Status of The CEPC Detector R&D

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CEPC味物理-新物理和相关探测技术研讨会

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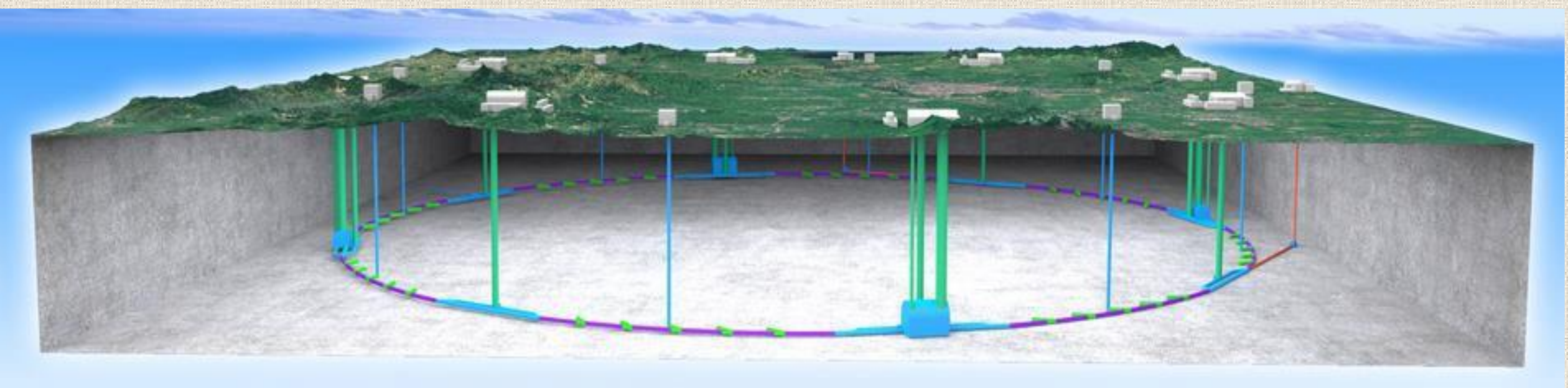
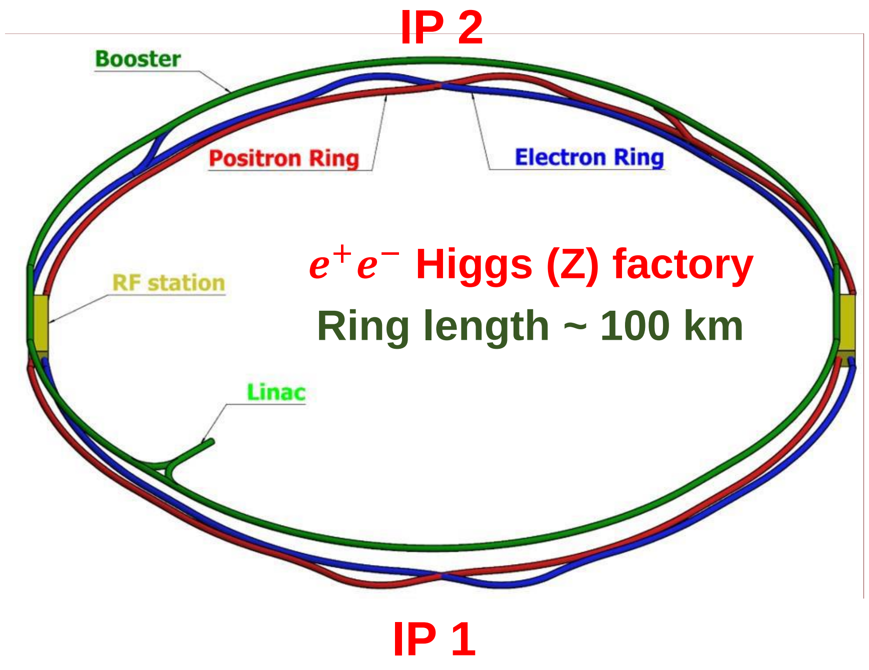


The Circular Electron Positron Collider (CEPC)

- ☐ 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 [$\times10^{34}$ 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 [$\times10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	50 MW	*L* / IP [$\times10^{34}$ 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

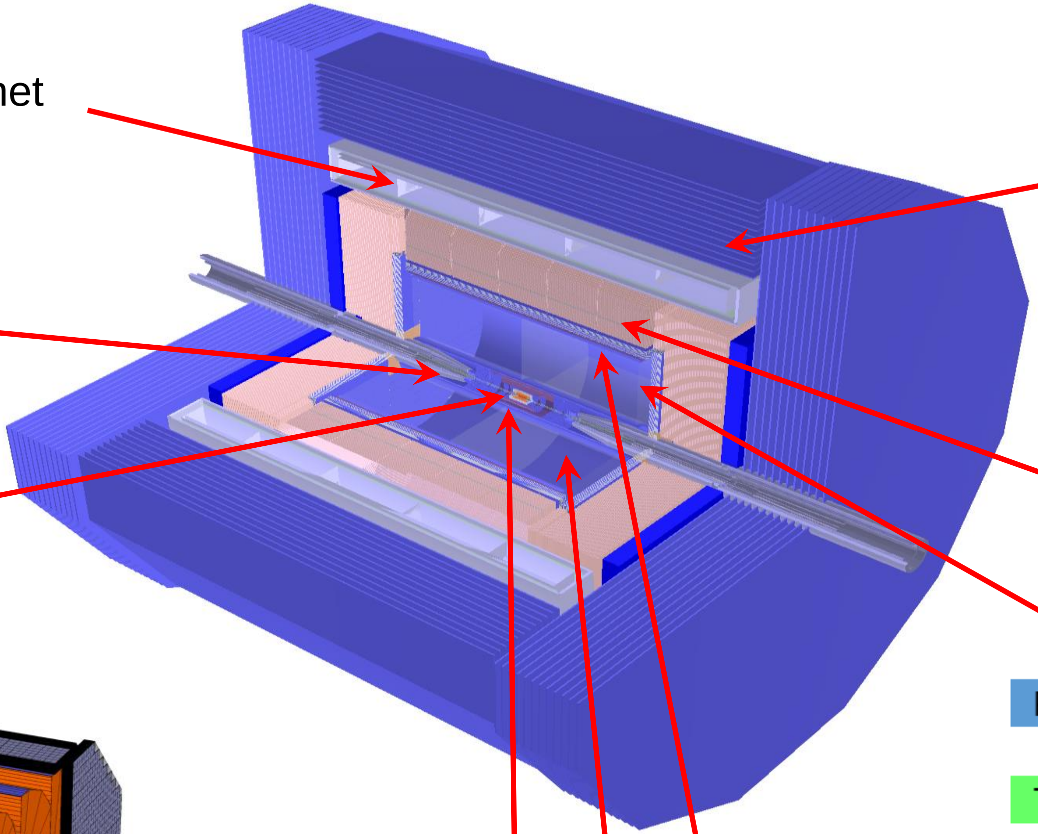
Requirements of Detector and Key Technologies

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
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	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$
	4D crystal calorimeter	Granularity $\sim 2 \times 2 \times 2\ \text{cm}^3$
Magnet system	Ultra-thin	Magnet field $2 - 3$ T
	High temperature	Material budget $< 1.5X_0$
	Superconducting magnet	Thickness < 150 mm
Hadron calorimeter	Scintillating glass	Support PFA jet reconstruction
	Hadron calorimeter	Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$
		Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

These specifications already include some of the 4th detector design

Detector Designs in The CDR

Particle Flow Algorithm (Baseline Detector)



3T / 2T
Solenoid Magnet

LumiCal

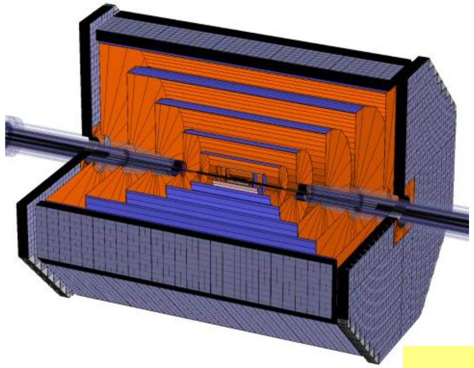
Si Pixel Vertex

Yoke + Muon (RPC or μ-RWELL)

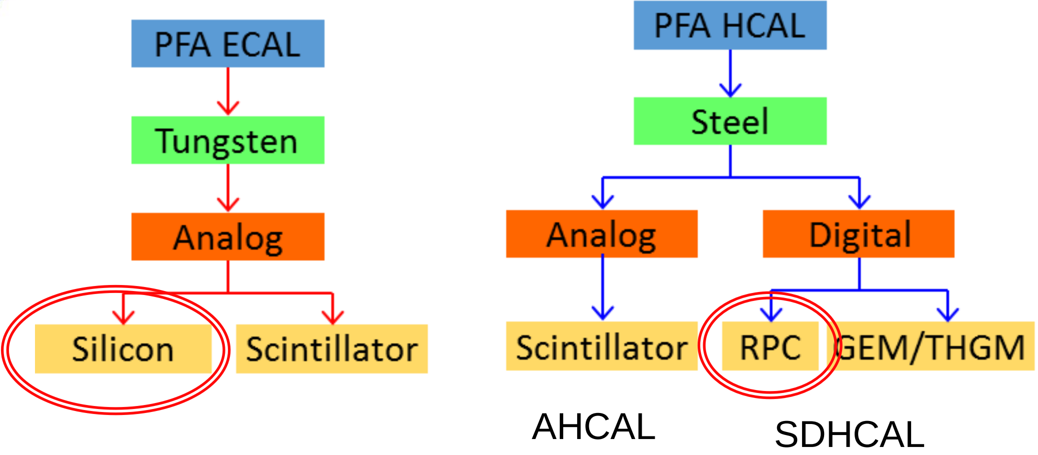
High granularity
sampling calorimeters

SIT **TPC** SET
FTD ETD

Full Silicon Tracker



An alternative plan,
especially if TPC has difficulty
in the high luminosity Z mode

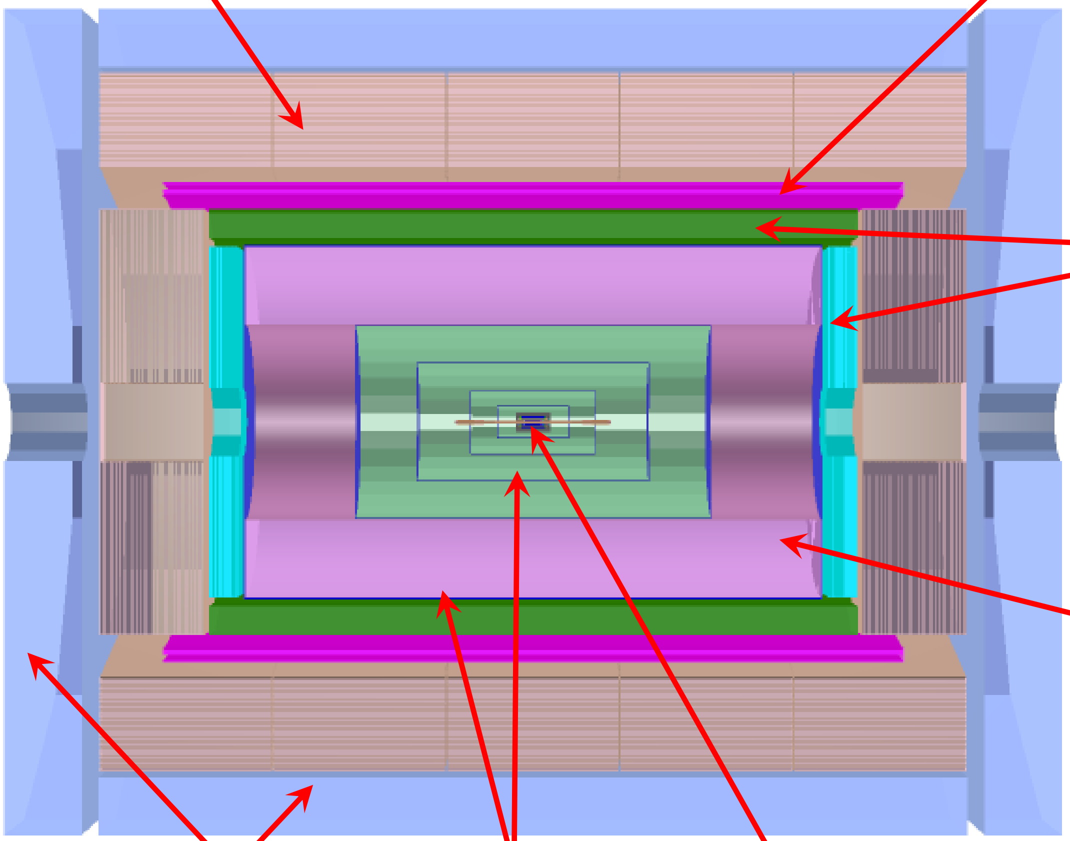


PFA ECAL → Tungsten → Analog → Silicon, Scintillator

PFA HCAL → Steel → Analog → Scintillator (AHCAL)

PFA HCAL → Steel → Digital → RPC, GEM/THGM (SDHCAL)

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

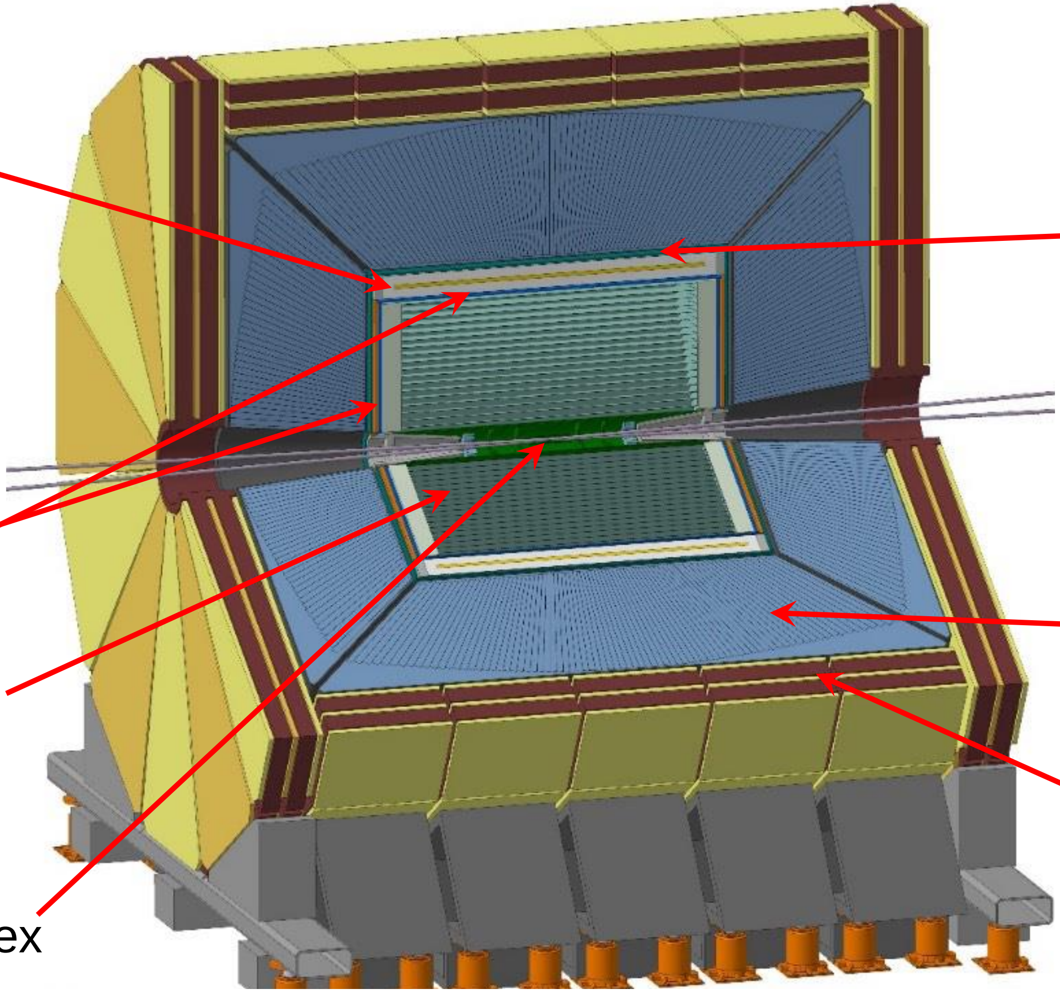
Advantage: Work at high luminosity Z runs

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

Muon+Yoke **Si Tracker** **Si Vertex**

IDEA Detector Design in The CDR

IDEA concept
(also proposed for FCC-ee)



2T Magnet

Pre-shower (μ-RWELL)

Silicon wrapper

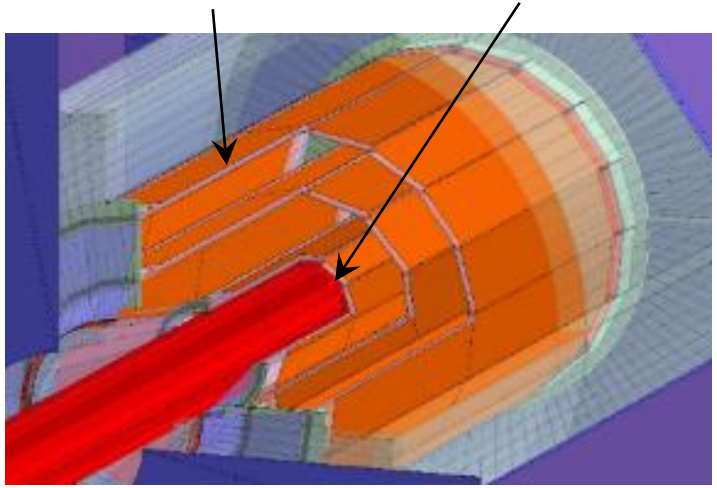
Dual-readout calorimeter

Drift chamber

Yoke + Muon (μ-RWELL)

Si Pixel Vertex

Silicon Pixel Chips for Vertex Detector


2 layers / ladder

R_{in}~16 mm

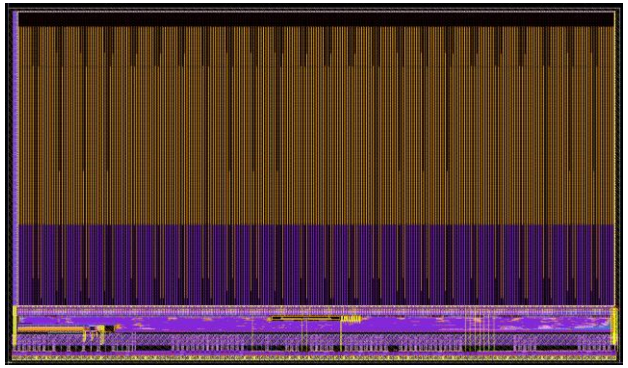
Goal: σ(IP) ~ 5 μm for high P track.

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**

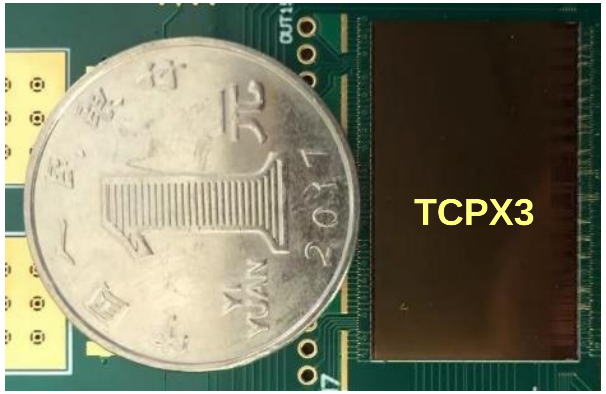
JadePix4 356×498 array of 20×29 μm^2



TowerJazz 180nm CIS process

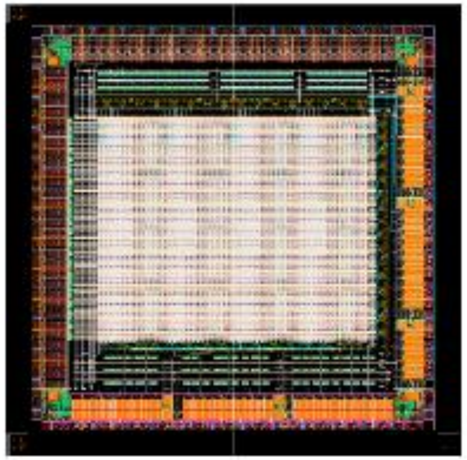
$\sigma_{x/y}$ ~ 3-4 μm, σ_t ~ 1 μs, ~100 mW/cm^2

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

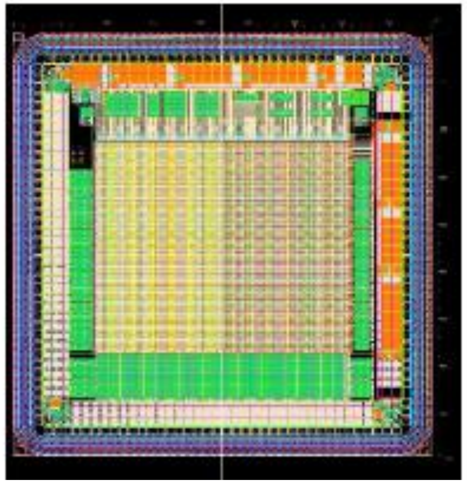


CPV4 (SOI-3D), 64×64 array
~21×17 μm^2 pixel size

Upper chip



Lower chip



LAPIS 200nm SOI process

Timeline of Silicon Pixel Sensor R&D

2015 **2017** **2019** **2021** **2023**

JadePix-1

JadePix-2/MIC4

JadePix-3

JadePix-4/MIC5

MOST1 (2016-2021)

MOST3 ? ?

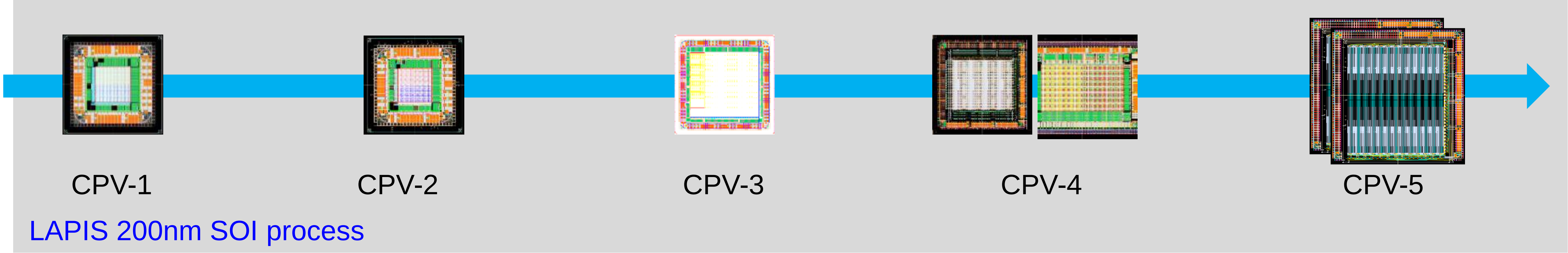
MOST2 (2018-2023)

TaichuPix-1

TaichuPix-2

TaichuPix-3

TowerJazz 180nm CIS process



CPV-1

CPV-2

CPV-3

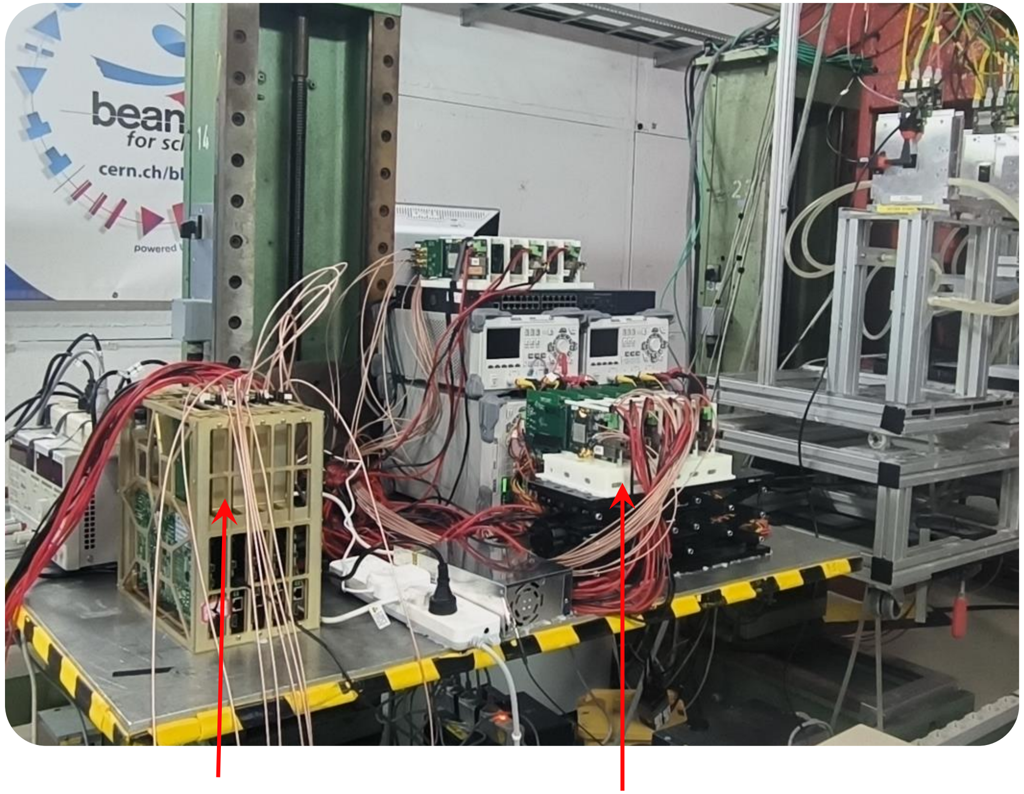
CPV-4

CPV-5

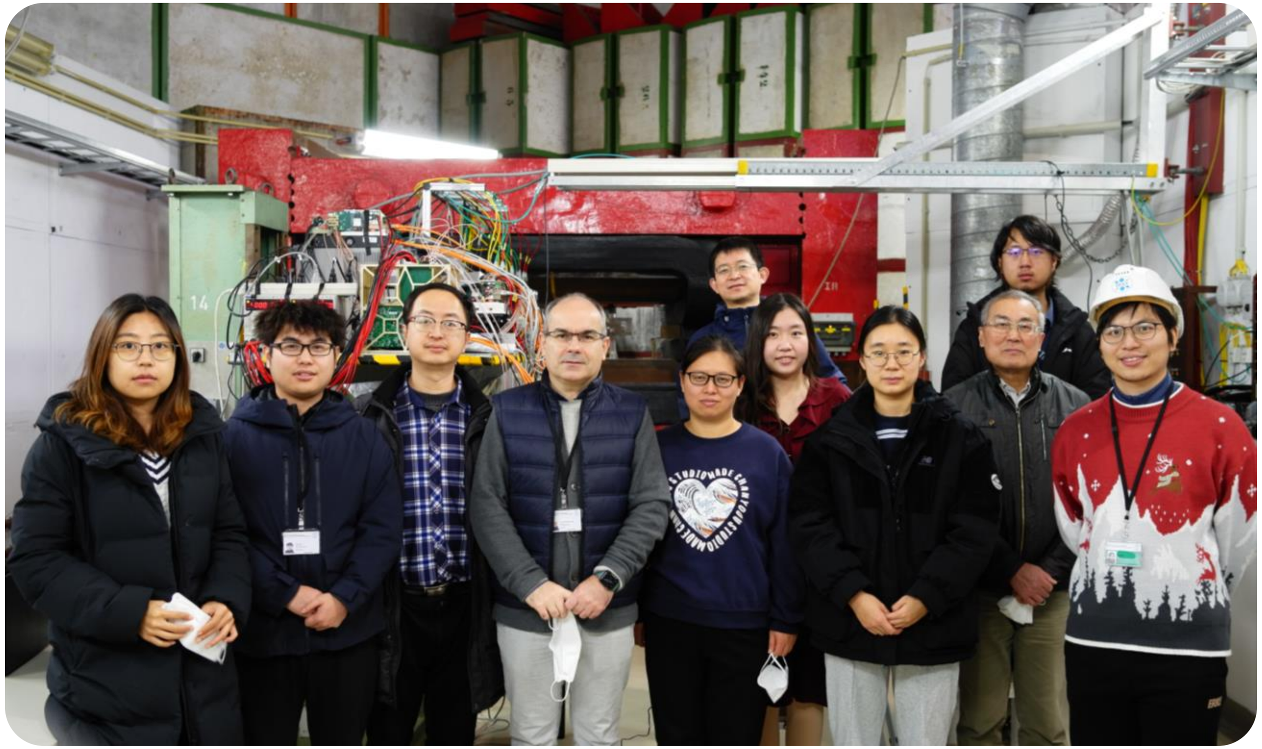
LAPIS 200nm SOI process

Test Beam of Single-Chip Board Telescopes

- ❑ Testbeam of single chip boards at DESY in Dec 2022, in a 4-6 GeV electron beam.
- ❑ JadePix boards and TaichuPix boards form two relatively independent telescopes

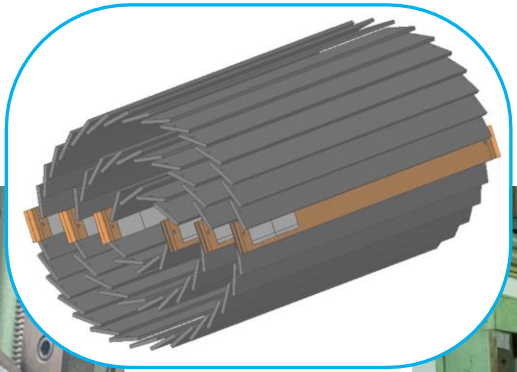


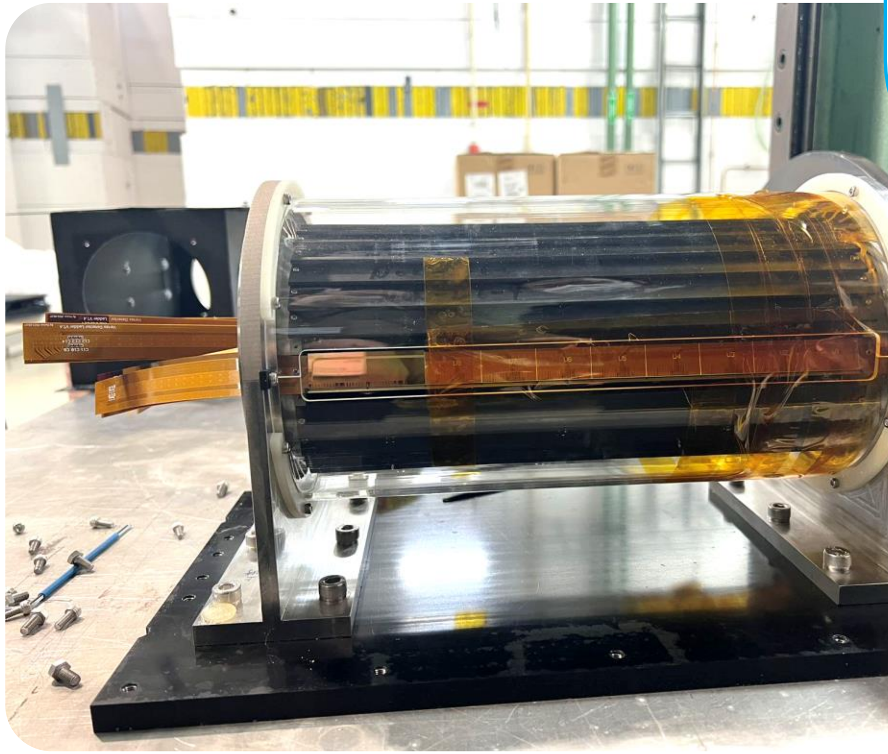
JadePix telescope TaichuPix telescope

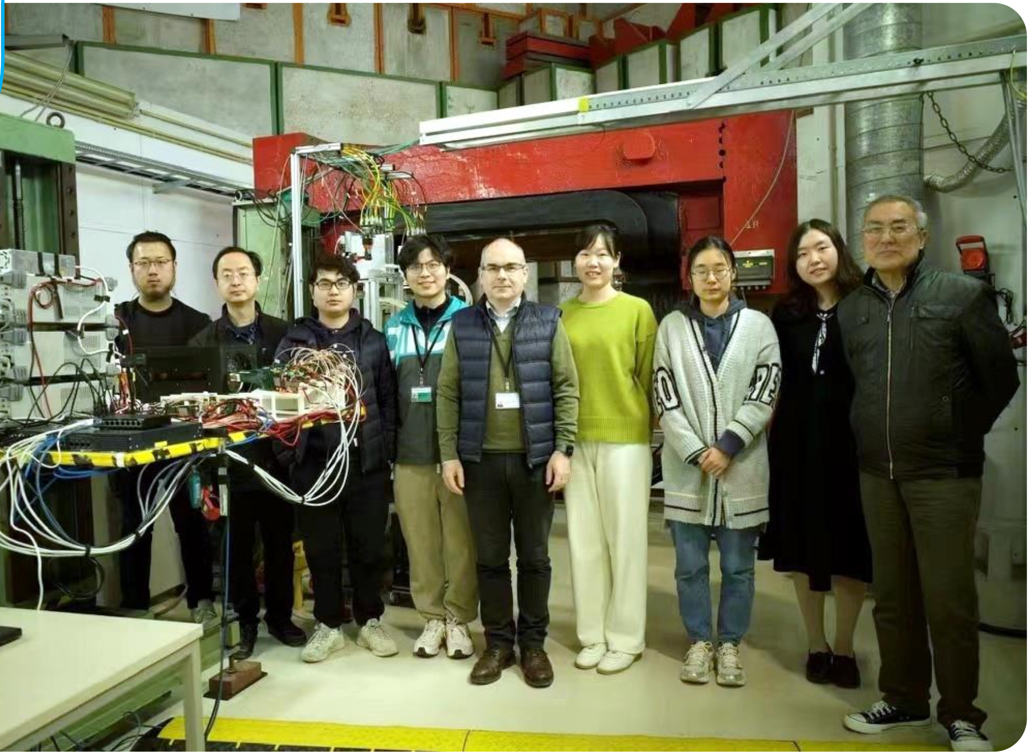


Prototyping Vertex Detector

- ❑ A prototype detector based on TaichuPix has been tested at DESY in April 2023
- ❑ Six double-sided ladders installed, effectively 12 layers for testbeam purpose.







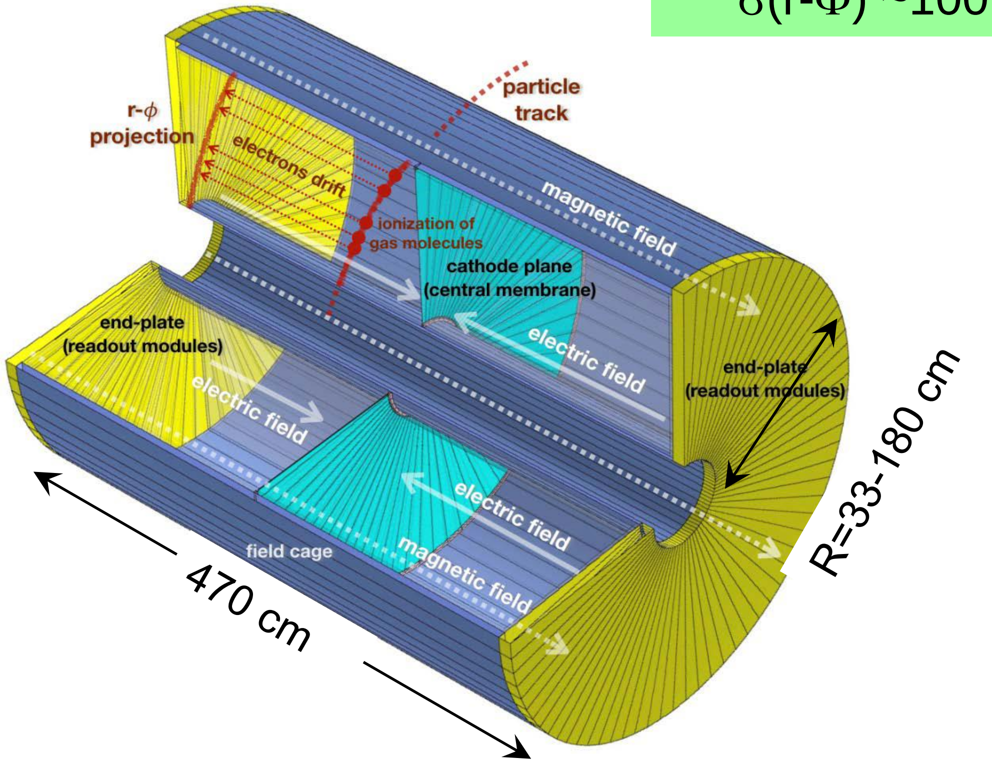
A Quest of Silicon Pixel Vertex Detector

	JadePix	**TaichuPix**	***MOST3***	**CDR**
Spatial resolution	2.7-5 μm for JadePix-3 Worse for JadePix-4	4.5 μm for single chip 4.9 μm for ladder	3 μm	3 μm
IP resolution	-	~5-6 μm for P= 4-6 GeV		
Power dissipation	72 mW/cm^2 for JadePix-3	60 mW/cm^2 @ 17.5 MHz ?? @ 40 MHz	100 mW/cm^2	
Time resolution	100 μs for JadePix-3 1 μs for JadePix-4	Time stamp resolution: 25 ns for modified process 50 ns for standard process	100 ns	
In-chip readout speed	100 μs / frame for Jadepix3 100 ns/hit for Jadepix4	50 ns / hit		
Material budget	-	0.45% X0 / layer	ASIC thinning + Al trace	0.15% X0 / layer
Radiation Hardness	> 1 Mrad	> 3 Mrad		1 Mrad/year at Z

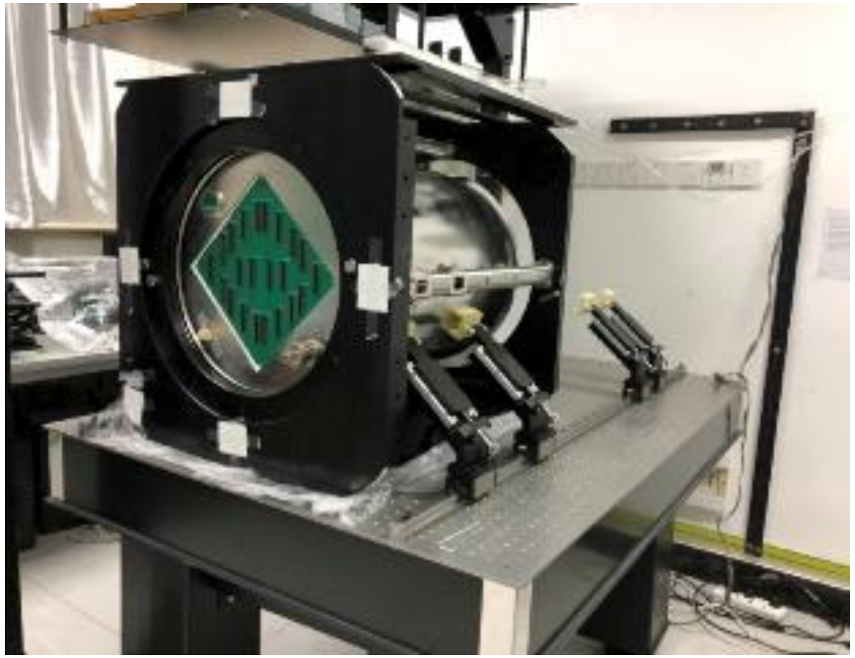
The performance can feed into more realistic simulation studies of the CEPC physics reach, while we improving further the performance.

Time Projection Chamber

Baseline main tracker
$\sigma(r\text{-}\Phi) \sim 100\ \mu m$



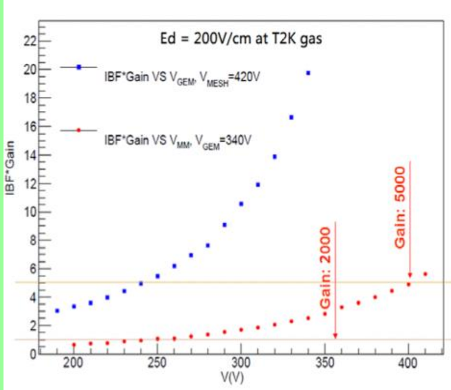
TPC Prototype + UV laser beams

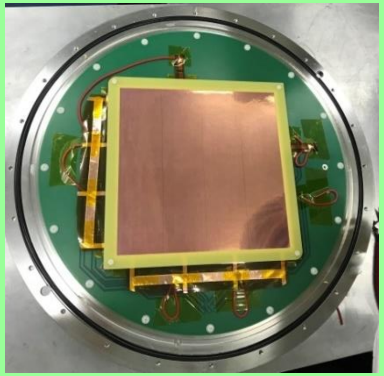


- Also provides nice particle identification, with dE/dx or dN/dx.
- Challenge: Ion backflow (IBF) affects the resolution. It can be corrected by a laser calibration at low luminosity, but difficult at high luminosity Z-pole.

Pixelated TPC Tracker

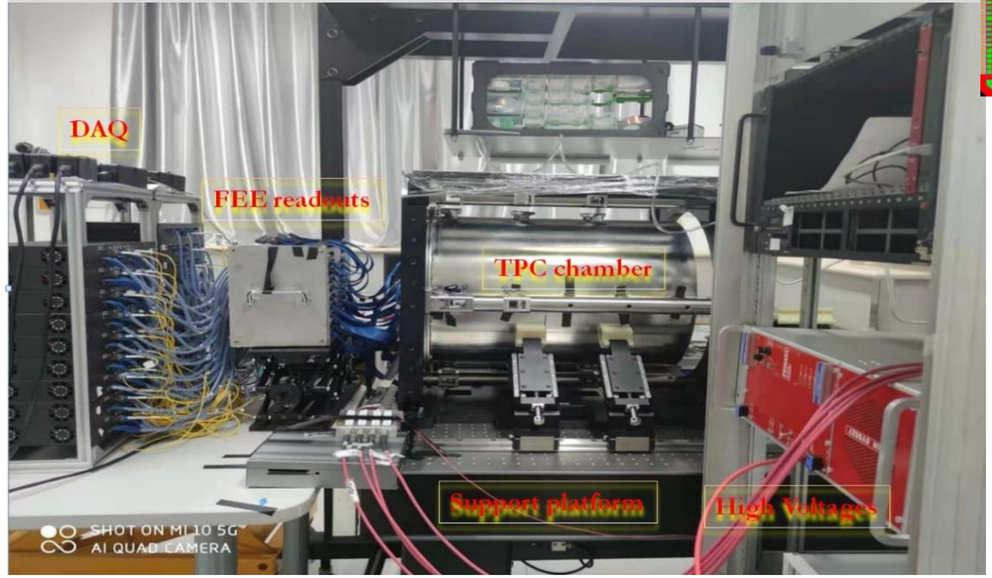
- CEPC TPC detector prototyping roadmap:
  - From TPC module to TPC prototype for beam test
  - Low power consumption FEE ASIC (<5mW/ch including ADC)
- Achievement so far:
  - Supression ions hybrid GEM+Micromegas module, IBF×Gain ~1 at Gain=2000 validation with GEM/MM readout
  - Spatial resolution of $\sigma_{r\varphi} \leq 100$ μm by TPC prototype
  - dE/dx for PID: <4%

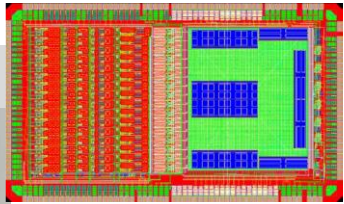




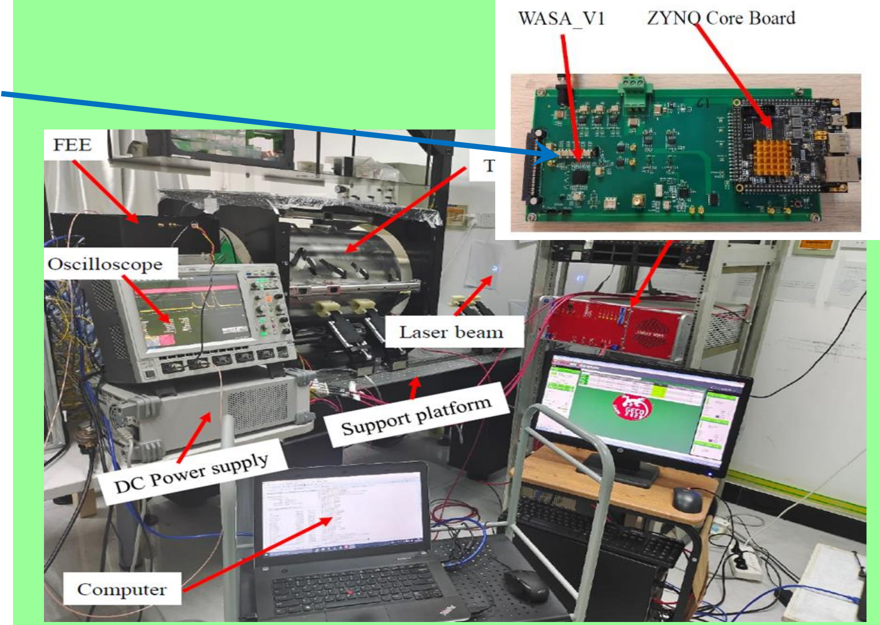
GEM+Micromegas module R&D

TPC prototype with integrated 266nm UV laser



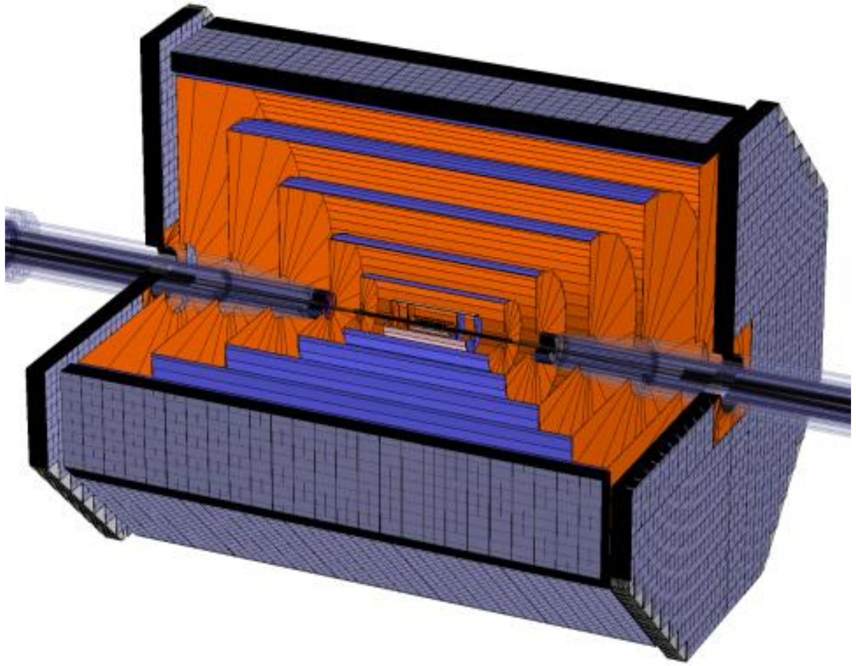


WASA_v1

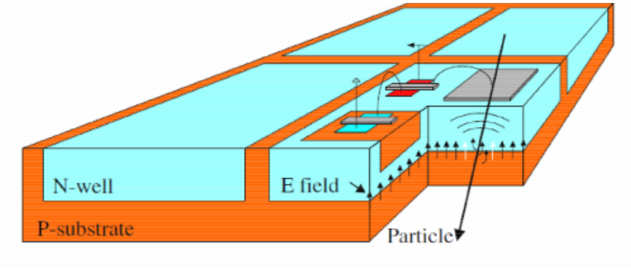


Low power consumption readout

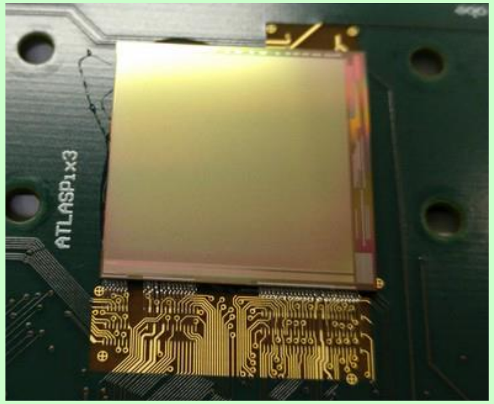
Full Silicon Tracker



Monolithic detector



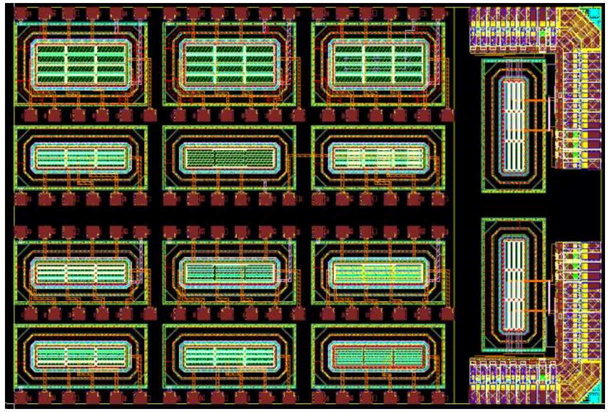
ATLASPix3
(AMS/TSI 180nm)
132×372 pixels of 150×50 μm^2



- A full silicon tracker has no difficulty dealing with the high interaction rate at CEPC.
- Total silicon area **~140 m^2** in the Full SiTrk plans. Even in TPC+SiTrk plan, area **~70 m^2**.
- R&D needs to emphasize the cost effectiveness, besides of high performance.
- We currently focus on a monolithic detector technology called HV-CMOS, study ATLASPix3 by KIT, and eventually produce CEPC-flavored chips.
- Goal in MOST3: $\sigma_{R/\phi} \leq 10\ \mu m$, ($\sigma_Z \sim 100\ \mu m$), $\sigma_t \sim 10$ ns, power dissipation ~ 200 mW/cm^2.

Aiming for A Smaller Feature Size

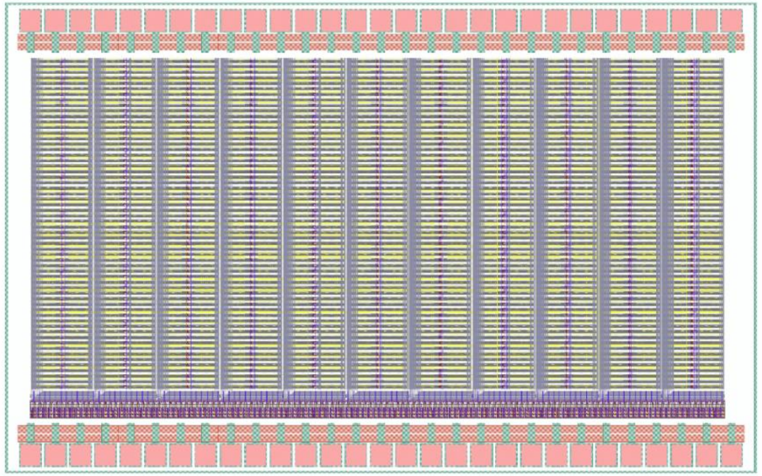
Aim for technology of smaller feature size, especially push for domestic foundries



First production using SMIC 55nm Low Leakage process

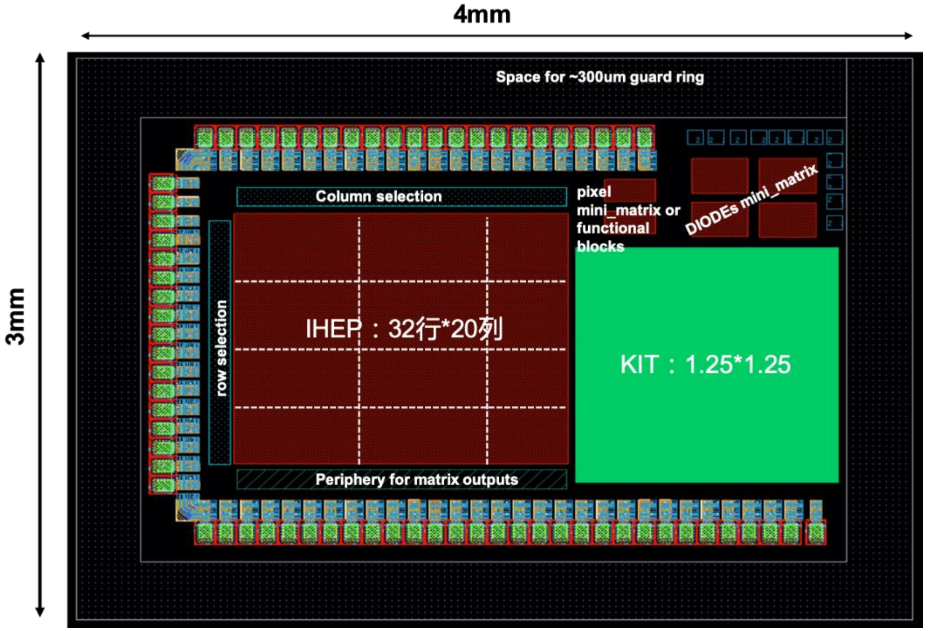
Only passive diode array and simple amplifiers by IHEP

Test results consistent with expectations



A design of pixel array by KIT using HLMC 55nm technology

No luck for a MPW production



Second design for SMIC 55nm HV HR process

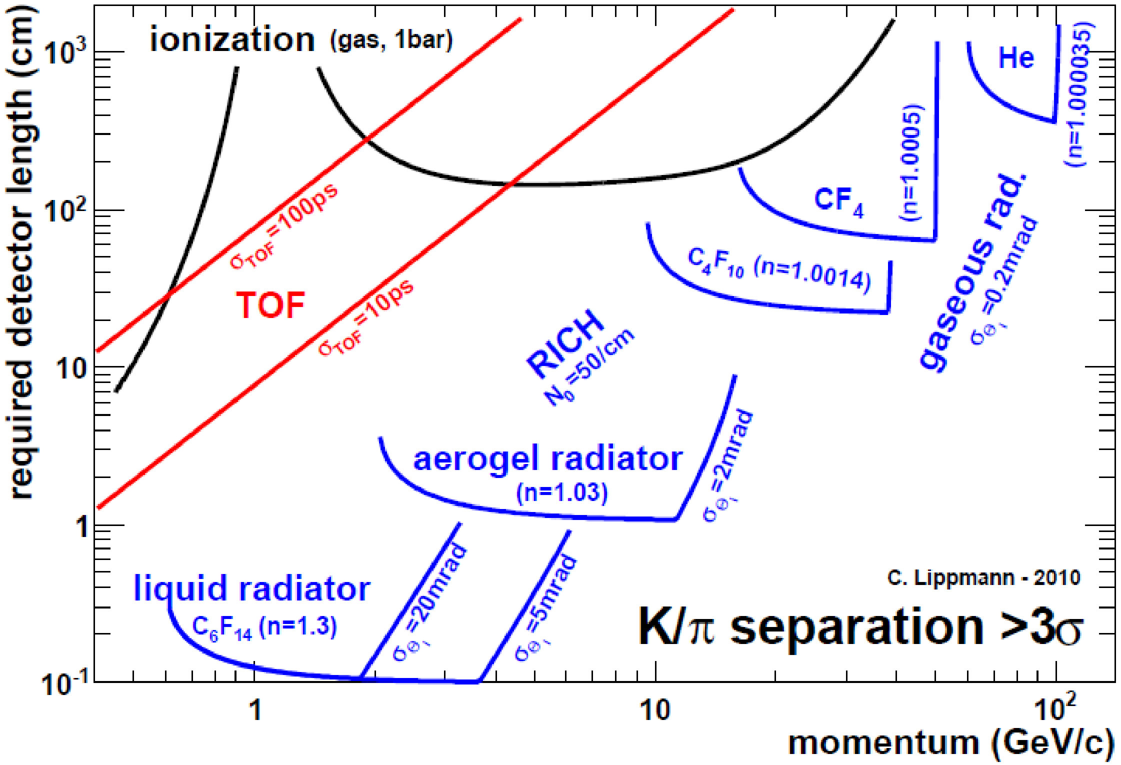
IHEP+KIT+ZJU+HNU

Submit shortly

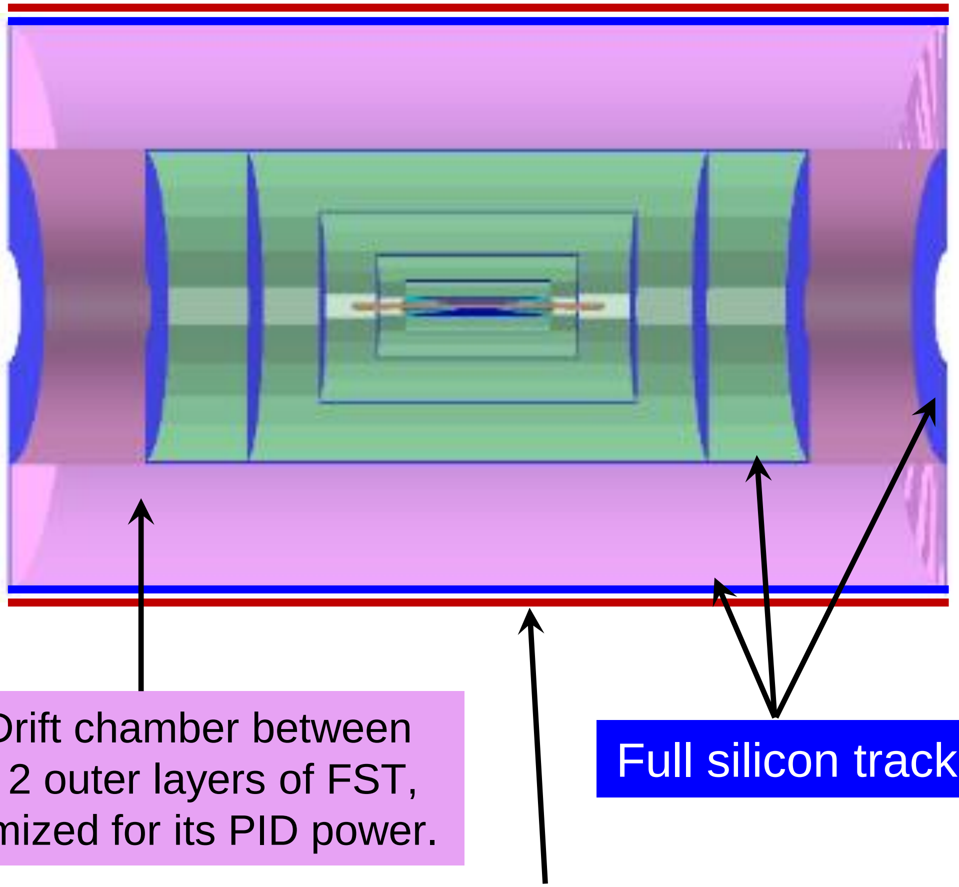
PID in Scenario of FST

In the scenario of a Full Silicon Tracker (FST), particle identification need to be taken care of by other detectors:

e.g. Drift Chamber (dE/dx, dN/dx), ToF, RICH



C. Lippmann - 2010

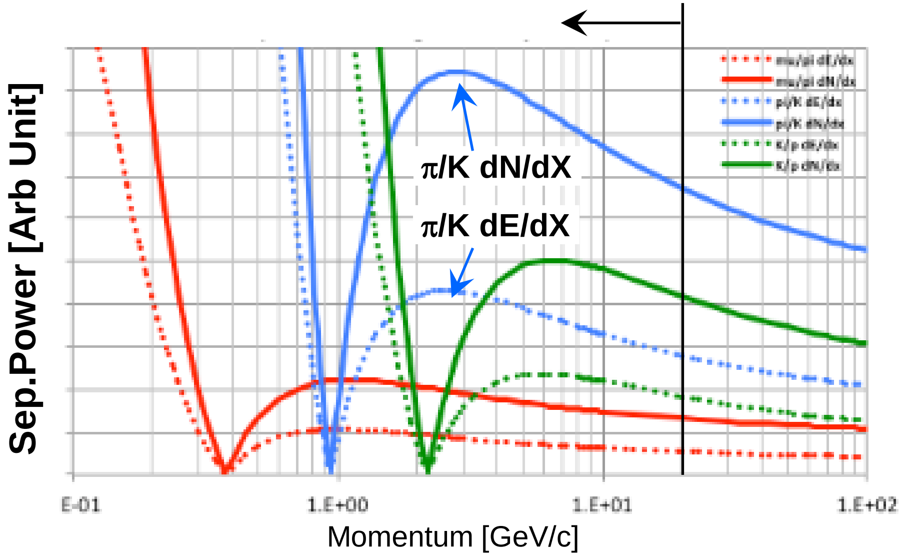


A Drift chamber between the 2 outer layers of FST, optimized for its PID power.

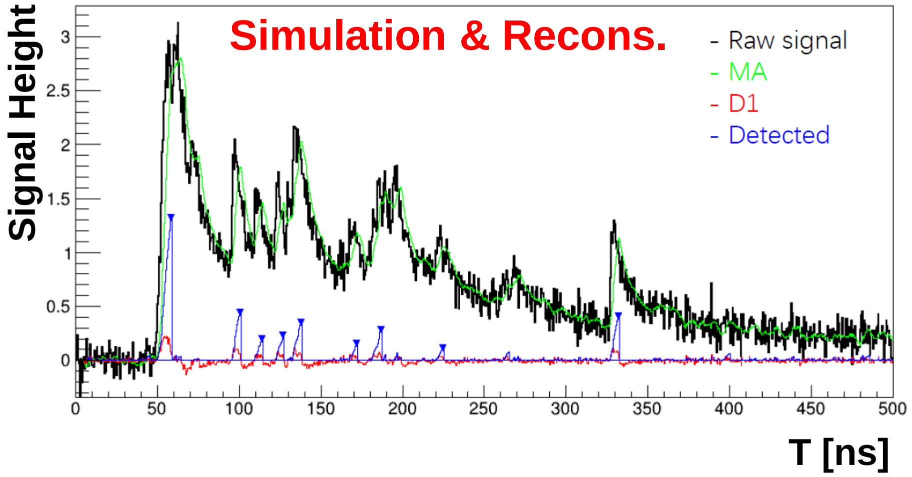
Full silicon trackers

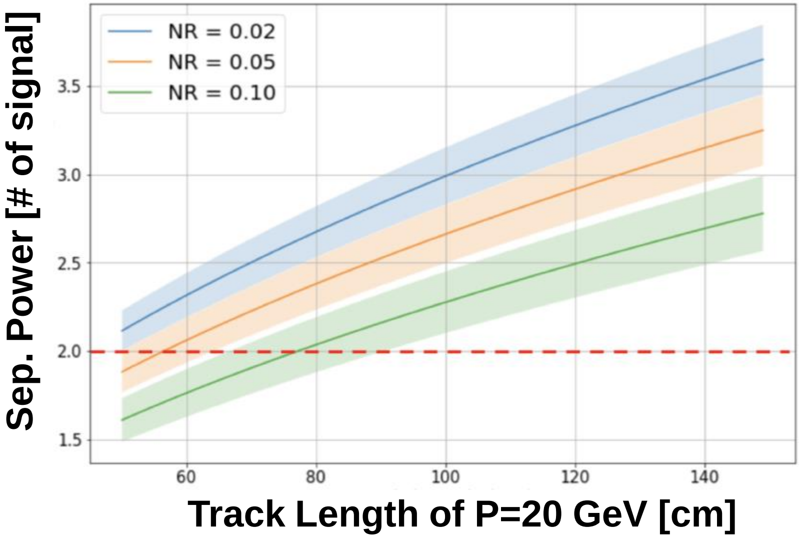
Supplementary **Time of Flight**, could be based on LGAD technology, even better if it acts as the outer SiTrk

Cluster Counting in PID Drift Chamber

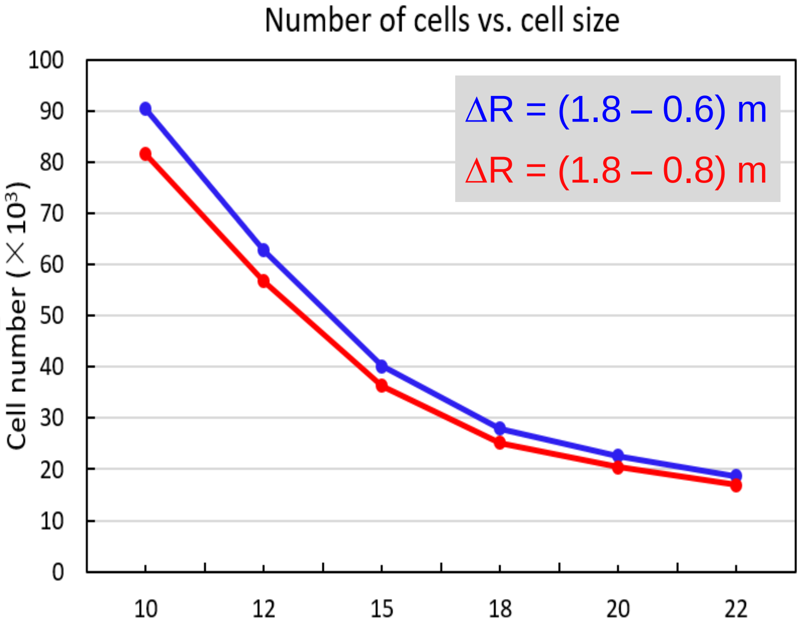


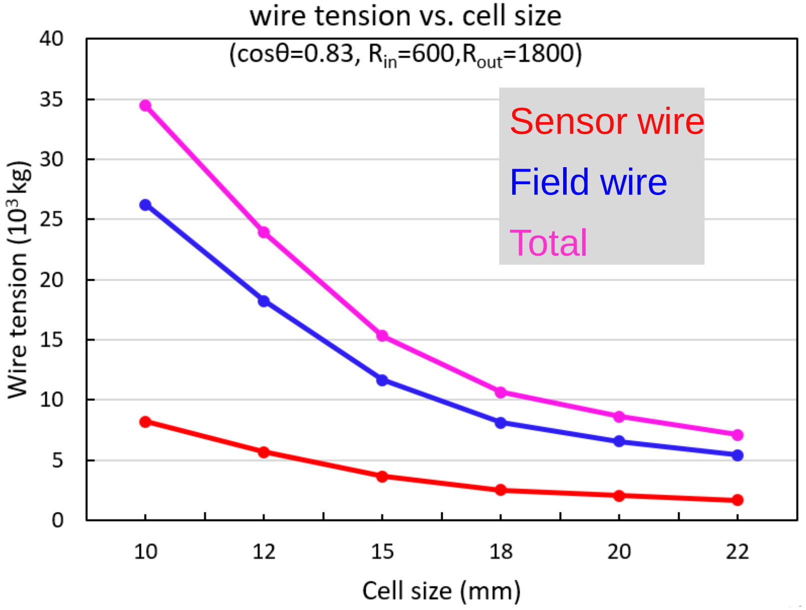
- ❑ Cluster counting algorithm (dN/dX) is more powerful than conventional dE/dx, but requires more in readout electronics.
- ❑ The goal is fit in between the outer 2 layers of FST, not to affect FST tracking quality, but has sufficient PID power.
- ❑ The separation vs P & angle can be properly modelled with continuous improvement.
- ❑ Need more study of bench mark physics performance using this PID modelling.





Mechanical Study of The PID Drift Chamber


Number of cells vs. cell size


wire tension vs. cell size

(cosθ=0.83, R_{in}=600, R_{out}=1800)

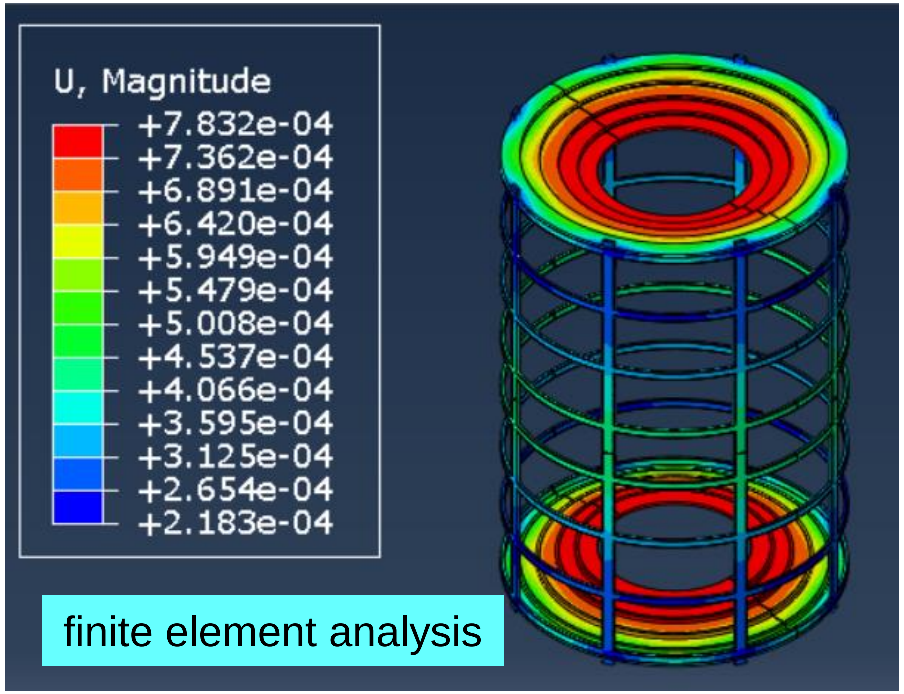
- ❑ Increasing the cell size has little effect on the PID performance.
- ❑ The number of wires can be reduced, hence the production difficulty, the number of readout channels, and the material of the supporting structure (mostly at the outer cylinder).
- ❑ The trade-off is its performance as a supplementary tracker.

L~5.4 m

Sag ~ 240 μm

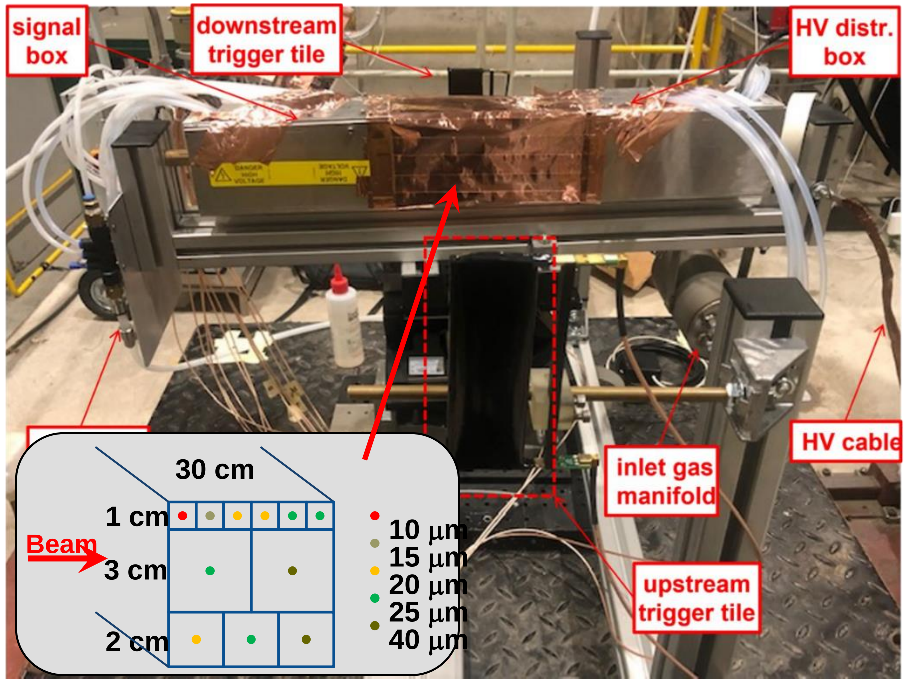
ΔR = (1.8 – 0.6) m

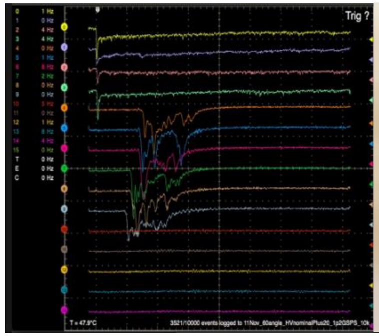
S:F ~ 1:3

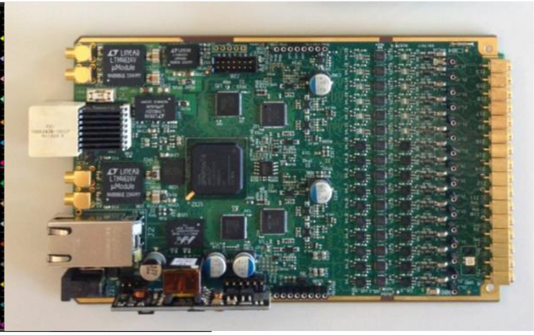

finite element analysis

Cluster Counting Beam Tests

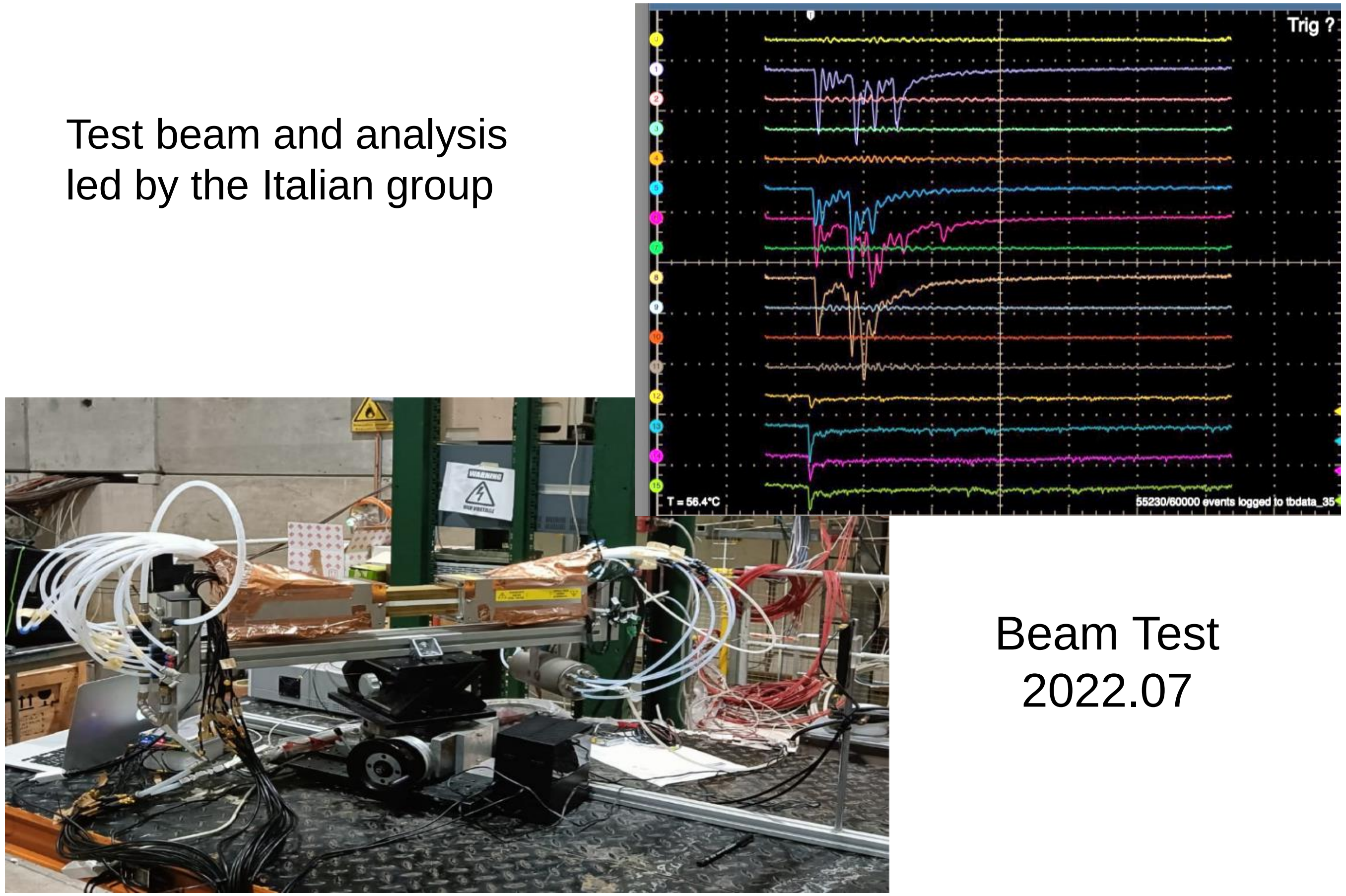
Beam Test 2021.11







Test beam and analysis led by the Italian group



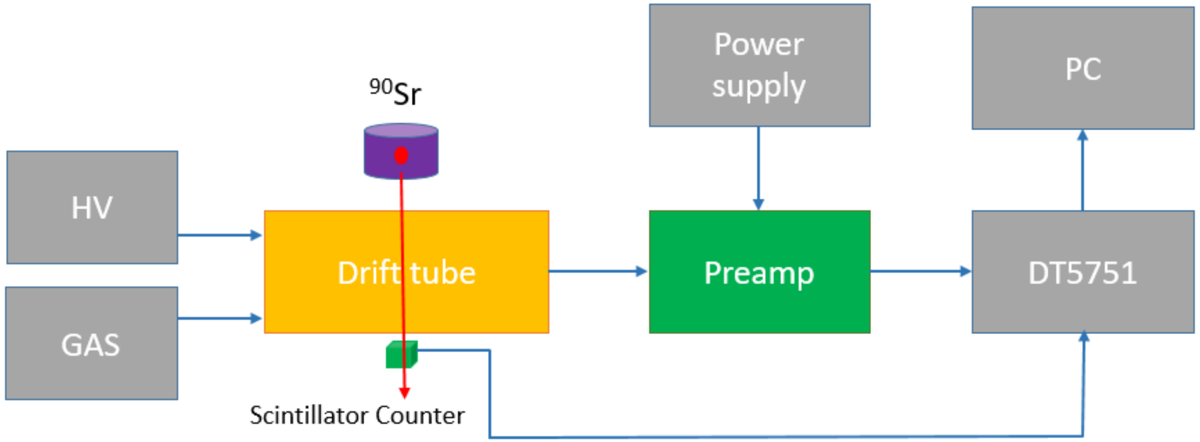
Beam Test 2022.07

- ❑ Apply cluster finding algorithm in a rea world.
- ❑ Measure number of clusters and efficiency
- ❑ Study effects of configuration (cell size, HV, gas)
- ❑ Apply more realistic parameters to simulation

PID Drift Chamber Test Setup at IHEP

- A prototype drift tube to study the PID performance
  - diameter of the tube: 30mm
  - gas mixture: He/iC_4H_{10}=90:10, study different ratios
- A preamplifier has been designed and developed

Diagram of test setup



HV

GAS

^{90}Sr

Drift tube

Scintillator Counter

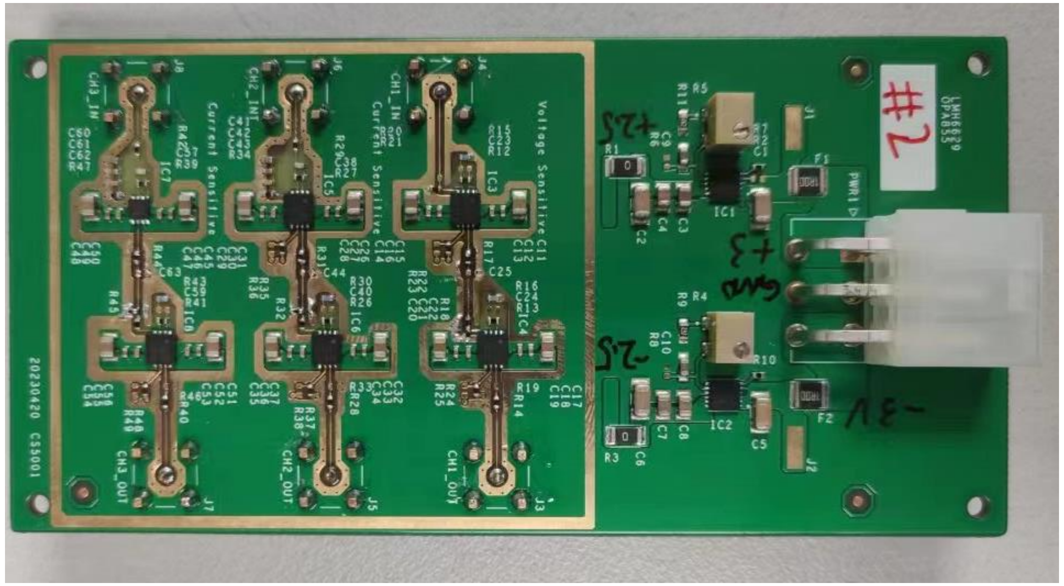
Power supply

Preamp

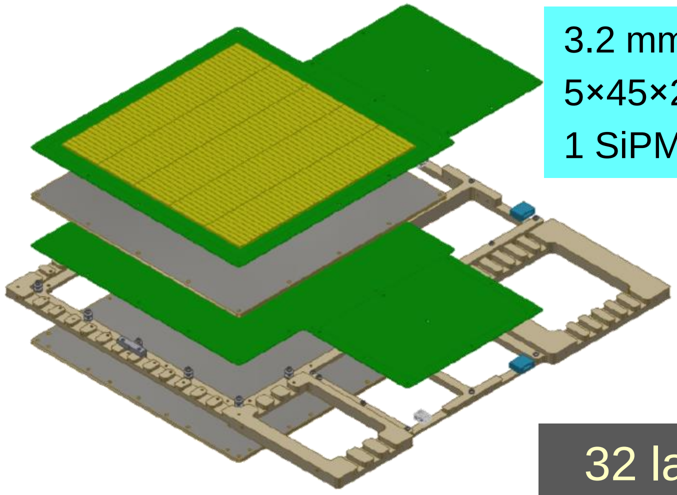
PC

DT5751

Preamplifier

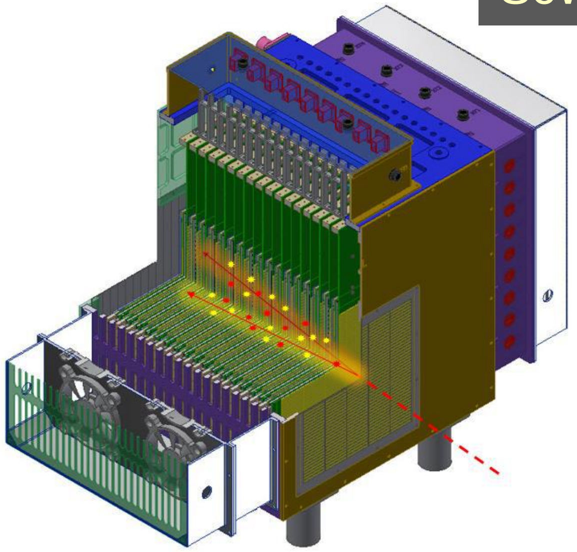


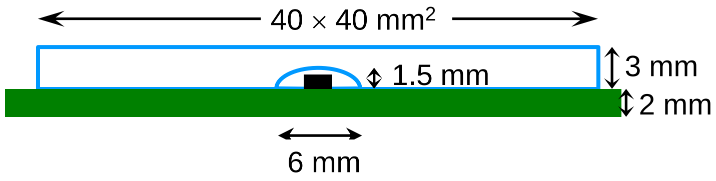
Prototype PFA Calorimeters

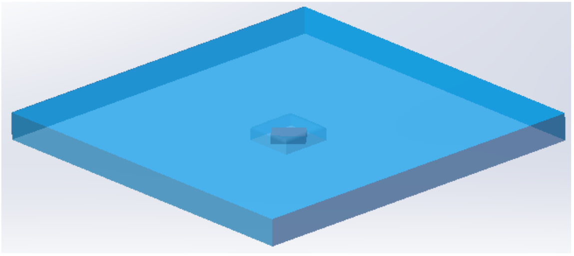


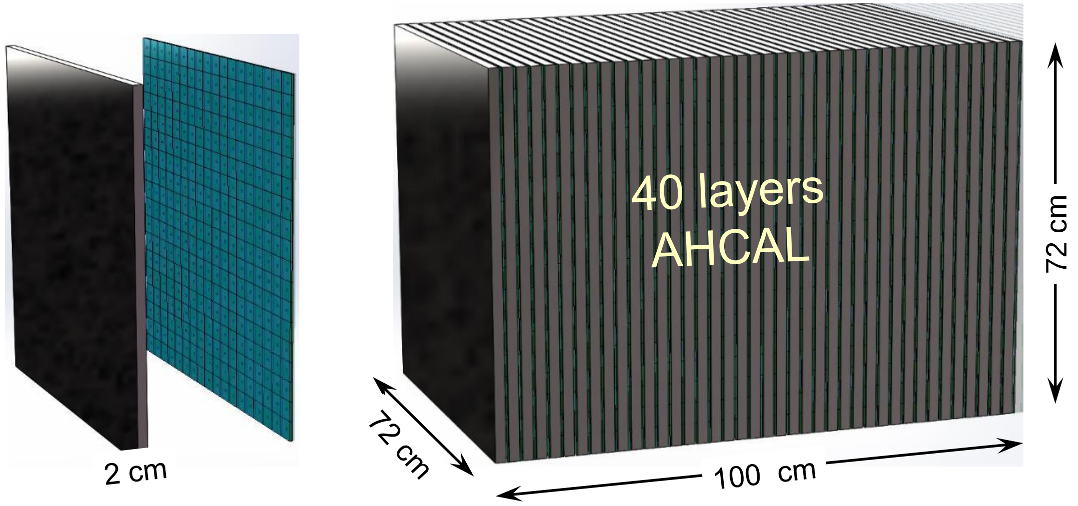
3.2 mm thick W-Cu plate,
5×45×2 mm³ scintillator bar
1 SiPM/bar.

32 layers
ScW-ECAL



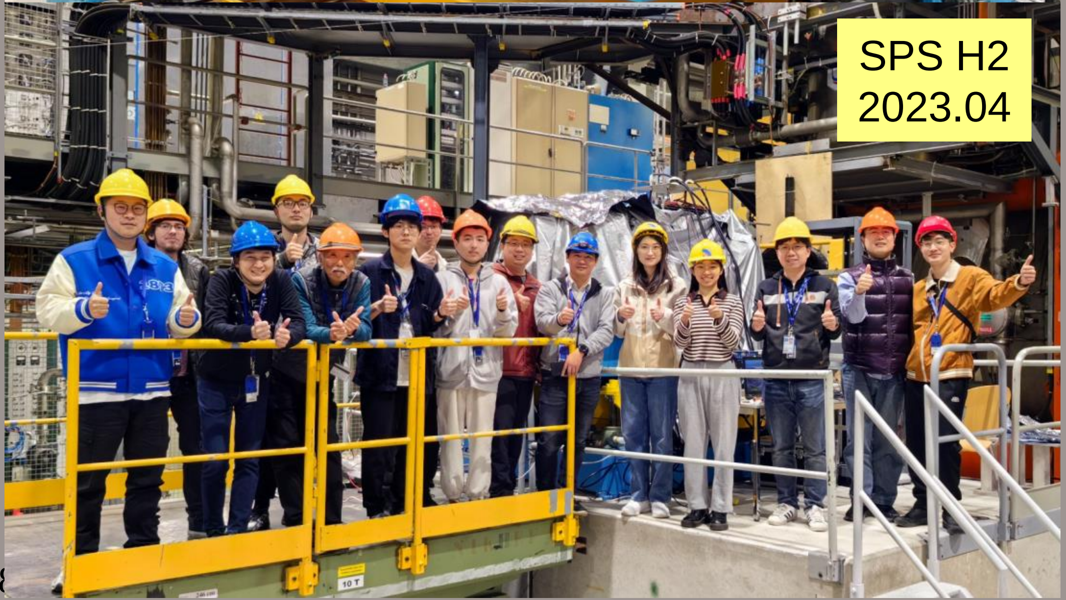




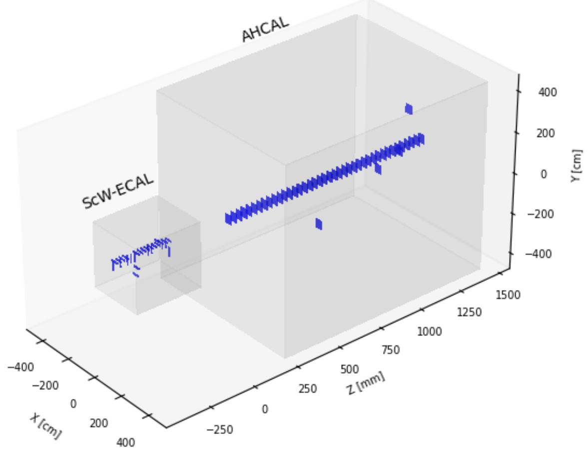


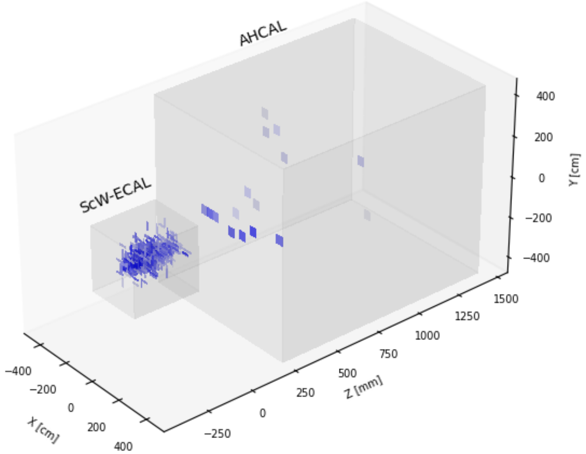
40 layers
AHCAL

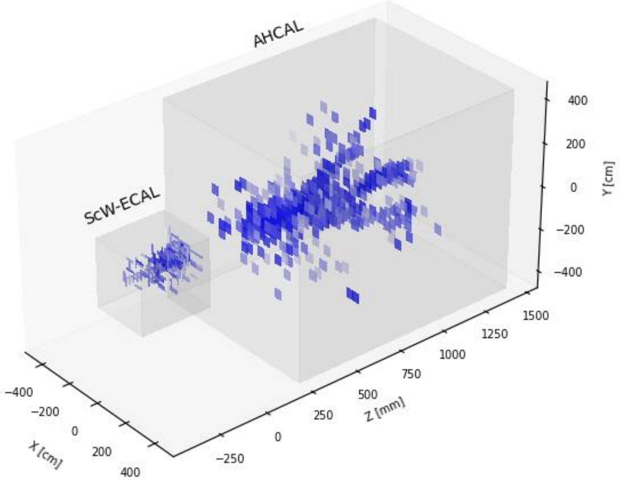
Beam Tests at CERN

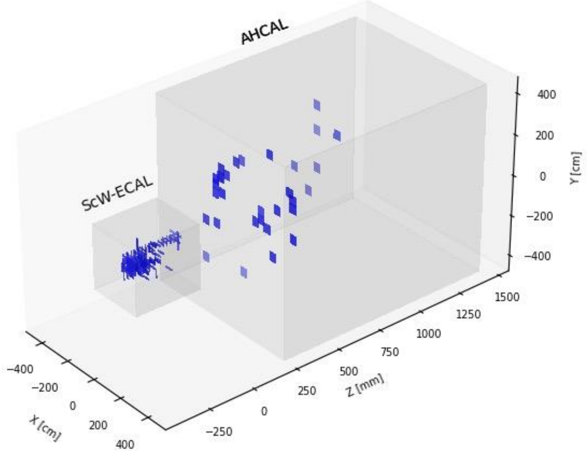


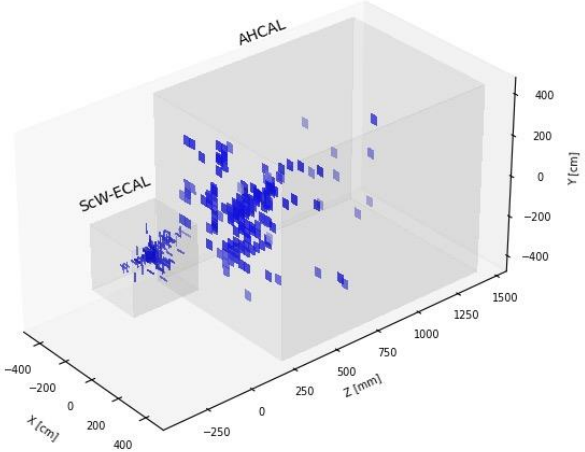
Selected Testbeam Events

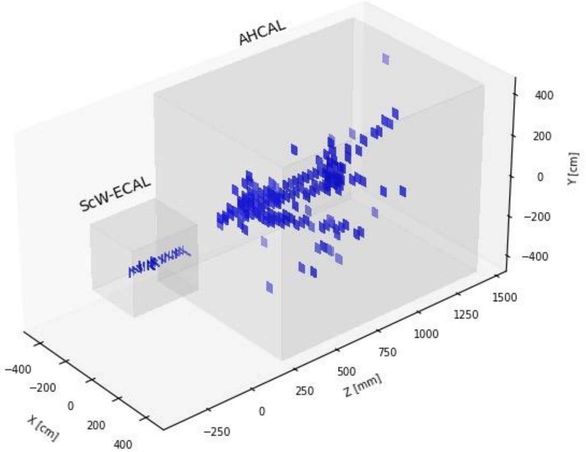

100 GeV μ^-


60 GeV e


60 GeV π^-


5 GeV π^-

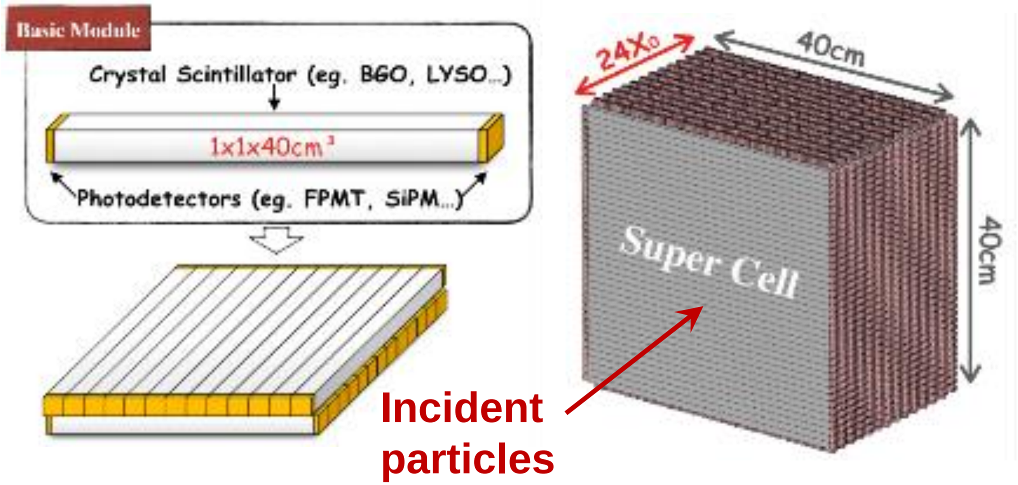

10 GeV π^-

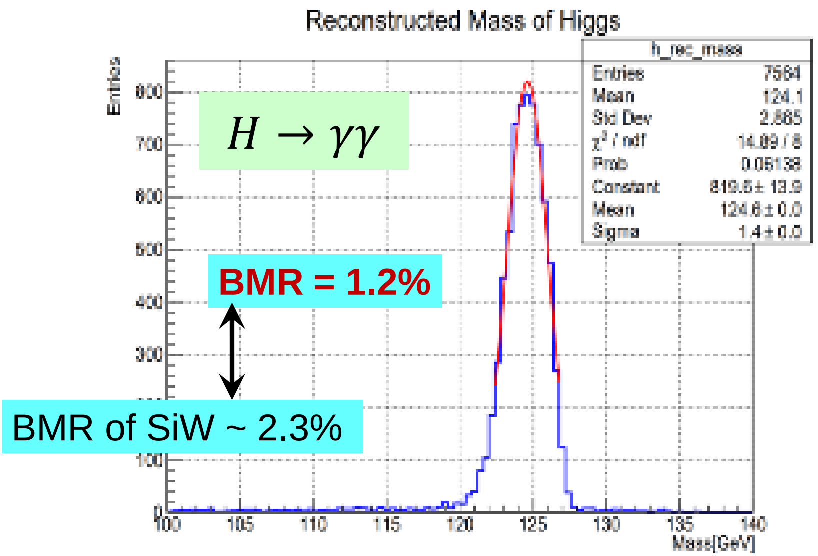

15 GeV π^-

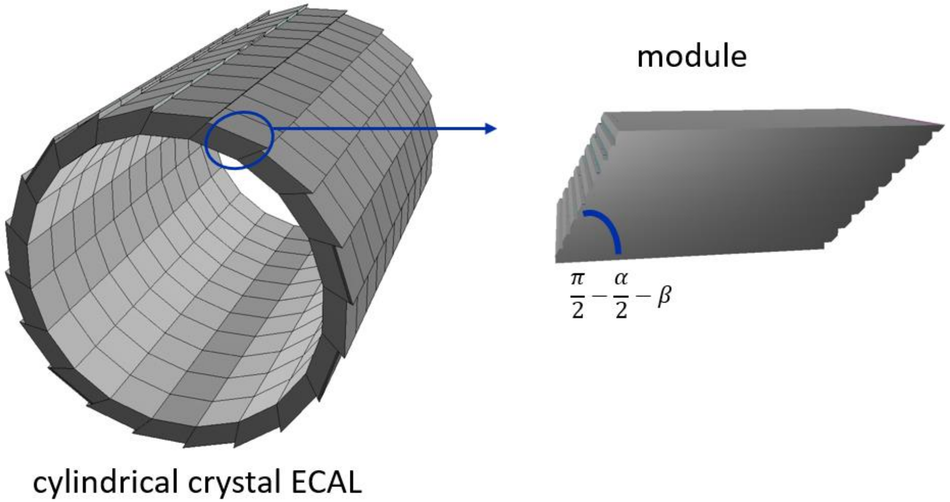
Within CALICE collaboration

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 for positioning along the 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**).



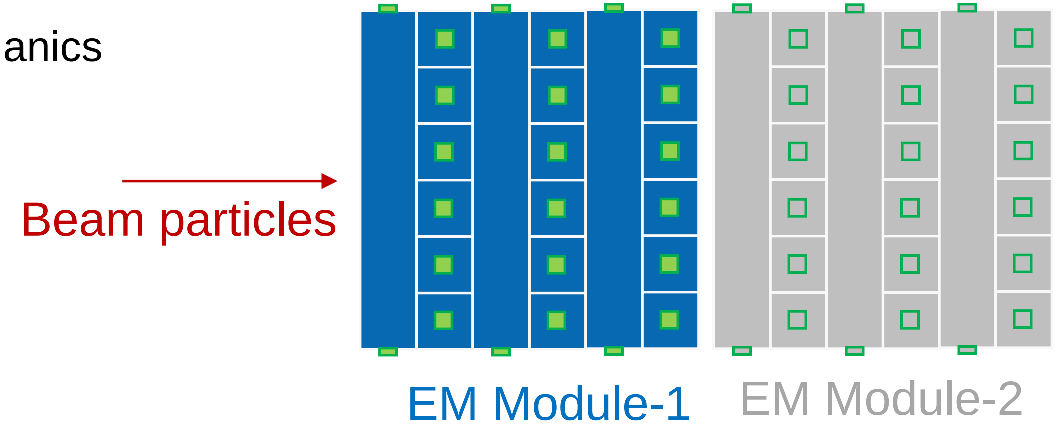


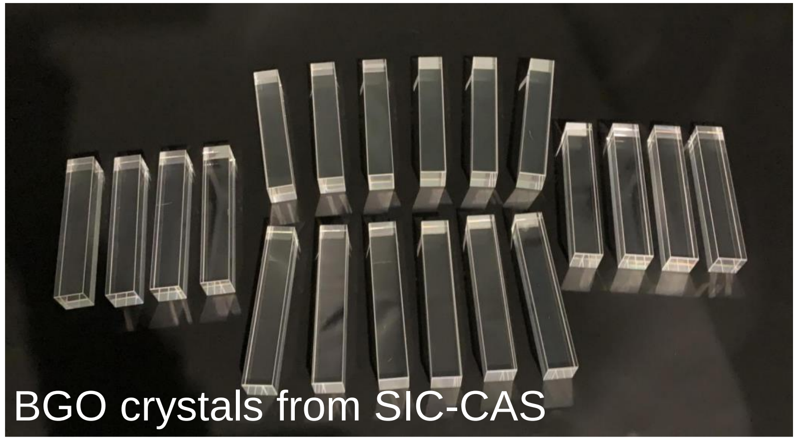


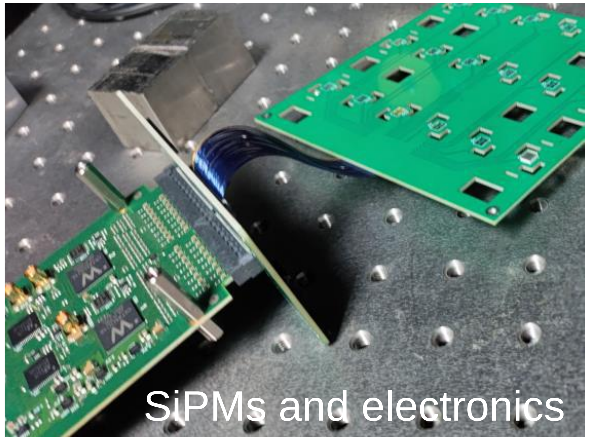
Small Size Crystal Module

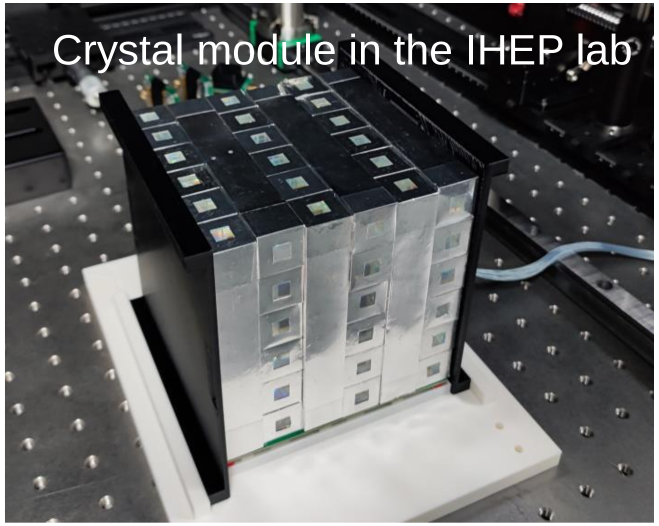
- Motivations: to address critical issues at system level
  - Validation: design of crystal-SiPM, light-weight mechanics
  - EM shower performance
- Plans: beamtests with 2 crystal modules
- The first crystal module development
  - Crystals: 40 BGO bars from SIC-CAS
  - SiPM: 3×3 mm² sensitve area, 10µm pixel pitch
  - Front-end electronics with ASICs (Citiroc-1A)

Single module: $12 \times 12 \times 12\text{cm}^3$

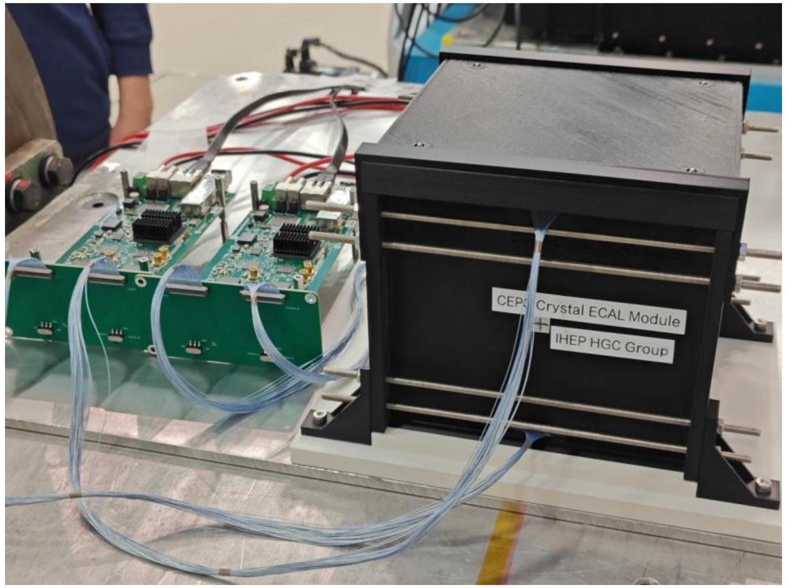



BGO crystals from SIC-CAS


SiPMs and electronics

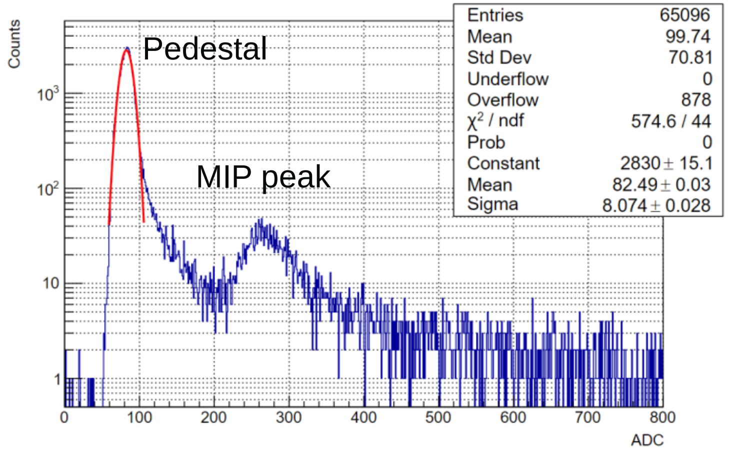

Crystal module in the IHEP lab

Crystal Calorimeter Testbeam

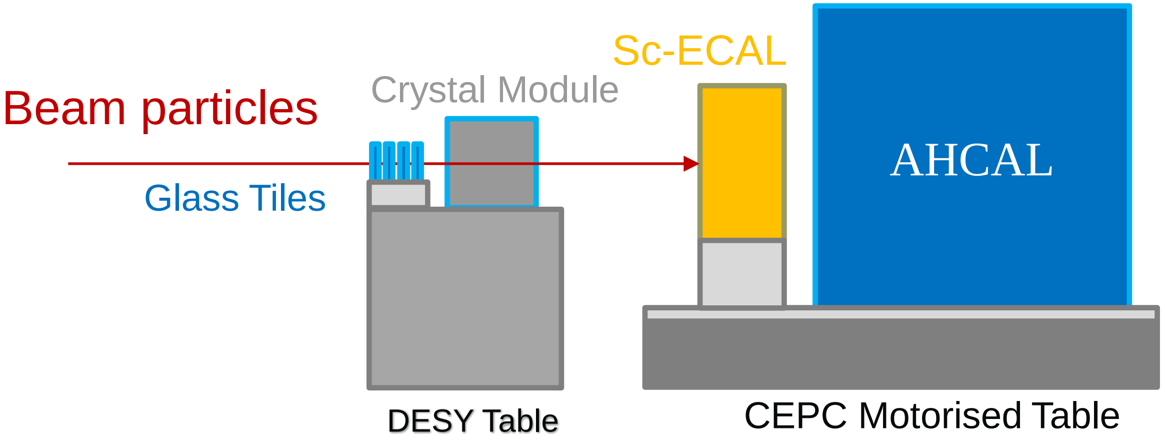


- Parasitic with SC-ECAL & AHCAL
- 5.5 M 10 GeV muon events
- 1 M electron events at low energy: 0.5, 1, 2, 3, 4, 5 GeV

Energy (ADC) in Low Gain



CALICE-CEPC calorimeter prototypes



Sc-ECAL

Crystal Module

Beam particles

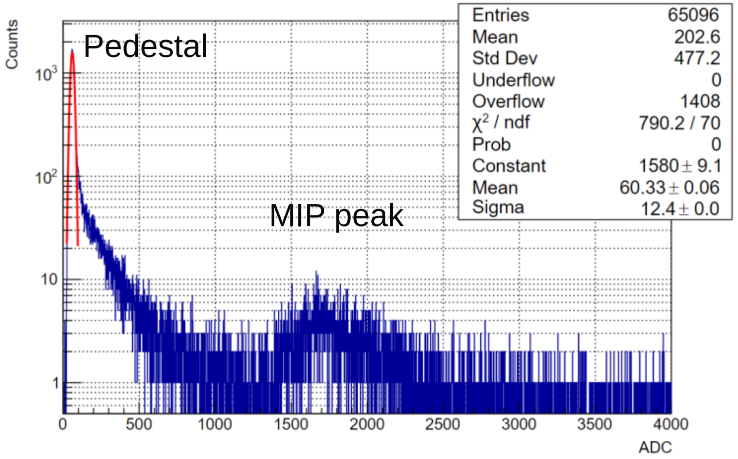
AHCAL

Glass Tiles

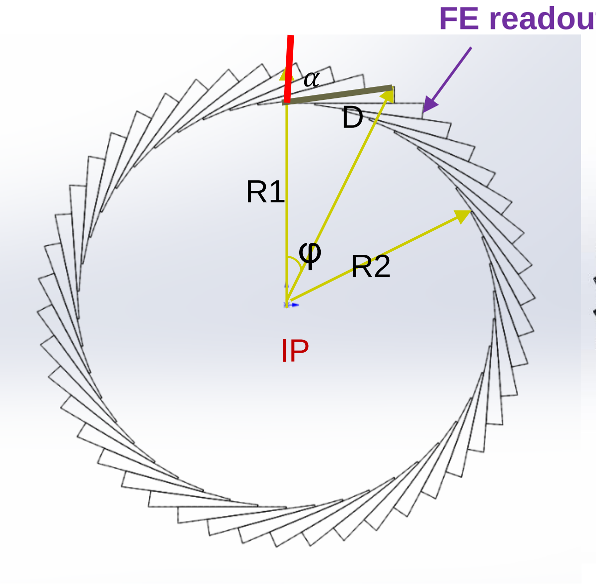
DESY Table

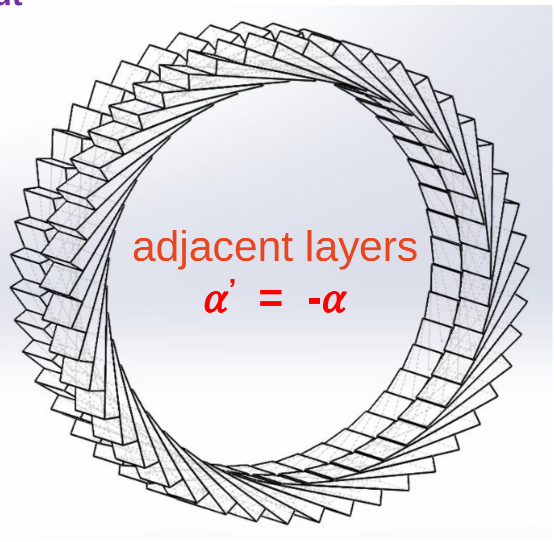
CEPC Motorised Table for prototypes

Energy (ADC) in High Gain

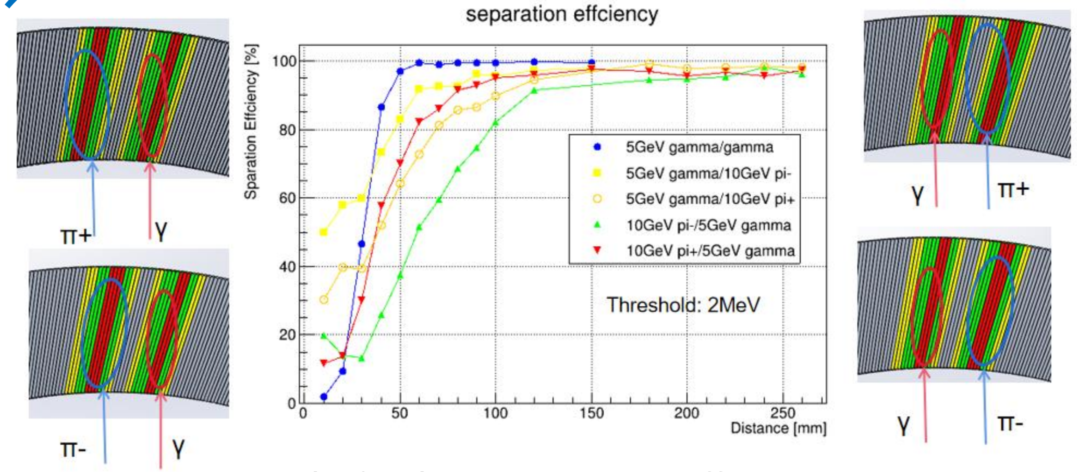


Stereo Crystal Electromagnetic CALorimeter: SCECAL



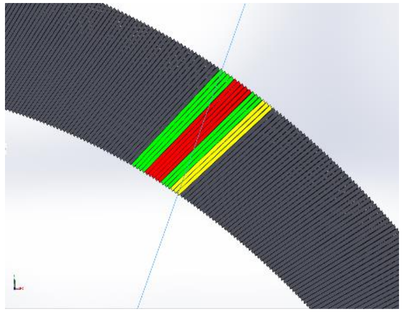


adjacent layers
α' = -α

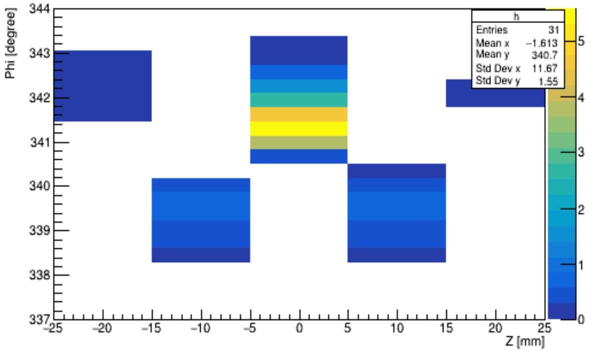


γ/γ & γ/π separation efficiency

α = 30 °, 14 layers

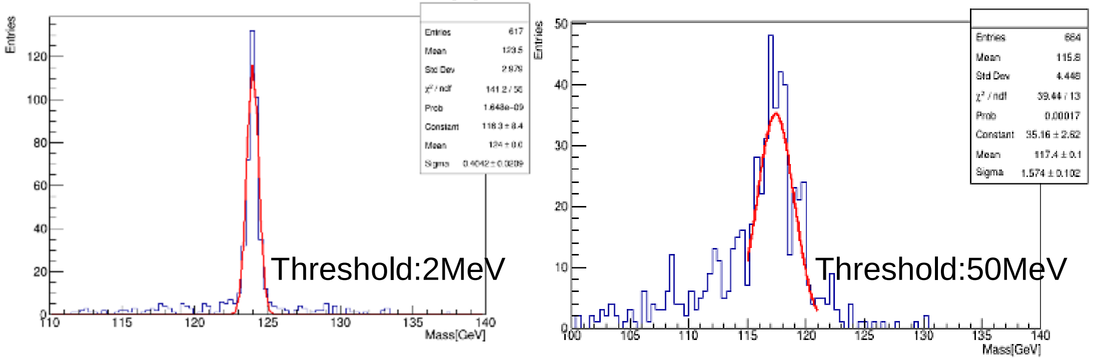


Particle from IP passes through ~14 layers max.



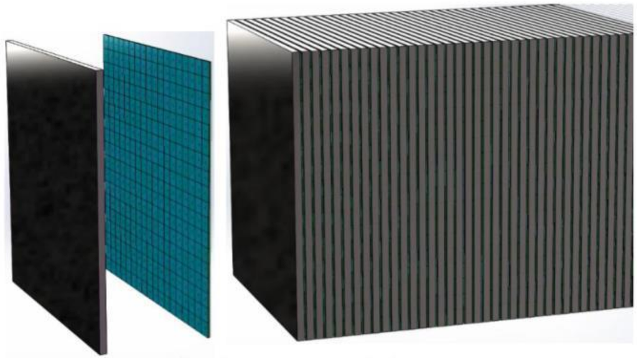
Event display on Z-φ plane

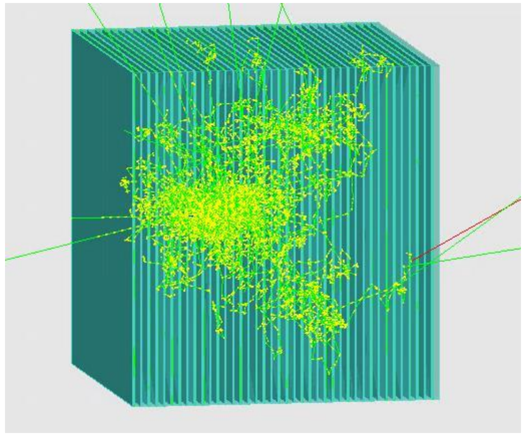
ZH→γγνν ,without ISR

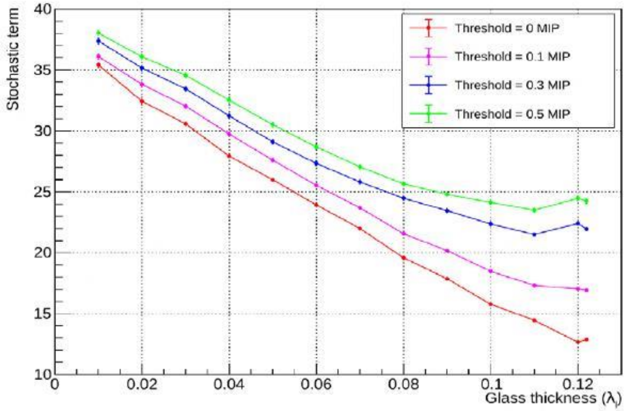


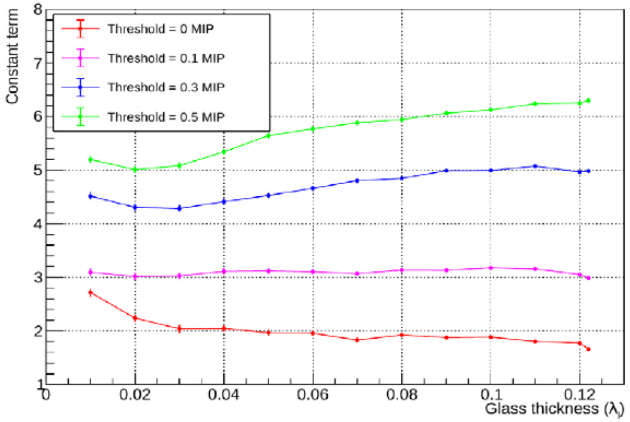
Boson mass resolution

Glass Scintillator HCAL: Performance Studies

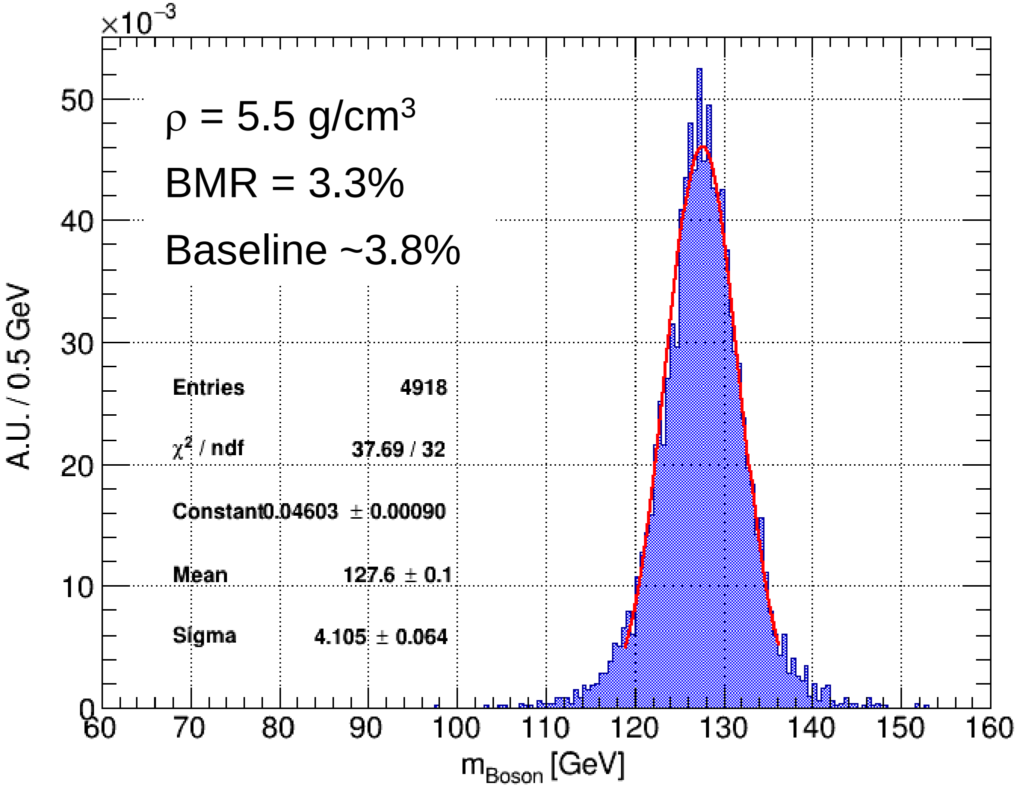








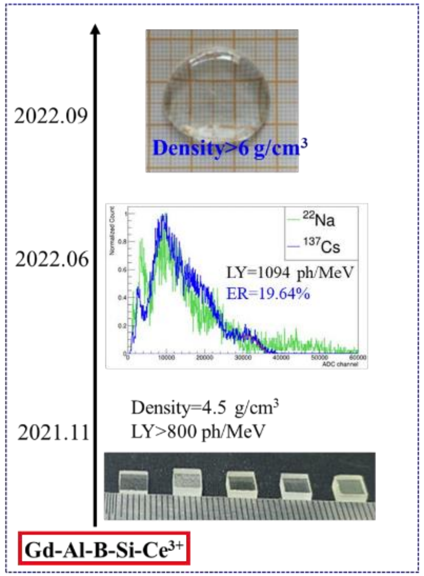
$ZH\ (Z \rightarrow \nu\nu,\ H \rightarrow gg)$ at 240 GeV

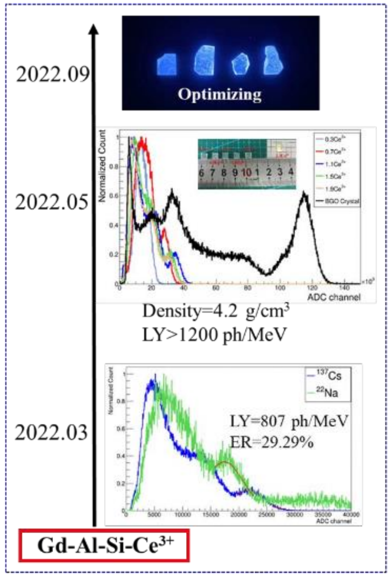


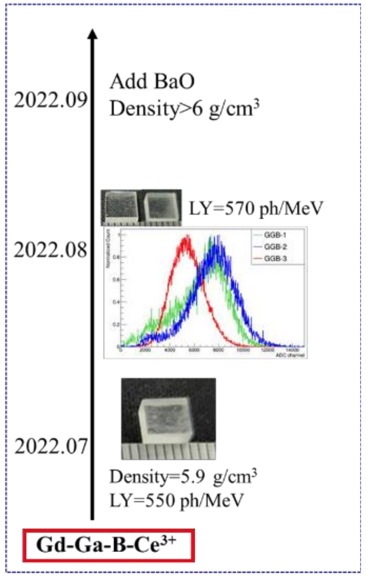
- New HCAL concept: use glass scintillator tiles, instead of plastic scintillator
- Performance studies: potentials with single hadrons and Higgs benchmarks

Scintillator Glass R&D Activities

- Replacing plastic scintillator in the PFA HCAL with high light yield, high density, low cost scintillating glass.
- Efforts on finding a proper material
  - Light yield: 1000 ~2000 photons/MeV
  - Density: 5~7 g/cm^3
  - Scintillation time: ~100 ns
  - Tiles in cm scale for PFA HCAL
- Proposal input to the ECFA DRD6

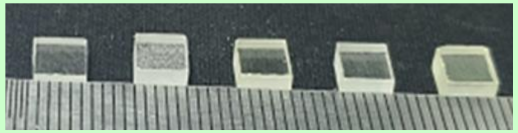




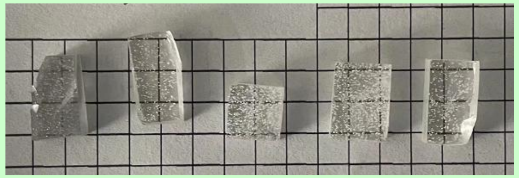


Aims: high density, high light yield, low cost ScintiGlass

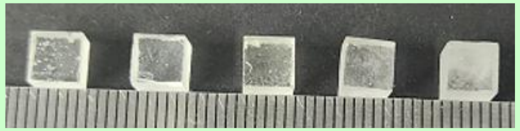
Nov 2021



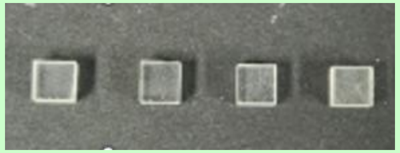
Jun 2022



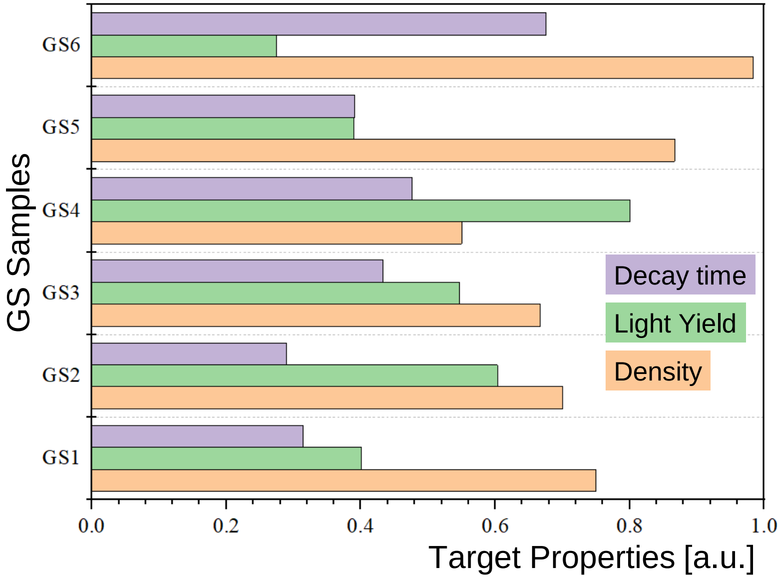
Nov 2022



Glass Scintillator Collaboration

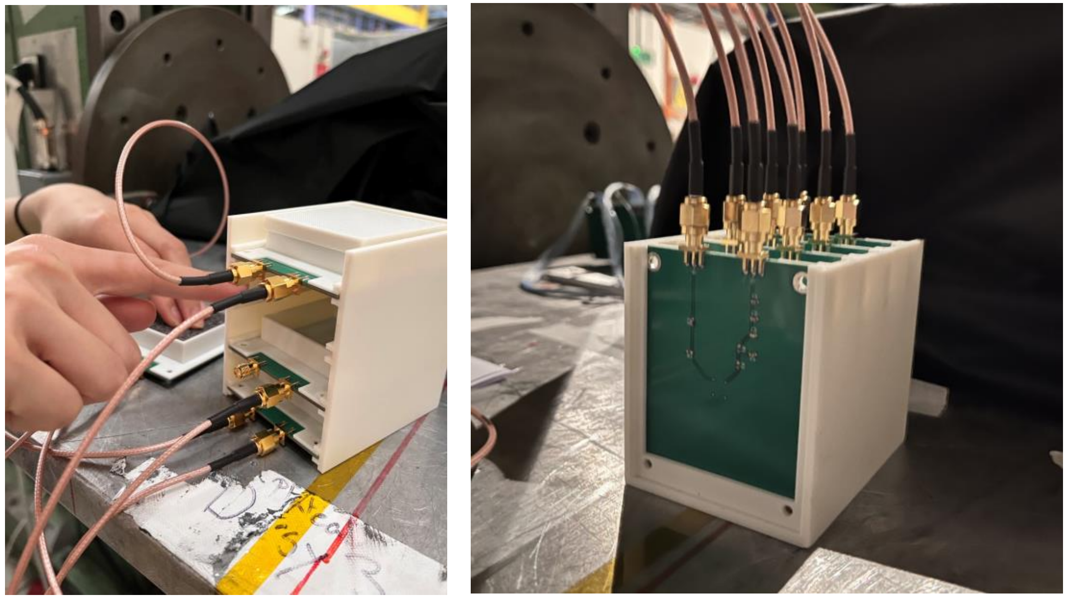


Feb 2023

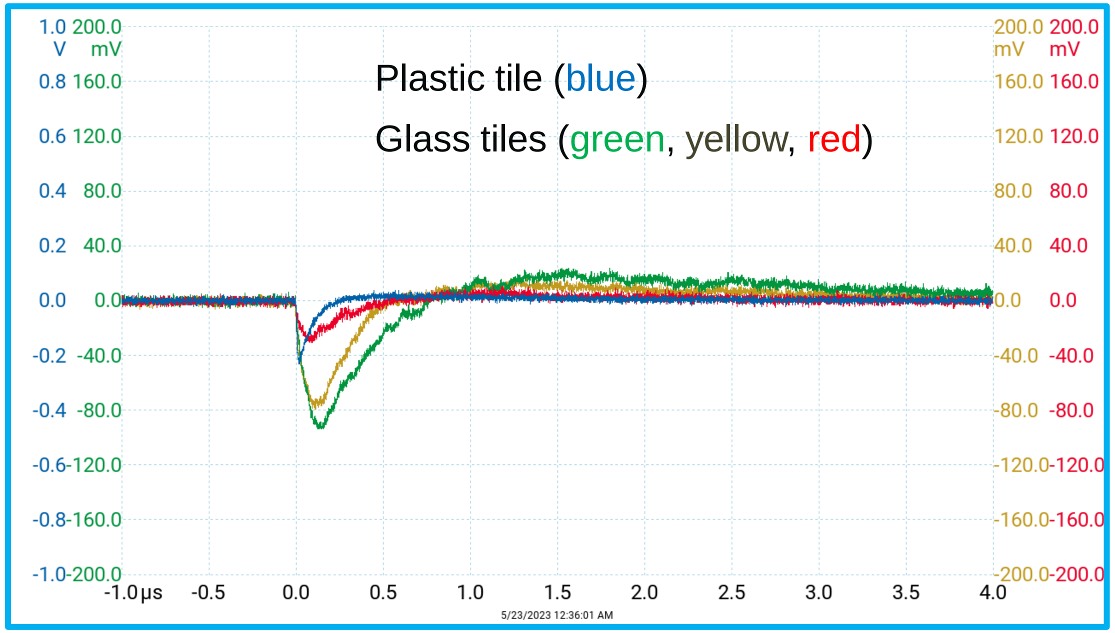


Scintillator Glass Testbeam

- 4 tiles with individual SiPM readout, 3 scintillator glass tiles + 1 plastic scintillator as reference.
- Total 11 SG tiles tested, 25-40 mm in length, 5-10mm in thickness
- DAQ using a 4-ch fast oscilloscope (5GS/s)

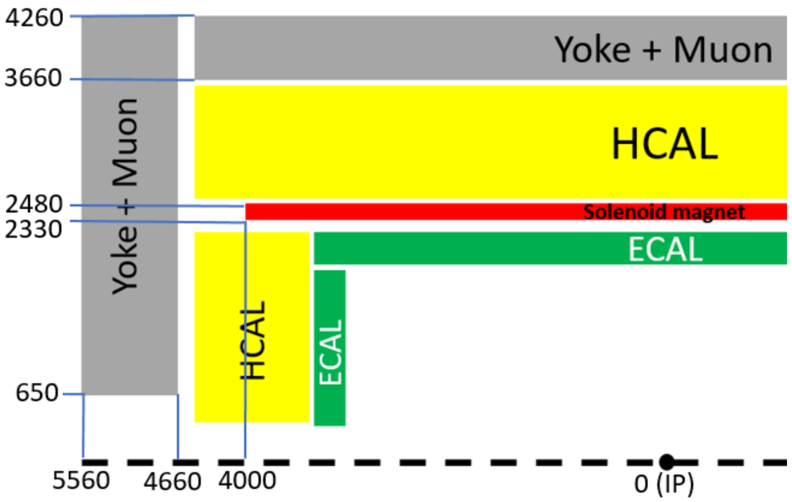


Typical waveforms with 10 GeV muon beam



- ❑ MIP response target: ~150 p.e./MIP for large-scale glass tiles (3-4cm) in length, 1cm in thickness
- ❑ Measurements show that the small size glass tile response: 15 – 74 p.e./MIP

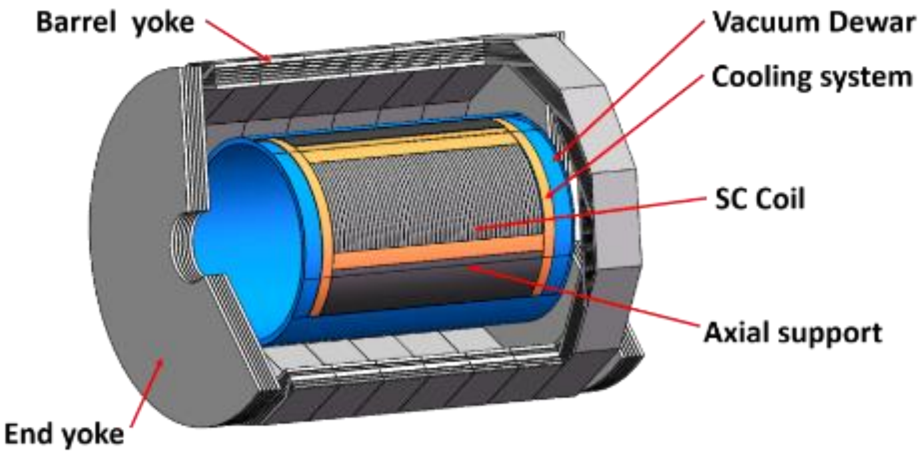
Solenoid Magnet



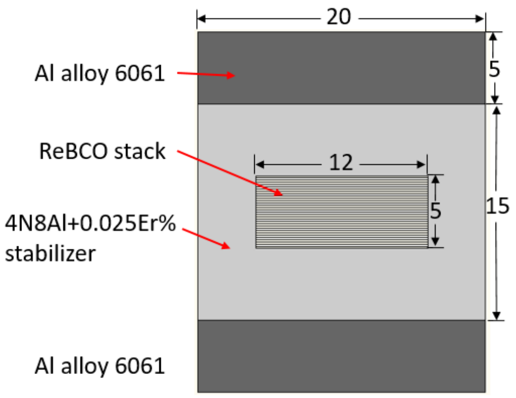
Challenges

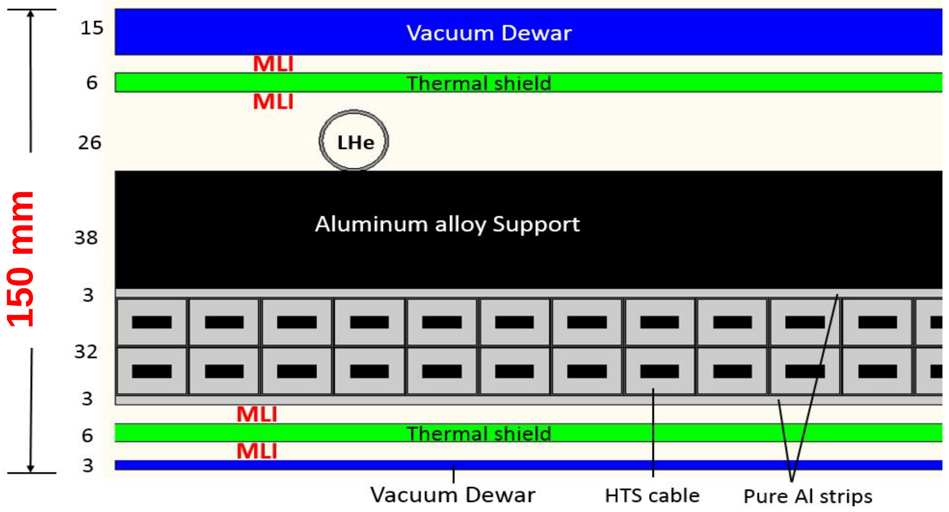
Low mass, ultra-thin, high strength cable

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



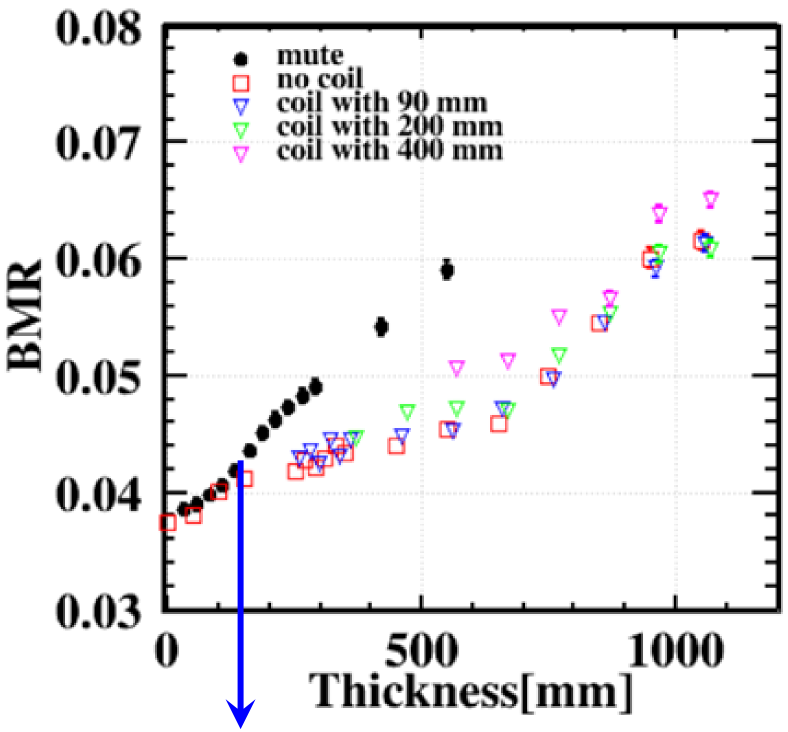
Al stabilized ReBCO stacked tape conductor (ASTC) cable

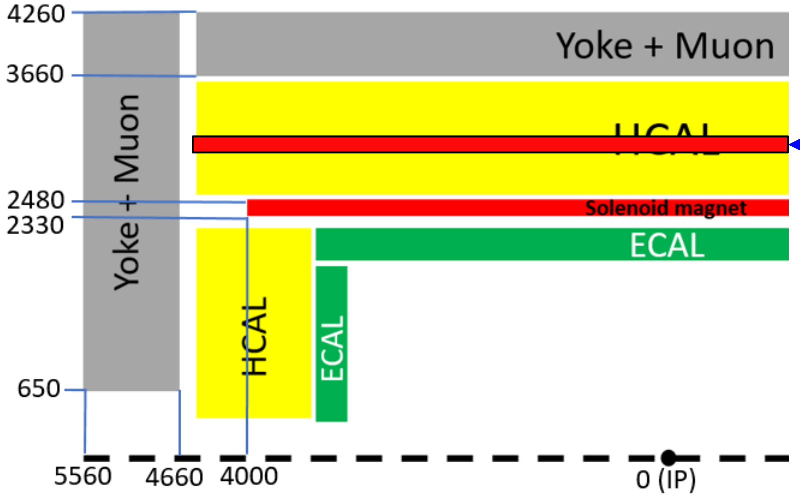




Magnetic field	3 T	Current	28000 A
Inner diameter	4660 mm	Inductance	1.27 H
Outer diameter	4960 mm	Stored energy	500 MJ
Magnet thickness	150 mm	Cold mass	27 ton
Length	8000 mm	HTS cable length	10.7 km
Total weight	48 ton	ASTC weight	16.6 ton

HTS Magnet on Physics Performance

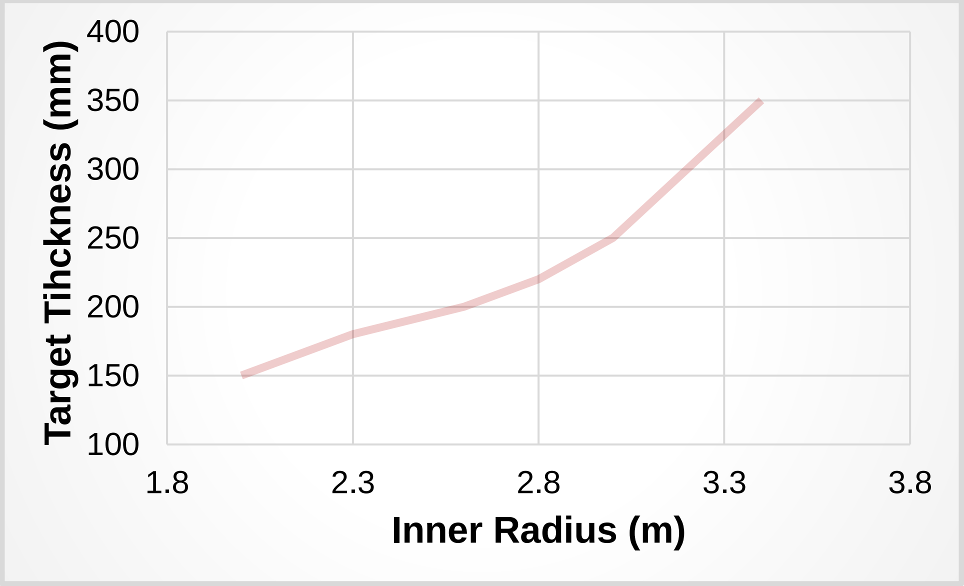




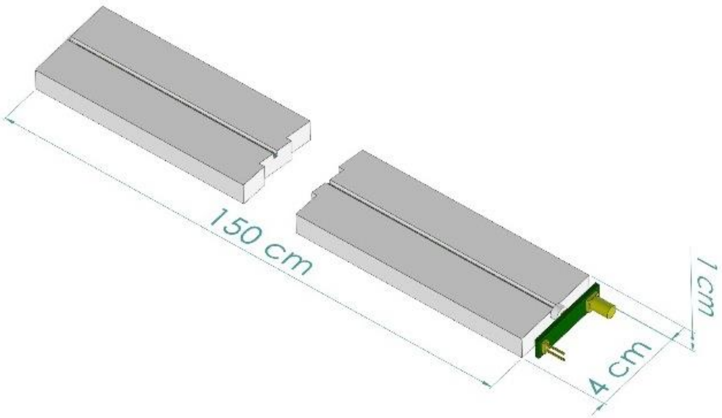
Split HCAL to inner and outer parts, and place magnet in between

Need proper simulation study to assess the idea

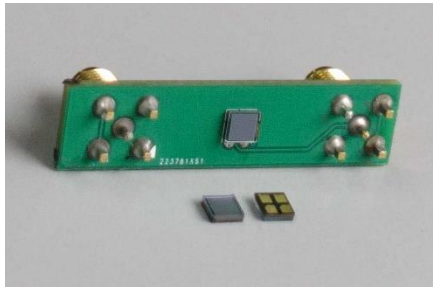
- Magnet radius 2330 - 2480 cm, thickness 150 mm
- Mass of magnet < $1.5X_0$
- Gap between ECAL & HCAL may be bigger due to different shapes. May considered irregular shape modules to minimize the effect.



A Scintillator Based Muon Detector

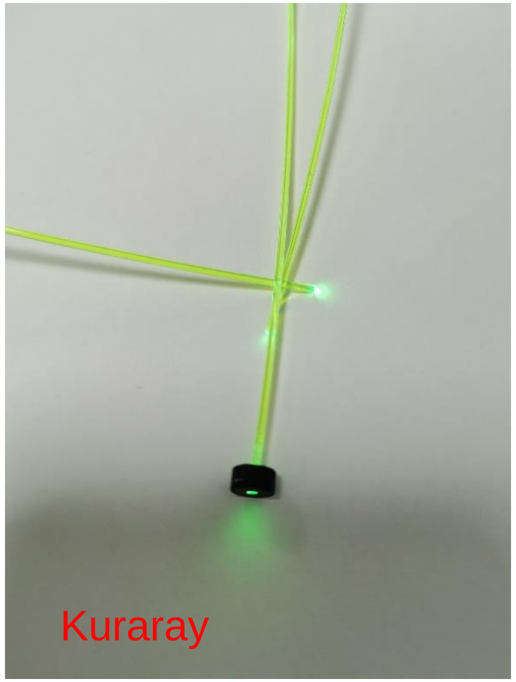


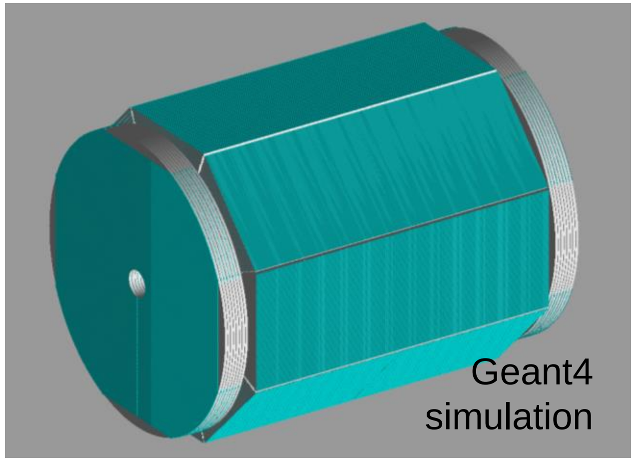
Scintillator + WLS fiber + SiPM

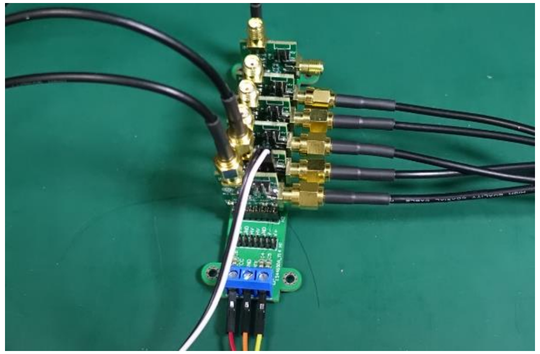


NDL SiPMs, 3×3 mm^2

Hamamatsu, 1.3×1.3 mm^2
S11360-1325/50/75cs







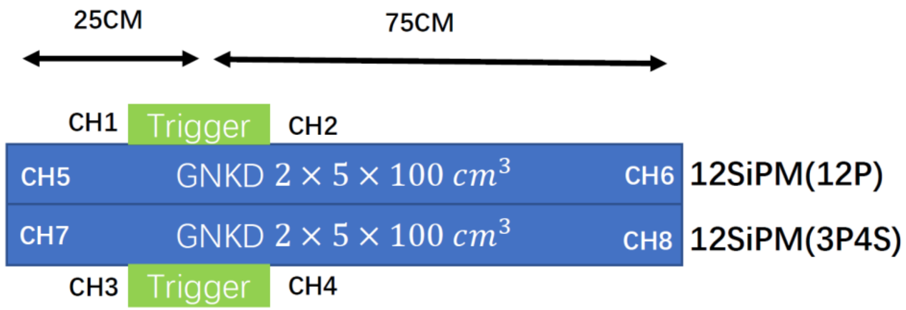
Preamplifier with high time resolution

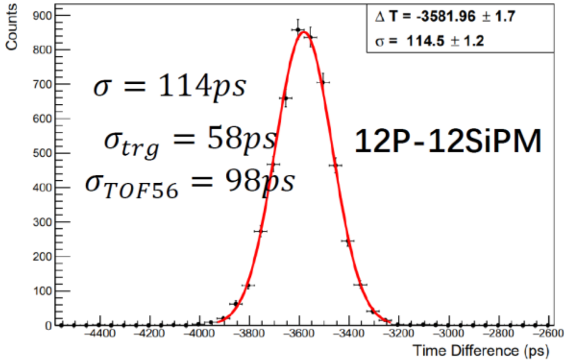
SiPM

Time Resolution

Achieve time resolution better than $80ps$ from 1 meter new scintillator.

New $1.5m$ long scintillator shows a time resolution of $124ps$ at the middle.

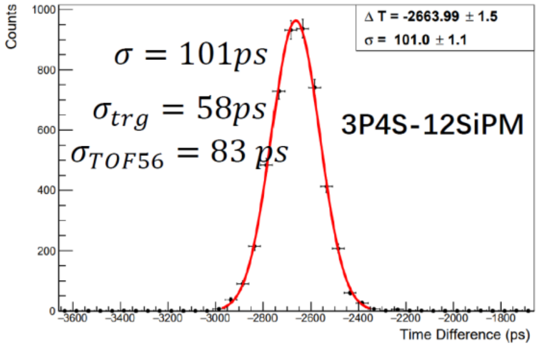




$\sigma = 114ps$

$\sigma_{trg} = 58ps$

$\sigma_{TOF56} = 98ps$

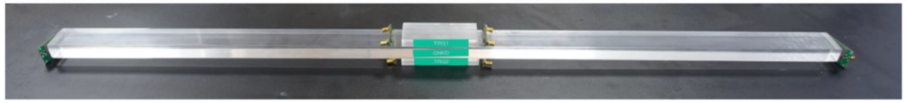


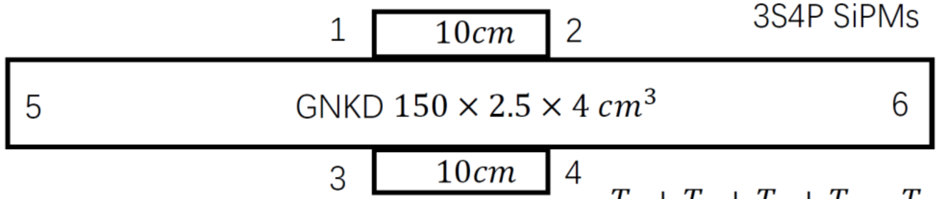
$\sigma = 101ps$

$\sigma_{trg} = 58ps$

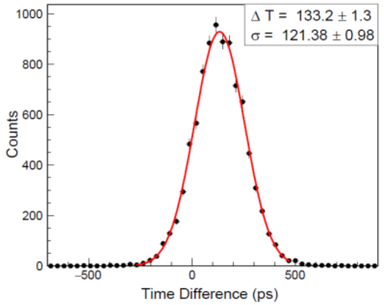
$\sigma_{TOF56} = 83\ ps$

Newest testing with trigger at 85cm, $\sigma_T = 72\ ps$.
Good agreement with calculation!



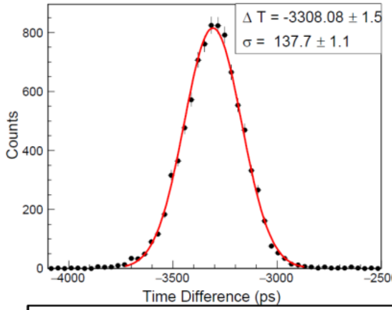


$$\frac{T_1 + T_2}{2} - \frac{T_3 + T_4}{2}$$



$\sigma_{trg} = 60.7\ ps$

$$\frac{T_1 + T_2 + T_3 + T_4}{4} - \frac{T_5 + T_6}{2}$$



$\sigma_{TOF} = 123.6\ ps\ @75cm$

ADC_5 mean: 51.8mV
ADC_6 mean: 47.6mV

Compared with 2cm thick GNKD,
2.5cm thick cause less photon collection and worse time resolution

CEPC R&D Projects

Det	Technology	Det	Technology
Pixel Vertex	JadePix	**Calorimeter**	Crystal ECAL
	TaichuPix		Stereo Crystal ECAL
	CPV(SOI)		Scint+W ECAL
	Stitching		Si+W ECAL
	Arcadia		Scint+Fe AHCAL
Tracker & PID	CEPCPix		ScintGlass AHCAL
	Silicon Strip		RPC SDHCAL
	TPC		MPGD SDHCAL
	Drift chamber		DR Calorimeter
	PID drift chamber	**Muon**	Scintillation Bar
	LGAD ToF		RPC
Lumi	SiTrk+Crystal ECAL		μ-Rwell
	SiTrk+SiW ECAL		HTS / LTS Magnet
	CEPC SW		MDI & Integration
	TDAQ		

- ❑ Many on-going and planned R&D projects aiming implementation on CEPC. Some are not mentioned here. But they are equally important.
- ❑ MDI, mechanical & integration plan matter to all subdetectors.
- ❑ TDAQ scheme may affect design strategy of all subdetectors.
- ❑ CEPC SW is crucial to all physics studies.

Closing Remarks

- We are all working towards a common goal, and should work together more closely.
- CEPC physics reach are not just affected by the number of interaction events. It is also coupled to what information the detecting system could provide, and the quality.
- We need to be very clear what detector specifications are crucial, and how important they are. Feedbacks from the physics bench marks guide the detector design.

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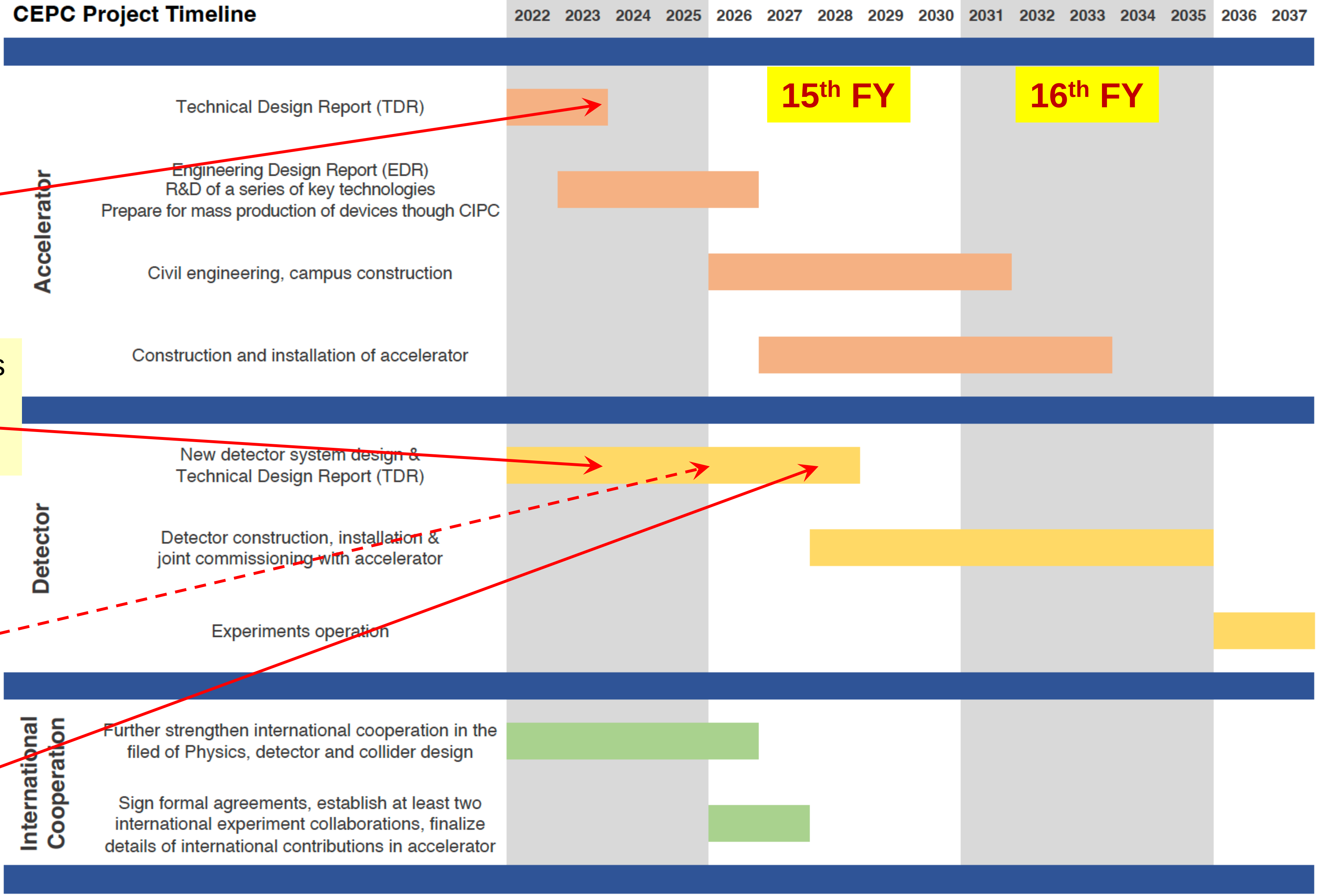
Optimal Timeline of CEPC



CEPC Project Timeline

2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037

15th FY

16th FY

Accelerator

Technical Design Report (TDR)

Engineering Design Report (EDR)
R&D of a series of key technologies
Prepare for mass production of devices though CIPC

Civil engineering, campus construction

Construction and installation of accelerator

Detector

New detector system design &
Technical Design Report (TDR)

Detector construction, installation &
joint commissioning with accelerator

Experiments operation

International Cooperation

Further strengthen international cooperation in the
filed of Physics, detector and collider design

Sign formal agreements, establish at least two
international experiment collaborations, finalize
details of international contributions in accelerator

Completion of
Accelerator TDR

Continue R&D on key technologies
System-level validations
……

Form
International Collaborations

Decide on technologies
and complete TDR