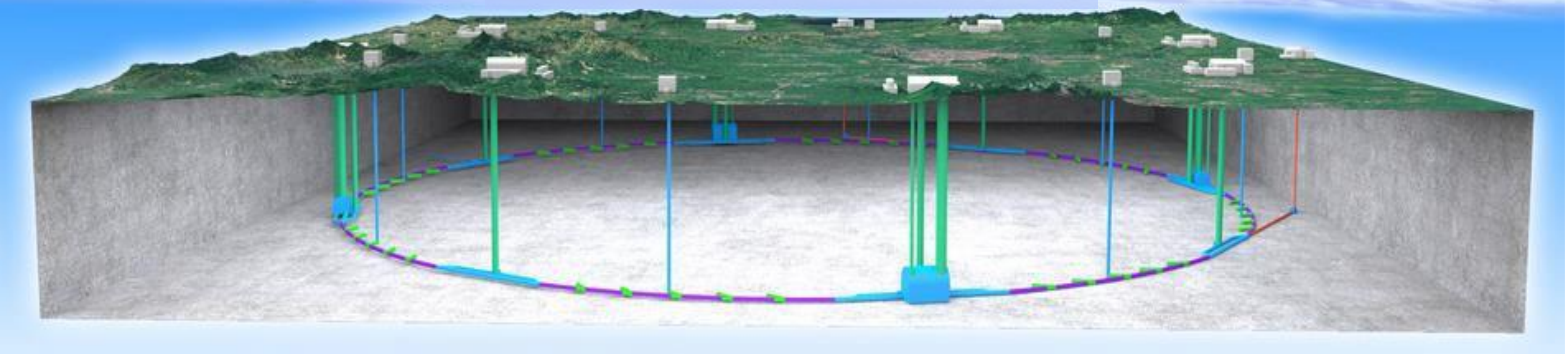
TDR of A Reference CEPC Detector

Jianchun Wang (IHEP, CAS)
For the CEPC Study Group

CEPC International Workshop, EU Edition
June 16-19, 2025, Barcelona



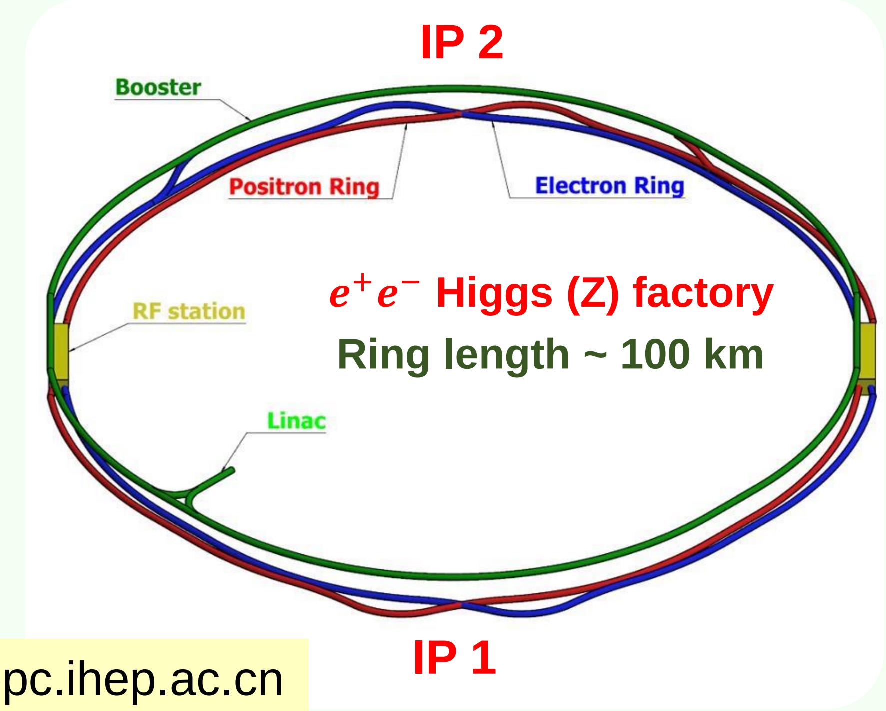
Outline

- Motivation of A Reference CEPC Detector TDR
- Baseline Technology Selections
- Status of R&D Projects
- R&D Team and International Collaborative Efforts
- Timeline of The Ref-TDR

Refer to the presentation at this workshop
CEPC Accelerator EDR Status and Beyond Jie Gao

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 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

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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

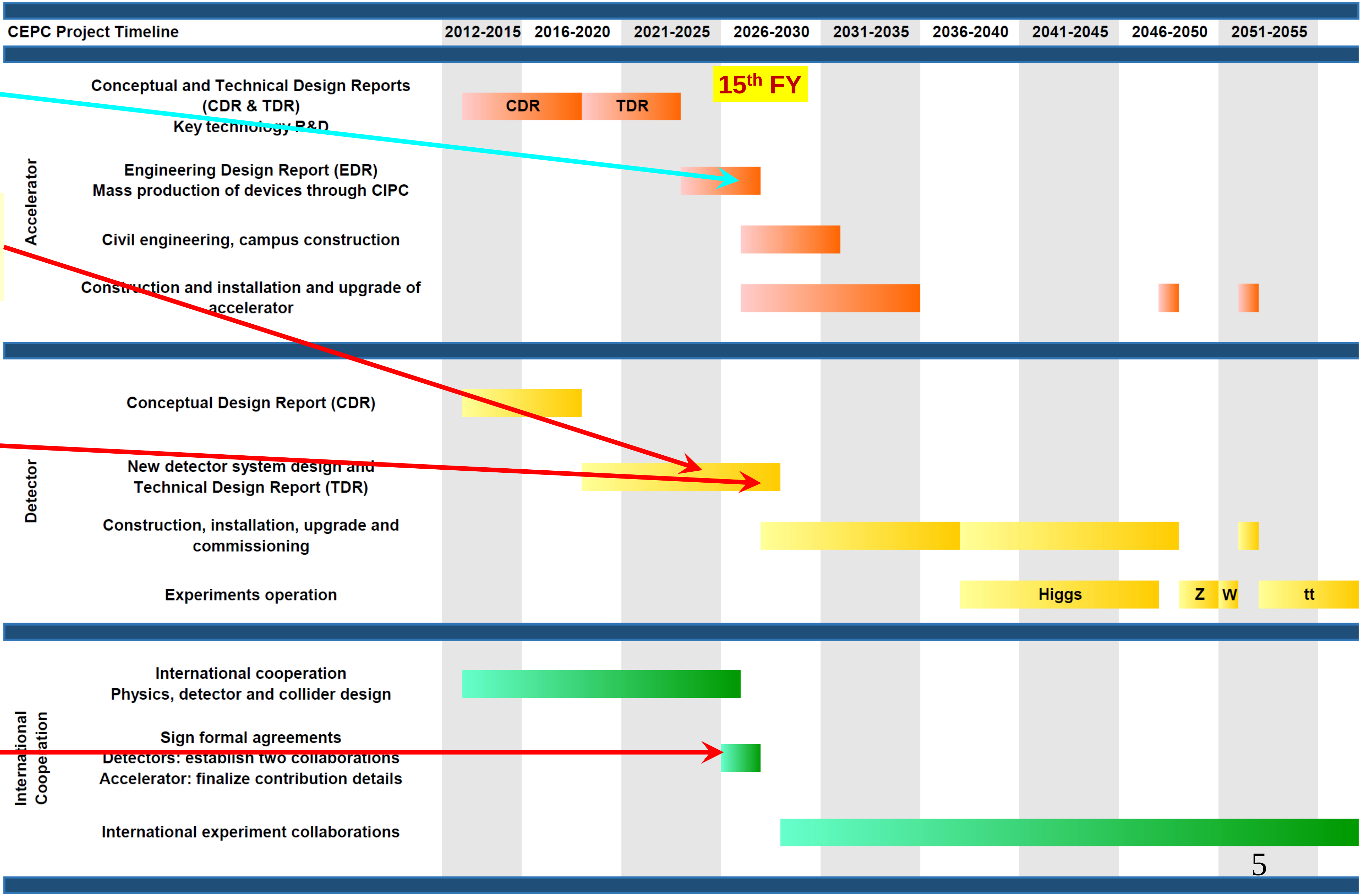
Completion of Accelerator EDR

Release TDR of A Reference Detector

Detector TDR × 2

Most Higgs factory detector systems are generic, e.g. ILD, IDEA

International Collaborations



TDR of A Reference CEPC Detector

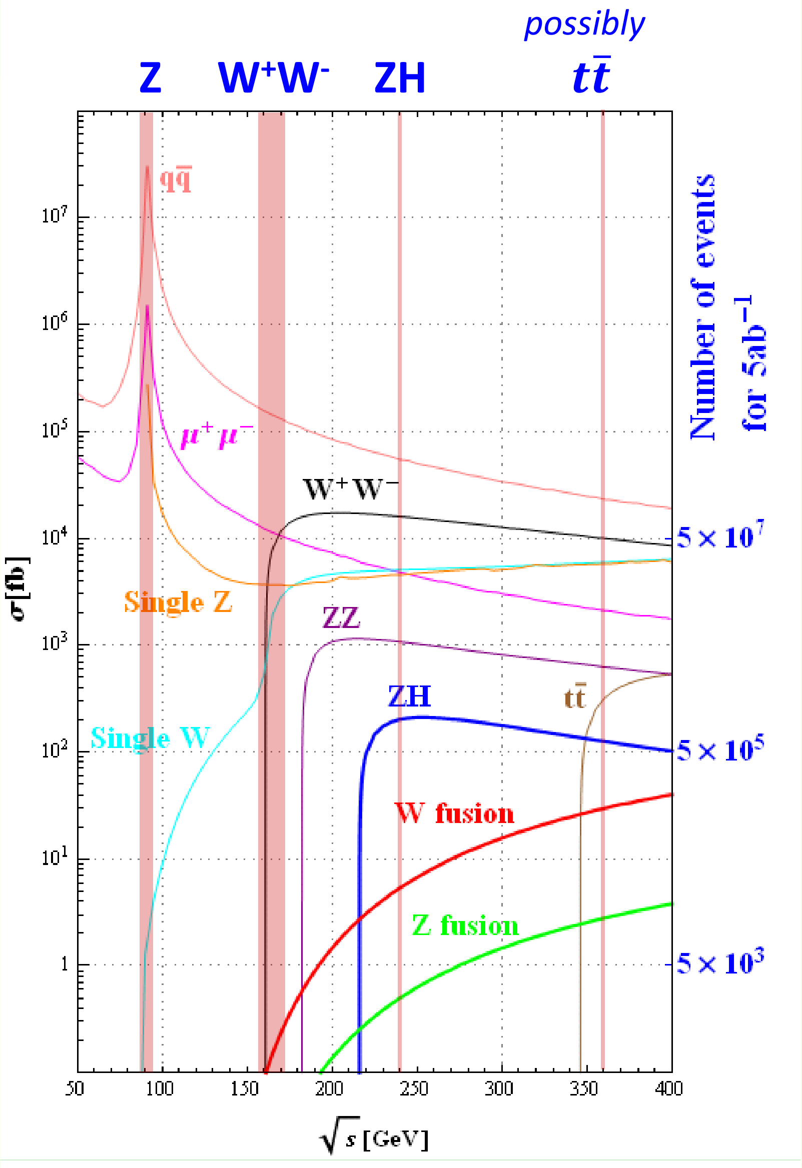
- The Ref-TDR needs to be released in a timely fashion, to **boost the possibility** of receiving an official endorsement for the 15th FYP

- The Ref-TDR mainly serves a **special purpose**, and is not to replace the TDRs for the real experiments. When the two international collaborations form, they will converge on the designs and deliver the corresponding detector TDRs.

- We treat it as a TDR of a real detector system to be built soon
  - Demonstrate the readiness and feasibility of detector technologies
  - Provide a realistic detector cost estimation
  - Assess requirements and availabilities of people power

- The exercise and efforts on the Ref-TDR will be very valuable assets, not only in technology development but also in team building.

CEPC Operation Plan



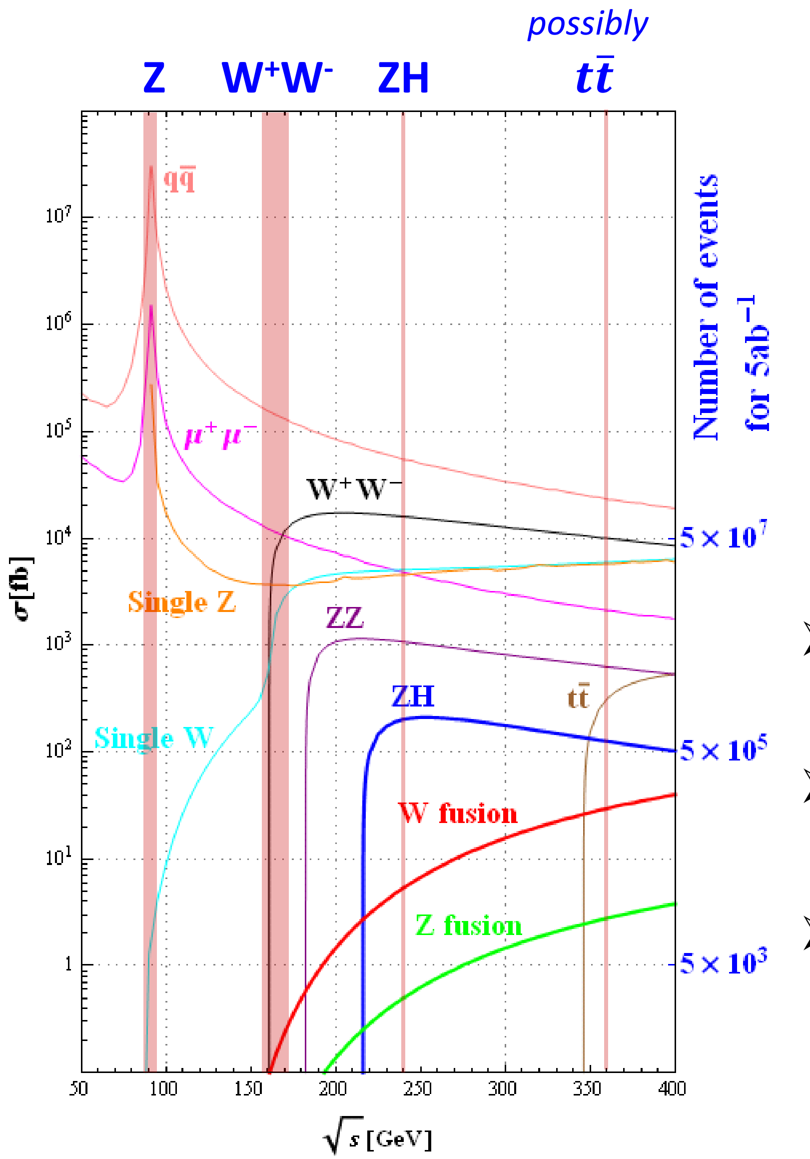
Operation mode		ZH	Z	W⁺W⁻	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times10^{34}$ 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)

CEPC Operation Plan: First 10 Years



SR Power Per Beam	Luminosity/IP [$\times 10^{34} cm^{-2} s^{-1}$]		
	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, Low-Lumin Z mode, and W^+W^- mode.
- The accelerator may be upgraded for High-Lumi Z mode and $t\bar{t}$ 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

Requirements on Detector Design

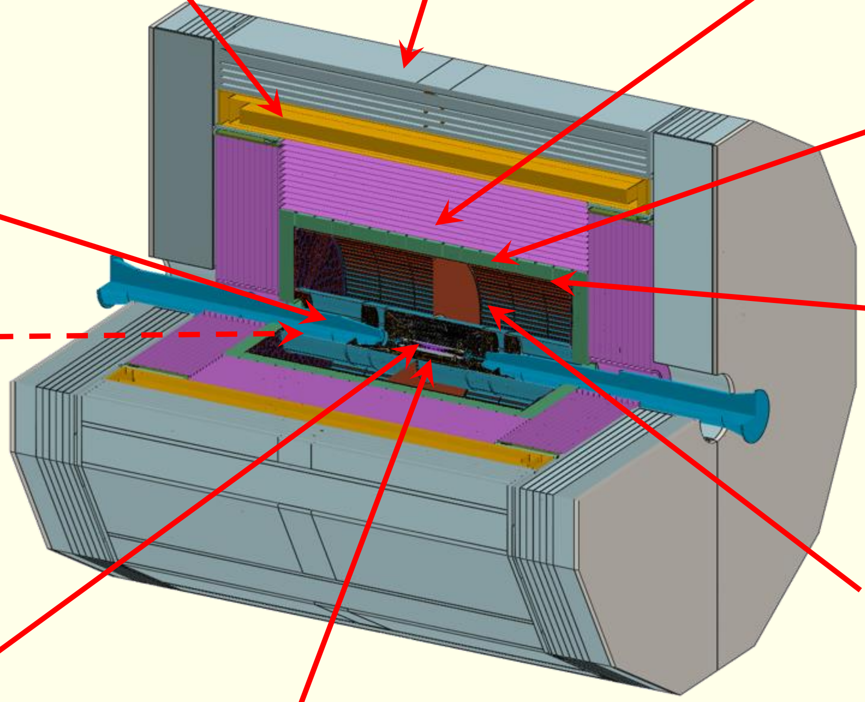
- The detectors should be able to operate for at least **10 years** in Higgs mode, or better ~**18 years** of HZ, Z, W^+W^-, and $t\bar{t}$ productions.

- The detectors should be optimized to operate at the CEPC base clock frequency of **43.3 MHz** (or period = 23.1 ns).

- The system needs to select and record interesting physics events.
  - In Higgs mode and L / IP (50 MW) = 8.3 $\times 10^{34}$ $cm^{-2}s^{-1}$:
    beam-beam crossing rate ~ 1.34 MHz, ZH ~16.6 mHz, $q\bar{q}$ ~ 5.0 Hz
  - In Z mode and L / IP (50 MW) = 1.92 $\times 10^{36}$ $cm^{-2}s^{-1}$:
    beam-beam crossing ~ 39.3 MHz, visible Z ~ 66 kHz

- Detectors can endure **radiation** damage and **noise hit** rates.
  - For example, in the Higgs mode at the Vertex detector:
    max noise hit rate ~ 0.6 MHz / cm^2, TID ~2.1 Mrad/year
  - The background study is very preliminary. The value can be off by an order of magnitude.
  - It is a relatively relaxed environment comparing to a hadron collider. Radiation resilience and noise hit rate should not be huge problems.

Baseline Detector Design in Ref-TDR

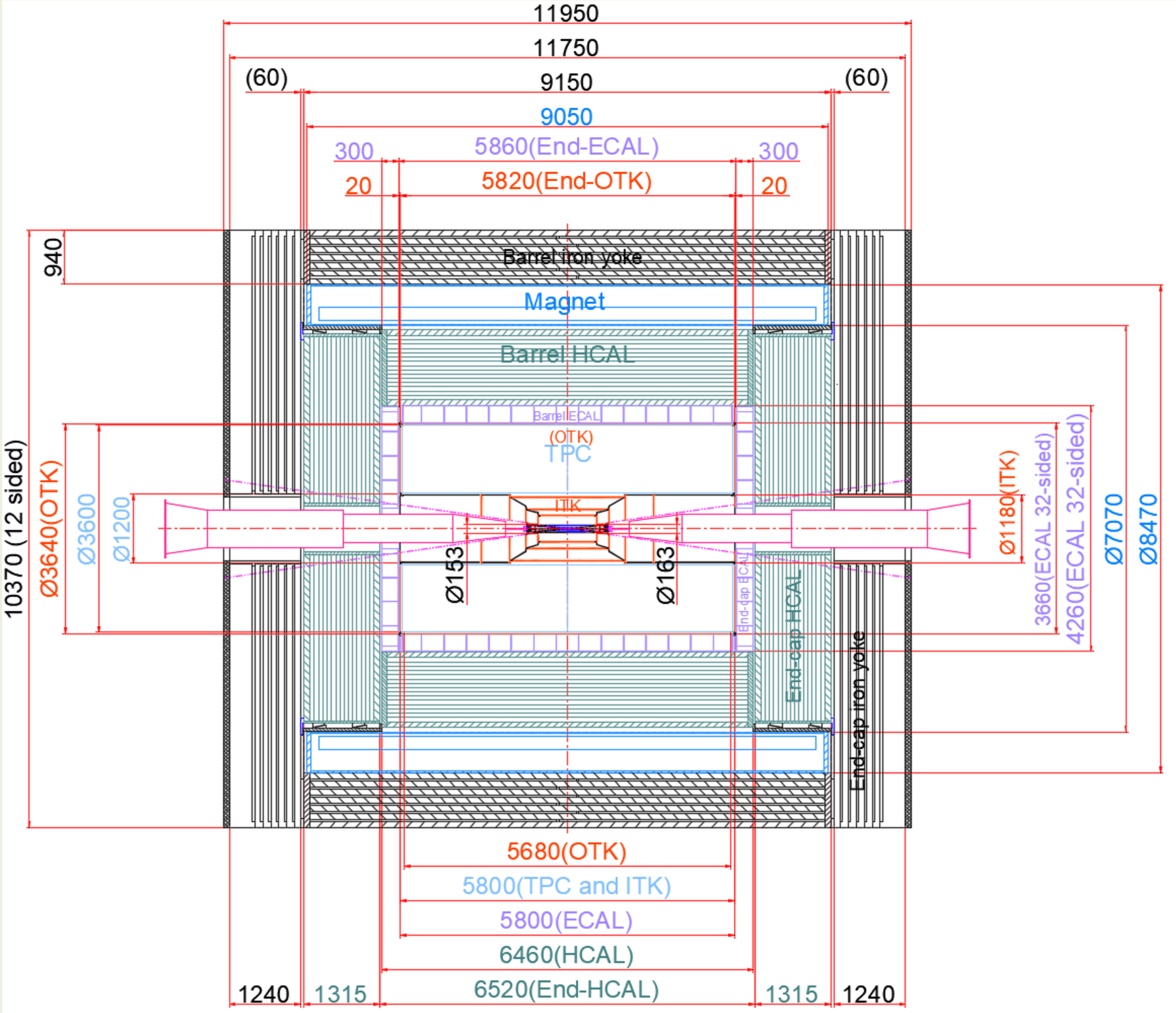


Detector Key Specifications

Sub-system	Key technology	Key Specifications
Vertex	6-layer CMOS SPD	$\sigma_{r\phi}$ ~ 3 μm, X/X_0 < 0.15% per layer
Tracking	CMOS SPD ITK, AC-LGAD SSD OTK, TPC + Vertex detector	$\sigma\left(\frac{1}{P_T}\right) \sim 2\times10^{-5} \oplus \frac{1\times10^{-3}}{P\times \sin^{3/2}\theta}(GeV^{-1})$
Particle ID	dN/dx measurements by TPC Time of flight by AC-LGAD SSD	Relative uncertainty ~ 3% σ(t) ~ 30 ps
EM calorimeter	High granularity crystal bar PFA calorimeter	EM resolution ~ $3\%/\sqrt{E(GeV)}$ Granularity ~ 1×1×2 cm^3
Hadron calorimeter	Scintillation glass PFA hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(GeV)}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(GeV)}$

- ❖ Design of the CEPC detector evolves with the R&D progressing and our better understanding of the physics reach.
- ❖ The key specifications continue to be optimized.

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

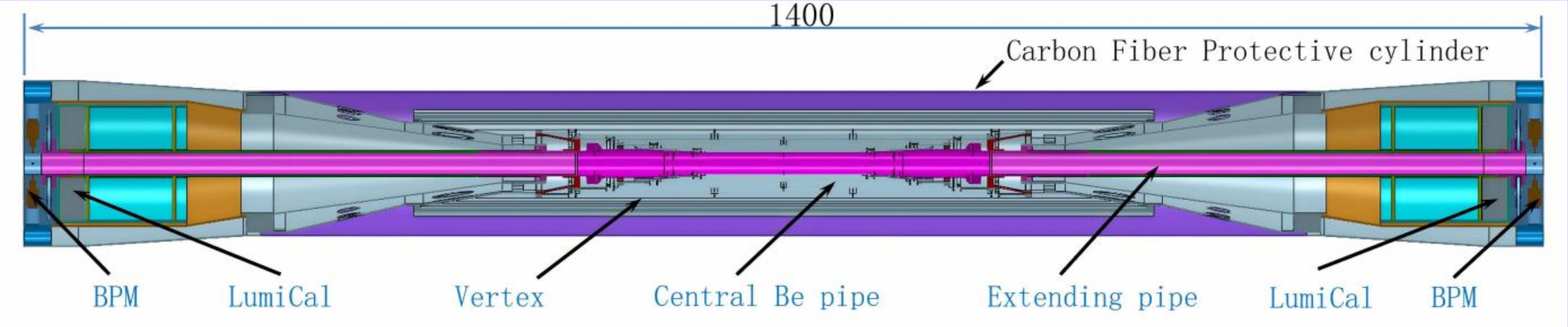
Detector Overall

Length: 11,950 mm

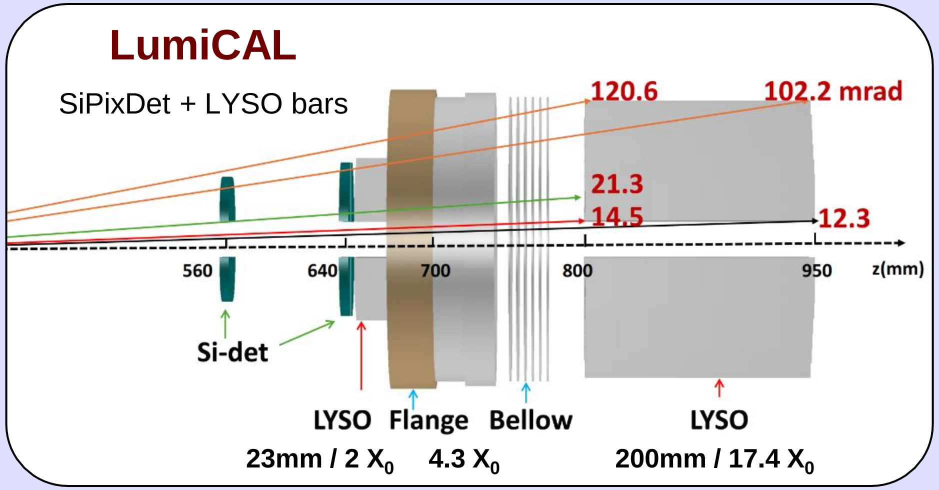
Height: 10,370 mm

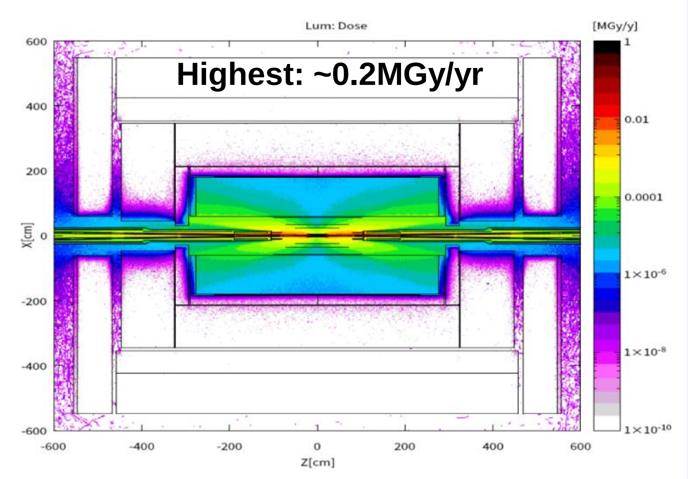
Weight: 5,290 t

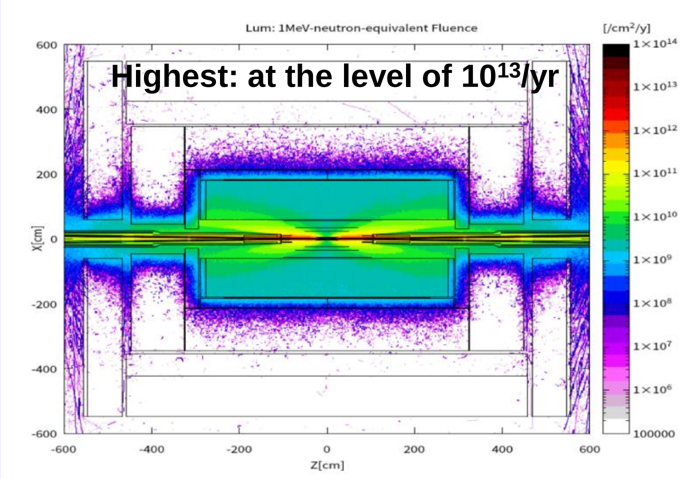
MDI, Beam Background and LumiCal



- 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

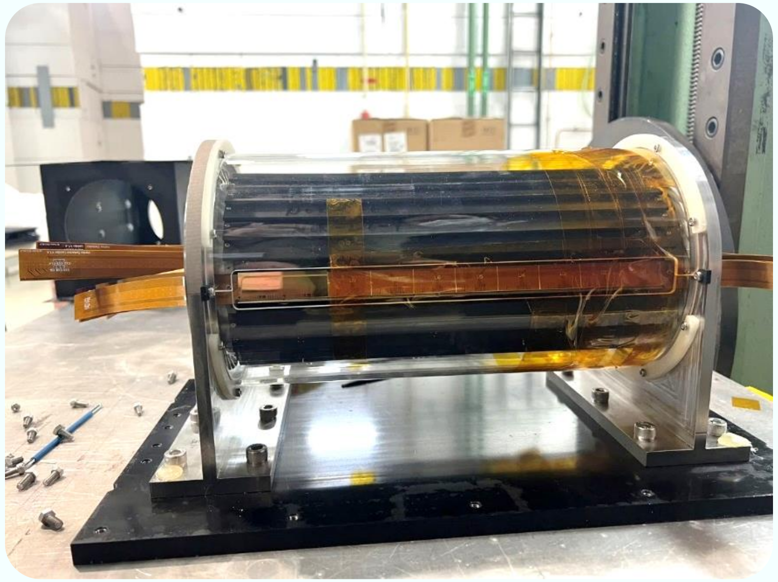




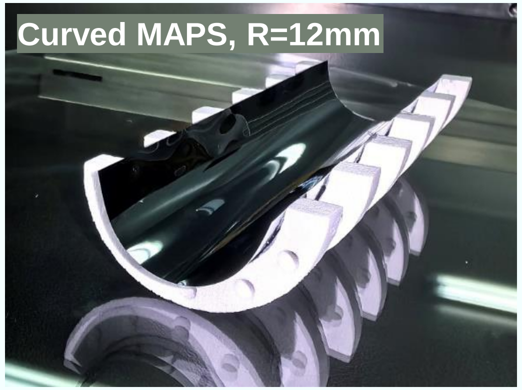


Silicon Pixel Vertex Detector

Strong collaboration from IFAE



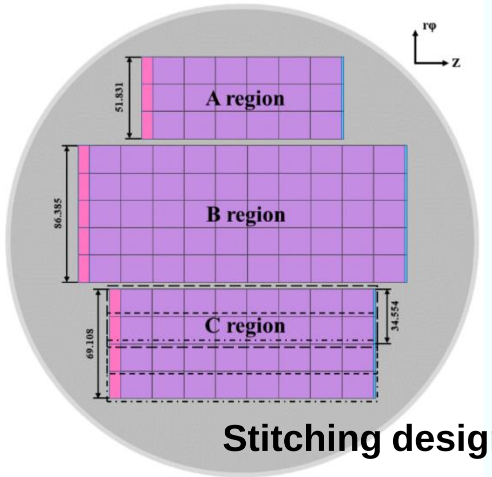
A TaichuPix-based prototype detector



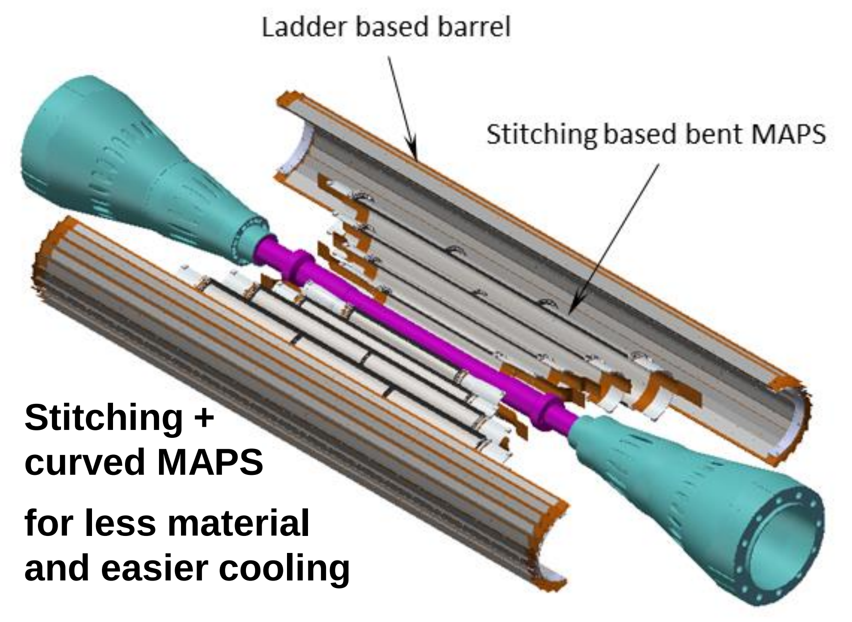
Goal: σ(IP) ~ 5 μm for high P

Key specifications:

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

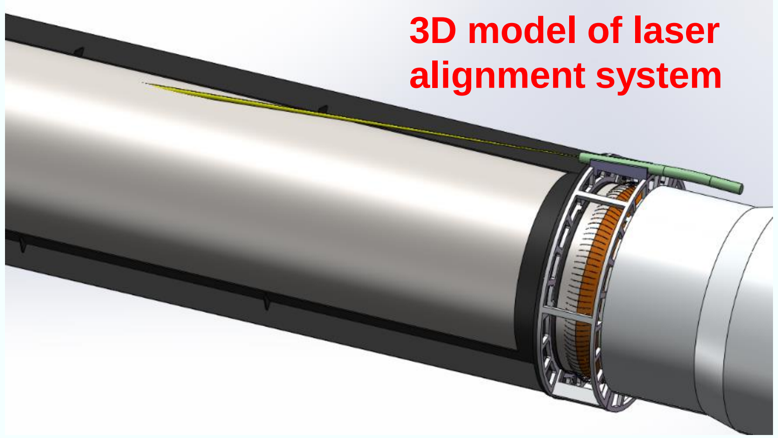


Stitching design



Stitching + curved MAPS

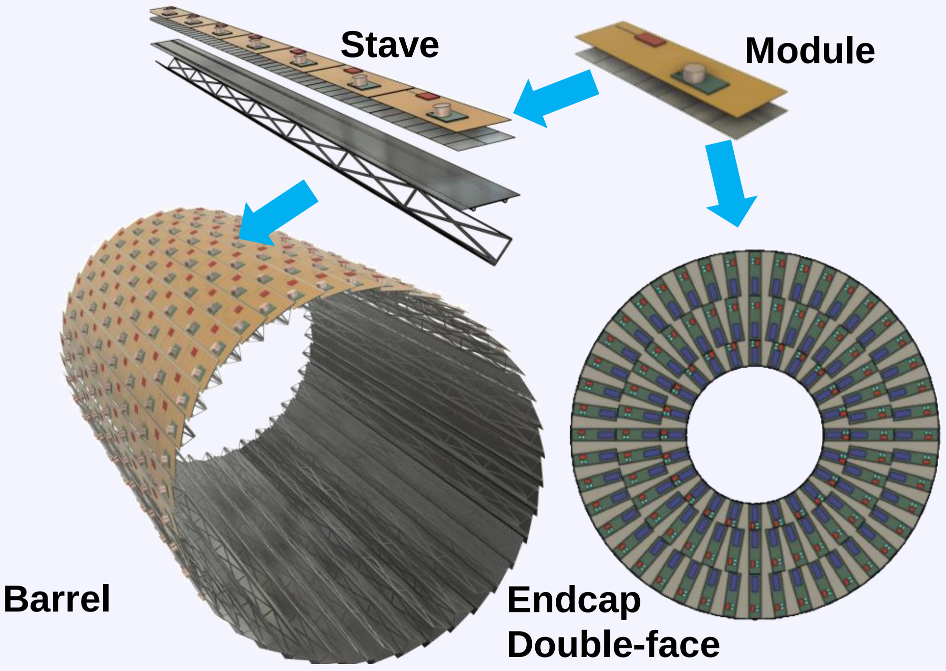
for less material and easier cooling



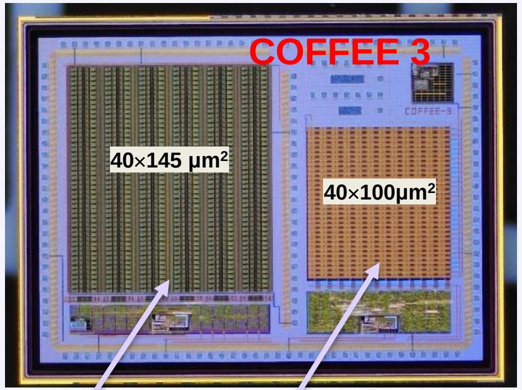
3D model of laser alignment system

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



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

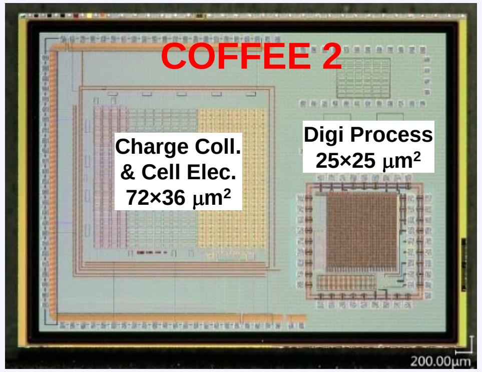


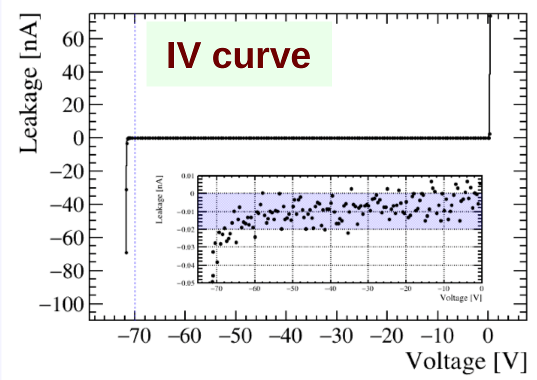
Goal

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

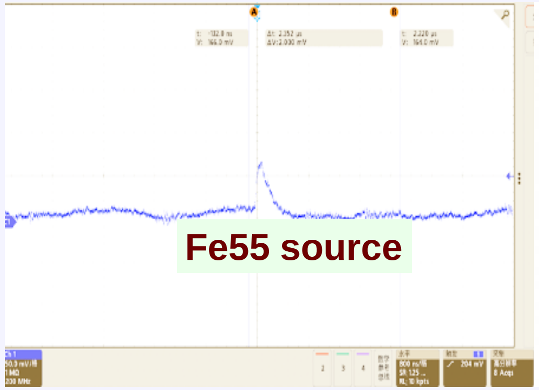
Architecture with in-pixel TDC for optimal timing

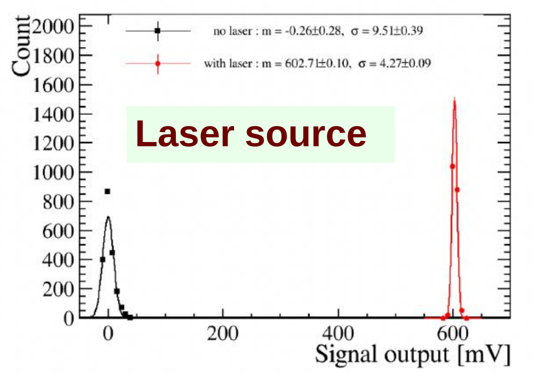
Digital functions in periphery for minimal interference w. signal





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

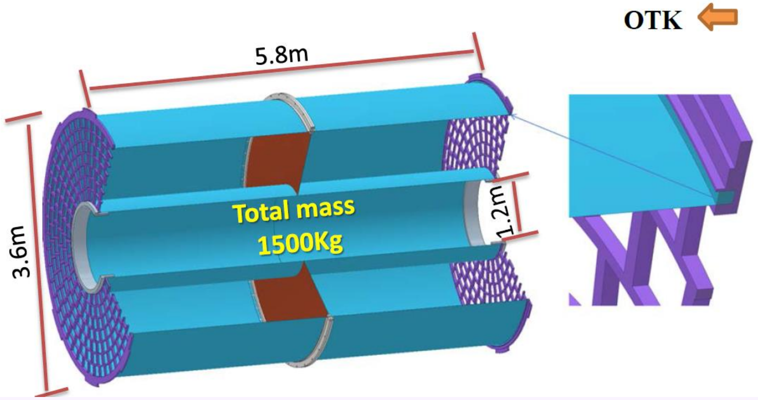


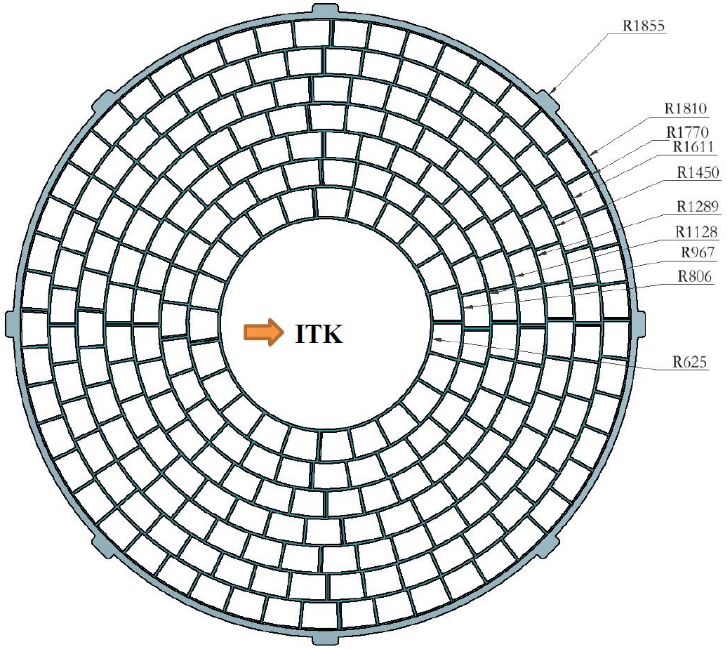


Pixelated Readout TPC

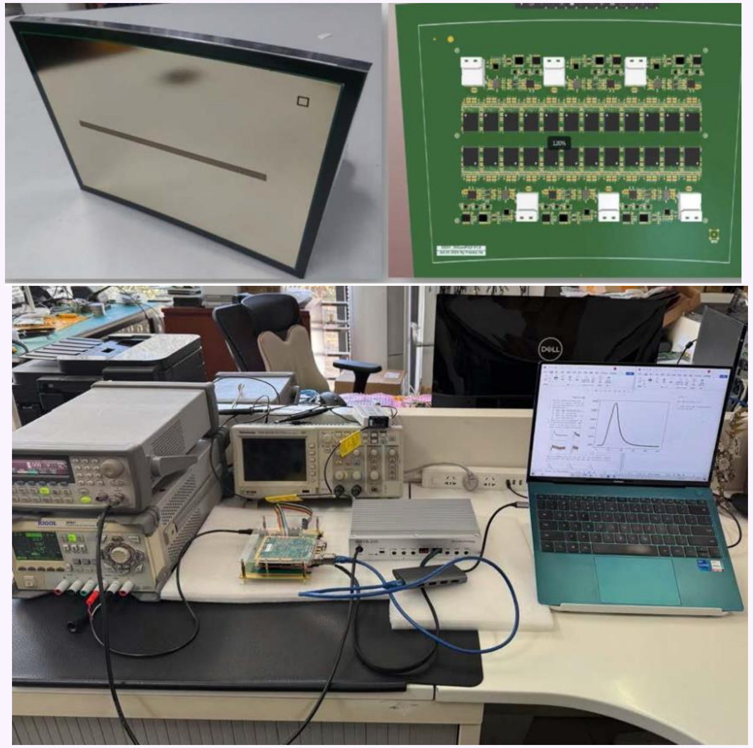
- Pixelated readout TPC can improve PID performance
  - Using the cluster of electrons, the full simulation study shows 3σ K/π separation at 20GeV
  - Balanced the total power consumption and readout channels, the pad size is optimized
- Readout pad size of **(500μm)^2** reduces IBF×Gain ~1@G=2000, achieves 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 in November to assess the performance and validate the design

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.9m
Potential at cathode	- 62,000 V
Gas mixture	T2K: Ar/CF4/iC4H10=95/3/2
Maximum drift time	34μs @ 2.75m
Detector modules	Pixelated Micromegas



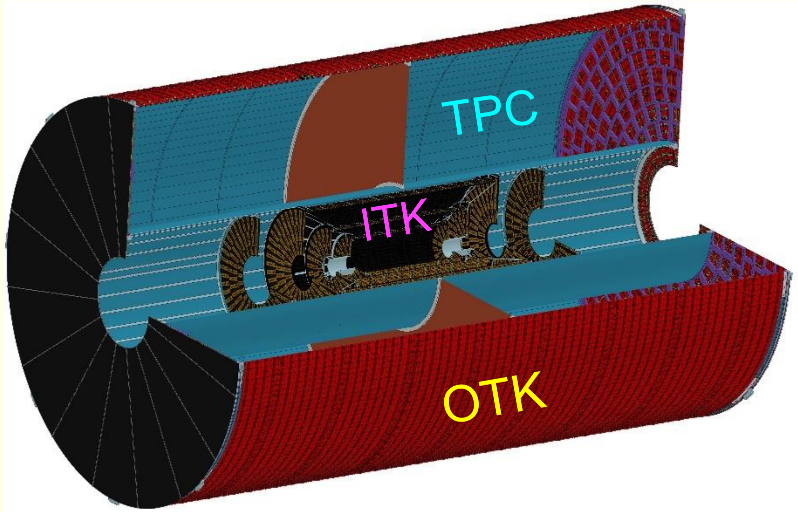


Detailed design of TPC detector in ref-TDR



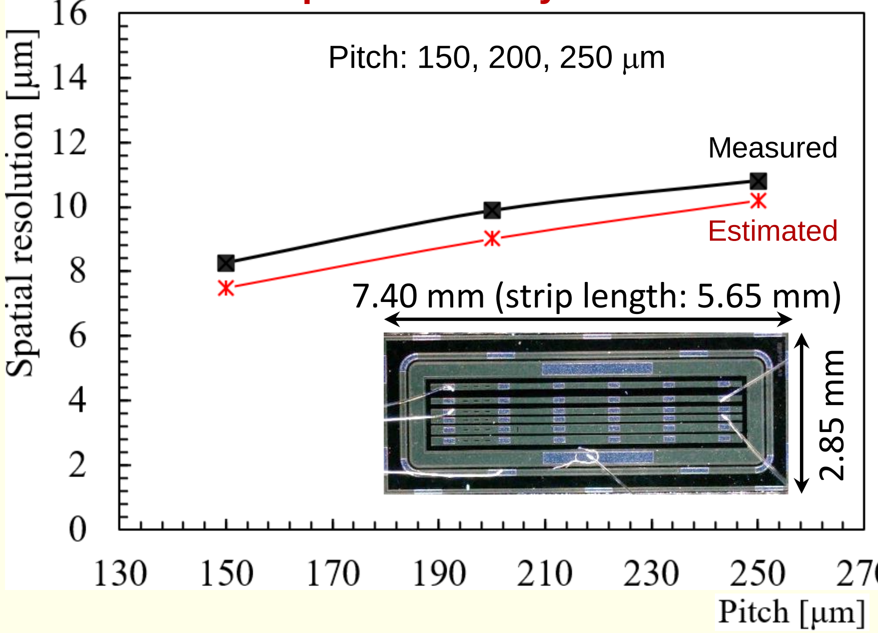
Photos TPC modules assembled for the beam test

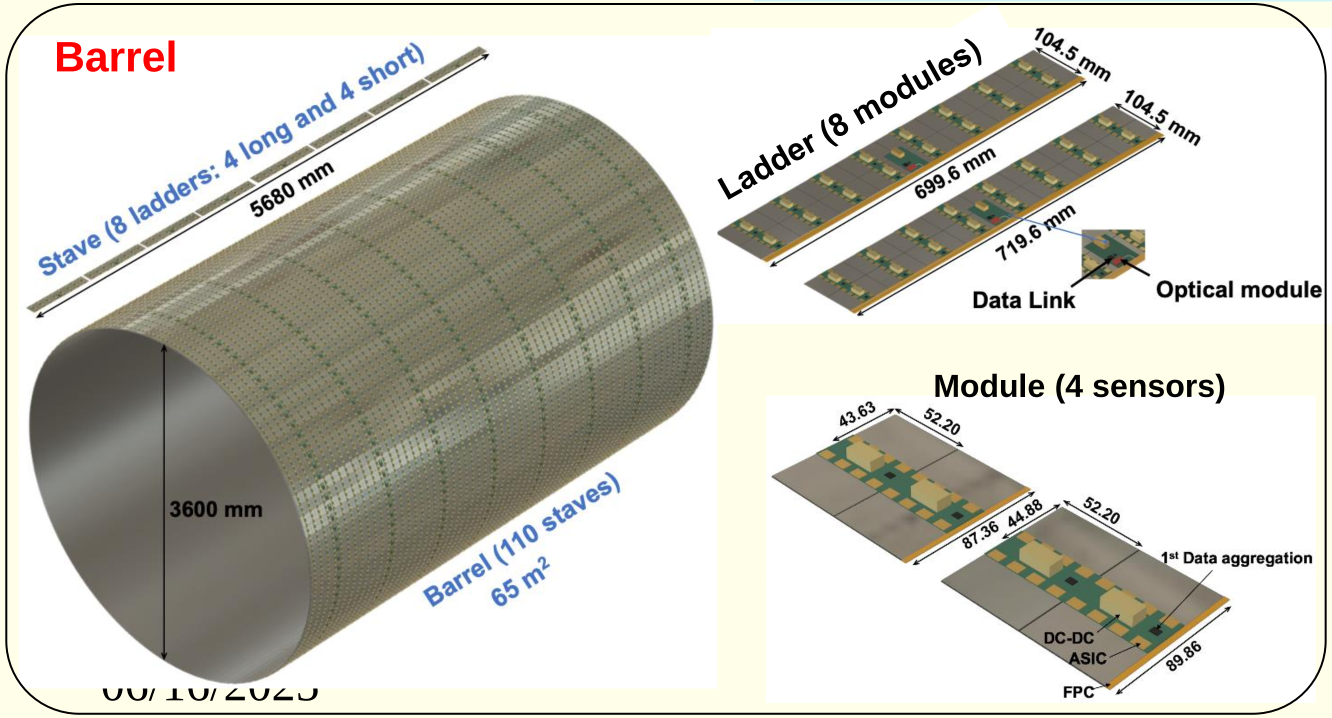
AC-LGAD OTK (Time Tracker)

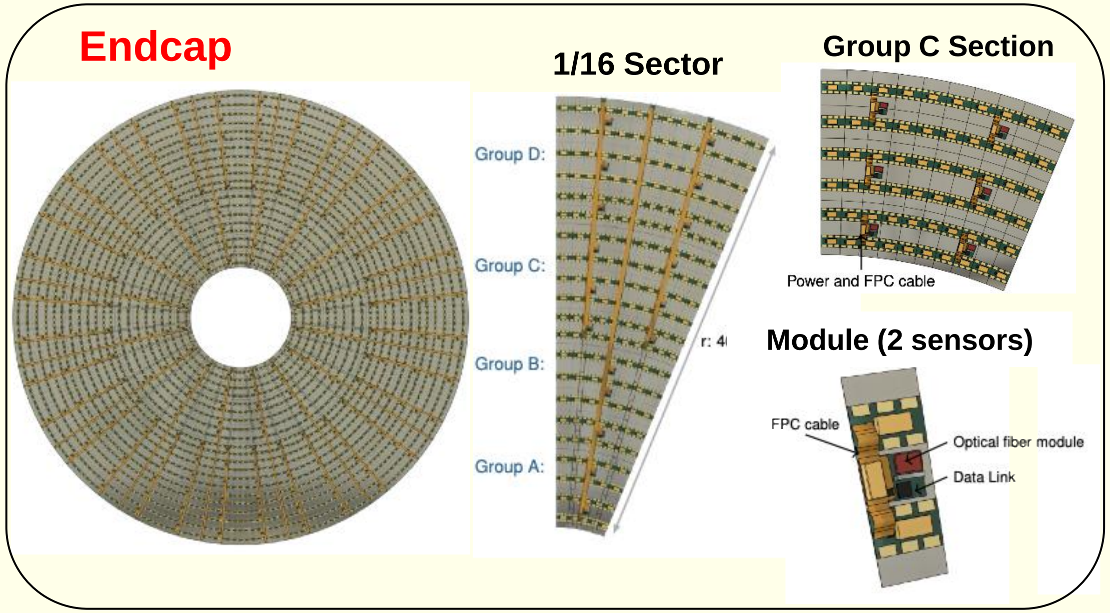


- The outer silicon tracker ~ 85 m^2, the Z precision is not crucial
  $\Rightarrow$ Cost-effective SSD
- A supplemental PID at low energy
  $\Rightarrow$ LGAD ToF
- An AC-LGAD Time Tracker combines the two needs in one detector. We expect σ_t ~50 ps, $\sigma_{R\Phi}$ ~10 μm
- Need to validate with full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

Strip AC-LGAD by IHEP / IME



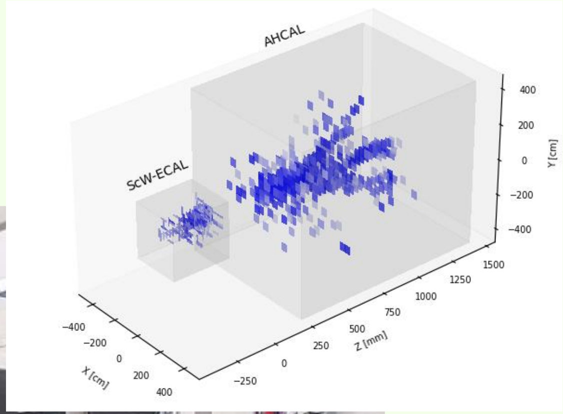


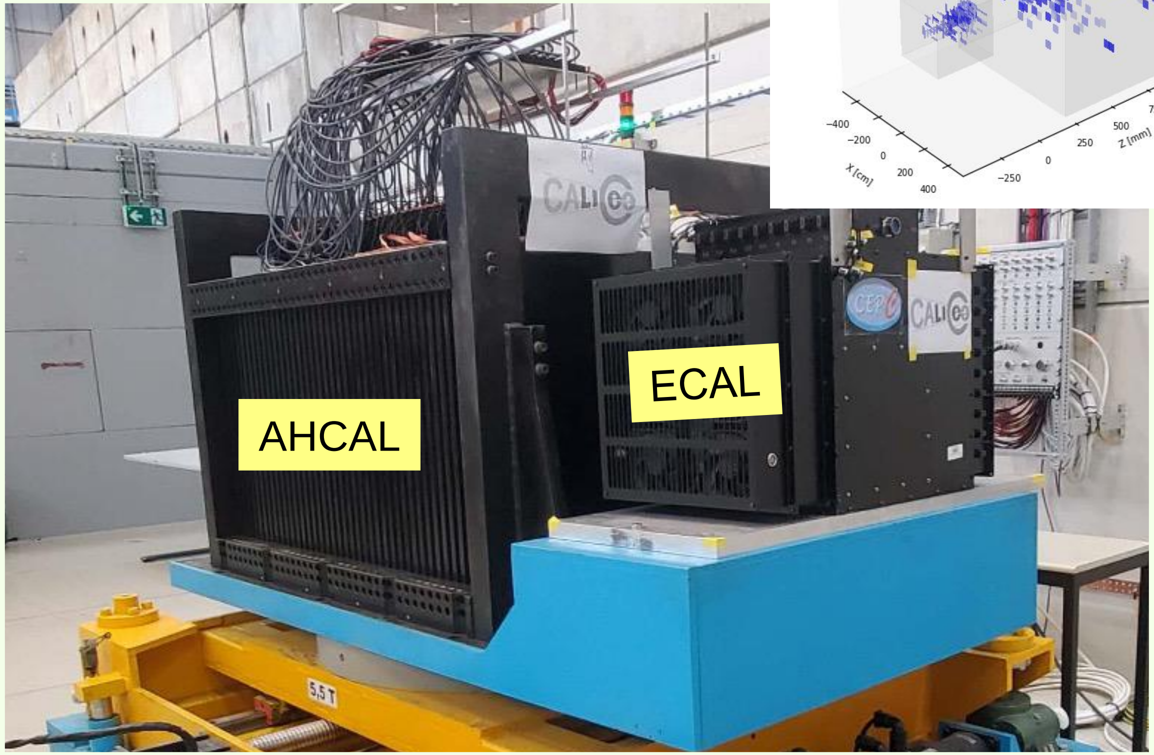


Prototype PFA Calorimeters

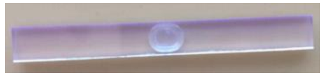
- ScW-ECAL: transverse 20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

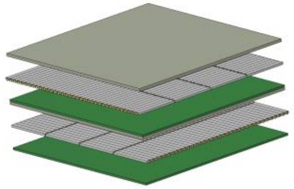
Several successful testbeams @ CERN

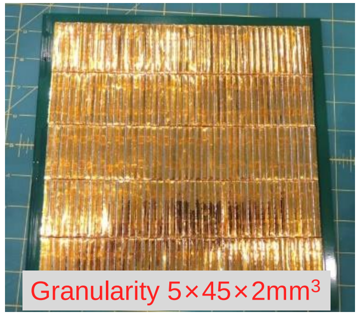




ECAL: scintillator(strip)+SiPM, CuW

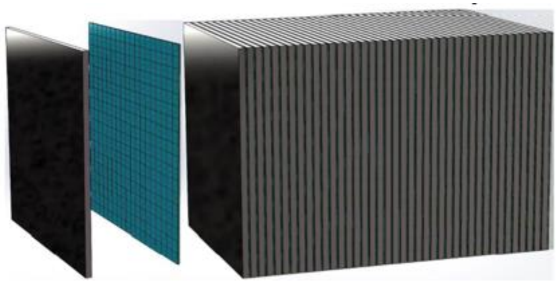


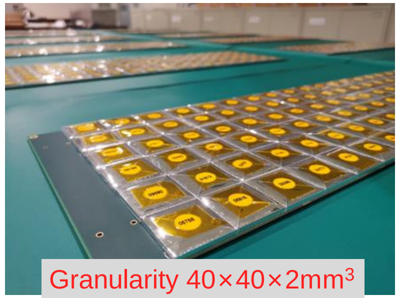




Granularity 5×45×2mm^3

HCAL: scintillator (tile)+SiPM, steel



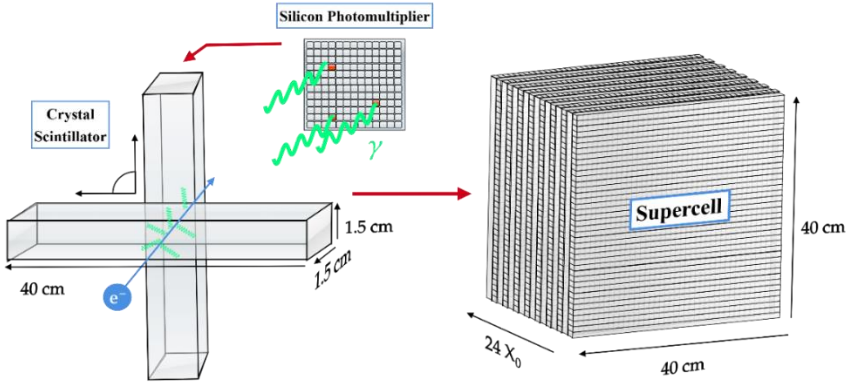


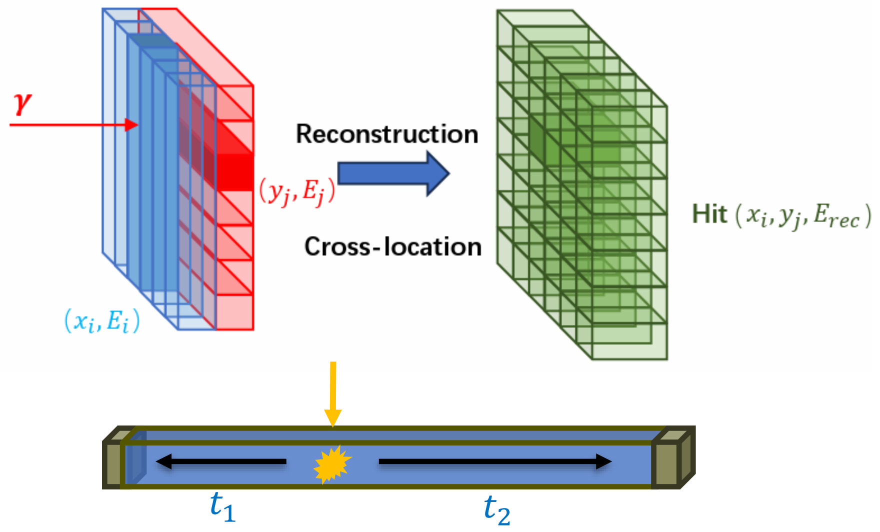
Granularity 40×40×2mm^3

Prototypes developed within **CALICE**

- China: IHEP, SJTU, USTC
- Japan: U. Shinshu, U. Tokyo
- France: CNRS Omega
- Israel: Weizmann Institute

Crystal Bar EM Calorimeter



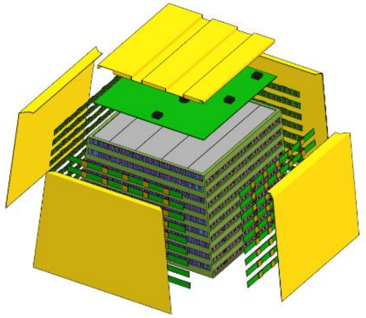


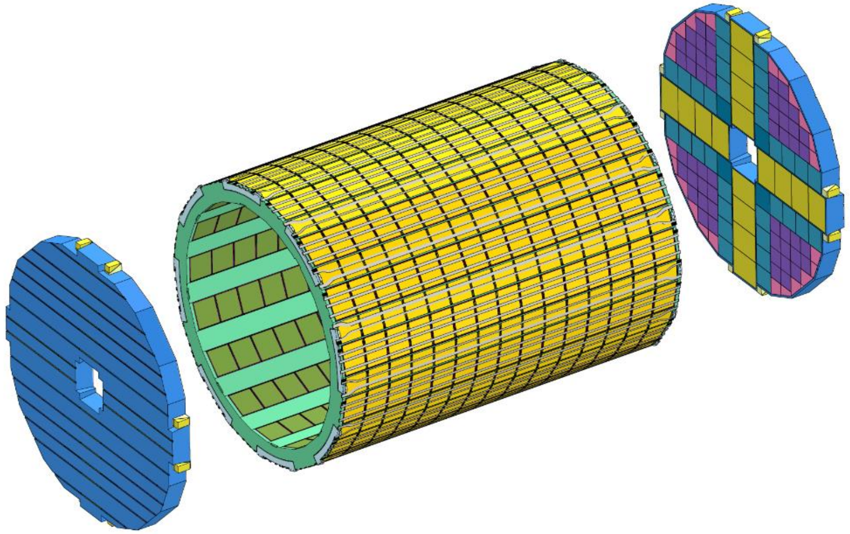
Achieve effective granularity 1×1×2 cm^3

- 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

Modular Design

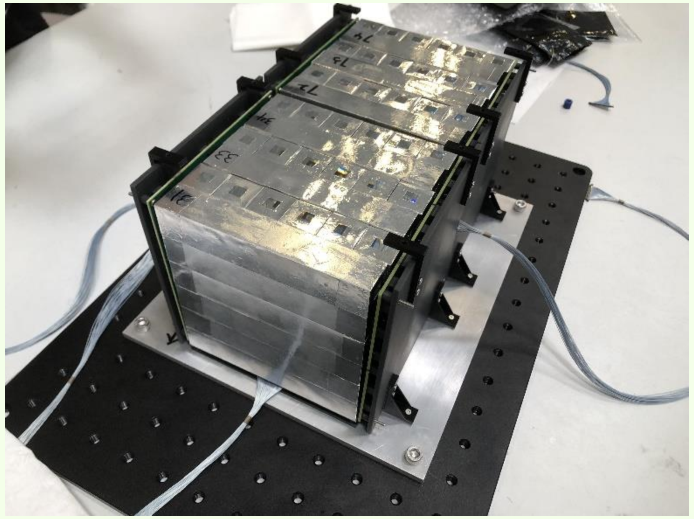
- 18 layers of crystals (24 X_0)
- Barrel: 32 towers per ring, 15 rings
- Endcap: 224 modules
- Total: 24m^3 BGO, 571k channels

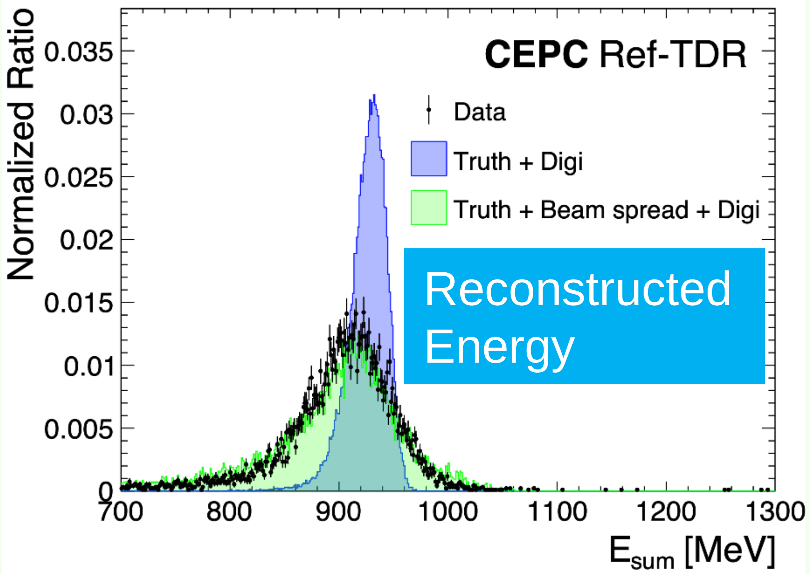


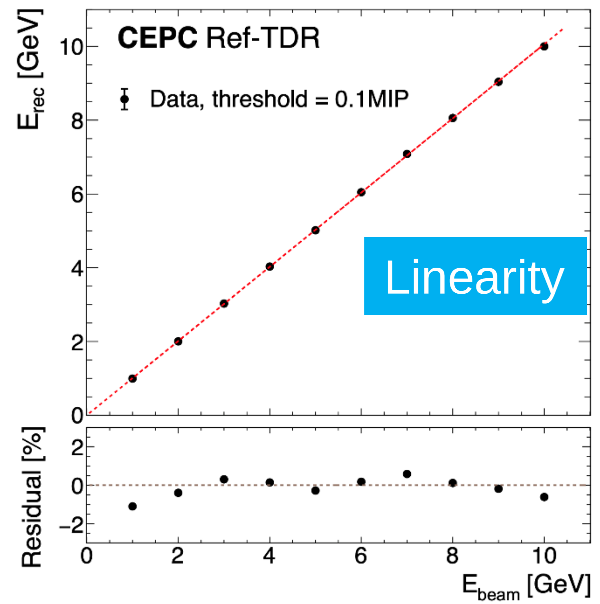


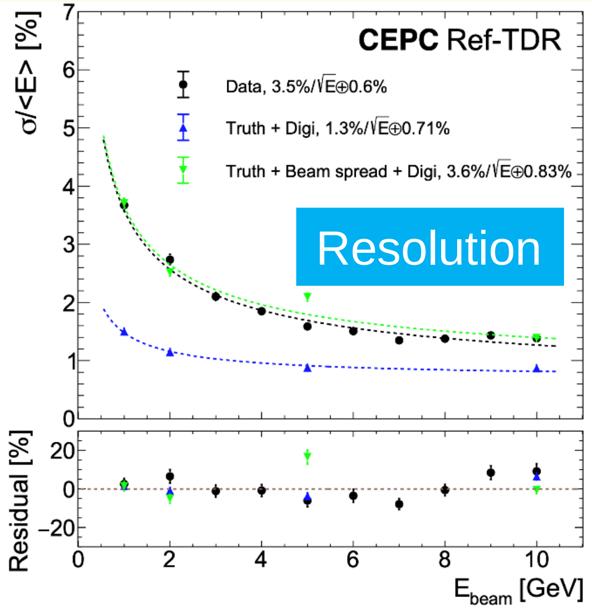
Testbeam of Prototype Crystal ECAL

- 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



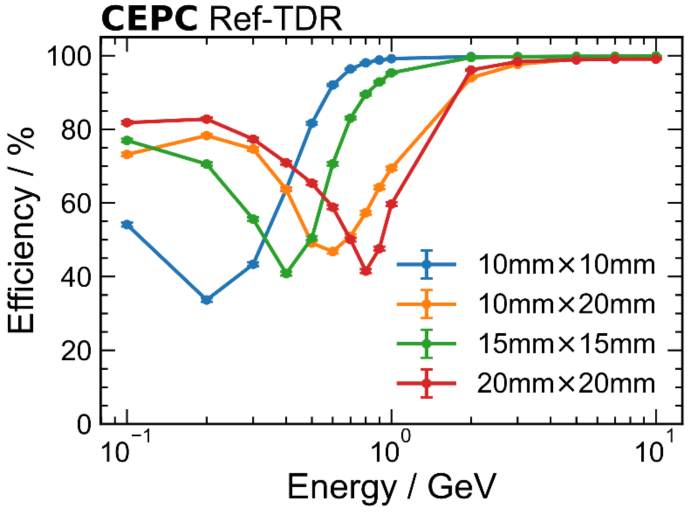




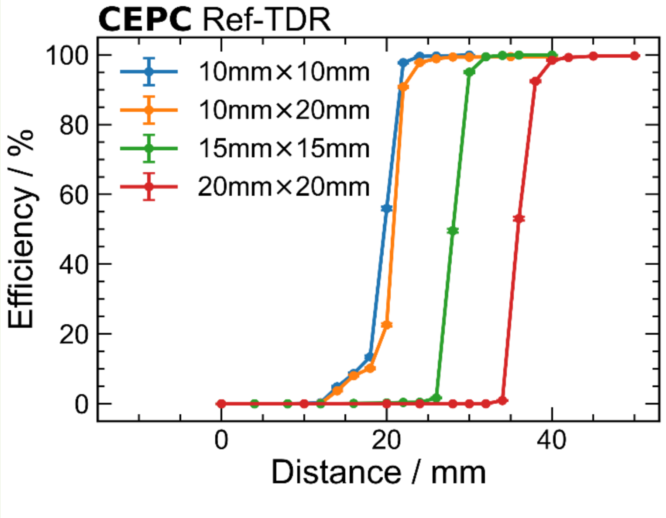


ECAL Granularity Optimization

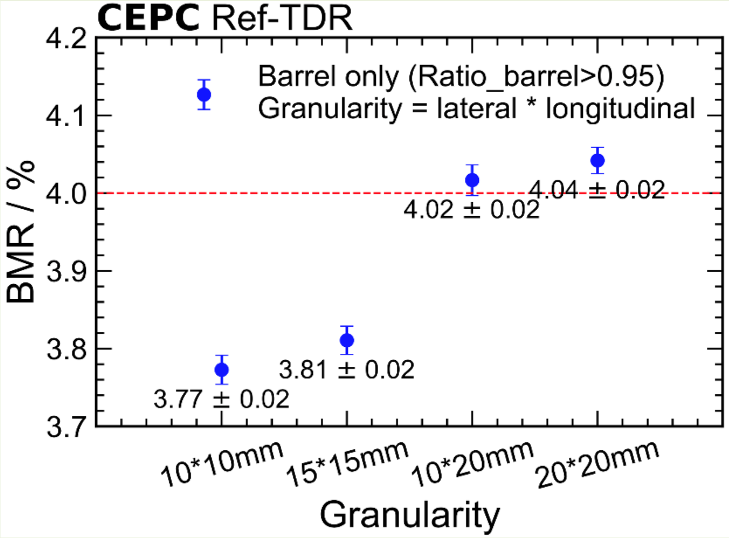
- ECAL granularity: balance of performance and readout
  - 10×10mm, 10×20mm, 15×15 mm and 20×20mm
- Figures of merit
  - Single photon reconstruction, separation power and jet performance



Major impact from ECAL longitudinal segmentation



Separation efficiency dominated by ECAL transverse granularity



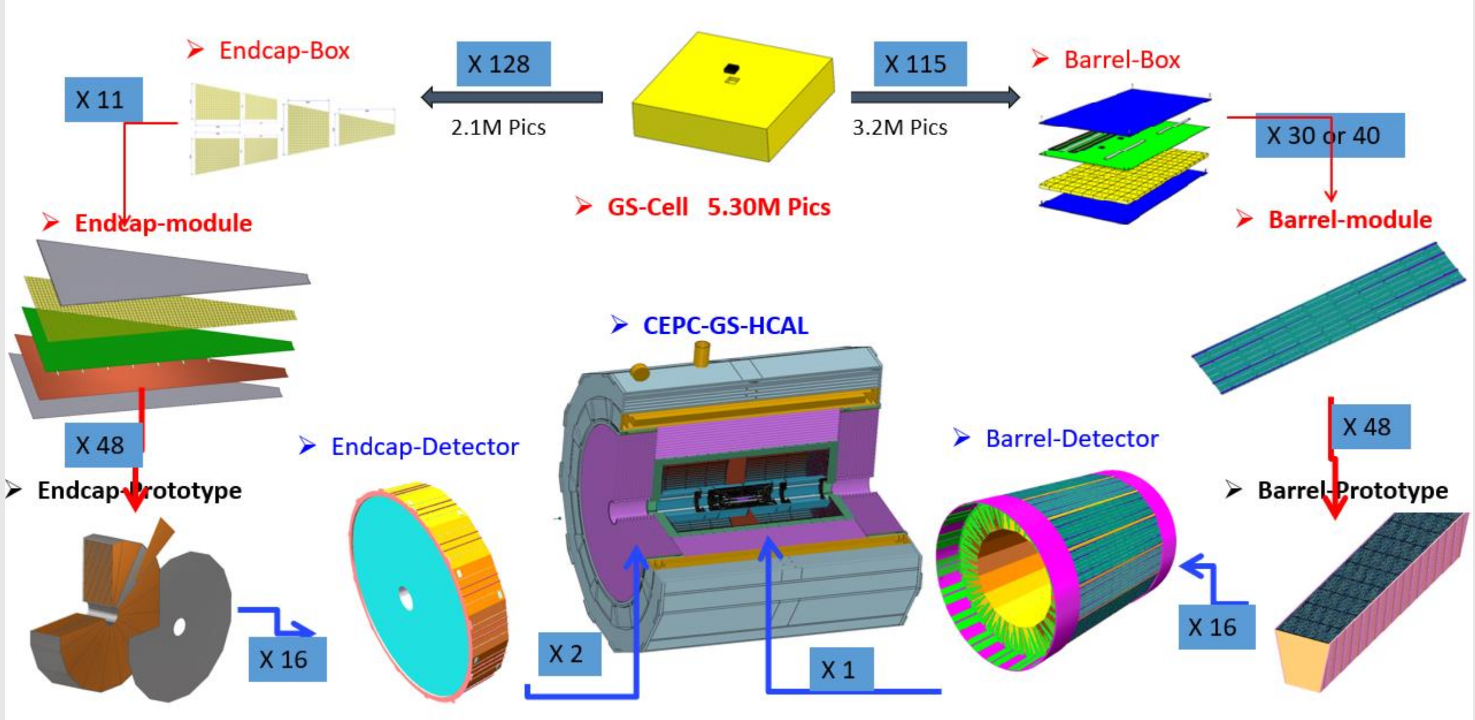
10x10mm and 15x15mm can meet physics requirement of BMR <4%

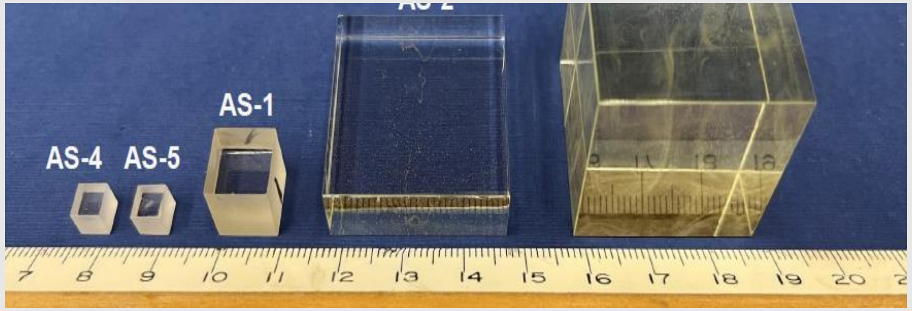
Conclusion: ECAL granularity of **15×15mm²** selected for ECAL

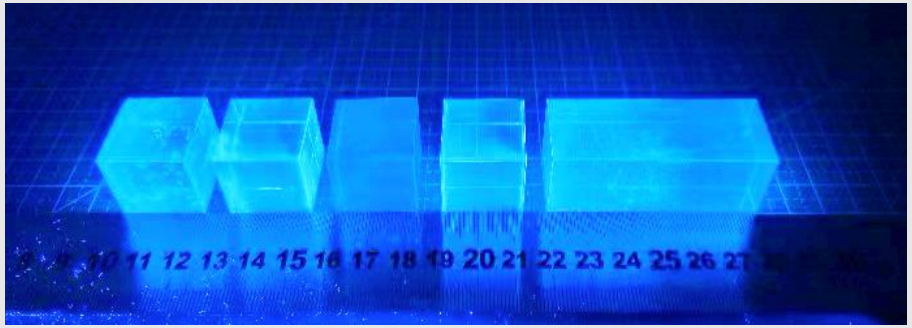
Glass Scintillator HCAL

- 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

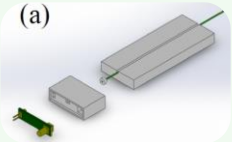


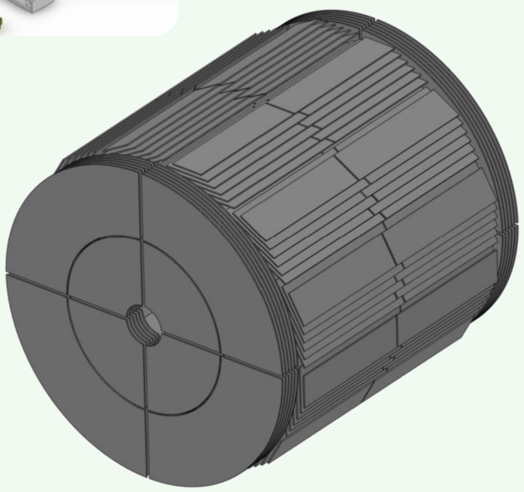


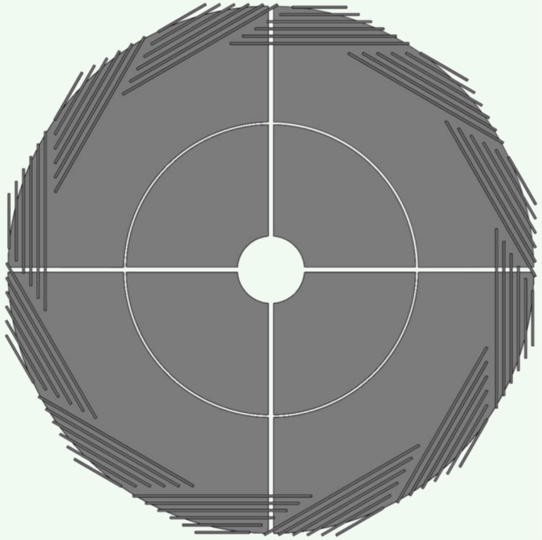


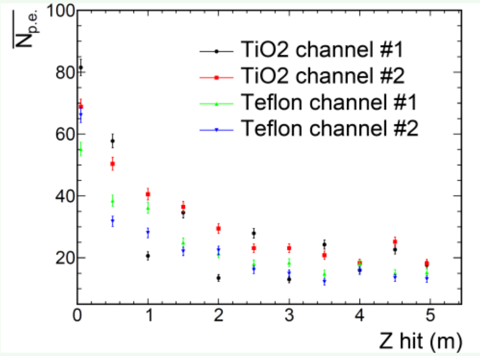
Muon Detector

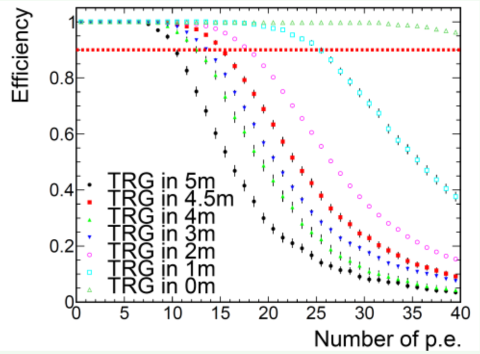
- Use extruded plastic scintillator (PS) technology, provide Muon ID > 95%, and pion fake rate < 1%
- Strip/channel structure: PS bar + WLS fiber + SiPM
- Solid angle coverage: $0.98 \times 4\pi$, total detection area ~ 4,800 m^2, ~43k channels
- Prototype of 5m channel: $\epsilon > 95\%$, $\sigma_T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

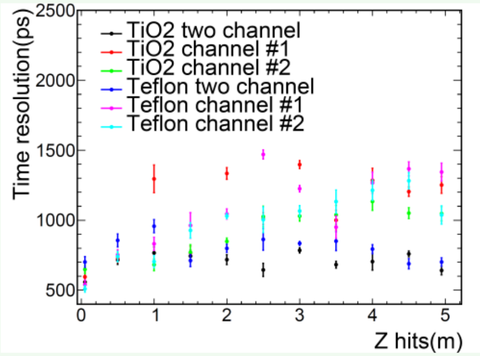




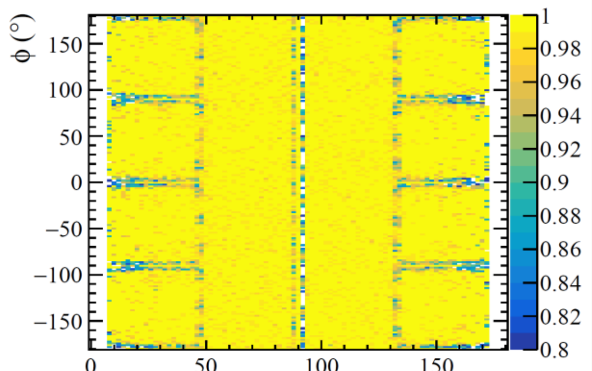




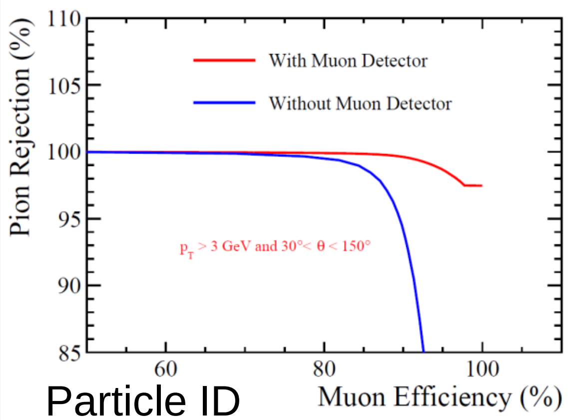




Simulation and performance

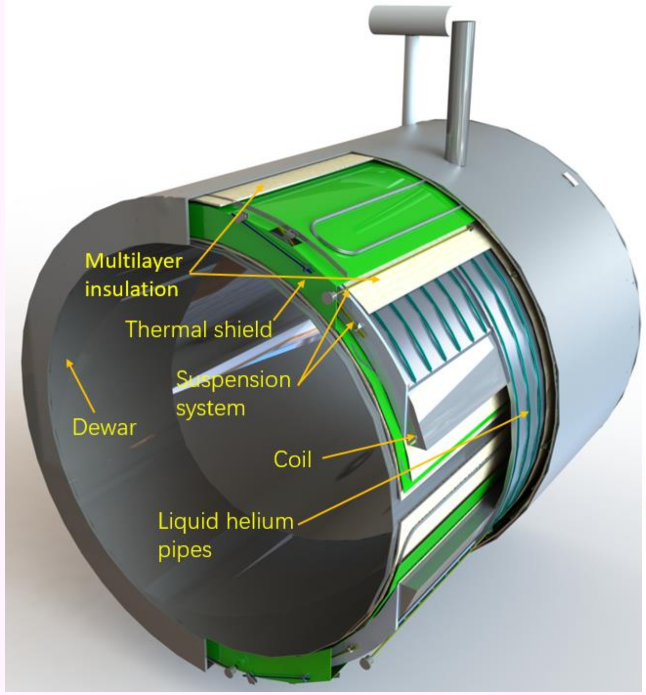


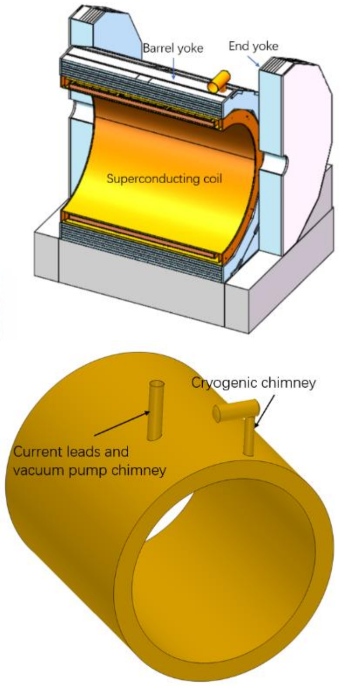
Detection efficiency



Particle ID

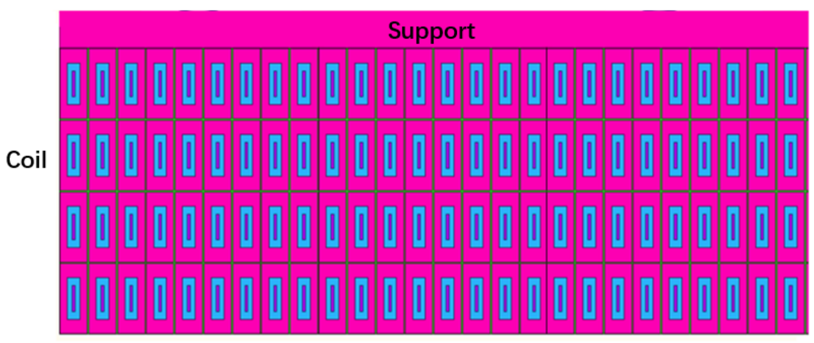
SC Solenoid Magnet





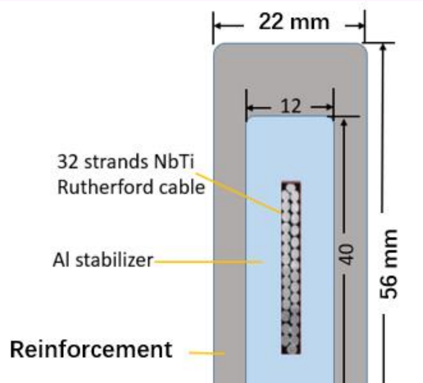
- ❑ Design of the overall structure and the supporting systems
- ❑ Production of short samples (5m) of Al-stabilized NbTi Rutherford cable

Central B field	3 T
Coil inner diameter	7300 mm
Coil outer diameter	7916 mm
Coil length	8150 mm
Operating current	17 kA
Coil module gap	50 mm
Inductance	11 H
Stored energy	1.54 GJ

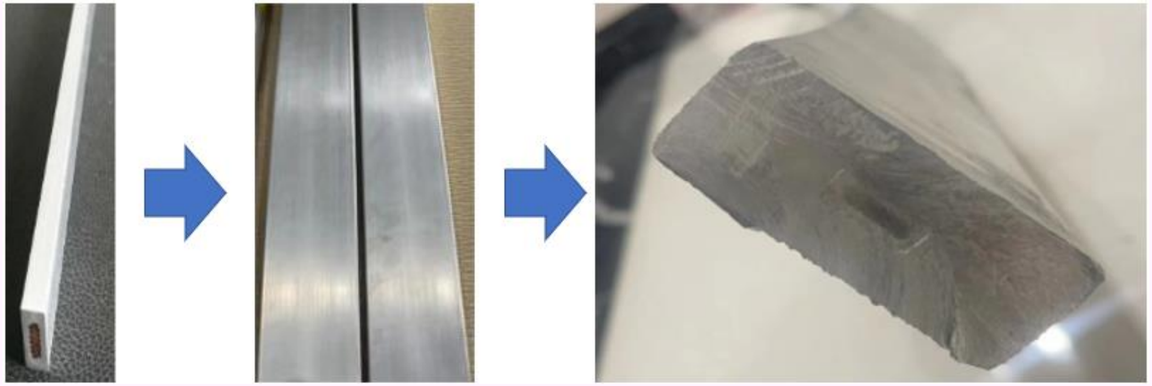


Coil structure

Inner diameter	7070 mm
Outer diameter	8470 mm
Thickness	700 mm
Length	9050 mm
Cold mass	185 tons
Yoke weight	2960 tons
Magnet weight	290 tons



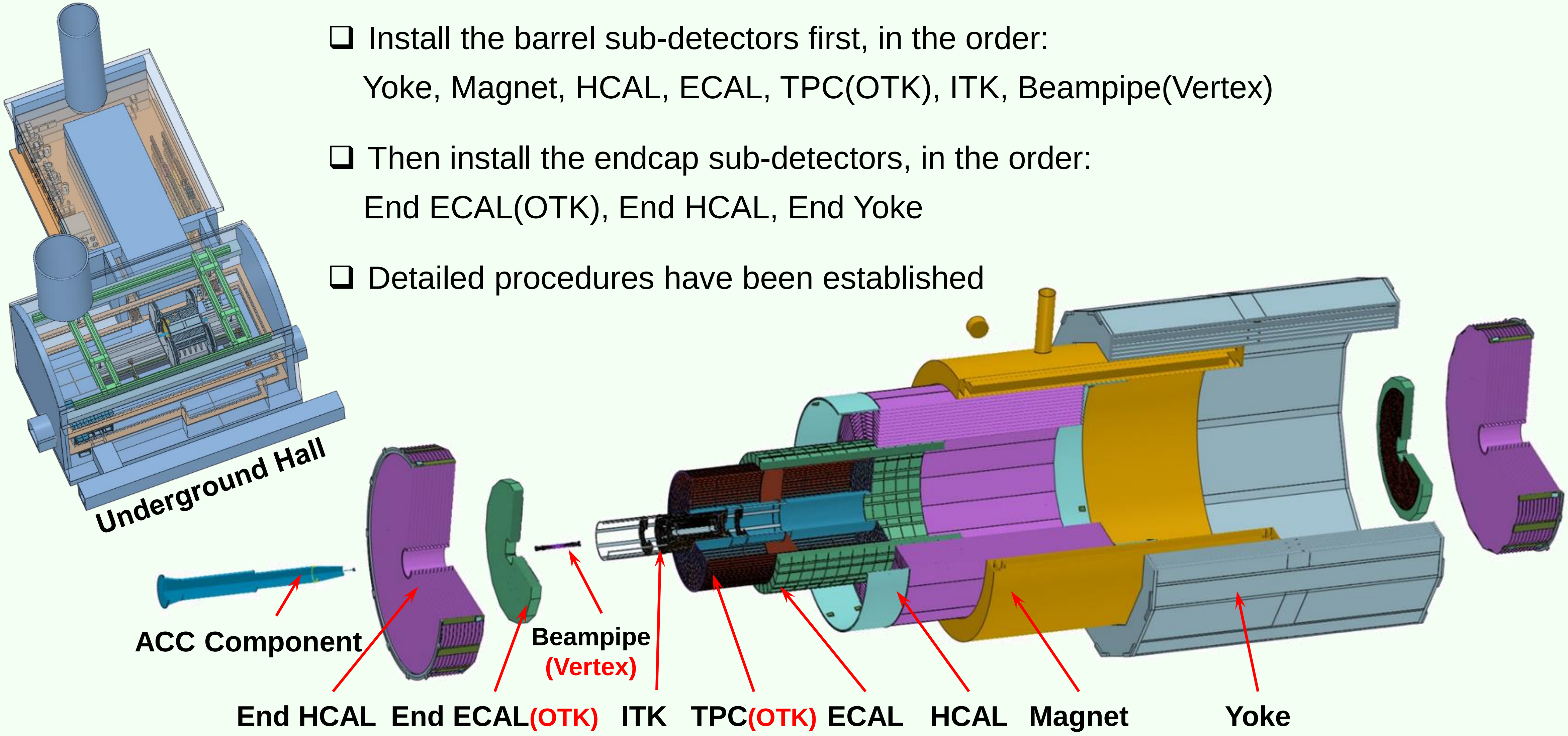
Cable structure



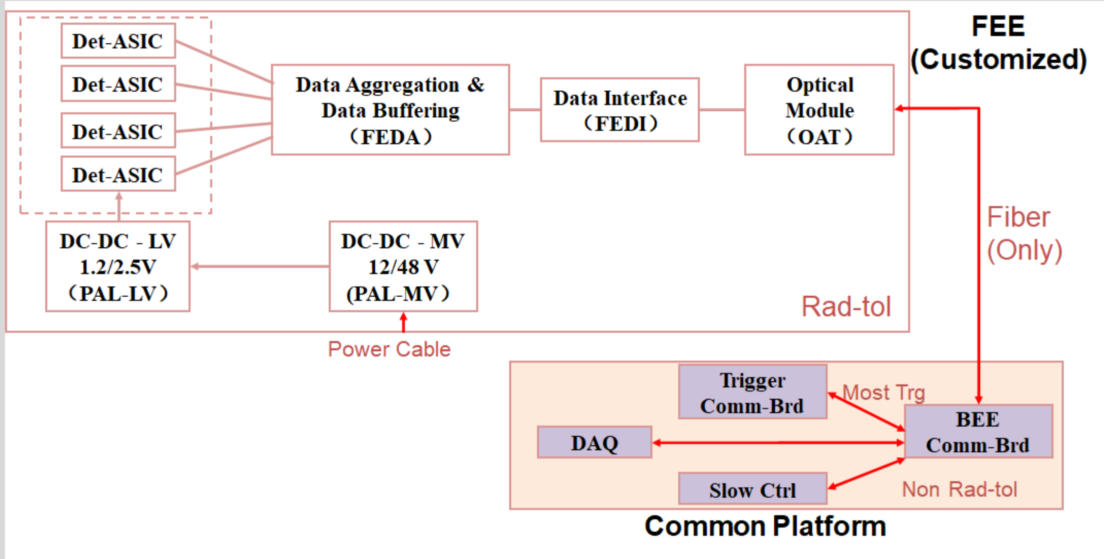
The 2nd co-extrusion process

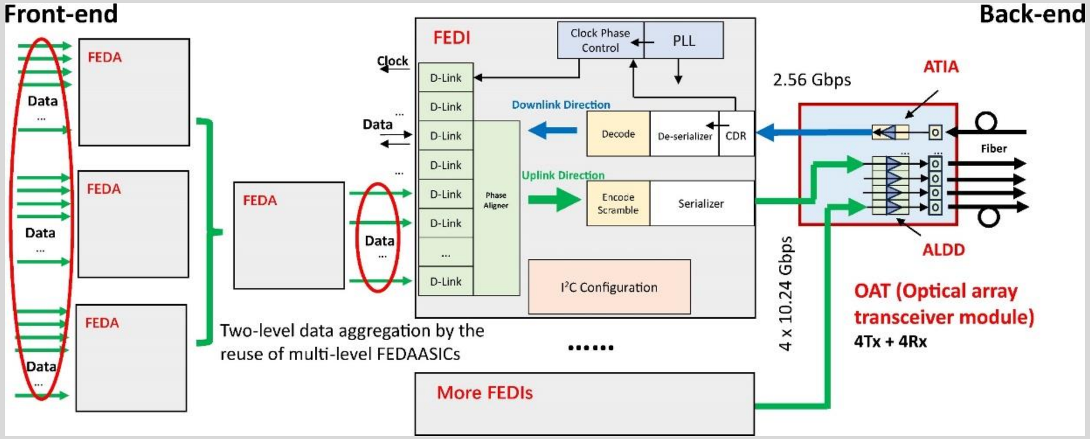
Detector Installation

- Install the barrel sub-detectors first, in the order:
  Yoke, Magnet, HCAL, ECAL, TPC(OTK), ITK, Beampipe(Vertex)
- Then install the endcap sub-detectors, in the order:
  End ECAL(OTK), End HCAL, End Yoke
- Detailed procedures have been established



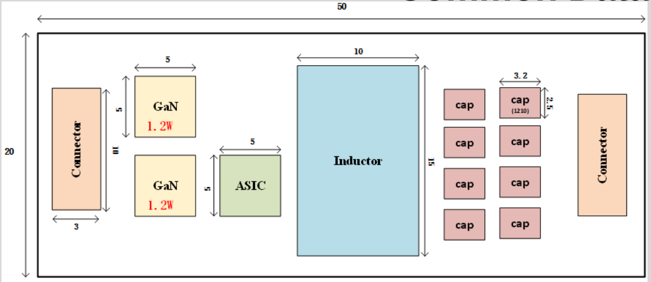
Electronics

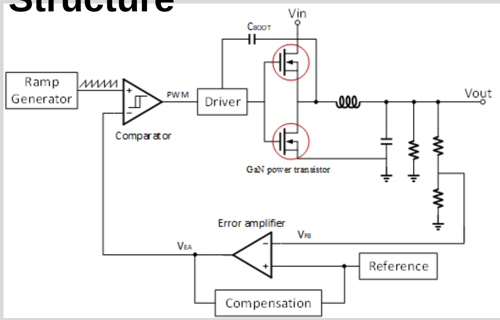




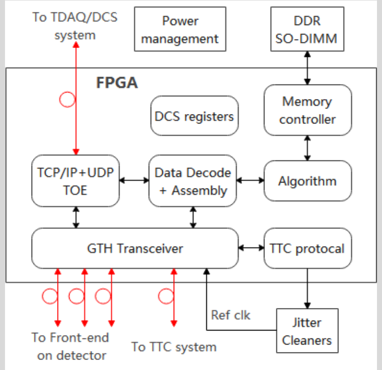
FEDA FEDI OAT

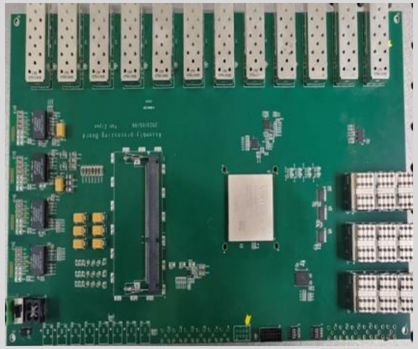
Common Data Link Structure





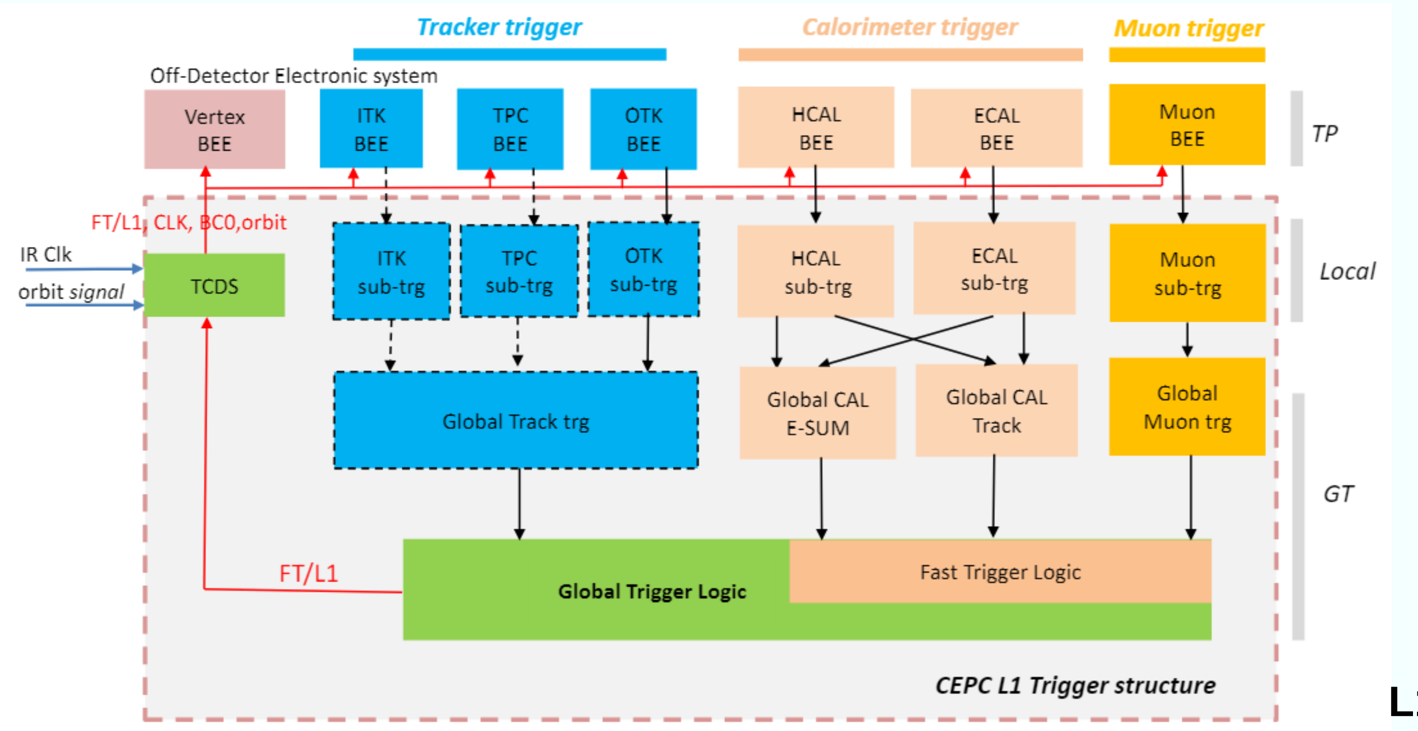
Common Powering Module （PAL）

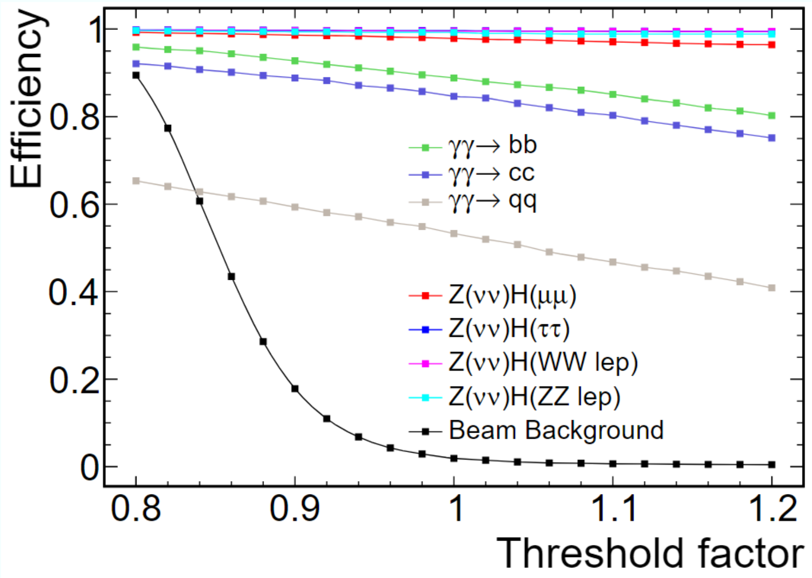




- Baseline: Triggerless FE readout & BE trigger
- Maximizing the common design:
  - Common FEE blocks, including data aggregation, transmission, optical, powering
  - Common BEE & Common Trigger: configurable for individual subsystems.

Trigger and Data Acquisition



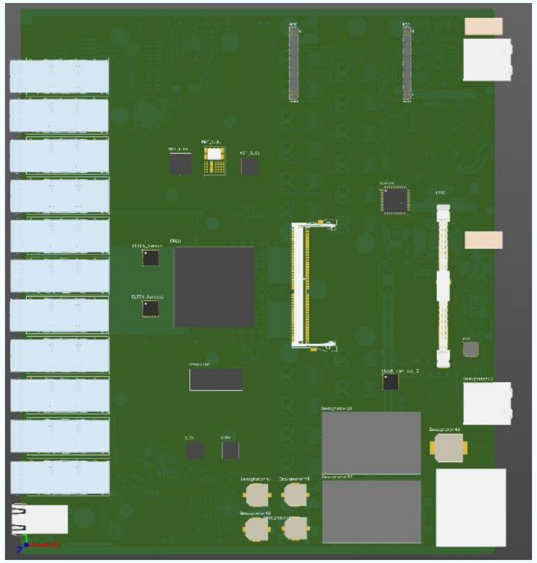


- Hardware trigger at BE + HLT software trigger
- L1 trigger on calorimeter, muon, and trackers
- Will explore a full software trigger with GPUs

L1 trigger board

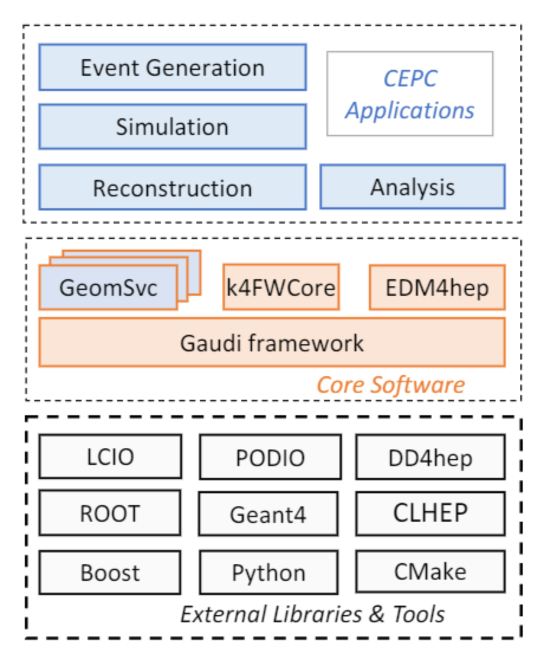
36-48 channels
×10-25Gbps
Optical interface

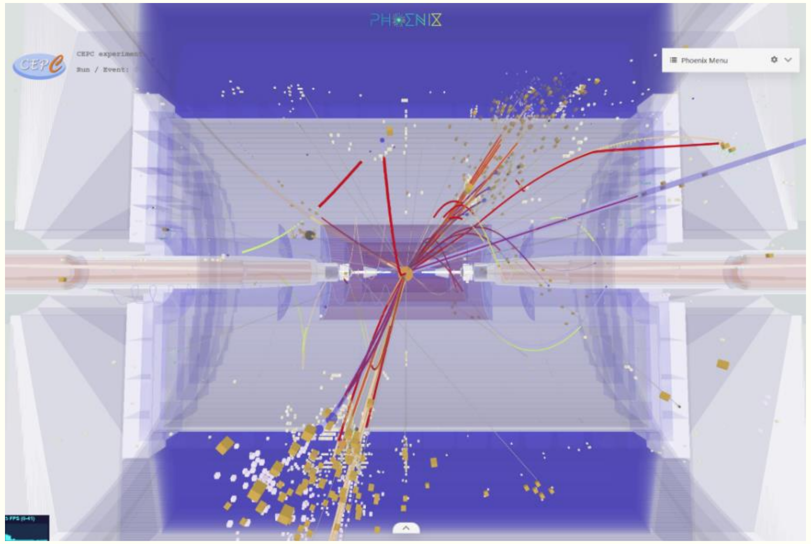
Xilinx Virtex FPGA

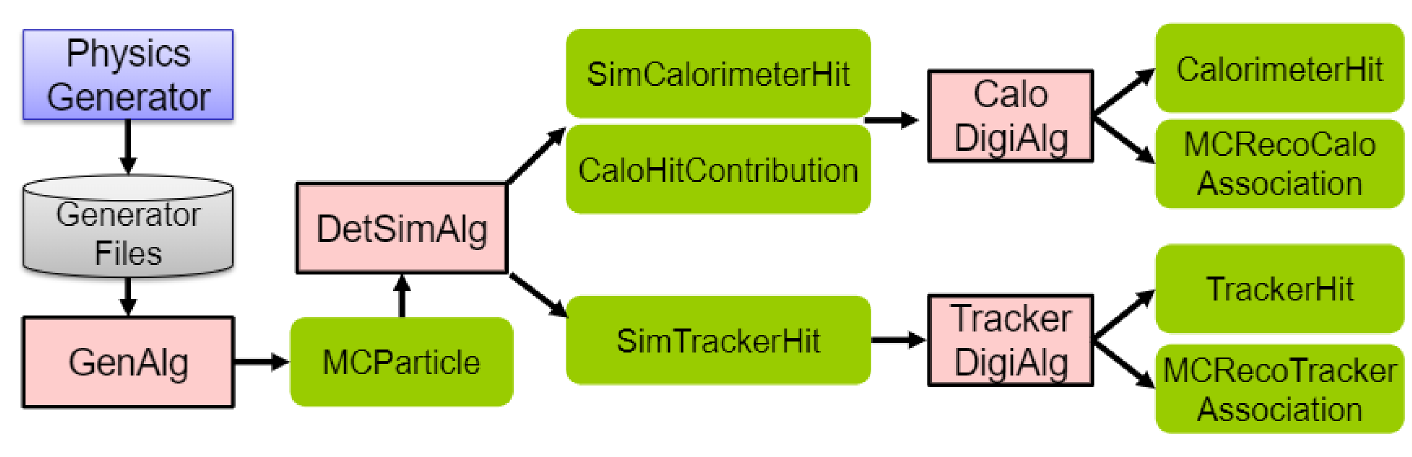


Offline Software and Computing

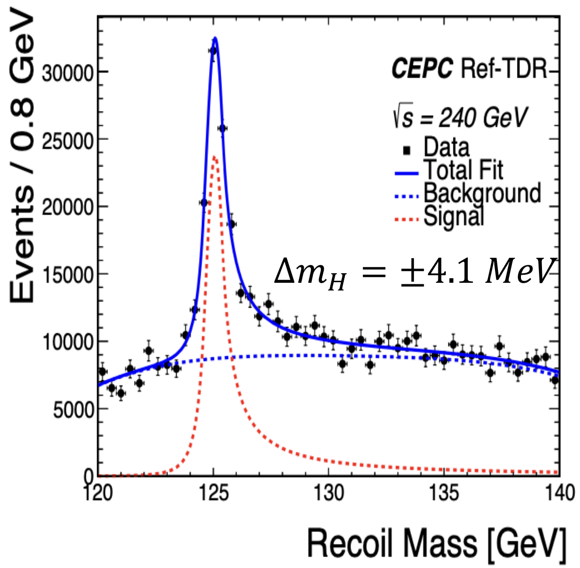
- **CEPCSW** bases on the **Gaudi** framework and **Key4hep** stack, using well-known HEP tools while creating new solutions to meet the experiment's needs
- The **Geant4**-based simulation has been used to generate Monte Carlo data, which has then been reconstructed to validate **detector performance** and assess the **physics potential**
- Continuous **refinement** of the software stack is crucial for ensuring optimal performance and reliability
- Incorporating **emerging technologies** such as AI and machine learning will be instrumental in overcoming critical challenges faced by the experiment

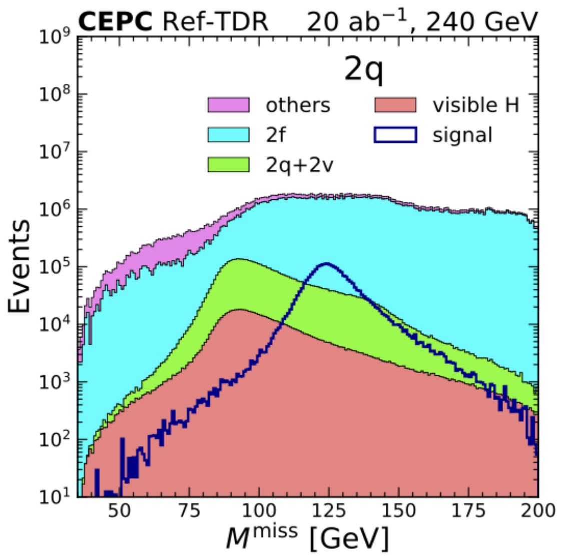




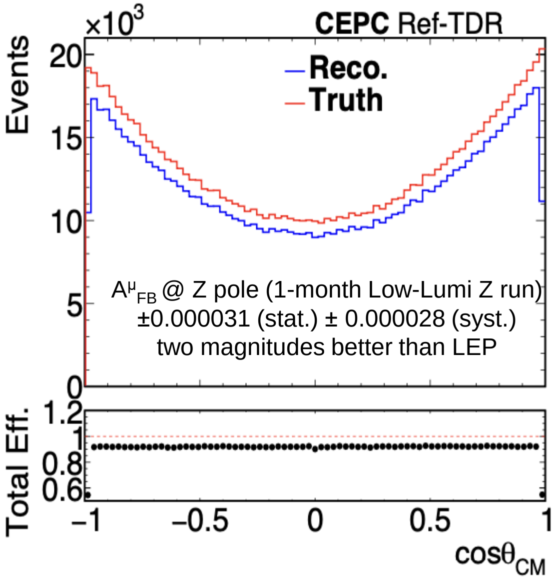


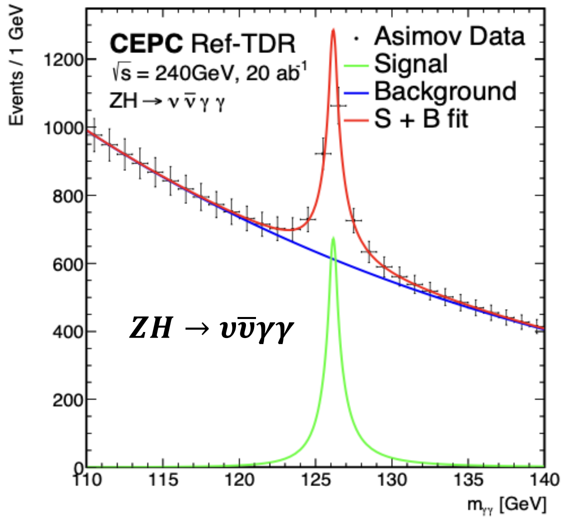
Selected Benchmark Performance

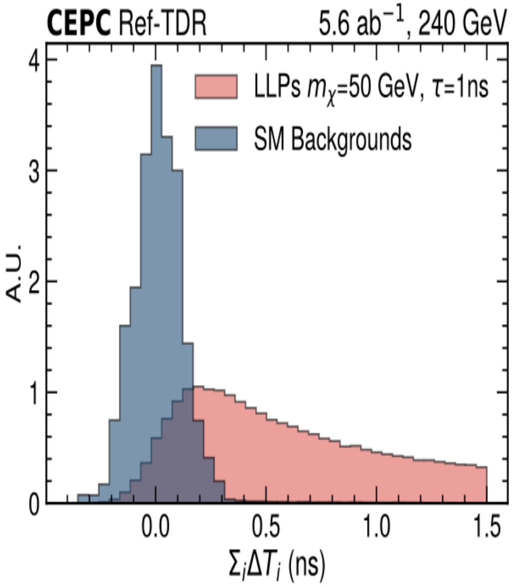


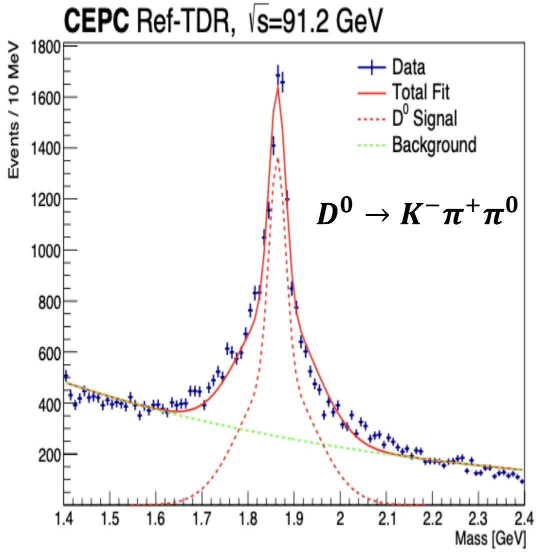


4.4σ for H→4ν,
UL for H→inv.: 0.05%@95%CL

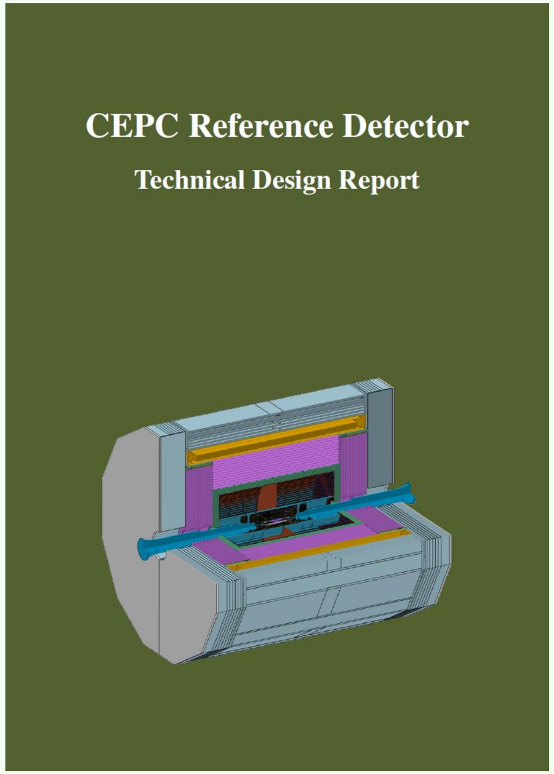








Status of The Ref-TDR



Version 0.4.1 of Jun 14, 2025

~ 650 pages

1) Introduction
2) Concept of CEPC Reference Detector
3) MDI and Luminosity Measurement
4) Vertex Detector
5) Silicon Trackers
6) Pixelated Time Projection Chamber
7) Electromagnetic Calorimeter
8) Hadronic Calorimeter
9) Muon Detector
10) Detector Magnet System
11) Readout Electronics
12) Trigger and Data Acquisition
13) Offline Software and Computing
14) Mechanics and Integration
15) Detector and Physics Performance
16) Timeline and Plans

Reviews By The IDRC

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

- The IDRC (International Detector Review Committee) had two reviews in October 2024 and April 2025
- The committee provided very helpful and detailed comments and recommendations.
- In general there is no showstopper.

R&D Teams and 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.

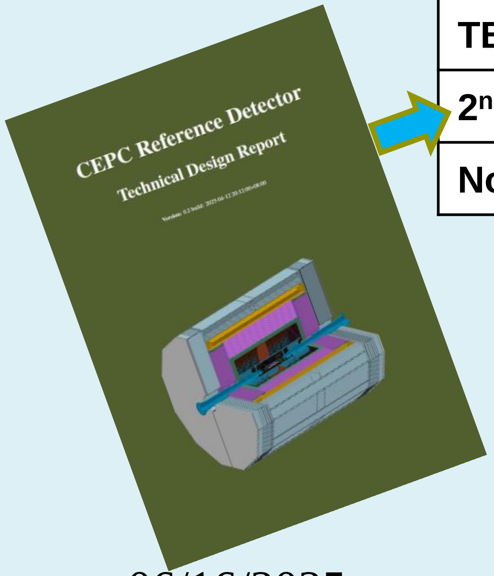
- Active member of the ECFA DRD program

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	

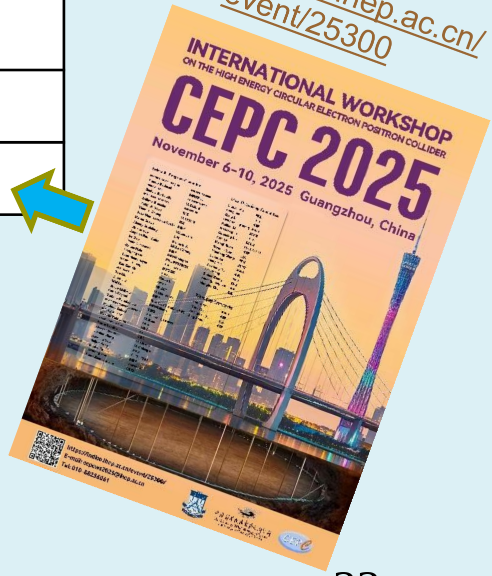
- Participating in the European Strategy for Particle Physics process (CEPC input).

Timeline of Ref-TDR

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 ref-TDR at the CEPC workshop, report progresses to the CEPC IAC
January 2025	The first draft of the ref-TDR is ready for internal reviews
Apr 14-16 2025	Review of ref-TDR progress by the IDRC
Jun 16-19, 2025	Discuss at the CEPC Barcelona workshop
TBD	Further iteration and review
2nd half of 2025	Publication of the ref-TDR
Nov 6-10, 2025	Report at the CEPC Guangzhou workshop



https://indico.ihep.ac.cn/event/25300



We welcome more teams to join the quest, help editing, sign up authorship to show support

Thank you for supporting CEPC!

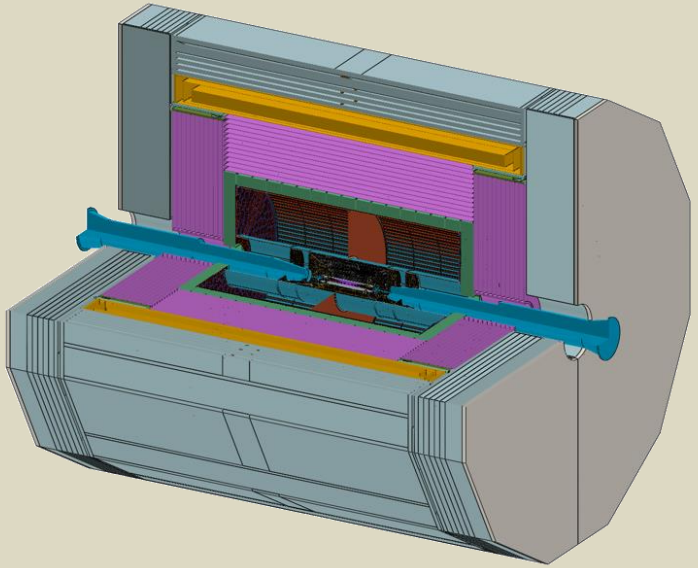
Backup Slides

Technologies for Ref-TDR

System	Technologies	
	Baseline	Backup / Comparison
Beam pipe	Φ20 mm	
LumiCal	SiTrk + Crystal	
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
Magnet	LTS	HTS
Muon	PS bar+SiPM	RPC
TDAQ	Conventional	Software Trigger
BE electr.	Common	Independent

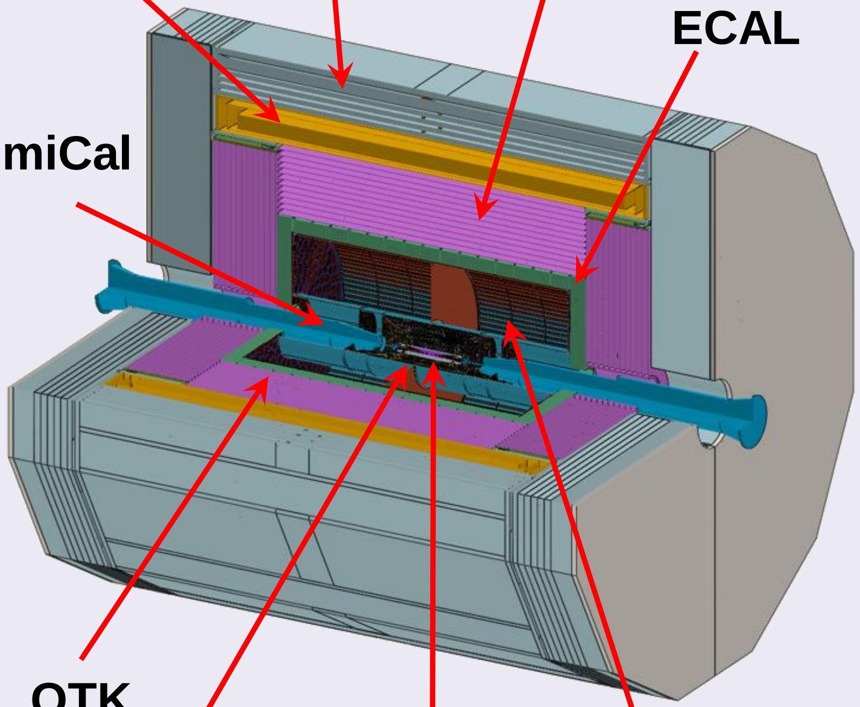
Radius

- The CEPC study group started to compare different technologies and chose the baseline technologies were chosen in the first half year of 2024
- Multiple factors were considered in the process: performance, cost, R&D efforts, technology maturity, …



- We will continue pursuing better technologies for the two final detectors at CEPC

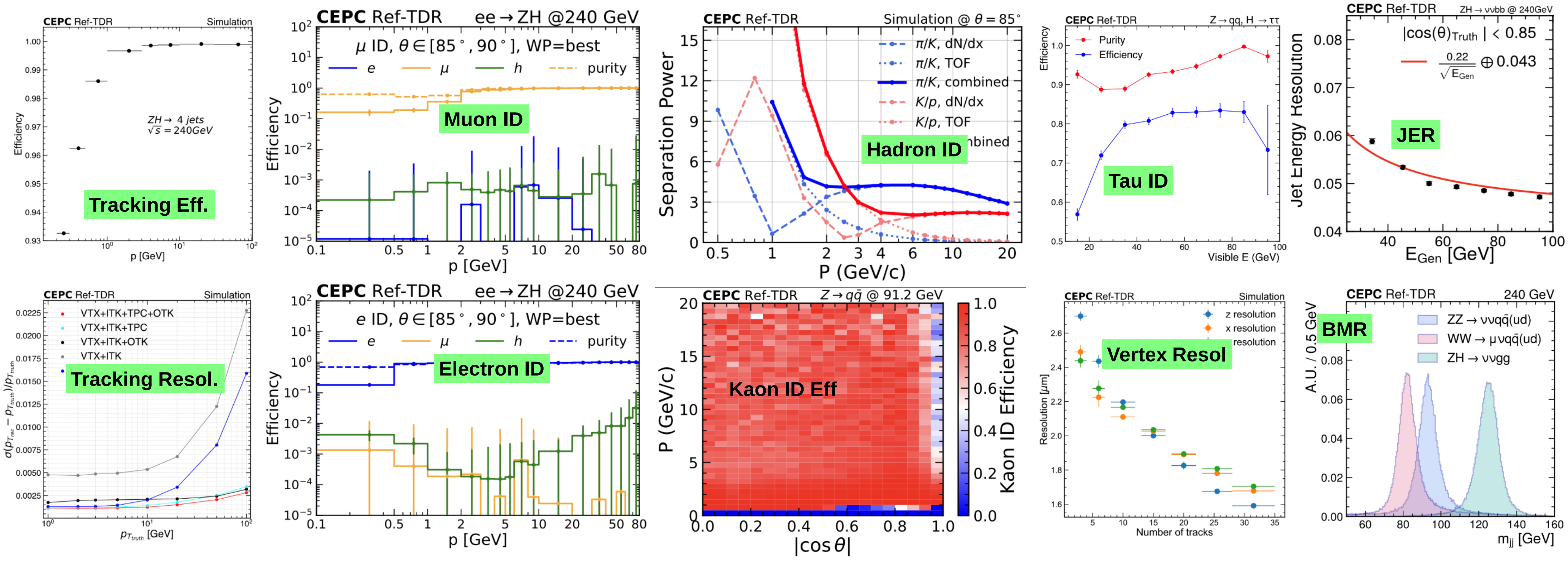
CEPC After The First 10 Years



SR Power Per Beam	Luminosity/IP [$\times 10^{34} cm^{-2}s^{-1}$]				
	H	Z (2T)	Z(3T)	W^+W^-	$t\bar{t}$
30 MW	5.0	115	50.3	16	0.5
50 MW	8.3	192	95.2	26.7	0.8
		2 yrs		1 yr	5 yrs

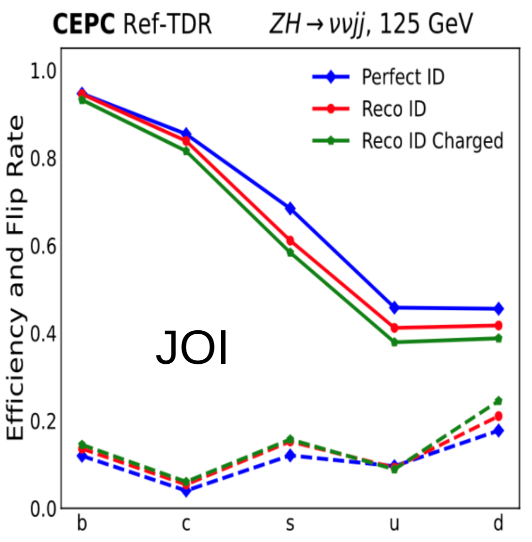
- **After the first 10-year operation,** the accelerator may be upgraded for High-Lumi Z mode and/or $t\bar{t}$ mode, subject to physics needs
- While the majority of the detector system remain, some sub-systems may be upgraded.
  - VTX: radiation hardness must likely is not an issue. However, new technology may bring in much better performance
  - TPC: to deal with high luminosity
  - Backend electronics and trigger system: to deal with much increased data rate

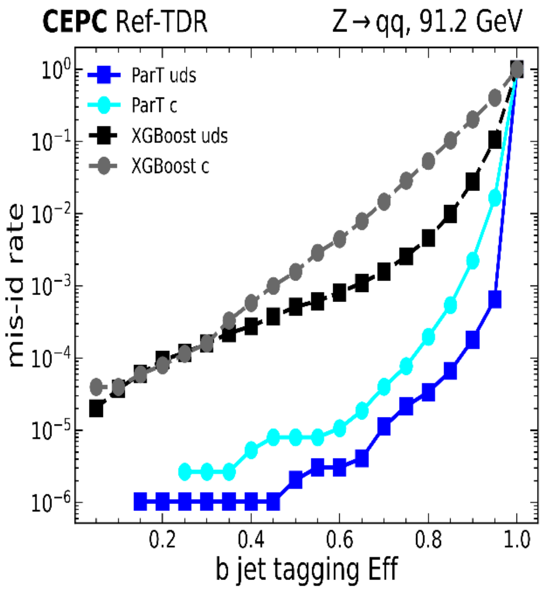
Object Performance

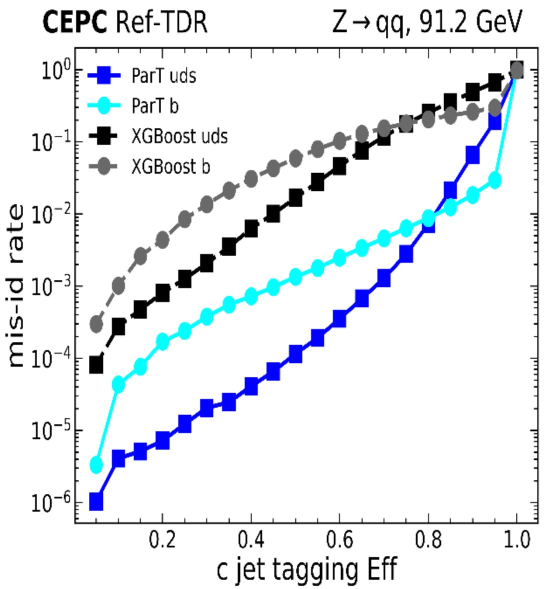


Tracking eff	Tracking σ_{pT}	VTX $\sigma_{x,y,z}$	π/K sep.	EM resl.	BMR
>99.7% (for p>1 GeV)	**~0.1%**	**< 3.5 mm**	**3σ** (1-20 GeV)	**1.5%/√E ⊕ 0.25%**	**3.87%** (H->gg)

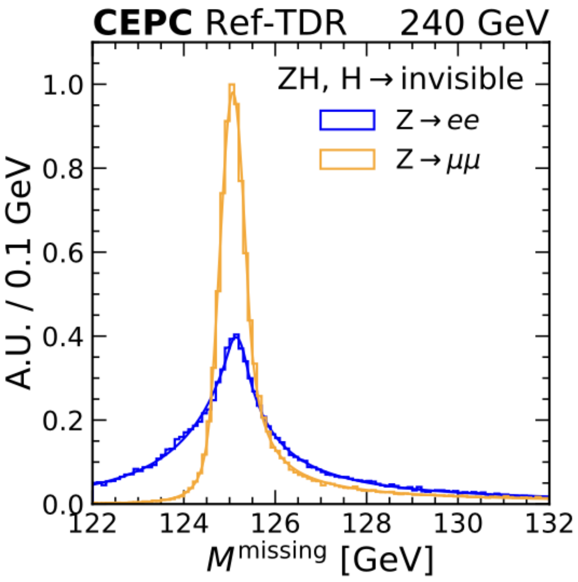
Flavor Tagging and Missing Mass

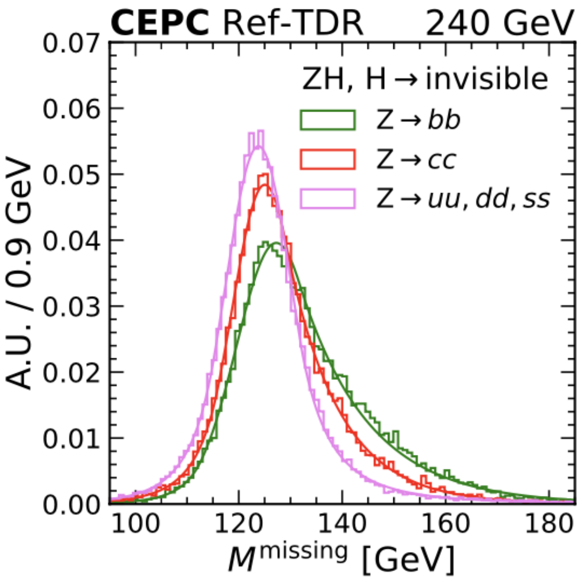


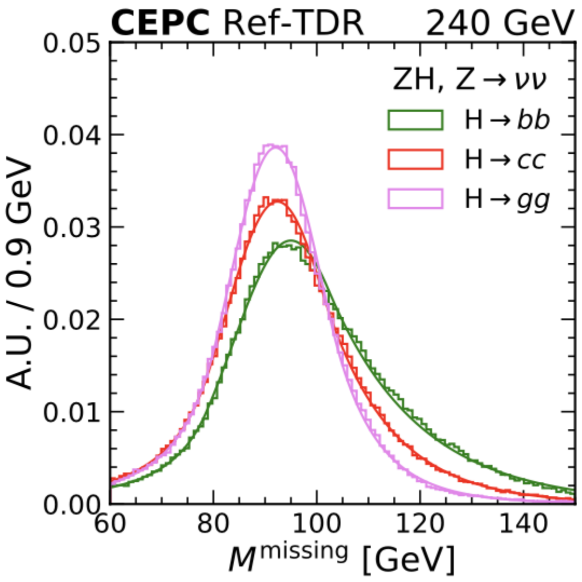




JOI performance is about one order of magnitude better compared to the BDT method.







Excellent missing mass reconstruction due to precise energy and momentum measurements, large coverage of the solid angle, and full knowledge of the initial state.