A silicon-based full active target for the PIONEER experiment

Rare pion decay workshop

UC Santa Cruz, Oct. 6-8 2022

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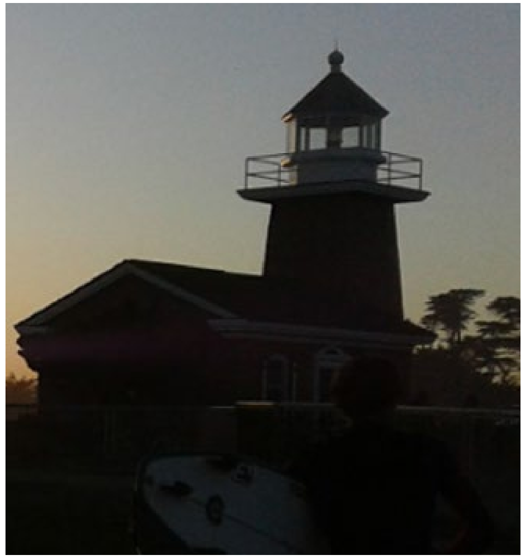
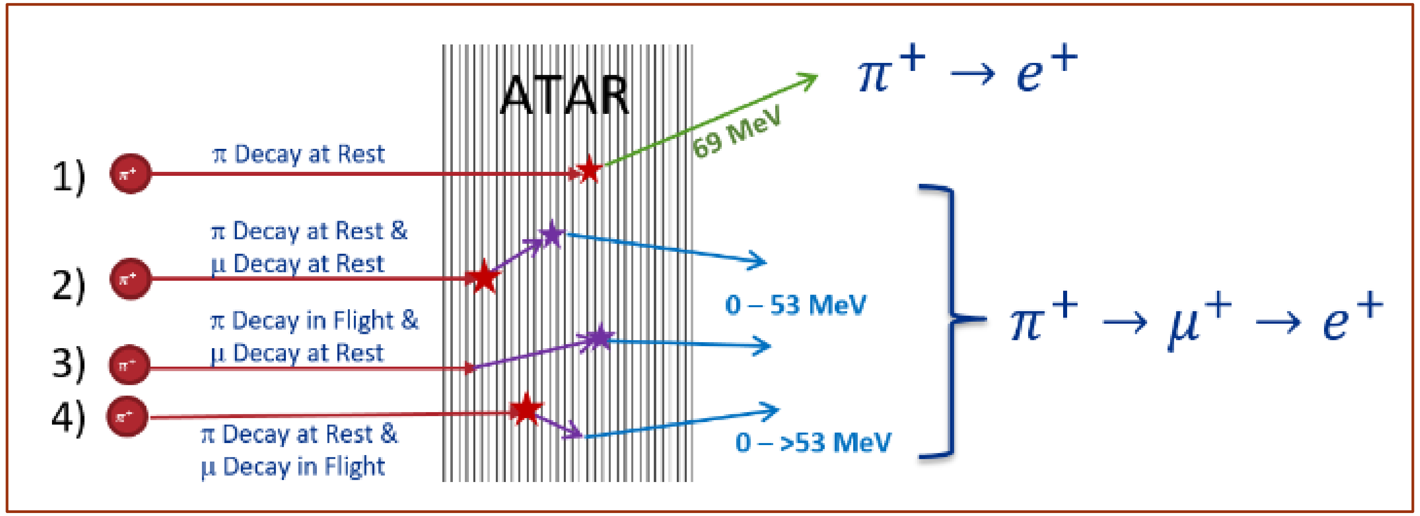
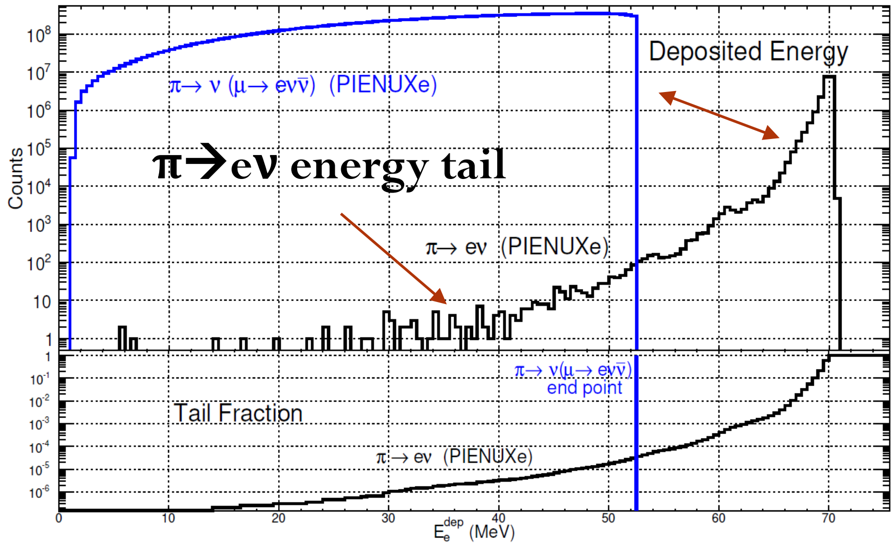


PIONEER detector design

- **Goal: separation of spectra of π→eν and π→μν→eνν**
  - Pions stops/decay in an active target where decays are tagged with energy and timing
  - Exiting positrons are tracked and the total energy is measured in a 3π calorimeter
  - Energy spectra of 2 vs 4 body decay: however 2-body energy tails overlaps with first spectrum
- **Two main detectors**: Active TARget (ATAR) and 25 X_0 calorimeter
  - **ATAR** with fast timing and high segmentation **allows to separate and tag π→eν and π→μν→eνν** this reduces pileup and π→eν energy tail
  - **Calorimeter** with high energy resolution (**liquid Xe** or LSO crystals) to reduce tail correction and pile-up uncertainties, plus improves uniformity

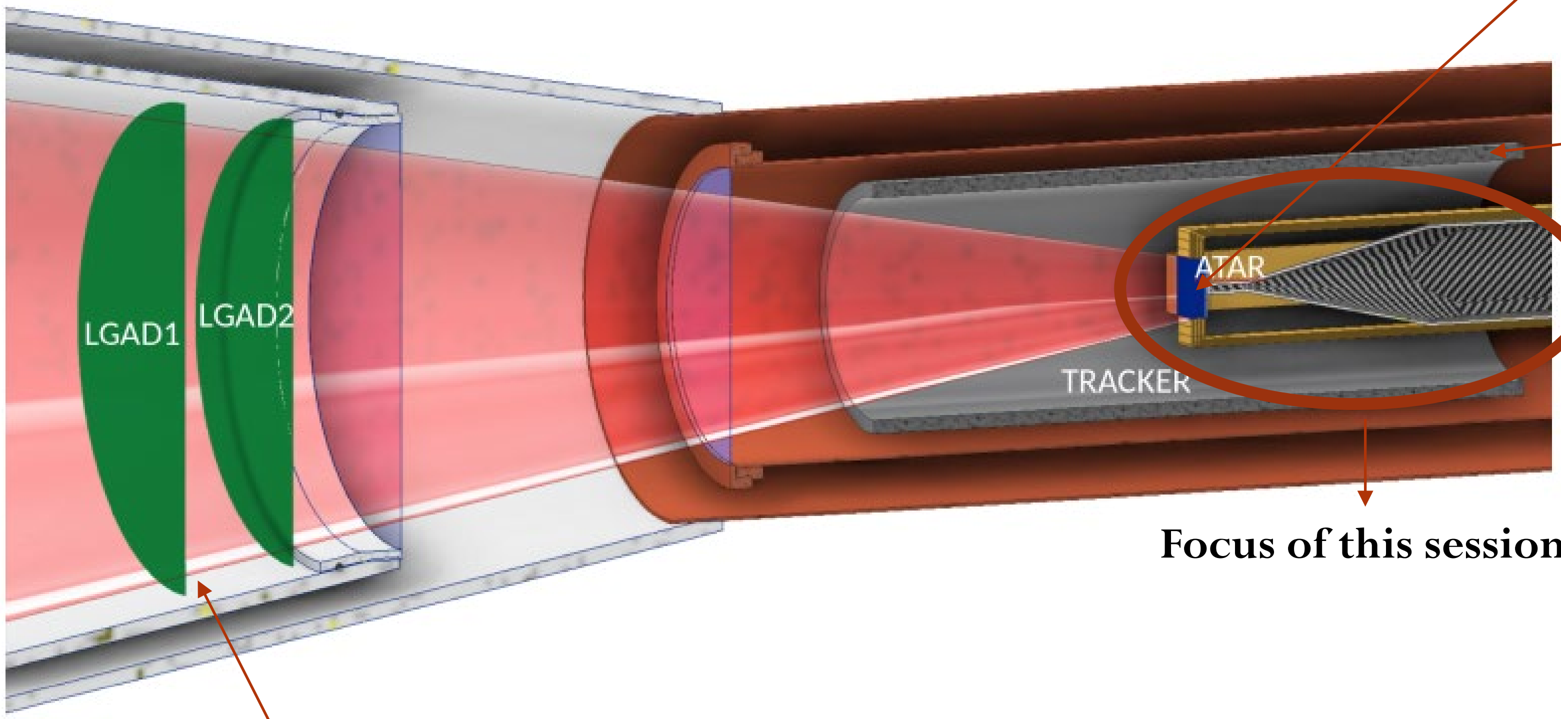




PIONEER detector design

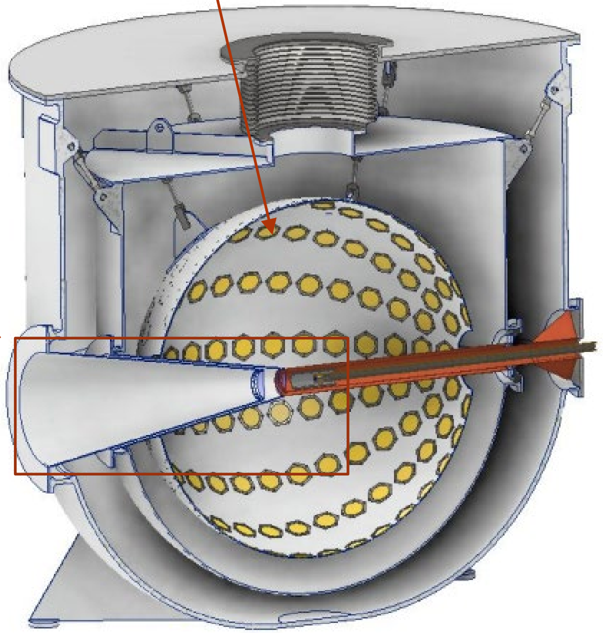
ATAR allows for decay chain separation

Intermediate tracker tracks exiting positron



Focus of this session

LXe calo provides positron position and energy



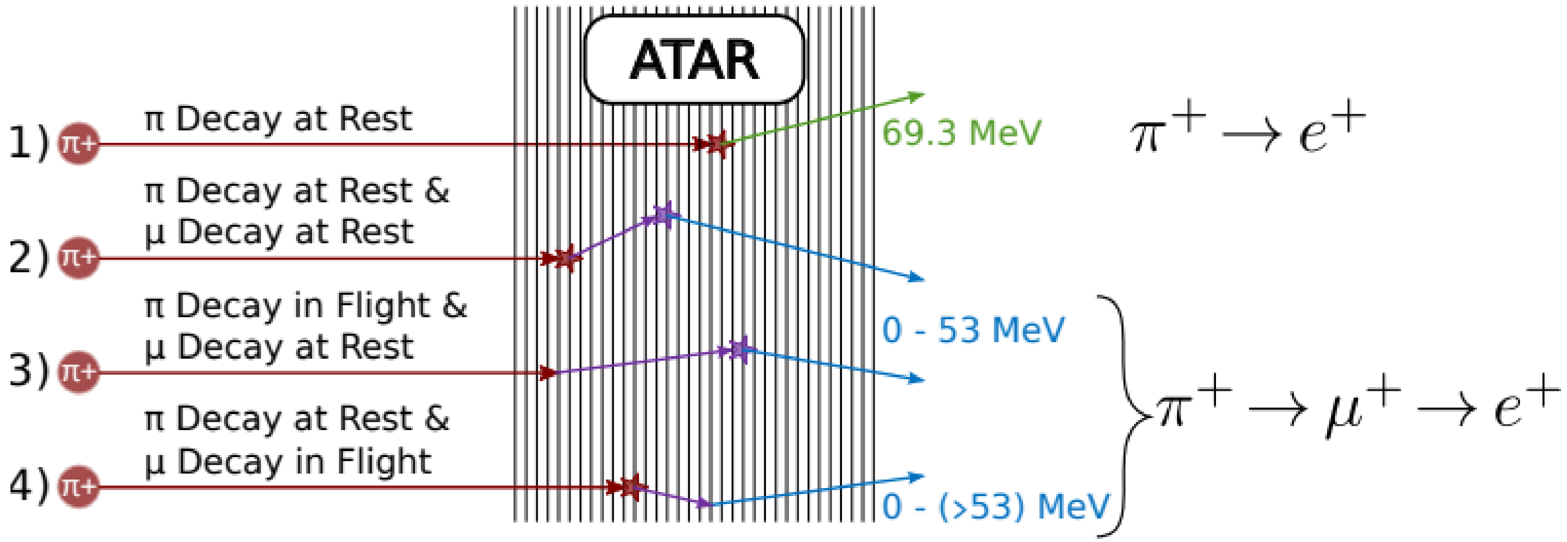
LGAD1 and LGAD2 provide event by event trajectory of entering particles

ATAR design and challenges

ATAR requirements

- Full silicon active target (ATAR): compact ~2x2 cm area of active silicon, 5.76 mm thick
  - Defines the fiducial pion stop region, provides high resolution timing information and selective event triggers
- **Goal**: for $\pi \rightarrow e\nu$ decays, the ATAR will suppress the $\pi \rightarrow \mu \rightarrow e$ decay at rest (πDAR) and pion and muon decay-in-flight (DIF) low energy backgrounds
  - DAR detected with good pulse pair resolution
  - DIF detected by track kinks, dE/dx measurements along the track and observed range in the target
- **Need**: high granularity in (X,Y, Z), fast full collection time, good energy response, high dynamic range
- Chosen sensor technology: **Low Gain Avalanche Detectors (LGADs)**

High segmentation, compact

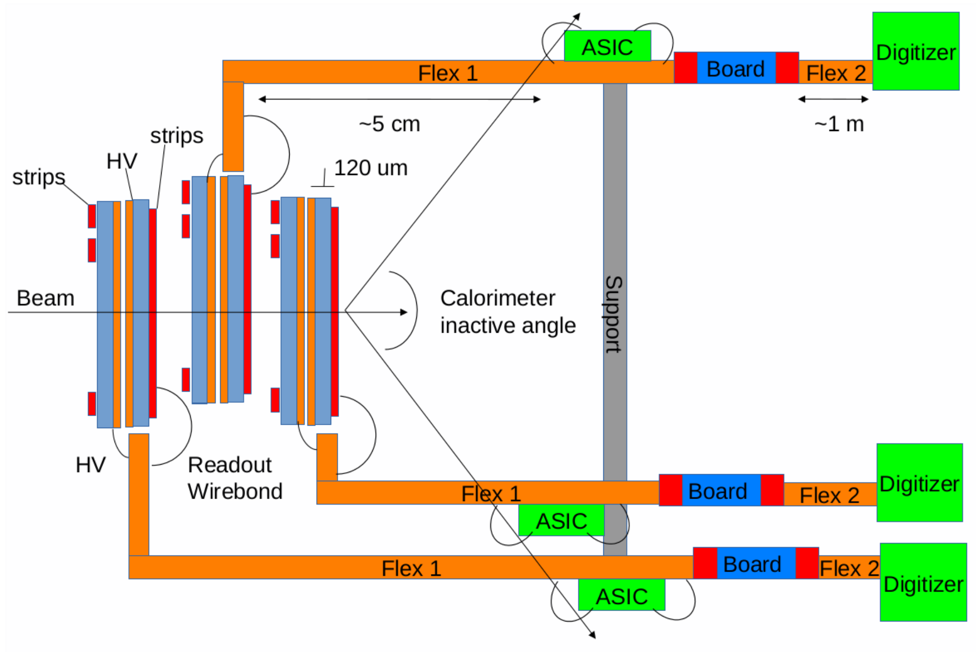


Current ATAR design

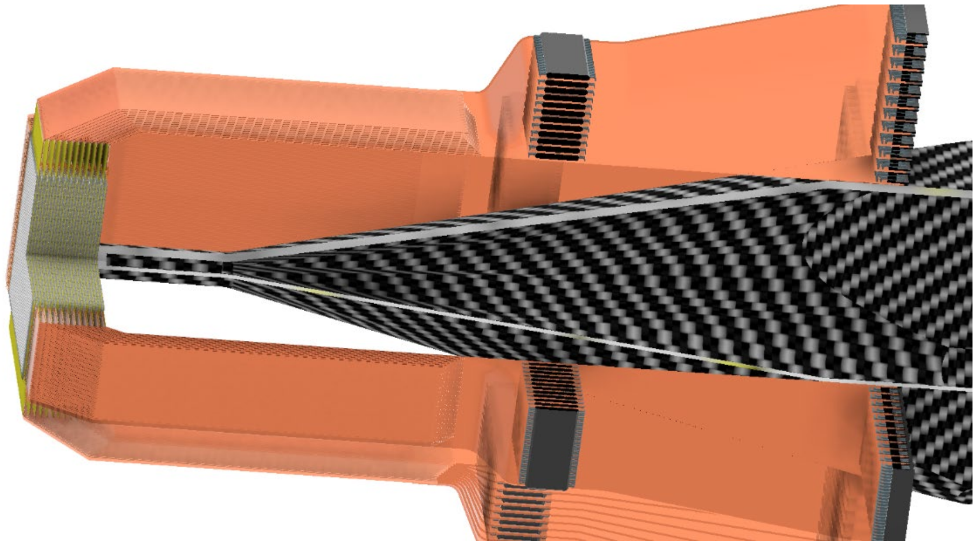
- The **chosen sensor for the ATAR is an LGADs high granularity** technology (AC-LGADs or TI-LGADs)
  - Very dense detector with high granularity that will pose many challenges in the development and construction
  - Requires expertise such as bonding, flex design, fast ASIC and digitization
- **ATAR initial design**
  - **48 layers of 120um thick LGADs**
  - 100 strips, 2 cm length, with 200 um pitch (2x2 cm area)
  - Compromise between granularity, total active area, timing and dead material

- **Readout flexes are on the four sides** alternating to allow space for the wire bonds
  - **First short (5 cm) flex carries the un-amplified signal from sensor to ASIC** with fast analog amplification mounted on the flex
- **Carbon fiber or Pyrolytic graphite supports for sensors and flexes** for low material budget and high thermal conductivity
- The **ATAR signals will be fully digitizer** in a region of interest (ROI, temporal or spatial) for each event
  - Smart trigger on the digitizer to minimize the amount of data needed for reconstruction
  - Advanced de-convolution analysis can identify pulses close in time

ATAR concept



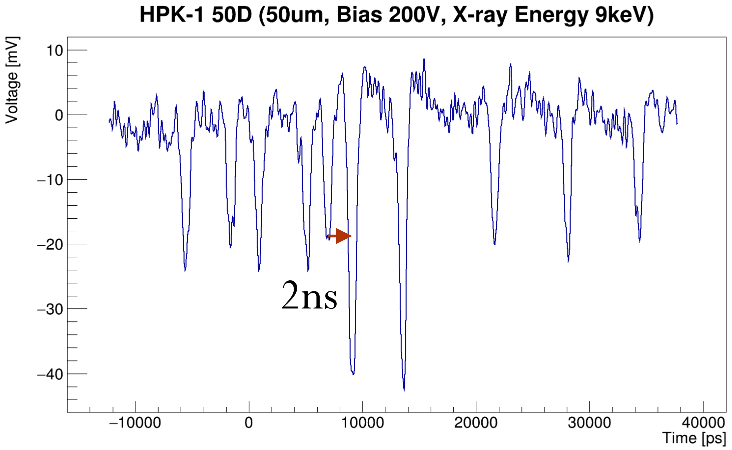
ATAR mechanical drawing



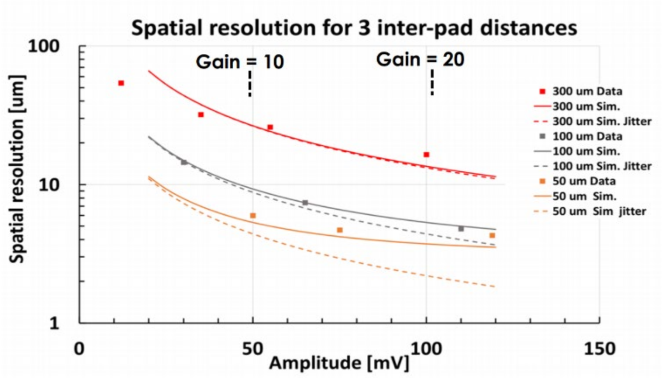
ATAR challenges

- **Recognize hits that are ~1 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 electrons** in the ATAR
  - Energy response of LGADs to be studied (preliminary around 10%)
- **Gain suppression mechanism** needs to be fully understood
- **Low material around ATAR** to reduce impact on positron energy, send un-amplified signal across a short flex
  - Prototype flex was produced and will be 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. blind: when decayed Muon travels along one strip
- **Compactness**: challenge for mechanical support
- **Complicated trigger scheme** to be interfaced with global trigger

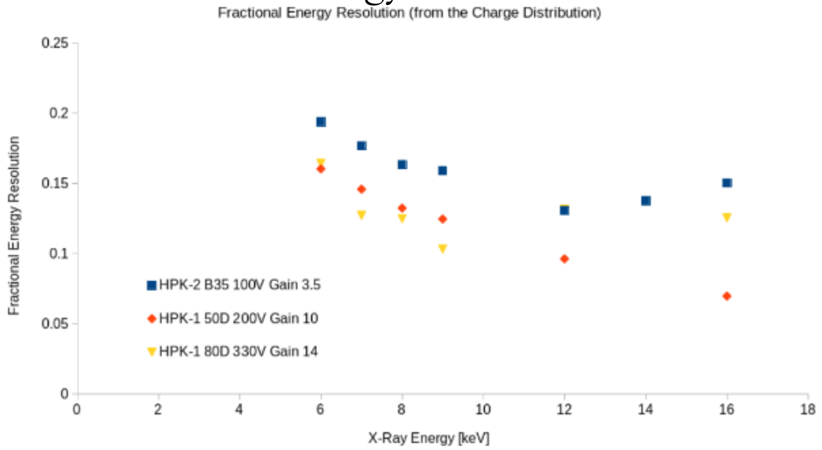
LGAD pulse pair separation (50 µm)



AC-LGAD position resolution

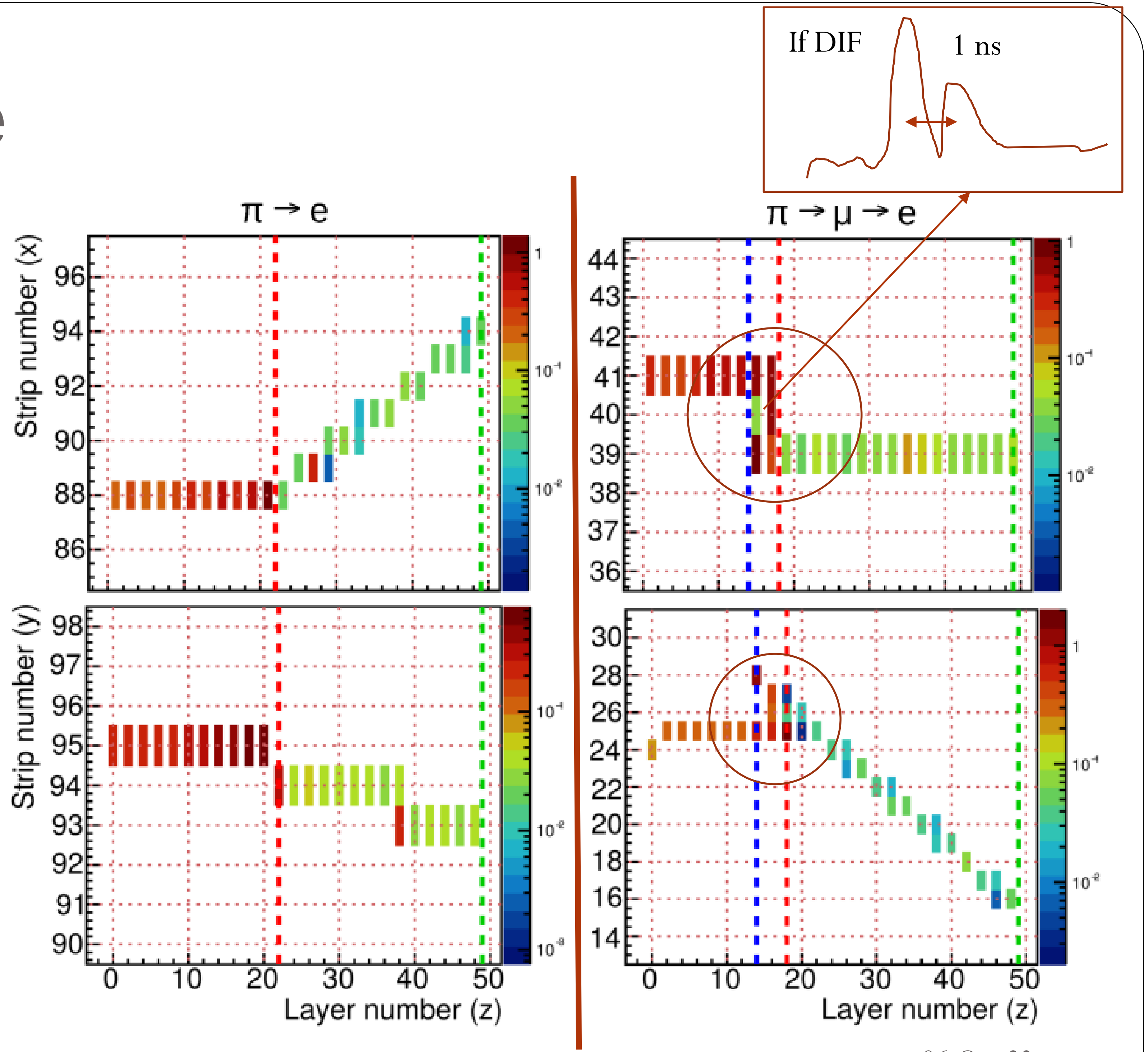


LGAD energy resolution



Event topology example

- Event simulation for $\pi \rightarrow e$ and $\pi \rightarrow \mu \rightarrow e$
  - Shown in X-Y planes with ATAR baseline granularity
- Pion beam entering from the left
  - Red dotted line: pion stop
  - Blue dotted line: muon stop
- **Energy deposit in each plane varies by a factor ~100**
- Highlighted Overlap of hits in for $\pi \rightarrow \mu \rightarrow e$ can be further resolved with **pulse pair resolution in time**
- Event reconstruction using advanced **machine learning algorithms** is also being pursued

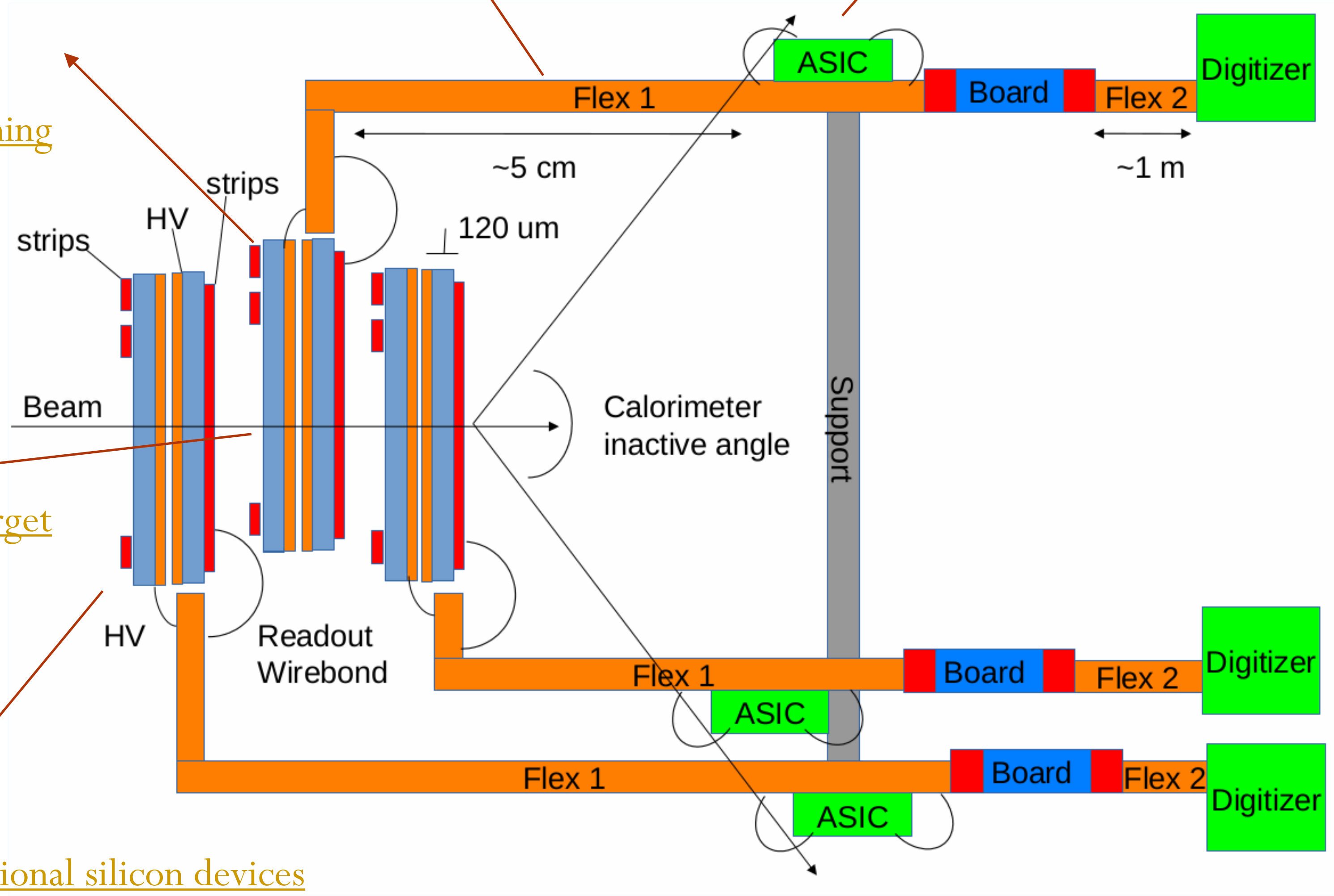


In this session…

Flex connection studies, see here:
High granularity fast silicon sensors for the active target

ASIC and digitization, see:
Front end electronics and digitization for fast silicon

Sensors, likely AC-LGAD strips, see studies here:
High granularity fast silicon sensors for the active target
Fast silicon sensor simulation with TCAD software
Sensor production plans here:
Overview of BNL Silicon sensor capability
BNL approved LDRD related discussion and planning
Production plans at FBK



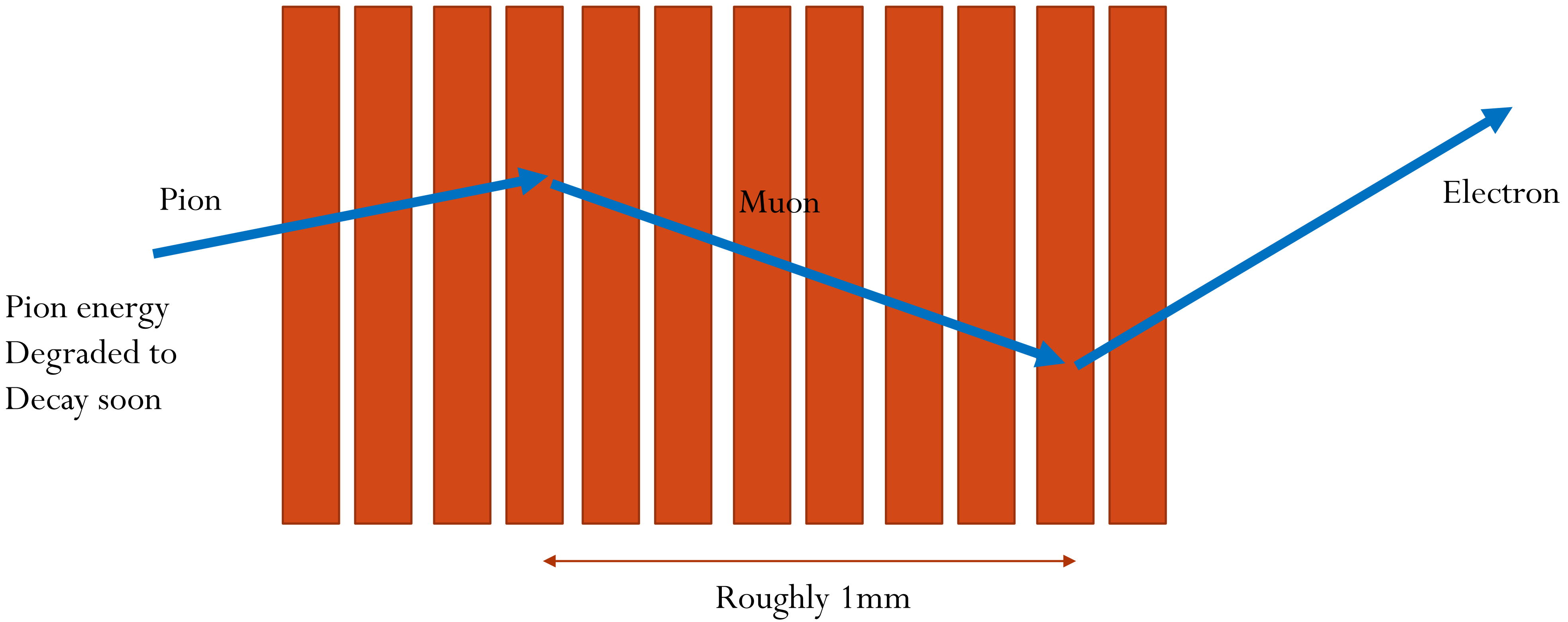
Event reconstruction, see:
Event simulation and reconstruction in the active target
Event reconstruction experience from Lar TPC

Alternative design, see:
Alternative active target design based on traditional silicon devices

ATAR v0.5 plans

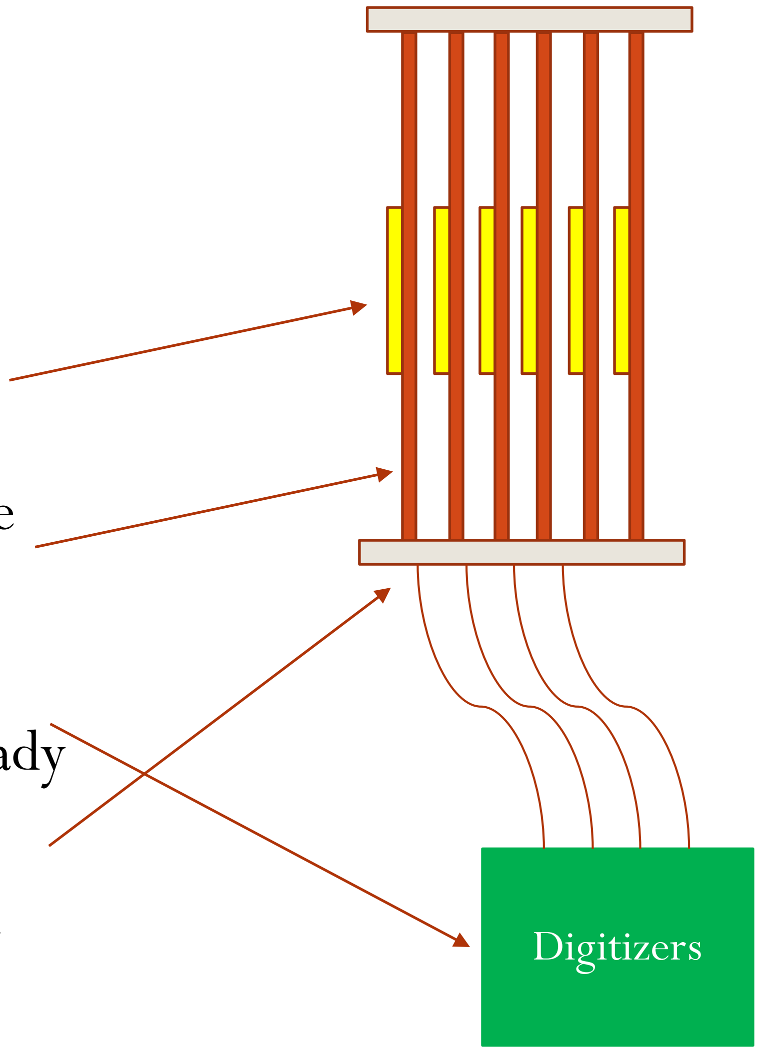
ATAR version 0.5 plans

- Goal is to see a few pion/muon decays in a stack of LGAD sensor
  - “proof of principle” of tail suppression
- Needs a few channels per layer times several layers, total thickness few mm, very compact
- Plan to design an electronic board for ATARv0.5 demonstrator
  - Might be with 100/200 um LGADs → ~10 layers, 8/16 channels per layer



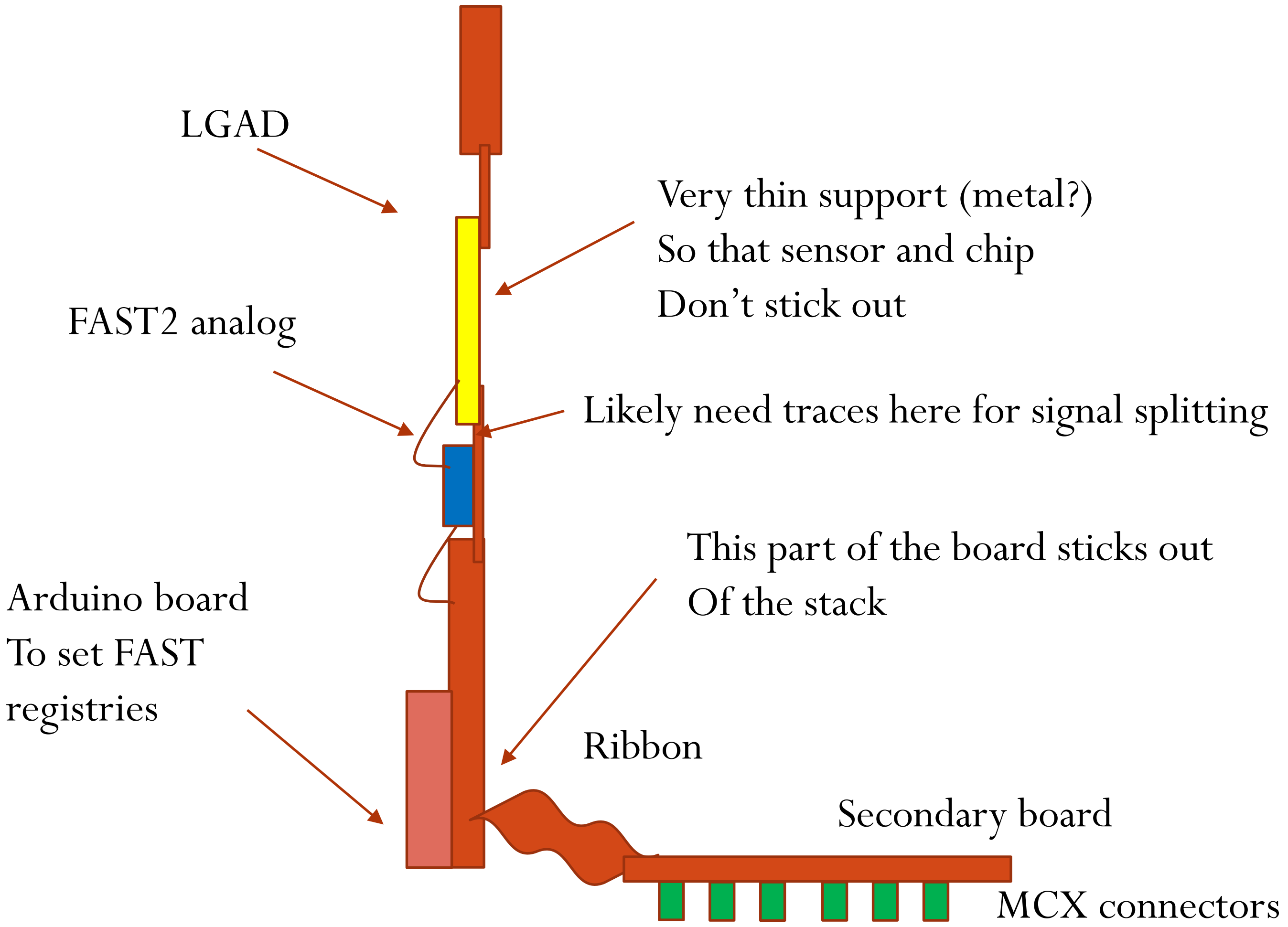
ATAR v0.5 what's needed

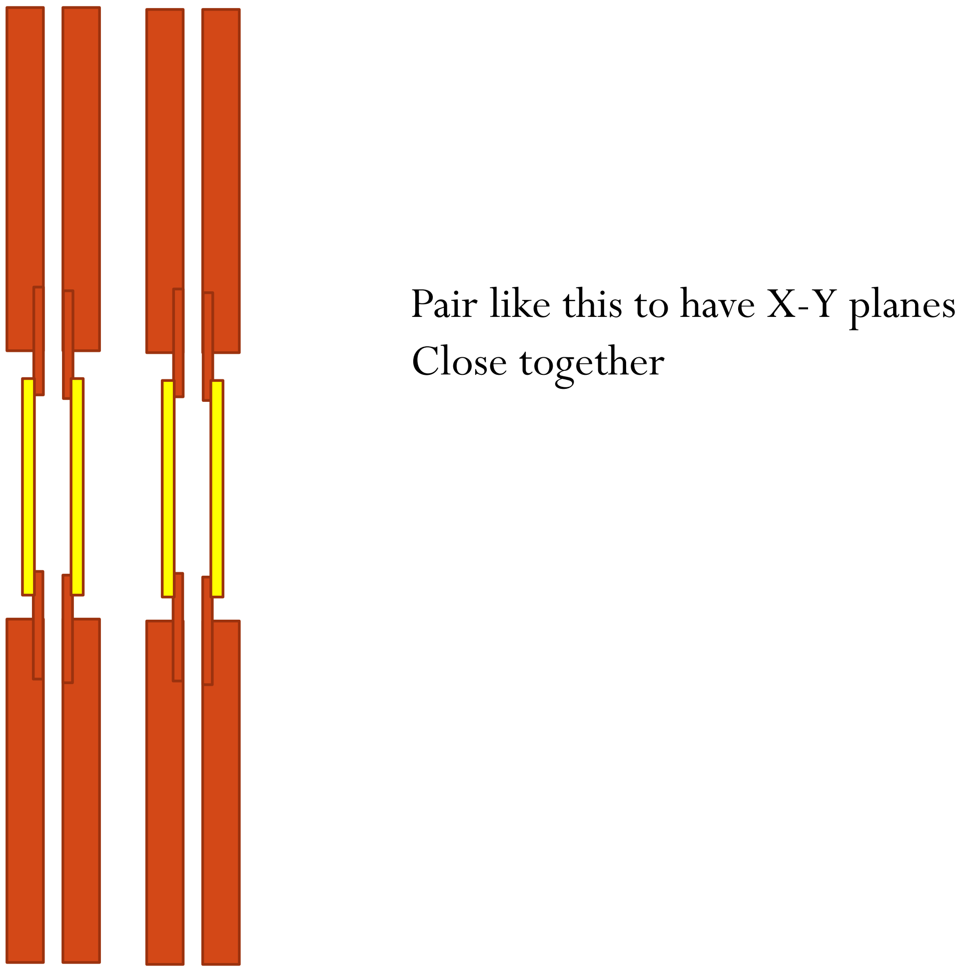
- To build the demonstrator ATAR we would need
  - A PIONEER-specific sensor (LGAD/PiN) production (thicker than usual 50um LGADs) – **BNL** working on it
  - A fast electronic board with large dynamic range that is stackable (see next slide) – **UW/UCSC** working on it
  - A digitizer to fully digitize all events – can be based on wave dream boards (since it's <200 channels) or one of the **NALU** chips if it's ready
  - Proper cable connection, mechanic design and assembly
- Overall there doesn't seem to be a showstopper for this smaller prototype version of the ATAR
  - Best to have all components prototyped and tested ~1 year from now and then work on assembly and design



ATARv0.5 board

- Board might be based on the FAST2 analog chip, with gap between active planes of ~1mm
  - Actually can be FAST3 (coming soon), will discuss in the next months with FAST group in Torino
- Other issue: large charge depositions (up to 100 MiPs), large dynamic range needed → Charge splitting at the amplifier input, going to FAST2 chip channels with two different gains:
  - High gain → electron, low gain → pion/muon
  - This also solves dynamic range issue in digitizer



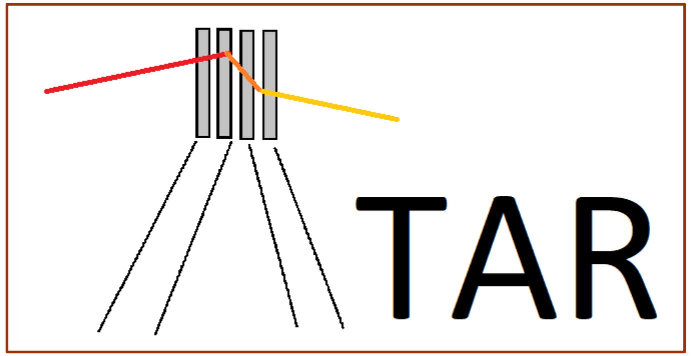


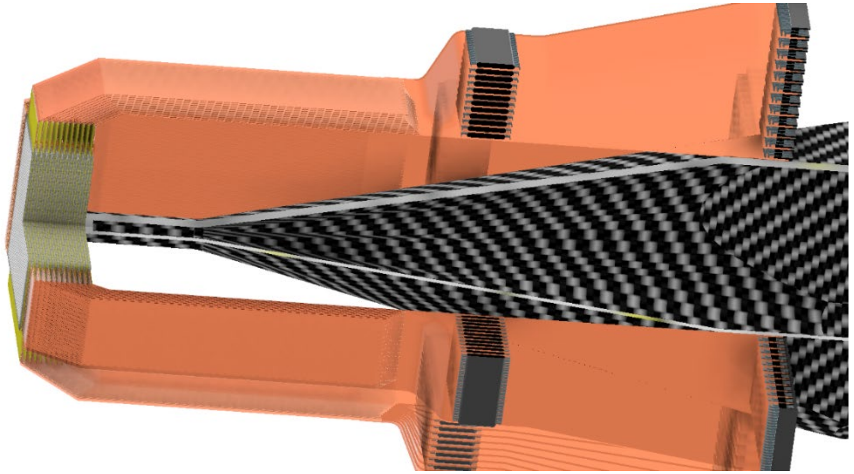
Conclusions

Conclusions

- 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
  - Alternative design based on standard silicon is being studied

- Plans to have a working **ATAR prototype in a couple years** to study pion/muon decays at PSI
  - ATAR v0.5 board is being designed





Today's session

Introduction to the ATAR project and session	*Simone Michele Mazza*	
Cervantes and Velasquez Room, UC Santa Cruz	13:10 - 13:30	
High granularity fast silicon sensors for the active target	*Dr Jennifer Ott*	
Cervantes and Velasquez Room, UC Santa Cruz	13:30 - 14:00	
Alternative active target design based on traditional silicon devices	*Xin Qian et al.*	
Cervantes and Velasquez Room, UC Santa Cruz	14:00 - 14:20	
Event simulation and reconstruction in the active target	*Vincent Wai Sum Wong*	
Cervantes and Velasquez Room, UC Santa Cruz	14:20 - 14:40	
Event reconstruction experience from Lar TPC	*Chao Zang*	
Cervantes and Velasquez Room, UC Santa Cruz	14:40 - 15:00	
Coffee		
Cervantes and Velasquez Room, UC Santa Cruz	15:00 - 15:20	
Fast silicon sensor simulation with TCAD software	*Mohammad Nizam et al.*	
Cervantes and Velasquez Room, UC Santa Cruz	15:20 - 15:50	
Front end electronics and digitization for fast silicon	*Abraham Seiden*	
Cervantes and Velasquez Room, UC Santa Cruz	15:50 - 16:10	
Overview of BNL Silicon sensor capability	*Dr Gabriele Giacomini et al.*	
Cervantes and Velasquez Room, UC Santa Cruz	16:10 - 16:20	
BNL approved LDRD related discussion and planning	*Volodya Tishchenko*	
Cervantes and Velasquez Room, UC Santa Cruz	16:20 - 16:30	
Conclusions and discussion	*Simone Michele Mazza*	
Cervantes and Velasquez Room, UC Santa Cruz	16:30 - 17:00	

Measuring pion beta decay in PIONEER	*Dinko Pocanic et al.*
Cervantes and Velasquez Room, UC Santa Cruz	09:00 - 09:30
Electronics (Kevin) + trigger (Dieter)	*Dieter Ries et al.*
Cervantes and Velasquez Room, UC Santa Cruz	09:30 - 10:00
Tracker possibilities from Stony Brook	*Dr Prakhar Garg et al.*
Cervantes and Velasquez Room, UC Santa Cruz	10:00 - 10:20
Coffee	
Cervantes and Velasquez Room, UC Santa Cruz	10:20 - 10:40
Production plans at FBK	*Matteo Centis Vignali*
Cervantes and Velasquez Room, UC Santa Cruz	10:40 - 10:55
DAQ overview	*Tim Gorringe*
Cervantes and Velasquez Room, UC Santa Cruz	10:55 - 11:15
PIONEER going forward; R&D; next PSI; Small funding	*David Hertzog*
Cervantes and Velasquez Room, UC Santa Cruz	11:15 - 11:30
DISCUSSION of these Systematics	
Cervantes and Velasquez Room, UC Santa Cruz	11:30 - 12:00

Don't miss tomorrow's talk on FBK production plans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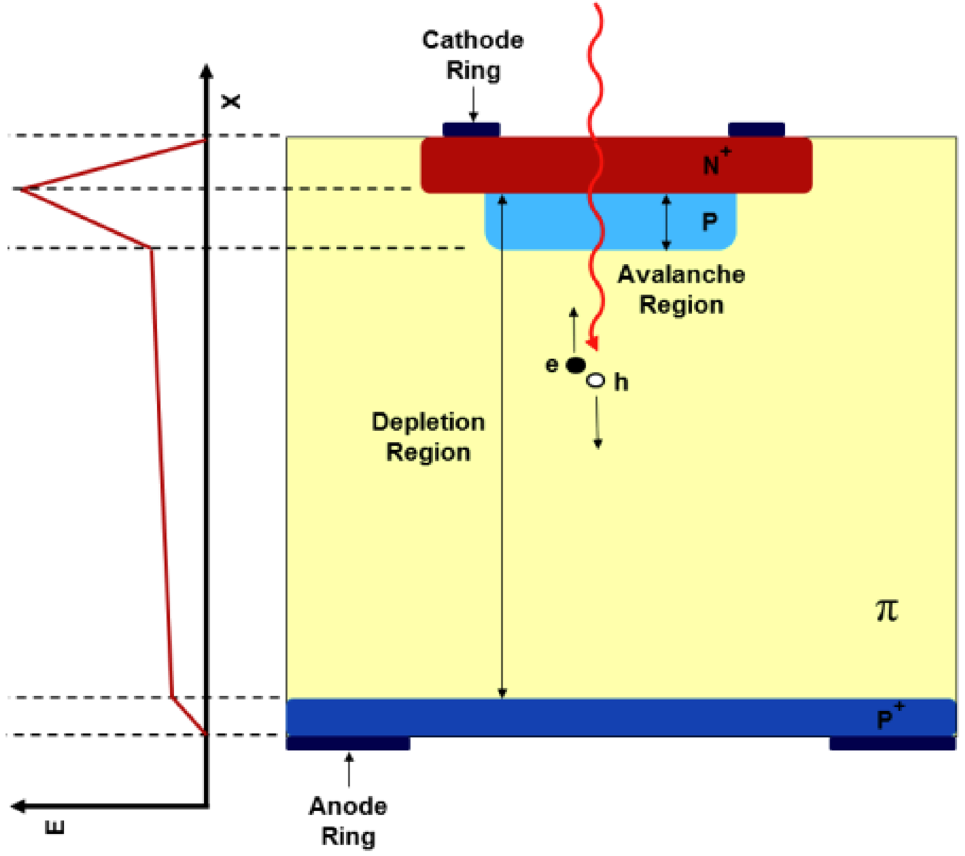
1868
Thank you

Low Gain Avalanche Detectors

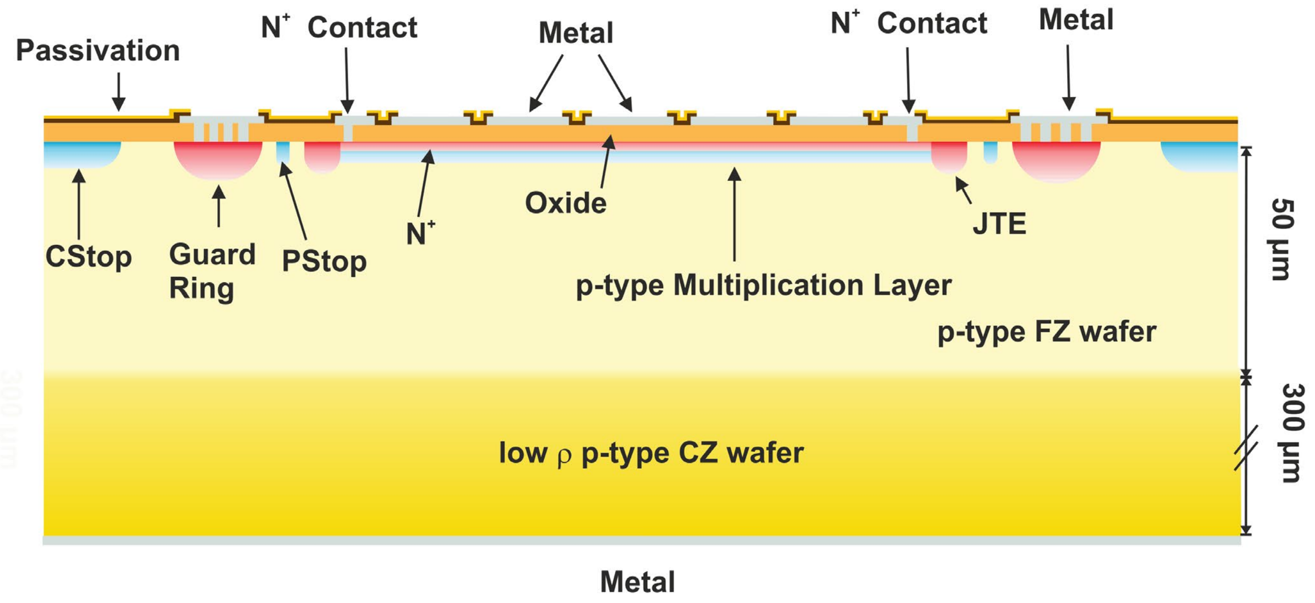
- LGAD: silicon detector with a thin (<5μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Electron multiplication but not hole multiplication (not in avalanche mode, controlled gain)
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Better signal to noise ratio, sharp rise edge
- Better signal to noise ratio and thin detectors means improved timing resolution
  - **Time resolution down to 20 ps**



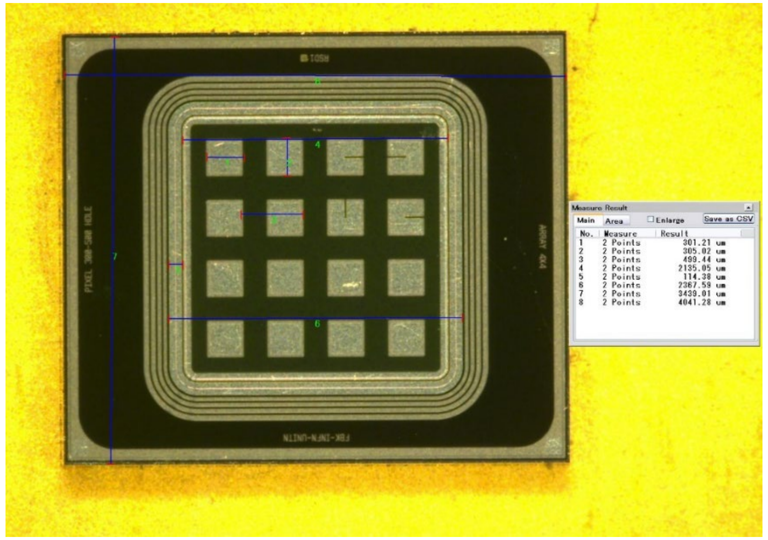
- Field protection structures currently limit granularity of LGADs
  - ~50-100 um inactive region between pixels
- But intensive R&D is ongoing to overcome this limitation

AC-LGADs

- Most advanced prototype of high granularity LGADs are **AC-LGADs**
  - (UCSC - US patent N. 9,613,993 B2, granted Apr. 4, 2017)
- Continuous sheets of multiplication layer and **N+ resistive layer**
  - 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
- Intrinsic charge sharing between metal electrodes
  - Allows for precision hit precision better than $\sqrt{12}$
  - 5 um precision achievable for 500 um pitch



- **The response of the sensors can be tuned by modifying several parameters**
  - Pad distance
  - Resistivity of N+ layer
  - Oxide thickness
  - Pad geometry and dimension



Prototype AC-LGAD from FBK, 500 um pitch, 300 um metal