

LGAD developments for Future Collider Experiments

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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

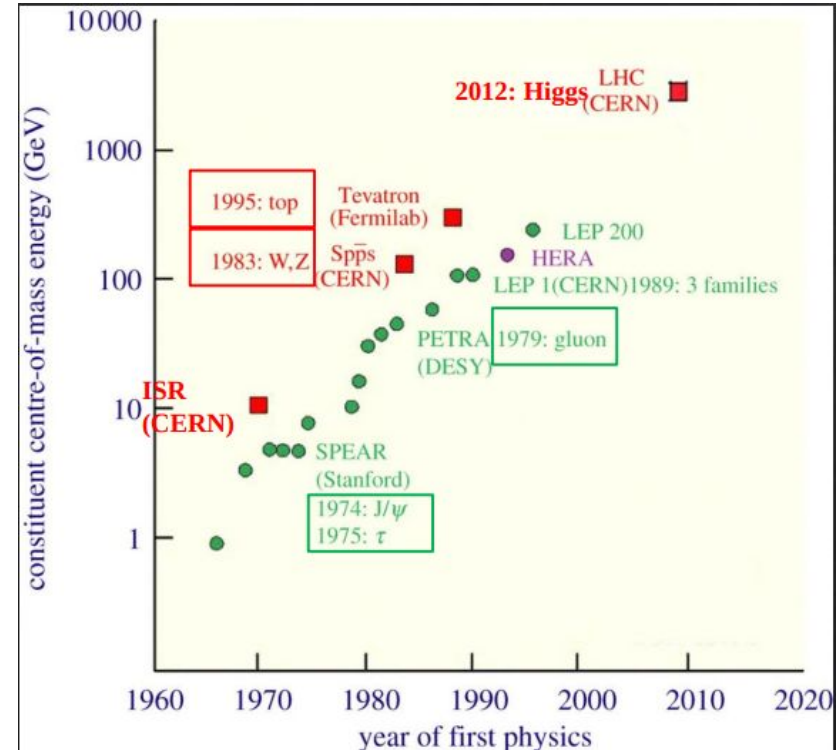
- 1989 : neutrino : 3 generation
- LEP Electroweak measurement

Complementarity:

SppS: W/Z observation → **LEP: measurement**

LEP: top mass expectation ? → **Tevatron: Top observation**

LEP : EW measurement + Tevatron: Top mass measurement → **LHC: Higgs observation**



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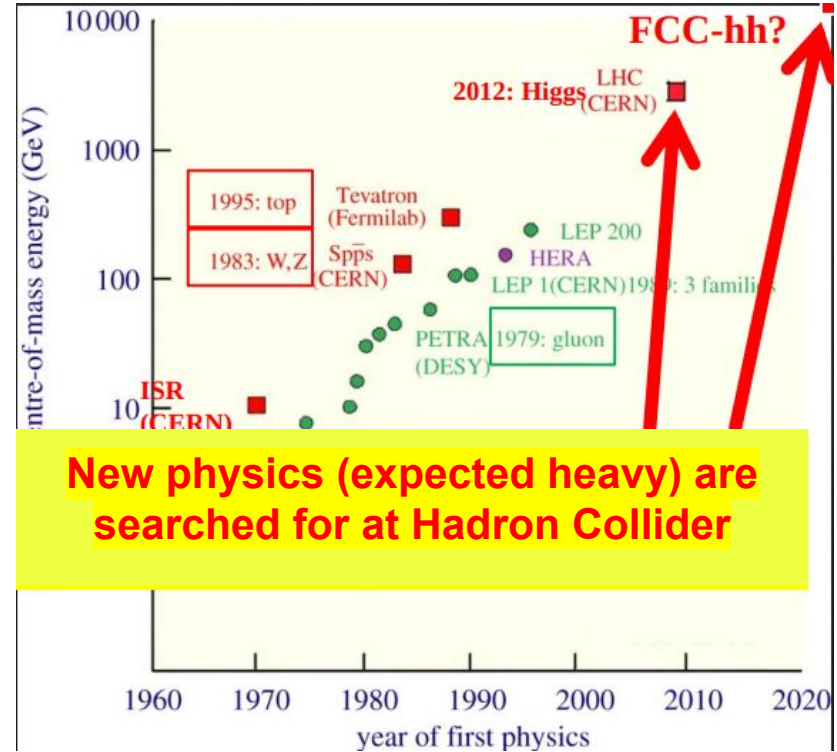
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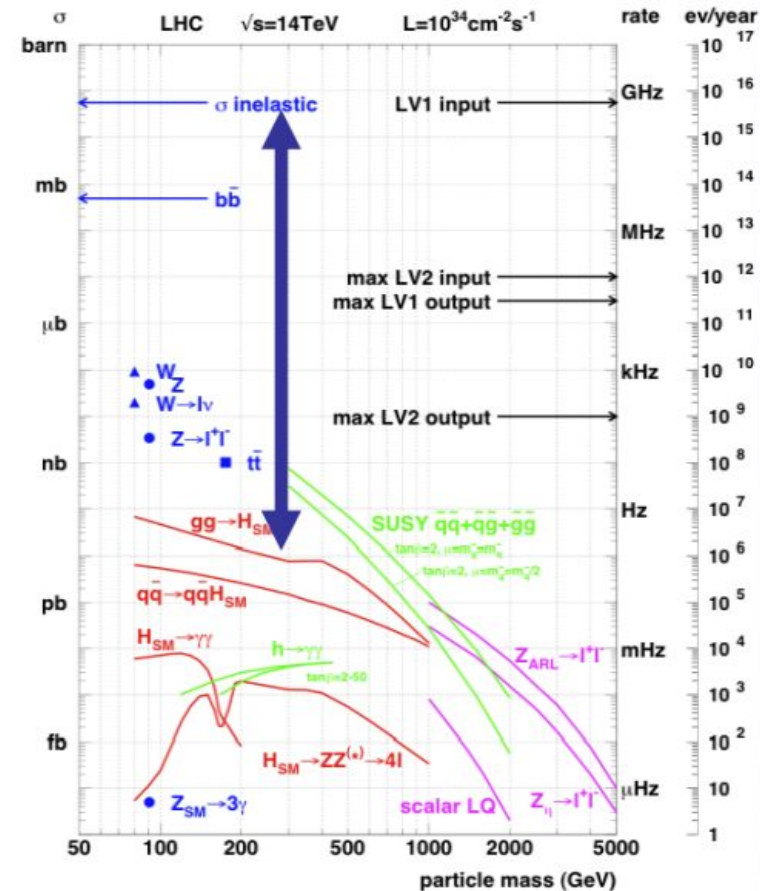
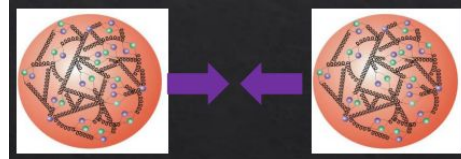
LEP : EW measurement + Tevatron: Top mass measurement → **LHC: Higgs observation**



Difficulty of Hadron Collider

[Difficulties in 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?

Improve granularity : Currently developing 50um pitch pixel detector and very difficult to further reduce

Timing information: Completely new information for tracking : possibility of dramatical improvement of track reconstruction →Should help if timing resolution achieved 1cm/c ~ 30ps

Impact for tracker with timing resolution: some examples include-

Improvement of Inner tracker
Very dense tracks

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

ATLAS event with 200 pileup

Improvement of granularity

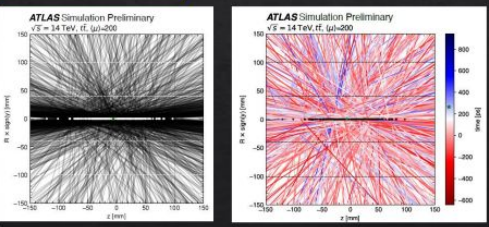
Smaller pixel size

e.g.
Current ATLAS (ATLAS IBL) 50um

HL-LHC upgrade (Pixel @HL-LHC) 250um 50um

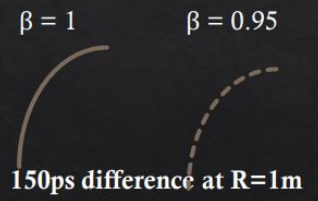
ϕ

4D tracking !

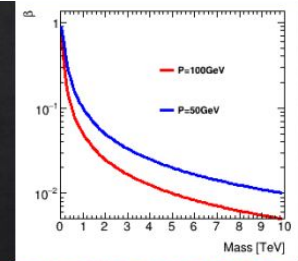


Solve pileup hits in an event

Particle identification



K+ π^+ separation



β measurement to obtain mass

e.g. Mass measurement for long-lived chargino

Operating and Planning Collider Experiment

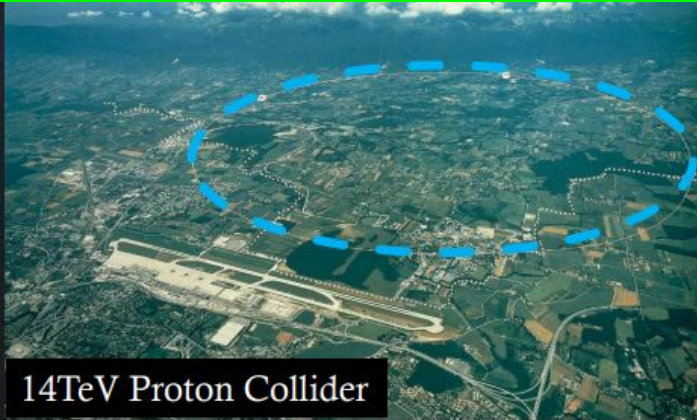
World highest energy collider !

2011~ **Large Hadron Collider (LHC experiment)**

13.6TeV Proton collider

x10 Luminosity

HL-LHC present schedule has first beams in June 2030 (2030~)



14TeV Proton Collider

High Energy LHC

Twice Energy

7 times Energy

Future Circular Collider (FCC-ee/hh)



100TeV Proton Collider

Planning Experiment

International Linear Collider (ILC)

Focusing on Higgs measurement (e+e-)

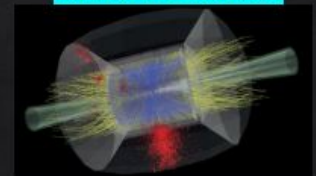


Electron Ion Collider (EIC)



Nuclear experiment

Muon Collider



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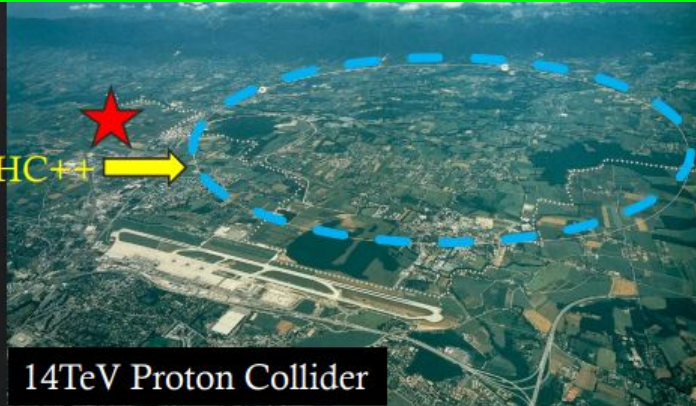


x10 Luminosity

Approved & constructing

HL-LHC present schedule has first beams in June 2030 (2030~)

2034?
HL-LHC++

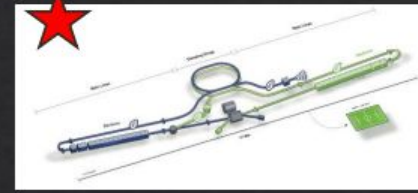


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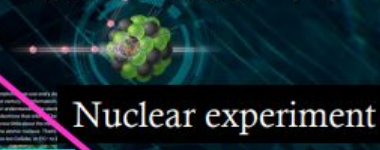
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Electron Ion Collider (EIC)

The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature



Nuclear experiment

High Energy LHC

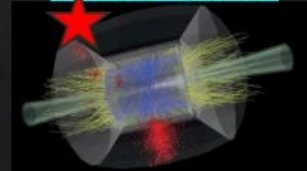
Twice Energy

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Future Circular Collider (FCC-ee/hh)



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A tracker with timing capabilities is necessary for all experiments at these colliders

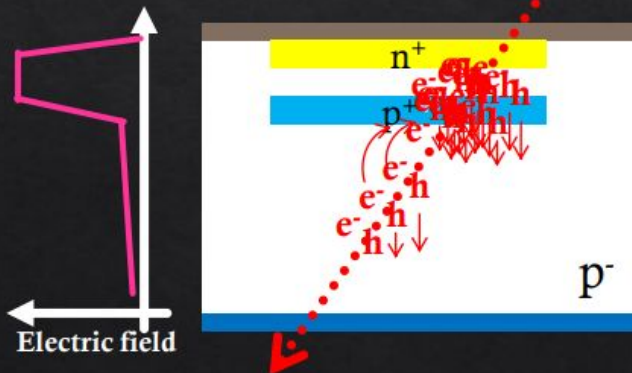
Low Gain Avalanche Diode (LGAD)

◇ Low gain Avalanche Diode (LGAD)

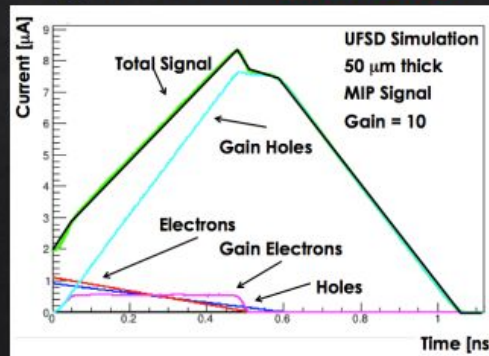
◇ General n^+ -in- p type sensor with p^+ gain layer under n^+ implant to make very high Electric Field at the surface.

→ Good timing resolution.

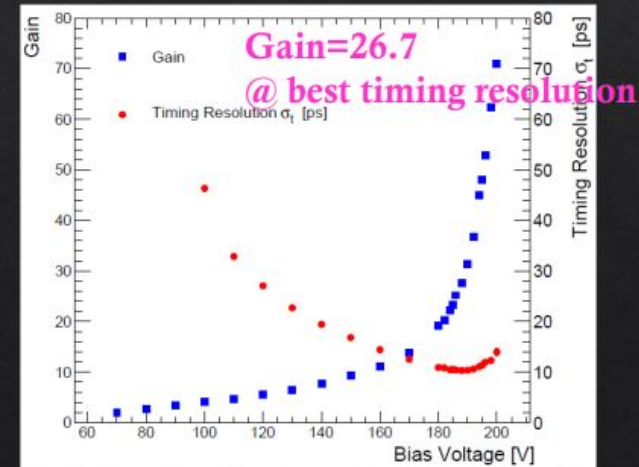
◇ **30ps timing resolution achieved already in 2015.**



Signal drivers : Gain Holes



Gain measurement (AC-LGAD):



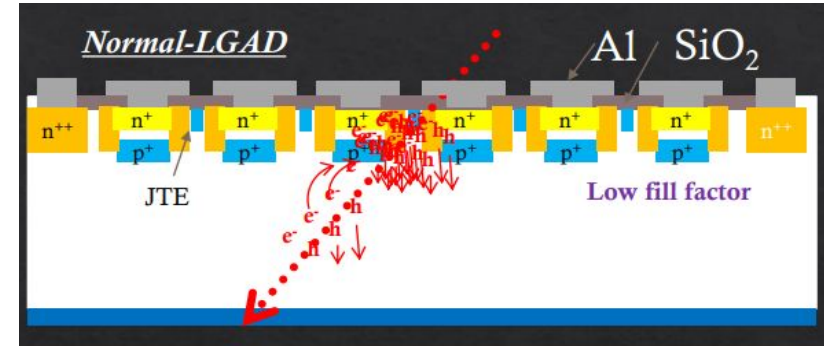
Spatial resolution of LGAD

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)



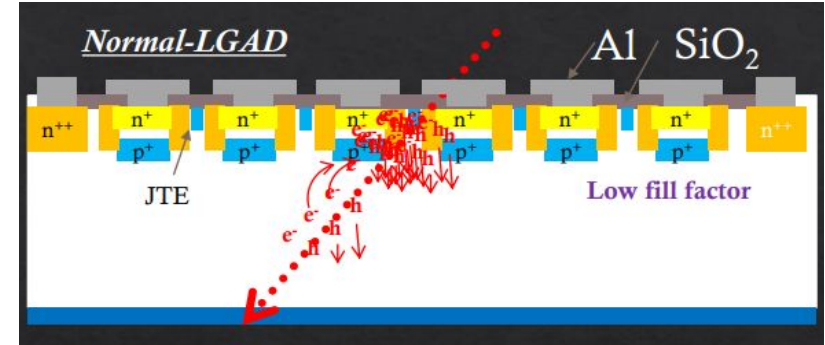
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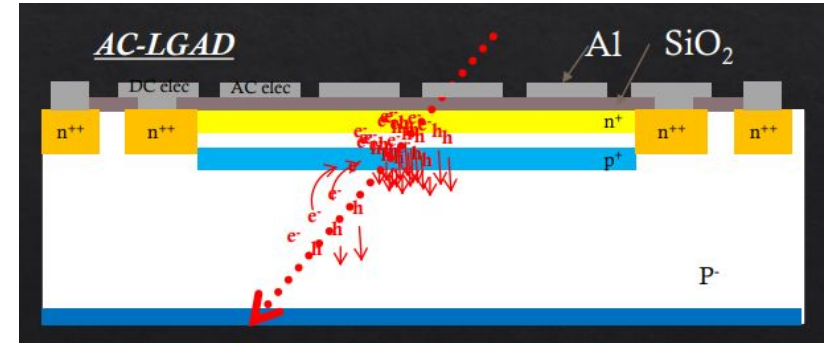
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Uniform gain layer with AC-Coupled electrode. (AC-LGAD)

In principle, **100% fill factor**.

Signal shared on neighboring electrodes.
- Need optimization of n+ resistivity



Two approaches for achieving good spatial resolution

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. : Smaller number of channel → Save ASIC
power consumption.

Cons. : Smaller signal size. Need high resolution
ADC. Large detector capacitance

Fine pitch electrode approach

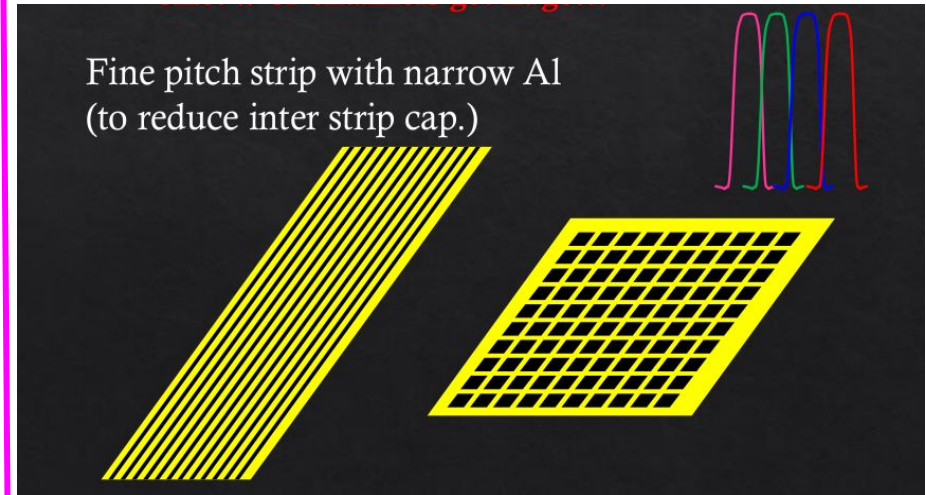
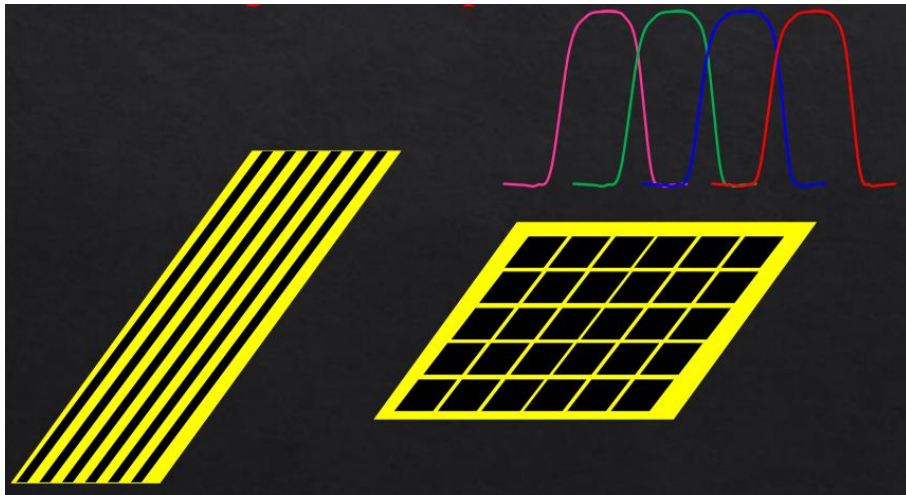
For High occupancy experiment like hadron collider.

Reduce crosstalk (charge sharing)

High n+ implant resistivity

Pros. : smaller occupancy and smaller data size like
digital readout. Smaller detector capacitance.

Cons. : Limitation of spatial resolution by electrode
size. # of channels get huge...



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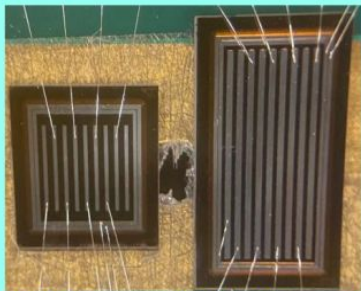
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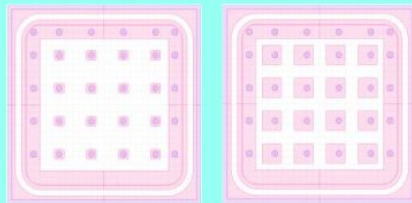
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BNL prototype
500um pitch strip

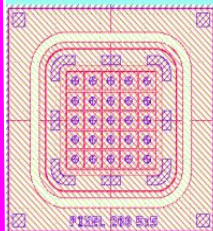


HPK EIC prototype
(500um pitch)

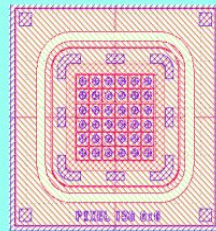


Both BNL and HPK produced 500um pitch pad/strip
for future colliders (e.g. EIC)

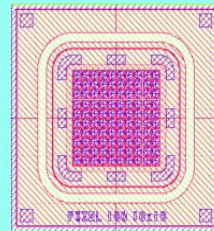
200um



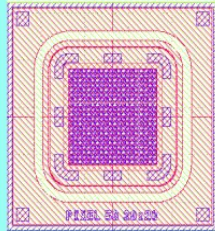
150um



100um



50um



KEK-Tsukuba group with HPK successfully develop :
100um (50um) pitch Pixel detector
80um pitch Strip detector

US-Japan Meeting 2023: <https://indico.physics.lbl.gov/event/2259/>

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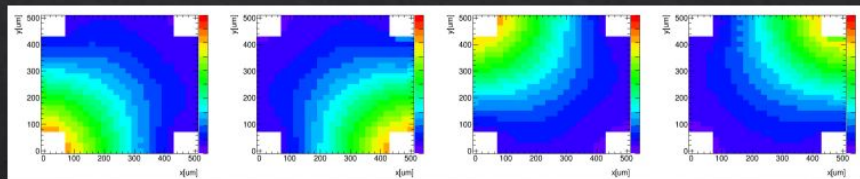
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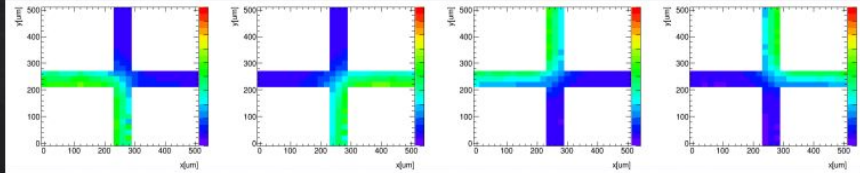
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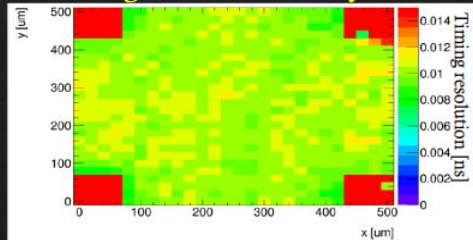
150um Al size



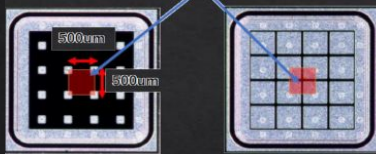
450um Al size



Timing resolution is very uniform



Scanned Area



150um Al size

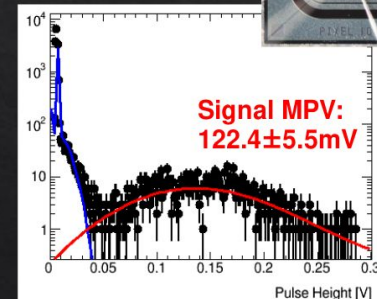
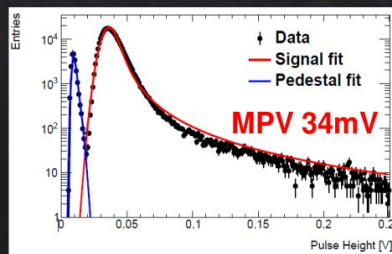
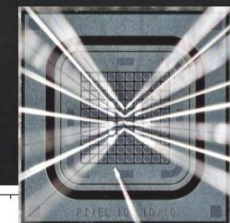
450um Al size

Smaller Electrode size showed quite linear behavior of charge ratio

Strip type
80um pitch
(10mm)



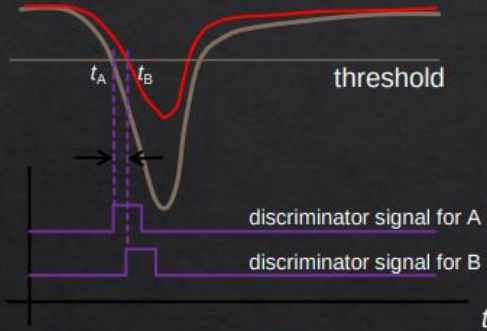
Pixel Type
100um pitch



How to improve the timing resolution?

Two effects that deteriorate the timing resolution :

1. Time walk

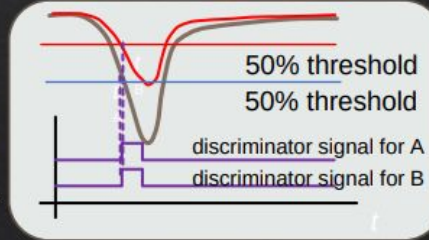


Different arrival time
for small and large signals

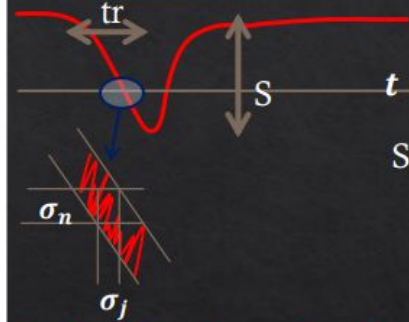
This is a matter of arrival time definition.

Solution:

The effect will be negligible
using constant fraction thr.



2. Time jitter



Arrival time is randomly
change by noise.

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

Size of noise

Slope of vol.

Size of signal

Ramping time

Solution :

To make smaller jitter

1. Smaller noise
2. Larger signal
3. Faster ramping time

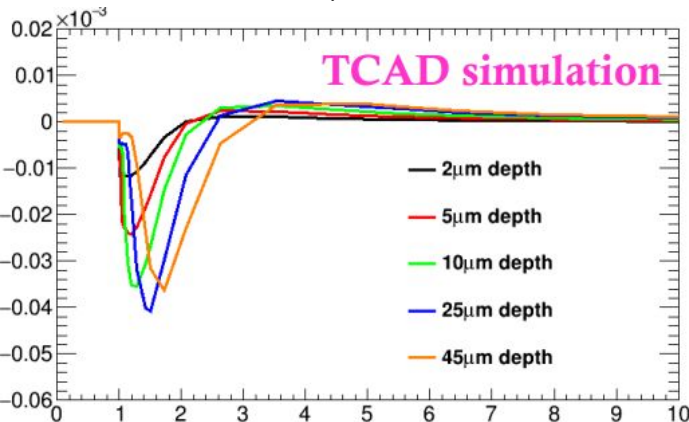
Faster signal turn on and good S/N ratio
should be the key to improve timing resolution

Timing resolution of LGAD sensor full picture

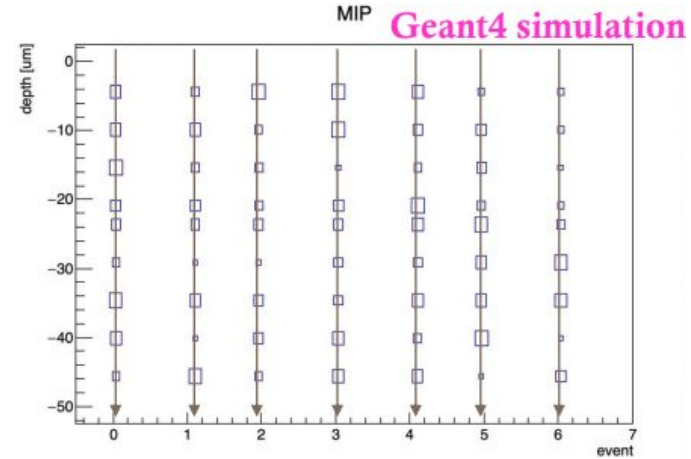
$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2 \longrightarrow \sigma_L : \text{Charge collection noise (Landau noise)}$$

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



Thinner active thickness will help to reduce the effect

50um thick sensor : $\sim 30\text{ps}$ CCN \rightarrow 35ps in actual device achieved.

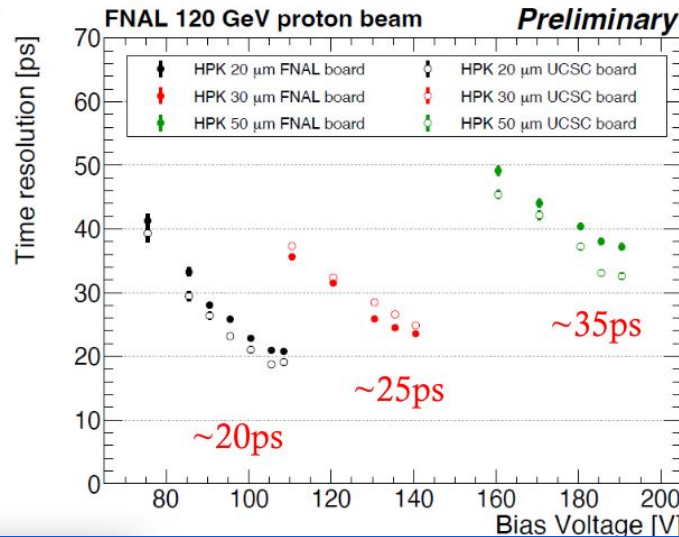
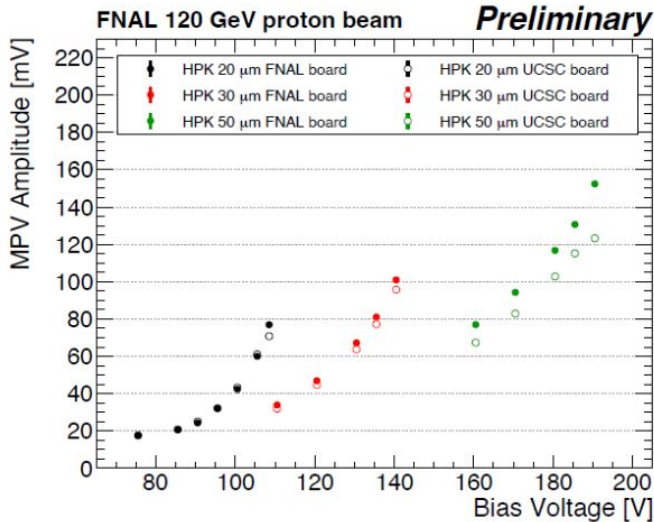
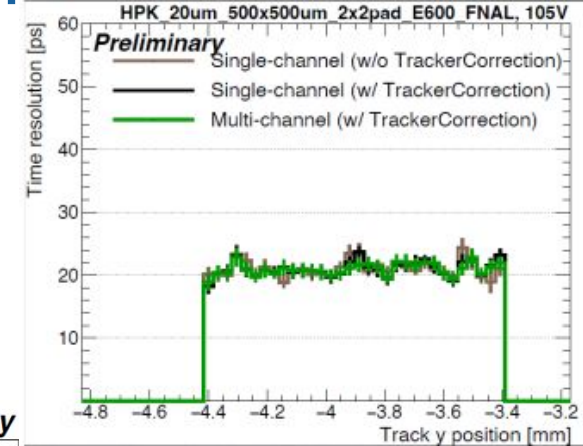
20um thick sensor : $\sim 15\text{ps}$ CCN \rightarrow 20ps in actual device achieved.

\rightarrow 10um thick sensor? Smaller signal size (worse jitter) but better CCN.

Improvement of timing resolution

To reduce Landau noise : Fabricated 50 μm , 30 μm and 20 μm thick sensors

- Signal size (amplitude) is smaller in thinner sensors.
- 20 μm thick sensor has the best timing resolution : $\sim 20\text{ps}$
- Uniform timing resolution at the gap region as well.



All results are for 500 μm pad detector

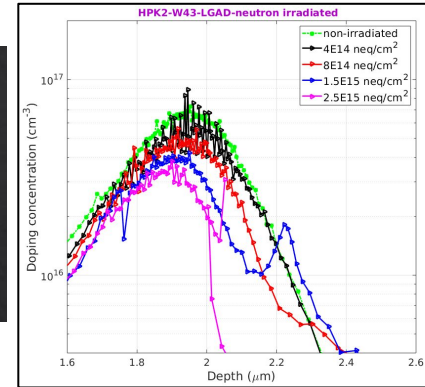
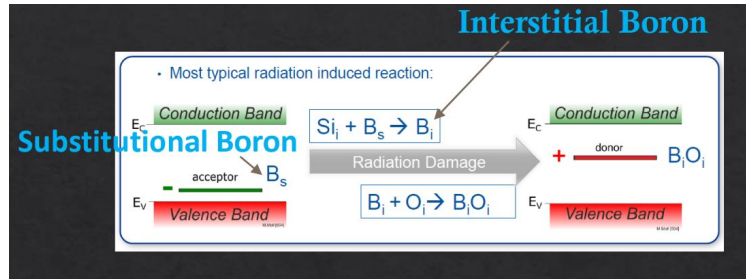
Radiation Tolerance of LGADs

Like normal silicon device

Bulk damage (NIEL) : Si lattice damage, Surface damage (TID) : charge up at SiO₂ -Si

In addition "Acceptor Removal" p+ in Gain layer reduced

Acceptor removal (low p+ concentration) introduce weaker field → Need higher voltage to keep high electric field at gain layer



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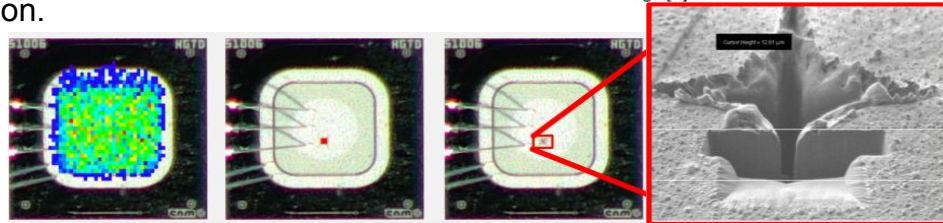
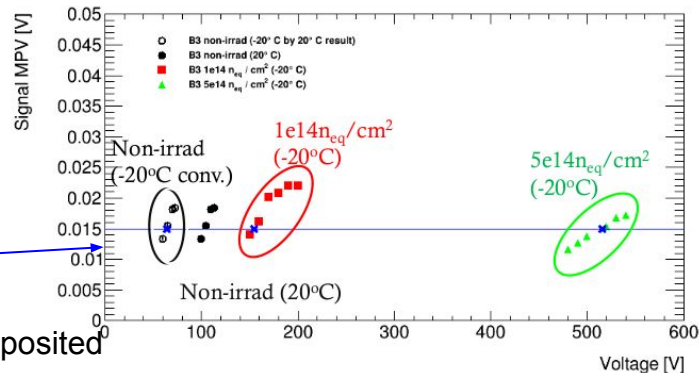
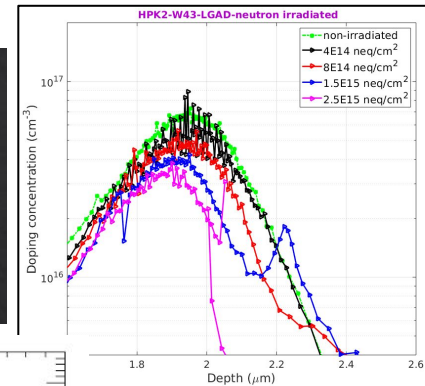
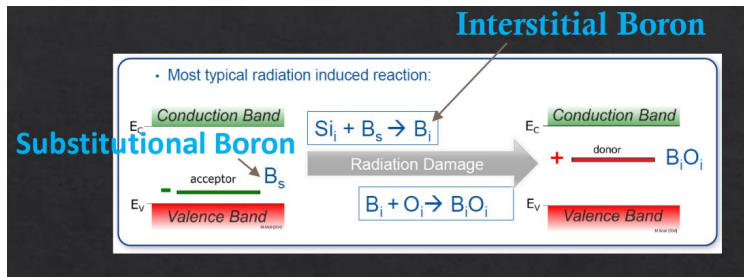
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Acceptor removal (low p+ concentration) introduce weaker field → Need higher voltage to keep high electric field at gain layer

Why "acceptor removal" is an issue?

- Active shallow acceptors are no longer active by defect.
- Increase gain voltage by fluence.
- Possible maximum operation voltage
- **Single Event Burnout (SEB)** happens if MIP particle deposited relatively high (~10 MeV) energy at high electric field region.
- This happened only ">12V/μm average E field" Independently by the gain layer concentration or radiation fluence.

V. Gkougkousis, "LGAD Safety and Stability Concerns"
– HGTD Sensor Meeting April 2018, CERN-OPEN-2023-017



Improvement in radiation tolerance of LGADs

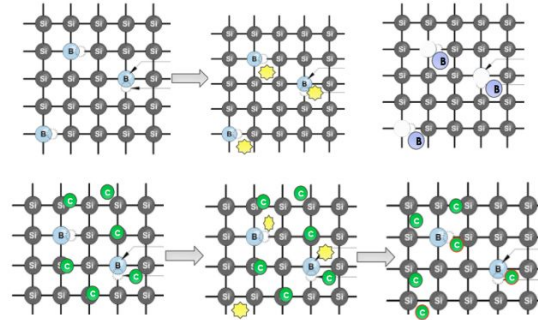
- Protection of gain layer is of key importance to reduce Acceptor removal
- New ideas:

1. **Carbon annealing** (confirmed by FBK) - studied rigorously both by ATLAS and CMS collaboration for Phase-2 Upgrade

Sensors with Carbon survive up to $2e15 n_{eq}/cm^2$: V_{op} can be below 550V

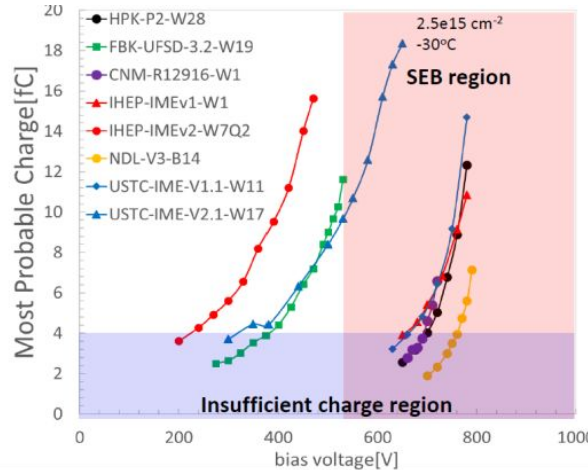
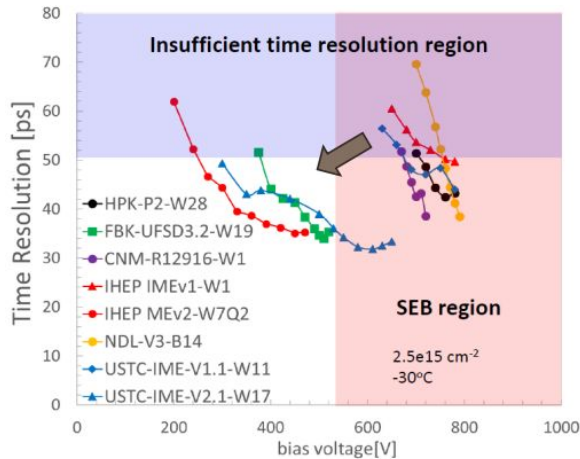
~300V lower V_{op} after $2e15 n_{eq}/cm^2$ irradiation.

Ref: R. Arcidiacono, TREDI (2019)



Boron
Radiation creates interstitial defects that inactivate the Boron

Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

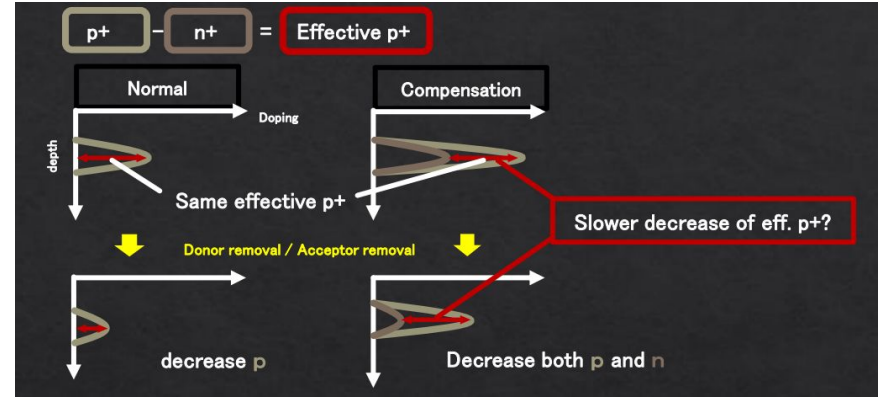


Next talk by Matteo !

Improvement in radiation tolerance of LGADs

2. **Compensation method:** Both Boron(p+) and Phosphorus(n+) are doped → should work if donor removal is faster than acceptor removal
 HPK successfully produced working LGAD with a few types of compensation parameters.
 Performed a couple of Irradiation Campaign at CYRIC

arXiv:2401.08108



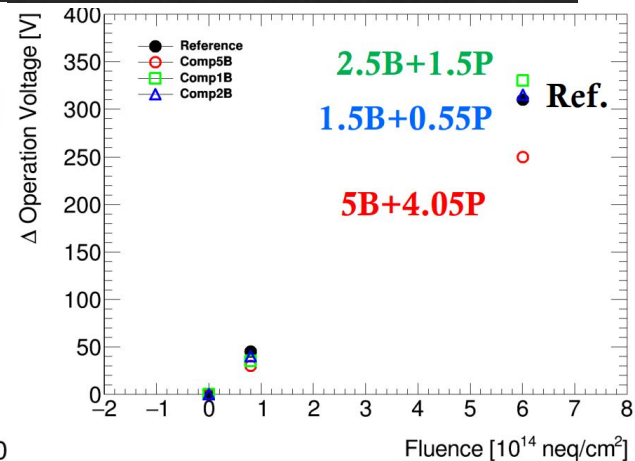
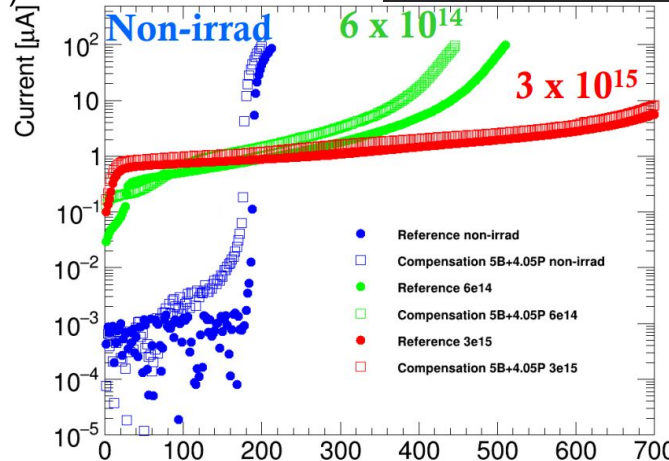
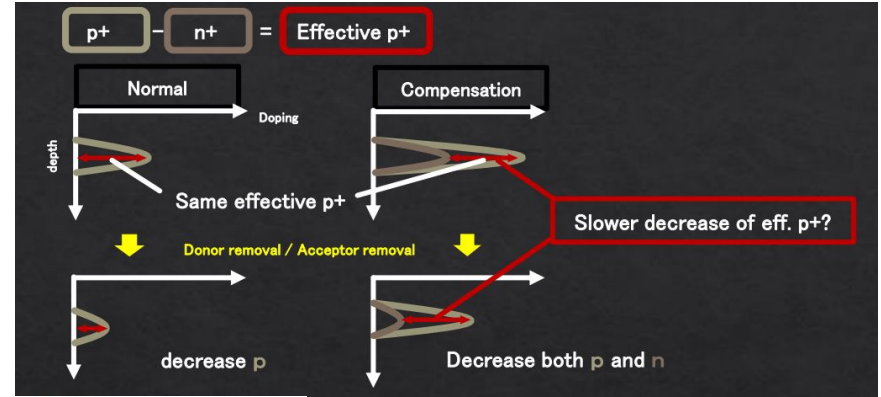
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Different compensation ratio:

- 1B (reference)
- 1.5B+0.55P : No visible improvement
- 2.5B+1.5P : No visible improvement
- 5B+4.05P : Saw slight improvement (~50V)
- 10B+9.2P : No significant signal observed



Improvement in radiation tolerance of LGADs

arXiv:2401.08108

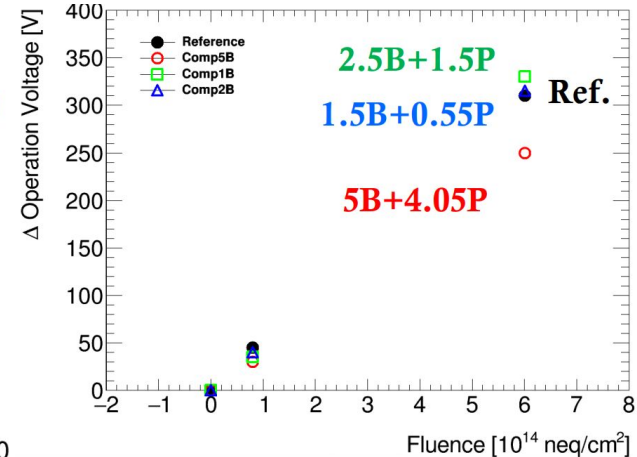
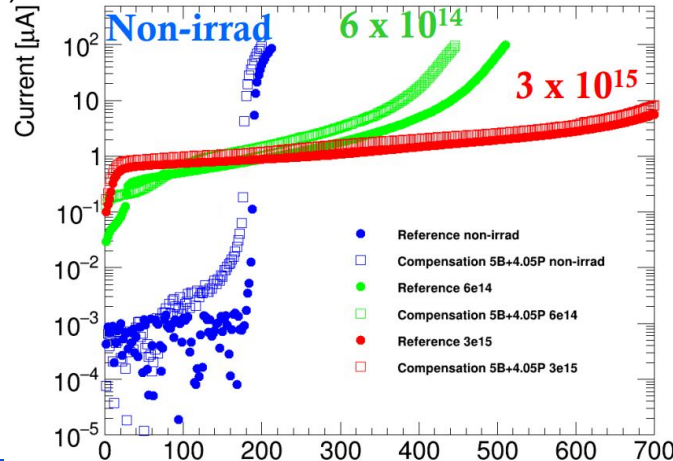
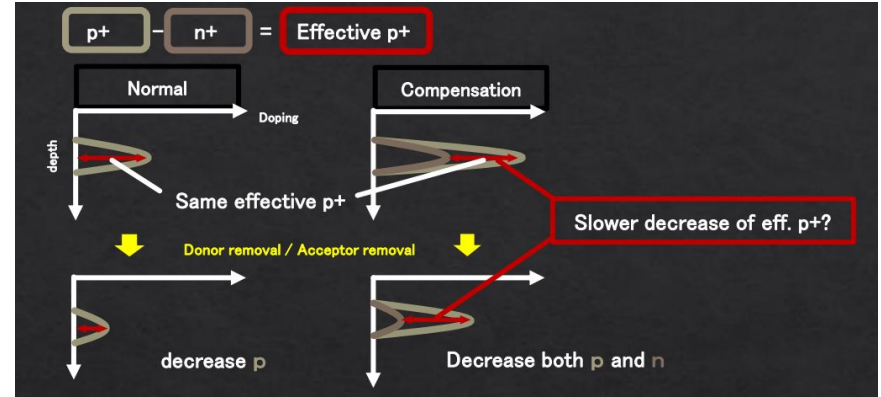
2. Compensation method: Both Boron(p+) and Phosphorus(n+) are doped → should work if donor removal is faster than acceptor removal
 HPK successfully produced working LGAD with a few types of compensation parameters.
 Performed a couple of Irradiation Campaign at CYRIC

Different compensation ratio:

- 1B (reference)
- 1.5B+0.55P : No visible improvement
- 2.5B+1.5P : No visible improvement
- 5B+4.05P : Saw slight improvement (~50V)
- 10B+9.2P : No significant signal observed

Inference:

- Small compensation doesn't work, because acceptance and donor removal is roughly the same.



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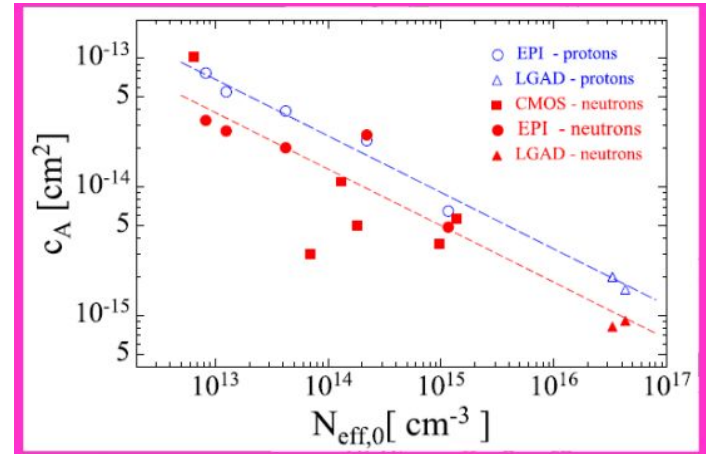
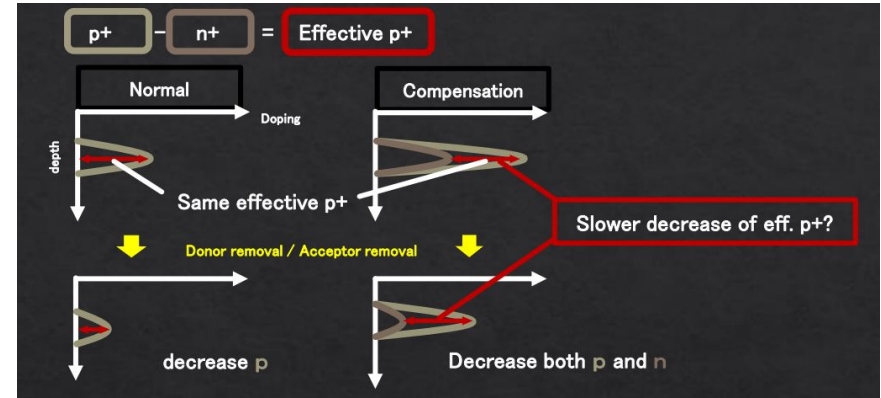
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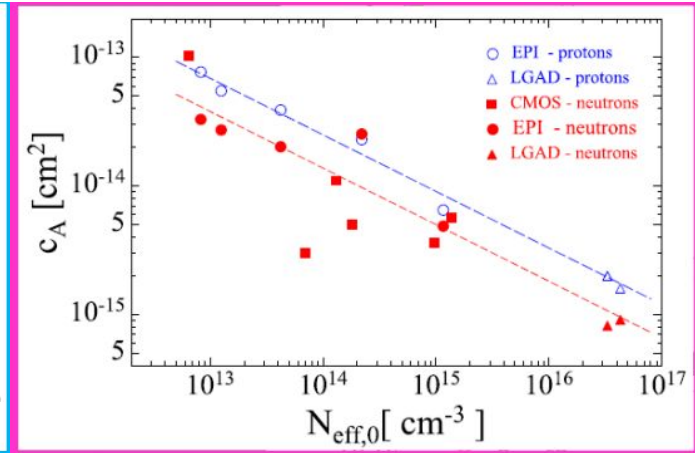
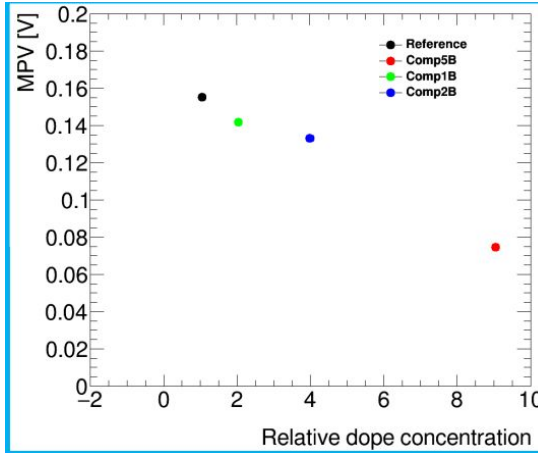
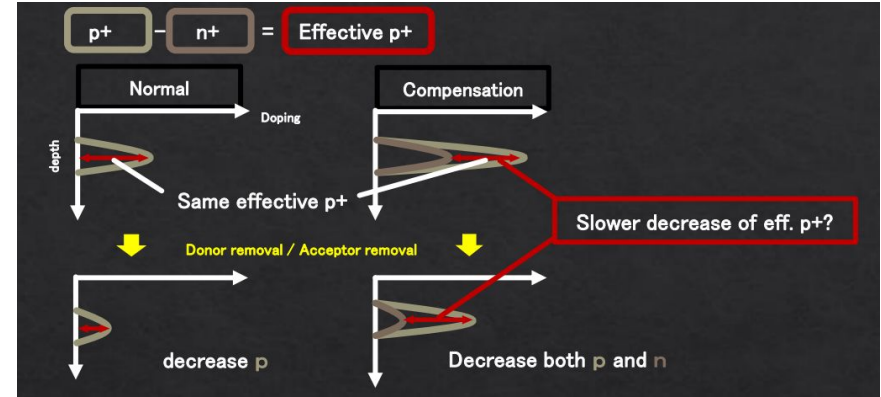
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- Problem: larger compensation have risk of reduction of signal size



Conclusions

- Timing information is crucial for tracking purposes in future collider experiments.
- LGADs will be used in Phase-2 operation of CMS and ATLAS detectors (HL-LHC).
- AC-LGAD development has been ongoing for 6 years - for improved spatial resolution and fill-factor (100%)

Fine pitch LGADs - improved spatial resolution

AC-LGAD with 80 μm pitch strip sensor

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

AC-LGAD with 100 μm x 100 μm pixel sensor

- Larger signal than strip sensor!!

Good timing resolution!

20 μm thick AC-LGAD was successfully developed by HPK

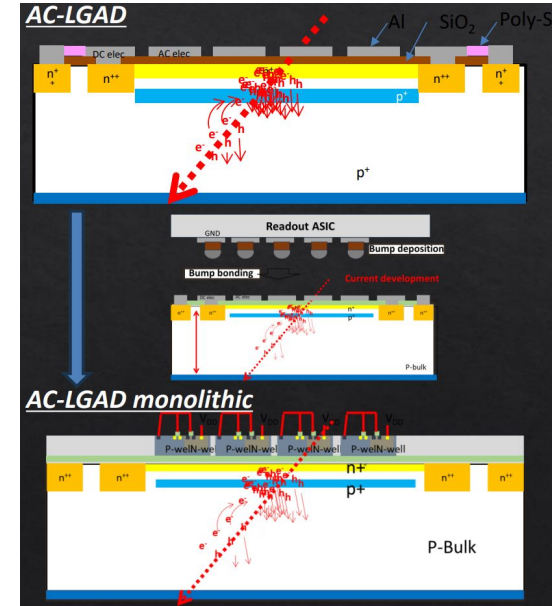
- achieved ~20ps level time resolution! → Need to test pixelated LGAD

Needs improvement

Radiation tolerance of LGADs :

- Tested carbon annealing and compensation method
- Next steps: to check compensation with carbon
- Fast & low power ASIC needs to be developed

In future, Development of monolithic detector - hybrid detector as intermediate step



Acknowledgements

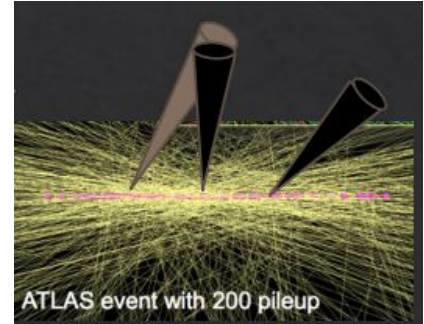
Special thanks to Koji Nakamura (KEK)

- Most results are taken from FNAL seminar (4.03.2024)

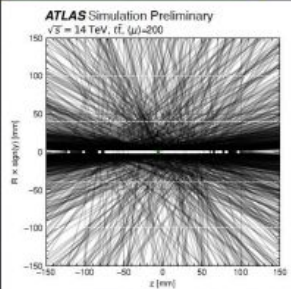
Backup Slides

Impact for tracker with timing resolution

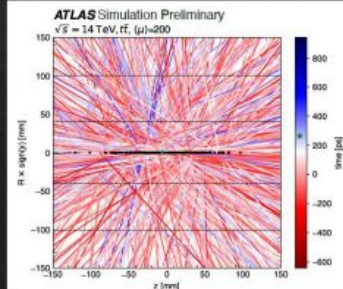
- Collider experiment gets high energy and high intensity. → Future Tracking detector should have timing information for all hits!
- Tentative Requirement – 30ps timing resolution & $\sim 10\mu\text{m}$ spatial resolution – (hadron collider) $\sim 10^{16} n_{eq}/\text{cm}^2$ radiation tolerance



4D tracking !



Solve pileup hits in an event

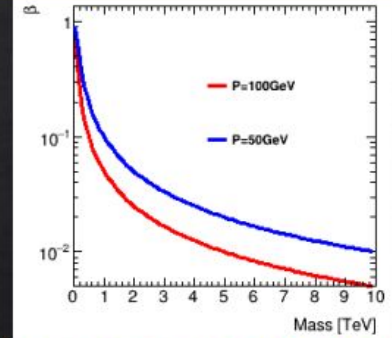


Particle identification

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



$K^+ \pi^+$ separation



β measurement to obtain mass

e.g. Mass measurement for long-lived chargino

Read-out principle of AC-LGAD

<https://indico.cern.ch/event/1495650/contributions/6317745/>

Read out principle of AC-LGAD

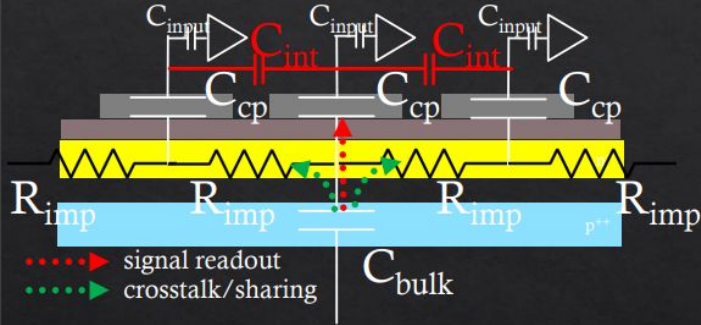
◇ Charge split : Impedance ratio

Assuming $Z_{C_{bulk}}, Z_{C_{int}} \gg Z_{C_{cp}}$

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

◇ Amount of produced charge: Q_0

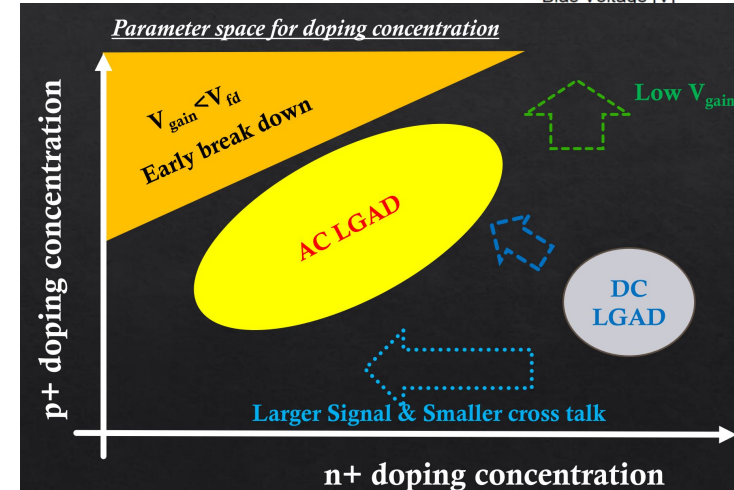
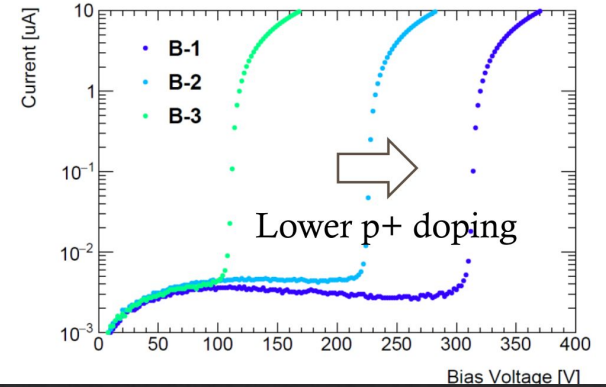
◇ Readout Charge : Q



• Additional cross talk is expected due to the inter-electrode capacitance C_{int}
 – Amount of crosstalk may also depend on input capacitance on the electronics.

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)



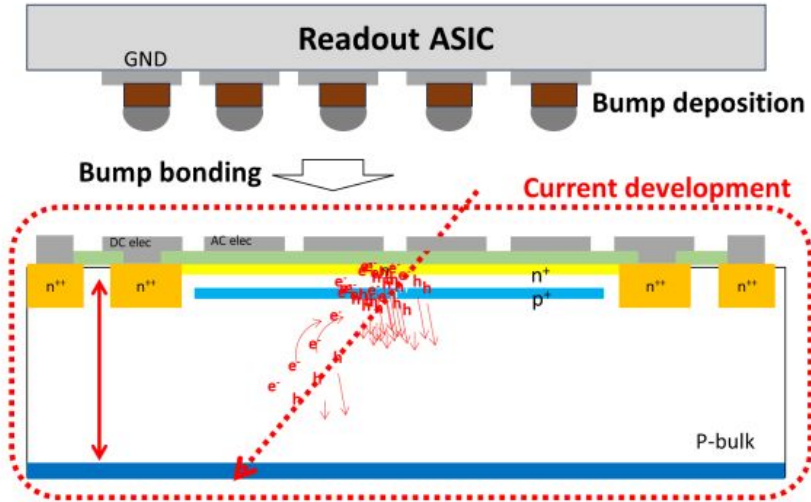
Two detector approaches for improving

- Readout ASIC (amplifier) with smaller noise:
 - 3D detector with CMOS ASIC
 - Time Spot
 - Various ASIC (TSMC 28nm)
 - Monolithic detector with Si-Ge BiCMOS
 - Monolith (Univ. of Geneva) by IHP
- Making sensor with larger signal and faster turn on
 - Low Gain Avalanche Diode (LGAD)

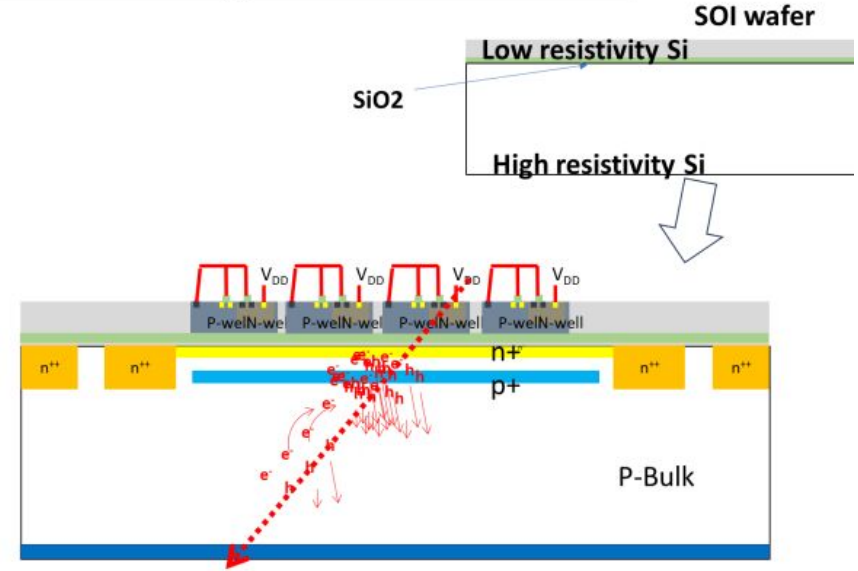
Both approaches may be realized at the same time.

Idea of monolithic AC-LGAD

Hybrid Type AC-LGAD detector



Monolithic type AC-LGAD detector

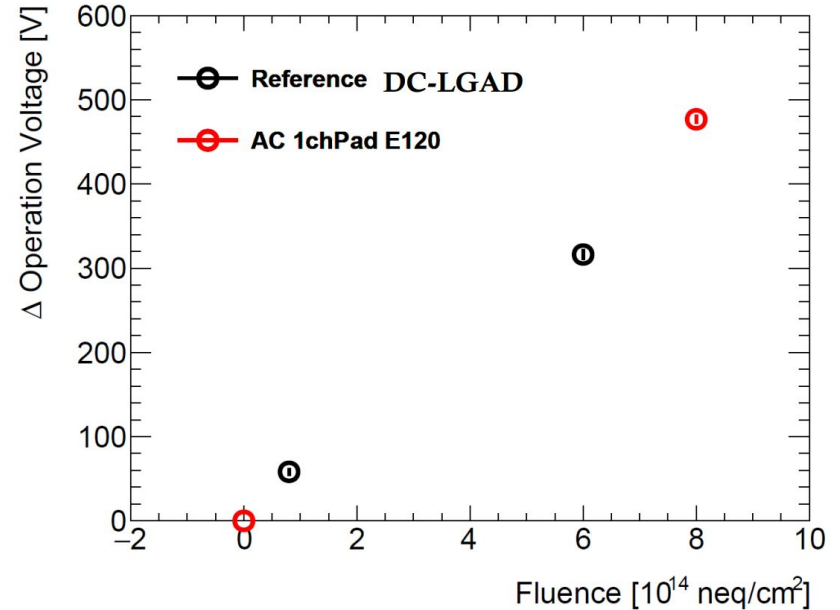


Radiation hardness comparison between DC- and AC-LGADs

may be a bit different between DC-LGAD and AC-LGAD

- p^+ doping concentration is different. Compared AC and DC LGAD with proton irradiated sensors.

DC- and AC- LGAD showed quite similar Radiation Tolerance



<https://indico.physics.lbl.gov/event/2779/>