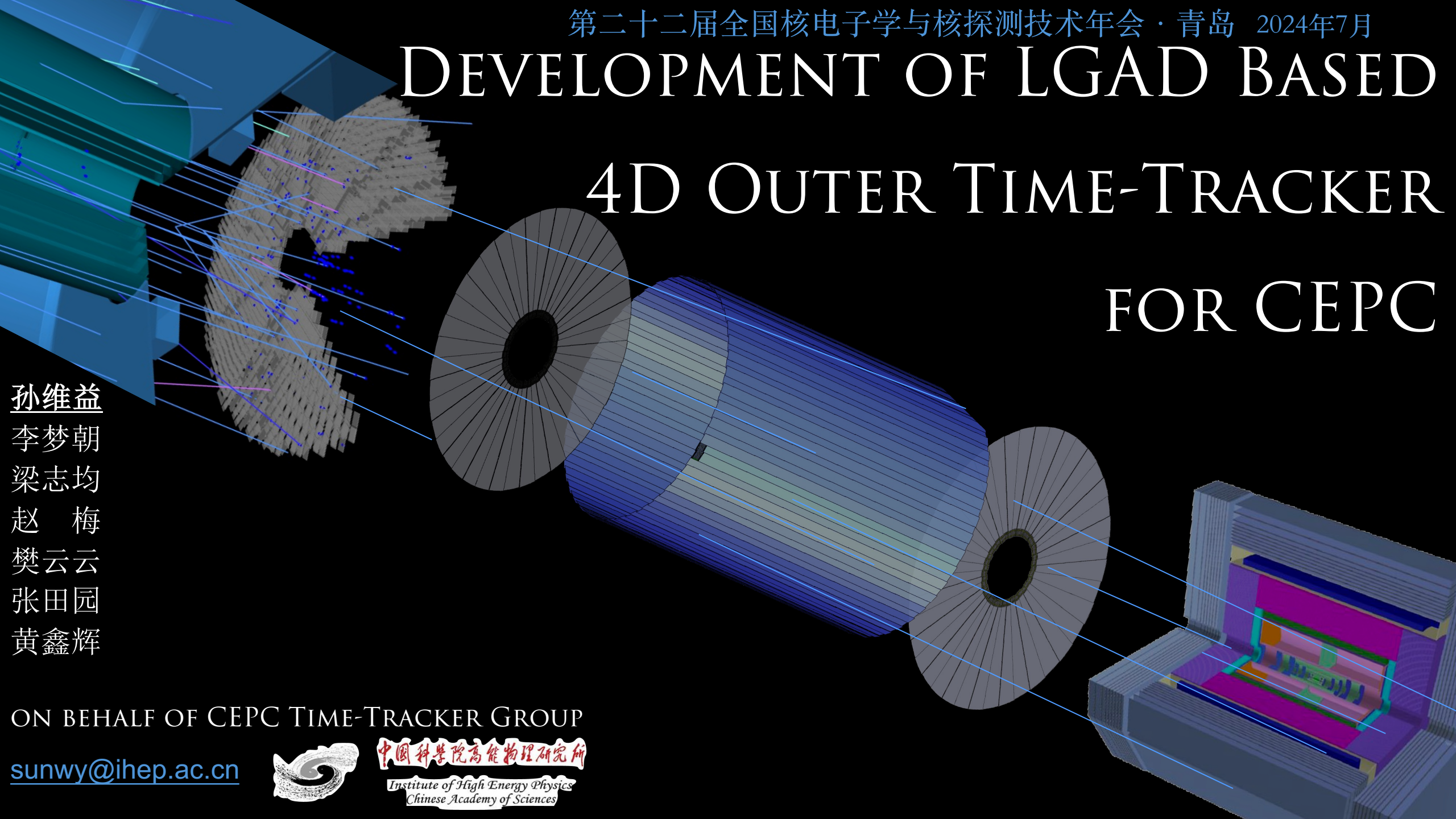
第二十二届全国核电子学与核探测技术年会 · 青岛 2024年7月

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



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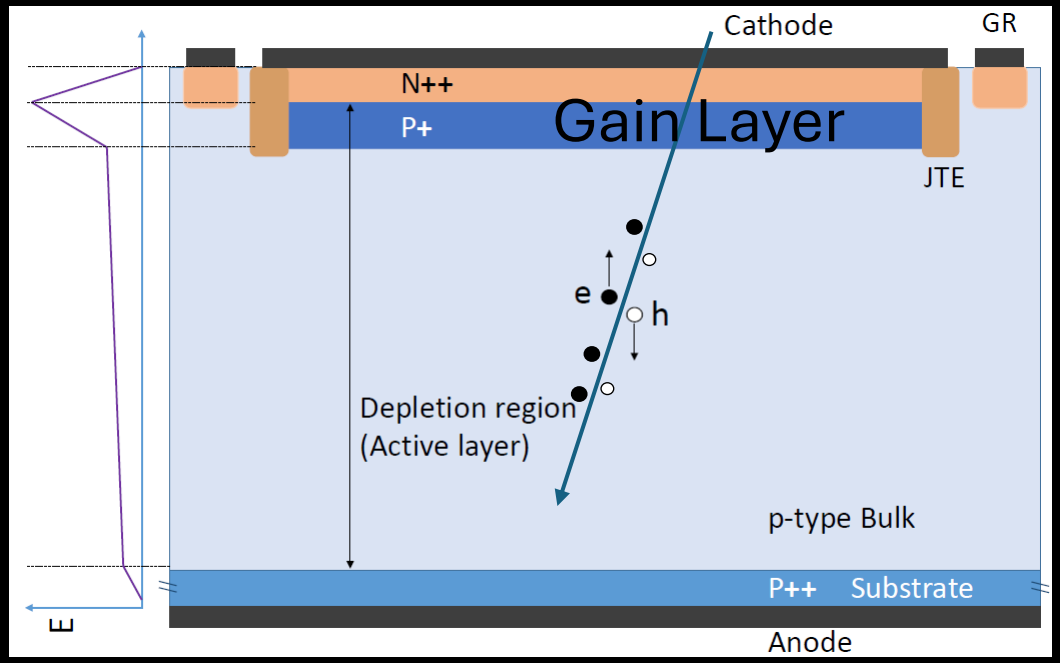
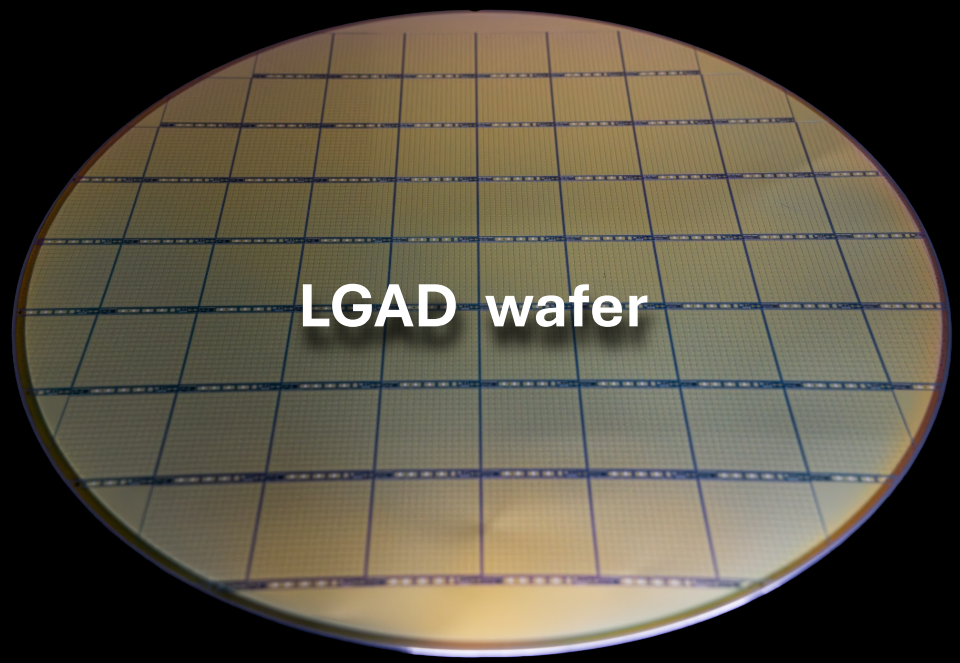
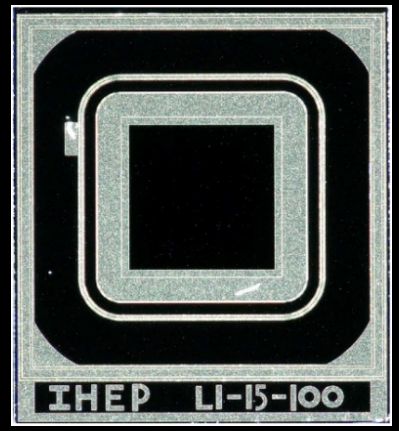
I Introduction | LGAD Overview





LGAD (Low-Gain Avalanche Diode)

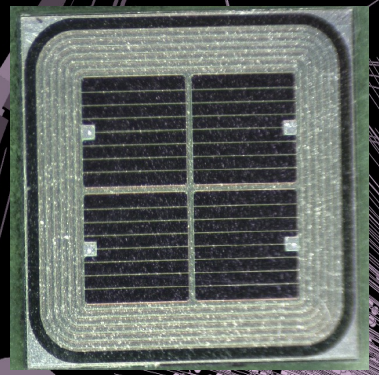
- **N-on-P silicon diode**, with highly doped p-layer beneath N++
- Excellent time resolution for MIP particles
- **Active thickness 50 μm**
- Low Gain 10-50 with fast signal and good signal to noise ratio
- **Time resolution ~ 30-50ps**

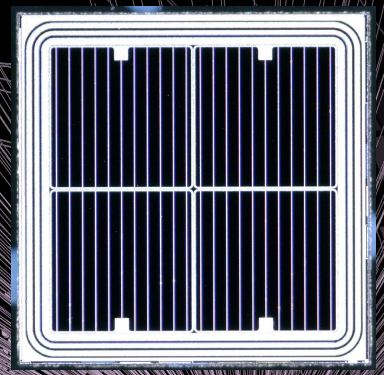


Single LGAD sensor

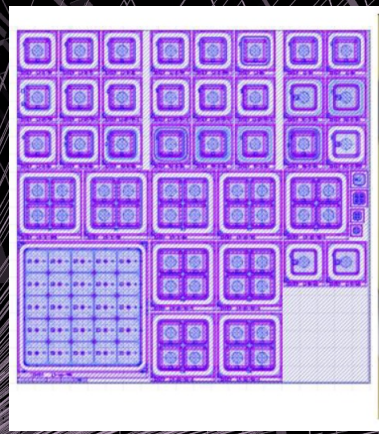
I Introduction | IHEP LGAD Timeline

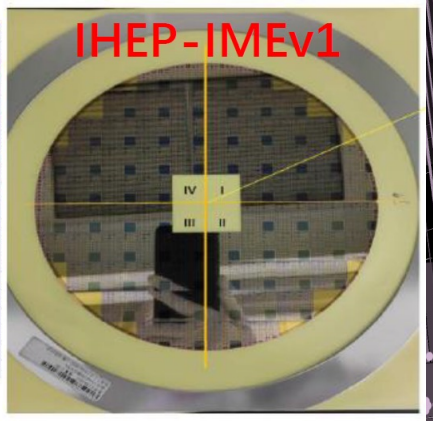
IHEP-NDL(2019)



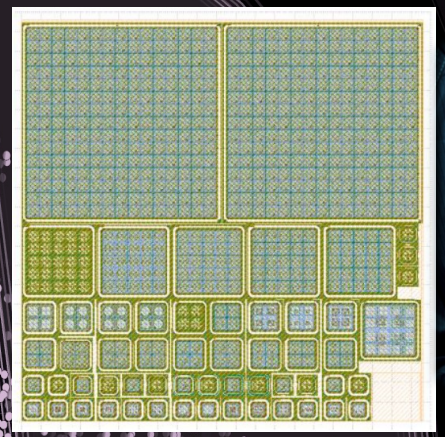


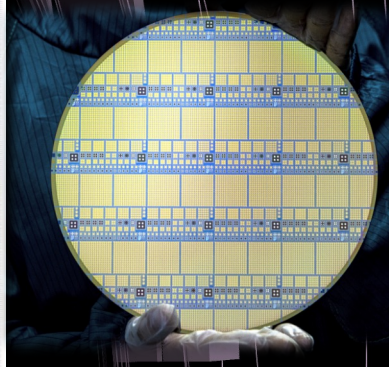
IHEP-IMEv1(2020.9)



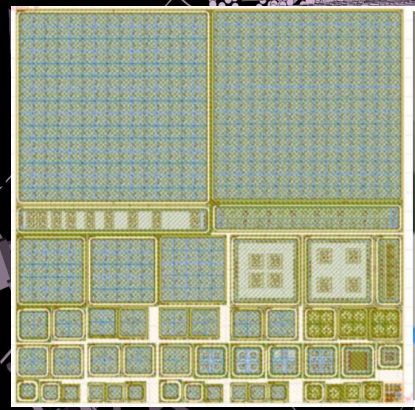


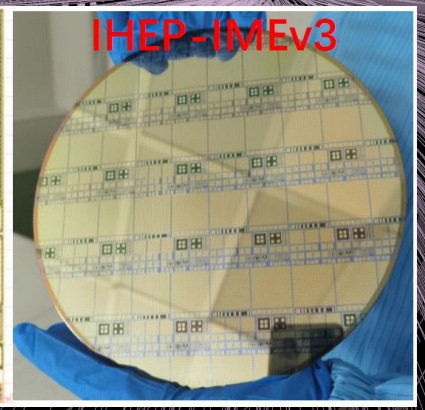
IHEP-IMEv2(2021.6)



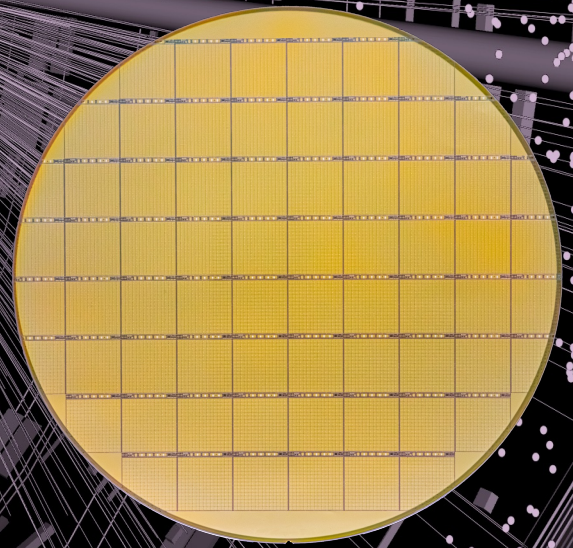


IHEP-IMEv3(2022.5)



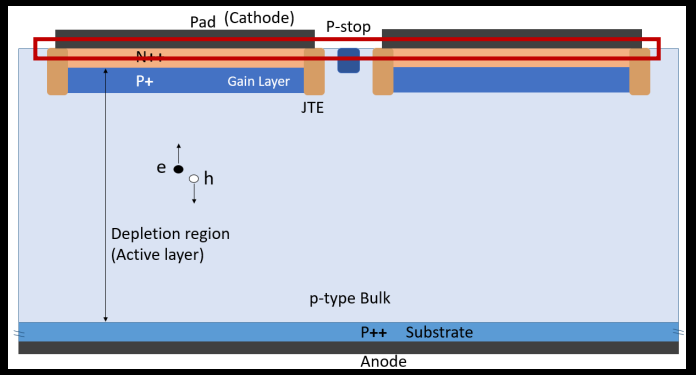


Pre-production for ATLAS (2023.7)

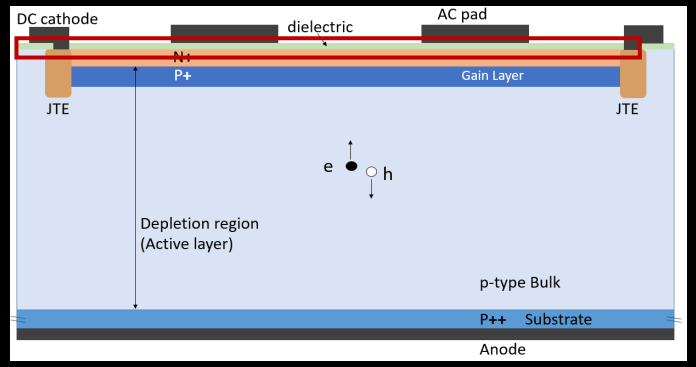


Mass production for ATLAS (2024.8-)

I Introduction | AC-LGAD



Dielectric

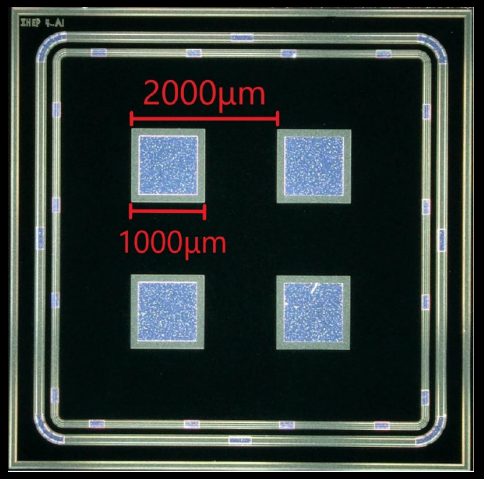


LGAD (Low-Gain Avalanche Diode)

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

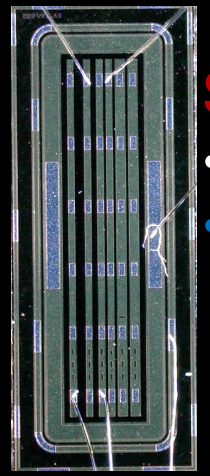
AC-LGAD (AC-coupled LGAD)

- 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:

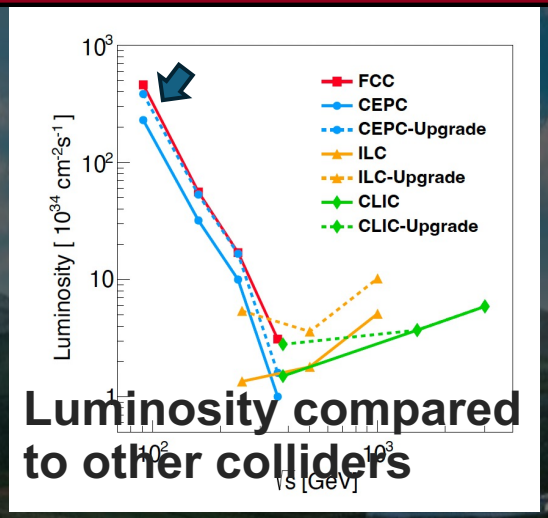
- Pitch size 2000um
- pad size 1000um



Strips AC-LGAD:

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

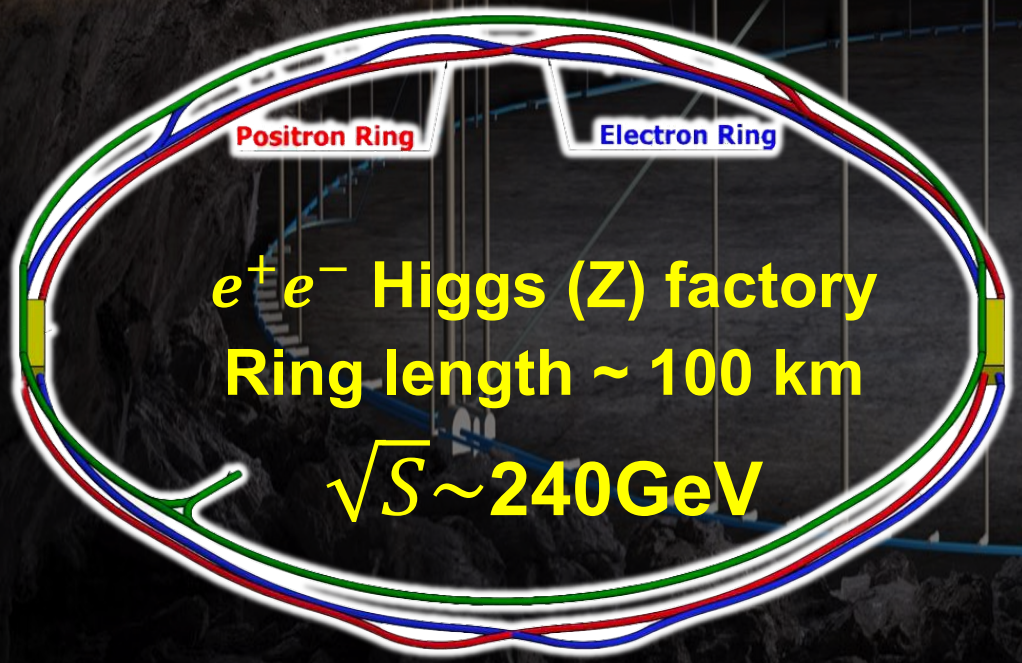
II CEPC | Overview



Luminosity compared to other colliders

Circular Electron-Position Collider--CEPC

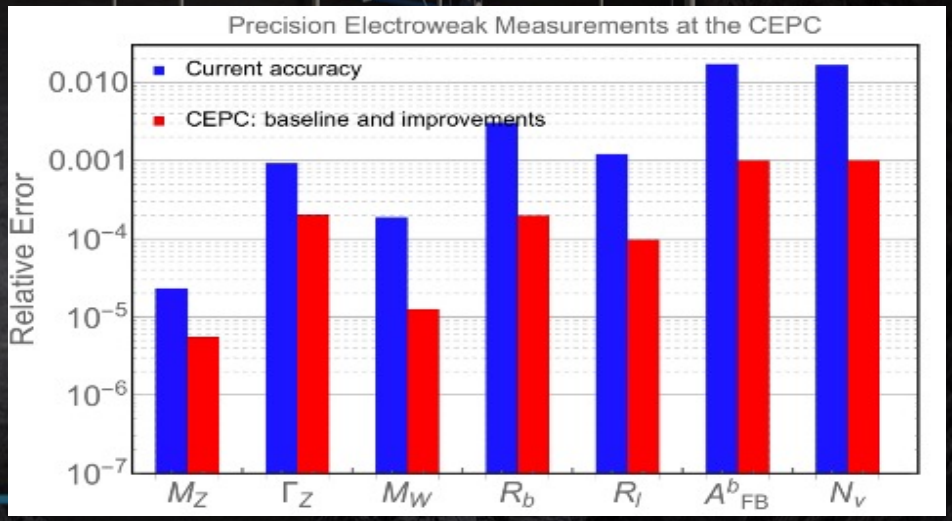
- Highest Energy
- Higgs factory
- Producing Higgs / W / Z bosons and top quarks
- Precision measurement
- Discovering new physics beyond the Standard Model



e^+e^- Higgs (Z) factory

Ring length ~ 100 km

$\sqrt{S}$~240GeV

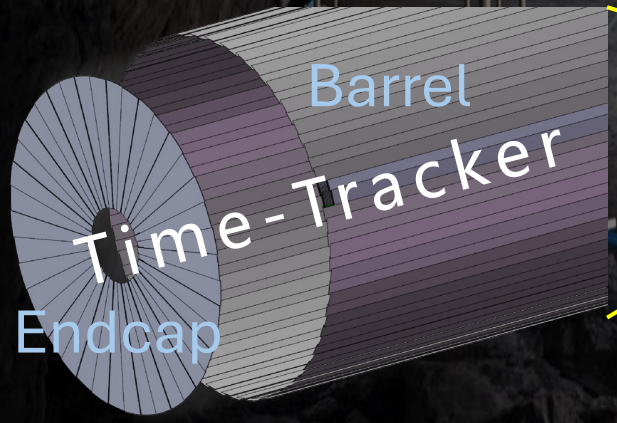


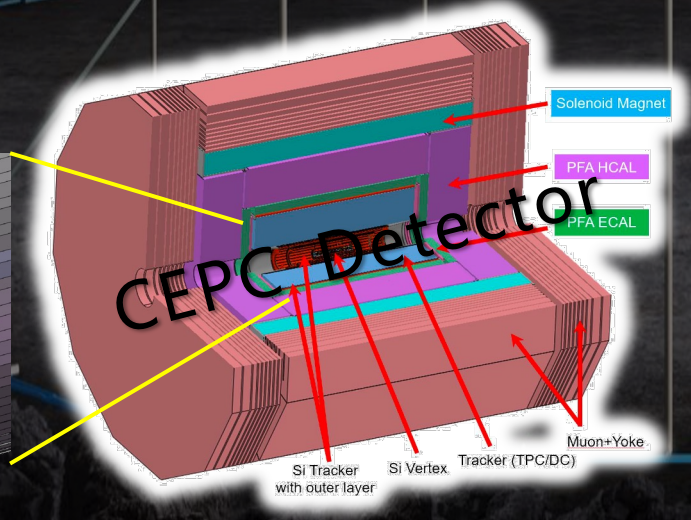
Improvement of EW measurement (lower is better)

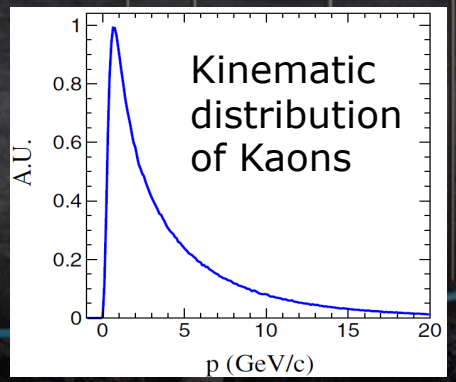
II CEPC | Overview

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

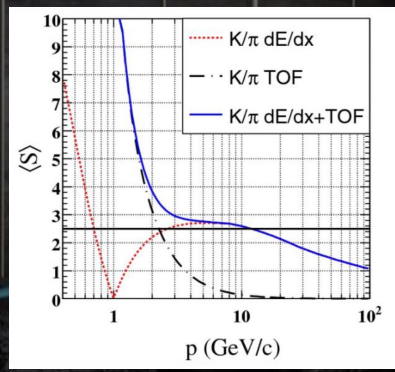
- **Produce 10^{12} Z boson at Z pole: Rich flavor physics program**
- **Particle separation problems** of Gas detector (dE/dx) :
  - 1 GeV for K/pi separation, 2 GeV for K/p separation
- **CEPC International Advisory Committee: one of the key recommendations**
  Precision timing detector should be determined as a matter of urgency (4D track)
- **Timing detector is complementary to gas detector:** 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**



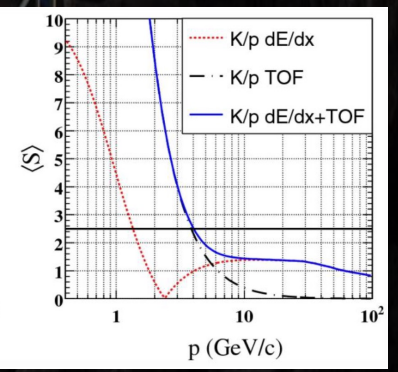




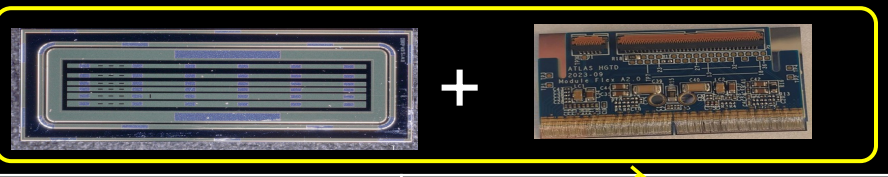
K/pi separation



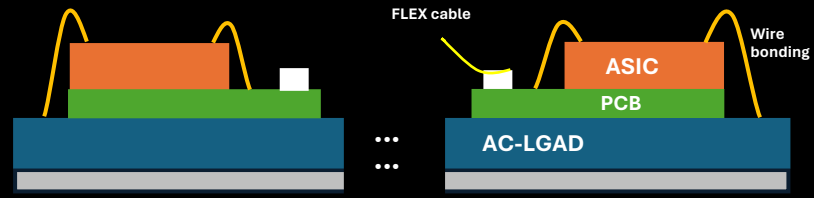
K/proton separation

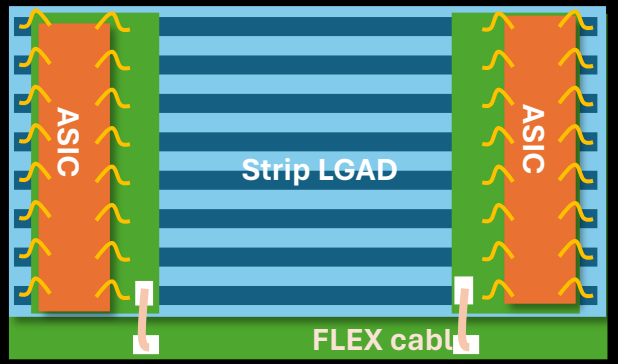


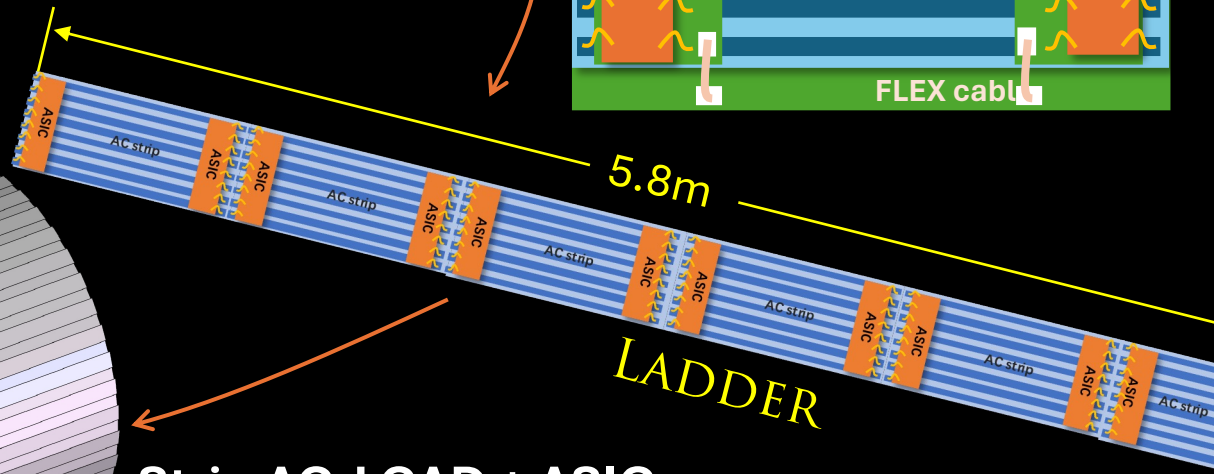
II CEPC | Time-Tracker Barrel

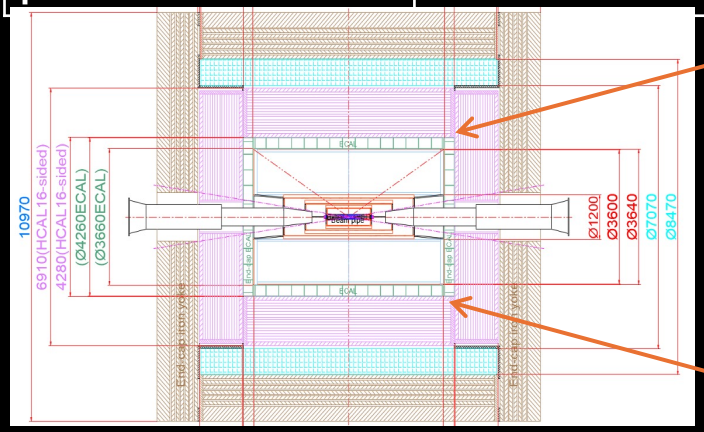


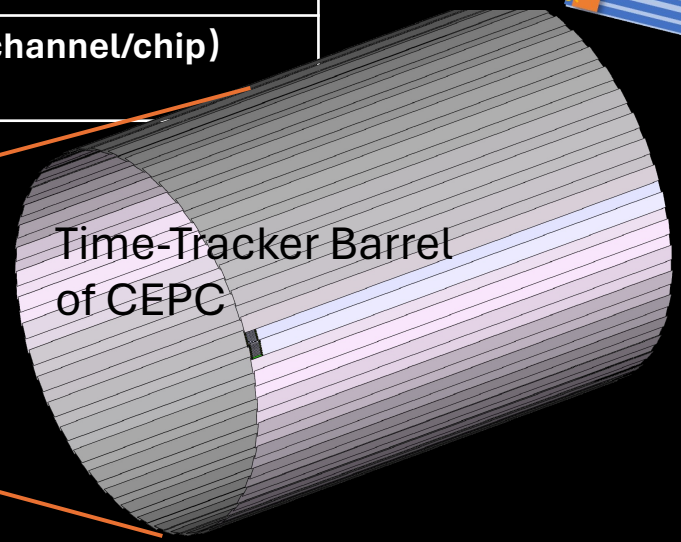
Time-Tracker Barrel Parameters	
Area (m^2)	~ 70 m^2
Radius	1.8m
Length	5.8m
Granularity	70mm × 0.1mm ($10cm^2$, 128channel/chip)
Channel number	~ 1×10^7 channels
MIP Time resolution	~50 ps
Spatial resolution	~ 10 μm (R-Φ) ~ 1 mm R-Z direction)
LGAD Sensor Area	14cm*14cm
Number of channels per module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







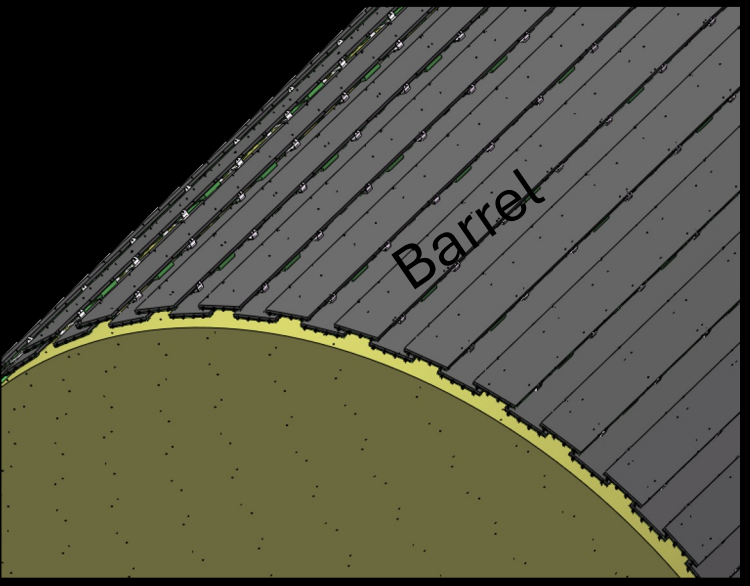


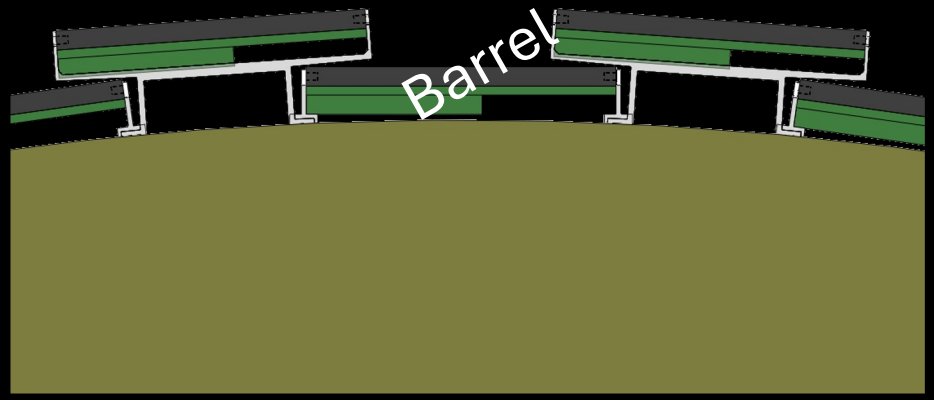


Strip AC-LGAD + ASIC :

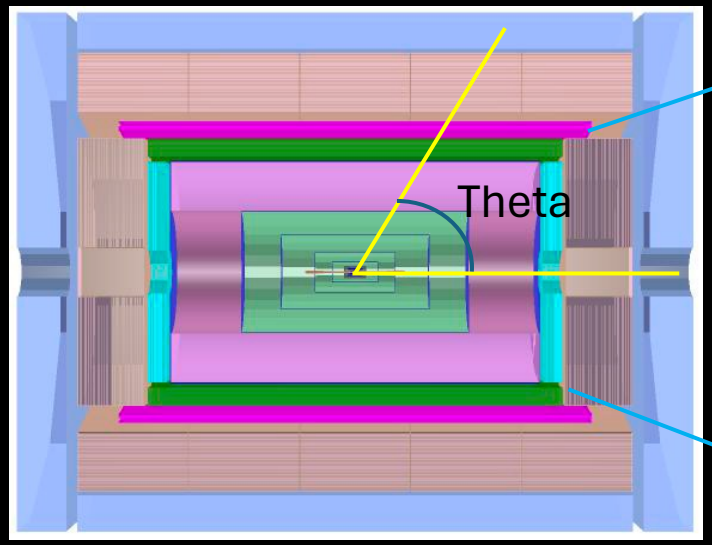
- TOT->amplitude->charge sharing->position
- TOA+TOT->timing (time–amplitude correction)

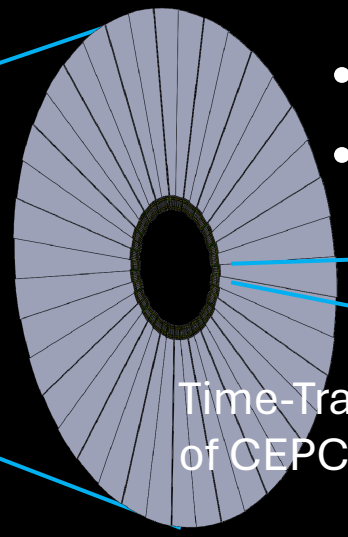
II CEPC | Time-Tracker Barrel & End-Cap



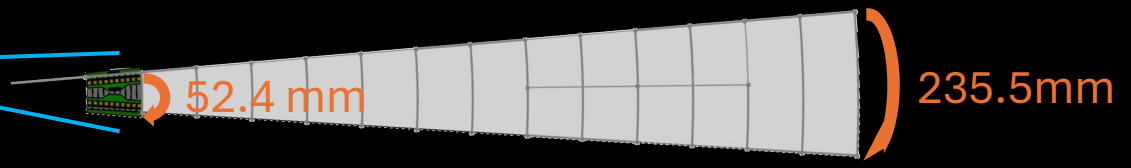


- two layers of ladders
- Partially overlapped
- ladder thickness 35 mm: 25 mm of sensors and electronics
- 10 mm of support embedded with cooling tubes



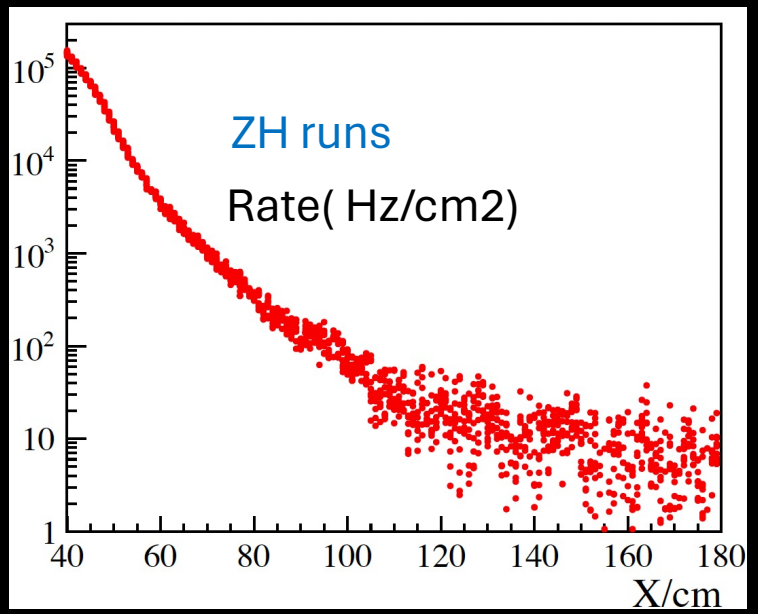


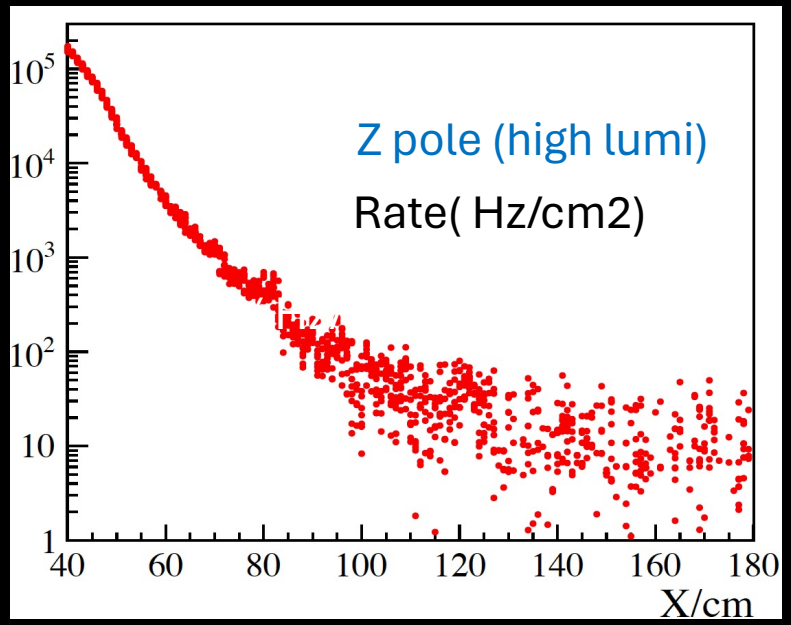
- Petals： one petal each 7.5°× **48** = 360°
- R： 400 mm - 1800 mm , 10 layers



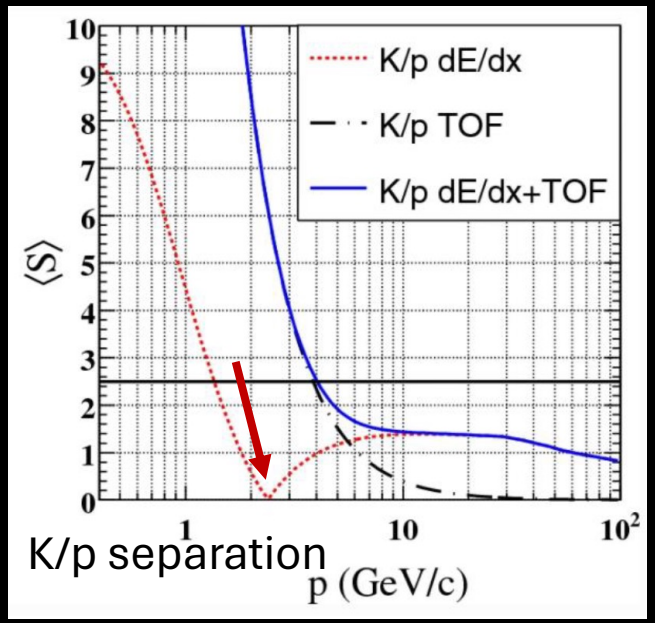
Time-Tracker End-Cap of CEPC

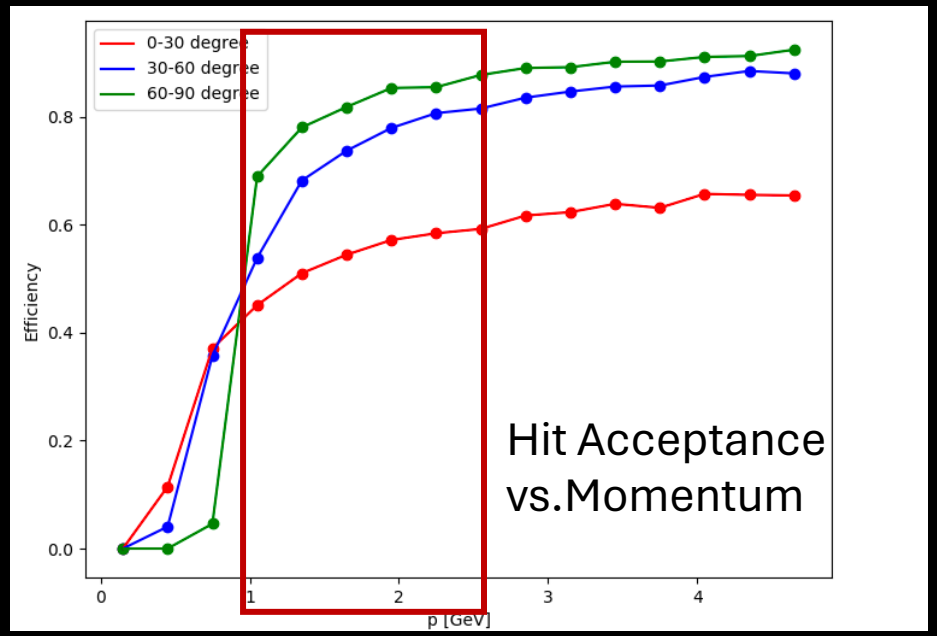
II CEPC | Hit Acceptance





- Overall pair production background of ZH and Z Pole
- Large hit rate
- Up to 1E5 Hz/cm^2



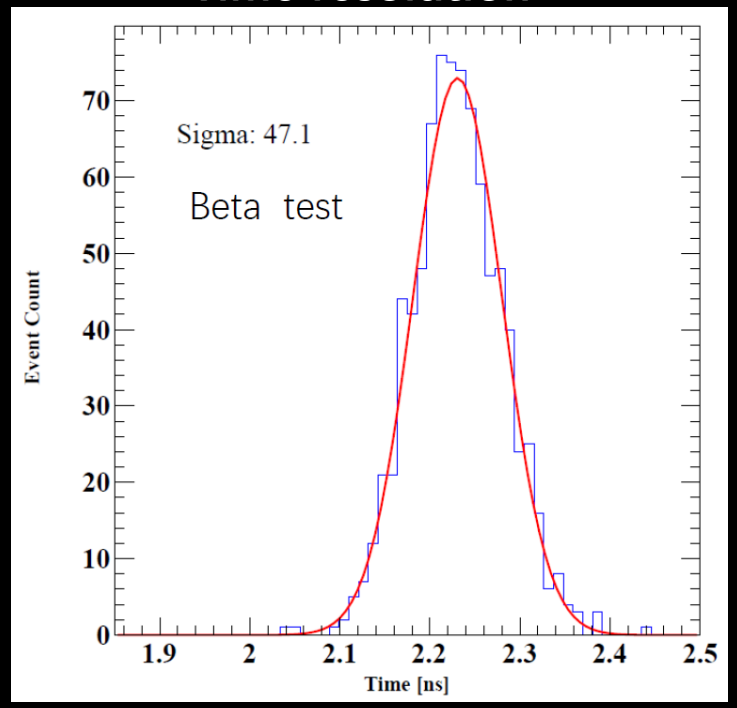


- 1-2.5 GeV is critical
- Overall hit acceptance

for Kaon @2GeV >0.7

III Performance of AC-LGAD | Timing Resolution

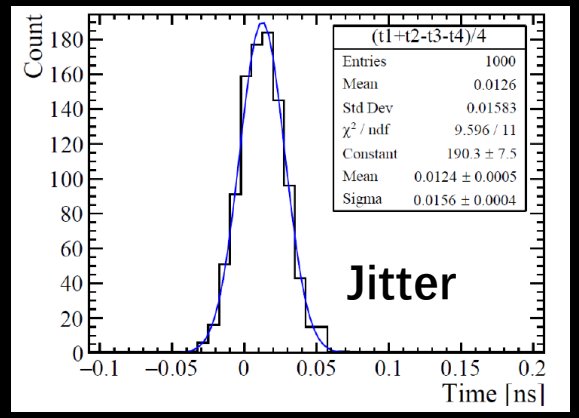
Time resolution



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

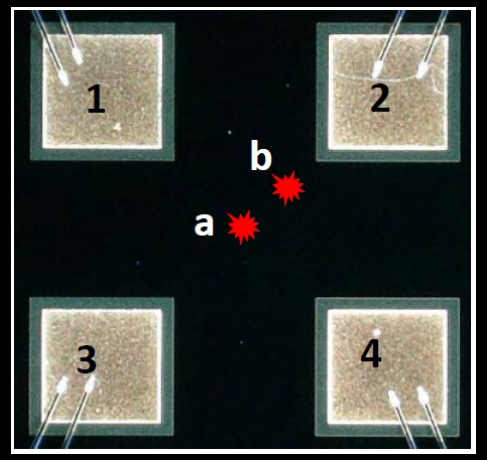
Weighted time resolution of AC-LGAD

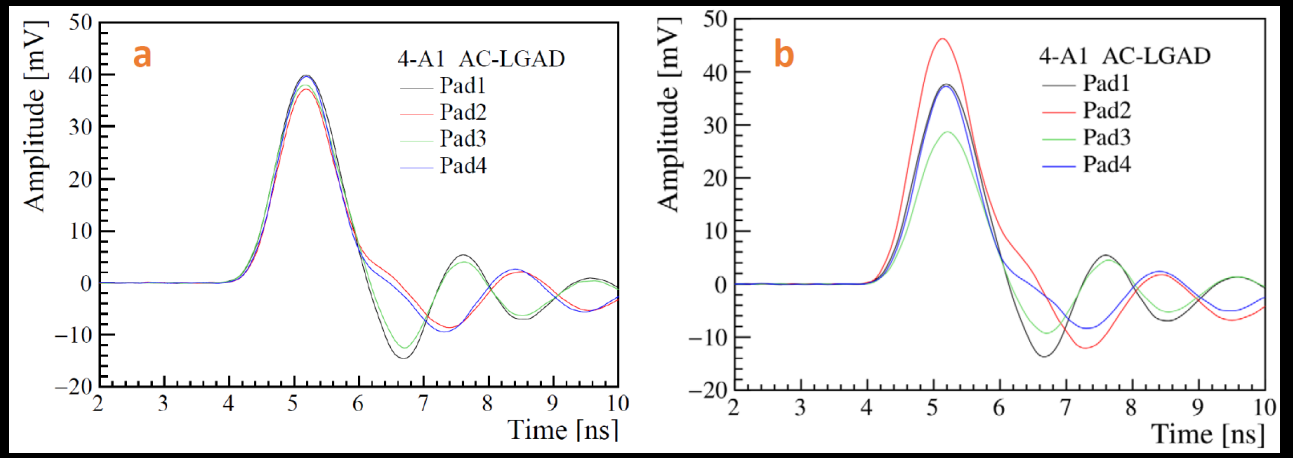
Area (m^2)	~ 70 m^2
Radius	1.8m
Length	5.8m
Granularity	70mm × 0.1mm ($10cm^2$，128channel/chip)
Channel number	~ 1×10^7 channels
MIP Time resolution	~50 ps
Spatial resolution	~ 10 μm (R-Φ) ~ 1 mm R-Z direction)
LGAD Sensor Area	14cm*14cm
Number of channels per module	2816 (22 chip，128channel/chip)

- 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.

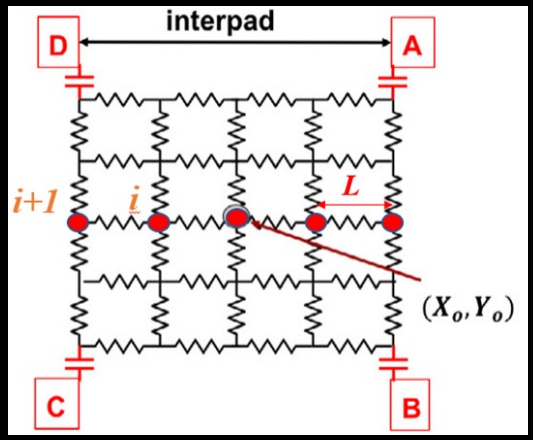
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

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

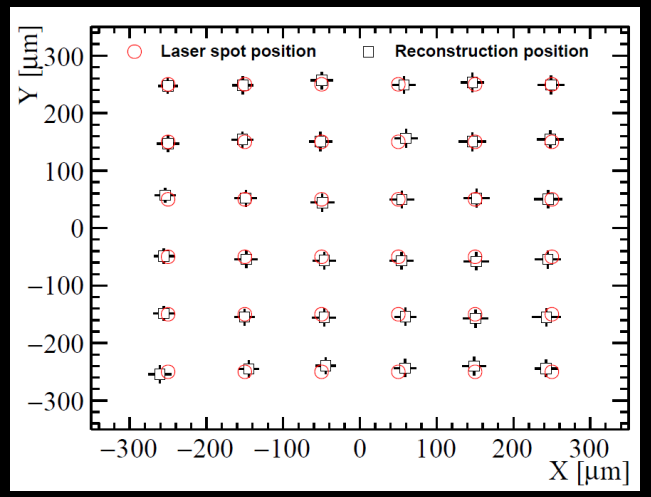




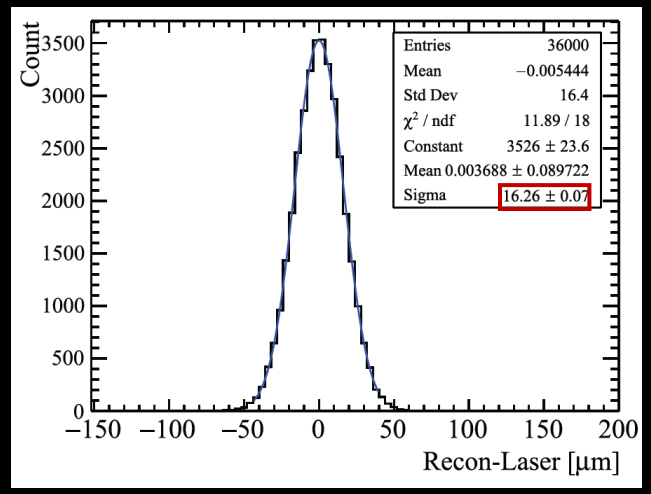
Signal Waveforms @ hit a and b



Discretized Positioning Circuit model (DPC)



Reconstructed 6x6 positions



Difference between reconstruction and laser

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

Spatial resolution

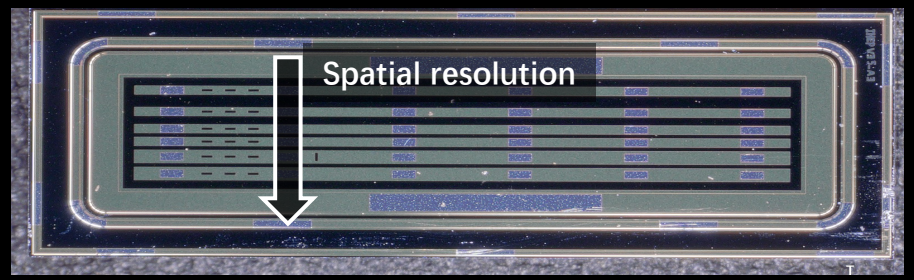
$16\mu m$ with 2mm x 2mm pitch

Spatial resolution :

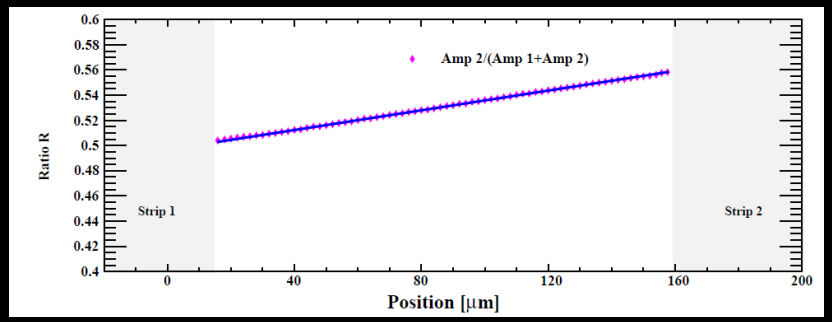
- the sigma of the difference between the laser and the reconstructed position

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

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



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

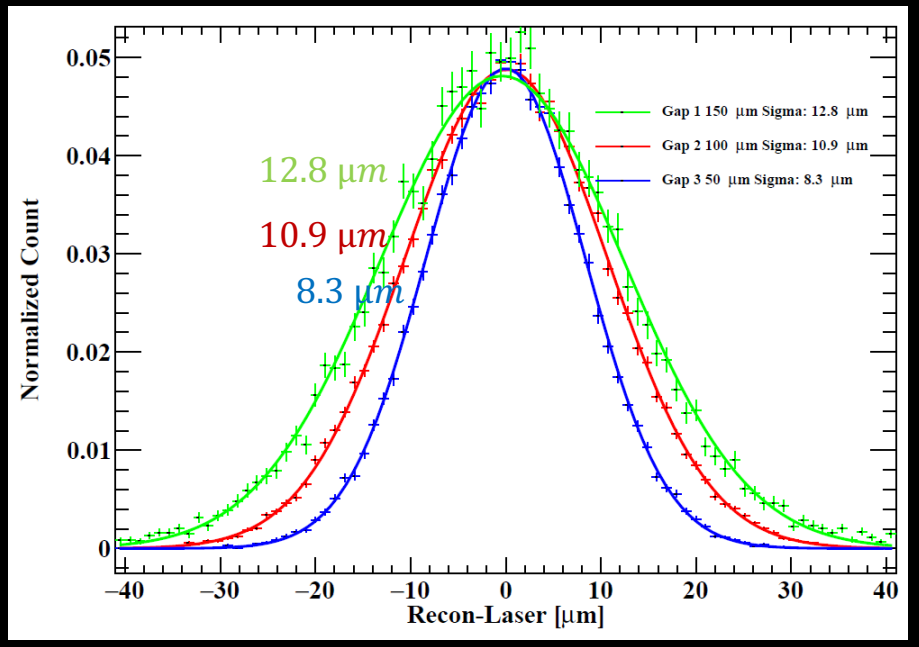


Linear distribution of R

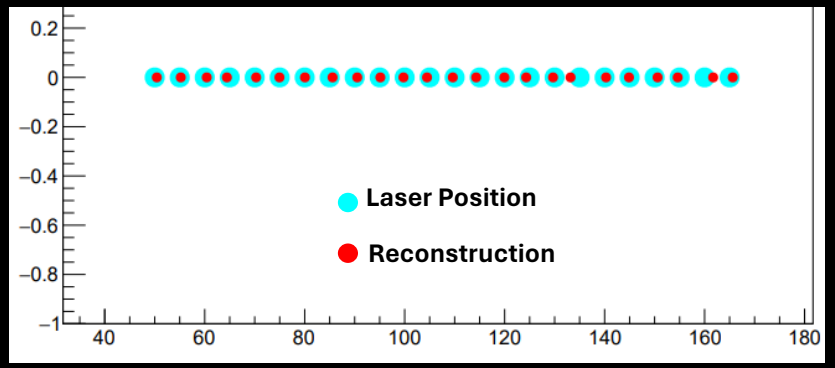
Spatial resolution：

8.3 μm

with 150 μm pitch



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



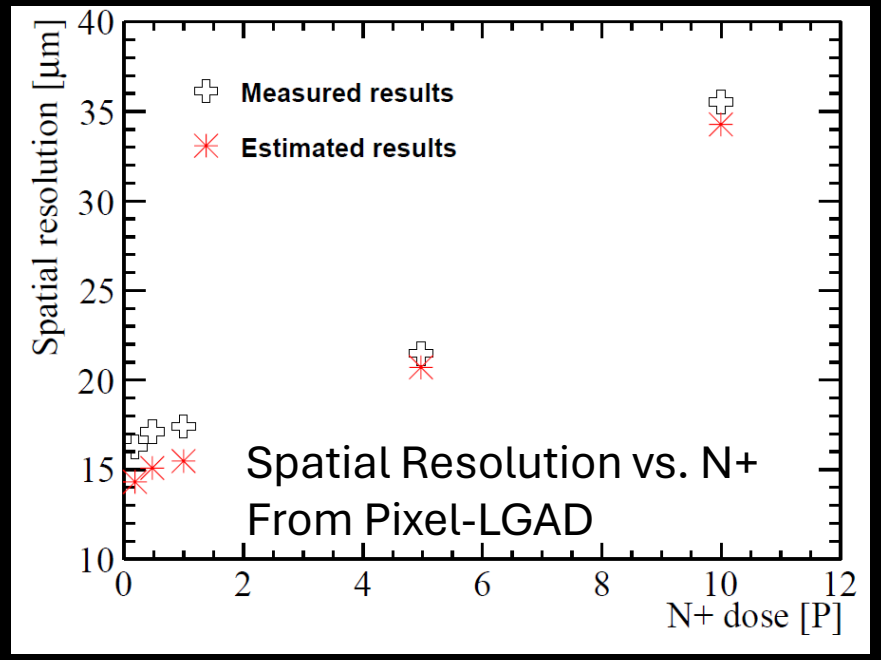
reconstructed positions

Position reconstruction:

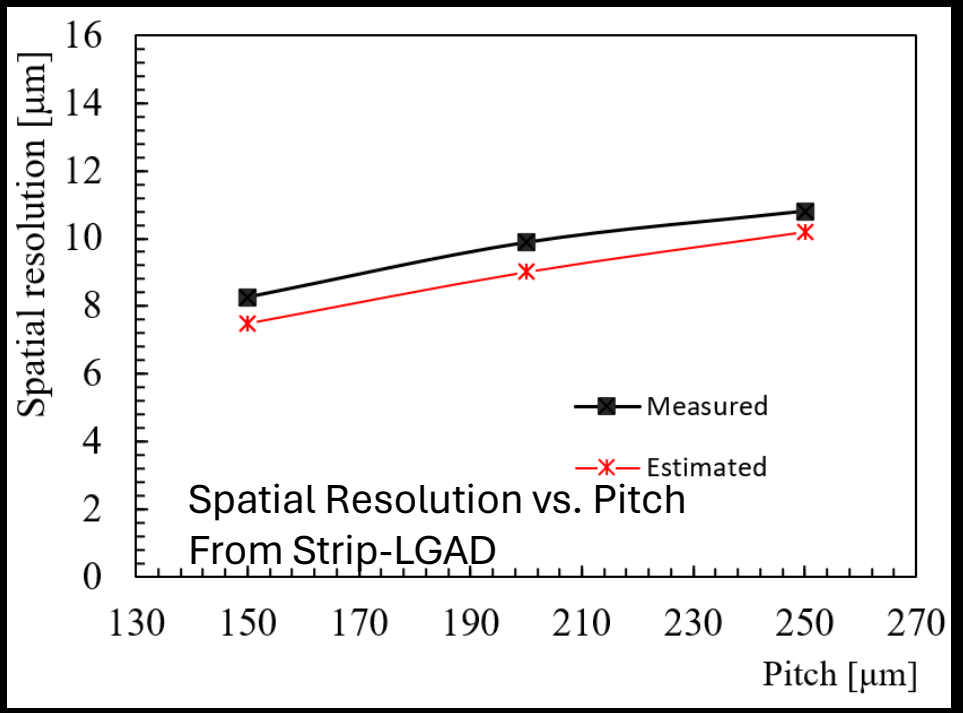
- The fraction of the signal (*R*) changes linearly with the movement of the laser.
  - Good consistency between the reconstruction position and the laser position
  - The smaller the pitch size, the better the spatial resolution

III Performance of AC-LGAD | Optimization

Spatial resolution Vs. N+ dose



Spatial resolution Vs. pitch size



Resolution estimation:

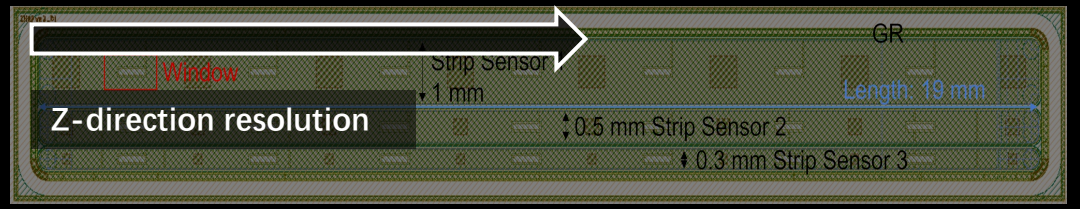
$$\sigma_{spatial} \approx \frac{N}{A}$$

A: signal attenuation factor

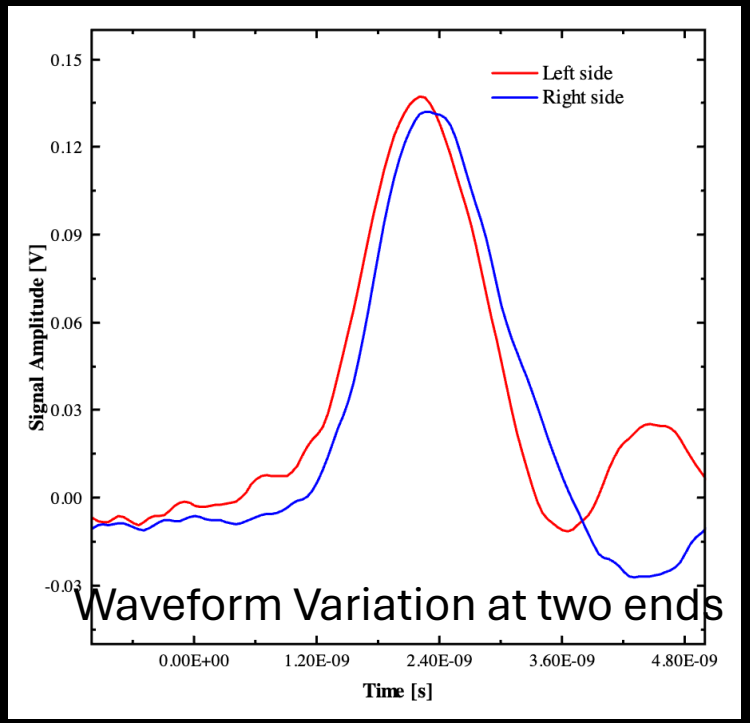
N: noise RMS (sensor + electronics)

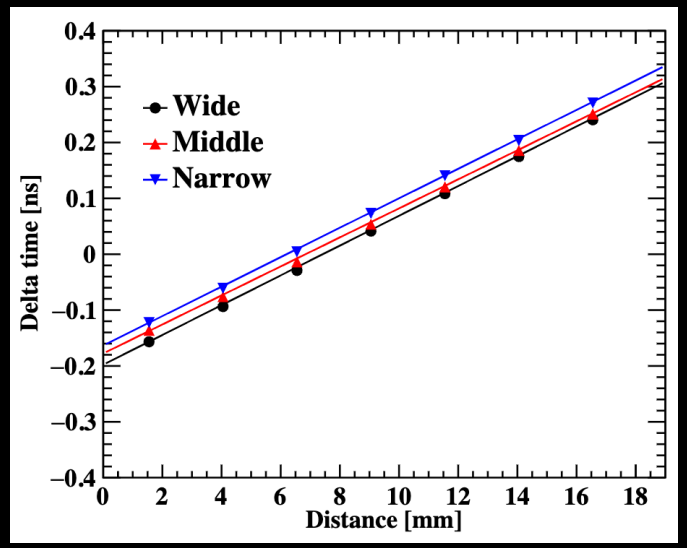
- N+ dose 10 P⟶0.2 P, spatial resolution 36 -> 16 μm (Pixel).
- **Lower N + dose** has higher resistivity and larger attenuation factor, ->**better spatial resolution**.
- Pitch size 250um ⟶ 150um,
  spatial resolution 11 -> 8 μm (Strip).
- **Smaller pitch sizes** result in faster signal attenuation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

III Performance of LGAD | Trial in Z-direction



Double-end Readout

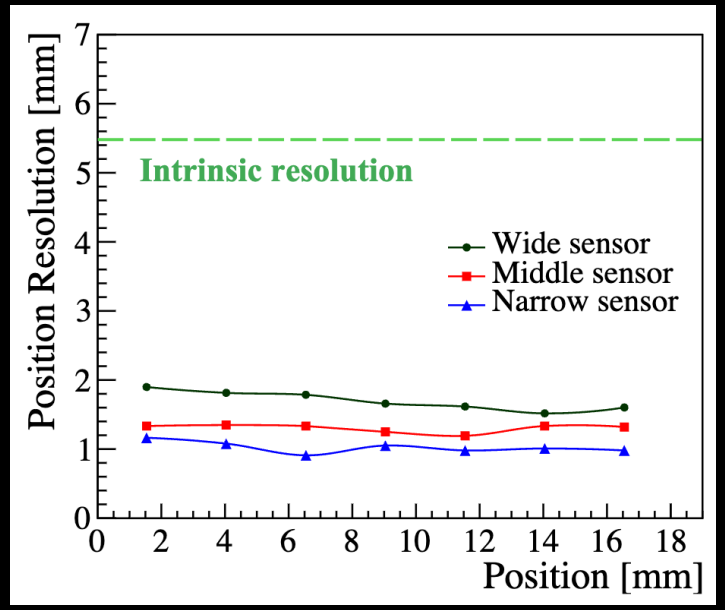




Position reconstruction:

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

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



Position resolution along Z

0.9 mm

Intrinsic: 5.5 mm

Total length: 19mm

Summary

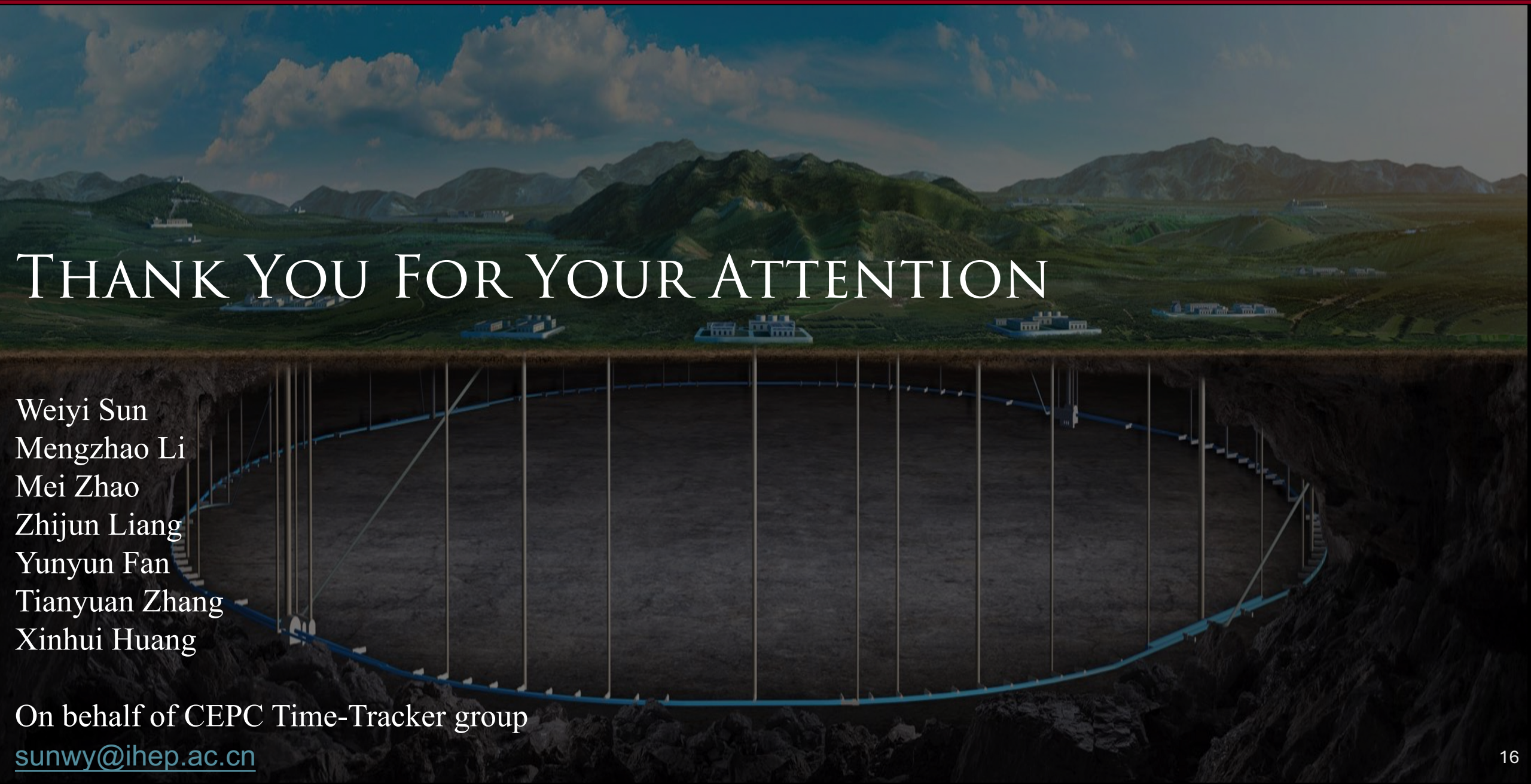
- AC-LGAD is a new 4D detector （position + time), pixel and strip are designed
- Strip AC-LGAD has been determined as the baseline scenario of CEPC Time-Tracker
- **The best spatial resolution of strips AC-LGAD ~8μm**
- **Jitte ~15 ps test by laser, time resolution 37.5ps test by beta source**
- **AC-LGAD 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	~ 1×10^7 channels
MIP Time resolution	~50 ps LGAD:37.5ps
Spatial resolution	~ 10 μm (R-Φ) LGAD:8μm ~ 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
- Oblique AC electrode
- Advanced algorithms for the reconstruction
- Ultra Low Noise Electronics
- CEPC Time-Tracker Reference-TDR Design
- ……



Thank You For Your Attention

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Mengzhao Li
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Zhijun Liang
Yunyun Fan
Tianyuan Zhang
Xinhui Huang

On behalf of CEPC Time-Tracker group
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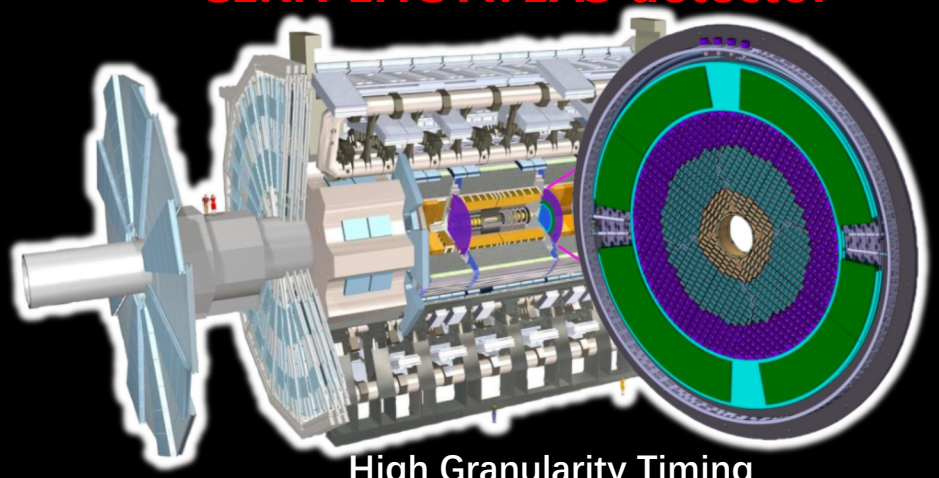
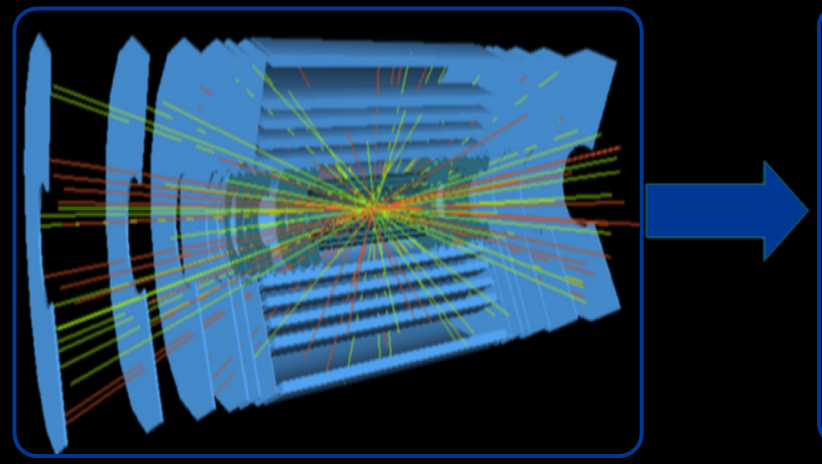
Motivation & HGTD

CERN LHC ATLAS detector

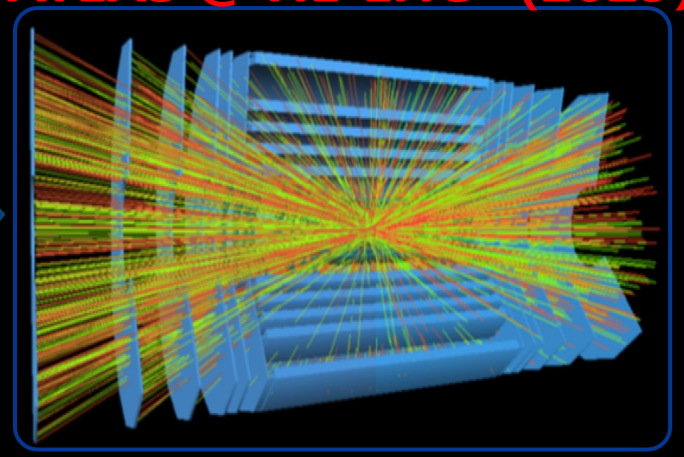


High Granularity Timing Detector (HGTD)

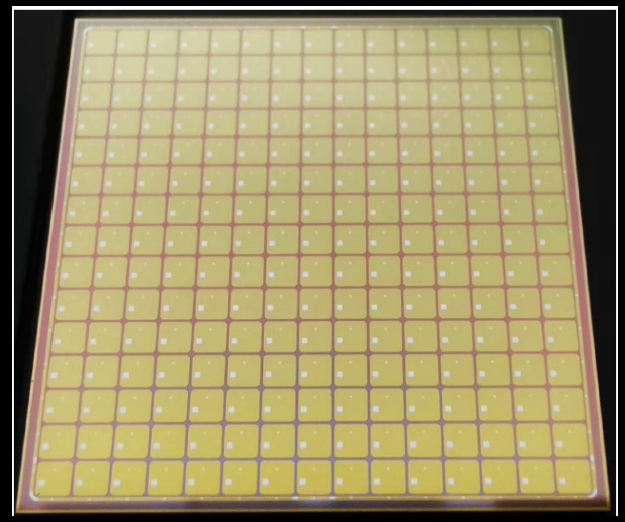
ATLAS @ LHC (Now)



ATLAS @ HL-LHC (2029)



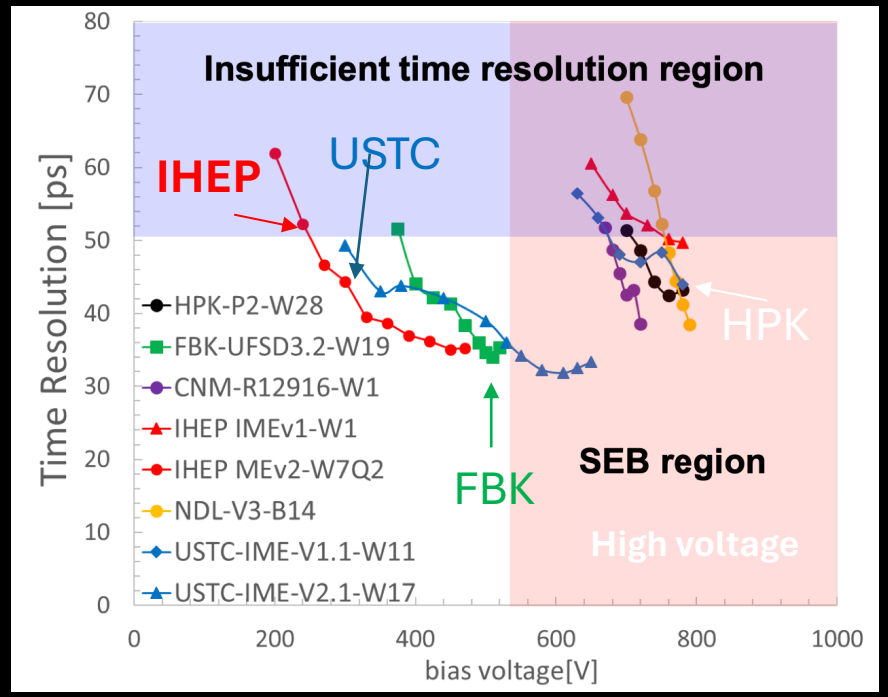
- The pile-up problem: High Time Resolution Devices
- **ATLAS High Granularity Timing Detector (HGTD)**
- **LGAD (Low-Gain Avalanche Diode)**
  - 15x15 LGAD sensors (2 cm×2 cm)
  - **Area 6.4 m^2, time resolution 30 ps**
  - Granularity ~mm, **readout channel > 3M**
  - **Irradiation fluence 2.5×10^{15} n_{eq}/cm^2**



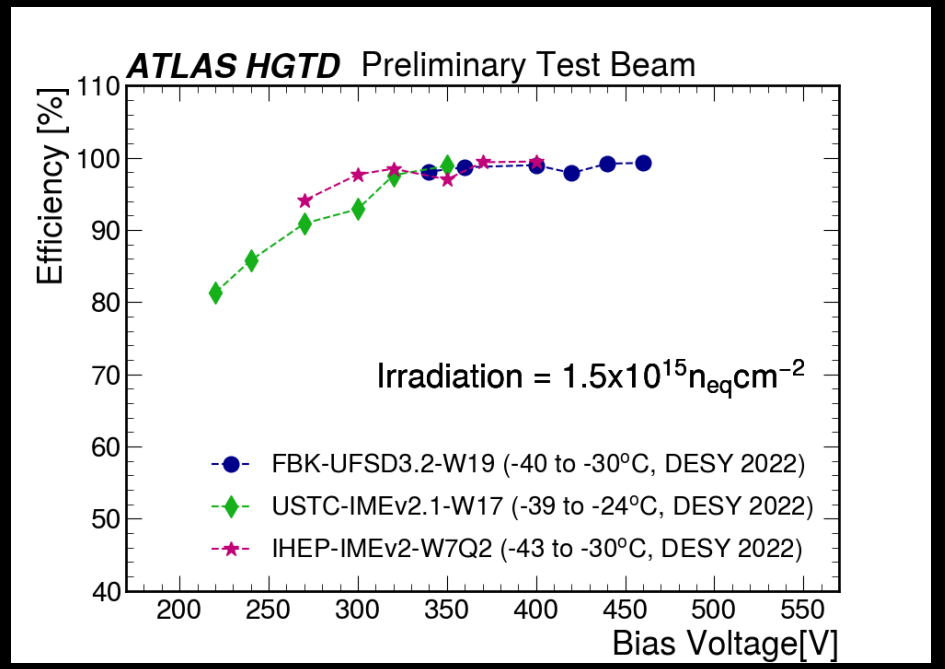
15x15 LGAD arrays for ATLAS HGTD

Performance of AC-LGAD | Irradiation Hardness

Time resolution @ **2.5×10^{15} n_{eq}/cm^2**

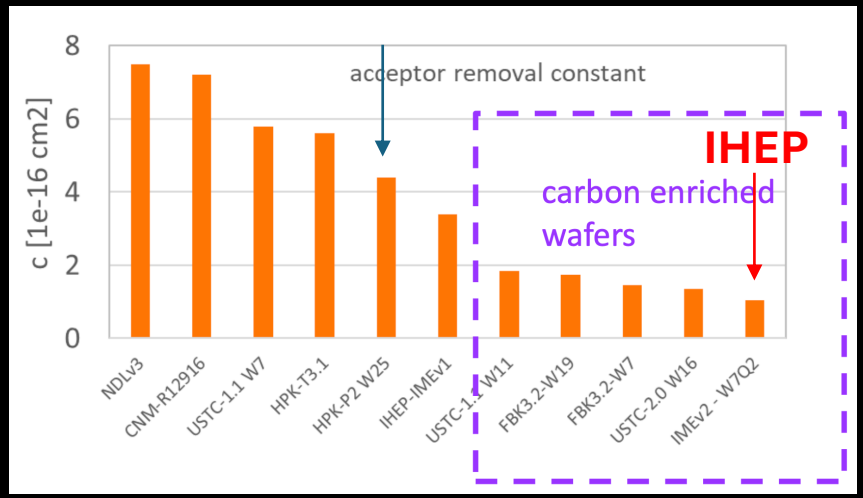


Efficiency >99% @ **2.5×10^{15} n_{eq}/cm^2**



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

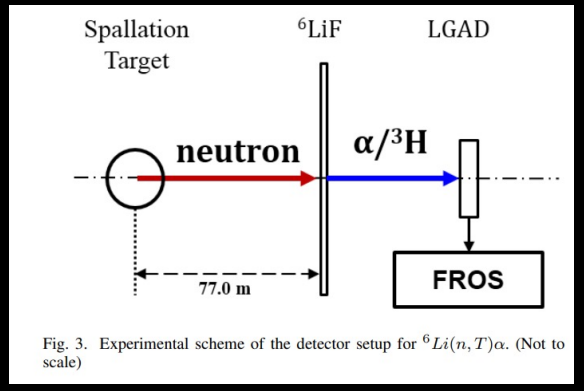


Fig. 3. Experimental scheme of the detector setup for $^6Li(n,T)\alpha$. (Not to scale)

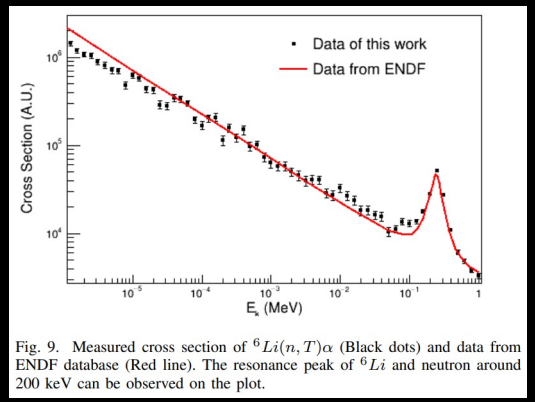
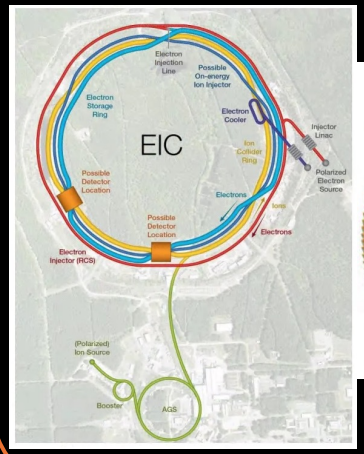
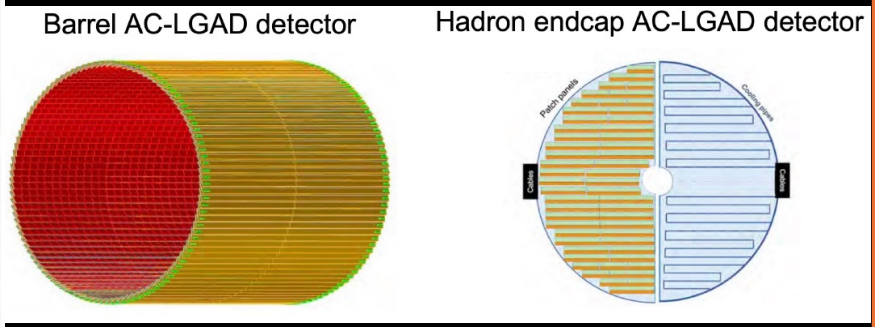


Fig. 9. Measured cross section of $^6Li(n,T)\alpha$ (Black dots) and data from ENDF database (Red line). The resonance peak of ^6Li and neutron around 200 keV can be observed on the plot.

Electron-Ion Collider (EIC): Timing-tracker

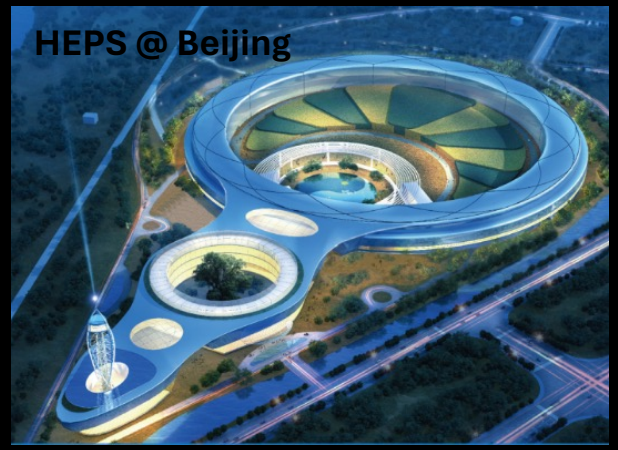


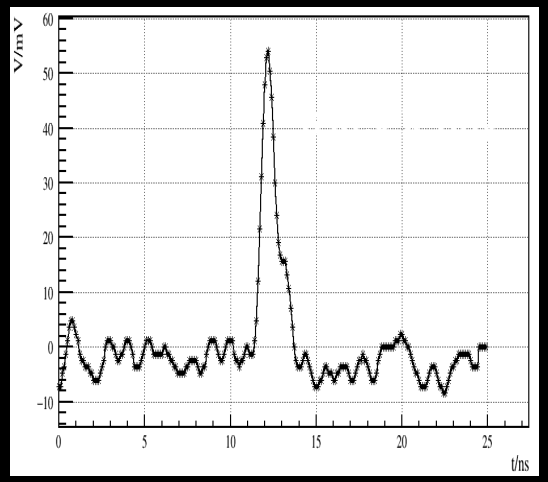


10.9 m^2

2.22 m^2

X-ray detectors @ advanced light sources



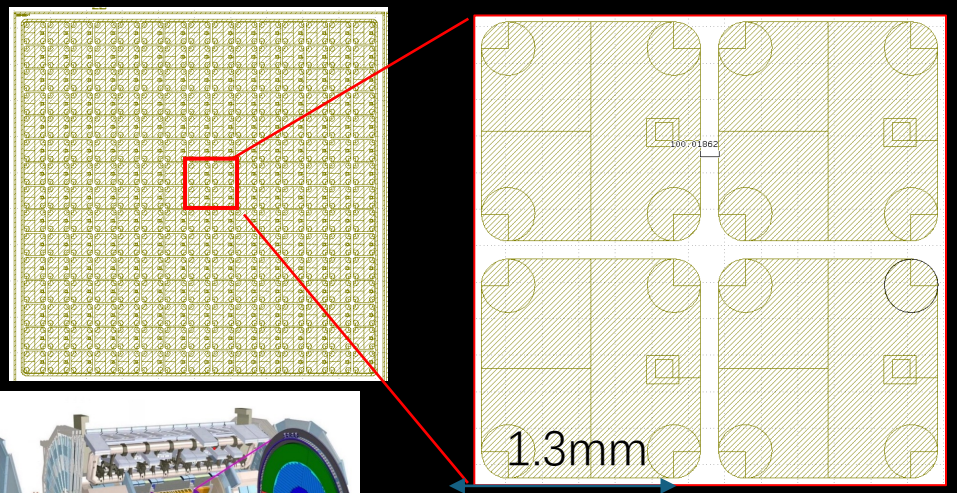


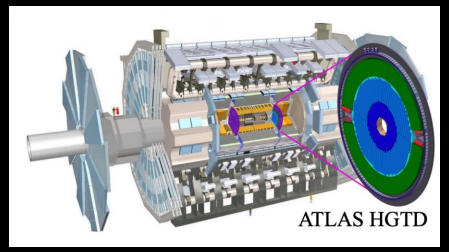
other applications

- 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

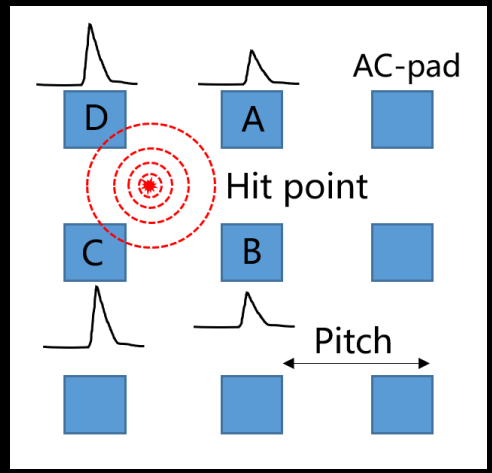


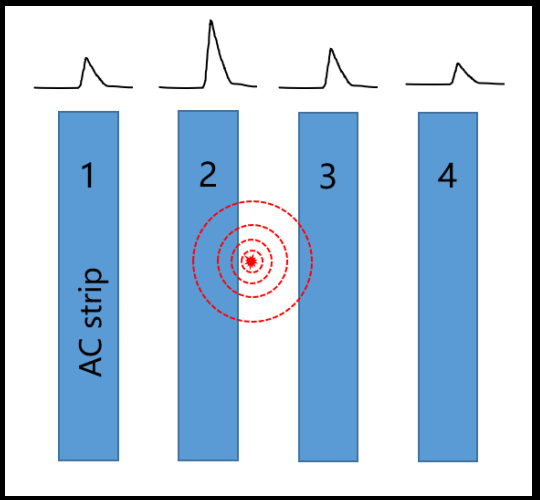


- Dead zone : ~0.1mm
- Pixel size: 1.3mm

Smaller Pixel LGADs -> Lower fill factor

AC-LGAD：two layout schemes for AC-pads





Pixels AC-LGAD:

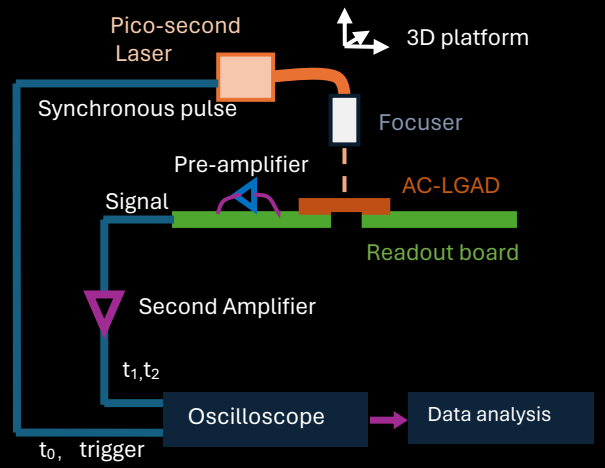
- Position information: 1 layer (x,y)
- Bump bonding

Strips AC-LGAD:

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

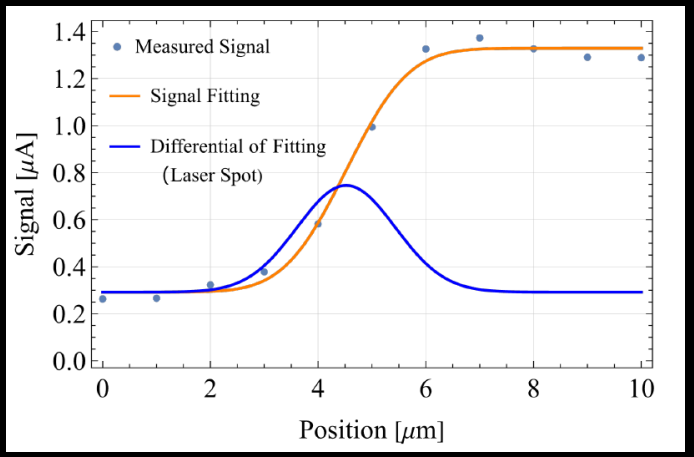
Spatial resolution
Timing resolution
Irradiation Hardness

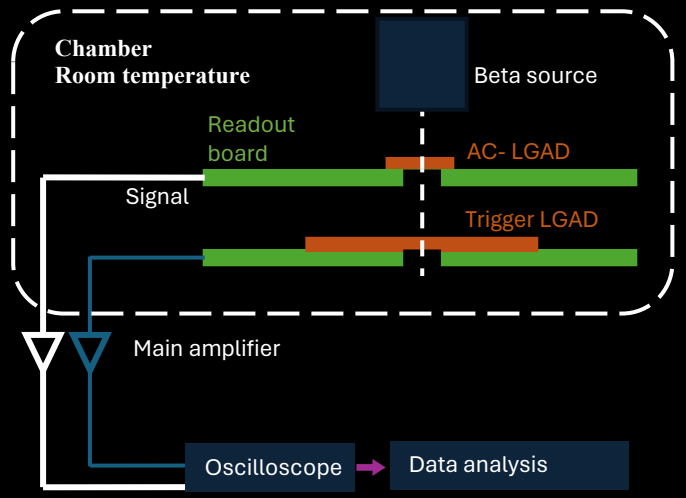
Performance of AC-LGAD | Test Platform



Picosecond laser scanning system

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





Beta Source Telescope

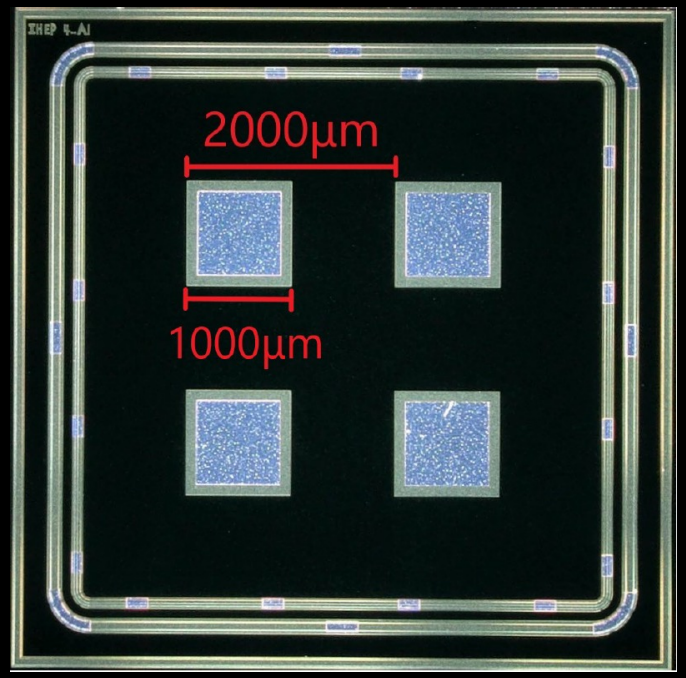
AC-LGAD sensors development by IHEP

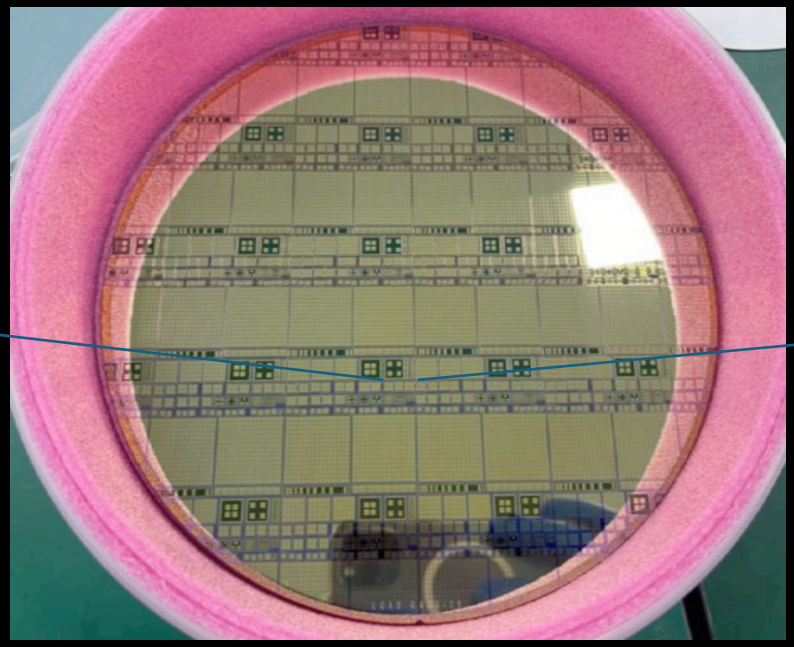
Pixels AC-LGAD：

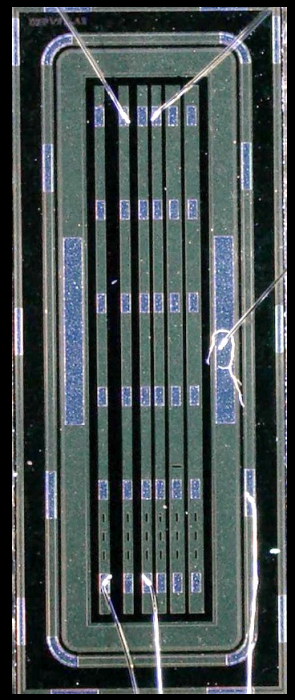
- Position information： 1 layer
- Pitch size 2000um, pad size 1000um

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