PIONEER: Conceptual design and LGAD test beam studies of the next-generation rare pion decays experiment

Jennifer Ott on behalf of the PIONEER collaboration*

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PIONEER Experiment

- New pion decay experiment approved at PSI, data taking to be started in 2028
- First test beam time assigned in May 2022, second in November 2023

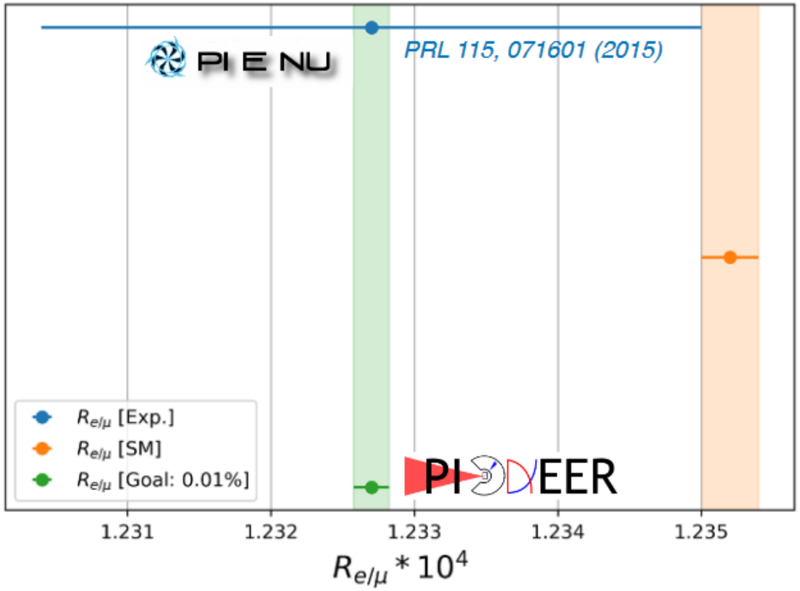
Phase 1

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$

Lepton flavor universality → charged lepton flavor universality violation?

SM prediction ca. 15x more precise than experiment!

Heavy neutrinos; light New Physics



https://arxiv.org/abs/2203.01981

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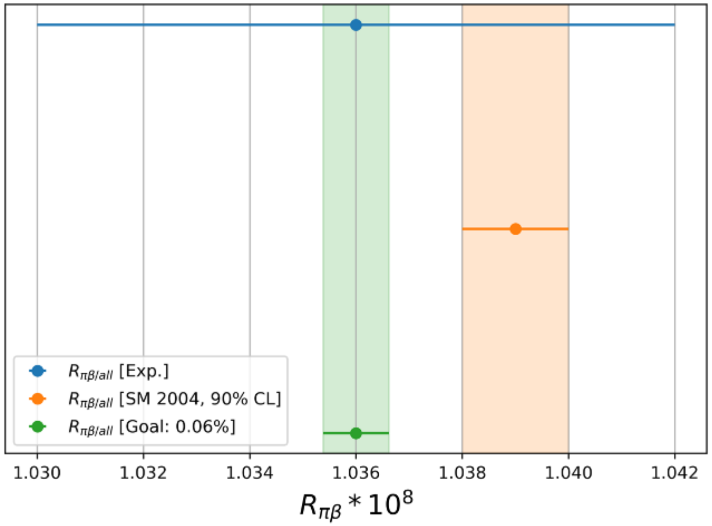
Phase 2 (3)

$$\pi^+ \rightarrow \pi^0 e^+\nu(\gamma)$$

CKM unitarity

$|V_{us}/V_{ud}|$

$|V_{ud}|$



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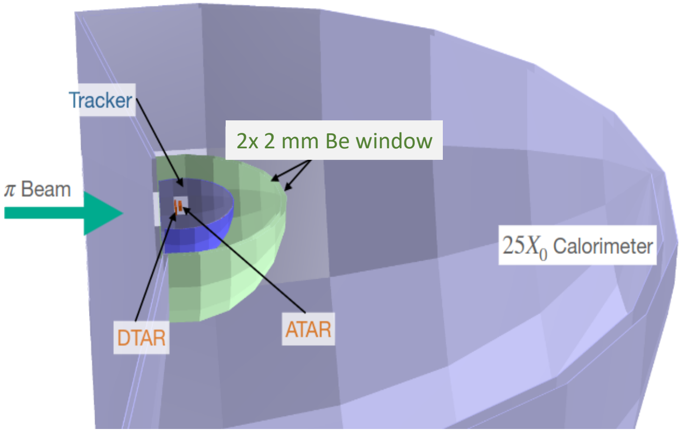
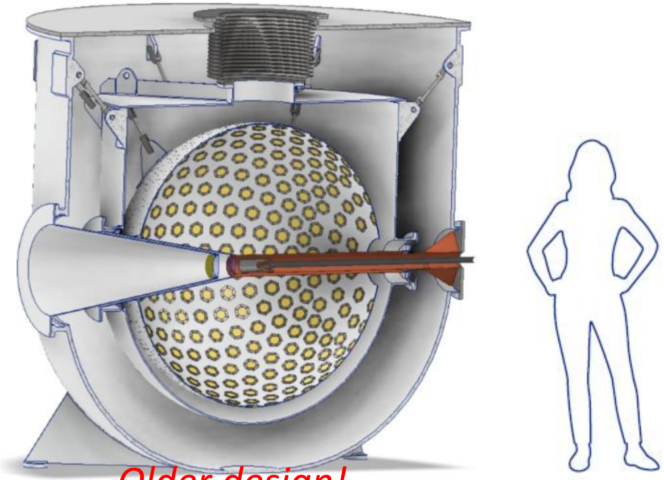
Detectors in PIONEER

Tracker
μ-RWELL

- Nominal design: homogeneous, cylindrical tracker
- Optimized experiment geometry: bullet-shaped or spherical?



Active Target



Older design!

~2π calorimeter
7t LXe

- Dense, uniform
- Fast response, excellent energy resolution
- Challenges: photosensors, cost, photonuclear effects
- **Alternative: LYSO:Ce crystal scintillators**
  - Recent beam test at PSI

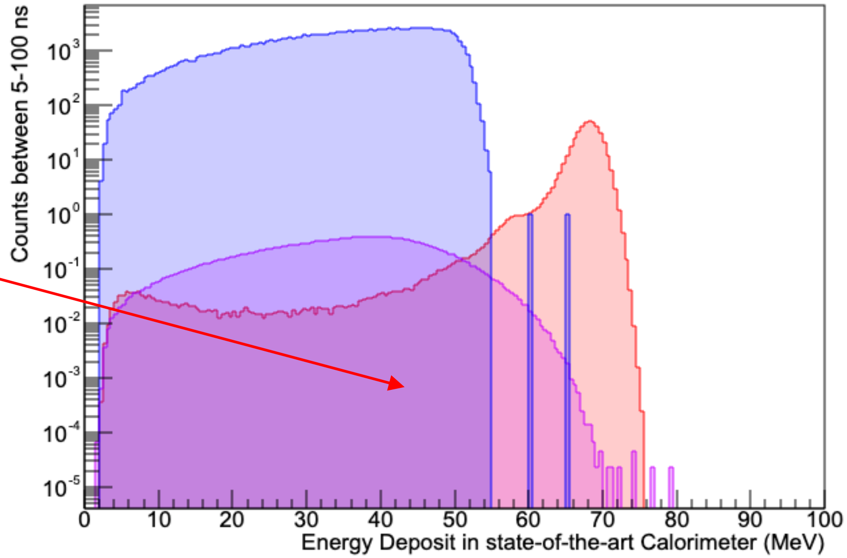
Degrader Target

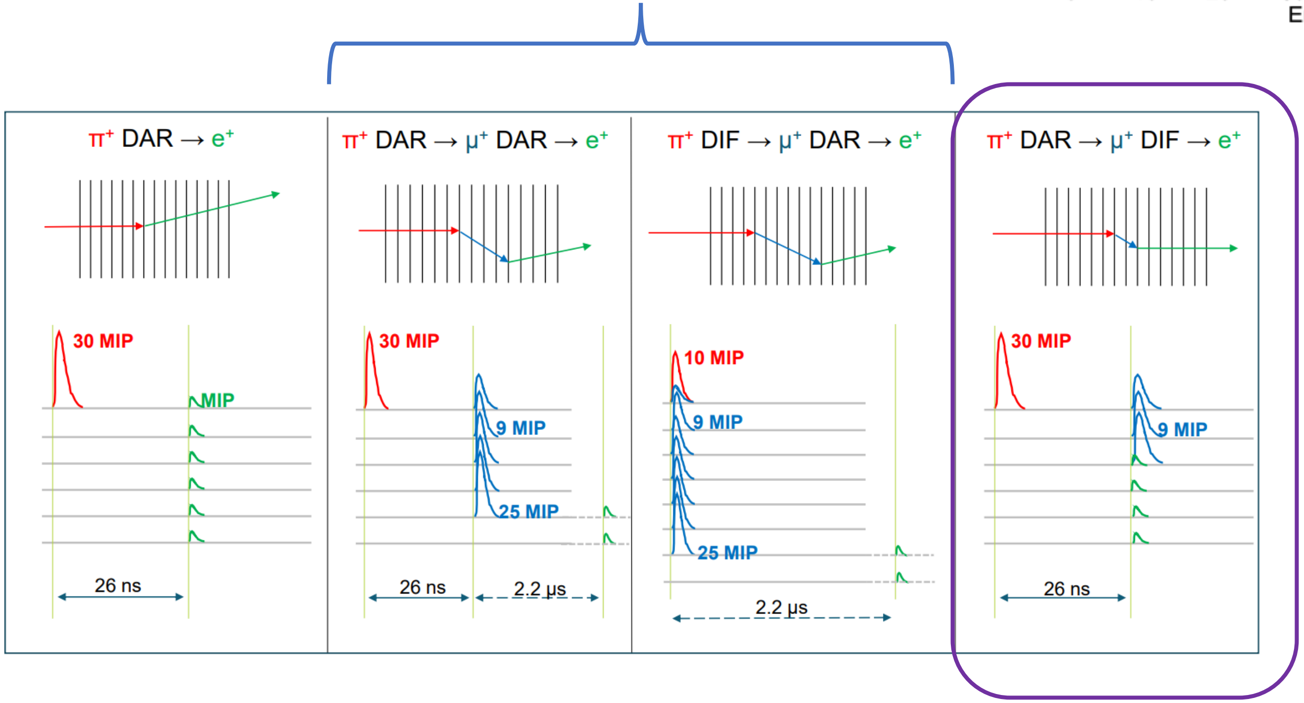
- Additional planes to slow down pion beam and potentially provide backward trigger/veto

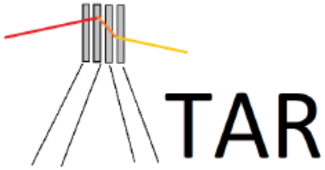
Towards 4D (5D) tracking: Active TARget detector

J. Ott, PIONEER and LGAD gain suppression, HSTD13

To achieve the PIONEER physics goal, it will be crucial to **separate the low-energy tail of *π*→e events** from *π*→*μ* →*e* decays in-flight and at-rest

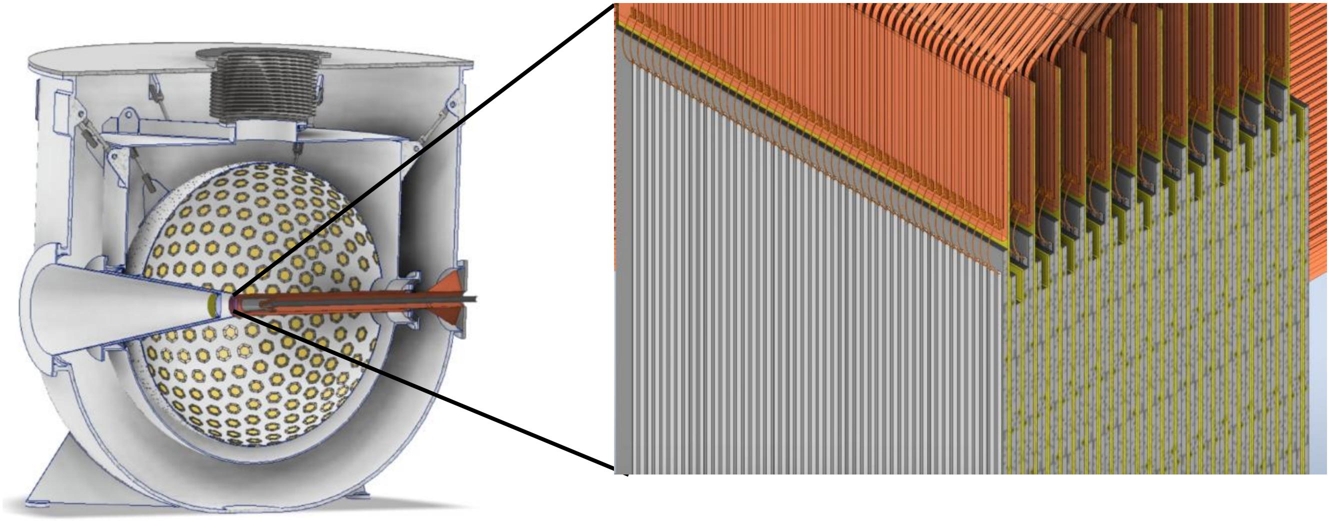






Towards 4D (5D) tracking: Active TARget detector

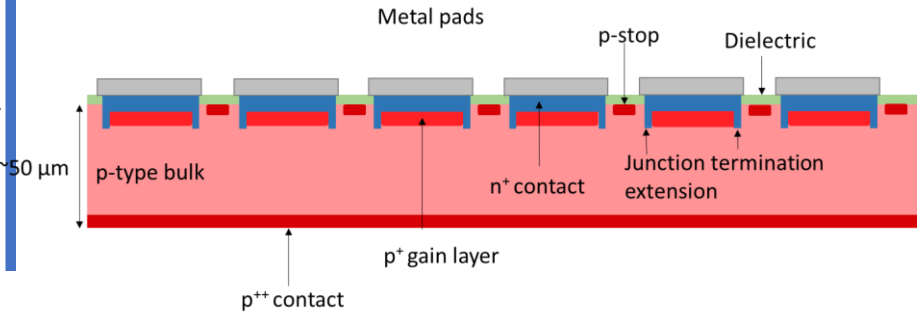
- Active TARget: 2x2 cm^2 area, ca. 6 mm thick: 60-75 MeV/c pions stop ~centrally
- ATAR requirements:
    - Spatial resolution <200 µm
    - Timing resolution < 100 ps
    - Large fill factor: traditional LGADs with gain termination structures not feasible
    - Inactive material not desirable! Support wafers cannot be used.
    - ➢ **Design baseline: 48 stacked planes of 120 µm thick AC-LGAD strips, pitch ca. 200 µm**
- Challenge: large energy deposits by stopping particles, up to 4 MeV muon kinetic energy as opposed to minimum-ionizing (30 keV) positron
    - Investigating possibility of using pin sensors: simplification of energy response, but drawbacks in spatial resolution, signal-to-noise ratio, electronics integration time / timing resolution requirements



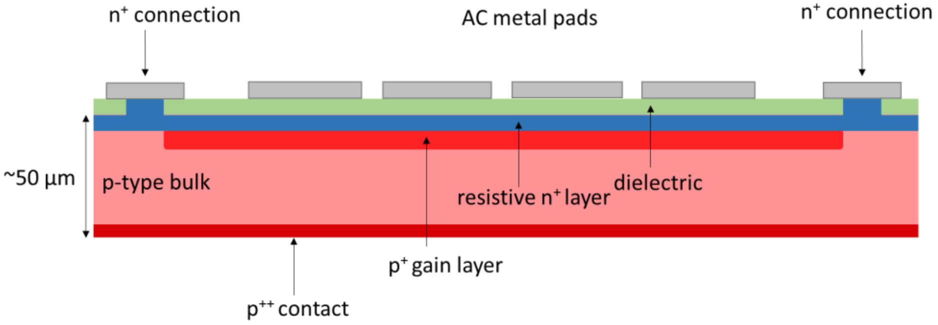
AC-coupled low gain avalanche diodes

- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, only the metal is patterned:
  - ➢ The signal is read out from metal pads on top of a continuous layer of dielectric
  - ➢ The underlying resistive n^+ implant is contacted only by a separate grounding contact
  - ➢ No junction termination extension: fill factor ~100
- The continuous n^+ layer is resistive, i.e. extraction of charges is not direct
  - ➢ Mirroring of charge at the n^+ layer on the metal pads: AC-coupling
  - ➢ Strong sharing of charge between metal pads
  - ➢ **Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels**

DC-LGAD



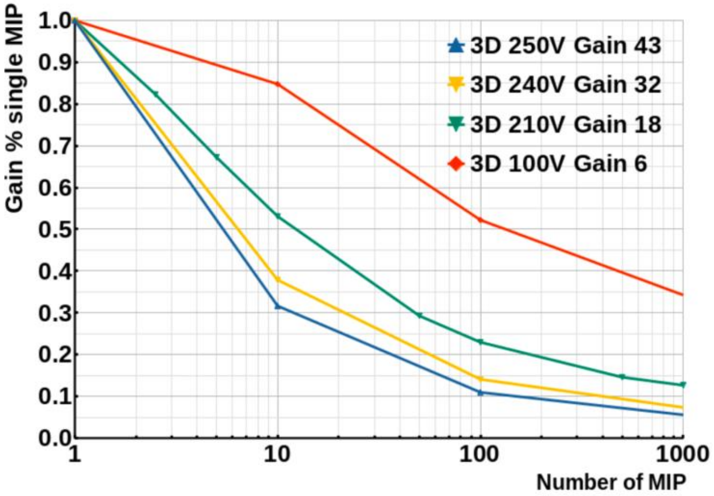
AC-LGAD



G. Giacomini *et al.,* Fabrication and performance of AC-coupled LGADs, *JINST* **2019**, 14, P09004
A. Apresyan *et al.,* Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam**,** *JINST* **2020**, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40

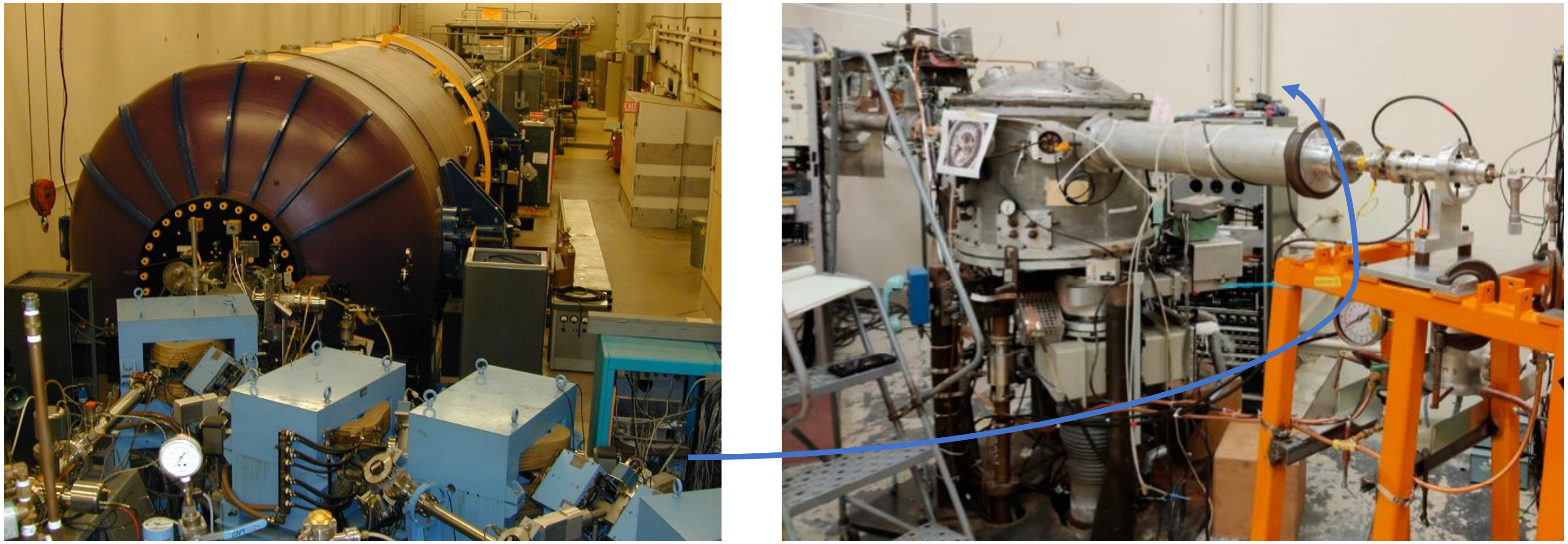
Gain suppression

- Large dynamic range is required for the ATAR readout electronics to resolve MIP-like energies as well as hits from pions and muons – in particular, distinguish muon track from positron to identify muon DIF
- **Limitations not only in the electronics: suppression of the gain** has been reported in LGADs at high gain and/or large charge deposits
  - Cloud of charges in the gain layer generates electric field counteracting the external field, and thus reduces or prevents multiplication of subsequent charge carriers
- Investigation of gain suppression:
  - *Injection with the laser higher power*
  - Alpha particles
  - X-rays (cf. Simone's presentation)
  - Degraded charged particle beam
  - TCAD simulations (e.g. Y. Zhao, CPAD 2022)
  - **Low-energy charged particle beam**



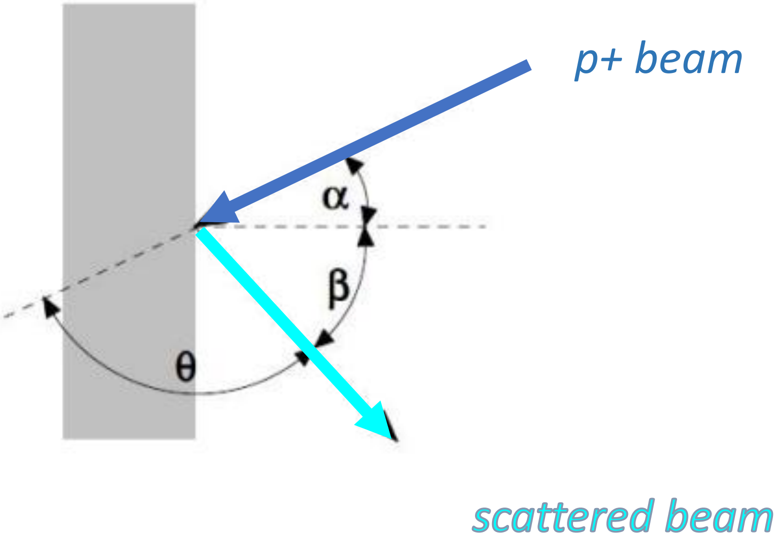
Experimental setup at CENPA

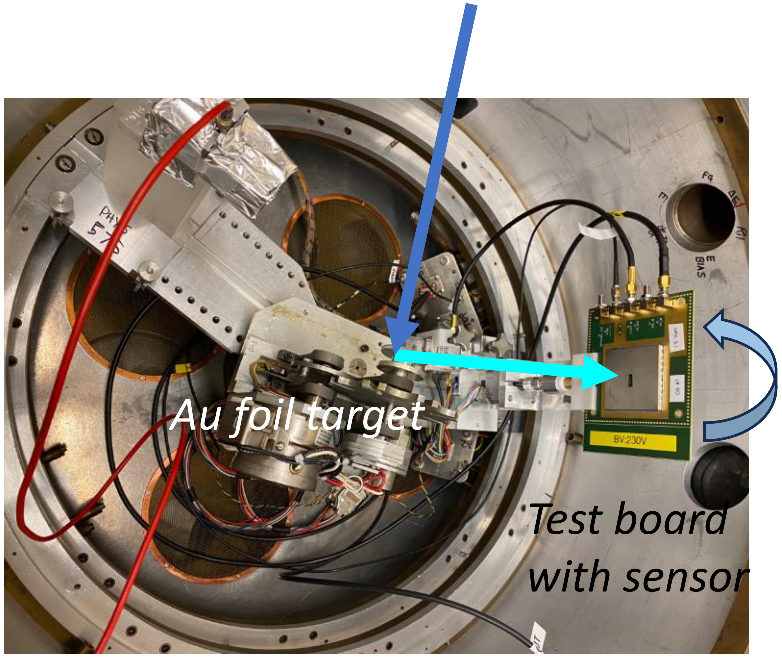
- Center for Experimental Nuclear Physics and Astrophysics at University of Washington
- Van de Graaff tandem accelerator: negative ions are injected and accelerated, electrons are stripped away and beam is emitted as positive ions
  - E.g. hydrogen gas to provide **protons**
  - Beam energy controlled by electric potential
  - **Energies used in this study: 1.8, 2, 3, 5 MeV**



Experimental setup at CENPA

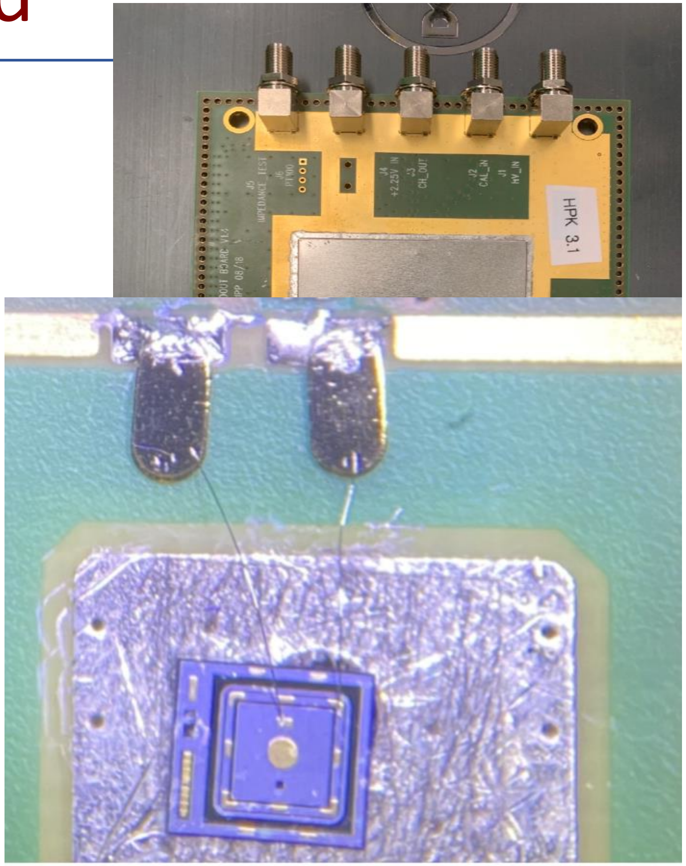
- Utilizing Rutherford Backscattering on a gold foil target to avoid direct exposure of the DUT to the beam
  - Scattering angle 110°
- Test board was mounted on a rotation stepping motor to vary the angle of the sensor with respect to the scattered beam
  - **Scanned 0°-75°**





Sensors tested

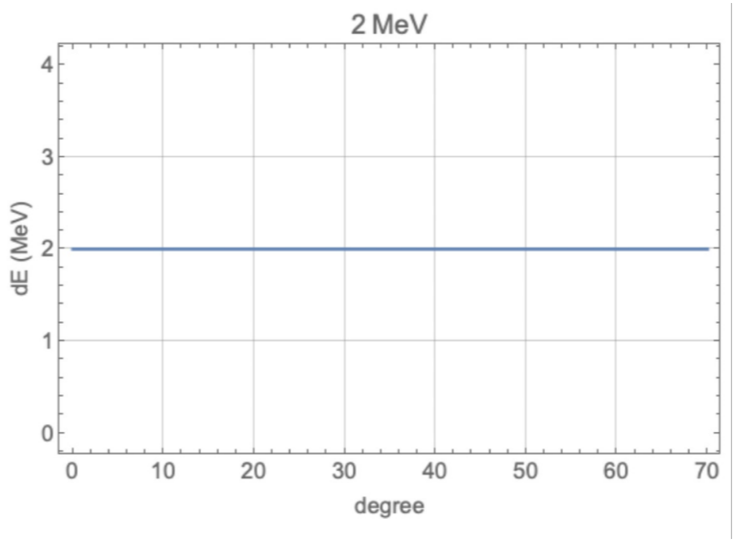
- Focus on a ‘simple system’: single-pad, standard DC-coupled LGADs
- Read out with UCSC 1-ch transimpedance amplifier board + 20 dB RF amplifier, and Tektronix DPO 7104 1 GHz oscilloscope
- **Sensors tested at different bias voltages** to study the effect of the gain itself on gain suppression

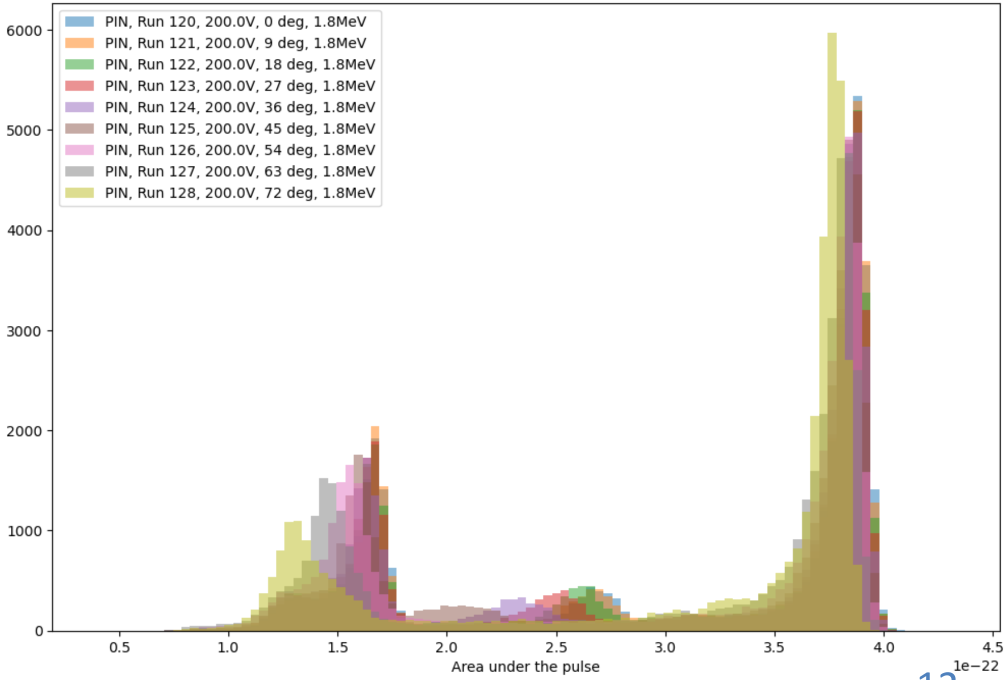


Sensor	Breakdown voltage (V)	Gain layer	Thickness (µm)	Pad size (mm)
HPK 3.1	230	Shallow (0.5-1µm)	50	1.3x1.3
HPK 3.2	130	Deep (1-2 µm)	50	1.3x1.3
HPK 3.2 pin	400	No gain	50	1.3x1.3

Pin sensor results

- At **1.8 and 2 MeV** beam energy, protons stop in the sensor even at normal incidence and protons deposit maximum energy
- At 3 MeV, signal charge increases with angle before stopping of the protons at ca. 50°





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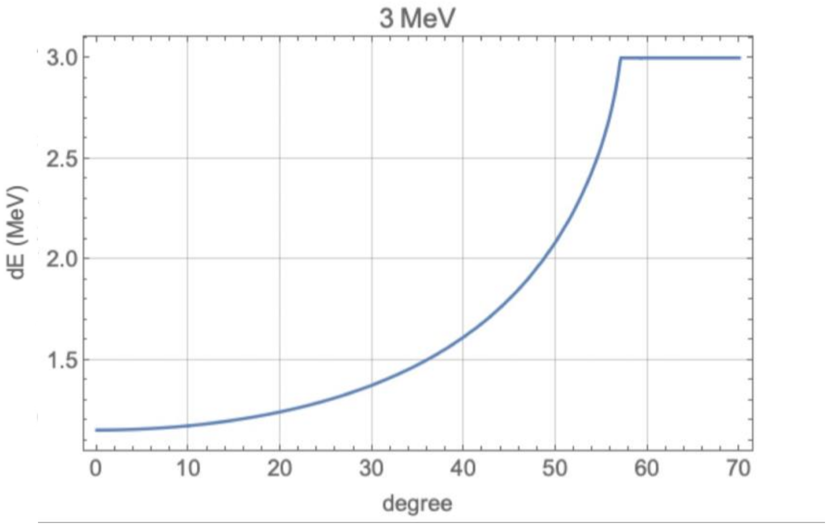
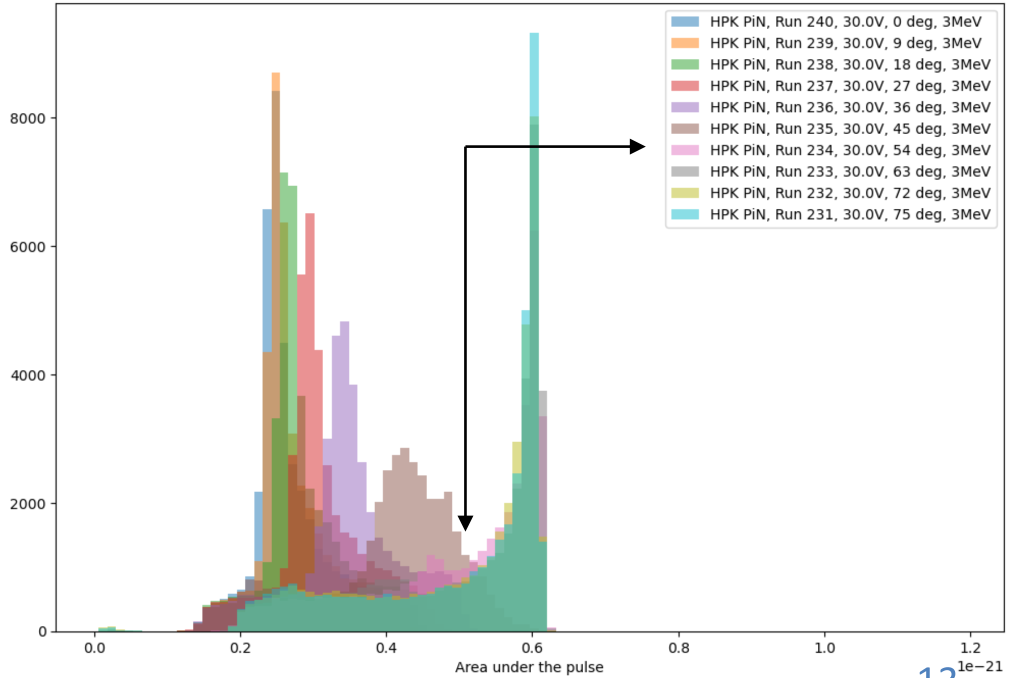
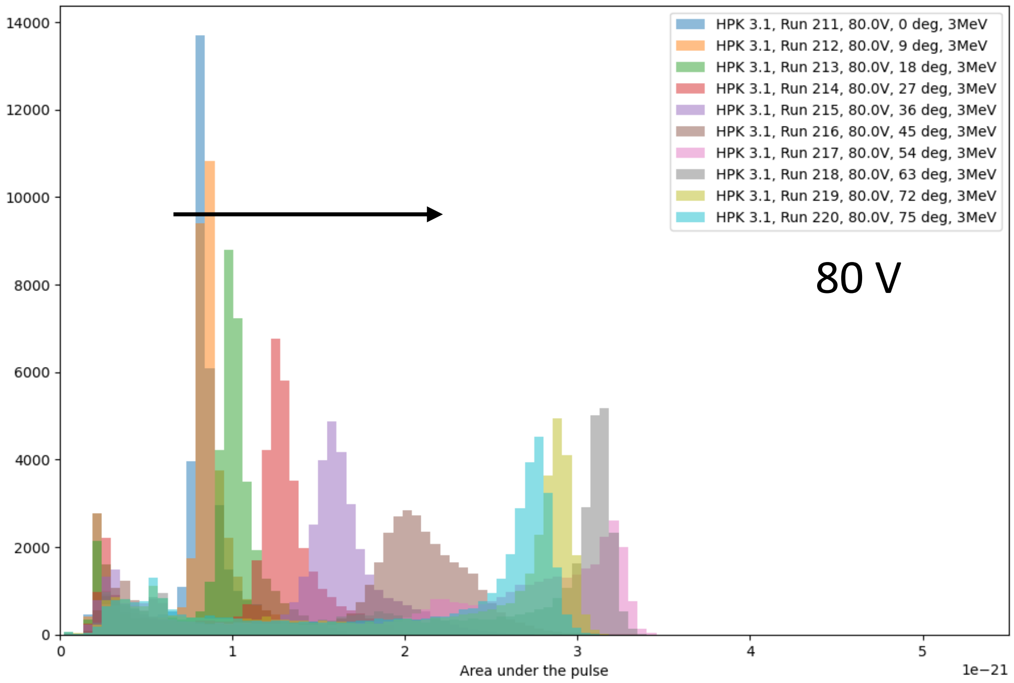


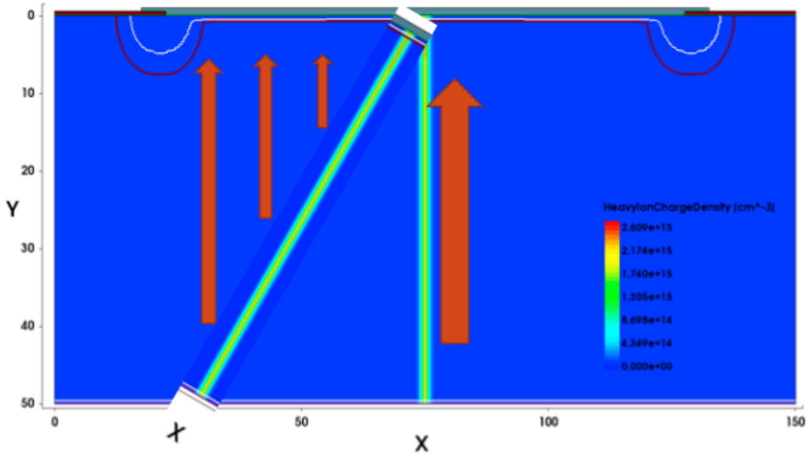


HPK 3.1 LGAD at 3 MeV

- Angular dependence of gain

- At <10°, energy deposit within the same area: gain suppressed
- At increasing incident angles, gain increases as proton energy deposit is spread out over wider depth

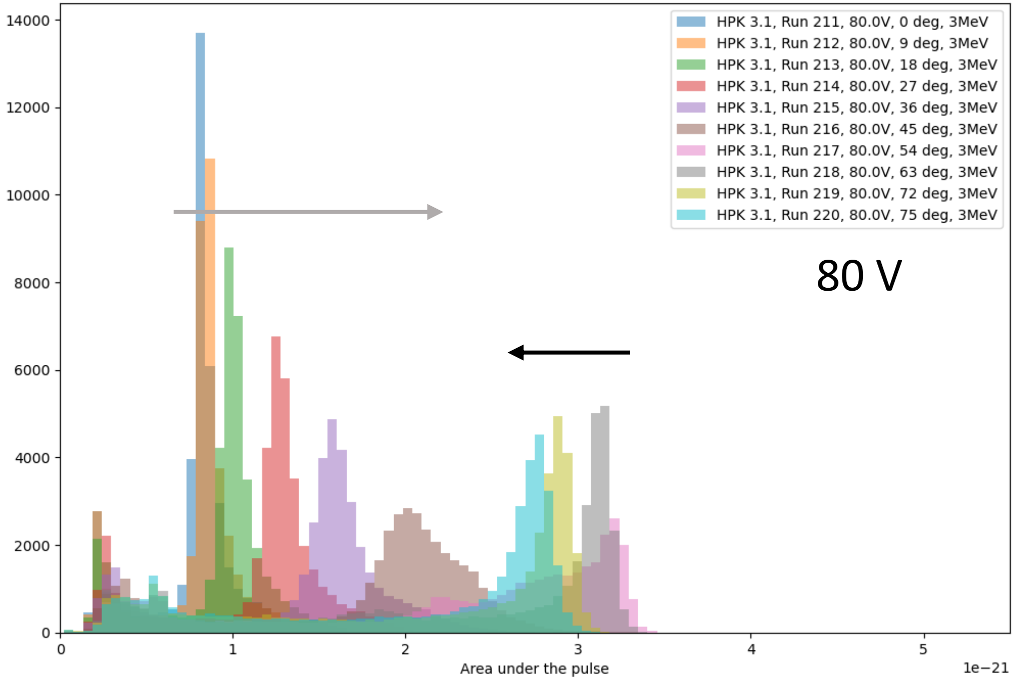


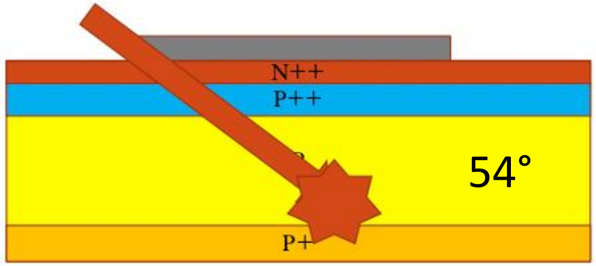


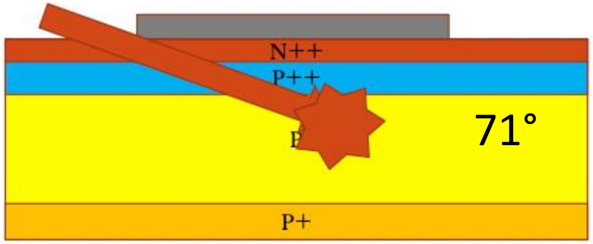
HPK 3.1 LGAD at 3 MeV

- Angular dependence of gain

- At higher angles (with the proton stopping in the sensor), the gain is suppressed again
    - Main energy deposit closer to the gain layer

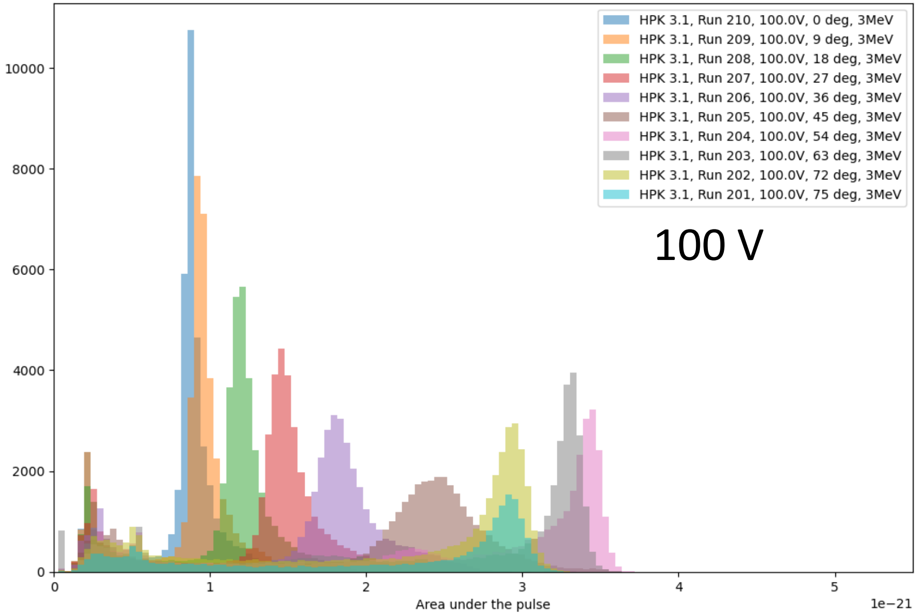


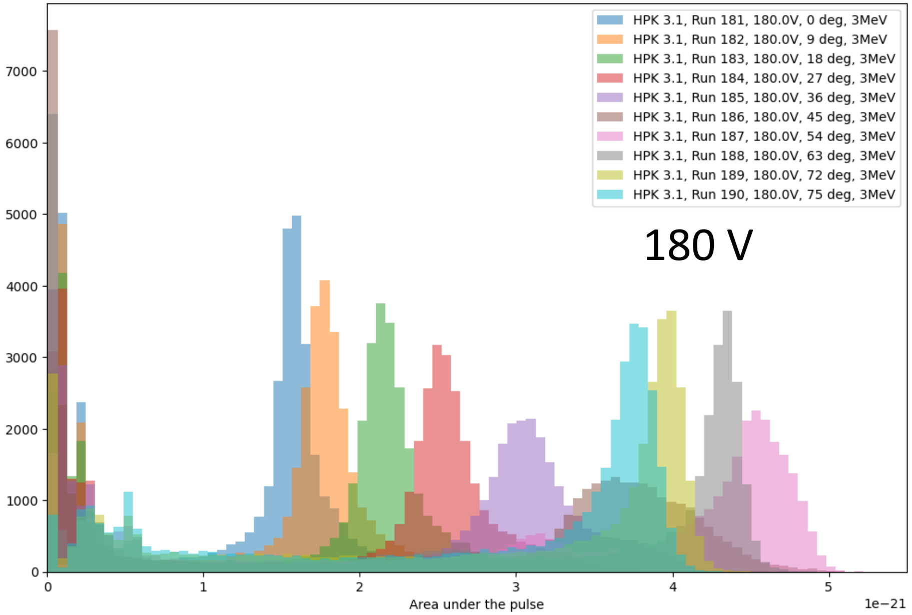




Effect of bias voltage

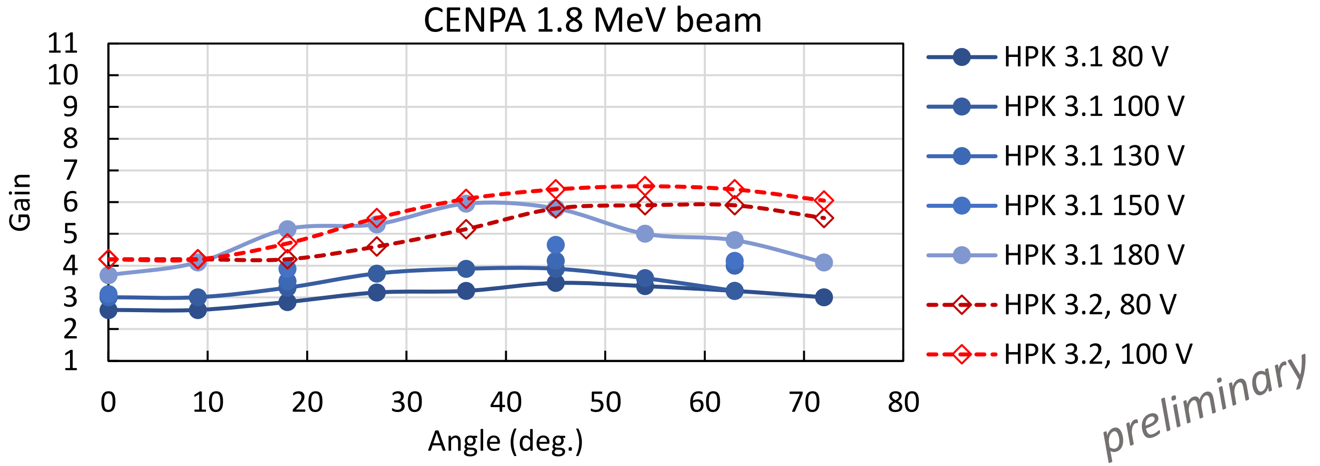
- Higher bias voltage: higher initial gain
  - Larger gain increase and spread
  - Stronger gain suppression effect
- Similar for HPK 3.2, but less suppression with angle?

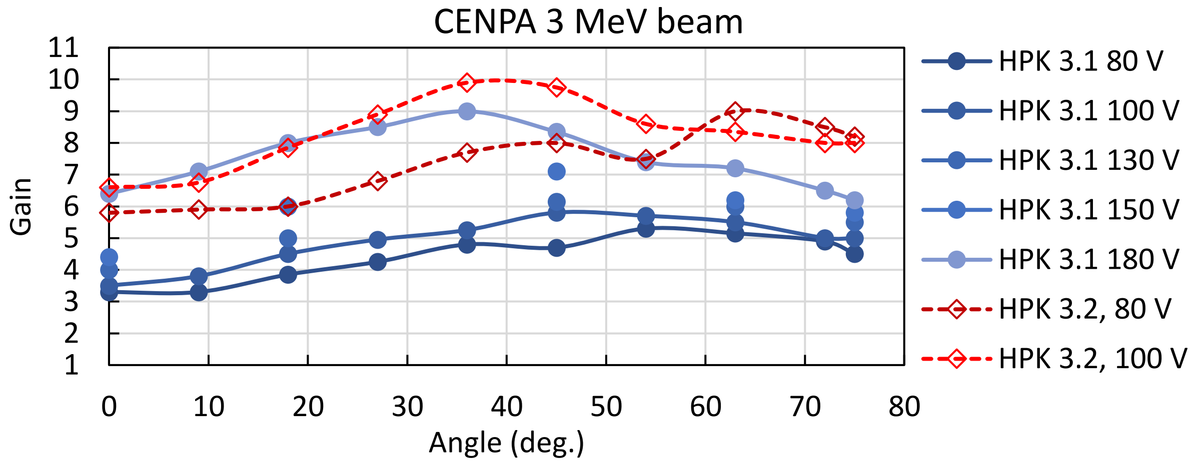




Gain as function of incidence angle

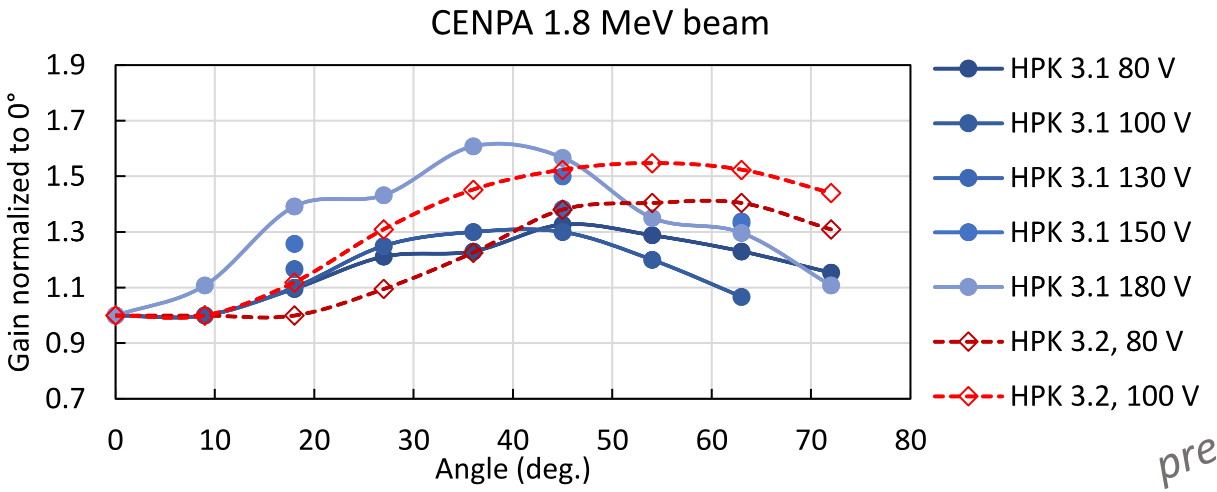
- Gain: pulse_area(device)/pulse_area(pin) for each angle and each bias voltage; pin at 200 V
- Higher gain for 3 MeV protons
- Less variation for HPK 3.2
- Gain suppression effect as function of incidence angle is stronger for higher bias voltages



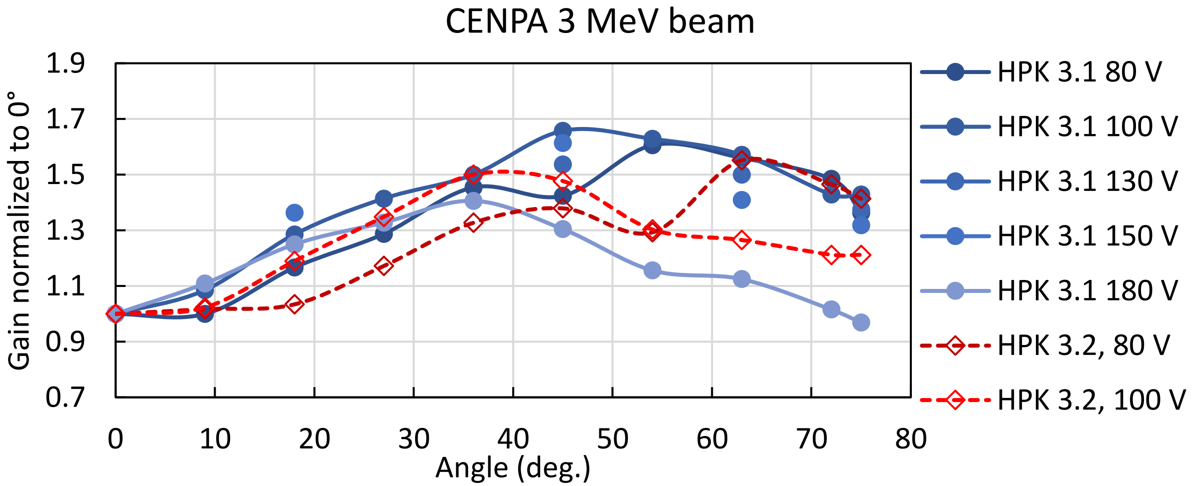


Gain relative to angle

- Less variation, less gain suppression for HPK 3.2
- At 1.8 MeV, higher bias voltages still provide high gain – at 3 MeV, angular dependence of gain suppression is more pronounced

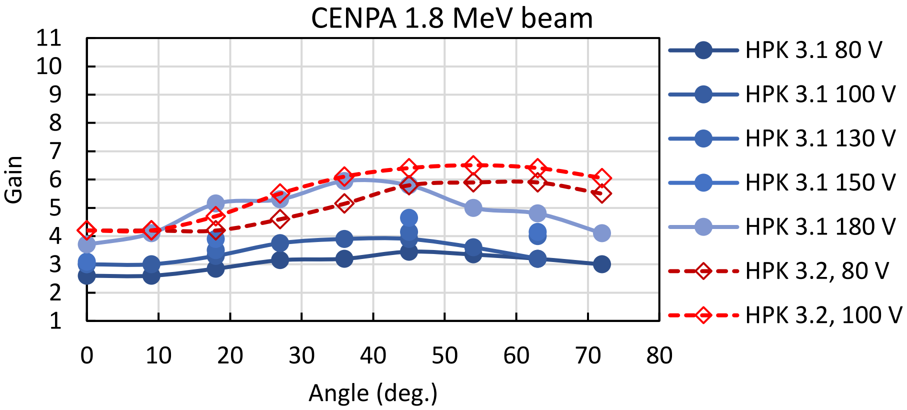

CENPA 1.8 MeV beam

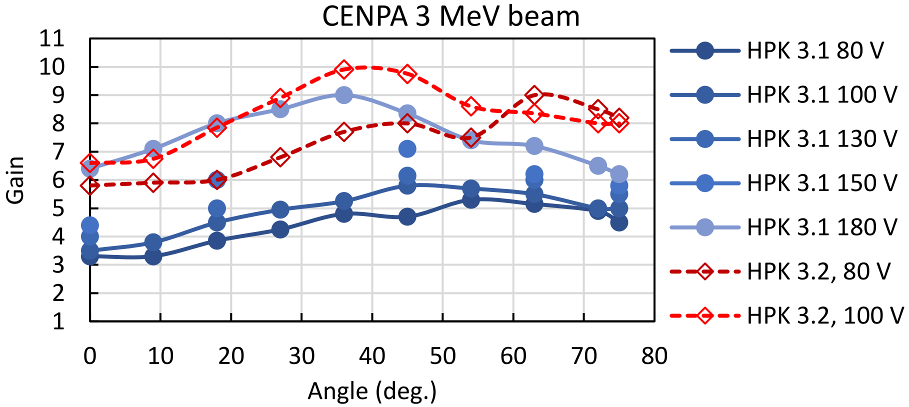
preliminary

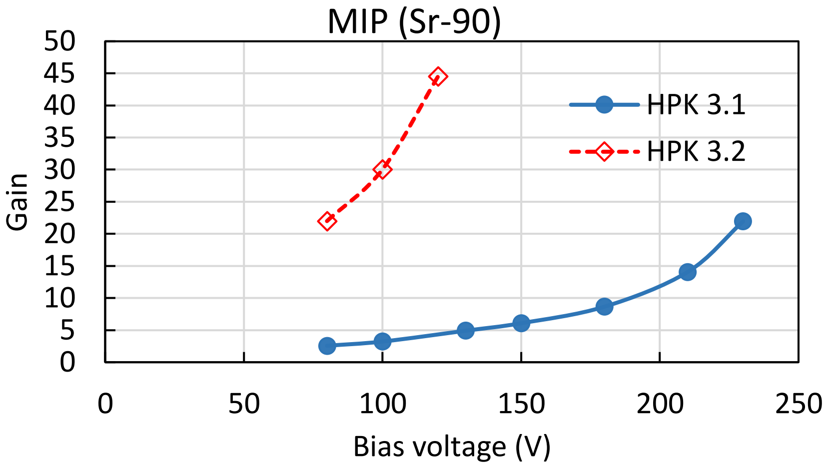

CENPA 3 MeV beam

Gain suppression compared to MIPs

- Indeed less variation for HPK 3.2, but this may be due to its gain being already heavily suppressed compared to MIP charge deposition
- Relation of HPK 3.1 data to gain determined with Sr-90 not entirely clear
- Some technical challenges:
  - It was not possible to consistently bias the sensors to the higher voltages = higher gains at the CENPA beamline: due to operation in vacuum? Ionization damage to the sensor surface or even the boards?
  - Measurements in the laboratory before and after CENPA test beam show some differences: not well understood; sensors possibly damaged during testing in beamline





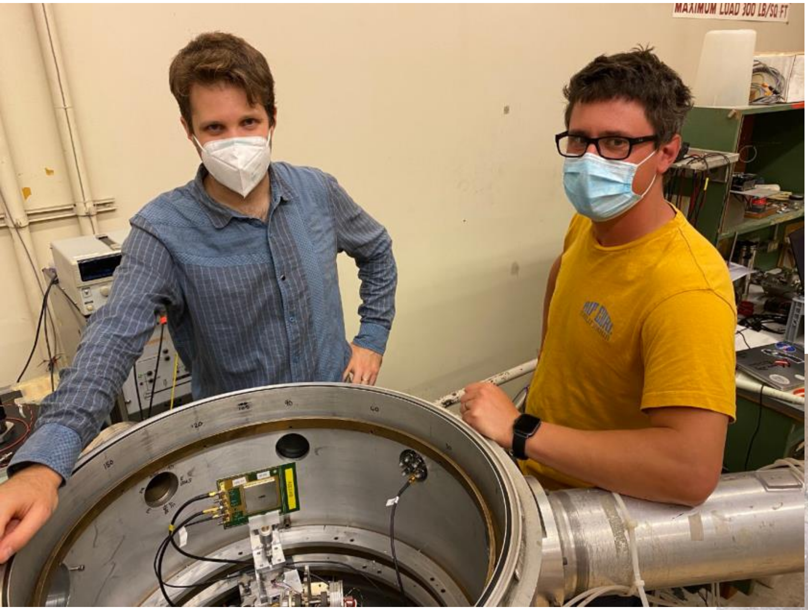


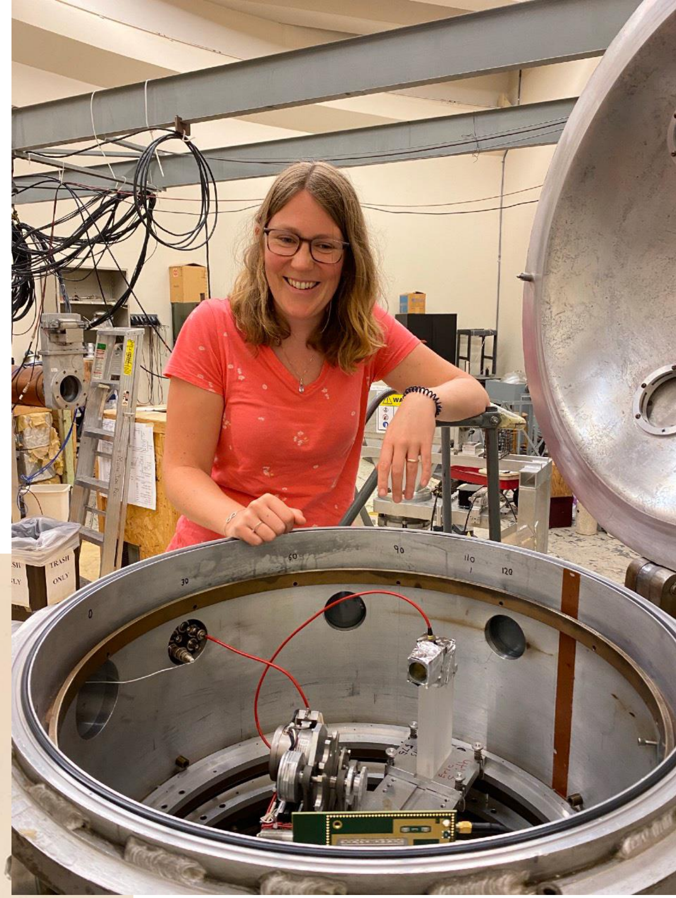
Conclusions

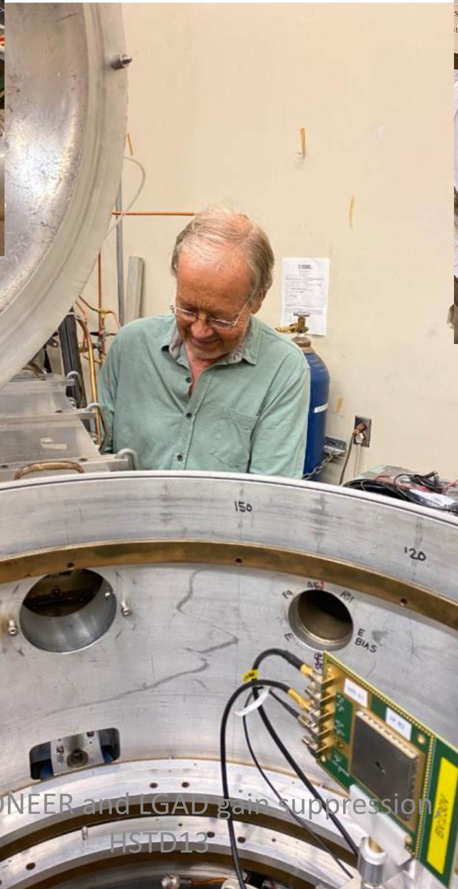
- Single-pad LGAD and pin sensors from HPK were tested with a proton beam at the University of Washington CENPA tandem accelerator for the first time
  - Beam energy, sensor bias voltage and incidence angle were varied
  - Gain suppression and stopping of protons were observed
- The gain suppression phenomenon is limiting, or at least complicating, energy resolution in LGADs for large charges deposited in a small volume and close to the gain layer
- For PIONEER, potentially other applications as well: explore gain layer fabrication options to **reduce the gain, i.e. ensure saturation of velocities** at moderate voltages before gain-induced breakdown
- Next tests: BNL sensor production with thicker sensors and modified gain layer – also open to testing other devices!

- **Angular dependence of gain – and signal sharing – to be studied more extensively in the laboratory: more complex for strip sensors and AC-LGADs!**
  - **2D laser scans**
  - **Alpha particle testing station in vacuum chamber**
- Simulations: gain suppression is observed in simulations and can be explained with existing physics models
- 3D simulations require a lot of computing capacity, but are needed for accurate reproduction of the experimental data

Thank you!







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Backup

PIONEER Collaboration

A next generation rare pion decay experiment

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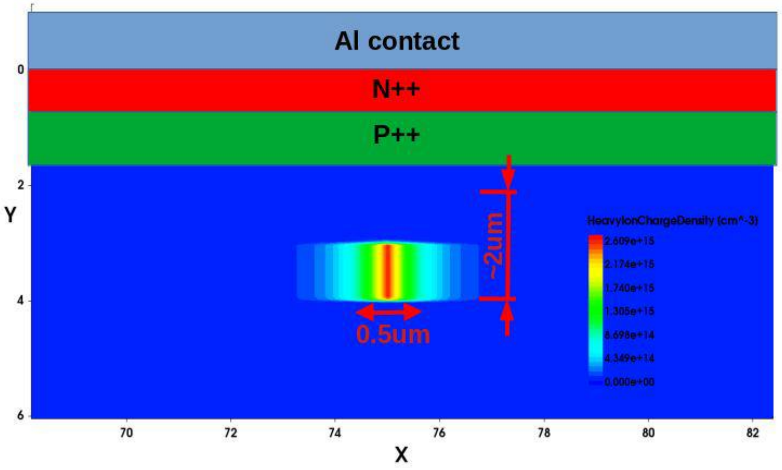
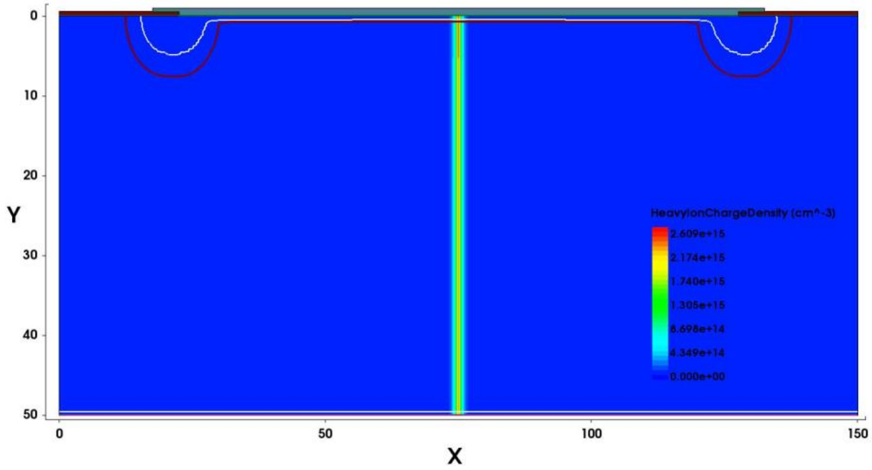
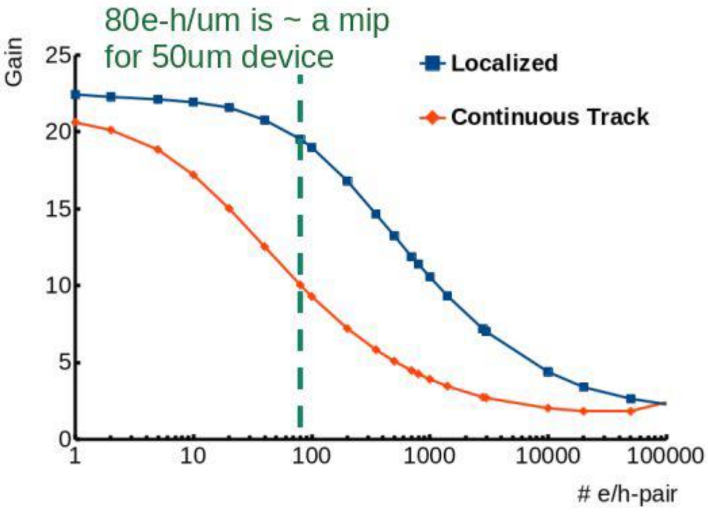
TCAD simulations: localized and spread charge

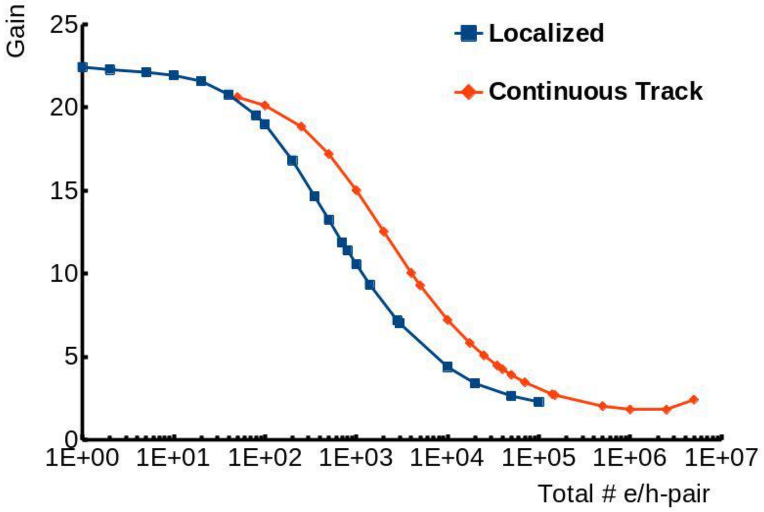
Localized charge



Track



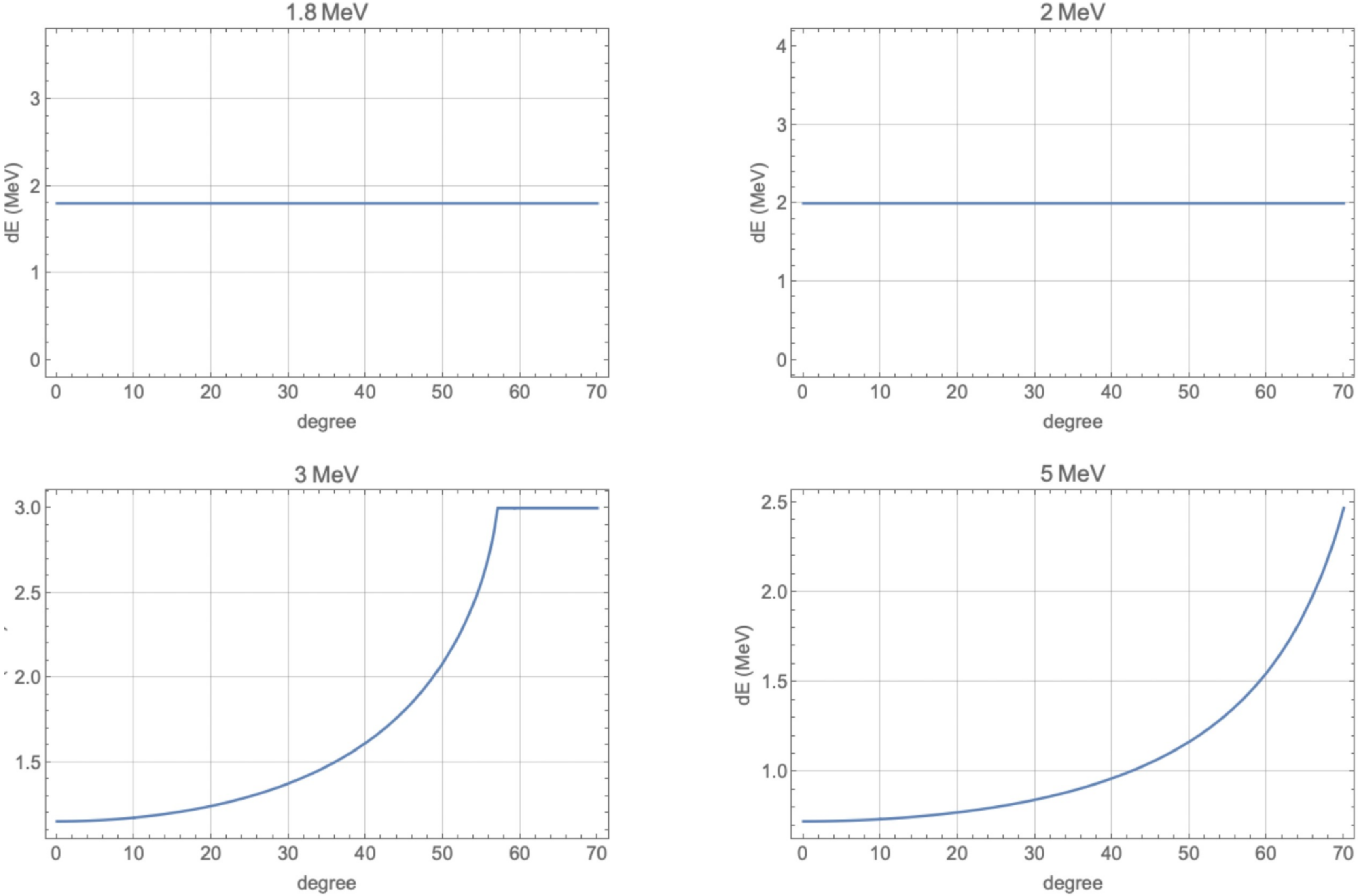




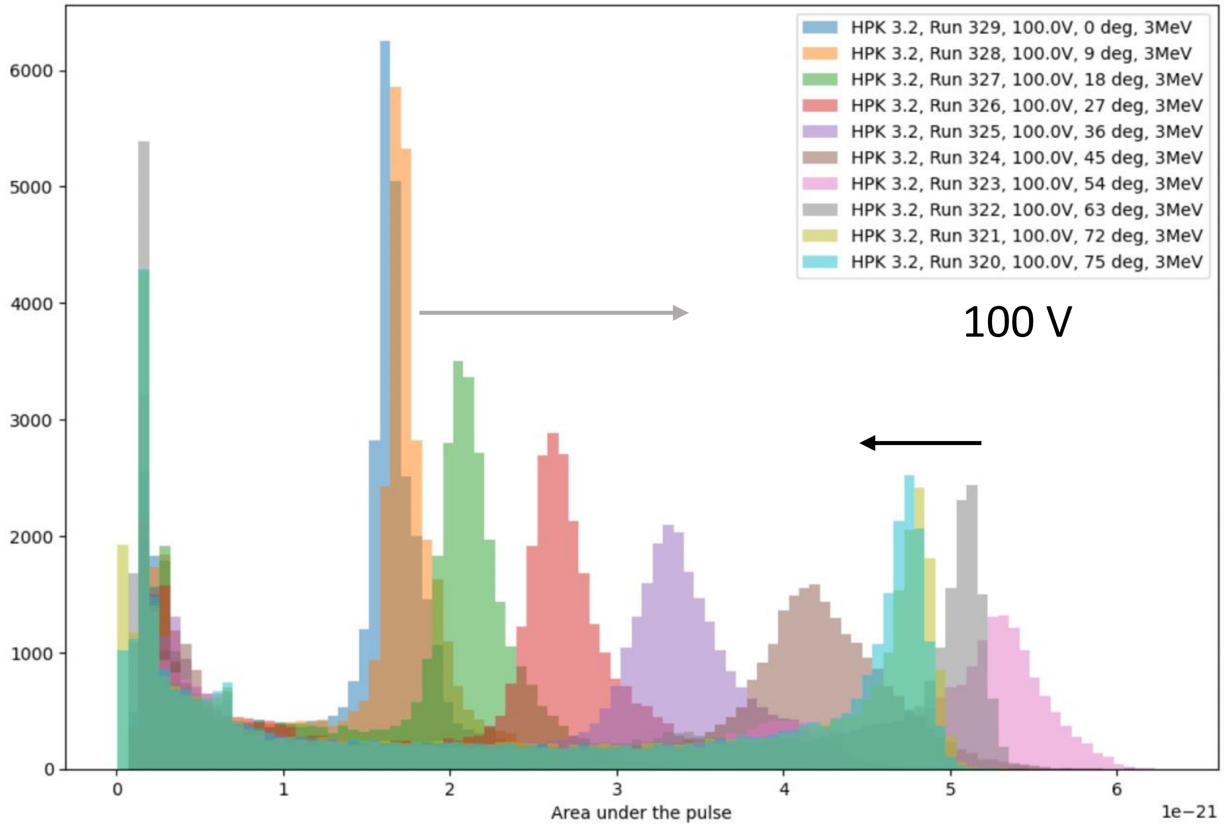
Y. Zhao, CPAD 2022

Energy deposit of protons in Si

Energy deposited as function of incidence angle in 50 µm Si



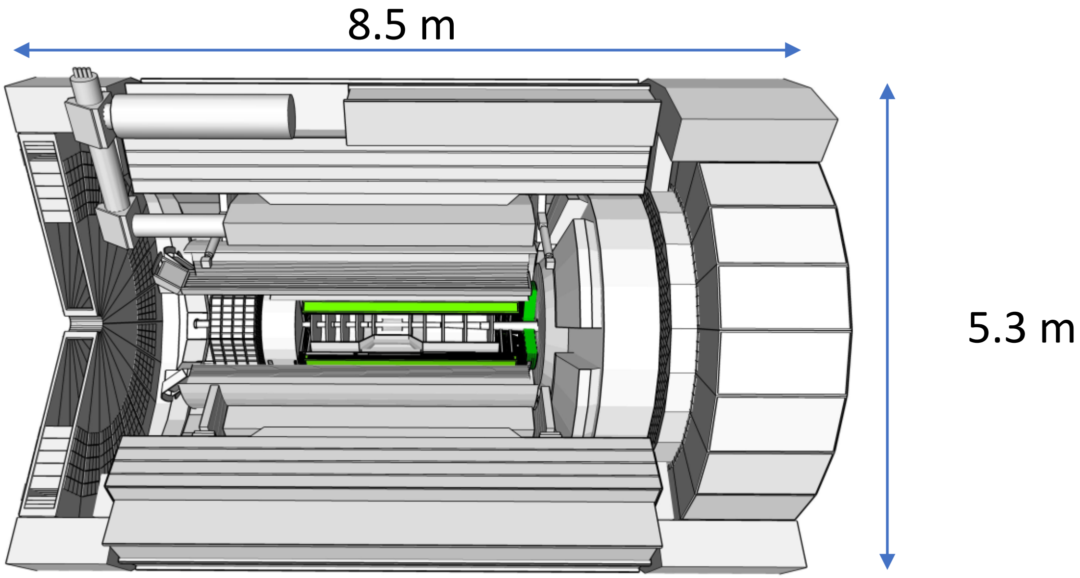
HPK 3.2 LGAD at 3 MeV



ePIC detector at the Electron-Ion Collider

- EIC Detector 1: recently issued recommendation, based on two proto-collaborations
    - ➢ Emerged as ePIC Detector collaboration in summer 2022

- Design includes AC-LGADs for time-of-flight particle ID, t_0 determination and timing, and serving as additional layer in Tracking
    - ➢ Efforts organized in the TOF-PID working group, and eRD112/LGAD consortium



https://indico.bnl.gov/event/17072/contributions/68825/
https://indico.bnl.gov/event/17072/contributions/70500/

ePIC detector at the Electron-Ion Collider

- EIC Detector 1: recently issued recommendation, based on two proto-collaborations
  - ➢ Emerged as ePIC Detector collaboration in summer 2022
- Design includes AC-LGADs for time-of-flight particle ID, t_0 determination and timing, and serving as additional layer in Tracking
  - ➢ Efforts organized in the TOF-PID working group, and eRD112/LGAD consortium
- Radiation hardness of timing detectors not very challenging - more important:
  - **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
  - Low material budget
- Current sensor design baseline:
  - Barrel: **strips, 500 µm pitch and 1 cm length**
  - Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**

Synergies for PIONEER ATAR sensor development!

Thank you!