CEPC探测器研发进展

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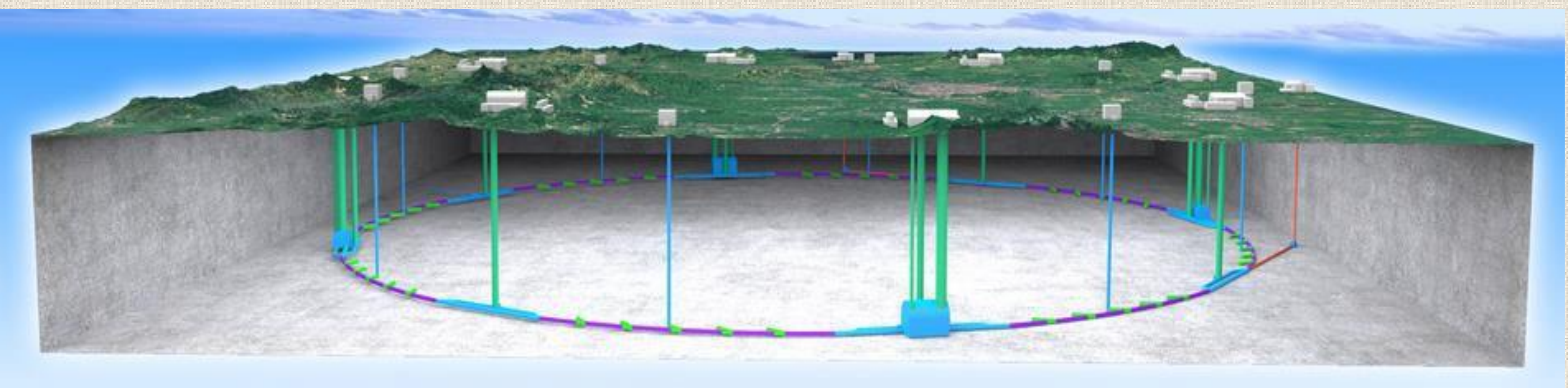
CEPC机械设计研讨会
河南洛阳，2024.08.22-24

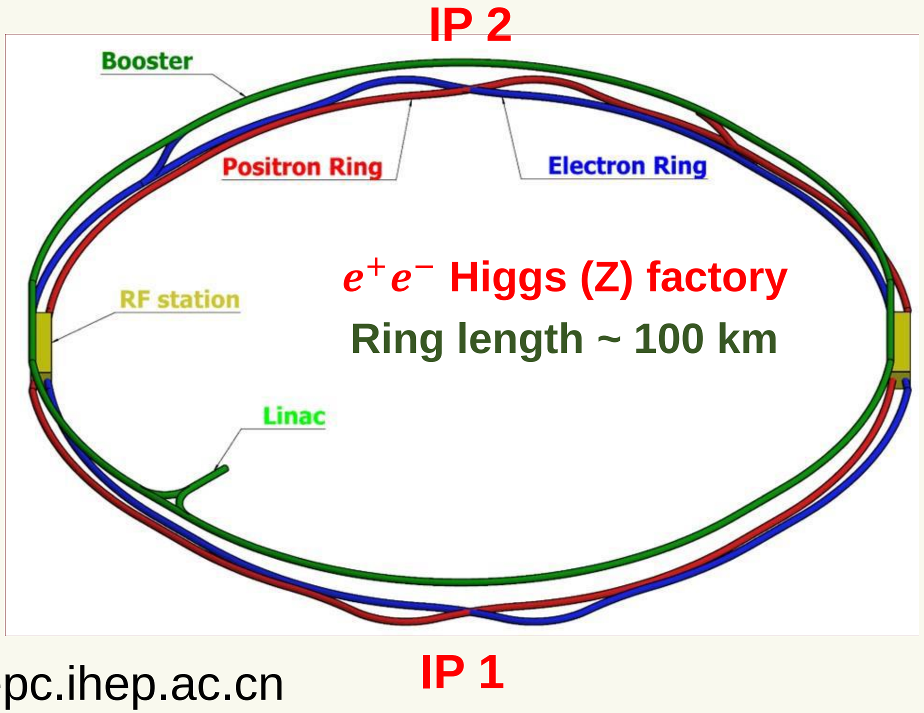


报告提纲

- 环形正负电子对撞机CEPC的重要性
- CEPC的性能和对探测器系统的要求
- 为CEPC进行的关键探测技术研发
- CEPC技术设计报告的准备
- 小结

环形正负电子对撞机(CEPC)

- ❑ 2012年希格斯发现后，中国科学家率先提出了环形正负电子对撞机方案(CEPC)，在本土建造100公里周长的希格斯/ W / Z 玻色子工厂。
- ❑ 以前所未有的精度测量希格斯性质、电弱相互作用参数、QCD和味物理，及寻找超出标准模型新物理(譬如暗物质，电弱相变，正反物质不对称，超对称粒子等)。
- ❑ 在研究尖端物理的同时，也带动技术的发展与进步，造福社会。
- ❑ 未来可以升级为超级质子质子对撞机(SPPC)，质心系能量达100TeV 。



http://cepc.ihep.ac.cn

正负电子希格斯工厂

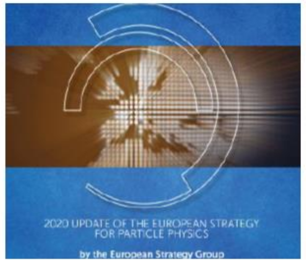
The scientific importance and strategical value of e^+e^- Higgs factories is clearly identified.

China

***2013, 2016**: China Xiangshan Science Conference concluded that **CEPC is the best approach** and a major historical opportunity for the national development of accelerator-based high-energy physics program.*

JAHEP Japan

2017:** Japan Association of High Energy Physicists (JAHEP) proposes to construct **A 250 GeV center of mass ILC promptly as a Higgs factory.

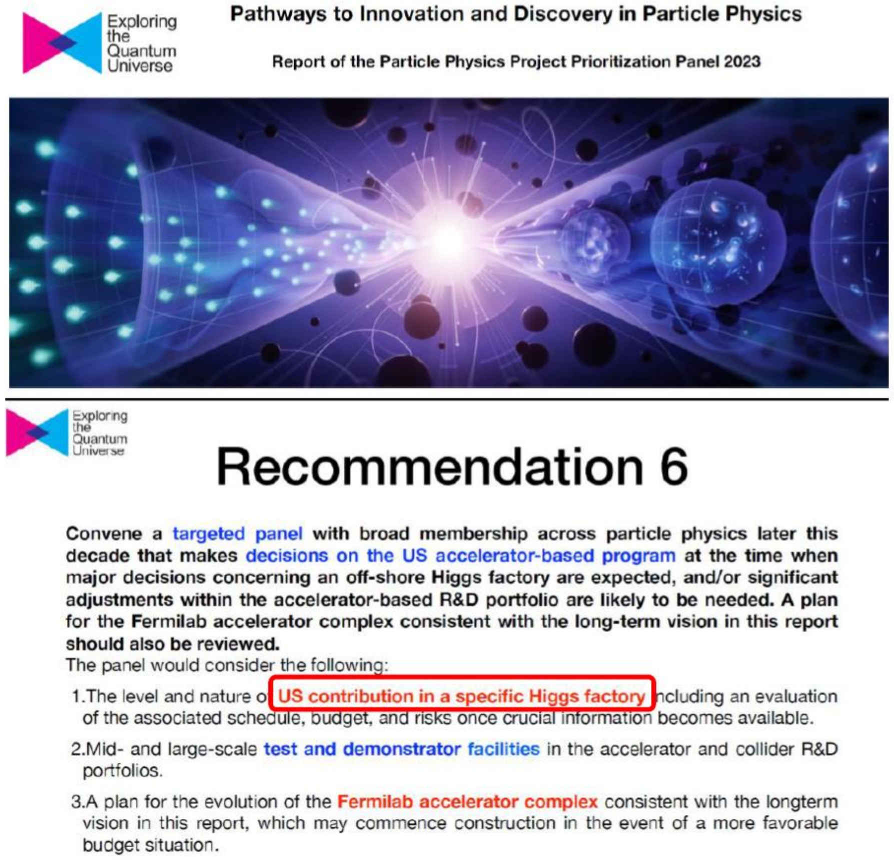


Europe

***2020:** European Strategy for Particle Physics, **An electron-positron Higgs factory is the highest priority next collider.** For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.*

ICFA

***2022,** ICFA "reconfirmed the international consensus on the importance of **a Higgs factory as the highest priority for realizing the scientific goals of particle physics**", and expressed support for the above-mentioned Higgs factory proposals*


Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

Exploring the Quantum Universe

Recommendation 6

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

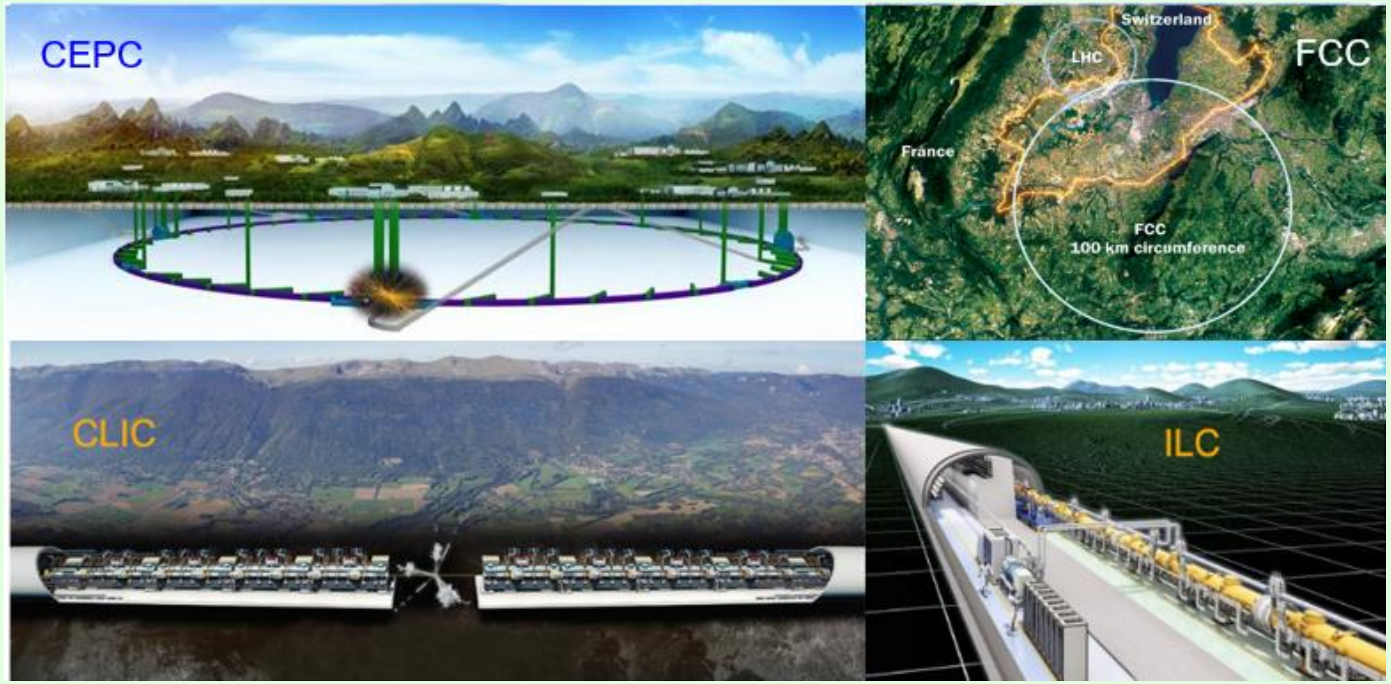
The panel would consider the following:

1. The level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale test and demonstrator facilities in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the Fermilab accelerator complex consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

P5 report, USA, 2023

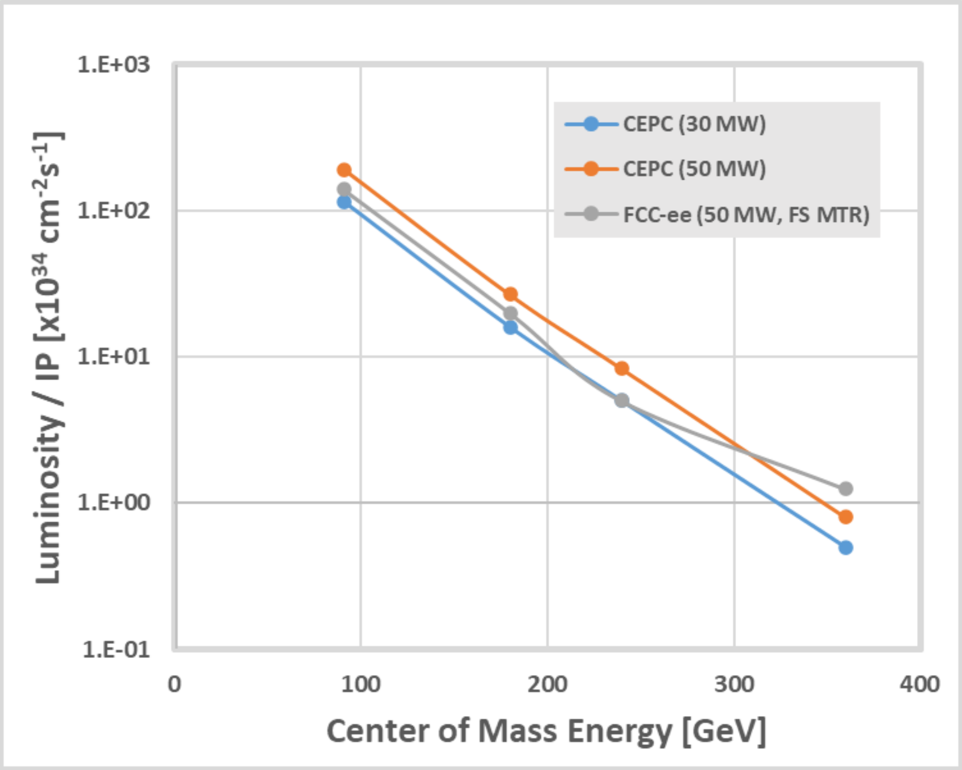
国际共识：正负电子希格斯工厂是优先级最高的下一代对撞机项目

国际希格斯工厂性能比较



相比其它希格斯工厂CEPC具有明显的优势

对撞亮度 / IP（CEPC vs FCC-ee)



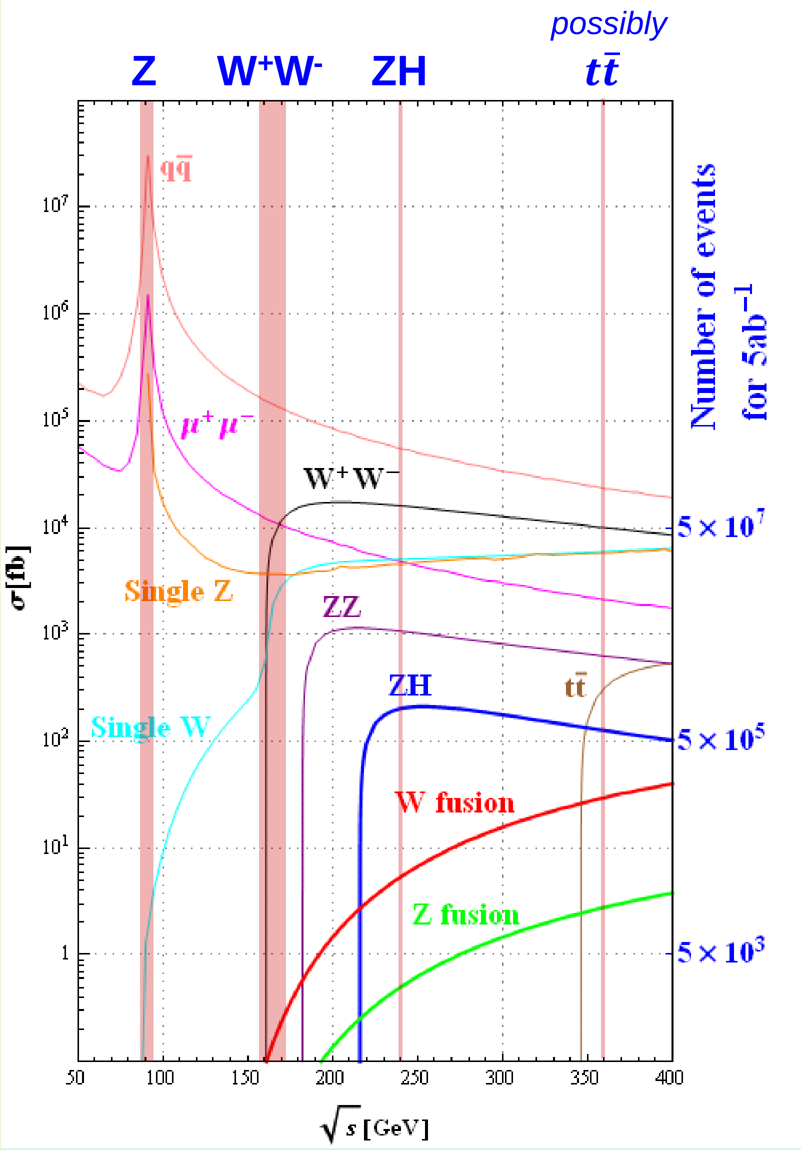
与FCC-ee相比

- o 运行时间更早（预期2030s vs. 2040s）
- o 隧道半径更大（兼容CEPC和SPPC）
- o 建造成本更低，性价比更高

与直线对撞机相比

- o 对撞亮度更高（H/Z/W）
- o 可升级为质子质子对撞机

CEPC 运行计划



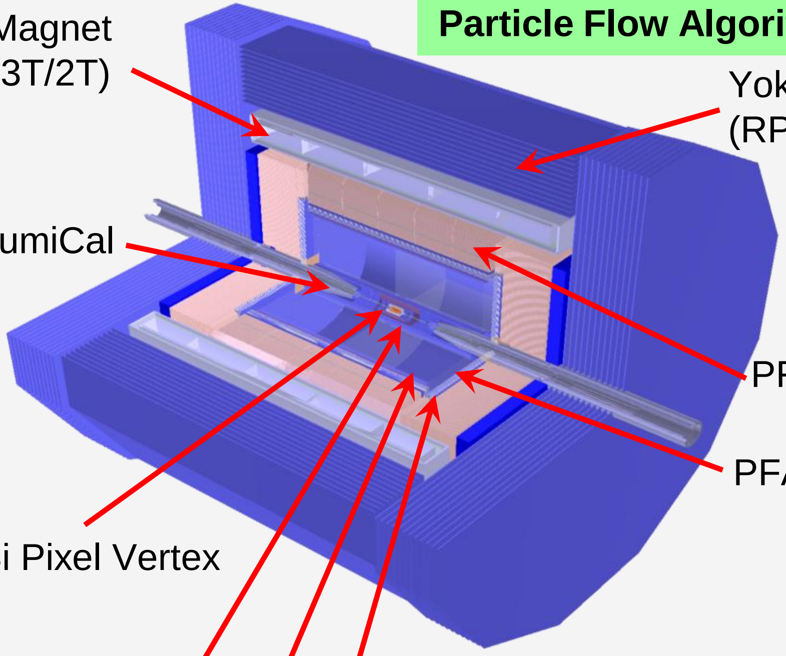
CEPC accelerator TDR (Xiv:2312.14363)

Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	~5
30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.6
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	22	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

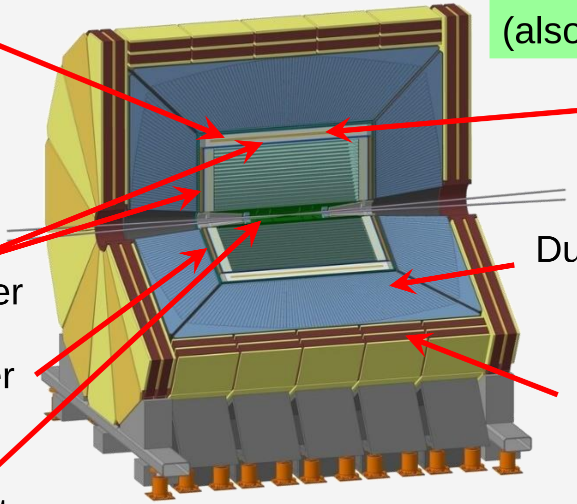
- 产生海量的 希格斯、Z、W 和顶夸克事例
- 超高精度测量：希格斯、电弱、味物理和QCD等测量将达到前所未有的精度
- 新物理探索：暗物质、电弱相变、超对称粒子等，探索新物理能标~10 TeV

CEPC 探测器概念设计

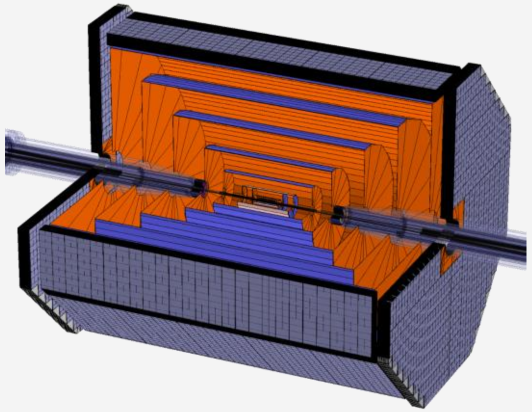
(Baseline Design)
Particle Flow Algorithm



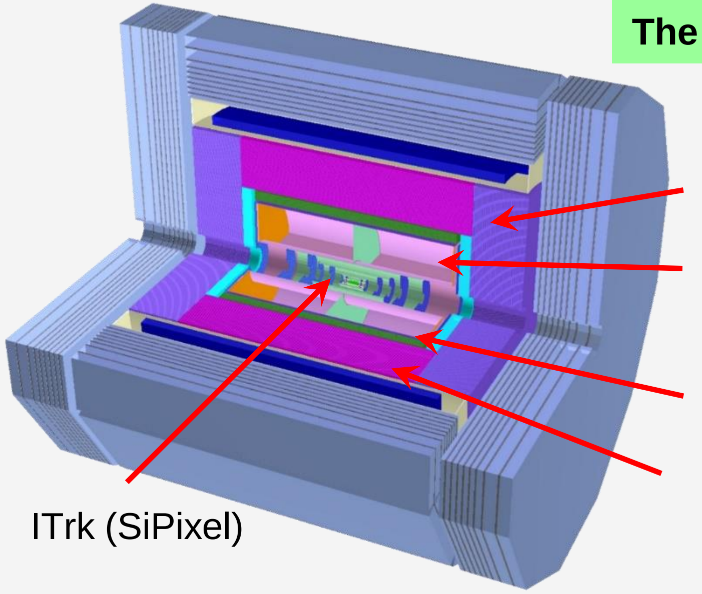
IDEA concept
(also proposed for FCC-ee)



FST concept
(Full Silicon Tracker)



The 4th Concept



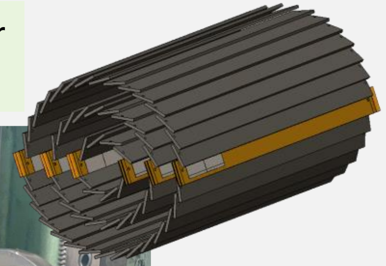
CEPC探测器重要设计指标

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 3%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$ Granularity $\sim 2 \times 2 \times 2\ \text{cm}^3$
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

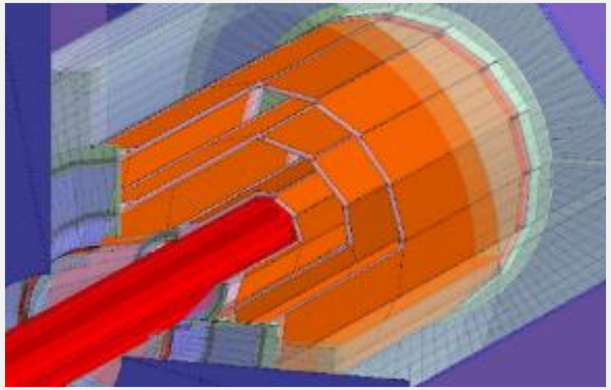
随着相关探测技术研发的进展 和 对CEPC物理潜力研究的深入，探测器的重要设计指标也在不断调整优化

半导体像素型顶点探测器

A TaichuPix-based prototype detector was tested at DESY in April 2023



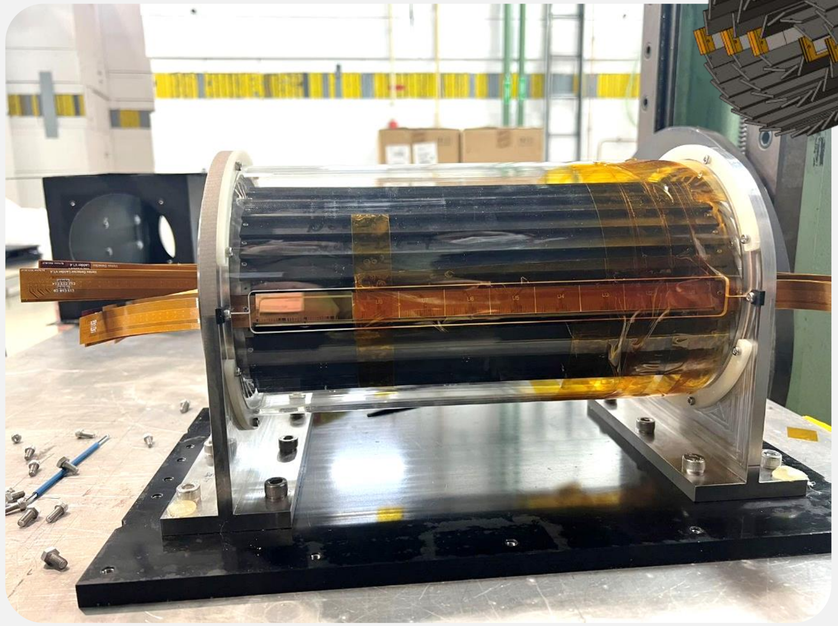
3 × dual-layer design



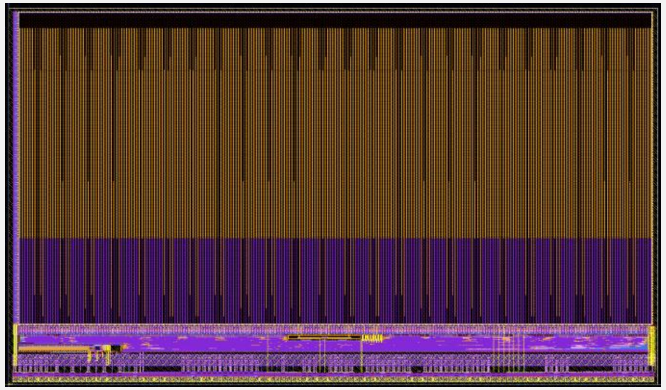
Goal: σ(IP) ~ 5 μm for high P

Key specifications:

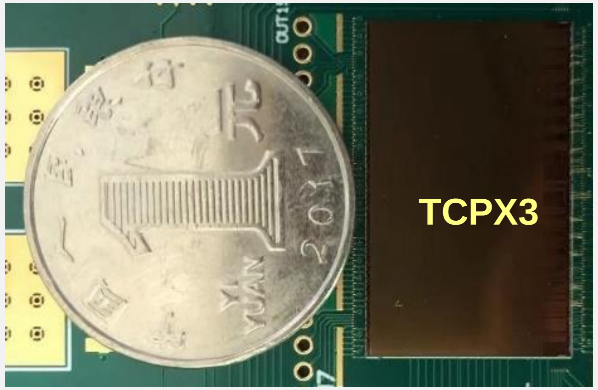
- Single point resolution ~ 3 μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm^2)
- Radiation hard (1 Mrad/year)



JadePix4
356×498 array of 20×29 μm^2
$\sigma_{x/y}$ ~ 3-4 μm, σ_t ~ 1 μs, ~100 mW/cm^2

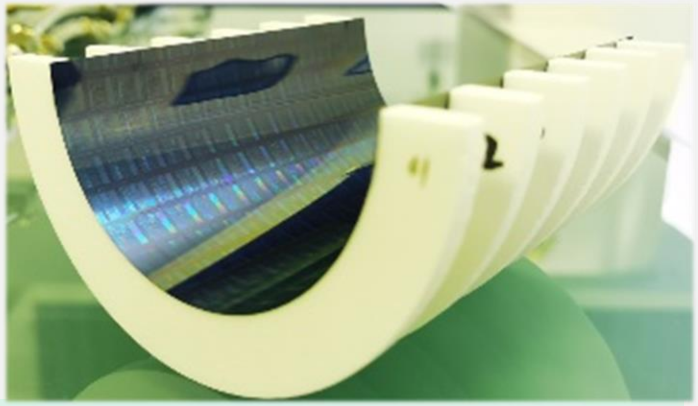


TaichuPix3
1024×512 array of 25×25 μm^2



TowerJazz 180nm CIS process

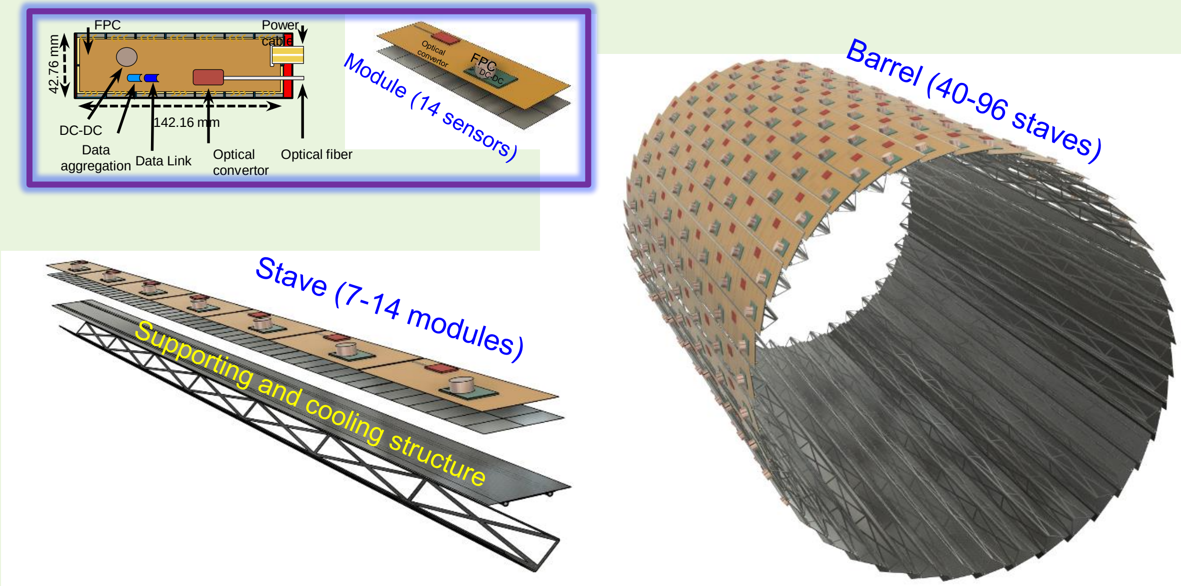
Curved MAPS



Looking into stitching technology

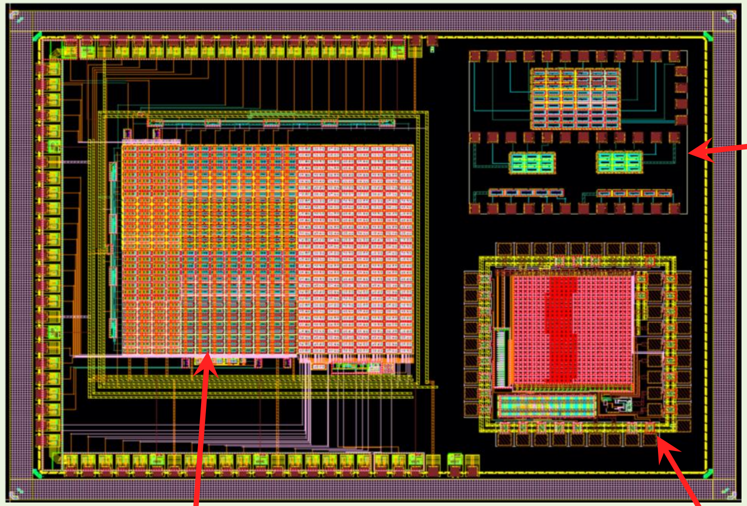
高压CMOS像素型径迹探测器

- Focus on HV-CMOS pixel inner tracker of ~15-20 m^2.
- Ladder design for barrel and disc for endcap
- Given what happened with the TSI 180nm production line, it is better to have backup foundries
- Exploring SMIC 55 nm and TPSCo 65 nm processes



Barrel detector design

COFFEE2 with SMIC 55nm process



Zone 1

6×9 pixels, 80×40μm^2

Diodes of different charge collection

Zone 2

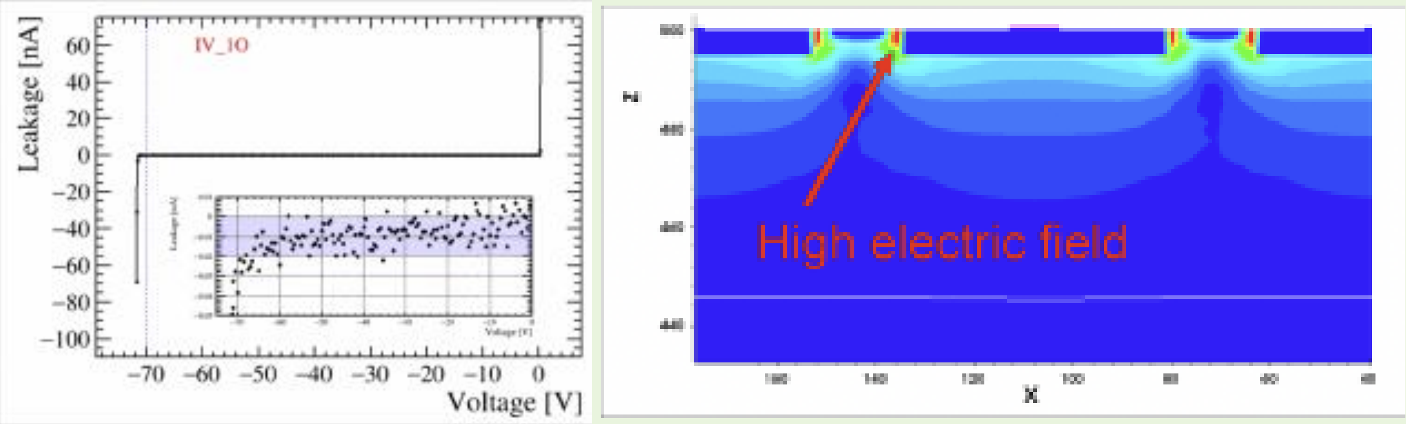
20×32 pixels, 72×36μm^2

Designs of charge collection & cell electronics

Zone 3

26×26 pixels, 25×25μm^2

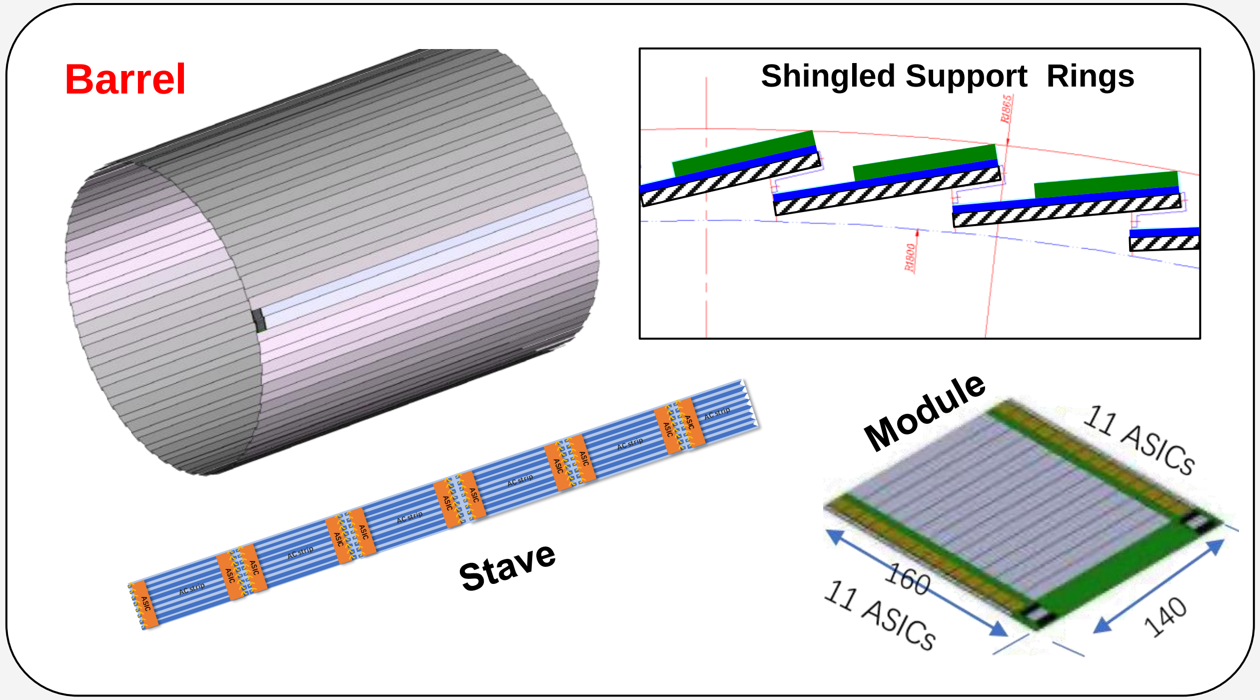
Peripheral digital processing and communication



Dark current and breakdown voltage study

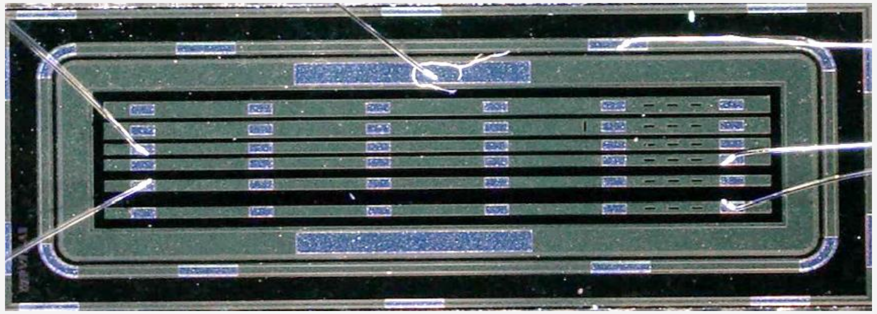
AC-LGAD 时间径迹探测器

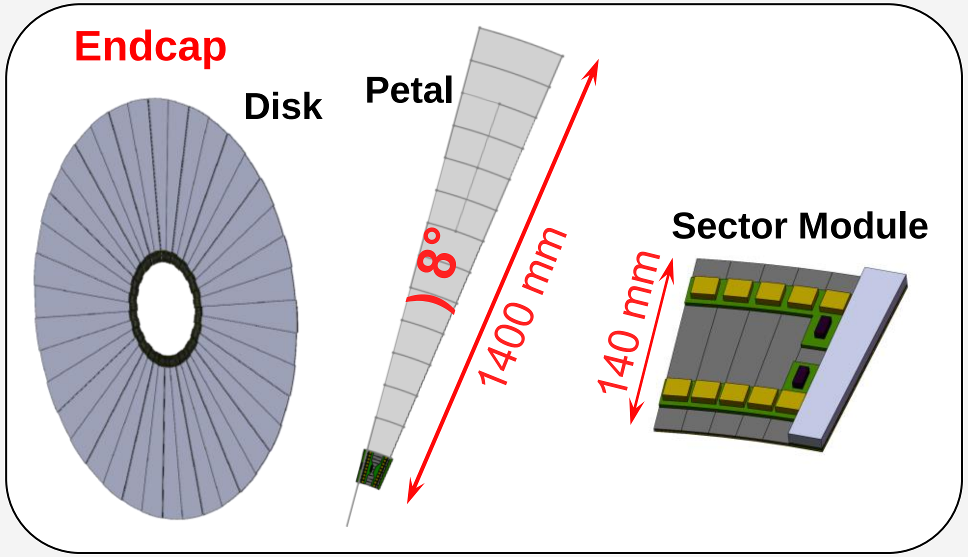
- The outer silicon tracker ~ 85 m^2, the Z precision is not crucial
  $\Rightarrow$ cost-effective Si strip detector
- Need a supplemental PID to TPC at low energy $\Rightarrow$ LGAD ToF
- AC-LGAD Time Tracker combines the two needs in one detector, and expect σ_t ~30-50 ps, $\sigma_{R\Phi}$ ~10 μm



Strip AC-LGAD by IHEP / IME

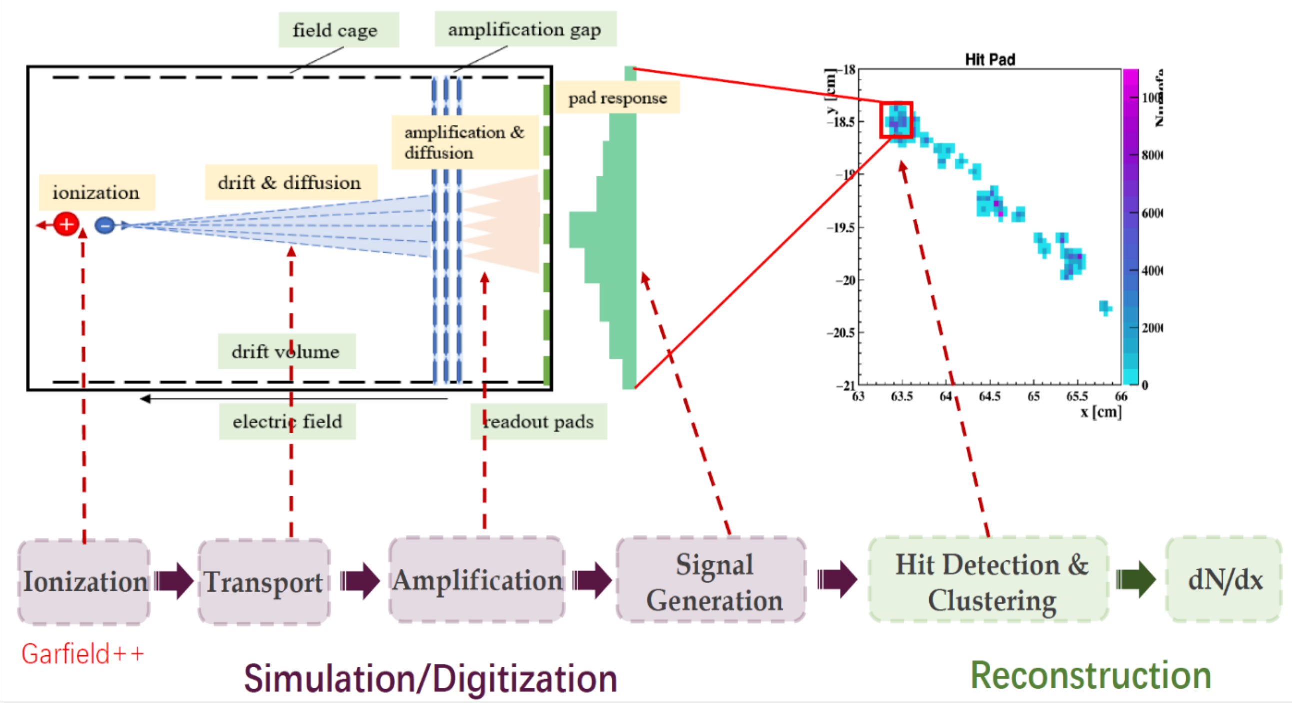
Strip size 5.6 mm × 100 μm
Pitch: 150, 200, 250 μm

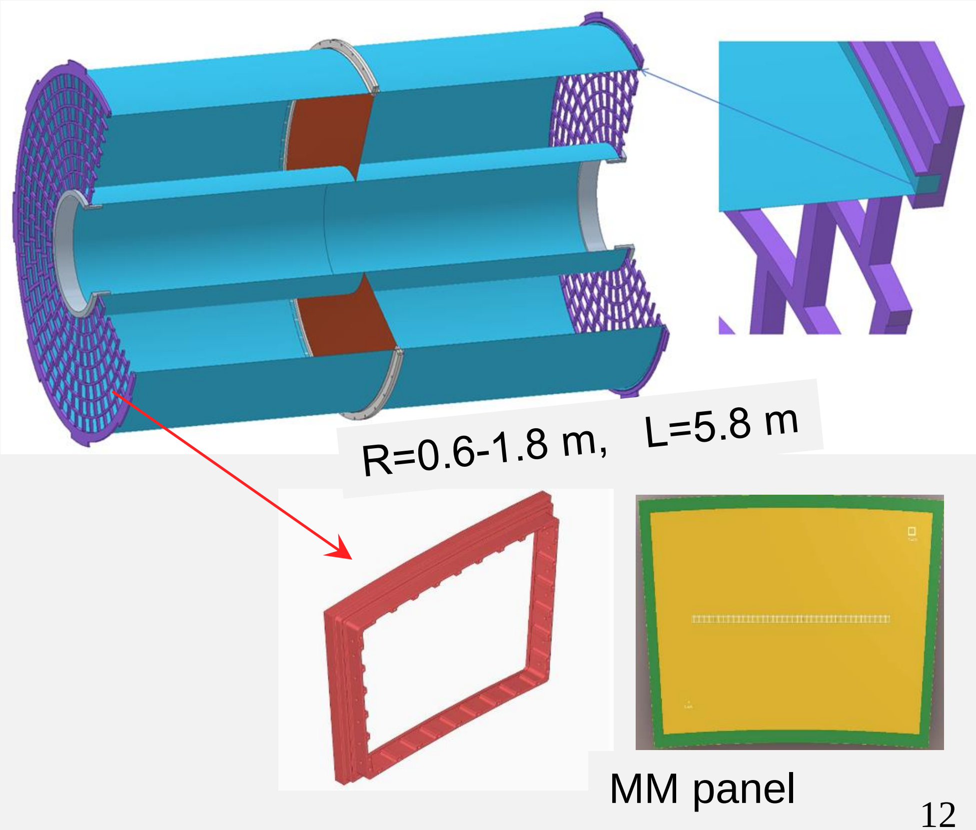




像素型时间投影室

- Initial TPC design has difficulty at high luminosity Z pole due to IBF
- A pixelated TPC achieves σ(r-Φ) ~100 μm, with $(500\ \mu m)^2$ readout pads, IBF×Gain ~1 at G=2000
- Full simulation study also shows 3σ K/π separation at 20GeV
- Preliminary mechanical design ⇒ RL = 15% X_0 for endcap and 0.55% X_0 for barrel part
- Plan to have a test beam this fall to characterize the performance and validate the design

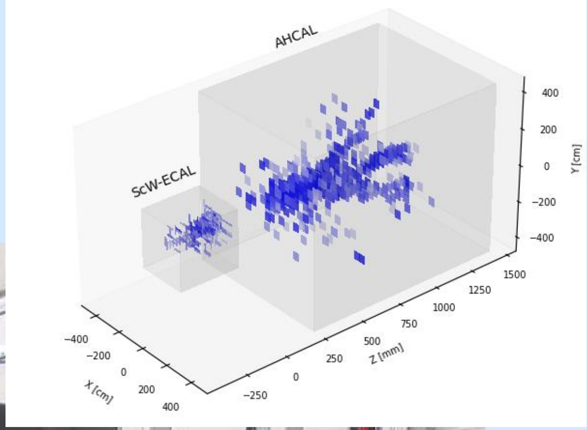


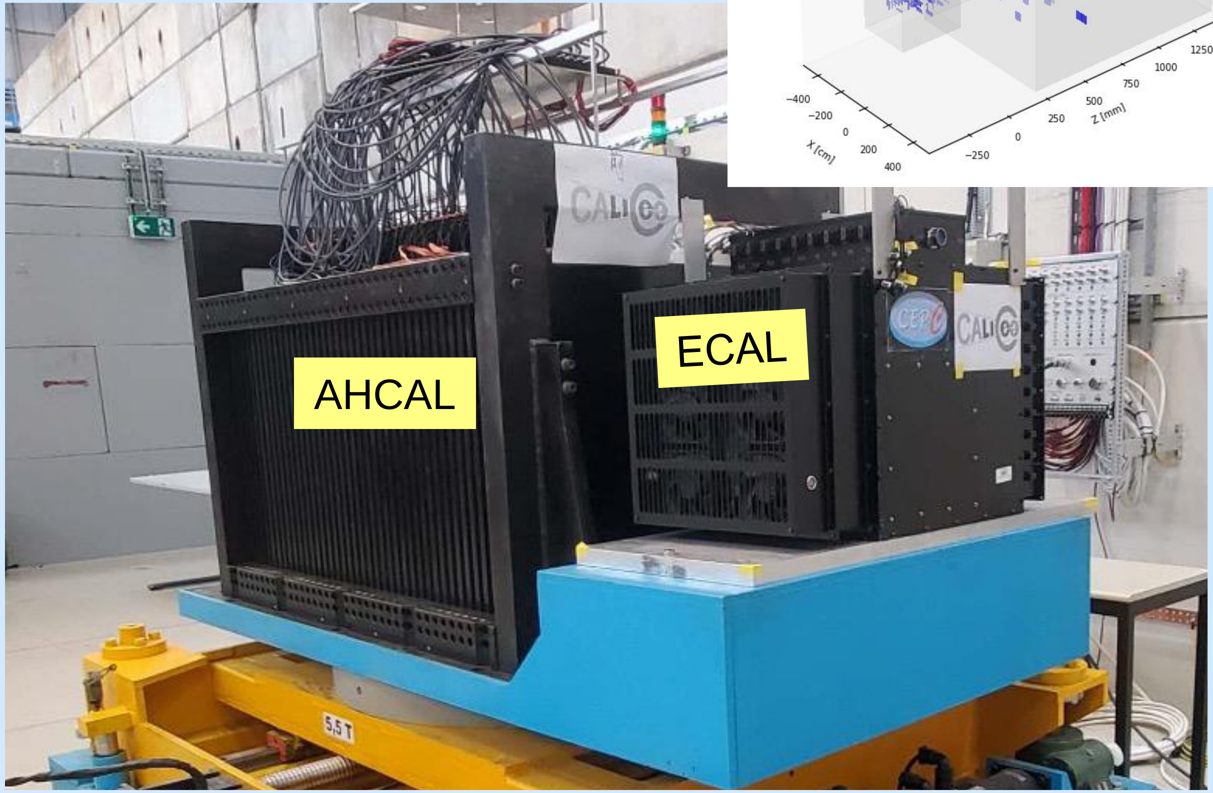


取样型量能器样机

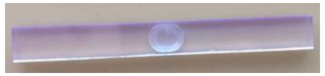
- ❑ ScW-ECAL: transverse 20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- ❑ AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

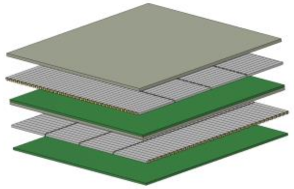
Several successful testbeams @ CERN

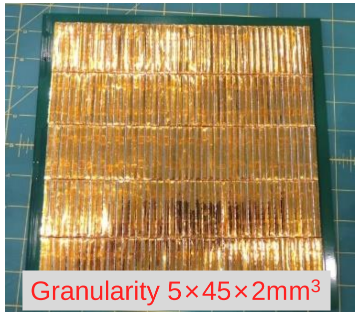




ECAL: scintillator(strip)+SiPM, CuW

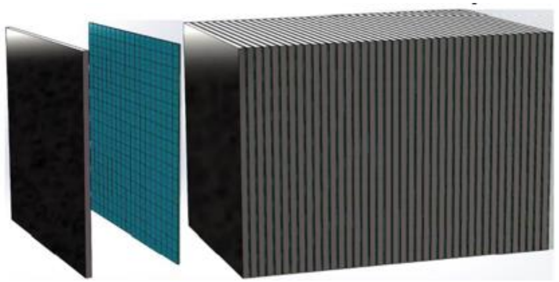


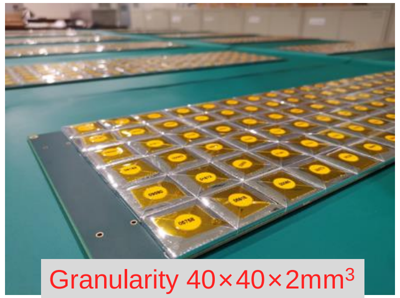




Granularity 5×45×2mm^3

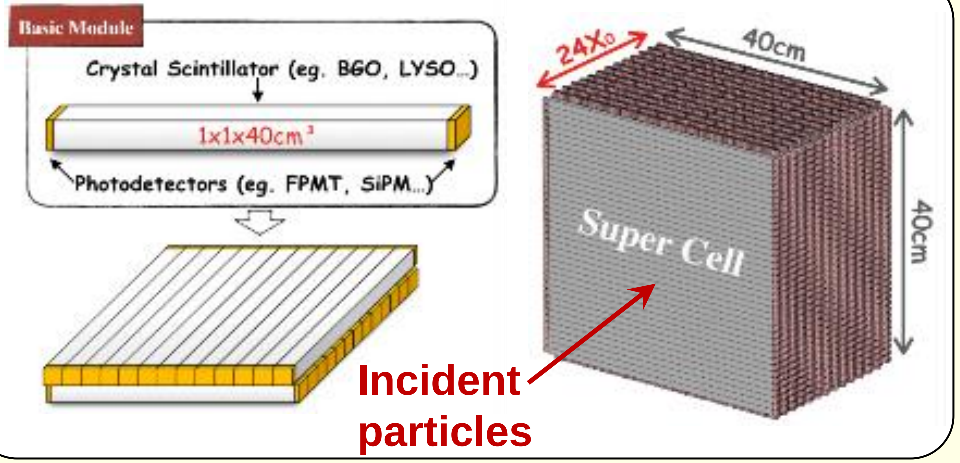
HCAL: scintillator (tile)+SiPM, steel

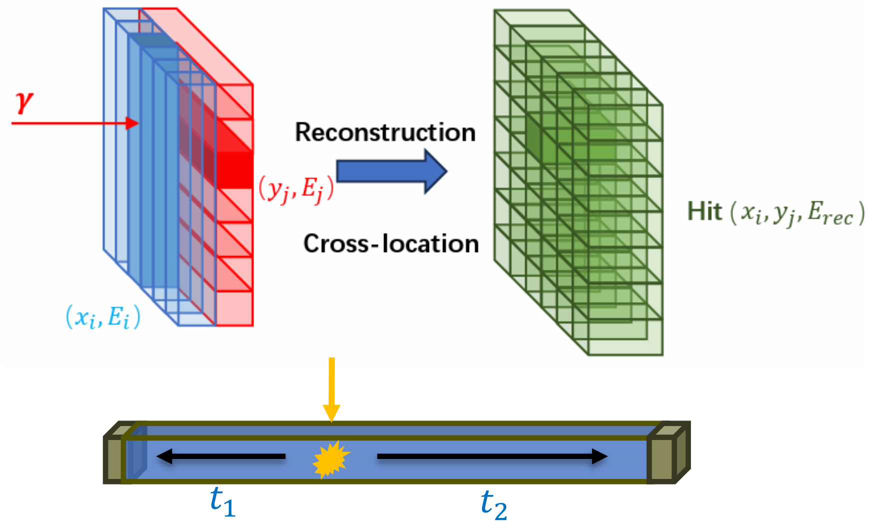




Granularity 40×40×2mm^3

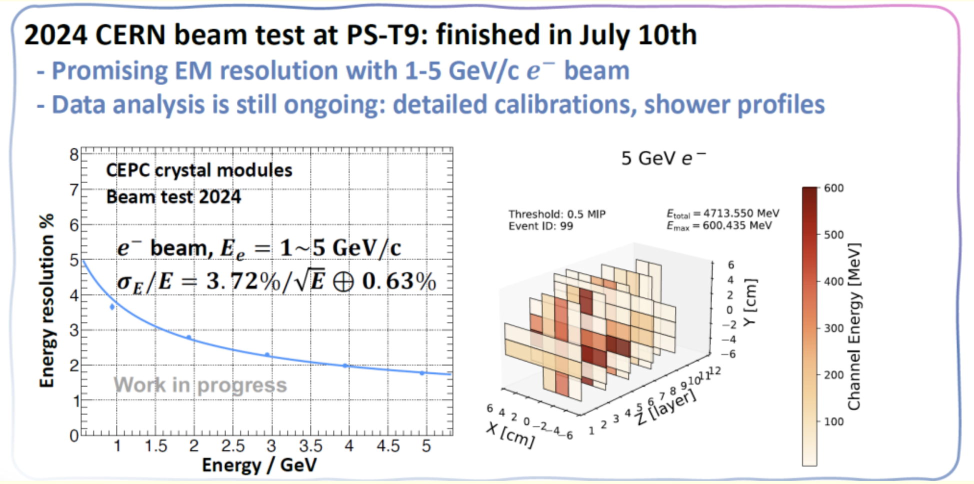
垂直晶体条4D电磁量能器

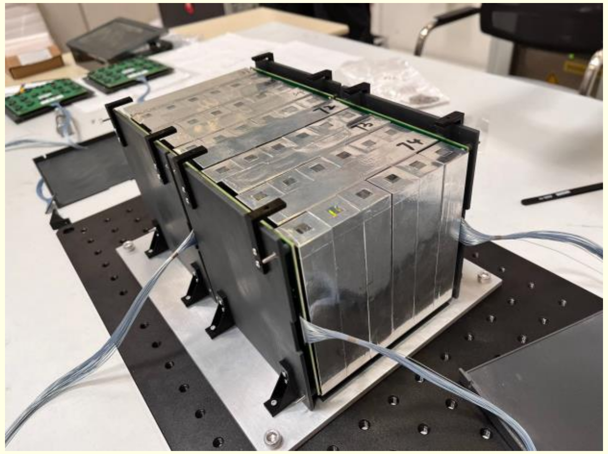




Achieve high granularity with adjacent layers

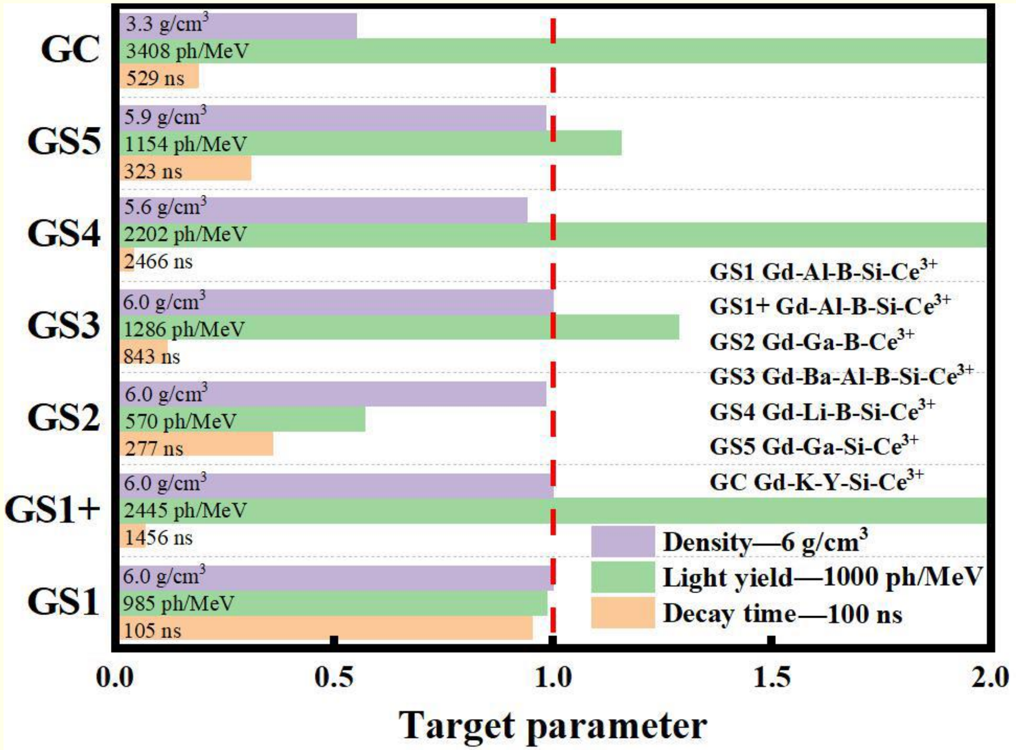
- ❑ Double-end readout, potentially positioning with timing
- ❑ Save readout channels, minimize dead area and material
- ❑ Challenging in pattern recognitions with multiple particles

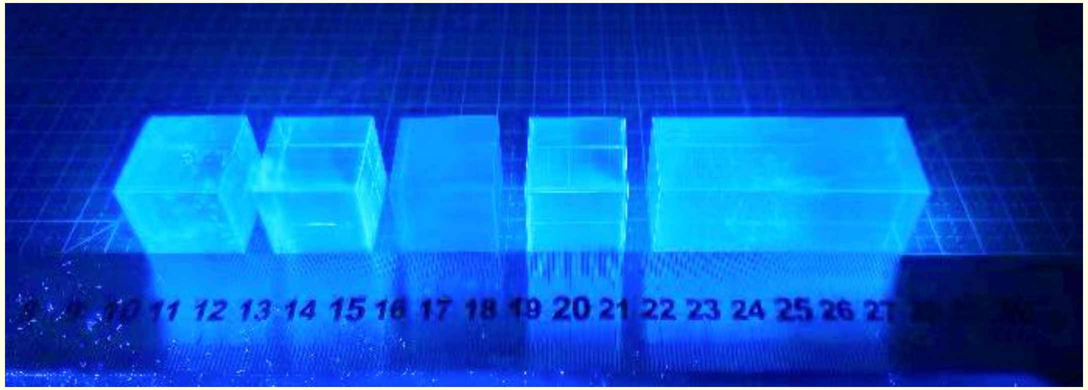


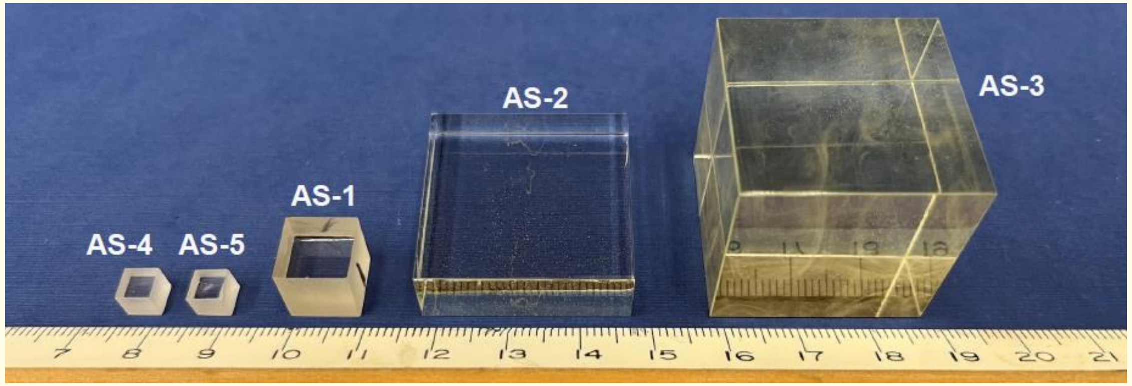


闪烁玻璃研发

- To replace plastic scintillator with high density, low cost glass scintillator, for better hadronic energy resolution and BMR
- Key specifications:
  - Light yield: 1000~2000 ph / MeV
  - Density: 5~7 g/cm^3
  - Scintillation time: ~100 ns
- The Scintillation Glass collaboration continues to progress on the quest for better GS
- The GS1 / GS5 measurements are from (5mm)^3 small size samples. Tiles of 40×40×10 mm^3 are needed for GS-HCAL

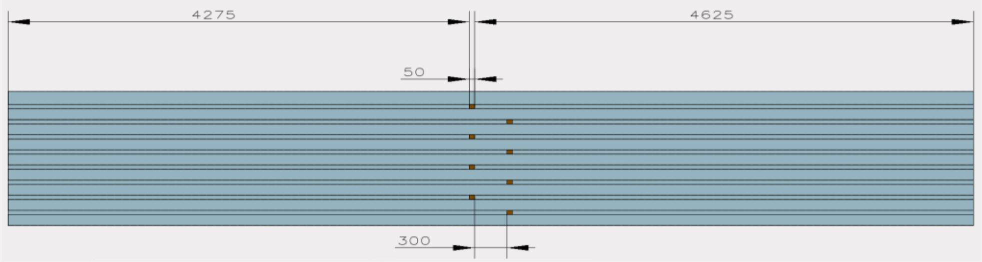


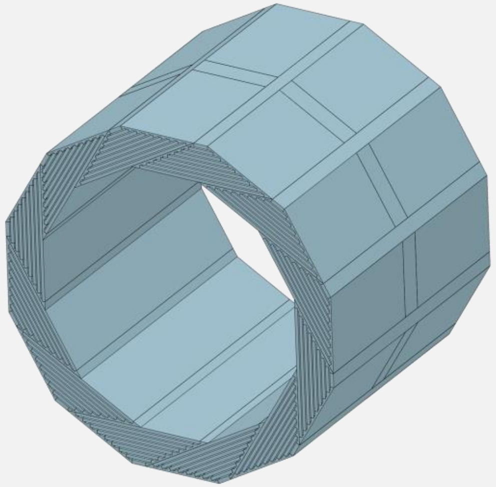




塑料闪烁体缪子探测器

- Muon ID, combining with magnet return
- Requirement: $\epsilon > 95\%$, σ_T ~1-2 ns
- Position resolution: $1.5\ cm$
- Total area ~ 6000 m^2, ~40k channels



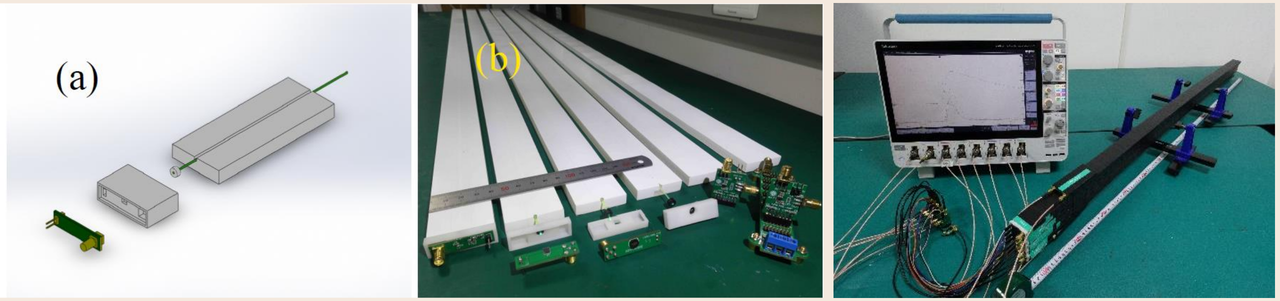


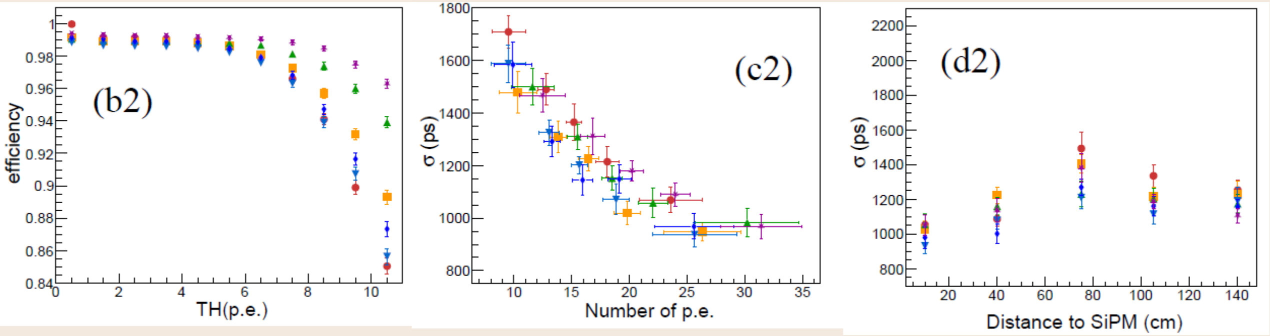
Barrel design

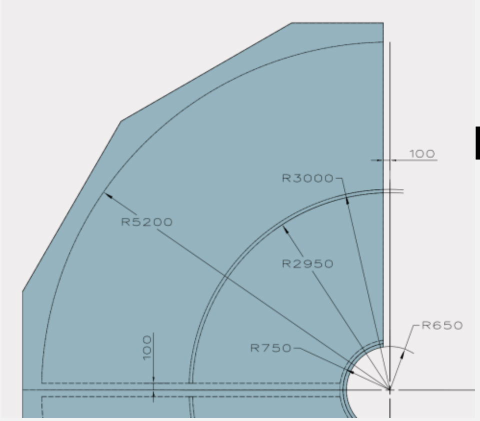
PS muon detector

Extruded plastic scintillator, WLS fibre, and SiPM

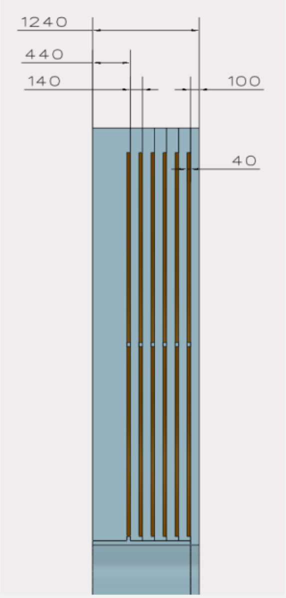
Preliminary results: $\epsilon > 95\%$ and $\sigma_T < 1.5\ ns$



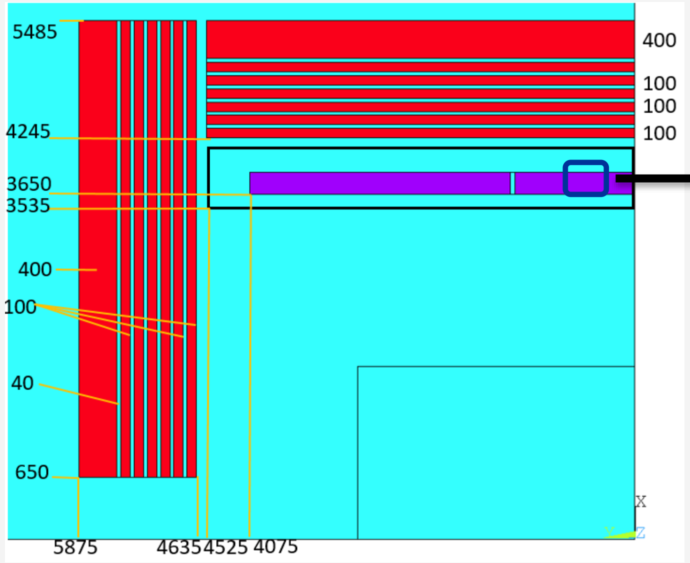


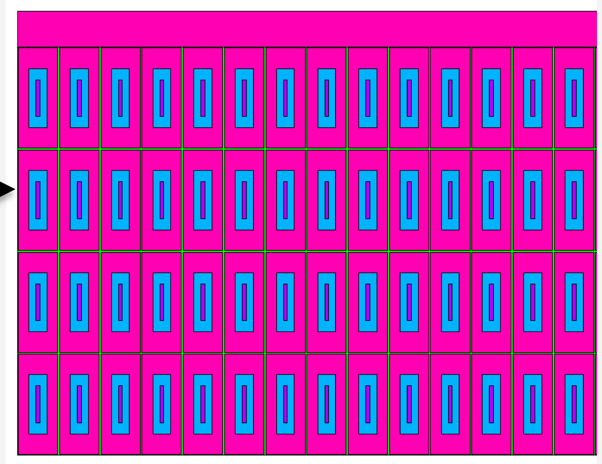


Endcap design

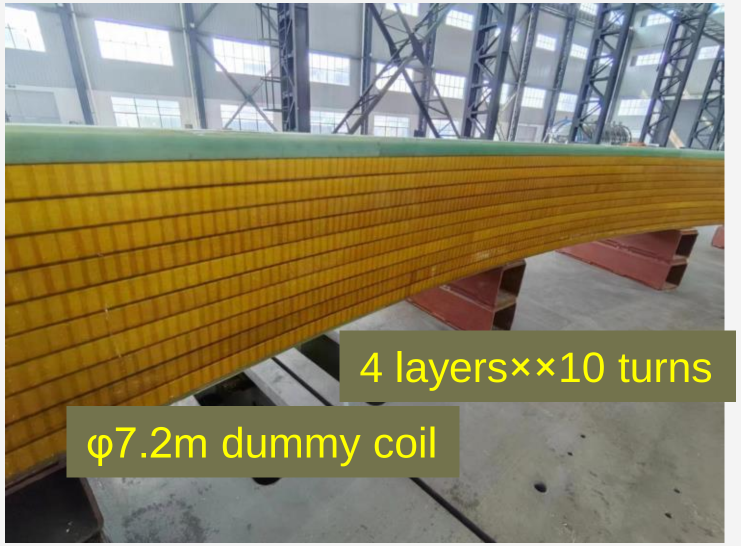


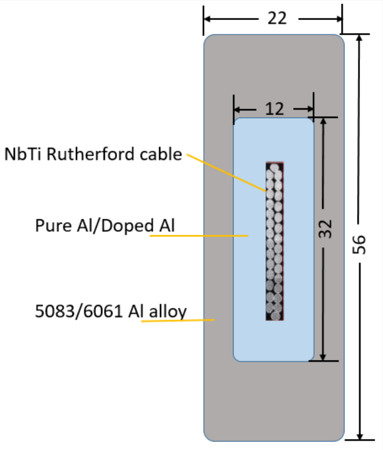
探测器超导磁铁





SC coil schematic diagram





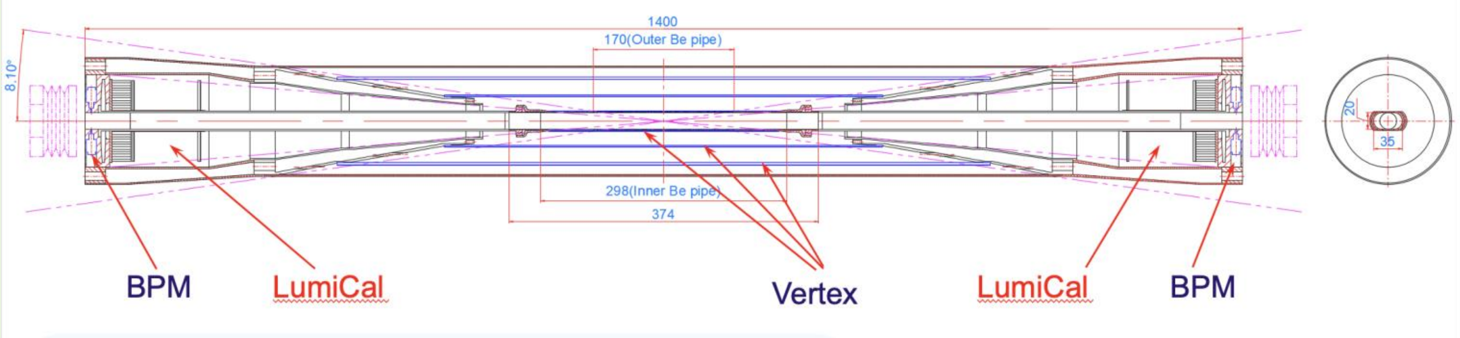
Aluminum stabilized
NbTi Rutherford cable

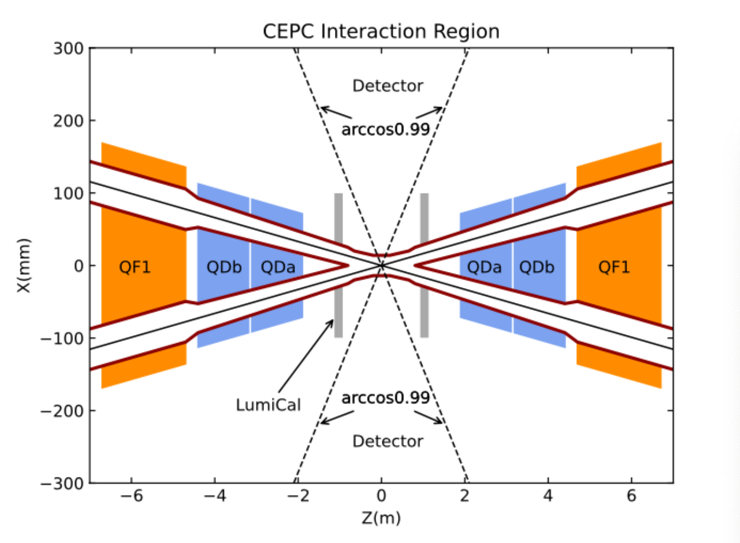
Coil parameters:

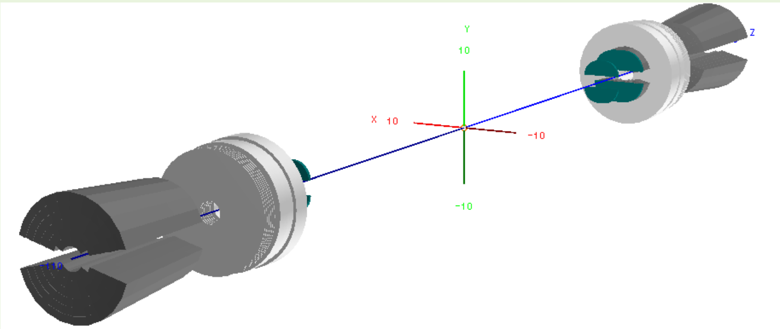
Central magnetic field	3 T
Inner diameter	7300 mm
Operating current	16702 A
Cable length	33 km
Inductance	11 H
Stored Energy	1.54 GJ

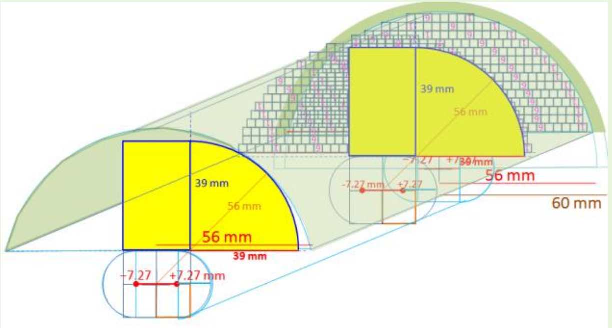
MDI与对撞亮度测量

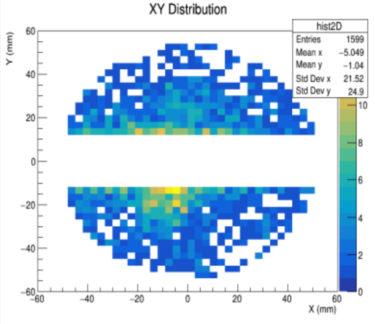
- Beam pipe
  - Inner Diameter 20mm
  - Inner Layer with thickness of 0.20mm
  - Gap for coolant with thickness of 0.35mm
  - Water chosen as coolant instead of paraffin
  - Outer Layer with thickness of 0.15mm
- LumiCal
  - 2 parts, first Si wafer + LYSO, second LYSO only
  - First Silicon Wafer locates at 560mm, than 640mm
  - First LYSO has a length of 23mm(starts from 647mm)
  - Second LYSO has a length of 200mm(starts from 900mm)
  - Half Moon-cake like design
  - Height ~ 39mm, radius ~ 56 mm



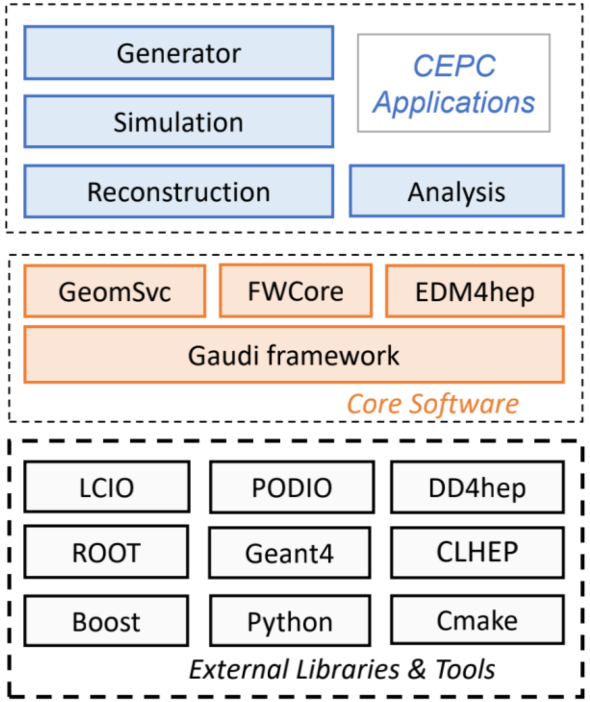






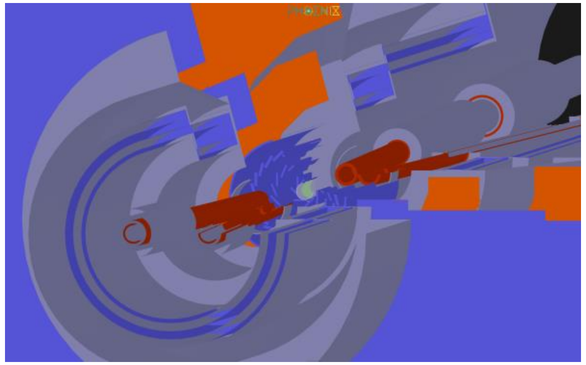


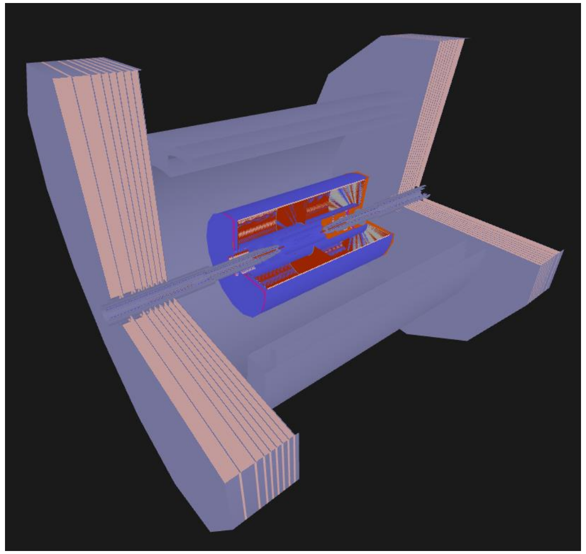
CEPC 软件系统

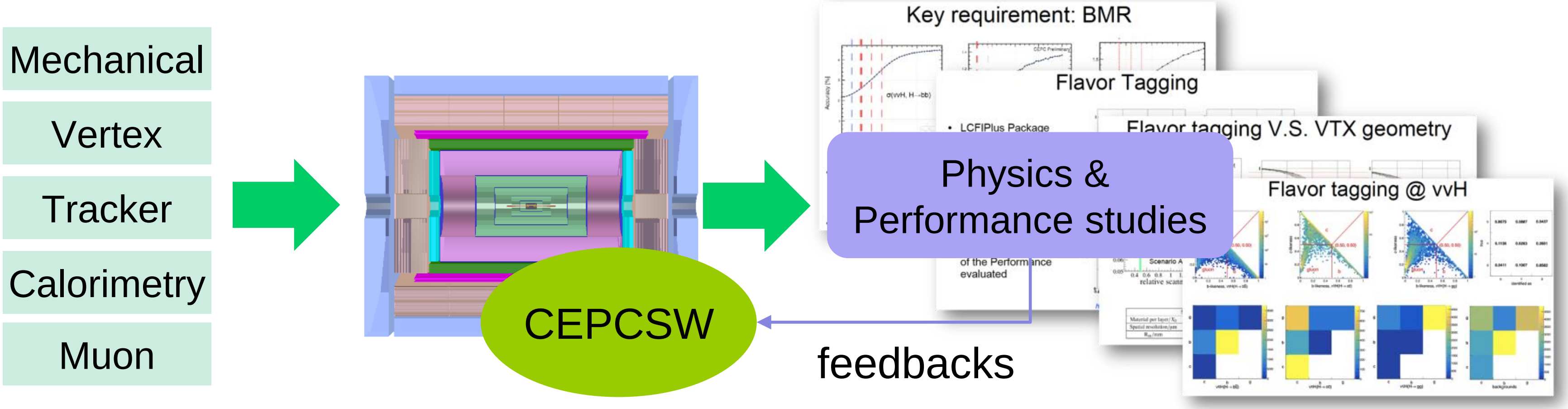


- **CEPCSW** has been developed based on components of Key4hep: Gaudi, EDM4hep, K4FWCore DD4hep
- Single source of detector information, but support multiple designs
- A web-based tool **Phoenix** for event and detector visualization

https://cepcvis.ihep.ac.cn/#/

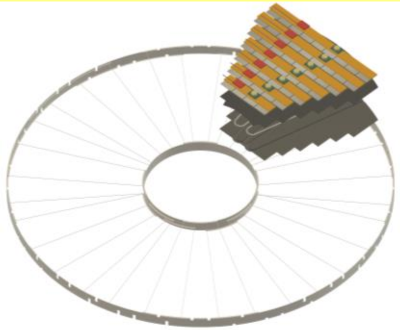




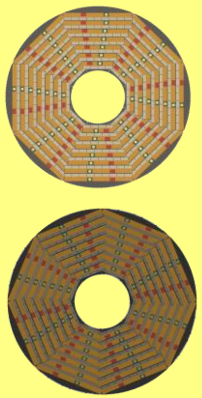


其它多项研发工作

Strip Endcap Inner Tracker

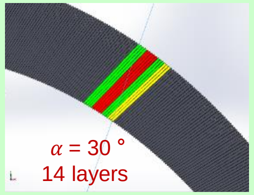


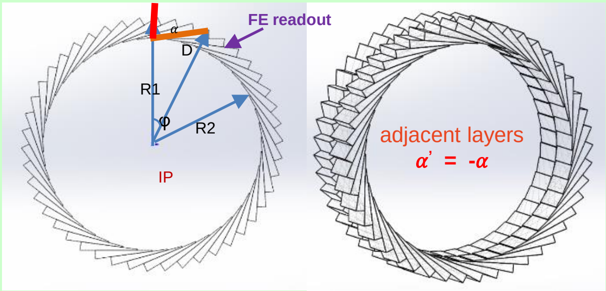
Front view



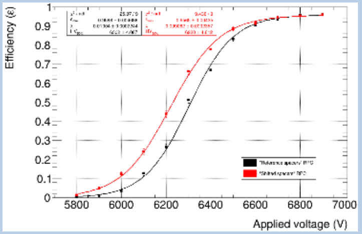
Back view

Stereo Crystal ECAL

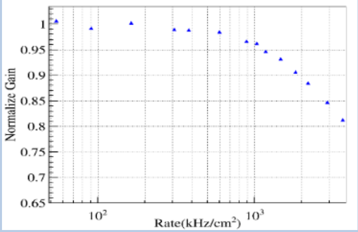




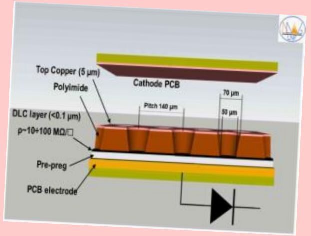
GRPC SDHCAL

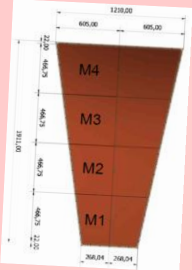


RWell SDHCAL

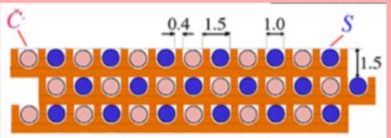


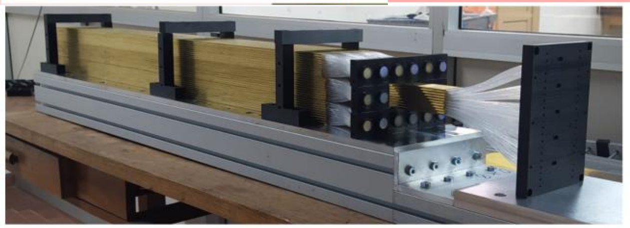
µRWELL for PS & Muon

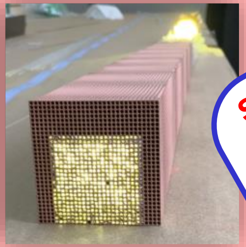




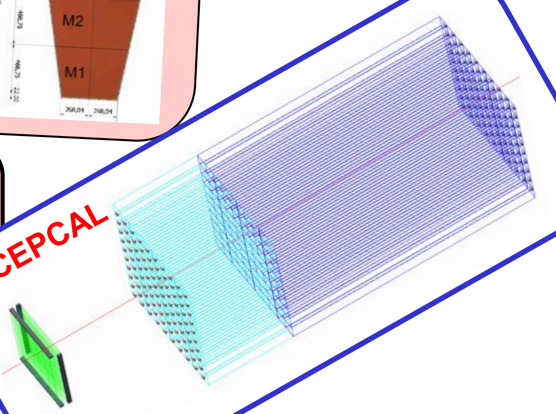
Dual Readout CAL



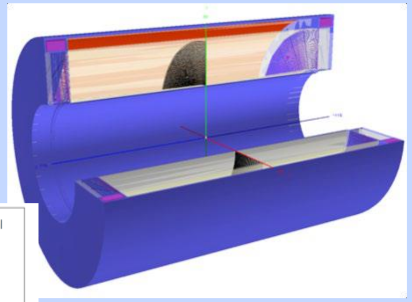


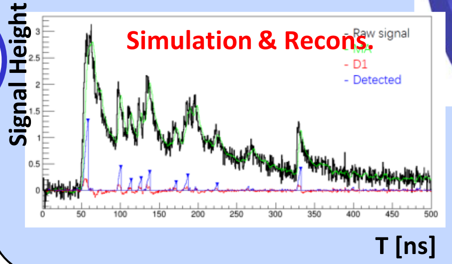


SCEPCAL



PID Drift Chamber





广泛合作的探测器研发

Det	Technology	Det	Technology
Pixel Vertex	JadePix	Calorimeter	4D Crystal ECAL
	TaichuPix		Stereo Crystal ECAL
	Arcadia		PS/SiPM+W ECAL
	CPV(SOI)		SiDet+W ECAL
	+Stitching		PS/SiPM+Fe AHCAL
Tracker & PID	CEPCPix / COFFEE		ScintGlass AHCAL
	Si Strip Detector		RPC SDHCAL
	TPC		MPGD SDHCAL
	Drift Chamber		DR Calorimeter
	PID DC	Muon	Scintillation Bar
	LGAD ToF		RPC
	AC-LGAD ToF+Trk		μ-Rwell
Lumi	SiTrk+Crystal ECAL	Misc	HTS / LTS Magnet
	SiTrk+SiW ECAL		MDI & Integration
	Fast LumMoni		TDAQ scheme

- 积极参加国际探测器研发合作组
  - Some detector R&D efforts were within the international detector R&D collaborations, e.g. CALICE, LCTPC, & RD*
  - Much broader participation now in the ECFA DRD program
- 国际合作团队参加CEPC的探测器研发工作：MAPS detector, TPC, PID DC, …
- 非常强的国内团队 （~300 人）：

  成功建造过在中国的国际合作大科学装置：BES, DYBay, LHAASO, JUNO, …

  在国际大科学装置也起到越来越重要的地位：ATLAS, CMS, LHCb, ALICE, AMS, …

国际合作架构

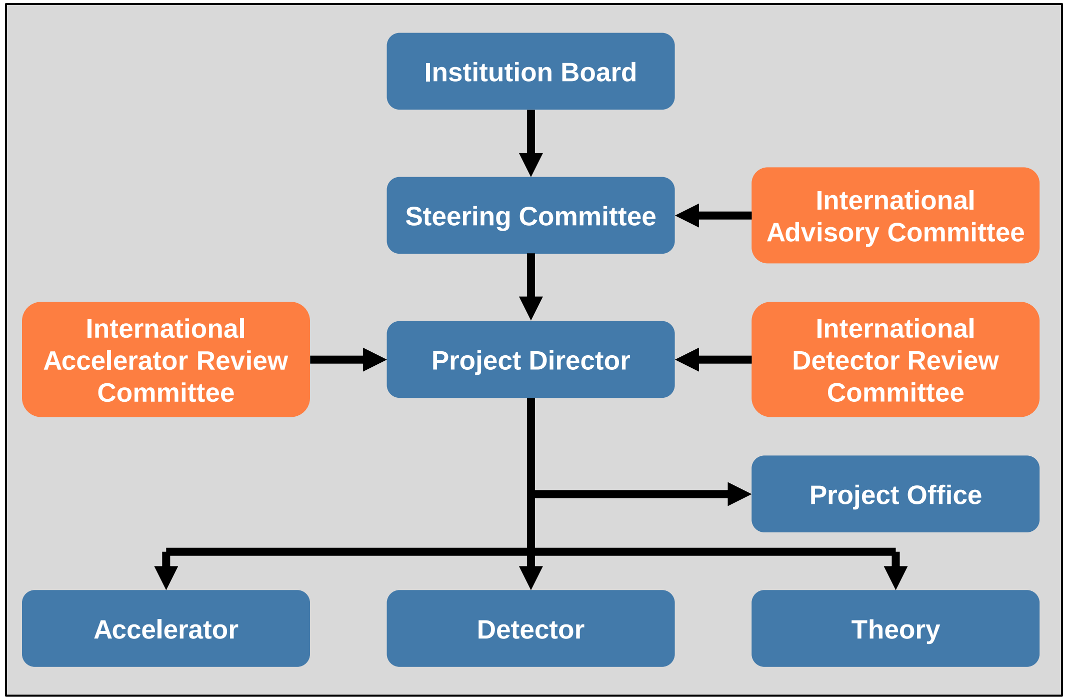


Table 7.2: Team of Leading and core scientists of the CEPC

Name	Brief introduction	Role in the CEPC team
Yifang Wang	Academician of the CAS, director of IHEP	The leader of CEPC, chair of the SC
Xinchou Lou	Professor of IHEP	Project manager, member of the SC
Yuanning Gao	Academician of the CAS, head of physics school of PKU	Chair of the IB, member of the SC
Jie Gao	Professor of IHEP	Convener of accelerator group, vice chair of the IB, member of the SC
Haijun Yang	Professor of SJTU	Deputy project manager, member of the SC
Jianbei Liu	Professor of USTC	Convener of detector group, member of the SC
Hongjian He	Professor of USTC	Convener of theory group, member of the SC
Shan Jin	Professor of NJU	Member of the SC
Nu Xu	Professor of IMP	Member of the SC
Meng Wang	Professor of SDU	Member of the SC
Qinghong Cao	Professor of PKU	Member of the SC
Wei Lu	Professor of THU	Member of the SC
Joao Guimaraes da Costa	Professor of IHEP	Convener of detector group
Jianchun Wang	Professor of IHEP	Convener of detector group
Yuhui Li	Professor of IHEP	Convener of accelerator group
Chenghui Yu	Professor of IHEP	Convener of accelerator group
Jingyu Tang	Professor of IHEP	Convener of accelerator group
Xiaogang He	Professor of SJTU	Convener of theory group
Jianping Ma	Professor of ITP	Convener of theory group

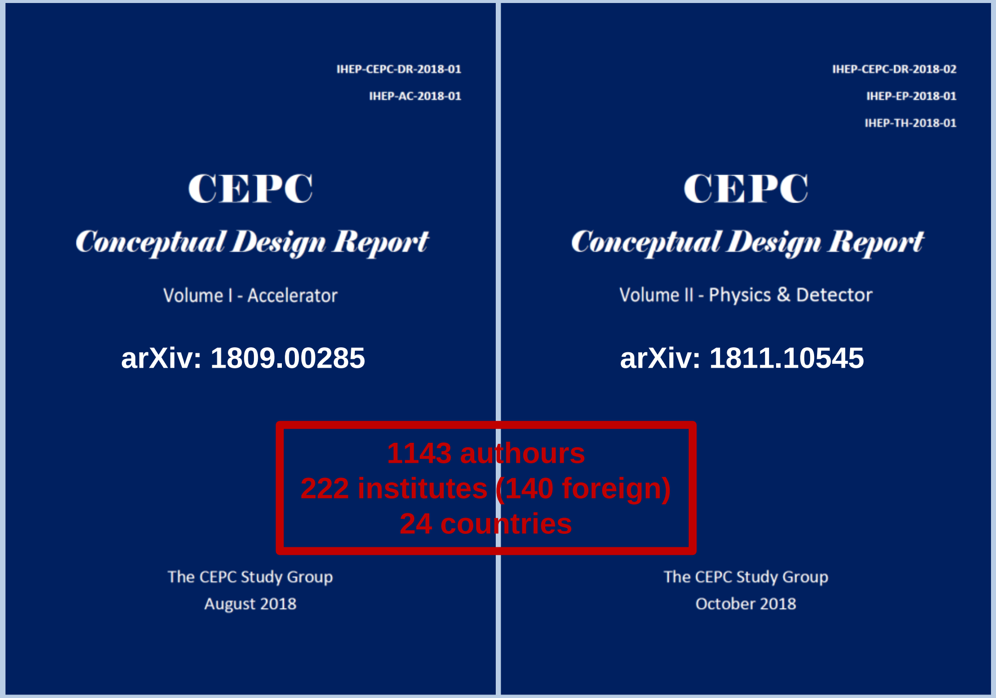
- Institution Board: 32 top domestic universities/institutes
- The International Advisory Committee (IAC) started in 2015, and held meeting yearly.
- Two international review committees for R&D: (IARC, IDRC) started in 2019.
- Currently the CEPC study group consists of ~1/4 international members. We hope to boost up international participation.

CEPC国际国内研讨会议

- 偏重于CEPC的大型国际研讨会议：
  - 在中国:　北京 (2017.11, 2018.11, 2019.11)，上海 (2020.10 / hybrid)，南京 (2021.11 / online，2022.11 / online, 2023.10), **杭州 (2024.10)**
  - 在欧洲:　Rome (2018.05), Oxford (2019.04), Edinburgh (2023.07), Marseille (2024.04), **Barcelona (2025.05)**
  - 在美国:　Chicago (2019.09), DC (2020.04 / online)
  - 香港科技大学自2015年起每年主办“IAS program on HEP”，明年在**(2025.01)**
- 在国内各地不定期举办各种专题研讨会议

CEPC概念设计报告CDR和技术设计报告TDR

CDR Released（2018.11）


IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01

CEPC
Conceptual Design Report
Volume I - Accelerator

arXiv: 1809.00285

The CEPC Study Group
August 2018

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

arXiv: 1811.10545

The CEPC Study Group
October 2018

1143 authours
222 institutes (140 foreign)
24 countries

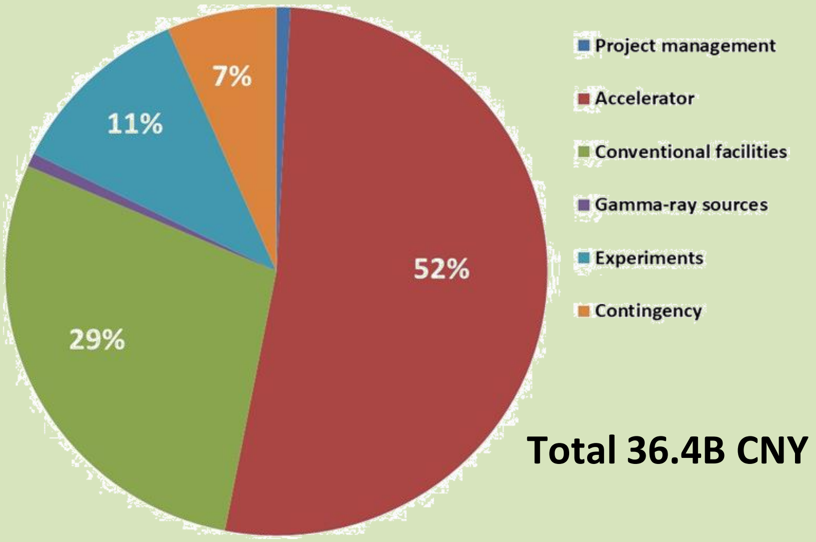

IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC
Technical Design Report
Accelerator

arXiv:2312.14363
1114 authors
278 institutes
(159 foreign institutes)
38 countries

The CEPC Study Group
December 2023

Accelerator TDR Released（2023.12.25）



- CEPC概念设计报告CDR（加速器篇、物理和探测器篇）在2018年11月发表
- CEPC加速器技术设计报告TDR在2023年12月完成
- 希望在2025年6月完成探测器的设计报告 **Ref-TDR**

CEPC规划与时间表

2027：完成加速器工程设计报告

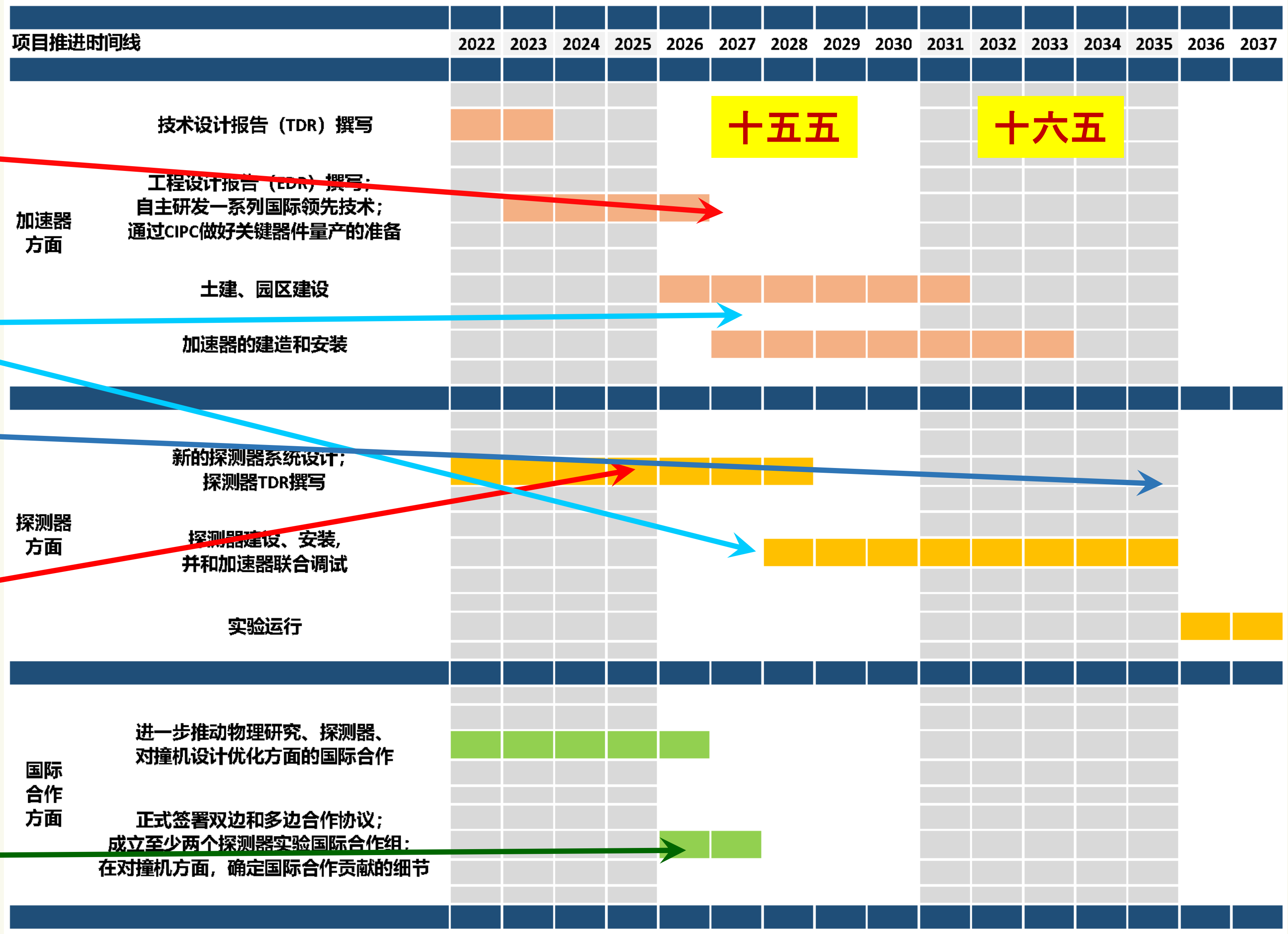
2027年开始项目施工

2035年完成项目建设

2025：完成探测器技术设计报告

2025：提交项目建议书

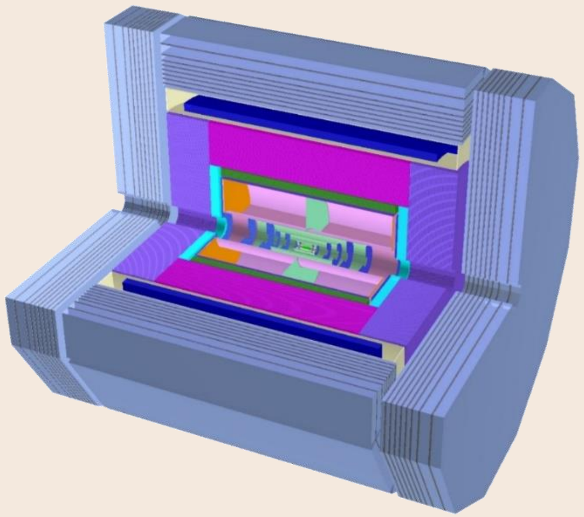
成立两个国际合作实验组



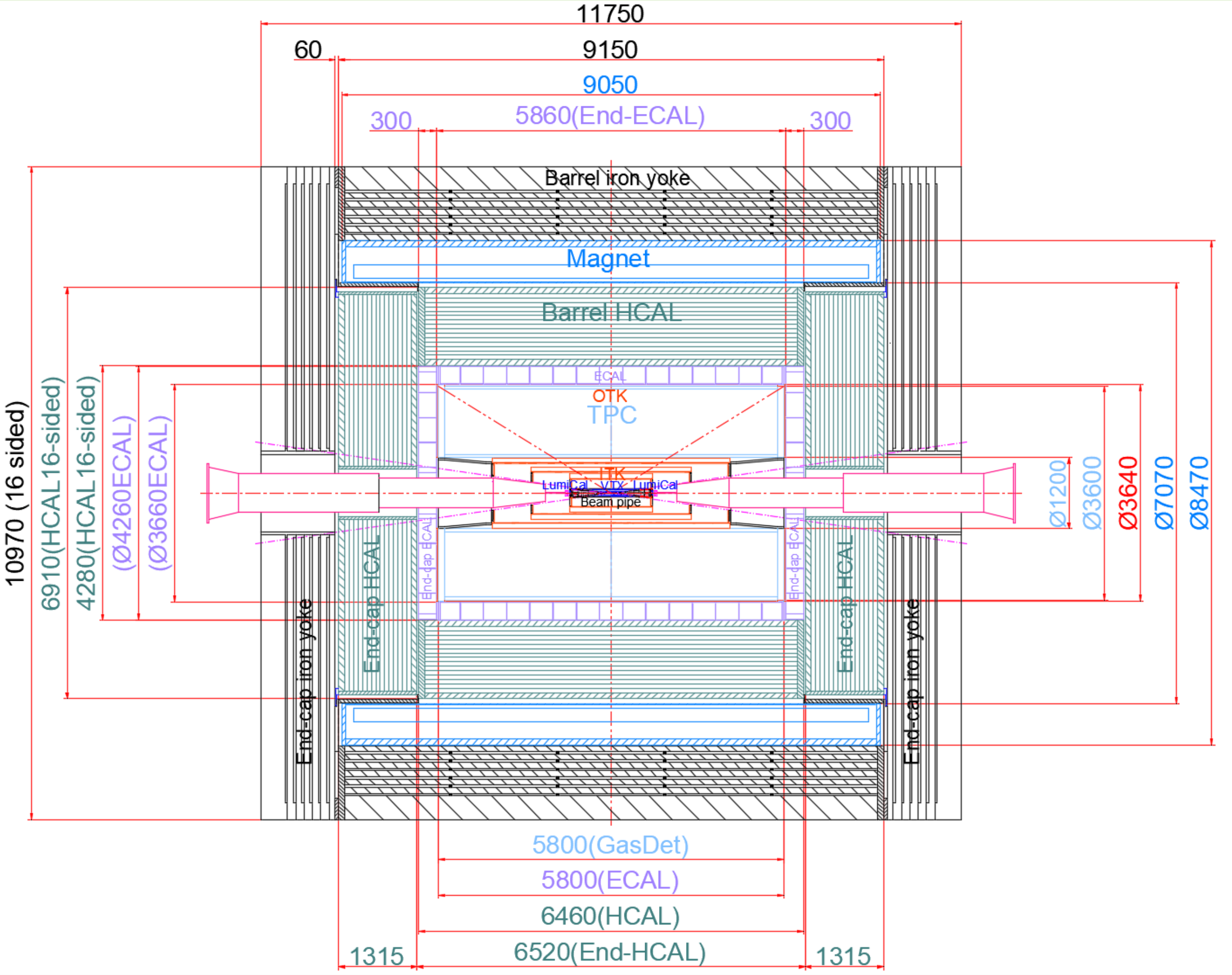
Ref-TDR的探测技术选择

System	Technologies	
	Baseline	For comparison
Beam pipe	Φ20 mm	
LumiCal	SiTrk+Crystal	
Vertex	CMOS+Stitching	CMOS Pixel
Tracker	CMOS SiDet ITrk	
	Pixelated TPC	PID Drift Chamber
	AC-LGAD OTrk	SSD / SPD OTrk
		LGAD ToF
ECAL	4D Crystal Bar	PS+SiPM+W, GS+SiPM, etc
HCAL	GS+SiPM+Fe	PS+SiPM+Fe, etc
Magnet	LTS	HTS
Muon	PS bar+SiPM	RPC
TDAQ	Conventional	Software Trigger
BE electr.	Common	Independent

- 自2024年初开始，CEPC团队对不同的探测器技术进行比较；
- 经过近半年的密集研究和讨论，团队选择了基准方案和后备技术
- 主要考量的因素包括：性能表现、造价、研发进展、技术成熟度 等等

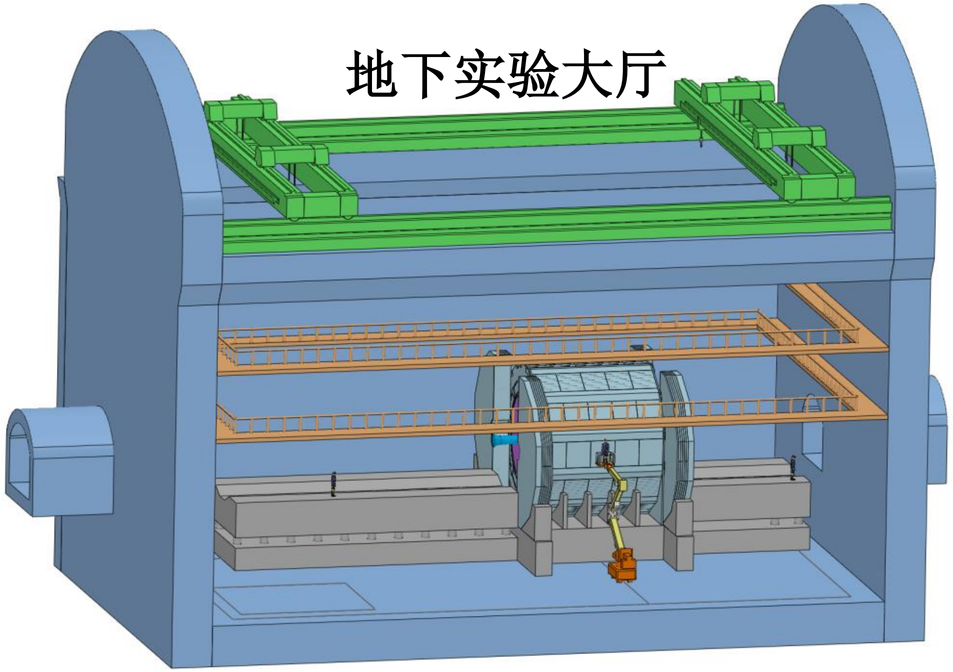


探测器几何设计与机械支撑

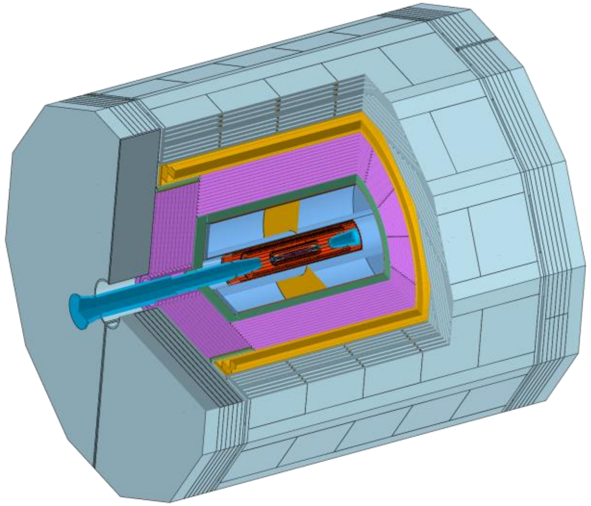


Subsystem	Supported By
Barrel Yoke	Base
Magnet	Barrel Yoke
Barrel HCAL	Barrel Yoke
Barrel ECAL	Barrel HCAL
TPC+ Barrel OTK	Barrel ECAL
ITK	TPC
Beampipe+VTX+LumiCal	ITK
Endcap Yoke	Base
Endcap HCAL	Barrel HCAL
Endcap ECAL+OTK	Barrel HCAL

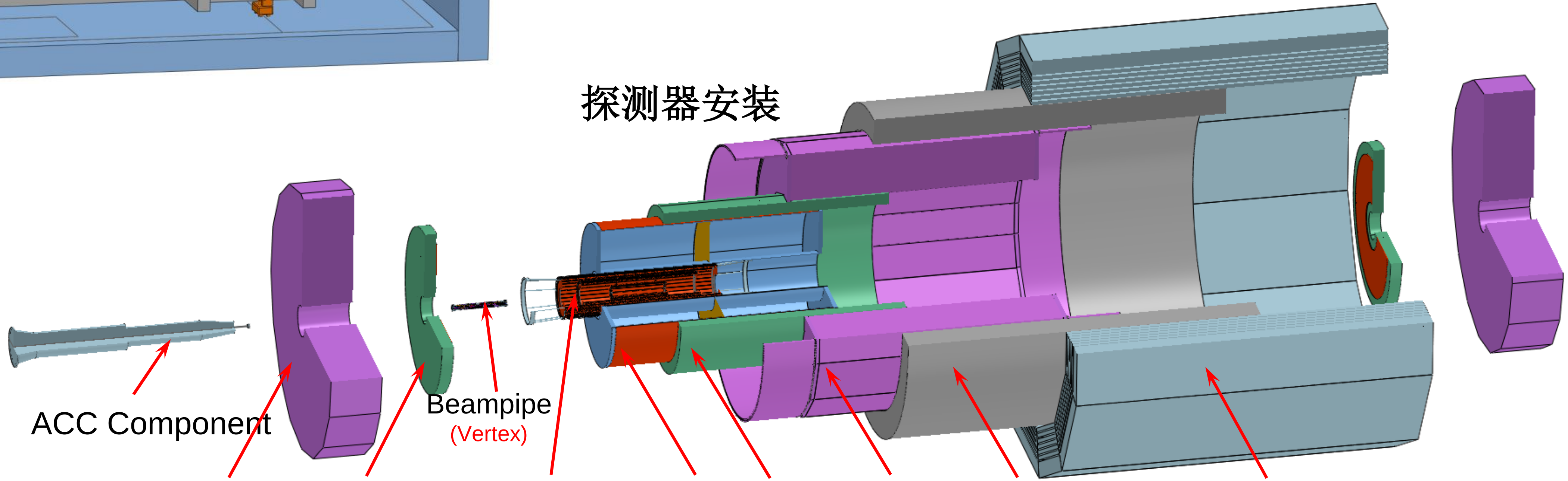
实验大厅总体布局和探测器安装



初步完成地下实验大厅的布局设计，确定探测器安装程序



探测器安装



技术设计报告的构架

- 已完成了技术设计报告的构架，初步规划共16章
- 各章的撰写团队相对独立，由国内外参与相关探测器研发的成员组成
- 赵天池老师担任主编，带领一个小而精的编辑团队

1) Physics goal and requirements
2) Concept introduction
3) MDI and beam measurement
4) Vertex detector
5) Silicon trackers
6) Gaseous trackers
7) Electron magnetic calorimeter
8) Hadron calorimeter
9) Muon detector
10) Magnet
11) General electronics
12) TDAQ and online
13) Software and computing
14) Mechanics, integration and installation
15) Global performance
16) Overall cost and timeline

探测器技术设计报告Ref-TDR时间线

Date	Actions and/or Expectations
Jan 1, 2024	Start the ref-TDR process by comparing different technologies
Jul 1, 2024	Baseline technologies are chosen; start to write TDR and address key issues
Aug 7, 2024	Report to the IDRC chair Prof Daniela Bortoletto
Oct 21-23, 2024	Review of ref-TDR progress by the IDRC
Oct 23-30, 2024	Discuss the ref-TDR at the CEPC workshop, report progresses to the CEPC IAC
Dec 31, 2024	The first draft of the ref-TDR is ready for internal reviews
April 30, 2025	Finish international reviews
Jun 30, 2025	The ref-TDR is ready 完成技术设计报告 ！

小结

- CEPC是粒子物理领域的前沿大科学装置，旨在解决本领域最重大的科学问题，有望取得革命性的突破，使得我国在该领域取得国际领先地位。
- CEPC团队经过近10年的努力，在加速器和探测器的关键技术取得了多项重要突破，达到国际先进水平。
- 团队已经完成包括加速器、物理和探测器的概念设计报告，加速器的技术设计报告，正在积极准备探测器技术设计报告。
- 借助于本次研讨会，我们对包括机械结构与支撑、探测器集成与安装、加速器与探测器界面等进行一次系统性的梳理和讨论，使得Ref-TDR自洽完善，为成功建造打下坚实基础。

感谢中信重工提供这样难得的机会！
感谢诸位参加讨论！