12–16 December 2022

La Fonda Hotel | Santa Fe, New Mexico, USA

TOPICS:
Pixel detectors in nuclear and particle physics, astrophysics, bioscience, and x-ray science, with emphasis on pixel sensor technology and device design, front-end readout electronics, radiation effects on devices, mechanics and integration, calibration, and data processing.

PIONEER

SCIPP
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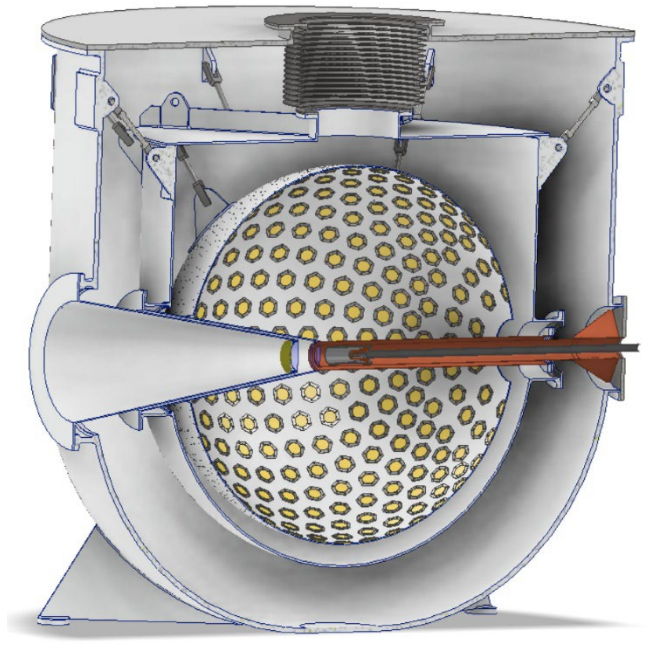
# An LGAD-based fully active target for the PIONEER experiment

**Dr. Simone M. Mazza** (UCSC) on behalf of the **PIONEER** collaboration

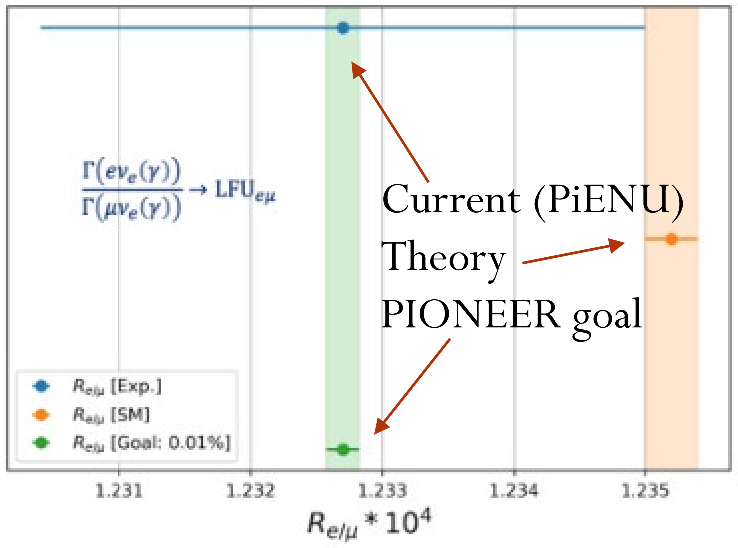
PIXEL 2022, Dec. 2022, Santa Fe, NM (US)

# PIONEER

- **PIONEER** is a next generation rare Pion decay experiment
  - Measurement of **charged lepton flavor universality $R_{e/\mu}$** : $\frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$
  - Ratio of pion decay to electrons and muons
  - Improving the **precision** from past experiments by an order of magnitude, making it **comparable with SM calculation** (a deviation would point to LFUV)
- Further physics goals
  - Increase precision by an order of magnitude of **Pion beta decay branching fraction $R_{\pi\beta}$**: $B(\pi^+ \to \pi^0 e^+ \nu)$, theoretically cleanest measurements of Vud
  - These measurements are sensible to new physics up to thousands of TeV
  - Searches for exotic physics (e.g. Axion-like particles)
- PIONEER will take place at PSI (Switzerland), πe1 or πe5 BLs
  - Proposal approved with high priority by the PSI committee in 2022
  - **Phased effort**: Phase I aimed at $R_{e/\mu}$ and phase II/III aimed at $B(\pi^+ \to \pi^0 e^+ \nu)$
- PIONEER encompasses groups from PIENU, PiBeta, muon g-2, ATLAS and it's a steadily growing collaboration (see https://arxiv.org/abs/2203.01981)
  - First PIONEER workshop at UCSC in Oct 2022: https://indico.cern.ch/event/1175216/

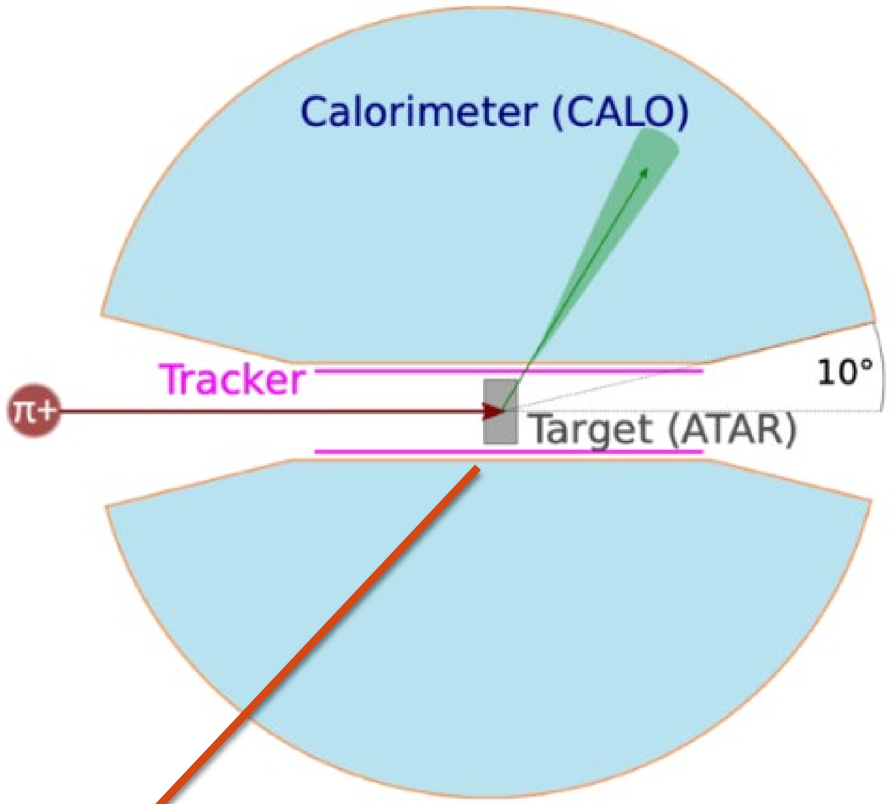


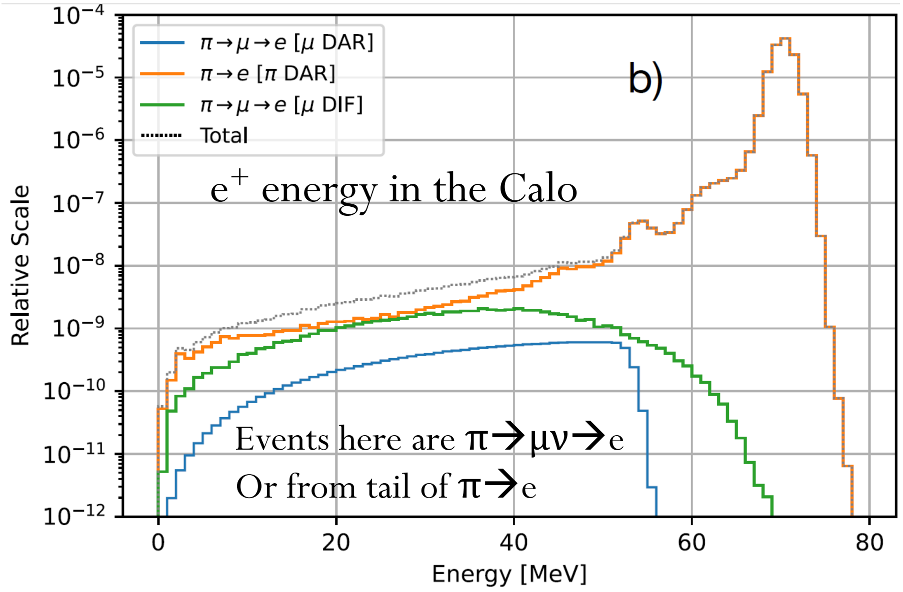
https://arxiv.org/abs/2203.01981

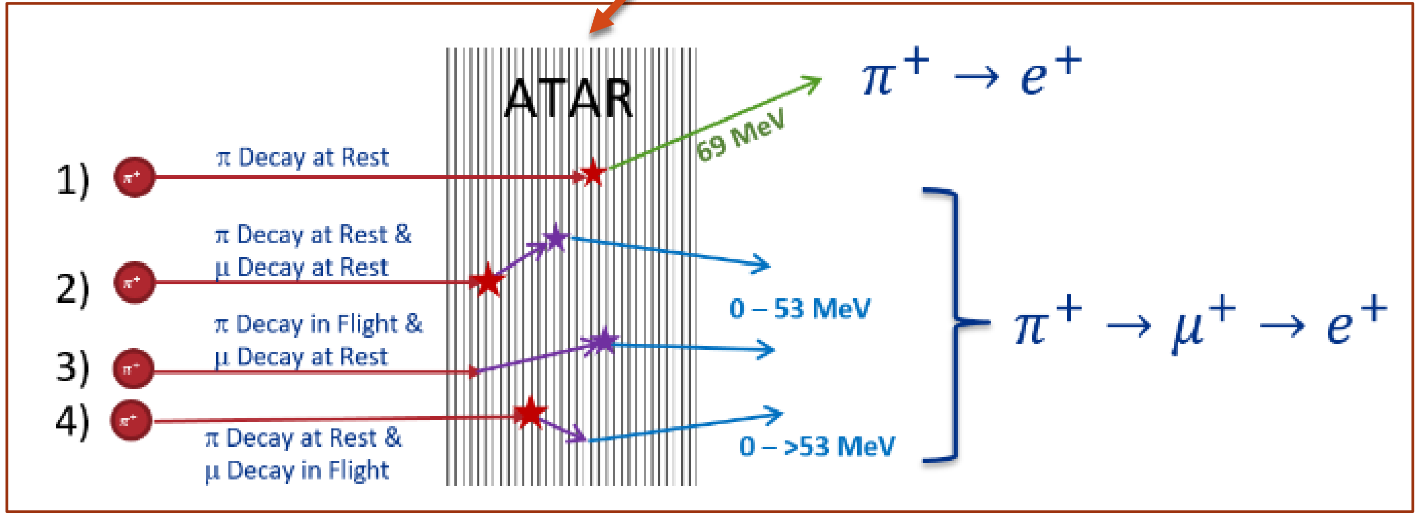


# PIONEER detector design

- **Three main detectors**:
  - **Active Target (ATAR)** with fast timing and high segmentation to identify and tag decays
  - **Calorimeter** with high energy resolution (1%) and 25 $X_0$ (**liquid Xe** or LYSO alternative)
  - **Low mass tracker** (μ-RWELL) in between to track positrons
- **Goal (phase I): separation of energy spectra of π→eν and π→μν→eννν**
- **Pions stop** or decay in **flight in an active target** where decay products are tagged
  - Energy deposited by each particle is very different $e^+$ is a MiP, pion/muon up to 100 MiP!
- **Final state positrons are tracked** and **the total energy is measured** in a 3π calorimeter
  - **e+ energy** in the calorimeter **from 2 (π→eν) vs 4 (π→μν→eννν)** body decay
  - However, the **2-body energy tail overlaps with 4-body energy spectrum**
- **ATAR is crucial to tag decays** to recognize events in the overlapping energy spectra!
  - **Needed to achieve to x10 improvement in precision**



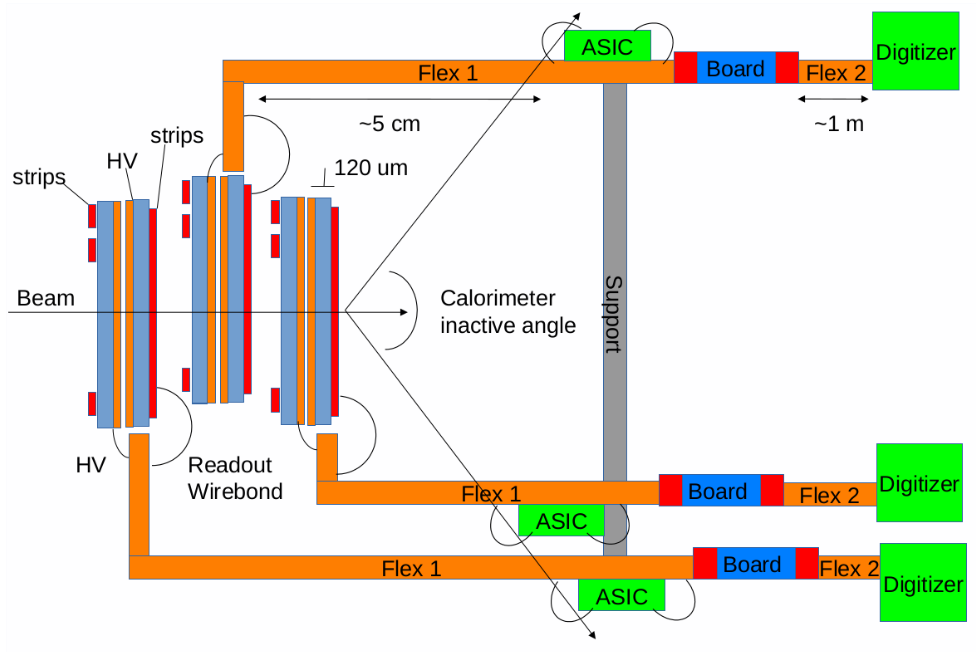



# ATAR design

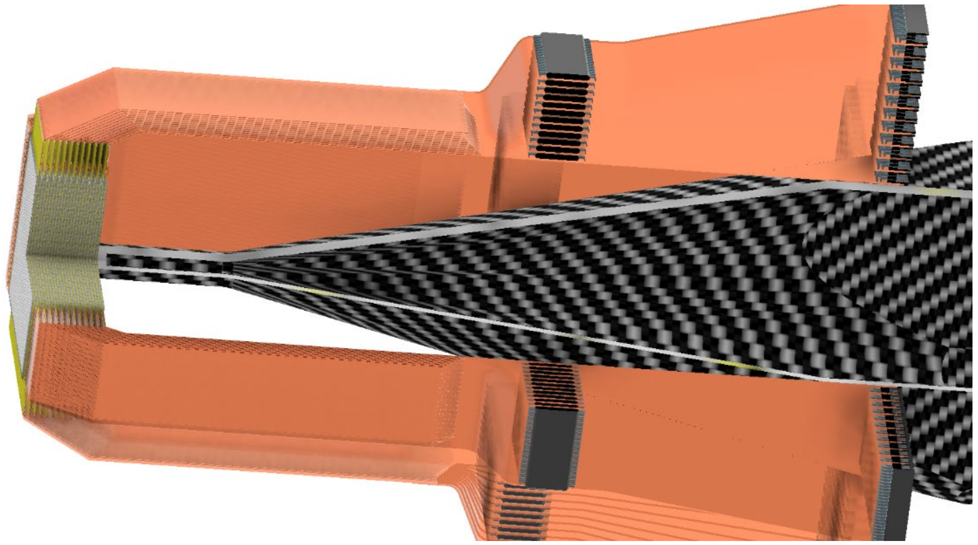
- **Full silicon active target (ATAR)**: ~2x2 cm area of silicon, ~6 mm thick
  - **High granularity** in (X,Y, Z), **fast full collection time**, good energy response, high dynamic range
- The **chosen sensor for the ATAR is an high granularity LGAD** technology (AC-LGADs or TI-LGADs)
  - https://indico.cern.ch/event/1175216/contributions/5064170/
- **Alternative design** is being studies with **standard silicon sensors**
  - https://indico.cern.ch/event/1175216/contributions/5064174/

- **ATAR initial design**
  - **48 layers of 120um thick sensors,** 200 um pitch strips
  - Layers have to be as close as possible
  - Compromise between granularity, total active area, timing and dead material
- Readout flexes alternating on the four sides to allow space for the wire bonds
  - **First (5 cm) flex carries the un-amplified signal from sensor to ASIC** with fast analog amplification mounted on the flex
- The **ATAR signals will be fully digitized** in a region of interest (ROI, temporal or spatial) for each event
  - Event reconstruction will use full waveforms from several channels

ATAR concept



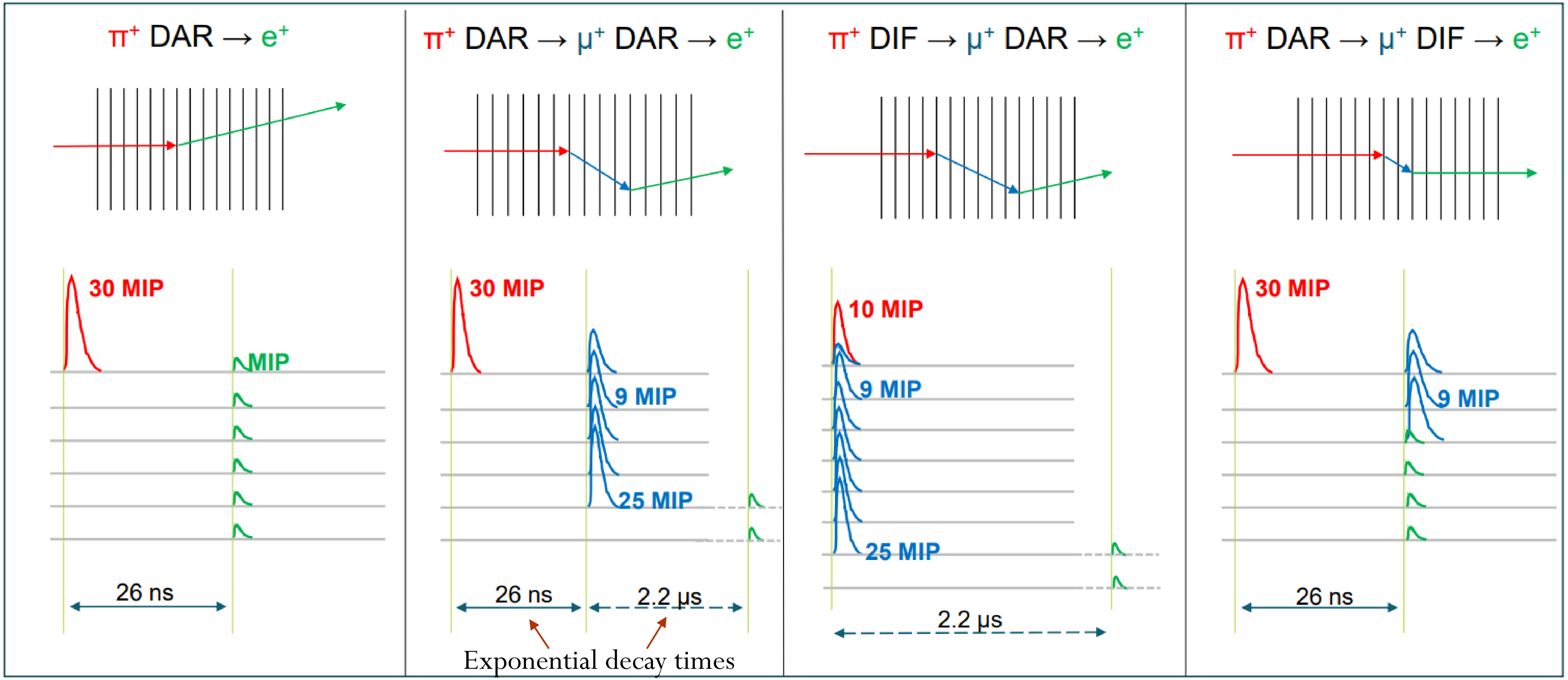

ATAR mechanical drawing



# Event Reconstruction

- Complex event reconstruction to detect all types of pion decays
- Reconstruction techniques using machine learning
- Expertise from BNL on LArTPC event reconstruction

**Reminder: to reach the target level of precision for PIONEER it is crucial to recognize π→e from π→μ→e events when final $e^+$ energy is the same!**



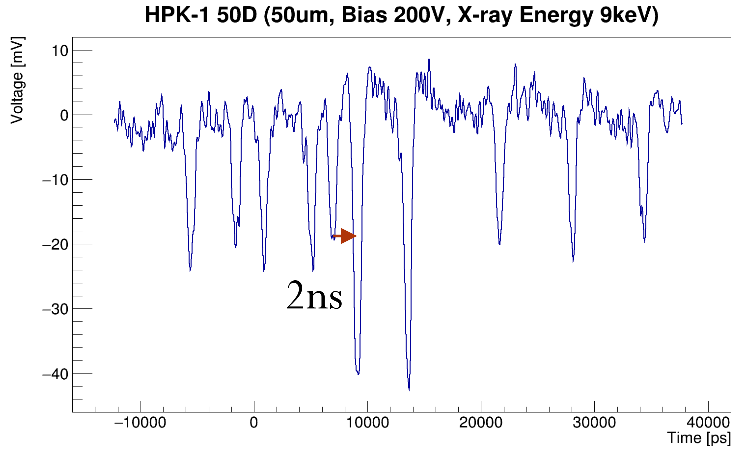



https://indico.cern.ch/event/1175216/contributions/5064176/
https://indico.cern.ch/event/1175216/contributions/5064175/

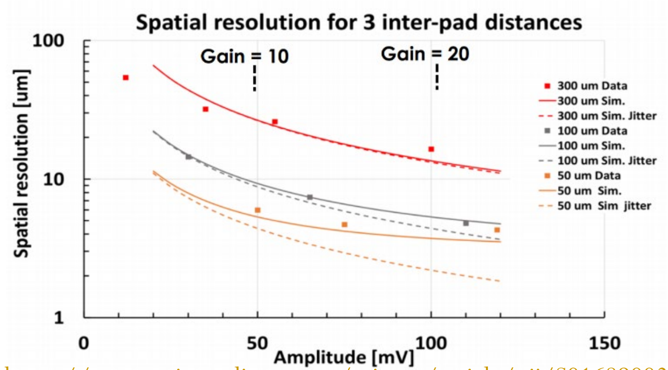
# ATAR challenges

- **Recognize hits that are few ns apart** with very different deposited energy while having **high spatial granularity in X/Y/Z**
- **Good energy resolution on the hits**
  - Able to recognize pions/muons deposits and measure the **energy lost by positron** in the ATAR (add to positron energy in the calorimeter)
  - Energy response of LGADs to be studied (preliminary around 10%)
- **Low material around ATAR** to reduce impact on positron energy, send un-amplified signal across a short flex
  - First prototype flex was produced and tested with prototype sensors
- **Amplifier and digitizer with large dynamic range** (~2000)
  - **Reduce cross talk** to avoid non-MiP events covering MiP events
- **Minimize blind regions and dead regions** in between layers
  - E.g.: when Muon travels along one strip
- **Compactness**: challenge for mechanical support
- **Complicated trigger scheme** to be interfaced with global trigger

LGAD pulse pair separation (50 μm)




AC-LGAD position resolution

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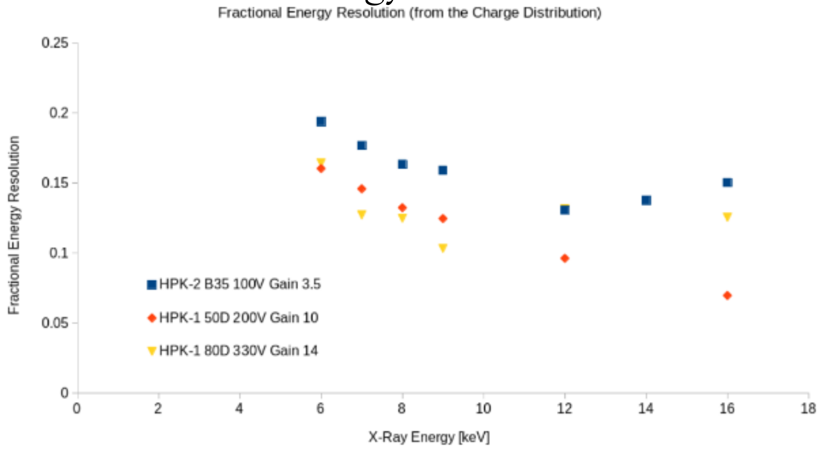
LGAD energy resolution

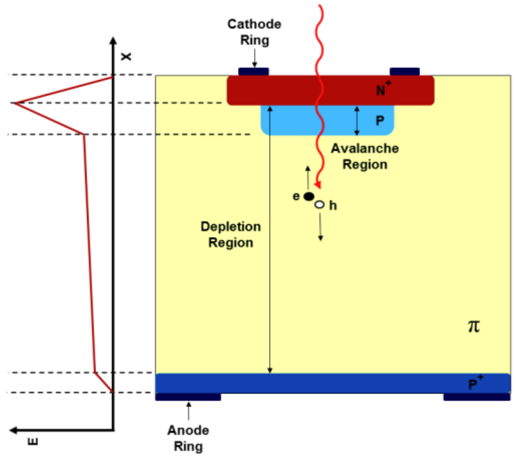


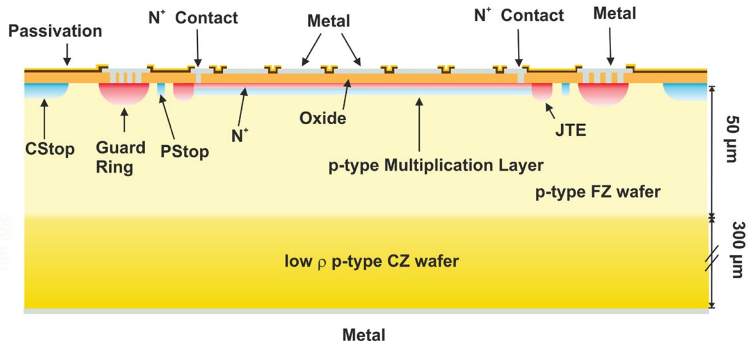
# Sensors

# Low Gain Avalanche Detectors (LGADs)

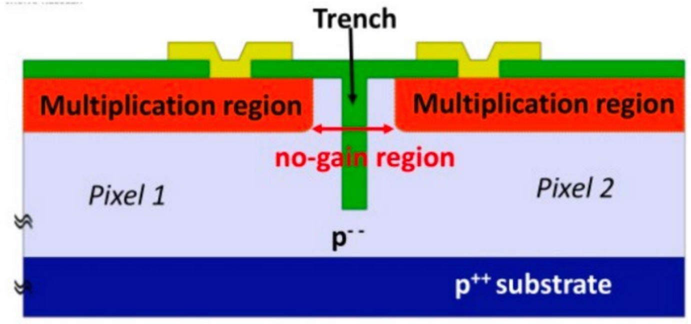
- **LGADs**: silicon detector with a highly doped multiplication layer
  - LGADs have intrinsic modest internal gain (10-50)
  - Great time resolution (20-30 ps) and fast charge collection time (1-2 ns)
- However **granularity** of LGADs is **limited to the mm scale**
  - **Solution: high granularity LGAD prototypes**

- **AC-LGADs:** multiplication layer and N+ resistive layer (BNL, FBK)
  - N+ layer is grounded through side connections
  - **Readout pads are AC-coupled** (Insulator layer between N+ and pads)
  - Allows for 100% fill factor and fine segmentation
- **TI-LGAD** with trench insulation between pads (FBK)
  - Proven to have very low IP gap: 5-10 um
- Other less developed prototypes: **DJ-LGADs**, DS-LGADs, iLGADs…
  - All prototypes have advantages and disadvantages to be evaluated




https://arxiv.org/abs/1906.11542

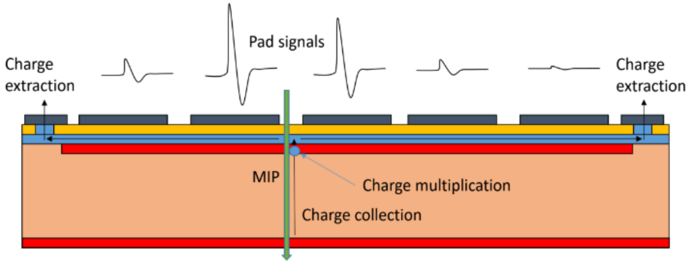


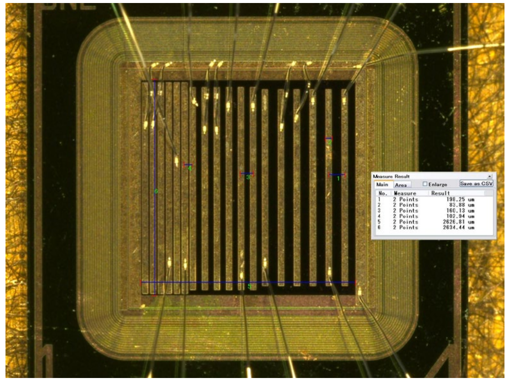

https://indico.cern.ch/event/861104/contributions/4514658/

# AC-LGAD studies

- Intrinsic **charge sharing** between strips
  - With a sparse pixelation of 200 um a <10 um hit precision can be achieved!
- **The response of the sensors can be tuned** by modifying several parameters
  - N+ layer resistivity, geometry, oxide thickness

- Experimental studies on a **BNL AC-LGAD prototype strip sensors** (50 um thick) with many geometries
- Same strip length and width, different pitches (studies made with FNAL TB data)
  - Close strips show a slightly better resolution, however the channel count goes up
- Same geometry but with different lengths (study made with focused IR laser TCT)
  - Longer strips show increased charge sharing profile



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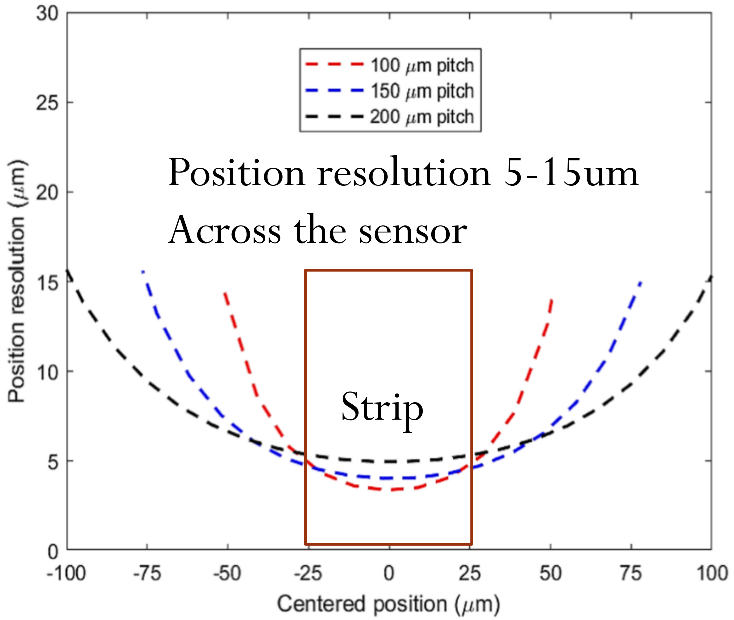
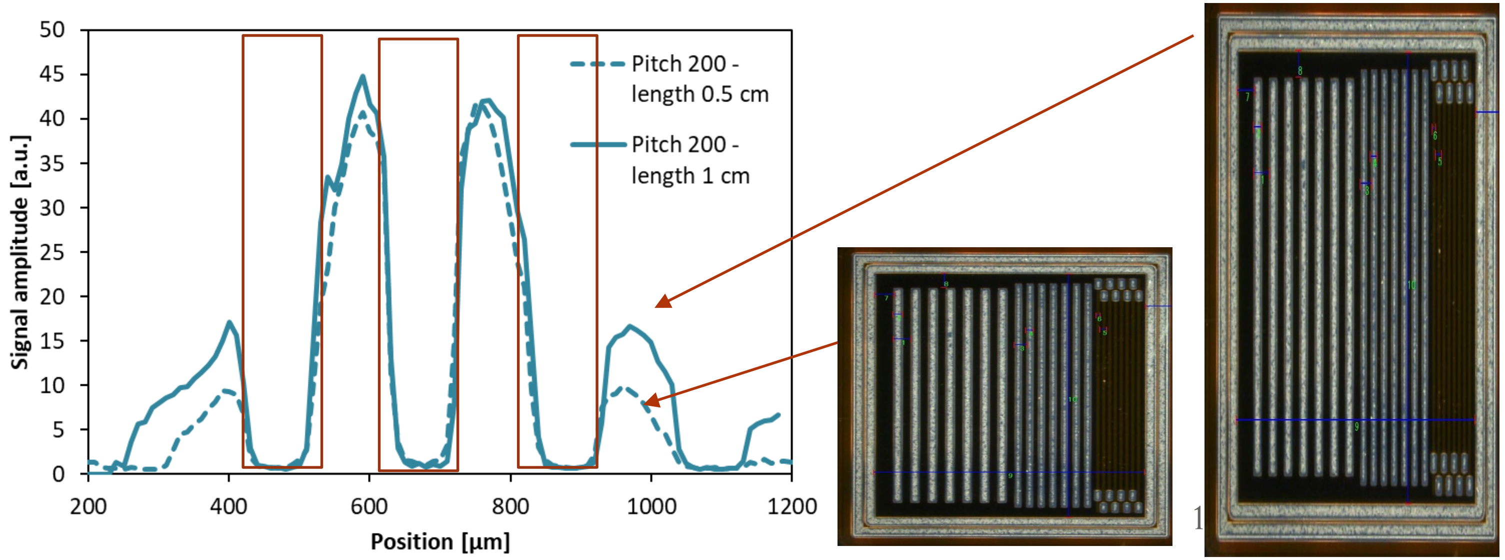
https://arxiv.org/abs/2006.01999




Position resolution vs position
for AC-LGAD strips of different pitch

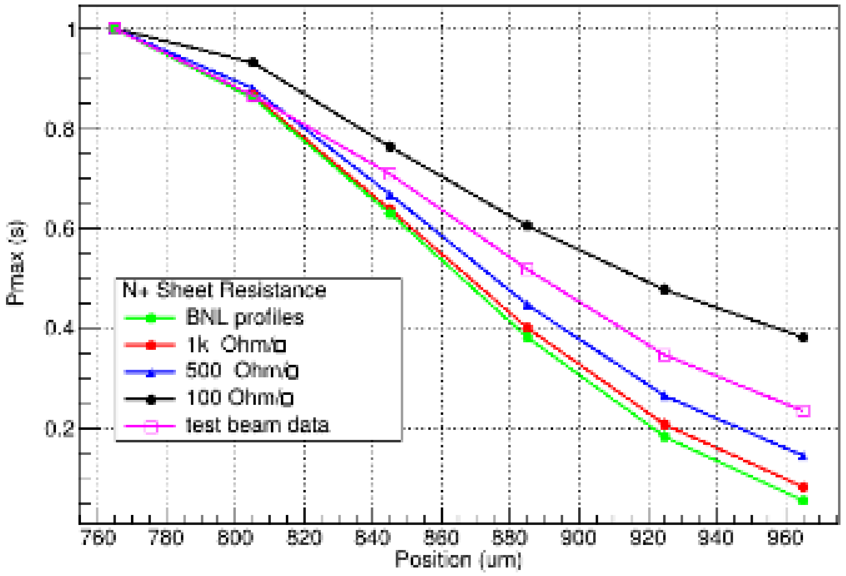


# AC-LGAD device simulation

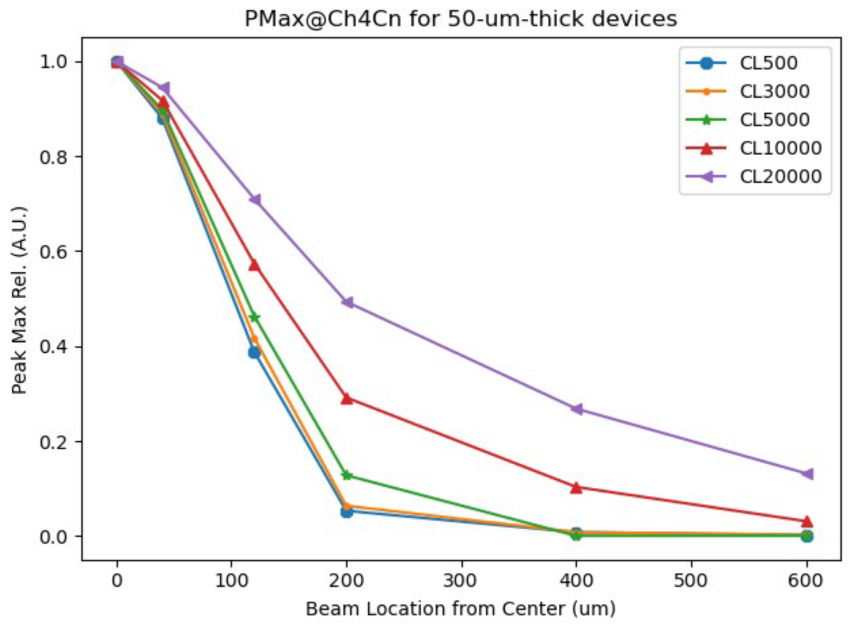
- **TCAD simulations to study AC-LGAD parameters variations**
  - Studies done with TCAD Silvaco and Sentaurus

- Study the effect of the N+ doping concentration to the charge sharing profile
  - **More resistive N+ reduce the charge sharing**
- Investigate strip geometry (pitch, length, width) effect on charge sharing
  - **Longer strip increase the charge sharing**

- Sensors studied are 50um thick, simulation is crucial to understand the behavior of 120um thick sensors for the baseline design
  - For most simulations TCAD in 3D mode is necessary to have realistic results (2D approximation is not enough)



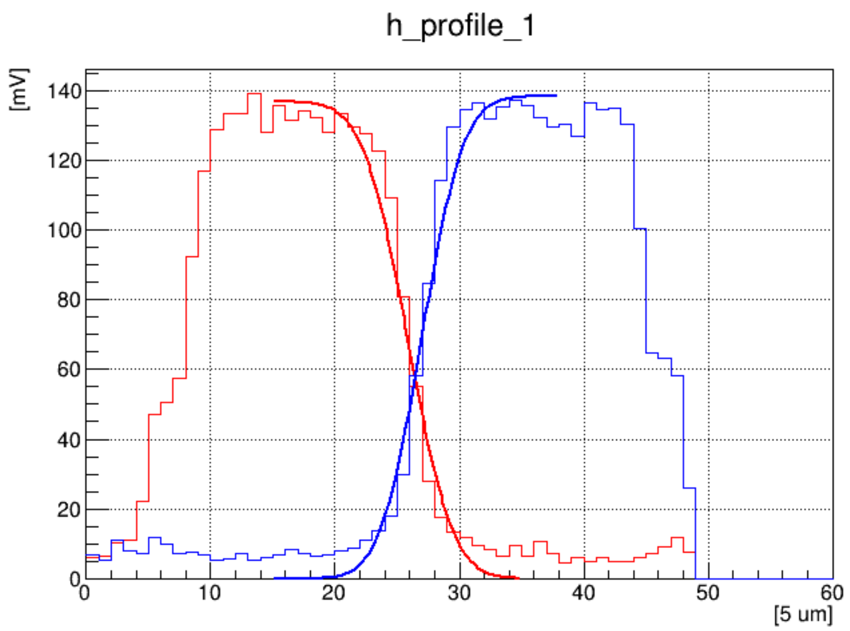

TCAD Silvaco simulation of charge sharing profile for different N+ resistivity

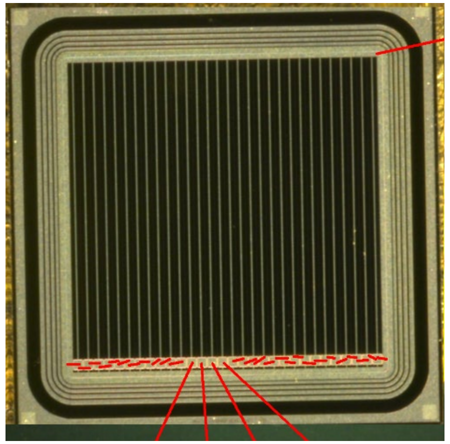



TCAD Sentaurus 3D simulation of charge sharing profile for different strip lengths

# Alternative LGAD technologies

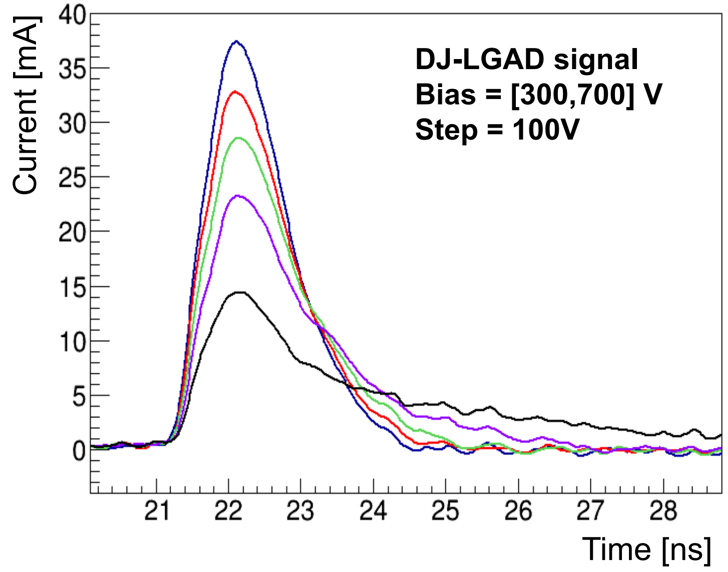
- **Trench insulated LGADs (TI-LGAD)**
- First prototypes successfully produced by FBK:
  - https://indico.cern.ch/event/861104/contributions/4514658/
- Very good performance observed!
  - IP gap 5-10 um or less
  - No cross talk
  - Good gain
- However, precision is limited to $\text{pitch}/\sqrt{12}$

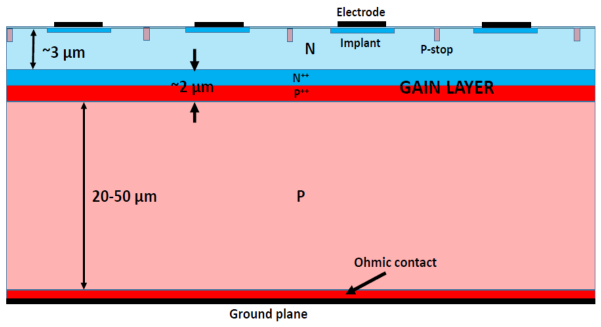


Prototype FBK TI-LGAD

- **Deep-Junction LGAD (DJ-LGAD)**
- Gain layer is buried, so the top can be segmented as in normal silicon detectors
  - https://arxiv.org/abs/2101.00511
- **First production completed** by Cactus material in collaboration with BNL and UCSC
  - Promising performance (gain of ~5) and good pad insulation (few um IP gap)



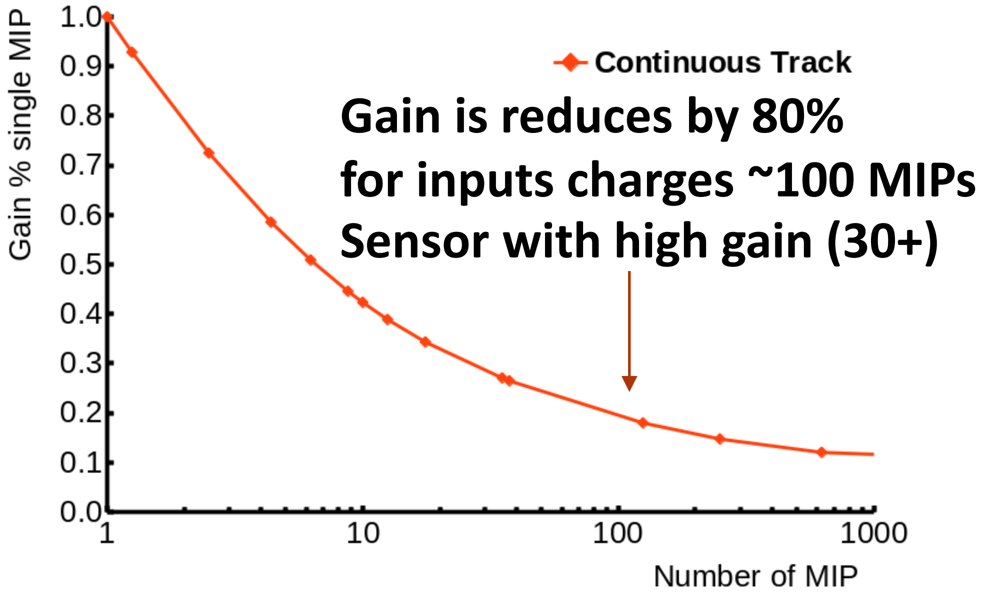
# Issue – gain saturation

- **LGAD gain suppression mechanism** needs to be fully understood (https://indico.cern.ch/event/983068/contributions/4223231/)
  - Gain suppression observed experimentally with large energy depositions
  - e+/pions/muons will deposit a **broad range of charge in the ATAR**
- **Effort to try and minimize this effect** in the ATAR

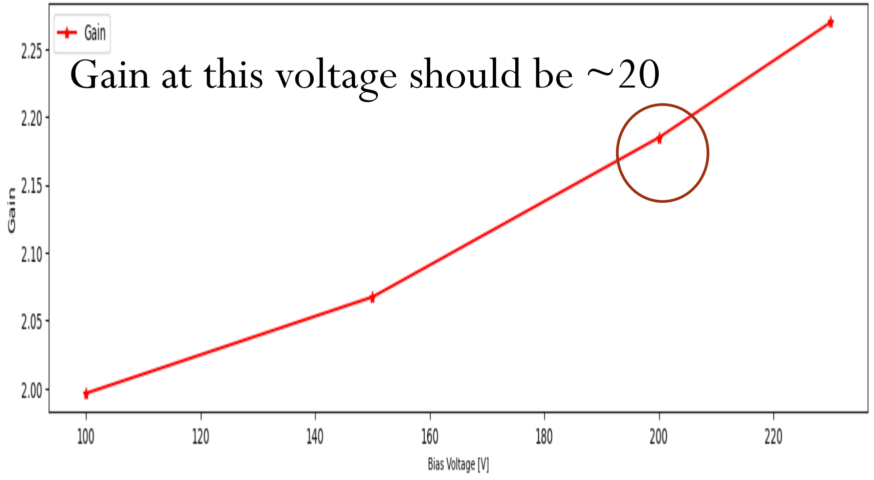
- Explore and characterize the gain suppression effects using **TCAD simulation**
  - Simulate significant gain loss for high gain detector and high deposition
  - Simulation shows that with a **low gain sensor the gain reduction is less**
  - Gain suppression can be reduced with adjustment in the sensor design
  - See: https://indico.bnl.gov/event/17072/contributions/70497/

- Gain suppression studied also with **alpha particles**
  - Deposition of ~100 MiP
  - High gain suppression observed for high gain sensor
  - **Several types of gain layer design under study**

Gain suppression simulated with Sentaurus

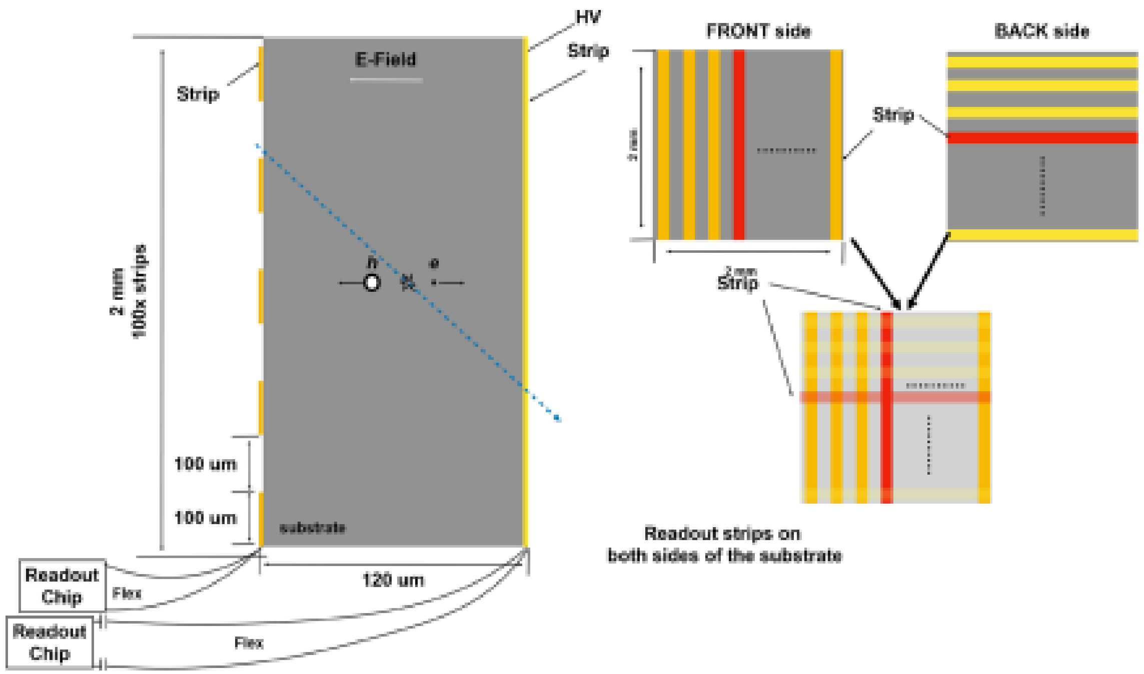



Gain suppression observed with alpha particles



# Alternative designs

- **Alternative sensor design**: double sided detector with AC strips on one side and DC perpendicular strips in the other
  - Better tracking (X-Y position information) and better energy reading from DC-pads
  - Channel density might be too high (need 2x channels)
- **Alternative detector design with PiN** (no gain)
  - Same geometry but based on PiN silicon sensors




**Pros**

- PIN is known to be **linear** in energy response to energy deposition from 1 to 100 MIP
  - Excellent stopping π/μ separation
- With the charge collection signal, much easier to calibrate the energy response (**uniform, stable and topology independent**)

**Cons**

- Need a working design of **pre-amp electronics to achieve > 9:1 signal-to-noise ratio for MIP signal, which requires more power**
  - With FAST, the S/N ~ 5:1 for MIP signal
  - Also have impact in timing resolution (to be elaborated in details)







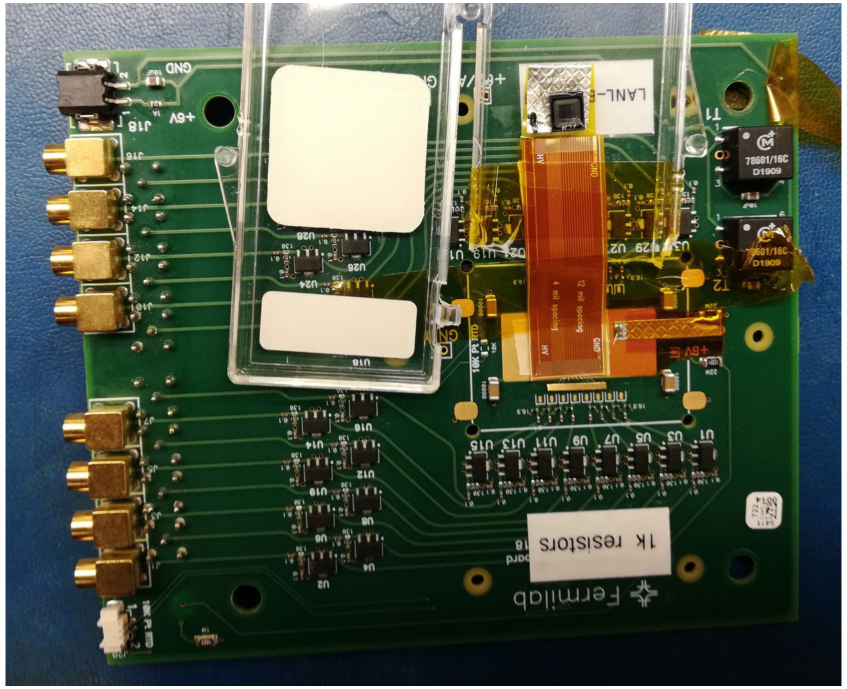
https://indico.cern.ch/event/1175216/contributions/5064174/attachments/2524418/4341713/Alternative_Design_ATAR.pdf

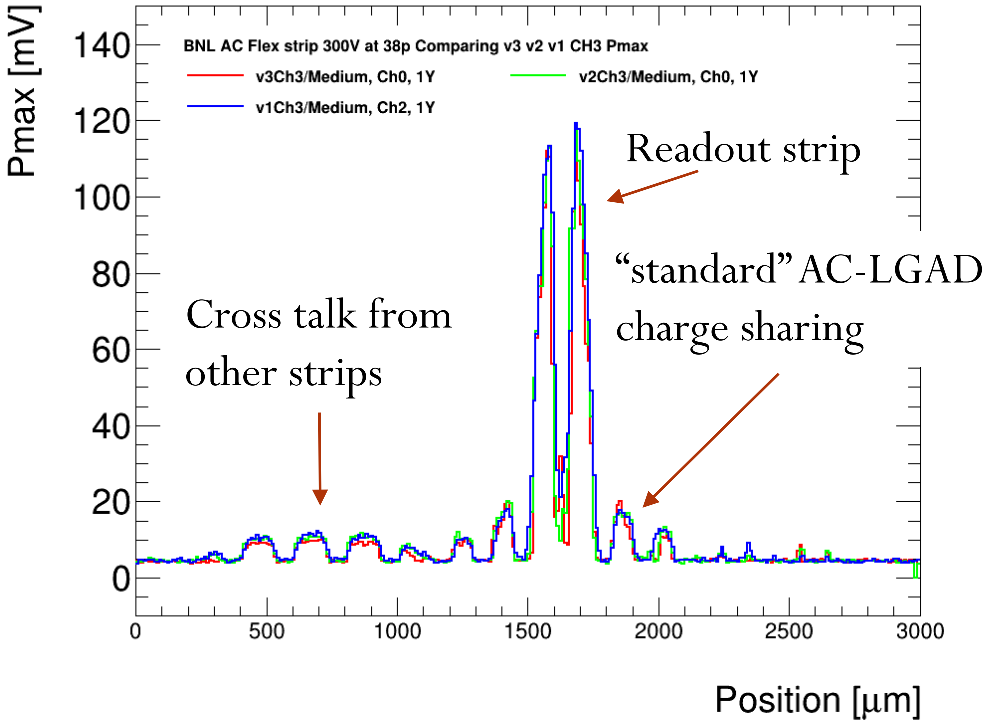
# Readout

# Flex prototype run

- Transfer of **raw signals** from the ATAR sensors **by flex cable**
- So that readout chips do not need to be positioned in the beam or in the calorimeter acceptance
  - Prototypes flexes produced: 3 – 7 cm long, 100 and 300 μm trace pitch

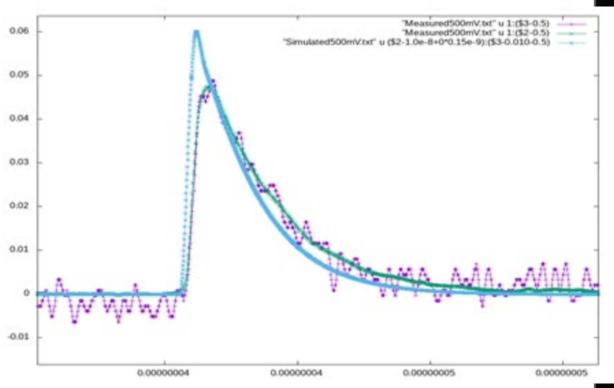
- **Test of response** by connecting to sensor and analog readout board, compare with direct bonding
  - Bonding of a sensor directly to the flex cable is mechanically challenging
- Charge sharing with neighbouring strip, and baseline noise of channels are increased when connected to the flex
- **Long-range pick-up** from strip connected to the flex
  - Attempts to reduce this by spacing connections further apart, grounding traces in between (red line): slight improvement, but not solved
- **Need flex re-design foreseen with the aid of simulation**
  - (e.g. Hyperlinx software)

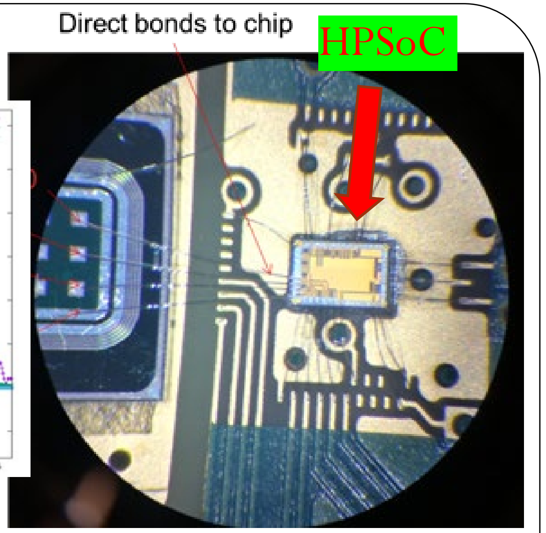


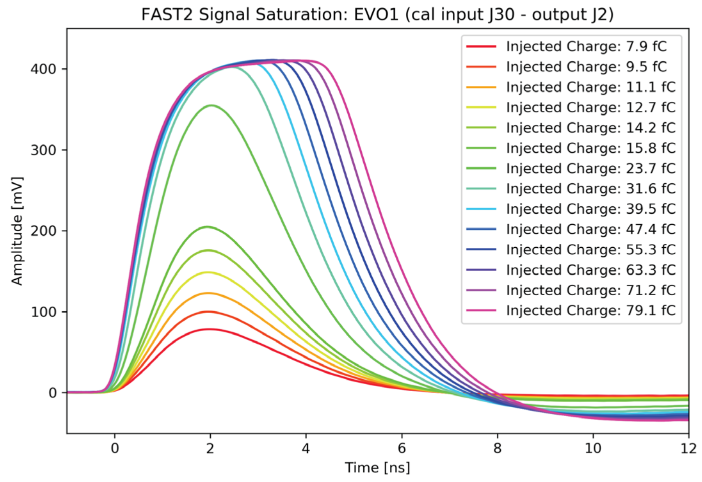


# Front-end amplifier

- ATAR will have **separate amplifier and digitizer stage**
  - Needs both an analog ASIC and a digitizer chip
- There are several ongoing efforts to produce a new type of timing chip
  - For PIONEER the following characteristics are needed: **good bandwidth** (~1GHz), **fast return to zero** to have good pulse pair separation, **large dynamic range** (pions/muons and electrons).
- UCSC is working on three ASICs that are being produced for other projects
  - Not aimed at PIONEER but could be viable choices
  - Power target ~ 1 mW per channel
  - FAST (INFN Torino), HPSoC (NALU scientific), ASROC (Anadyne)
  - Funded by SBIR grants and INFN
- **Front-end amplifier for PiNs** also in development

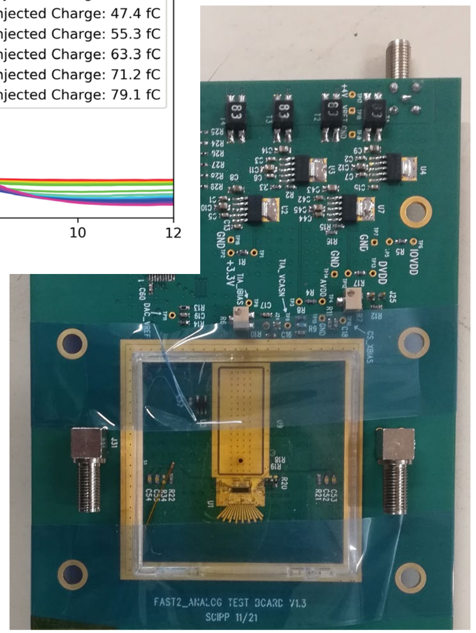





| Institution | Name | Technology | Output | # of Chan | Funding | Specific Goals | Status |
|---|---|---|---|---|---|---|---|
| INFN Torino | FAST | 110 nm CMOS | Waveform & TDC | 20 | INFN | Large Capacitance TDC | Testing |
| NALU Scientific | HPSoC* | 65 nm CMOS | Waveform | 5 (Prototype) > 81 (Final) | DoE SBIR | Digital back-end | Testing |
| Anadyne Inc | ASROC** | Si-Ge BiCMOS | Discrim. | 16 | DoE SBIR | Low Power | Simulations |

FAST2 chip
Evaluation board



# Digitizer stage

- **Back-end is a digitizer chip**: ~5000 channels to be digitized
  - **Commercial solution** readily available (e.g. DRS4), however it **would be too expensive**
  - Not all channels can be digitized for each event, need good triggering scheme

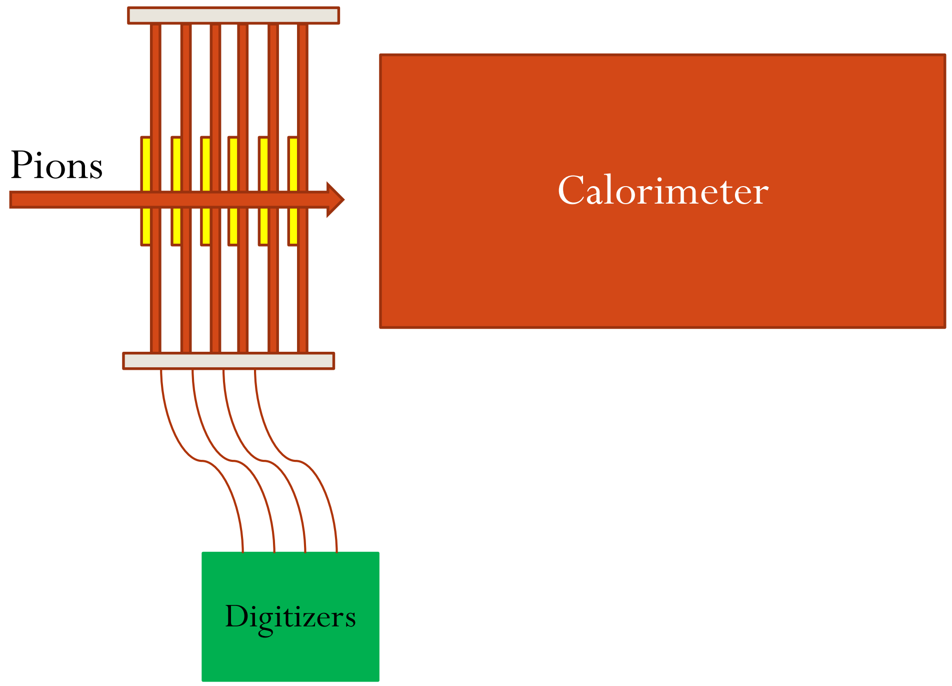
- **HD-SoC from Nalu Scientific** in evaluation at UCSC: 32 channel, 1Gs/s digitizer chip
  - Complex triggering capabilities
  - Next version: 64 channels
  - Collaboration with Nalu Scientific to understand the triggering capabilities of the chip


HD-SoC evaluation board

# Conclusions

# PIONEER v0.5

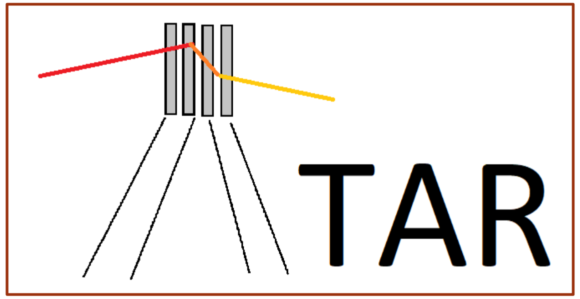
- Current plan is to **build a v0.5 of the experiment** to **take data at PSI by 2027** (PSI shutdown)
  - Limited ATAR prototype (less channels, less layers)
  - ~10 layers, 16 channels per layer
  - Small Calorimeter with limited acceptance
- Goal of having a **first physics measurement** before the PSI shutdown (2027)
- Plan to have an **ATAR prototype in the beam by 2025**
  - BNL is producing the first prototype 120um thick sensors (expected spring 2023)
  - A board is being designed (UW+UCSC) based on the FAST2-3 analog chip. Compact stackable design to keep the detector planes close together
  - ATAR digitization: either HD-SoC or wavedream boards
- **Calorimeter prototype** being designed as well

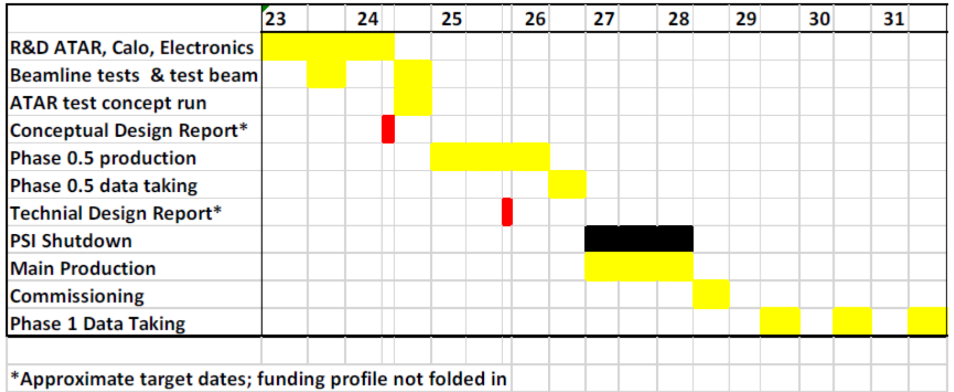


# Conclusions

- **PIONEER** is a next generation rare Pion decay experiment to measure $R_{e/\mu}$ and Pion beta decay branching fraction with **unprecedented precision**
- PIONEER's active target (ATAR) **is a very ambitious detector**
  - High granularity, high density and good timing capabilities
  - Need large dynamic range and good energy resolution
  - **Many challenges** still need to be solved
- Baseline technology for sensors: **AC-LGADs**
  - But other high density LGADs are being evaluated (TI-LGAD, DJ-LGAD)
  - Alternative design based on standard silicon is being studied
- **Readout and electronics development in progress**

- Plans to have a working **PIONEER prototype** (PIONEER v0.5) **ready in a couple years** to study pion decays at PSI
  - Currently in the process of applying for funding
- **PIONEER is a growing collaboration, if you're interested let us know!**




# Thanks for the attention

**Many thanks to the SCIPP group students and technicians!**

Thanks to the FBK and BNL teams for producing and providing the sensors for this study

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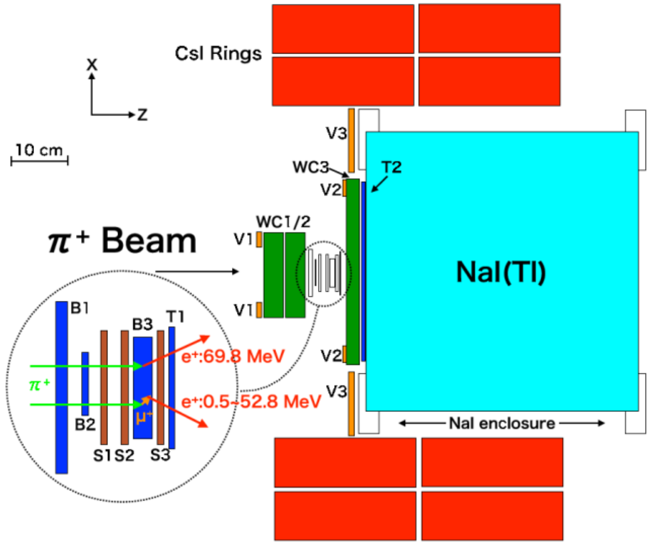
This work was partially performed within the CERN RD50 collaboration

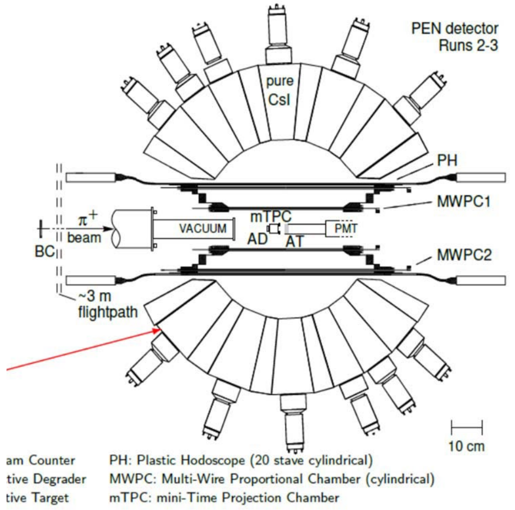
# Past pion experiments

- Rare pion decay experiments showed **significant results in the past decades**

- **PIENU** (TRIUMF)/**PEN** (PSI) best measurement up to date of $\mathbf{R_{e/\mu}}$
  - $\mathbf{R_{e/\mu}}$ **: pion to electron/muon decay ratio**
    - Precision measurement of lepton-flavor universality (LFU) for electron-muon
  - Foreseen final uncertainty (PEN/PIENU) < 0.1% (current 0.25%)
  - Located at the pion beam lines at TRIUMF (PIENU, https://pienu.triumf.ca/) and PSI (PEN, https://inspirehep.net/experiments/1511062)

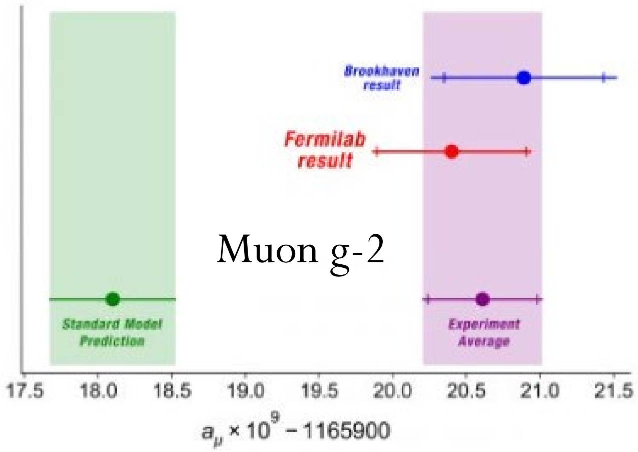
- **PiBeta** (PSI) has the best measurement of **Pion beta decay branching fraction** $\mathbf{B(\pi^+ \rightarrow \pi^0 e^+ \nu)}$
  - Final uncertainty 0.64%
  - Located at PSI (https://inspirehep.net/experiments/1108722)



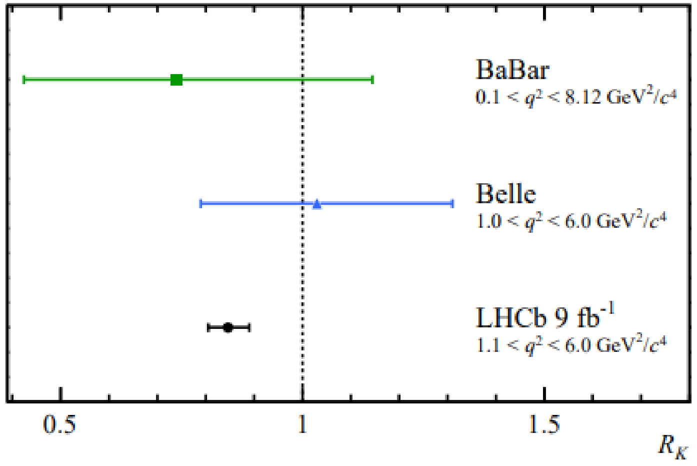



# Recent results on Flavor universality tensions

- **Topic of Lepton flavor universality (LFU) violation is of great interest these days**
  - Several high precision measurements of accurately predicted SM processes show possible indications of violating LFU
  - Charged LFU was tested at $O(10^{-3})$ in π, τ and K decays
- Furthermore recent results showed indication of CKM non-unitarity




- **Muon g-2 recent result**: 4.2 σ deviation from theory
  - https://news.fnal.gov/2021/04/first-results-from-fermilabs-muon-g-2-experiment-strengthen-evidence-of-new-physics/
- **B decays**: $B \rightarrow D^*\tau\nu / B \rightarrow D^*\mu\nu$; $B \rightarrow K^*\mu\mu / B \rightarrow K^*ee$
  - R(D(*)),R (K*), R(K): (3-4 σ deviation from expected SM LFU)
  - Showing a O(10%) deviations from universality
  - With both heavy quarks and leptons involved
  - (e.g. recent LHCb results on R(K) https://arxiv.org/abs/2103.11769)



# PIONEER main physics goals ($R_{e/\mu}$)

- **Precision measurement of charged lepton flavor universality ($R_{e/\mu}$)**
- SM theory calculation is precise to O(10E-4)
- But current theory calculation is still one order of magnitude away from experimental measurement

$$R_{e/\mu}^{theory} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = (1.2352 \pm 0.0002)\, x10^{-4}$$

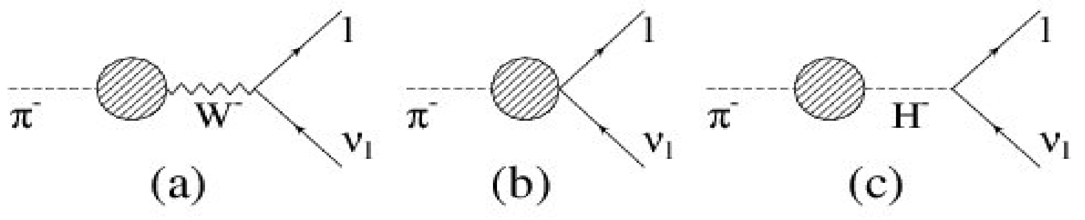
Current Result (PDG): $R_{e/\mu}^{exp} = 1.2327 \pm 0.0023x10^{-4}$ (±0.19%)

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$

PEN, PIENU goals ($R_{e/\mu}^{exp} \leq \pm 0.1\%$)

PIONEER goals

Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} : O(\pm 0.01\%)$

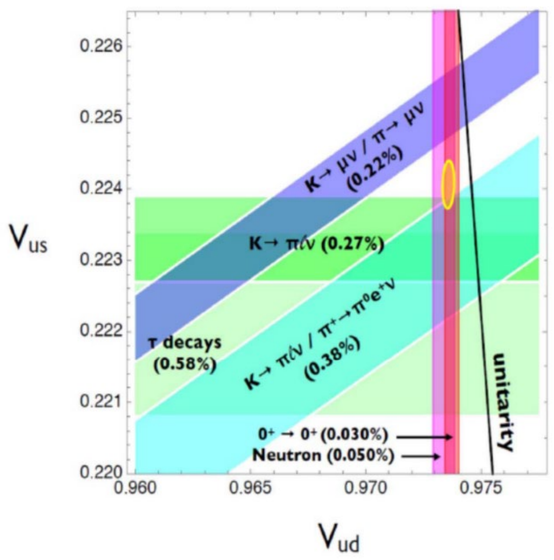



- **The goal of PIONEER is to reach the same precision as the theory calculation**
- **Process of π→eν** is helicity suppressed and **very sensitive to pseudo-scalar and scalar couplings that are absent in SM**
  - A disagreement between theory and experimental value for $R_{e/\mu}$ would be a clear indication of BSM
  - E.g. Charged Higgs BSM coupling (to 3000 TeV)
  - But many others!

# PIONEER main physics goals ($R_{\pi\beta}$)

- Precise measurement of **Pion beta decay branching fraction $R_{\pi\beta}$** :$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$
  - Important to test CKM unitarity
  - It is a **clean Vud measurement**
  - New constrain in the (Vus – Vud) plane
- Current precision 0.64 % (PIBETA)
  - PIONEER precision goal: 0.2-0.05 % (Phase II-III)

Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \rightarrow \pi^0 e^+ \nu)}{\Gamma(\pi^+ \rightarrow all)}$: $O(\pm 0.2\% \rightarrow \pm 0.05\%)$




- **Additional physics searches** are also foreseen
  - Such as Axion Like Particles (ALPs), Majorons and massive neutrino searches

Improve search sensitivities by an order of magnitude

e.g. $\pi \rightarrow e\nu_H ; \pi \rightarrow \mu\nu_H ; \pi \rightarrow e/\mu\nu\nu\bar{\nu} ; \pi \rightarrow e/\mu\nu X$

# Alternative LGAD technologies

- **Deep-Junction LGAD (DJ-LGAD)**
- Gain layer is buried, so the top can be segmented as in normal silicon detectors
  - https://arxiv.org/abs/2101.00511
- **First production completed** by Cactus material in collaboration with BNL and UCSC
  - Promising performance (gain of ~5) and good pad insulation