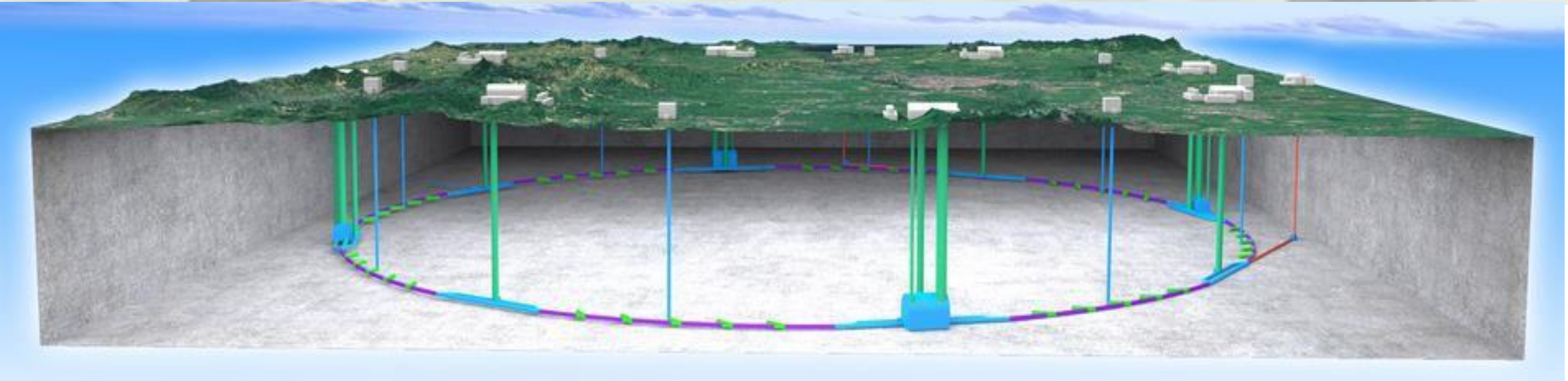
TDR of A Reference CEPC Detector

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

CEPC2024 Workshop, Oct 23-27, 2024, Hangzhou



Outline

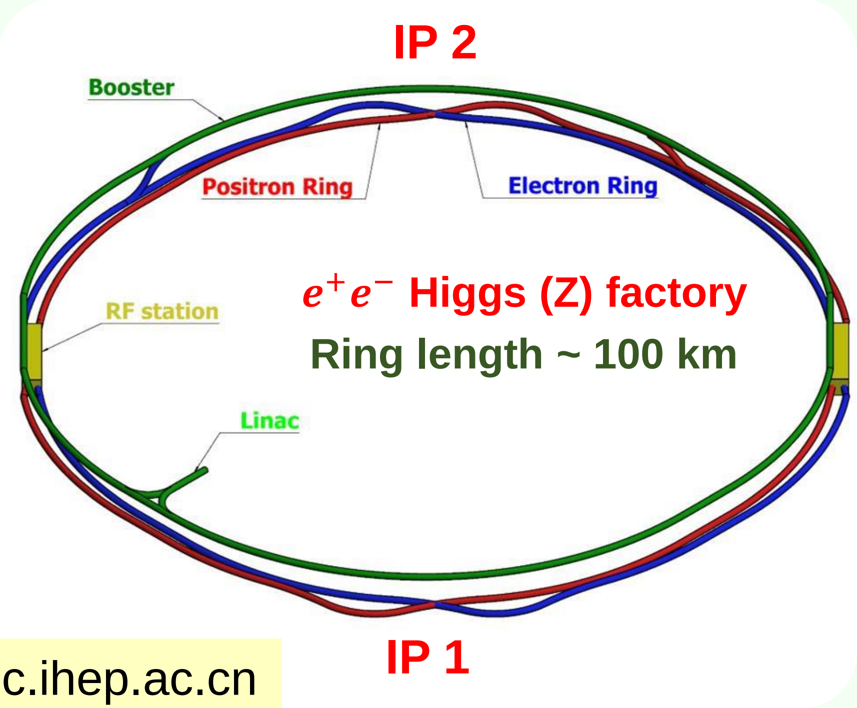
- Motivation of A Reference CEPC Detector TDR
- Technology Selections
- Status of R&D Projects
- R&D Team and International Collaborative Efforts
- Timeline of The Ref-TDR

Refer to the presentations at this workshop

Overview of The CEPC	**Xinchou Lou**
The CEPC Accelerator EDR	**Jie Gao**

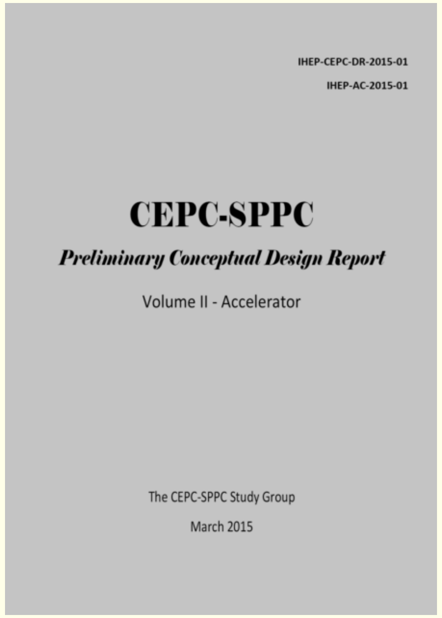
The Circular Electron Positron Collider

- ☐ 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.



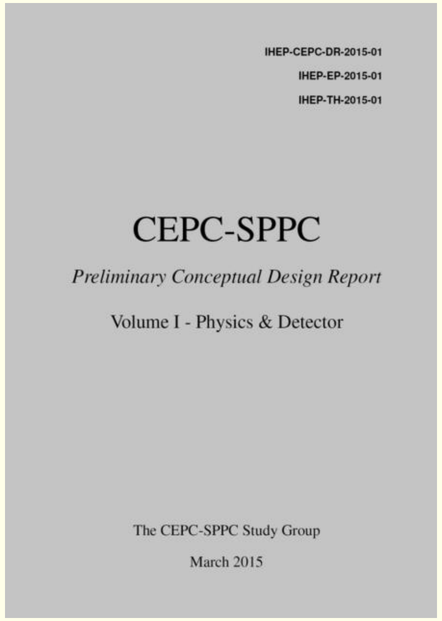
http://cepc.ihep.ac.cn

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

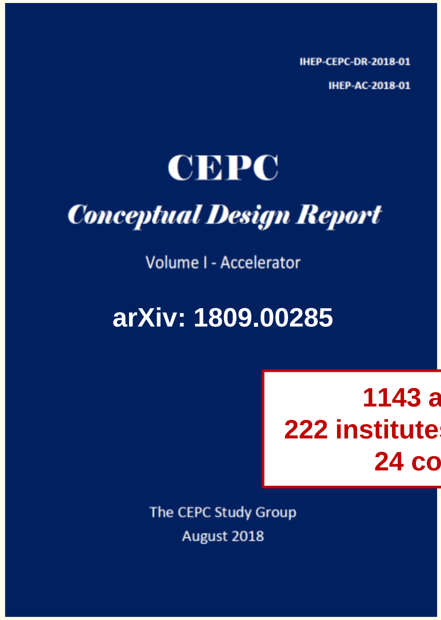

IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC
Preliminary Conceptual Design Report
Volume I - Physics & Detector

The CEPC-SPPC Study Group
March 2015

Pre-CDR Released (2015.03)

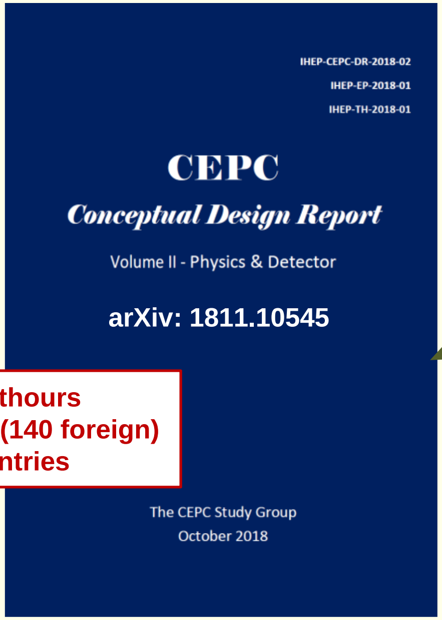
CDR Released (2018.11)


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

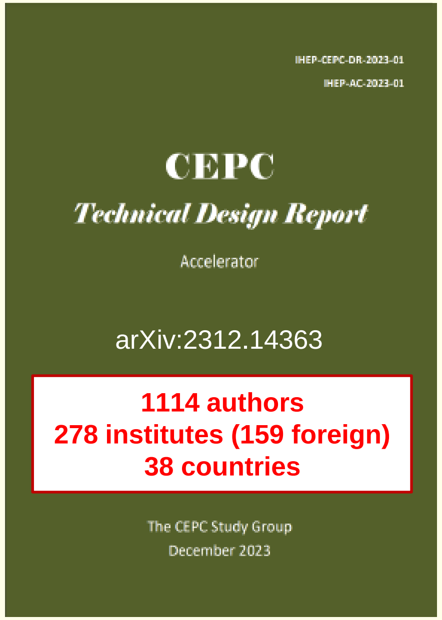
CEPC
Conceptual Design Report
Volume II - Physics & Detector

arXiv: 1811.10545

The CEPC Study Group
October 2018

1143 authours
222 institutes (140 foreign)
24 countries

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
TDR
Detector

??


CEPC
Engineering Design Report
EDR of
Accelerator

2027

10/26/2024

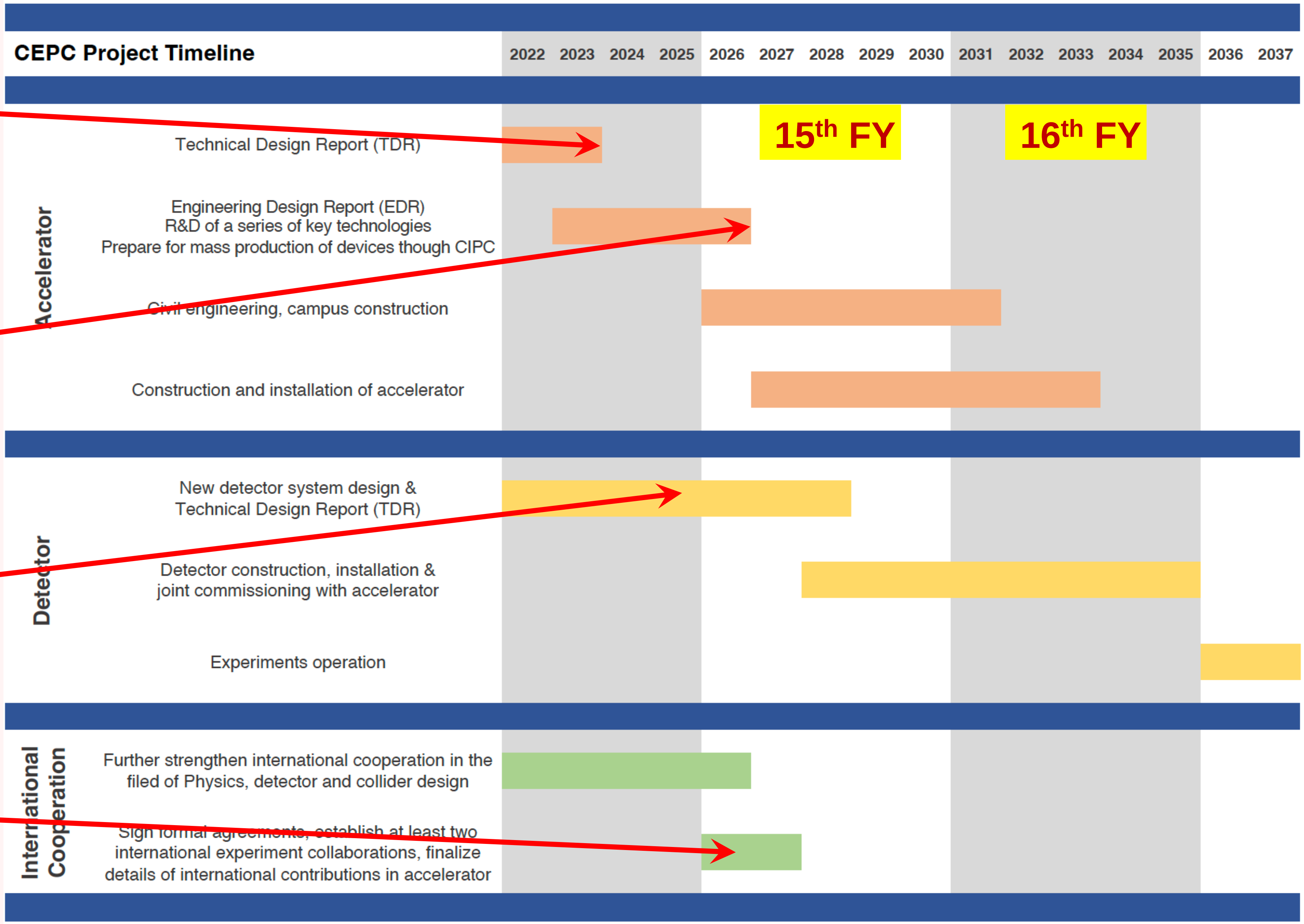
Ideal Timeline of CEPC

Completion of Accelerator TDR

Completion of Accelerator EDR

TDR of a Ref-Detector @ June 30, 2025

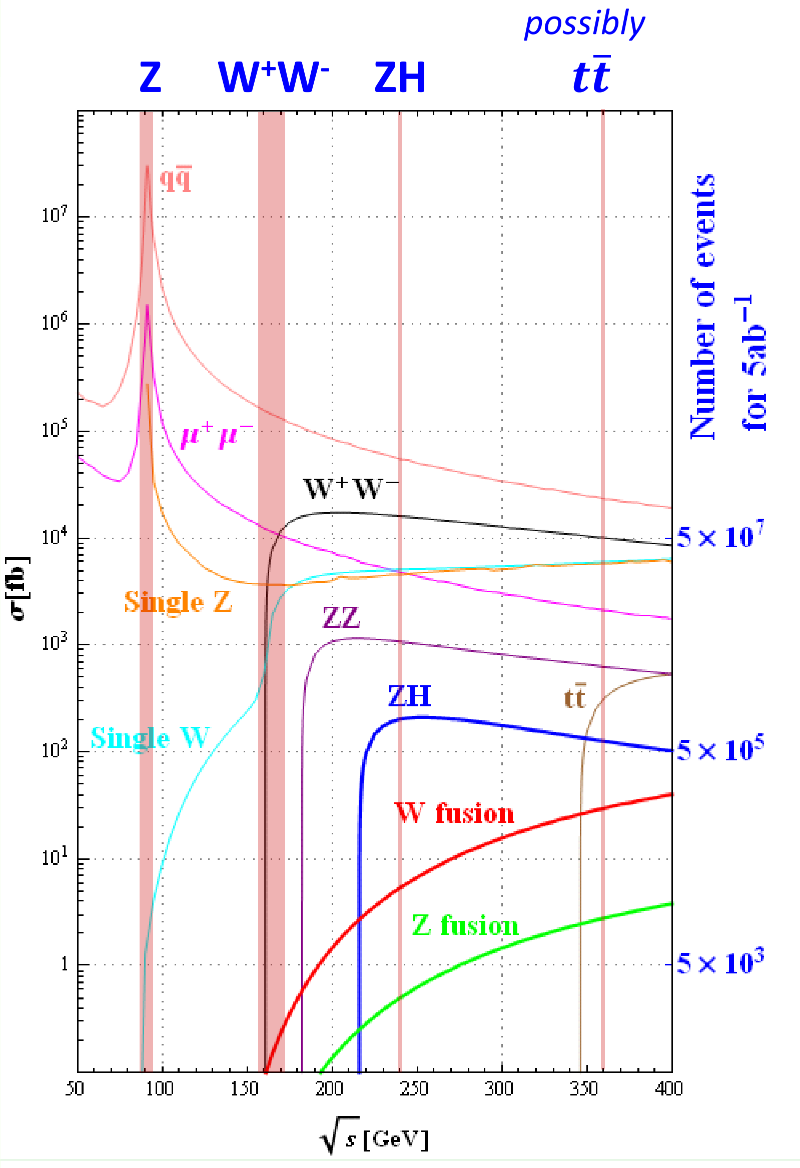
International Collaborations



TDR of A Reference CEPC Detector

- The Ref-TDR needs to be released in a timely fashion, by June 2025, hopefully to boost the chance to receive an official endorsement for the 15th FYP
- We treat it as a TDR of real detector system to be built very soon
  - Demonstrate the readiness and feasibility of detector technologies
  - Provide a realistic detector cost estimation
  - Assess requirements and availabilities of people power
- We are working on a TDR as a reference. When the two international collaborations are formed, they will deliver TDRs of two detectors for the real experiments.
- 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)

While aiming to have a detector that matches the needs of the whole energy range, we emphasize more on the Higgs operation mode.

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.

- Optimized to the CEPC base clock frequency of 43.3 MHz (or period = 23.1 ns).

- The system should be able to handle relevant event rates.
  - 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

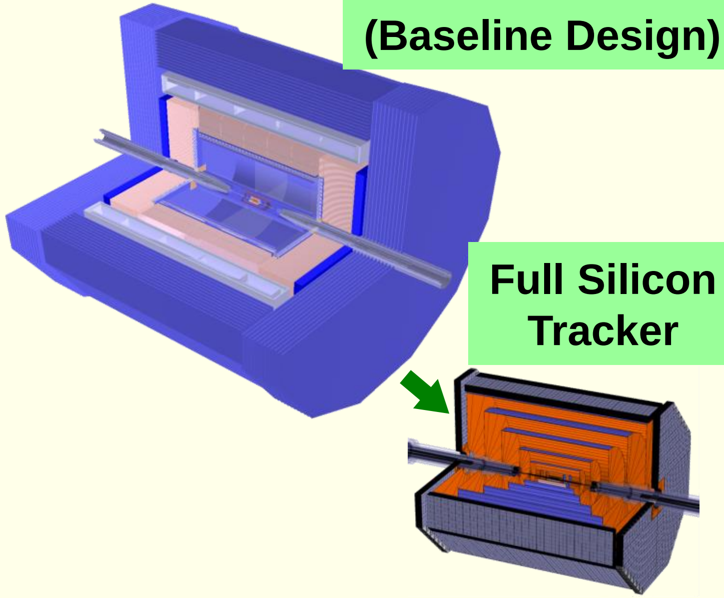
- The detectors can endure radiation damage and noise hit rates, accordingly.
  - According to very preliminary studies, in the Higgs mode at the Vertex detector:
    max noise hit rate ~ 0.6 MHz / cm^2, max TID ~2.1 Mrad/year
  - It is relatively friendly environment comparing to a hadron collider. Radiation resilience and noise hit rate should not be huge problems.

Detector Key Specifications

Sub-system	Key technology	Key Specifications
Vertex	6-layer CMOS SPD	$\sigma_{r\phi} \sim 3\ \mu m$, $X/X_0 < 0.15\%$ per layer
Tracking	CMOS SPD ITK, AC-LGAD SSD OTK, TPC + Vertex detector	$\sigma\left(\frac{1}{P_T}\right) \sim 2\times10^{-5} \oplus \frac{1\times10^{-3}}{P\times sin^{3/2}\theta}\left(GeV^{-1}\right)$
Particle ID	dN/dx measurements by TPC Time of flight by AC-LGAD SSD	Relative uncertainty ~ 3% $\sigma(t) \sim 30$ ps
EM calorimeter	High granularity crystal bar PFA calorimeter	EM resolution ~ $3\%/\sqrt{E(GeV)}$ Granularity ~ $1\times1\times2\ cm^3$
Hadron calorimeter	Scintillation glass PFA hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(GeV)}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(GeV)}$

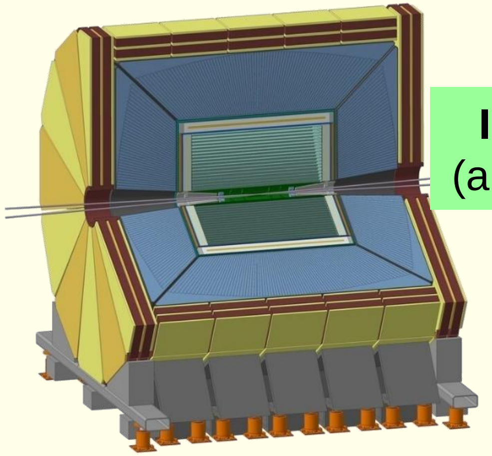
- ❖ Design of the CEPC detector evolves with the R&D progressing and our better understanding of the physics reach.
- ❖ The key specifications continue to be optimized.

Conceptual Detector Designs



(Baseline Design)

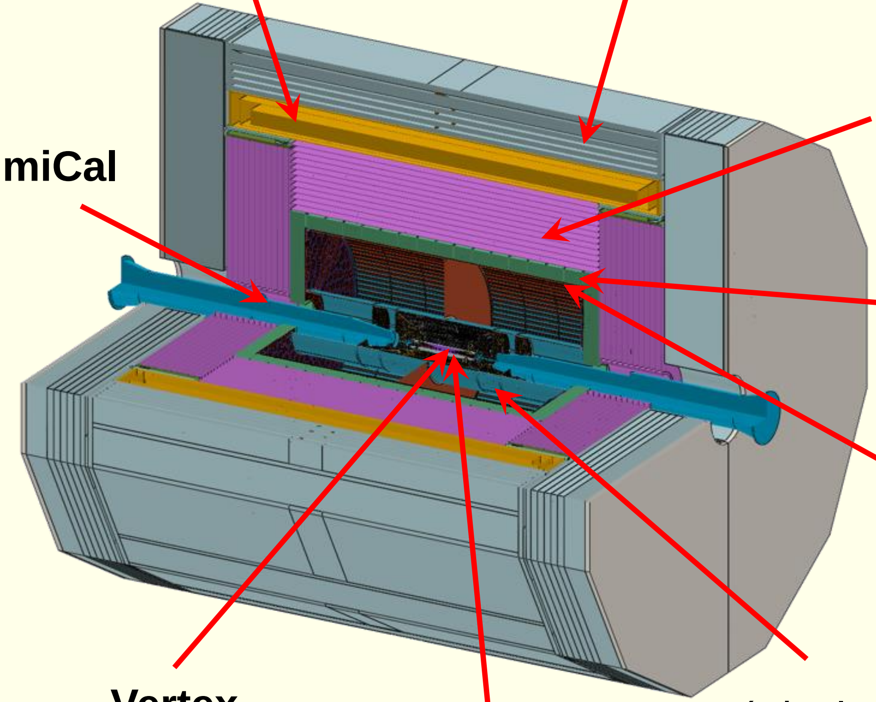
Full Silicon Tracker



IDEA concept
(also for FCC-ee)

The 4th Concept

Ref-TDR is based on this configuration



SC Magnet
(3T/2T)

Yoke +
Muon (PS+SiPM)

PFA HCAL
(Scintillation Glass)

LumiCal

Crystal **PFA ECAL**
(Transverse bar)

OTK
(AC-LGAD)

TPC
(Pixelated readout)

Vertex
(MAPS SiPixel)

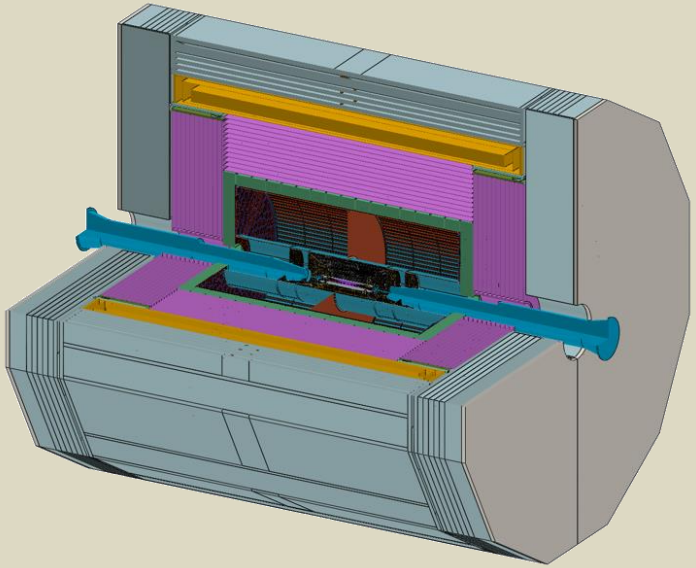
ITK
(MAPS SiPixel)

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

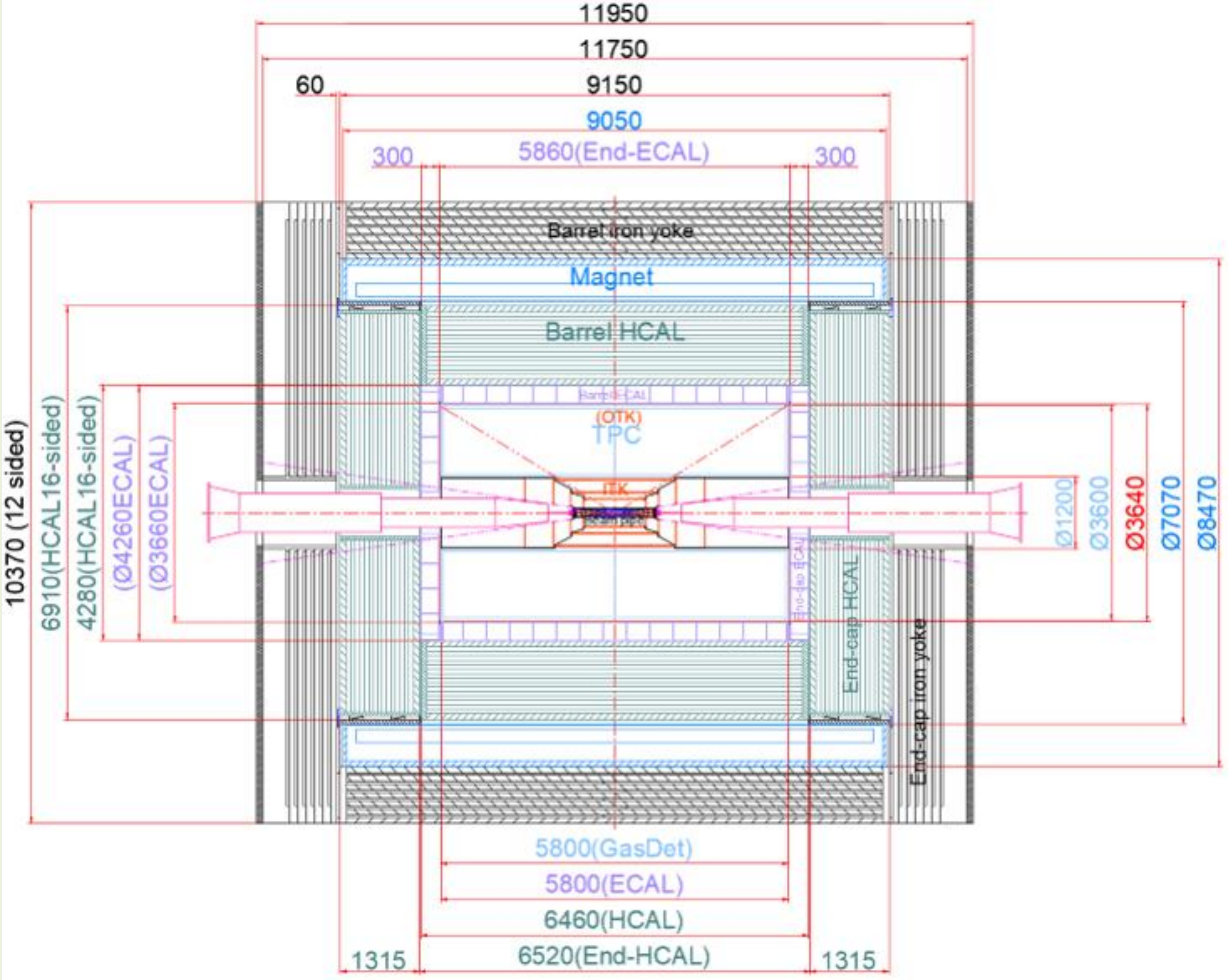
Radius

- The CEPC study group started to compare different technologies in January, 2024
- By the end of June, 2024 the baseline technologies were chosen.
- 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

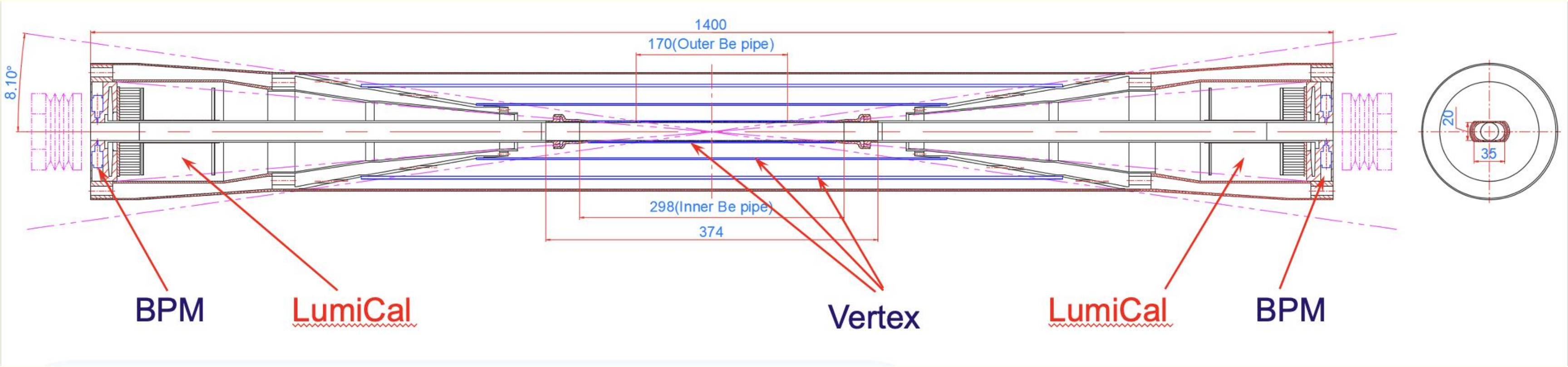
Geometry and Mechanical Support

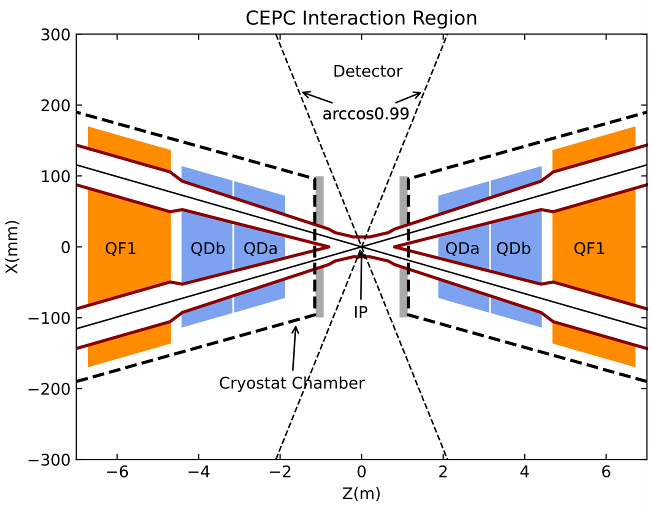


Subsystem	Supported By
Barrel Yoke	Base
Magnet	Barrel Yoke
Barrel HCAL	Barrel Yoke
Barrel ECAL	Barrel HCAL
TPC+ Barrel OTK	Barrel ECAL
ITK	TPC
Beampipe+VTX+LumiCal	ITK
Endcap Yoke	Base
Endcap HCAL	Barrel HCAL
Endcap ECAL+OTK	Barrel HCAL

Planning: detector installation, order of mechanical support, layout of the experimental hall

MDI, Beam Background and LumiCal

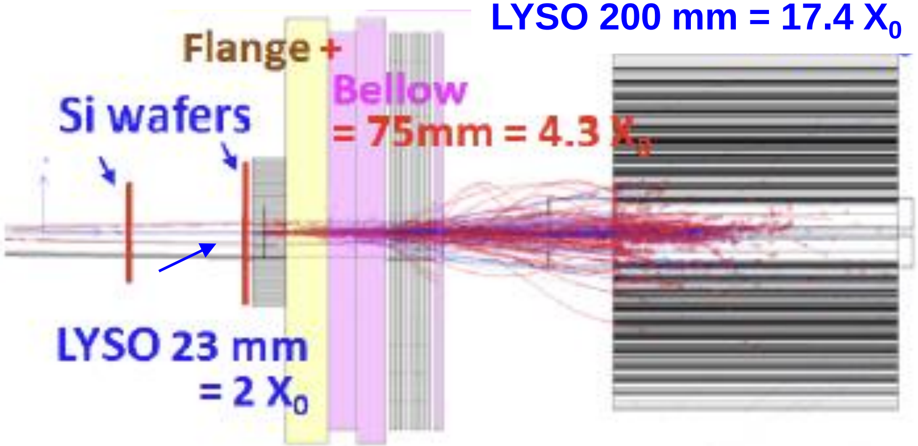




- ☐ Design of the CEPC interaction region, beam pipe and LumiCal
- ☐ Preliminary estimate of beam-induced background, taking into account the collimators and shielding. The worst point at Vertex detector ~2.1 Mrad/year in Higgs mode
- ☐ LYSO bar and SPD based LumiCal design for a 10^{-4} luminosity precision, yet to be validated.

LumiCAL

SiPixDet ×2 + LYSO bars 3×3×(23+200) mm^3

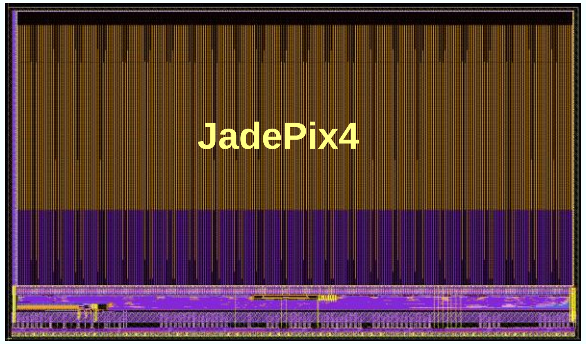


Z= 560-700 **900 - 1100 mm**

Silicon Pixel Vertex Detector

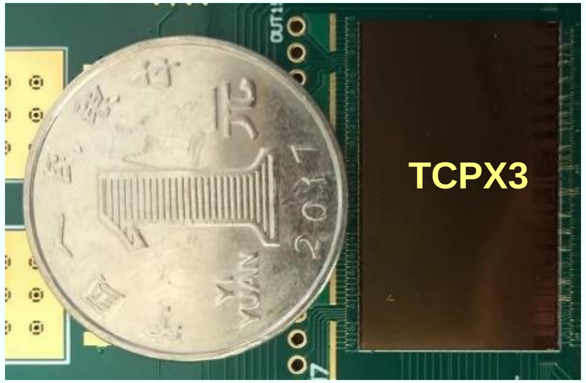
356×498 pixels of 20×29 μm^2

$\sigma_{x/y}$ ~ 3-4 μm, σ_t ~1 μs, ~0.1 W/cm^2



TaichuPix3

1024×512 array of 25×25 μm^2



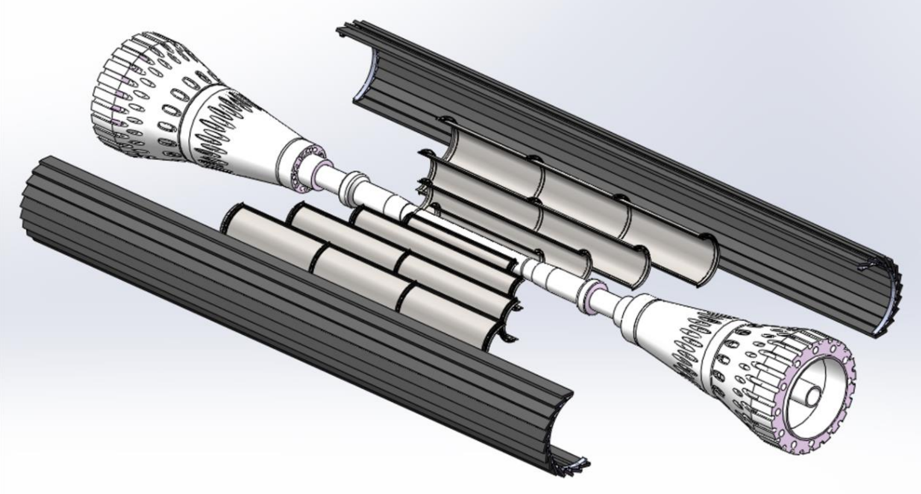
TowerJazz 180nm CIS process

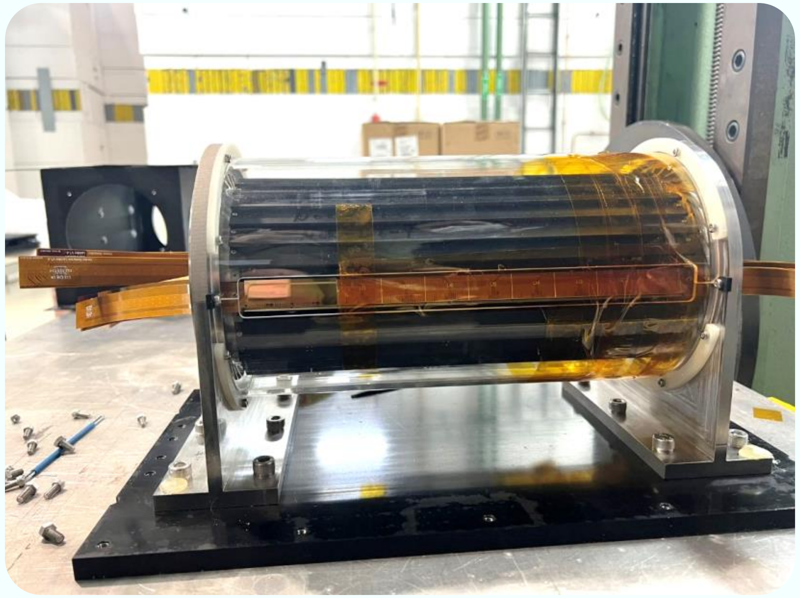
Goal: σ(IP) ~ 5 μm for high P

Key specifications:

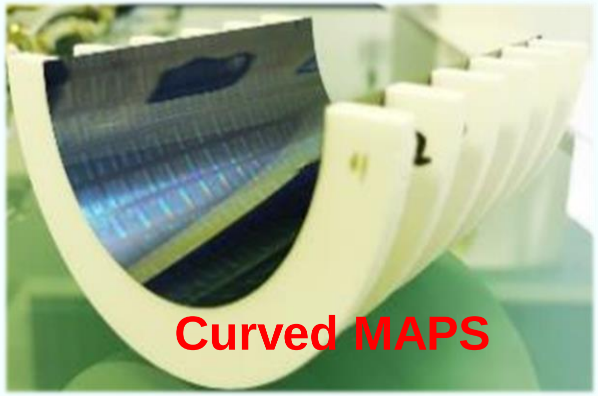
- Single point resolution ~ 3 μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm^2)
- Radiation hard (1 Mrad/year)

Look into stitching + curved MAPS for less material and easier cooling



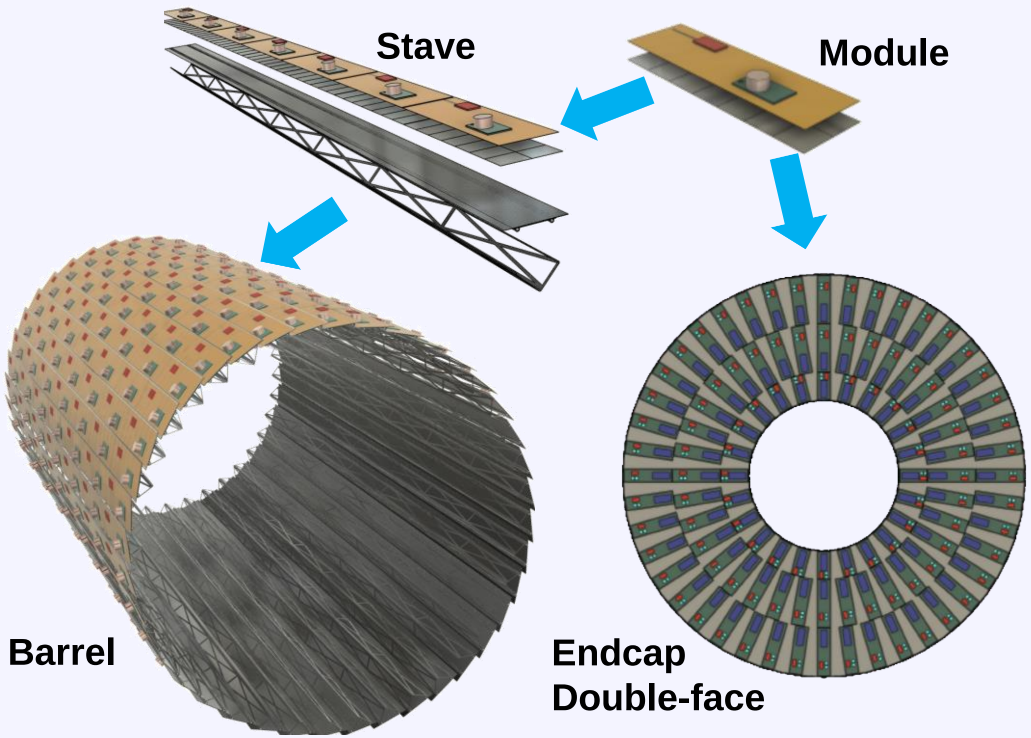


A TaichuPix-based prototype detector was tested at DESY in 2023. SP resolution ~4.9 μm. Thermal and material properties need further improvement.

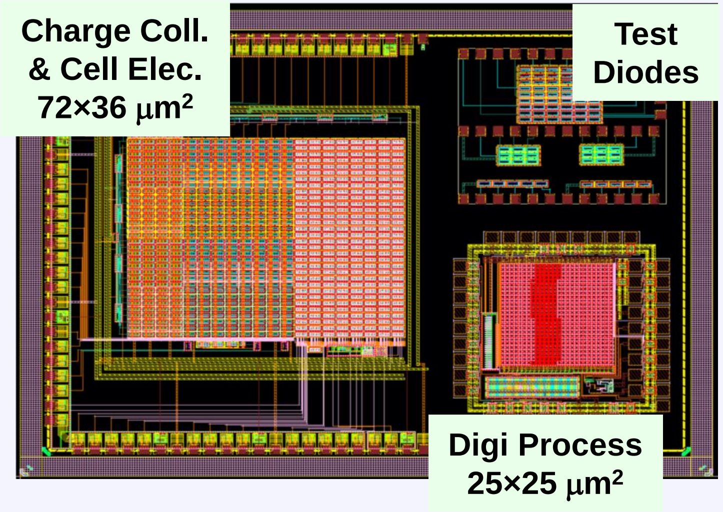


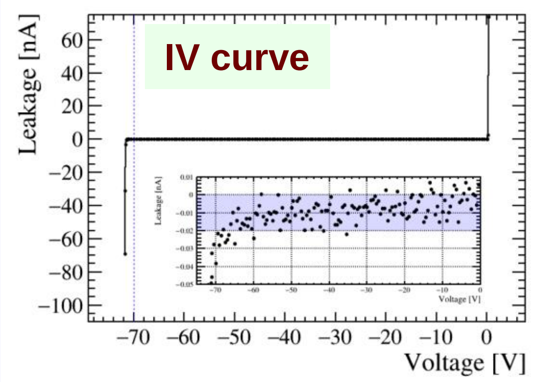
Silicon Pixel Inner Tracker

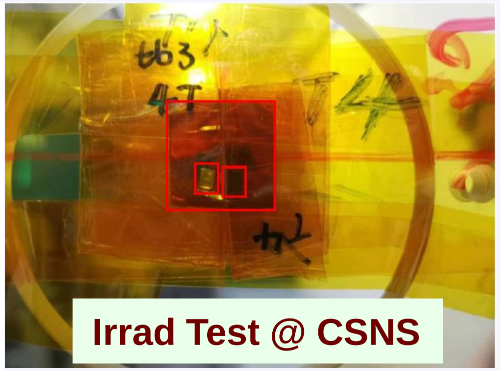
- ☐ Focus on HV-CMOS pixel detector of ~15-20 m^2.
- ☐ Exploring SMIC 55 nm and other processes
  - COFFEE2 chip: V_{bd} ~ 70V, C(1 pixel) ~ 30-40 fF, $I_{Leakage}$ ~10 pA→1 nA after $10^{14}\ n_{eq}/cm^2$ irradiation, response to laser and rad source
  - New MPW submission next spring
- ☐ Overall detector design based on typical chip size

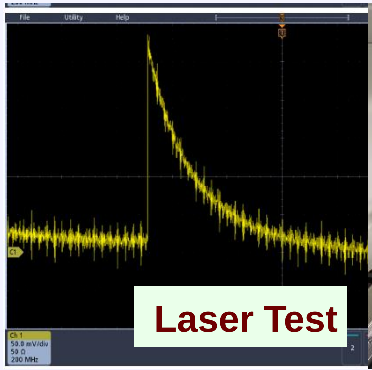


SMIC 55 nm, COFFEE chip



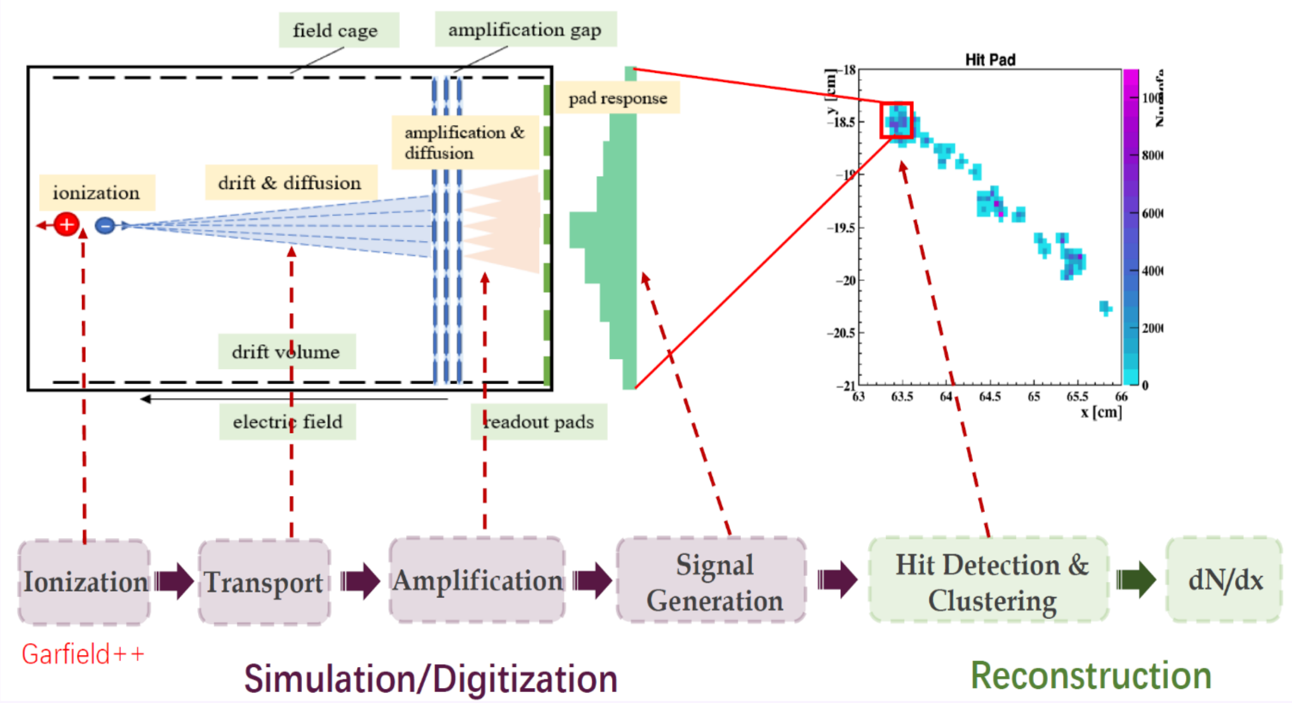


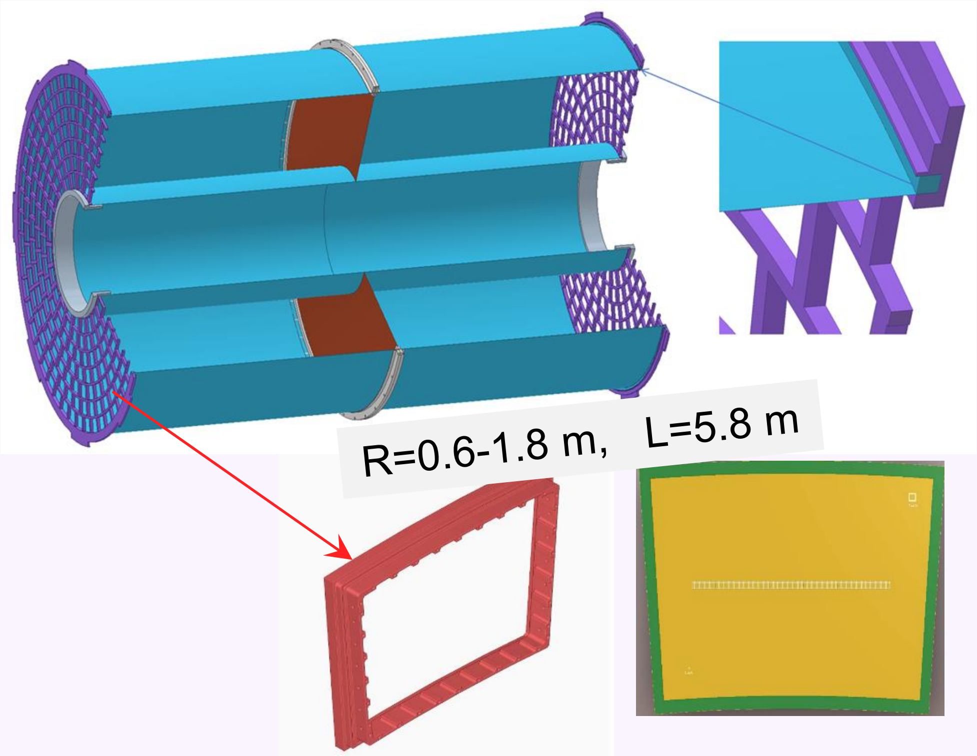




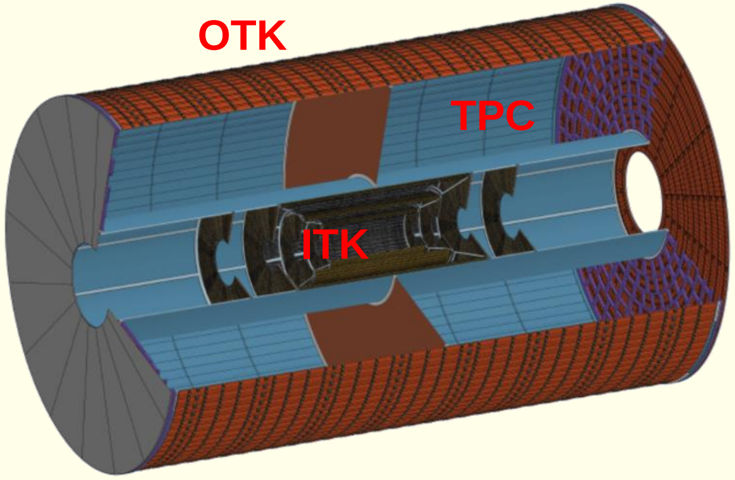
Pixelated TPC

- Initial TPC design has difficulty at high luminosity Z pole due to IBF
- A pixelated TPC of (500 μm)^2 readout pad size could reduce IBF×Gain ~1 @ G=2000, achieves σ(r-Φ) ~100 μm. Optimization of the pad size is in on-going.
- 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.
- Plan to have a test beam this fall to assess the performance and validate the design

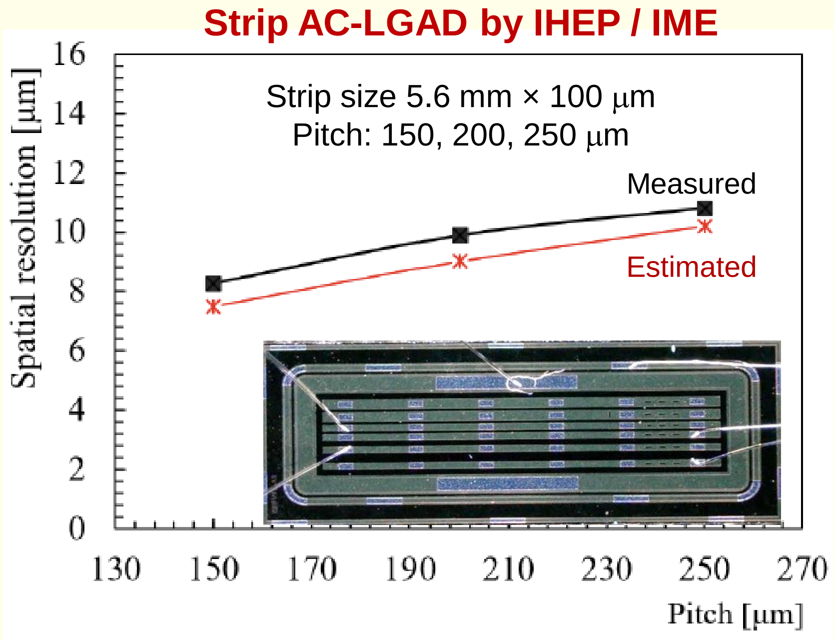




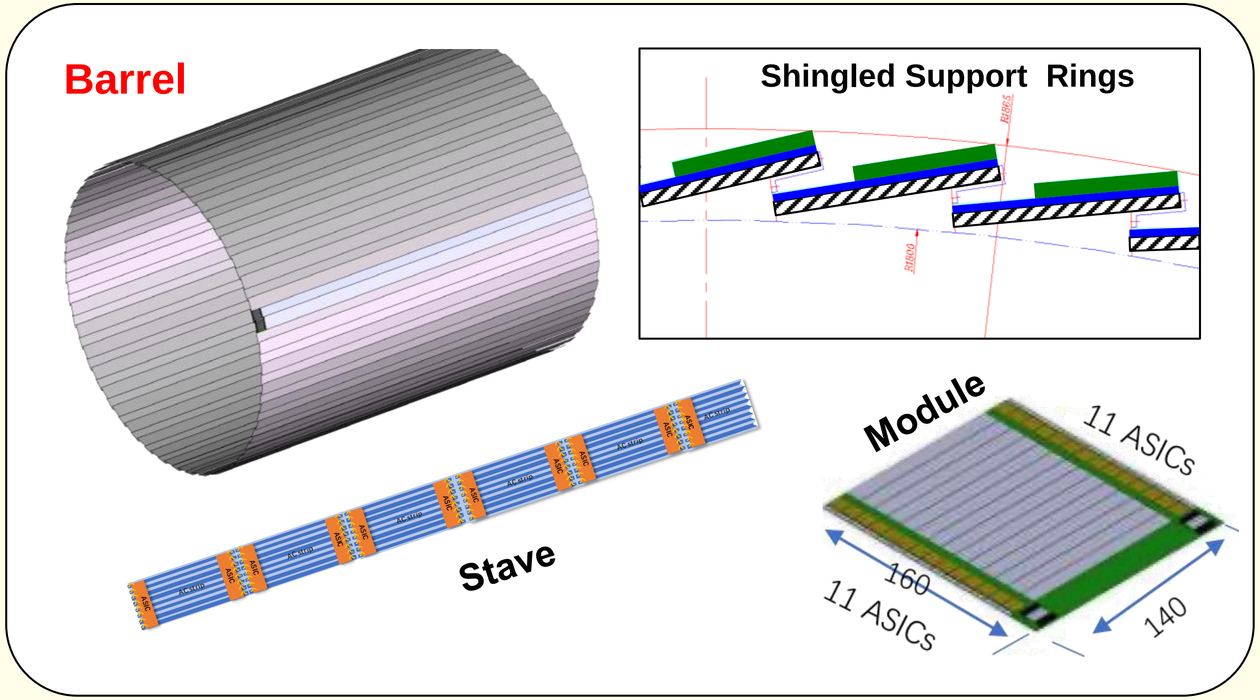
AC-LGAD OTK (Time Tracker)

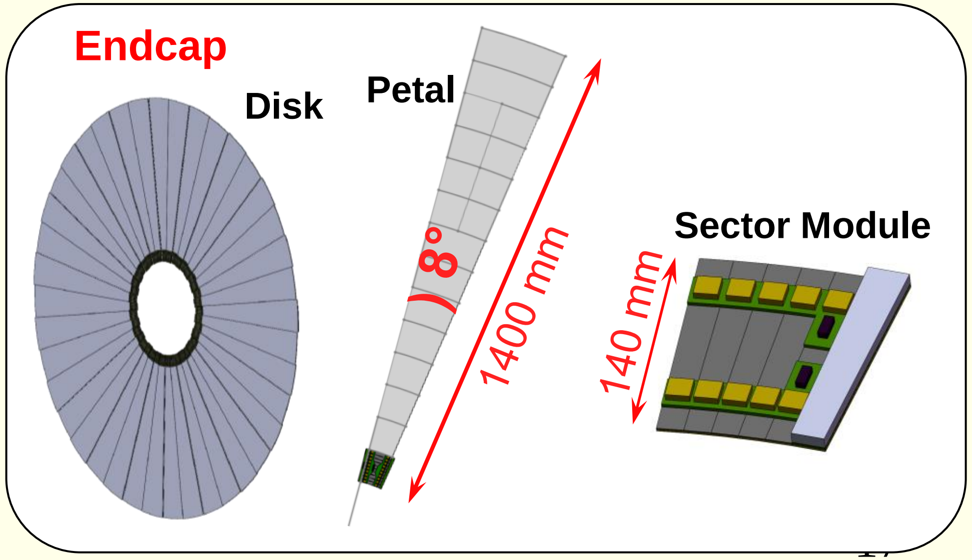


- The outer silicon tracker ~ 85 m^2, the Z precision is not crucial
  ⇒ Cost-effective SSD
- A supplemental PID at low energy
  ⇒ LGAD ToF
- An AC-LGAD Time Tracker combines the two needs in one detector. We expect σ_t ~30 ps, $\sigma_{R\Phi}$ ~10 μm
- Need to validate with full size sensors


Strip AC-LGAD by IHEP / IME

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

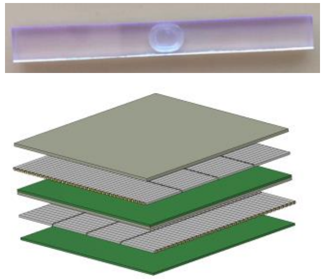


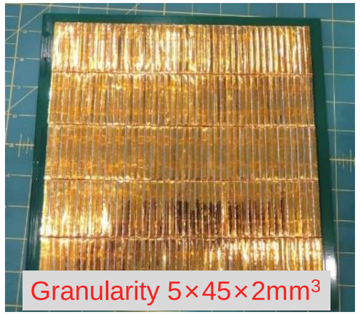


Prototype PFA Calorimeters

- ☐ 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)

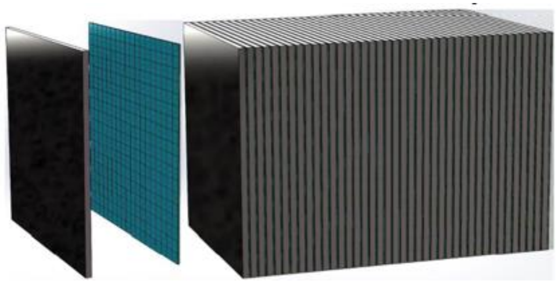
ECAL: scintillator(strip)+SiPM, CuW

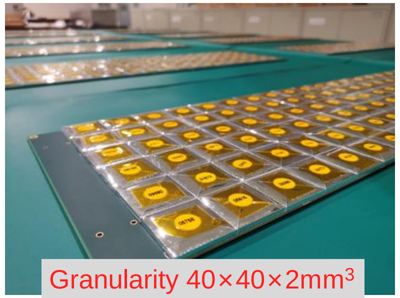




Granularity 5×45×2mm^3

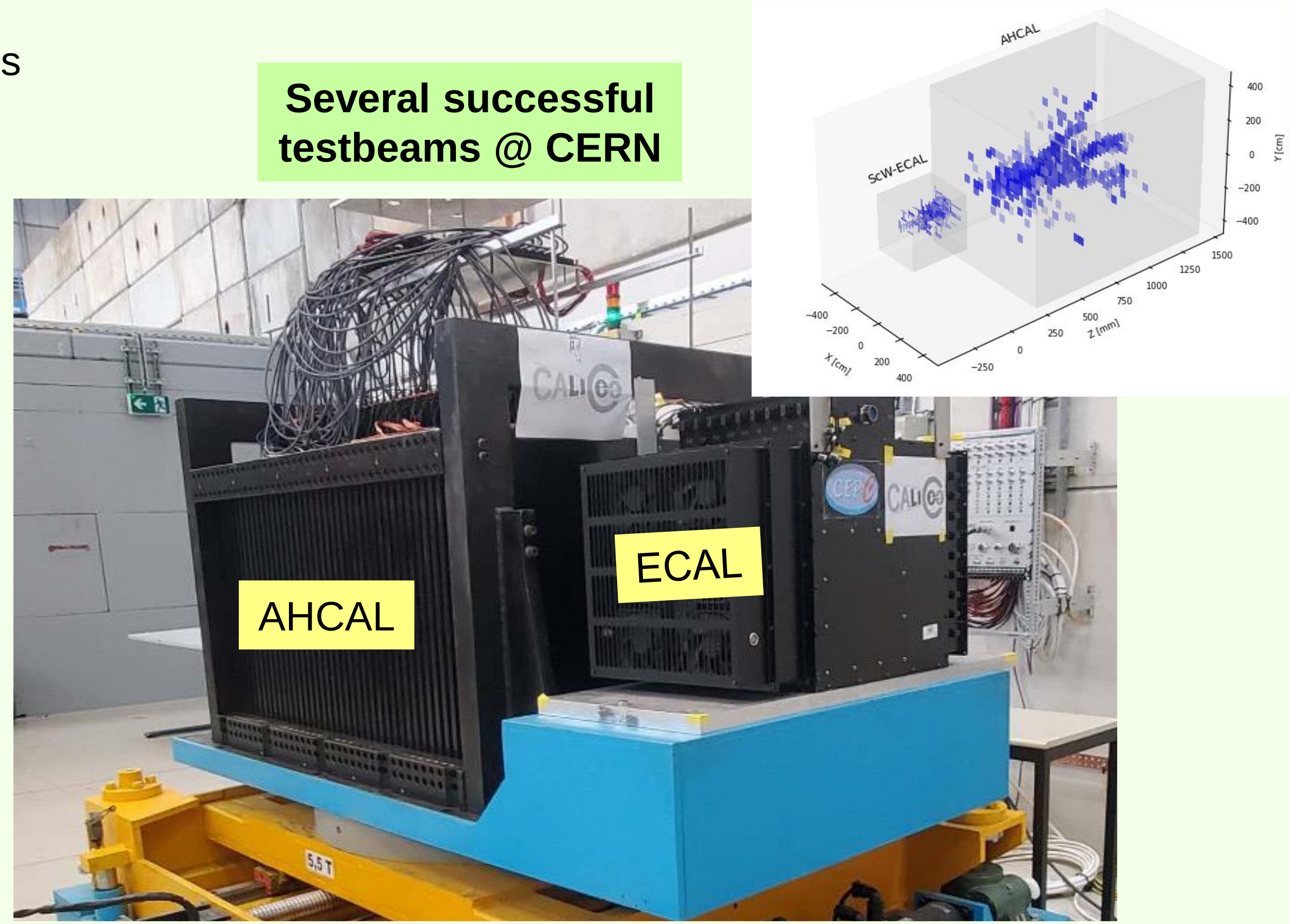
HCAL: scintillator (tile)+SiPM, steel





Granularity 40×40×2mm^3

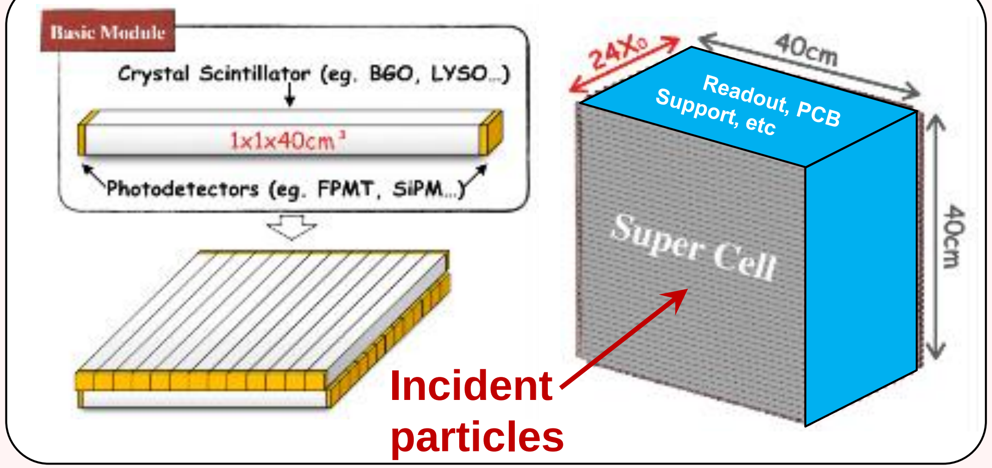
Several successful testbeams @ CERN

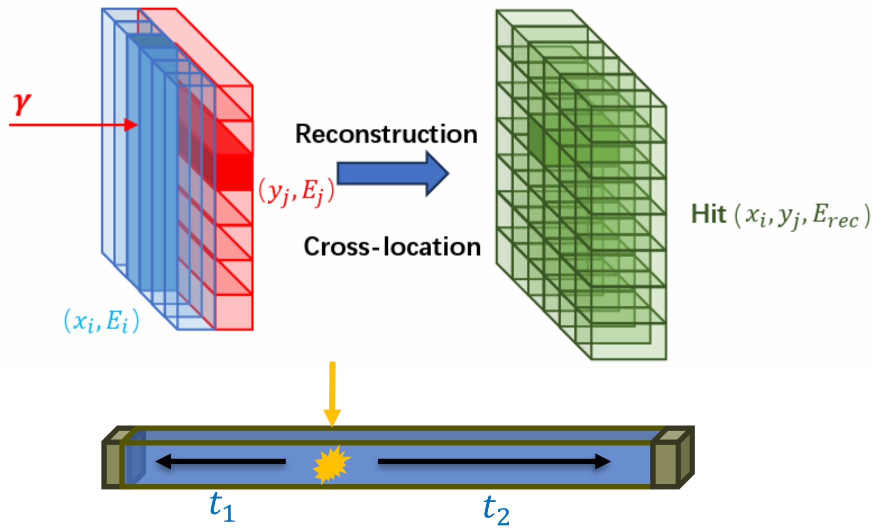


Prototypes developed within **CALICE**

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

Crystal Bar EM Calorimeter

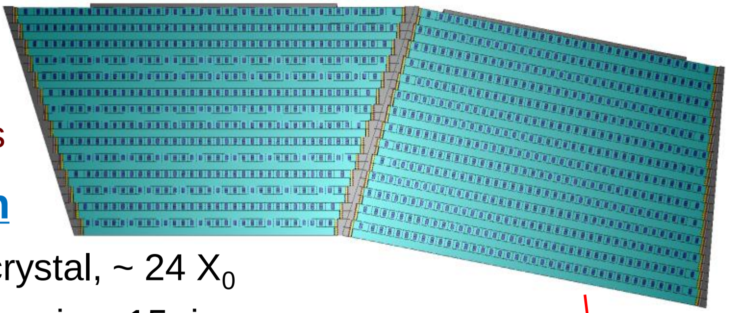




Achieve effective granularity 1×1×2 cm^3

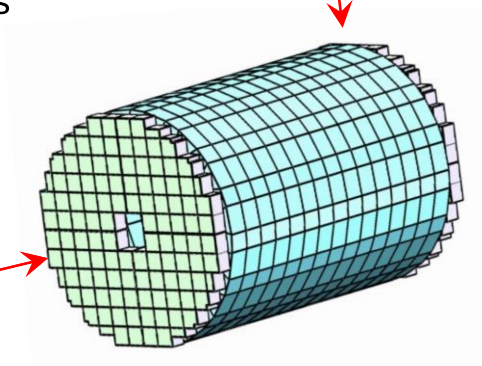
- Compatible to PFA: Boson mass resolution BMR(H→jj) < 4%
- Optimal EM performance: $\sigma_E/E < 3\%/\sqrt{E}$, BMR(H→γγ) ~ 0.6 GeV
- Save readout channels, minimize dead materials
- Challenging in pattern recognitions with multiple particles

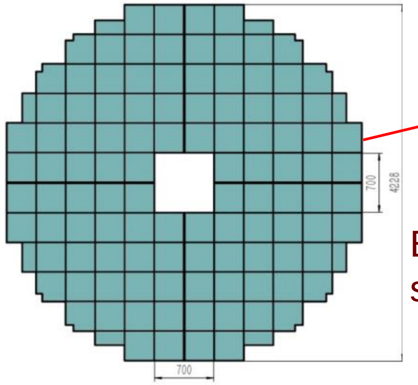
Cylindrical barrel with alternately arranged trapezoidal supercells



Preliminary design

- 27 layers of BGO crystal, ~ 24 X_0
- Barrel: 32 towers per ring, 15 rings
- Endcap: 2×117 towers
- Total ~ 720 k crystals

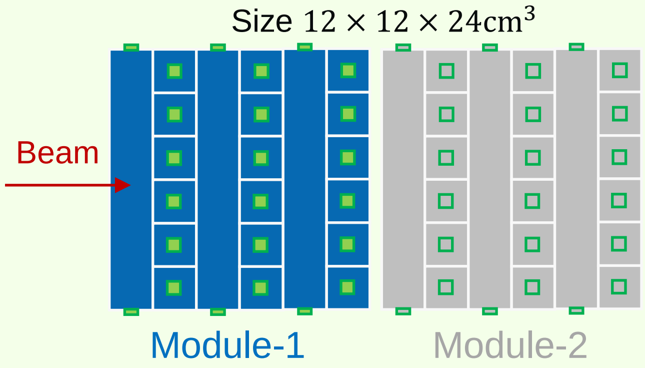


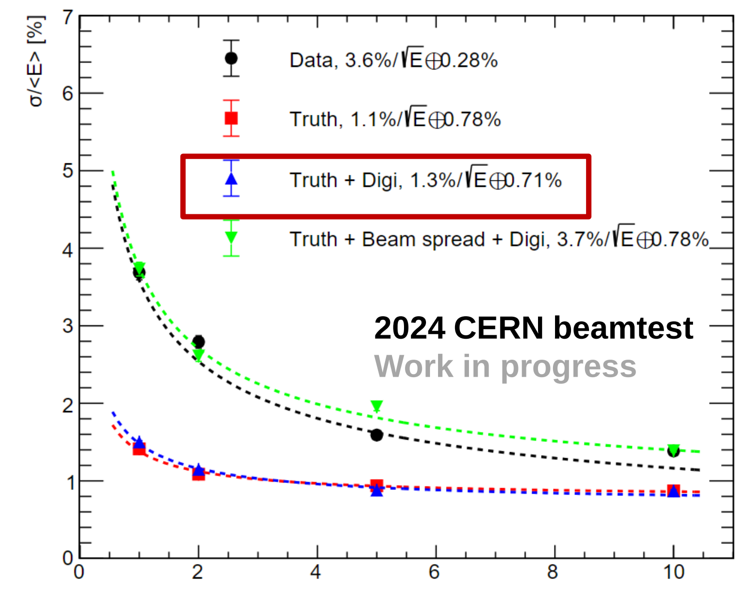


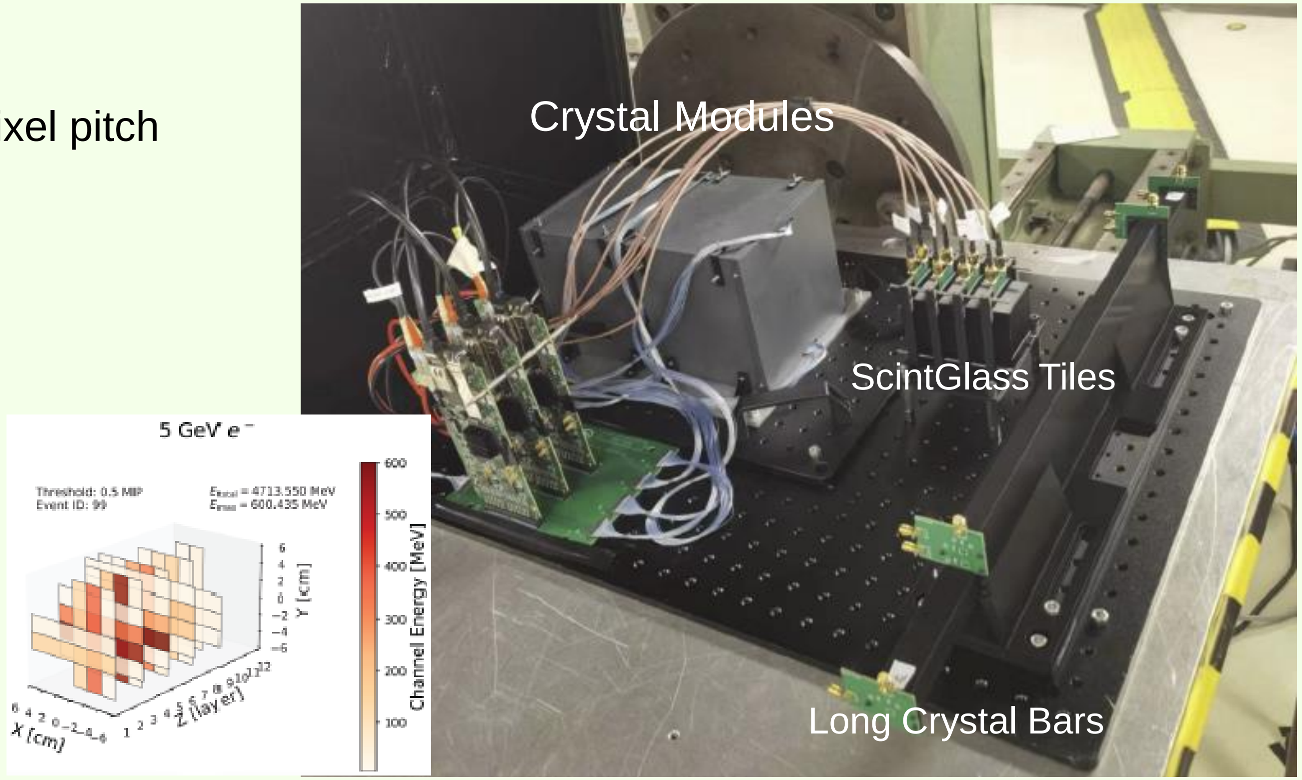
Endcap disc of square towers

Testbeam of Prototype Crystal ECAL

- Successful testbeam @ DESY, CERN, 2023-2024 with small prototype
  - 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 size prototype will be constructed
- Module development
  - BGO crystal bars from SIC-CAS
  - SiPM: 3×3 mm² sensitve area, 10µm pixel pitch



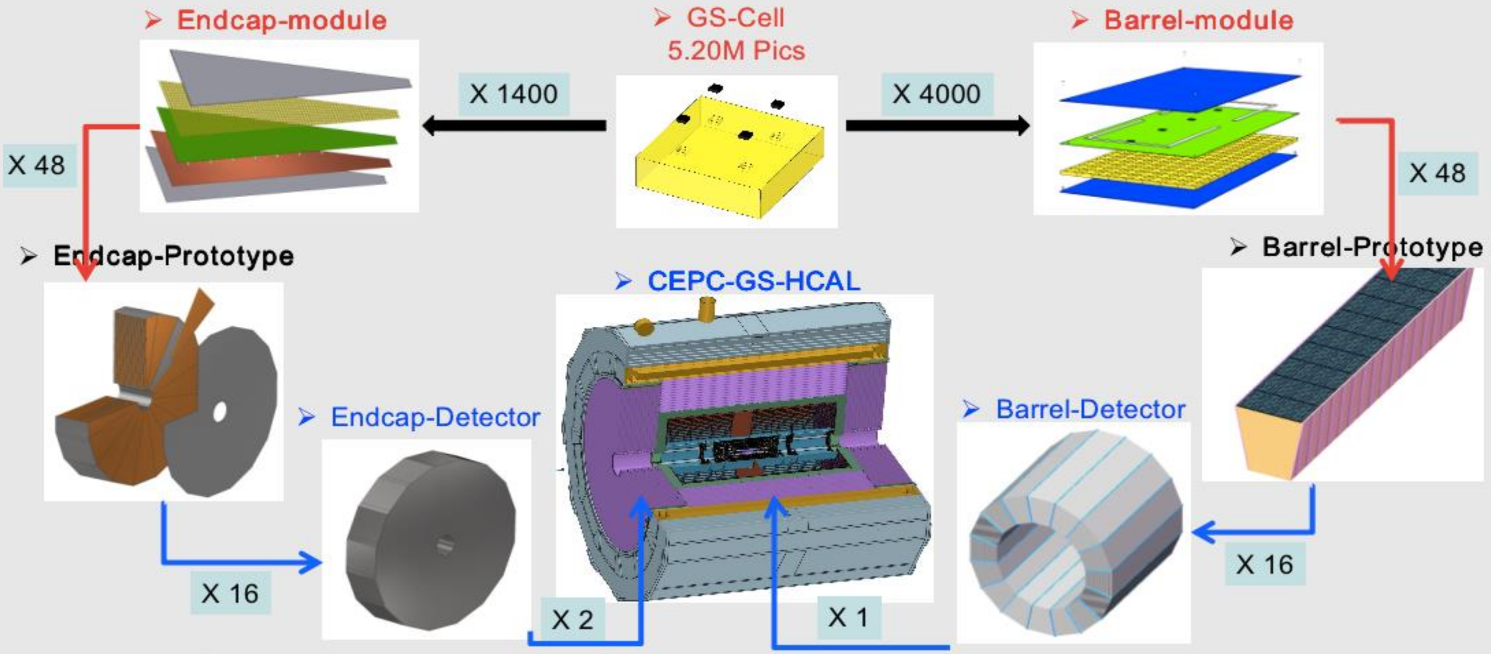


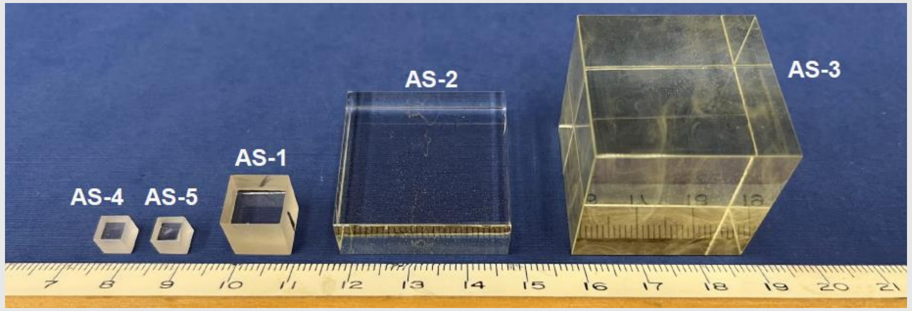


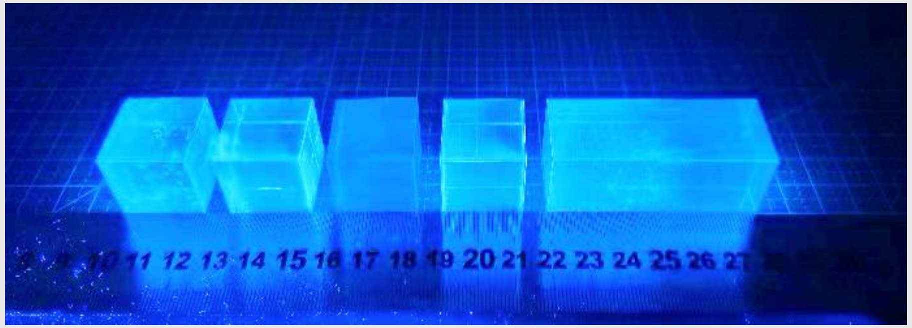
Glass Scintillator HCAL

- 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

Parameters	Unit	Goal	BGO	GS1	GS1+	GS5
Density	g/cm^3	6	7.13	6.0	6.0	5.9
Rad. Length, X_0	cm		1.12	1.59	1.60	1.61
Transmittance	%		82	70	80	80
Refractive Index	--		2.1	1.74	1.71	1.75
Emission Peak	nm		480	400	390	390
Light Yield, LY	ph/MeV	1000	8000	985	2445	1154
Energy Resol, ER	%		9.5	30.3	25.8	25.4
Decay time	ns	~100	60, 300	36, 105	101, 1456	90, 300

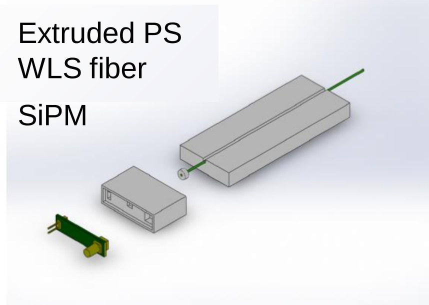


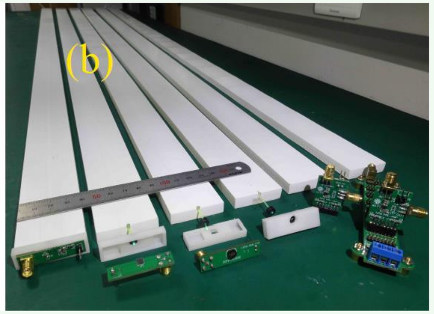


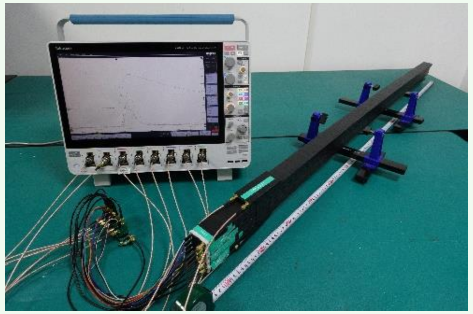


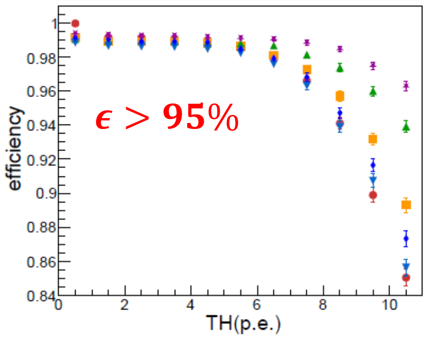
Muon Detector

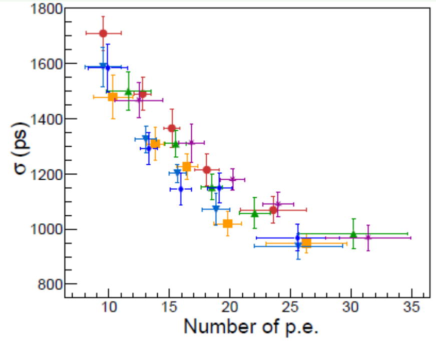
- Use extruded plastic scintillator technology, provide Muon ID (P>4 GeV)
- The magnet return yoke is used as muon absorber
- Solid angle coverage: 0.98 × 4π, total detection area ~ 4500 m^2, ~40k channels
- To build a prototype detector, measure performance, and validate the design

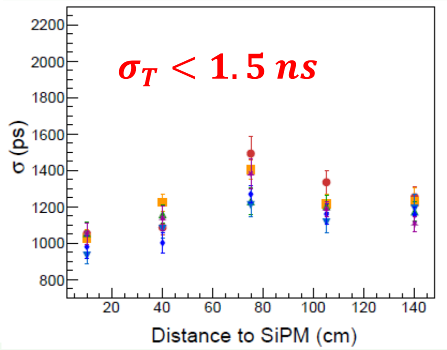


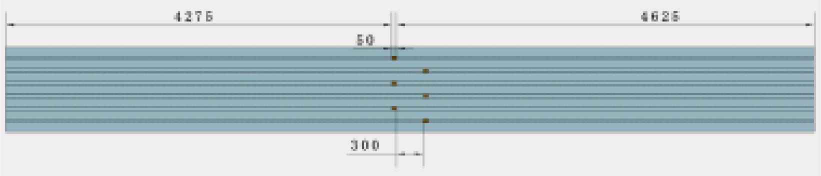




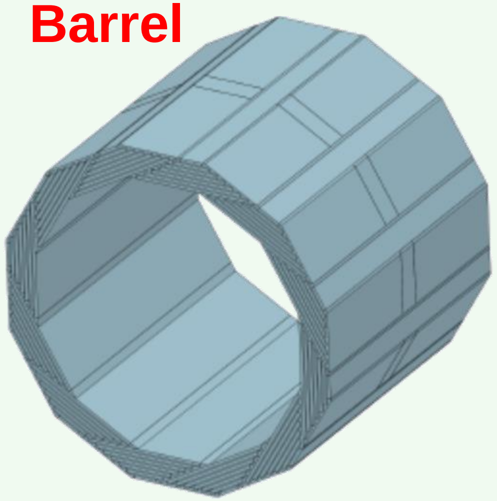


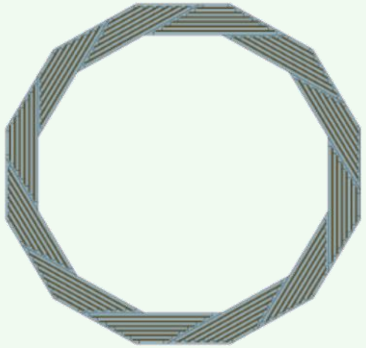




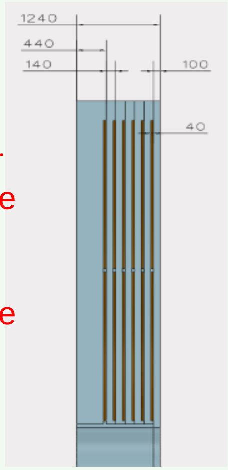


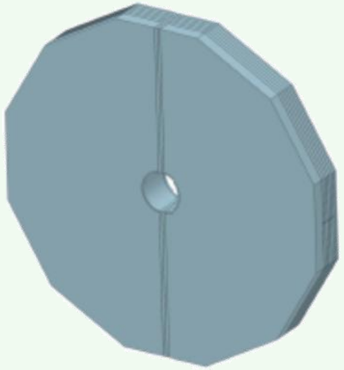
Barrel

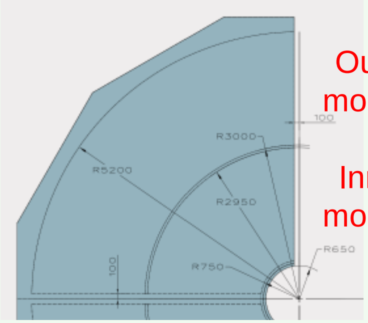




reversed trapezoidal shape to form a spiral dodecagon







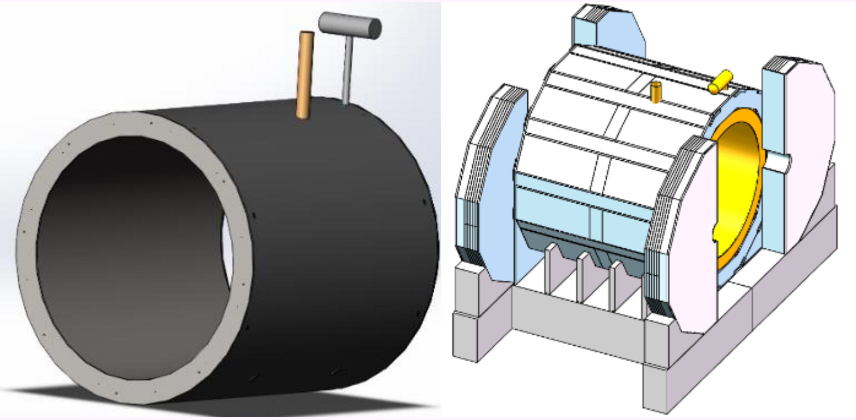
Outer module

Inner module

Endcap

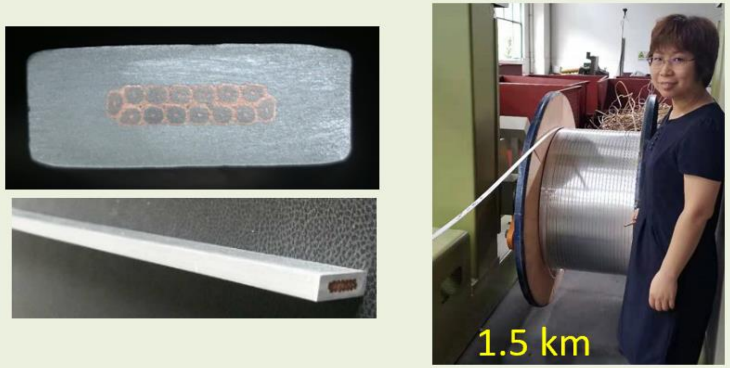
SC Solenoid Magnet

Central B field	3 T
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

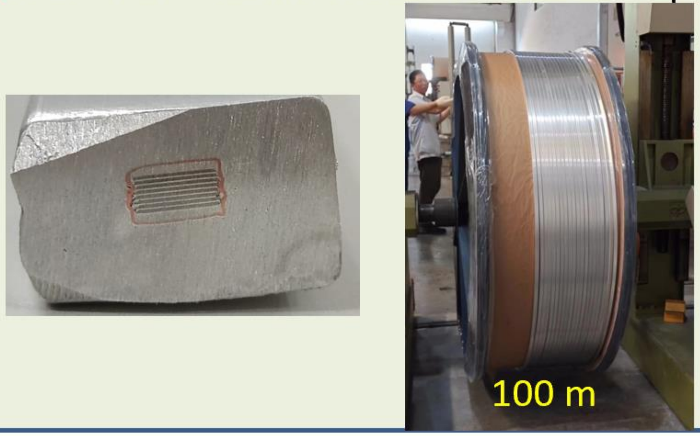


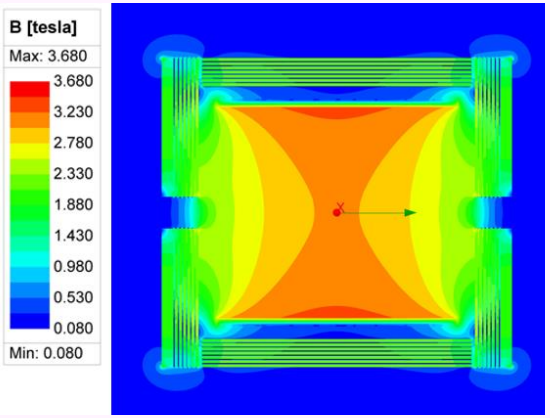
- Optimizing the baseline LTS design for better uniformity, thinner space, and cost-effectiveness.
- R&D on HTS cable continues

LTS: Aluminum stabilized NbTi Rutherford cable

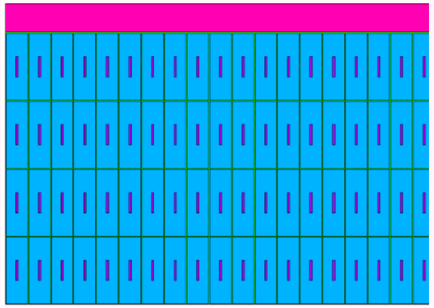


HTS: Aluminum stabilized Stacked REBCO Tape Cable

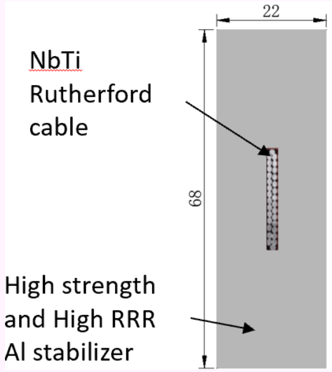




Magnetic field simulation

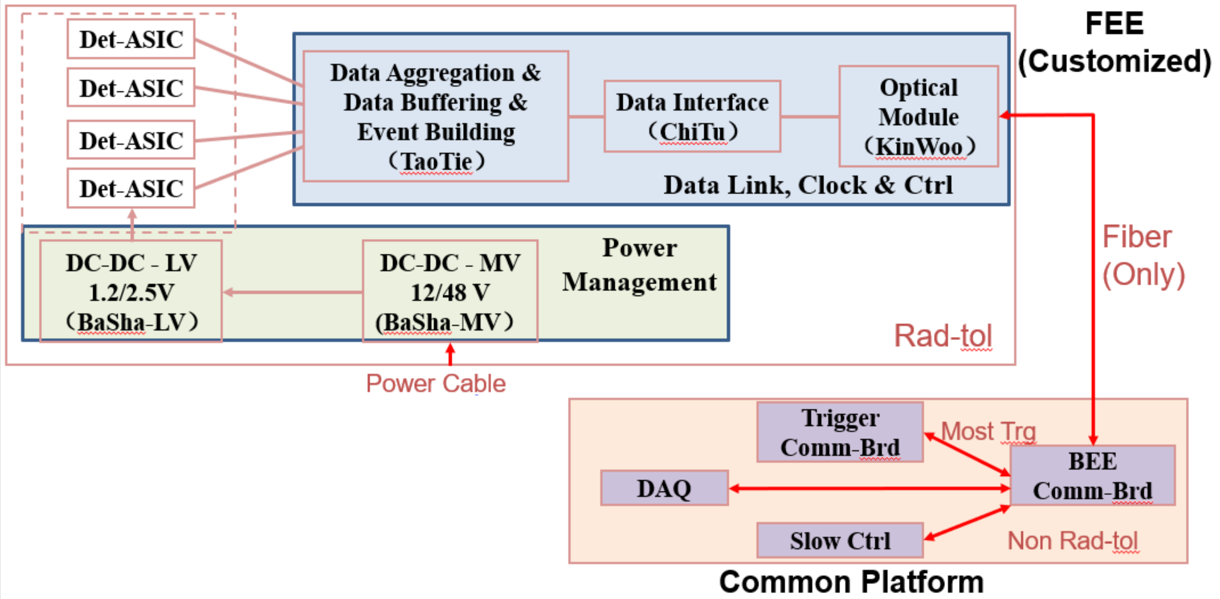


Coil structure

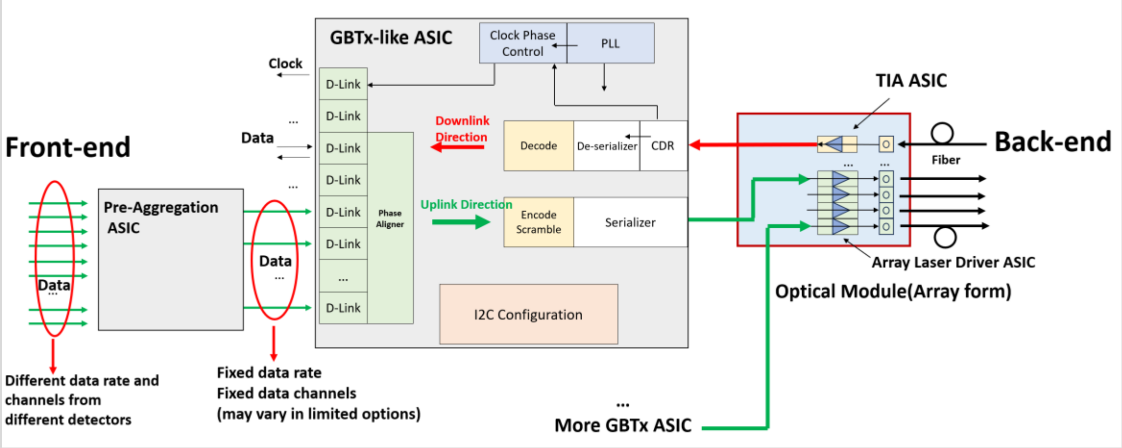


Cable structure

Electronics and TDAQ

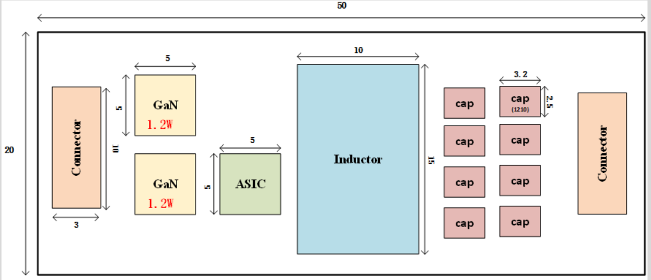


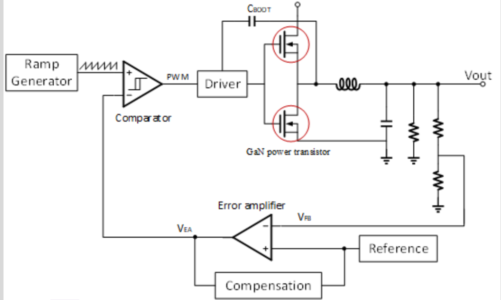
Common Platform



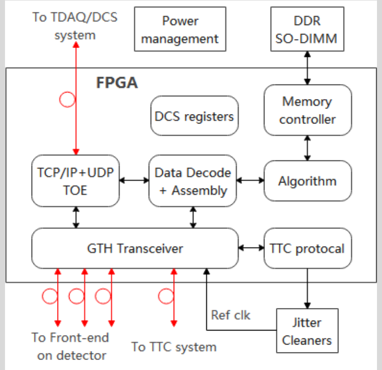
饕餮-TaoTie **赤兔-ChiTu** **金乌-KinWoo**

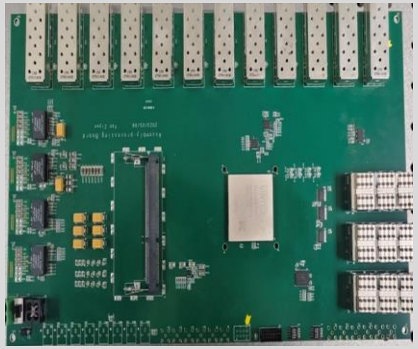
Common Data Link Structure





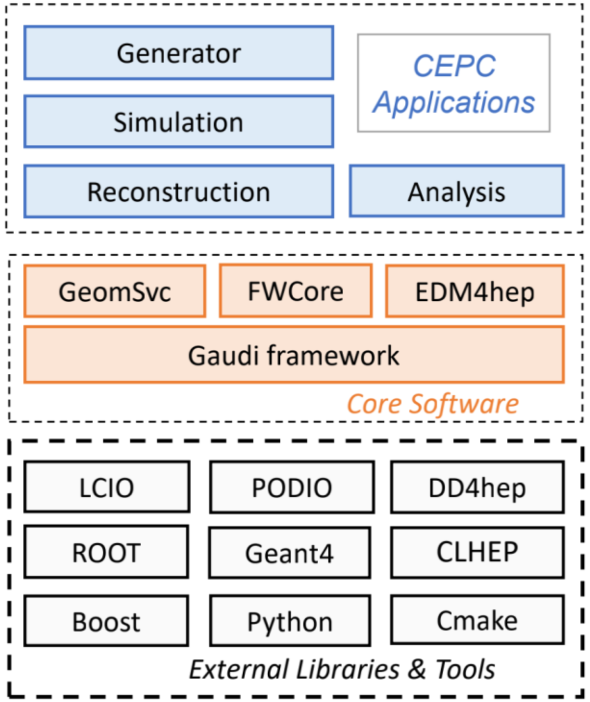
Common Powering Module （霸下BaSha）





- 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.

CEPC Software



Generator

Simulation

Reconstruction

CEPC Applications

Analysis

GeomSvc

FWCore

EDM4hep

Gaudi framework

Core Software

LCIO

PODIO

DD4hep

ROOT

Geant4

CLHEP

Boost

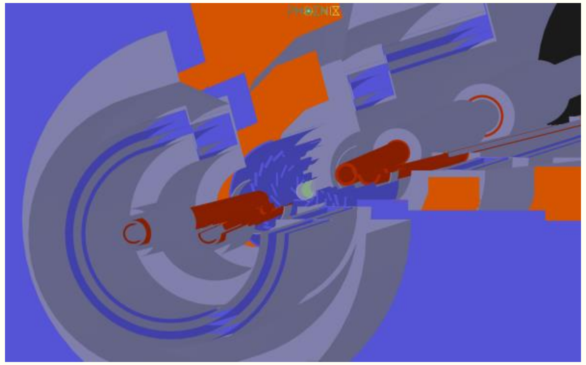
Python

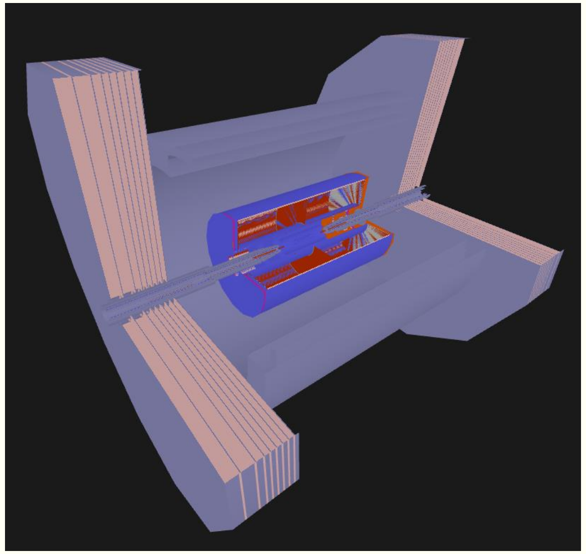
Cmake

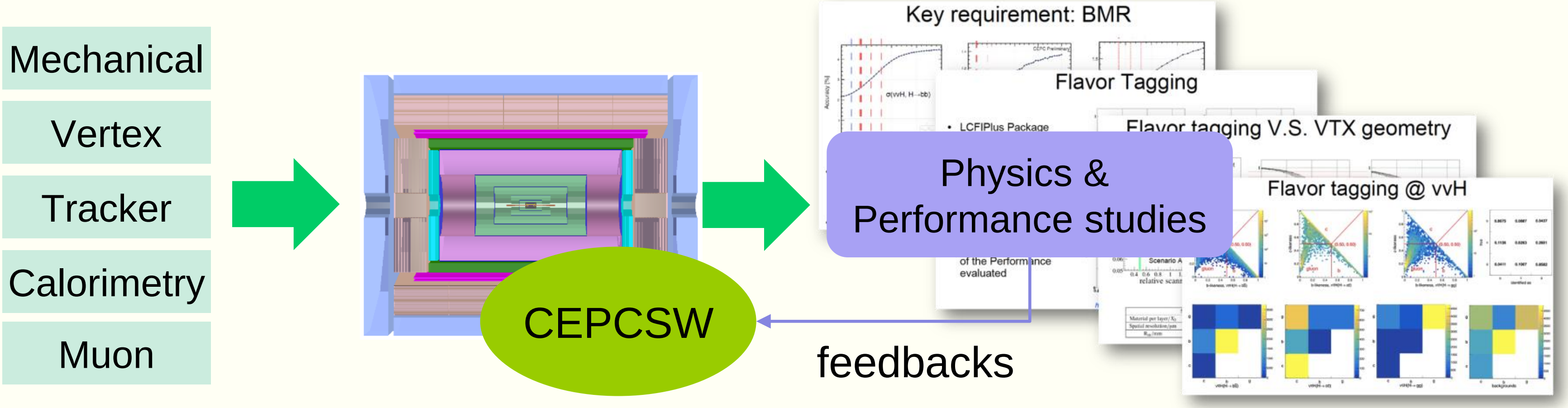
External Libraries & Tools

- **CEPCSW** is developed based on components of Key4hep: Gaudi, EDM4hep, K4FWCore DD4hep
- Web-based **Phoenix** tool for visualization
- Several releases in the past few months, aiming to meet the requirements of the RefTDR
- Use as close as possible the full simulation
- Evaluation of physics performance also provides feedbacks to the CEPCSW

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







Mechanical

Vertex

Tracker

Calorimetry

Muon

CEPCSW

Physics & Performance studies

feedbacks

R&D Teams on CEPC Detector

- ❑ Researchers from ~**35** major domestic research institutes actively participate in the CEPC detector R&D projects. More are joining while the projects progressing and funding support increasing.
- ❑ About **90** staff members from IHEP are working on the CEPC detector and physics, and close to **200** from other institutes.

- ❑ Many of them were key members in building major China-based successful experiments: BES, DayaBay, JUNO, LHAASO, …
- ❑ Some take fast rising roles in major experiments abroad: ATLAS, CMS, LHCb, ALICE, AMS, …
- ❑ JUNO will switch to operation mode soon. More researchers, especially engineers, will shift their focus onto CEPC.

- ❑ International participations **(~20** institutes) in subdetector R&Ds, e.g. MAPS detector, TPC, PID Drift chamber, …
- ❑ When the CEPC receives official endorsement, more international teams will join and propose detector design ideas, and eventually form two international collaborations.

International Collaborative Efforts

- The CEPC detector design incorporates experience from other future Higgs factory proposals, e.g. ILD.

- International detector R&Ds
  - Some detector R&D efforts were within the international detector R&D collaborations, e.g. CALICE, LCTPC, & RD*
  - Much broader participation in 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	**1, 6**	Mechanical and Integration	***(8)***
Outer Silicon Tracker	**3**	Machine Detector Interface	***(8)***	General Electronics	***(7)***
Gas Tracker	**1 (TPC/DC)**	Luminosity Calorimeter		Trigger and DAQ	***(7)***
Muon Detector	**1 (RPC)**	Fast Luminosity Monitor	**3**	Offline Software	

- Direct participation from international collaborators in the CEPC R&Ds.

Document Structure of Ref-TDR

- The ref-TDR has 16 chapters, which may be re-structured later.
- Each chapter has a responsible team, including members from domestic and international institutes.
- An editorial team has been established.

1) Physics Goal and Requirements
2) Concept Introduction
3) MDI and Luminosity Detectors
4) Vertex Detector
5) Silicon Trackers
6) Gaseous Trackers
7) Electromagnetic Calorimeter
8) Hadron Calorimeter
9) Muon Detector
10) Superconducting Solenoid Magnet
11) General Electronics
12) Trigger and Data Acquisition
13) Software and Computing
14) Mechanics and Integration
15) Physics Performance
16) Overall Cost and Project Timeline

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

- ❑ The CEPC IDRC (International Detector Review Committee) held a meeting at IHEP, Oct 21-23, 2024, reviewed the status and plan of Ref-TDR
- ❑ Generally, there is no showstopper. The committee provided very helpful recommendations which will guide the work in the following months.

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 the Ref-TDR plan by the IDRC
Oct 23-27, 2024	Report at the CEPC workshop
Oct 29-30, 2024	Report progresses to the CEPC IAC
~ January 2025	The first draft of the ref-TDR is ready for internal reviews
~ April 2025	Finish international reviews
Jun 30, 2025	The ref-TDR is ready to release

We welcome more international and domestic teams to join the quest.