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# 大型强子对撞机上ATLAS 实验高颗粒度时间探测器

梁志均

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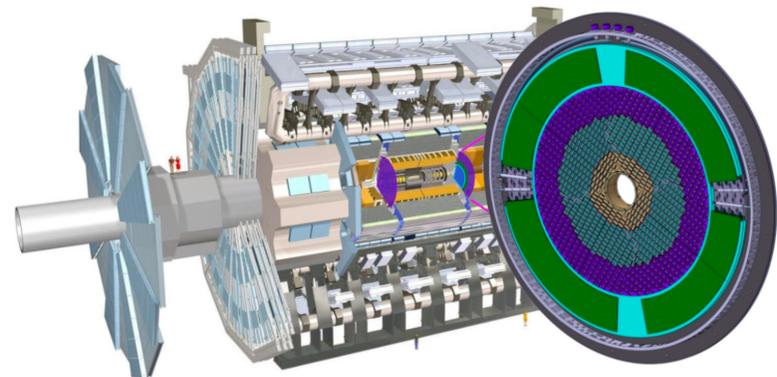
Zhijun Liang (IHEP)

中国物理学会高能物理分会第十四届全国粒子物理学术会议(2024)

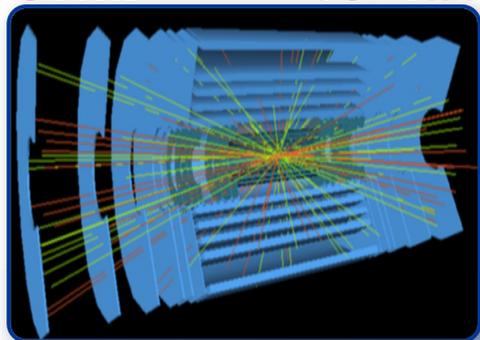
# High Granularity Timing Detector (HGTD)

## ATLAS实验高颗粒度时间探测器

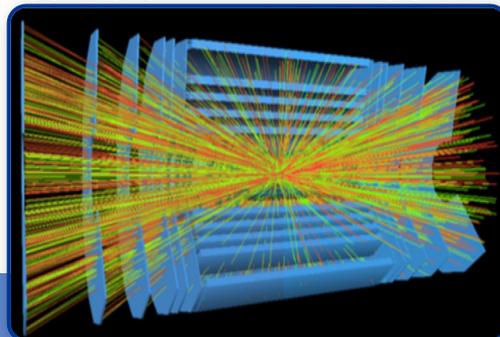
- 把粒子到达时间的测量精度提高2个数量级（数纳秒→30皮秒）
- 解决高亮度LHC对撞事例堆积问题
  - 6.4平方米的硅探测器，30皮秒的时间分辨
  - 毫米级的颗粒度，超过三百万个读出通道
  - 能承受 $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ 的等效中子通量的辐照
- 中国组主导探测器研制
  - 45%探测器组装（34% 高能所，11%科大）
  - 100%抗辐照高时间分辨传感器（90% 高能所-微电子所，10%科大-微电子所）
  - 100%前端电子学（高能所，南大），50% ASIC晶圆测试（高能所，山大，科大）
  - 34%柔性电路尾板（山大），>16% 高压电子系统（山大，高能所）



目前的ATLAS探测器



高亮度LHC升级后的ATLAS探测器



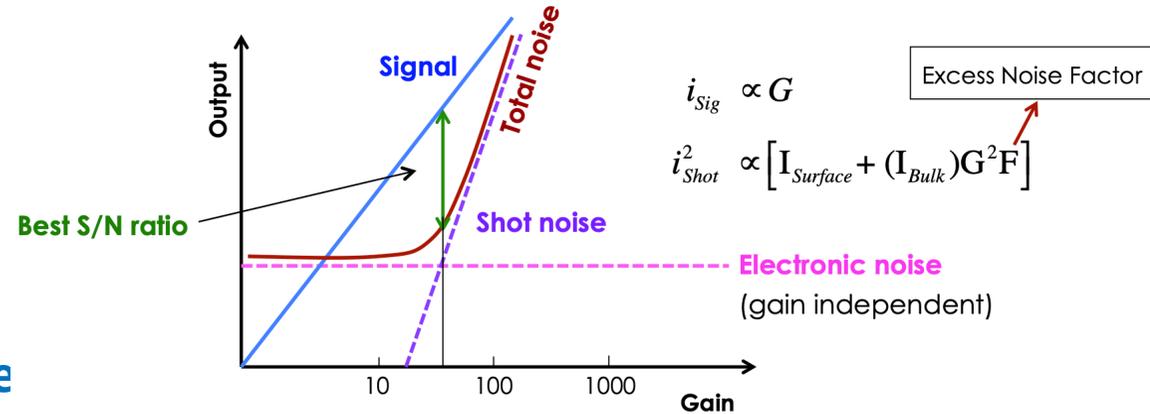
# Low Gain Avalanche Detectors (LGAD)

## 低增益雪崩硅传感器

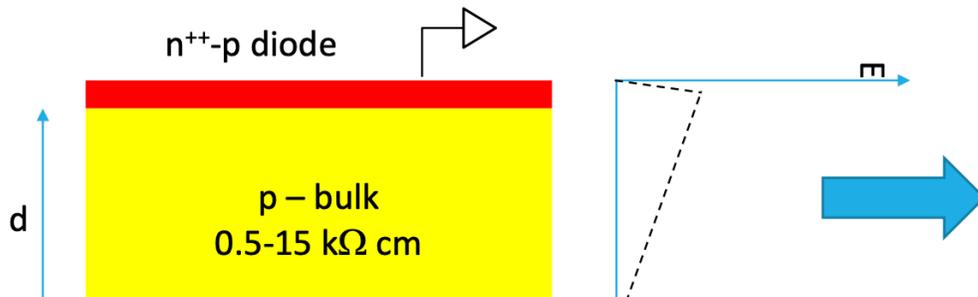
- LGAD是近年出现新型硅传感器，可以高精度测量时间（20-30皮秒）
- 与APD 和 SiPM比较, LGAD has 适中的增益 (~50)
- 信噪比高，无自触发
- 减薄耗尽区，提高电子漂移速度

$$\sigma_{jitter}^2 = \left( \frac{t_{rise}}{S/N} \right)^2$$

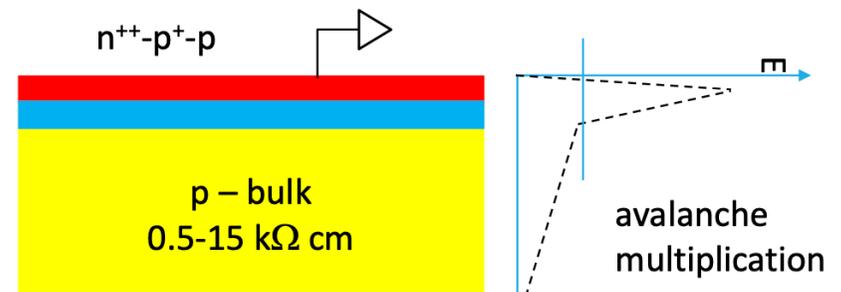
- Modest gain to increase S/N
- Need thin detector to decrease



一般的 PiN结传感器

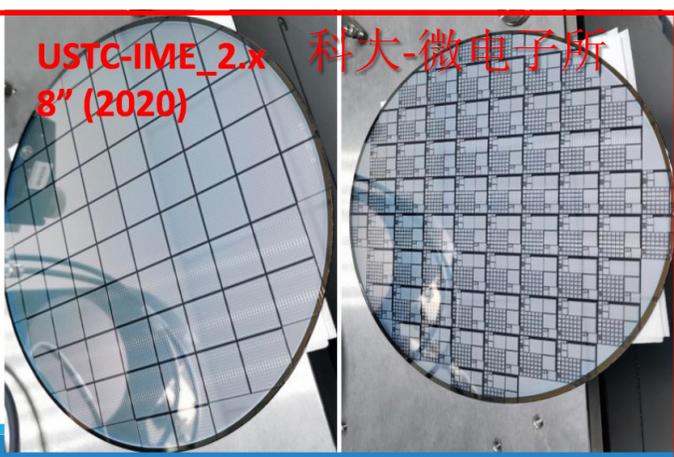
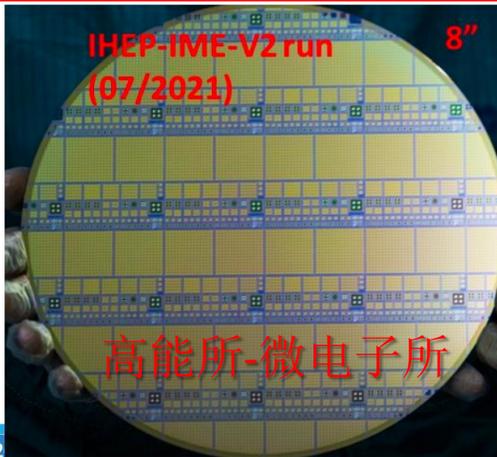
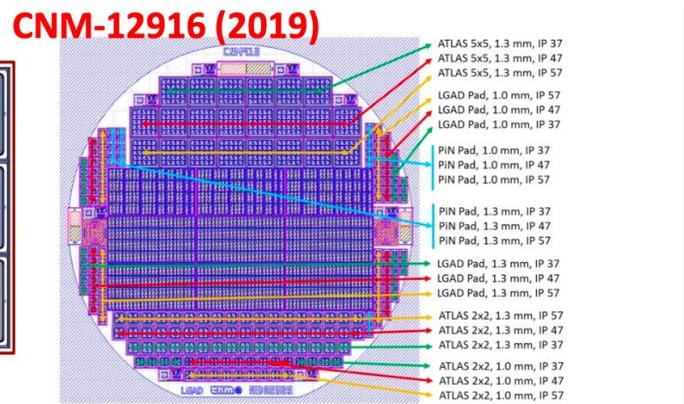
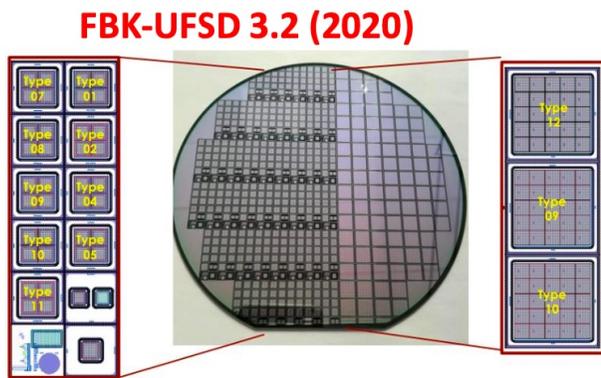
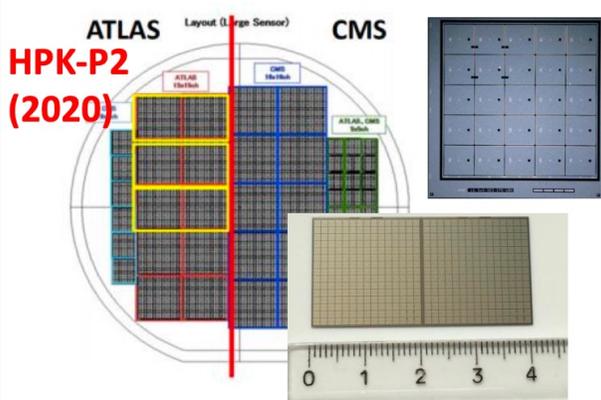


低增益雪崩硅传感器  
P+ gain layer on top of PIN diode



# LGAD低增益雪崩硅传感器：国内外形势

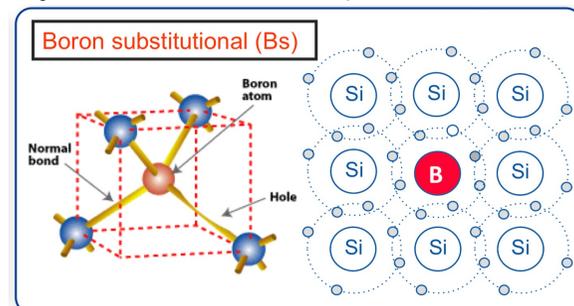
- 近年来，全世界范围涌现出很多研制LGAD硅传感器的单位
  - 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(高能所-北师大)
  - 国际：滨松HPK (Japan) , FBK (意大利), CNM (西班牙) ...
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片



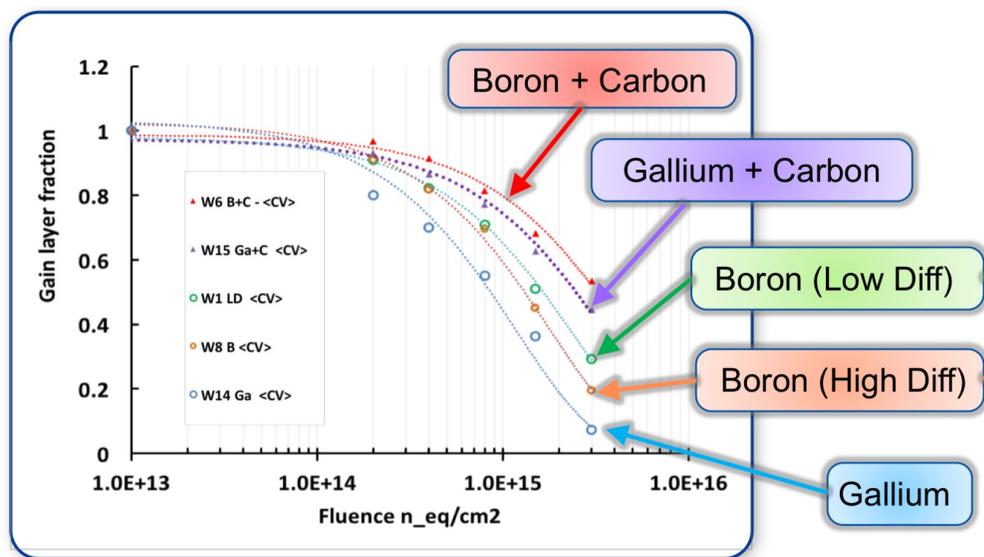
PLANAR TECHNOLOGY – more vendors (e2V, BNL, Micron ...)

# LGAD传感器辐照后硼掺杂移除 (Acceptor removal)

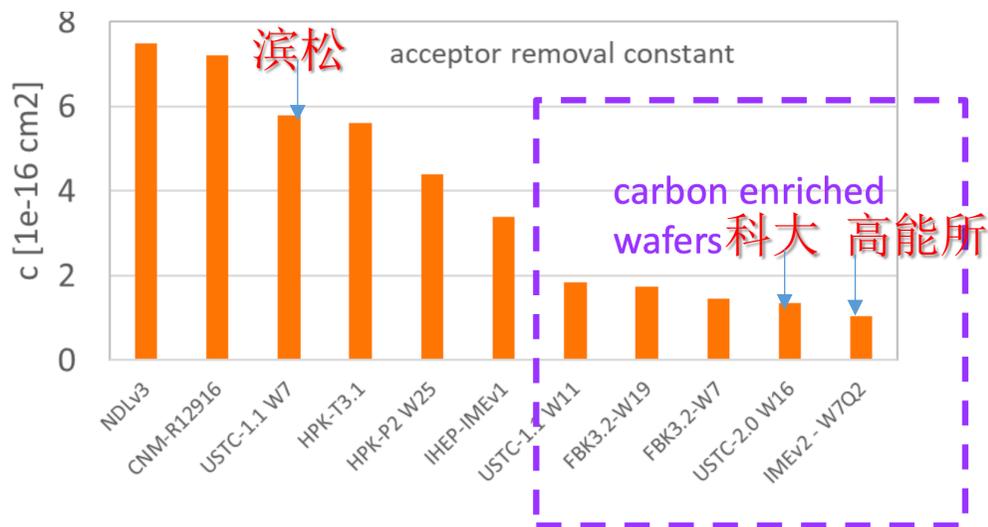
- 辐照后，硼掺杂失去活性，LGAD传感器增益下降(Acceptor removal)
- 高能所、科大等国产LGAD采用掺碳工艺
  - 显著减低辐照后损伤（减低硼移除率）
  - 抗辐照性能显著提高
  - 目前抗辐照性能优于滨松



高能所传感器、科大研发传感器  
目前移除率最低（最佳抗辐照性能）



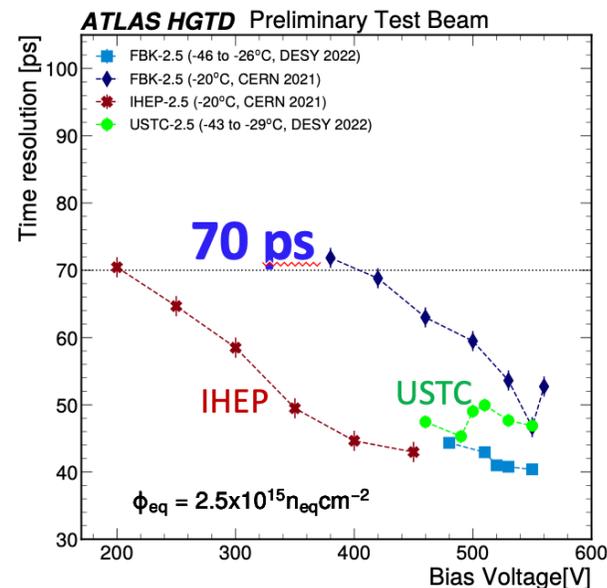
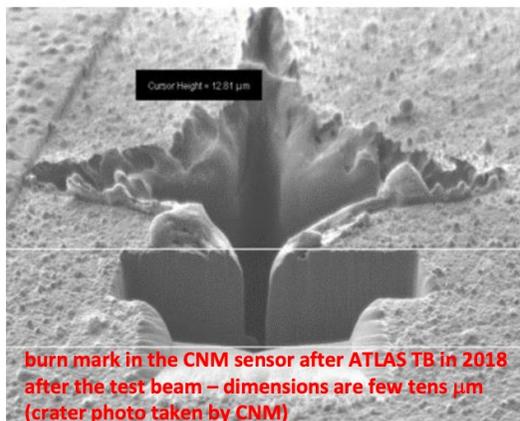
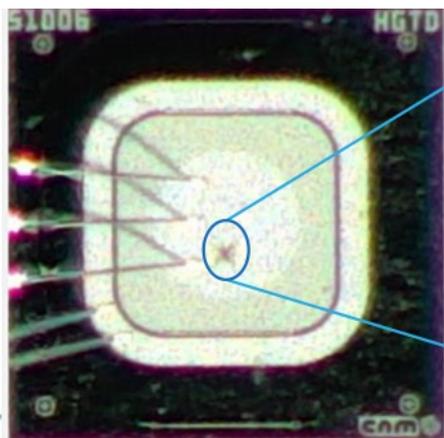
[G.Paternoster, FBK, Trento, Feb.2019]



# 硅传感器的单粒子烧毁风险 Single Event Burnout (SEB)

- RD50, CMS and ATLAS 合作组在2021年确认LGAD的单粒子烧毁风险
- 高电压与高电场导致烧毁，工作电压要控制到<550 V（50微米的硅传感器）
- ATLAS合作组开展欧洲核子中心（CERN）的高能质子流测试
  - 辐照后，不掺碳的LGAD（滨松，西班牙CNM）烧毁率较高
  - 国产掺碳的LGAD基本能通过测试（高能所，中科大），无烧毁
    - 在 $2.5 \times 10^{15} n_{eq}/cm^2$ 的强辐照下，时间分辨率仍达到40皮秒

## 单粒子烧毁后LGAD（滨松/CNM）

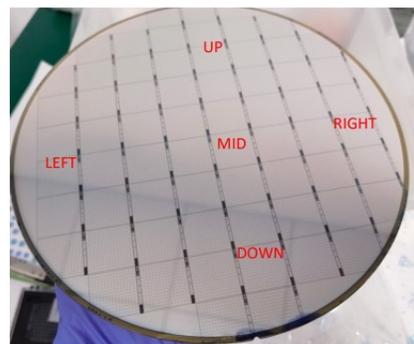
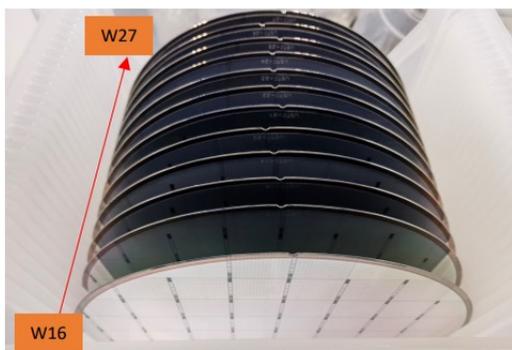


# LGAD传感器的量产

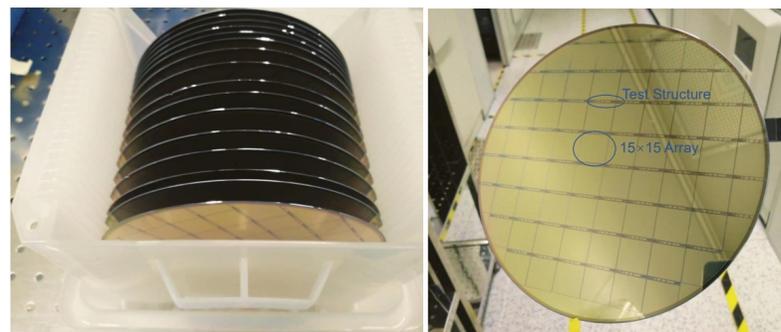
详见赵梅的报告

- 2023年高能所-微电子所赢得CERN的LGAD招标订单（>1.5万个传感器）
  - 在日本滨松、意大利FBK等竞争下，高能所-微电子所赢下招标
  - 欧洲核子中心（CERN）首次采购中国产的硅传感器
  - 象征着国产硅传感器国际地位显著提升
- 各单位在该项目LGAD传感器的贡献比重
  - 高能所-微电子所：90%（66% CERN采购+ 24%实物贡献）
  - 中科大-微电子所：10%实物贡献

中科大-微电子所LGAD预生产

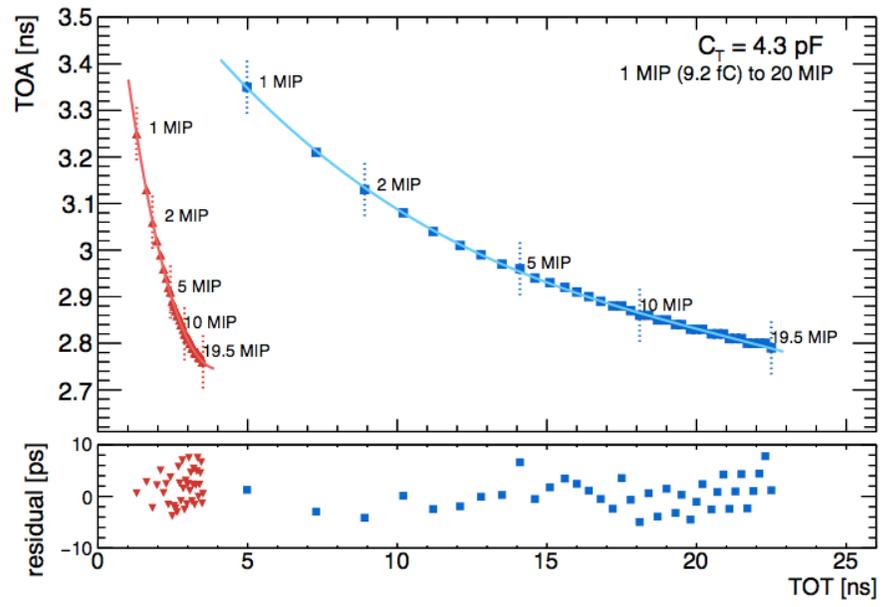
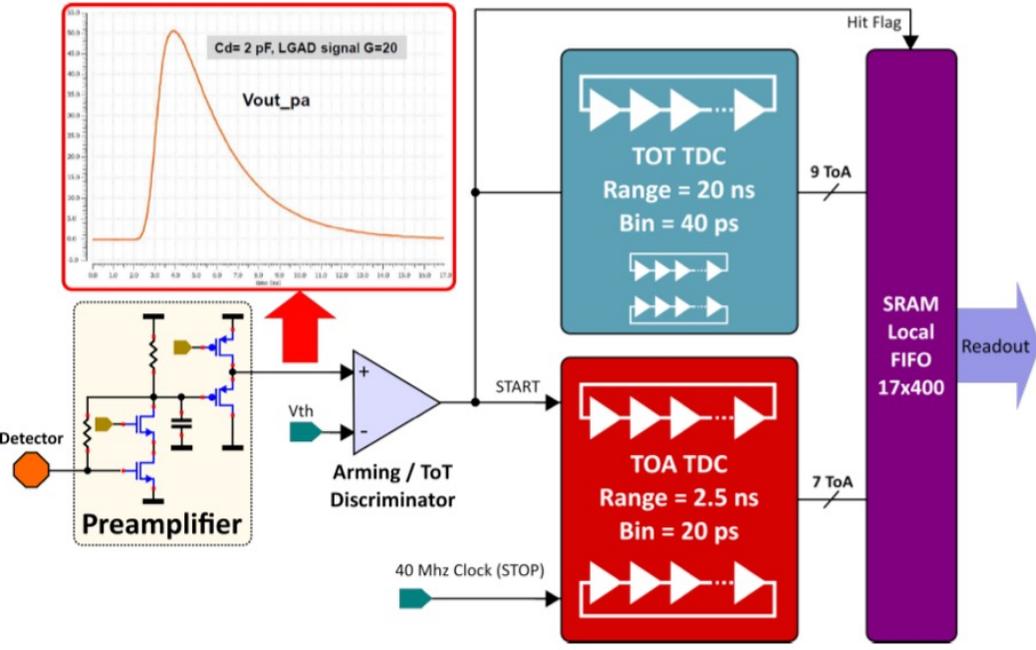
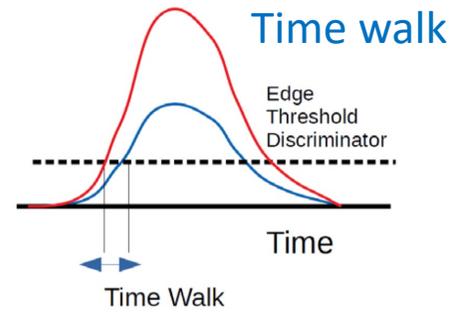


高能所-微电子所LGAD预生产



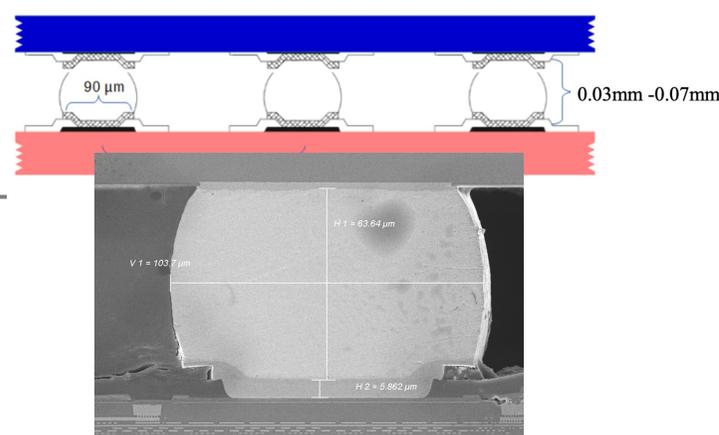
# ALTIROC : 超快读出ASIC

- ATLAS时间探测器研发超快读出ASIC芯片，多个单位参与
  - 高能所参与ASIC中数字电路部分的设计，承担50%的晶圆测试
- 225通道，每个通道有一个前端放大器，甄别器，两个TDC:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of **2.5 ns** and a bin of **20 ps** (7 bits)
    - Time Over Threshold (TOT) : range of **20 ns** and a bin of **40 ps** (9 bits)
  - One Local memory: to store the 17 bits of the time measurement until L0/L1 trigger (~ 1 MHz)



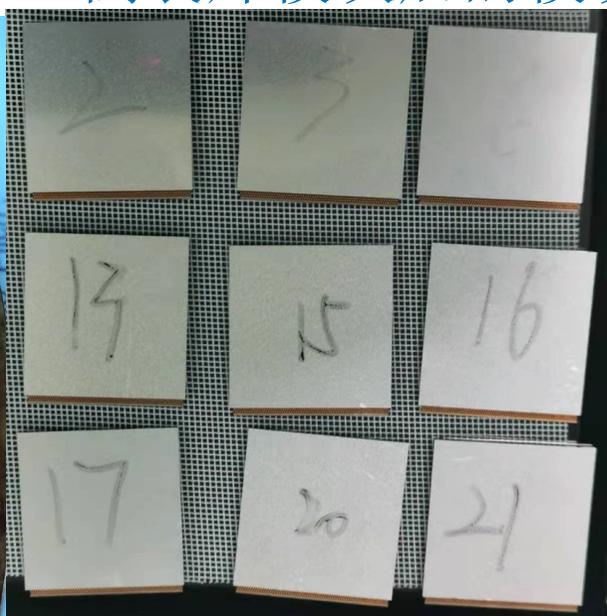
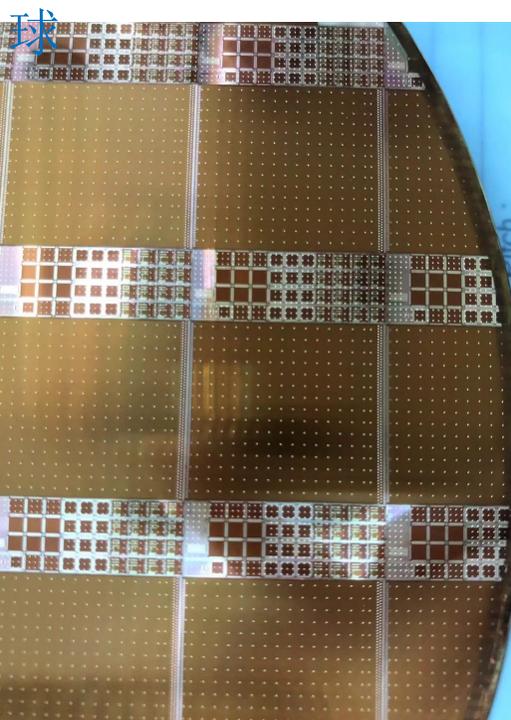
# 探测器模块：倒装焊封装

- 高能所承担项目中**50%**的倒装焊封装任务
- 高能所在国内已经研制出**200+**倒装焊模块
  - ALTIROC读出芯片 + 高能所-微电子所LGAD

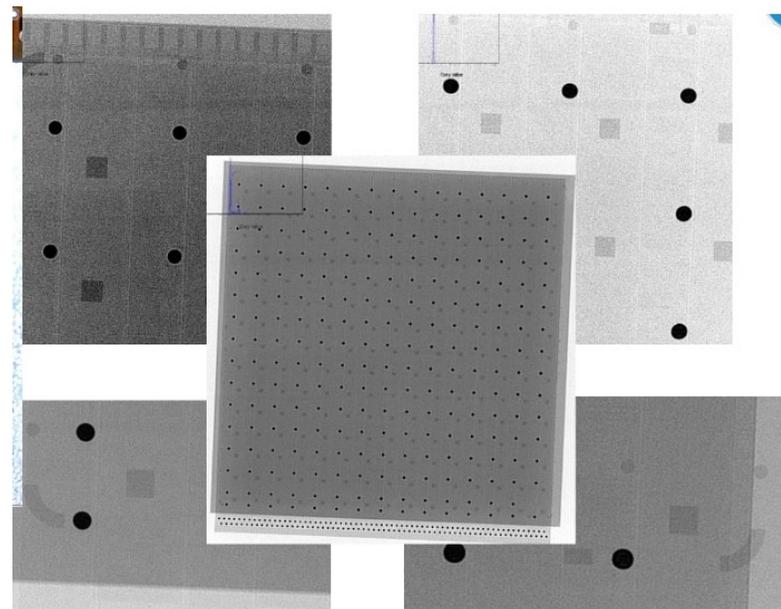


ALTIROC2 芯片晶圆植

倒装焊模块后的模块



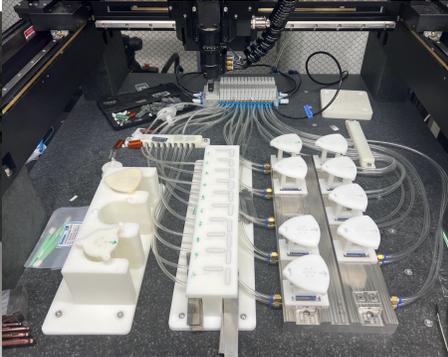
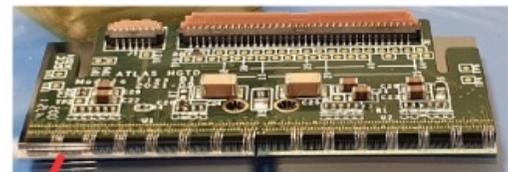
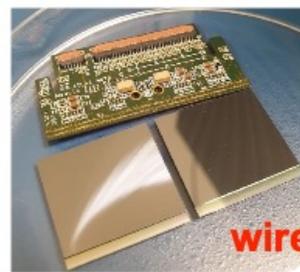
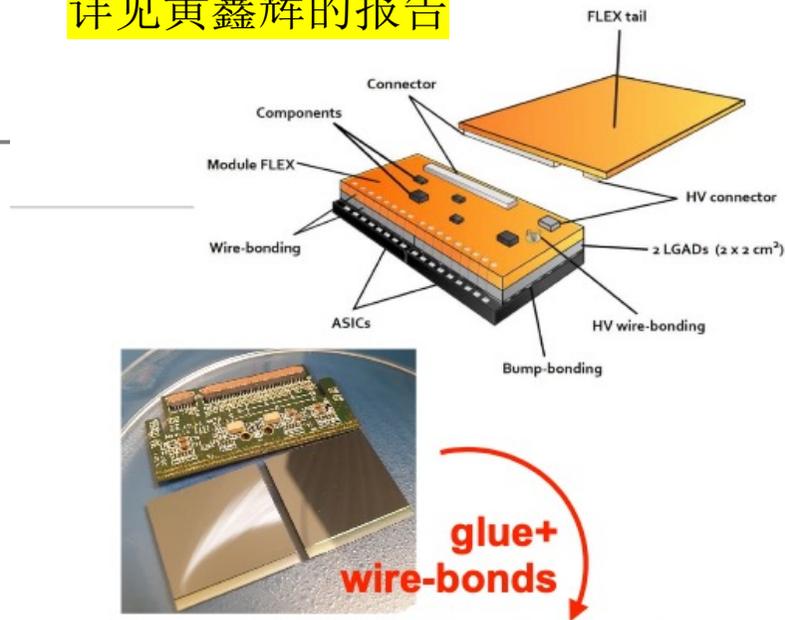
X-ray image of full-size hybrid



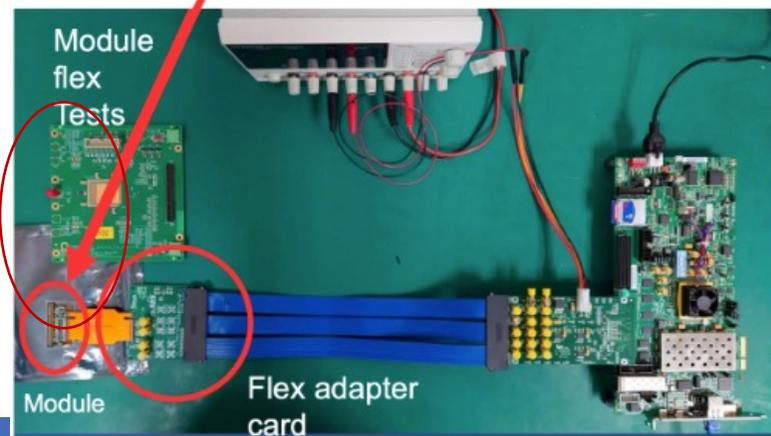
# ATLAS时间探测器模块组装

详见黄鑫辉的报告

- HGTD项目总共需要8032个探测器模块
- 6个模块组装生产中心
  - 高能所，科大，德国，法国，西班牙，摩洛哥
  - 高能所是最大的生产中心，组装34%的模块
  - 中科大承担10%的模块组装
- 高能所与国内公司研制国产自动组装系统
  - 有高分辨图像系统，做芯片图像识别
  - 自动芯片组装、点胶
  - 位置组装精度达到微米级



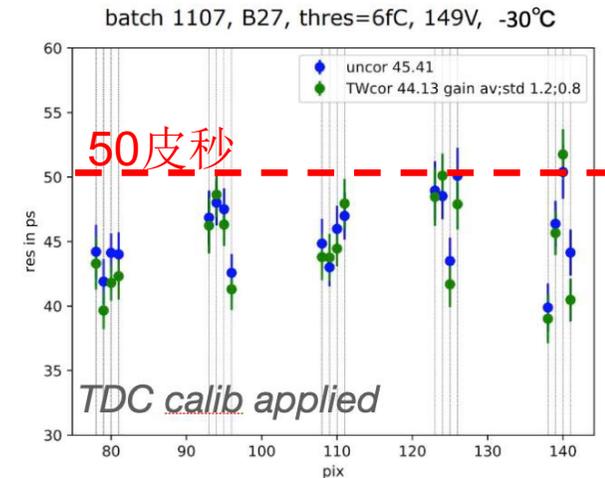
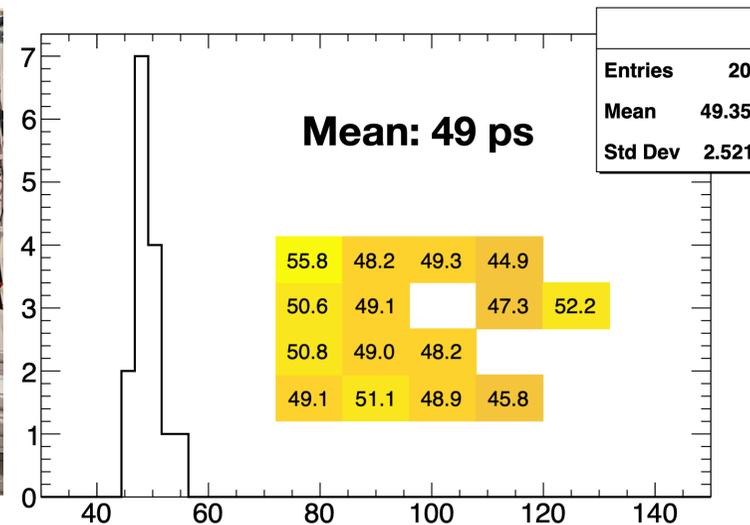
Picking tool    Picking dummy sensor    Placing dummy sensor    Picking flex



# 探测器模块级别的测试

- 探测器模块级束流测试

- 用高能所预生产的LGAD与ALTIROC3芯片
- 多个通道同时实现好于50皮秒的时间分辨
- 未来数年，ATLAS时间探测器将实现350万像素同时实现50皮秒的时间分辨率



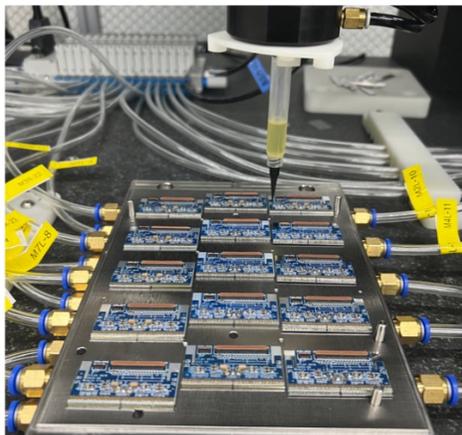
~45 ps after calibration  
and time walk correction

# ATLAS时间探测器模块组装

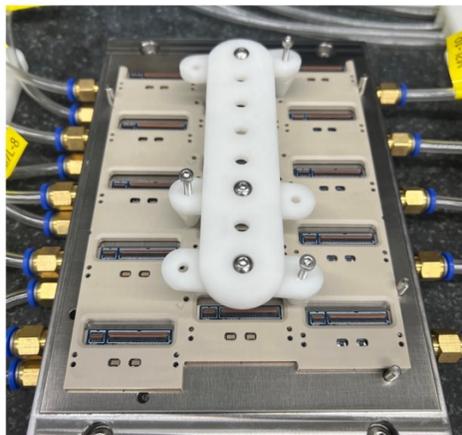
详见黄鑫辉的报告

- 高能所研制第一个 基于高能所LGAD+ALTIROC3 芯片的探测器单元
  - 用自动组装机器人，实现大面积多模块的组装与点胶

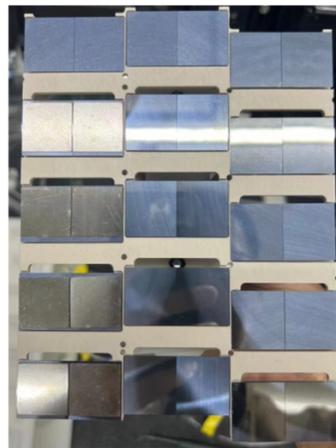
Dispensing with GluingTool



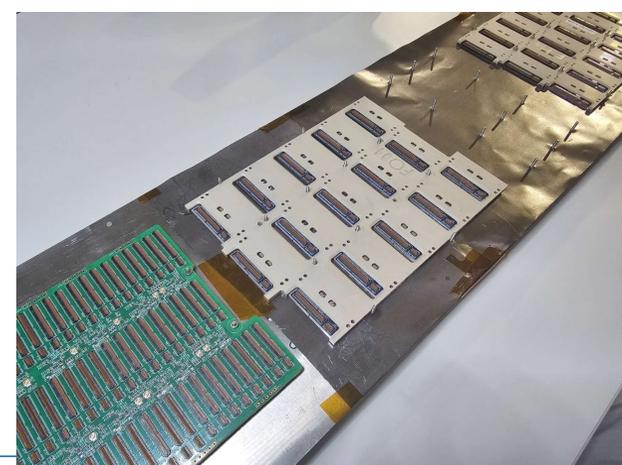
Put the support unit



Backside view after removal

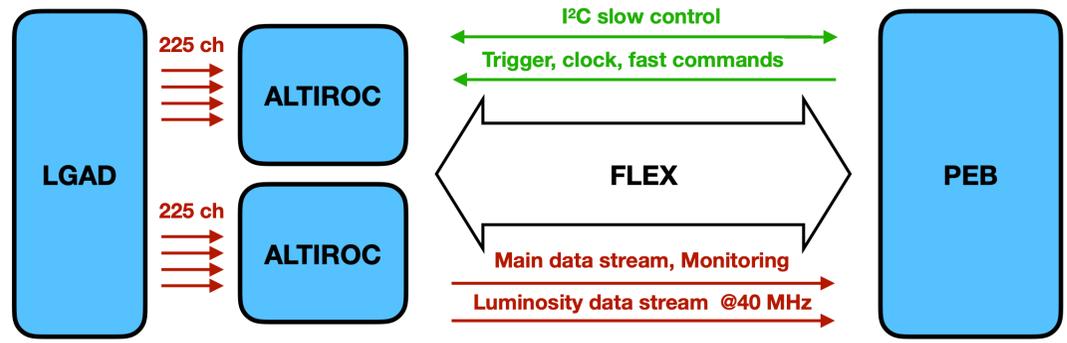


Detector unit shipped to CERN

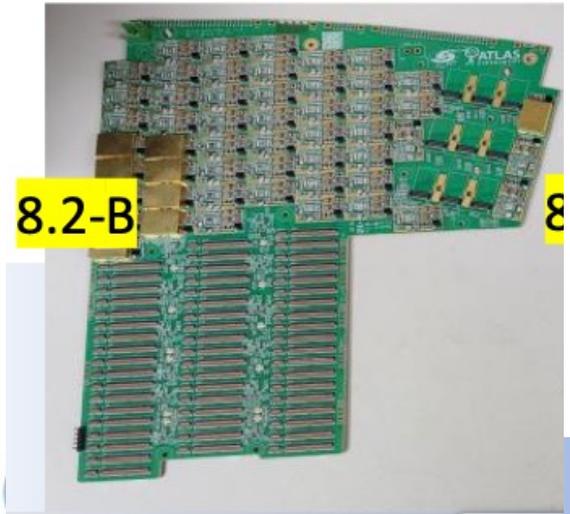


# 时间探测器电子学系统

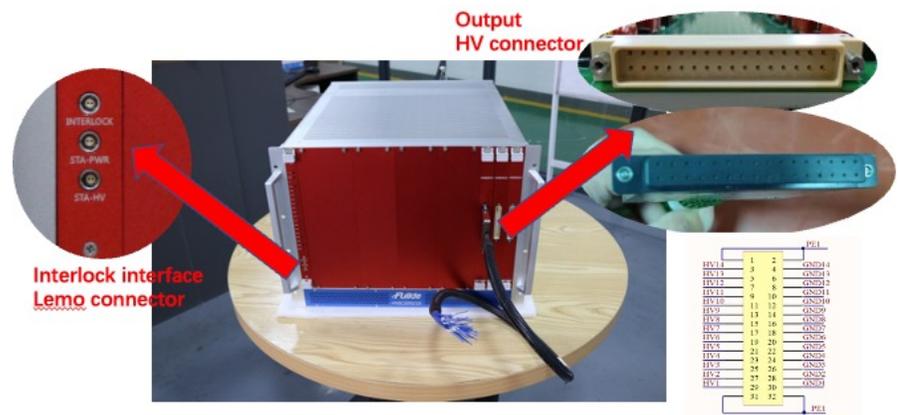
- 高能所与南大负责前端电路板的研发
- 山大负责研发超长的柔性电路尾板 (~75cm)
- 高能所、山大研发高压系统



Modular Peripheral Electronics Boards prototype



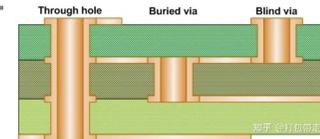
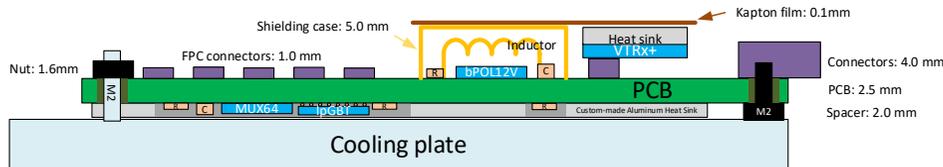
High voltage power supply prototype



Long Flex tail prototype (75cm)



# 前端电路板研制

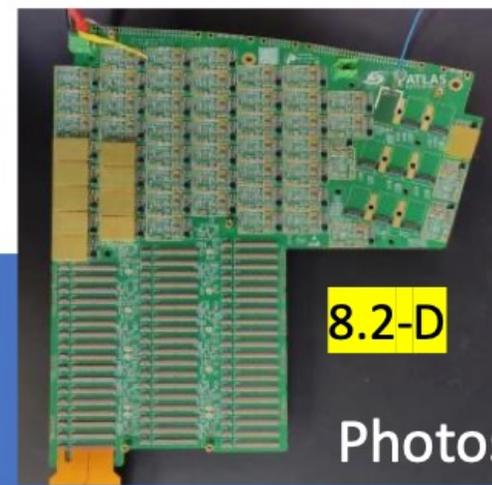
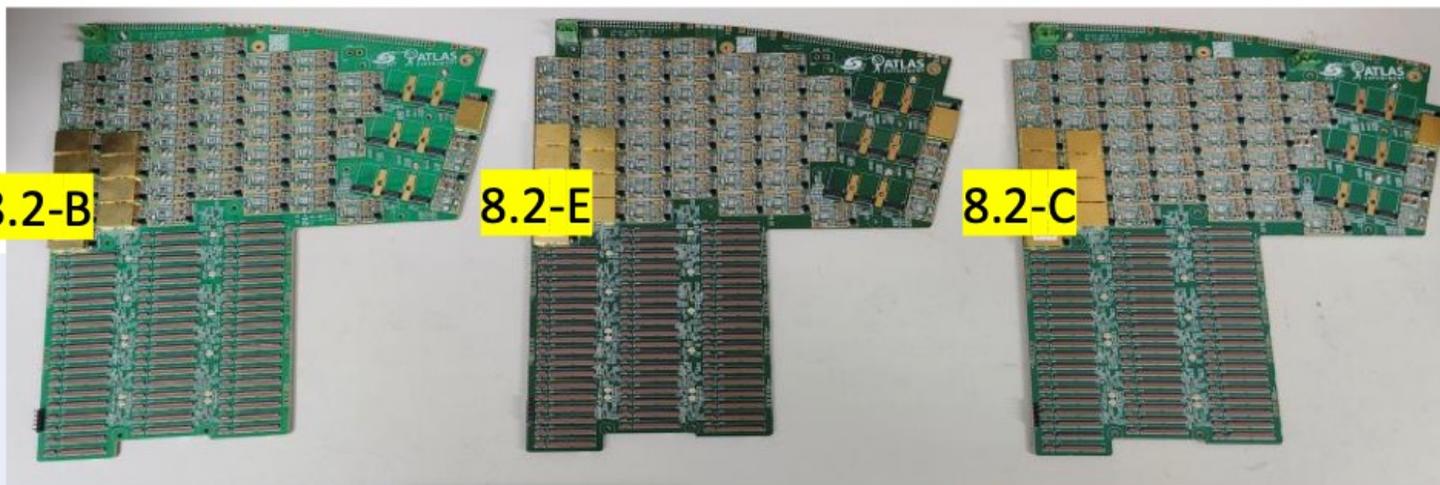


## 挑战

- 不规则形状的22层电路板，三千多器件，一万多个焊点
- 集成多个高速数据传输与电源模块，需要同时与数十个模块通讯
- 欧洲核子中心在 2023年对LHC升级项目P2UG评审意见
- **It is comparable with the most difficult boards manufactured for HEP projects**

## 最新进展

- 高能所与南大完成第一个前端电路板样机设计
- 南大与国内4个公司合作，都分别研制出前端电子学板的样机



Photos

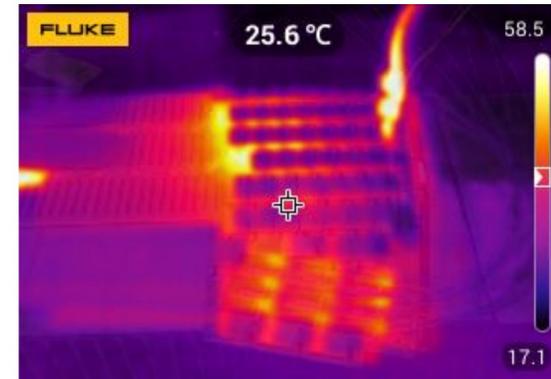
# 时间探测器系统级测试系统

- 高能所和南大在探测模块与系统级电子学系统调试中发挥重要作用
  - 张杰（高能所）、葛振武（南大）主导HGTD时间探测器系统级测试
  - 首次实现数十个模块的系统级电子学读出与校准

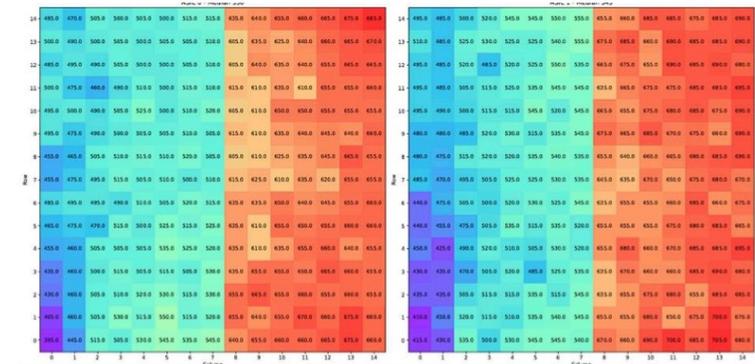


HV, LV, Cooling plate prototype

Electronics : PEB 1F + flex tails + 54 modules mounted on 4 support units (detector unit)



With 20 thermal emulators



Module threshold scan obtained in demonstrator test

# 高压电源系统

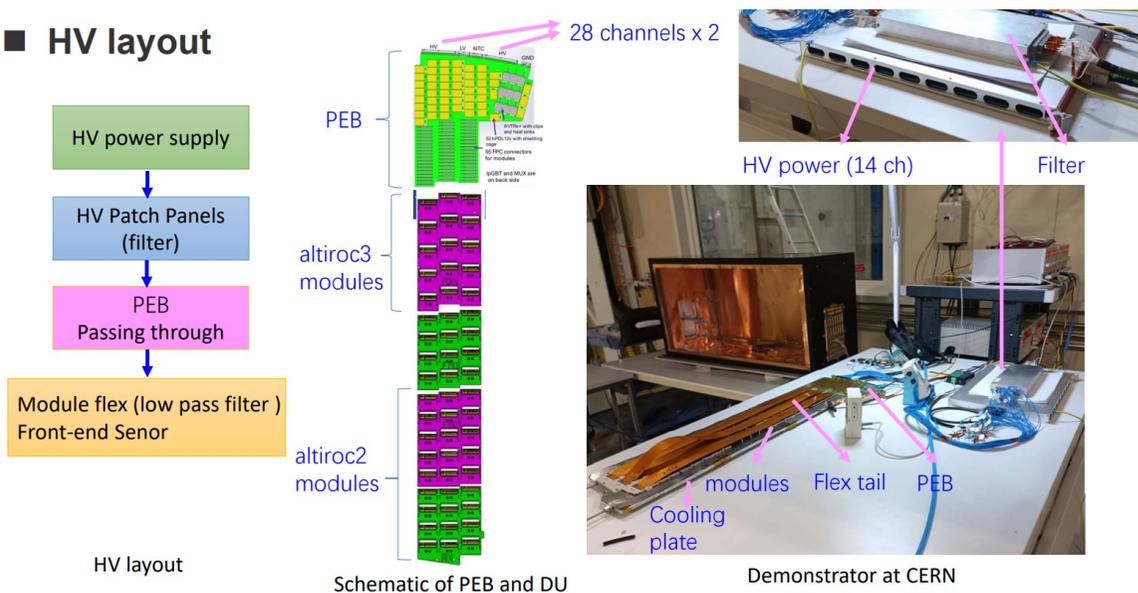
## 挑战:

- 高压电源系统对漏电流测量精度达到百纳安级，需要8000多路独立高压系统
- 1000V级别的高压，100nA级别高精度漏电流检测
- 面临CANE等国际公司的强力竞争

## 最新进展

- 高能所、山大与国内公司合作研制高压电源，优化漏电流监测部分的电路
- 主导ATLAS实验HGTD项目电子学设计，测试不同接地方案对探测器的影响

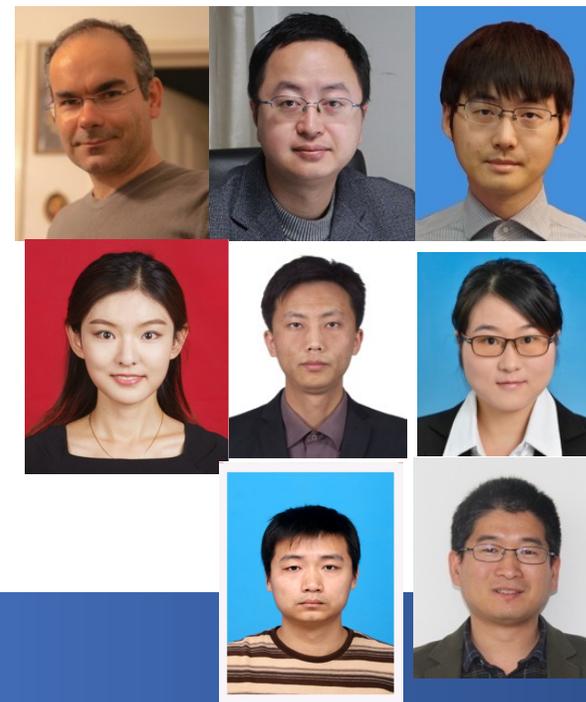
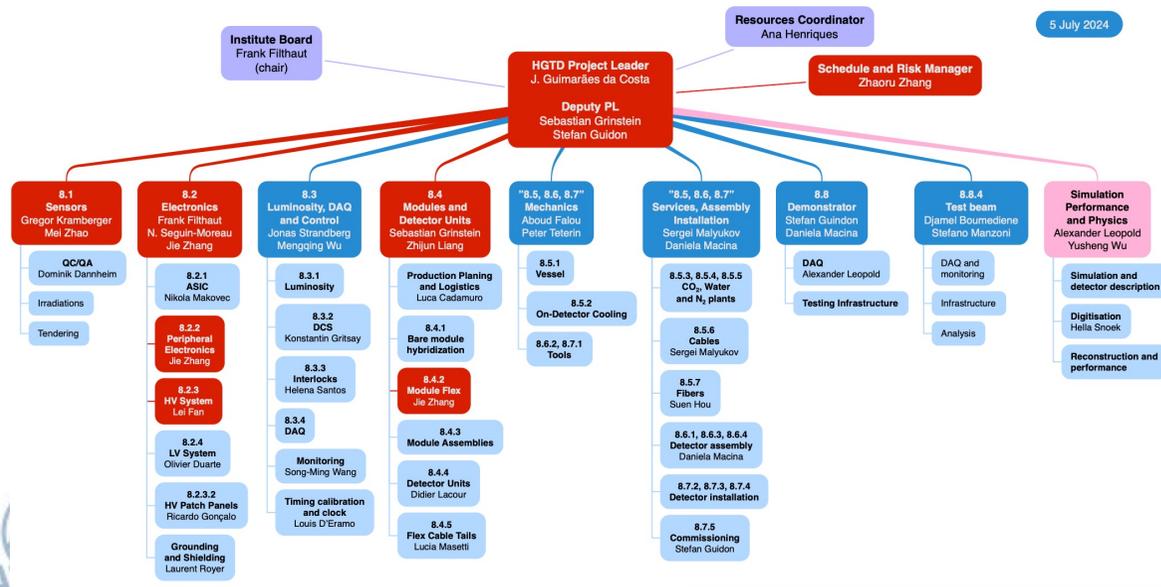
### ■ HV layout



# ATLAS高时间分辨探测器：重要管理职位

- 中国组在ATLAS高颗粒的时间探测器项目（HGTD）中起主导作用
  - 高能所Joao担任HGTD项目经理，ATLAS实验Level-1管理职位
    - 中国组首次在LHC实验子探测器担任项目经理
  - 5人担任Level-2召集人（梁志均，赵梅，张杰，张照茹、吴雨生）
  - 2人担任Level-3召集人（张杰，樊磊）
  - 1人担任speaker committee（刘衍文）

## HGTD项目的管理架构



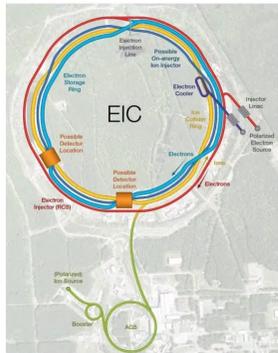
## 小结: ATLAS实验高颗粒度时间探测器

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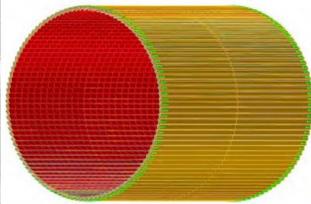
- 中国组在项目中占**主导地位**，担任**项目经理**等多个领导职务。
- LGAD传感器：
  - 高能所赢得欧洲核子中心（CERN）国际招标采购的订单
    - **CERN首次采购中国产的硅传感器**
  - 高能所、科大承担100%传感器研制（高能所90%，科大10%）
- 外围电路：
  - 高能所，南大主导了100%外围电路板的设计与研制工作
    - **研制出电路板读出系统原型机。**
- 探测器模块：
  - 中国组（高能所，科大）将组装~4000个模块，**占项目45%**
- 高压系统：高能所、山大研制出高压电源原型
- 柔性尾板：山大研制出首批原型

# 未来发展： LGAD探测器的未来应用

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

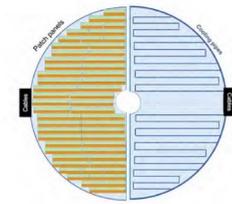


Barrel AC-LGAD detector



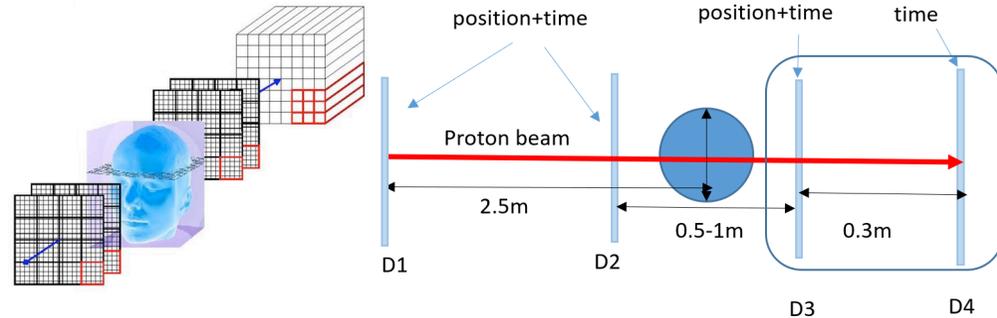
10.9 m<sup>2</sup>

Hadron endcap AC-LGAD detector

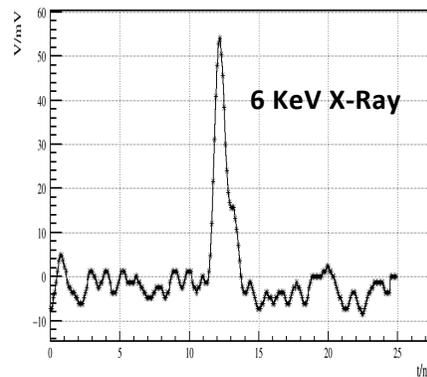


2.22 m<sup>2</sup>

## Nuclear Medicine Instruments: Such as proton therapy and proton CT



## X-ray detectors @ advanced light sources



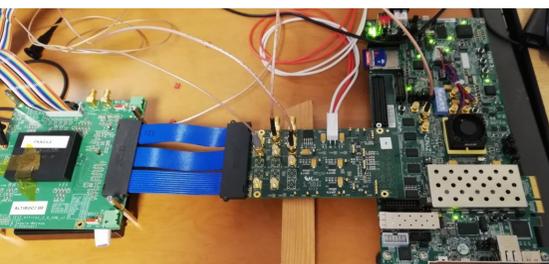
## other applications

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

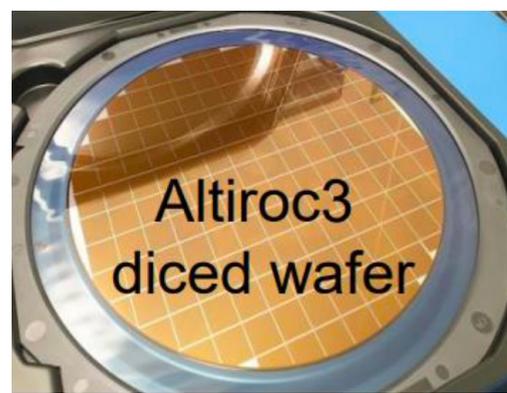
# ALTIROC R & D

- IHEP is responsible for **50%** of ALTIROC ASIC wafer testing
  - IHEP joined the digital part of ALTIROC ASIC design
- **ALTIROC2/ ALTIROC3**– 15x15 array with almost complete functionalities
  - **~15 ps jitter @ 15 fC**, better than **70 ps jitter@ 4 fC**
  - Full-size ASIC prototype  $\sim 2 \times 2 \text{ cm}^2$  with 225 readout channels
  - Large amount of digital data, limited power consumption (**1.2W/ASIC**  $\rightarrow$  **5.3 mW/ channel**)

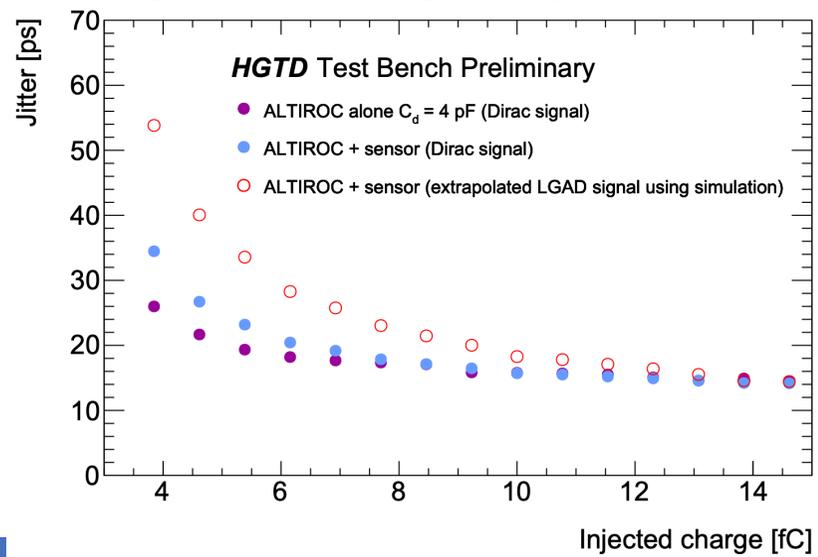
ALTIROC and test board



ALTIROC3 wafer@IHEP

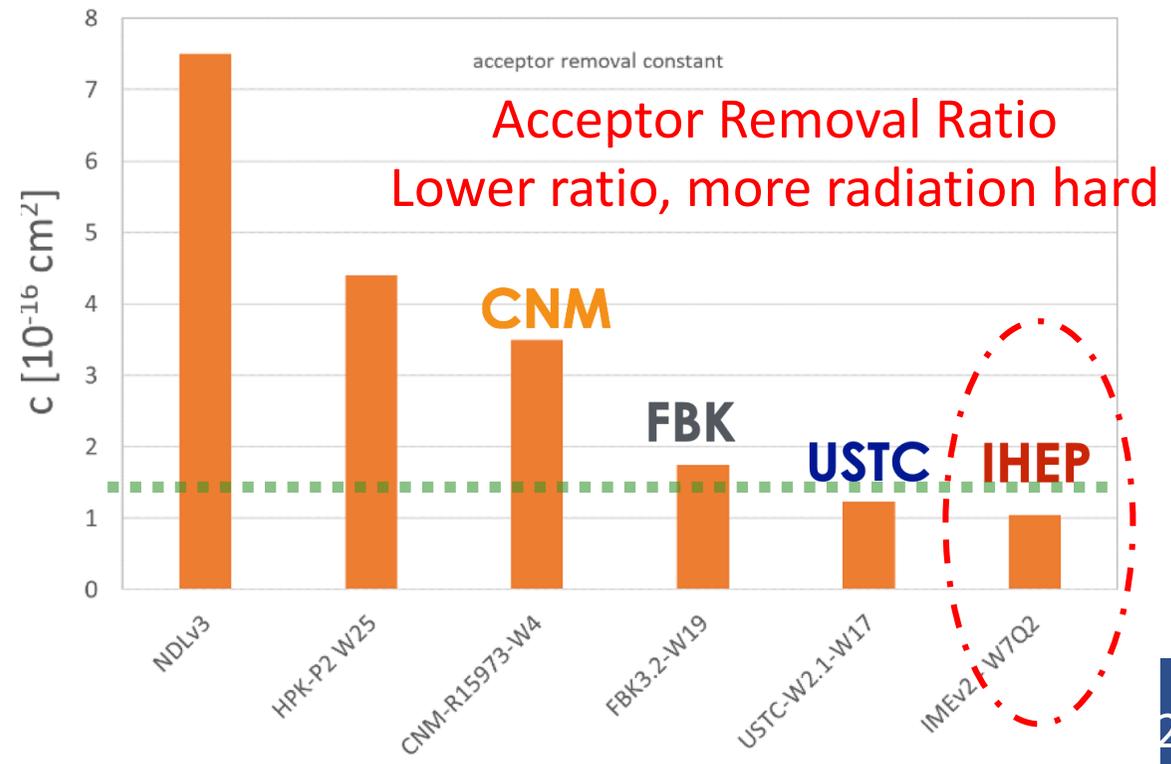
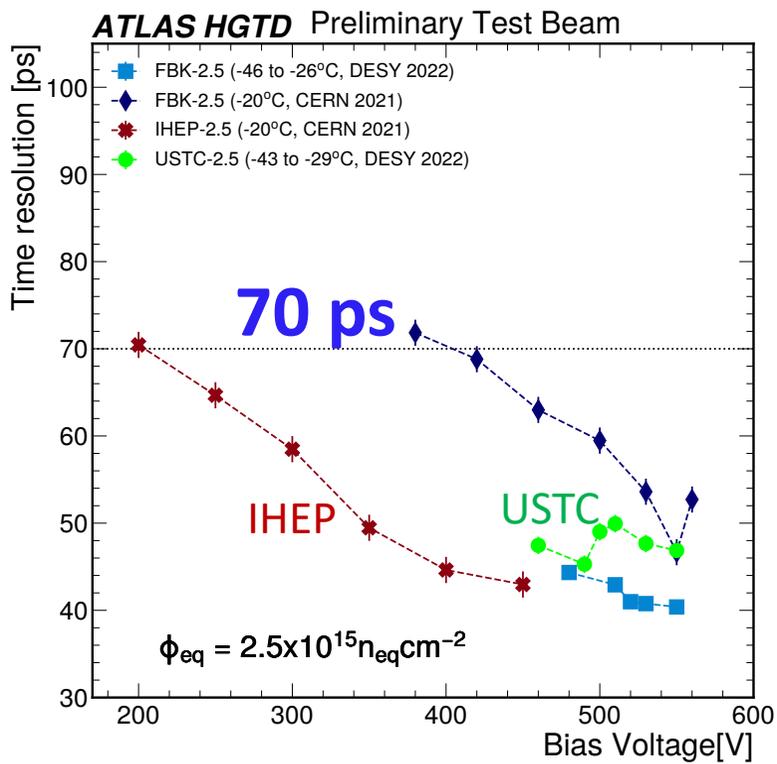


## Injected charge Vs jitter



# LGAD sensor after Irradiation

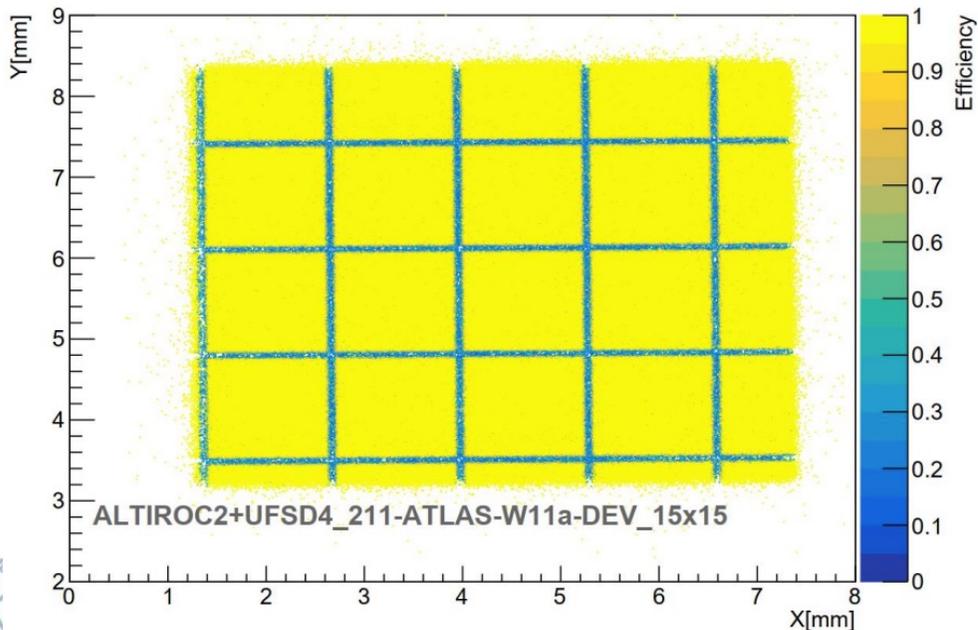
- Lots of prototypes R&D in LGAD in last few years, active vendors includes:
  - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) ...
- IHEP-IME and USTC-IME LGAD with carbon-enriched doping
  - Significantly lower acceptor removal ratio, the most radiation hard
- After  $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ , LGADs can operated below 550 V  $\rightarrow$  avoid single event breakdown



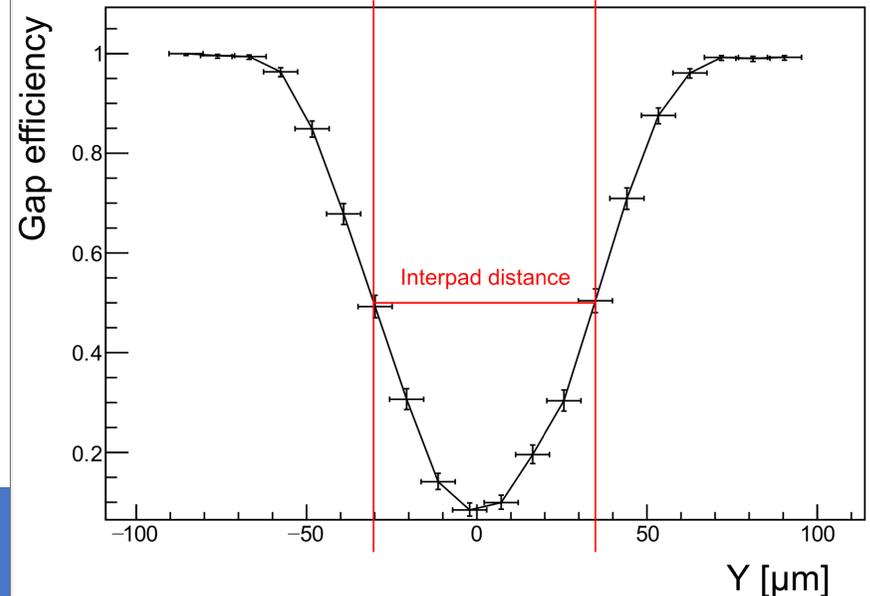
# Hybrid test beam result

- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
  - Sensor bias voltage is -180 V, corresponding to a charge of  $\sim 20$  fC
  - ASIC threshold 4.8 fC
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is about  $50\mu\text{m}$

ATLAS HGTD Test Beam Preliminary

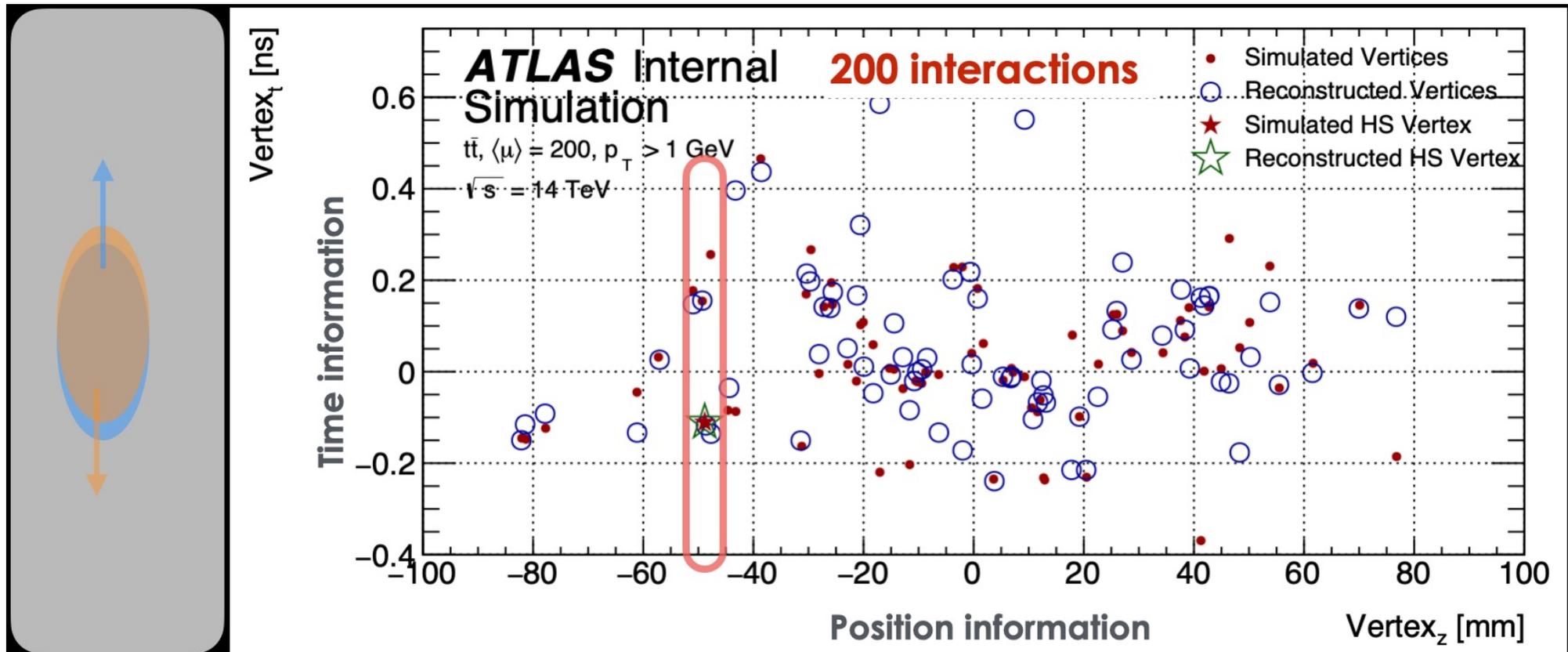


ATLAS HGTD Test Beam Preliminary



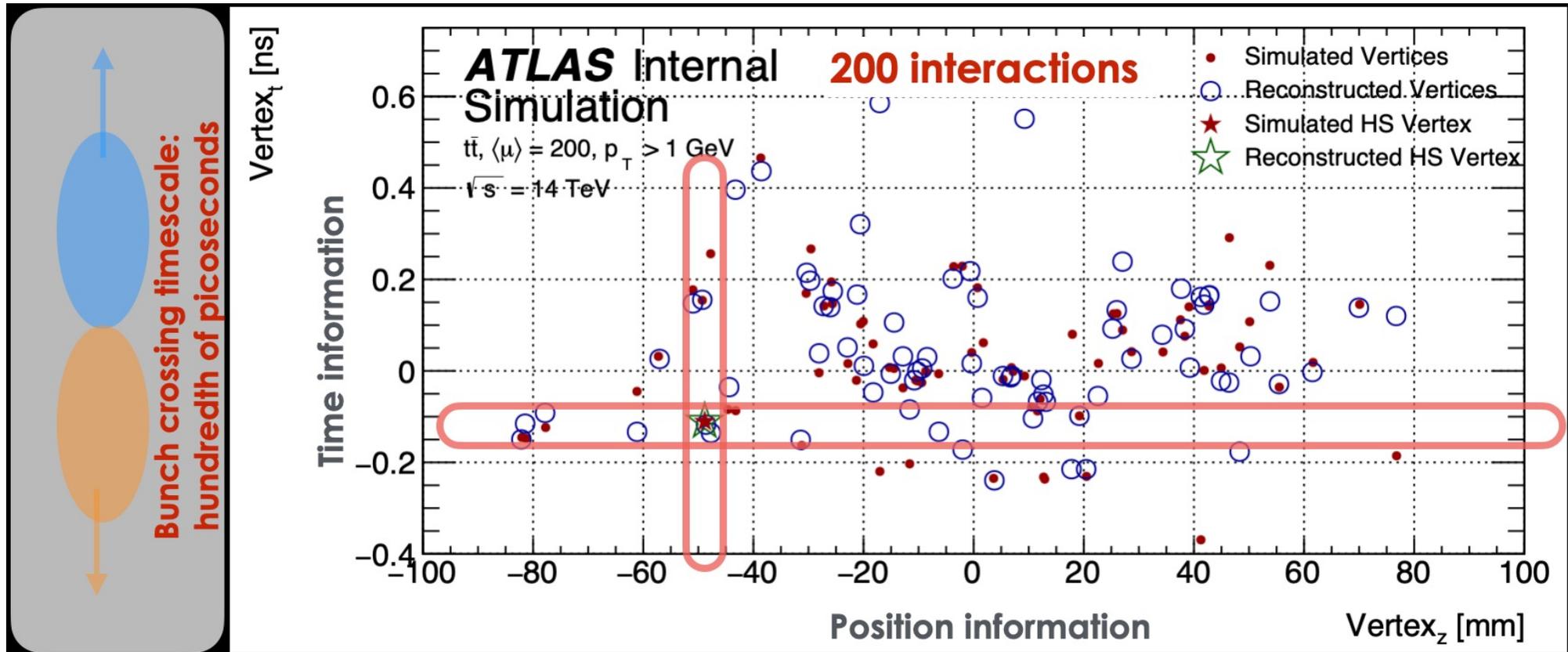
# Motivation

- Pileup background is major challenges at high luminosity LHC
- High precision timing info can reduce the pileup by one order of magnitude



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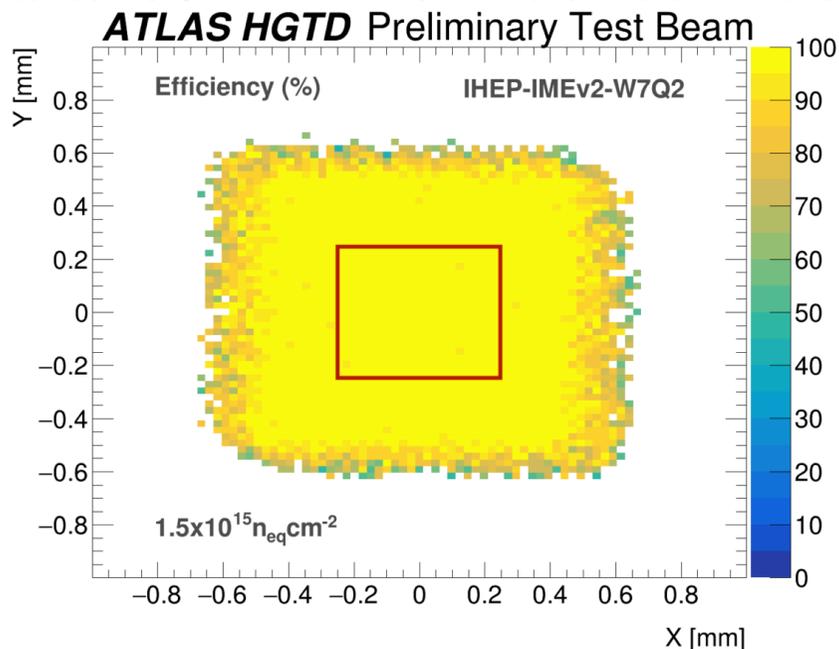
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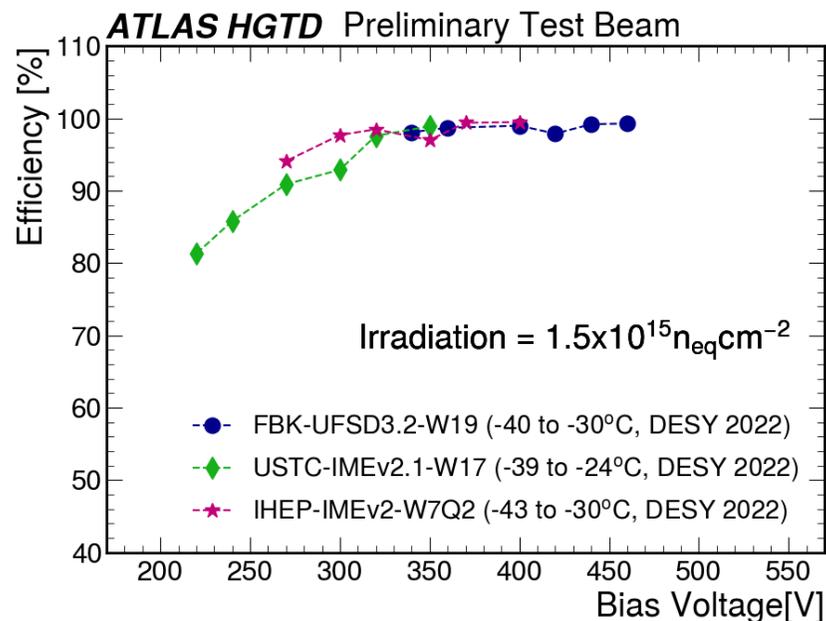
# 辐照后LGAD传感器在束流测试的性能

- 辐照后，掺碳LGAD传感器束流测试中有>99% 探测器效率
- 高能所、科大LGAD通过欧洲核子中心CERN的Market Survey
  - 国产硅传感器首次在LHC实验上得到应用

## 高能所传感器在束流测试中探测效率

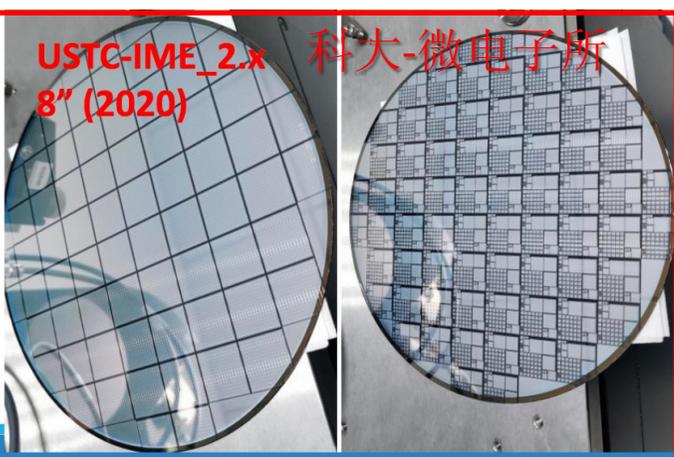
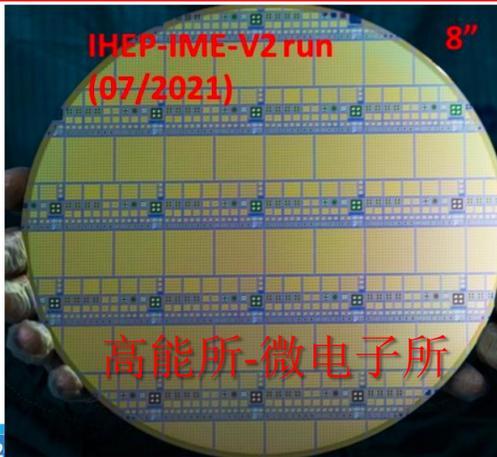
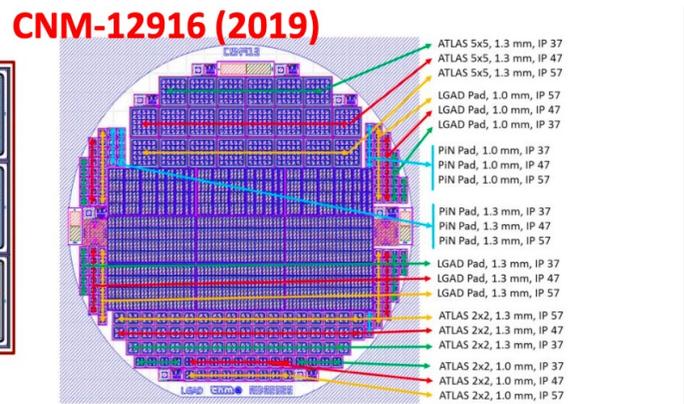
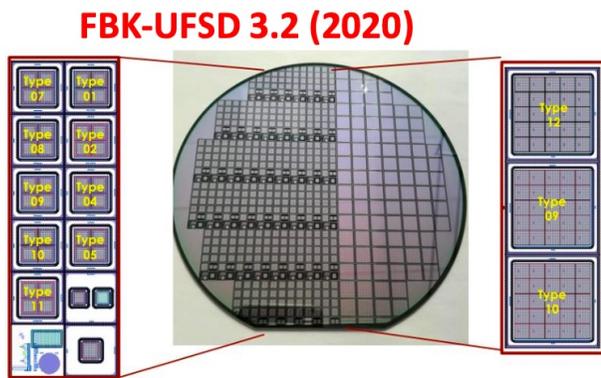
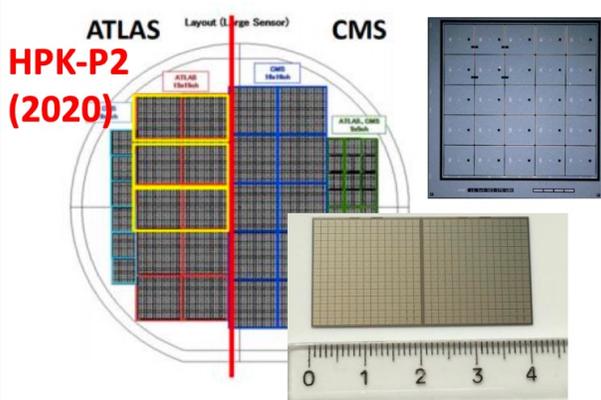


## 探测效率 VS 偏置电压



# LGAD低增益雪崩硅传感器：国内外形势

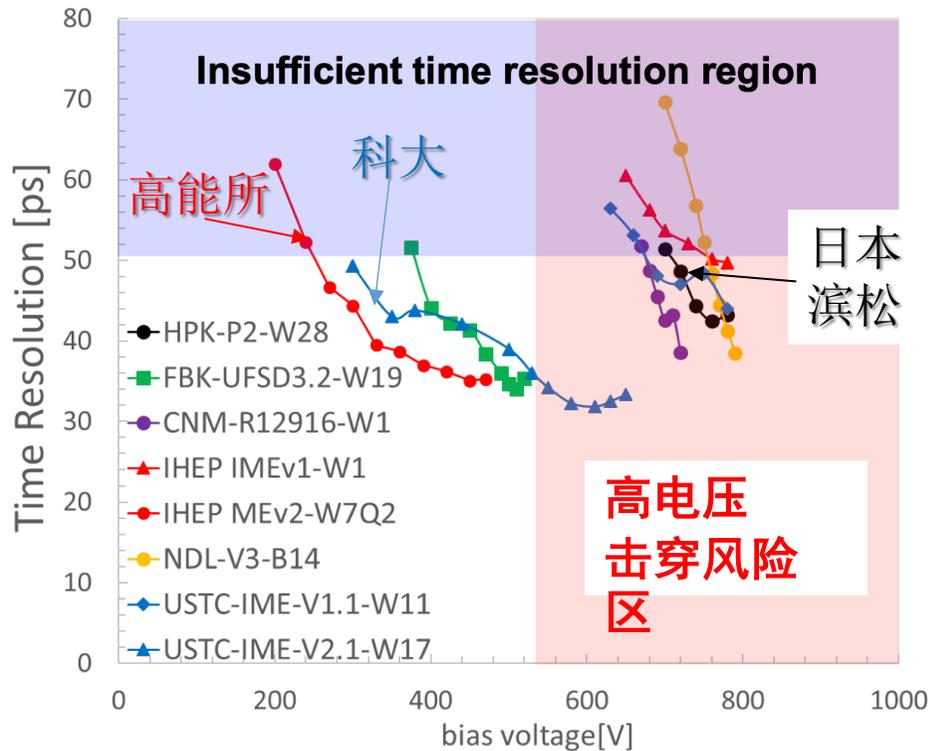
- 近年来，全世界范围涌现出很多研制LGAD硅传感器的单位
  - 国内：IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(高能所-北师大)
  - 国际：滨松HPK (Japan), FBK (意大利), CNM (西班牙) ...
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片



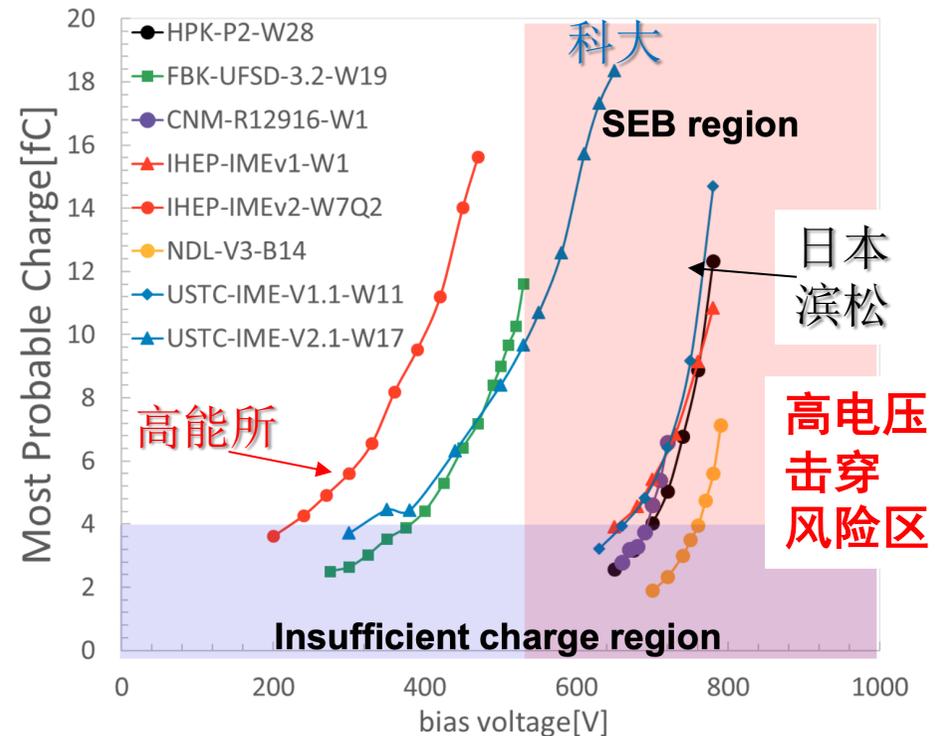
# LGAD传感器在辐照后的性能 ( $2.5e15 \text{ cm}^{-2}$ 等效中子通量)

- 掺碳的LGADs 满足ATLAS实验的 HGTD 要求 (高能所, 科大, 意大利FBK)
  - 30-50皮秒的时间分辨率
  - 4fC以上的电荷收集, 工作电压低于550V (避免烧毁)

### 时间分辨率 vs 偏置电压



### 电荷收集 vs 偏置电压

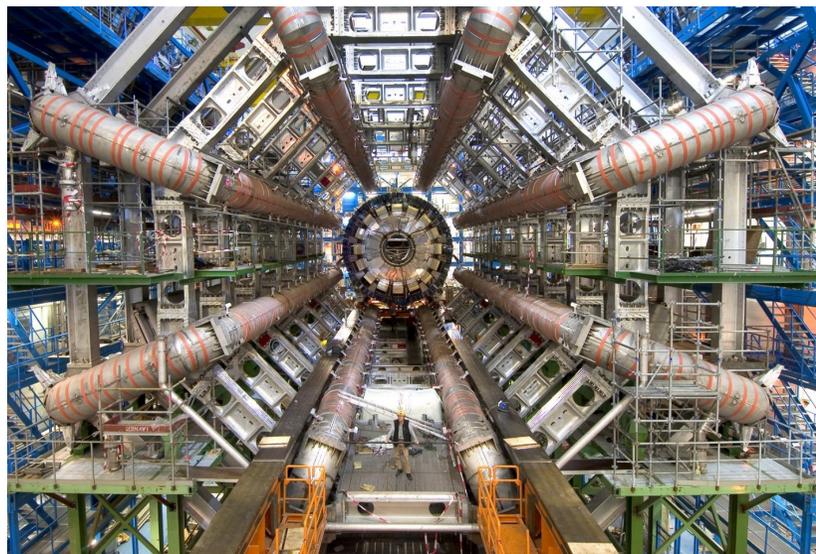


# 大型强子对撞机与ATLAS实验



## 大型强子对撞机

- 周长**27km**，总投资**40亿美元**
- 世界能量**最高**的加速器
- 质心系能**14TeV** ( $14 \times 10^{12} \text{eV}$ )
- 位于瑞士与法国边境



## ATLAS探测器

- 大约**3000人**的一个实验组
- **6层楼高** (**25米**) 的大型探测器
- 探测对撞产生粒子能量与动量