LGAD R&D Status & Future

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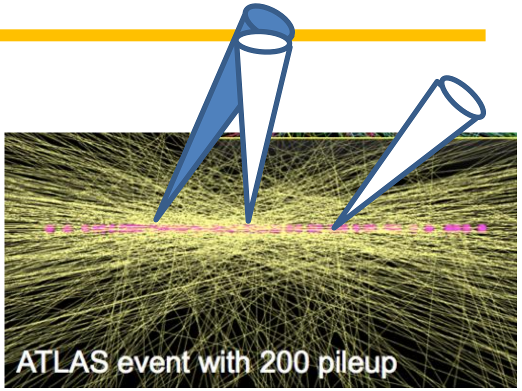
Tracking detector with timing resolution

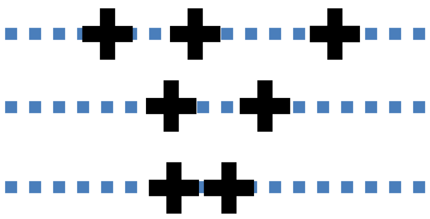
- **Collider experiment gets high energy and high intensity.**
  - Solving pileup issue is required for tracking, **Timing resolution helps!**
  - **→Future Tracking detector should have timing information for all hits!**



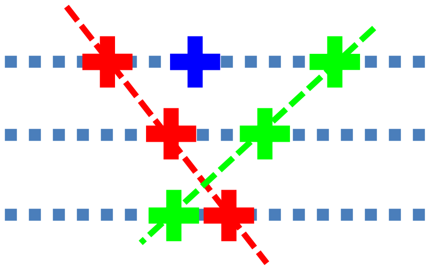
- **Tentative Requirement**
  - **30ps timing resolution**
  - **~o(10)um spatial resolution (Pixel type).**
  - **(hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance**

4D tracking！

Detector Hit



Tracking



Solve pileup hits in an event

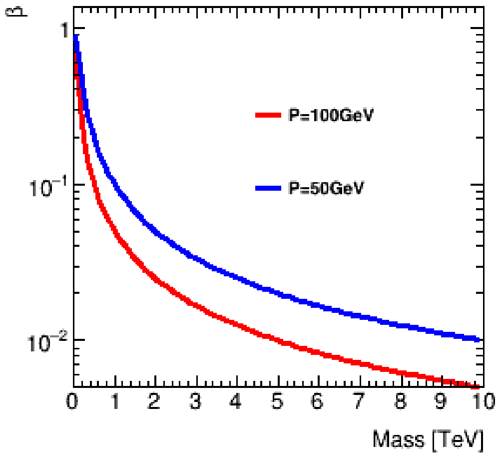
Particle identification

$\beta = 1$ $\beta = 0.95$

150ps difference at R=1m

K+ π+ separation

Mass spectrum for new particle

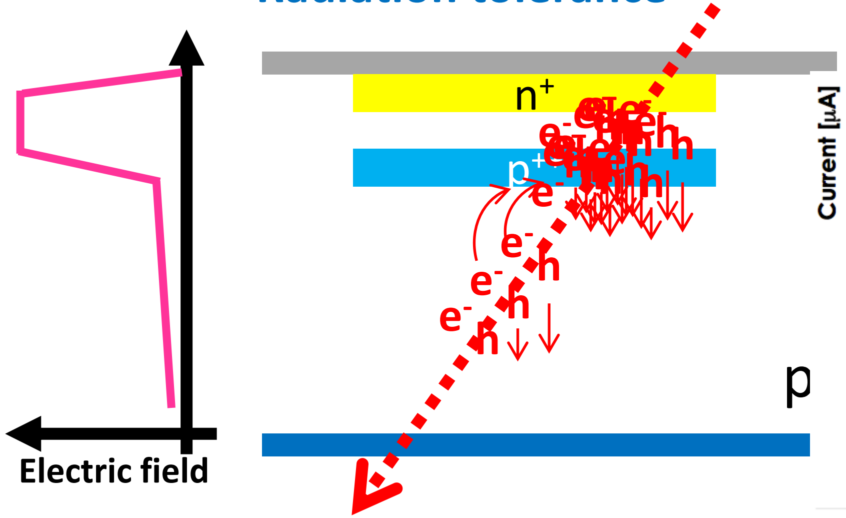


β measurement to obtain mass

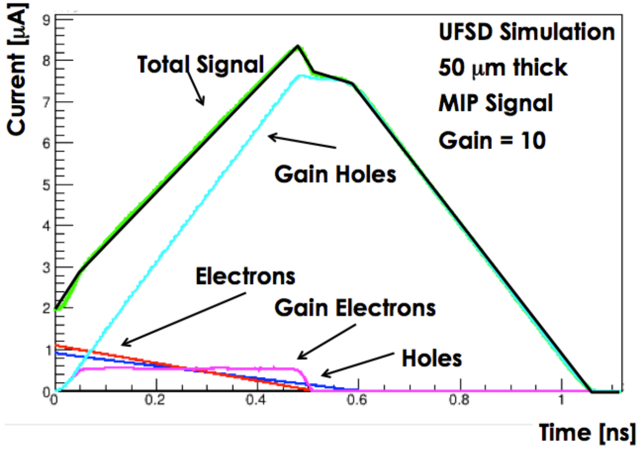
e.g. Mass measurement for Long lived chargeno

LGAD detector and spatial resolution (AC-LGAD)

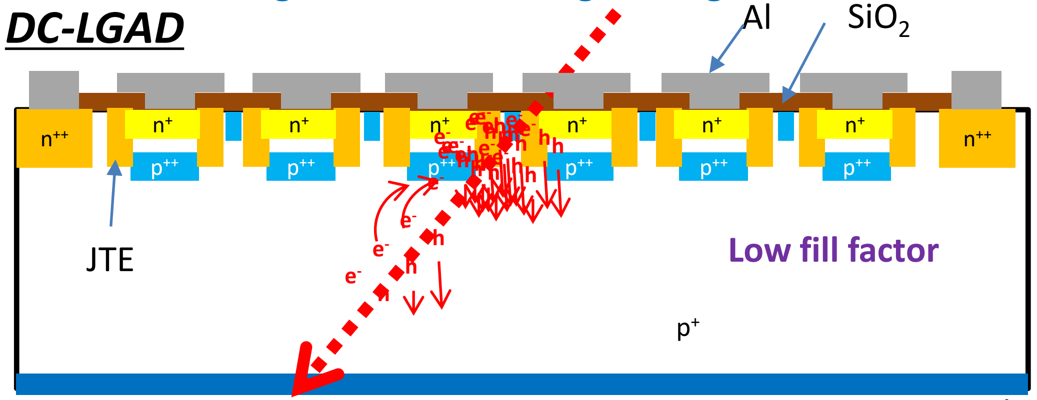
- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make higher Electric Field
    → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**
  - R&D topics
    - **Finer electrode separation for spatial resolution**
   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

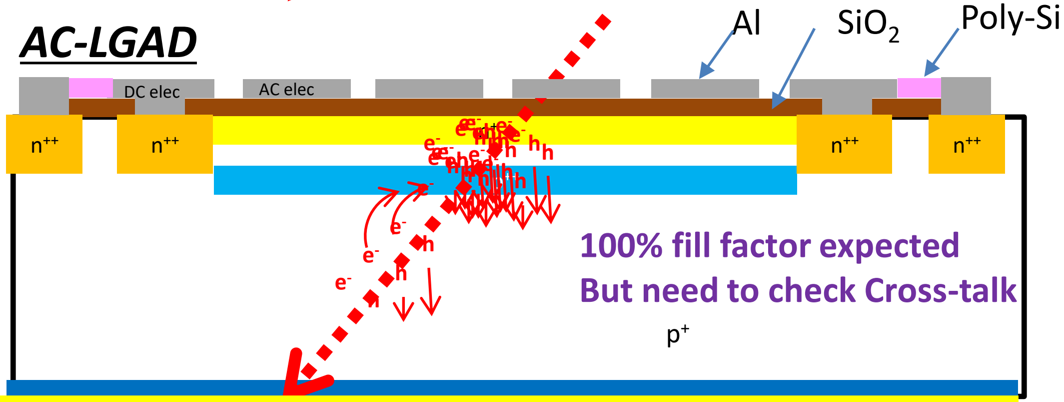


Signal drivers : **Gain Holes**



- Limitation 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.**

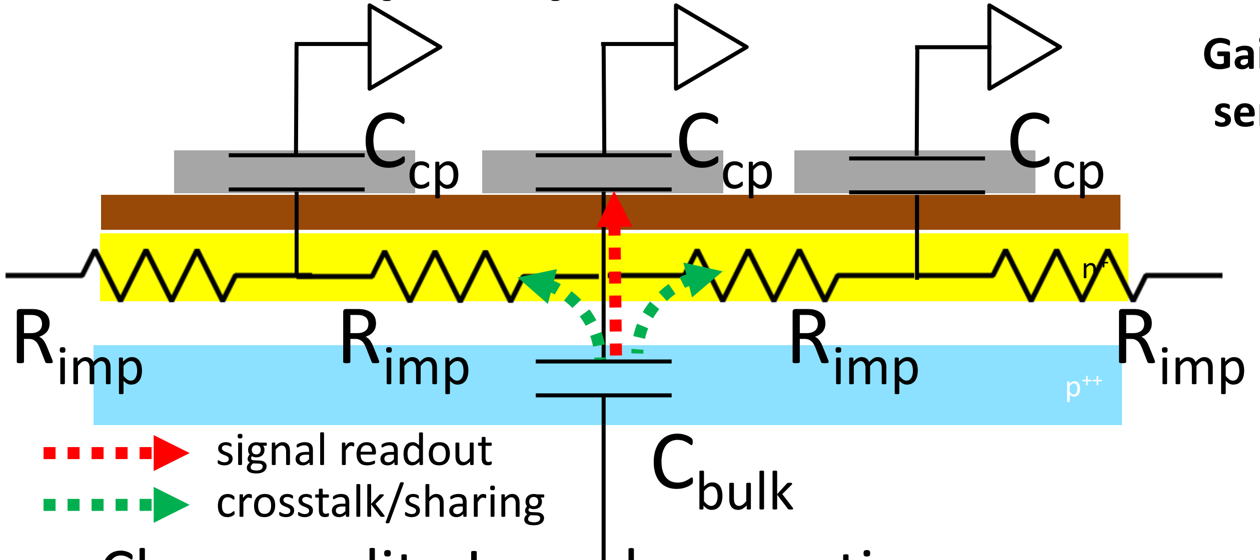




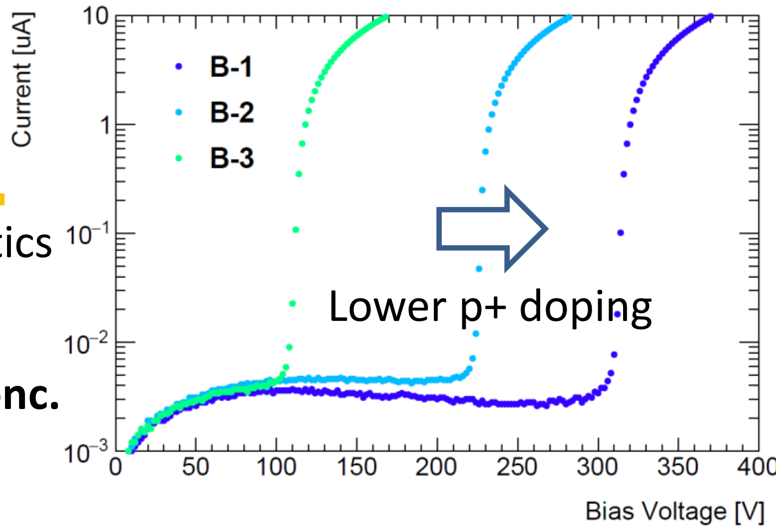
For finer electrode LGAD, Gain Uniformity is extremely important and no other way possible.

AC-LGAD detector

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



I-V characteristics

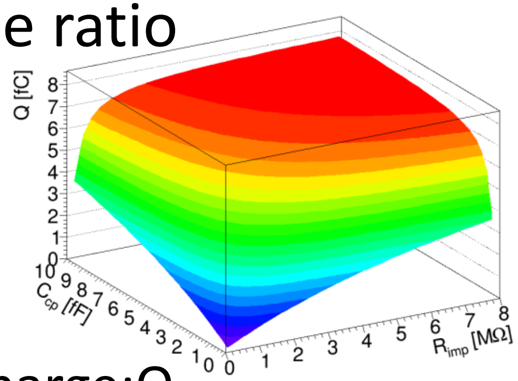


Gain Voltage (V_{gain}) is quite sensitive to the p+ doping conc.

- Charge split : Impedance ratio

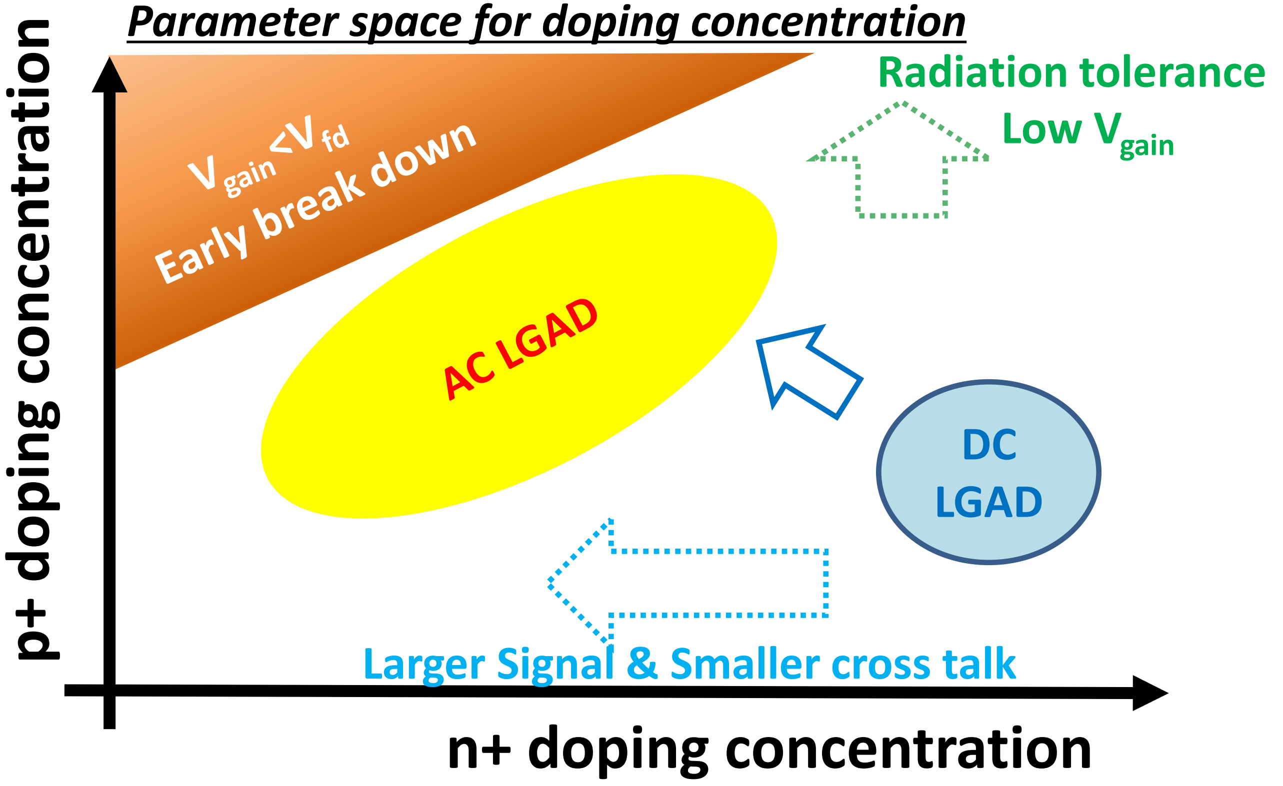
Assuming $Z_{Cbulk} >> Z_{Ccp}$…

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



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

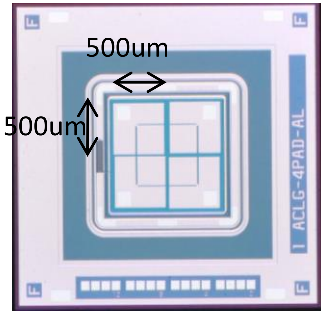
Parameter space for doping concentration



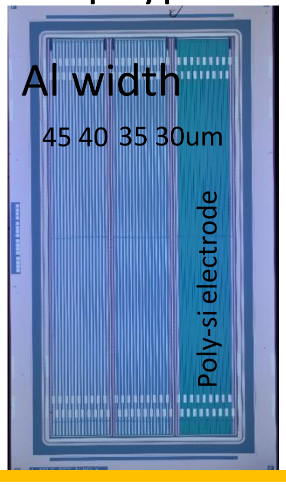
HPK LGAD development

- JFY2015-JFY2018 DC-LGAD
  - **We contributed only first prototype.** HGTD took over.
- JFY2019, JFY2020 AC-LGAD production Run I
  - 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

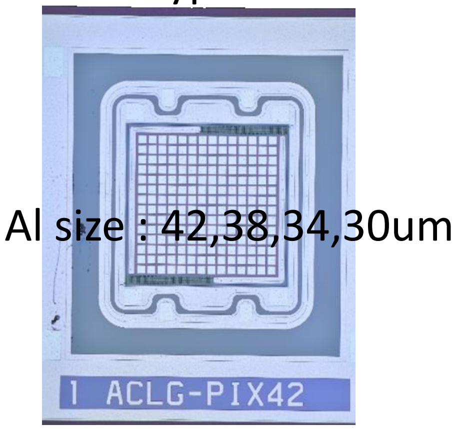
Pad type

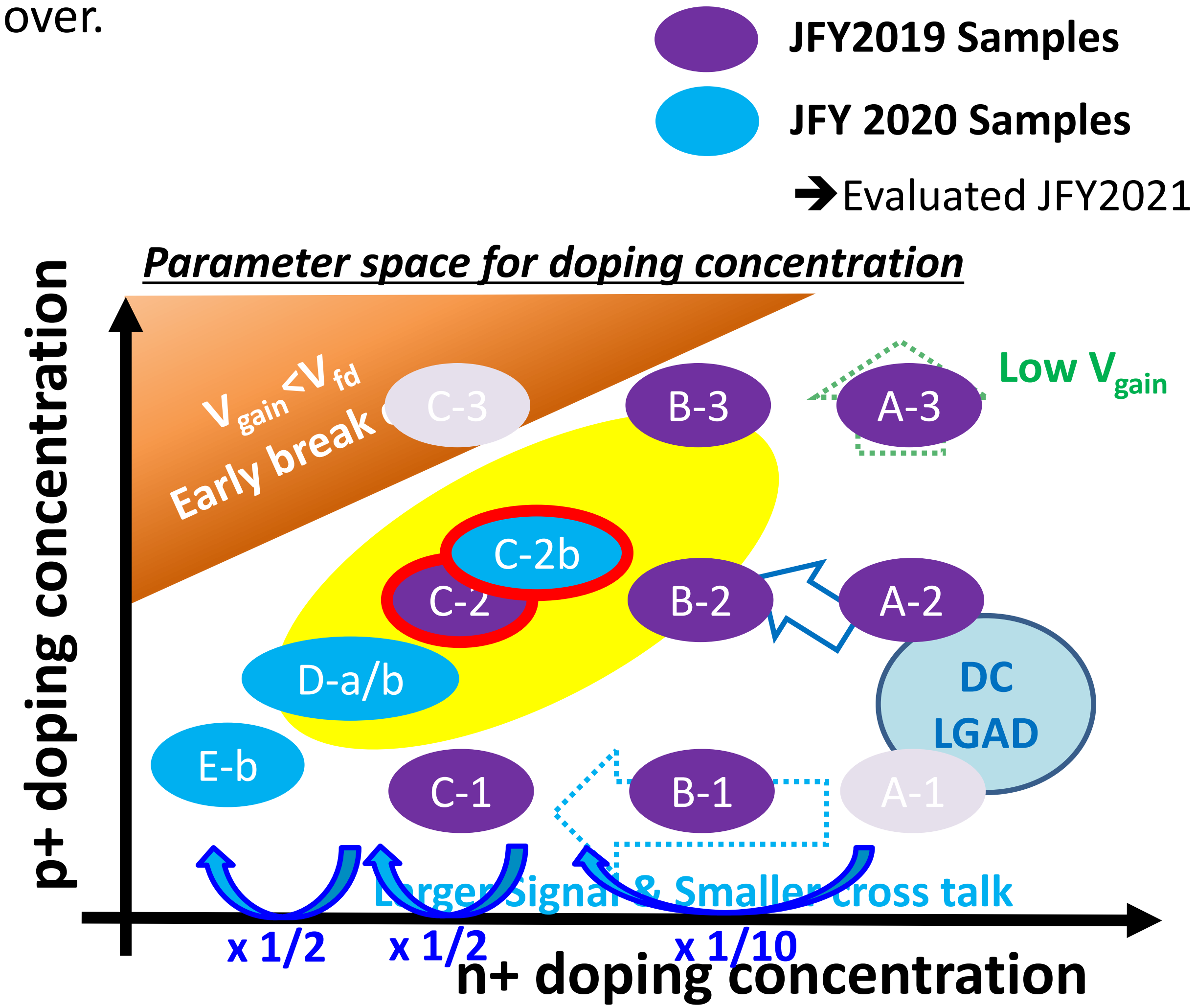


Strip type



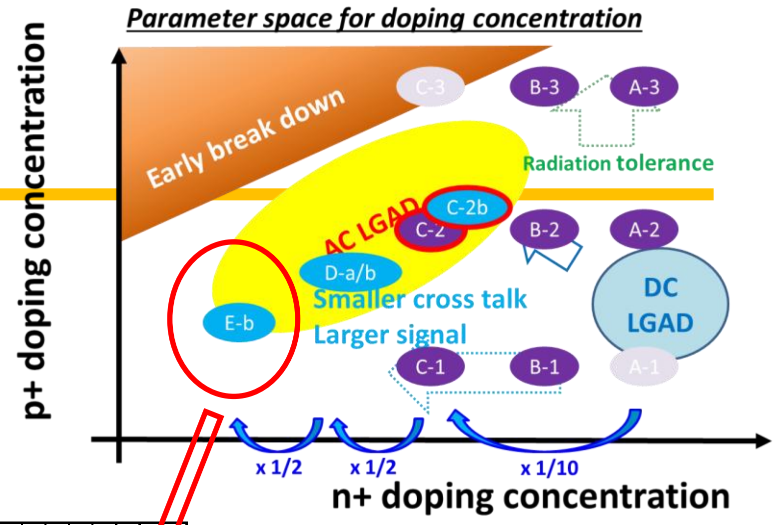
Pixel type

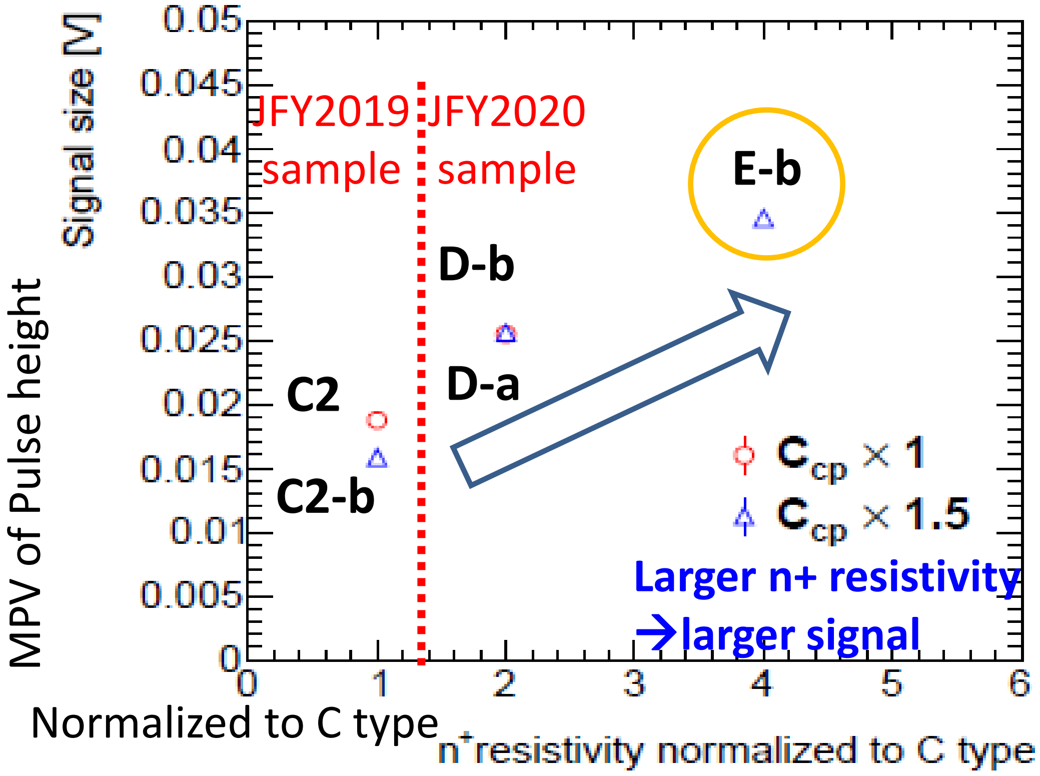


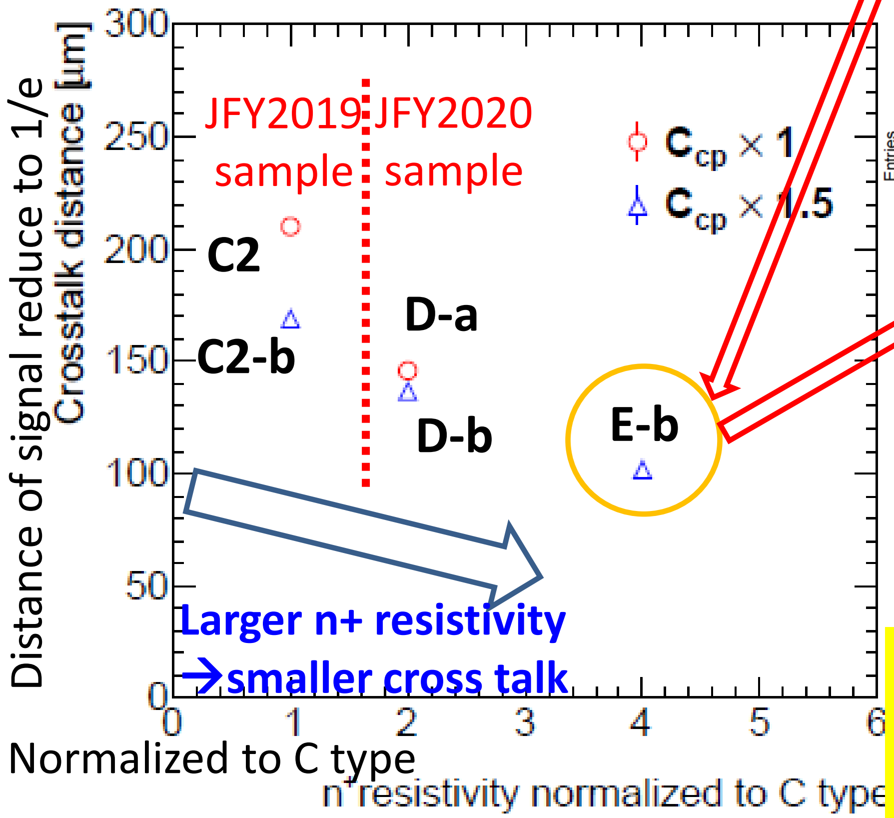


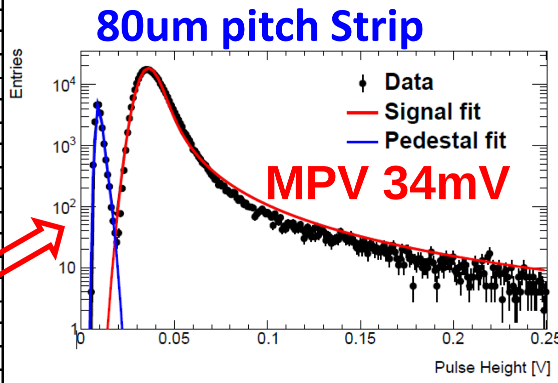
Signal size and crosstalk

- **80um pitch Strip type :** Signal size and Crosstalk
  - n+ resistivity dependence of signal size and crosstalk.
  - **Large n+ resistivity →Large signal & Smaller crosstalk**







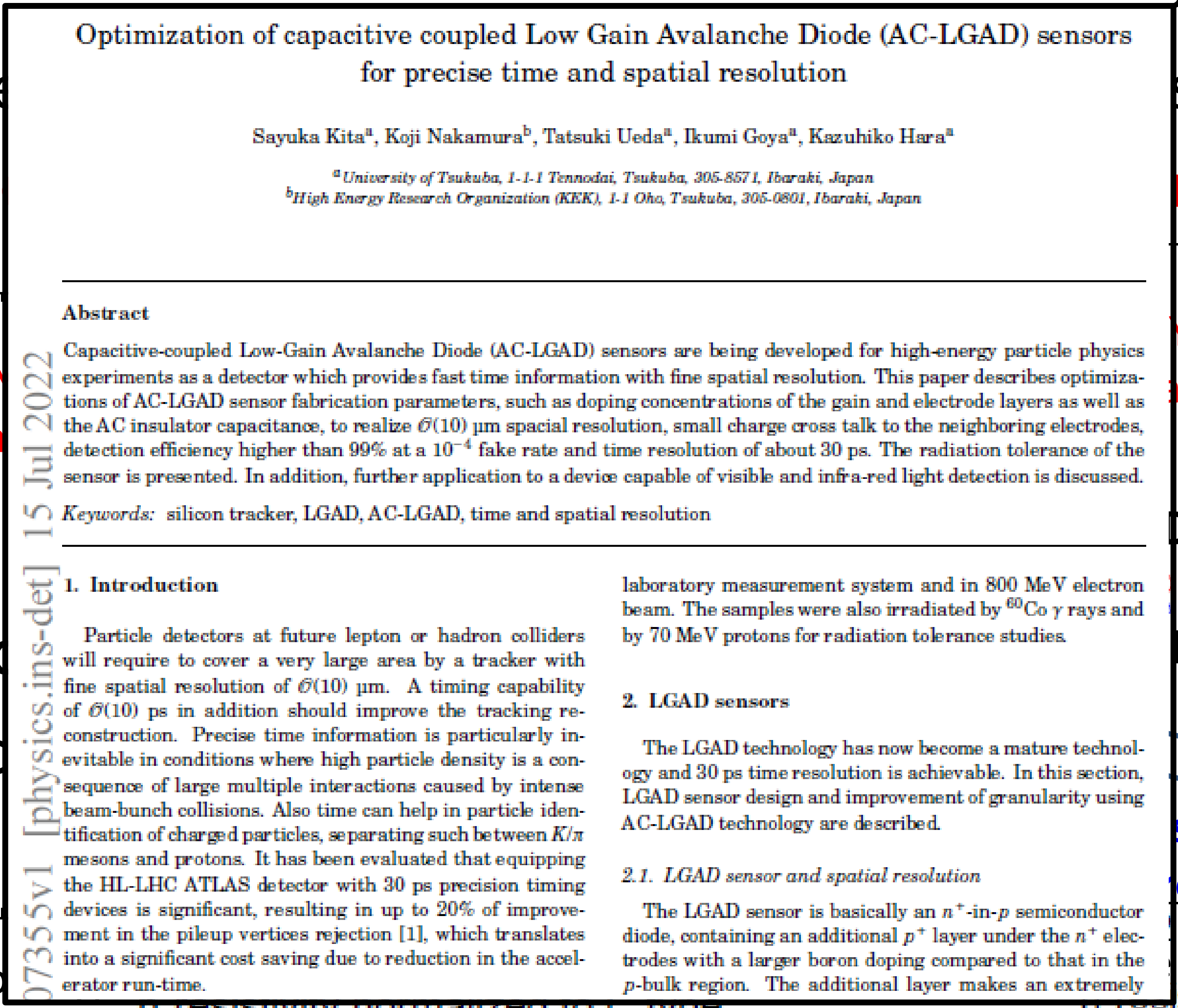


Successfully developed Good S/N 80um pitch strip detector!

Signal size and crosstalk

- **80um** p... stalk
  - n+ re... sstalk.
  - **Larg... rosstalk**

Submitted to NIM A in July 2022 https://arxiv.org/abs/2207.07355



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

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Abstract

Capacitive-coupled Low-Gain Avalanche Diode (AC-LGAD) sensors are being developed for high-energy particle physics experiments as a detector which provides fast time information with fine spatial resolution. This paper describes optimizations of AC-LGAD sensor fabrication parameters, such as doping concentrations of the gain and electrode layers as well as the AC insulator capacitance, to realize $\mathcal{O}(10)$ µm spacial resolution, small charge cross talk to the neighboring electrodes, detection efficiency higher than 99% at a 10^{-4} fake rate and time resolution of about 30 ps. The radiation tolerance of the sensor is presented. In addition, further application to a device capable of visible and infra-red light detection is discussed.

Keywords: silicon tracker, LGAD, AC-LGAD, time and spatial resolution

1. Introduction

Particle detectors at future lepton or hadron colliders will require to cover a very large area by a tracker with fine spatial resolution of $\mathcal{O}(10)$ µm. A timing capability of $\mathcal{O}(10)$ ps in addition should improve the tracking reconstruction. Precise time information is particularly inevitable in conditions where high particle density is a consequence of large multiple interactions caused by intense beam-bunch collisions. Also time can help in particle identification of charged particles, separating such between K/π mesons and protons. It has been evaluated that equipping the HL-LHC ATLAS detector with 30 ps precision timing devices is significant, resulting in up to 20% of improvement in the pileup vertices rejection [1], which translates into a significant cost saving due to reduction in the accelerator run-time.

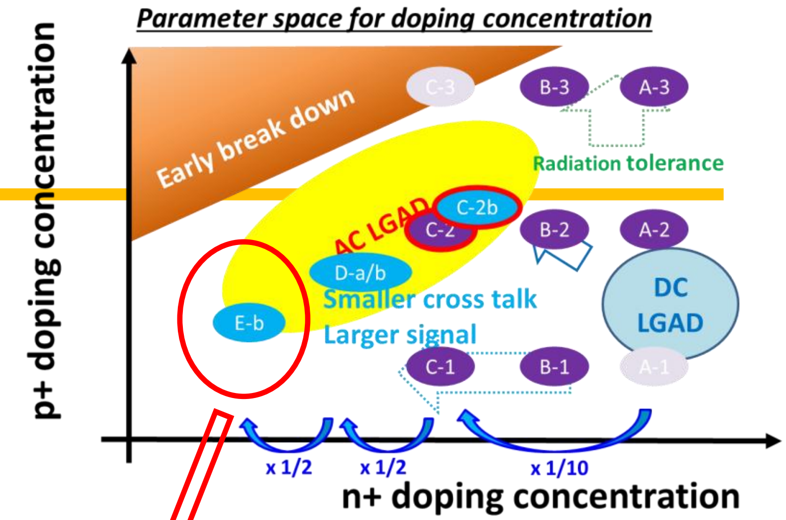
laboratory measurement system and in 800 MeV electron beam. The samples were also irradiated by ^{60}Co γ rays and by 70 MeV protons for radiation tolerance studies.

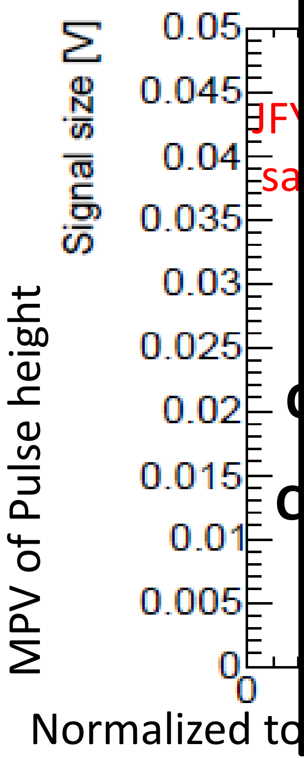
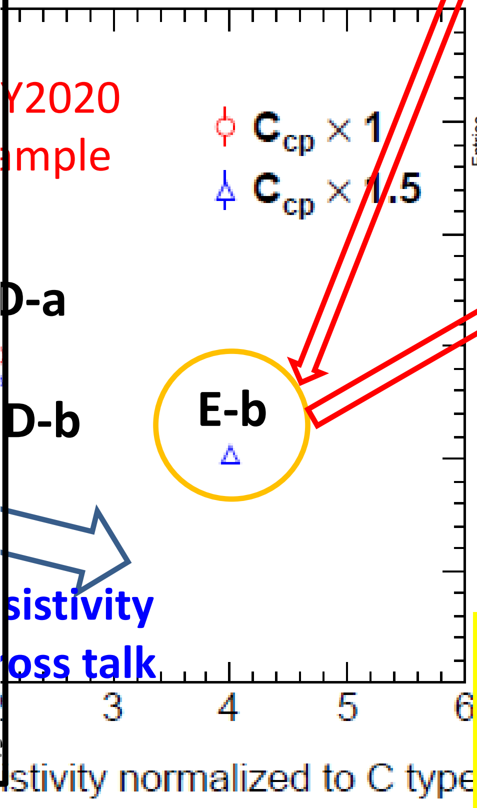
2. LGAD sensors

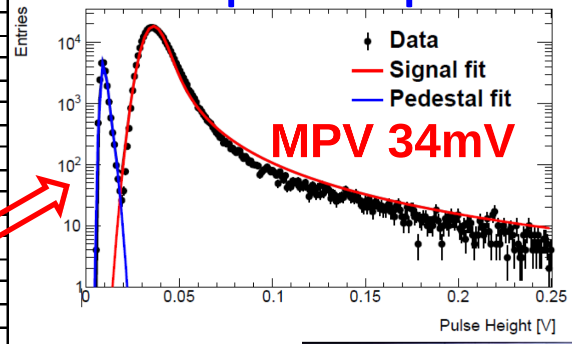
The LGAD technology has now become a mature technology and 30 ps time resolution is achievable. In this section, LGAD sensor design and improvement of granularity using AC-LGAD technology are described.

2.1. LGAD sensor and spatial resolution

The LGAD sensor is basically an n^+-in-p semiconductor diode, containing an additional p^+ layer under the n^+ electrodes with a larger boron doping compared to that in the p-bulk region. The additional layer makes an extremely



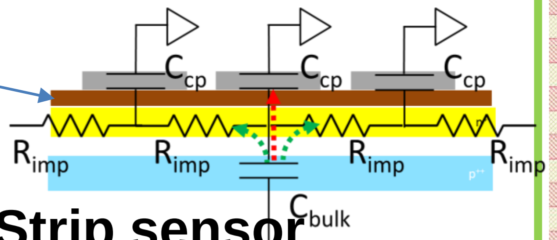


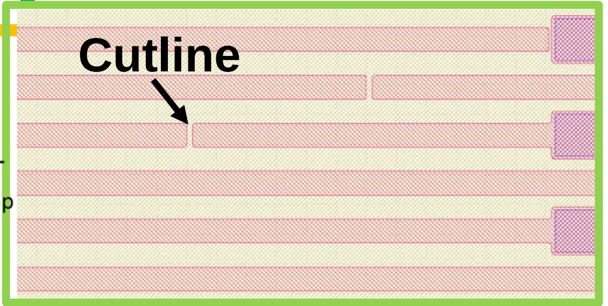
Successfully developed Good S/N 80um pitch strip detector!

AC-LGAD run II (2021 sample) : in April 2022

Used thinner di-electric layer (Oxide layer)

→ Electrode capacitance increased by factor of 5 !!



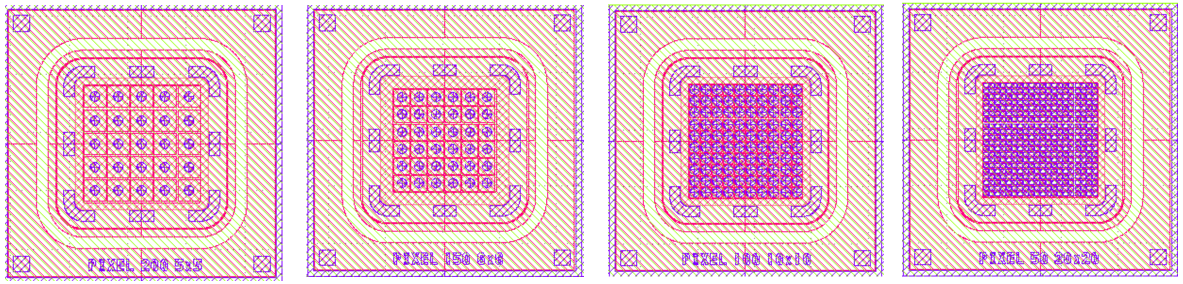


Pixel sensor

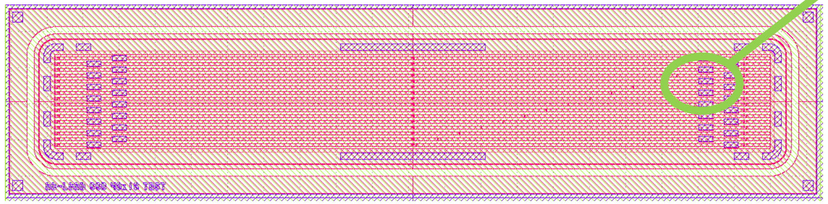
Strip sensor

- Various of pitch

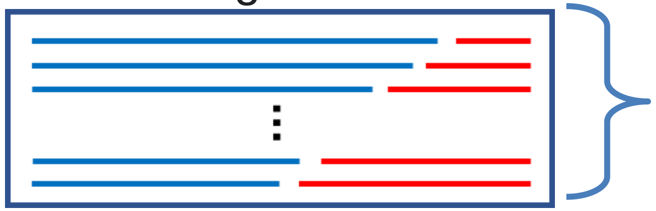
200um 150um 100um 50um



- Strip sensor which has different electrode length (to study inter electrode cap.)



Pattern diagram



- 5 times larger Ccp compared with E-b (2020) type : E-600

R_{imp} [Ω/□]			
1600	E120	E240	E600
400	C120	C240	C600

C_{cp} [pF/mm^2]

AC-LGAD run II-b 17th November 2022

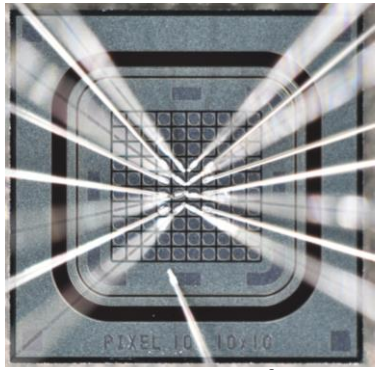
Received new wafers with the same design :

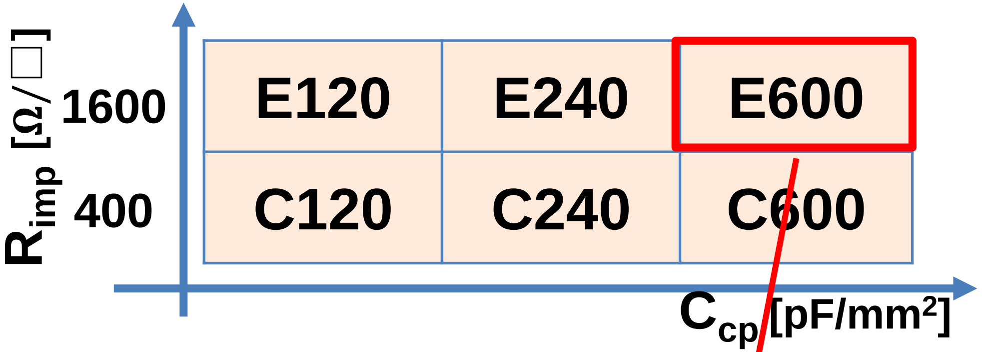
reduced active thickness 50um→30/20um

Expecting better timing resolution (no results today)

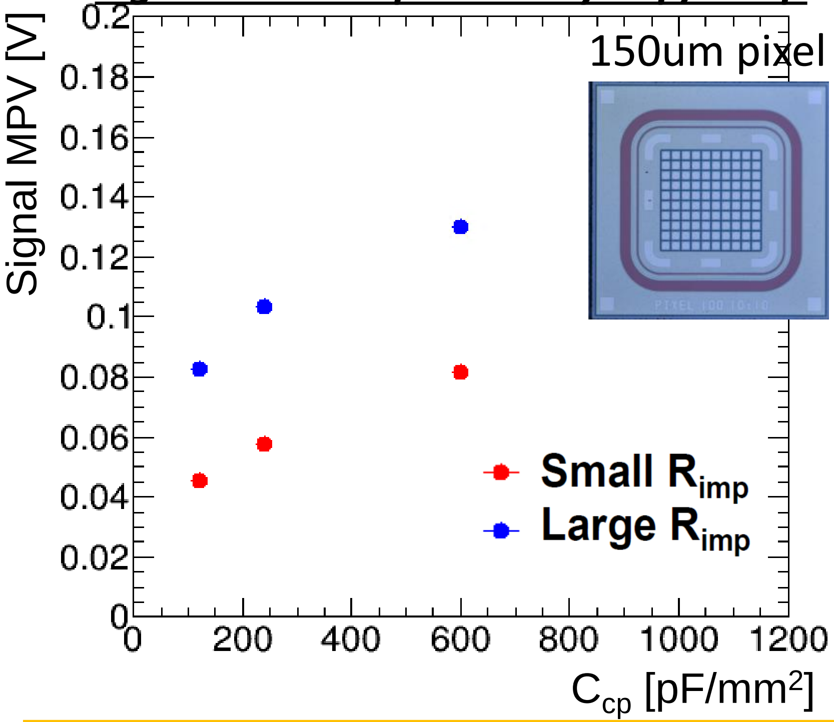
Results for AC-LGAD pixel detector

- Compared signal size of 6 types C_{cp}/R_{imp}.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types
- Compared signal size of 3 pixel size
  - 100/150/200um pitches are compared.

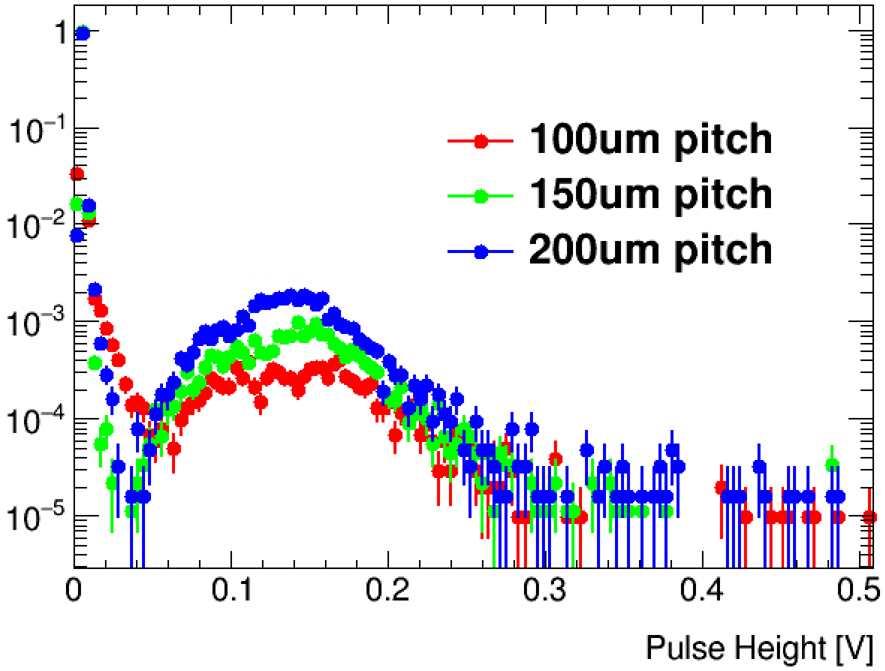




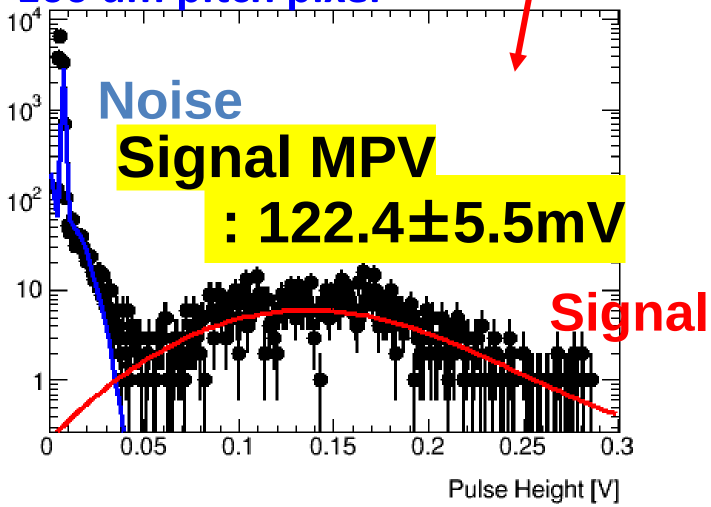
Signal size comparison by Ccp/Rimp



Pulse height comparison by pixel pitches



100 um pitch pixel

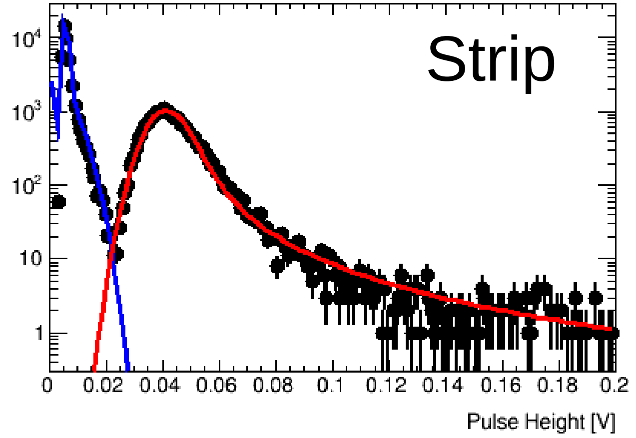


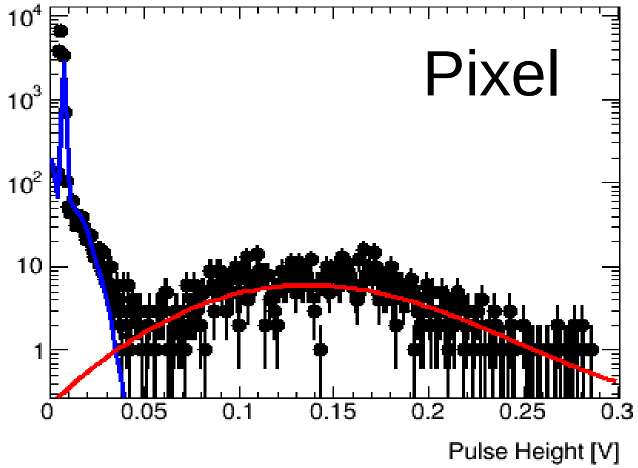
Successfully developed Good S/N 100um pitch pixel detector!

Inter electrode capacitance effect ??

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

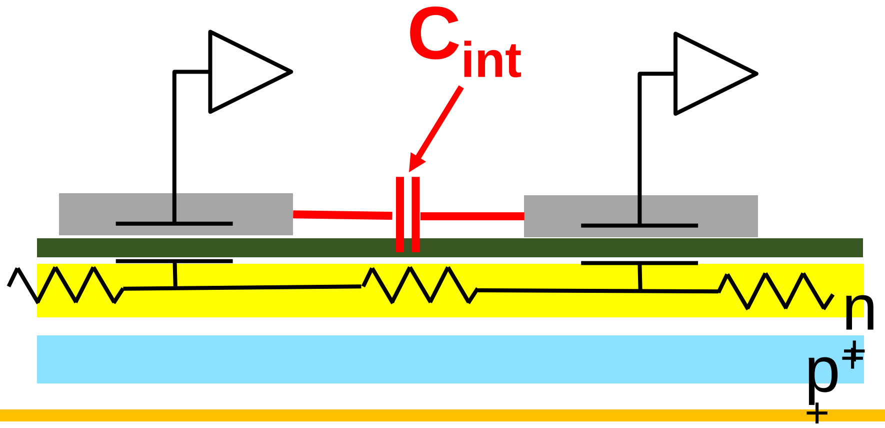
Comparison of pulse height distribution between strip and pixel …





	Strip	Pixel
Area of electrode	9880x45 um^2	100x100 um^2
C_{cp} size of electrode	large	small
Signal size (**expected** from C_{cp})	large	small
Signal height (**actual result**)	39.26±0.08mV small	122.4±5.5mV large

Inter electrode capacitance



To check C_{int} effect…

Compared signal size & cross talk

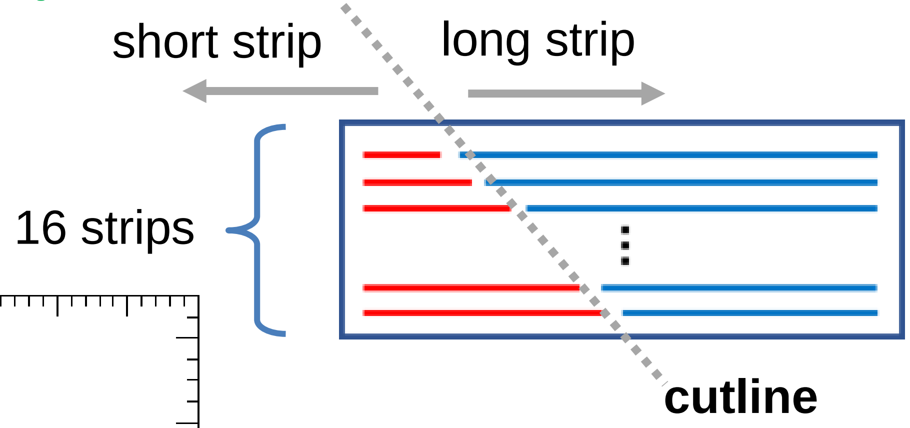
For various length of strip electrodes

Pattern diagram

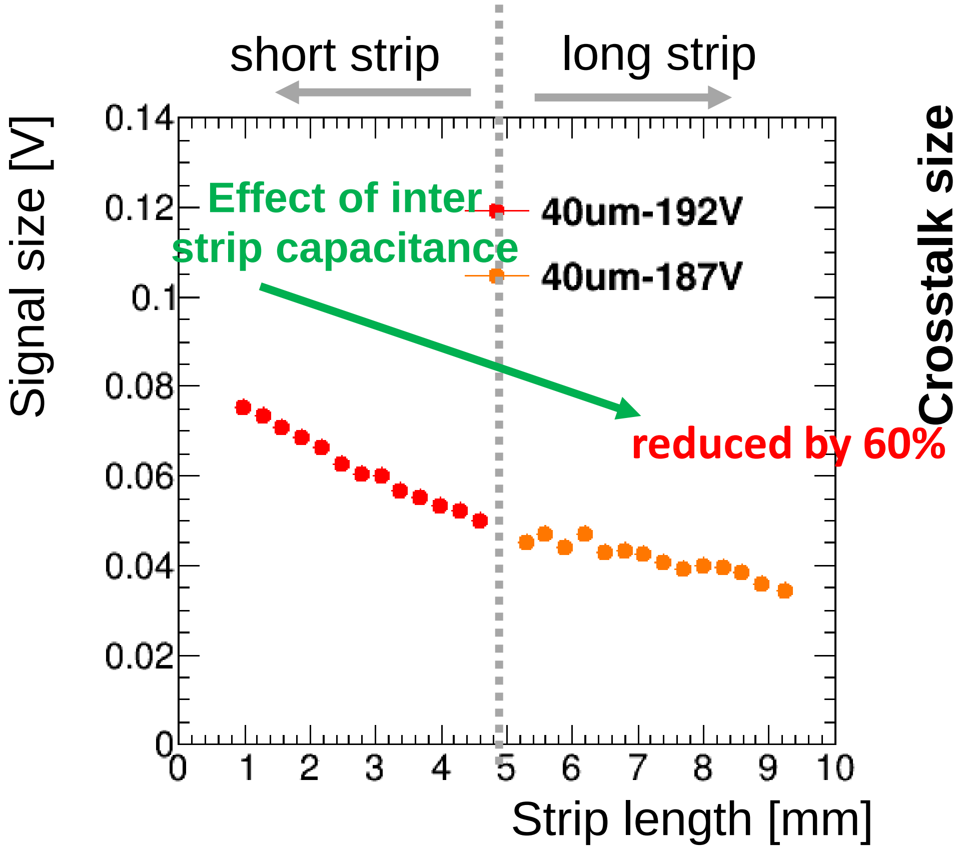
32 variation strip lengths

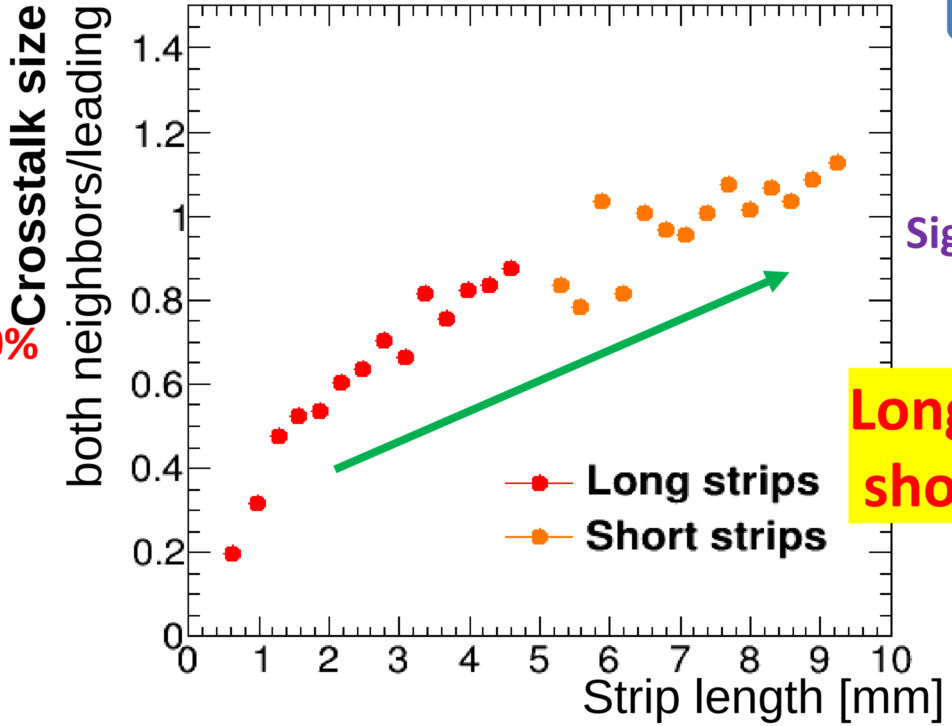
Strip type electrode : inter strip capacitance

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

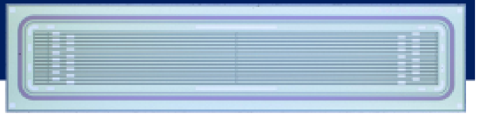
Longer strip detector should have worse S/N ratio

Usual a few cm strip might not possible….

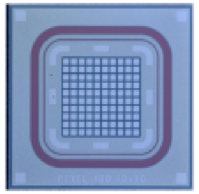
Results & publication

Sayuka Kita ***et. al.*** VERTEX 2022 conference @ Tateyama Japan

Conclusion



For inner tracker in hadron collider,
<u>finer pitch AC-LGAD sensors</u> are prototyped with HPK.



⬇

Parameter optimization was performed.

Best type sensor (larger R_{imp} and C_{cp}) : Larger signal height and smaller crosstalk !

successfully developed !!

Pixel (100um pitch) → **larger area prototype** with **ASIC**

Strip (80um pitch) C_{int} makes strip signal smaller
→ **Test longer strip sensor** to check if the crosstalk effect is saturated

<u>Todo</u>
- Timing resolution
- radiation tolerance

11/26/2022 Vertex2022 18

Writing Proceedings for these results and will submit to JPS proceeding

11:50 AM **[F08] Development of AC-LGAD detector with finer pitch electrodes for high energy physics experiment** 15m

Low-Gain Avalanche Diode (LGAD) sensor is one of candidate sensors for tracker at future hadron collider. To use this sensor as tracking detector, AC-LGAD sensor was developed which has both timing and spatial resolution. In high luminosity environment, a 30ps of timing resolution and O(10um) spatial resolution helps to reduce pileup effect and reconstruct tracks precisely. By optimization fabrication parameters, 80um pitch strip and 100um pitch pixel sensors are successfully produced. In this talk, I will present the performance of fine electrode pitch sensors such as pulse height, crosstalk size, timing resolution, inter electrode capacitance and radiation hardness evaluated using a beta-ray source and in 800MeV electron testbeam.

Speaker: Sayuka Kita (University of Tsukuba(JP))

Vertex2022_kita.pdf

What's next? : 3 key development

Timing resolution of pixel and strip detector

- Improvement
- measurement
  - MCP-PMT
  - Infra Red Laser

Radiation tolerance

- Improvement

Large size prototype
Gain Uniformity

- EIC prototype
- HGTD prototype

Fermilab testbeam

New Application to Collider detector

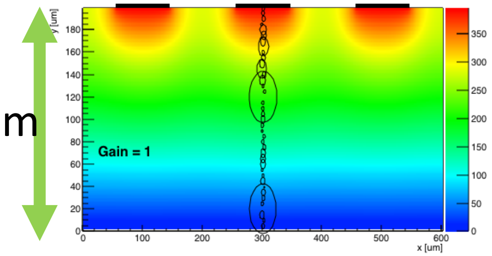
What's next? : 3 key development

Timing resolution of pixel and strip detector

Improvement

Non-Uniform charge deposition

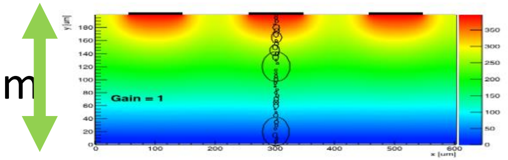
50um



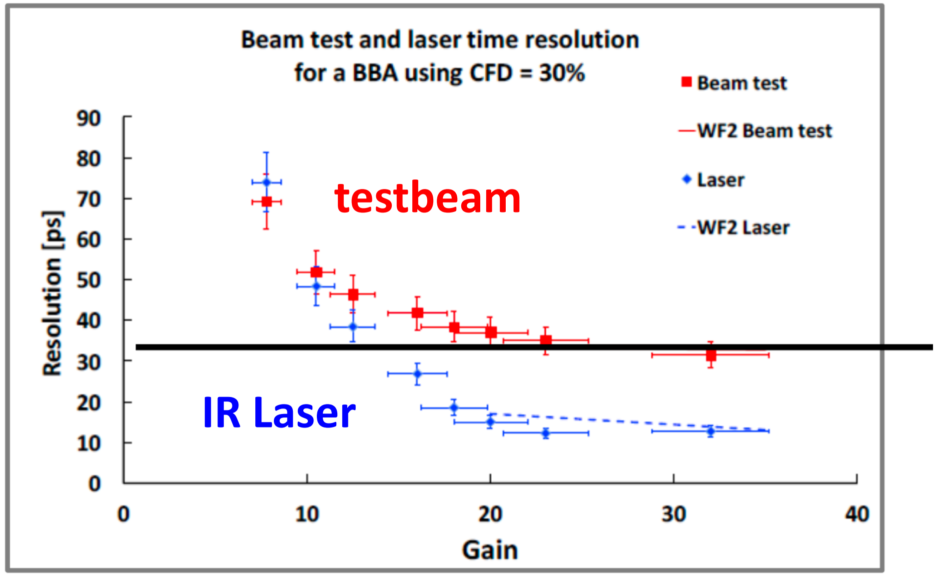
$$I_{ind} = \sum_i q_i \vec{v}_{drift,i} \cdot \vec{E}_{w,i}$$

Introduces landau fluctuation of induced charge

20um



Thinner active thickness will help to reduce the effect



30um and 20um active thick sensor have been received this month.

→ Results will come soon

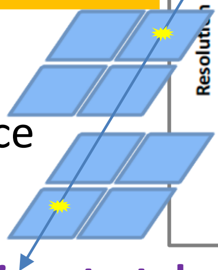
What's next? : 3 key develo

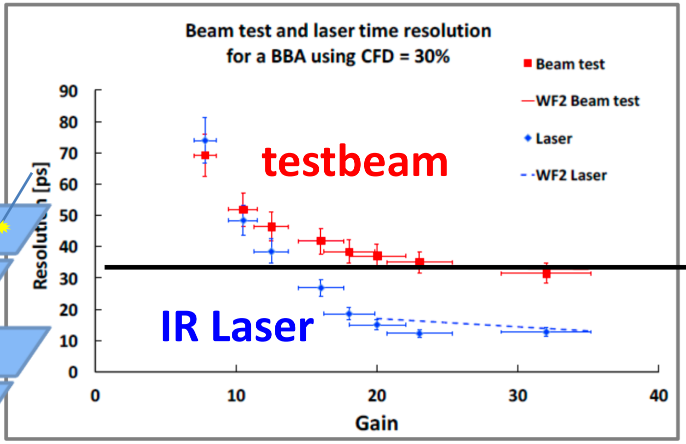
Timing resolution of pixel and strip detector

Previously…

2 layer coincidence

$\rightarrow\ \sigma_t = \sigma_{\Delta t}/\sqrt{2}$

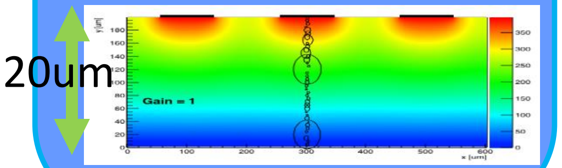




Takes very long time to take data for small electrode

Improvement

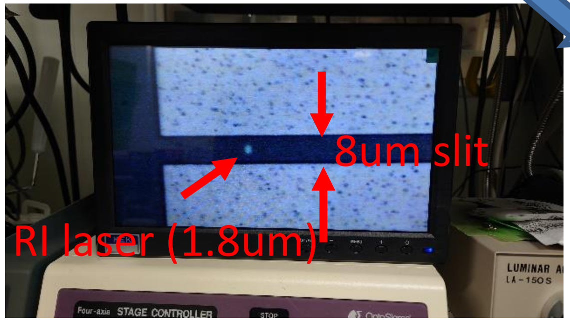
New prototype wafer to reduce Landau noise



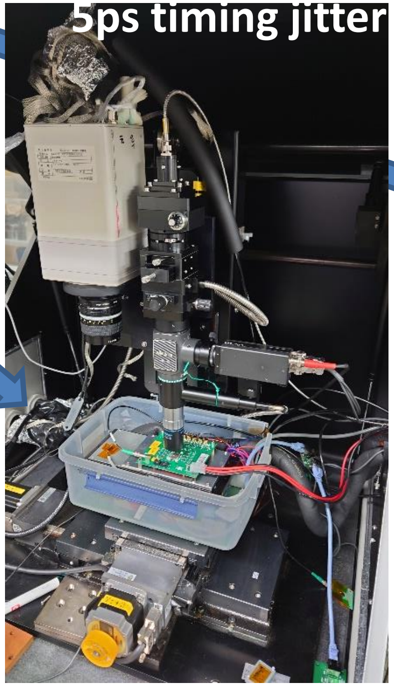
measurement

MCP-PMT

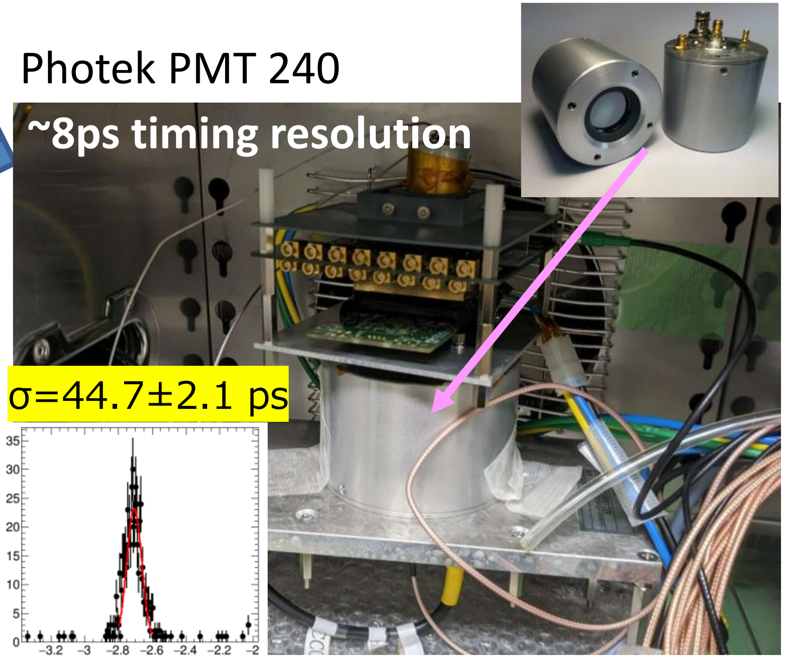
Infra Red Laser



RI laser (pico second)



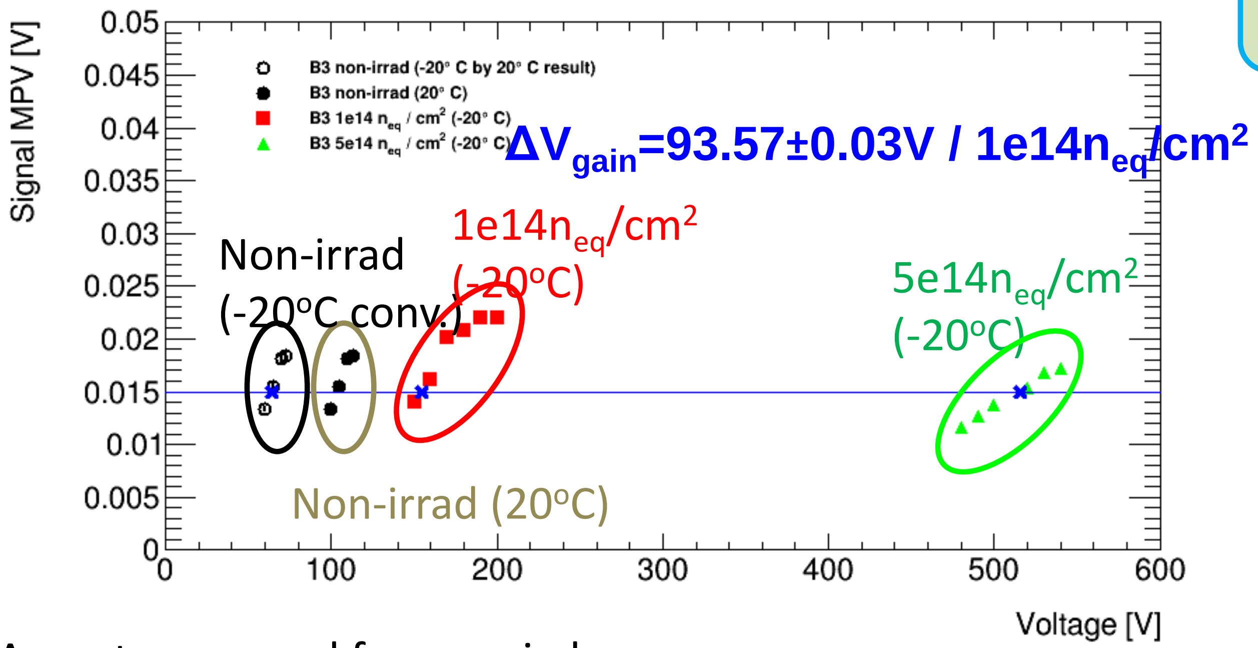
Photek PMT 240



What's next?　: 3 key development

Radiation torerance for the current sensor is not optimal.

➔ Survive only upto <1e15n_{eq}/cm^2



Radiation tolerance

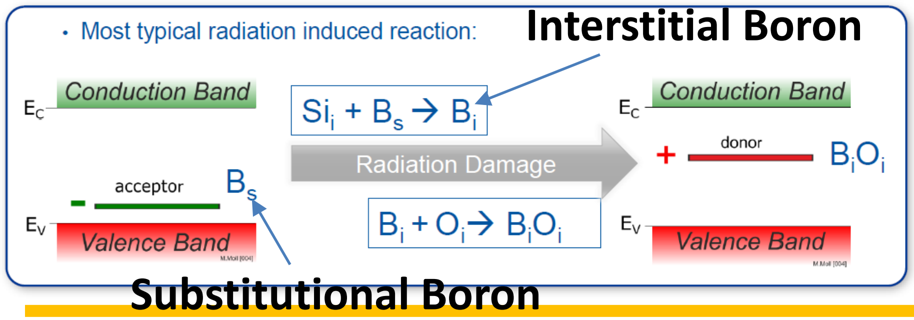
Large size prototype
Gain Uniformity

Improvement

EIC prototype

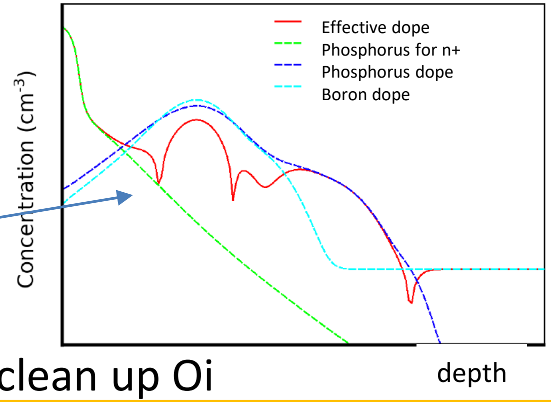
HGTD prototype

Accepter removal for p+ gain layer



Waiting New Samples

1. Carbon annealing
   - $B_i + C_s \rightarrow B_iC_s{}^* \rightarrow B_s + C_i$
2. Compensation method
   - Add Boron + Phosphorus
3. In-active Boron?
   - 10 times Bi at the beginning to clean up Oi

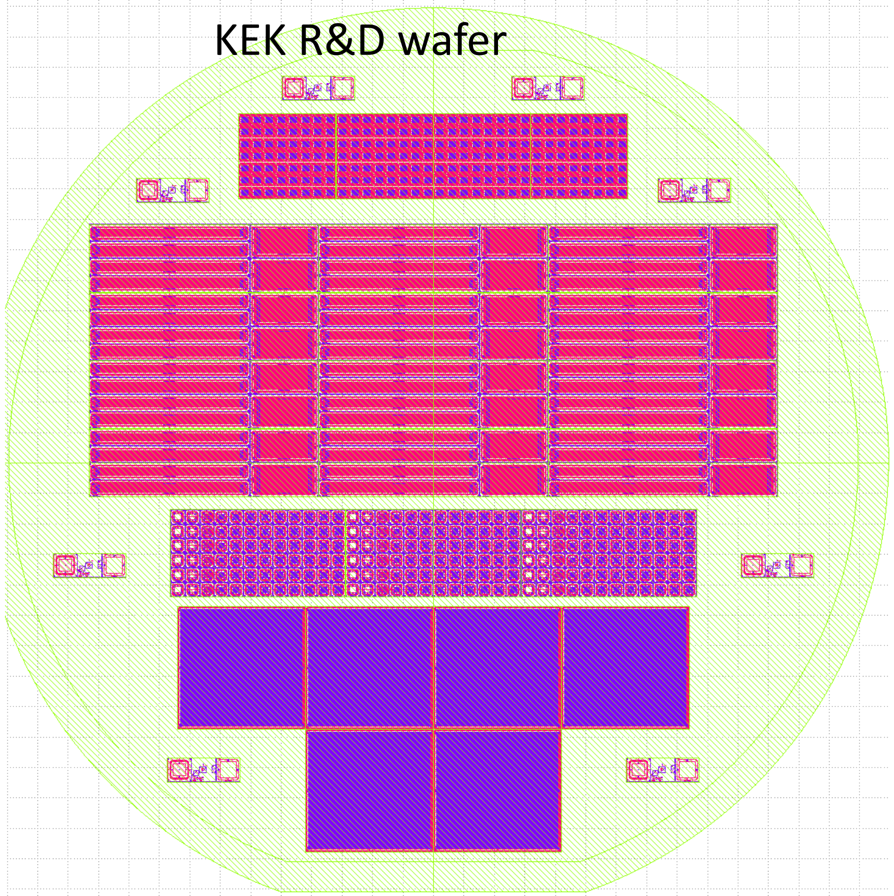


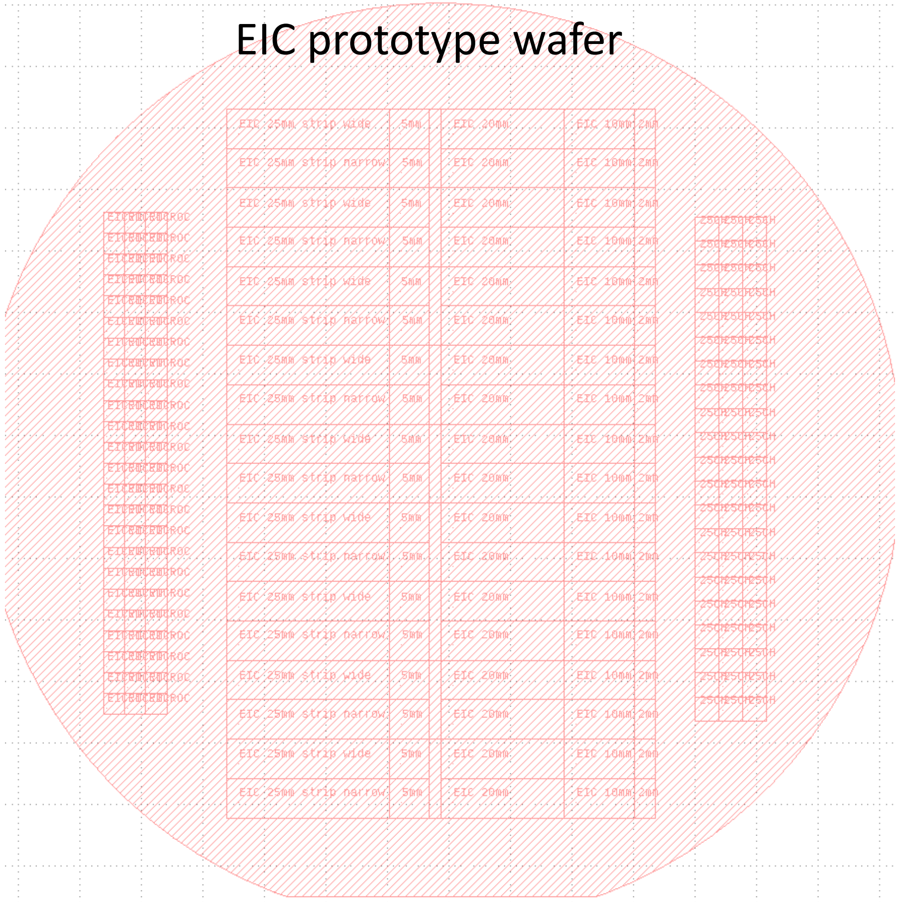
What's next? : 3 key development

JFY 2022 sample

Implemented 20mm x 20mm pixel sensor (compatible to ATLAS ITk chip)

KEK R&D : smaller electrodes, EIC prototype : all 500um pitch strip and pad





Could be a candidate of ATLAS HGTD replacement?

Large size prototype
Gain Uniformity

EIC prototype

HGTD prototype

New Application to Collider detector

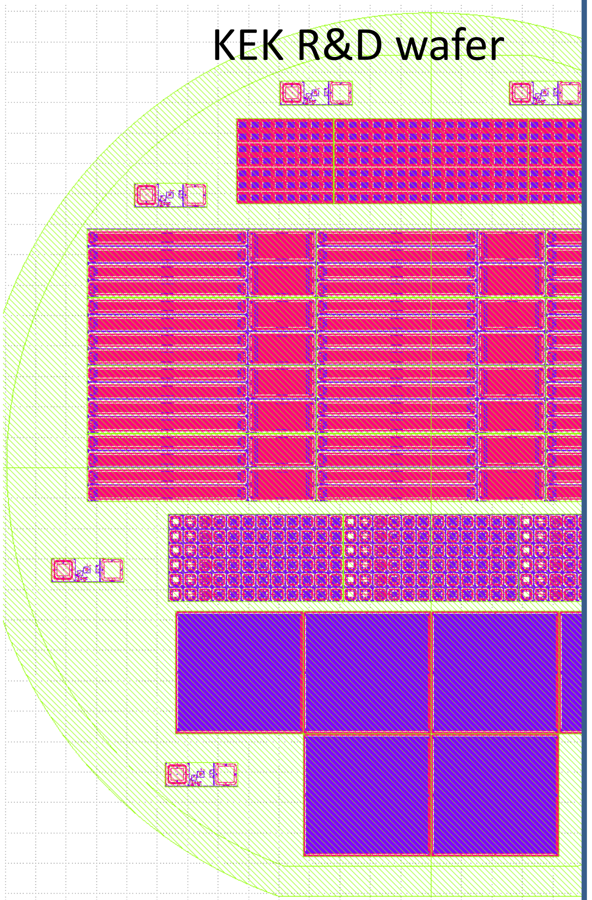
What’s next?　: 3 key development

JFY 2022 sample

Implemented 20mm x 20r

KEK R&D : smaller electro

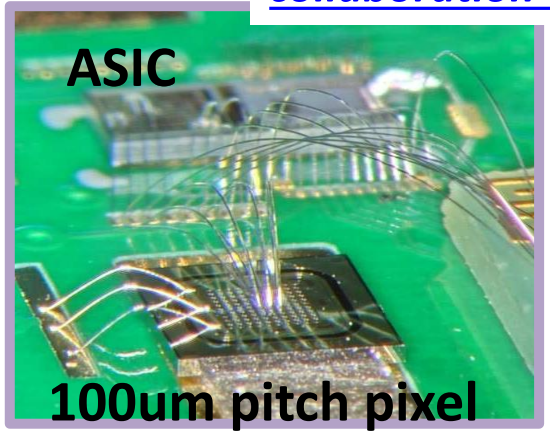
KEK R&D wafer



Could be a candidate of ATLAS

Certainly… need fast and multi-channel readout ASIC

Fulvio Martinelli et. al. Si-Ge Bi-CMOS ASIC
collaboration with University of Geneva



10x10 channels (100um pitch)
with 3 analog + 1 discri. output

e size prototype
in Uniformity

C prototype

TD prototype

Application to
llider detector

What's next?　: 3 key development

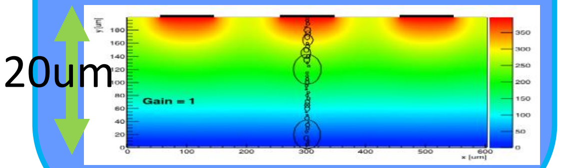
Timing resolution of pixel and strip detector

Radiation tolerance

Large size prototype
Gain Uniformity

Improvement

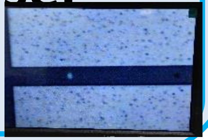
New prototype wafer
to reduce Landau noise



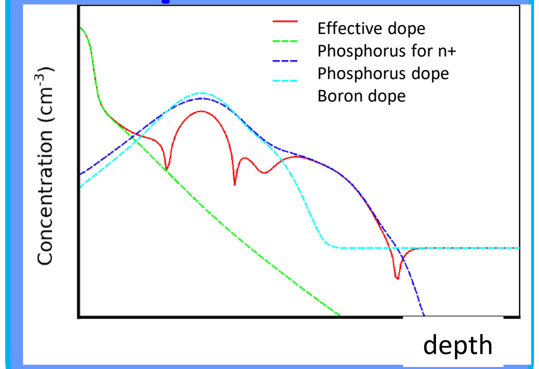
measurement

MCP-PMT
8ps timing resolution

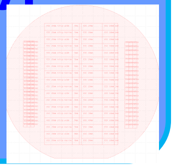
Infra Red Laser
5ps timing jitter
1.8um focus size



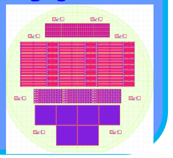
Improvement



EIC prototype
3cm length
500um pitch strip



HGTD prototype
2cm x 2cm
100um pitch pixel



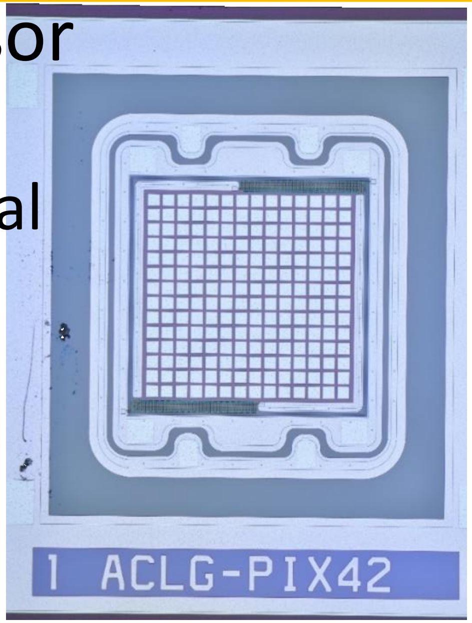
Fermilab testbeam : Feb-March 2023 @ FTBF

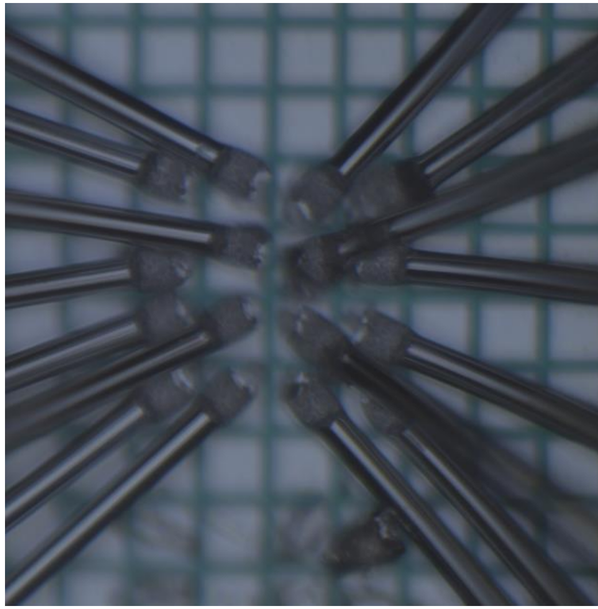
New Application to Collider detector

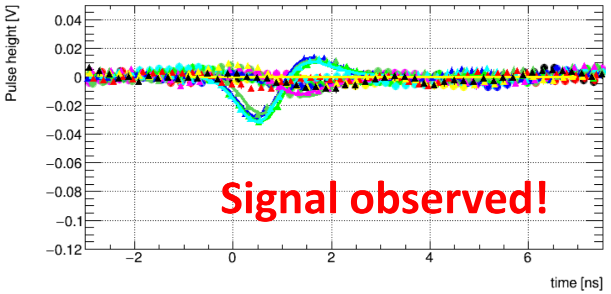
backup

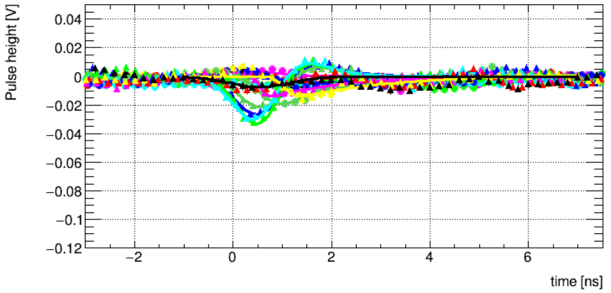
Challenge : Pixel detector

- 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.**

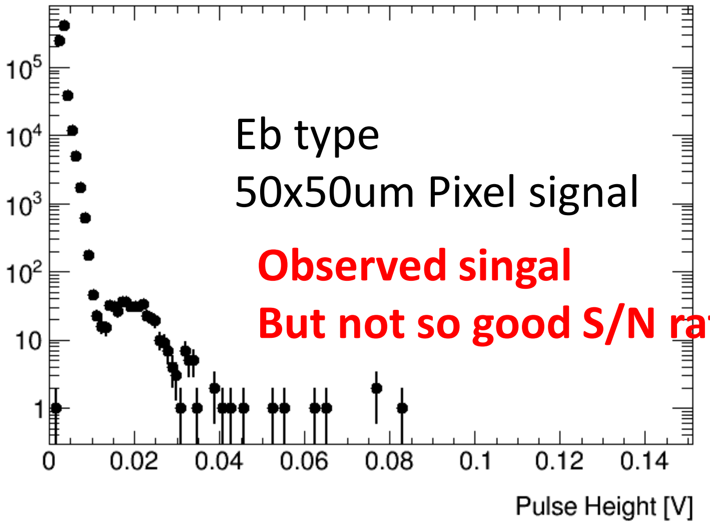


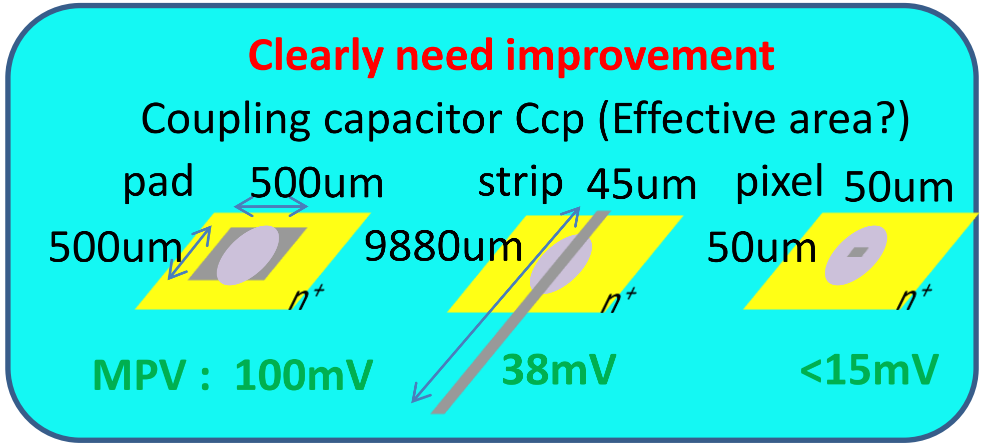






Pulse height distribution

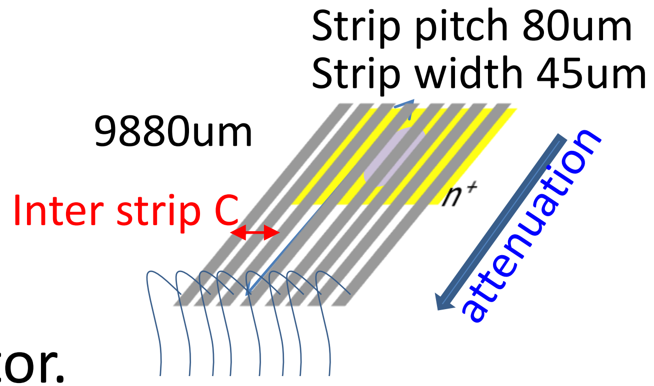




Need high Ccp sensors → JFY2021 sample to be tested

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.

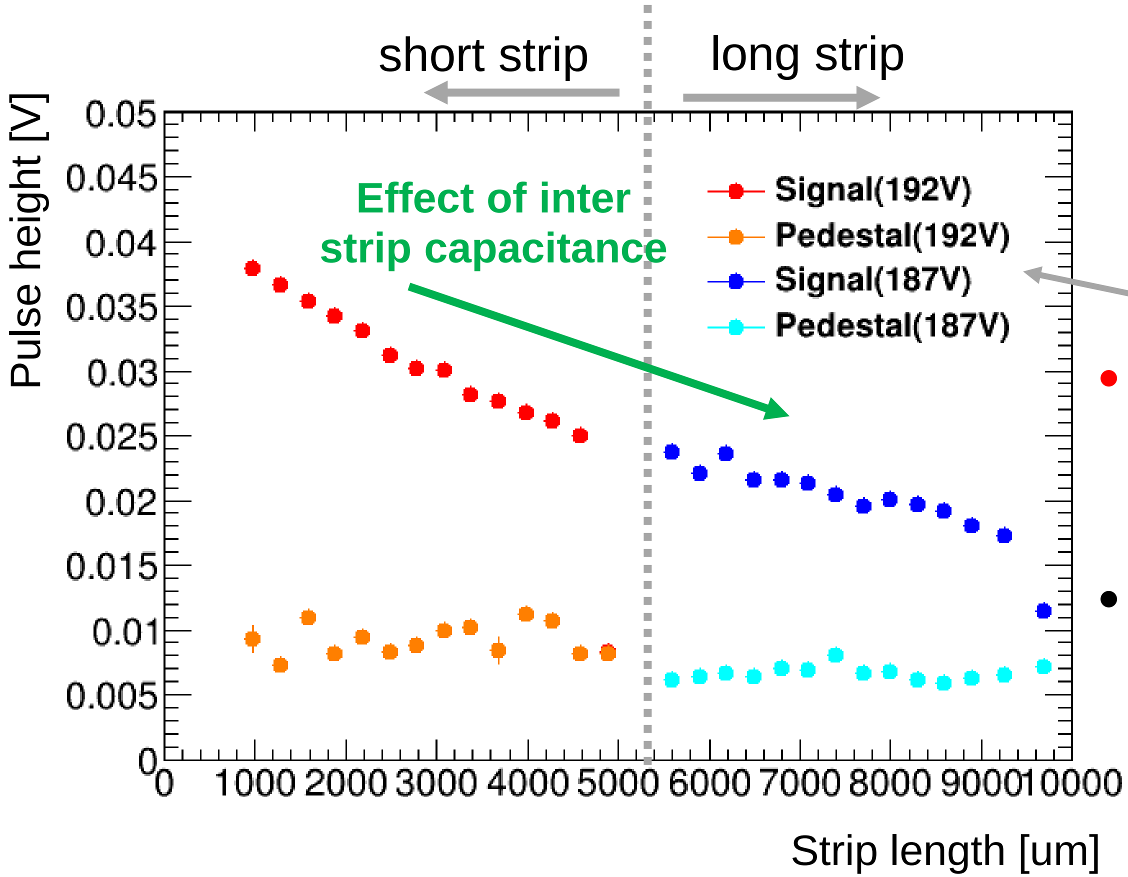


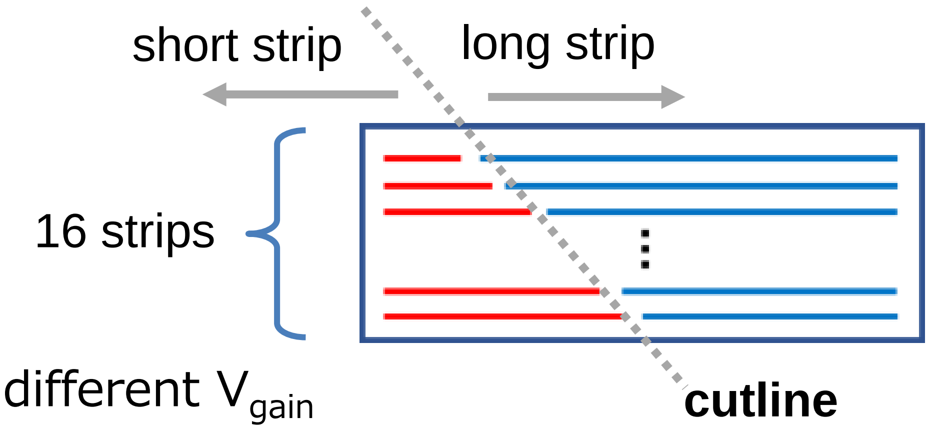
- **Certainly we want to develop pixel type detector.**
  - **First 50um x 50um pixel sensor does not have enough signal size.**
  - **What is the minimum pixel size we can see good S/N signal?**
  - **What is the effective area for electrode capacitance ?**

Preliminary results : Strip type electrode

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

E-600 type of strip sensor with cutline





Due to different V_{gain}

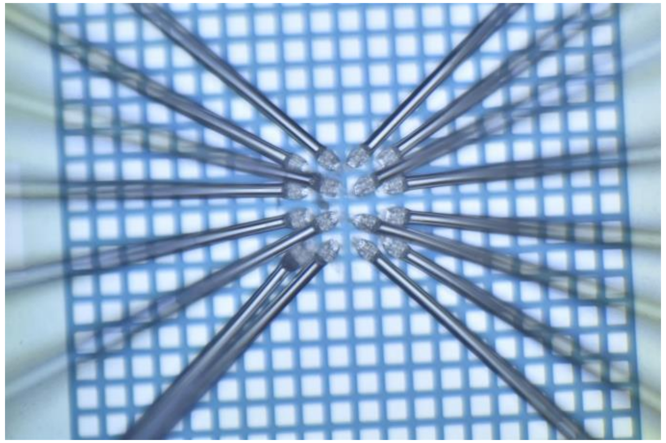
- **Signal reduced by 60% in ~10mm**
  - **Because of inter strip capacitance?**
  - **Because of signal attenuation?**
- We will test smaller gap sample. (the same pitch)
  - Current gap 40um → 20um
  - **Smaller gap have larger inter strip capacitance and smaller attenuation**

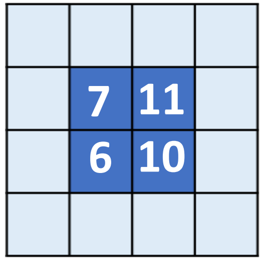
Preliminary results : Pixel type electrode

What is the minimum pixel size we can see good S/N signal?

E-600 type of pixel sensor

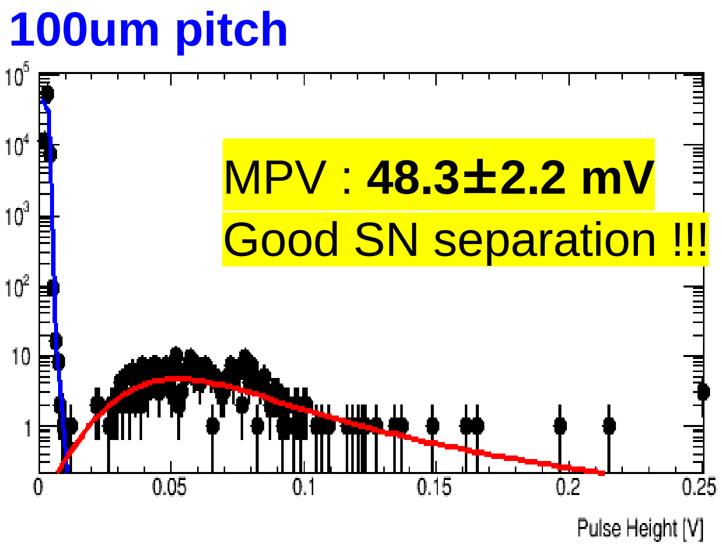
4x4 pixels are wirebonded.



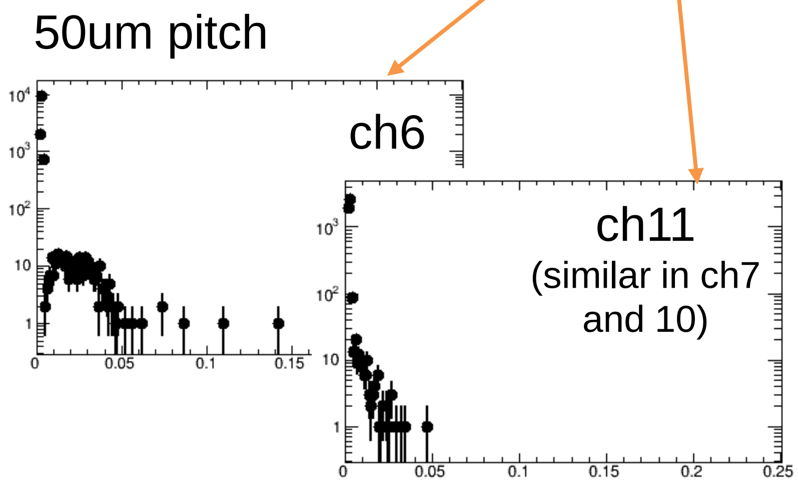


Analysis
Only center 2x2 channels was used.
(To avoid crosstalk effect)

Pulse height distribution



4 electrodes in the middle observed different pulse height MPV for ch6 and the other



Electrode short in ch6 ?

under investigation …

First Pixelated AC-LGAD in the World! (100um x 100um)

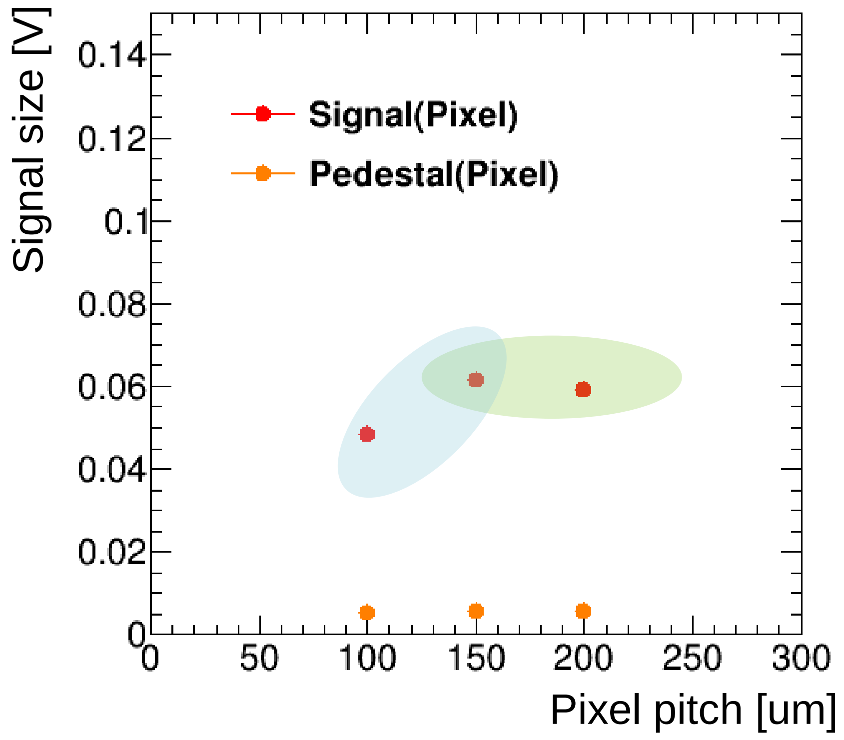
We need to understand the 50um x 50um pixel

Preliminary results : Pixel type electrode

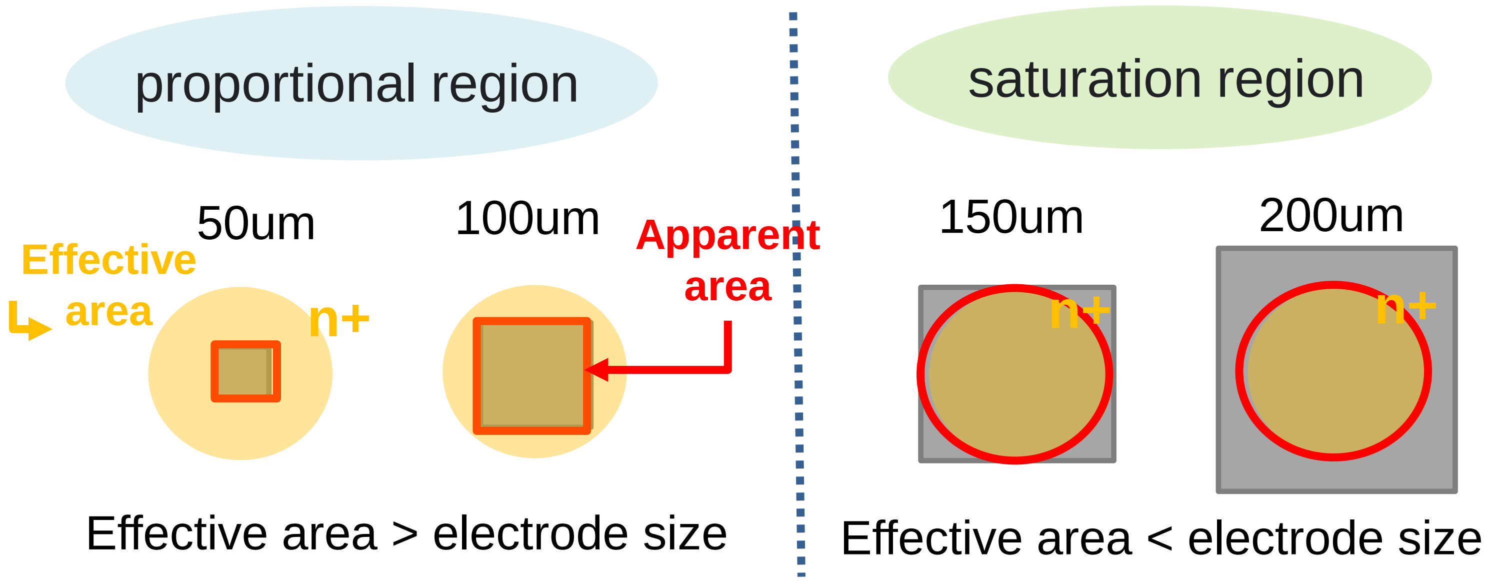
What is the effective area for electrode capacitance ?

E-600 type of pixel sensor

(all suppried 190V)

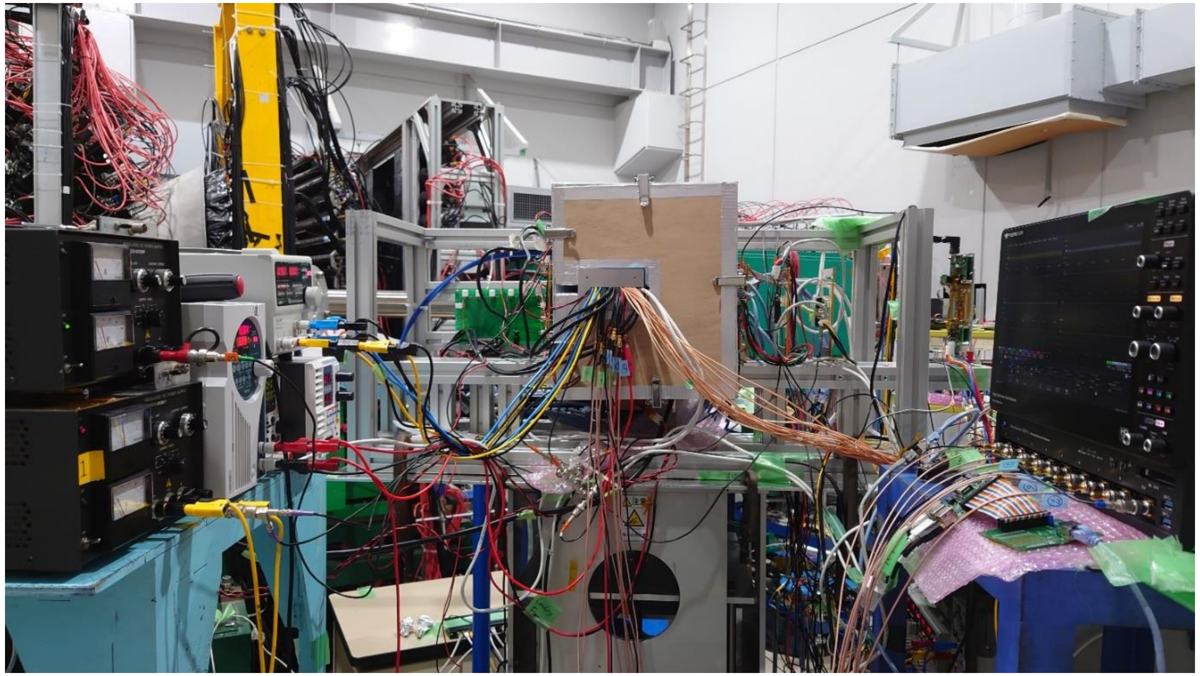


Tested various size of pixel sensor to see the saturation of signal size



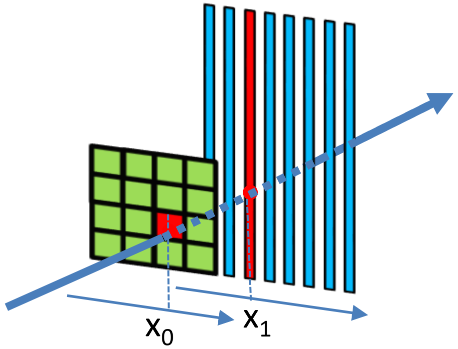
- **Signal seems like saturated at ~150um**
  - It makes sense small signal of 50um x 50um sample
  - **Will test smaller n+ resistivity sample**
    - Expected larger effective area.

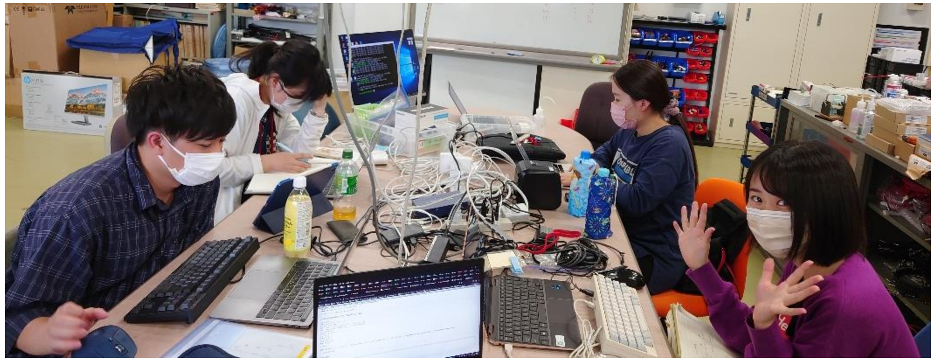
Snap shot from on-going ELPH testbeam



- 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

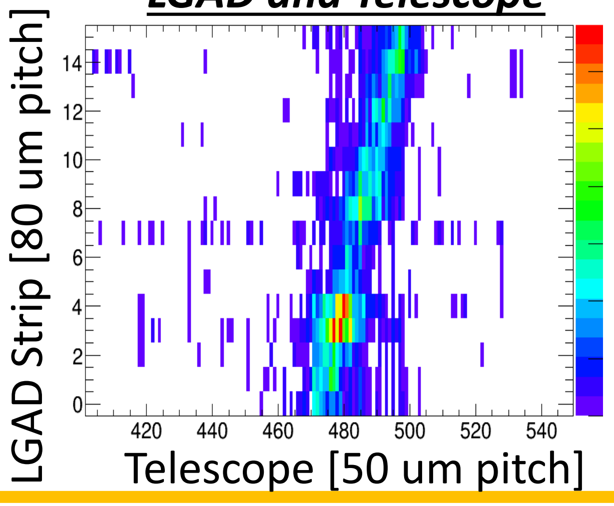
    →First LGAD tracker!!



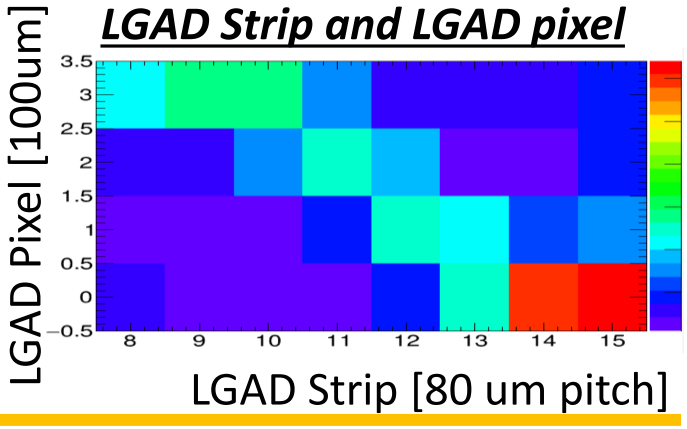


Correlation of x position of two planes

LGAD and Telescope



LGAD Strip and LGAD pixel



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?
attenuation in strip?
→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 $1.0\times10^{15} n_{eq}/cm^2$

backup

Next generation of Collider experiment

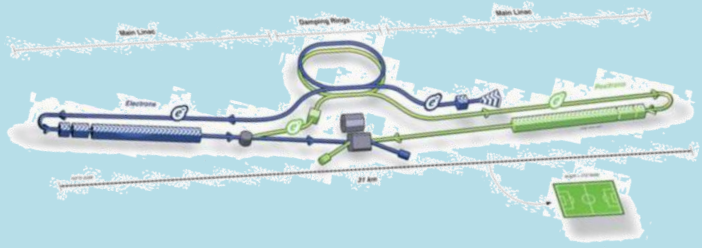
- Need "Higher Luminosity" and/or "Higher Energy"
  - *High Luminosity LHC (HL-LHC)*
    - 20 times more data (~3000-4000fb^{-1}) at **14TeV**
    - Plan : Start at 2029
  - *High Energy LHC (HE-LHC)*
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **28TeV** collider in the same tunnel as LHC.
  - *Future Circular Collider (FCC-hh)*
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **100TeV** collider with 100km tunnel at CERN.
  - *International Linear Collider (ILC)*
    - 250GeV e+ e- collider in Japan

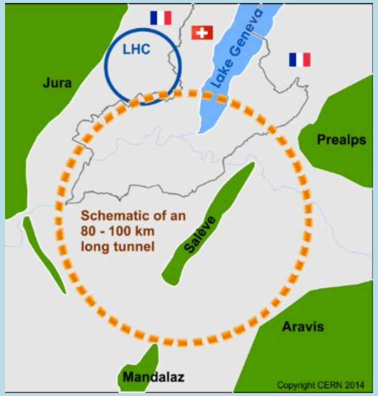
Coming soon

Discussion Started

Discussion Started

Final decision soon

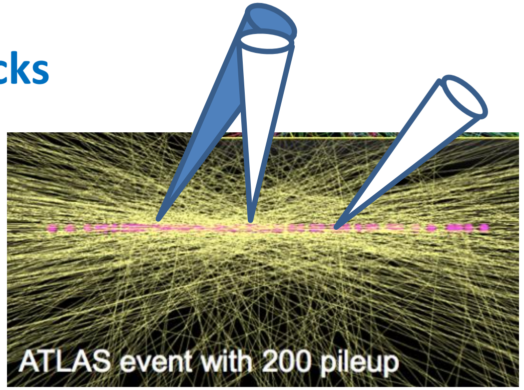




Inner Tracking system

Very high density tracks

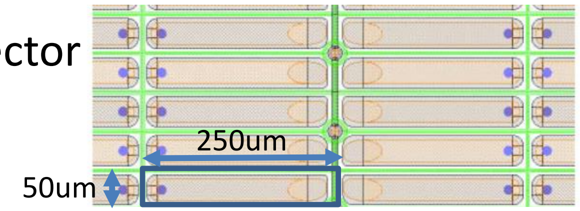
140 pileup @ HL-LHC
1500 pileup @ FCC-hh



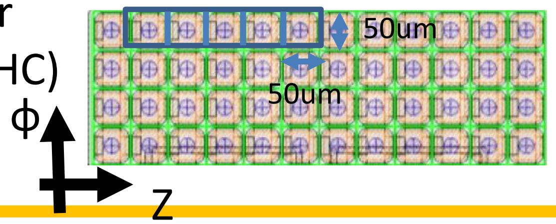
Only way to solve this so far…

finer pixel pitch

Current detector (ATLAS IBL)

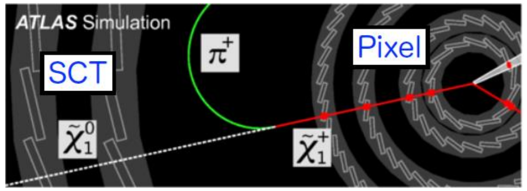


New detector (Pixel @HL-LHC)



Physics impact of timing detector

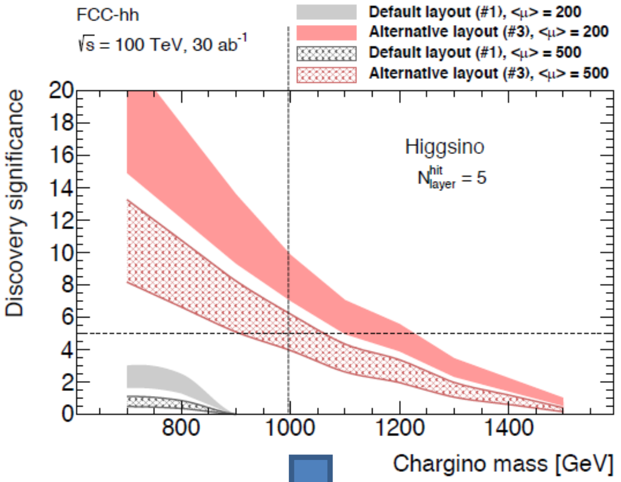
Higgsino production by using disappearing track



LSP: higgsino

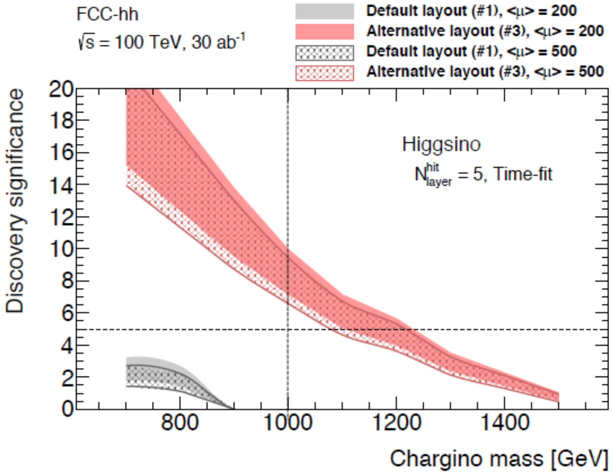
$\Delta m(\tilde{\chi}^{\pm}, \tilde{\chi}^{0})$~300MeV

$\tau_{\tilde{\chi}^{\pm}}$~0.04ns (cτ~12mm)

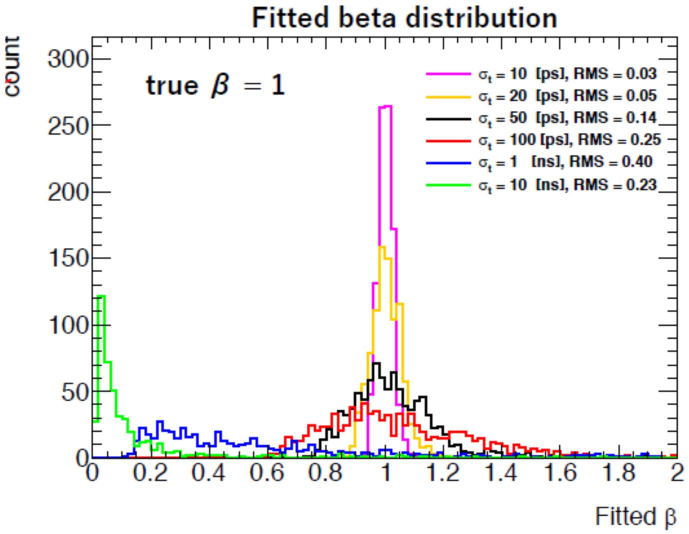


Used timing information only for pileup removal

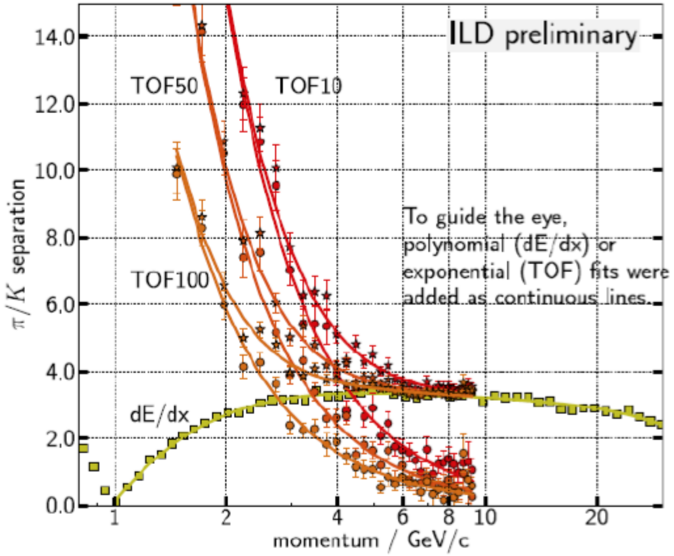
50ps timing information



β measurement in FCC detector



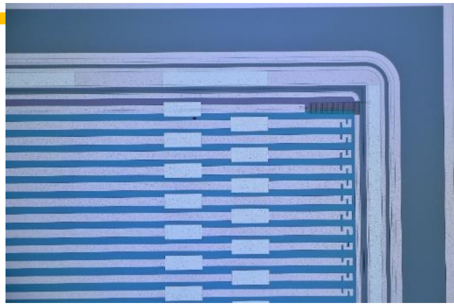
ILC K/π separation



- See more information in timing detector workshop in 2018:

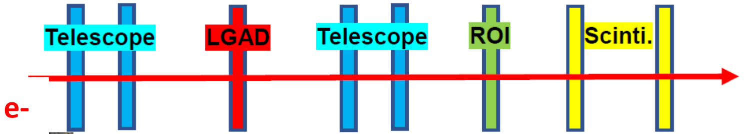
https://indico.cern.ch/event/747424/timetable/#20181208

Spatial resolution measurement at ELPH TB



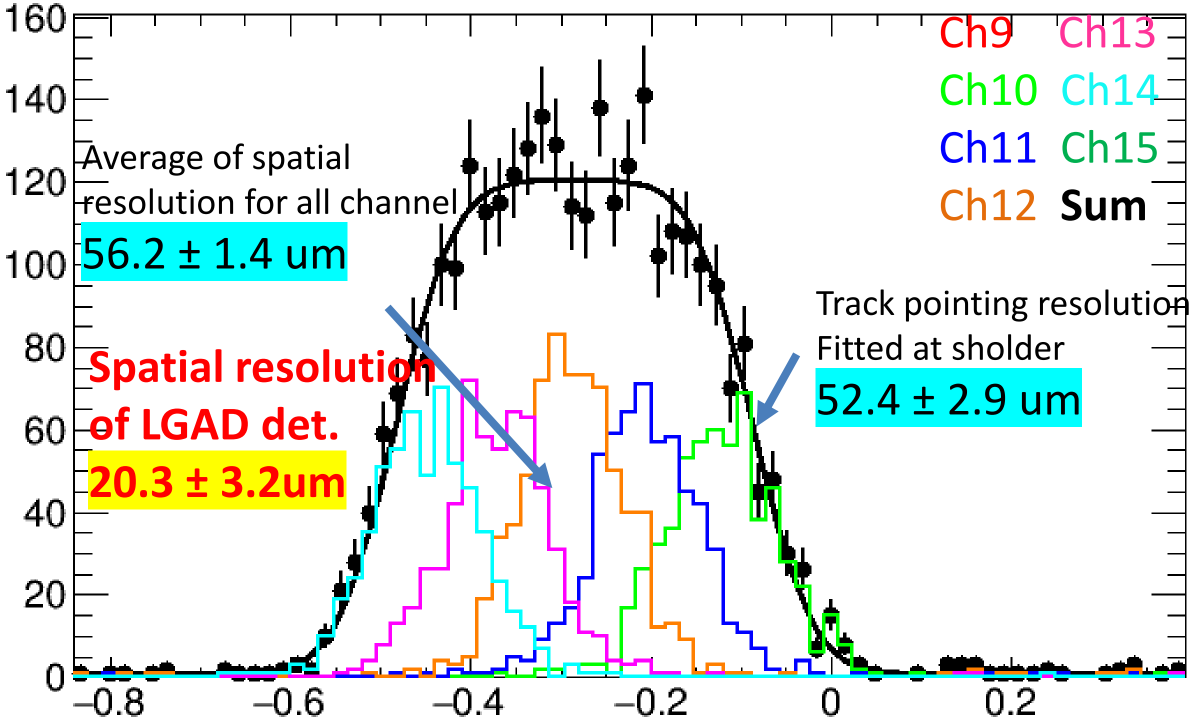
- In principle, no dead area and small crosstalk
  - At least 23um($80um/\sqrt{12}$) resolution by binary readout
- ELPH testbeam at Tohoku Univ. (8-9 July 2021)
  - 800MeV electron beam
  - Trigger rate 200-400Hz
  - Strip E-b type 170V @ 20°C

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.

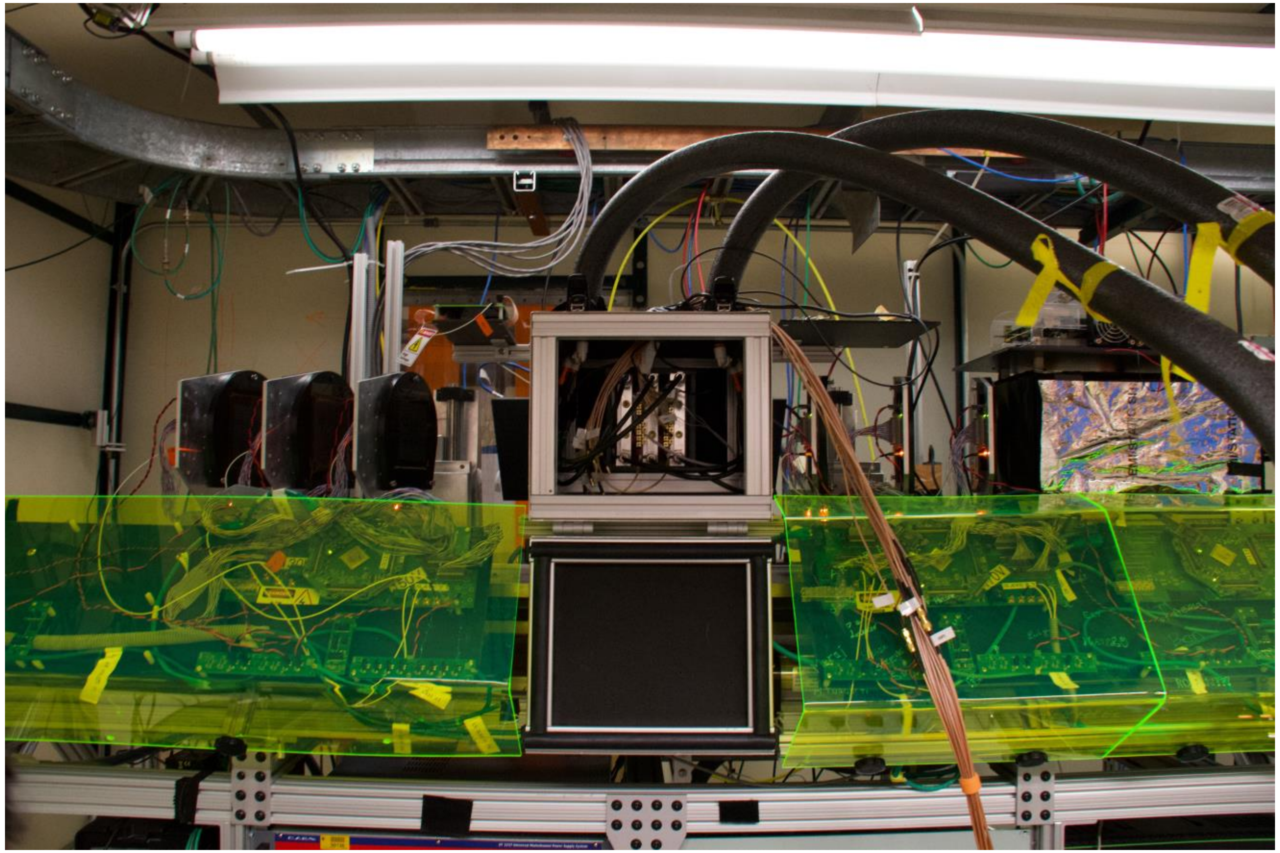


Timing resolution for AC-LGAD detector

Fermilab Test Beam Facility (FTBF)

120GeV proton beam

Strip Detector based Telescope : ~15um pointing resolution



Timing reference Detector

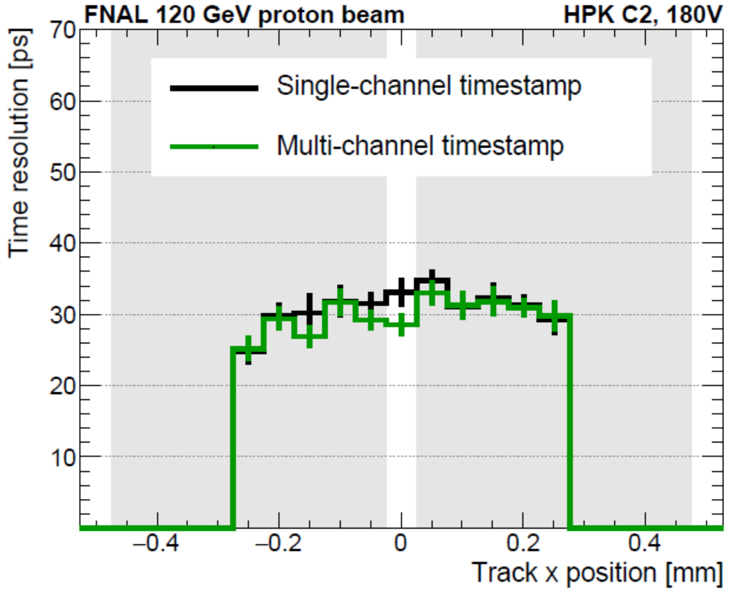
PHOTEK MCP photomultipliers (PMT140)

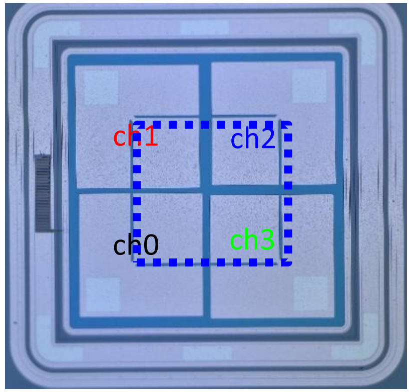
450ps FWHM with 5e3 Gain

~5ps timing resolution

(SPEC: Multi-photon jitter below 10 ps)

Position dependent Timing resolution





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