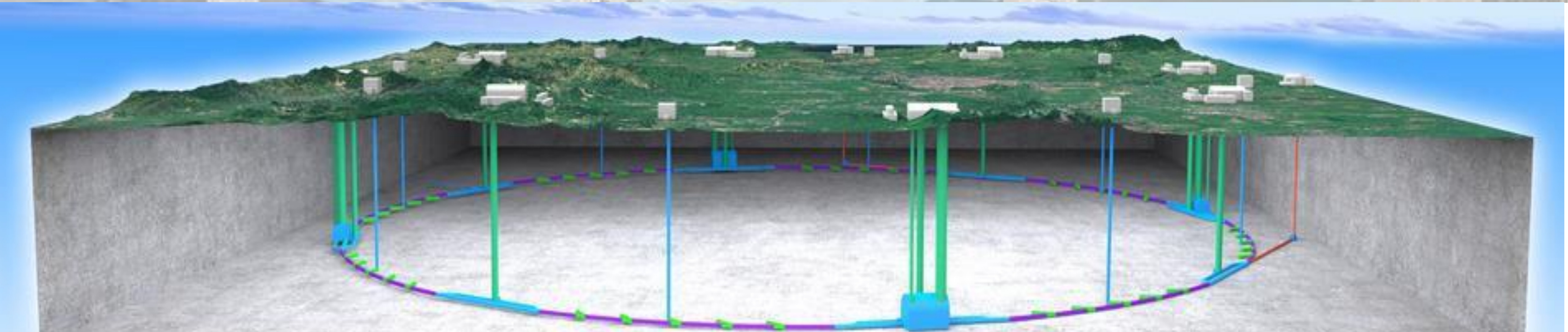
CEPC 探测系统规划

王建春

测试束流与先进探测技术研讨会

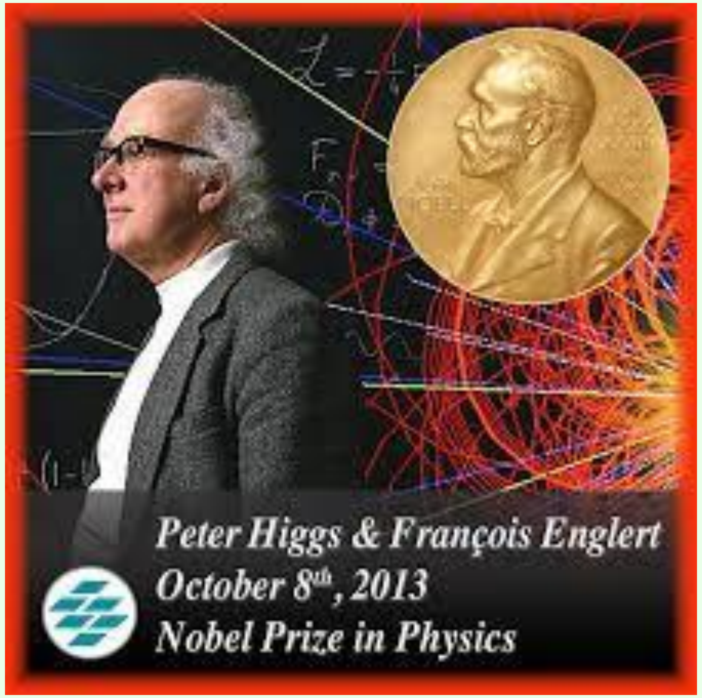
2025.8.15-16, 河南登封



Outline

- Introduction of CEPC
- Baseline Technologies of A Reference Detector
- Collaborative Efforts
- Closing Remarks

希格斯粒子：探索新物理的工具



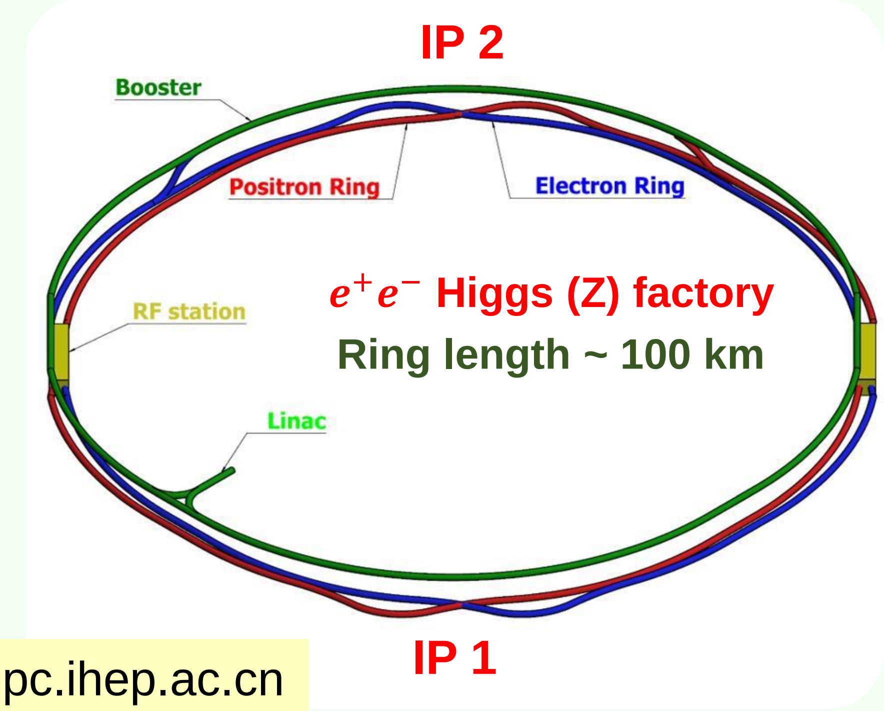
2012年LHC发现希格斯粒子 是粒子物理发展的重要里程碑

希格斯粒子是标准模型的最后一块拼图 → **希格斯粒子成为探索新物理的关键探针**

希格斯粒子质量 = 125 GeV

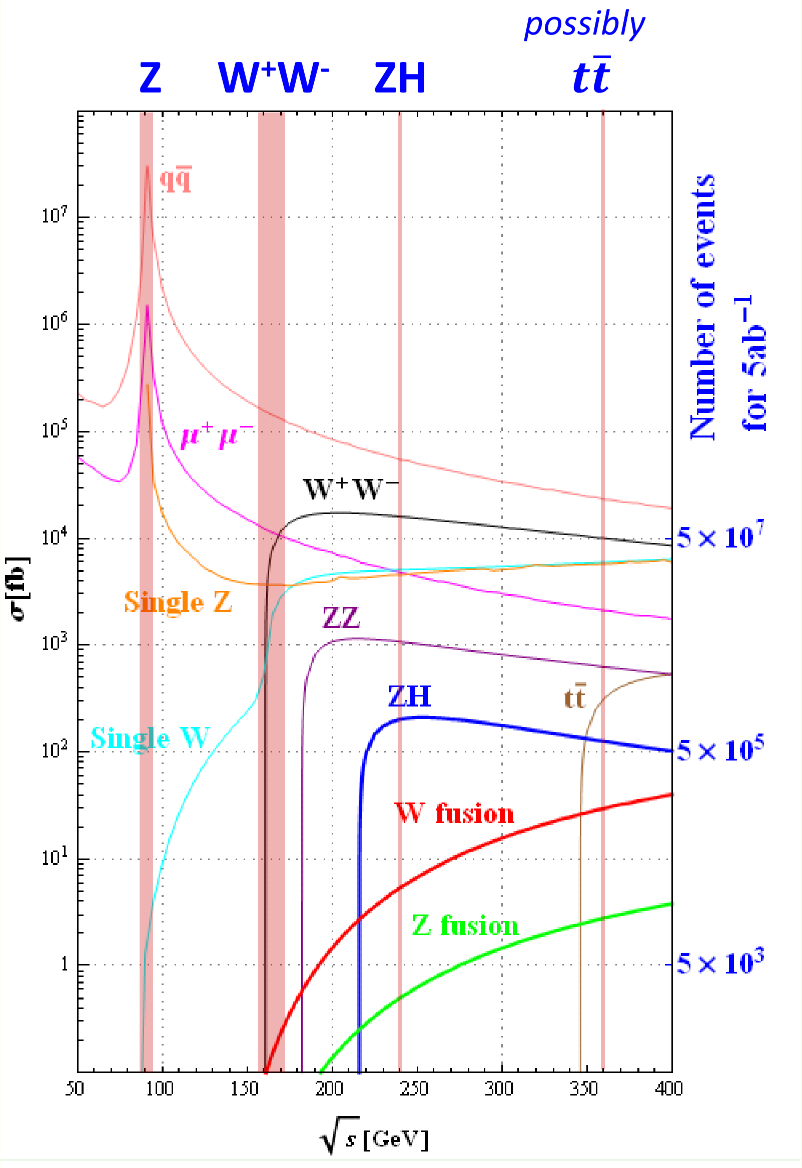
The Circular Electron Positron Collider

- The CEPC was proposed in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as an e^+e^- Higgs / Z factory.
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.
- It is possible to upgrade to a *pp* collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



http://cepc.ihep.ac.cn

CEPC Operation Plan



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 [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

CEPC accelerator TDR (Xiv:2312.14363)

CEPC Physics White Papers

- Precision Higgs Physics at CEPC (CPC V43, No. 4 (2019) 043002)
- Flavor Physics at CEPC (arXiv:2412.19743)
- New Physics Search at CEPC (arXiv:2505.24810)
- White papers of EW and QCD are in preparation

CEPC Design Reports

IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

The CEPC-SPPC Study Group
March 2015

IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group
March 2015

Pre-CDR Released (2015.03)

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 authhours
222 institutes (140 foreign)
24 countries

Accelerator TDR Released (2023.12)

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

CEPC

Technical Design Report

Accelerator

arXiv:2312.14363

1114 authors
278 institutes (159 foreign)
38 countries

The CEPC Study Group
December 2023

CEPC

Technical Design Report

~~Detector TDR(s)~~

TDR of A Reference Detector

CEPC

Engineering Design Report

EDR of Accelerator

2027

Ideal Timeline of CEPC

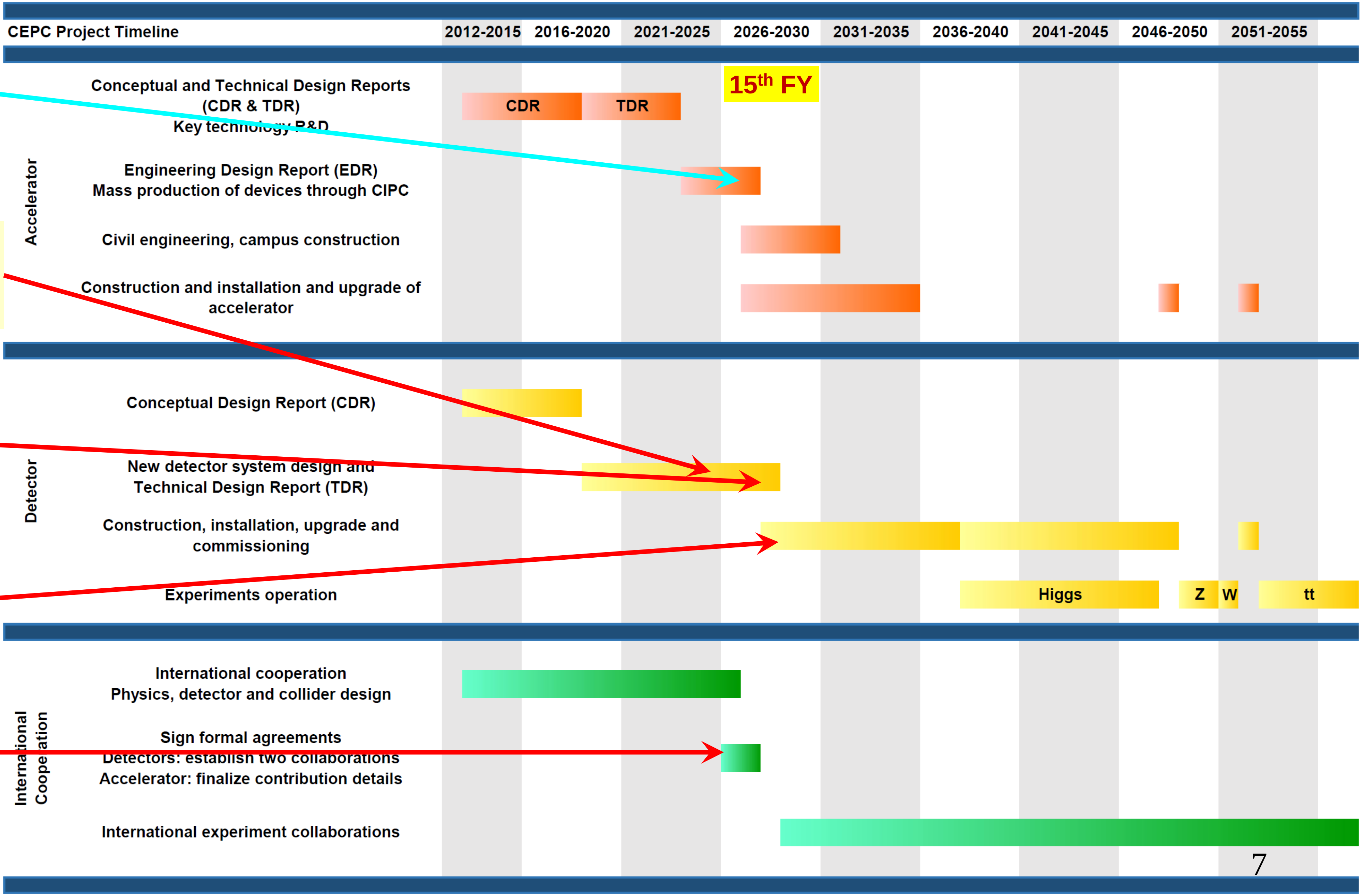
Completion of Accelerator EDR

Release TDR of A Reference Detector

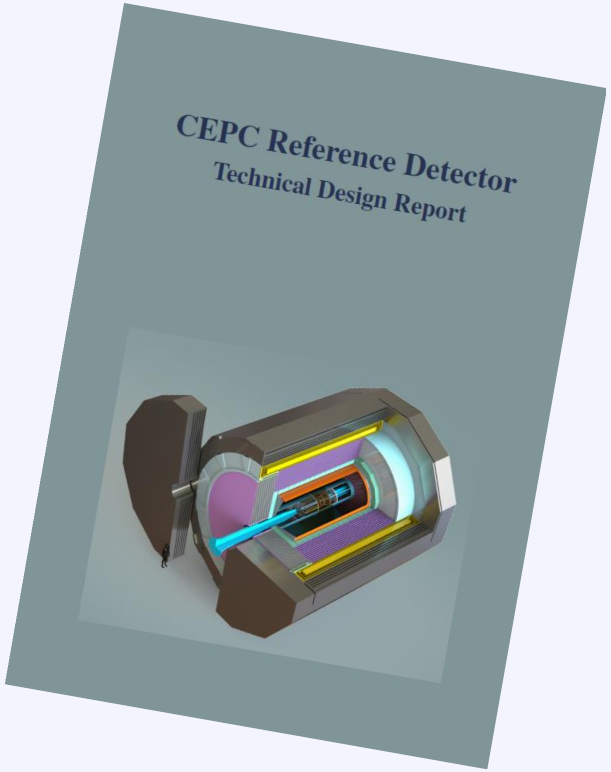
Detector TDR × 2

Construction of Detectors

International Collaborations



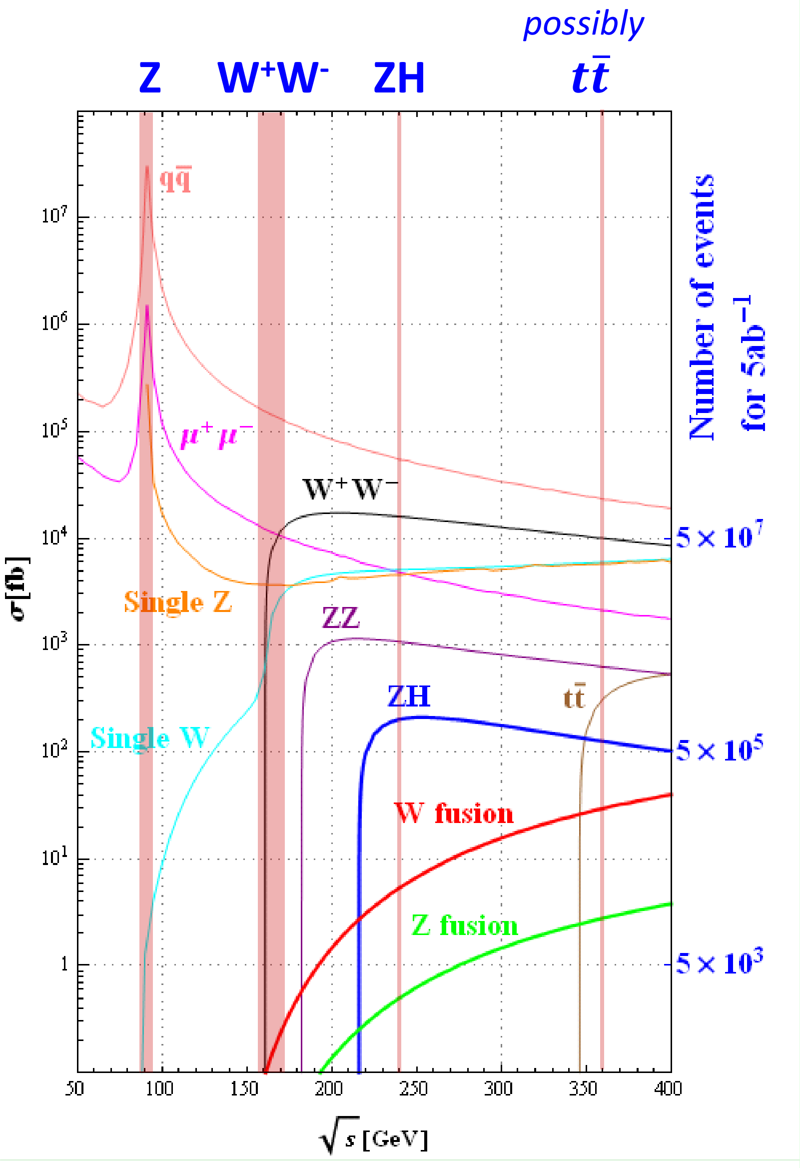
TDR of A Reference CEPC Detector



- Demonstrate the technical readiness and feasibility of the proposed detector technologies
- Provide a more realistic evaluation of the personnel resources and budgetary commitments to construct the detector and the timeline
- The exercise and efforts will be very valuable assets, not only in technology development but also team building

Date	Actions and/or Expectations
Jan 1, 2024	Start the process with comparison of different technologies
Jul 1, 2024	Baseline technologies are chosen; start to write and address key issues
Aug 7, 2024	Report to IDRC chair Prof Daniela Bortoletto
Oct 21-23, 2024	Review progress by the IDRC
Oct 23-30, 2024	Discuss at the Hangzhou CEPC workshop, report progresses to the CEPC IAC
January, 2025	The first draft is ready for internal reviews
Apr 14-16, 2025	Review progress by the IDRC
Jun 16-19, 2025	Discuss at the CEPC Barcelona workshop
Sept ?, 2025	Further iteration and review by the IDRC
Fall of 2025	Publication of the ref-TDR
Nov 6-10, 2025	Report at the Guangzhou CEPC workshop

CEPC Operation Plan: First 10 Years

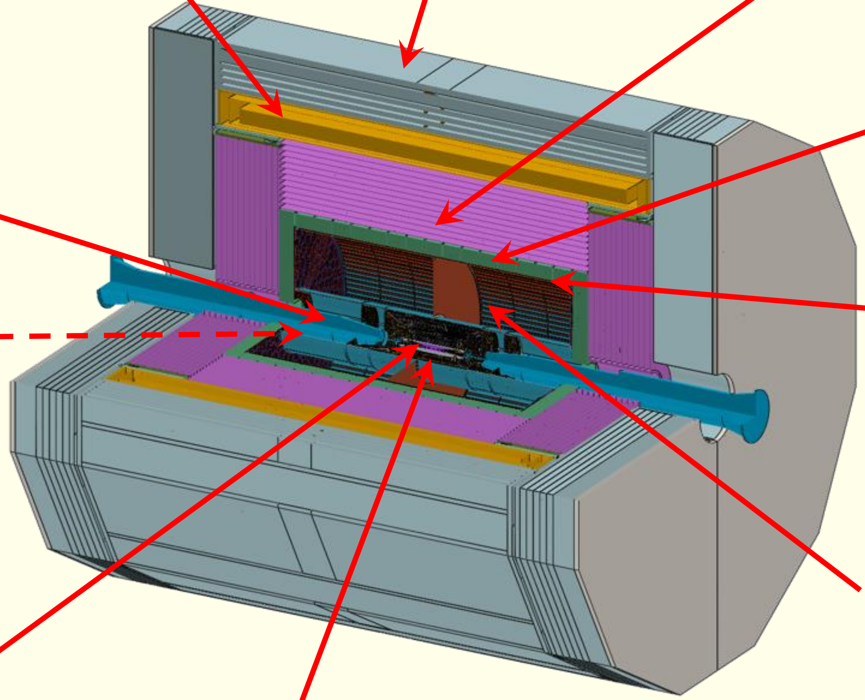


SR Power Per Beam	Luminosity/IP [$\times10^{34}cm^{-2}s^{-1}$]		
	H	Z	W^+W^-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7

B = 3T
all modes

- **The first 10-year operation** includes: the Higgs mode, the Low-Lumi Z mode, and the W^+W^- mode.
- The accelerator may be upgraded for the High-Lumi Z mode and the $t\bar{t}$ mode after 10 years operation, subject to physics needs
- The reference detector focuses on the first 10 years operation. There may be future upgrade of the detector if the accelerator is to be upgraded

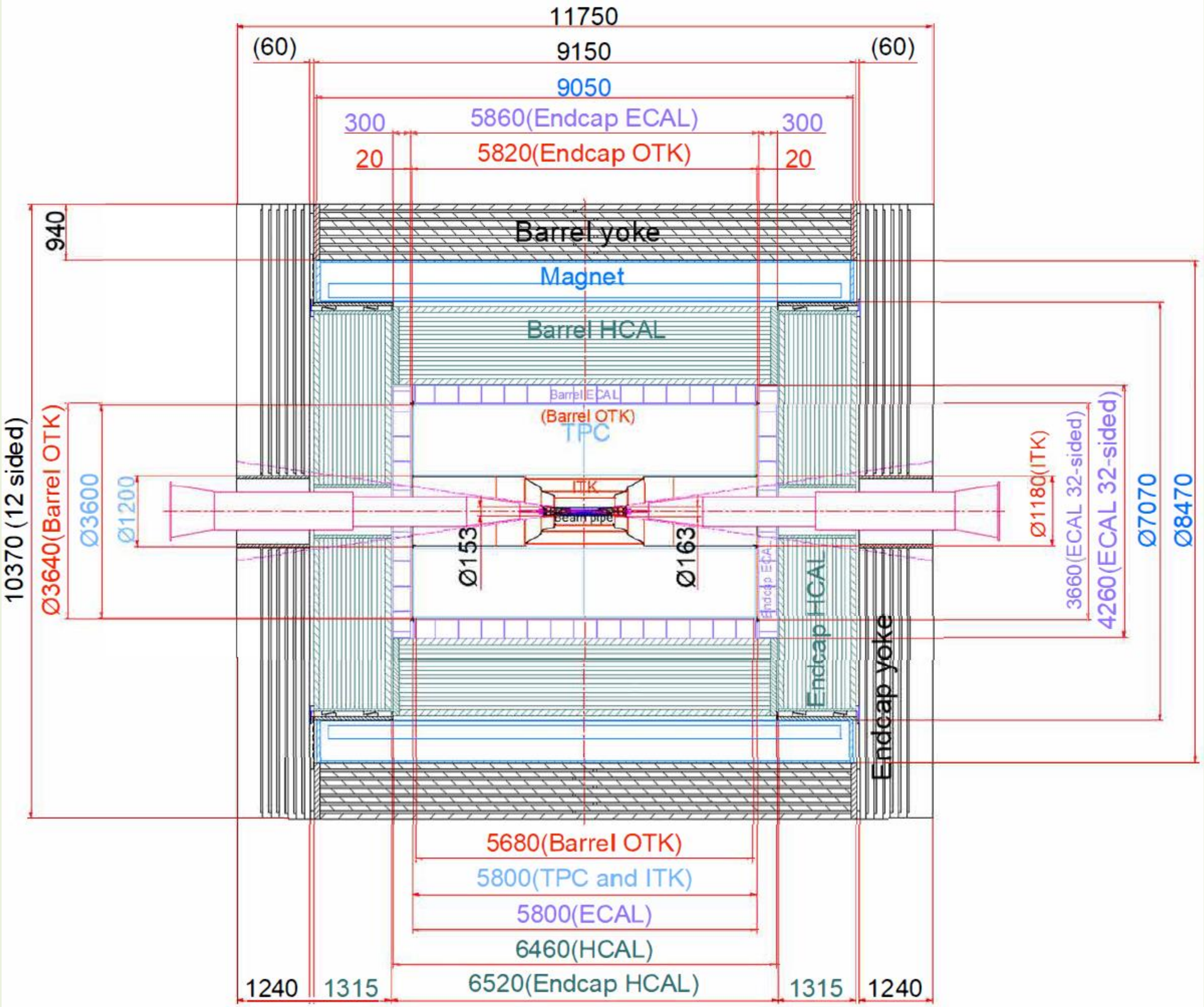
Baseline Detector Design in Ref-TDR



Detector Key Requirements

Physics Objects	Measurands	Detector Subsystem	Performance Requirement
Tracking	Coverage Recon. Efficiency Resolution in Barrel Resolution in Endcap	Tracker	$\|\cos\theta\| \leq 0.99$ $\geq 99\%$ ($p_T > 1$ GeV) $\sigma_{p_T}/p_T < 0.3\%$ ($30^\circ < \theta \leq 90^\circ$) $\sigma_{p_T}/p_T < 3\%$ ($10^\circ < \theta \leq 30^\circ$)
Leptons (e, μ)	PID Efficiency Mis-ID Rate	Tracker, ECAL, HCAL, Muon	$\geq 99\%$ ($p > 5$ GeV, isolated) $\leq 2\%$ ($p > 5$ GeV, isolated)
Photons	PID Efficiency Mis-ID Rate Energy Resolution	ECAL	$\geq 99\%$ ($E > 3$ GeV, isolated) $\leq 5\%$ ($E > 3$ GeV, isolated) $\sigma_E/E \leq 3\%/\sqrt{E(\text{GeV})} \oplus 1\%$
Vertex	Position Resolution	Vertex Detector	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\text{GeV})\times\sin^{3/2}\theta}(\mu\text{m})$
Hadronic Jets	Energy Resolution Mass Resolution	Tracker, ECAL, HCAL	$\sigma_E/E \sim 30\%/\sqrt{E(\text{GeV})} \oplus 4\%$ BMR $\leq 4\%$
Jet Flavor Tagging	b-tagging Efficiency c-tagging Efficiency	Full Detector	$\sim 80\%$, mis-ID of uds $< 0.3\%$ $\sim 50\%$, mis-ID of uds $< 1\%$
Charged Kaon	PID Efficiency, Purity	Tracker, TOF	$\geq 90\%$ (inclusive Z sample)

Geometry and Mechanical Support



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

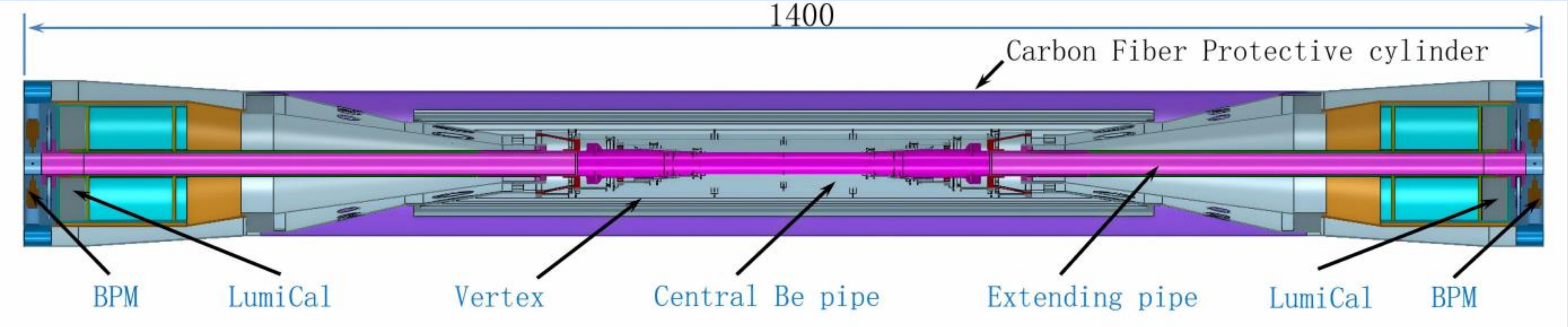
Detector Overall

Length: 11,750 mm

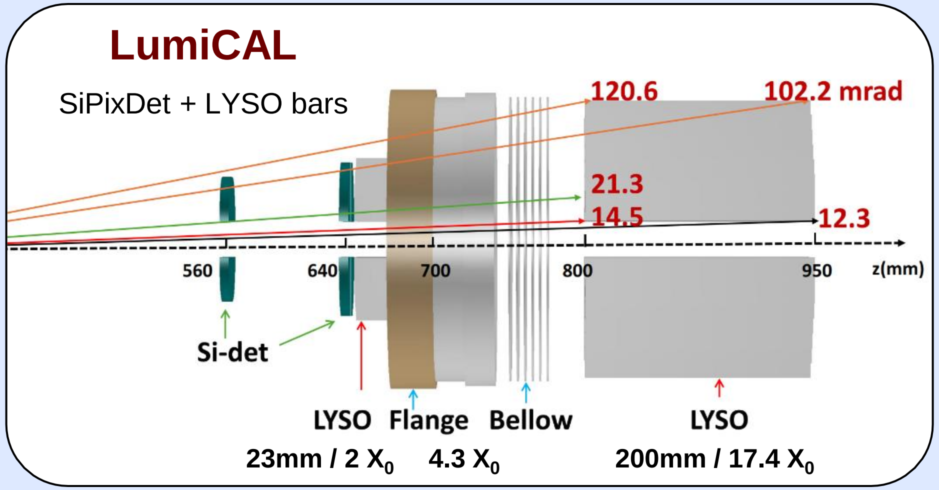
Height: 10,370 mm

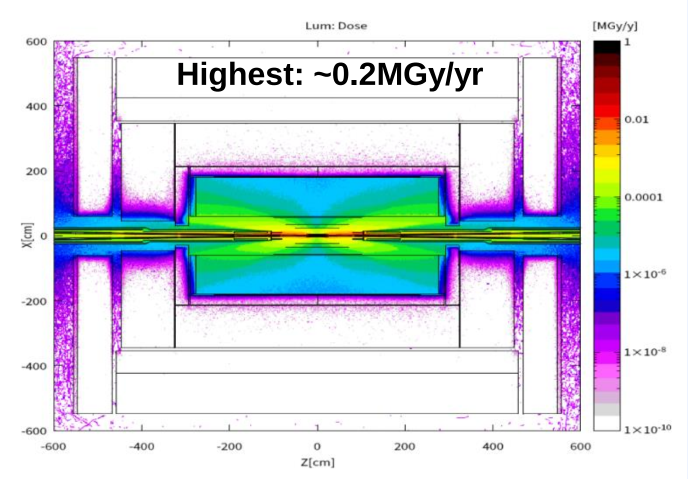
Weight: 5,205 ton

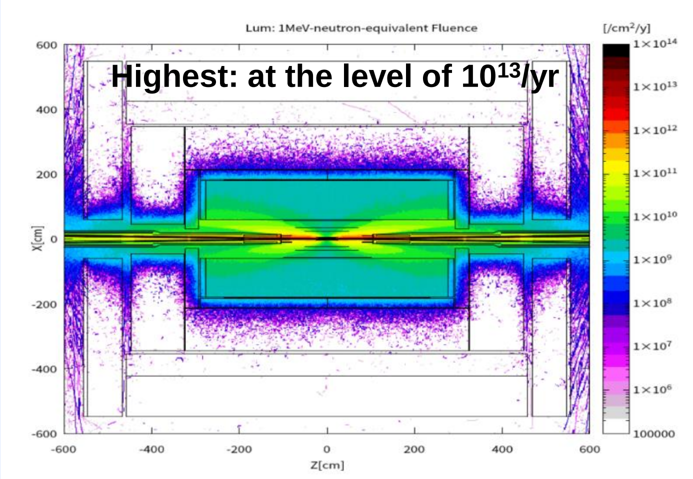
MDI, Beam Background and LumiCal



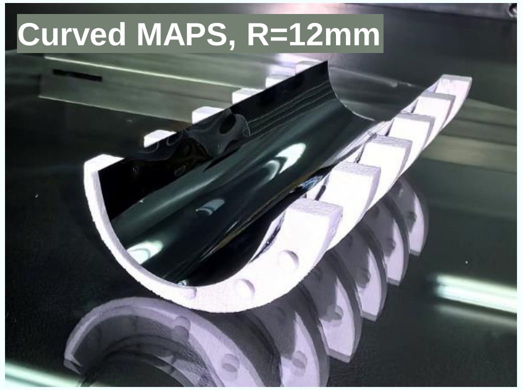
- Design of the CEPC interaction region, beam pipe and LumiCal
- LYSO bar and SPD based LumiCal design for a 10^{-4} luminosity precision, yet to be validated.
- Beam-induced background and radiation levels are estimated with updated model and improved design of collimators and shielding







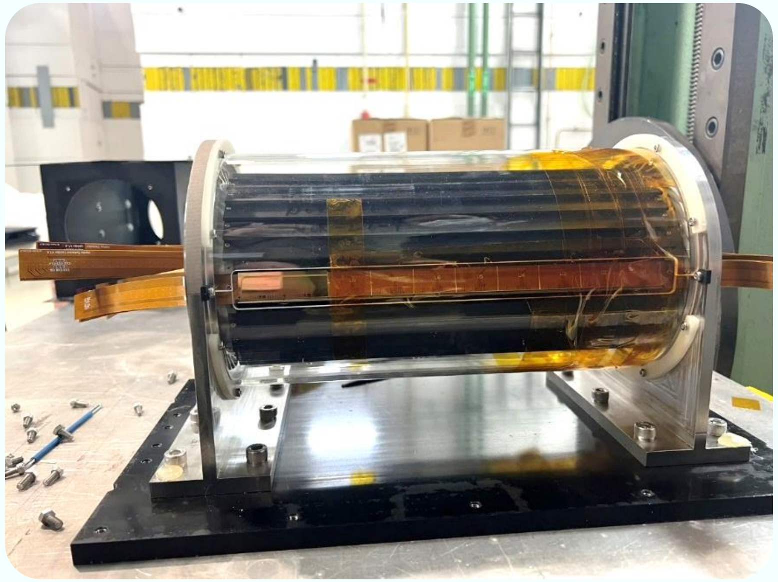
Silicon Pixel Vertex Detector



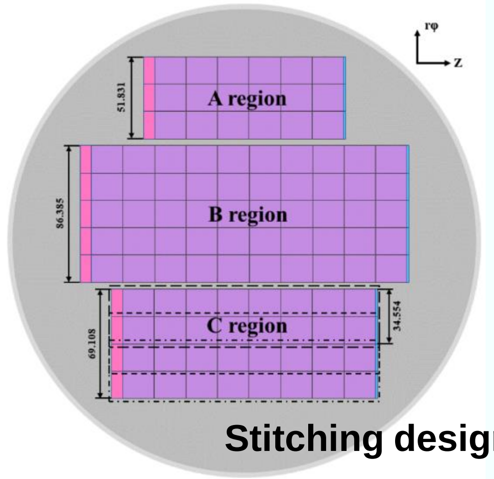
Goal: σ(IP) ~ 5 μm for high P

Key specifications:

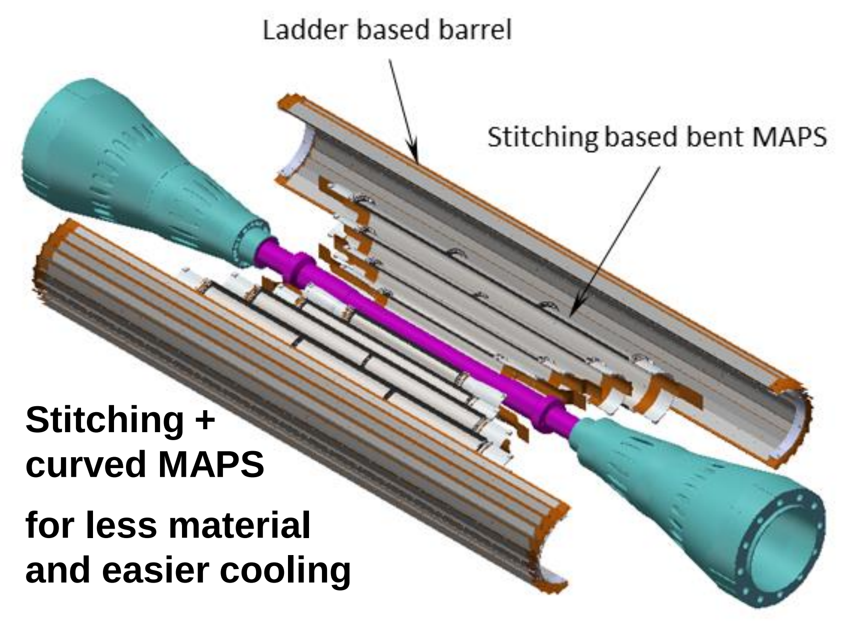
- Single point resolution ~ 5 μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm^2)



A TaichuPix-based prototype detector

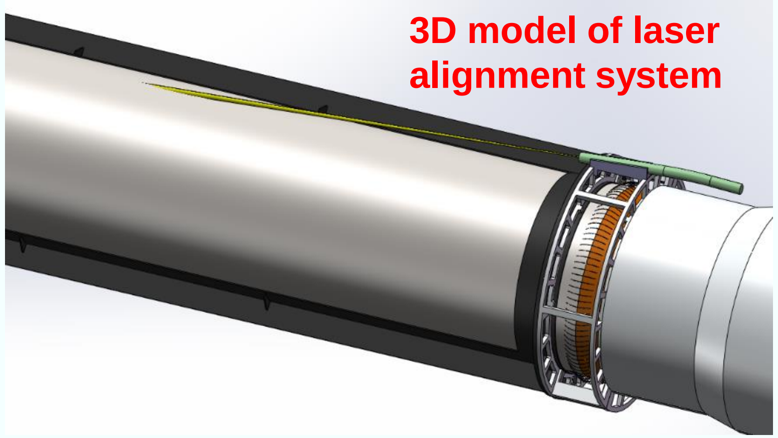


Stitching design



Stitching + curved MAPS

for less material and easier cooling

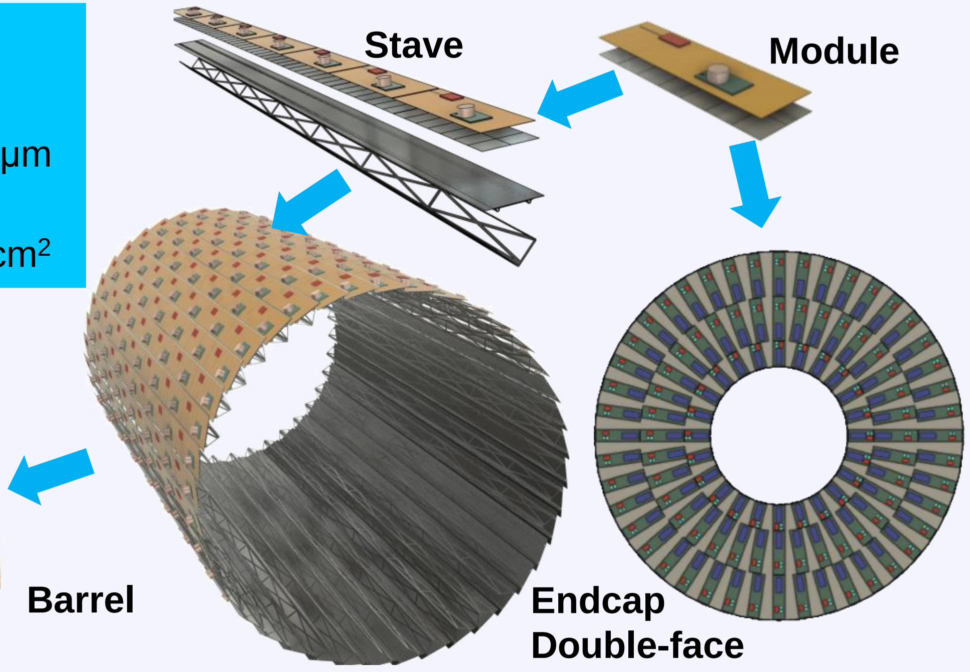


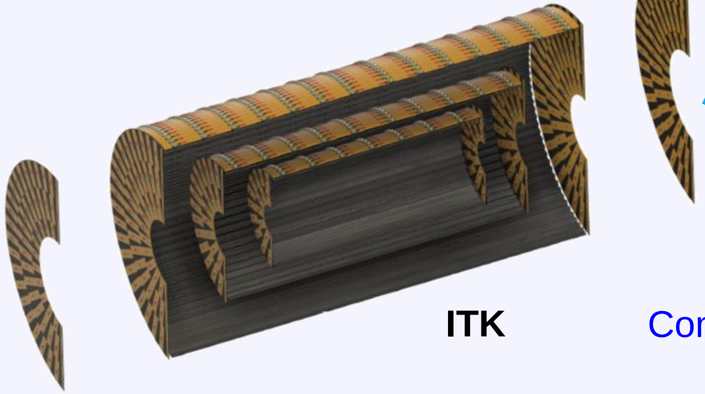
Silicon Pixel Inner Tracker

- Focus on HV-CMOS pixel detector of ~15-20 m^2.
- Exploring SMIC 55 nm and other processes
  - COFFEE2: 1st prototype as validation of process
  - COFFEE3: just produced, with full digital functions
- Overall detector design based on typical chip size

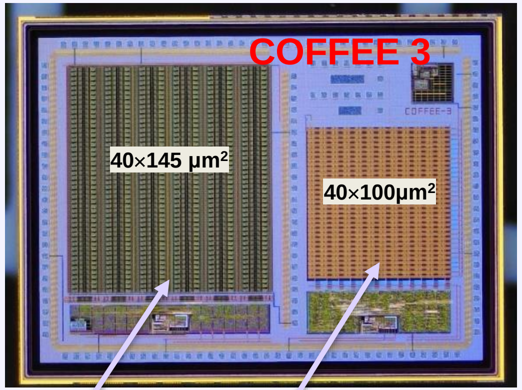
Goal

- Cost effective
- Spatial resol. < 10 μm
- Timing 3-5 ns
- Power < 200 mW/cm^2



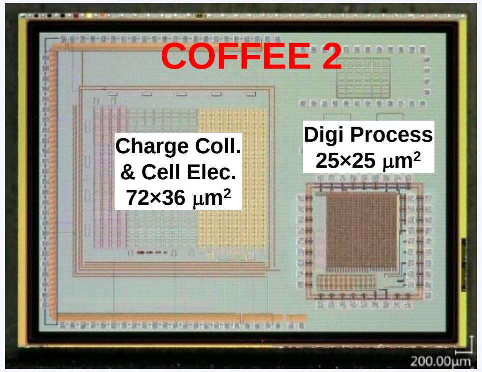


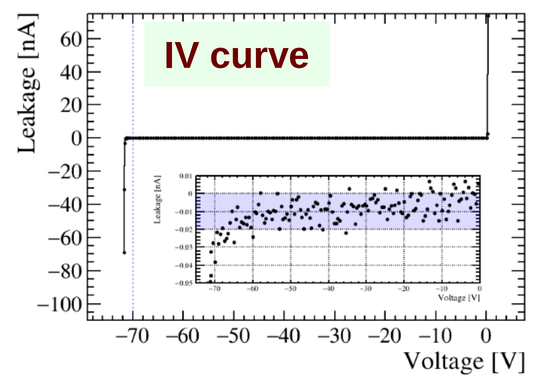
Common module design for barrel & endcap; < 1% X_0 / layer



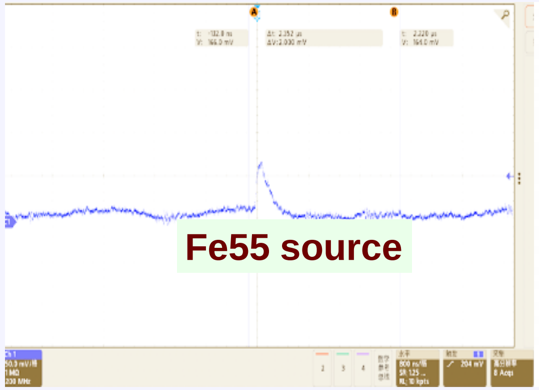
Architecture with in-pixel TDC for optimal timing

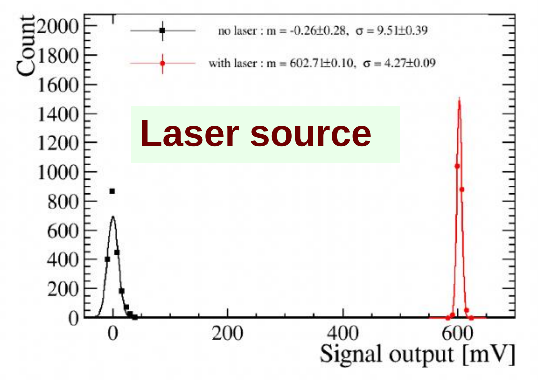
Digital functions in periphery for minimal interference w. signal





Breakdown at -70V,
to increase with high-res wafer

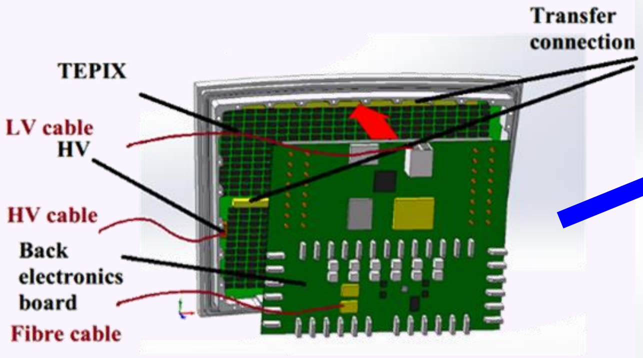


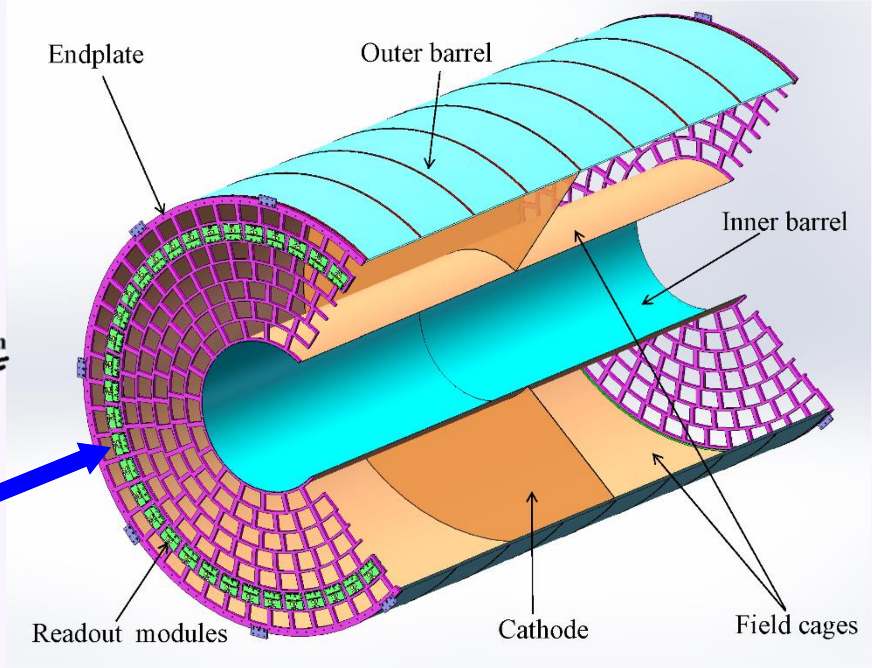


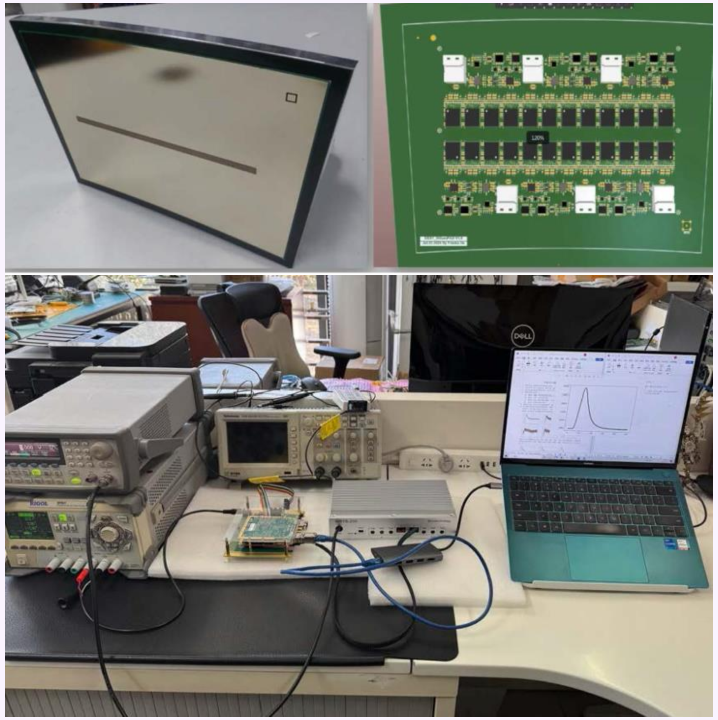
Time Projection Chamber

- Pixelated readout TPC can improve PID performance
  - Using the cluster of electrons, the full simulation study shows 3σ K/π separation at 20GeV
  - Balanced the total power consumption and readout channels, the pad size is optimized
- Readout pad size of **(500μm)^2** reduces IBF×Gain ~1@G=2000, achieves σ(r-Φ) ~100 μm.
  - Maximum Δrφ can be reduced to hundred *μm*@Low Z (detailed optimization of MDI)
- Plan for a test beam at DESY to assess the performance and validate the design

TPC detector	Key Parameters
Modules per endplate	248 readout modules
Potential at cathode	-62,000 V
Gas mixture	T2K: $Ar/CF_4/iC_4H_{10}$ = 95/3/2
Maximum drift time	34 μs
Cooling	Water cooling circulation system
Detector modules	Pixelated readout MicroMegas

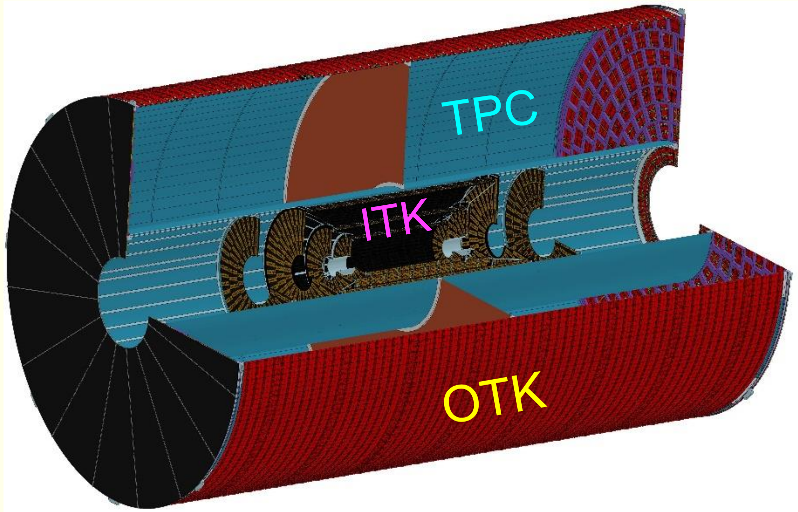






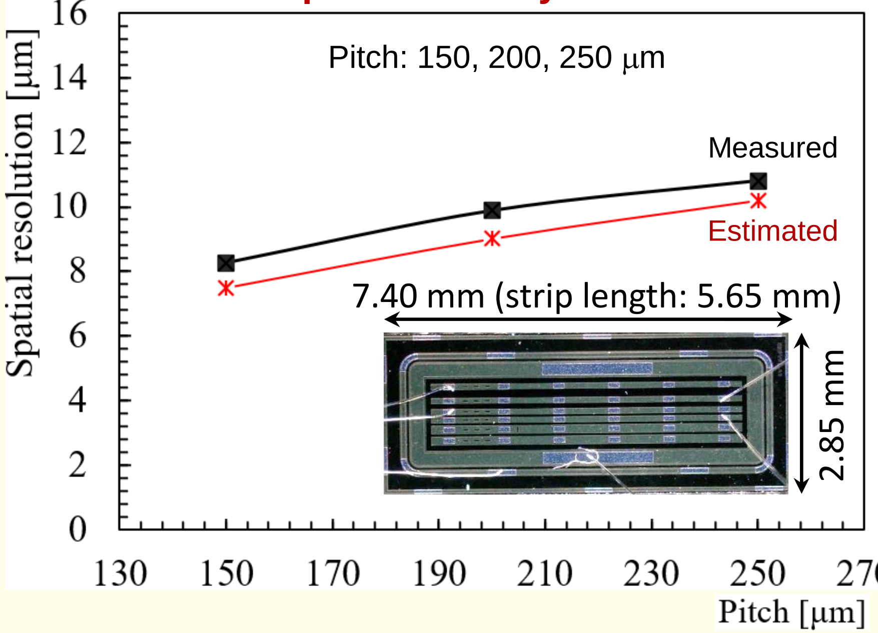
TPC modules assembled for the beam test

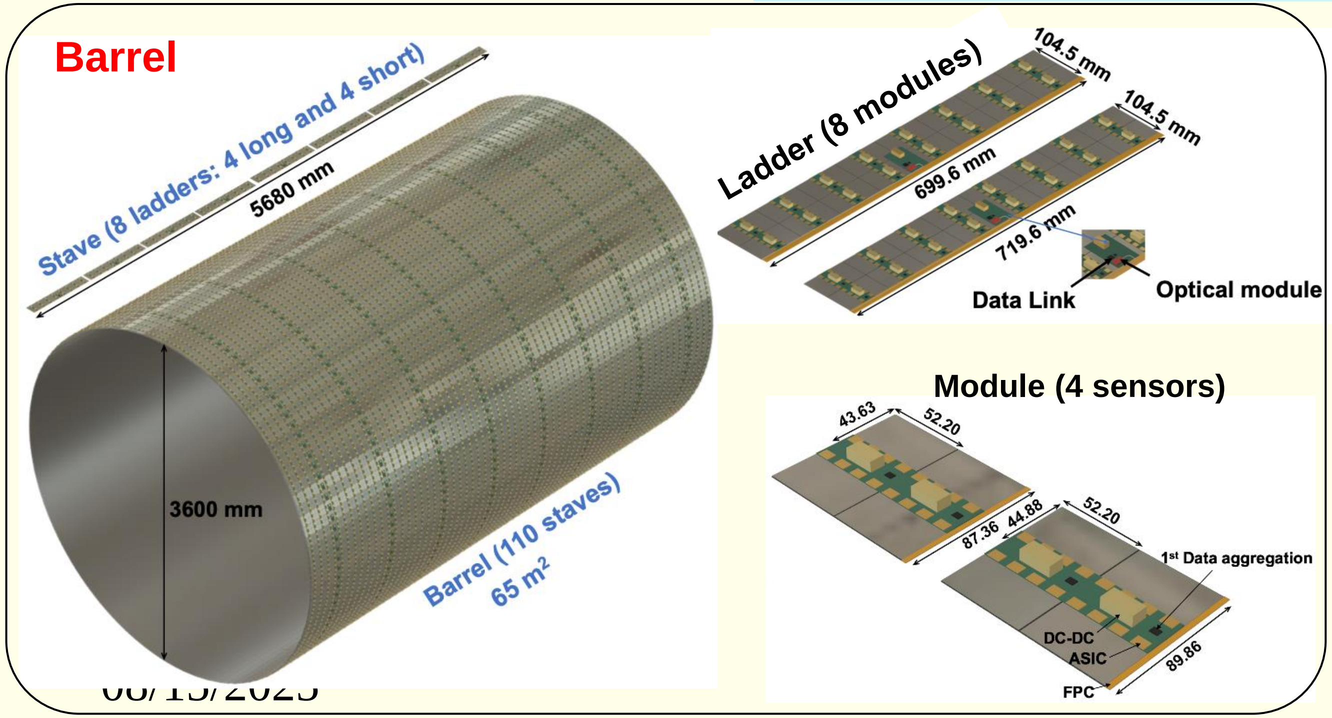
AC-LGAD OTK (Time Tracker)

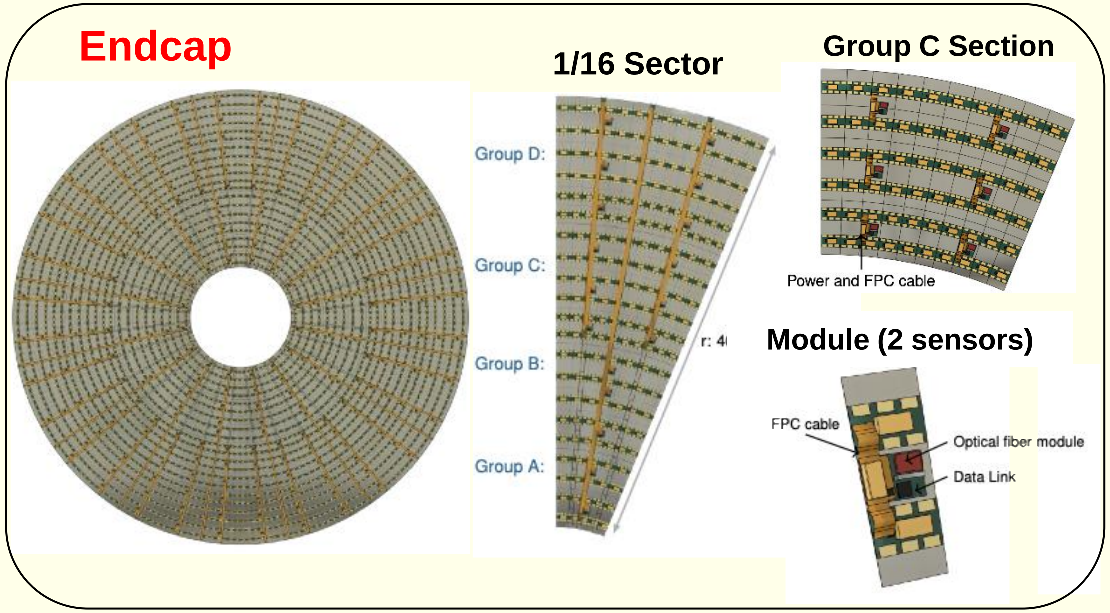


- The outer silicon tracker ~ 85 m^2, the Z precision is not crucial
  $\Rightarrow$ Cost-effective SSD
- A supplemental PID at low energy
  $\Rightarrow$ LGAD ToF
- An AC-LGAD Time Tracker combines the two needs in one detector. We expect σ_t ~50 ps, $\sigma_{R\Phi}$ ~10 μm
- Need to validate with full size sensors

Strip AC-LGAD by IHEP / IME



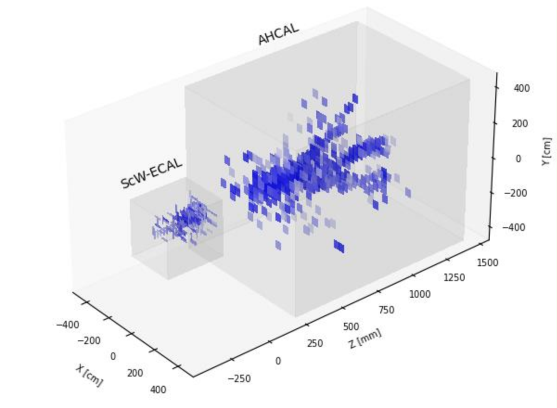




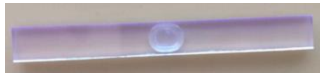
Prototype PFA Calorimeters

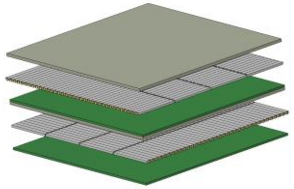
- ScW-ECAL: transverse 20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

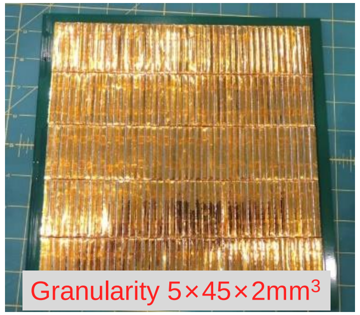
Several successful testbeams @ CERN



ECAL: scintillator(strip)+SiPM, CuW

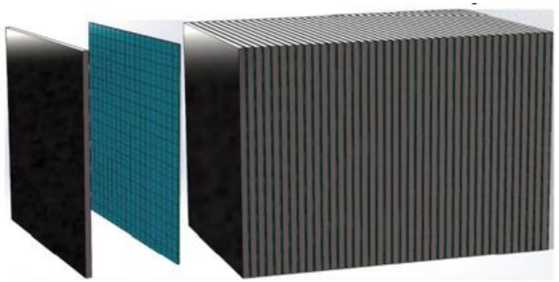


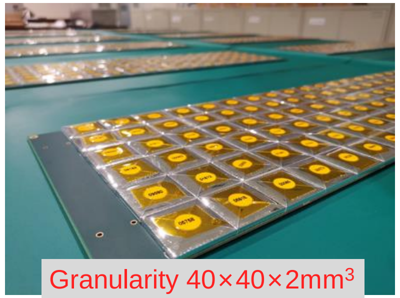




Granularity 5×45×2mm^3

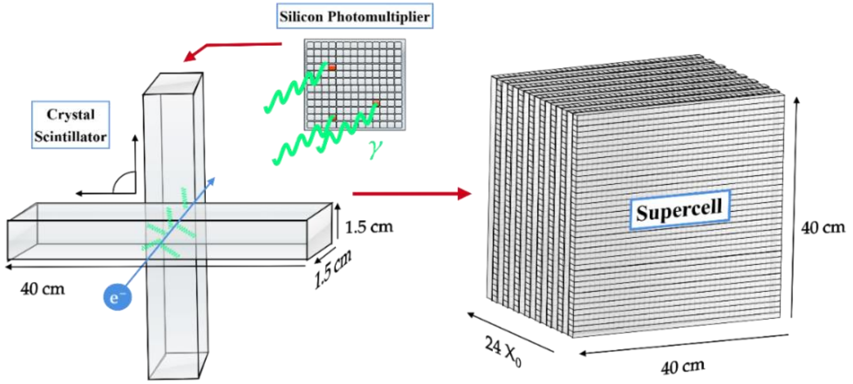
HCAL: scintillator (tile)+SiPM, steel



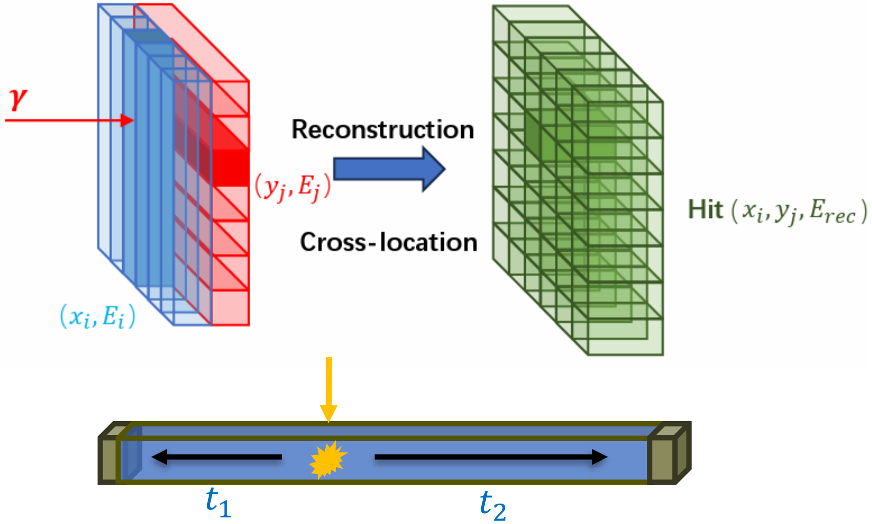


Granularity 40×40×2mm^3

Crystal Bar EM Calorimeter



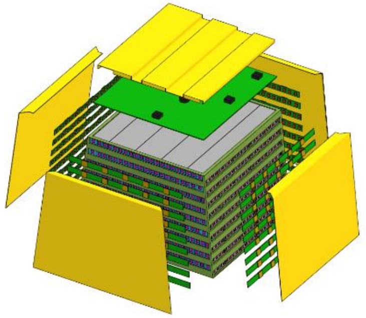
- Compatible to PFA: Boson mass resolution BMR(H→jj) < 4%
- Optimal EM performance: $\sigma_E/E < 3\%/\sqrt{E}$, BMR(H→γγ) ~0.6 GeV
- Save readout channels, minimize dead materials
- Challenging in pattern recognitions with multiple particles

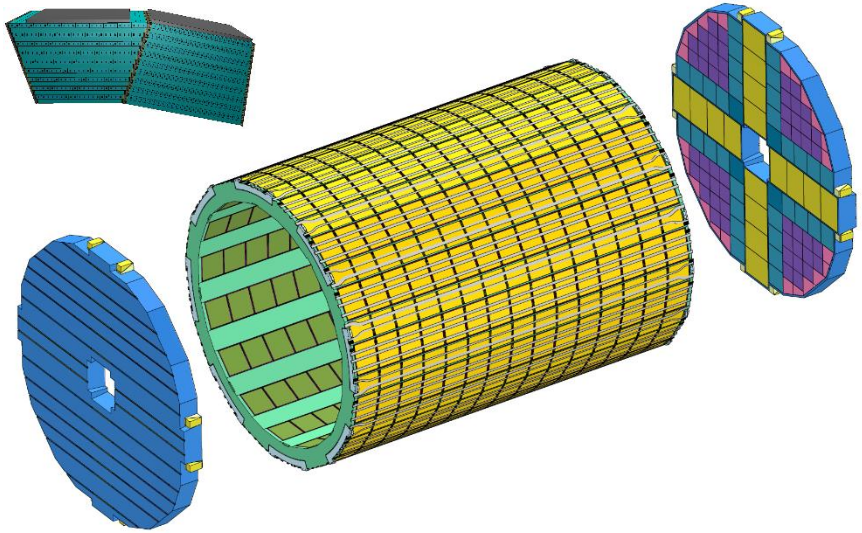


Achieve effective granularity 1.5×1.5×3 cm^3

Modular Design

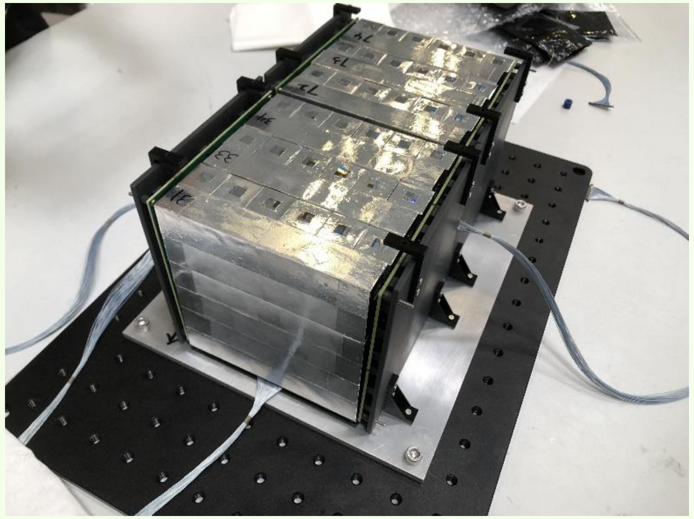
- 18 layers of crystals (24 X_0)
- Barrel: 32 towers per ring, 15 rings
- Endcap: 224 modules
- Total: 24m^3 BGO, 571k channels

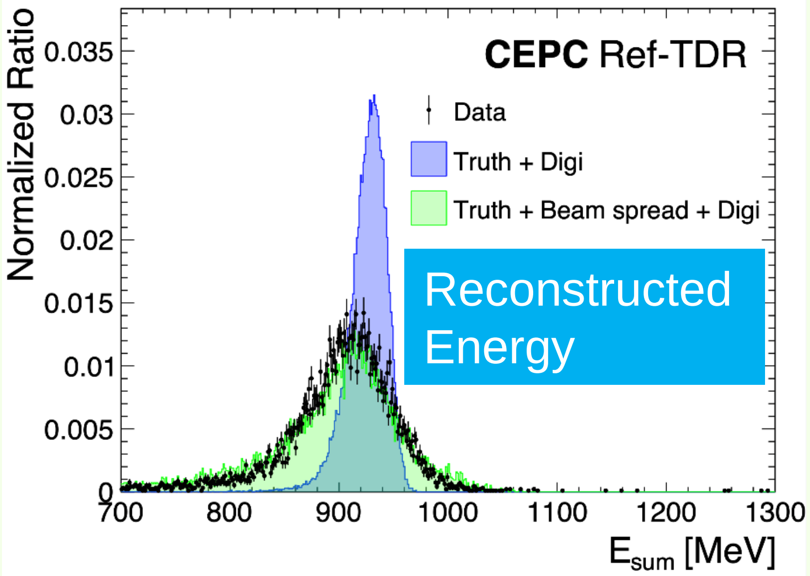


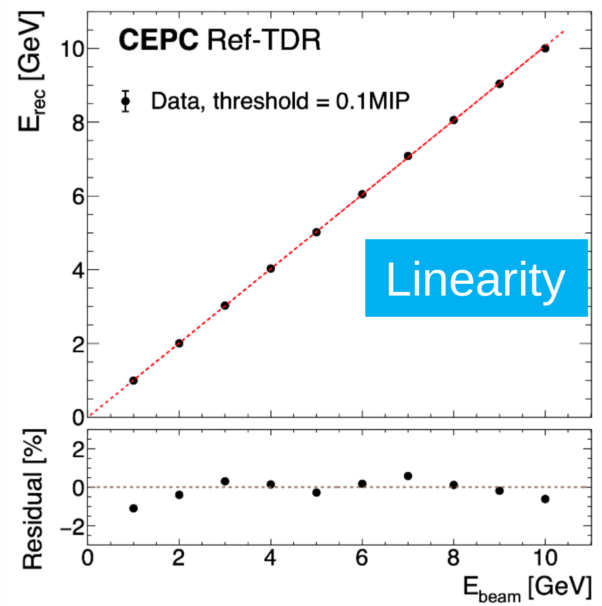


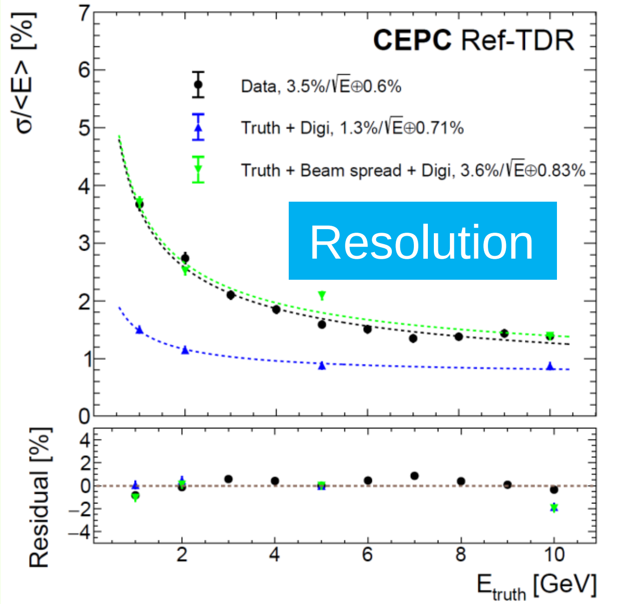
Testbeam of Prototype Crystal ECAL

- EM-scale crystal prototype development
  - **BGO** crystal bars from SIC-CAS, (also considering **BSO**)
  - SiPM: 3×3 mm² sensitve area, 10µm pixel pitch
- Successful testbeam at CERN with 1-10 GeV electron beam
  - EM resolution (preliminary): $1.3\%/\sqrt{E} \oplus 0.7\%$
- To address critical issues at system level, validate design of crystal-SiPM, light-weight mechanical structure
- A full-scale prototype will be constructed



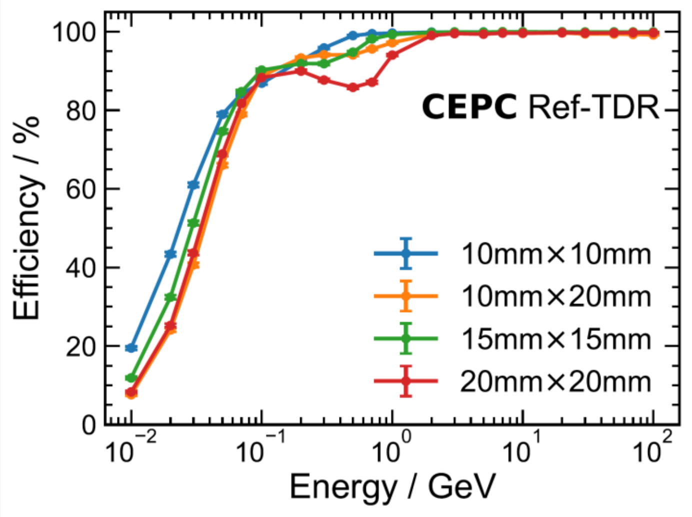




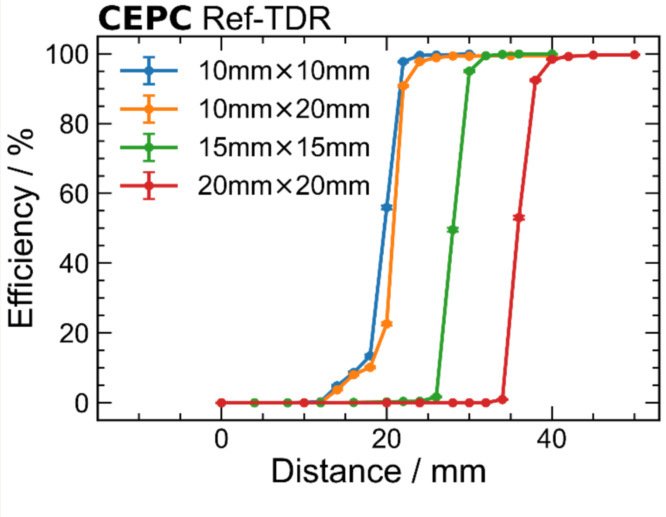


ECAL Granularity Optimization

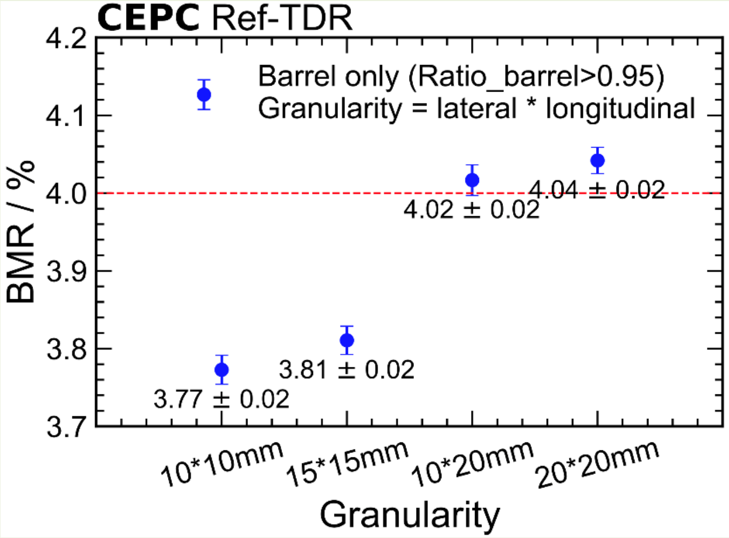
- ECAL granularity: balance of performance and readout
  - 10×10mm, 10×20mm, 15×15 mm and 20×20mm
- Figures of merit
  - Single photon reconstruction, separation power and jet performance



Major impact from ECAL longitudinal segmentation



Separation efficiency dominated by ECAL transverse granularity



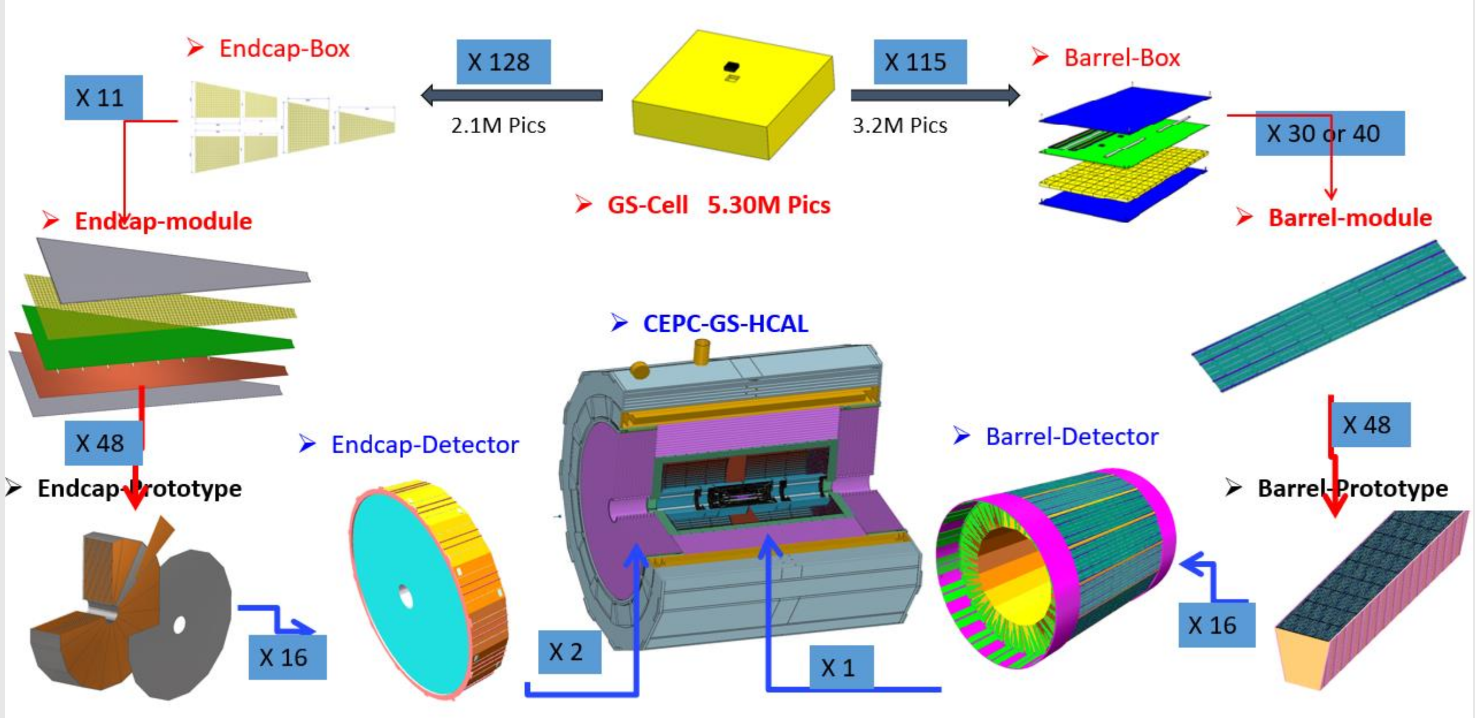
10x10mm and 15x15mm can meet physics requirement of BMR <4%

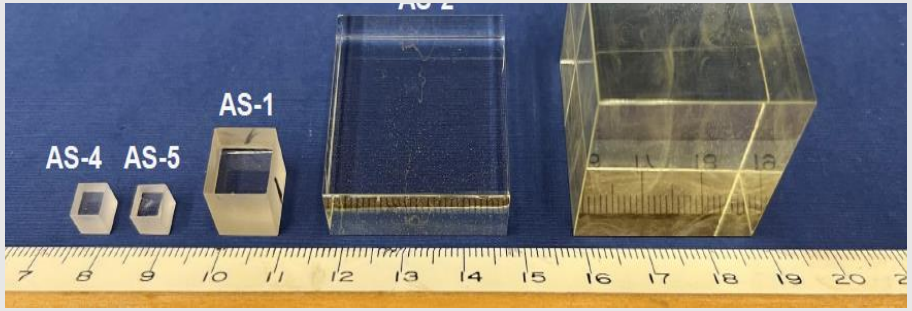
Conclusion: ECAL granularity of **15×15mm²** selected for ECAL

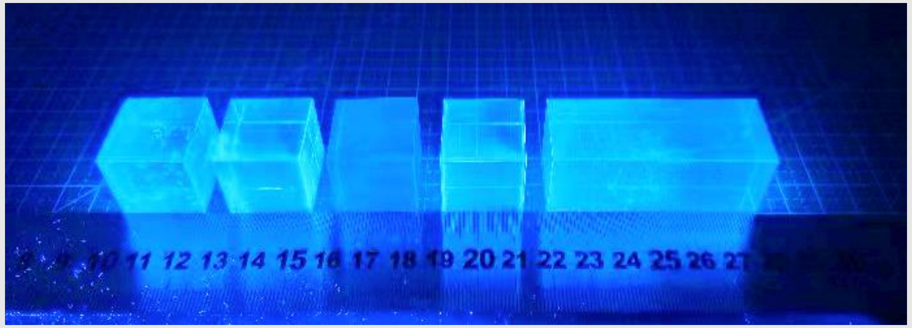
Glass Scintillator HCAL

- To replace plastic scintillator with **high density**, low cost glass scintillator for better hadronic energy resolution and BMR
- The Scintillation Glass collaboration continues to progress on the quest for better GS, and technique for mass production
- To produce a full-scale GS-HCAL prototype with integrated electronics for beam test

Key parameters	GFO glass	BGO	DSB Glass
Density (g/cm^3)	6.0	7.13	4.2
Melting point (°C)	1250	1050	1550
Radiation Length (cm)	1.59	1.12	2.62
Molière radius (cm)	2.49	2.23	3.33
Nuclear interaction length (cm)	24.2	22.7	31.8
Z_{eff}	56.6	71.5	49.7
dE/dX (MeV/cm)	8.0	8.99	5.9
Emission peak (nm)	400	480	430
Refractive index	1.74	2.15	
Light yield (ph/MeV)	~ 1500	7500	2500
Energy resolution (% @662keV)	~ 23	9.5	
Scintillation decay time (ns)	~ 60 and 500	60, 300	90, 400

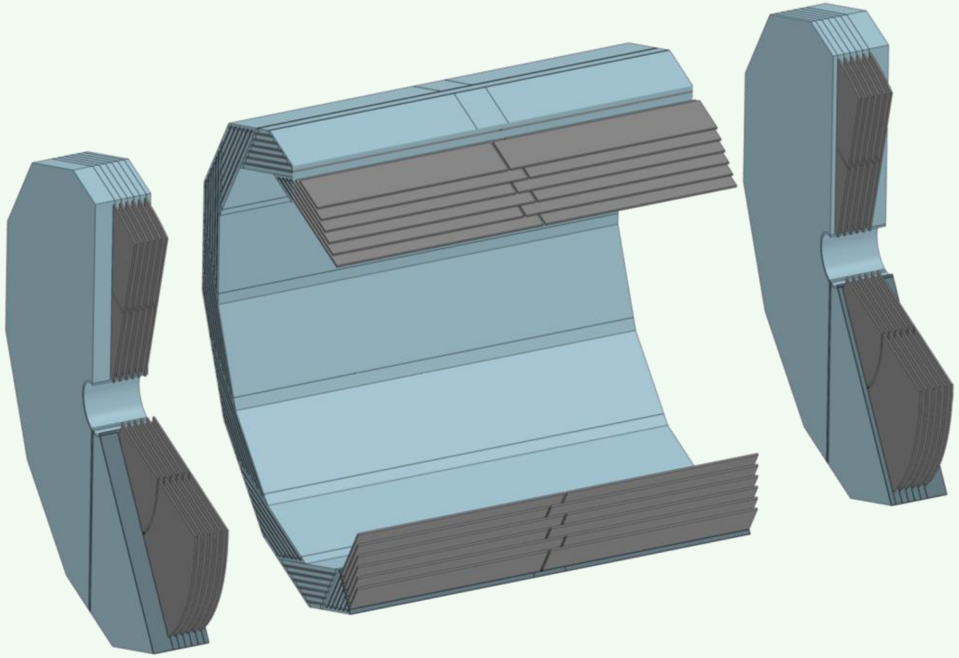


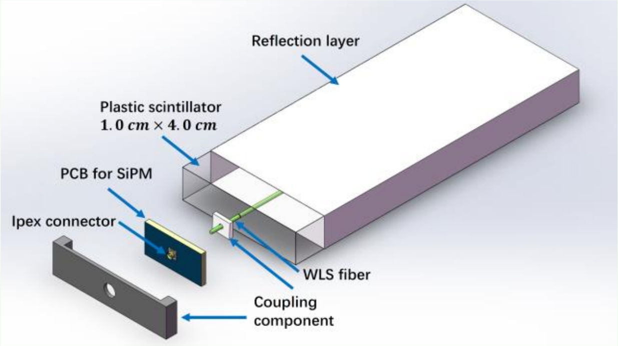


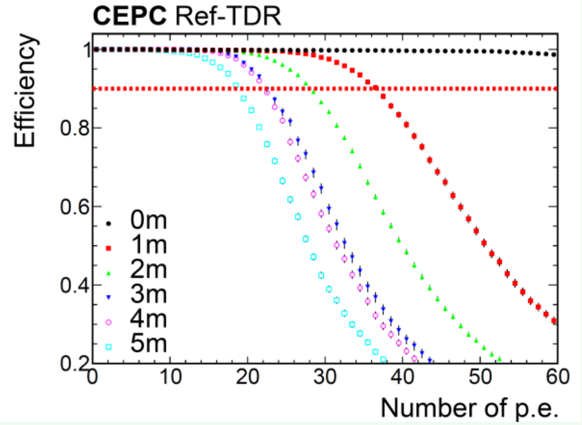


Muon Detector

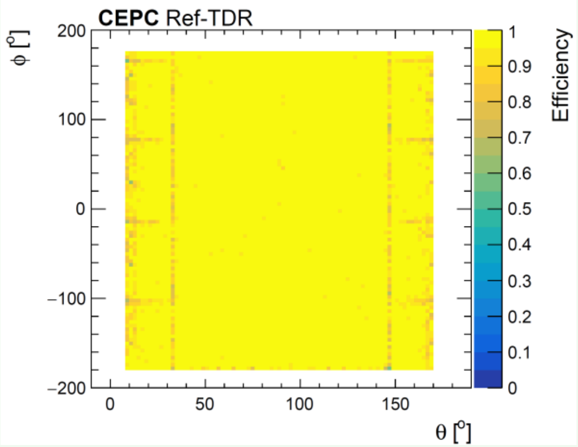
- Use extruded plastic scintillator (PS) technology, provide Muon ID > 95%, and pion fake rate < 1%
- Strip/channel structure: PS bar + WLS fiber + SiPM
- Solid angle coverage: $0.98 \times 4\pi$, total detection area ~ 4,800 m^2, ~43k channels
- Prototype of 5m channel: $\epsilon > 95\%$, $\sigma_T \sim 1ns$



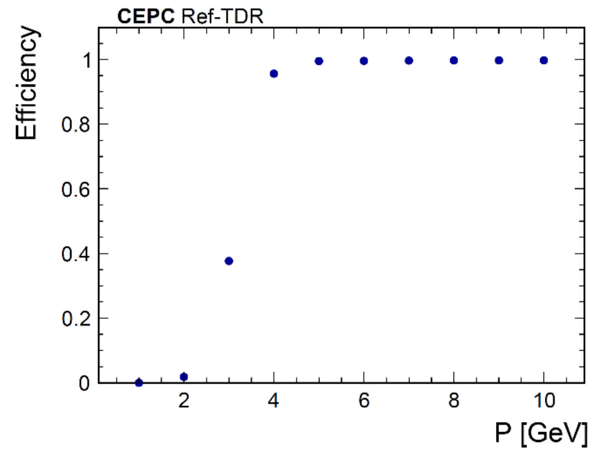




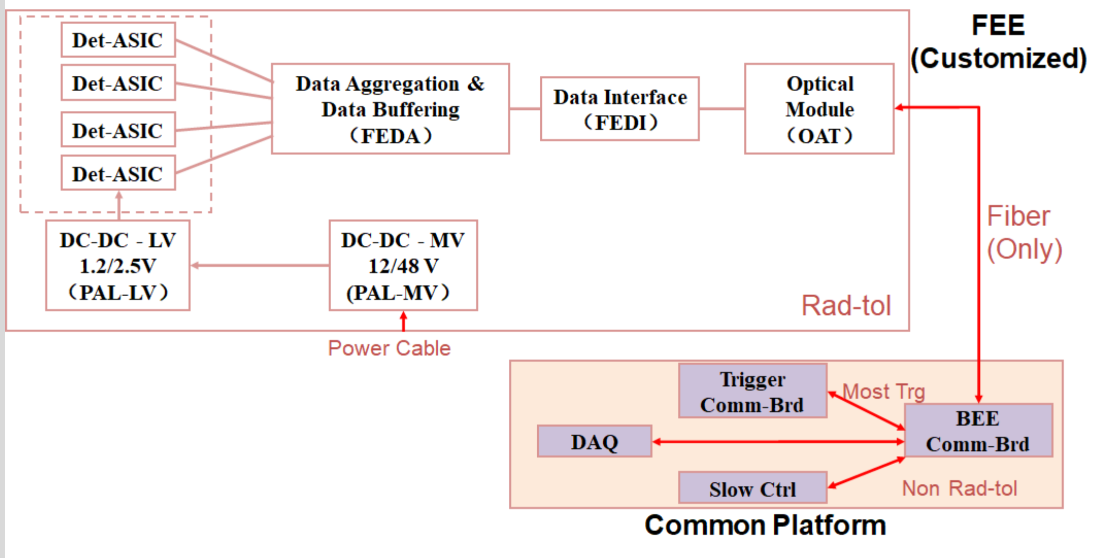
Detection efficiency

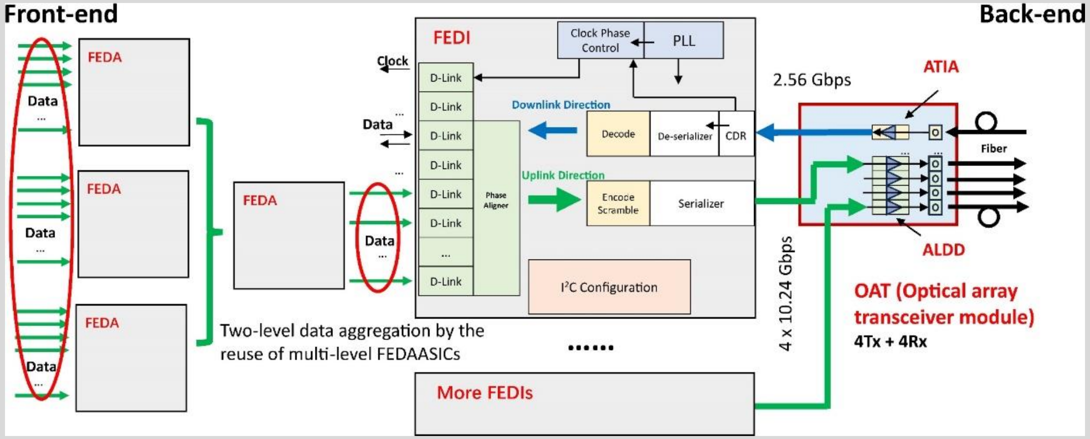


Particle ID



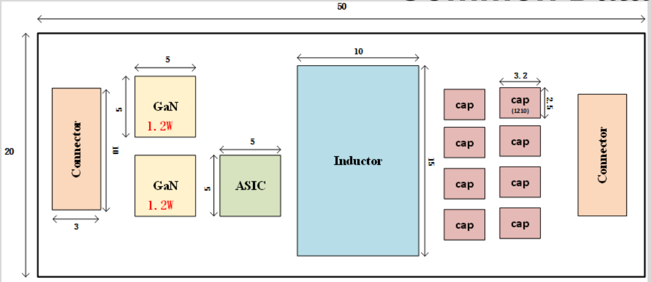
Electronics

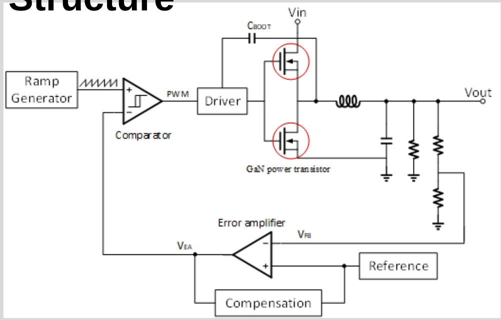




FEDA **FEDI** **OAT**

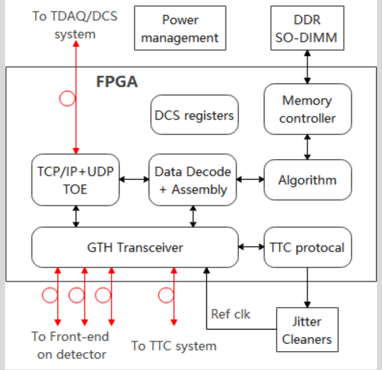
Common Data Link Structure

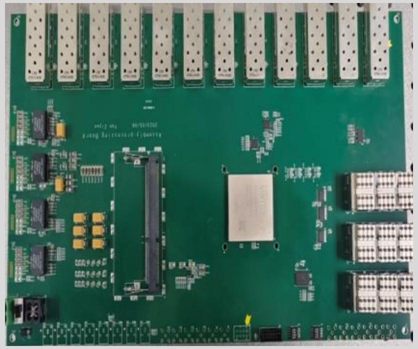




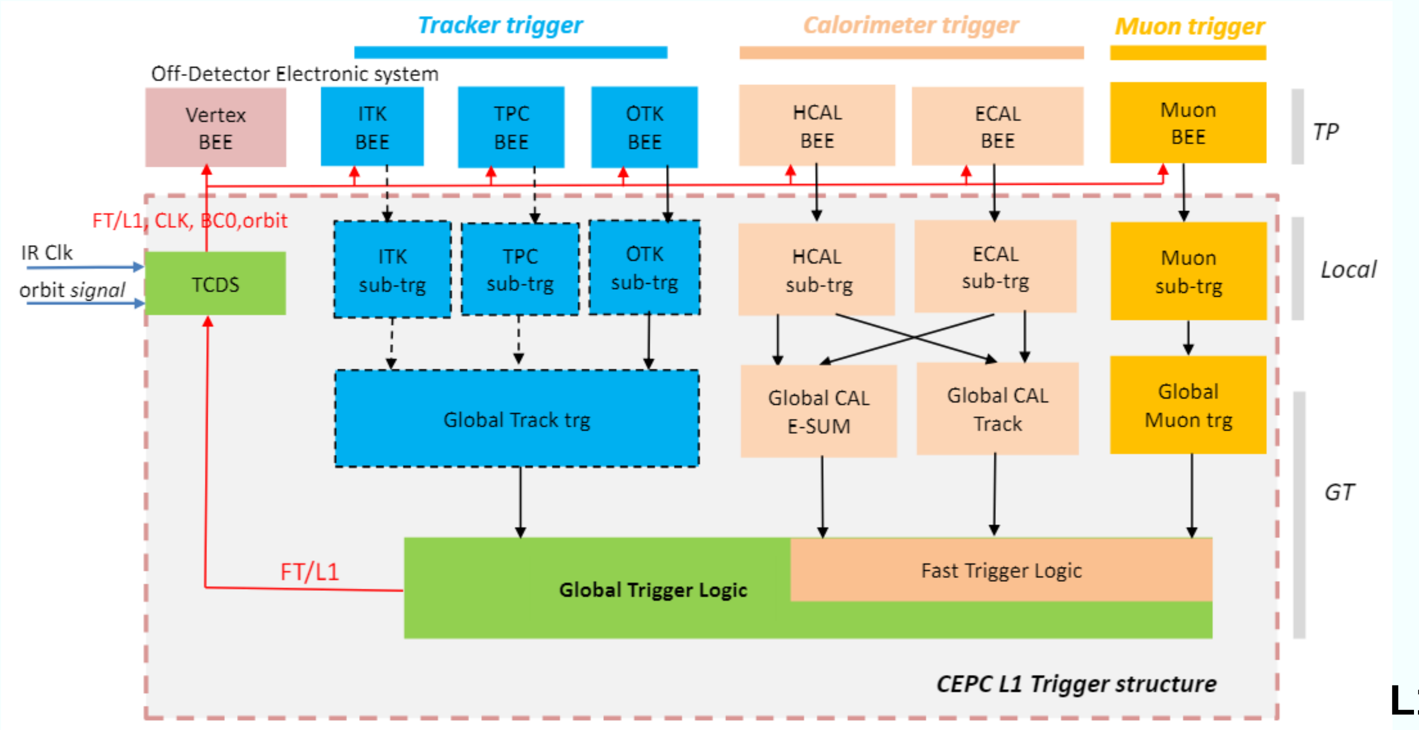
Common Powering Module （PAL）

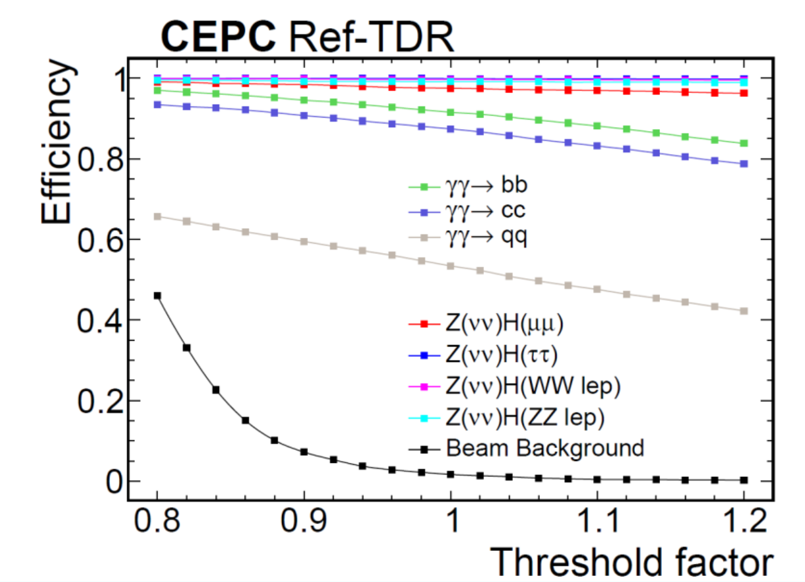
- Baseline: Triggerless FE readout & BE trigger
- Maximizing the common design:
  - Common FEE blocks, including data aggregation, transmission, optical, powering
  - Common BEE & Common Trigger: configurable for individual subsystems.





Trigger and Data Acquisition

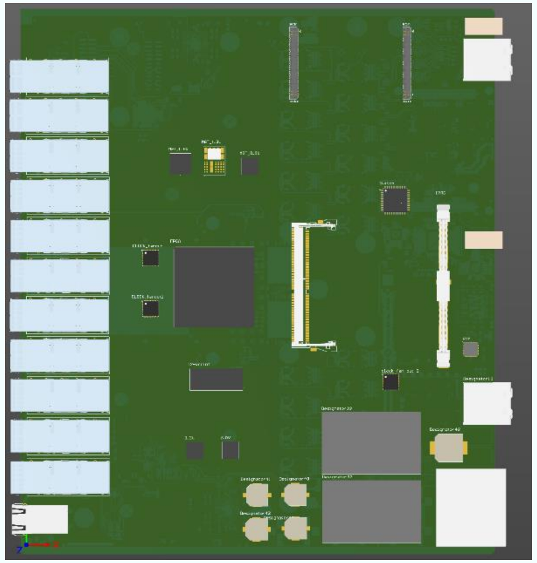




L1 trigger board

36-48 channels ×10-25Gbps Optical interface

Xilinx Virtex FPGA

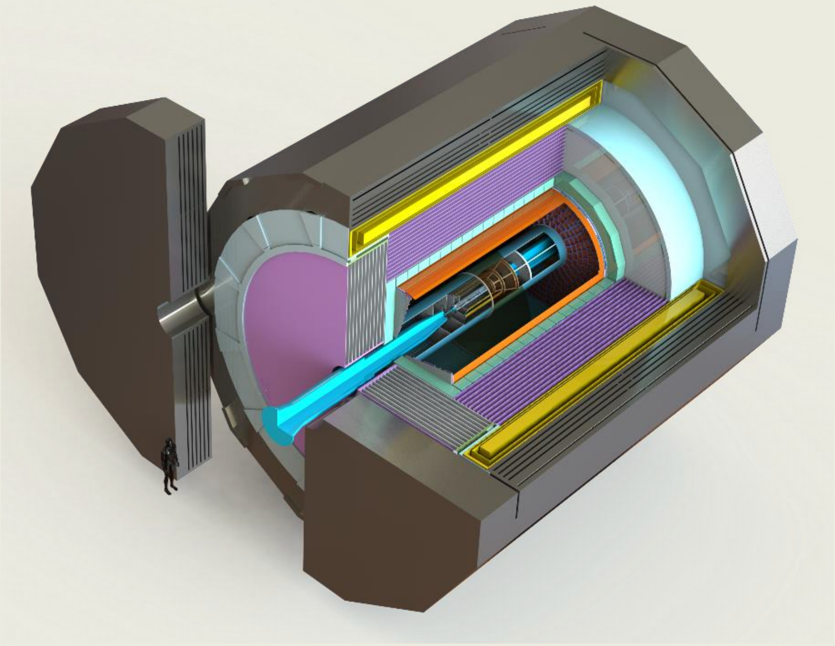


- Hardware trigger at BE + HLT software trigger
- L1 trigger on calorimeter, muon, and trackers
- Will explore a full software trigger with GPUs

Review By The CEPC IDRC

Ivan Villa Alvarez	IFCA
Daniela Bortoletto (Chair)	U. Oxford
Jim Brau	U. Oregon
Anna Colaleo	INFN/Bari
Paul Colas	CEA Saclay
Cristinel Diaconu	CPPM
Frank Gaede	DESY
Colin Gay	UBC
Liang Han	USTC
Gregor Kramberger	IJS
Bob Kowalewski	U. Victoria
Roman Poeschl	IJCLab
Burkhard Schmidt	CERN
Maxim Titov	CEA Saclay
Tommaso Tabarelli de Fatis	INFN/Milano-Bicocca
Roberto Tenchini	INFN/Pisa
Christophe De La Taille	OMEGA/CNRS
Hitoshi Yamamoto	Tohoku U.
Akira Yamamoto	KEK

Post-TDR R&D Activities



System	Technologies	
	Baseline (Ref-TDR)	Alternative
Beam pipe	Φ20 mm	
LumiCal	SiTrk + LYSO ECAL	SiTrk + SiW ECAL
Vertex	CMOS + Stitching	CMOS Si Pixel
Tracker	CMOS Si Pixel ITK	SSD + RO Chip, CMOS SSD
	Pixelated TPC	PID Drift Chamber
	AC-LGAD OTK	SSD / SPD OTK
		LGAD ToF
ECAL	4D Crystal Bar	Stereo Crystal Bar, GS+SiPM, PS+SiPM+W, SiDet+W
HCAL	GS+SiPM+Fe	PS+SiPM+Fe, RPC+Fe, MPGD+Fe
Magnet	LTS	HTS
Muon	PS bar+SiPM	RPC, μ-Rwell
TDAQ	Semi-Conventional	Software Trigger
BE electr.	Common	Independent

- Prototyping individual detectors already started and will continue with all subsystems
- The prototypes will be integrated into a full-scale slice system to evaluate their performance under realistic and integrated operating conditions
- Detector in the Ref-TDR is not the final design. We will continue pursuing better technologies in the following years for the two final detectors

Collaborative Efforts

- The Ref-TDR preparation process provided a unique opportunity for the CEPC study group to expand collaboration.
  - Domestic research institutes ~ **50,** international institutes ~ **40**
  - We hope that the number will continue to increase, especially during the Ref-TDR authorship sign-ups. It will help future R&D and lead to formation of the two experiment collaborations.

- Active member of the ECFA DRD program

Sub-system	DRD	Sub-system	DRD	Sub-system	DRD
Pixel Vertex Detector	3	Electromagnetic Calorimeter	6	Super Conducting Magnet	
Inner Silicon Tracker	3	Hadron Calorimeter	4, 6	Mechanical and Integration	8
Outer Silicon Tracker	3	Machine Detector Interface	8	General Electronics	(7)
Gas Tracker (TPC / DC)	1	Luminosity Calorimeter		Trigger and DAQ	(7)
Muon Detector	1 (RPC)	Fast Luminosity Monitor	3	Offline Software	

International Workshops

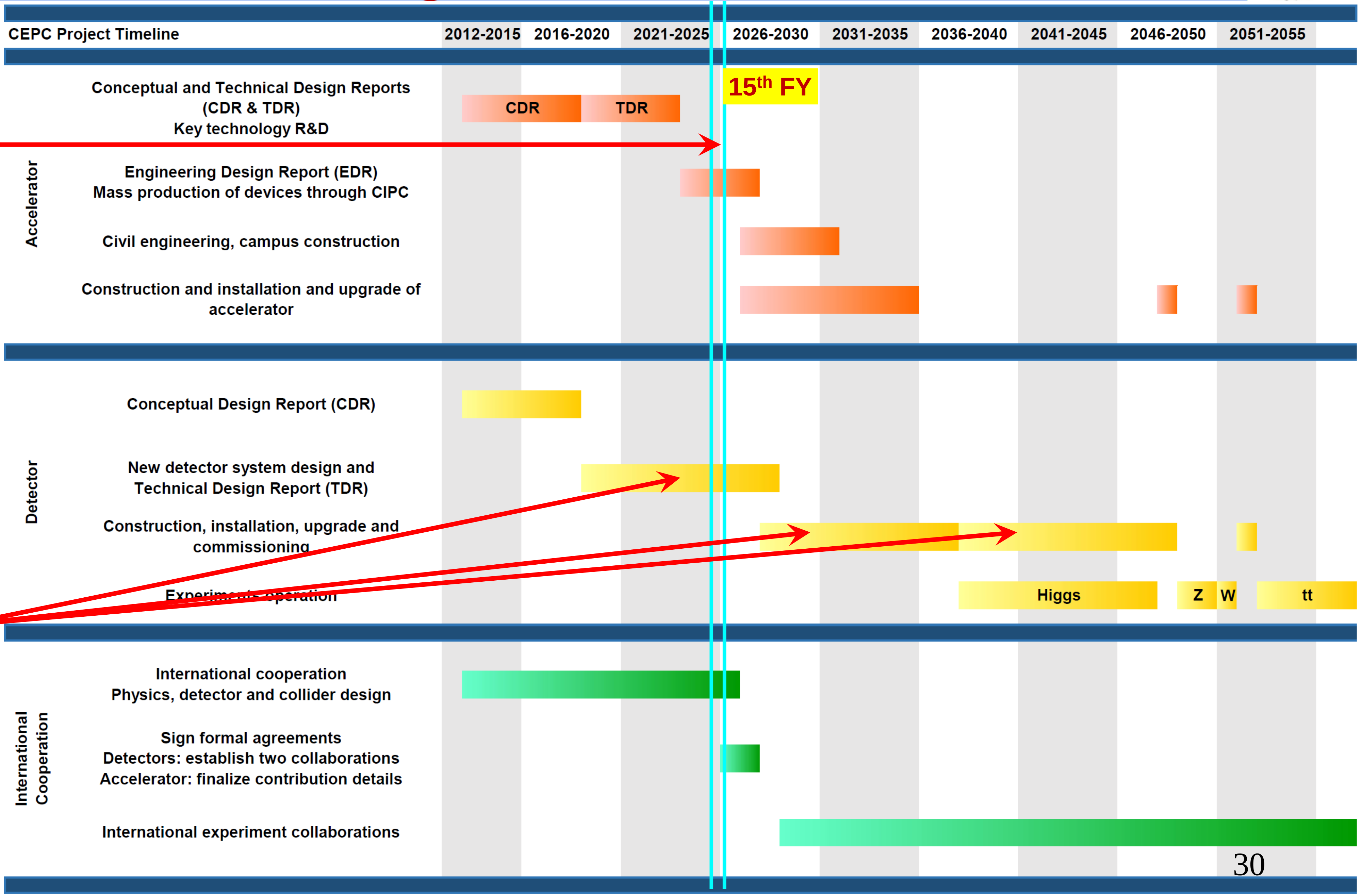
The 2024 International Workshop on the High Energy Circular Electron Positron Collider

October 22-27, 2024, Hangzhou, China

- International workshops (with emphasis on the CEPC):
  - In China: Beijing (2017.11, 2018.11, 2019.11), Shanghai (2020.10 / hybrid), Nanjing (2021.11 / online, 2022.11 / online, 2023.10), Hangzhou (2024.10), **Guangzhou (2025.11)**
  - In Europe: Rome (2018.05), Oxford (2019.04), Edinburgh (2023.07), Marseille (2024.04), Barcelona (2025.05), Lisboa (2026.?)
  - In USA: Chicago (2019.09), DC (2020.04 / online)
  - Annual IAS program on HEP (HKUST) since 2015. The upcoming one (2026.01?)
- Many topic-specific workshops at various sites

Closing Remarks

Critical to CEPC



HPES will play an important role in this quest