Towards TDR of a Reference Detector for CEPC

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IHEP

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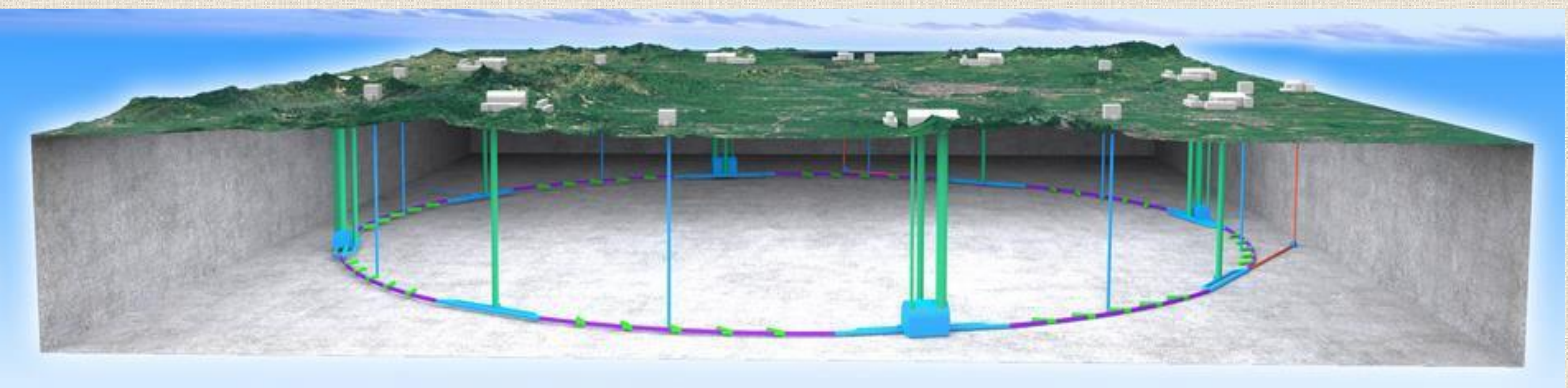
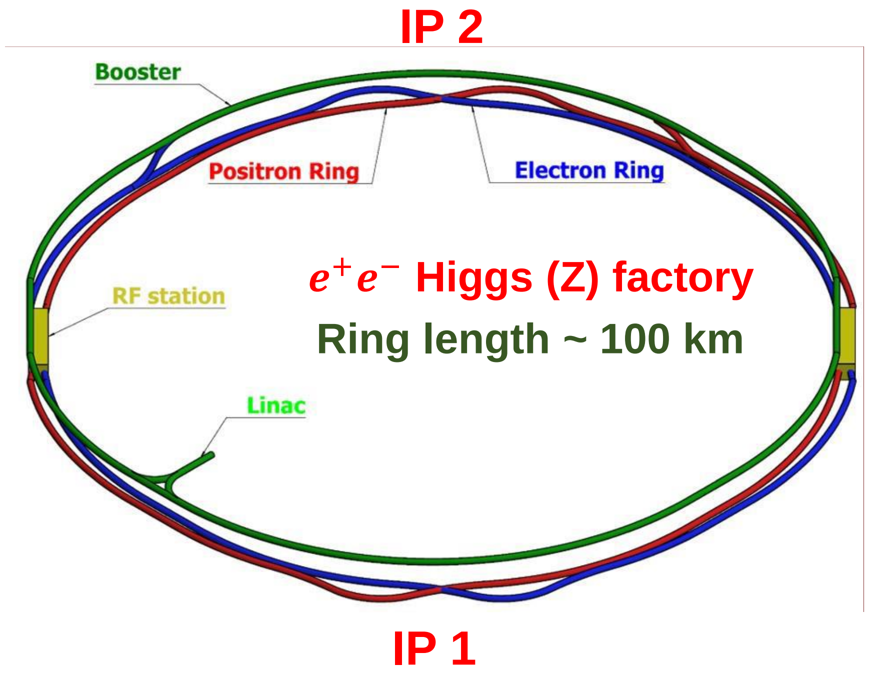


The Circular Electron Positron Collider (CEPC)

- 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.

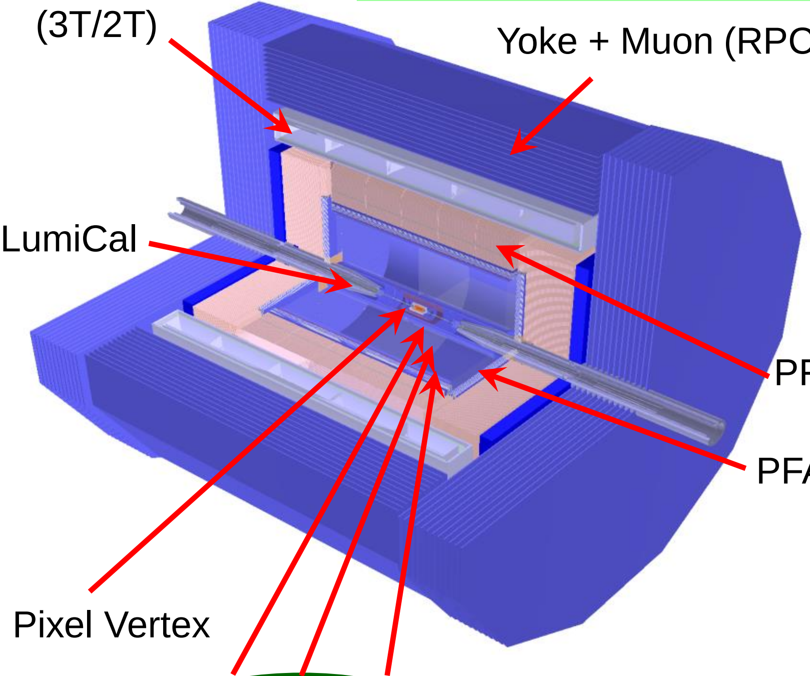


Operation mode			**ZH**	**Z**	**W⁺W⁻**	$t\bar{t}$
$\sqrt{s}$ [GeV]			~240	~91.2	~160	~360
Run time [years]			7	2	1	-
CDR (30 MW)		*L* / IP [×10^{34} $cm^{-2}s^{-1}$]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run Time [years]			10	2	1	~5
Latest	**30 MW**	*L* / IP [×10^{34} $cm^{-2}s^{-1}$]	**5.0**	**115**	**16**	**0.5**
	50 MW	*L* / IP [×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



Magnet (3T/2T)

Yoke + Muon (RPC or μ-RWELL)

LumiCal

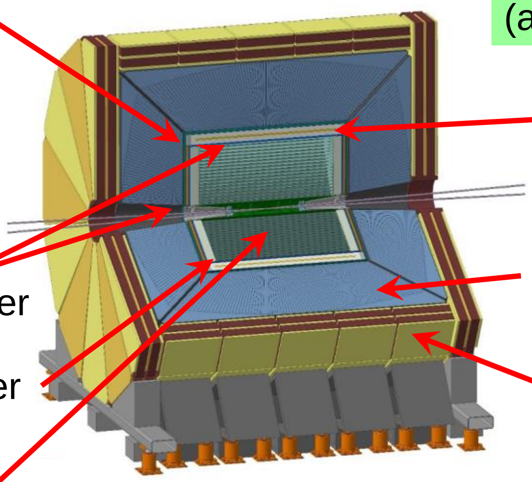
PFA HCAL

PFA ECAL

Si Pixel Vertex

SIT TPC SET
FTD ETD

IDEA concept
(also proposed for FCC-ee)



2T Magnet

Preshower (μ-RWELL)

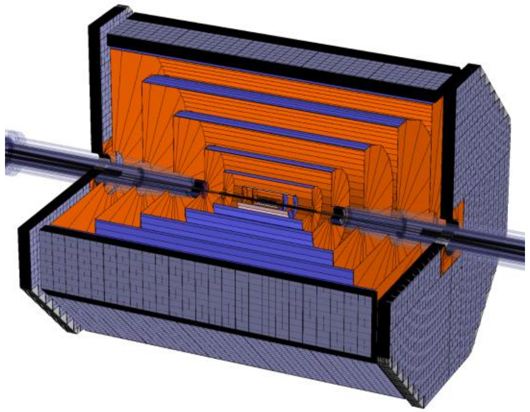
Silicon wrapper

Dual-readout calorimeter

Drift chamber

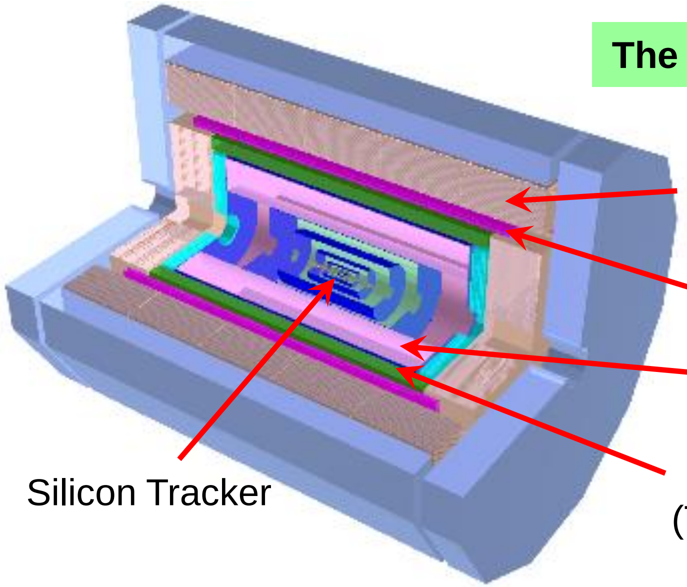
Yoke + Muon (μ-RWELL)

Si Pixel Vertex



FST concept
(Full Silicon Tracker)

The 4th Concept



Scint Glass HCAL
Partially Yoke

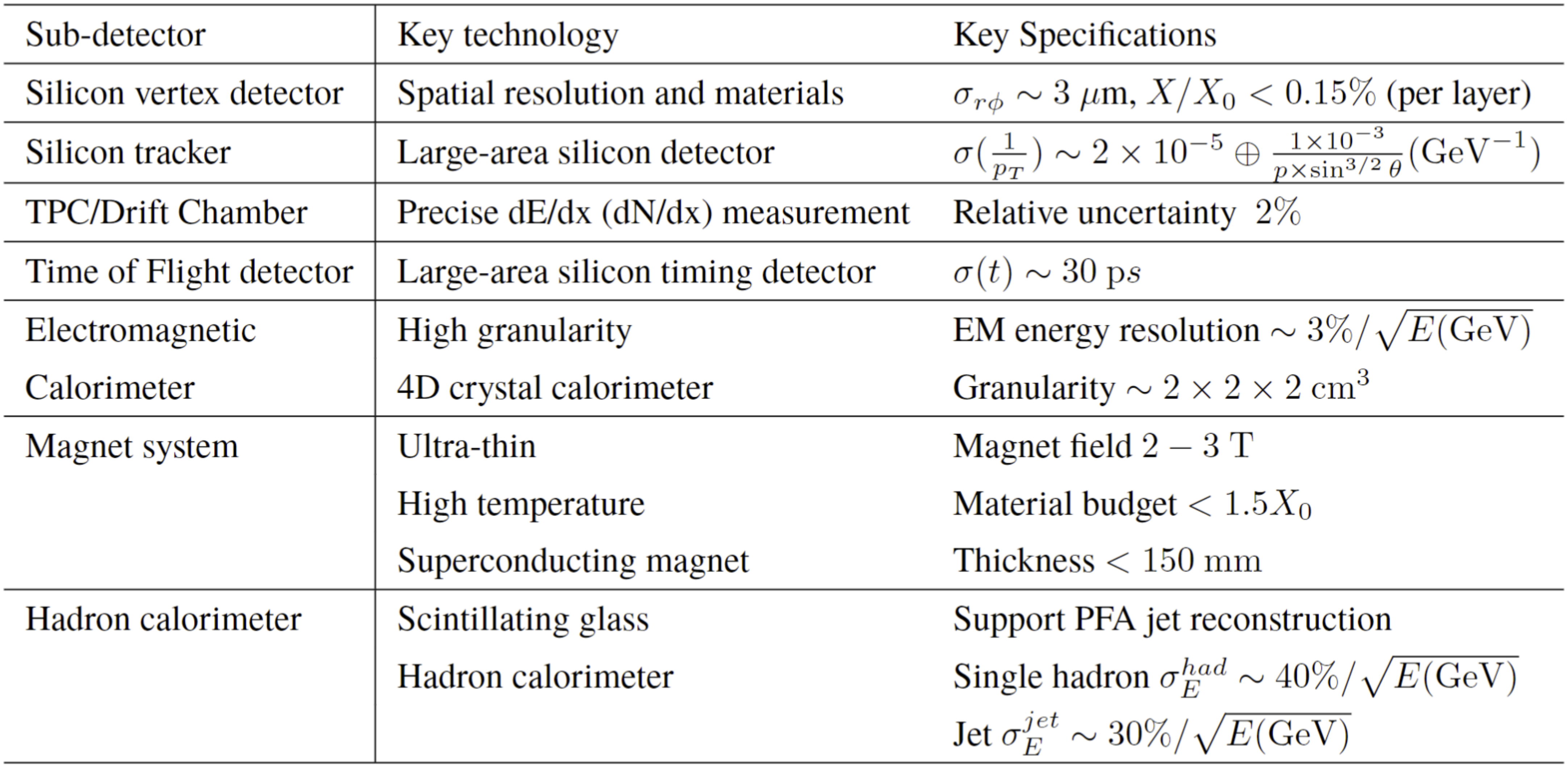
Magnet (3T/2T)

PID (DC+ToF)

Silicon Tracker

Crystal ECAL
(Transverse bar)

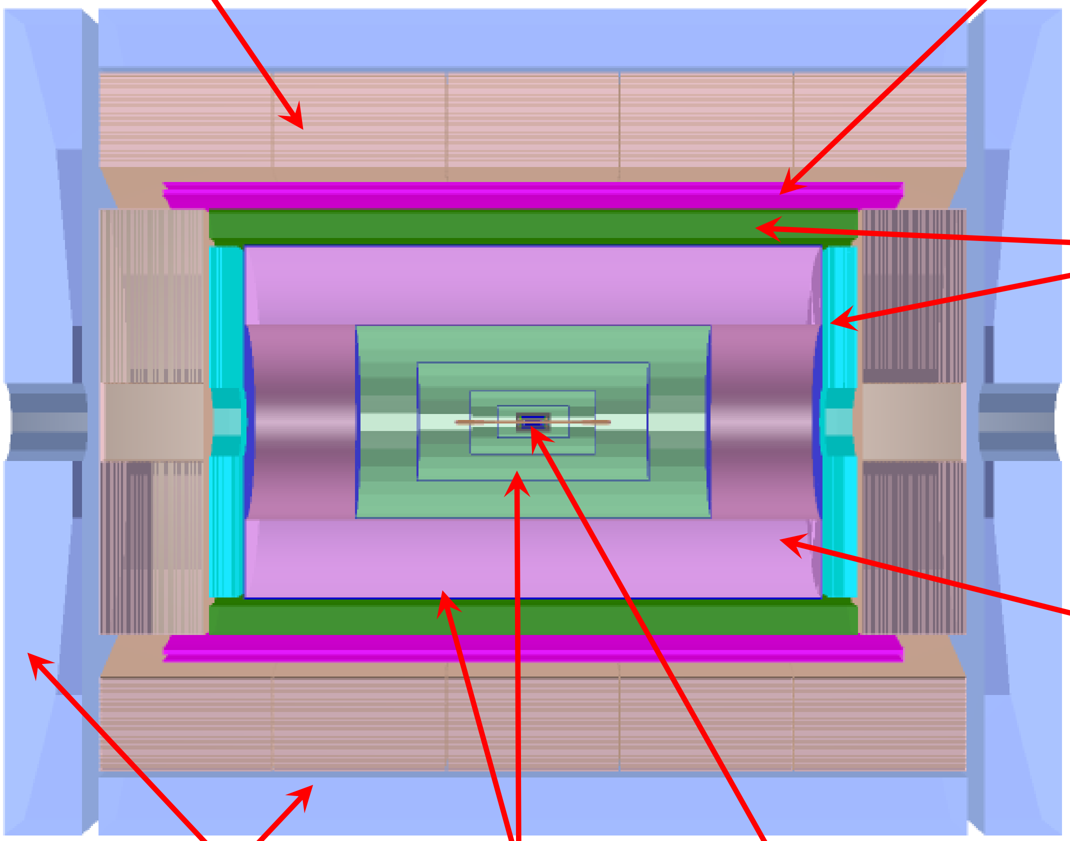
Requirements of Detector and Key Technologies



Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\mathrm{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\mathrm{GeV}^{-1})$
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 $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2 - 3$ T Material budget $< 1.5X_0$ 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 already include some of the 4th detector design

The 4th Conceptual Detector Design



Scint Glass PFA HCAL

Advantage: Cost efficient, high density

Challenges: Light yield, transparency, radiation hardness, massive production

HTS Solenoid Magnet (3T / 2T)
Between HCAL & ECAL, or inside HCAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber
that is optimized for PID

Advantage: Work at high luminosity Z runs

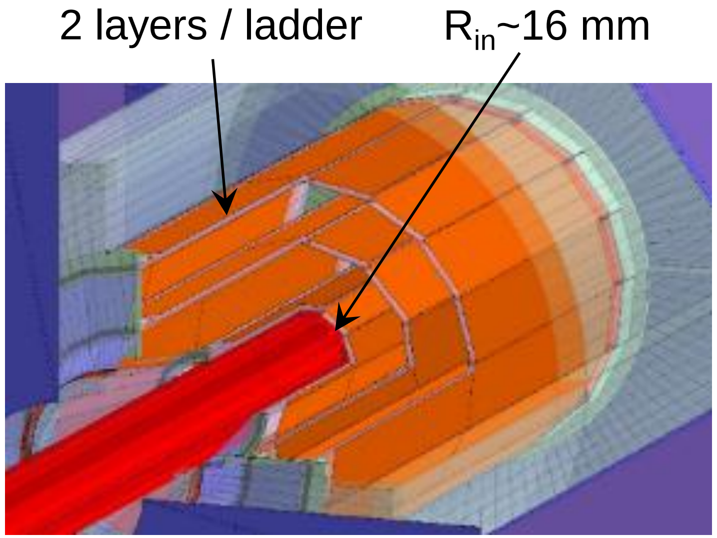
Challenges: sufficient PID power; thin enough not to affect the moment resolution. Need a supplementary ToF detector

Muon+Yoke

Si Tracker
Outer+ToF

Si Vertex

Silicon Pixel Chips for Vertex Detector



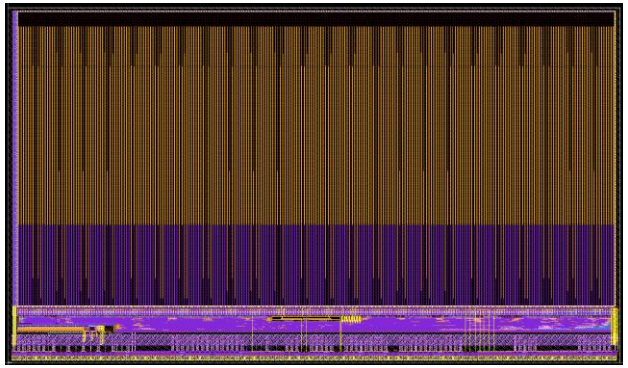
Goal: $\sigma(IP) \sim 5\ \mu m$ for high P track.

CDR design spec:

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

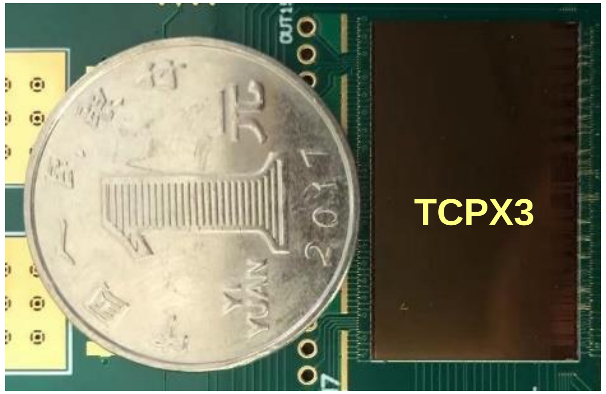
Silicon pixel sensor develops in 3 series:
JadePix / MIC, **TaichuPix**, **CPV**

JadePix4 356×498 array of 20×29 μm^2



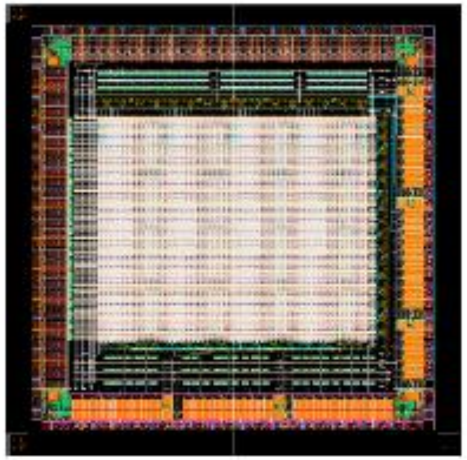
TowerJazz 180nm CIS process
$\sigma_{x/y} \sim 3\text{-}4\ \mu m$, $\sigma_t \sim 1\ \mu s$, ~100 mW/cm^2

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

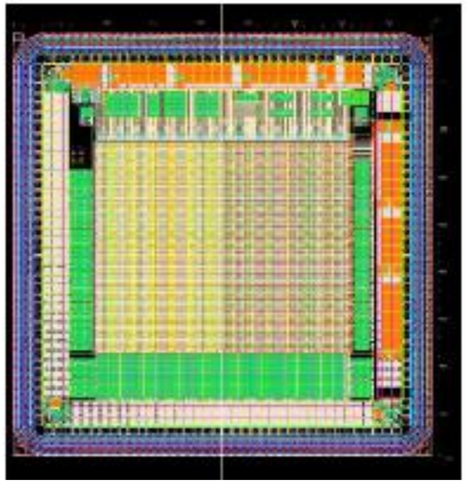


CPV4 (SOI-3D), 64×64 array
~21×17 μm^2 pixel size

Upper chip



Lower chip



LAPIS 200nm SOI process

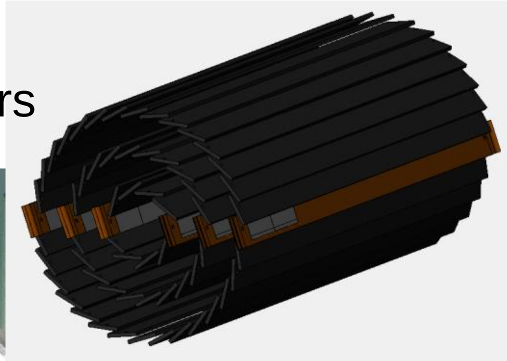
Prototyping Vertex Detector

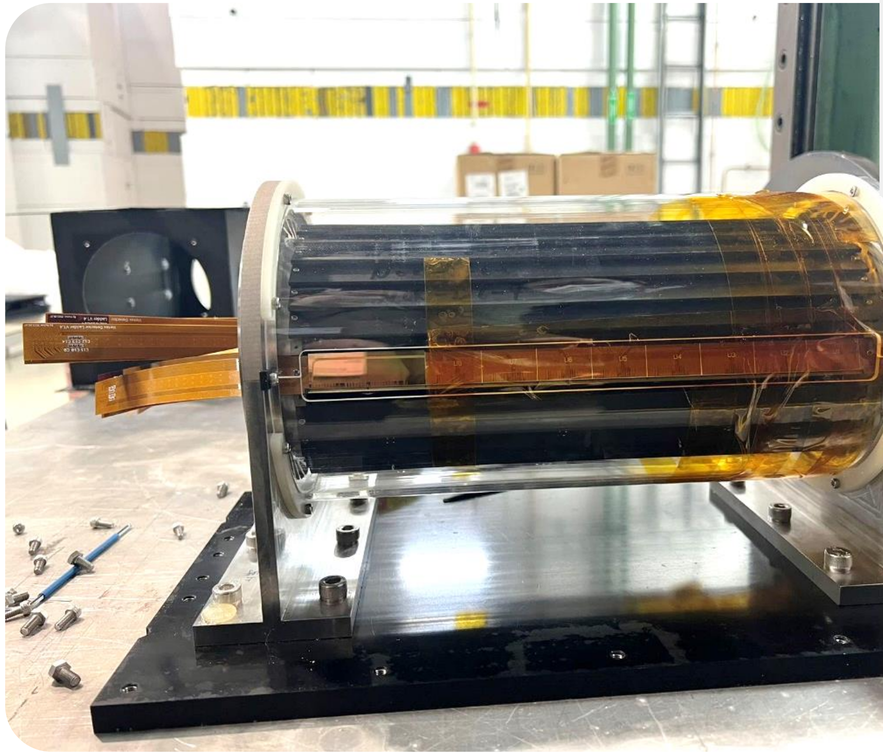
Ladder readout system

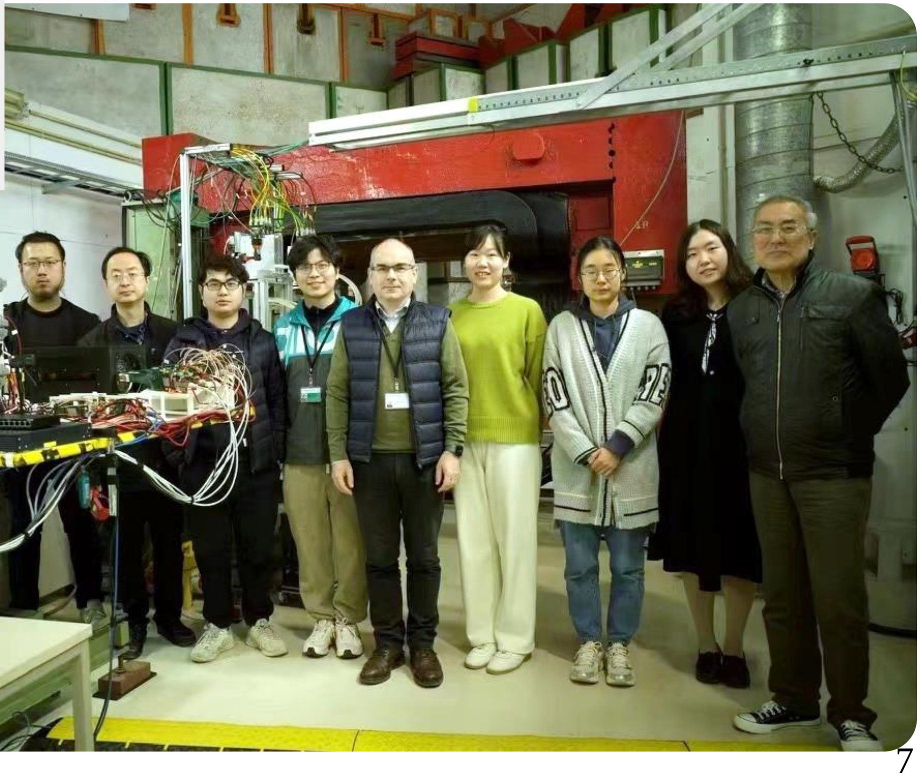
TaichuPix-based prototype detector tested at DESY in April 2023

Spatial resolution ~ **4.9 μm**

6 double-sided ladders





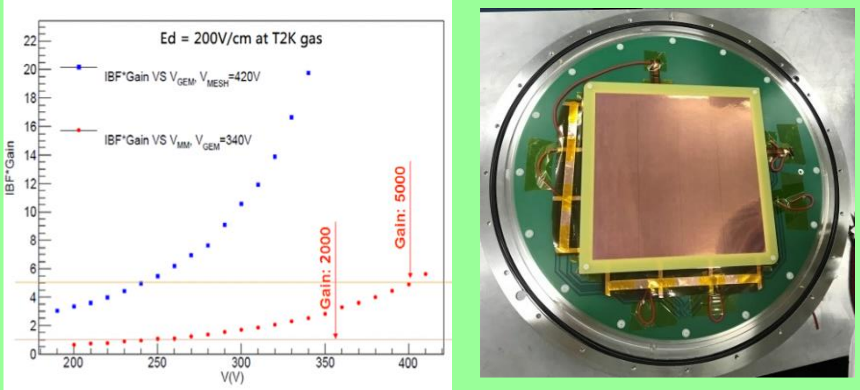


Pixelated TPC Tracker

- Initial TPC design has difficulty @high luminosity Z mode due to IBF. Decide to use pixelated TPC
- R&D roadmap:
  - From a module to a prototype
  - Low power consumption FEE ASIC
- Achievement so far:
  - Hybrid GEM+Micromegas module: IBF×Gain ~1 at G=2000
  - Spatial resolution of $\sigma_{r\varphi} \leq 100$ μm, dE/dx for PID: <4%
  - WASA chip: ~3 mW/ch with ADC, 32 channels/chip

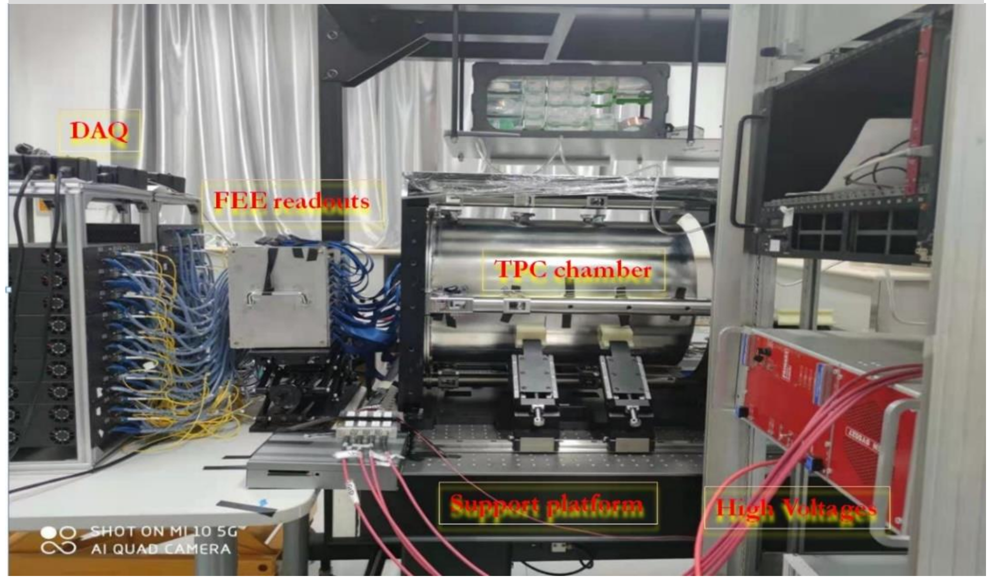
Goal:

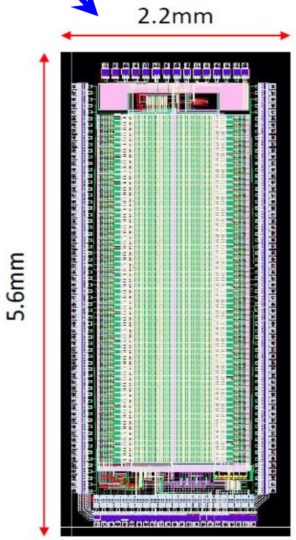
$\sigma(r\text{-}\Phi)$ ~100 μm

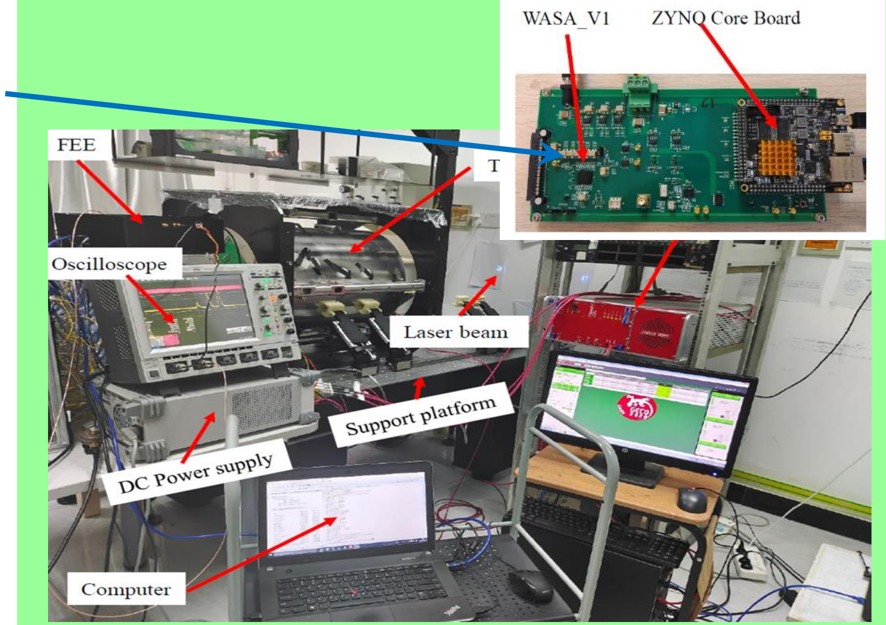


GEM+Micromegas module R&D

TPC prototype with integrated 266nm UV laser



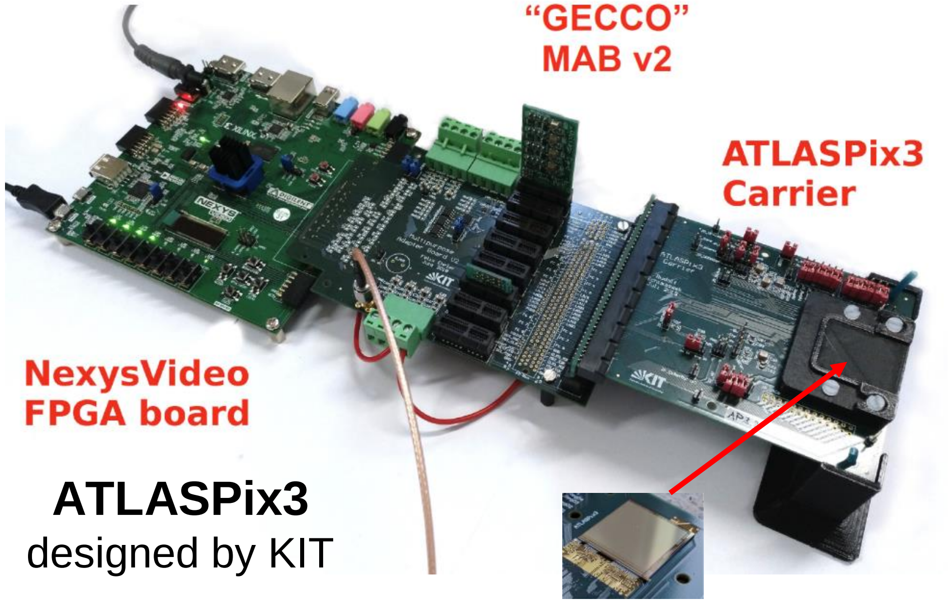




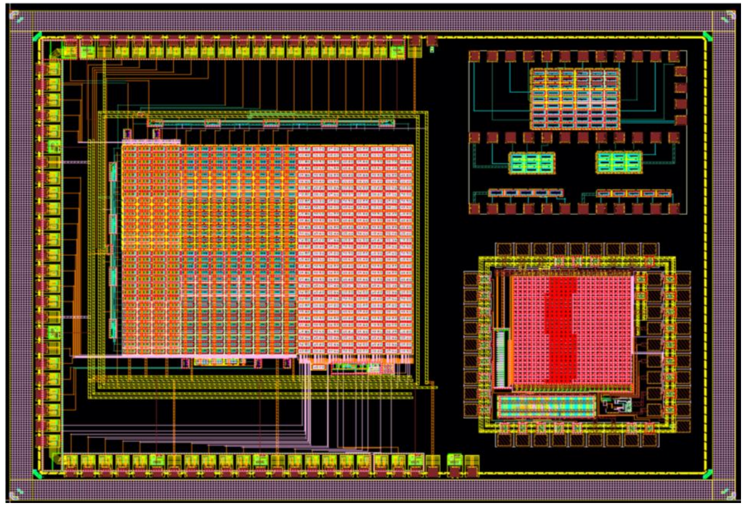
Low power consumption readout

Silicon Pixel Tracker

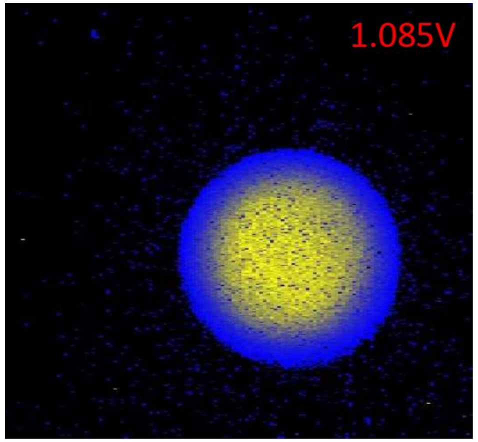
- ☐ Large area: **~140 m^2** in Full SiTrk, or **~70 m^2** in TPC+SiTrk
  ➔ Cost effectiveness
- ☐ Focus on MAPS pixel tracker, also started SSD for outer layers
- ☐ Joint efforts on an ATLASPix3 based demonstrator
- ☐ ATLASPix & MightyPix use TSI 180nm HV process
  ➔ Long term support (?)
- ☐ Exploring SMIC 55 nm HV HR process
  ➔ Smaller feature size & alternative foundry
- ☐ Other possibilities, e.g. MALTA3, TPSCo-65nm



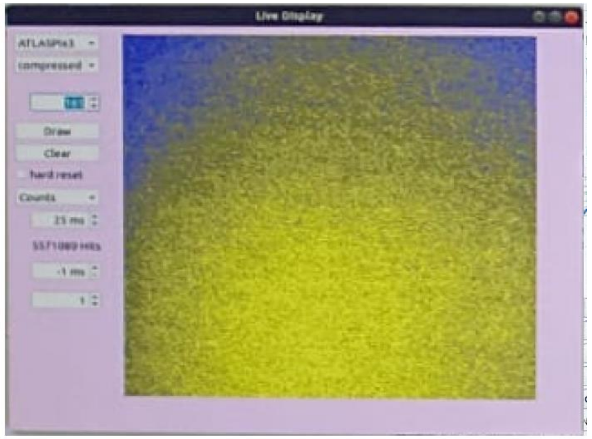
ATLASPix3
designed by KIT



The 2nd design for SMIC 55nm HV HR process

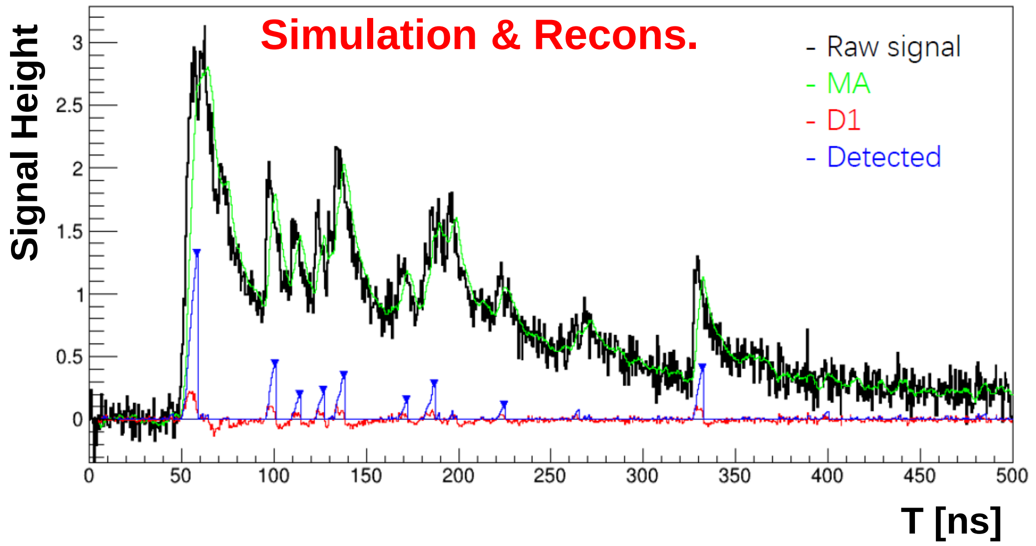


Hitmap with Fe55 source

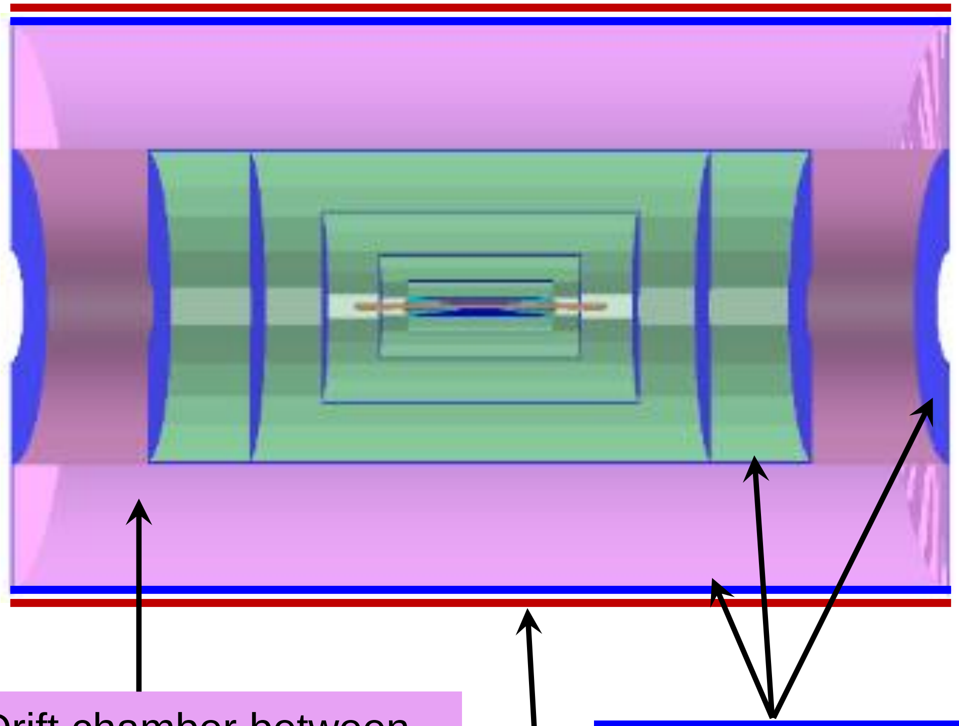


Hitmap with electron beam

PID in The Scenario of FST



- A drift chamber optimized for PID: no stereo, larger cell, optimal gas mixture and HV
- Cluster counting algorithm (dN/dX) is more powerful than conventional dE/dx, but requires much more in the readout electronics.
- Studies: dNdX reconstruction algorithm, readout electronics, prototype test in beam



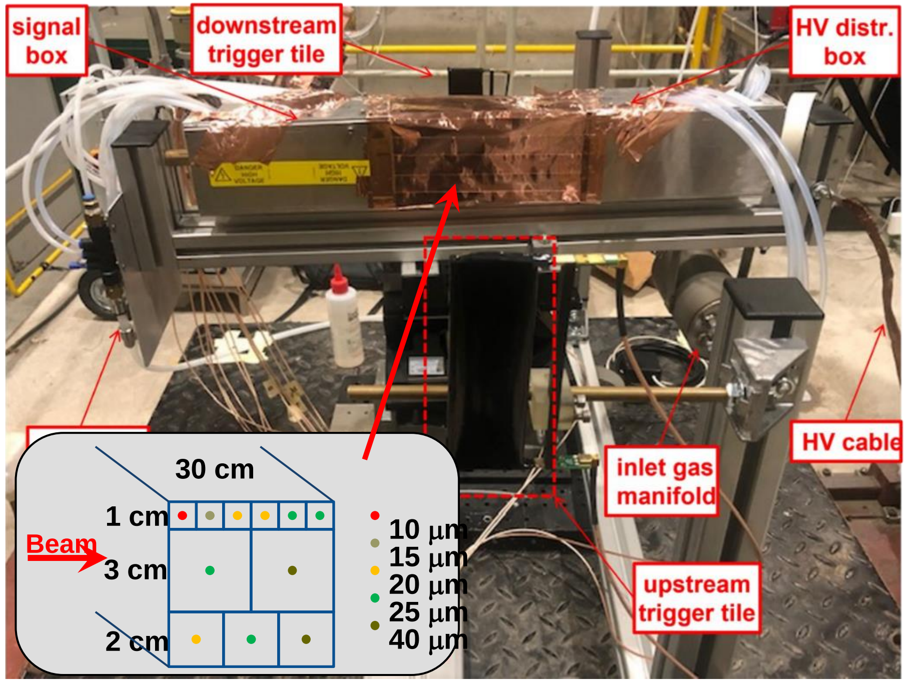
A Drift chamber between the 2 outer layers of FST, optimized for its PID power.

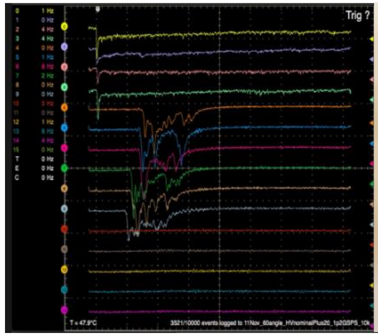
Full silicon trackers

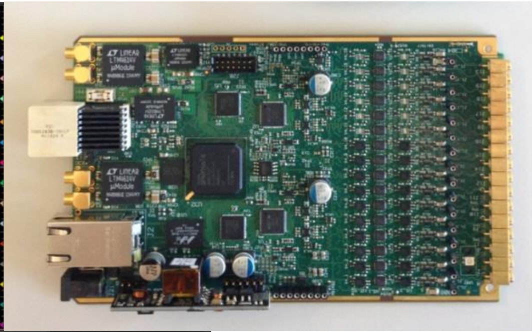
Supplementary **Time of Flight**, could be based on LGAD technology, even better if it acts as an outer SiTrk

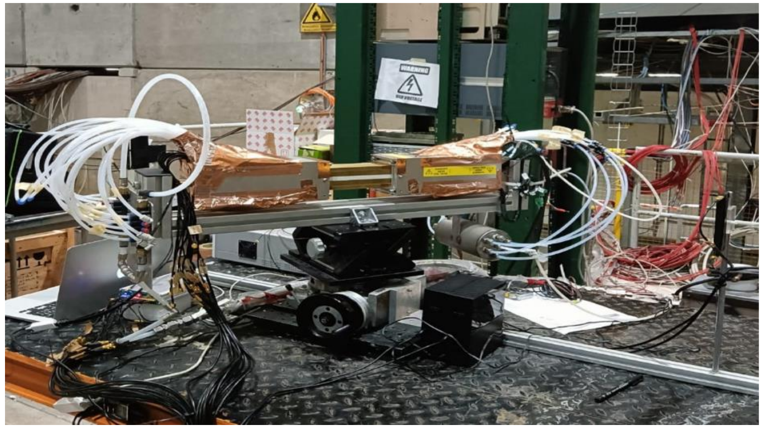
Cluster Counting Beam Tests

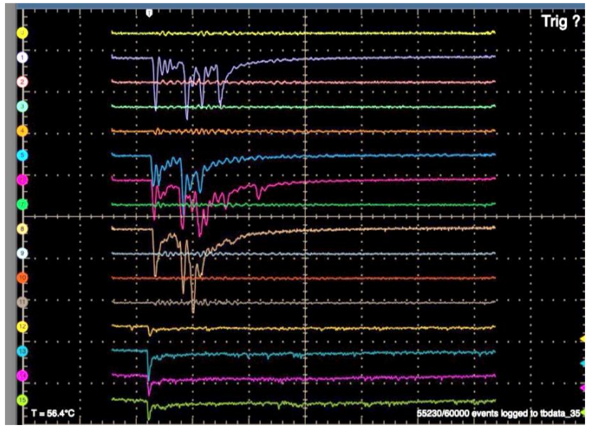
Test Beam 2021.11











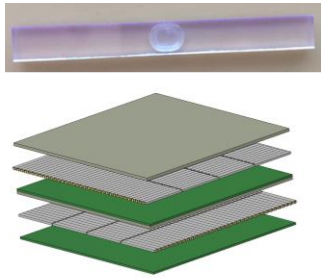
TB 2022.07

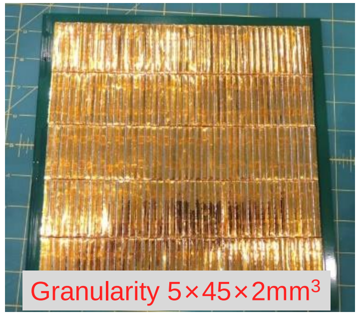
TB 2023.07

- ❑ Test beam and analysis led by the Italian group
- ❑ Measure number of clusters & efficiency, study effects of configuration
- ❑ Apply clustering algorithm in the real world, more realistic parameters to simulation

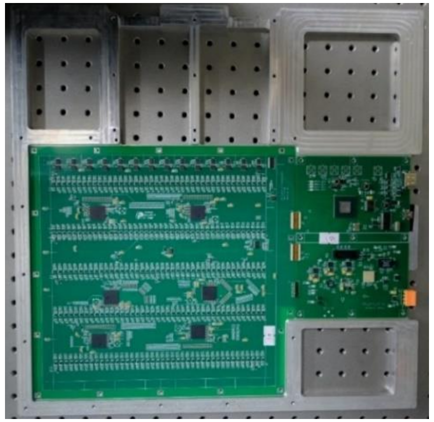
Prototype PFA Calorimeters

ECAL: scintillator(strip)+SiPM, CuW

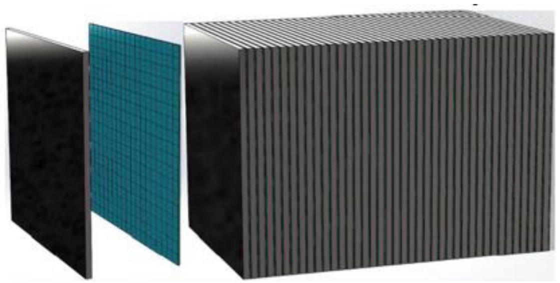


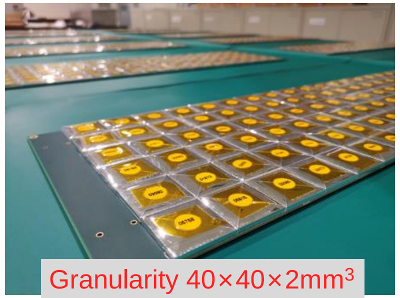


Granularity 5×45×2mm^3

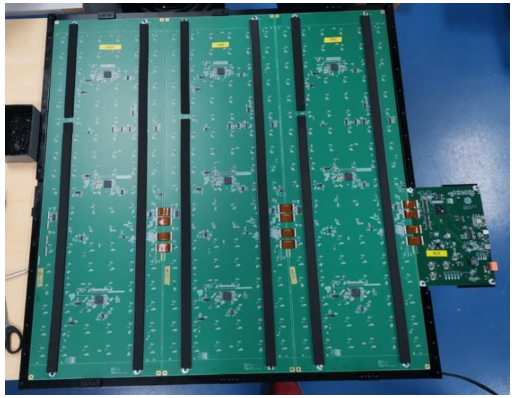


HCAL: scintillator (tile)+SiPM, steel





Granularity 40×40×2mm^3



AHCAL

Sci-W ECAL

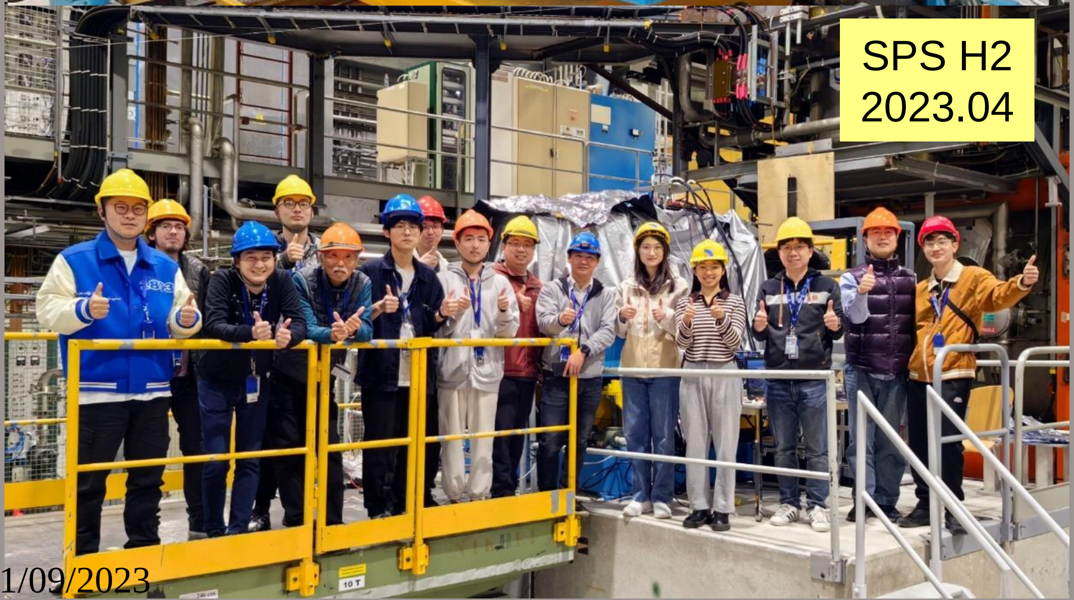
- ☐ ScW-ECAL: transverse ~20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- ☐ AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

Prototypes developed within **CALICE**

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

Testbeam of Prototype PFA Calorimeters

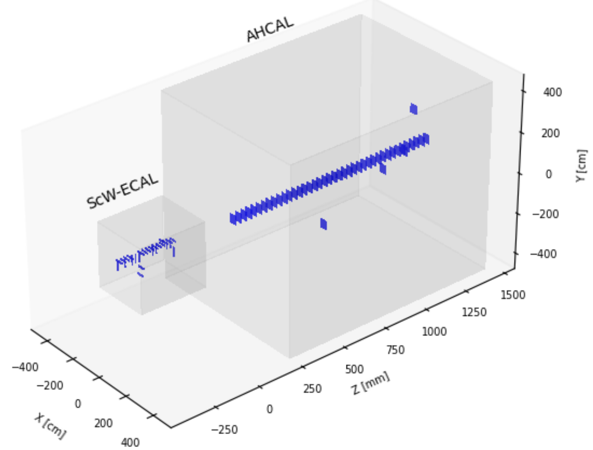

SPS H8
2022.10


SPS H2
2023.04

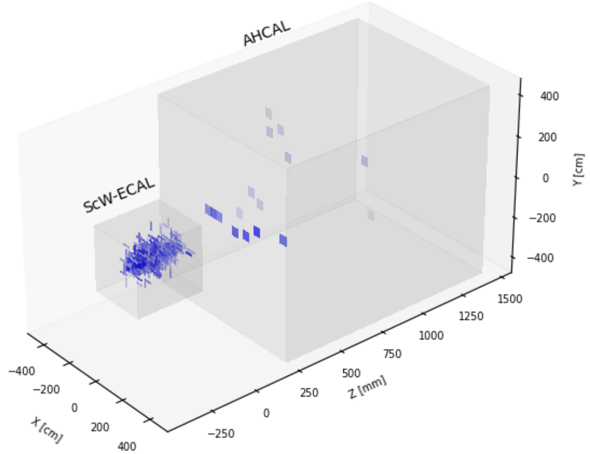

PS T9
2023.05

Selected Testbeam Events

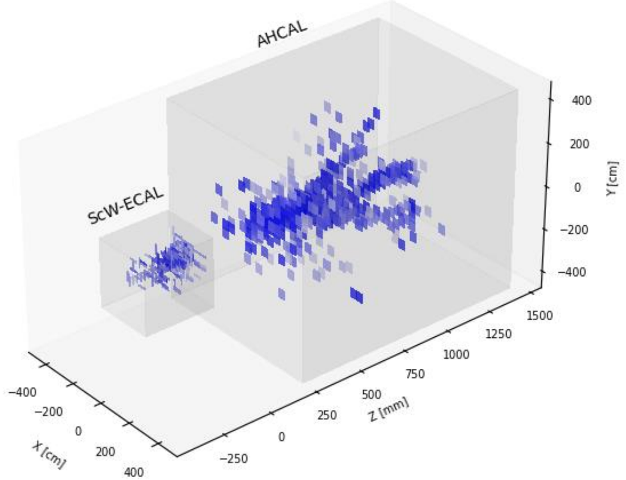
100 GeV μ^-



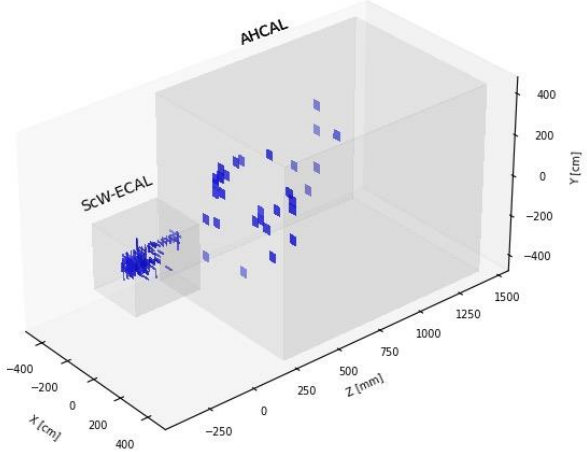
60 GeV e



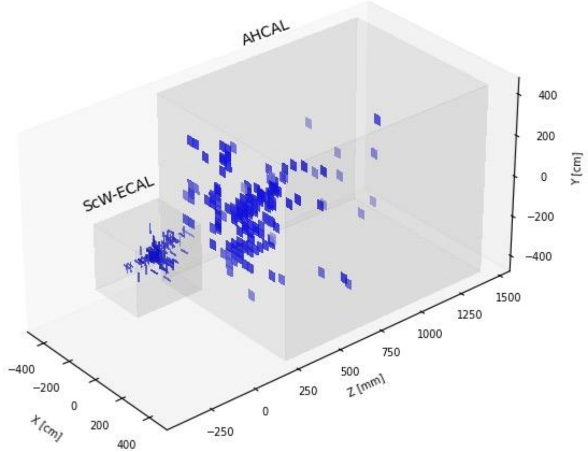
60 GeV π^-



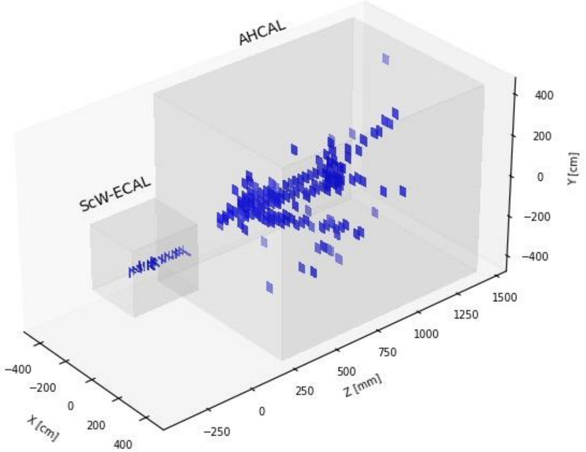
5 GeV π^-



10 GeV π^-



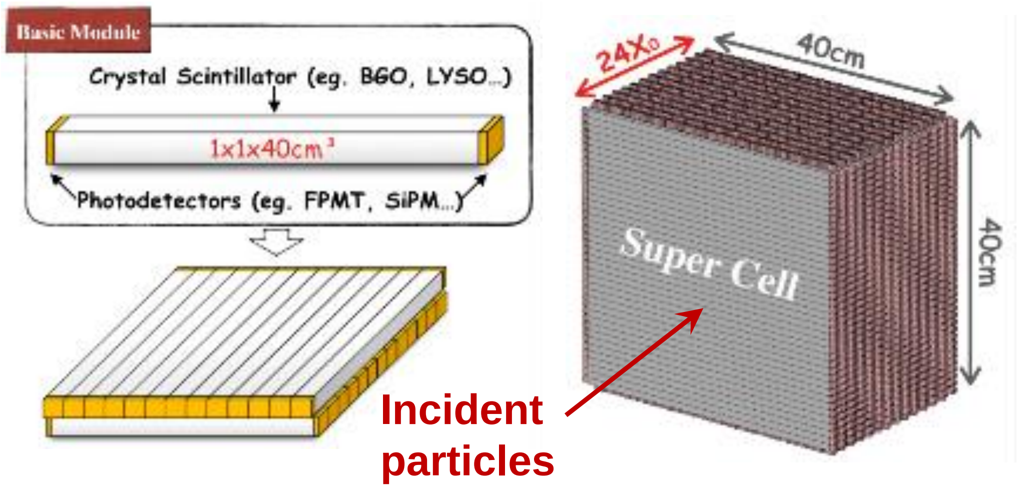
15 GeV π^-

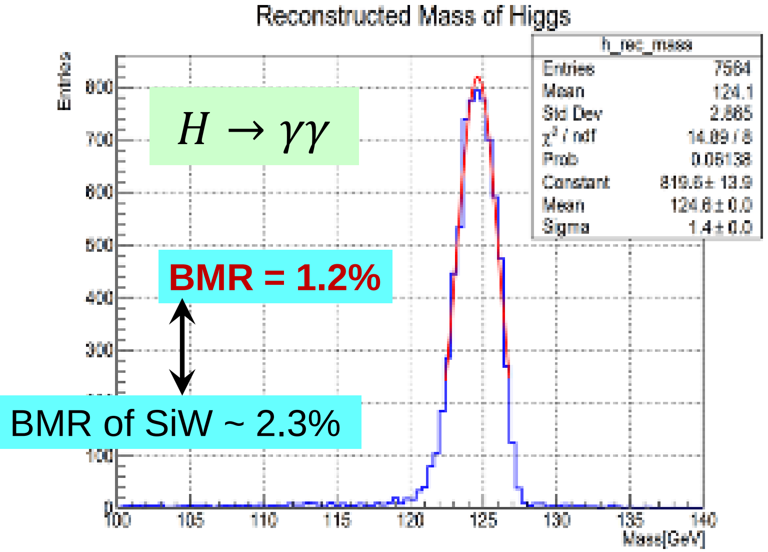


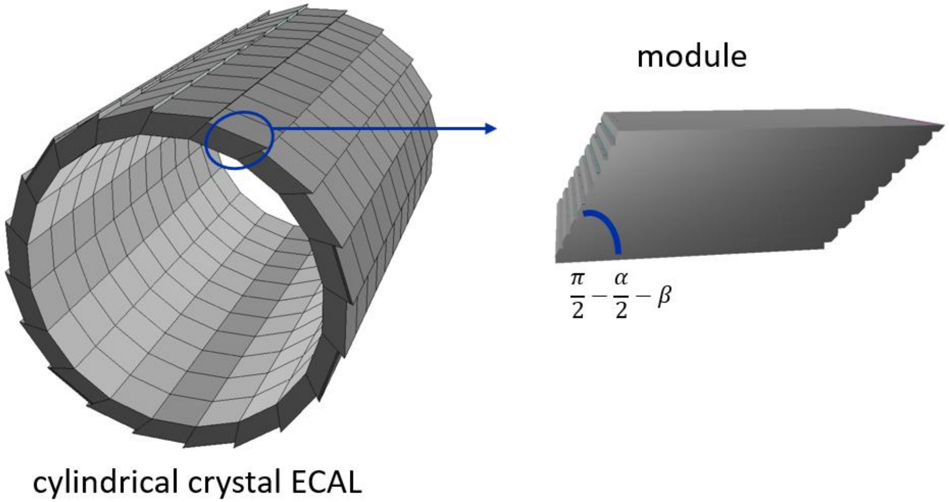
Within CALICE collaboration

4D Orthogonal Crystal Calorimeter

- Goal
  - Comparable BMR resolution as with the Si+W ECAL.
  - Much better sensitivity to γ/e, EM resolution $\leq 3\%/\sqrt{E(GeV)}$
- Features:
  - Timing at two ends of the crystal bar
  - Crossed arrangement in adjacent layers.
  - High granularity with reduced readout channels
- Key issues:
  - Ambiguity caused by 2D measurements (**ghost hit**).
  - Identification of energy deposits from particles (**confusion**).

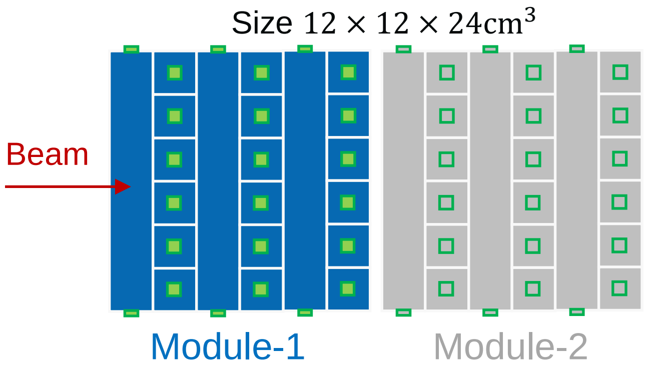


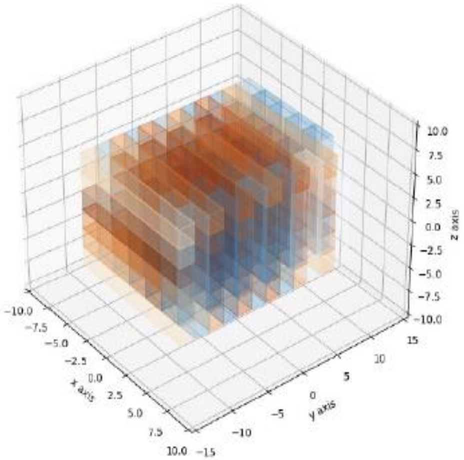


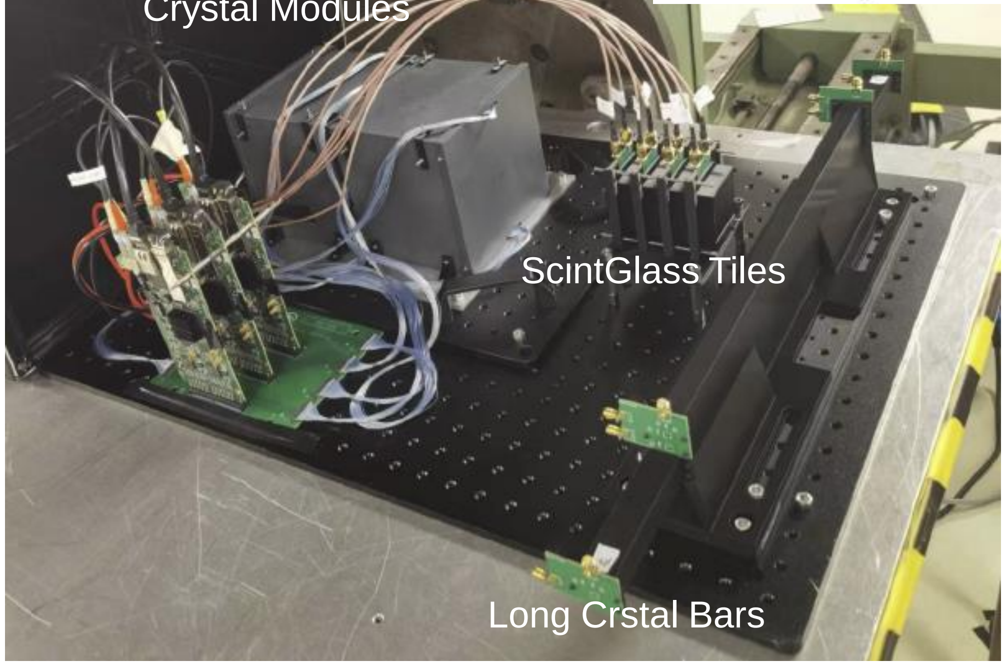


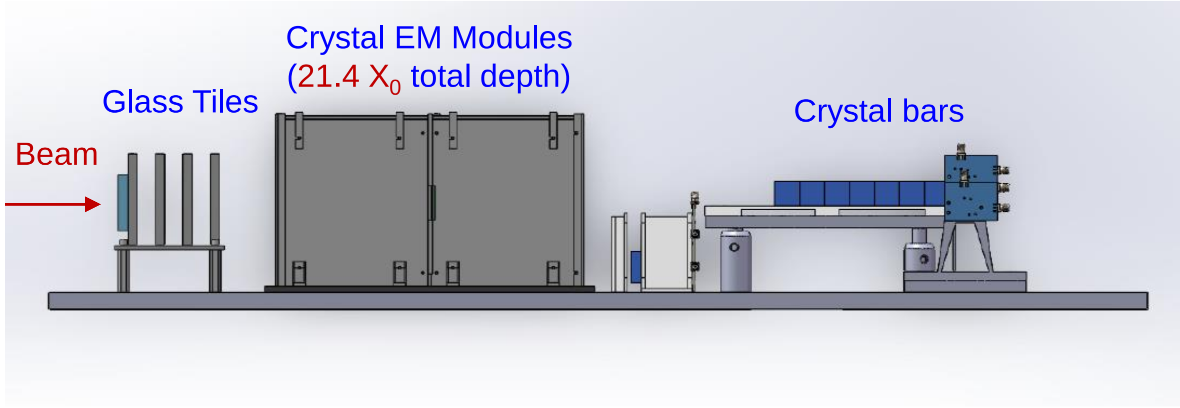
Testbeam of Prototype 4D Crystal ECAL

- 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



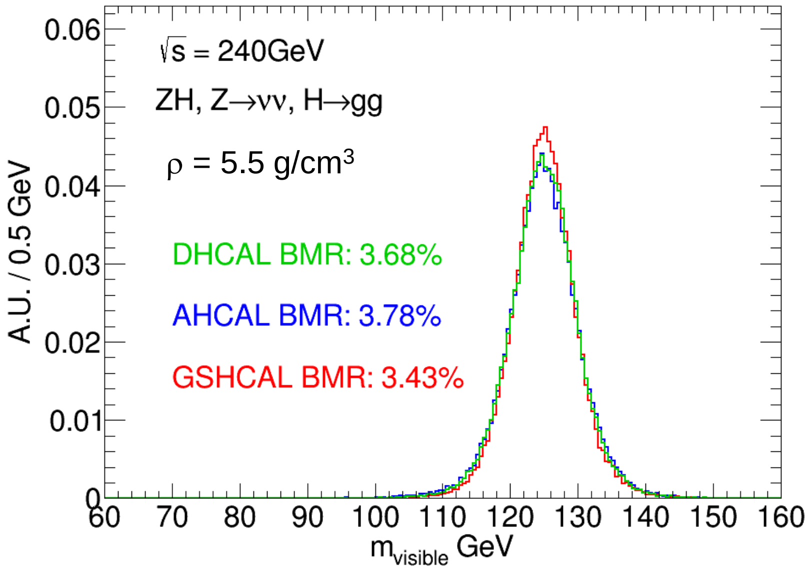




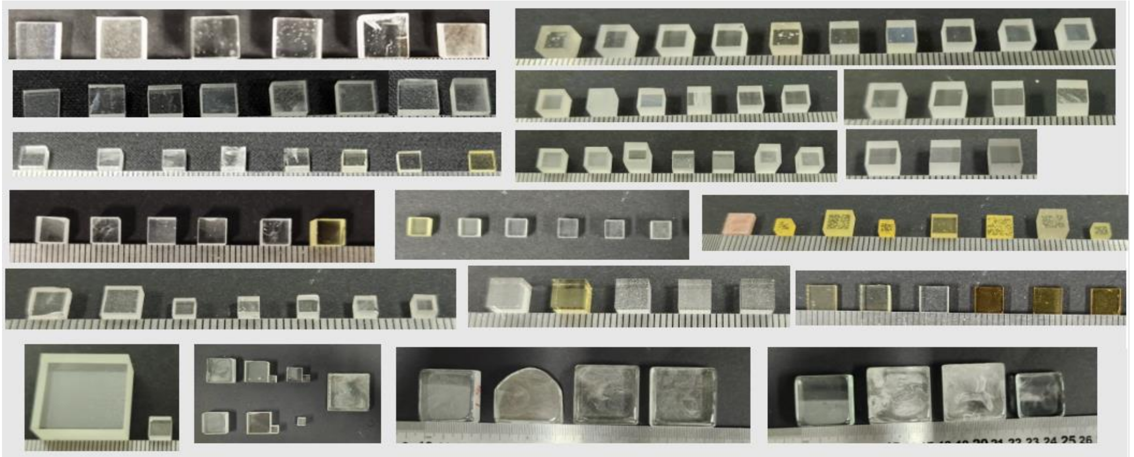


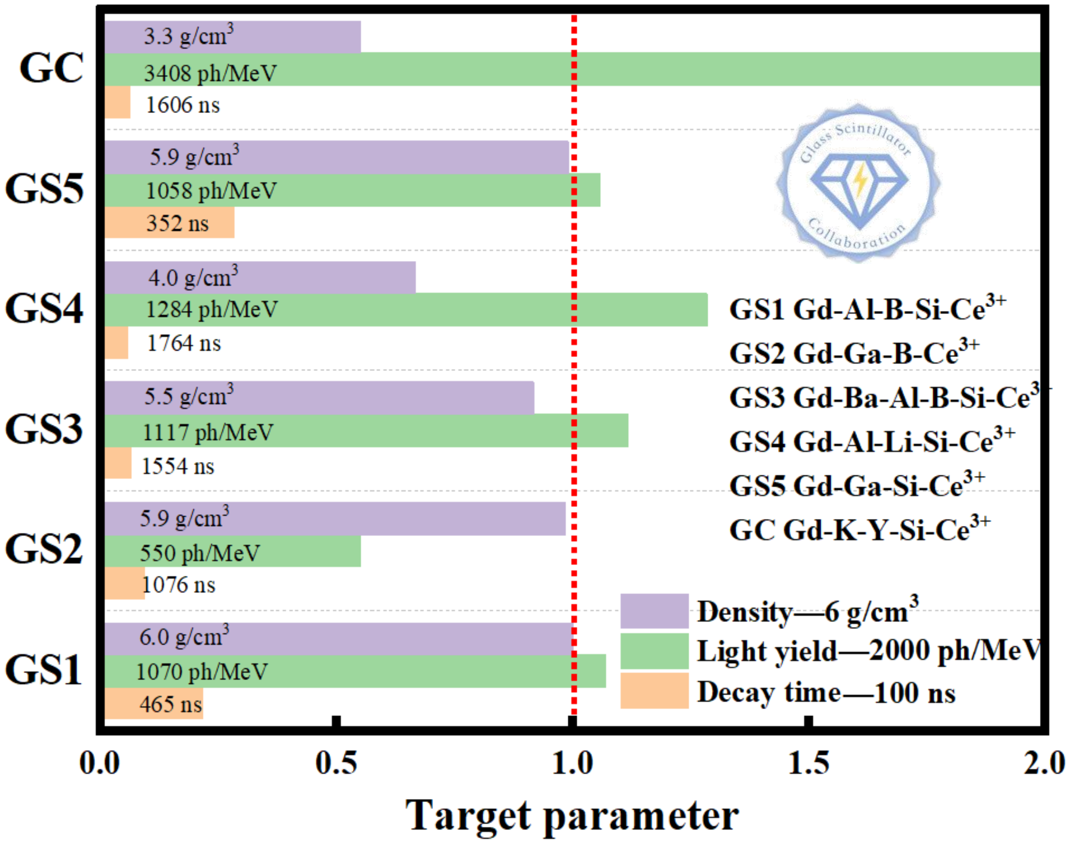
Glass Scintillator HCAL

Replacing plastic scintillator with high density glass scintillator

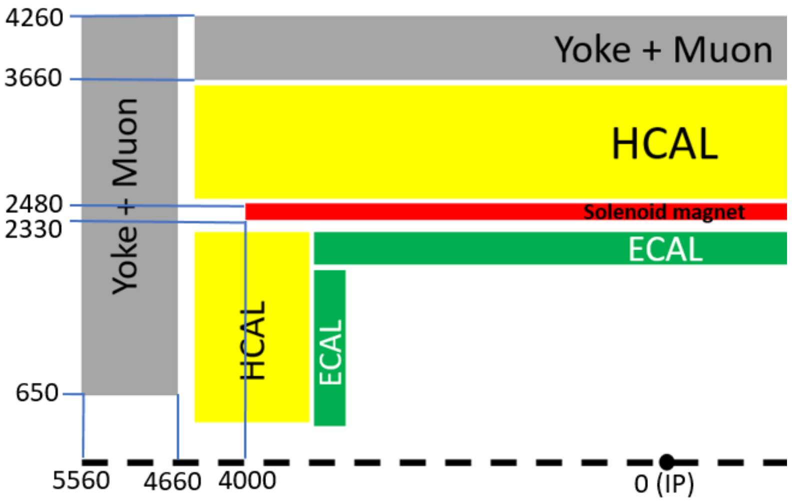


- ❑ Light yield: 1000~2000 ph / MeV
- ❑ Density: 5~7 g/cm^3
- ❑ Scintillation time: ~100 ns
- ❑ Low cost
- ❑ Tiles in cm scale for PFA HCAL





Solenoid Magnet



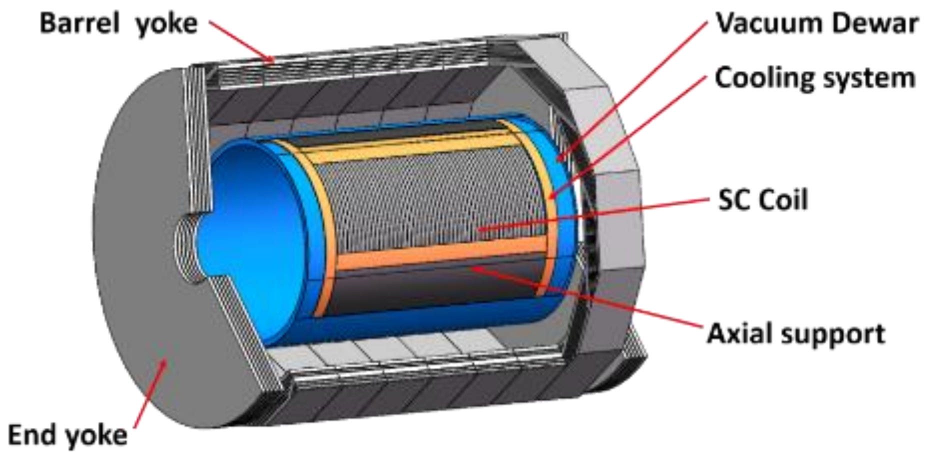
Challenges

Low mass <$1.5X_0$

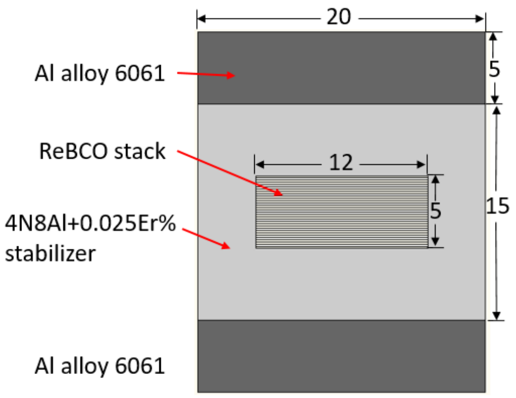
ultra-thin <150 mm

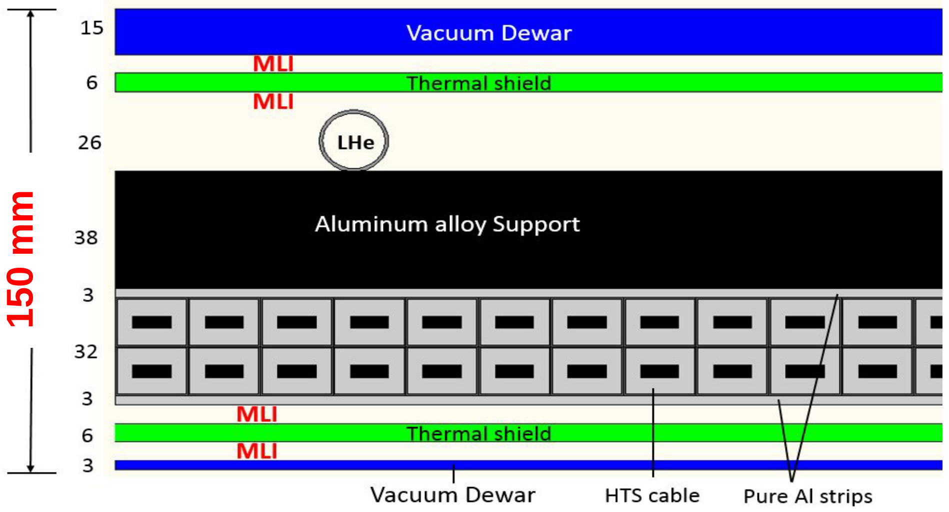
high strength cable

R&D: high strength HTS cable, ultra-thin cryostat.



Al stabilized ReBCO stacked tape conductor (ASTC) cable

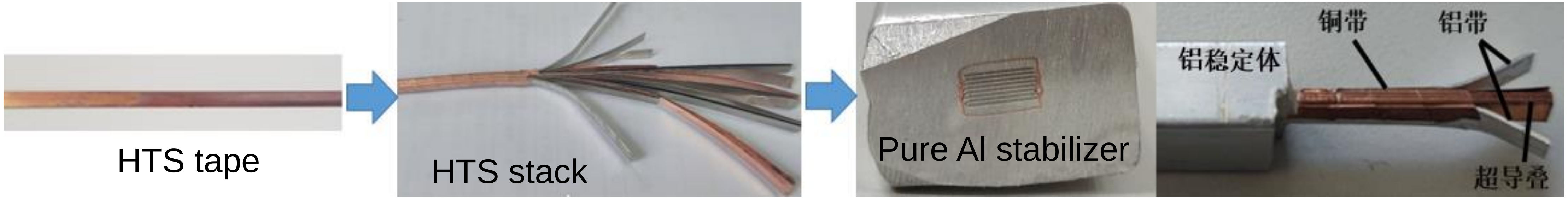




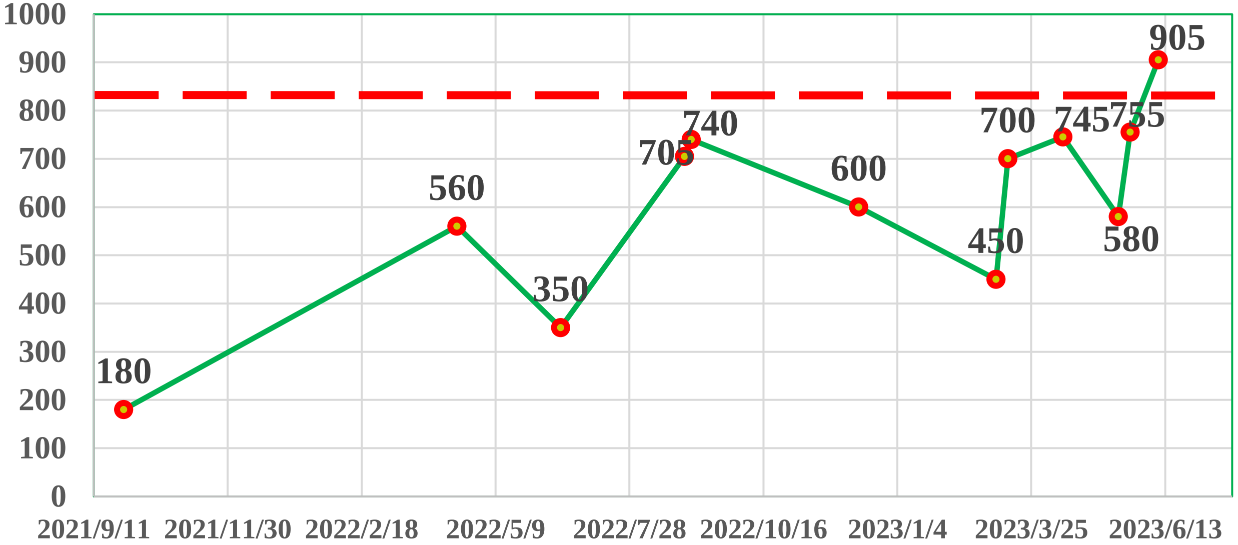
Magnetic field	3 T	Current	28000 A
Inner diameter	4660 mm	Inductance	1.27 H
Outer diameter	4960 mm	Stored energy	500 MJ
Magnet thickness	150 mm	Cold mass	27 ton
Length	8000 mm	HTS cable length	10.7 km
Total weight	48 ton	ASTC weight	16.6 ton

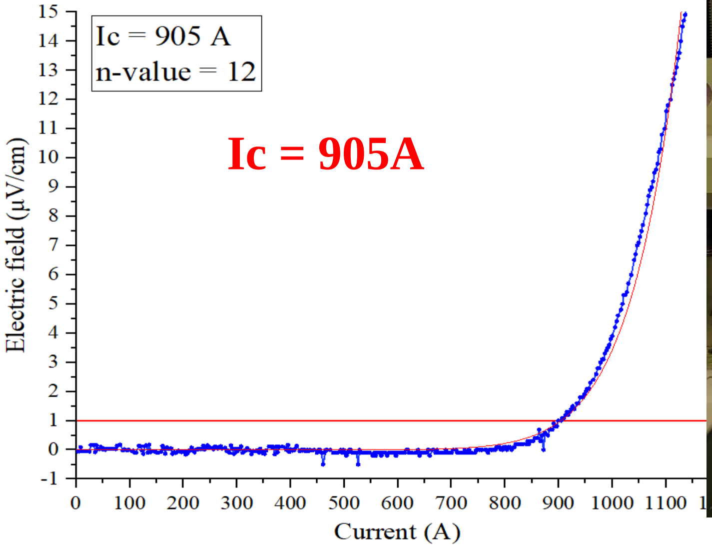
HTS Cable Development

Significant progress !



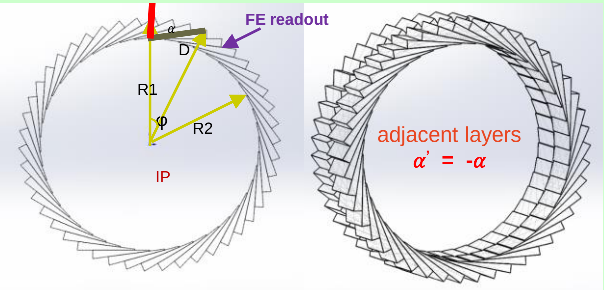
Object： single tape core Ic > 100 A@77K； 14-core cable Ic > 830 A@77K, self-field.





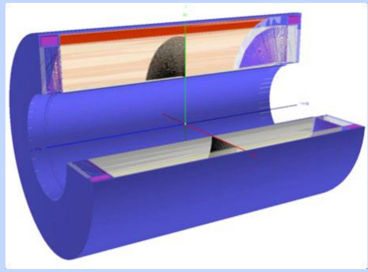
Many Other Detector R&Ds

Stereo Crystal ECAL



LGAD ToF

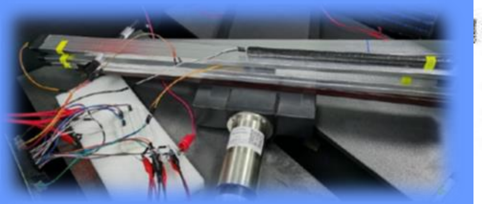
Drift Chamber

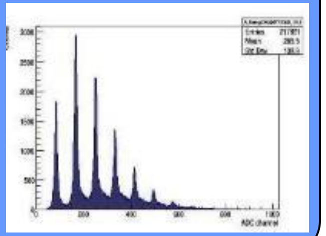


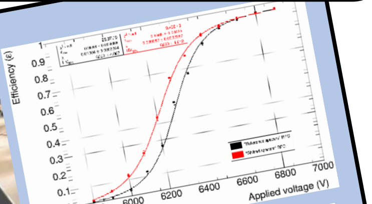
AD9689 – 2000 EBZ

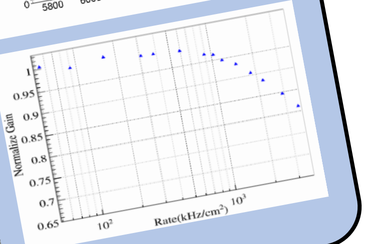
Xilinx KCU105

Scintillator Bar Muon

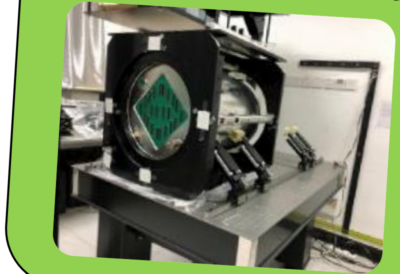


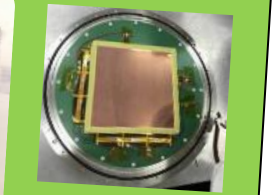




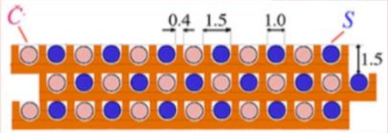


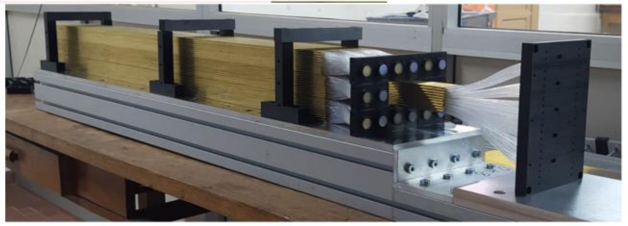
TPC Prototype

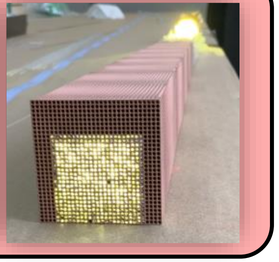


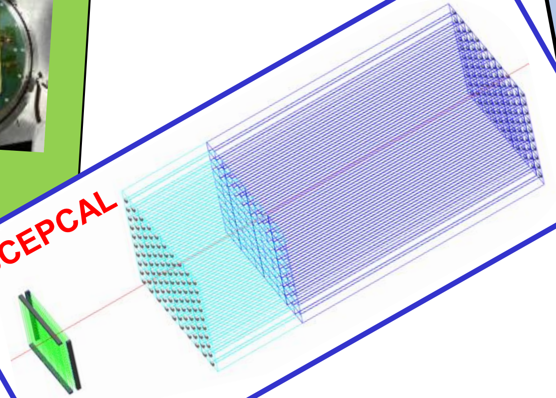


Dual Readout CAL

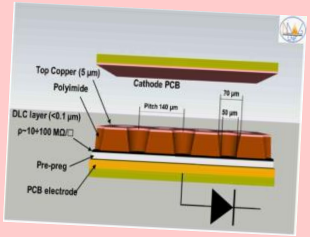


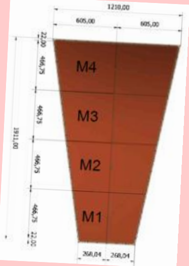




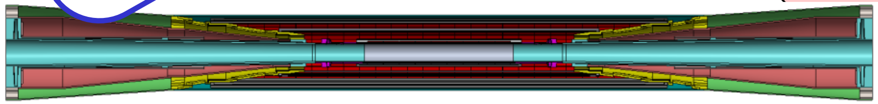


μRWELL for PS & Muon





Beampipe Design



R&D Efforts for Future Higgs Factories

Det	Technology
Pixel Vertex	JadePix
	TaichuPix
	CPV(SOI)
	Stitching
	Arcadia
Tracker & PID	CEPCPix
	Silicon Strip
	TPC
	Drift chamber
	PID DC
	AC-LGAD ToF
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL
	Fast LumMoni
	CEPC SW

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

- Some R&D efforts are already associated with international collaborations: CALICE, LCTPC, & RD*
- The ECFA DRDs cover much broader scopes, with more general supports, e.g. testbeam facilities
- We will never stop seeking for better technologies.
- However, we need to converge for TDR of a reference detector
  - Start preparation in January of 2024
  - A draft version by December of 2024
  - Official release by **June 30, 2025**

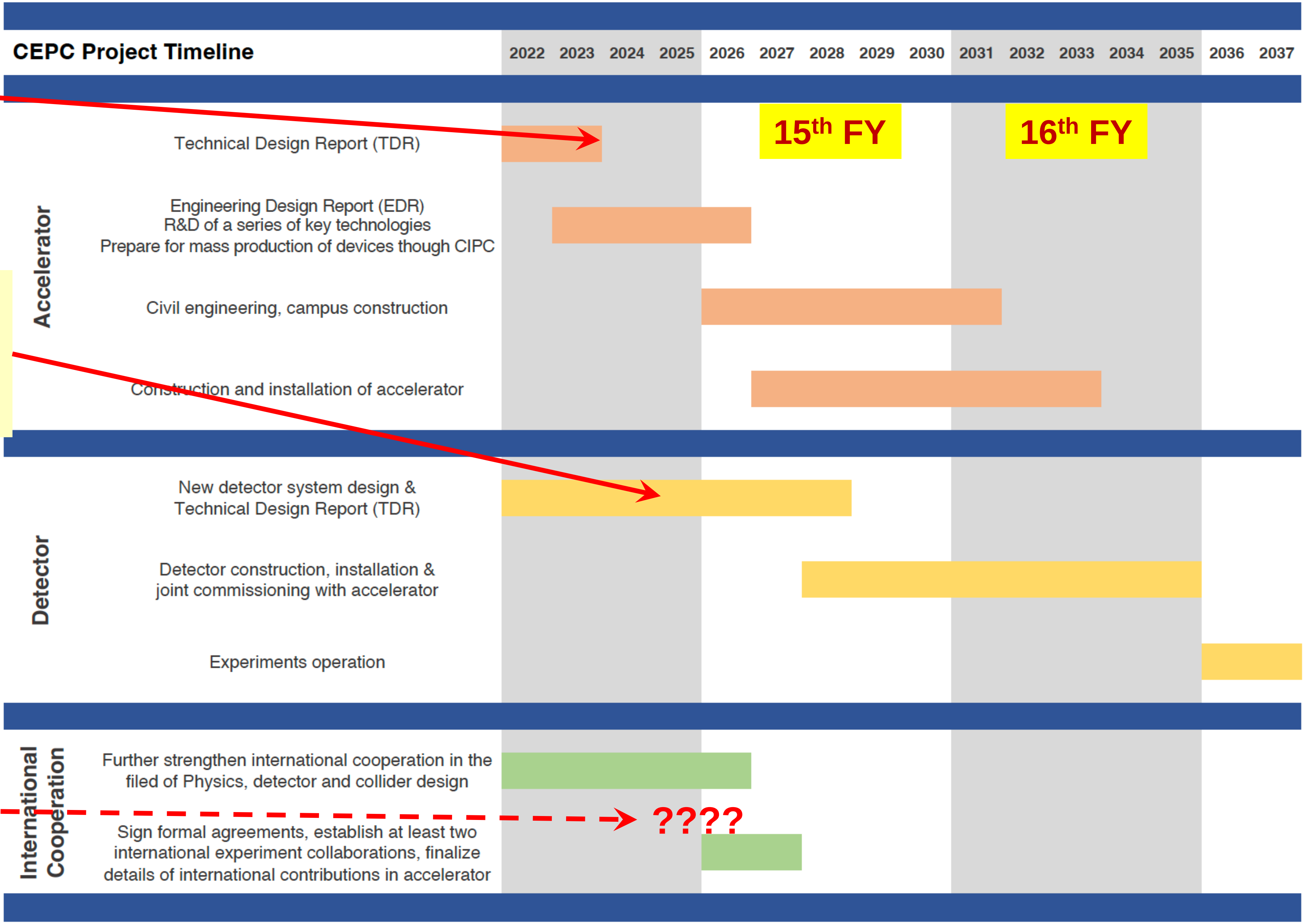
Optimal Timeline of CEPC

Completion of Accelerator TDR

Goal

TDR of a Reference Detector @ June 30, 2025

International Collaborations



11/09/2023