# Development of LGAD Based 4D Outer Time-Tracker for CEPC

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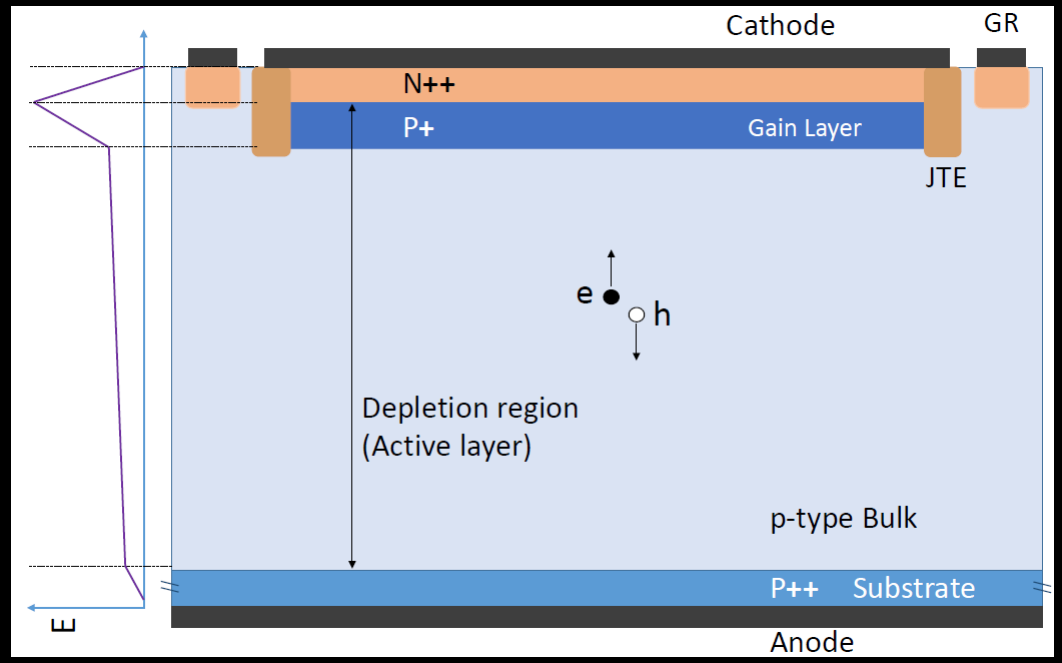
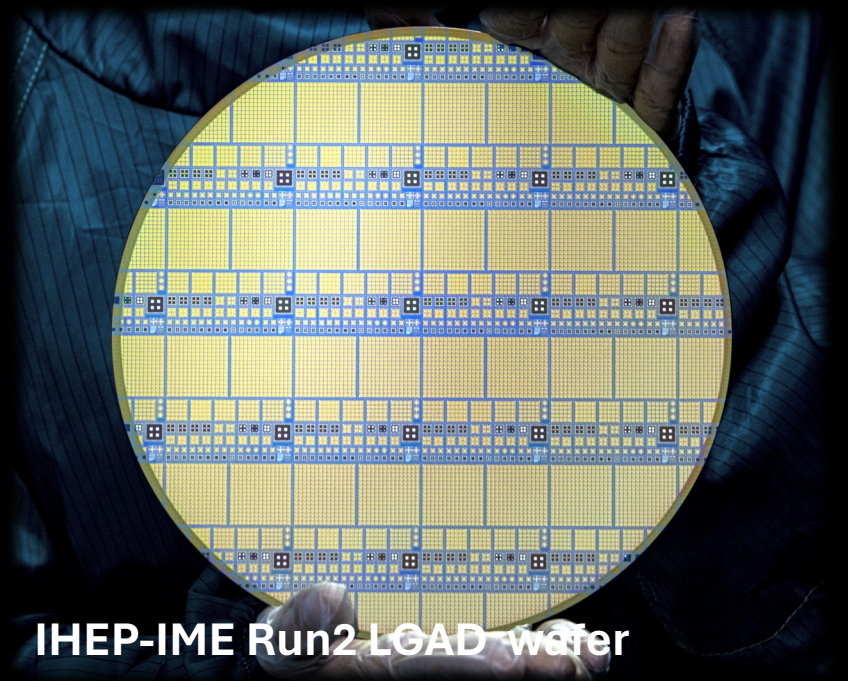
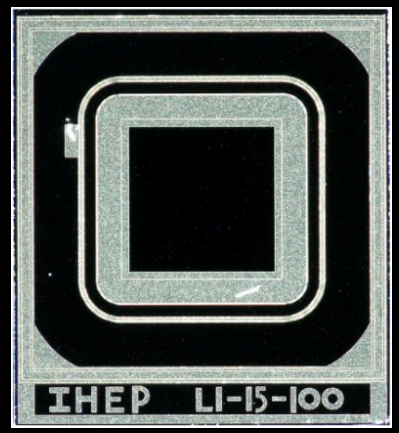
# I Introduction | LGAD Overview





IHEP-IME Run2 LGAD wafer

**LGAD (Low-Gain Avalanche Diode)**

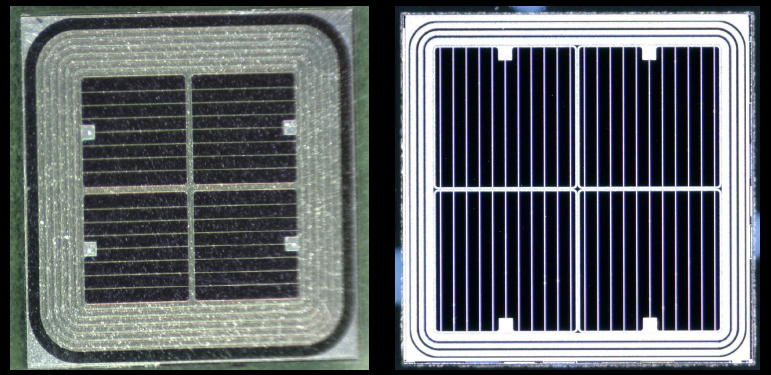
- **N-on-P silicon diode**, with highly doped p-layer Excellent time resolution for MIP particles
- **Active thickness 50 μm**
- Low Gain 10-50 with fast signal and good signal to noise ratio
- **Time resolution ~ 30-50ps**



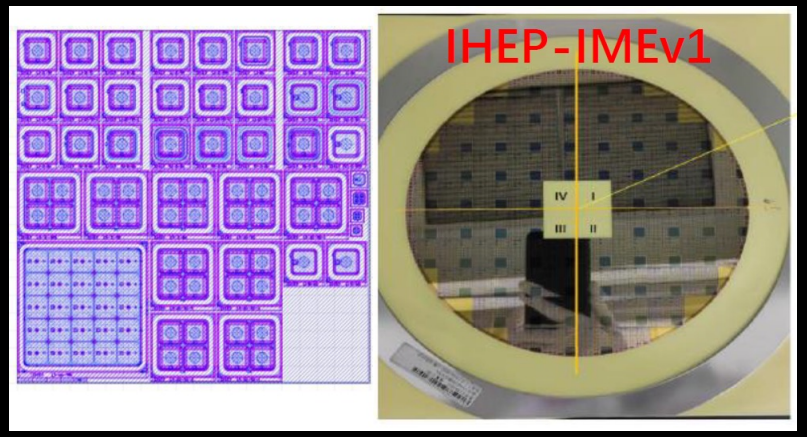
Single LGAD sensor

# I Introduction | IHEP LGAD Timeline

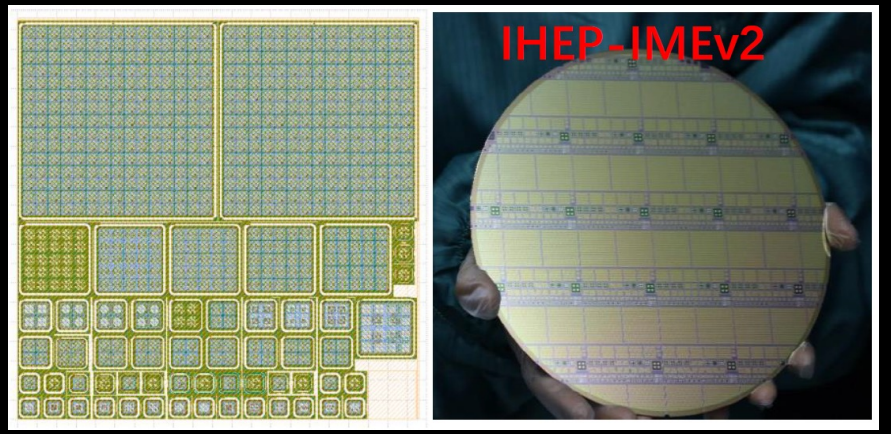
IHEP-NDL(2019)



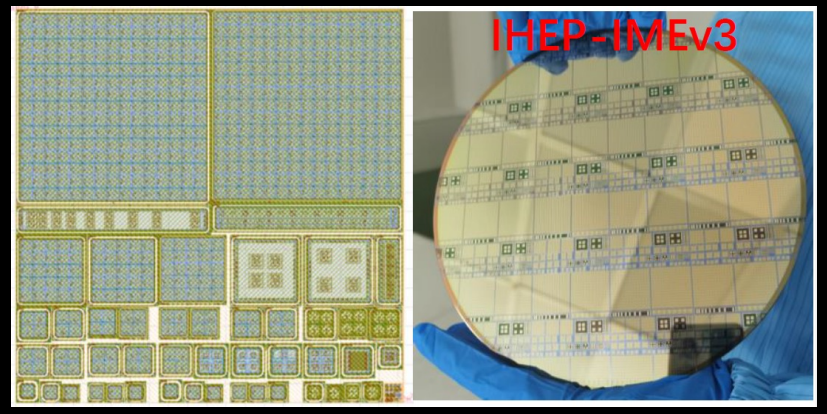
IHEP-IMEv1(2020.9)



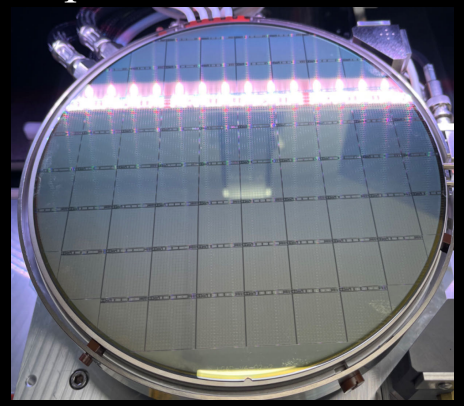

IHEP-IMEv2(2021.6)

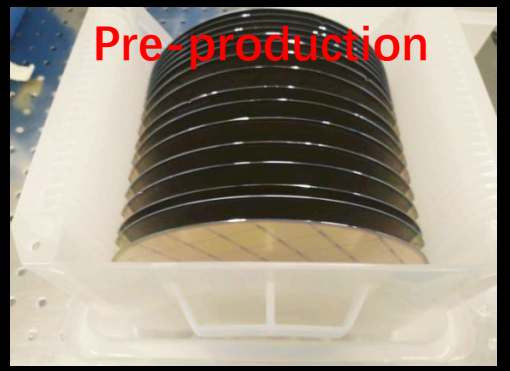



IHEP-IMEv3(2022.5)



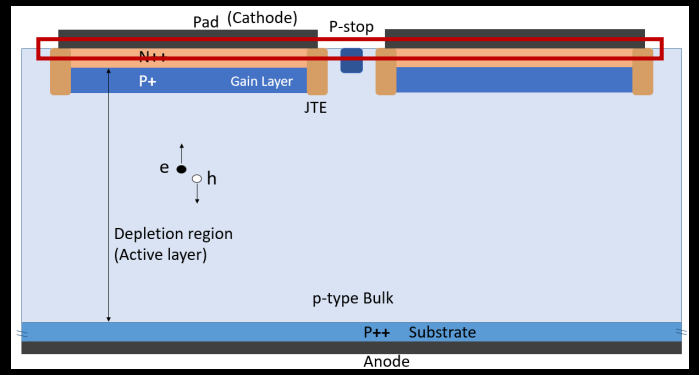

Pre-production for ATLAS (2023.7)





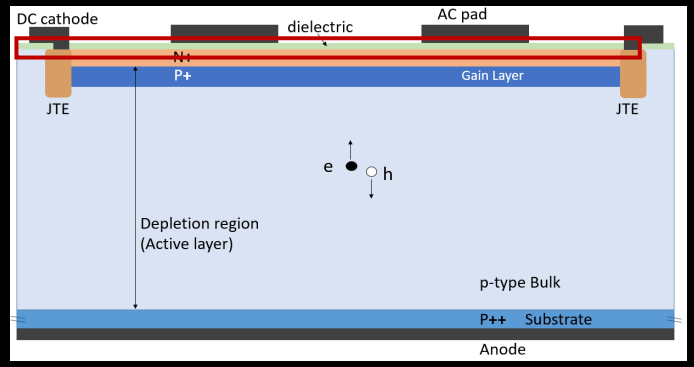

→ Mass production for ATLAS (2024.6)

# I Introduction | AC-LGAD



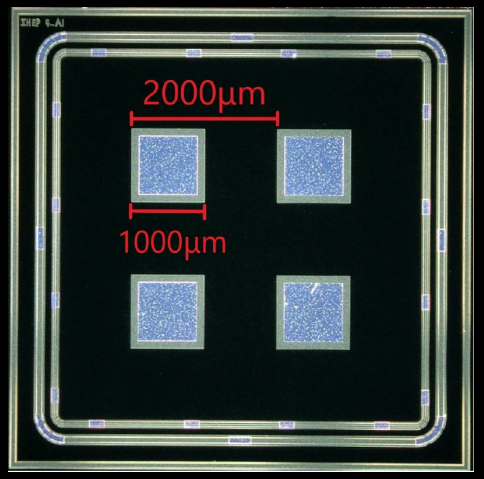

**LGAD (Low-Gain Avalanche Diode)**

- Metal pads are connected to n++ layer
- Time resolution ~ 30ps
- Position resolution: pixel size/$\sqrt{12}$
- Radiation hardness: $10^{15}$ ~$10^{16}n_{eq}/cm^2$



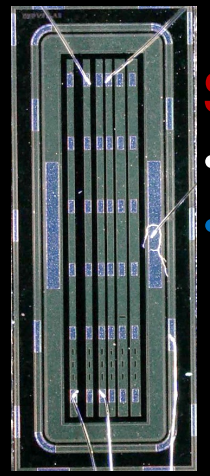

**AC-LGAD (AC-coupled LGAD)**

- Metal AC-pads are separated
- No dead zone (100% fill factor)
- Time resolution ~ 30ps
- Position resolution: 5~10 um
- Radiation hardness: $10^{15}$ ~$10^{16}n_{eq}/cm^2$




**Pixels AC-LGAD:**

- Pitch size 2000um
- pad size 1000um

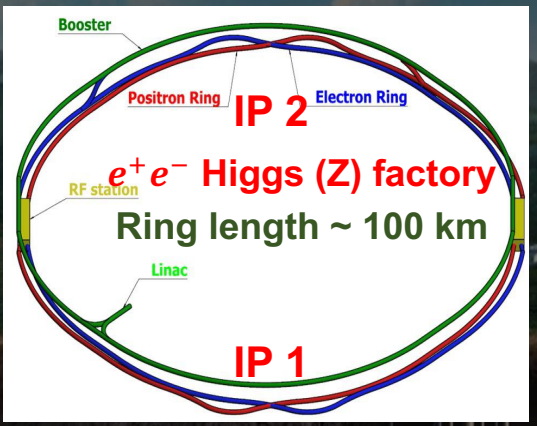


**Strips AC-LGAD:**

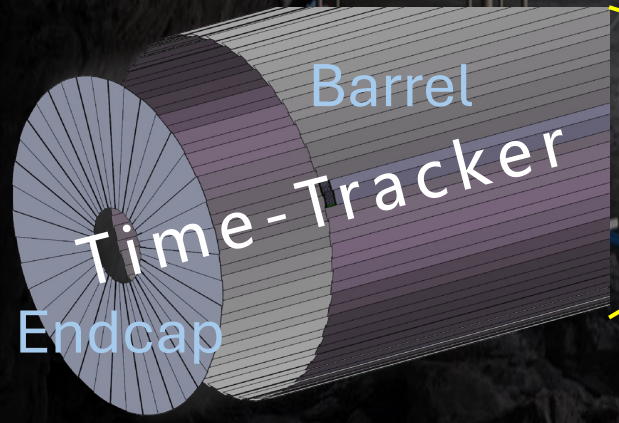
- Strip length 5.6mm, width 100um
- Different Pitch size:
  - **150um、200um、250um**

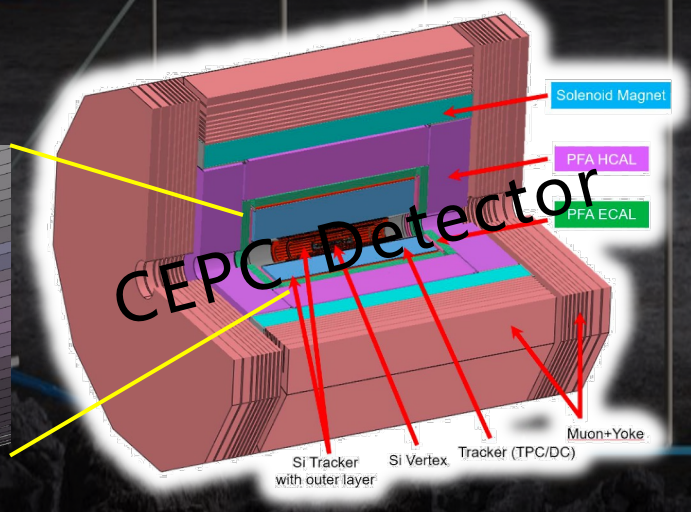
# II CEPC | Overview

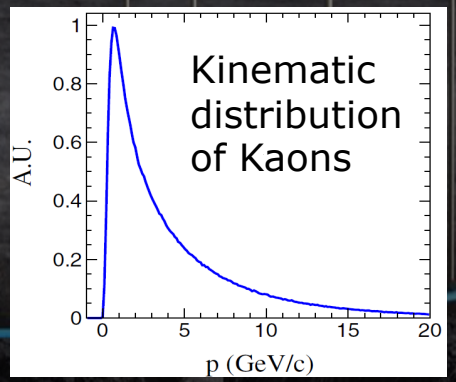
- CEPC--huge measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top



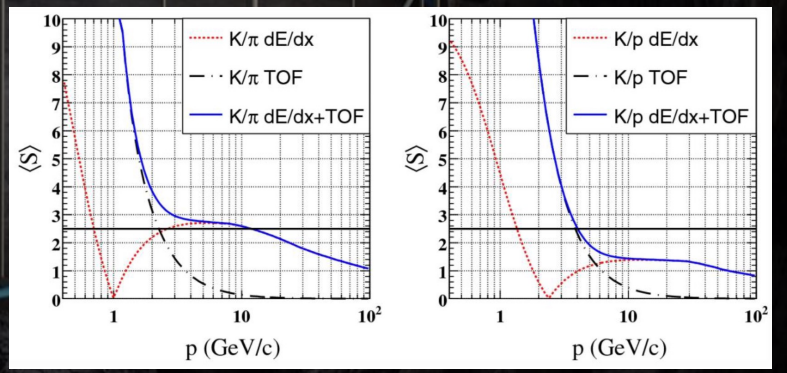

- **Produce $10^{12}$ Z boson at Z pole: Rich flavor physics program**
- **Particle separation problems** of Gas detector (dE/dx) :
  - 1 GeV for K/pi separation, 2 GeV for K/p separation
- **CEPC International Advisory Committee: one of the key recommendations**
  Precision timing detector should be determined as a matter of urgency (4D track)
- **Timing detector is complementary to gas detecto:** improves the separation ability
  **0 - 4 GeV** for K/pi separation, **0 – 8 GeV** for K/p separation
- **Outer layer adjacent to TPC, Barrel : 50 $m^2$ , Endcap 20 $m^2$**



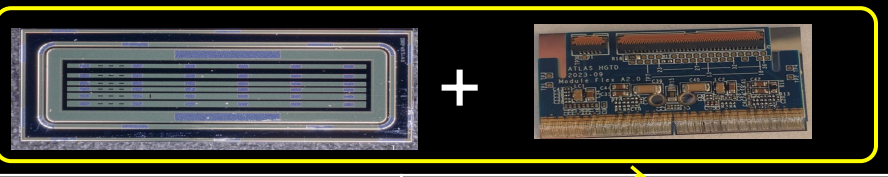




**K/pi separation** **K/proton separation**

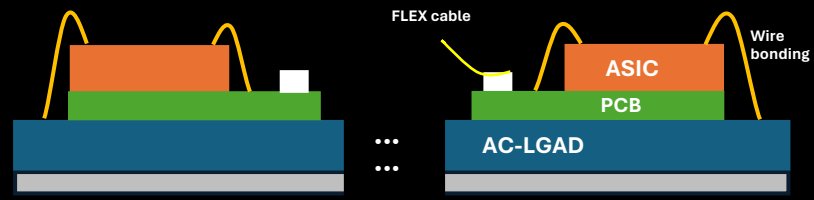


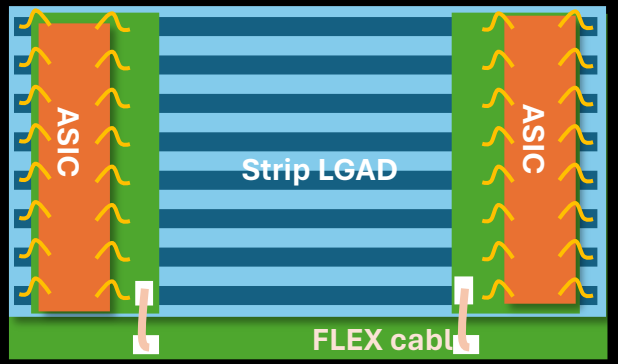
# II CEPC | Time-Tracker Barrel

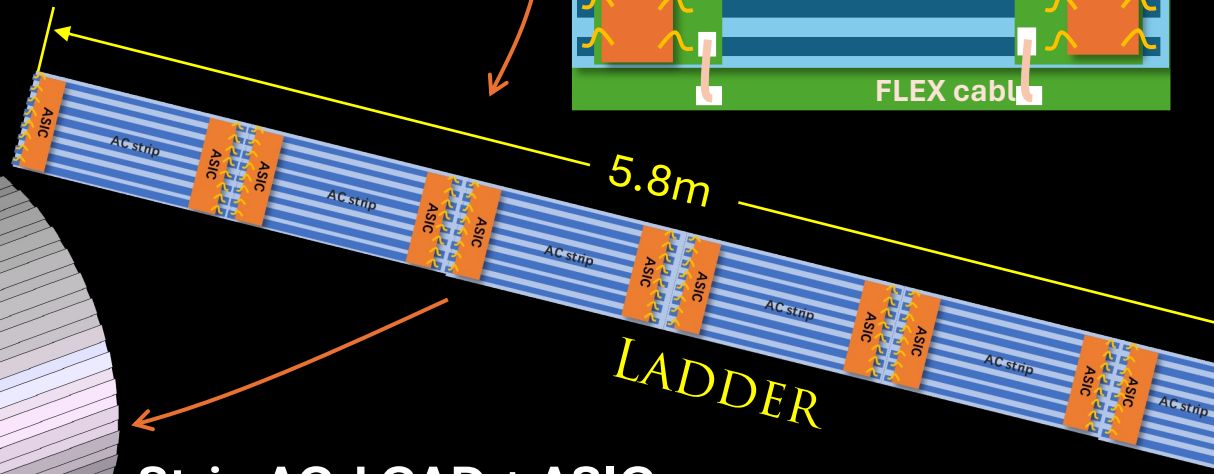


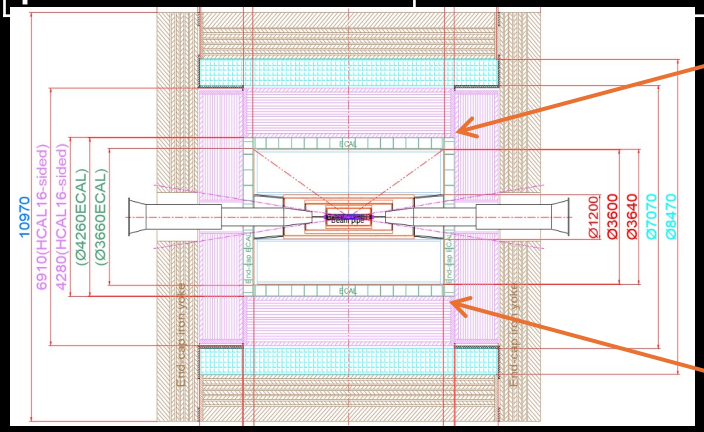
Time-Tracker Barrel Parameters

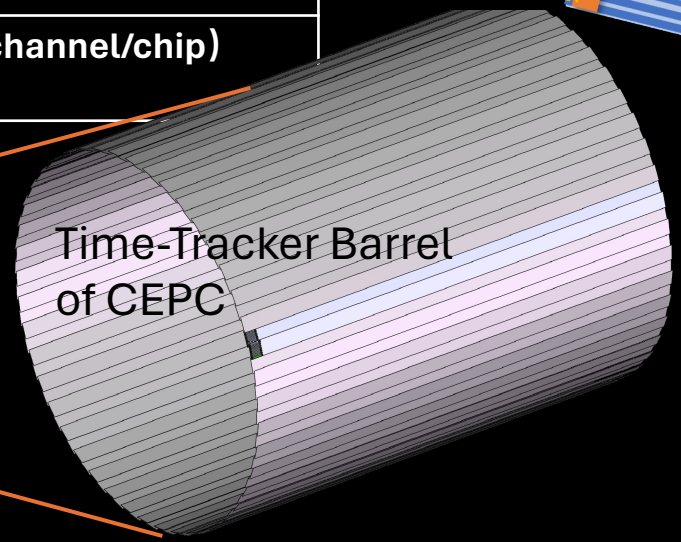
| | |
|---|---|
| Area ($m^2$) | ~ 70 $m^2$ |
| Radius | 1.8m |
| Length | 5.8m |
| Granularity | 70mm × 0.1mm ($10cm^2$, 128channel/chip) |
| Channel number | ~ $1 \times 10^7$ channels |
| MIP Time resolution | ~50 ps |
| Spatial resolution | ~ 10 μm (R-Φ) ~ 1 mm R-Z direction) |
| LGAD Sensor Area | 14cm*14cm |
| Number of channels per module | 2816 (22 chip, 128channel/chip) |



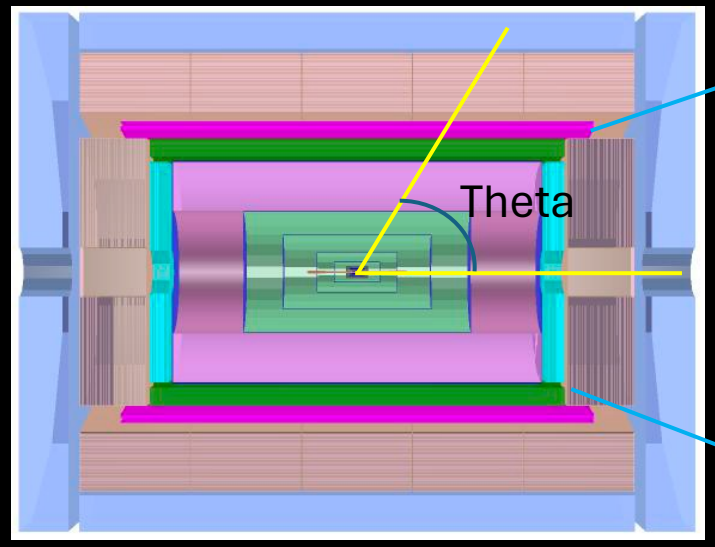



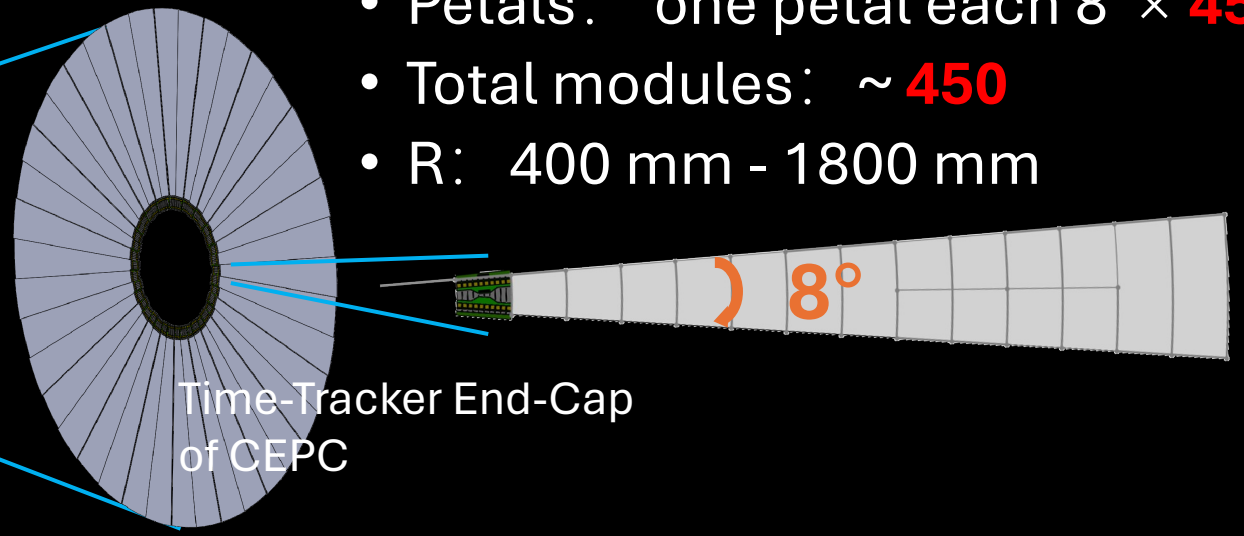




**Strip AC-LGAD + ASIC :**

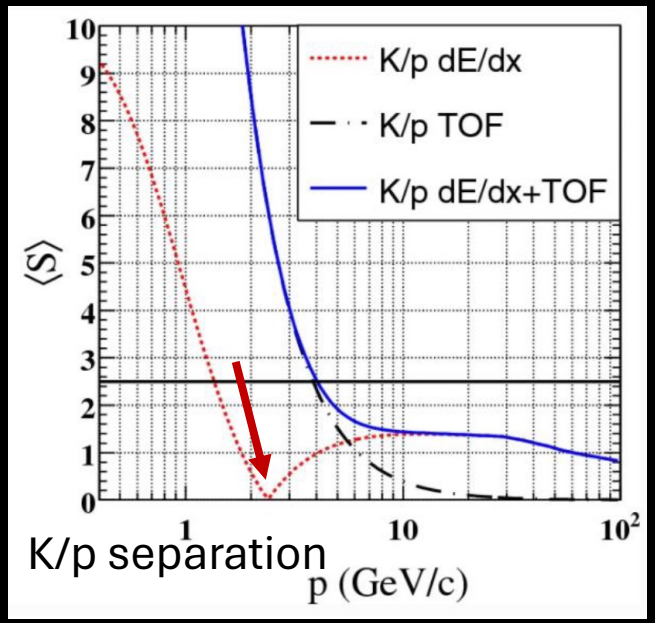
- TOT->amplitude->charge sharing->position
- TOA+TOT->timing (time–amplitude correction)

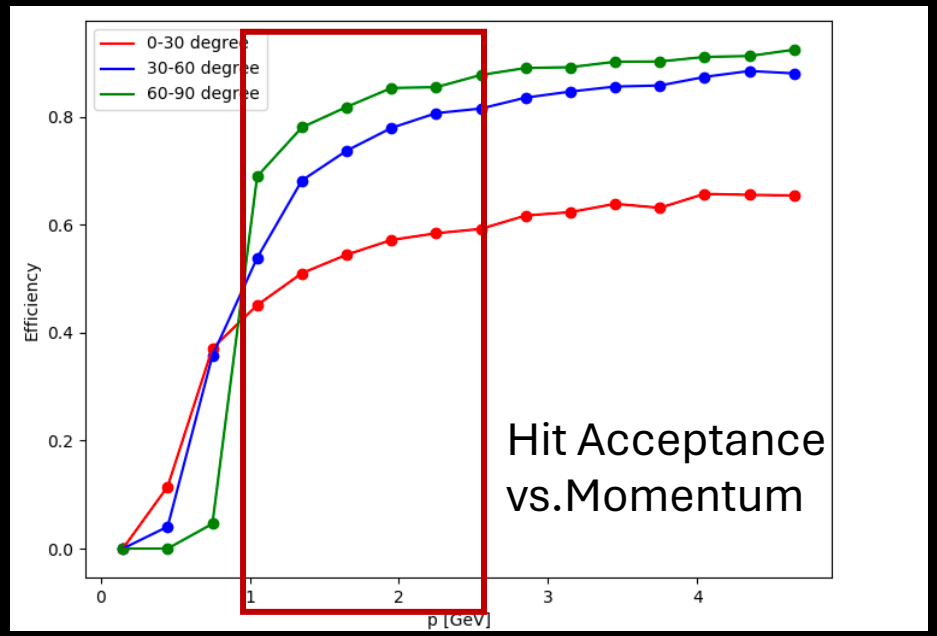
# II CEPC | Time-Tracker End-Cap & Hit Acceptance




- Petals： one petal each 8°× **45** = 360°
- Total modules： ~ **450**
- R： 400 mm - 1800 mm

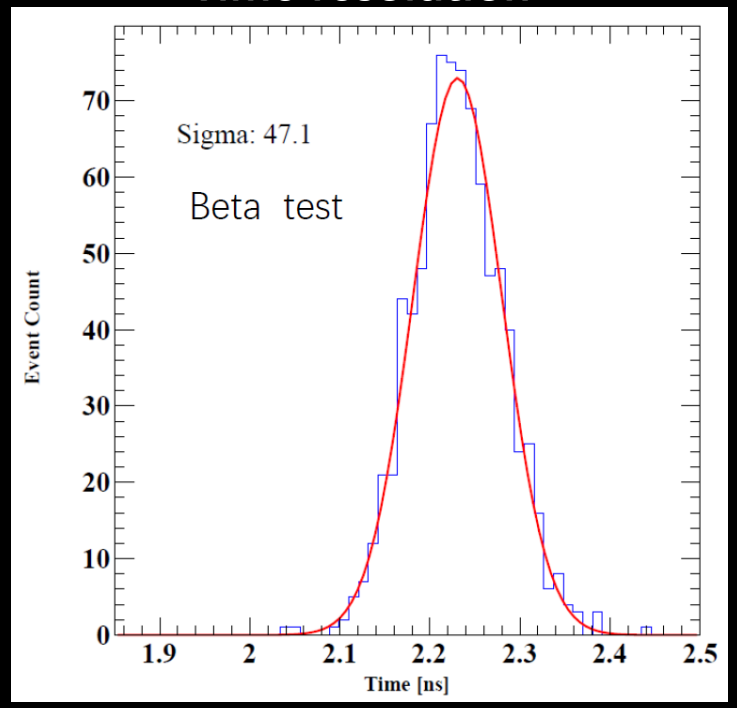



- 1-2.5 GeV is critical
- Overall hit acceptance for Kaon @2GeV >0.7

# III Performance of AC-LGAD | Timing Resolution

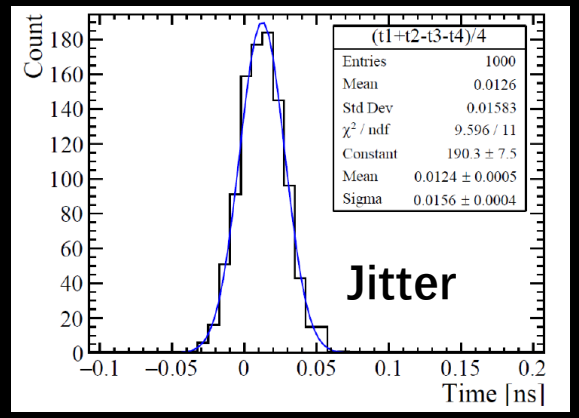
Time resolution




Sigma Δt = 47.1 ps

Sigma AC-strip： **37.5 ps**

Jitter ~ 15ps




Time Resolution

$$\Delta T = T_{trigger} - \frac{\sum_i a_i^2 T_i}{\sum_i a_i^2}$$

Time resolution of trigger

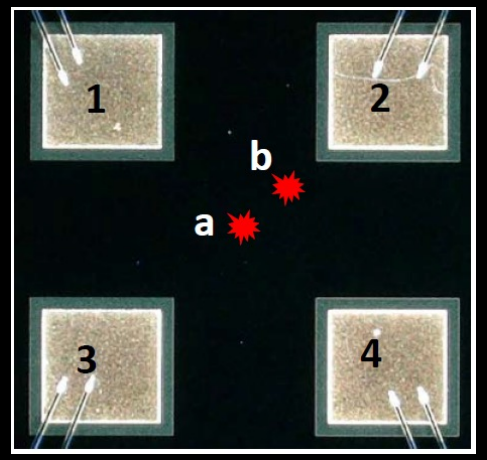
Weighted time resolution of AC-LGAD

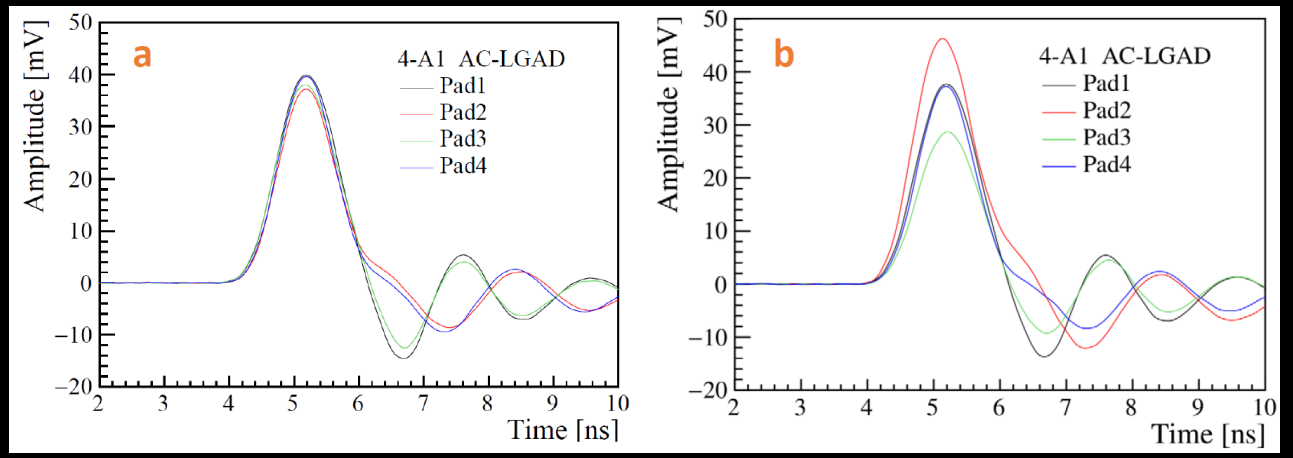
| | |
|---|---|
| Area ($m^2$) | ~ 70 $m^2$ |
| Radius | 1.8m |
| Length | 5.8m |
| Granularity | 70mm × 0.1mm ($10cm^2$, 128channel/chip) |
| Channel number | ~ $1 \times 10^7$ channels |
| MIP Time resolution | ~50 ps |
| Spatial resolution | ~ 10 μm (R-Φ) ~ 1 mm R-Z direction) |
| LGAD Sensor Area | 14cm*14cm |
| Number of channels per module | 2816 (22 chip, 128channel/chip) |

- No significant change in timing resolution was observed among pixel and strip LGADs.
- Timing resolution improves as increasing in SNR, same trend as in spatial resolution.
- Saturation may be observed in jitter, ~ 10 ps.
- 37.5 ps timing resolution, via Beta source test.

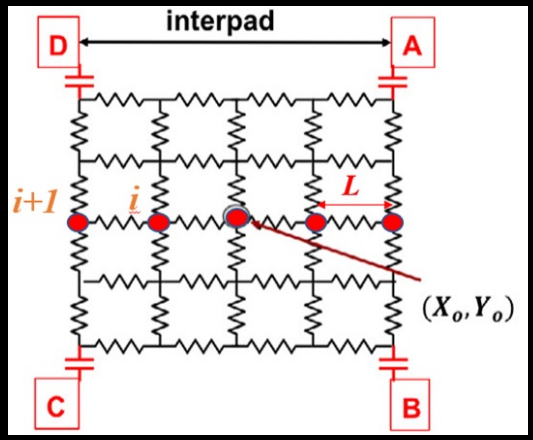
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

# III Performance of AC-LGAD | Spatial Resolution--Pixel

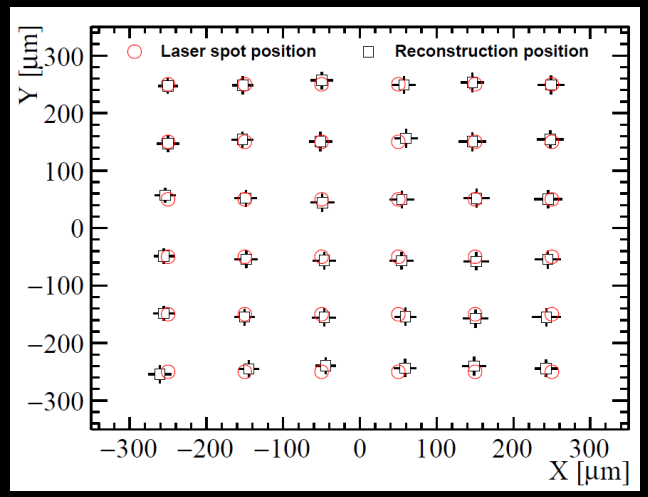


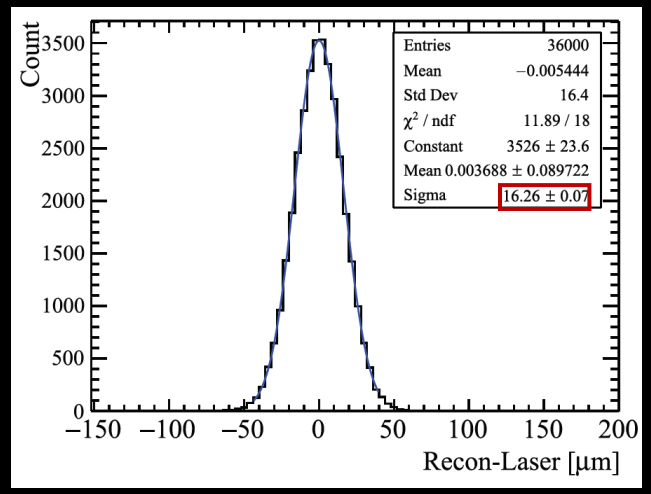

Signal Waveforms @ hit a and b




Discretized Positioning Circuit model (DPC)




Reconstructed 6x6 positions




Difference between reconstruction and laser

| | |
|---|---|
| **Barrel Spatial Resolution Target** | **~ 10 μm (R-Φ)**<br>**~ 1 mm (R-Z direction)** |

Spatial resolution

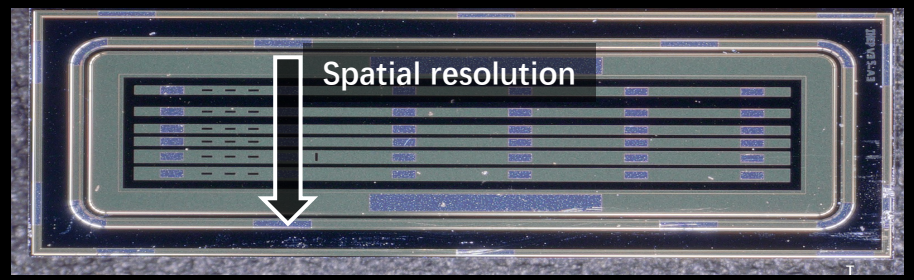
**$16\mu m$** with 2mm x 2mm pitch

**Spatial resolution :**

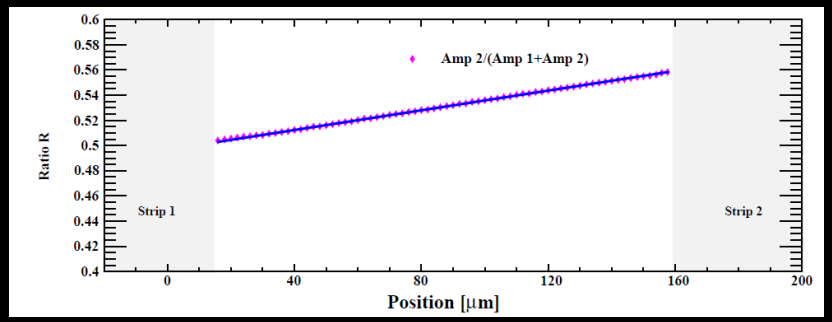
- the sigma of the difference between the laser and the reconstructed position

$$\sigma_{spatial} = \sigma_{reconstruction-laser}$$

# III Performance of AC-LGAD | Spatial Resolution--Strip




$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

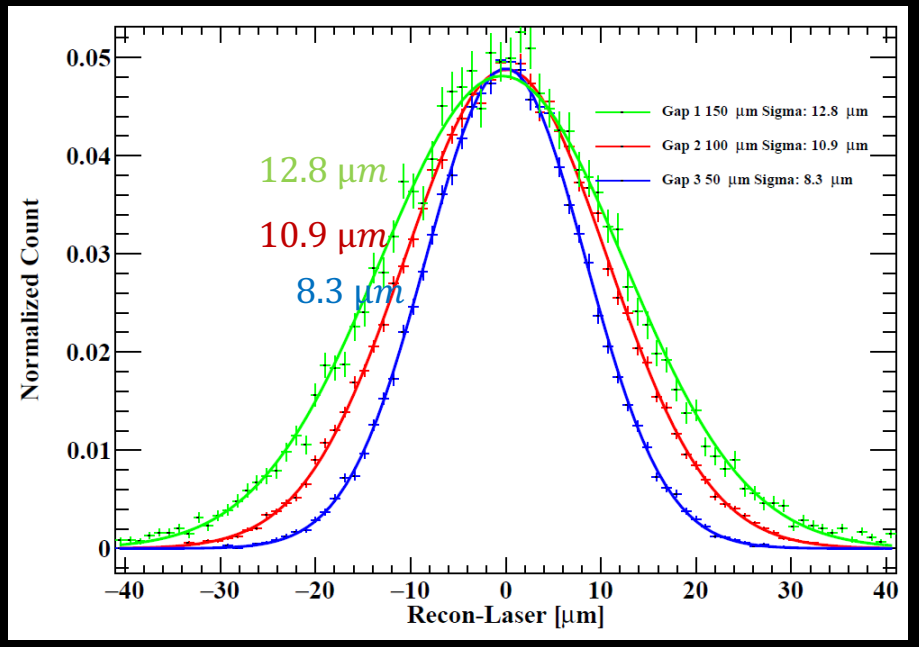



Linear distribution of R

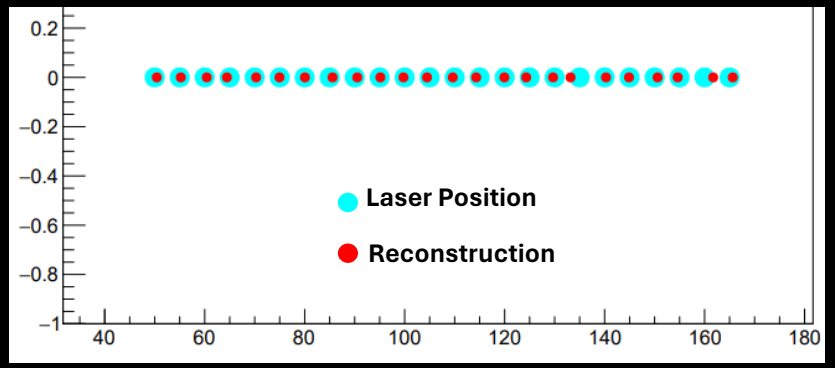
Spatial resolution：

**8.3 $\mu m$**

with 150 μ$m$ pitch




| | |
|---|---|
| **Barrel Spatial Resolution Target** | **~ 10 μm (R-Φ)**<br>**~ 1 mm (R-Z direction)** |



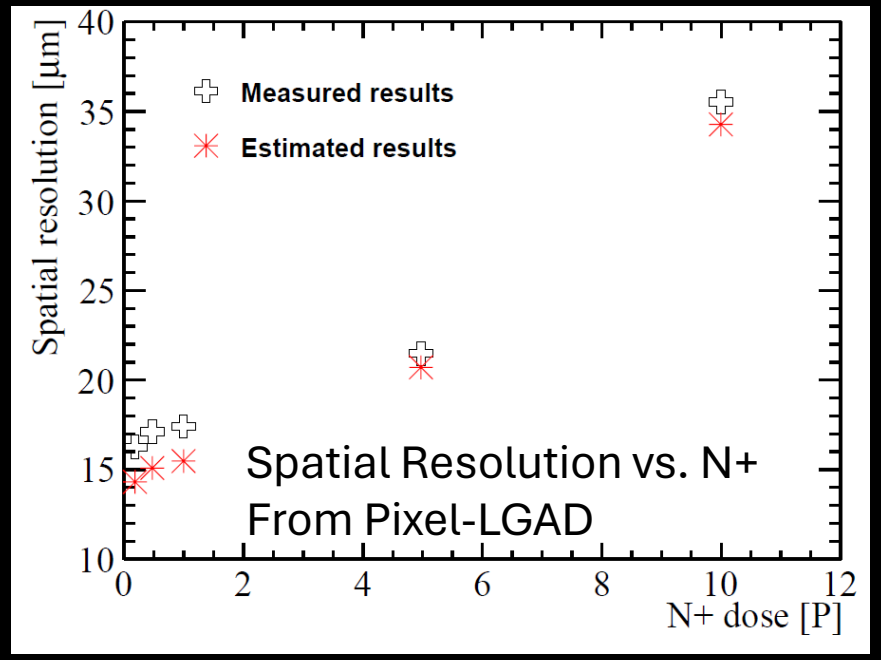

reconstructed positions

**Position reconstruction:**

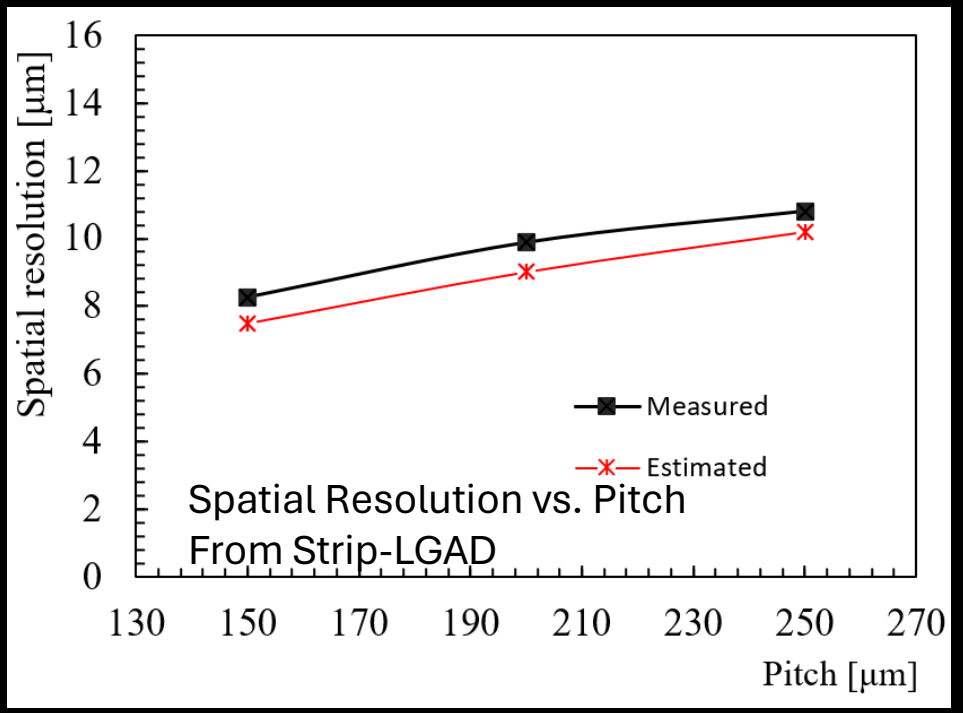
- The fraction of the signal (*R*) changes linearly with the movement of the laser.
  - Good consistency between the reconstruction position and the laser position
  - The smaller the pitch size, the better the spatial resolution

# III Performance of AC-LGAD | Optimization

Spatial resolution Vs. N+ dose




Spatial resolution Vs. pitch size




**Resolution estimation:**

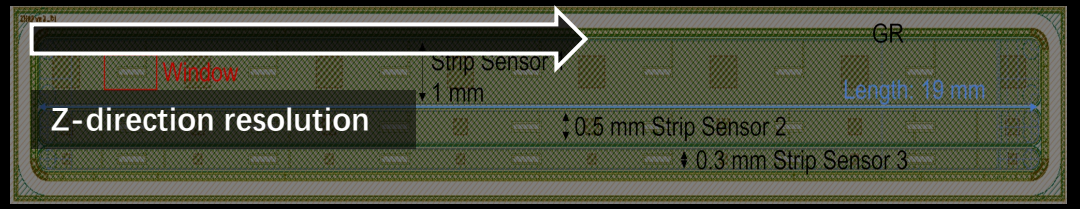
$$\sigma_{spatial} \approx \frac{N}{A}$$

*A*: signal attenuation factor

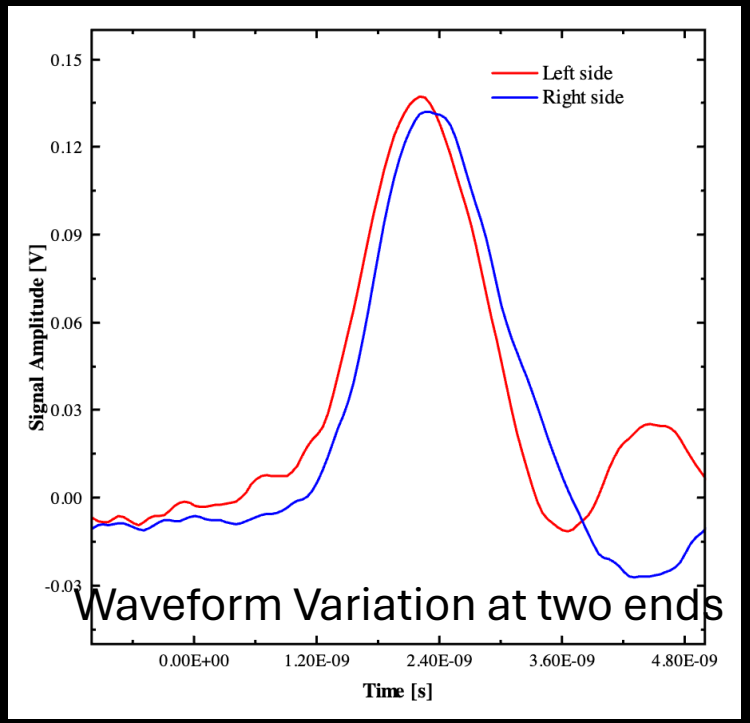
*N*: noise RMS (sensor + electronics)

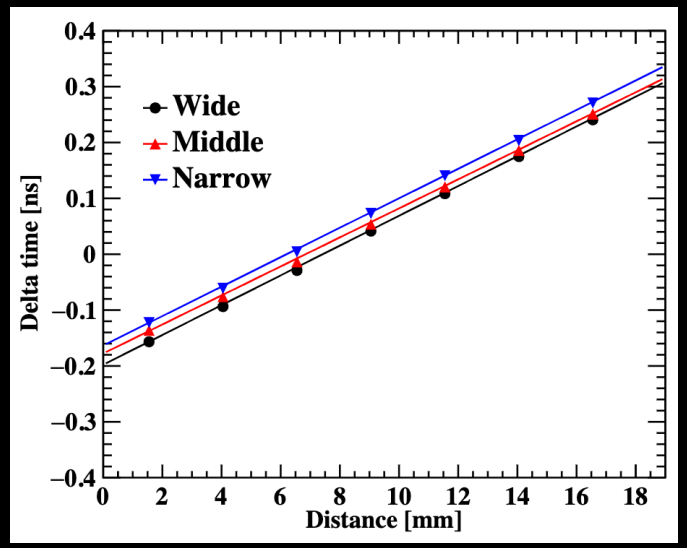
- N+ dose 10 P⟶0.2 P, spatial resolution 36 -> 16 μm (Pixel).
- **Lower N + dose** has higher resistivity and larger attenuation factor, ->**better spatial resolution**.
- Pitch size 250um ⟶ 150um,
  spatial resolution 11 -> 8 μm (Strip).
- **Smaller pitch sizes** result in faster signal attenuation and larger attenuation factor, ->**better spatial resolution**

# III Performance of LGAD | Trial in Z-direction




## Double-end Readout

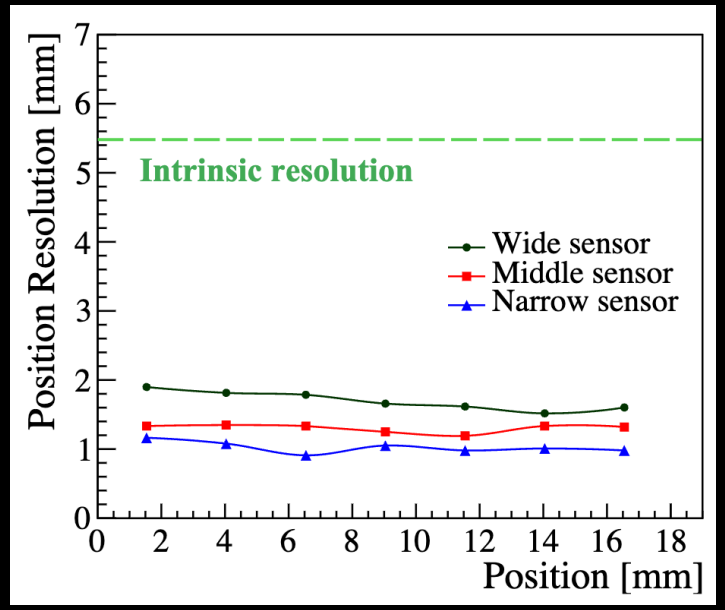



**Position reconstruction:**

- Based on time-lag between two ends
- Good linearity

| | |
|---|---|
| **Barrel Spatial Resolution Target** | **~ 10 μm (R-Φ)**<br>**~ 1 mm (R-Z direction)** |




**Position resolution along Z**

**0.9 mm**

**Intrinsic: 5.5 mm**

**Total length: 19mm**

# Summary

- AC-LGAD is a new 4D detector （position + time), pixel and strip are designed
- Strip AC-LGAD has been determined as the baseline scenario of CEPC Time-Tracker
- **The best spatial resolution of strips AC-LGAD ~8μm**
- **Jitte ~15 ps test by laser, time resolution 37.5ps test by beta source**
- **AC-LGAD satisfied all requirements of Time Tracker**

Time-Tracker Parameters

| | |
|---|---|
| Area ($m^2$) | ~ 70 $m^2$ |
| Radius | 1.8m |
| Length | 5.8m |
| Granularity | 70mm × 0.1mm ($10cm^2$，128channel/chip) |
| Channel number | ~ $1\times10^7$ channels |
| MIP Time resolution | ~50 ps LGAD:37.5ps |
| Spatial resolution | ~ 10 μm (R-Φ) LGAD:8μm<br>~ 1 mm (R-Z direction) LGAD:0.9mm |
| LGAD Sensor Area | 14cm*14cm |
| Number of channels per module | 2816 (22 chip，128channel/chip) |

**The next plan of IHEP AC-LGAD**

- Test beam
- Optimize process parameters and AC-electrodes
- Advanced algorithms for the reconstruction
- Ultra Low Noise Electronics
- CEPC Time-Tracker Reference-TDR Design
- ……

# Thank You For Your Attention

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On behalf of CEPC Time-Tracker Group

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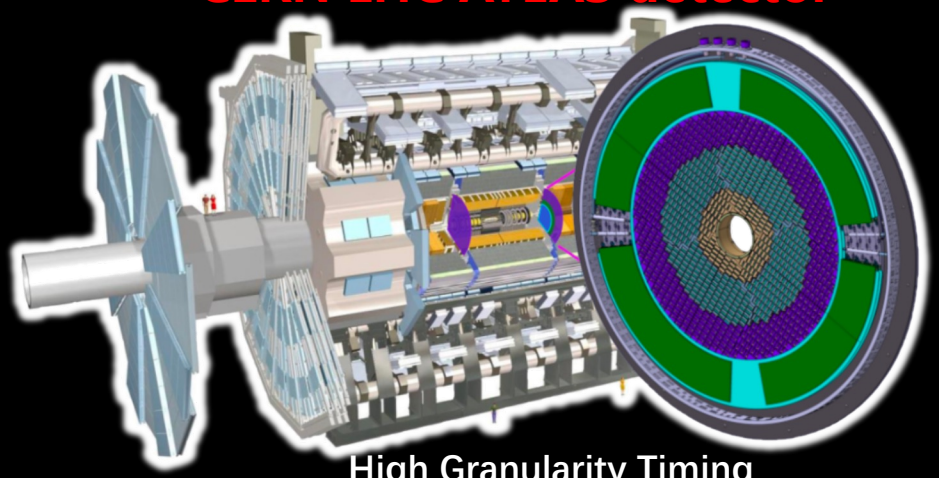
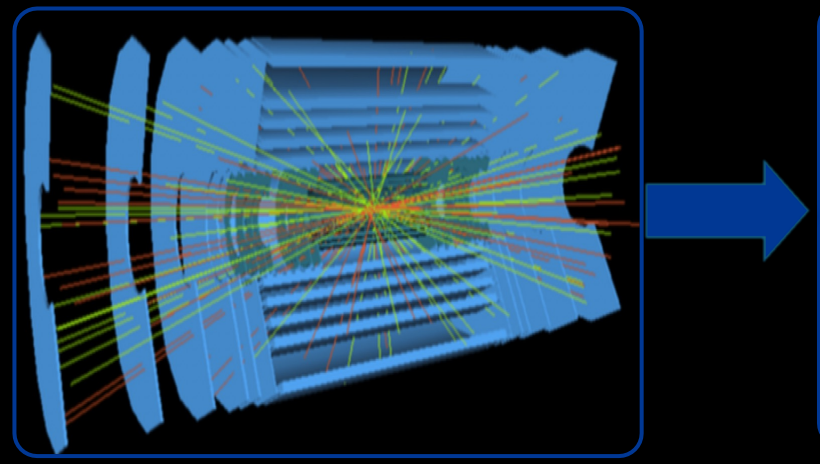
# Motivation & HGTD

**CERN LHC ATLAS detector**

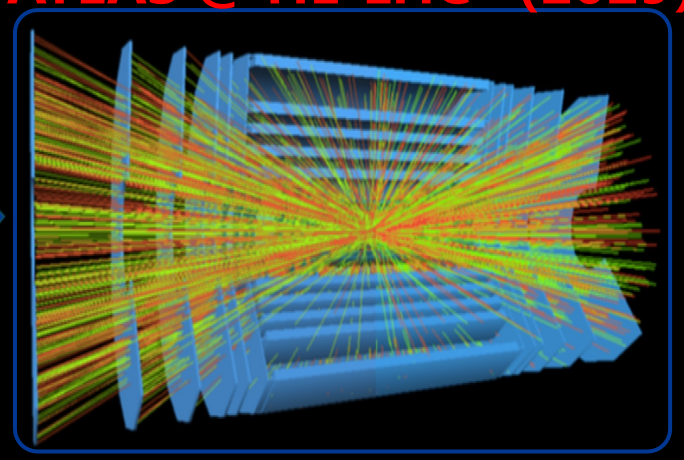


High Granularity Timing Detector (HGTD)

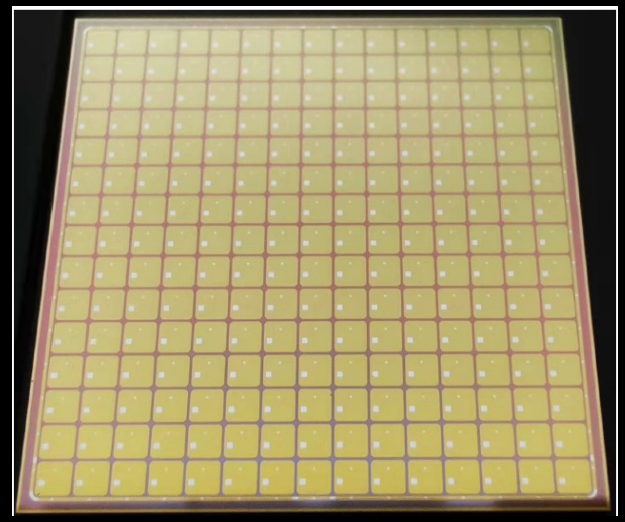
**ATLAS @ LHC (Now)**



**ATLAS @ HL-LHC (2029)**



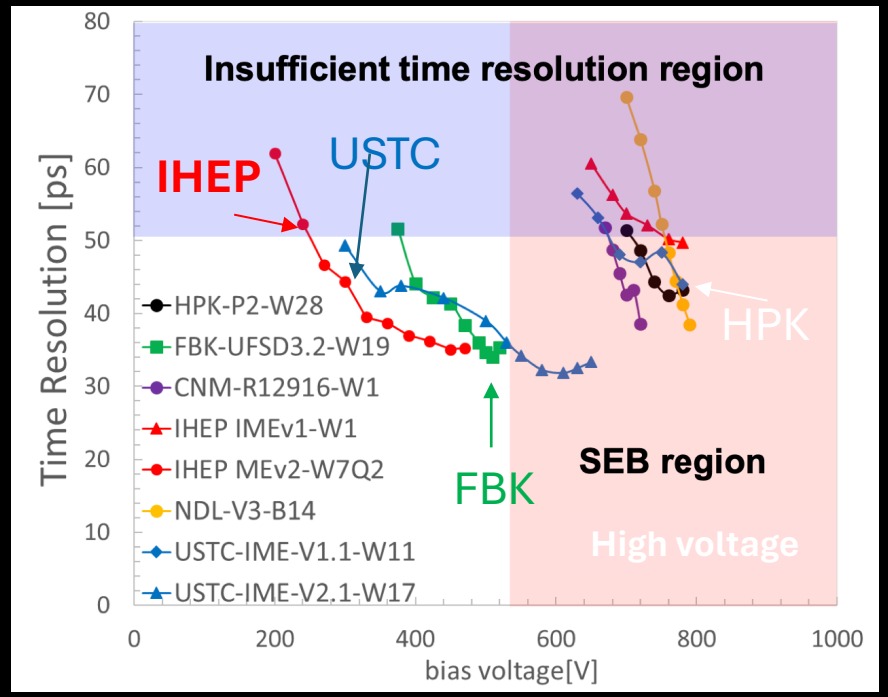
- The pile-up problem: High Time Resolution Devices
- **ATLAS High Granularity Timing Detector (HGTD)**
- **LGAD (Low-Gain Avalanche Diode)**
  - 15x15 LGAD sensors (2 cm×2 cm )
  - **Area 6.4 $m^2$, time resolution 30 ps**
  - Granularity ~mm, **readout channel > 3M**
  - **Irradiation fluence $2.5\times10^{15}$ $n_{eq}/cm^2$**



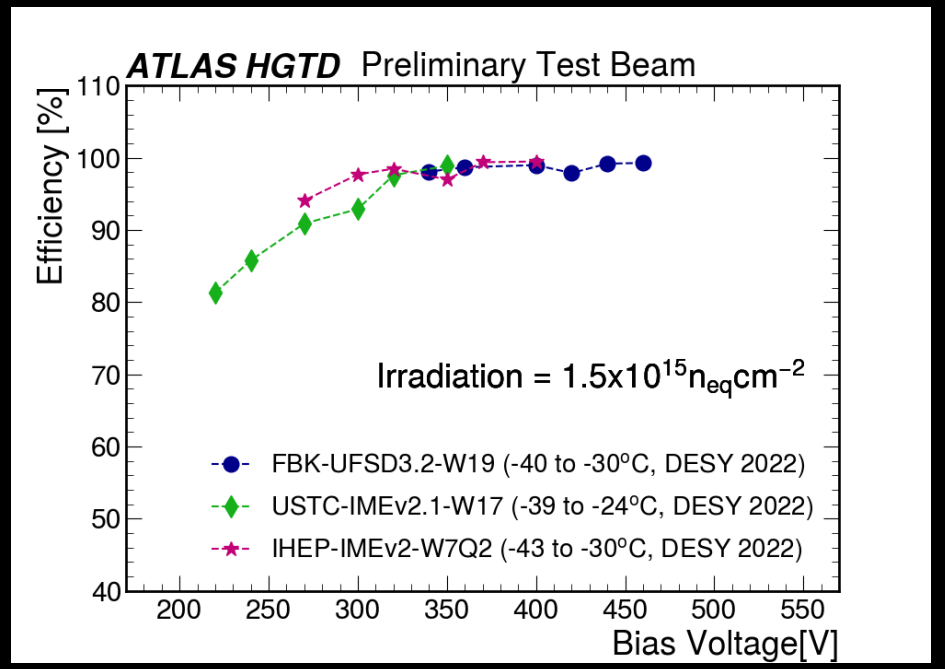
15x15 LGAD arrays for ATLAS HGTD

# Performance of AC-LGAD | Irradiation Hardness

Time resolution @ **$2.5\times10^{15}$ $n_{eq}/cm^2$**

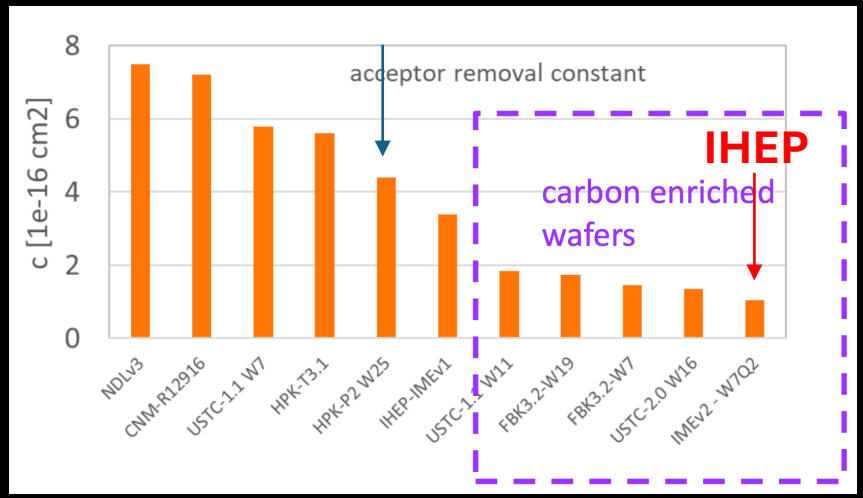



Efficiency >99% @ **$2.5\times10^{15}$ $n_{eq}/cm^2$**




## IHEP LGAD sensors after irradiation

- Unique radiation resistant process
- Currently, the world's smallest acceptor removal constant C ($1.01\times10^{-16}cm^2$)
- The time resolution reaches 34.5ps, and the highest collected charge is 12fC
- Operating voltage 350V @4fC, this is currently the lowest internationally and can avoid the single particle burn (SEB) problem
- Strong irradiation performance compared to Japanese HPK and Italian FBK
- The shallow carbon process avoids the problem of carbon boron deactivation in FBK




Acceptor removal constant ***C***

# Application

**Neutron Source**:
Neutron Flux Monitor

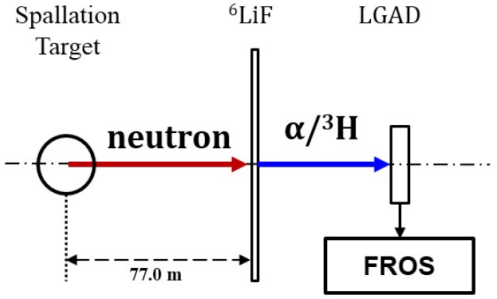



Fig. 3. Experimental scheme of the detector setup for $^6Li(n,T)\alpha$. (Not to scale)

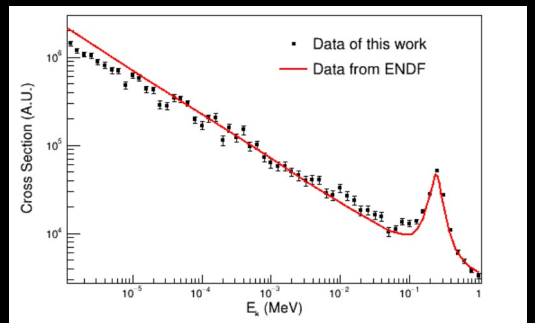
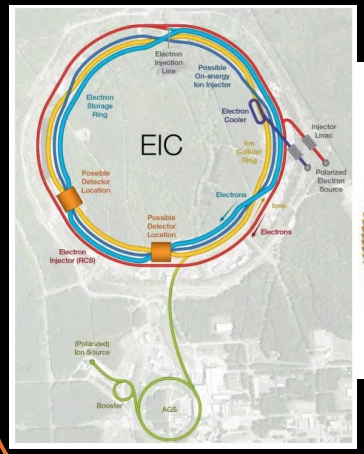
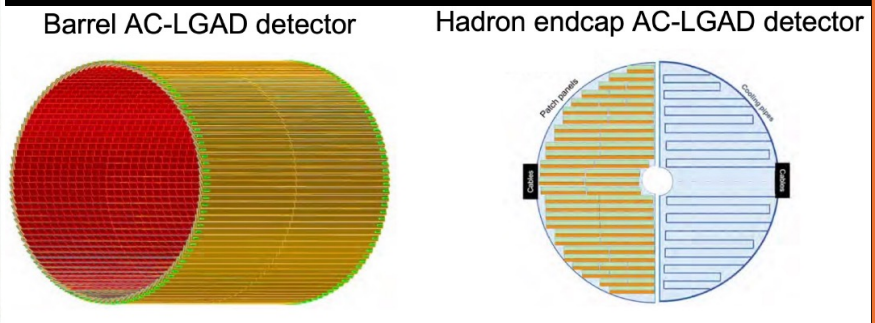



Fig. 9. Measured cross section of $^6Li(n,T)\alpha$ (Black dots) and data from ENDF database (Red line). The resonance peak of $^6Li$ and neutron around 200 keV can be observed on the plot.

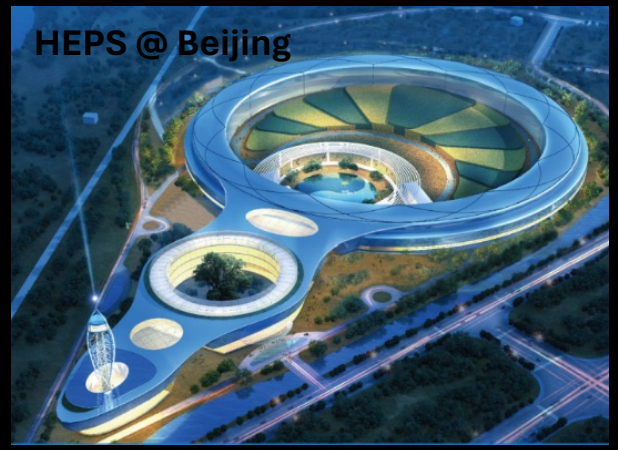
**Electron-Ion Collider (EIC)**: Timing-tracker

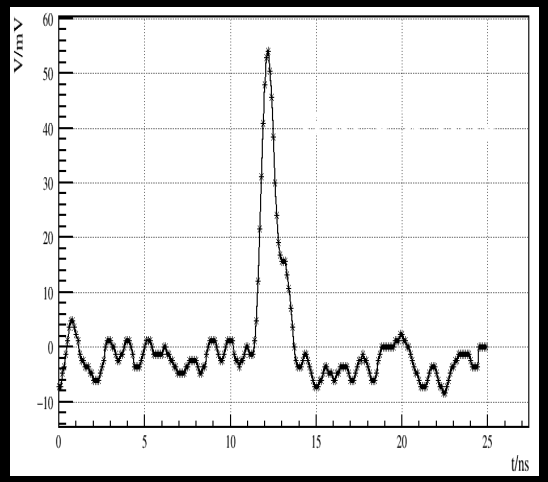



10.9 m$^2$ 2.22 m$^2$

**X-ray detectors** @ advanced light sources



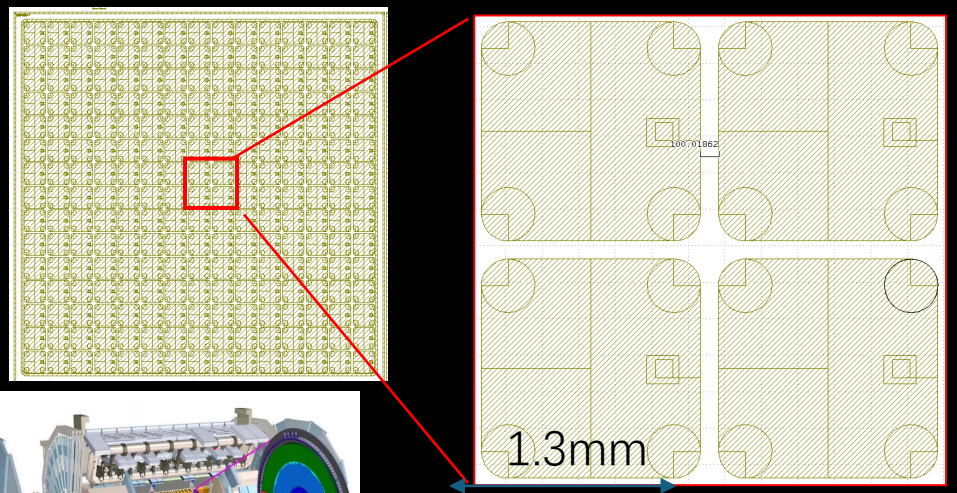



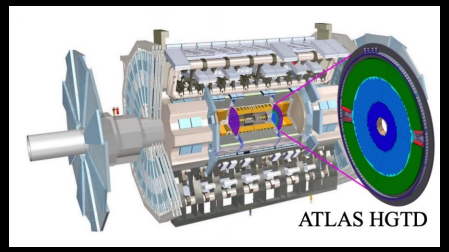

## other applications

- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

# Introduction to AC-LGAD

## 15×15 LGAD for ATLAS HGTD project

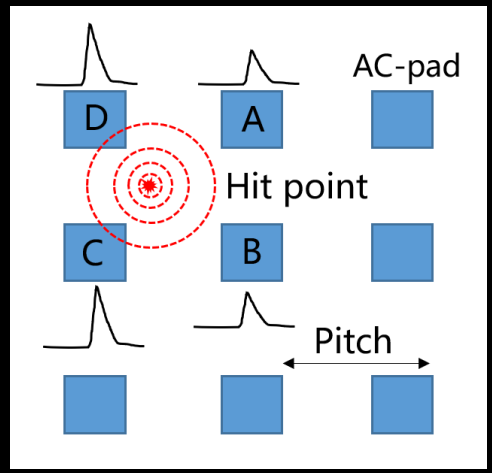


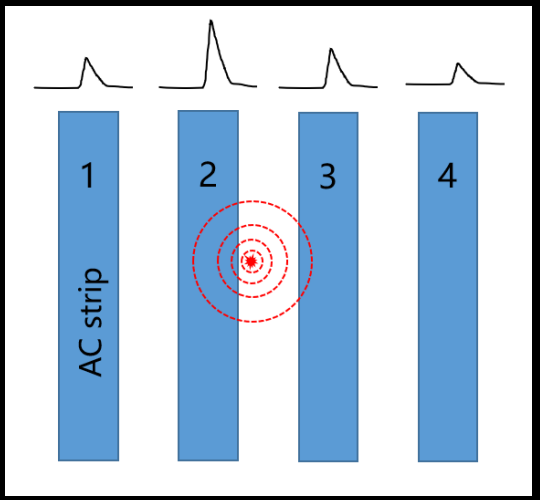




- Dead zone : ~0.1mm
- Pixel size: 1.3mm

Smaller Pixel LGADs -> Lower fill factor

## AC-LGAD：two layout schemes for AC-pads




**Pixels AC-LGAD**:

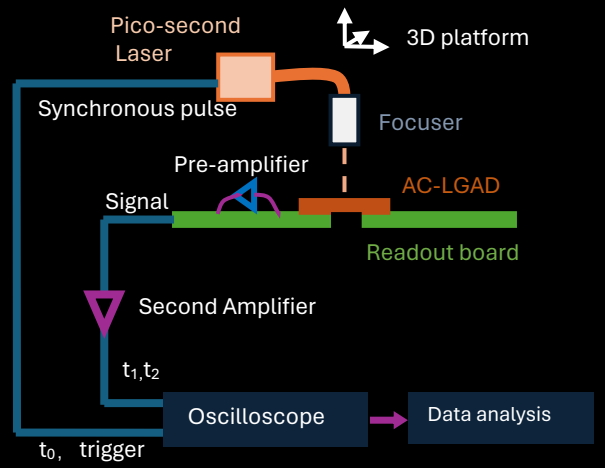
- Position information: 1 layer (x,y)
- Bump bonding

**Strips AC-LGAD**:

- Lower readout electronics, no bump bonding
- Position information: 2 layers for (x,y)

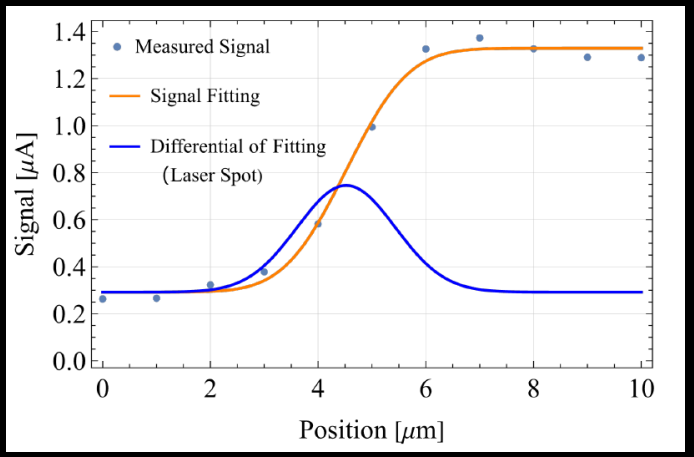
Spatial resolution
Timing resolution
Irradiation Hardness

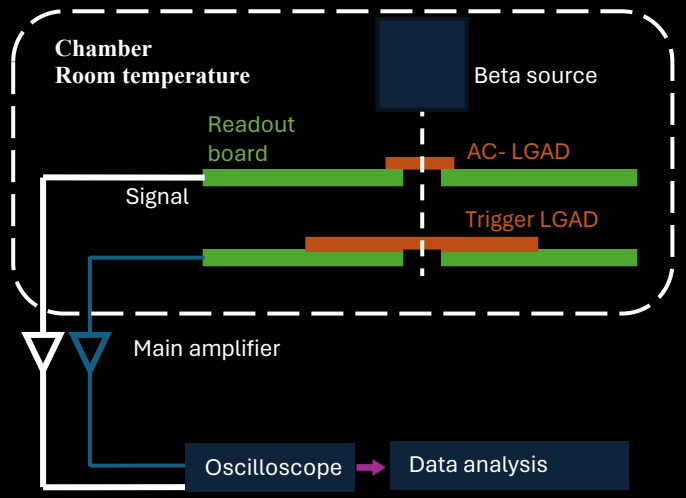
# Performance of AC-LGAD | Test Platform




## Picosecond laser scanning system

- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size 2~5 μm




## Beta Source Telescope

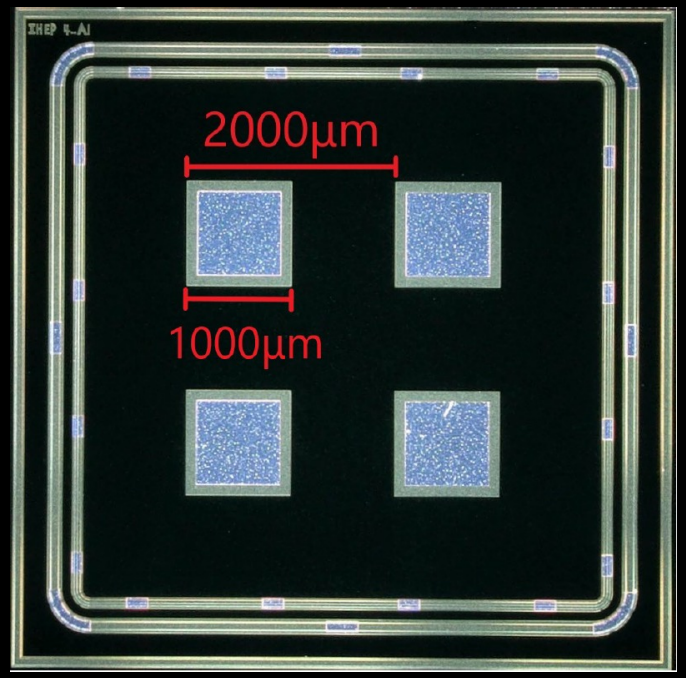
# AC-LGAD sensors development by IHEP

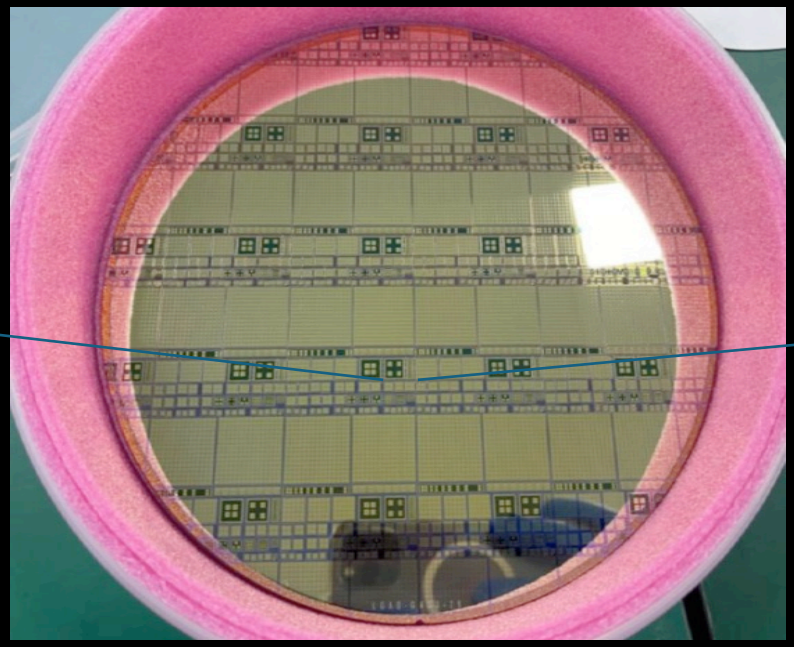
**Pixels AC-LGAD：**

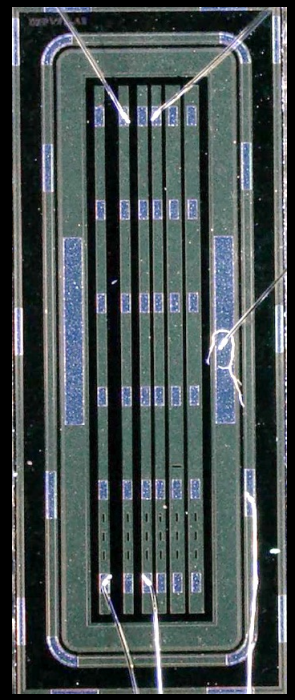
- Position information： 1 layer
- Pitch size 2000um, pad size 1000um

**Strips AC-LGAD：**

- Position information： 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size：
  - **150um、200um、250um**





Spatial resolution
Timing resolution
Irradiation Hardness