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

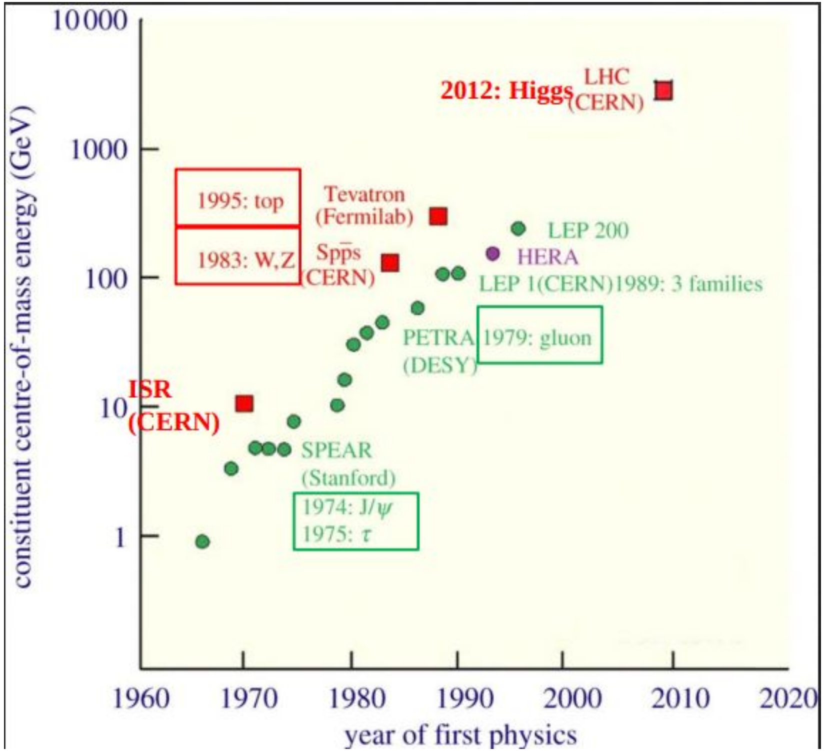
- 1989 : neutrino : 3 generation
- LEP Electroweak measurement

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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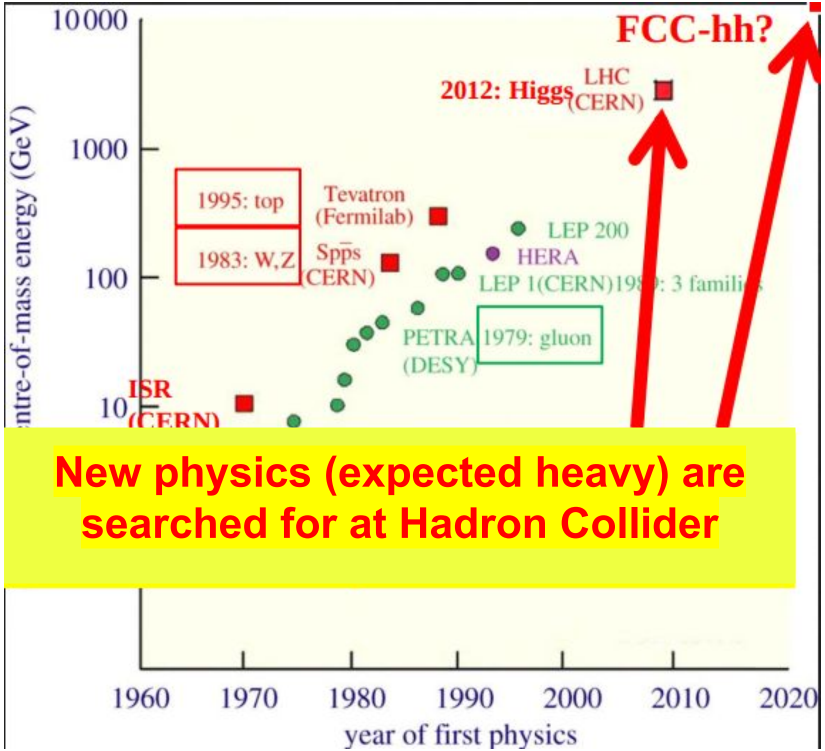


Complementarity:

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

[Difficulties in pp collider analysis]

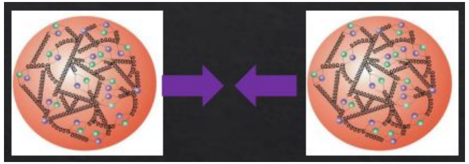
• Difference of center-of-mass energy and energy used for collisions.

– Parton Distribution Function (PDF)

• Complicated collision due to composite particle of proton

– Huge QCD background

– Spectator of the proton collisions

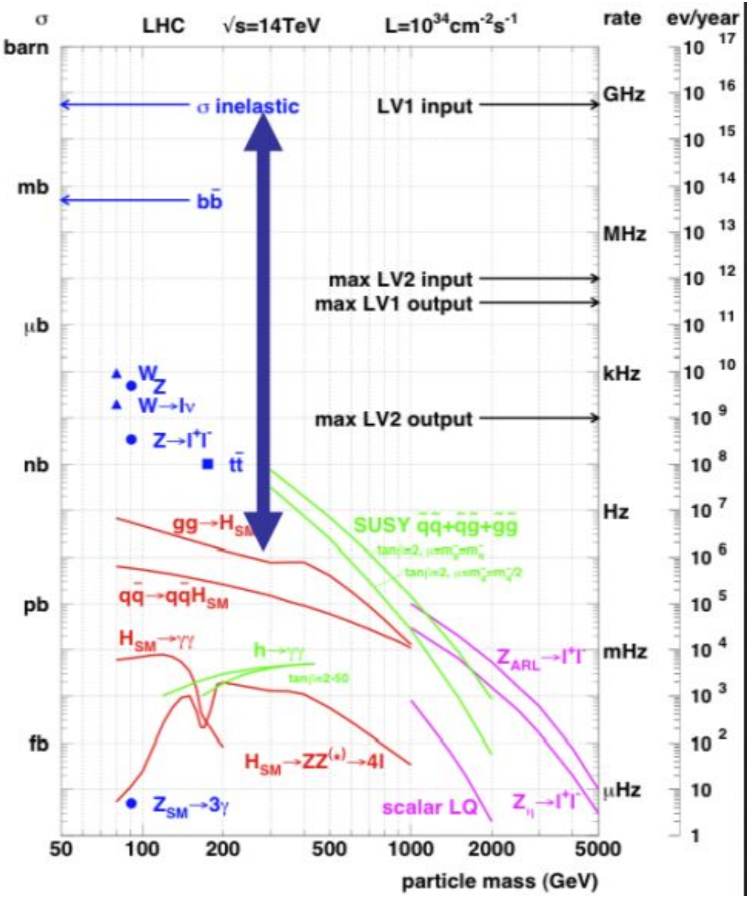


→Underlying event

– Multiple collisions in a bunch crossing

→Pile-up

– 10 order of magnitude difference between pp cross section and interesting events.



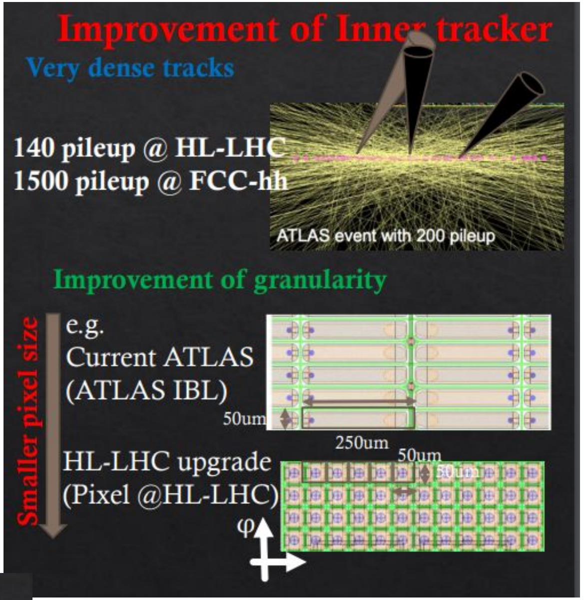
Challenge of the Tracking Detector

Multiple interaction in an event at HL-LHC : 140-200 collision in an event, Future collider: 1500 !

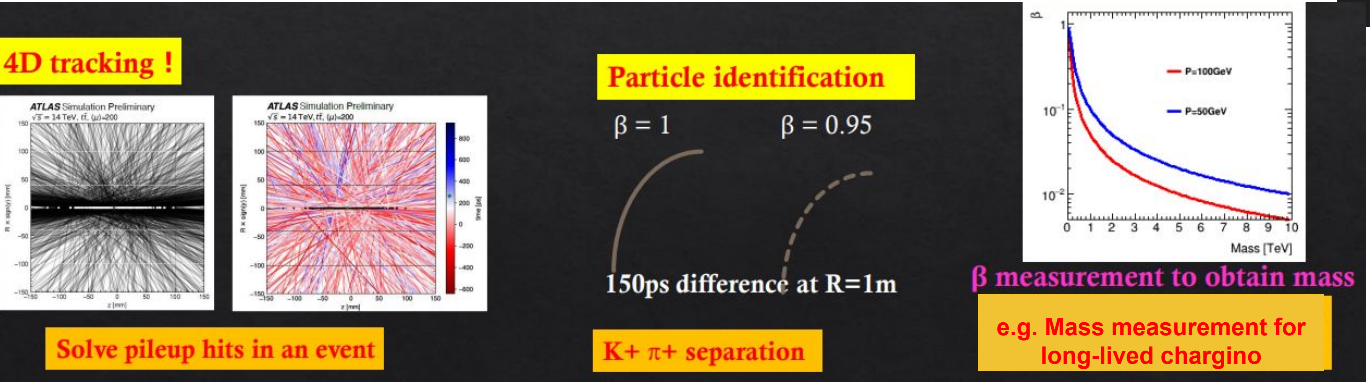
How to solve this issue?

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

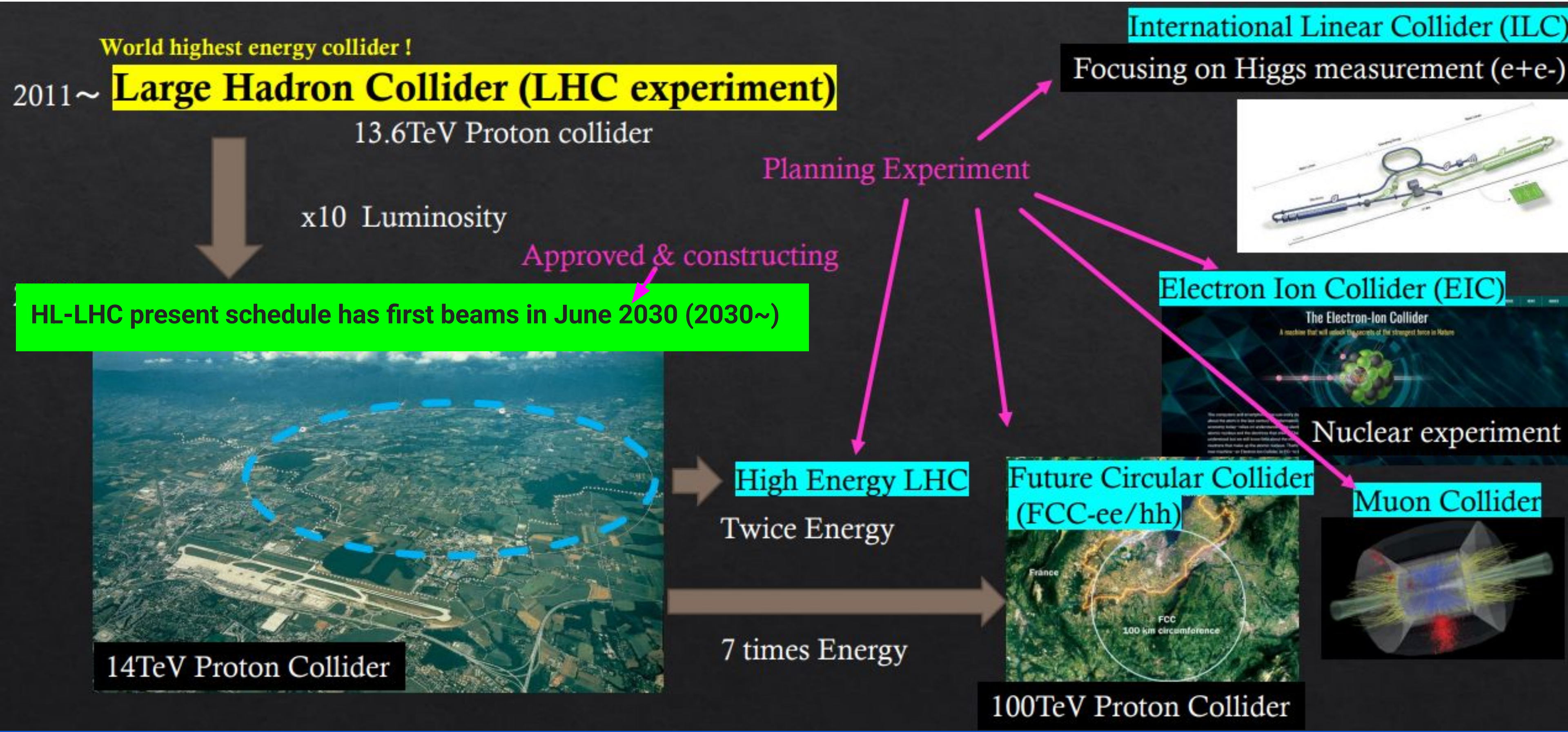
Timing information: Completely new information for tracking : possibility of dramatical improvement of track reconstruction
→Should help if timing resolution achieved 1cm/c ~ 30ps



Impact for tracker with timing resolution: some examples include-



Operating and Planning Collider Experiment



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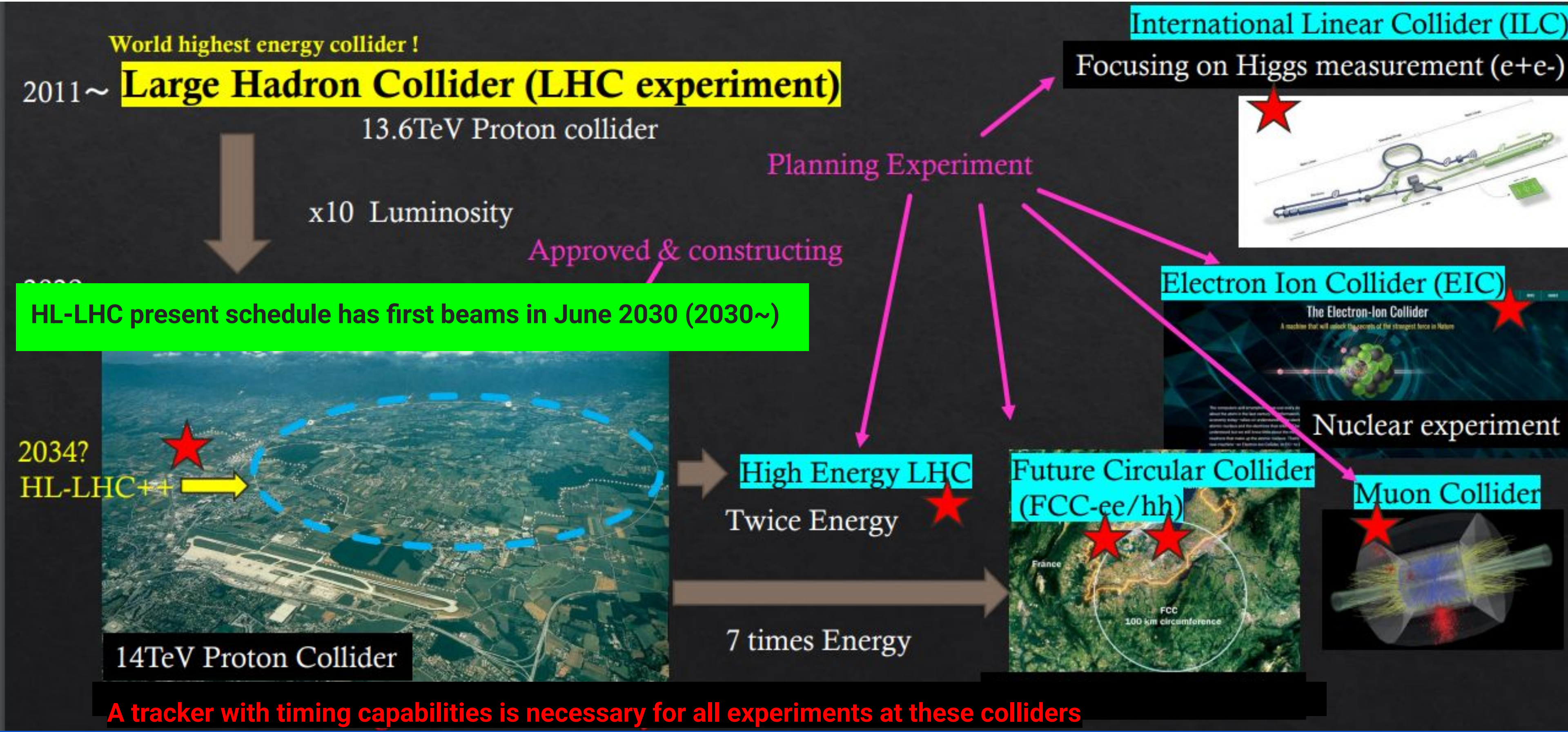
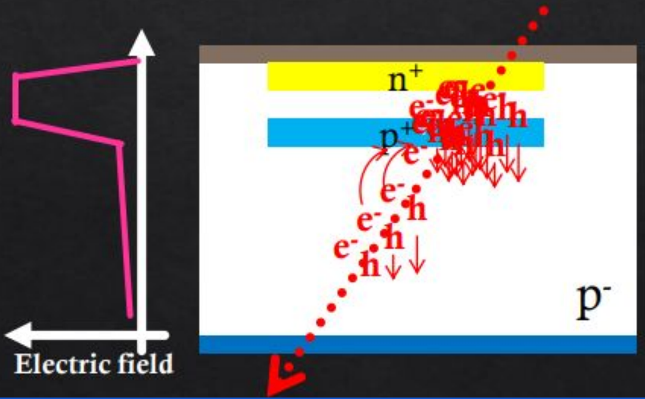


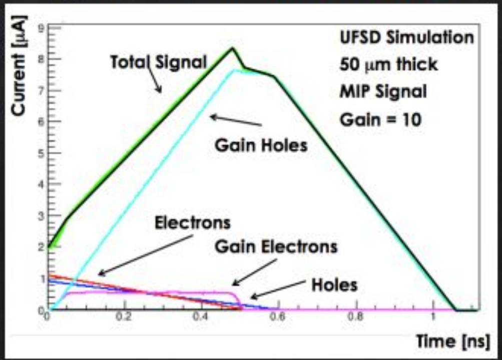
Low Gain Avalanche Diode (LGAD)

- 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.

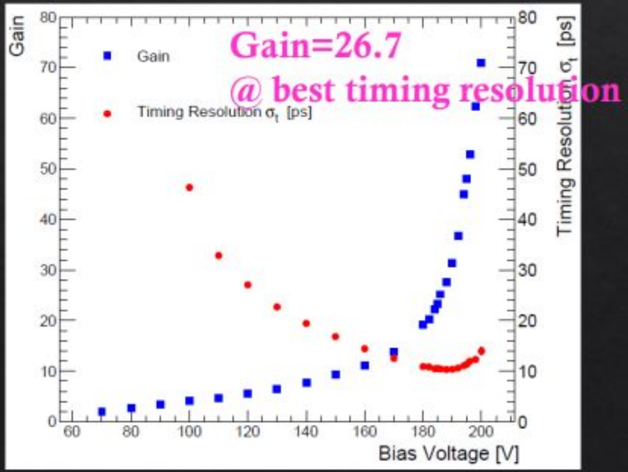
    → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**



Signal drivers : **Gain Holes**



Gain measurement (AC-LGAD):



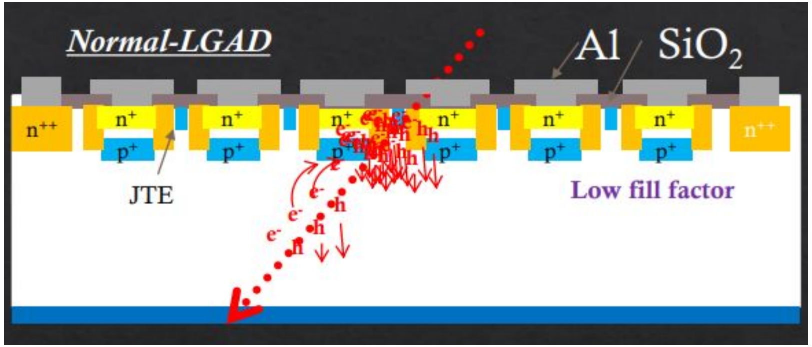
Spatial resolution of LGAD

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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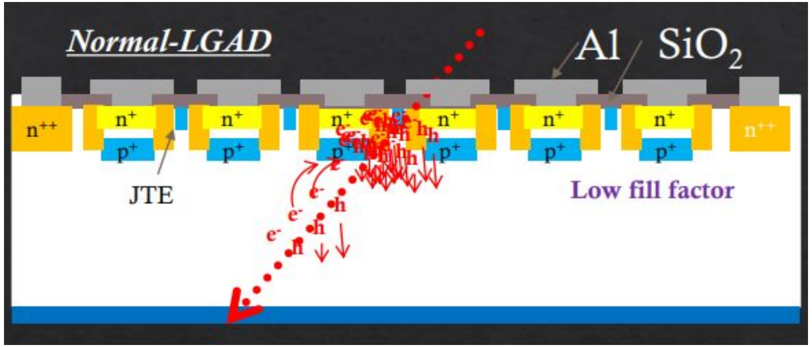
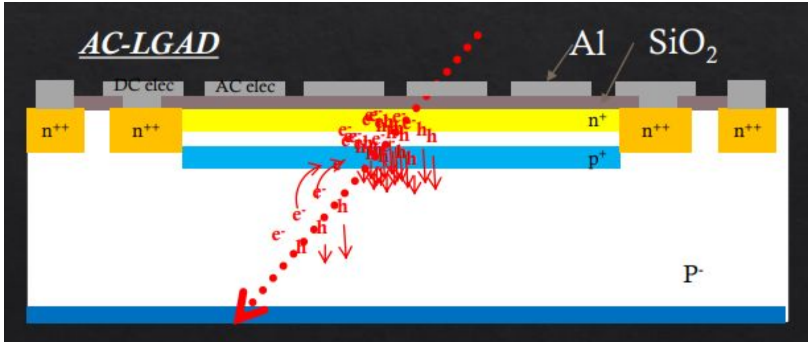


Uniform gain layer with AC-Coupled electrode. (AC-LGAD)

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

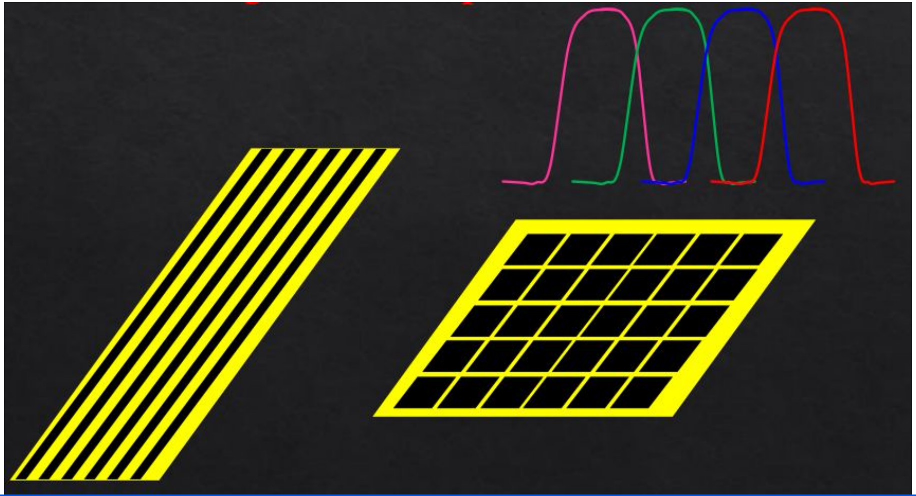
For lepton collider or other low occupancy colliders.

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

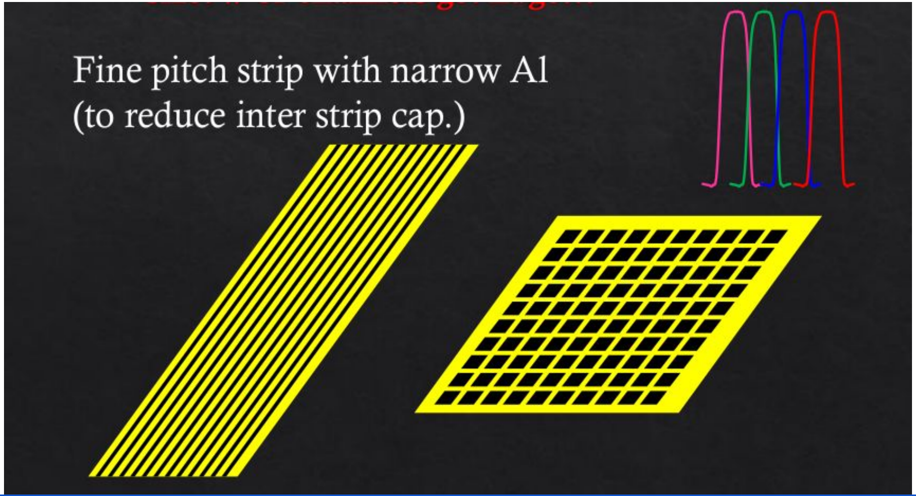
For High occupancy experiment like hadron collider.

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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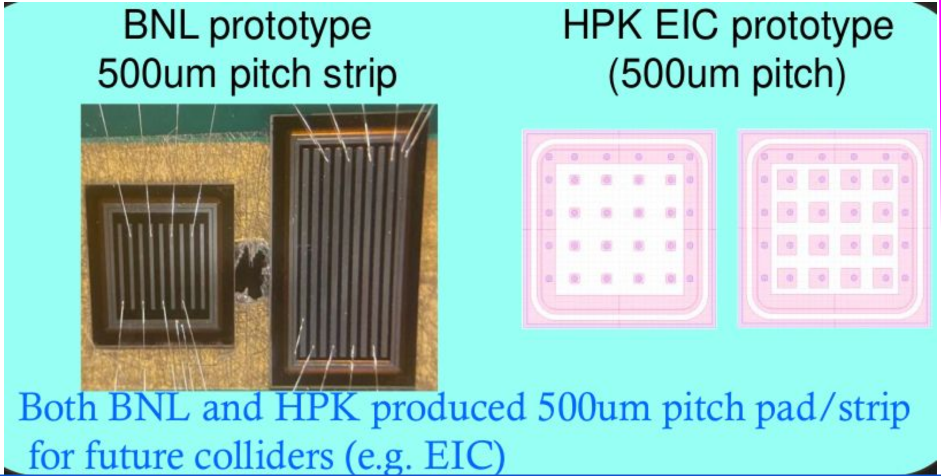

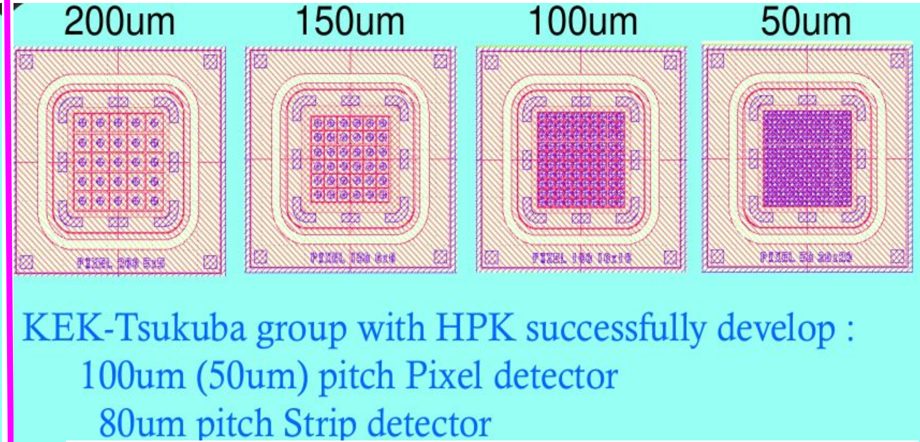

US-Japan Meeting 2023: https://indico.physics.lbl.gov/event/2259/

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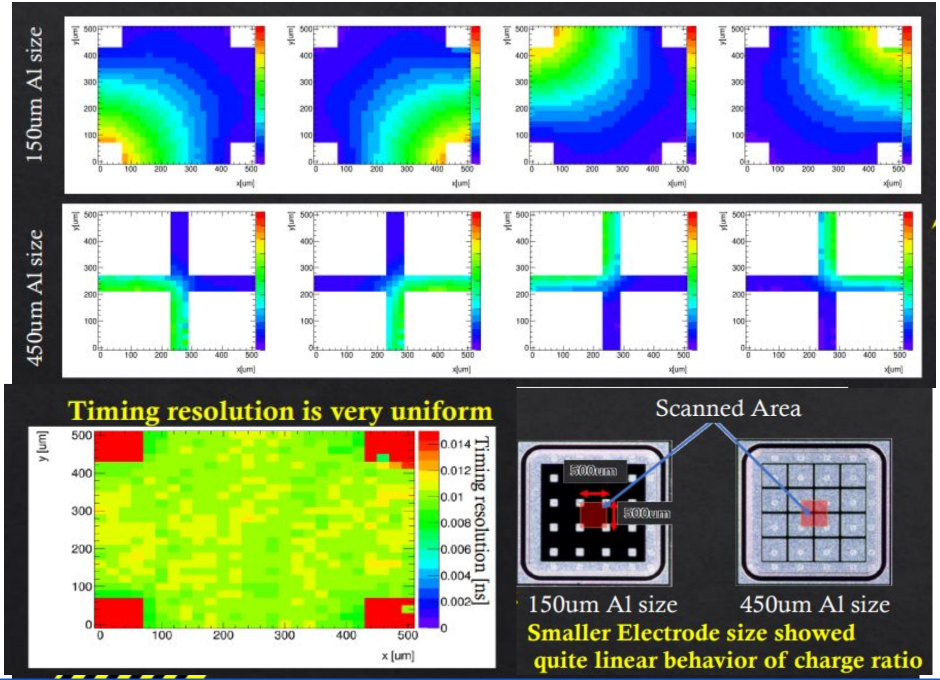

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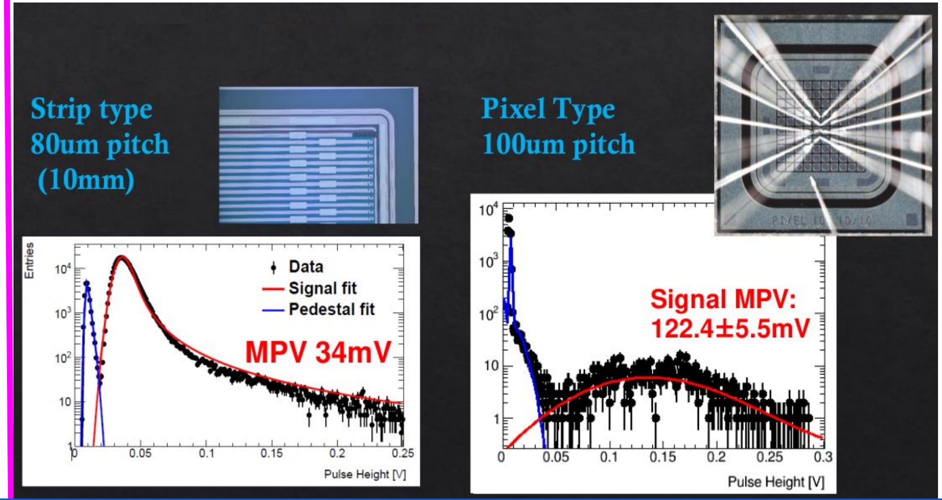
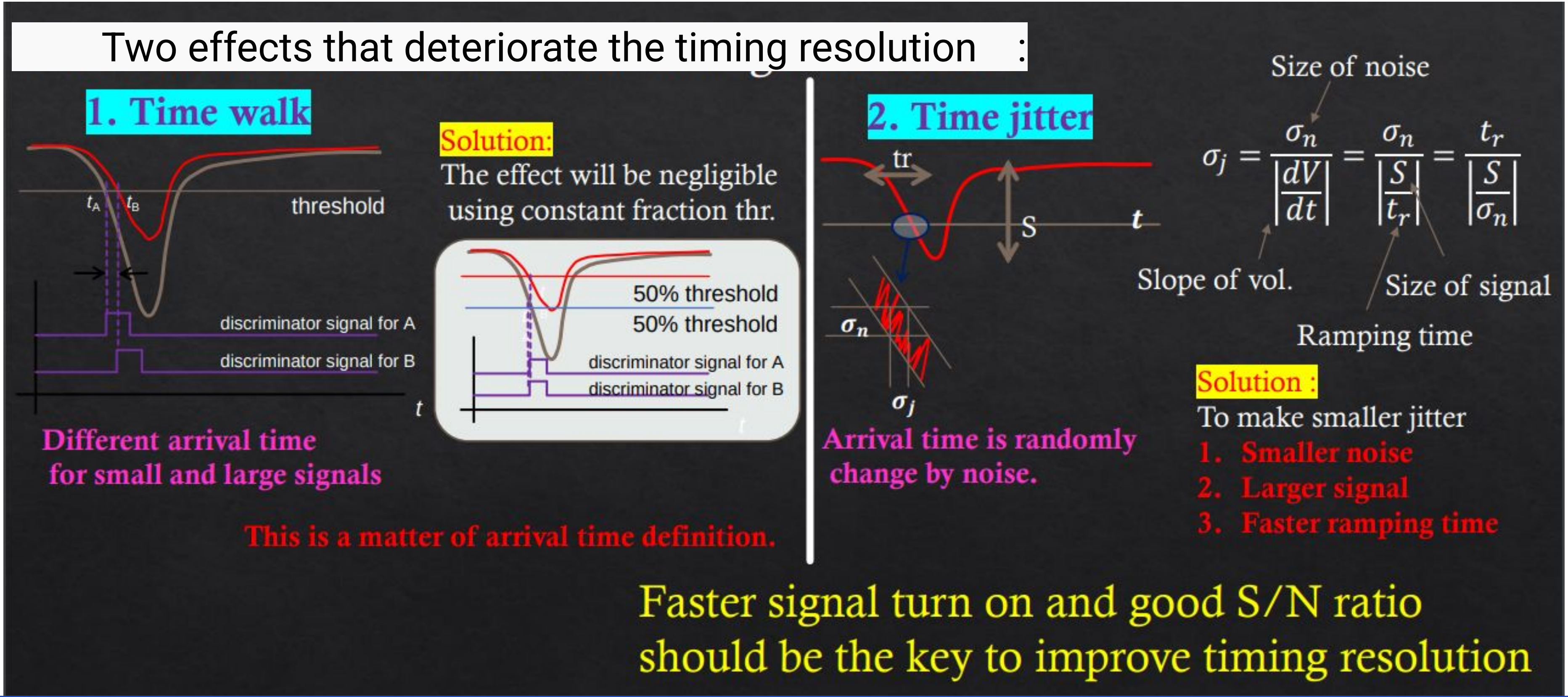


How to improve the timing resolution?



Timing resolution of LGAD sensor full picture

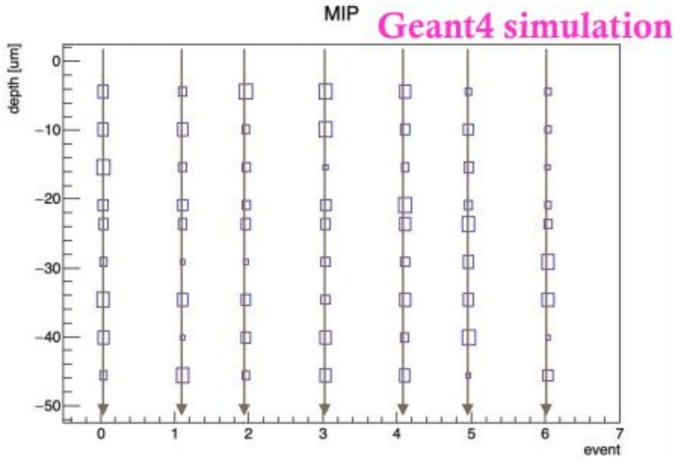
$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

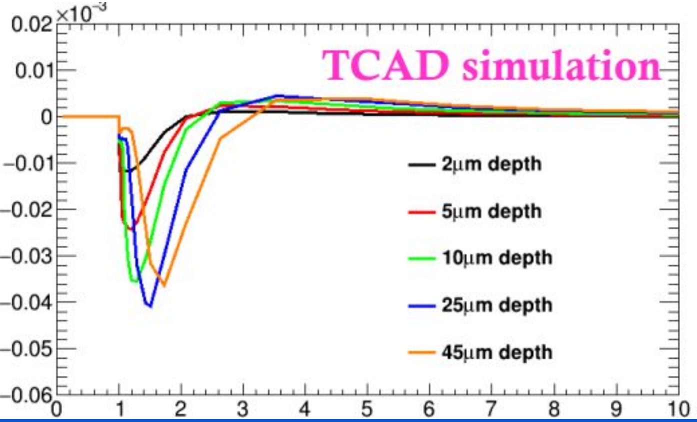
→ σ_L : Charge collection noise (Landau noise)

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 : ~30ps CCN → 35ps in actual device achieved.

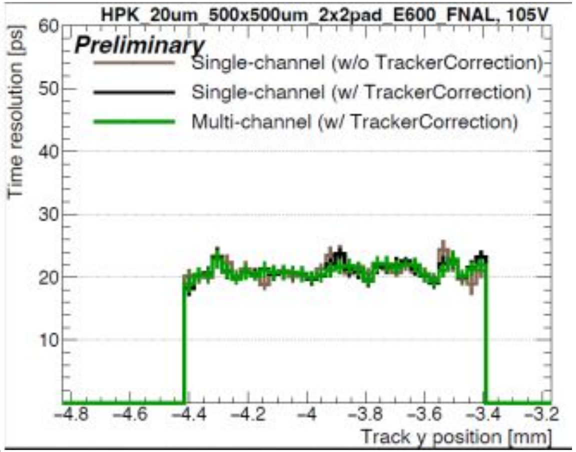
20um thick sensor : ~15ps CCN → 20ps in actual device achieved.

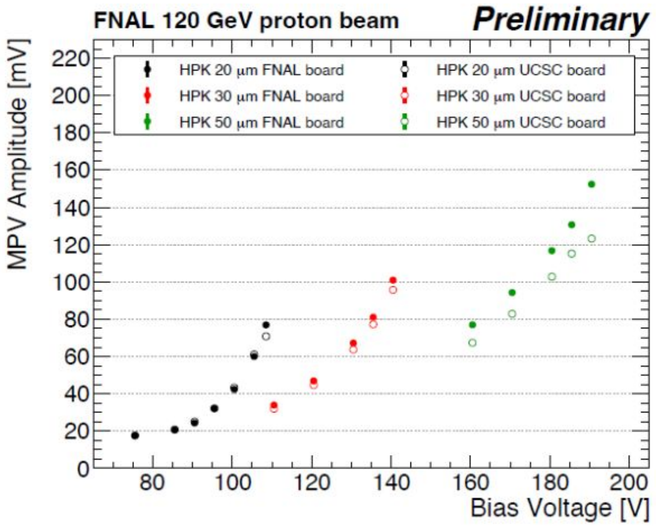
➔10um thick sensor? Smaller signal size (worse jitter) but better CCN.

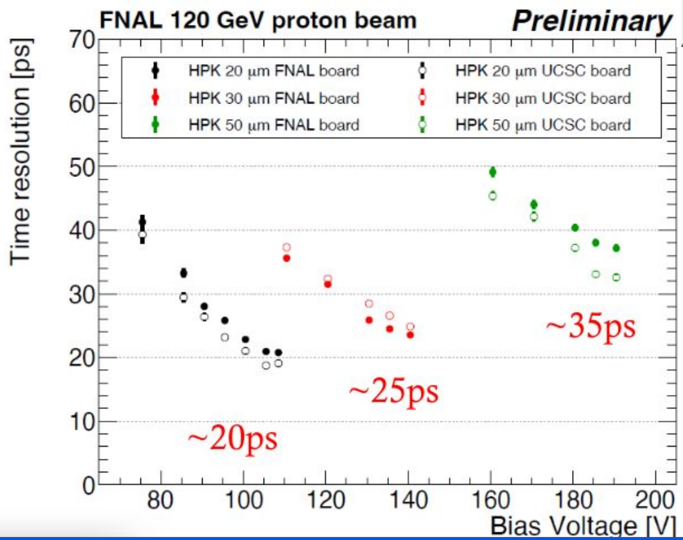
Improvement of timing resolution

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

- 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.







All results are for 500μm pad detector

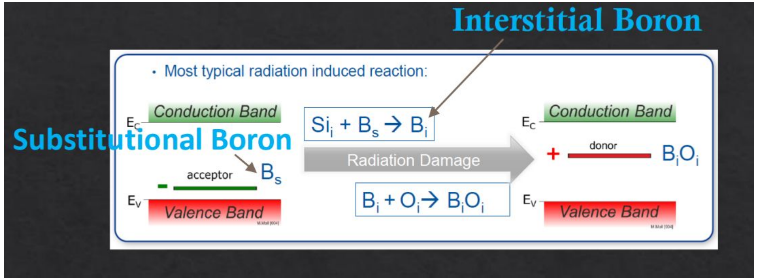
Radiation Tolerance of LGADs

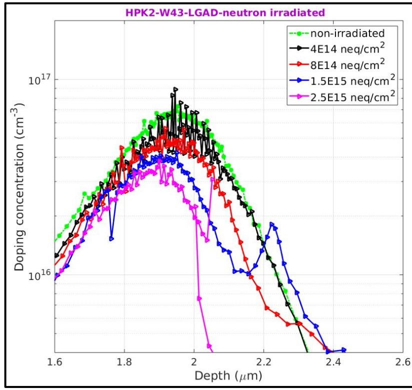
Like normal silicon device

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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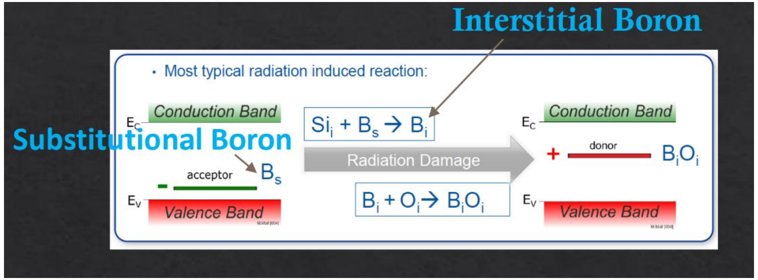

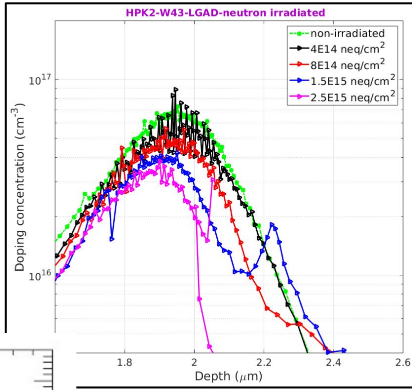

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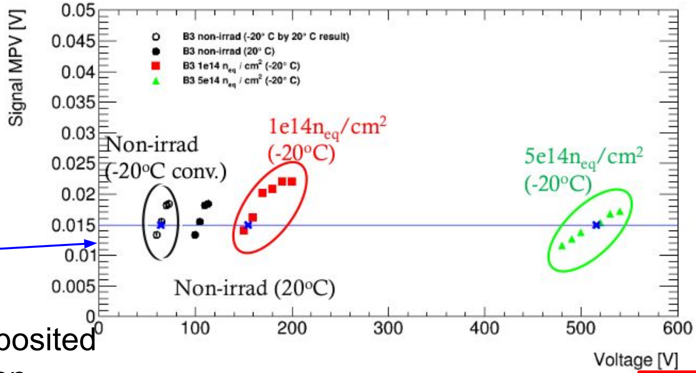
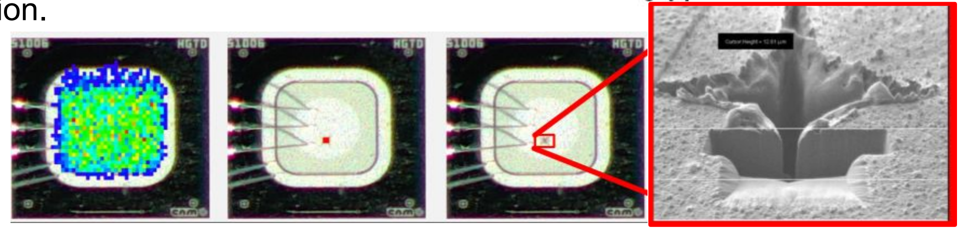


Why "acceptor removal" is an issue?

- 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

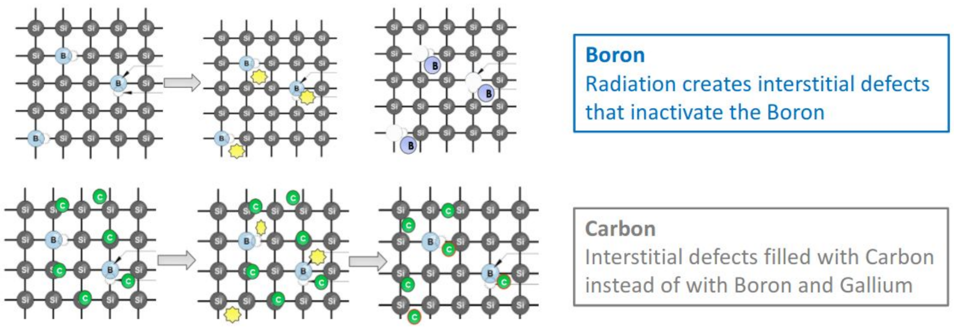
- Protection of gain layer is of key importance to reduce Acceptor removal
- New ideas:

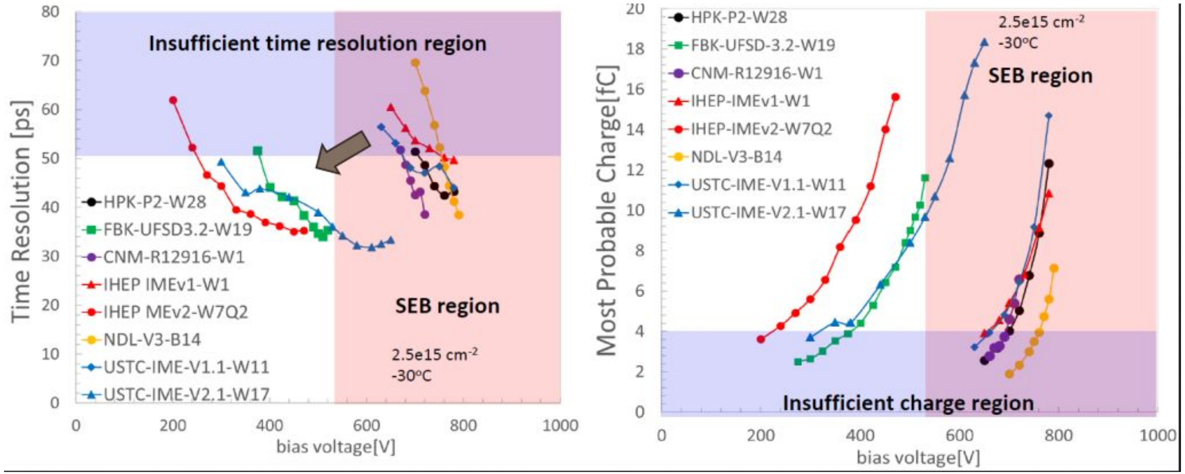
1. **Carbon annealing** (confirmed by FBK) - studied rigorously both by ATLAS and CMS collaboration for Phase-2 Upgrade

   Sensors with Carbon survive up to 2e15n_{eq}/cm^2 : V_{op} can be below 550V

   ~300V lower Vop after 2e15n_{eq}/cm^2 irradiation.

Ref: R. Arcidiacono, TREDI (2019)





Next talk by Matteo !

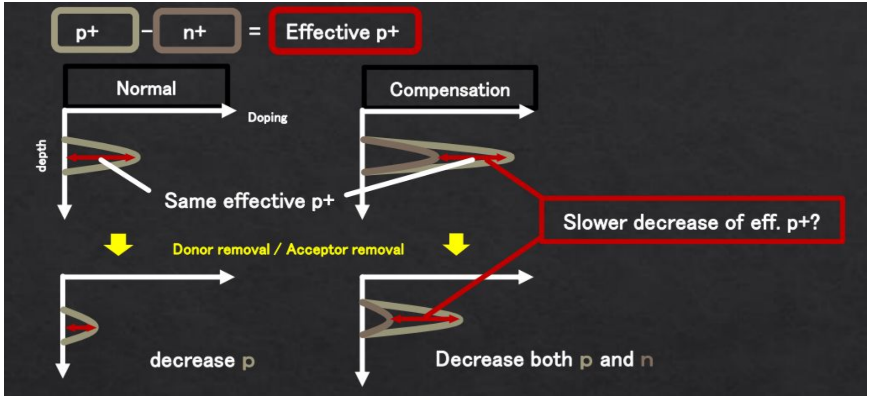
Improvement in radiation tolerance of LGADs

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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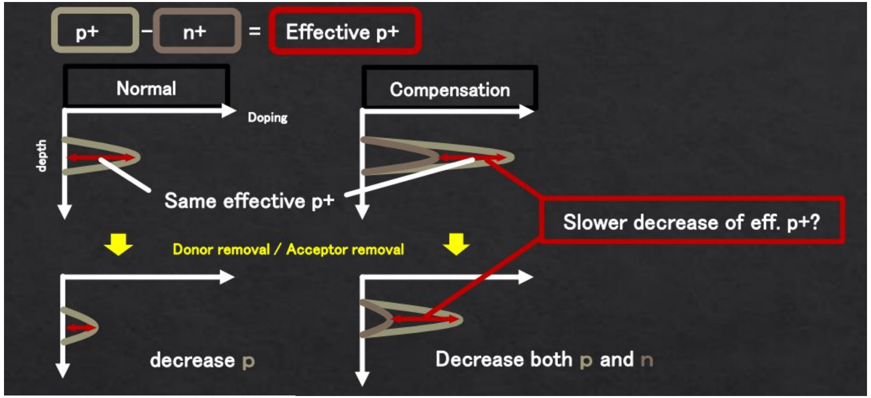


Different compensation ratio:

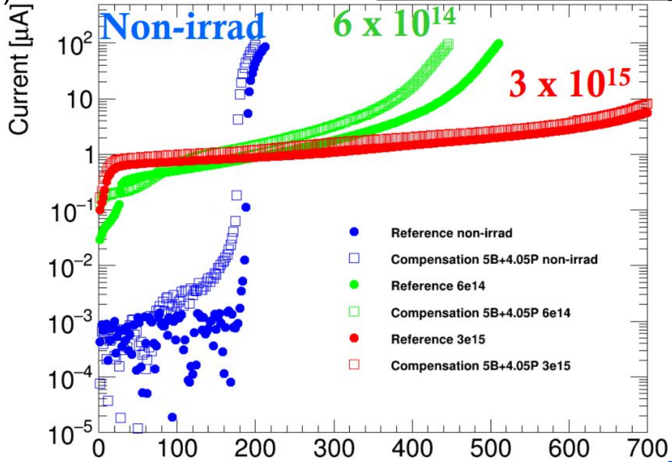
1B (reference)

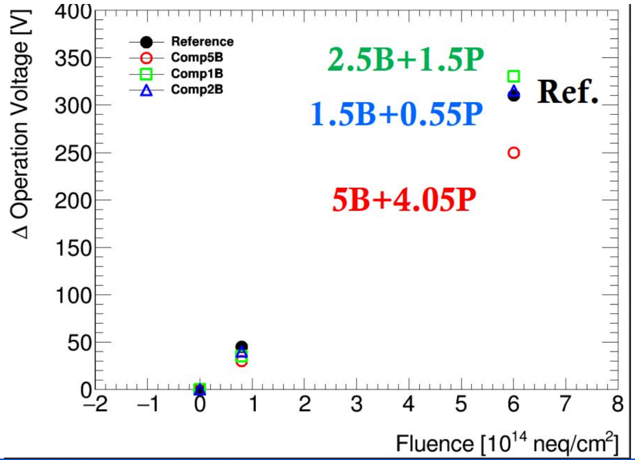
1.5B+0.55P : No visible improvement

2.5B+1.5P : No visible improvement

5B+4.05P : Saw slight improvement (~50V)

10B+9.2P : No significant signal observed





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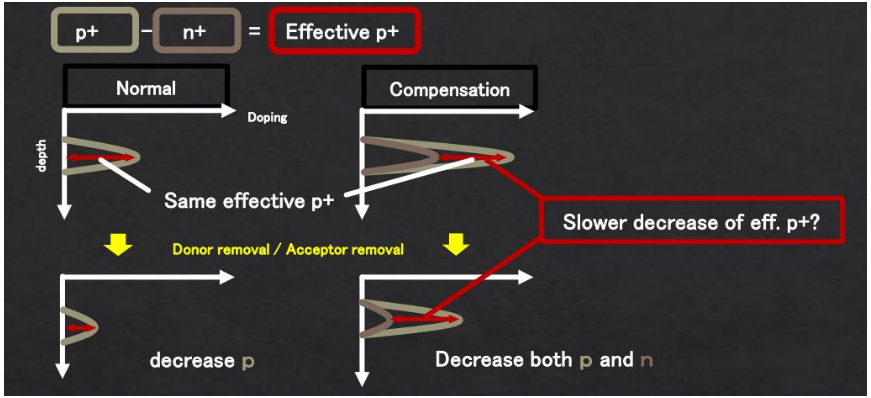

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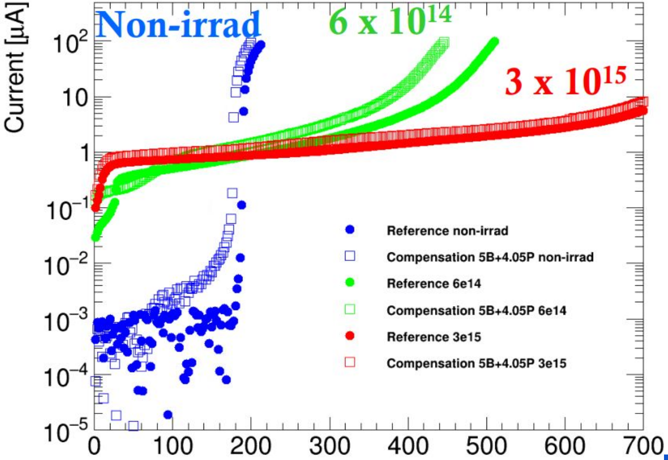
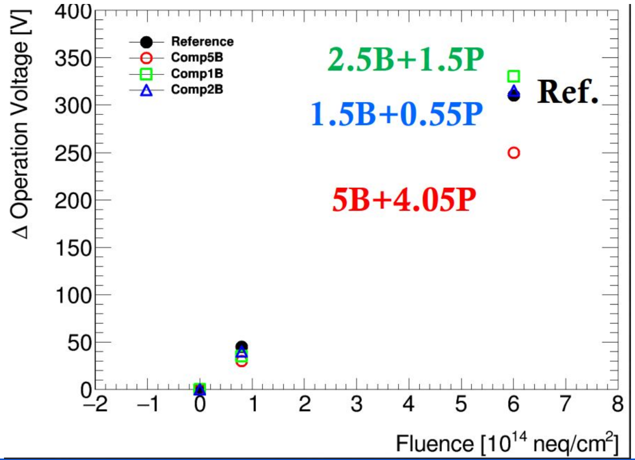
Inference:

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





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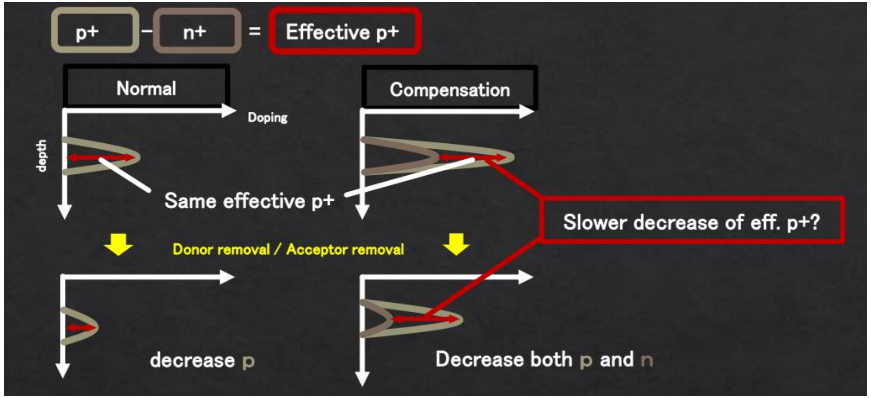

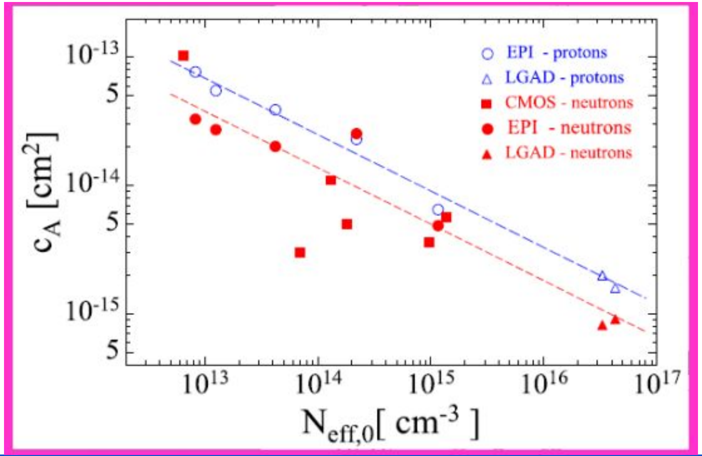

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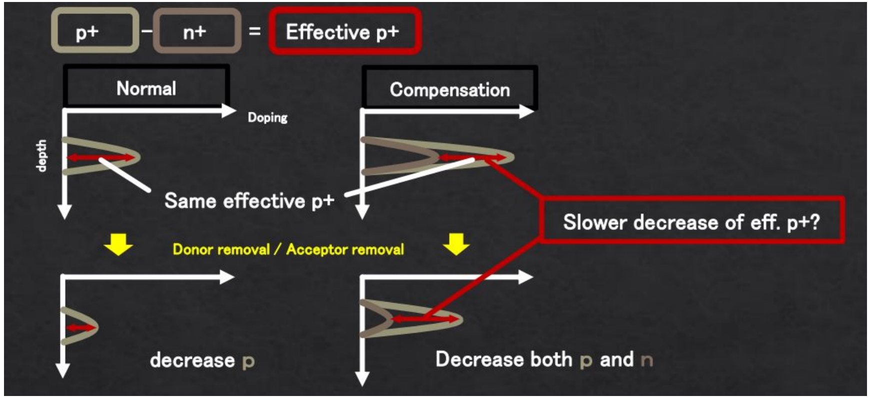

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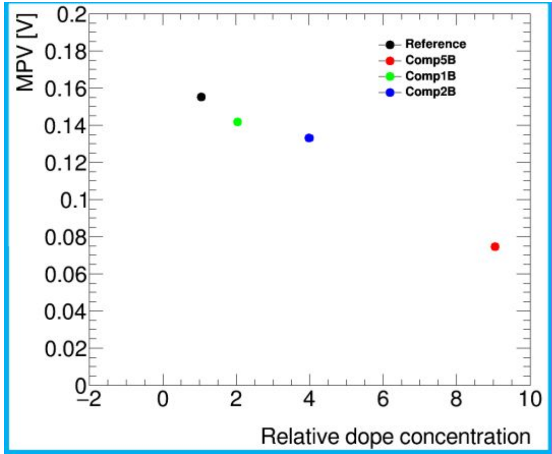

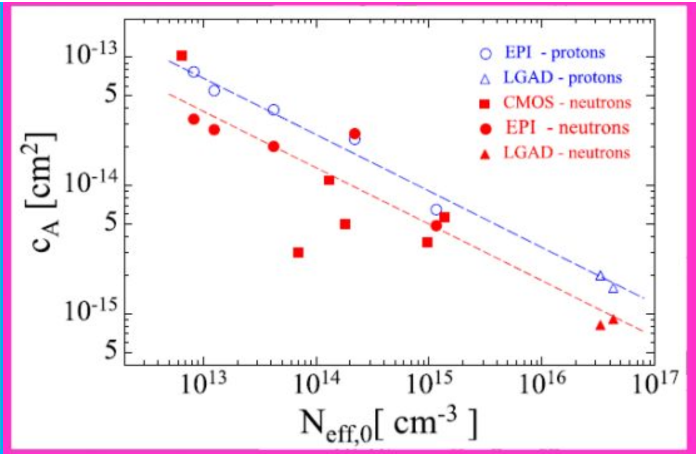

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- Problem: larger compensation have risk of reduction of signal size

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 80μm pitch strip sensor
- Good S/N ratio : 99.98% at 1e-4 noise rate

AC-LGAD with 100μm x 100μm pixel sensor
- Larger signal than strip sensor!!

Good timing resolution!

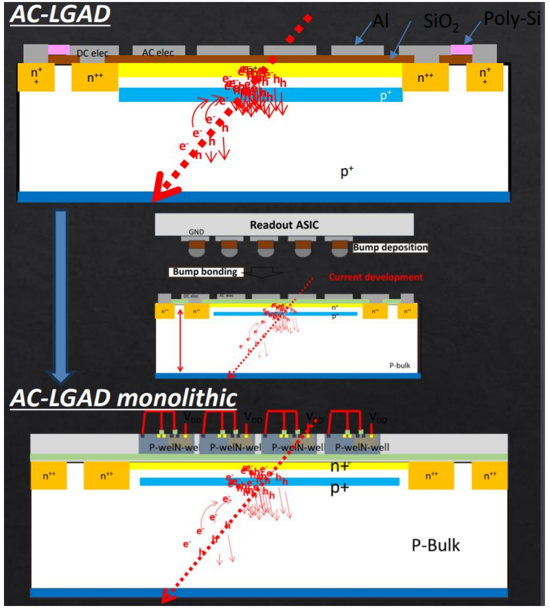
20μm thick AC-LGAD was successfully developed by HPK
- achieved ~20ps level time resolution! → Need to test pixelated LGAD

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)

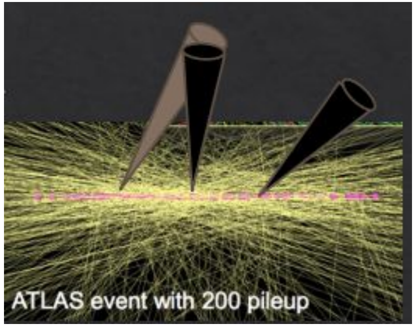
- Most results are taken from FNAL seminar (4.03.2024)

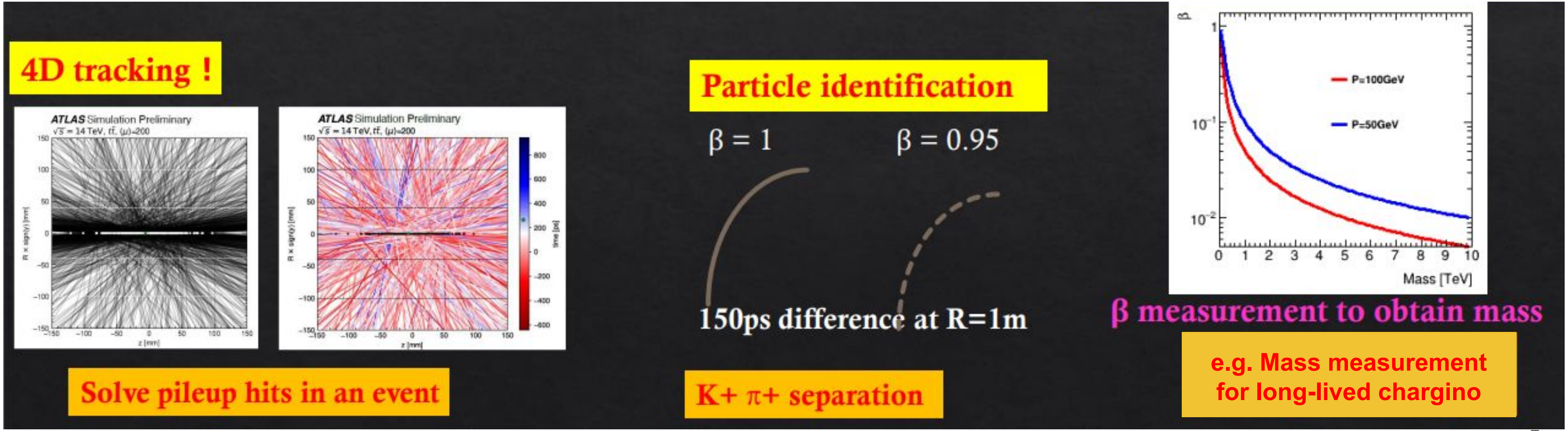
Backup Slides

Impact for tracker with timing resolution

• Collider experiment gets high energy and high intensity. →Future Tracking detector should have timing information for all hits!

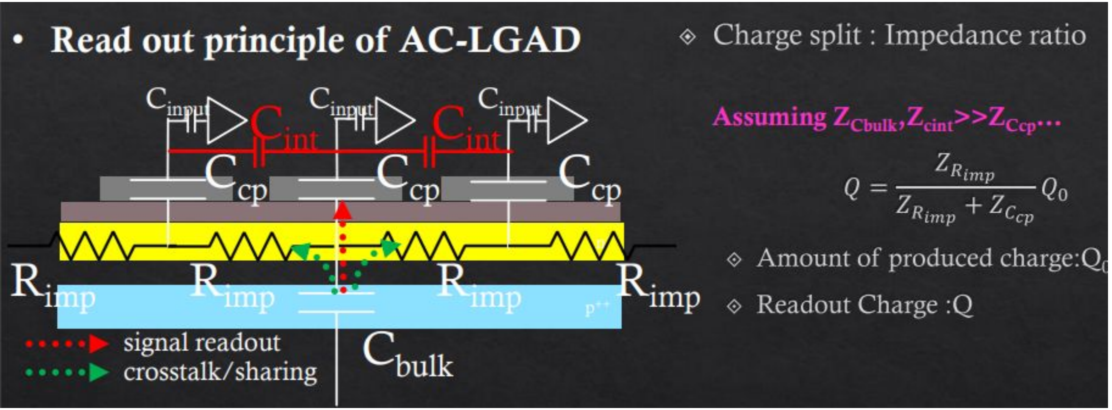
• Tentative Requirement – 30ps timing resolution &~o(10)μm spatial resolution – (hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance

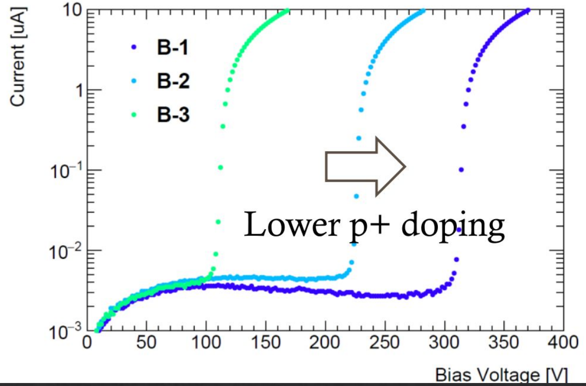




Read-out principle of AC-LGAD

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

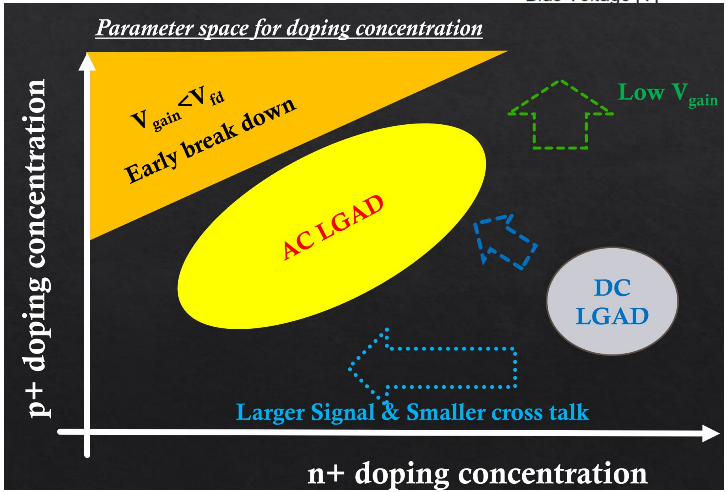




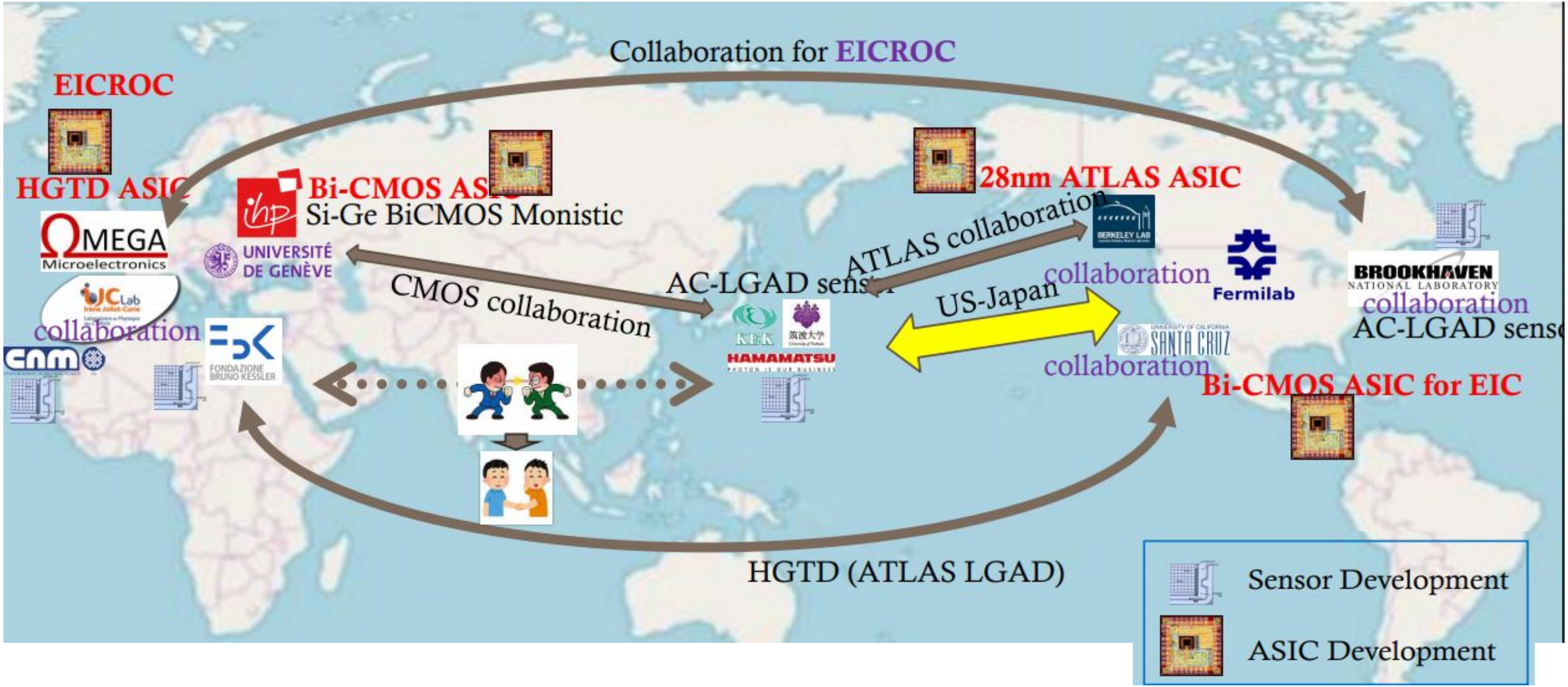
• Additional cross talk is expected due to the inter-electrode capacitance C_{int} – Amount of crosstalk may also depend on input capacitance on the electronics.

<u>Parameter space in n+ and p+ doping concentration has been optimized.</u>

- 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)



AC- LGAD collaboration



Two detector approaches for improving

- Readout ASIC (amplifier) with smaller noise:

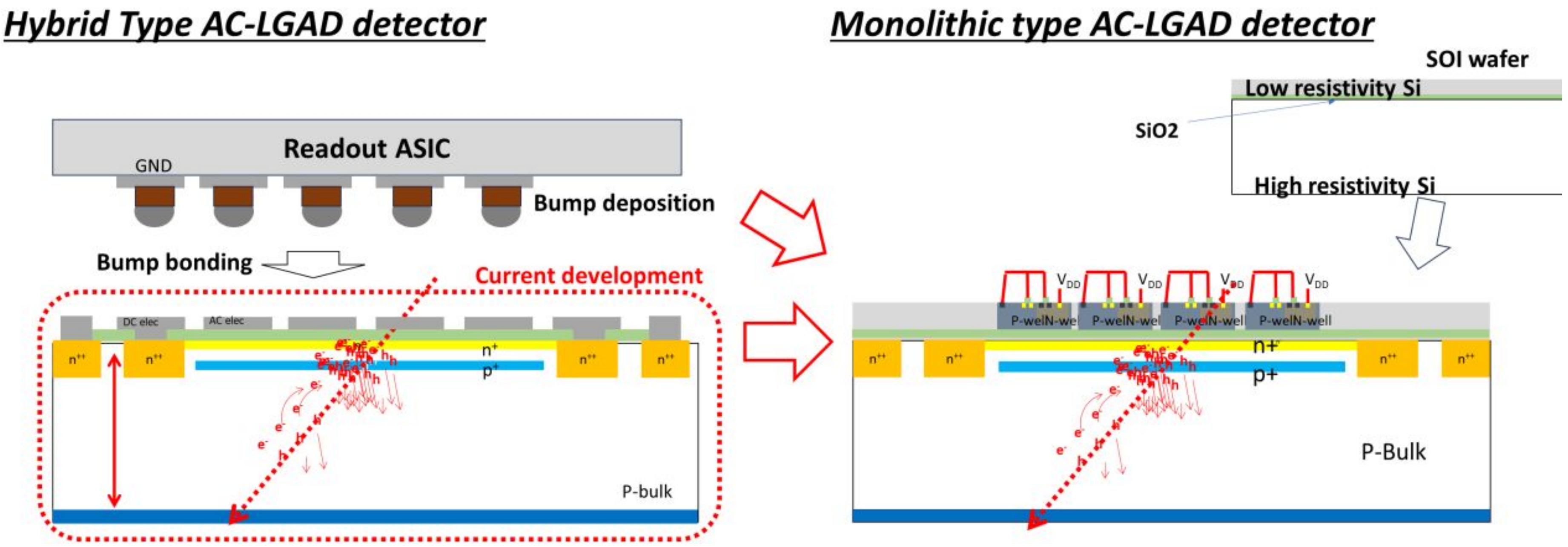
- 3D detector with CMOS ASIC
  - Time Spot
  - Various ASIC (TSMC 28nm)

- 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

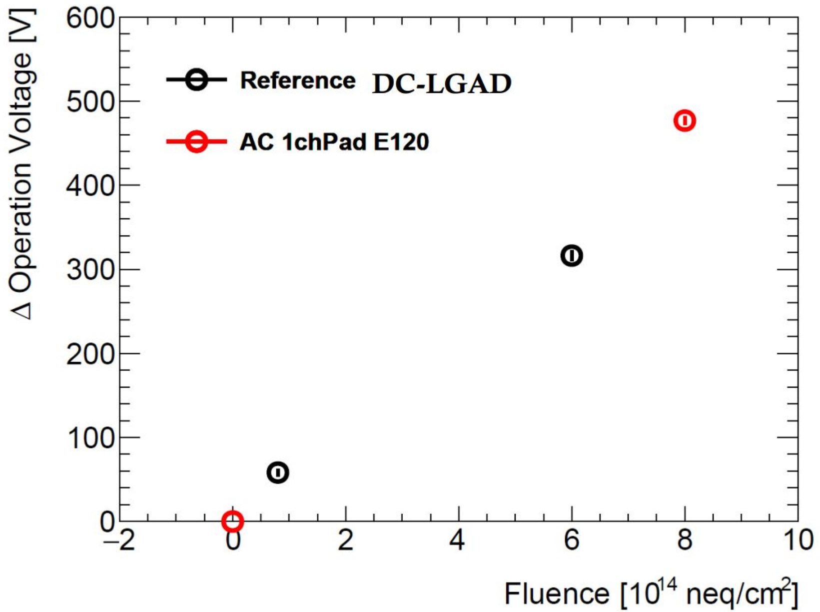


Radiation hardness comparison between DC- and AC-LGADs

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/