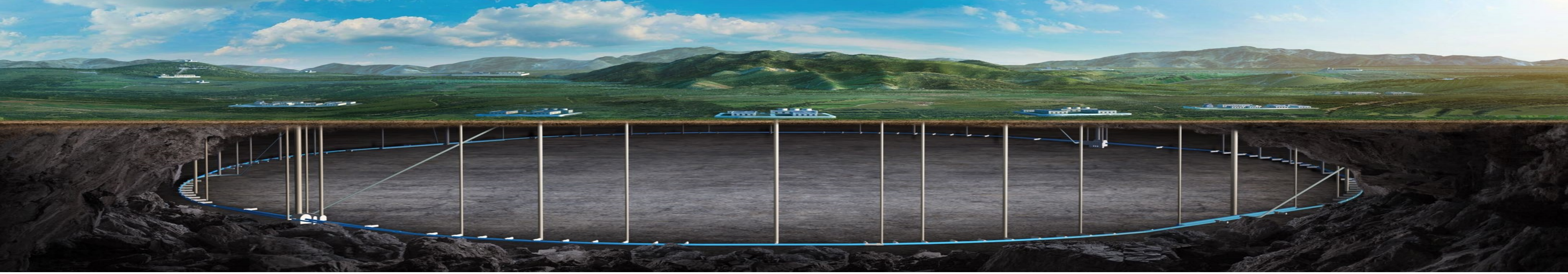

CEPC 探测器研发进展
Development of CEPC Reference Detector

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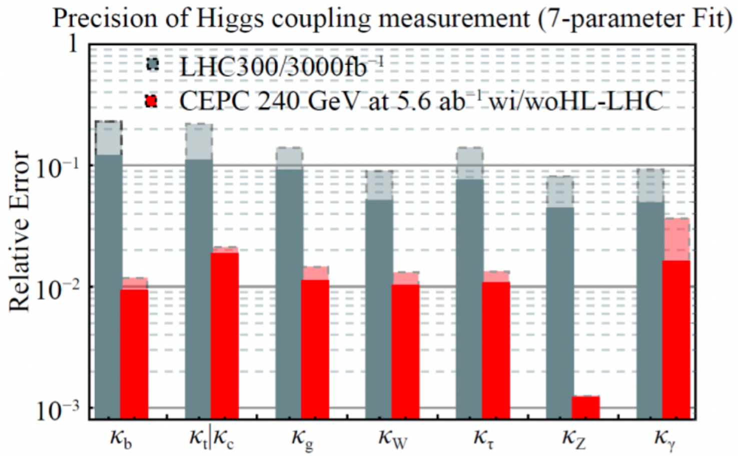
轻强子专题研讨会@安阳，2025年5月9日
Light Hadron Workshop @ Anyang, 9 May 2025

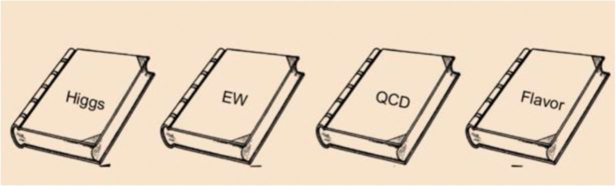
Content

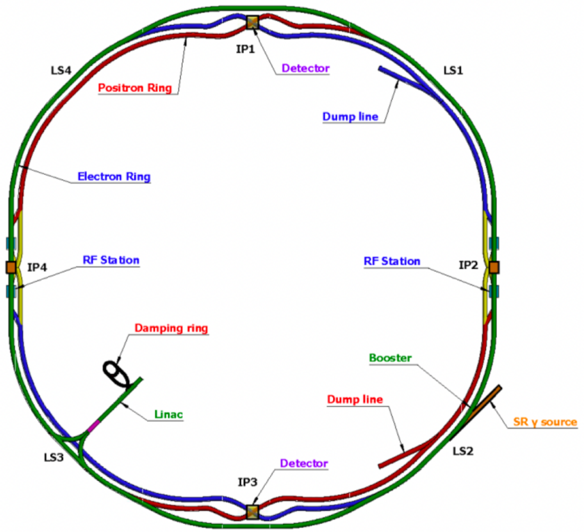
- CEPC – an introduction
- Preparation of Ref-TDR:
  - What, when and who
  - Technical options and highlights
- Summary

Circular Electron Positron Collider

- CEPC is proposed by Chinese physicists in 2012 right following Higgs discovery
  - A Higgs factory, to measure its properties to unprecedented level – portal to New Physics?
  - Also a factory of Z / W / ttbar, for precision EW studies and heavy flavour studies
- A ring of ~100km, at least two interaction points
- Potential of upgrade to a pp collider of $\sqrt{s}$ ~ 100 TeV in the future

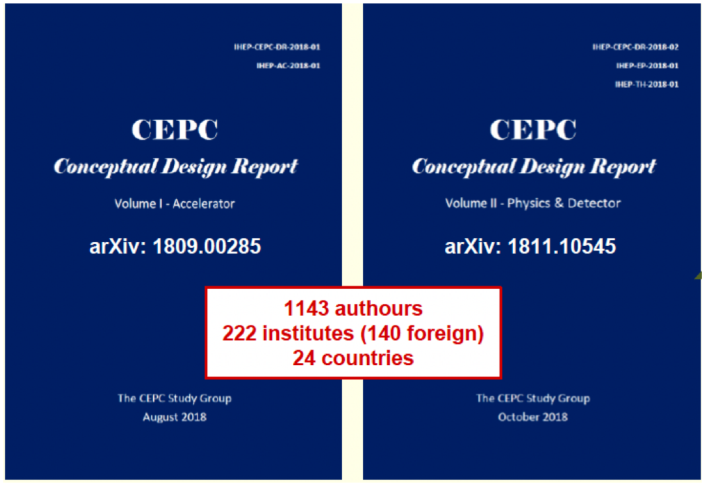


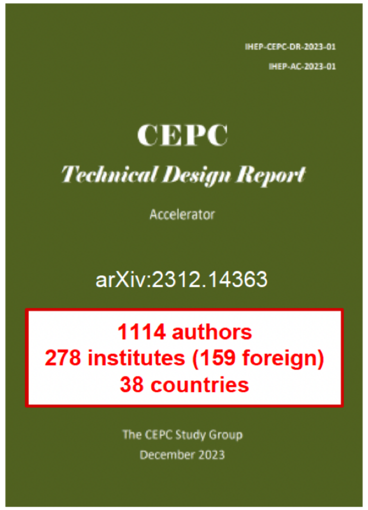




Milestones

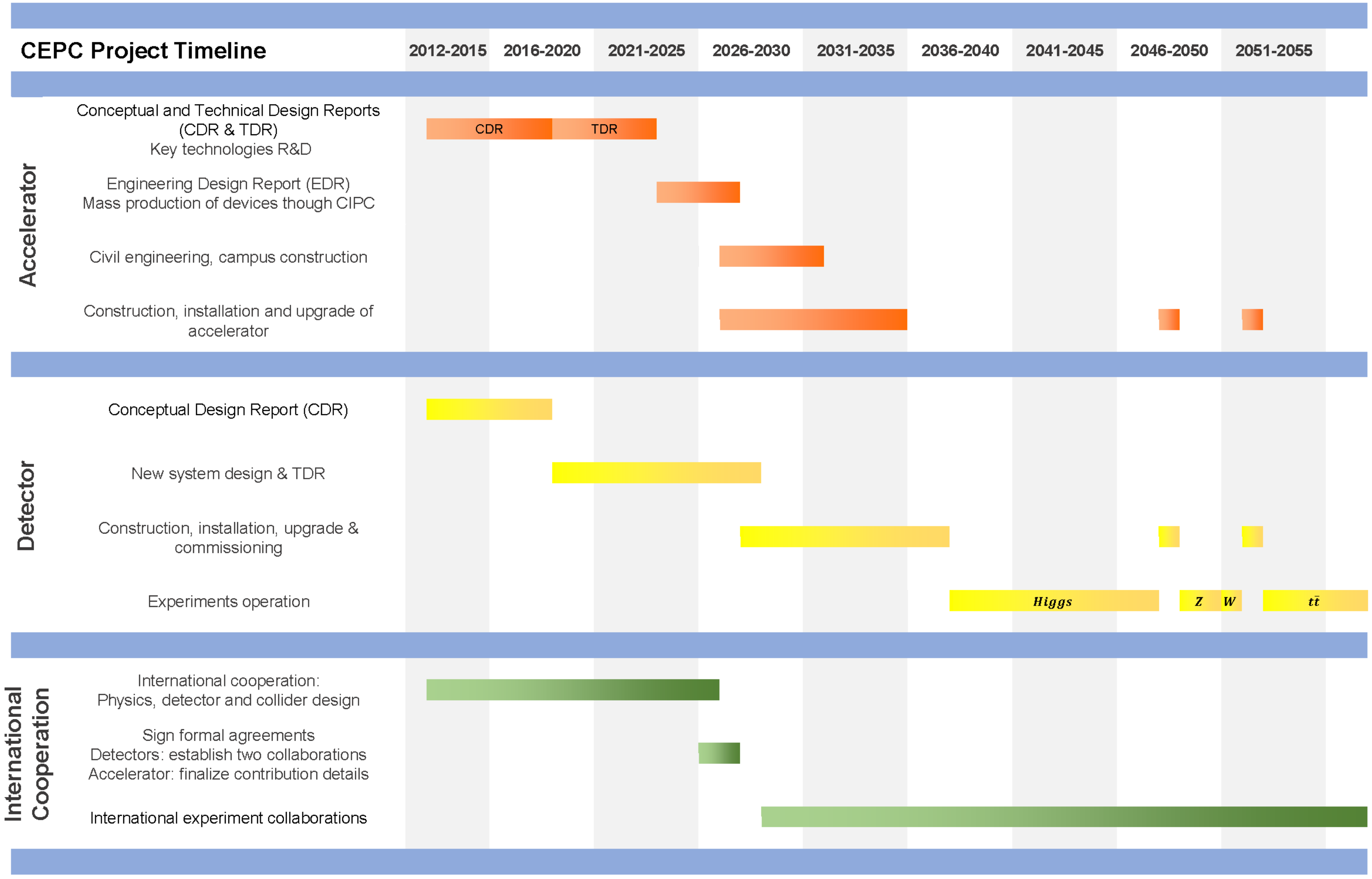
- 2012.09 proposed
- 2013.09 kickoff meeting
- 2015.03 Pre-CDR
- 2018.11 CDR release
- 2023.12 Accelerator TDR release





Timeline

- 2025.06 release of Reference detector TDR
- 2025: CEPC proposal
- 2027: Accelerator EDR
- 15th Five-Year: Construction starts?

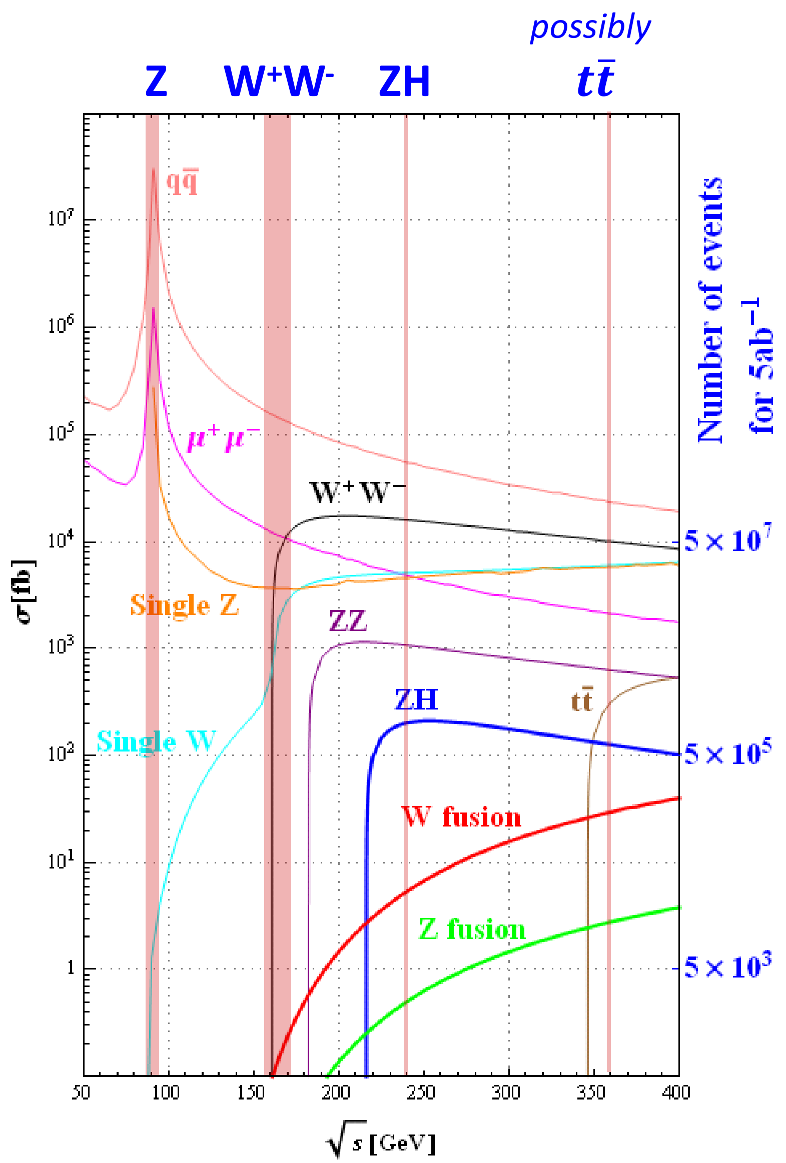


CEPC Reference Detector TDR

- The CEPC study group is preparing for a Reference Detector TDR (Ref-TDR) aiming at release in June 2025, for domestic endorsement
- Better technologies and R&D will continue be pursued
  - Final detectors (>=2) will be determined within international collaborations

Date	Actions and/or Expectations
Jan 1, 2024	Start the process by comparing different technologies
Jun 30, 2024	Baseline technologies, general geometric configuration and key issues are decided
Oct 31, 2024	Discuss the ref-TDR at the CEPC workshop, report progresses to the CEPC IAC
Dec 31, 2024	The first draft of the ref-TDR is ready for internal reviews
Apr 15, 2025	international review
Jun 30, 2025	The ref-TDR for ready for public reviews
Oct 30, 2025	Submit the ref-TDR for publication

Operation plan



SR Power Per Beam	Luminosity/IP [$\times10^{34}cm^{-2}s^{-1}$]		
	H	Z	W^+W^-
12.1 MW	-	26	-
30 MW	5.0	-	16
50 MW	8.3	-	26.7

10 yrs

- Ref-TDR mainly designed for the first 10 years:
  - Higgs, low-lumi Z, WW
- Accelerator might be upgraded for high-lumi Z or ttbar after first 10-year, subject to physics needs

SR Power Per Beam	Luminosity/IP [$\times10^{34}cm^{-2}s^{-1}$]				
	H	Z (2T)	Z(3T)	W^+W^-	$t\bar{t}$
30 MW	5.0	115	50.3	16	0.5
50 MW	8.3	192	95.2	26.7	0.8

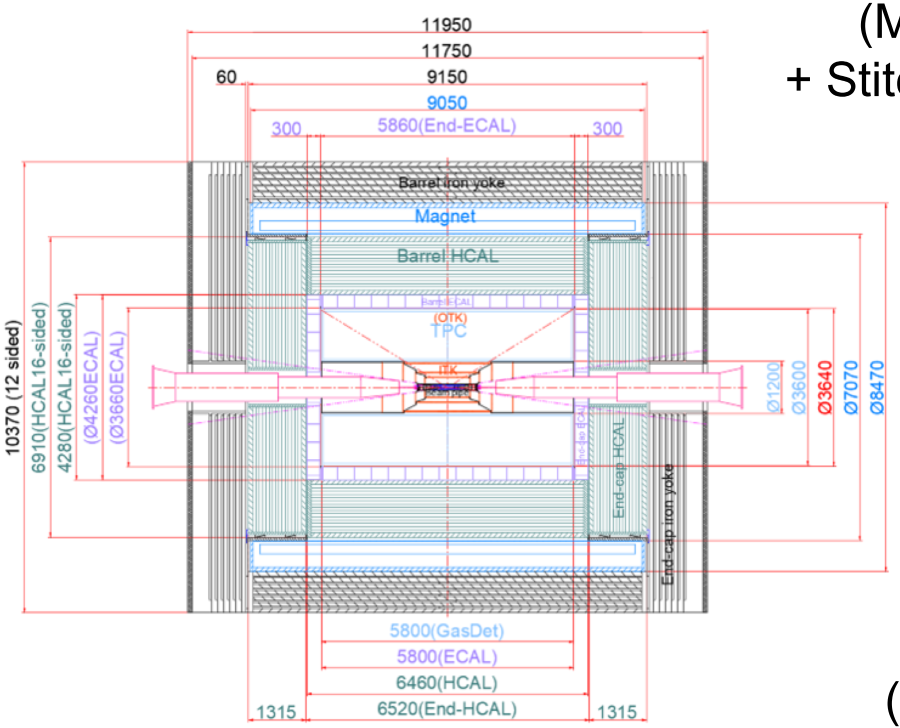
2 yrs 1 yr 5 yrs

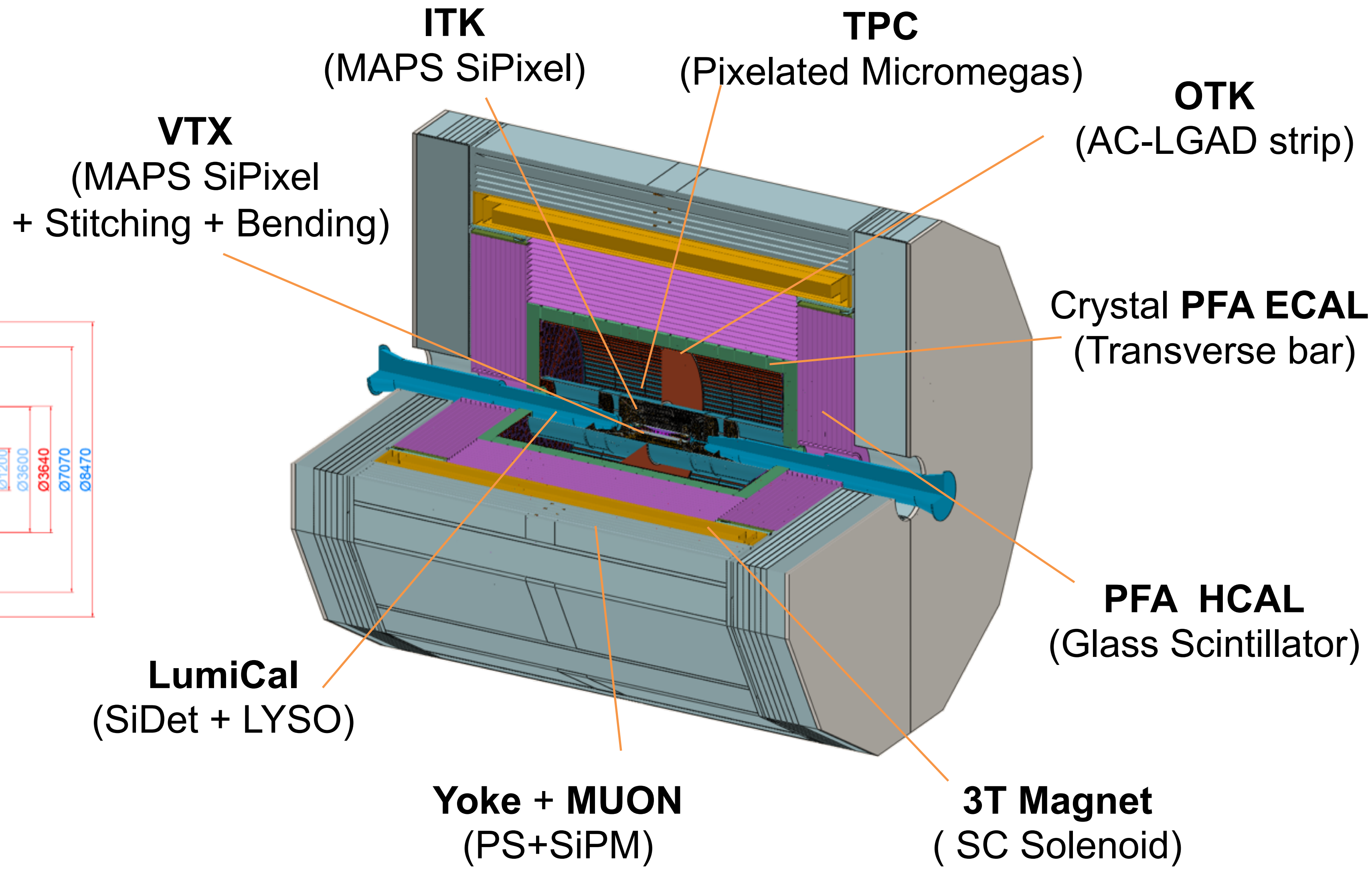
Key requirements

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

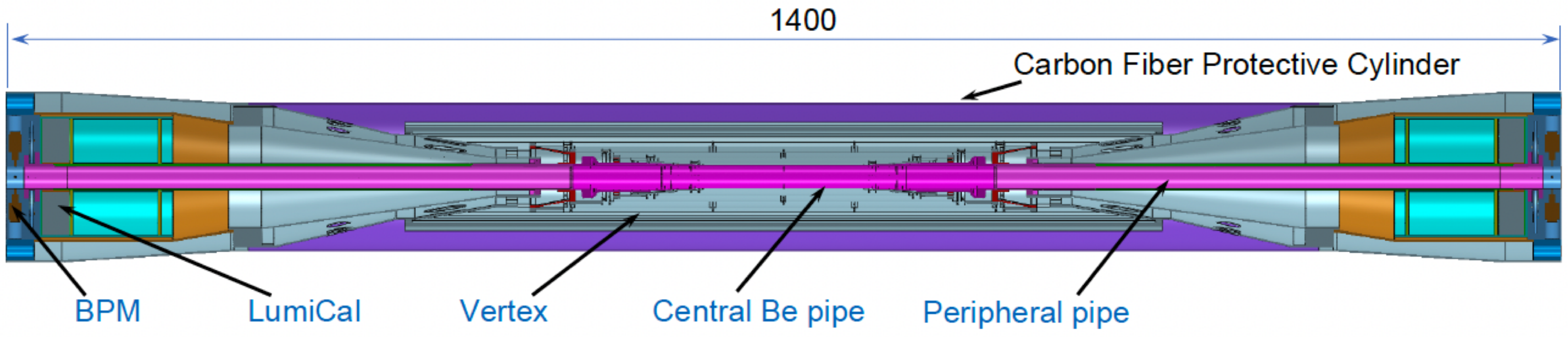
- Key specification continue to be optimised
  - Iterative process as understanding of physics reach evolves

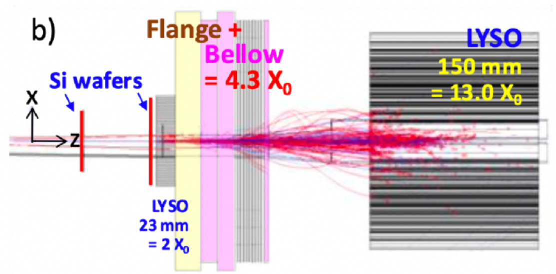
Detector overview





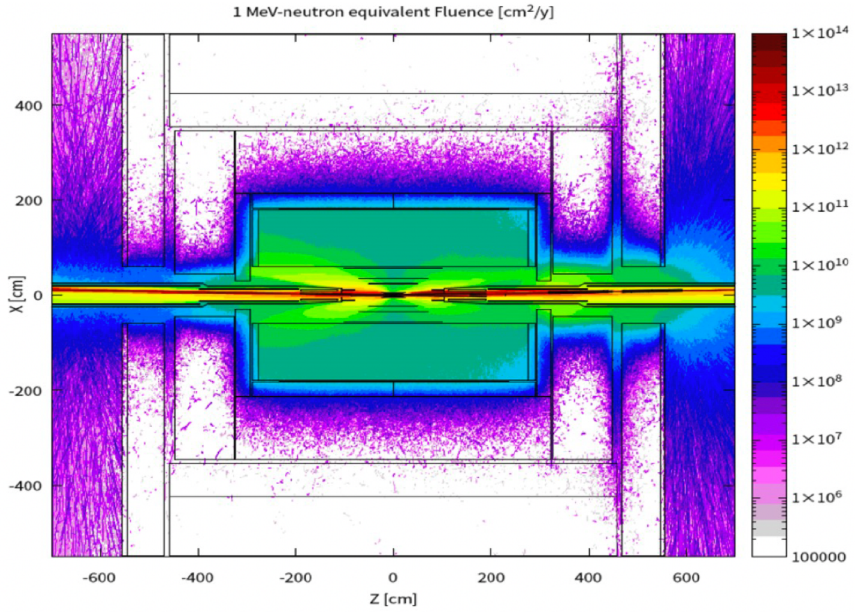
MDI, beam background & LumiCal





LumiCal

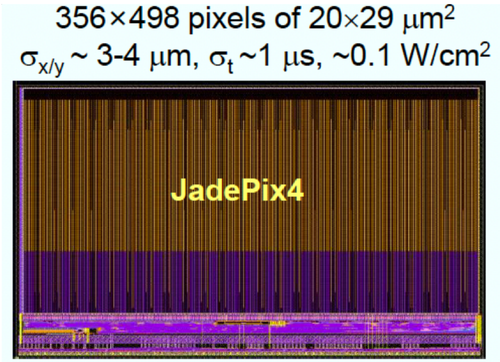
- Machine-Detector Interface involves design of central beampipe
- Background rate are simulated and digitized – essential input for shielding design and subdetectors
- LumiCal based on LYSO bar and silicon strips aiming for 1e-4 precision

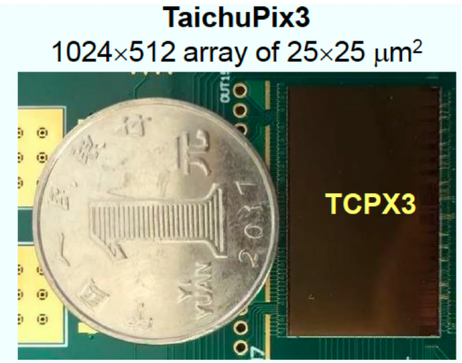


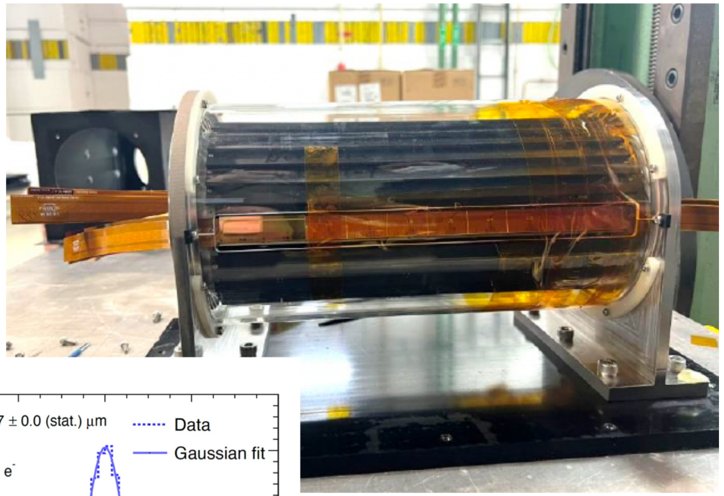
Fluence map caused by pair-production

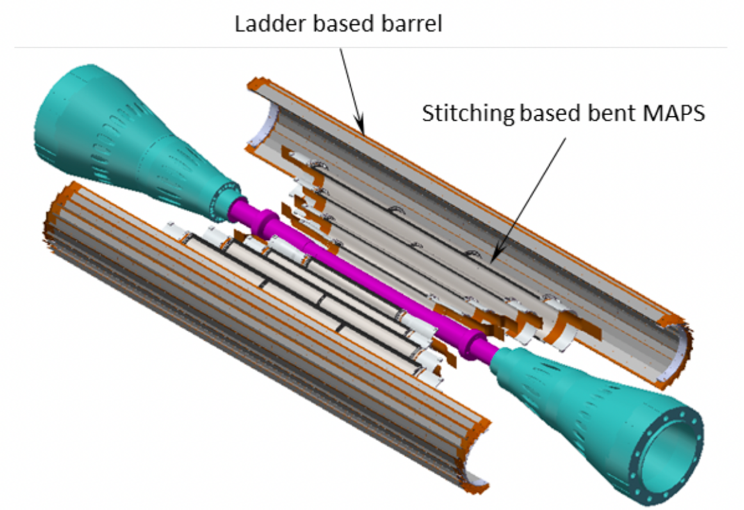
Vertex detector

- R&D on MAPS for > 10 years
  - Large-size chips achieve <5 um point resolution; aiming for 3um
  - Module prototype successfully tested in beams
- Baseline: stitching + bent MAPS
  - For ultimate goal of $0.15\%X_0$ material budget
  - Easier cooling with air









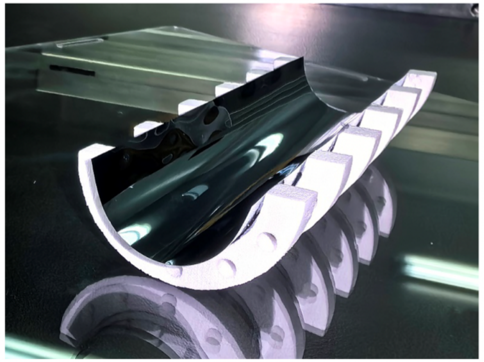
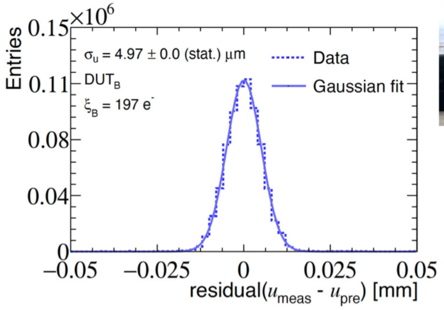
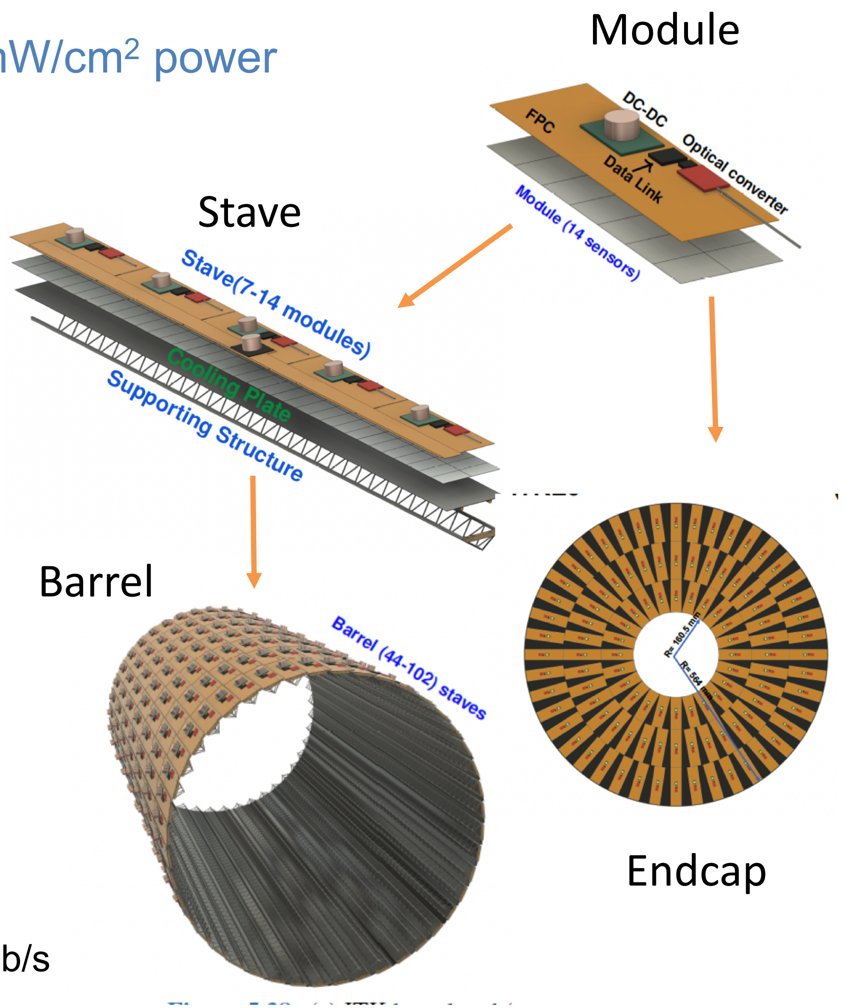


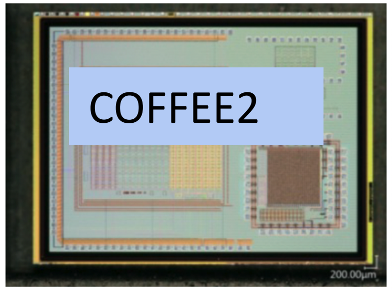
Figure 4.26: 12 mm bending radius.

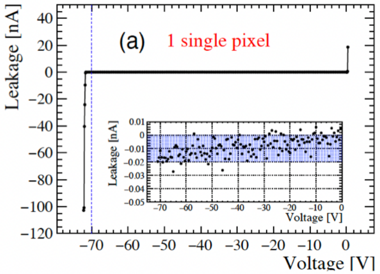


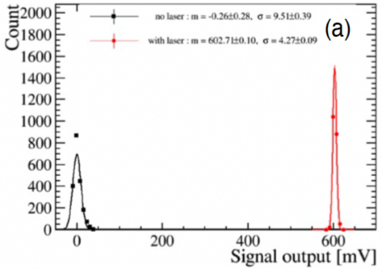
Inner Tracker

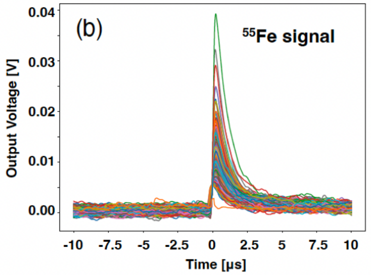
- Focus on HVCMOS pixel technology
  - Key specs: ~8 um spatial resolution, 3-5 ns timing resolution, <200 mW/cm^2 power
- Exploring domestic 55nm HVCMOS process
  - COFFEE2 chip: tested as validation of the process
  - COFFEE3: submitted for full array readout
- System design using common modules for barrel & endcap

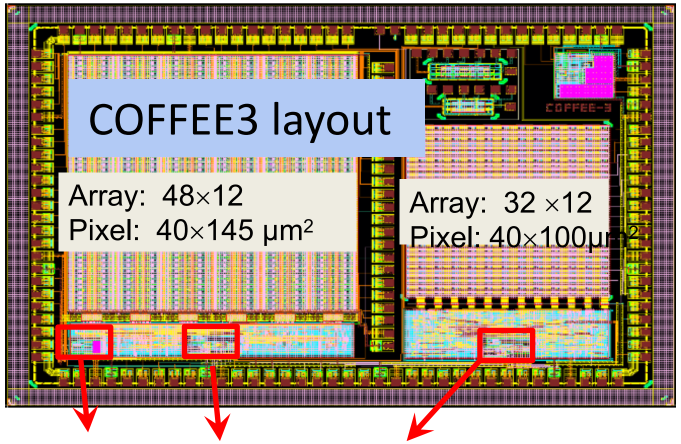








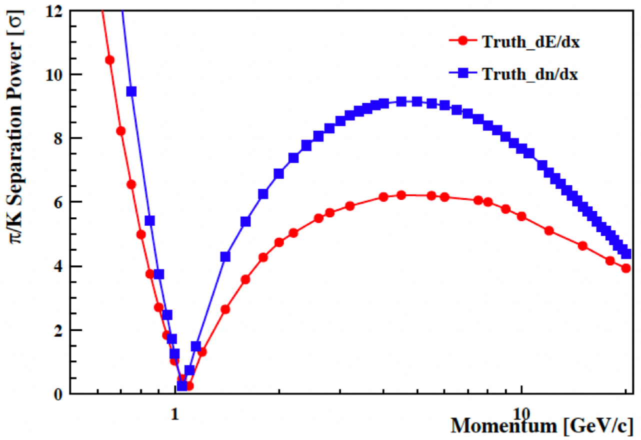


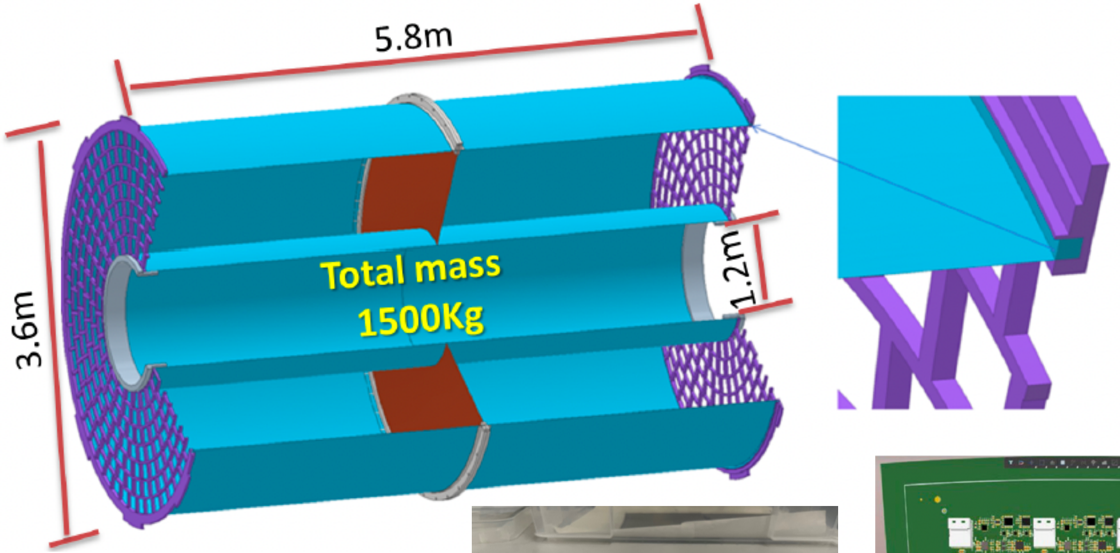


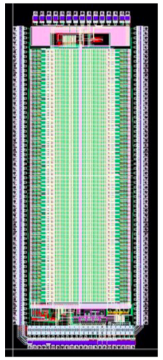
DLL LVDS driver/receiver up to 1.28Gb/s

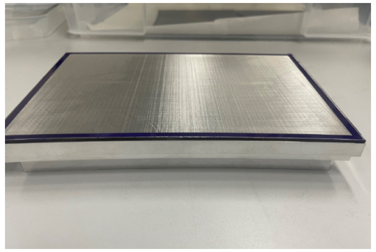
TPC

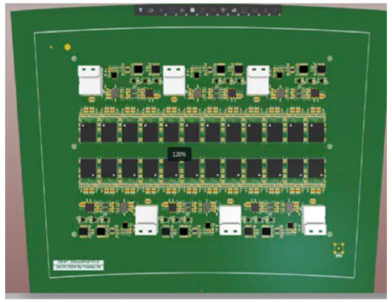
- Key component for tracking (esp. low p) and PID
- Pixelated TPC with pad size 500um to suppress Ion Back Flow
- Novel cluster counting method (dN/dx) for 3σ K/π separation

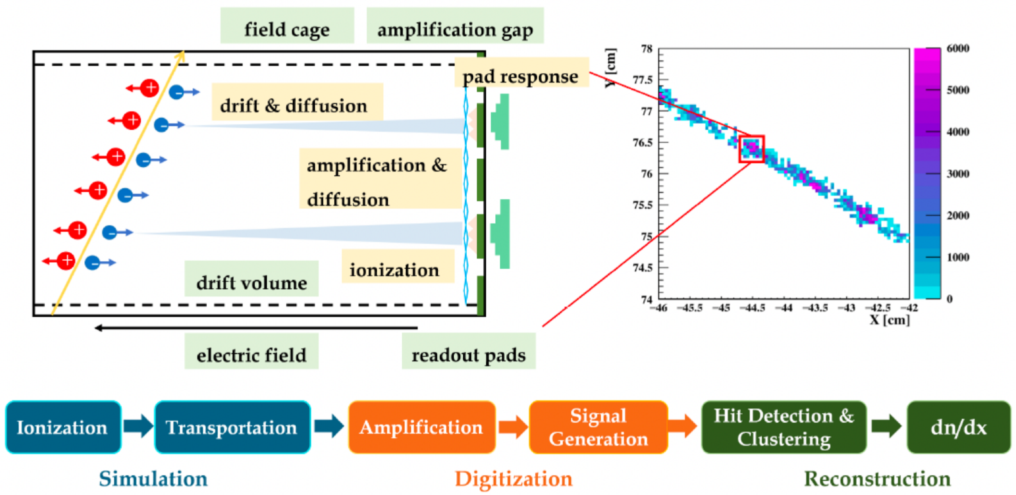






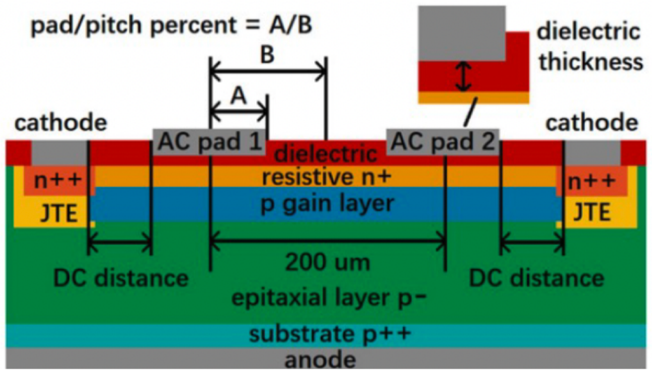


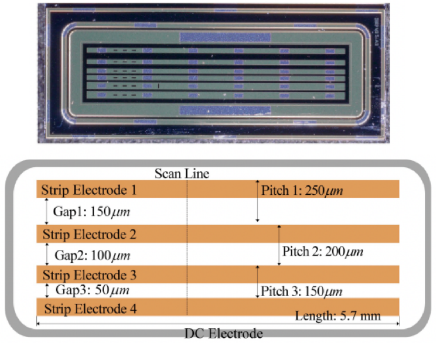


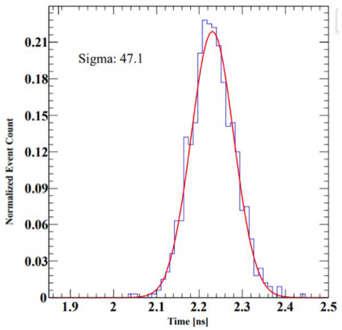


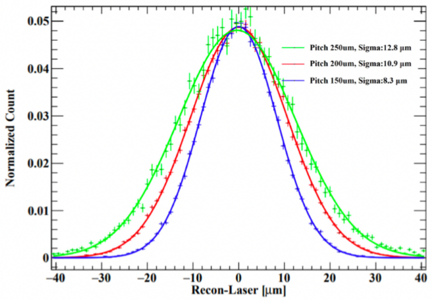
(Timing and) Outer Tracker

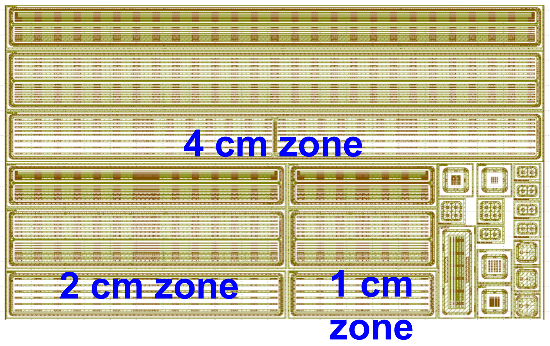
- Outermost tracking layer ~ 85m^2 with $\sigma_{r\phi}$ ~ 10 um
- σ_t ~ 50 ps to cover low-momentum PID
- AC-LGAD strips to provide both spatial and timing
- Sensor prototype submitted for full-length validation





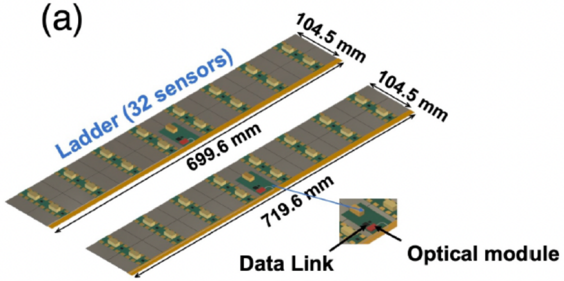


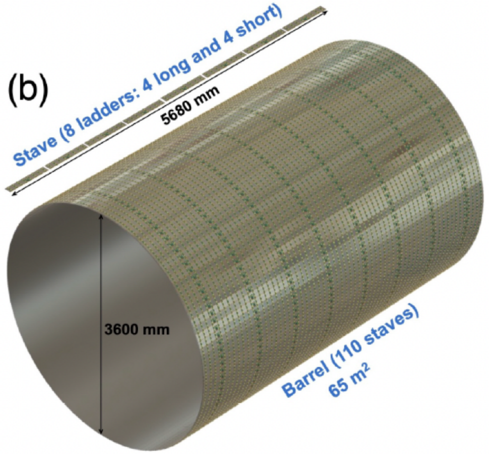


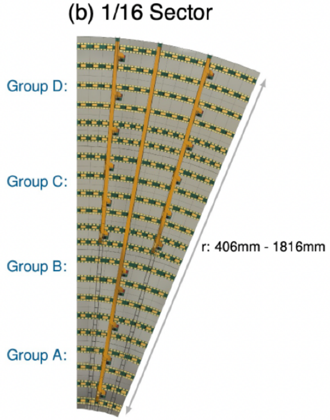


AC-LGAD Sensor

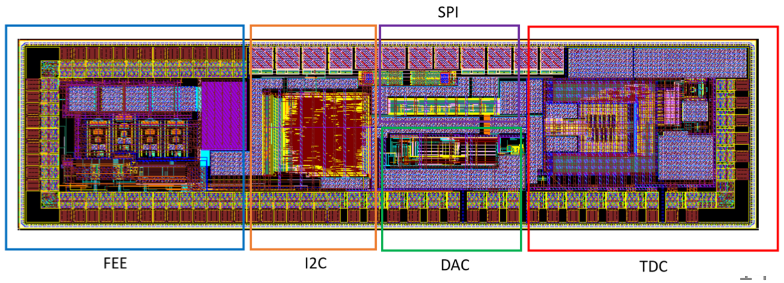
Length = 1, 2, 4 cm
Pitch=100, 200, 500 μm





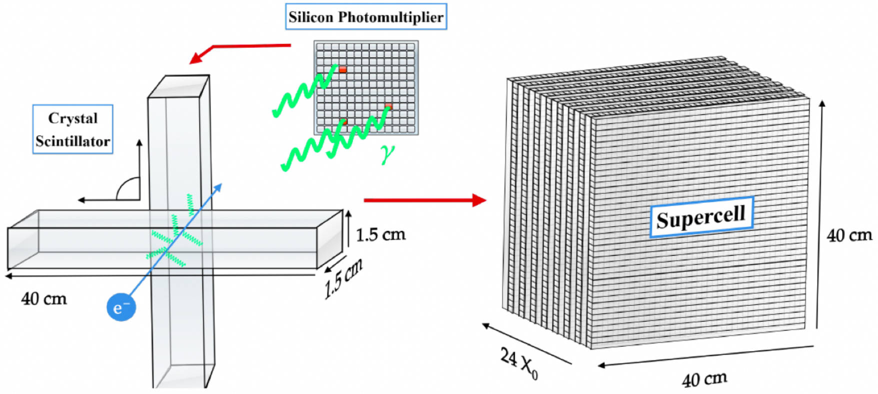


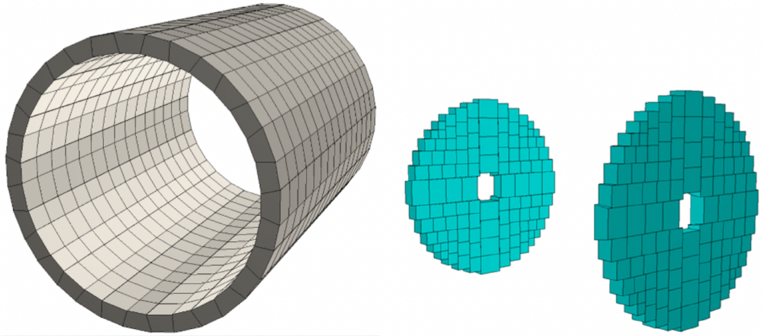
Readout ASIC

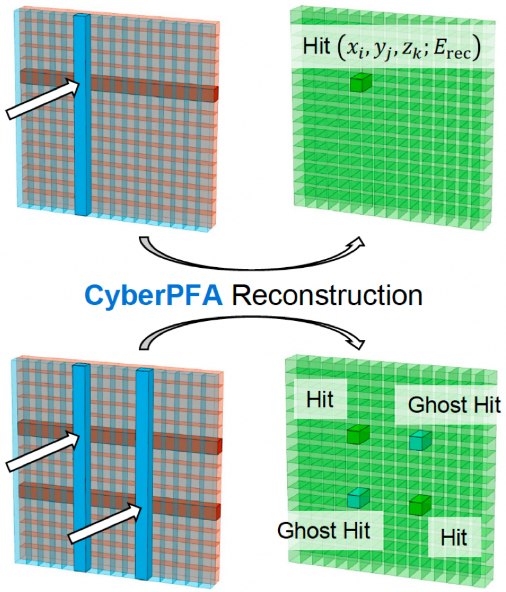


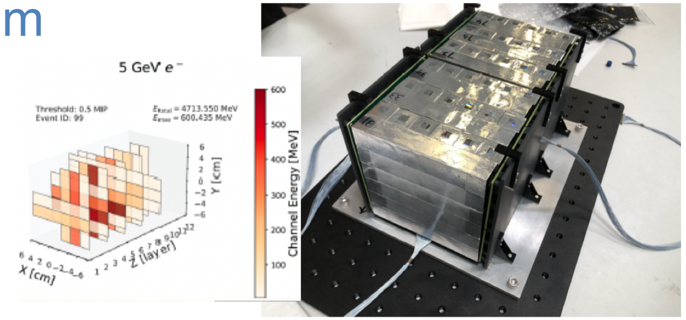
Electromagnetic Calorimeter

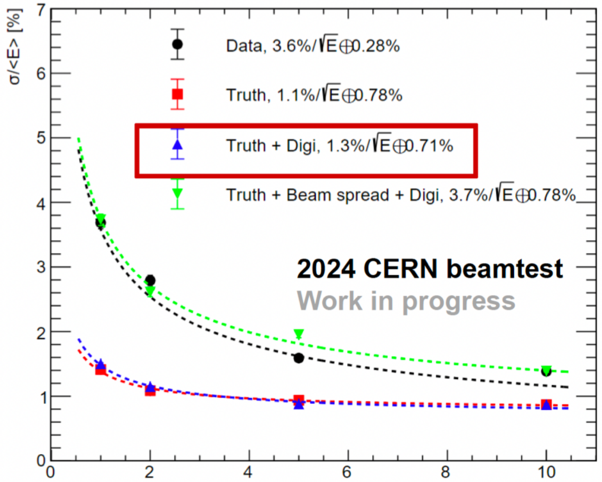
- PFA-based calorimetry to achieve Boson Mass Resolution (H→jj) < 4%
- Long BGO crystal + SiPM, targeting $\sigma_E/E < 3\%/\sqrt{E}$, BMR (H→$\gamma\gamma$) ~0.6 GeV
  - Save readout channels, minimise dead materials
  - Challenging for pattern recognition: dedicated CyberPFA algorithm
  - Prototype tested in beams; granularity being optimised





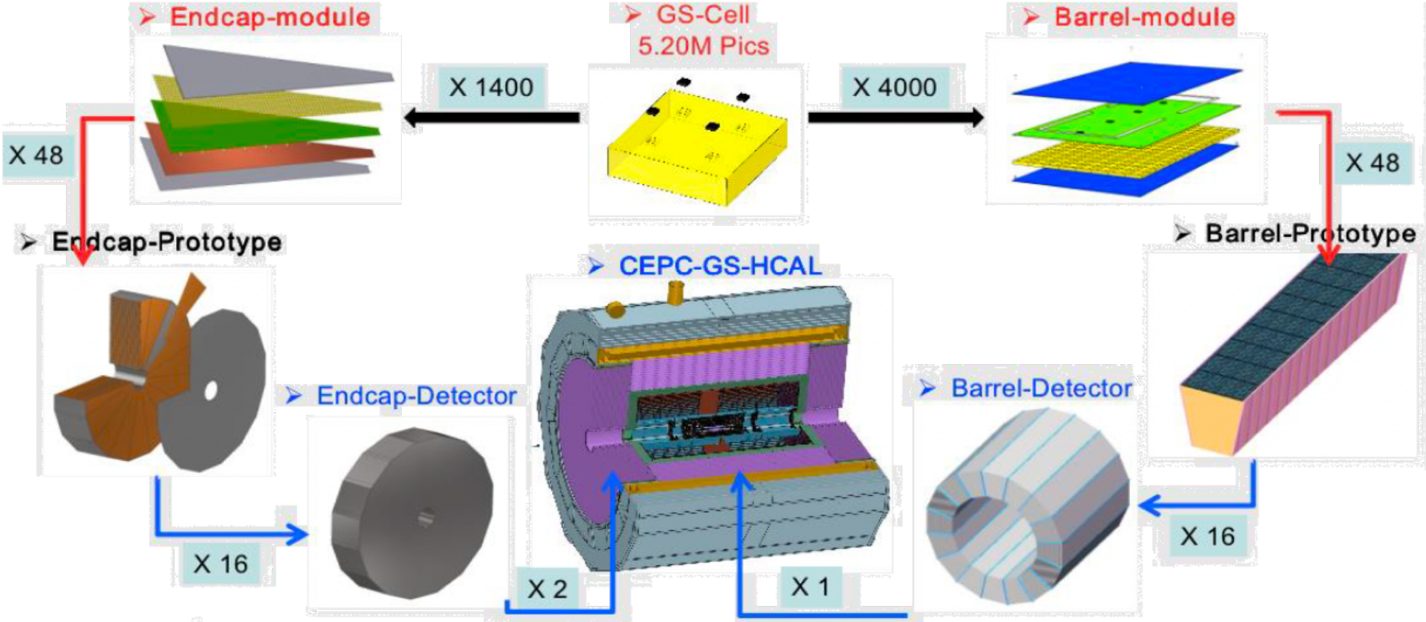




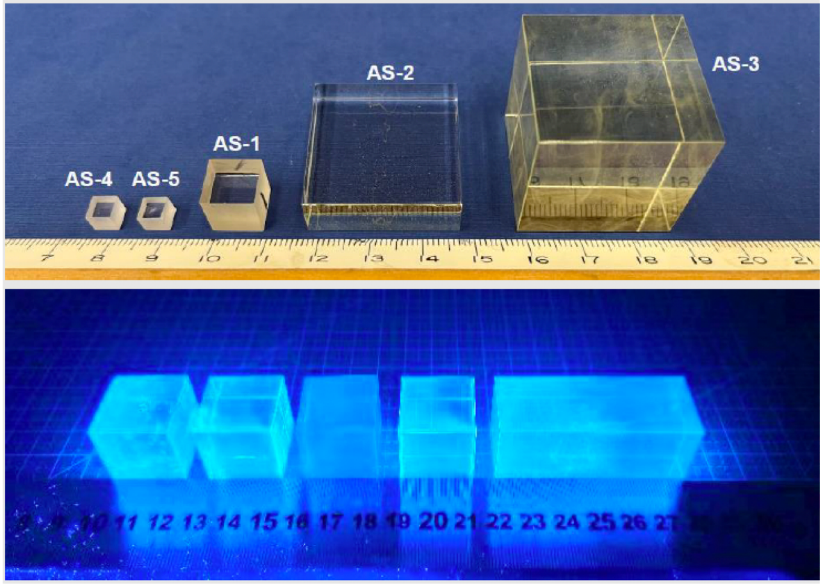


Hadron Calorimeter

- Jet energy of 30%/ $\sqrt{E}$ required for WW/ZZ separation
- Glass scintillator + SiPM explored:
  - High density, low cost
- GS collaboration formed for better glass and mass production
- A full-scale prototype being built for beamtest

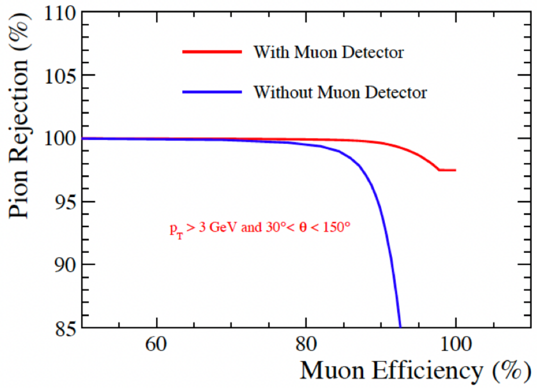


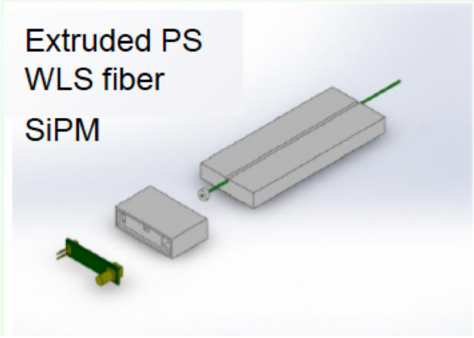
Parameters	Unit	Goal	BGO	GS1	GS1+	GS5
Density	g/cm^3	6	7.13	6.0	6.0	5.9
Rad. Length, X_0	cm		1.12	1.59	1.60	1.61
Transmittance	%		82	70	80	80
Refractive Index	--		2.1	1.74	1.71	1.75
Emission Peak	nm		480	400	390	390
Light Yield, LY	ph/MeV	1000	8000	985	2445	1154
Energy Resol, ER	%		9.5	30.3	25.8	25.4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

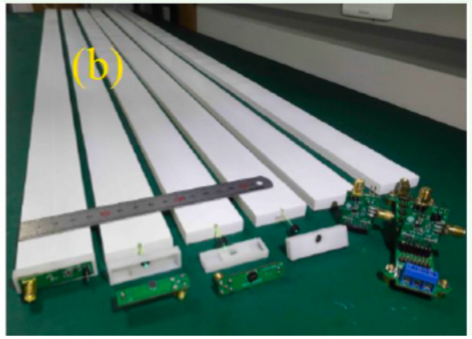


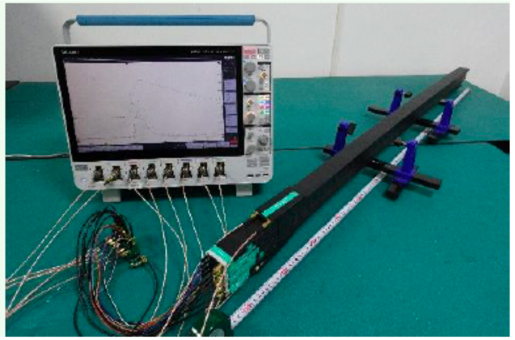
Muon Detector

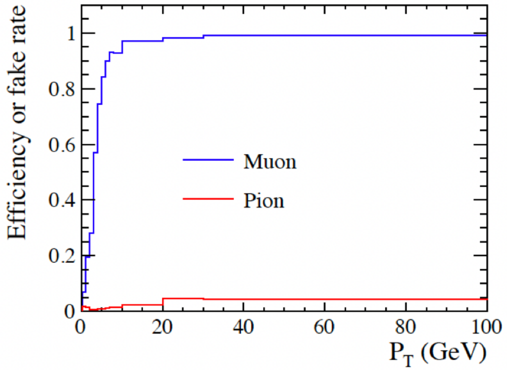
- Extruded plastic scintillator + WLS fibre + SiPM
- Magnet return yoke as muon absorber
- Provide Muon ID for p > 4 GeV
- Total detection area ~4500 m^2, ~40k channels

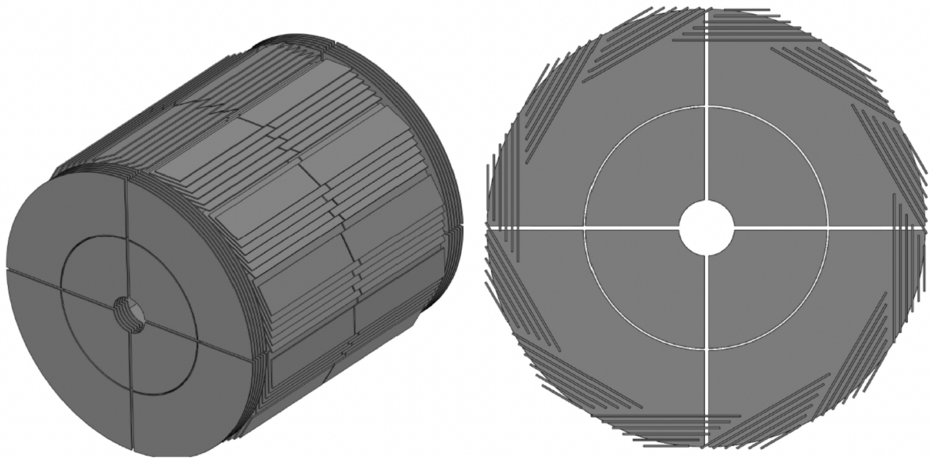


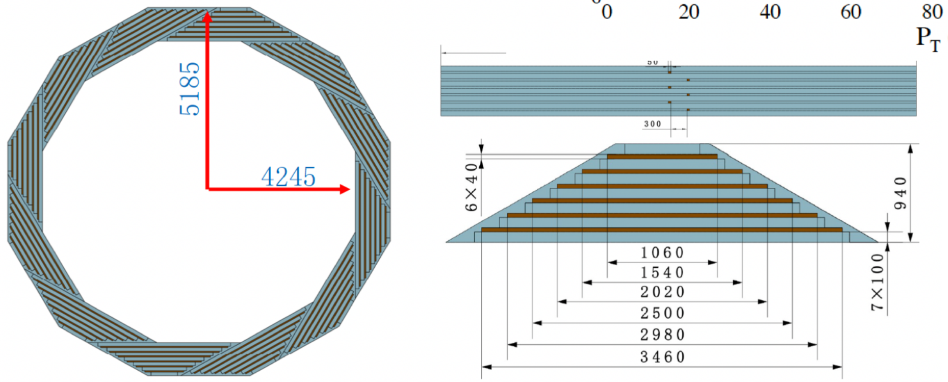






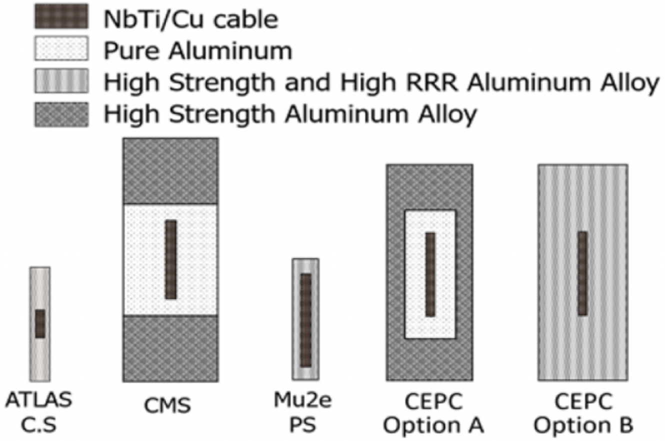




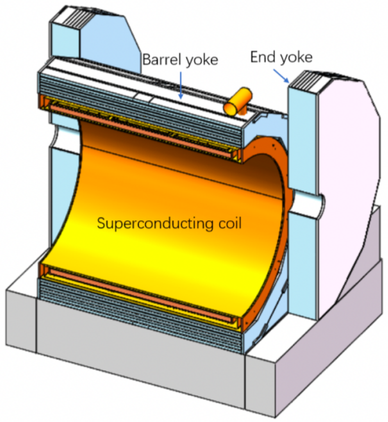


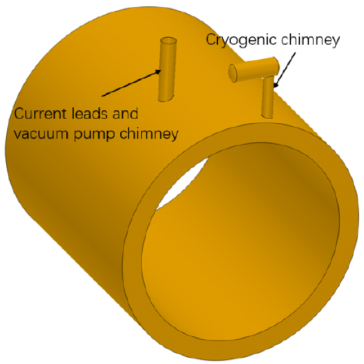
Superconducting Solenoid

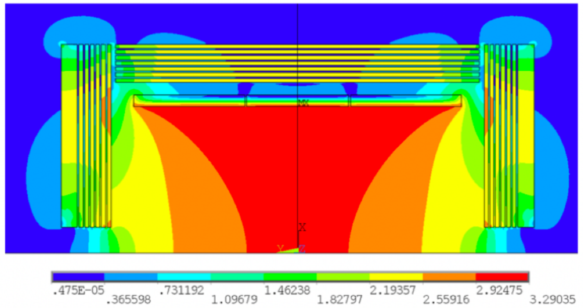
- Baseline: Low-temperature SC design
  - For better uniformity, less space, cost-effectiveness
  - Sample of 5m Aluminum stabilized NbTi Rutherford Cable produced
- R&D on high-temperature SC continues

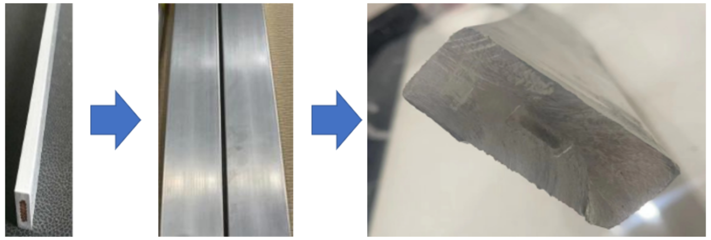


Central B field	3 T
Inner diameter	7070 mm
Outer diameter	8470 mm
Thickness	700 mm
Length	9050 mm
Cold mass	185 tons
Yoke weight	2960 tons
Magnet weight	290 tons

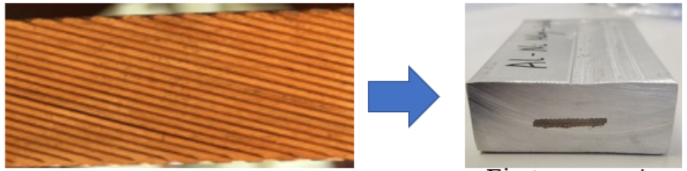








Opt. A: Second co-extrusion process

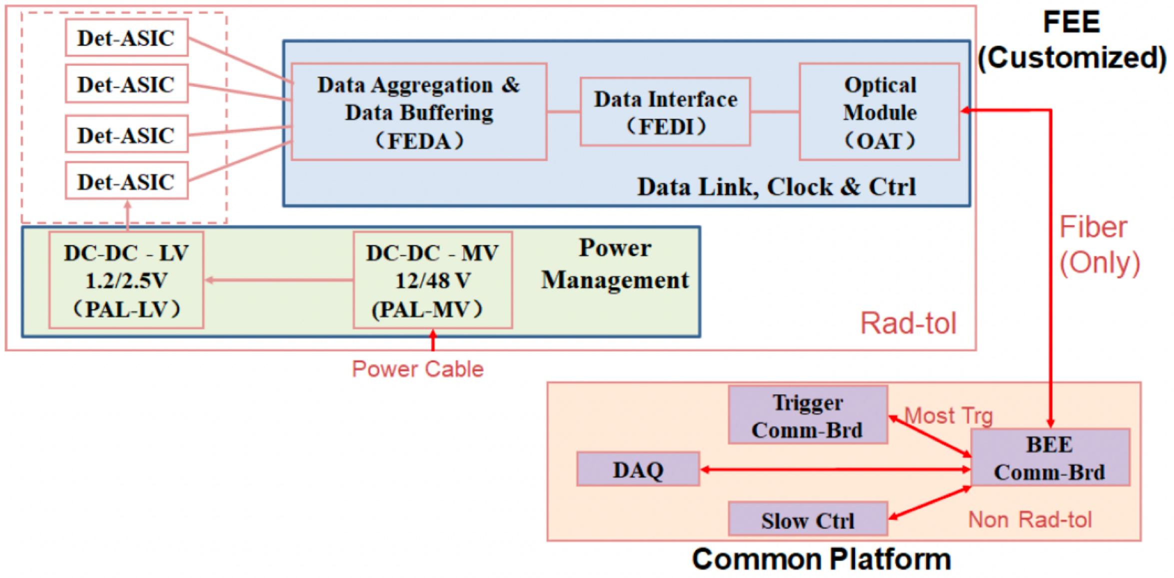


32 strands Rutherford cable

First co-extrusion Al-Ni-Be stabilizer +Rutherford cable

Opt. B: The Al-Ni-Be stabilizer conductor sample

Electronics and TDAQ



- Triggerless frontend readout + backend trigger
- Maximising common designs
  - Common FE ASICs: data aggregation, transmission, optical conversion, SiPM readout,…
  - Common BE & common trigger
- Alternative R&D on wireless transmission to reduce cabling hence material

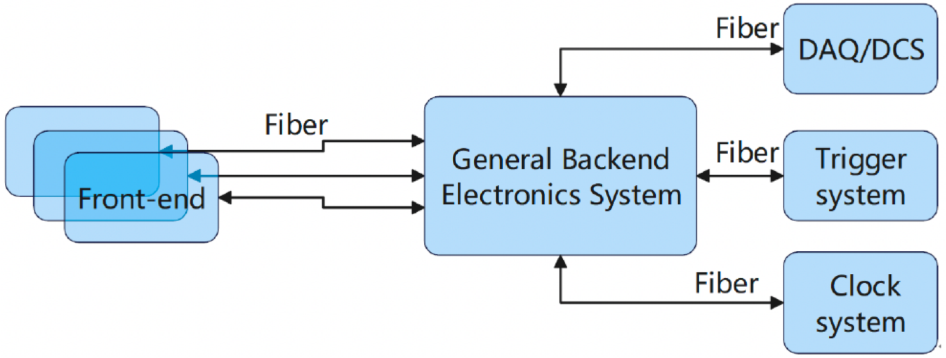
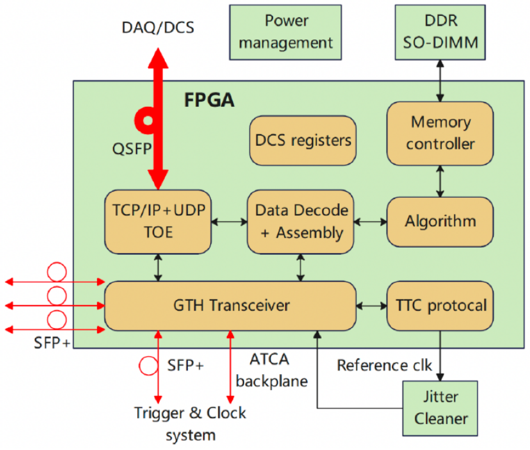
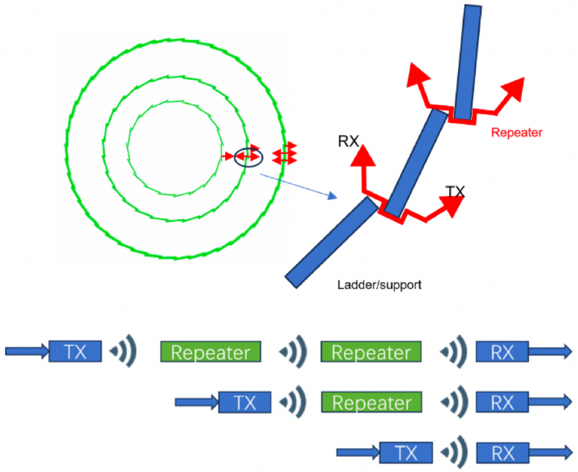
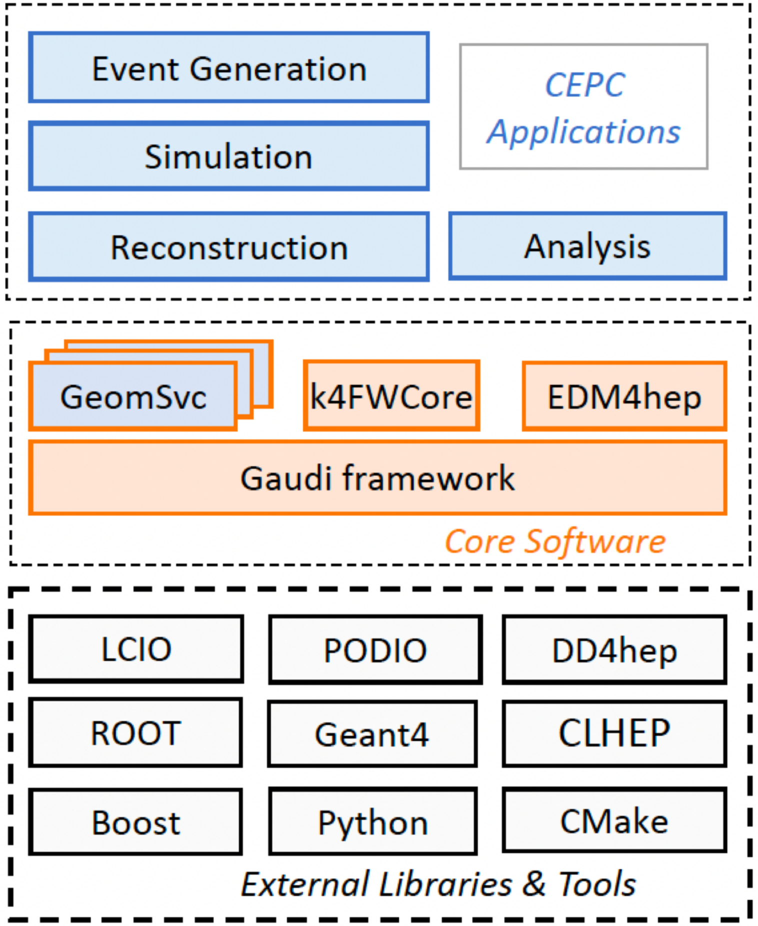


Figure 11.57: General off-detector electronics system connection



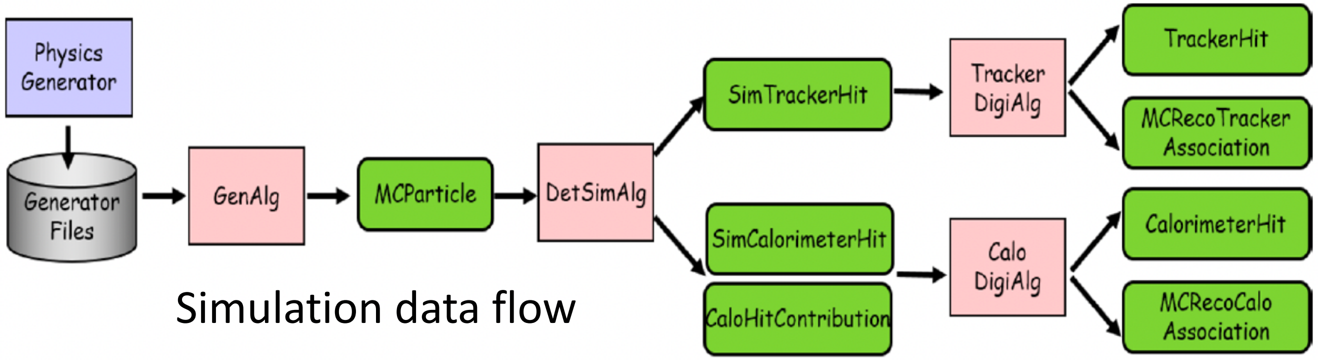


Software and computing

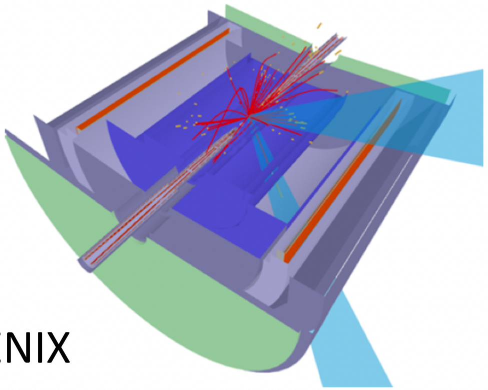


CEPCSW structure

- CEPCSW framework built upon common HEP packages:
  - Gaudi, EDM4hep, k4FWCore,DD4hep
- Web-based PHOENIX tool for visulisation
- RefTDR detector implemented & released for performance study
- Novel technologies being explored: eg. Quantum algorithms



Simulation data flow



PHOENIX

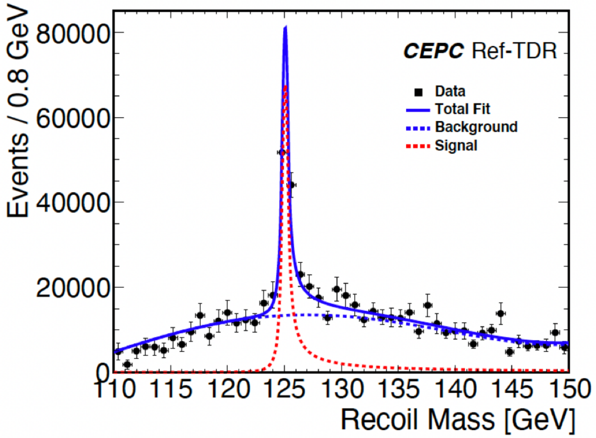
Table 13.2: Estimation of computational and storage resources

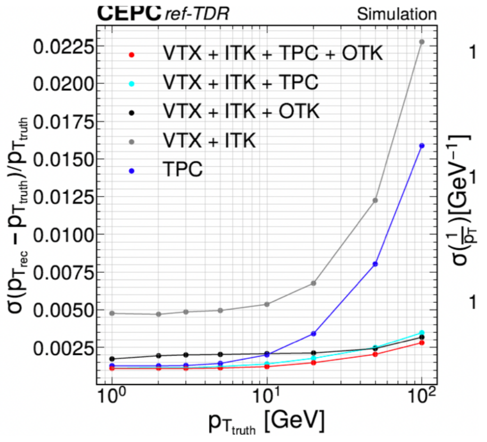
Mode	Disk (PB)	Tape (PB)	CPU (KHS23/KHS06)
Higgs	48	48	220
Low-lumi Z	436	436	1,760
Total	484	484	1,980

Key performance

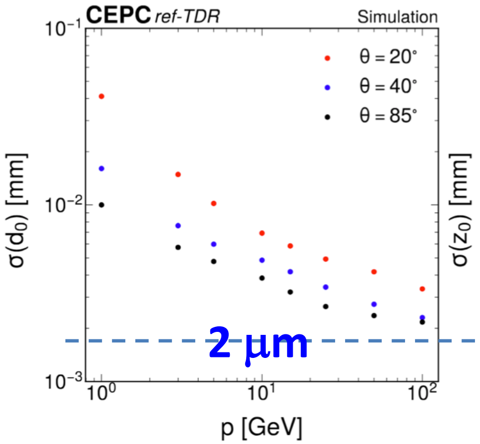
- With recent CEPCSW release, benchmarking physics processes identified and being studied
- Key performance of tracking, PID, jet and PFA are studied

Physics Benchmarks	Process @ c.m.e	Domain	Relevant Det. Performance
$H \to \gamma\gamma$	ZH @ 240 GeV	Higgs	photon ID, EM resolution
Recoil H mass	$\mu\mu H$ @ 240 GeV	Higgs	Tracking
$H \to$ hadronic decays	ZH @ 240 GeV	Higgs	PID, Vertexing, PFA (+ JOI)
$H \to$ invisible	$\mu\mu H$ and qqH @ 240 GeV	Higgs/NP	PFA, MET, BMR
$H \to$ LLP	ZH @ 240 GeV	NP	Tracker, Calo, muon detectors
Smuon pair	@ 240 GeV	NP	Tracking
W fusion Xsec	$\nu\nu H$ @ 360 GeV	Higgs	PFA, b-tagging
Top mass & width	Threshold scan @ $\sim$ 345 GeV	Top	Beam energy
A_{FB} $Z \to \mu\mu$	$Z \to \mu\mu$ @ 91.2 GeV	EW	Tracking, Acceptance
R_b	$Z \to$ hadronic @ 91.2 GeV	EW	PFA + JOI
CPV in $D^0 \to \pi^+\pi^-\pi^0$	@ 91.2 GeV	Flavor	PID, vertex, π^0, EM resolution

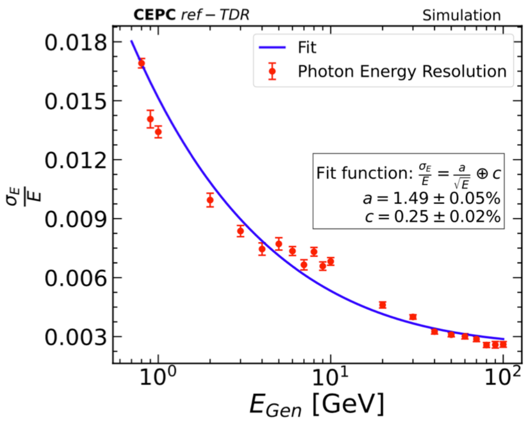




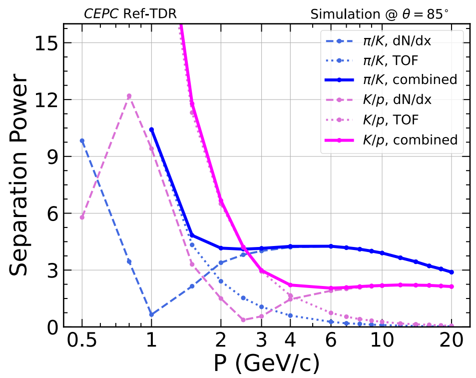
Momentum resolution



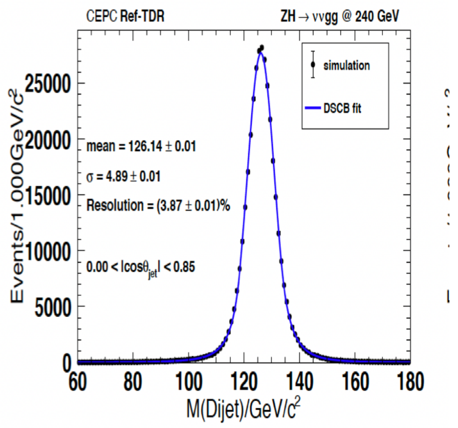
IP resolution



Photon energy



PID



BMR

Mechanics

- Detailed design for detector mechanical structure and installation
- Infrastructure, cooling and experimental hall design in place

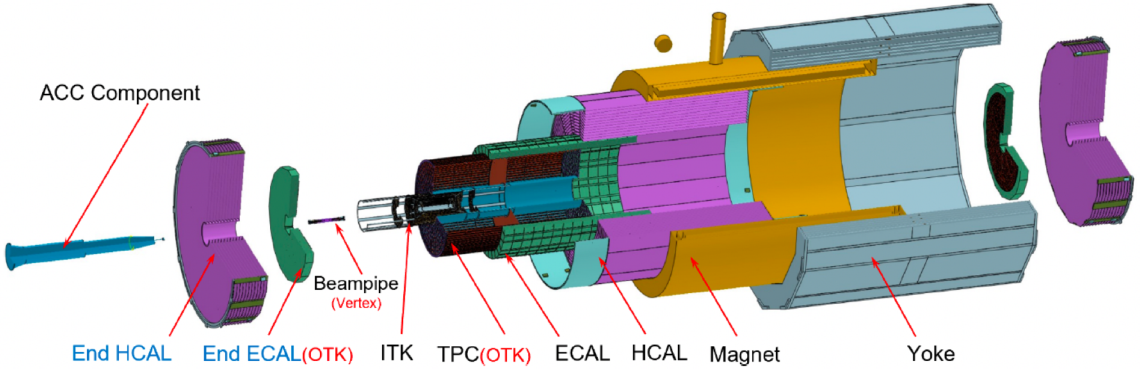


Figure 14.51: Exploded view of sub-detector installation

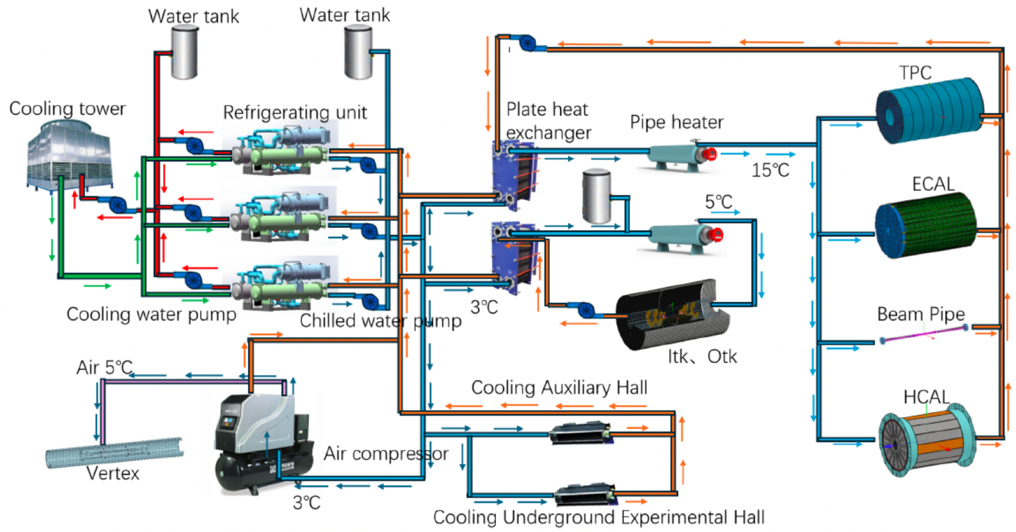


Figure 14.112: Flowchart of the cooling system

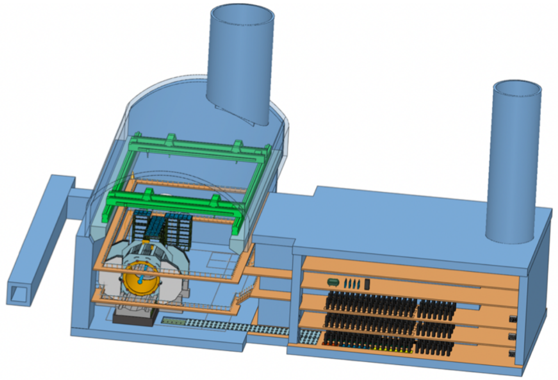


Figure 14.137: Electronics room

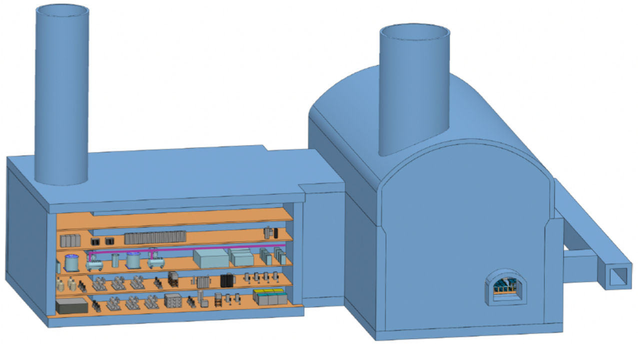


Figure 14.134: Layout of the auxiliary hall

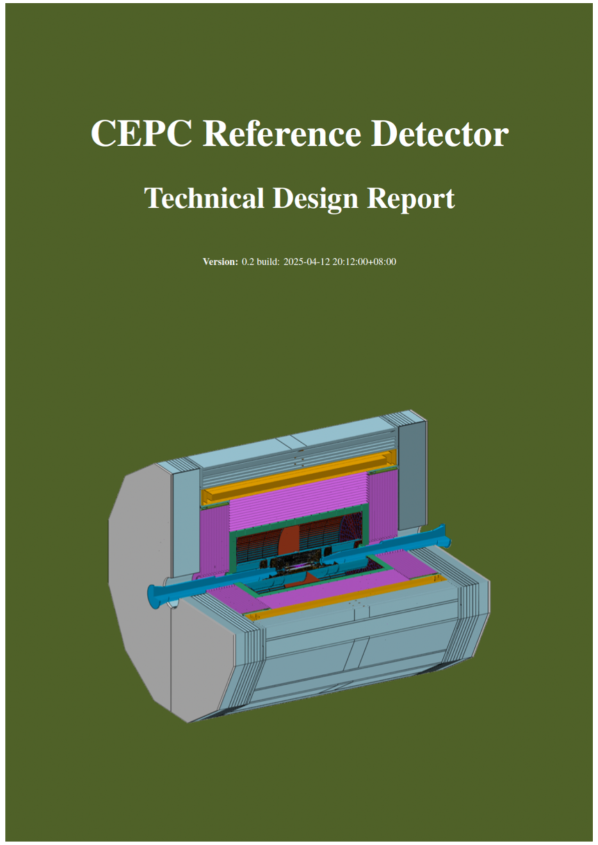
All team work!

1	IHEP, CAS	All
2	Inst of Microelectronics	SiDet,Elec
3	Shanghai Inst of Ceramics	ECal,HCal
4	Shanghai Inst of Optics & Fine Mechics	HCal
5	Zhangjiang Laboratory	SiDet
6	Ganjiang Innovation Academy	HCal
7	Instittute of Modern Physic, CAS	GasD
8	China Institute of Atomic Energy	GasD
9	Shandong Inst of Advanced Tech	SiDet,GasD
10	Peking U	GasD,Phys
11	Tsinghua U	SiDet,GasD,Elec,Phys
12	Fudan U	HCal,Mu,Sftw,Phys
13	Shanghai Jiaotong U	MDI,SiDet,ECal,HCal,Mu,Mag,Phys
14	Zhejiang U	SiDet,HCal
15	Nanjing U	MDI,VTX,SiDet,Elec,Sftw,Phys
16	U of Sci & Tech	ECal,Elec,Sftw
17	Beihang U	Phys
18	Southeast U	Mu,Phys
19	Wuhan U	Sftw
20	Harbin Inst of Tech	HCal
21	Xi'an Jiaotong U	SiDet
22	Nankai U	VTX,SiDet,Mu,Tdaq,Sftw,Phys
23	Sun Yat-Sen U	SiDet,GasD,HCal,Sftw
24	Sichuan U	HCal
25	NorthWest Polytechnical U	VTX,SiDet,Elec
26	Shandong U	VTX,SiDet,GasD,Elec,Tdaq,Sftw
27	Jilin U	MDI,GasD,Sftw
28	Hunan U	SiDet,Mech
29	Lanzhou University	GasD
30	Zhengzhou U	VTX,SiDet,GasD,HCal,Tdaq,Sftw,Phys
31	Southwest Jiaotong U	MDI,Mag
32	Central China Normal U	VTX,Elec
33	North China Electric Power U	Mag
34	Harbin Engineering U	HCal
35	Wuhan University of Technology	GasD,HCal
36	South China Normal U	Mu,Sftw,Phys
37	Hefei University of Technology	SiDet
38	Nanchang U	VTX,SiDet
39	Taiyuan University of Technology	SiDet

40	Dalian Minzu U	SiDet
41	Liaoning Normal U	Phys
42	U South China	SiDet
43	Wuhan Textile U	SiDet,Elec
44	Hubei Polytechnic U	SiDet,Elec
45	Jinggangshan U	HCal
46	China Jiliang U	HCal
47	yanshan University	SiDet
48	Zhengzhou University of Light Industry	SiDet,Mech
49	Gannan Normal University	SiDet,Elec
50	Beijing Conveyi Limited	SiDet
51	China Building Material Academy	HCal
52	Beijing Glass Research Inst	HCal
53	Shanghai Superconducting Tech Co	Mag
54	Citic Heavy Instructries Co	Mech
55	Yellow River Engineering Consulting Co	Mech
56	Wuxi Toly Electric Works Co	Mag

1	CERN ECFA DRD collaborations	Nearly All
2	ALICE collaboration	VTX,SiDet
3	INFN / Milano	SiDet,GasD
4	INFN / Torino	SiDet,GasD
5	INFN / Bari, Politecnico U of Bari	GasD
6	INFN LNF (Frascati)	ECal
7	IN2P3 / IPHC, Strasbourg	VTX
8	IN2P3 / IJCLab, Orsay	ECal
9	IN2P3 / LLR, Palaiseau	ECal
10	IN2P3 / IP2I, Lyon	ECal
11	IN2P3 / CPPM, Marseille	VTX
12	CEA / IRFU, Saclay	GasD
13	KIT	SiDet
14	Bonn U	GasD
15	DESY	SiDet,GasD
16	Lancaster U	SiDet
17	Edinburgh U	SiDet
18	Bristol U	SiDet
19	NIKHEF	GasD
20	IFAE (Inst De Fiscia d'Altes Energies)	VTX
21	ULB (Universite Libre de Bruxelles)	HCal
22	LPI (Lebedev Physical Inst, RAS)	ECal,Mu,Phys
23	HSE (University Higher School of Economics)	Mu
24	MIPT (Moscow Institute of Physics and Technology)	Mu
25	BINP (Budker Inst of Nuclear Physics, RAS)	ECal,HCal,Mu
26	INR (Inst of Nuclear Research,RAS)	HCal
27	JINR (Joint Inst of Nucl Research)	SiDet,GasD,ECal,HCal
28	ISPM (Inst of Synthetic Polymeric Materials,RAS)	HCal
29	Vinca Inst of Nuclear Sciences	MDI
30	University of Belgrade	Phys
31	AGH University of Krakow	MDI
32	JSI (Jozef Stefan Institute,Ljubljana)	SiDet
33	University of Montenegro	SiDet
34	Institute of Physics, IPAS	MDI,Elec
35	National Centre for Physics, Pakistan	Phys
36	Tokyo U	GasD,ECal
37	Shinshu U	ECal
38	Iwate U	GasD
39	KEK	GasD

Ref-TDR status and timeline



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

- 16 chapters
- Two iteration of IDRC review
  - Oct 2024 / Apr 2025
  - A lot of constructive suggestions & recommendations
- Finalising the draft – expected release in end June and publication for journal later

Summary

- CEPC is preparing for a Reference detector TDR
- Many new technologies explored with huge amount of R&D work
- Detector design is being optimised for better physics performance
- The document is expected to release soon – stay tuned
- … and your interest and participation is most welcome!

发扬红旗渠精神，建设科学界的红旗渠！

自力更生
艰苦创业
团结协作
无私奉献