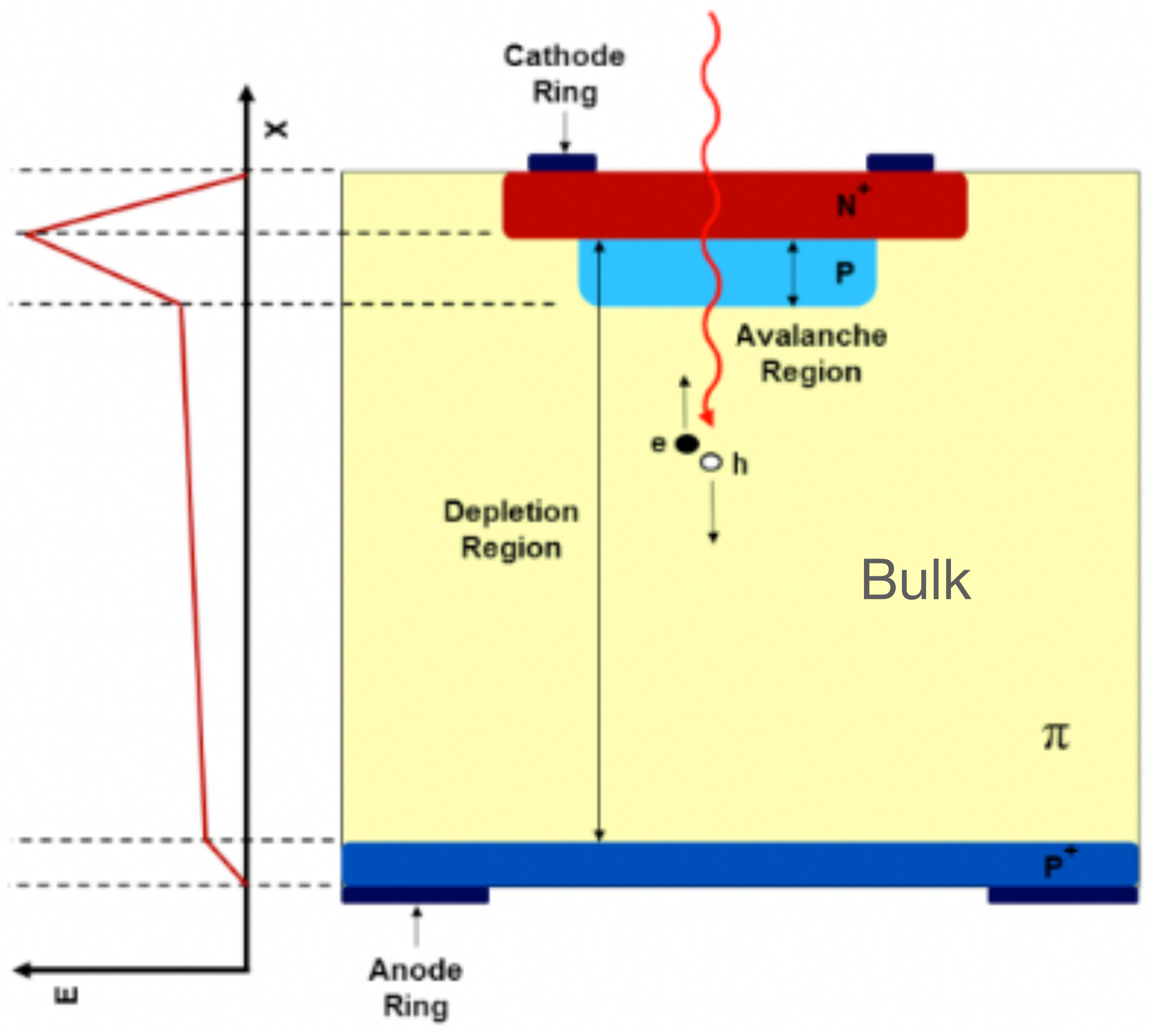
Preliminary results of CENPA beam test

Svende Braun PIONEER Collaboration Meeting 2023, Seattle October 16th

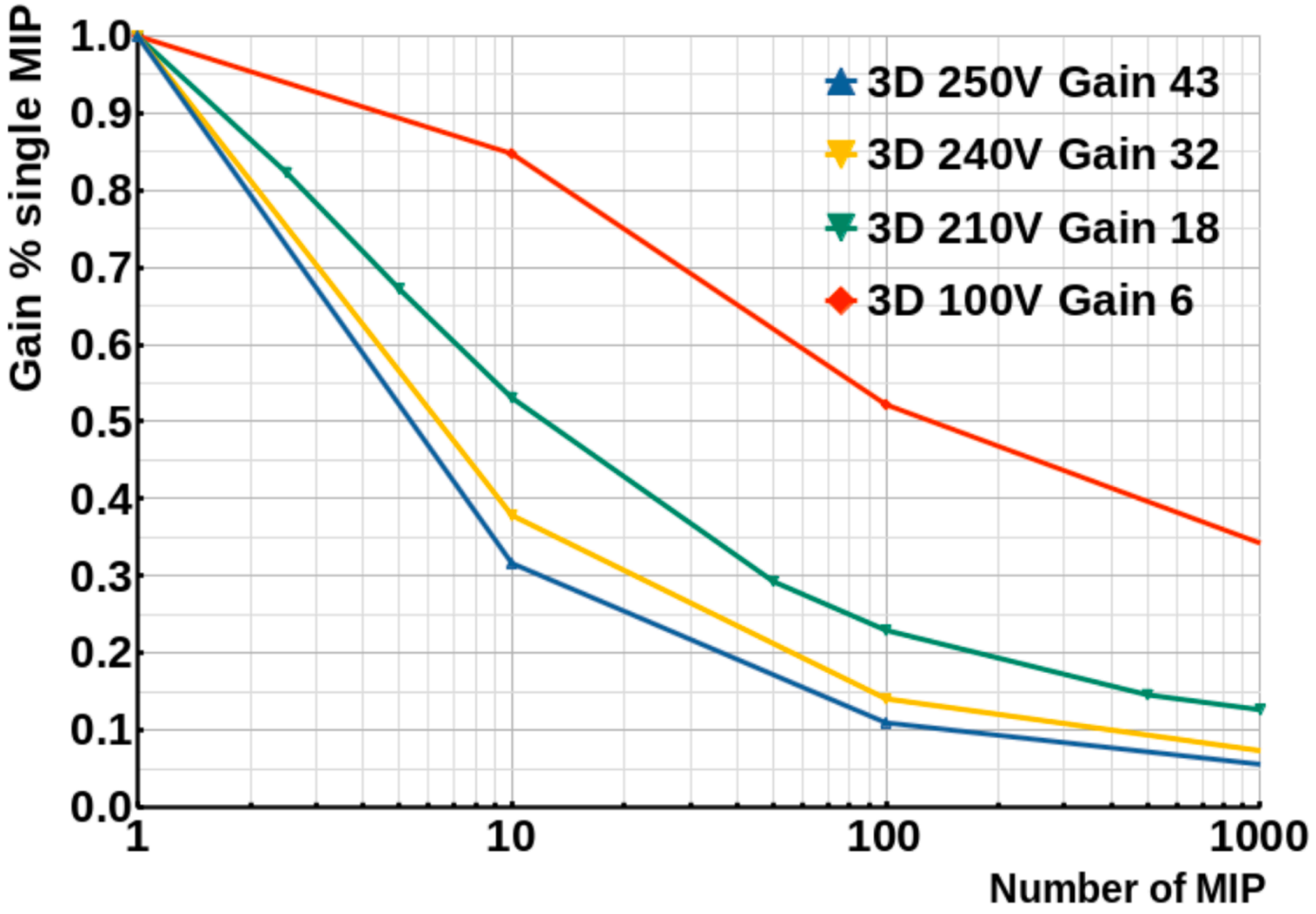
LGAD technology

- Silicon detector with thin (<5um) and highly doped (~10^16 P) gain layer
    - High electric field -> high enough for electron multiplication, not for holes
    - Intrinsic low to moderate internal gain (10-50): gain=Q(LGAD)/Q(PIN)
    - Controlled tunable gain with applied bias voltage
- Great hit time resolution: <20ps
- Gain saturation: gain suppression observed with large energy deposits
- Several producers (typical thickness: 50 um):
    - HPK (Japan), FBK (Italy), BNL (USA), CNM (Spain), NDL (China)



Gain saturation

- LGAD gain suppression observed experimentally with large energy deposits
- Large density of carriers: gain electrons/holes -> effectively screen external field=field shielding effect -> reduce field
    - local effect in time and space
- Tested by many groups with ion beams, lasers, alpha sources, etc…
- Bad for PIONEER to distinguish positrons from muons -> try to minimize effect
- Explore and characterize gain suppression using TCAD simulations (UCSC):
    - Significant gain loss for high gain detector & high deposition
    - Lower gain sensor -> less gain reduction -> adjust sensor design to reduce it



Goal of test beam:

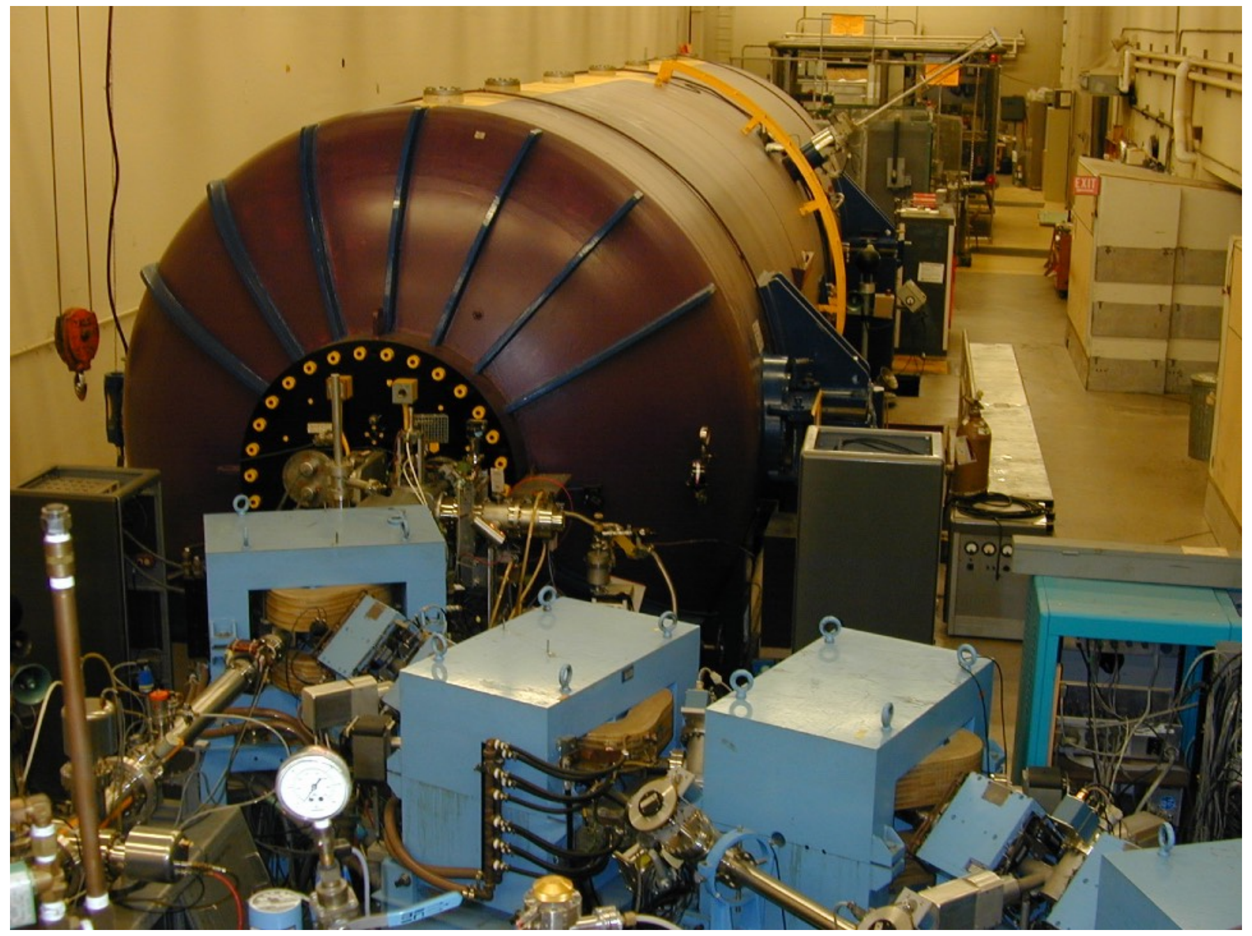
- Study gain suppression effect with CENPA tandem accelerator
- Inject large amount of charge (several MIPS) with low energy proton beam
- Test energy resolution with large depositions: so far tested only up to ~70keV (SSRL test beam)
- Different devices:
    - See larger effect of higher gain & at same gain level structure influences suppression?
    - Similar gain suppression is less?

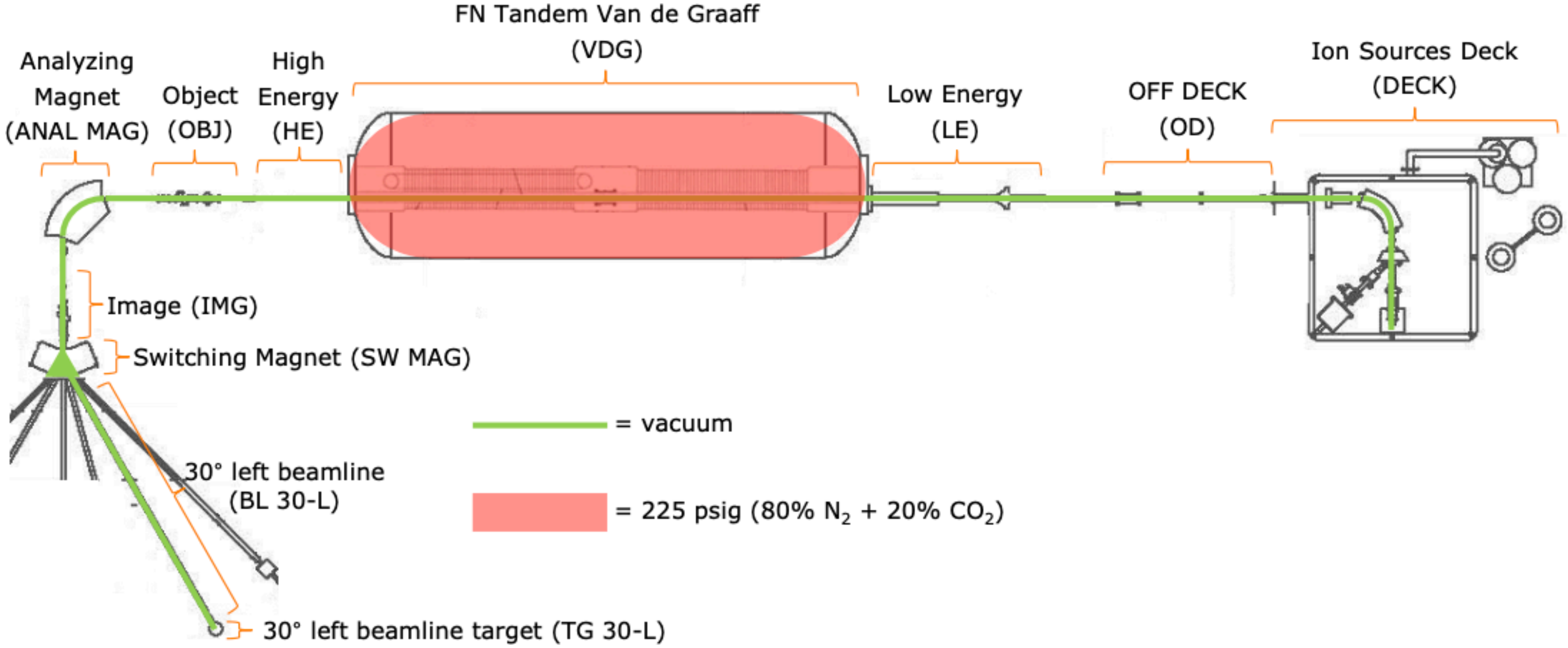
CENPA test beam

CENPA tandem van de Graaff accelerator

- Negatively charged ions injected from source accelerated by attractive force into tandem accelerator
- High electric potential at center of machine from van de graaff generator
- Stripper foil inside accelerator strips off electrons -> positively charged and accelerated away by repulsive force
- Two accelerations of particles
- Use hydrogen as source for proton beam

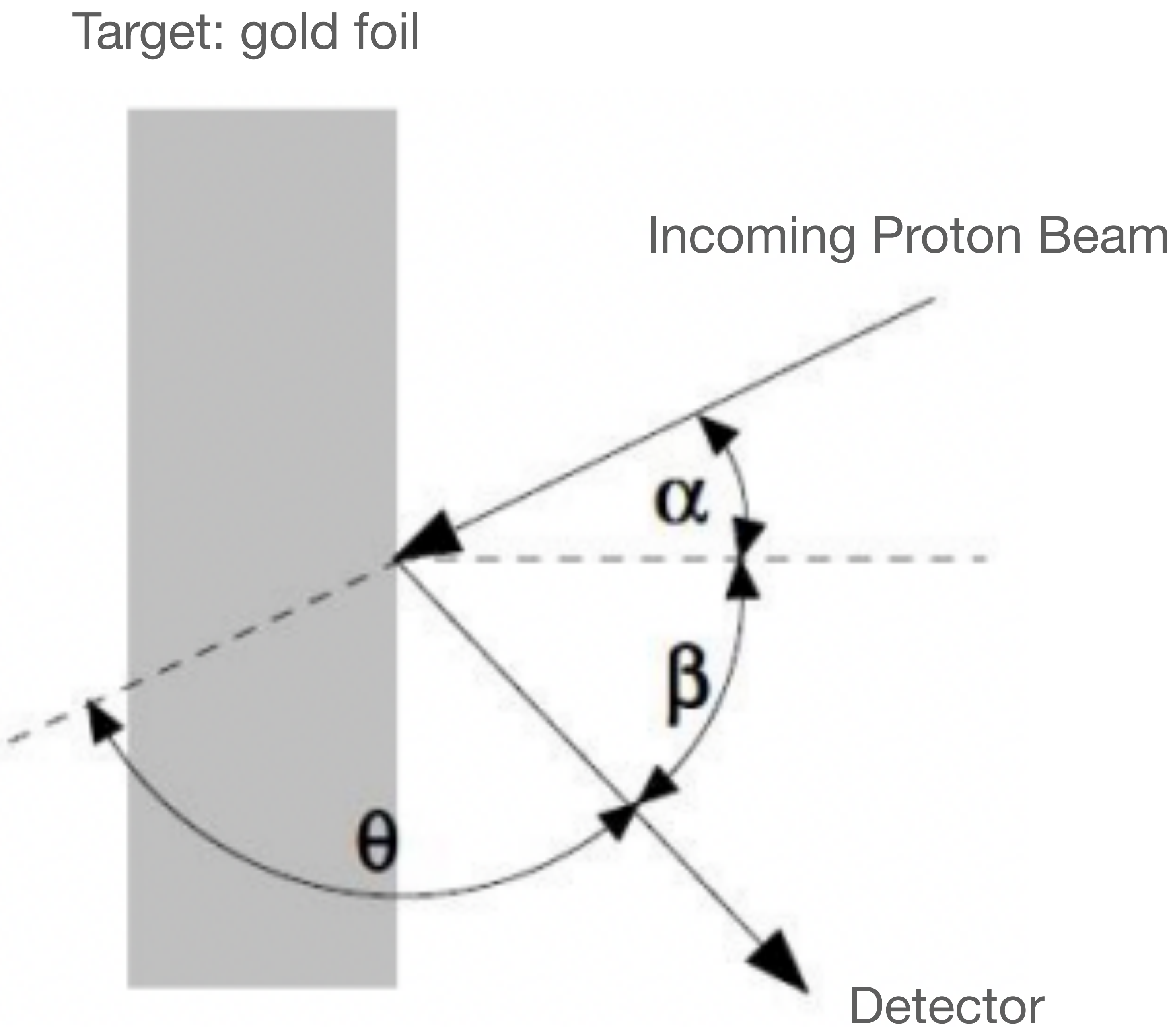
https://www.npl.washington.edu/cenpa/history#storm





Rutherford Backscattering SpectrometryBS

- Proton beam hits gold foil target, scattering of beam into detector -> to avoid direct beam on target

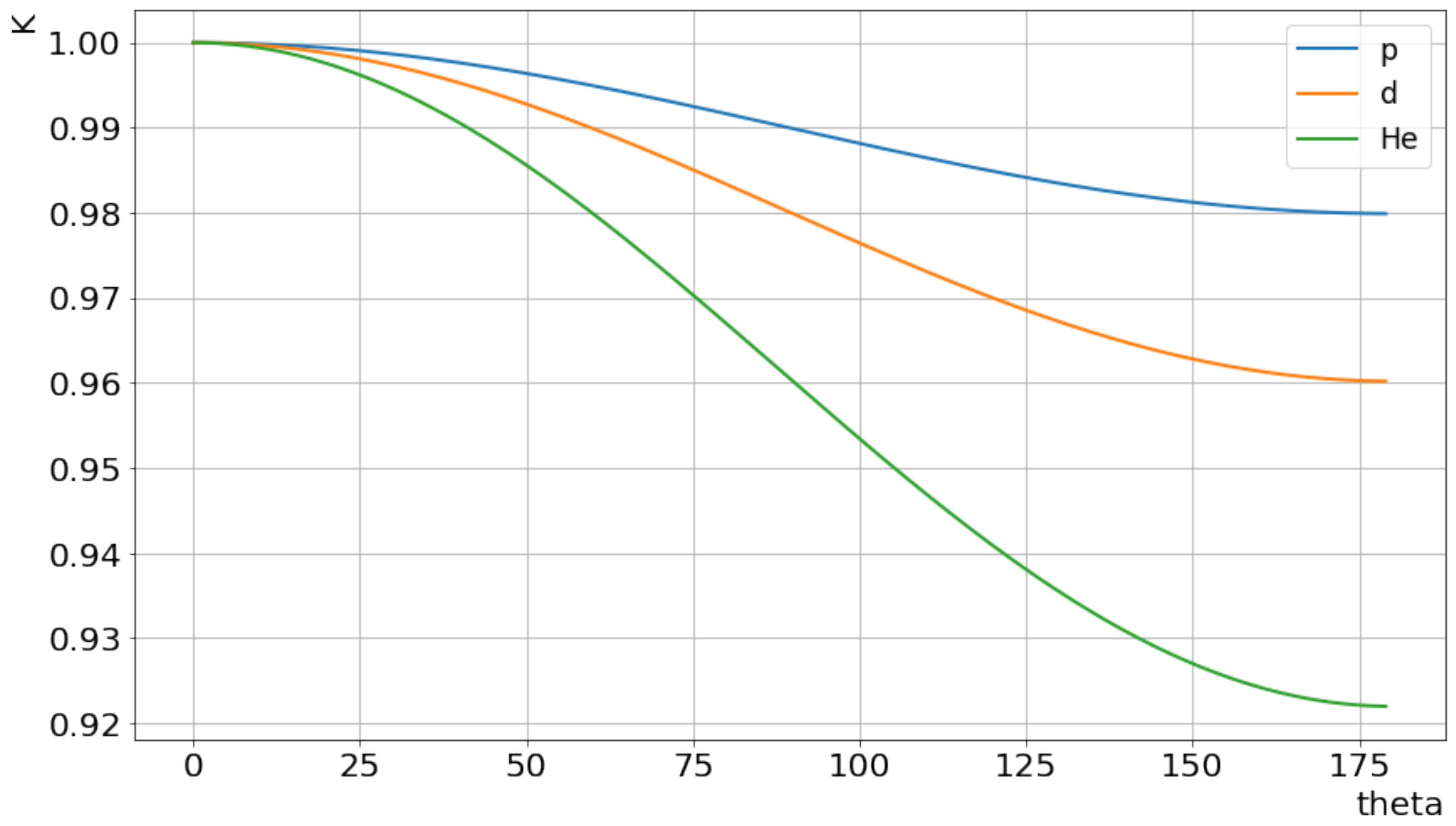


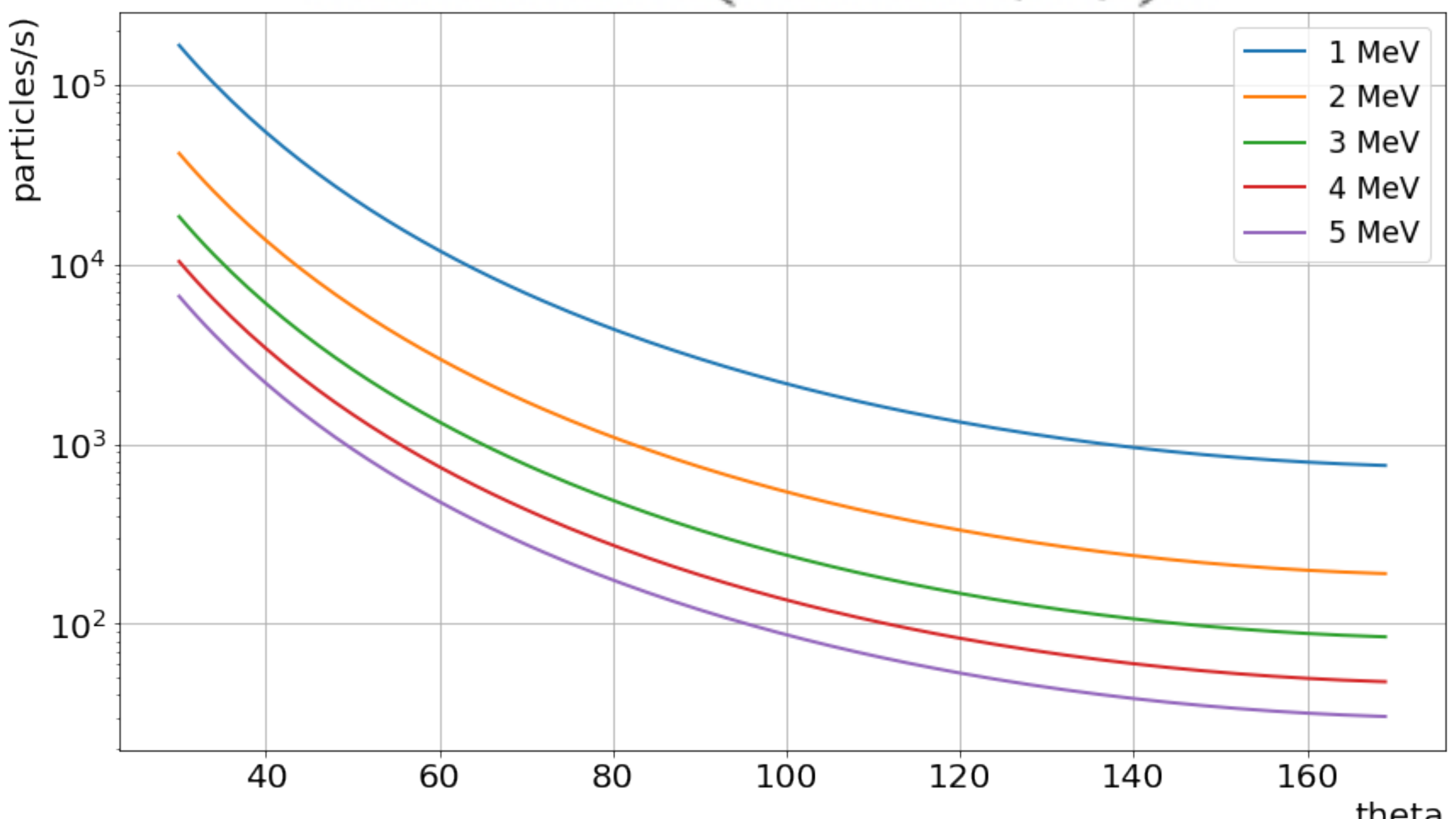
- Kinematic factor k:

$$k = \frac{E_1}{E_o} = \left[\frac{\left(M_2^2 - M_1^2 \sin^2\theta\right)^{1/2} + M_1 \cos\theta}{M_2 + M_1} \right]^2$$

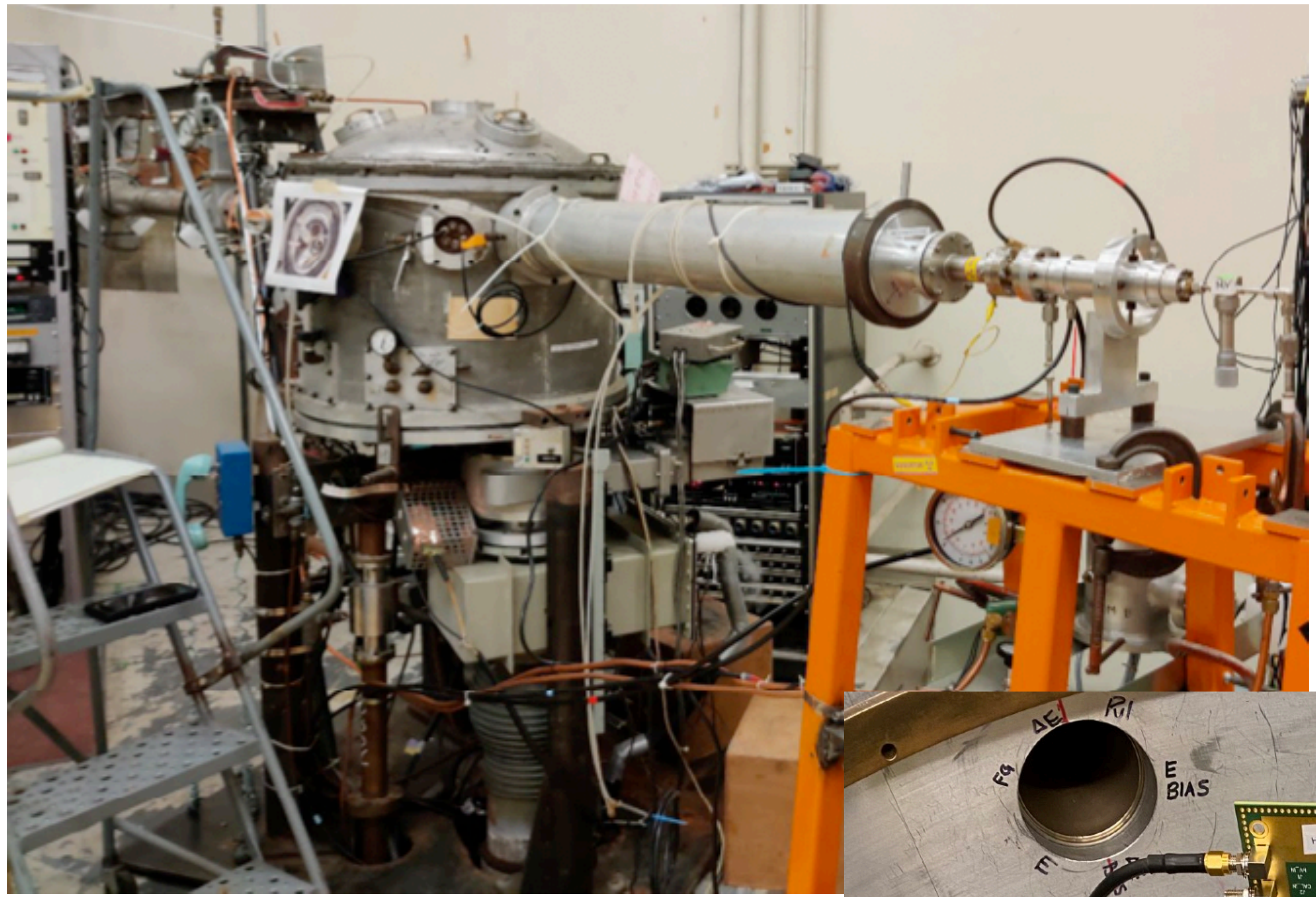
- Scattering cross section:

$$\frac{d\sigma}{d\Omega} \equiv \sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E \ \sin^2\left(\frac{\theta}{2}\right)} \right)^2$$



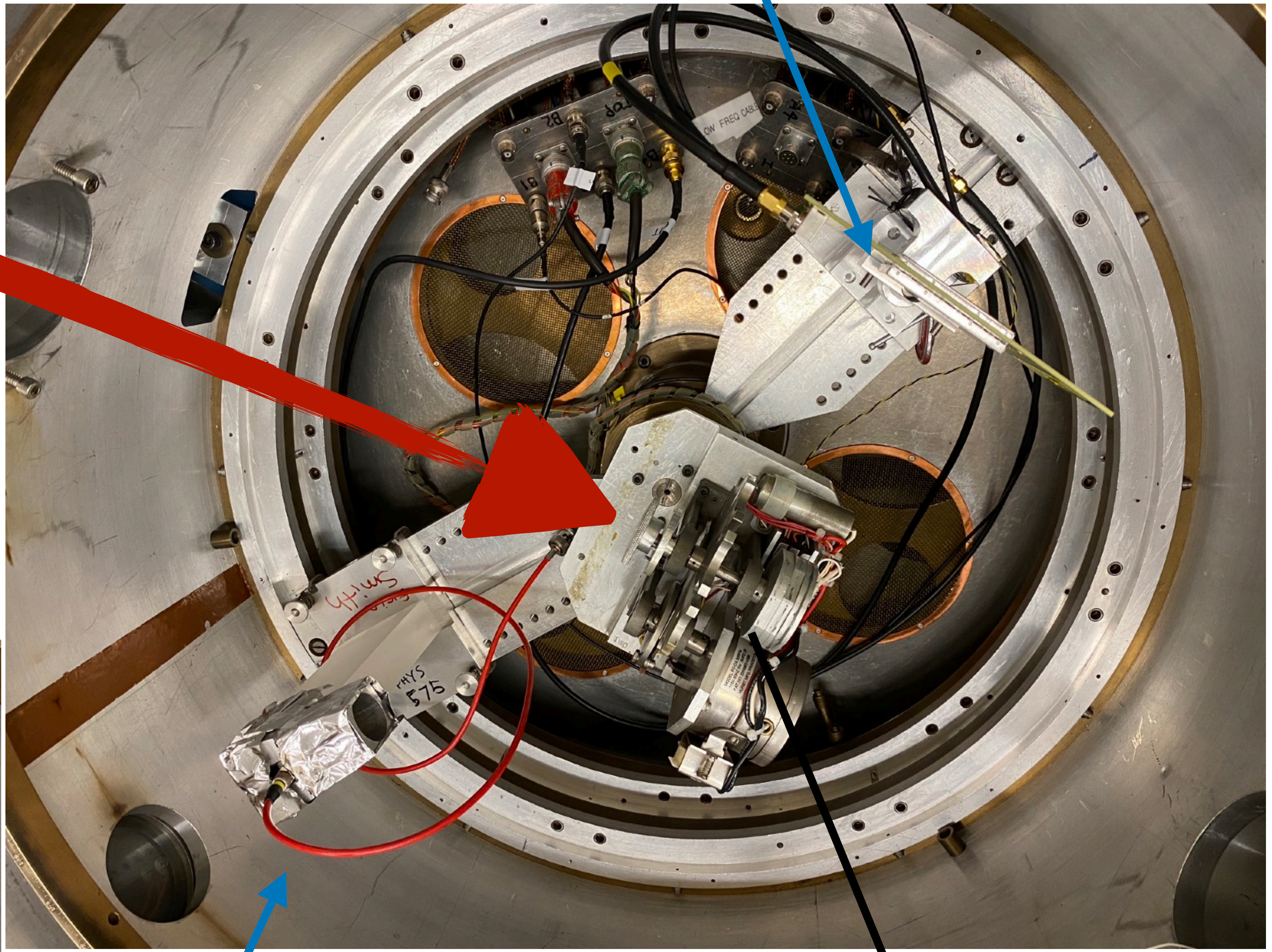


Experimental setup

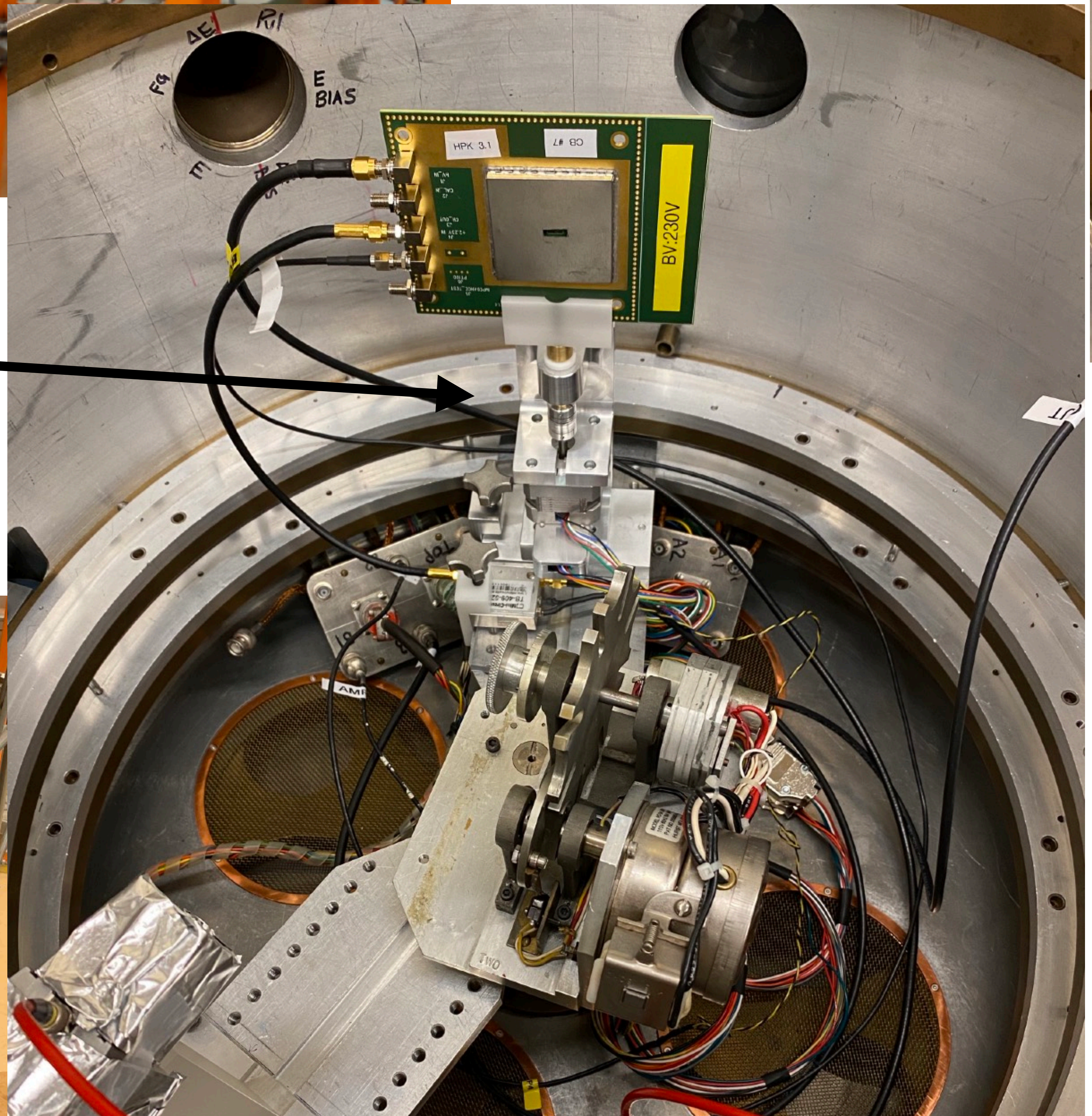


Proton BEAM

LGAD detector

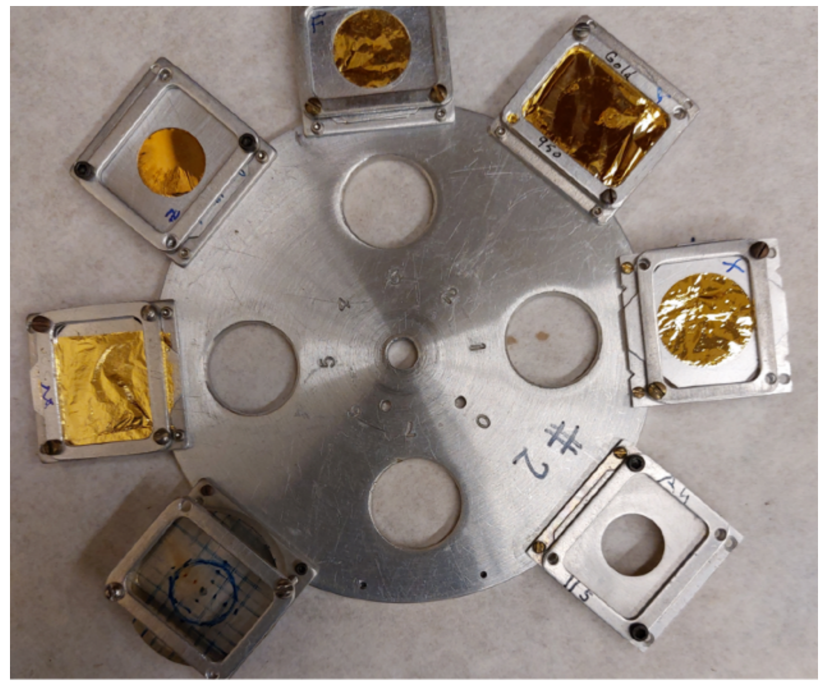


Mounted on rotation device:
Stepper motor to change
Detector angle wrt scattered beam



Eric's PIPS detector

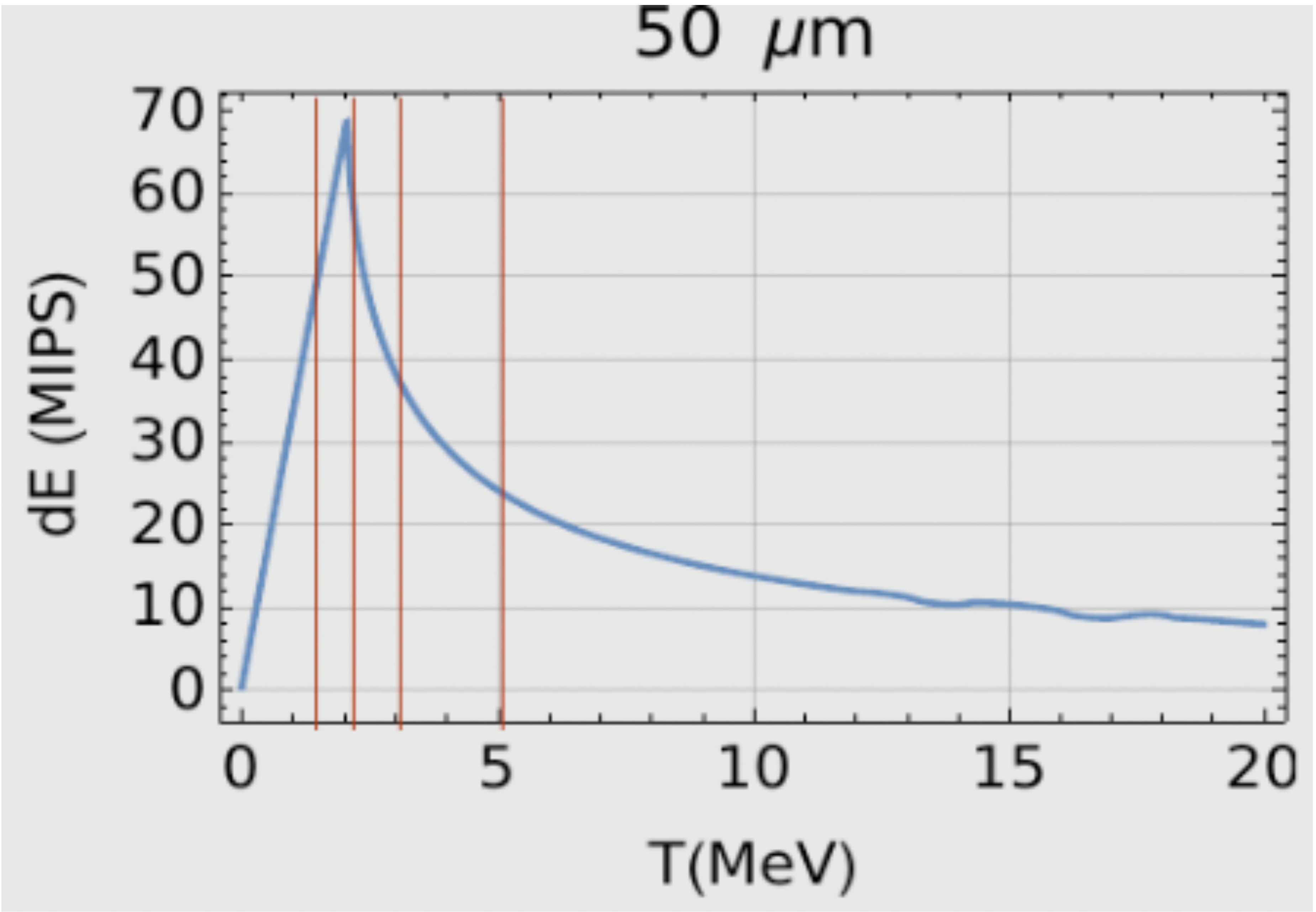
Target gold foil

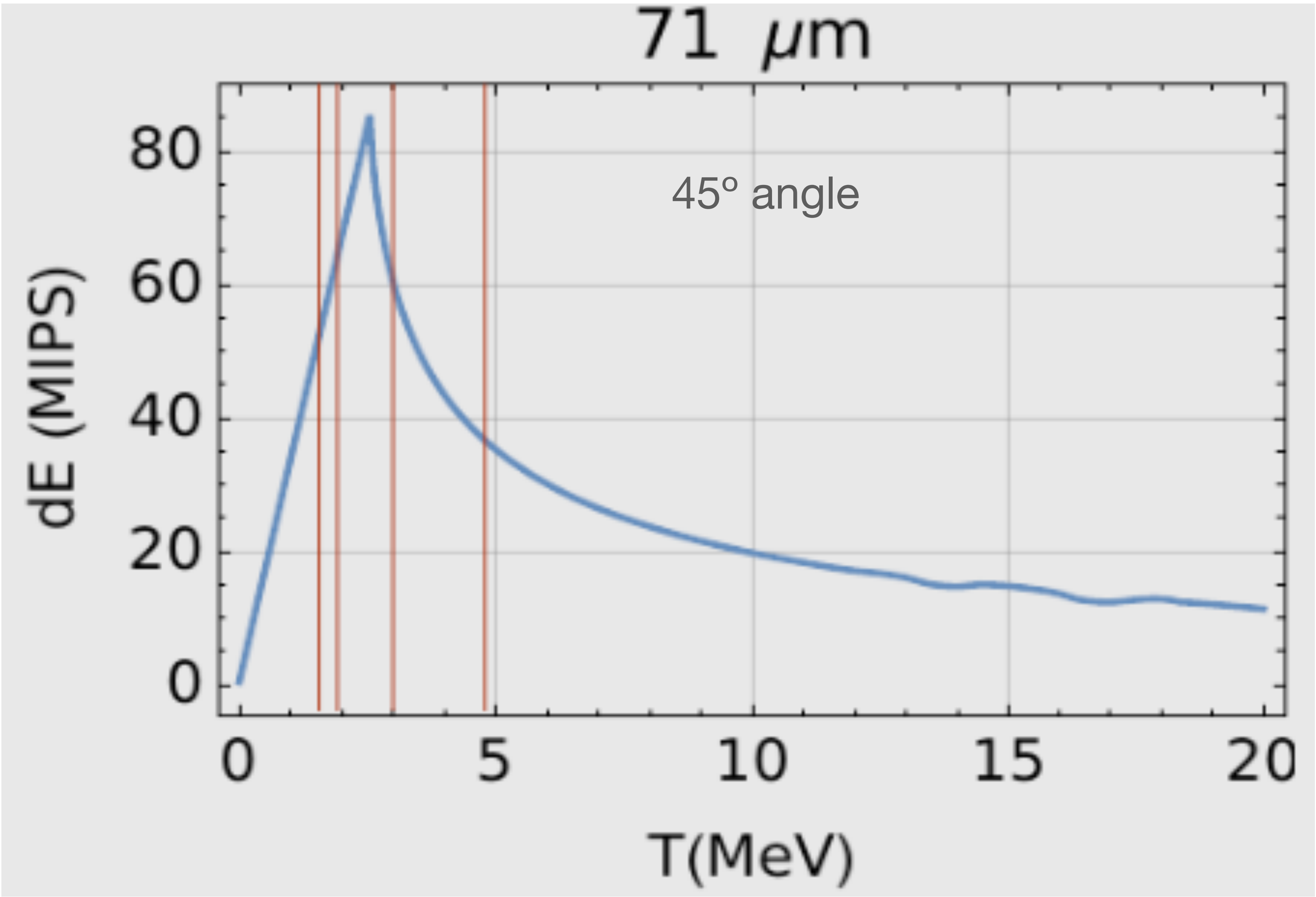


Experimental Setup

- Scattering angle of 110°
- Proton beam energies: 1.8, 2, 3, 5 MeV
  - Energy deposit in silicon vs. proton energy:
- Vary bias voltage across sensors to test different gain:
  - HPK 3.1: 80, 100, 130, 150,180V
  - HPK 3.2: 80,100V
  - PIN: 30V & 200V
- Vary LGAD angle wrt. Scattered beam: 0°-75°

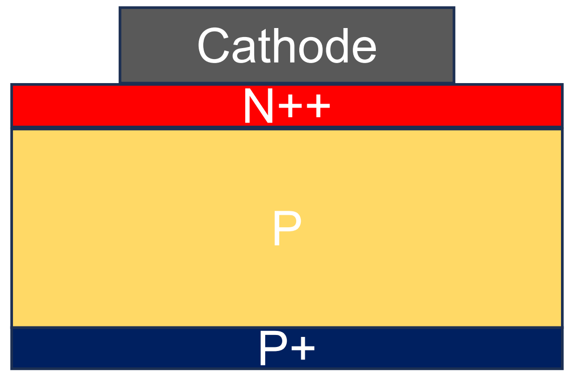
-> Test stopping & passing through of protons

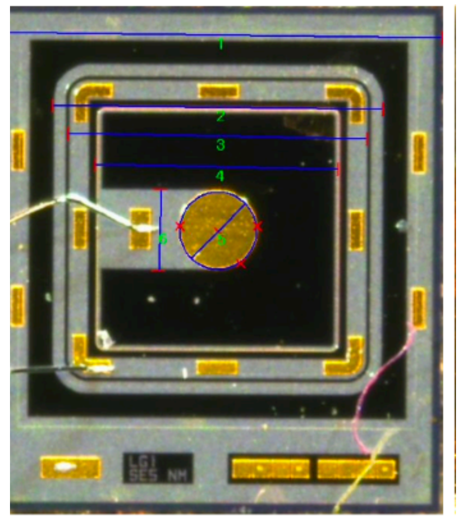




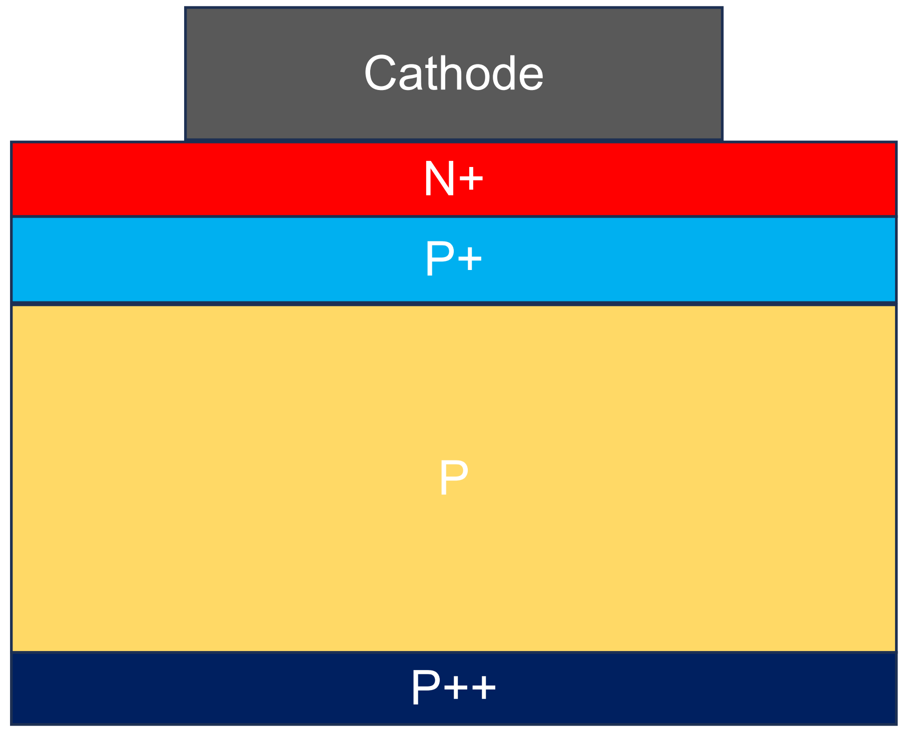
Tested boards

- 2 single pad 1.3x1.3mm^2 LGADs: Hamamatsu Photonics sensors (50um thick)
    - HPK 3.1:
        - Shallow gain layer: 0.5-1um
    - HPK 3.2:
        - deeper gain layer: 1-2um
- 1 PIN: no gain layer
    - Same geometry

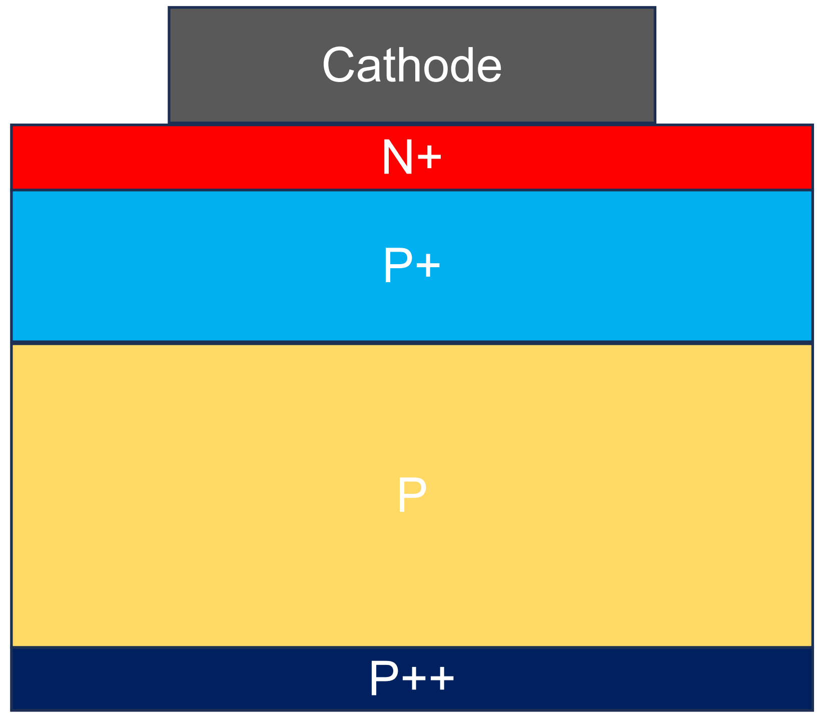


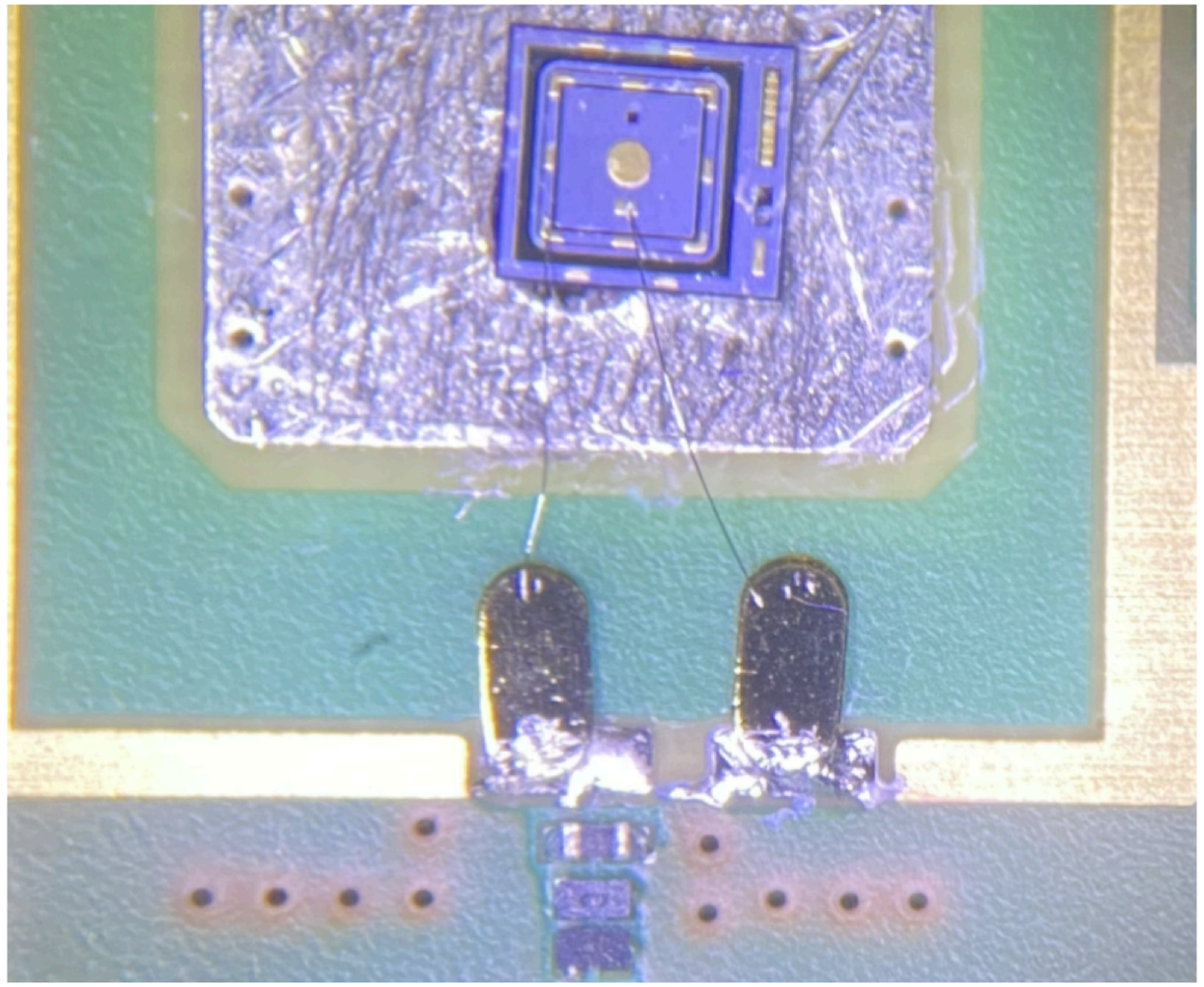


HPK 3.1



HPK 3.2

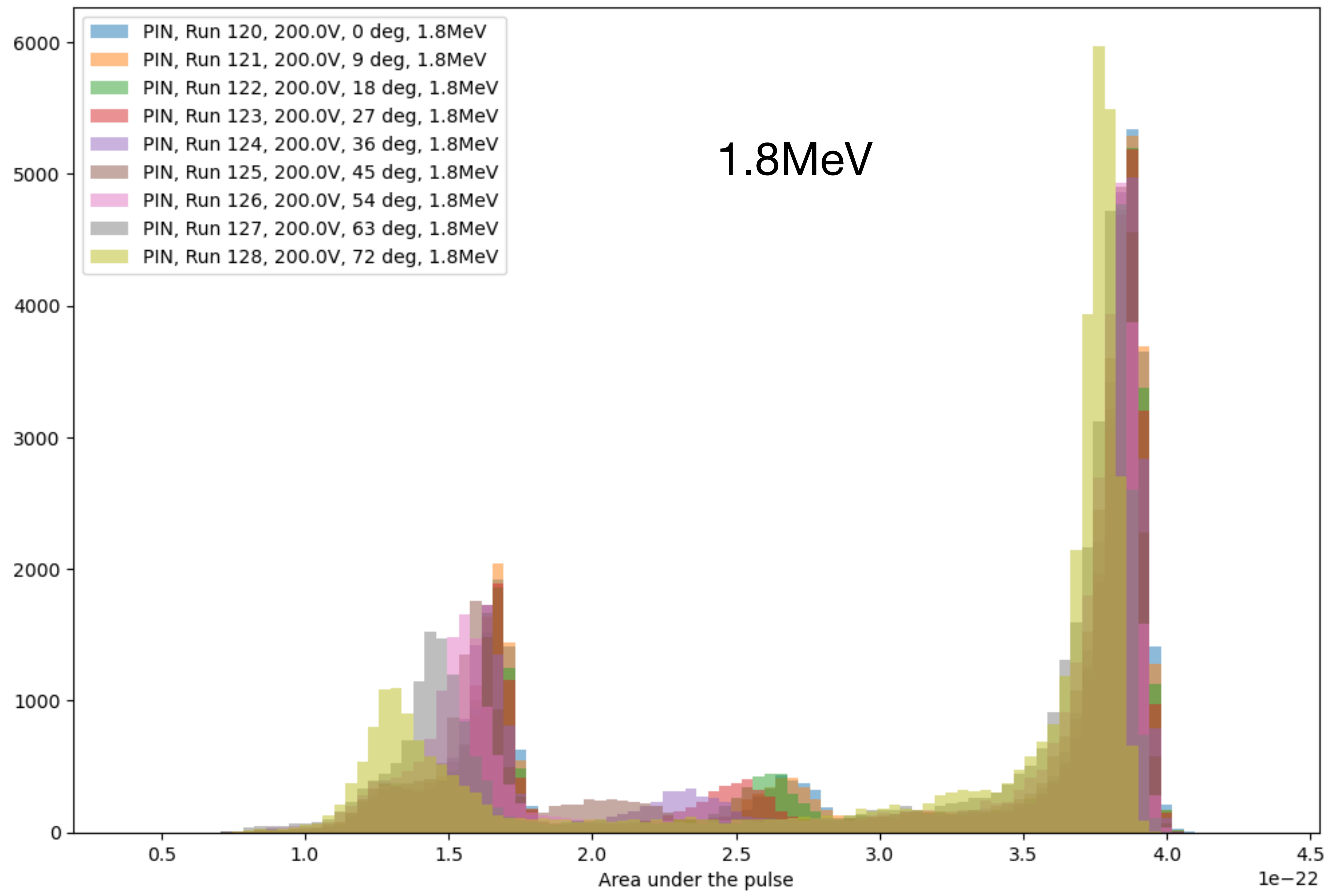


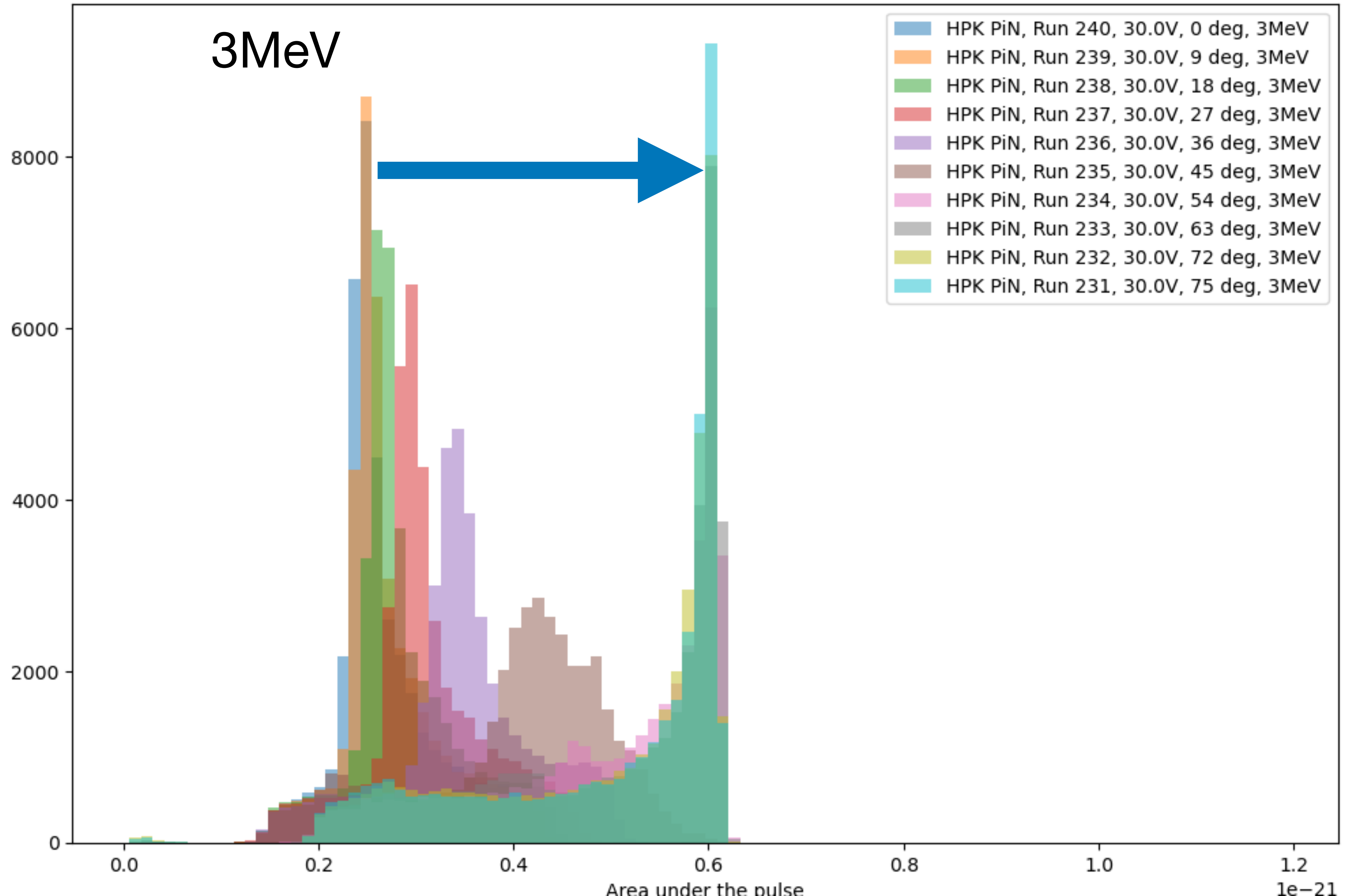


Preliminary Results:

>2 weeks of data talking in July/August
-> 350 runs, way too much to show for 15min

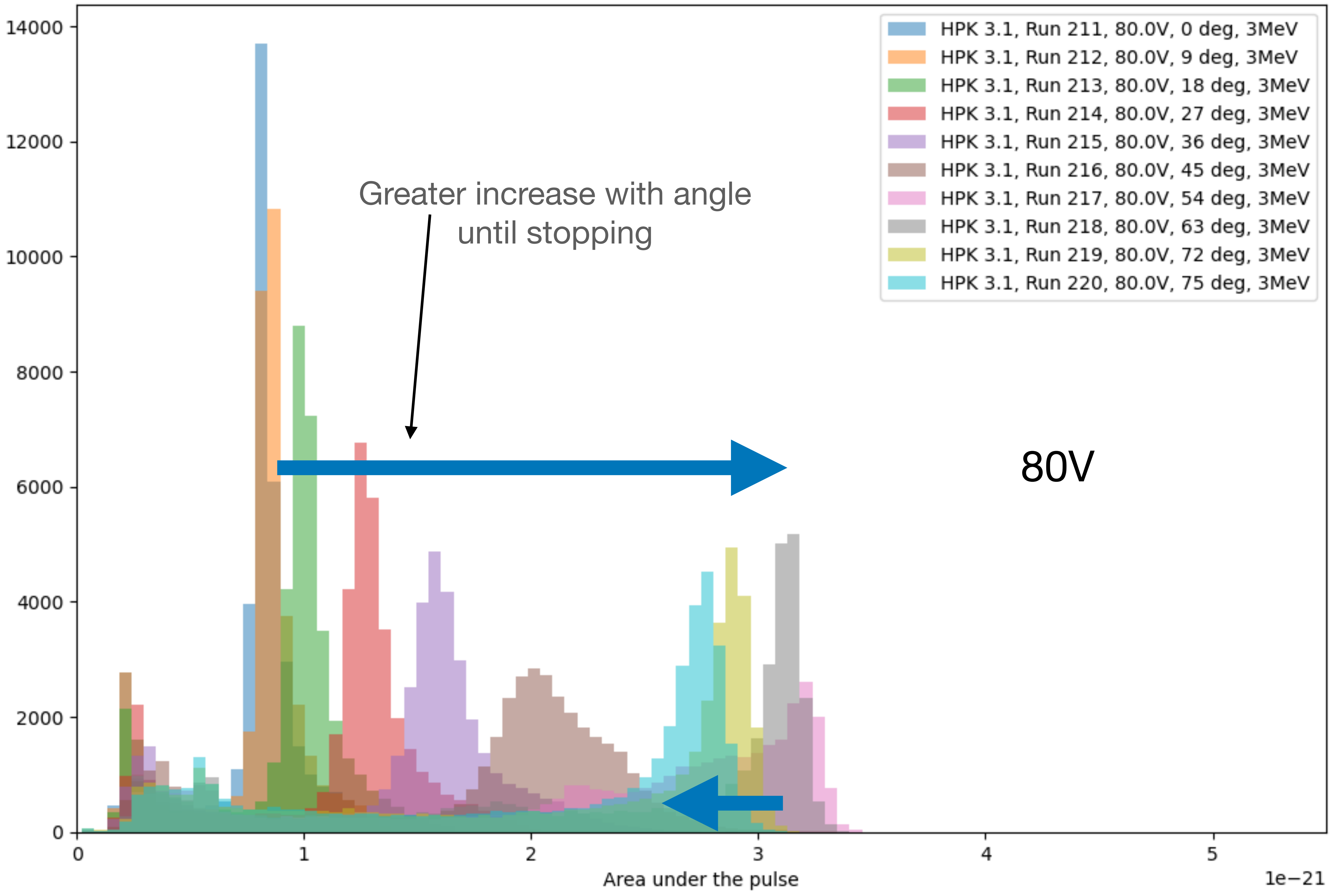
PIN data



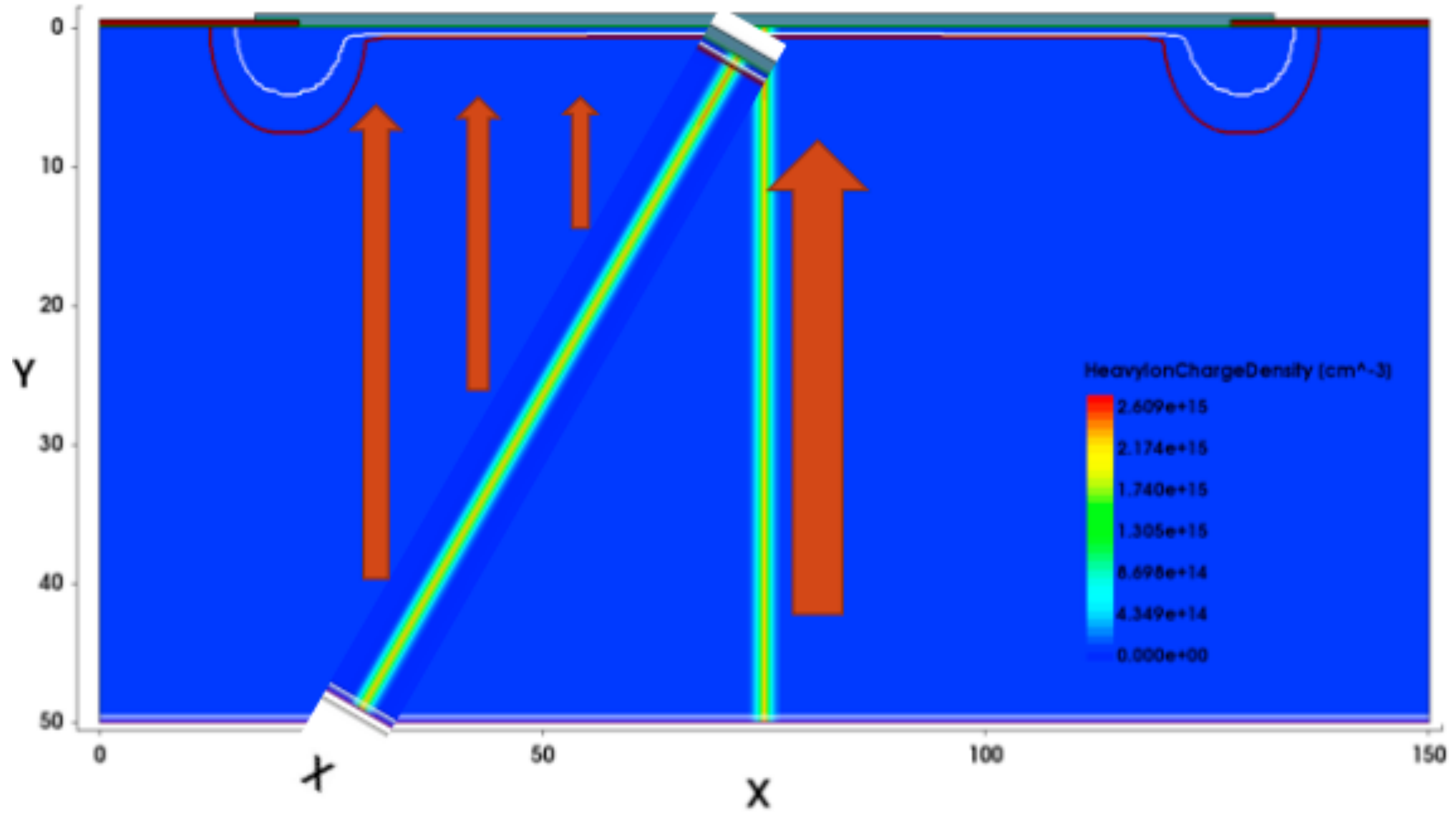


- Energy deposit constant vs. angle at 1.8 & 2 MeV -> Proton stops & deposits max. amount in sensor
- 3MeV: proton punches though -> PIN response increases linear with angle $\sqrt{2}$ until it stops at ~50°

HPK 3.1 data, 3 MeV



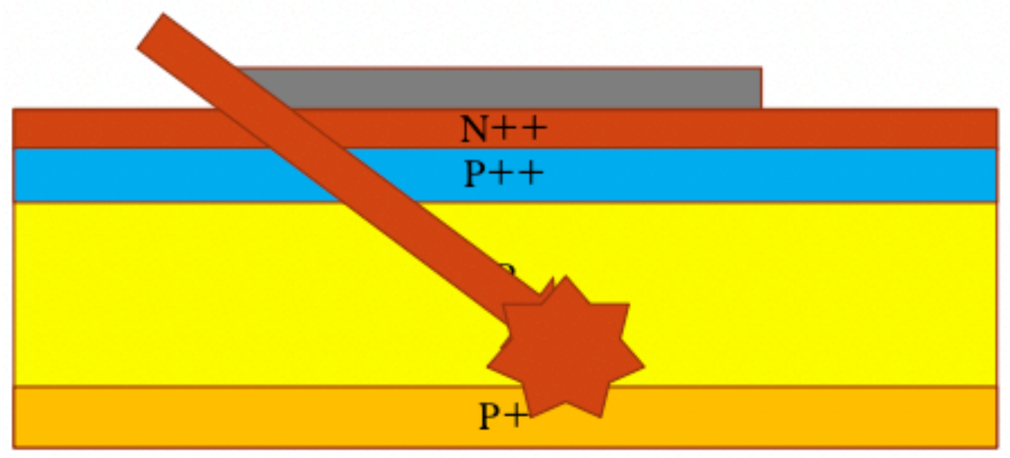
- Gain suppressed at low angle: large charge deposit
- Factor >2: as angle increases smaller gain suppression -> charge spread out over larger area



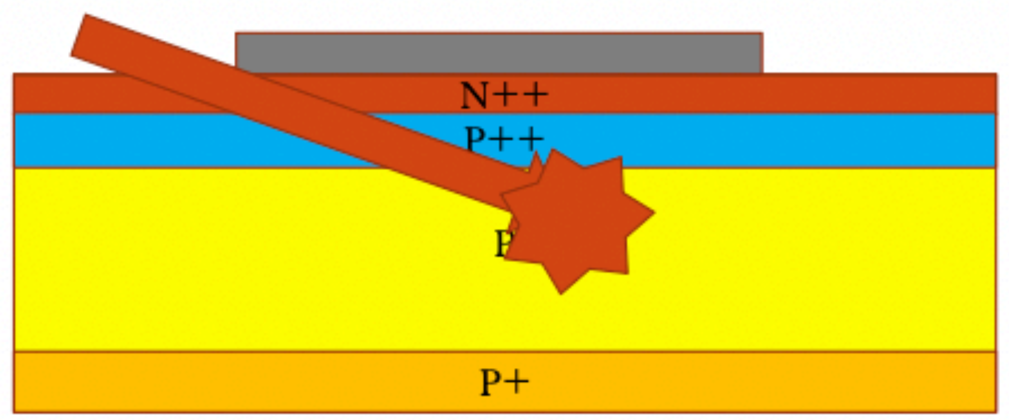
- Decrease of gain at largest angles not fully understood
  - Hypotheses: deposit at different depth of device

-> less lateral drift closer to gain layer -> larger gain suppression

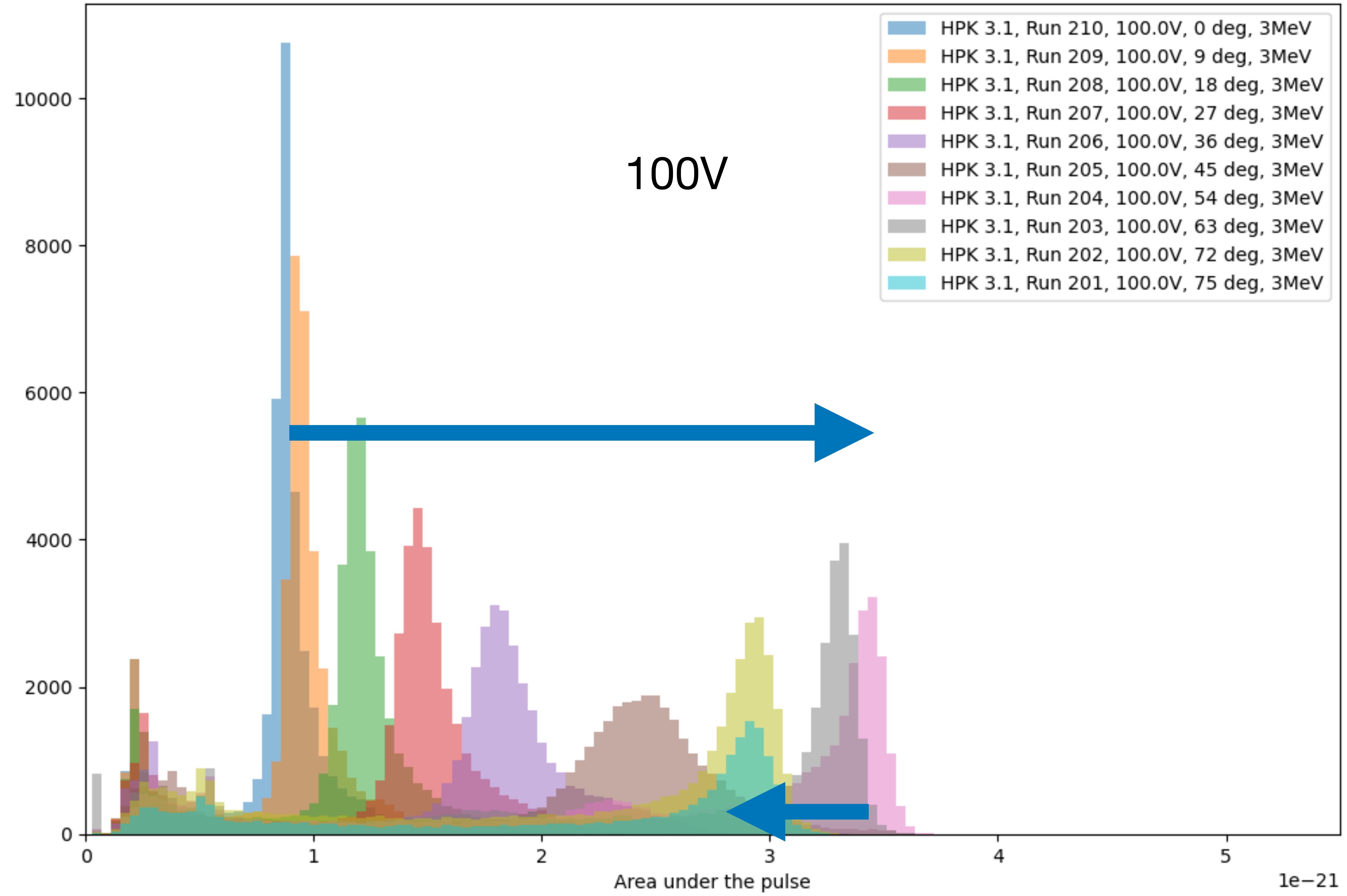
54°

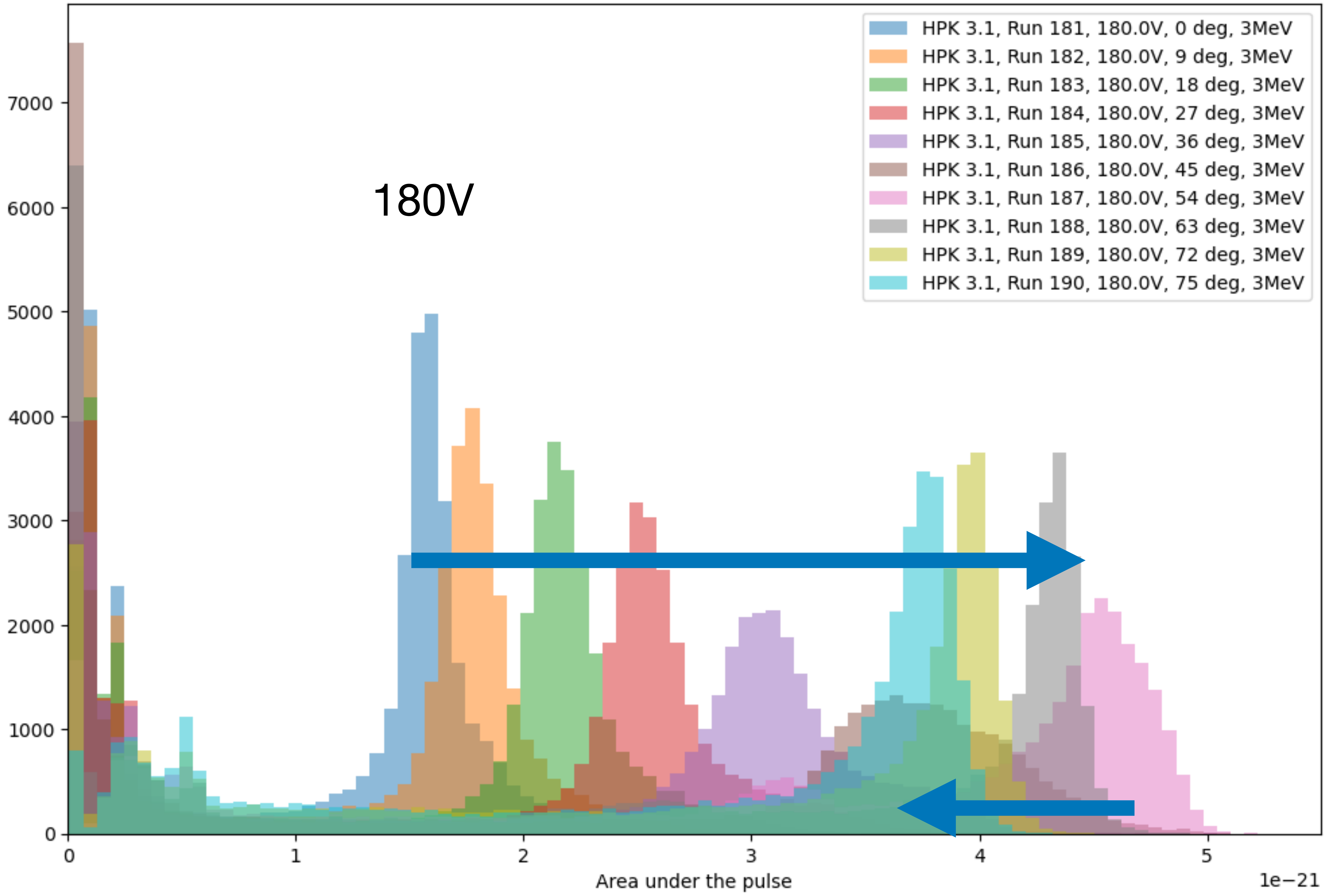


75°



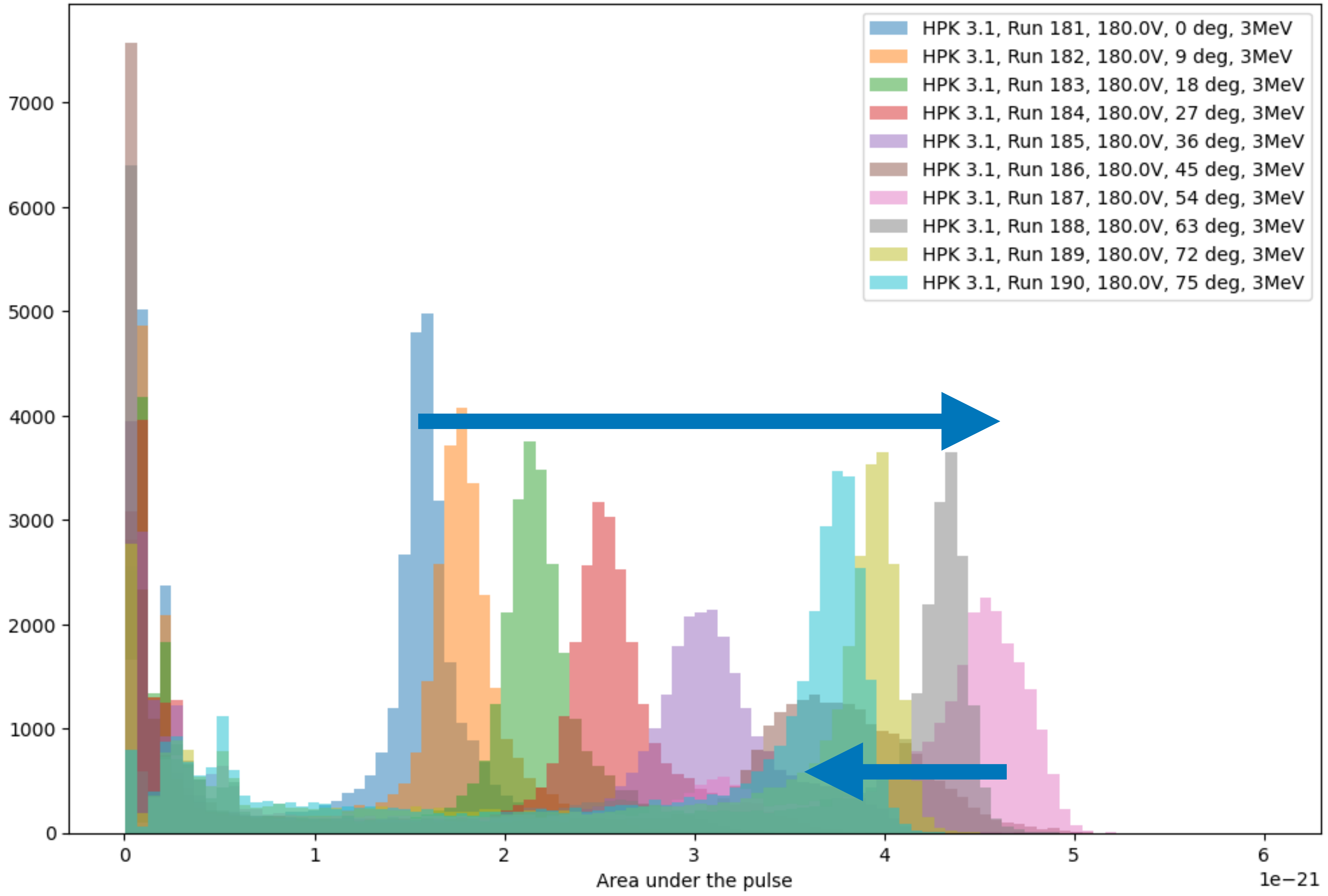
HPK 3.1 data, 3 MeV

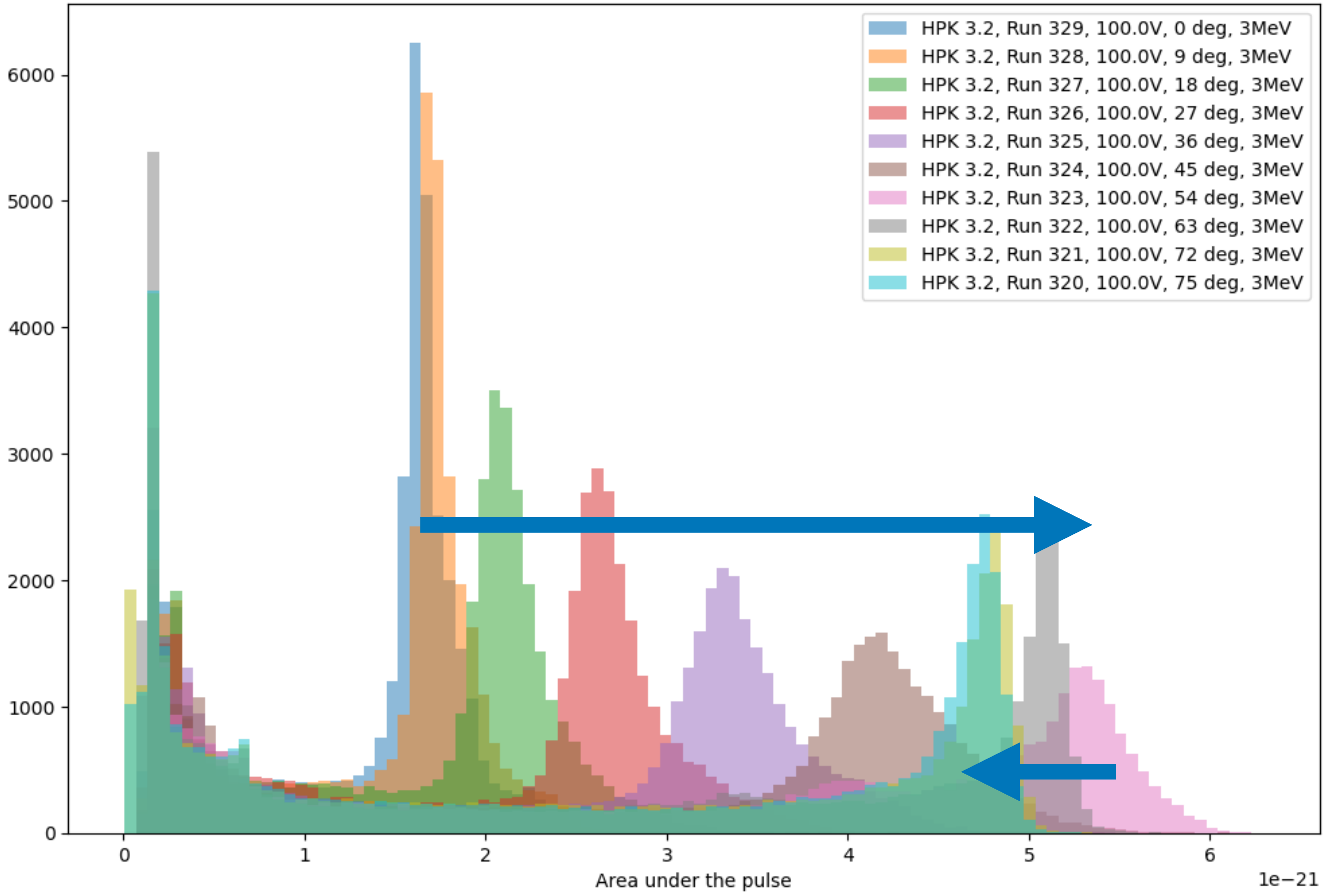




- At higher bias voltage higher initial gain
  - larger gain increase=larger spread
  - Larger effect in total

HPK 3.1 data vs HPK 3.2, 3 MeV





- HPK 3.2: larger gain increase=larger spread, but less gain suppression at high angles and less suppression at low angles?

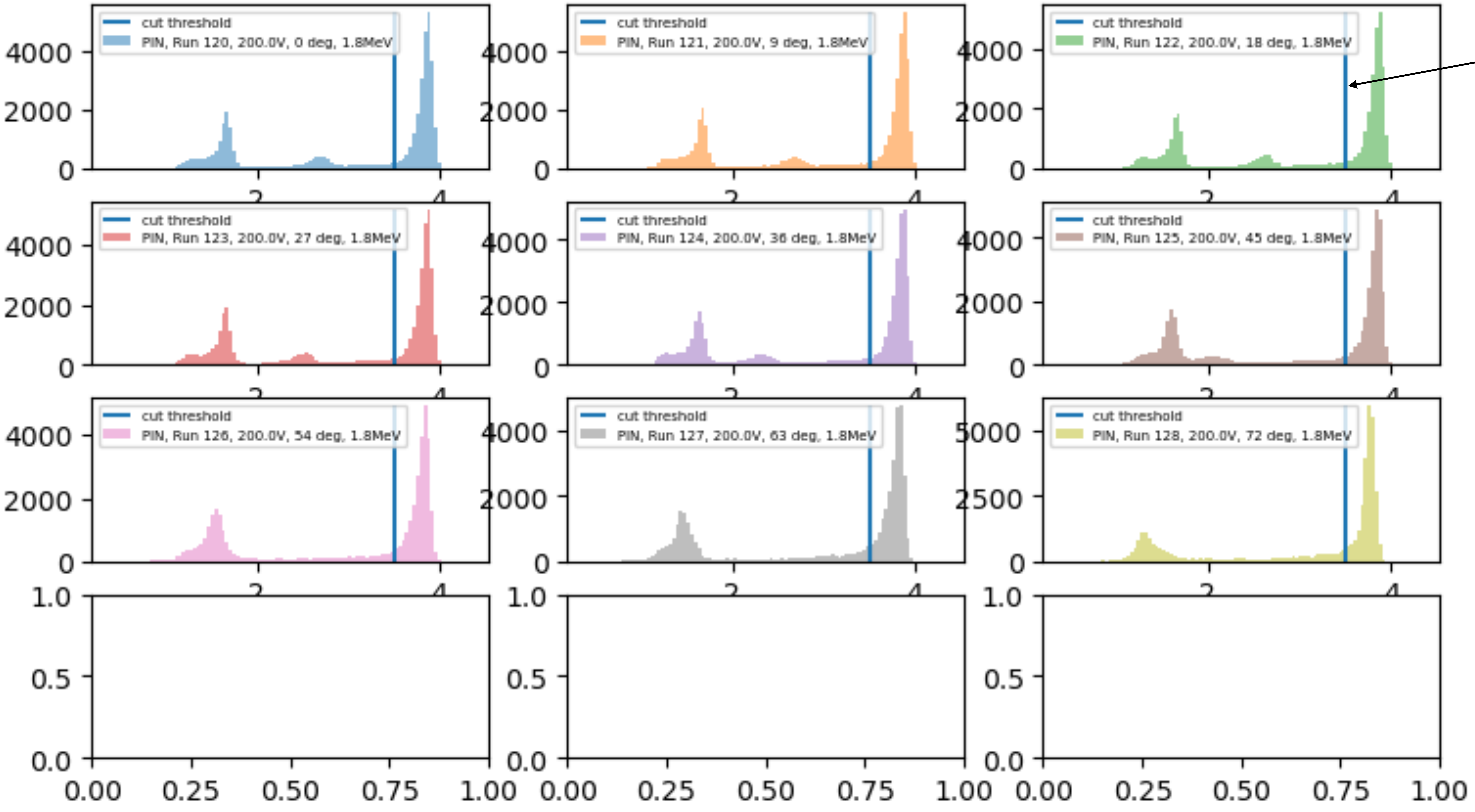
Pulse shape analysis - Introduction

- Analysis of average pulses to

  1. Assess quality of data: select regions where pulses are stable-> compute average and standard deviation
  2. Look for features of gain layer
  3. Input for TCAD simulation
  4. Determine gain vs. angle and gain vs bias voltage for selected regions

Example pulse analysis for 1.8 MeV

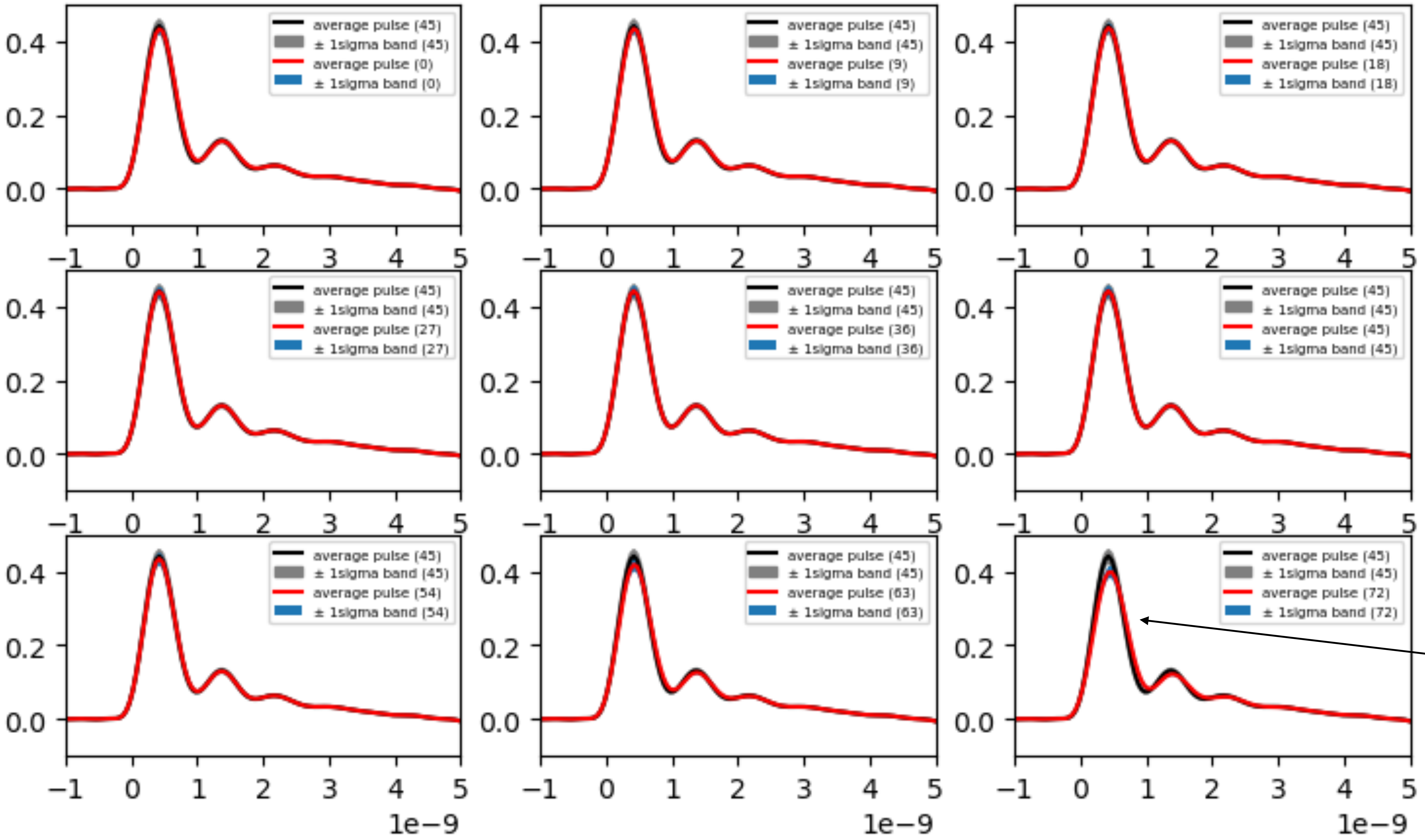
Example PIN pulse analysis: 1.8MeV, 200V



Placing of cut value

Lower energy bkg & 2nd Peak angle dependent?

Example PIN pulse analysis: 1.8MeV, 200V

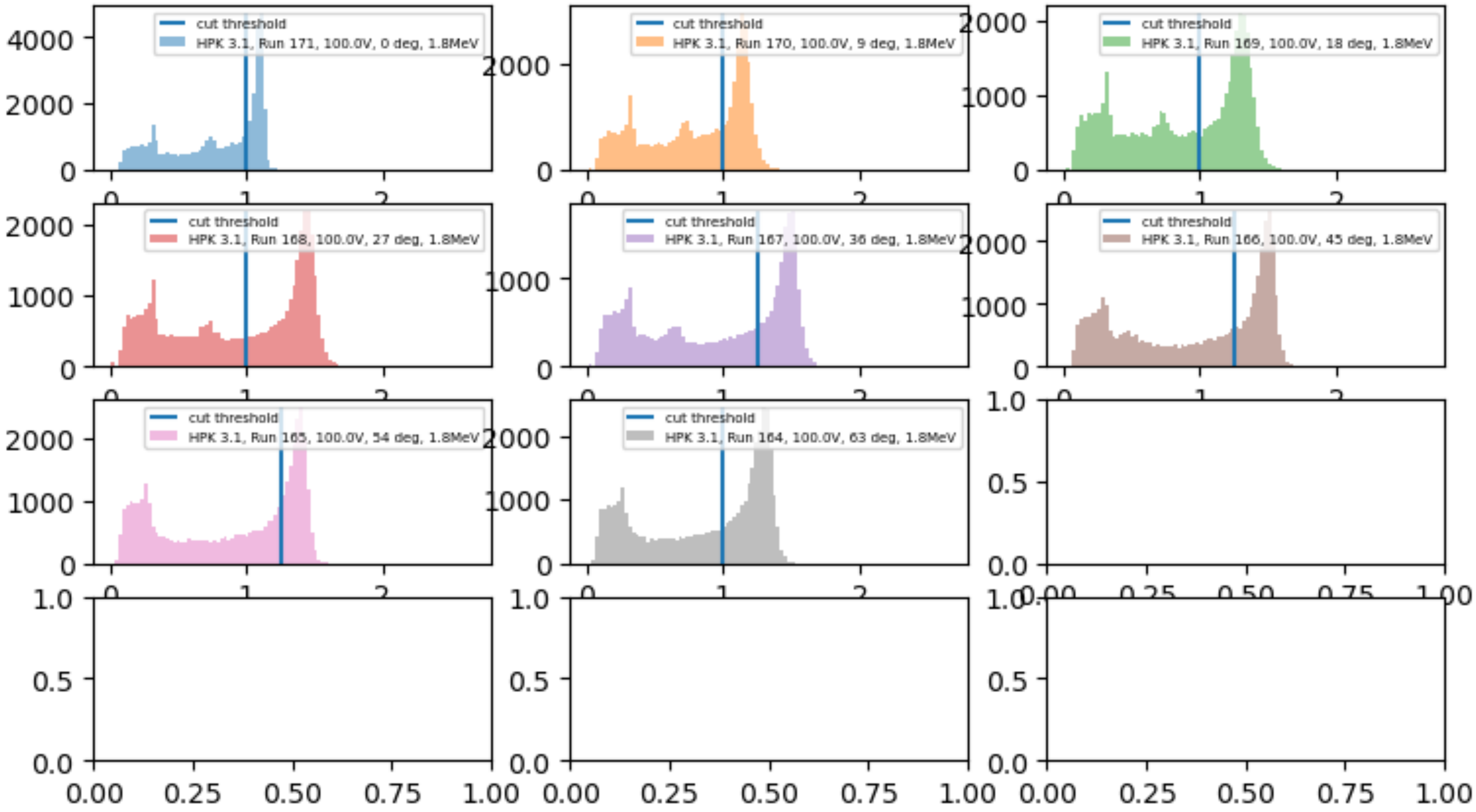


Same pulse max amplitude and area at all angles
-> same charge collection for stopping

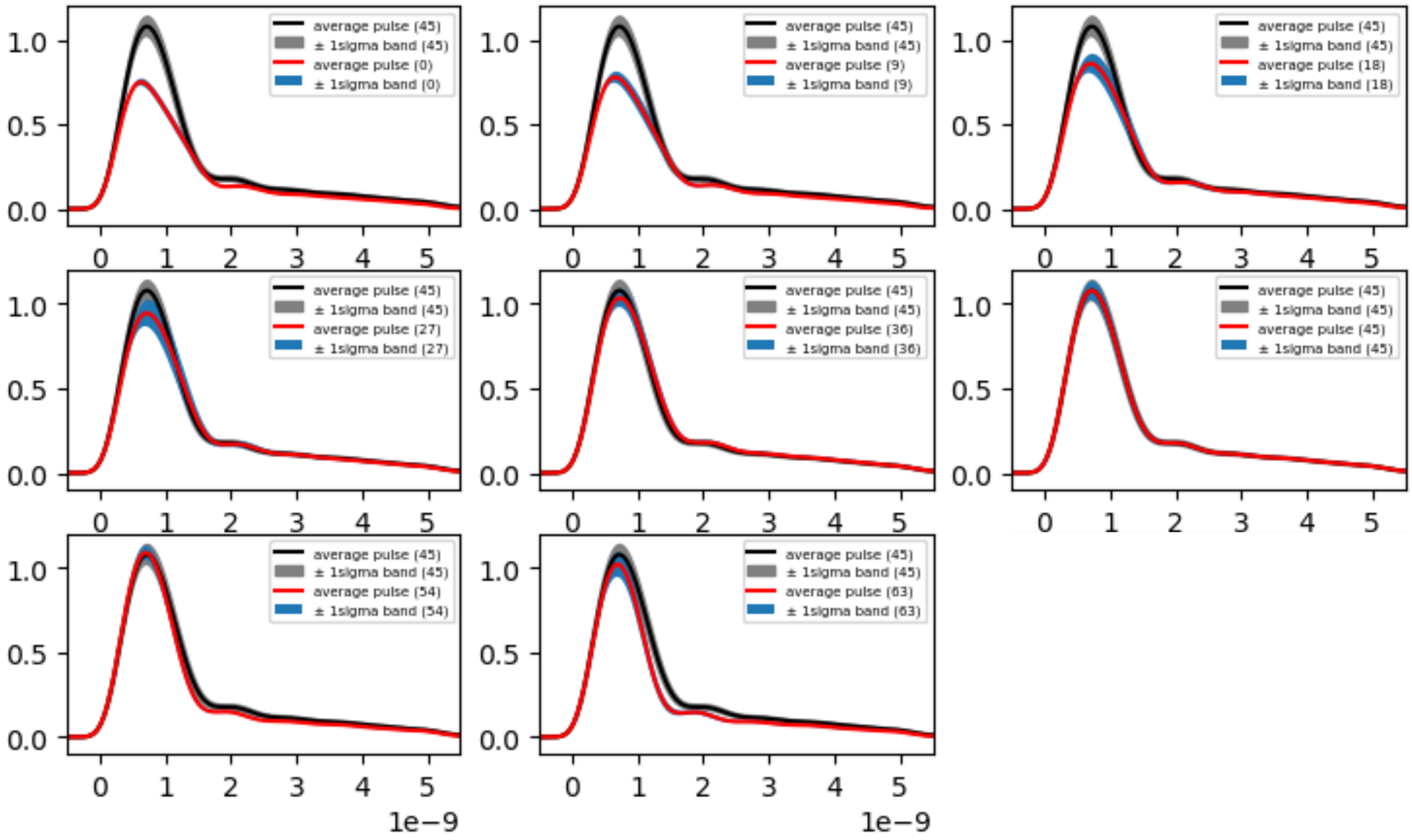
Not clear where 2nd & 3rd peak come from?
Ideas: amplifier saturation, physics effect ???

Area under pulse decreases slightly for large angles

Example HPK 3.1 pulse analysis: 1.8MeV, 100V



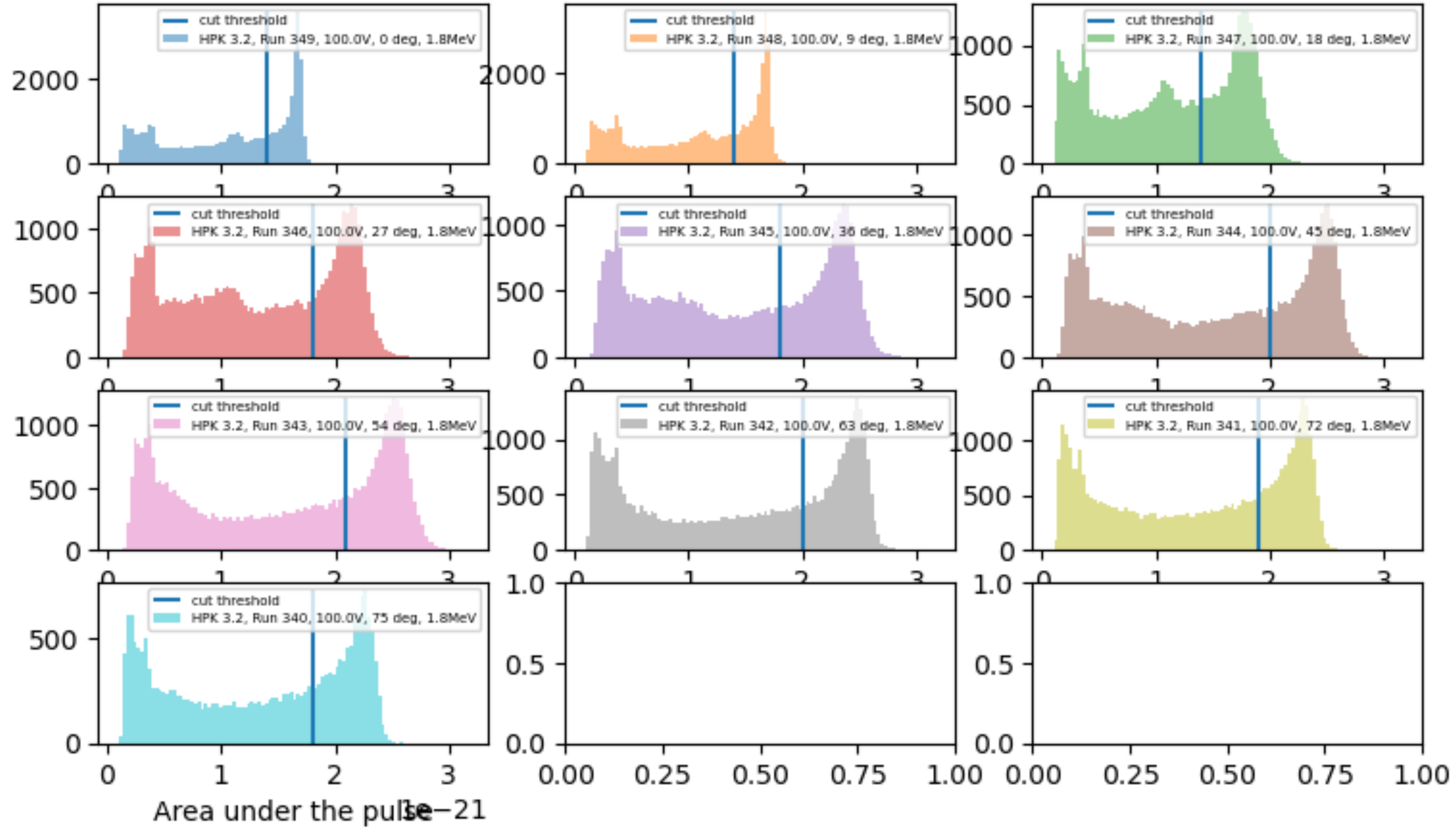
Example HPK 3.1 pulse analysis: 1.8MeV, 100V



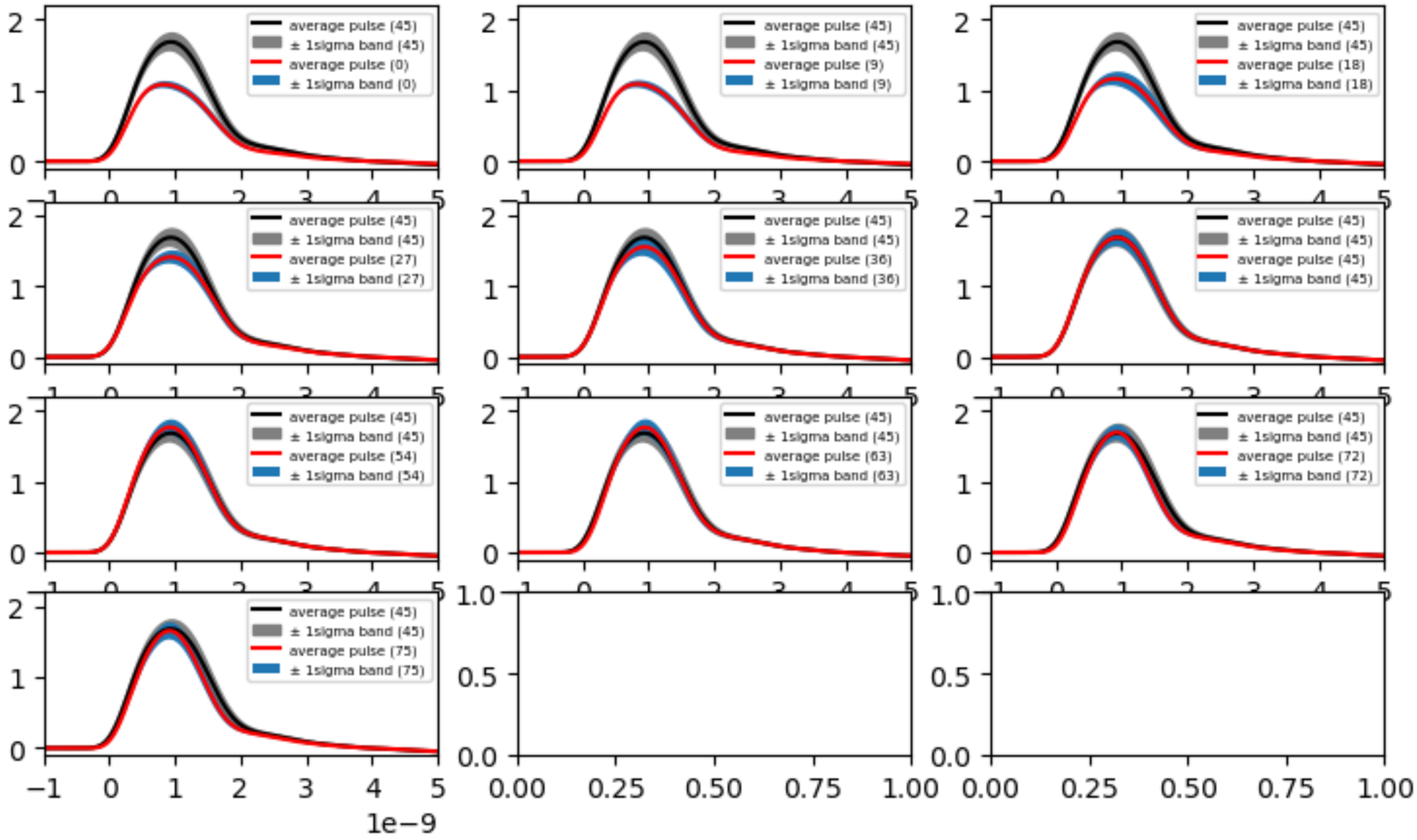
Gain layer saturation
@low angle

Less lateral drift
@high angles
-> gain suppression

Example HPK 3.2 pulse analysis: 1.8MeV, 80V



Example HPK 3.2 pulse analysis: 1.8MeV, 80V

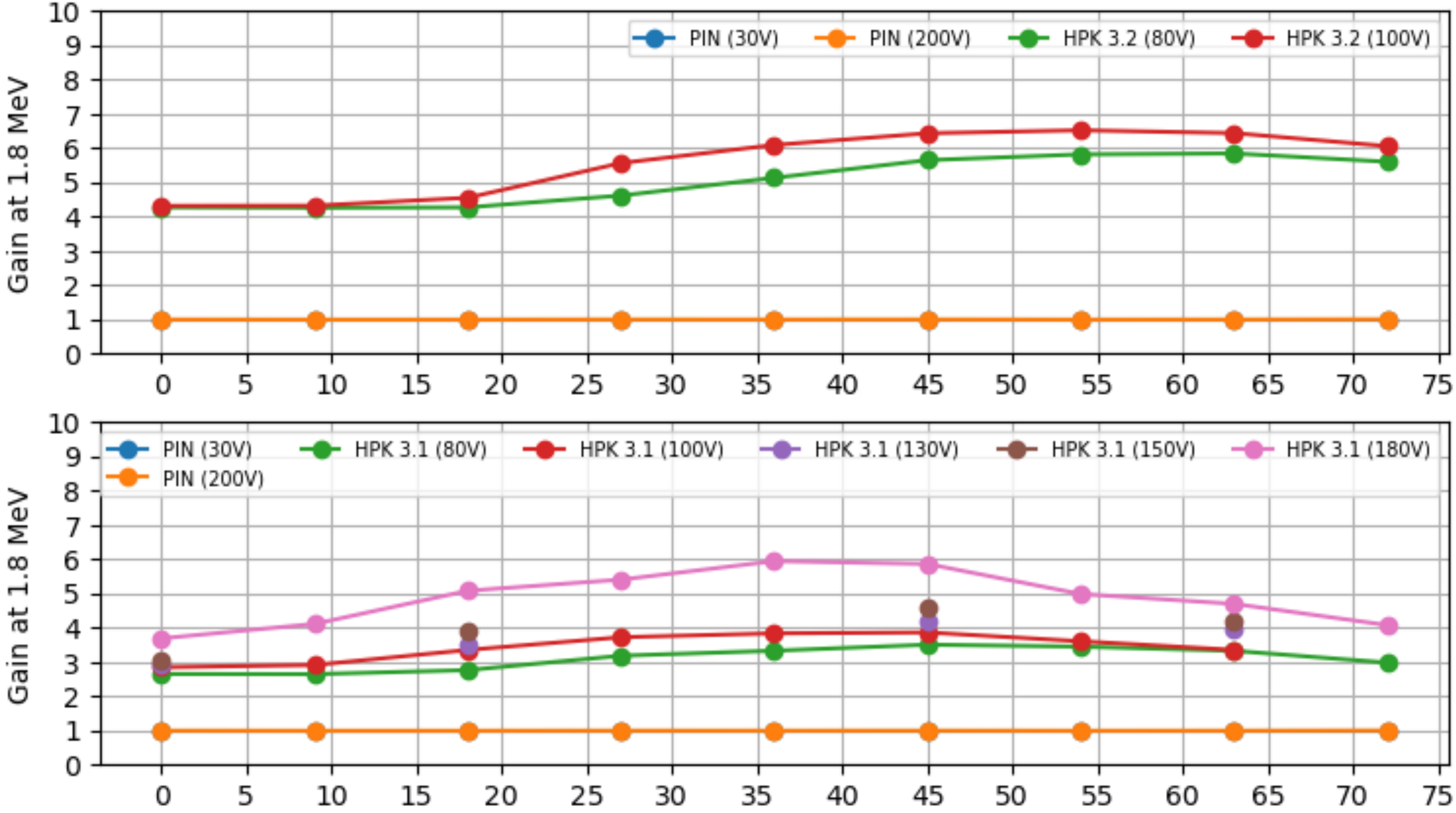


Same feature @low angles

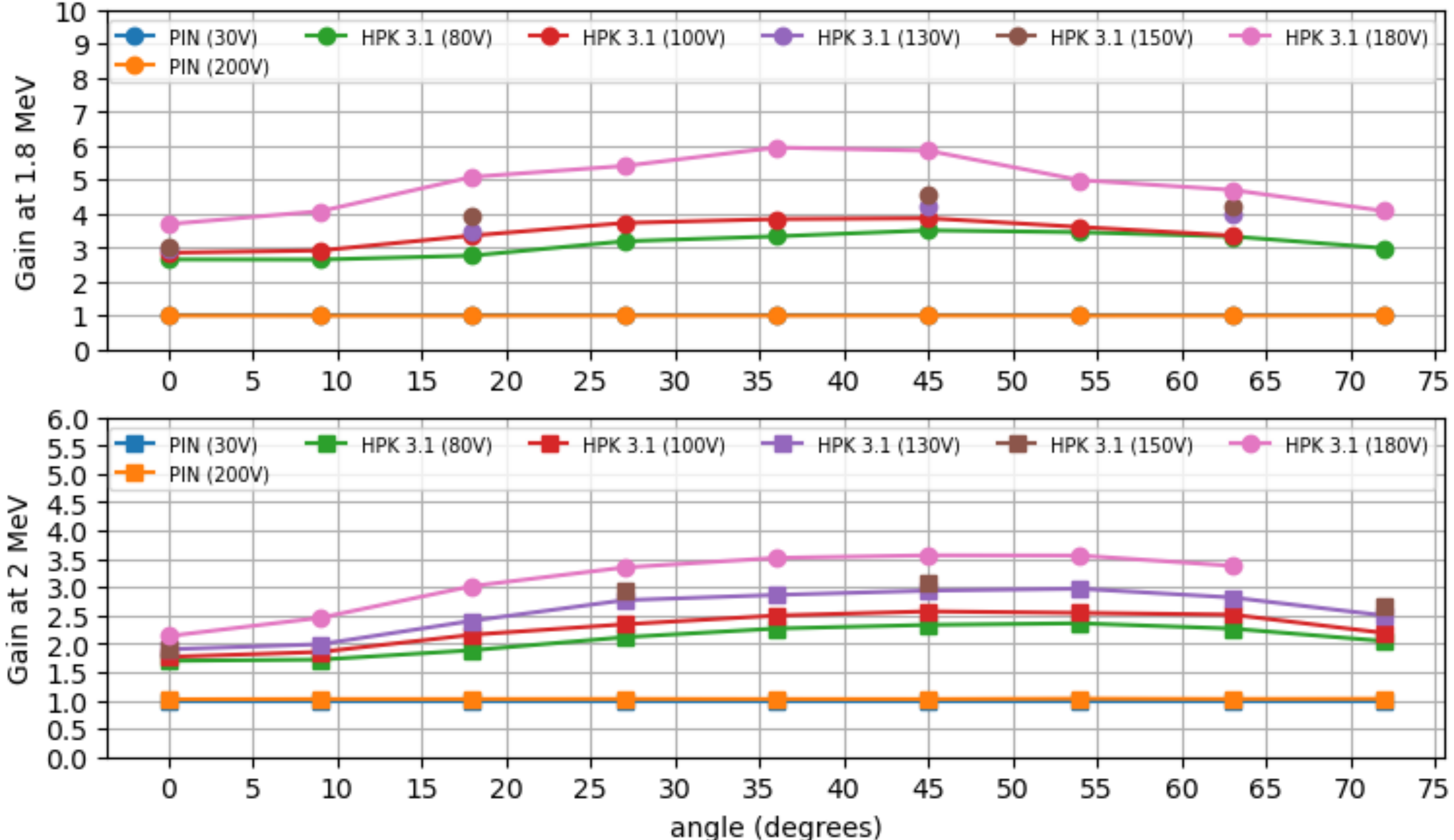
Less gain suppression @high angles

-> larger amplitude and much slower signal as HPK 3.1

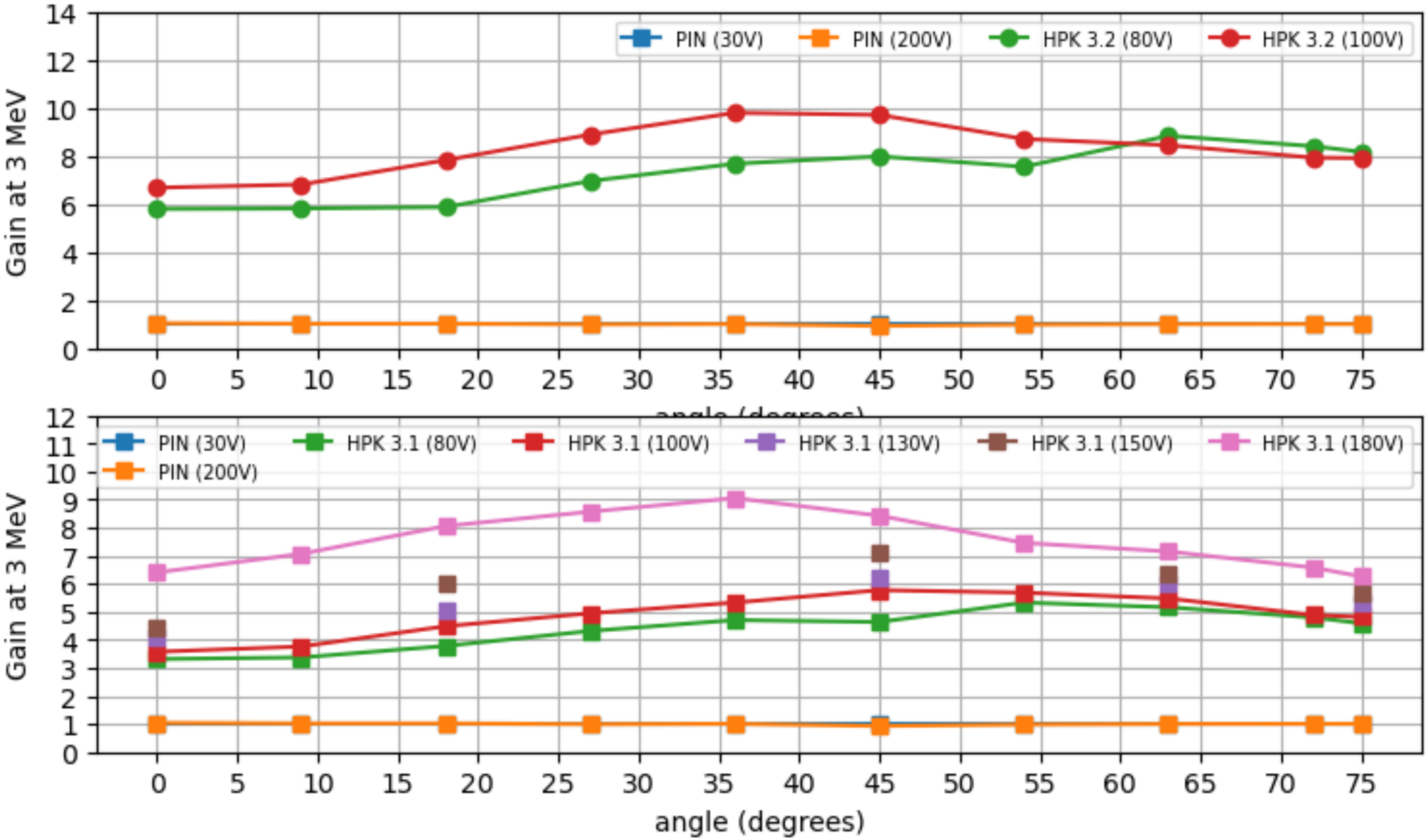
Gain @1.8MeV - HPK 3.2 vs 3.1



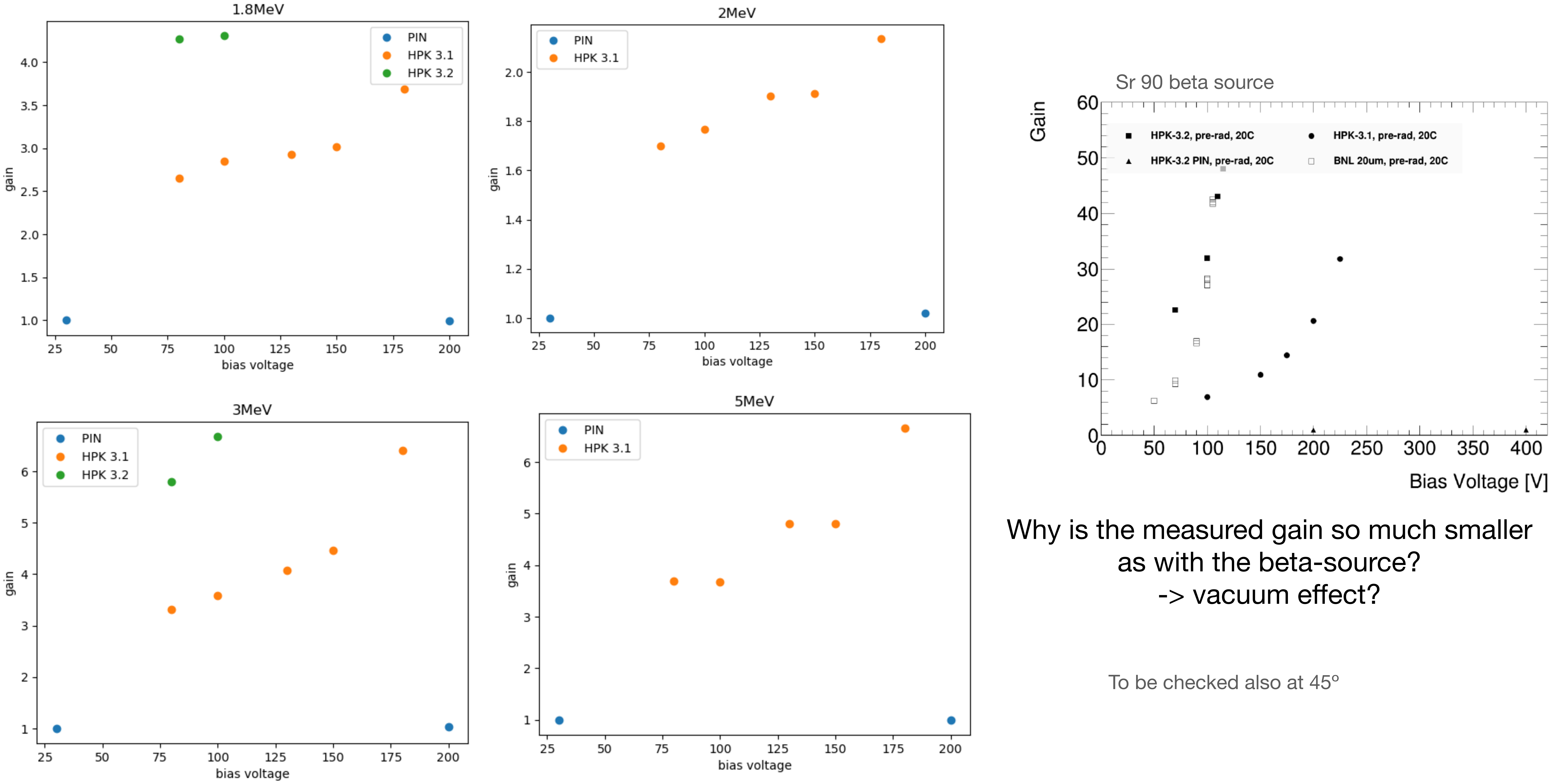
Gain @1.8MeV& 2 MeV



Gain @3MeV - HPK 3.2 vs 3.1



Gain vs. bias voltage at 0º



Why is the measured gain so much smaller as with the beta-source?
-> vacuum effect?

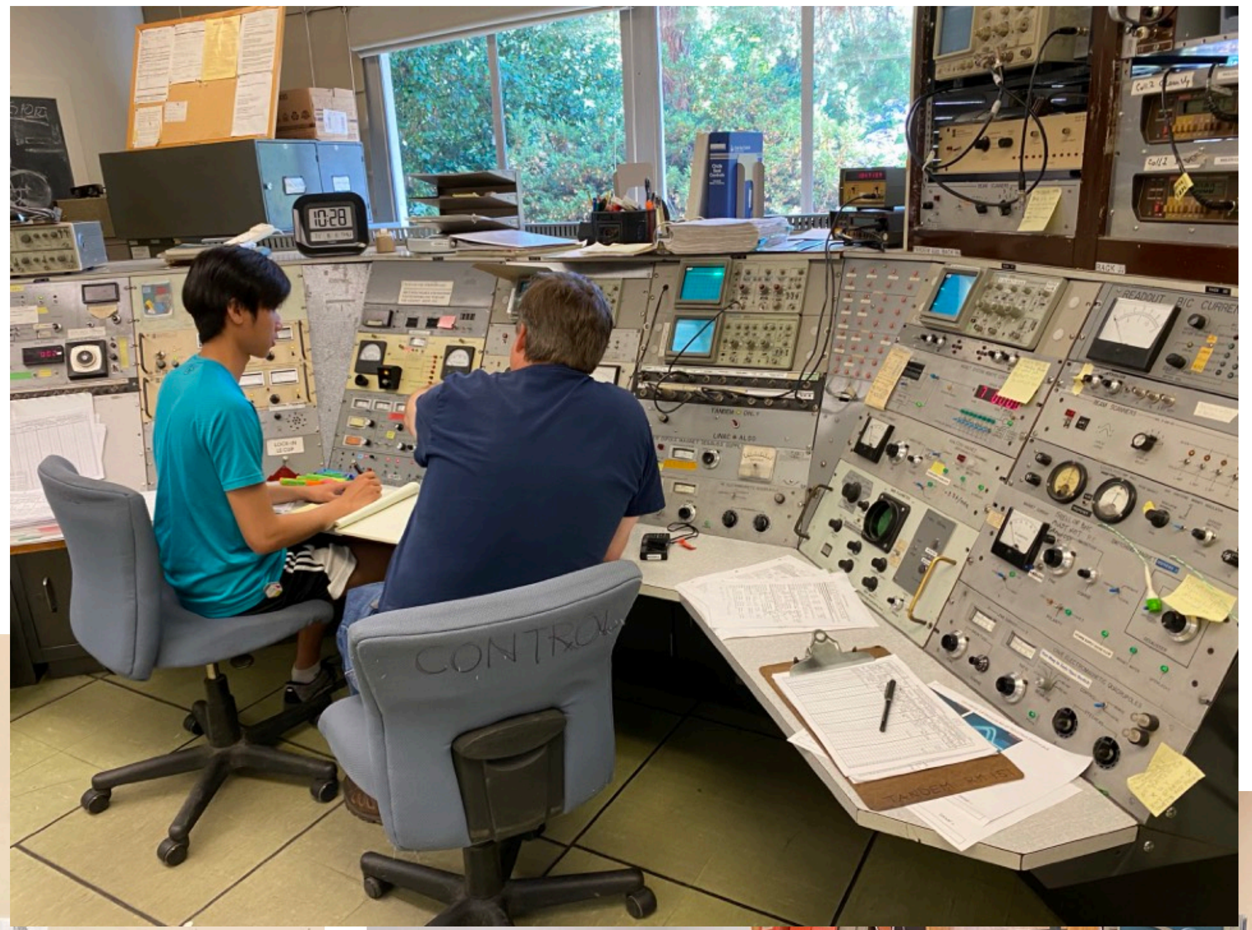
To be checked also at 45º

Conclusion/Outlook

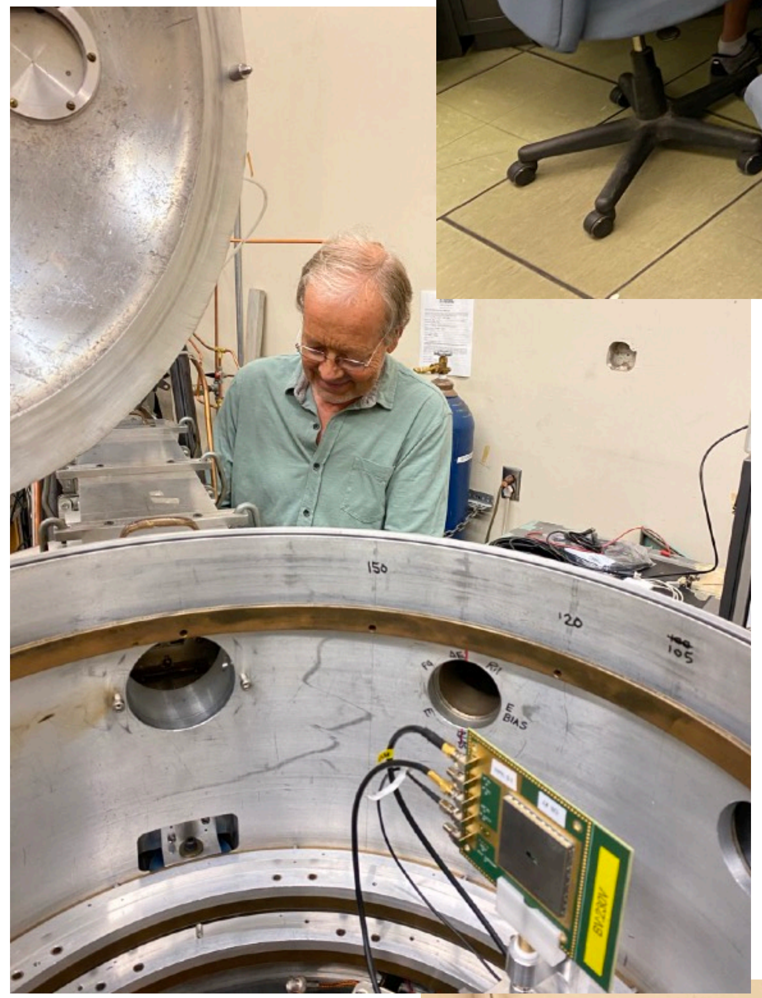
- We tested LGAD and PIN devices for PIONEER at a test beam at the CENPA tandem accelerator
  - Used different beam energies, varying detector angles and different bias voltages
- Observed gain suppression and full stopping of protons
  - Need to quantify effect and understand it better from analysis comparisons with TCAD/Geant4 simulation
  - Goal: reduce gain suppression for PIONEER
- Have done gain analysis vs. angle and pulse analysis for all energies
  - Energy resolution study in progress: Chris from UCSC
  - Energy spectra still to be better understood by comparing to Eric's PIPS data
  - Many more puzzles to be understood!
- Planning future test beam with 120 & 200um thick BNL sensors as well as AC-LGADs

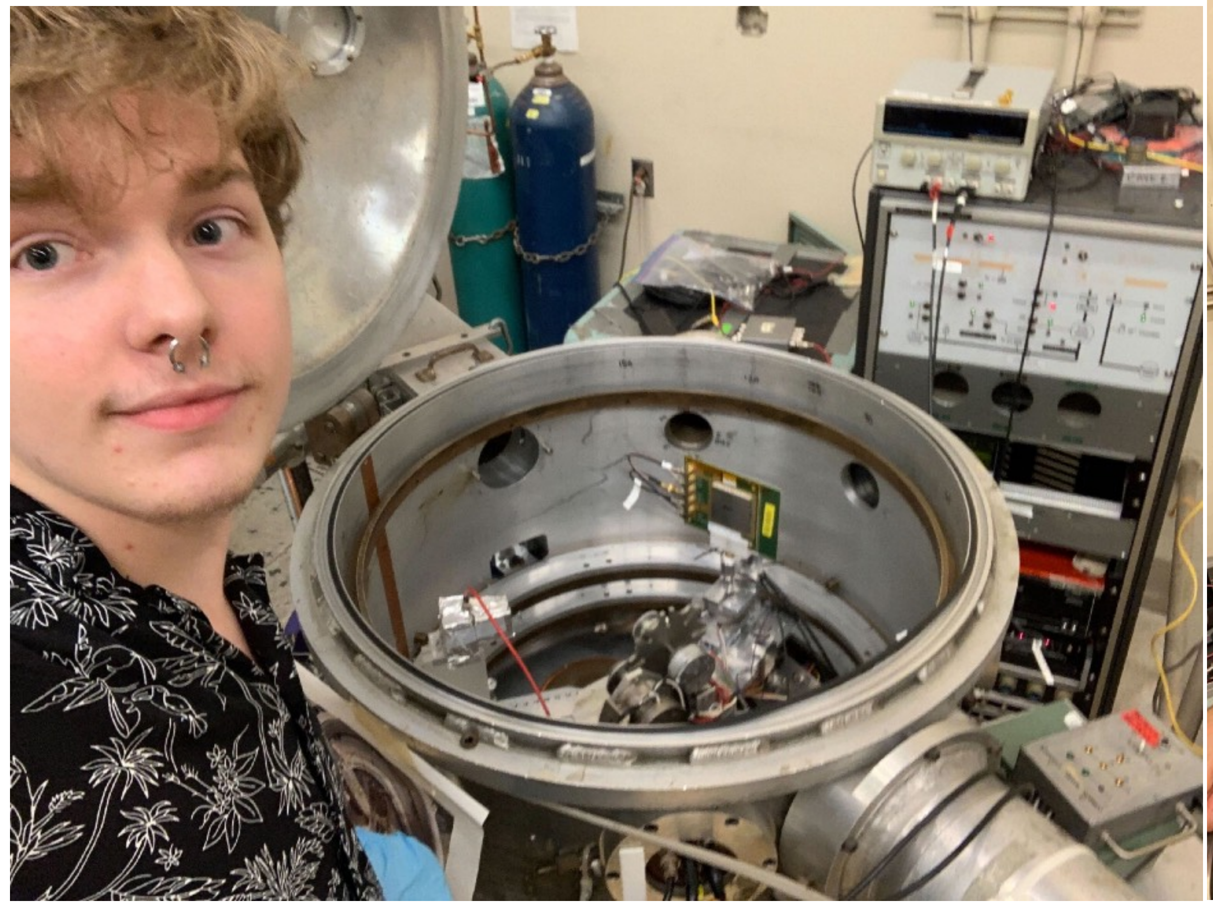
Thanks a lot to everyone involved! Stay tuned for updates!

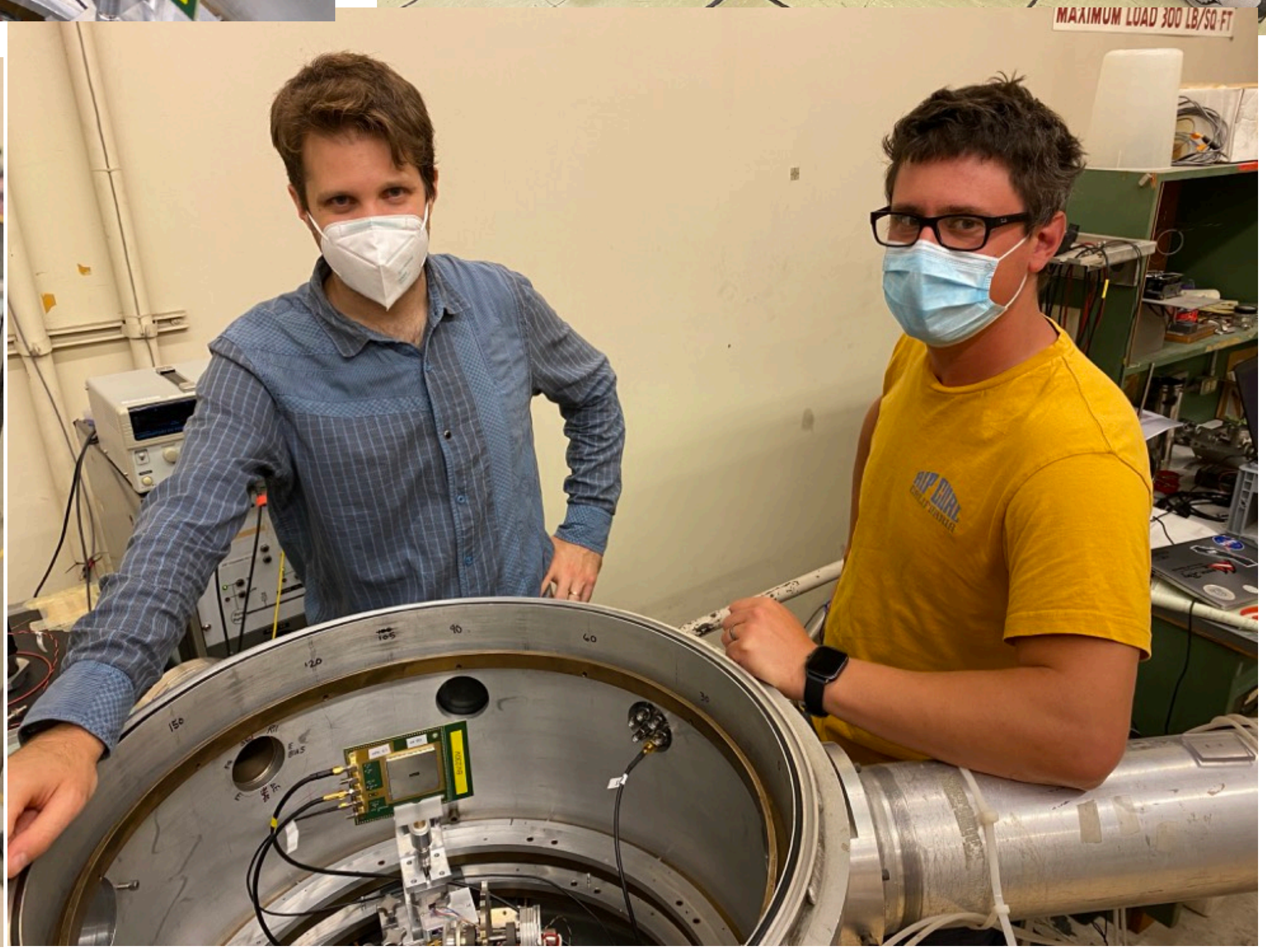
Big THANK YOU to the whole CENPA team:



- Eric & Brittney with help from Anthony, Alex & Arif -> providing us with beam
- Ryan and Nate -> building & designing our detector holder, 3D-printing pieces, machining parts …
- David Peterson -> setting up and testing the motor as rotation device, …
- Gary -> helping with network support
- Peter & Quentin -> making it happen
- Simone (UCSC) -> LGAD expert
- Caleb -> REU student
- Adam-> processing data







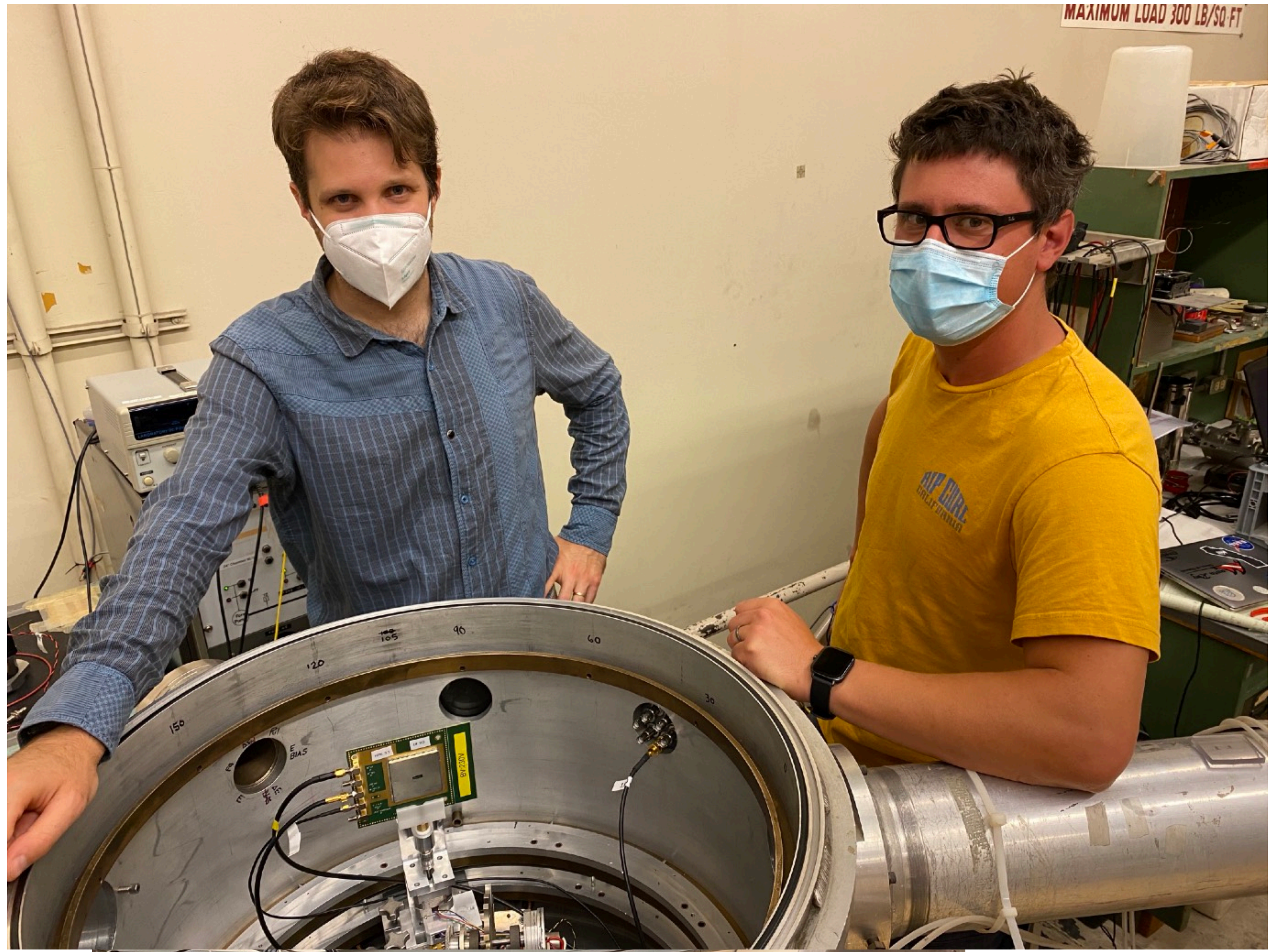
Outlook

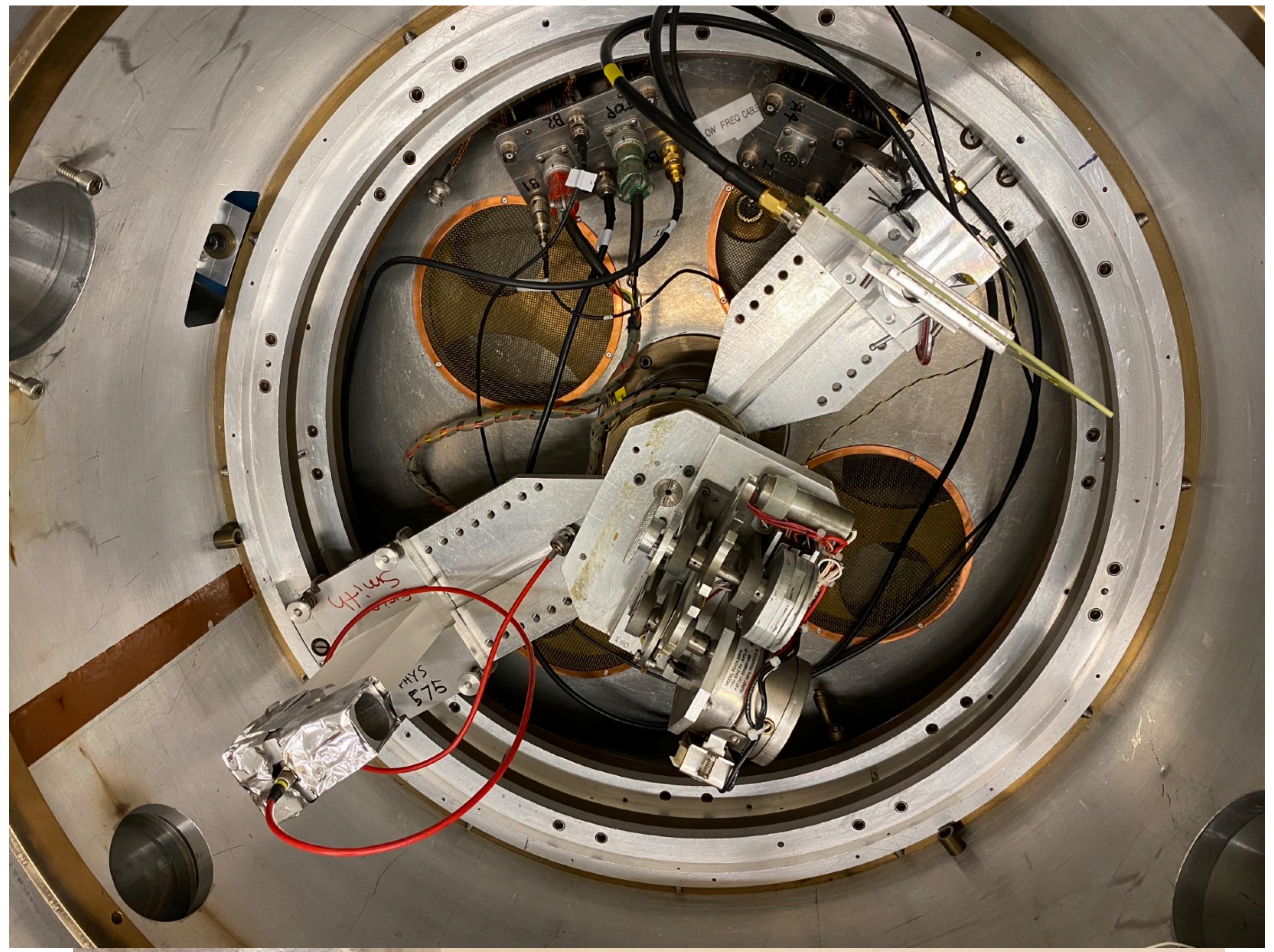
- Can we verify results using TCAD simulations?
  - Effort started from Yuzhan (UCSC): https://pioneer.npl.washington.edu/docdb/0002/000204/001/CENPA_TCAD.pdf
  - Use GEANT4 to simulate energy deposit as input for TCAD, same procedure as for alpha & beta-source test stands at UCSC
  - Then 2D simulations for sensor -> 3D simulation needed for more accurate results, but needs very long computing time

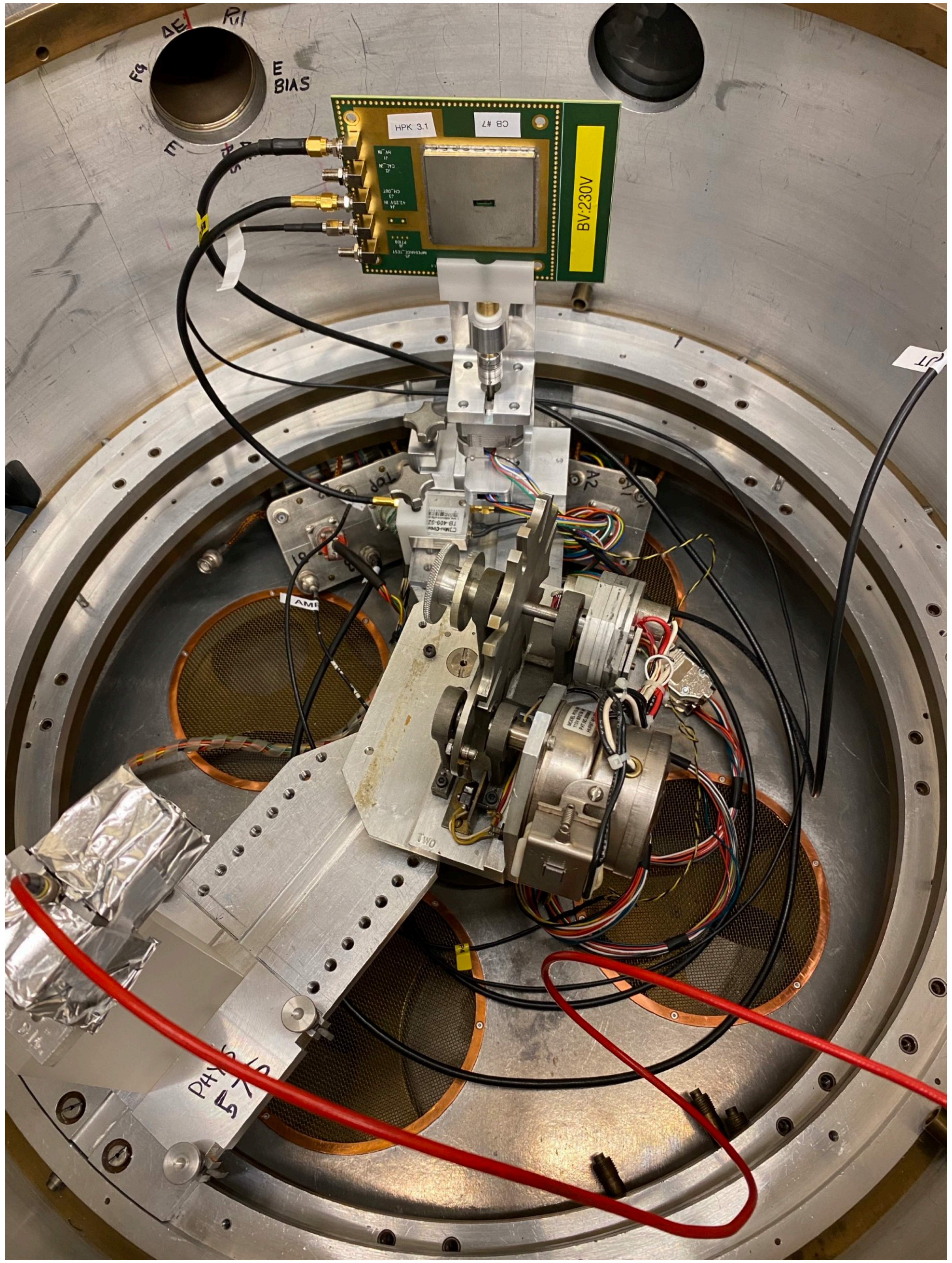
-> to be continued, stay tuned

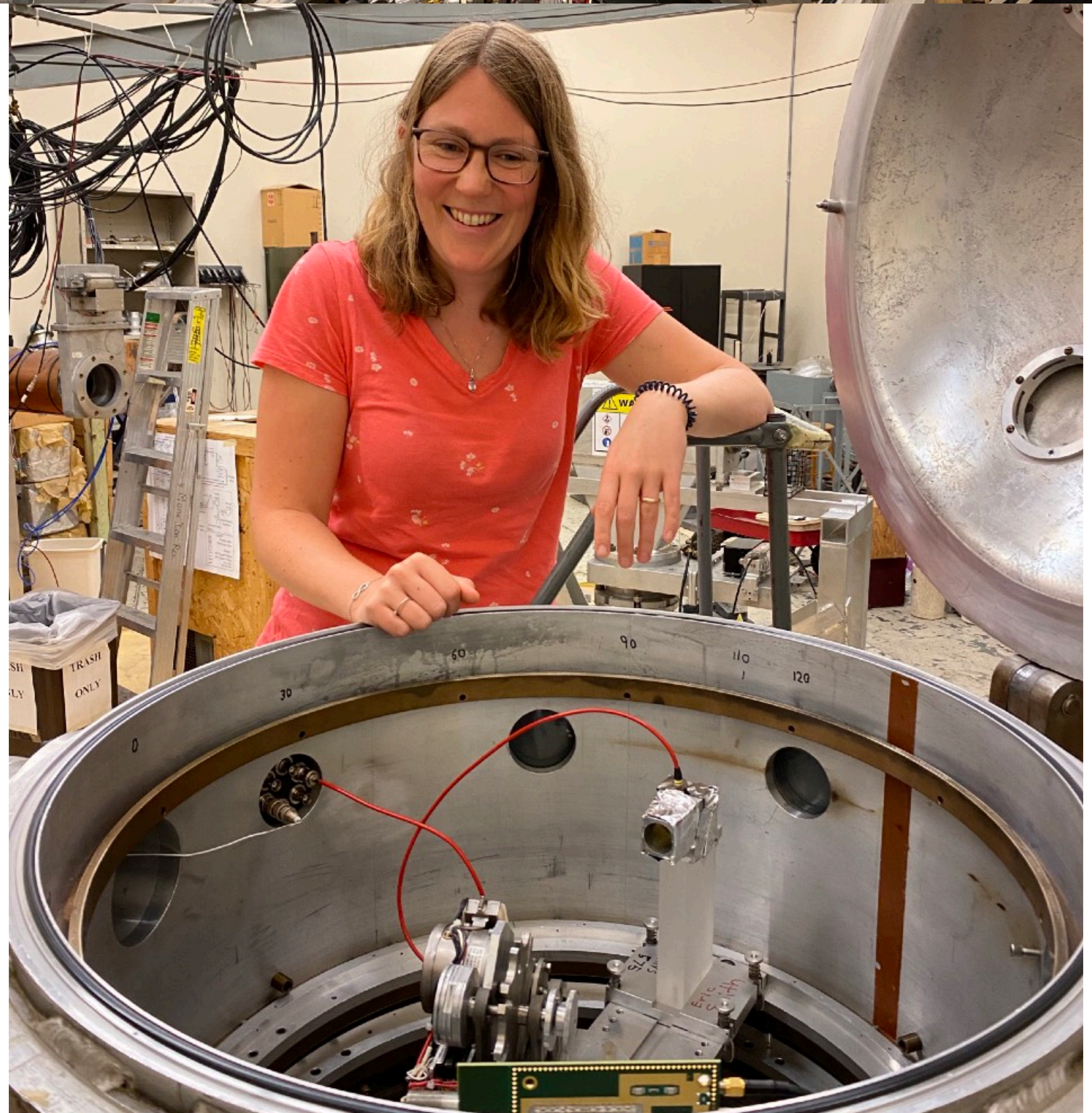
Backup slides

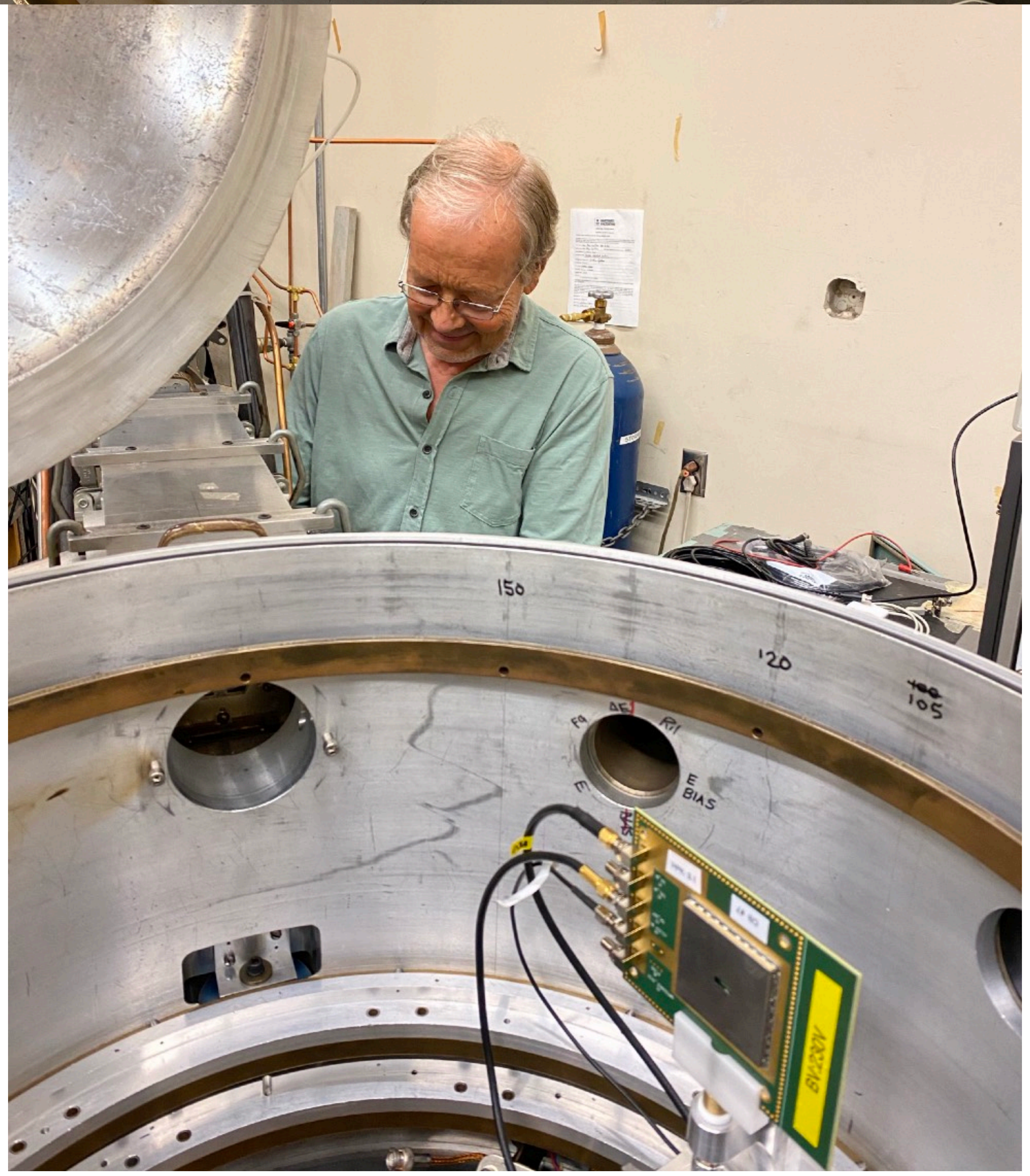
LGAD CENPA testbeam pictures



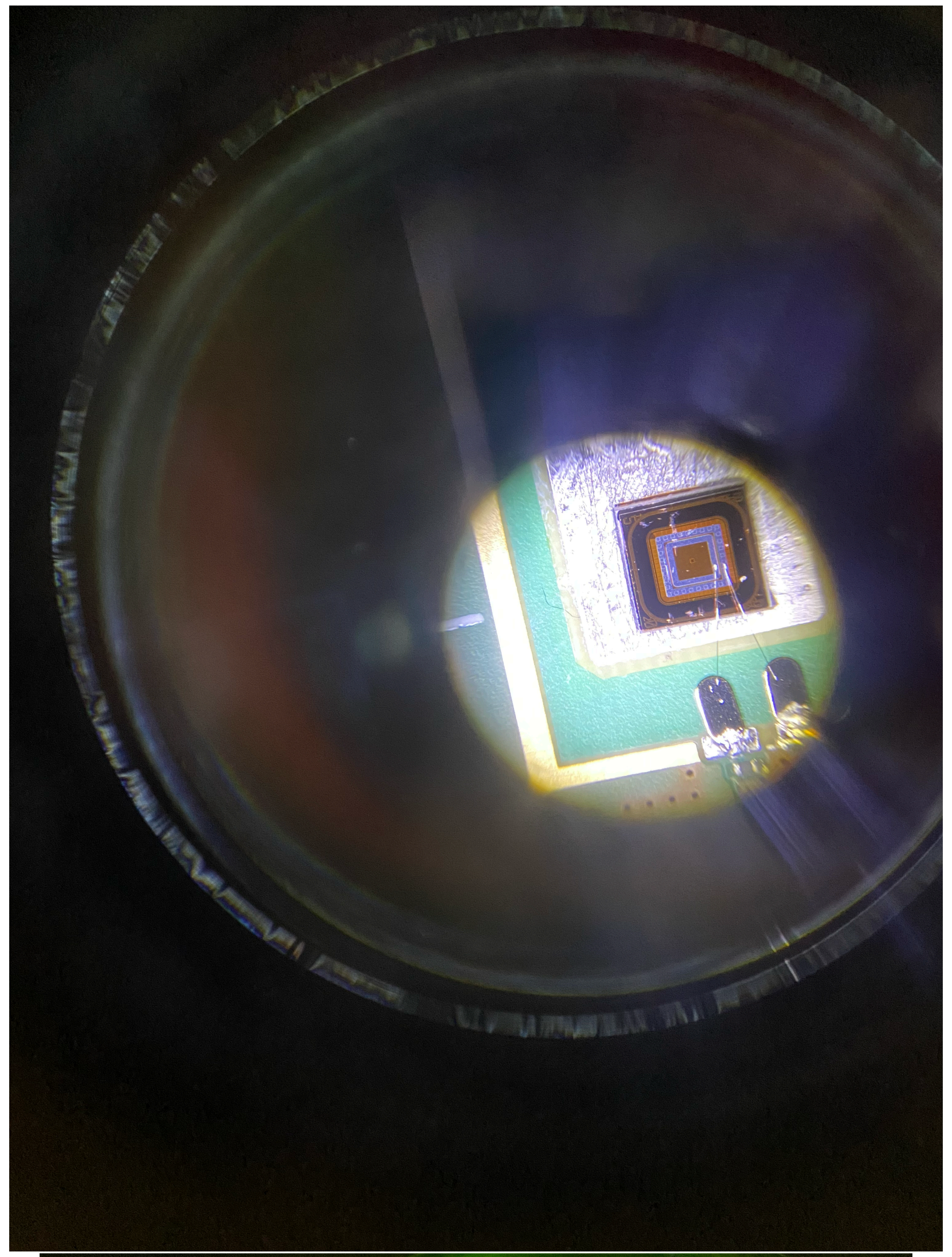


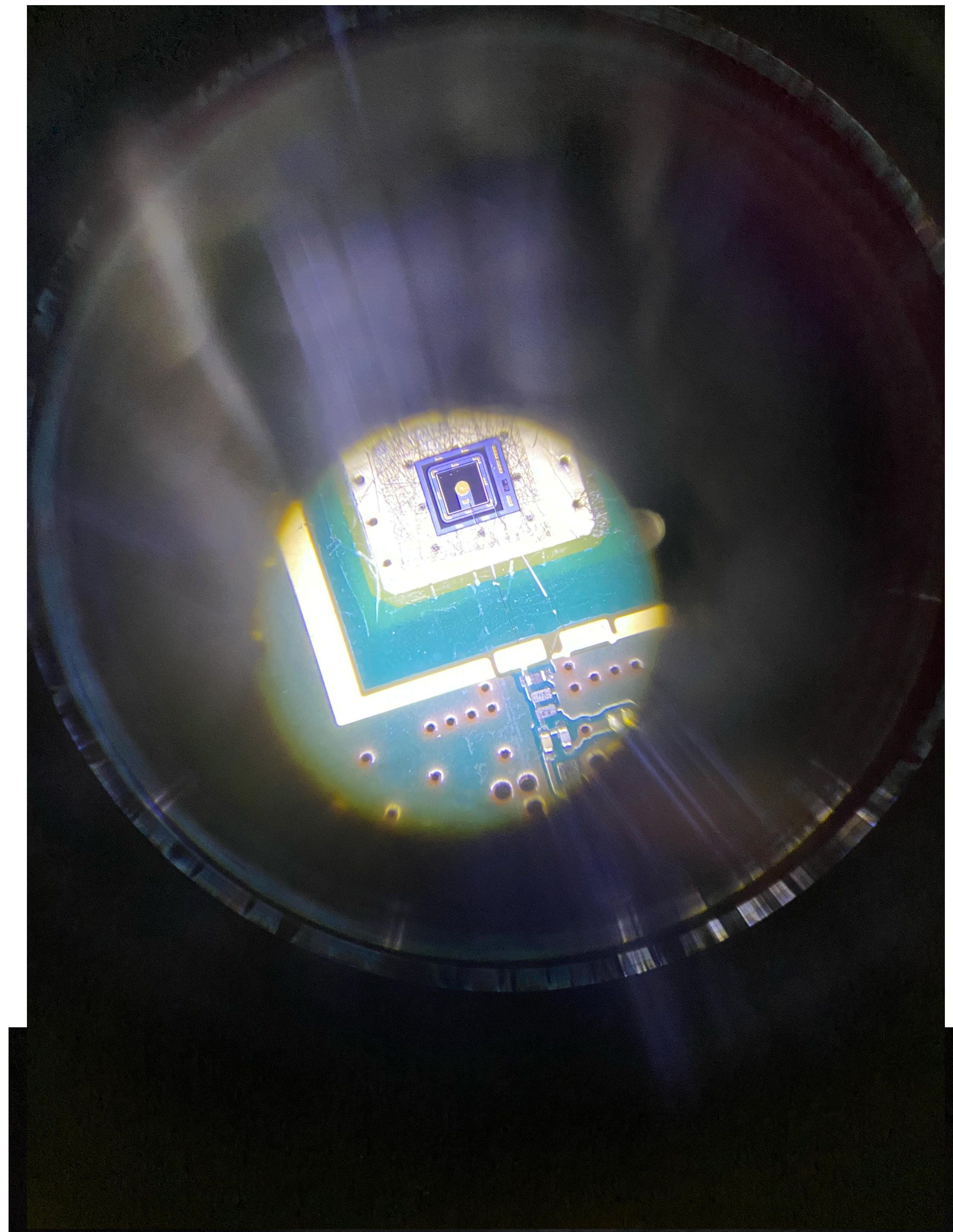


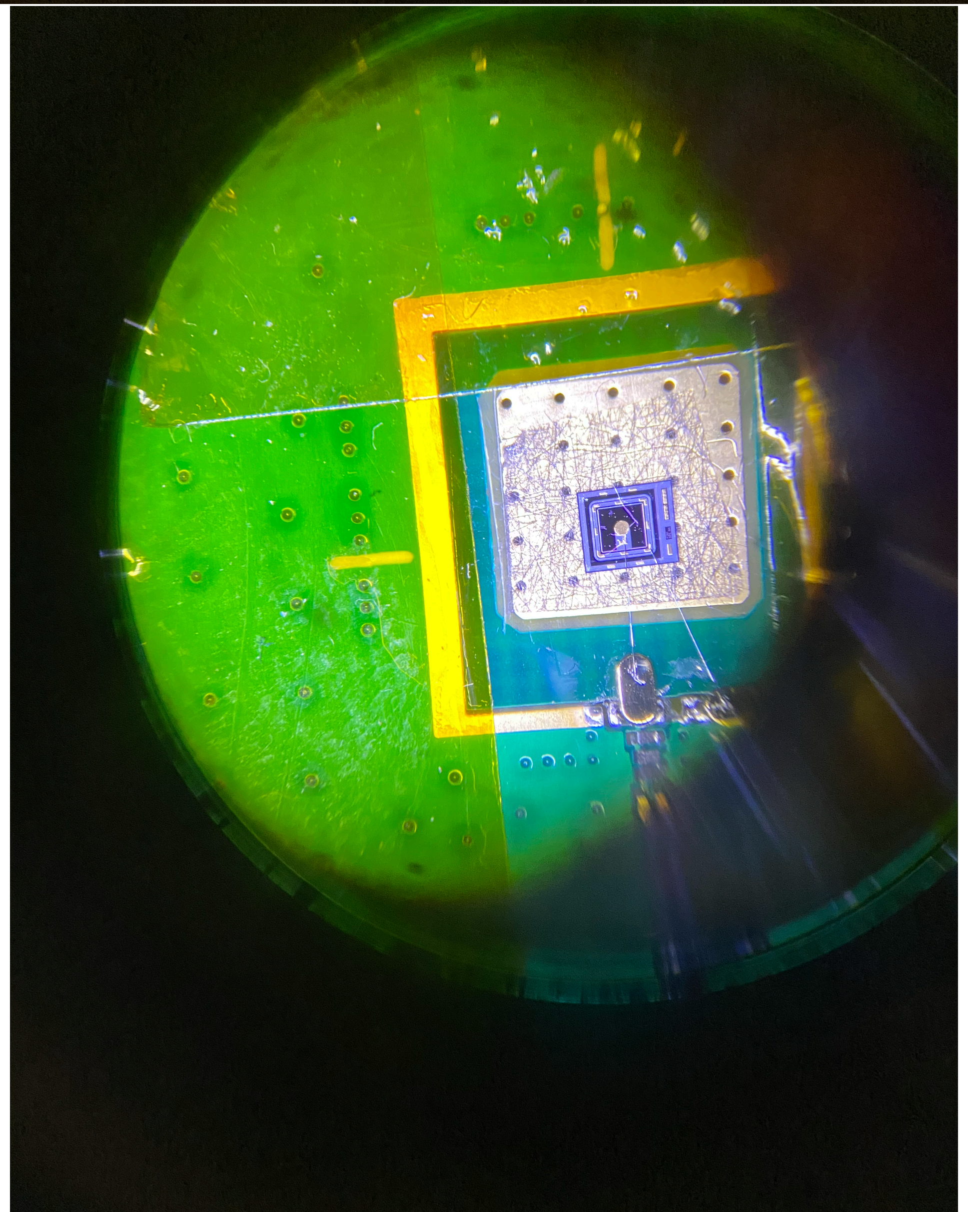


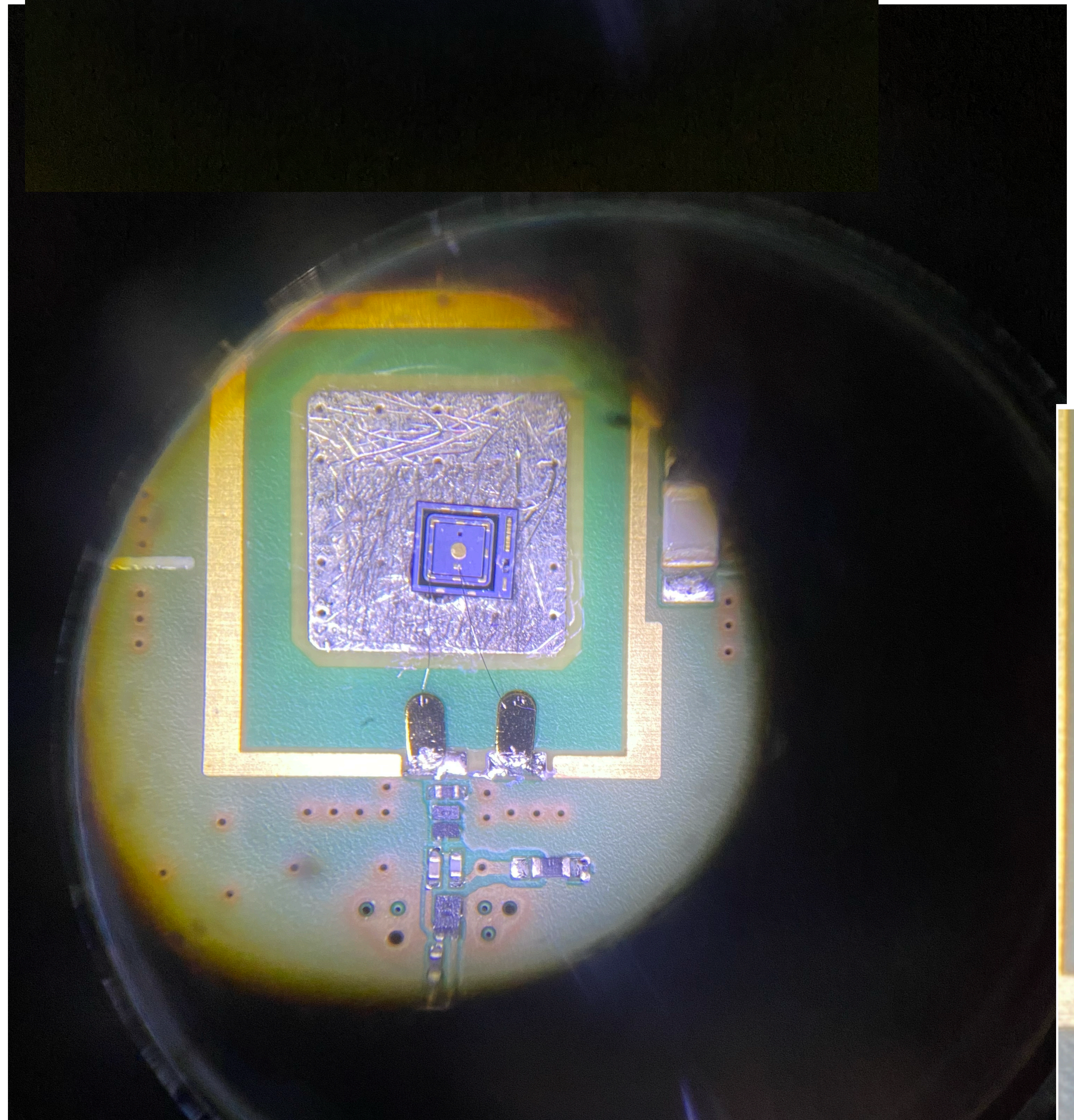


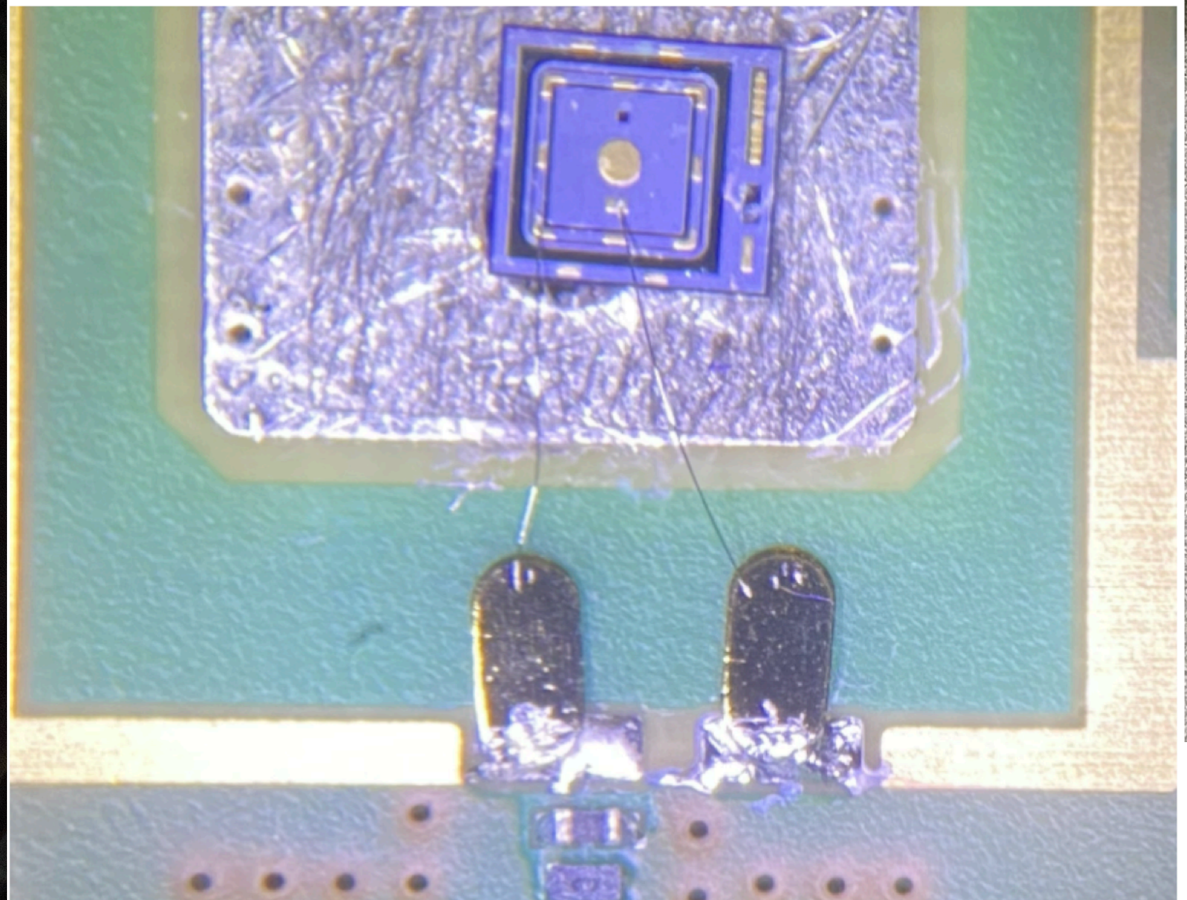
Testing 4 different LGADs:











Puzzles:

- PIN stops @1.8 MeV & 2MeV at all angles
- PIN stops @3MeV from angle 54° onwards
  - Energy deposit not the same:
- LGAD expected to also stop -> compare gain at different energies:
  - Why is the gain different when is stops in each case?

Comparison of **PIN peak position (=energy deposit)** @30V bias voltage:

1.8 MeV	**2 MeV**	**3 MeV** (54°)
3.89373E-22	4.22998E-22	6.0648E-22

Comparison of **HPK 3.2 gain** @100V bias voltage:

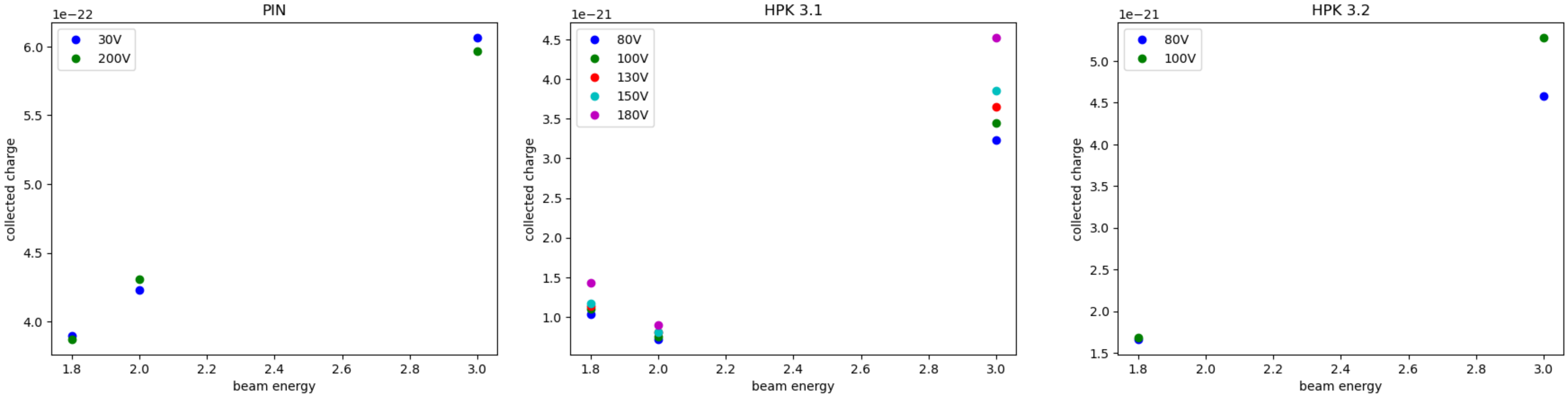
HPK 3.2 Angle/	**1.8 MeV**	**3 MeV**
0°	4.3	6.7
54°	5.81	8.7
63°	5.84	8.45

Comparison of **HPK 3.1 gain** @100V bias voltage:

HPK 3.1 Angle/Energy	**1.8 MeV**	**2 MeV**	**3 MeV**
0°	2.8	1.8	3.6
54°	3.6	2.54	5.7
63°	3.35	2.51	5.5

Punch through

Puzzles: collected charge vs. energy



Linearity expected for proton stopping

Puzzles:

- Energy deposit not the same for LGAD either:

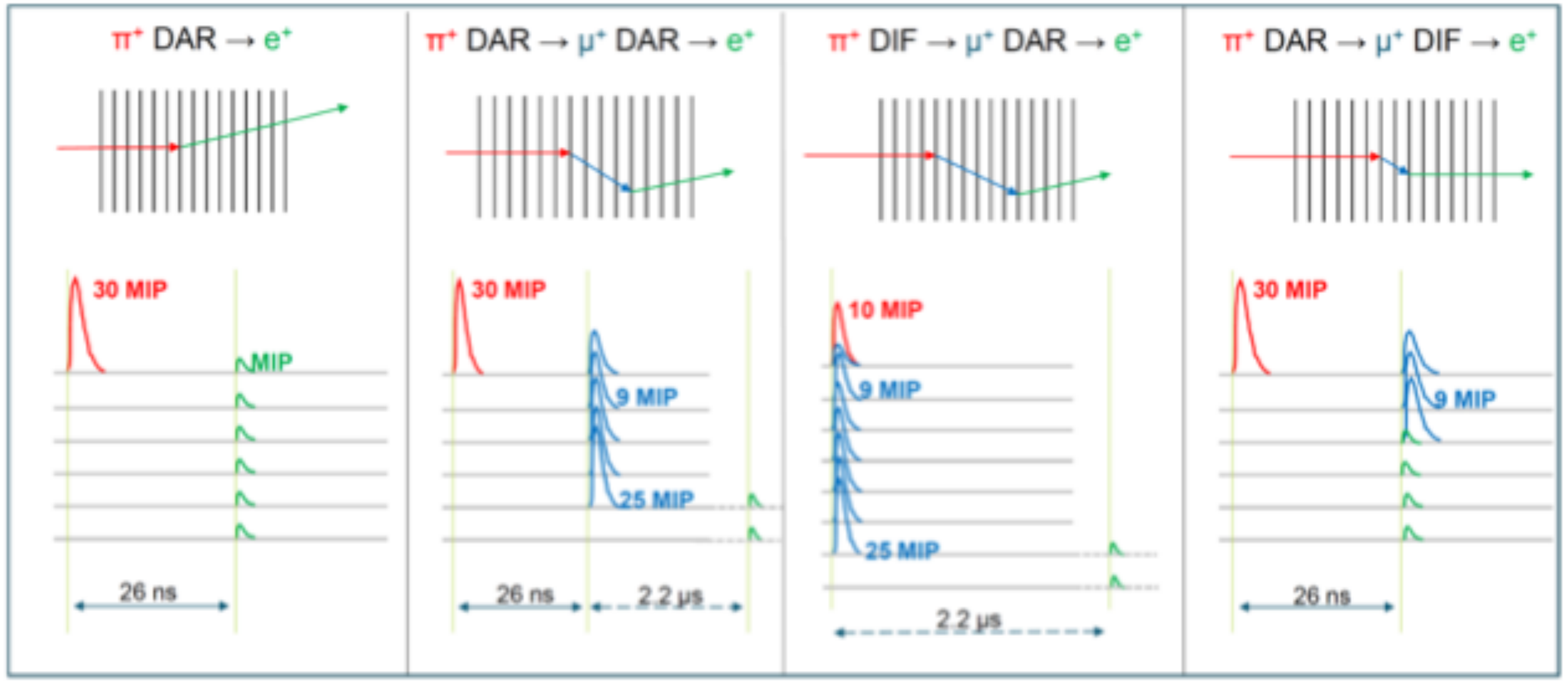
Comparison of **HPK 3.1 peak** @100V bias voltage:

HPK 3.1 Peak pos./Energy	1.8 MeV	2 MeV	3 MeV
0º	1.10772E-21	7.47839E-22	8.78195E-22
54º	1.39733E-21	1.05702E-21	Punch through 3.44749E-21
63º	1.2881E-21	1.04647E-21	3.32169E-21

Comparison of **HPK 3.2 peak** @100V bias voltage:

HPK 3.1 Peak pos./Energy	1.8 MeV	3 MeV
0º	1.6785E-21	1.64016E-21
54º	2.52744E-21	5.28046E-21
63º	2.47386E-21	5.12098E-21

ATAR



- Full silicon active target based on low-gain avalanche diode (LGAD) technology

- Requirements:

  - High longitudinal segmentation: to detect stopping pion and emitted muon

  - Compact: reduce dead material (incl. air) as much as possible

  - Fast timing: separate pulses to reconstruct pion decay chain

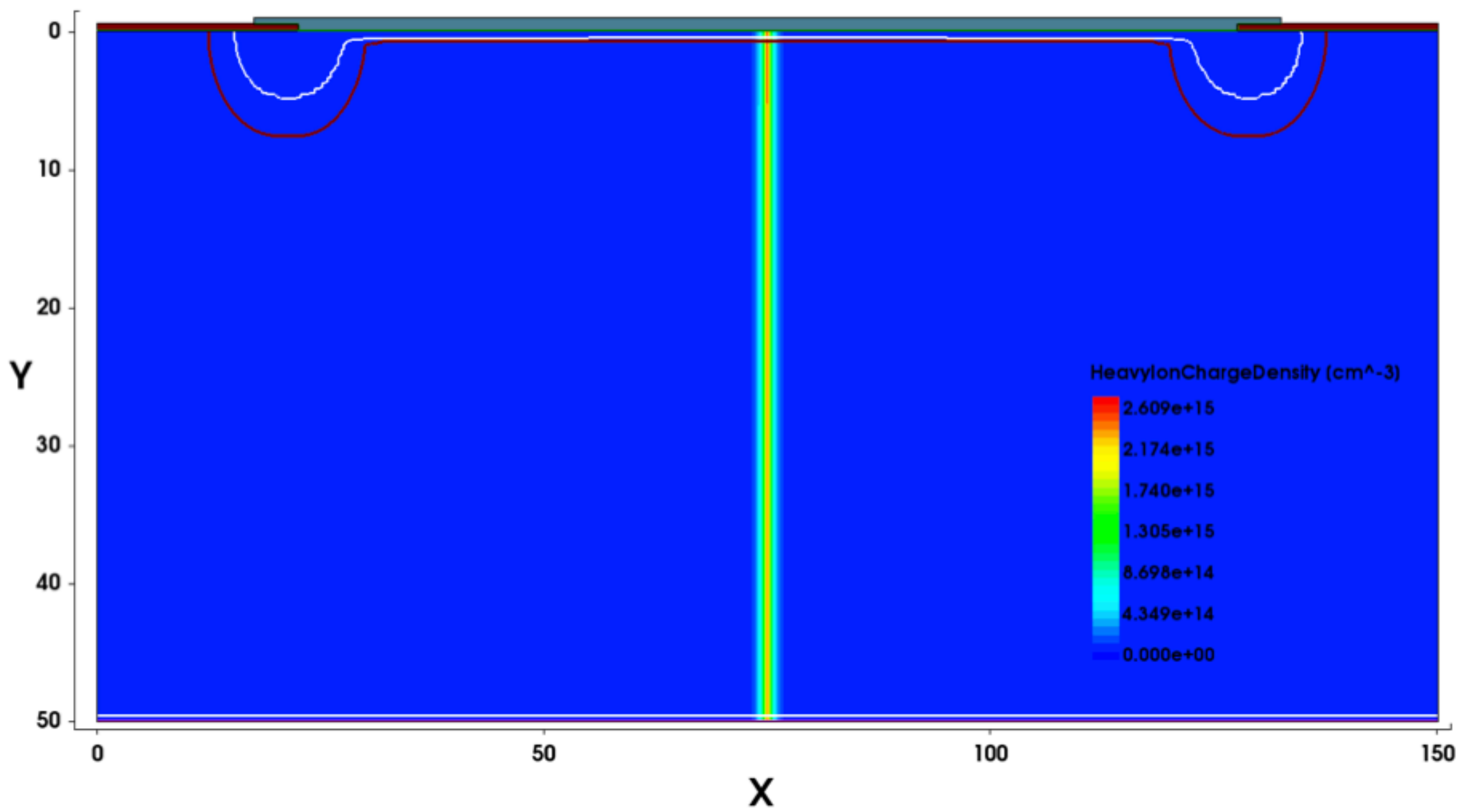
  - Large dynamic range: detect energy deposit from positrons (MiP) & slow pions/muons (non-MiP)

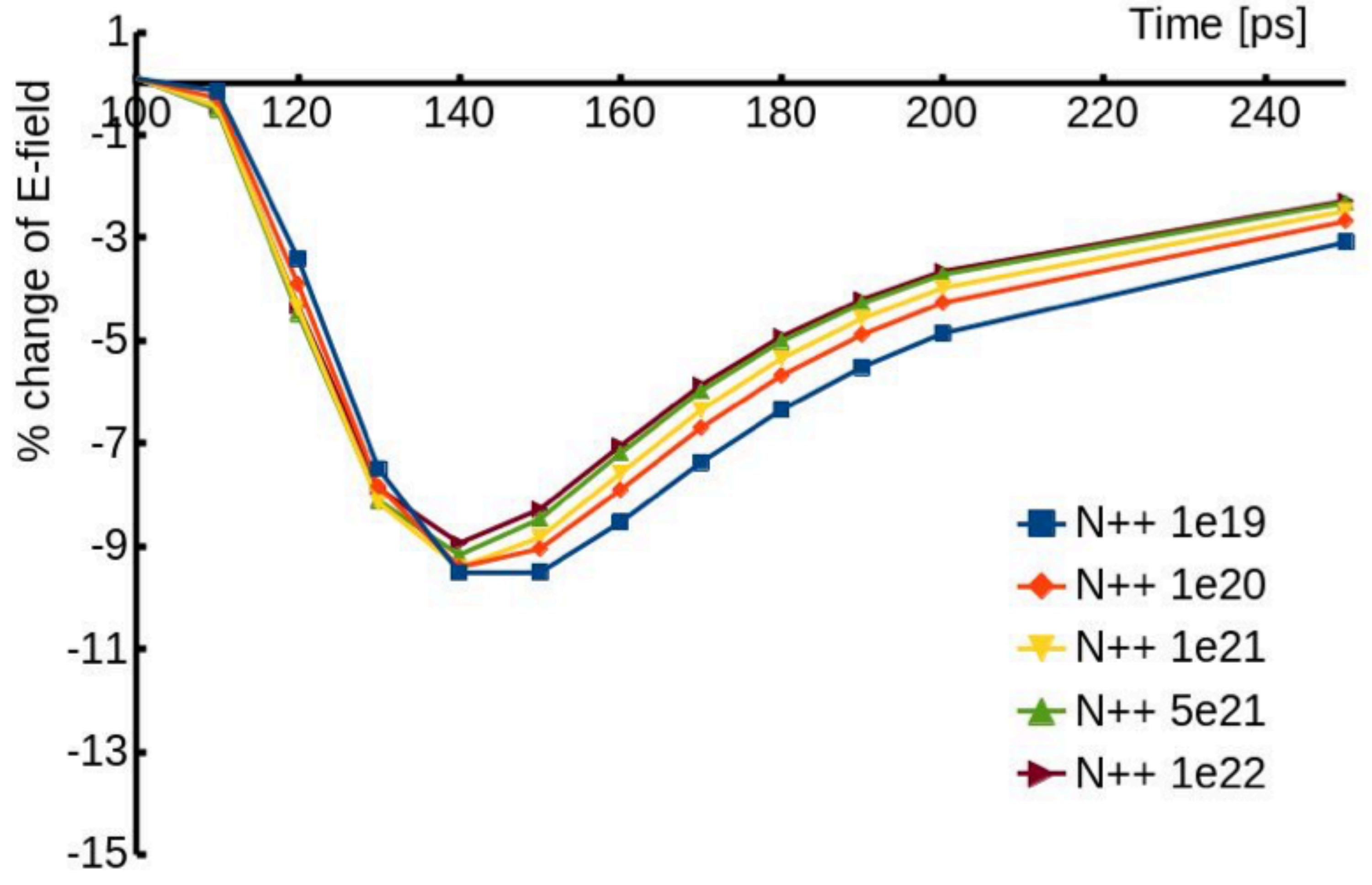
TCAD simulations

- Simulation shows large gain suppression effect with high input charge density
- Gain suppression reduced if input charges are spread even -> less localized
- Gain of LGAD produced by impact ionization in high field region of gain layer
    - Very sensitive to electric field magnitude
    - Study time evolution of electric field within gain layer:
        - Local effect (5um) & recovery time: electric field returns to normal in few hundred ps

-> improve recovery time by draining away charges faster -> can be achieved with increasing conductivity of gain layer ->larger N++ doping

Track of charges

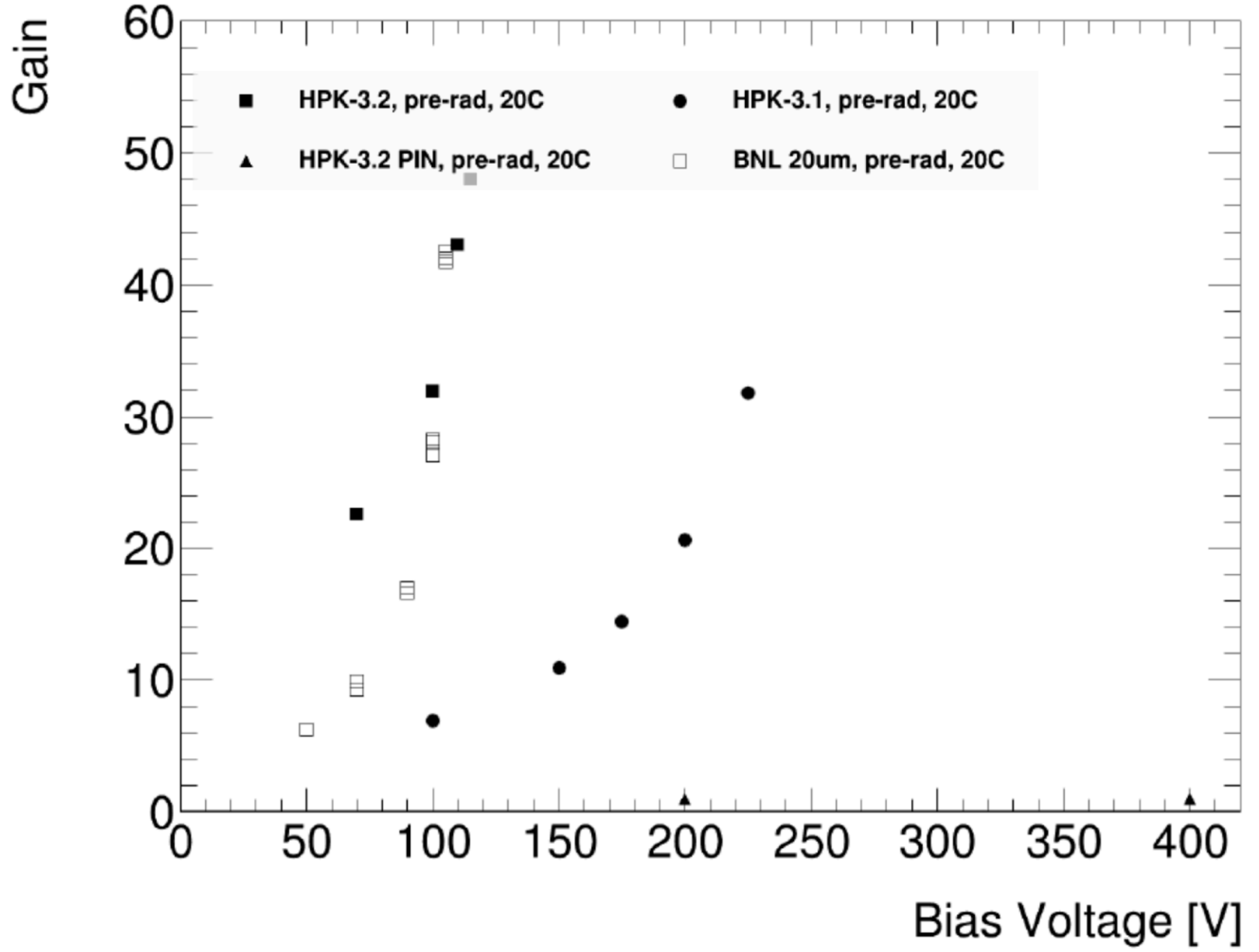


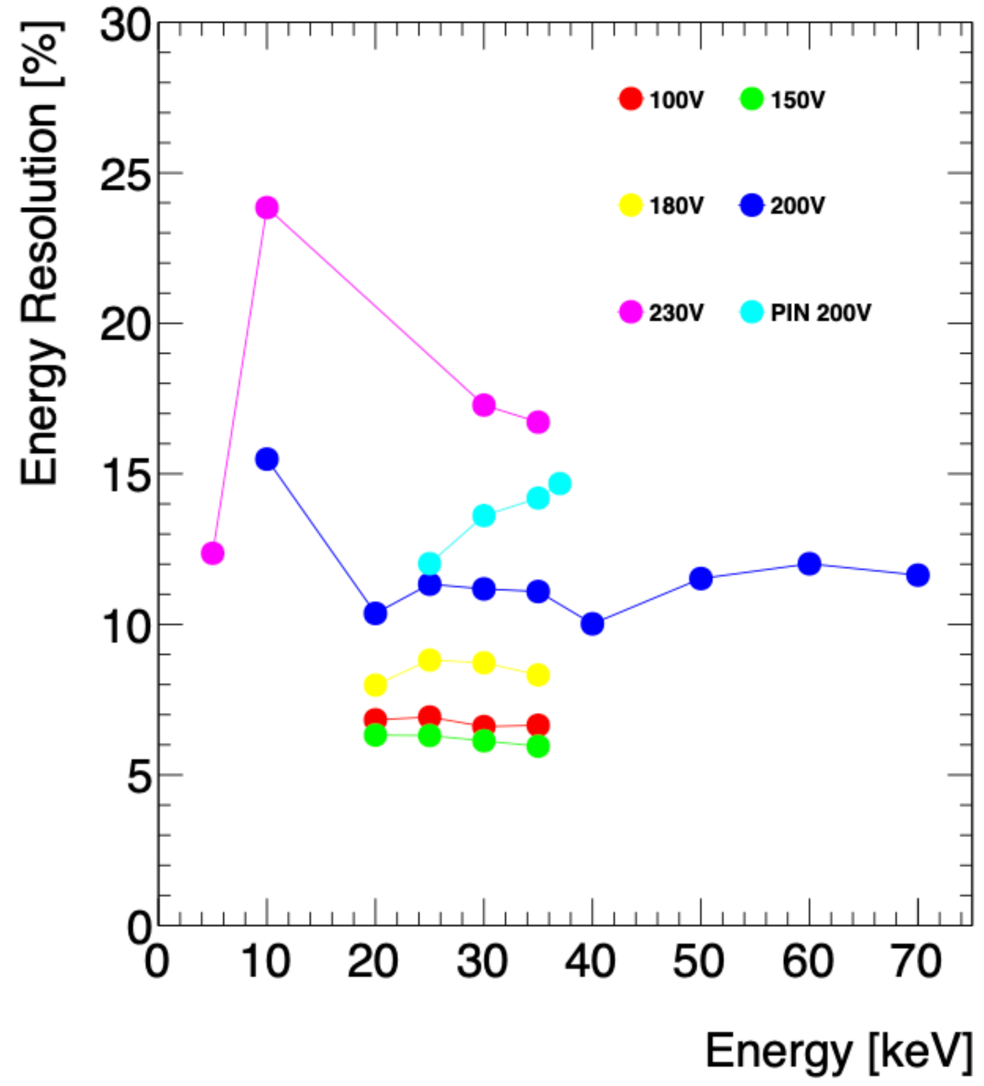


SSRL test beam

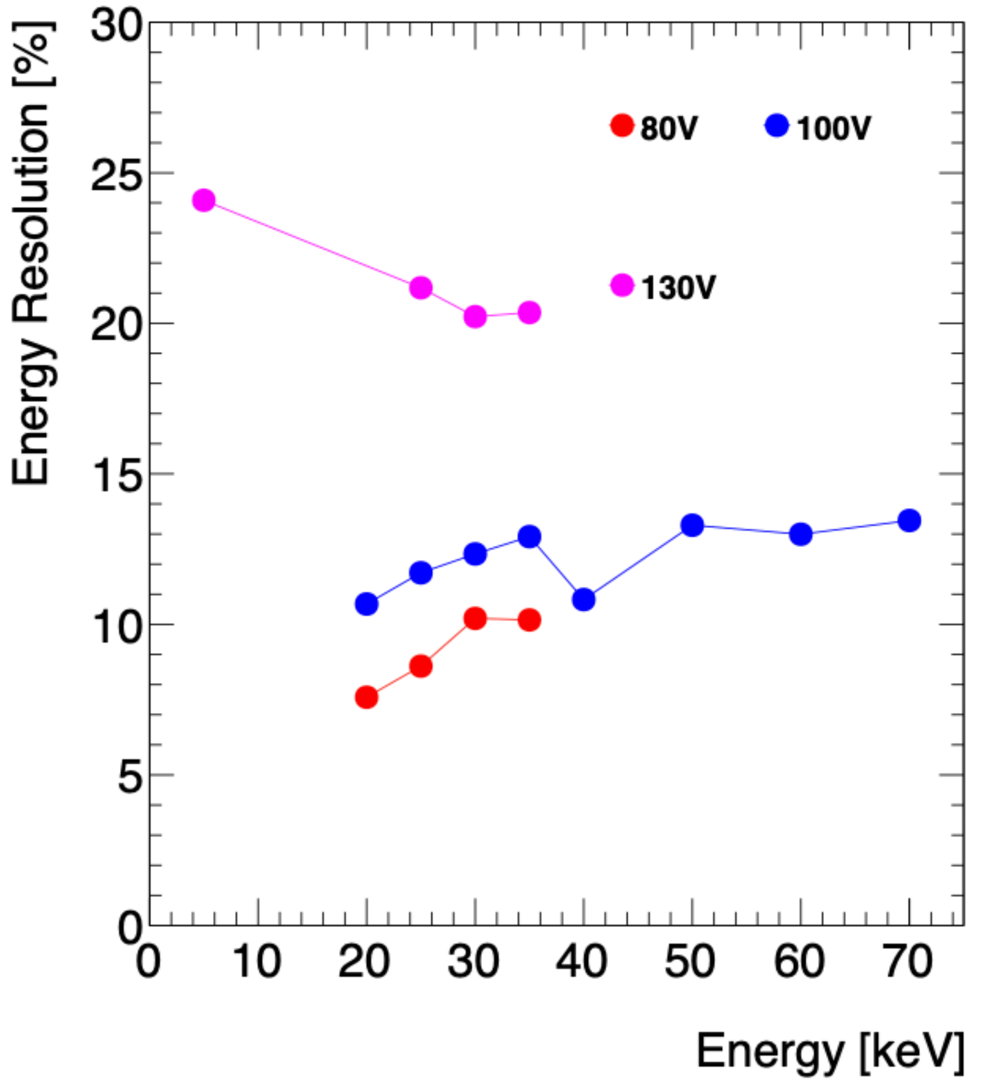
- Study low energy deposits with X-rays with the Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC
- 5-70keV X-rays in air at room temperature
- Simulation:
    - Geant4 for interaction rate with devices
    - TCAD Centaurus for charge collection mechanism of X-ray interaction in sensor
- Measured energy resolution at 20 & 35keV to be ~10% for low gain: 5-15
    - Depends on bias voltage: higher V -> worse resolution
    - The best energy resolution (6%) with LGADs operated at low voltage with gain of ~10
- Also studied linearity of energy response (<4%) & timing resolution
    - Best timing for maximum voltage -> slower drift time

MIP response: Sr 90 beta source with coincidence timing trigger





(a) HPK PIN and type 3.1 LGAD



(b) HPK type 3.2 LGAD

Pre-amp saturates after 100V & 3 MeV: pmax distributions