A High Granularity Timing Active Target for the PIONEER Experiment

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on Behalf of the PIONEER Collaboration

PIONEER Experiment Motivation

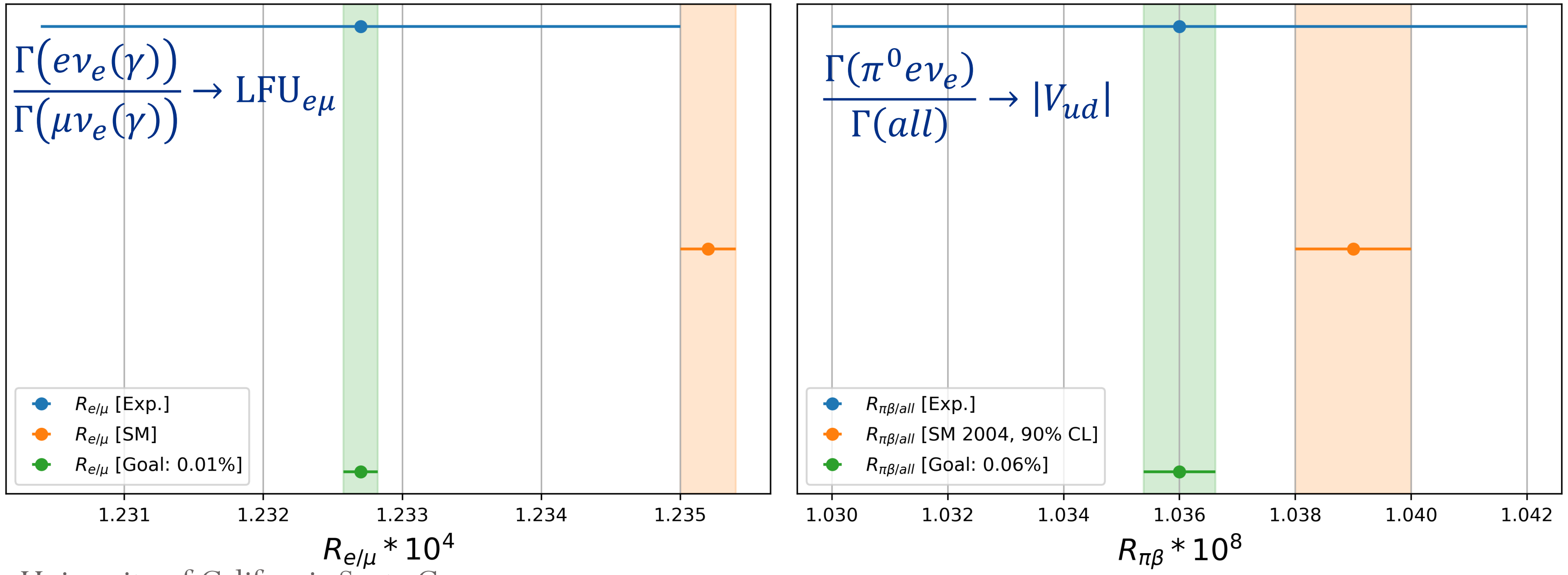
Phase I

- Measure $R_{e/\mu} = \frac{\Gamma(\pi^+ \to e + \upsilon(\gamma))}{\Gamma(\pi^+ \to \mu + \upsilon(\gamma))}$ to unparalleled sensitivity (10^{-4})
- Unprecedented test of Lepton Flavor Universality (LFU) of which there has been hints of violations such as in the g-2 experiment

Phase II + III

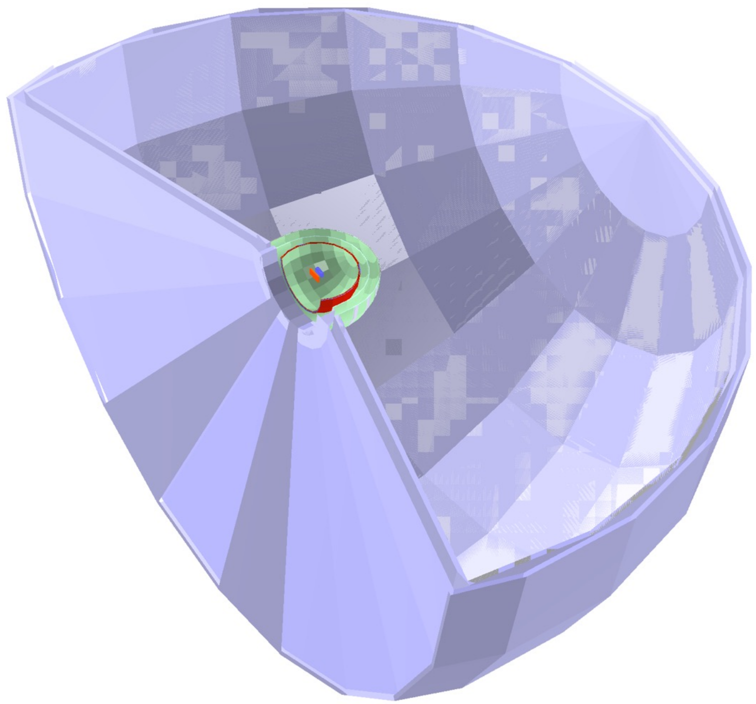
- Measure the branching fraction of Pi beta decay $\frac{\Gamma(\pi^+ \to \pi^0 e^+ \upsilon)}{\Gamma(\text{total})}$ to a higher experimental precision
- Phase II will increase the precision 3x and phase III will increase 10x
- II: Will allow for CKM unitarity test via $\frac{|V_{us}|}{|V_{ud}|}$ currently limited by this branching ratio
- III: Will allow for $|V_{ud}|$ extraction in the theoretically cleanest way

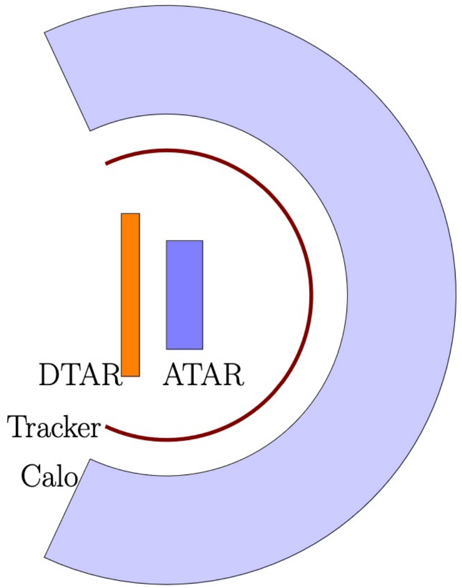
Goals for the PIONEER Measurements



PIONEER Experiment at a Glance

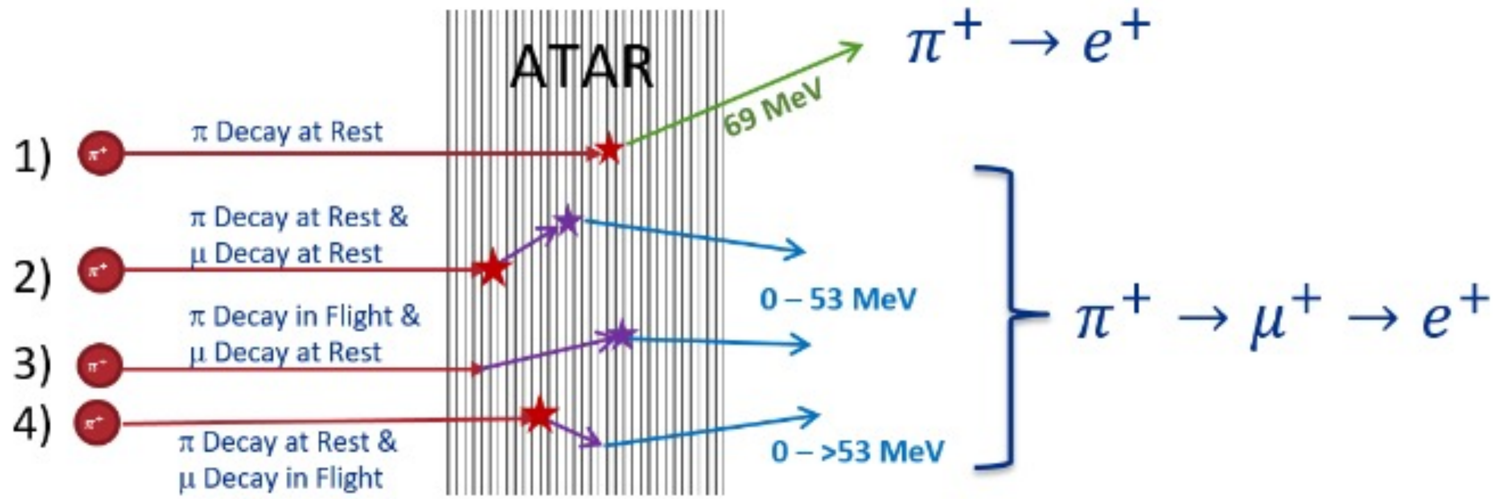
- PIONEER will run in the PiE5 beam line the world's most intense pion beam
- The pions will be degraded by an active likely silicon based Degrading TARget (DTAR)
- In the center of the experiment a silicon based Active TARget (ATAR)
- MPGD based tracker
- Calorimeter either LYSO or Liquid Xenon





PIONEER's ATAR

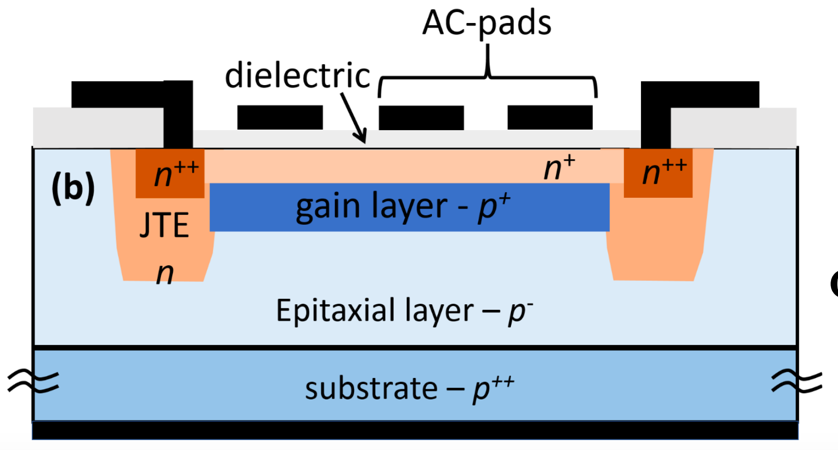
- The center of the PIONEER experiment will be instrumented with a highly granular active target that will be used primarily for event identification
- ATAR will differentiate the two-stage dominant kinked decay of the pion to muon background from the monoenergetic single stage decay of the pion to an electron
- 5-dimensional tracking (3 dimensions of space, time, and energy) will be necessary to instrument the ATAR
- High rate and large dynamic range environment going from 1 MIP (e^+) to 100s of MIPs (μ^+ and π^+)



PIONEER's Four Dominant Decay Modes (3 of background 1 of signal)

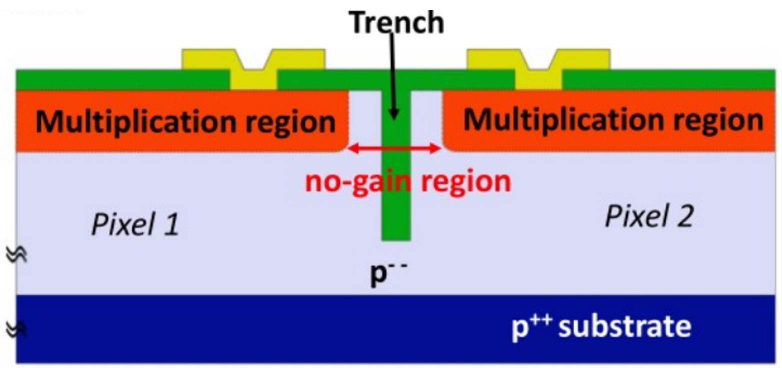
Silicon Sensor Breeds and Challenges for PIONEER

- 1.25 fc (7800 e^-) for the minimum ionizing particle (MIPs) traveling through 120μm thick silicon
- Nominally, the ATAR will have 48 layers of 120μm thick 200μm pitch silicon sensors
- Each LGAD type has its own challenges and advantages
- Additionally, a traditional Silicon PiN diode sensor is being considered as an alternative design to an LGAD sensor



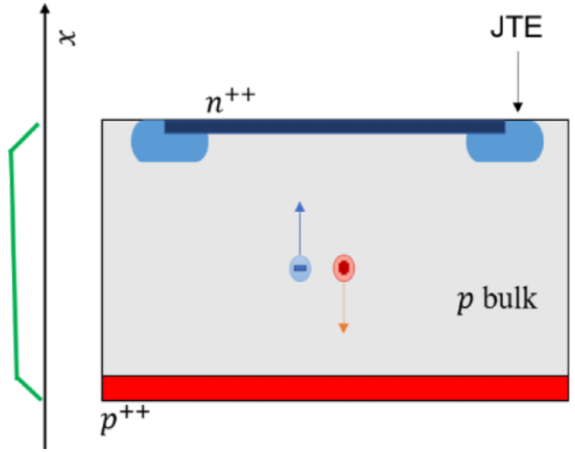
AC-LGAD

Or



TI-LGAD

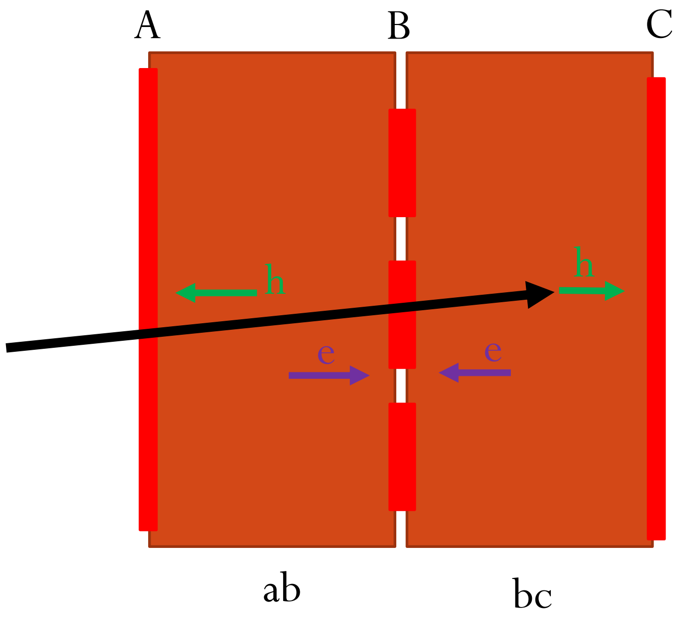
Or



PiN

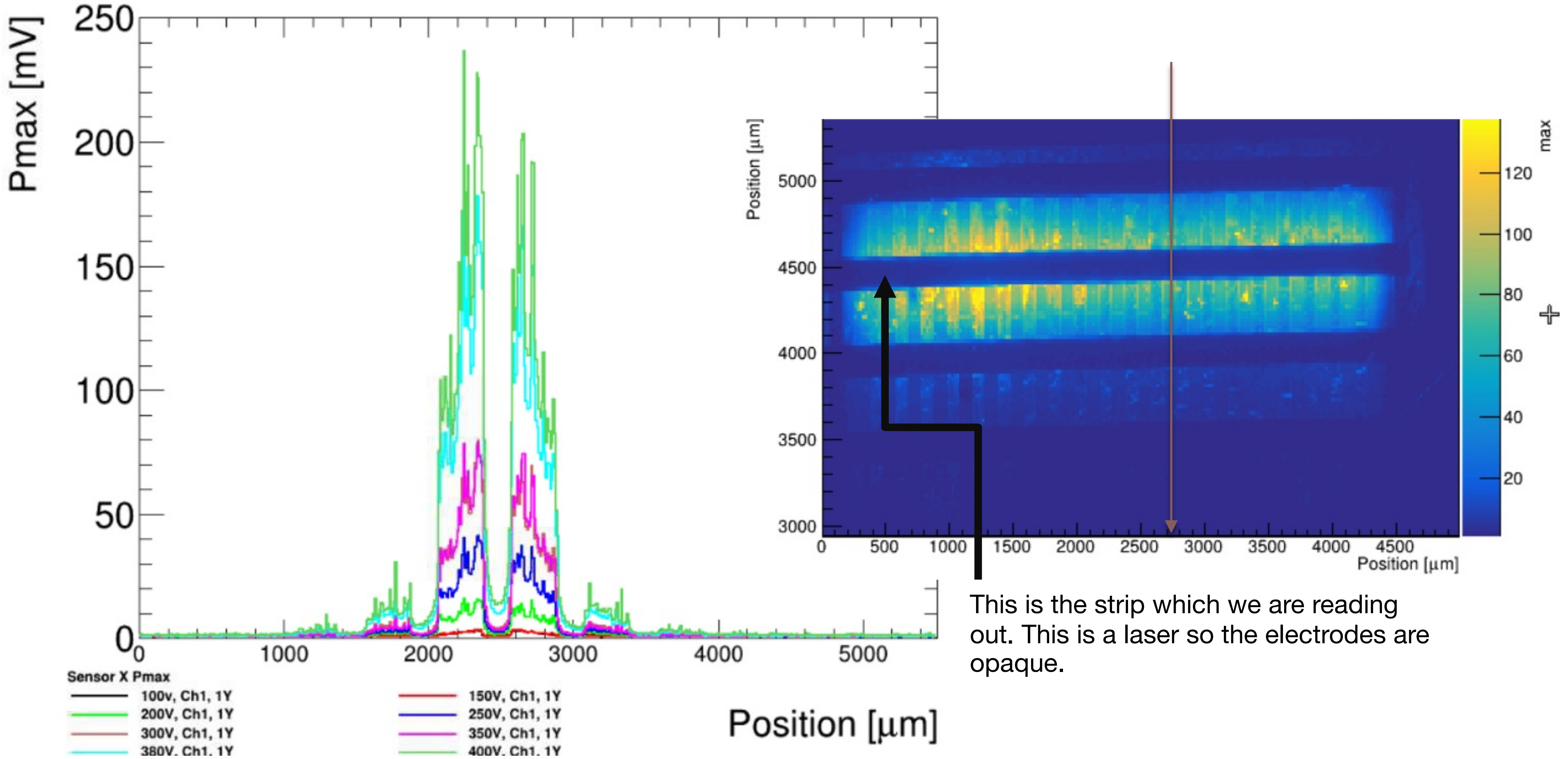
Double Sided Variant

- Another technology being considered for the PIONEER experiment are double sided silicon detectors (developed at BNL) can either be LGADs or PiN type sensors
- This would allow for x and y directionality in one layer of the ATAR and minimization of dead material
- First prototype Sensors from BNL are being studied at SCIPP
- Reduction of nominal 25μm air gap (aiming to be below 5μm)



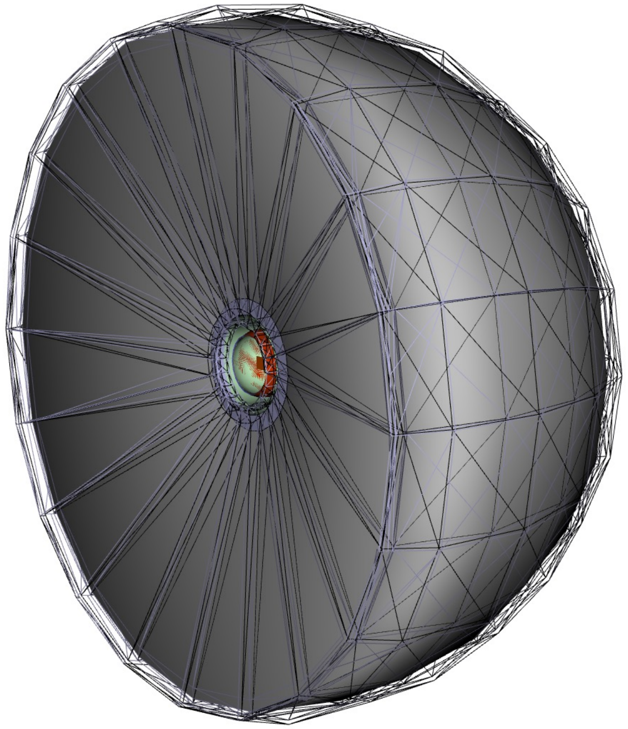
BNL Double Sided AC/DC Laser Studies

- Nonuniformities in the response potentially from reflections on the backplane either from DC strips or conducting tape
- Low amount of sharing to neighboring strips

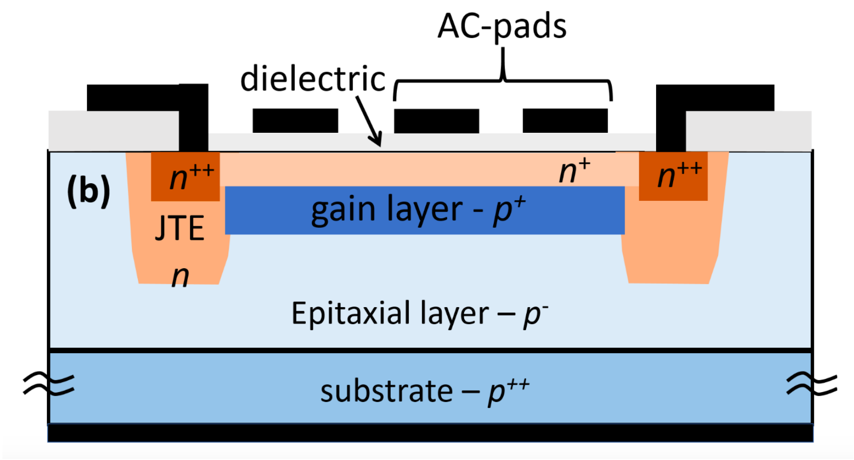


PIONEER ATAR Simulation

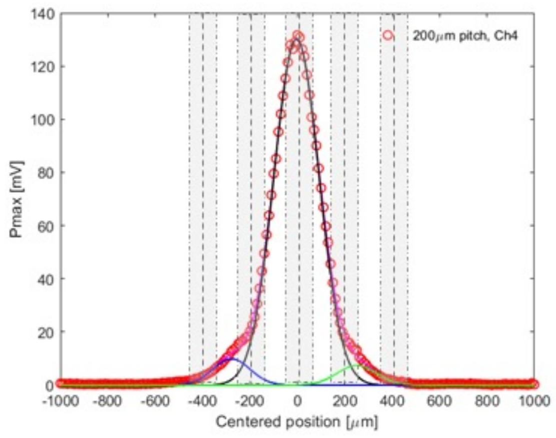
- As the burgeoning collaboration is in its infancy stage it is imperative to understand the capabilities of the ATAR given these different sensors in simulation
- The unique challenges of the experiment call for a minimization of dead material and a robust understanding of all of the detector elements
- We are using the simulation to study the following elements amongst others:
  - Dead Material
  - Energy Resolution
  - Bulk Thickness
  - Position Resolution including AC-LGAD charge sharing reco
  - TI-LGAD trenches
  - Pulse Separation Resolution
  - Strip Pitch
  - Double Sided Readout
  - Cross Talk
  - Hit Time Resolution



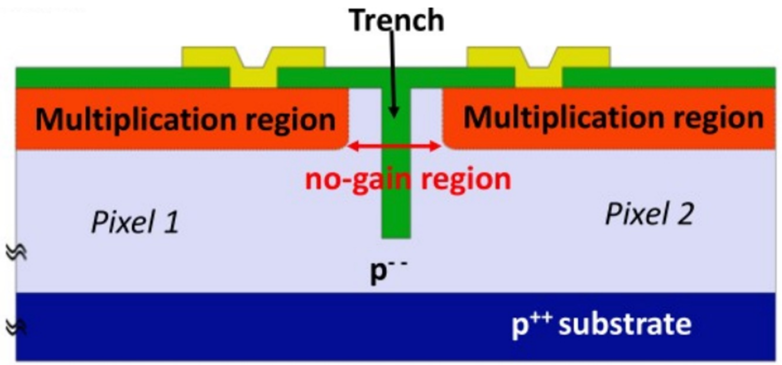
PIONEER Simulation Work- Detector Response



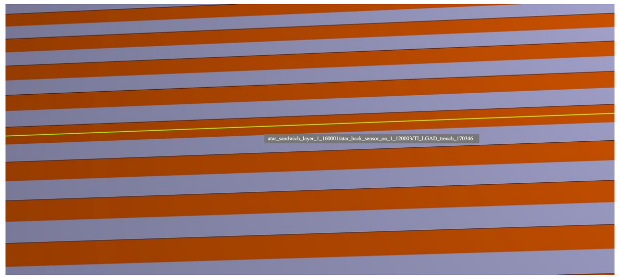
AC-LGADs exhibit a mechanism known as charge sharing. Currently implementing a charge sharing model in the simulation.



Triples Gaussian charge sharing model currently being implemented for PIONEER



TI-LGADs have trench regions of no gain.

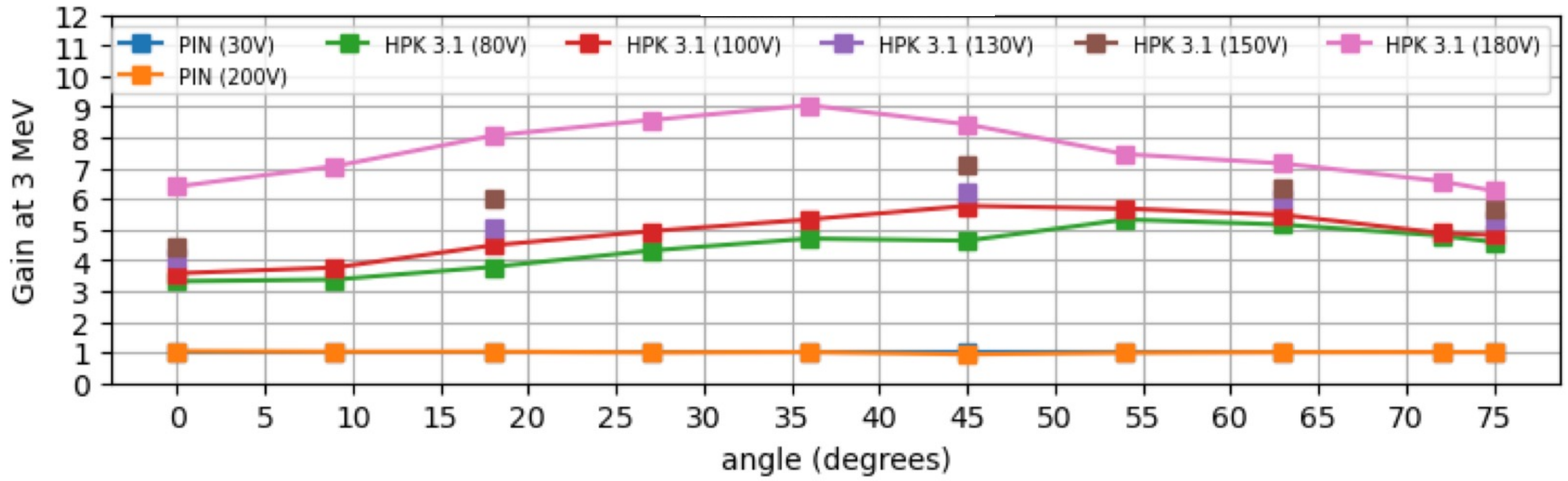


Implemented TI-LGADs into the PIONEER simulation by a geometry only approach. Trench regions considered dead material.

Gain Saturation

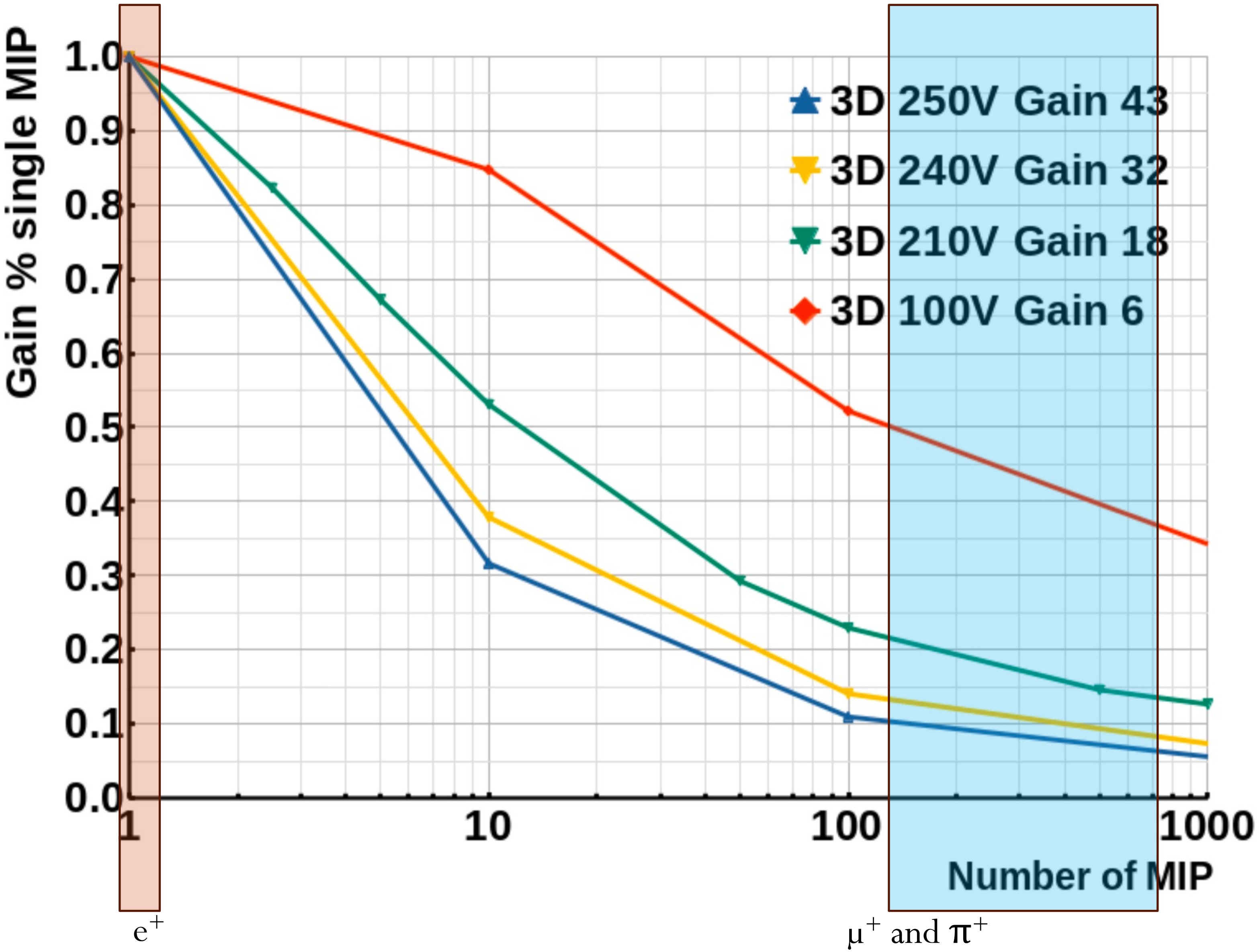
- For the PIONEER experiment it will be critical to differentiate the ionization deposit differences of positrons, muons, and pions
- LGADs exhibit the behavior of gain suppression where the space charge cloud reduces the amplification field
- It is crucial that PIONEER is able to unfold the non linear gain saturation response of the LGADs in the ATAR

3 MeV Protons from CENPA Tandem Accelerator



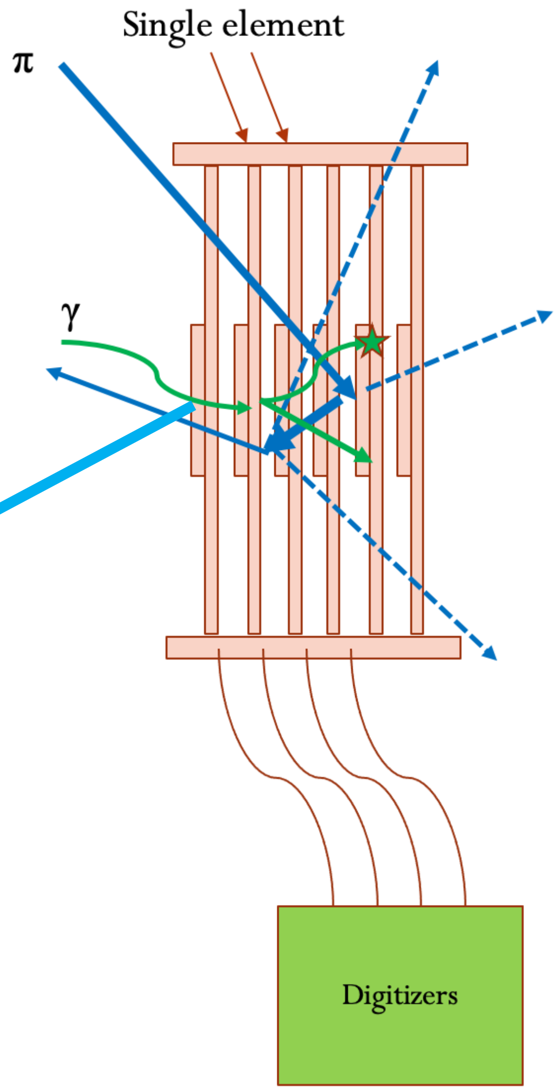
Gain Saturation in Simulation

- Lower gain reduces the gain saturation effect
- Moving towards lower gain nominal design

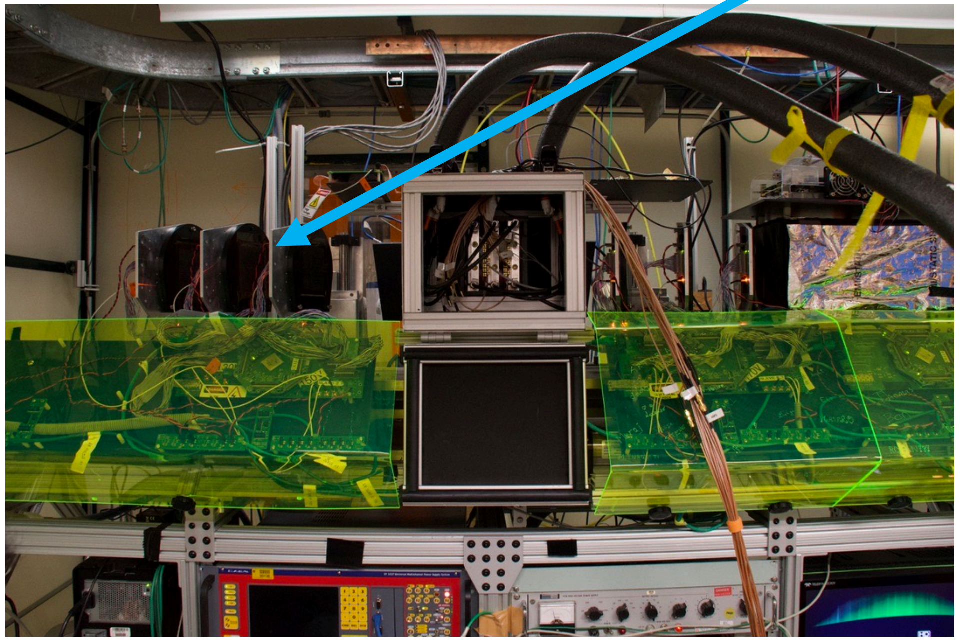


Generalizing to a 5D Tracker

- The future of many fields of physics instrumentation require test beam experimentation
- Growing need for high rate studies with great spatial and timing precision

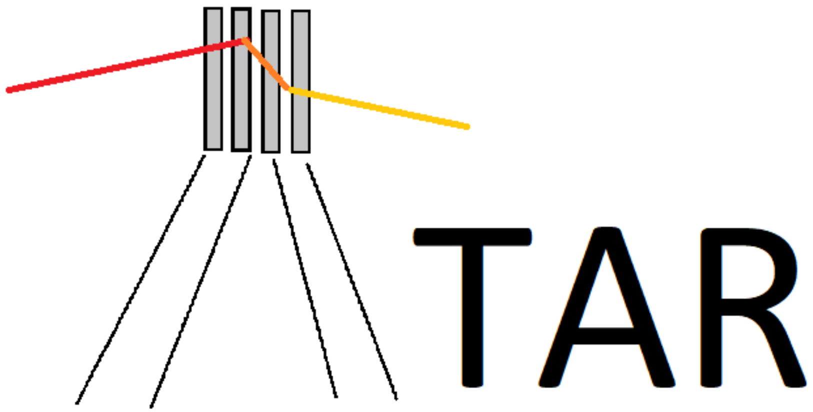


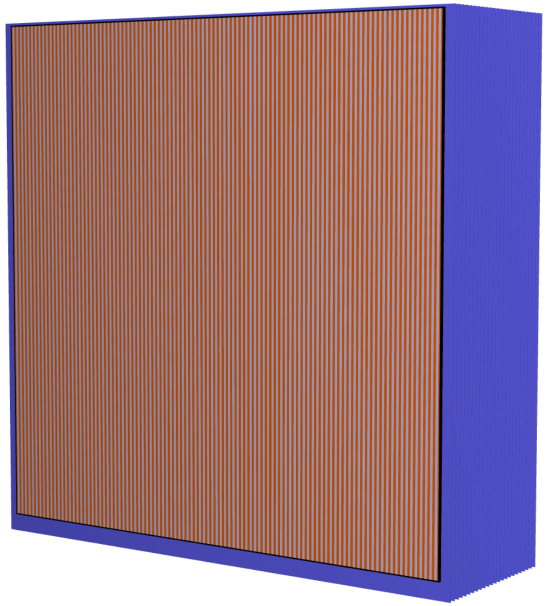
- The PIONEER ATAR can be straightforwardly generalized to a setup that can be input into dozens of test beams facilities throughout the world
- Giving excellent spatial granularity, spectacular timing response, good energy resolution, and high dynamic range



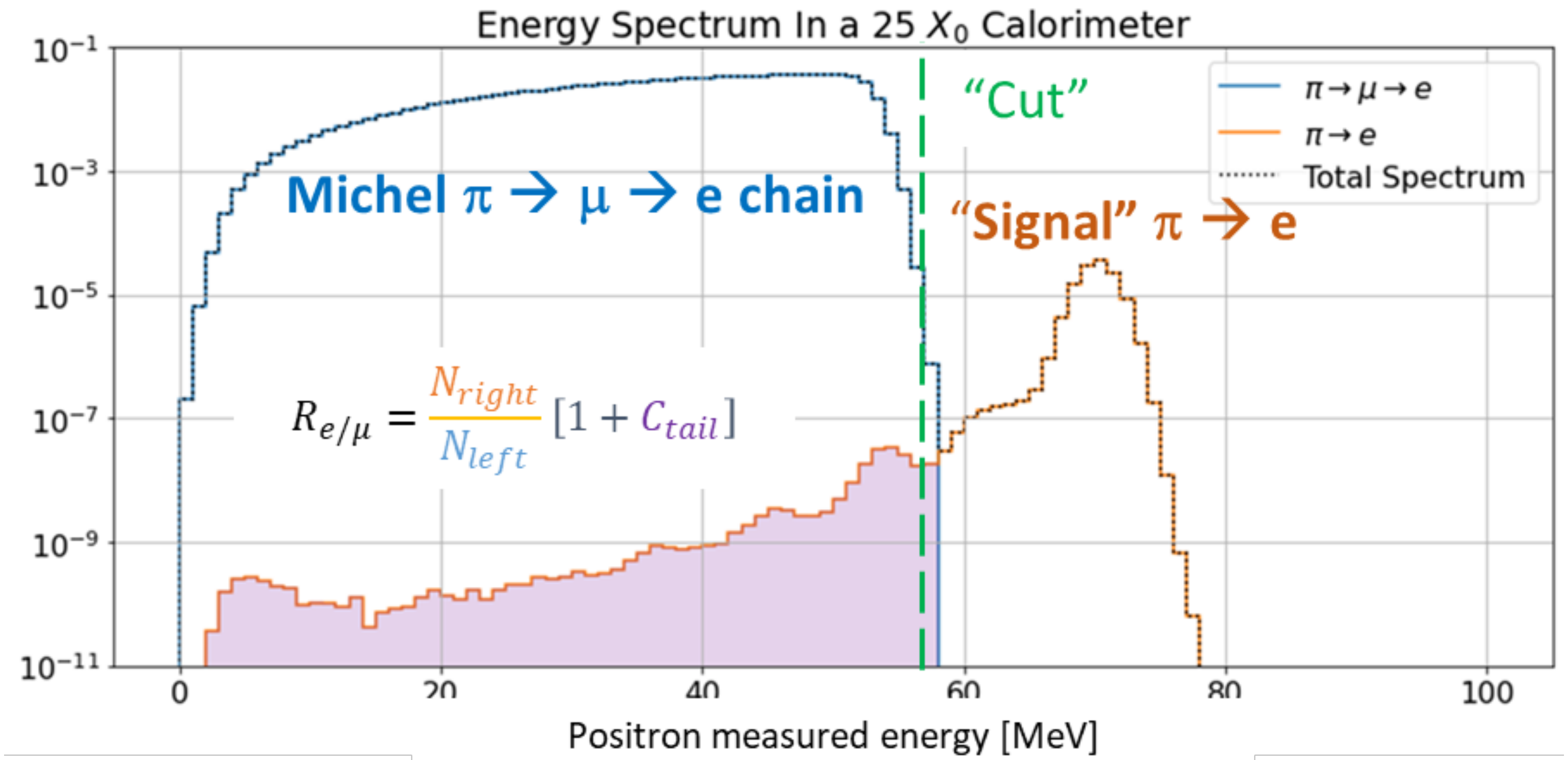
Conclusions

- PIONEER is an exciting experiment probing many hot physics topics to an extreme precision (LFU violation, exotic searches, and PiBeta)
- The ATAR is an ambitious detector requiring much research and development and will be a particularly challenging system integration problem
- ATAR has many design choices that need to be answered through simulation: silicon sensor type, double sided sensors, dead material, etc.
- Once completed the ATAR can be generalized to upgrade existing test beam facilities





Back Up



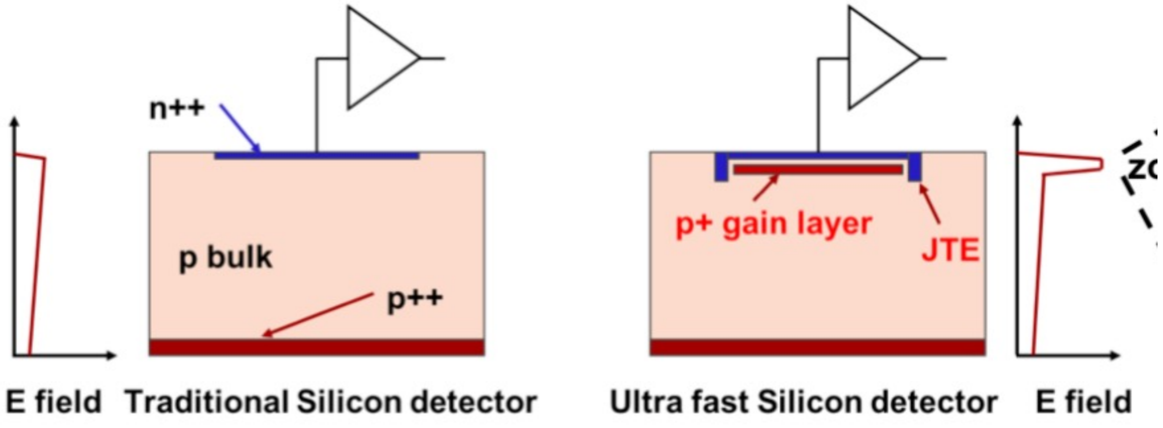
Energy Spectrum In a 25 X_0 Calorimeter
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
0
20
40
60
80
100
Positron measured energy [MeV]
"Cut"
$\pi \rightarrow \mu \rightarrow e$
$\pi \rightarrow e$
Total Spectrum
Michel π → μ → e chain
"Signal" π → e
$R_{e/\mu} = \frac{N_{right}}{N_{left}}[1 + C_{tail}]$

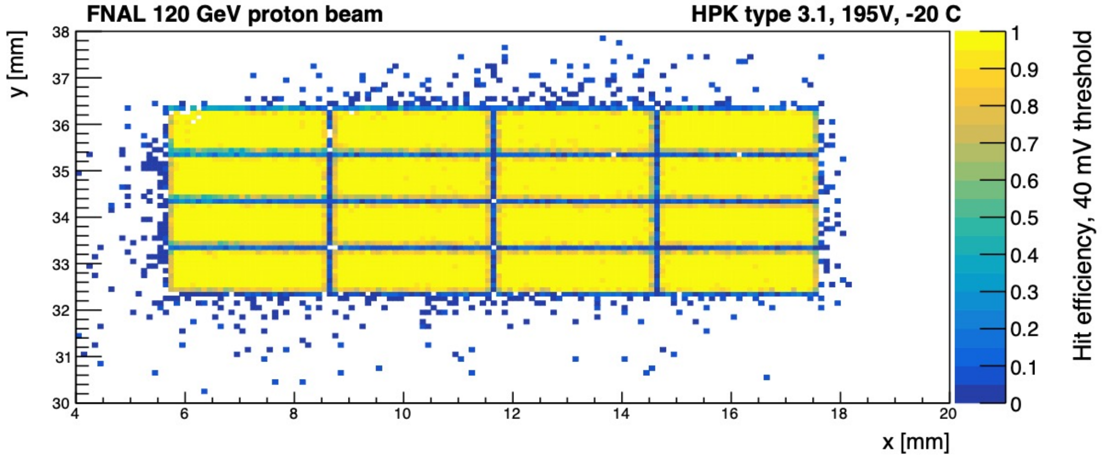
Mode			Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\mu^+\nu_\mu$	[1]	$(99.98770 \pm 0.00004)\%$		30
Γ_2	$\mu^+\nu_\mu\gamma$	[2]	$(2.00 \pm 0.25) \times 10^{-4}$		30
Γ_3	$e^+\nu_e$	[1]	$(1.230 \pm 0.004) \times 10^{-4}$		70
Γ_4	$e^+\nu_e\gamma$	[2]	$(7.39 \pm 0.05) \times 10^{-7}$		70
Γ_5	$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
Γ_6	$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
Γ_7	$\mu^+\nu_\mu\nu\bar{\nu}$		$< 9 \times 10^{-6}$	CL=90%	30
Γ_8	$e^+\nu_e\nu\bar{\nu}$		$< 1.6 \times 10^{-7}$	CL=90%	70

From the PDG

LGAD Technology

- LGADs or Low Gain Avalanche Detectors are a next generation silicon detector technology that improves the timing capability of silicon detectors by adding a region of high gain amplifying intrinsically fast but small signals
- Timing resolution of O(10ps) and spatial resolution (10μm)
- Major downfall of traditional LGADs is the necessity of terminating junction extensions for the high field implants reducing fill factor



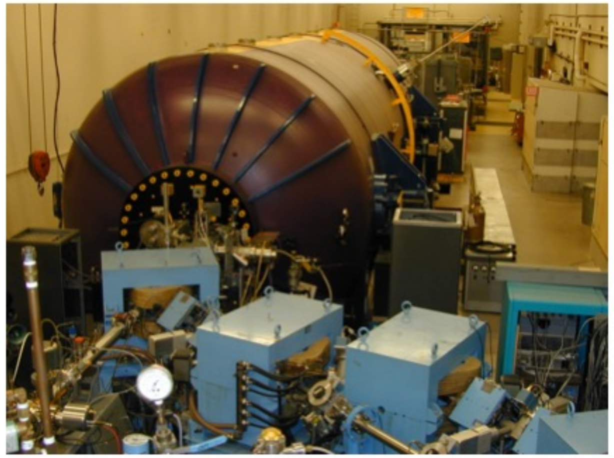


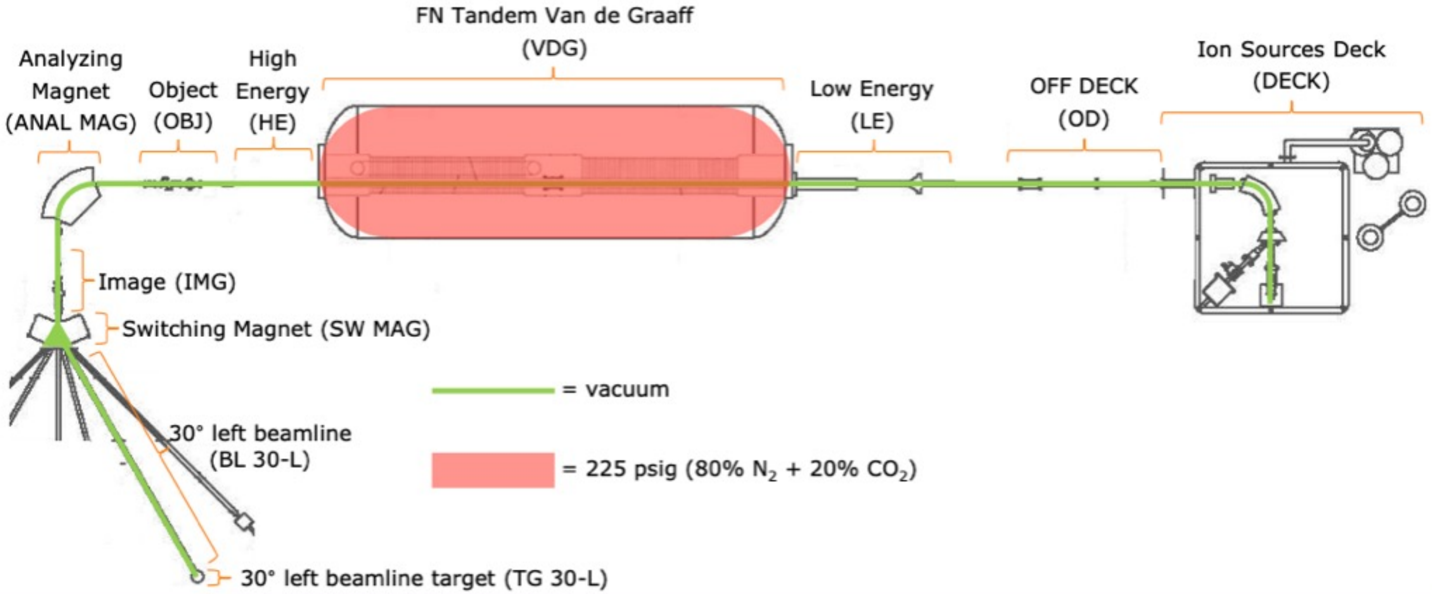
Efficiency plot showcasing LGAD fill factor

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





Credit to Svende Braun

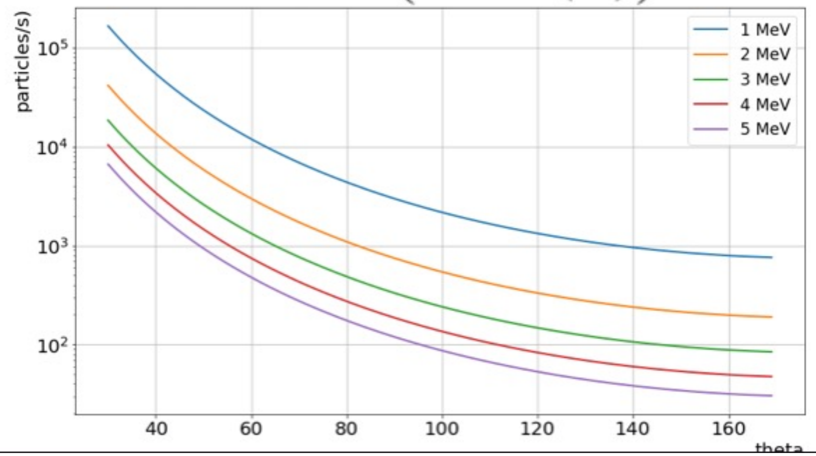
Rutherford Backscattering SpectrometryBS

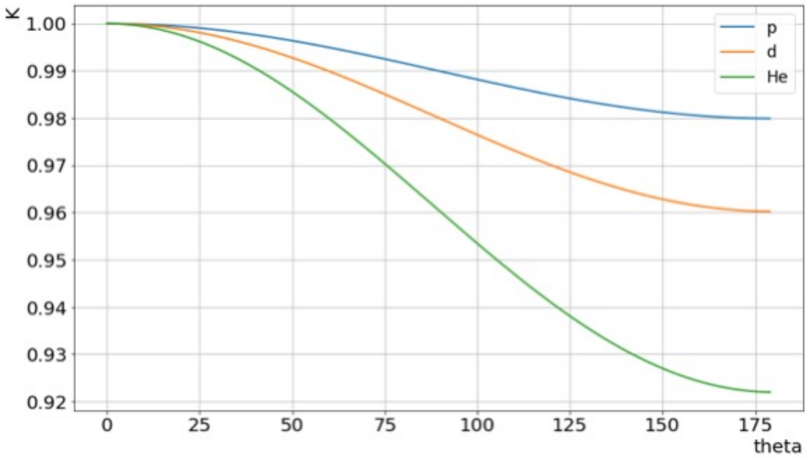
- Proton beam hits gold foil target, scattering of beam into detector -> to avoid direct beam on target

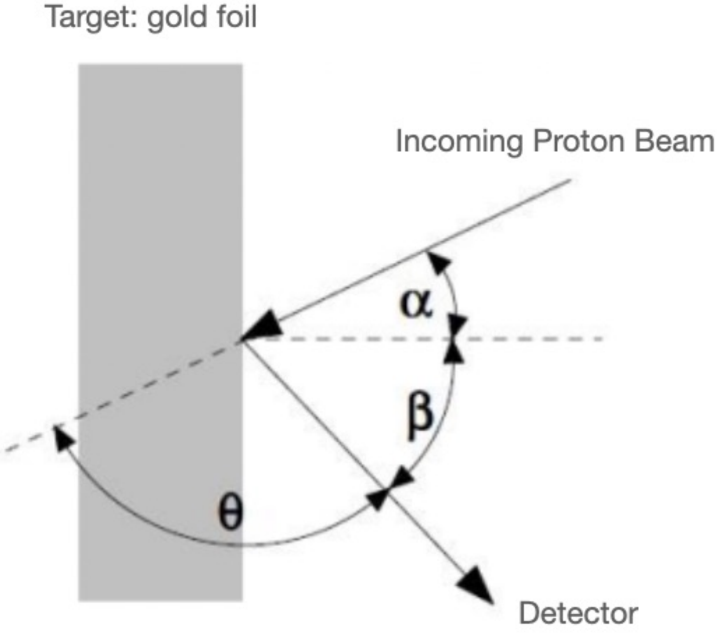
- Kinematic factor k: $$k = \frac{E_1}{E_o} = \left[\frac{\left(M_2^2 - M_1^2 \sin^2\theta\right)^{1/2} + M_1 \cos\theta}{M_2 + M_1} \right]^2$$

- Scattering cross section:

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







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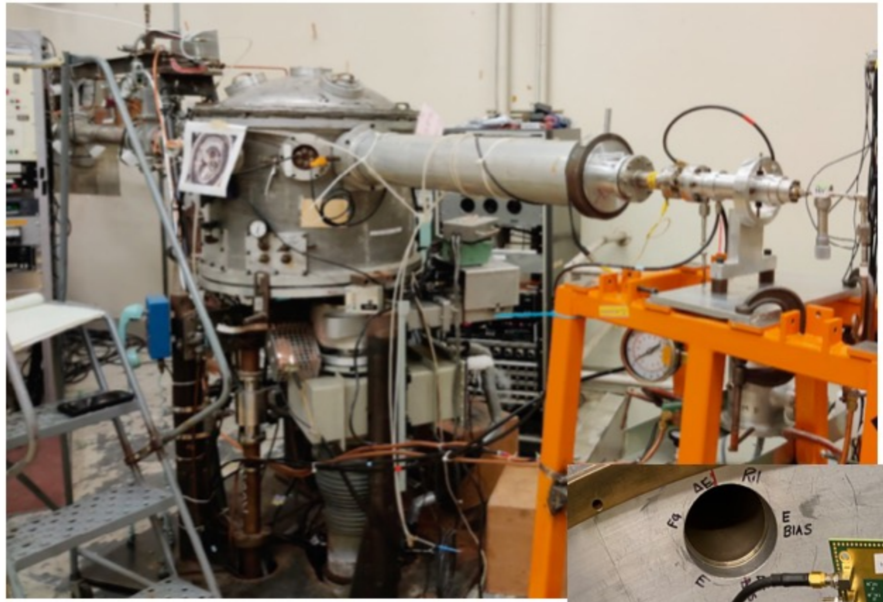
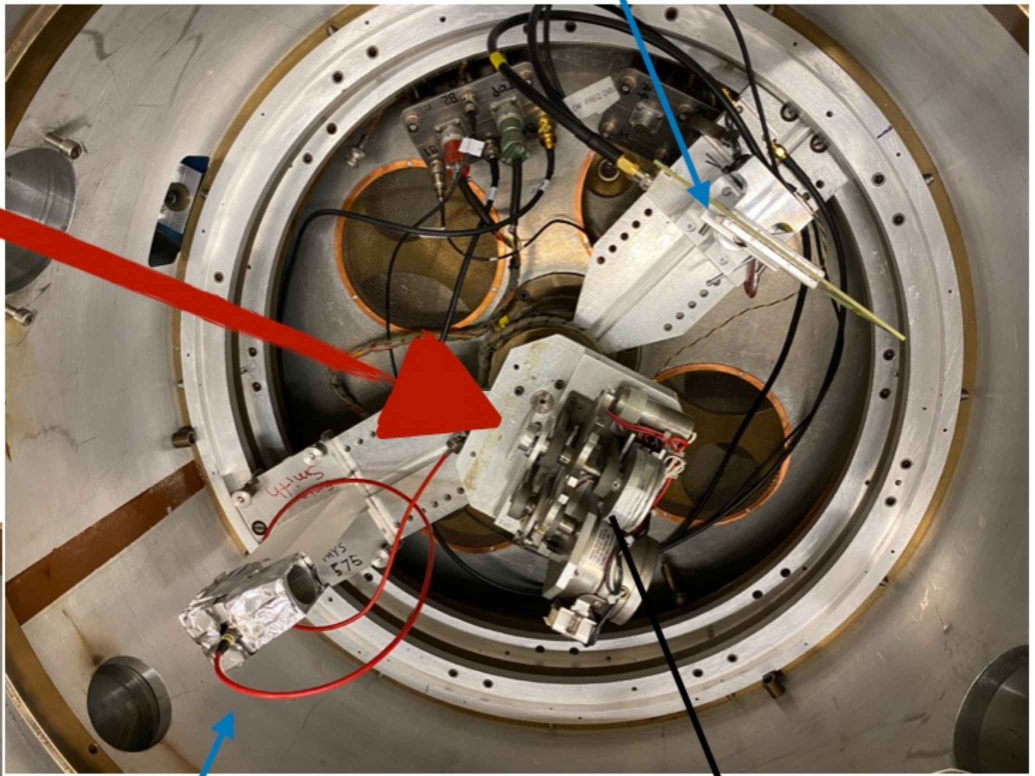
Experimental setup

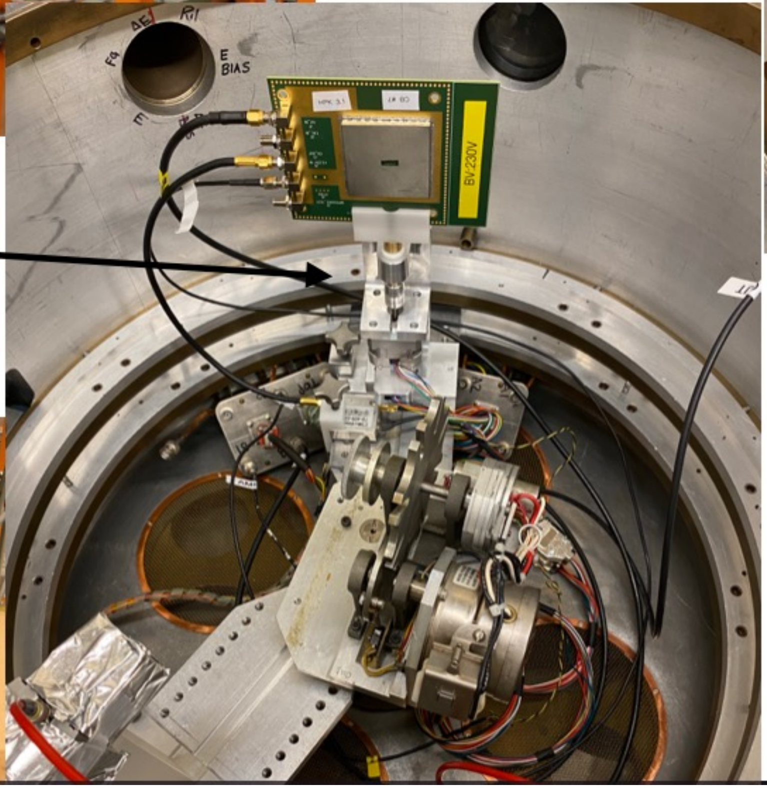


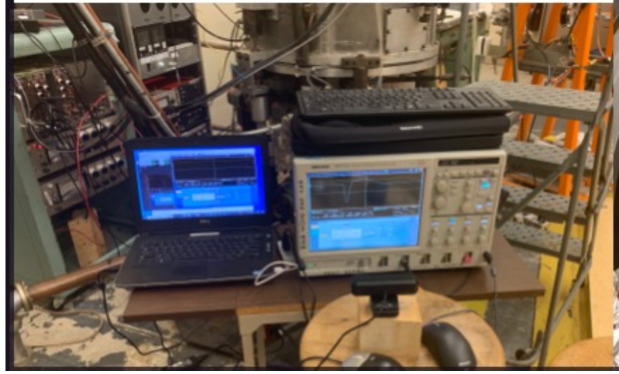
Proton BEAM

LGAD detector



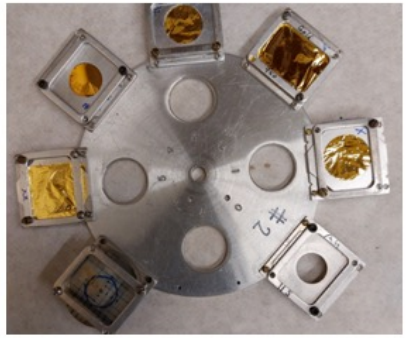
Mounted on rotation device:
Stepper motor to change
Detector angle wrt scattered beam





Eric's PIPS detector

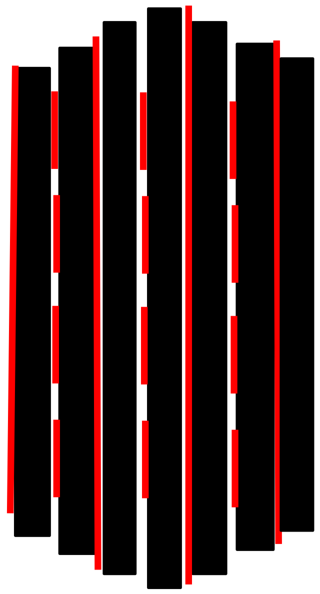
Target gold foil



Credit to Svende Braun

Concept of Alternative Design (v2.0)

- Two adjacent layers shared the same readout strips (N --anode or P -- cathode)
  - 48 layers → 49 x 100 channels (100 channels more than default)
  - 2-sided readout for each layer
  - Minimize both C_{in} and C_{ct}
  - Eliminate the gap/dead materials → 1-2 um?

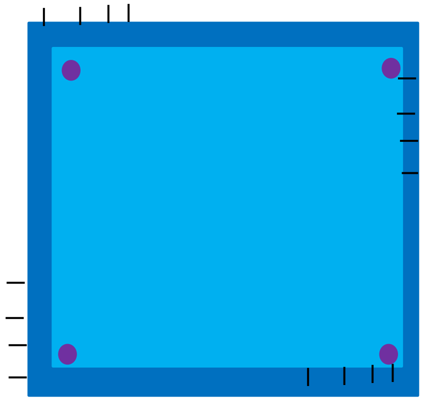


Bulk (120 um)

Readout strip (200 um pitch, 100 width)

Layers are gradually increased/decreased, so that we can readout from the sides

- Each side has about 12 (13) readout cables, separated by ~ 0.5 mm



1f → readout right

1b/2f → readout top

2b/3f → readout left

3b/4f → readout bottom

4b/5f → readout right

Anchoring points?

Mini-Unit: Pyramid Shape (Yichen)

- Base substrate size 2.11 cm x 2.11 cm x 120um, metal layer thickness 2um
- Guard ring at the edge: 0.5 mm
- Strip width: 100 um
- Gap between strips: 100 um
- Strip length: 1.99cm, 1.86 cm, 1.73 cm, 1.60 cm
- # of strips: 100, 94, 87, 81
- Strip Readout wire simulated at the end of each strip with 10 um wire size for demo, height ~ 0.5 mm