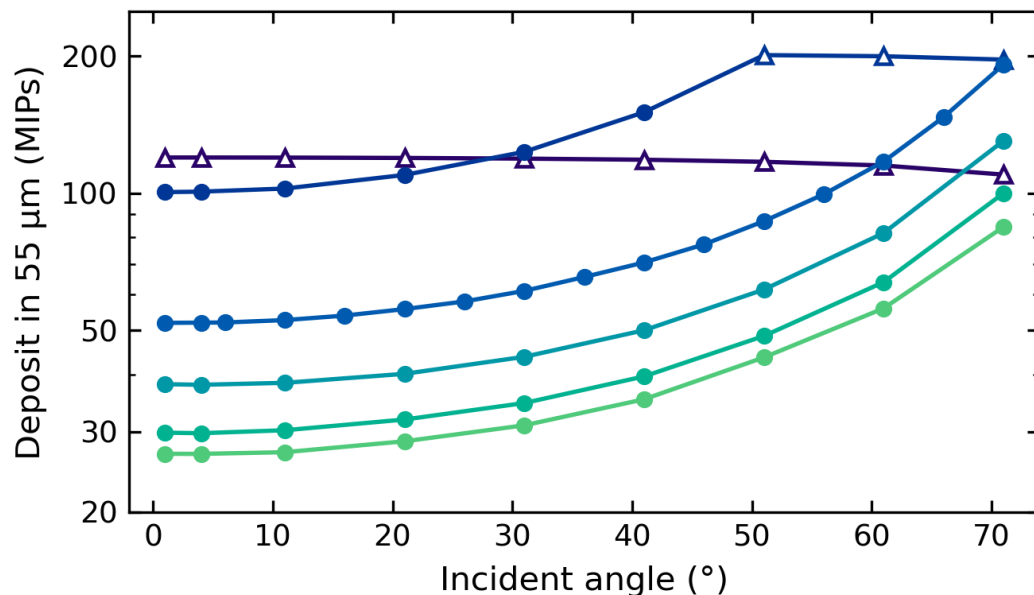
Thank You!



Backup Slides

Proton Deposit in MIPs

● 1.8 MeV ● 6 MeV ● 12 MeV ● punch-through
● 3 MeV ● 9 MeV ● 14 MeV ▲ stopping



One MIP: 13.25 keV, the most probable Sr-90 deposit in the 55 μm layer; the W1PIN peak over it

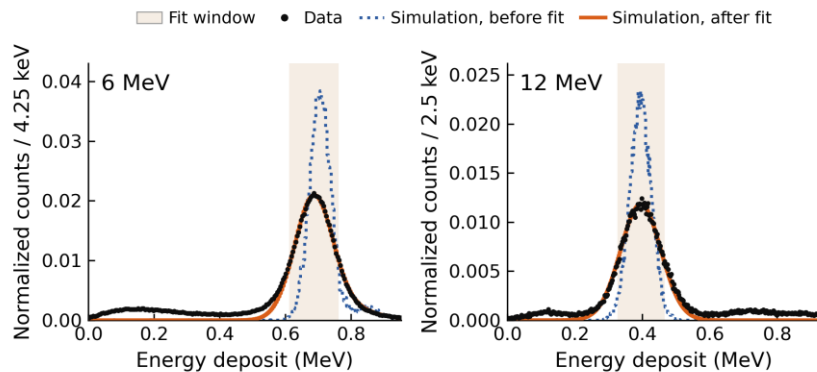
Punch-through: rises with angle, the longer path; 27 MIPs at 14 MeV near normal incidence

Stopping: all the energy is left in the sensor; up to 200 MIPs at 3 MeV

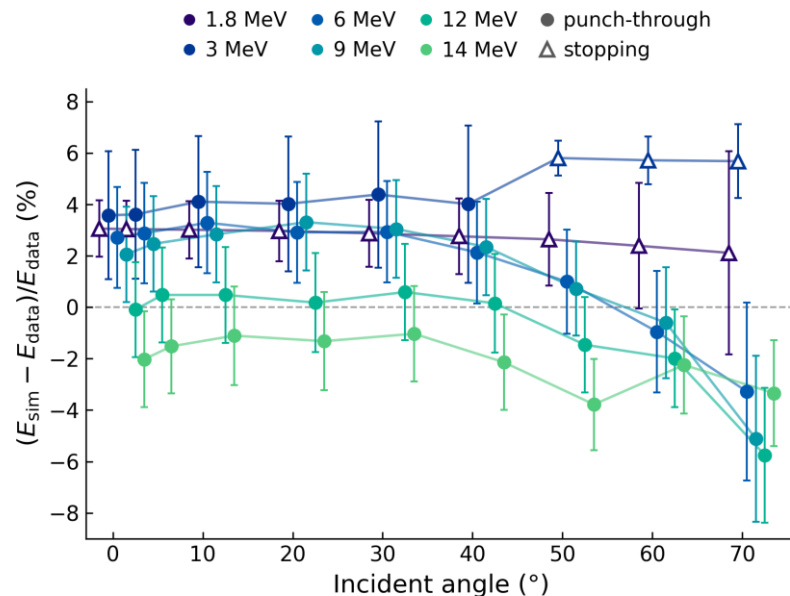
Far above a MIP: ≥ 27 MIPs everywhere, ≥ 100 MIPs at 1.8 and 3 MeV

W1PIN Reference, Measured vs. Geant4

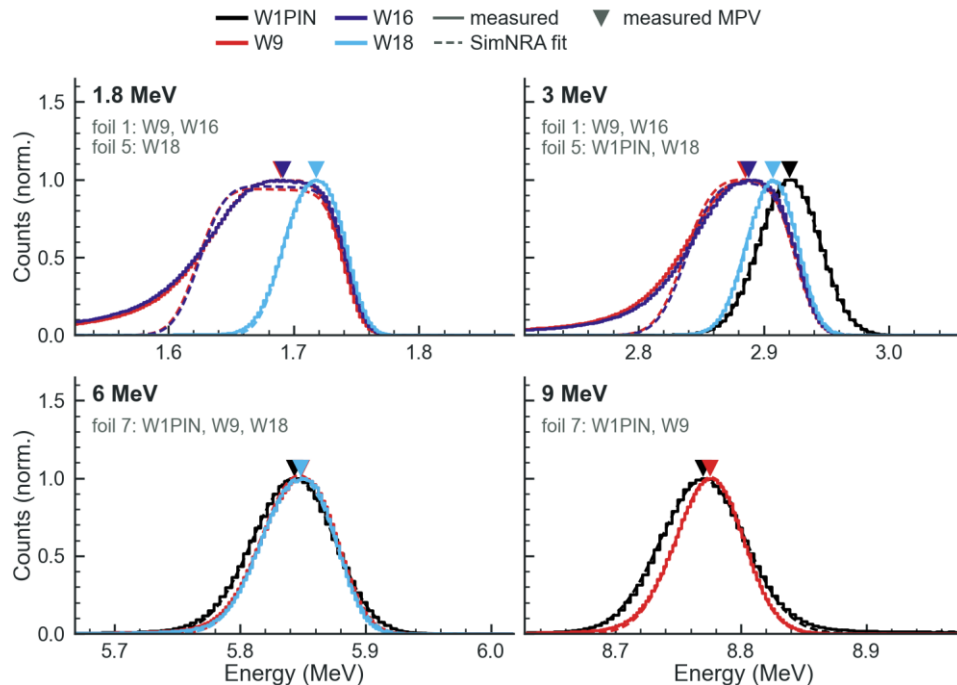
Geant4 reproduces the W1PIN peak within its uncertainty, except 3 MeV stopping protons



Fit: normalization, energy shift, Gaussian smearing. 3 MeV stopping runs (open triangles from 51°): simulation +6% (150 keV), not understood. The reference error is the larger of the shift and its uncertainty, 1.8–5.8%.



SimNRA Fit of the SiMon Spectra



Gain error: beam-energy differences add at most 2.9% (W9, 3 MeV, 41°), below 0.6% at 6 MeV and above

Fit: one thickness per foil, one beam offset per run, one resolution per energy

Agrees: peak positions and run-to-run differences within 2 keV

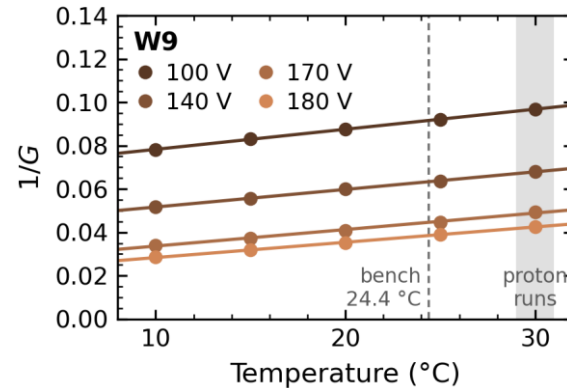
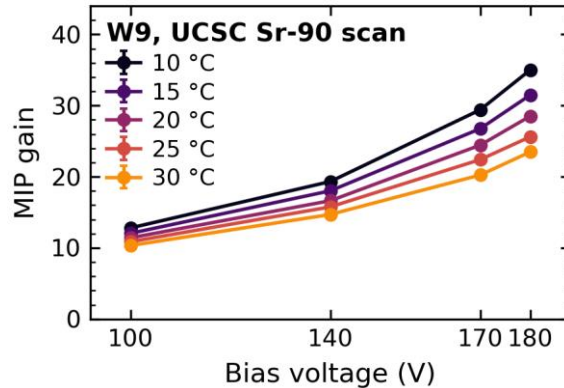
Misses: shapes behind foil 1: one uniform gold layer, no C/O or plural scattering

Foil shift: foil 1 (0.60 μm): peak 27–35 keV below foil 5 (0.27 μm)

Temperature Correction of the MIP Gain

$$G = \frac{1}{1 - I}, \quad I(T) = I(T_0) - c(T - T_0) \quad \Rightarrow \quad \frac{1}{G(T)} = \frac{1}{G(T_0)} + c(T - T_0)$$

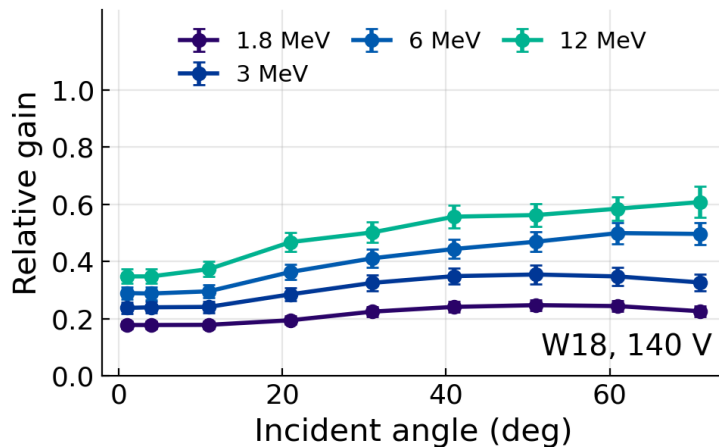
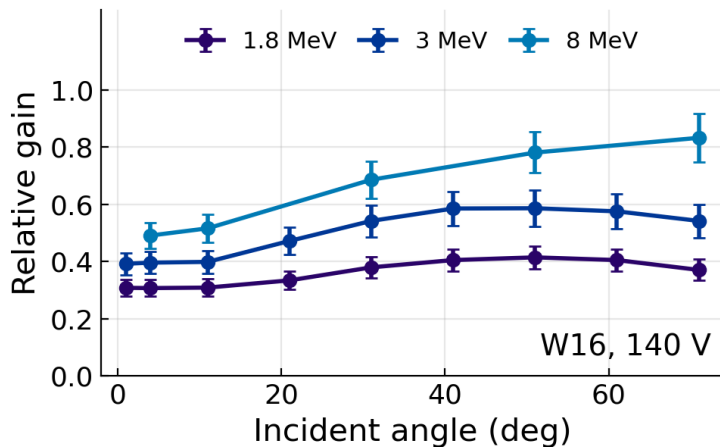
Warmer → shorter mean free path → fewer ionizations (lower I) → lower gain



$$G_{30} = \left[\frac{1}{G_{\beta}} + c(30^{\circ}\text{C} - T_{\beta}) \right]^{-1} \quad \text{lowers the MIP gain by 3–11\%}$$

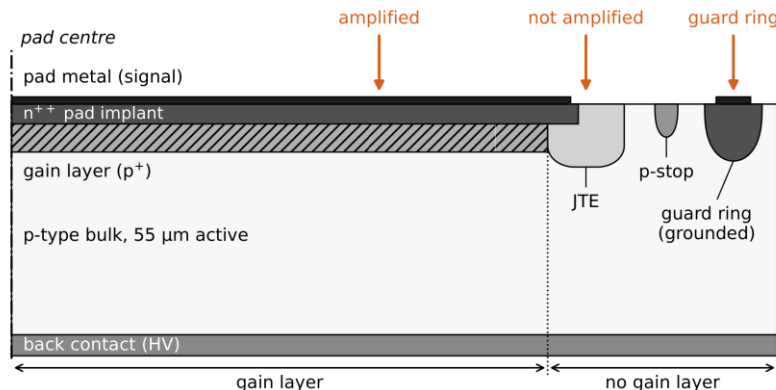
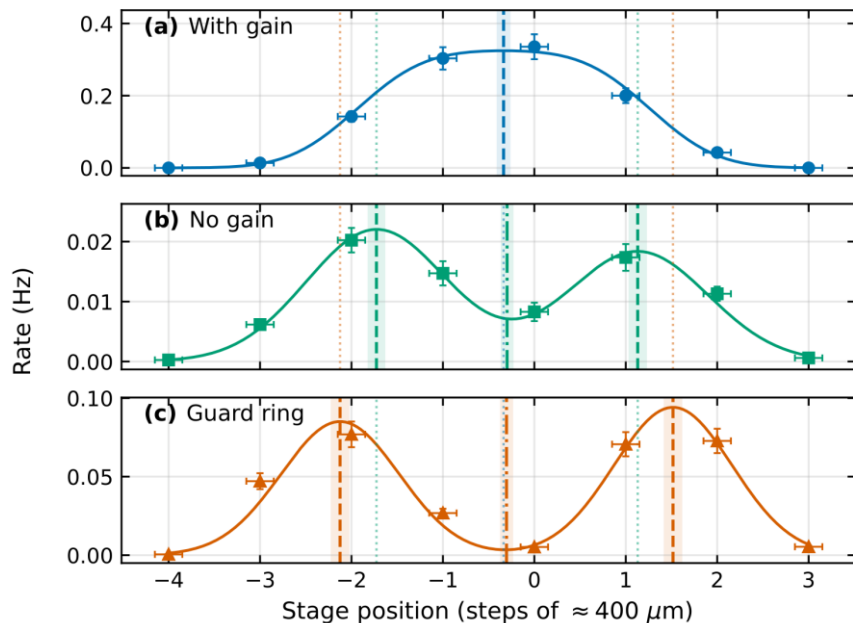
Relative Gain of W16 and W18

The same trends as W9: relative gain rises with incident angle and with beam energy, and is lower for higher gain sensors.



Pinhole Scan and Edge Effects

Every energy spectrum has two small peaks besides the main one; a ^{244}Cm pinhole scan finds where on the pad each comes from



Scan: ^{244}Cm alphas, 500 μm pinhole, steps of about 400 μm , W18 at 140 V

With gain: a plateau 1.28 mm wide, against the 1.3 mm pad

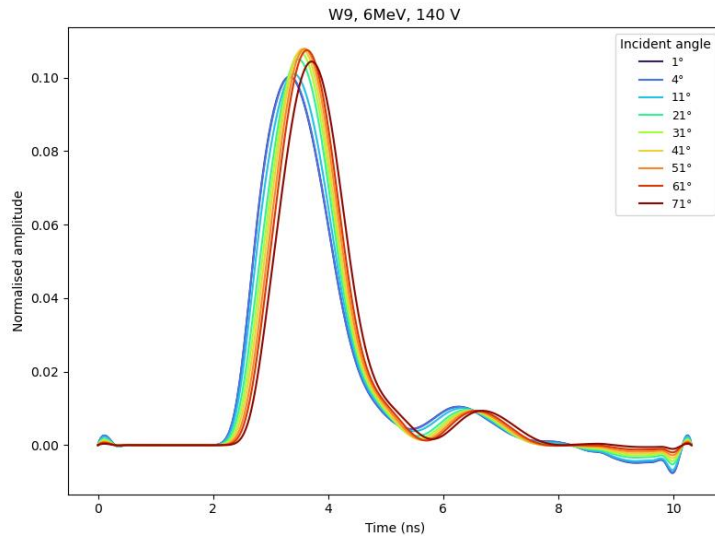
No gain: just inside the end of the gain layer; follows the W1PIN peak in the proton spectra

Guard ring: further out; induces a positive pulse on the pad

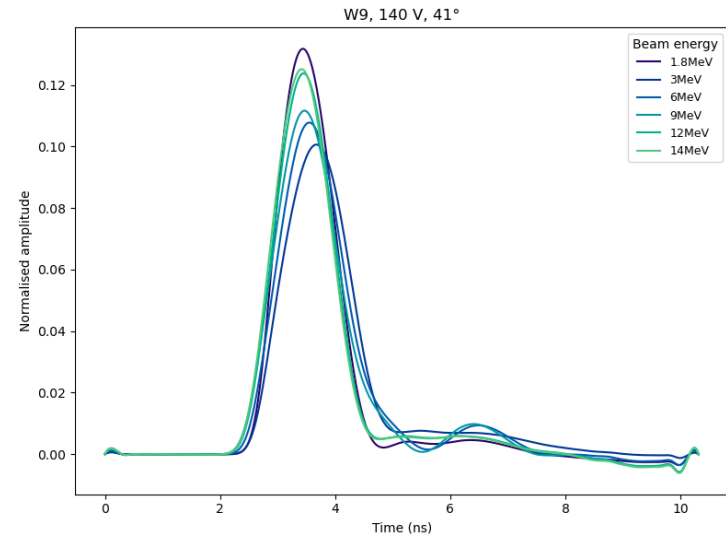
So: the gain fit uses only the main peak; PIONEER's TI-LGADs narrow the no-gain region

Average Waveforms

Normalized average pulses of W9: the pulse delays and broadens with incident angle and changes height with beam energy.

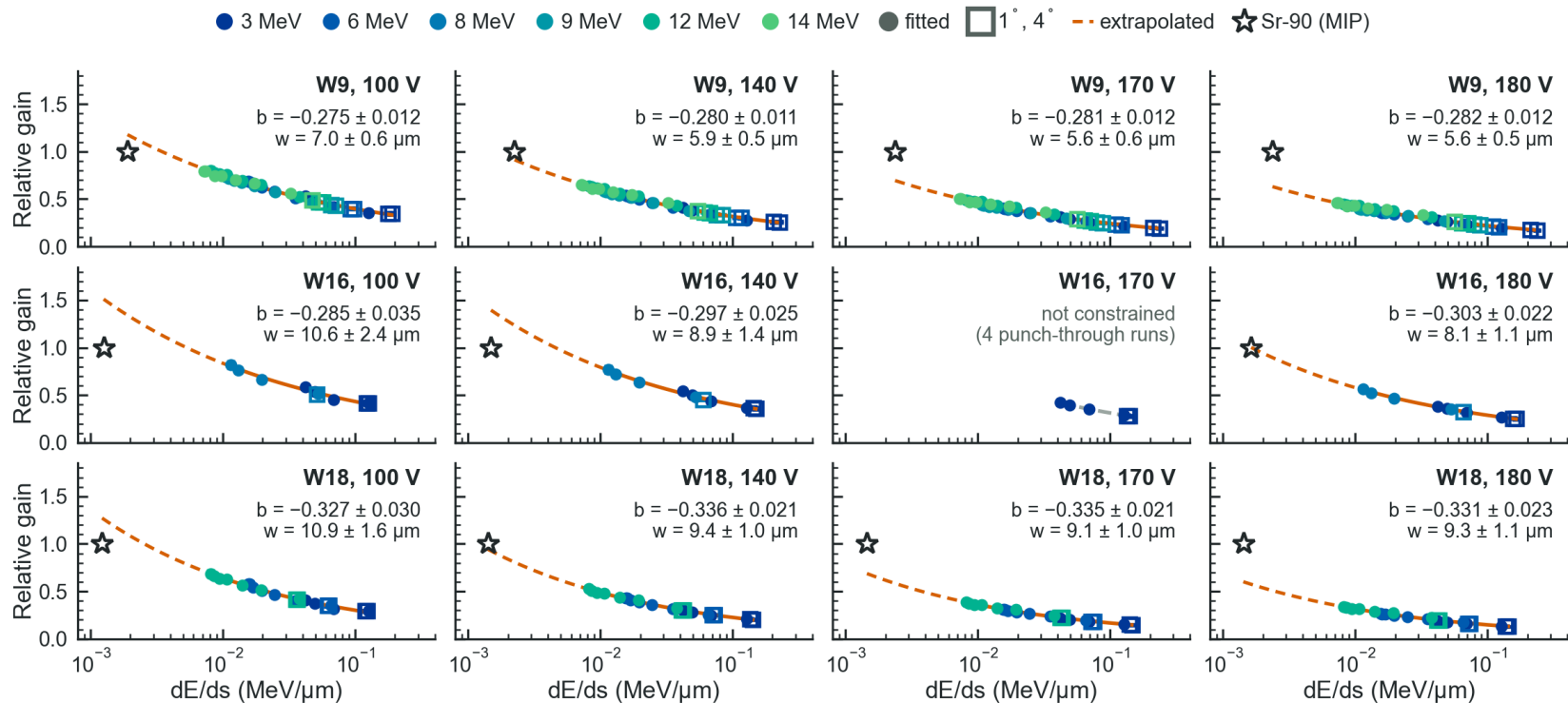


W9, 6 MeV, 140 V, by incident angle



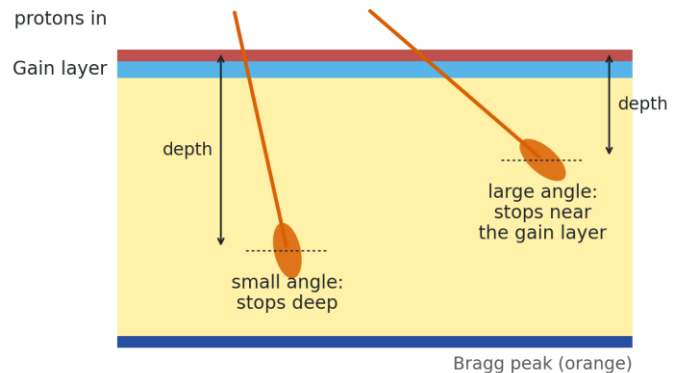
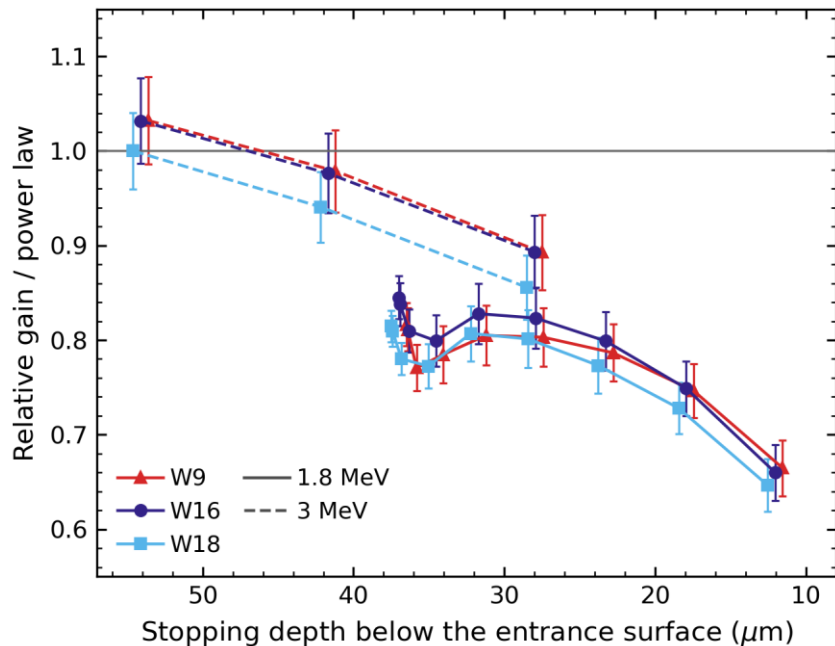
W9, 140 V, 41°, by beam energy

Power-Law Fits



Stopping Protons

Relative gain over the power law at 140 V, against the depth where the proton stops; the gain layer is to the right



Not fitted: the charge sits in a Bragg peak, which the mean dE/ds over the path does not describe

3 MeV: 1.02 of the law stopping at 54 μm , 0.88 at 28 μm

1.8 MeV: 0.79–0.83 from 37 to 23 μm (angles $\leq 51^\circ$), 0.66 at 12 μm

dE/ds sets the angle dependence at small angles, the depth at large ones. Not modeled; stopping pions and muons in PIONEER need the depth profile too

Why Muons Fall Below the Proton Data

dE/ds of whole ATAR layers against incident angle: muons at large angles fall below the proton data range.

