Development of Capacitive coupled Low Gain Avalanche Diode (AC-LGAD) sensors for precise time and spatial resolution

Koji Nakamura

Sayuka Kita, Ikumi Goya,

Tomoka Imamura, Kazuhiko Hara

筑波大学
University of Tsukuba

KEK

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

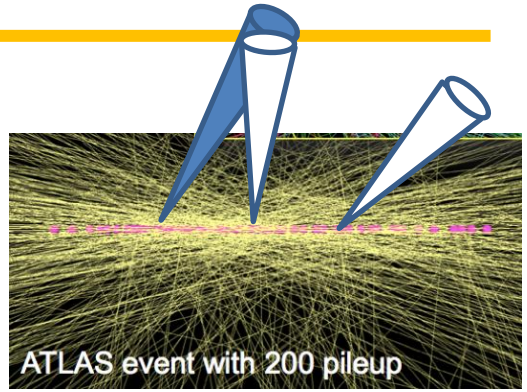
BROOKHAVEN
NATIONAL LABORATORY

Fermilab

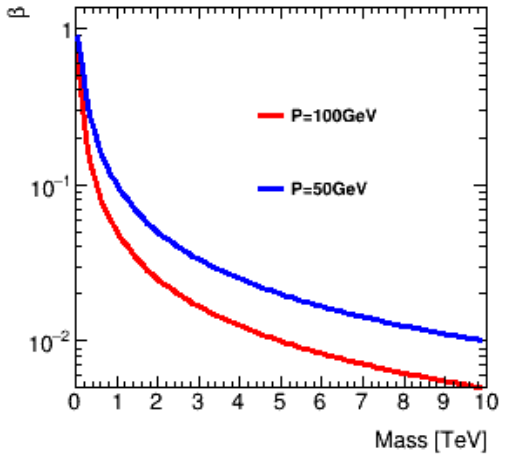
Tracking detector with timing resolution

- **Collider experiment gets high energy and high intensity.**
  - Solving pileup issue is required for tracking, **Timing resolution helps!**

  →Future Tracking detector should have timing information for all hits!
- **Tentative Requirement**
  - **30ps timing resolution**
  - **~o(10)um spatial resolution (Pixel type).**
  - **(hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance**



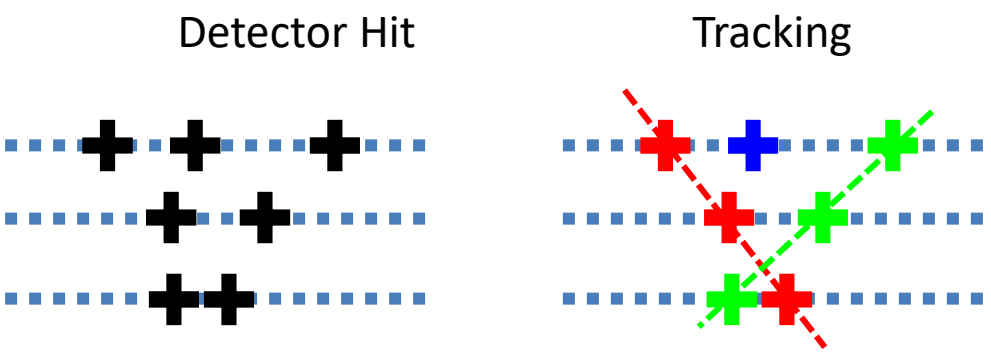
Mass spectrum for new particle



β measurement to obtain mass

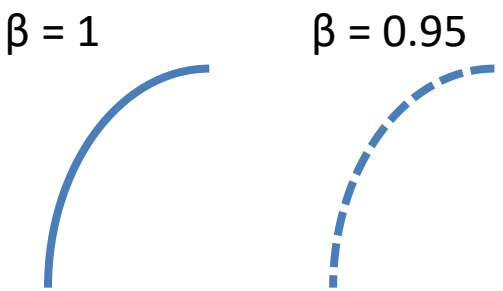
e.g. Mass measurement for Long lived chargeno

4D tracking !



Solve pileup hits in an event

Particle identification

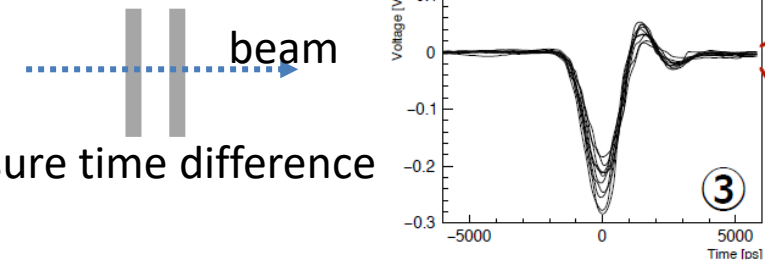


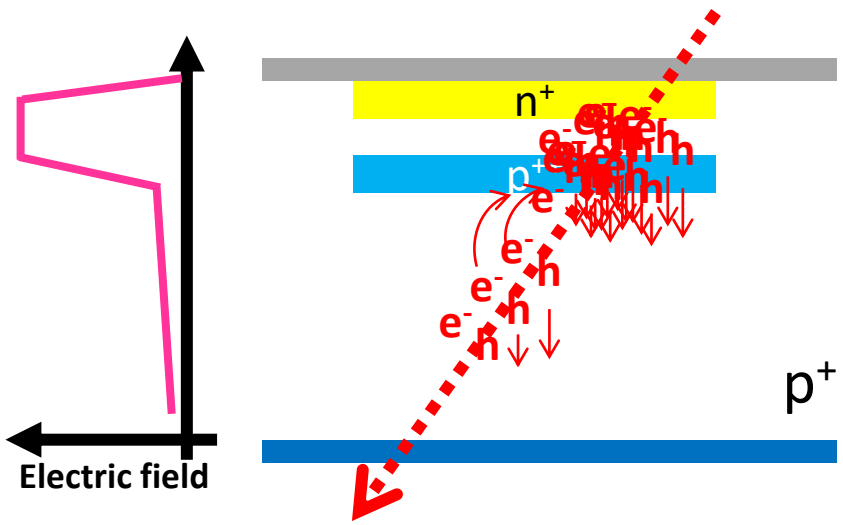
150ps difference at R=1m

K+ π+ separation

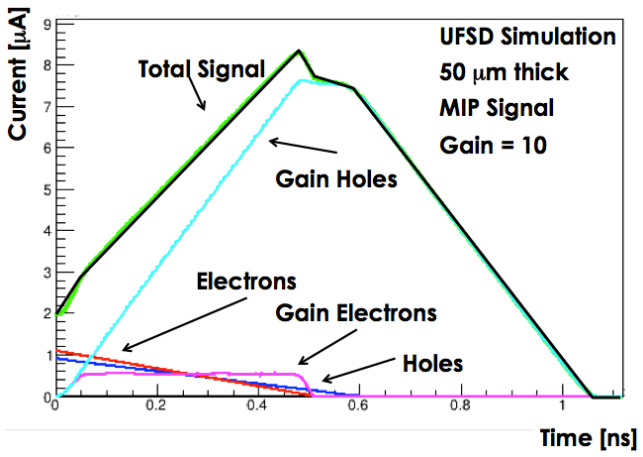
Low gain Avalanche Diode (LGAD)

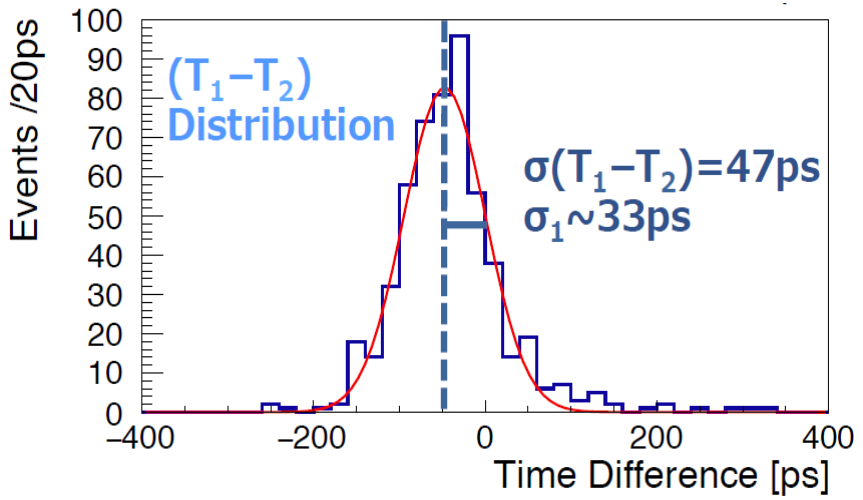
- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make higher Electric Field → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**
  - Next development
    - **Finer electrode separation for spatial resolution**
    - **Radiation tolerance**





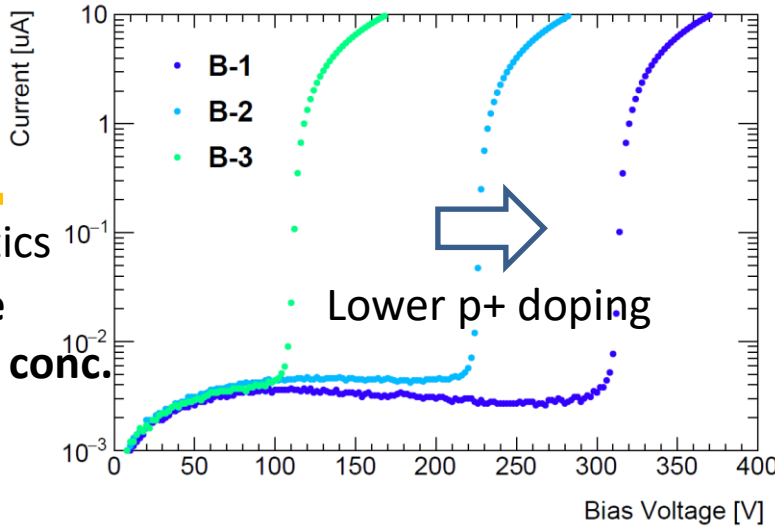
Signal drivers : **Gain Holes**





AC-LGAD detector

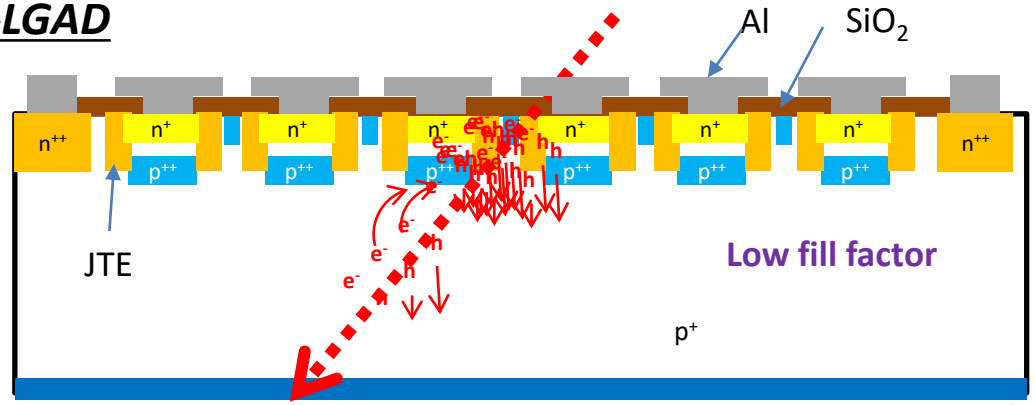
- Limits of LGAD :
  - Need JTE and p-stop structure to have individual gain layer
    →**Low fill factor (20% for 80um strip)**
- AC-LGAD :
  - **Uniform gain layer with AC-Coupled electrode. 100% fill factor. Signal shared on neighboring electrodes.**



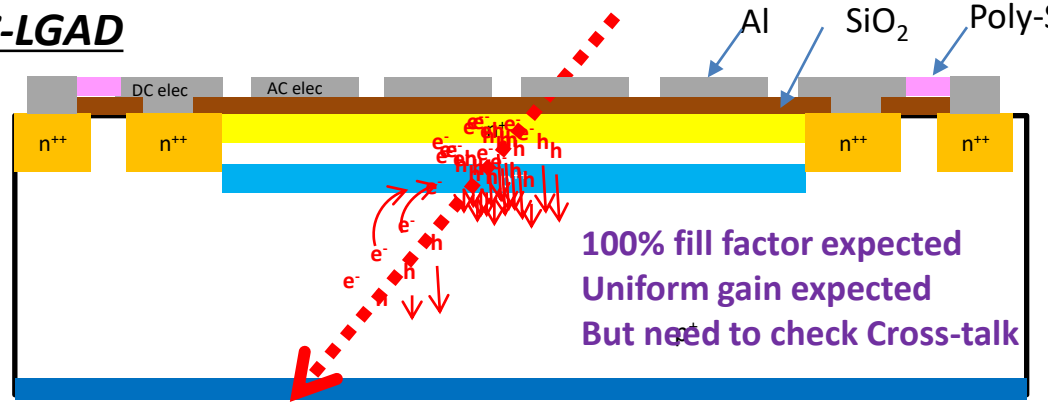
I-V characteristics

Gain Voltage (V_{gain}) is quite sensitive to the p+ doping conc.

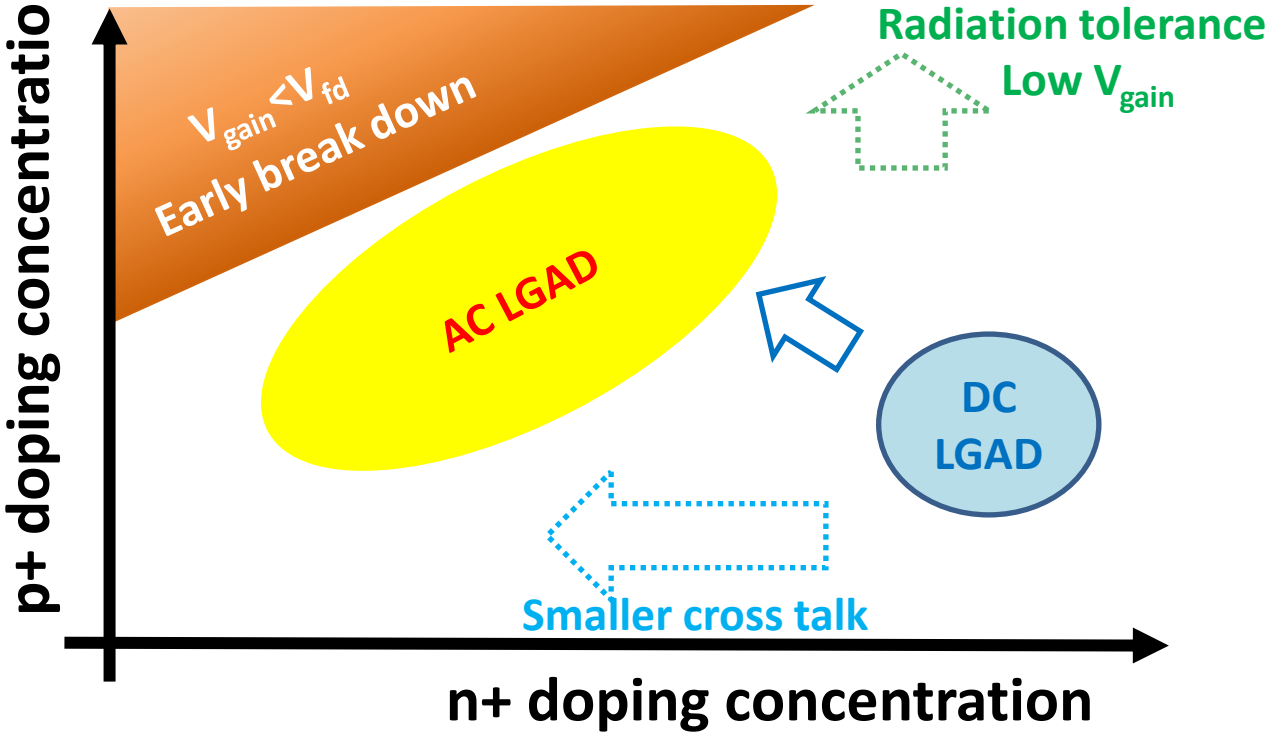
DC-LGAD



AC-LGAD

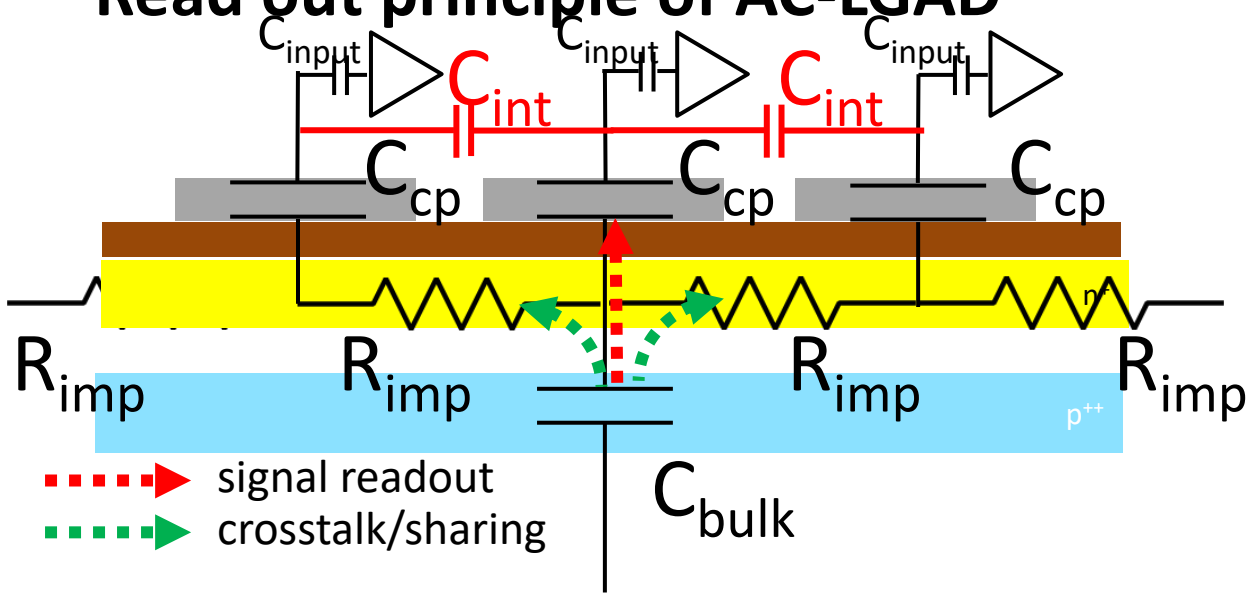


Parameter space for doping concentration



AC-LGAD detector

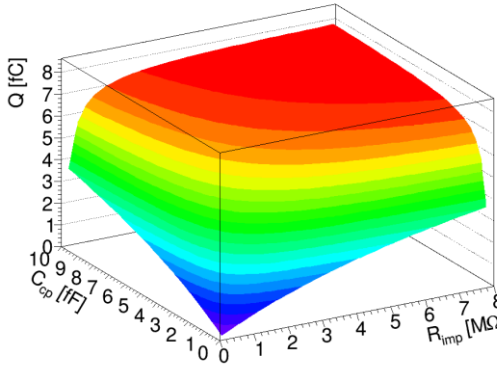
- **Read out principle of AC-LGAD**



- Charge split : Impedance ratio

Assuming $Z_{Cbulk}, Z_{cint} >> Z_{Ccp}$…

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$



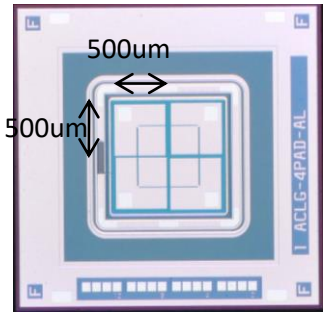
  - Amount of produced charge:Q_0
  - Readout Charge :Q

- Additional cross talk is expected due to the inter electrode capacitance C_{int}
  - Amount of cross talk may also depend on input capacitance on the electronics.
  - Effect must be understood → Sensor with smaller Cint should be important

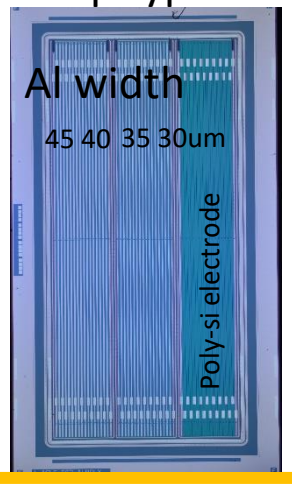
HPK LGAD development : 2019-2020

- JFY2015-JFY2018 DC-LGAD
  - **We contributed only first prototype.** HGTD took over.
- JFY2019, JFY2020 AC-LGAD production
  - Vary n+ and p+ dope (A-E, 1-3)
  - Vary thickness of SiO_2 (capacitance : C_b=1.5xC_a)
- Electrode type
  - Pad type: 500um sq. 4pad/sensor
  - **Strip type : 80um pitch** *First goal*
  - Pixel type : 50um sq. 14x14 electrode

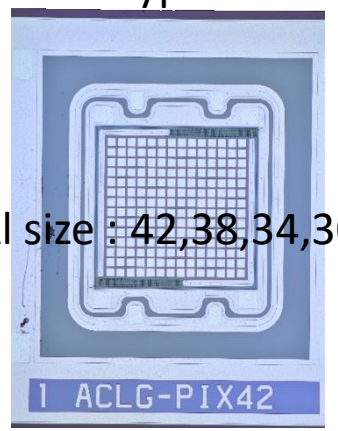
Pad type



Strip type



Pixel type

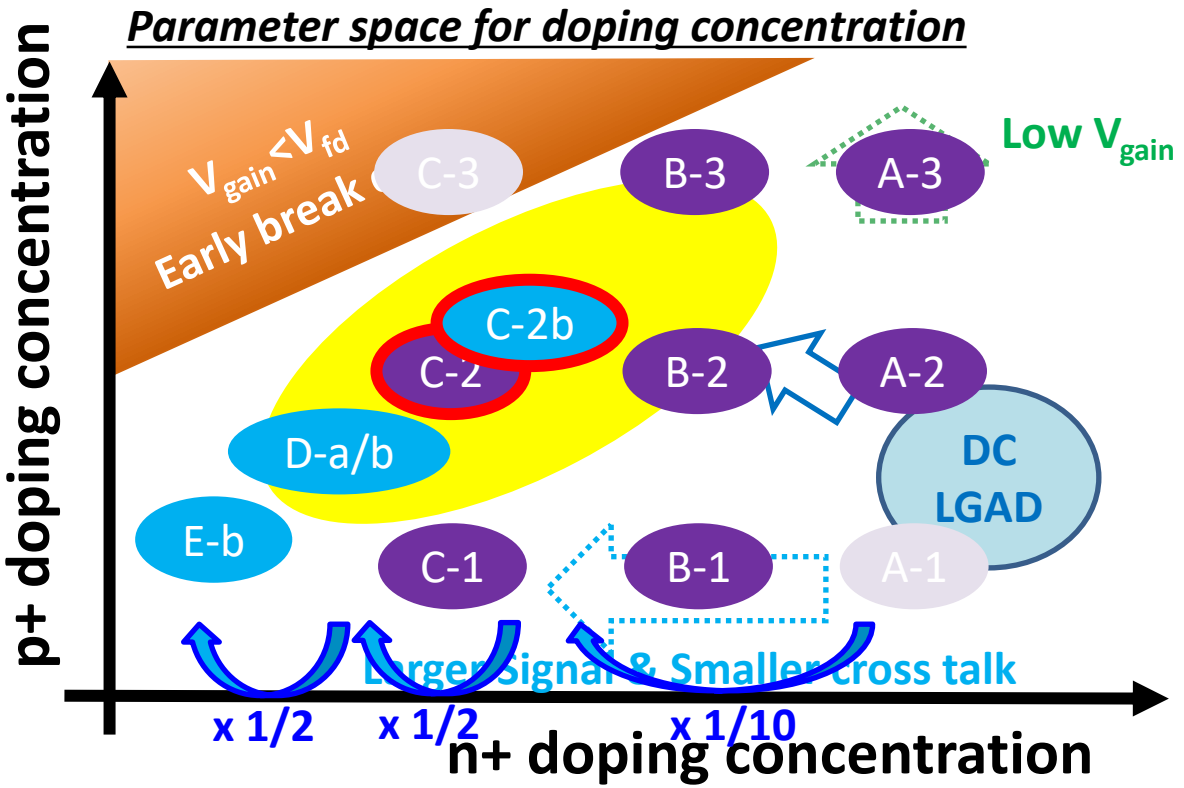


Al size : 42,38,34,30um

JFY2019 Samples

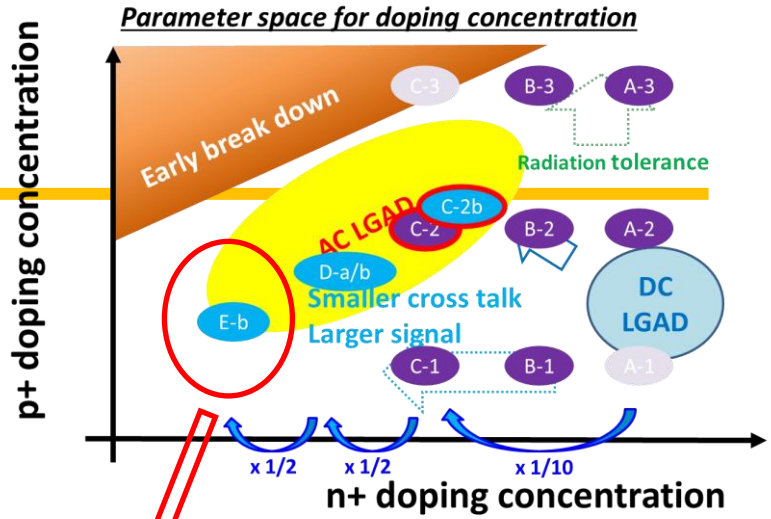
JFY 2020 Samples

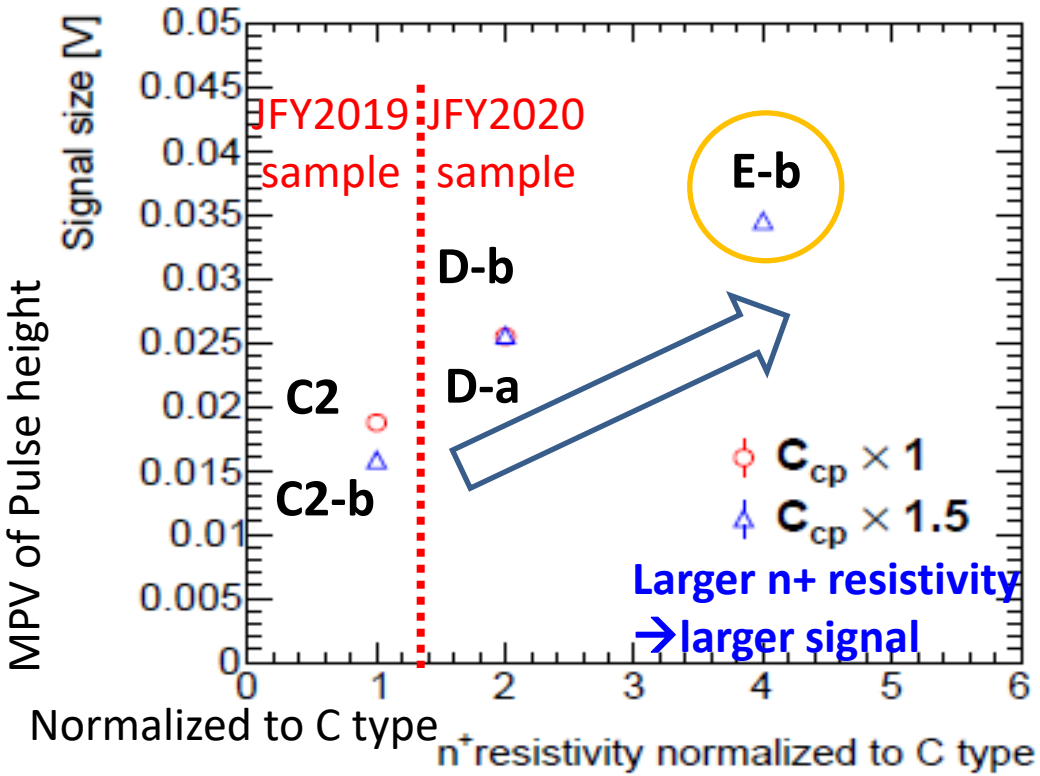
➔Evaluated JFY2021

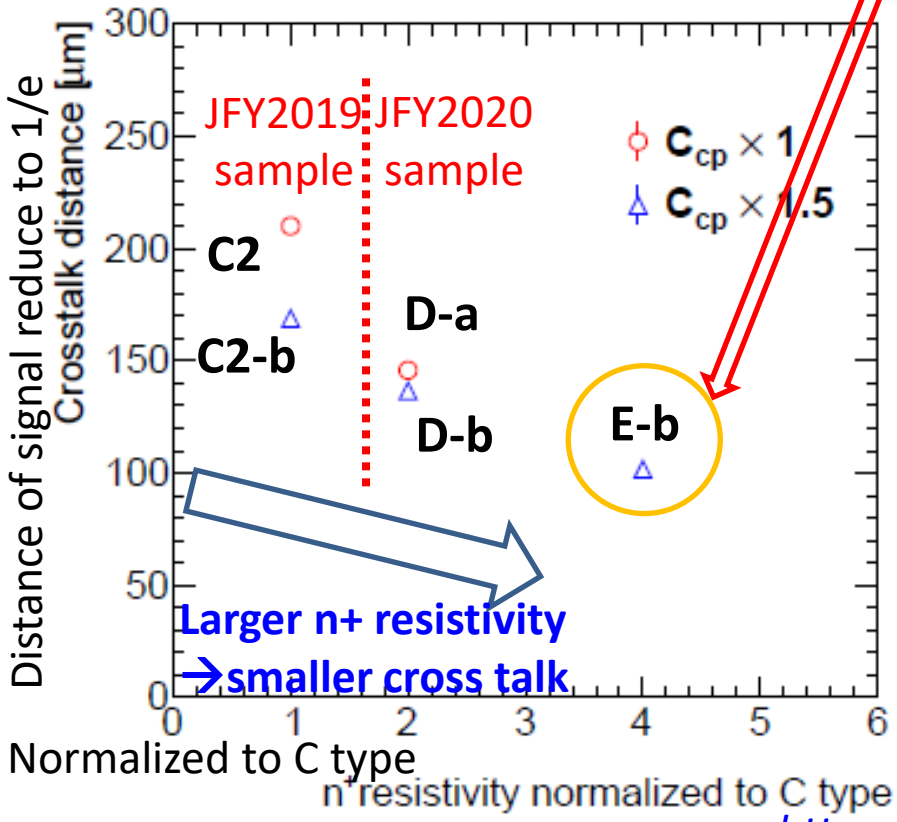


Signal size and crosstalk

- **Strip type :** Signal size and Crosstalk
  - n+ resistivity dependence of signal size and crosstalk.
  - **Large n+ resistivity →Large signal & Smaller crosstalk**

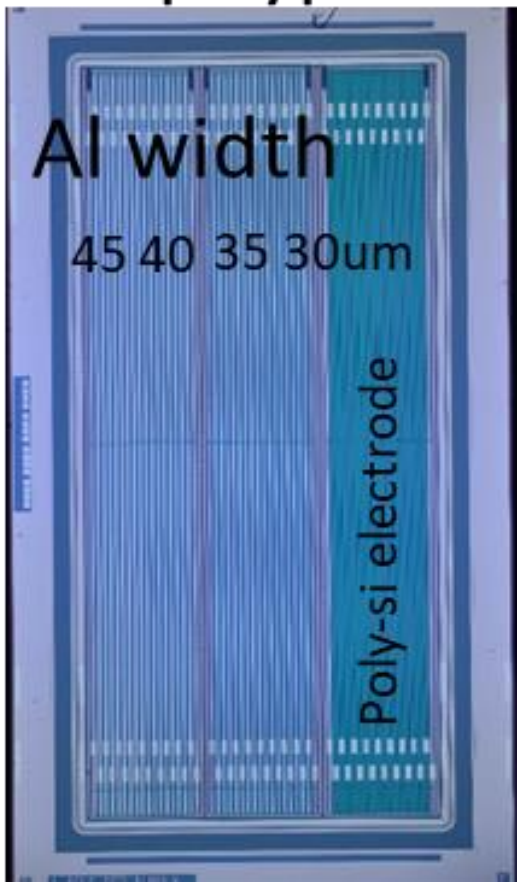




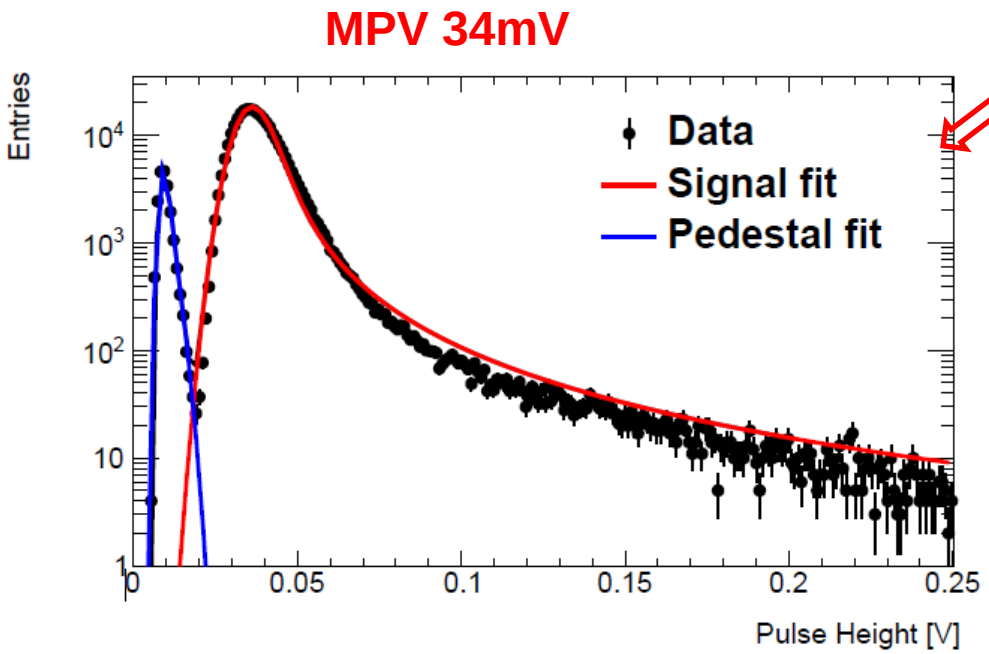


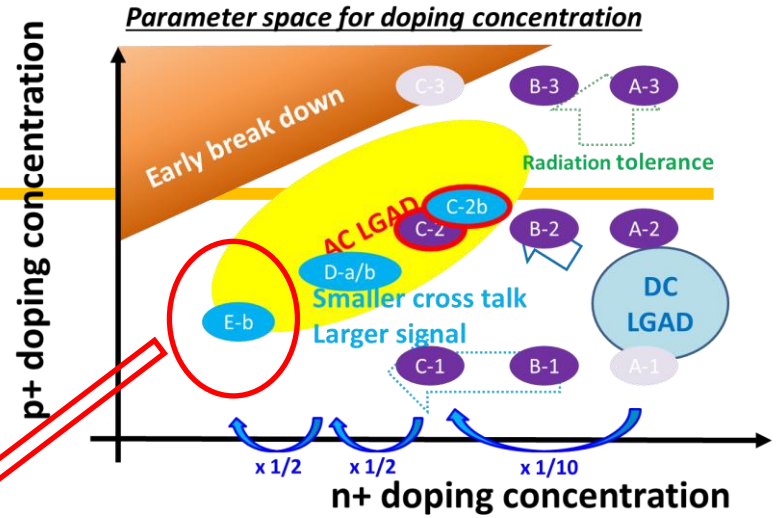
https://arxiv.org/abs/2207.07355

Mile stone : 80um Strip detector



Pulse height distribution





Noise rate 10^{-4} Efficiency 99.98%

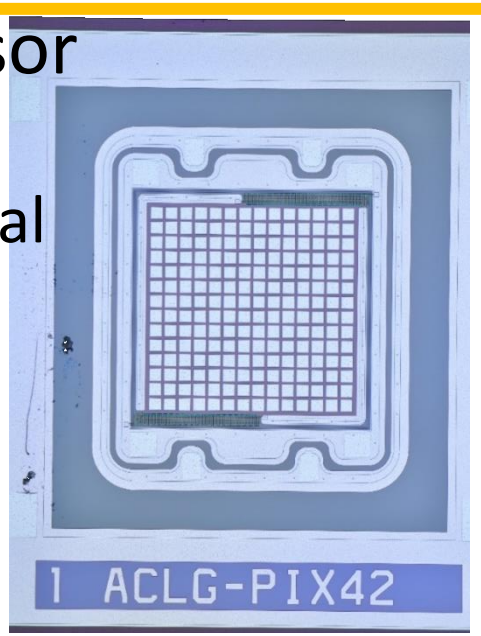
Successfully developed Good S/N strip detector!

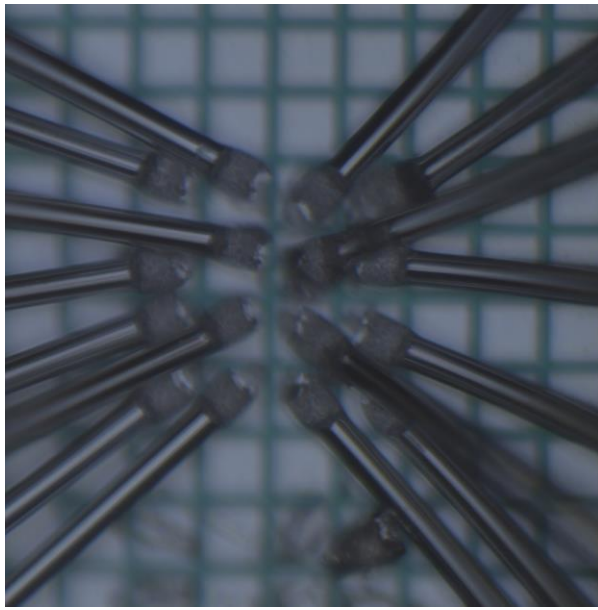
Spatial resolution were tested at testbeam :
20.3 ± 3.2um
assuming binary readout (@ELPH)

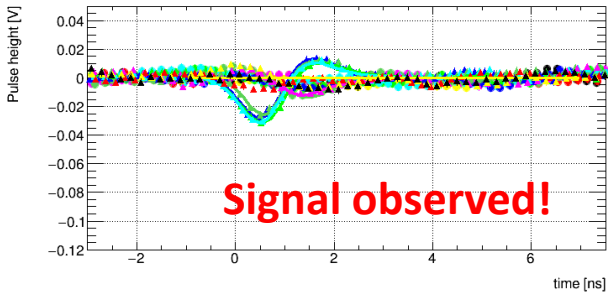
https://arxiv.org/abs/2207.07355

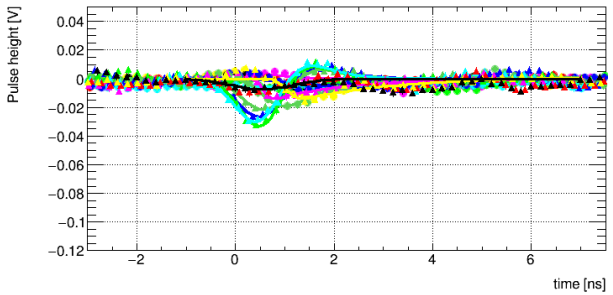
Challenge : Pixel detector

- Prototype of 50um x 50um pitch pixel sensor
  - Wirebonded only 4x4 array at the center.
  - First observation of AC-LGAD pixel sensor signal
    - Smaller signal and larger cross talk observed
    - **S/N ratio is not enough and need improvement.**

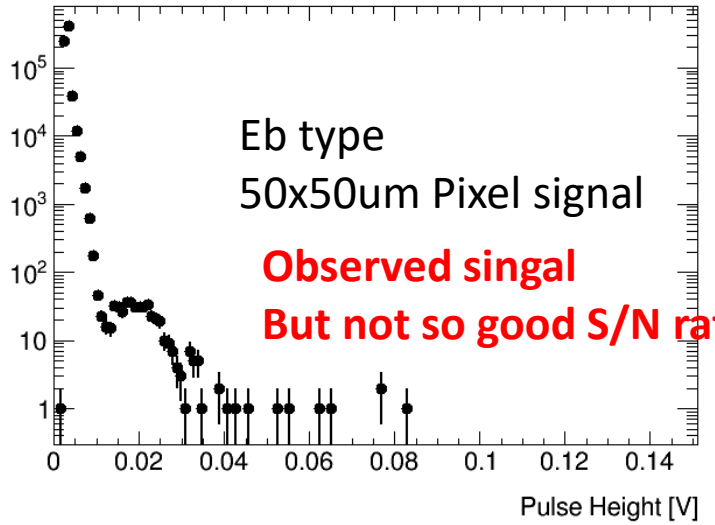






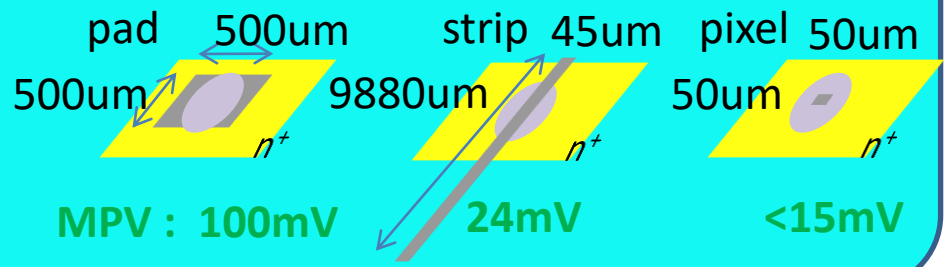


Pulse height distribution



Clearly need improvement

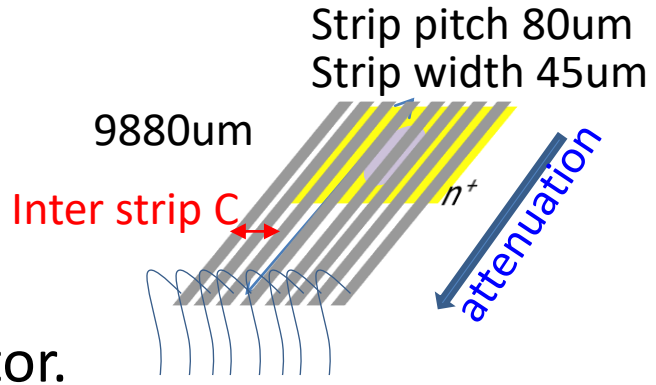
Coupling capacitor Ccp (Effective area?)



Need high Ccp sensors → JFY2021 sample to be tested

What should be understood and what's next?

- ***Understand Strip detector***
  - **Why so small signal?**
  - **How much effect of interstrip capacitance?**
    - Significantly smaller signal compared with pad type detector.
  - **How much signal attenuation in the strip?**
    - This might affect to the signal size un-uniformity and delay of signal readout.



- **Certainly we want to develop pixel type detector.**
  - **First 50um x 50um pixel sensor does not have enough signal size.**
  - **What is the minimum pixel size we can see good S/N signal?**
  - **What is the effective area for electrode capacitance ?**

New sample (2021 sample) : received in April 2022

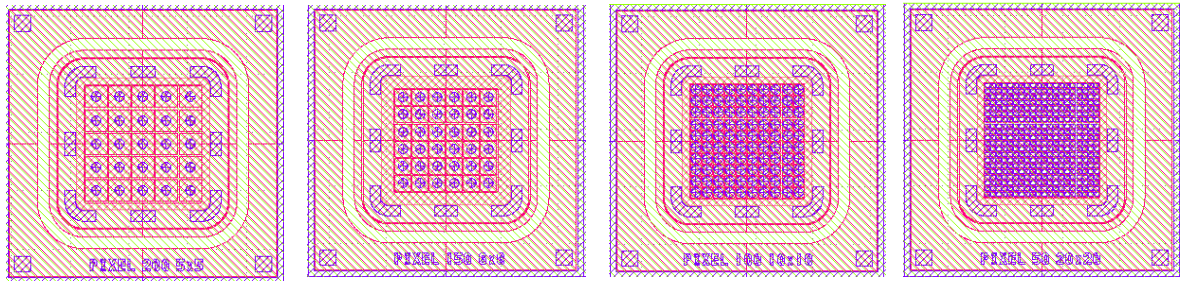
Improvement : Used thinner di-electric layer (Oxide layer)

→ Basic electrode capacitance increased by factor of 5 !!

Pixel sensor

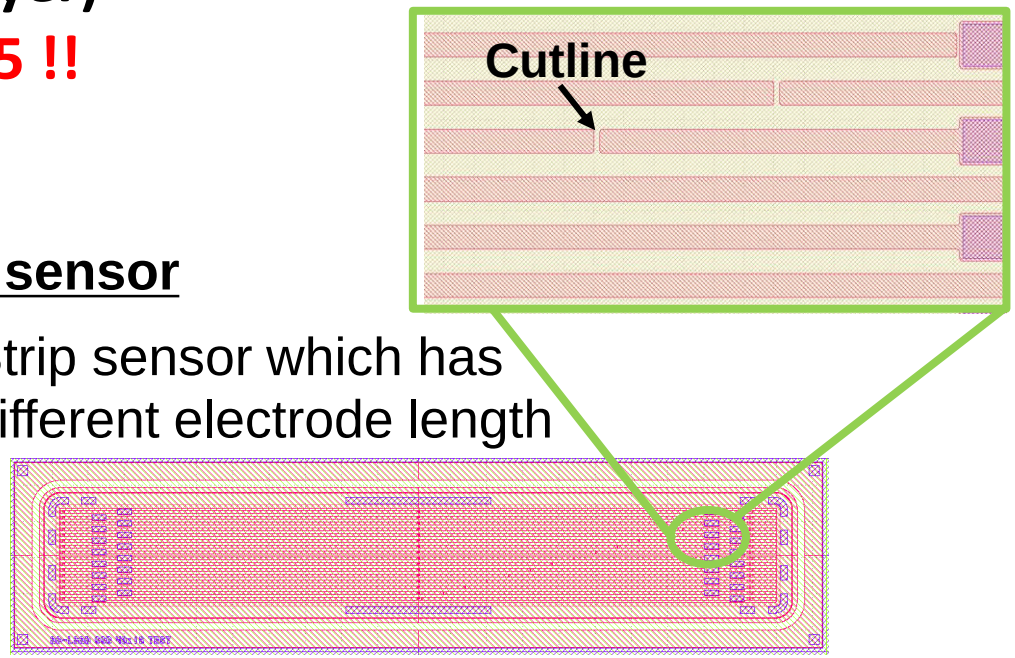
- 1-5 times larger Ccp compared with E-b (2020) type : E-120, E-240, E-600
- Various of pitch

200um 150um 100um 50um

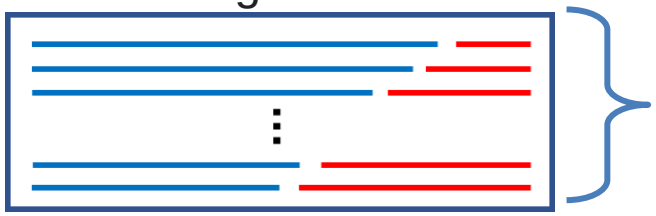


Strip sensor

- Strip sensor which has different electrode length



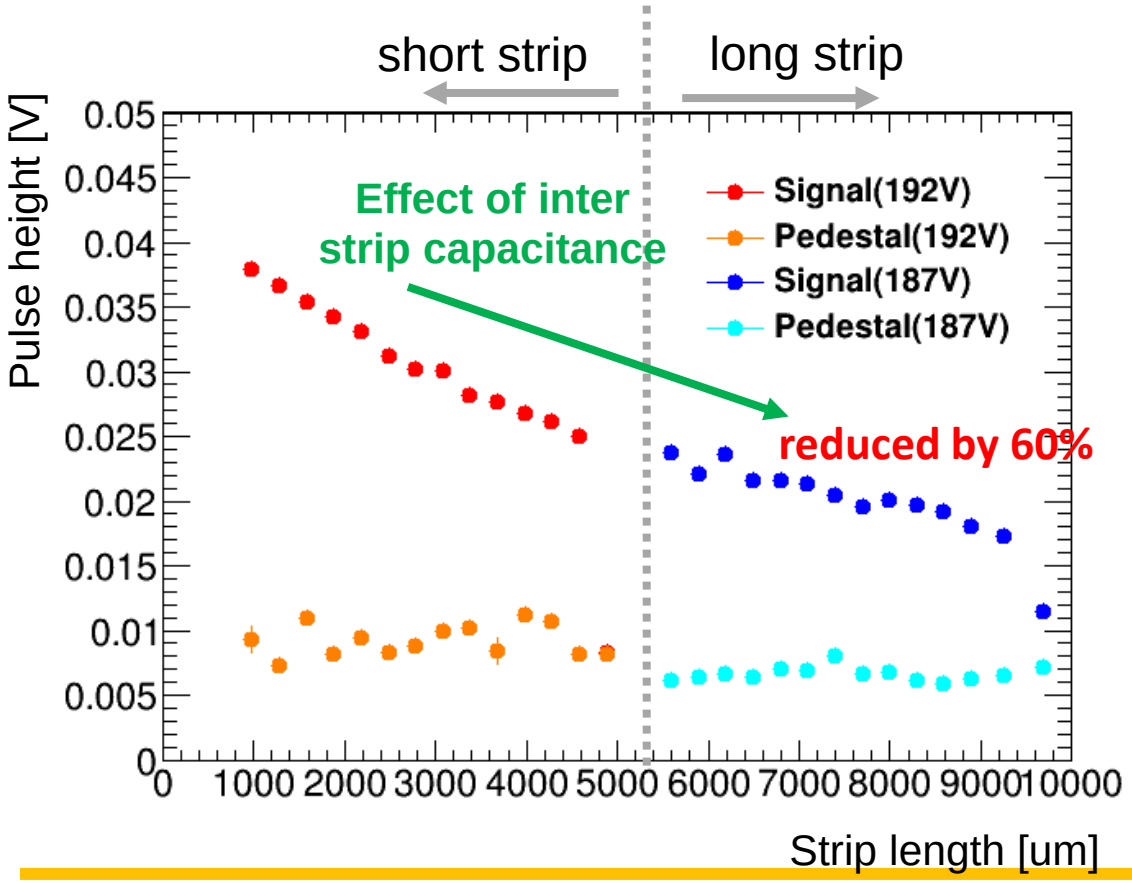
Pattern diagram

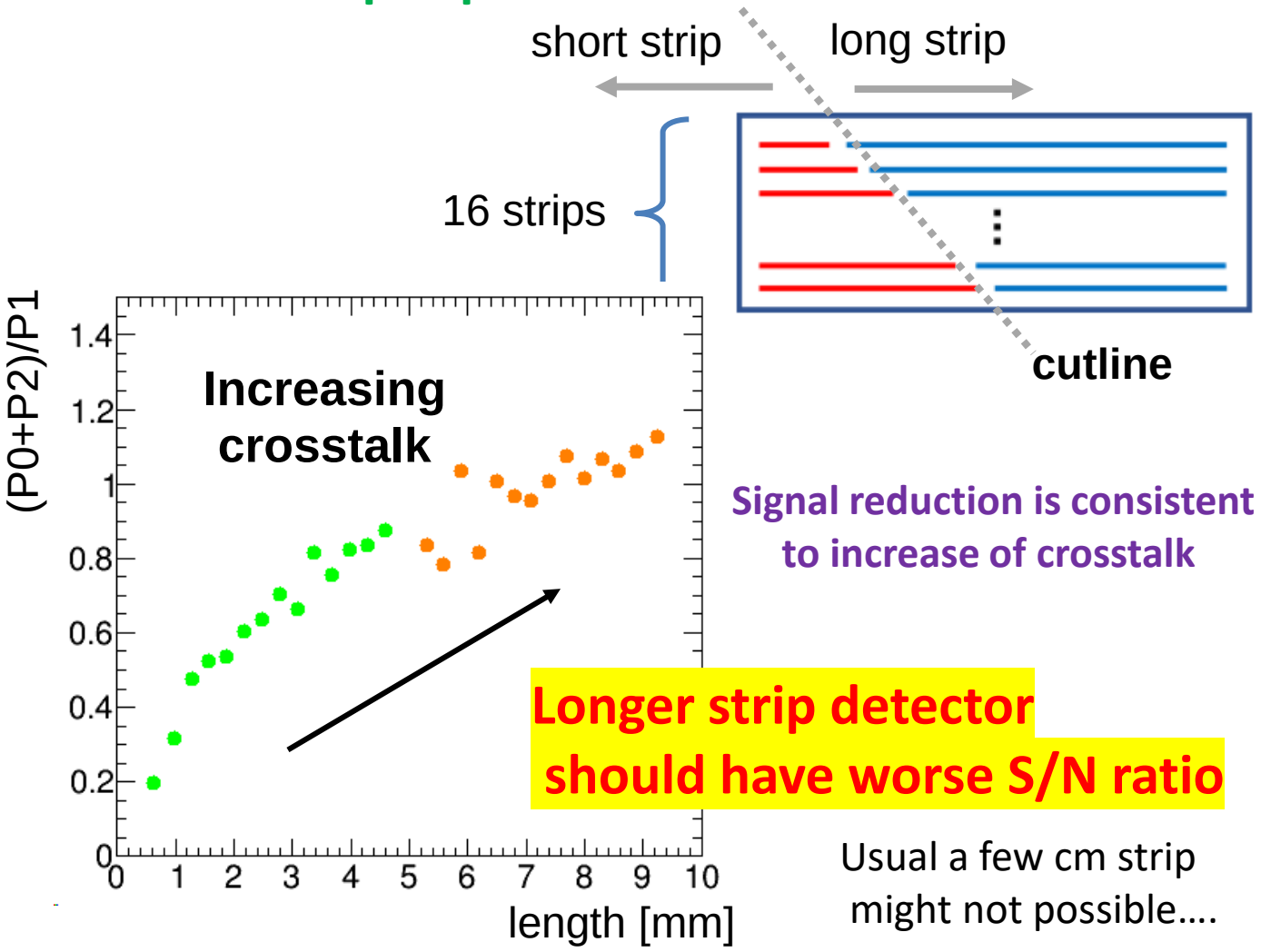


Strip type electrode : inter strip capacitance

To evaluate the effect of signal attenuation and inter strip capacitance :

E-600 type of strip sensor with cutline





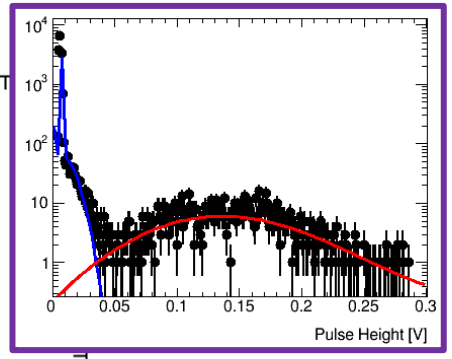
Signal reduction is consistent to increase of crosstalk

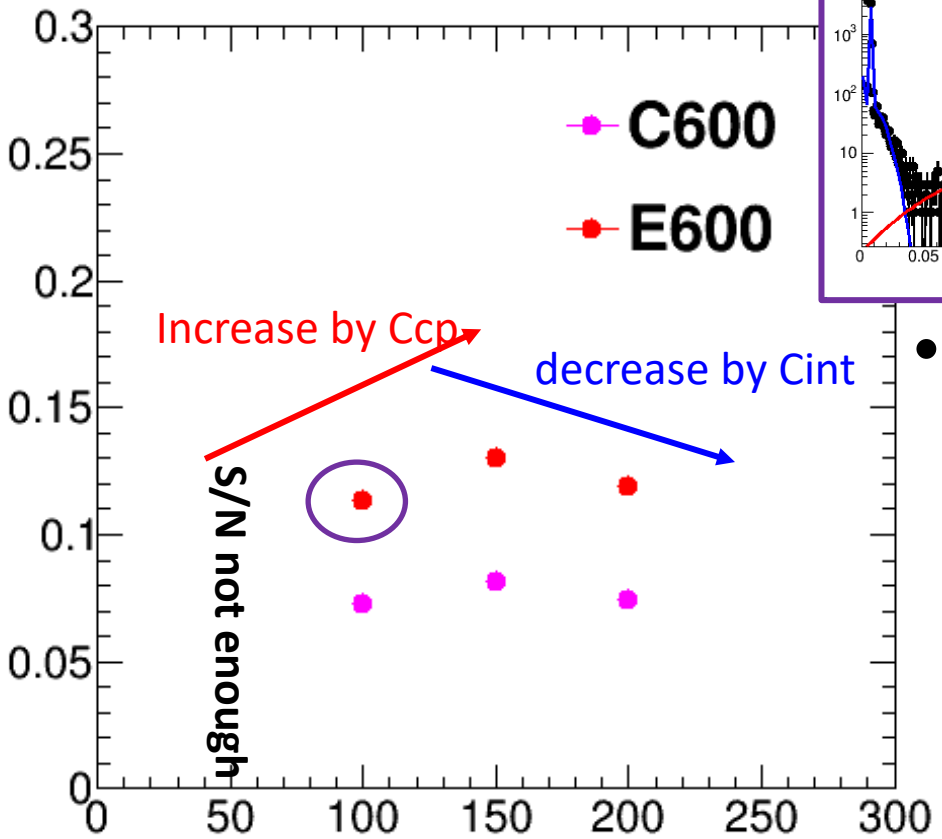
Longer strip detector should have worse S/N ratio

Usual a few cm strip might not possible….

Pixel type electrode : pixel size dependence

- Compared signal size of 6 types.
  - Two n+ resistivity types and 3 electrode size

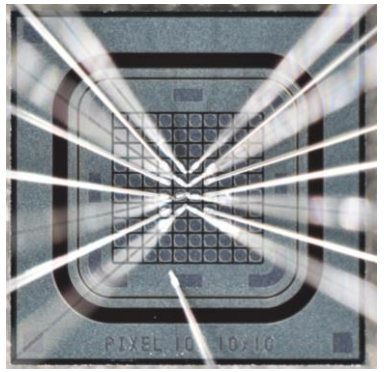




R_{imp}		
E120	E240	E600
C120	C240	C600

C_{cp}

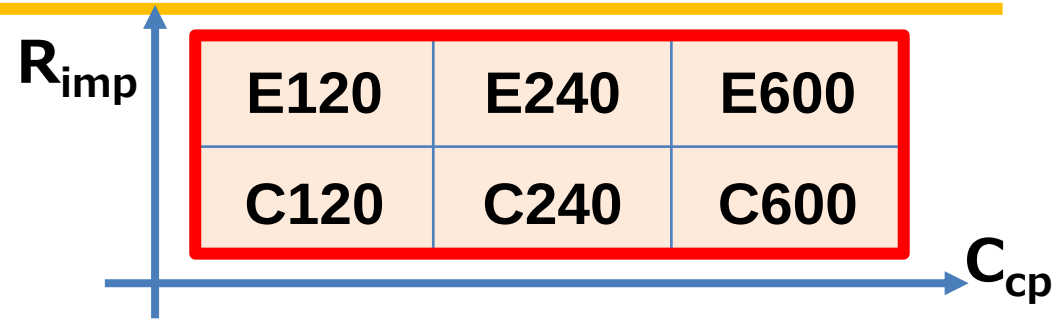
Successfully developed 100um x 100um pixel sensors!

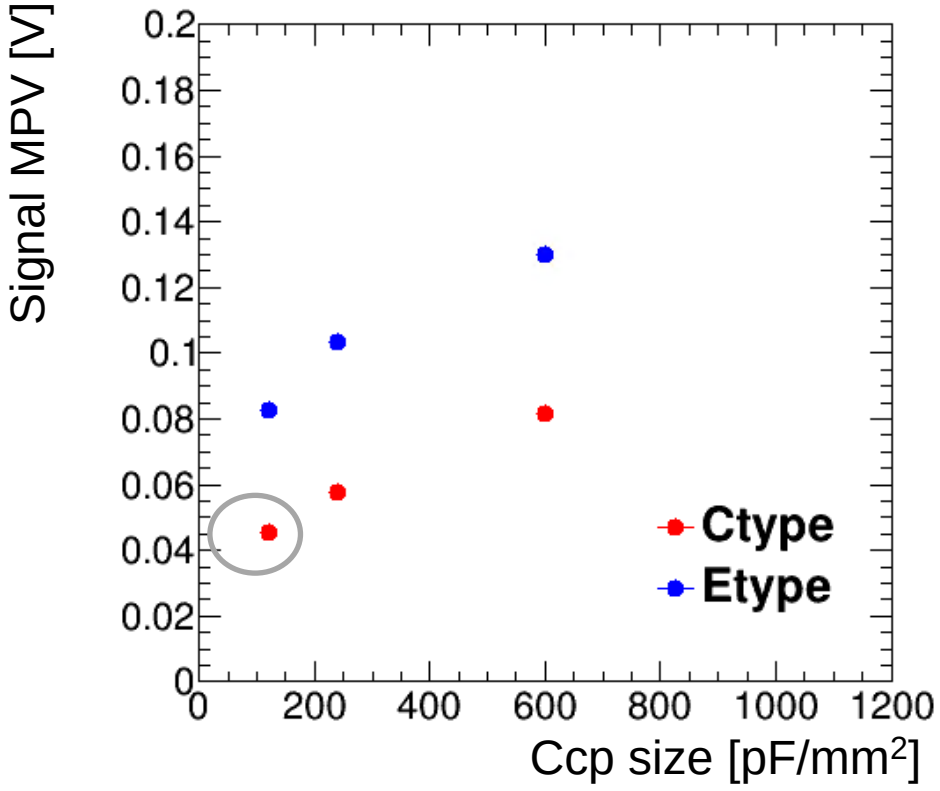


- Signal size is maximum at 150um
  - Signal size is not largely different.
  - Similar effect for two different resistivity samples.
  - Probably compensating two effects :
    - Signal increase by size due to Ccp increase.
    - Signal reduces by the size due to inter pixel capacitance.

Pixel type electrode : Ccp dependence

- Compared signal size of 6 types.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types



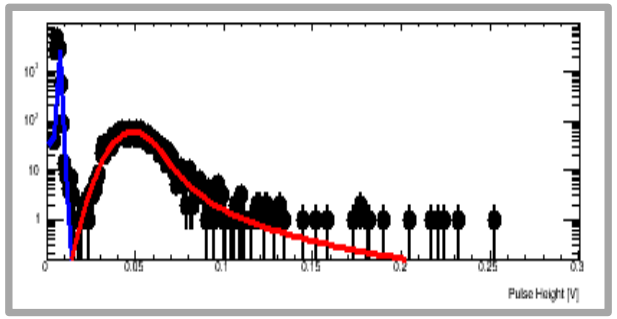


- Signal size increase by Ccp
  - All 6 types have enough S/N ratio.
  - 5 times Ccp increase signal size by factor of 1.5

    →ZR : Zc = 7 : 1 in case of 150um E-type pixel sensor

    (i.e. 60-90% of produced charge could be read out)

    * ignored all Cbulk and Cint effect



$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

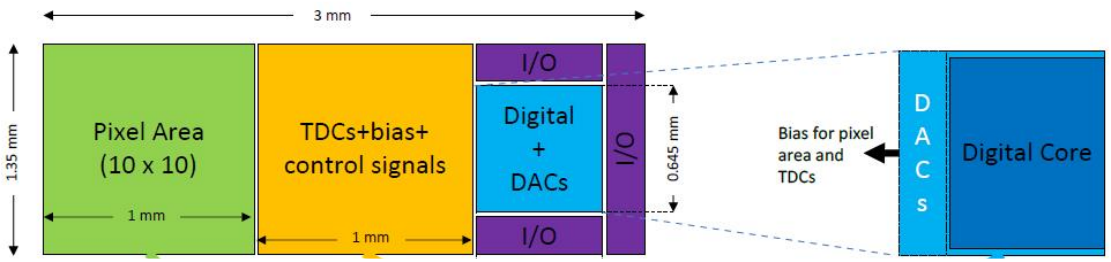
Plan for next samples

- Samples with better timing resolution
  - Timing resolution is limited by the active thickness of the bulk.
  - Processing **20um active thick sensor** (was 50um). Available in November.
- Larger prototype sensors
  - Producing new mask with larger prototype sensors to check gain uniformity.
    - Mask is together with EIC experiment.
    - **20mm x 20mm size pixel sensor with 100umx100um electrode** (to be connected ATLAS Itkpix-v1 ASIC)
    - Various length of Strip detector.
    - Many R&D smallish sensors
- Improvement of radiation tolerance
  - Discussing possibility of Carbon doped p+ layer

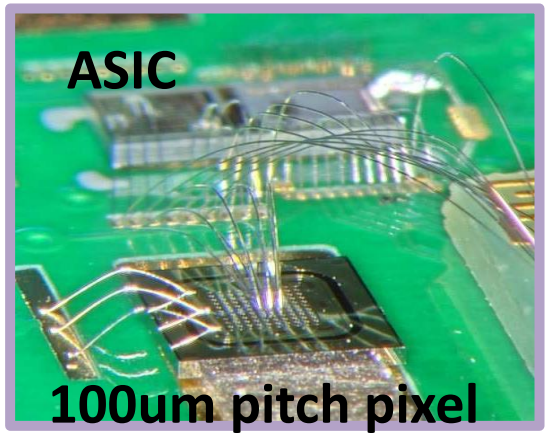
Certainly… need fast and multi-channel readout ASIC

- Possible candidates :
  - 500um pitch ASIC for EIC (by US collaborator)
    - BNL collaborating to Omega people (EICROC)
    - UCSC producing Si-Ge Bi-CMOS ASIC for EIC
  - Finer pitch ASIC (~100um pitch pixel)
    - **Collaborating with University of Geneva Si-Ge Bi-CMOS ASIC**
    - KEK will try to produce TSMC 65nm ASIC (longer time scale)

Fulvio Martinelli et. al. Si-Ge Bi-CMOS ASIC



10x10 channels with 3 analog + 1 discri. output



Conclusion

2019,20 sample

ACLGAD with 80um pitch strip sensor

Good S/N ratio : 99.98% at 1e-4 noise rate

First high spatial resolution LGAD!

Small signal due to :
inter strip capacitance
→Strip specific issue

2021 sample

ACLGAD with 100um x 100um pixel sensor

Larger signal than strip sensor!!

First pixelated LGAD!

New

Much better solution !

Home work 1

LGAD detector with 50um x 50um
Challenging but need to find a way

Home work 2

LGAD detector with Radiation tolerance
Currently up to $1.0 \times 10^{15} n_{eq}/cm^2$

backup

Next generation of Collider experiment

- **Need "Higher Luminosity" and/or "Higher Energy"**
  - ***High Luminosity LHC (HL-LHC)***
    - 20 times more data (~3000-4000fb^{-1}) at **14TeV**
    - Plan : Start at 2029

Coming soon

  - ***High Energy LHC (HE-LHC)***
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **28TeV** collider in the same tunnel as LHC.

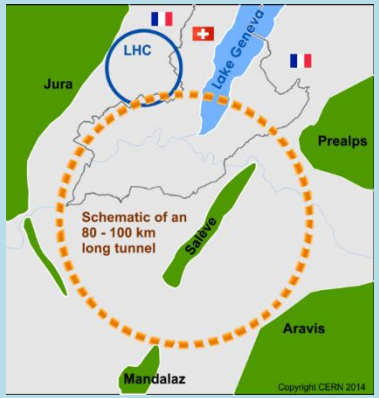
Discussion Started

  - ***Future Circular Collider (FCC-hh)***
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **100TeV** collider with 100km tunnel at CERN.

Discussion Started

  - ***International Linear Collider (ILC)***
    - 250GeV e+ e- collider in Japan

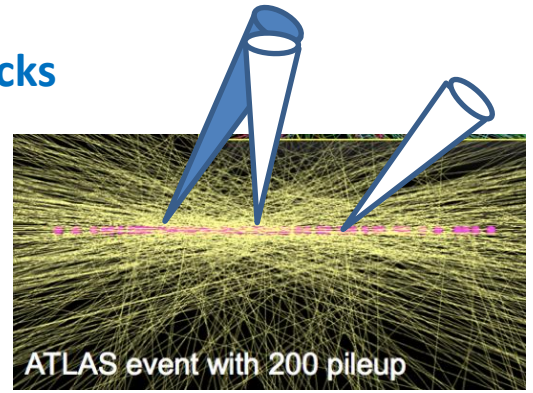
Final decision soon



Inner Tracking system

Very high density tracks

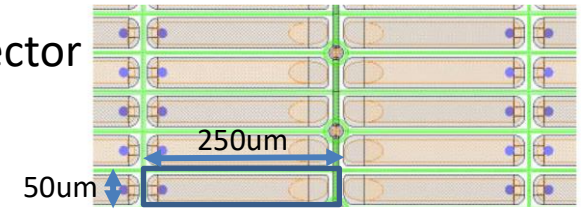
140 pileup @ HL-LHC
1500 pileup @ FCC-hh



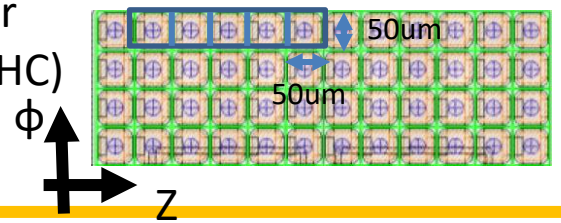
Only way to solve this so far…

finer pixel pitch

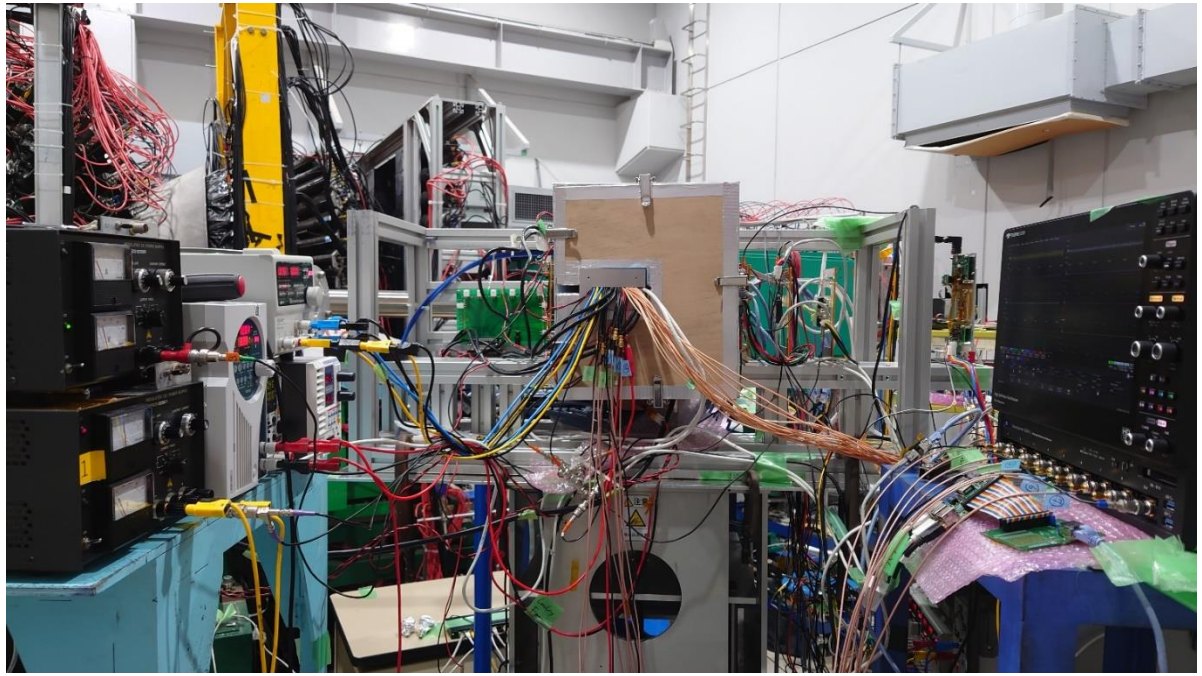
Current detector
(ATLAS IBL)



New detector
(Pixel @HL-LHC)

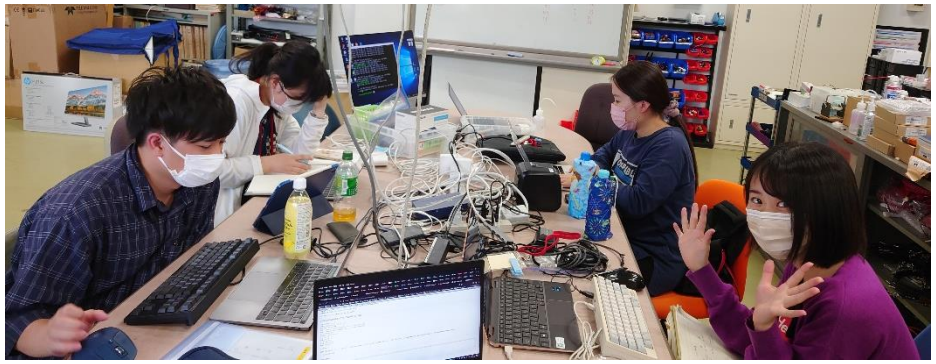


Snap shot from on-going ELPH testbeam

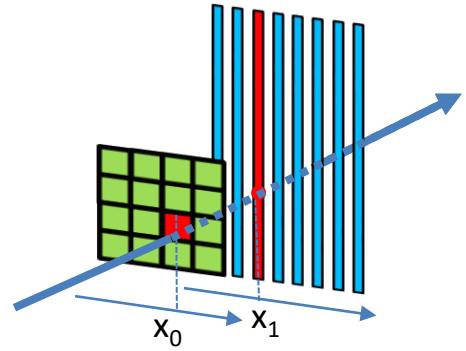


- ELPH testbeam (6/17-24)
  - 800MeV electron beam
- Took huge set of data
  - Pad/Strip/Pixel sensors
  - Combined run with 100um pixel and 80um strip sensor

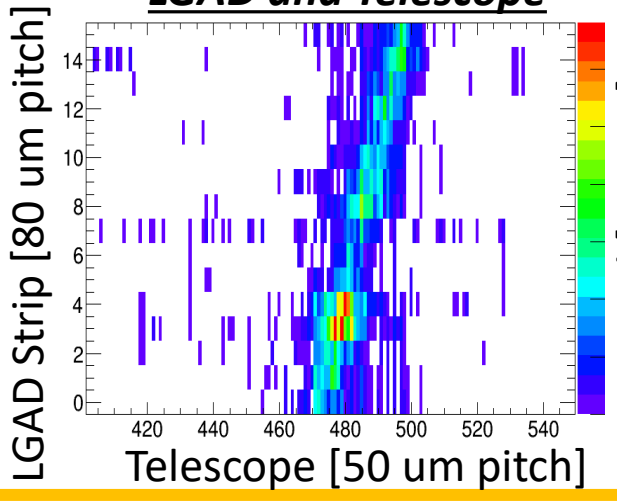
→First LGAD tracker!!



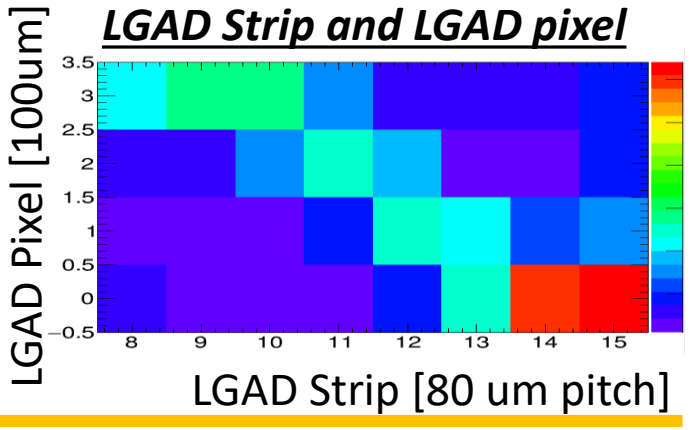
Correlation of x position of two planes



LGAD and Telescope



LGAD Strip and LGAD pixel



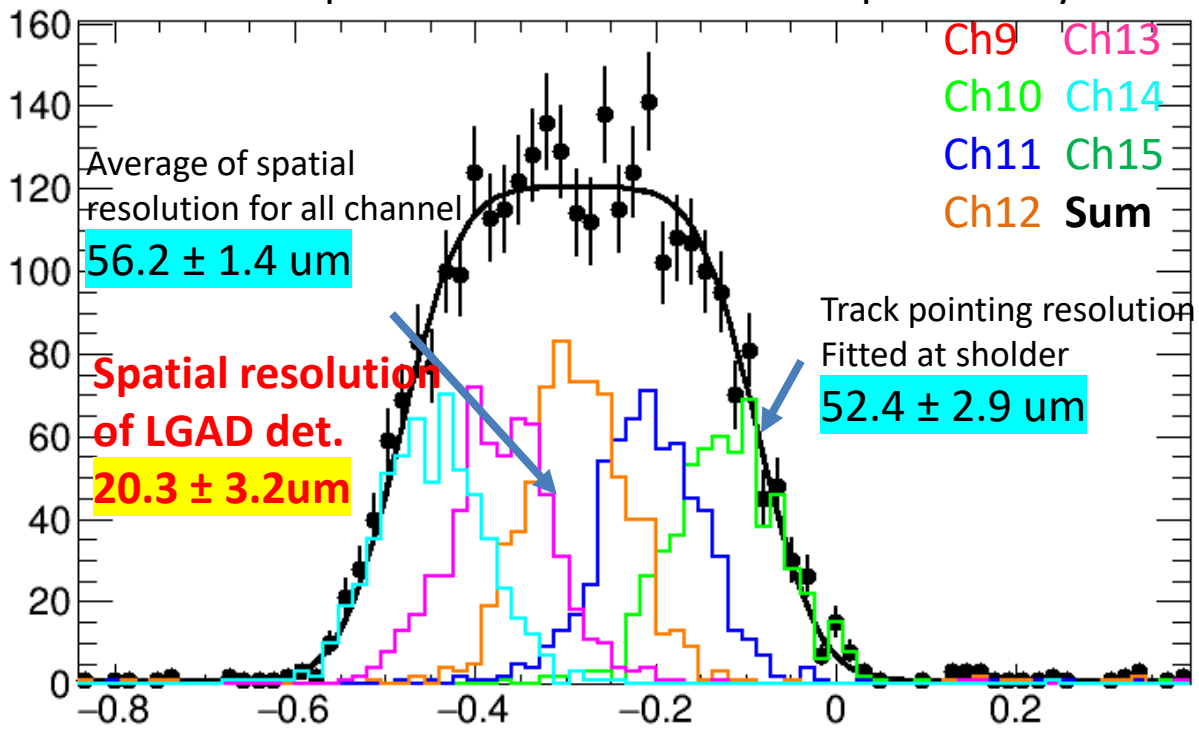
Spatial resolution measurement at ELPH TB

- In principle, no dead area and small crosstalk
  - At least 23um(80um/$\sqrt{12}$) resolution by binary readout
- ELPH testbeam at Tohoku Univ. (8-9 July 2021)
  - 800MeV electron beam
  - Trigger rate 200-400Hz
  - Strip E-b type 170V @ 20°C

Huge Multiple-Scattering

5 layer of Telescope
2 upstr. + 3 downstr.
(25um x 500um pixel)
Scintillator + MPPC trigger
Region of interest (ROI)

Residual distribution
of hit position and reconstructed position by tracking.

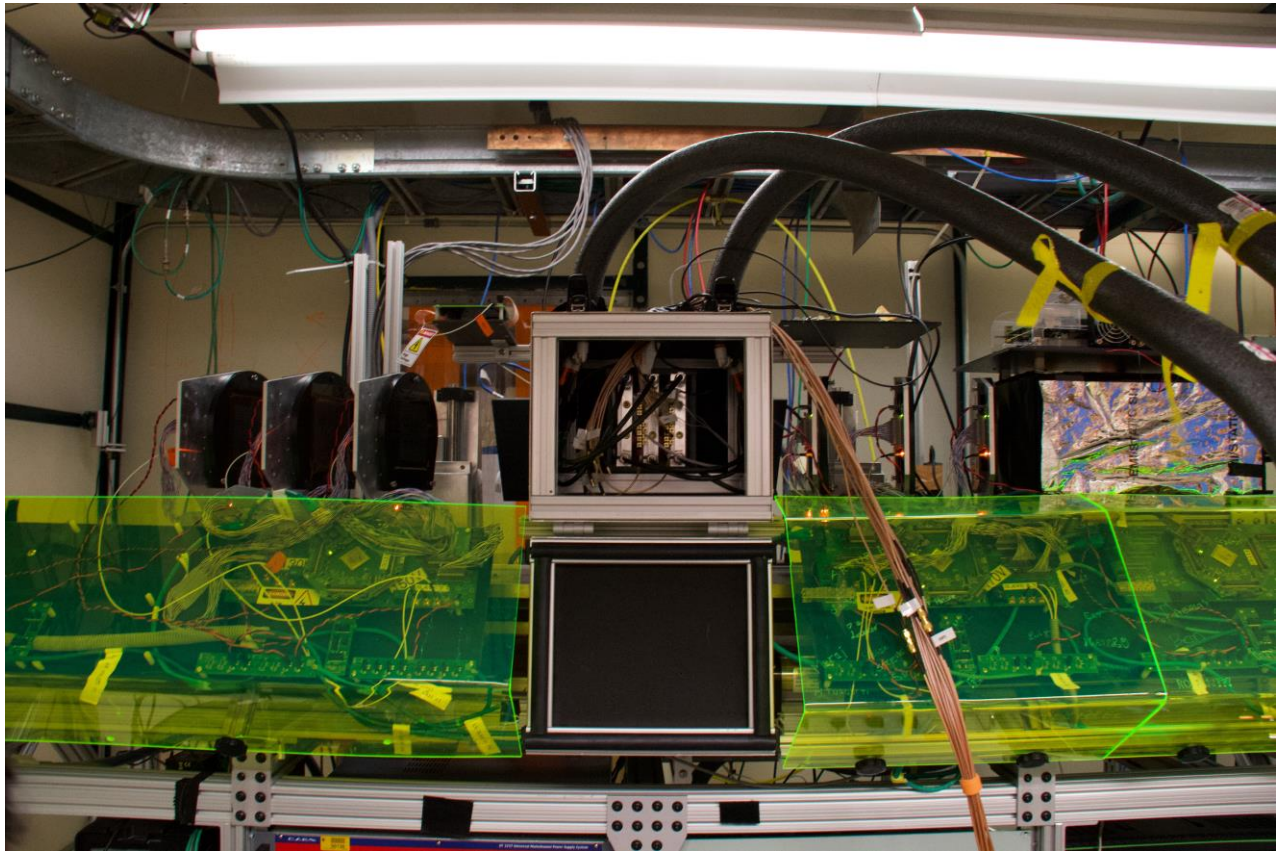


Timing resolution for AC-LGAD detector

Fermilab Test Beam Facility (FTBF)

120GeV proton beam

Strip Detector based Telescope : ~15um pointing resolution



Timing reference Detector

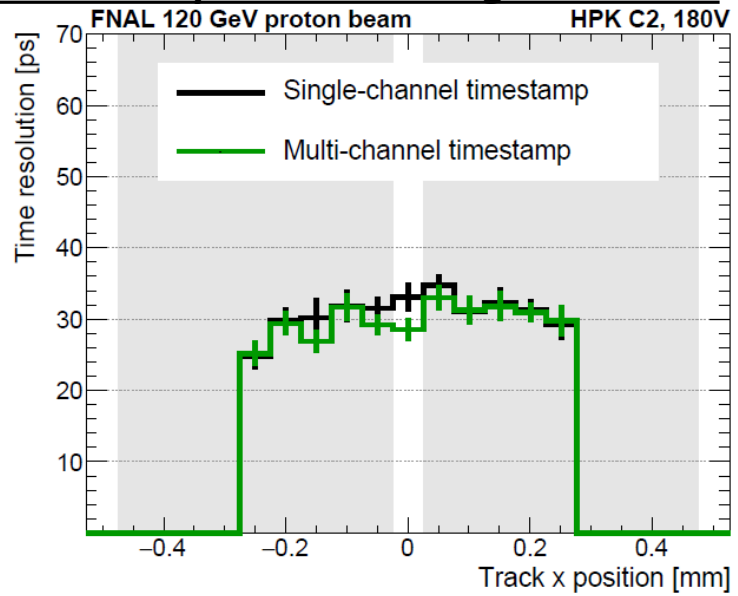
PHOTEK MCP photomultipliers (PMT140)

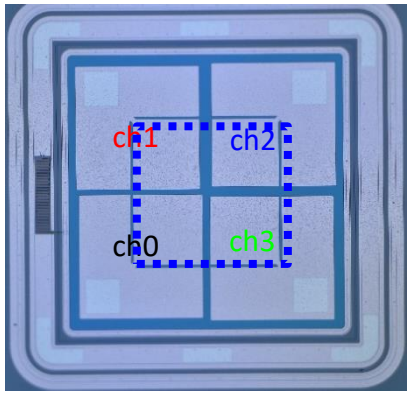
450ps FWHM with 5e3 Gain

~5ps timing resolution

(SPEC: Multi-photon jitter below 10 ps)

Position dependent Timing resolution





- **25-35 ps timing resolution uniformly!**