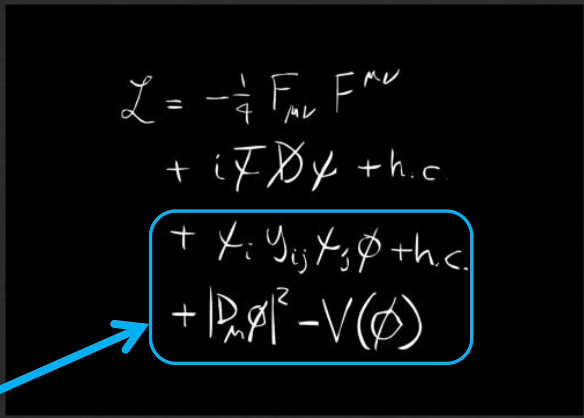
Development of tracking detector with capability of precise time and spatial resolution for future collider experiments

Koji Nakamura (KEK)

What we want to know?

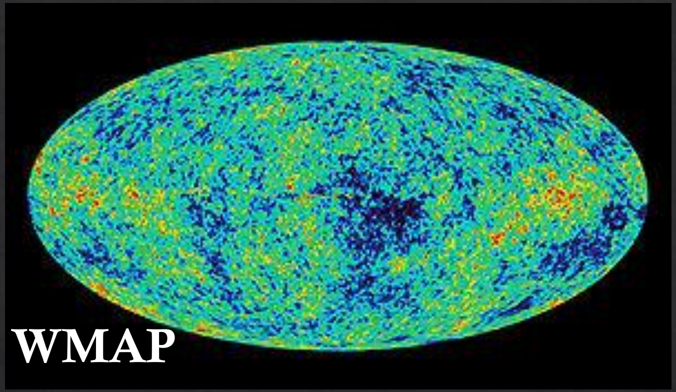


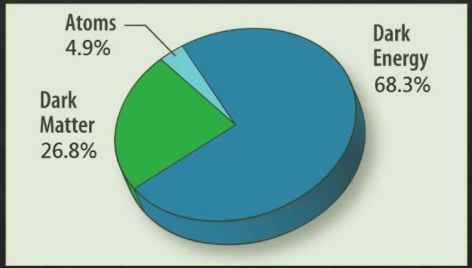
- Origin of Universe
  - Standard Model for Particle Physics
    - Observation of Higgs Boson indicate **"What we expect"** was right.
  - But at the same time we cannot describe everything only by **"What we expect"**
    - What is **Dark Matter** and **Dark Energy**?
    - Why matter > anti-matter?
    - Neutrino Mass?
    - Hierarchy Problem
    - Quantization of Gravity etc

These must be hints of new physics?

Huge progress in this 15years.
→ Very interesting phase to prepare new exp.

Why accelerator experiment?





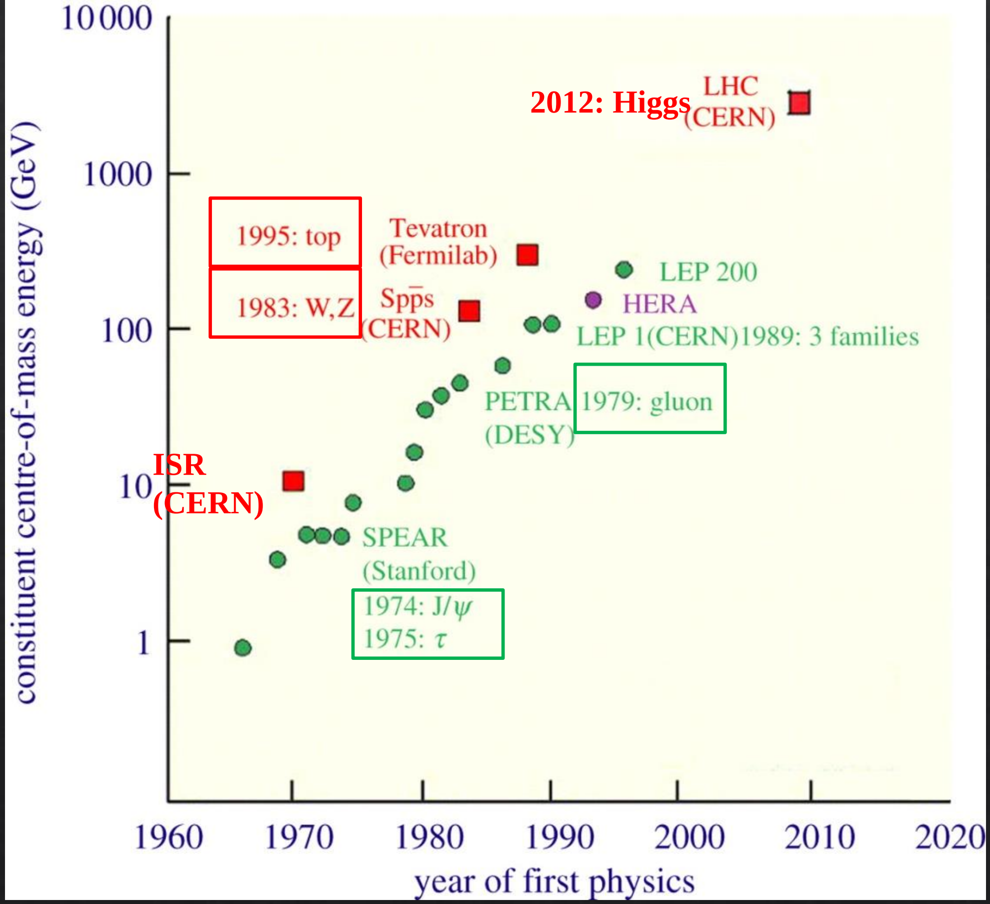
- Non-Accelerator Experiment
  - Cosmic Microwave Background (CMB)
    - COBE and WMAP measured temperature uniformity of CMB. These measurement indicate existence of Dark Matter/Energy as well as age of the universe.
  - Search for WIMP Dark Matter
    - XENON1T, LUX etc.. Under ground experiment
    - Fermi-LAT, AMS-02 etc… Experiment at Satellite or International Space Station.
- Accelerator Experiment
  - **To measure observed phenomena precisely, we need to precisely control the production of phenomena.**
  - **Once we succeed the production, we can measure the phenomena very precisely.**
  - But we need to create huge energy/mass phenomena (10s GeV to a few TeV)

  → Need huge accelerator

How big?
How much data?

History of the collider experiment

- Before 1980s
  - **e+ e- collider** : Observation of low mass particles (~ a few GeV)
    - 1974 J/ψ
    - 1975 τ
    - 1979 gluon
- After 1980s
  - **Proton collider :** Observation of heavier mass particles.
    - 1983 W,Z
    - 1995 top
    - 2012 Higgs
  - **e+ e- collider :** Precision measurement
    - 1989 : neutrino : 3 generation
    - LEP Electroweak measurement



Complementarity :

SppS : W/Z observation →LEP : mesurement
LEP : top mass expectation? → Tevatron : Top observation
LEP : EW measurement +Tevatron : Top mass measurement → LHC : Higgs observation

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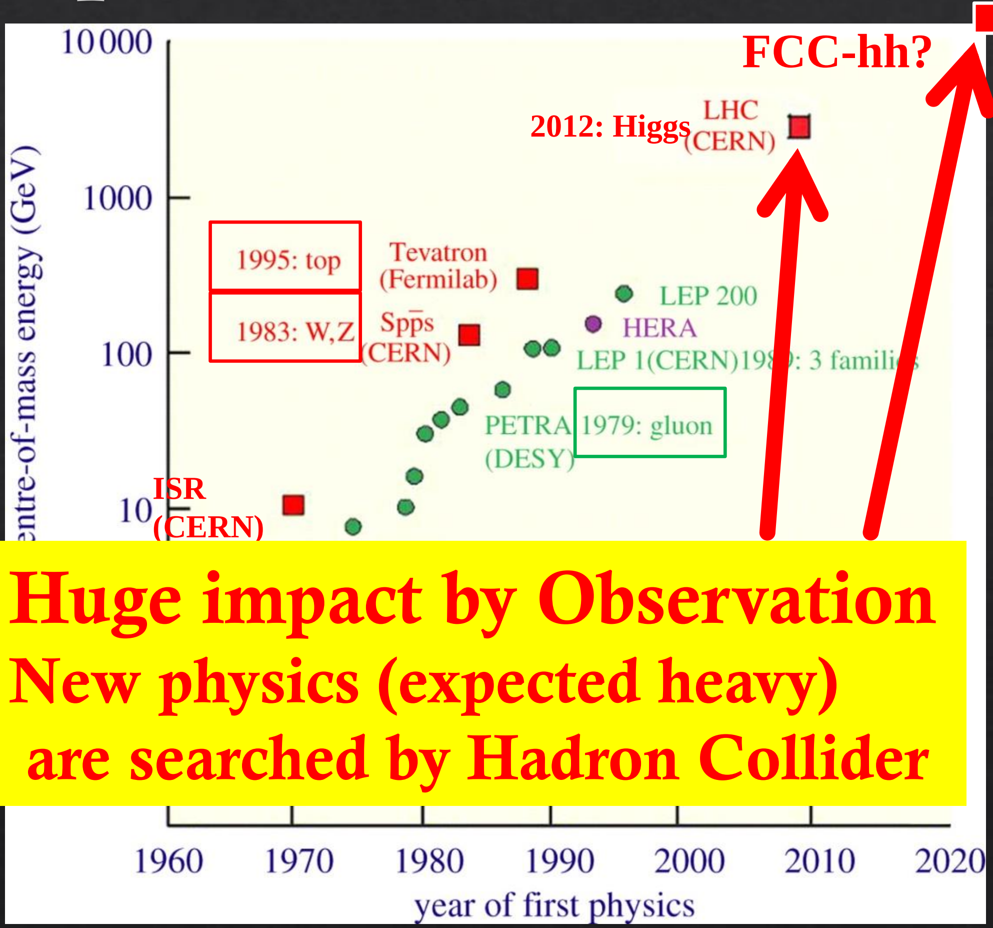


Huge impact by Observation
New physics (expected heavy)
are searched by Hadron Collider

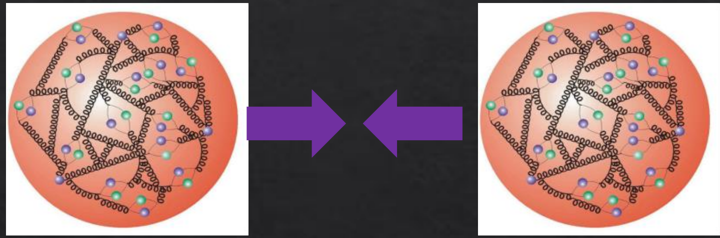
Complementarity :

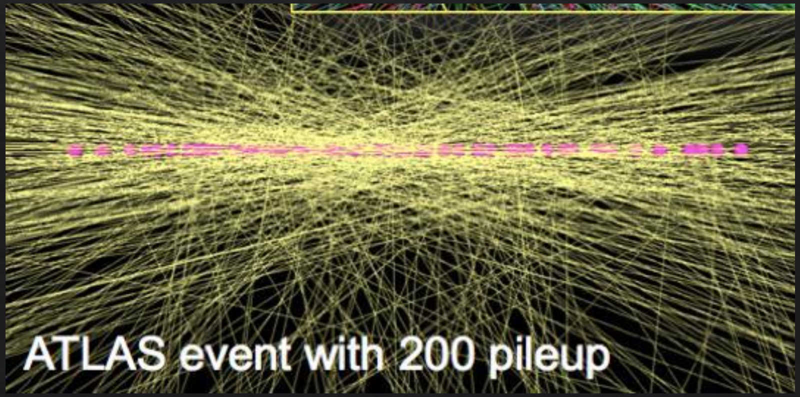
SppS : W/Z observation →LEP : measurement
LEP : top mass expectation? → Tevatron : Top observation
LEP : EW measurement +Tevatron : Top mass measurement → LHC : Higgs observation

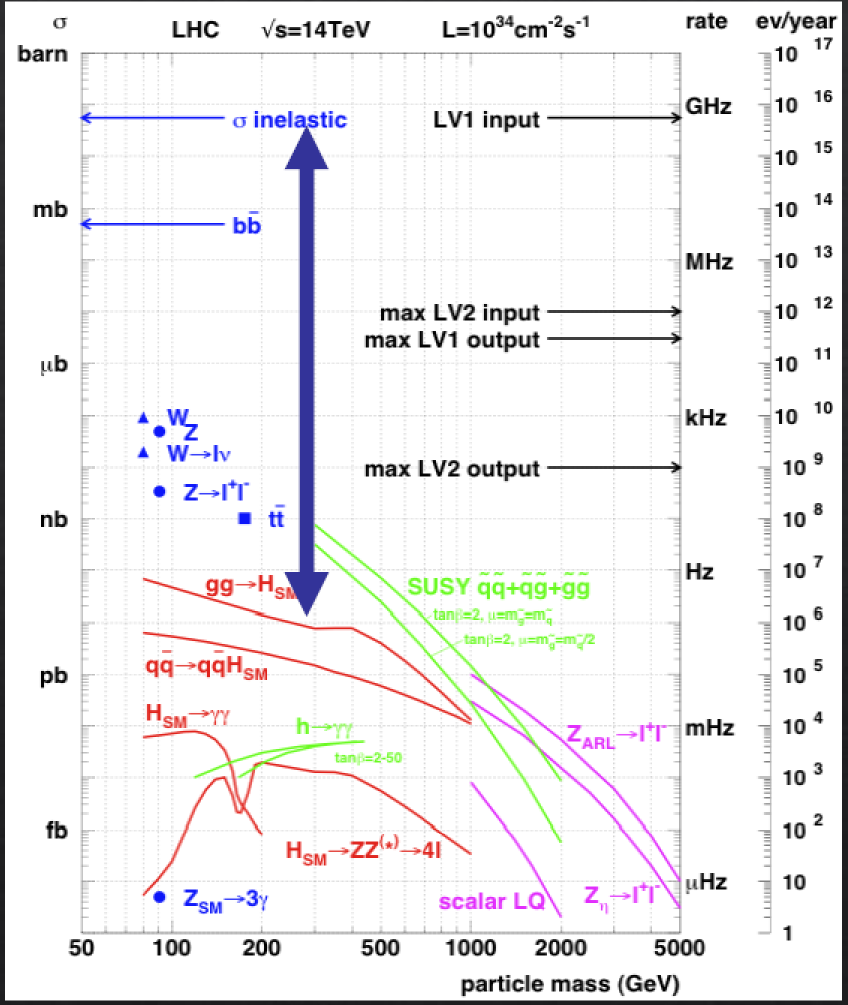
Difficulty of Hadron Collider

[Difficulty of pp collider analysis]

- Difference of center-of-mass energy and energy used for collisions.
  - Parton Distribution Function (PDF)
- Complicated collision due to composite particle of proton
  - Huge QCD background
  - Spectator of the proton collisions
    - →Underlying event
  - Multiple collisions in a bunch crossing
    - →Pile-up
  - **10 order of magnitude difference between pp cross section and interesting events.**







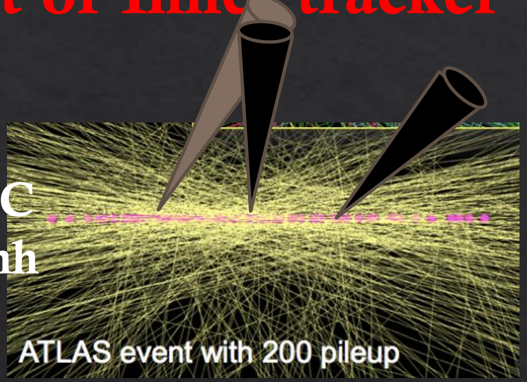
Challenge of the tracking detector

- Multiple interaction in an event at
  - HL-LHC : 140-200 collision in an event,
  - Future collider: 1500 !
- How to solve this issue?
  1. ***Improve granularity*** : Currently developing 50um pitch pixel detector and not possible to make smaller…
  2. ***Timing information***: Completely new information for tracking : possibility of dramatical improvement of track reconstruction →Should help if timing resolution achieved 1cm/c ~ **30ps**

Improvement of Inner tracker

Very dense tracks

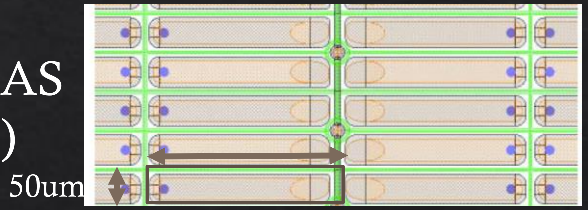
140 pileup @ HL-LHC
1500 pileup @ FCC-hh



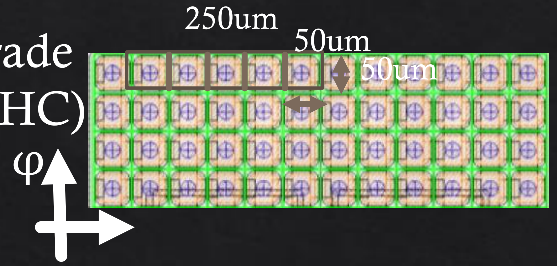
Improvement of granularity

Smaller pixel size

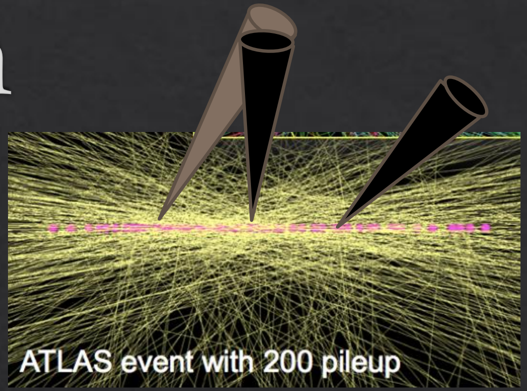
e.g.
Current ATLAS
(ATLAS IBL)



HL-LHC upgrade
(Pixel @HL-LHC)



Impact for tracker with time resolution



- Collider experiment gets high energy and high intensity.
  →Future Tracking detector should have timing information for all hits!
- Tentative Requirement
  - 30ps timing resolution &~o(10)um spatial resolution
  - (hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance

4D tracking !

Detector Hit

Tracking

Solve pileup hits in an event

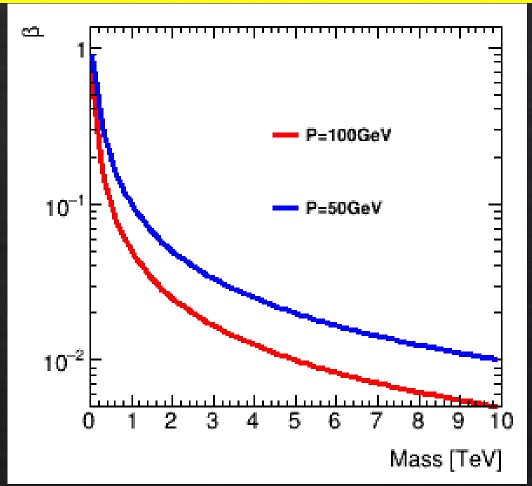
Particle identification

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

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

How to improve the timing resolution?

Timing resolution:

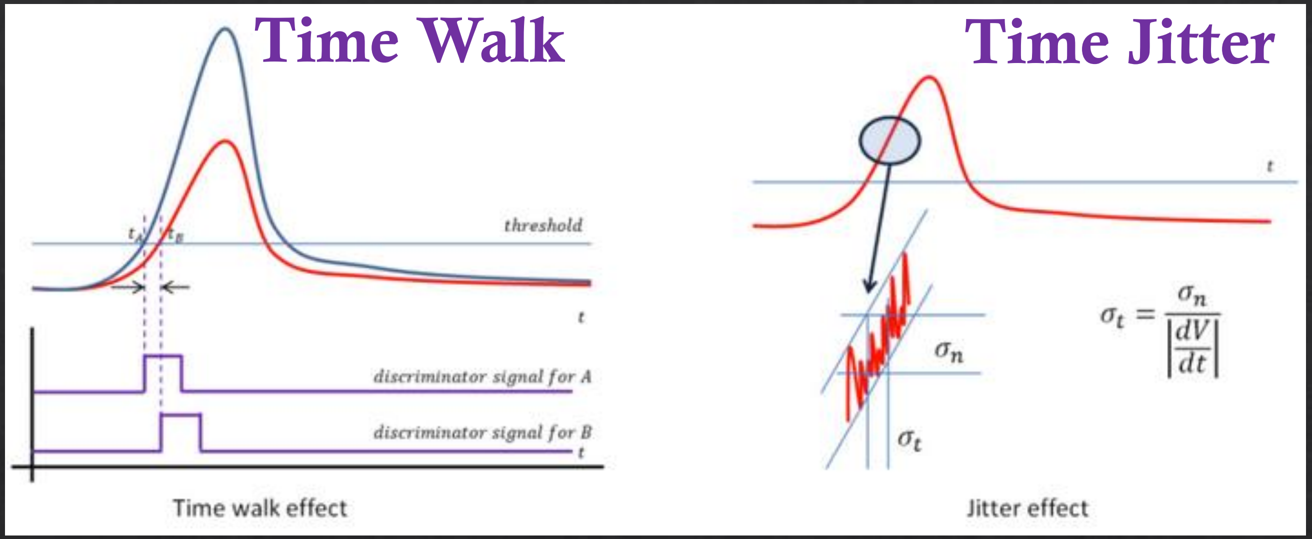
$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2$$

σ_{tw} :Time walk

σ_j : Jitter (electronics)

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

S : pulse height
σ_n : Noise
t_r : rise time



Time walk :

can be reduced by using Constant Fraction Threshold

Jitter (electronics) :

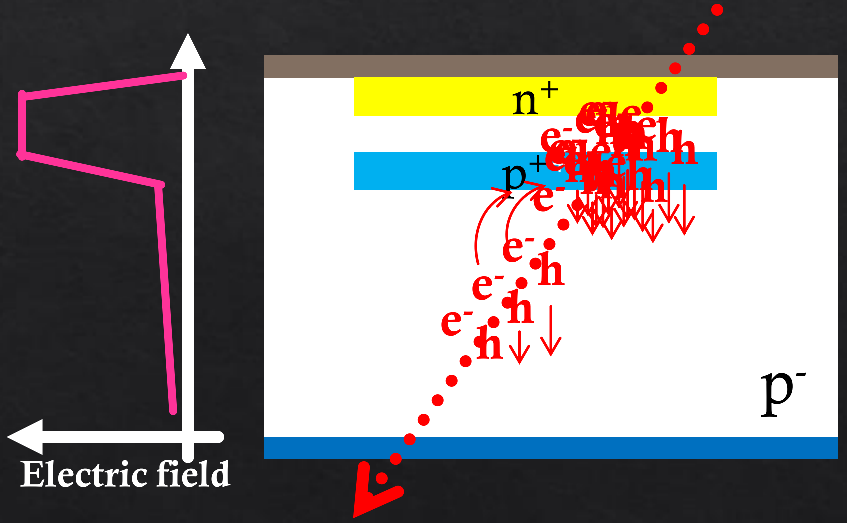
can be reduced faster rise time or larger signal

Faster signal turn on and good S/N ratio should be the key to improve timing resolution

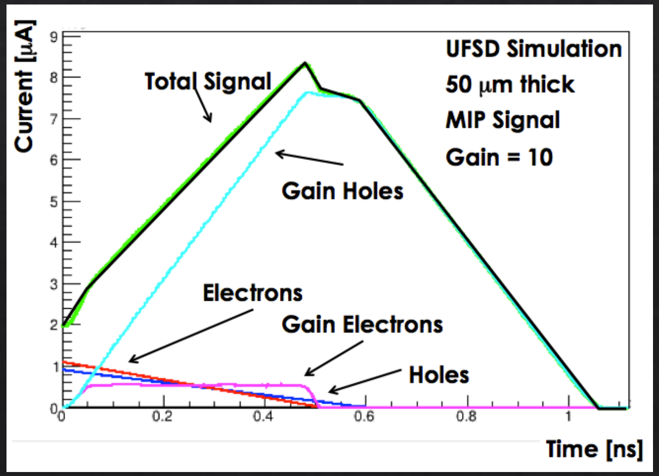
Low Gain Avalanche Diode (LGAD)

- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make very high Electric Field at the surface.

    → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**



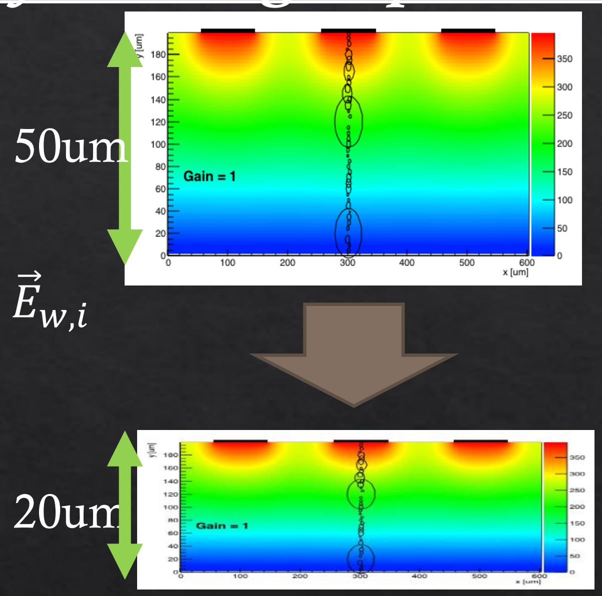
Signal drivers : **Gain Holes**



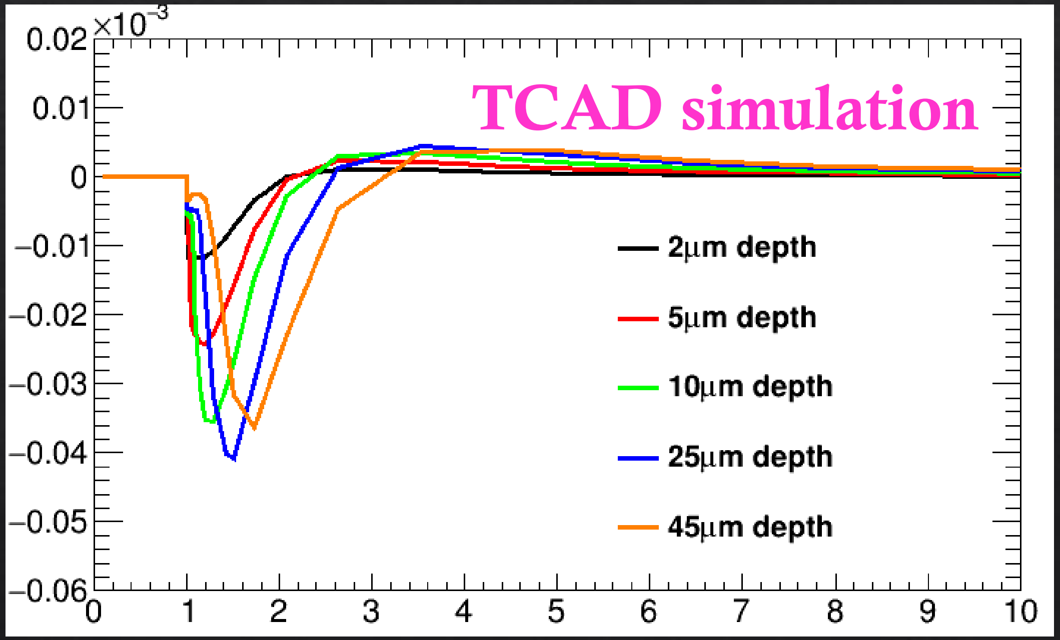
Charge Collection Noise (Landau Noise)

- For Minimum Ionization Particle (MIP), charge deposition is not uniform depth profile.
  - This effect makes timing resolution get worse.
    - The slower turn on for charge at deep region. (**the thinner sensor the better**)
    - Signal increase by depth but saturated at some point (25um in simulation)

Non-Uniform charge deposition



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



Thinner active thickness will help to reduce the effect

Timing resolution of LGAD sensor full picture

$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

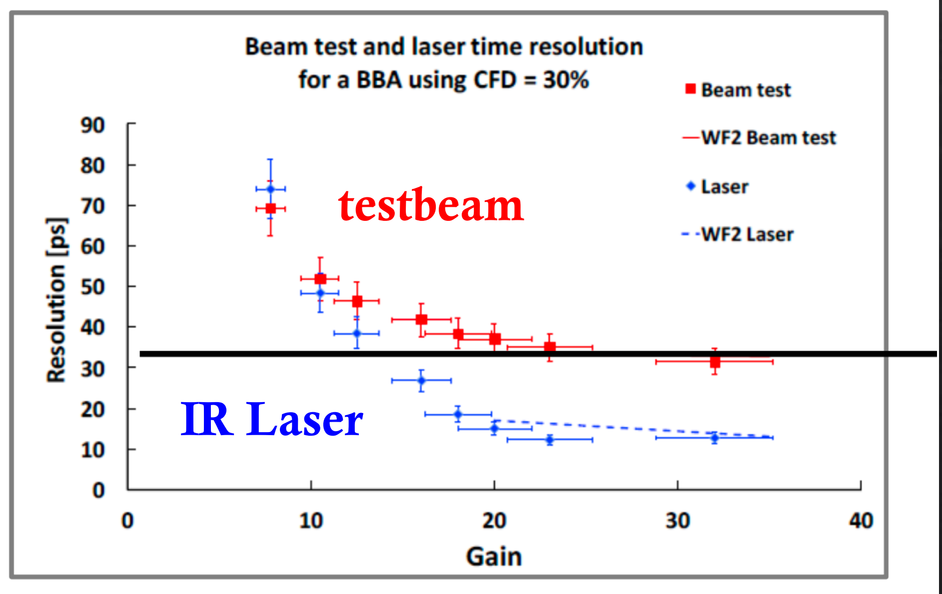
$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

~~σ_{tw} :Time walk~~

S : pulse height
σ_n : Noise
t_r : rise time

σ_j: Jitter (electronics)

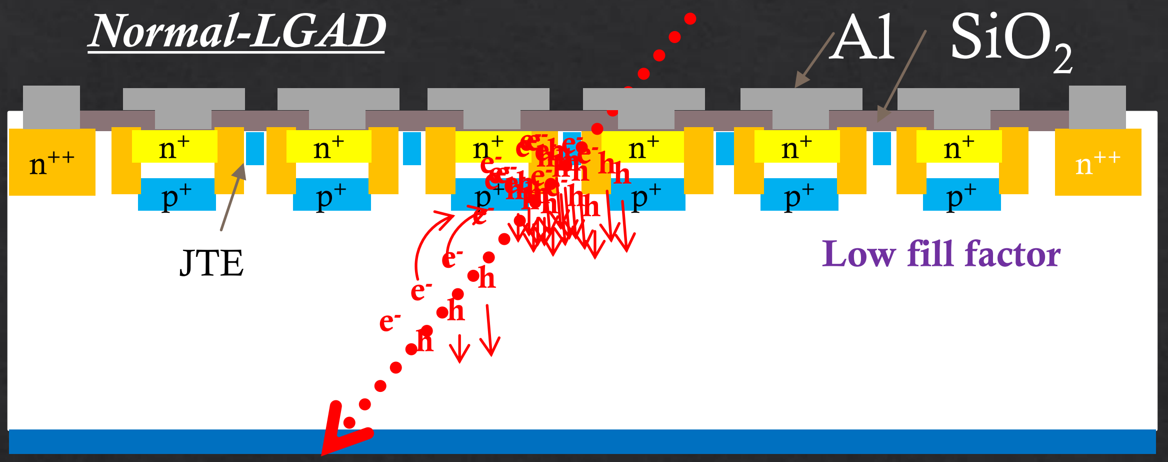
σ_L: Landau noise



50um thick sensor : saturated timing resolution ~30ps
Thinner sensor should have better resolution.

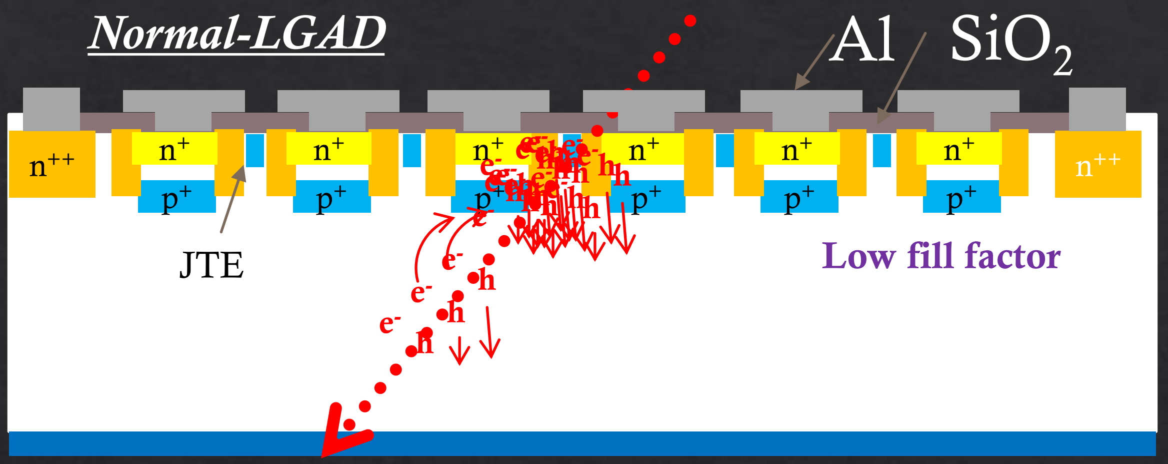
Spatial resolution of LGAD

- Segmented LGAD :
  - To have spatial resolution, strip sensors has been processed.
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**

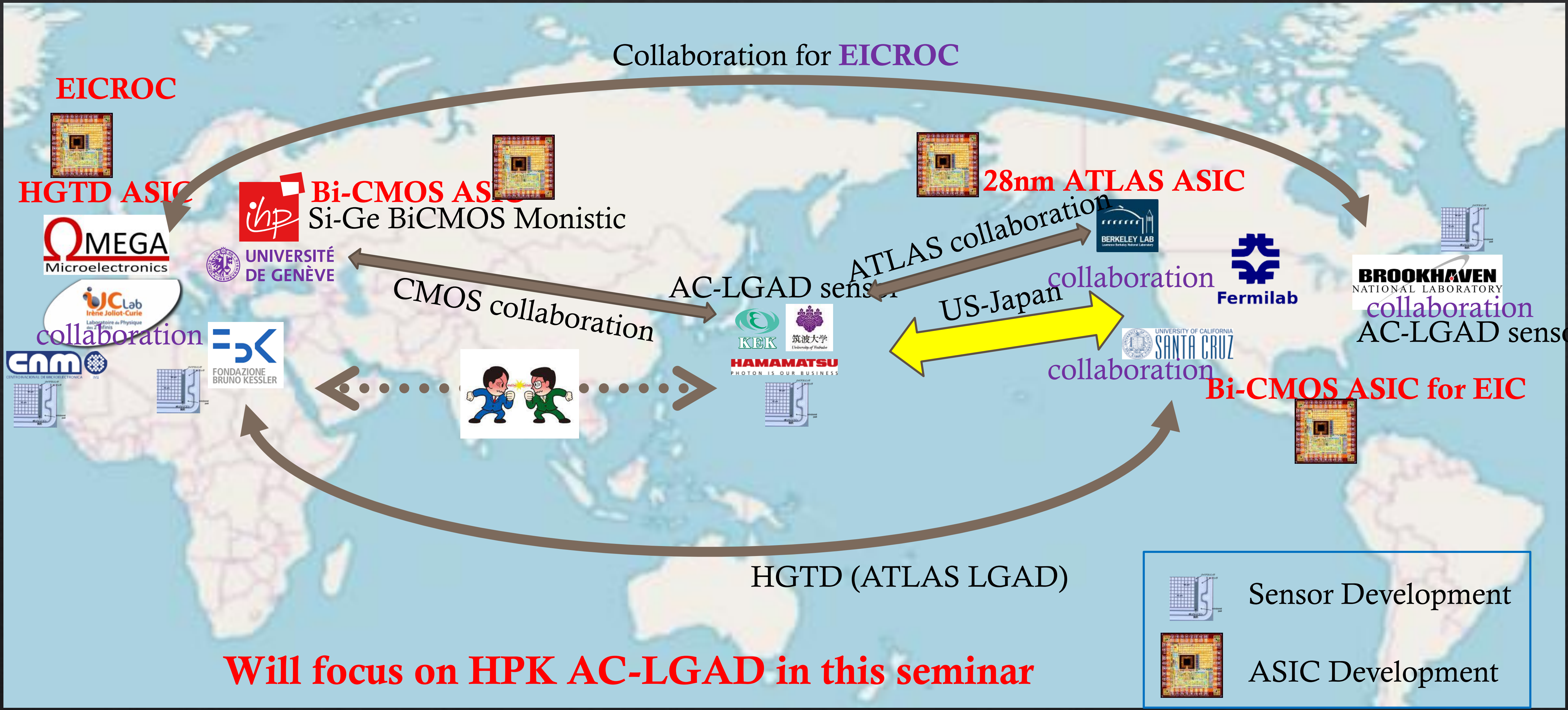


Spatial resolution of LGAD

- Segmented LGAD :
  - To have spatial resolution, strip sensors has been processed.
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**
- **Uniform gain layer with AC-Coupled electrode. (AC-LGAD)**
  - **In principle, 100% fill factor.**
  - **Signal shared on neighboring electrodes.**
    - Need optimization of n+ resistivity

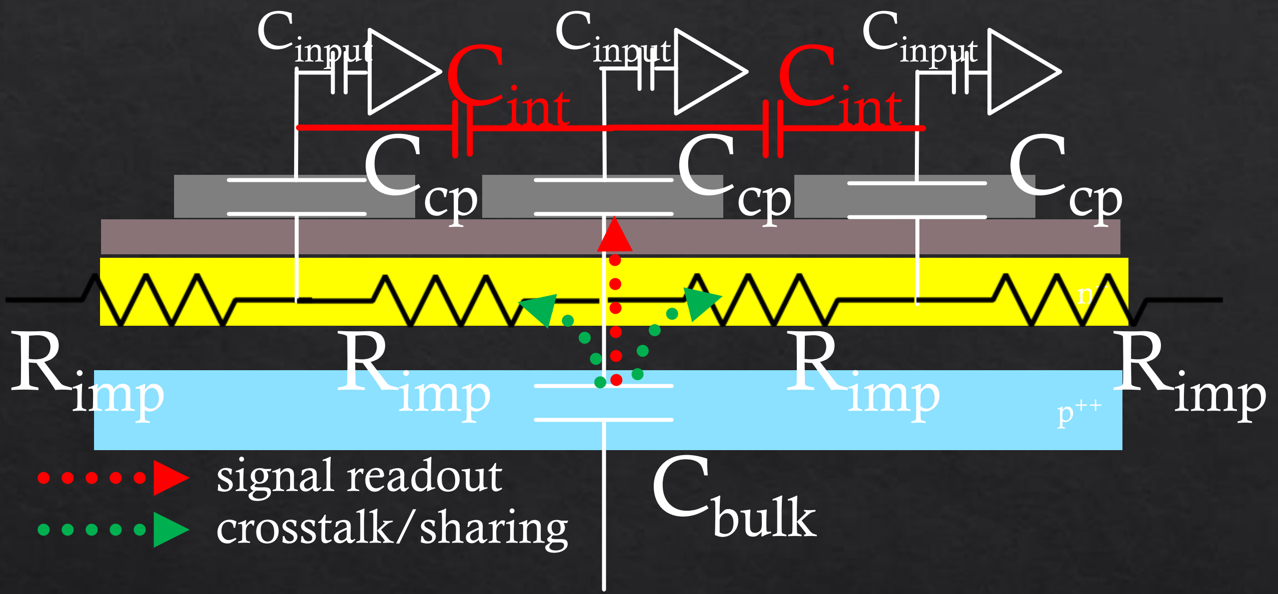


AC-LGAD collaboration

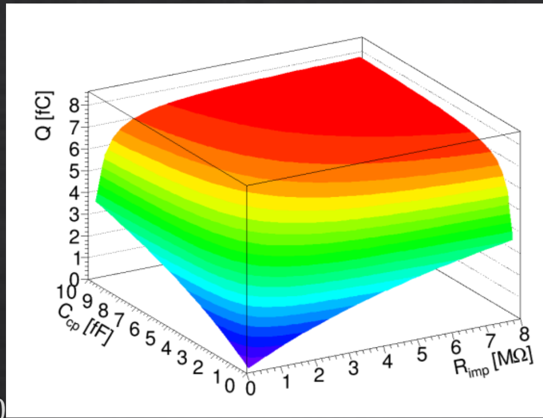


AC-LGAD sensors

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



◈ Charge split : Impedance ratio



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

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

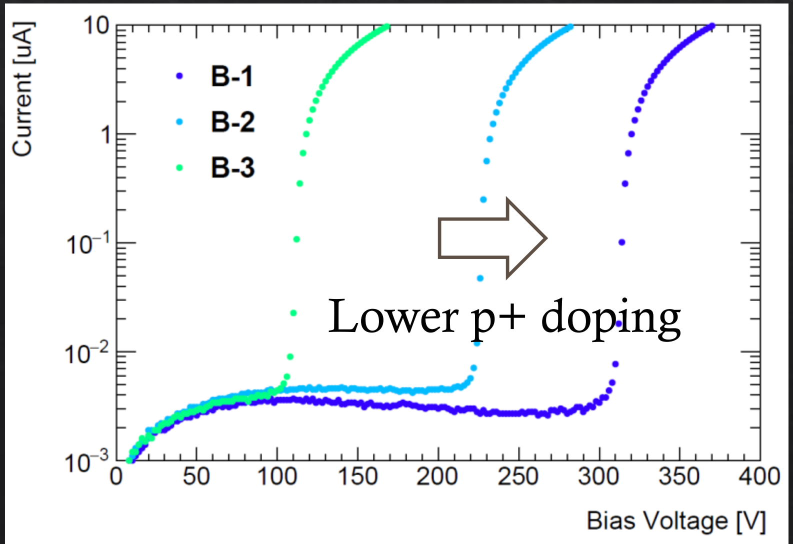
◈ Amount of produced charge: Q_0

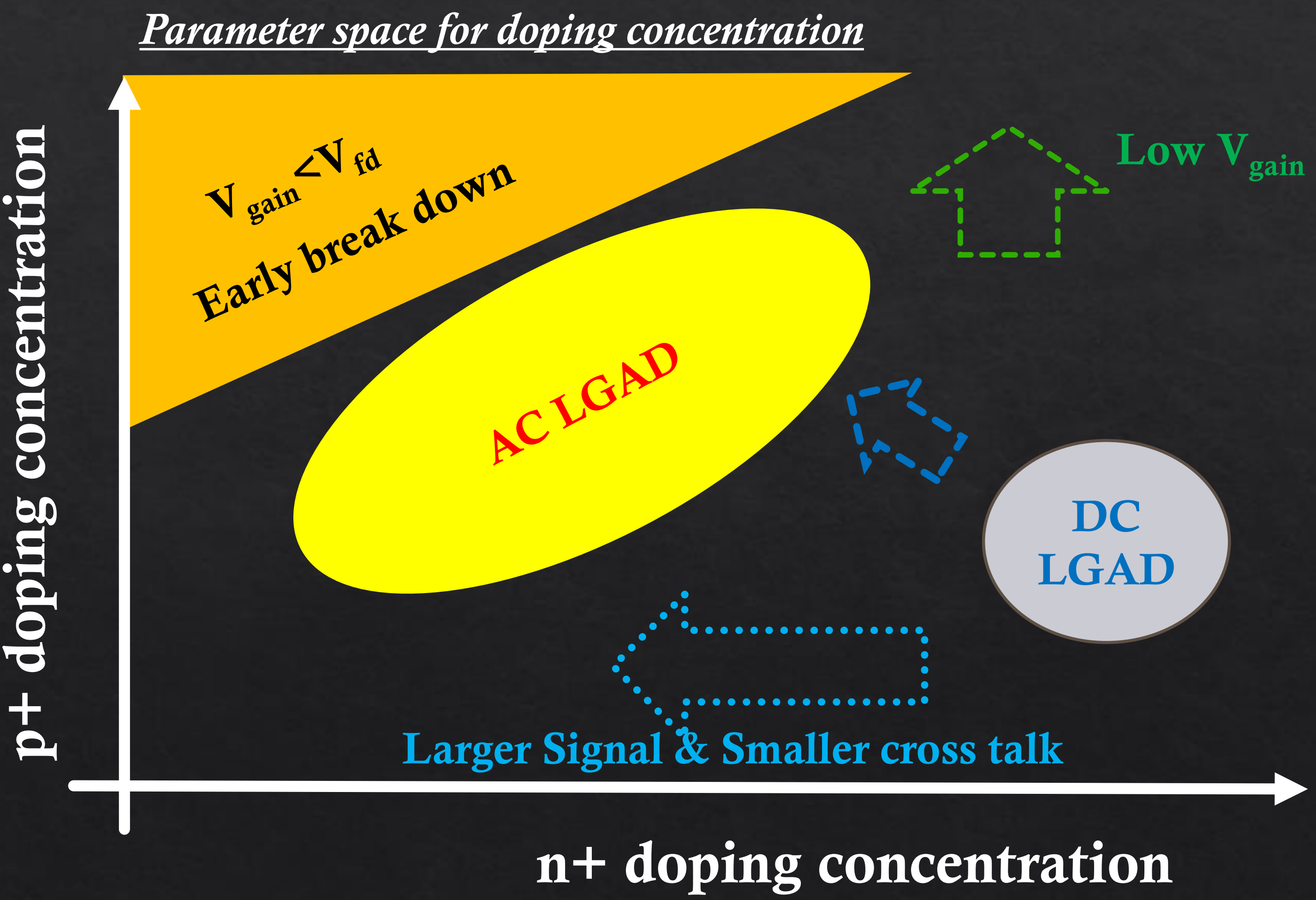
◈ Readout Charge : Q

- 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

Optimization of process parameters

- Parameter space in n+ and p+ doping concentration has been optimized.
  - n+ concentration should be lower than Normal (DC) LGAD to reduce charge sharing (Crosstalk).
  - p+ doping concentration is used to tune operational voltage (i.e. avalanche voltage)

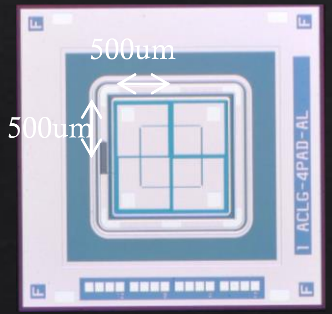




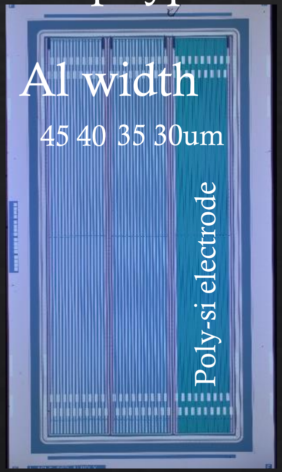
Optimization of process parameters

- 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**
  - Pixel type : 50um sq. 14x14 electrode

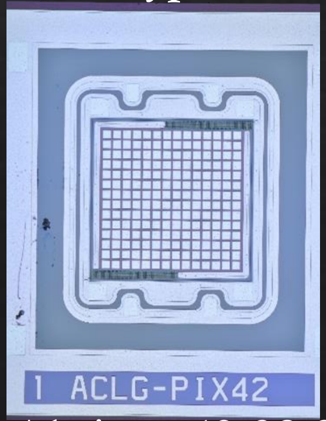
Pad type



Strip type

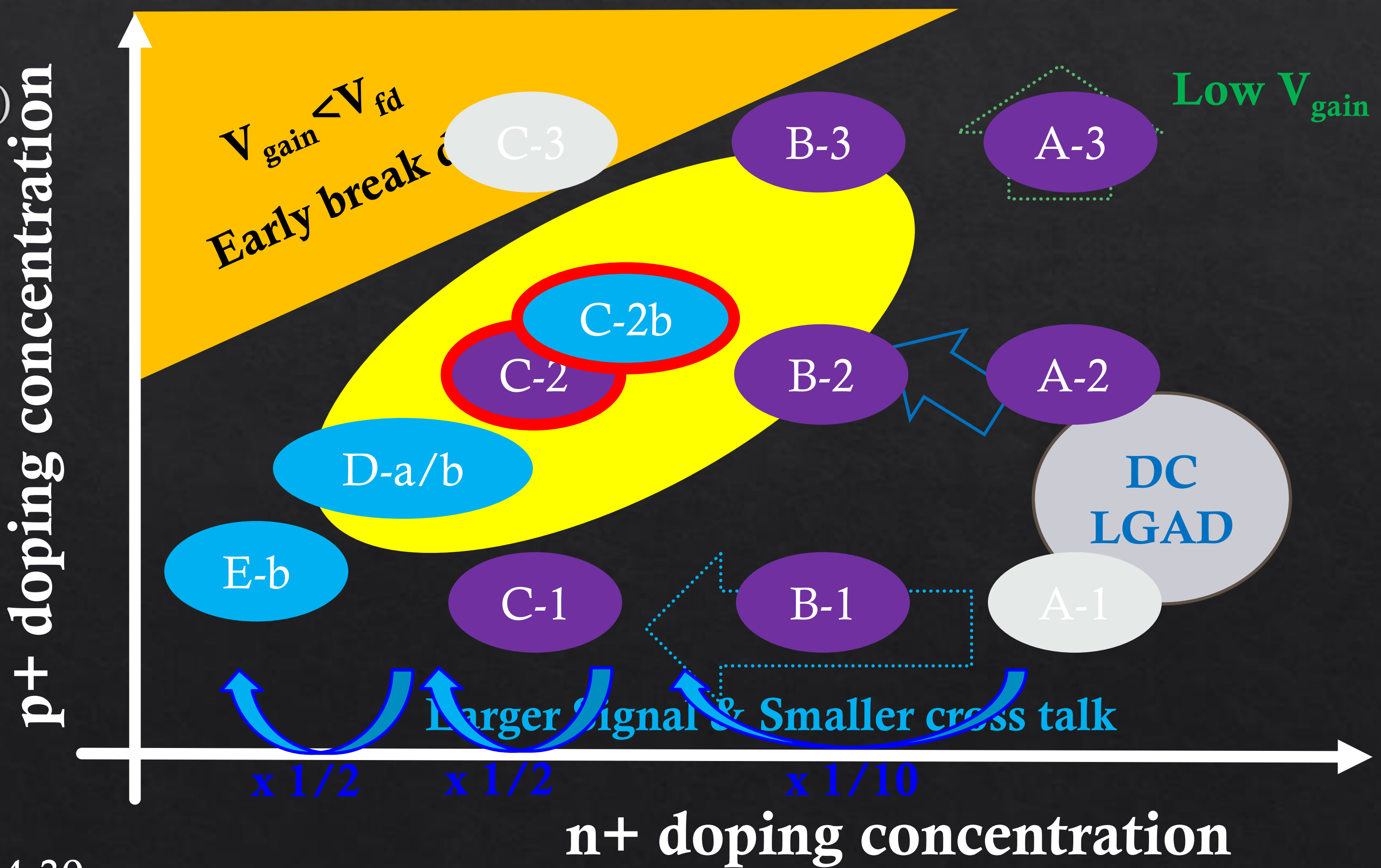


Pixel type



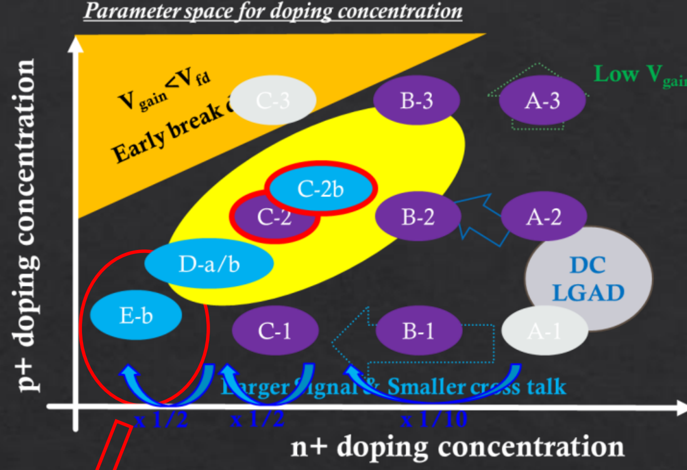
Al size : 42,38,34,30um

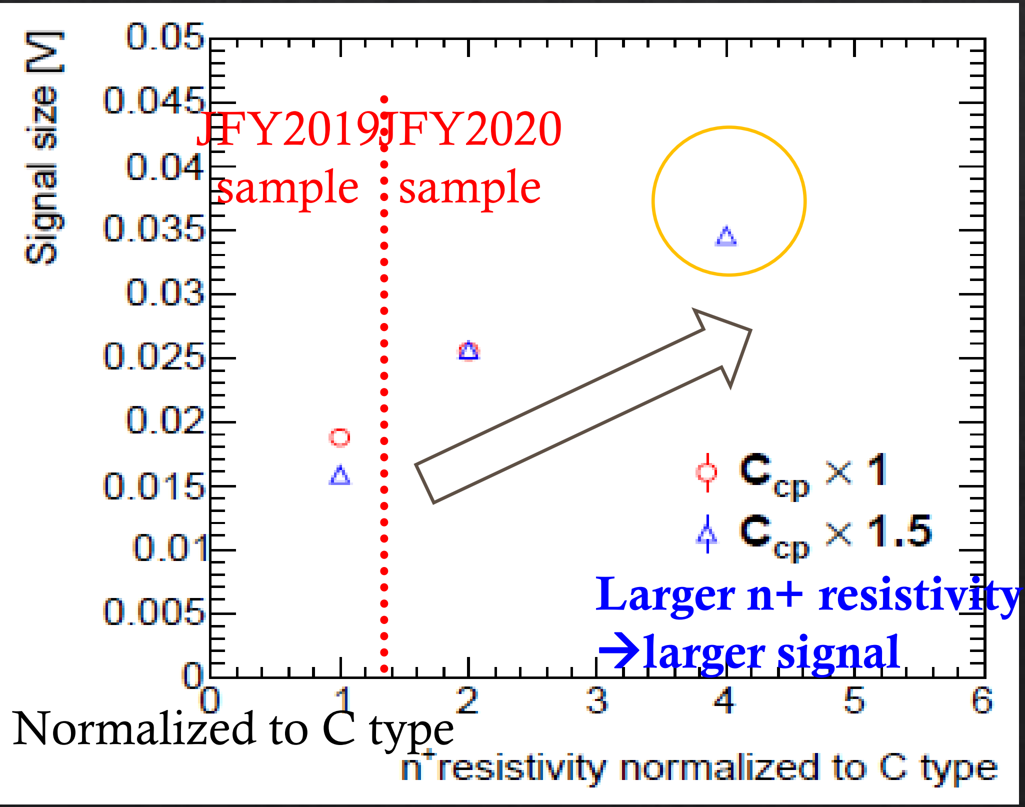
Parameter space for doping concentration

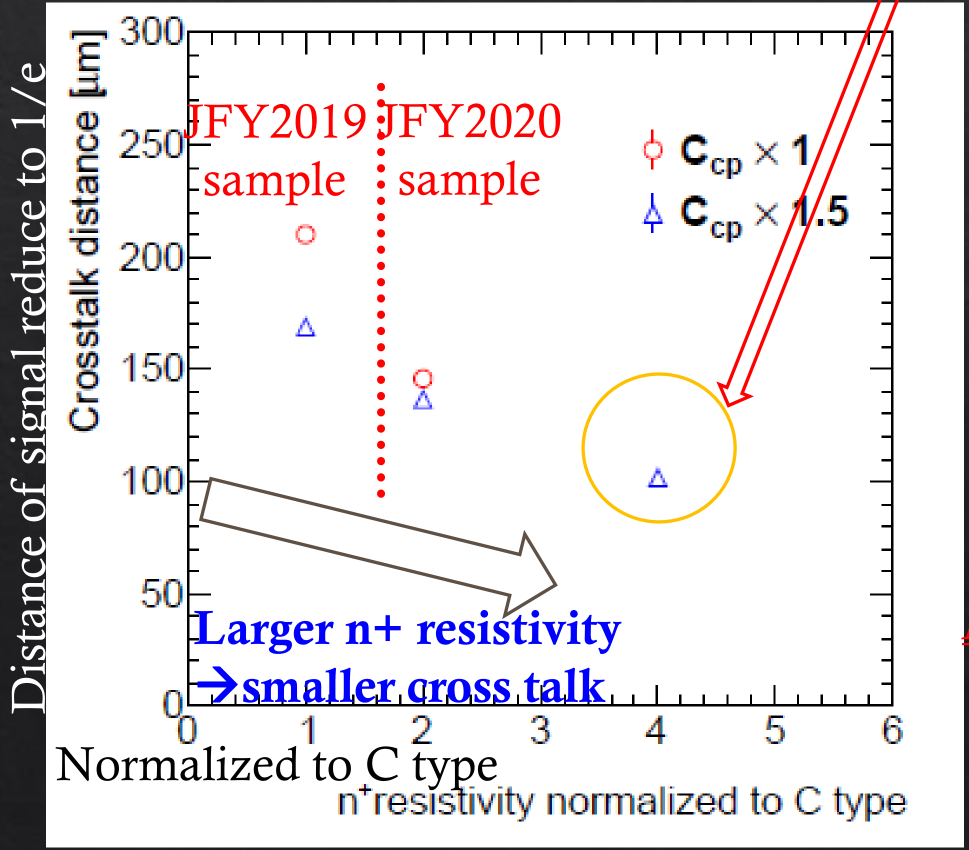


Signal size and crosstalk

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







All C to E types works fine.
→ Can choose depends on application

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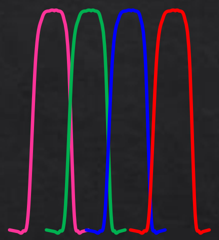
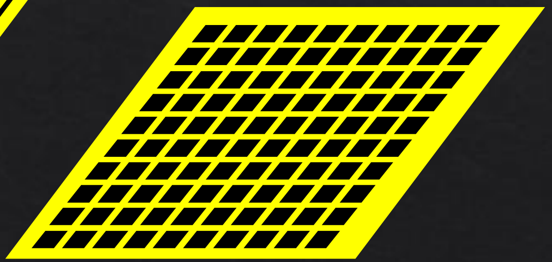
Two approaches to have good spatial resolution

- ***Fine pitch electrode approach***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : smaller occupancy and smaller data size like digital readout**
  - **Cons. : Limitation of spatial resolution by electrode size. # of channels get huge…**

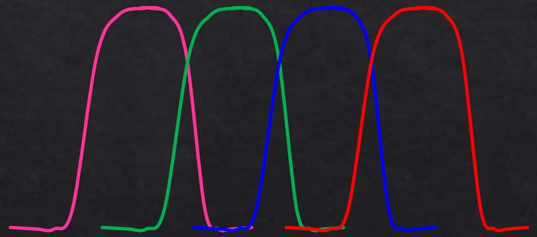
Fine pitch strip with narrow Al
(to reduce inter strip cap.)

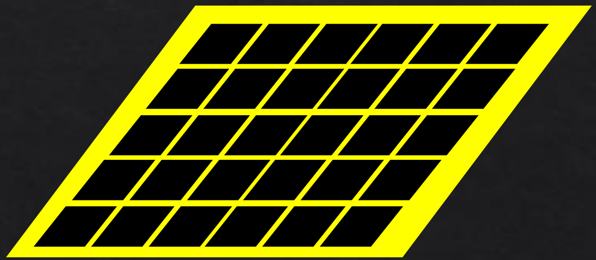




HPK strip/pixel approach

- ***Charge sharing approach***
  - **For lepton collider or other low occupancy colliders.**
  - Reconstruct particle position using charge sharing (charge fraction to next channels)
    - Relatively low n+ implant resistivity
  - **Pros. : Very good spatial resolution if high resolution ADC used.**
  - **Cons. : Smaller signal size. Need high resolution ADC.**



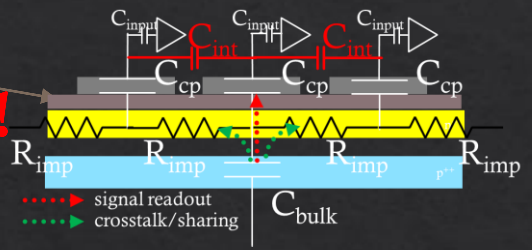


HPK pad and BNL sensor approach

How small electrode could we achieve?

Used thinner di-electric layer (Oxide layer)

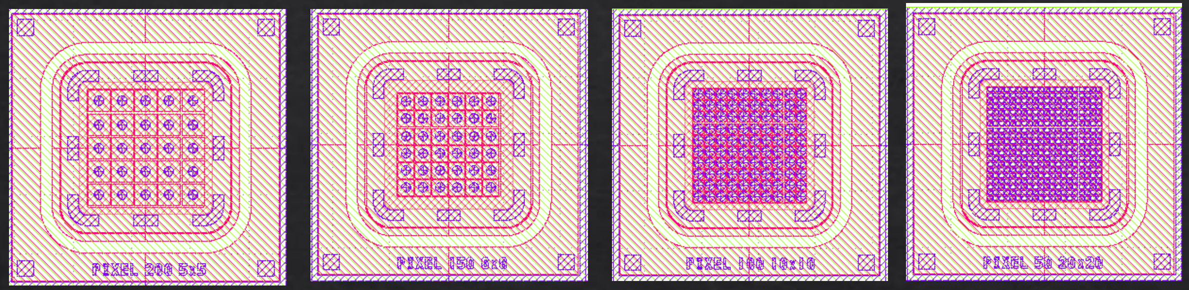
→ Electrode capacitance increased by factor of 5 !!



Pixel sensor

- Various of pitch

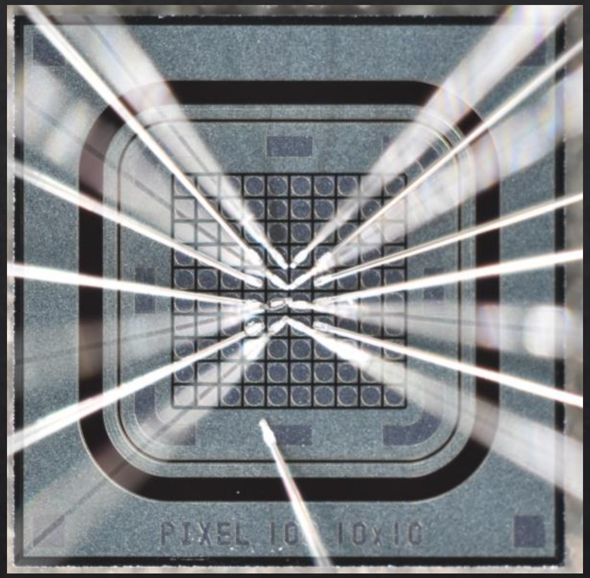
200um 150um 100um 50um



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

R_{imp} [Ω/□] vs. C_{cp} [pF/mm²]

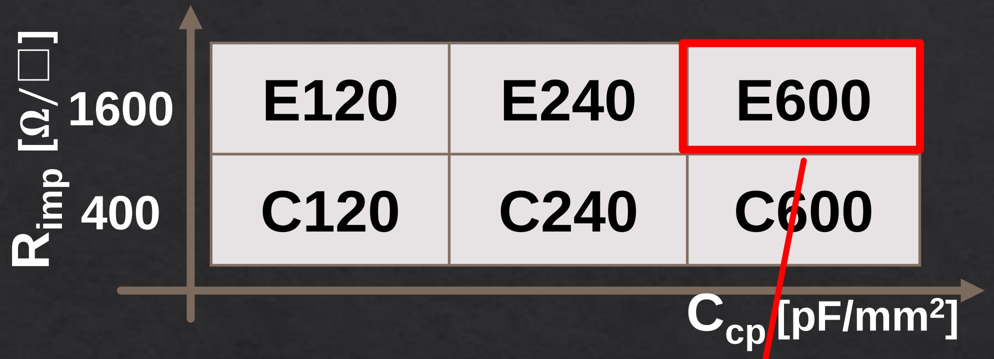
R_{imp} [Ω/□]			
1600	E120	E240	E600
400	C120	C240	C600



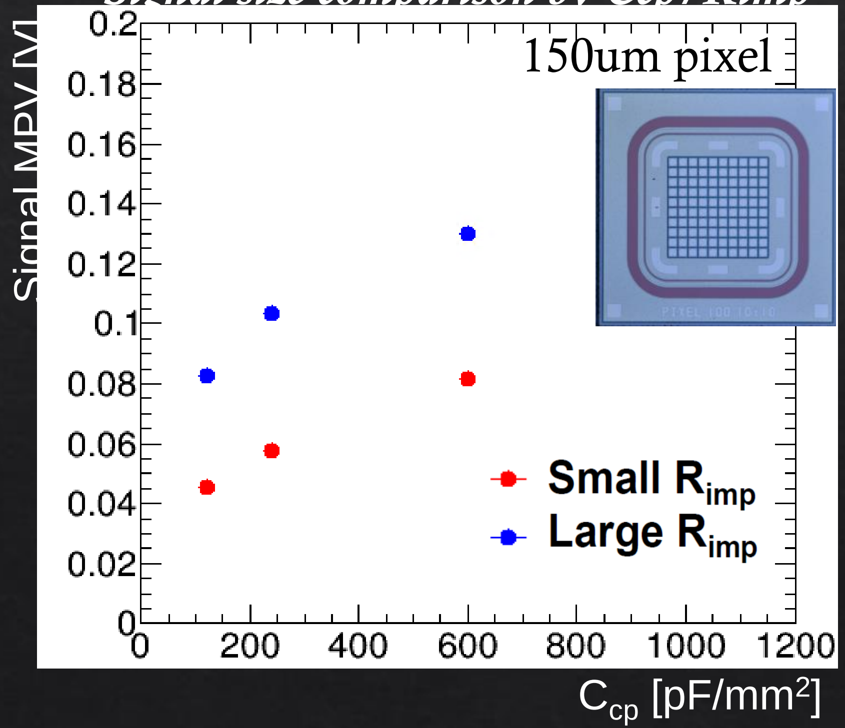
50um pitch electrode sensor has not been yet tested due to difficulty of wire bonding.

How small electrode could we achieve?

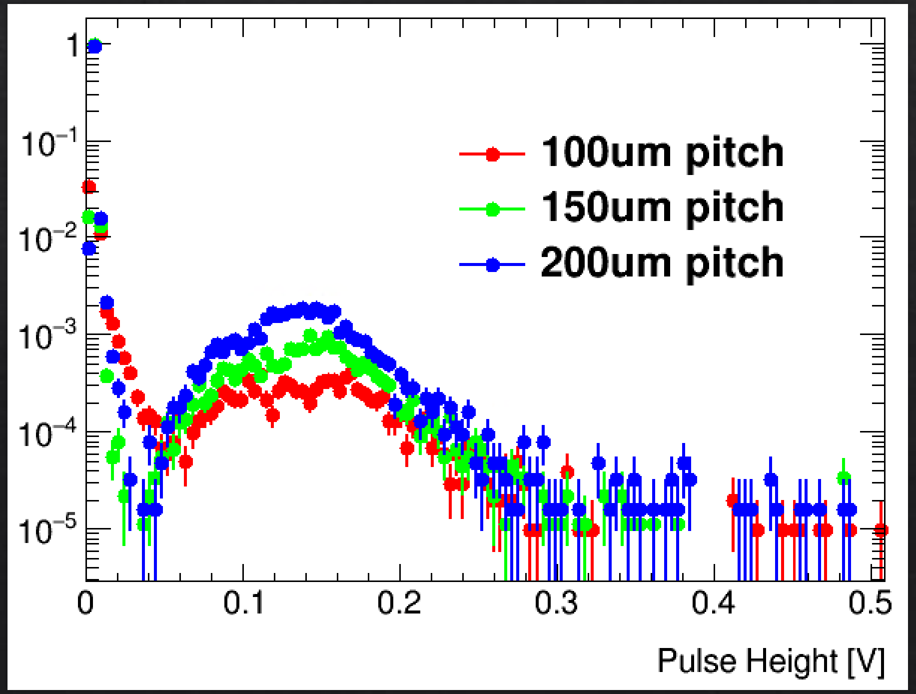
- Compared signal size of 6 types C_{cp}/R_{imp}.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types
- Compared signal size of 3 pixel size
  - 100/150/200um pitches are compared.

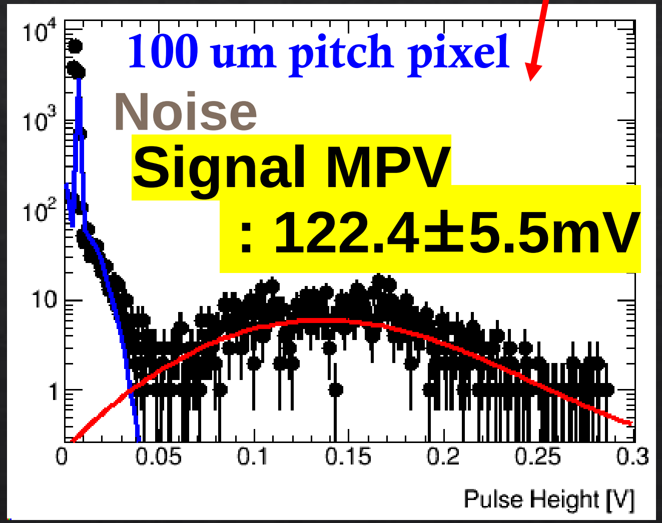


Signal size comparison by Ccp/Rimp



Pulse height comparison by pixel pitches



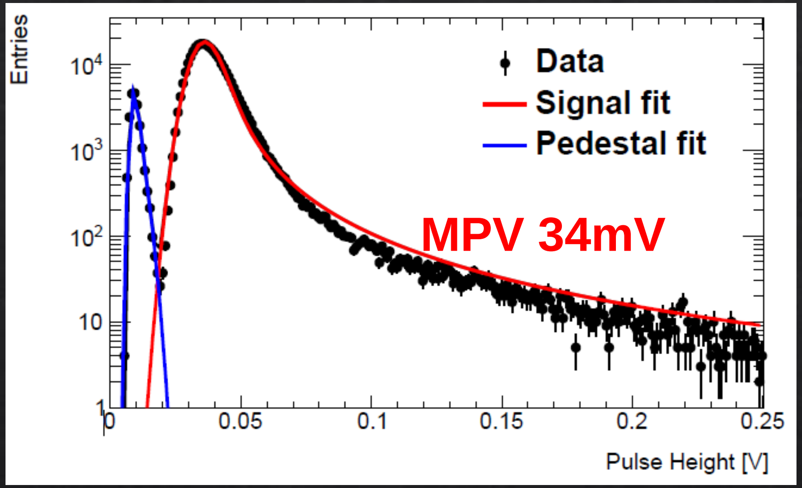


Successfully developed Good S/N 100um pitch pixel detector!

Is Strip type electrode possible?

- For collider experiments, outer layers should use Strip type electrode to reduce readout channels.

80um pitch Strip



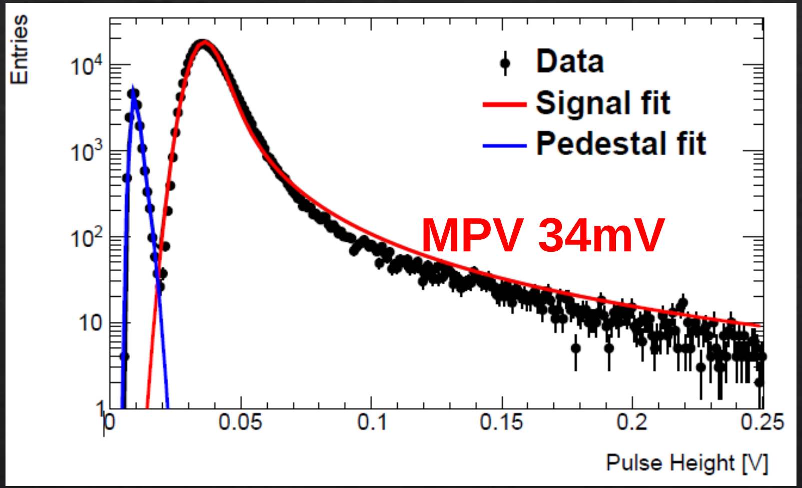
Successfully developed
Good S/N 80um pitch strip detector!

Is Strip type electrode possible?

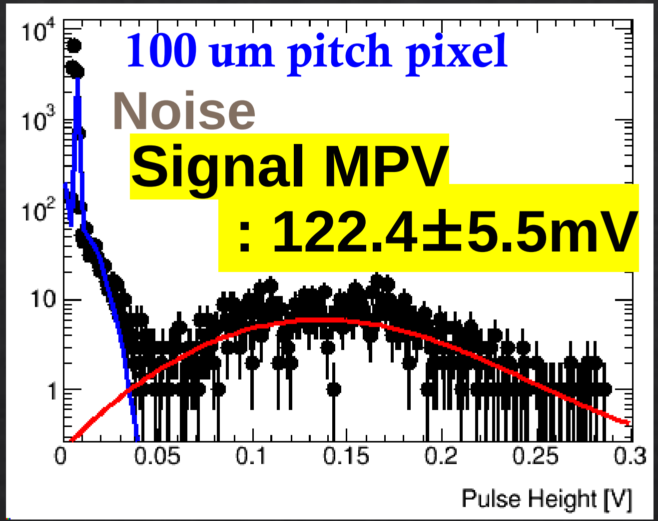
- For collider experiments, outer layers should use Strip type electrode to reduce readout channels.

However, the signal size is much smaller than pixel sensors

80um pitch Strip



(c.f.)



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

Why so small signal?

How much effect of interstrip capacitance?

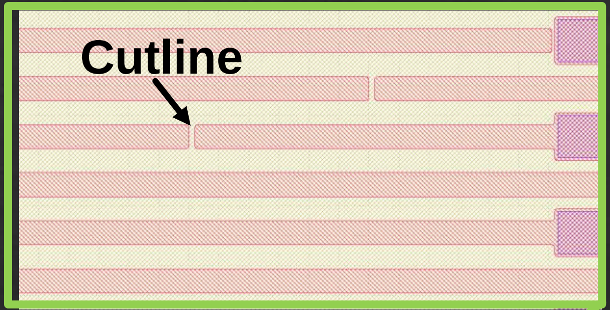
Significantly smaller signal compared with pad type detector.

How much signal attenuation in the strip?

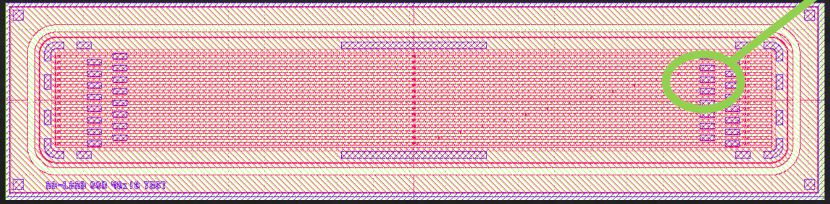
This might affect to the signal size un-uniformity and delay of signal readout.

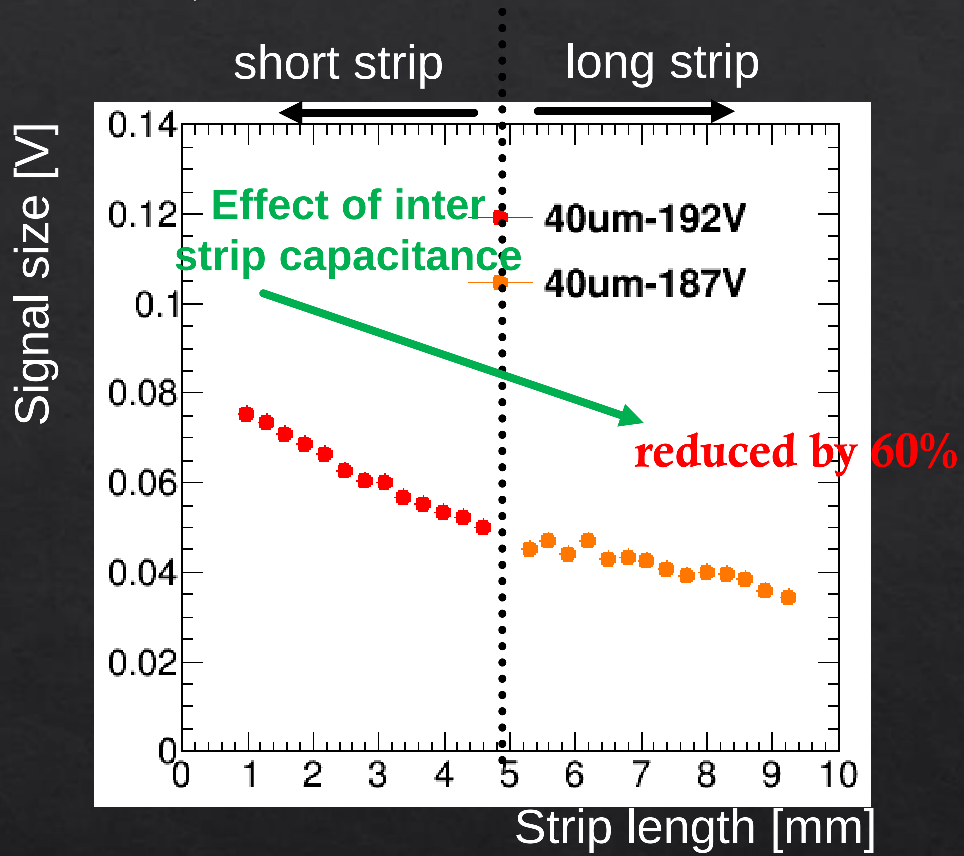
Inter strip capacitance (Cint) effect

Strip sensor with cut line



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

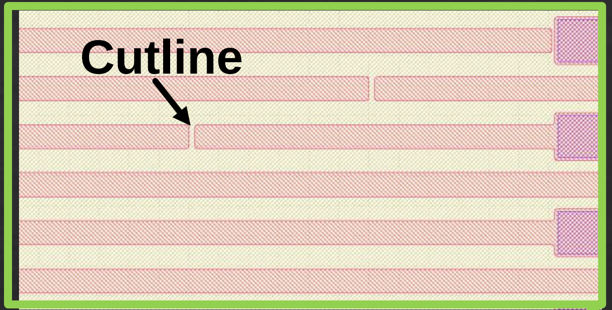




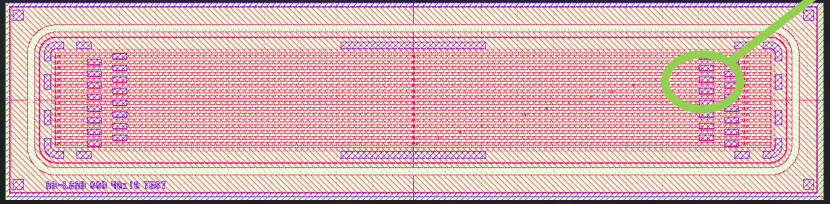
Where signal disappeared?

Inter strip capacitance (Cint) effect

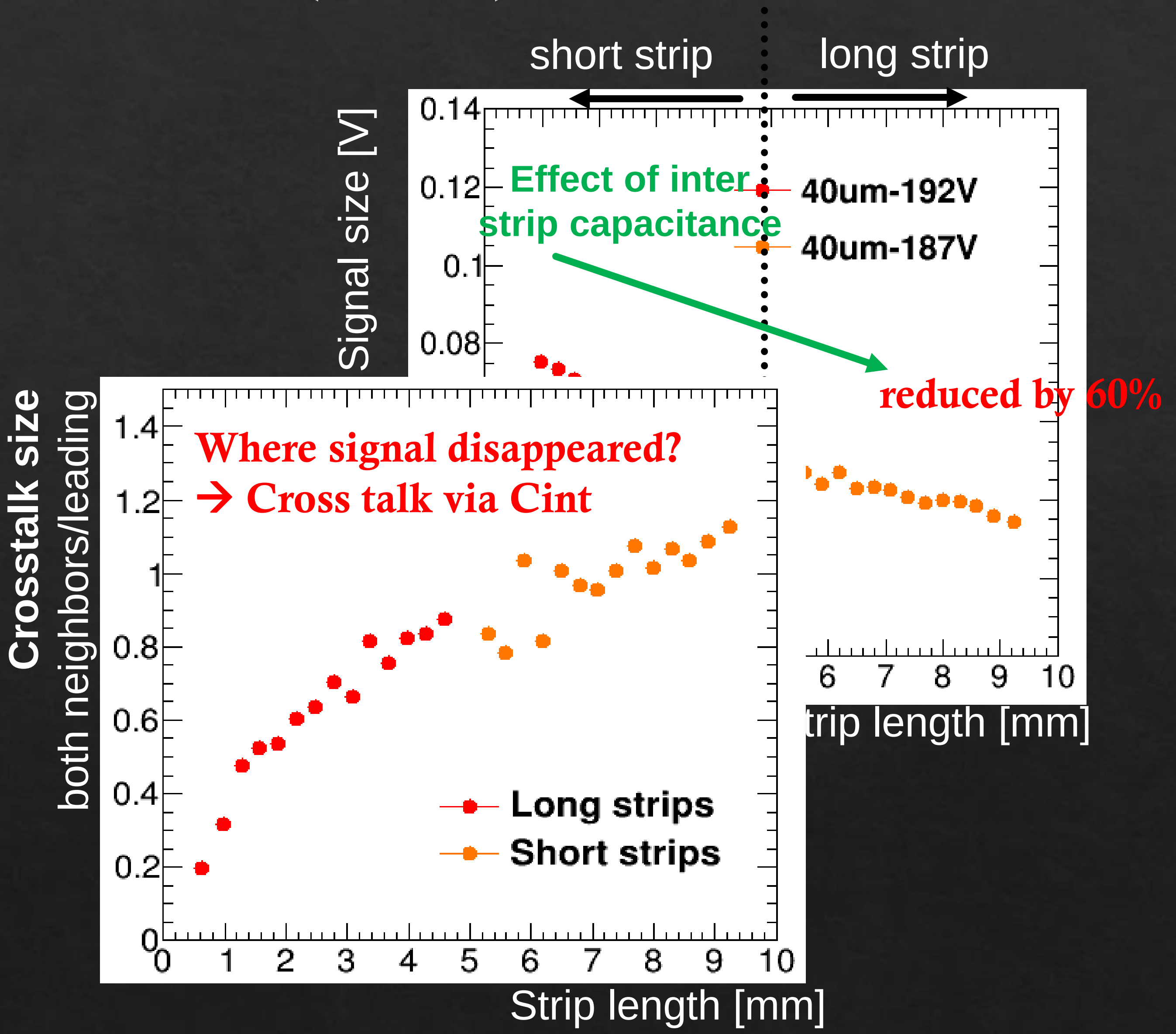
<u>Strip sensor with cut line</u>



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

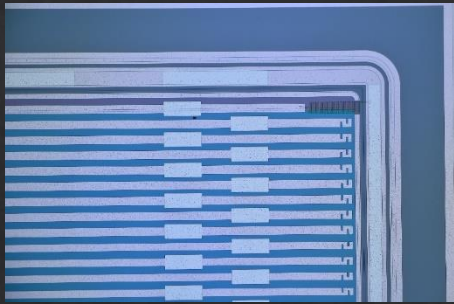


16 strips x 2



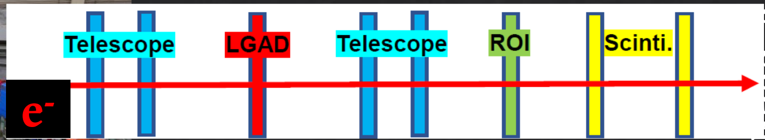
Position reconstruction by fine pitch approach

- HPK 80um pitch strip sensor with highest implant resistivity (E-b type)
  - Position resolution : 23um($80um/\sqrt{12}$) is expected in case of binary readout



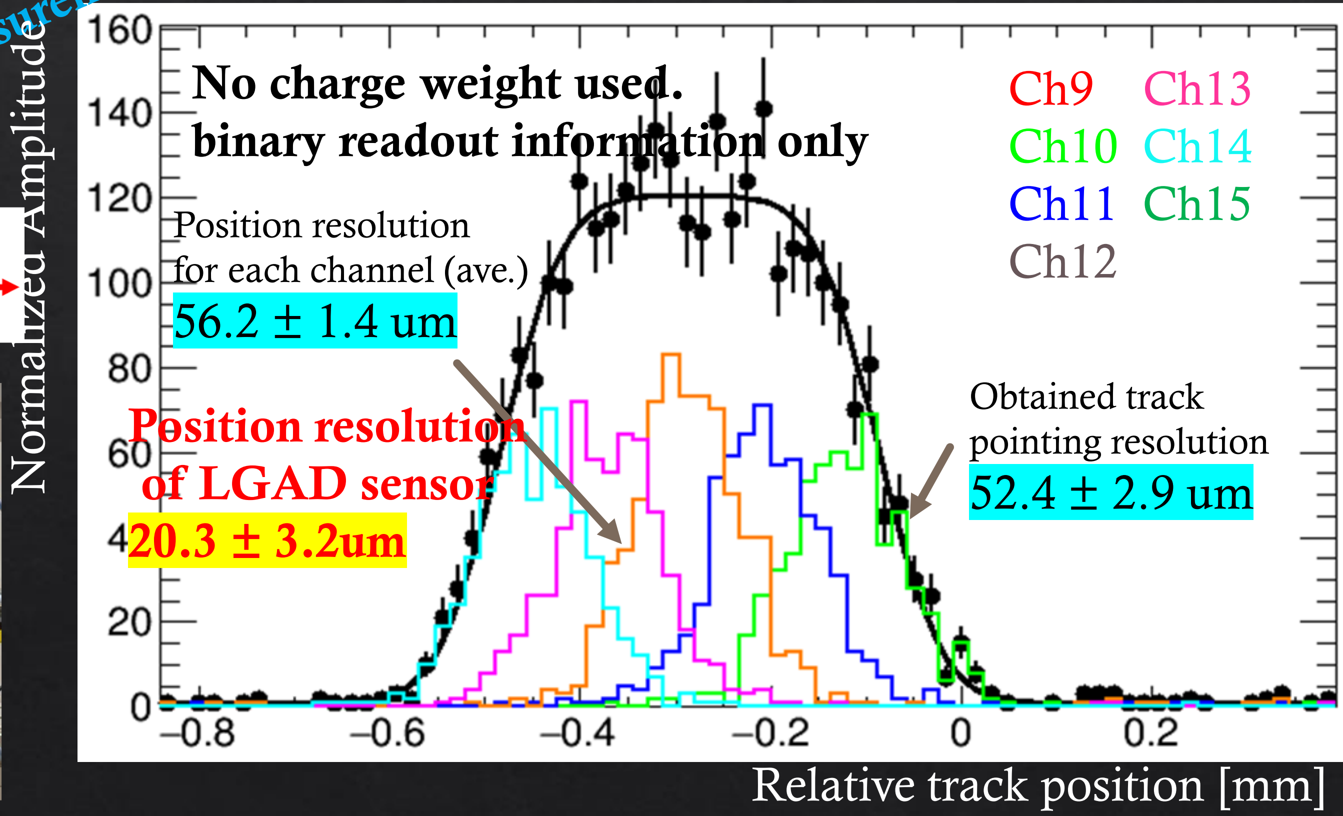
- Testbeam @ Tohoku University (ELPH)
  - 800MeV electron beam
  - Trigger rate : 200-400Hz
  - Strip E-b type 170V @ 20^{o}C

High Multiple-Scattering effect
Just repeated measurement at 120GeV proton



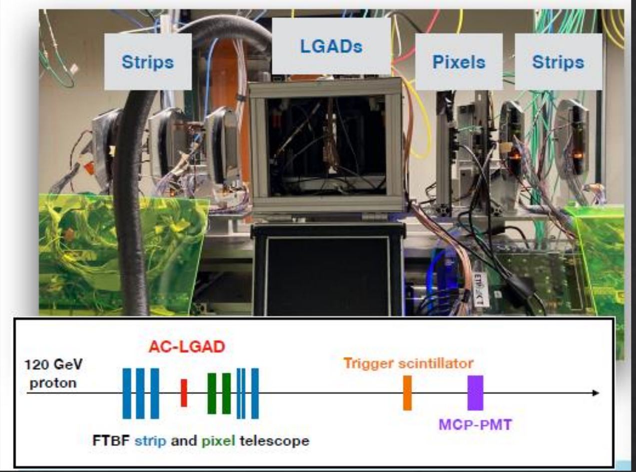
4 layer of Telescope
(25um x 500um pixel)
Trigger by scintillator
Specify region (ROI)

Amplitude distribution with residual

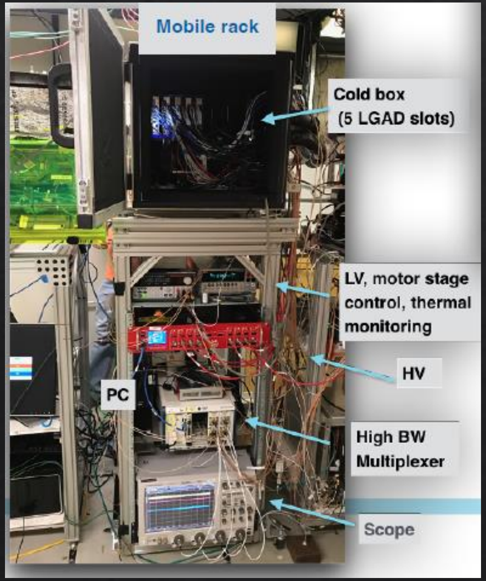


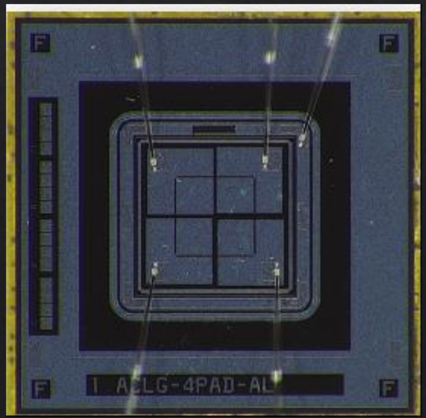
Position reconstruction using charge sharing

- Fermilab group is measuring our sample at Fermilab TestBeam Facility (FTBF) : 120GeV proton beam



- Permanent setup in FTBF
  - Movable : slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls : sensor temperature (-25°C to 20°C), and humidity, monitoring
  - Time reference with ~10ps resolution (Photeck PMT240 : MCP)
  - DAQ : high bandwidth, high ADC resolution 8-channel scope (LeCroy WR8208)

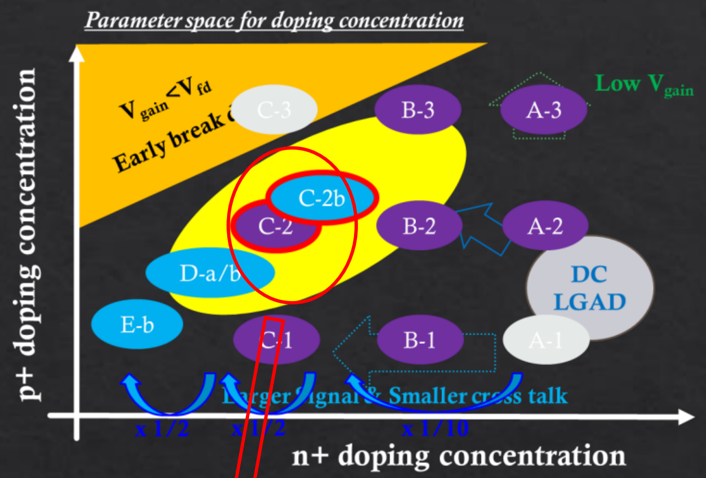




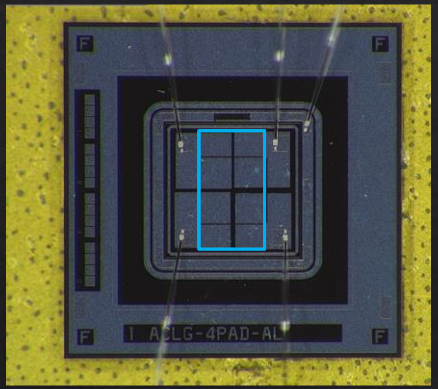
Tested :
2x2 pad (500um x 500um electrode size)
Three different thickness : 50um, 30um and 20um

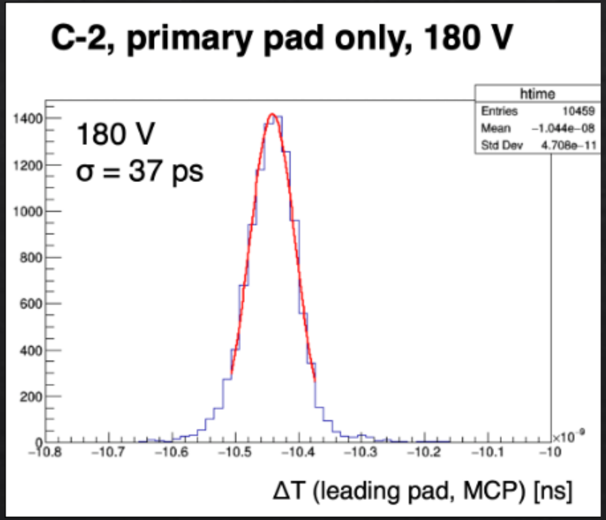
Position reconstruction using charge sharing

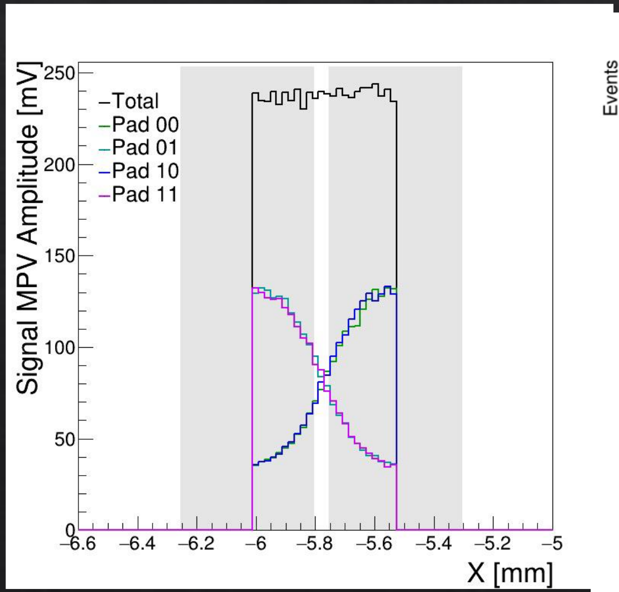
- **Charge Sharing information can be used to have position even pad sensor**
  - Fermilab testbeam at Feb 2021, HPK ACLGAD (Pad type)
  - 500um☐ pad sensor with C-2 type instead of best type E-b
  - **Timing resolution 37ps**
  - **Position resolution in middle 500um area : 15um resolution including tracker resolution.**

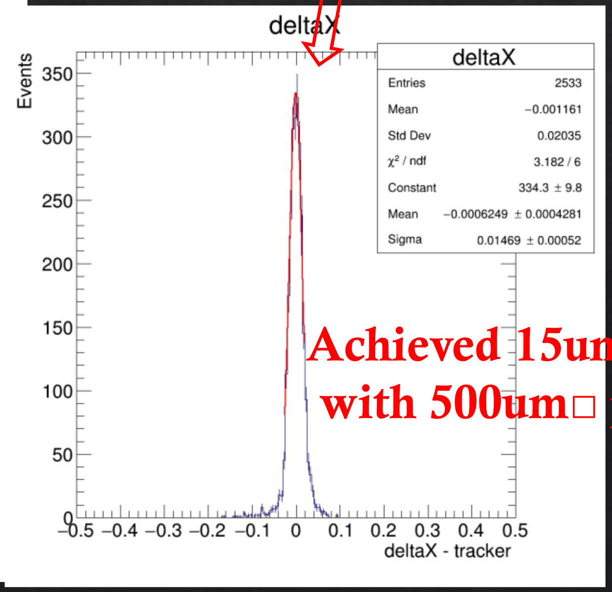


HPK AC-LGAD Pad (C-2 type)









Achieved 15um resolution with 500um□ pad sensor

Measurement of timing resolution

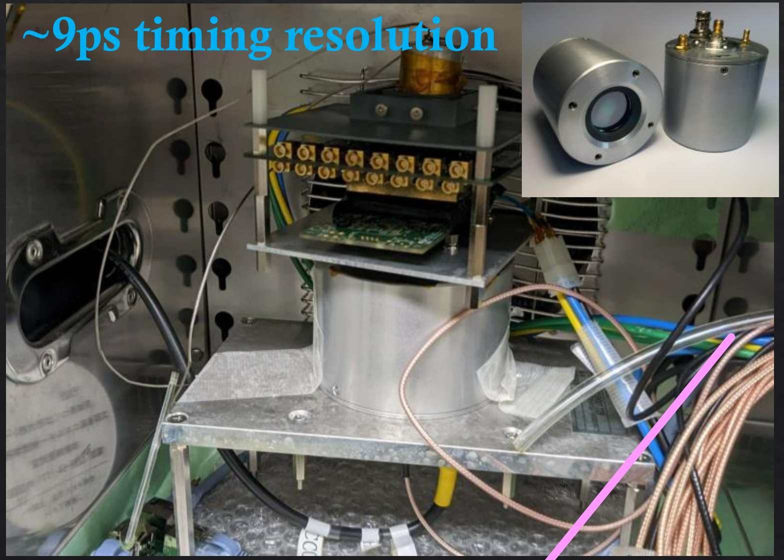
- Measurement of timing resolution for fine electrode sensors are challenging.
  - Taking time if we use two layer coincidence

Old method

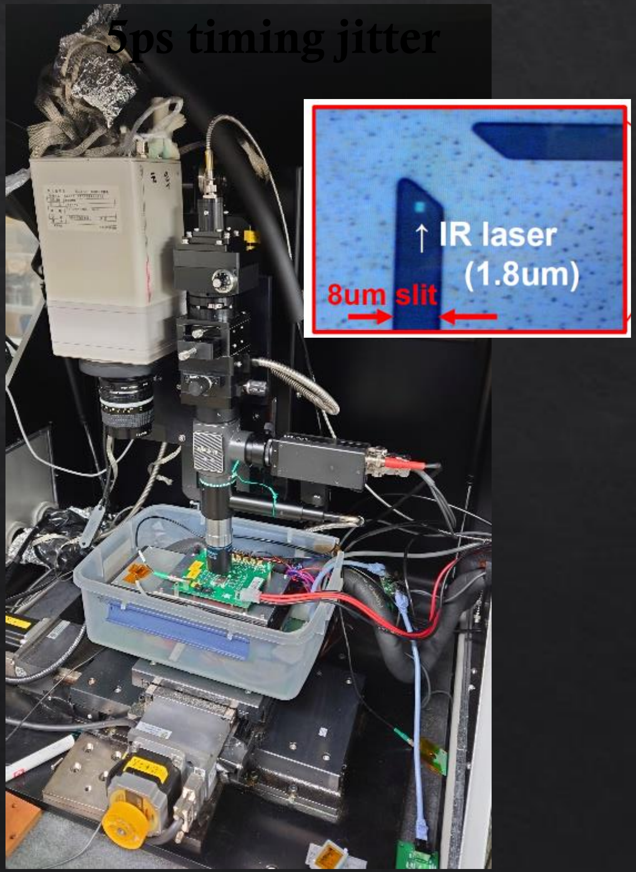
2 layer coincidence

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

Photek PMT 240 (^{90}Sr source)



Infra-Red (pico sec) laser



Timing resolution

$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

~~σ_{tw}:Time walk~~

σ_j: Jitter (electronics) **MIP** **IR**

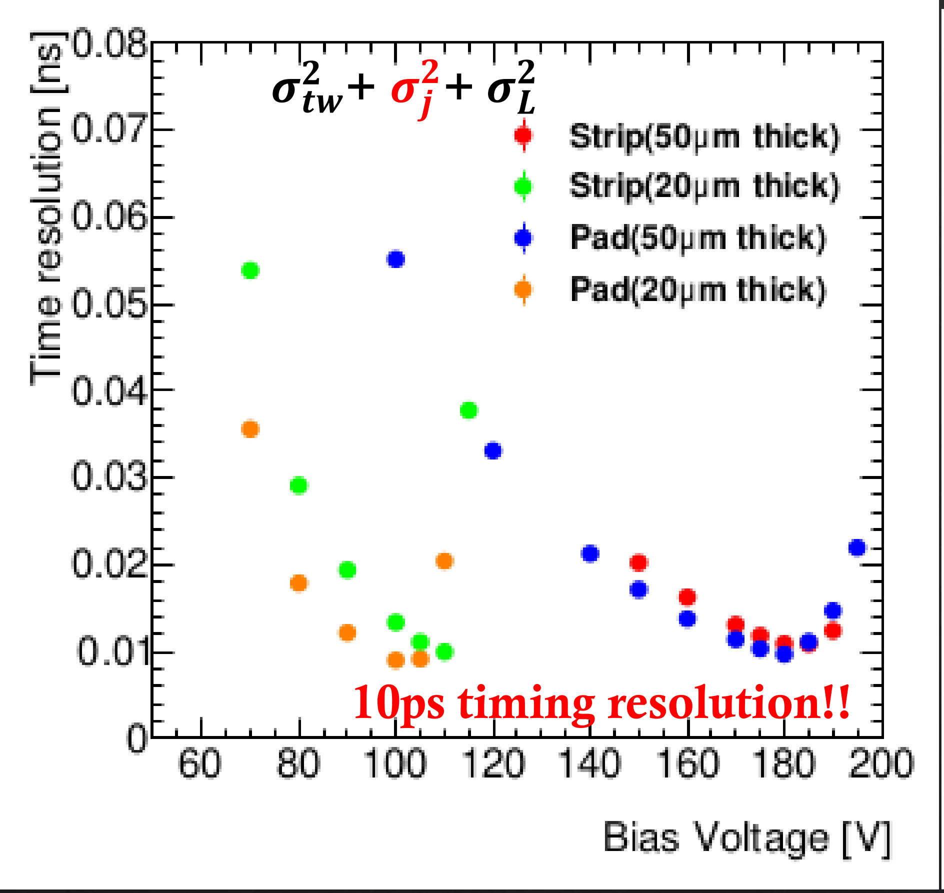
σ_L: Landau noise **MIP**

- Photek PMT240 (MCP-PMT)
  - Mes. Of timing resolution to MIP
  - **9ps PMT240 resolution (reference)**
  - **Don't know injecting position.**
- Infra-red (pico sec) laser
  - Known injecting position(Size : 1.8um)
  - **5ps jitter**
  - **No landau noise**

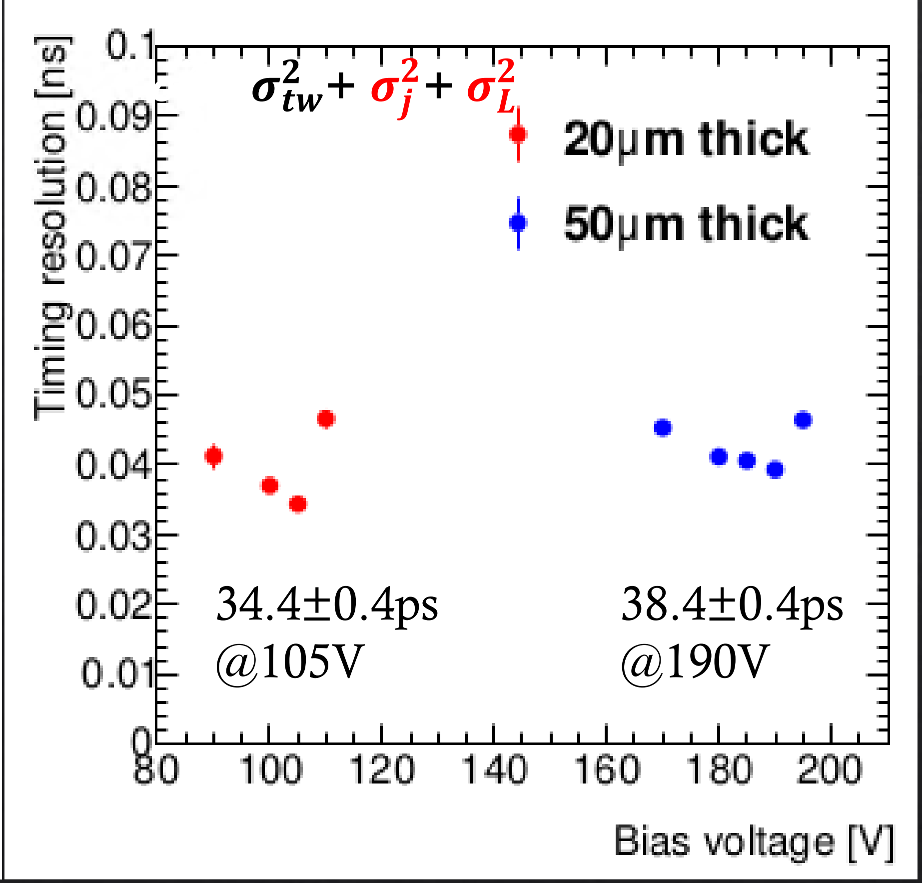
Timing resolution results

- Timing resolution measurement by two methods

Infra-red laser (E_{dep}~ a few times MIP)



Beta-ray measurement



$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

By laser measurement, calculated noise for each Volt.

Calculate jitter for MIP meas.
Evaluated Landau term.

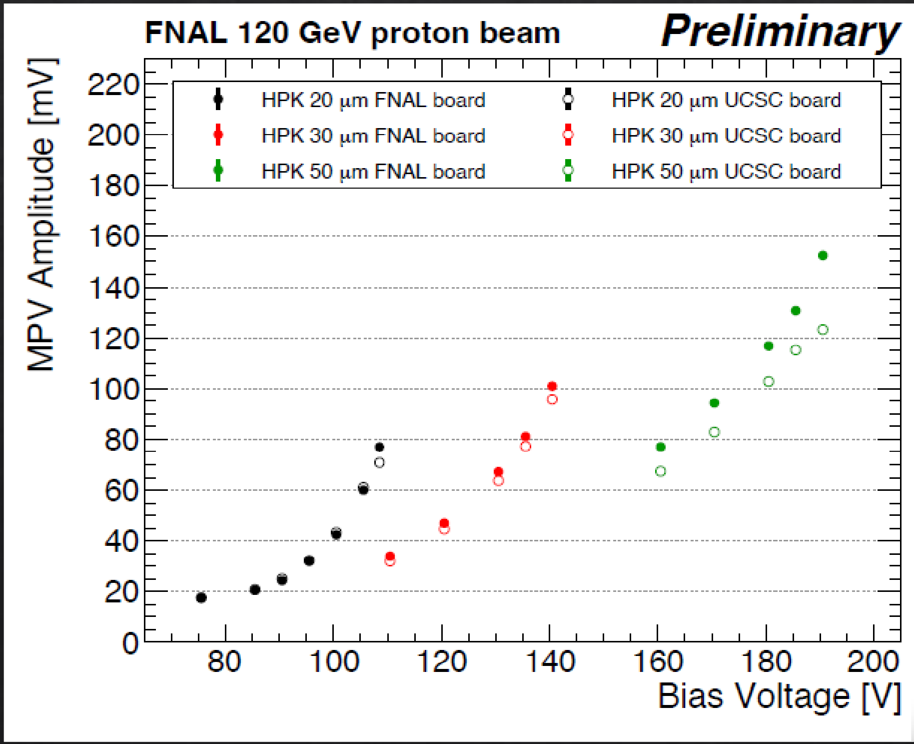
	t=50um	t=20um
σ_t	38.4ps	34.4ps
σ_j	26.8ps	30.7ps
σ_L	27.1ps	15.5ps

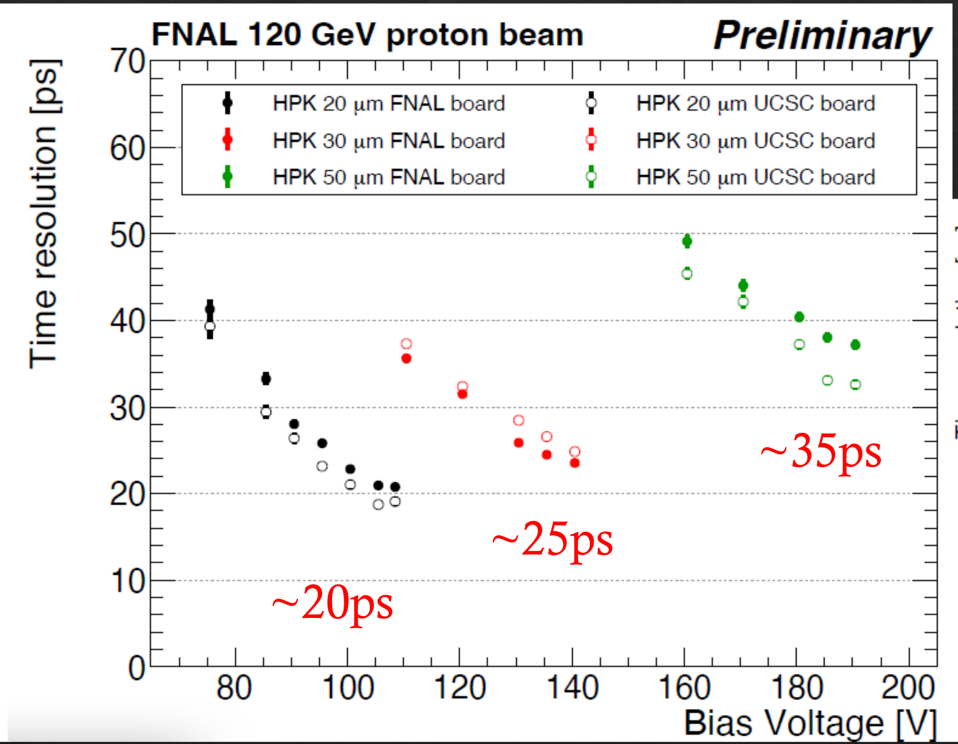
20um sensor have smaller landau term in timing resolution.

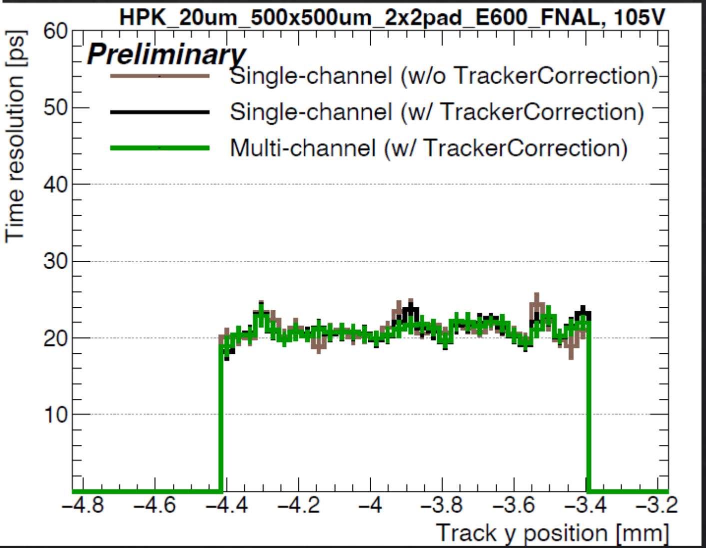
Need to reduce jitter to obtain better timing resolution →ASIC?

Timing resolution measurement at testbeam

- Results for 2x2 pad sensors with 50um, 30um and 20um thickness
  - Signal size (amplitude) is smaller in thinner sensors.
  - 20um thick sensor has the best timing resolution : ~20ps
  - Uniform timing resolution at the gap region as well.





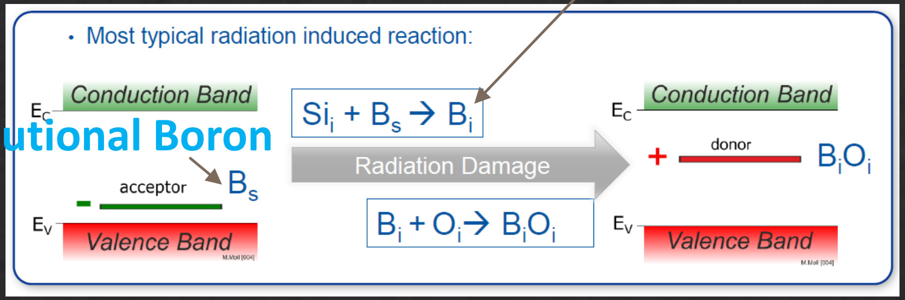


Radiation tolerance of LGAD detector

- Like normal silicon device
  - Bulk damage (NIEL) : Si lattice damage
  - Surface damage (TID) : charge up at SiO_2-Si
- **In addition "Acceptor Removal"**
  - *p*+ in Gain layer reduced

Interstitial Boron

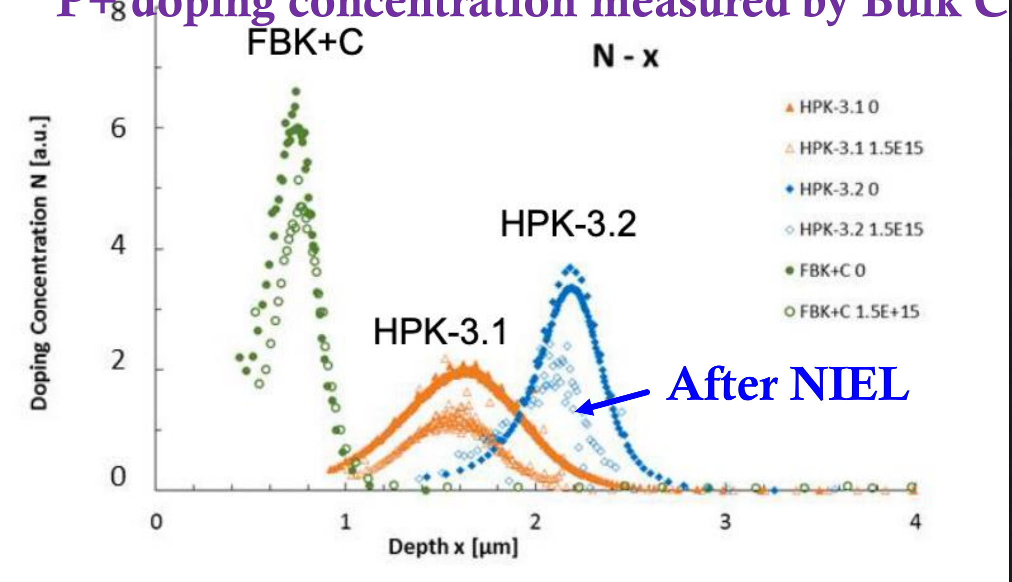
Substitutional Boron

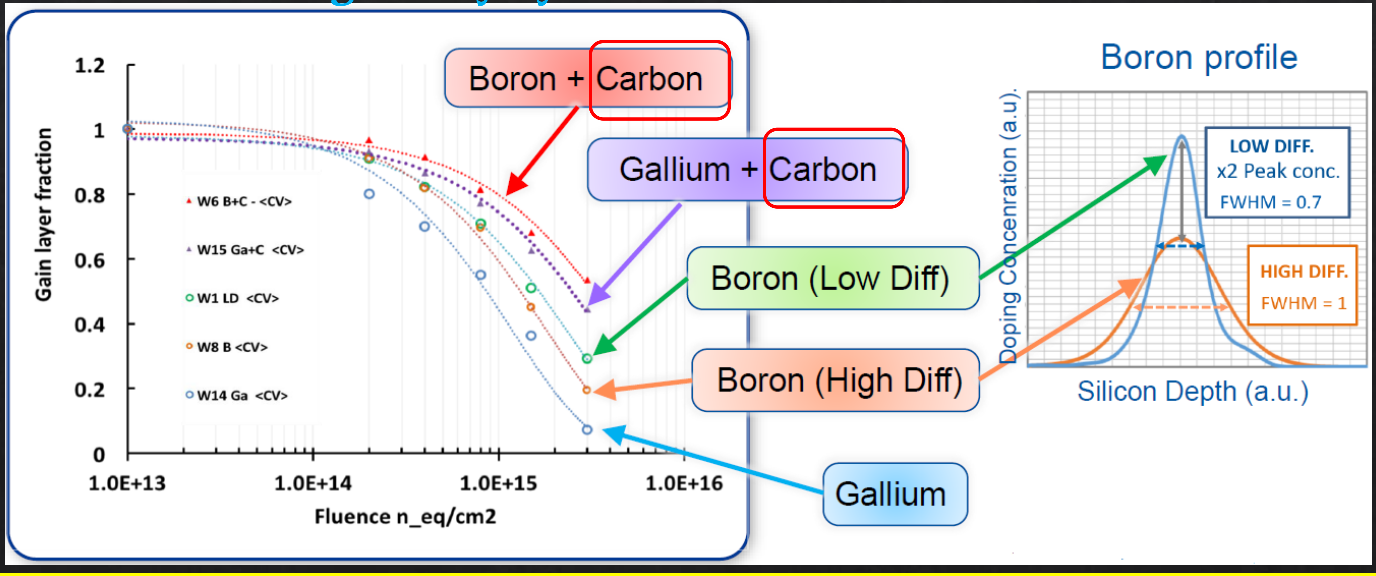


Carbon annealing $B_i + C_s \rightarrow B_iC_s^* \rightarrow B_s + C_i$

Radiation damage study by FBK sensors

P+ doping concentration measured by Bulk C



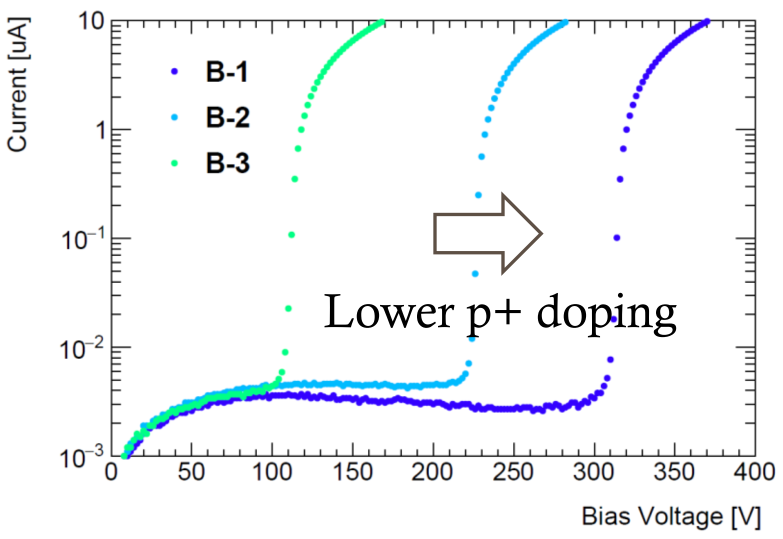


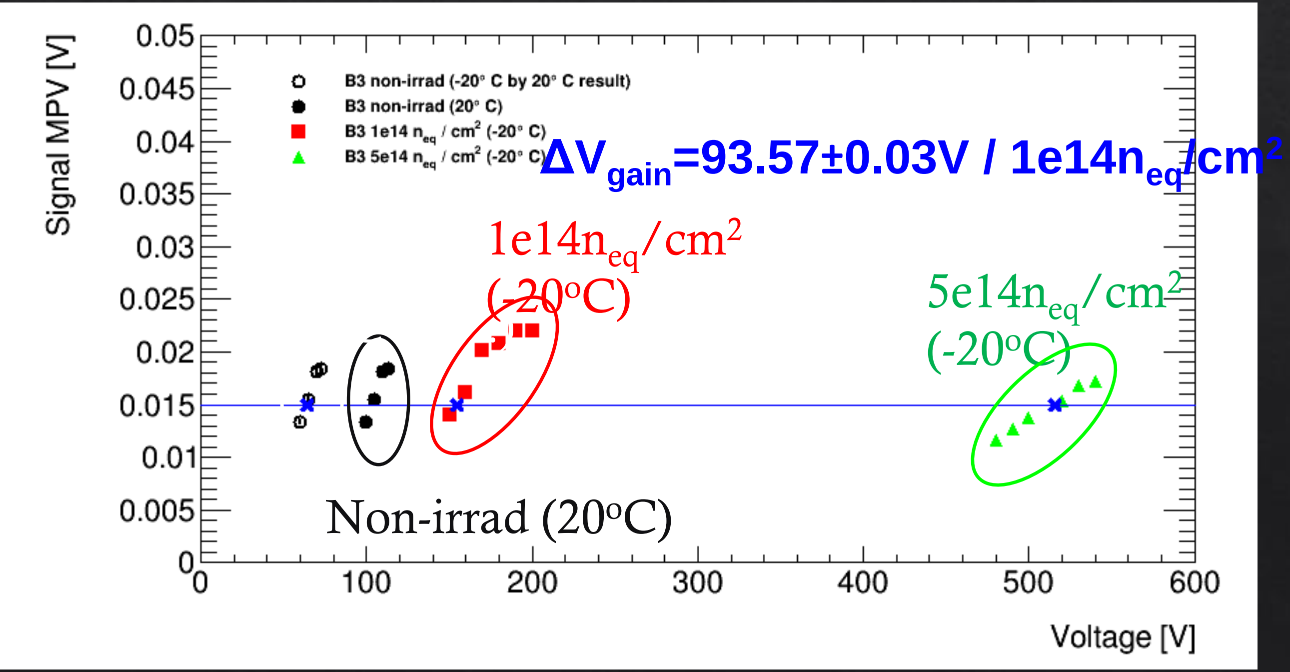
Depends on : *p*+ concentration, type of dopant and diffusion of p+

Why is the acceptor removal issue?

- Reducing active shallow dopant increase Avalanche voltage.
  - Confirmed by non-irrad samples with different p+ concentration.
  - Operational voltage increase and get over voltage limit of device.
  - Current limit is 1-2 x 10^{15}neq/cm^2

Non-irrad : p+ dope dependence





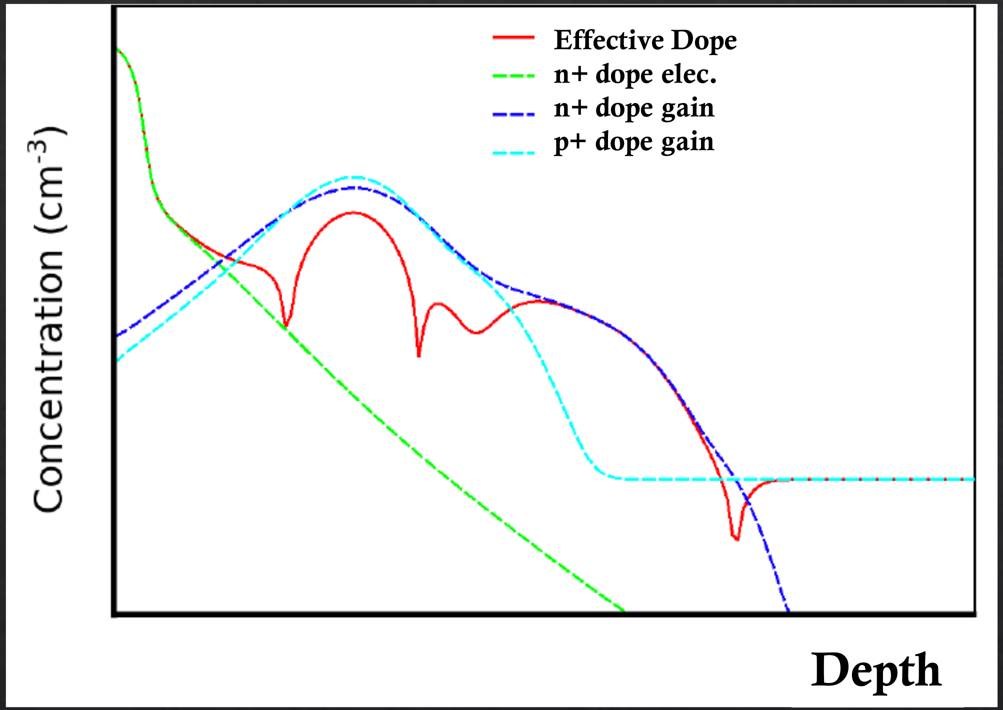
Drastic improvement is necessary to use in Future hadron colliders.

New idea for improvement?

- The issue is :
  - electrically active shallow acceptors are transformed into defect complexes that are no longer having the properties of those shallow dopants.
- New idea
  - Carbon annealing **(not possible by HPK)**
    - Improvement is just a factor of 2 or so…
  - **Compensation method**
    - Add Boron + Phosphorus
    - If acceptor removal is smaller than donner removal this method should work!
  - **In-active Boron?**
    - 10 times Bi at the beginning to clean up Oi

Compensation method

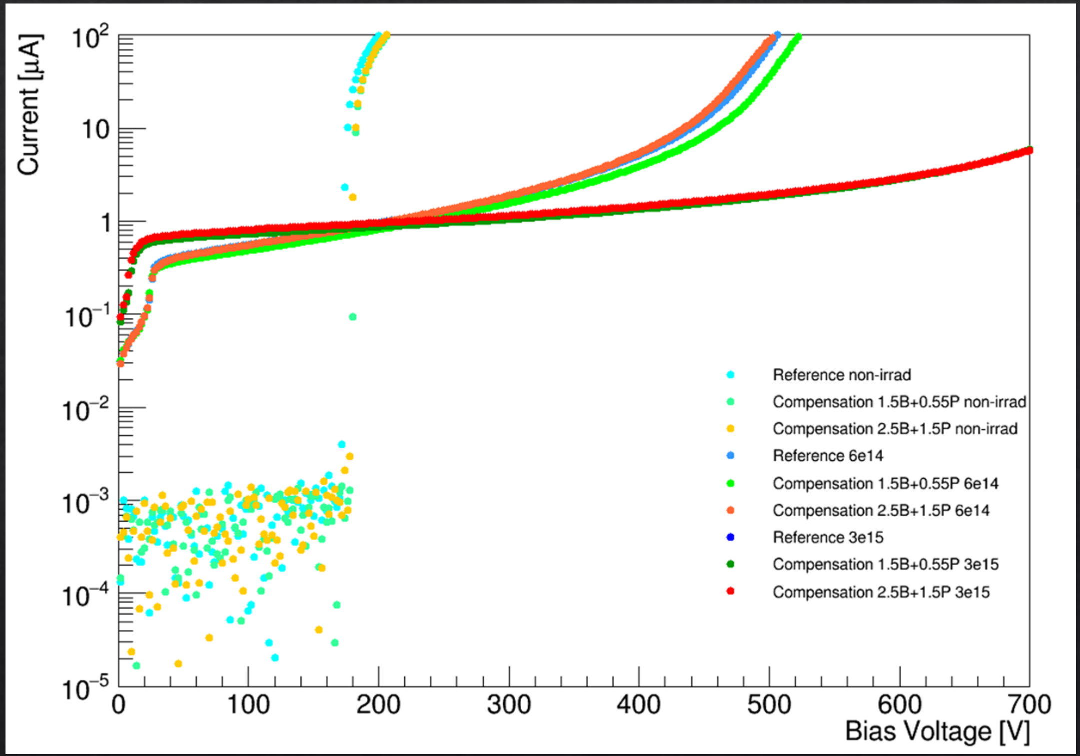
- Both Boron(p+) and Phosphorus(n+) are doped.
  - Operating with effective p+ (difference of p+ and n+)
  - Due to the mass difference of Boron and Phosphorus, depth profile of p+ and n+ are slightly different. (effective dope is not simple Gaussian like depth profile)
  - But we could successfully produced working LGAD sensors with a few types of compensation parameters.



Irradiation has been performed first compensation prototype (DC-LGAD) in January 2023 and measured quickly → we can show first results today!

Radiation tolerance results of Compensation LGAD

- Three different conditions are compared
  - Boron and Phosphorus doping
    - 2.5B+1.5P
    - 1.5B+0.55P
    - 1B (reference)
  - 3 different fluence points (non-irrad, 6e14, 3e15 neq/cm^2)
- Result shows not very promising
  - Expected quite big jump of Vbd to either higher or lower.
  - What does this mean?



Removal of Dopant

- Active dopant will reduce by exponential function by fluence (Φ)

$$N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$$

$$N_D(\emptyset) = N_D(0) \cdot e^{-C_D \emptyset}$$

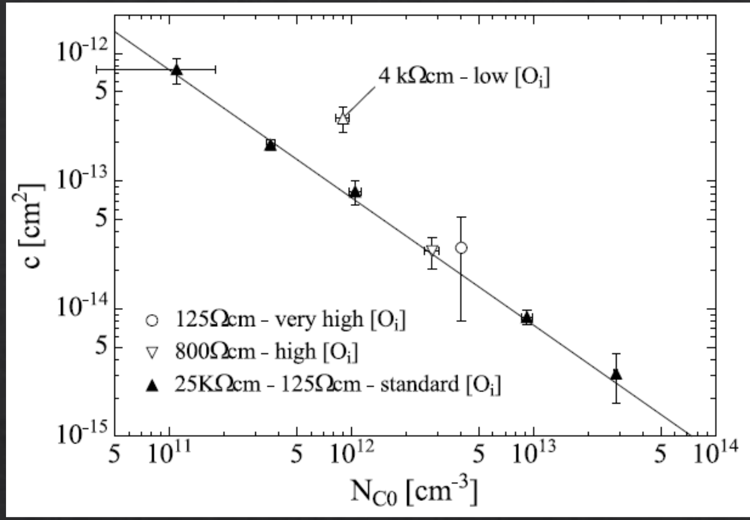
Any idea of CA and CD from past measurement?

CD=2.4 x 10^{-13} cm^2 for phosphorus and CA=2.0 x 10^{-13} cm^2 for boron in very high resistivity p-type and n-type materials (>1kΩcm).
→ How about lower resistivity ? (like 1 x 10^{16} cm^{-3} p+ concentration)

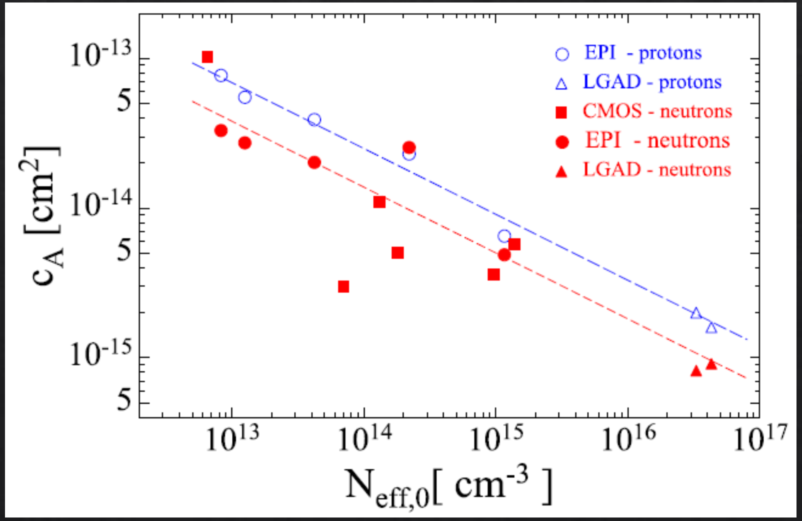
Compensated effective p+ gain layer will change by following formula

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

Donor removal



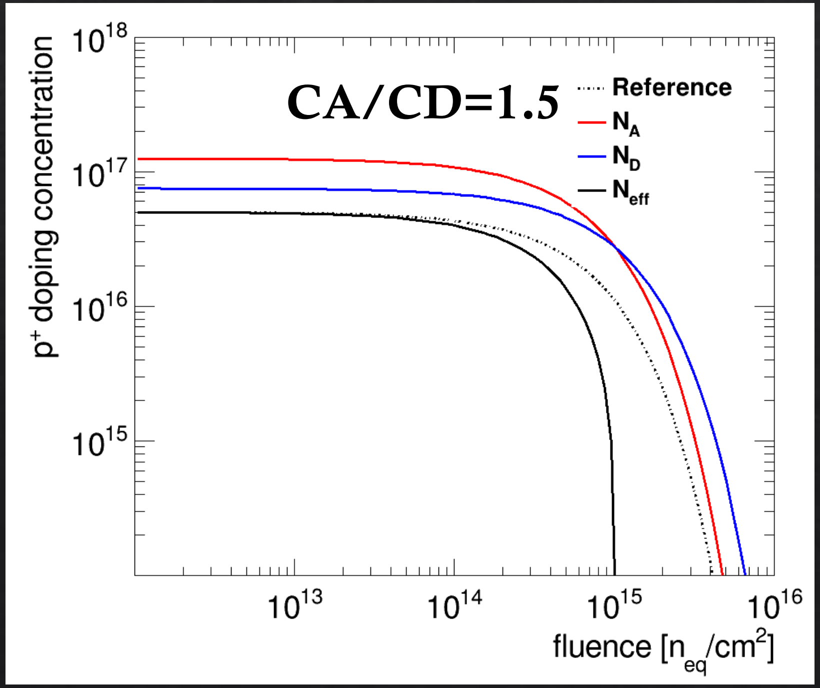
Acceptor removal



How to understand results?

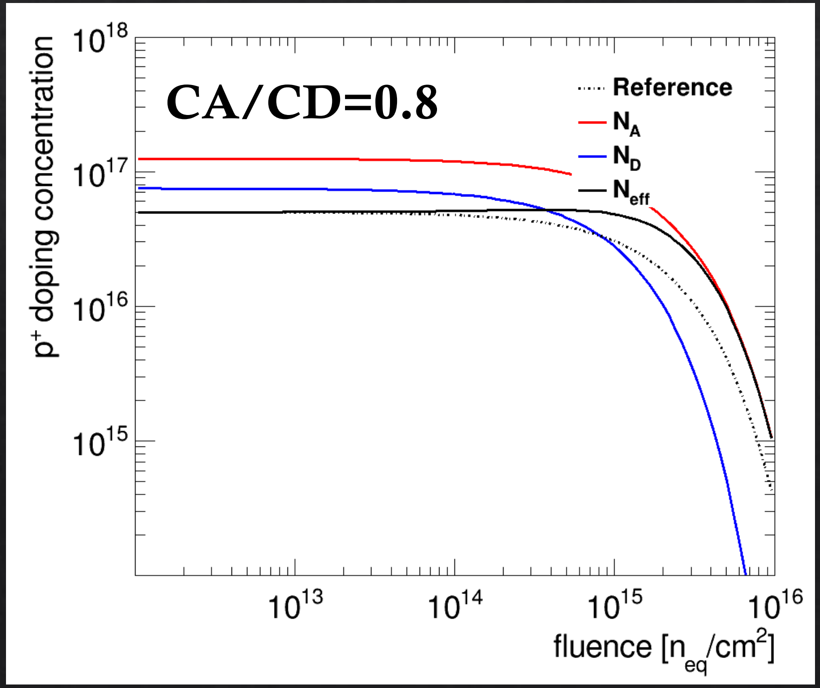
If CA>CD ?

Shorter life time



If CA<CD ?

Slightly longer life time
Not detreated performance until some point



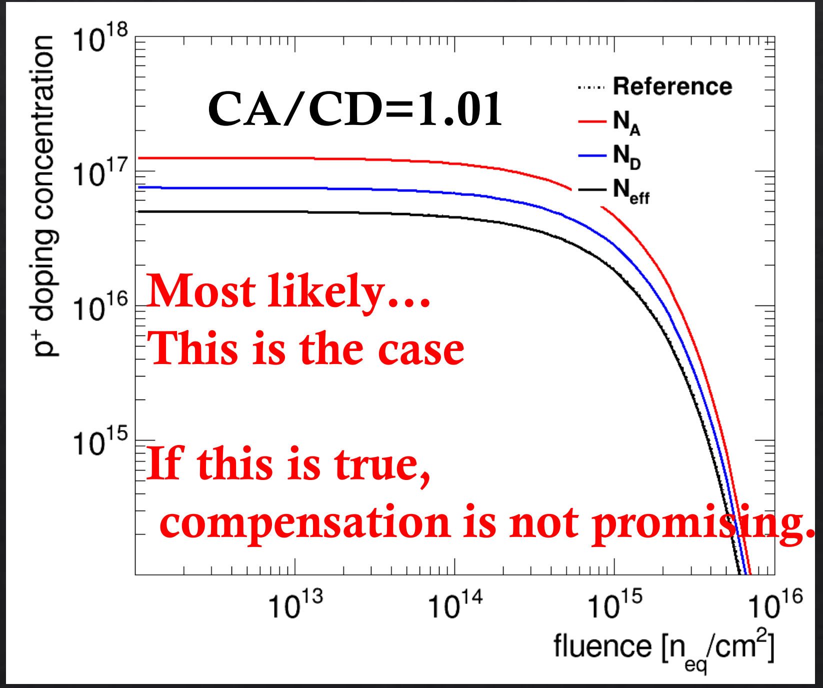
If CA=CD ?

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

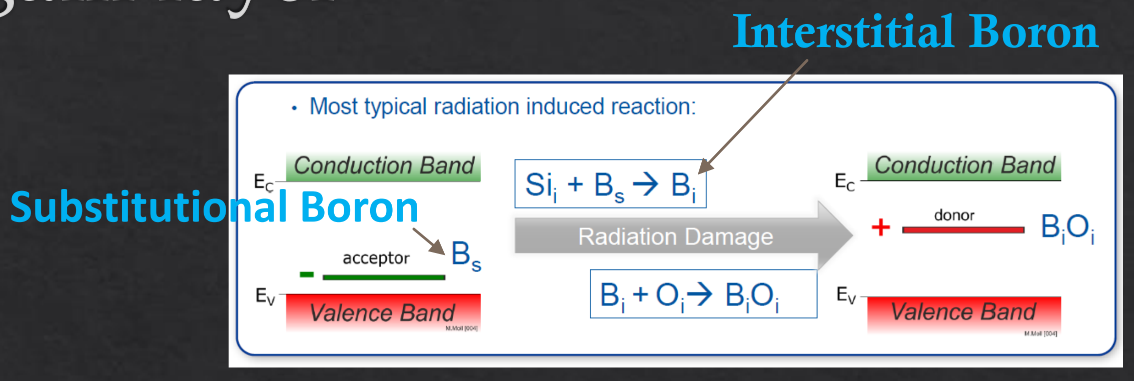
$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A \emptyset}$$

reference $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$

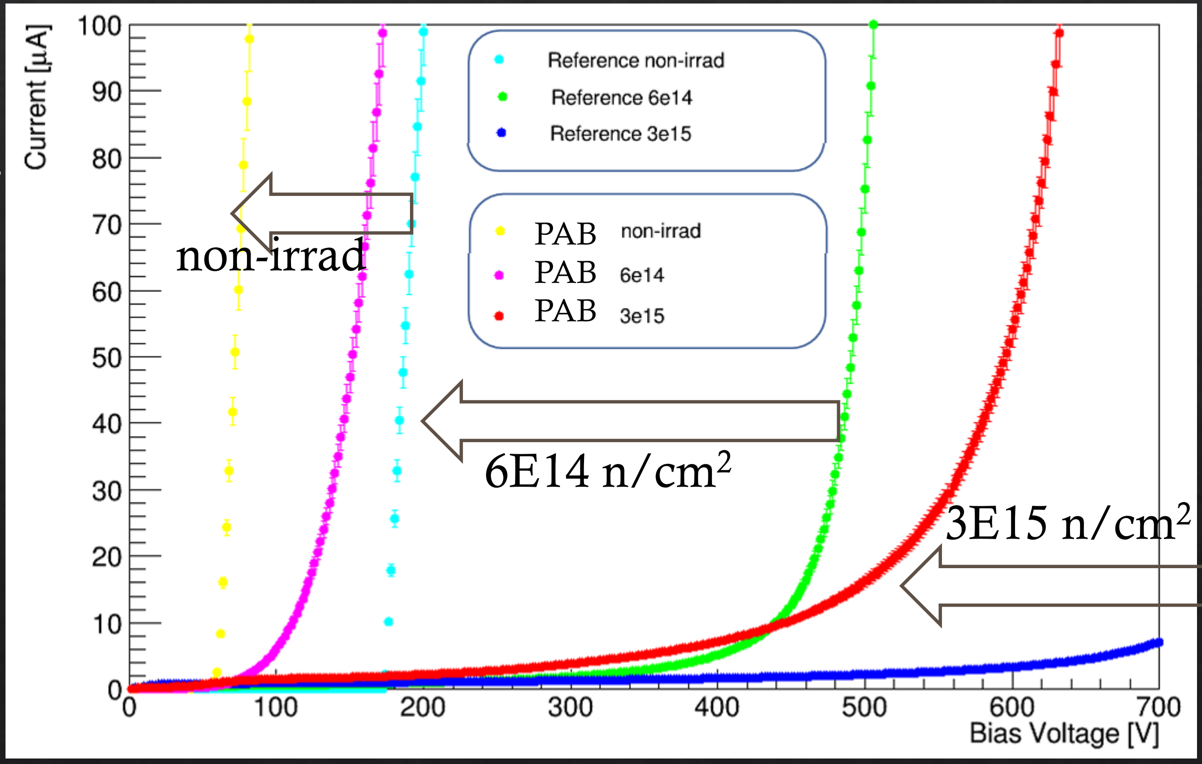
Reduction of effective p+ must be the same as non-compensated case



Partially-activated Boron(PAB) in gain layer



- Doped larger Boron but baked with lower temperature not to activate all Boron. (i.e. lots of Bi with some Bs)
- Probably Oi is cleaned up by Bi+Oi->BiOi process.
- First prototype shows very low Vbd before irradiation. (i.e. too much active Bs)
- Vbd after 3e15neq/cm2 fluence is ~400-500.
  - Much lower Vbd than normal sample (>>700V)
- Will tune the Vbd before irradiation to make the sample works before irradiation. →Next prototype.



This method is promising to study further.

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!

Much better solution !

20um thick ACLGAD successfully developped
We achived ~20ps level time resolution!

Home work

LGAD detector with Radiation tolerance
Compensation method may not work
Partially activated Boron is promissing

Future

- Improvement of radiation tolerance (con't)
  - Tune Partially Activated Boron samples.
  - Apply PAB to AC-LGAD
- Large size prototype
  - Gain uniformity is important for larger sensor.
    - Producing KEK R&D and EIC prototype masks
    - Will receive samples by the end of this month!
- ASIC development
  - Need high speed ASIC with "not-too-high power consumption"
    - Hope it's less than $0.5 W/cm^2$ power consumption
  - Collaborating with Si-Ge ASIC (Uni. Geneva)
  - ATLAS/CMS/EIC will produce their own ASIC for the colliders.
- Will builds modules for future collider experiments

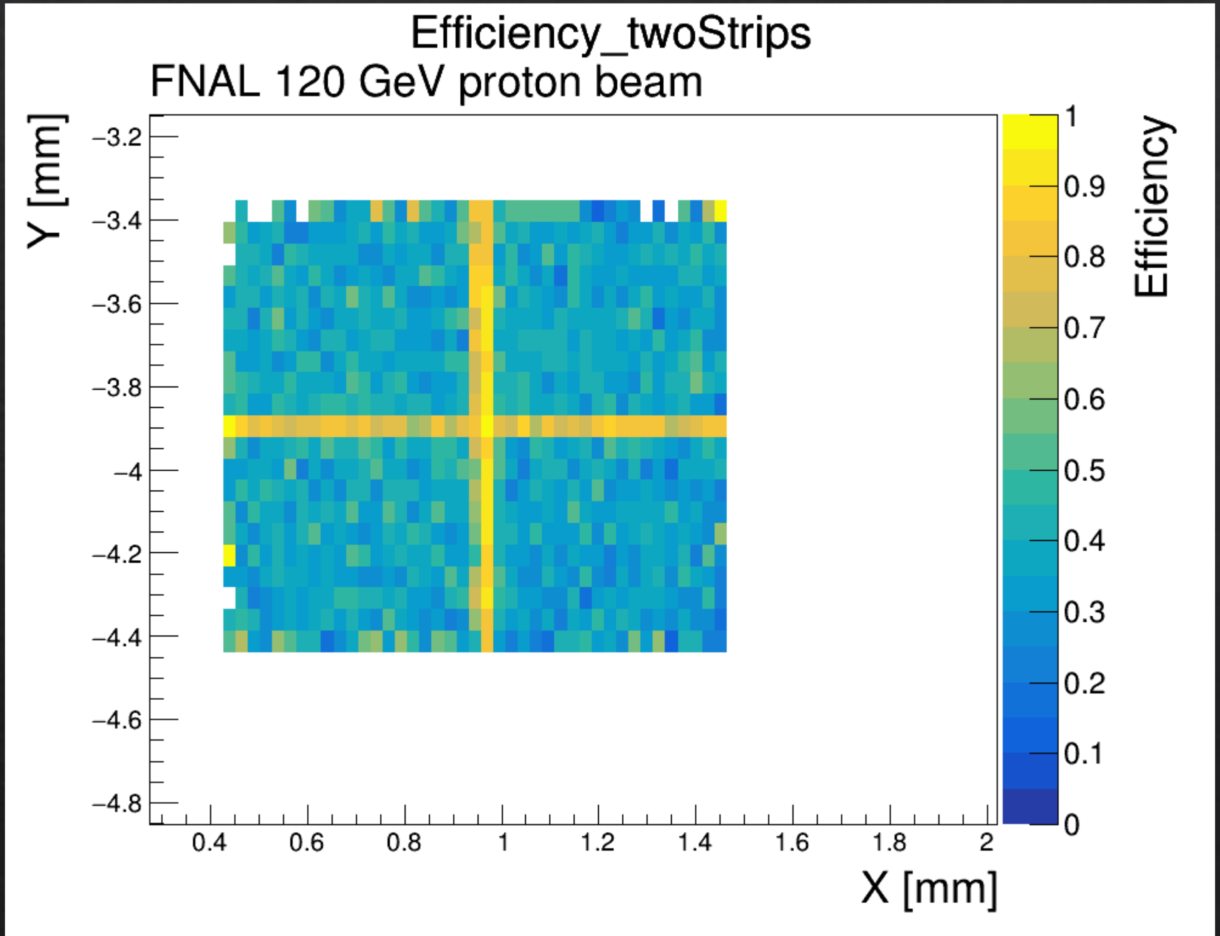
Large size prototype
Gain Uniformity

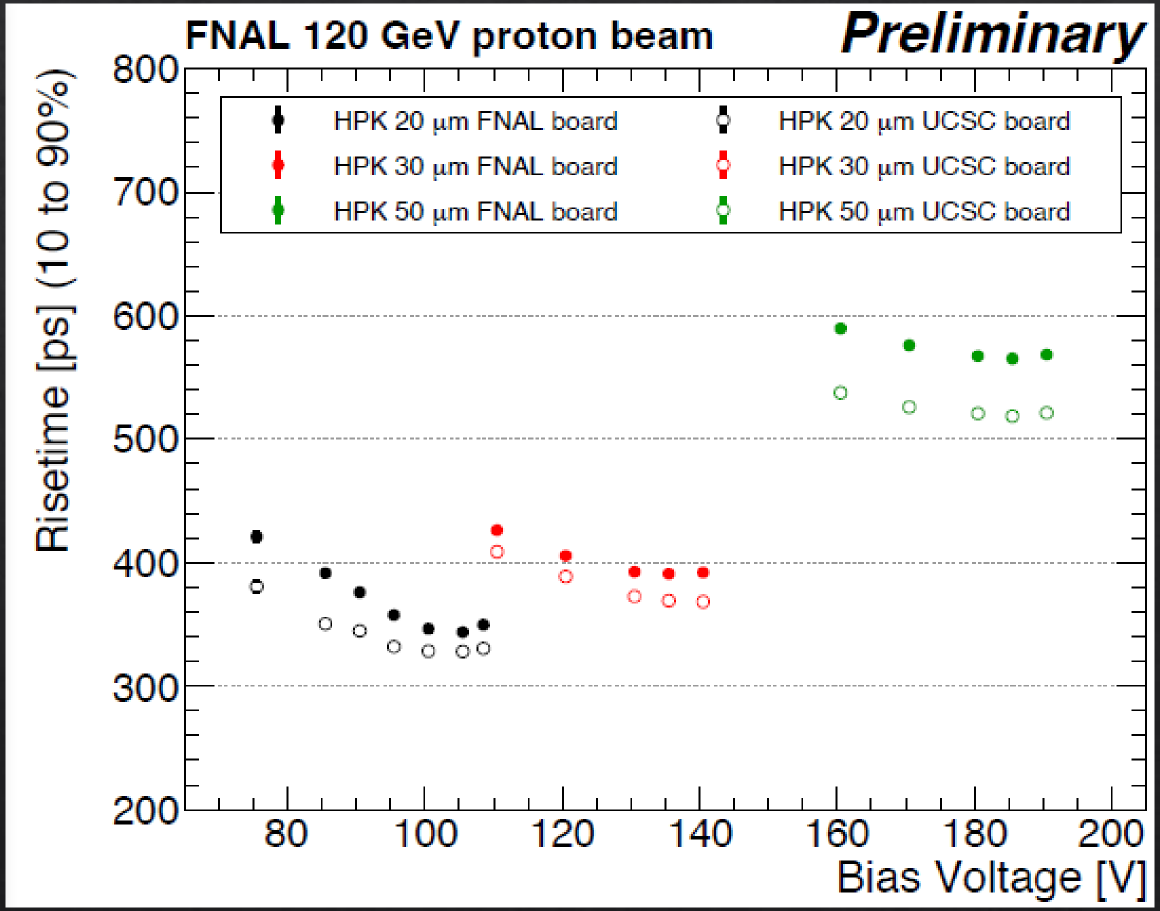
EIC prototype
3cm length
500um pitch strip

HGTD prototype
2cm x 2cm
100um pitch pixel

New Application to Collider detector

Backup


Efficiency_twoStrips
FNAL 120 GeV proton beam
Y [mm]
X [mm]
Efficiency


FNAL 120 GeV proton beam
Preliminary
HPK 20 μm FNAL board
HPK 30 μm FNAL board
HPK 50 μm FNAL board
HPK 20 μm UCSC board
HPK 30 μm UCSC board
HPK 50 μm UCSC board
Risetime [ps] (10 to 90%)
Bias Voltage [V]