CEPC Physics and Detector highlights

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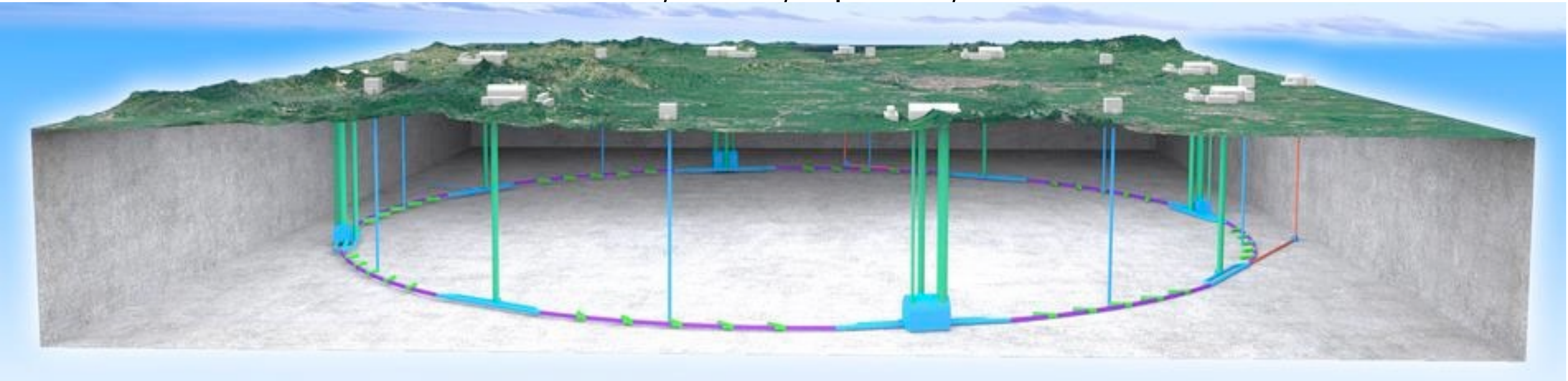
(On behalf of the CEPC physics and detector group)

Institute of High energy physics, CAS

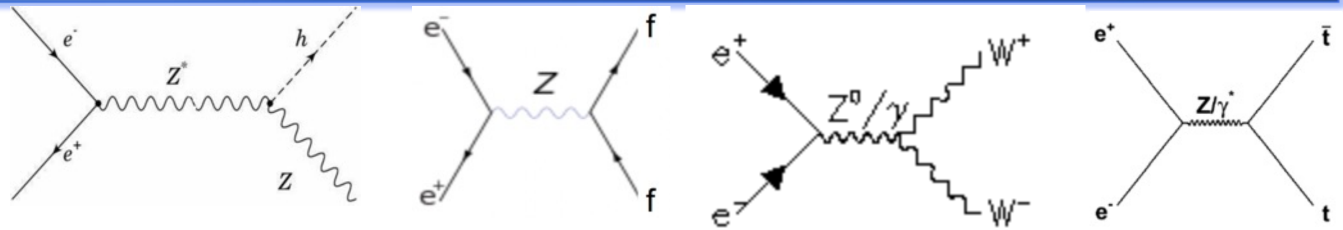
The 2024 International Workshop on the Circular Electron Positron Collider
Marseille, France, Apr 8–11, 2024



CEPC physics program

An extremely versatile machine with a broad spectrum of physics opportunities

→ Far beyond a Higgs factory



Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			~240	~91.2	~160	~360
Run time [years]			10	2	1	5
CDR (30 MW)		L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	-
Run Time [years]			10	2	1	~5
Latest	30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	8.3	191.7	26.6	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	20	96	7	1
		Event yields [2 IPs]	4×10^6	4×10^{12}	5×10^7	5×10^5

- **Huge measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top**
- **Searching for exotic or rare decays of H, Z, B and τ, and new physics**
- **CEPC community joined ECFA Phy focus**
  - **Aiming towards next ESPPU Updates.**

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

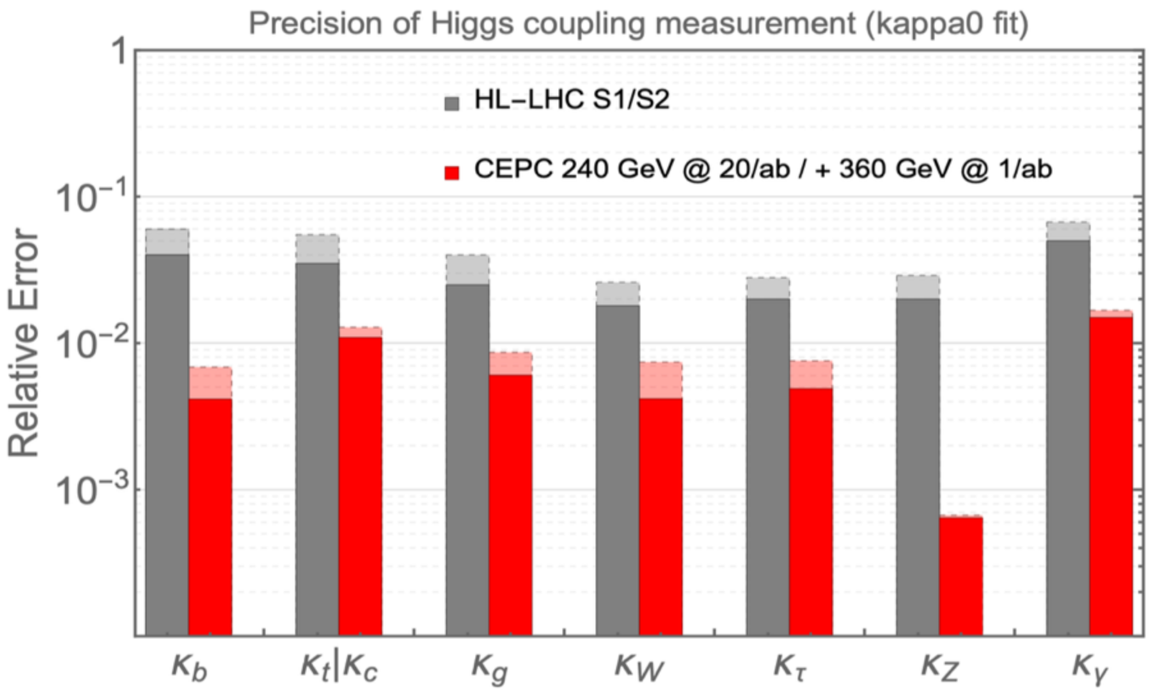
Higgs Precision measurements @ ZH runs

Translated the latest accelerator performance into Higgs measurements

Higgs		
Observable	HL-LHC projections	CEPC precision
M_H	20 MeV	3 MeV
Γ_H	20%	1.7%
$\sigma(ZH)$	4.2%	0.26%
$B(H \to bb)$	4.4%	0.14%
$B(H \to cc)$	-	2.0%
$B(H \to gg)$	-	0.81%
$B(H \to WW^*)$	2.8%	0.53%
$B(H \to ZZ^*)$	2.9%	4.2%
$B(H \to \tau^+\tau^-)$	2.9%	0.42%
$B(H \to \gamma\gamma)$	2.6%	3.0%
$B(H \to \mu^+\mu^-)$	8.2%	6.4%
$B(H \to Z\gamma)$	20%	8.5%
Bupper$(H \to$ inv.)	2.5%	0.07%

Higgs width measurement benefits enormously from 360-GeV run

Exploring the full potential of the CEPC with the latest TDR design for Higgs measurements by combining 240-GeV and 360-GeV runs.

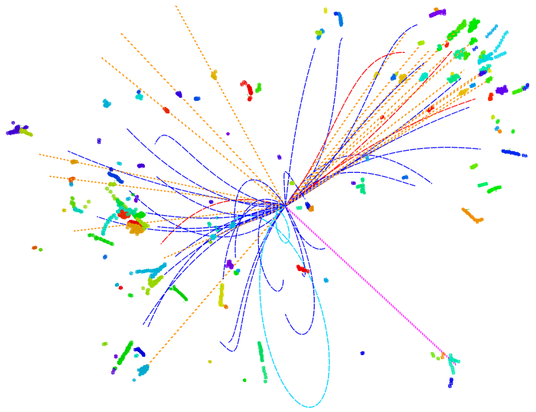


Outperforming HL-LHC significantly

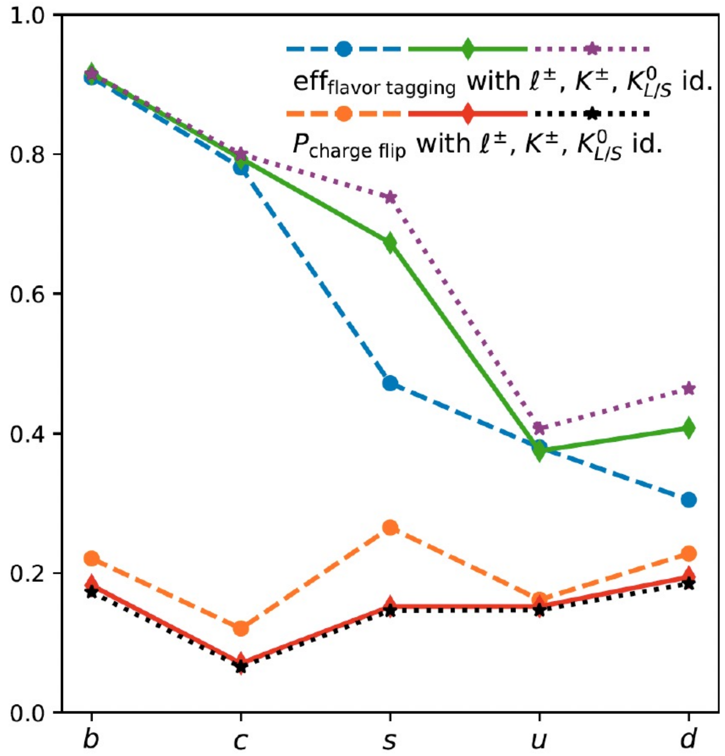
Higgs Precision measurements： Jet origin identification

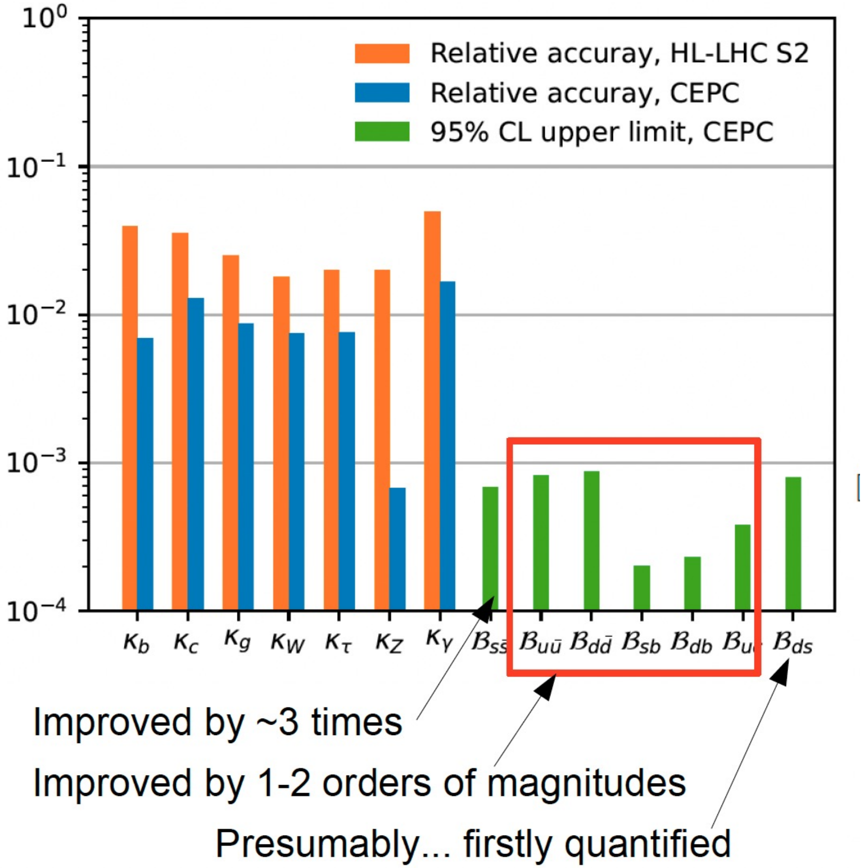
- **Higgs coupling to quarks can be measured to unprecedented precisions**
  - Especially for light quarks (strange quarks) …
- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging…
  - PFA algorithm Arbor + ParticleNet (Deep Learning Tech.)

More details in Manqi 's Talk in physics section



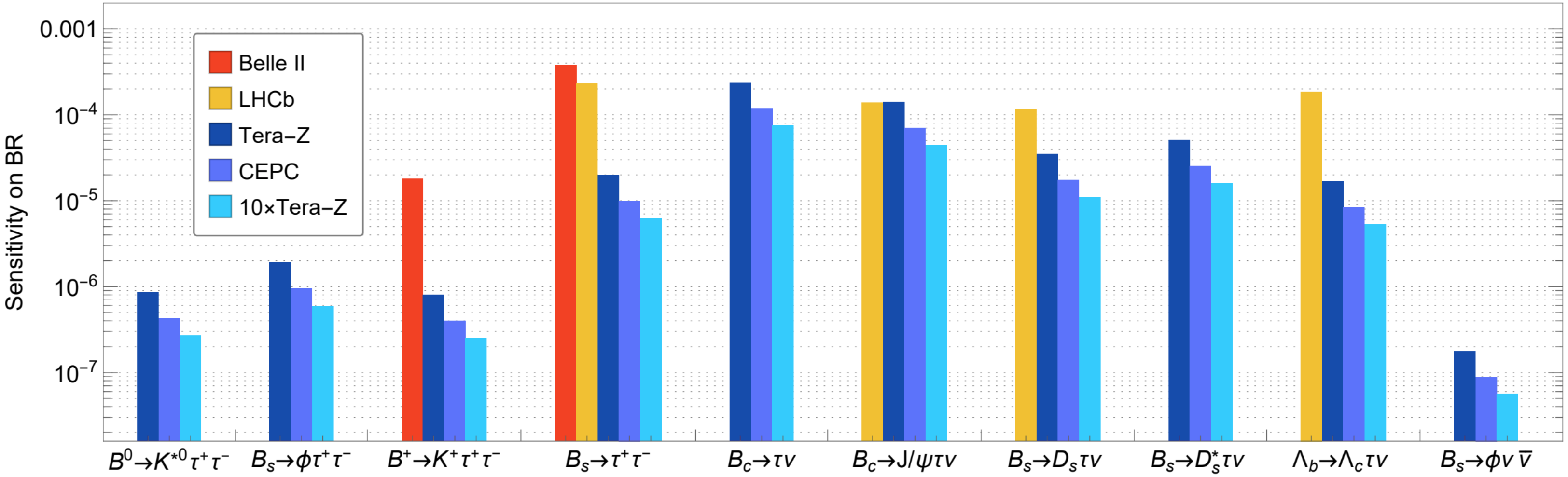
ArXiv:2310.03440
Arxiv:2309.13231

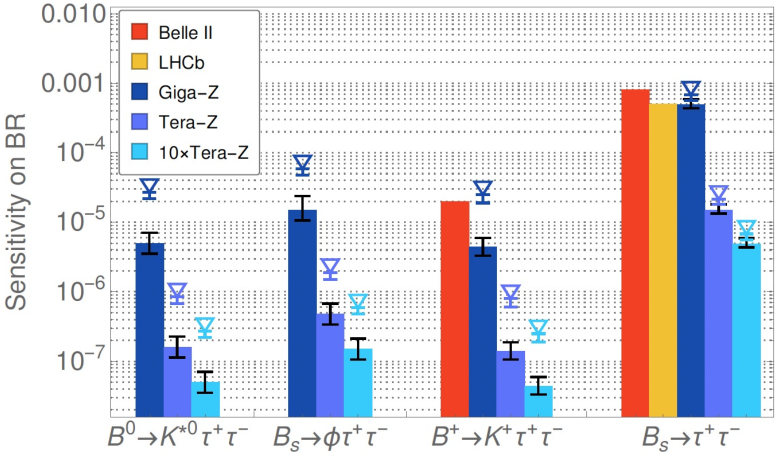




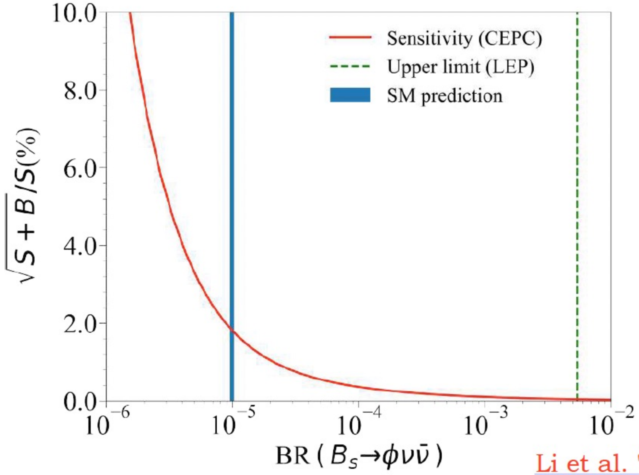
Flavor physics studies @ Z pole

CEPC provides a unique opportunity to study Z LFV decays, rare B decays, tests of LFU in tau decays or Bc decays etc.





Li L. and Liu T. '20



Li et al. '22

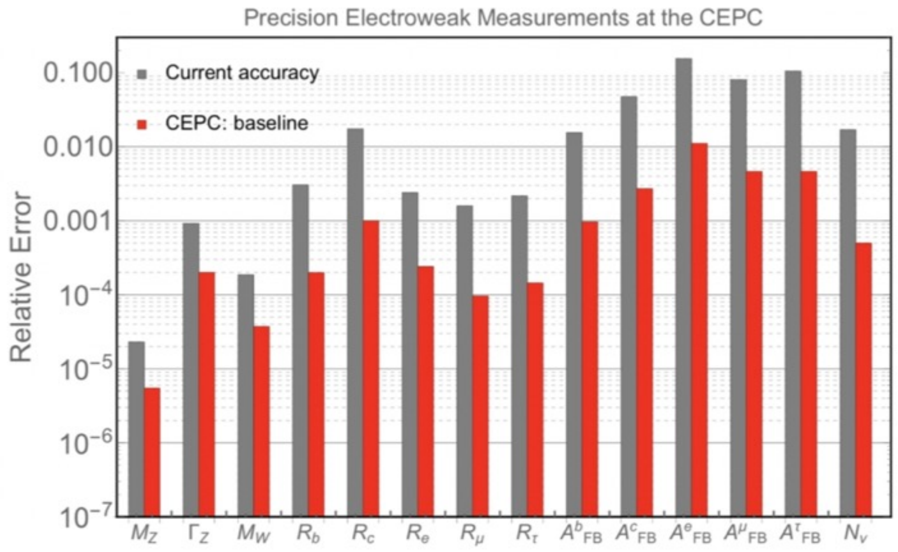
White paper draft

Contents

More details in flavor physics section

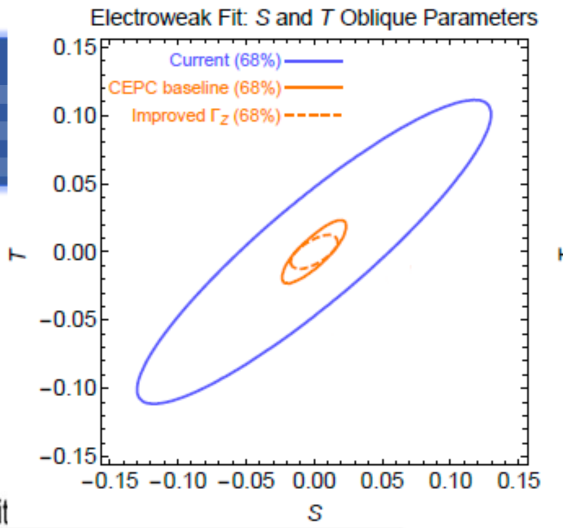
EWK precision measurements (ZH, Z pole, WW runs)

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale

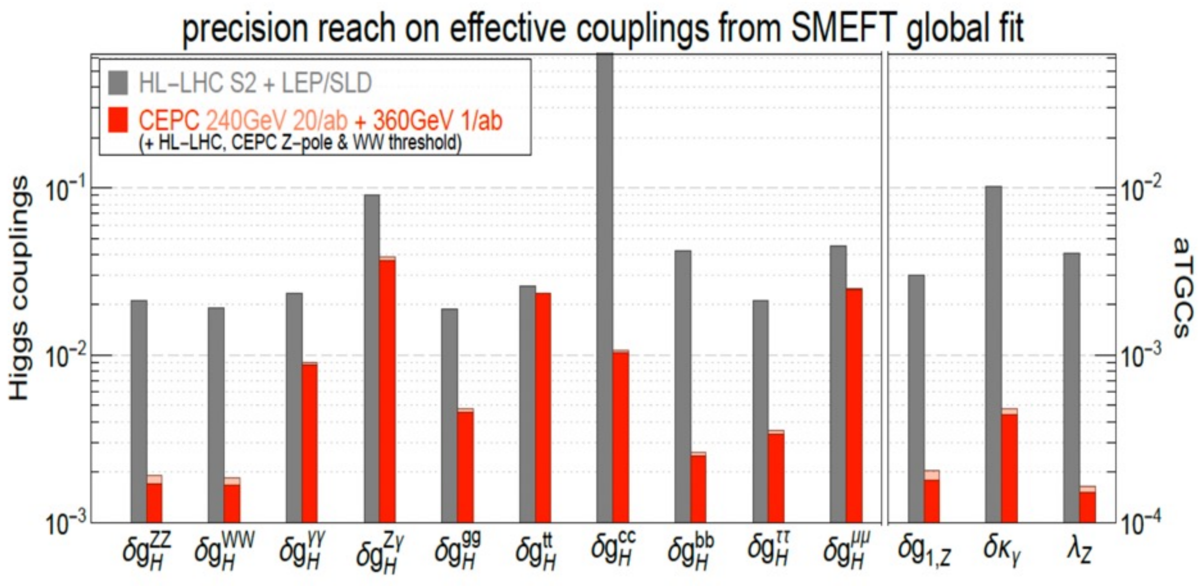


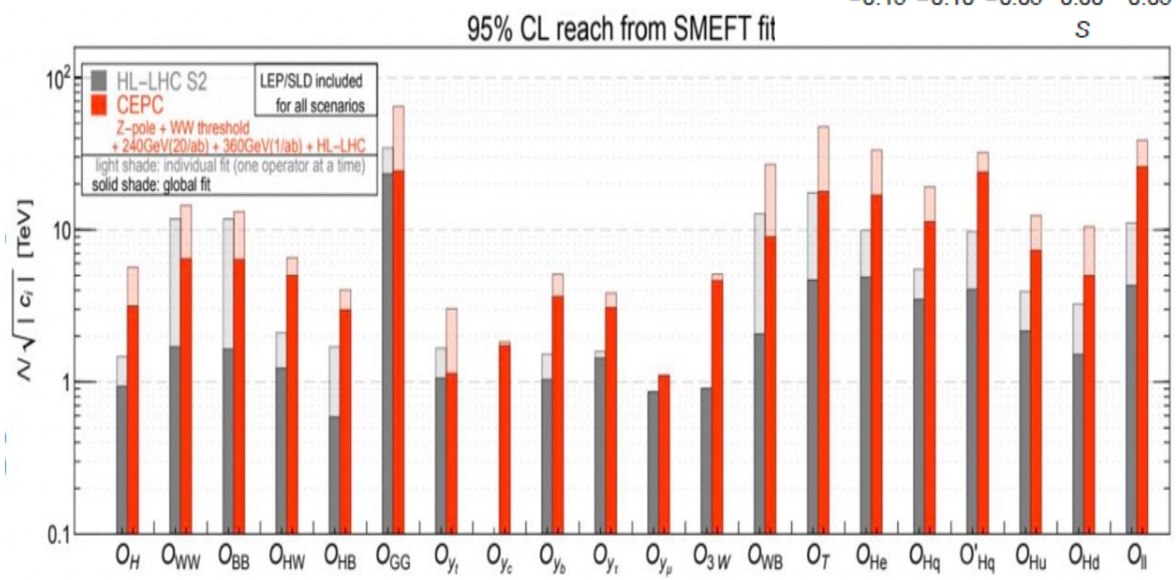
CEPC is expected to improve the current precision by 1-2 orders of magnitude, offering a great opportunity to test the consistency of the SM.

Global fit with SMEFT: new physics constrains



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

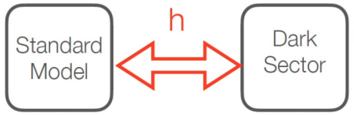




CEPC has potential to reveal new physics @10 TeV by combining Higgs, EWK and top measurements → power of precision

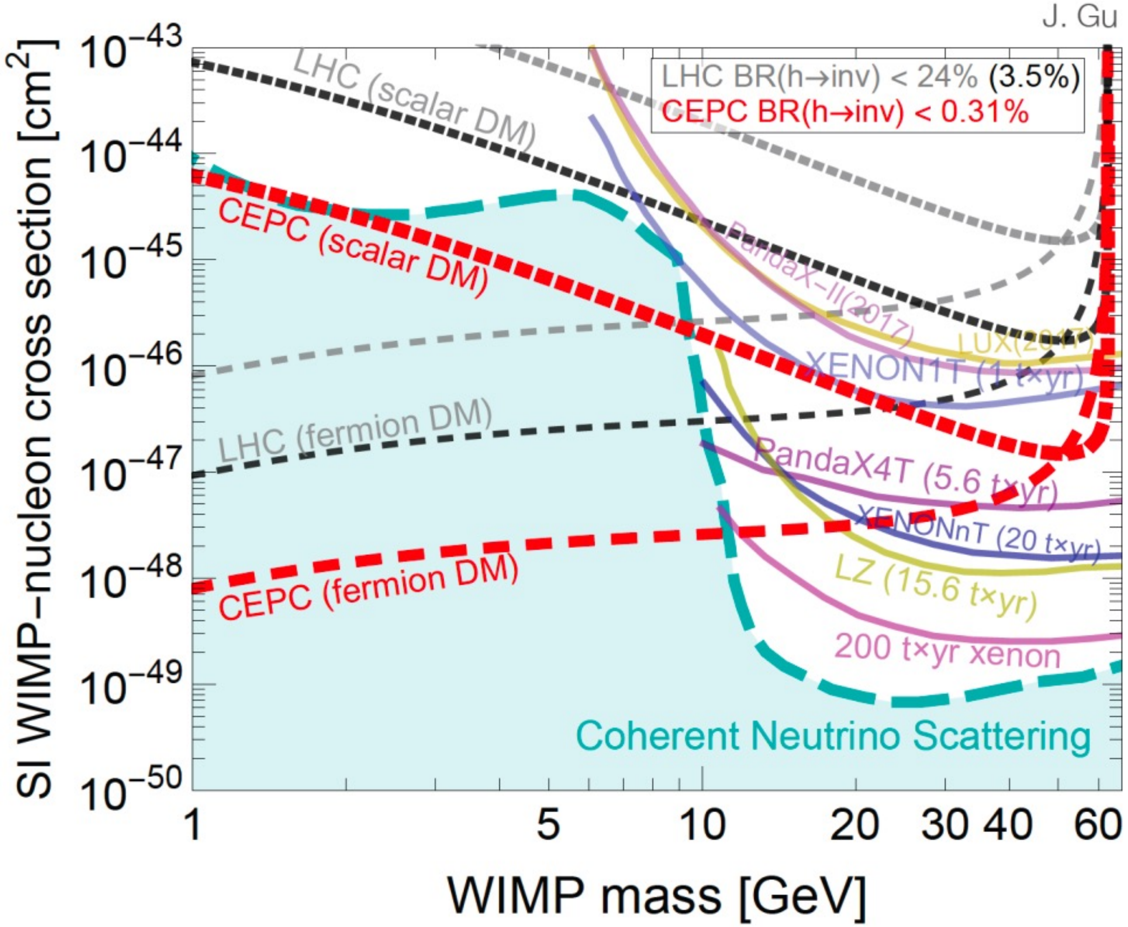
BSM searches: dark matter, SUSY…

❖ **Significantly better detection sensitivity to dark matter and SUSY**

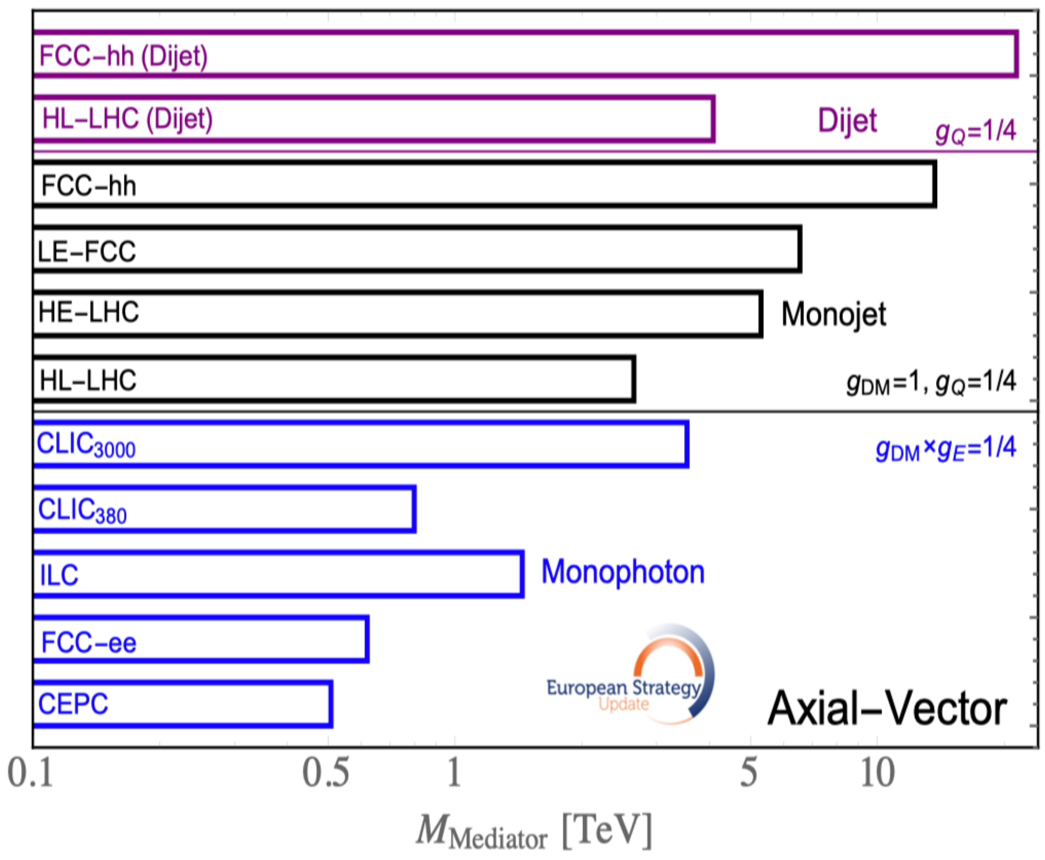


$h \rightarrow X_{dm} X_{dm}$

Higgs-portal Dark matter



SUSY Dark matter

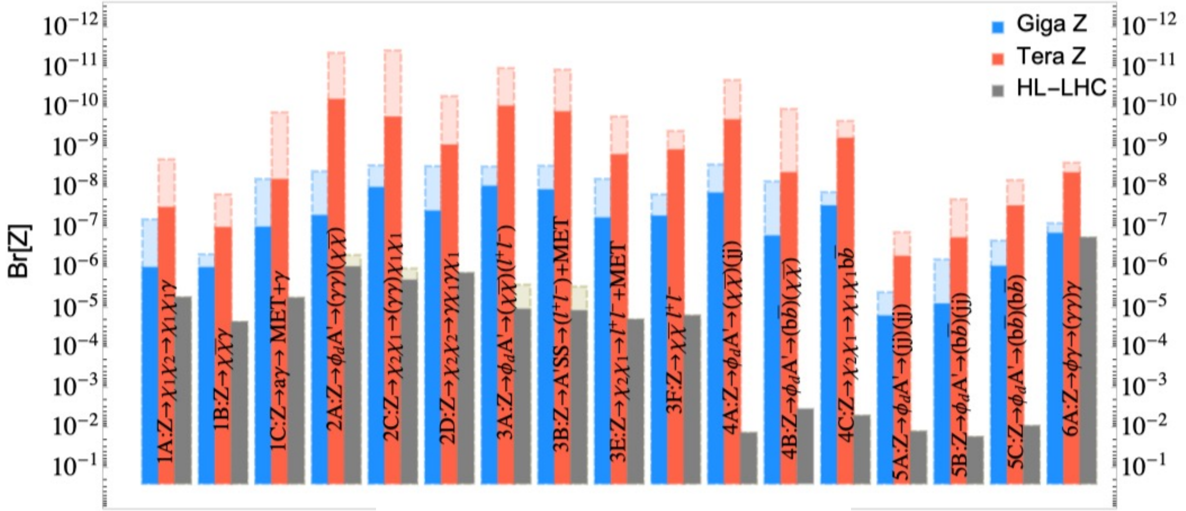


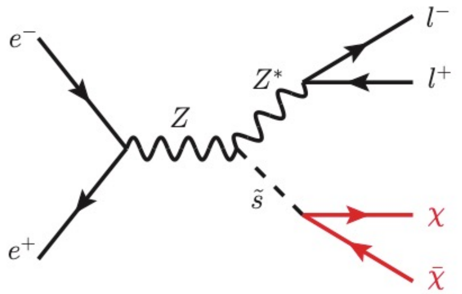
BSM searches: exotic decays, Dark Sector…

❖Significantly better detection sensitivity to Higgs/Z exotic decays than HL-LHC

Dark Sector via exotic Z decay

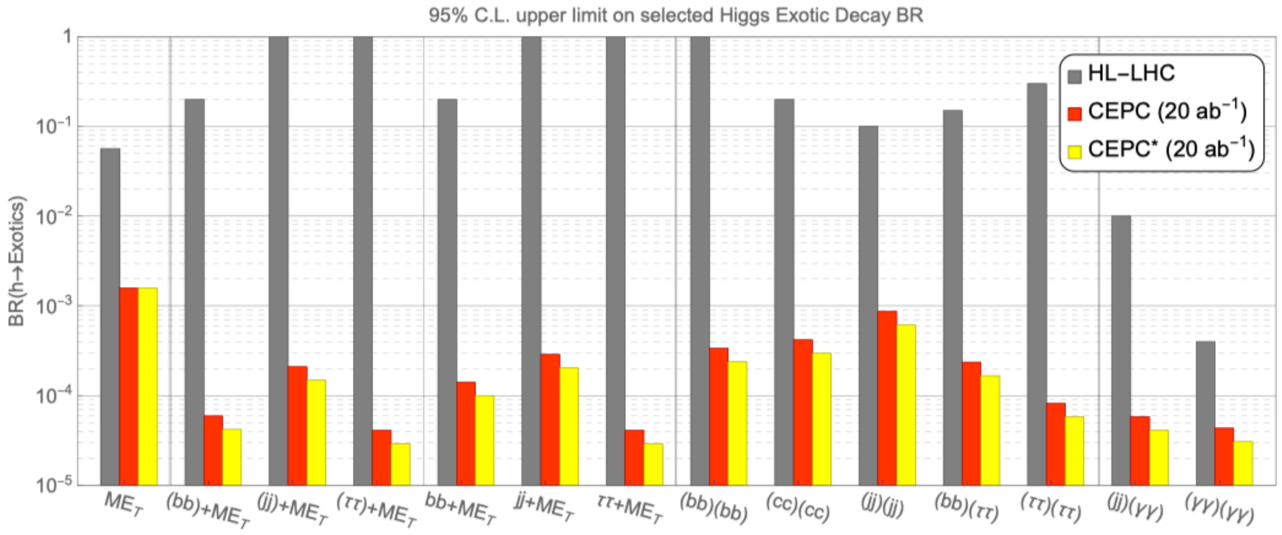
Z. Liu et al. 1612.09284., J. Liu et al. 1712.07237





Good sensitivity of exotic Higgs decay

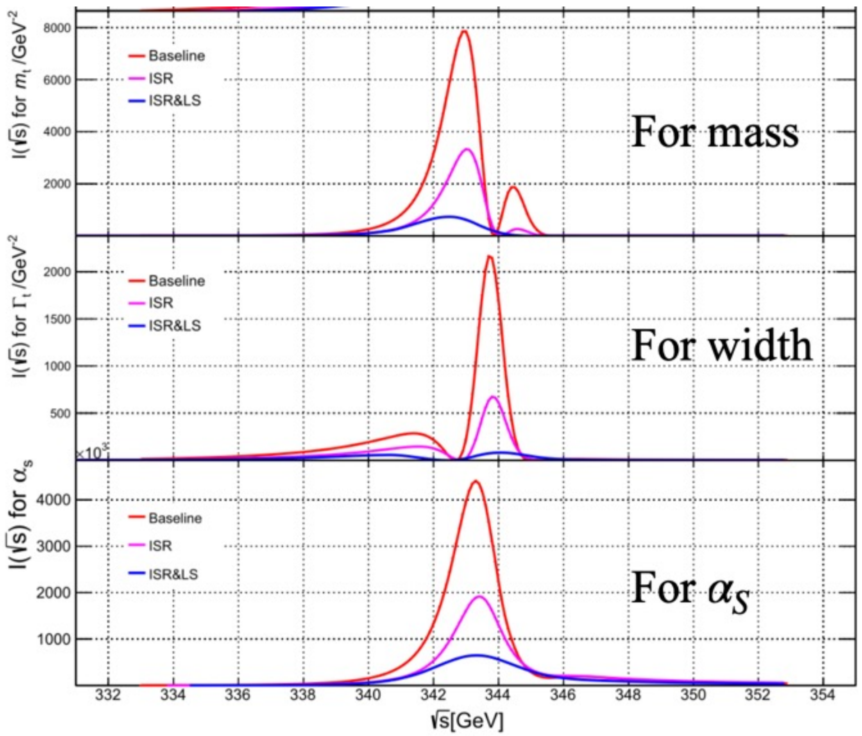
Z. Liu et al 1612.09284.



Top quark measurements @ ttbar threshold runs

$t\bar{t}$ modes are considered as upgrades.

Choice of the optimal energy point



√s (GeV)	Δm_{top}	$\Delta \Gamma_{top}$	$\Delta \alpha_S$
342.75	9 MeV	343 MeV	0.00041
344.00	> 50 MeV	26 MeV	0.00047
343.50	15 MeV	40 MeV	0.00040

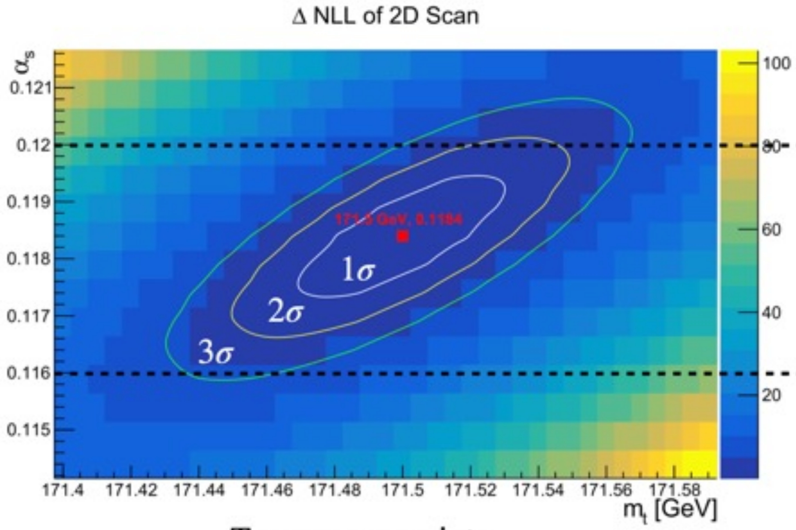
In the table, 342.75 GeV, 344.00 GeV and 343.50 GeV are optimal energy points for top quark mass, width and α_S, respectively

	Top mass uncertainties (MeV)	
	Optimistic	Conservative
Statistics	9	9
Theory	8	24
Quick scan	2	2
α_S	17	17
Width	10	10
Experimental efficiency	5	44
Background	2	14
Beam energy	2	2
Luminosity spectrum	3	6
Total	24	57

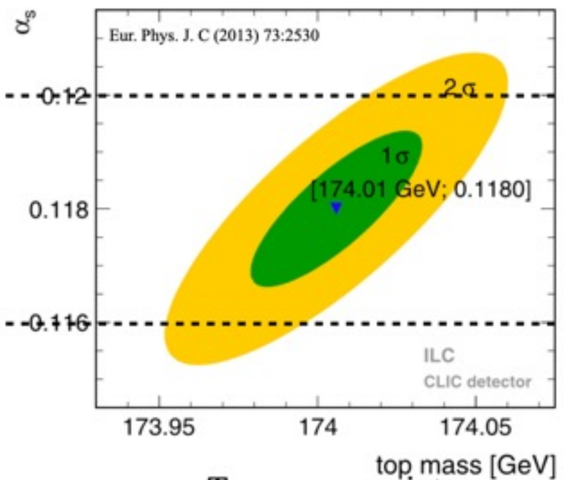
The top quark mass can be measured with an unprecedented precision (one order of magnitude better than hadron colliders can achieve) .

CEPC ttbar runs physics potential is competitive

Top mass Vs alpha_s likelihood

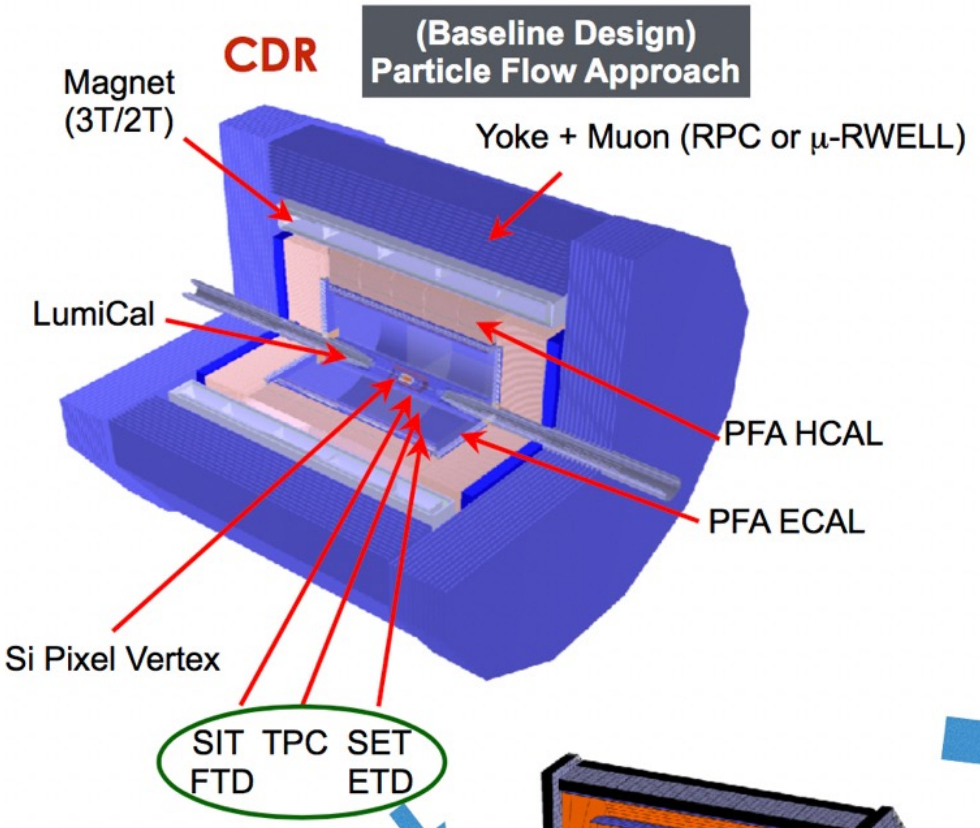


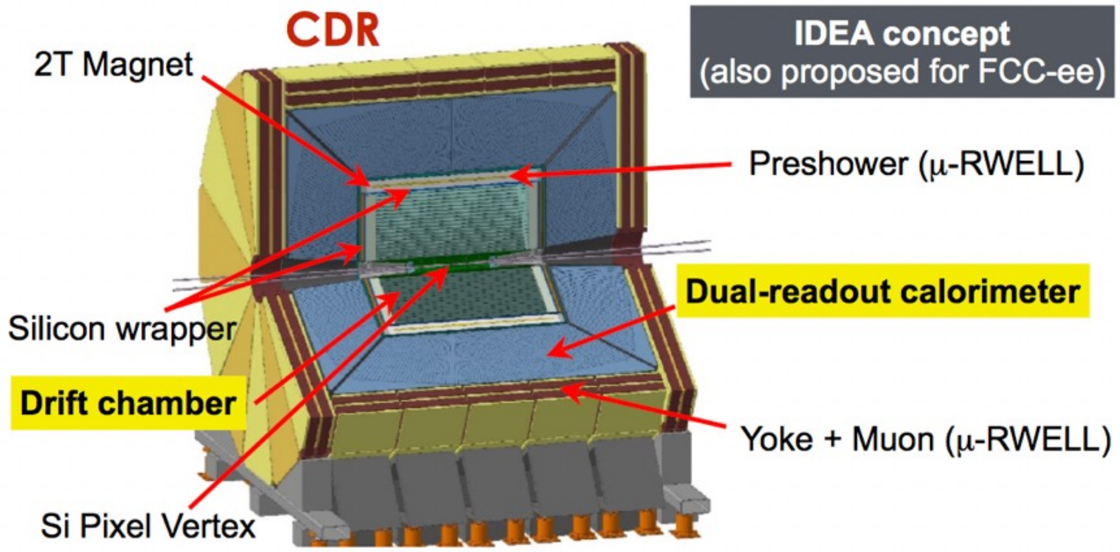
Two energy points

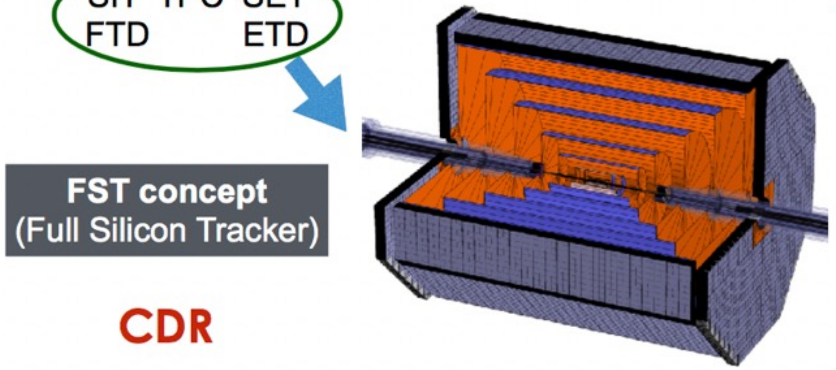


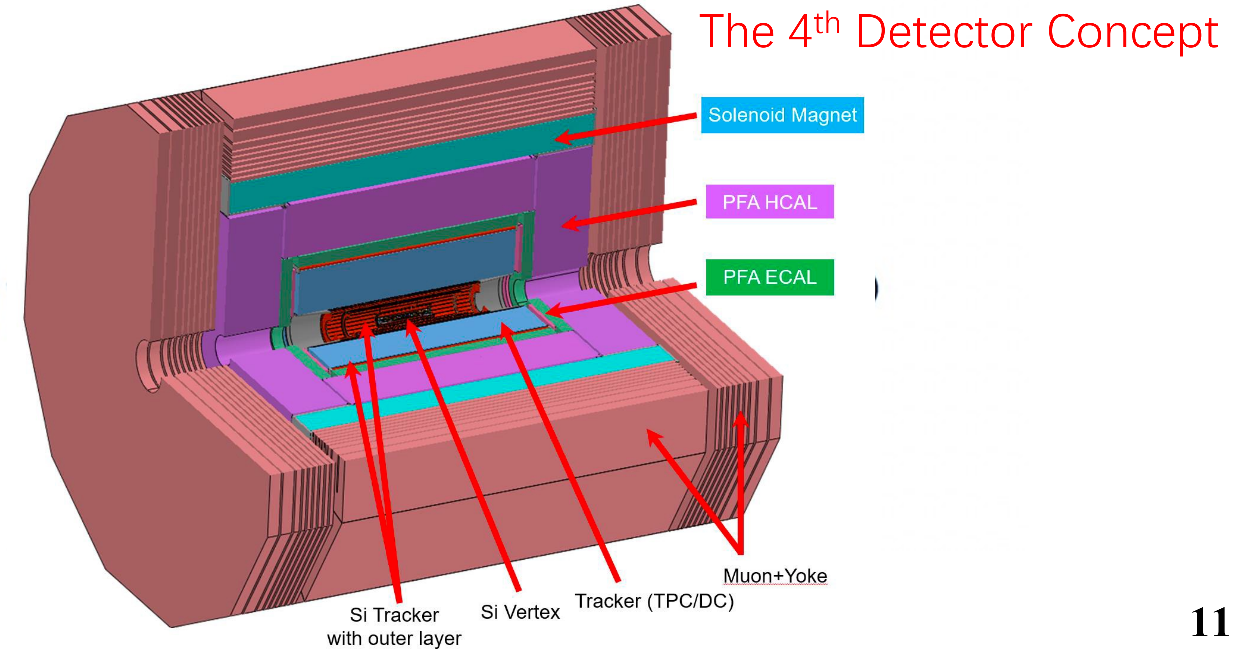
Ten energy points

CEPC Detector Conceptual Designs









The 4th Detector Concept

❖ **Silicon combined with TPC or DC and TOF**

→better tracking and PID

- Good k/pi separation up to 20GeV

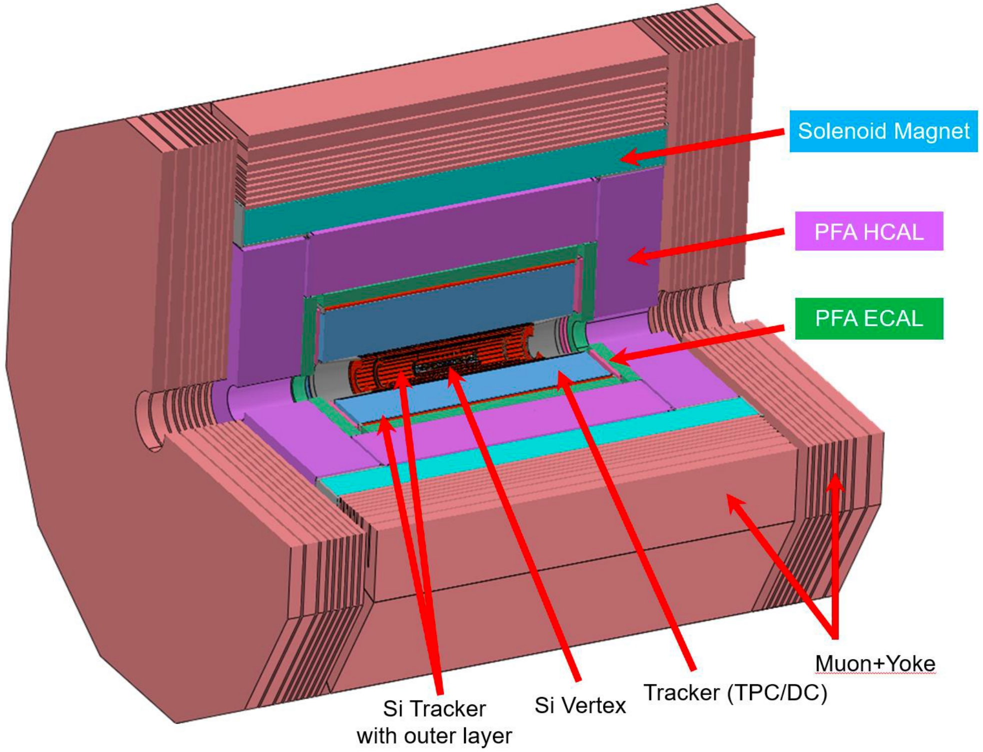
❖ **4D Crystal ECAL with timing**

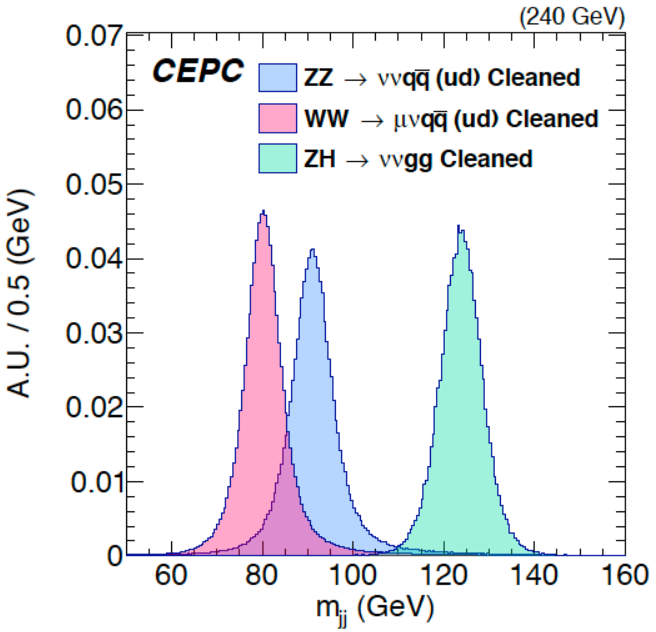
- For PFA and with better EM resolution

❖ **Scintillating glass HCAL:**

- Cost effective, better jet resolution

❖ **Boson mass resolution (BMR):4% → 3%**

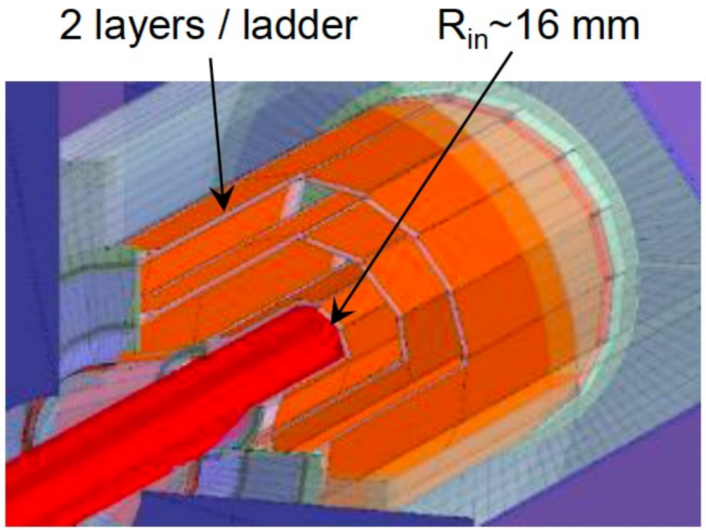




R&D for the baseline detector concept

- ❖ Silicon detector R & D (vertex, silicon tracker, LGAD TOF detector)
- ❖Gas detector (TPC, drift chamber)
- ❖PFA calorimetry : ECAL and HCAL
- ❖Solenoid Magnet

Silicon Pixel Chips for Vertex Detector



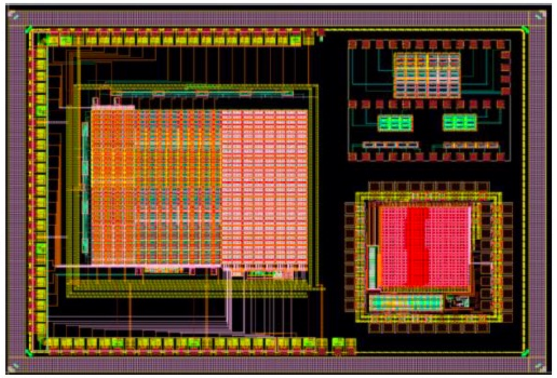
Goal: σ(IP) ~ 5 μm for high P track

CDR design specifications

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

Silicon pixel sensor develops in 5 series:
JadePix, TaichuPix, CPV, Arcadia, COFFEE

Develop **COFFEE** for a CEPC tracker using SMIC 55nm HV-CMOS process

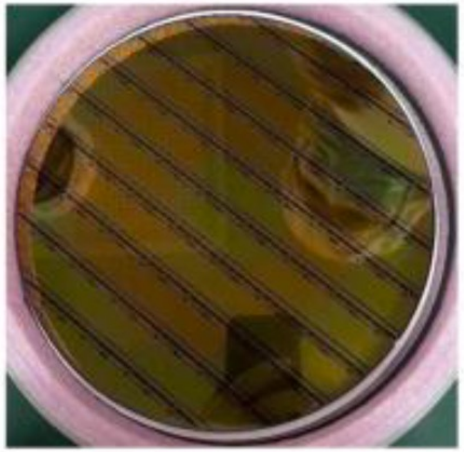


JadePix-3 Pixel size ~16×23 μm^2

Tower-Jazz 180nm CiS process
Resolution 5 microns, 53mW/cm^2

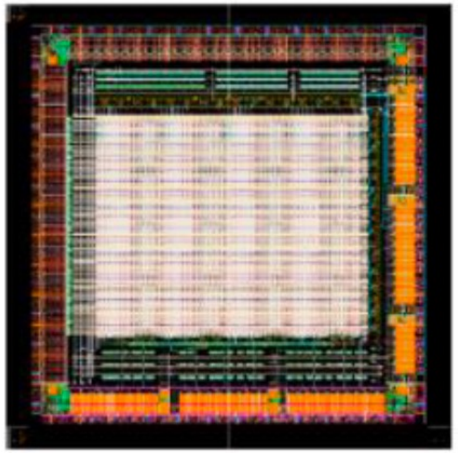
MOST 1

TaichuPix-3, FS 2.5x1.5 cm^2
25×25 μm^2 pixel size

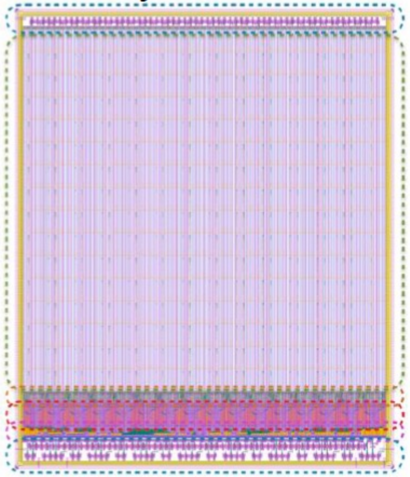


MOST 2

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

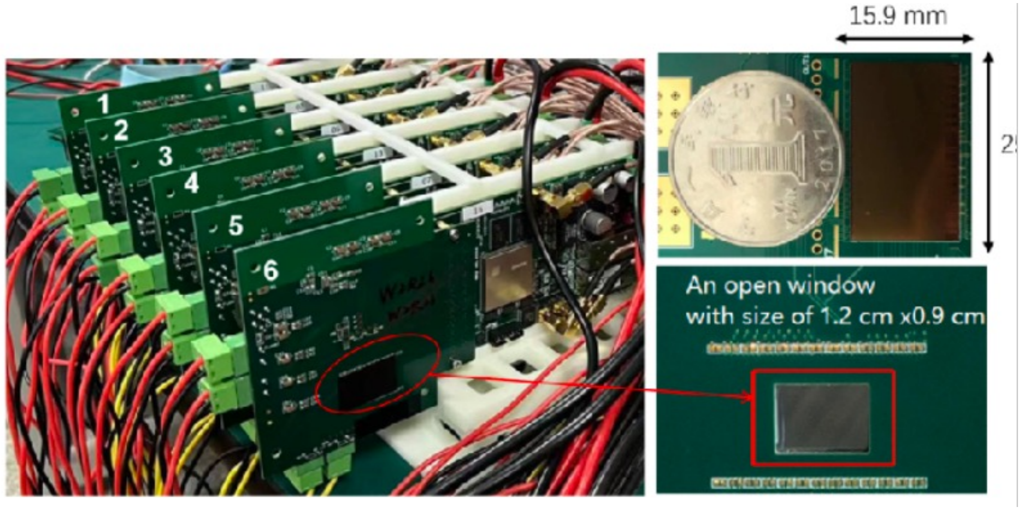


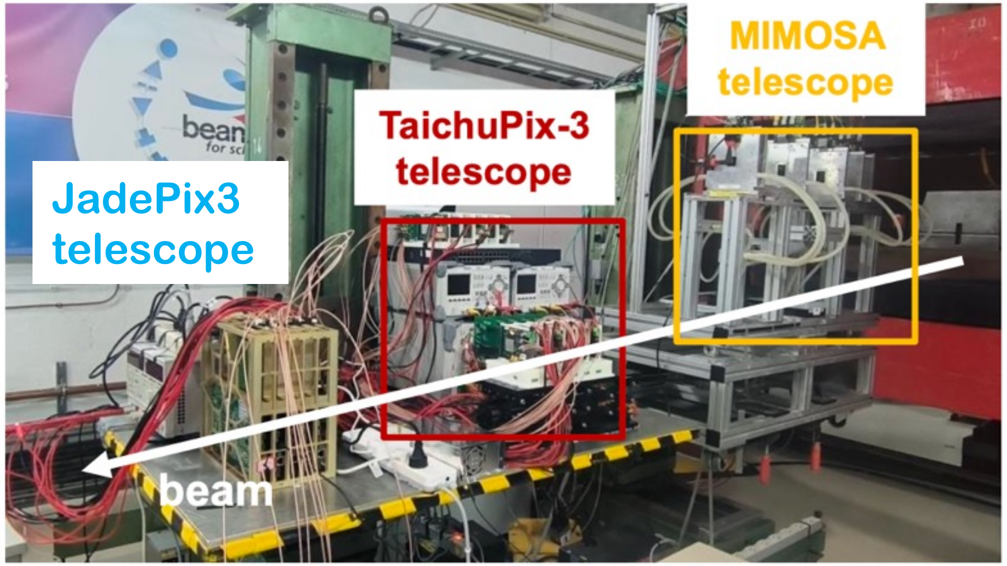
Arcadia by Italian groups for IDEA vertex detector
LFoundry 110 nm CMOS



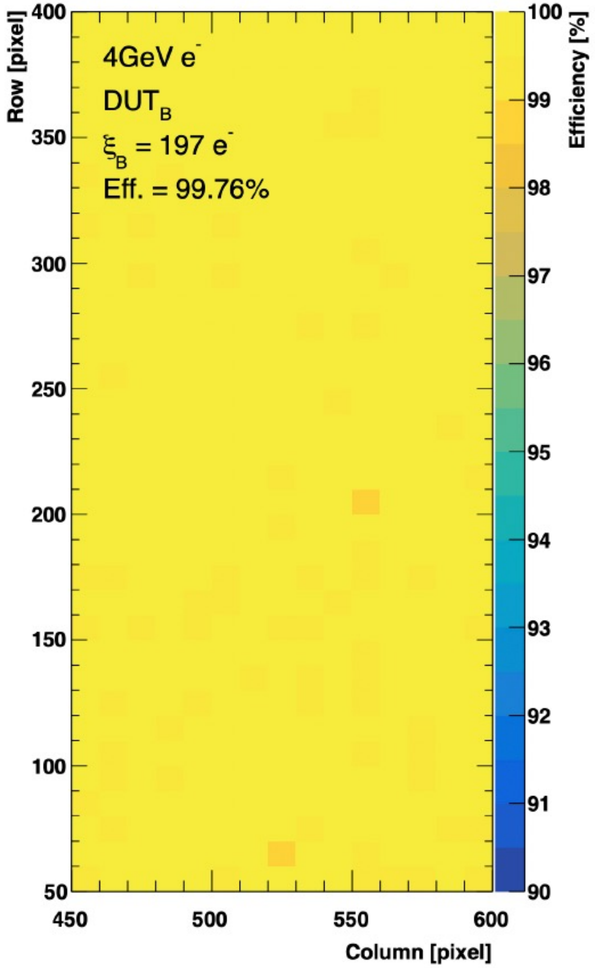
Jadepix3/TaichuPix3 beam test @ DESY

Spatial resolution 4~5um, Efficiency >99%

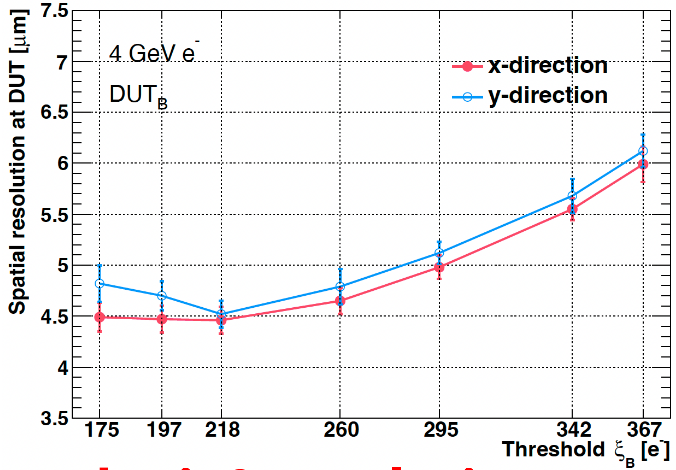




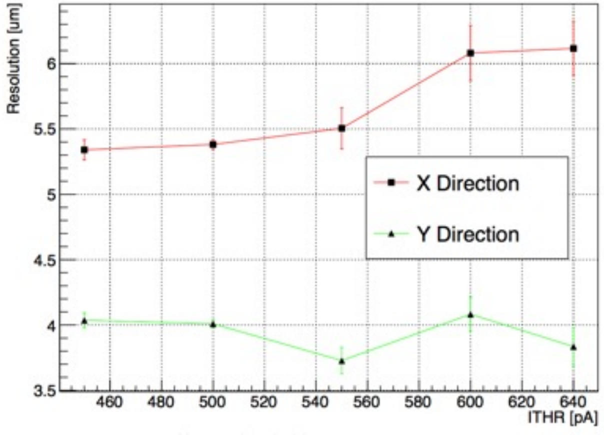
TaichuPix3 efficiency



TaichuPix3 resolution



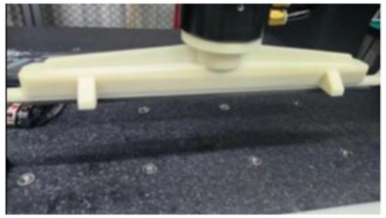
JadePix3 resolution



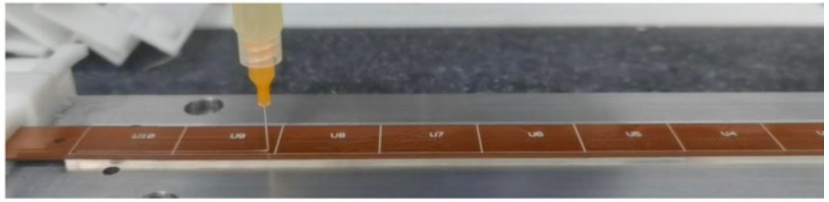
Collaboration with CNRS and IFAE in Jadepix/TaichuPix R & D

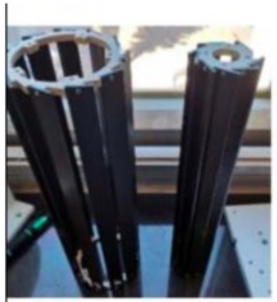
TaichuPix3 vertex detector prototype

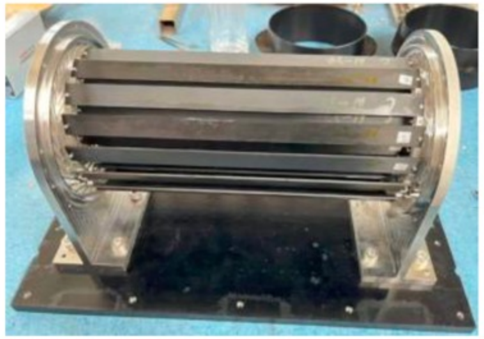
New pickup tools

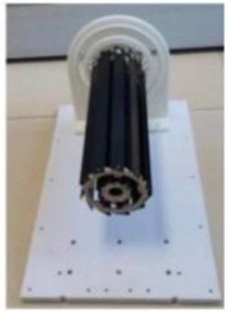


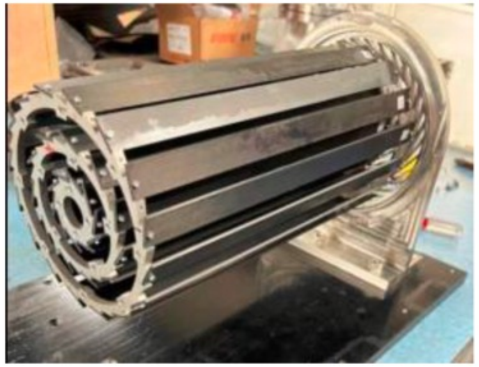
Dummy ladder glue automatic dispensing using gantry





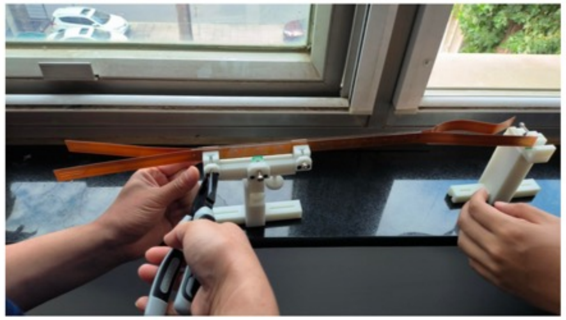






Ladder on wire bonding machine

Dummy Ladder on holder



The first vertex detector (prototype) ever built in China

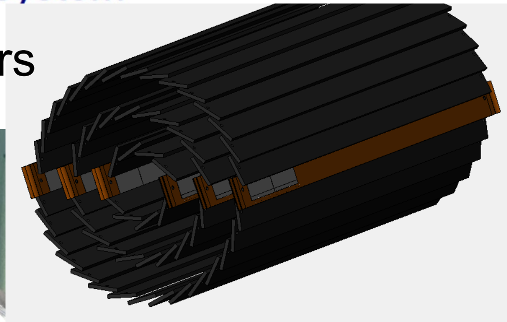
TaichuPix3 vertex detector prototype beam test @ DESY

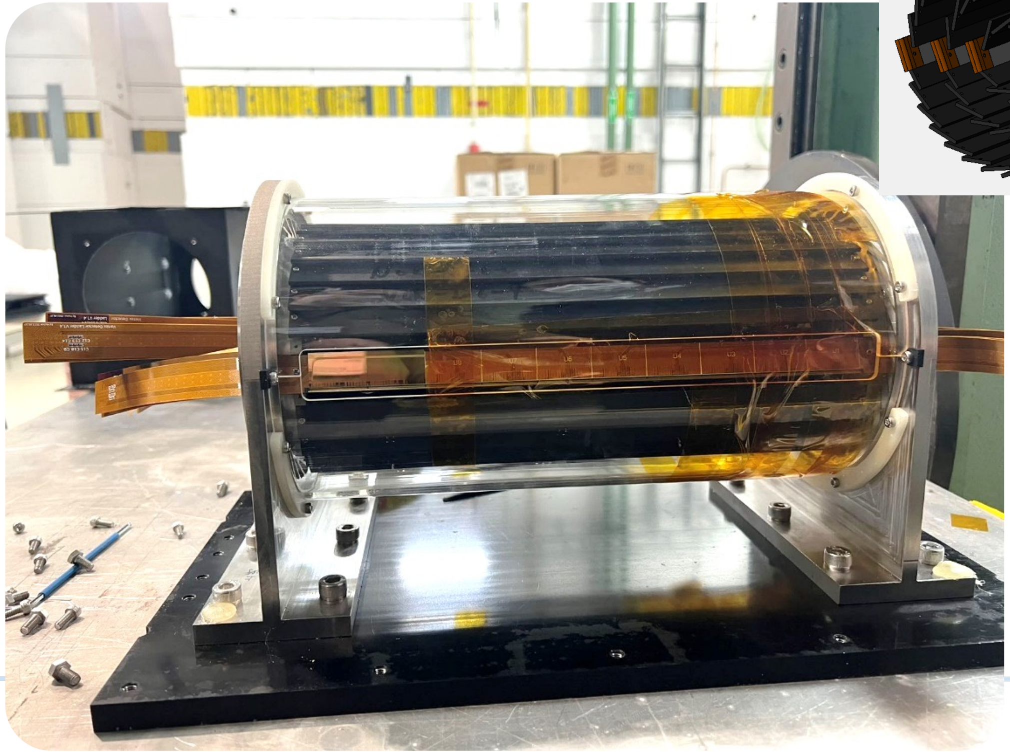
Ladder readout system

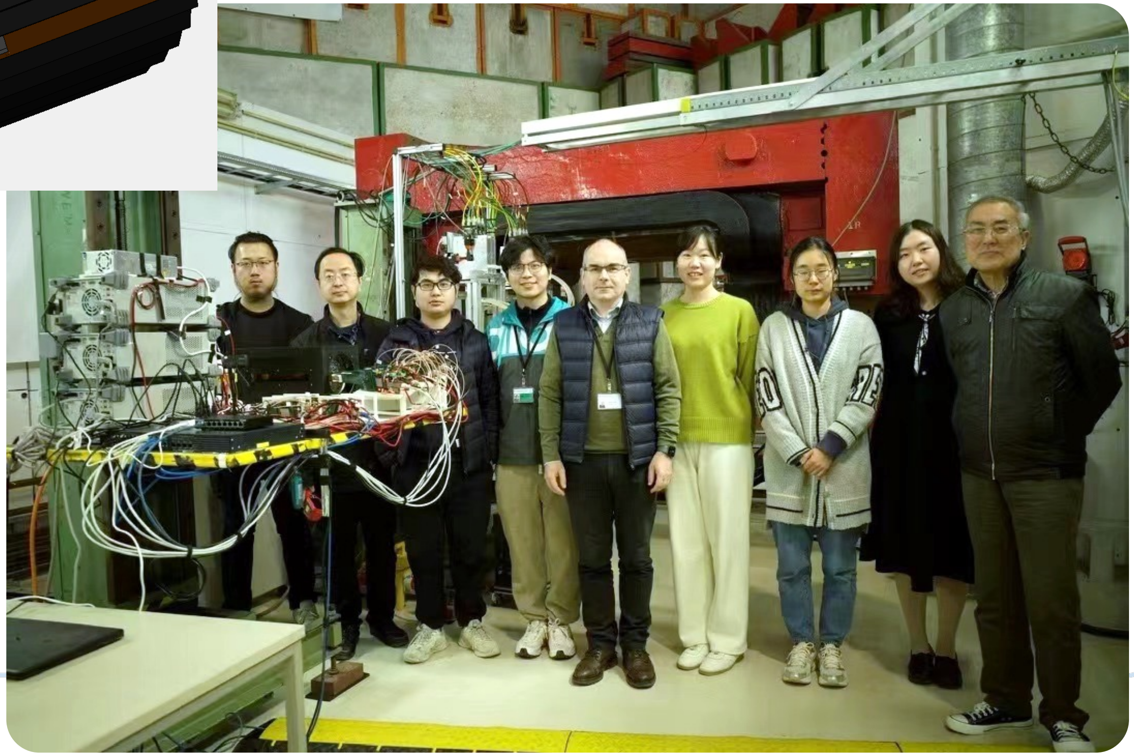
TaichuPix-based prototype detector tested at DESY in April 2023

Spatial resolution ~ **4.9 μm**

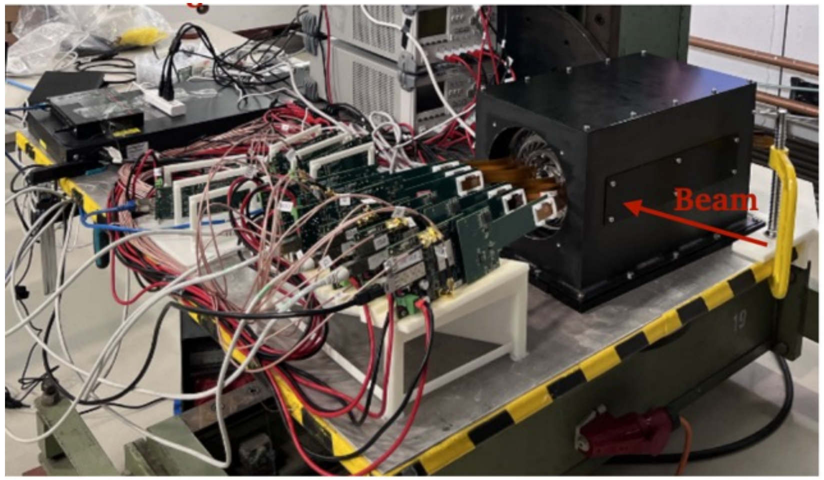
6 double-sided ladders

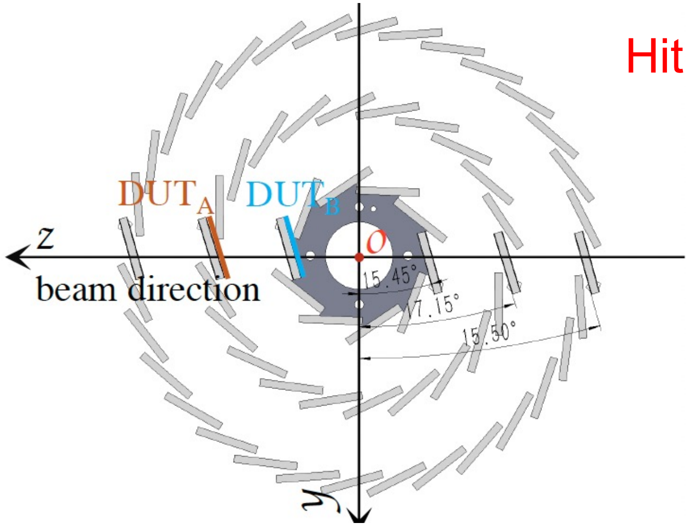






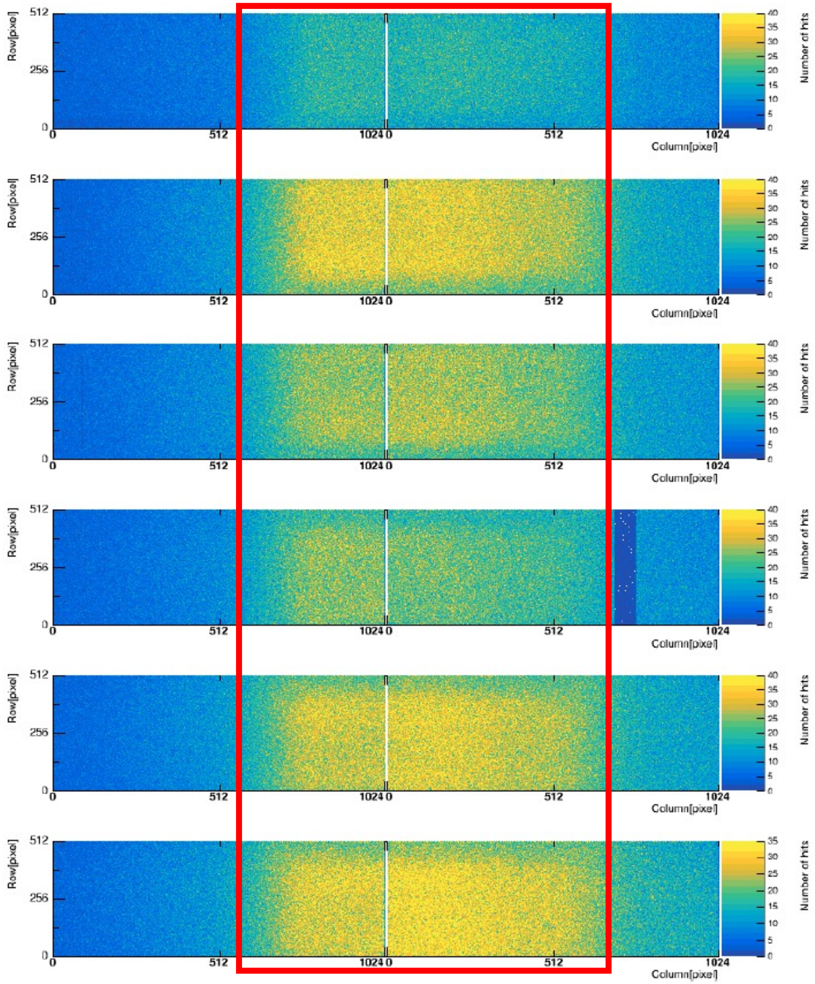
TaichuPix3 vertex detector prototype beam test @ DESY



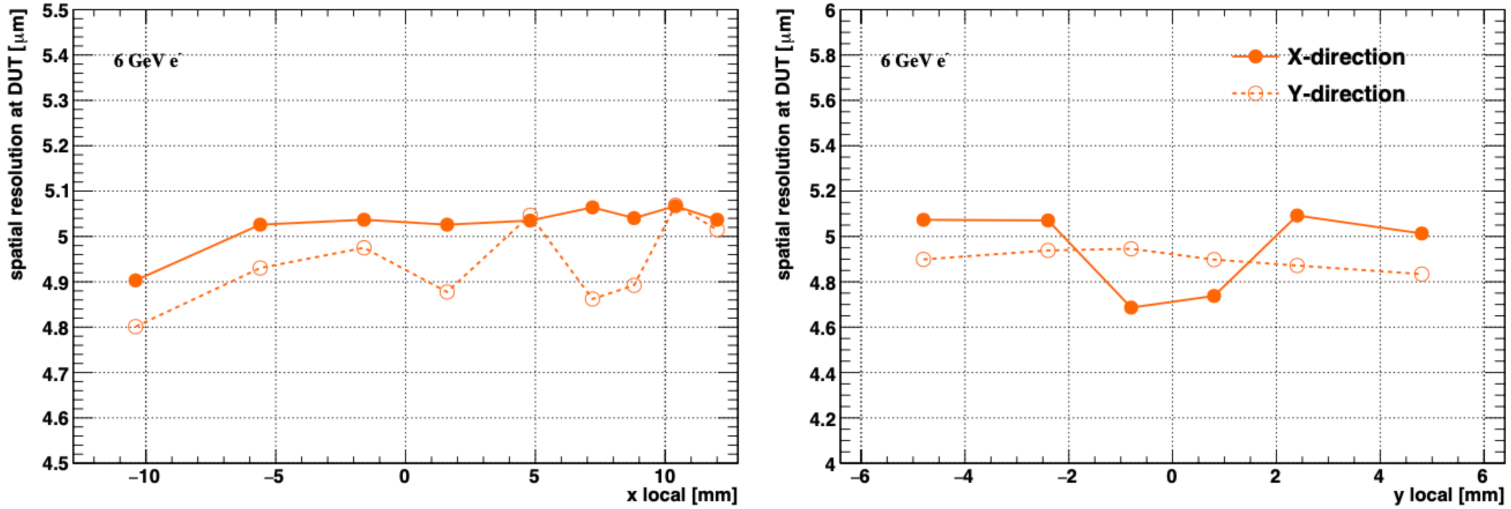


Hit maps of multiple layers of vertex detector

Beam spot

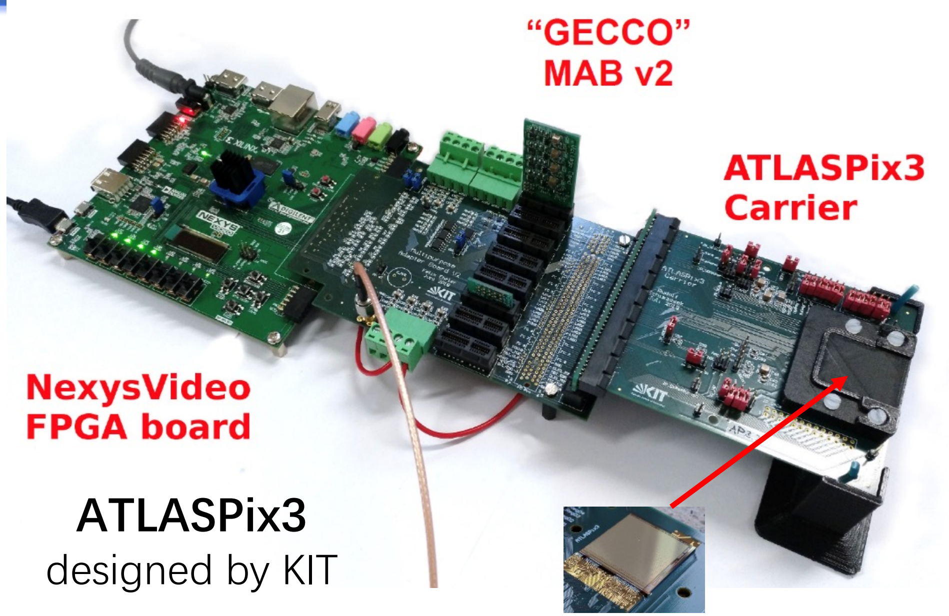


Spatial resolution ~ **5 μm**

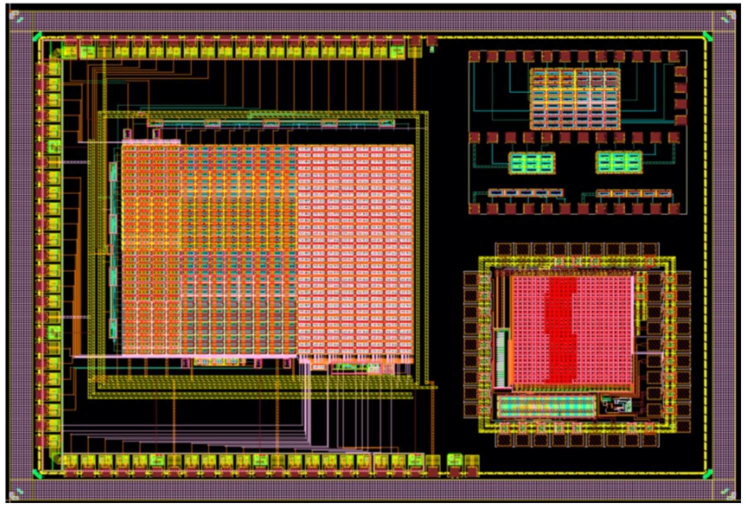


Silicon Tracker using HV-CMOS: ATLASPix → CEPCPix

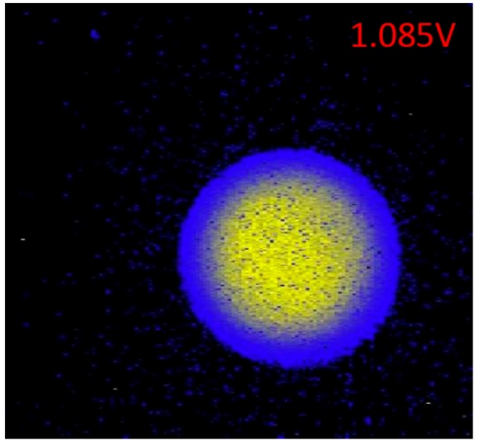
- ❑ Large area: **~70 m²** in TPC+SiTrk ➔ Cost effectiveness
- ❑ Focus on MAPS pixel tracker, also started SSD for outer layers
- ❑ Joint efforts on an ATLASPix3 based demonstrator
- ❑ ATLASPix & MightyPix use TSI 180nm HV process
- ❑ Exploring SMIC 55 nm HV HR proces
  - ➔ Smaller feature size & alternative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



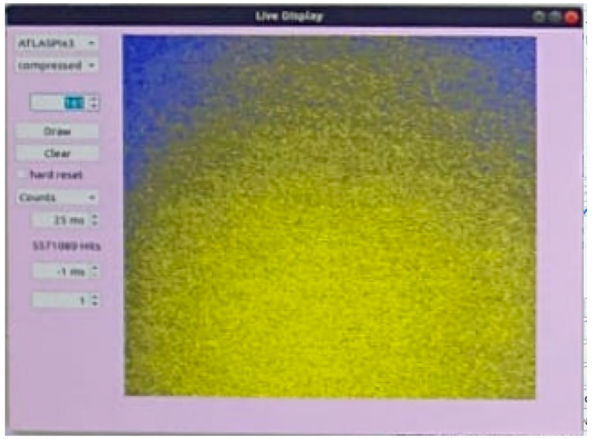
ATLASPix3
designed by KIT



The 2nd design for SMIC 55nm HV HR process



Hitmap with Fe55 source



Hitmap with electron beam

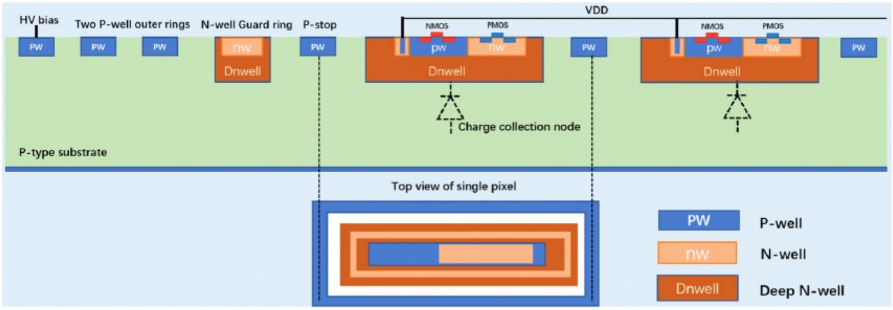
Collaboration with UK/Germany/Italy colleague

Silicon Tracker using HV-CMOS: the SMIC 55nm chips

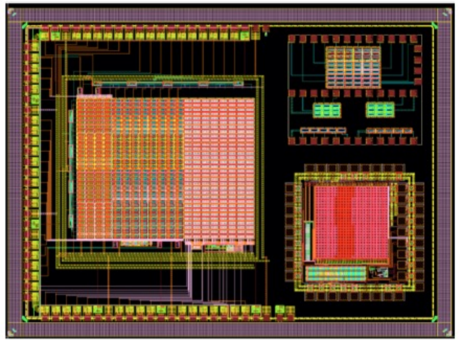
❖ MPW SMIC 55nm HVCMOS （COFFEE2 chip)

- CMOS SENOSR IN FIFTY-FIVE NM PROCESS (COFFEE)
- Submitted in Aug 2023, Received at the end of 2023.
- High-res wafer of 1k or 2k Ωcm available
- Breakdown voltage up to – 70V (enough depleted depth)

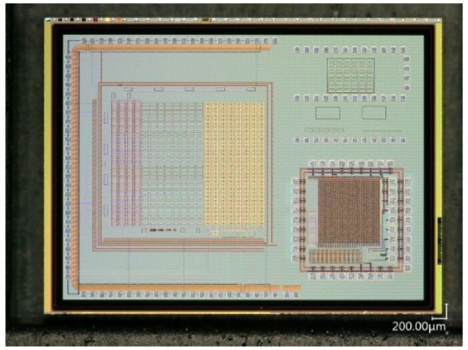
Cross-section of pixel strucure



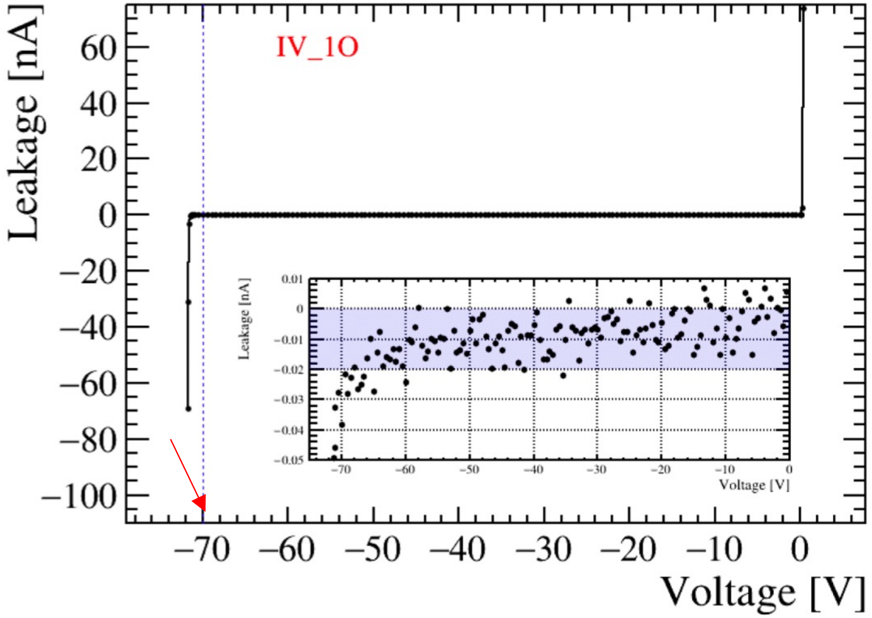
COFFEE2 floorplan



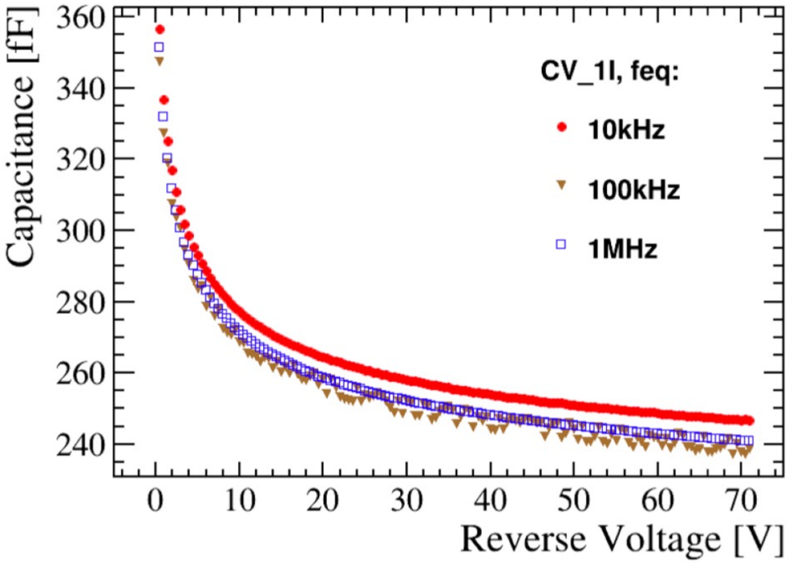
COFFEE2 photo



IV test



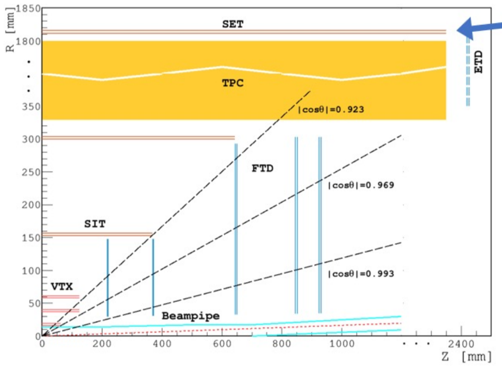
CV test
1 single Pixel



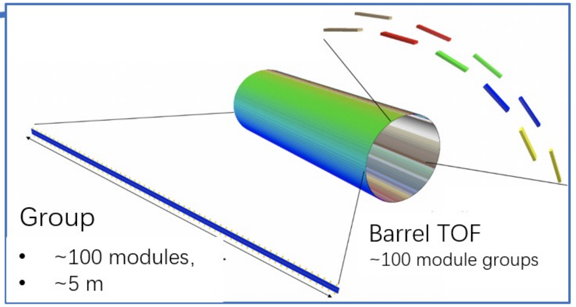
Time of flight detector

- **A new type of TOF detector for CEPC is under R & D**
  - Based on Low Gain Avalanche Detector (LGAD) technology
  - Synergy with ATLAS high granularity timing detector
  - Aim to have good time and spatial resolution(50ps and 10um)

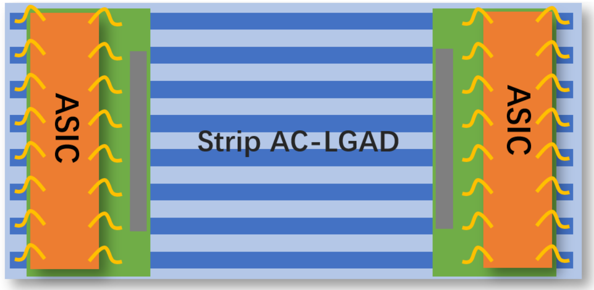
Baseline detector concept in CDR



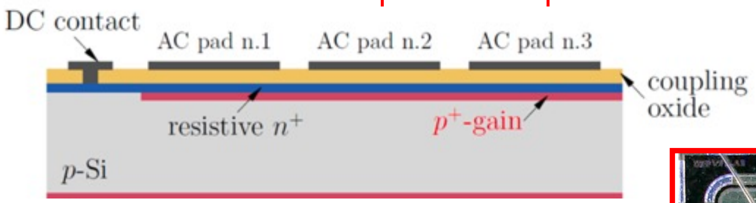
LGAD timing detector in Barrel region

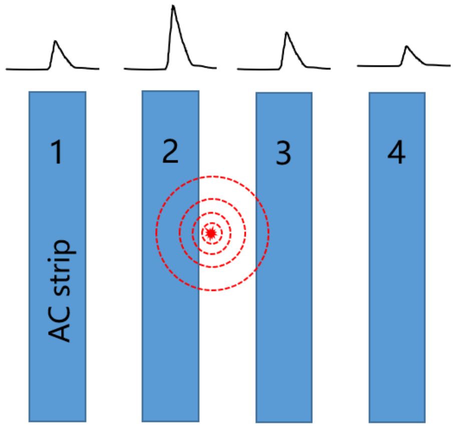


Strip LGAD module



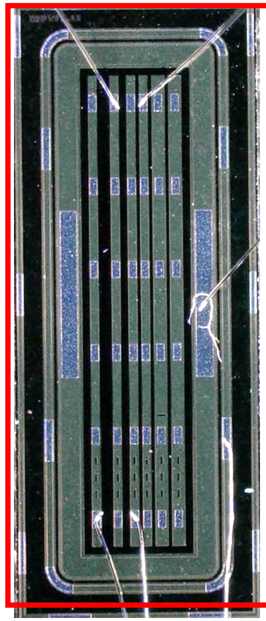
AC-coupled strip LGAD



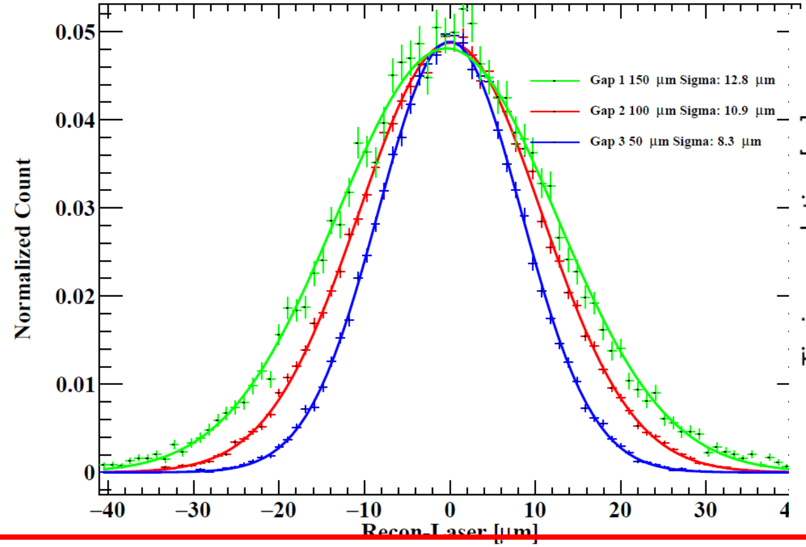


More details in Mei's talk in detector section

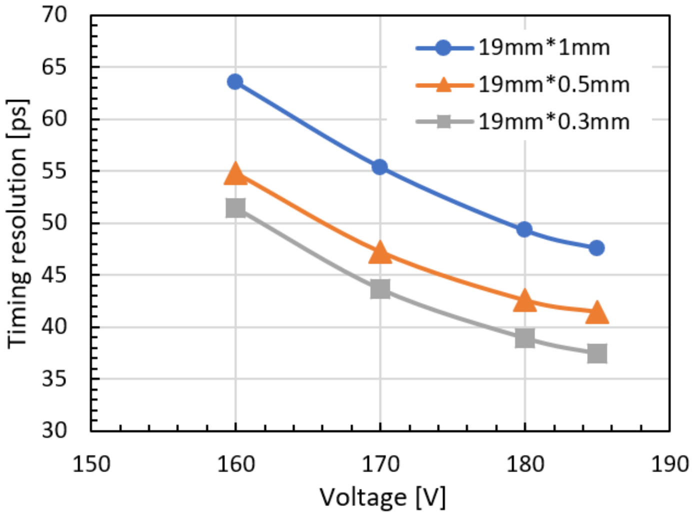
LGAD based strip silicon sensor prototype by IHEP



Spatial resolution (~10um)



Time resolution (30-50ps)



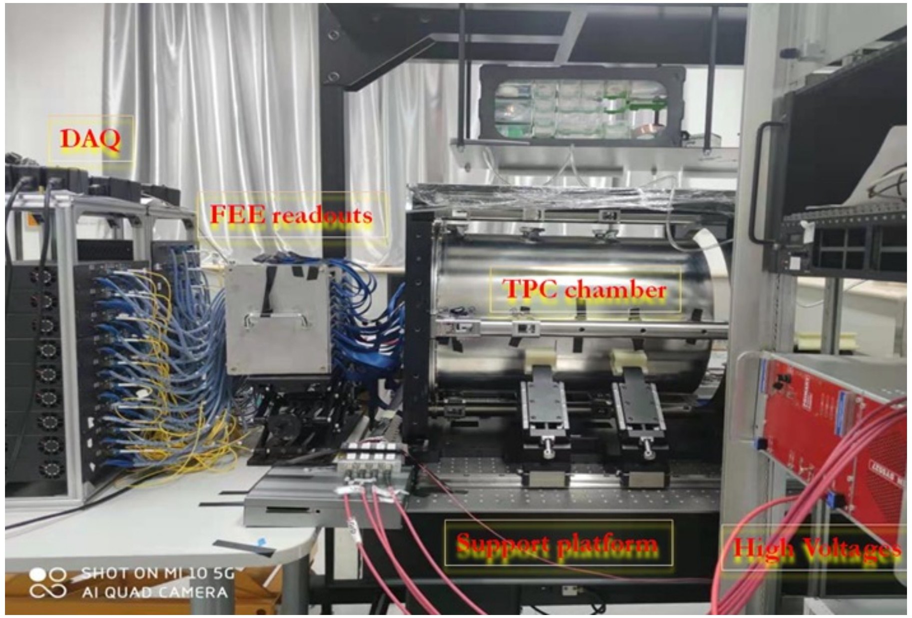
R&D for the baseline detector concept

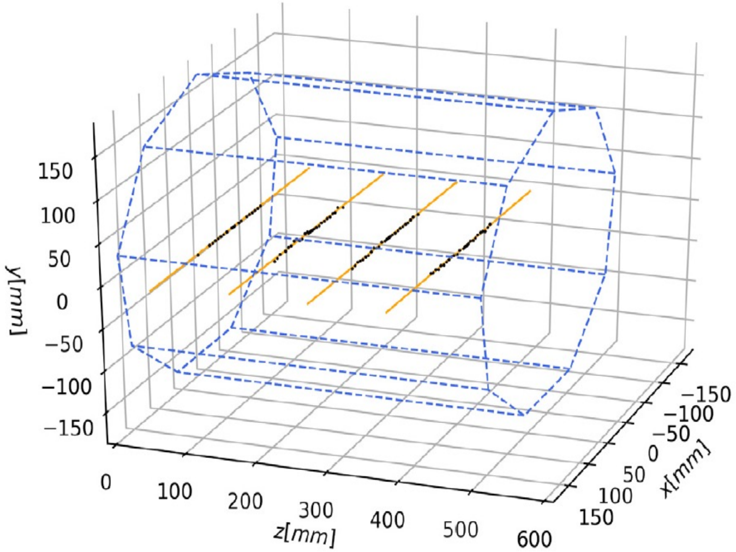
- ❖ Silicon detector R & D (vertex, silicon tracker, LGAD TOF detector)
- ❖Gas detector (TPC, drift chamber)
- ❖PFA calorimetry : ECAL and HCAL
- ❖Solenoid Magnet

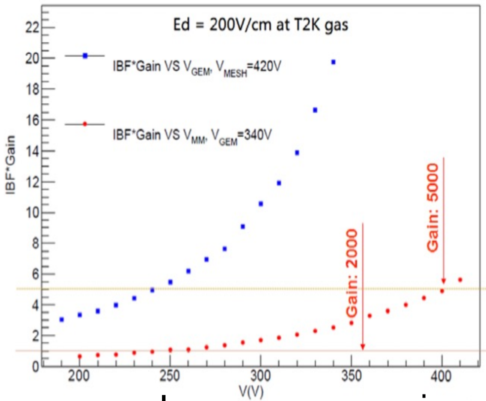
Roadmap of CEPC TPC detector R&D

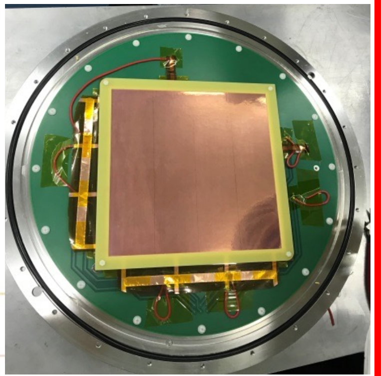
- **CEPC TPC detector prototyping roadmap:**
  - From TPC module to TPC prototype R&D for Higgs and Tera-Z
  - Easy-to-install modular design of **Pixelated readout TPC for CEPC TDR**
- **Achievement by far:**
  - Supression ions hybrid GEM+Micromegas module
    - IBF×Gain **~1 @ G=2000** validation with hybrid TPC module
  - Spatial resolution of **$\sigma_{r\varphi} \leq 100\ \mu m$** and dE/dx resolution of 3.6%
  - FEE chip: reach **~3.0mW/ch** with ADC and the pixelated readout R&D

TPC prototype with integrated 266nm UV laser

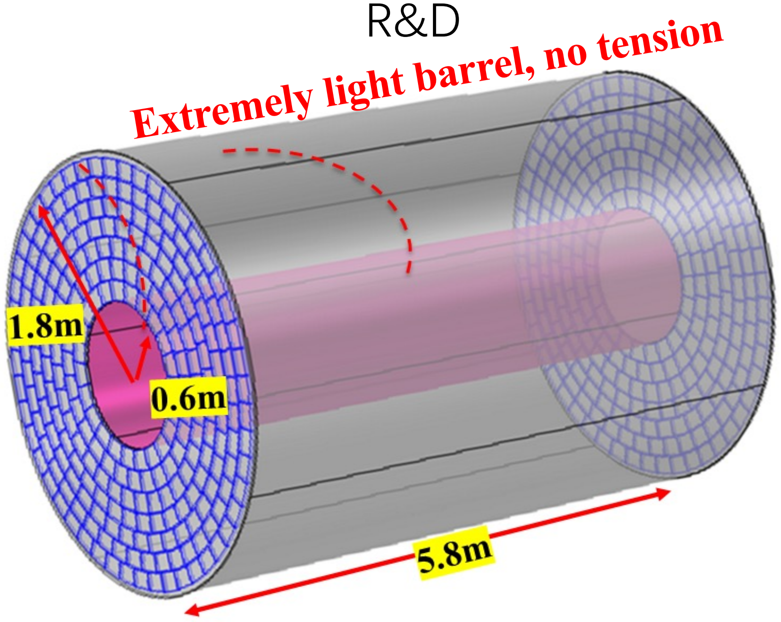








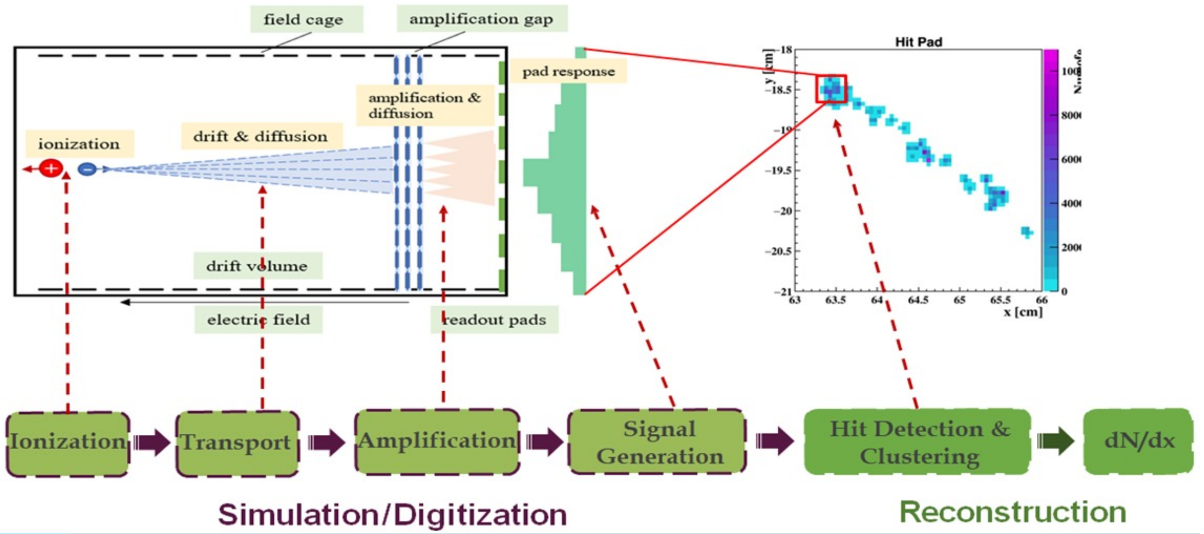
Ion suppression TPC module R&D



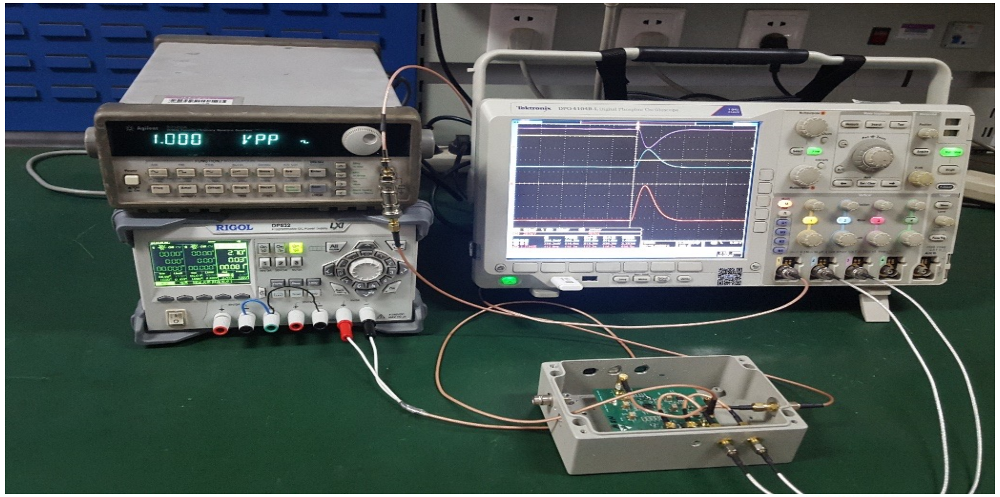
TPC for CEPC reference TDR

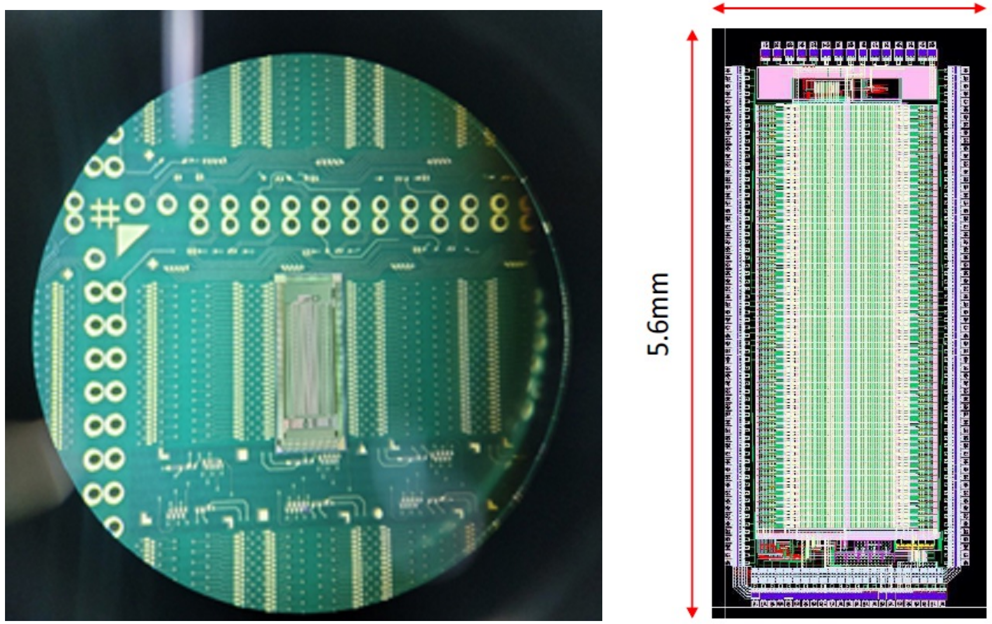
Status of Pixelated readout TPC for CEPC TDR

- **Simulation and R&D of Pixelated TPC readout for CEPC TDR**
  - Macro-Pixel TPC ASIC chip was started to developed and 2nd prototype wafer has done and tested
    - 500μm×500μm pixel readout designed
    - Noise of FEE: 100e
    - Time resolution: 14bit (5ns bin)
    - Power consumption: ~100mW/cm2 (2nd prototype)
- **Prototyping pixelated TPC detector at IHEP**
  - Principle of the prototype is no problem for testing
  - Developed prototype and aim for beam test @ DESY in 2024 with LCTPC collaboration



Framework of simulation at IHEP



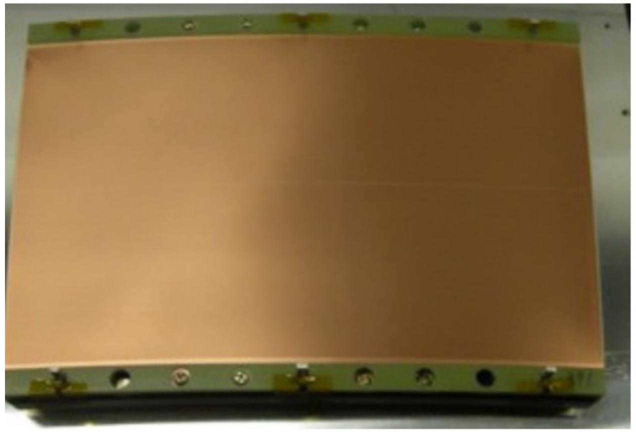


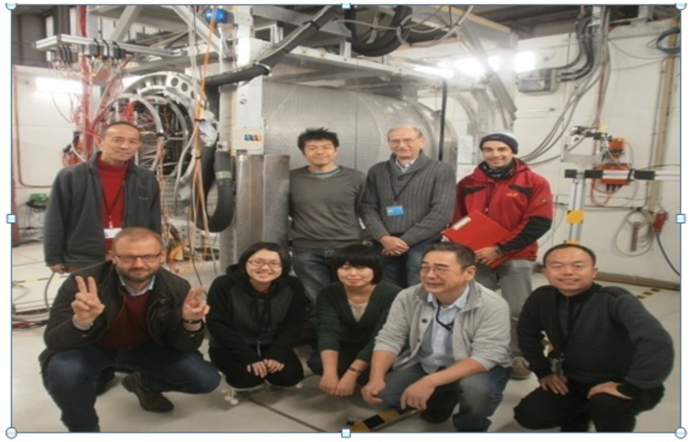
FEE ASIC chip R&D

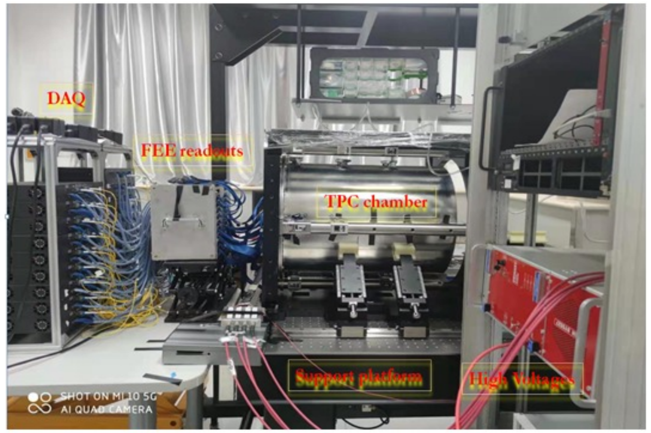
Activity international collaboration - TPC technology R&D

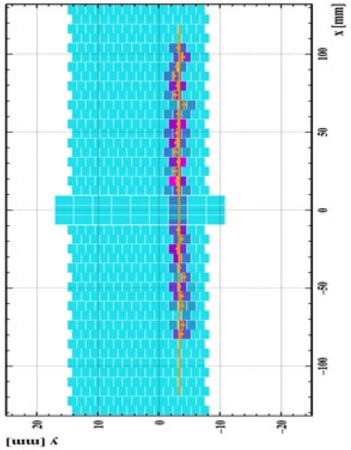
- Activity collaboration: Pixelated readout and Pad readout from IHEP and LCTPC collaboration
  - Large Prototype setup have been built to compare different detector readouts for Tera-Z
  - PCMAG: B < 1.0T, bore Ø: 85cm, Spatial resolution of $\sigma_{r\phi} \leq 100$ μm
  - Collaboration implement improvements in **a pixelated readout TPC for CEPC TDR**

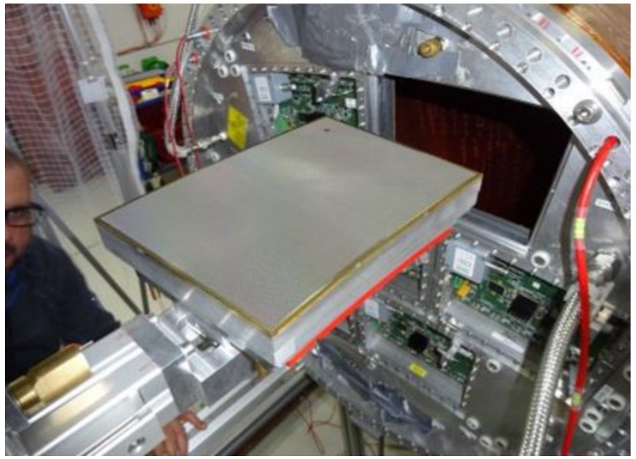
ArXiv. (2023)2006.08562
NIM A (2022) 167241
ArXiv (2022)2006.085
JINST 16 (2021) P10023
JINST 5 (2010) P10011
NIM A608 (2009) 390-396

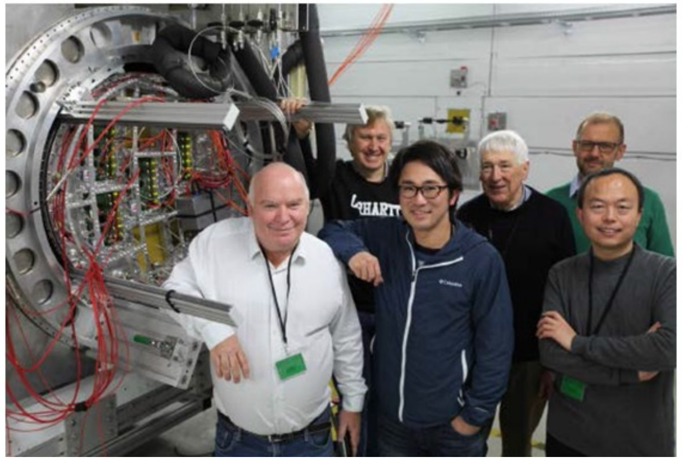


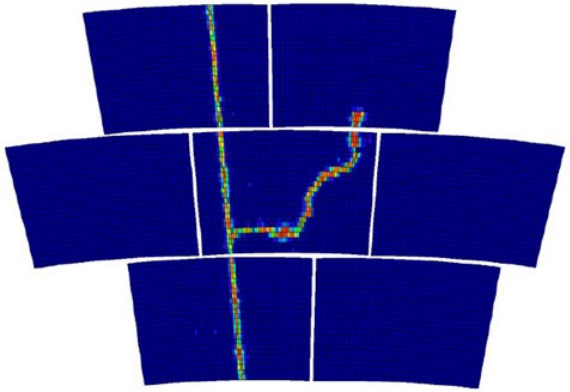




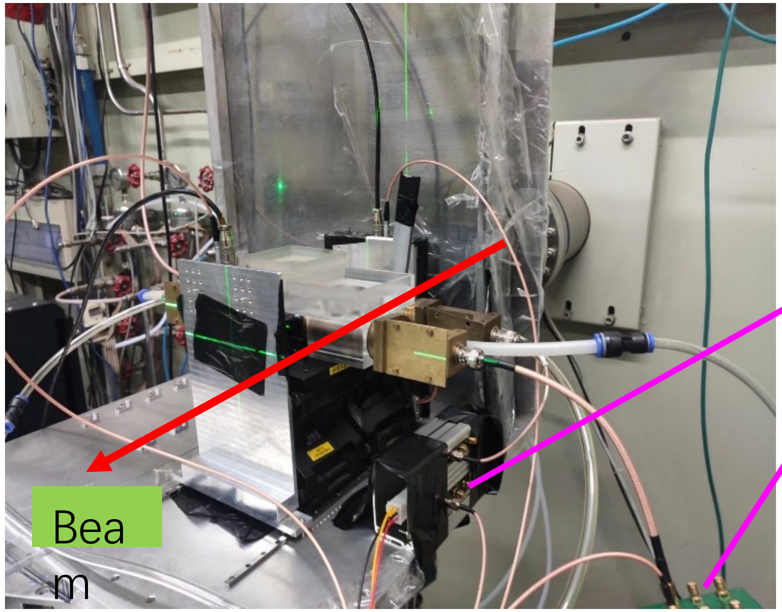


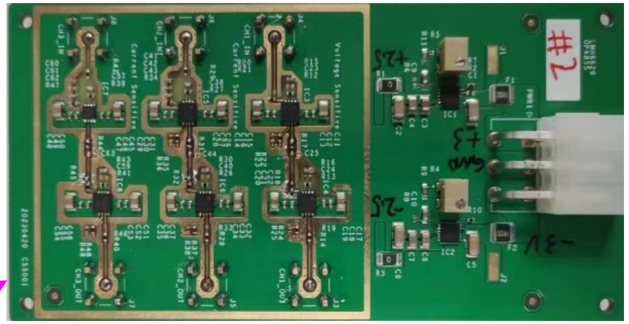


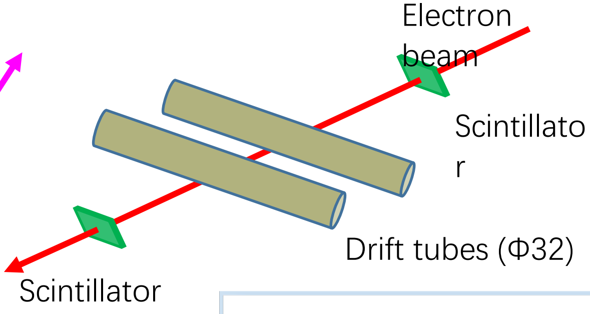


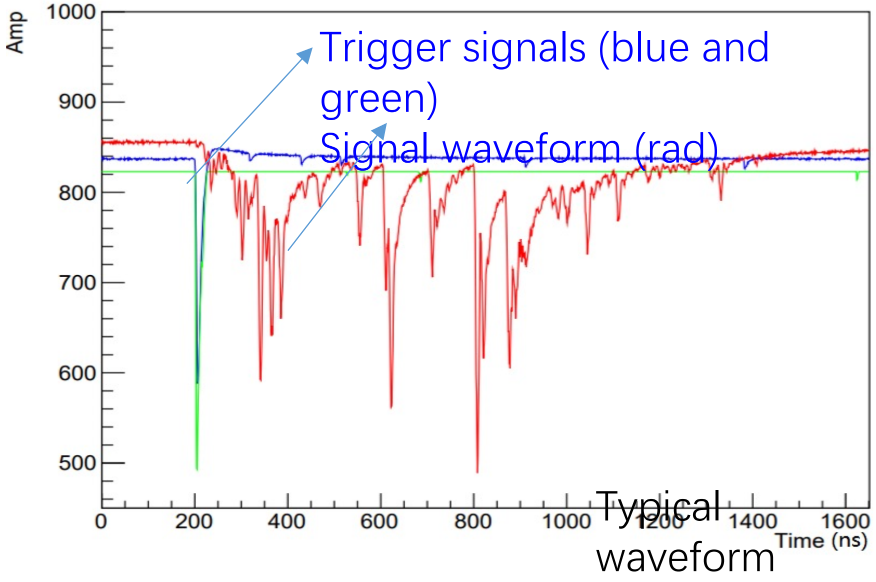


Drift chamber R&D and beam test



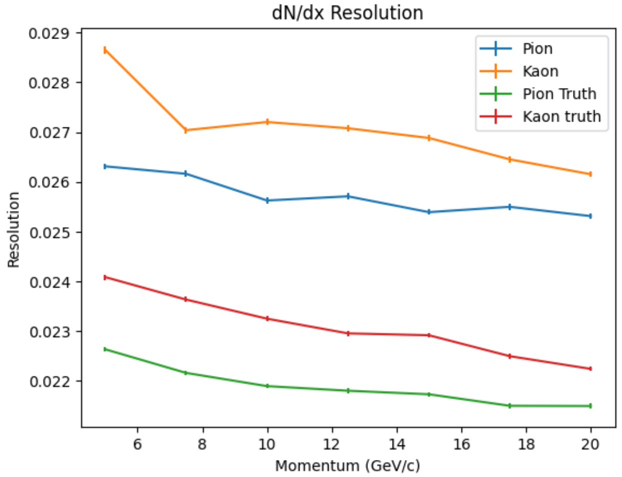




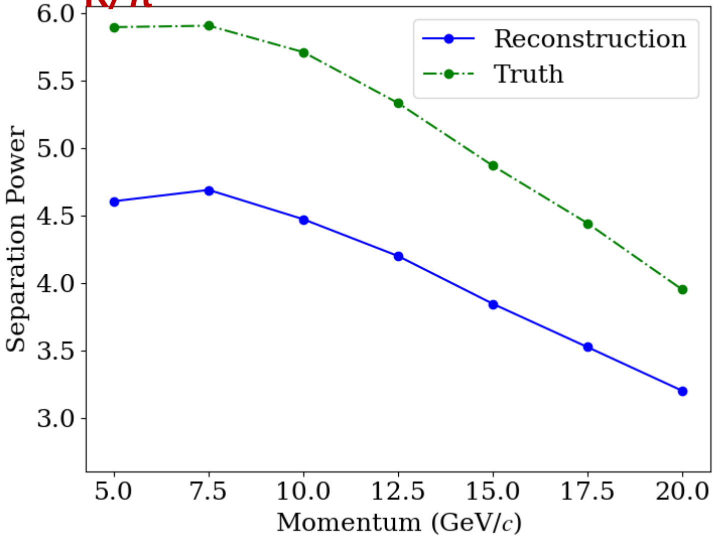


- Two drift tubes + preamps + ADC (1GHz)
- Two scintillators provide trigger signals
- Tested with electron beam at IHEP
- Clear peaks, low noise, ~ ns rise time

dN/dx resolution: ~2.5% for pion

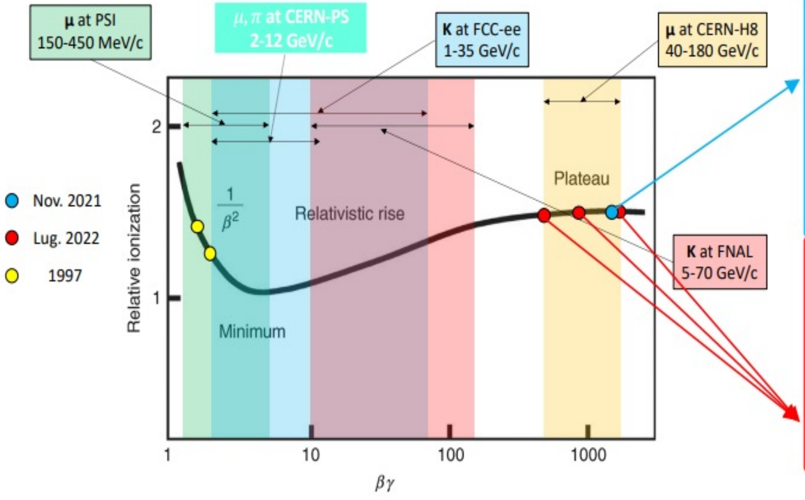


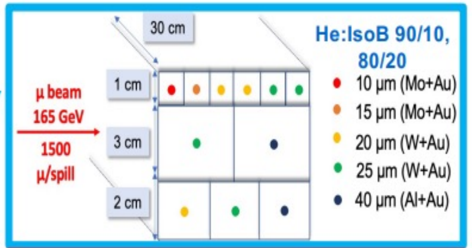
Separation: 3.2σ for 20 GeV/c K/π

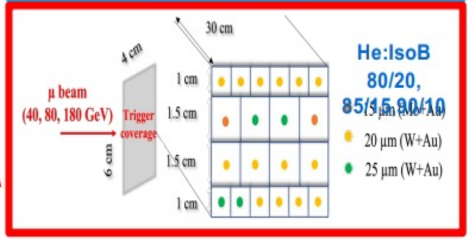


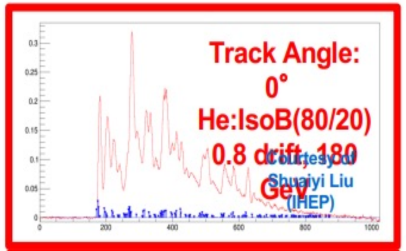
Drift chamber R&D, Synergy with IDEA

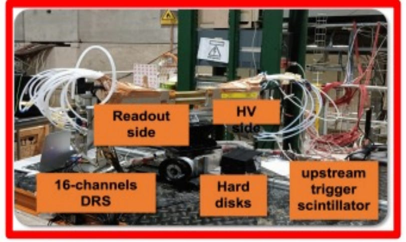
- **Beam tests organized by INFN group:**
  - Two muon beam tests performed at CERN-H8 (βγ > 400) in Nov. 2021 and July 2022
  - A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN
  - Ultimate test at FNAL-MT6 in 2024 with π and K (Bγ = 10-140) to fully exploit the relativistic rise.
- **Contributions from IHEP group:**
  - Participate data taking and collaboratively analyze the test beam data
  - Develop the machine learning reconstruction algorithm

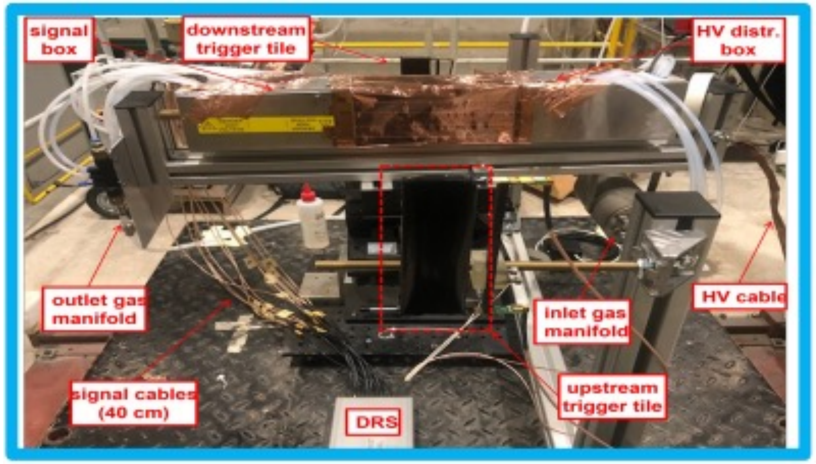










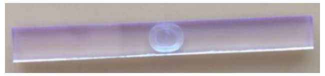


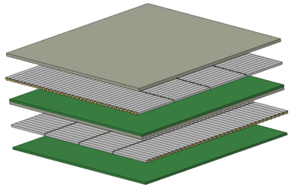
R&D for the baseline detector concept

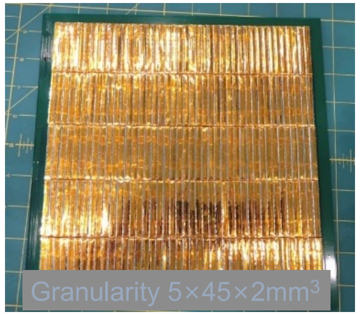
- ❖ Silicon detector R & D (vertex, silicon tracker, LGAD TOF detector)
- ❖Gas detector (TPC, Drift chamber)
- ❖PFA calorimetry : ECAL and HCAL
- ❖Solenoid Magnet

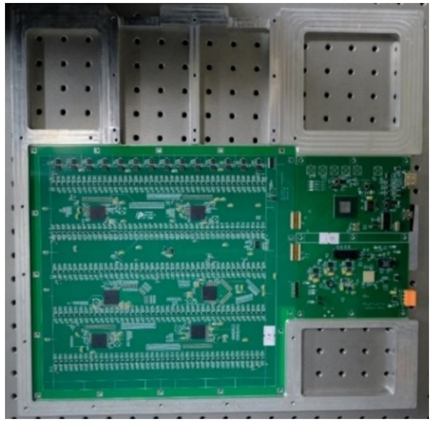
High granularity Sci-W ECAL and Sci-Fe HCAL (AHCAL)

ECAL: scintillator(strip)+SiPM, CuW

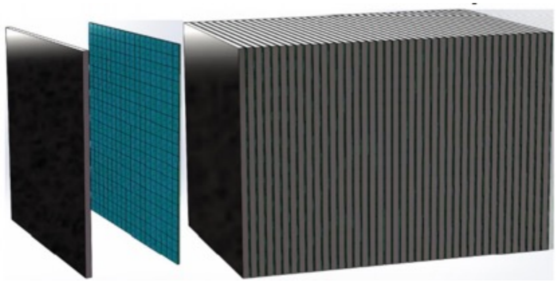


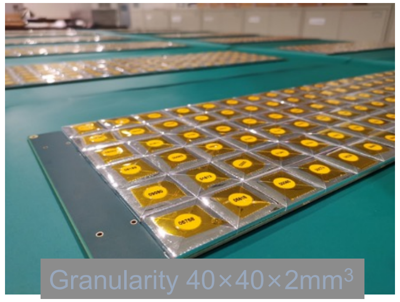


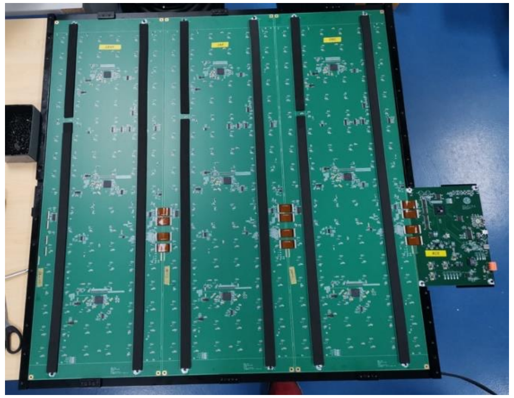




HCAL: scintillator (tile)+SiPM, steel







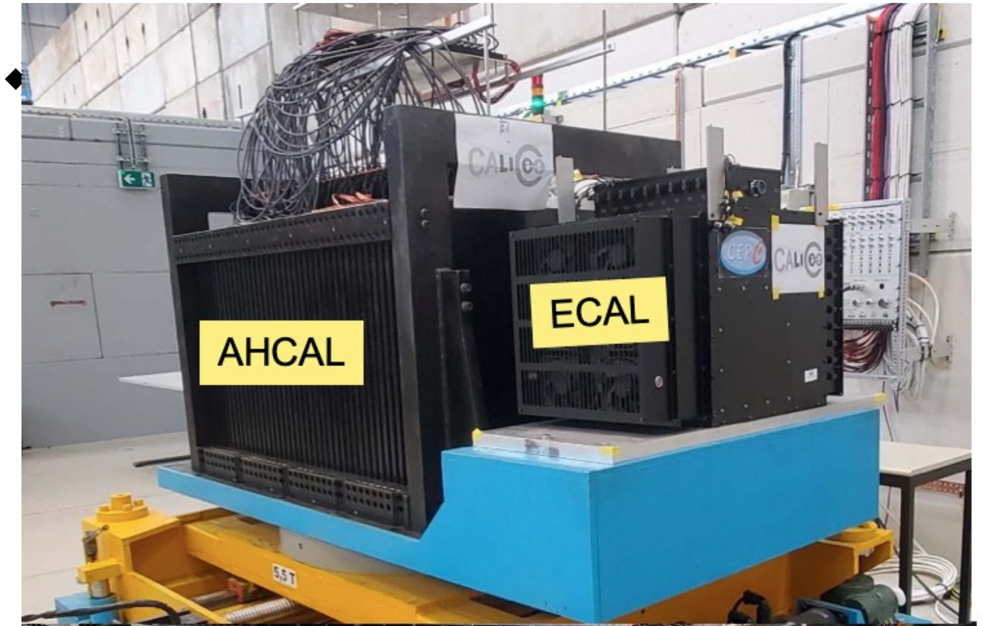
- ScW-ECAL: transverse ~20×20 cm, 32 sampling layers
  - ~6,700 channels, SPIROC2E (192 chips)
- AHCAL: transverse 72×72 cm, 40 sampling layers
  - ~13k channels, SPIROC2E (360 chips)

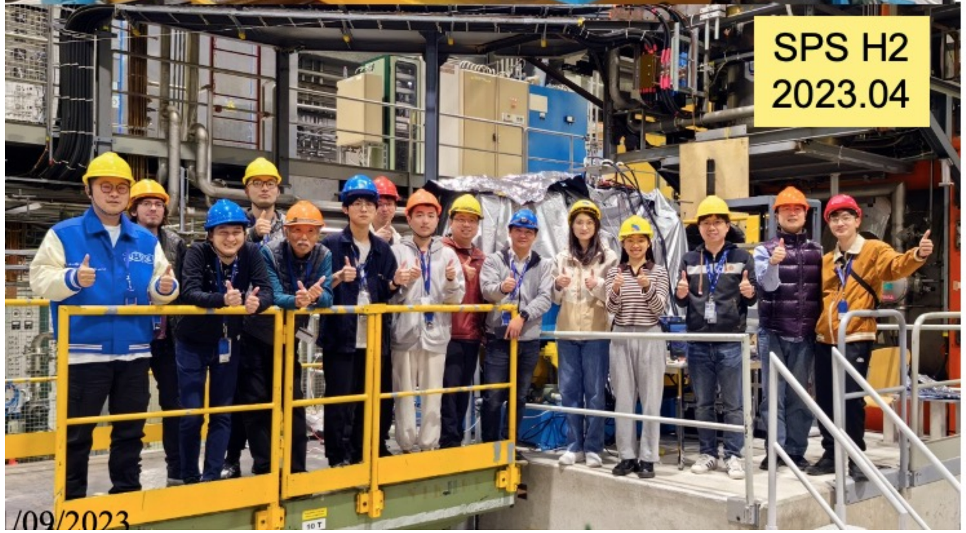
Prototypes R & D Collaboration with **CALICE**

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

Testbeam of Prototype PFA Calorimeters

◆



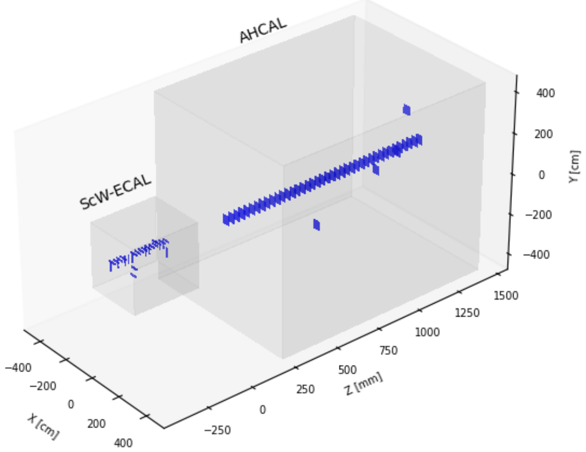


/09/2023

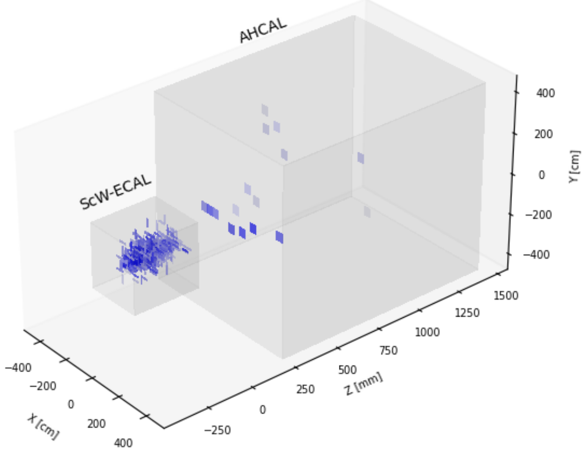
Display of hadronic showers : display of the imaging power

- **The calorimeter system is able to contain high energy hadronic showers and record their details.**

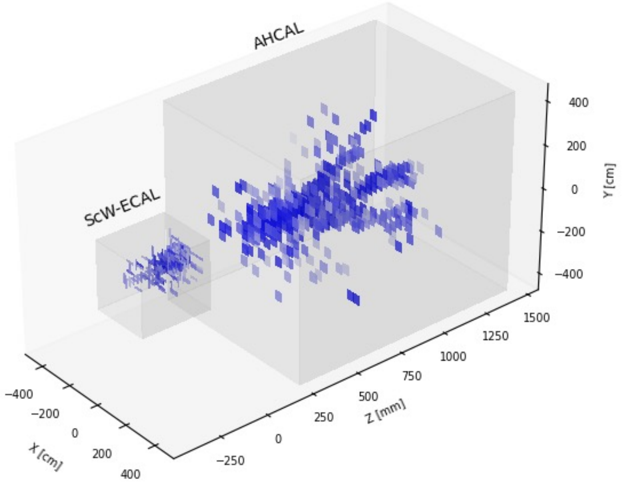
100 GeV μ^-



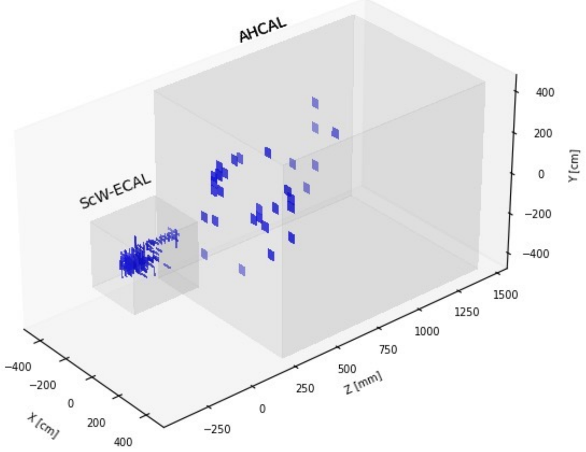
60 GeV e



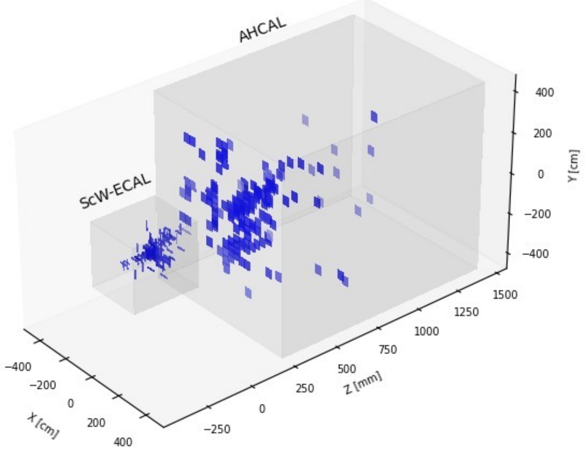
60 GeV π^-

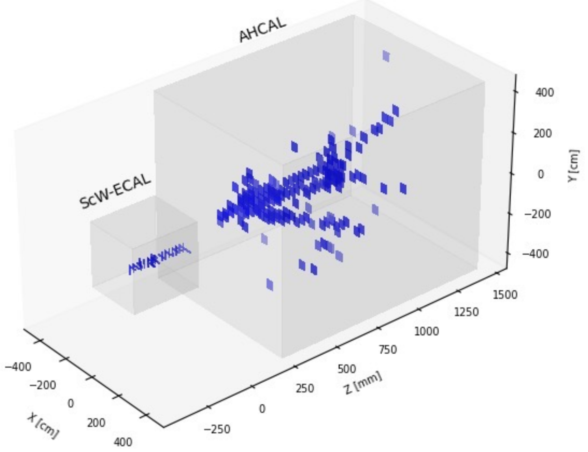


5 GeV π^-



10 GeV π^-

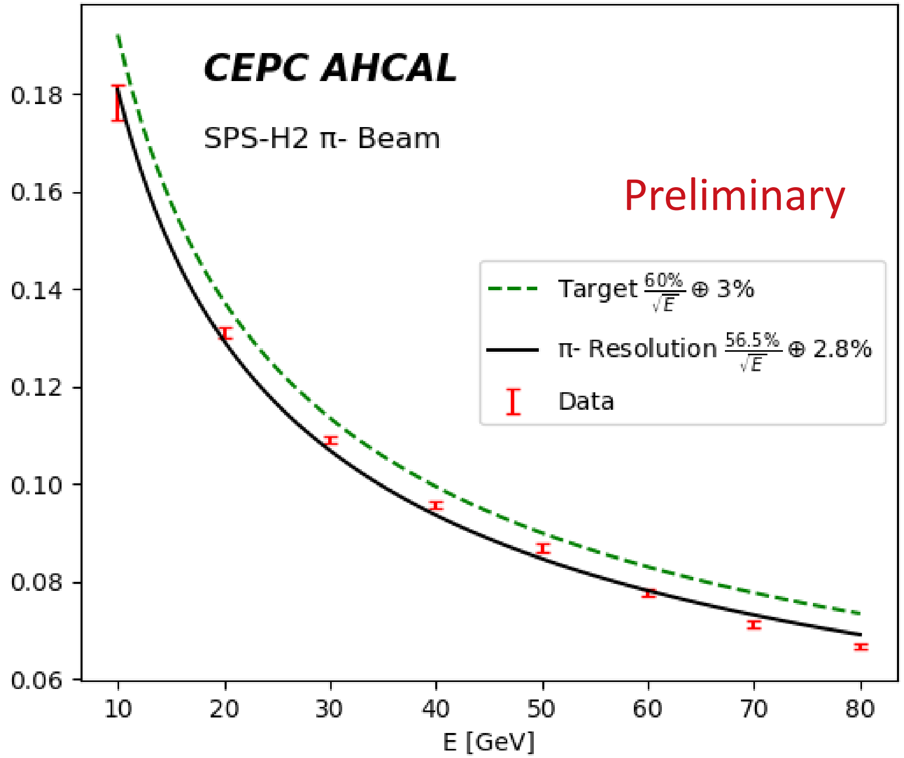


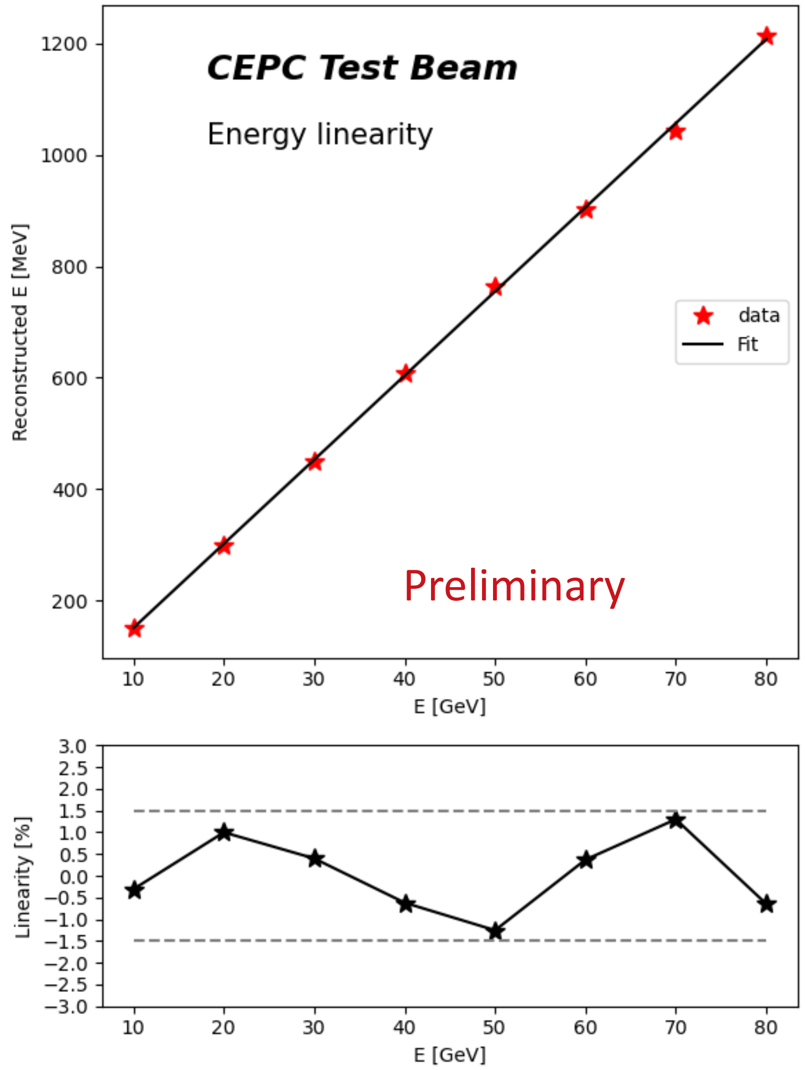


Within CALICE collaboration

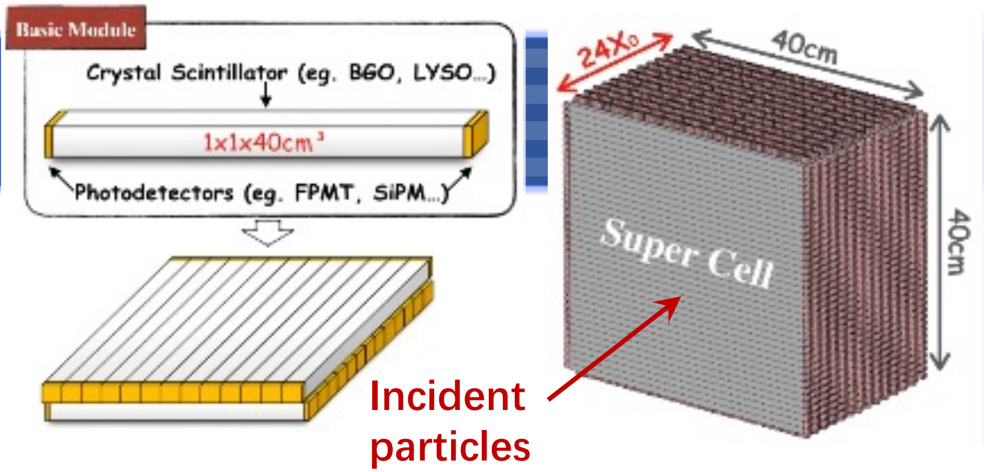
AHCAL energy linearity and resolution for pions

- **AHCAL preliminary results: data sets with PID selections**
  - Energy linearity within $\pm 1.5\%$
  - Hadronic energy resolution: $56.5\%/\sqrt{E(GeV)} \oplus 2.8\%$
  - Consistent with expectation: $60\%/\sqrt{E(GeV)} \oplus 3\%$

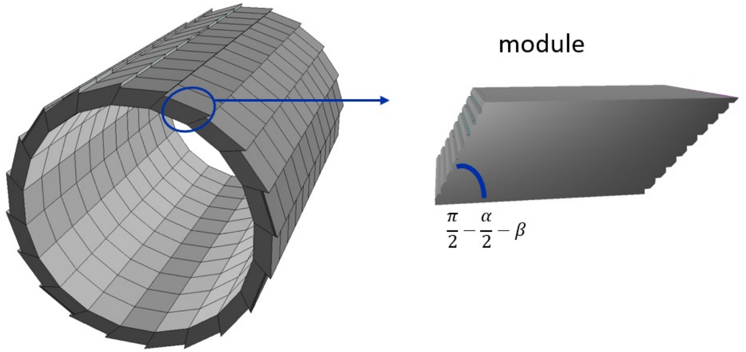


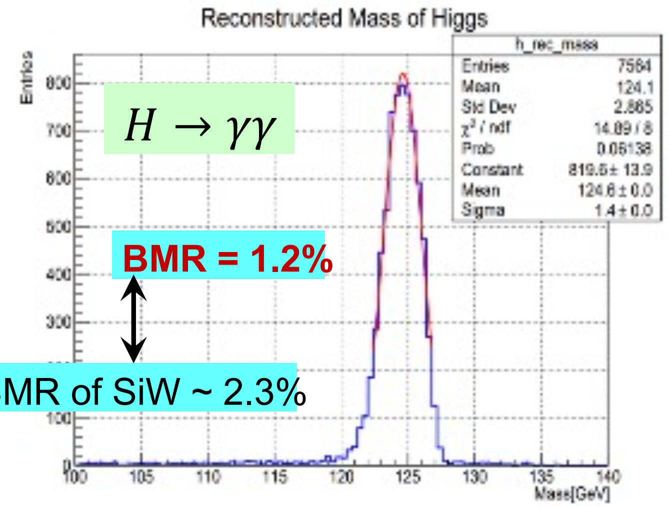


4D Orthogonal Crystal Calorimeter

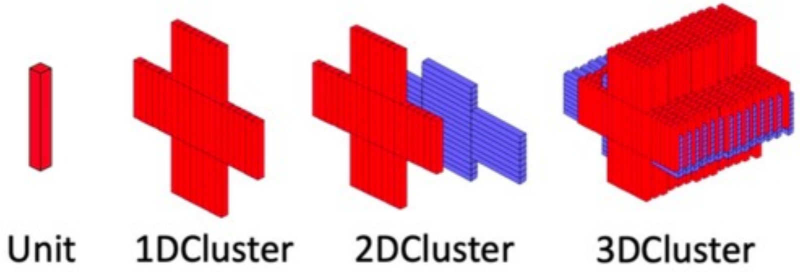


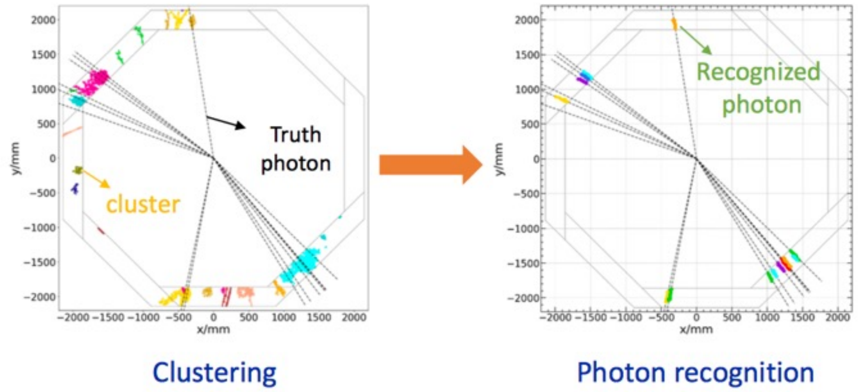
- Goal
  - Comparable BMR resolution as with the Si+W ECAL.
  - Much better sensitivity to γ/e, EM resolution $\leq 3\%/\sqrt{E(GeV)}$
- Features:
  - Timing at two ends of the crystal bar
  - Crossed arrangement in adjacent layers.
  - High granularity with reduced readout channels
- Key issues:
  -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





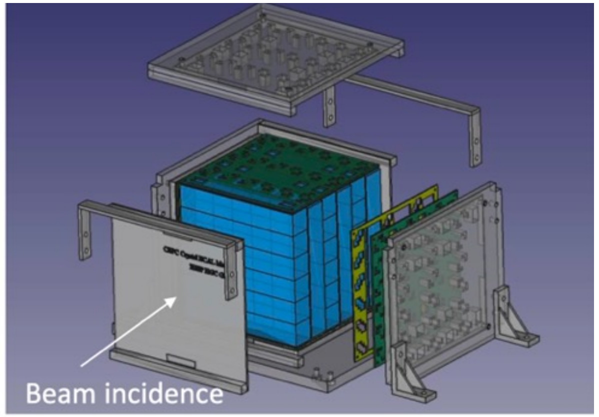
Reconstruction

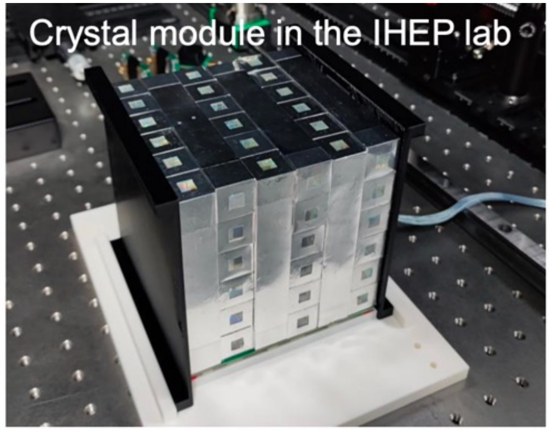




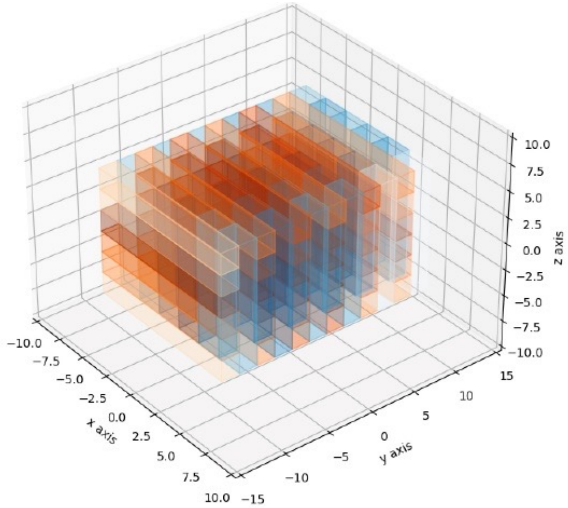
4D Crystal ECAL module prototype and beam test

- ❖ **Module prototype design and developed**
- ❖ **Successful beam test @ DESY 2023**



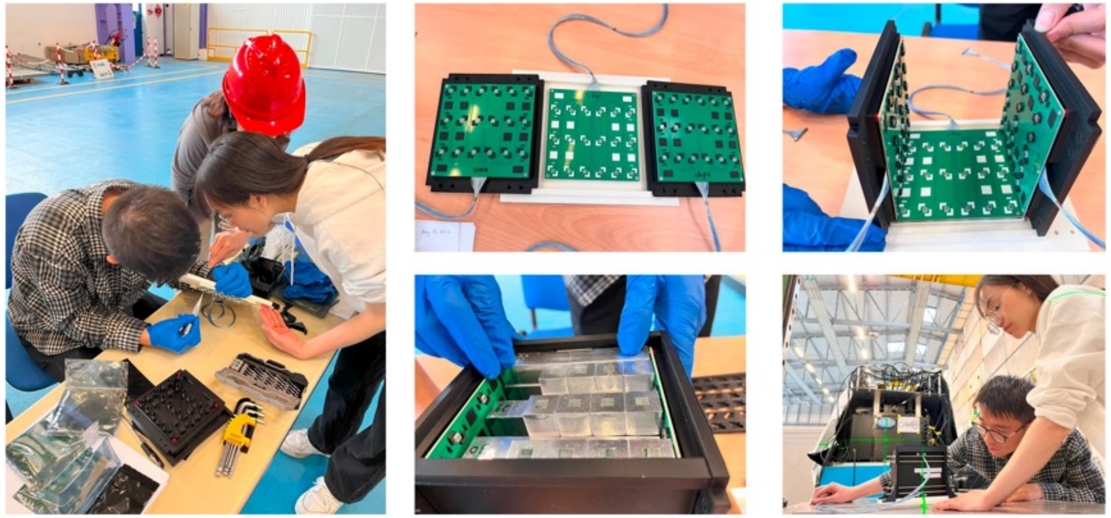


Event display of test beam

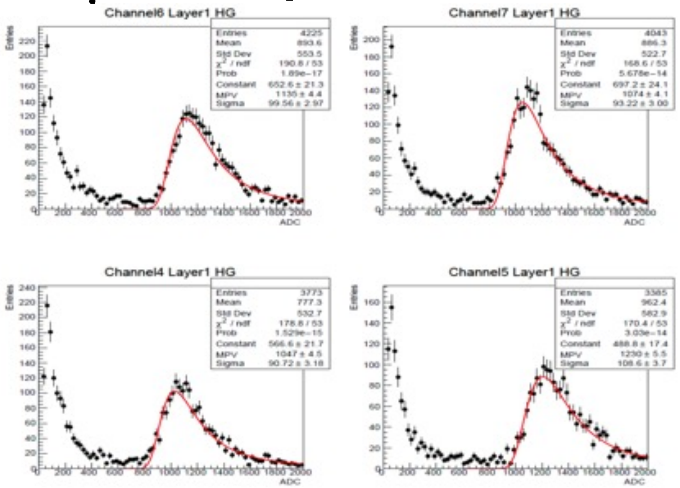


2*2*12cm^3 crystal barswith3*3mm^2 SiPMs

Module assembling at CERN PS beam site



Tested with 10 GeV μ and π, and 0.5-5 GeV e

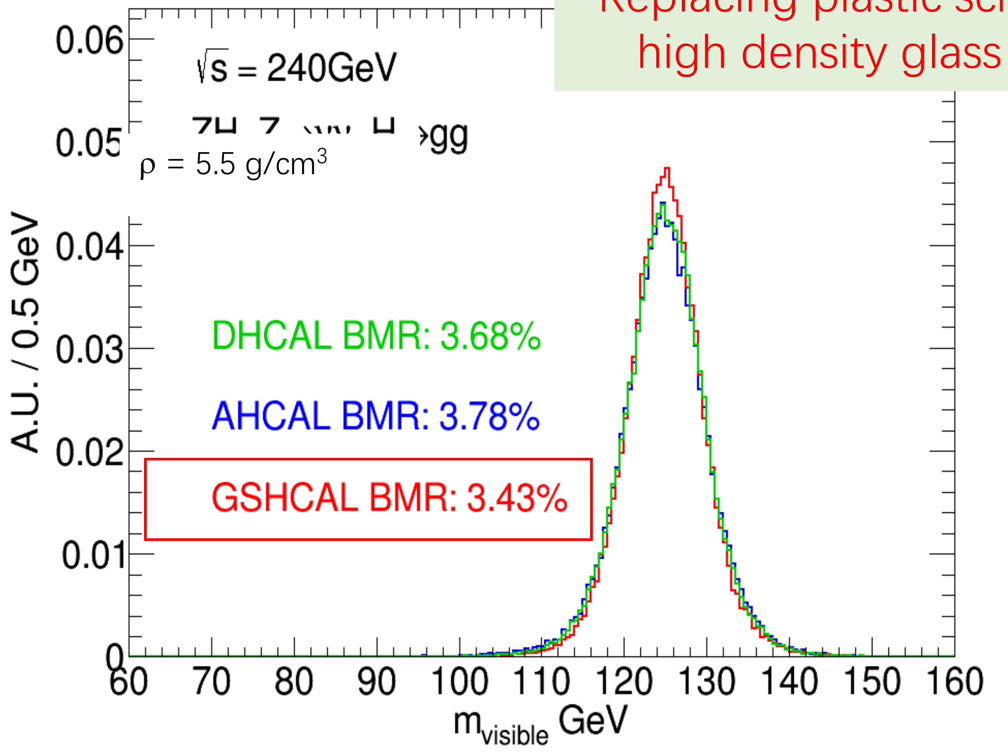


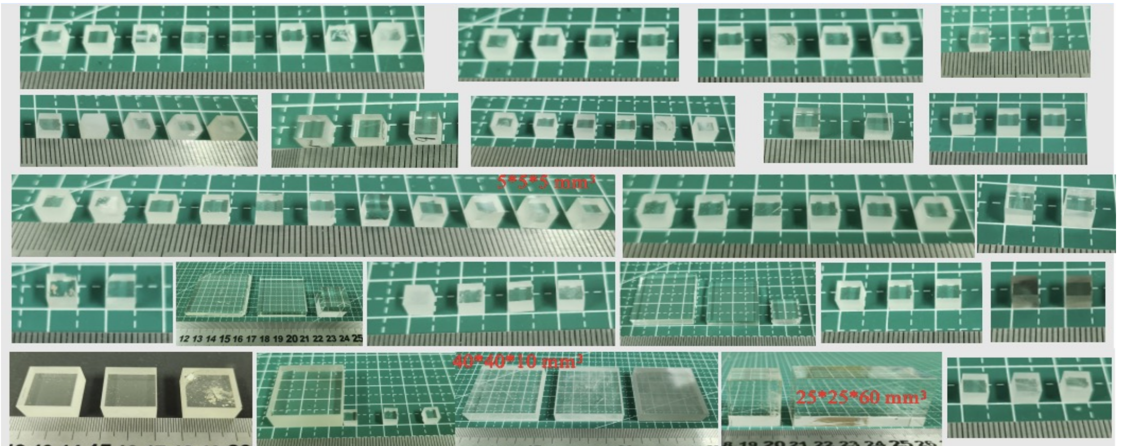
Data analysis is underway

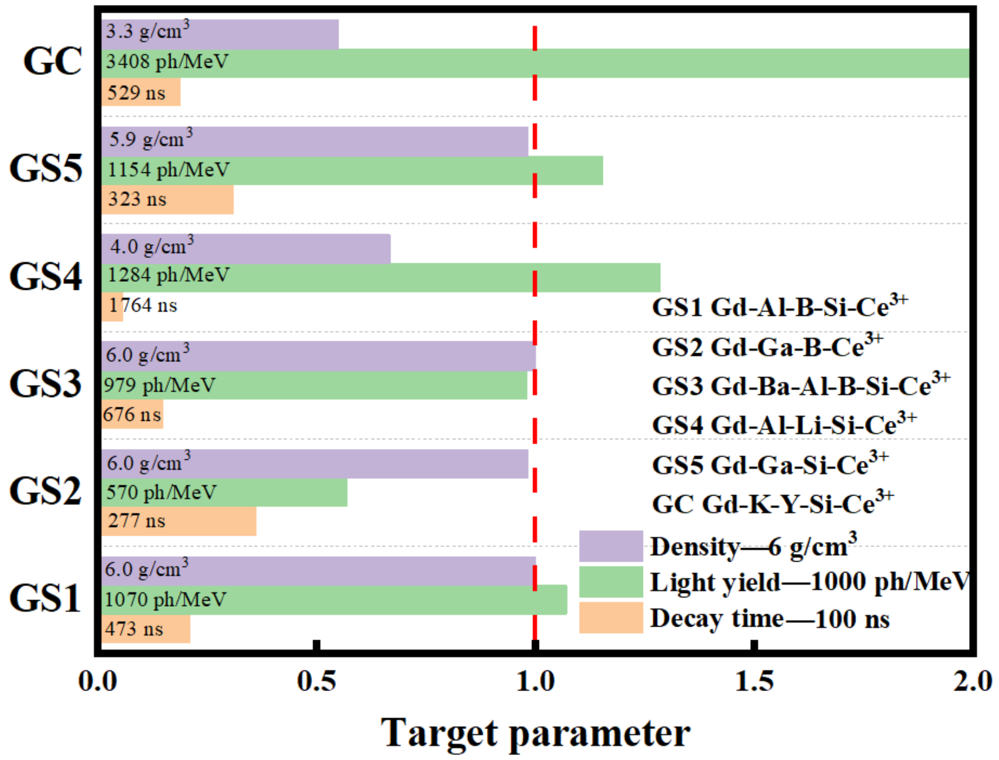
A new AHCAL concept with glass scintillator tiles

Replacing plastic scintillator with high density glass scintillator

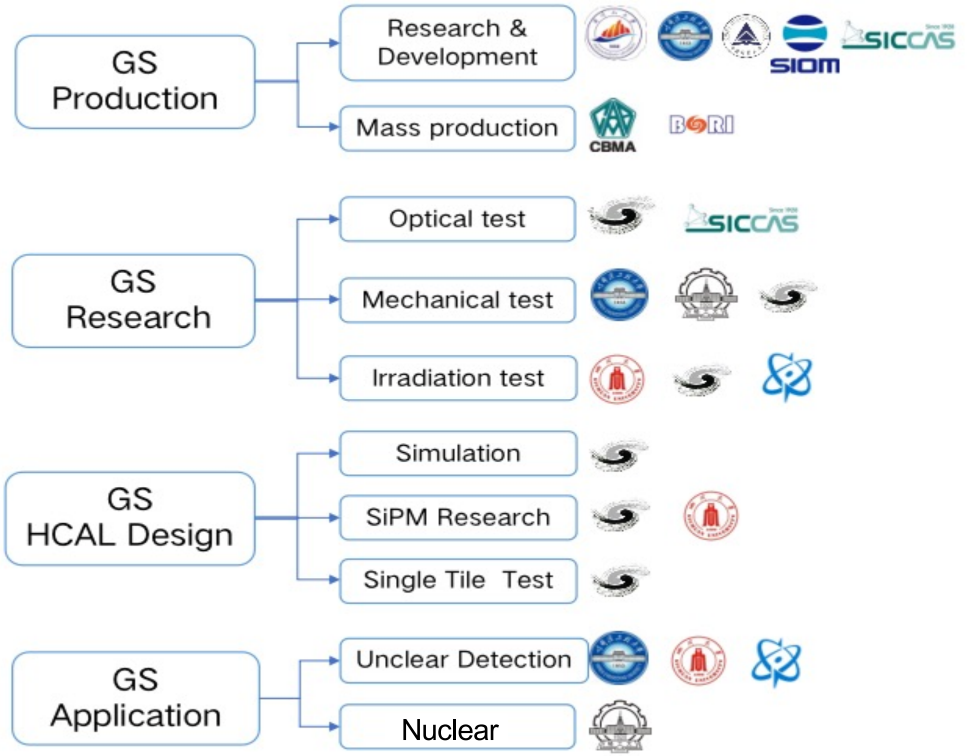
- Light yield: 1000~2000 ph / MeV
- Density: 5~7 g/cm^3
- Scintillation time: ~100 ns
- Low cost
- Tiles in cm scale for PFA HCAL







Introduction of the GS Collaboration



Institute of High Energy Physics，CAS
中国科学院高能物理研究所

Jinggangshan University
井冈山大学

Beijing Glass Research Institute
北京玻璃研究院

China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

Harbin Engineering University
哈尔滨工程大学

Harbin Institute of Technology
哈尔滨工业大学

Sichuan University
四川大学

Shanghai Institute of Ceramics，CAS
中国科学院上海硅酸盐研究所

Shanghai Institute of Optics and Fine Mechanics，
中国科学院上海光学精密机械研究所

CNNC Beijing Unclear Instrument Factory
中核（北京）核仪器有限责任公司

Glass Scintillator Collaboration
闪烁玻璃合作组

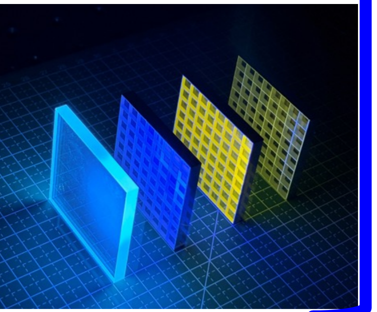
The Sixth Workshop of GS Jan.2024.

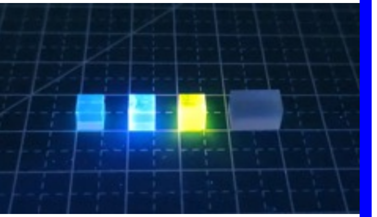
-- Since 2021, the GS collaboration was established and has been devoted to the large-area & high-performance GS meeting the requirements of nuclear and high energy physics.

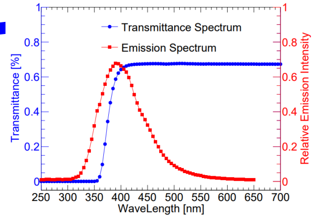
-- The GS collaboration was led by the IHEP and the members include 3 Institutes of CAS, 5 Universities, 3 Factories currently.

-- The Experts of the GS in the University, Institute and Industry are still welcomed to join us **(qians@ihep.ac.cn)**.

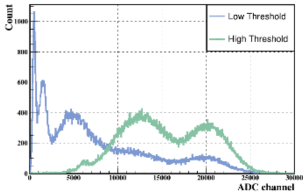
The Scintillator Test Facilities for GS



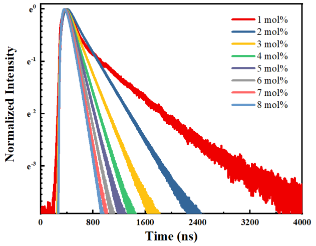




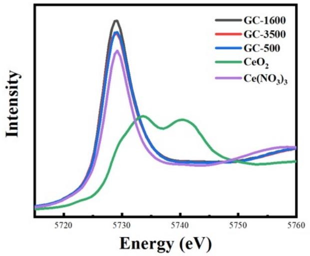
- Transmittance
- Absorbance
- Refractive index
- Emission peak



- Light yield
- Energy resolution
- MIP response
- Neutron discrimination



- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time



- Valence state
- Coordination
- Elemental analysis
- Structural analysis

Others

……

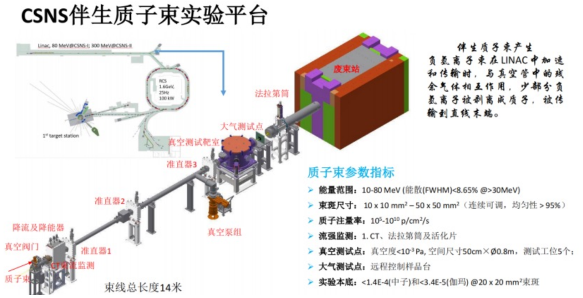
- Faraday effect
- Radiation resistance
- Homogeneity

- IHEP--PMT Lab for Scintillator Test

- IHEP--Radioactive Test

- IHEP--XAFS

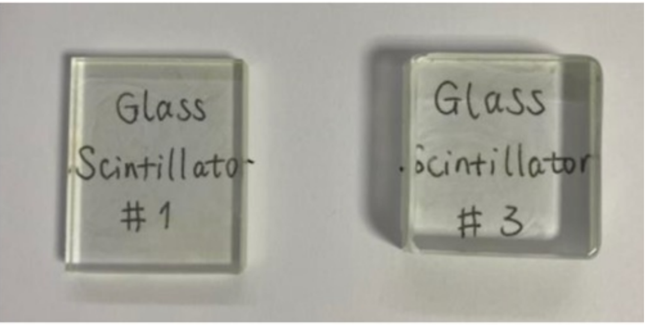
- IHEP-CSN-- P Beam

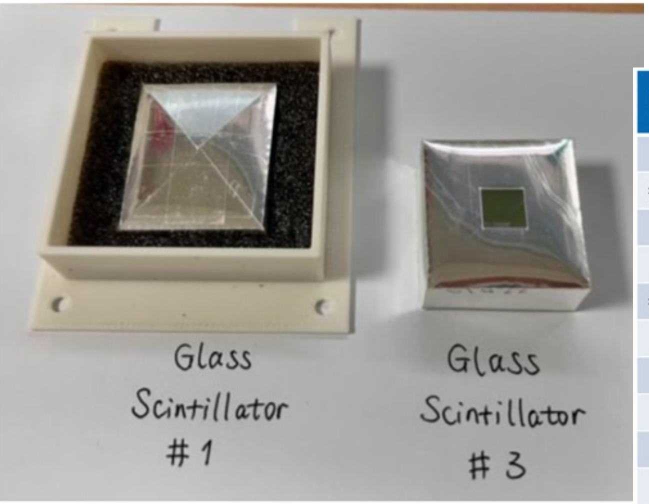


- CERN-MUON Beam

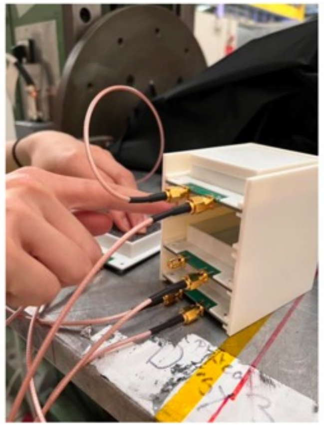
A new AHCAL concept: Beam test of scintillator glass samples

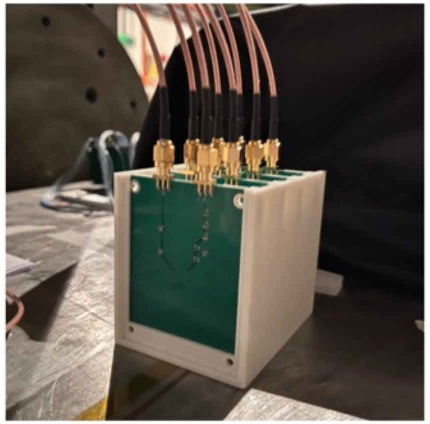
Scintillator glass samples

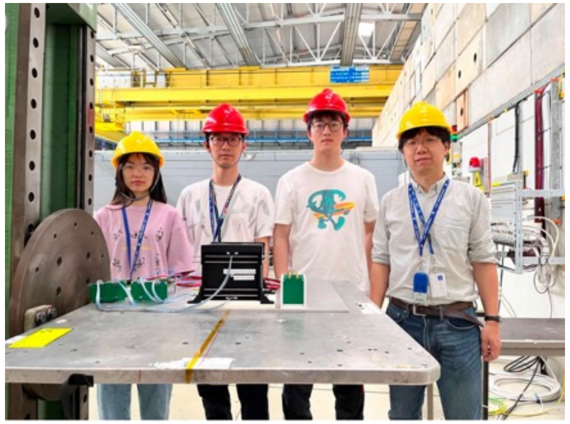


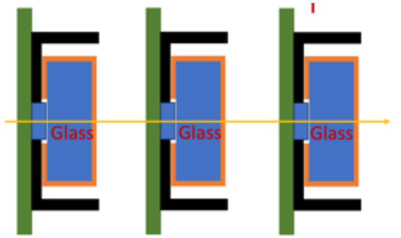


Tested with 10 GeV μ @ CERN PS





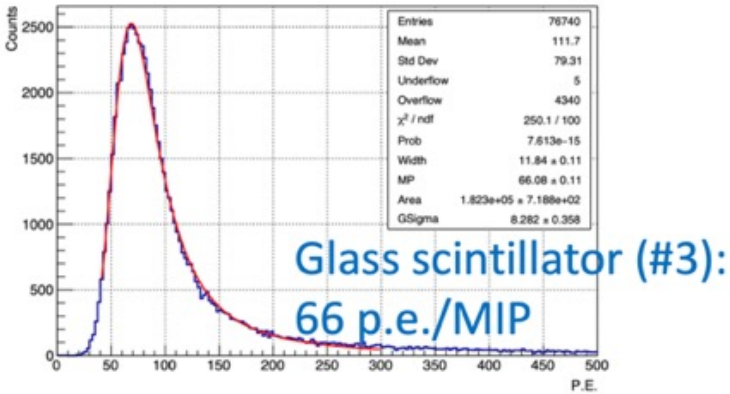




Light yields for MIP (10 GeV muon)

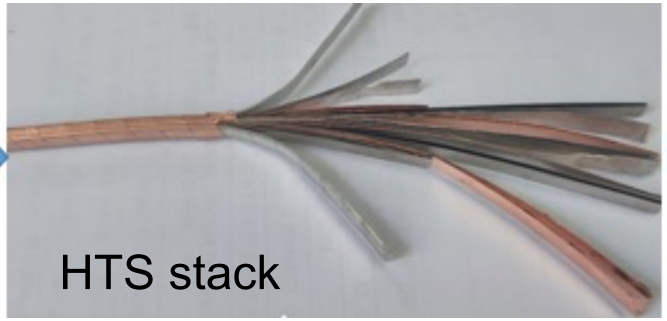
Index	Dimensions (mm)	Transmittance	Decay Time (ns)	Muon response (p.e./MIP)	Scale to 10mm thickness (p.e/MIP)
#1	33.5×27.6×5.1	69 %	300 (19%), 881	15	29
#1 ESR				42	82
#2	30.2×29.5×6.6	61 %	114 (11%), 770	35	53
#3	29.9×28.1×10.2	70 %	90 (6%), 754	66	65
#3 ESR				69	68
#4	37.2×35.1×5.3	80 %	96 (6%), 1024	31	59
#5	40.0×35.1×4.2	78 %	335 (26%), 1068	38	91
#6	30.3×29.8×9.4	55 %	134 (5%), 1132	67	71
#7	34.8×34.8×7.5	65 %	113 (27%), 394	60	80
#8	27.8×25.6×5.0	81 %	136 (23%), 933	41	82
#9	34.6×34.7×7.5	49 %	141 (12%), 771	69	92
#10	34.7×35.2×7.4	64 %	129 (10%), 819	74	100
#11	30.5×30.0×8.7	81 %	153 (12%), 1085	73	84

Typical energy spectrum for MIP



Solenoid Magnet： HTS Cable Development

HTS tape



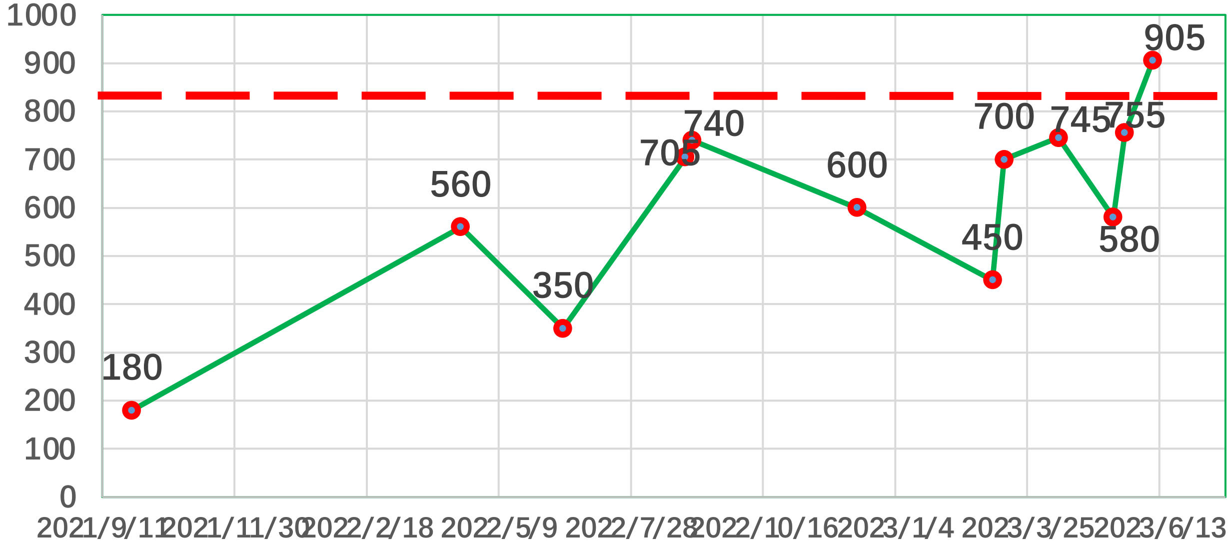
Challenges

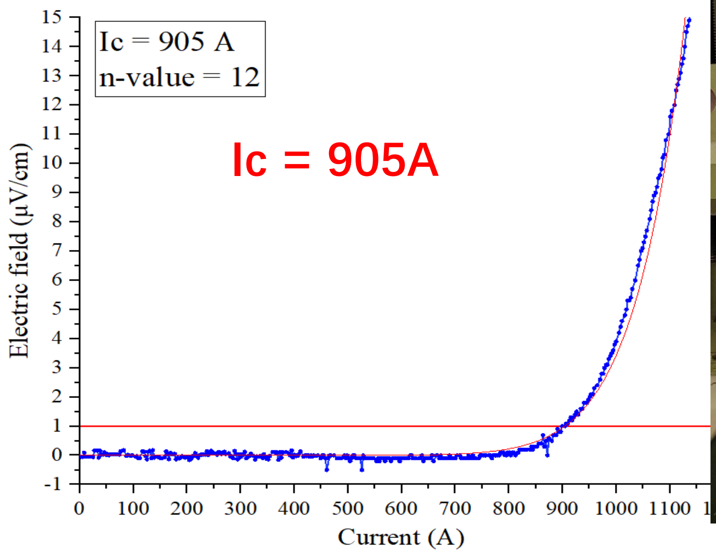
ultra-thin <150 mm

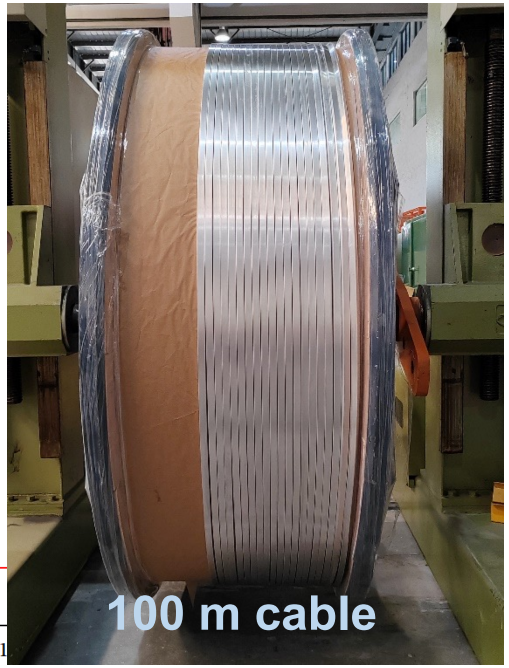
high strength cable

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

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

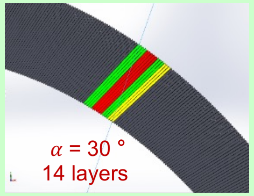


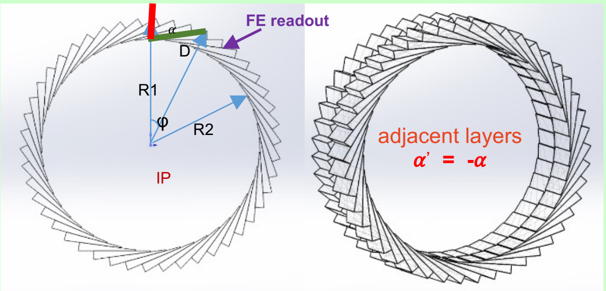




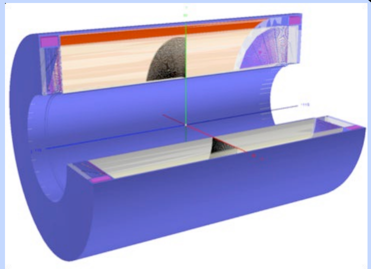
Other R & D activities

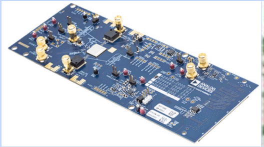
Stereo Crystal ECAL





Drift Chamber

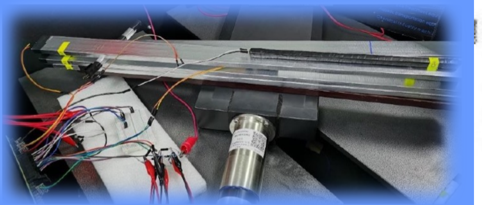


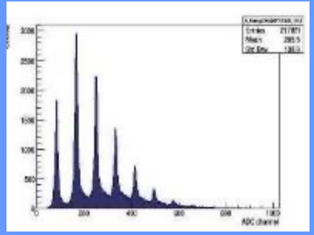


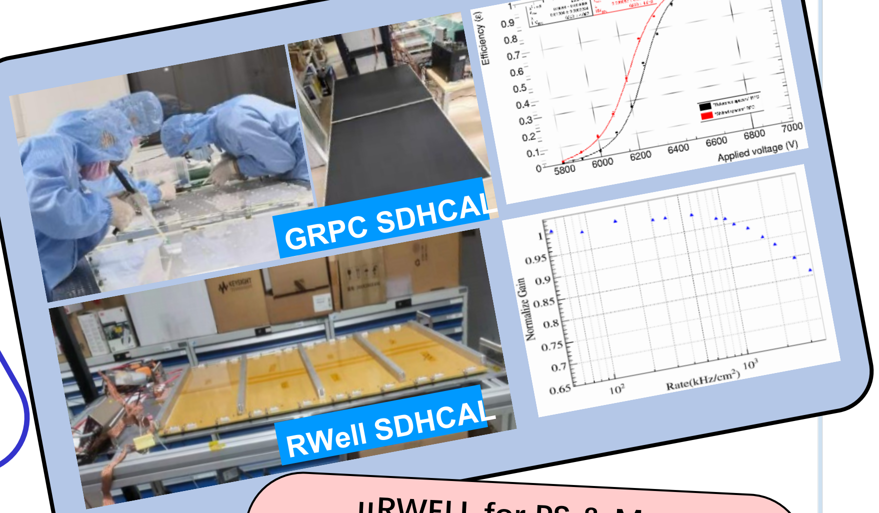
AD9689 – 2000 EBZ

Xilinx KCU105

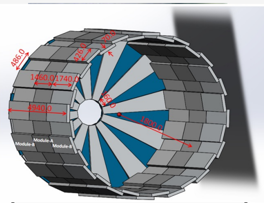
Scintillator Bar Muon



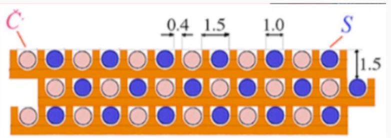


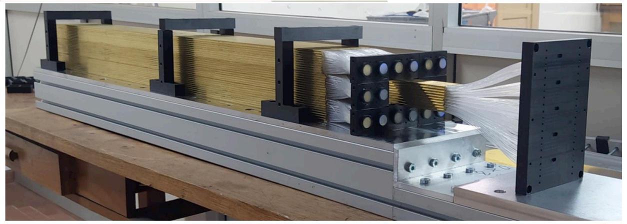


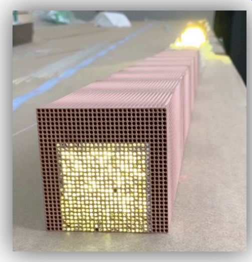
MRPC TOF

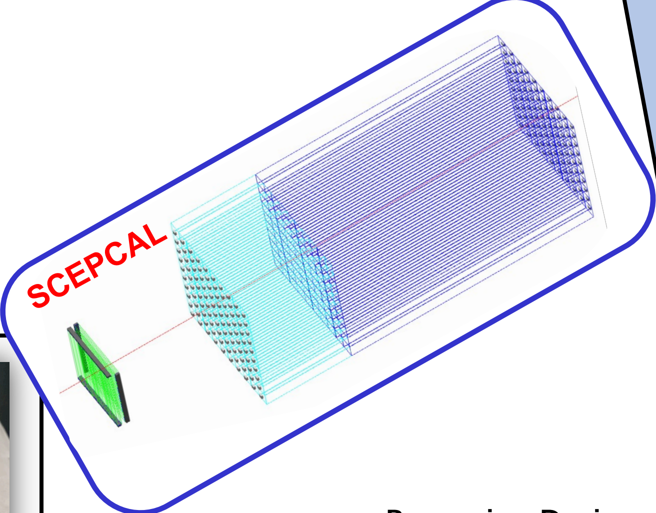


Dual Readout CAL

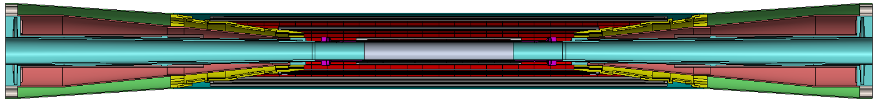




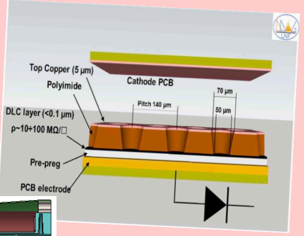


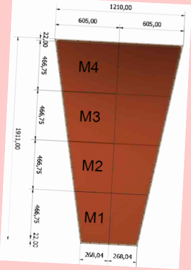


Beampipe Design



µRWELL for PS & Muon





CEPC Reference Detector TDR

❖ **A reference detector TDR needed for the proposal of China's 15th 5-year plan.**

- Not the final detector TDR, which is only after international collaboration is formed
- A draft version reference TDR needs to ready by Dec 2024, Final version by middle of 2025
- Converge on baseline technology, baseline design with electronics and mechanics
- Physics performance of reference detector

Physics benchmark for reference TDR

	Processes @ c.m.s.	Domain	Total Det. Performance
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)
H->inv	qqH	Higgs/NP	PFA
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI
α_S	Z->tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id
B->DK	91.2 GeV	Flavor	PFA + Particle (Kaon) id
Weak mixing angle	Z	EW	JOI
Higgs recoil	llH	Higgs	Leptons id, track dP/P
H->bb, cc, gg	vvH	Higgs	PFA + JOI
	qqH	Higgs	PFA + JOI + Color Singlet id
H->di muon	qqH	Higgs	PFA, Leptons id
H->di photon	qqH	Higgs	PFA, Photons id
W mass & Width	WW@160 GeV	EW	Beam energy
Top mass & Width	ttbar@360 GeV	EW	Beam energy
Bs->vvPhi	Z	Flavor	Object in jets; MET
Bc->tauv	Z	Flavor	-
B0->2 pi0	Z	Flavor	Particle/pi-0 in jets

Legend	Baseline	Comparison	To-be-decided
System	**Technologies**		
Beam pipe	Φ20 mm		
Vertex	CMOS Pixel	SOI	CMOS+Stitching
Tracker & PID	SPD ITrk		
	Pixelated TPC	PID Drift Chamber	
	SSD OTrk	SPD OTrk	AC-LGAD Otrk
	LGAD ToF		
ECAL	4D Crystal Bar	PS+SiPM+W	Stereo Crystal Bar
	SiDet+W	GS+SiPM	
Magnet	HTS	LTS	
HCAL	GS+SiPM+Fe	PS+SiPM+Fe	RPC+Fe
Muon	PS Bar+SiPM	RPC	
LumiCal	SiTrk+Crystal		
TDAQ	Conventional	Software Trigger	
BE electr.	Common	Independent	

CEPC Reference Detector TDR activities

- CEPC Phys-Det meetings Wednesday Morning CERN time (bi-weekly)
  - Compare different options of reference TDR detector design
  - Bench mark physics topics for combined quality comparisons
- Sub-system meeting every week
  - Physics, Software, Electronics, Mechanics, Magnet,
  - Vertex, Tracker, Calorimeter, Muon, MDI/Lumical
- For sub-detector meeting
  - Work and fill the key specifications that can be used to compare different solutions
  - Work with Electronics, software/physics, Mechanics to refine the detector design

❖Your contribution/input is very important

- Please consider to join us

CEPC Phys-Det meetings: https://indico.ihep.ac.cn/category/324/
Sub-system indico page: https://indico.ihep.ac.cn/category/1041/

Summary

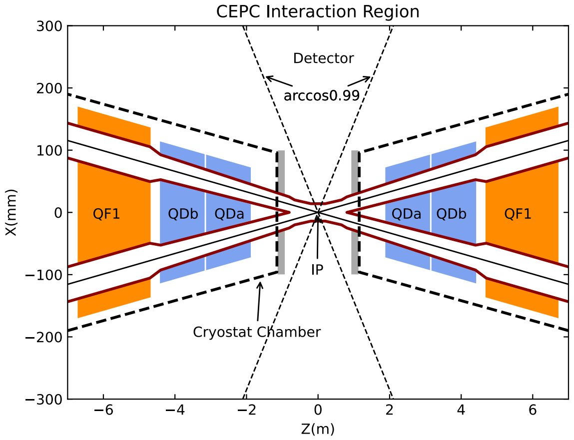
- ❖ **CEPC physics studies constantly updated, improved and expanded to fully explore the CEPC physics potential.**
- ❖ **Reference detector TDR under preparation, to be completed by the mid-2025 for the proposal of China's 15th 5-year plan.**
- ❖ **Intense R&D activities are underway on the baseline detector concept targeting key technologies of all sub detectors. Significant progress has been made and several R&D projects have reached milestones.**
- ❖ **It is important to expand international collaboration and explore synergies with other international projects.**
  - ▶ Existing collaboration: CALICE Collaboration (PFA calorimeters), LCTPC Collaboration (TPC), INFN(Drift chamber), CMOS tracker Collaboration (Silicon tracker), French and Spain institutes (CMOS pixel), DRD1-8 Collaboration

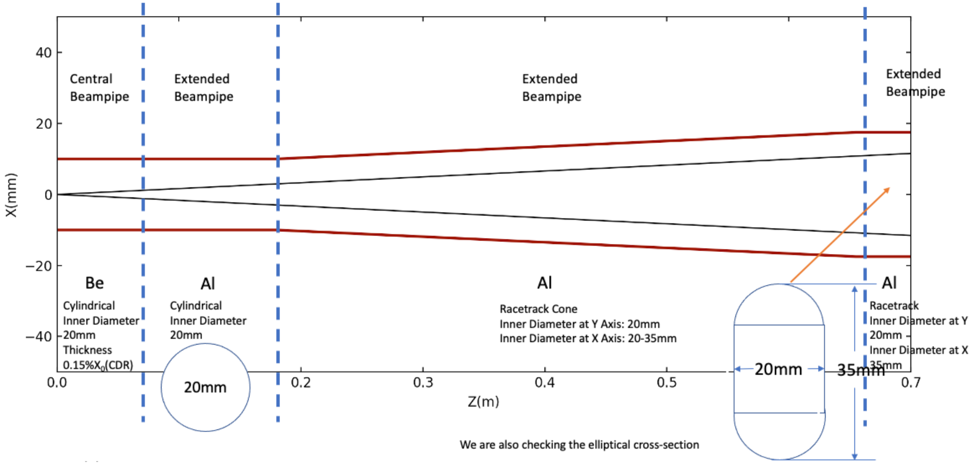
Detector requirements and R&D status

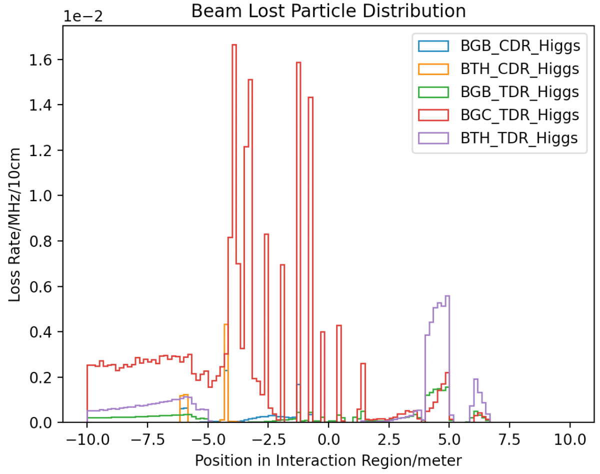
Sub-detector	Specification	Requirement	CEPC prototype
Pixel detector	Spatial resolution	$\sim 3\ \mu m$	$3 - 5\ \mu m$ [14–16]
TPC/drift chamber	dE/dx (dN/dx) resolution	$\sim 2\%$	$\sim 4\%$ [19–21]
Scintillator-W ECal	Energy resolution Granularity	$< 15\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2\ \mathrm{cm}^2$	Prototype built and tested
4D crystal ECal	EM energy resolution 3D Granularity	$\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$	Prototyping [25] $\sim 3\%/\sqrt{E(\mathrm{GeV})}$ $\sim 2 \times 2 \times 2\ \mathrm{cm}^3$
Scintillator-Steel HCal	Support PFA, Single hadron σ_E^{had}	$< 60\%/\sqrt{E(\mathrm{GeV})}$	Prototype built and tested
Scintillating glass HCal	Support PFA Single hadron σ_E^{had}	$\sim 40\%/\sqrt{E(\mathrm{GeV})}$	Prototyping $\sim 40\%/\sqrt{E(\mathrm{GeV})}$
Low-mass Solenoid magnet	Magnet field strength Thickness	$2\ \mathrm{T} - 3\ \mathrm{T}$ $< 150\ \mathrm{mm}$	Prototyping

Highlights of CEPC machine detector interface (MDI)

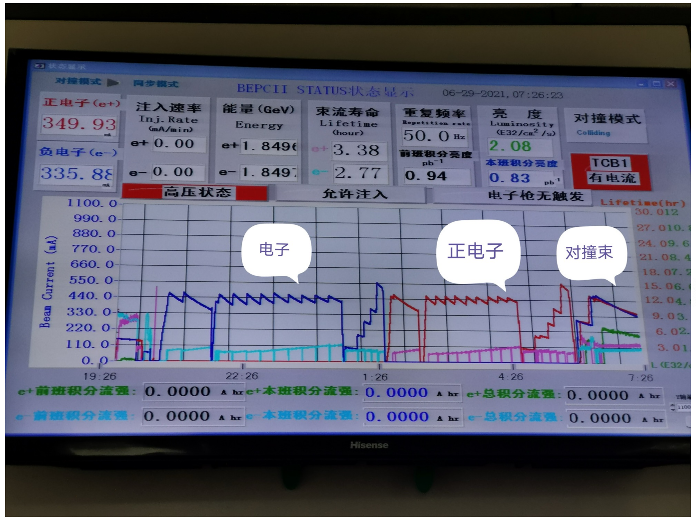
The design based on Accelerator TDR has been done. The background simulation is performing.

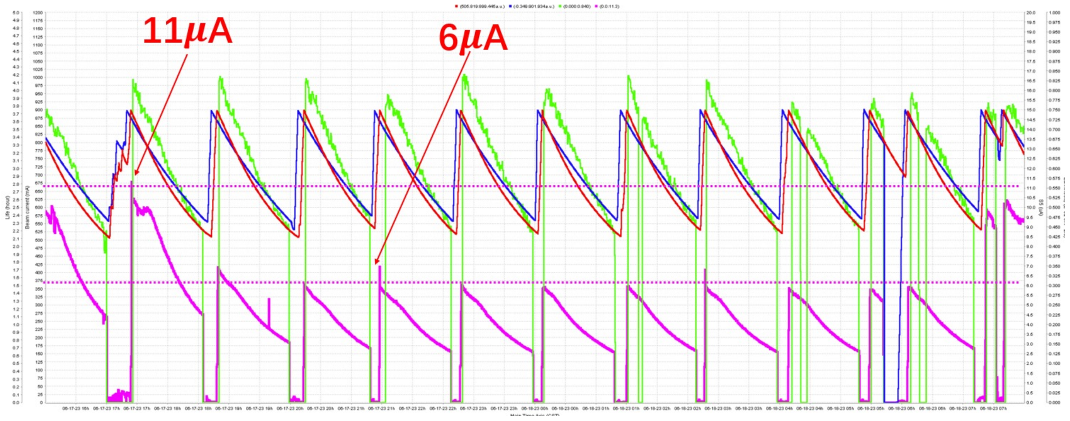






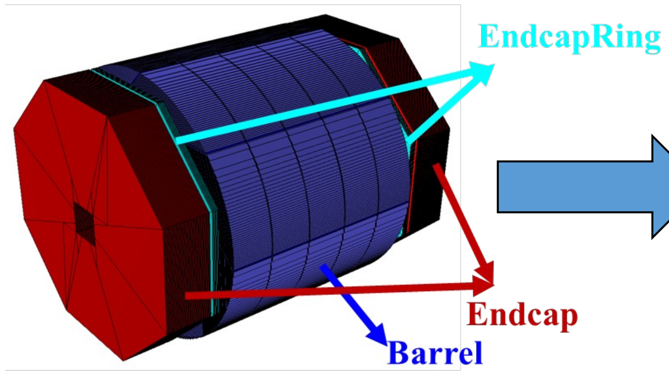
The experiment at BEPCII has been done several times to validate the code.



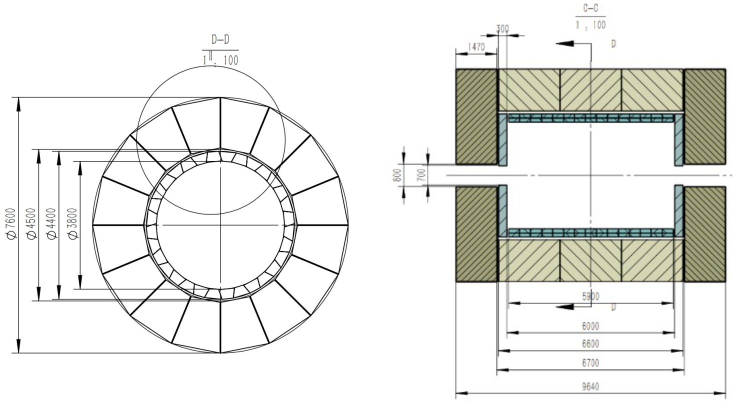


The collaboration on beam induced background study between different groups has been formed.

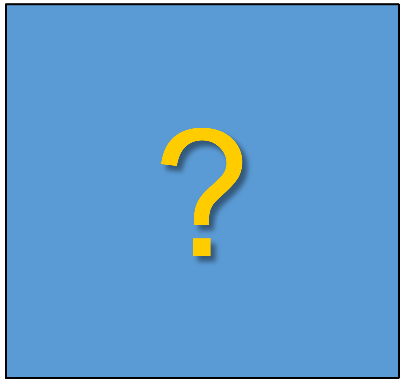
GSHCAL Simulation Studies



Based on CDR
(Finished)



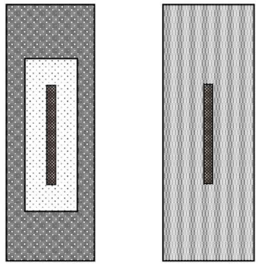
Based on Pre TDR
(Ongoing)



Based on TDR
(To do)

Status	Design Option	Material	BMR	No. Layer	Layer Thick. (GS/PS + Steel)	Inter. Length	Trans. Cell Size	Mat. Density	HCAL Thick.	HCAL Volume (GS/PS + Steel)	No. Cells
CDR	AHCAL	PS	3.77%	40	3mm+20mm	5 lambda	4x4 cm^2	1 g/cm^3	931 mm	$14m^3 + 91m^3$	$2.8x10^6$
CDR	GSHCAL1	GS	3.7%	40	3mm+18.8mm	5 lambda	4x4 cm^2	6 g/cm^3	873 mm	$13m^3 + 81m^3$	$2.7x10^6$
CDR	GSHCAL2	GS	3.59%	40	10mm+13.8mm	5 lambda	4x4 cm^2	6 g/cm^3	962 mm	$46m^3 + 64m^3$	$2.9x10^6$
CDR	GSHCAL3	GS	3.37%	40	29.7mm GS	5 lambda	4x4 cm^2	6 g/cm^3	1218 mm	$159m^3$ (GS)	$5.4x10^7$
Pre-TDR	GSHCAL4	GS	3.49%	48	10mm+13.8mm	6 lambda	2x2 cm^2	6 g/cm^3	1170 mm	$62m^3 + 86m^3$	$3.9x10^6$
TDR	GSHCAL5	GS	?	?	?	6 lambda	?	?	?	?	?

LTS cable R&D

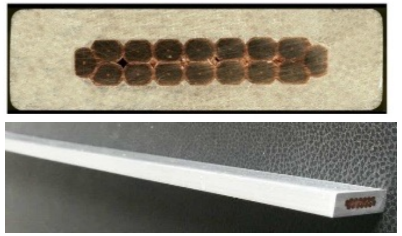


- Development of 32 strands and 16 strands NbTi Rutherford cables.
- 1 km 16 strands aluminum stabilized superconducting cable used in the superconducting magnet prototype of the China spallation neutron source EMuS project.
- Long Dummy cable and dummy coil, 6061 + copper, **22*56m**
- Continue the research of secondary aluminum coating

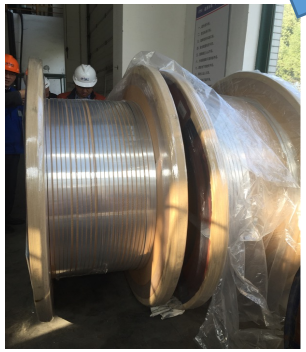
EMuS coil

NbTi/Cu cable
Pure Aluminum
High Strength and High RRR Aluminum Alloy
High Strength Aluminum Alloy

NbTi Rutherford cable



Small size Al stabilized cable 4.7*15mm²



Long small size cable

Dummy cable 22*56mm²

Long Dummy cable (22*56mm²)

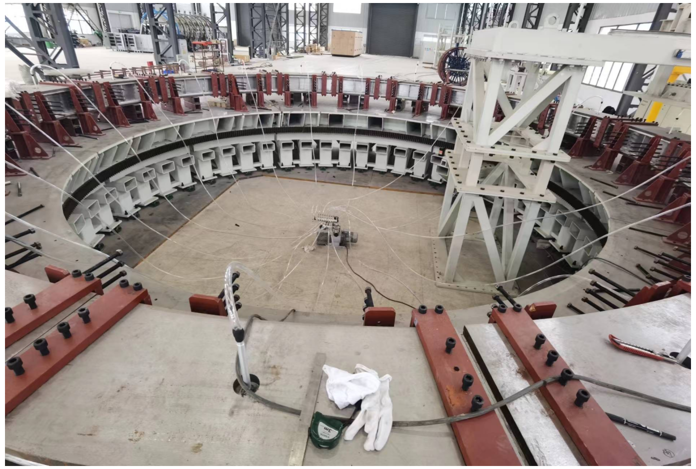
Prototype Coil R&D

Winding platform of Dummy coil

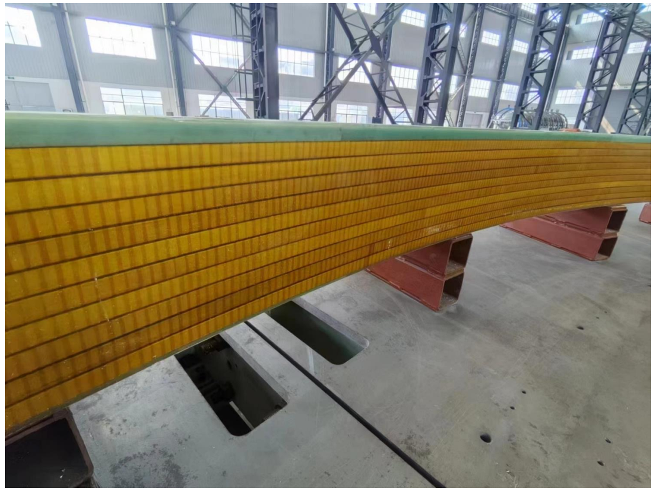
- Dummy cable: 6061 Aluminum alloy, cross section 56mm*22mm
- Dummy coil: 4 layers, 10 turns per layer.

Winding platform

Dummy coil winding



Leak detection before vacuum impregnation



coil after vacuum epoxy impregnation

CEPC Reference Detector TDR

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		

- **Large number of detector technology options and R&D projects on-going, they are not at similar level of maturity.**
- **Need to converge technology options towards a CEPC reference detector TDR**
  - Start preparation in Jan. 2024
  - A draft version of TDR in Dec. 2024
  - **Official release of TDR in Jun. 2025**
- **Int. detector collaborative efforts**
  - DRD proto-collaboration (DRD1-8), more than 130 colleagues from 11 Chinese institutes joined so far.
  - HL-LHC detector R&D efforts help to prepare teams for CEPC detectors.

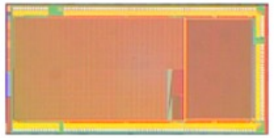
CMOS MAPS sensors development

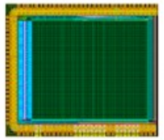
All developed with TowerJazz CIS 180 nm process

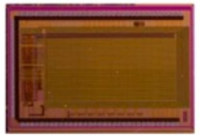
	JadePix1 (2015)	JadePix2 (2017)	MIC4 (2017)	JadePix3 (2019)
Architecture	Roll. Shutter + Analog output ➡	Roll. Shutter + In pixel discri.	Data-driven r.o. + In pixel discri.	Roll. shutter + end of col. priority encoder
Pitch (μm²)	33 × 33 /16 × 16	22 × 22	25 × 25 ➡	16 × 26 16 × 23.11
Power con. (mW/cm²)	--	--	150 ➡	~ 55* / <100
Integration time (μs)*	--	40-50	~3	~100
Prototype size (mm²)	3.9 × 7.9 (36 individual r.o)	3 × 3.3	3.1 × 4.6 ➡	10.4 × 6.1
Main goals	Sensor optimization	Small binary pixel	Small pixel + Fast readout+ nearly full functional	Smaller pixel + Low power + fully functional

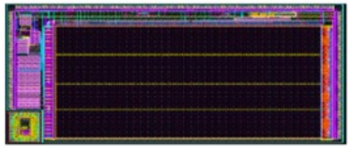
* Assuming a matrix of 512 ×1024 pixels

All prototypes in TowerJazz 180 nm process

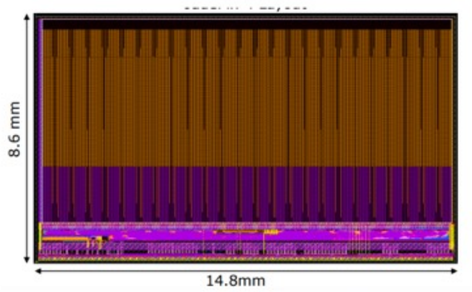

JadePix1 (IHEP)


JadePix2 (IHEP)


MIC4 (CCNU & IHEP)


JadePix3 (IHEP, CCNU, Dalian Minzu Unv., SDU)

JadePix4 **Design finalized, to be taped off**

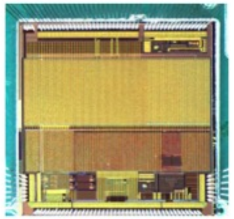


	S.P. resolution	Integration time	Average power
JadePix-4	<5 μm	~1 μs	< 100 mW/cm²
JadePix-3	<3 μm	<100 μs	< 100 mW/cm²

Optimized for fast readout

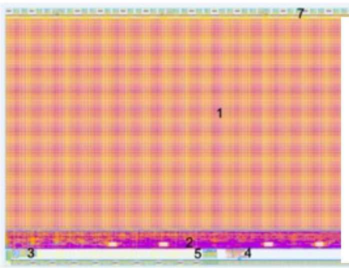
Taichupix1

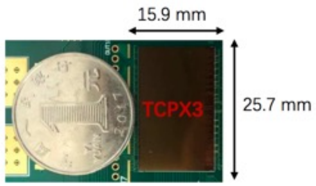
Taichupix2



Chip size: 5 mm × 5 mm
Pixel size: 25 μm × 25 μm

Full-size Taichupix





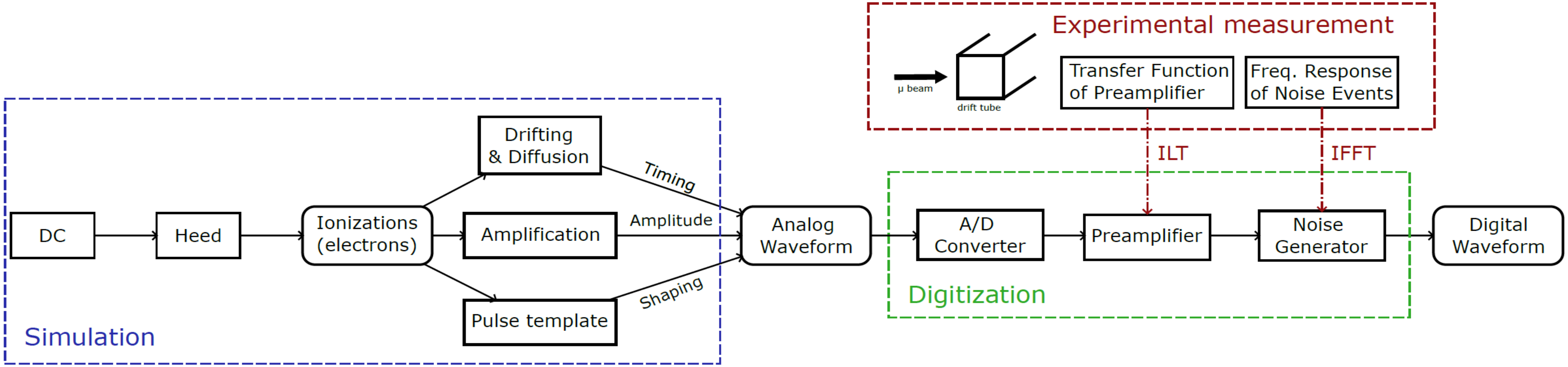
TaichuPix3
Pixel size: 25 μm × 25 μm

1024*512 pixel array, FE-I3-like

High speed, deadtime~50ns@40MHz,
time stamp precision 25/50ns

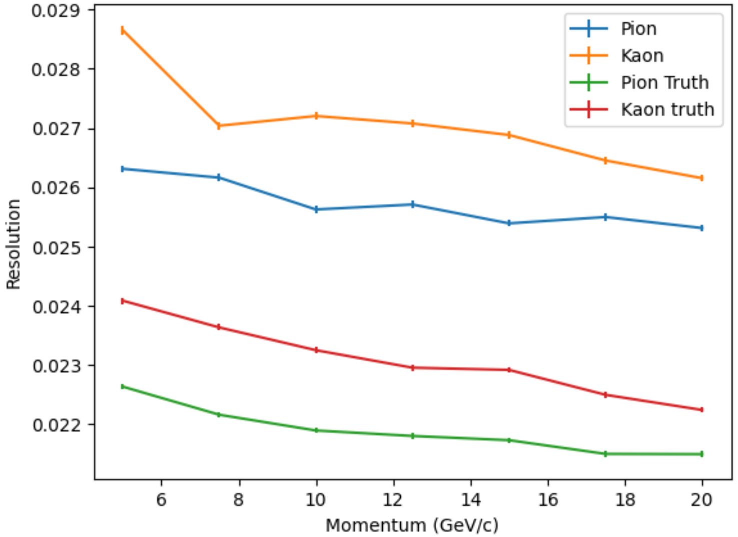
Full-size chips produced and tested

Drift chamber full simulation and updated parameters

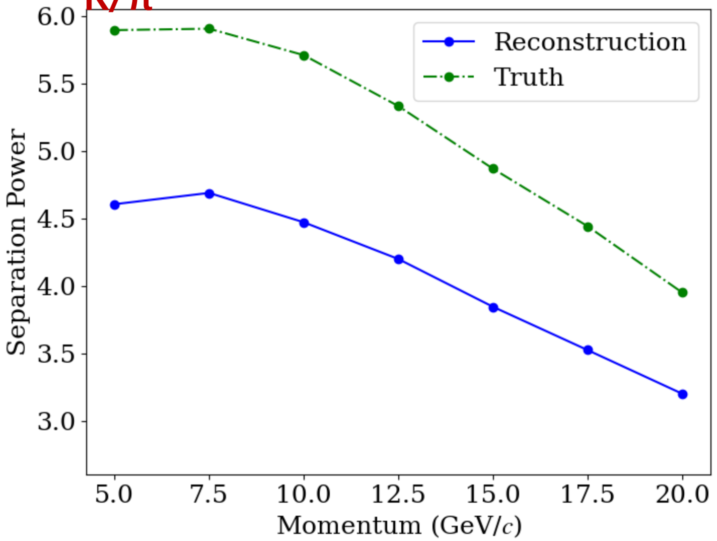


R extension	600-1800mm
Length of outermost wires（cosθ=0.85	5800mm
Thickness of inner CF cylinder: (for gas tightness, without load)	200μm
Thickness of outer CF cylinder: (for gas tightness, without load)	300μm
Outer CF frame structure：	Equivalent CF thickness: 1.8 mm
Thickness of end Al plate:	20mm / 25mm
Cell size:	~ 18 mm × 18 mm
Cell number	27623
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10

dN/dx resolution: ~2.5% for pion



Separation: 3.2σ for 20 GeV/c K/π



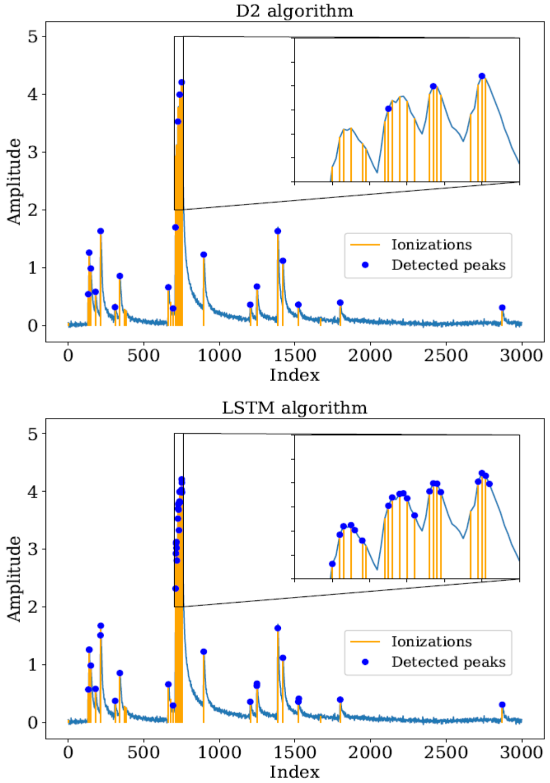
Machine learning reconstruction algorithm

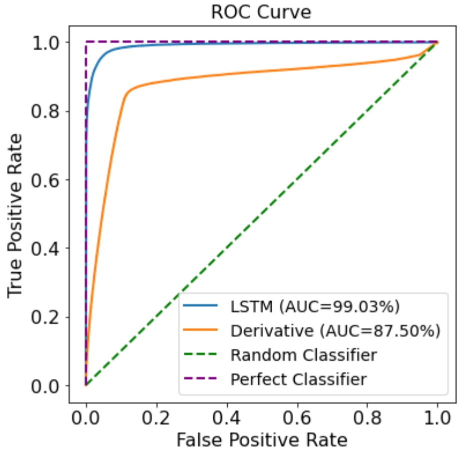
- ❖ **LSTM-based peak finding and DGCNN-based clusterization**
- ❖ **~10% improvement of PID performance with ML**

Long Short-Term Memory (LSTM)-based peak finding

higher efficiency than the derivative-based algorithm,

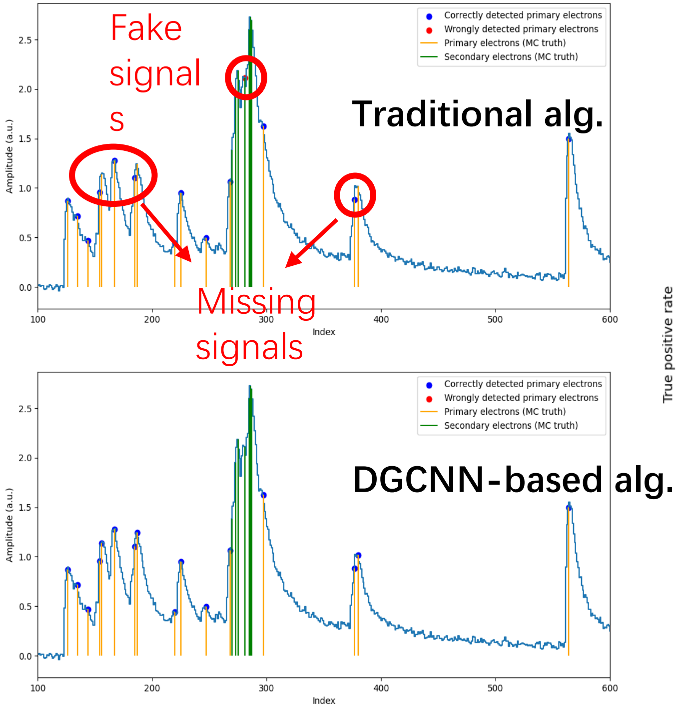
overy

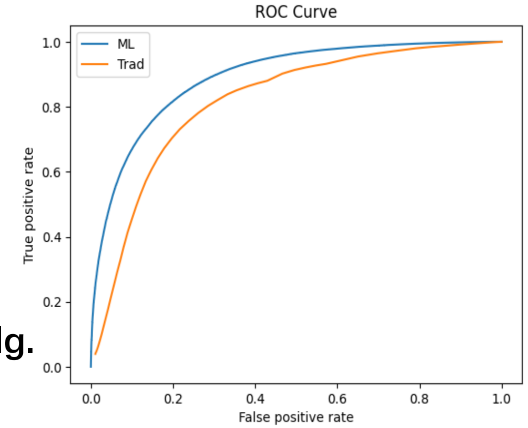




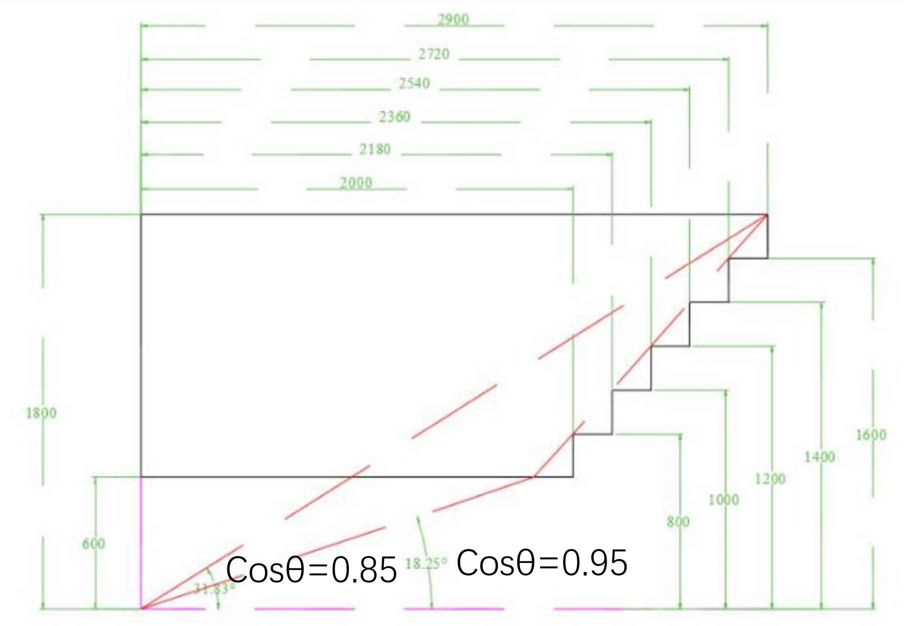
Dynamic Graph CNN (DGCNN)-based clusterization

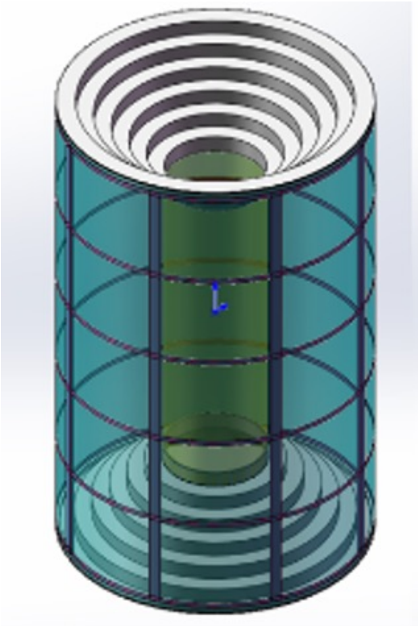
higher efficiency, and lower fake rate

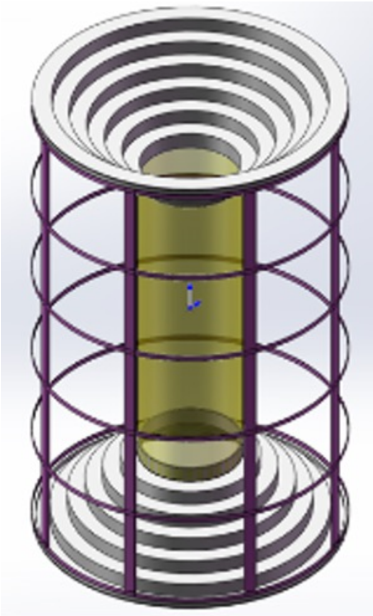




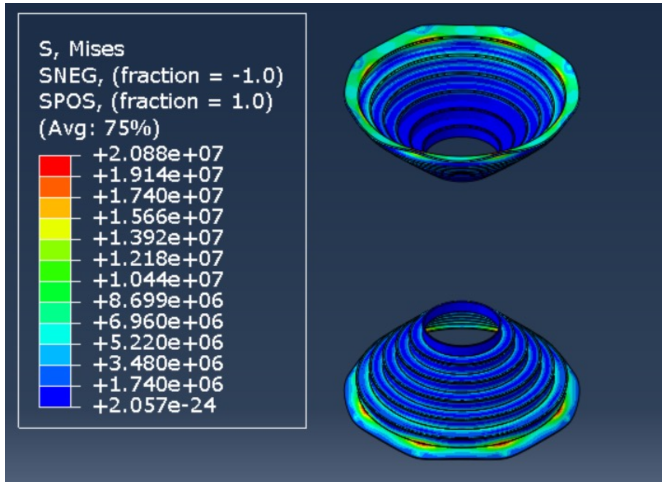
Optimized mechanical design and FEA

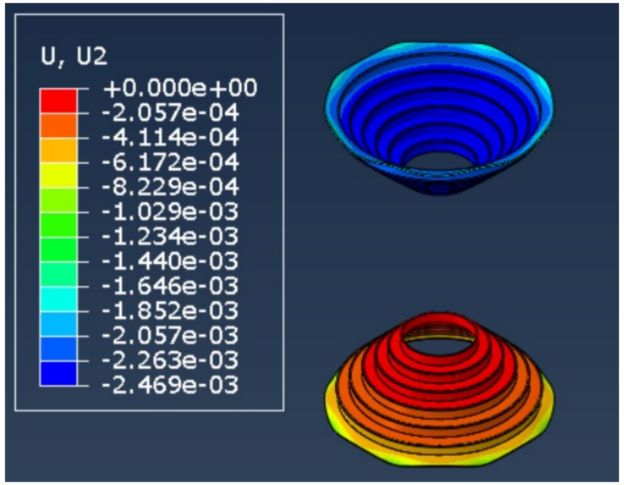


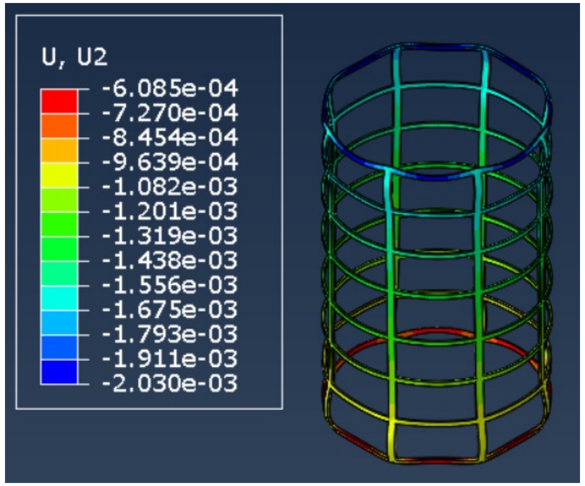




- Frame CF support structure
- stepped end plates
- inner and outer CF cylinders

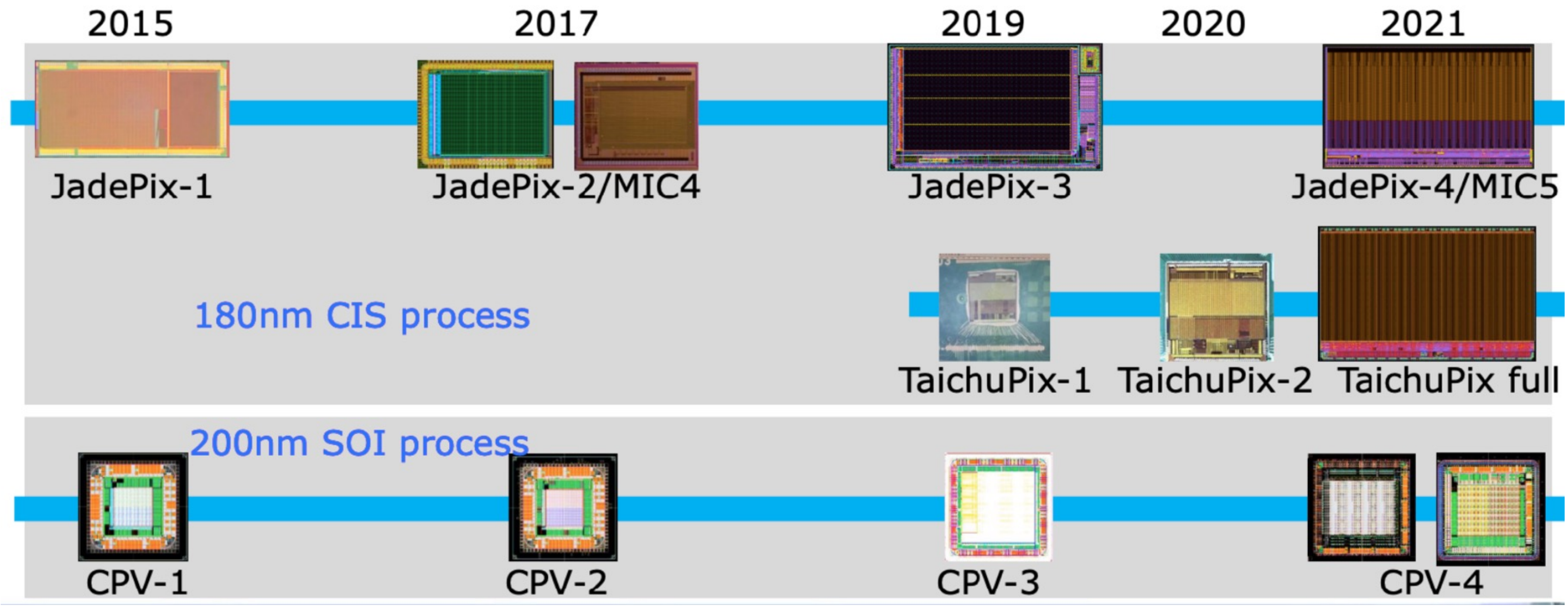




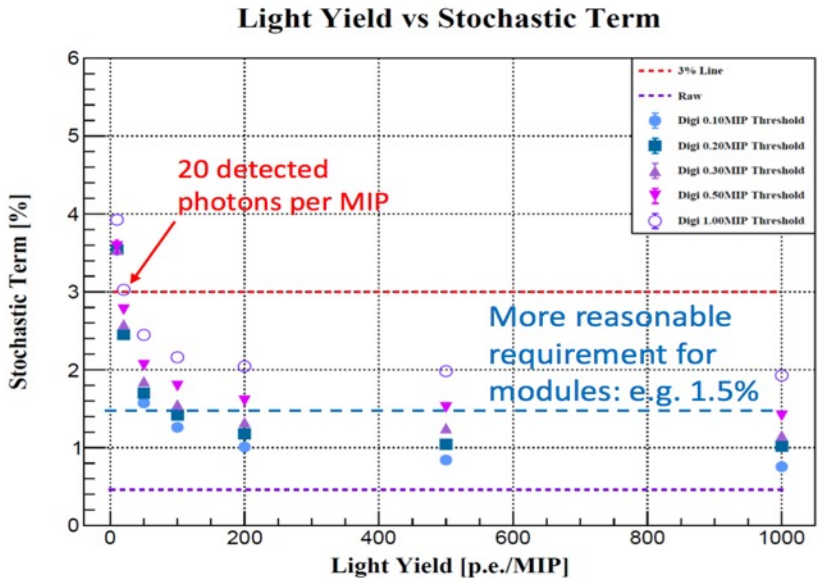


- FEA with loads of wire tension and self weight
- Small deformation
- Stable structure

Vertex detector sensor R&D timeline

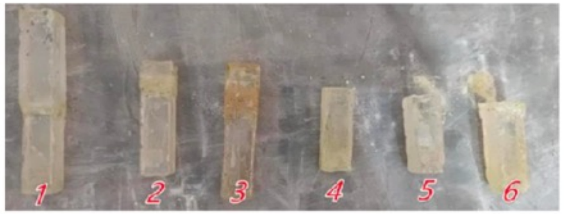


Crystal ECAL R&D

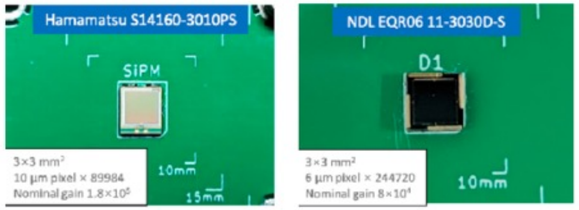


Study of crystal-SiPM units

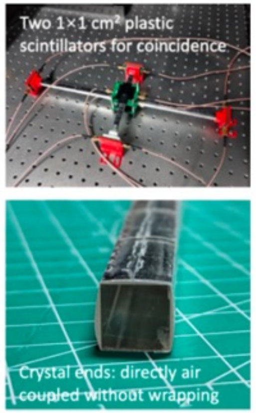
BGO crystals

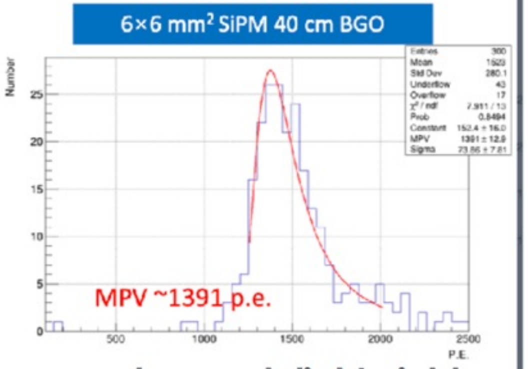


Large dynamics SiPMs



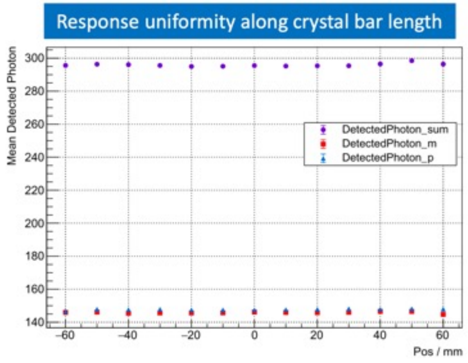
Cosmic ray test

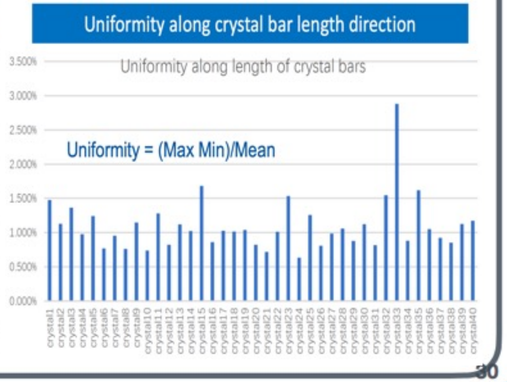




good enough light yield

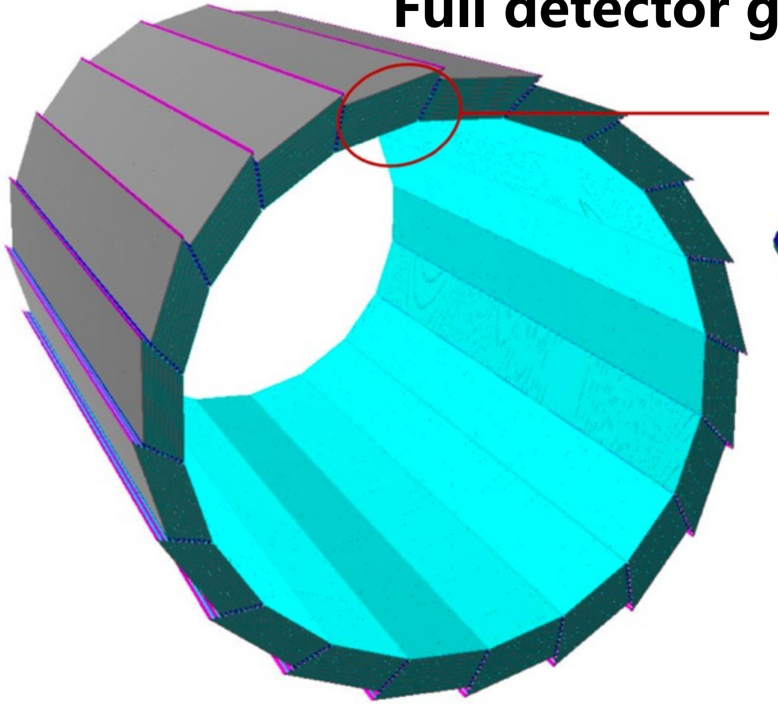
Response uniformity

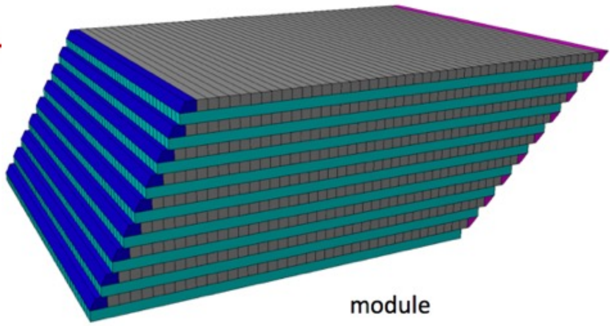




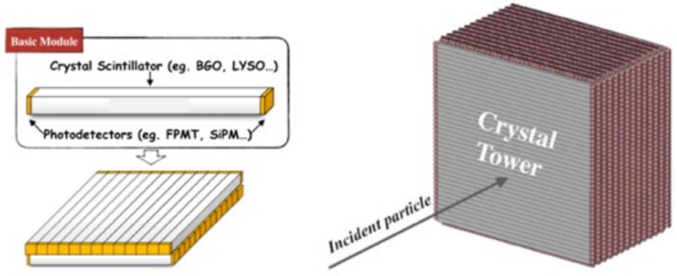
High granularity crystal ECAL with long bars

Full detector geometry

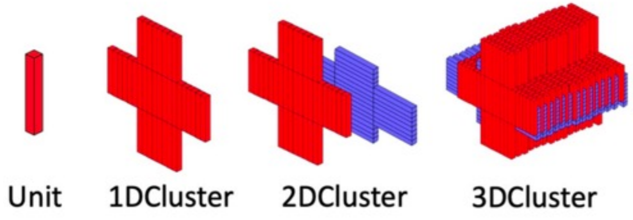


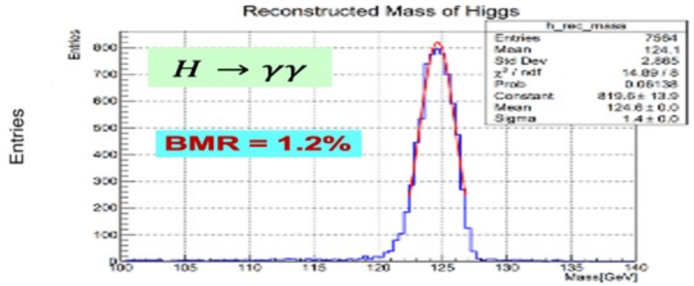


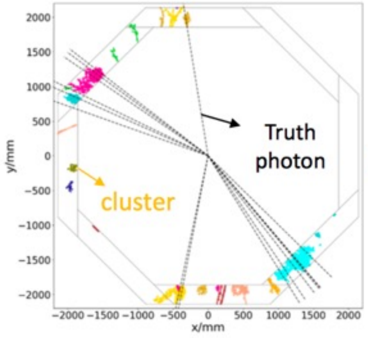
transverse size: 1-2 cm
length 40-60cm



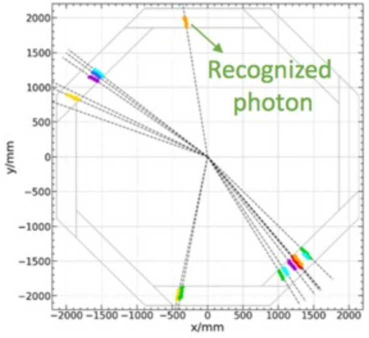
Reconstruction



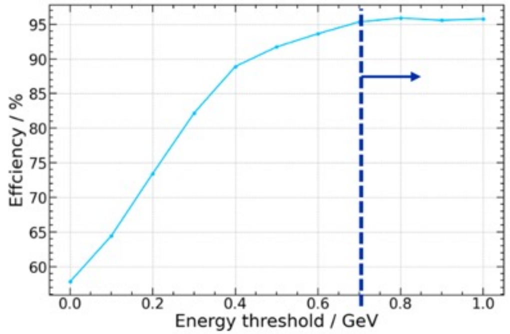




Clustering



Photon recognition

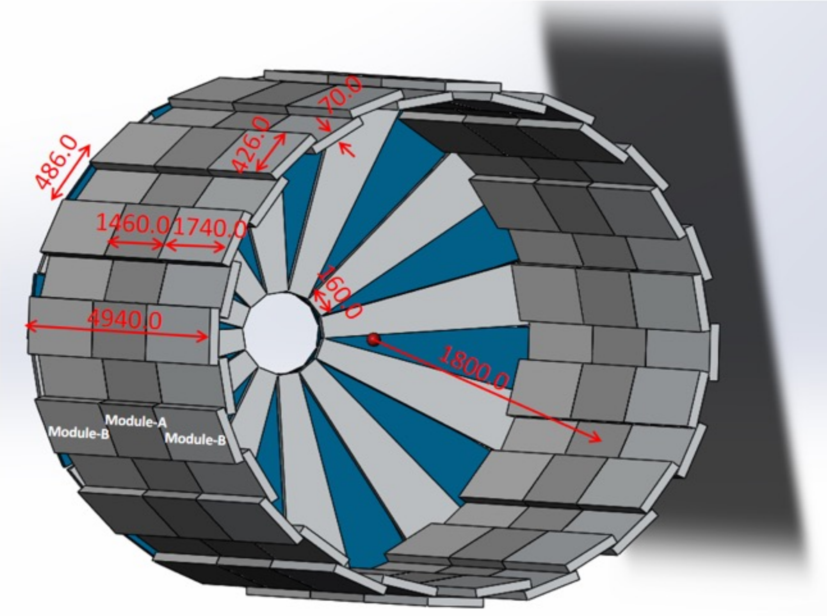


Recognition efficiency

Photon identification efficiency > 95% when E > 0.7 GeV

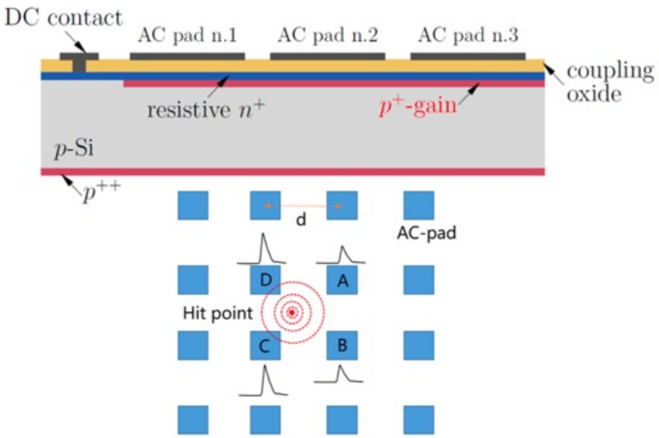
TOF detector options

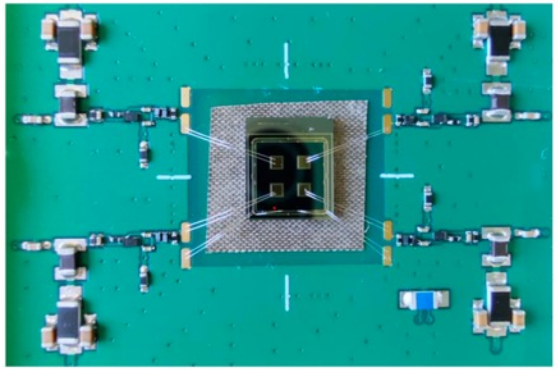
MRPC

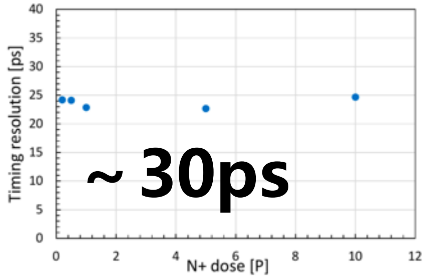


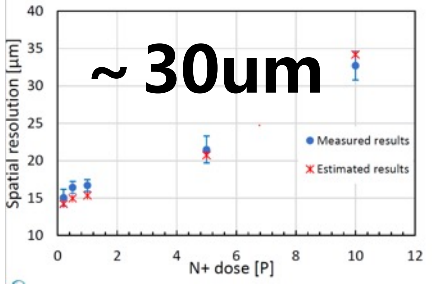
1、时间分辨：<35ps
2、PID of π/k: 2.5GeV @3σ
3、TOF面积：~77m²
4、电子学道数：37632
5、电子学功耗：17mW/道
6、造价估算：3420万RMB (MRPC 784万元)

AC-LGAD

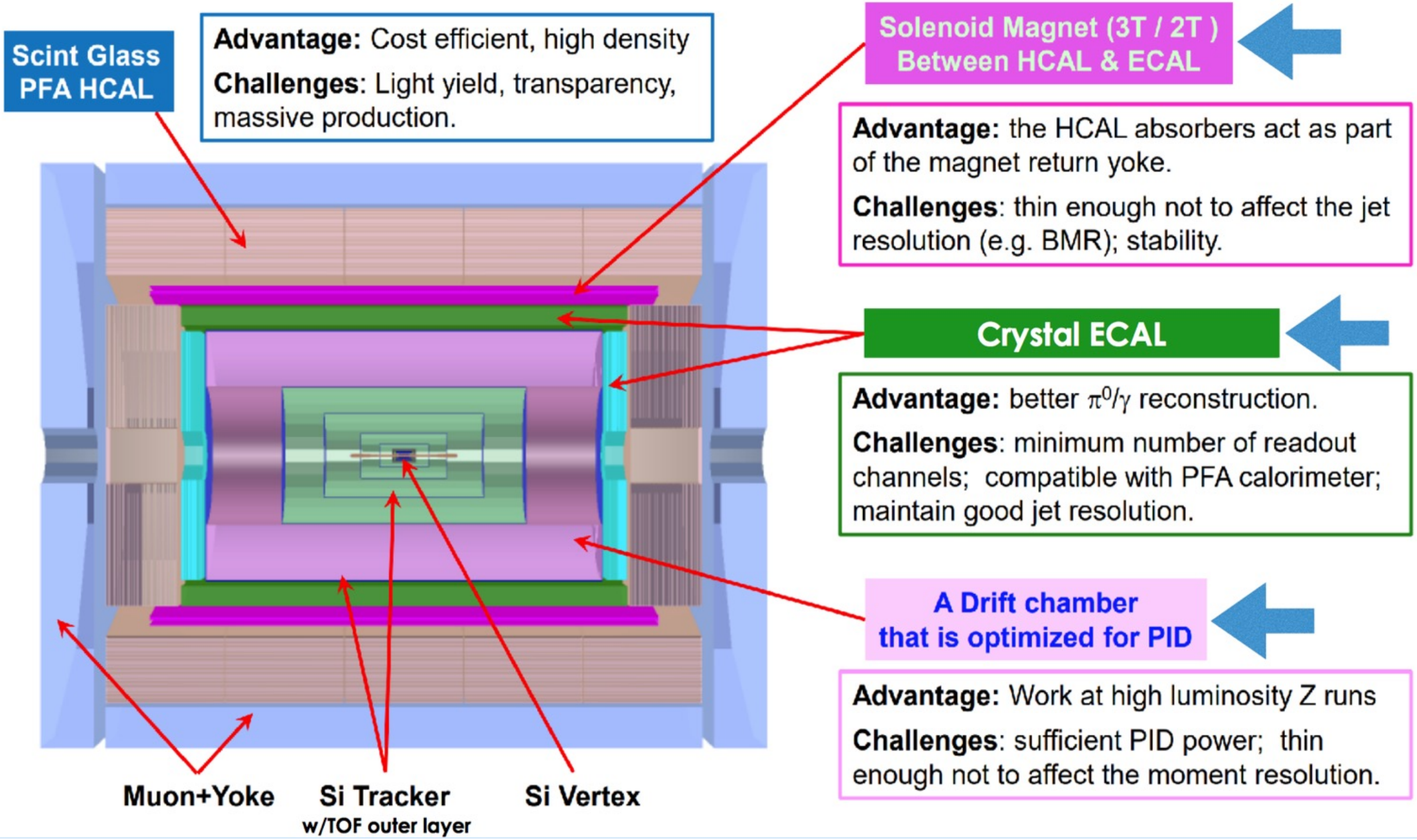








The 4th Detector Concept



Excellent e/gamma energy resolution;

PID capability;

Better hadronic energy resolution;

Magnet in much reduced size.

BMR: 4% → 3%