CMS实验高颗粒度量能器升级

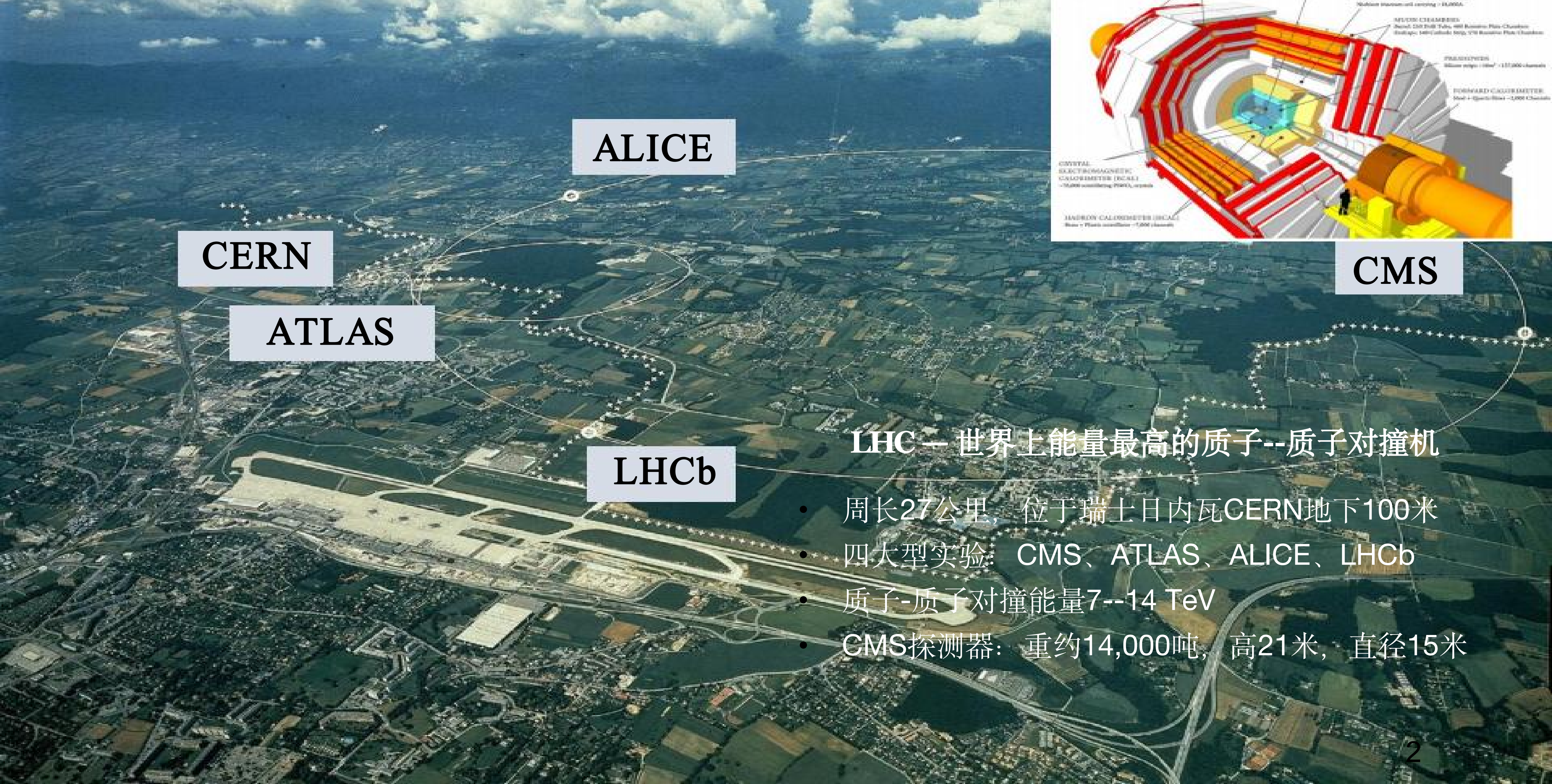
王峰
高能所
代表中国HGCal团队

广州 华南师范大学 2026年7月15日

报告内容

- 背景介绍
  - 大型强子对撞机（LHC）和CMS探测器
  - LHC升级--高亮度LHC（HL-LHC）
  - CMS探测器为应对HL-LHC进行升级
- 端盖量能器升级--高粒度量能器（HGCal）
  - HGCal的设计
  - HGCal性能验证（抗辐照性能与能量、位置、时间分辨率）
  - HGCal建造
  - 高能所站点承担的建造任务及现状
- 总结与展望

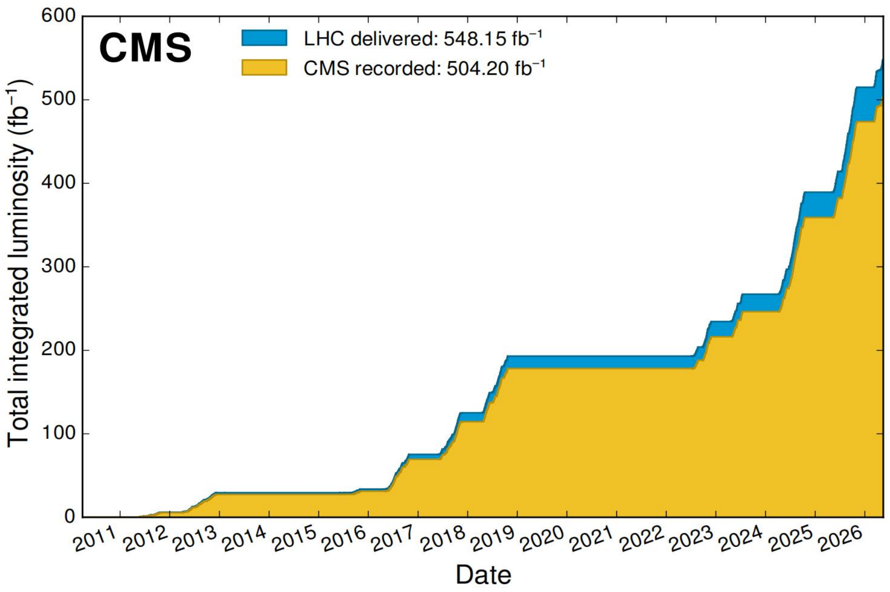
大型强子对撞机（LHC）和CMS探测器

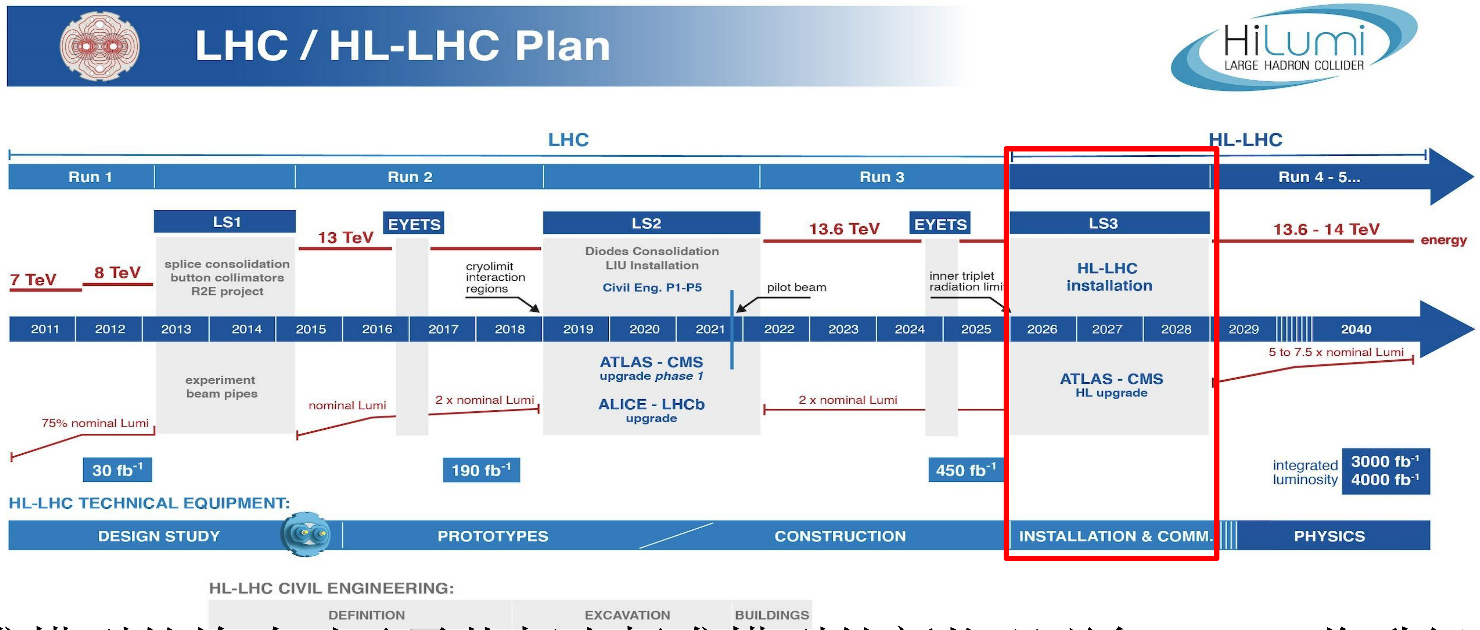


LHC – 世界上能量最高的质子--质子对撞机

- 周长27公里，位于瑞士日内瓦CERN地下100米
- 四大型实验：CMS、ATLAS、ALICE、LHCb
- 质子-质子对撞能量7--14 TeV
- CMS探测器：重约14,000吨，高21米，直径15米

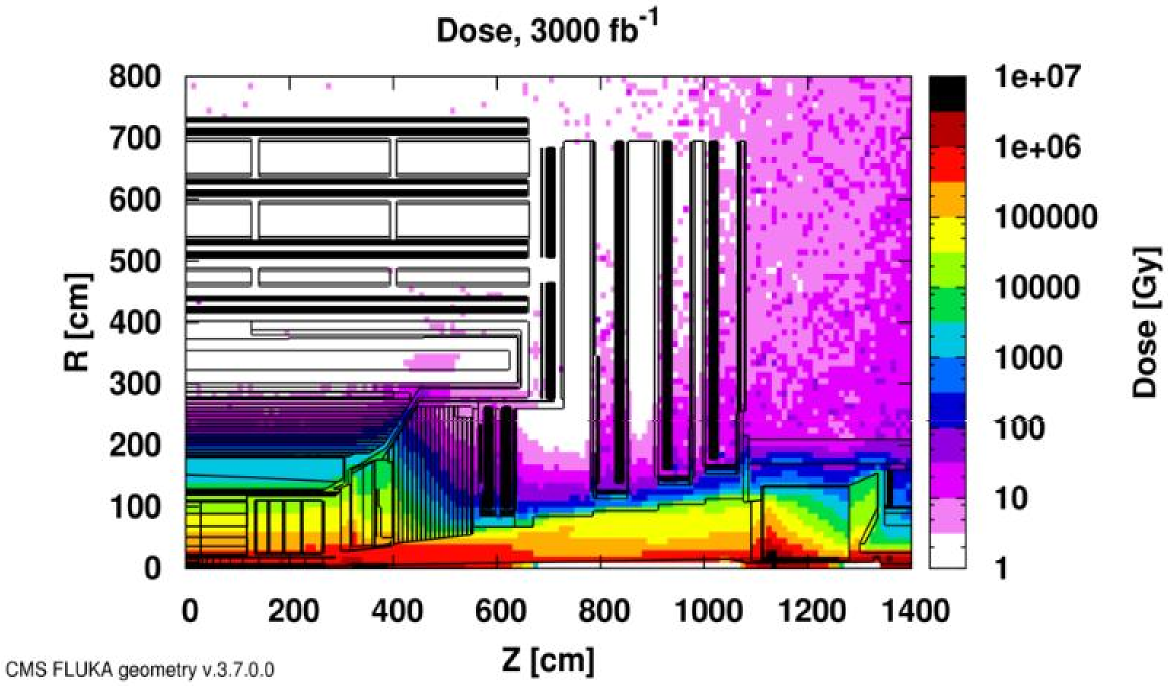
LHC升级--高亮度LHC（HL-LHC）

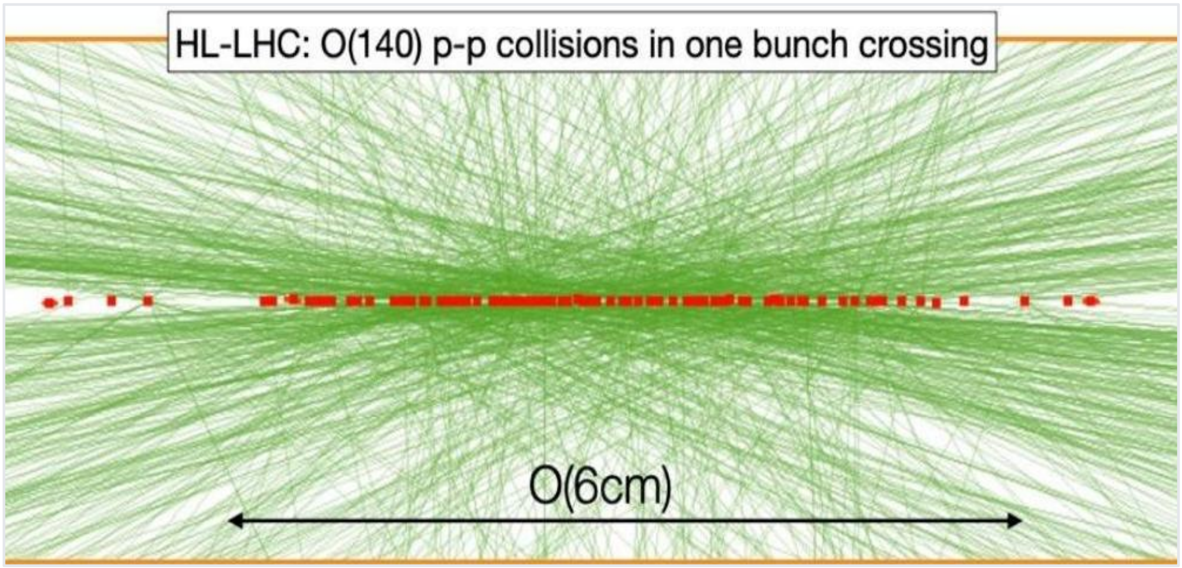




- 为了希格斯玻色子的精密测量、标准模型的检验以及寻找超出标准模型的新物理现象，LHC将升级为HL-LHC
- 2026年6月29日Run3结束取数，整个LHC运行阶段总的取数量548.15fb^{-1}
- 目前正处于LS3长期停机与隧道改造 → 2028年完成探测器安装 →2030年HL-LHC (Run 4) 正式启动
- Run4阶段计划取数～3000fb^{-1}
- 升级后HL-LHC瞬时积分亮度$5\times10^{34}cm^{-2}s^{-1}$(提升5-7倍)

HL-LHC阶段CMS探测器将面临的挑战





- ❑ 极端的辐射环境
  - ❑ |η|~3区域将暴露在10^{16}neq/cm²的等效中子通量的辐照下
  - ❑ 吸收剂量高达2 MGy

- ❑ 严重的粒子堆积 (Pileup)
  - ❑ 140 ~ 200PU，是目前阶段的3到5倍

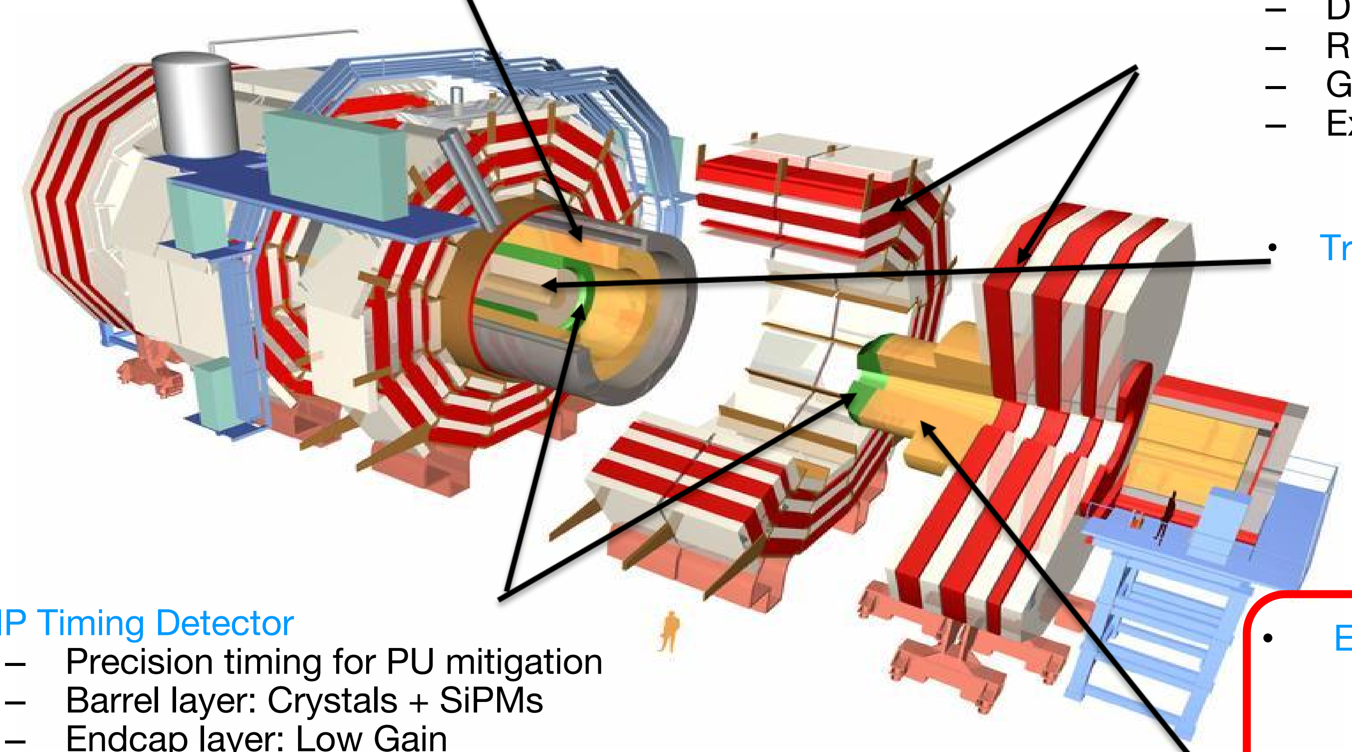
目前的端盖量能器是针对总计积分亮度仅为500 fb^{-1}的条件设计的，HL-LHC阶段性能将会下降

CMS探测器二期升级

- Barrel Calorimeters
  - ECAL crystal granularity readout at 40 MHz
  - Precision timing for e/γ at 30 GeV, for vertex localization (H → gg)
  - ECAL and HCAL new Back-End board

- L1-Trigger/HLT/DAQ
  - Tracks in L1-Trigger at 40 MHz
  - PFlow-like selection 750 kHz output
  - HLT permanent event storage rate ~7.5 kHz (200 PU)

- Muon systems
  - DT & CSC new FE/BE readout
  - RPC back-end electronics
  - GEM/RPC 1.6 < |η| < 2.4
  - Extended GEM coverage to| η| ≃ 3



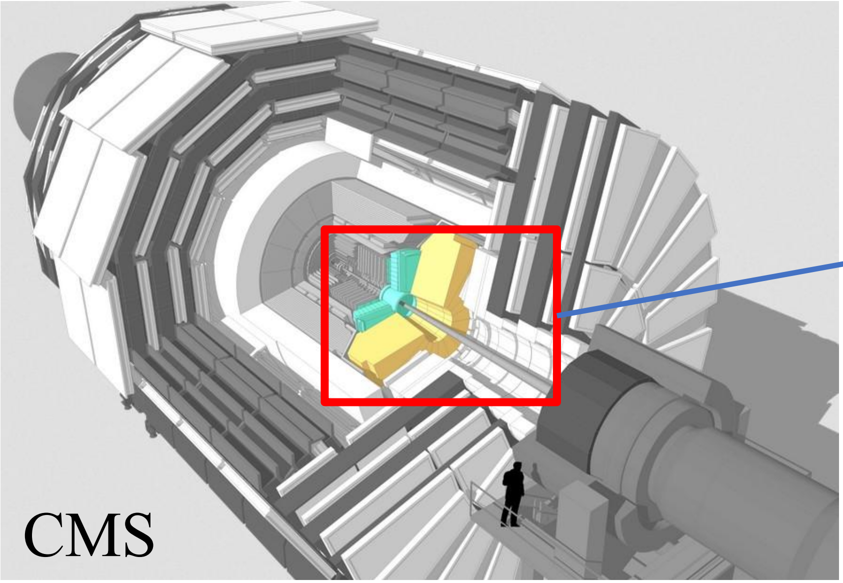
- Tracker
  - module design for tracking in L1-Trigger
  - Extended coverage to |η| ≃ 3.8
  - Much reduced material budget
  - Si-Strip and Pixels increased granularity

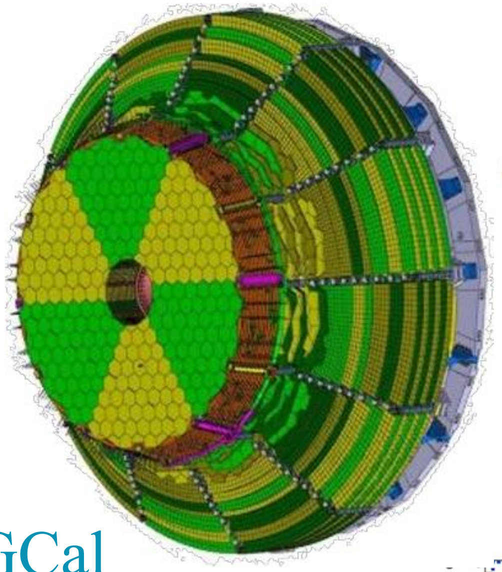
- MIP Timing Detector
  - Precision timing for PU mitigation
  - Barrel layer: Crystals + SiPMs
  - Endcap layer: Low Gain
  - Avalanche Diodes

- Endcap Calorimeters
  - 3D showers imaging for pattern recognition
  - Precision timing for PU mitigation
  - Si, Scint+SiPM in Pb/W-SS

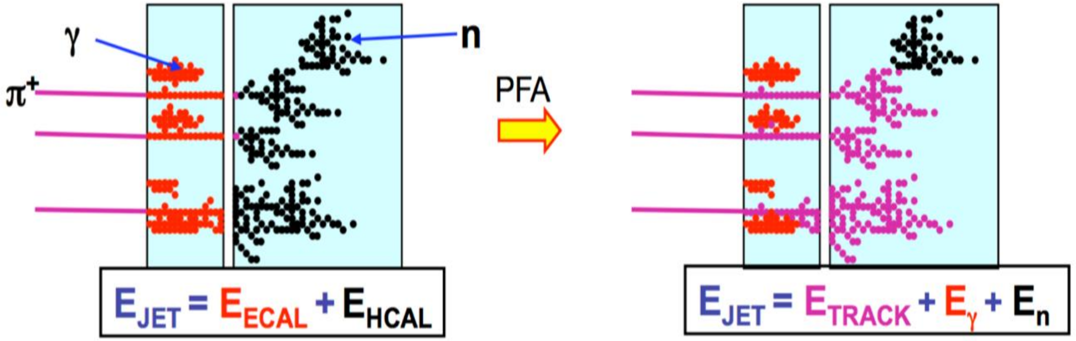
高粒度量能器（HGCal）代替现有的端盖量能器

HGCal：应对挑战的解决方案

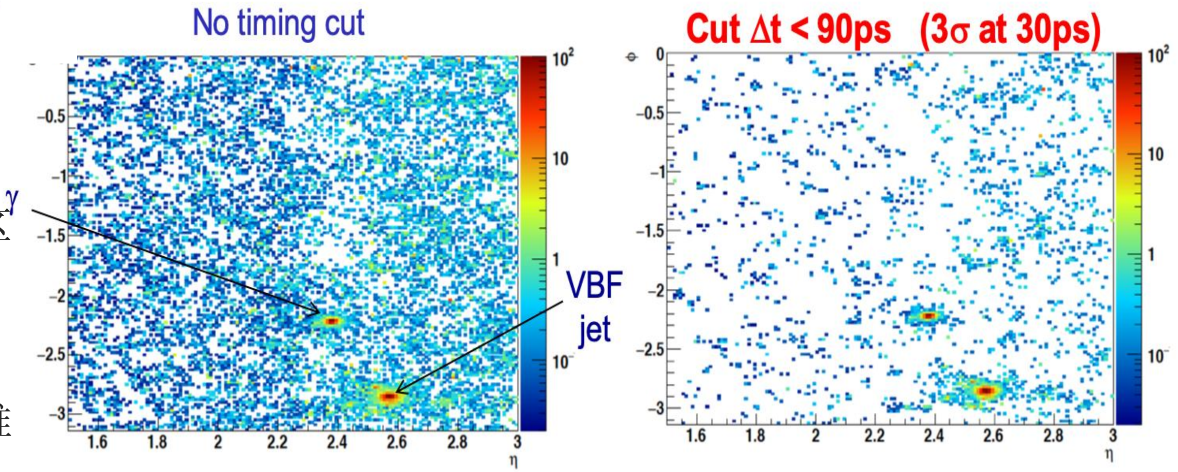




HGCal

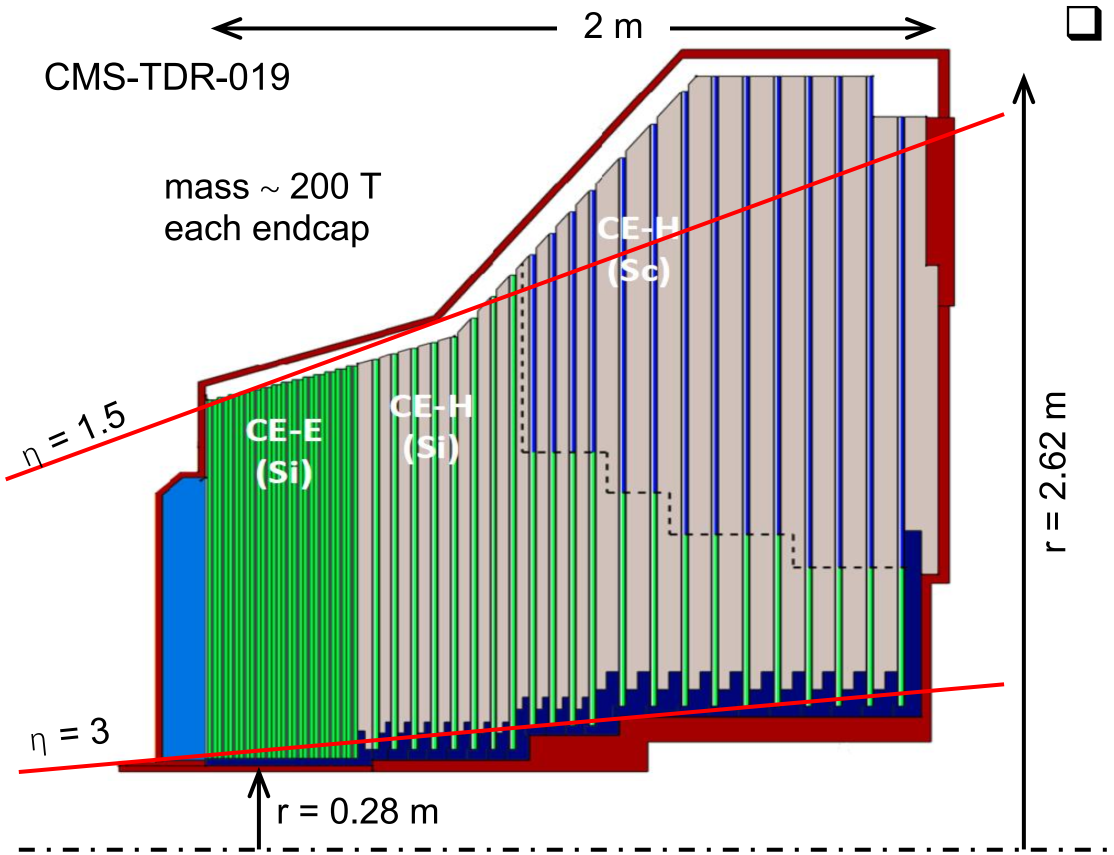


CMS-TDR-019



- ❑ 混合架构：抗辐照性能与成本的最优解
  - ❑ 高辐射区部署硅传感器以确保抗辐照性能与快速响应；低辐射区采用塑料闪烁体瓦片，以更低成本实现大面积覆盖。
- ❑ 高颗粒度设计：“5D” 量能器
  - ❑ ~1cm^{3}一个读出通道，结合PFA算法捕捉粒子的五维特征：三维空间位置(x,y,z)、能量沉积(E)
  - ❑ 硅模块前端电子学的ToA功能+硅传感器快响应=粒子到达时间(t)。
- ❑ 高精度时间分辨率：抑制Pileup效应

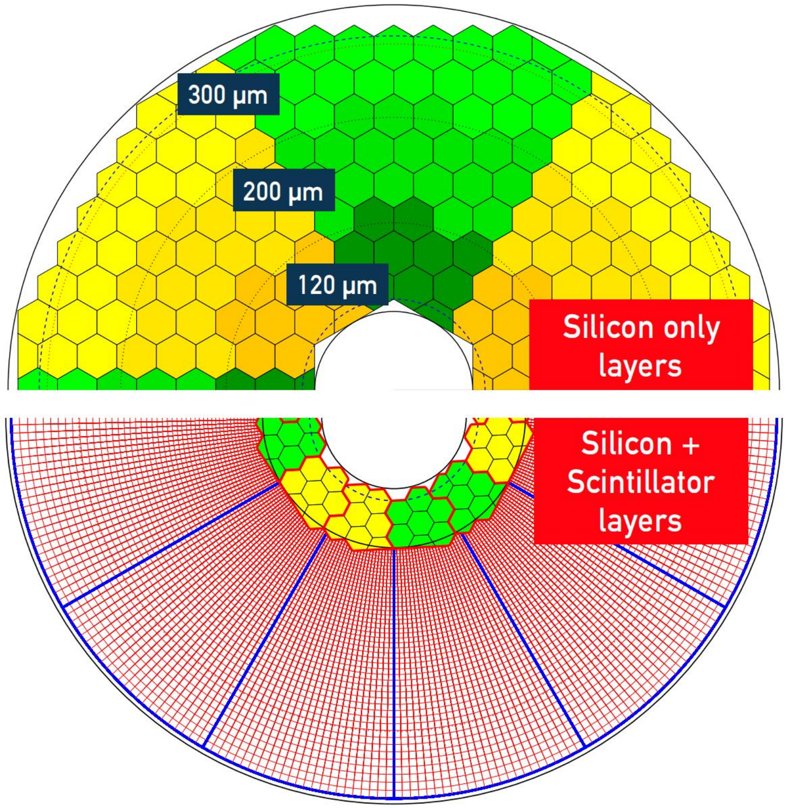
HGCal设计



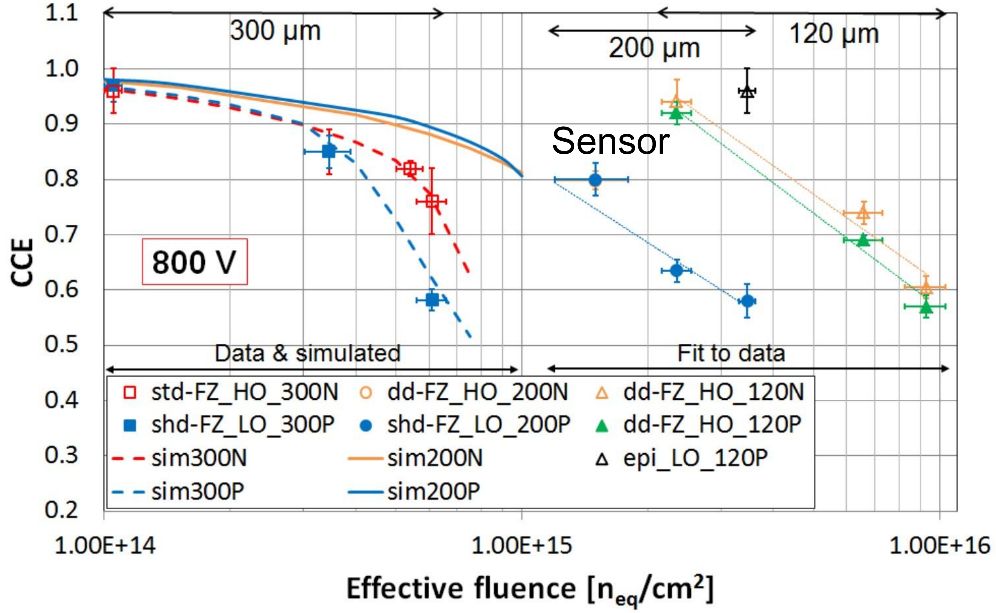
- 关键指标:
  - $1.5 < |\eta| < 3.0$
  - –30 摄氏度运行
  - 硅传感器总面积约 620 m^2
    - 硅读出通道共~600万道
    - 硅像素~0.5 or 1.1 cm^2
    - 硅模块总数约~26000块
  - 闪烁体总面积约 370 m^2
    - 读出通道共~34万道
    - 模块尺寸 4--30cm^2
    - 闪烁体模块总数~3700块
  - 高亮度 LHC 运行时单侧端盖功耗约~110 千瓦
- 性能指标:
  - 能量分分辨率:
    25%/ sqrt(E) ⊕ 1%
  - 时间分辨率: 50 ps
  - 抗辐照要求 :
    1×10^{16} 1MeV neq/cm^2

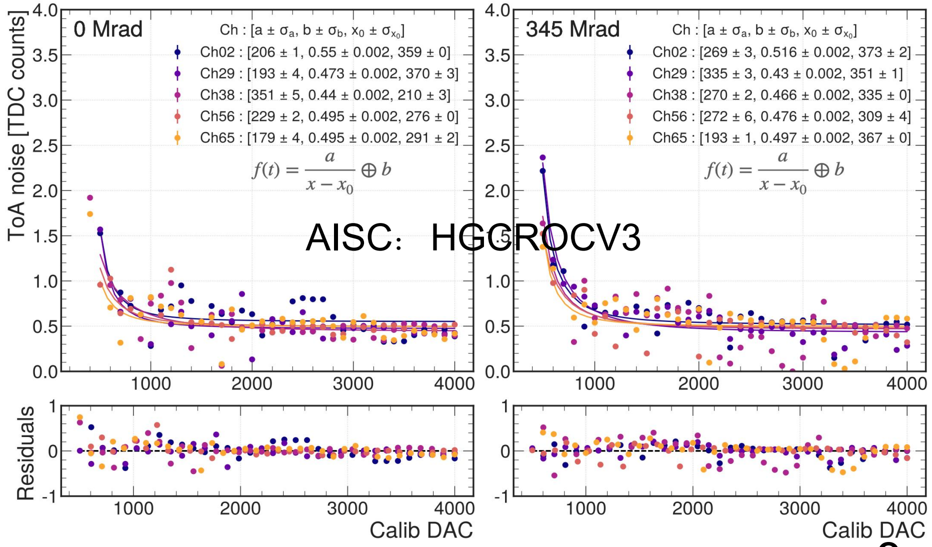
端盖量能器电磁部分 (CE-E): Si, Cu & CuW & Pb absorbers, 26 layers, 25.5 X_0 & ~1.3λ
端盖量能器强子部分(CE-H): Si & scintillator, steel absorbers, 21 layers, ~8.5λ

HGCal的性能验证 (抗辐照性能)



2020 JINST 15 P09031



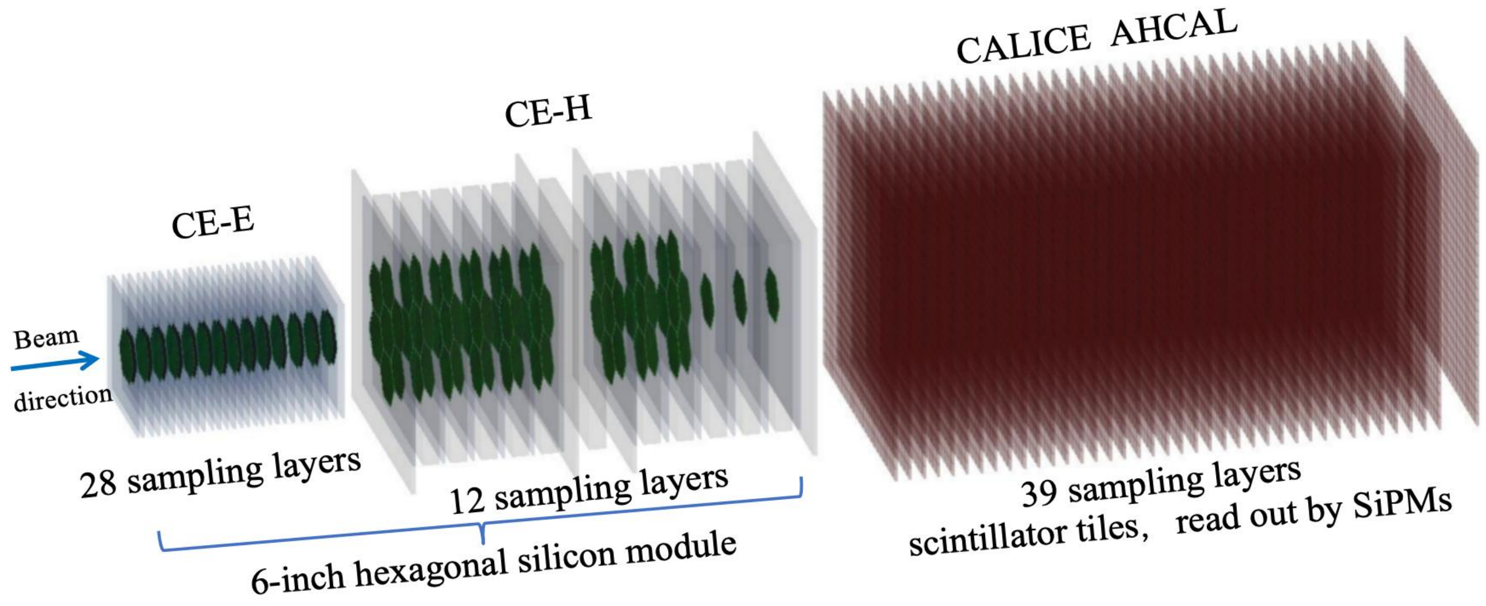


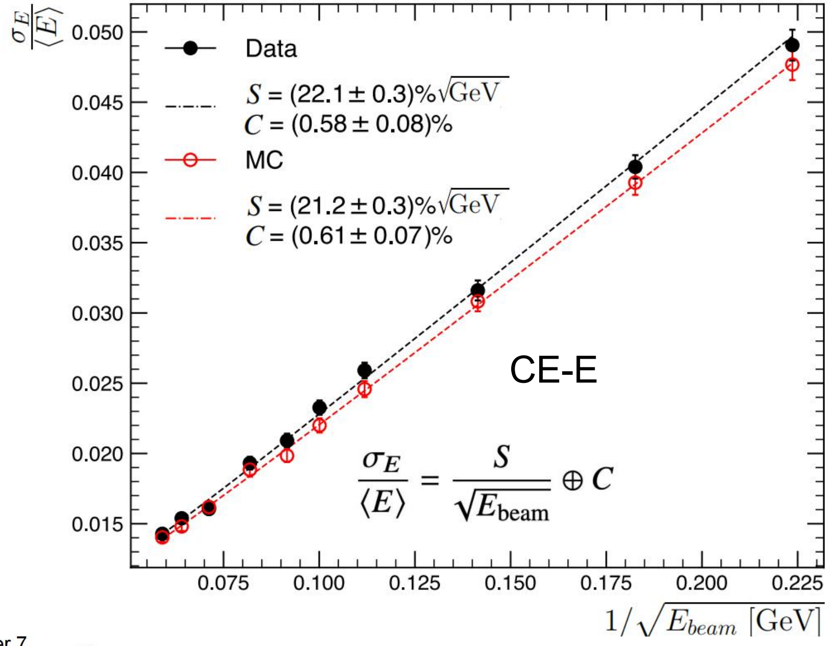
- 120µm厚的Sensor接受了最高达10^{16}neq/cm²抗辐照测试，200µm，300µm厚的sensor也接受了相对应的抗辐照测试
- 前端读出电子学AISC接受并通过了345Mrad的抗辐照测试，最终版采用HGCROC V3
- CuW合金底板和kapton薄膜的粘贴工艺也通过抗辐照测试（具体参看16页）

doi: 10.1109/NSS/MIC44845.2022.10399091

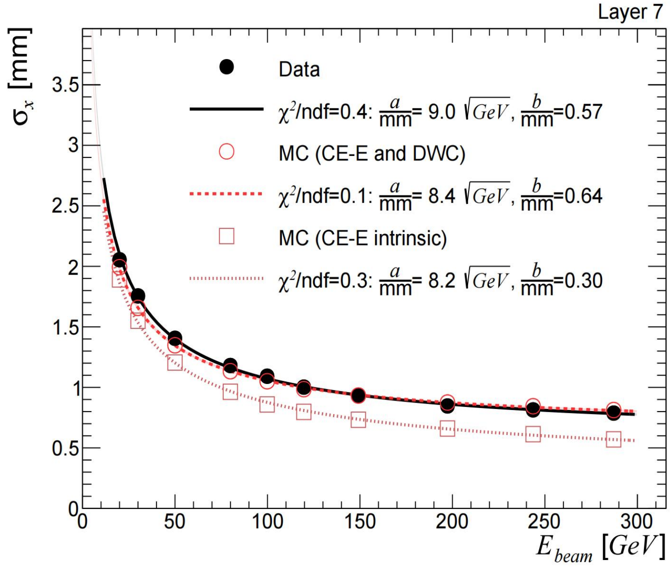
HGCal的性能验证 (能量、位置、时间分辨)

JINST 17 (2022) 05, P05022

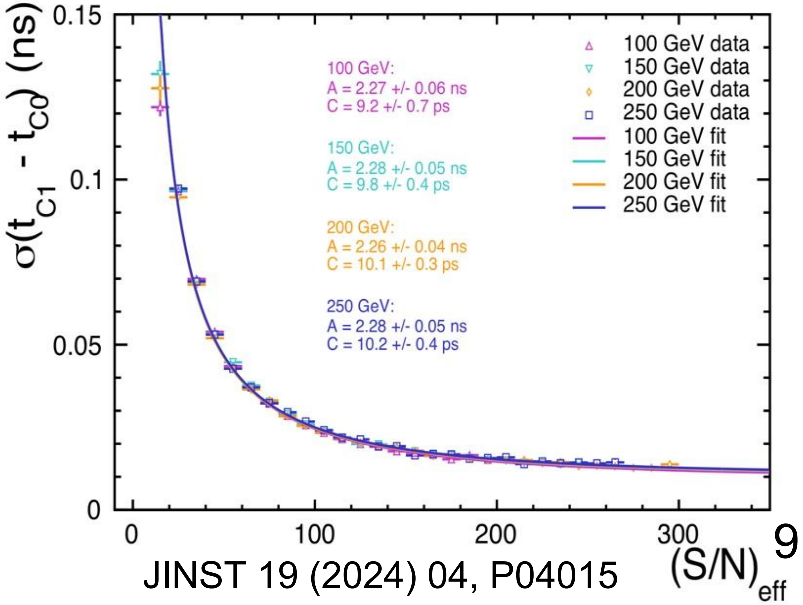




- 2016－2018多次束流测试对HGCal原型机性能进行验证
  - 6英寸硅模块（SKIROC）+Sci. AHCAL(CALICE)
  - 电磁量能器（CE-E）的能量分辨率好于 $25\%/\sqrt{E} \oplus 1\%$（电子）
  - 位置分辨率小于1mm（高能区）
  - 时间分辨率通过相邻cell的时间差测定，分辨率小于50ps



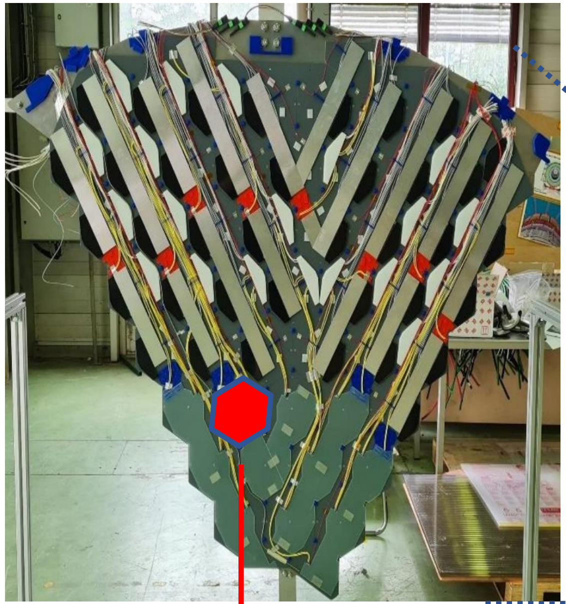
JINST 18 (2023) 08, P08014

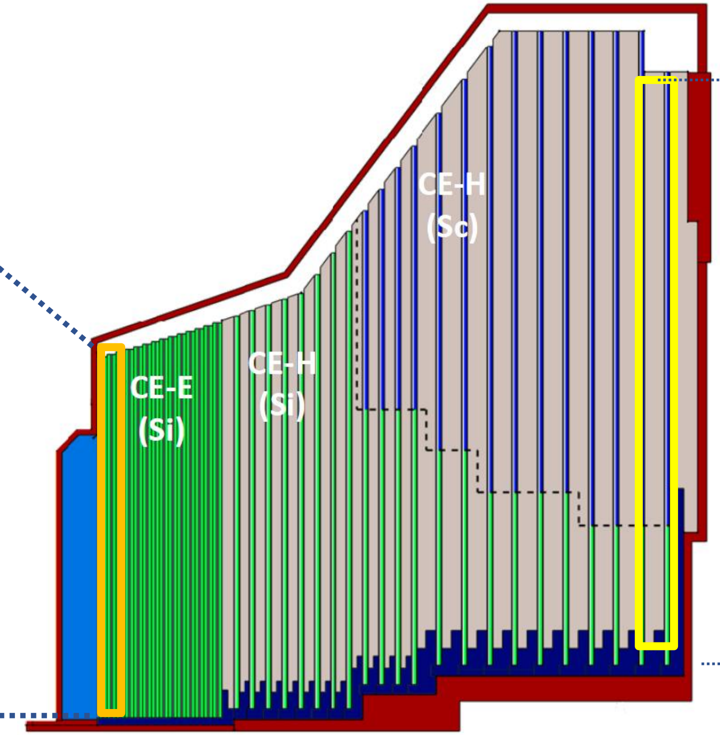


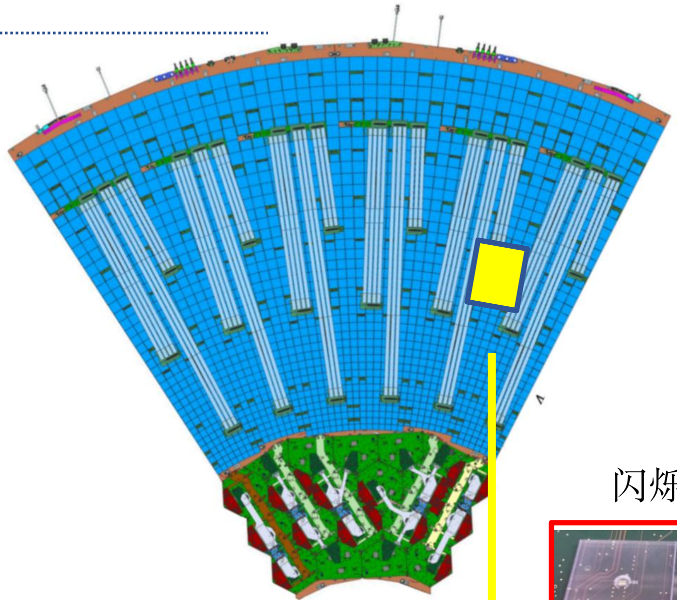
JINST 19 (2024) 04, P04015

HGCal的建造

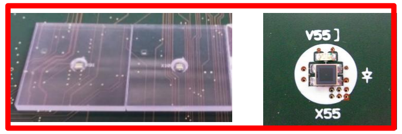
Cassette

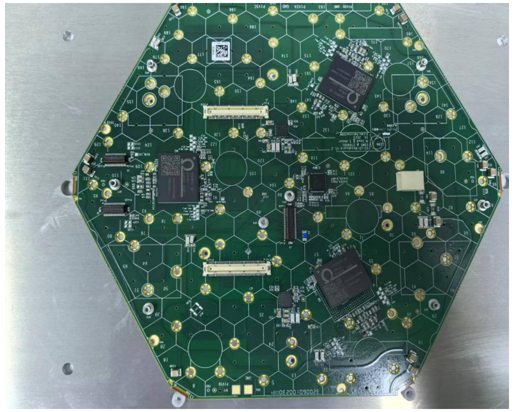






闪烁体 + SiPMs





8英寸全尺寸
低密度硅模块

- ❑ 硅模块和闪烁体模块均已进入量产阶段
  - ❑ CE-H共包含3744个闪烁体模块
  - ❑ DESY（1920），Fermilab（1824）
- ❑ CE-E和CE-H共包含～26000块8英寸全尺寸和部分尺寸硅模块
  - ❑ 高能所，台湾大学，UCSB，CMU，TTU，TIFR
  - ❑ 所有站点采用统一的生产工艺，以保证模块质量的一致性

闪烁体模块

高能所HGCal硅模块组装中心

- 140平米洁净间
- 生产了合作组首块8英寸的硅模块
- 21年是首批3家通过认证的硅模块组装中心之一
- 合作高校：清华，复旦，南师，浙大
- 承担任务：～100m²全尺寸低密度硅模块建造，～90%全尺寸钨铜（CuW）合金底板和Kapton的生产（与国内企业合作），部分尺寸硅模块前端电子学板设计

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
COMPACT MUON SOLENOID COLLABORATION
URL : http://cms.cern

Dr. Karl Gill
CMS HGCAL Project Manager
Principal Applied Physicist
CERN - EP Department
CH - 1211 GENEVA 23
Switzerland

Tel. +41 75 411 4712
E-mail Karl.Aaron.Gill@cern.ch

December 15, 2021

Subject: ***Certification of qualification the HGCAL Module Assembly Centre at IHEP, Beijing***

To whom it may concern,

I am writing as Project Manager for the CMS endcap calorimeter upgrade project (HGCAL) to certify that the silicon module assembly center (MAC) at IHEP Beijing, led by Prof. Huaqiao Zhang, has been qualified for the HGCAL project as ready to move into the Pre-Series phase of construction.

HGCAL will replace several of the present CMS sub-detectors: the silicon/lead endcap pre-shower detector, the lead-tungstate crystal electromagnetic endcap calorimeter, and the plastic/brass endcap hadron calorimeter. HGCAL is a novel sampling calorimeter, based on a large-scale deployment of silicon modules (a grand total of approximately 26000 installed, plus 5% spares), positioned between dense layers of absorber. The silicon modules will be complemented with plastic scintillator tiles instrumented by silicon photomultipliers (SiPMs) in regions of the detector where particles arrive with lower intensity.

The qualification of the IHEP Beijing MAC has been completed on time to meet the corresponding project milestone. The MAC is set up in a Class 1000 clean room that is dedicated to this facility and all of the equipment for mass production of silicon modules for HGCAL has been installed in the clean room and commissioned. This equipment includes a gantry machine for automated module assembly, a wire-bonding machine, an optical inspection and coordination measurement machine, and a silicon module test-stand. The IHEP Beijing team has been trained in how to use the MAC equipment, and they have practiced extensively on dummy module components before moving onto using live components.

Fully functional prototype silicon modules have been assembled successfully in the IHEP Beijing MAC (in June and September 2021), using the latest prototype parts available, which included 8-inch silicon sensors developed together with Hamamatsu, custom circuit boards ("hexaboards") developed at CERN, and custom ASICs (HGCROCv2 and v3) developed by Omega group (IN2P3, France). The modules assembled at IHEP Beijing were then sent to CERN and have been used successfully in HGCAL system tests, including particle beam tests at CERN, in the autumn of 2021.

This certification of the qualification of the IHEP Beijing MAC means that the MAC is now ready for the next step of assembling final prototype pre-series modules. The pre-series exercises should result in several hundred working modules (total from all MACs), which will be used for the integration of larger prototype assemblies ('cassettes') of the HGCAL detector. The pre-series phase will exercise all the handling, the tooling, and the QA/QC procedures associated with large scale module assembly and testing. It will also permit a deep study and characterization of the robustness of the pre-series modules with large statistics.

We plan to start the pre-series assembly in 2022, once the component parts are all available, and beyond the pre-series, we look forward to ramping up the IHEP Beijing MAC for full-scale mass production.

Yours faithfully,

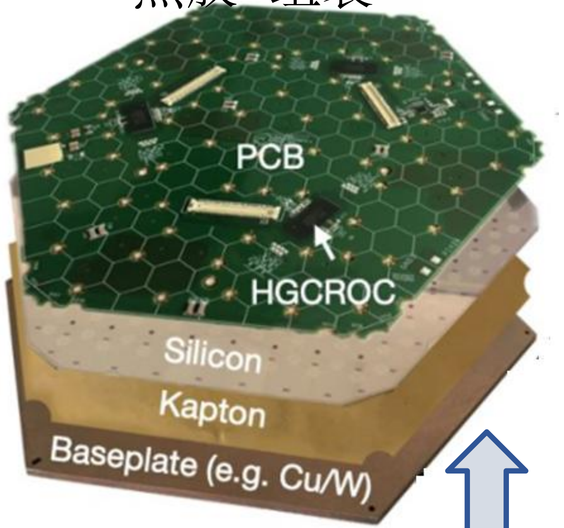
Karl A. Gill
CMS HGCAL Project Manager

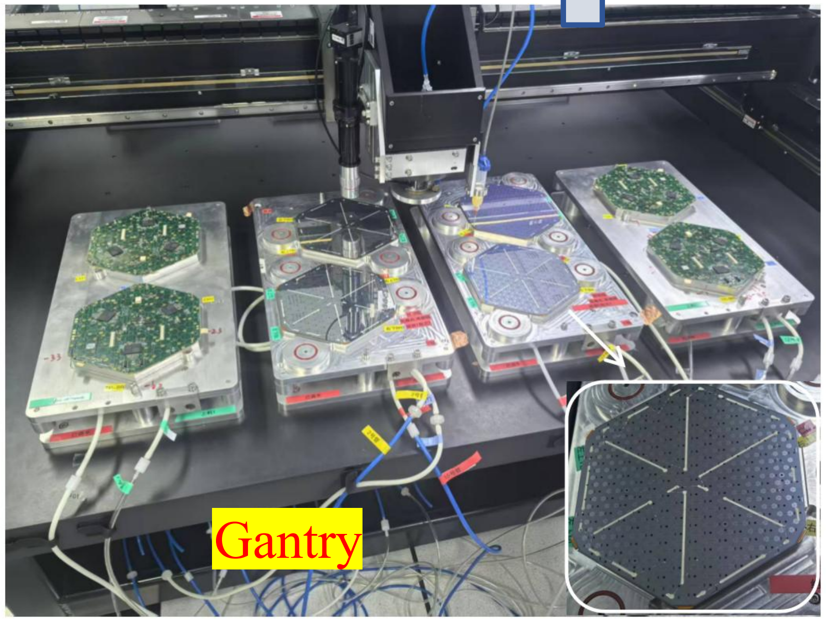
CERN提供的硅模块组装中心的认证信

高能所硅模块组装中心洁净间

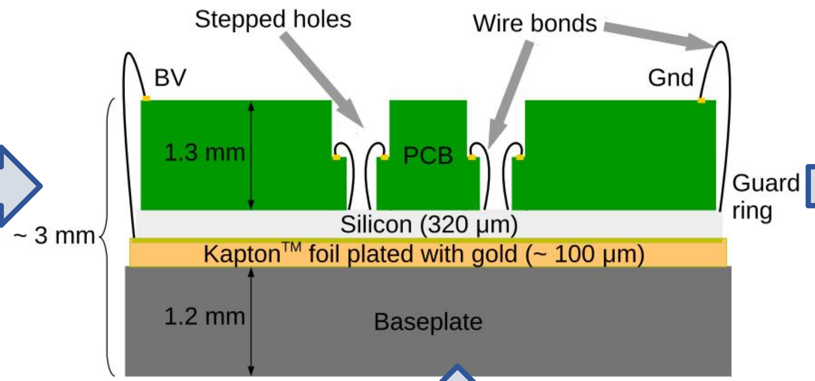
HGCal硅模块自动化生产工艺

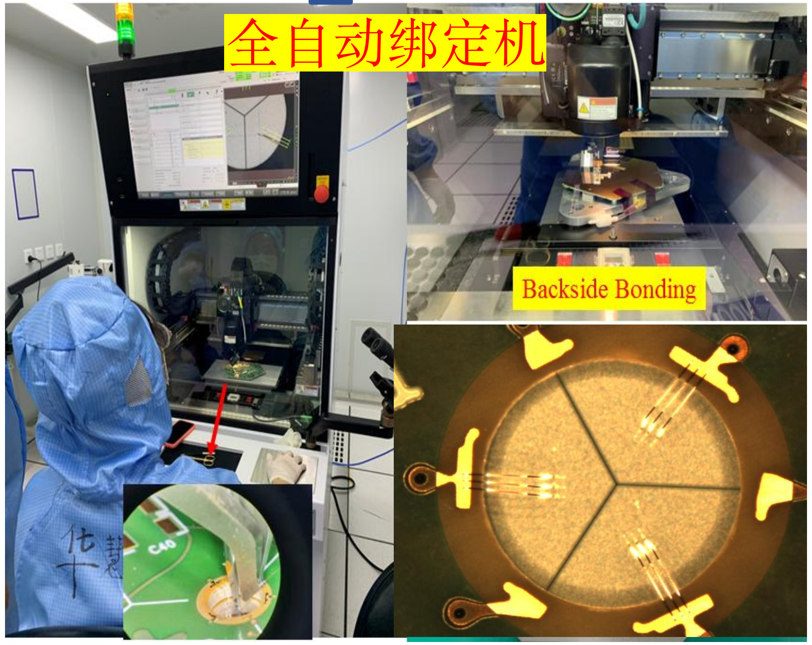
点胶+组装





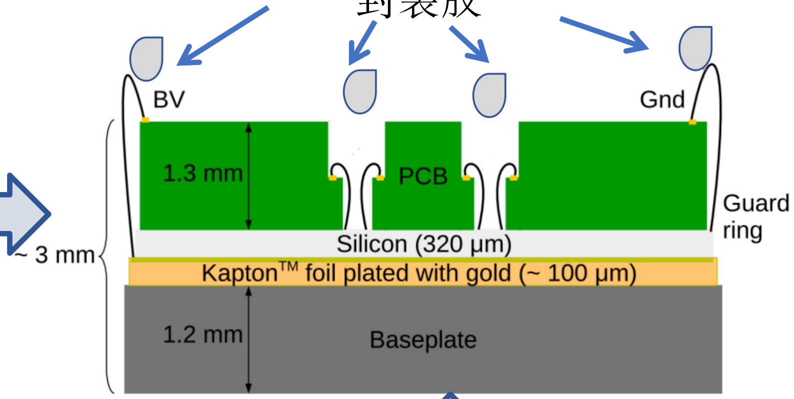
导线绑定





封装

封装胶



HGCal硅模块制作QC&QA

Hexaboard taping

↓

Electronic test

↓

Gantry assembly

↓

OGP inspection

↓

Bonding

↓

Electronic test

↓

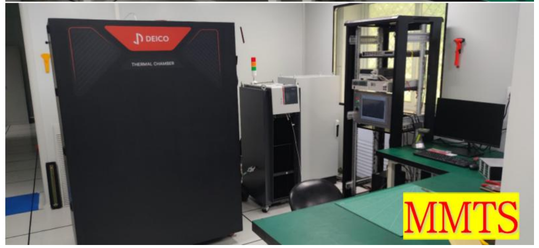
Encapsulation

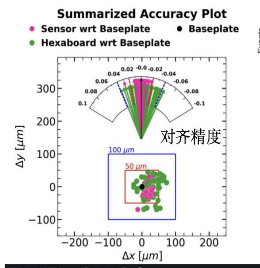
↓

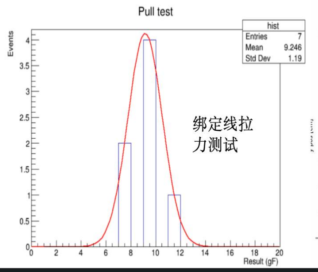
MMTS thermal cycle + 3 IV scans

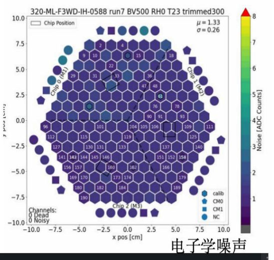
↓

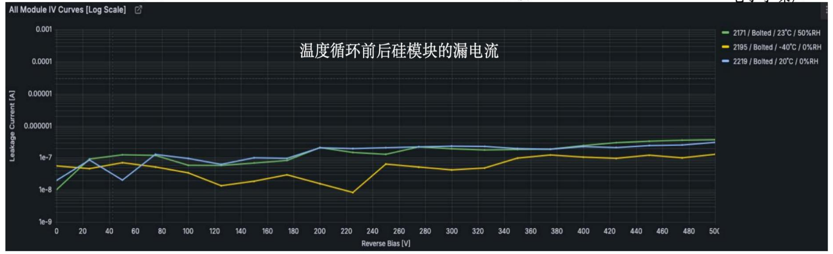
Electronic test











- ❑ 硅模块元器件接收检查
  - ❑ CuW合金底板出厂100%检查测试，高能所5%抽查
  - ❑ Sensor在CERN100%检查测试，高能所5%抽查
  - ❑ 前端电子学板（Hexaboard）接收后，贴胶前后100%检查
- ❑ 硅模块制造质量控制
  - ❑ 组装后：对齐精度，厚度，平面度
  - ❑ 绑定后：电子学噪声，抽检绑定线的拉力
  - ❑ 封装后：温度循环测试（20度到-40度，循环6次）：漏电流，电子学噪声

HGCal硅模块量产

Joseph Incandela 2026/2/2 HGCal workshop上的报告

CMS

Upcoming 5% milestone: ~500 modules to go

Conservative production estimates - based on ***known*** shipments today

Optimistic - based on ***expected*** shipments

	Max Rate of Assembly to Date	Demonstrated Consecutive Days Rate Listed	Projected total modules completed in February	Projected total modules completed in March	More optimistic total modules completed both Feb and March
			Based on component availability of current shipments and assembly with manageable rate		Requires February shipments to arrive as planned and no lapses in production
CMU	8/day	8/day	90	150	290
IHEP	16/day	16/day	80	150	280
NTU	8/day	8/day	60	160	270
TIFR	4/day	2/day	20	45	100
TTU	16/day	12/day	50	150	225
UCSB	12/day	4/day	80	140	270
			Total for February 370	Total for March 795	Max Feb + March 1329

HGC Workshop – Modules –Feb. 2, 2026 - J.Incandela

首个CE-E Cassette中的全尺寸低密度硅模块全部由高能所站点提供

CERN Accelerating science

ABOUT NEWS

CERN news 2026/01/29

News ›

Voir en français

Groundbreaking CMS calorimeter for the High-Luminosity LHC

CMS has recently completed the first prototype slice of its innovative High-Granularity

HGCAL physicist Dimitra Tsionou placing a hexagonal module on a large copper cooling plate, using a vacuum support tool to avoid physical damage. Each module consists of a hexagonal silicon sensor sandwiched between a high-density copper-tungsten alloy baseplate and a printed circuit board. These modules come from six different module assembly centres: IHEP in Beijing, NTU in Taipei, TIFR in Mumbai, UCSB in Santa Barbara, CMU in Pittsburgh and TTU in Texas. (Image: CERN)

高能所在新闻报道中被排在第一位

- ❑ 高能所是首个实现16块/天（0.32 m²/天）生产速度的站点
  - ❑ Gantry每批次4块，每天4批次（90分/批次）
  - ❑ 绑定：～20分钟/块；封装：～15分/块
  - ❑ 温度循环测试：24块/每批次，～24小时
- ❑ 2025/7-2026/6，高能所共生产了500+块硅模块（～10m²），完成承担任务的～10%。

HGCal硅模块量产统计

- 硅模块良品率：94.2%（507/538）
  - 组装对齐精度A/B 级：99.8%
  - 通道良道率：98.7%
  - 温度循环后A/B 级：95.0%
- 各个硅模块组装中心（MAC）统计

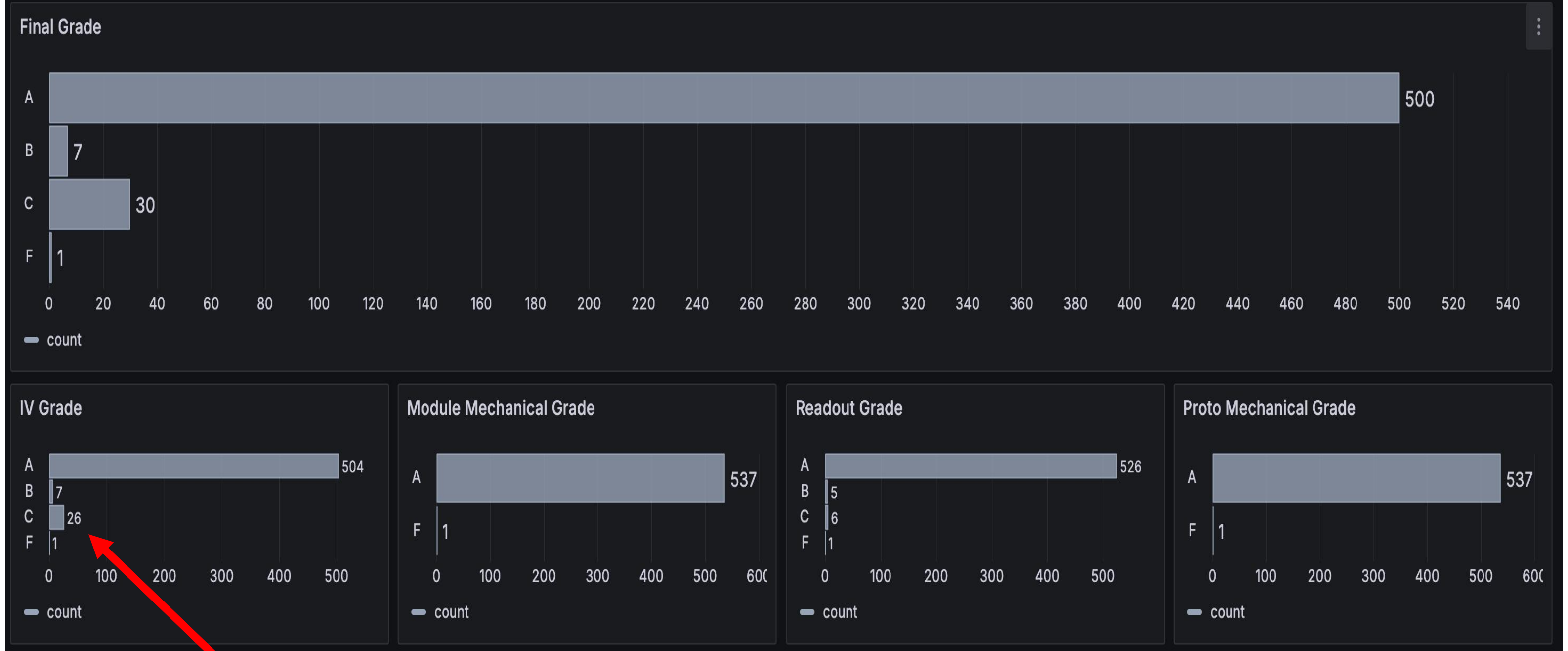
MAC	Total number	Garade A+B	Yield
IHEP	538	507	94.2%
CMU	230	216	93.9%
TTU	375	332	88.5%
UCSB	636	590	92.8%
NTU	772	697	90.3%
TIFR	2	-	-

截止到2026年7月

高能所站点硅模块统计
CERN 数据库

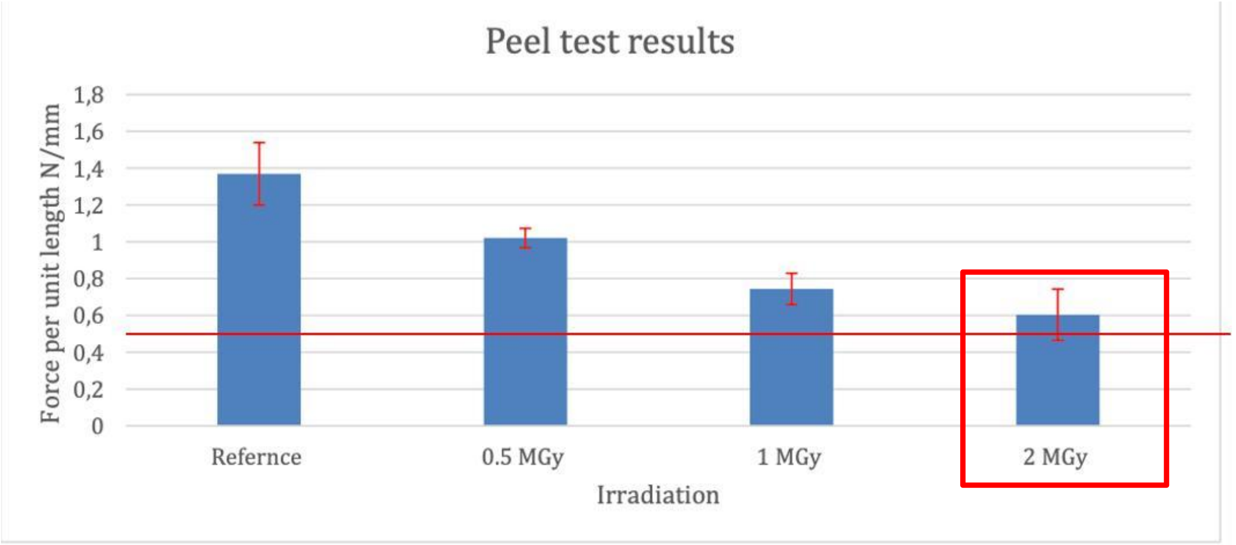
Grade Summary by Series

Series ↓	Total Graded	A	B	C	F	A+B (Installable)	% Installable
MLF3WD	379	343	7	28	1	350	92.3%
MLF3WC	159	157	0	2	0	157	98.7%
All	538	500	7	30	1	507	94.2%



主要问题：
I-V，正在调查

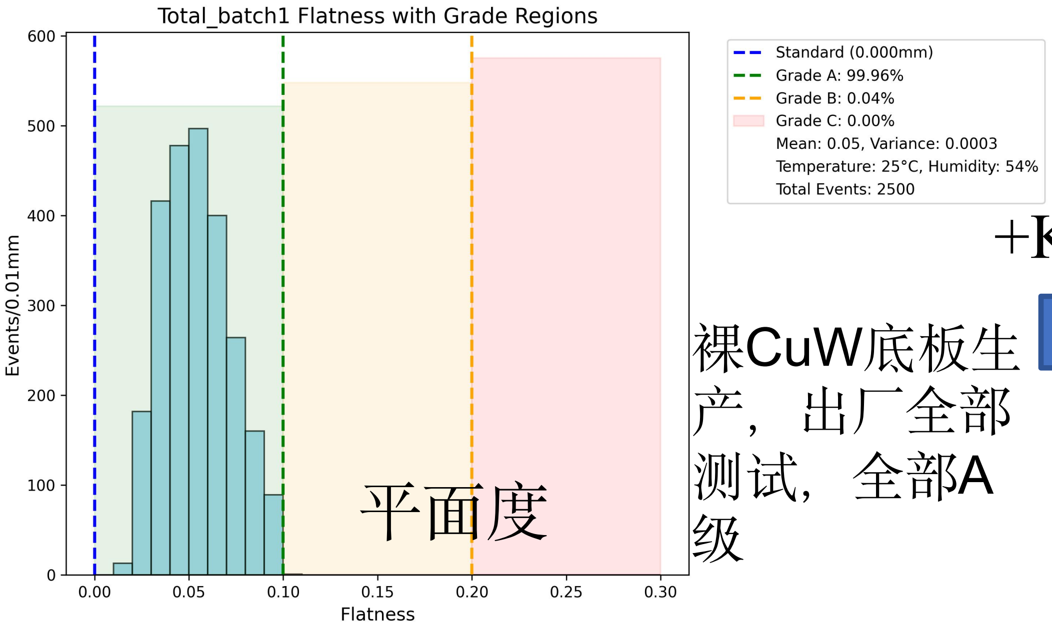
CE-E的CuW R&D



	CF	Alumina	CuW (1.4 mm)	Titanium	PCB
Si Max Stresses (MPa)	139	94	84	91	115
Module Max. vertical def. (mm)	0.126	0.070	0.018	0.047	0.024

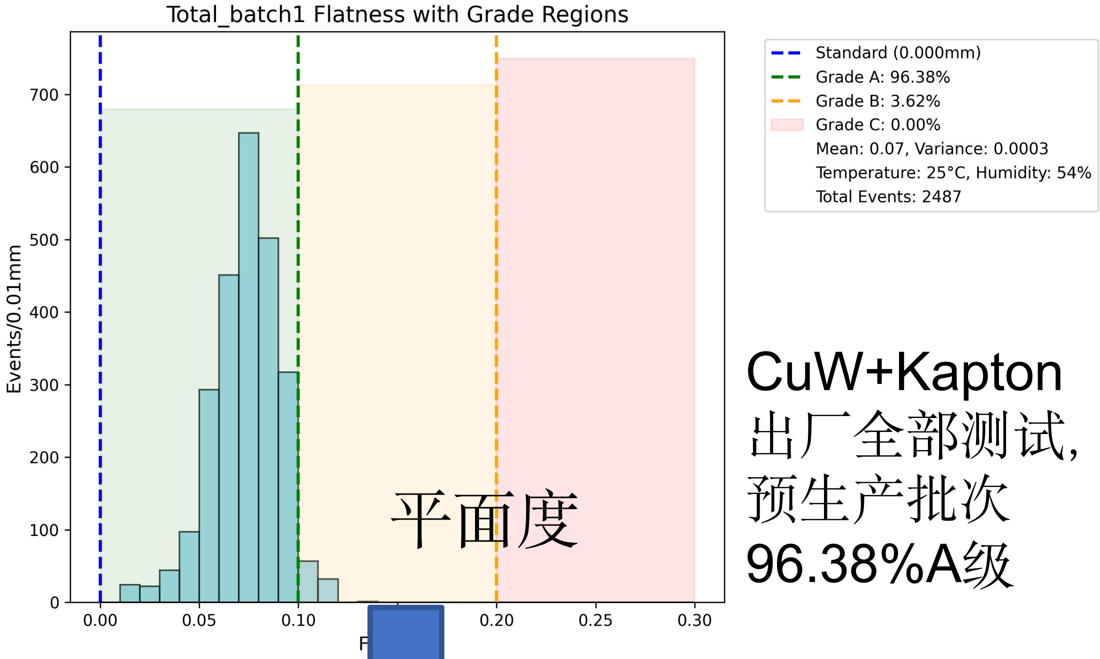
- ❑ 辐照测试（CIEMET，KIT），拉力测试（CERN）
  - ❑ 总辐照计量0.5MGy, 1MGy, 2 MGy
  - ❑ 在最大接收了2 MGy辐照之后，Kaptoon薄膜与CuW之间没有明显的开裂，并且Kaptoon薄膜与CuW之间的拉力满足要求
- ❑ 模拟研究
  - ❑ 应力测试（CERN）：-35度，CuW+Si承受压力84Mpa（<350MPa）
  - ❑ 热传导测试（UCSB）；热传导的变化和梯度分布表现正常
- ❑ 高能所提出的CuW和Kapton薄膜的方案，通过了CERN的抗辐照测试。2024年CMS合作组确定：～90%的全尺寸CuW和kapton由高能所和国内的企业共同提供。

CuW+kapton薄膜的生产

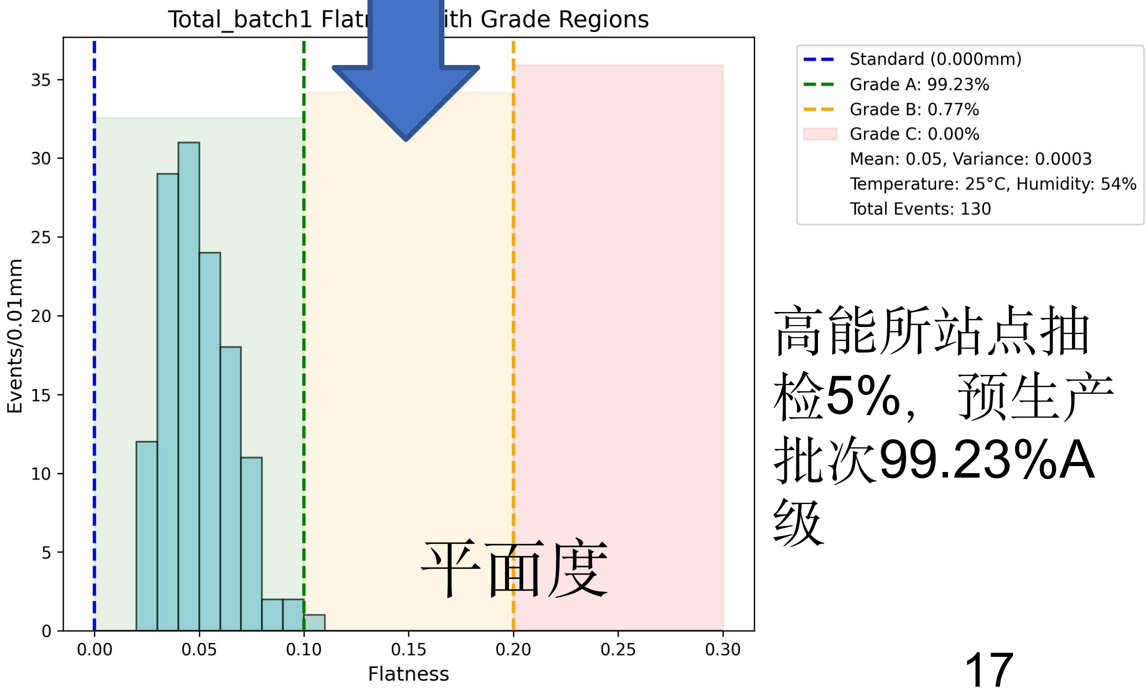


裸CuW底板生产，出厂全部测试，全部A级

+Kapton



CuW+Kapton出厂全部测试，预生产批次96.38%A级



高能所站点抽检5%，预生产批次99.23%A级

- CuW+kapton薄膜板生产质量控制
  - 裸CuW板生产只接收A级
  - 粘贴Kaptoon薄膜后，A级比例控制在99%
  - 高能所5%抽查，抽查A级比例好于99.5%
- 2025年8月～26年3月，生产交付了2个批次共3700块CuW+Kapton底板
- 全部预计2027年4月全部交付

总结与展望

- ❑ HGCal是全新一代5D抗辐照量能器
  - ❑ 满足提供抵抗10^{16}neq/cm^{2}的要求
  - ❑ 除了能量和位置的高精度测量，还具有～50ps的时间测量能力（压低Pile-up）
- ❑ HGCal升级进展（截止到2026年7月）
  - ❑ HGCal原型机的性能验证：抗辐照，能量，位置以及时间分辨率
  - ❑ 8英寸硅模块的生产工艺验证，闪烁体模块的生产工艺验证
  - ❑ 2026年初开始HGCal模块的批量化生产建造，同时开始Casstte的集成验证和组装
- ❑ HGCal模块生产预计于2027年底完成，2028年完成探测器安装
- ❑ 中国CMS组在HGCal中承担了重要的任务
  - ❑ ～100m^{2}硅模块生产（目前生产～10%），～90%全尺寸CuW+kapton生产（目前完成～30%）
  - ❑ 前期还参与了部分尺寸硅模块前端电子学的设计，样机束流测试以及性能验证
- ❑ 继续深入参与HGCal探测器的性能研究以及相关的物理分析工作

感谢大家

中国HGCal团队部分人员合影