ATLAS 实验硅径迹探测器升级

史欣

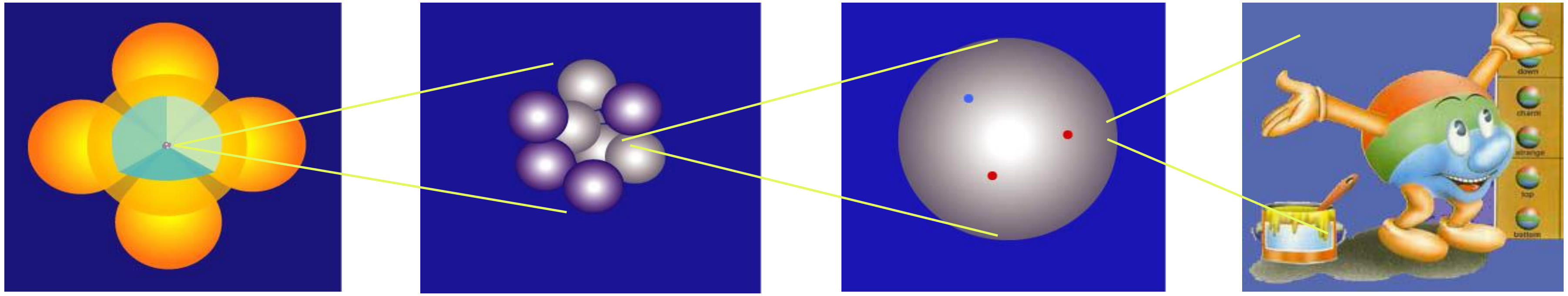
中国科学院高能物理研究所

2026年7月27日

科创计划交流

粒子物理

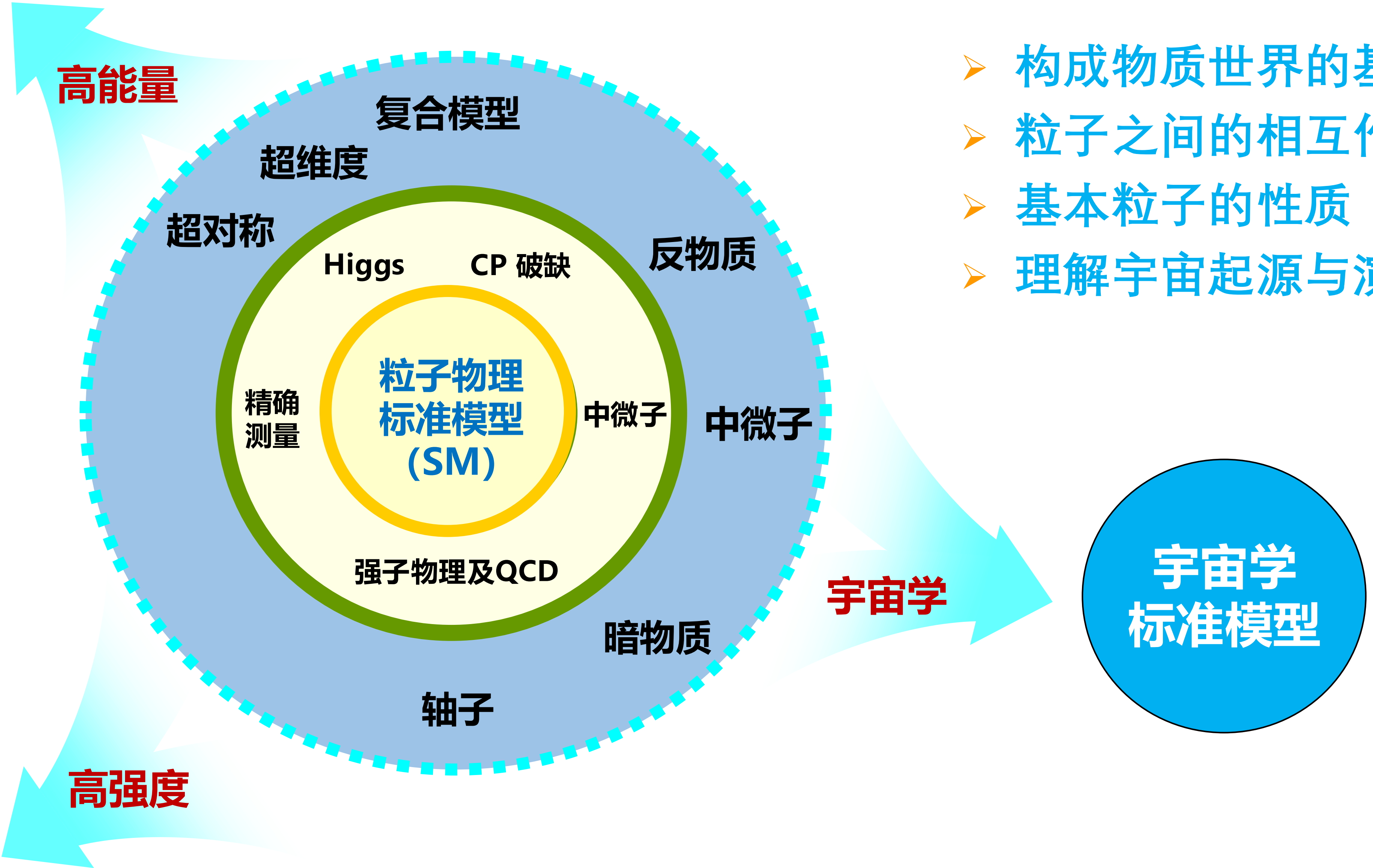
- **粒子物理，也称高能物理, 是对分子(→化学)、原子(→凝聚态物理)、原子核(→核物理) 研究的自然发展与深化**



atom	nucleus	nucleon	quark
原子	原子核	核子(质子、中子)	夸克
10^{-10} m	10^{-14} m	10^{-15} m	$<10^{-17}$ m

物质世界的基本组分及其相互作用是自然界最基本的科学问题之一

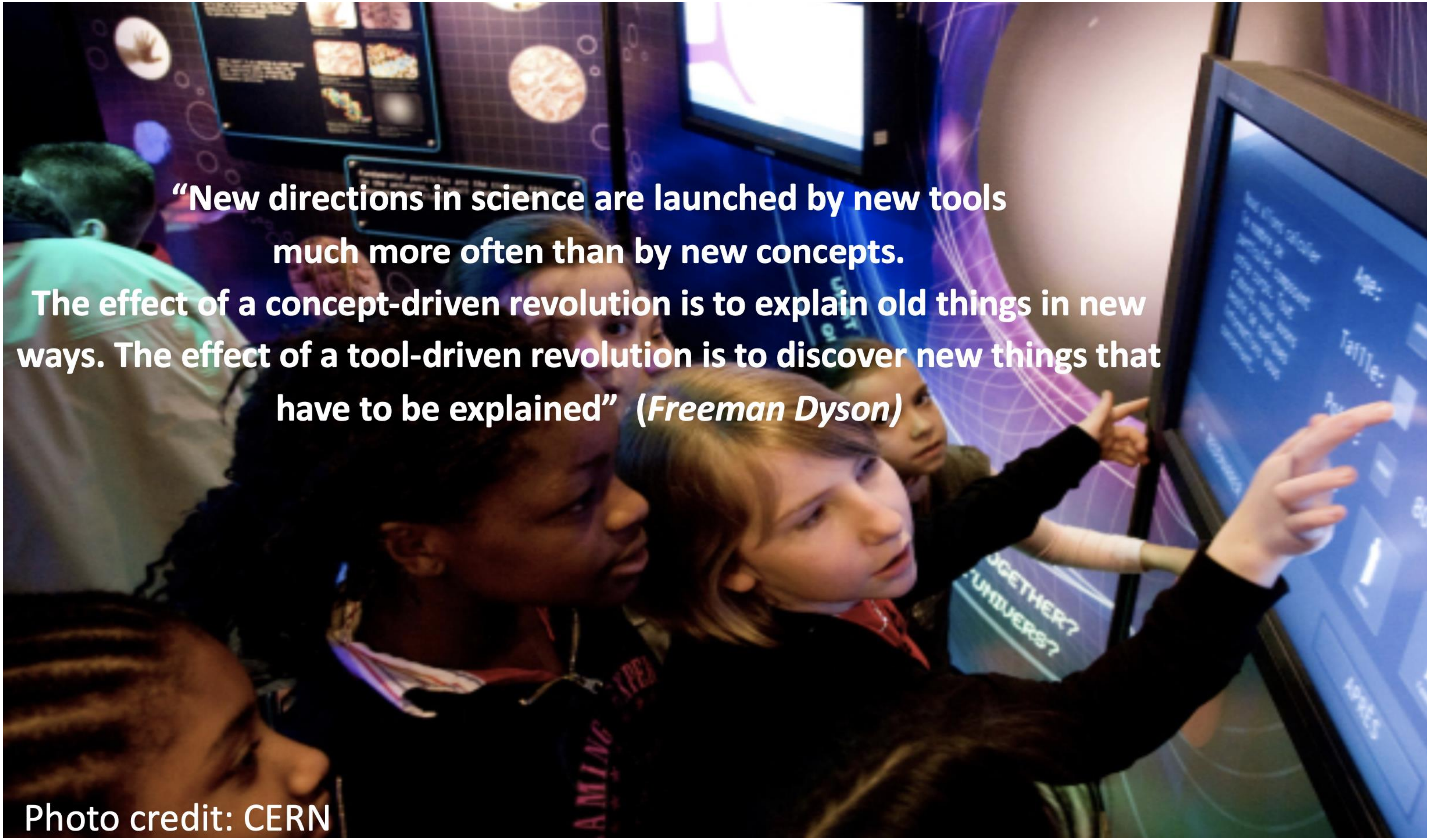
粒子物理研究的内容与目标



- 构成物质世界的基本粒子
- 粒子之间的相互作用
- 基本粒子的性质
- 理解宇宙起源与演化


Smiling Face
10 Centimeters

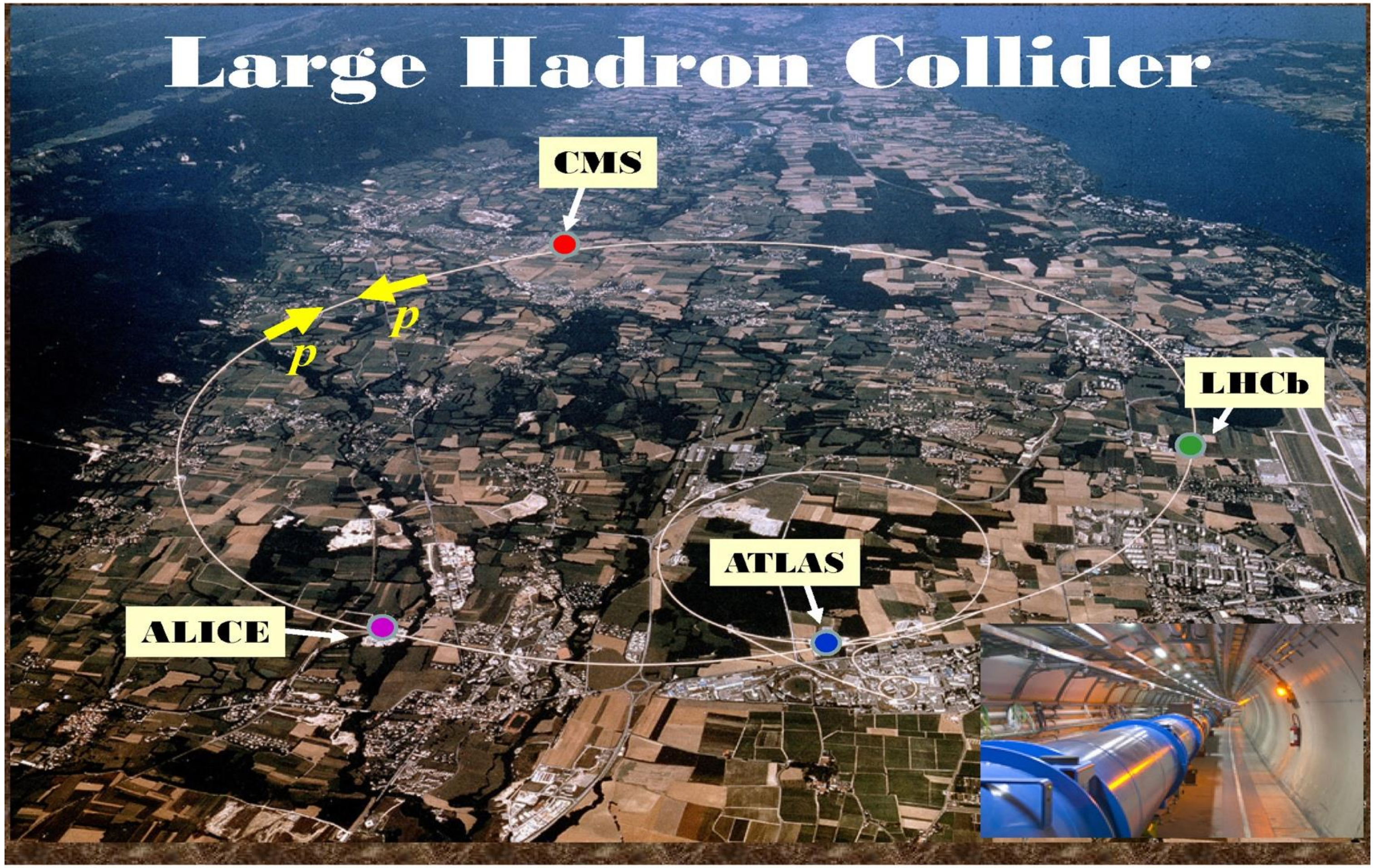
只要有绝妙的物理“概念”就好了，
为什么还要创造新的工具？



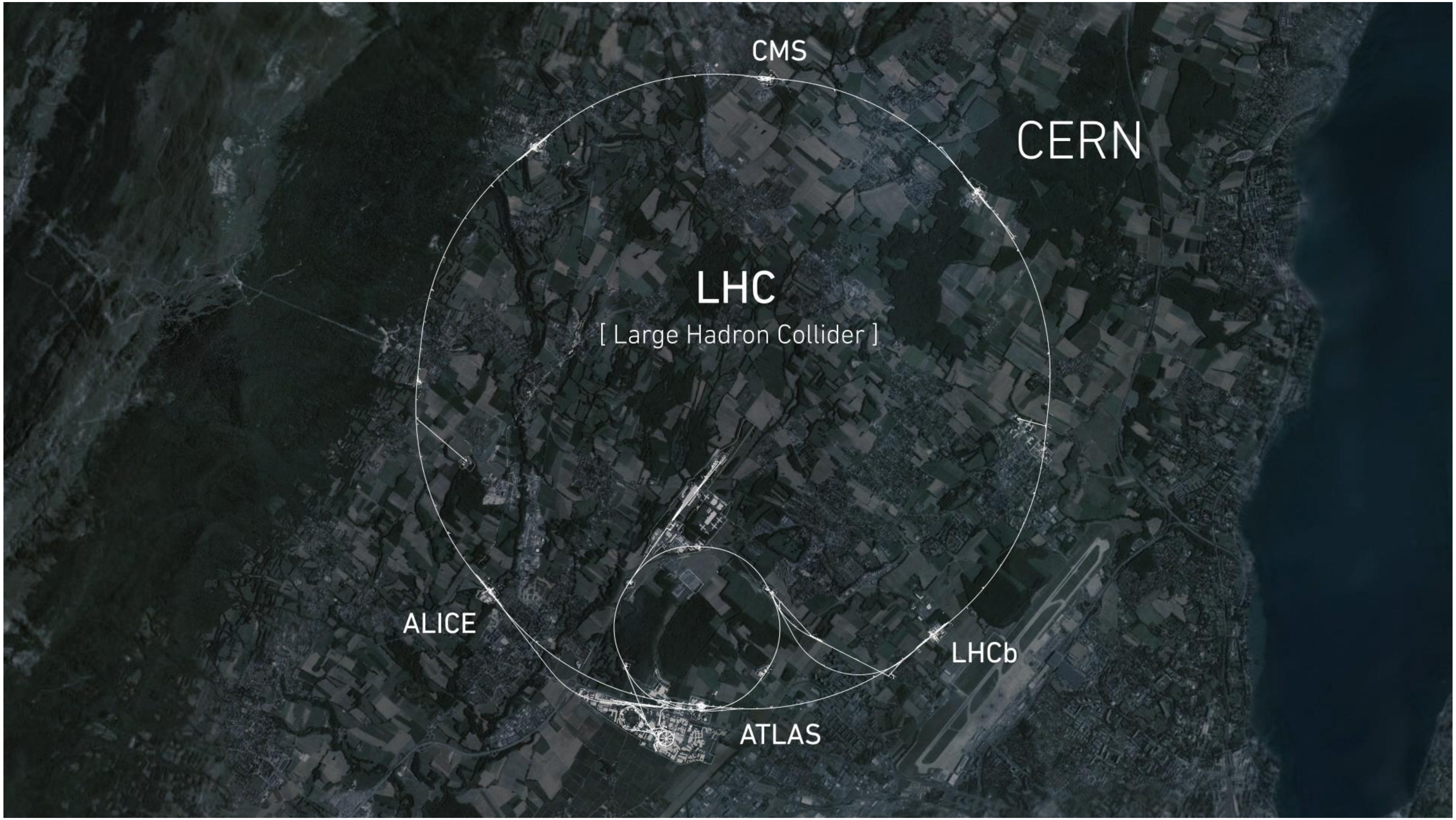
“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained” (*Freeman Dyson)*

Photo credit: CERN

CERN – LHC 大型强子对撞机

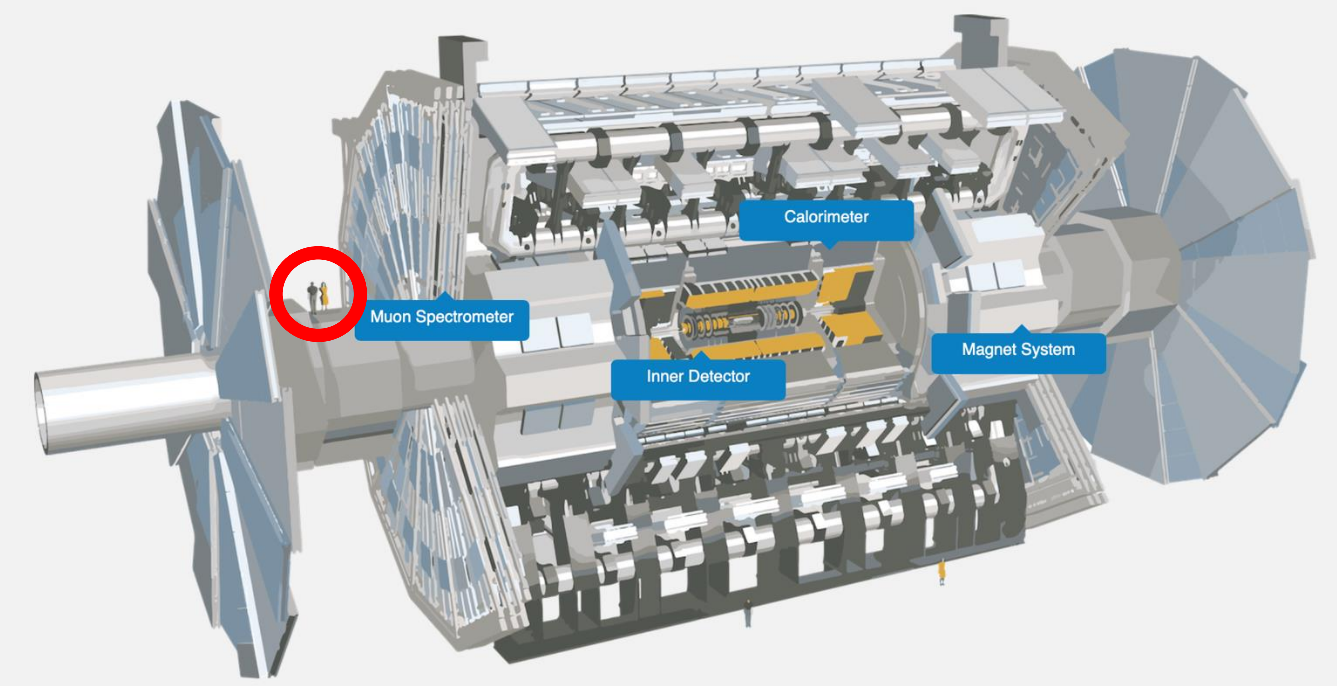


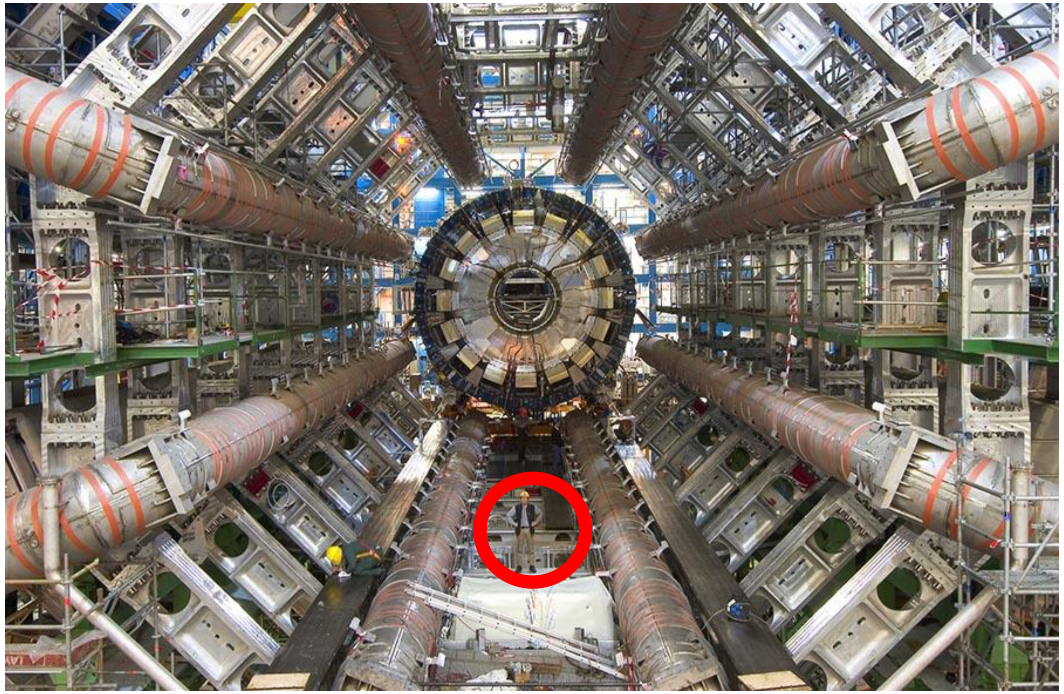
- 世界上最大的高能粒子物理实验装置
- 上万名世界各地的科学家
- 四大对撞实验
  （ATLAS，CMS，ALICE, LHCb)
- 2012 发现希格斯粒子
- 2013 诺贝尔奖 
- 2025 “基础物理学突破奖”


CMS
CERN
LHC
[Large Hadron Collider]
ALICE
LHCb
ATLAS

ATLAS EXPERIMENT

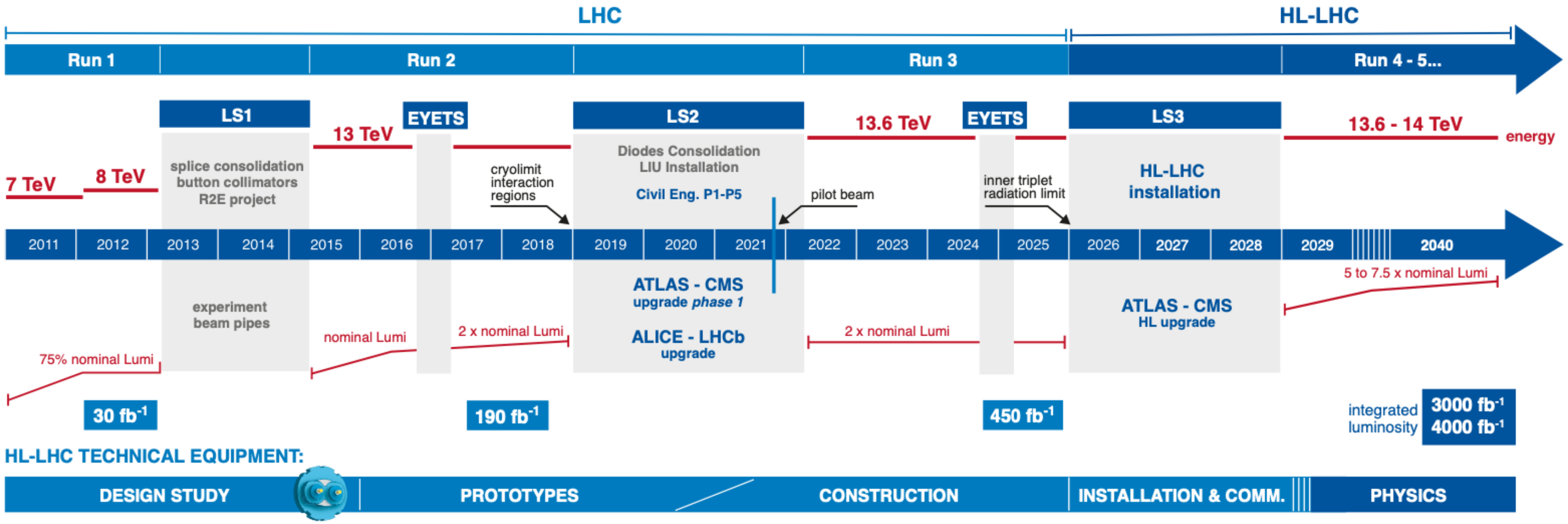
https://atlas.cern

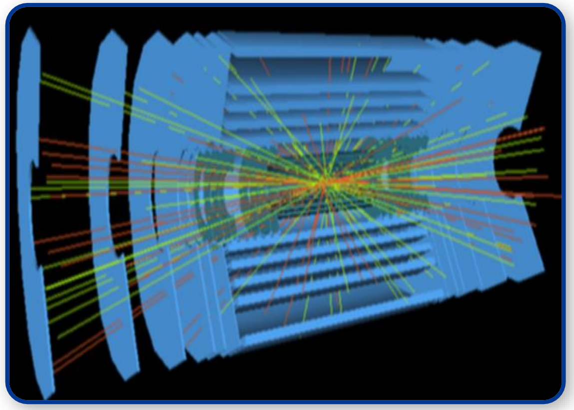


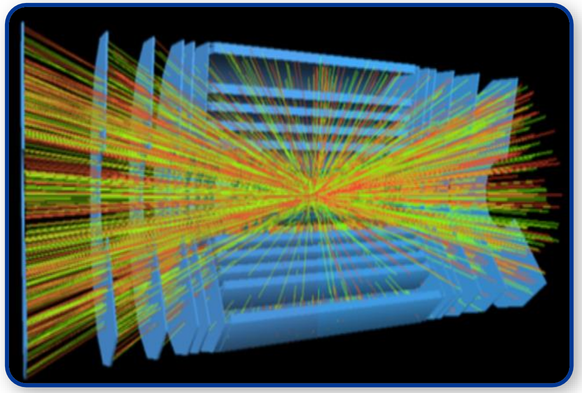


- 世界最大的粒子探测器
  (46 米长，25 米高，7000 吨)
- 成员超过 5500 人，科学家 3000 人
- 42 个国家，182 个单位

大型强子对撞机高亮度升级 （HL-LHC）

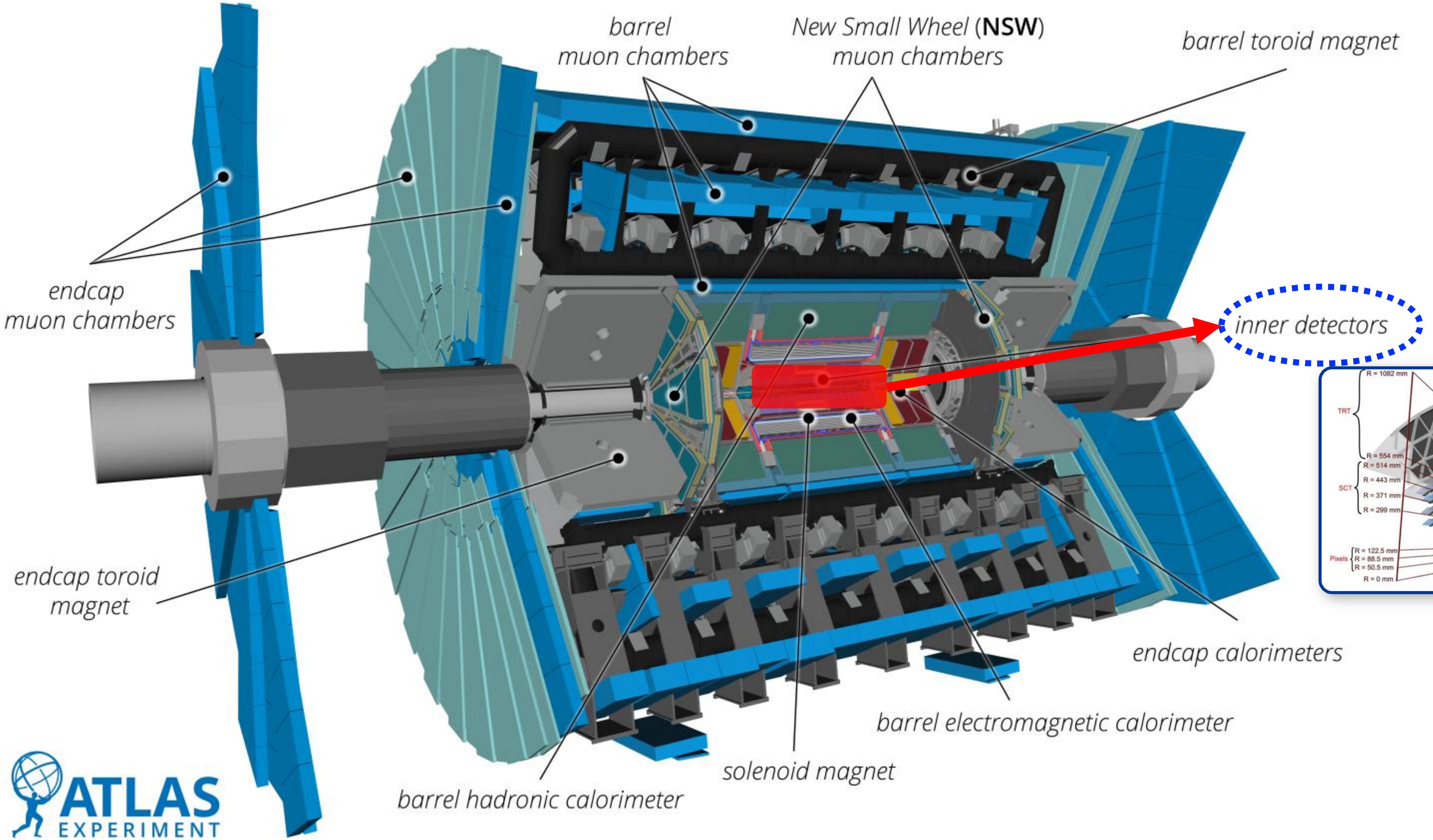


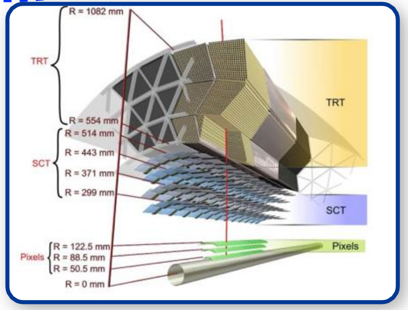




- 计划提高10倍积分亮度，~2030年完成
- 瞬时亮度高达 $7.5\times10^{34}\ cm^{-2}s^{-1}$
- 每次对撞堆积事例数高达200

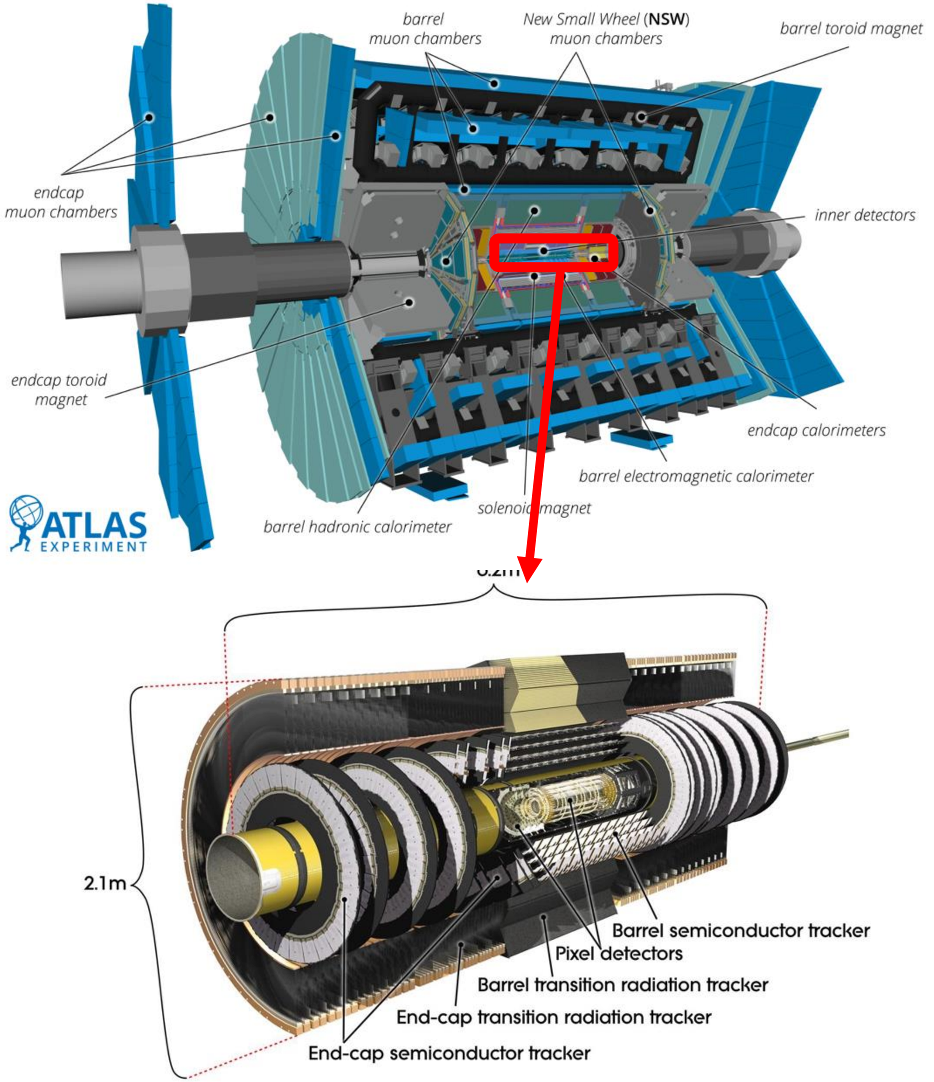
Current ATLAS Detector





ATLAS Inner Detector

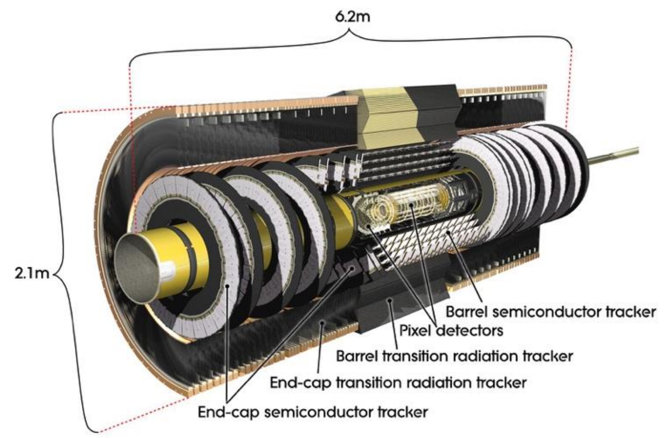
- The current running Inner Detector (ID) is playing a pivotal role in ATLAS physics analyses



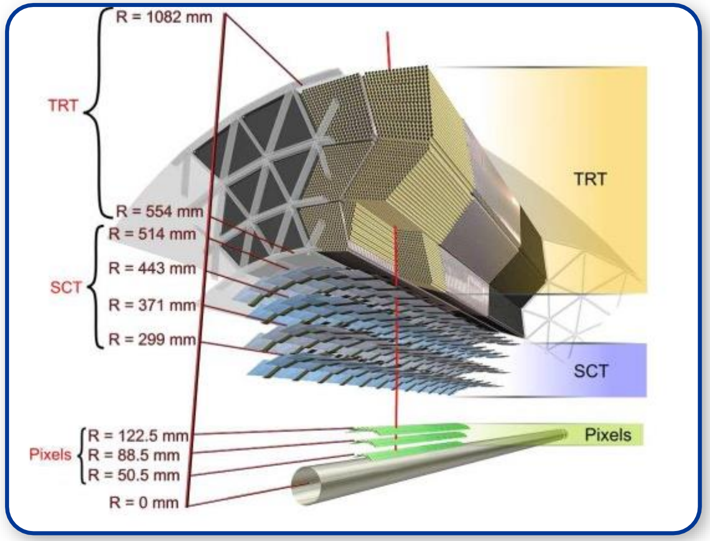
- Charged-particle reconstruction, heavy-flavor tagging, identification of electrons, photons, muons and tau-leptons
- Identification of primary and secondary vertices
- Full reconstruction of exclusive decay modes, tracking of interactions and photon conversions
- Pile-up vertices and pile-up jet rejection
- Particle identification through transition radiation and dE/dx
- Improve jet energy measurements, determination of isolation criteria and measurement of missing transverse energy

Motivation of Inner Tracker Upgrade

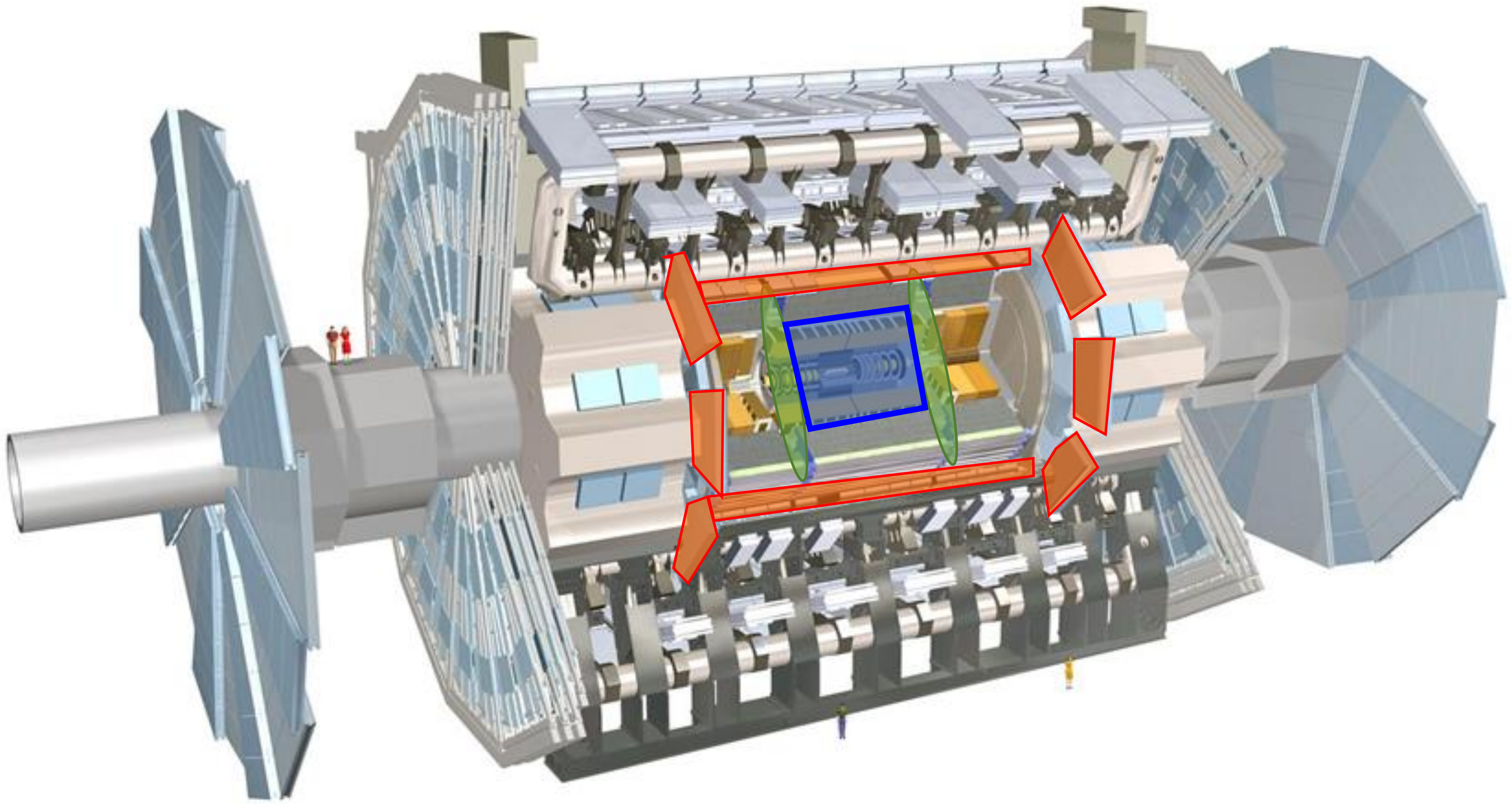
- Radiation Damage
  - Current tracking detector can not meet the HL-LHC: 4000 /fb
    ID (400 /fb) SCT (700/fb), IBL (850/fb)
  - Above the design fluences, the intrinsic hit efficiencies drop and leakage currents exceed power supplies limits, affect on-detector power and cooling system
- Bandwidth Saturation
  - Current front-end electronics can not handle luminosity 7.5×10^{34} $cm^{-2}s^{-1}$, <PU>200
    Pixel and SCT: 2×10^{34} $cm^{-2}s^{-1}$, <PU>50
- Detector Occupancy
  - TRT occupancy will reach 100%



Current Inner Detector



ATLAS Phase-2 Upgrade



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

Additional small upgrades

- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

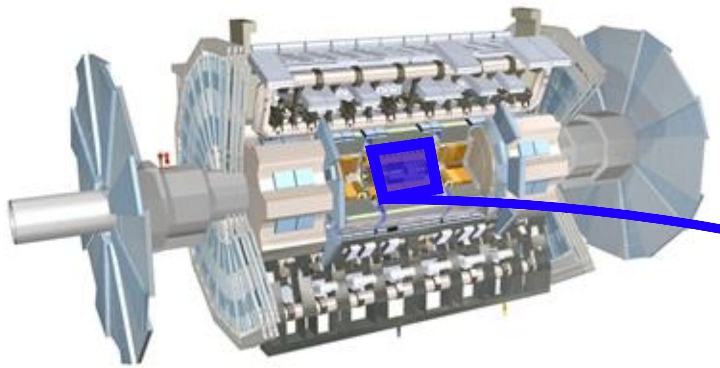
New Muon Chambers

- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

New Inner Tracking Detector (ITk)

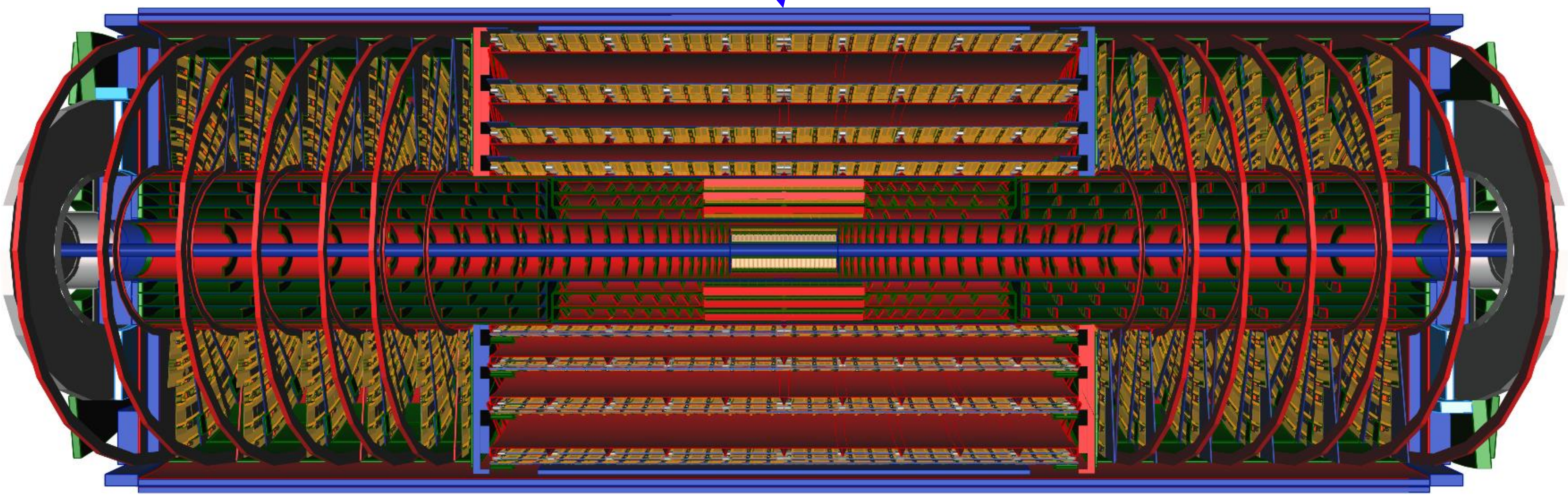
- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

ATLAS Inner Tracker (ITk) Upgrade



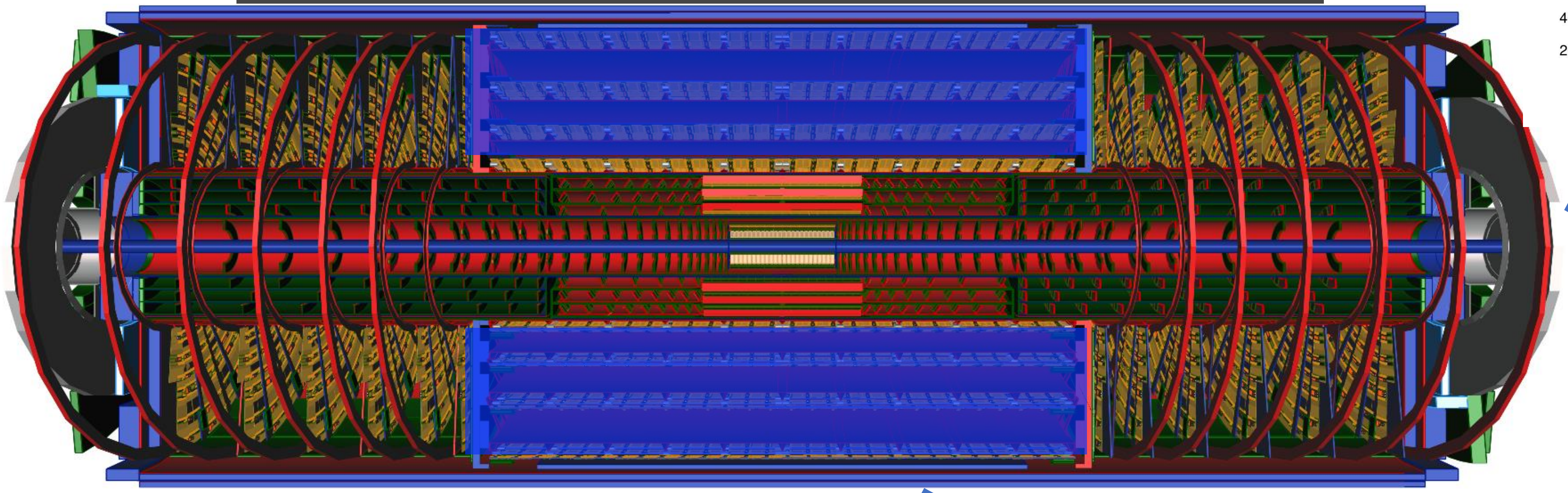
Inner Tracking Detector (ITk)

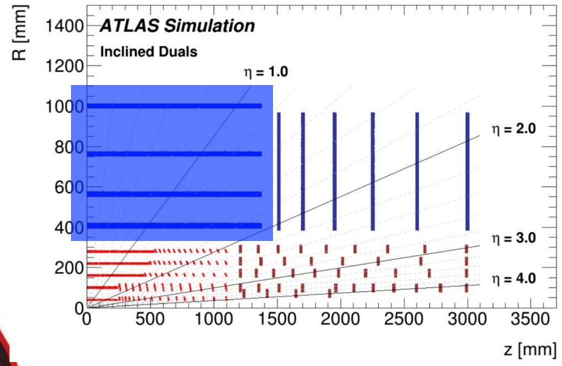
- All silicon with at least 9 layers up to |η| = 4
- Less material, finer segmentation

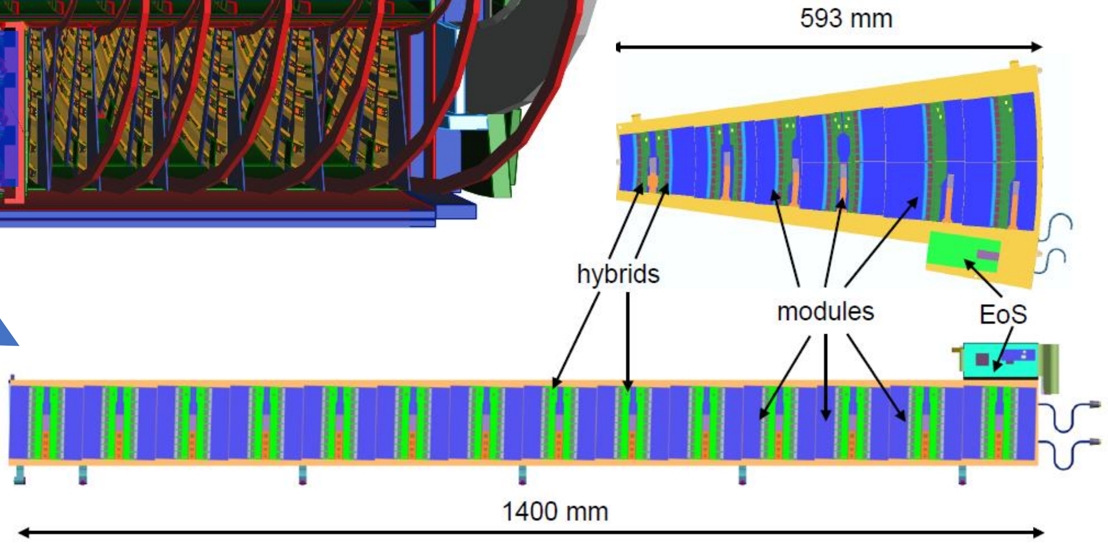


ATLAS 内径迹硅微条探测器

约18000 个模块 / 6千万道读出 / 165m^2

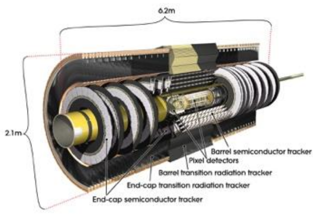


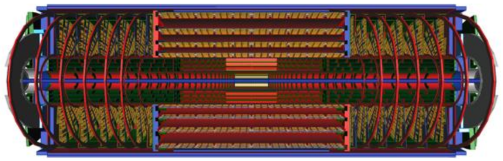


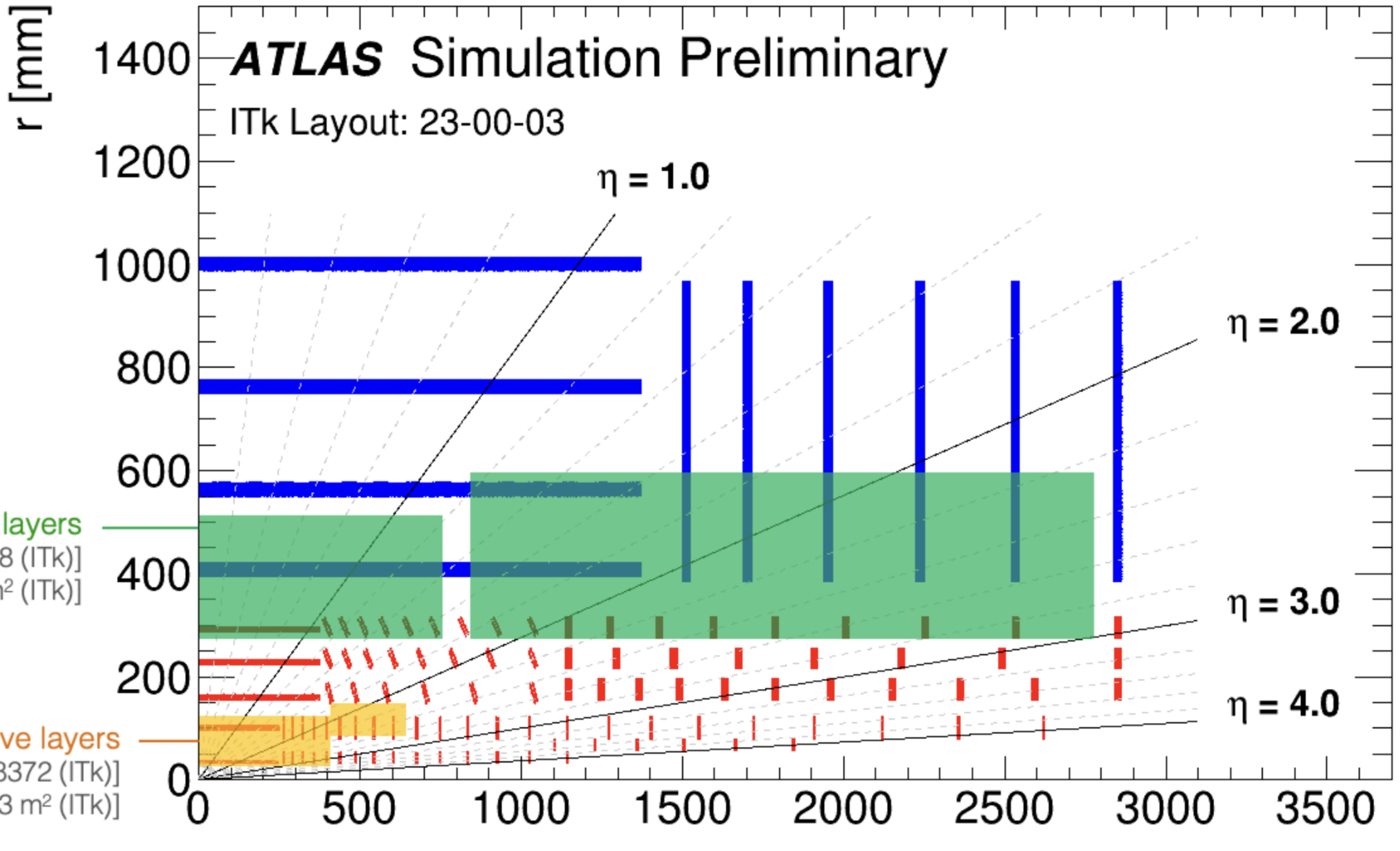


- 全硅探测器
- 高空间分辨
- 抗辐照
- 低物质量

ATLAS New Inner Tracker (ITk)

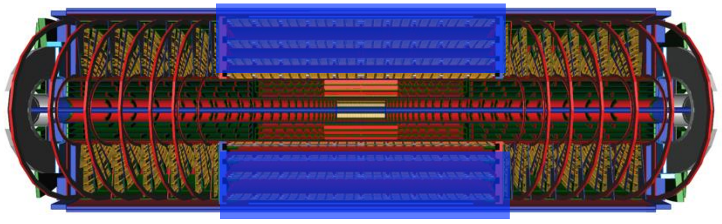






Currently 100 M channels (Pixels) —> 5 B channels (ITk Pixels)

ITk Strip Barrel Detector

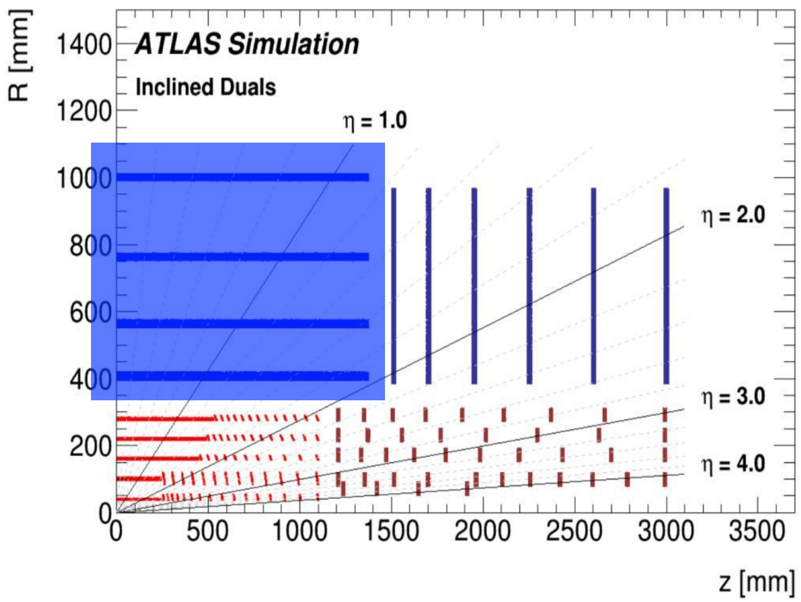


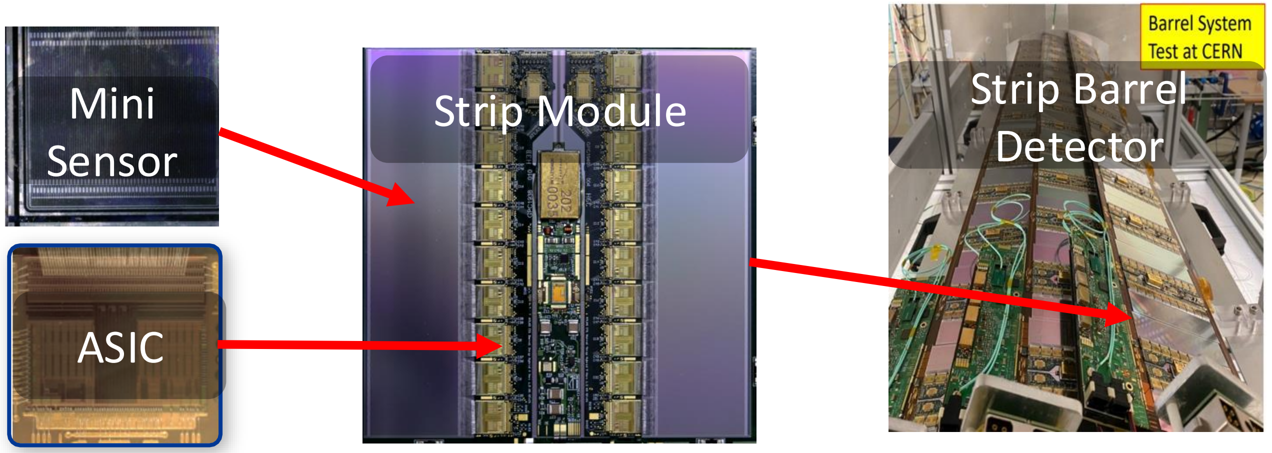
Deliverables

- Complete strip barrel detector with 25μm spacial resolution
- Provide strip module spacial resolution evaluation report

Contents

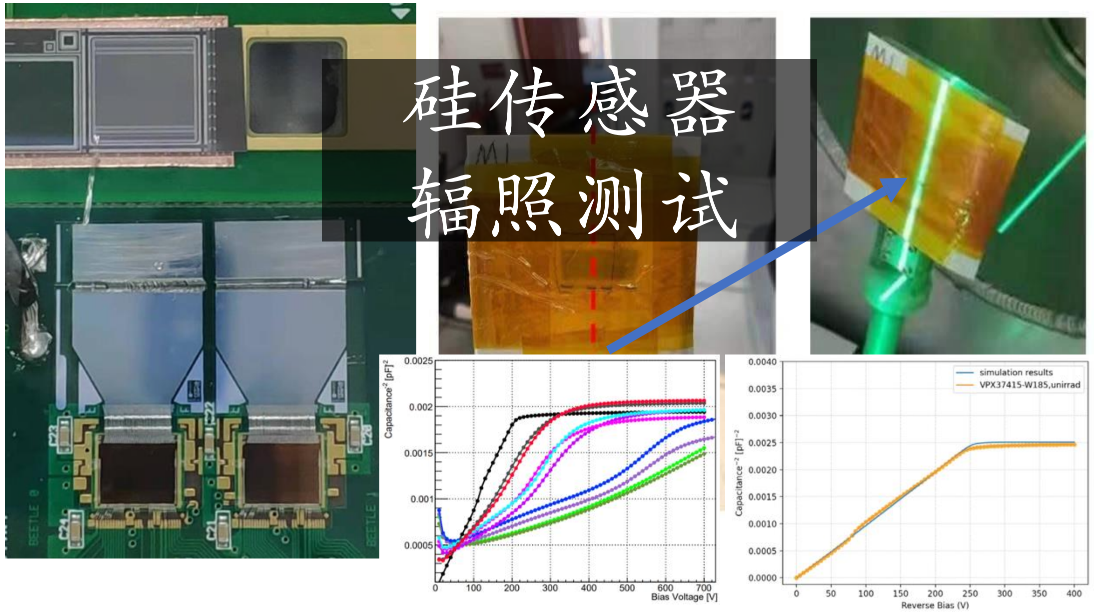
- Radiation hard sensor and readout ASIC study
- High performance strip detector module production
- Complex silicon detector system integration





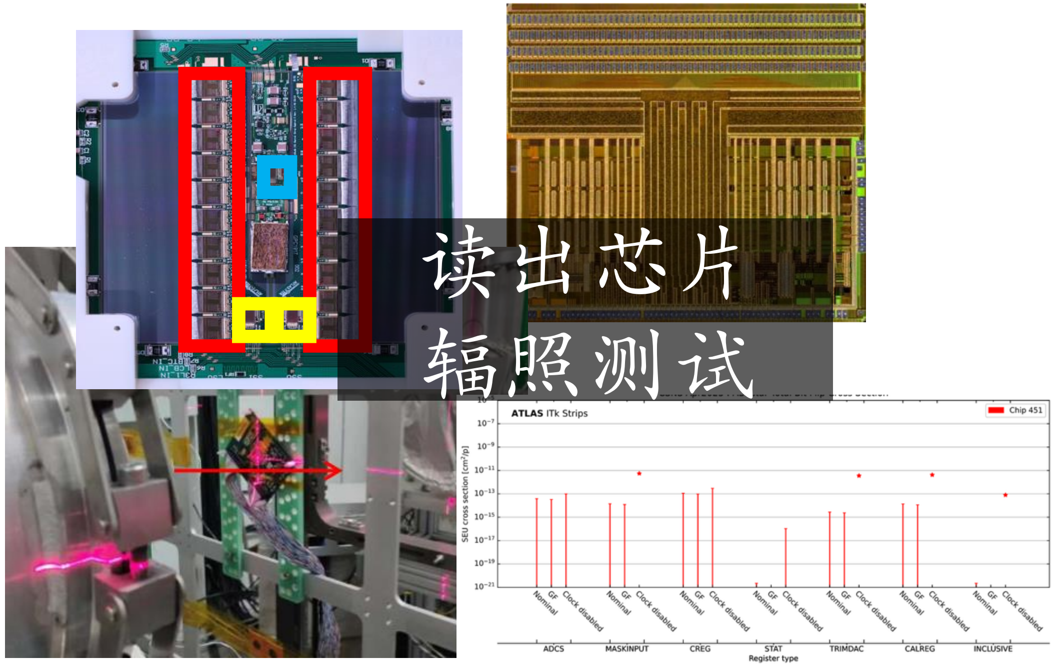
ATLAS硅微条传感器与读出芯片抗辐照研究

- 利用**散裂中子源**伴生质子束开展读出芯片与硅微条传感器辐照研究
  - 开展辐照测试、器件标定、恒温箱制备、仿真模拟等
  - 正式成为硅传感器质量保证（QA）**国际辐照站点**



Feasibility study of CSNS as an ATLAS ITk sensor QA irradiation site

Hui Li [a,b,*], Zhan Li [b], Shudong Wang [b], Zijun Xu [b], Xin Chen [a], Mingming Xia [a], Yingjun Huang [d], Yang Liu [d], Zhixin Tan [e,b], Hantao Jing [e,b], Suyu Xiao [f,g], Vitaliy Fadeyev [h], Miguel Ullan [i], Yoshinobu Unno [j], Xin Shi [b,c]



Single event effect in ABC ASICs for ITk strip upgrade

Shaogang Peng [a,b], Matthew Basso [c,d], Xin Chen [a], Jeff Dandoy [e], Bruce Gallop [f], Jaya John John [g], Hantao Jing [h], Paul Keener [i], Pedro Leitao [j], Weiguo Lu [b,k,*], Peilian Liu [b,k], Qiang Li [h], Yang Liu [l], Hui Li [a], Godwin Mayers [m], Mitchell Newcomer [m], Peter Phillips [f], Xin Shi [b,k], Zhixin Tan [h], Matt Warren [n], Chengwei Wang [b], Mingming Xia [a], Yan Zhou [a]

ATLAS 硅微条探测器模块研制合作

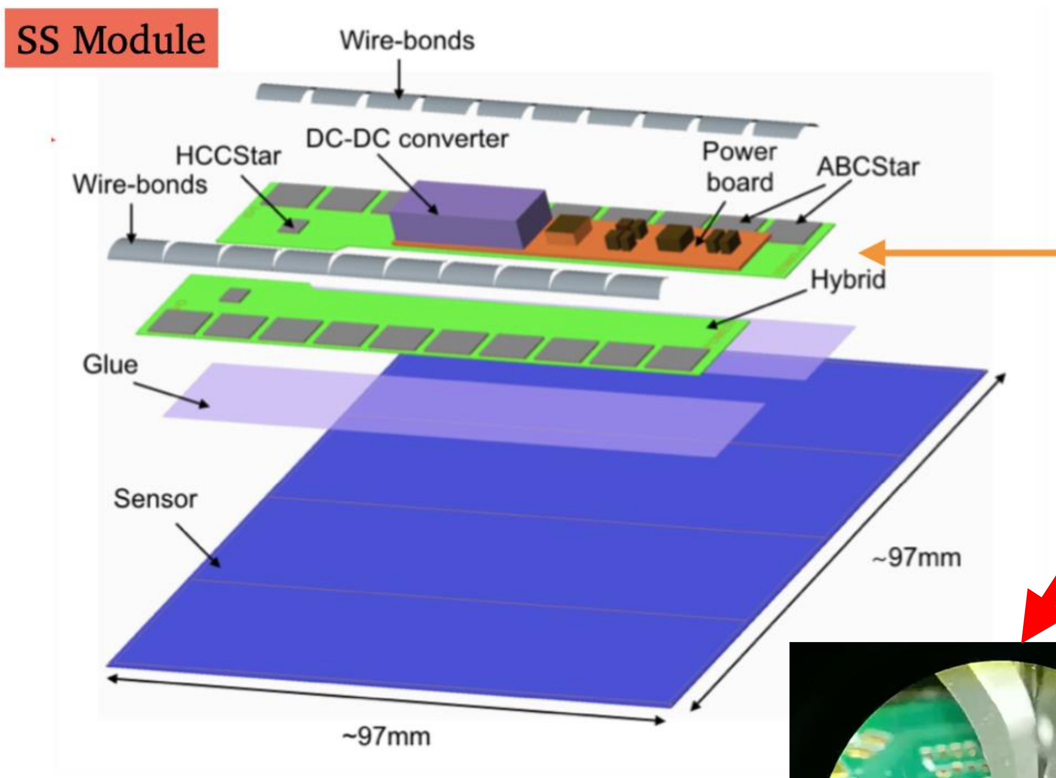
16个不同的资助机构的50个单位共同承担

中国：高能所、清华、中山、上交、山大
承担 1000 个模块制造 （$10m^2$ 硅探测器）

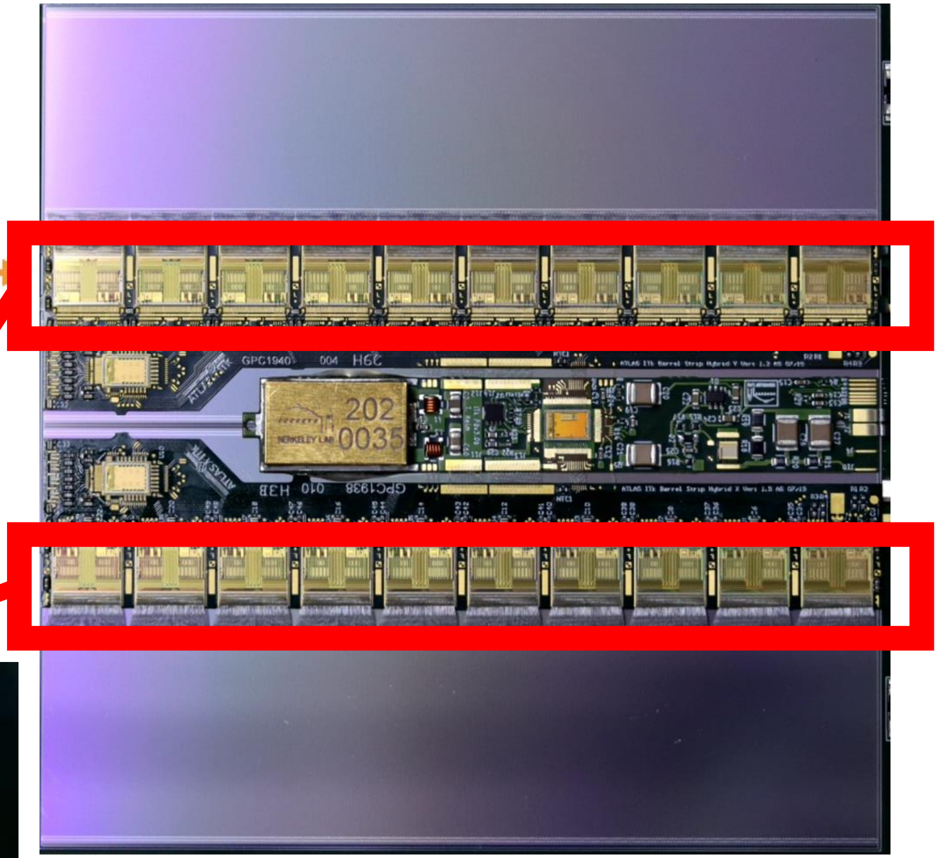
中英集群
50%桶部硅微条探测器

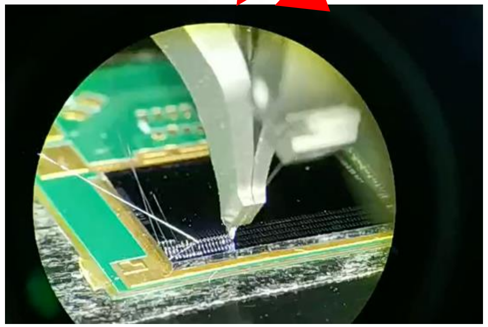
硅微条探测器模块研制

硅微条模块的基本组成



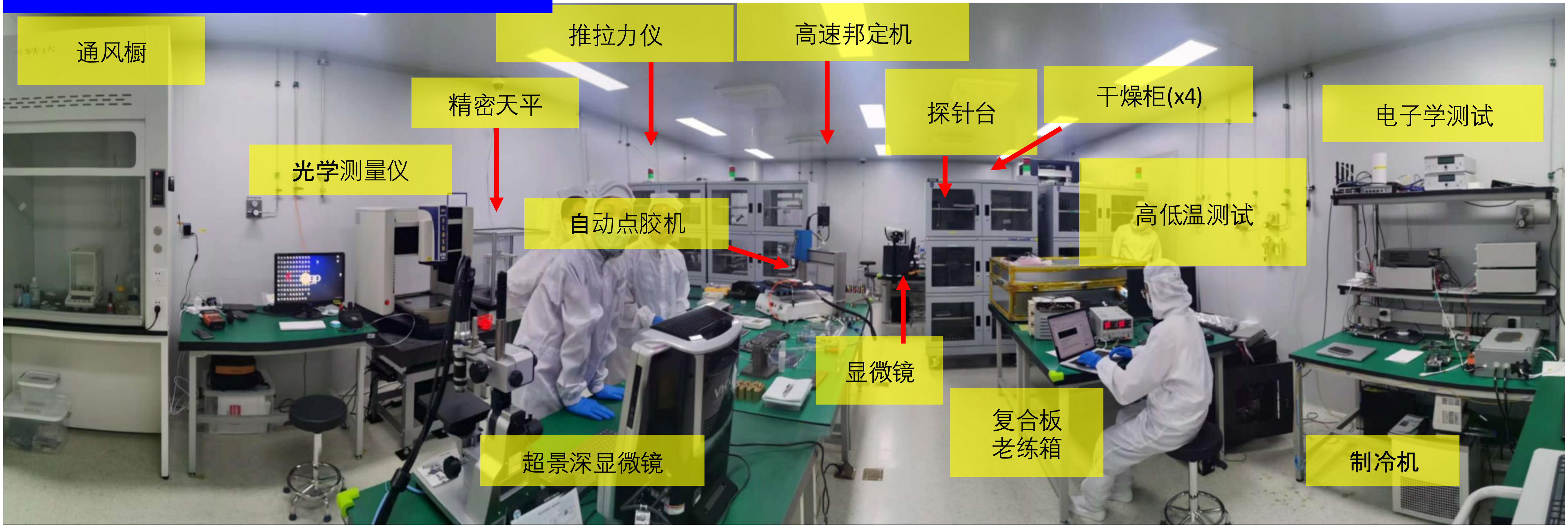
短微条模块





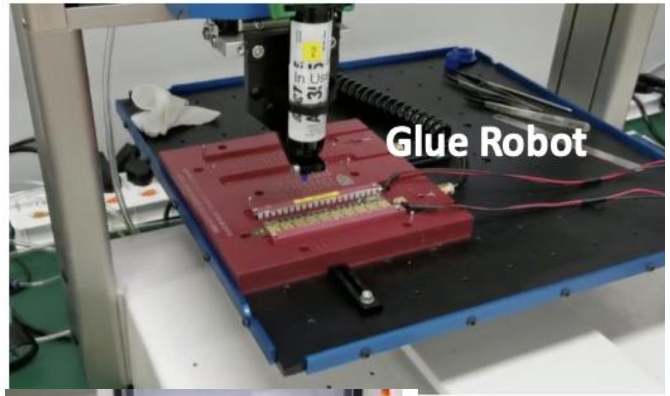
硅微条探测器研制实验室

高能所万级洁净间

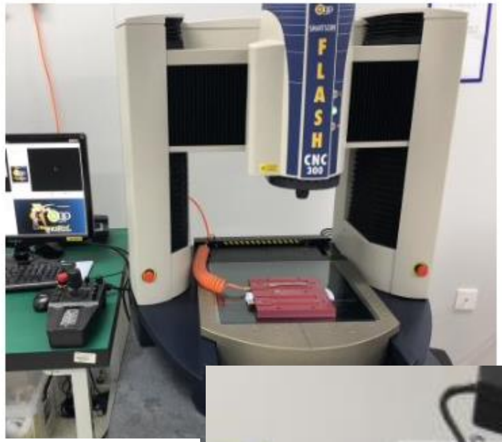


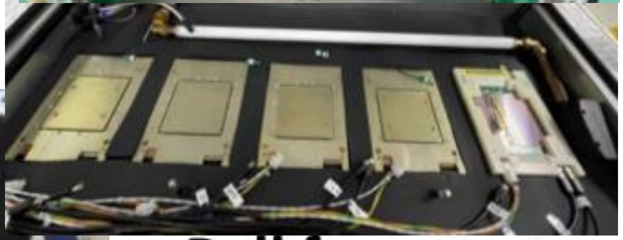
硅微条模块研制关键流程

Calibration of glue amount

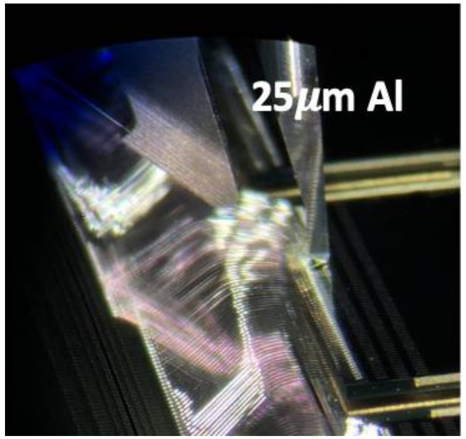


Metrology of glue thickness

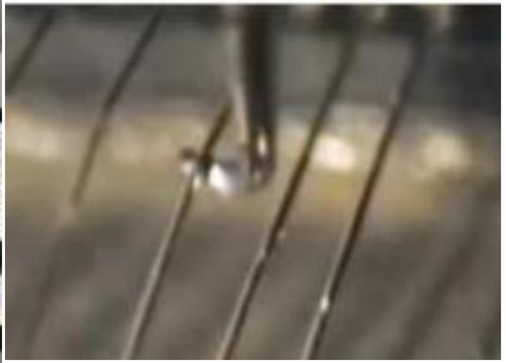


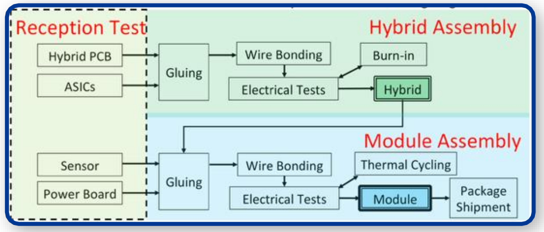


Wire bonding



Pull force test



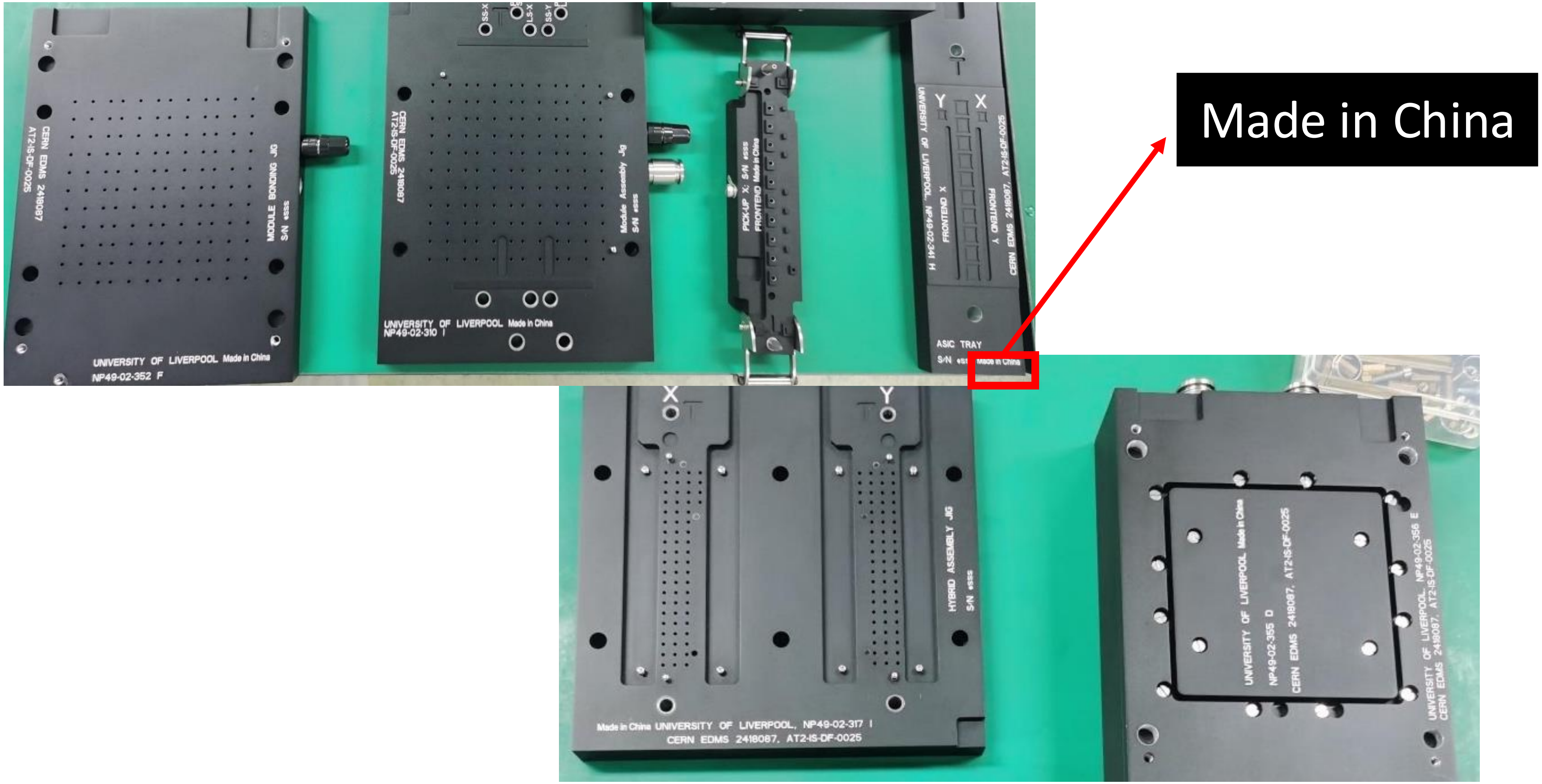


Step Number	Qualification Step	Review End Date
3.2	Sensor Storage	finished: 2021-06-17
6.1	PB Reception	finished: 2022-01-11
6.2	PB E tests	finished: 2022-07-14
6.3	PB Vis Insp	finished: 2021-12-16
6.4	PB Storage	finished: 2021-06-17
8.2	Storage + shipping of glue	finished: 2021-08-26
8.3	Assembling hybrids	finished: 2021-11-20
8.4	Glue weight measurements	finished: 2021-11-21
8.5	Bonding procedures: hybrids	finished: 2022-05-31
8.6	Metrology: hybrids	finished: 2023-03-07
8.7	Visual inspection: hybrids	finished: 2021-08-06
8.8	Hybrid Burn-in	finished: 2023-05-25
8.10	Hybrid Storage	finished: 2021-06-17
8.11	hyb[illegible]: single panel testing	finish[illegible]2-08-25
11.1	Storage of modules	finis[illegible]21-06-17
11.2	Cleaning module jigs	finished: 2021-06-16
11.4	Storage + shipping of glue	finished: 2021-11-29
11.5	Removing hybrids from panel	finished: 2021-12-09?
11.6	Module Assembly	finished: 2022-02-25
11.7	Metrology: modules	finished: 2023-07-10
11.8	Bonding procedures: modules	finished: 2022-05-25
11.9	Visual inspection: modules	finished: 2021-07-19
11.10	Module Thermal Cycling	finished: 2023-10-29
11.11	Single Module Electrical Test	finished: 2022-10-23
12.1	Shipping modules	finished: 2022-04-25
13.1	Cleanroom standards	finished: 2021-11-25
13.2	ASIC Compliance & Handling	finished: 2021-06-03
13.3	Bond Pulling Procedures	finished: 2021-12-03
14.1	Module Reception	Finished: 2022-01-25

29 步
研制流程

高精度工具国产化

- **国内厂家共同研制精密工装夹具**，精度达到国际合作组标准



Automatic Module Assembly Machine at IHEP

- Steamline the lifting procedure after apply the glue
- Improve the uniformity between different operators

Standard Operating Procedure (SOP)

- Developed at IHEP for local production
  - All SQ 29 steps have been implemented in SOP
  - Interact with ITk central Production Database

http://atlasitk.ihep.ac.cn

IHEP ATLAS-ITk

Standard Operating Procedure

⚡ Powered by itkdb ⚡

2026-05-26 @ 09:42:48

Temperature 22.1°C ↑ 0.0°C

Humidity 52.4 % ↑ 0.1 %

Connect to ITk Production Database

📌 Bulletin Board

2026-05-26 @ 09:42:48

Module | Hybrid | DUMMY | Inventory

Module Work Table

Local Name	Current Local Stage	Next Stage	Next Operat...	Next Operator
IHEP-Module-iLS-PRODUCTION-28	E-TESTED	THERMAL-CYCLE_DONE		
IHEP-Module-iLS-PRODUCTION-30	MEASURED	BONDED	WIRE-BONDING	Rabia
IHEP-Module-iLS-PRODUCTION-32	E-TESTED	THERMAL-CYCLE_DONE		
IHEP-Module-iLS-PRODUCTION-33	MEASURED	BONDED	WIRE-BONDING	Rabia
IHEP-Module-iLS-PRODUCTION-35	HV_TAB_ATTACHED	GLUED	ASSEMBLY	Hang Li
IHEP-Module-iLS-PRODUCTION-36	HV_TAB_ATTACHED	GLUED	ASSEMBLY	Qi Cai
IHEP-Module-iLS-PRODUCTION-37	HV_TAB_ATTACHED	GLUED		
IHEP-Module-iLS-PRODUCTION-38	HV_TAB_ATTACHED	GLUED		
IHEP-Module-iLS-PRODUCTION-39	HV_TAB_ATTACHED	GLUED		
IHEP-Module-iLS-PRODUCTION-40	HV_TAB_ATTACHED	GLUED		

Production Monitoring

Select component type: Module

Select component: IHEP-Module-iLS-PRESERIES-10

Component current local stage: SHIPPED

Component basic info:

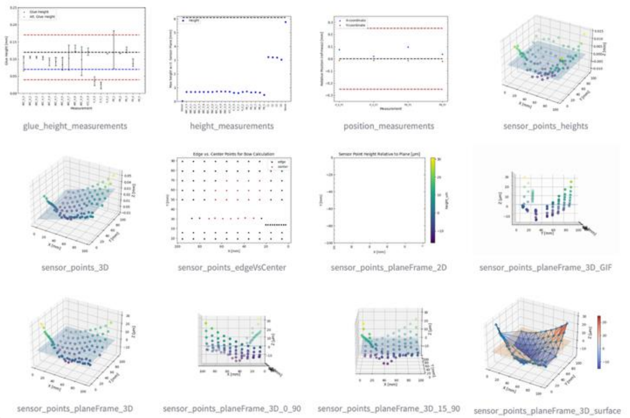
	IHEP-Module-iLS-PRESERIES-10
ATLAS SN	20USBML1235504

Module Metrology Results

Select metrology run to plot: CDF_run_1

Select metrology bow test run to plot: CDF_bow_run_1

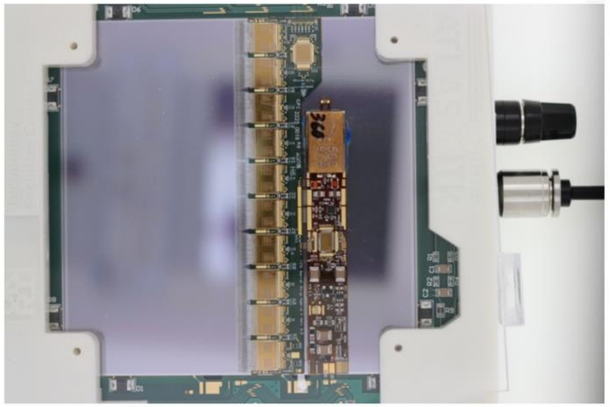
Outputs:



Module Wire Bonding Visual Inspection Results

Select the run number: 1

Run Number	Test Date	Passed	Problems
1	2025-06-16T12:23:00.000+08:00	☑	☐



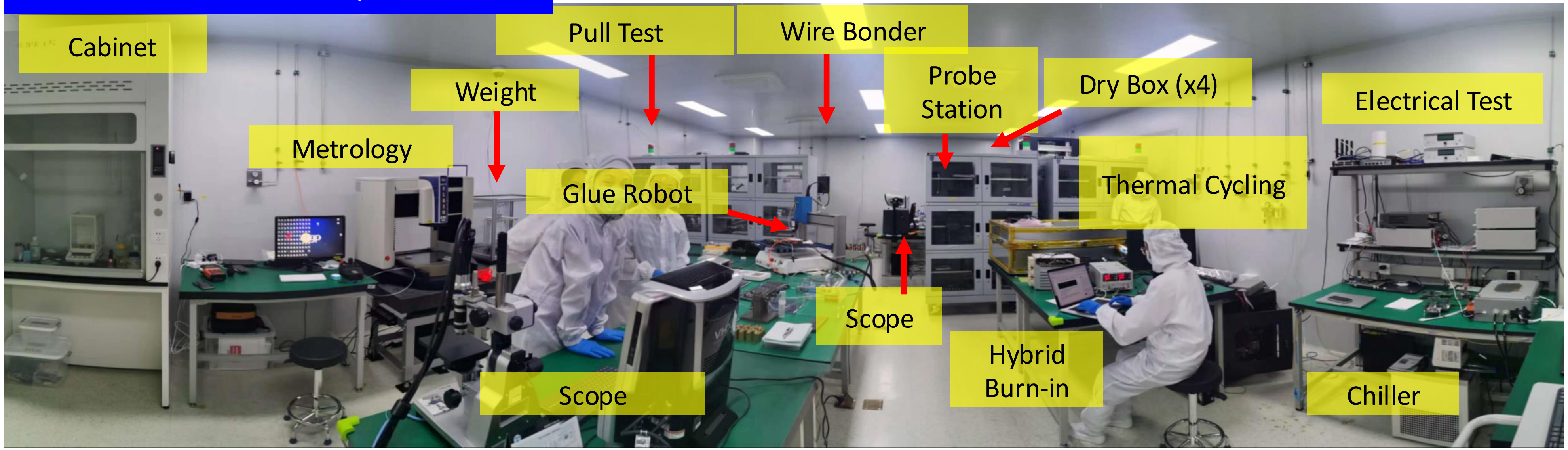
IHEP Site Module Production Status

- Passed PRESERIES stage for Module production
  - Produced 75 PRESERIES modules (15@IHEP / ~ 50@ RAL)
  - Produced ~134 PRODUCTION modules (34 @IHEP / ~100@RAL)
- Manufactured 11 production tooling set and one automatic machine in China

Automatic Tool at IHEP

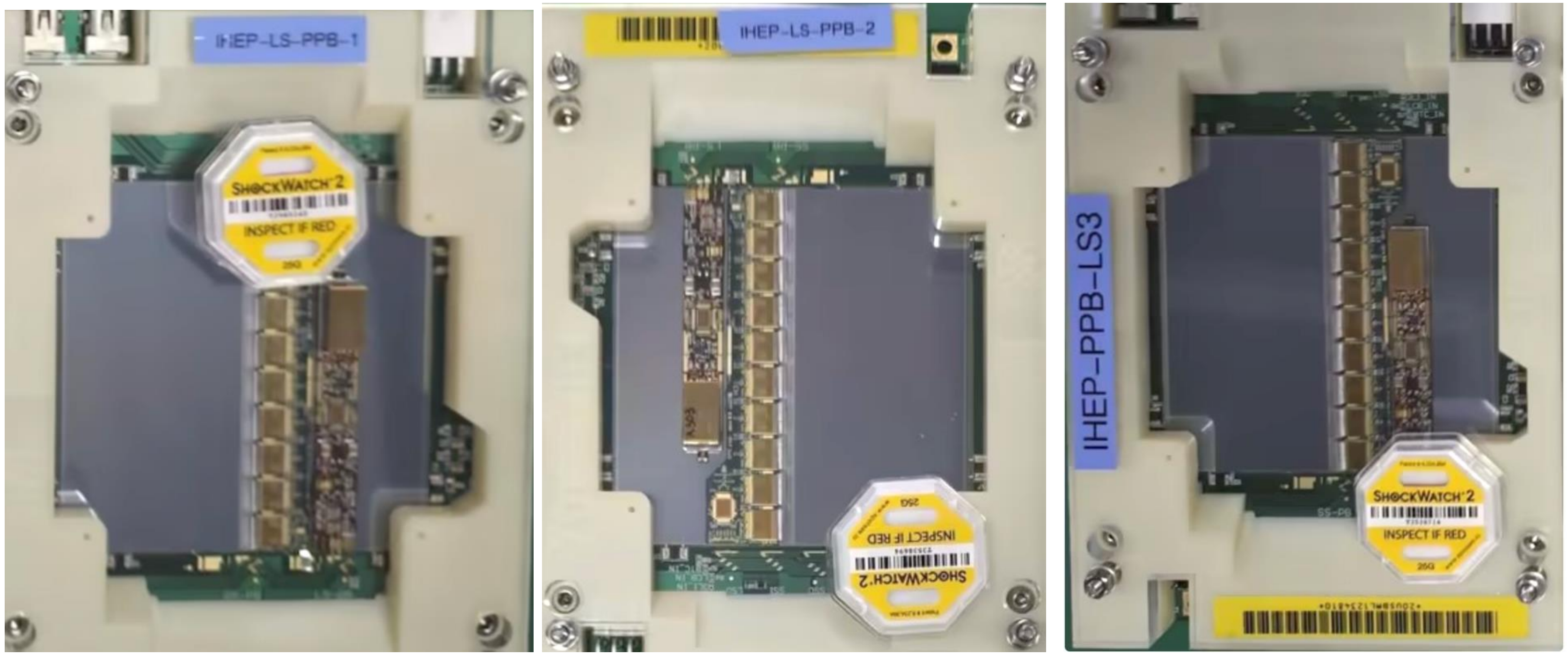
New tools made in China

IHEP Site for ITk Strip Module

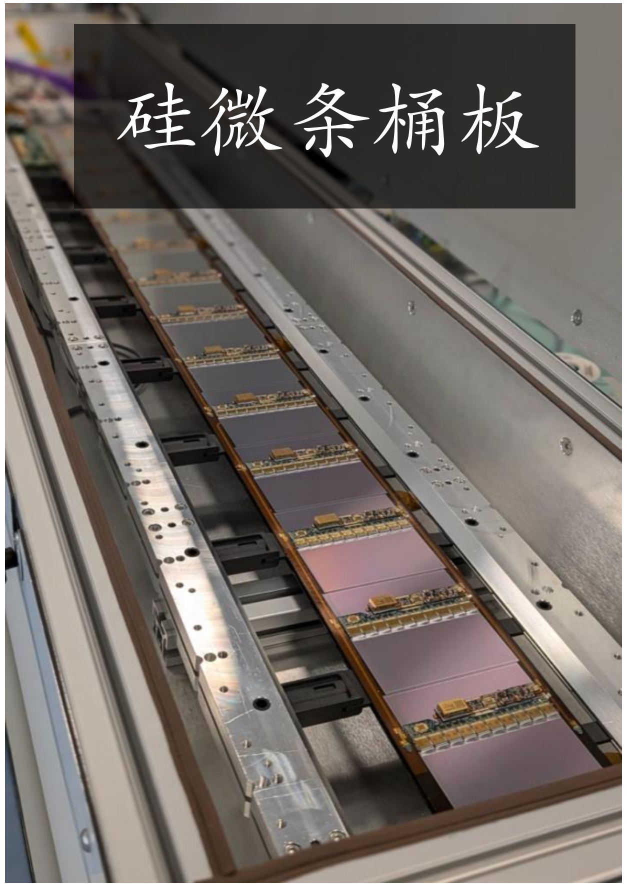


PRODUCTION Module (x134)

硅微条探测器研制



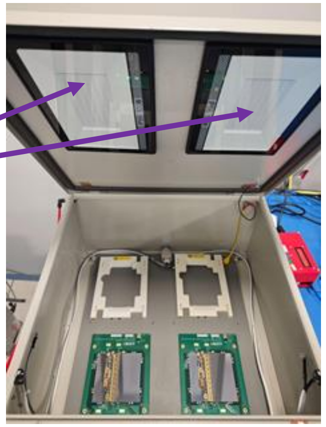
中国组研制硅微条模块



硅微条桶板

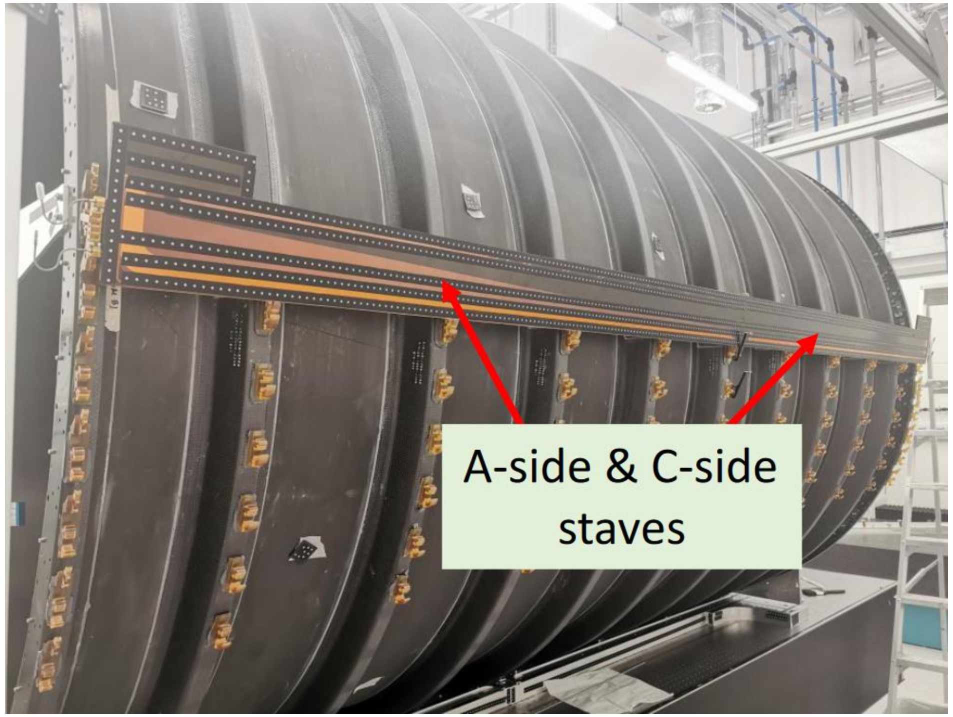
China ITk @ RAL

- Two FTEs from China based at RAL
- Assembled ~100 modules for China share
- Participated in stave loading activities
- Assist in logistics for IHEP and UV light setup for module recovery



CERN Integration

- Strip barrel stave loading
  - Mount 28 modules (14 each side) on the stave
    - Modules on each side rotated by +/-26 mrad
  - Thermal cycle the stave after loading



- Barrel tracker system integration
  - Tracker with four concentric carbon cylinders
  - Four-barrel layers consists 392 staves
  - Perform power, cooling, data acquisition, system test
  - Started stave reception test at CERN

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

Photo credit: Michael Hoch/CERN

思考题

- Q1: ATLAS 有几个主要的子探测器，在Higgs 发现的过程中分别起到怎样的作用?

- Q2: ATLAS 径迹探测器是如何工作的？空间分辨精度能达到多少?

- Q3: 硅微条径迹探测器如何实现二维平面的分辨?