Tomonaga Center for the History of the Universe
光量子計測器開発部門

2020.6.15
宇宙史研究センター
構成員会議

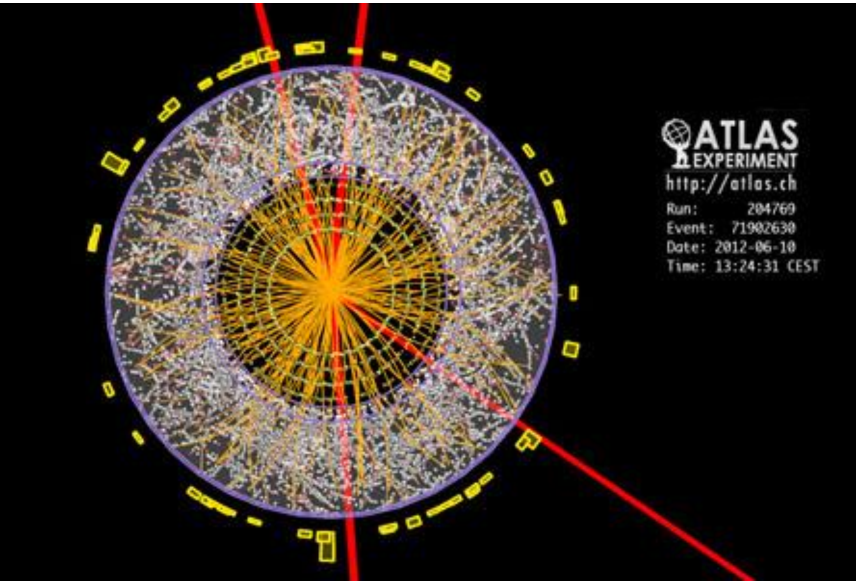
4次元飛跡検出器の開発
Development of 4D Tracking Detector

LGAD: low-gain avalanche detector

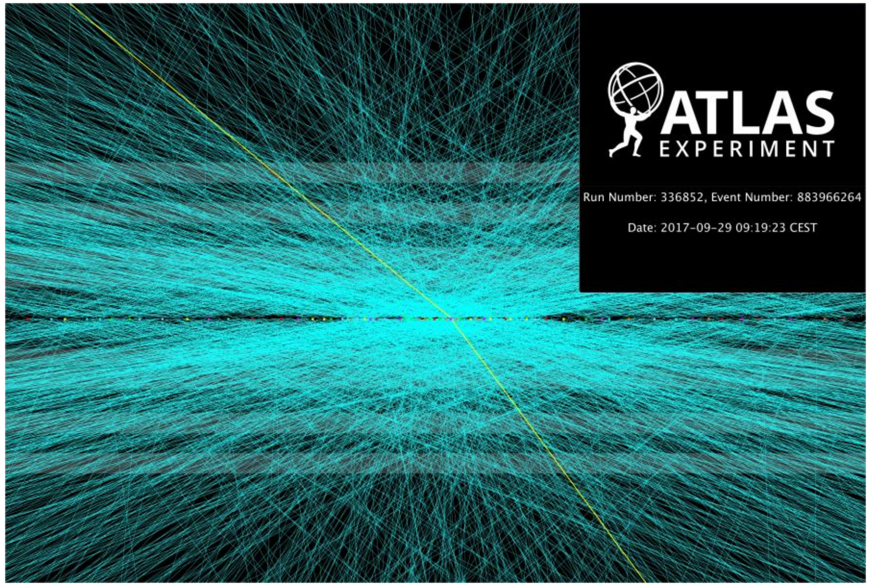
原、中村(KEK)、海野（KEK）、和田(D2)、大鳴(卒業)、植田(M1)

2015年度から開発を始めた
科研費B、新学術応募、日米科学協力

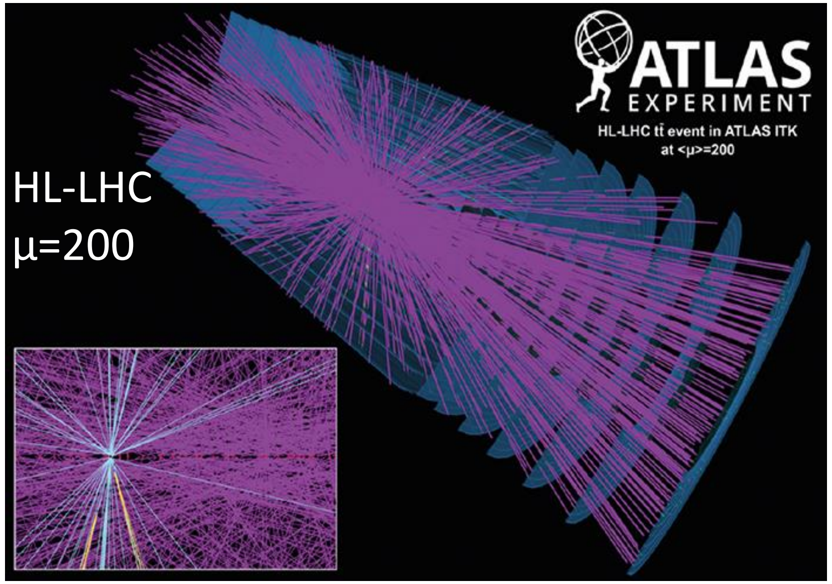
Tracking at the LHC-ATLAS



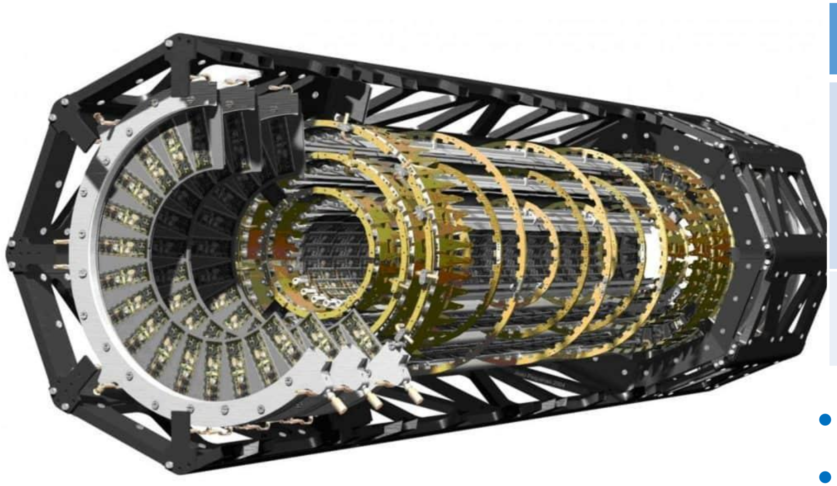
Run1: 2012 $1\text{x}10^{33}$ $cm^{-2}s^{-1}$ (μ=6)



Run2: 2017 $2.5\text{x}10^{34}$ $cm^{-2}s^{-1}$ (μ=66)



HL-LHC: 2027〜 $7.5\text{x}10^{34}$ $cm^{-2}s^{-1}$ (μ=200)



R=3cm, 5~12cm

	Run1	Run2/Run3	HL-LHC
Pixel size	50x400 um (B-Layer, L1,L2) (5<R<12cm)	50x250 um (IBL) 50x400 um (B,L1-L3) (3cm, 5<R<12cm)	50x50 um 5 layers (4<R<28cm)
ASIC	FE-I3 (250nm)	FE-I4 (130nm)	ITKpix (65nm)

- ピクセルサイズの微細化で対処する
- ASICのプロセス細分化で対応できた

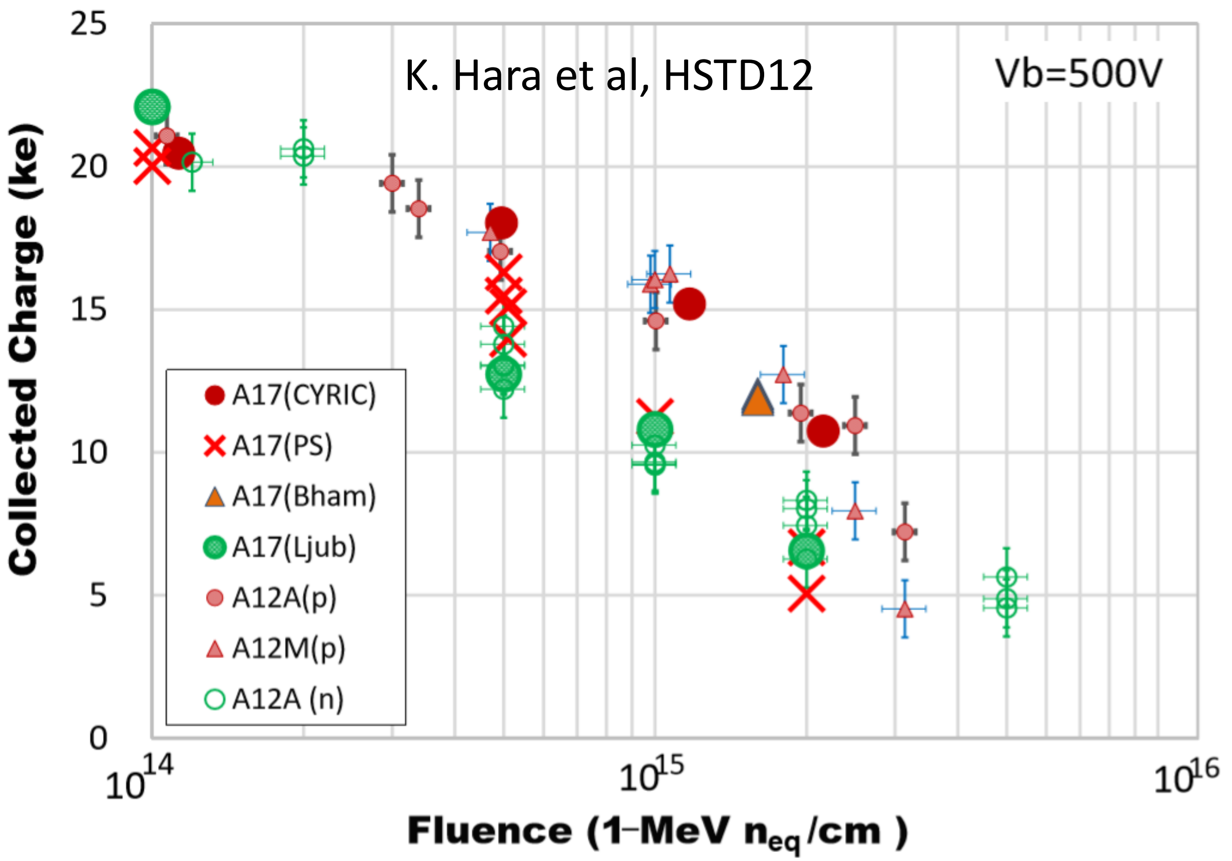
☛ 空間以外の情報？

Radiation at hadron colliders

Run1: 2012 1x10^{33} $cm^{-2}s^{-1}$ (μ=3) Run2: 2017 2.5x10^{34} $cm^{-2}s^{-1}$ (μ=66) HL-LHC: 2027〜 7.5x10^{34} $cm^{-2}s^{-1}$ (μ=200)

Radiation environment $\mathcal{L}$=300 /fb ⇒ 4000 /fb >2x 10^{16} n_{eq}/cm^2

300 um thick/74um pitch sensorでの電荷収集量



電荷収集量の低下 : キャリアのトラップ

厚いセンサー(物質量、トラップのため増えない)

- ▷ 電極間を短くする
- ▷ 電圧を上げる
- ▷ アンプのノイズを下げる

HL-LHCでは

- ▷ 3つとも採用

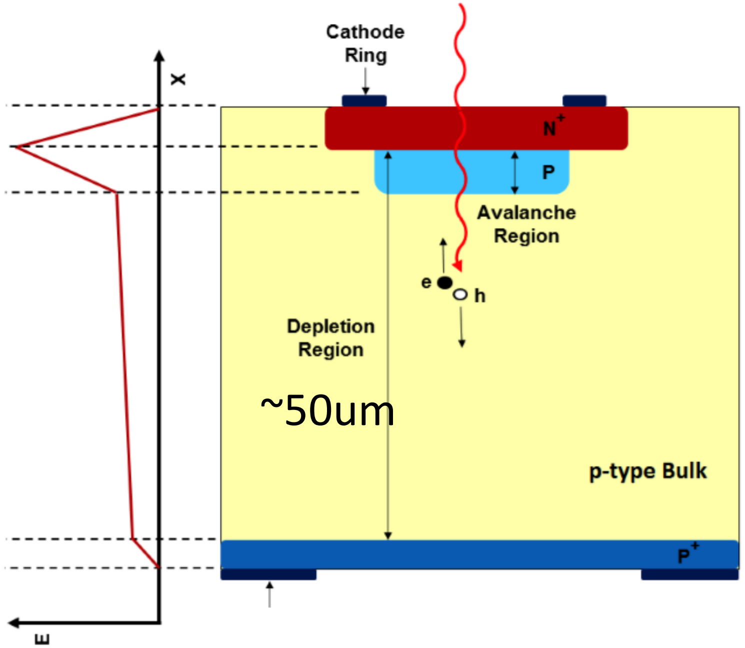
さらには

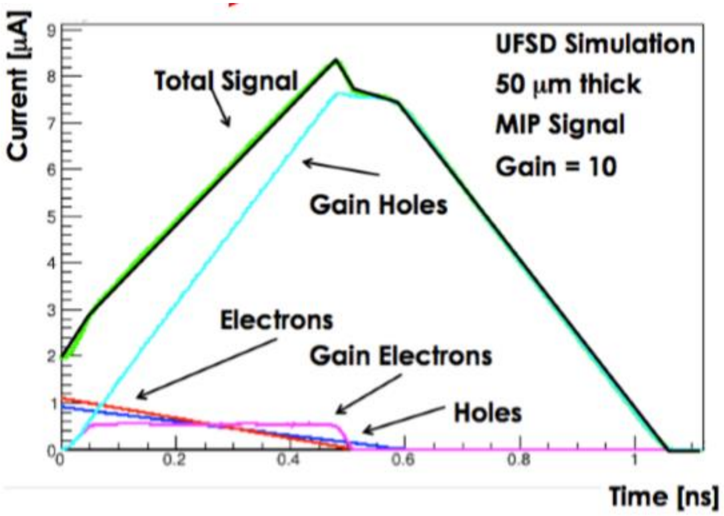
☛ ゲインのあるセンサー？

R&D with HPK since 2015.

LGAD low gain avalanche detector

A thin highly-doped p-layer provides an internal gain

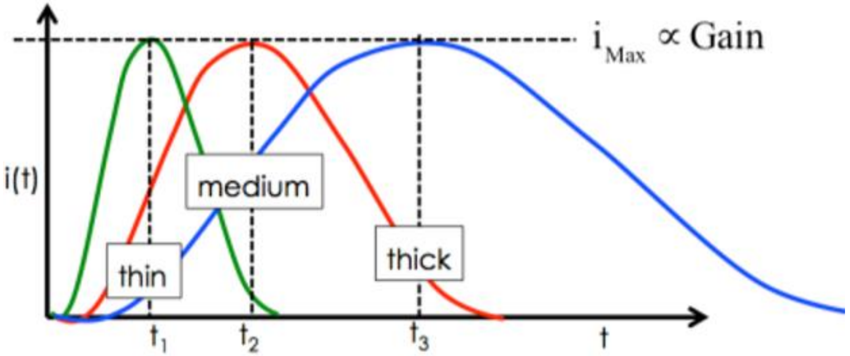




Rise time: 0.5 ns

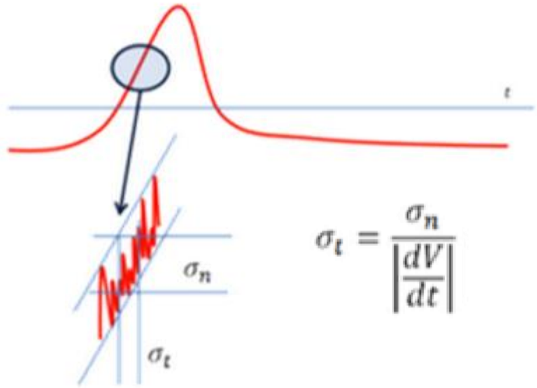
Gain: 10-50

"large gain in short time"

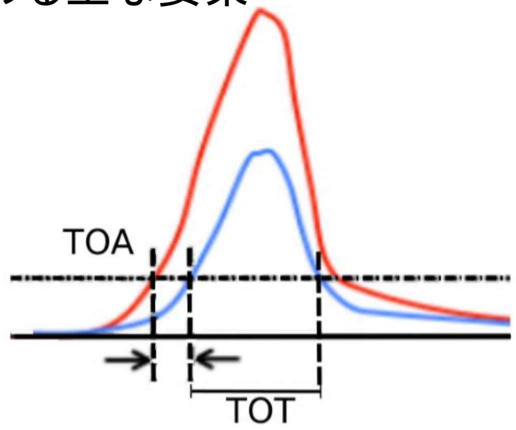


Thicker active sensor will not improve pulse amplitude, degrading the rise time

時間分解能を決める主な要素



jitter: noise, 1/riseT



Time walk: 1/riseT

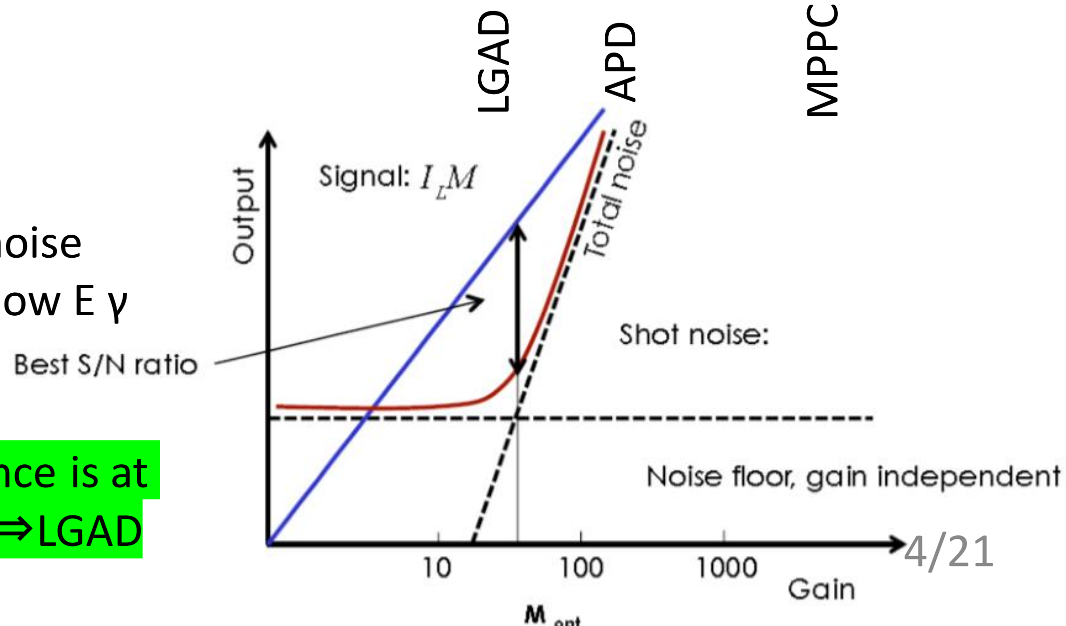
Larger gain

⇒wider pulse

⇒larger shot noise

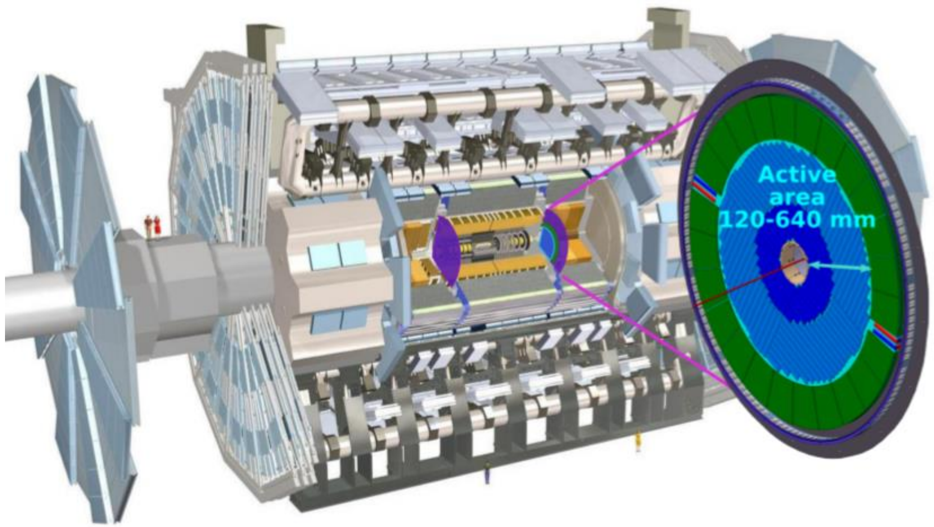
⇒sensitive to low E γ

Best performance is at low gain (10-) ⇒LGAD

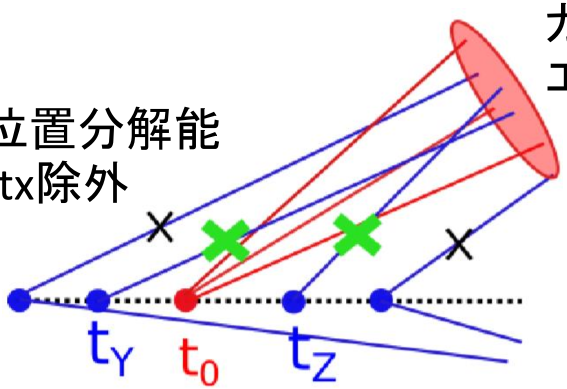


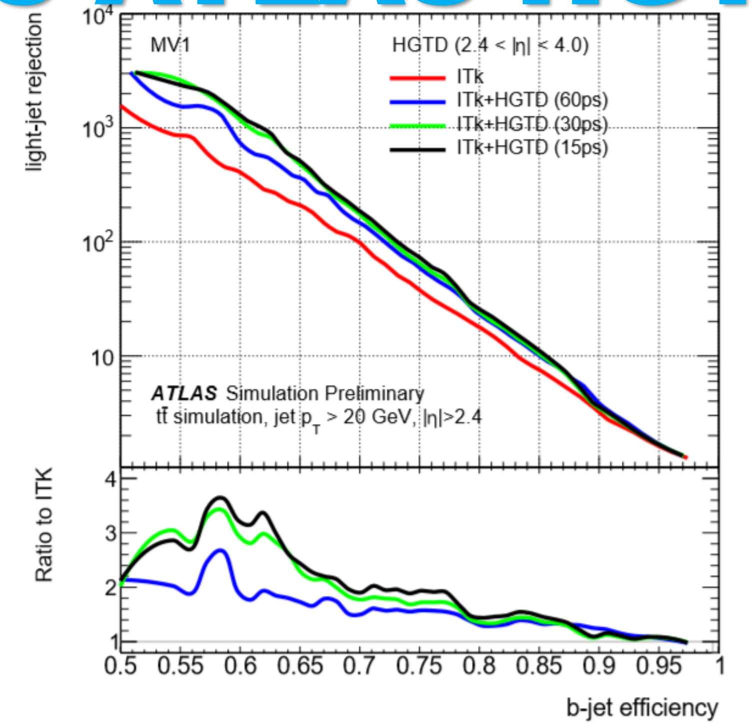
LGAD@HL-LHC ATLAS HGTD

HGTD: high granularity timing detector



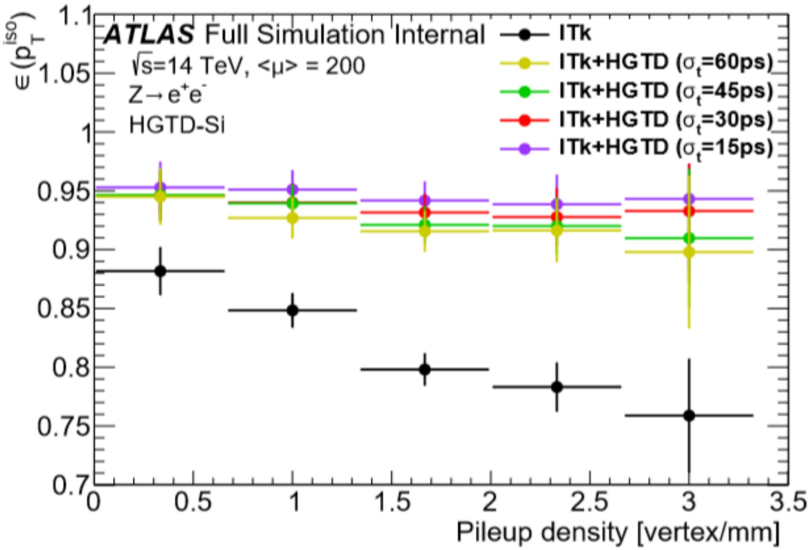
前方領域 (2.4<|η|<4.0)のカロリメータ直前





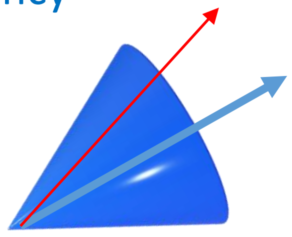
HSTD TDR

Heavy flavor tagging vs Light-jet rejection



HSTD TDR

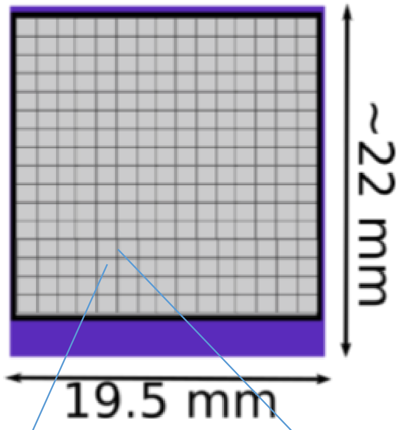
Lepton isolation efficiency

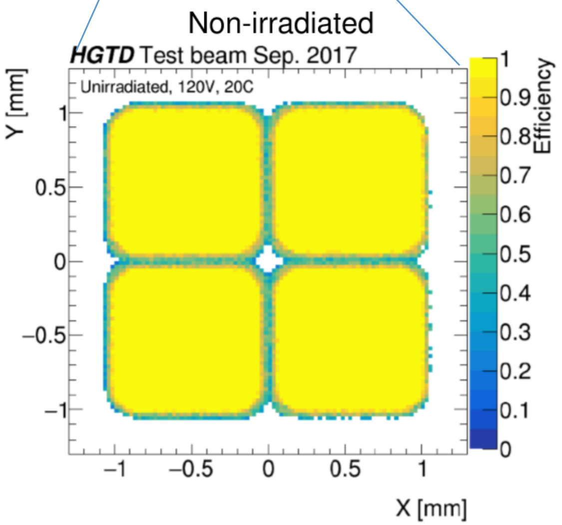


LGAD@HL-LHC ATLAS

sensor

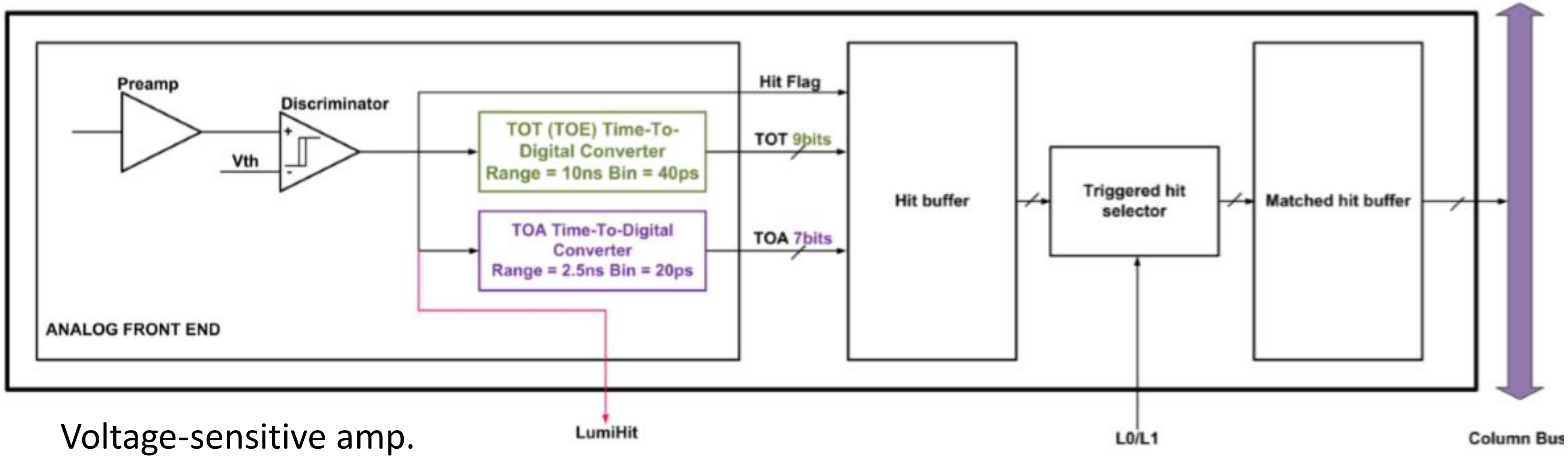
15x15=225 array



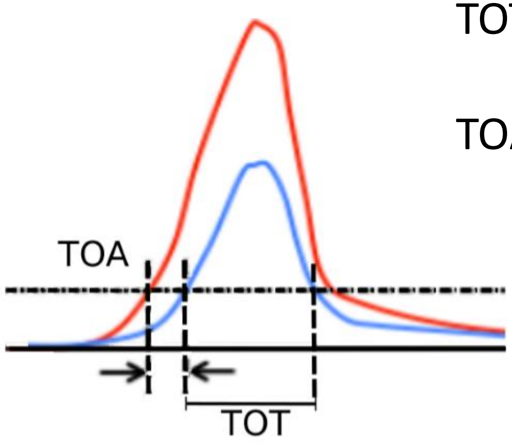


パッドサイズ：1.3mm□
(occupancy~10%)

ALTIROC ASIC (65nm)



Voltage-sensitive amp.
(fixed threshold)

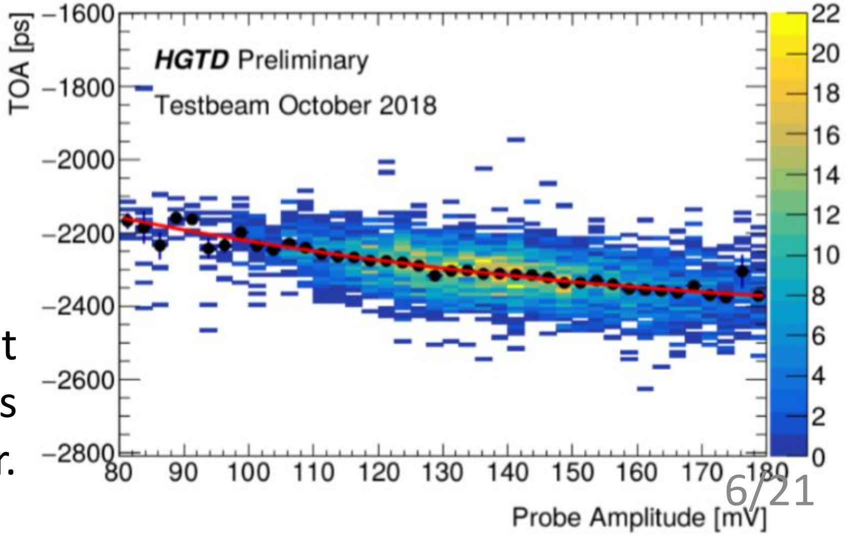


Hit flag

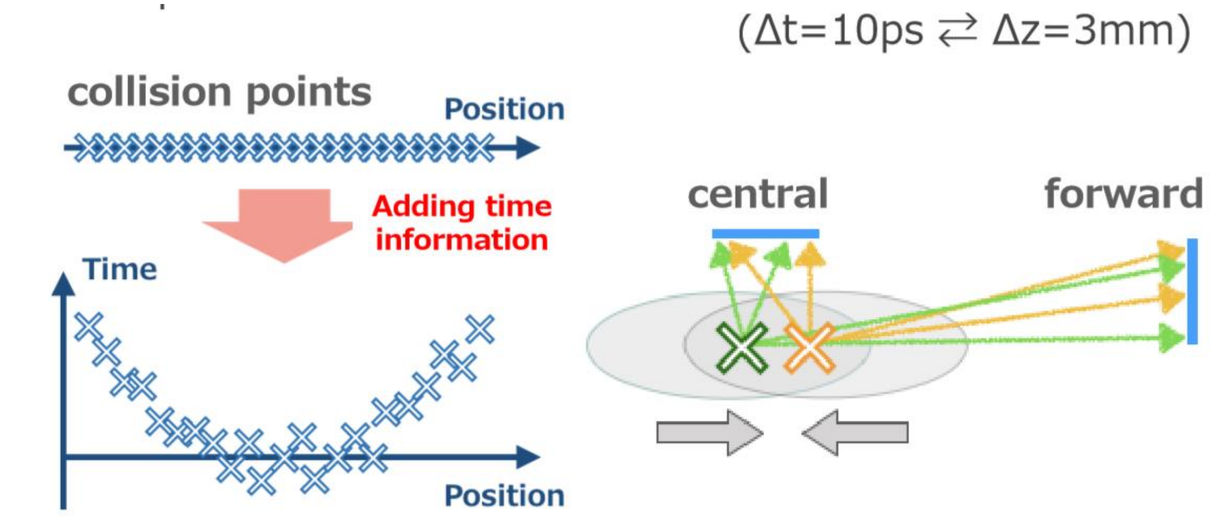
TOT: Time over threshold
(40ps/9bit)

TOA: Time of arrival
(20ps/7bit)

Testbeam result
45→36ps
w/o w/ amp. Corr.



4-D Tracker



ATLAS HGTD: pad-type LGADs
TOF ⇒ Vertex Point

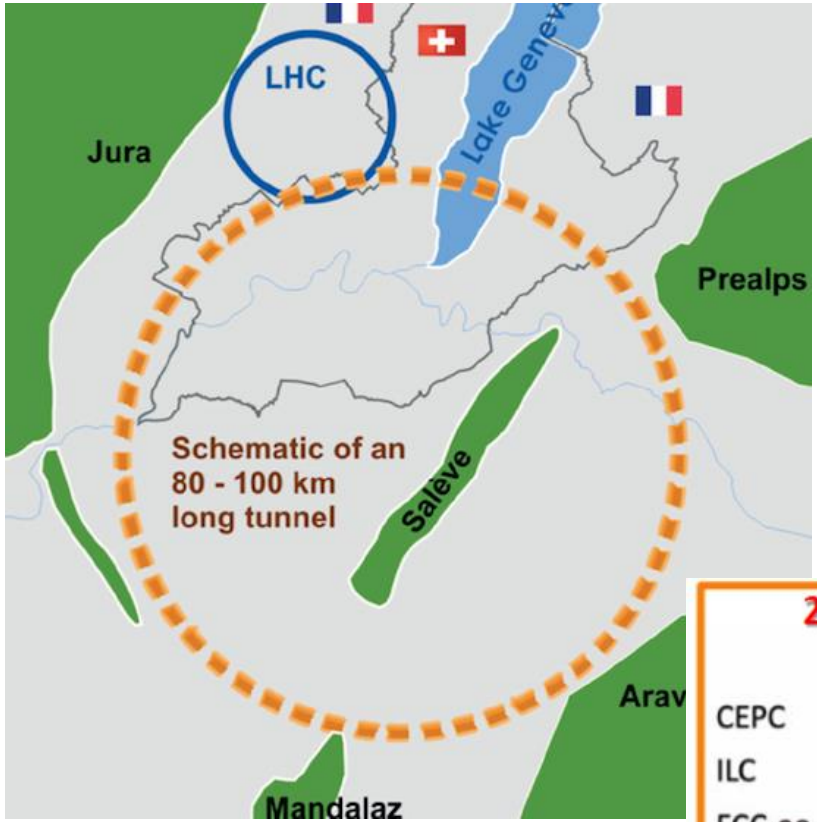
Future Circular Hadron Collider (FCC)
Add time information to each hit

- ☐ Reconstruct tracks using proper time differences
- ☐ Help reduce wrong hit combinations and effective in reducing the track reconstruction CPU

⇒ innovation in tracking

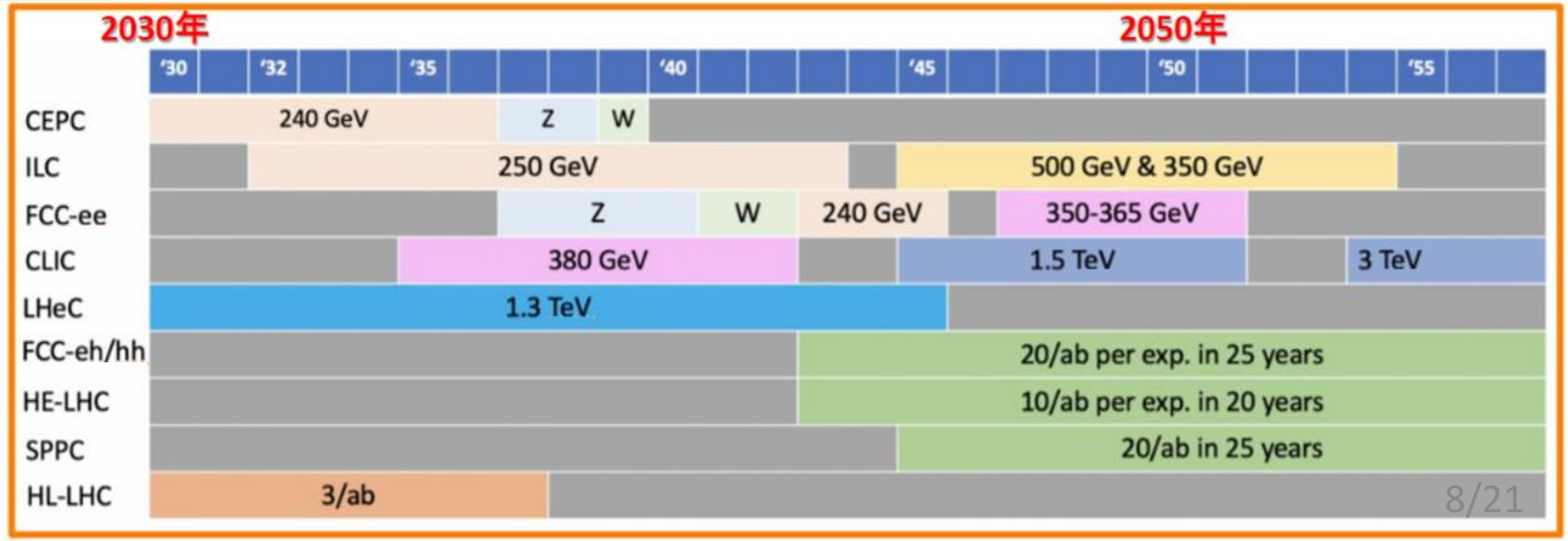
Fine segmentation/good timing are both required
= 4-D Tracker

FCC (future circular collider)



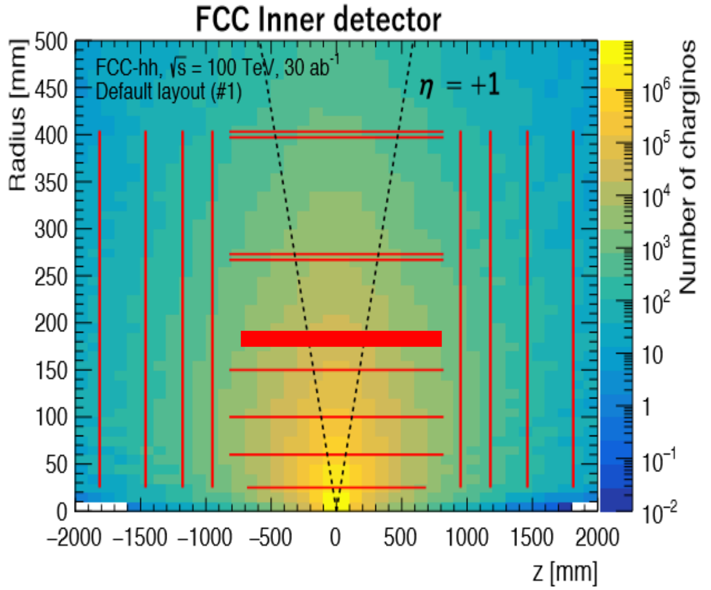
100 TeV hadron collider (FCC-hh)
2019 Technical Design Report

LHC ⇒ HL-LHC (2027- 10年間) ⇒

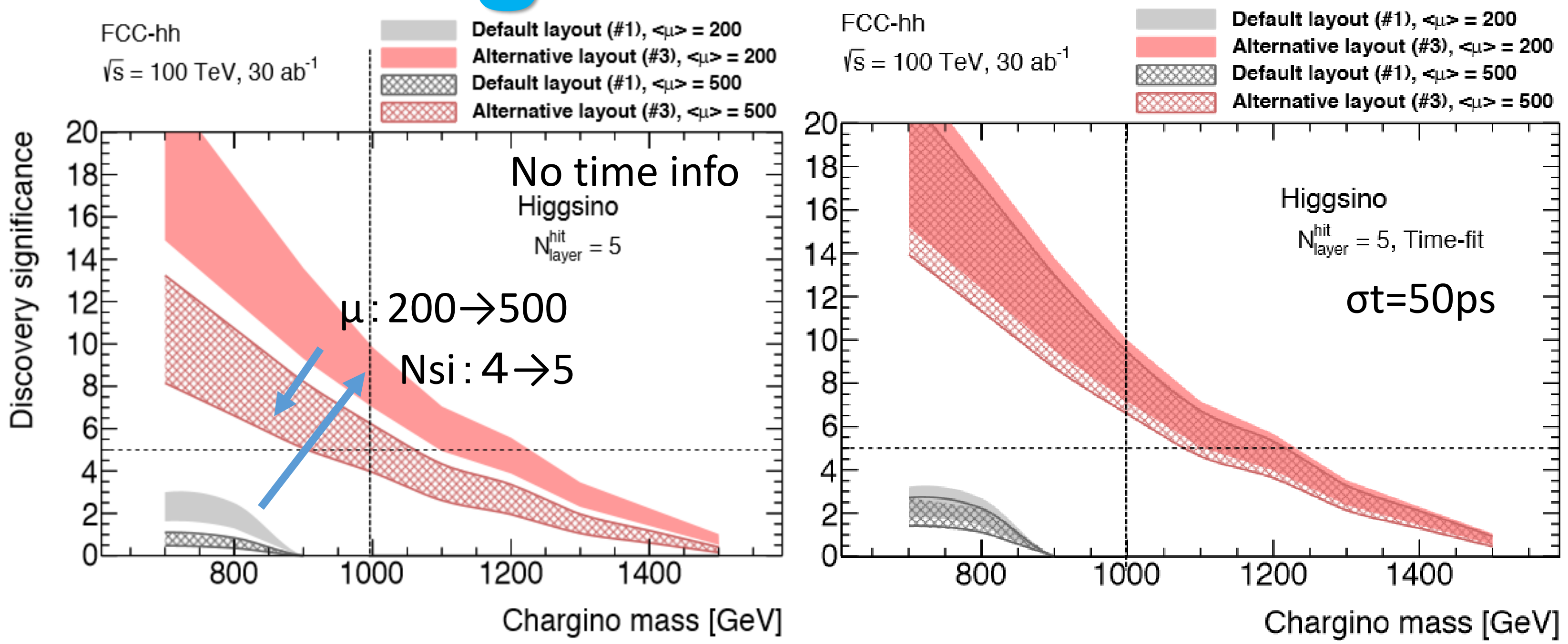


M. Saito (ICEPP) presented at LGAD workshop, Dec 8, 2018 @U. Tsukuba

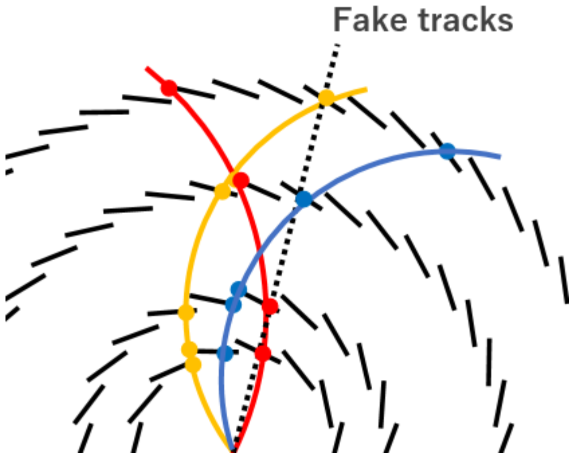
Tracking at FCC



4 pixel layers in default
5 pixel layers in alternative layout



✓ Time information helps reduce degradation for larger μ

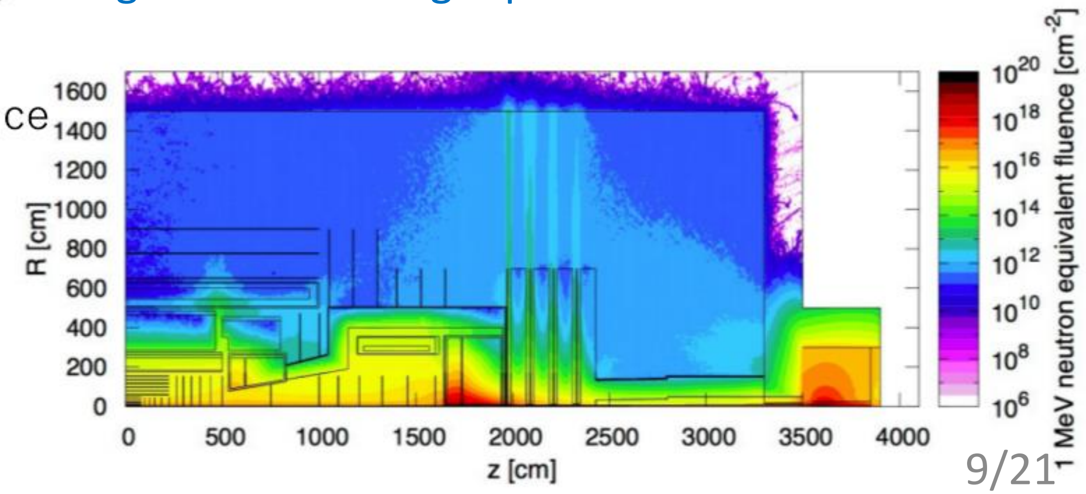


1 MeV neutron equivalent fluence for 30 ab^{-1}

- **8×10^{17} /cm^2 @ r=2.5cm**
- 1×10^{16} /cm^2 @ r=40 cm

Charged particle rate for L=30×10^{34} cm^{-2}s^{-1}

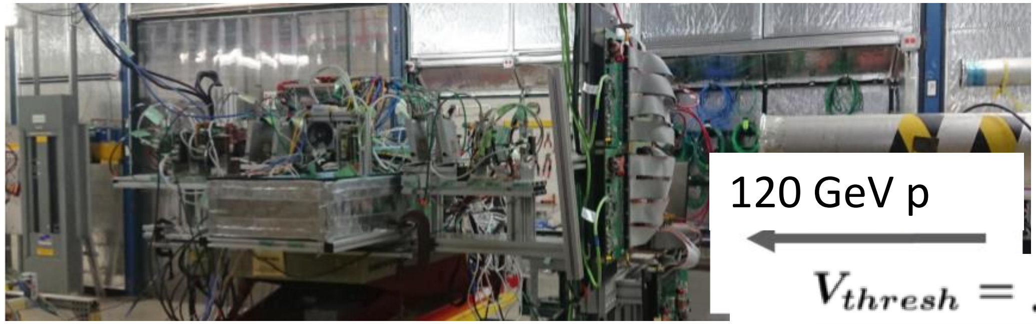
- **8 GHz/cm^2 @ r=2.5cm**
- c.f. 0.8 GHz/cm^2 for HL-LHC

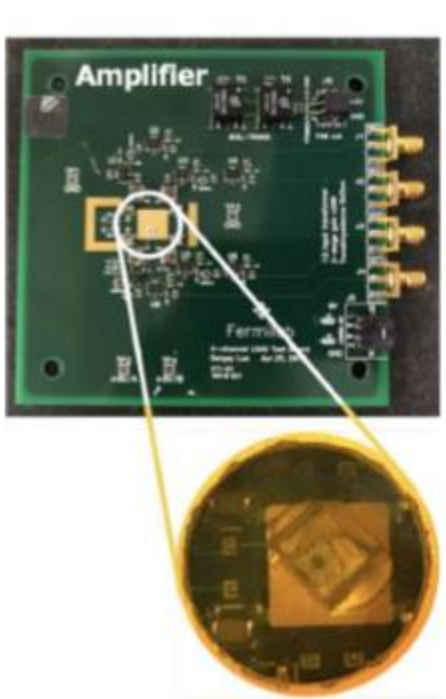


LGAD time resolution

2017 TB S. Wada

FNAL testbeam





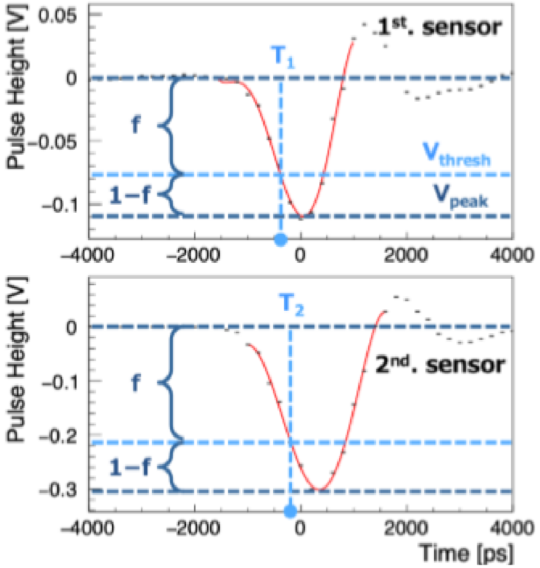
Stacked 3 LGAD sensors

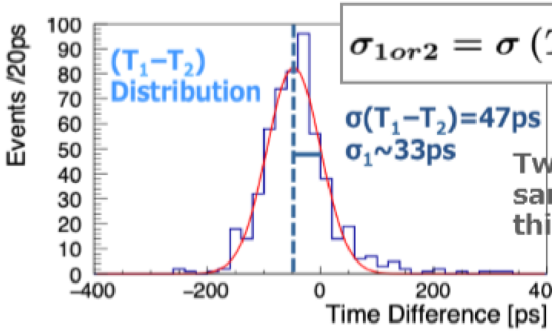
3GHz wideband InGaP HBT

CAEN V1742

5G/s FADC

$$V_{thresh} = f \times V_{peak}$$



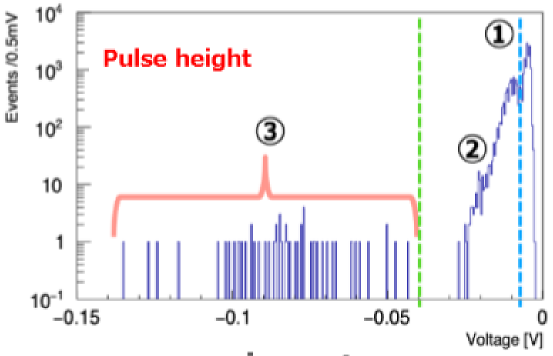


$$\sigma_{1or2} = \sigma\left(T_1 - T_2\right)/\sqrt{2}$$

$\sigma(T_1-T_2)$=47ps

σ_1~33ps

Two LGADs are same active thickness (50μm)

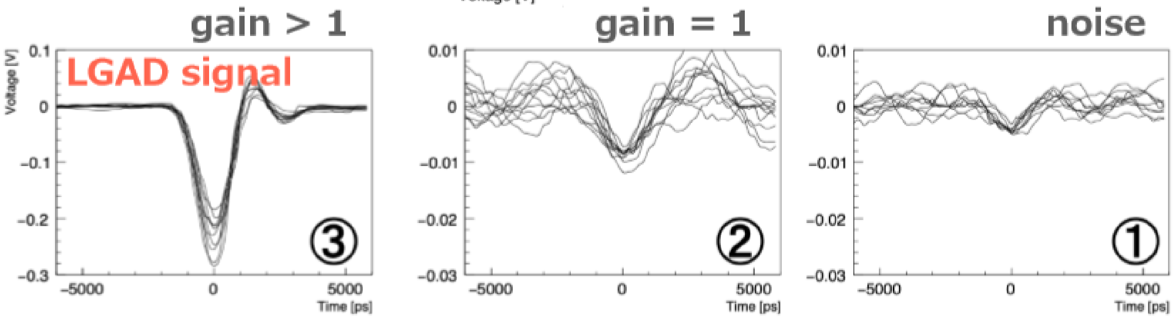


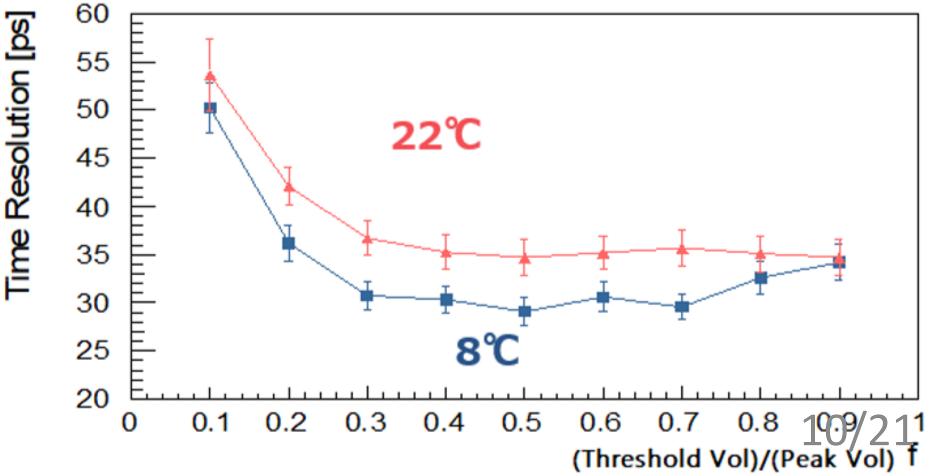
① noise only

② beam hit the gain=1 region

③ beam hit the LGAD region

③ → timing resolution evaluated

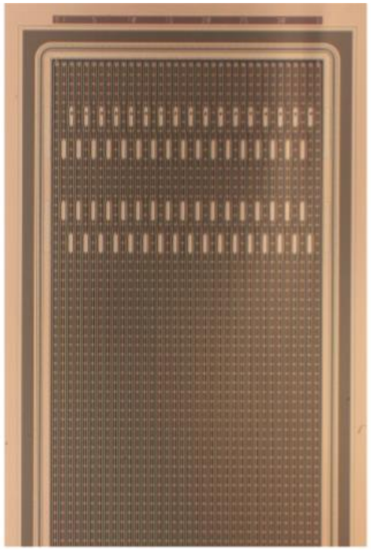


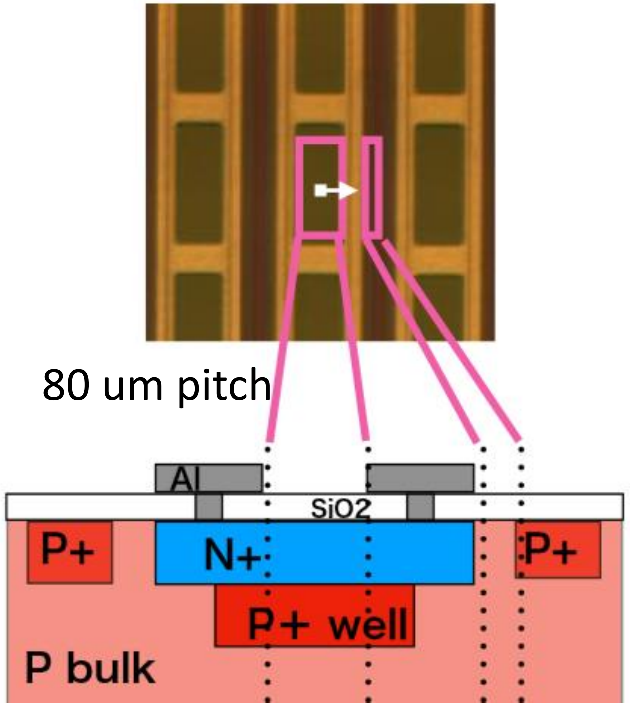


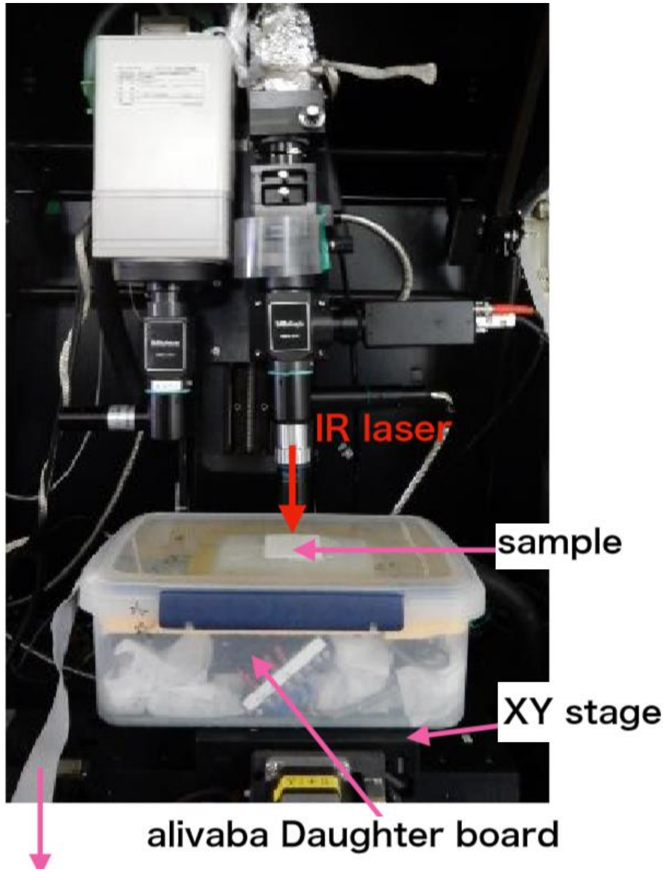
1st segmented
HPK LGAD

LGAD gain (uniformity)

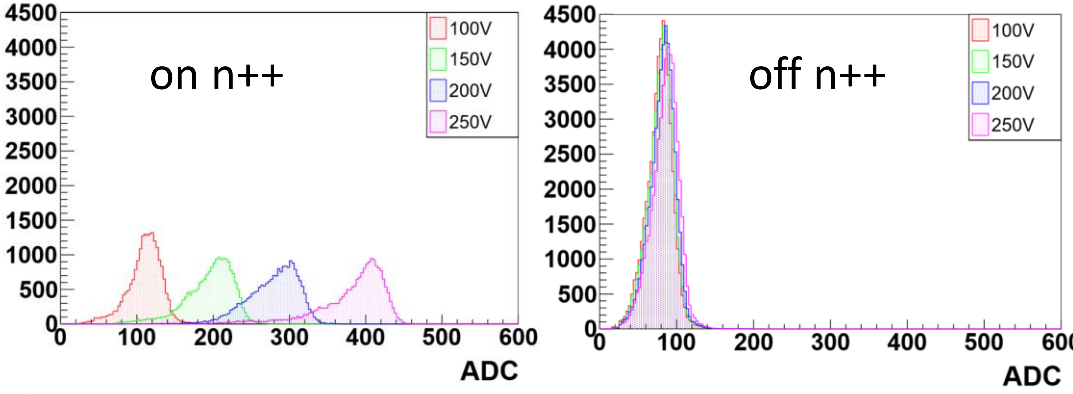
2017 K. Onaru

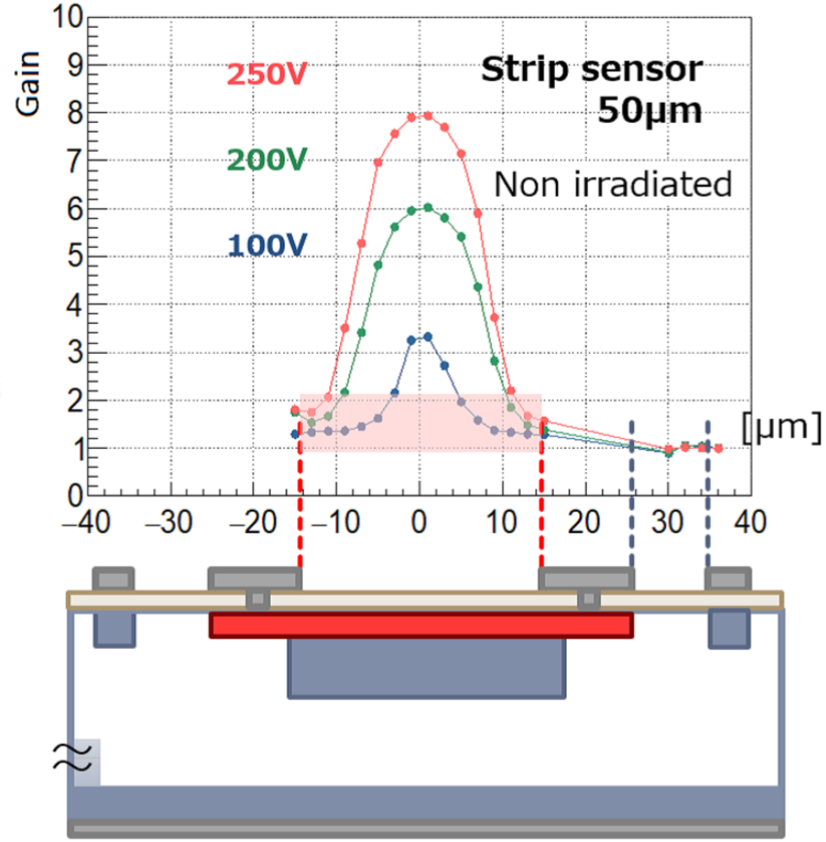






Collimated IR laser
Analog signal r/o with
Alibava system

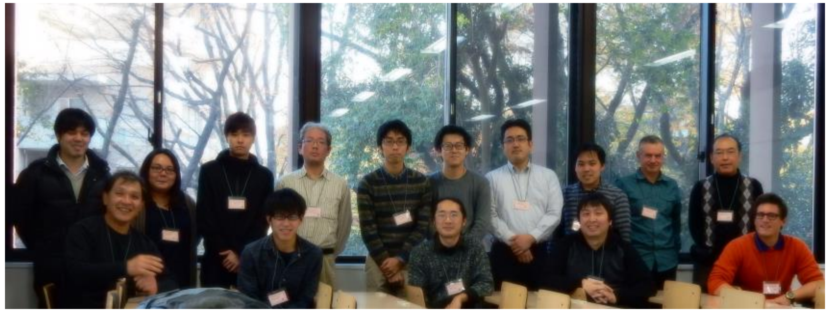




This segmentation is not uniform and not appropriate for 4D tracker
OK for HGTD

Boosting LGAD development

2018 LGAD workshop @ Tsukuba (Tokyo)

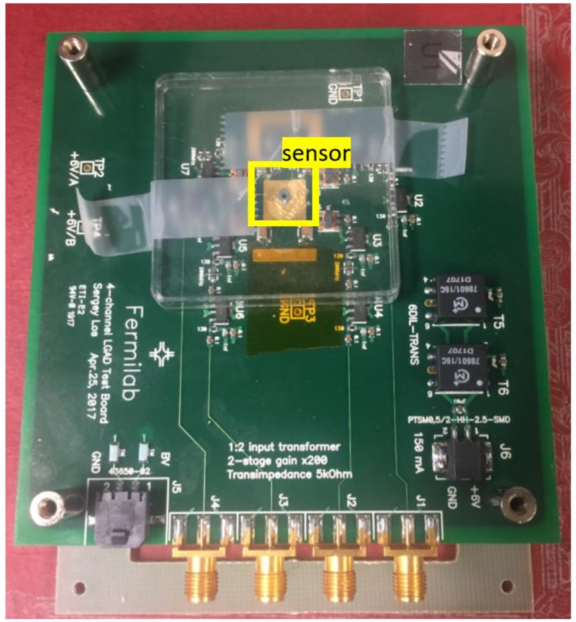


2019-2022 科研費(原)「高時間分解能を併せもつ高位置分解能4次元半導体検出器の実現」
2019-2020 新学術(中村)「医療機器 TOF-PET に用いる半導体検出器の開発」
2018,19,20 日米科学協力（中村）

✓ 細分化された一様性のあるLGAD

2018： TRENCH (S. Wada)
2019： AC-LGAD (K. Onaru)

✓ β線を用いた時間分解能測定

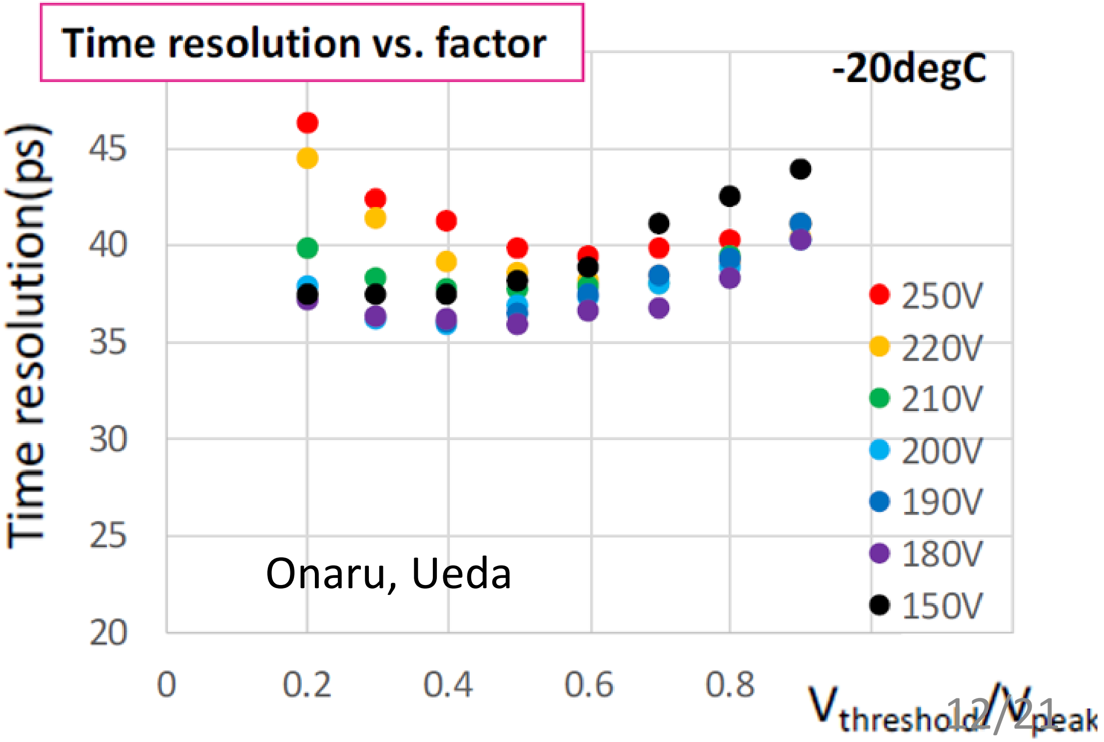


Fast amp. (A. Apresyan FNAL/日米）

CAEN DT5742 FlashADC

5GHz (12bit) FADC

簡便に時間性能
評価が可能

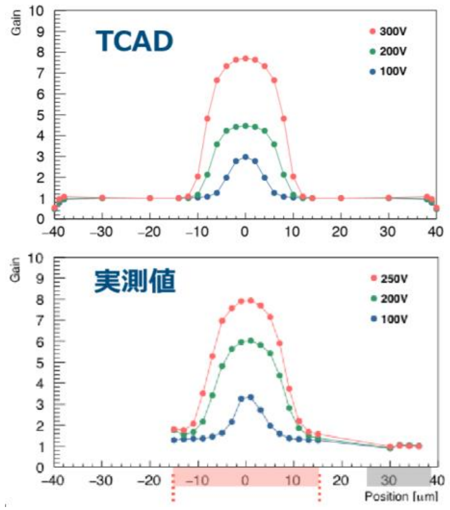


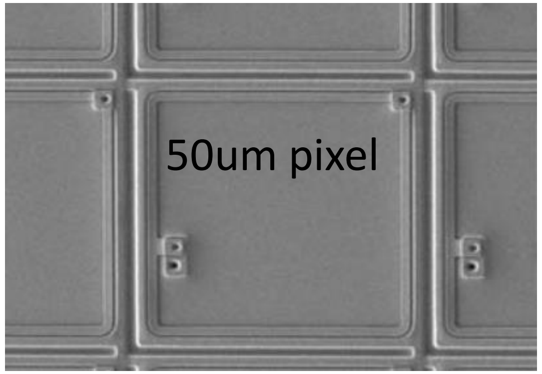
LGAD segmentation by Trenches

Vertex2019, S. Wada et al.

TCAD simulation

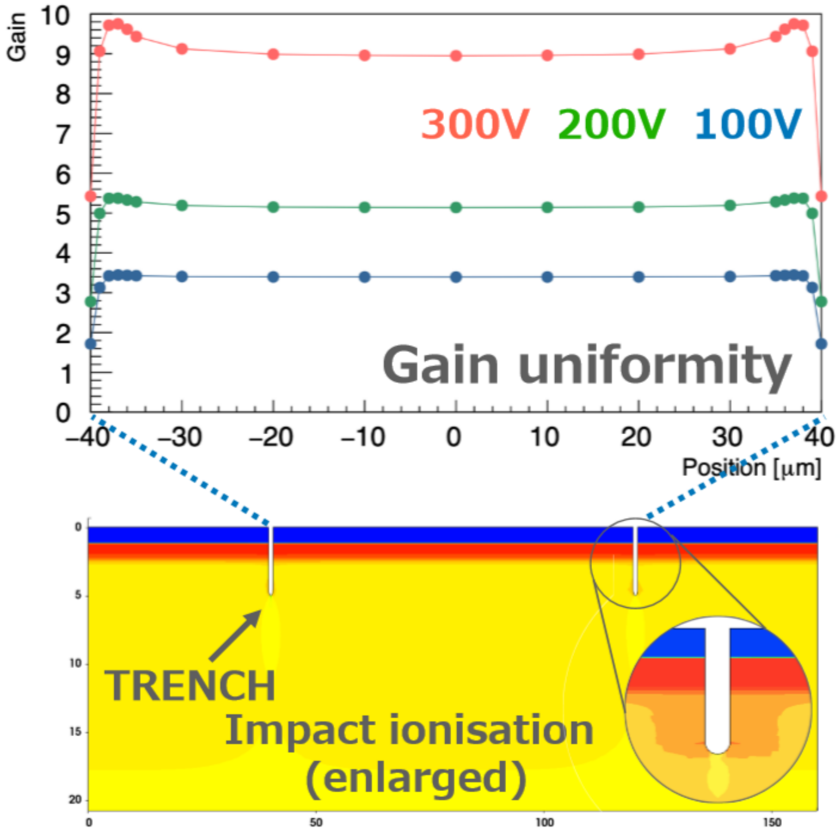
Parameters tuned to reproduce response of an existing segmented LGAD

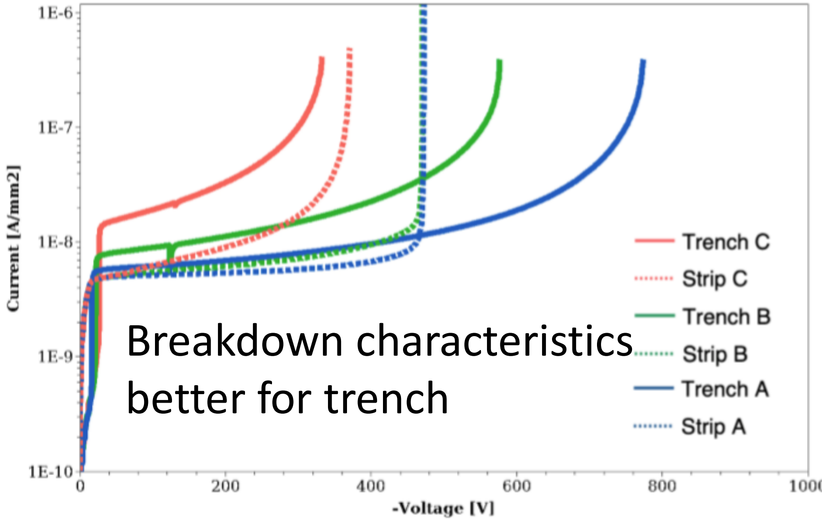


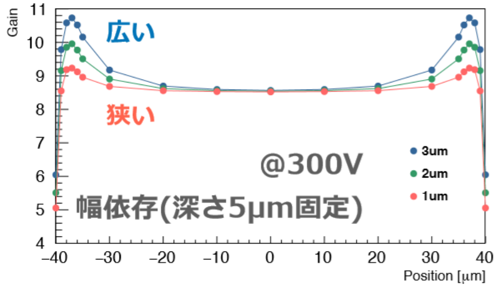


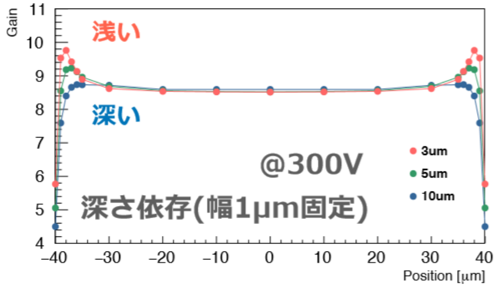
MPPC trenches (HPK hp)

5um deep, 1um wide







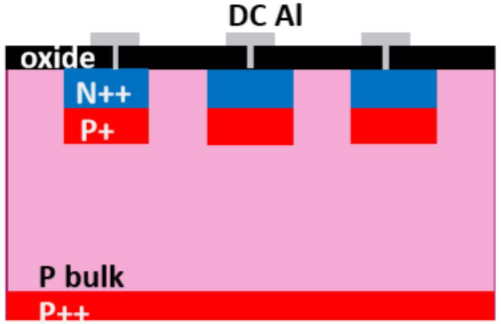


HPK has good experiences of trenches for MPPCs (X-talk suppression)

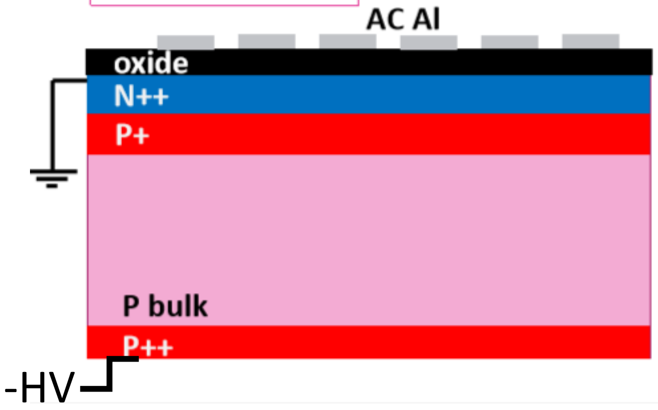
⇒ HV range is different (V_{MPPC}<~60V)

LGAD segmentation in AC-LGAD

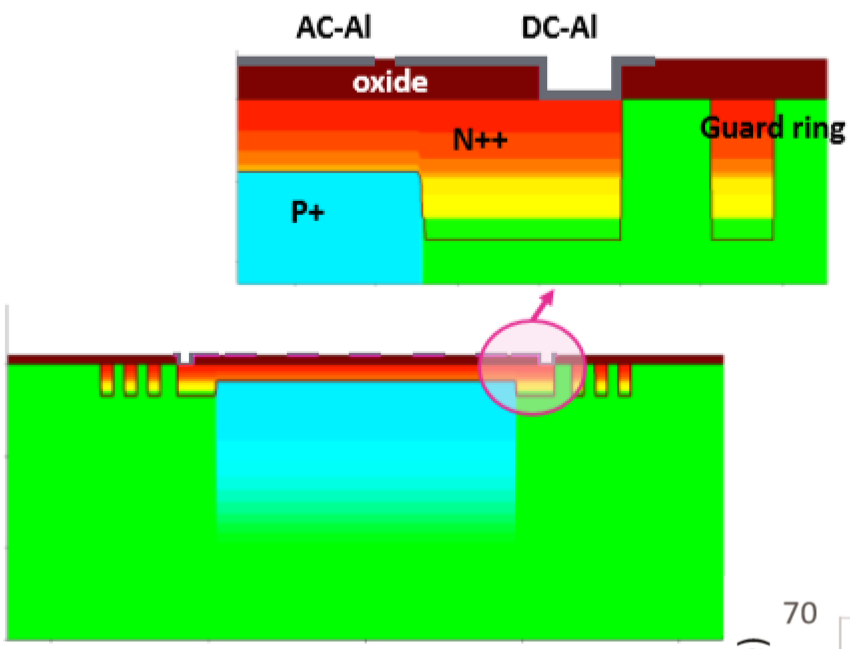
Conventional LGAD structure



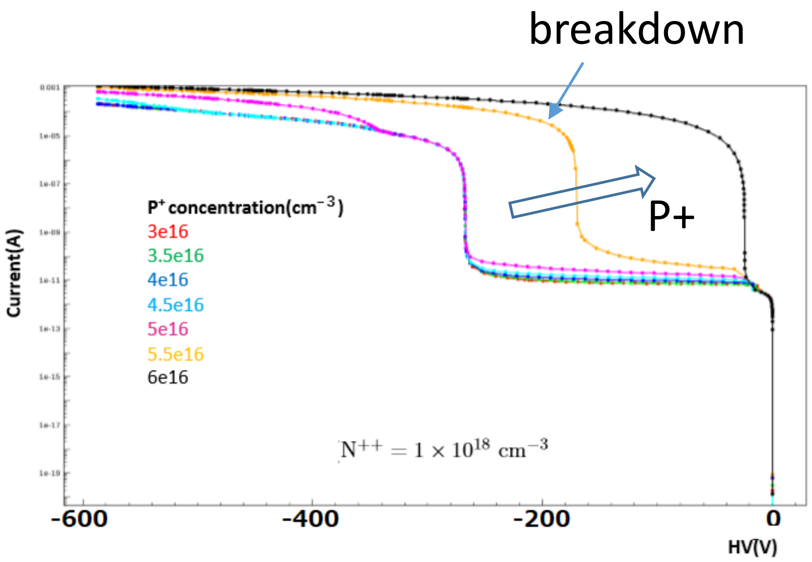
AC-LGAD structure

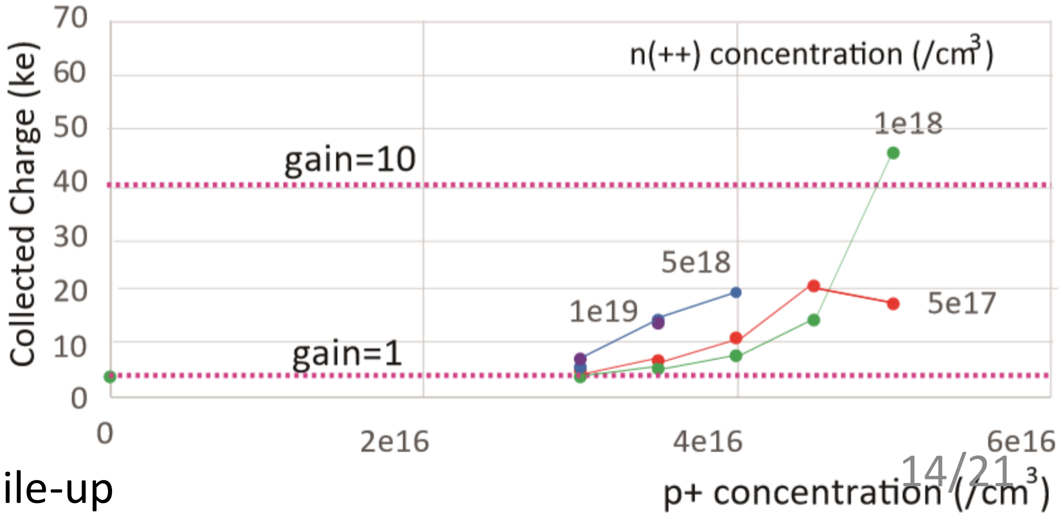


TCAD simulation



HSTD12, K. Onaru et al.





Signals are read out via AC coupled electrodes
Segmentation of readout electrodes is independent to the uniform multiplication layer

Concerns: resistivity (doping) of n++ layer
too low ⇒ good gain but signals spread out
too high⇒ good isolation but low gain/signal pile-up

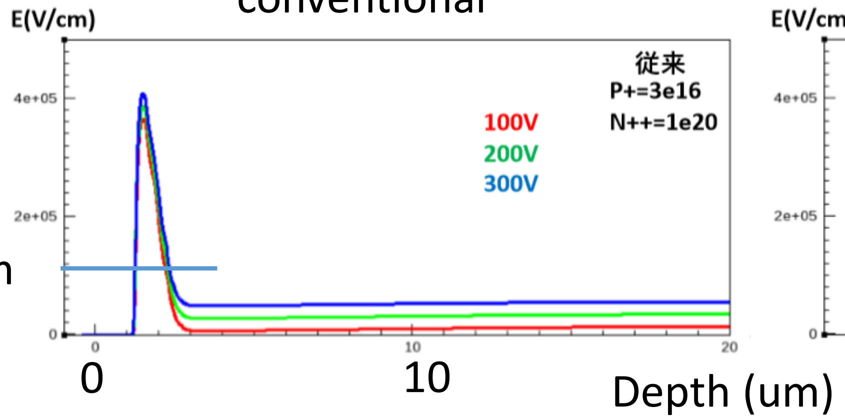
LGAD segmentation in AC-LGAD

HSTD12, K. Onaru et al.

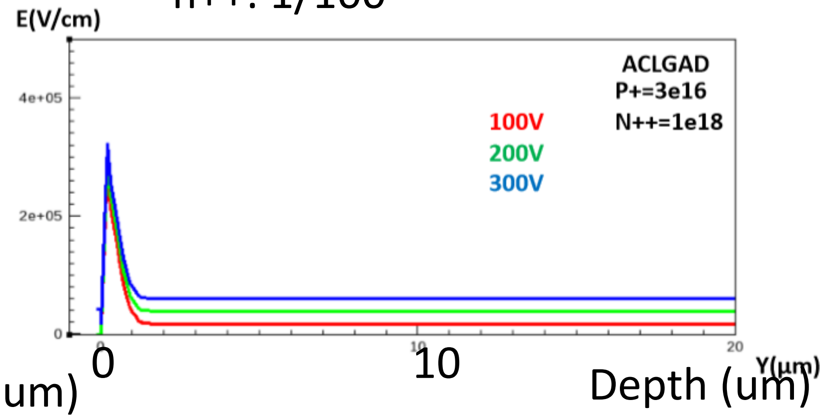
TCAD simulation

conventional

E=10^5 V/cm



n++: 1/100

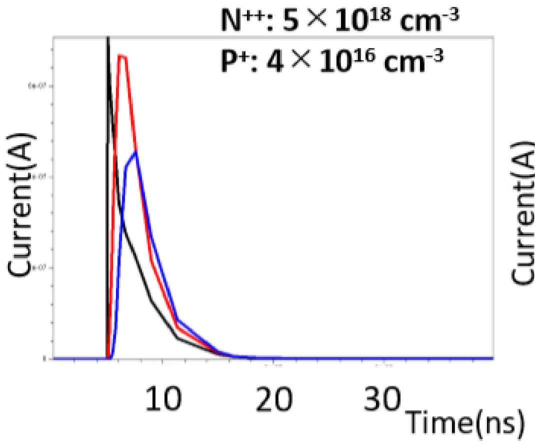


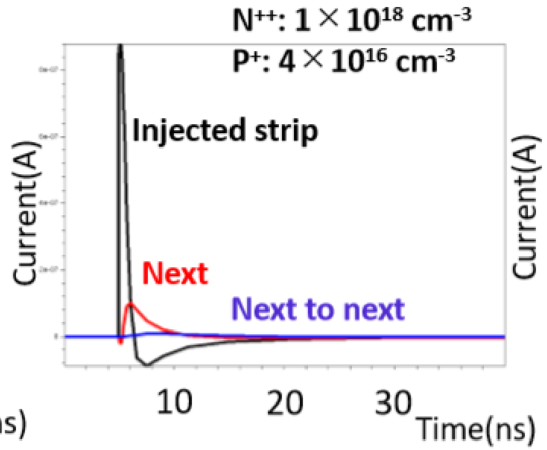
n++: too high
Signal spread to the neighbors

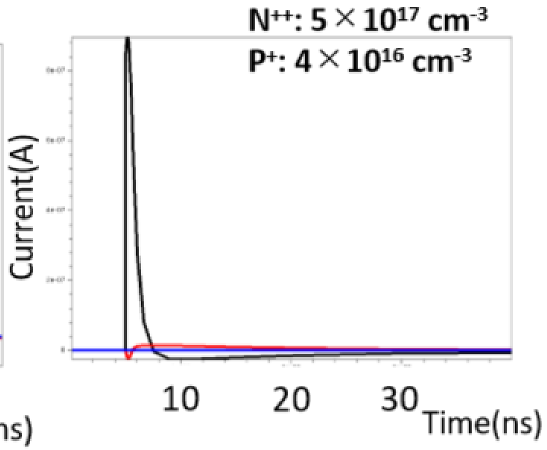
n++: optimum
Small spread

n++: too low
Signal may pile-up

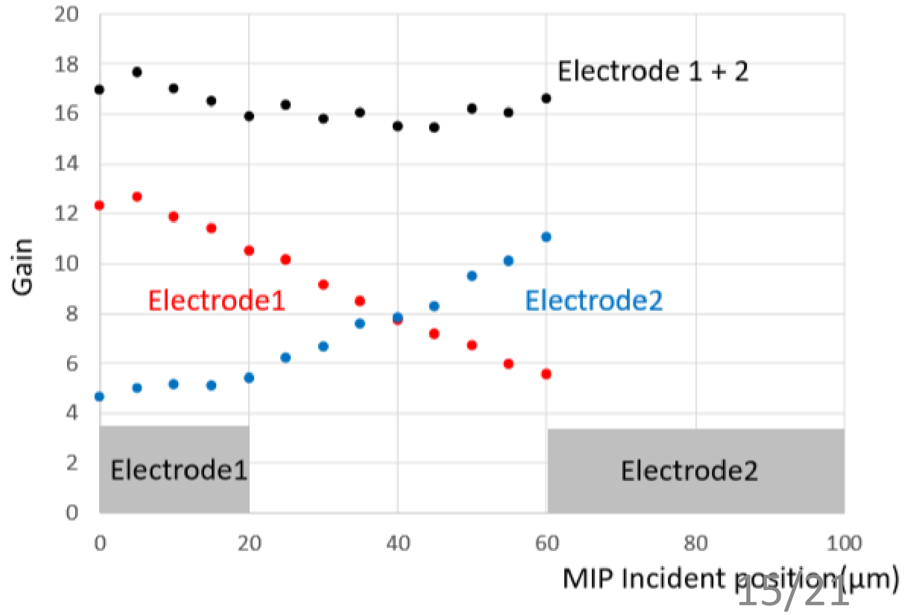
HV : -300V



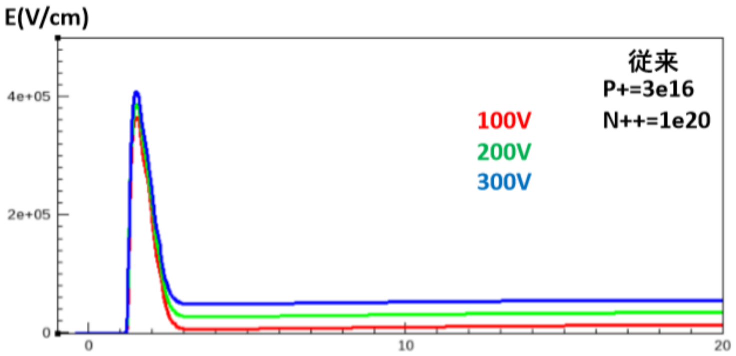


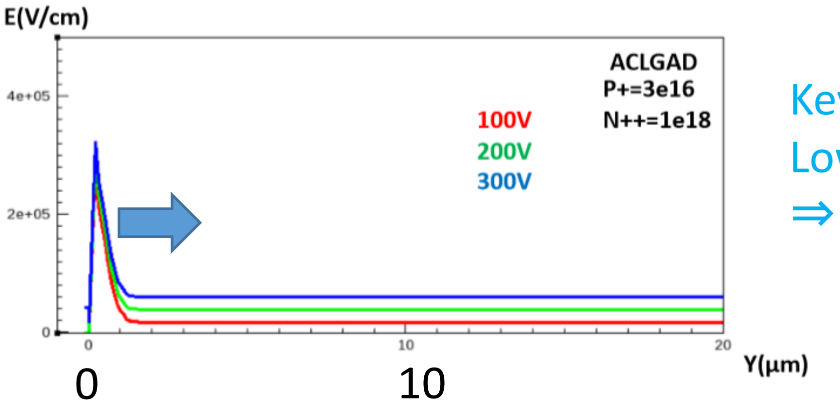


Uniform gain should be achievable

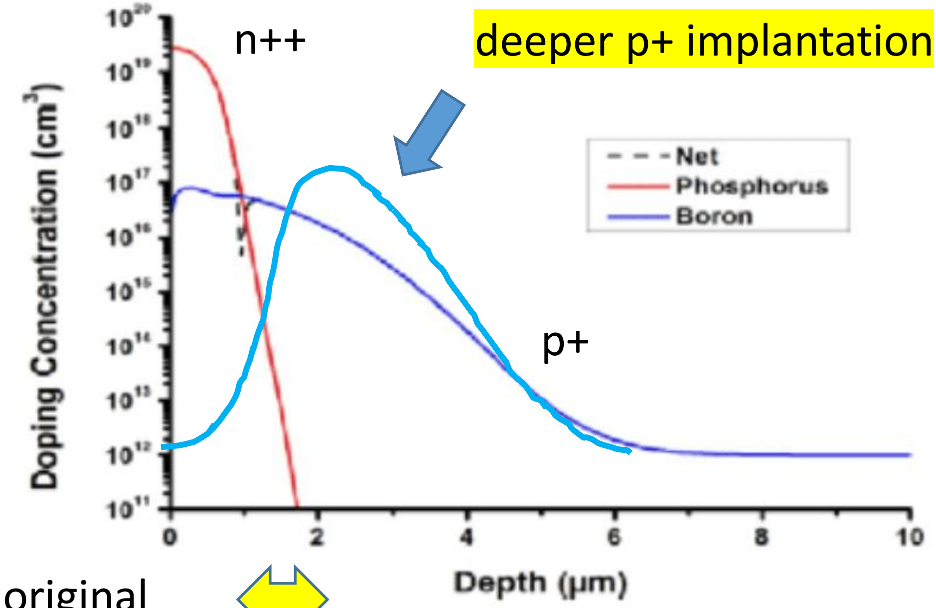


Stable LGAD operation





Key point:
Lower operation voltage
⇒ Widen the gain region

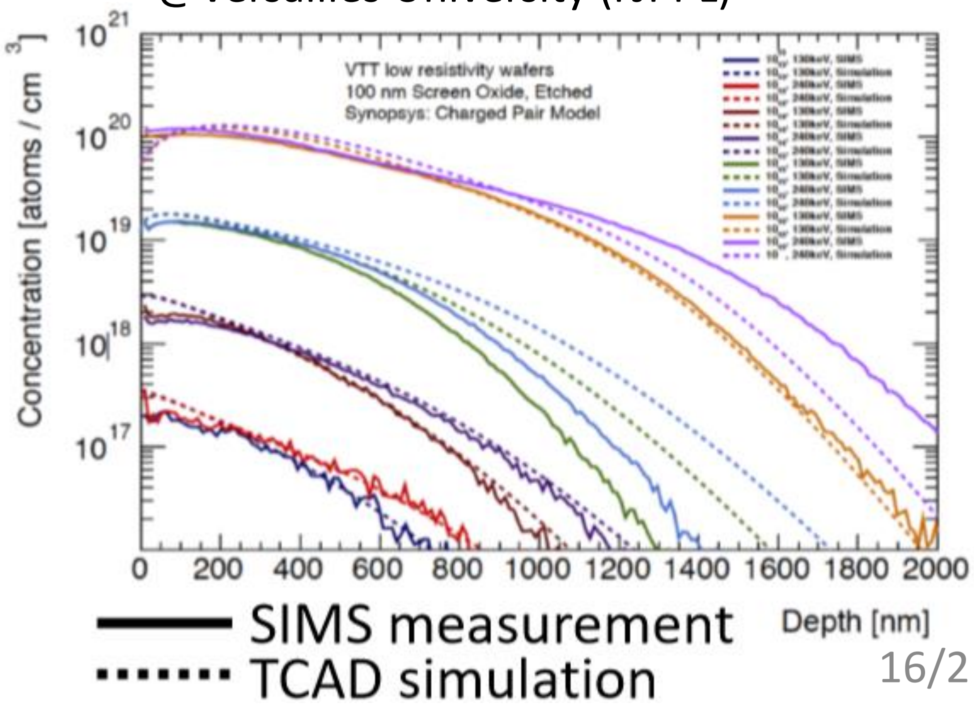


original

modified

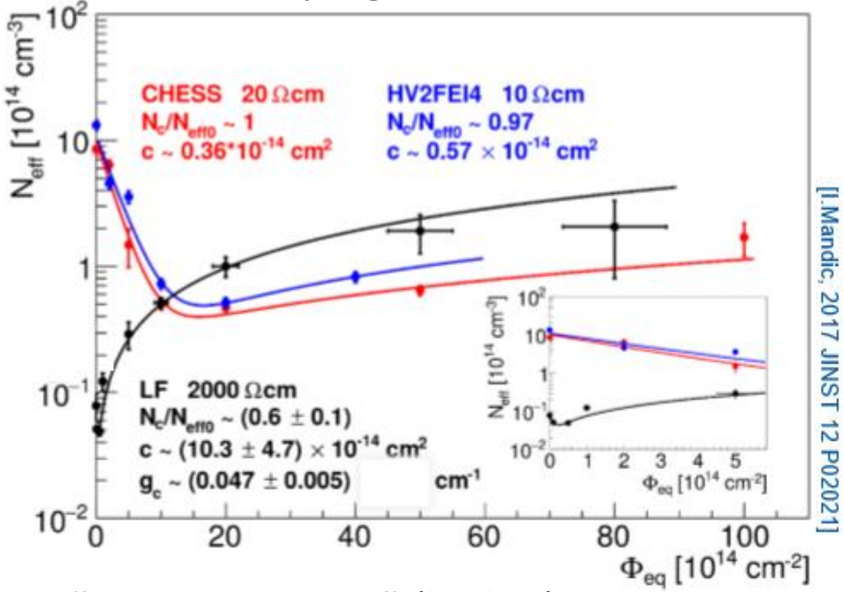
Wider high E-filed region
(sufficient gain at lower voltage)

Secondary Ion Mass Spectrometry
@Versailles University (FJPPL)



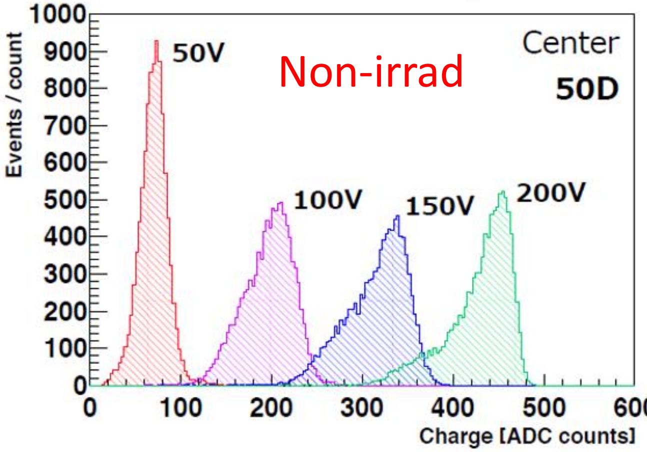
Rad-hard LGAD

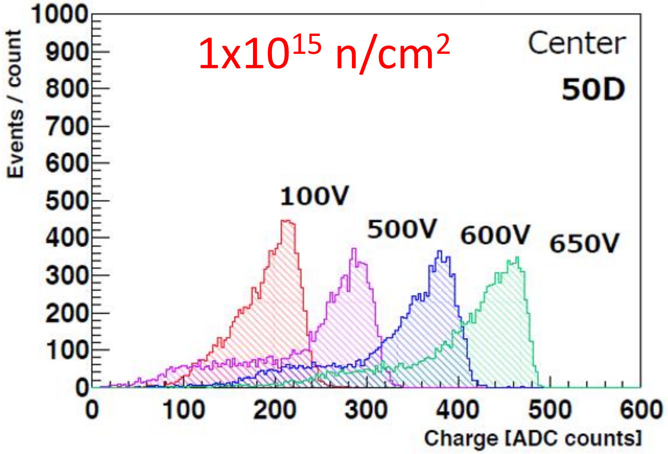
RD50
Radiation induced change of the effective doping concentration

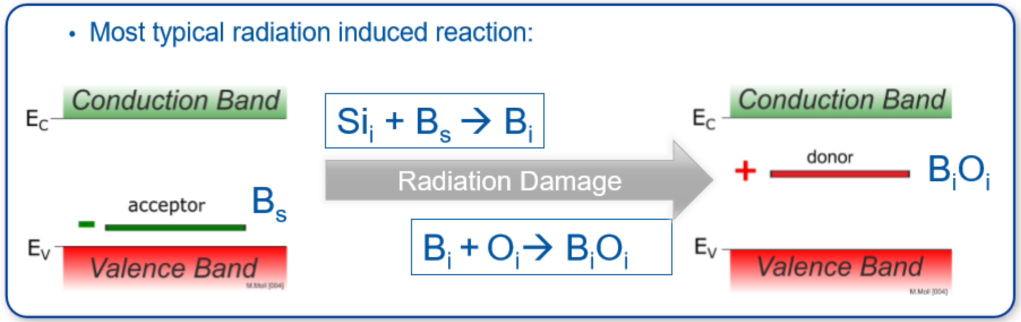


"Donor creation" (high Z)
"Acceptor removable" (low Z)

S. Wada et .al. (HSTD11)

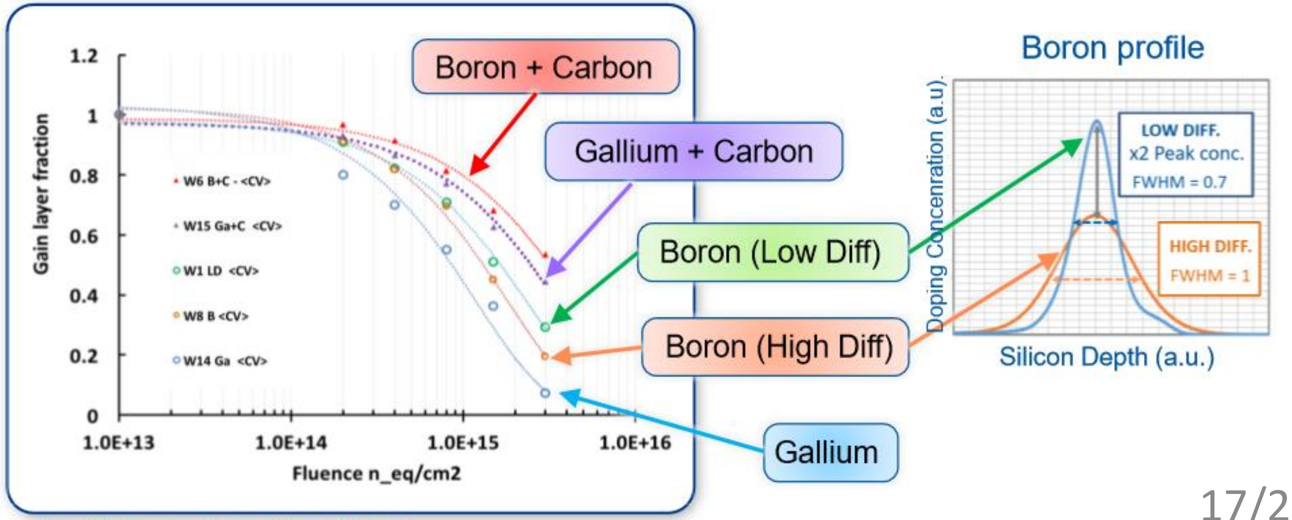






M.Moll Vertex2019

BiOi (donor)
BiCi (acceptor)

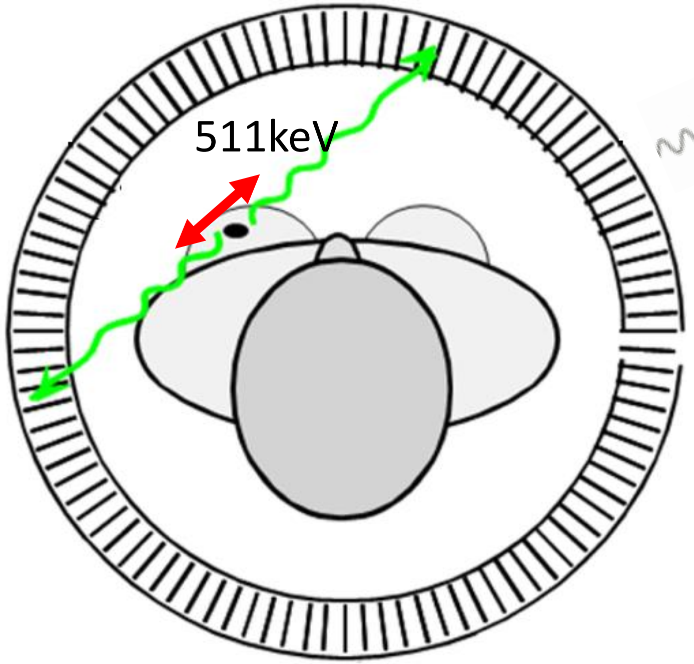


[G.Paternoster, FBK, Trento, Feb.2019]

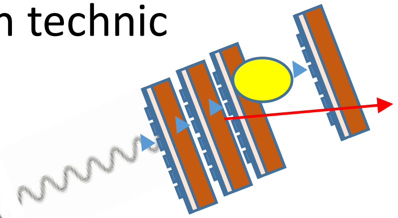
LGAD development for bio-science

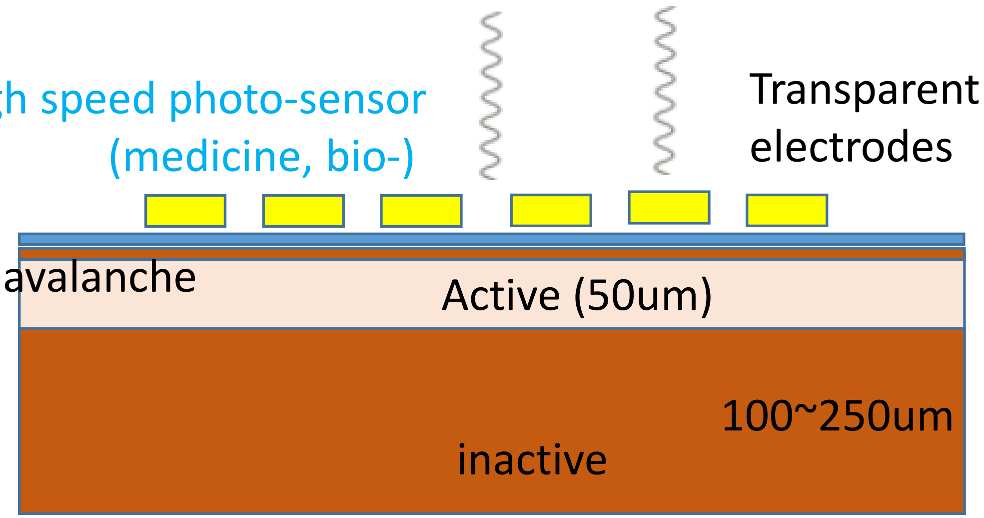
2019-2020 新学術(中村)「医療機器 TOF-PET に用いる半導体検出器の開発」

TOF-PET



Compton technic





Discussions with
山谷(放医研)
高橋(ICEPP)

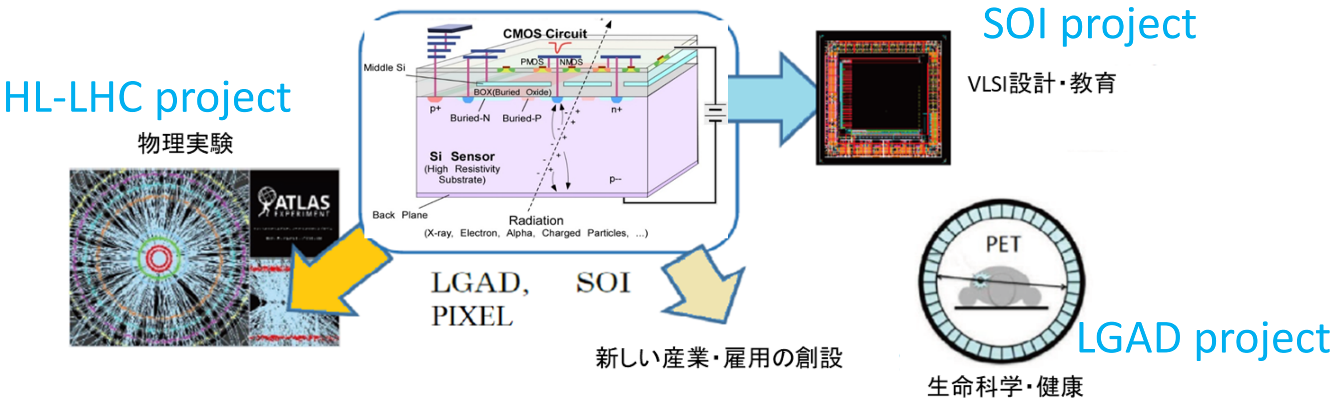
Scintillator bars (~5x5mm□)

TOF: ~1cm, realized with MPPCs

Improve position resolution with LGAD …

Silicon is not heavy for gamma conversion…

Sustainable Development Goals: SDGs



光量子計測器開発部門がめざす「半導体センサーが拓く持続的なイノベーション」プロジェクト

Summary

Finely segmented LGADs as the 4-D detector
- Breakthrough device in future high intensity HEP experiments
- Unique photo sensor

New (first) HPK AC-LGAD samples have been fabricated
Uniformity (timing, position) to be evaluated

In addition -
  Improve radiation hardness
  Development of multi-channel readout amplifiers (w/ FNAL)
  Development of ASIC … RD53