



LGAD R&D

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Fermilab



筑波大学

University of Tsukuba



KEK



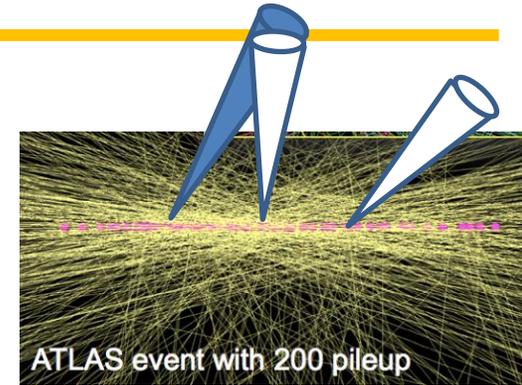
UNIVERSITY OF CALIFORNIA

SANTA CRUZ

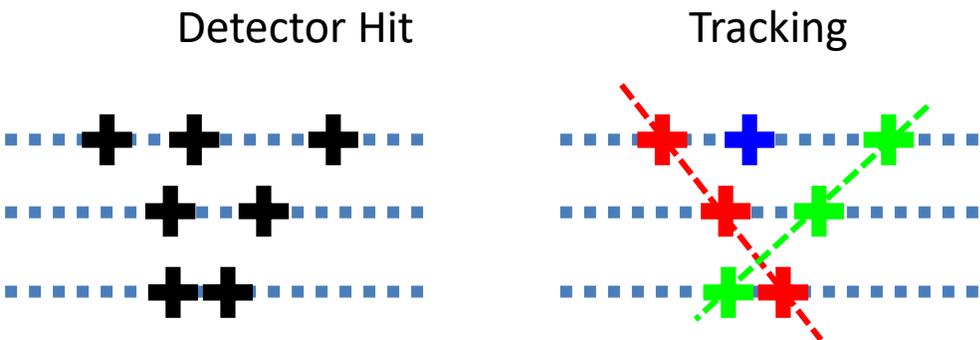


Tracking detector with timing resolution

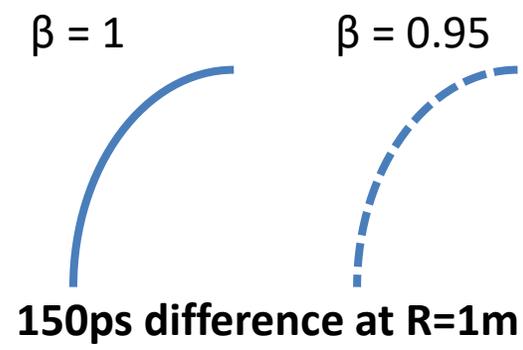
- Collider experiment gets high energy and high intensity.
 - Solving pileup issue is required for tracking, **Timing resolution helps!**
 - **Future Tracking detector should have timing information for all hits!**
- Tentative Requirement
 - **30ps timing resolution**
 - **~o(10)um spatial resolution (Pixel type).**
 - (hadron collider) **~o(10¹⁶)n_{eq}/cm² radiation tolerance**



4D tracking !

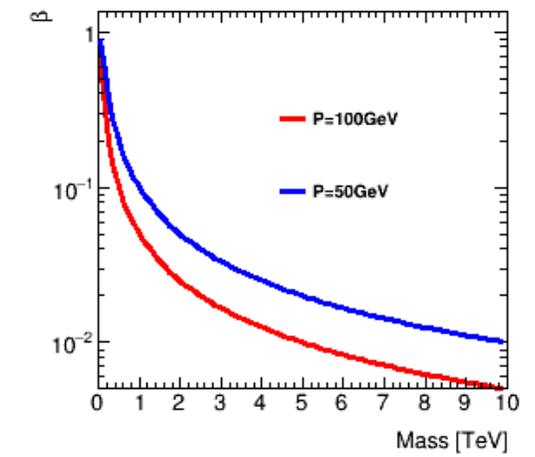


Particle identification



K+ π^+ separation

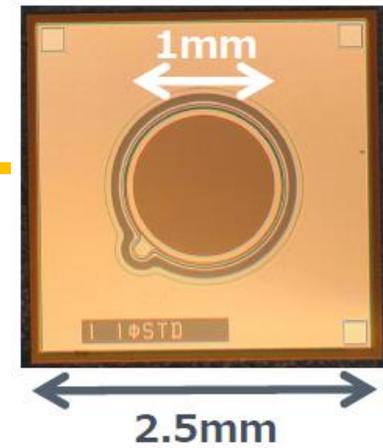
Mass spectrum for new particle



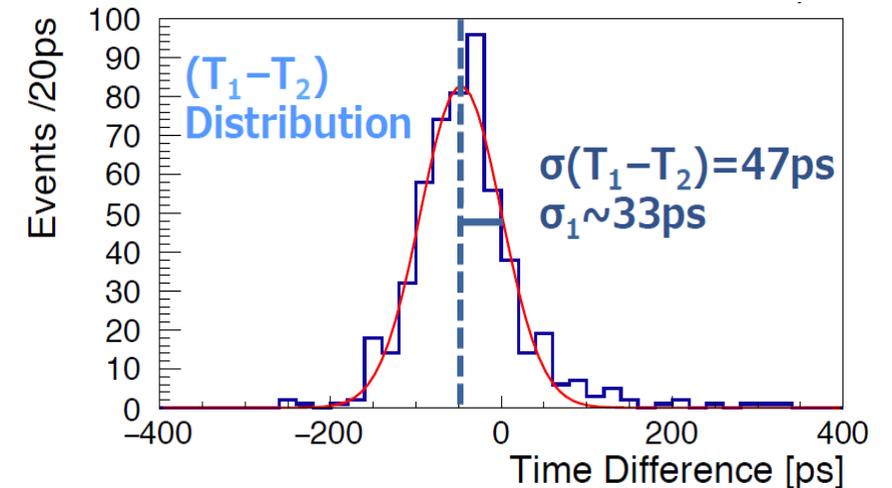
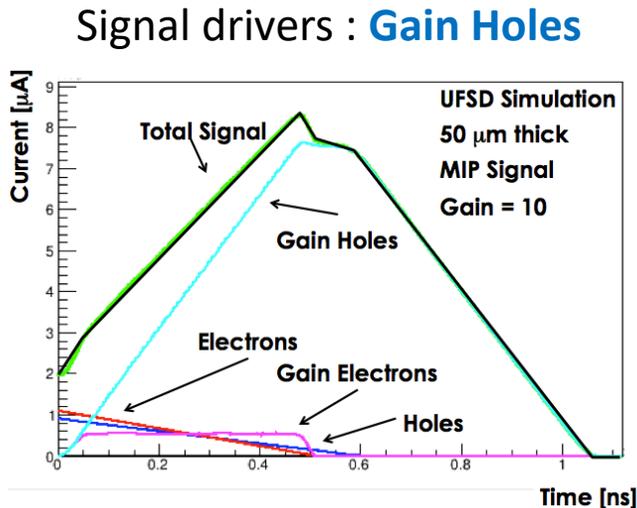
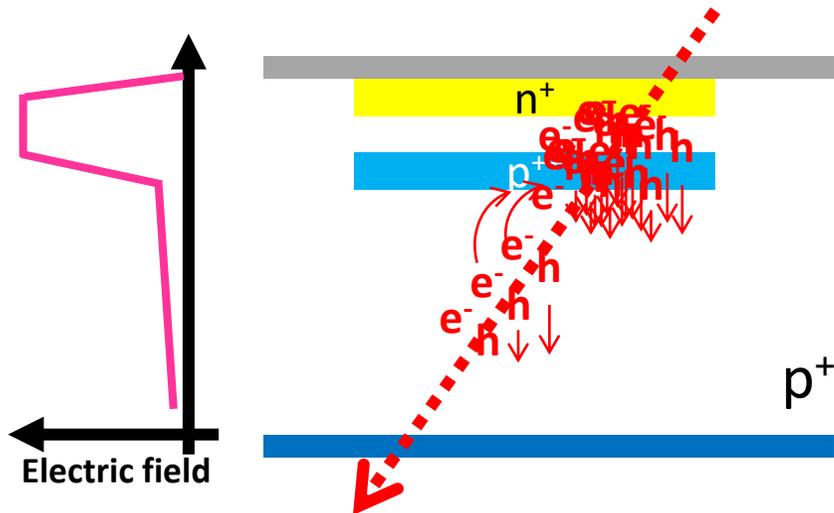
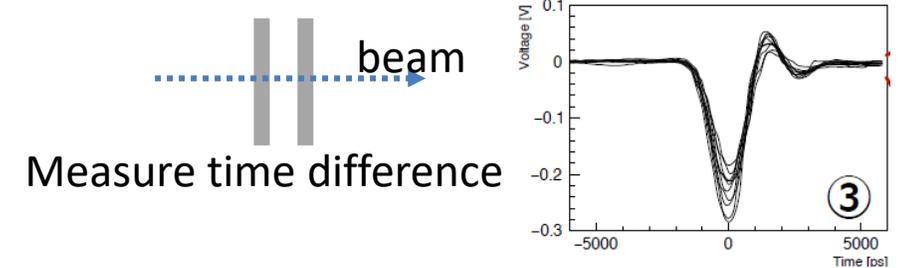
β measurement to obtain mass

e.g. Mass measurement for Long lived chargino

Low gain Avalanche Diode (LGAD)



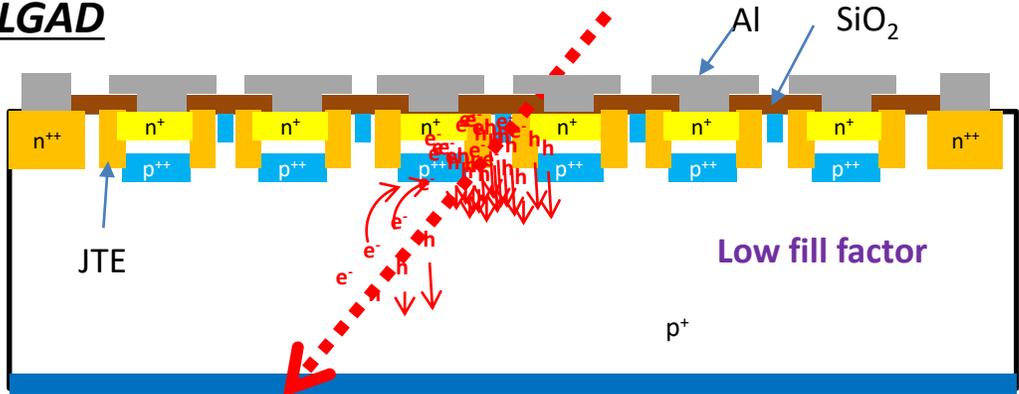
- Low gain Avalanche Diode (LGAD)
 - General n^+ -in- p type sensor with p^+ gain layer under n^+ implant to make higher Electric Field \rightarrow Good timing resolution.
 - **30ps timing resolution achieved already in 2015.**
 - Next development
 - **Finer electrode separation for spatial resolution**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



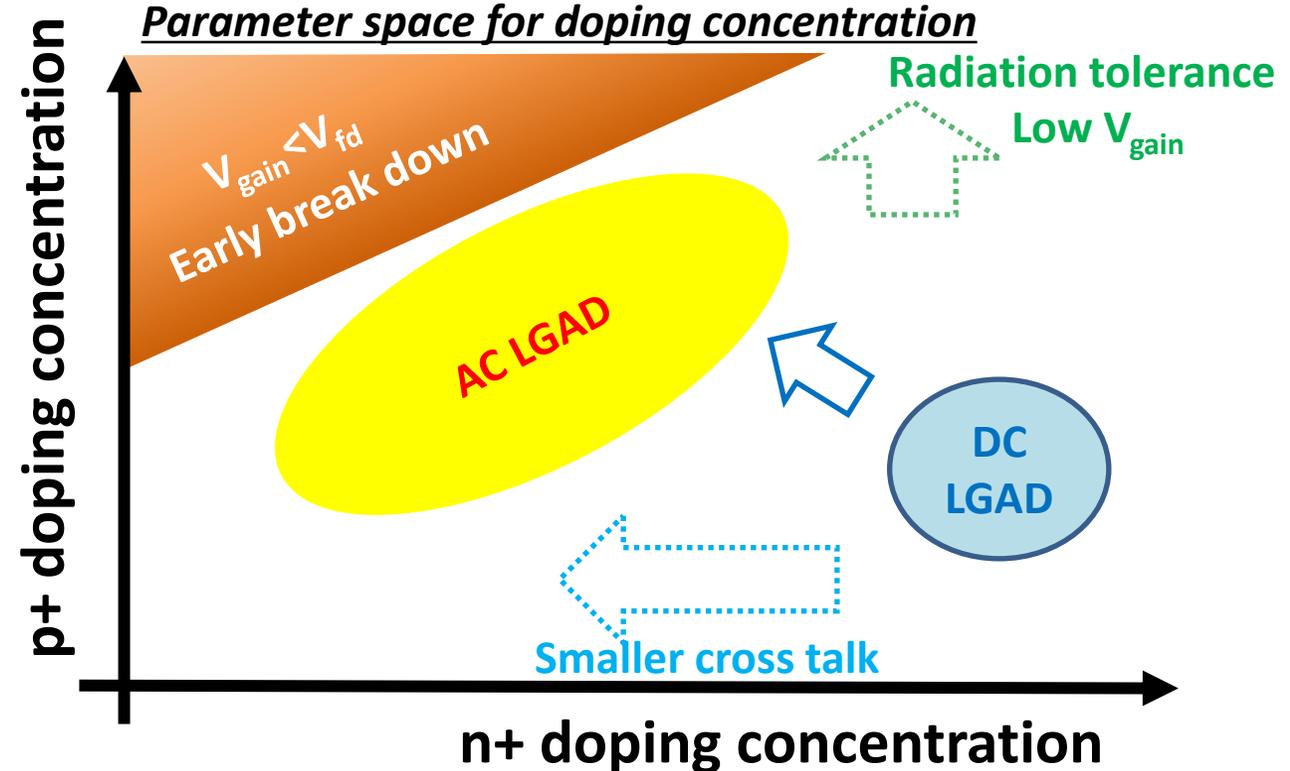
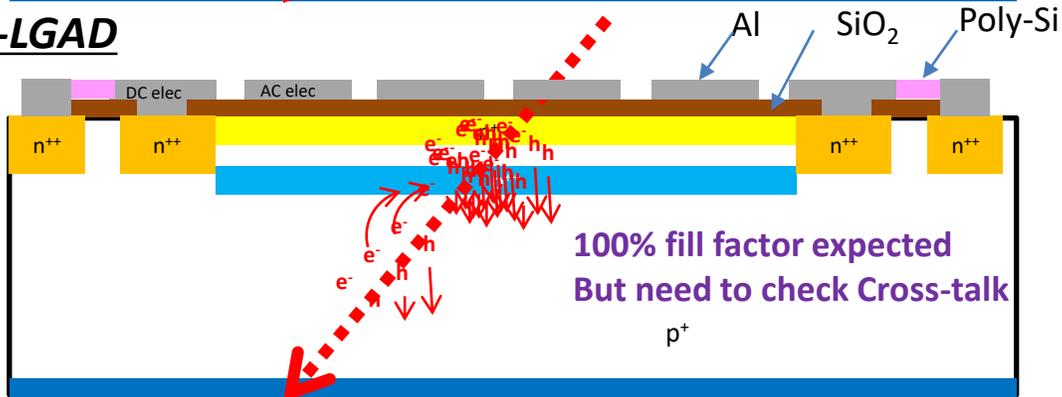
AC-LGAD detector

- 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.**

DC-LGAD

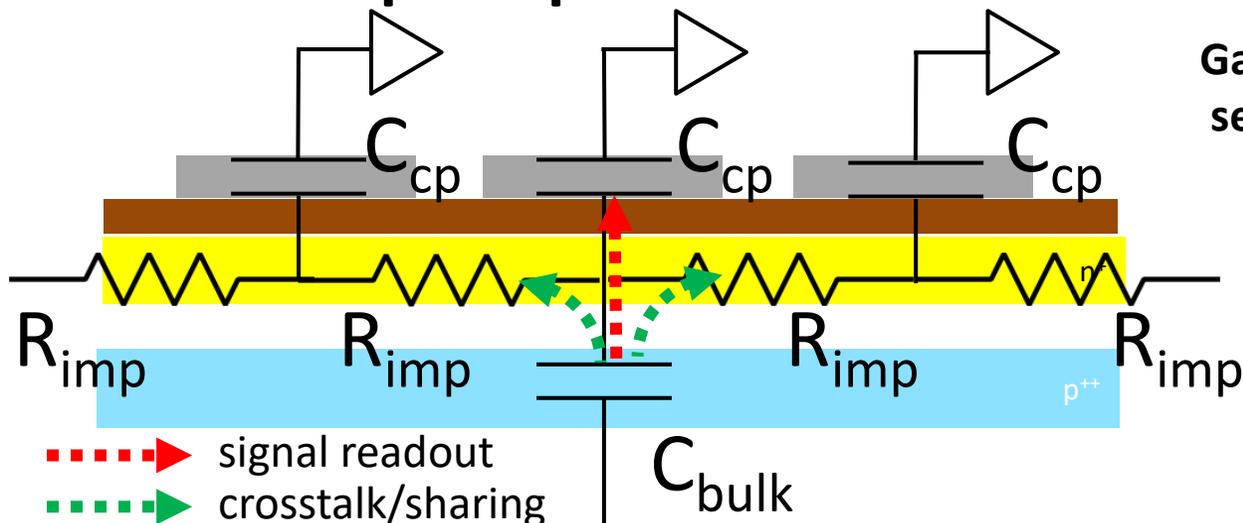


AC-LGAD



AC-LGAD detector

Read out principle of AC-LGAD

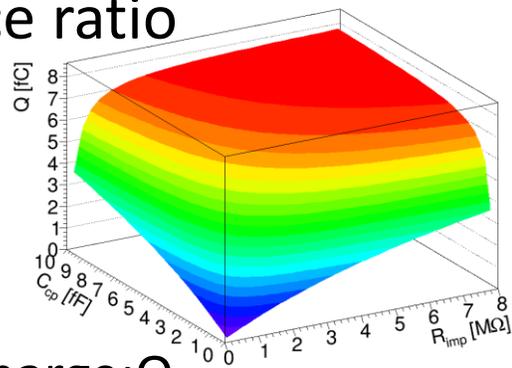


Charge split : Impedance ratio

Assuming $Z_{C_{bulk}} \gg Z_{C_{cp}}$...

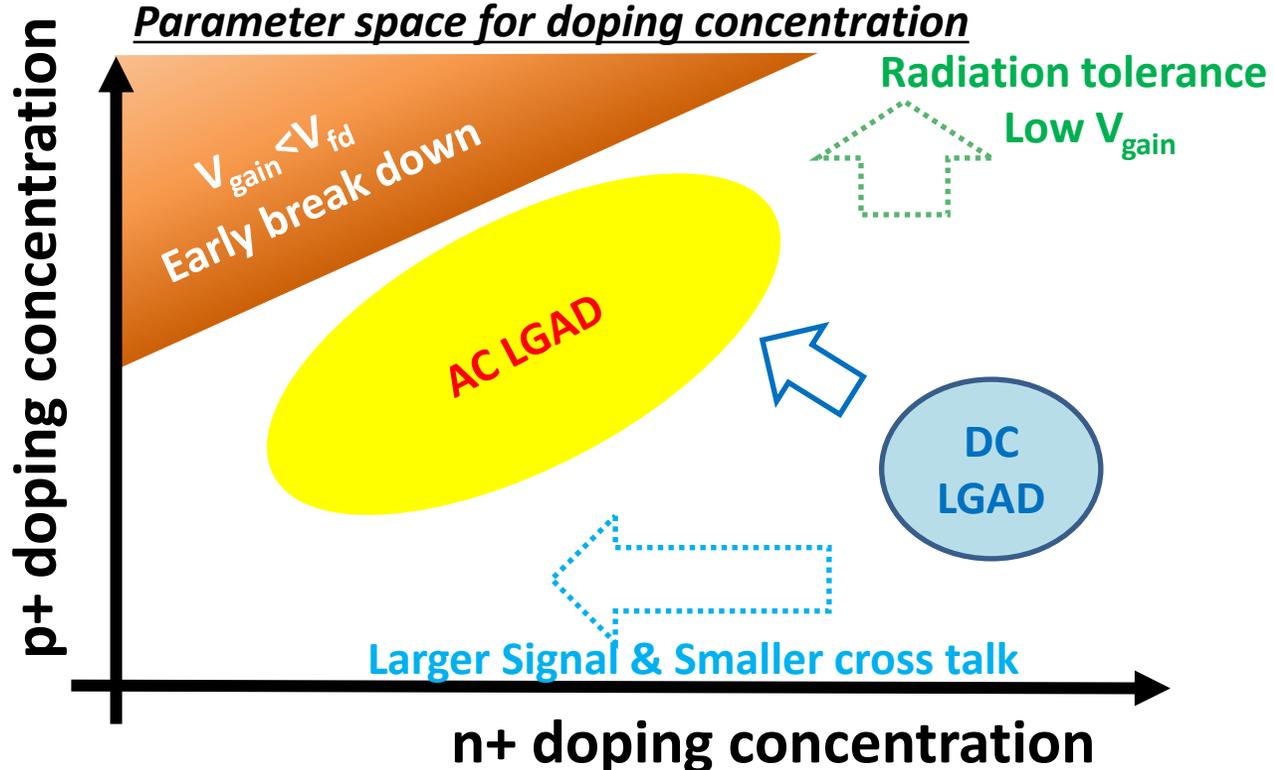
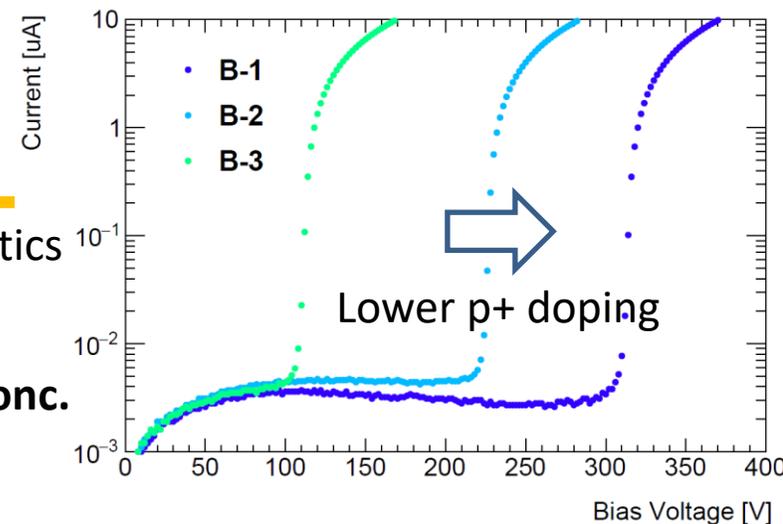
$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

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



I-V characteristics

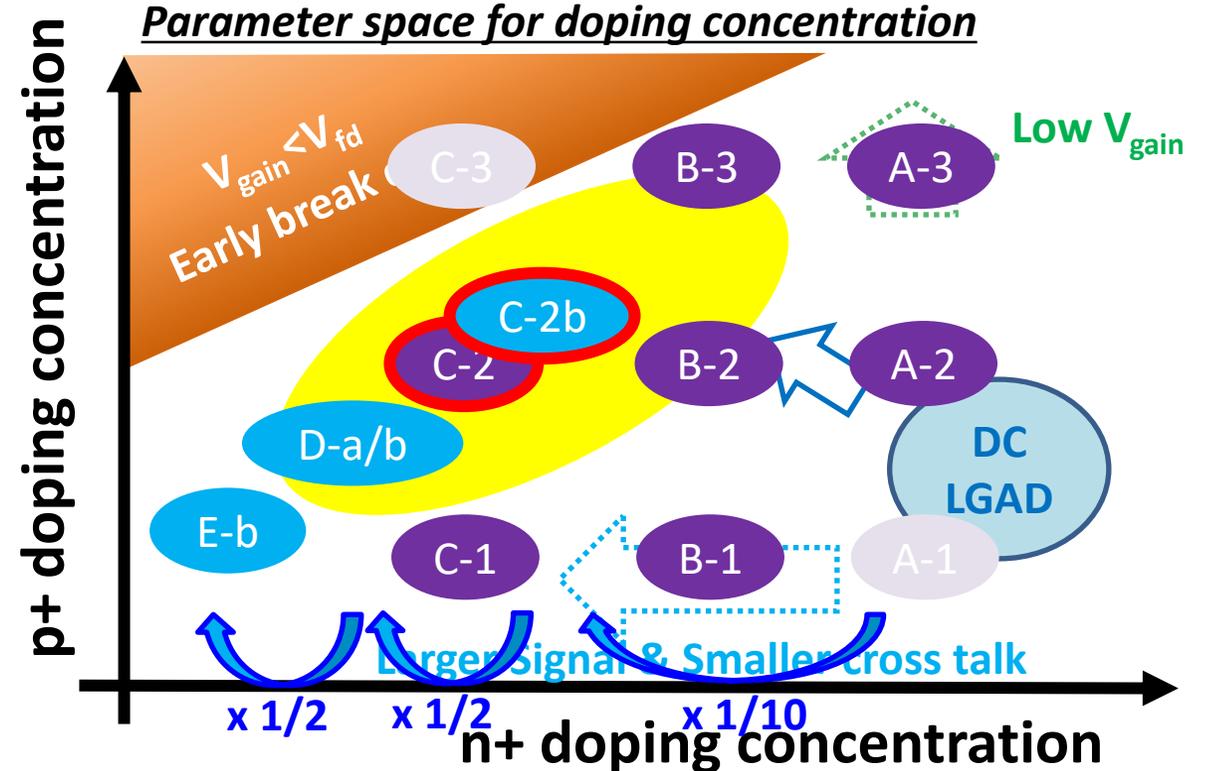
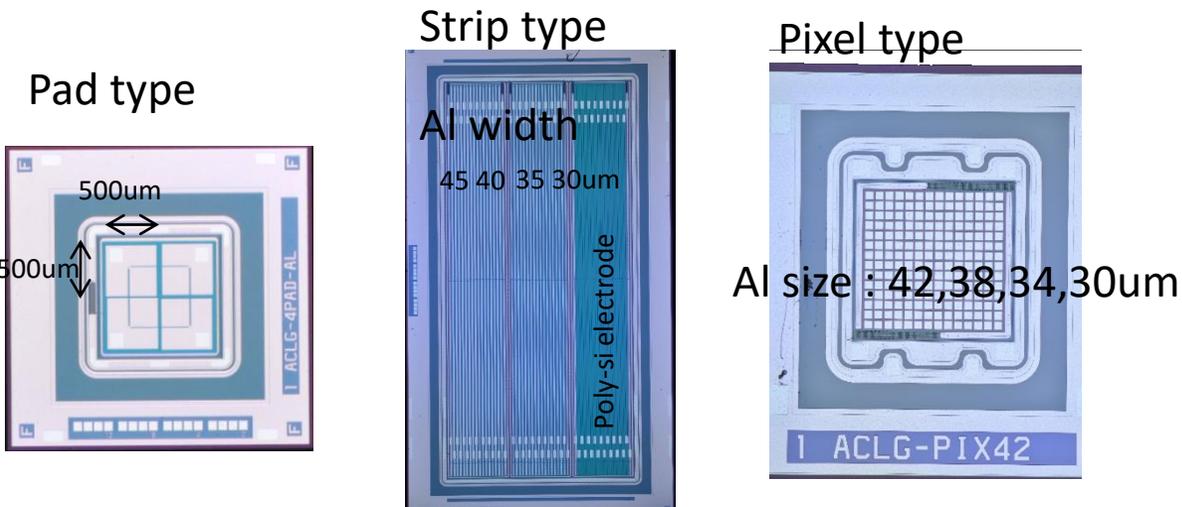
Gain Voltage (V_{gain}) is quite sensitive to the p+ doping conc.



HPK LGAD development

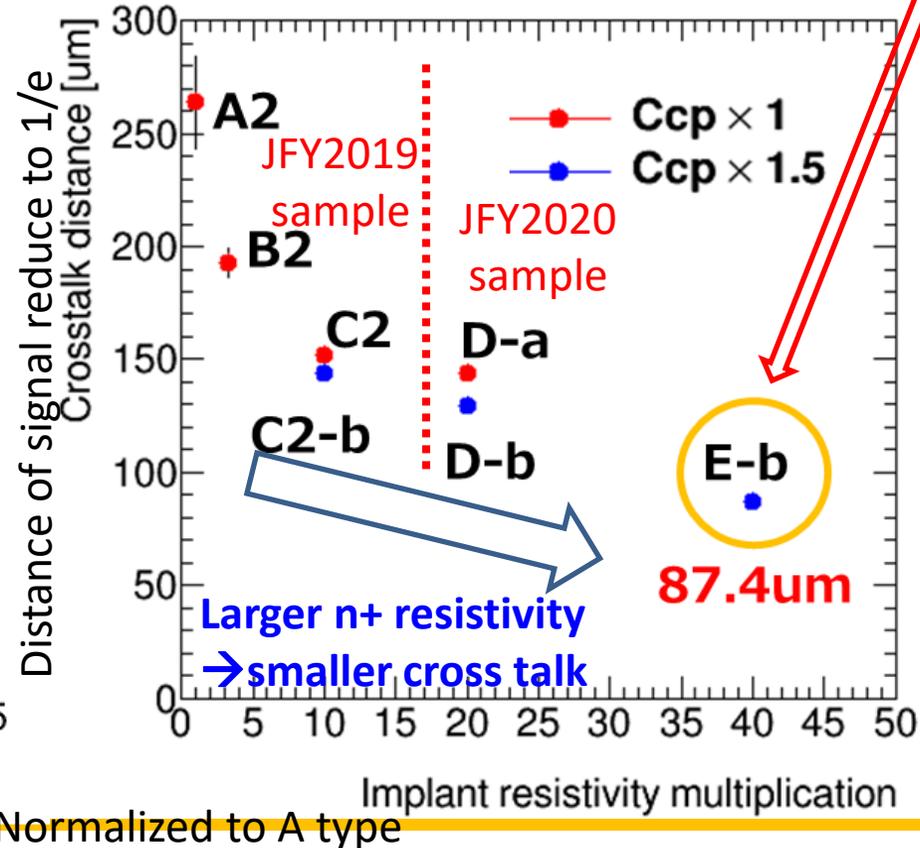
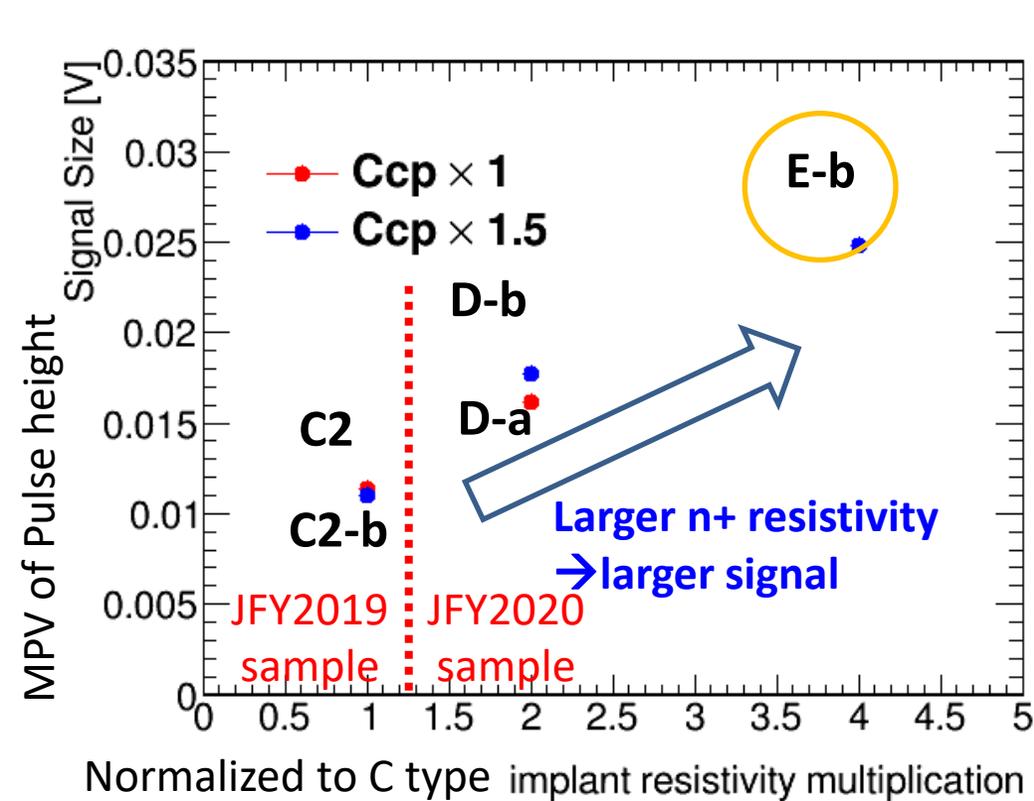
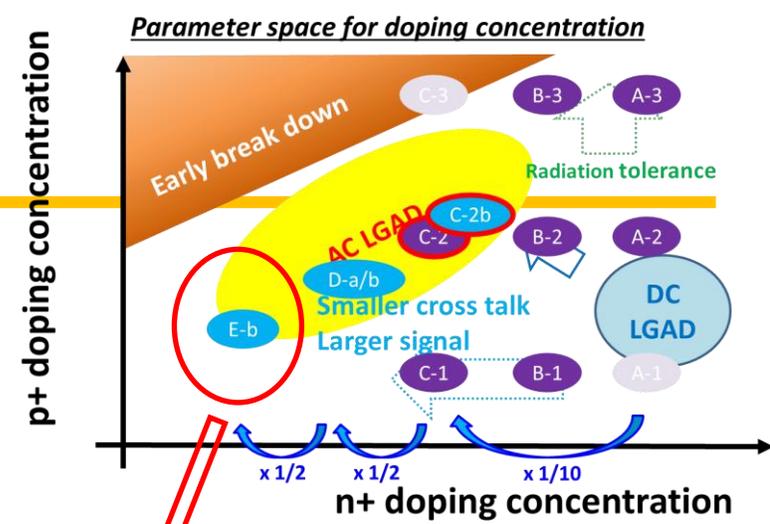
- JFY2015-JFY2018 DC-LGAD
 - **We contributed only first prototype.** HGTD took over.
- JFY2019, JFY2020 AC-LGAD production
 - Vary n+ and p+ dope (A-E, 1-3)
 - Vary thickness of SiO₂ (capacitance : C_b=1.5xC_a)
- Electrode type
 - Pad type: 500um sq. 4pad/sensor
 - **Strip type : 80um pitch**
 - Pixel type : 50um sq. 14x14 electrode

- 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**

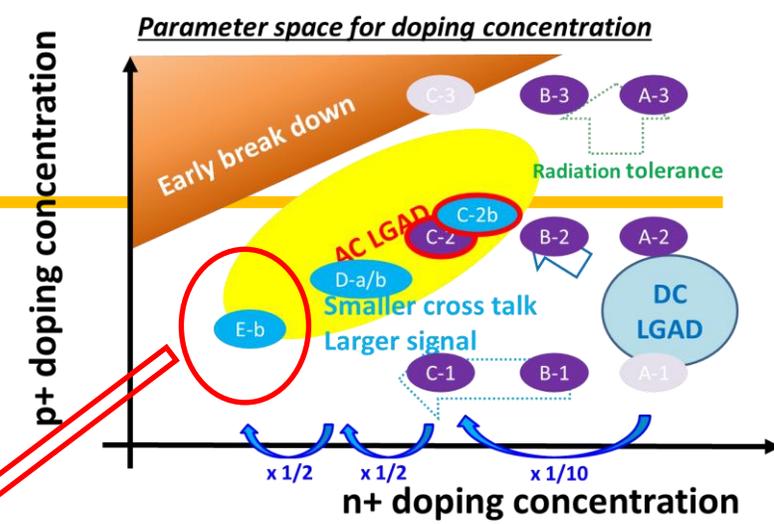
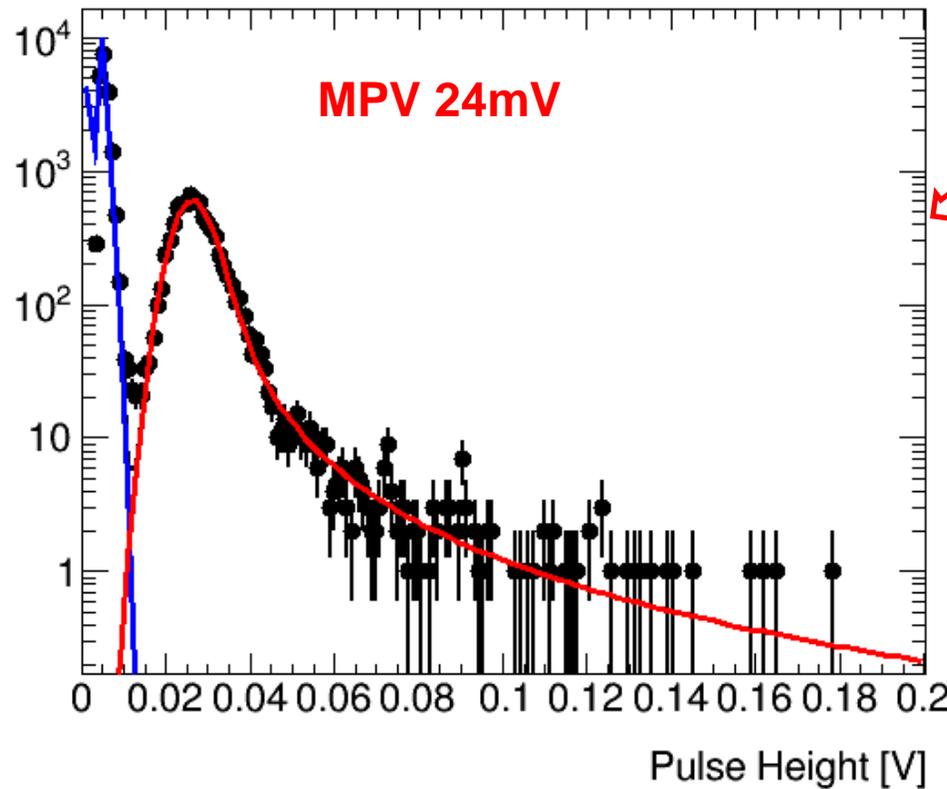


Mile stone : 80um Strip detector

Strip type



Pulse height distribution



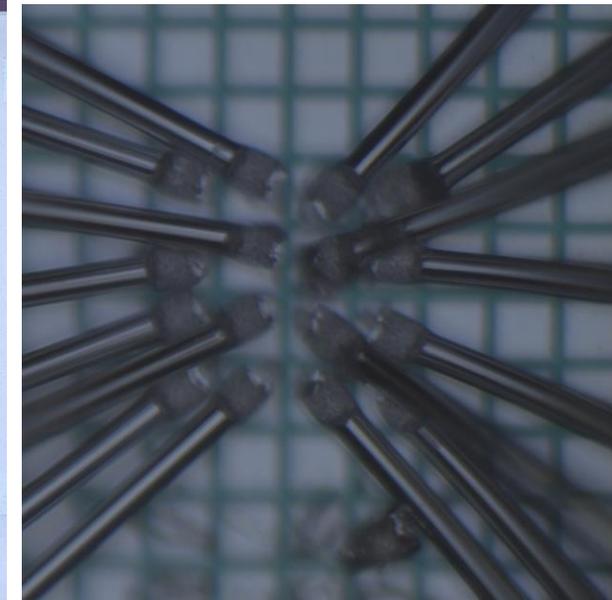
Noise rate 10⁻⁴ Efficiency 99.98%

**Successfully developed
Good S/N strip detector!**

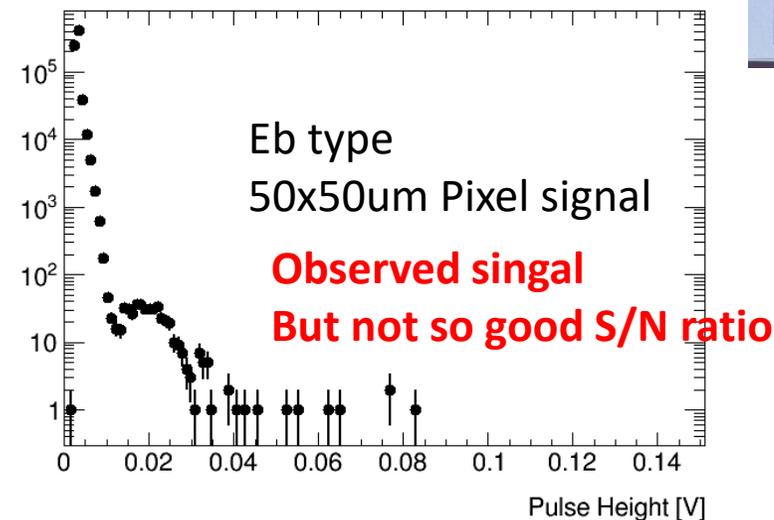
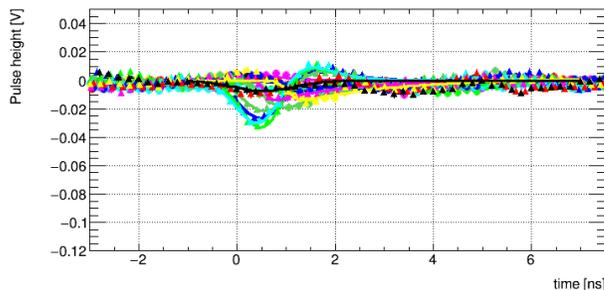
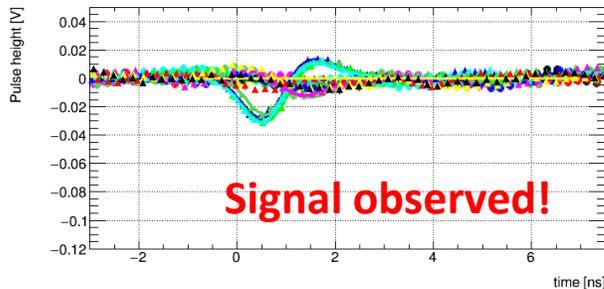
Spatial resolution were tested at testbeam :
20.3 ± 3.2um
assuming binary readout (@ELPH)

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 C_{cp} (Effective area?)

pad	strip	pixel
500um	45um	50um
500um	9880um	50um
n^+	n^+	n^+
MPV : 100mV	38mV	<15mV

Need high C_{cp} 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?

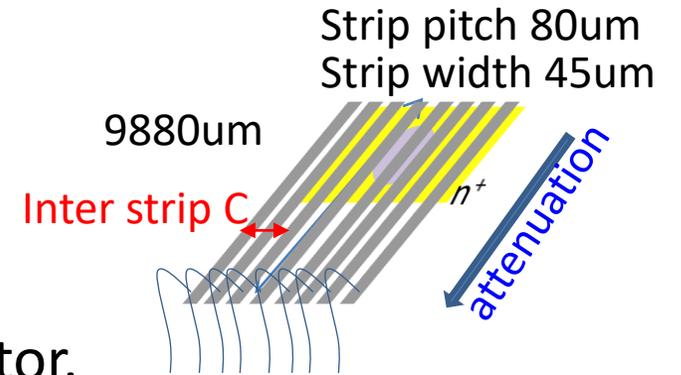
- This might affect to the signal size un-uniformity and delay of signal readout.

- **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 ?



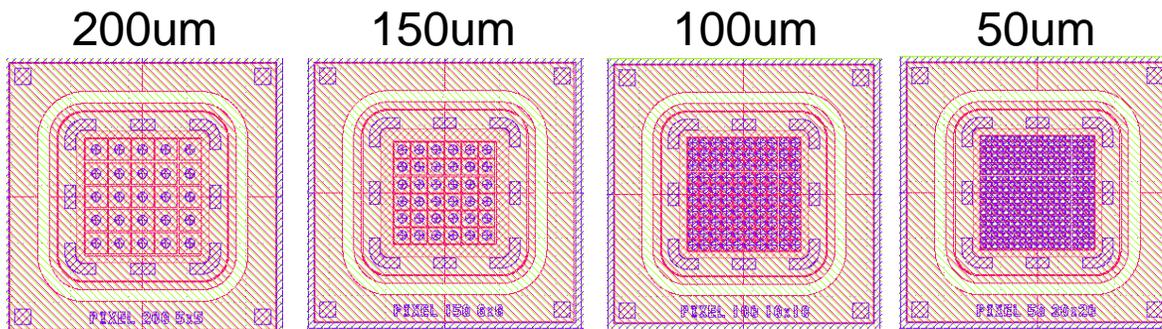
New sample (2021 sample) : received in April 2022

Used thinner di-electric layer (Oxide layer)

→ Basic electrode capacitance increased by factor of 5 !!

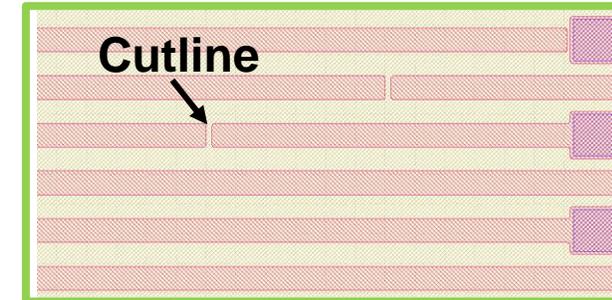
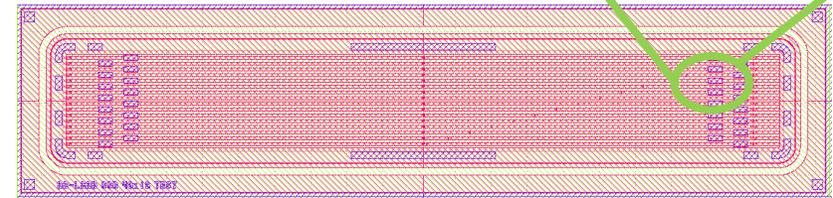
Pixel sensor

- 5 times larger C_{cp} compared with E-b (2020) type : E-600
- Various of pitch

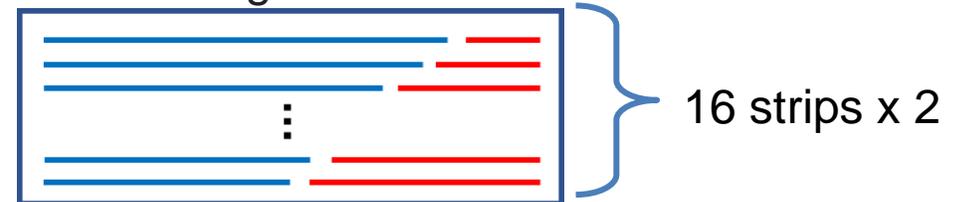


Strip sensor

- Strip sensor which has different electrode length



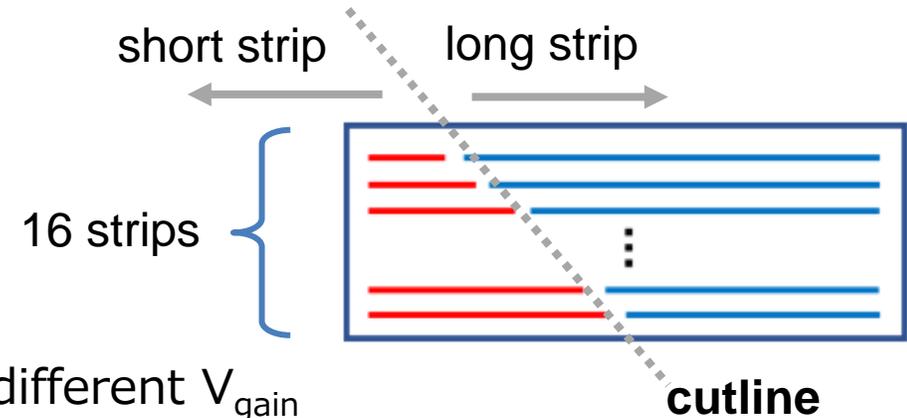
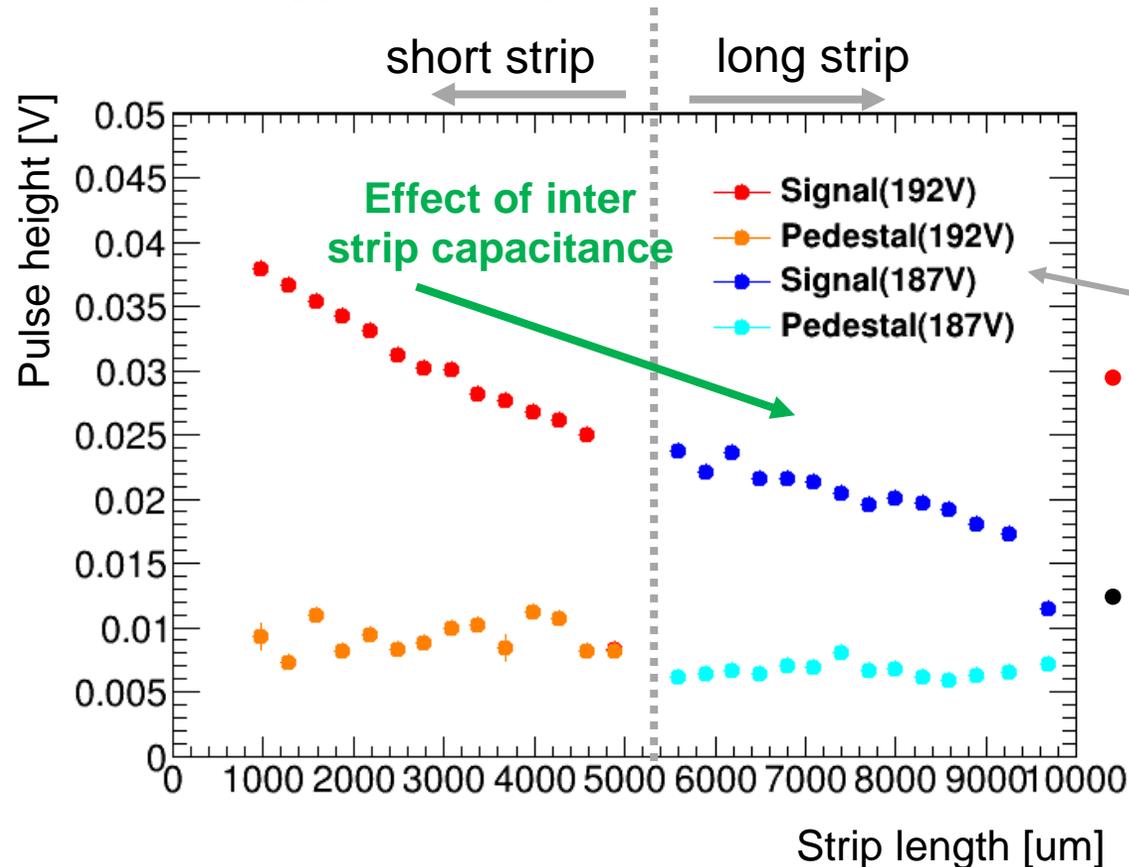
Pattern diagram



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}

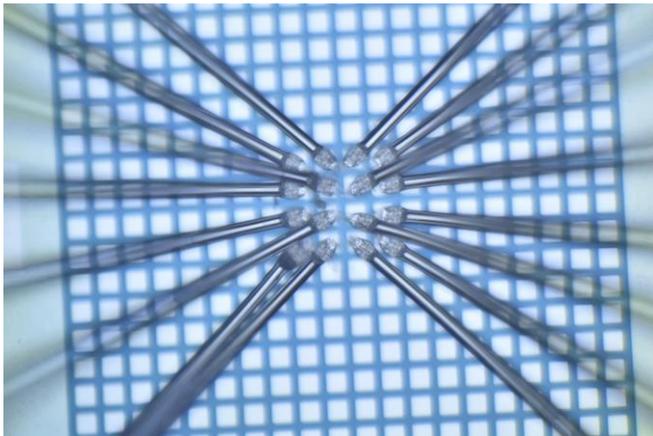
- **Signal reduced by 60% in ~10mm**
 - Because of inter strip capacitance?
 - Because of signal attenuation?
- We will test smaller gap sample. (the same pitch)
 - Current gap 40um \rightarrow 20um
 - **Smaller gap have larger inter strip capacitance and smaller attenuation**

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.



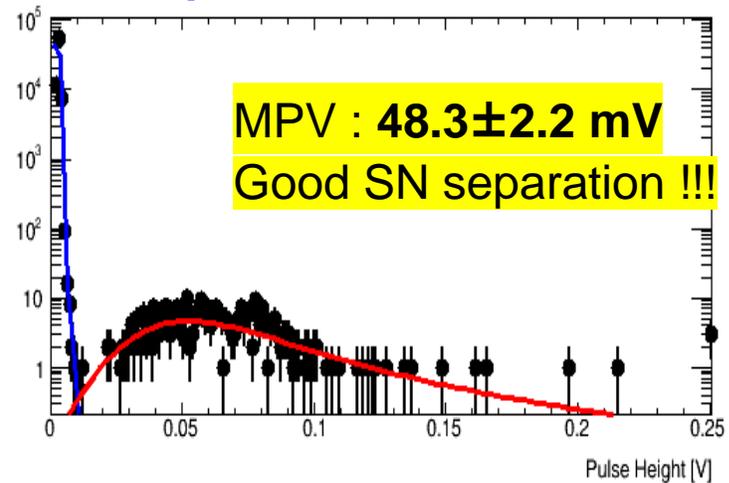
	7	11	
	6	10	

Analysis

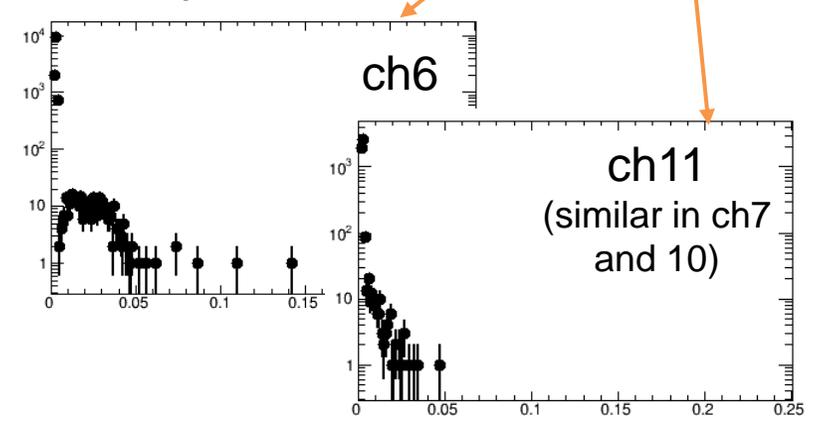
Only center 2x2 channels was used.
(To avoid crosstalk effect)

Pulse height distribution

100um pitch



50um pitch



Electrode short in ch6 ?
under investigation ...

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

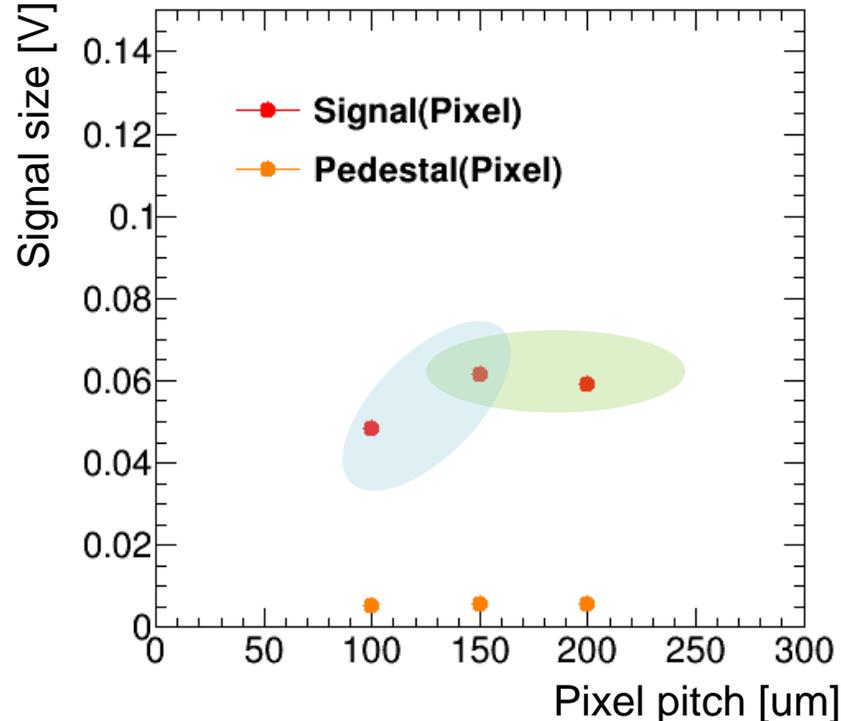
We need to understand the 50um x 50um pixel

Preliminary results : Pixel type electrode

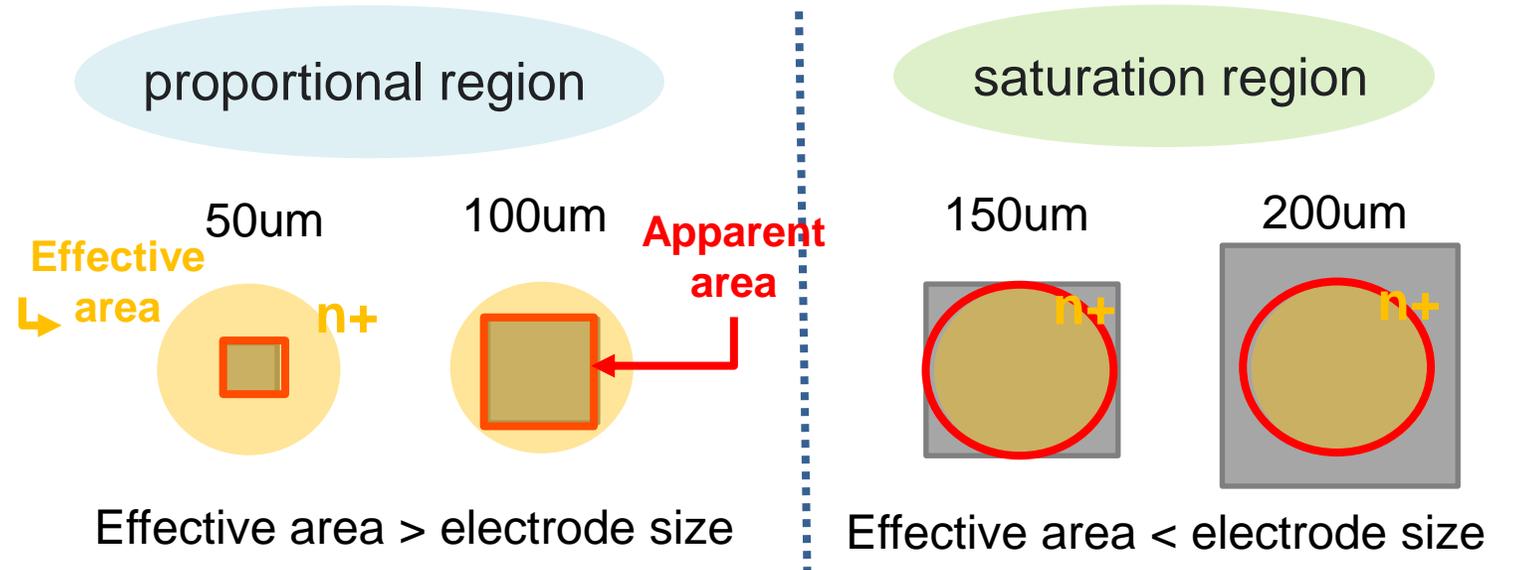
What is the effective area for electrode capacitance ?

E-600 type of pixel sensor

(all supplied 190V)



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

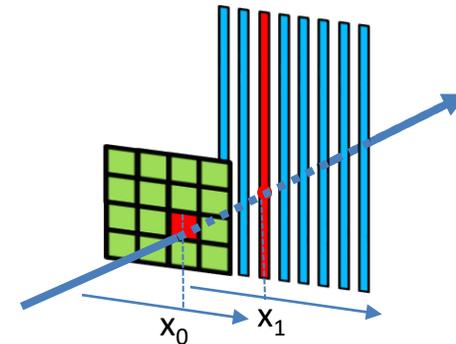


- **Signal seems like saturated at ~150um**
 - It makes sense small signal of 50um x 50um sample
 - **Will test smaller n+ resistivity sample**
 - Expected larger effective area.

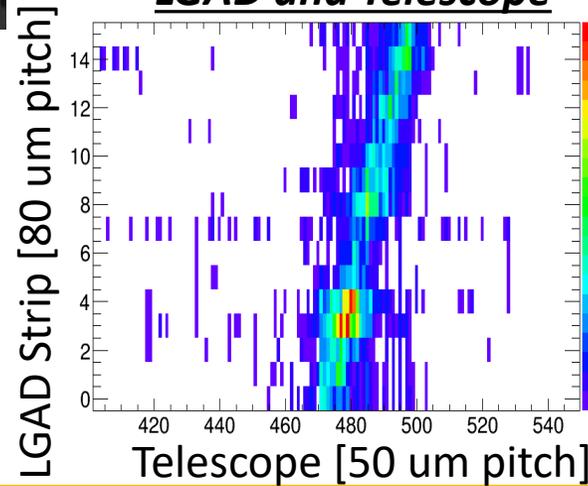
Snap shot from on-going ELPH testbeam

- 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!!

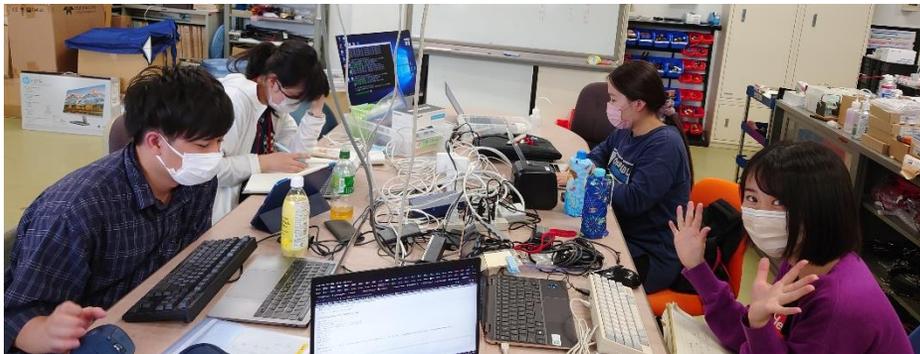
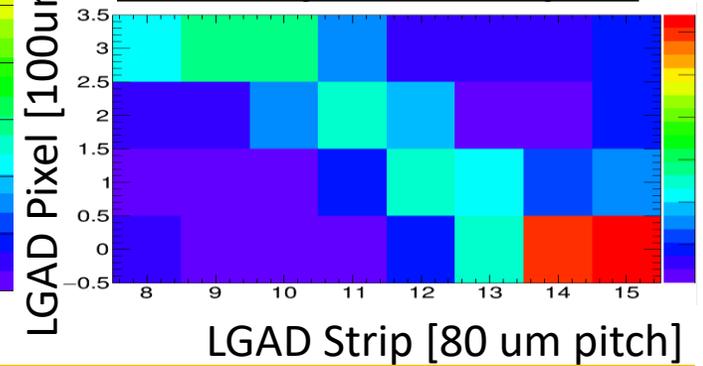
Correlation of x position of two planes



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!



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

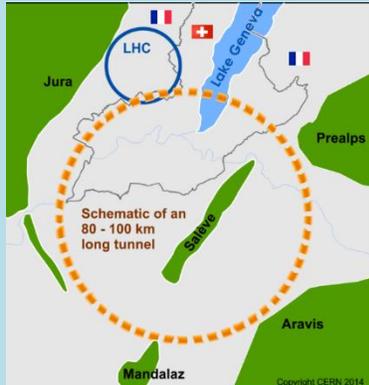
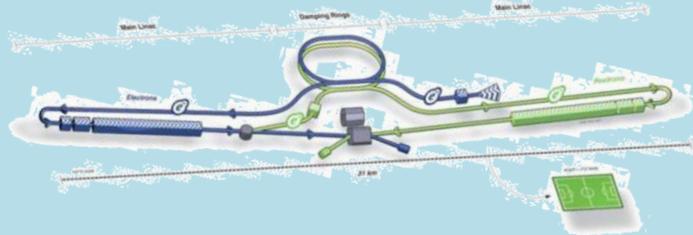
- Need “Higher Luminosity” and/or “Higher Energy”
 - High Luminosity LHC (HL-LHC)
 - 20 times more data ($\sim 3000-4000\text{fb}^{-1}$) at **14TeV**
 - Plan : Start at 2029
 - High Energy LHC (HE-LHC)
 - Use Super Conducting Magnet with Higher Magnetic field(16T)
 - **28TeV** collider in the same tunnel 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

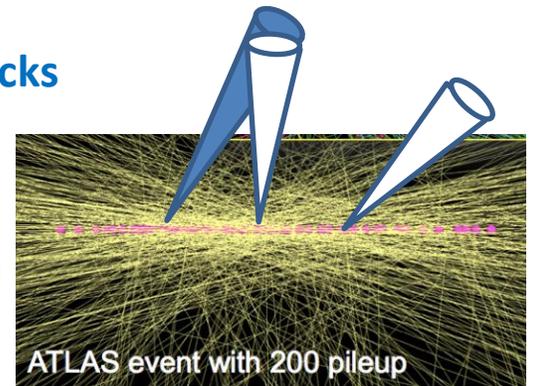
Final decision soon



Inner Tracking system

Very high density tracks

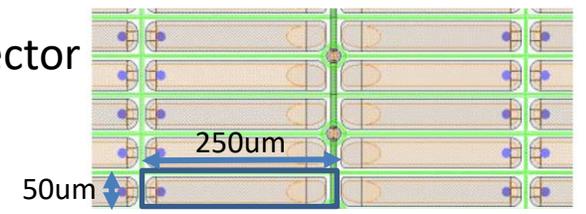
140 pileup @ HL-LHC
1500 pileup @ FCC-hh



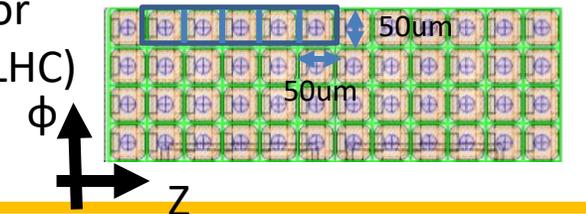
Only way to solve this so far...

finer pixel pitch

Current detector (ATLAS IBL)

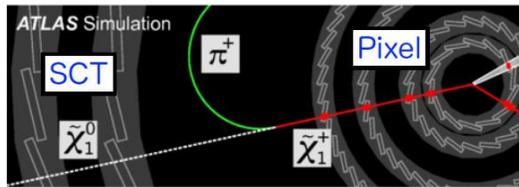


New detector (Pixel @HL-LHC)



Physics impact of timing detector

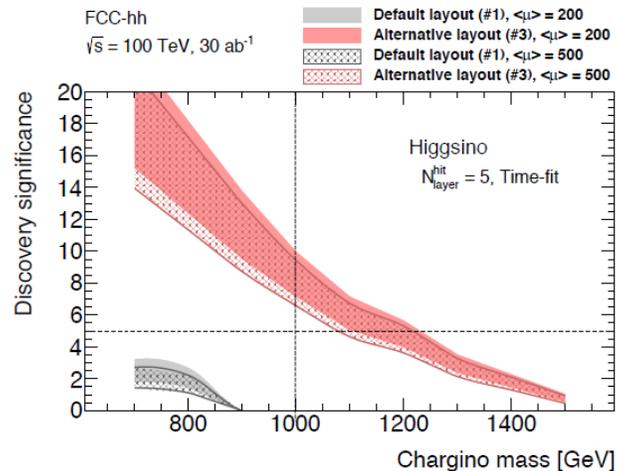
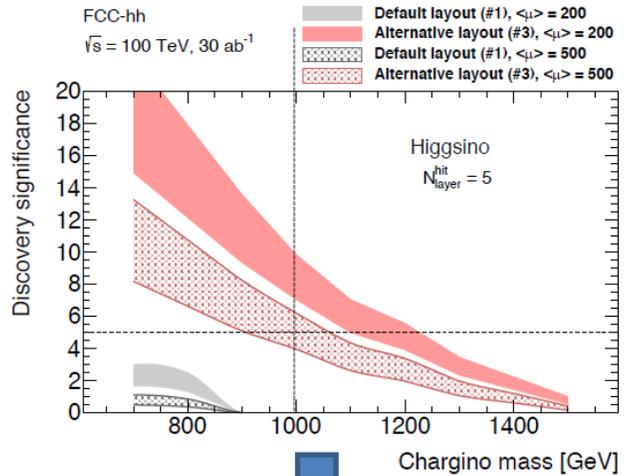
Higgsino production by using disappearing track



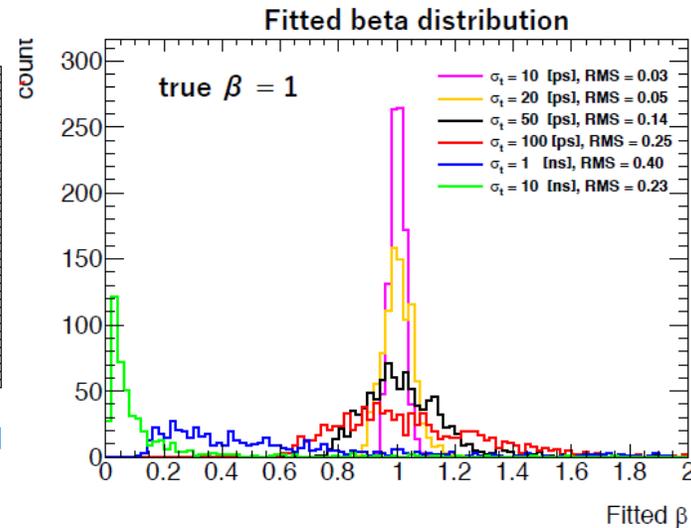
LSP: higgsino
 $\Delta m(\tilde{\chi}^{\pm}, \tilde{\chi}^0) \sim 300 \text{ MeV}$
 $\tau_{\tilde{\chi}^{\pm}} \sim 0.04 \text{ ns}$ ($c\tau \sim 12 \text{ mm}$)

Used timing information
 only for pileup removal

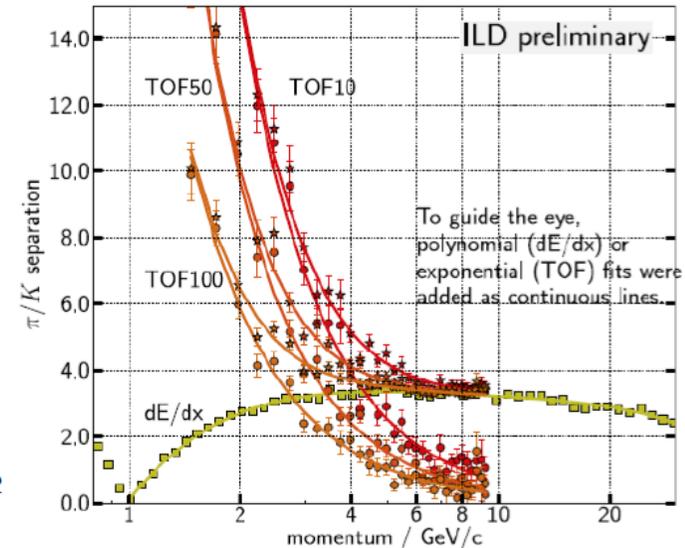
50ps timing
 information



β measurement in FCC detector



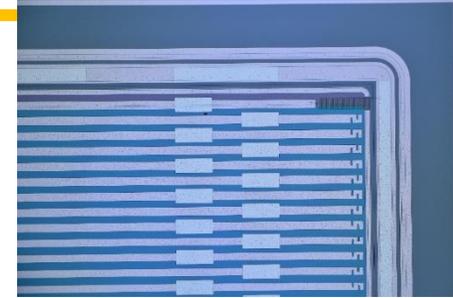
ILC K/pi separation



- See more information in timing detector workshop in 2018:

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

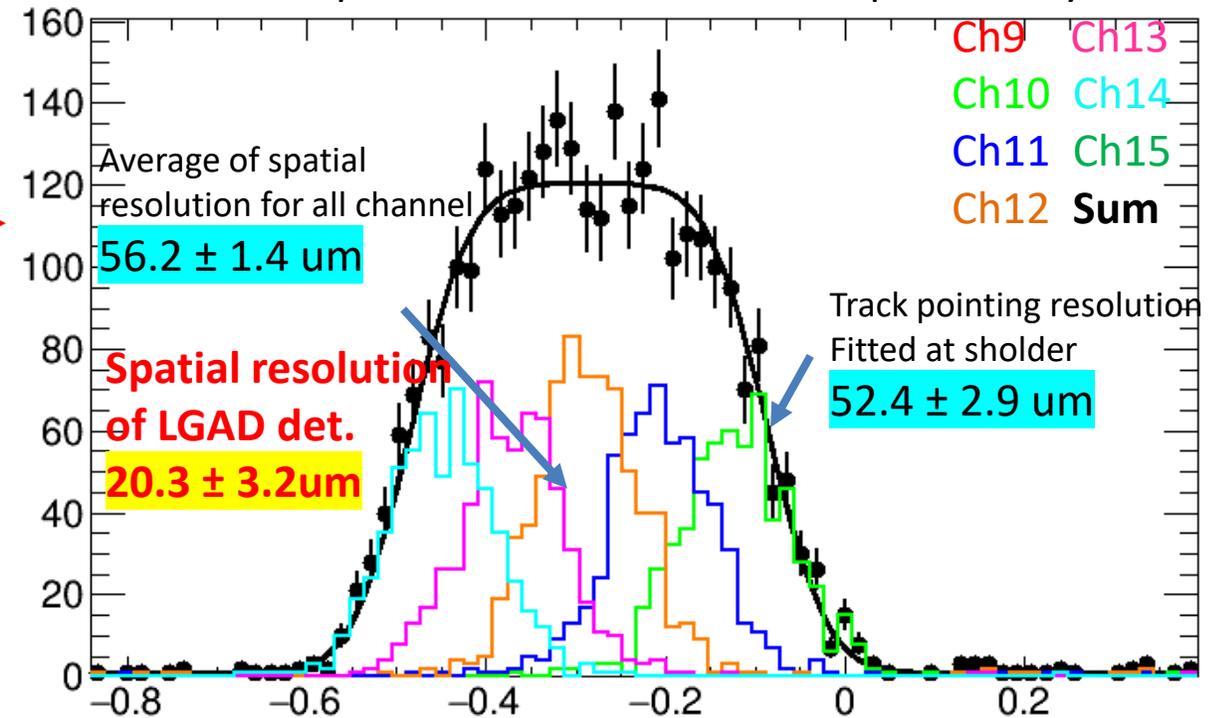
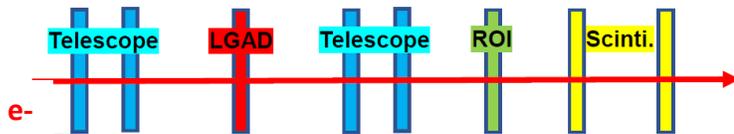
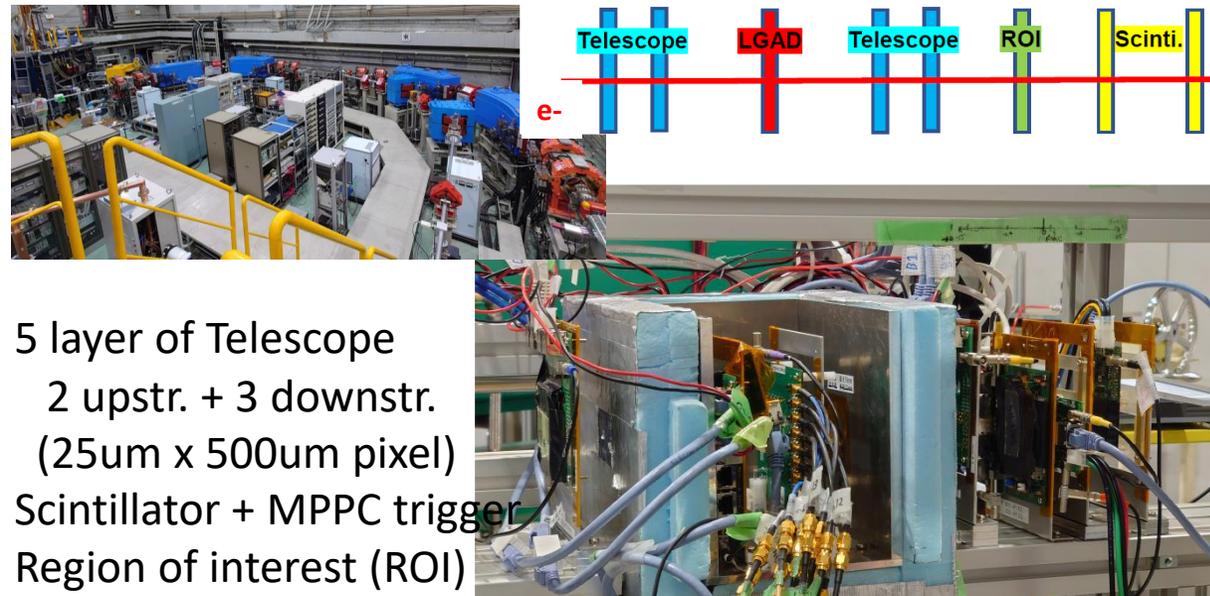
Spatial resolution measurement at ELPH TB



- In principle, no dead area and small crosstalk
 - At least $23\mu\text{m}(80\mu\text{m}/\sqrt{12})$ 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

Residual distribution of hit position and reconstructed position by tracking.



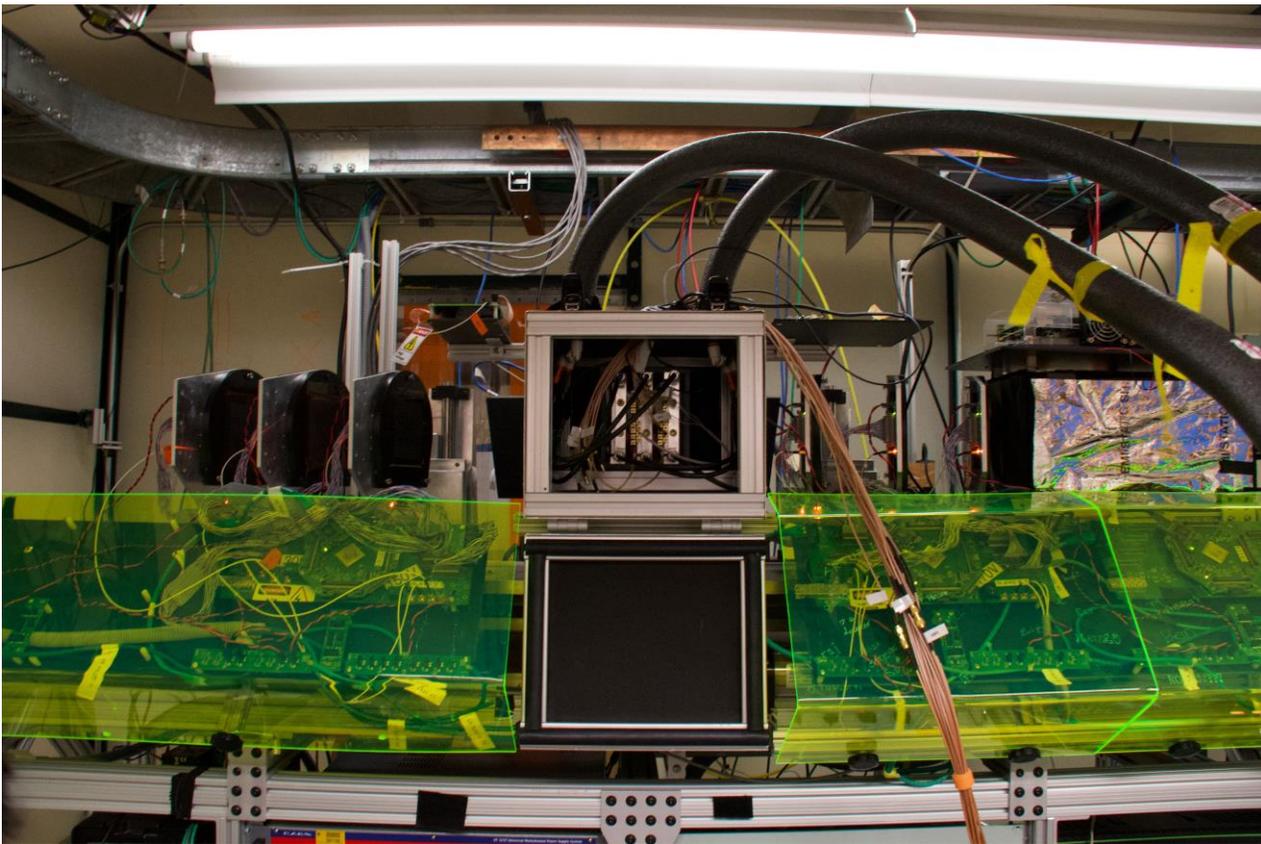
5 layer of Telescope
 2 upstr. + 3 downstr.
 (25μm x 500μm pixel)
 Scintillator + MPPC trigger
 Region of interest (ROI)

Timing resolution for AC-LGAD detector

Fermilab Test Beam Facility (FTBF)

120GeV proton beam

Strip Detector based Telescope : $\sim 15\mu\text{m}$ pointing resolution



Timing reference Detector

PHOTEK MCP photomultipliers (PMT140)

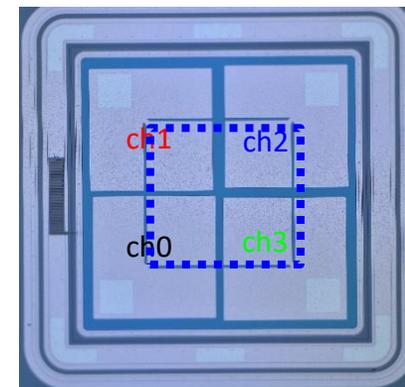
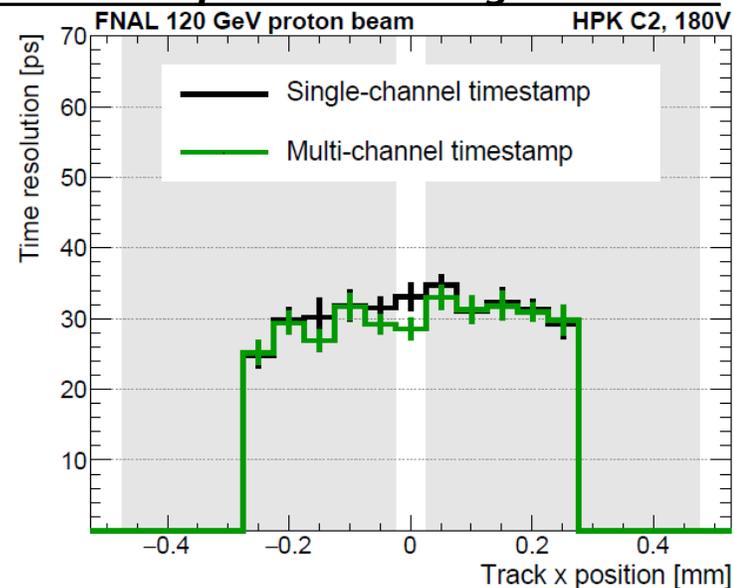
450ps FWHM with $5e3$ Gain

$\sim 5\text{ps}$ timing resolution

(SPEC: Multi-photon jitter below 10 ps)



Position dependent Timing resolution



- $25\text{-}35\text{ ps}$ timing resolution uniformly!**