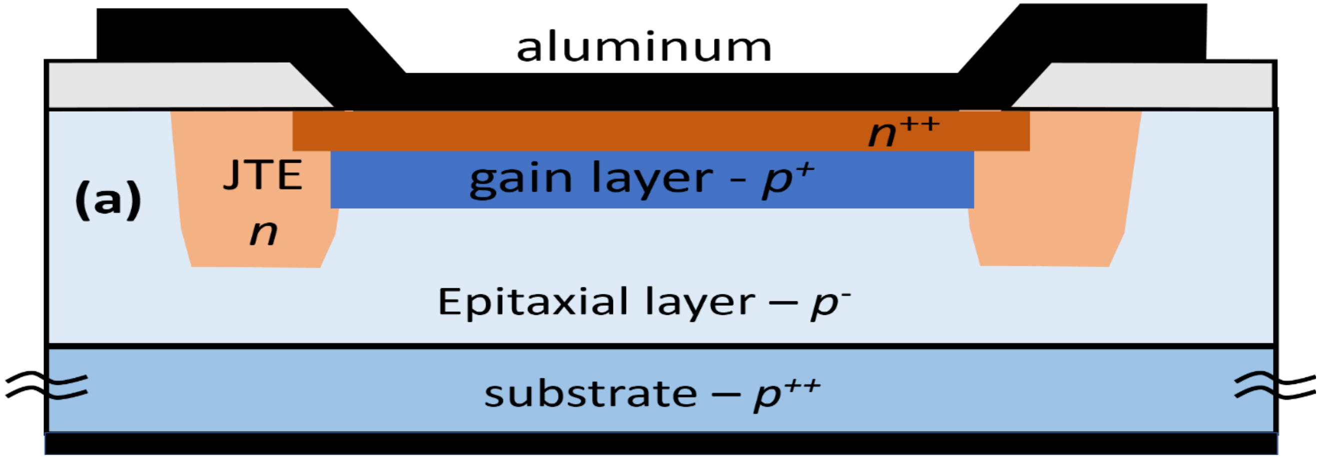
# Fast Timing Silicon Tracking Detectors
# TIPP 2021

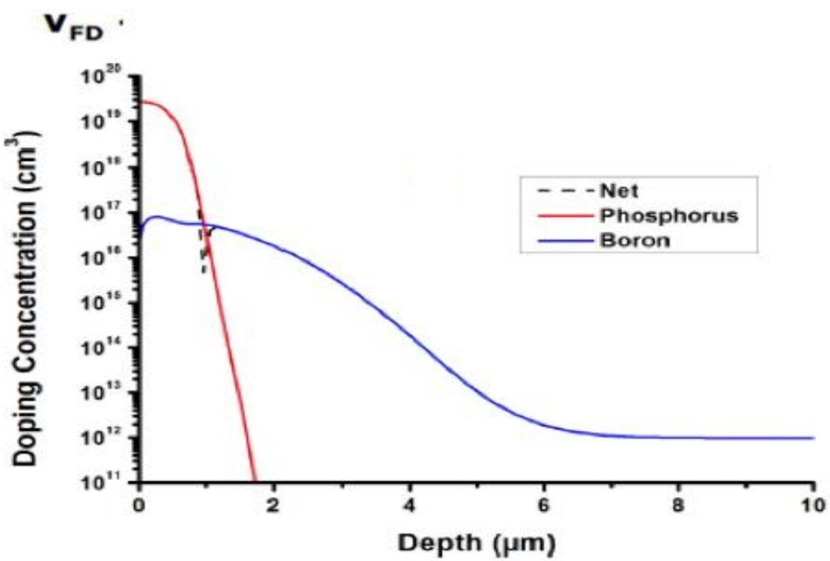
Low Gain Avalanche Detectors (LGADs, also called UFSD for Ultra-Fast Silicon Detectors) are silicon sensors with moderate gain (~20) achieved through the addition of an extra p-implantation in the sensor fabrication process. The inclusion of moderate gain allows for thin sensors with fast signals and high slew rate. This opens the door to large scale silicon tracking with excellent timing resolution.

**Topics for this talk:**

- Near term applications of 50 $\mu$m thick LGADs.
- Use of thinner sensors to improve timing resolution and speed.
- Elaborations of design aimed at improving the sensor fill factor.
- AC-LGADs (also called RSD for resistive silicon detector), which should provide 4D tracking: <15 microns spatial resolution, <15 picoseconds timing resolution for thin sensors.
- Will mention a few experiments planning to use LGADs.
- Backup: Details on the experiments planning to use LGADs.

# First LGAD application: Sensors planned for HL-LHC (high luminosity LHC upgrade) forward single charged particle detectors.

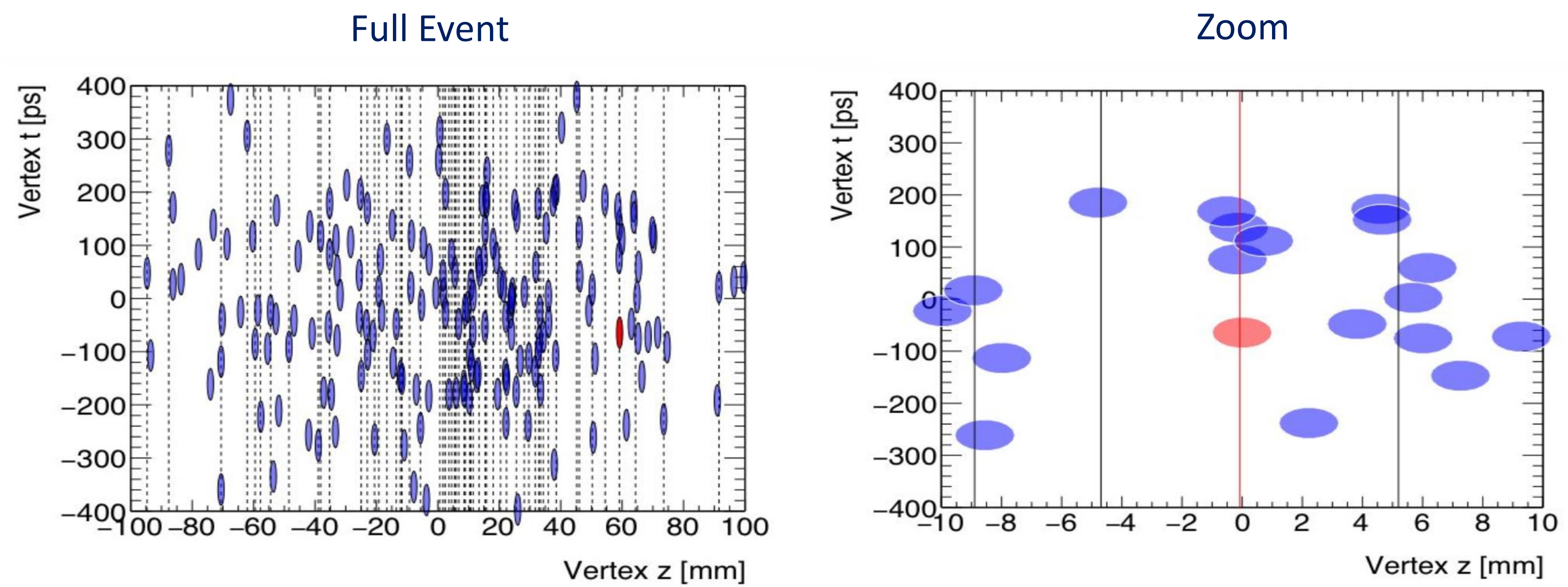



**Goal: Gain field ~ 300 kV/cm over ~ 1 µm near junction. Bulk field in rest of sensor ~ 20 kV/cm, gives a saturated electron drift velocity ~ $10^7$cm/sec. Want to have gain for electrons but not holes, leads to gain ~ 20. Sensor thickness choice for HL-LHC is 50 µm.**

**Many square meters of detectors to be built made of individual modules 2cmx4cm bump bonded to two 2cmx2cm readout chips. Each LGAD pad is 1.3x1.3 mm so position resolution is modest. First produced by CNM, now successfully made by several vendors.**

# Why LGADS? One Problem at the HL-LHC: Vertex Association

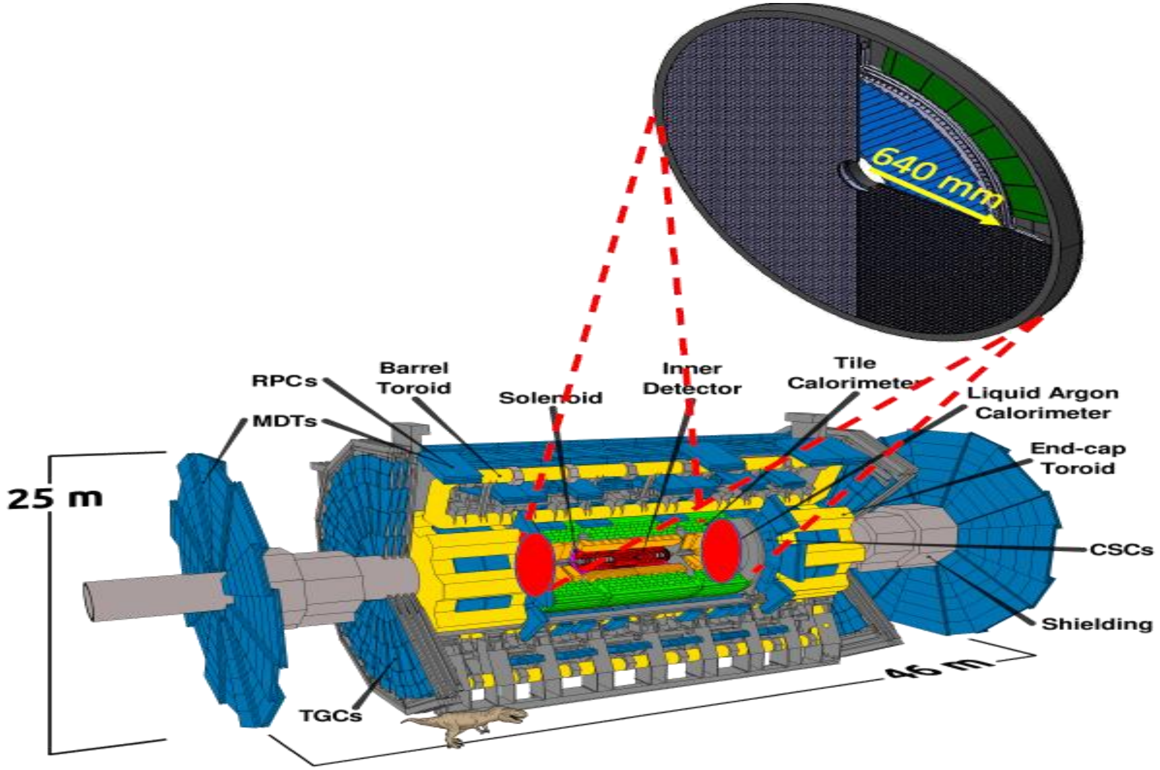



Event display showing the time and z position of all vertices in an event with 200 additional interactions. Blue ellipses correspond to truth vertices. The size of the ellipses are 30ps and 1mm. The red ellipse indicates the truth hard-scatter vertex. The dotted lines indicate the position of the reconstructed primary vertices in the event. The right plot is a zoom around the hard-scatter vertex.

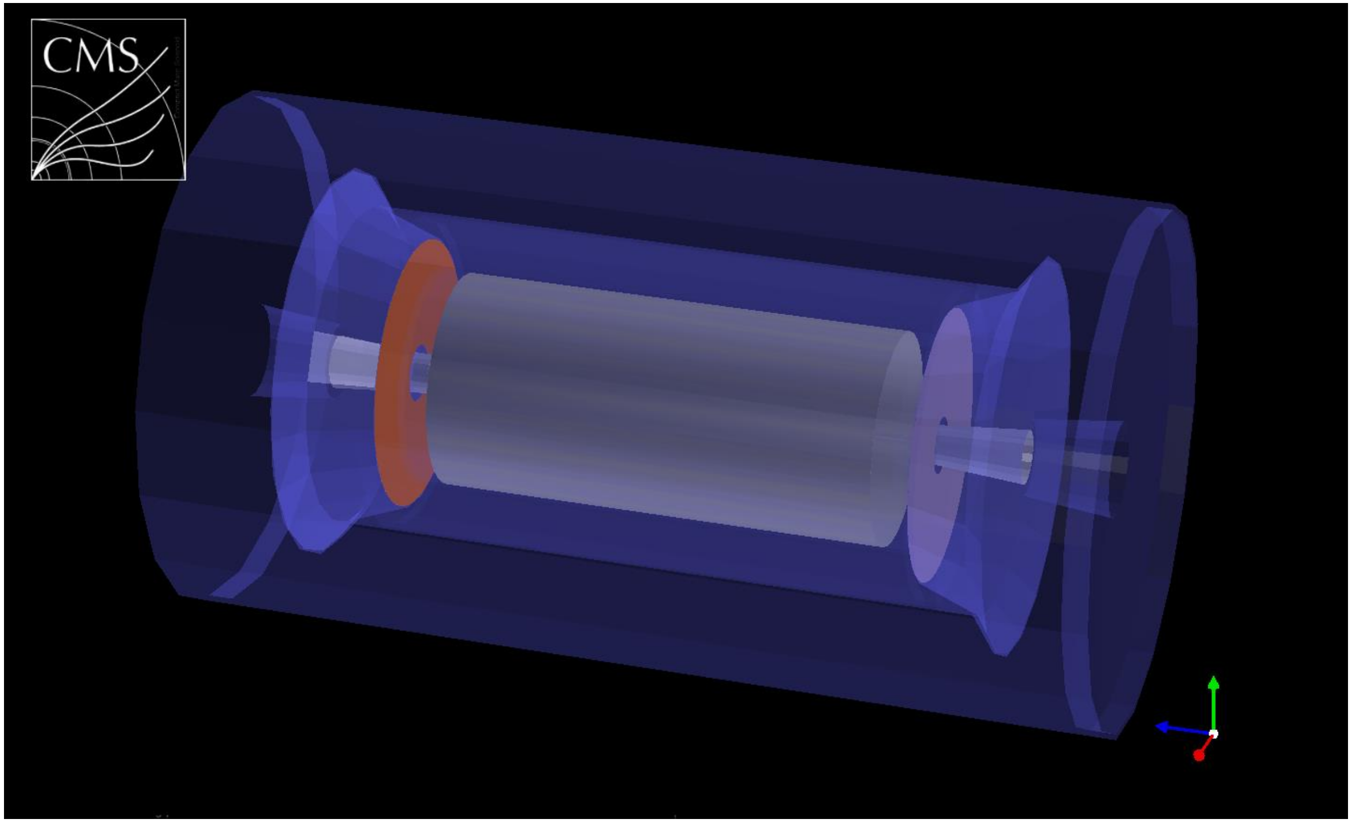
**Simulation for 200 pile-up events at the HL-LHC. Timing information can add powerful pile-up rejection capabilities. Vertex of interest is in red.**

# ATLAS HGTD, the ATLAS Timing Upgrade

**HGTD (High Granularity Timing Detector): placed between tracker and end-cap calorimeter. LGADs provide time for hits to be linked with ITk (ATLAS HL-LHC new inner tracker) pixel tracks and calorimeter clusters. Common times for tracks nearby in space indicate that they are likely from the same vertex. Also used to measure instantaneous luminosity for every bunch crossing by counting number of hits. Luminosity important for precision measurements. Rapidity coverage from 2.4 to 4.0. Several measurements per track, goal is 30 psec per track.**



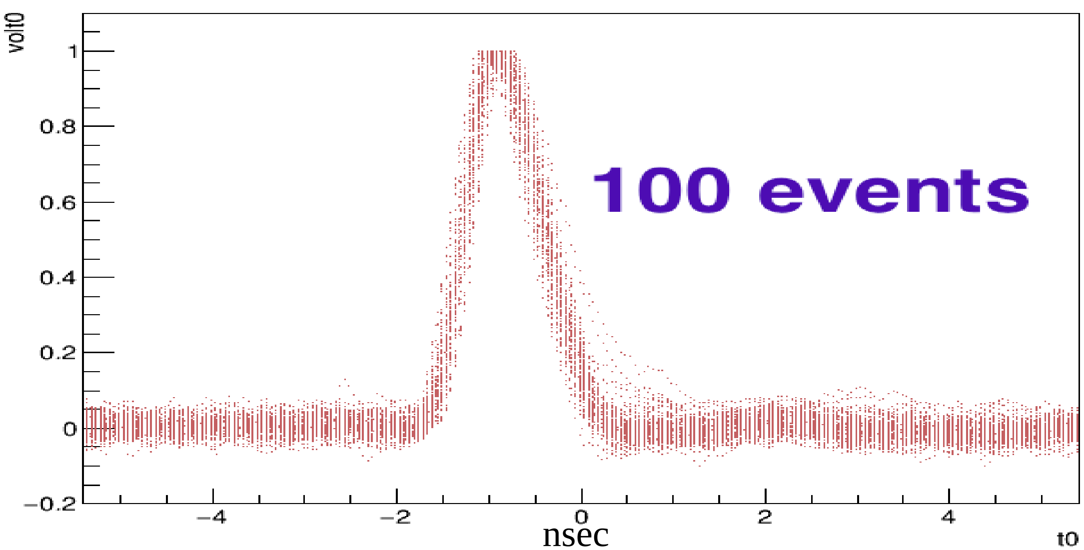
# CMS MIP Timing Detector (MTD)




**CMS Timing Detectors to measure individual charged tracks. Covers rapidity from -3 to +3. Outside tracker and inside calorimeters. Barrel at a radius of 117 cm made of crystals read-out by SiPM's. End-caps require finer granularity and more radiation hardness. They will be made of LGADs, similar to the choice for ATLAS. Expected timing resolution of ~30 psec per track everywhere for CMS.**

# Understanding LGAD signals: Beam Test of a 50 μm Thick Sensor

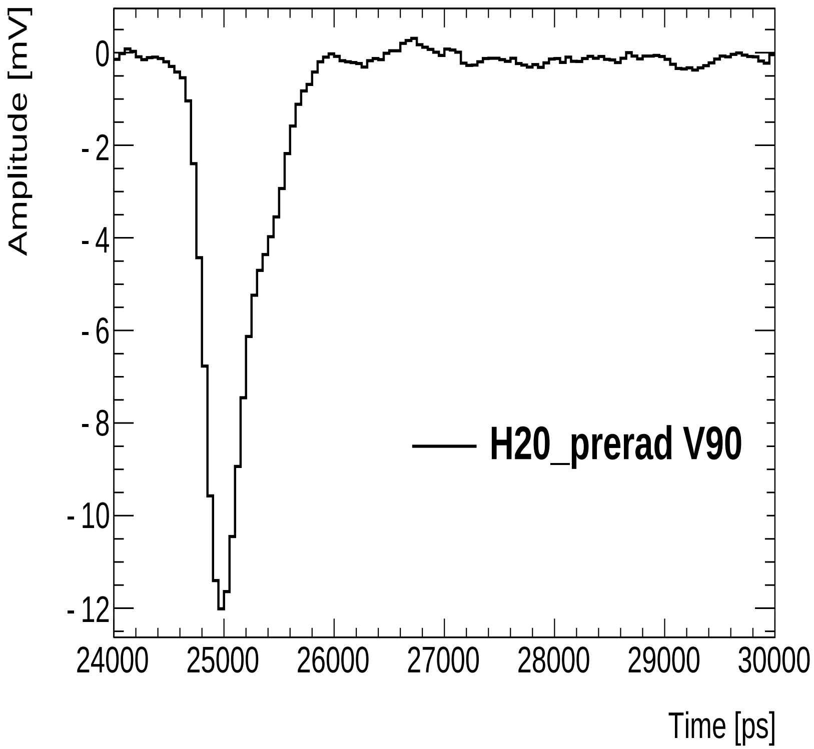
- In general the time of the pulse maximum is determined by the collection time of the last drifting electron.  This is determined by the detector thickness and the (saturated) electron drift velocity providing a fixed time.
- At this point all gain holes are still drifting.
- So for constant weighting field and constant velocity, the time of the peak, to good approximation, is independent of the ionization and gain (determines the total number of holes drifting) and Landau fluctuations (determines the clumping of the ionization).
- This uniformity in arrival time of the peak is very useful for measuring time.




Sensor signals scaled so peak is always equal to 1, allows looking at shape independent of height.  Pulse duration ~ 1.5 nsec for 50 μm thick sensor.

Many Signals from Sensor overlayed, very constant shape!

# Thinner sensors offer the potential for even better timing resolution than achieved with 50 μm thick sensors.



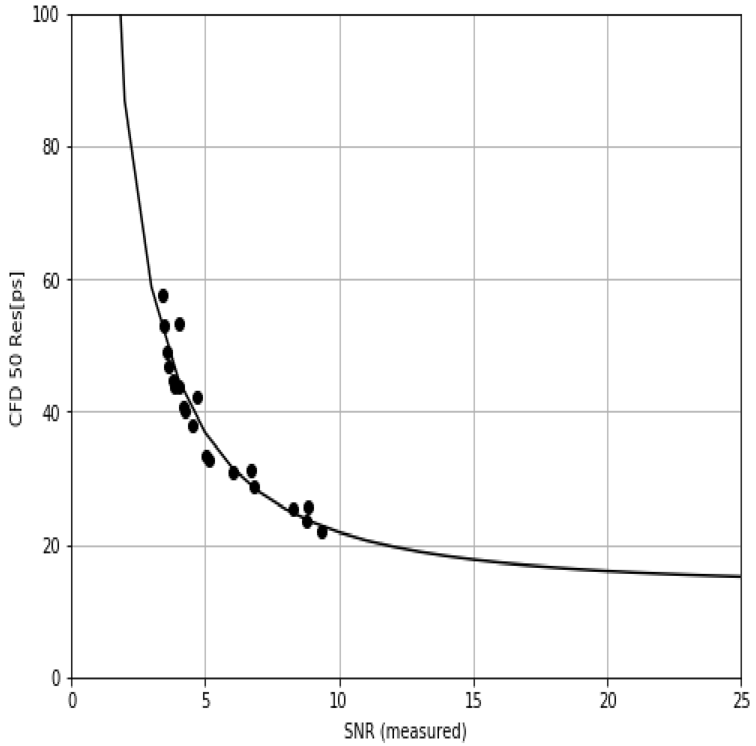

Pulse for 20 micron thick LGAD. Gain ~ 8.

**Sensors fabricated by HPK in Japan.**

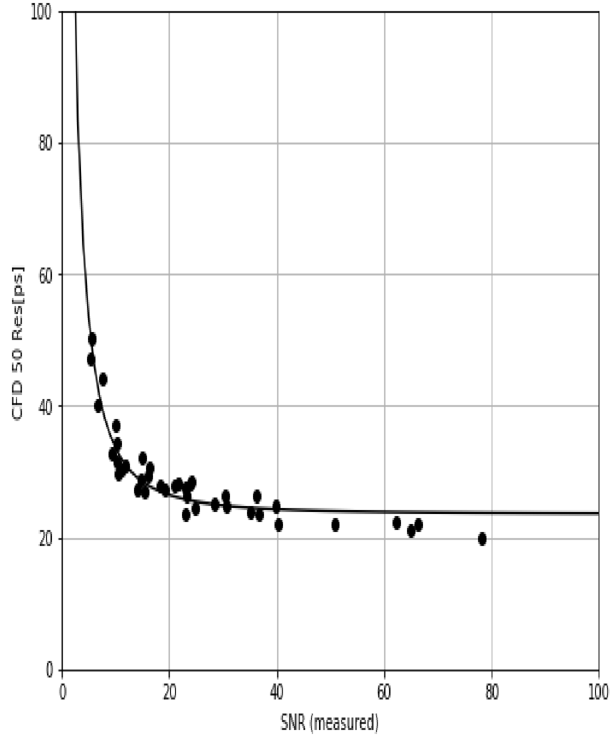
Rise-time (10-90%) about 170 picoseconds compared to about 430 picoseconds for 50 micron thick sensors. Contribution to the time resolution from Landau fluctuations is proportional to the detector thickness so smaller for thinner detectors (expected to be less than 15 picoseconds for the 20 micron thick sensor).

# Measured time resolution versus signal-to-noise ratio for thin detectors

20 micron thick sensor



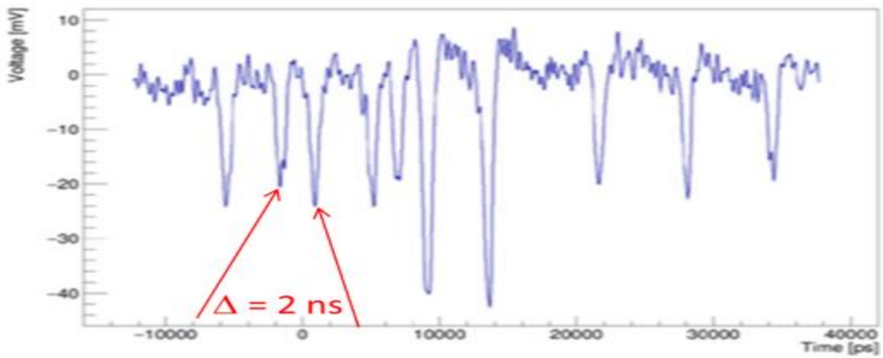

35 micron thick sensor



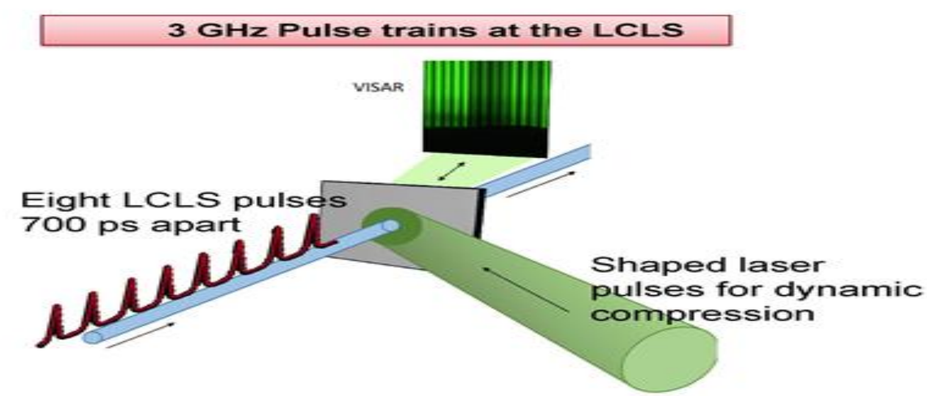

Time resolution for minimum ionizing particles measured for thin detectors versus the signal-to-noise ratio. Signal is defined as the peak height and can be adjusted by changing the detector voltage (and gain). Left: for 20 micron thick detector. Right: for 35 micron thick detector. Note the modest value of signal-to-noise required to get to about 20 picosecond time resolution for the 20 micron thick sensor.

# X-Ray Detection: Speed is a goal for the future.

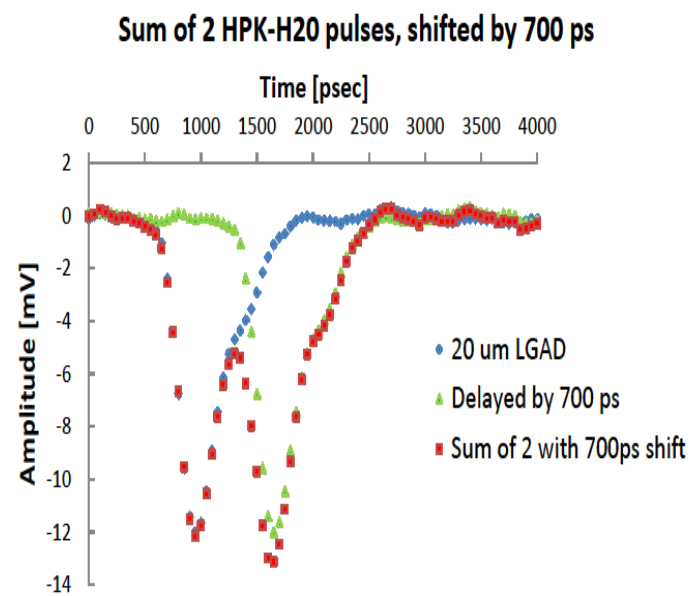
**X-rays 2ns apart recorded in 50 μm thick LGAD.**



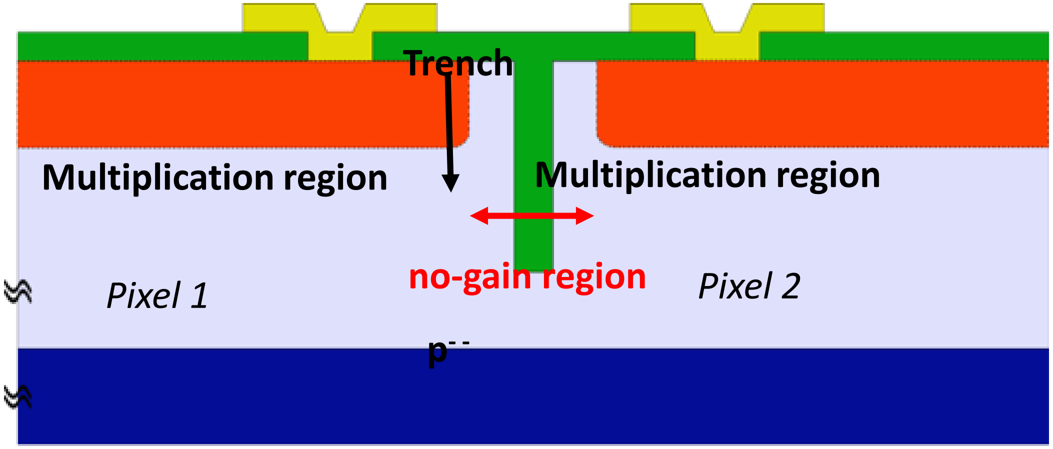

**Planned set-up at the Stanford LCLS –II will have even more closely spaced X-rays. Example:** 8 LCLS pulses 700 ps apart are scattering off material that is dynamically compressed by shaped laser. The time history of the state of deformation is recorded.



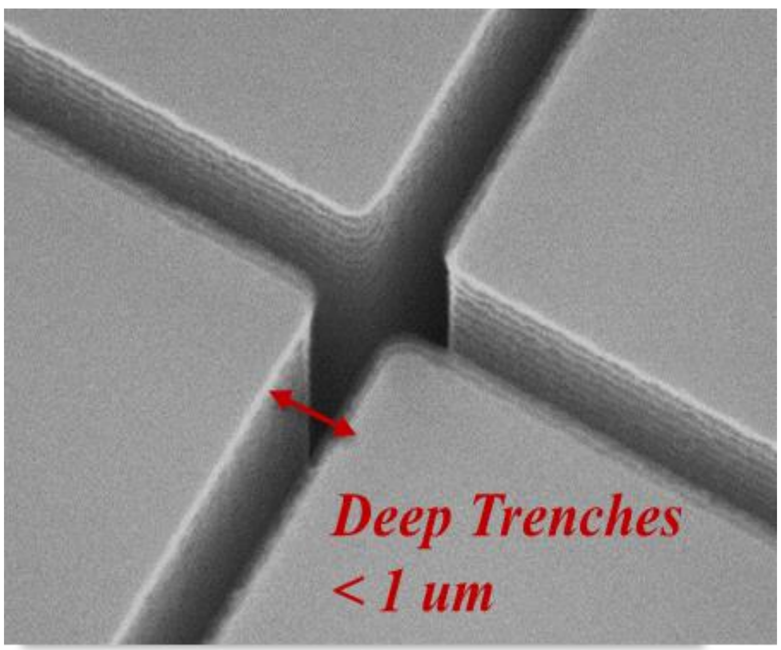

**Could LGADs detect the X-ray train?** Two LGAD pulses (shown earlier) for 20 micron thick sensor are superimposed following each other after 700 ps. Tail could be improved with somewhat higher bandwidth amplifier, as intrinsic signal is faster than the amplified signal.



# Elaboration of basic design: Deep Trench Isolation Technology – TI LGAD




- **JTE and p-stop, which limit fill-factor, are replaced by a single trench.**
- Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.




- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

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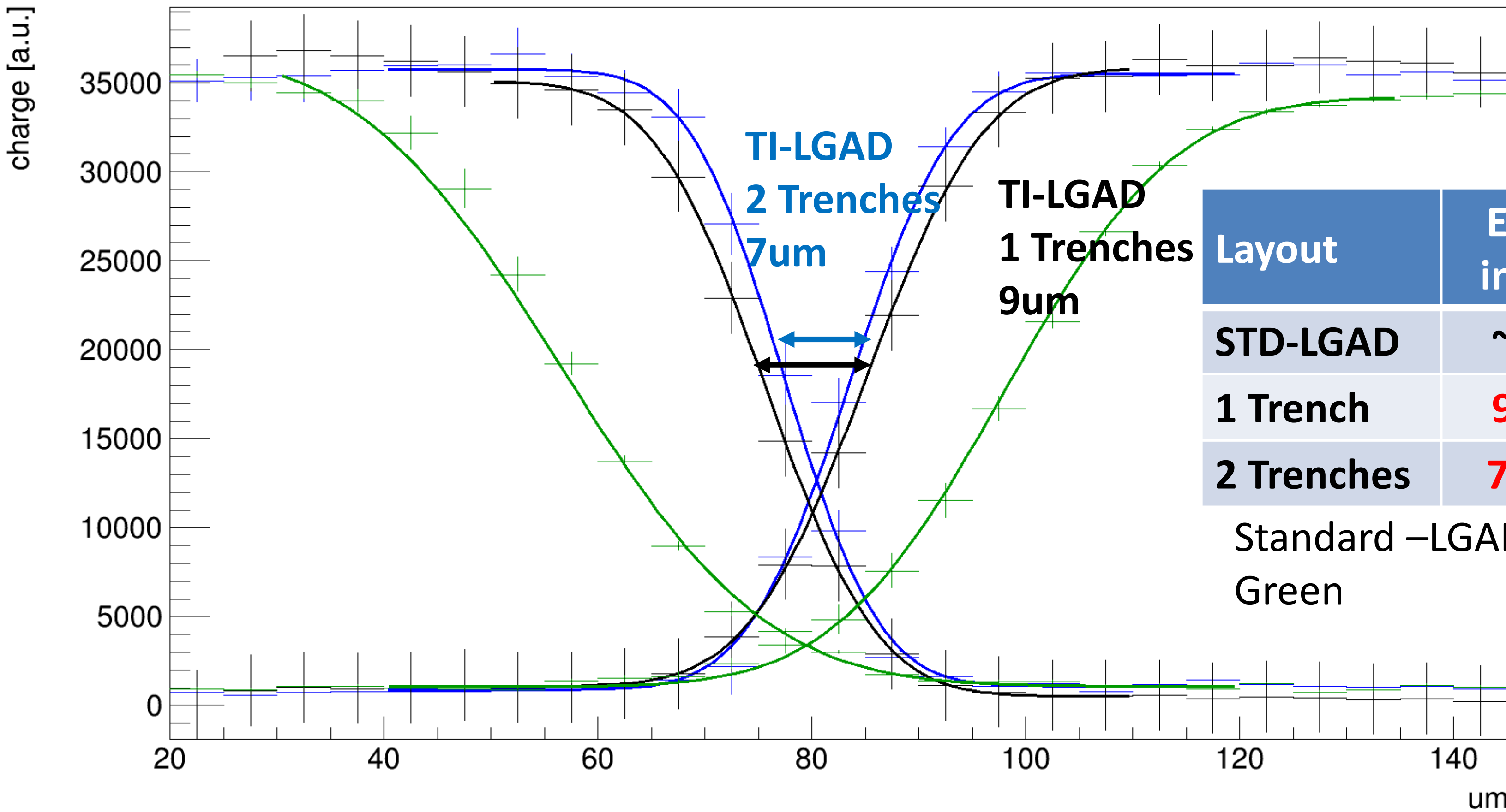
# TI-LGAD inter-pad Characterization (TCT laser Setup)




| Layout | Effective inter-pad |
|---|---|
| STD-LGAD | ~ 38 um |
| 1 Trench | 9 ± 1um |
| 2 Trenches | 7 ± 1 um |

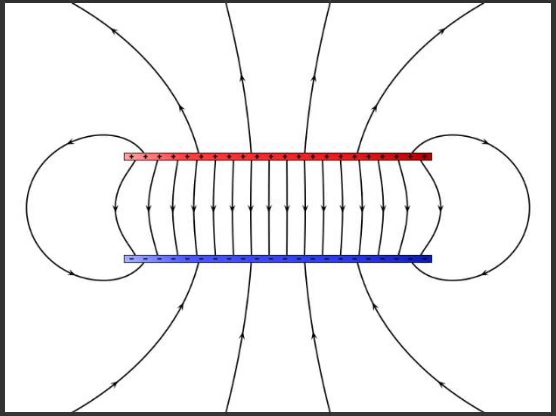
Standard –LGAD in Green

Measurements performed in Torino Silicon Lab (University of Torino - INFN)
F. Siviero – 35th RD50 Workshop, Nove,ber 2019

# Another Elaboration on Basic Design

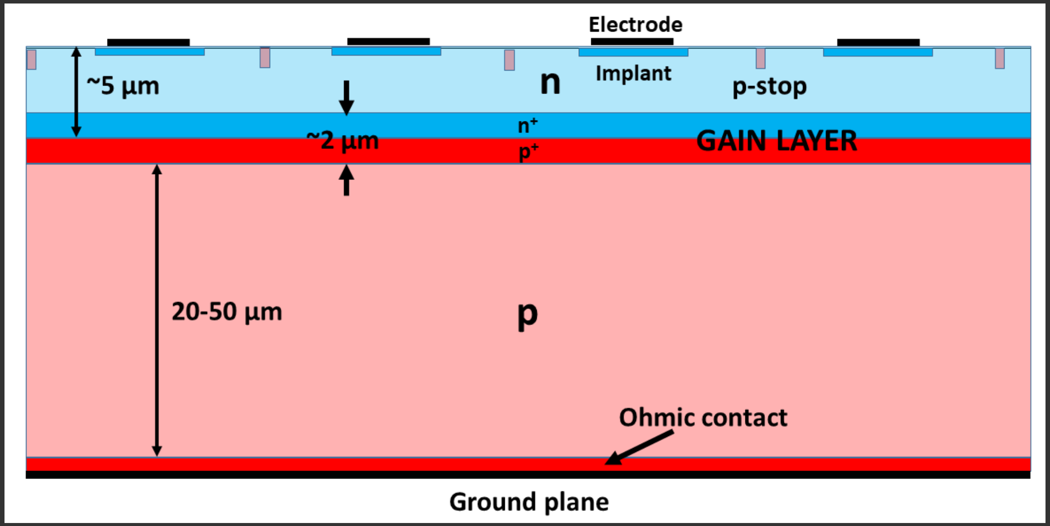
## The Deep Junction (DJ) LGAD Concept

Basic inspiration is that of the capacitive field: Locally large, but surrounded by low-field region beyond the plates.

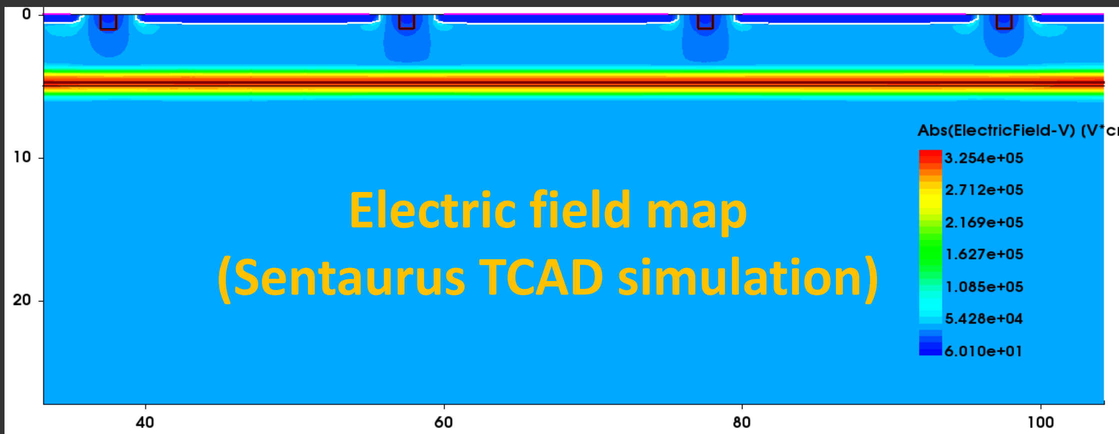


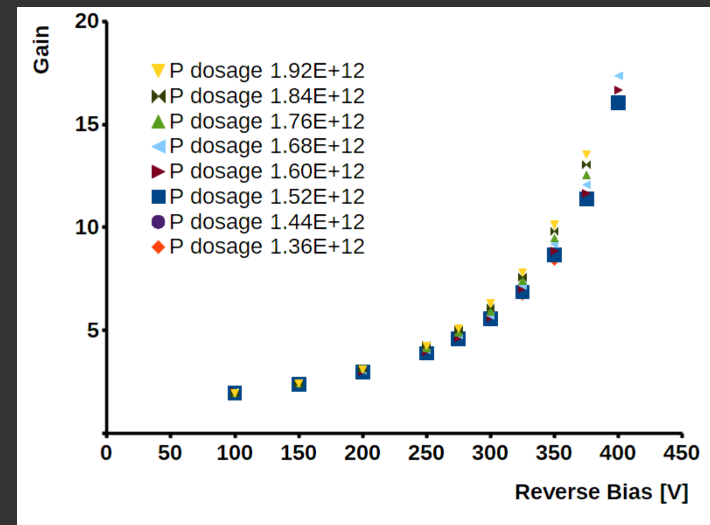
- Use symmetric P-N junction to act as an effective capacitor
- Localized high field in junction region creates impact ionization gain ("GAIN LAYER")
- Bury the P-N junction so that fields are low at the surface, allowing conventional granularization

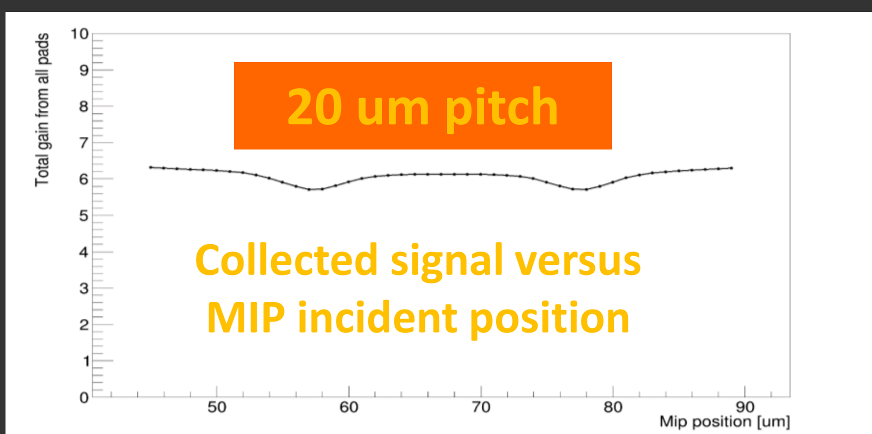
➔ "Deep Junction" LGAD (DJ-LGAD)



# DJ-LGAD Simulated Performance



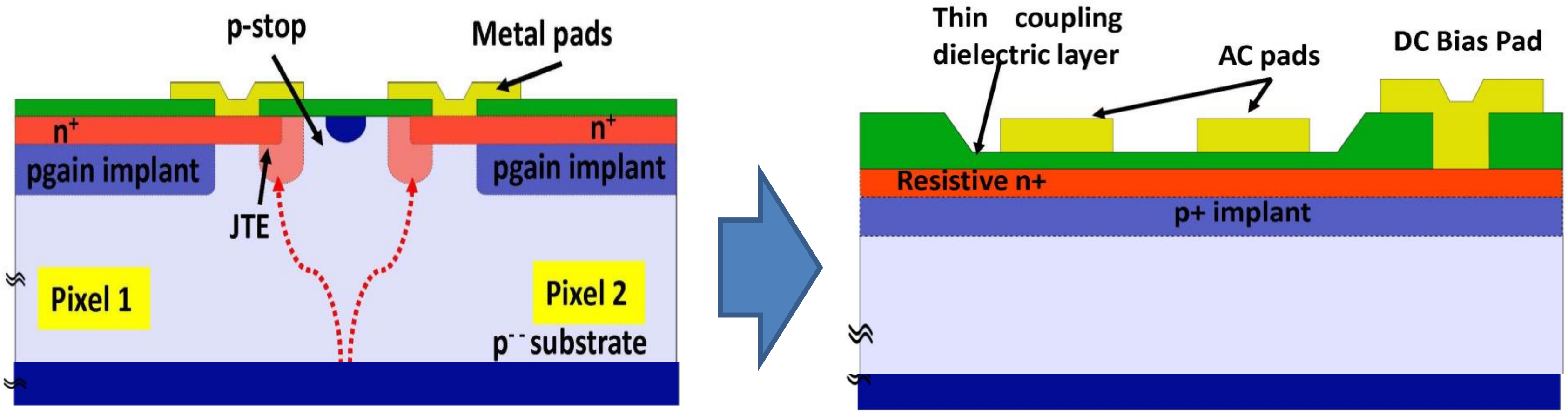




- Concept developed at SCIPP
- First prototypes under development through a Cactus/BNL/SCIPP collaboration
- SBIR and LDRD funding

# AC-LGAD: goal in addition to precision timing is excellent position resolution via signal sharing.

To go from LGAD on the left to AC-LGAD on the right have to remove physical pixelization of LGAD:

- Make n++-implant at the junction more resistive and extend it as a continuous sheet over the gain layer across the entire sensor.
- Add dielectric layer for isolation and AC-coupling into readout pads, which are connected to the electronics. Results in 100% fill factor.
- Simplification of design and production (no p-stop, JTE, inter-pad gap).

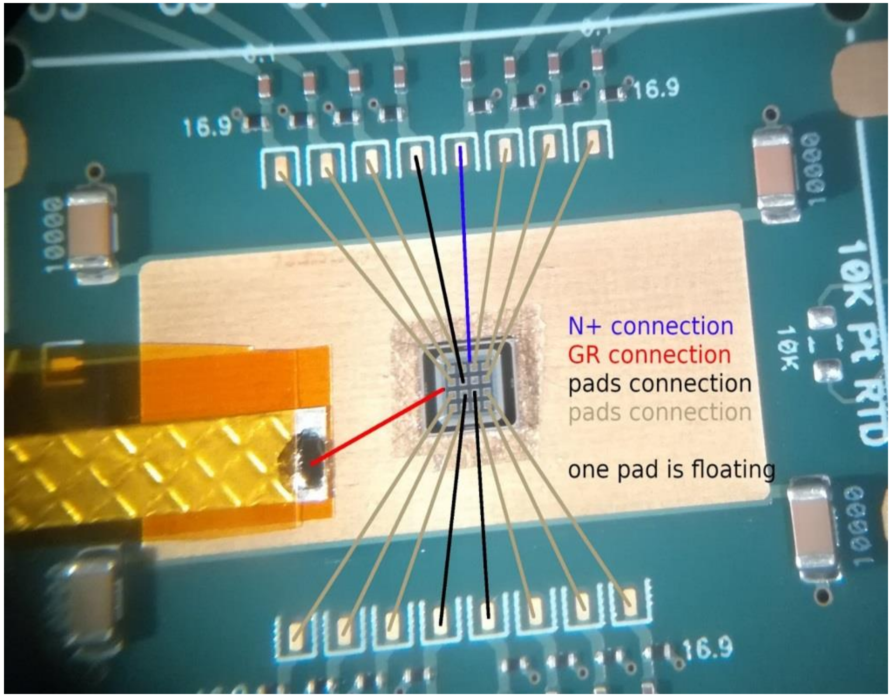



**Result**:

- Can use sparse readout with pulse sharing between ~ 4 pads for precision spatial resolution. Sparse metallization results in lower capacitance, and lowered power by limiting channel count. The signal (defined by peak height) summed over the pads is very close to constant independent of hit location and can be made large because of the LGAD gain.

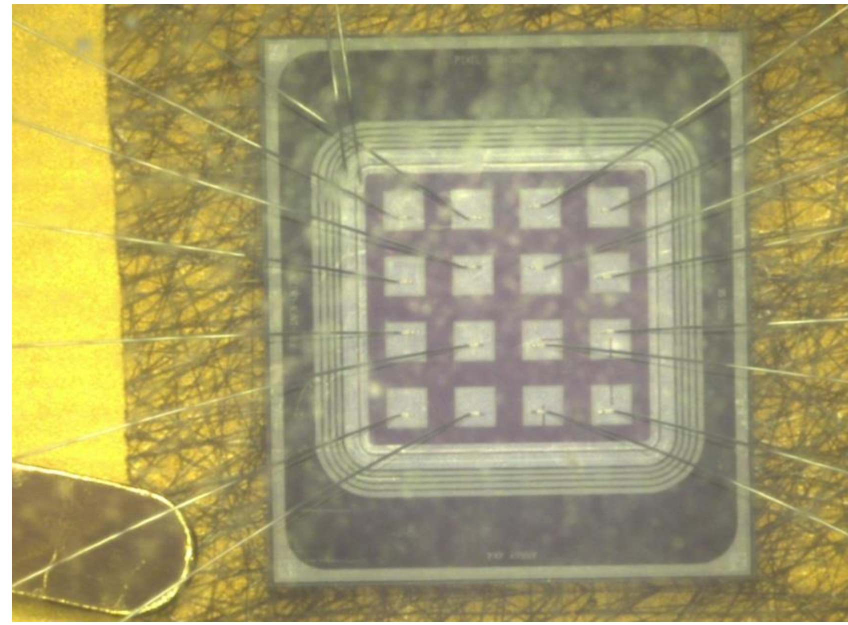
# AC-LGAD Setup for IR Laser Scan

**16 channel board courtesy of FNAL**




**16 Channel AC-LGAD**

**AC-LGAD pad detectors provided by FBK in Italy.**



Laser scans were performed to measure sensor signals for ~ mip equivalent energy deposit. Sensors 55 micron thick, gain ~ 20. Signals saved using storage scope. Time reference provided by laser. Laser spot size ~ 20 microns.

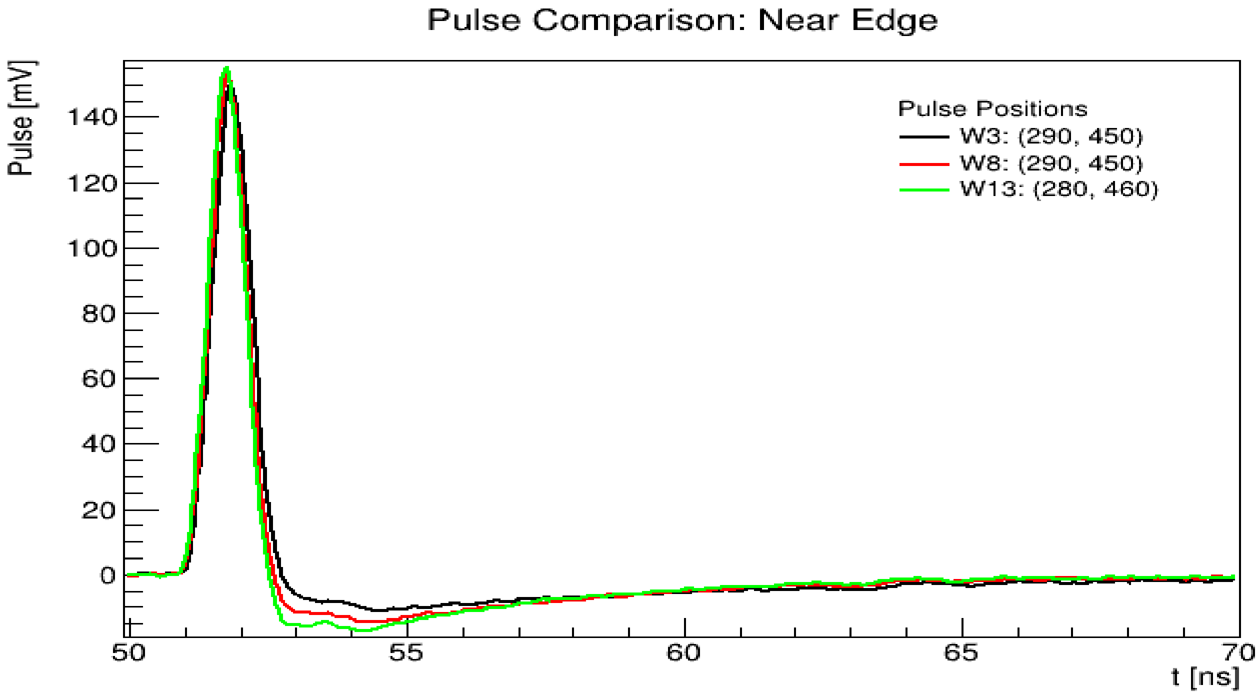
Most scans from front, in some cases the backside metal was removed and scans from the backside were performed. **Sensors designed and made by FBK in collaboration with the Universities of Trento and Torino.**

# What Have We Tested?

| | | |
|---|---|---|
| | RSD1 run at FBK | |
| | square matrices | |
| **pitch [um2]** | **pad size [um2]** | **# of pads** |
| 200x200 | 100x100 | 3x3 |
| | 150x150 | |
| | 190x190 | |
| 300x300 | 150x150 | 2x2 |
| | 200x200 | |
| | 290x290 | |
| 500x500 | 200x200 | 3x3 |
| | 300x300 | 4x4 |
| | 490x490 | |

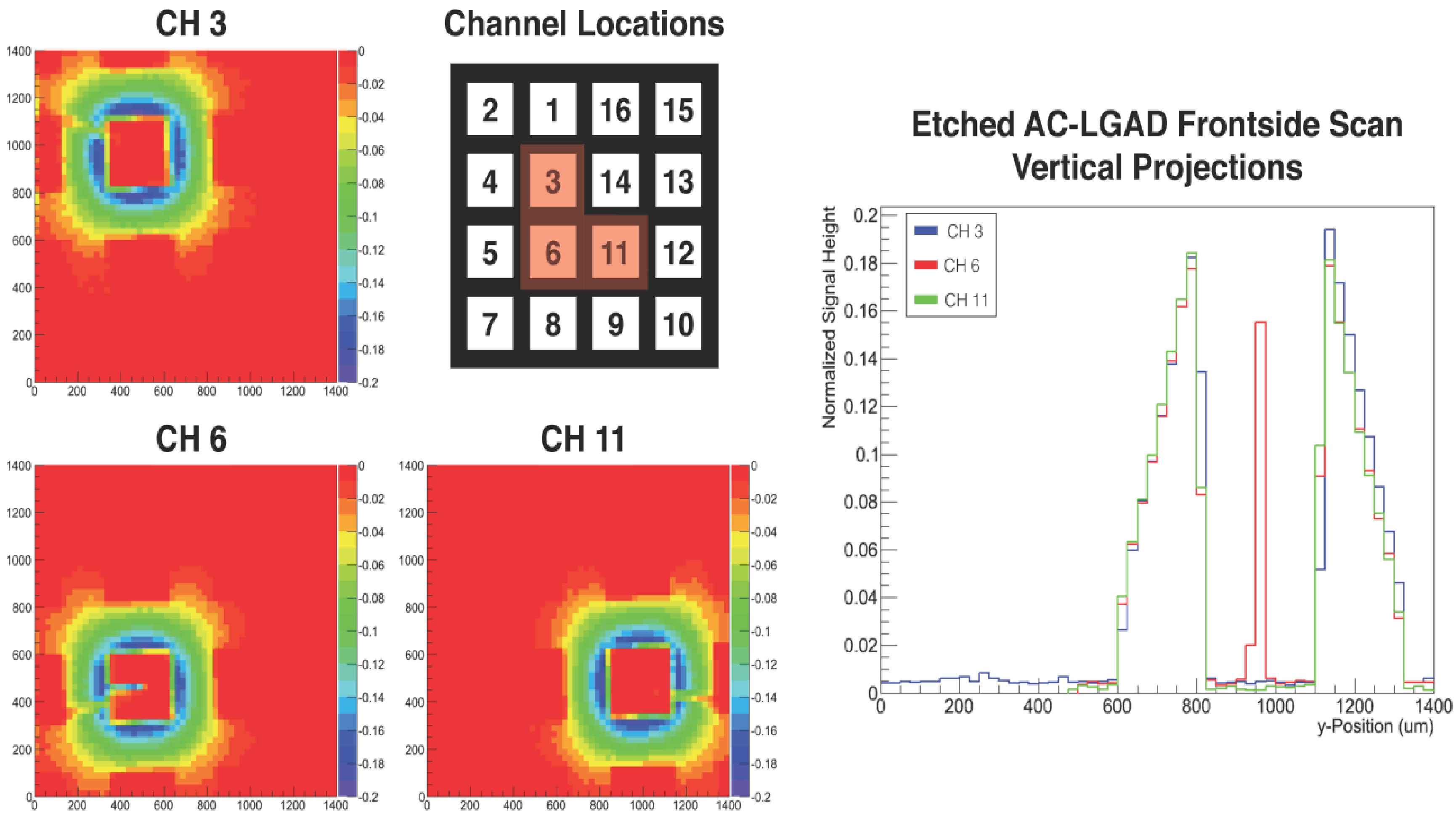
Indicate sensors via Pitch – Pad size. Find that 500-490 has capacitive cross talk between neighbors ~ 10% and poor position resolution since little sharing. 500 μm pitch with the smaller pads (300 and 200) have negligible cross-talk. Have focused effort on 500-300 and 500-200 since 500 μm pitch is closest to what we might want from the point of view of power limitations and space limitations for circuitry in a chip. Want to understand effect of termination of the n+ layer, its resistivity, and oxide thickness. Example, next slide.

# Pulse Comparison: 3 Different n+ doping concentrations.




Doping of n+ layer for sensor indicated as W8 in figure is ~1/10 of standard DC-coupled LGAD. W3 is ½ as doped, W13 twice as doped. Small changes observed, with under shoot dependent on doping choice. Key parameters for timing such as rise-time vary by < 5%. We find that the first nanosecond of signal largely independent of details of sensor (n+ resistivity, oxide thickness or termination of n+). RC of undershoot return to baseline varies between 2.5 and 8 nsec for range of parameters of sensors fabricated and tested.

# Example of IR Laser Scan, maximum pulse height versus position (FBK RSD1 500-300)




Laser Scan from the front, normalized signal height: No signal in pad area due to reflections from metal, except for signal for the slit on one pad (channel 6). Very consistent signals for all pads.

# Pulse Shapes for Front or Back Laser Irradiated Sensor

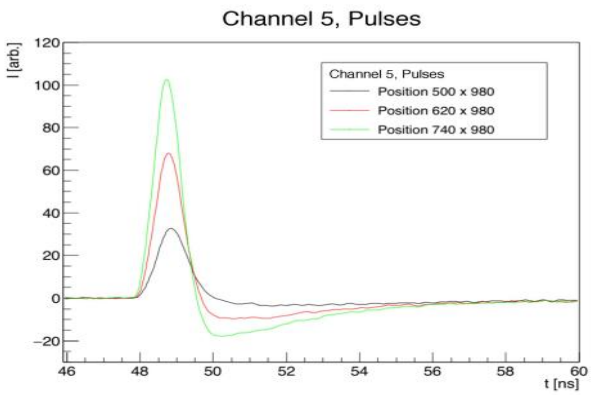
**Pixel Pitch = 500µm, Pad Size = 200µm**

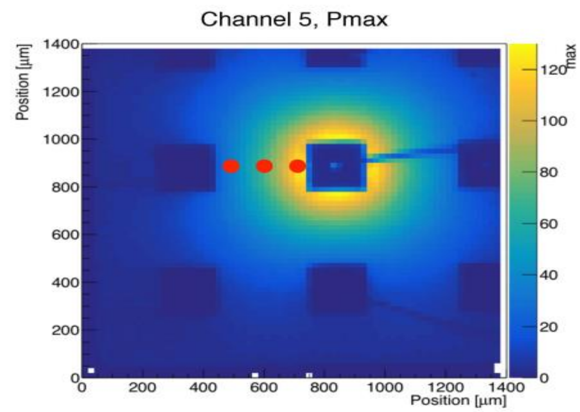
Laser irradiation, locations shown by red dots in figures. Front-side, can't irradiate location of metal pad, backside can explore full detector response.

**Pulses have very consistent rise and fall times. 10-90% rise-time about 530 psec. Different amplitudes basis of position interpolation.**

## Frontside Scan: Pulse Comparison

In Between Pad 4 and 5:

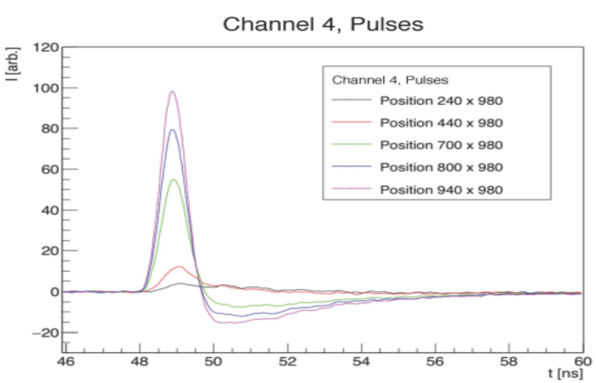


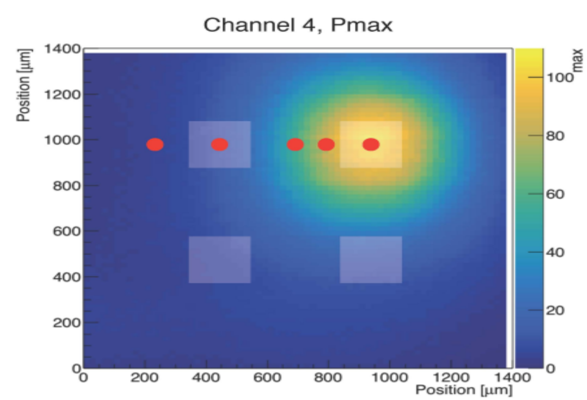




Pulse locations

## Backside Scan: Pulse Comparison

In Between Pad 4 and 5:



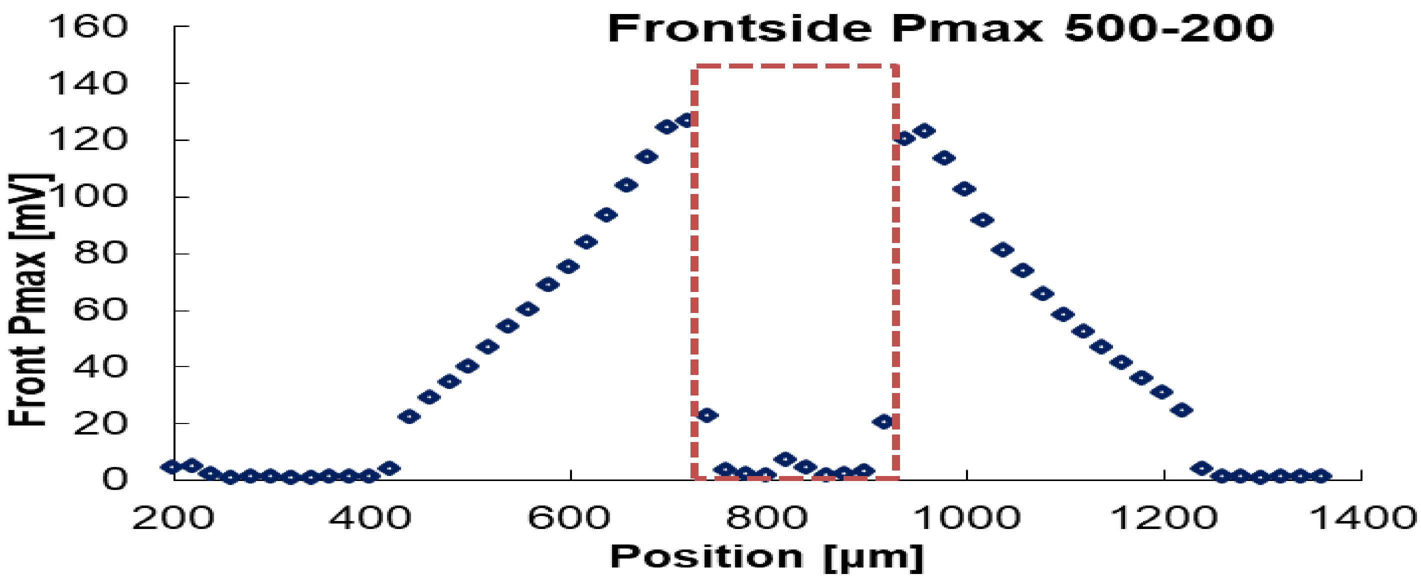




Pulse locations

Boxes indicate approximate pad locations

Pmax under next neighbor pad: ~ 10% of hit pad.
Pmax beyond next neighbor pad: less than 2%.

# Position Measurement for 500-200



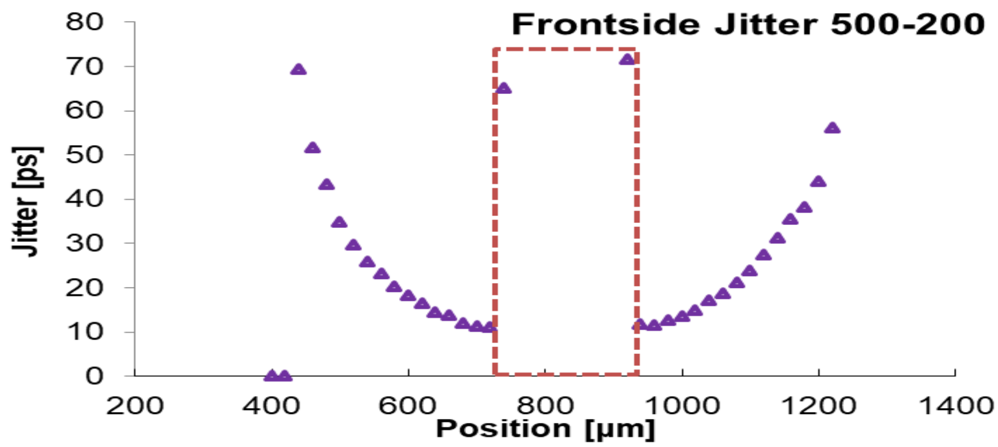

Pulse maximum decreases nearly linearly as we move away from the pad in a direction given in the previous figure. A measurement of the coordinate along the direction we are scanning, referenced to the center between the pads, is therefore approximately: x = (P1 – P2)/(P1+P2) where P1 is shown above and P2 is pulse height for neighbor (not shown). (P1 + P2) is nearly constant independent of location in x. From this one can calculate the expected error on x in terms of the uncorrelated variation on the pulse heights from electronics noise. The linear approximation gives for the error on x:

**$\sigma_x$ = [Interpad Spacing/ signal-to-noise ratio] f**

The signal-to-noise ratio is (P1 + P2) divided by the electronics noise (assumed to be the same for each pad) and f is a factor near 1 given by: [0.5/(maximum value of (P1-P2)/(P1+P2)] sqrt ($P1^2$ + $P2^2$)/(P1+P2). The position resolution varies only a little with x.

# Time Measurement for 500-200

**500-200: Jitter = 11 ps near pad (note no Landau contribution for Laser). Further away use time measurements of several pads.**

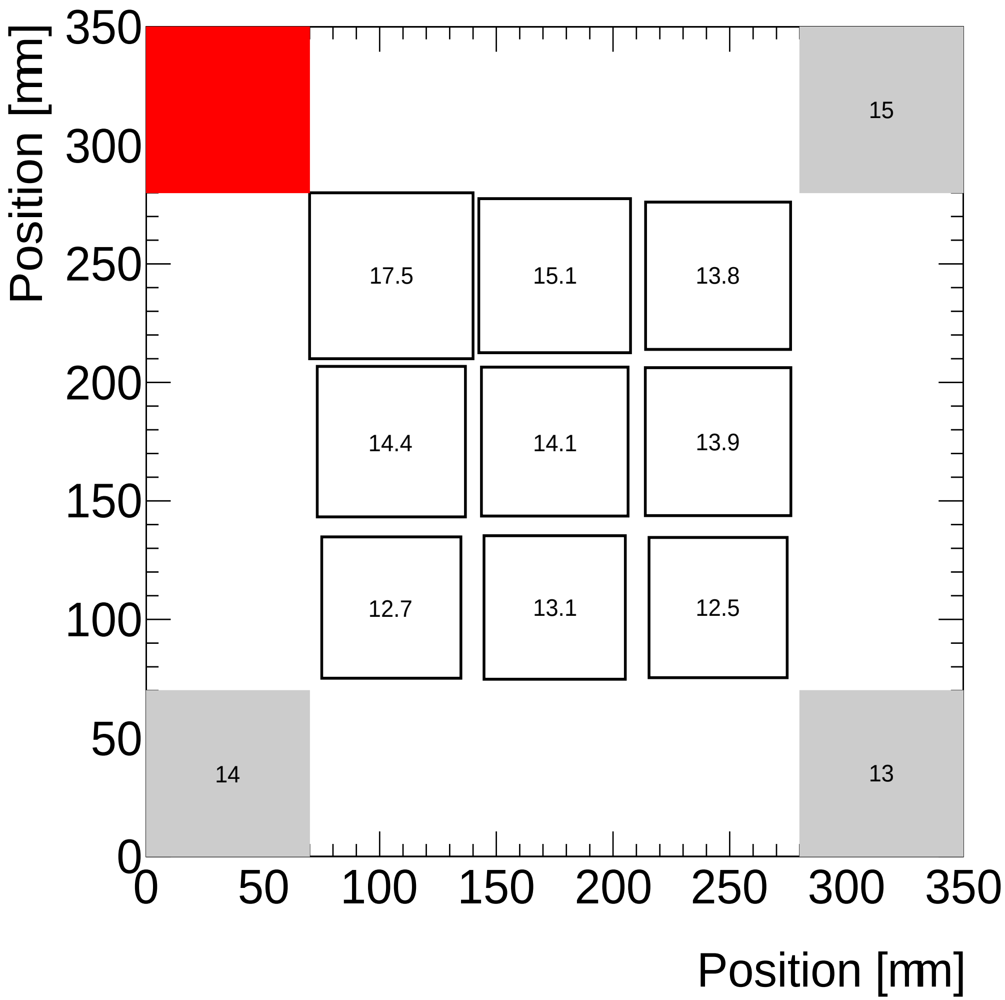



We have a collection of times measured on several pads and need to combine for a best value and error estimate. Assume any systematics have been corrected and we have times $t_i$ for the various pads (usually 3 or 4). The jitter for each (where jitter is the contribution from the electronics system) is then estimated to be $T_{MAX}/ (P_i/\sigma_{NOISE})$. Here $T_{MAX}$ is the 10-90% rise-time of the signal, $\sigma_{NOISE}$ is the electronics noise, and $P_i$ is the maximum pulse height. Assuming that $T_{MAX}$ and $\sigma_{NOISE}$ are in common we can then calculate that the best estimate for the time and its error:

$$t = \Sigma\, t_i\, P_i^2 / \Sigma P_i^2 \quad \text{with} \quad \sigma_t = T_{MAX}/ [\mathrm{sqrt}\,(\Sigma P_i^2) / \sigma_{NOISE}\,]$$

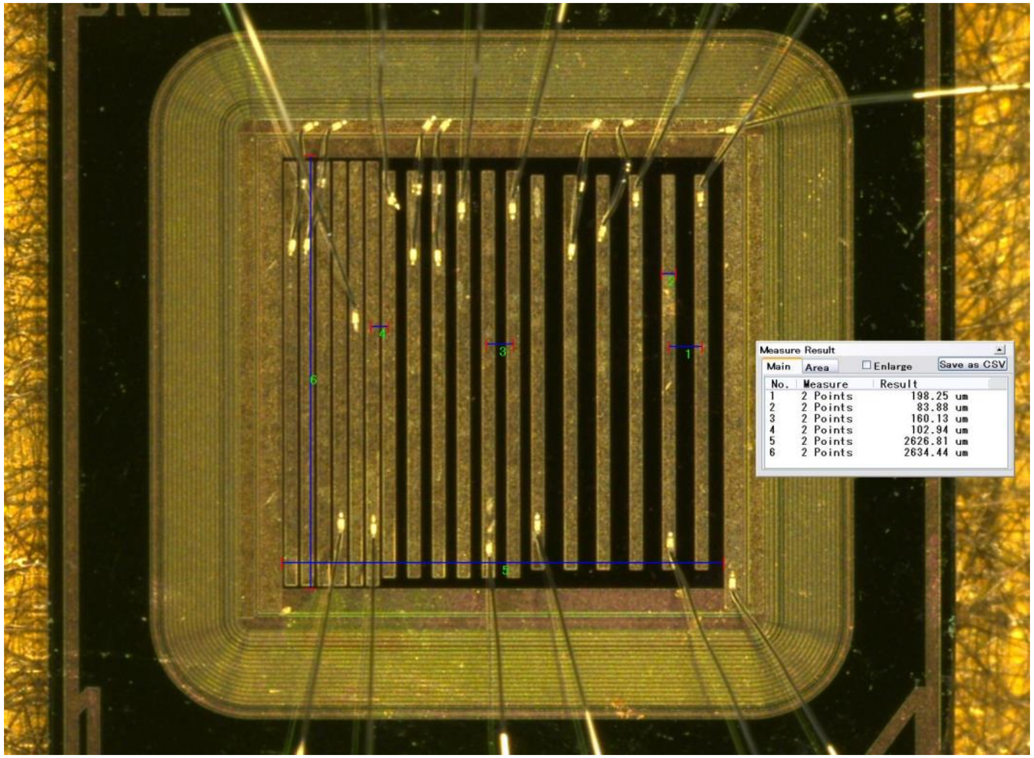
Data above for one pad follow expectation that resolution is inversely proportional to the pulse height.

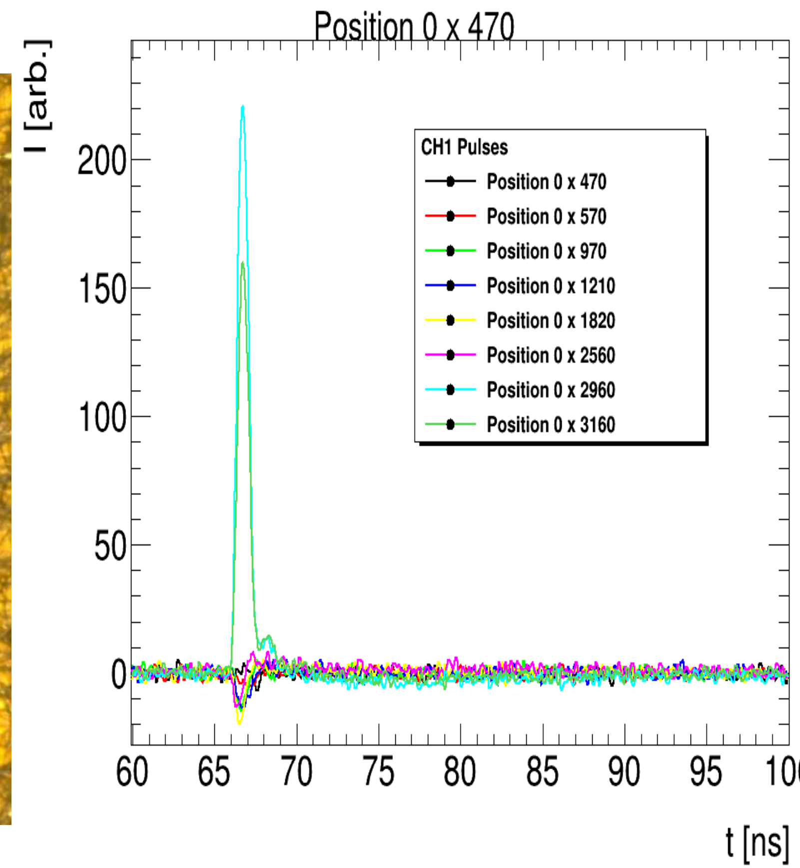
# Time Resolution Using 3 Pads (red Pad Not Read out)




Box indicates center for laser irradiation, number in box is the jitter in picoseconds using 3 pads. Irradiations explore region of maximal sharing.

For AC-LGAD great flexibility in choosing metal pattern, here strips. Can also choose less conventional patterns (for example circles, zig-zag, etc.) .




**AC-LGAD detector made by BNL to explore different pitches (100, 150, 200 μm) with 80 μm metal width.**

Signals seen on strip on right side of sensor (200 μm pitch) as laser moves between strips to the left. Large signals for laser on each side of a given strip.

# Some Expected Applications

- LGADs have opened up the possibility of excellent timing using silicon sensors for MIP signals. Requires good signal to noise and thin sensors.
- The very recent AC-LGADs combine the advantages of gain from the LGAD with signal-sharing to allow very good time resolution and position resolution. Allows sparse readout to minimize overall power in electronics.

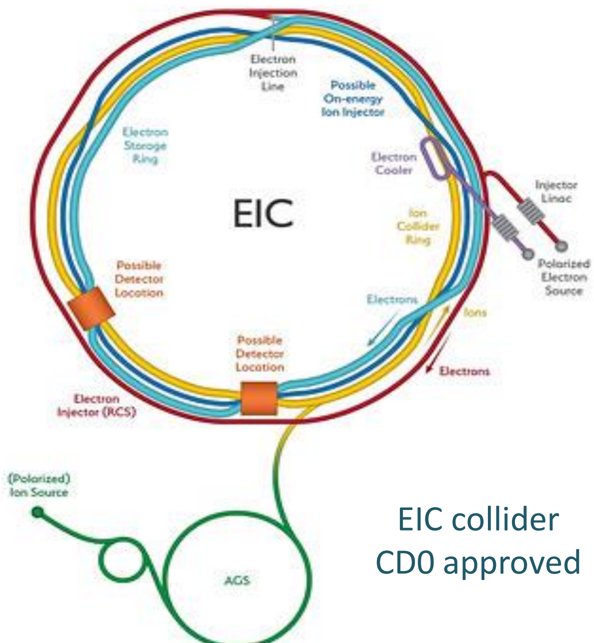
- A number of applications are now being envisioned where various signal features are important depending on the experimental details: for example best possible timing resolution for TOF, very high rate capability, 4-D tracking capability. Some examples of experiments being designed beyond the HL-LHC experiments (some presented in posters at TIPP):

❖ For the Electron Ion Collider to be built at BNL, several large detector proposals exploring use of LGADs, also very forward Roman Pots Detector.
❖ Experiment proposed for TRIUMF to measure with high precision the ratio of pion leptonic decays to an electron compared to a muon.
❖ High Acceptance Di-Electron Spectrometer (HADES) for heavy ions at GSI.
❖ Future detectors in space.

# Further Applications for LGADs: Backup Slides

# The Electron-Ion Collider (EIC) detector requirements

- The future Electron-Ion Collider (EIC) will utilize high luminosity high energy electron+proton and electron+nucleus collisions to solve several fundamental questions in high energy nuclear physics.




EIC collider
CD0 approved

- The bunch crossing rate is around 1-10ns, to identify the physics collisions and suppress background from neighboring collisions, fast timing detectors are required for the future EIC project detector.
- Fast timing detector can provide time of flight measurements to identify particle species.
- Meanwhile, the EIC detector is required to have low material budgets and fine spatial resolutions.

# LGAD Consortium (for the EIC)

- **Collaborative effort to foster and develop LGAD-based detector technologies**
  - Share expertise in HEP and NP on common aspects of the underlying LGAD-based technology that transcend any specific detector realization
  - Not meant as a replacement of specific detector projects
  - Horizontal effort to study common challenges and develop common solutions across different detector projects
- **EIC is an initial stepping stone for other, longer-term applications of LGADs**

- **Submission of EOI for EIC detectors based on LGADs on Oc. 30th, 2020**
  - **LINK**, 14 Institutes, 33 people
  - Coordinators: W. Li (Rice, wl33@rice.edu), A. Tricoli (BNL, atricoli@bnl.gov)
- **Interests in different detector concepts**
  - **TOPSiDE**
  - **4pi Hybrid LGAD/SOI Tracker**
  - **Generic 4D Tracker**
  - **TOF**
  - **Roman Pots**
  - **Preshower**
- **Interests and expertise in several different areas**
  - **Sensors**
  - **Electronics**
  - **System Design, Engineering and Construction**

Expression of Interest (EOI):
Fast timing silicon detectors for EIC detectors

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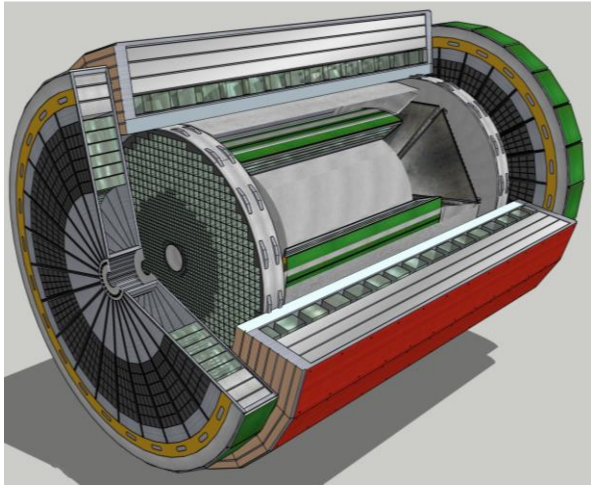
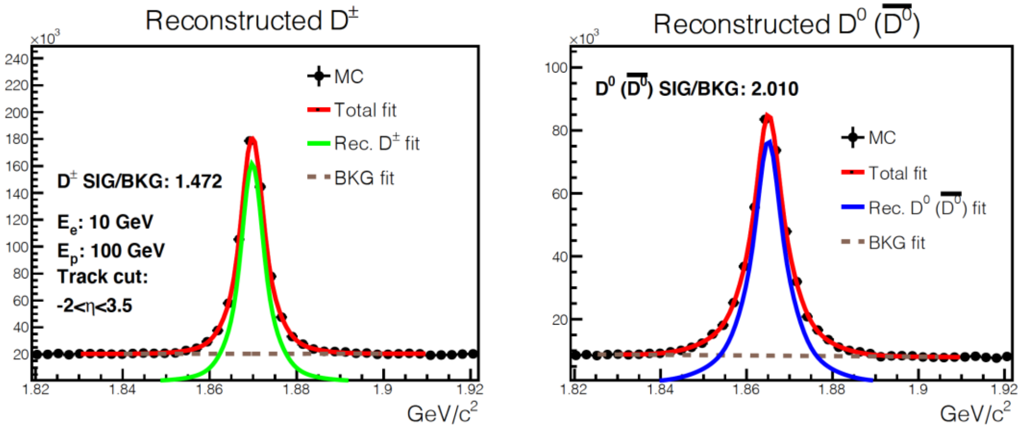
- Brookhaven National Lab (BNL)
- Organisation de Micro-Électronique Générale Avancée (OMEGA), Ecole Polytechnique
- Fermi National Lab (FNAL)
- Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN)
- Laboratoire de Physique des 2 Infinis Irène Joliot Curie (IJCLAB)
- Los Alamos National Lab (LANL)
- Massachusetts Institute of Technology (MIT)
- Oak Ridge National Lab (ORNL)
- Rice University (Rice)
- Stonybrook University (Stonybrook)
- University of California, Santa Cruz (UCSC)
- University of Illinois, Chicago (UIC)
- University of Kansas (KU)

# Time of flight measurements is critical for heavy flavor studies at the EIC

**The reference detector from the EIC CDR, a ToF detector is considered to be part of it.**



**Better than 3 sigma PID separate of $\pi$/K/p together with precise silicon vertex/tracking detector help identify heavy flavor hadron signals at the EIC**




Work carried out by the LANL 20200022DR project.
arXiv: 2009.02888, arXiv: 2103.05419

- LGAD (AC-LGAD) is one of preferred technology candidates to build the EIC ToF detector. Meanwhile, this technology will provide the desired spatial resolution for the track reconstruction with the other EIC tracking subsystems.

# LGADs for TOPSiDE concept at the EIC

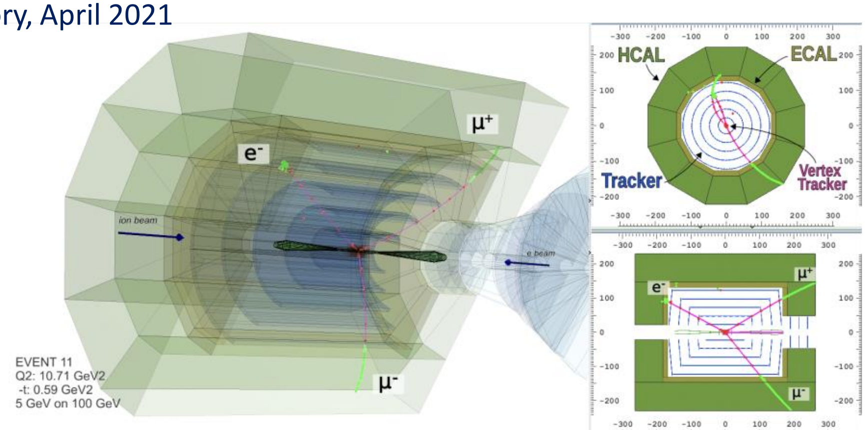
Whitney Armstrong, Ian Cloët, Manoj Jadhav, Sylvester Joosten, Jessica Metcalfe, Zein-Eddine Meziani    Argonne National Laboratory, April 2021

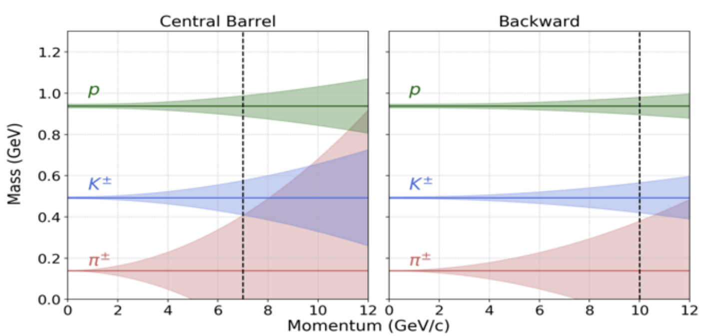
## ❖ The TOPSiDE detector concept at the EIC

- Central Detector Region (-3 < η < 3 )
- Symmetric design with close to $4\pi$ coverage

## ❖ UFSDs for Particle Identification using ToF

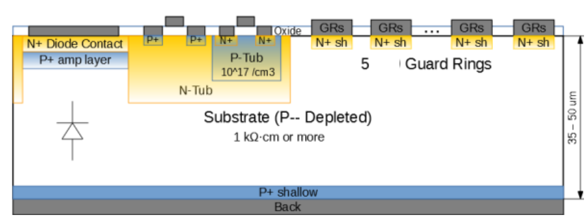
- **Time resolution of about 10 ps or less needed**
- **$\pi$ - K - p separation up to 7 GeV/$c$**
- **Provides PID necessary for the EIC physics**

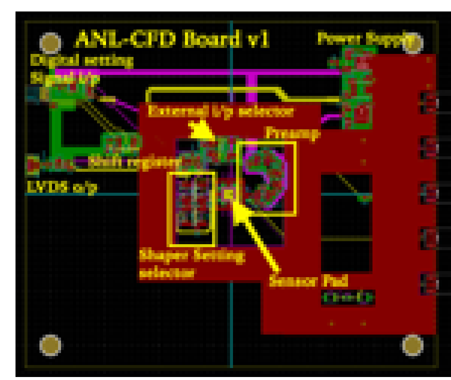



**Time-Of-Flight measurements**

- **ASIC design:**
  - Development of CFD-boards and FPGA programing
  - FPGA Ultra96 - programmable for up to 4 channels
  - To demonstrate the on-pixel electronics concept for monolithic LGADs



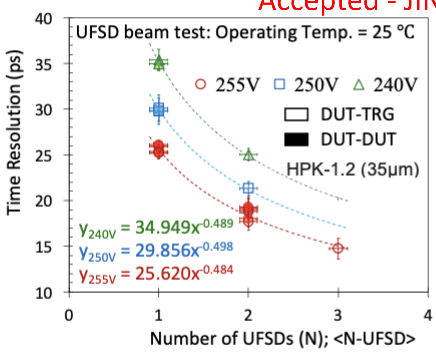

- **Sensor**
  - LGAD prototyping is ongoing
  - Sensor with pad size of 1 ✕ 1 mm$^2$ and thickness 50 µm
  - TCAD design of monolithic LGAD sensors
  - Dr. Taylor Shin is working jointly with UCSC and ANL.

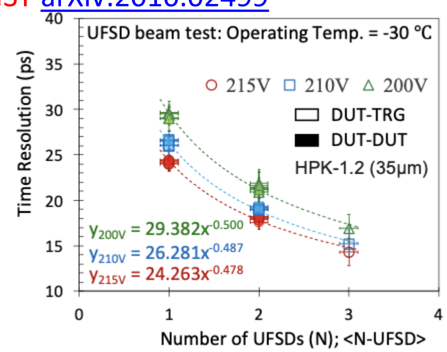
# LGADs for TOPSiDE concept at the EIC

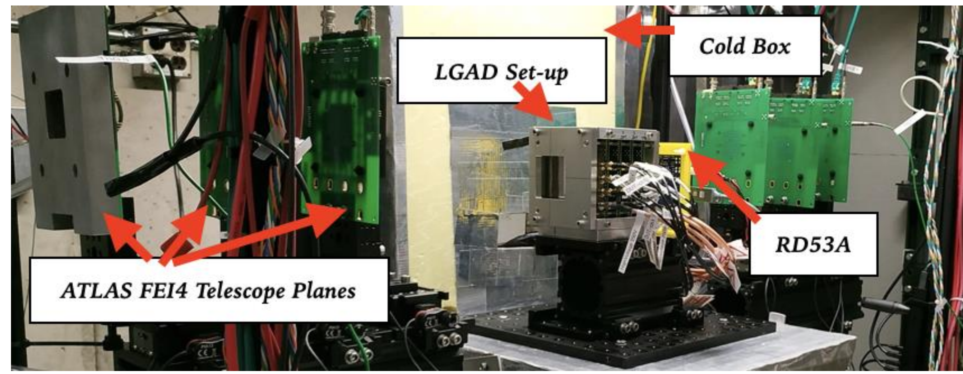
❖ **Timing measurements with a precision of 10 ps are expected to provide pion-kaon-proton identification up to 7 GeV/c with TOPSiDE concept ( > = 4 layers Si) at the EIC**

- Low-Gain Avalanche Detectors (LGADs) are tested with 120 GeV proton beam at the Fermilab Test Beam Facility
- Results shows timing resolution of 14.3 ps using three planes at -30 ℃
- Fastest test beam measurements to date for a three layer system

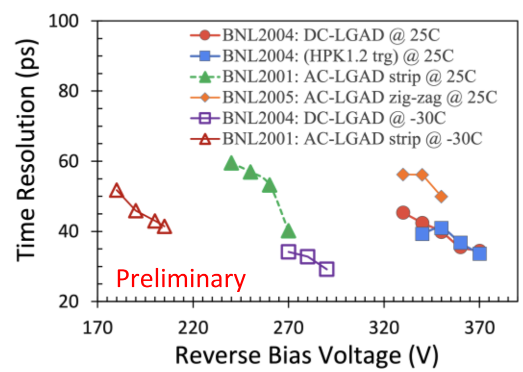
Accepted - JINST arXiv:2010.02499

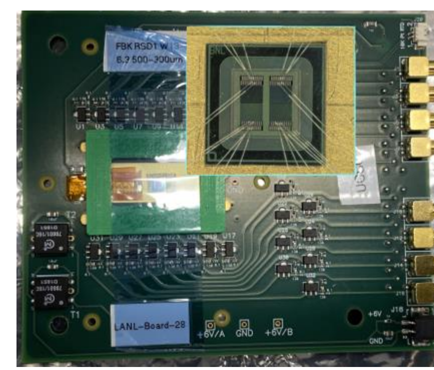


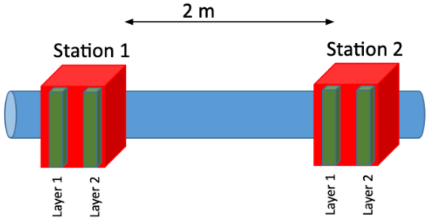

- **AC-LGADs and Multi-Channel Boards:**
  - The AC-coupled LGADs are tested at the test beam in collaboration with UCSC and BNL as a part of the EIC LGAD consortium
  - The LGADs with strip and pixel array geometry are mounted on multi-channel readout boards and will be tested for timing measurements.

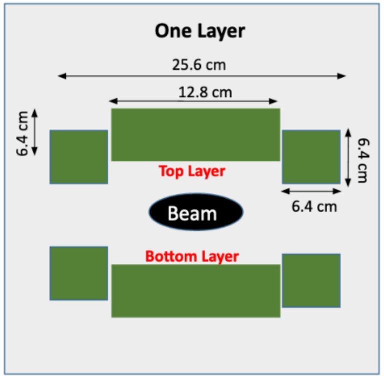


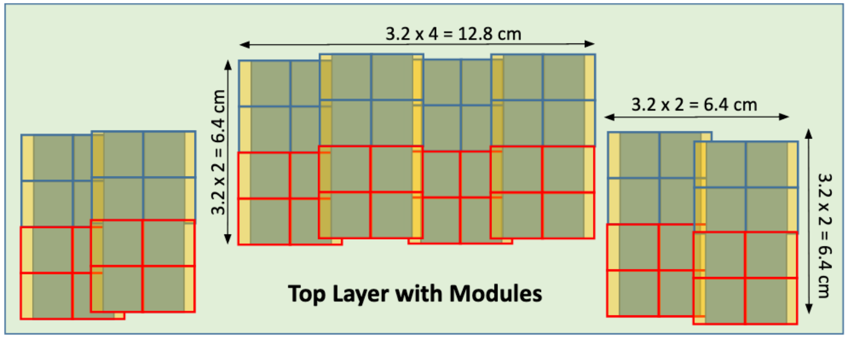
# Roman Pots for the EIC

- **Roman Pots at EIC are crucial for exclusive and diffractive physics**
  - Tagging of protons and light nuclei close to the beam from coherent processes, protons from nuclear breakup, etc.
- **Performance specifications are met by AC-LGADs**
  - **Time resolution 30-50 ps**
  - **500 x 500 μm$^2$ pixels**
  - **Edgeless (inactive edges ≲ 150 μm)**




- **Sensor:** AC-LGAD prototyping ongoing
- **ASIC design:**
  - modification of ALTIROC (TSMC 130 nm) used in ATLAS timing detector (HGTD): TDC for time-of-arrival and ADC for signal amplitude - aim for <3 mW/pixel power dissipation





**Project members**
E.C. Aschenauer (BNL), A.Tricoli (BNL), A. Jentsch (BNL), S. Fazio (U. Calabria, Rende, Italy), A. Kiselev (BNL), G. Giacomini (BNL), Cinzia da Via (Manchester/SBU), M. Benoit (BNL), A. Seiden (UCSC), H. Sadrozinski (UCSC), B. Schumm (UCSC), R. Dupré (IJCLAb, Orsay, FR), D. Marchand (IJCLAb, Orsay, FR), C. Munoz Camacho (IJCLAb, Orsay, FR), L. Serin (IJCLAb, Orsay, FR), C. de La Taille (Omega, Palaiseau, FR), M. Morenas (Omega, Palaiseau, FR)


| ASIC size | ASIC Pixel pitch | # Ch. per ASIC | # ASICs per module | Sensor area | # Mod. per layer | Total # ASICs | Total # Ch. | Total Si Area |
|---|---|---|---|---|---|---|---|---|
| 1.6x1.8 cm$^2$ | 500 $\mu$m | 32x32 | 4 | 3.2x3.2 cm$^2$ | 32 | 512 | 524,288 | 1,311 cm$^2$ |

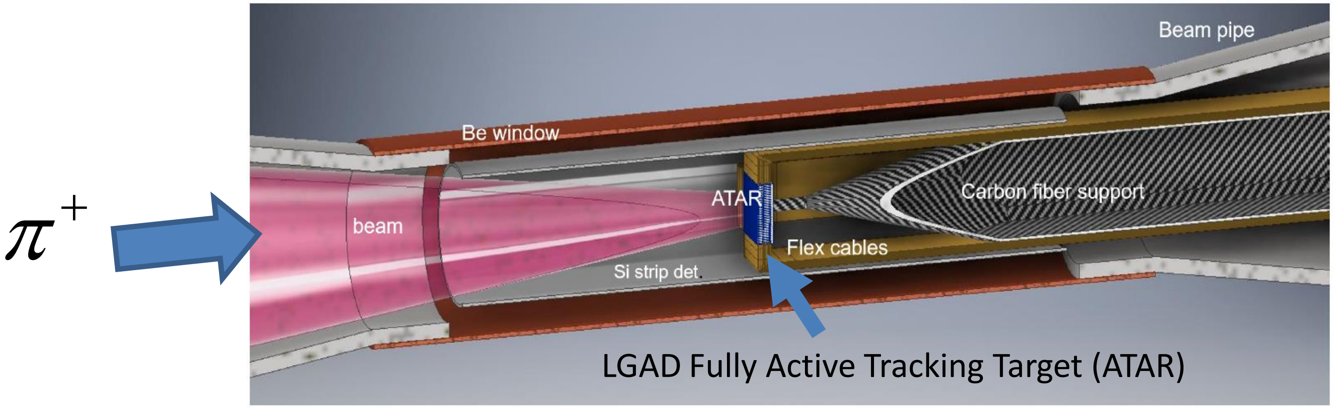
# Next Generation Rare Pion Decay Experiment : PIENUX

Goals:

- Measure $R_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$ : $O(\pm 0.01\%)$
- Measure $R_{\pi\beta} = \dfrac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$ : $O(\pm 0.05\%)$
- Improve search sensitivities by an order of magnitude

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

# PIENUX: Target Region Concept




Additional LGAD Si strip beam and positron tracking (not shown).

Low Gain Avalanche Detector (4D)

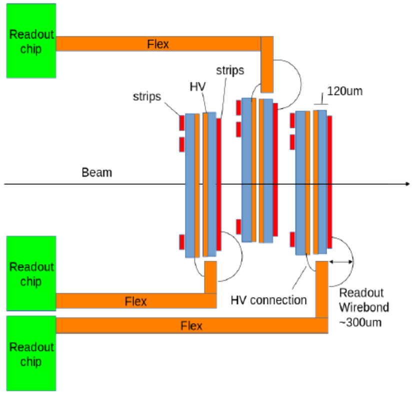
Active Target (ATAR) concept;

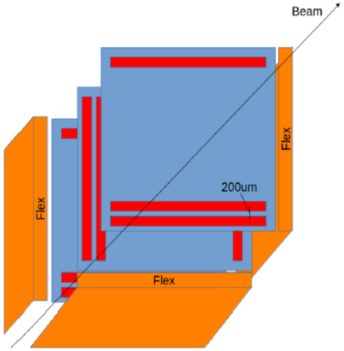
$\pi \to \mu \to$ e tracking;

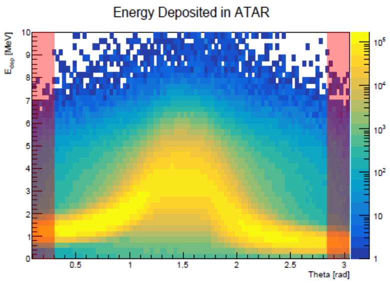
48 layers of 200 $\mu$m wide X/Y strips.

Fast pulses, timing;

Fully active for energy measurements.

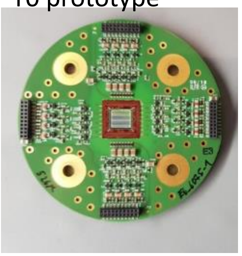


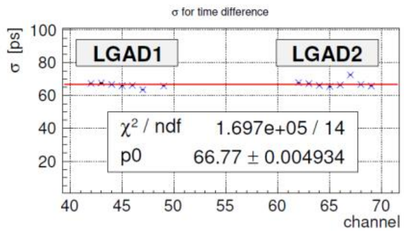



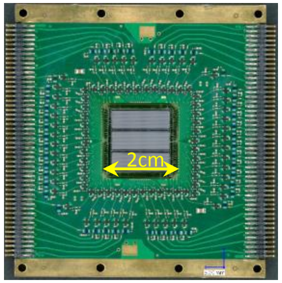
# HADES T0 detector and beyond

T0 prototype






Full size T0 PCB with FEE




ExHiLo-ASIC
TUDa

**HADES T0 detector for p beam based on LGAD sensors**

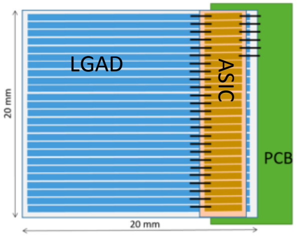
- Leading-edge discriminators / FPGA based TDC (trb.gsi.de)
- At 10 kHz / channel → MHz/cm²
- Without active cooling, at 30°

  → **LGAD timing precision 47 ps**

  J. Pietraszko *et al.*, Eur.Phys.J.A 56 (2020) 7, 183

**Future Plans**

- Ongoing sensor production at FBK (Q2-2021)
- Test of FAST2 ASIC with strip LGAD sensors
- ASIC development for Strip sensors (Amplifier/Discriminator/TDC)
- Large area LGAD detector for 4D tracking




**Applications**

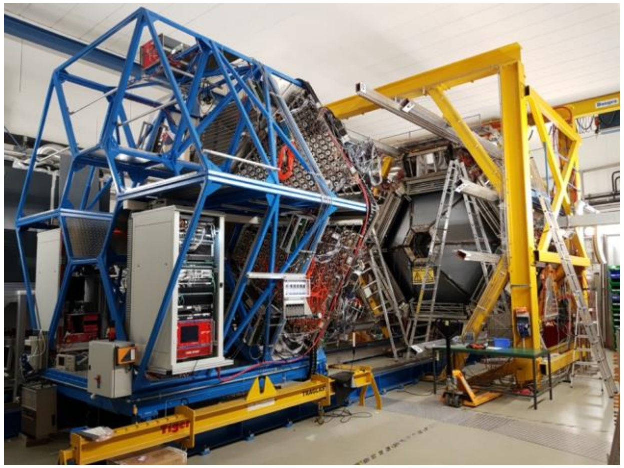
- HADES Forward Wall system
- HADES T0 barrel
- ToF systems for IonCT
- Energy Recovery Linacs (TU-Darmstadt)
- Tracking system for *ee* experiment
- EDM searches, JEDI at COSY
- Beam monitoring at GSI/FAIR
- T0 system for CBM at FAIR

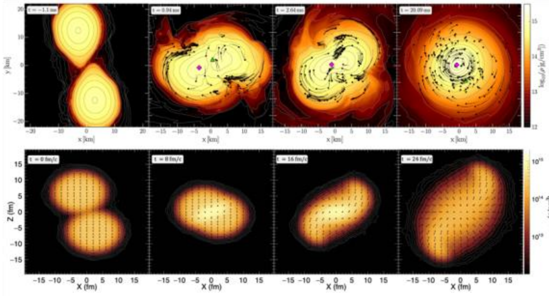
….

# High Acceptance DiElectron Spectrometer

HADES

at heavy-ion synchtortron SIS18, GSI Helmholtzcenter for heavy-ion research





Neutron start merger simulations

$T$ <70 MeV, $\rho$ =2-3 $\rho_0$ for both strong synergy between the fields

Au+Au $\sqrt{s_{NN}}$ = 2.4 GeV

[HADES], Nature Phys. 15(2019) 1040

- HADES explores the QCD phase structure at highest net-baryon densities
- Focus on rare and electromagnetic signals
- Study heavy-ion and $\pi$, p collisions

- High acceptance: full azimuthal coverage, 18°-85° polar angle
- Efficient track reconstruction using low-mass tracking
- Precise : mass resolution few %
- Fast : interaction rate up to 50kHz trigger rate

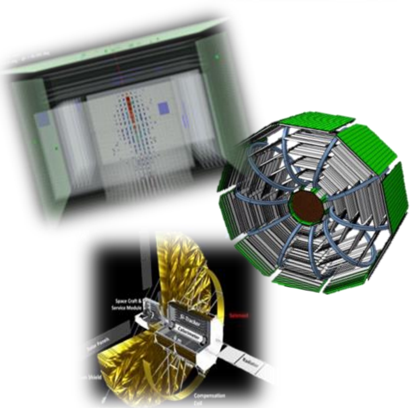
**HADES T0 detector for p beam based on LGAD sensors**

- Time precision with $\sigma_T$ < 60ps
- Active area of 4-8 cm$^2$
- Particle fluxes of $10^7$ p/(cm$^2$s)
- Vacuum operation capability

# Silicon Microstrip detectors in space

Most of space detectors for charged cosmic ray and γ-ray measurements require **solid state tracking systems based on Si-microstrip (SiMS) sensors.**

SiMS detectors are the only solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space**



| Operating Missions | | | | | | |
|---|---|---|---|---|---|---|
| | Mission Start | Si-sensor area | Strip-length | Readout channels | Readout pitch | Spatial resolution |
| Fermi-LAT | 2008 | $\sim 74\,m^2$ | 38 cm | $\sim 880 \cdot 10^3$ | 228 $\mu$m | $\sim 66\,\mu m$ |
| AMS-02 | 2011 | $\sim 7\,m^2$ | 29–62 cm | $\sim 200 \cdot 10^3$ | 110 $\mu$m | $\sim 7\,\mu m$ |
| DAMPE | 2015 | $\sim 7\,m^2$ | 38 cm | $\sim 70 \cdot 10^3$ | 242 $\mu$m | $\sim 40\,\mu m$ |

| Future Missions | | | | | | |
|---|---|---|---|---|---|---|
| | Planned operations | Si-sensor area | Strip-length | Readout channels | Readout pitch | Spatial resolution |
| HERD | 2030 | $\sim 35\,m^2$ | 48–67 cm | $\sim 350 \cdot 10^3$ | $\sim 242\,\mu m$ | $\sim 40\,\mu m$ |
| ALADInO | 2050 | $\sim$ 80-100 $m^2$ | 19–67 cm | $\sim 2.5 \cdot 10^6$ | $\sim 100\,\mu m$ | $\sim 5\,\mu m$ |
| AMS-100 | 2050 | $\sim$ 180-200 $m^2$ | $\sim$ 100 cm | $\sim 8 \cdot 10^6$ | $\sim 100\,\mu m$ | $\sim 5\,\mu m$ |


[1] HERD Collaboration. *HERD Proposal, 2018* https://indico.ihep.ac.cn/event/8164/material/1/0.pdf

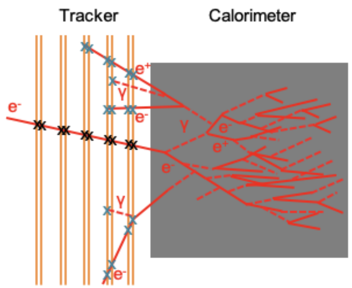
[2] Battiston, R.; Bertucci, B.; *et al. High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. https://doi.org/10.1007/s10686-021-09708-w

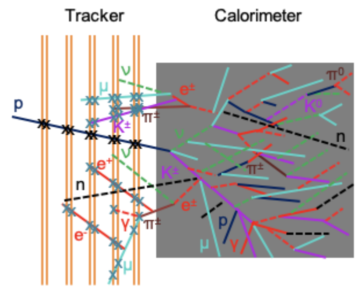
[3] Schael, S.; *et al. AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2*. NIM-A 2019, 944, 162561. https://doi.org/10.1016/j.nima.2019.162561

# Why timing in AstroParticle?

**IMPROVED TRACK FINDING**
**Hit timing information improves track reconstruction on high rate environments and identifies back-scattering hits from downstream calorimeters**

**TIME OF FLIGHT**
**Hit timing resolutions of ~ 100 ps enable ToF measurements with SiMS complementary to scintillators with fast light readout**

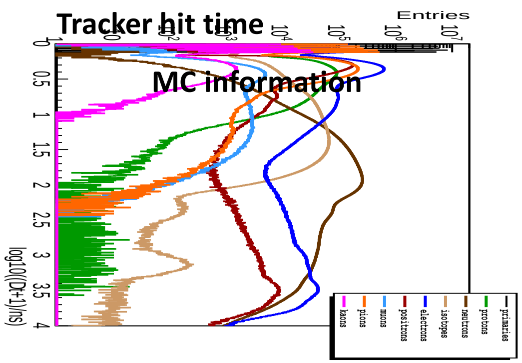


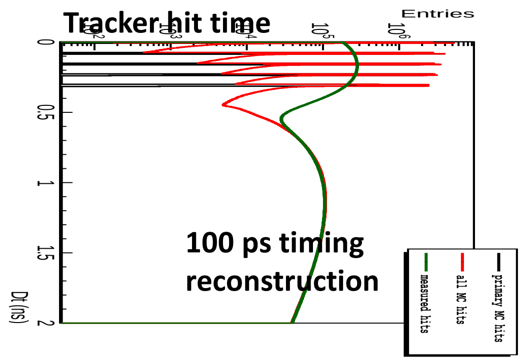




**REMOVE "GHOST" HITS**
**Separating tracks in time can mitigate the ambiguity of "ghost" hits in SiMS with strips running in perpendicular directions**

**PARTICLE ID**
**Track timing identifies slow low-energy particles backscattering from downstream calorimeters for primary hadronic particle crossings**

## Verifications with MC simulations



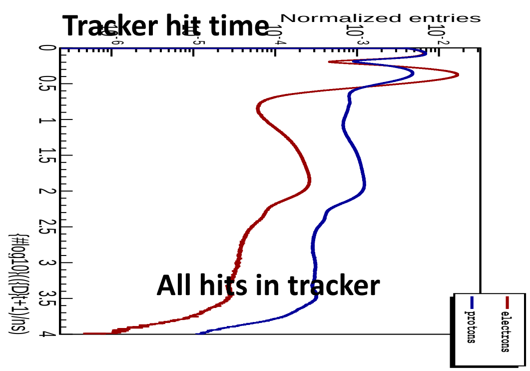



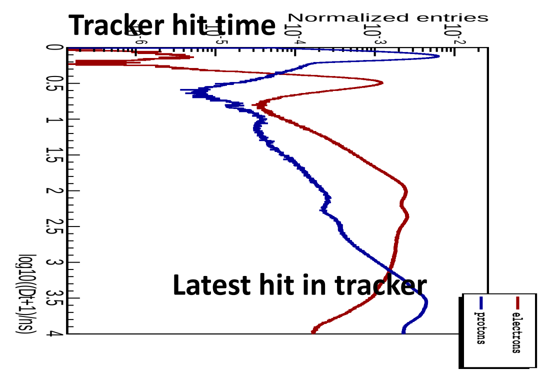

100 ps resolution allows to separate hits from primary particles and from secondary backsplash

Prospects for improved tracking efficiency

Different timing signatures from p and $e^{+/-}$ showers

Prospects to use in MVA classifiers for e/p separation



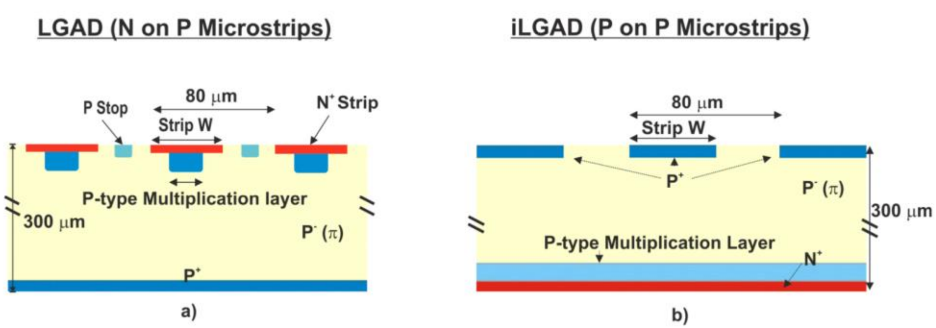



# How to cope with power limitations?

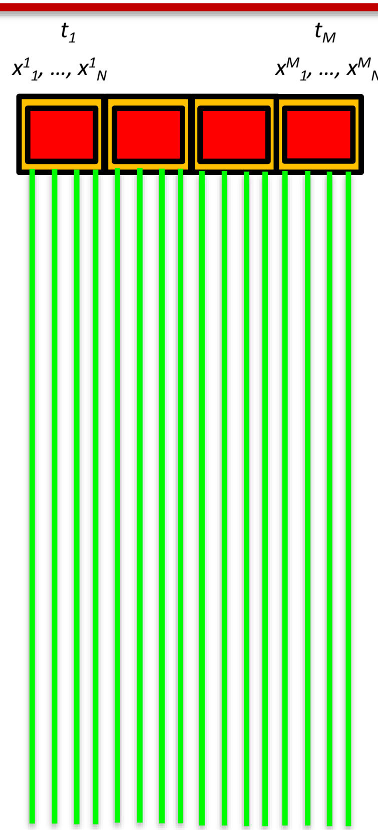
→ Si LGAD microstrips

→ "group" N *position* channels into one *timing* channel, or create large timing channels

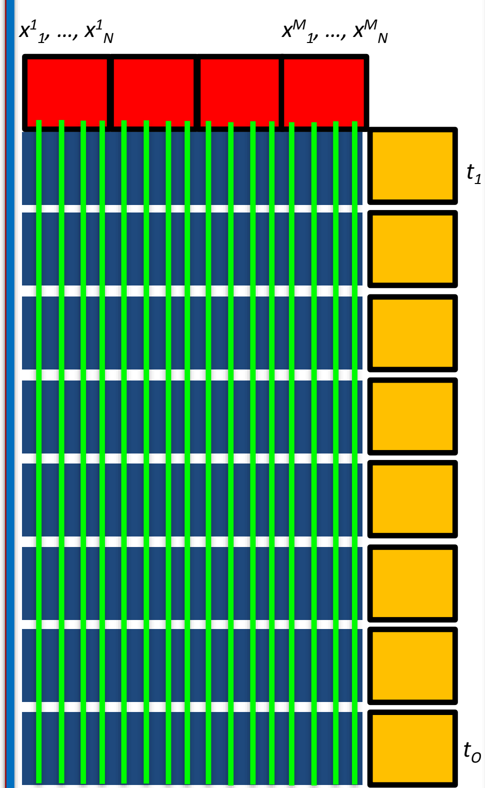
cfr.
M. Duranti, V. Vagelli *et al.*, *Advantages and requirements in time resolving tracking for Astroparticle experiments in space*, accepted for publications in Instruments




taken from
E. Currás, et al. *Inverse Low Gain Avalanche Detectors (iLGADs) for precise tracking and timing applications,* NIM-A Volume 958, 2020, 162545,
https://doi.org/10.1016/j.nima.2019.162545




- standard LGAD with a dedicated Front-End ASIC
- iLGAD with separate Front-End ASICs for position and timing (on the back)




- positon and timing strip orthogonal
- iLGAD (or AC-LGAD?) for the timing

# Comment on Power in the Electronics for a Large Area Tracker

- For a large area tracker the power in the electronics presents an important constraint on the design.
- For example the AC-LGAD results shown were for 500 μm pitch. The power question has motivated our focus on 500 μm pitch.
- The number of channels for a 2cmx2cm chip would be 1600 for 500 μm pitch.. A goal of ~1 watt/chip would put this in a comparable range to other large silicon detectors built or planned.
- The 500 μm pitch also provides a reasonable amount of space for each electronics channel assumed to be bump bonded to the sensor.
- A number of electronics efforts have begun for AC-LGADs. Will be very important if we are to get the full potential from the sensor signal performance. Note, chips have already been made for the HL-LHC LGAD application.