TDR of A Reference Detector for The CEPC

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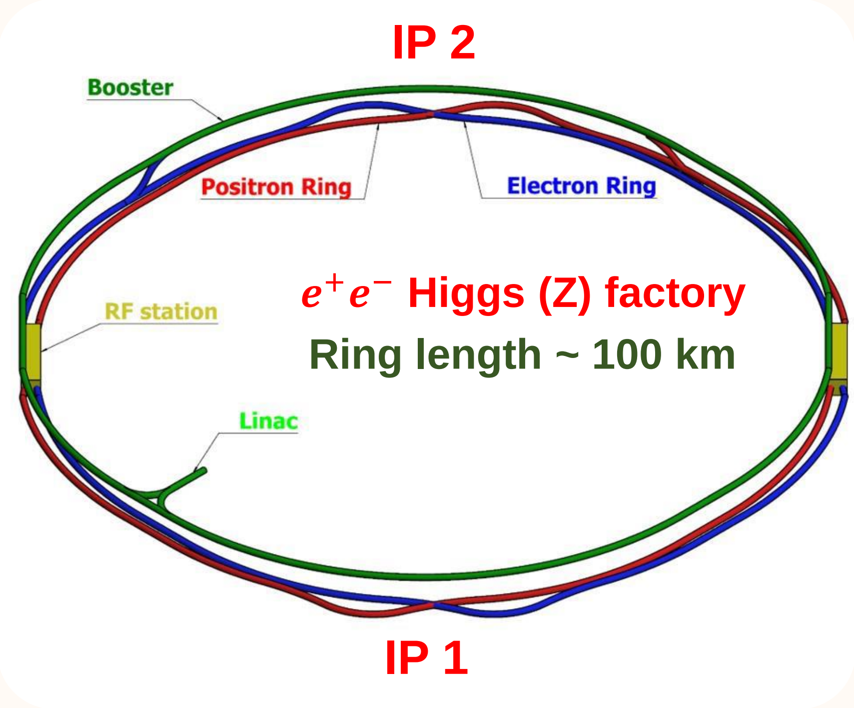
15^{th} France China Particle Physics Network/Laboratory Workshop

June 10-14, 2024, Bordeaux

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.

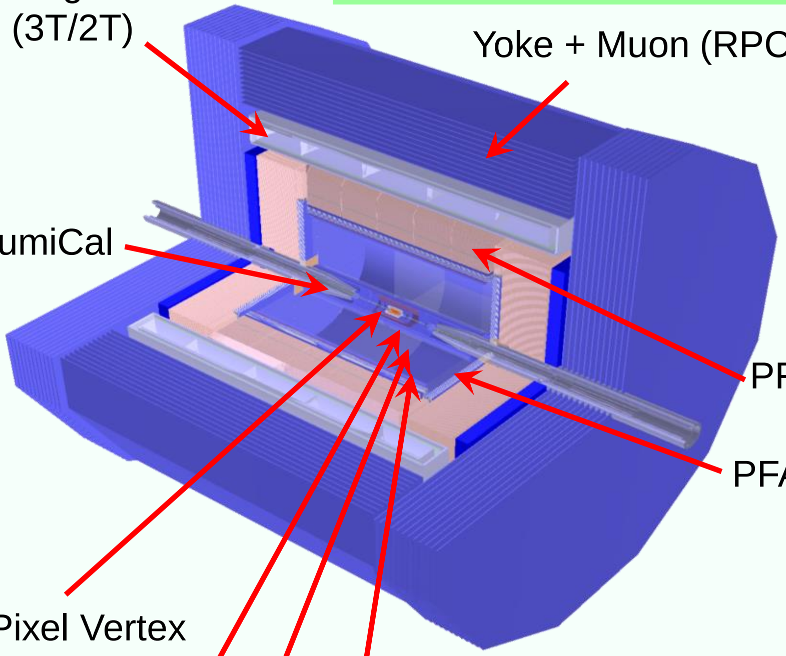


Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91.2	~160	~360
Run Time [years]		10	2	1	~5
30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**191.7**	**26.6**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	20	96	7	1
	Event yields [2 IPs]	4×10^6	4×10^{12}	2×10^7	5×10^5

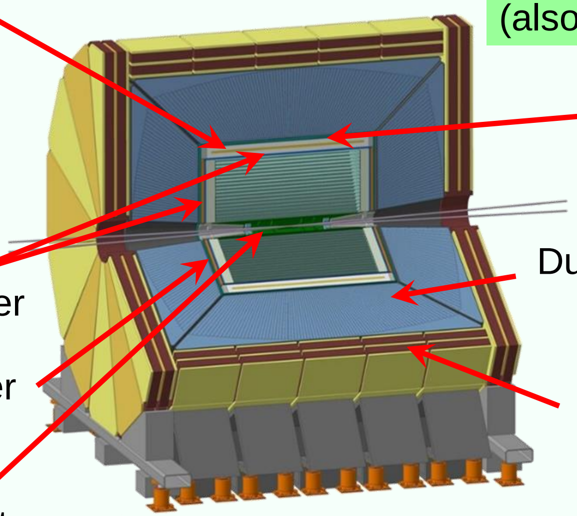
Both **50 MW** and $t\bar{t}$ modes are considered as upgrades

Conceptual Detector Designs

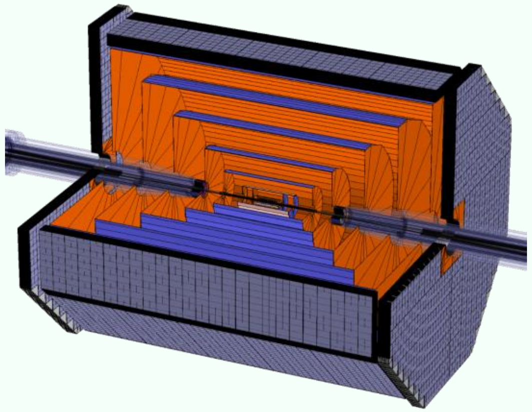
(Baseline Design)
Particle Flow Algorithm



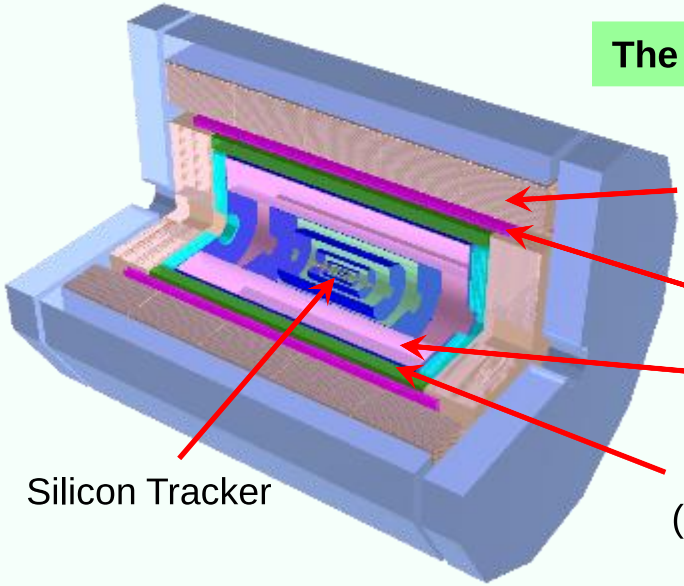
IDEA concept
(also proposed for FCC-ee)



FST concept
(Full Silicon Tracker)



The 4th Concept



Requirements of Detector and Key Technologies

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3$ μm, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\mathrm{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 2%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ Granularity $\sim 2 \times 2 \times 2$ cm^3
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2 - 3$ T Material budget $< 1.5 X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\mathrm{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\mathrm{GeV})}$

These specifications continue to be optimized

International Efforts on Detector R&D

Det	Technology
Pixel Vertex	JadePix
	TaichuPix
	Arcadia
	CPV(SOI)
	+Stitching
Tracker & PID	CEPCPix / COFFEE
	Si Strip Detector
	TPC
	Drift Chamber
	PID DC
	LGAD ToF
	AC-LGAD
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL
	Fast LumMoni

Det	Technology
Calorimeter	4D Crystal ECAL
	Stereo Crystal ECAL
	PS/SiPM+W ECAL
	SiDet+W ECAL
	PS/SiPM+Fe AHCAL
	ScintGlass AHCAL
	RPC SDHCAL
	MPGD SDHCAL
	DR Calorimeter
Muon	Scintillation Bar
	RPC
	μ-Rwell
Misc	HTS / LTS Magnet
	MDI & Integration
	TDAQ scheme

- International detector R&D efforts for the future Higgs factories
- Some were within the international detector R&D collaborations: CALICE, LCTPC, & RD*
- Now much broader participation in the ECFA DRD program

Technologies for Ref-TDR

System	Technologies		
Vertex	CMOS Pixel	CMOS+Stitching	SOI
Tracker & PID	SPD ITrk		
	Pixelated TPC	PID Drift Chamber	
	AC-LGAD OTrk	SSD OTrk	SPD OTrk
		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	

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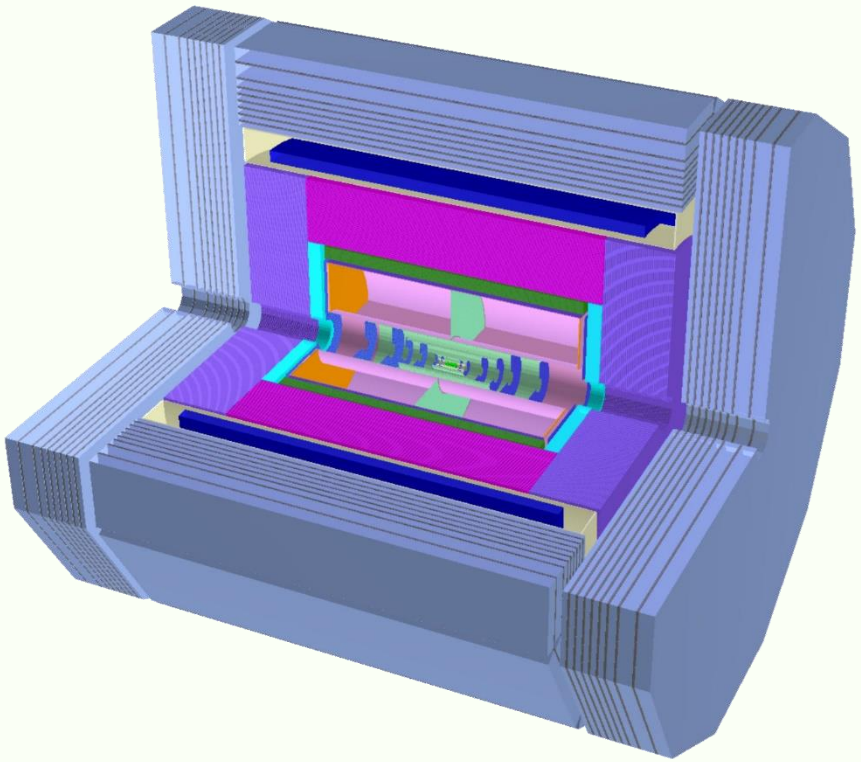
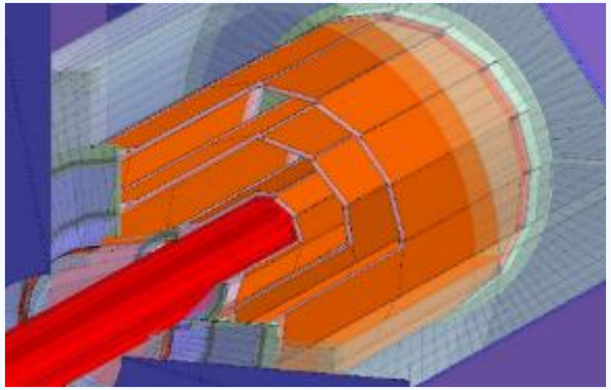
Baseline | **For Comparison** | **To Be Decided**



- Prepare TDR of a reference detector, aiming for domestic endorsement, as recommended by the CEPC IAC
- Will continue to seek for better technologies, and decide the final detectors within the CEPC international collaborations

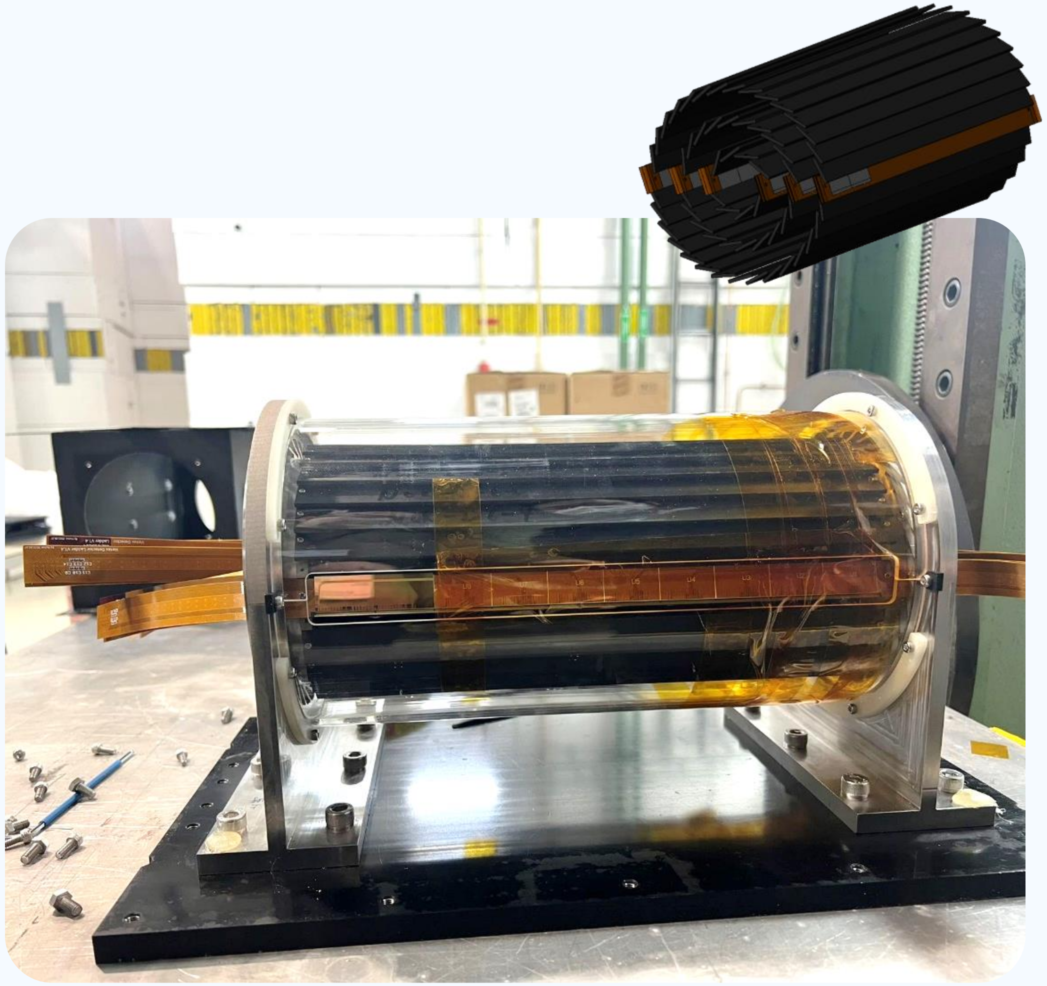
3 × dual-layer design



Goal: σ(IP) ~ 5 μm for high P

Key specifications:

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



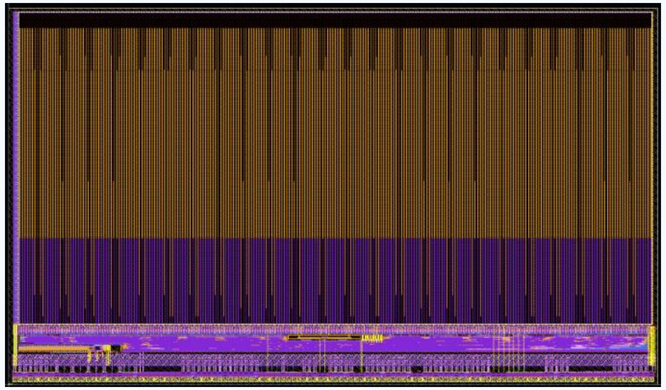
A TaichuPix-based prototype detector was tested at DESY in April 2023

Spatial resolution ~ 4.9 μm

JadePix4

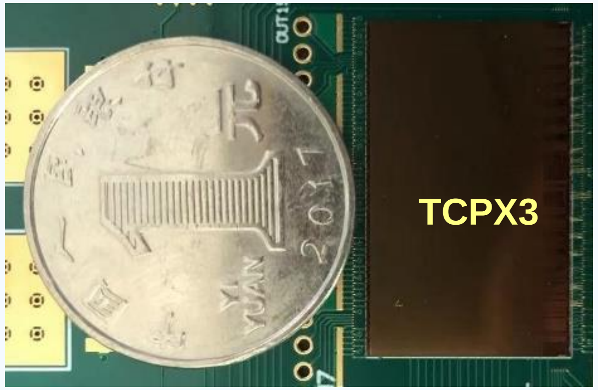
356×498 array of 20×29 μm^2

$\sigma_{x/y}$ ~ 3-4 μm, σ_t ~ 1 μs, ~100 mW/cm^2



TaichuPix3

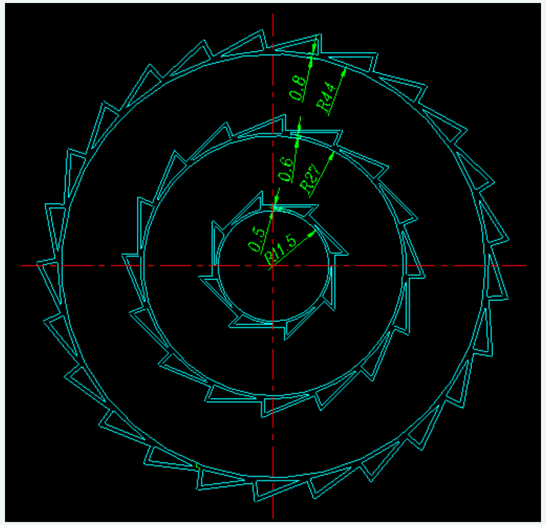
1024×512 array of 25×25 μm^2



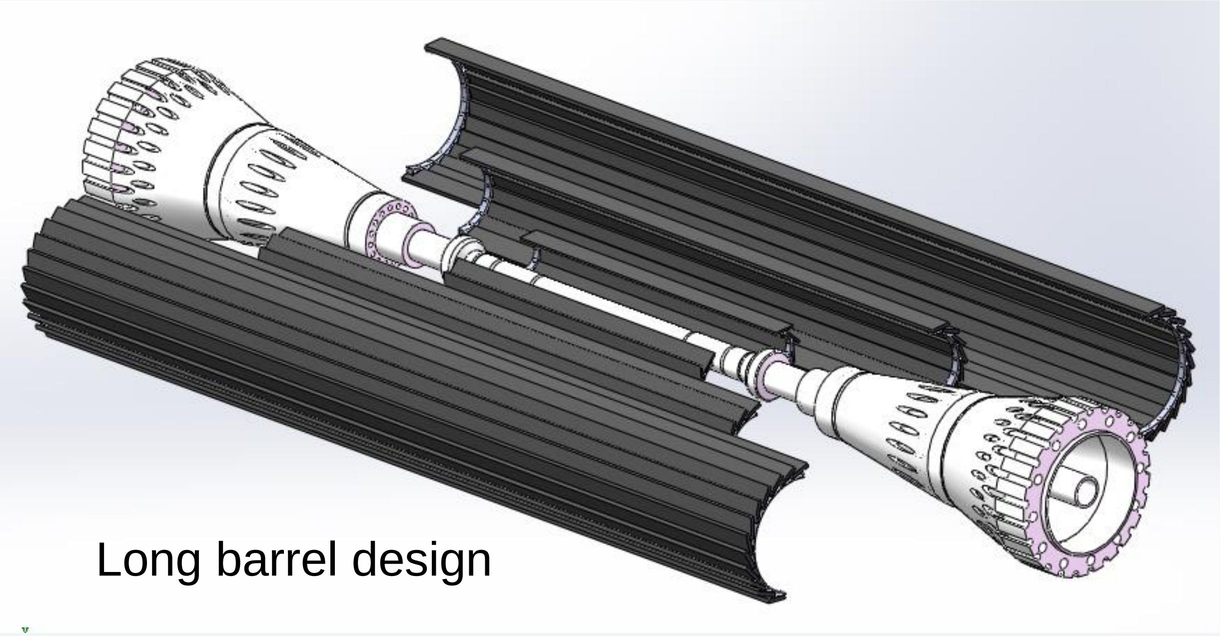
TowerJazz 180nm CIS process

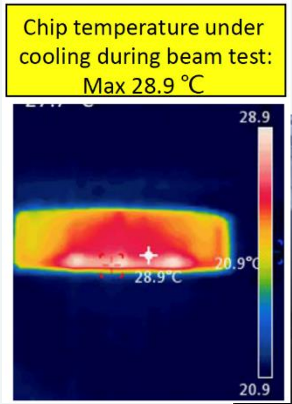
Continued R&D on The Vertex Detector

- Further efforts on the sensor design to reach key specifications
  - MOST3 goal: $\sigma_{x/y} \sim 3\ \mu m$, $\sigma_t \sim 100$ ns, heat dissipation ~100 mW/cm^2
  - Using 65 nm instead of 180 nm technology can reduce power to ~30%
- Optimize the mechanical support structure, cabling & cooling scheme
- A design of long barrel only vs a combination of short barrel + endcap
- Air cooling for 25-28 °C operation temperature, air speed ~2.3 m/s
  - Assume that 40 mW/cm^2 can be reached
  - Thermal contact of the inner layer with the beam pipe at 16 °C



Al alloy support rings

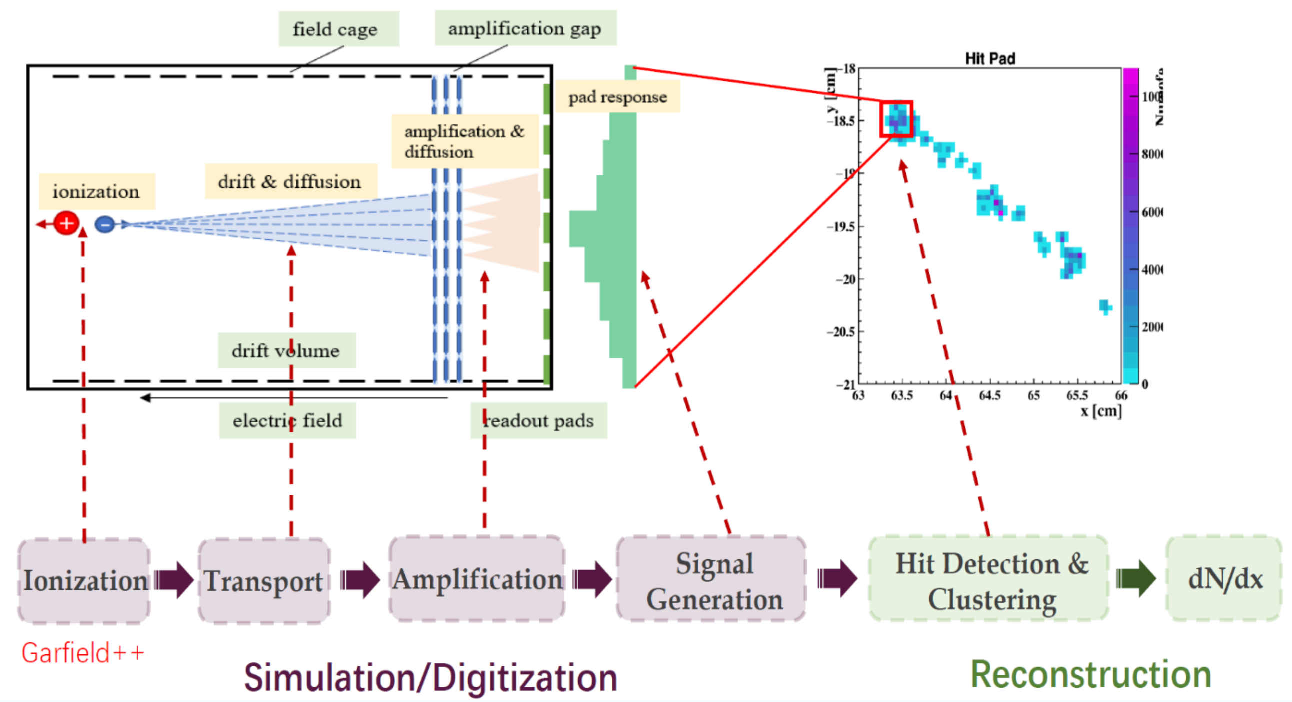

Long barrel design

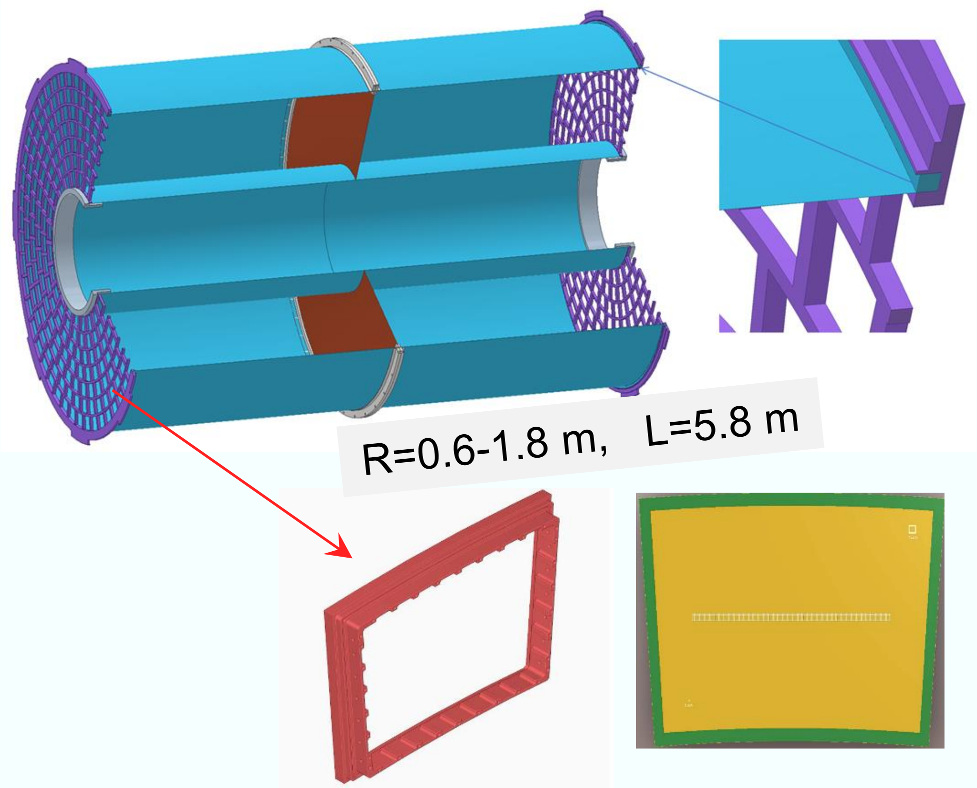


Air cooling test setup

Pixelated TPC

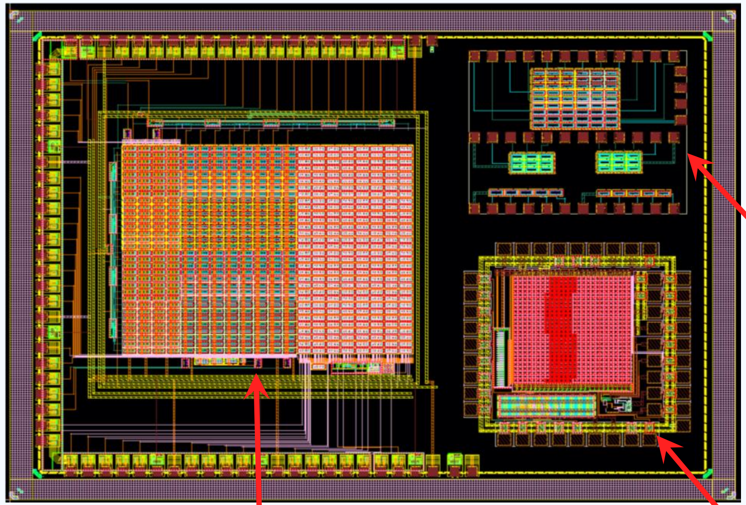
- Initial TPC design has difficulty at high luminosity Z pole due to IBF
- A pixelated TPC of (500 μm)^2 readout pads reduces IBF×Gain ~1 at G=2000, and achieves σ(r-Φ) ~100 μm
- Full simulation study also shows 3σ K/π separation at 20GeV
- Preliminary mechanical design ⇒ RL = 15% X_0 for endcap and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





Silicon Pixel Inner Tracker

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



COFFEE2 chip with SMIC 55 nm process

Zone 1

6×9 pixels, 80×40μm^2

Diodes of different charge collection

Zone 2

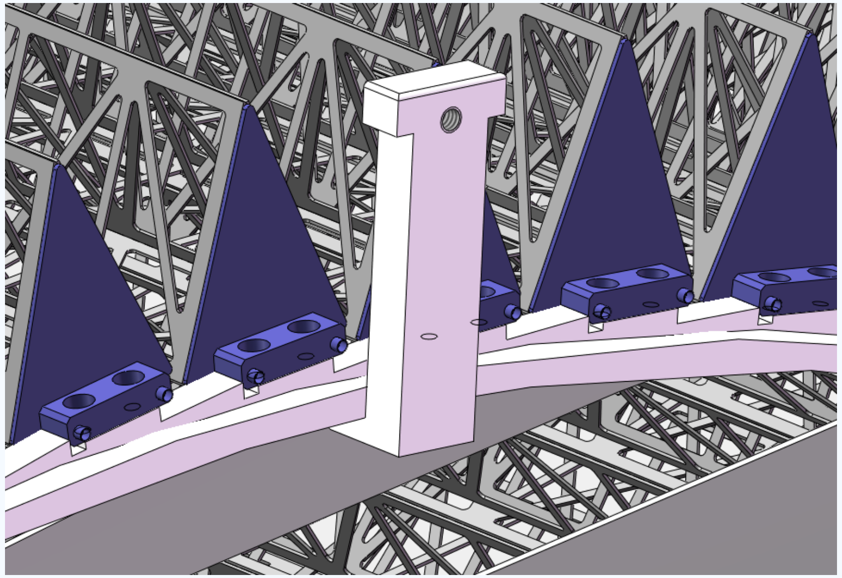
20×32 pixels, 72×36μm^2

Designs of charge collection & cell electronics

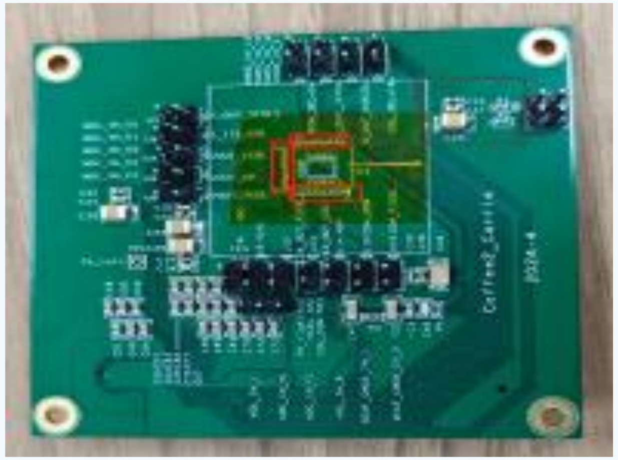
Zone 3

26×26 pixels, 25×25μm^2

Peripheral digital processing and communication



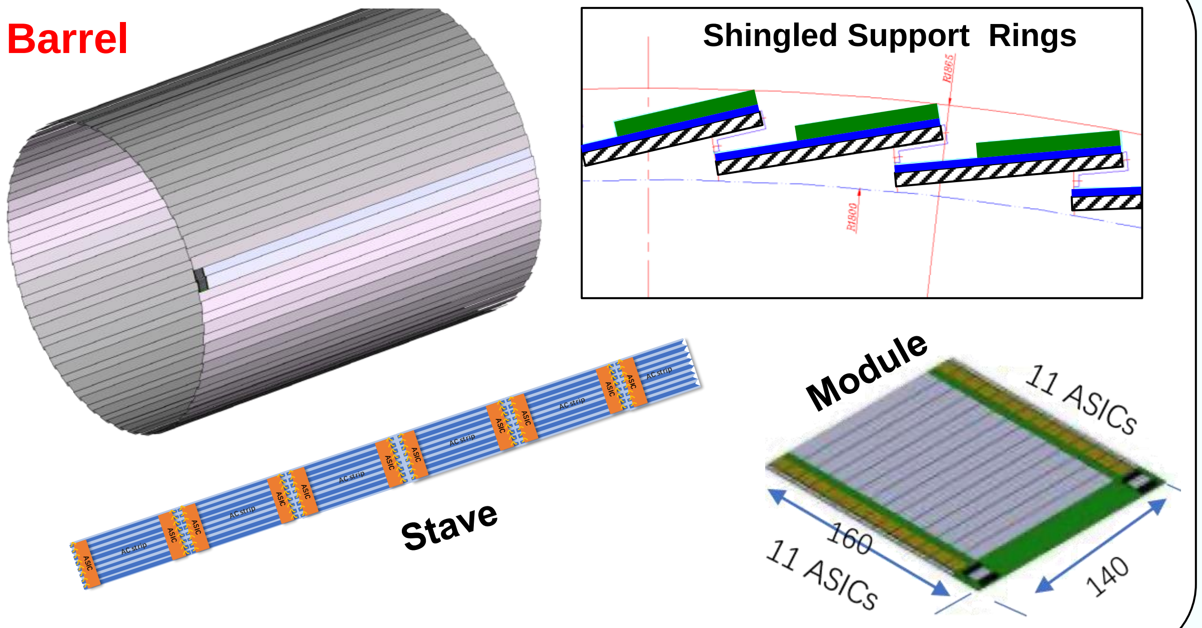
CFRP truss structure: ~0.18% X_0
Outer layer may be attached to TPC

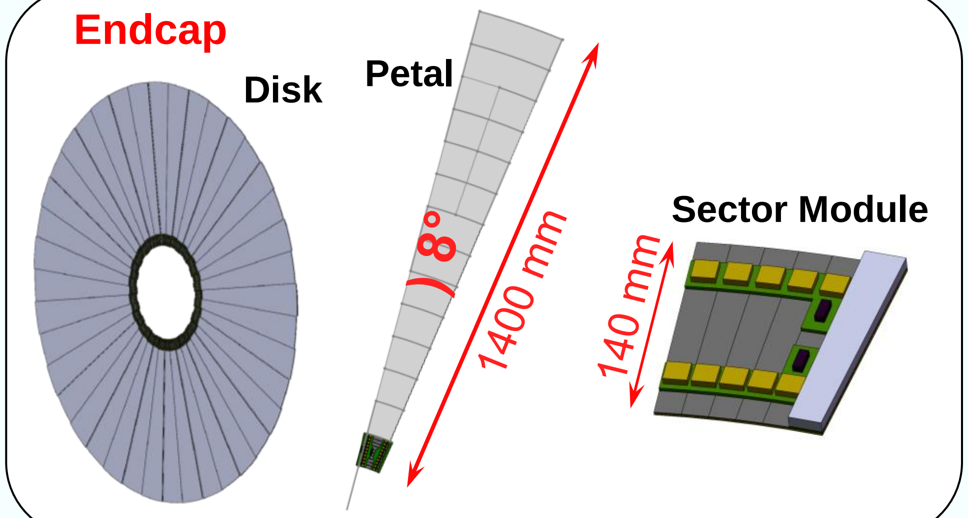


COFFEE2 Test Board

AC-LGAD Outer Tracker (Time Tracker)

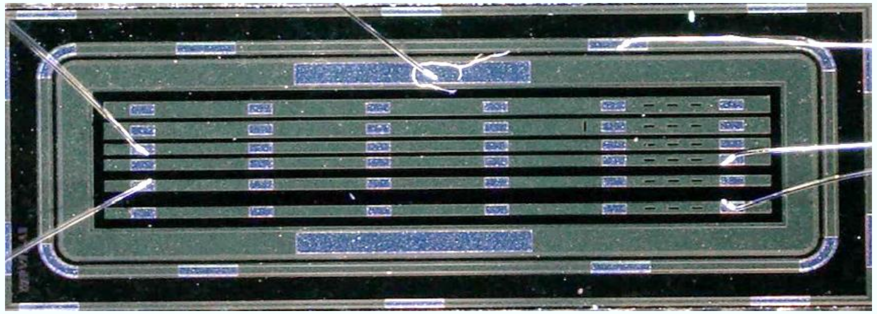
- The outer silicon tracker ~ 85 m^2, the Z precision is not crucial
  $\Rightarrow$ cost-effective Si strip detector
- Need a supplemental PID to TPC at low energy $\Rightarrow$ LGAD ToF
- AC-LGAD Time Tracker combines the two needs in one detector, and expect σ_t ~30 ps, $\sigma_{R\Phi}$ ~10 μm





Strip AC-LGAD by IHEP / IME

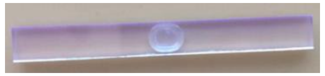
Strip size 5.6 mm × 100 μm
Pitch: 150, 200, 250 μm

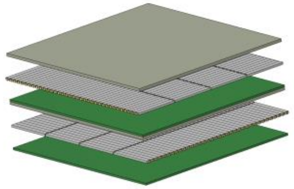


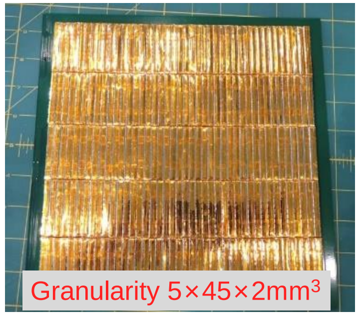
Prototype PFA Calorimeters

- 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

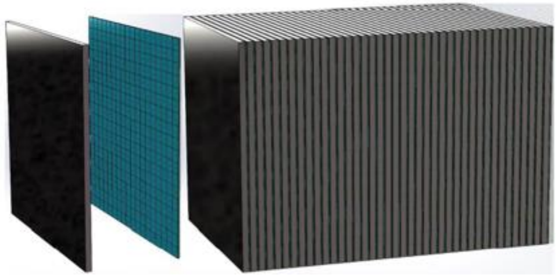


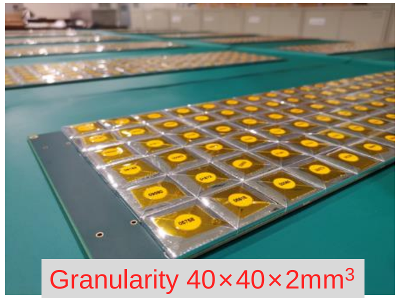




Granularity 5×45×2mm^3

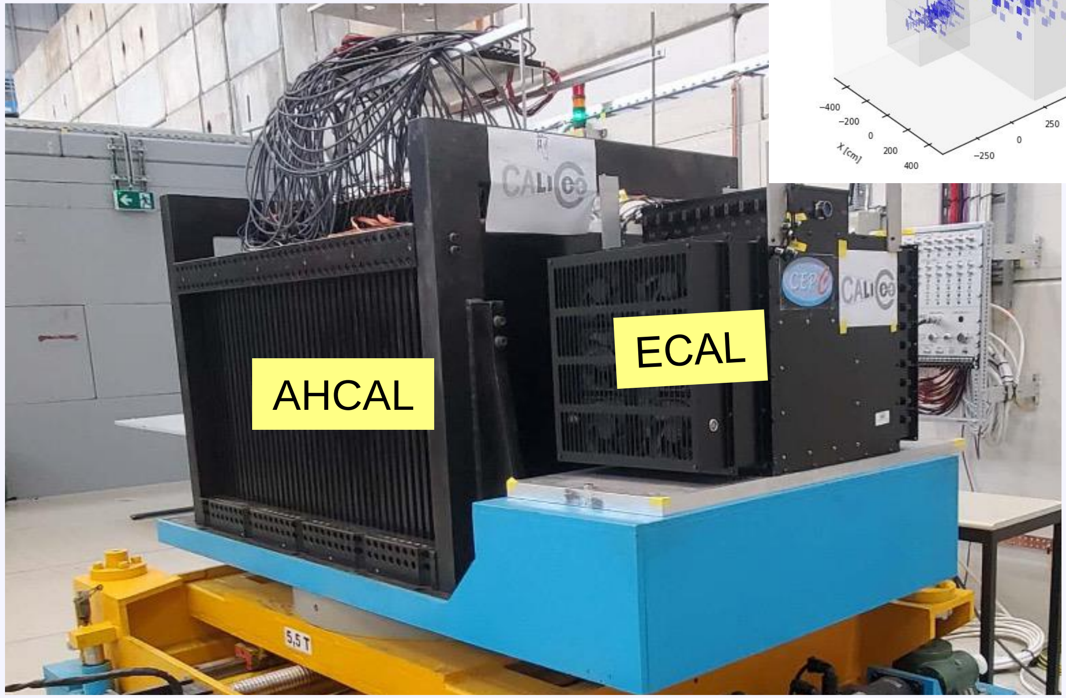
HCAL: scintillator (tile)+SiPM, steel

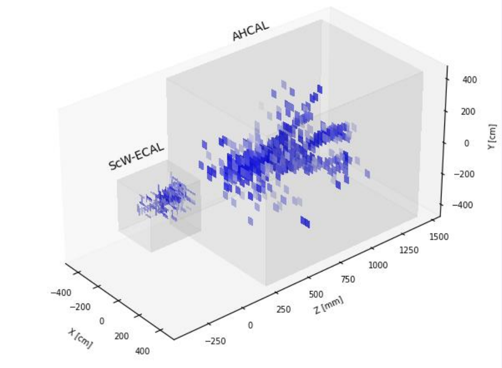




Granularity 40×40×2mm^3

Sveral successful testbeams @ CERN

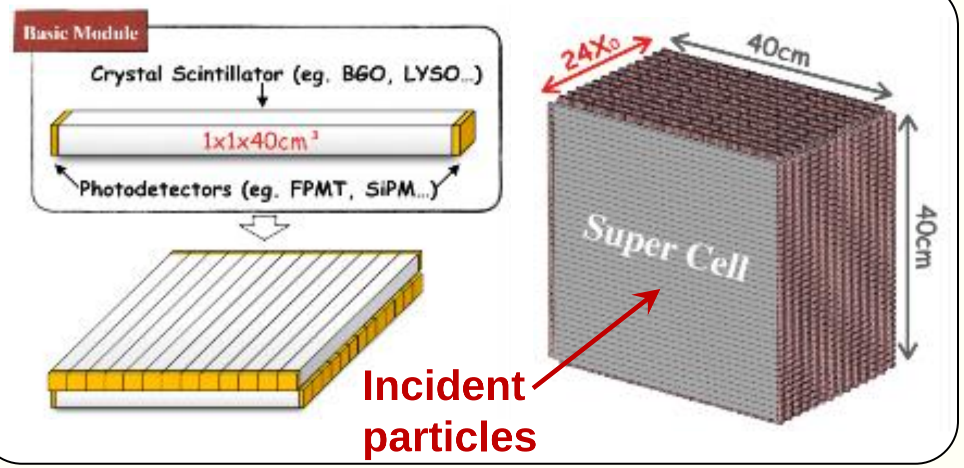


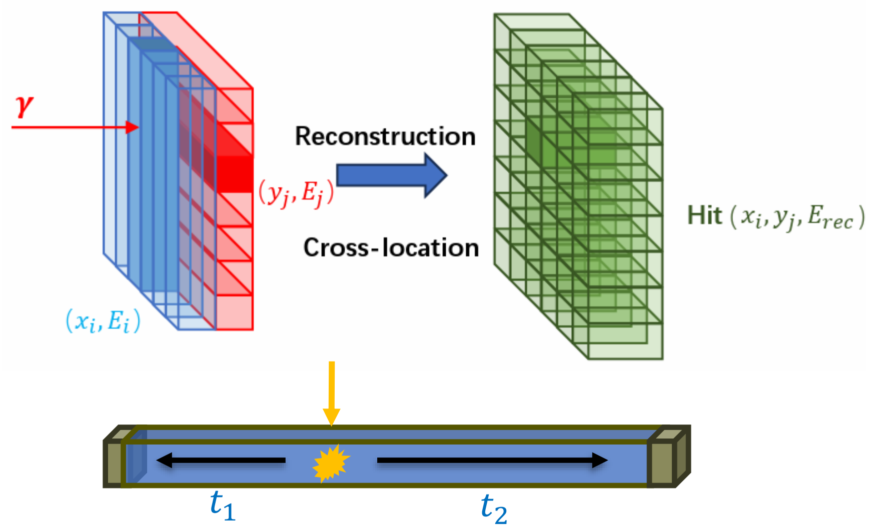


Prototypes developed within **CALICE**

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

4D Long Crystal Bar Calorimeter

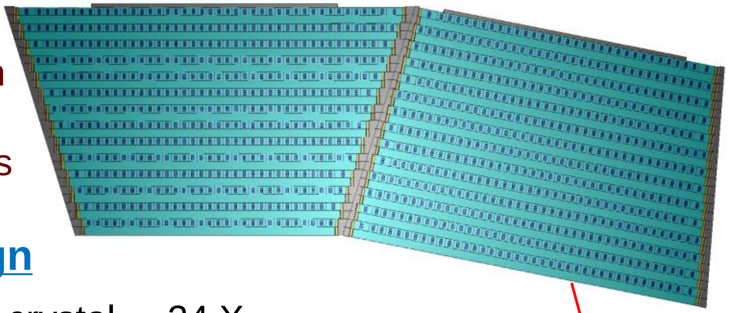




Achieve high granularity with adjacent layers

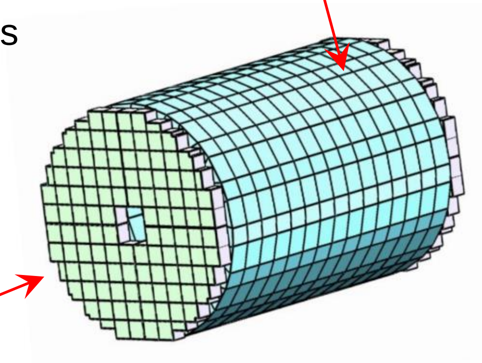
- ❑ Double-end readout, potential positioning with timing
- ❑ Save readout channels, minimize dead materials
- ❑ Challenging in pattern recognitions with multiple particles

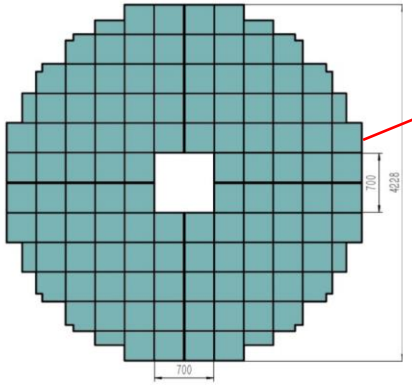
Cylindrical barrel with alternately arranged trapezoidal supercells



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

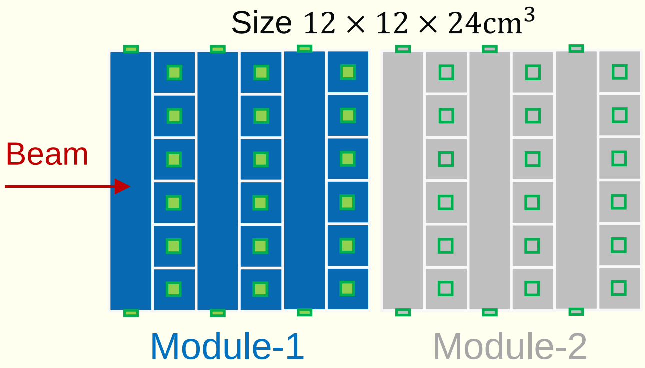


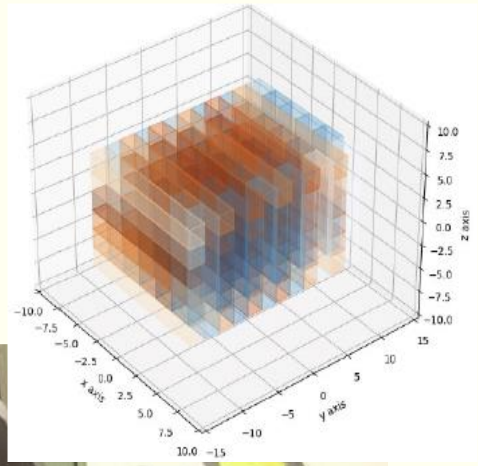


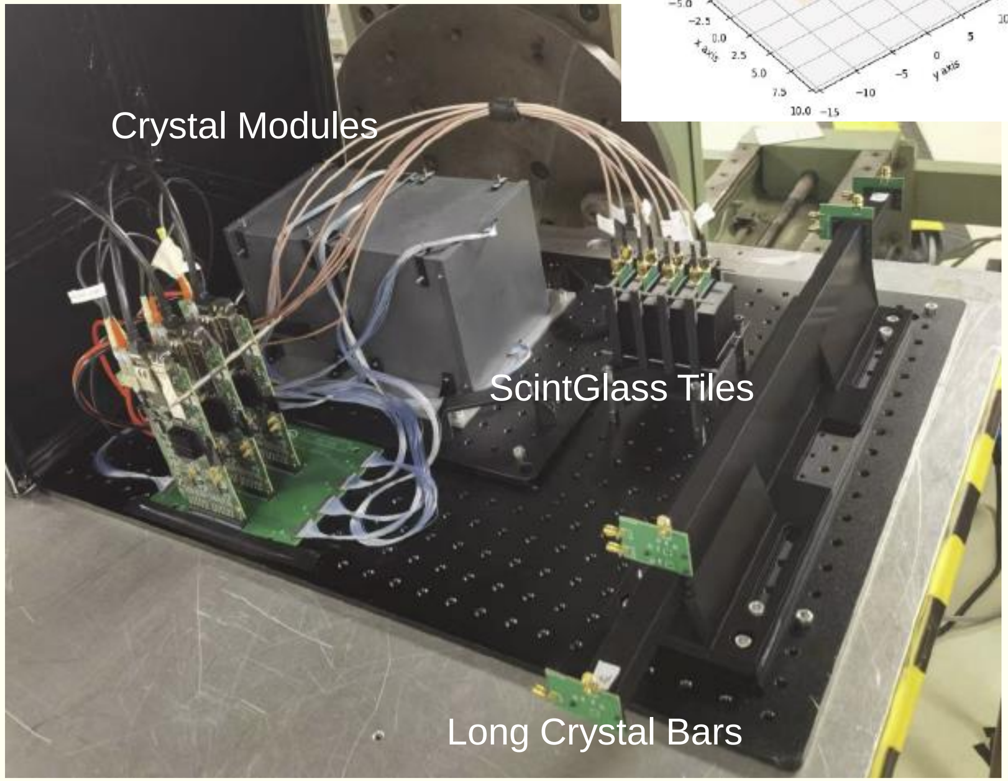
Endcap disc of square towers

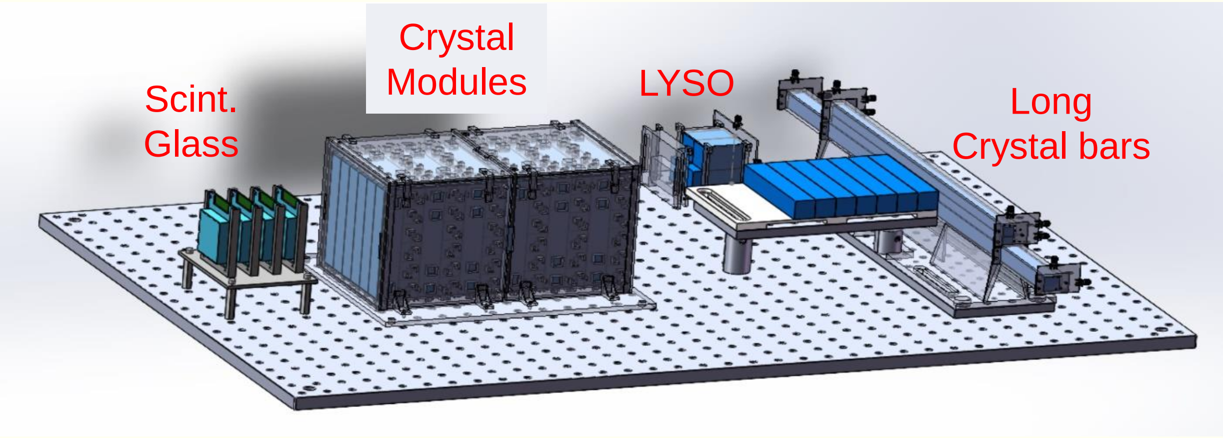
Testbeam of Prototype 4D Crystal ECAL

- A successful testbeam @ DESY, Oct 2023
- To address critical issues at system level
  - Validation: design of crystal-SiPM, light-weight mechanical structure
  - EM shower performance
- Module development
  - BGO crystal bars from SIC-CAS
  - SiPM: 3×3 mm² sensitve area, 10μm pixel pitch
  - Front-end electronics with CITIROC, by **CNRS OMEGA.** An ASIC with a large dynamic range would be more desirable





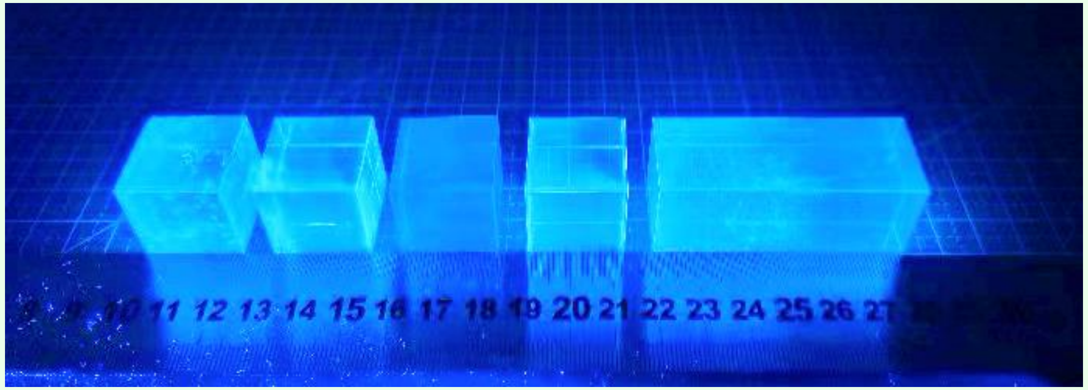


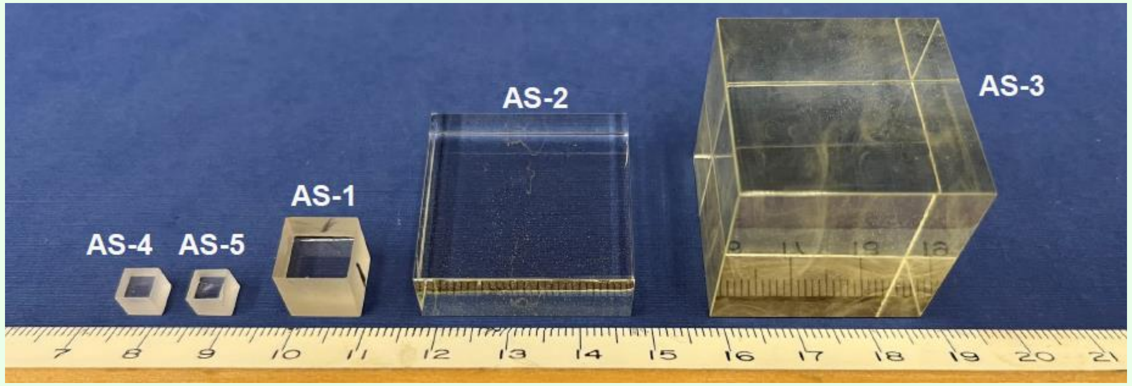


Glass Scintillator HCAL

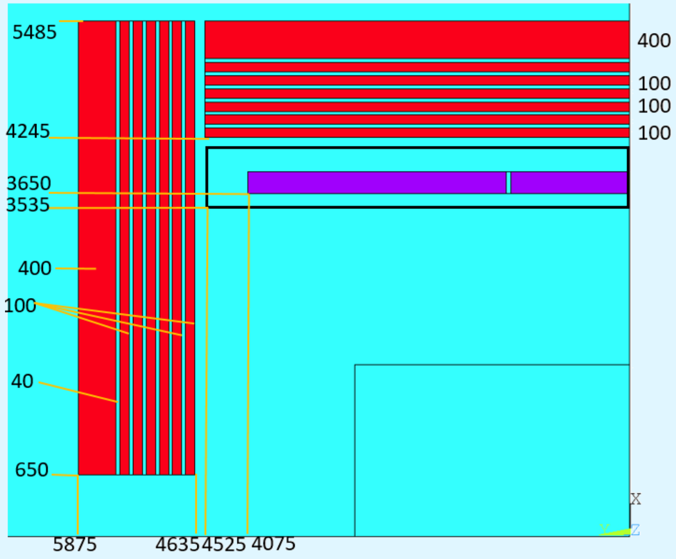
- To replace plastic scintillator with high density, low cost glass scintillator, for better hadronic energy resolution and BMR
- Key specifications:
  - Light yield: 1000~2000 ph / MeV
  - Density: 5~7 g/cm^3
  - Scintillation time: ~100 ns
- The Scintillation Glass collaboration continues to progress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

Parameters	Unit	BGO	LYSO	GAGG	GS1	GS5
Density	g/cm^3	7.13	7.5	6.6	6.0	5.9
Hygroscopicity	--	No	No	No	No	No
Rad. Length, X_0	cm	1.12	1.14	1.63	1.59	1.61
Transmittance	%	82	83	80	80	80
Refractive Index	--	2.1	1.82	1.91	1.74	1.75
Emission peak	nm	480	420	520	390	390
Light yield, LY	ph/MeV	8000	3000	54000	1347	1154
Energy resol., ER	%	9.5	7.5	5.0	25.3	25.4
Decay time	ns	60, 300	40	100	80,600	90,300





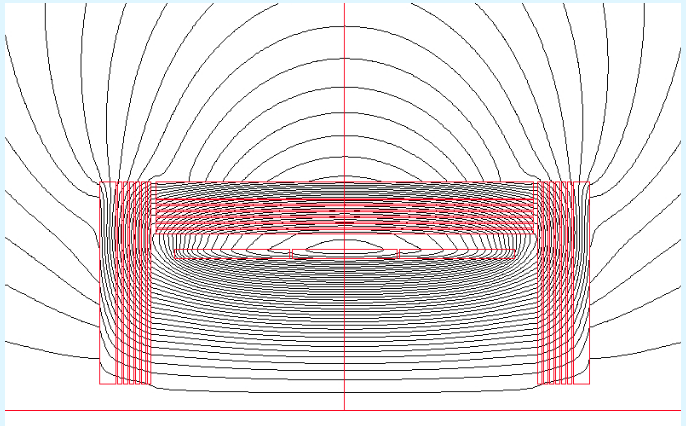
LTS-based Superconducting Solenoid Magnet



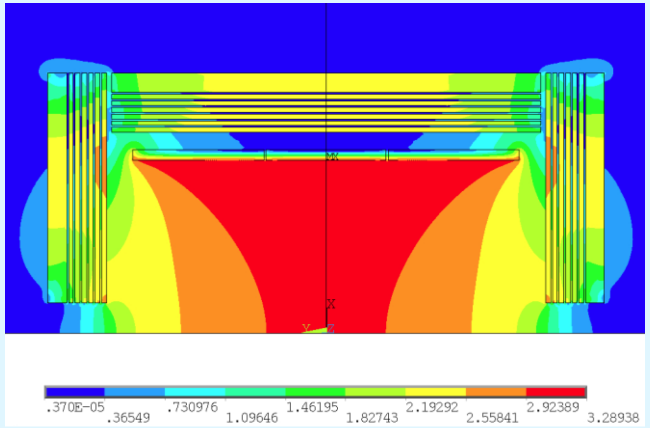
- The baseline solenoid magnet was moved back to outside of HCAL with LTS coil
- Optimizing the design for better uniformity, thinner space, and cost-effectiveness.
- R&D on HTS cable continues

Yoke Parameters	
Barrel yoke weight	2300 ton
Endcap yoke weight / 2	754 ton
Total weight	3808 ton
Diameter	10.97 m
Length	11.75 m

Magnetic flux distribution



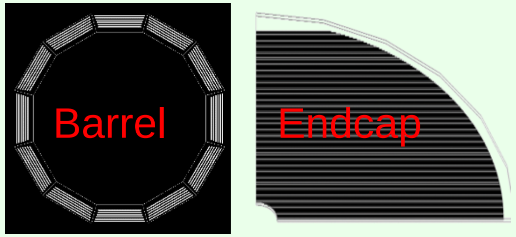
Magnetic field distribution



Coil Parameters	
Central magnetic field	3 T
Inner diameter	7300 mm
Operating current	16702 A
Cable length	33 km
Inductance	11 H
Stored Energy	1.54 GJ
Total mass	265 tons

Muon Detector

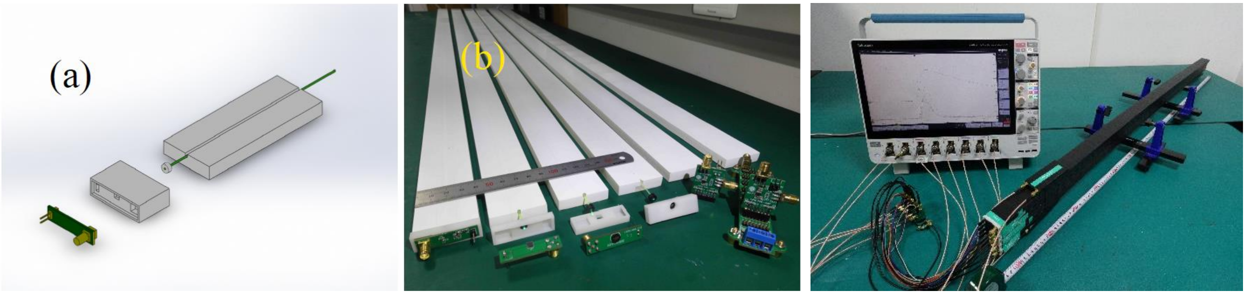
- Muon ID, combining with magnet return
- Requirement: $\epsilon > 95\%$, σ_T ~1-2 ns
- Total area ~ 4500 m^2, ~40k channels
- Top options: plastic scintillator and RPC

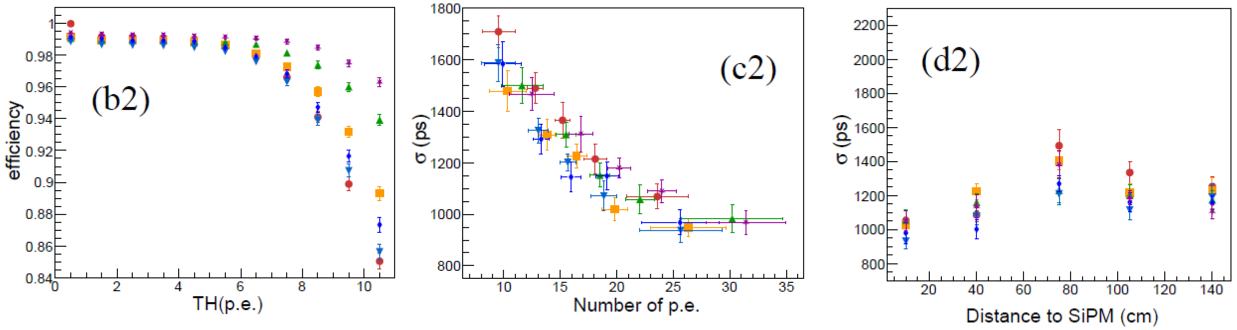


PS muon detector

Extruded plastic scintillator, WLS fibre, and SiPM

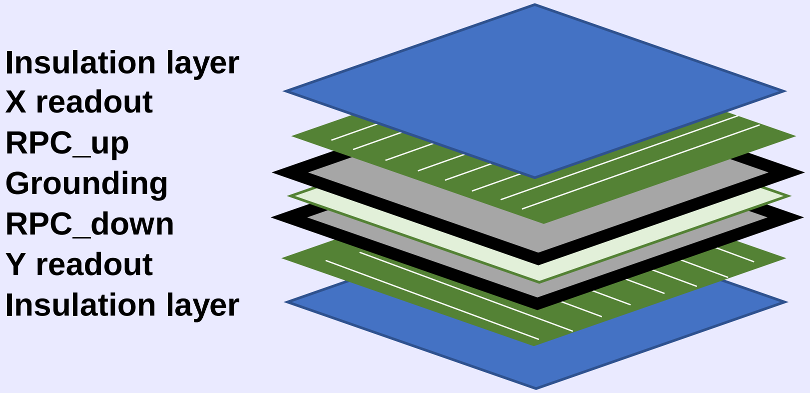
Preliminary results: $\epsilon > 95\%$ and $\sigma_T < 1.5\ ns$

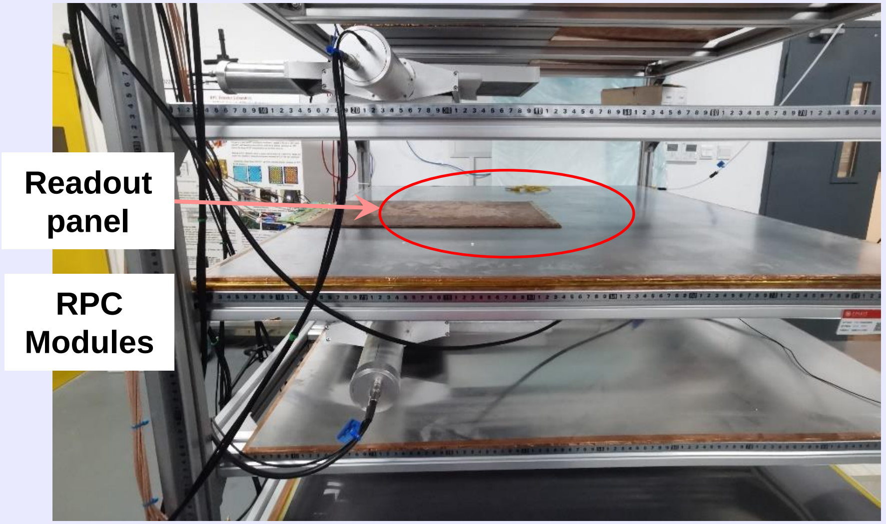




RPC muon detector

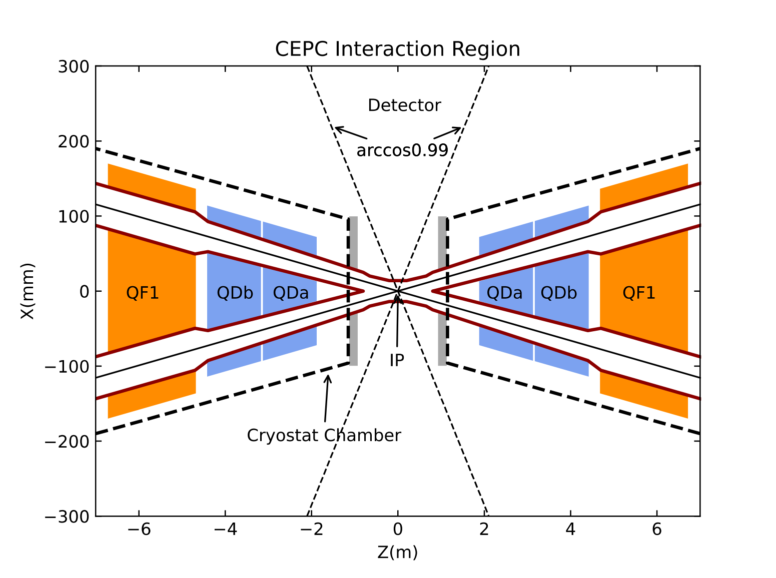
Experience from BES, DYB experiments





MDI, Beam Background, LumiCAL

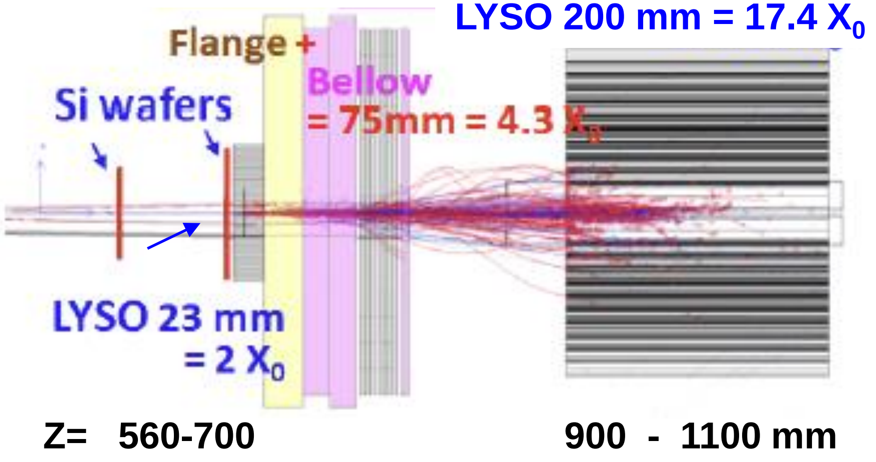
- Interaction Region Layout/Parameters
  - The inner diameter of central beampipe is 20mm
  - L* = 1.9m / Detector Acceptance = 0.99
  - The length of Interaction Region is ±7m at TDR Phase
- Beam Induced Background Estimation
  - Include major sources, both single beam and luminosity related
  - Multi-turn accelerator tracking when needed
- LYSO bar and Si pixel detector based LumiCal design



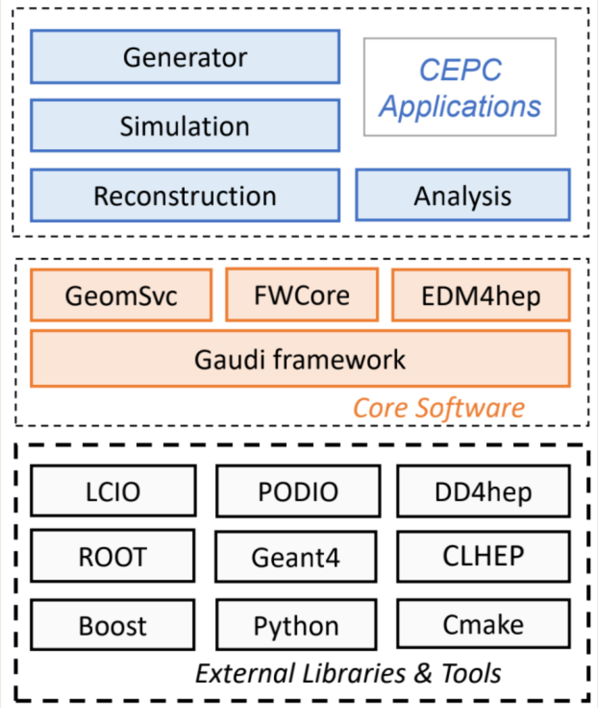
Background	Generation	Tracking	Det Simu.
Synchrotron Radiation	BDSim	BDSim/Geant4	Mokka CEPCSW FLUKA
Beamstrahlung/Pair Production	Guinea-Pig++	SAD	
Beam-Thermal Photon	PyBTH[Ref]		
Beam-Gas Bremsstrahlung	PyBGB[Ref]		
Beam-Gas Coulomb	BGC in SAD		
Radiative Bhabha	BBBREM		
Touschek	TSC in SAD		

LumiCAL

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

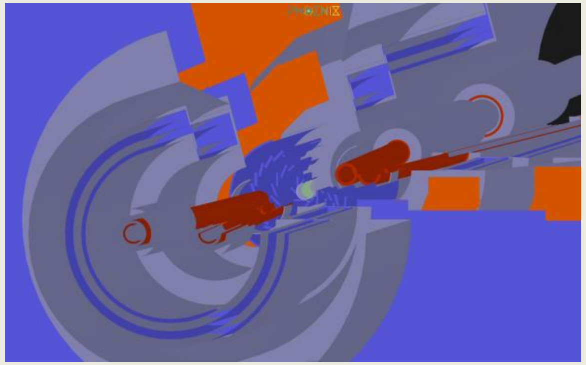


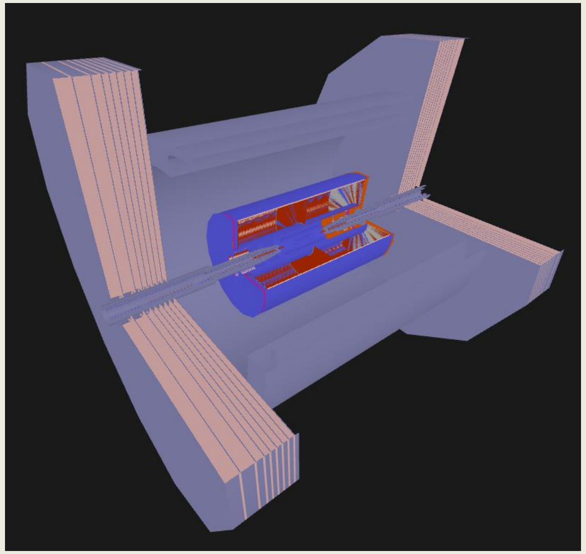
CEPC Software

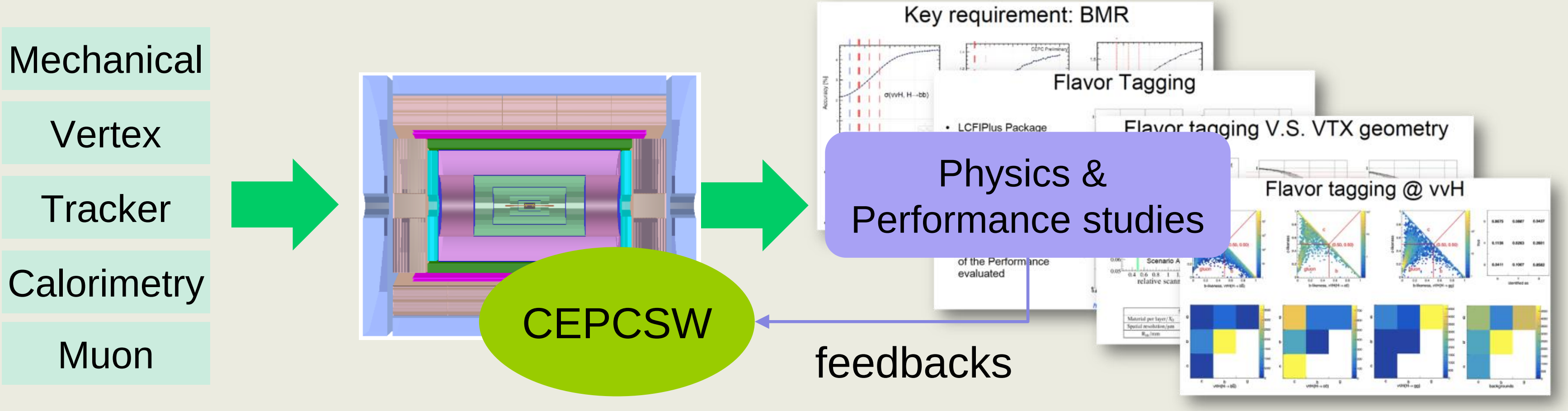


- **CEPCSW** is developed based on components of Key4hep: Gaudi, EDM4hep, K4FWCore DD4hep
- Single source of detector information, but support multiple designs
- Web-based **Phoenix** tool for visualization
- Releases towards ref-TDR
  - tdr24.3 including core software
  - tdr24.4 including tracking and bkg mixing
  - tdr24.5 including PID and muon
  - tdr24.6 including calorimeters

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

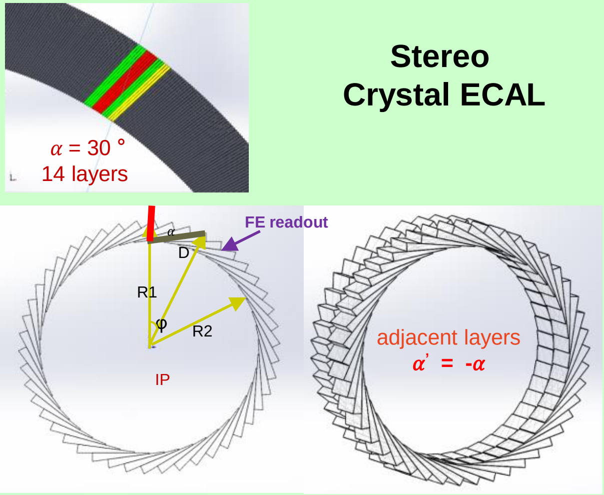






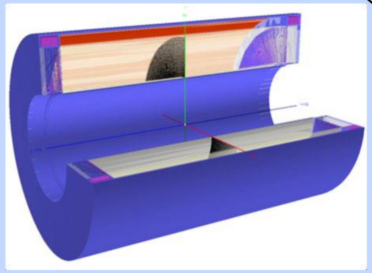
Many Other Detector R&Ds

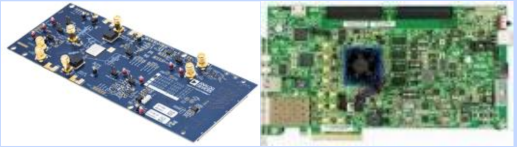
Stereo Crystal ECAL



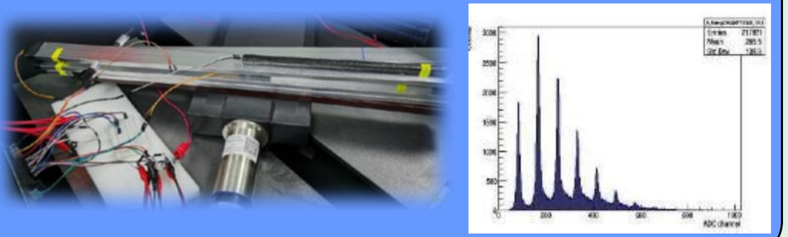
LGAD ToF

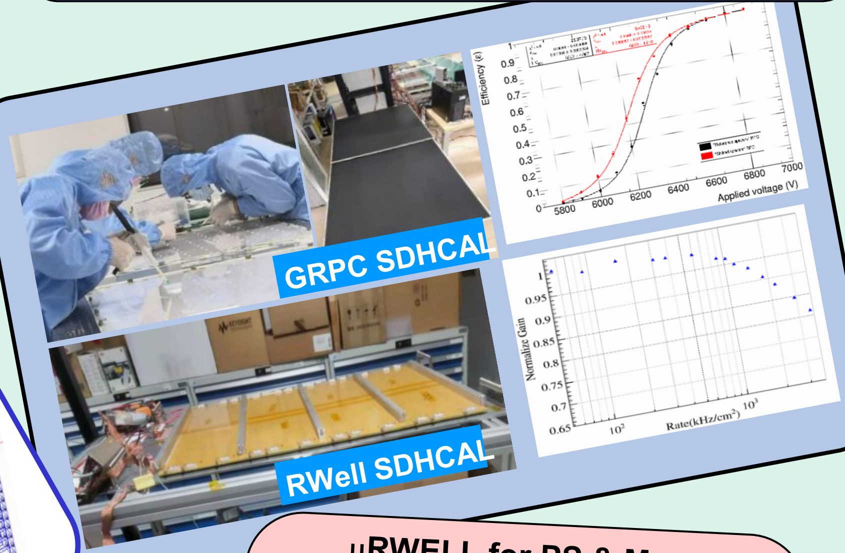
Drift Chamber




AD9689 – 2000 EBZ
Xilinx KCU105

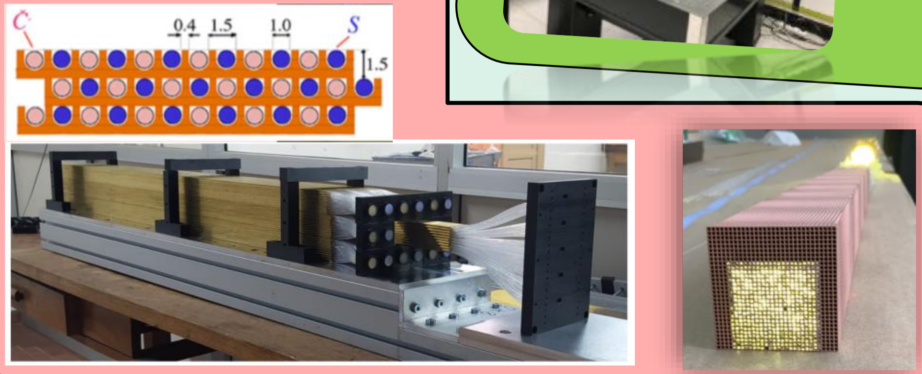
Scintillator Bar Muon

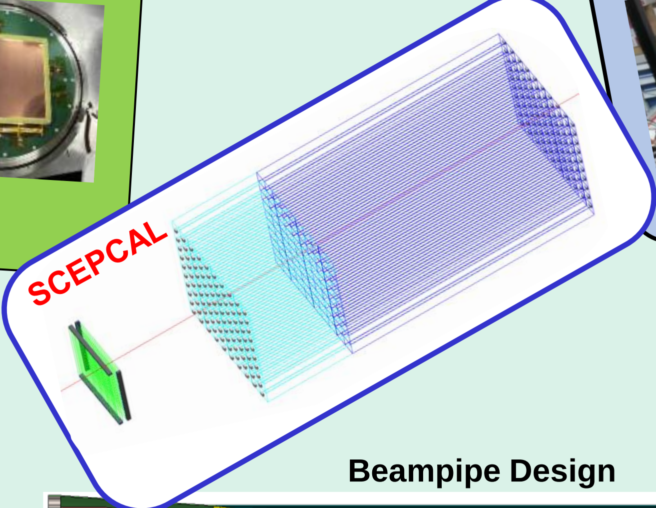




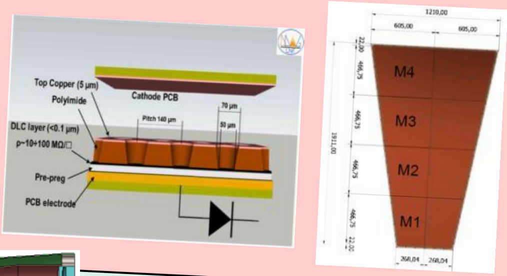
TPC Prototype

Dual Readout CAL

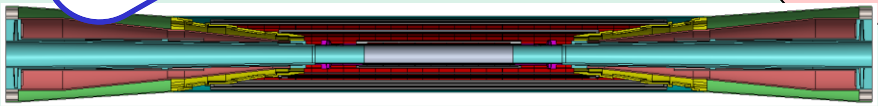




μRWELL for PS & Muon



Beampipe Design



Optimal Timeline

Completion of Accelerator TDR

Goal

TDR of a Reference Detector @ June 30, 2025

The **IDRC**, led by Prof Daniela Bortoleto, will review the progresses and provide recommendations

International Collaborations