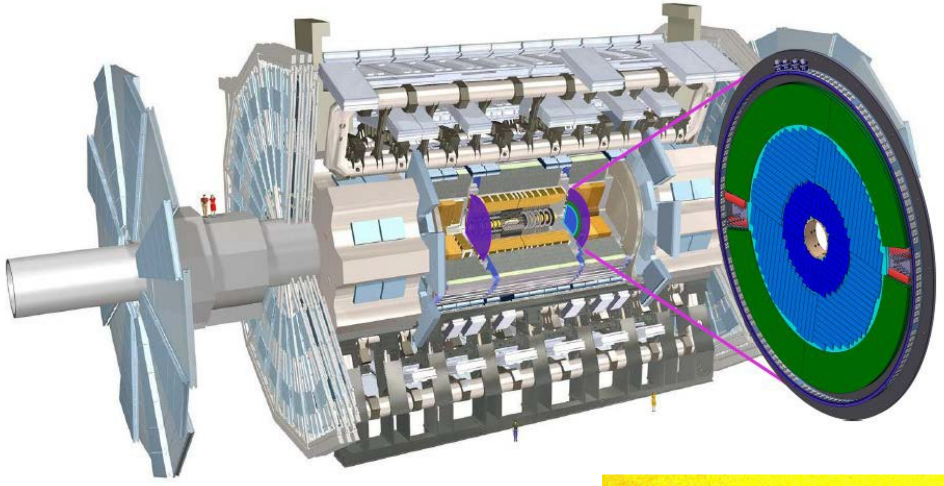
Development of 4/5D detectors for near-future Higgs factories and nuclear physics experiments

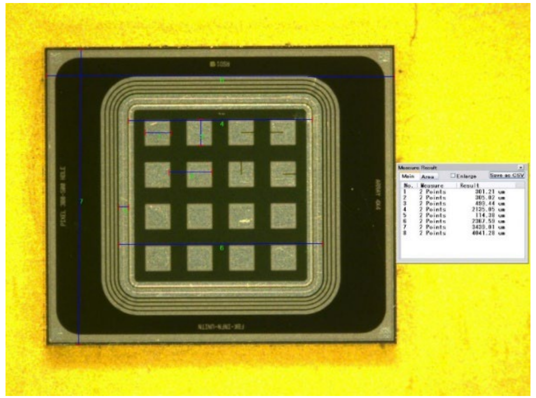
Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)

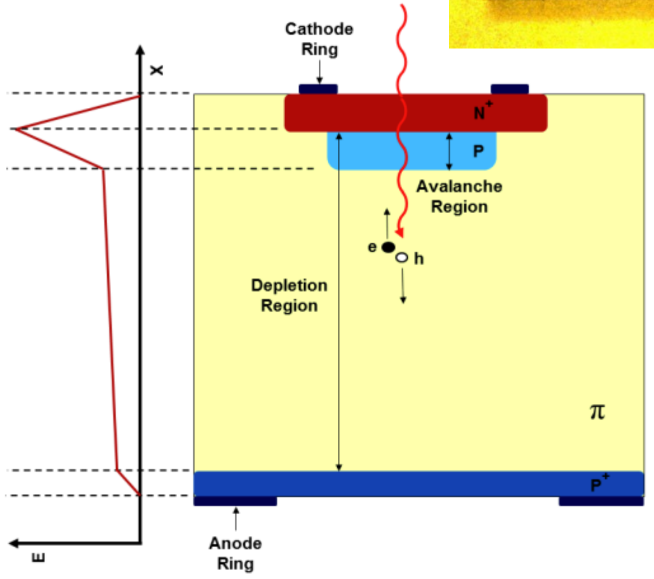
HEPCAT lecture May 2024

Talk overview

I. 4D tracking and LGAD technology
II. Radiation resistant LGAD design
III. High granularity LGADs
IV. LGAD applications in HEP and NP
V. X-ray detection with LGADs and other applications



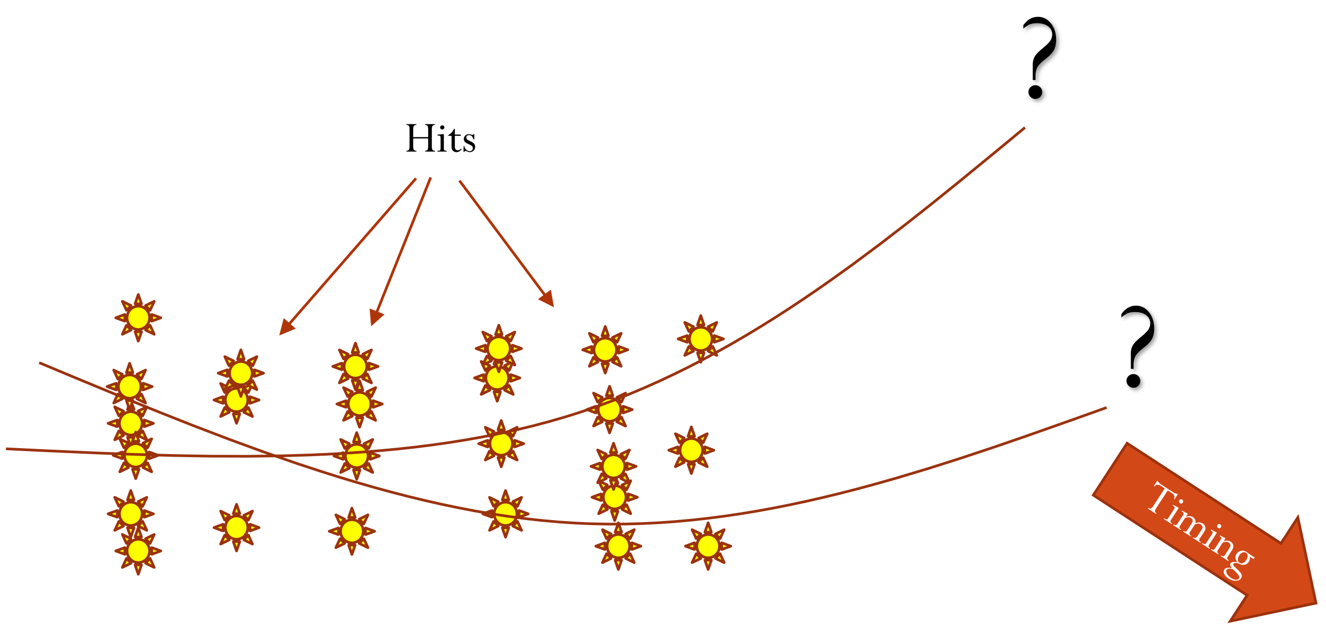




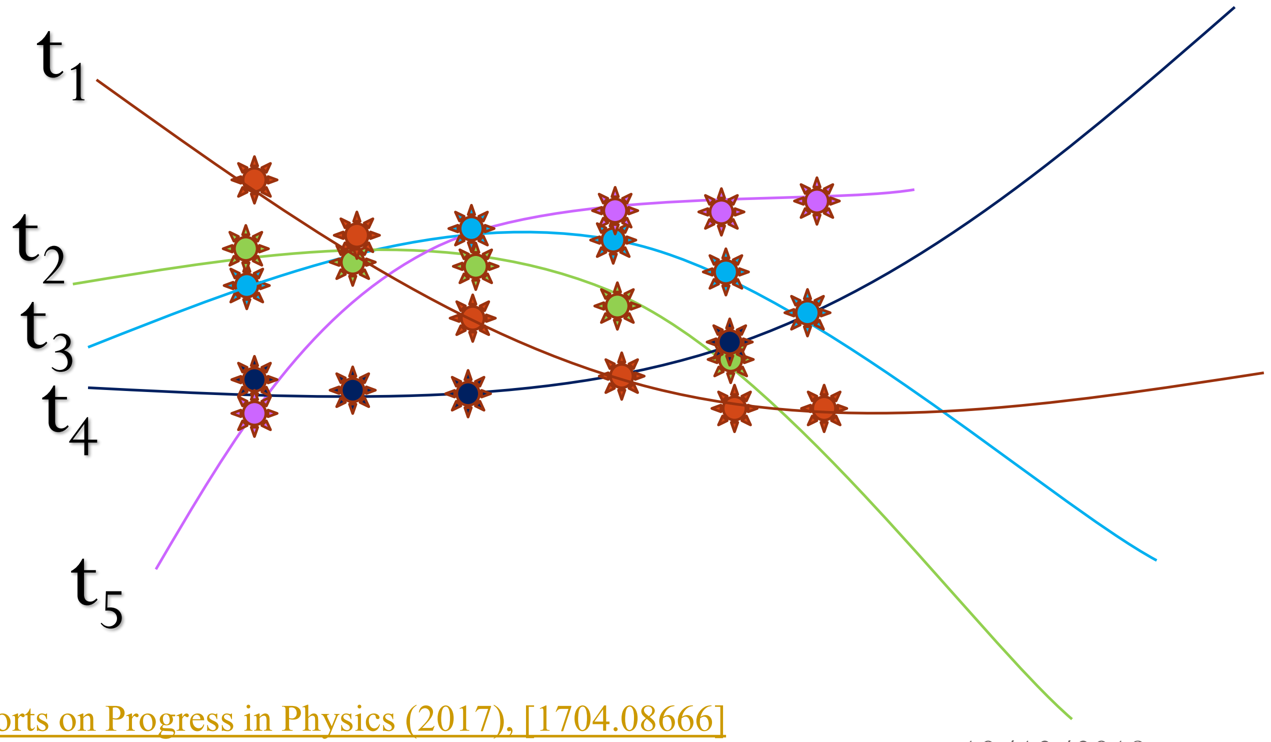
I. LGAD technology

Time resolution challenge

4D tracking - concept



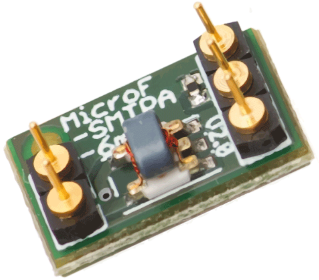
- Efficient tracking in dense environment
  - Pile-up suppression
  - Long Lived Particle detection
  - Appearing/Disappearing tracks identification
  - ToF-based particle identification
  - Jet flavor tagging enhancement



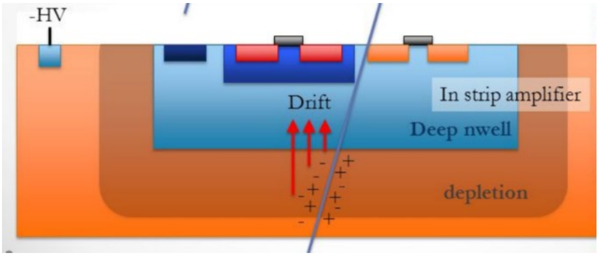
- Collection of hits for multiple tracks in dense environment
  - Harder to reconstruct tracks with usual algorithms
- But if particles have different initial position (vertex) or delayed in time (from pileup)
  - We can exploit the **time** of the single hits
- Easier to reconstruct single tracks
- ~ps → ~mm at speed of light, 1→100ps is the needed time resolution for usual collider beam spot size

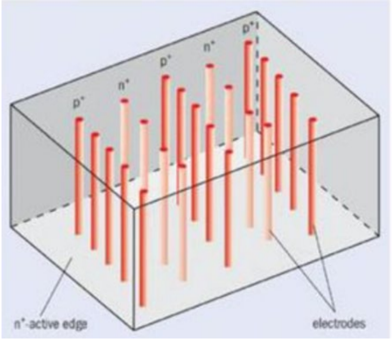
Reports on Progress in Physics (2017), [1704.08666]

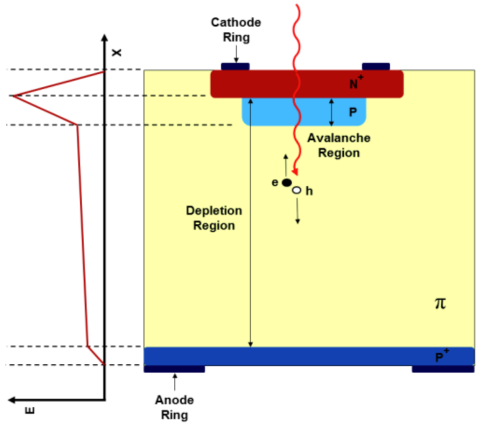
Time precision sensors



- **Which technology has sufficient time resolution for 4D tracking?**
- SiPM (Silicon photomultiplier)
  - But very little radiation hardness
- HV CMOS detector
  - Embedded amplification in the design, ~50-100 ps of time resolution
- 3D silicon sensors
  - Perpendicular charge collection, ~20-30ps of time resolution, limitation due to dead areas and non-homogeneous field
- **Low Gain Avalanche Detectors (LGADs) → see next!**
  - Intrinsic gain, thin bulk, ~ 20-30ps of time resolution
- In the future: LGAD CMOS? New materials (diamond)?

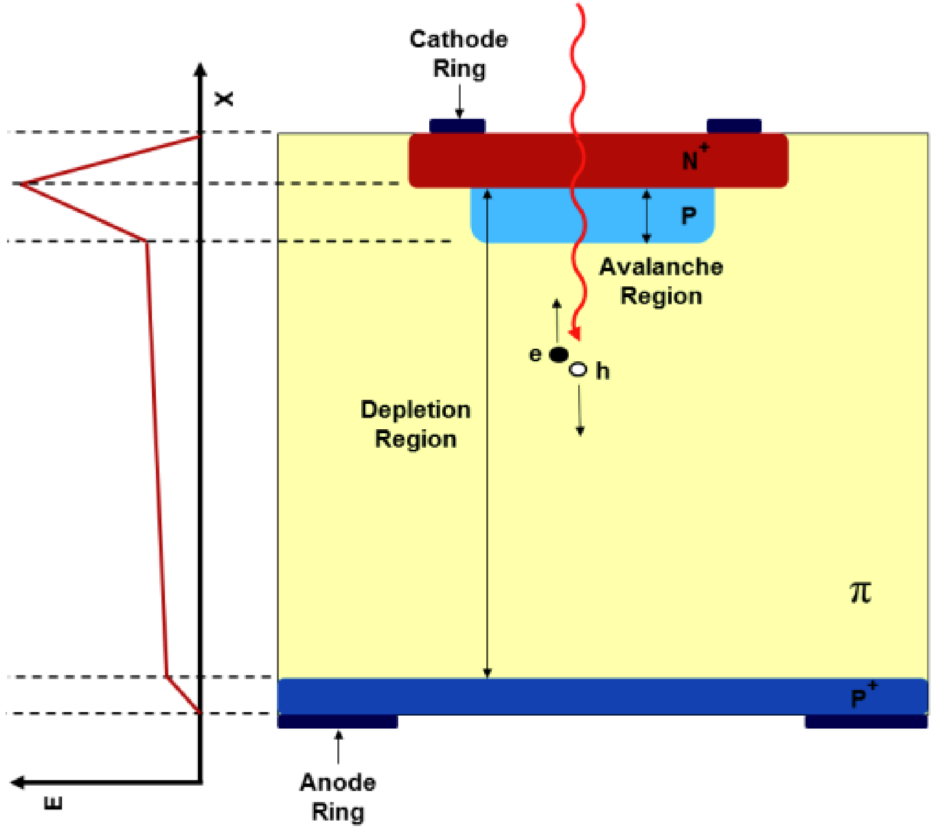






Low Gain Avalanche Detectors

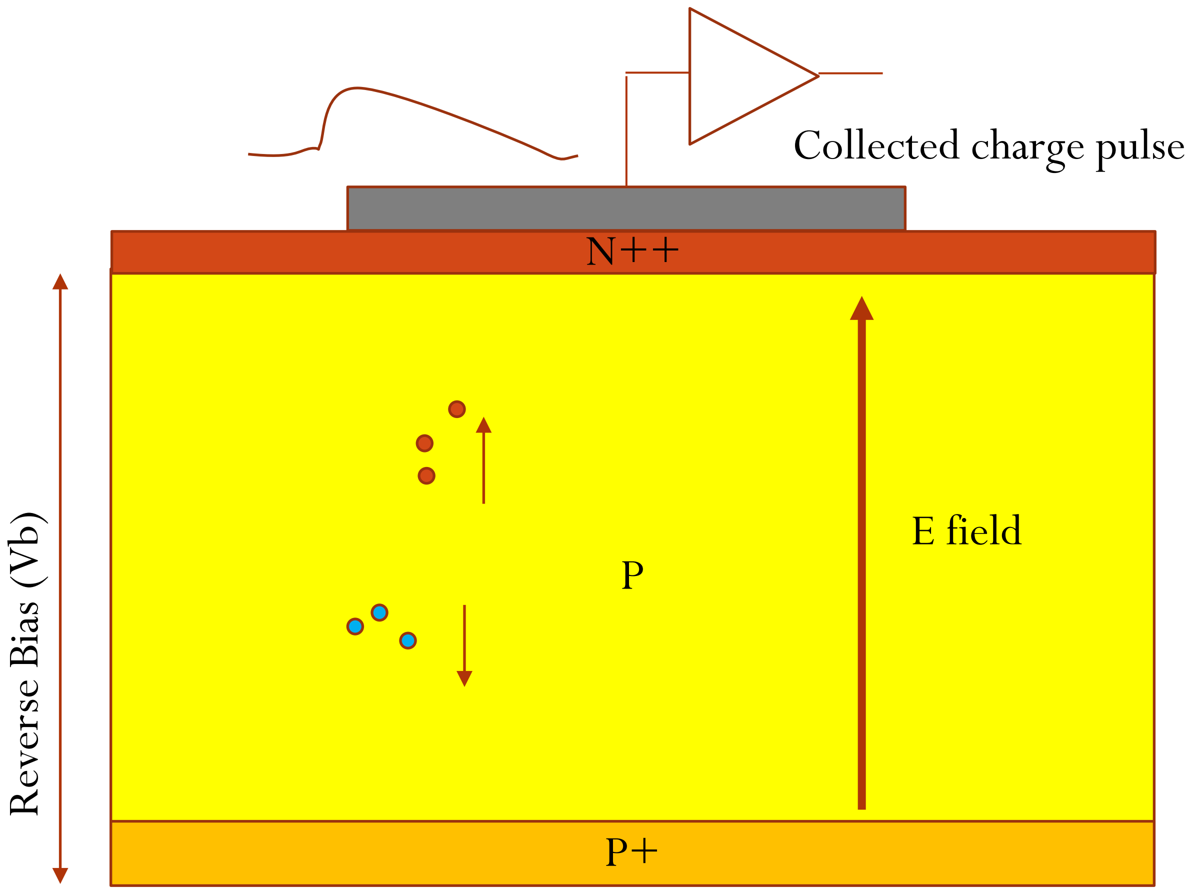
- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
- **Great hit time resolution: <20 ps!**



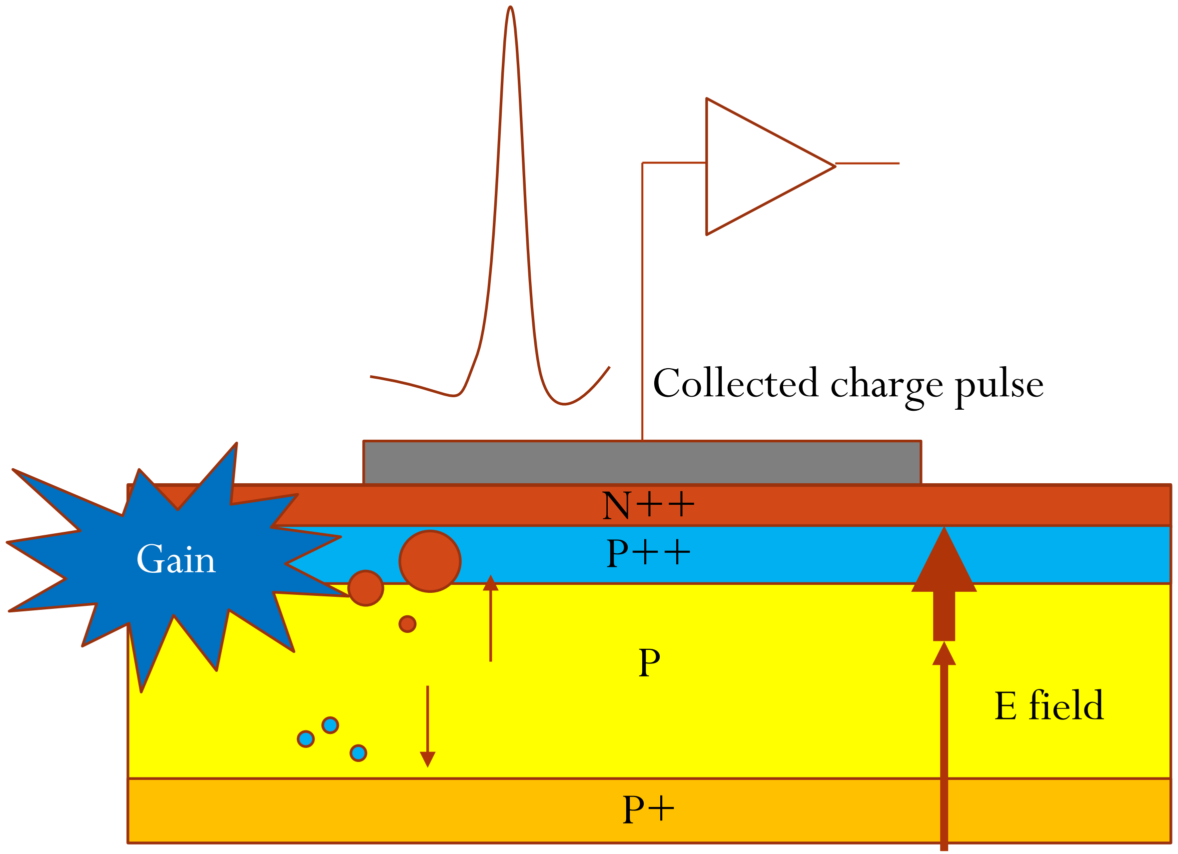
- Several producers of experimental LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL (China)

Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

Silicon detector

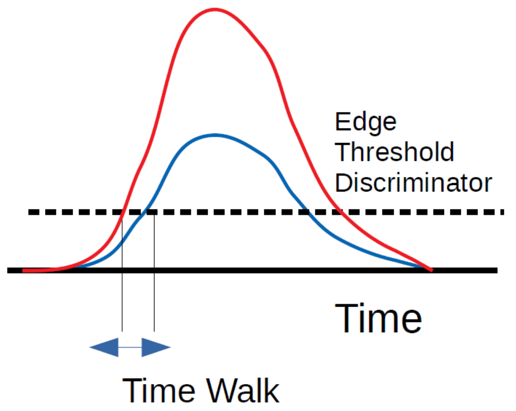


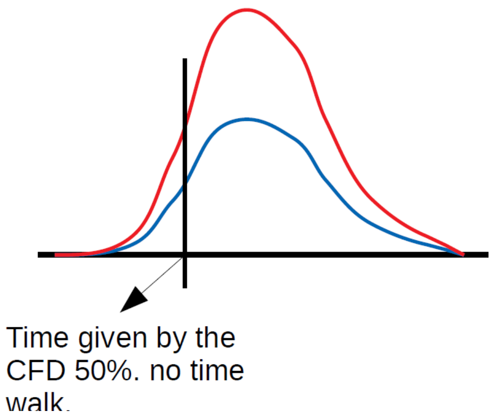
LGAD

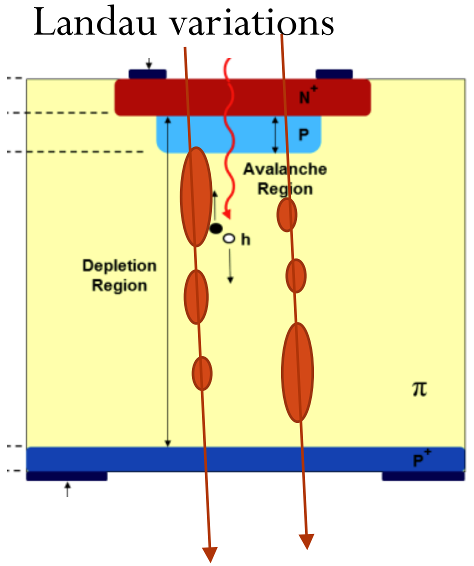


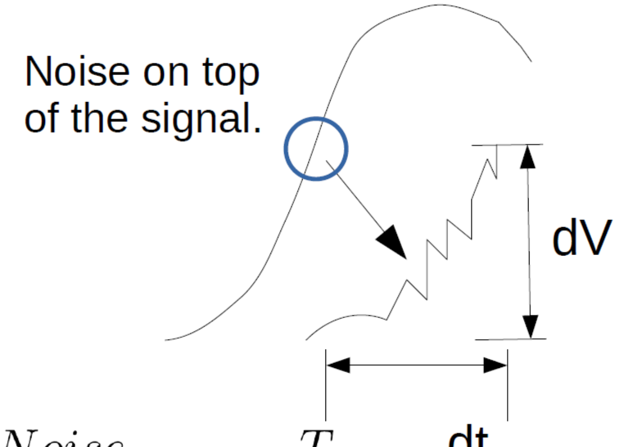
- Collected charge from a MiP is proportional to sensor thickness: a standard silicon detector needs to be a few 100s um thick to get a decent S/N
- **Thanks to gain LGADs can be thinner, with a shorter pulse with better S/N**

Time resolution









$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

Sensor time resolution main terms

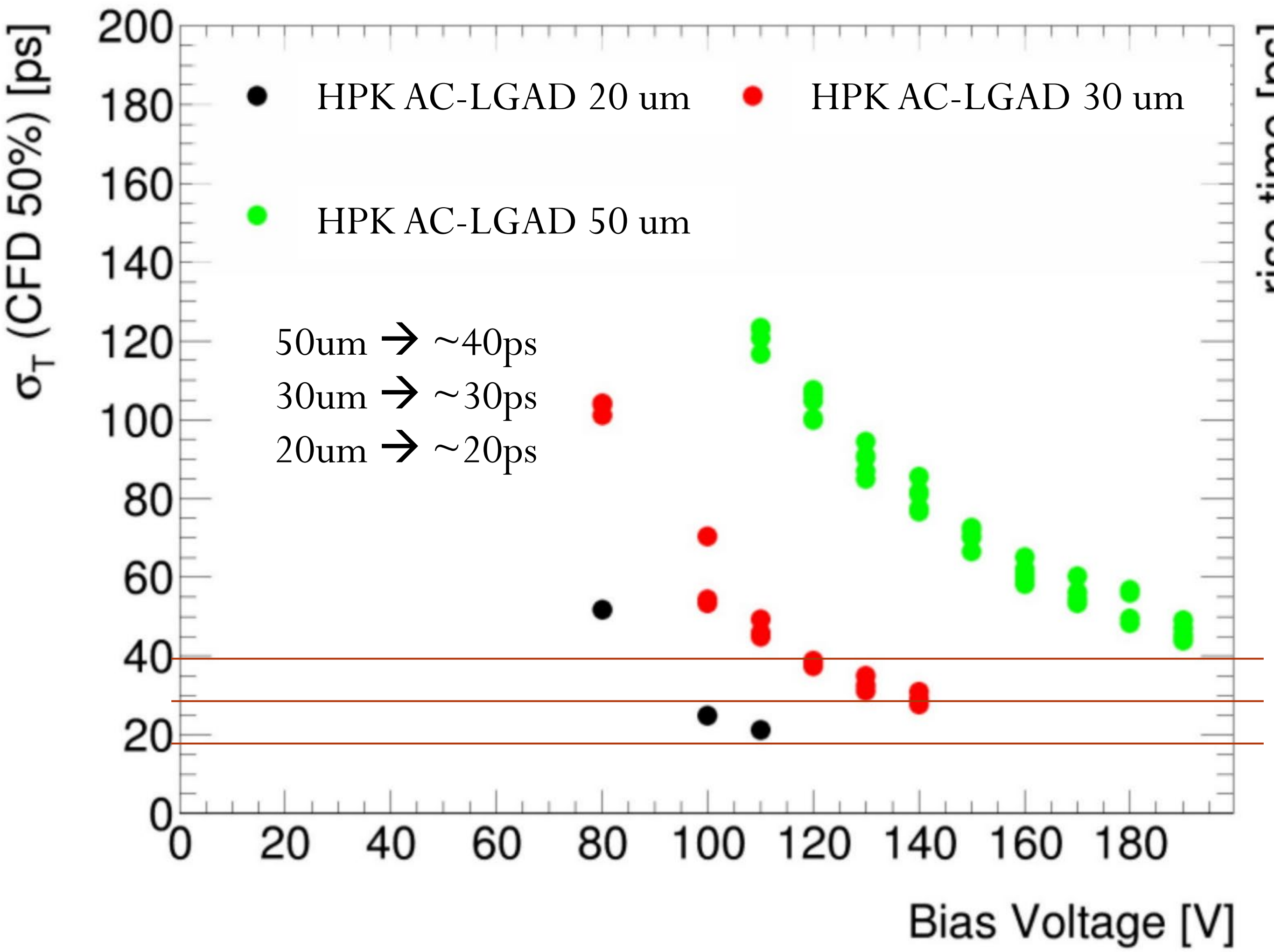
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

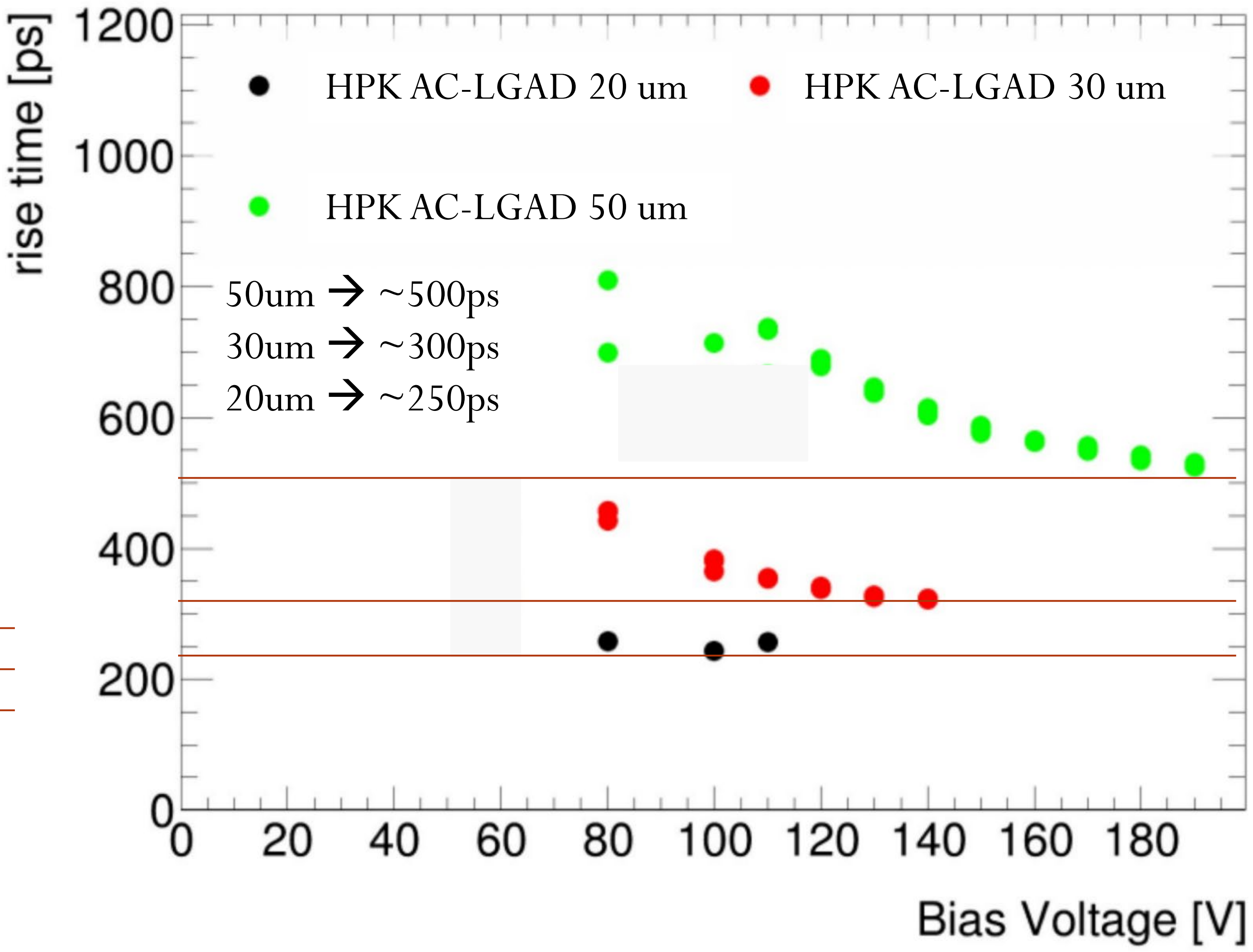
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to ${}^{1}\big/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)
- **Landau term**: proportional to silicon sensor thickness
  - Reduced for thinner sensors
  - Dominant term at high gain

- **Bottom line: thin detectors with high S/N**

Time resolution vs thickness

- When sensor has high gain there's **very low jitter contribution** to the time resolution, ultimately driven by Landau component → **Depends on sensor thickness**

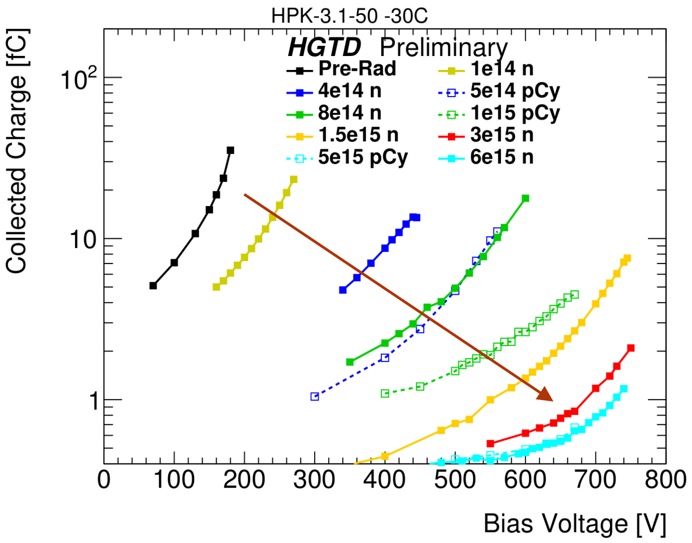


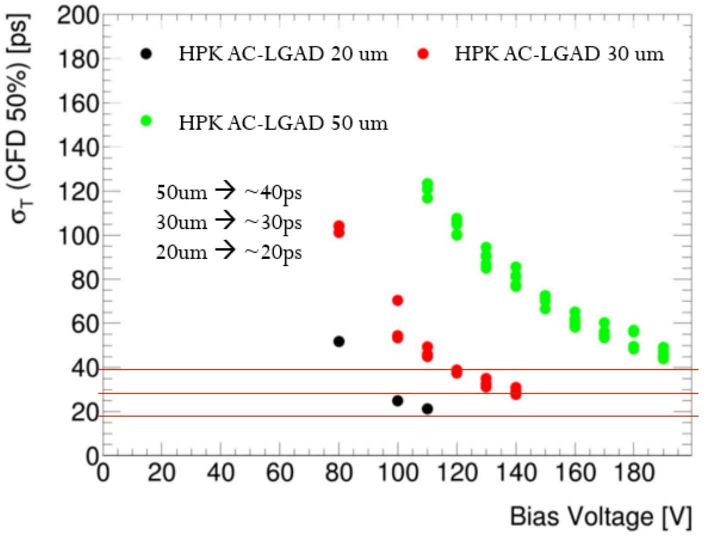


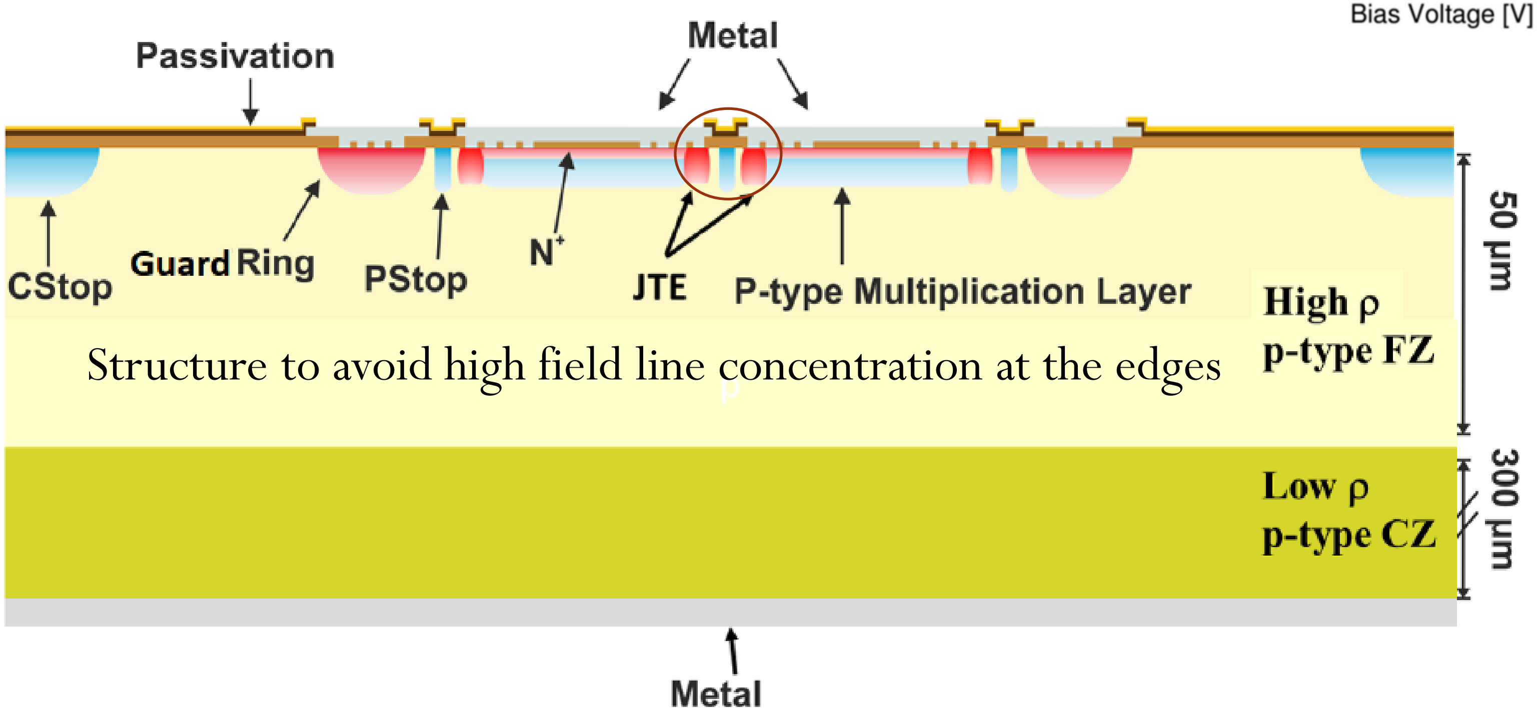
Data by: J. Ding

LGADs limitations

- **Radiation hardness:**
  - LGADs work well up to a few 10e15Neq, then lose all gain
- **Granularity:**
  - Protection structures limit the current granularity of LGADs to the mm
- **Time resolution:**
  - LGADs can push to 20ps, but reaching 10ps or even 15ps is very challenging
- But intensive R&D is ongoing!
  - Some are also a challenge for the readout electronics







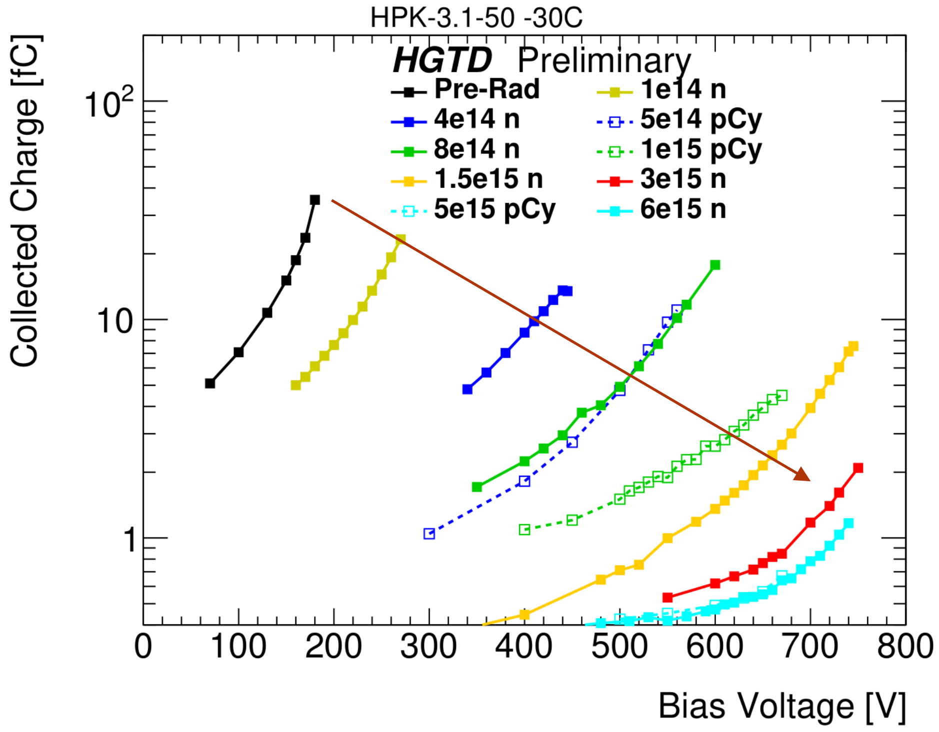
II. Radiation resistant LGAD design

Radiation hardness challenge

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

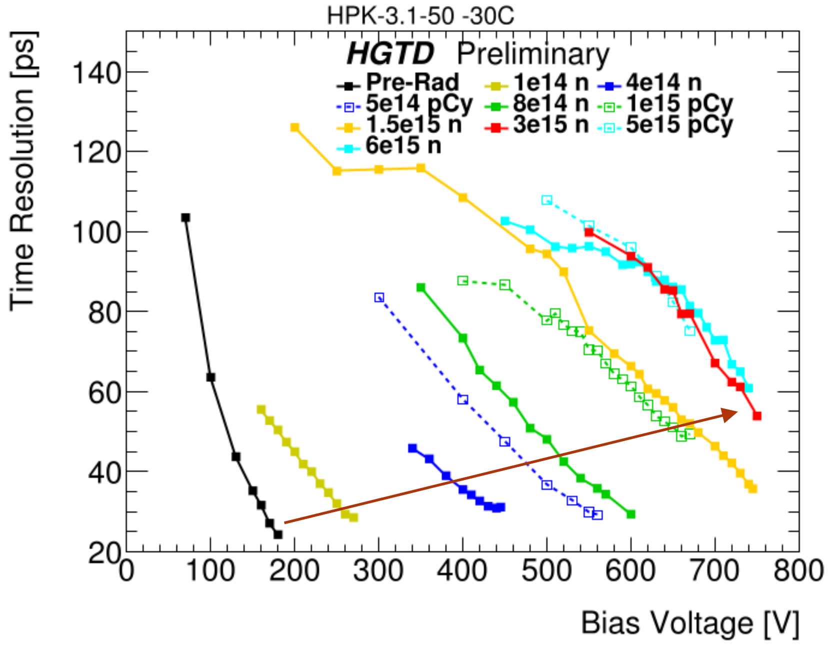
LGAD and radiation damage

- LGADs while operating in high energy physics experiments will sustain radiation damage
  - Both in terms of fluence and ionization dose
- Change in performance caused by reduced doping concentration in the gain layer by **acceptor removal mechanism**
  - Some details: https://doi.org/10.1016/j.nima.2018.11.121



Performance effects of radiation damage (E.g. on 50um sensor)

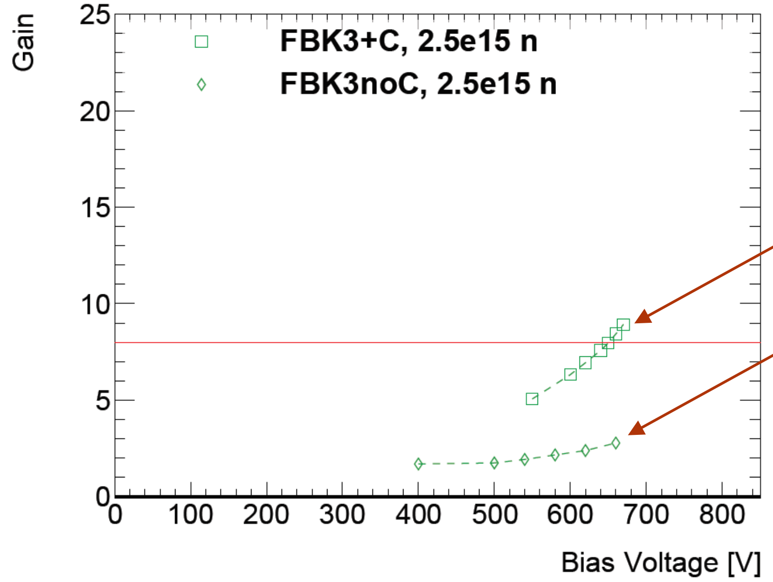
- Partly the performance can be recovered by increasing the bias Voltage applied to the diode (~200V → ~700V)
- **Reduction of gain and collected charge**
  - Charge collected up to 30fC (Gain ~50) before irradiation to 1fC (gain 2-3) after a fluence of 6E15 Neq/cm^2
  - (Neq: equivalent 1 MeV neutrons on cm^2)
- **Increased time resolution**
  - Time res. of 25ps to 60ps after a fluence of 6E15 Neq/cm^2



Radiation hard LGAD design

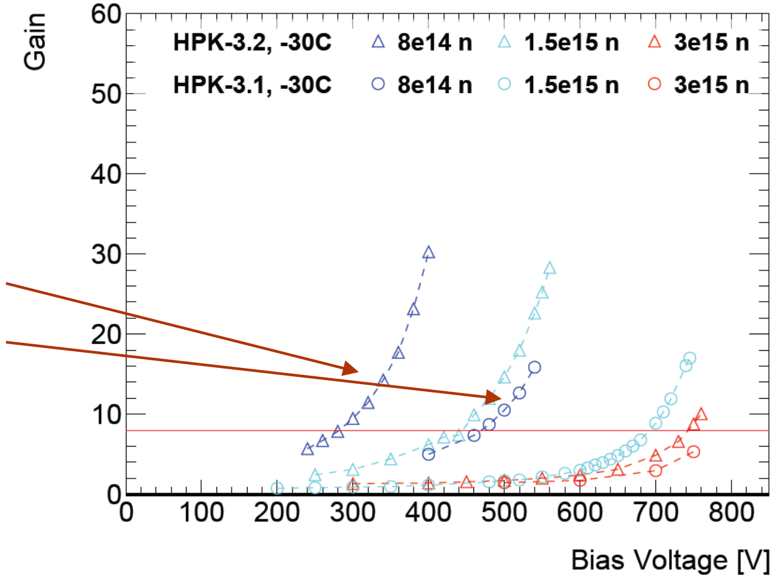
Radiation hardness of LGADs can be increased by:

- **Thin but highly doped gain layer**
- **Addition of Carbon**
  - Carbon is electrically inactive (no effect pre-irradiation), catches interstitials instead of Boron, reduces acceptor removal after irradiation
- **Deeper gain layer**
  - High field for larger volume
  - Allows for better recovery of the gain from increased bias voltage after radiation damage
- The combination of all techniques (by FBK) allowed to **produce a sensor with gain ~20 at 2.5E15 Neq**



With Carbon

Without Carbon



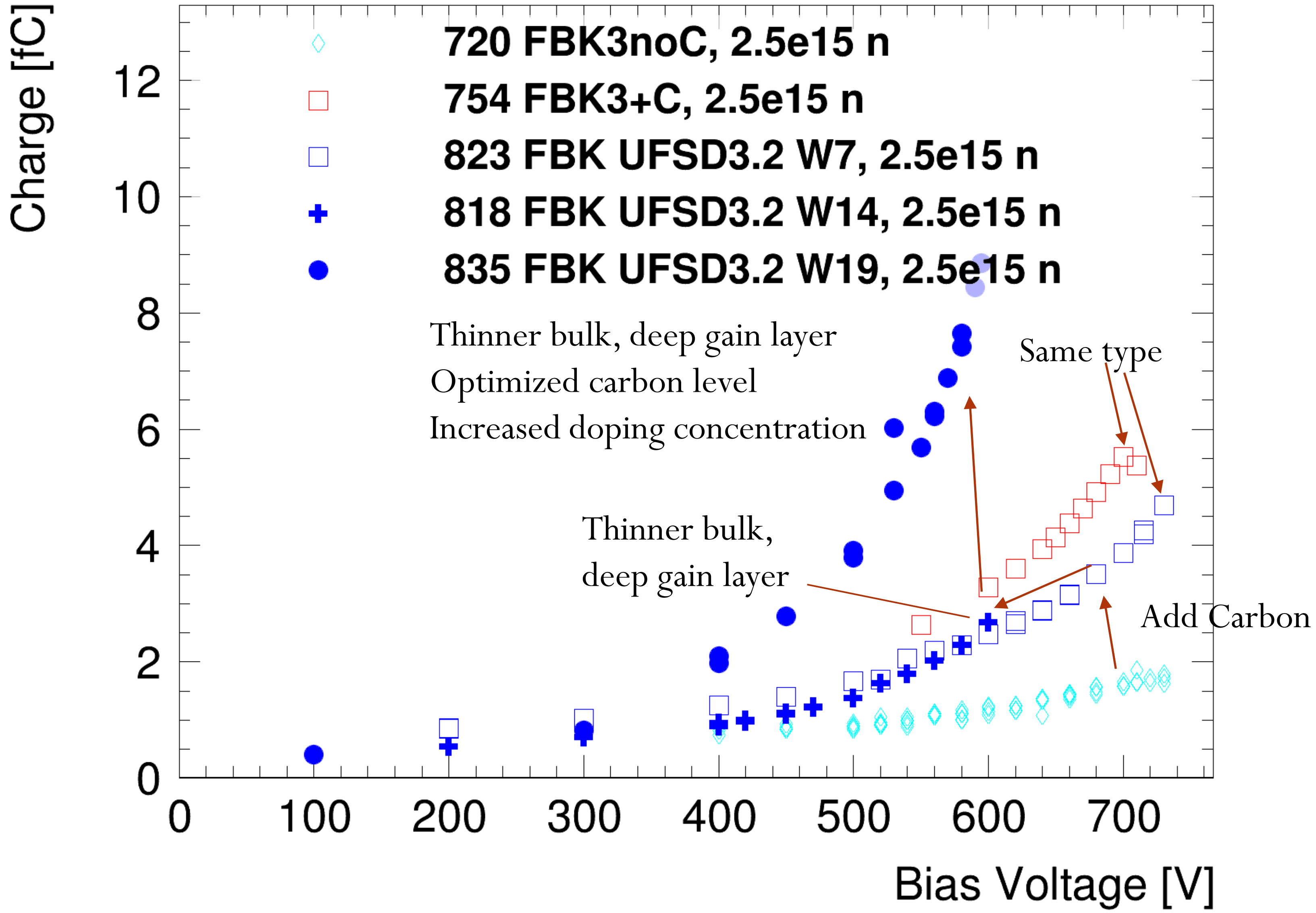
Deeper gain layer (triangles)

Less deep gain layer (circles)

(same color, same fluence)

- Resources
  - https://iopscience.iop.org/article/10.1088/1742-6596/2374/1/012173/meta
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/10/P10003
  - https://www.sciencedirect.com/science/article/pii/S0168900218317741
  - https://doi.org/10.1088/1748-0221/15/04/T04008
  - https://doi.org/10.1016/j.nima.2018.08.040

FBK LGAD performance at maximum irradiation



- **FBK UFSD3.2 sensors show the great potential of deep gain layer and Carbon implantation**
- FBK3noC (no carbon) has the worse performance
- FBK3+C and FBK UFSD3.2 (same structure with Carbon) have much better performance
- FBK UFSD3.2 W14 with deep gain layer is similar to FBK3+C but has thinner bulk
  - lower initial charge, but better time resolution
- FBK UFSD3.2 W19 (highly doped, deep gain layer, optimized Carbon) best performance
  - **W19 has a higher starting point in gain layer doping to increase the radiation reach**

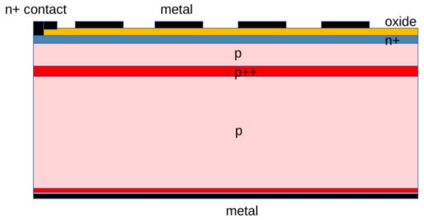
https://indico.cern.ch/event/983068/contributions/4223171/attachments/2191347/3703735/020221_TREDI_LGAD_radhard.pdf
https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf
https://indico.cern.ch/event/983068/contributions/4223215/attachments/2192222/3705404/Siviero_TREDI2021.pdf

Radiation hardness for future colliders

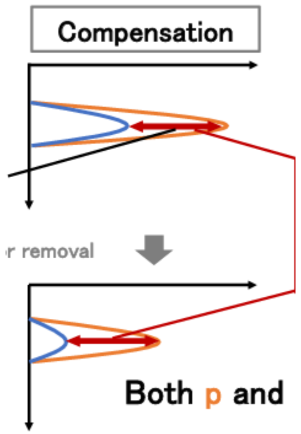
- **New technology** needs to be developed for future colliders with **high radiation hardness requirements** ($10^{16\text{-}17}$ Neq/cm^2) and **high occupancy** (e.g.: FCC-hh)
- With R&D effort in ATLAS/CMS in ~6 years **x10 improvement in radiation hardness,** up to 2.5E15 Neq/cm^2
  - Need for order of magnitude increase in radiation hardness and higher granularity
- **Many efforts are ongoing to push the radiation hardness of LGADs**
  - Rad-hard timing electronics also needs to be developed hand-in-hand

Radiation hard

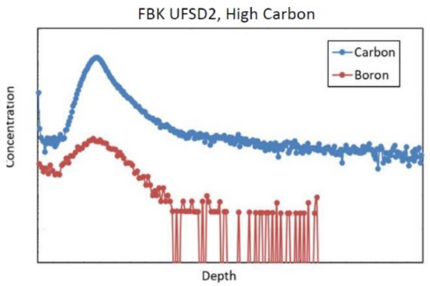
Buried-LGAD



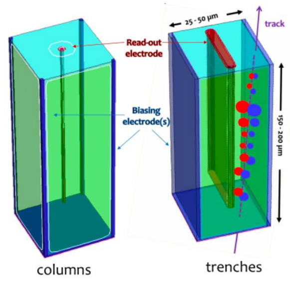
Compensated gain layer



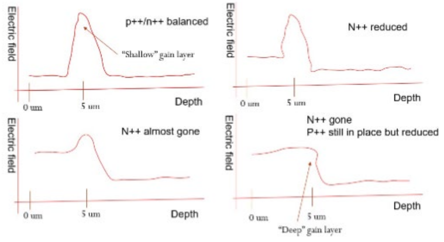
Carbon implantation
Carbon shielding



3D trenches



Adaptive gain layer



Inactive Boron,
Low diffusion

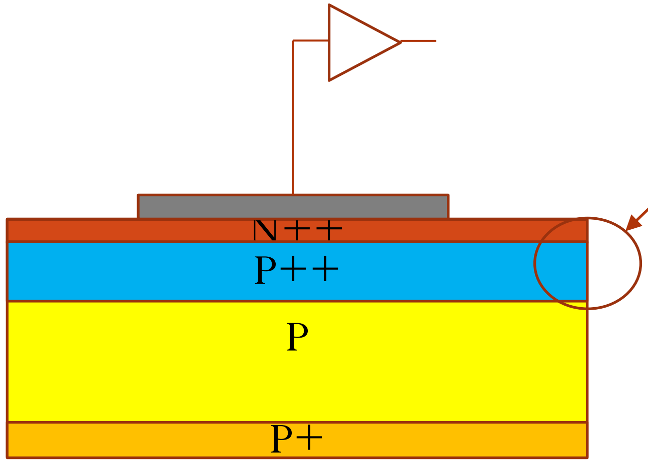
LGAD CMOS

Snowmass papers: 4D tracking paper, CMOS, Electronics, SiC, 3D integr.

III. High granularity LGADs

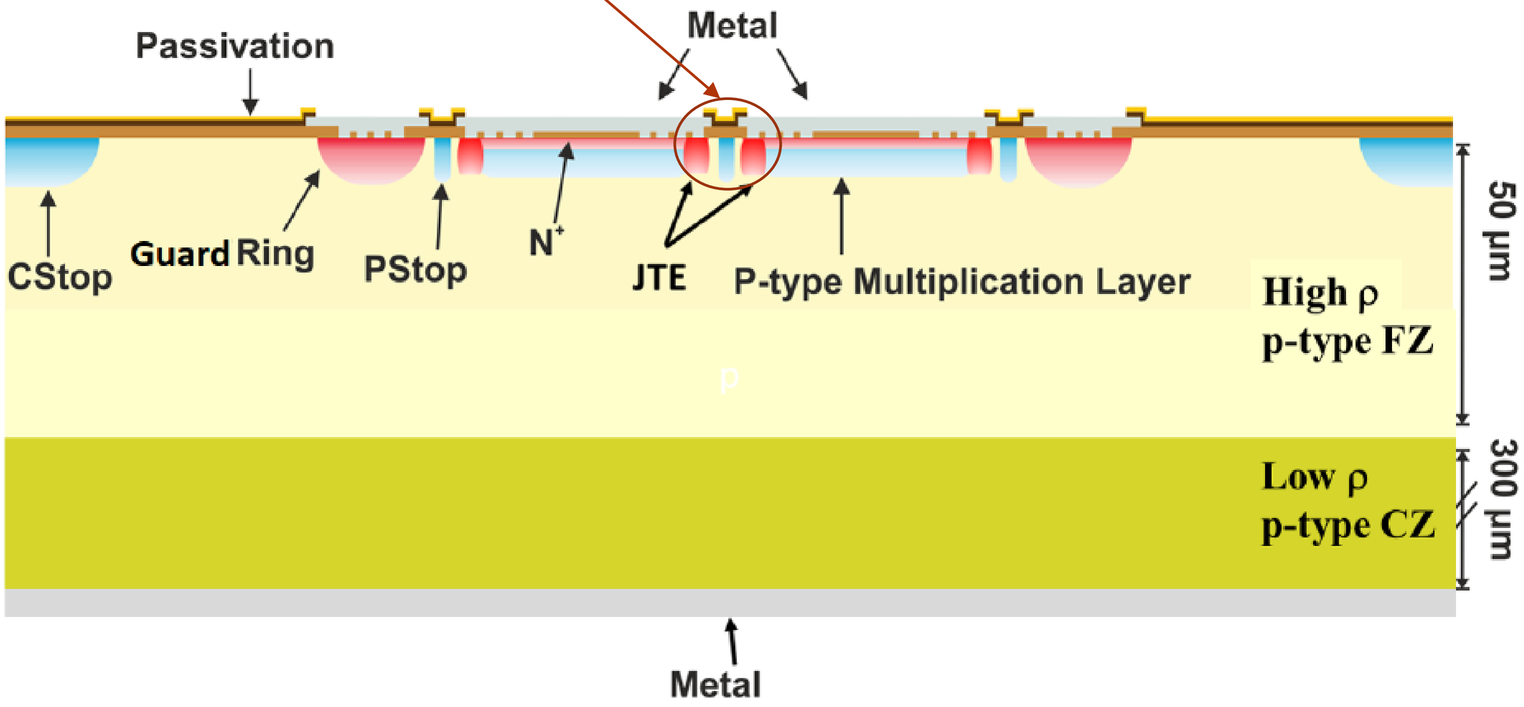
Granularity challenge

LGAD arrays structure



Very high field area, induces early breakdown

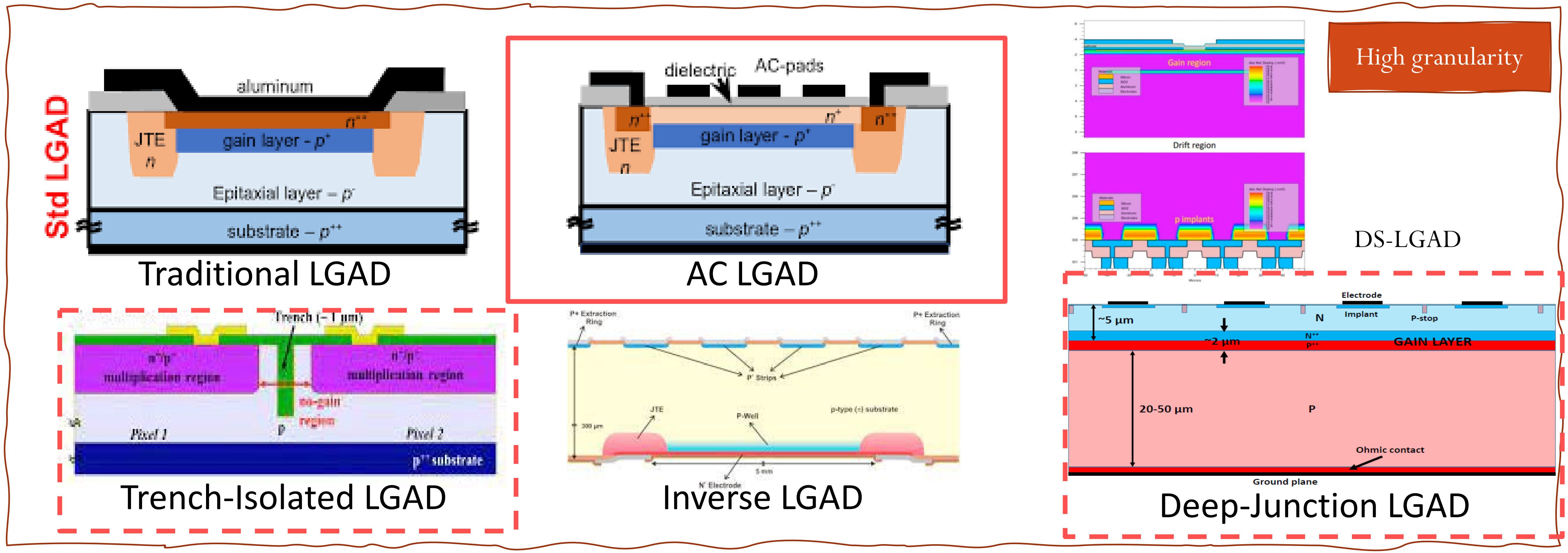
Structure to avoid high field line concentration at the edges
Junction Termination Extension (JTE)
Separation between the pads of an array **~50-100 um**



- Protection structures limit the current granularity of LGADs
- ~100 um pixel size would mean ~50% active area
- But intensive R&D is ongoing to overcome this limitation

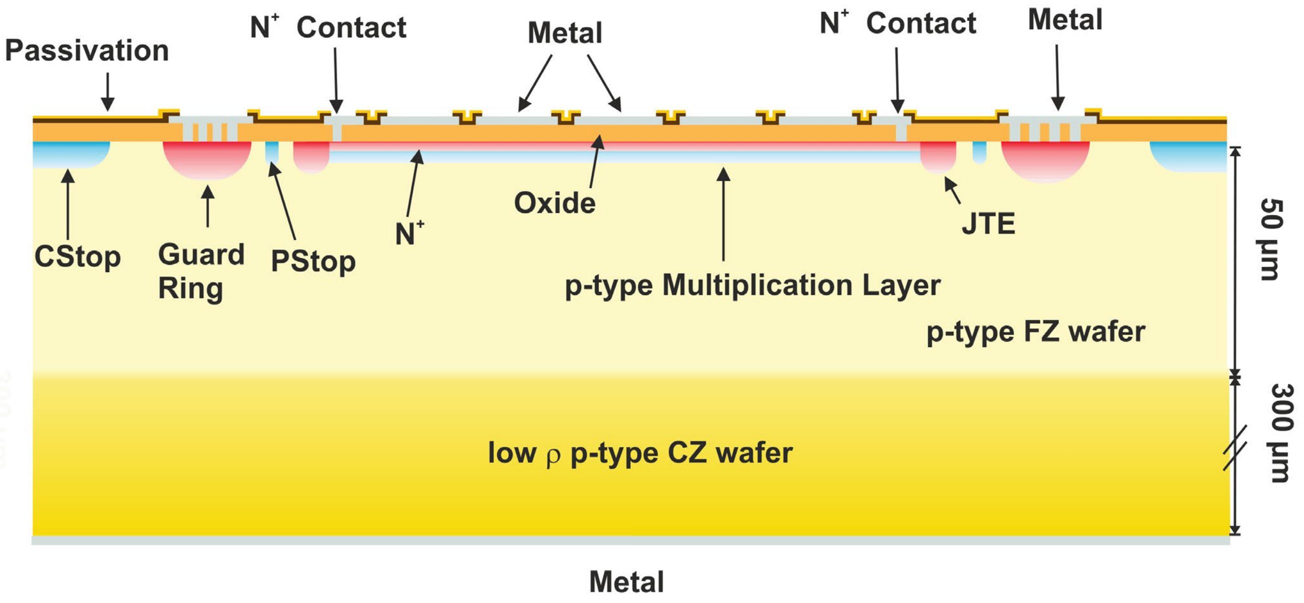
High granularity LGADs

- First LGADs relatively new (6-7 years ago)
- **Many recent innovative prototypes to increase LGAD granularity**

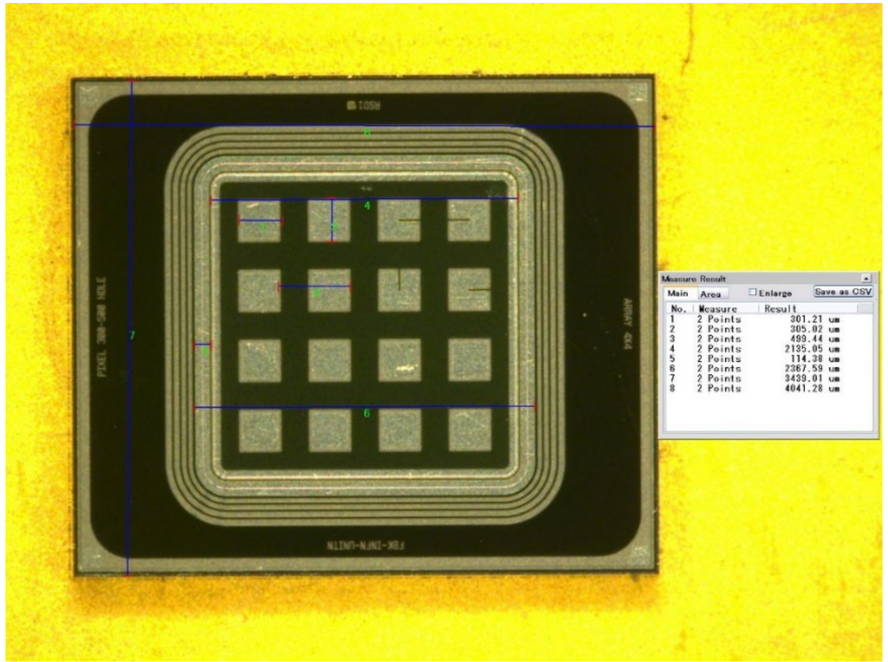


AC-LGADs

- Most advanced prototype are AC coupled LGAD
  - Finer segmentation and easier implantation process
- Continuous sheets of multiplication layer and N+ layer
- **N+** layer is **resistive** and grounded through side connections
- **Readout pads are AC-coupled**
  - Insulator layer between N+ and pads
- Prototypes produced by CNM, FBK, BNL, HPK



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

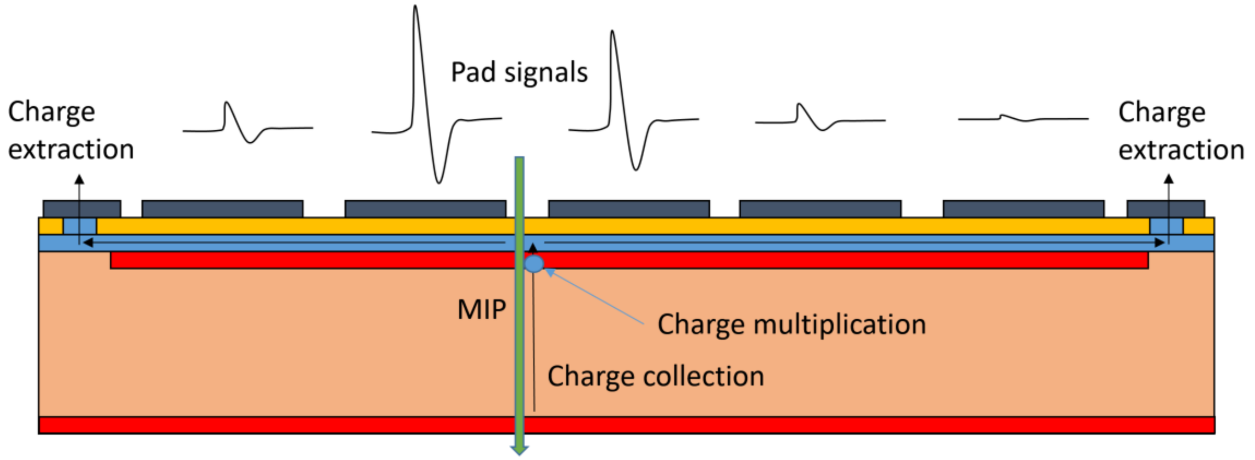


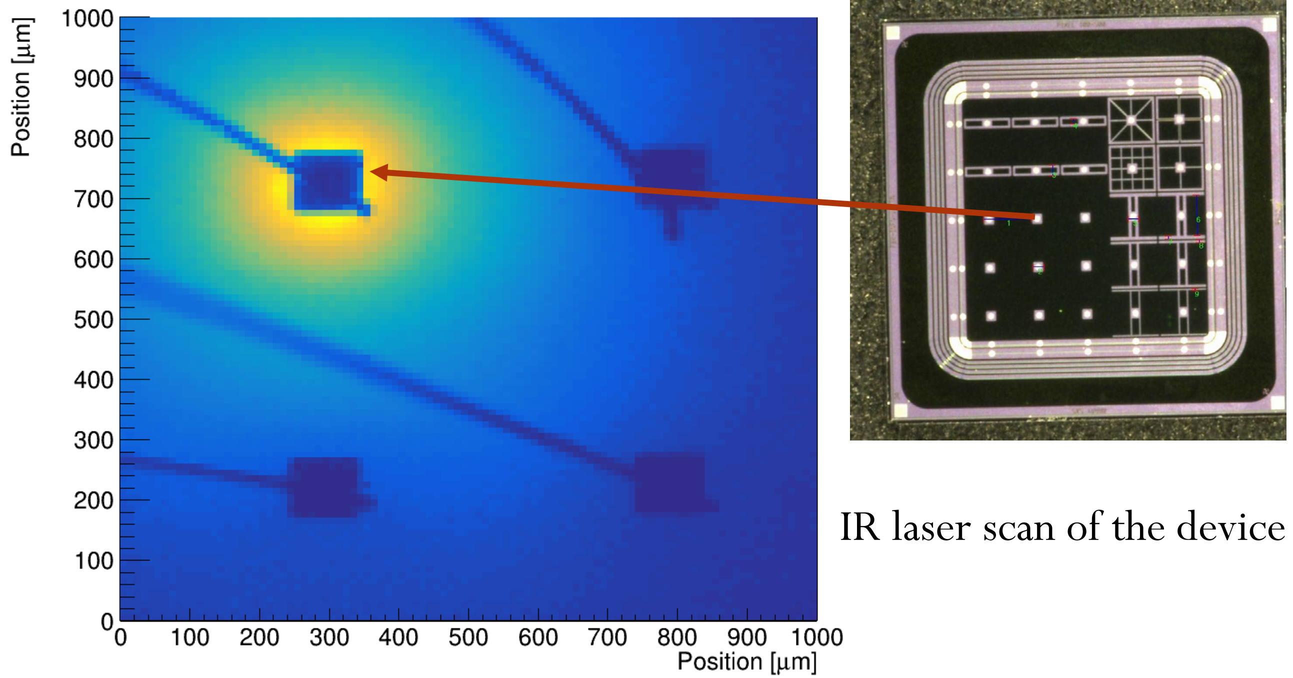
AC-LGAD hit reconstruction

References:
https://indico.physics.lbl.gov/event/1262/
https://indico.cern.ch/event/918298/contributions/3880516/
https://arxiv.org/abs/2006.01999

- AC-LGAD has **intrinsic charge sharing**
  - Gain increases the S/N and allows for smaller metal pads
- Charge sharing can be a great feature for low density tracking environment
  - Using information from multiple pixels for hit reconstruction
- **With a sparse pixelation of 300 um a <10 um hit precision can be achieved!**
  - Combination of time of arrivals as well
- **Sparse readout is extremely useful for channel density and power dissipation**
- Metal layout can be in any shape and size

- Technology being consider for
  - The PIONEER experiment at PSI
  - ePIC, future detector at Electron-ion collider (EIC) at BNL

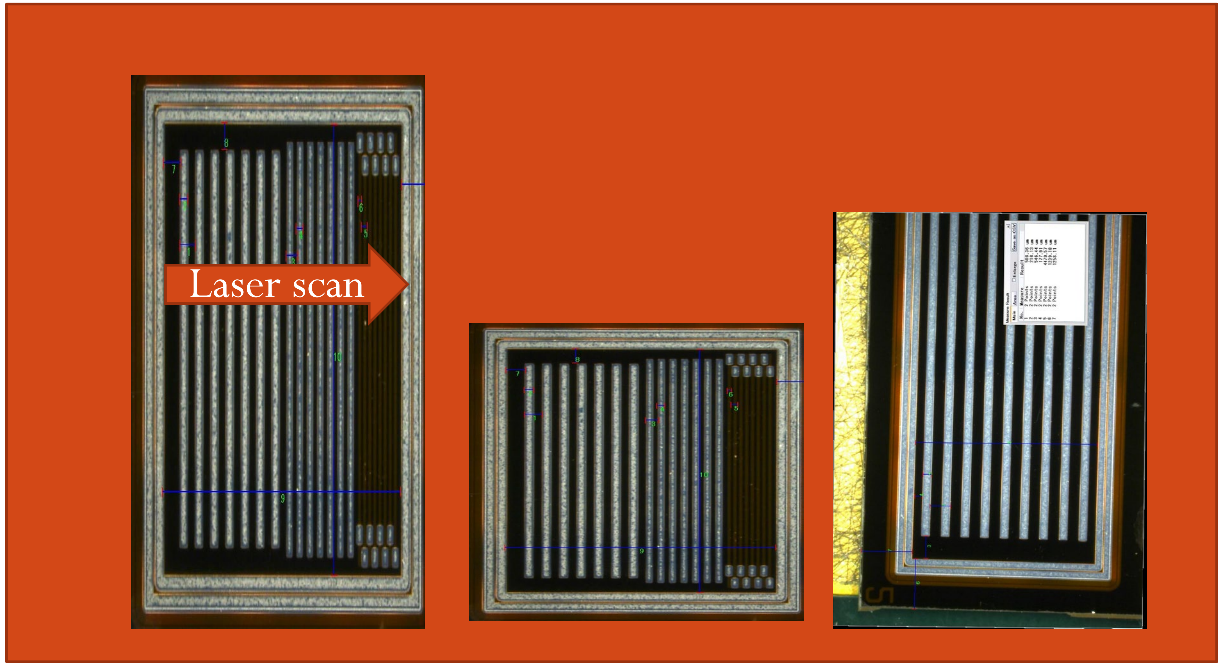


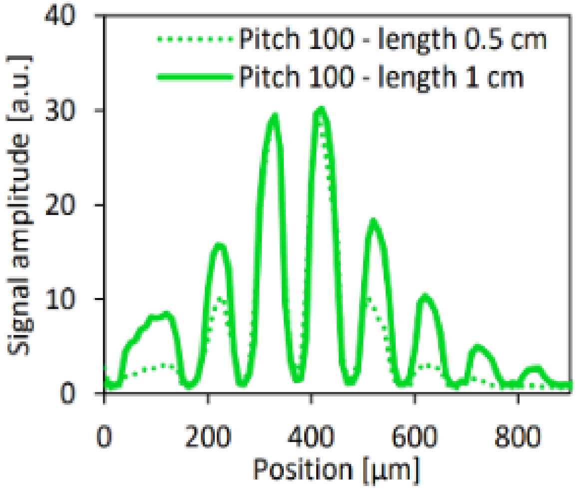


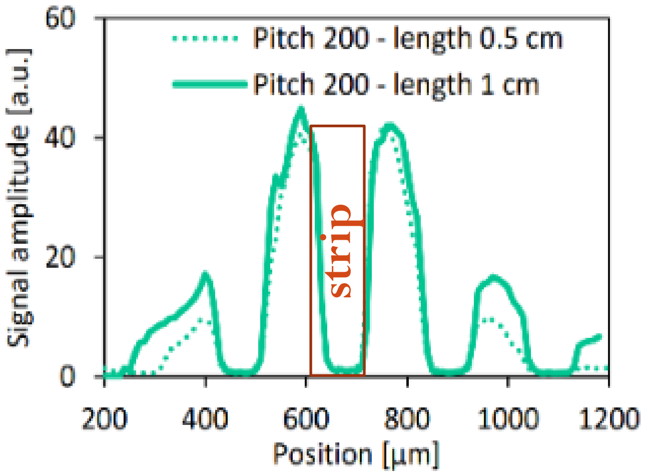
IR laser scan of the device

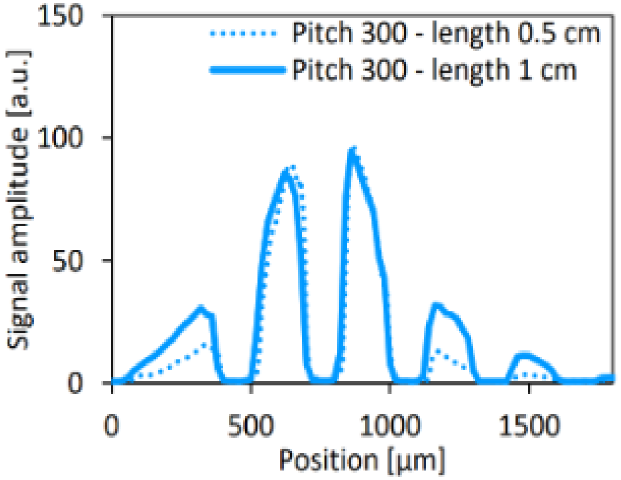
AC-LGAD strips studies

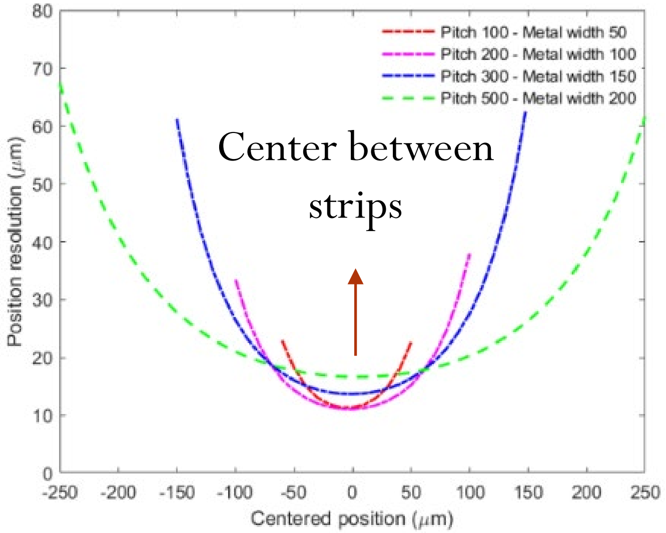
- BNL strip AC-LGADs with same geometry but different lengths
- Pitch and width in three configurations (width = pitch/2)
  - 300-150 um, 200-100 um, 100-50 um
  - 0.5 cm and 1 cm long sensors
- 2.5 cm long sensor with strips of 500-200 um
  - Charge sharing present up to ~2mm
- Direct comparison of geometry shows that **longer strips have increased charge sharing,** also depending on strip pitch/width
- Position resolution is similar in the 4 sensors in the center between strips, increases under the strip
  - **Position resolution is << than pitch/√12!**









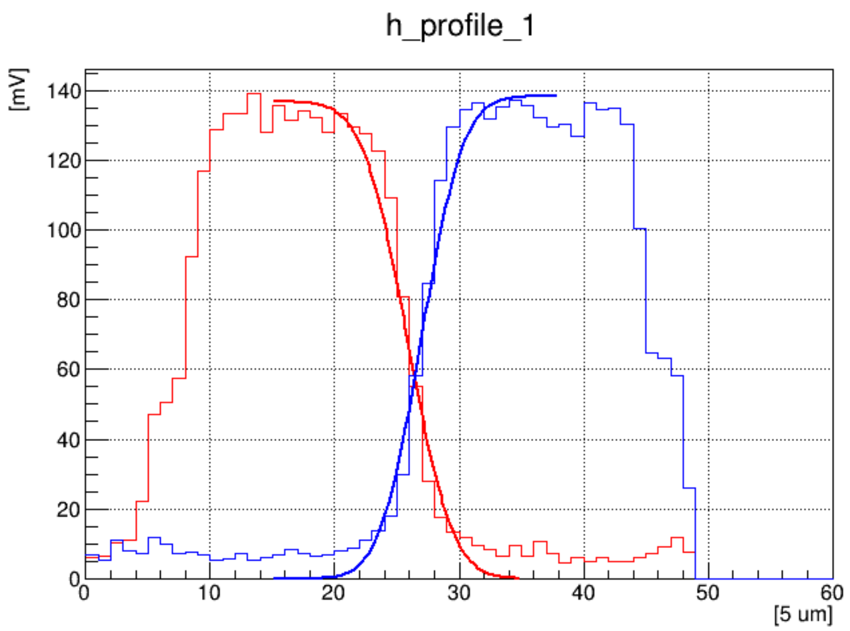


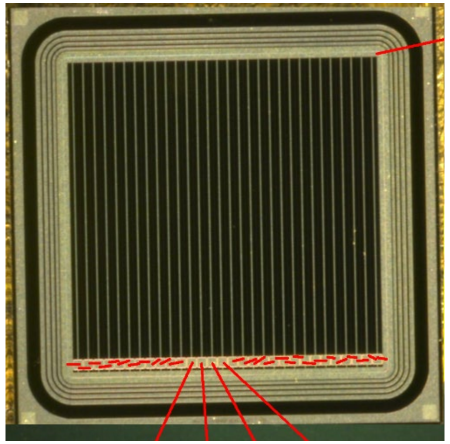
Response of one strip, data taken with IR laser (metal strips are opaque)

Data by: A. Das, C. Bishop, N.Yoho

Other high granularity LGAD technologies

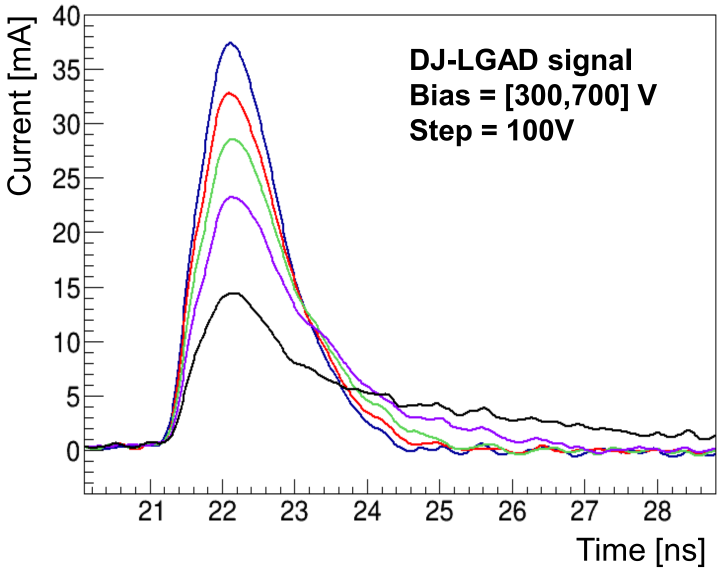
- **Trench insulated LGADs (TI-LGAD)**
- Pads insulated by deep trenches filled with oxide
- First prototypes successfully produced by FBK:
  - https://indico.cern.ch/event/861104/contributions/4514658/
- Very good performance observed!
  - IP gap 5-10 um or less
- Similar granularity as regular silicon sensors

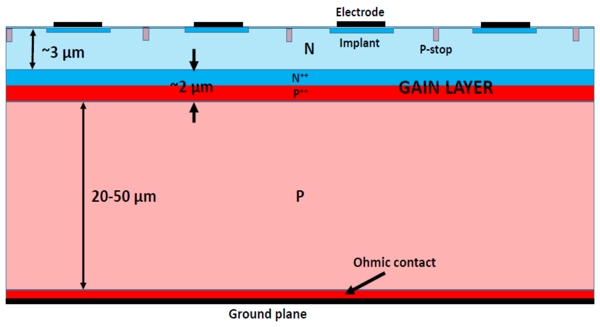




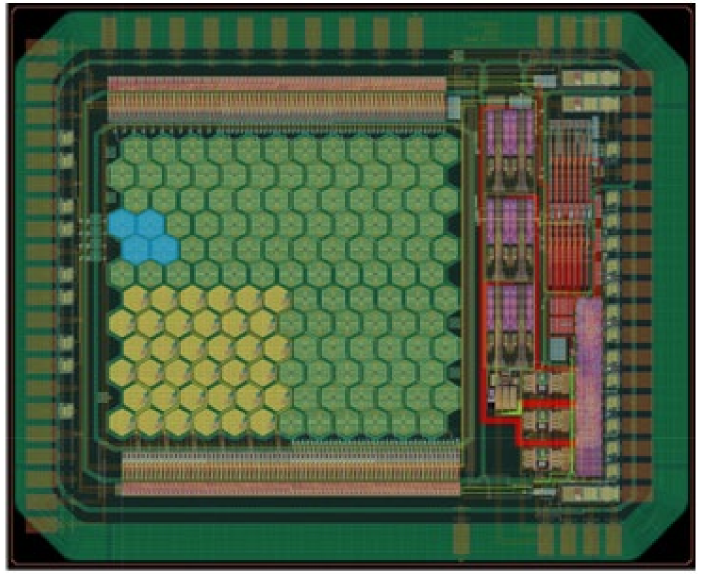
Prototype FBK TI-LGAD

- **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)
- Similar granularity as regular silicon sensors

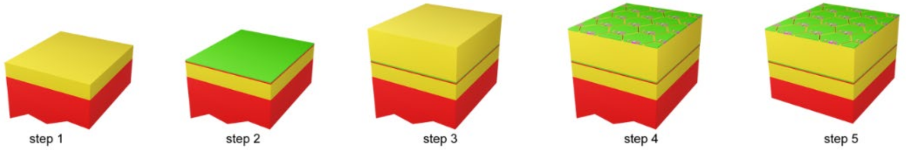




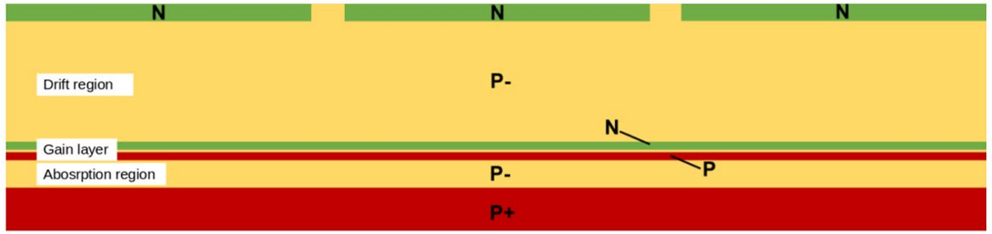
Monolithic LGAD



- All LGADs require to be 'hybridized' in some way with the readout chip
  - Wire-bonding, bump-bonding, etc…
- **Combination of HV-CMOS technology and LGAD technology**
  - Internal gain by LGAD-like gain layer and embedded amplification
- Many groups are working on developing such technology
  - LBNL, BNL, SLAC etc…
- First issue is LGADs' gain layer has high electric field near the surface, not easy to work with CMOS tech in it
- Also LGADs are mostly produced on 4" and 6" wafers, CMOS foundries work with 8" wafers and up → need 8" LGAD technology (not straightforward due to gain layer implantation)

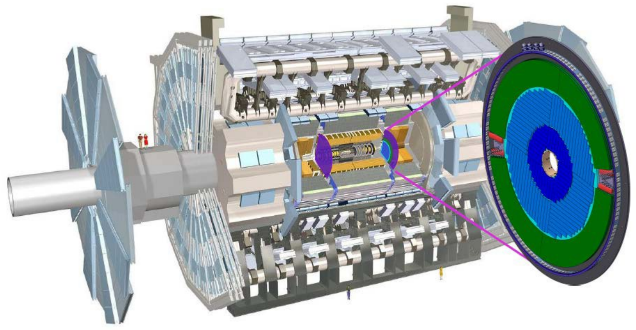


- First successful LGAD CMOS: picoAD by UniGe group
  - https://iopscience.iop.org/article/10.1088/1748-0221/17/10/P10032
  - Using a deep junction with epitaxial growth process

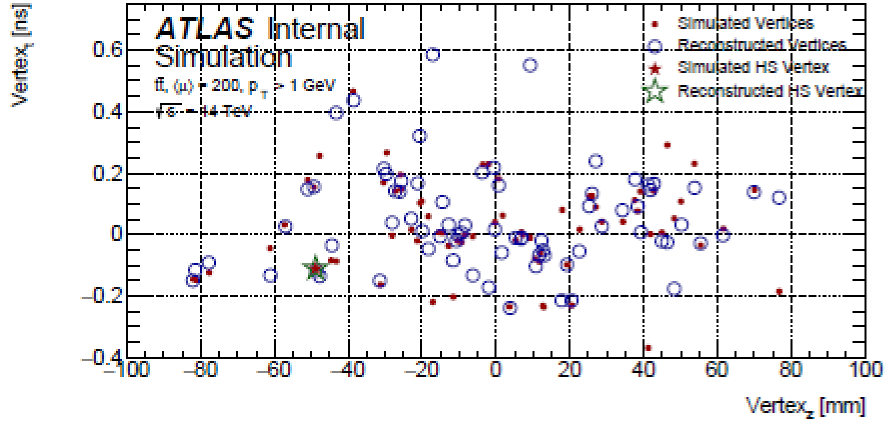


IV. LGADs application in HEP and NP

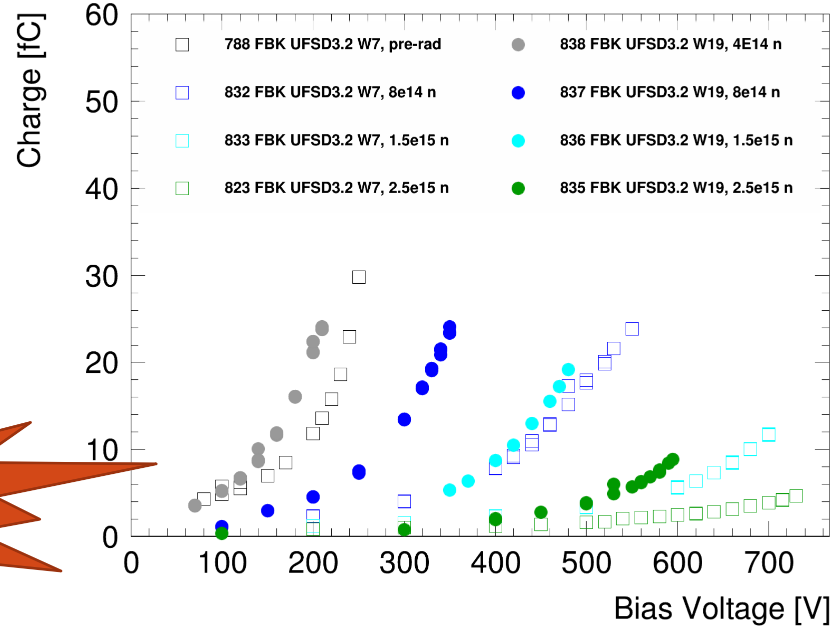
HGTD - LHC high luminosity and ATLAS



- LHC will be upgraded in 2027 to High Luminosity LHC
  - Instantaneous luminosity will be ~3 times past run conditions
- First application of LGADs in HEP experiments at HL-LHC
  - Timing layers in the end-cap (forward) region to mitigate pile-up
- **ATLAS and CMS detector will be upgraded with a new end-cap pixel timing detector with LGADs**
  - High granularity timing detector (HGTD) for ATLAS https://cds.cern.ch/record/2719855
  - End-cap timing layer (ETL) for CMS https://cds.cern.ch/record/2667167



- Radiation hardness was the most challenging thing for LGADs and was the core of the R&D made at UCSC until ~2020
  - After many years of development, a device with enough gain at 2.5E15 Neq (HGTD requirement) was produced

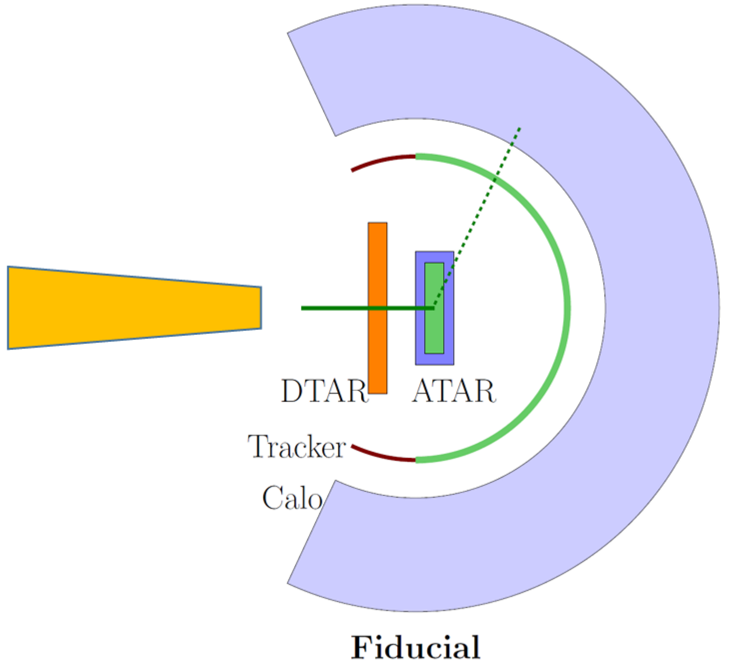


LGAD use case: reduce pileup

PIONEER

- **PIONEER** is a next generation rare Pion decay experiment
- The goal is to **improve the precision of $R_{e/\mu}$** and **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** by an order of magnitude
  - **$R_{e/\mu}$** is the ratio of pion decay to electron a muon: precision measurement of **lepton flavor universality**
  - **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** is the cleanest measurement of Vud: very important to test **CKM matrix unitarity**
- PIONEER will run at PSI (Switzerland), πe1 or πe5
  - Phased effort: Phase I aimed at $R_{e/\mu}$, phase II/III aimed at $R_{\pi\beta}$
  - Growing collaboration, let me know if you're interested!
  - https://arxiv.org/abs/2203.01981
- PIONEER will feature a high granularity, time resolved fully silicon active target (a 5D tracker!)

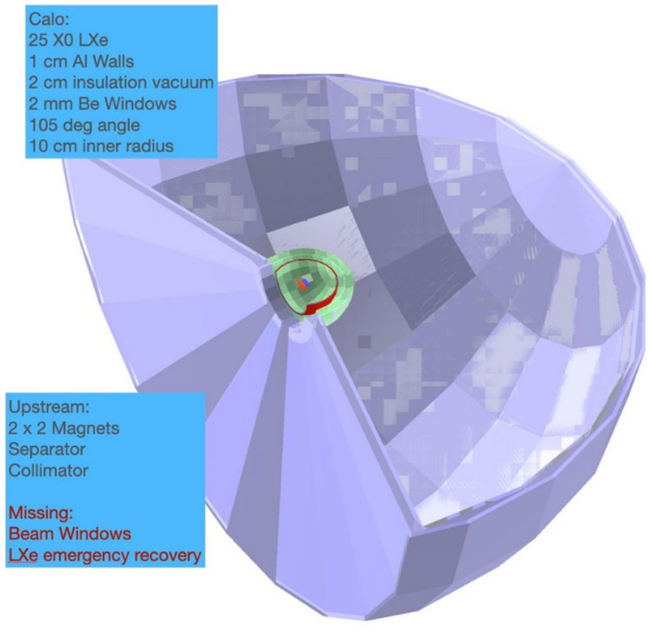
Temporary logo



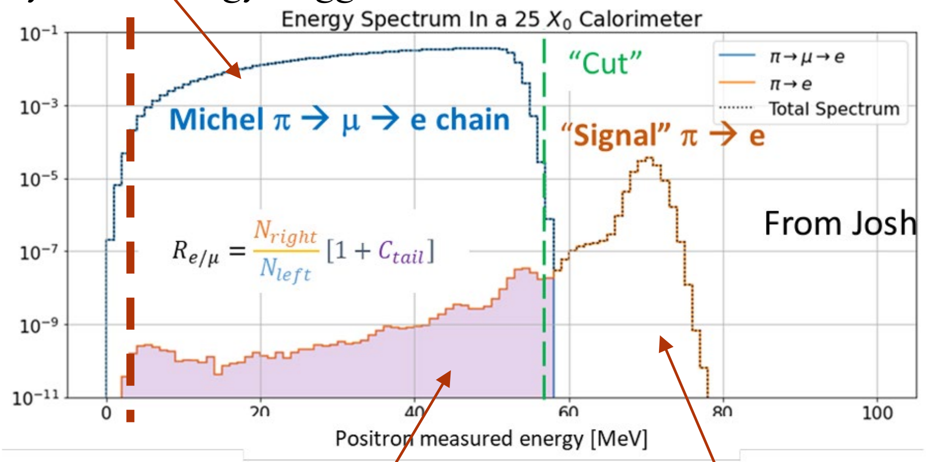
PIONEER experimental design

- Two main detectors:
  - Active TARget, ATAR with fast timing and high segmentation
  - Calorimeter with high energy resolution (liquid Xe or LySO crystals) to reduce tail correction and pile-up uncertainties, and improved uniformity
- Plus, a tracker in between
- **Goal: Separation of deposited energy spectra of π→eν and π→μν→eνν**

- ATAR allows to separate and tag π→eν and π→μν→eνν decays using topology, energy and timing: a 5D tracker!
  - Based on LGAD timing technology, measures (x, y, z, t, Energy)
  - 'Live' tracking of pion decay to see positron and muon decay channels
  - Plus, ATAR helps recognizing decay in flight events
  - Exiting positrons are tracked and the total energy is measured in the calorimeter
  - https://www.mdpi.com/2410-390X/5/4/40



Easy: low energy trigger



At some point e+ won't make it to the Calo

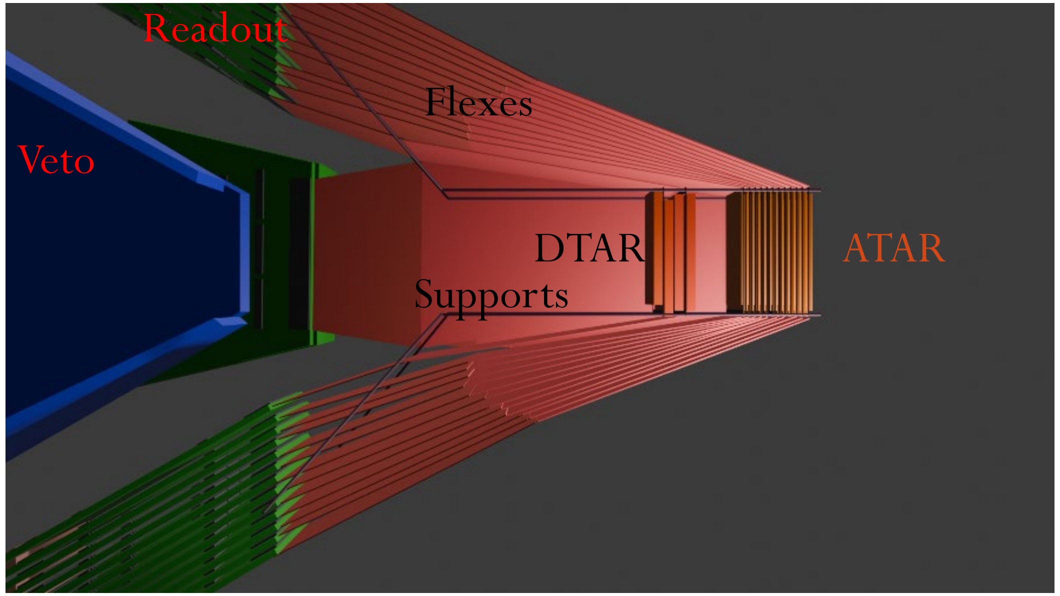
Easy: high energy trigger

This is the hard part

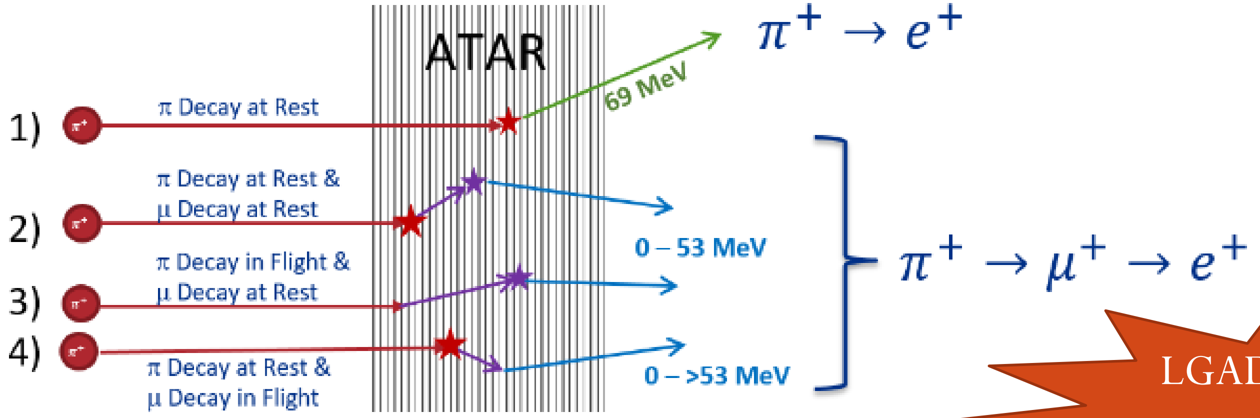
Tail fraction trigger

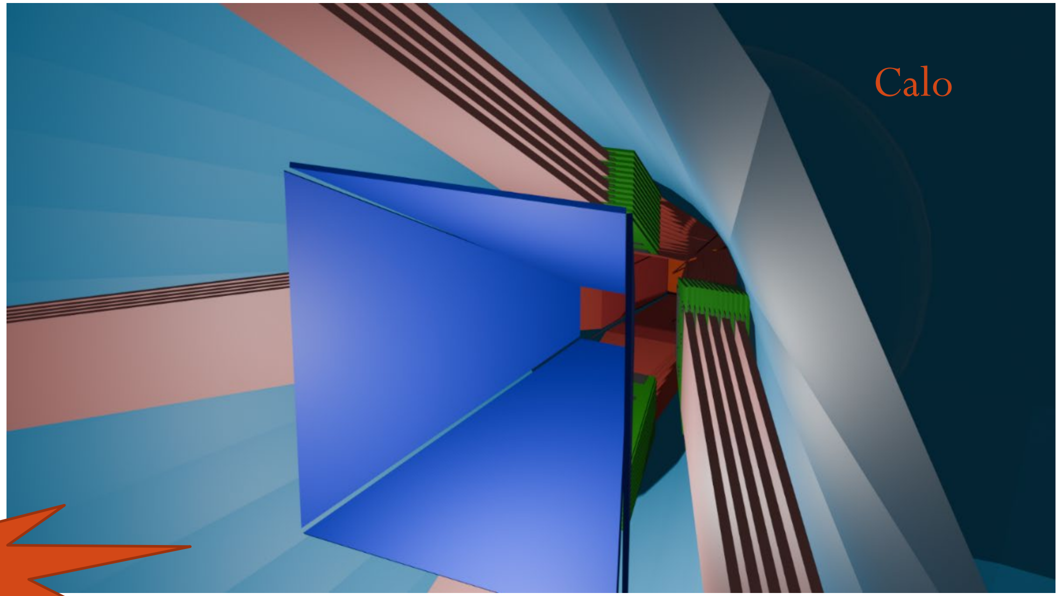
PIONEERS's ATAR design

- The chosen device for the ATAR is an LGADs high granularity technology (AC-LGADs or TI-LGADs)
- ATAR baseline design:
  - 48 layers of 120um thick 2x2 cm LGADs (200um pitch)
- Short (~5 cm) readout flexes carry the un-amplified signal to the ASIC
- ASIC does analog amplification and ships the signal to back-end digitizers
  - The ATAR signals will be fully digitizer in a region of interest (ROI, temporal or spatial) for each event



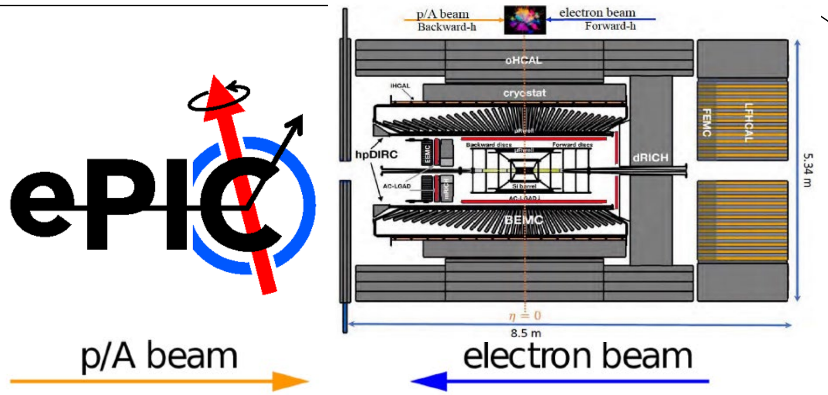
- Advanced de-convolution analysis can identify pulses close in time
  - Detect and identify $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu\nu \rightarrow e\nu\nu$ and π or μ decay in flight



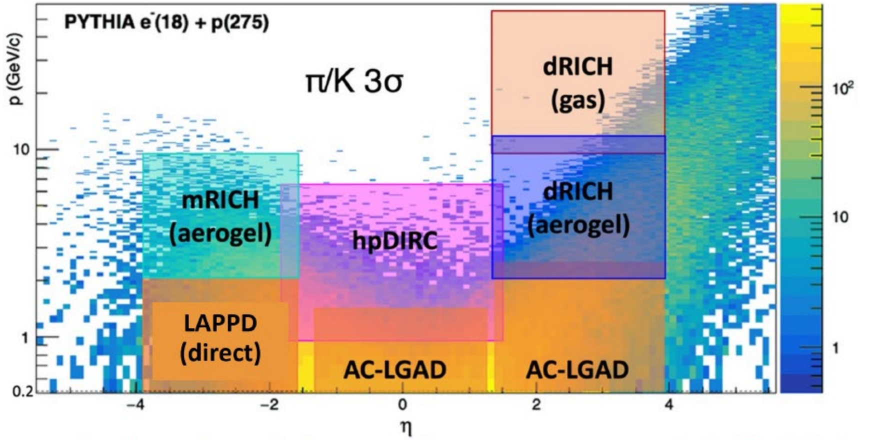


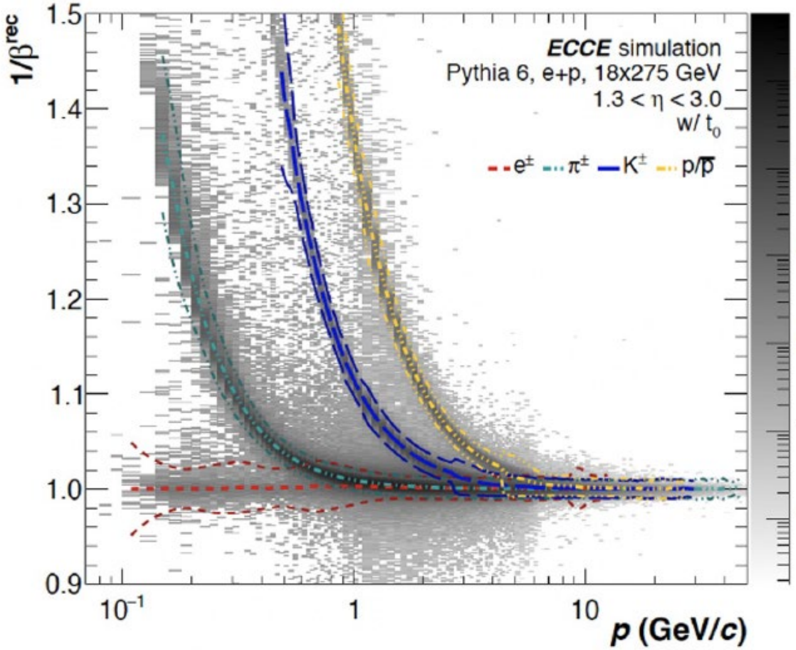
LGAD use case:
pattern tracking

Electron-Ion collider (https://www.bnl.gov/eic/)



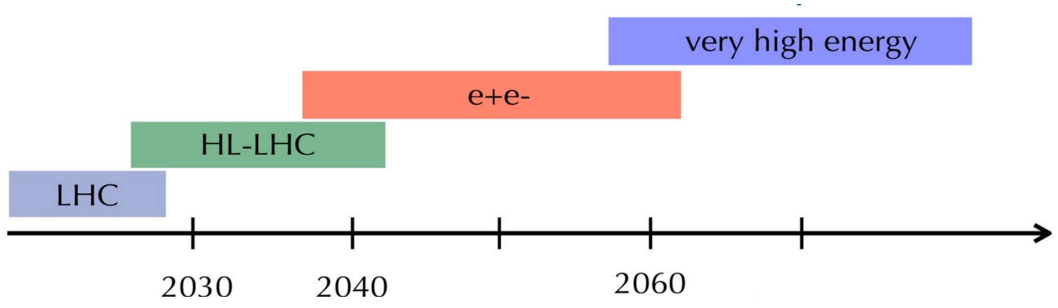
- **4D tracking is one of the key point in the ePIC detector**
- **AC-LGAD** is foreseen for both barrel and end-cap in EPIC
  - 500 um x 1 cm strip, ~1% X0 for **barrel**
  - 500 x 500 um pixel, 8% X0 for **forward**
  - 25 ps single hit time resolution
  - ~30 µm spatial resolution
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
- Require good time resolution and meaningful flight distance
  - Better with 4π coverage for t_0 determination
  - E.g. around 30 ps at 0.5m (70ps at 1m) is required to have PID with momentum <0.5 GeV in the barrel
- **Experiment installation in 2030**

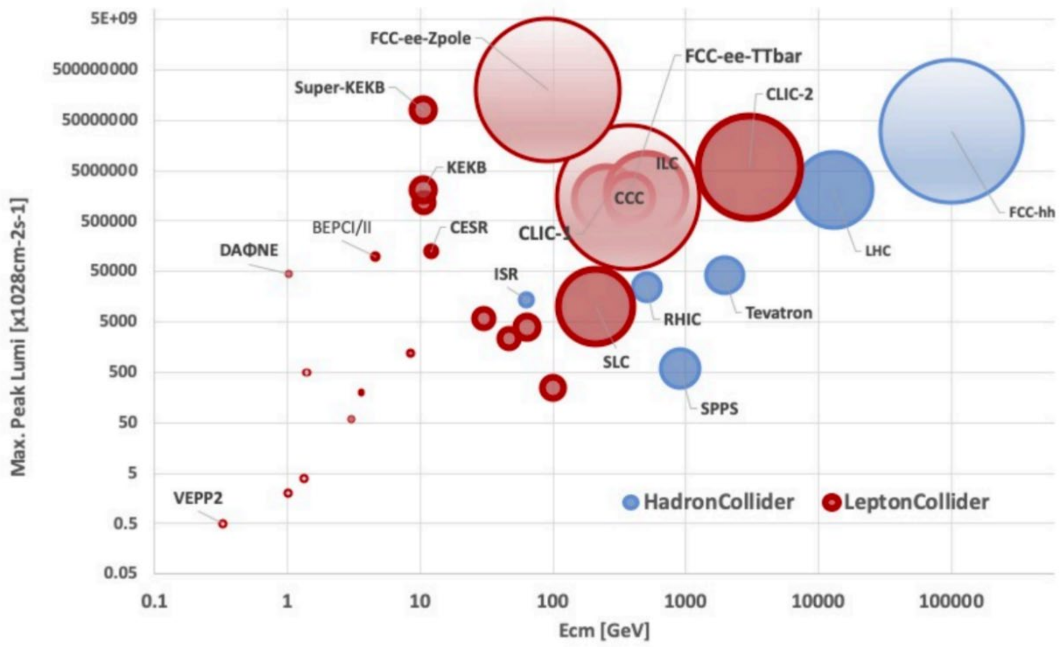




LGAD use case:
TOF PID

Far-future colliders





Higgs discovery

Study the Higgs interactions
Timescale 2040s

e+e- colliders:
Higgs factories

FCCee, CLIC, CEPC, ILC?
Collision of elementary particles: clear signature
Precision measurements of Higgs couplings, di-Higgs vertex and VEV
But: limited energy reach and low discovery potential

Timescale ?

Muon collider

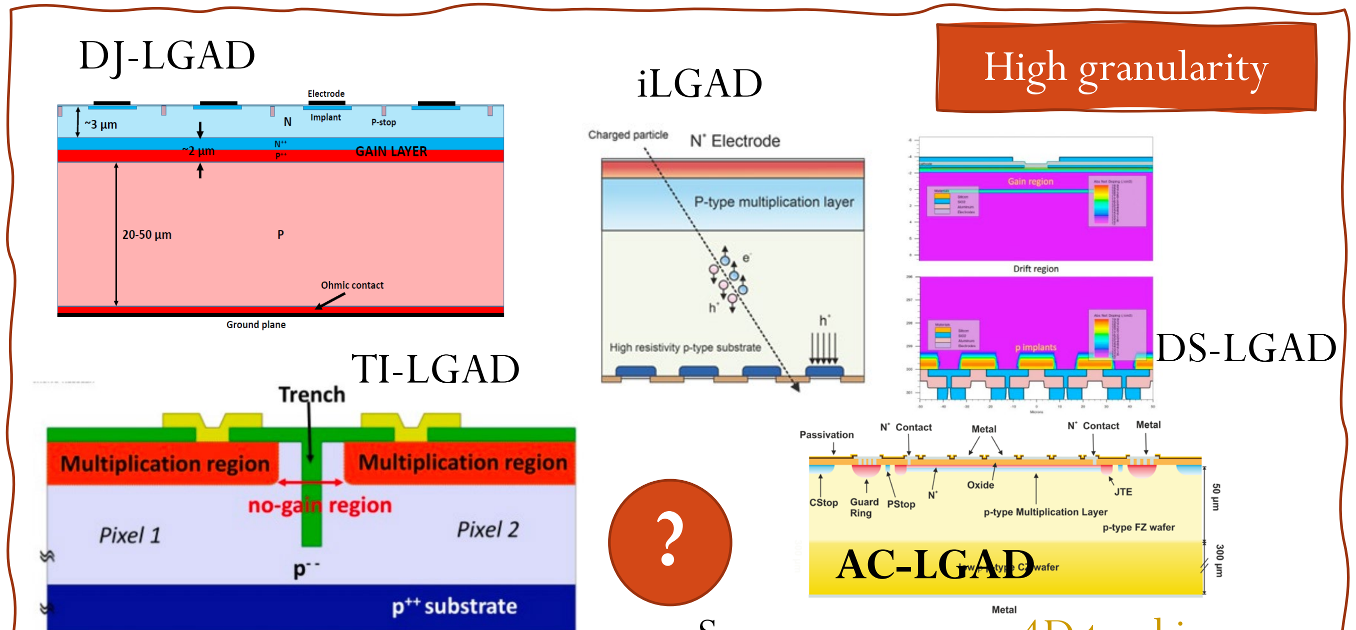
Discover new frontiers
Timescale 2060s

Future hadron collider: FCChh
Collision of partons
Complex events with large pileup
Explore up to 100TeV c.d.m.

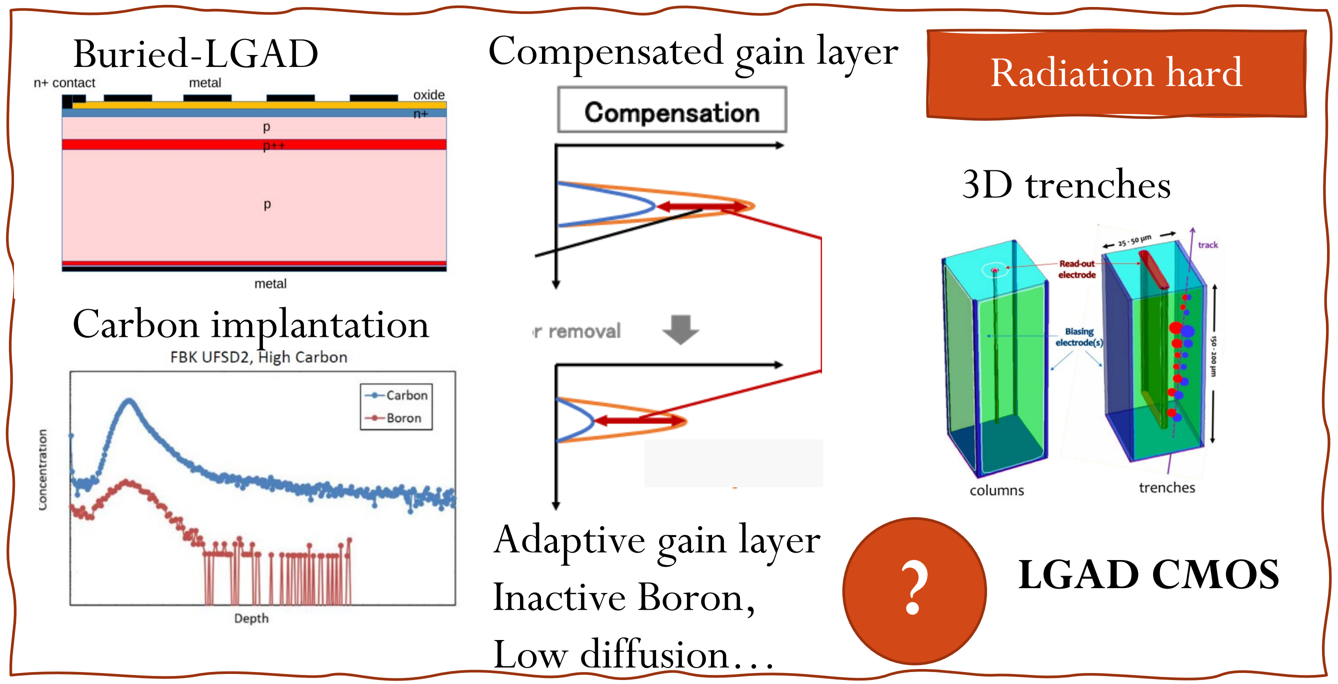
Next generation 100TeV hadron colliders

Long-term development of LGAD detectors - FCC

- **Great time resolution, high granularity and low power dissipation needed**
- AC-LGADs can cover the short timescale: PIONEER, ePIC, ee colliders
  - E.g. **IDEA: FCCee tracker that could involve a Si wrapper timing layer using AC-LGADs**
- But for FCChh: High radiation hardness requirements ($10^{16\text{-}17}$ Neq/cm^2) and high occupancy
  - Need for order of magnitude increase in radiation hardness
  - Lower power electronics needs to developed at the same time!
- Critical need to continue developing LGAD sensor technology and low-power readout for far future applications!



Snowmass papers: 4D tracking paper

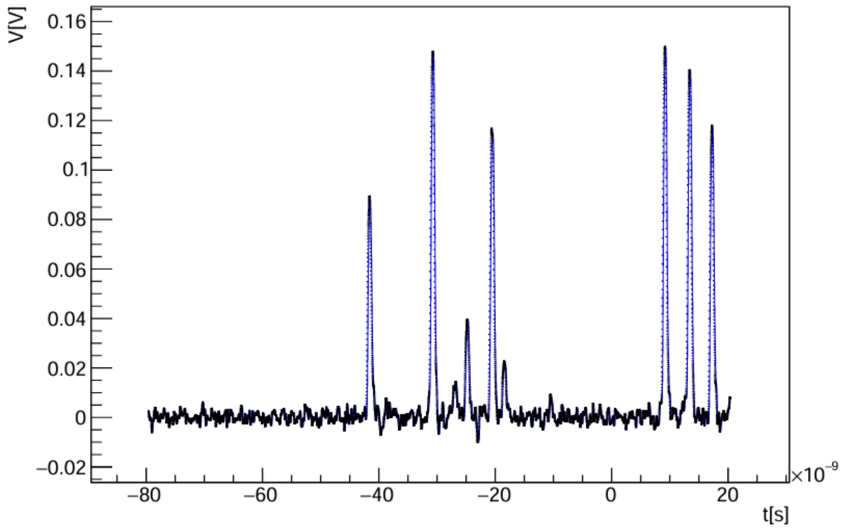


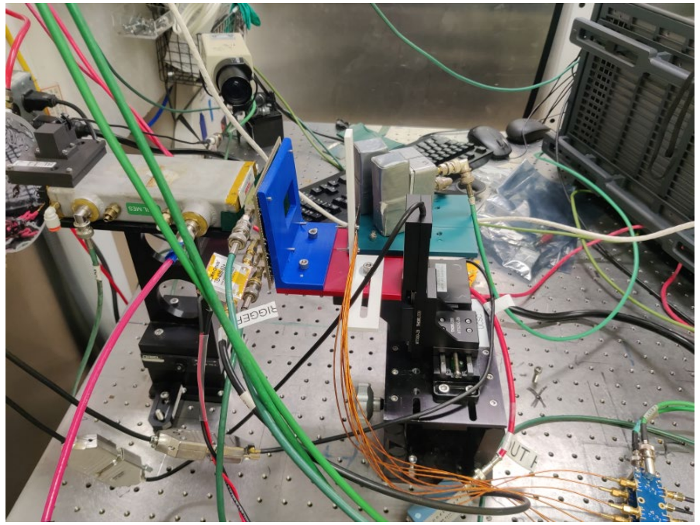
V. X-ray detection with LGADs and more

LGADs with X-rays - SSRL

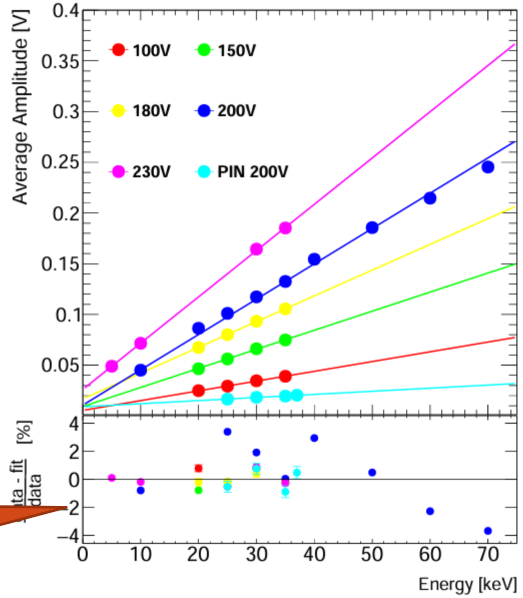
- LGAD tested for X-ray detection at the **SLAC** Stanford Synchrotron Radiation Light source **(SSRL)**
- X-rays of energy range [5, 70] KeV
- Definite pulses even with a **2ns beam separation**
- Linearity and the energy resolution of different LGADs at different bias voltages
  - Good linearity, best energy resolution at lower voltages (low gain) of <10%
  - Thin PiN (no gain) device has energy resolution 15-20%
- Good time resolution ~100ps
- Tested with focused beam as well, results in progress…

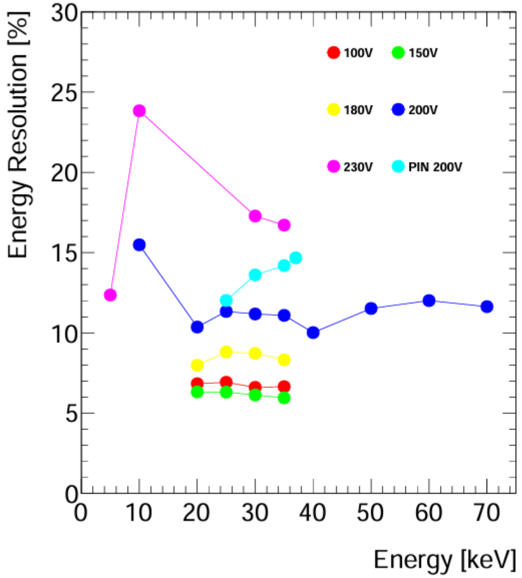
LGAD use case: Cyclotrons

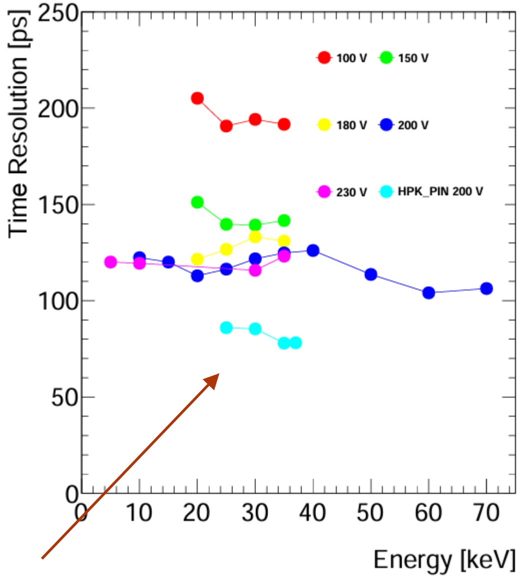




DOI 10.1088/1748-0221/18/10/P10006



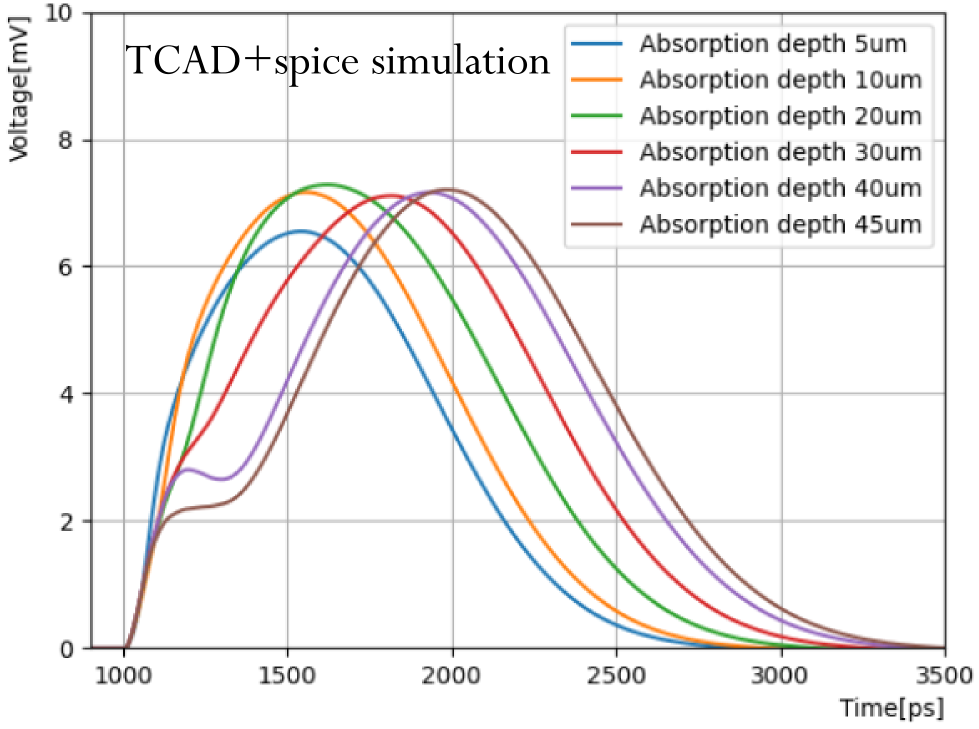




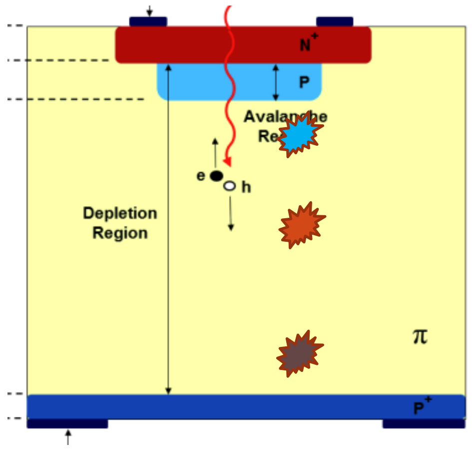
Why is PiN better at time resolution? See next slide!

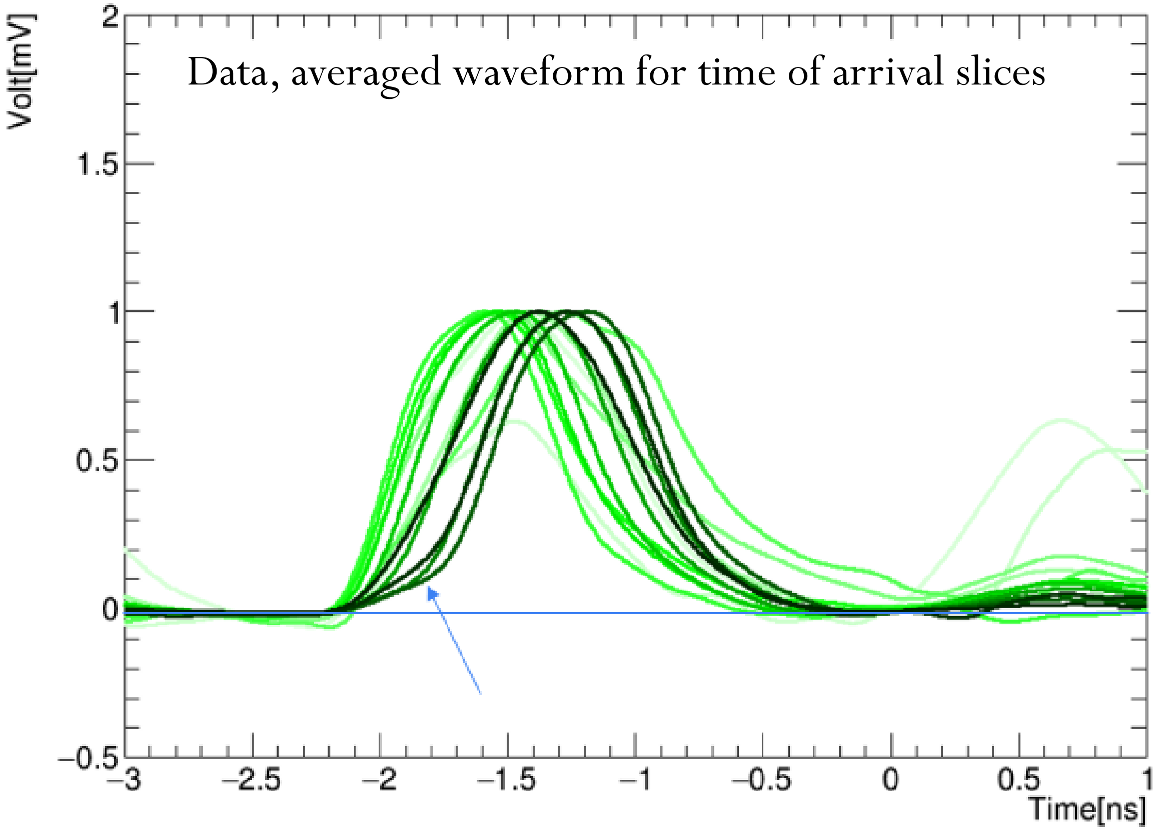
X-rays detection with LGADs

- X-ray interactions at different absorption depth in the LGAD: simulate with TCAD Sentaurus
  - Initial "flat top" of the pulse because of charge travel to the gain layer, delaying the gain process
- Observed the same behavior in the data
- This doesn't happen in the PiN since current is instantaneous



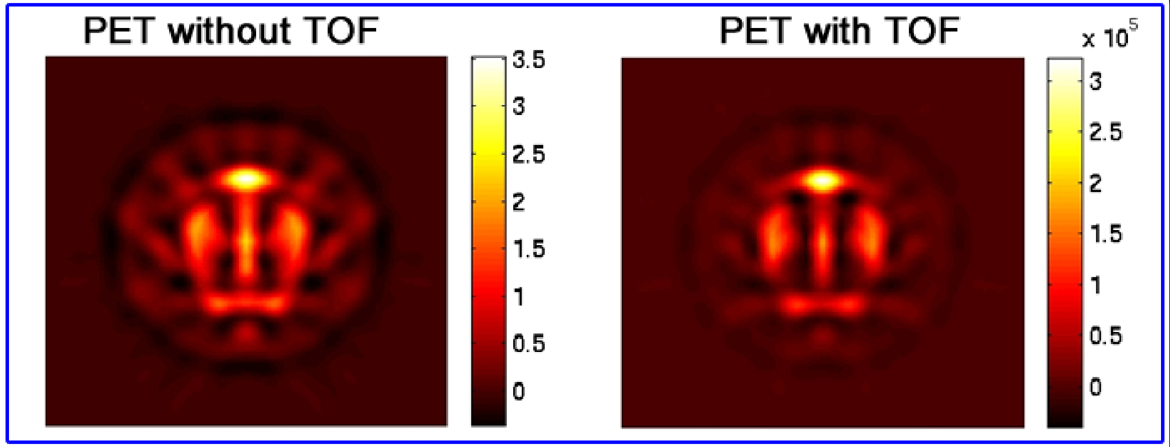
(b) Convoluted voltage signal with TIA.

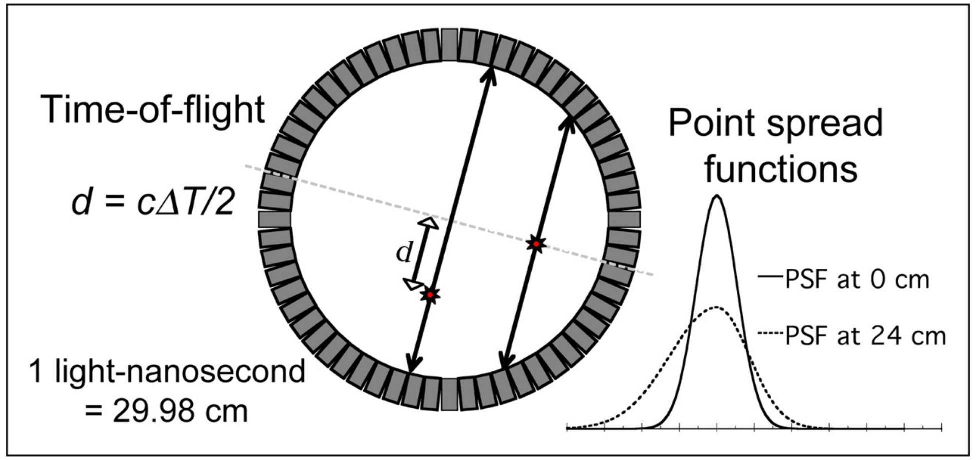




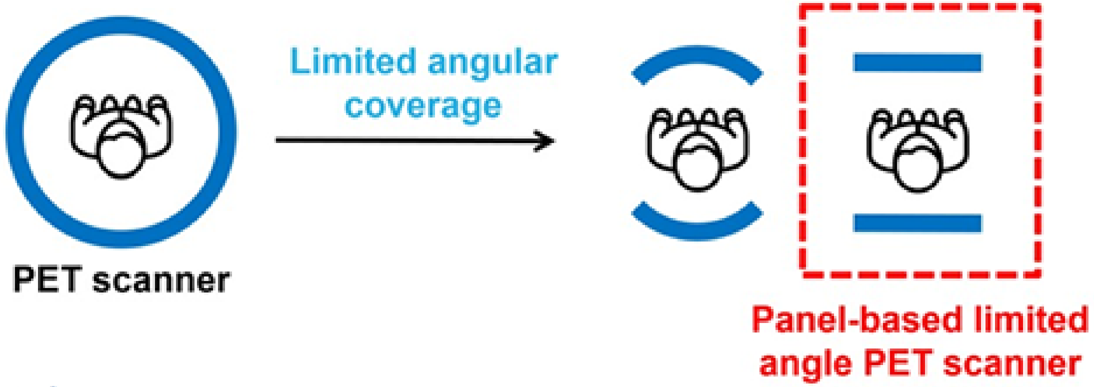
Timing in medical applications

- Time-of-flight (TOF) measurement in PET scanners allows a more accurate image reconstruction and/or a lower delivered radiation dose
- TT-PET project: Time of flight PET scanner for small animals
  - https://pos.sissa.it/contribution?id=PoS(TWEPP-17)043
- Planar PET: PetVision (easier to move, lightweight)
  - https://indico.cern.ch/event/1255624/contributions/5445368/
- Necessary a timing precision of ps
- One way to do it: LGADs (although not mentioned in this applications)



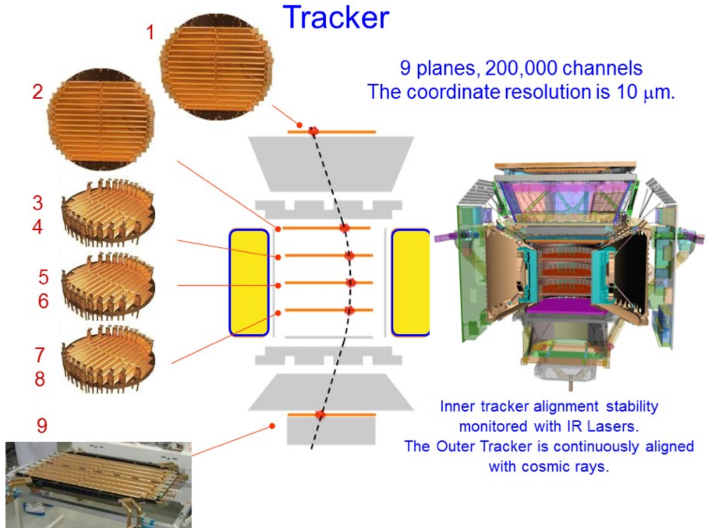


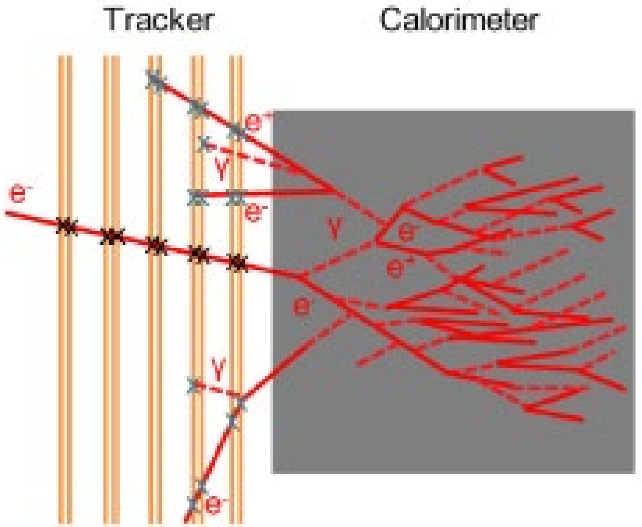
LGAD use case:
time of flight PET

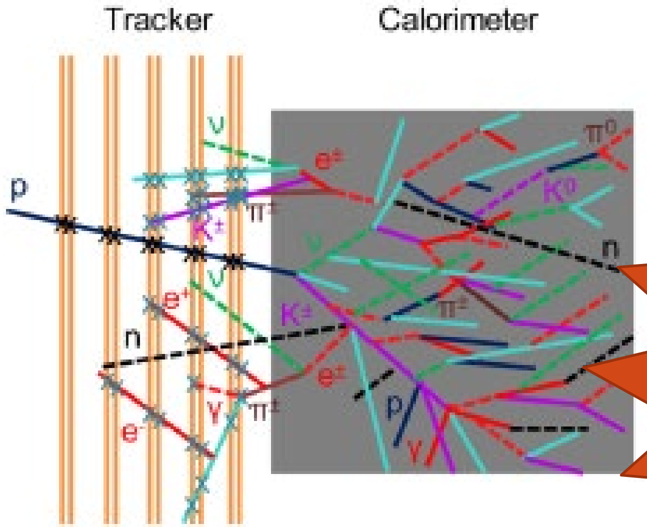


LGAD space applications

- Many space experiments (FERMI, DAMPE, AMS) use a standard silicon tracker to detect cosmic rays outside of the hearth atmosphere
- The choice of silicon tracking sensors with a hit time resolution of about 100 ps can solve
  - Back-scattered particles from the calorimeter
  - Differentiate electrons and hadrons
  - ToF measurement for particle direction (charge measurement in a magnetic field)
- Perfect application for LGADs! https://inspirehep.net/literature/2145697





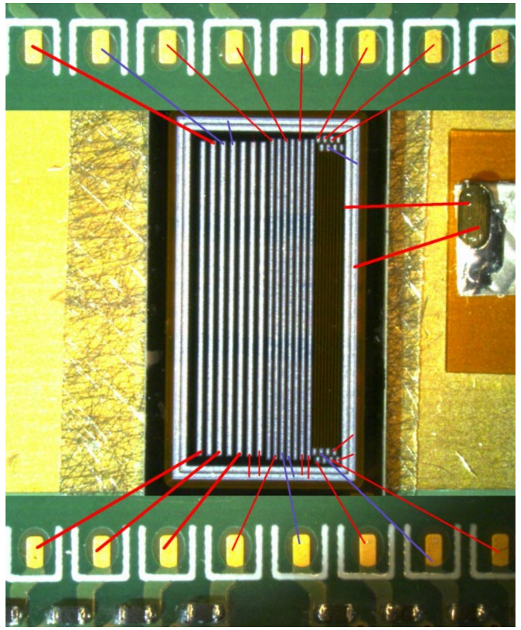


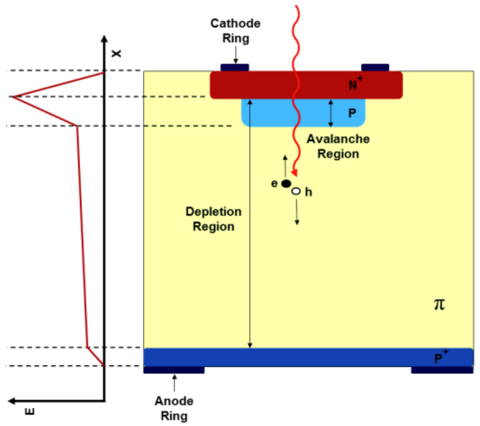
LGADs use case: timing in space

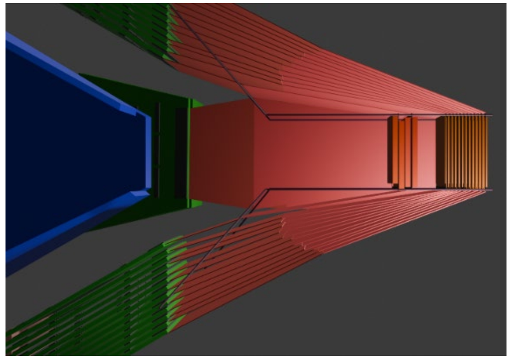
Conclusions

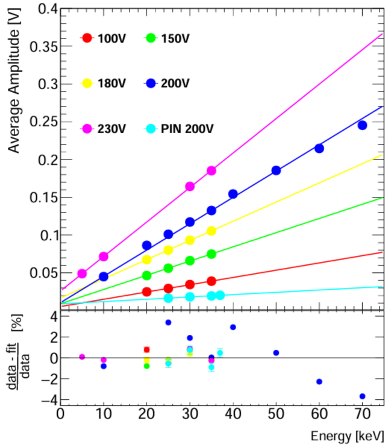
Conclusions

- **LGADs are an interesting "new" (<10y) technology**
  - Fast pulses (~1ns), internal gain of 20-50, exceptional time resolution
- **Radiation hardness proven up to few 1E15 Neq**
  - Push to reach 1E16 Neq and beyond for future colliders
- **New technologies will allow dense LGAD pixelation**
  - TI-LGADs, iLGADs, AC-LGADs, DJ-LGADs
  - Maintain fast pulses (~1ns), internal gain of 20-50 and exceptional time resolution of LGADs but allow dense LGAD pixelation
- **Future LGAD applications in many fields**
  - High energy physics (ATLAS/CMS)
  - Nuclear physics (ePIC, PIONEER)
  - Future colliders
  - Low energy X-ray detection
  - Fast beam monitoring … Medical science (TOF PET) … space …









Thanks for the attention

Many thanks to the SCIPP group students and technicians!

Thanks to FBK, HPK, BNL to have provided sensors for this study

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CACTUS DJ-LGAD SBIR
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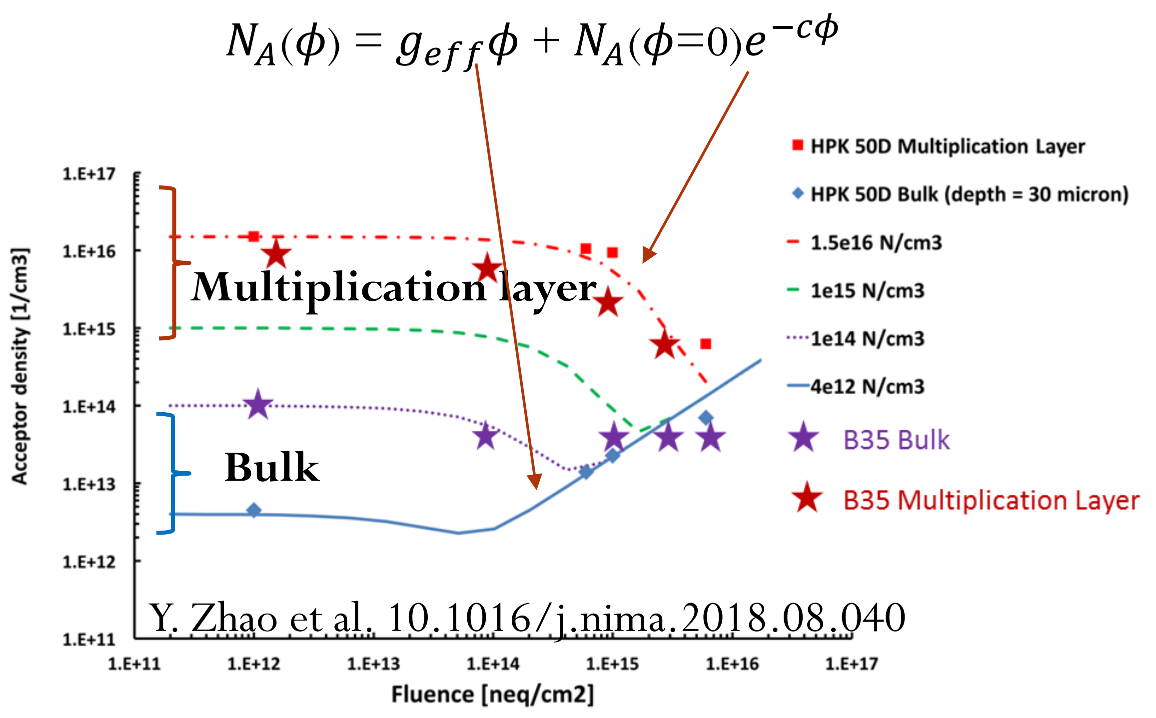
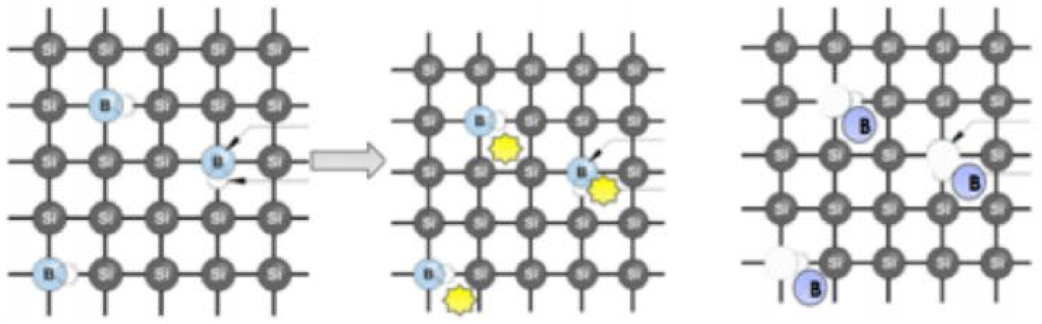
The group from USP acknowledges support from FAPESP (grant 2020/04867-2) and CAPES.

Radiation damage model

- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Reduction of doping concentration in the multiplication layer → reduction of gain
  - **C-factor (acceptor removal constant) depending on detector type**



Y. Zhao et al. 10.1016/j.nima.2018.08.040

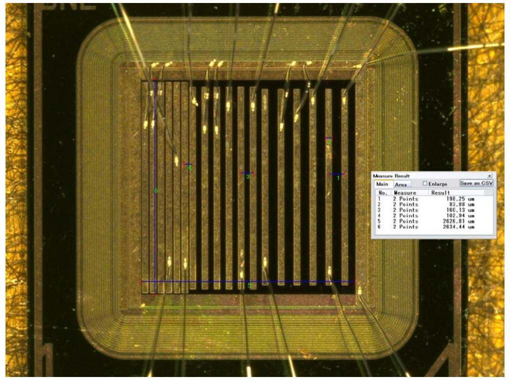


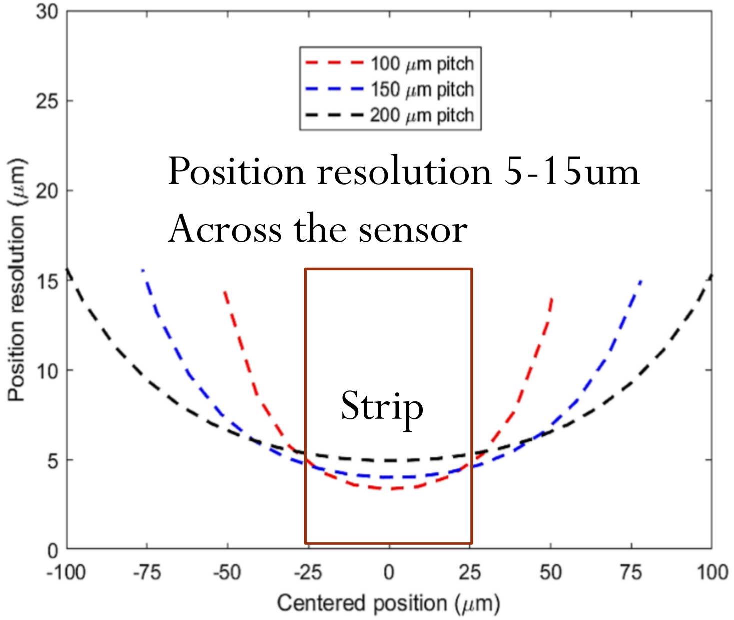
Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s → Si_s + B_i
B_i might interact with Oxigen, creating a donor state

AC-LGAD strips

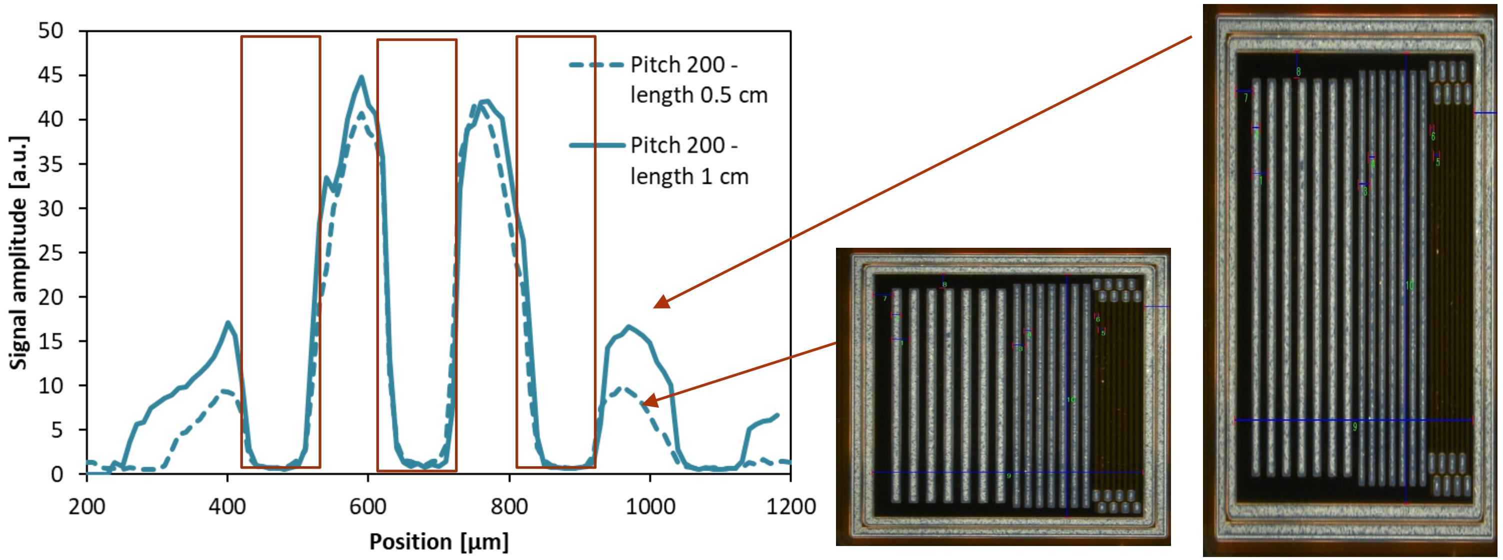
- Testing of **AC-LGAD prototype strip sensors** (50 um thick) with several geometries
  - Sensors produced at BNL for the EIC
- Same strip length and width, different pitches
  - Finer strips show a slightly better resolution, but higher channel count
  - Hit position resolution in direction perpendicular to the strip 5-15 um
  - Study made with FNAL TB data
- Same geometry but with different lengths (study made with focused IR laser TCT)
  - Sensors with longer strips show increased charge sharing profile
  - Effect to be understood with simulation

- **For PIONEER 2 cm long strips with substrate thickness of 120um**
  - **Best behavior**: charge shared only between two strips to have largest S/N
  - TCAD Simulation to study the charge sharing



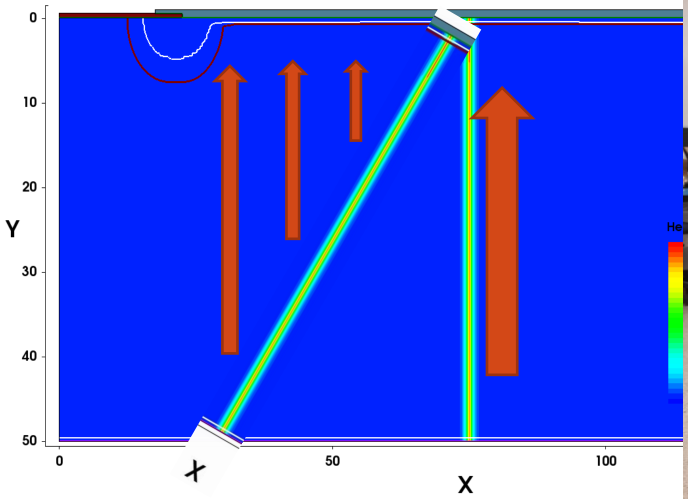


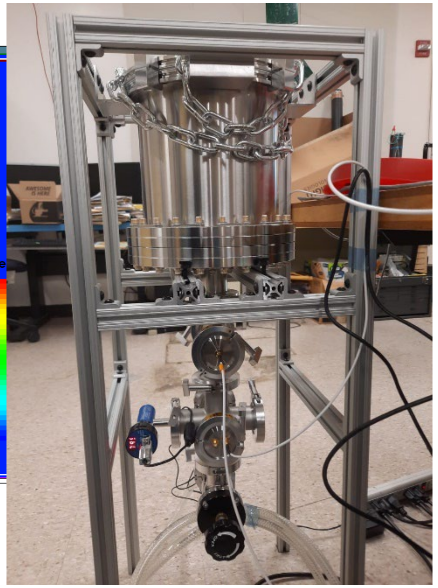
Position resolution vs position
for AC-LGAD strips of different pitch



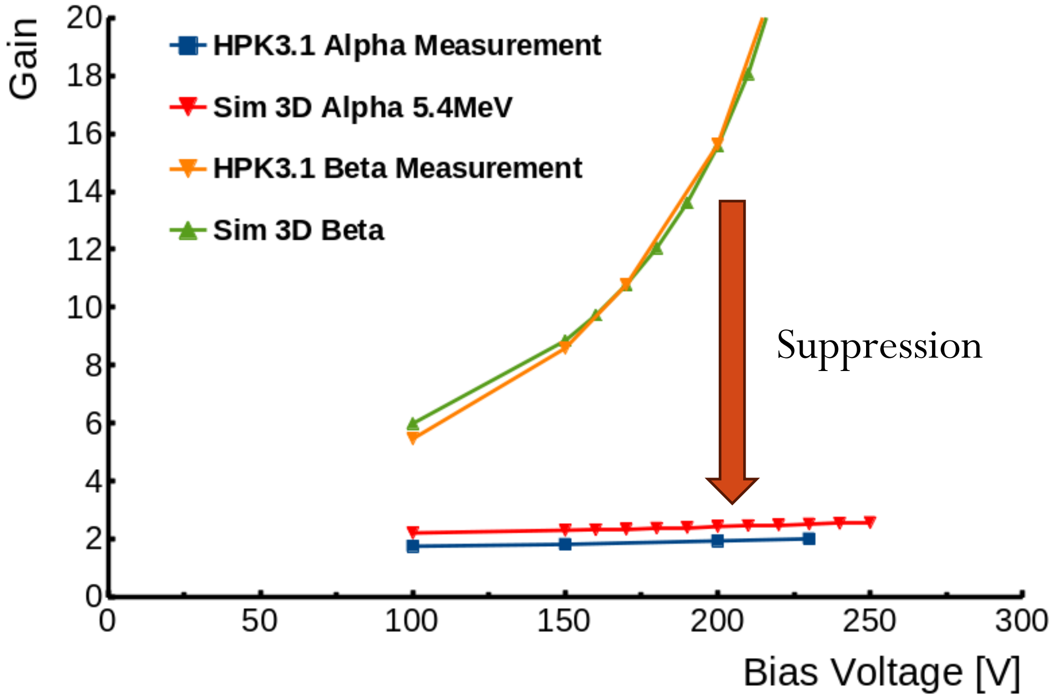
Alpha particle

- Gain suppression studied with **alpha particles**
  - Deposition of ~100 MiP
  - Studied in a vacuum chamber to reduce energy spread
- High gain suppression observed for high gain sensor
  - **Several types of gain layer design under study**
- The effect is expected to change with angle of incidence
  - What matters is the local charge concentration in the gain layer, so the "projection" of the track to the gain layer
- **Compare the suppression with alpha particles with simulation**





Gain suppression observed with alpha particles



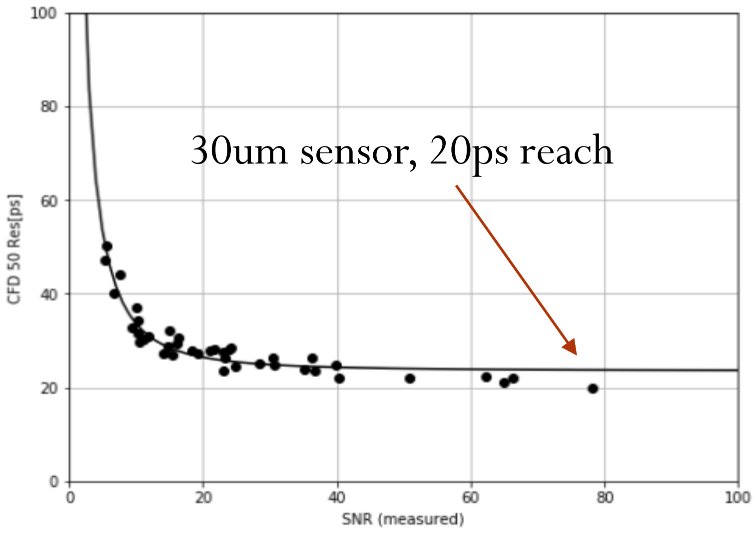
Courtesy of M. Nizam

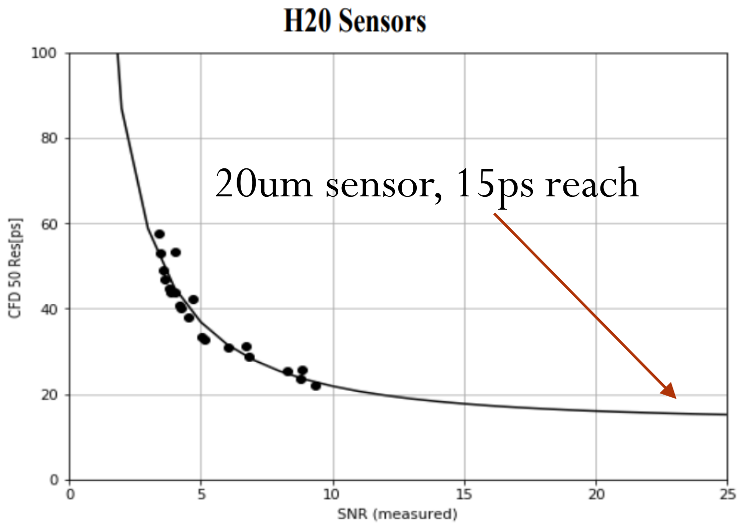
Very thin LGAD sensors future uses

- **Very thin 20 um prototype LGAD**
- Possible improvements down to 15ps of time resolution
- Compared with 50um sensors (30-35 ps reach) and 30um sensors (25ps reach)
  - https://arxiv.org/abs/2006.04241
- However, new productions of 20 um devices from BNL, HPK and FBK still at 20ps level
- **Proper design is needed to surpass 20ps of resolution**

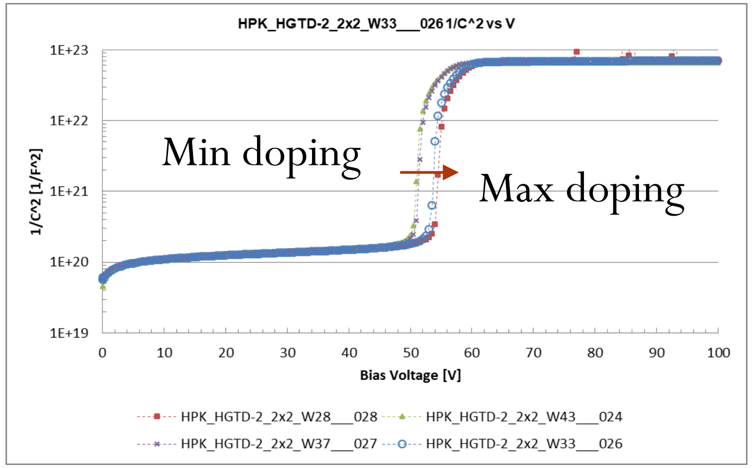
- **Very thin sensors** are also be candidates **for extreme radiation environments**
  - After substantial radiation damage thick detectors requires 1000s of V for depletion (Even though there is evidence of Charge trapping saturation)
- But a 50um sensor at 1E17Neq is fully depleted at 500V
- Gain helps in having sufficient collected charge
- Can be operated in extreme radiation environment
- e.g. for vertex detection very close to the beam line in colliders
  - https://doi.org/10.1016/j.nima.2020.164383
  - https://agenda.hep.wisc.edu/event/1391/session/12/contribution/60

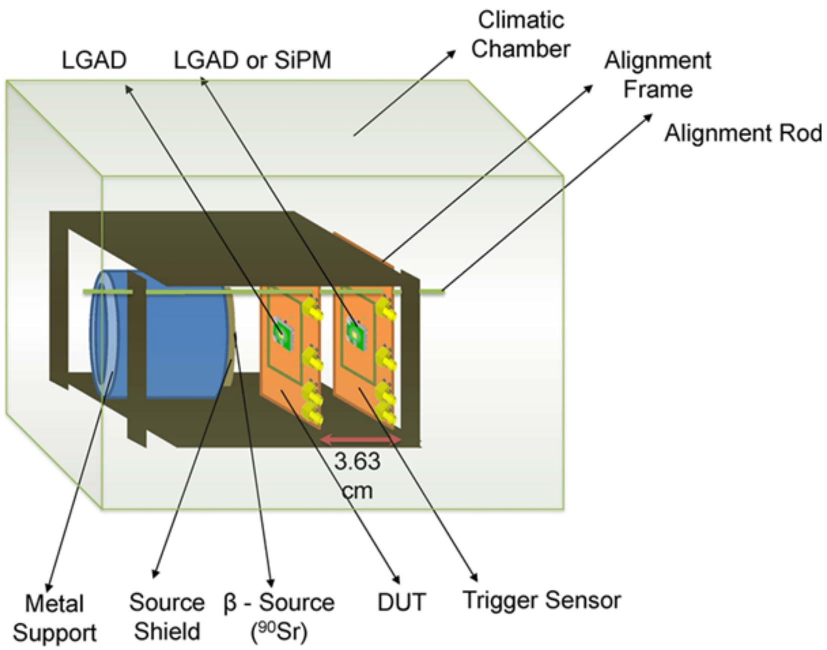
G30 sensor





Sensor testing –probe station, charge collection





- **Probe station electrical testing**
- Current of voltage (IV) and Capacitance over voltage (CV)
- CV is used to probe the doping profile of the gain layer

- **Laboratory charge collection**
- Using MiP electrons from a Sr90 β-source (β-telescope)
  - Signal shape, noise, **collected charge**, gain, **time resolution**
- Using Alpha source in vacuum (Am237), ~100 MIPs deposition
- Using X-ray gun

- **Laser TCT studies**
  - IR laser mimics a MiP response and allows charge injection as a function of position
  - Particularly useful to test arrays and AC-LGADs (see later)

- **Test beam at facilities (CERN, DESY, FNAL)**
  - Allows the study of MiP response with position information through an external tracker