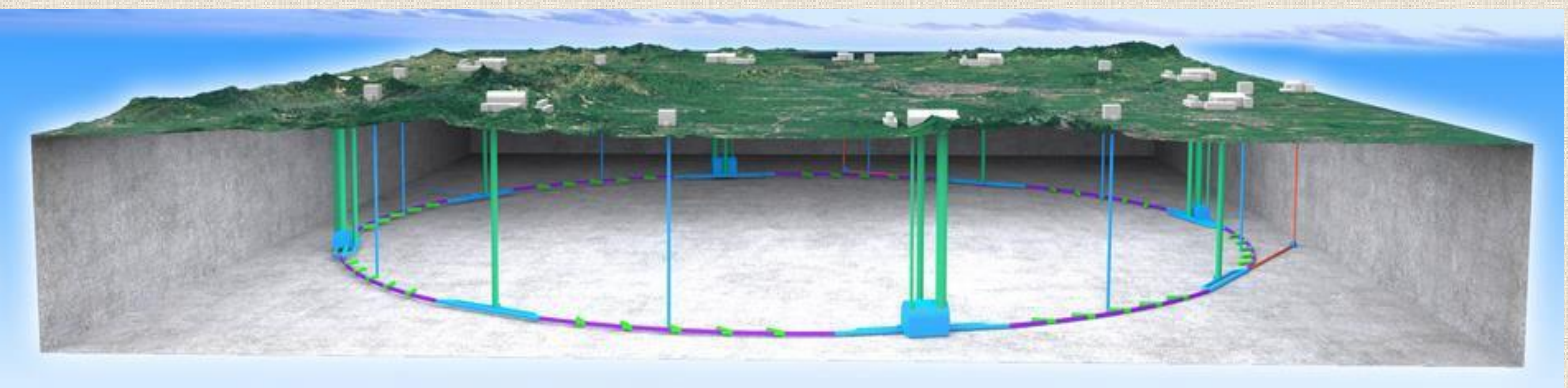
Status and Perspective of the CEPC

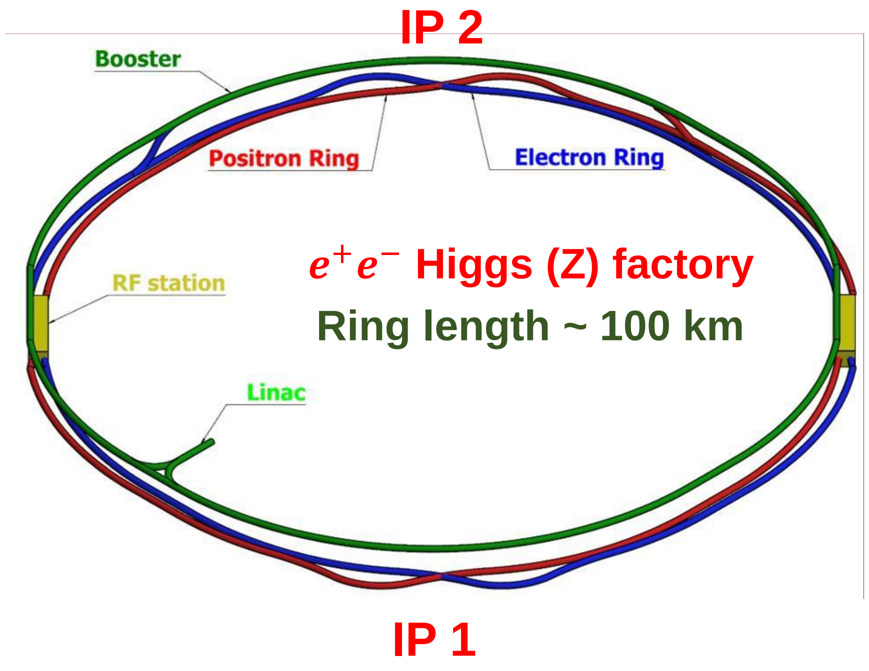
Jianchun Wang (IHEP, CAS)
For the CEPC Study Group

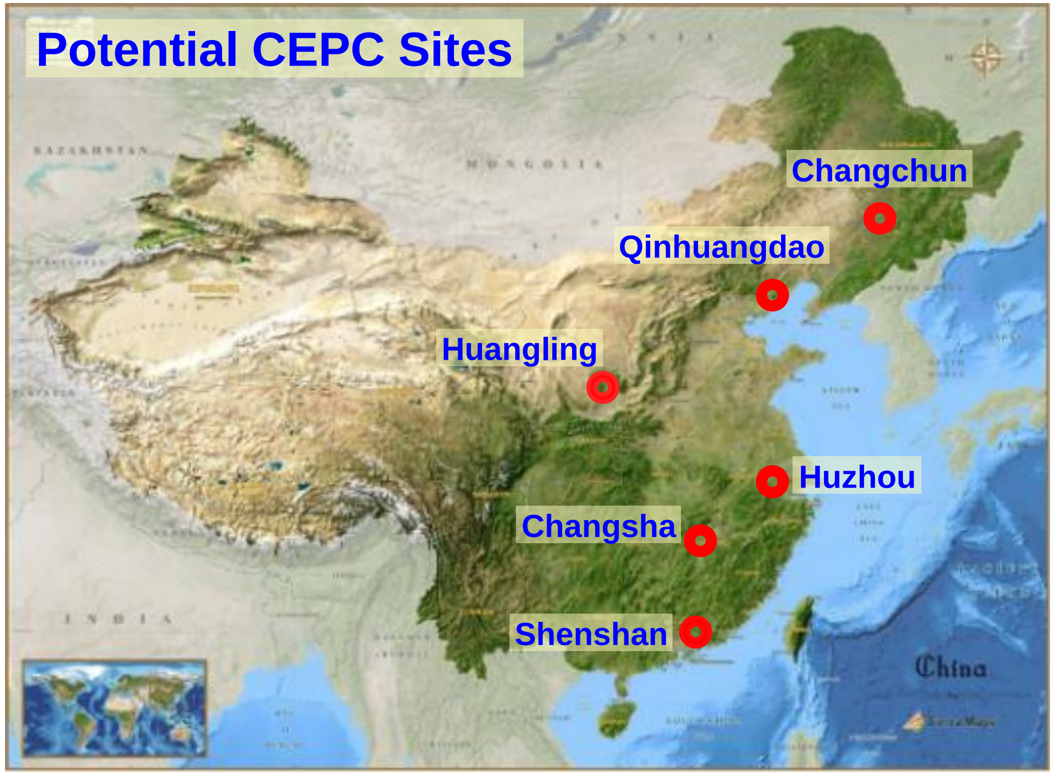
The 9th China LHC Physics Workshop
Nov 16-20, 2023, Shanghai



The Circular Electron Positron Collider (CEPC)

- The CEPC was proposed by Chinese HEP community in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as a Higgs / Z / W factory in China.
- 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.



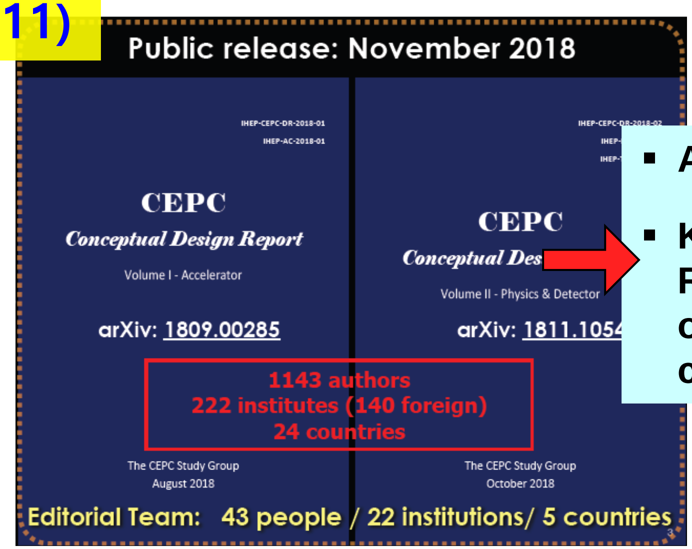


Major Milestones

CEPC-SppC Kickoff (2013.9)

CEPC IAC Meeting (2015.9)

CEPC CDR Released (2018.11)

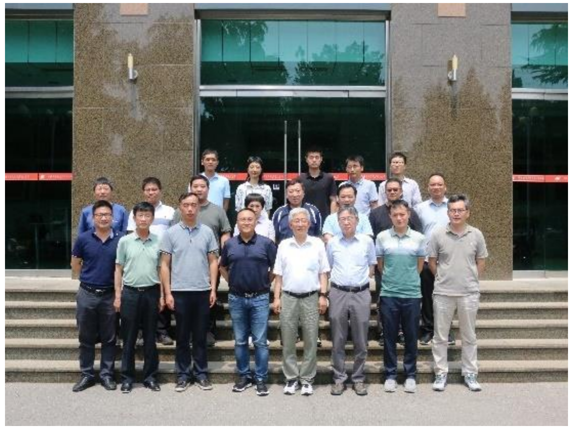


- Accelerator TDR (2023)
- Key detector technology R&D and establishment of seeds for international collaborations

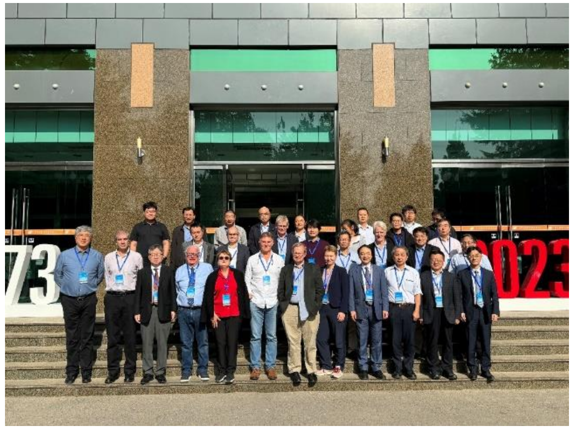
CEPC Accelerator TDR

International Technical Review @ HK, Jun 12-16, 2023

International Cost Review @ HK, Sept 11-15, 2023



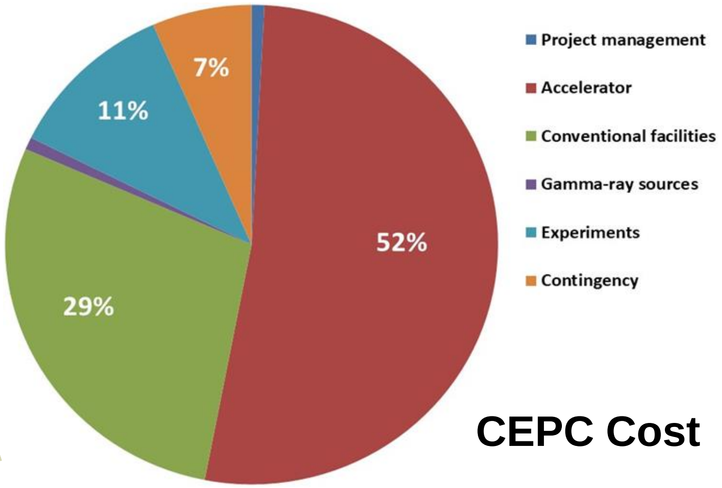
Domestic Civil Engineering Cost Review, June 26, 2023



Endorsed by CEPC IAC Oct 29-31, 2023

The CEPC Accelerator TDR covers

- Design, knowledge and progress of the CEPC
- Advancement of technologies that CEPC depends upon, delivered through a comprehensive R&D program, HEPS experience, international contributions and cooperation
- Innovative ideas and future upgrades to make the CEPC state-of-the-art as time moves forward
- Cost of the CEPC

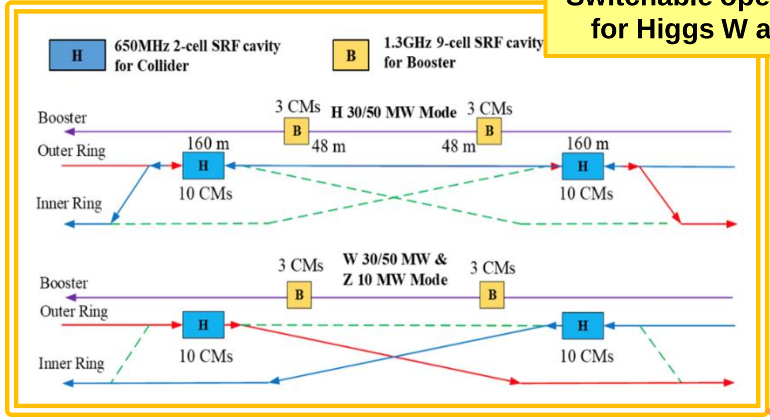


The CEPC accelerator TDR will be released on **Dec 15, 2023,** when the author list is finalized

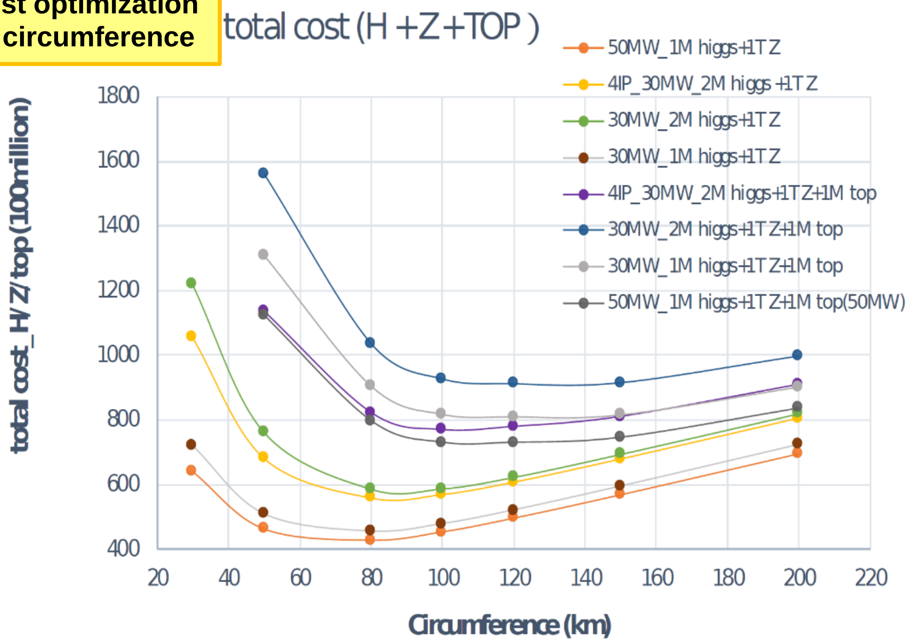
CEPC Layout and Design Essentials

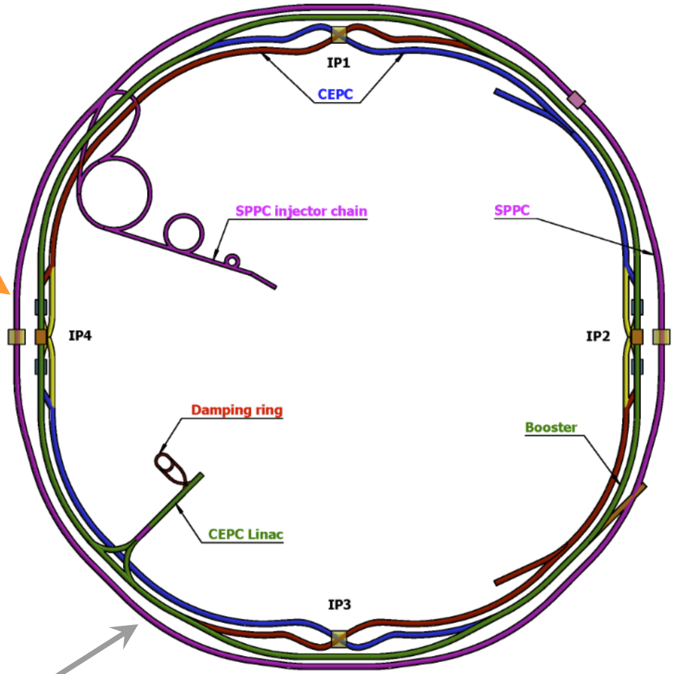
D. Wang *et al* 2022 *JINST* **17** P10018

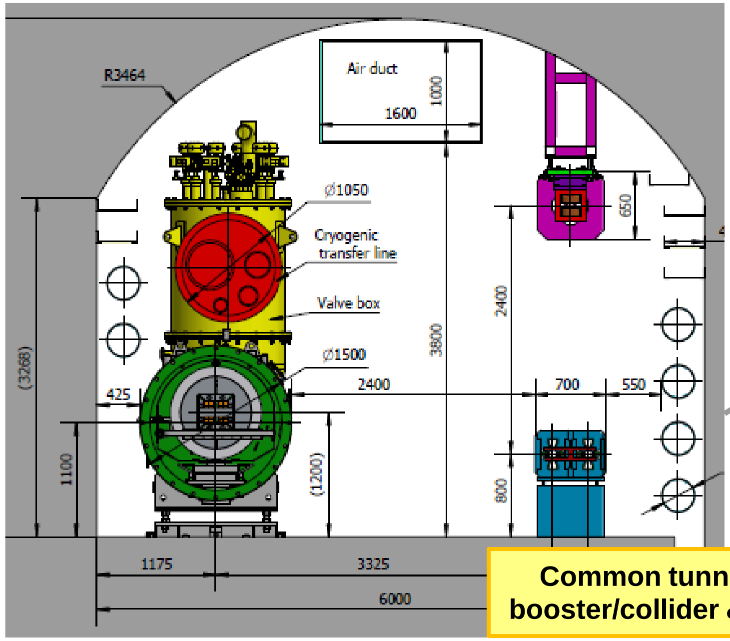
Switchable operation for Higgs W and Z



Cost optimization vs circumference



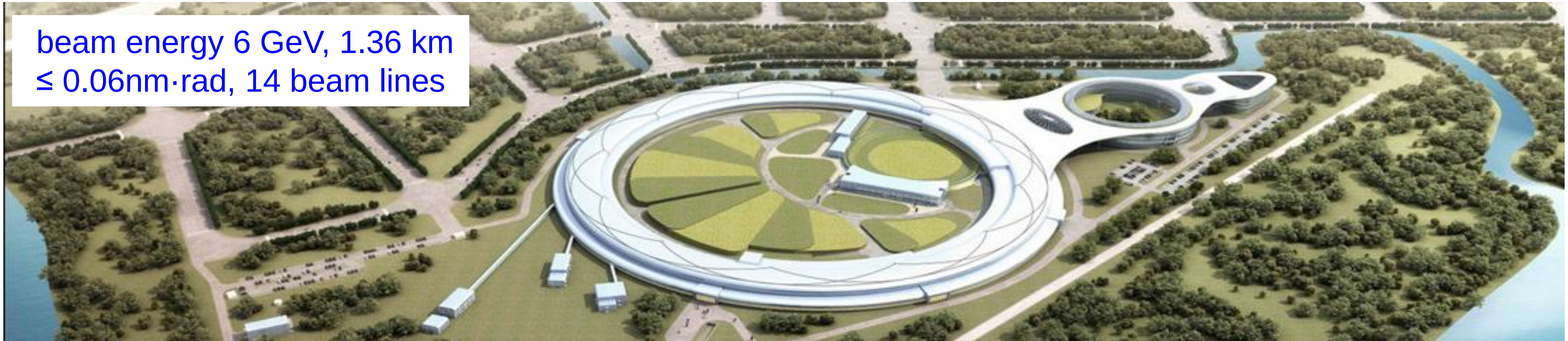




Common tunnel for booster/collider & SppC

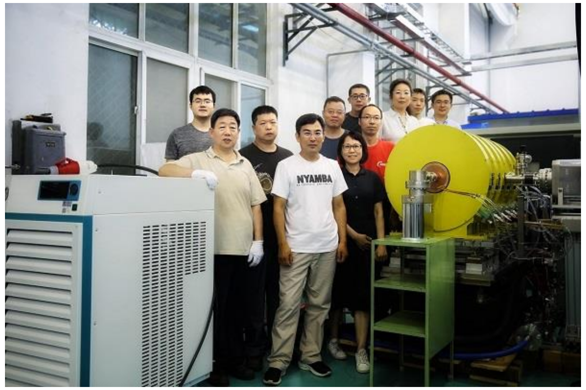
- Optimal **100 km circumference**
- **Shared tunnel** for booster, collider and SppC
- Baseline: 30 MW, **upgradable** to 50 MW and $t\bar{t}$
- **Switchable** between Higgs, W/Z, and top modes

High Energy Photon Source under Construction

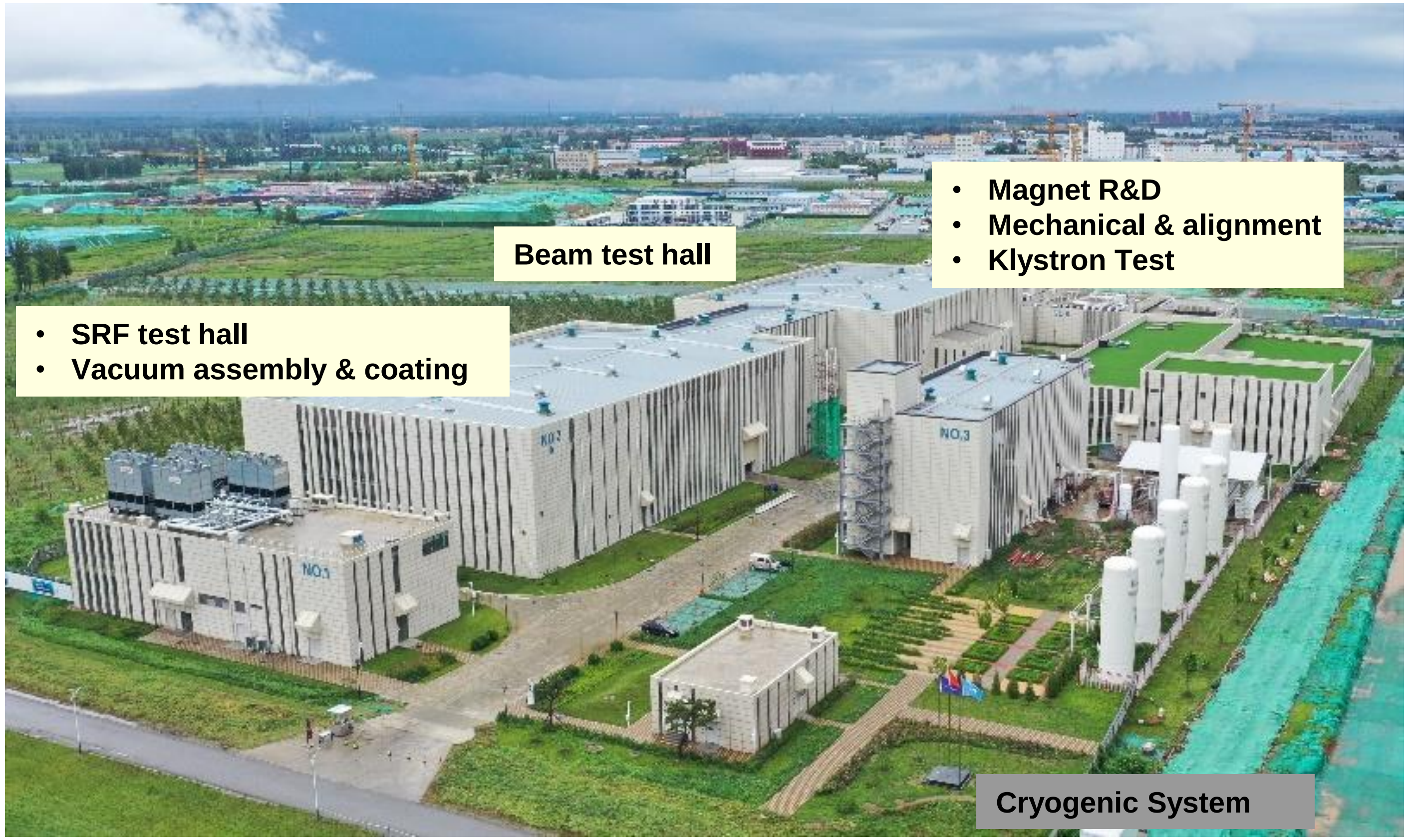


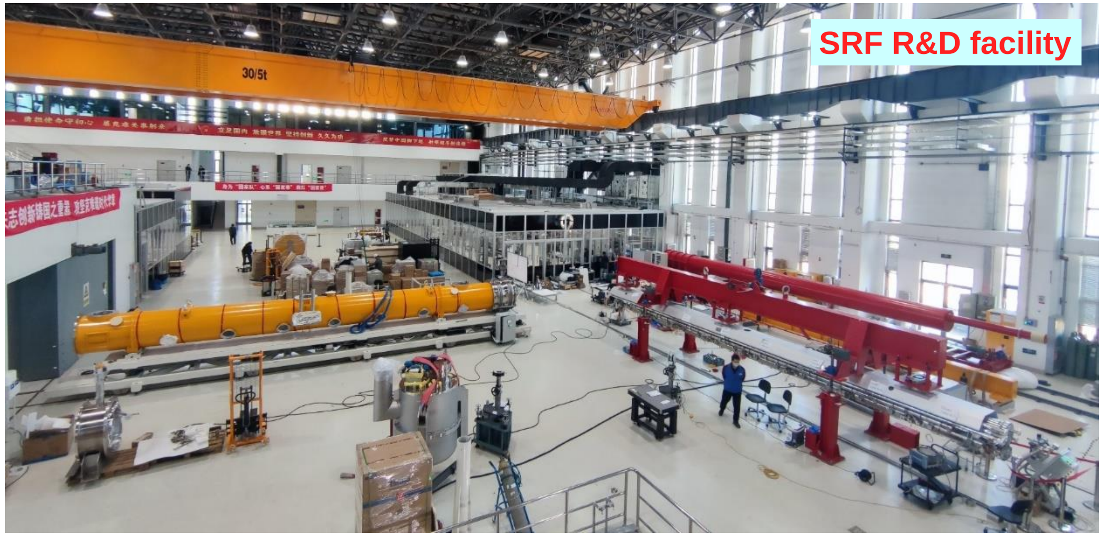
beam energy 6 GeV, 1.36 km
≤ 0.06nm·rad, 14 beam lines

To be completed in 2025, great training and preparation for CEPC



Platform for Key Technology R&D

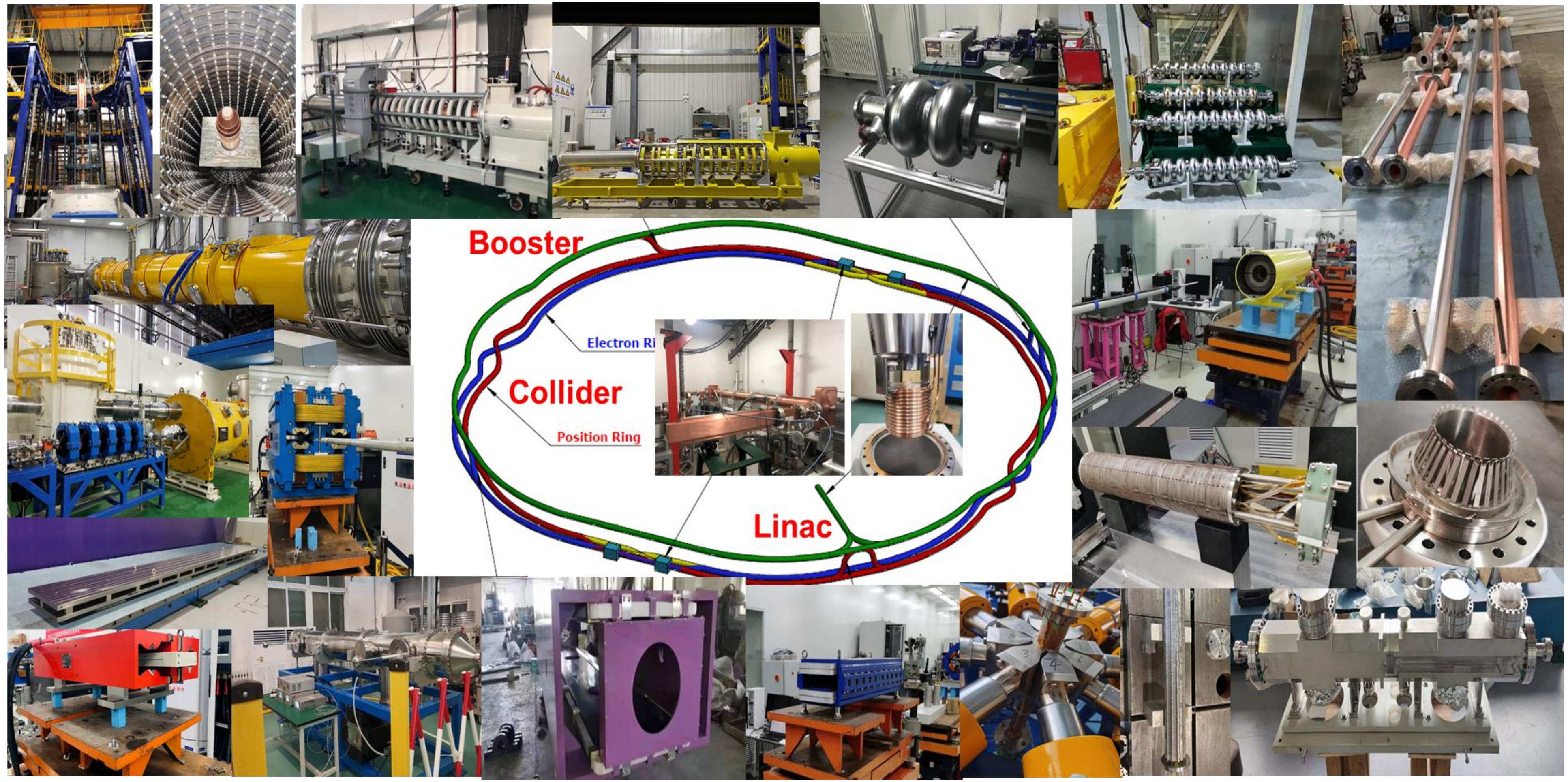




Accelerator key technology R&D platform was established:

- SRF cavity and module
- High precision magnet
- Vacuum assembly & coating
- High efficiency Klystron
- Mechanics and alignment
- Beam test facility

Key Components and Prototype R&D



✔ **Specification Met**

☑ **Prototype Manufactured**

Accelerator	Fraction
✔ Magnets	27.3%
✔ Vacuum	18.3%
☑ RF power source	9.1%
✔ Mechanics	7.6%
✔ Magnet power supplies	7.0%
✔ SC RF	7.1%
✔ Cryogenics	6.5%
✔ Linac and sources	5.5%
✔ Instrumentation	5.3%
☑ Control	2.4%
☑ Survey and alignment	2.4%
✔ Radiation protection	1.0%
☑ SC magnets	0.4%
✔ Damping ring	0.2%

Key technology R&D spans over all components listed in the CEPC CDR

Key Technology Readiness

- CEPC received ~ 260 Million CNY for R&D from MOST, CAS, NSFC, …
- Large amount of key technologies validated in other projects by IHEP: BEPCII, HEPS, …

CEPC R&D ~ 40% cost of acc. components	▪ High efficiency klystron ▪ SRF cavities ▪ Positron source ▪ High performance accelerator	▪ Novel magnets: Weak field dipole, dual aperture magnets ▪ Extremely fast injection/extraction ▪ Electrostatic deflextor ▪ MDI
BEPCII / HEPS ~ 50% cost of acc. components	▪ High precision magnet ▪ Stable magnet power source ▪ Vacuum chamber with NEG coating ▪ Instrumentation, Feedback system	▪ Survey & Alignment ▪ Ultra stable mechanics ▪ Radiation protection ▪ Cryogenic system ▪ MDI

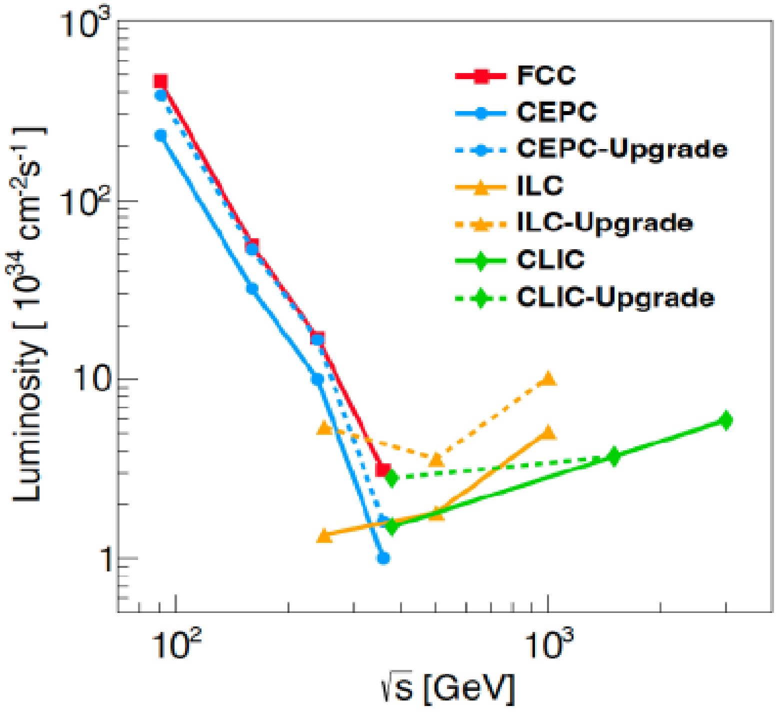
~10% missing items consist of anticipated challenges in the machine integration, commissioning etc to be completed by 2026, and the corresponding international contributions.

CEPC Operation Plan

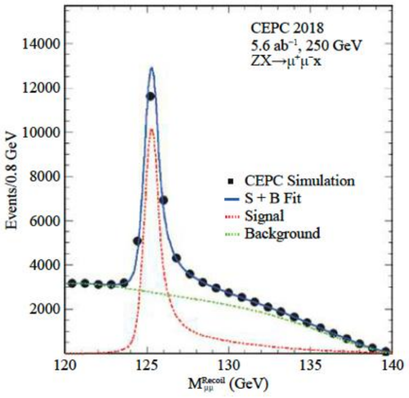
Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			~240	~91.2	~160	~360
Run time [years]			7	2	1	-
CDR (30 MW)		L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^{6}	7×10^{11}	2×10^{7}	-
Run Time [years]			10	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}	5×10^{7}	5×10^{5}

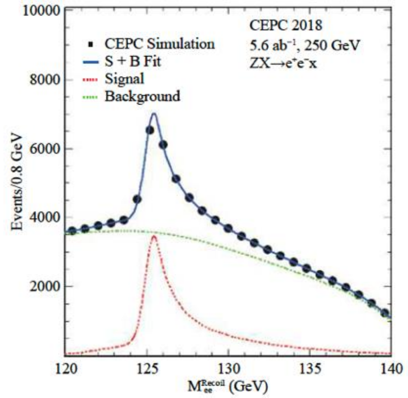
Both 50 MW and $t\bar{t}$ modes are currently considered as upgrades.

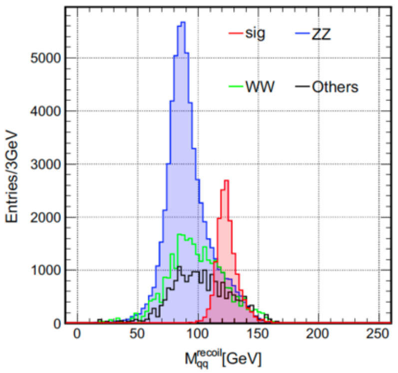
CEPC Accelerator white paper for Snowmass21, arXiv:2203.09451

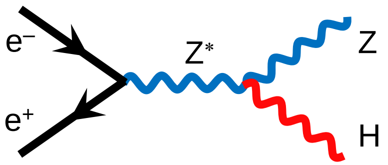


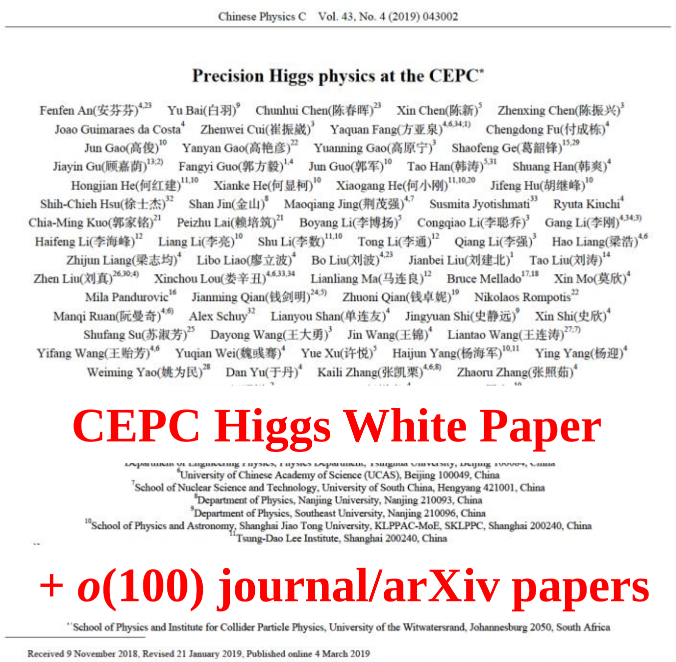
Physics Opportunities @ CEPC











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Precision Higgs physics at the CEPC*

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CEPC Higgs White Paper

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+ $o(100)$ journal/arXiv papers

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Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
Bupper$(H \to$ inv.$)$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude
- EW: Precision improved from current limit by 1-2 orders
- Flavor Physics, sensitive to NP of 10 TeV or even higher
- Sensitive to varies of NP signal
- ...

White paper on **Higgs** physics was published in 2019.

White papers on **EW, Flavor** physics**, NP, QCD** are likely to be released in year 2024

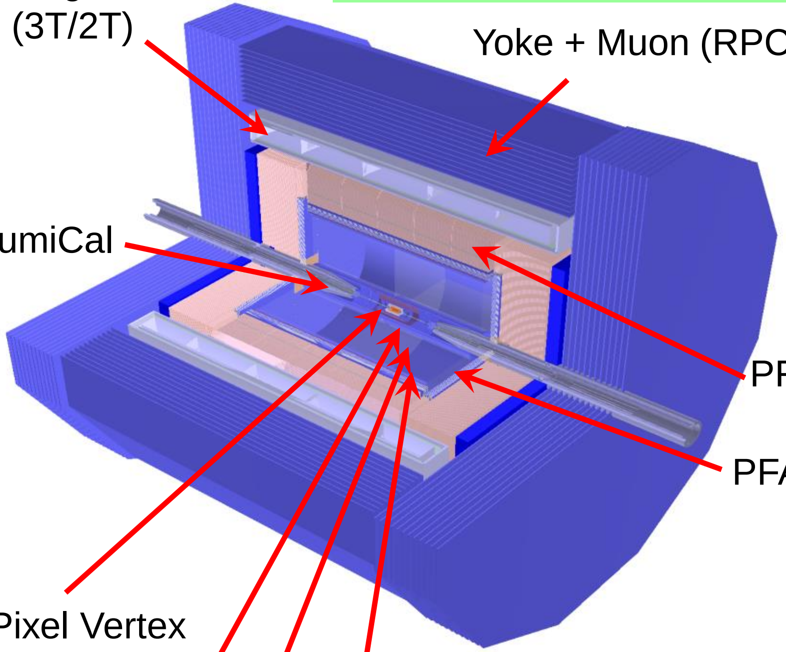
Requirements of Detector and Key Technologies

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu$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 $\sigma_E^{jet} \sim 30\%/\sqrt{E(\mathrm{GeV})}$

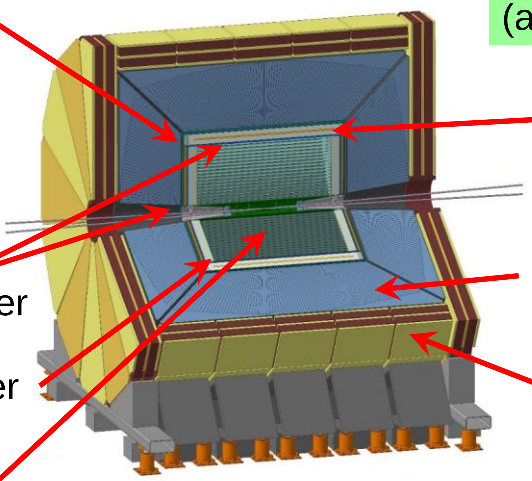
Requirements evolute with better understanding of the detector technologies and physics goals

Conceptual Detector Designs

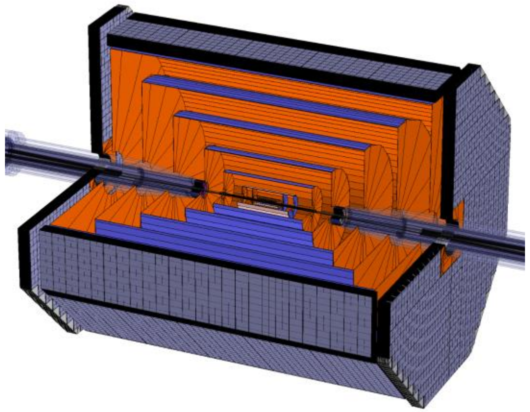
(Baseline Design)
Particle Flow Algorithm



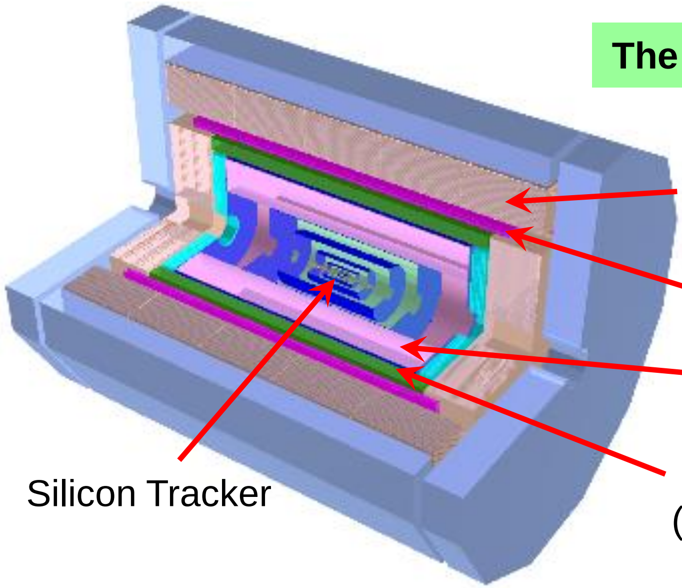
IDEA concept
(also proposed for FCC-ee)



FST concept
(Full Silicon Tracker)



The 4th Concept



The 4th Conceptual Detector Design

Scint Glass PFA HCAL

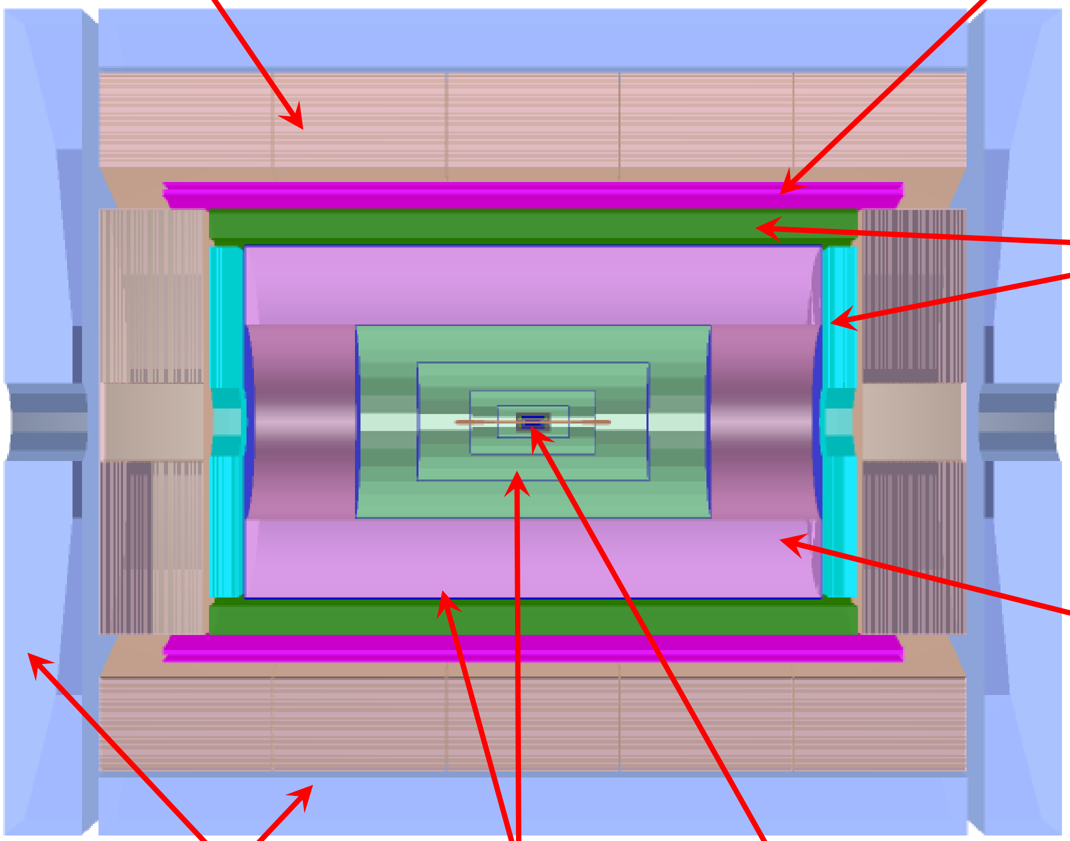
Advantage: Cost efficient, high density

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.

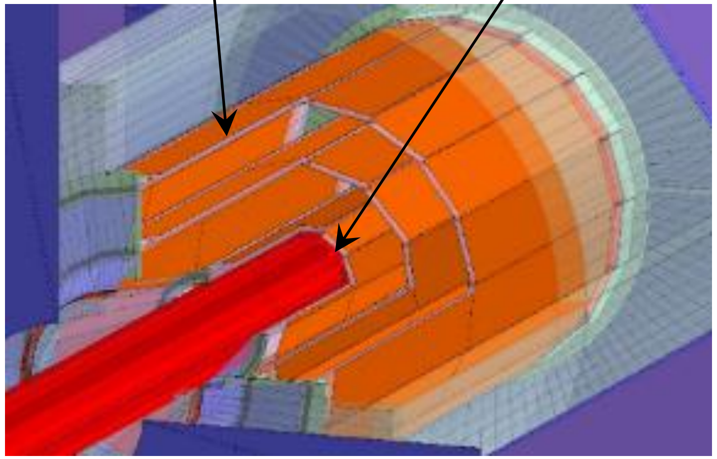
A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs

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

Silicon Pixel Chips for Vertex Detector

2 layers / ladder R_{in}~16 mm



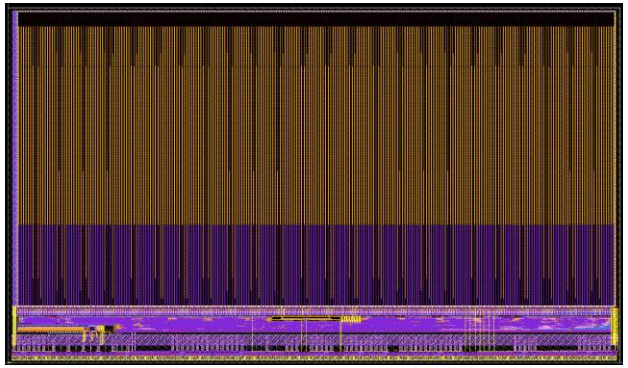
Goal: σ(IP) ~ 5 μm for high P track.

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)

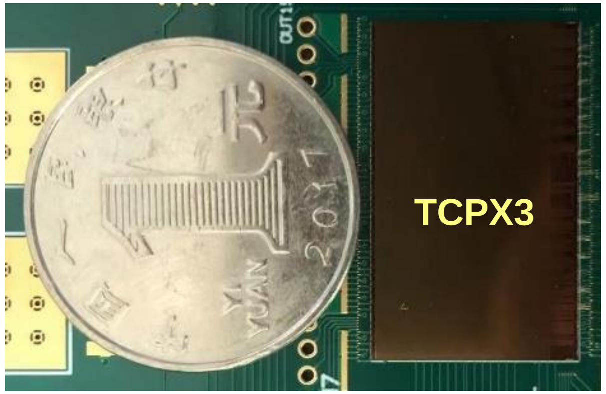
Silicon pixel sensor develops in 3 series:
JadePix / MIC, **TaichuPix**, **CPV**

JadePix4 356×498 array of 20×29 μm^2



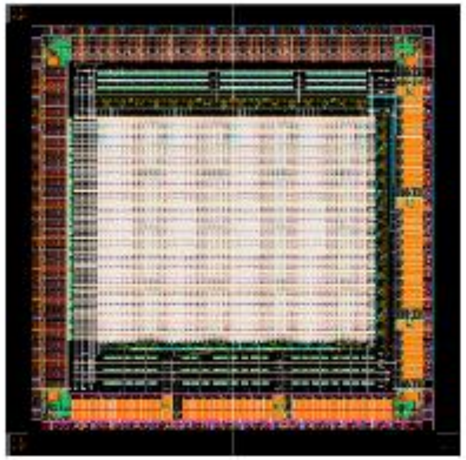
TowerJazz 180nm CIS process
$\sigma_{x/y}$ ~ 3-4 μm, σ_t ~ 1 μs, ~100 mW/cm^2

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

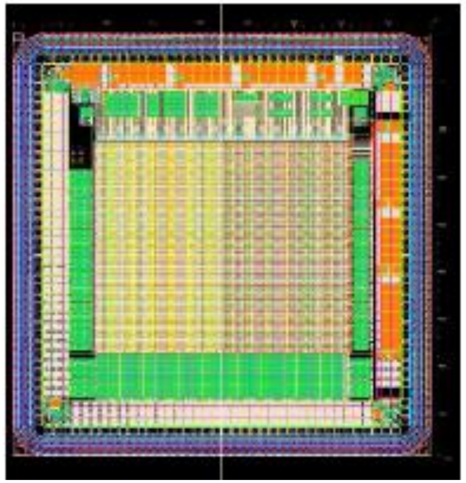


CPV4 (SOI-3D), 64×64 array
~21×17 μm^2 pixel size

Upper chip

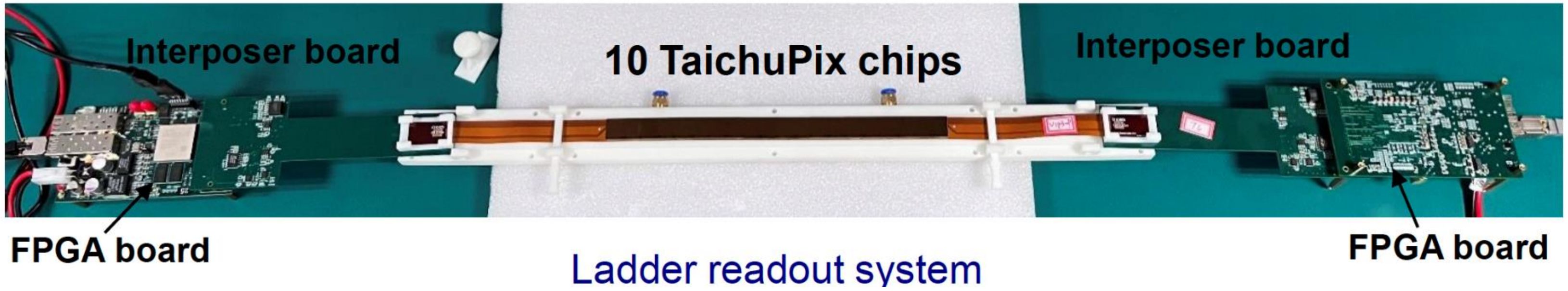


Lower chip



LAPIS 200nm SOI process

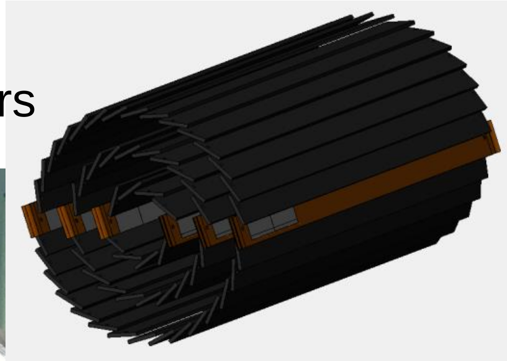
Prototyping Vertex Detector

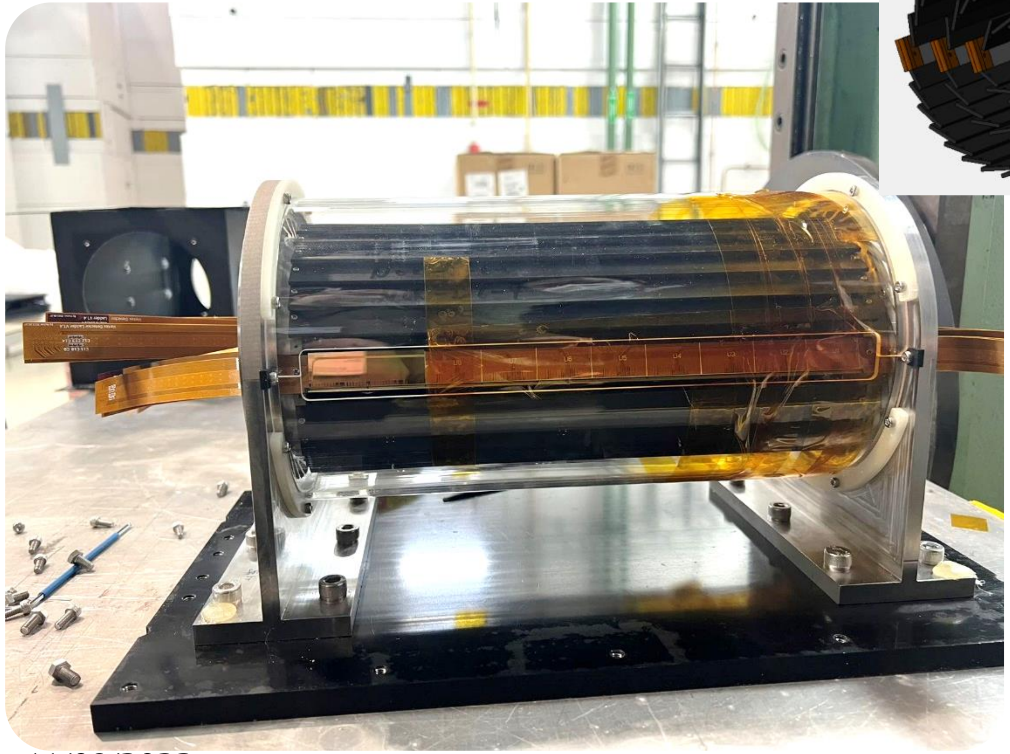


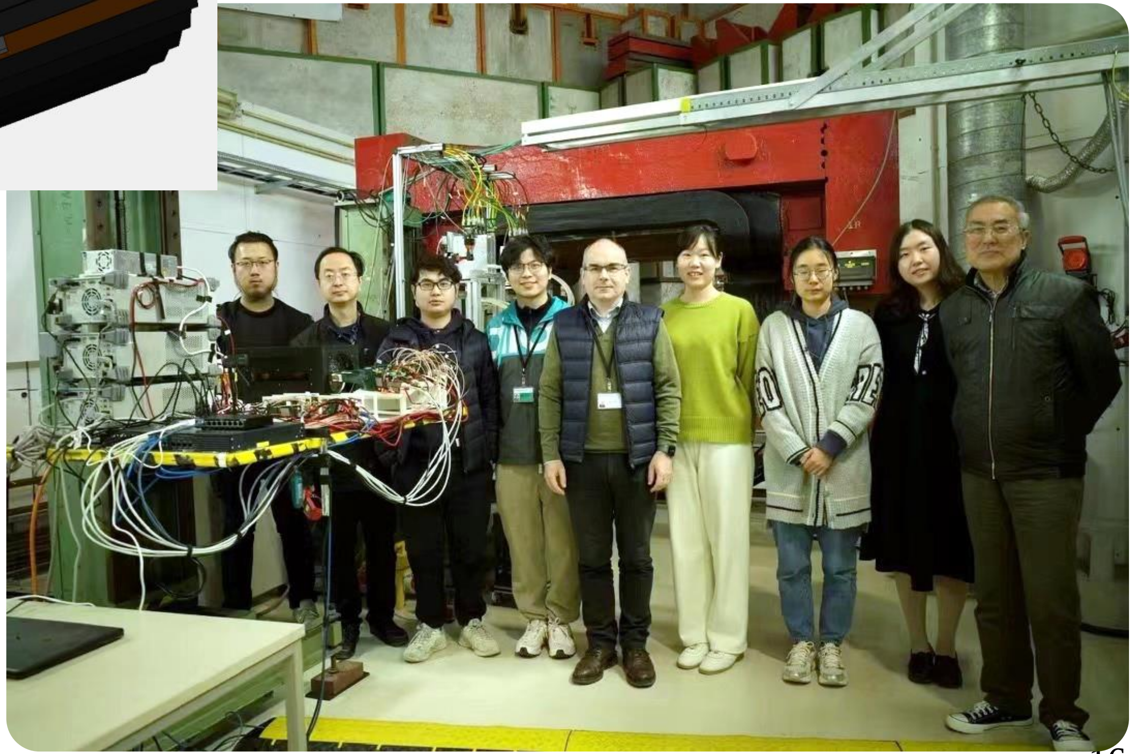
TaichuPix-based prototype detector tested at DESY in April 2023

Spatial resolution ~ **4.9 μm**

6 double-sided ladders





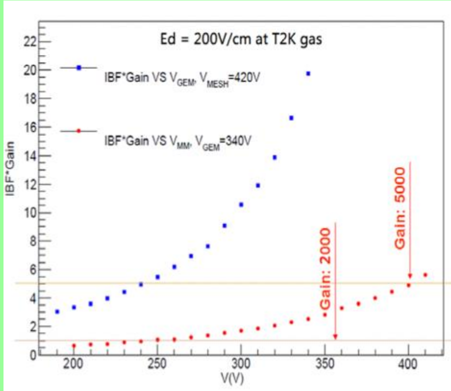


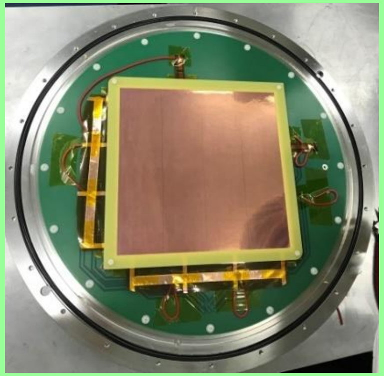
Pixelated TPC Tracker

- 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:

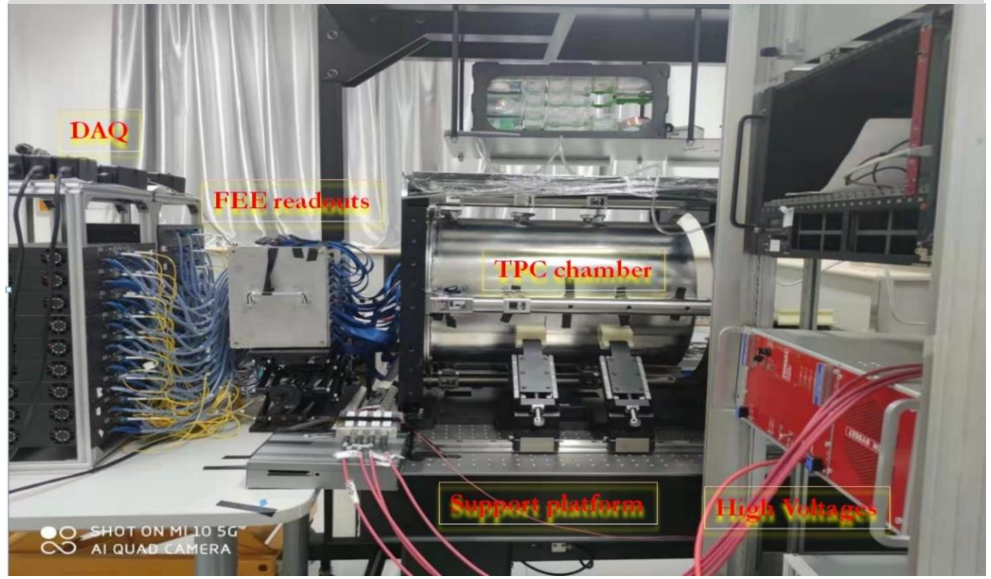
$\sigma(r\text{-}\Phi)$ ~100 μm

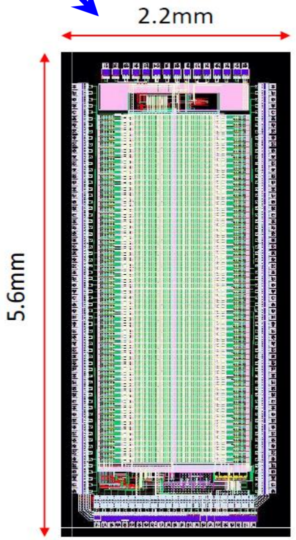


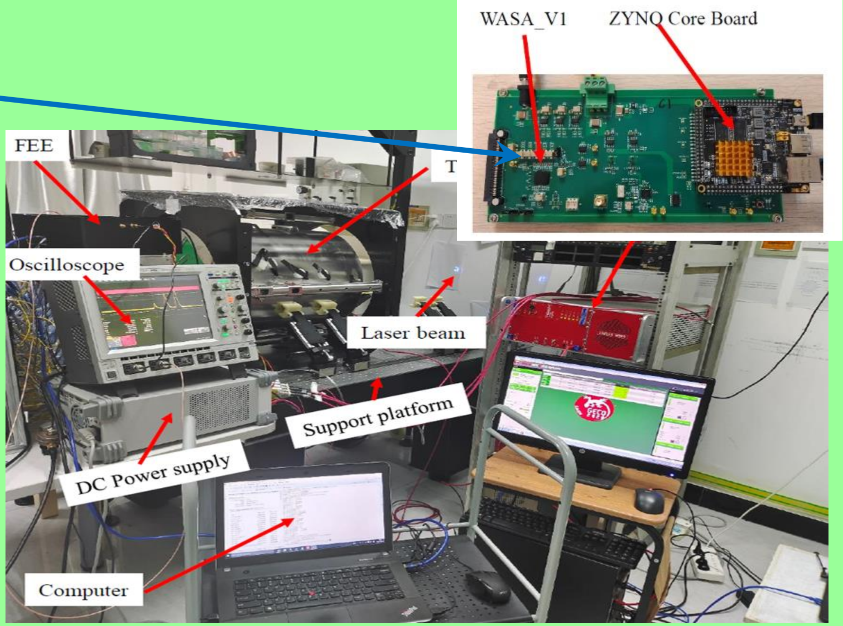


GEM+Micromegas module R&D

TPC prototype with integrated 266nm UV laser



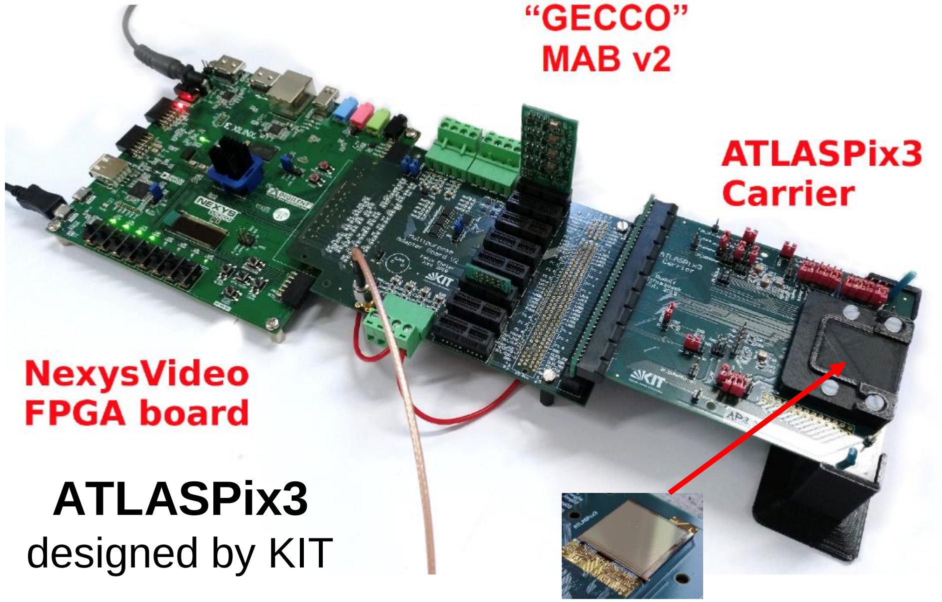




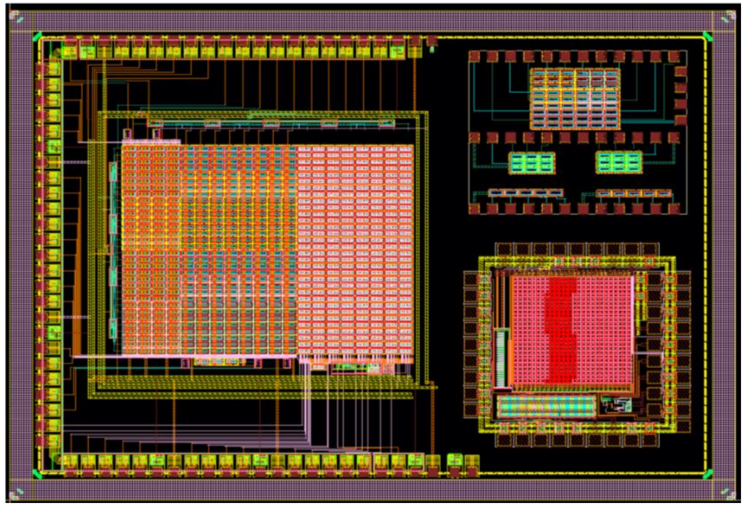
Low power consumption readout

Silicon Pixel Tracker

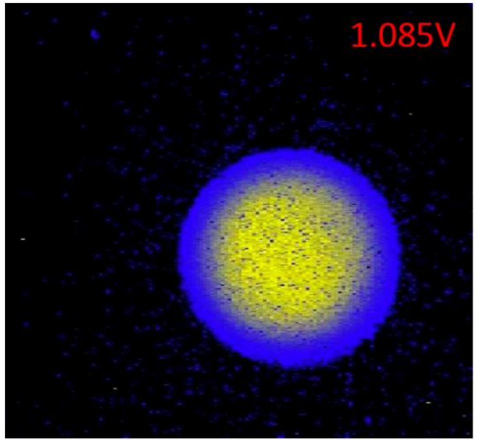
- Large area: **~140 m²** in Full SiTrk, or **~70 m²** in TPC+SiTrk
  ➔ Cost effectiveness
- Focus on MAPS pixel tracker, also started SSD for outer layers
- Joint efforts on an ATLASPix3 based demonstrator
- ATLASPix & MightyPix use TSI 180nm HV process
  ➔ Long term support (?)
- Exploring SMIC 55 nm HV HR process
  ➔ Smaller feature size & alternative foundry
- Other possibilities, e.g. MALTA3, TPSCo-65nm



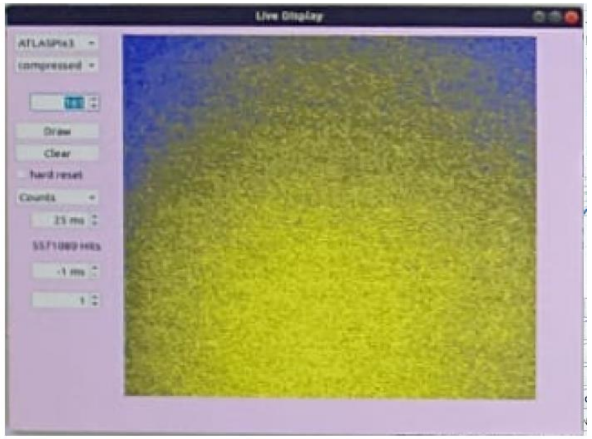
ATLASPix3
designed by KIT



The 2nd design for SMIC 55nm HV HR process

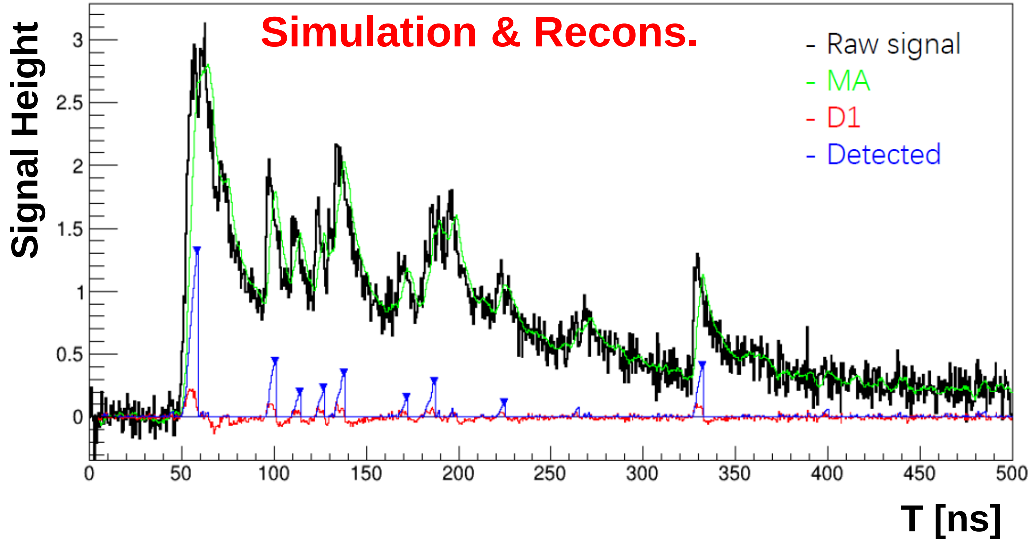


Hitmap with Fe55 source

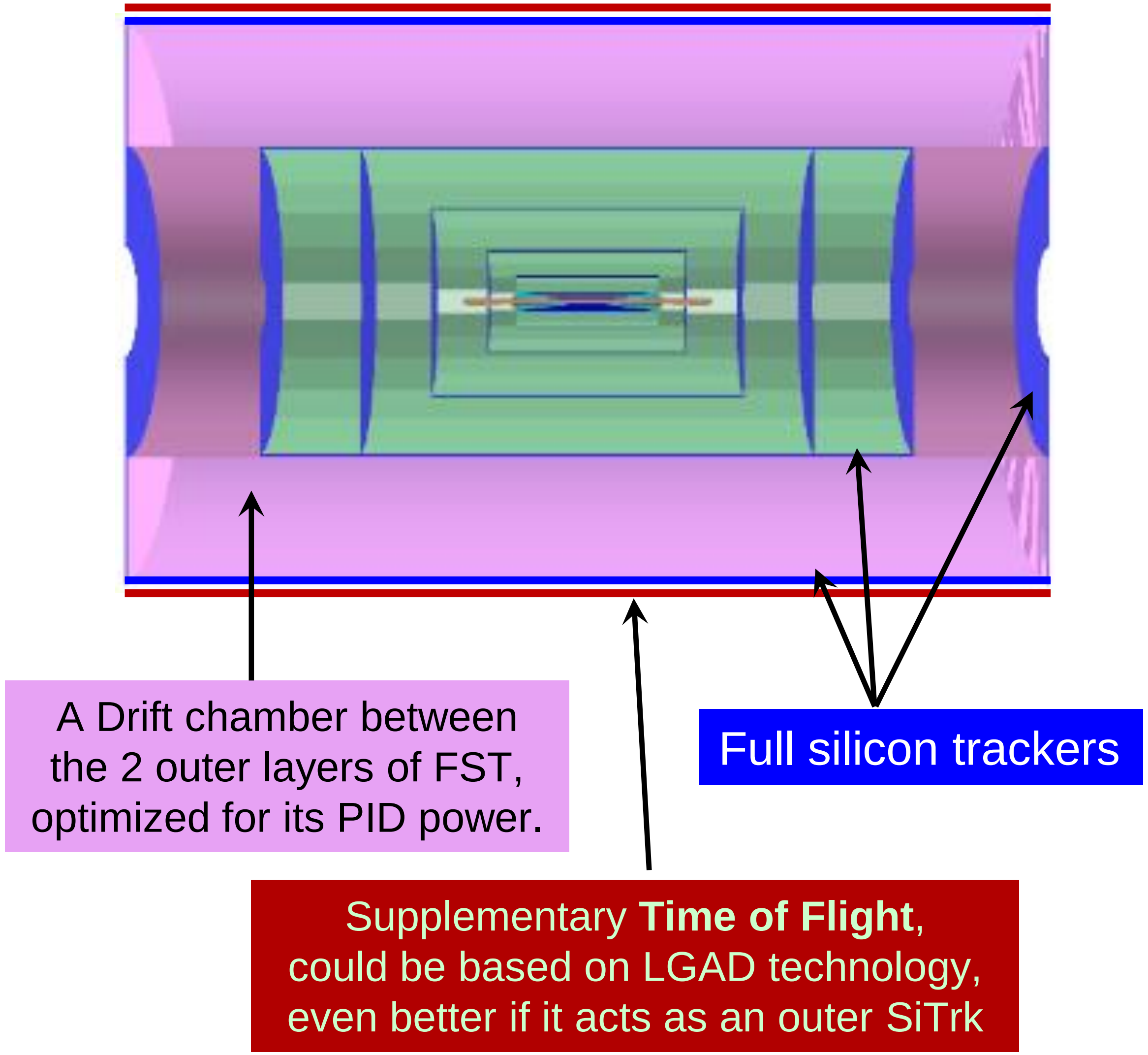


Hitmap with electron beam

PID in The Scenario of FST

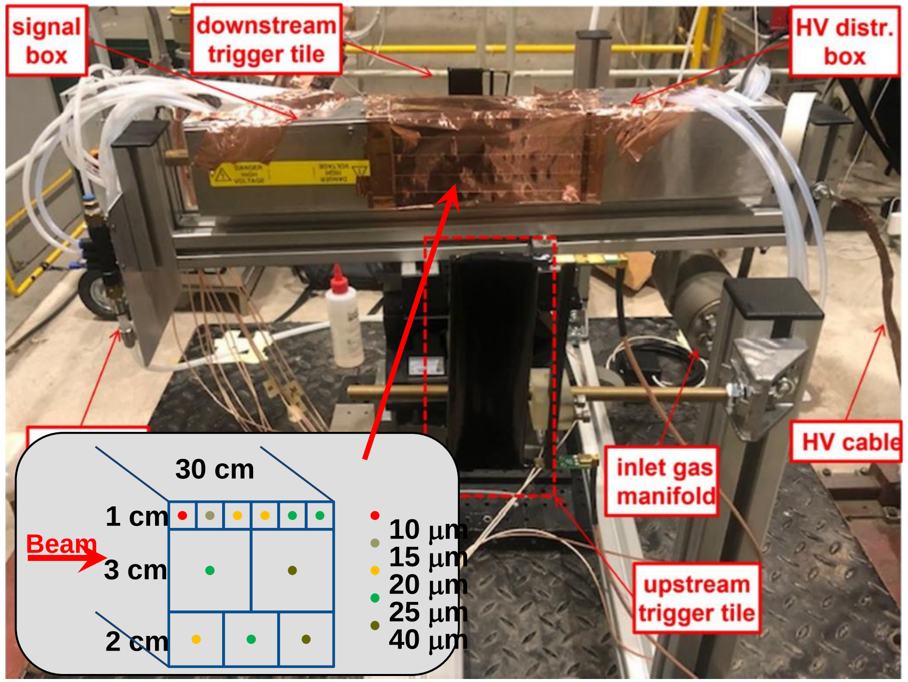


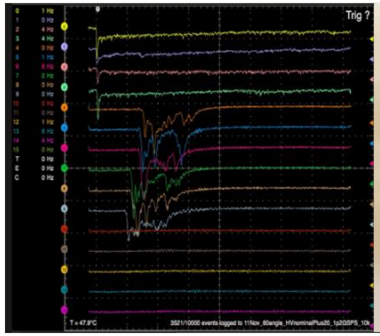
- A drift chamber optimized for PID: no stereo, larger cell, optimal gas mixture and HV
- Cluster counting algorithm (dN/dX) is more powerful than conventional dE/dx, but requires much more in the readout electronics.
- Studies: dNdX reconstruction algorithm, readout electronics, prototype test in beam

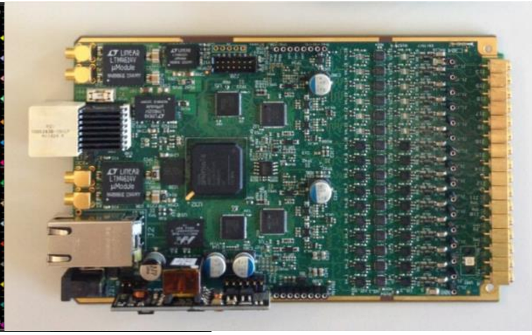


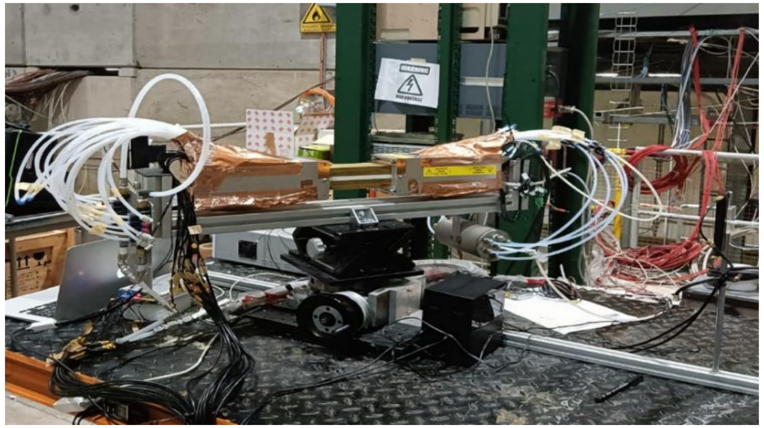
Cluster Counting Beam Tests

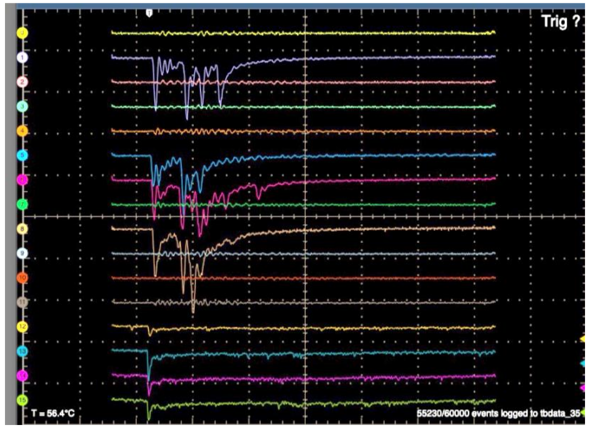
Test Beam 2021.11











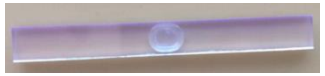
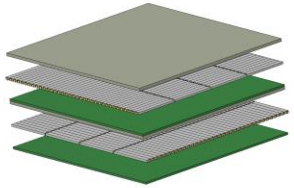
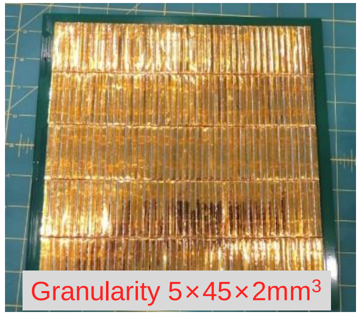
TB 2022.07

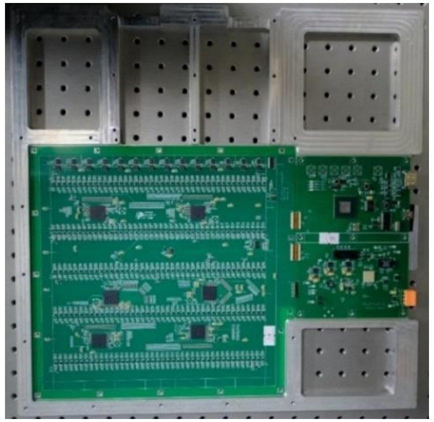
TB 2023.07

- 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, obtain more realistic parameters to simulation
- Preparing a test setup in China

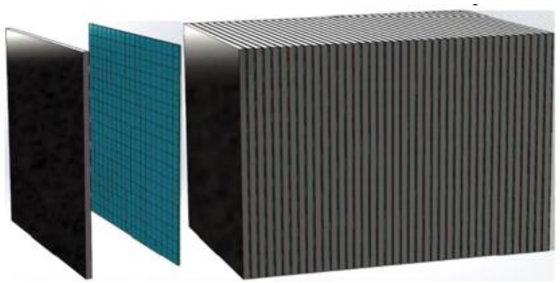
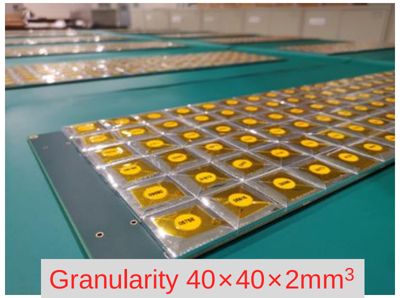
Prototype PFA Calorimeters

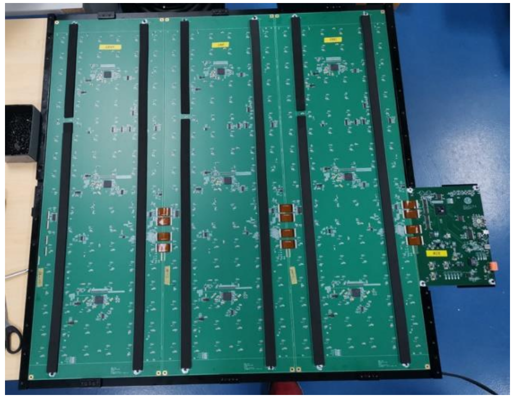
ECAL: scintillator(strip)+SiPM, CuW




HCAL: scintillator (tile)+SiPM, steel

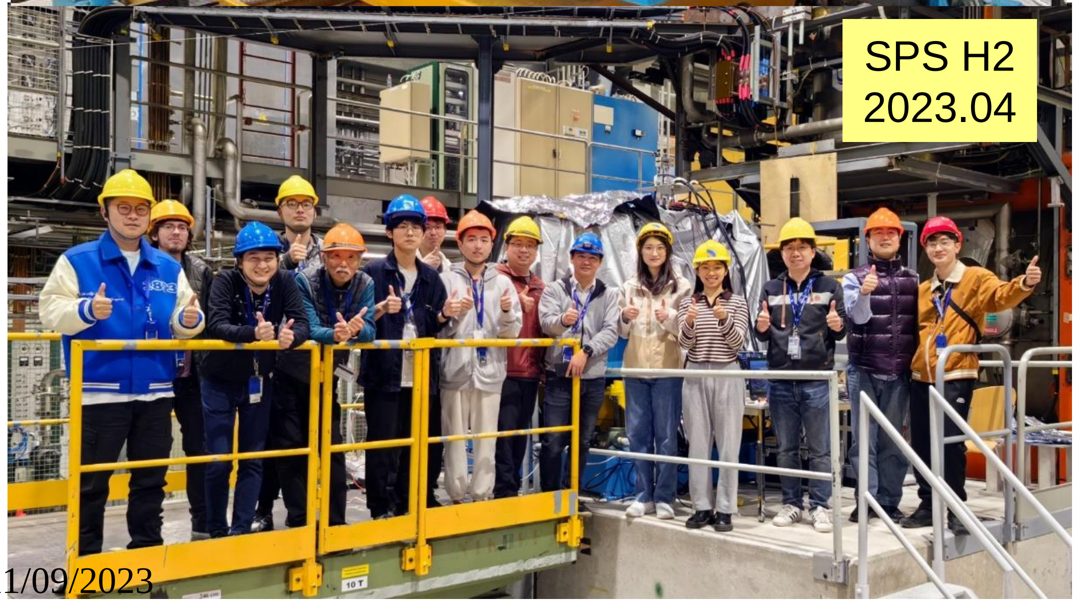






- ScW-ECAL: transverse ~20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

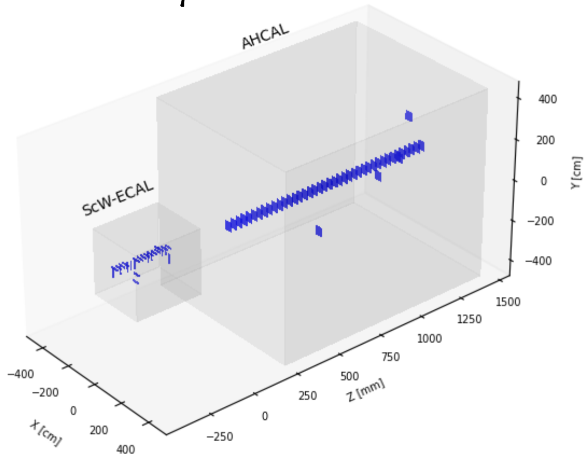
Prototypes developed within **CALICE**
- China: IHEP, SJTU, USTC
- Japan: U. Shinshu, U. Tokyo
- France: CNRS Omega
- Israel: Weizmann

Testbeam of Prototype PFA Calorimeters

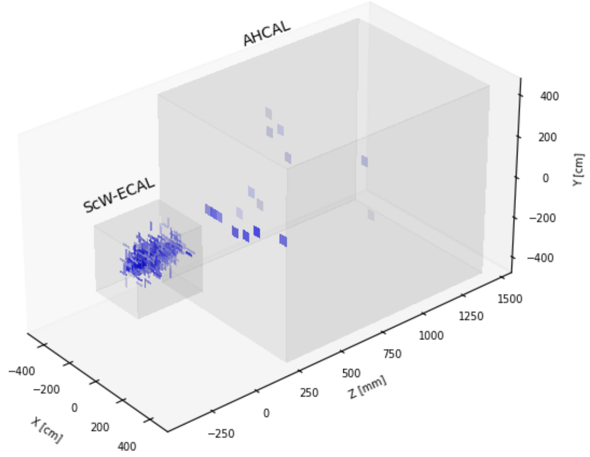


Selected Testbeam Events

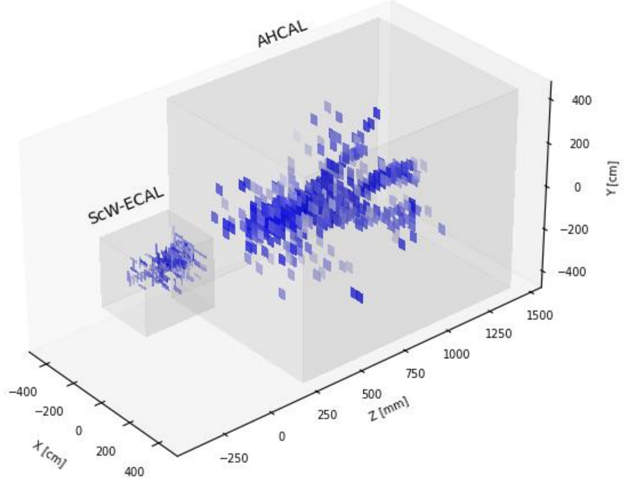
100 GeV μ^-



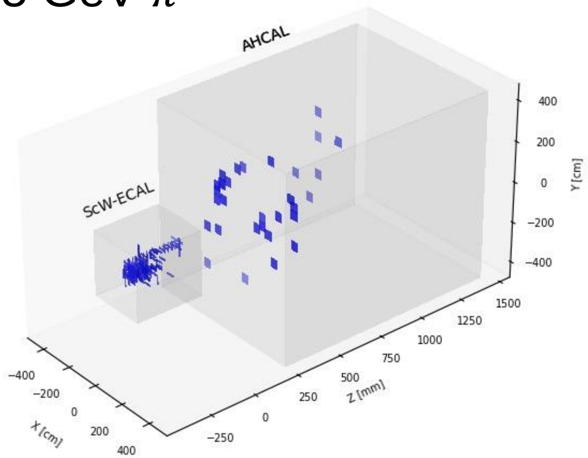
60 GeV e



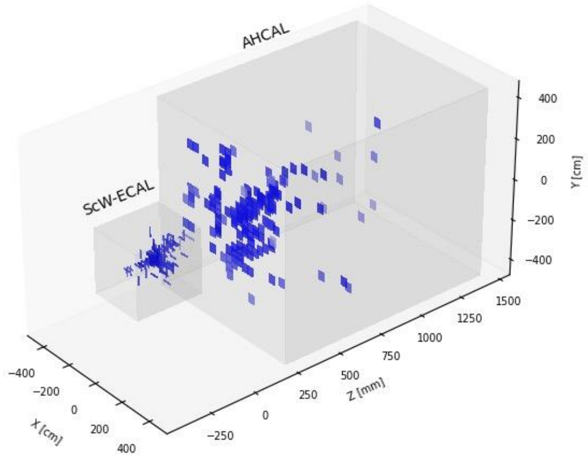
60 GeV π^-



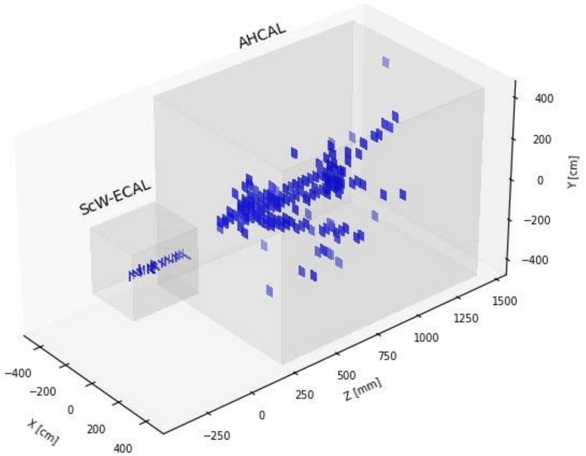
5 GeV π^-



10 GeV π^-



15 GeV π^-



Institute of High Energy Physics
Chinese Academy of Sciences

SHINSHU UNIVERSITY

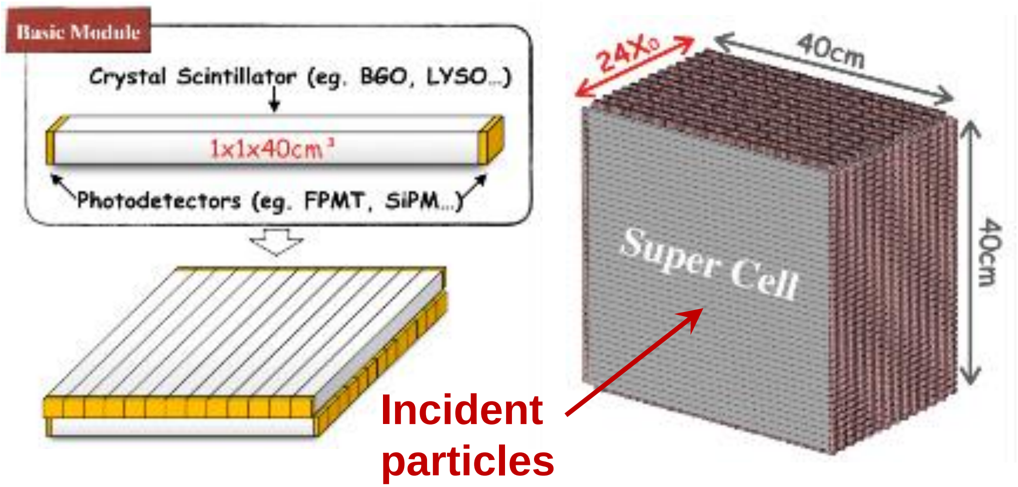
THE UNIVERSITY OF TOKYO

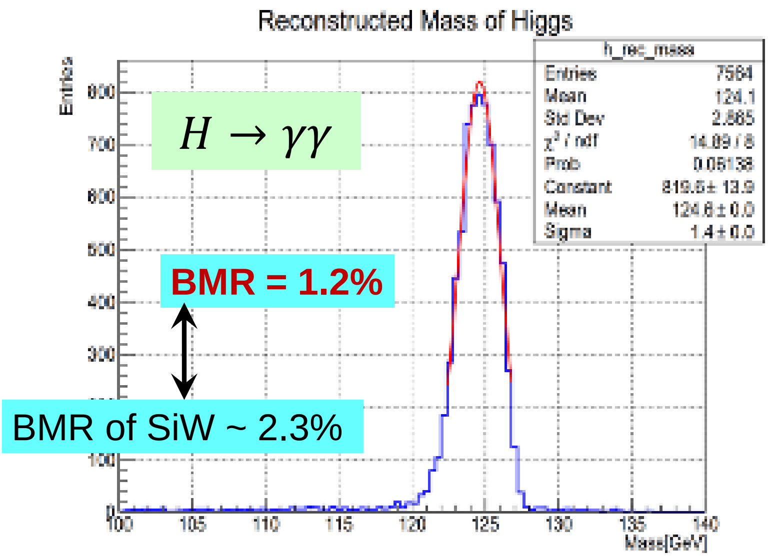
WEIZMANN INSTITUTE OF SCIENCE

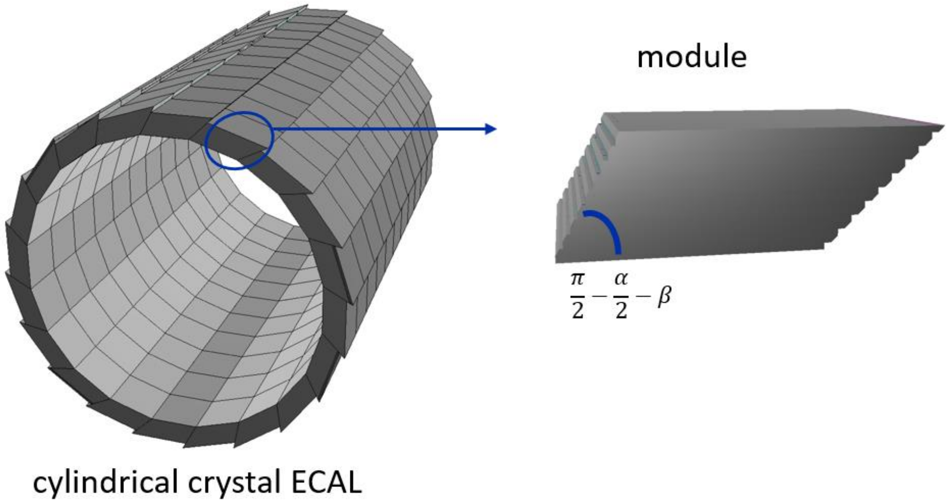
Within CALICE collaboration

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**).

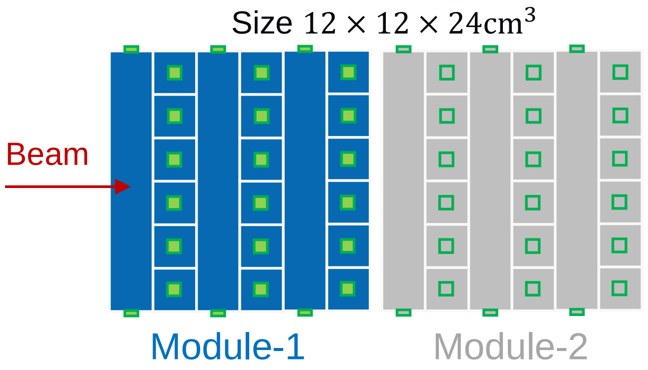


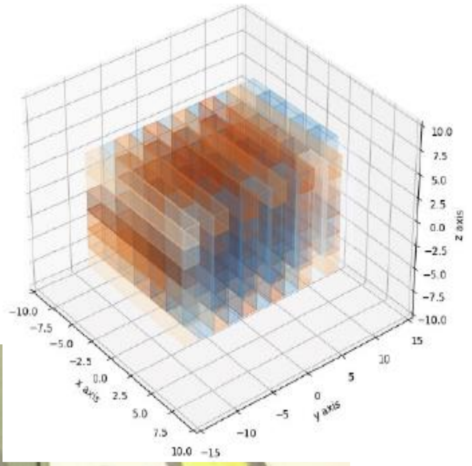


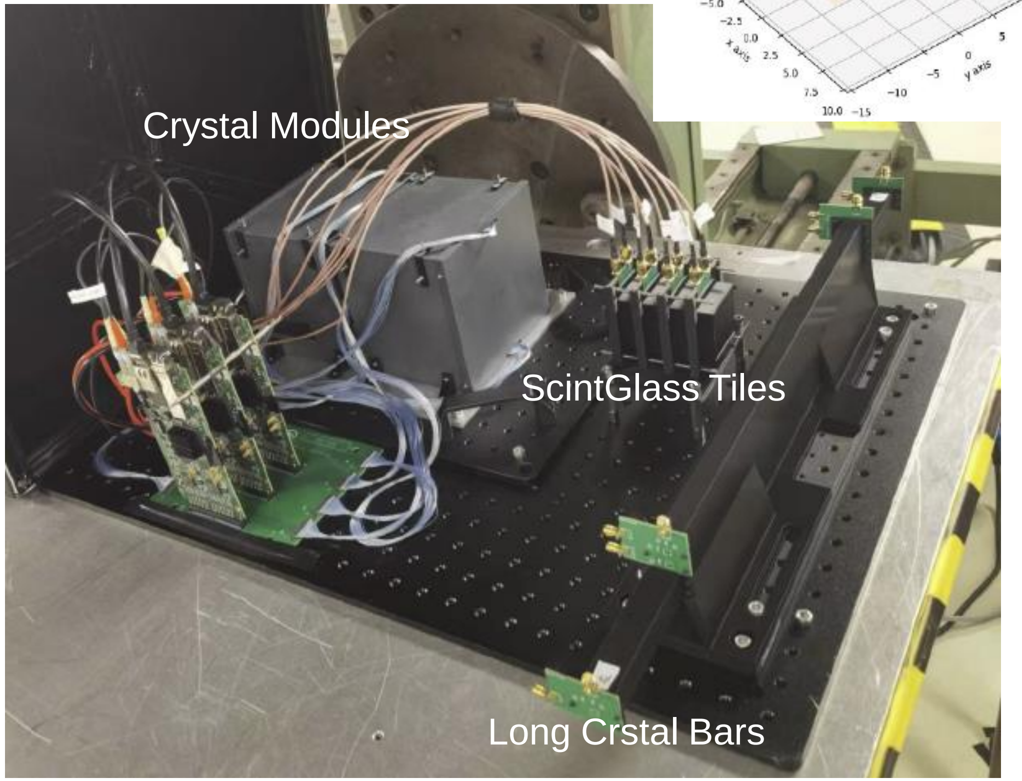


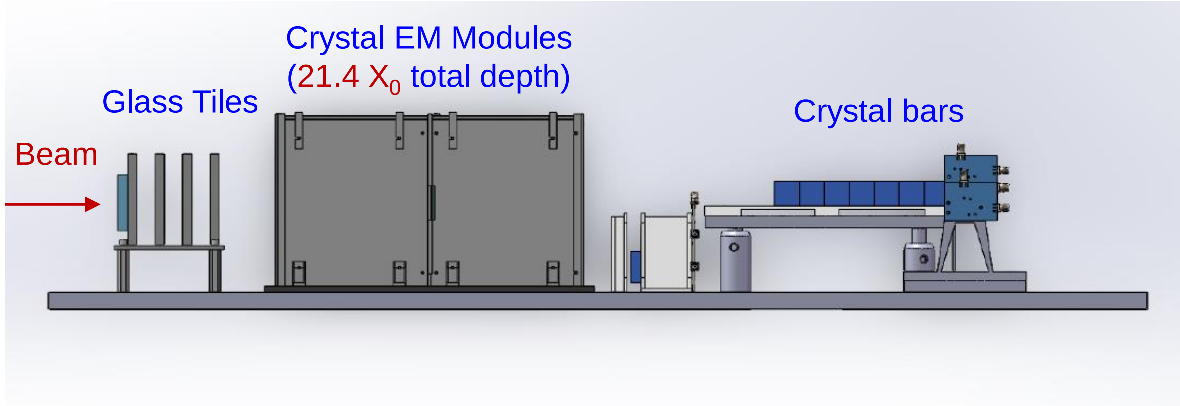
Testbeam of Prototype 4D Crystal ECAL

- 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**.** An ASIC with a large dynamic range would be more desirable



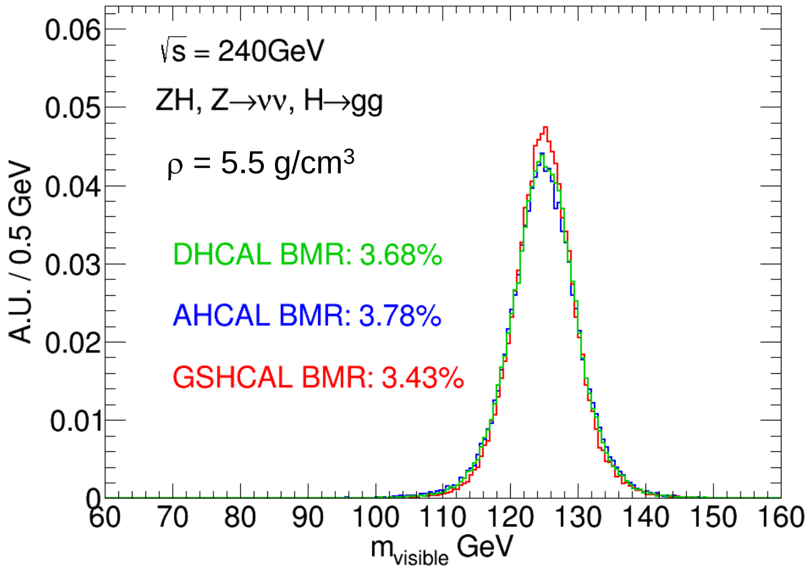


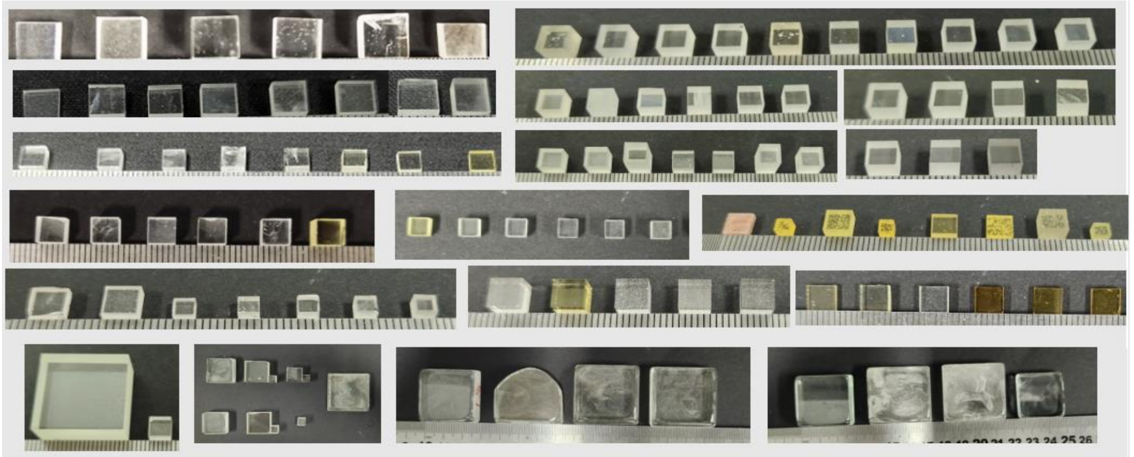




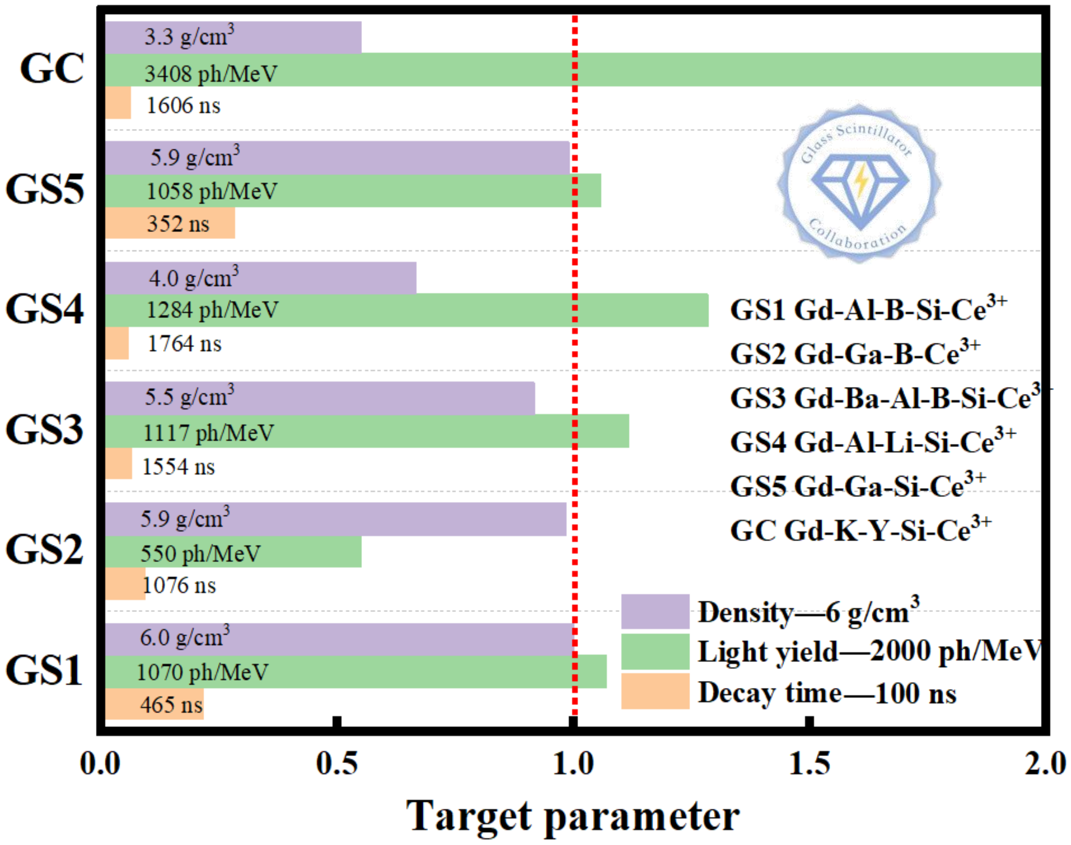
Glass Scintillator HCAL

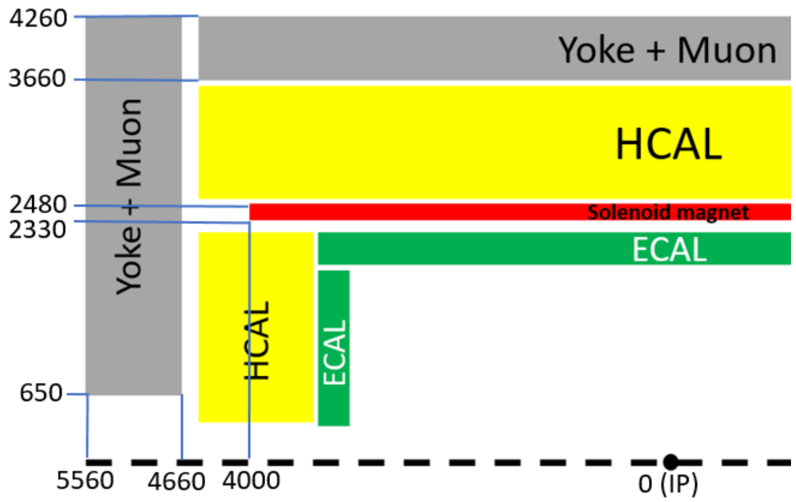
Replacing plastic scintillator with high density glass scintillator





- 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

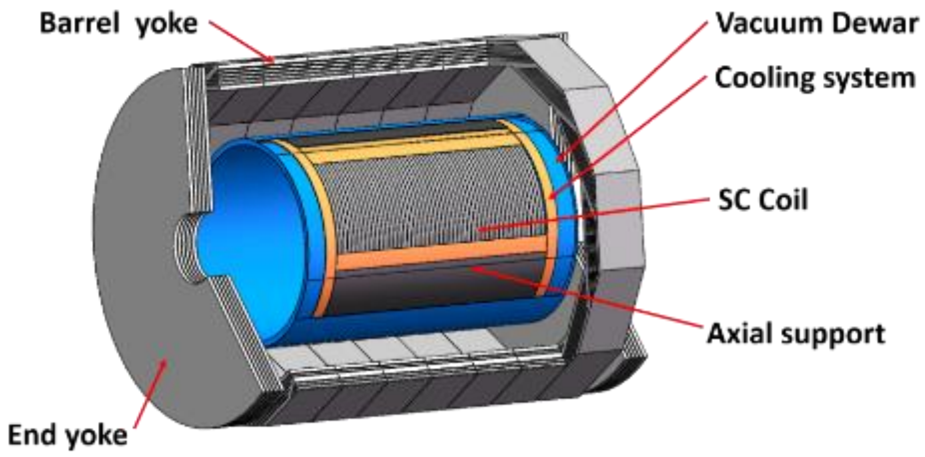




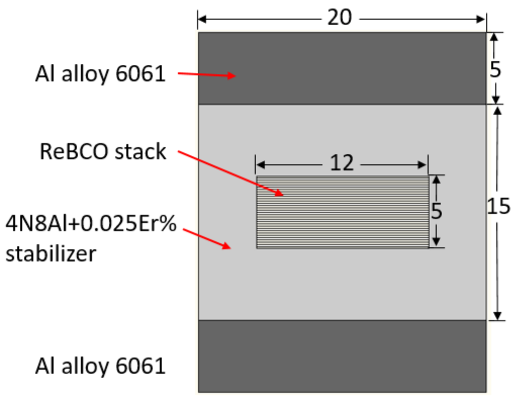
Challenges

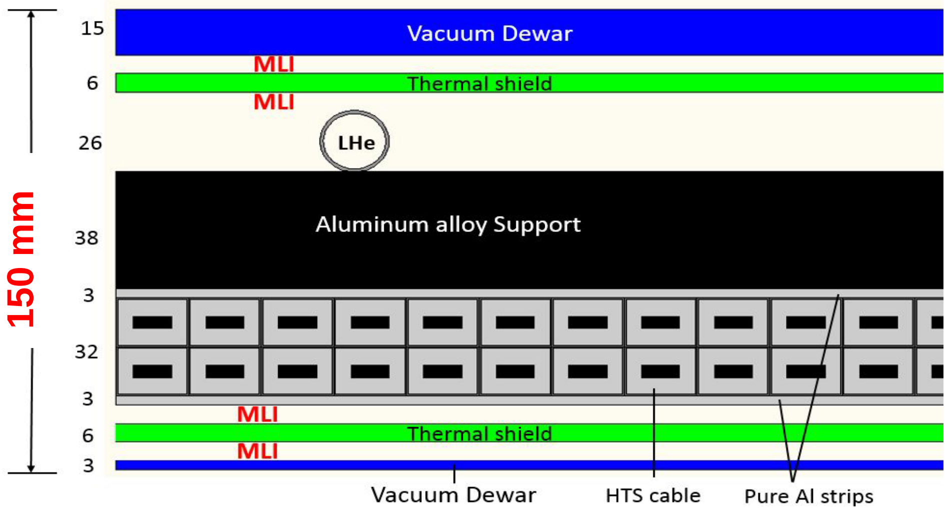
Low mass <1.5X_0
ultra-thin <150 mm
high strength cable

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



Al stabilized ReBCO stacked tape conductor (ASTC) cable

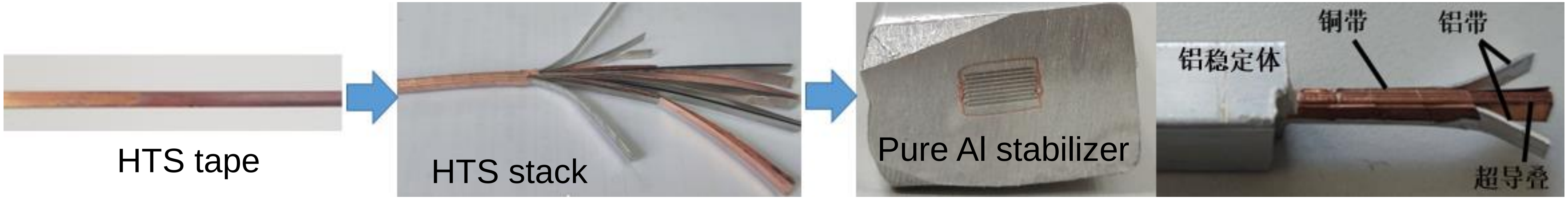




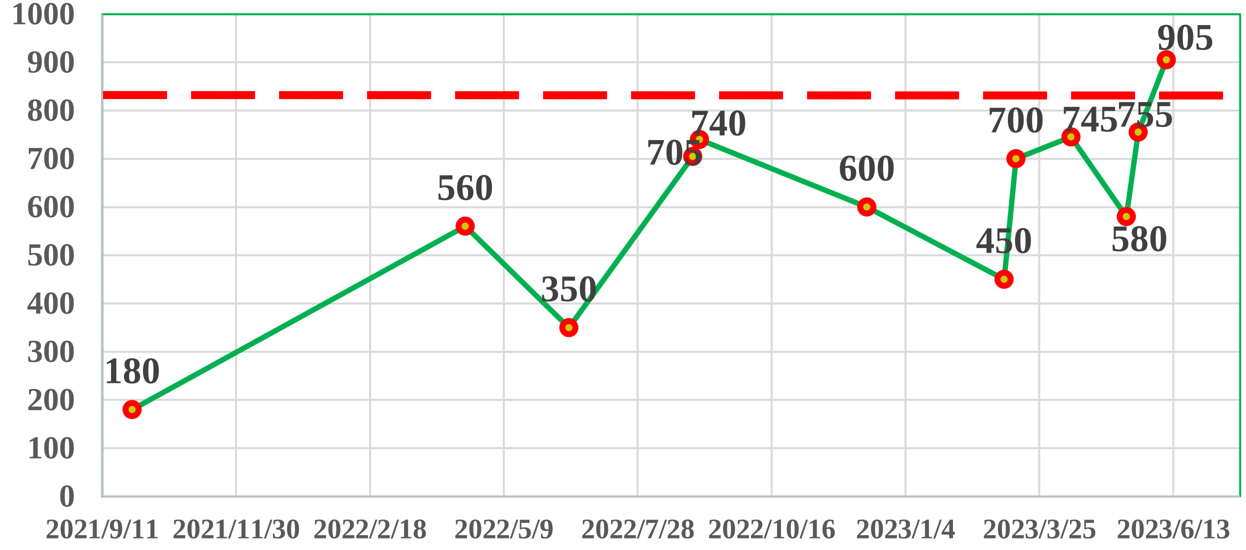
Magnetic field	3 T	Current	28000 A
Inner diameter	4660 mm	Inductance	1.27 H
Outer diameter	4960 mm	Stored energy	500 MJ
Magnet thickness	150 mm	Cold mass	27 ton
Length	8000 mm	HTS cable length	10.7 km
Total weight	48 ton	ASTC weight	16.6 ton

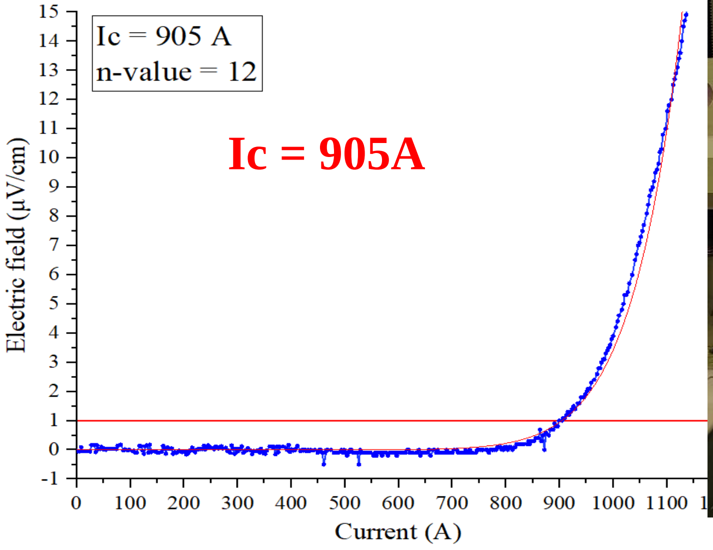
HTS Cable Development

Significant progress !



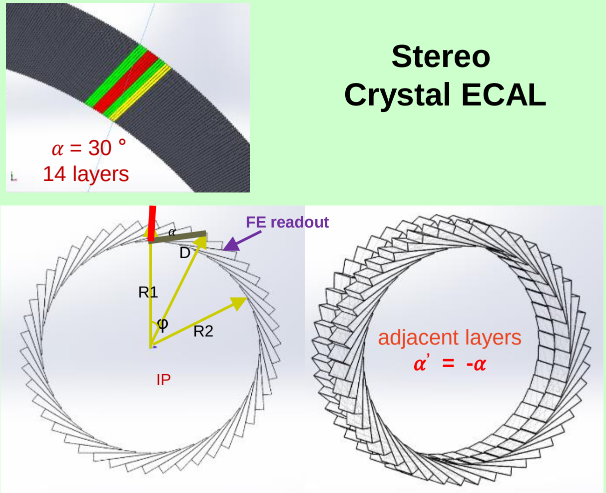
Object： single tape core Ic > 100 A@77K； 14-core cable Ic > 830 A@77K, self-field.



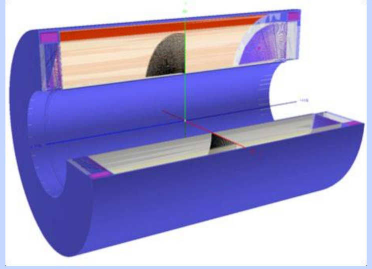


Many Other Detector R&Ds

Stereo Crystal ECAL



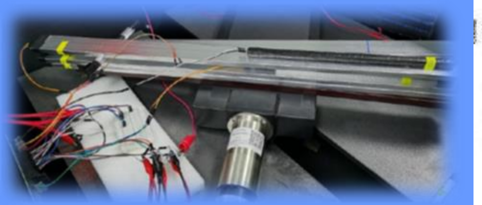
Drift Chamber

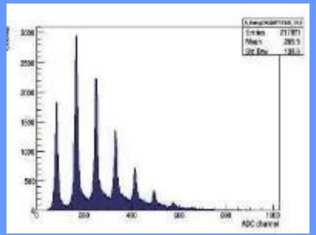


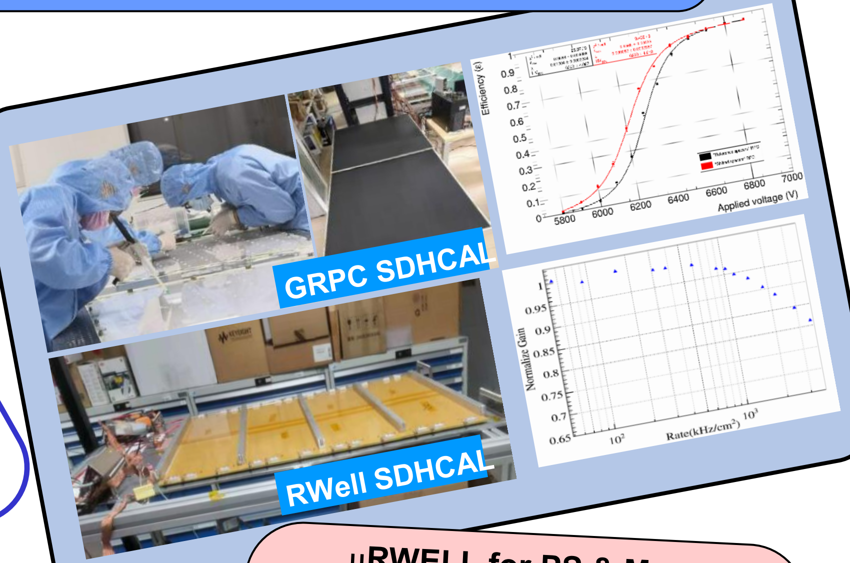
AD9689 – 2000 EBZ

Xilinx KCU105

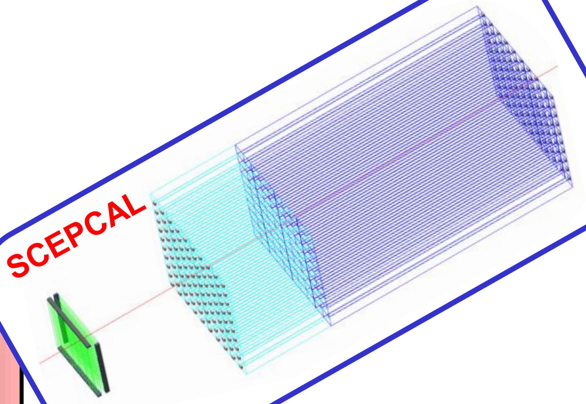
Scintillator Bar Muon



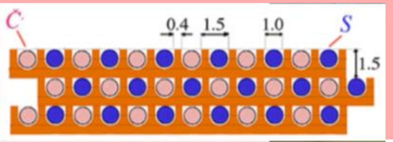


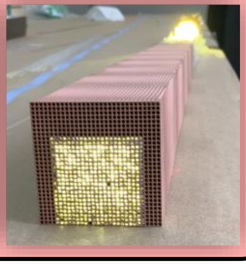


LGAD ToF

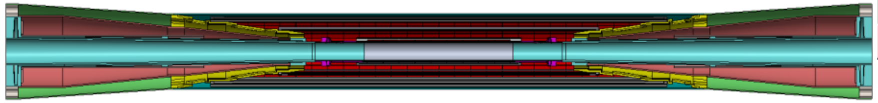


Dual Readout CAL

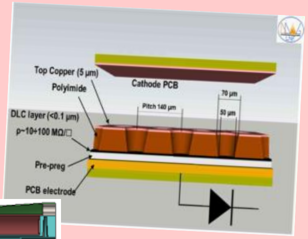


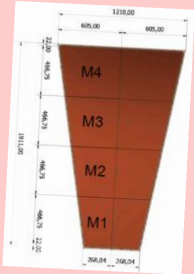


Beampipe Design



μRWELL for PS & Muon





R&D Efforts for Future Higgs Factories

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 DC	Muon	Scintillation Bar
	AC-LGAD ToF		RPC
Lumi	SiTrk+Crystal ECAL		μ-Rwell
	SiTrk+SiW ECAL	Misc	HTS / LTS Magnet
	Fast LumMoni		MDI & Integration
	CEPC SW		TDAQ scheme

- Some R&D efforts are already associated with the international collaborations: CALICE, LCTPC & RD*
- The **ECFA DRDs** cover much broader scopes, with more general supports, e.g. testbeam facilities.

If you **forgot to submit** your proposal somehow, or if you **did not fill in the survey** that we sent around, please contact Haijun Yang or Jianchun Wang

- We plan 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**
- You are welcome to join

Collaboration With Industry

CEPC 650MHz Klystron at Kunshan Co.

CERN HL-LHC CCT SC magnet

CEPC SC QD0 coil winding at KEYE Co.

CIPC (CEPC Industrial Promotion Consortium) was established in Nov 2017. So far 70+ companies have joined.

CEPC Detector SC coil winding tools at KEYE Company (Diameter ~7m)

CEPC long magnet measurement coil

1) Superconduting materials (for cavity and for magnets)
2) Superconducting cavities
3) Cryomodules
4) Cryogenics
5) Klystrons
6) Magnet technology
7)Vacuum technologies
8) Mechanical technologies
9)Electronics
10) SRF
11) Power sources
12) Civil engineering
13) Precise machinery
.....

More than 40 companies joined in first phase of CIPC，
and 70 companies now.

International Efforts Towards Collaborative Experiments

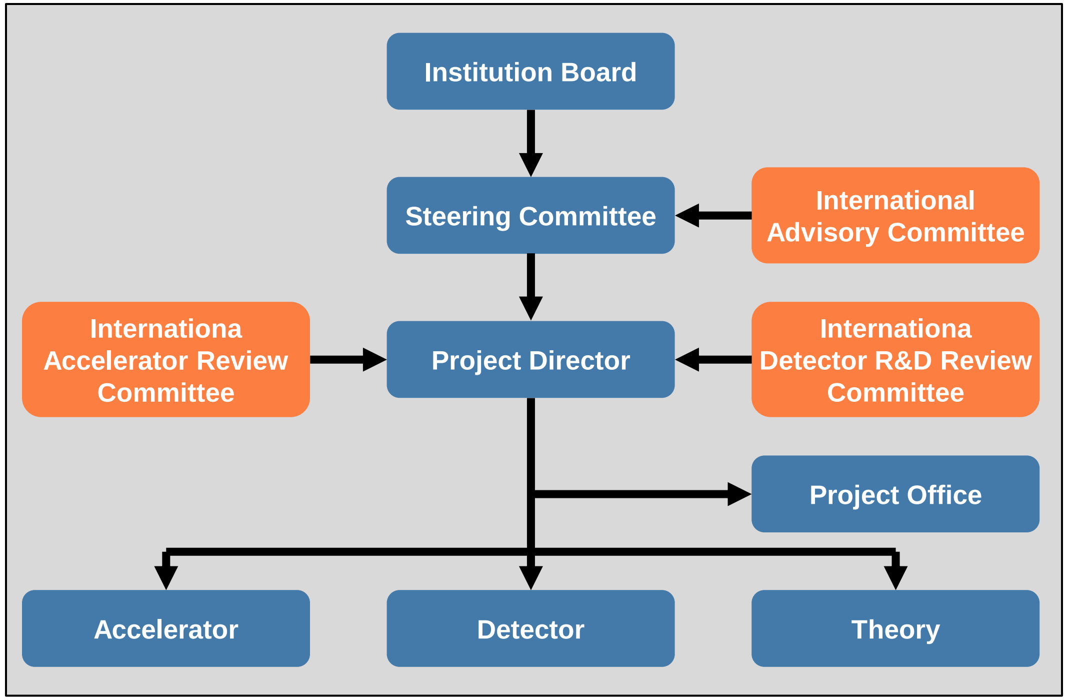


Table 7.2: Team of Leading and core scientists of the CEPC

Name	Brief introduction	Role in the CEPC team
Yifang Wang	Academician of the CAS, director of IHEP	The leader of CEPC, chair of the SC
Xinchou Lou	Professor of IHEP	Project manager, member of the SC
Yuanning Gao	Academician of the CAS, head of physics school of PKU	Chair of the IB, member of the SC
Jie Gao	Professor of IHEP	Convener of accelerator group, vice chair of the IB, member of the SC
Haijun Yang	Professor of SJTU	Deputy project manager, member of the SC
Jianbei Liu	Professor of USTC	Convener of detector group, member of the SC
Hongjian He	Professor of USTC	Convener of theory group, member of the SC
Shan Jin	Professor of NJU	Member of the SC
Nu Xu	Professor of IMP	Member of the SC
Meng Wang	Professor of SDU	Member of the SC
Qinghong Cao	Professor of PKU	Member of the SC
Wei Lu	Professor of THU	Member of the SC
Joao Guimaraes da Costa	Professor of IHEP	Convener of detector group
Jianchun Wang	Professor of IHEP	Convener of detector group
Yuhui Li	Professor of IHEP	Convener of accelerator group
Chenghui Yu	Professor of IHEP	Convener of accelerator group
Jingyu Tang	Professor of IHEP	Convener of accelerator group
Xiaogang He	Professor of SJTU	Convener of theory group
Jianping Ma	Professor of ITP	Convener of theory group

- Institution Board: 32 top universities / institutes in China
- The International Advisory Committee (IAC) started in 2015, and held meeting yearly.
- Two international review committees for accelerator and detector R&D: (IARC, IDRC) started operating since 2019.
- Currently the CEPC study group consists of ~1/4 international members. We hope to boost up international participation.

International Workshops

- International workshops (with emphasis on the CEPC):
  - In China: Beijing (2017.11, 2018.11, 2019.11), Shanghai (2020.10 / hybrid), Nanjing (2021.11 / online, 2022.11 / online, **2023.10 / in-person**), **TBD (2024.10-11)**
  - In Europe: Rome (2018.05), Oxford (2019.04), **Edinburgh (2023.07), Marseille (2024.04.08-12)**
  - In USA: Chicago (2019.09), DC (2020.04 / online)
  - Annual IAS program on HEP (HKUST) since 2015, **(2024.01.18-25)**
- Various topic-specific workshops at different sites. Let us know if you are interested to host.

Optimal Timeline and Upcoming Events

Completion of Accelerator TDR

Completion of Accelerator EDR

TDR of a Reference Detector @ June 30, 2025

International Collaborations