CEPC Detector R&D, Collaboration and Plan

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CEPC Physics Program

Factory of Higgs / W / Z / top quarks

High precision Higgs, EW, flavor physics and QCD studies, and probe for physics BSM

Operation mode			ZH	Z	W^+W^-	
			~240	~91.2	~160	~360
Run time [years]			7	2	1	-
CDR (30 MW)		L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		[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**
		[ab^{-1}, 2 IPs]	20	96	7	1
		Event yields [2 IPs]	**4×10^{6}**	**4×10^{12}**	**2×10^{7}**	**5×10^{5}**

Physics potential similar to FCC-ee, ILC, CLIC

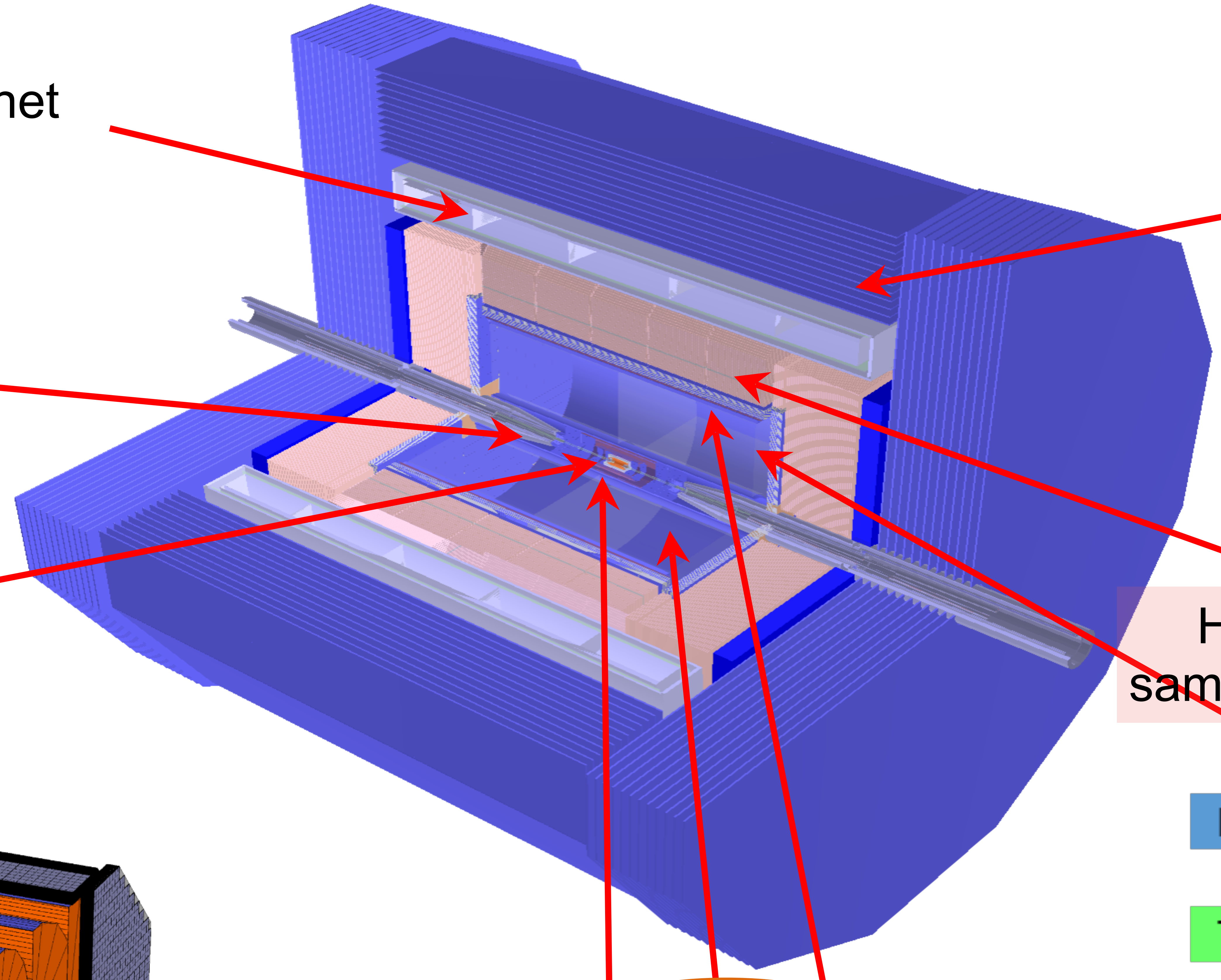
Requirements of Detector and Key Technologies

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

These specifications already include some of the 4^{th} detector design

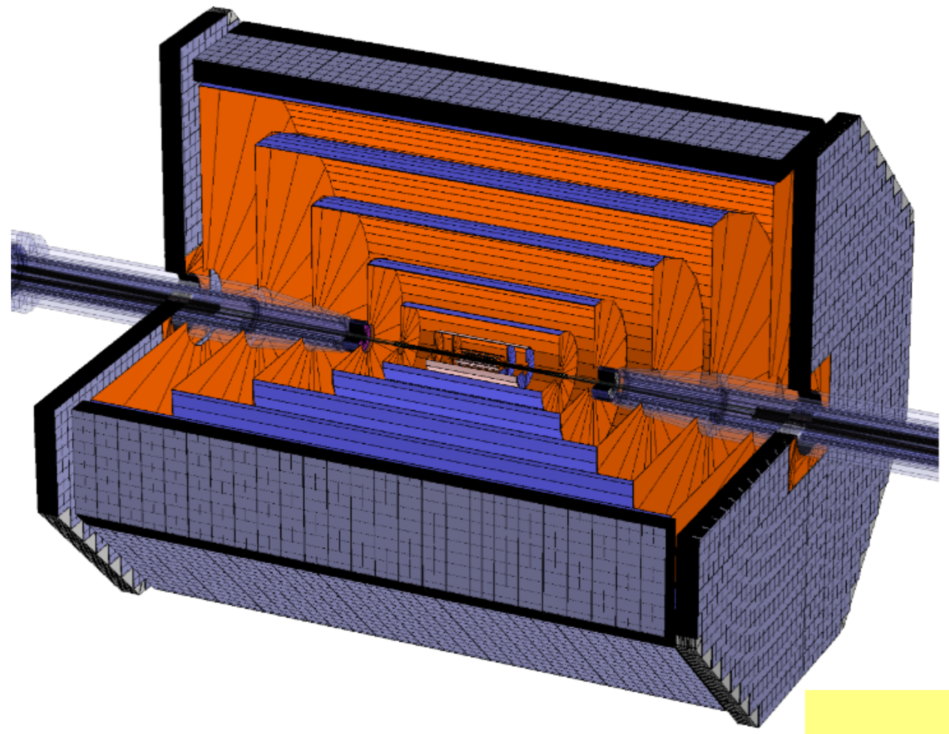
Detector Design in CEPC CDR

Particle Flow Detector (Baseline Detector)



Integrated detector studied

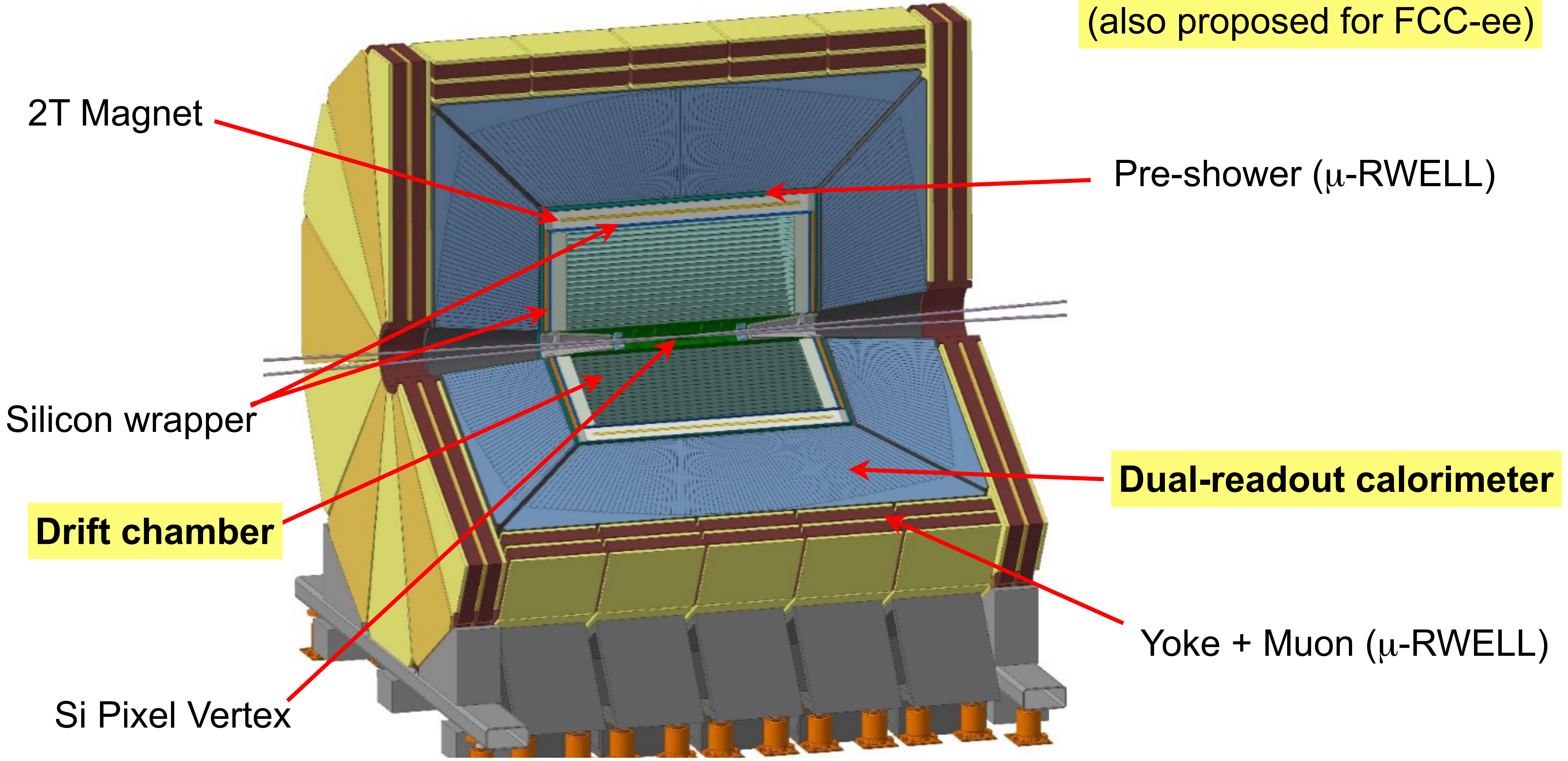
Full Silicon Tracker



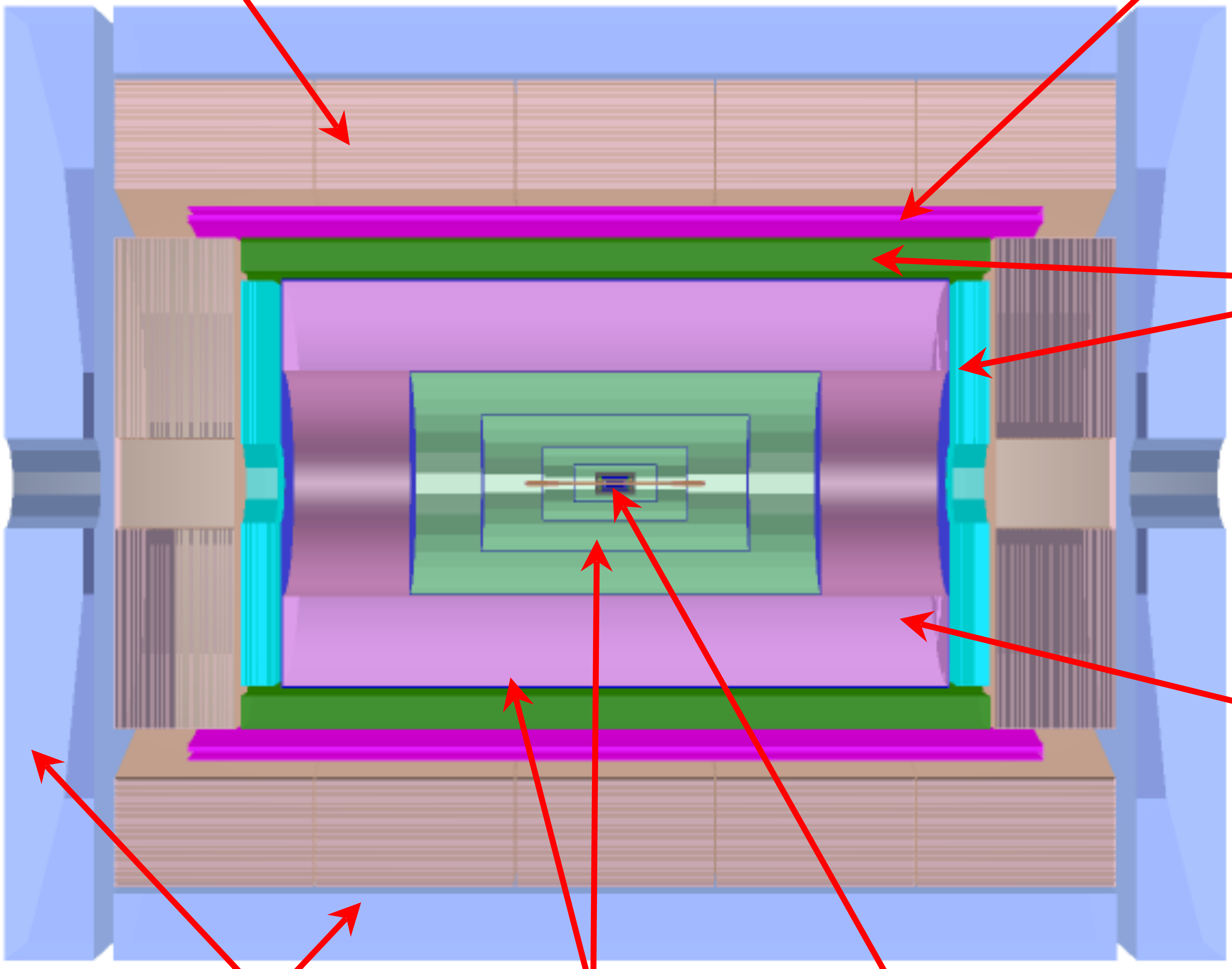
An alternative plan, especially if TPC has difficulty in the high luminosity Z mode

IDEA Detector Design in CEPC CDR

IDEA concept
(also proposed for FCC-ee)



The 4th Conceptual Detector Design



Advantage: Cost efficient, high density

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

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

Challenges: Thin enough not to affect the jet resolution; Stability.

Advantage: Better π^0/γ reconstruction

Challenges: Minimum number of readout channels; Compatible with PFA calorimeter; Maintain good jet resolution.

Advantage: Work at high luminosity Z runs

Challenges: Sufficient PID power; Thin enough not to affect the moment resolution; Need supplementary ToF detector

Detector R&D Breakdown

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

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

Large number of detector R&D projects on-going

Not all at the same level of maturity

Some have reach the large-scale prototype level

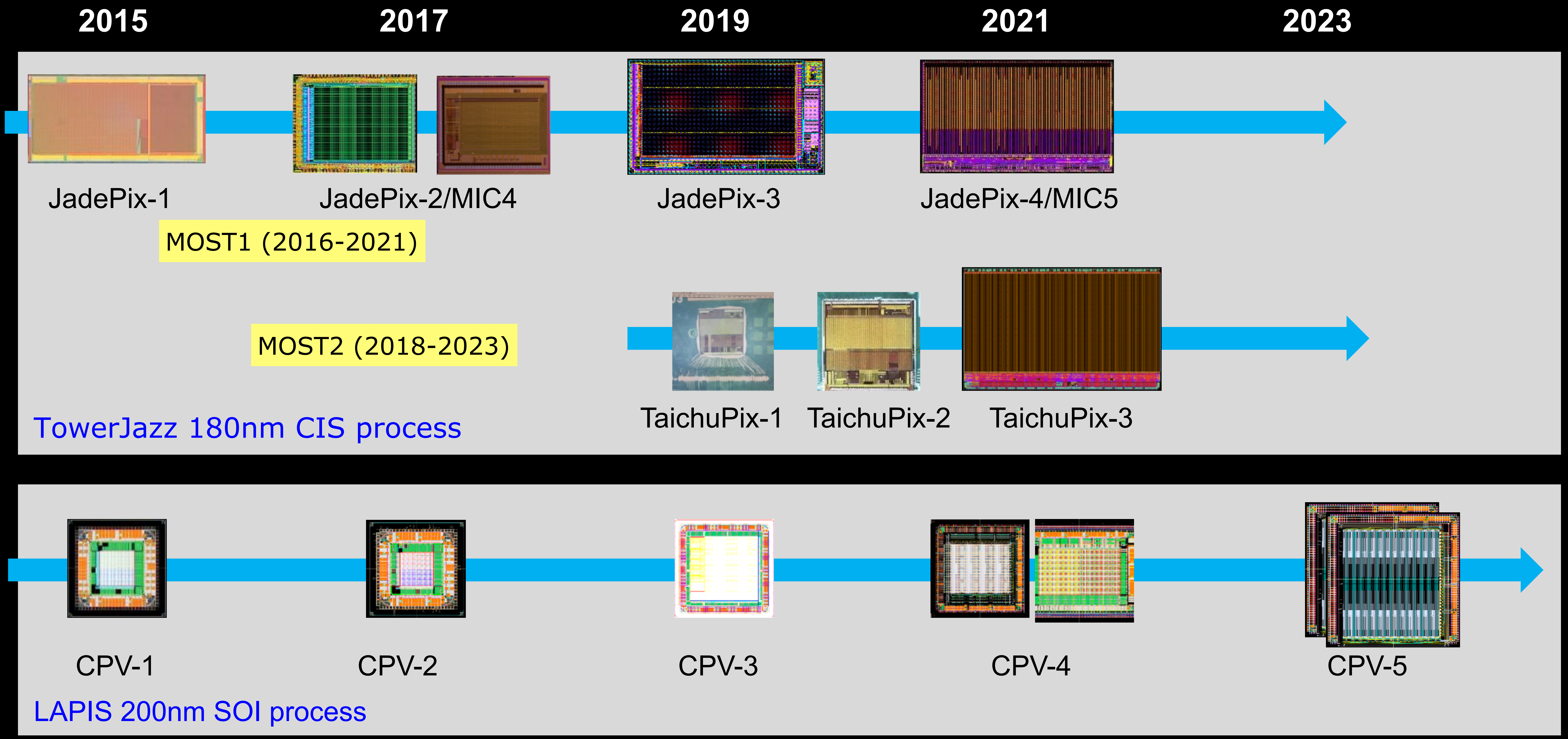
Prototypes under evaluation

PFA calorimeter

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 to be measured $0.5 \times 0.5\ \mathrm{cm}^2$
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}	$< 60\%/\sqrt{E(\mathrm{GeV})}$	Prototyping
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 mm	Prototyping

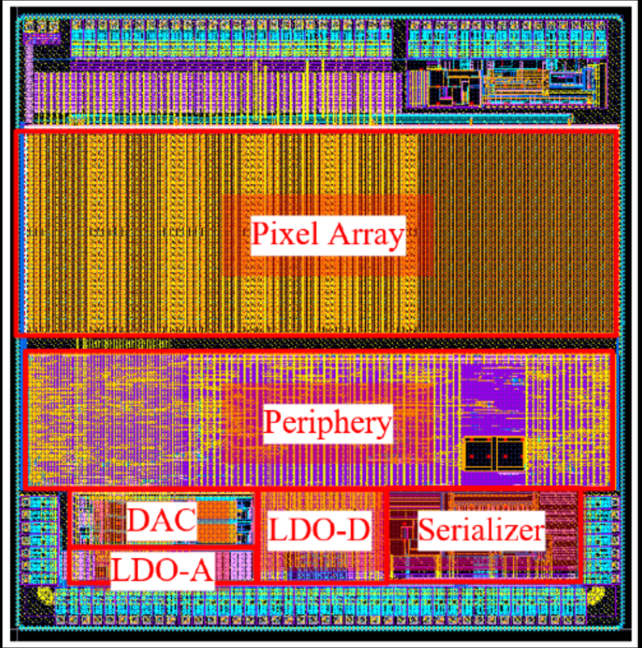
Pixel Vertex Detector

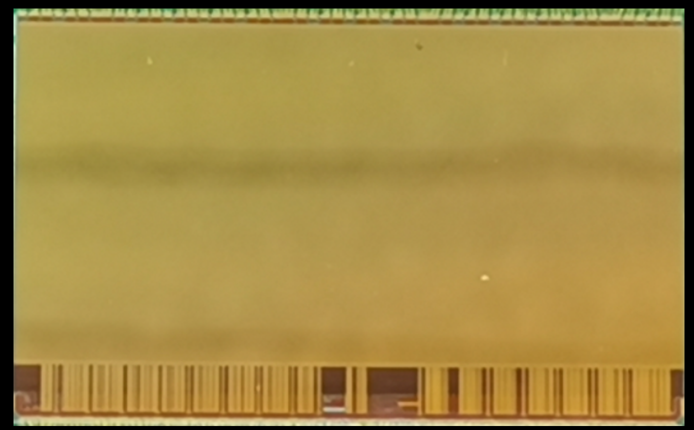
Timeline of Silicon Pixel Sensor R&D



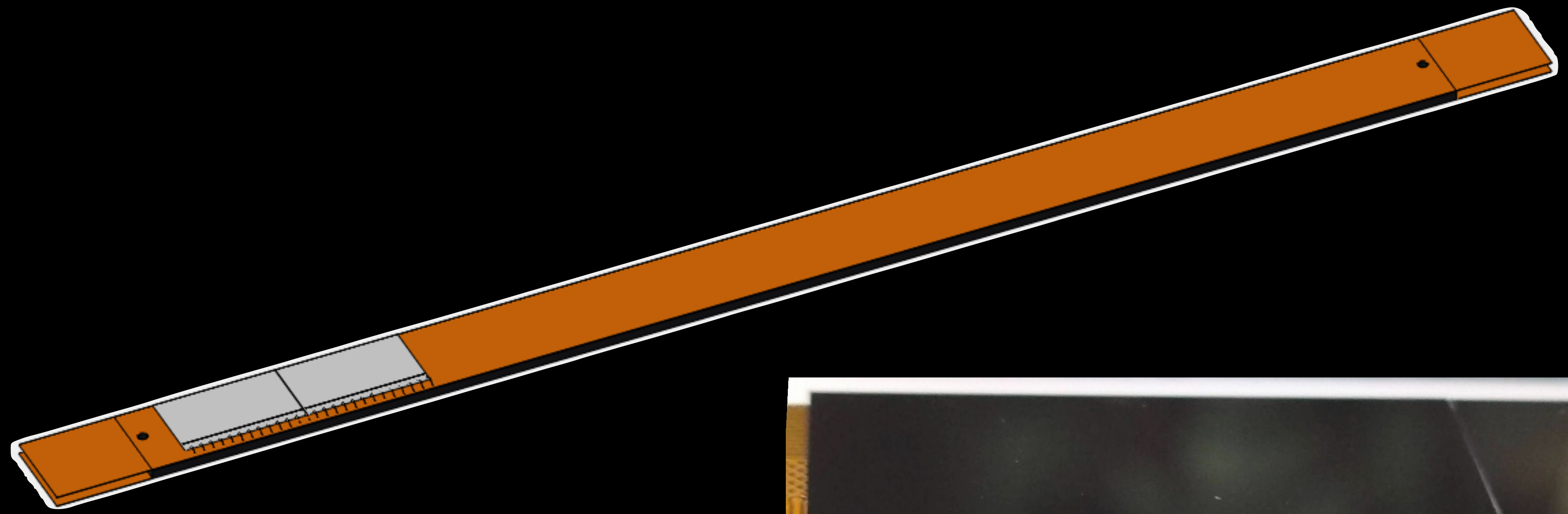
Overview of CEPC vertex detector R & D

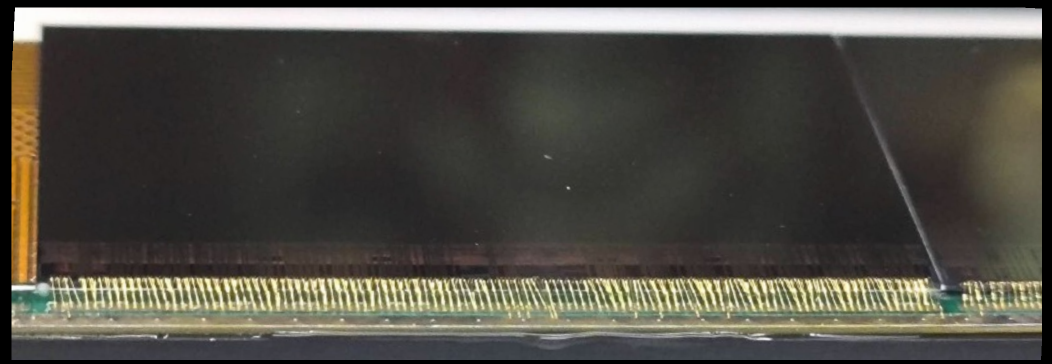
CMOS imaging sensor prototyping





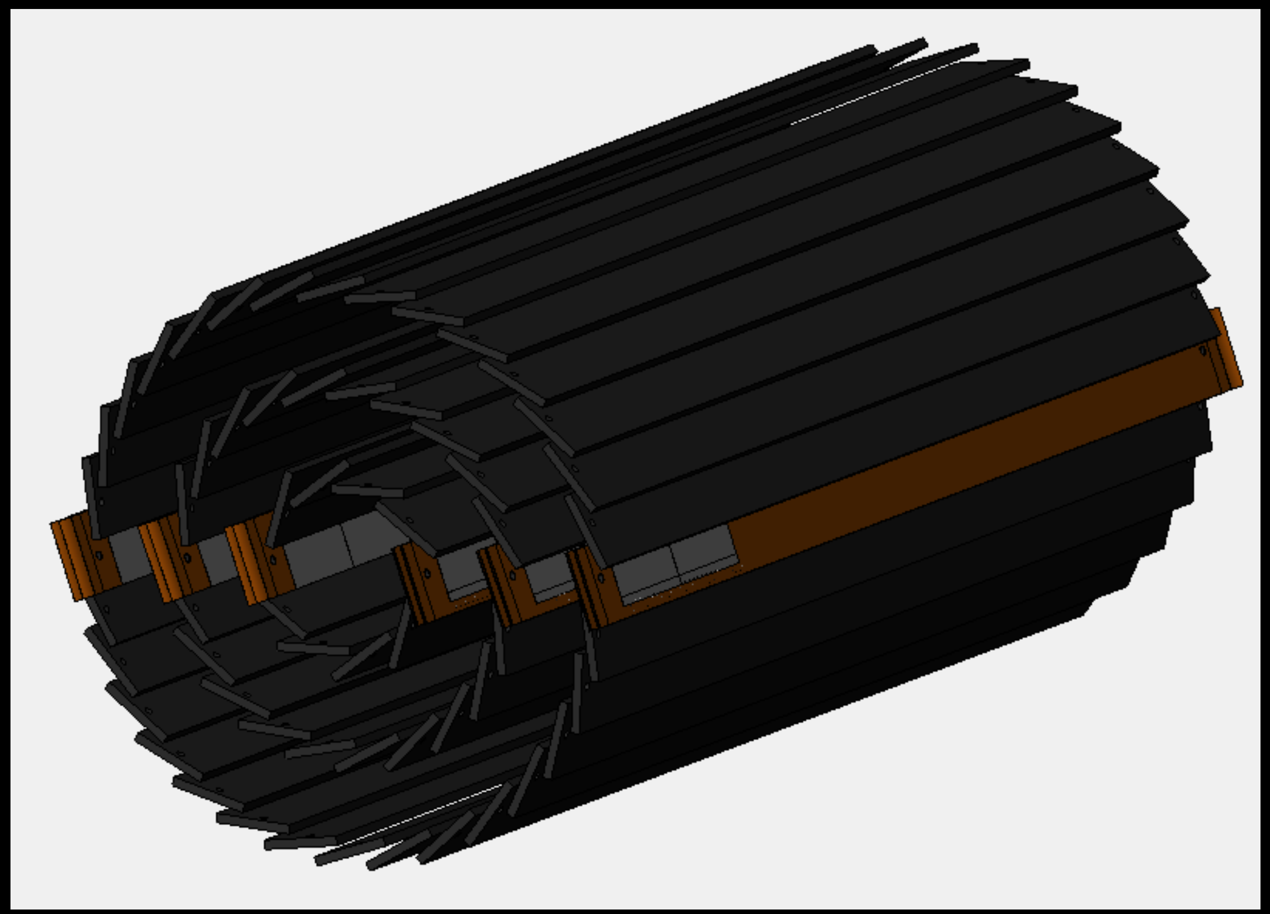
Detector module (ladder) Prototyping

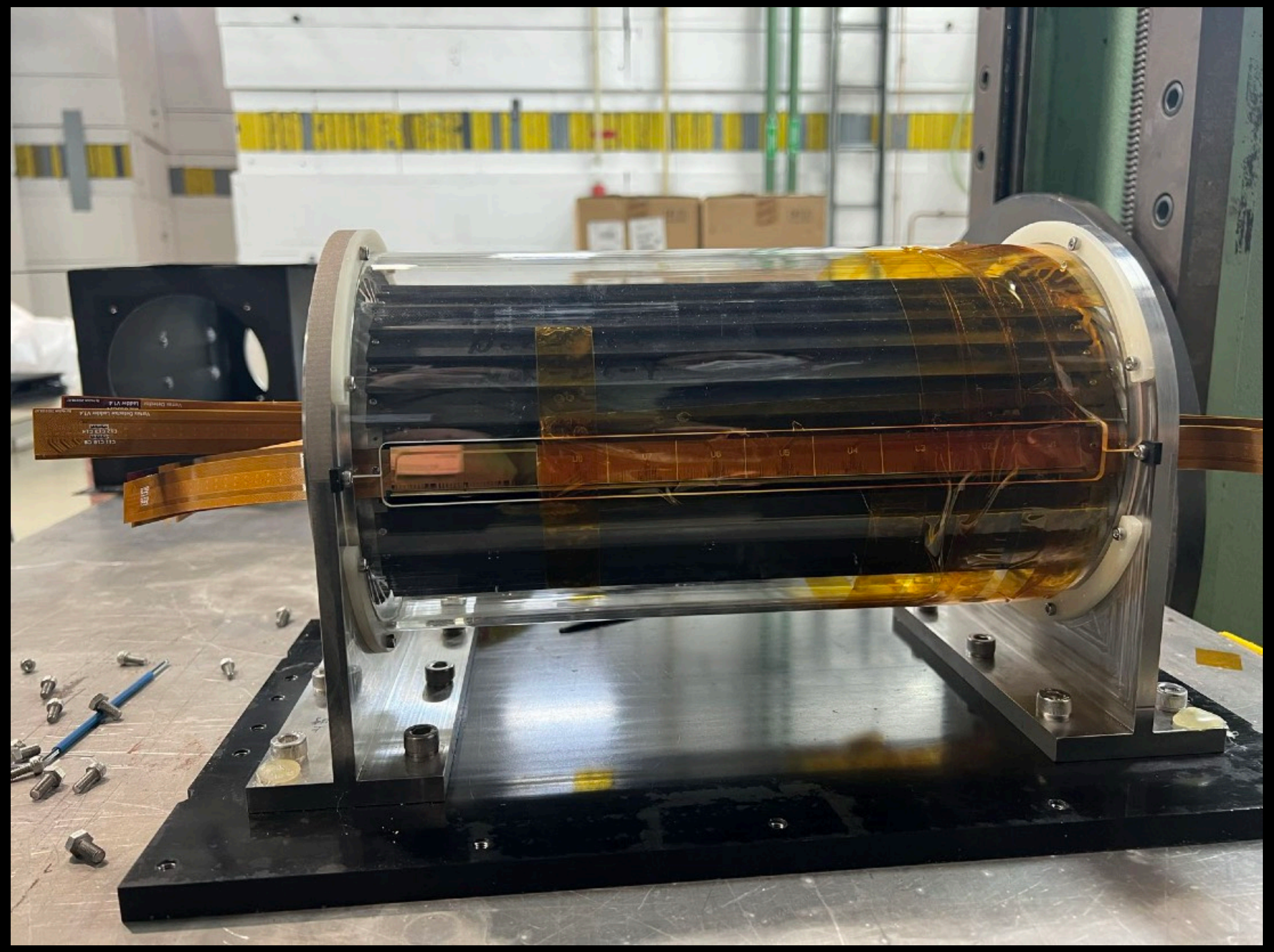




Ladder readout system

Vertex detector Prototype





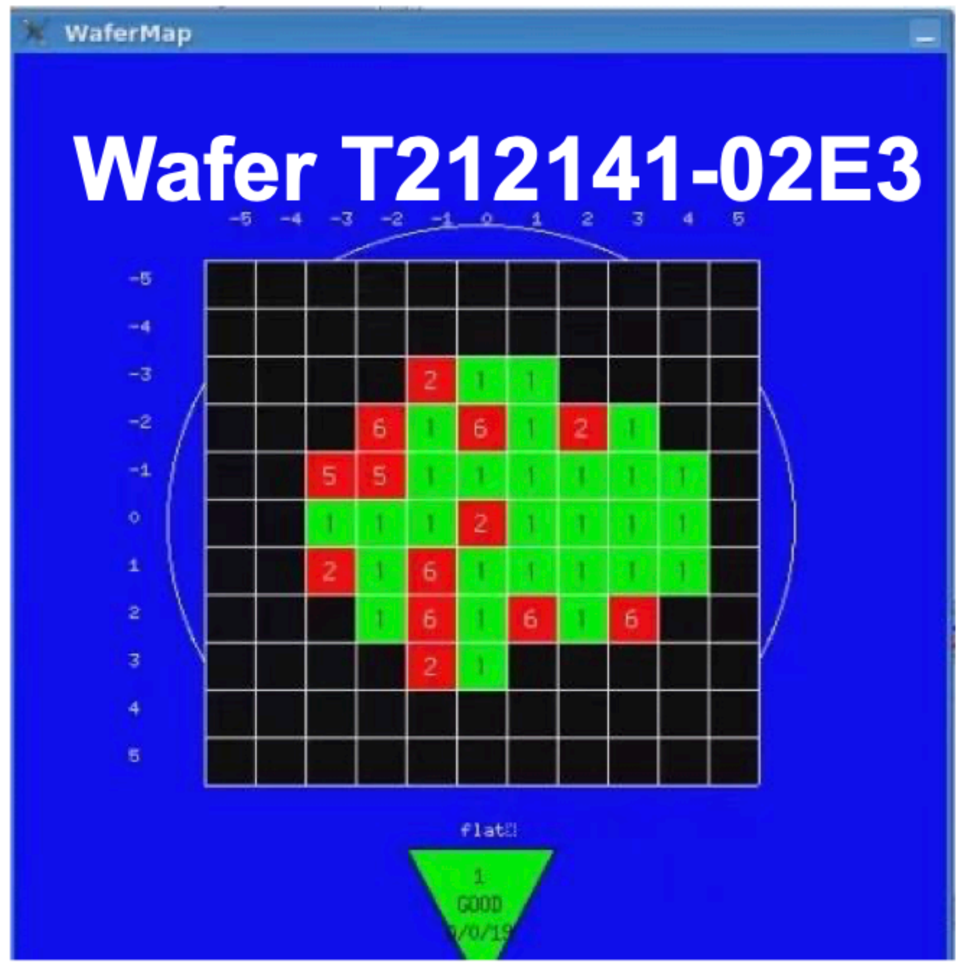
- Design CMOS imaging sensor chip
- Detector Module prototyping
- Vertex Detector assembly and testbeam

MOST 2

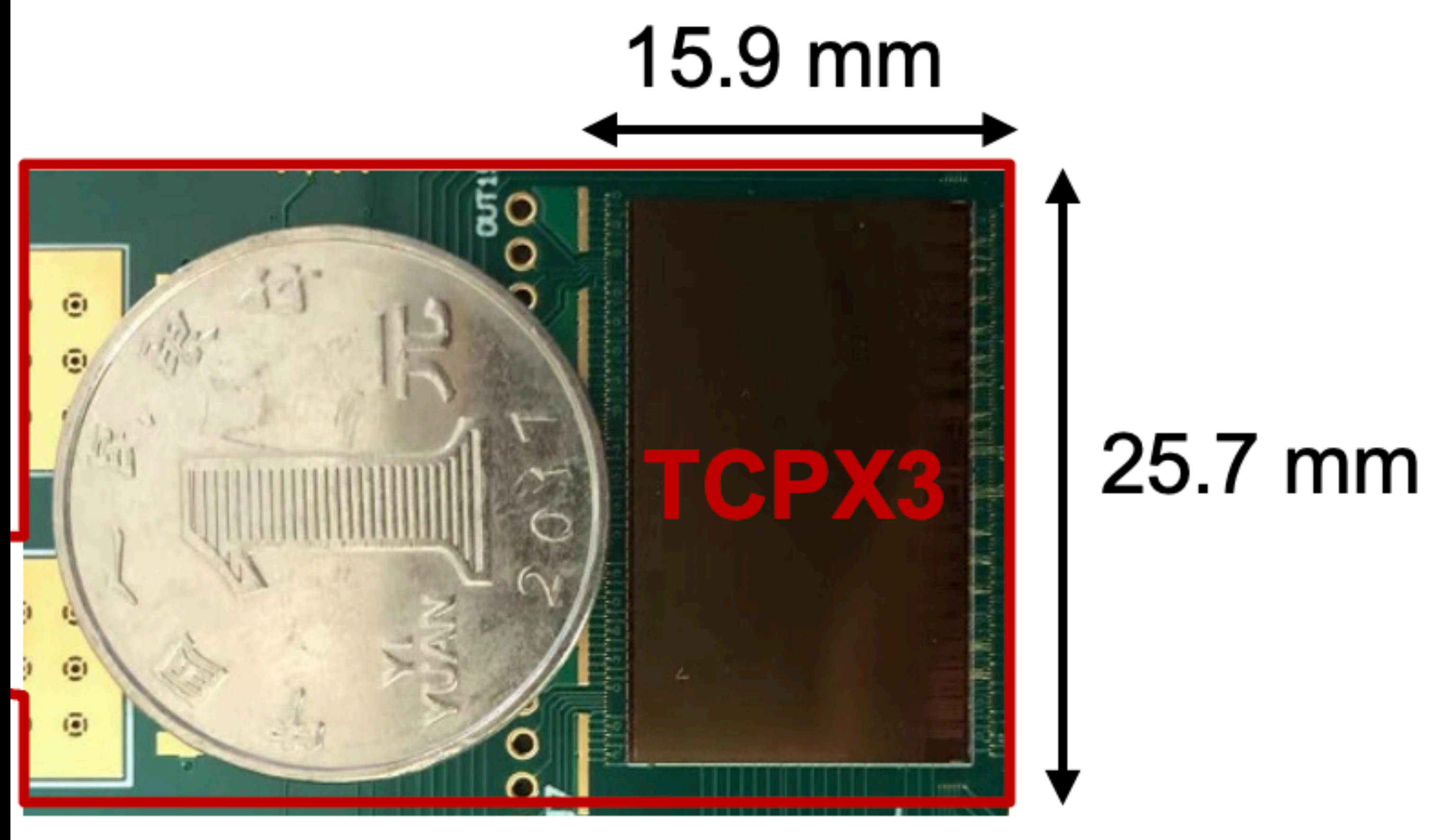
Full-size TaichuPix3 prototyping (engineering run)

- **Developed the first full-size CMOS pixel sensor for particle detector in China**
  - **Full size 1024×512 Pixel array, Chip Size： 15.9×25.7mm**
    - **25μm×25μm pixel size → high spatial resolution**
    - **Process: Towerjazz 180nm CIS process**
  - **Fast Periphery digital readout, high-speed data interface**

	ALPIDE	ATLAS-MAPS (MONOPIX / MALTA)	MIMOSA
Pixel size	√	X	√
Readout Speed	X	√	X
TID	X (?)	√	√



An example of wafer test result



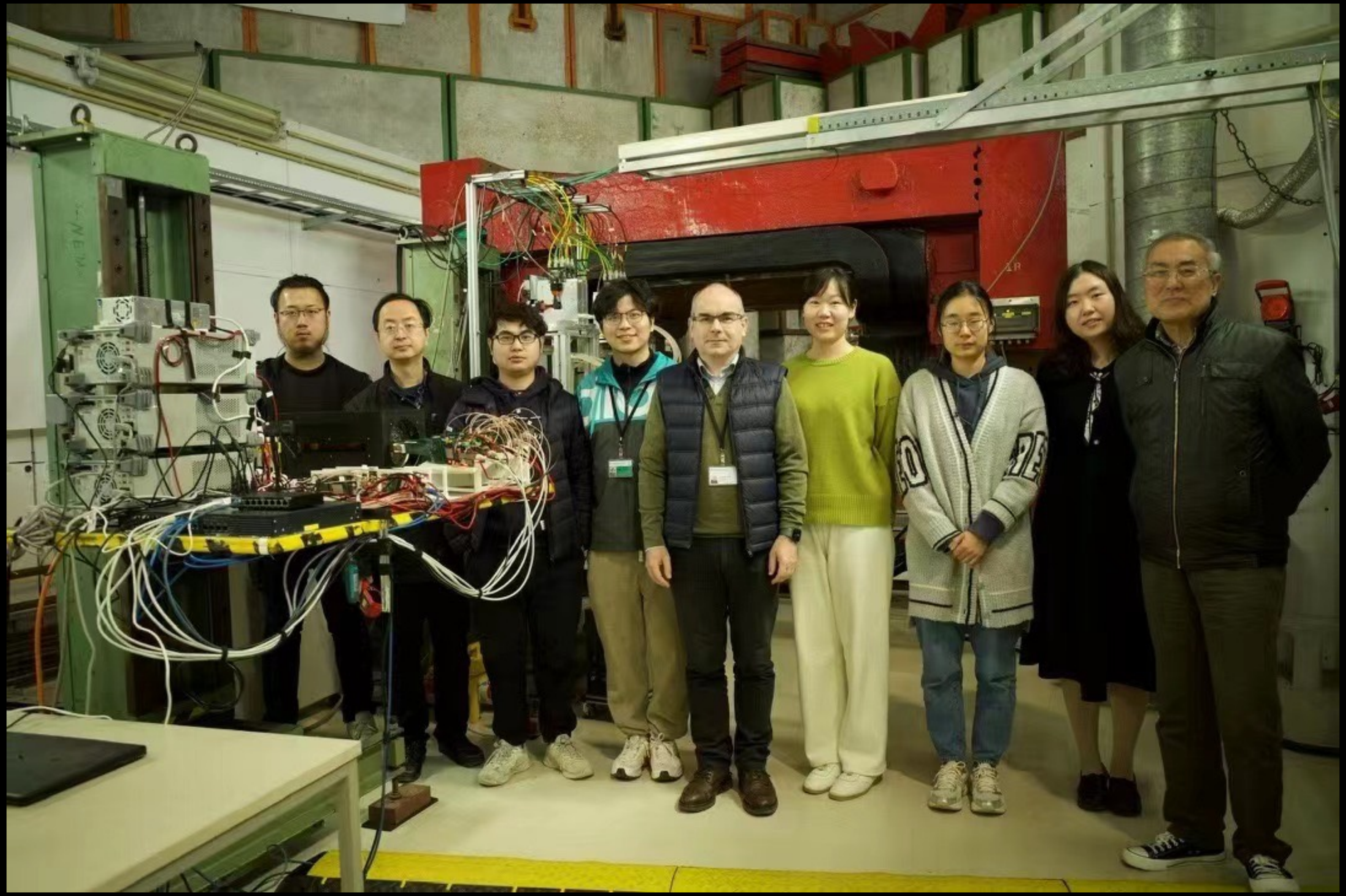
TaichuPix-3 chip vs. coin

Test beam @ DESY

- 2nd testbeam: April 11-23 2023 DESY test beam in Germany (4-6 GeV electron)
  - Vertex detector prototype testbeam
- 1st testbeam: Dec 12-22 2022 DESY test beam in Germany (4-6 GeV electron)
  - TaichuPix Beam Telescope testbeam

2022 DESY test beam

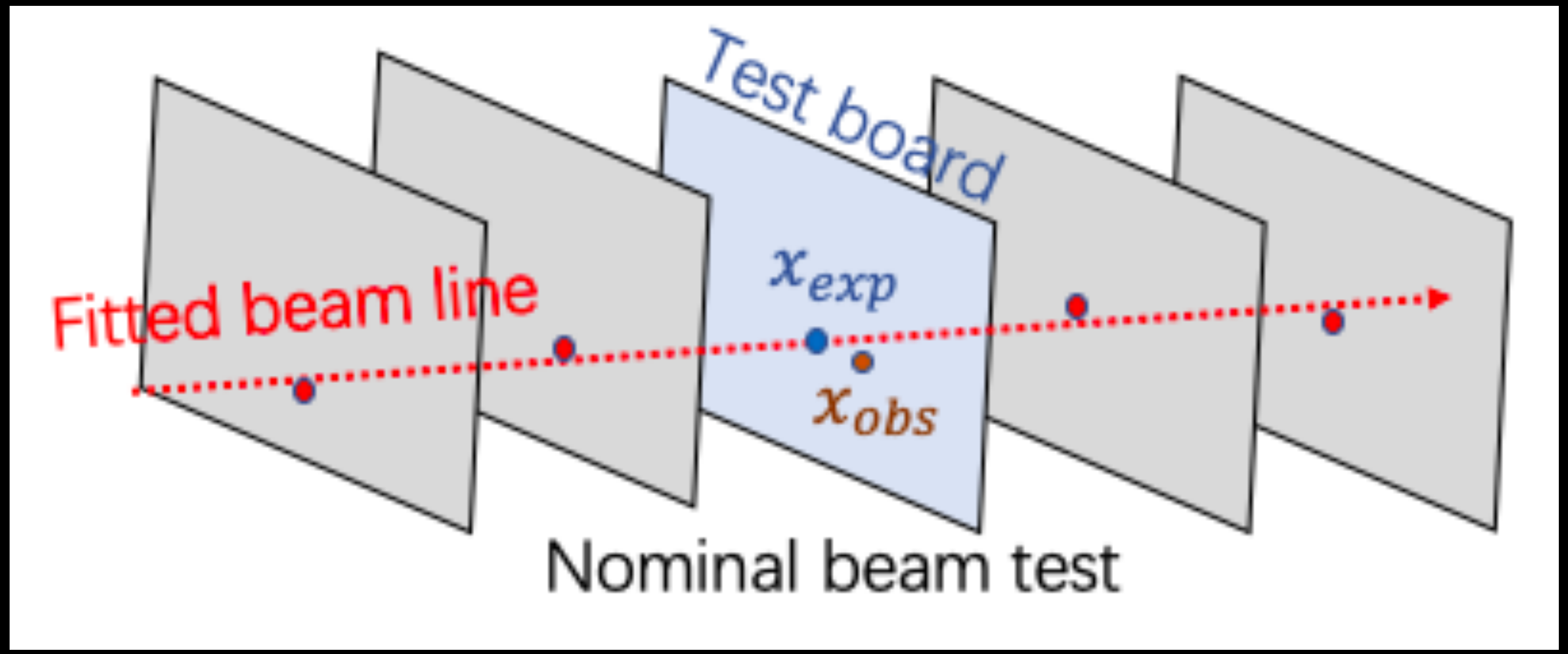
2023 DESY test beam



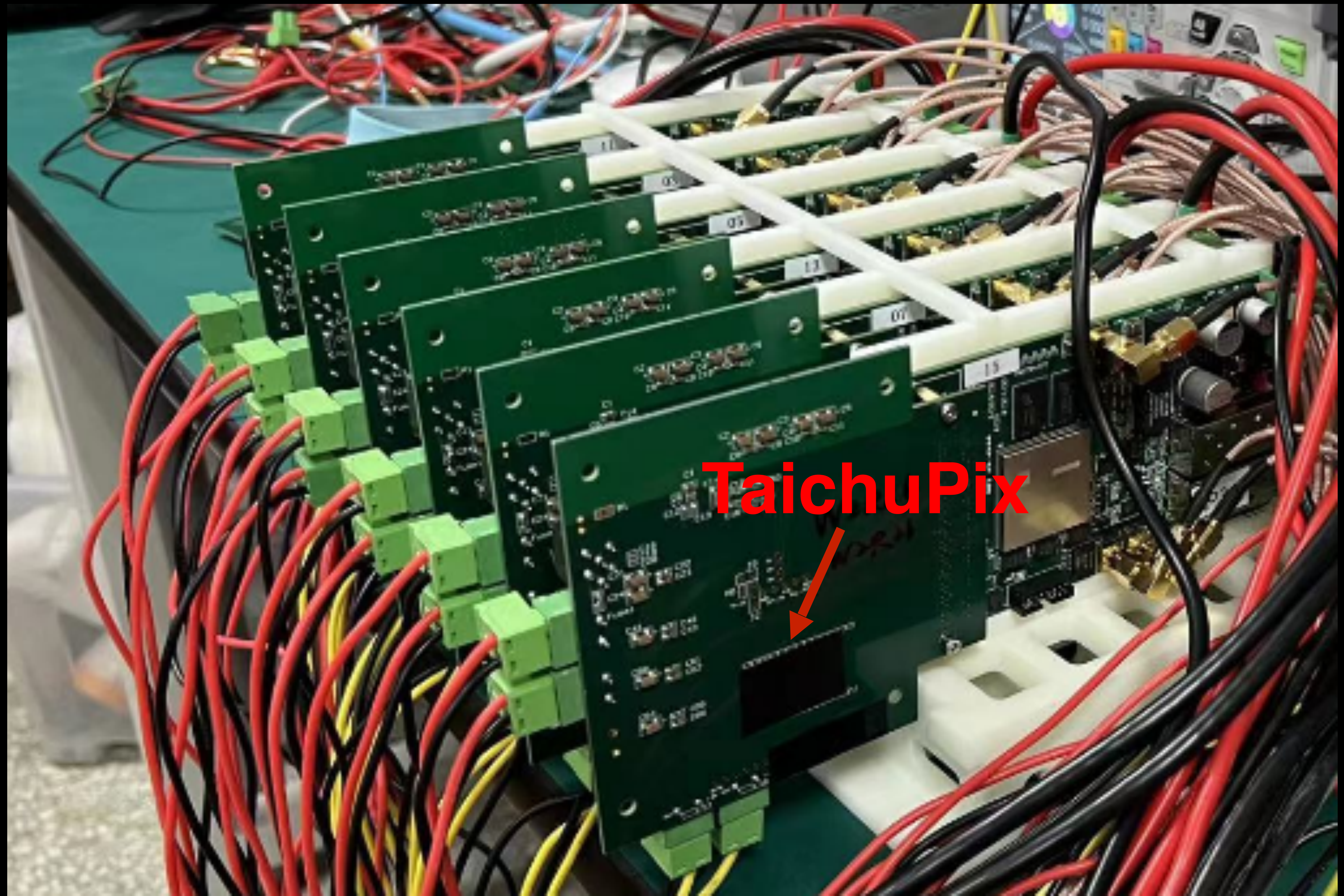
Excellent collaboration with DESY testbeam team

Spatial resolution for Taichupix

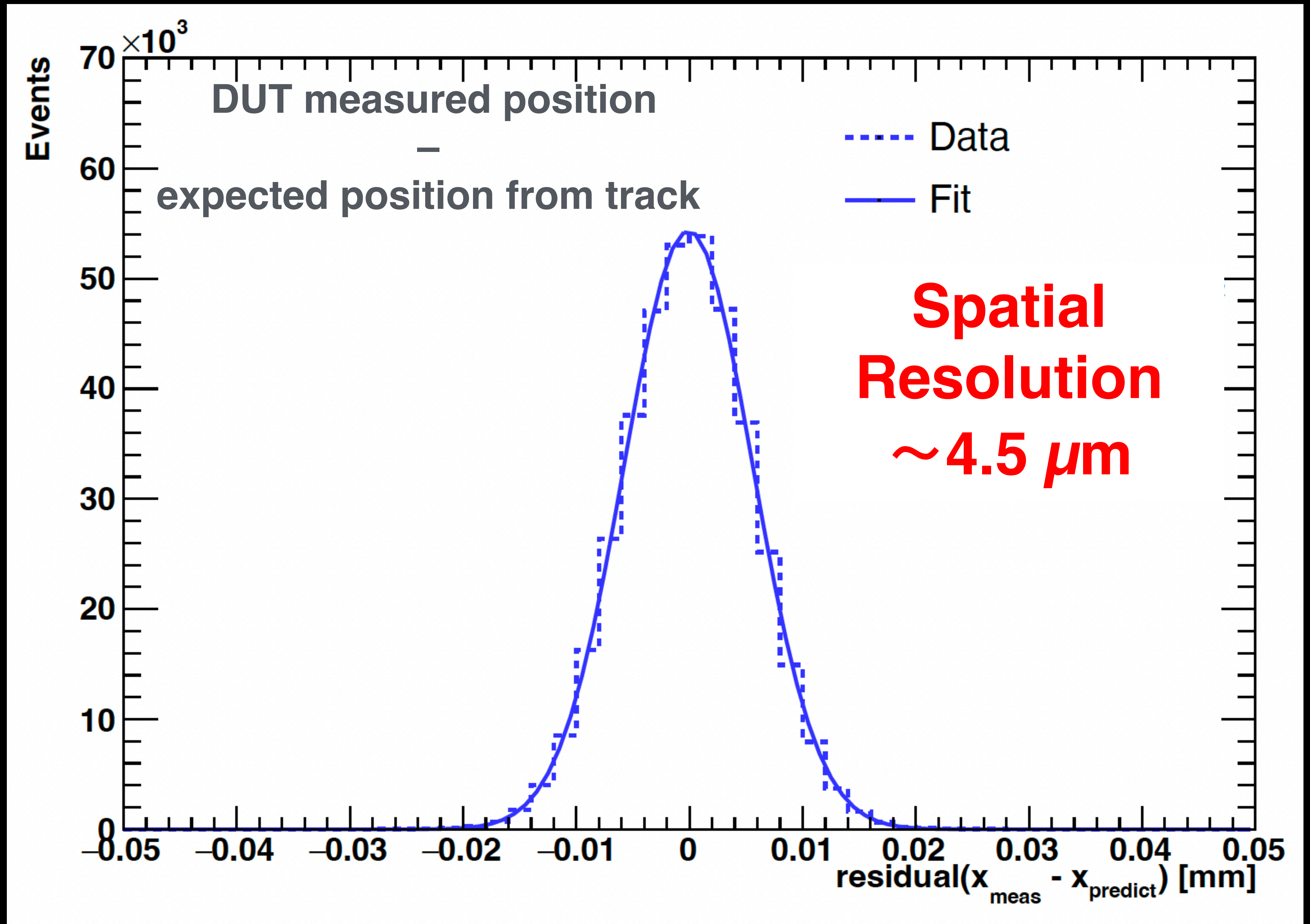
- **The 6-layer of TaichuPix-3 telescope built**
  - Tested at DESY with 4-5 GeV electron beam, 1kHz rate
  - One layer of TaichuPix used as Detector-Under-Test (DUT)
  - Other five layers as beam telescope used for track fitting
  - Spatial resolution of TaichuPix reach 4.5 μm



Setup for Taichupix beam telescope



Residual distribution

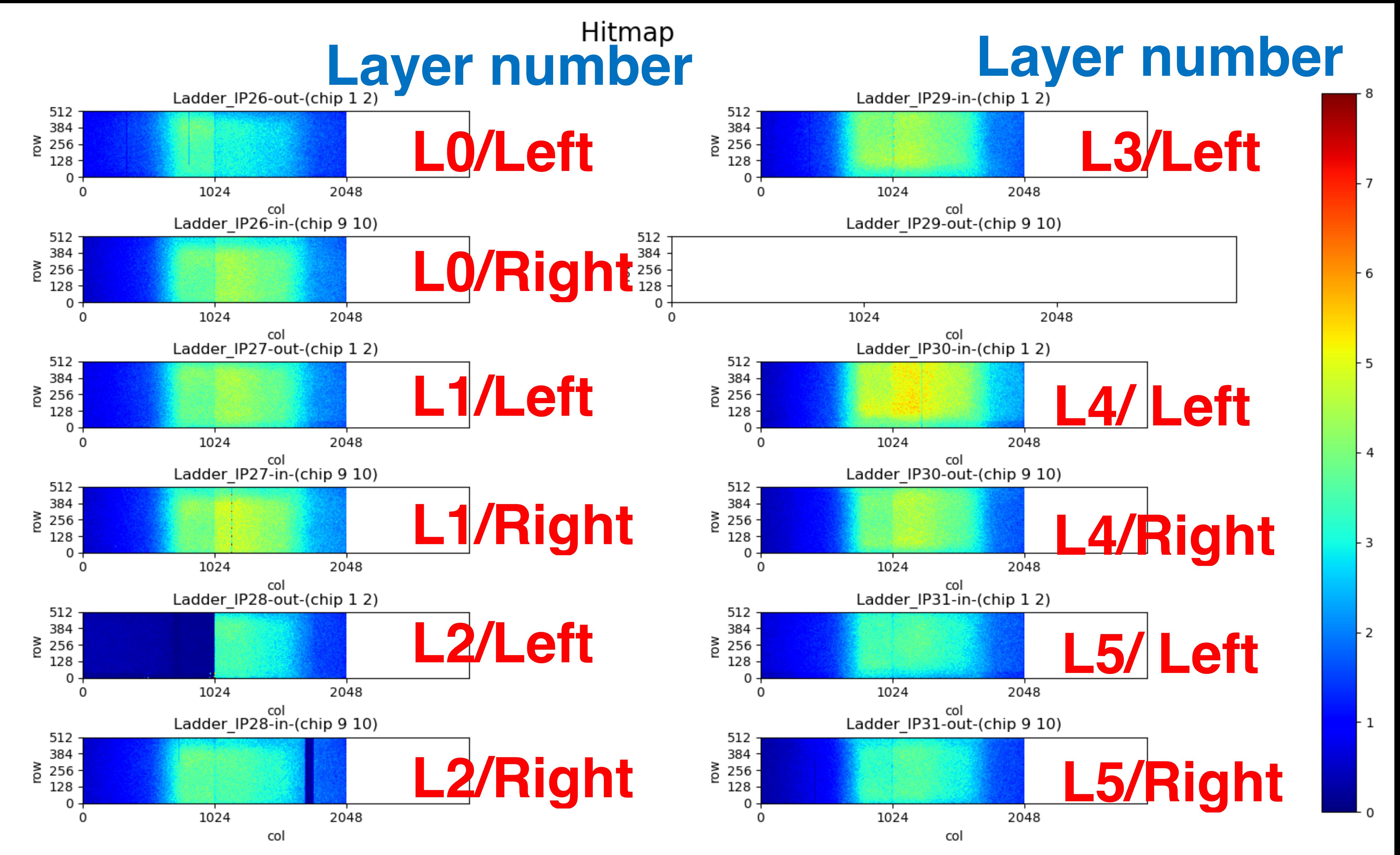


Test beam @ DESY for vertex detector prototype

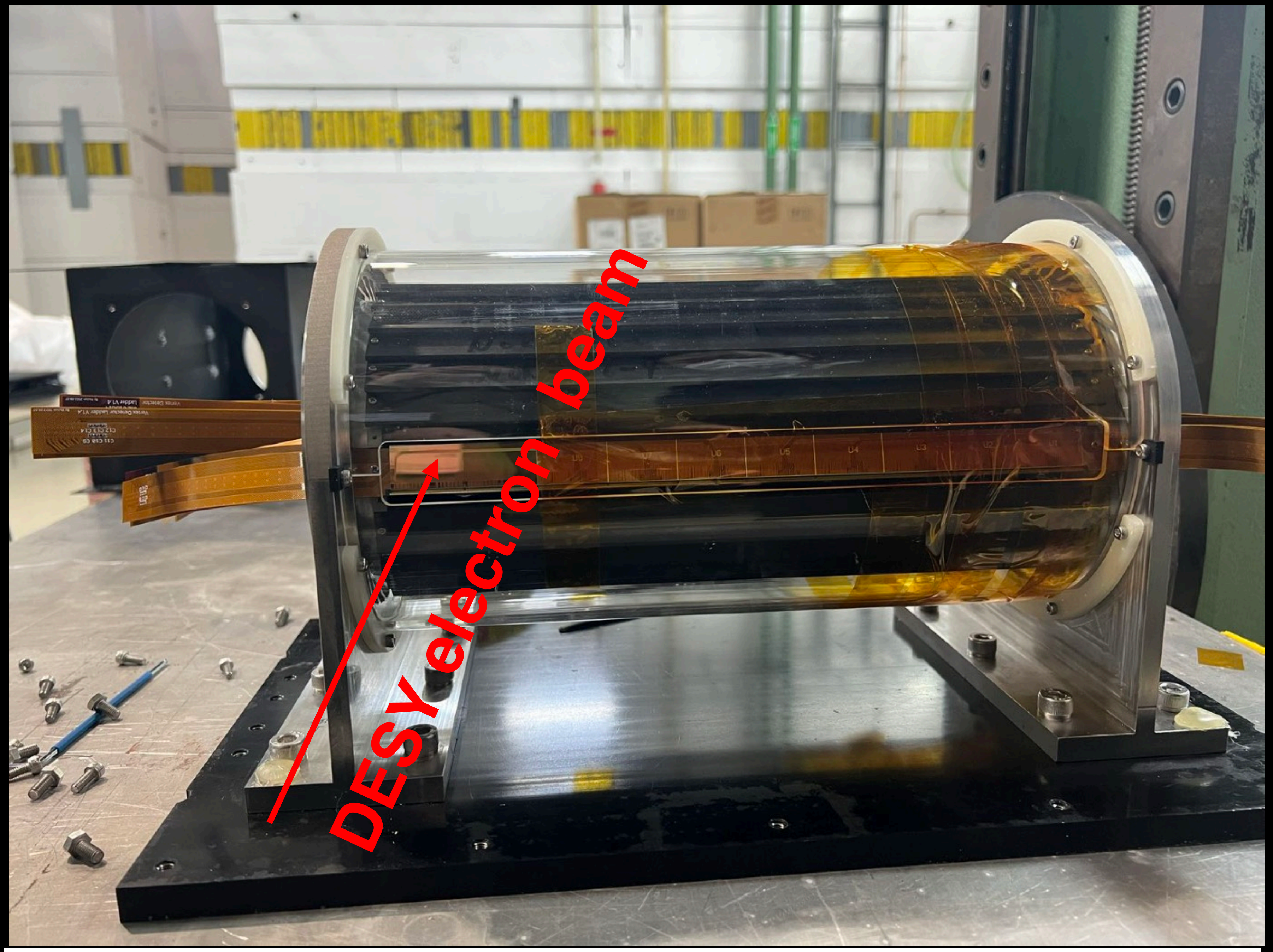
- **Six double-side ladders installed on the vertex detector prototype for DESY testbeam**
  - 12 flex PCB , 24 Taichupix chips installed on detector prototype
  - Beam spot (~2×2cm) is visible on detector hit map

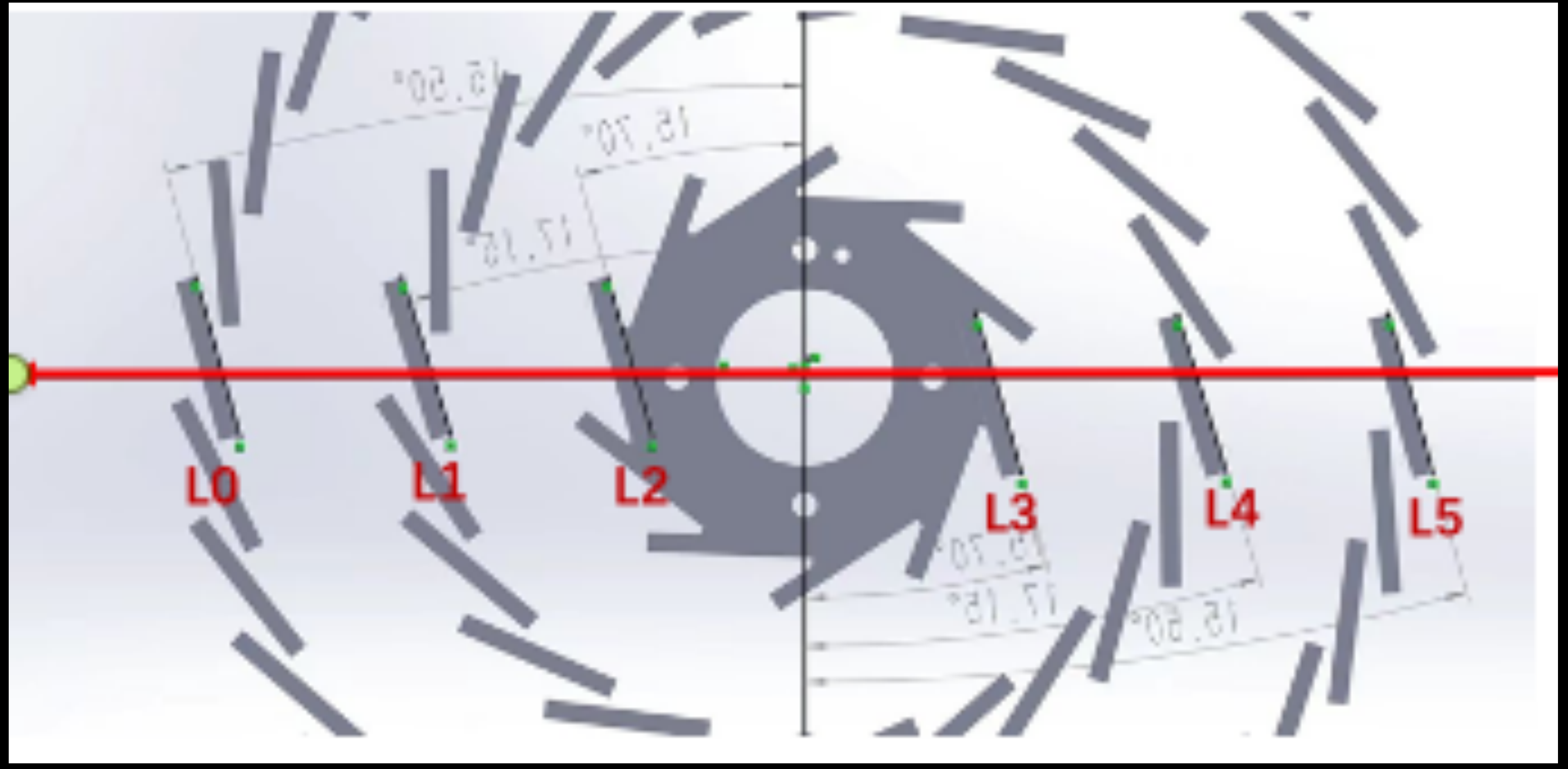
Spatial resolution 4.9 μm with vertex prototype

Hit maps of all layers taichupix on prototype



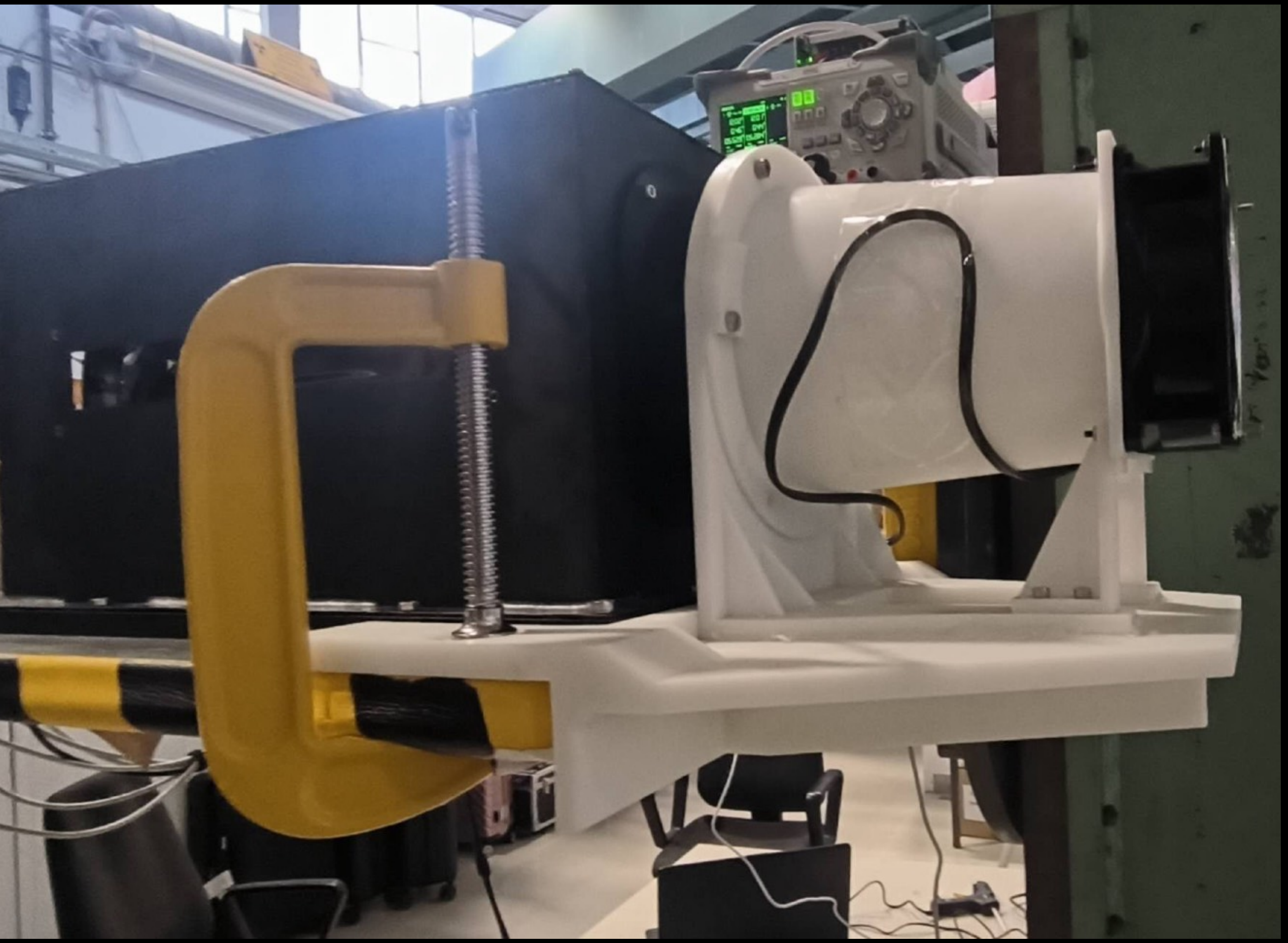
Detector prototype in testbeam

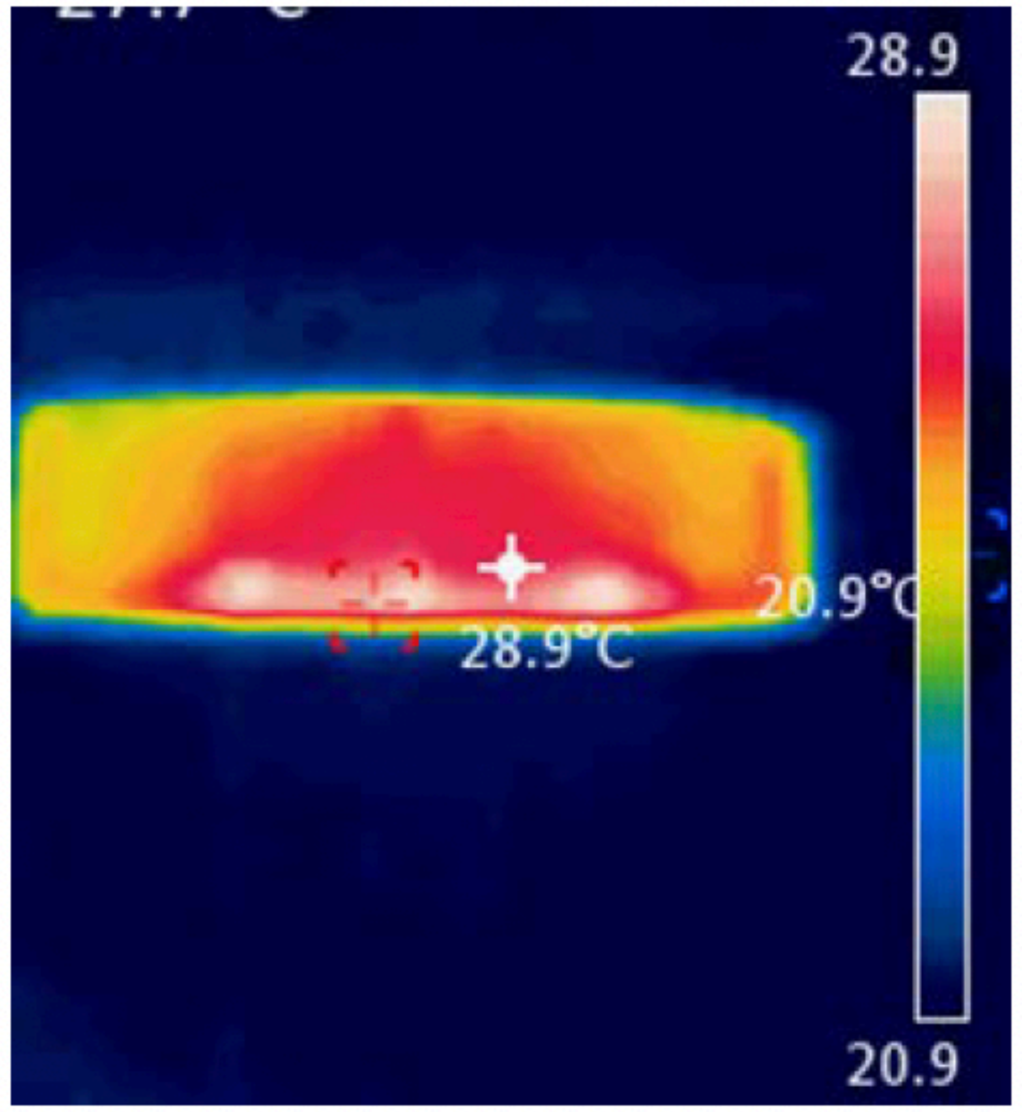




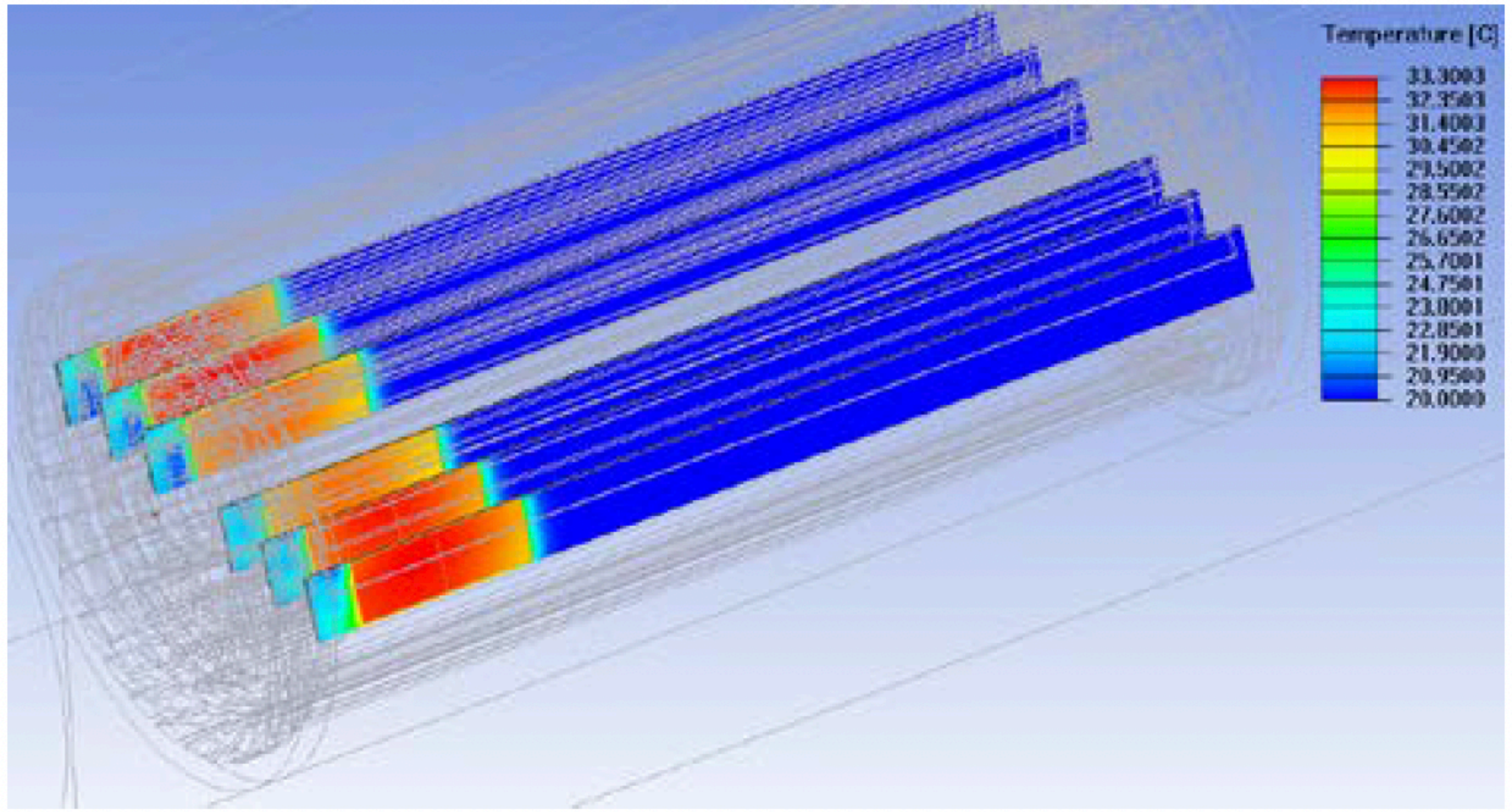
Air Cooling for vertex prototype

- Dedicated air cooling channel designed in prototype.
  - Measured Power Dissipation of TaichuPix chip: ~60 mW/cm2 (17.5 MHz clock in testbeam)
  - Before turning on the fan, chip temperature can go above 41 °C.
  - With air cooling, chip temperature can reduced to 25 °C (on average)
    - In good agreement to our cooling simulation
  - No visible vibration effect observed in position resolution offline analysis when turning on the fan





Chip temperature under cooling during beam test: Max 28.9 ℃



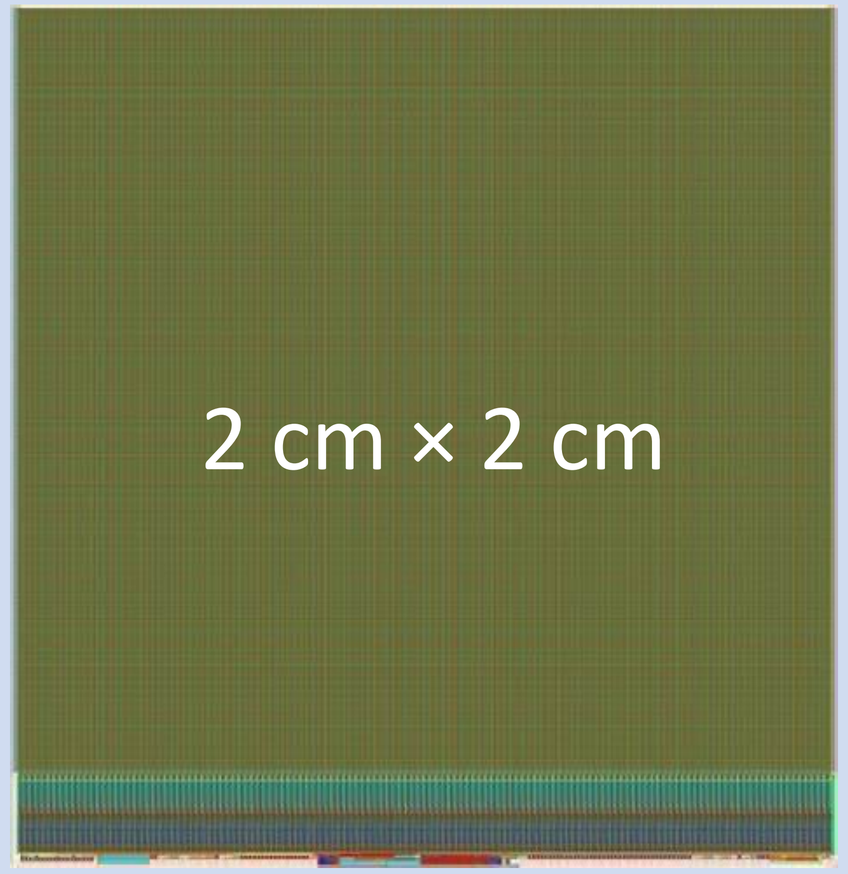
Prototype cooling simulation： Max 33.3 ℃

Silicon Tracker

Sensors with HVCMOS

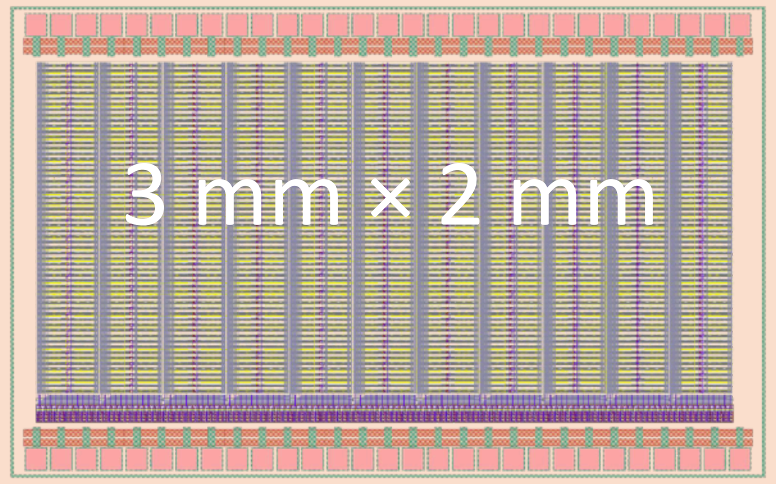
Silicon sensors with high-voltage CMOS considered a promising technology for the CEPC silicon tracker, utilizing the excellent timing and spatial resolutions and moderate costs to cover a large area (O(100 m^2))

Started with ATLASPix3.0/3.1 (TSI 180 nm)

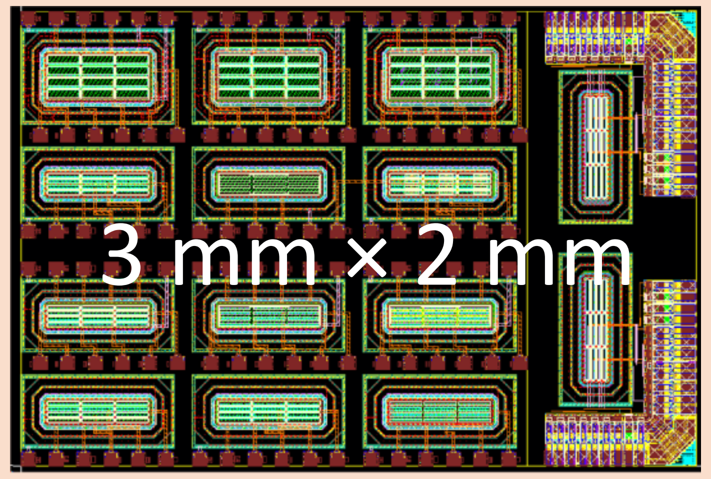


Performance deeply and widely characterized, used for QuadModule prototypes and stave(let) designs

Initial Design effort with Foundry A 55 nm (on hold)

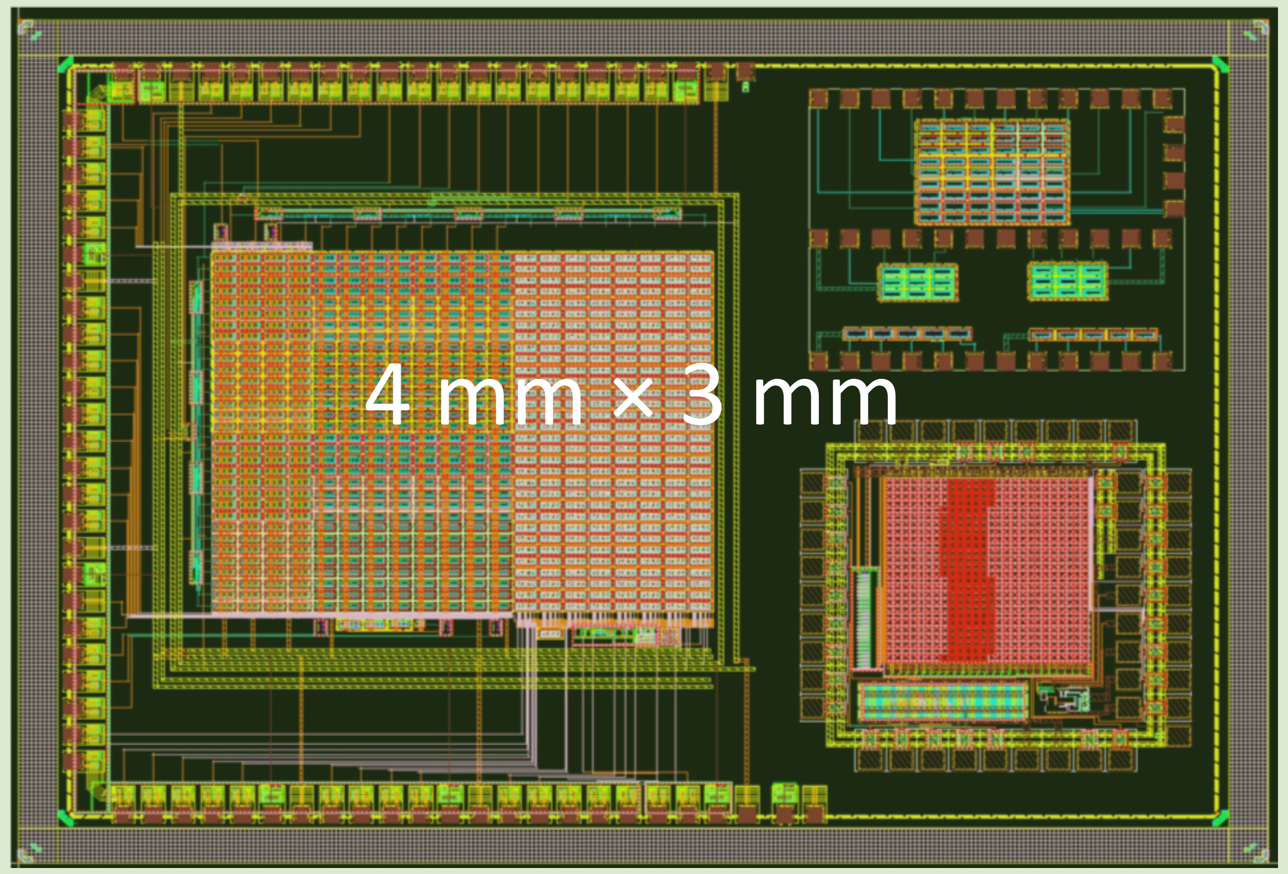


Trial with Foundry B 55 nm (Low Leakage, not HV)



Chips under test

1st Design with Foundry B 55 nm HV-CMOS (+ high bulk resitivity)



Passive diodes and two pixel arrays with readout electronics; Chips expected in December

Submission: Oct 2022

Aug 2023

More on 55 nm HVCMOS

- Smaller feature size: potential for more functionalities with reduced power consumption
- **Technology evaluation** with a promising 55nm HVCMOS process being conducted (high voltage combined with high bulk resistivity → high bias voltage, drift collection & large signal); decent technical support from the vendor
- **Synergies** with other projects (the LHCb Upstream Tracker and MightyTracker, extendable to readout electronics, DAQ etc.), possible applications in medical imaging
- **International collaboration** based on mutual interests (attractive process of small feature size/expected higher performance, limited accessible venders)
- With the coming MOST funding support, multiple MPW designs will be scheduled, with the hope to realize a fully functional full reticle-sized chip in a few years.
  - Target performance: spatial resolution <10 μm, timing resolution <10 ns

MOST 3

International Collaboration in Silicon Tracker Project

- Australia
  - University of Adelaide
- China
  - Harbin Institute of Technology
  - Hunan University
  - Institute of High Energy Physics, CAS
  - Northwestern Polytechnical University
  - Shandong University
  - T. D. Lee Institute – Shanghai Jiao Tong University
  - University of Science and Technology of China
  - University of South China
  - Zhejiang University
- Germany
  - Karlsruhe Institute für Technologie
- Italy
  - INFN Sezione di Milano, Università degli Studi di Milano e Università degli Studi dell'Insubria
  - INFN Sezione die Pisa e Università di Pisa
  - INFN Sezione di Torino e Università degli Studi di Torino
- UK
  - Lancaster University
  - Queen Mary University of London
  - STFC – Daresbury Laboratory
  - STFC – Rutherford Appleton Laboratory
  - University of Bristol
  - University of Edinburg
  - University of Liverpool
  - University of Oxford
  - University of Sheffield
  - University of Warwick

Gas trackers:
TPC and Drift Chamber

Roadmap of CEPC TPC detector R&D

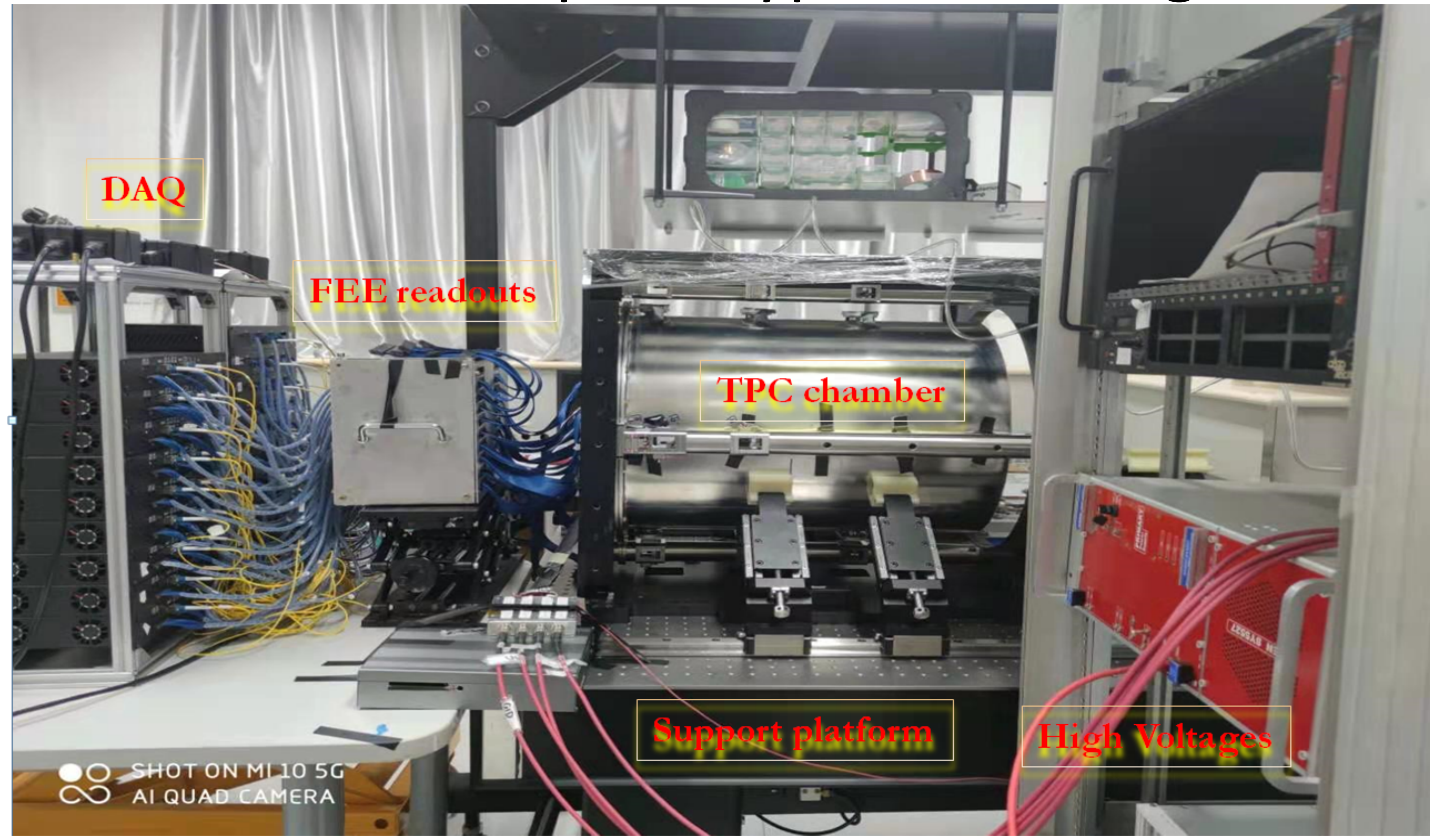
CEPC TPC detector prototyping roadmap:

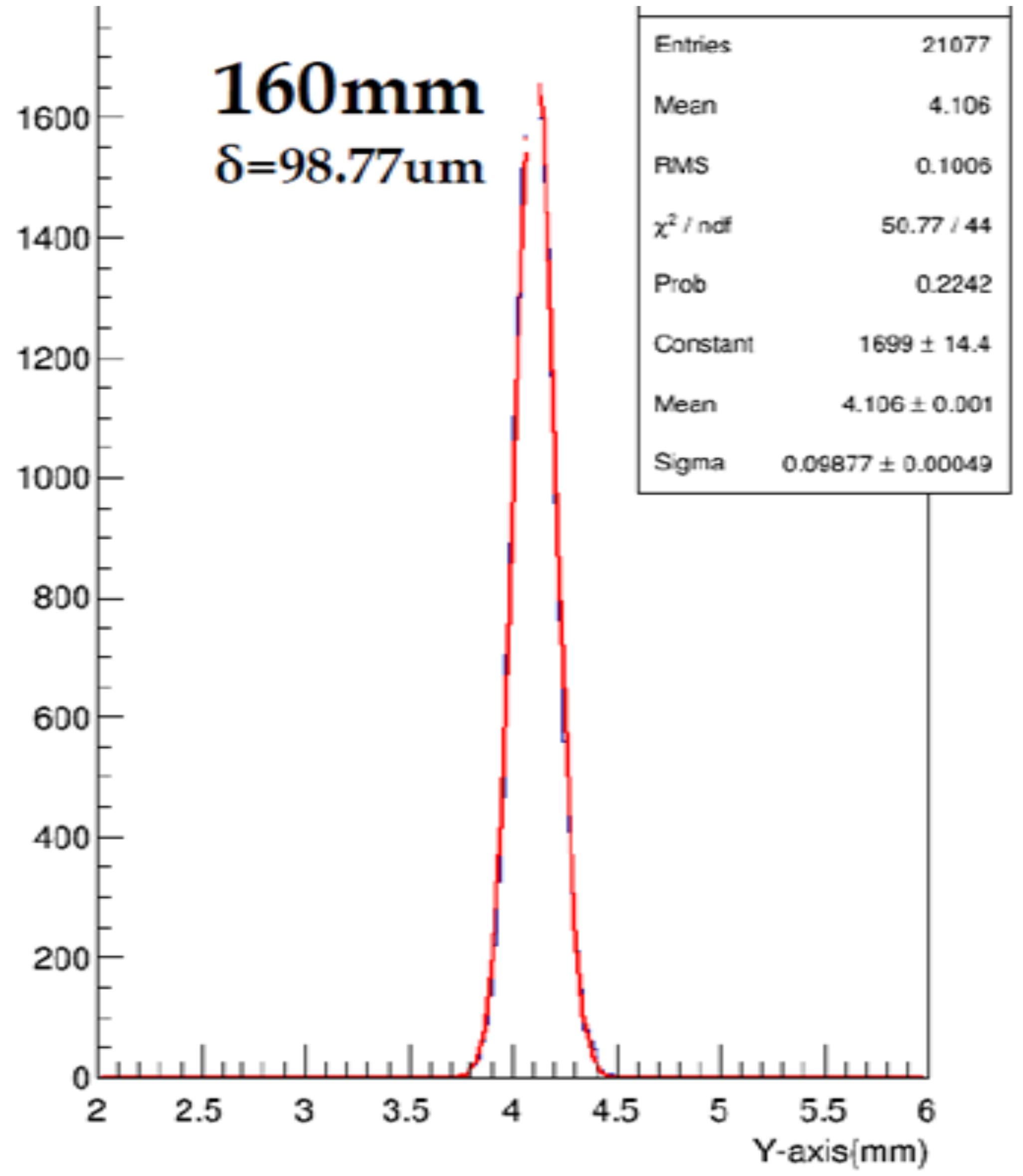
- From TPC module to TPC prototype R&D for Higgs and Tera-Z
- Low power consumption FEE ASIC R&D

Achievement so far:

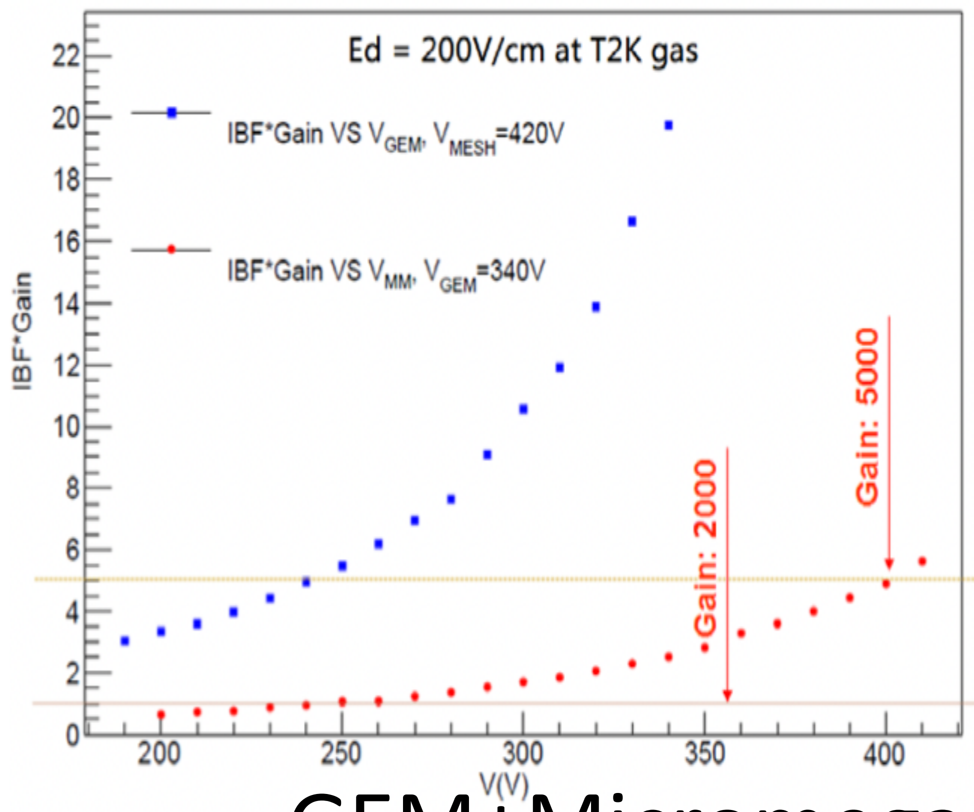
- Supression ions hybrid GEM+Micromegas module
  - IBF×Gain **~1 @ G=2000** validation with hybrid GEM/MM
- Spatial resolution of **$\sigma_{r\phi}$≤100 μm** and dE/dx resolution of **<4%**
- WASA chip: reach **~3.0mW/ch** with ADC, 32channels/chip

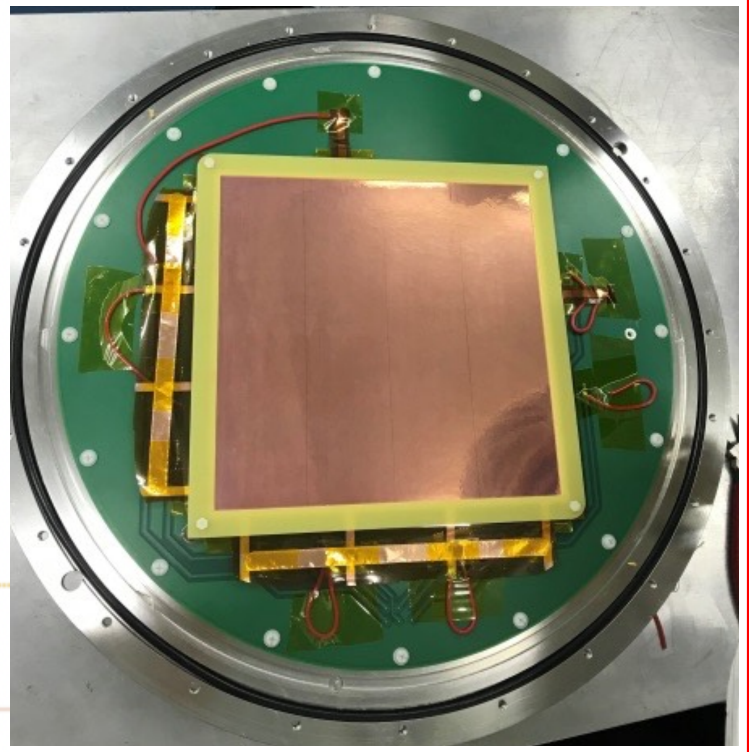
TPC prototype with integrated 266nm UV laser



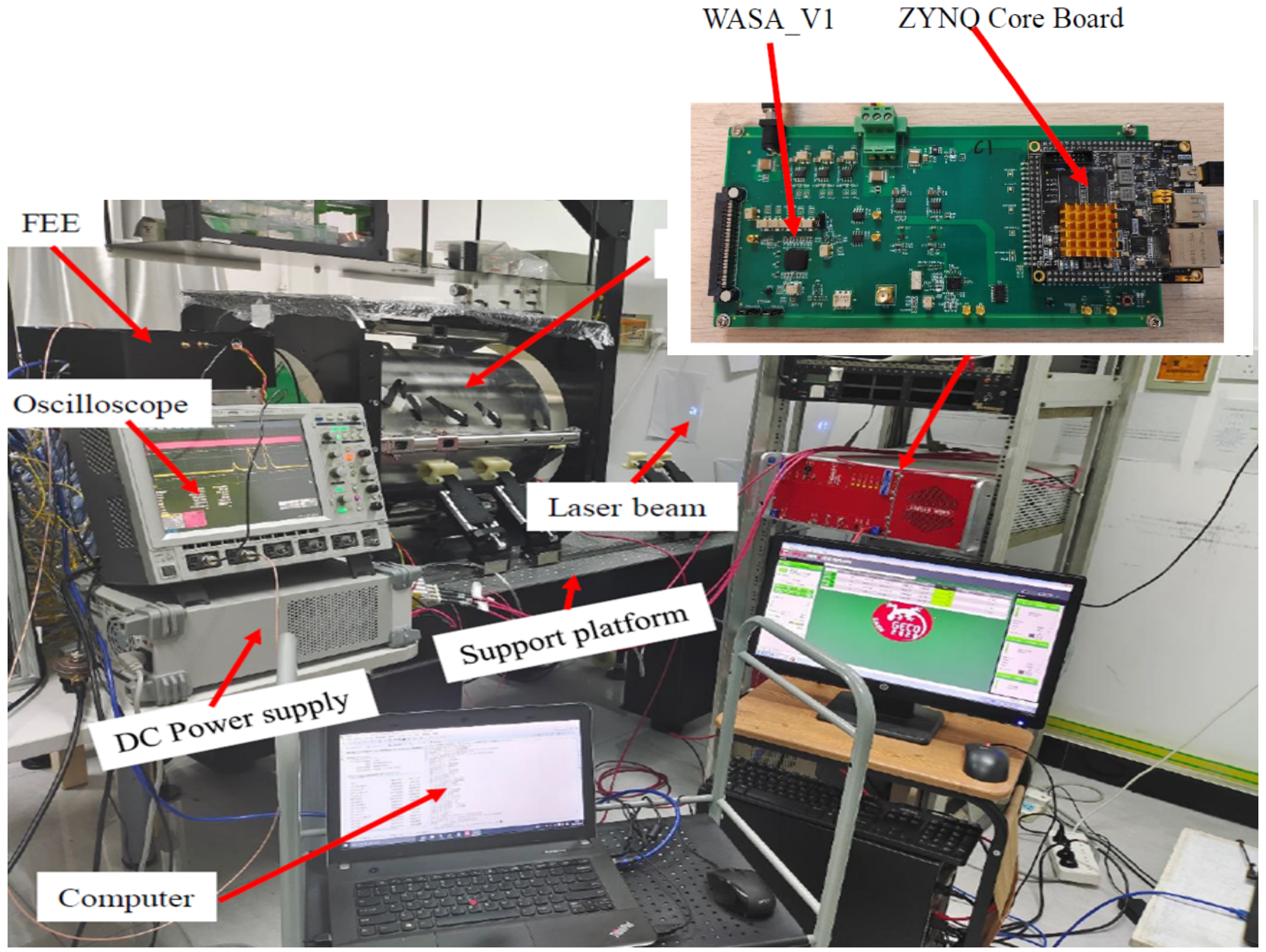


Achievement





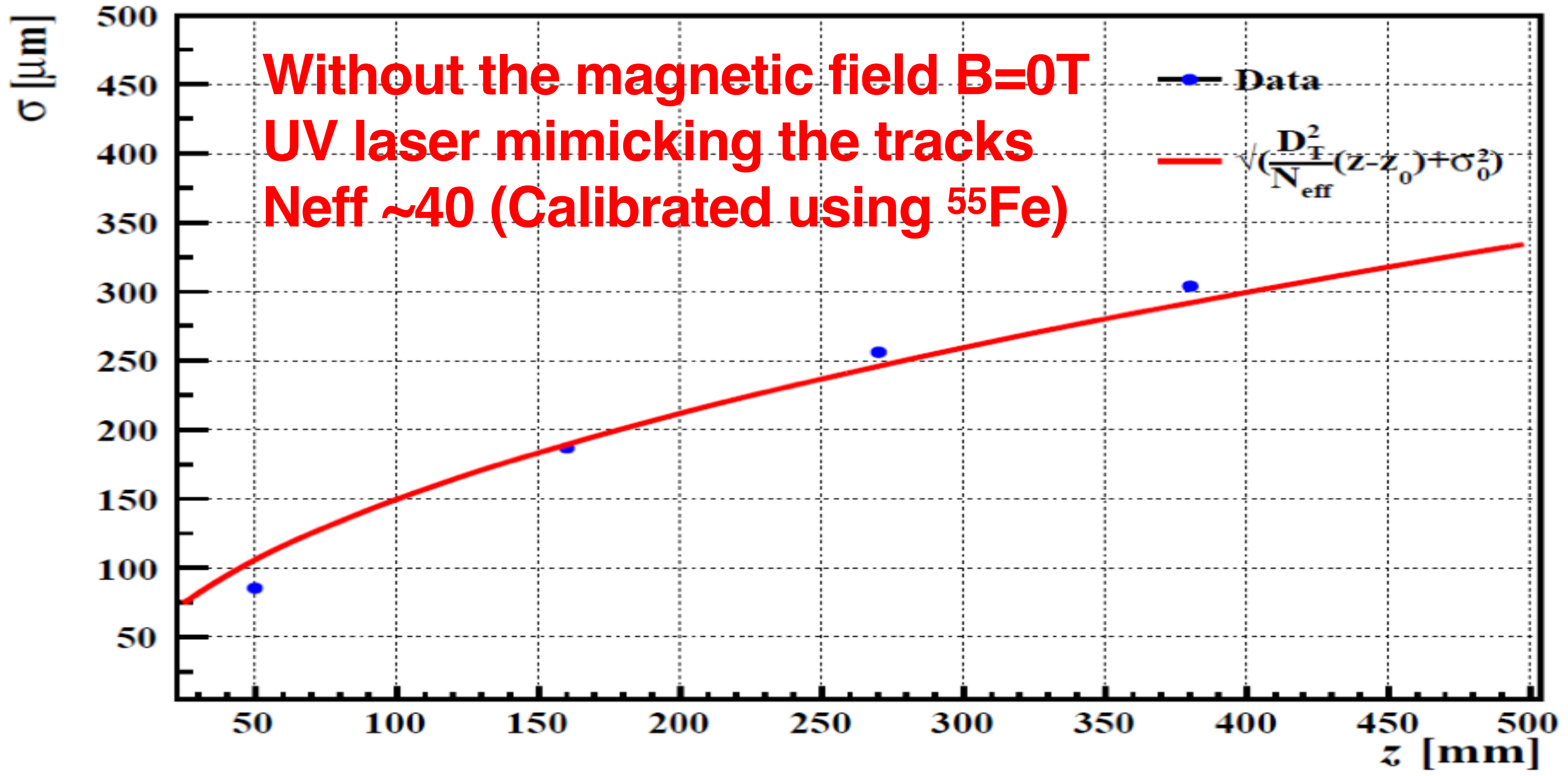
GEM+Micromegas module R&D

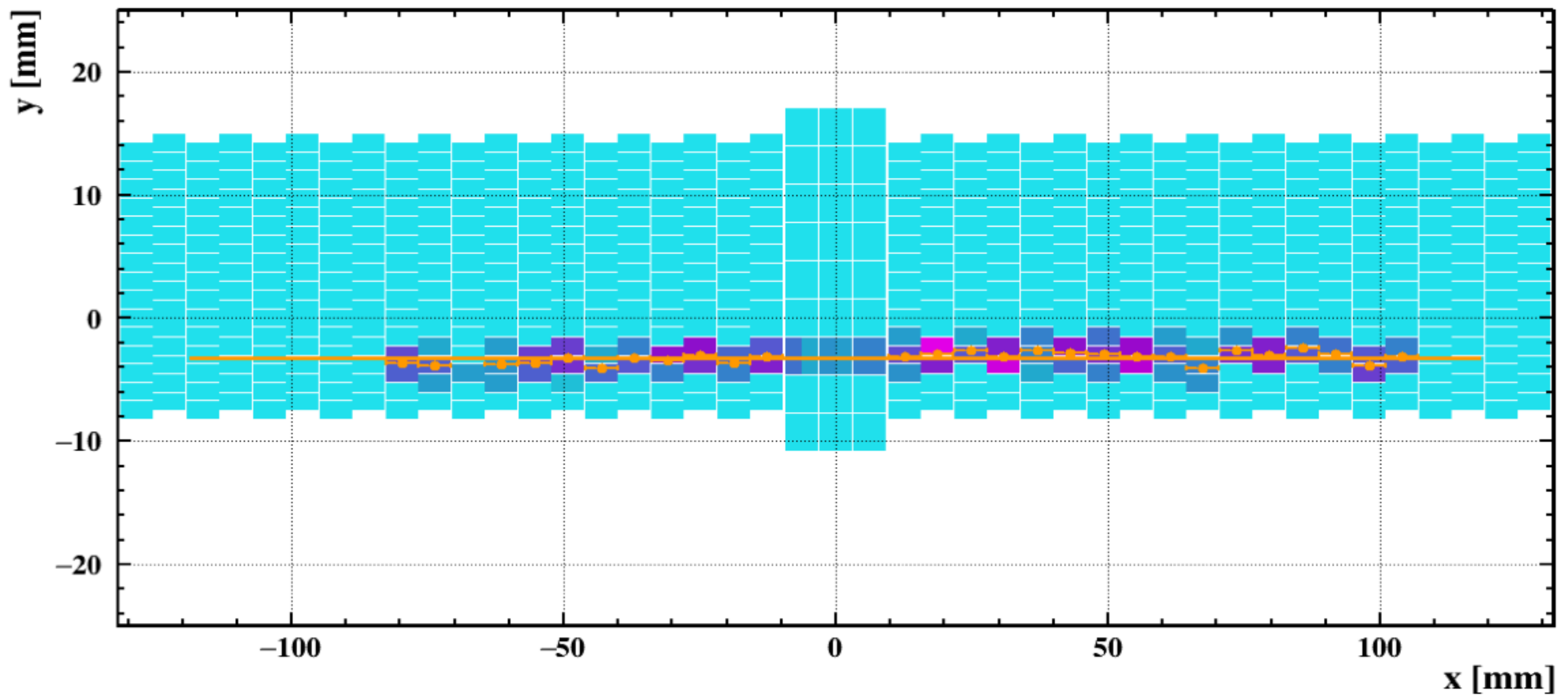


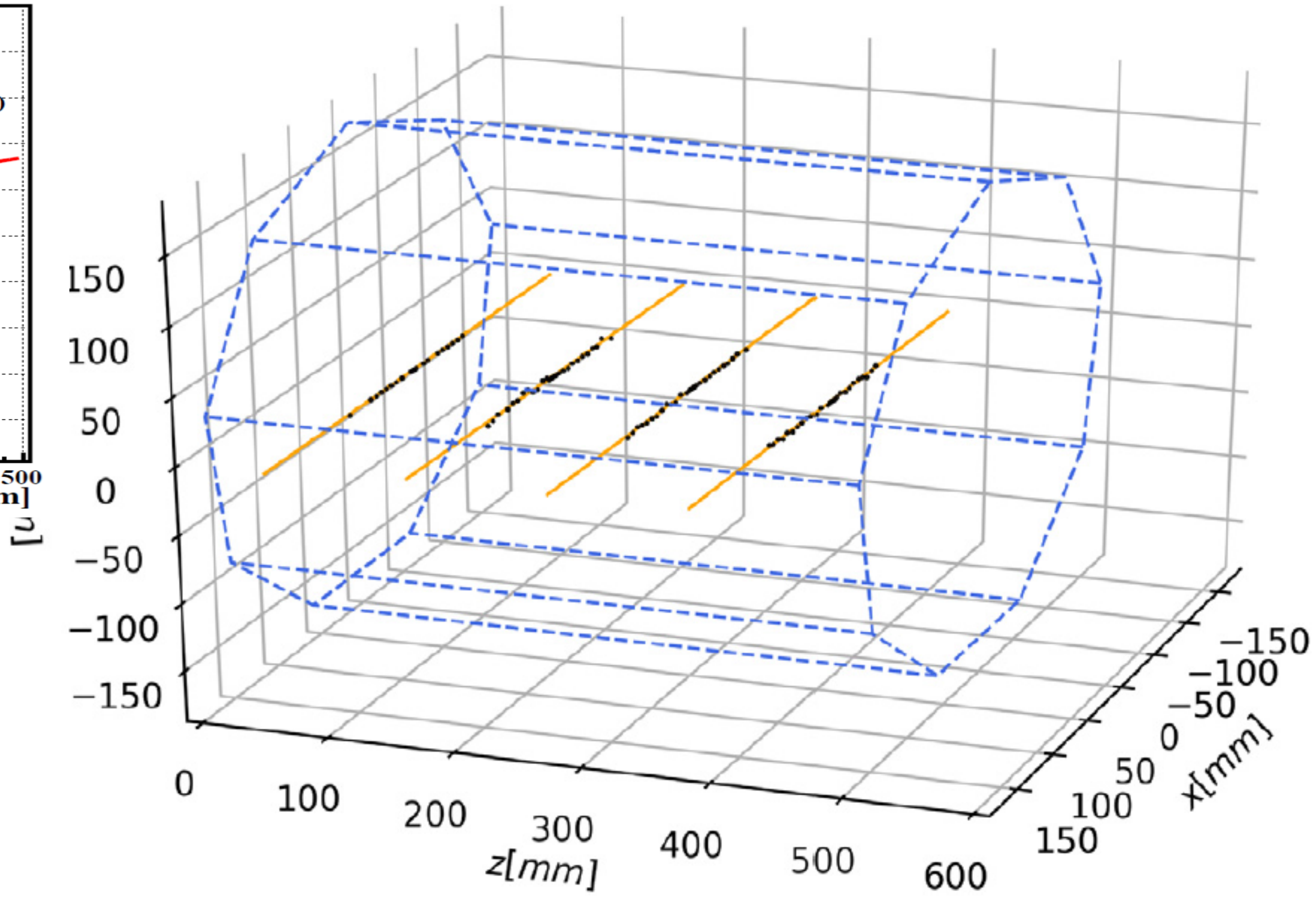
Low power consumption readout

Status of Pad readout TPC

- Highlights of CEPC TPC detection technology R&D
  - Massive production and assemble MPGD lab has been setup at IHEP
  - TPC prototype integrated 266nm UV laser tracks has been studied and analyzed the UV laser signal, **all are pretty good to Higgs run.**
  - Track correction and the spatial resolution of TPC prototype are analyzed and ongoing. (Referenced with ALICE collaboration)

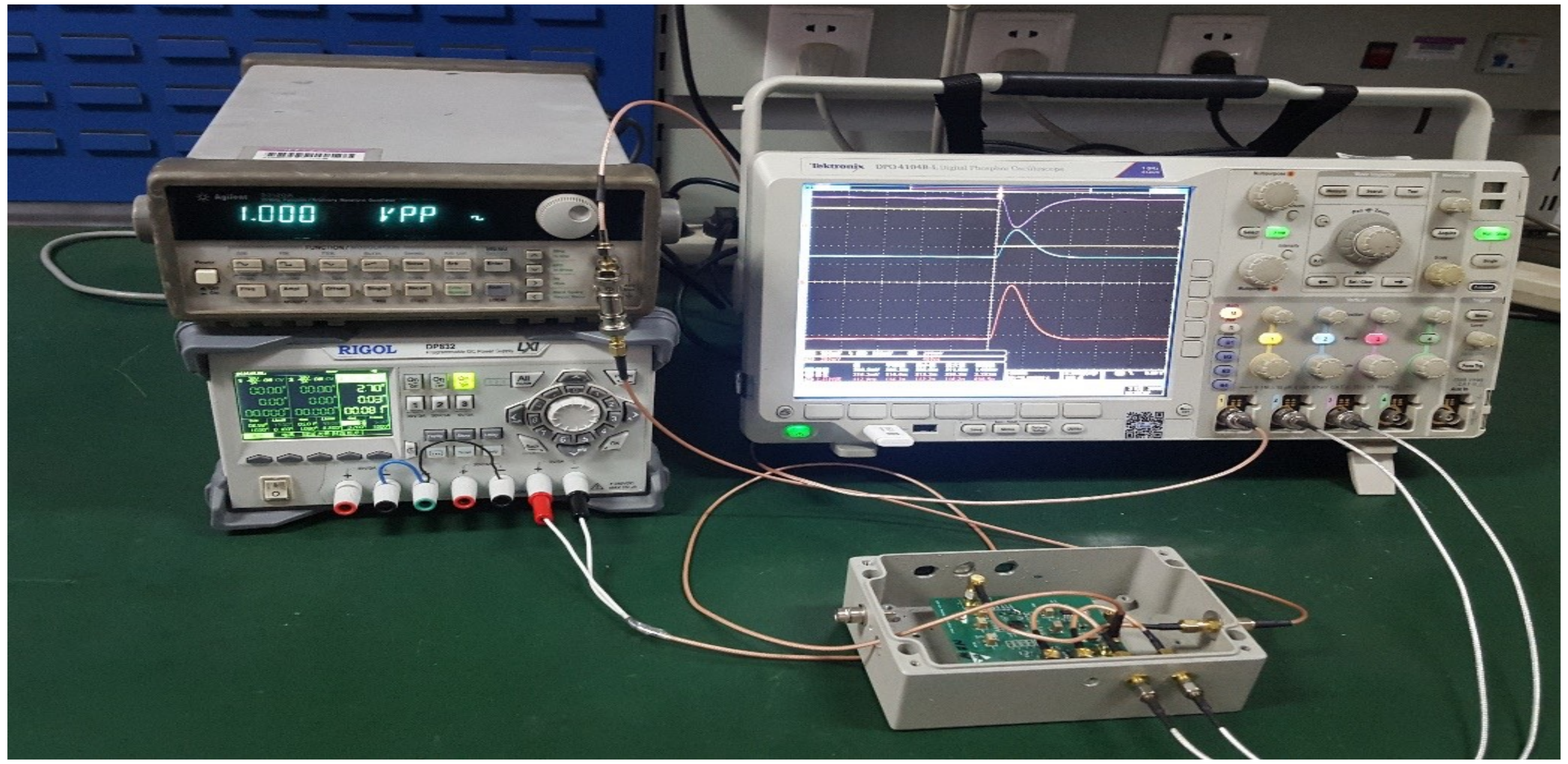


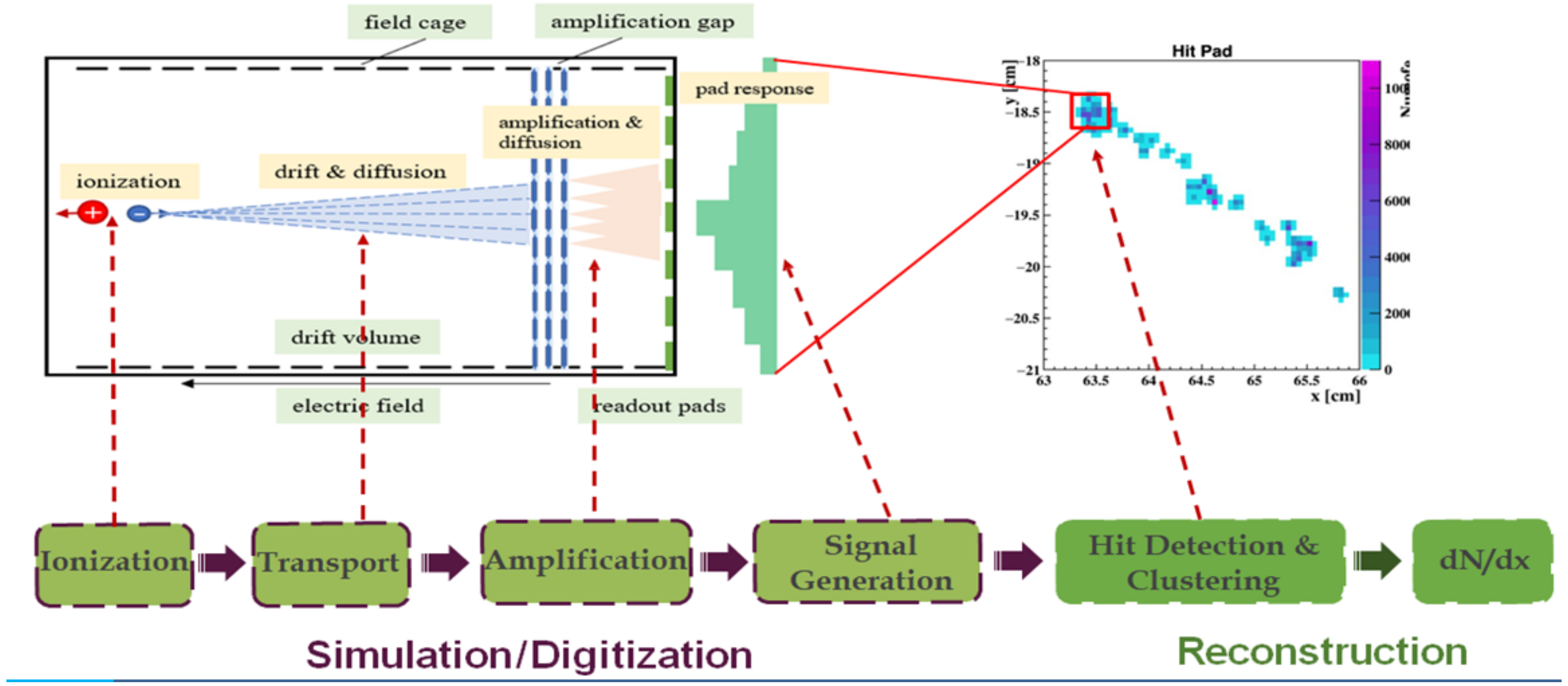


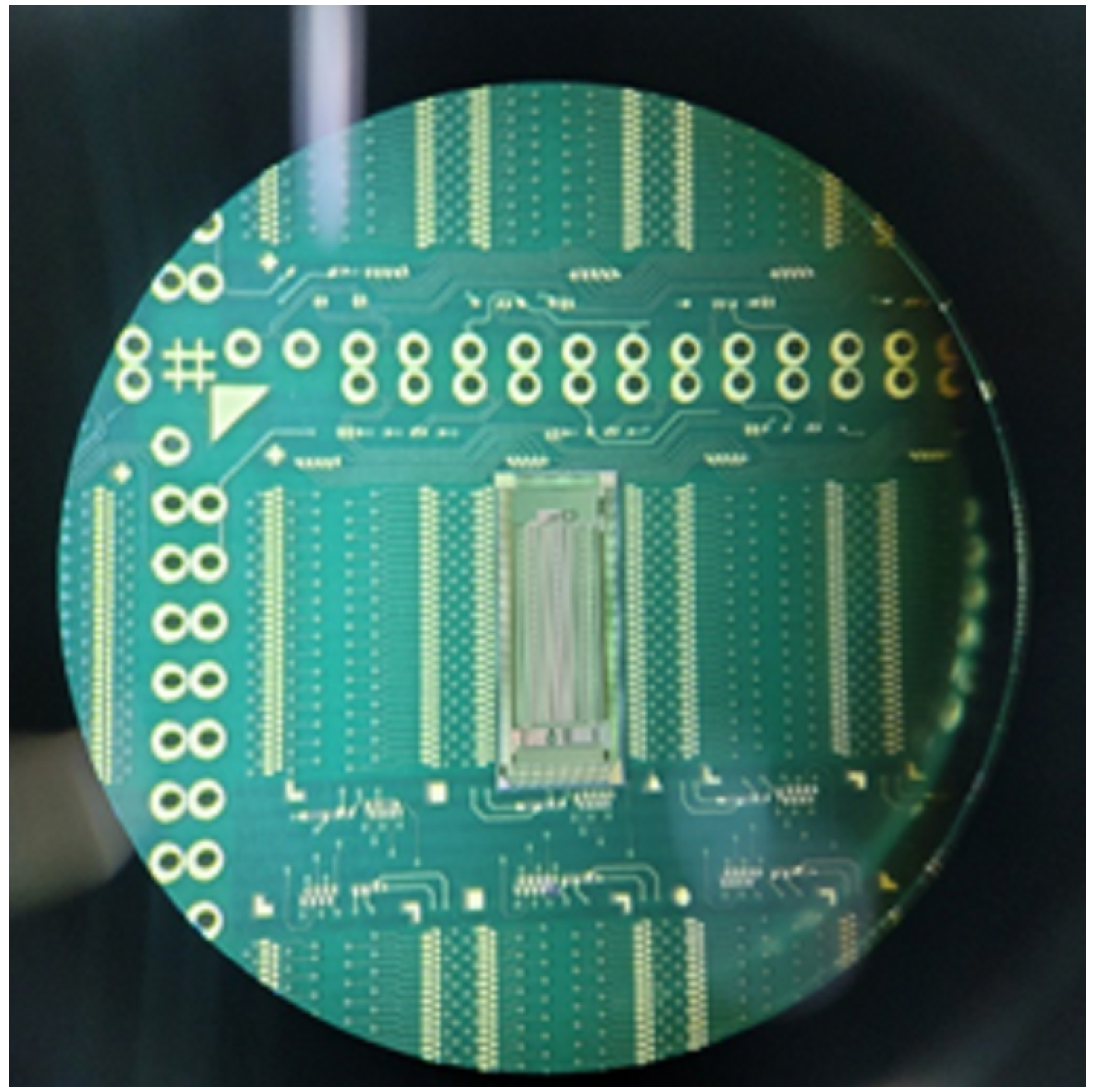


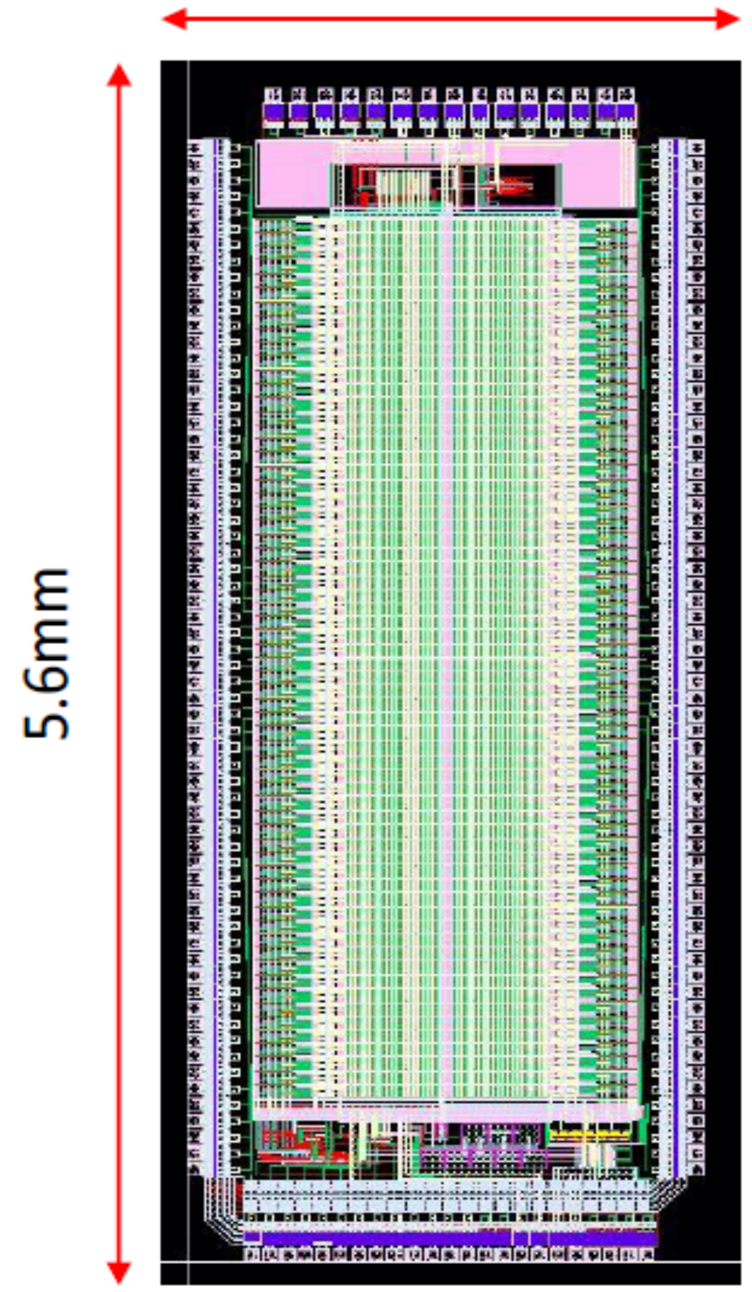
Status of Pixelated readout TPC

- R&D on pixel TPC readout for CEPC at 2023
  - Smaller pad size improved momentum resolution via dE/dx and dN/dx
  - High readout granularity VS the cluster size optimization
  - Pixel TPC ASIC chip has started development
    - Power consumption: <1.1mW/ch (1st prototype)
      - **<400mW/cm² (Test)**
  - 2nd prototype wafer design done and ongoing
      - **<200mW/cm² (Simulation)**









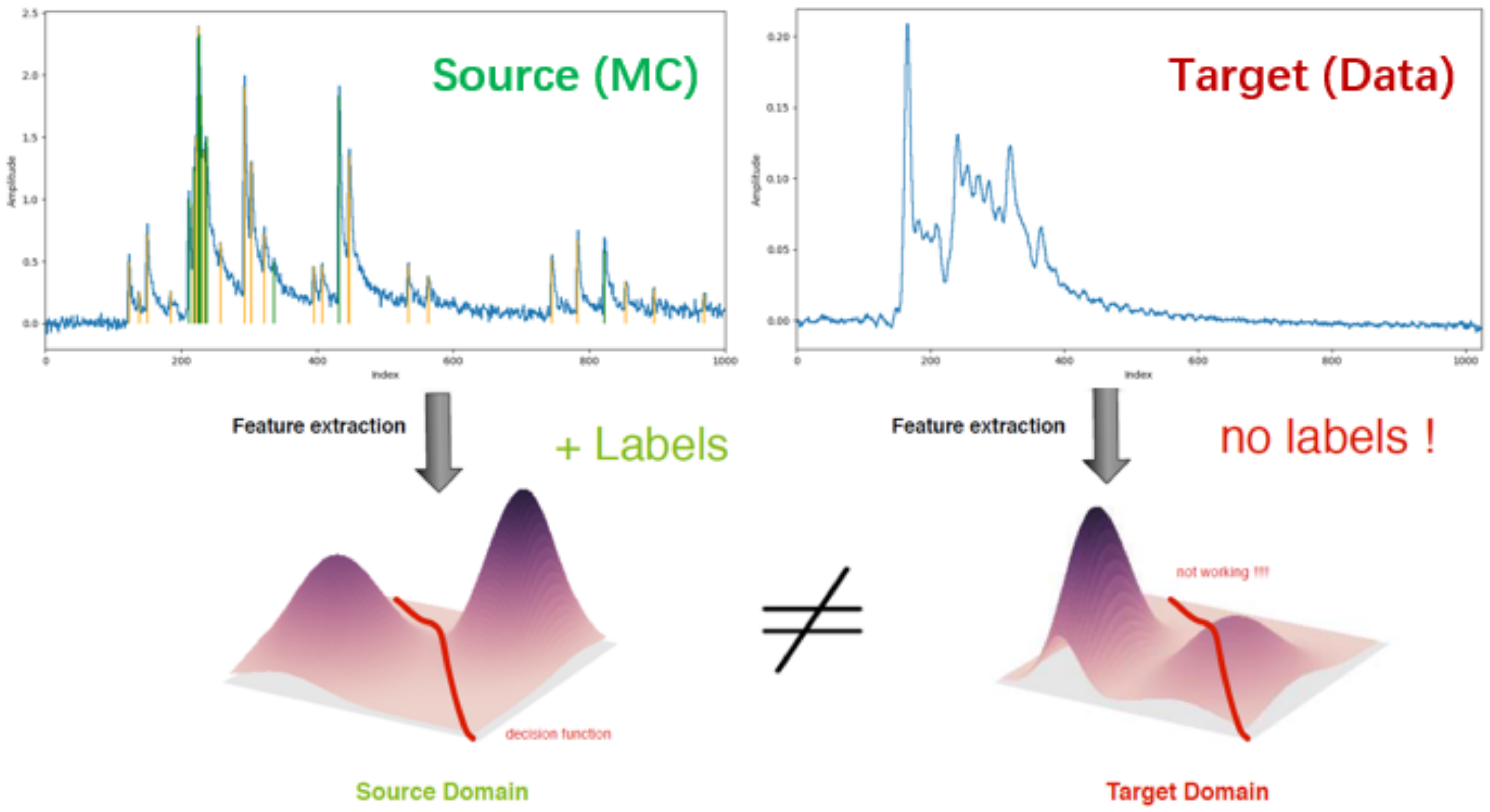
International collaboration R&D

- Activities in LCTPC collaboration
  - IHEP contributed in **Ion backflow and pixelated R&D.**
  - MPGDs for TPC readout is a baseline solution and further R&D features many benefits in LCTPC:
    - Small pitch of gas amplification regions => strong reduction of E×B-effects
    - No preference in direction => all 2 dim. readout geometries possible
    - **Ion backflow** can be reduced significantly (Gating, Hybrid structure…)
    - Continue electronics, cooling, UV laser track and low power consumption FEE development
- All research will be integrated with **DRD1 of CERN** from 2023
  - LCTPC will be integrated in DRD1.
  - CEPC TPC study group joined in DRD1.
- Collaboration with internal University in China
  - **Tsinghua University**: Low power consumption ASIC R&D and the pixelated Readout
  - **Shandong University**: Ion backflow R&D with the graphene layer
  - Others actives: CIEA, IMP/CAS,…

Drift Chamber

Progress of Drift Chamber Cluster Counting: test beam analysis

1. Model based on optimal transport

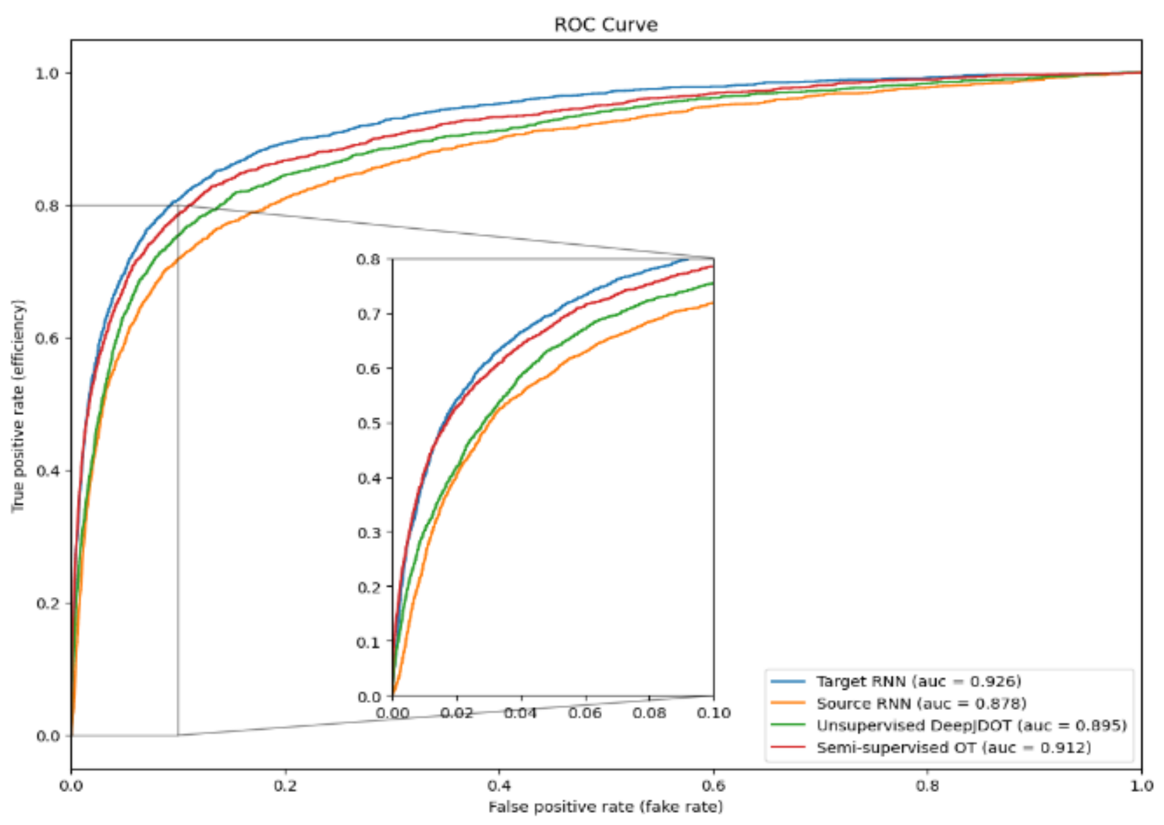


- Domain shift between MC/data
- Lack of labels in data

➔ Semi-supervised DeepJDOT

Collaboration with INFN

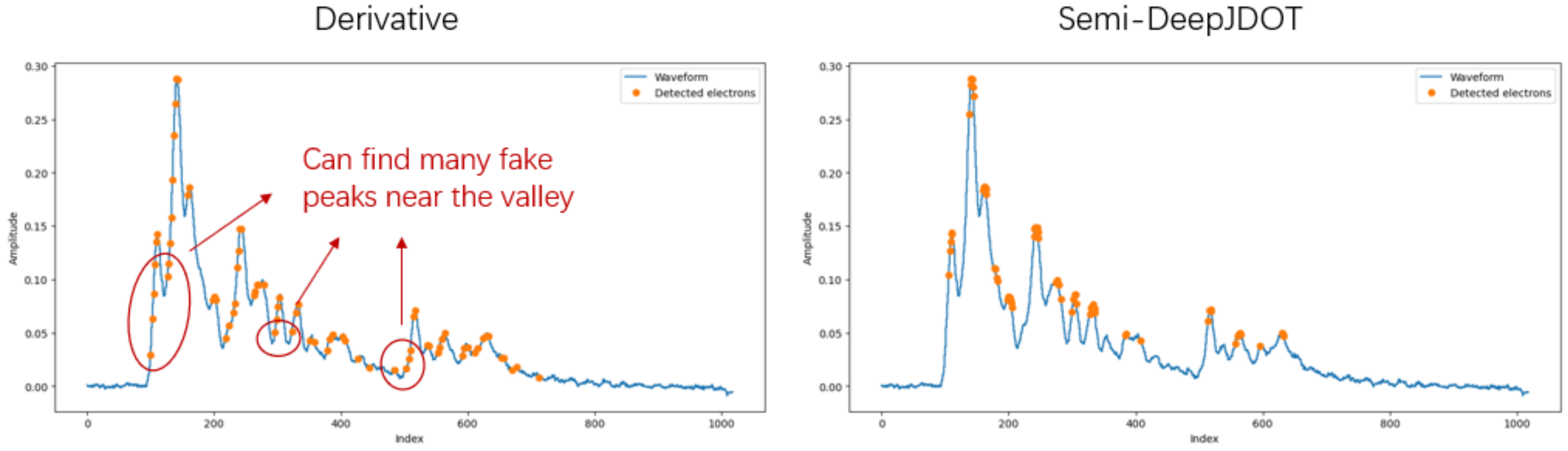
2. Validation on MC experiment



Model	AUC	pAUC (FPR<0.1)
Target RNN*	0.926	0.812
Source RNN	0.878	0.749
Unsupervised DeepJDOT	0.895	0.769
Semi-supervised DeepJDOT	**0.912**	**0.793**

* Supervised model assuming there are labels in the training sample

3. Apply on test beam data

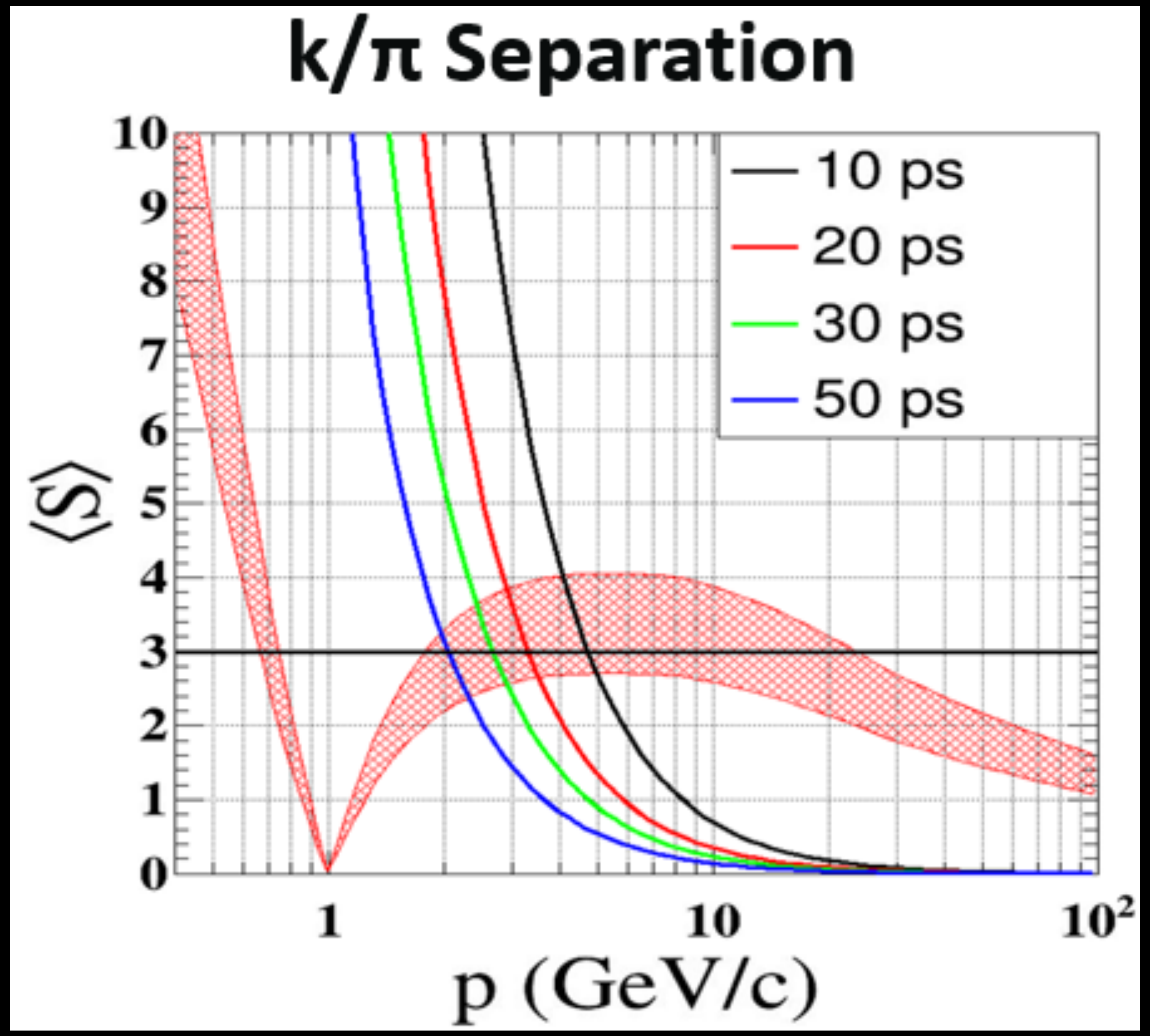


Outperform the derivative-based algorithm. Can find peaks reasonably on data.

Time of flight detector

Time of flight detector

- Combining a gas detector with time of flight detector the particle separation ability improves
  - 0 - 4 GeV for K/π separation, 0 – 8 GeV for K/p separation



- **Main technology:**

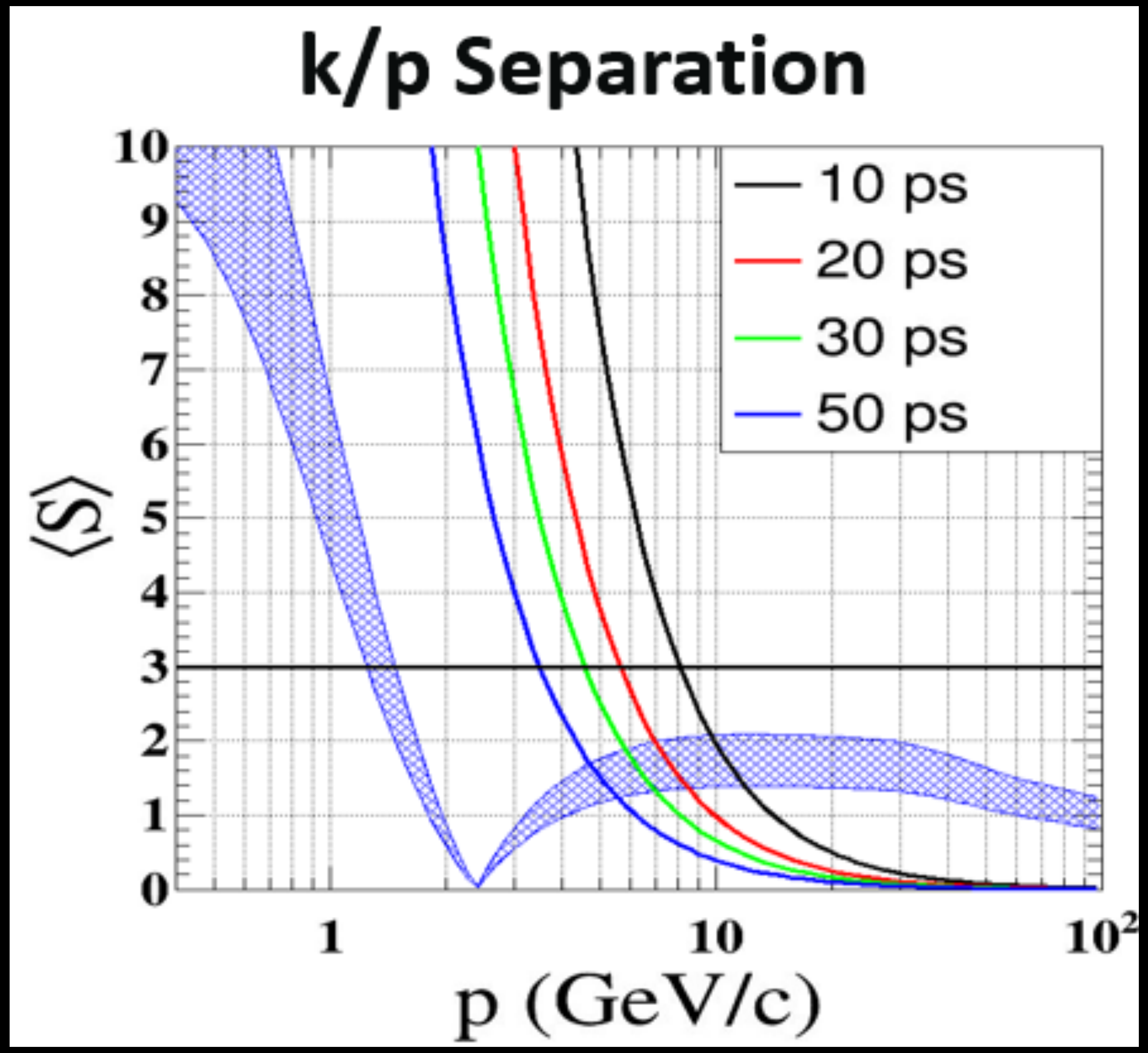
CEPC time of flight detector based on LGAD：

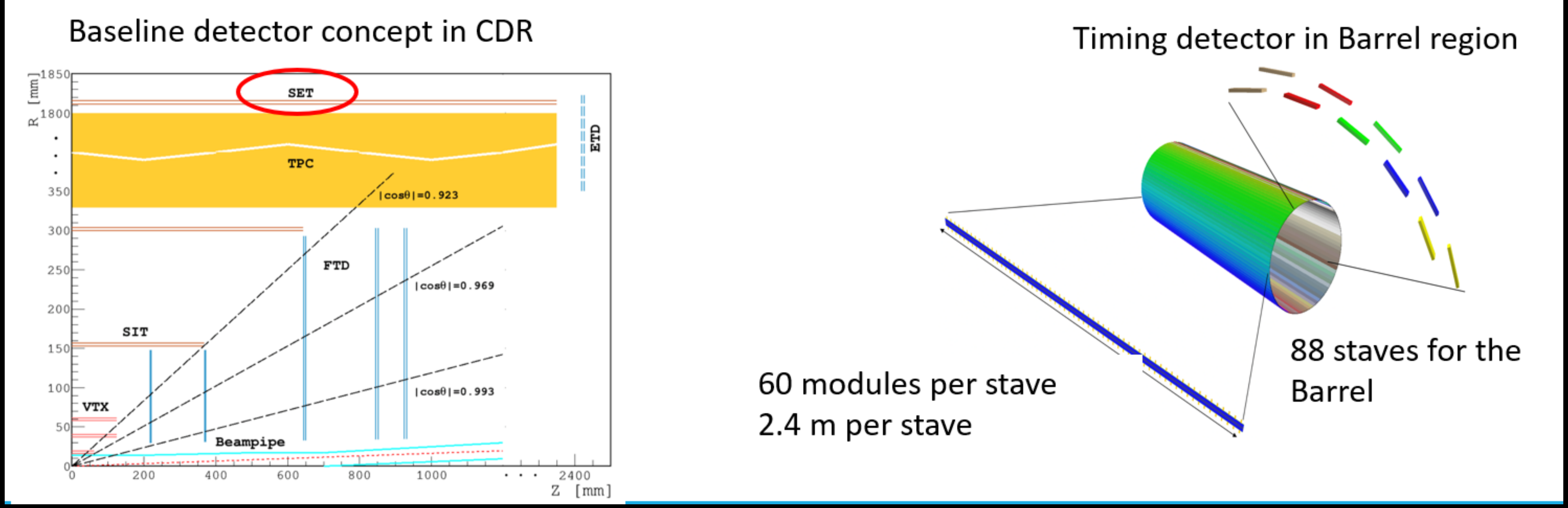
Part of SET (silicon wrapper layer outside TPC or drift chamber)

Timing resolution: <30, Spatial resolution: ~ 10 μm

Area of detector (Barrel : 50 m^2 , Endcap 20 m^2)

Strip-like sensor (each strip: 4 cm × 0.1 cm): to reduce readout channels

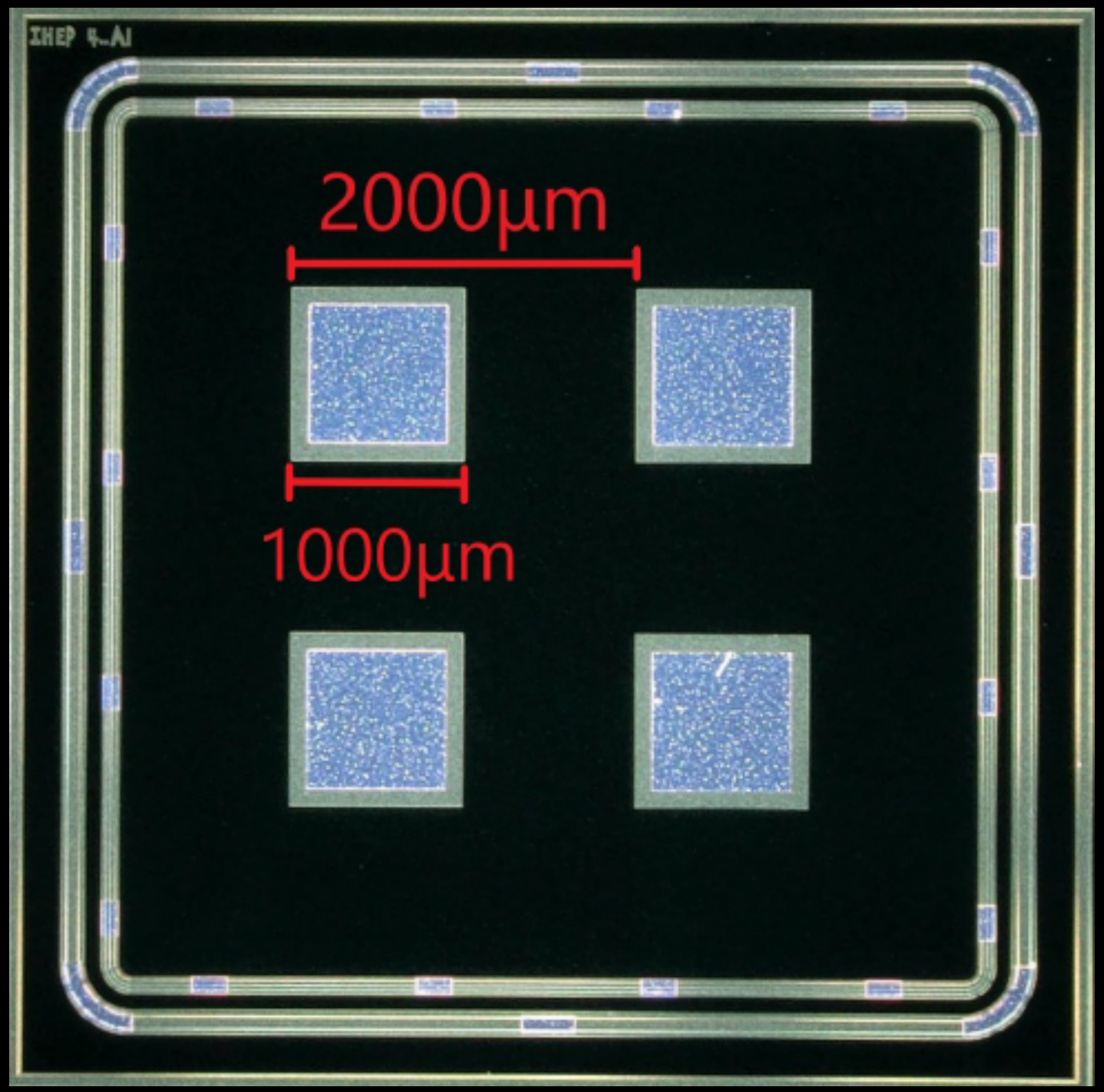




IHEP AC-LGAD

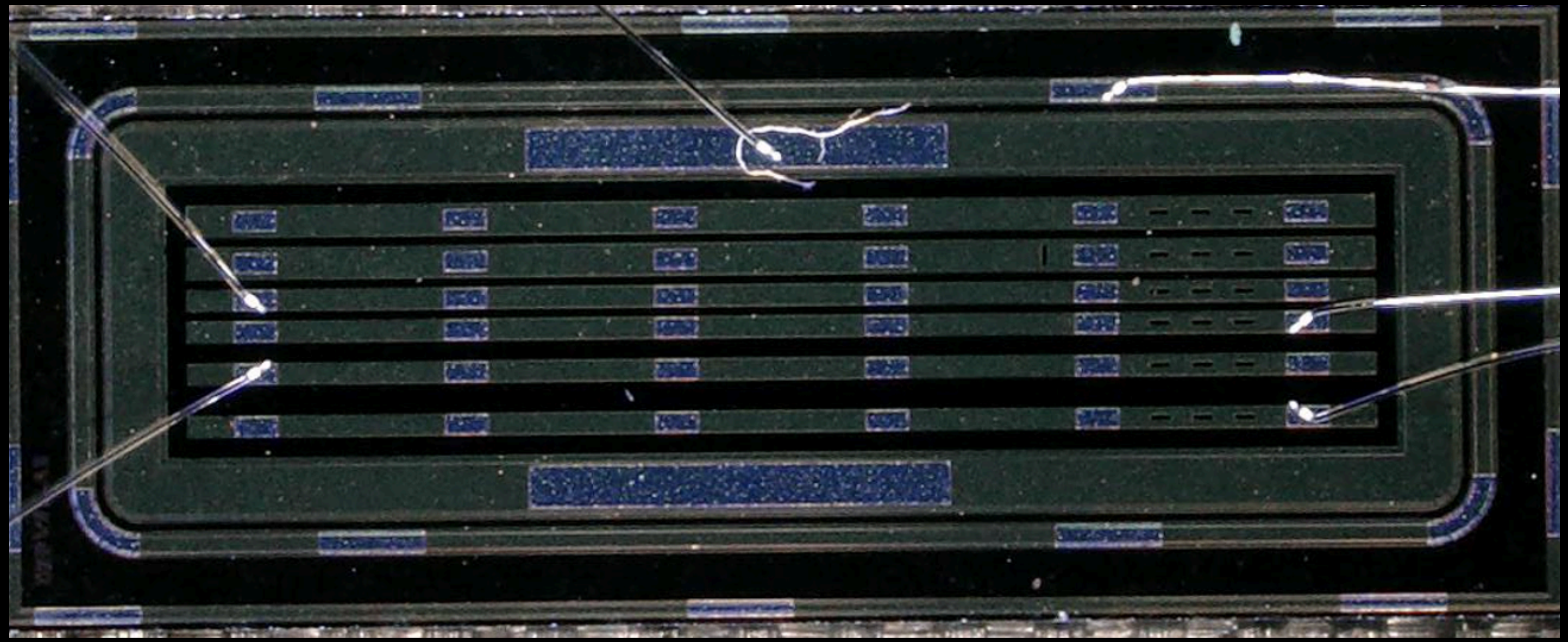
- Two type of AC-LGAD have been fabricated and tested: Pixel AC-LGAD and Strip AC-LGAD.
- Spatial resolution of sensors with different process parameter and structures design studied

Pixel AC-LGAD



Different process parameters:
n+ dose(phosphorus): 10P to 0.2P

Strip AC-LGAD



- Strip length 5.6mm
- pitch-pad:
  - 250-100um
  - 200-100um
  - 150-100um

Timing resolution <30ps

Spatial resolution ~10um

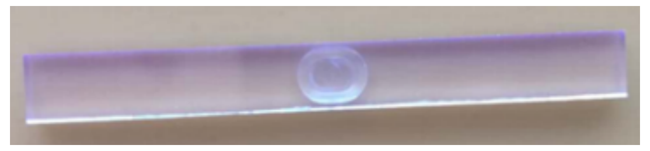
Calorimeters

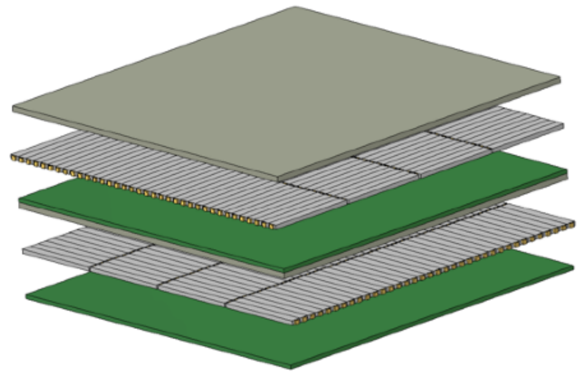
CEPC calorimeter prototypes: developments

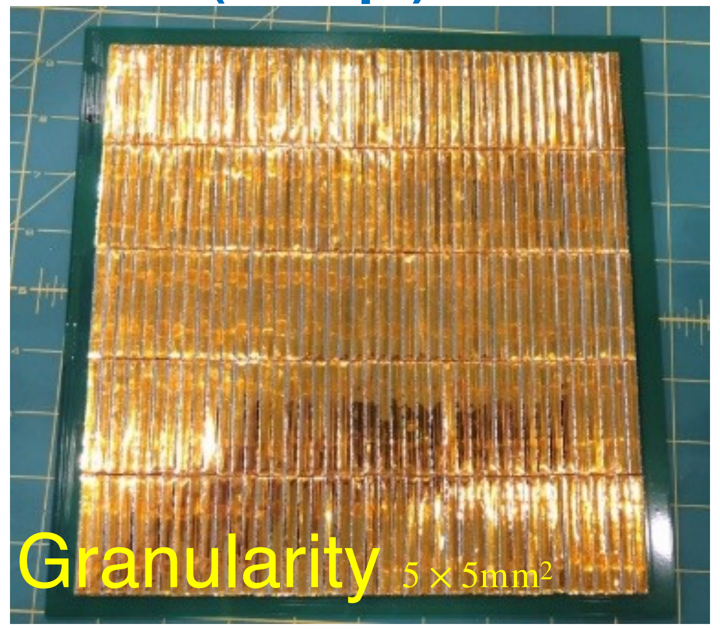
ECAL prototype： scintillator (strip)+SiPM, CuW

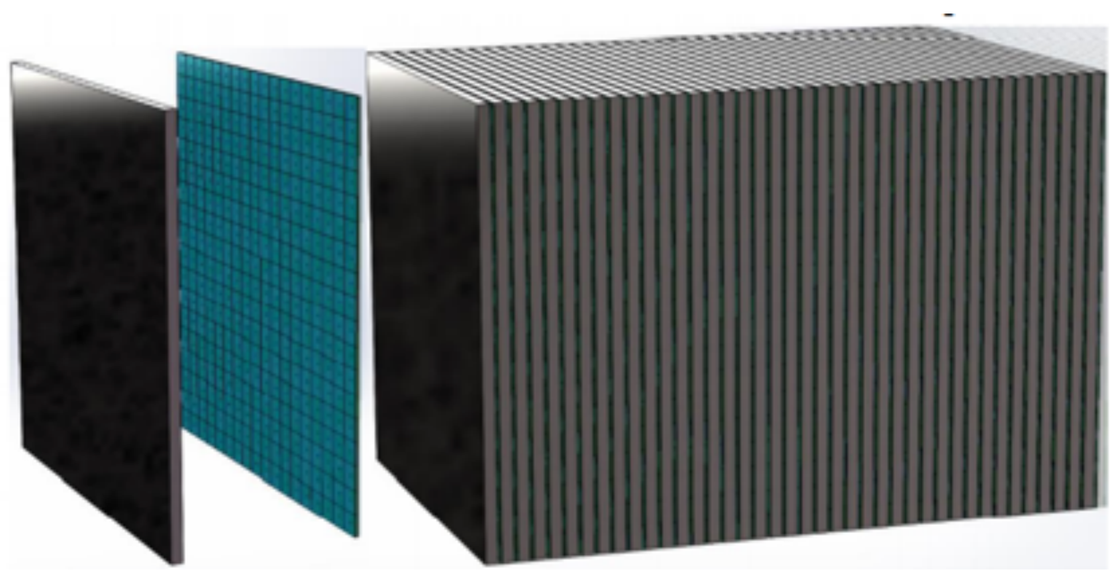
HCAL prototype： scintillator (tile)+SiPM, steel

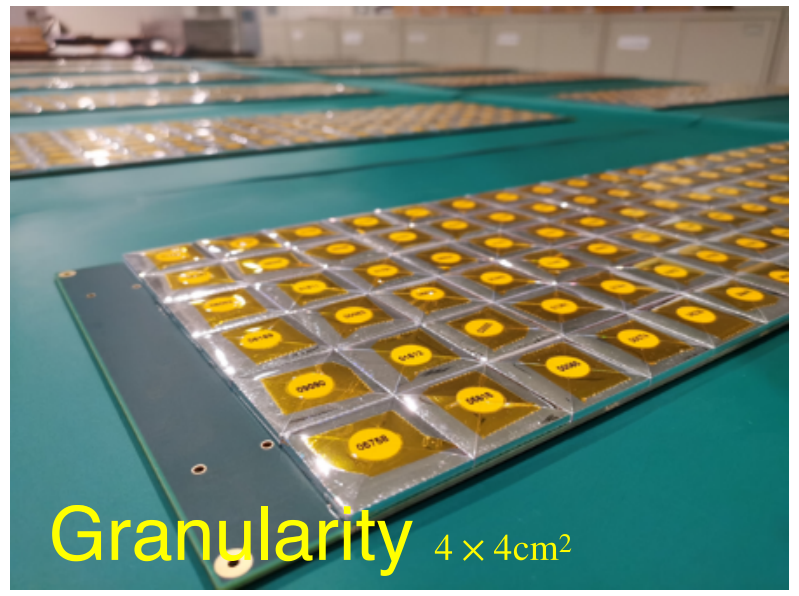
MOST 2

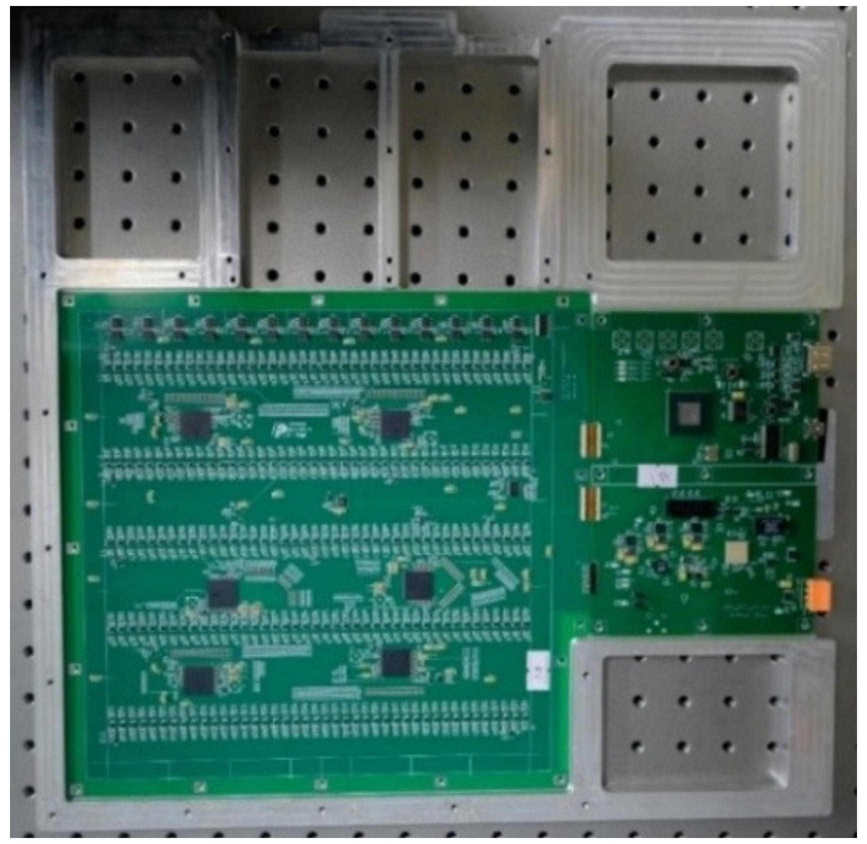


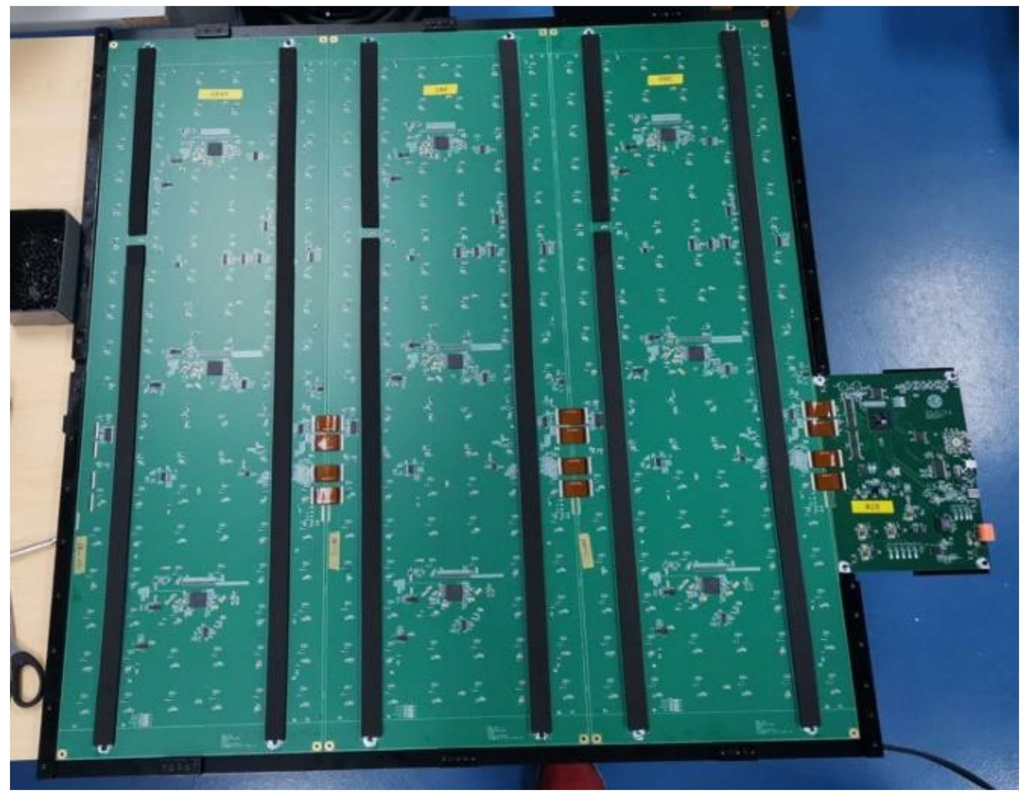










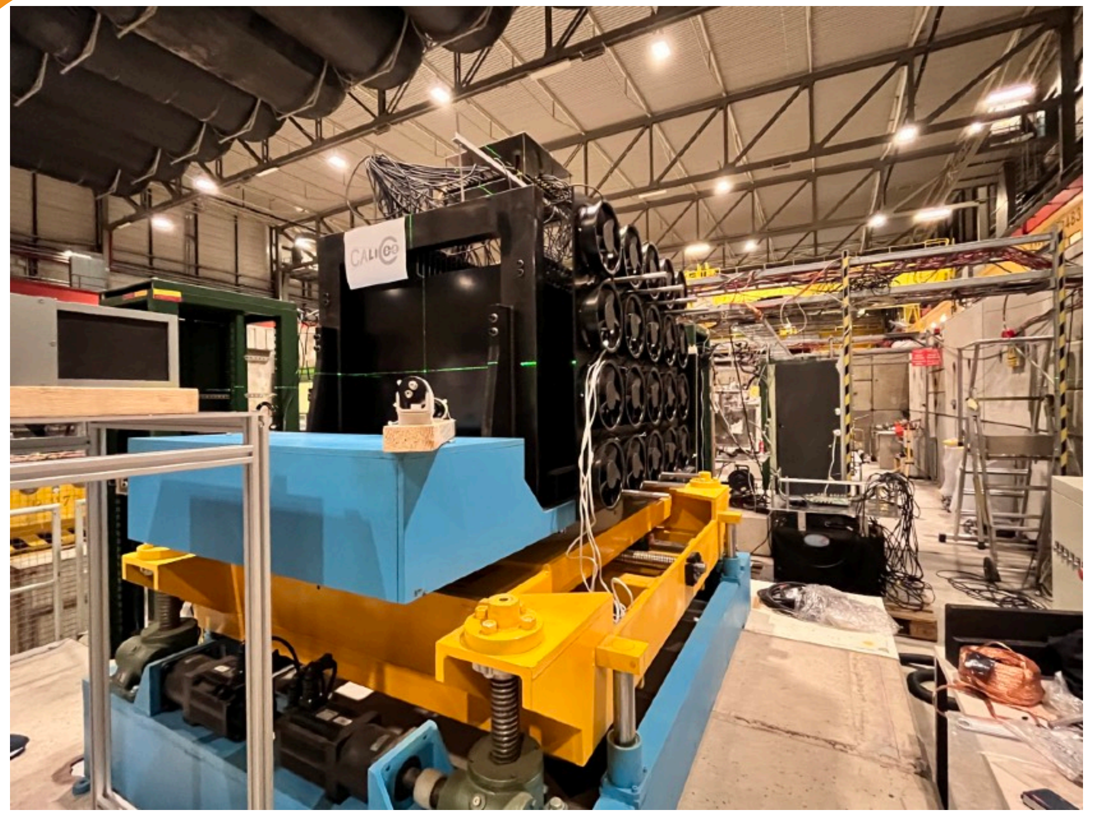


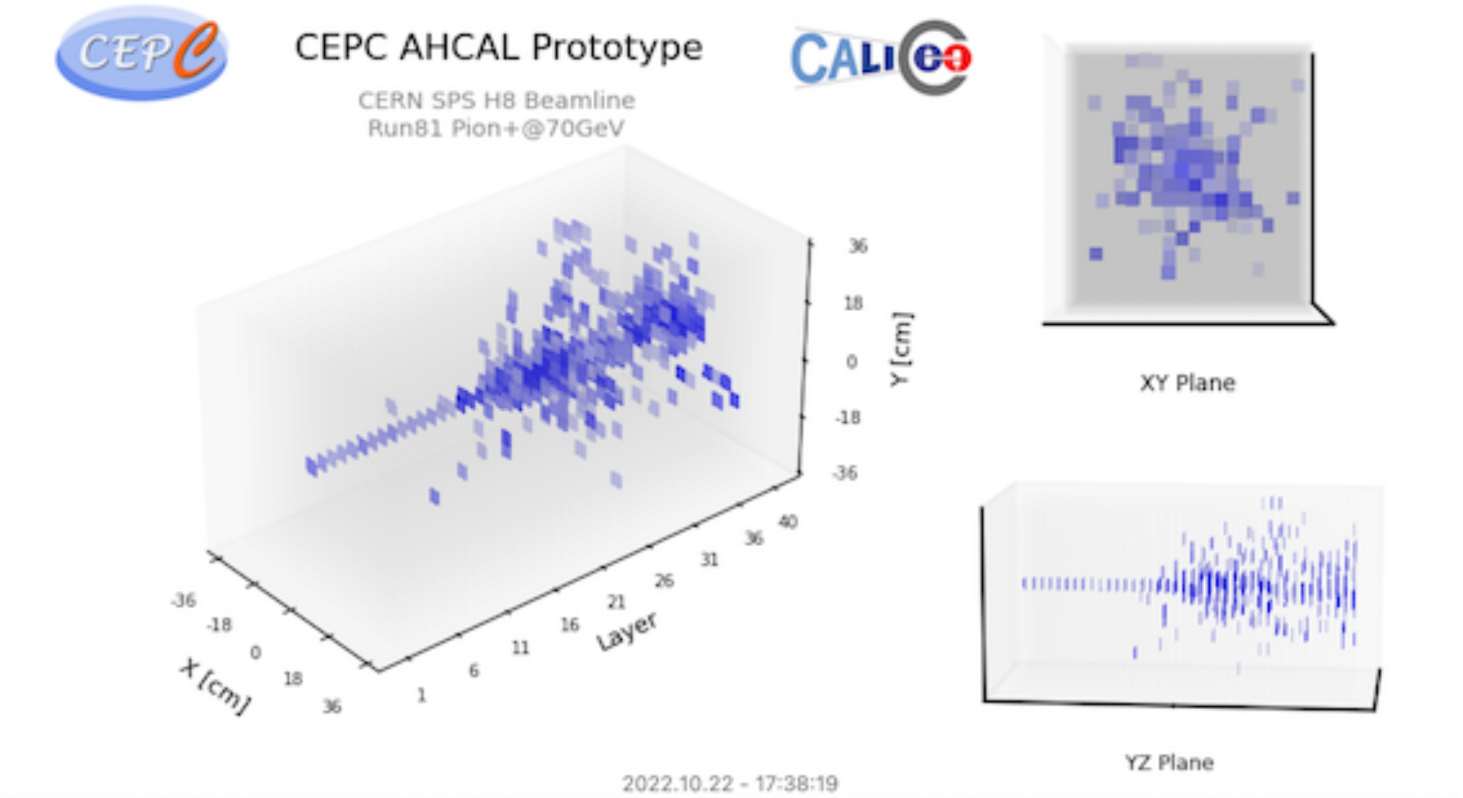
- ScW-ECAL prototype: transverse ~20x20 cm, 32 sampling layers
  - ~6,700 channels, ~350 kg, **SPIROC2E** (192 chips), **developed in 2016-2020**
- AHCAL prototype: transverse 72x72 cm, 40 sampling layers
  - ~13k channels, ~5 tons, **SPIROC2E** (360 chips), **developed in 2018-2022**

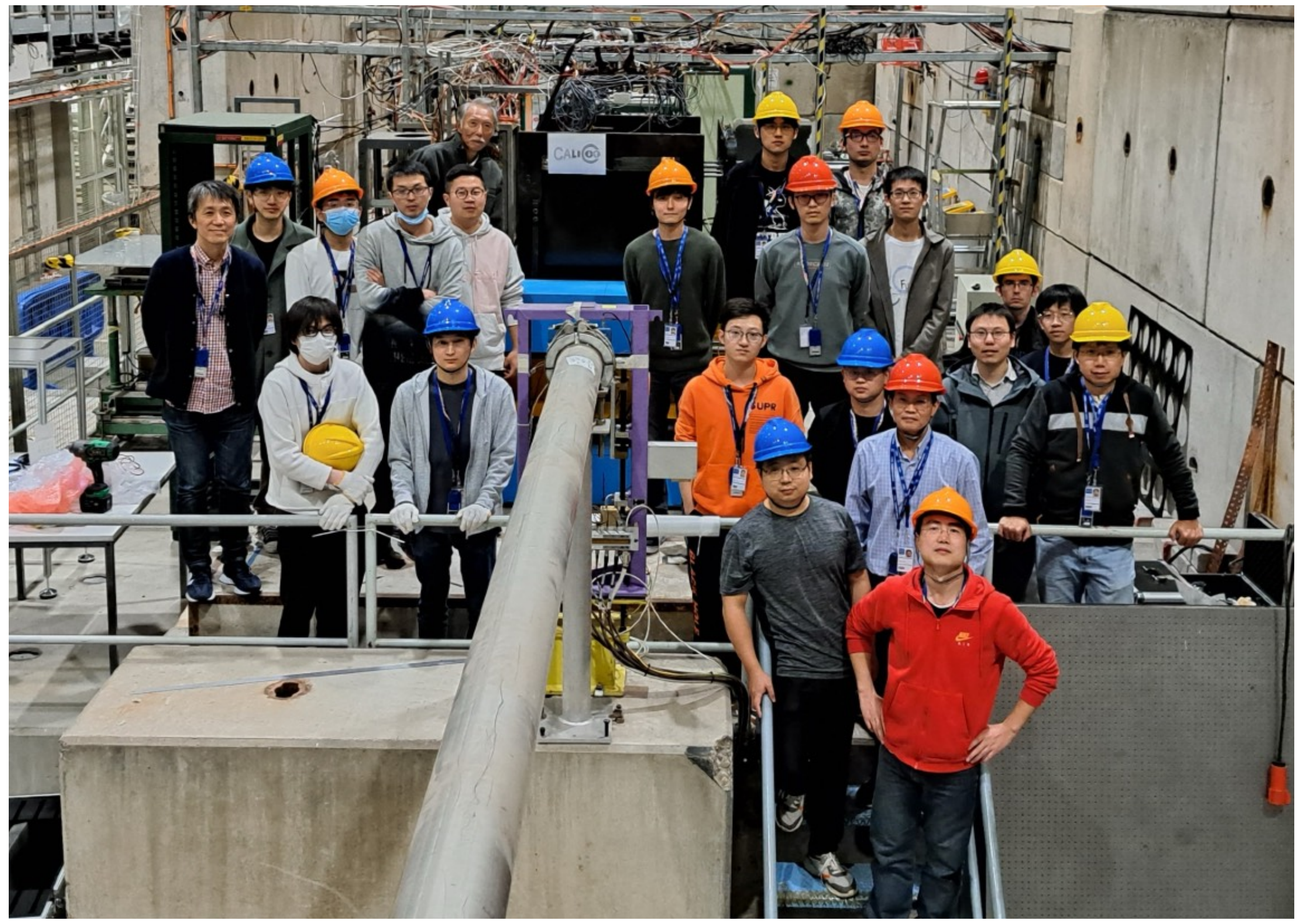
Prototypes developed within CALICE

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

CEPC calorimeter prototypes: beamtest in 2022







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Institute of High Energy Physics
Chinese Academy of Sciences

信州大学
SHINSHU UNIVERSITY

東京大学
THE UNIVERSITY OF TOKYO

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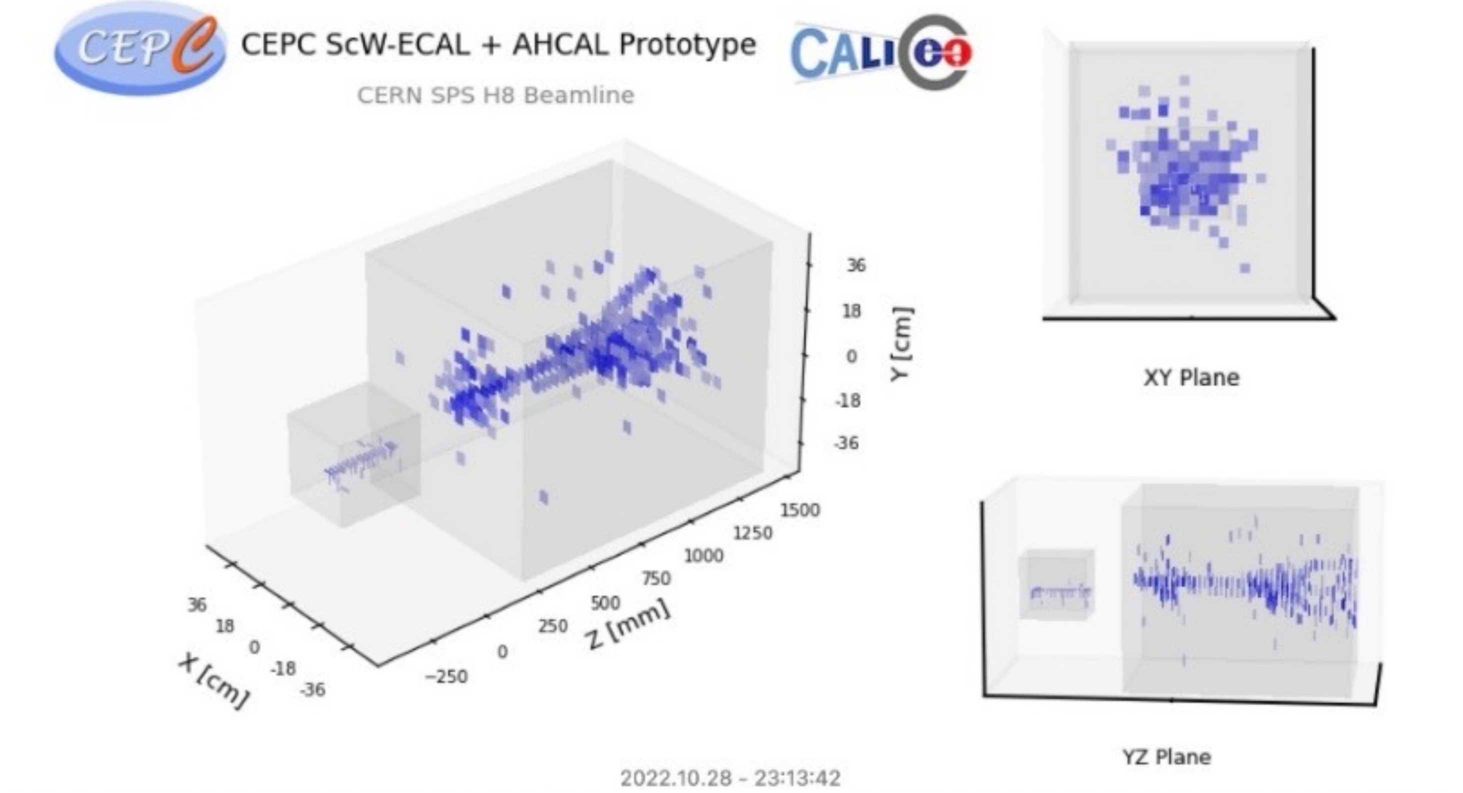
WEIZMANN INSTITUTE OF SCIENCE

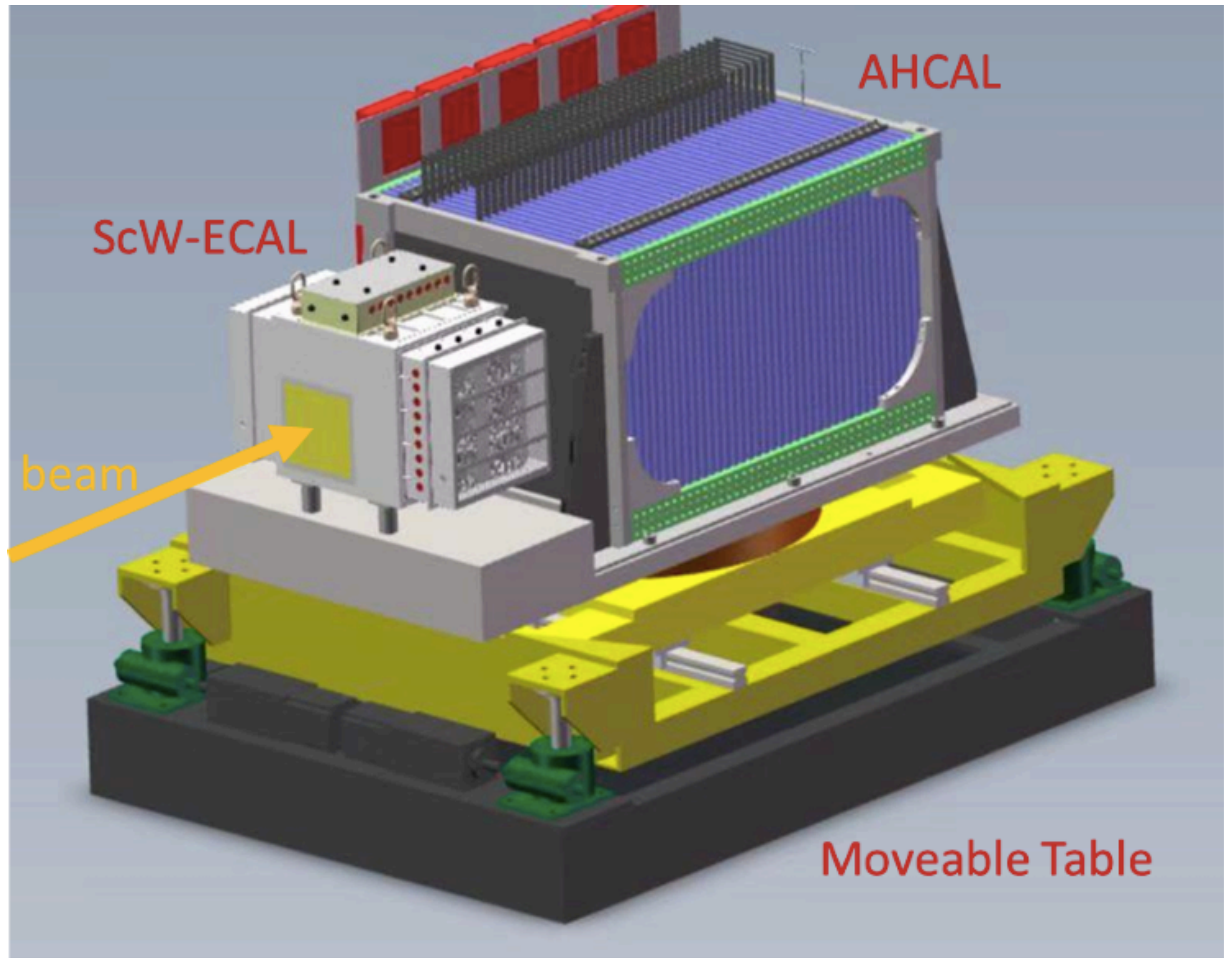


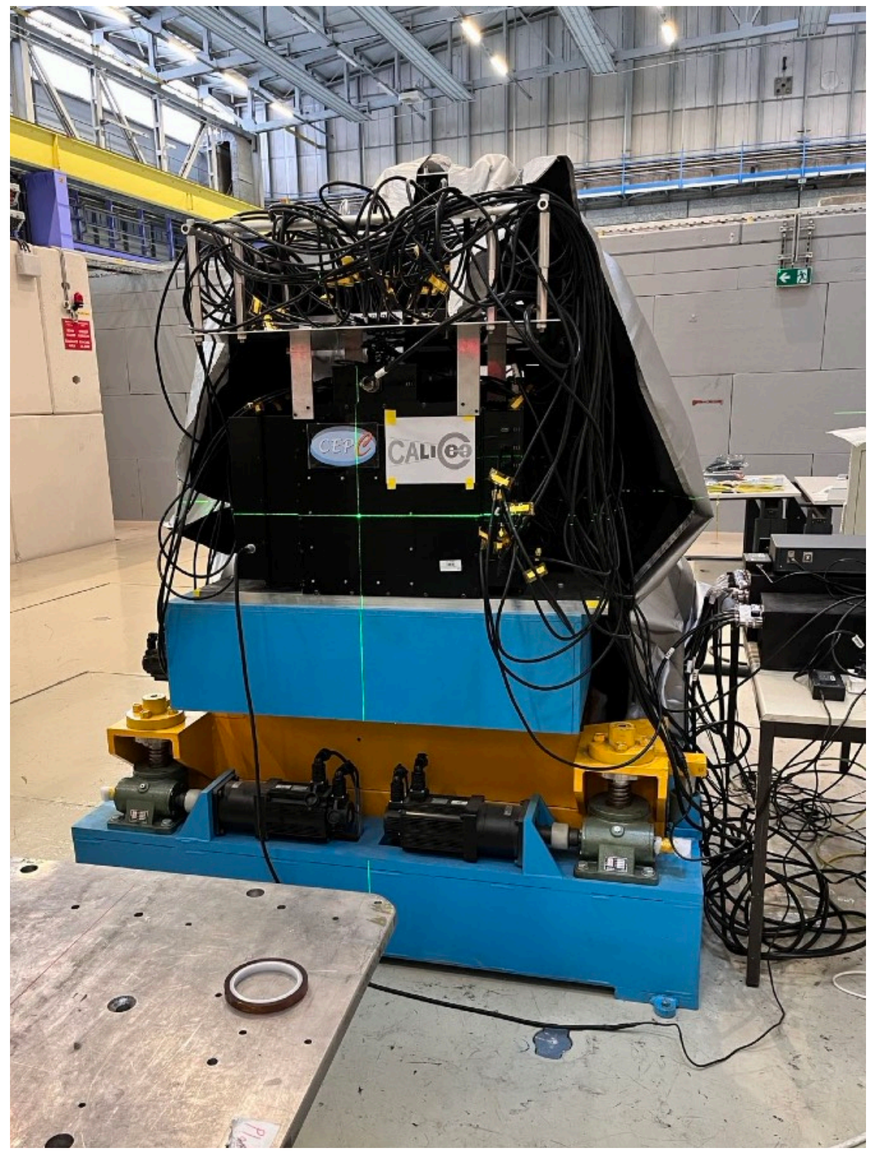
- Successful beamtest at CERN SPS H8: **Oct-Nov, 2022**
  - High energy particle beams: muons, positrons and hadrons (10 - 160 GeV)
  - Suffered from beam purity issue in pion and positron beams

CEPC calorimeter prototypes: beamtests in 2023

- Beamtest campaigns
  - First period (16 days): CERN SPS-H2 in Apr. - May 2023
  - Second period (15 days): CERN PS-T09 in May 2023

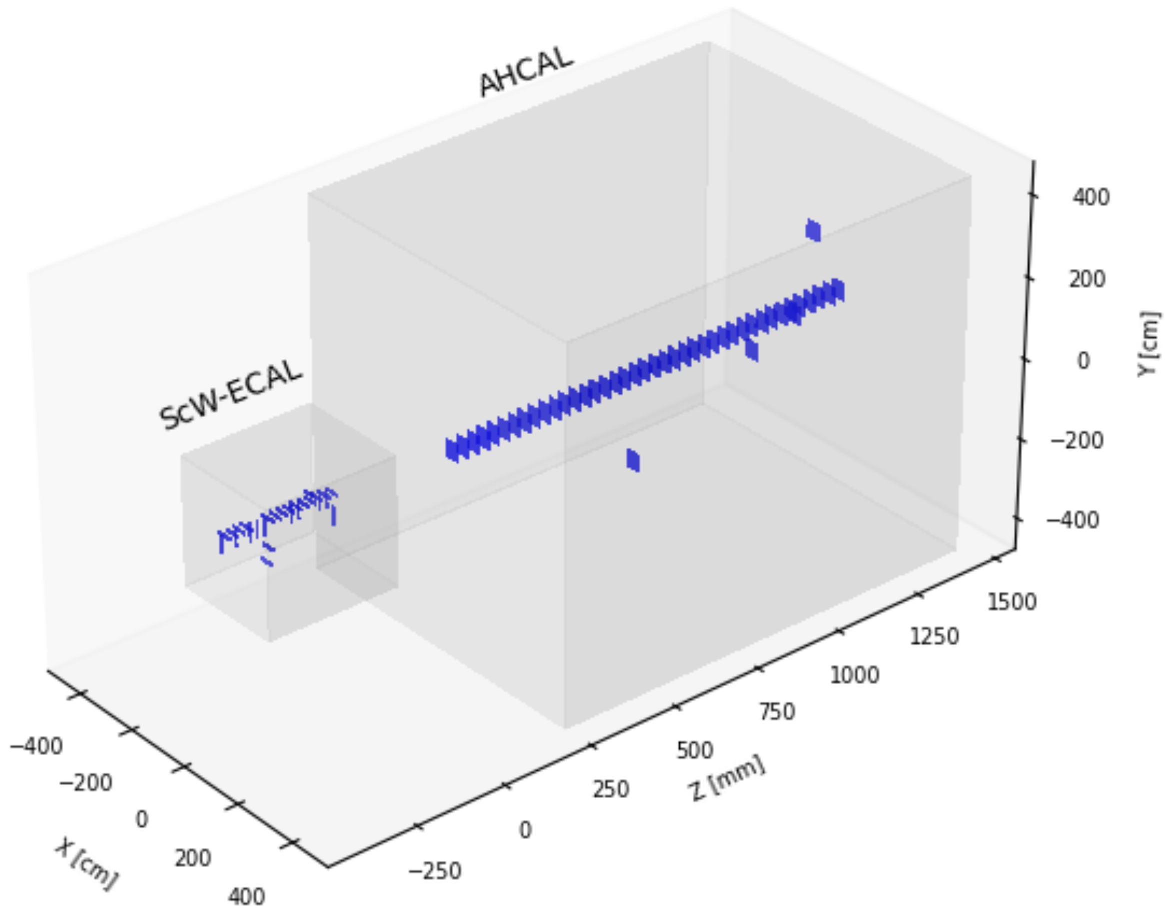
- Data sets: significantly improved beam purity than 2022
  - Collected decent statistics, enabling detector performance evaluation, validation of Geant4 simulation, particle-flow studies, etc.

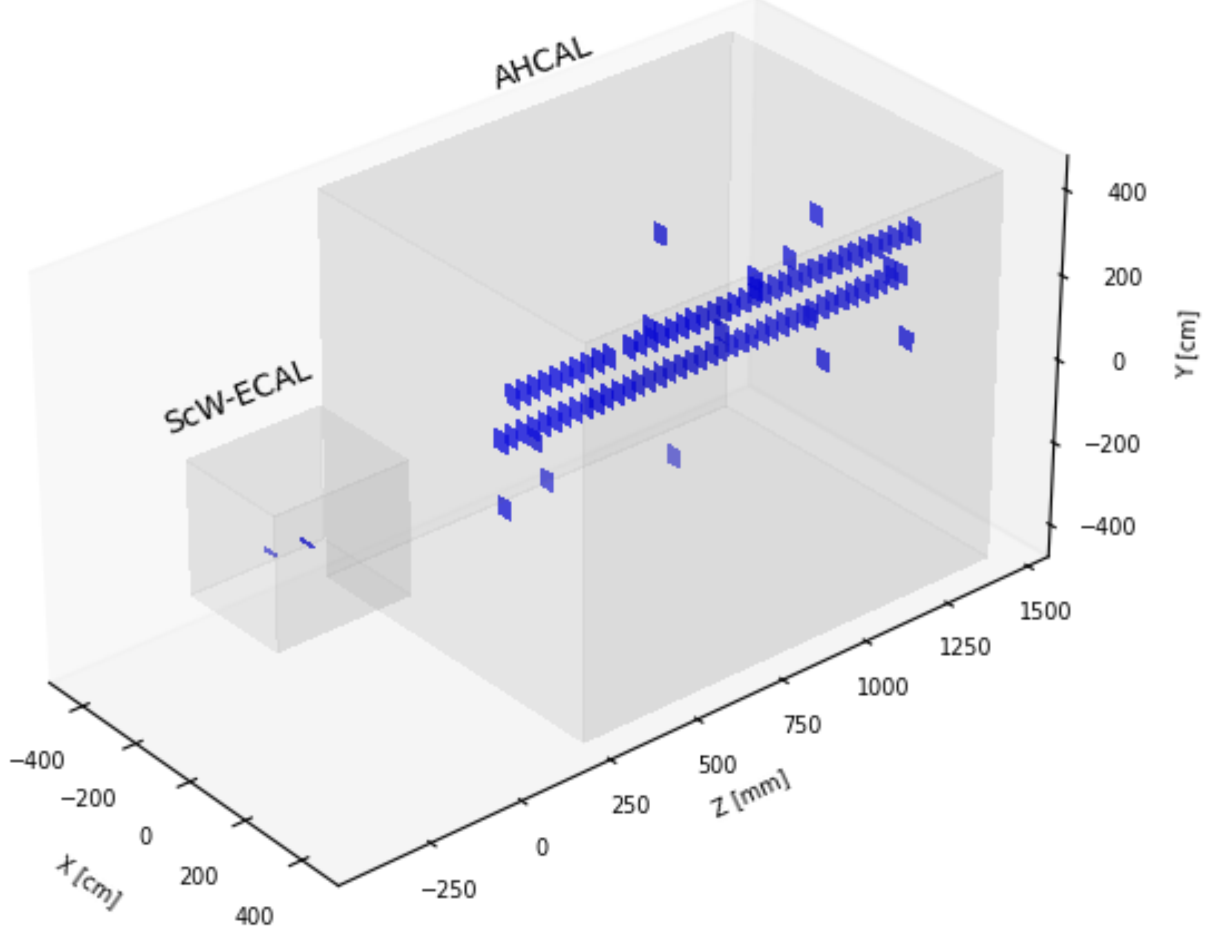




Event display with ScECAL+AHCAL

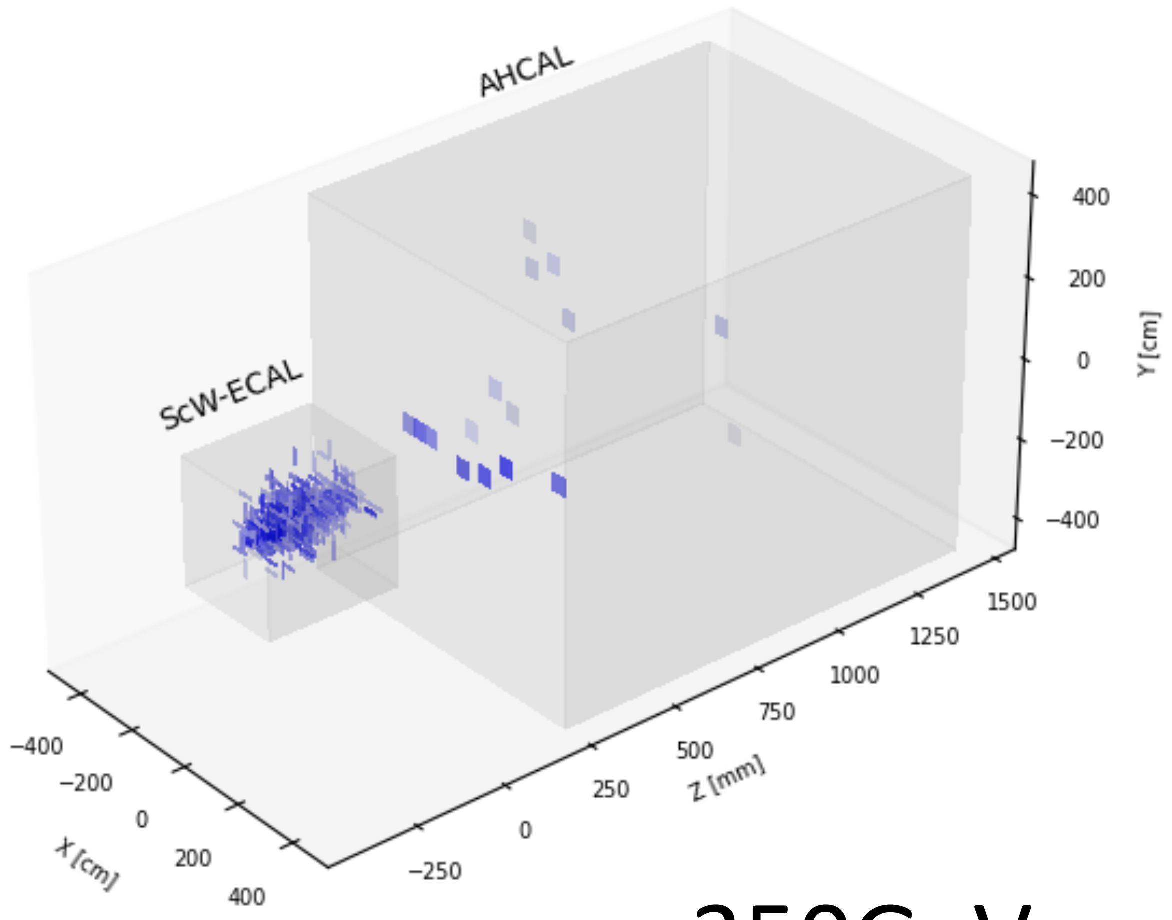
100 GeV mu-



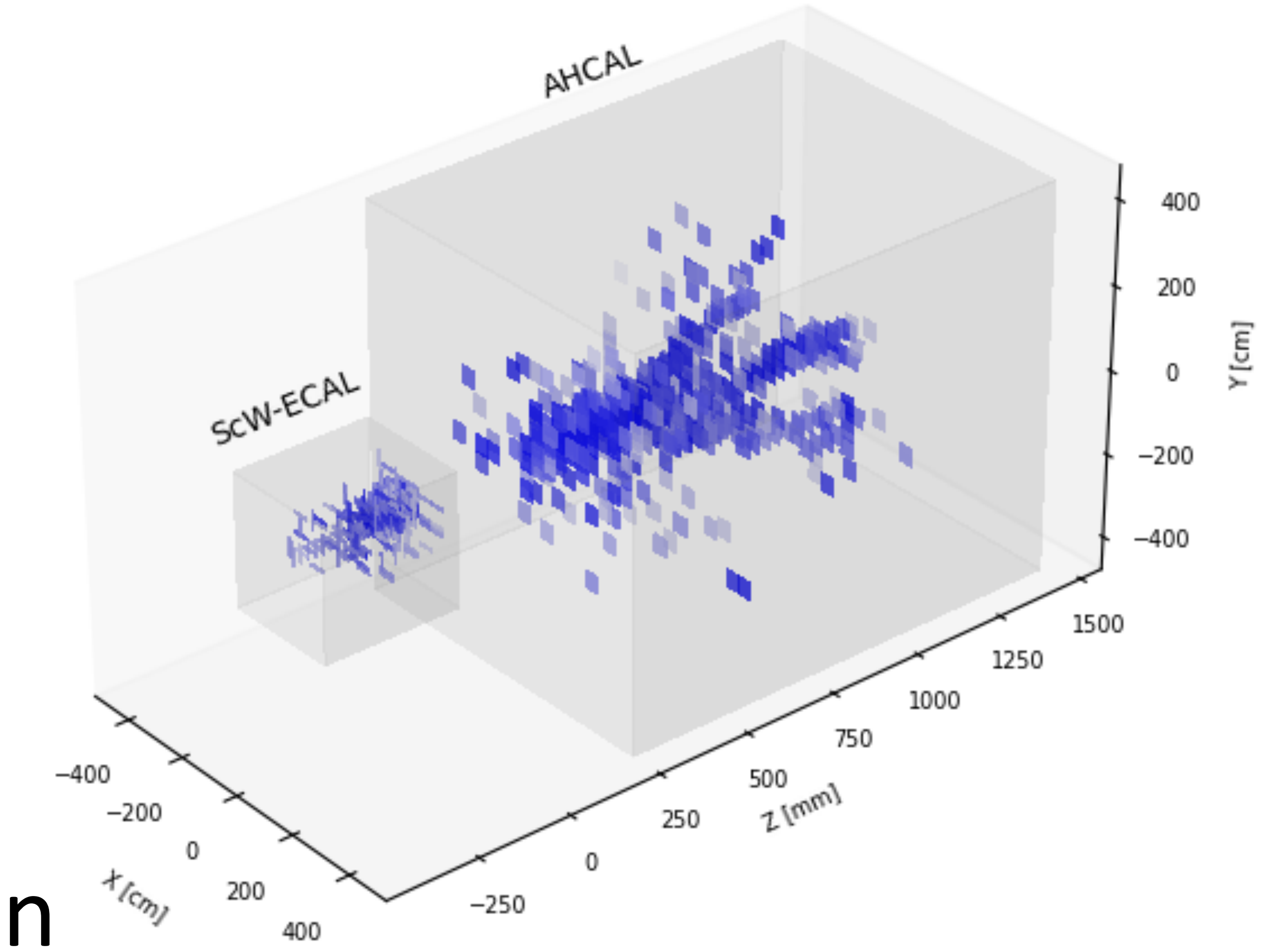


One run of different position scans: muon beam out of ScW-ECAL acceptance

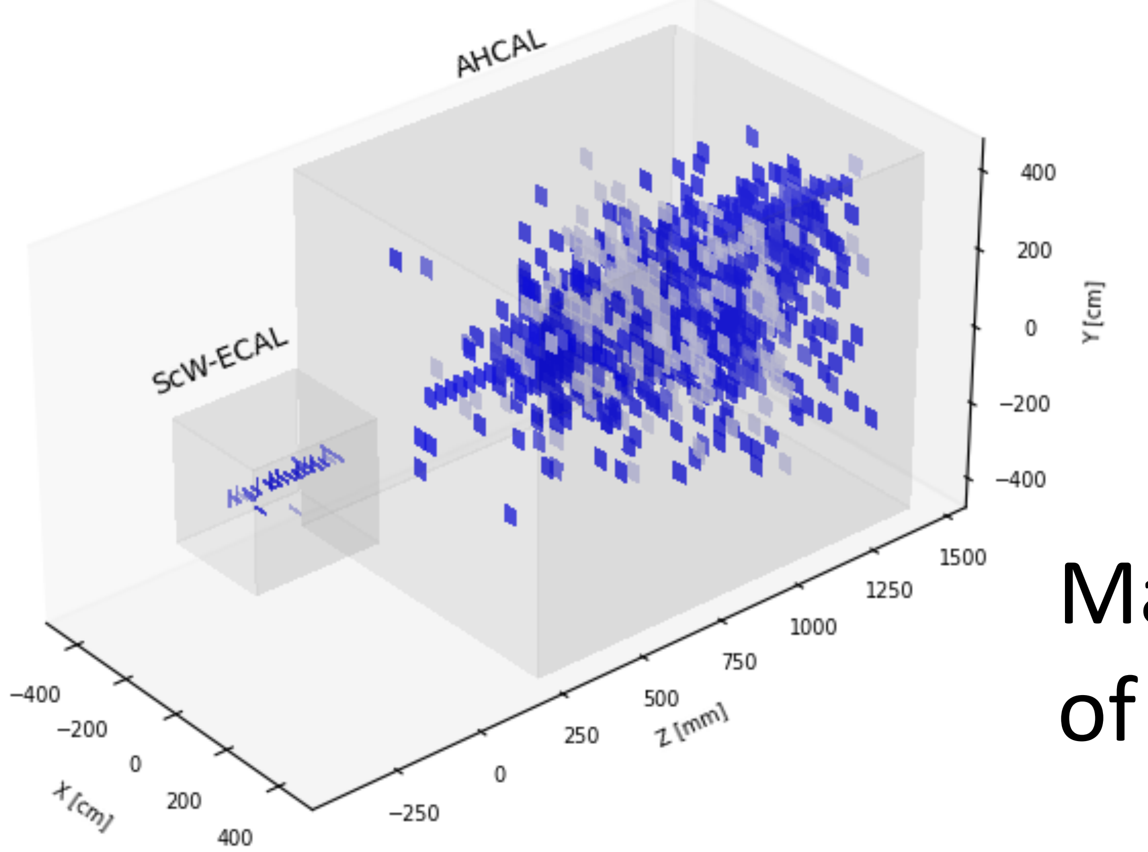
60GeV electron



60GeV negative pion



350GeV negative pion

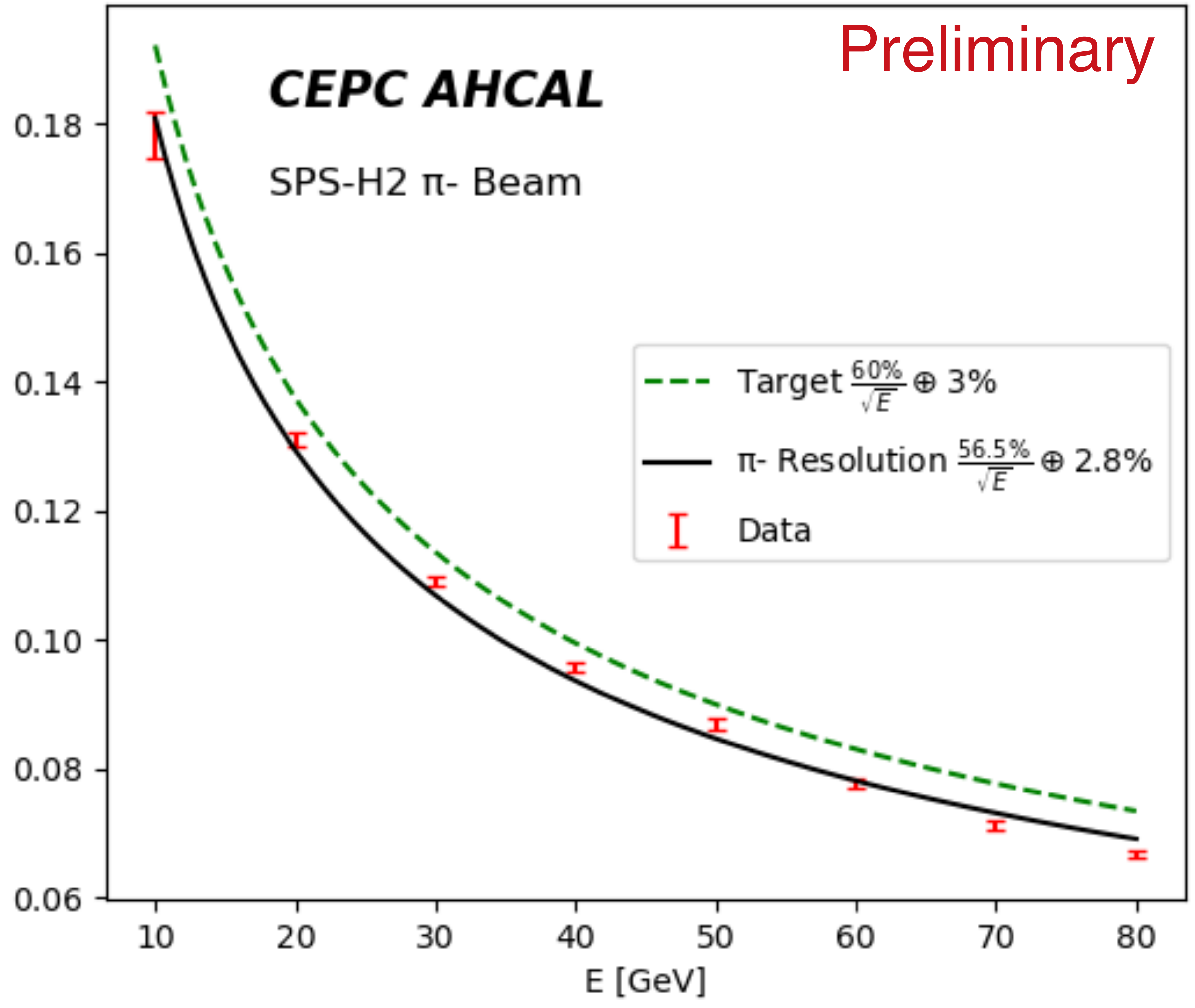


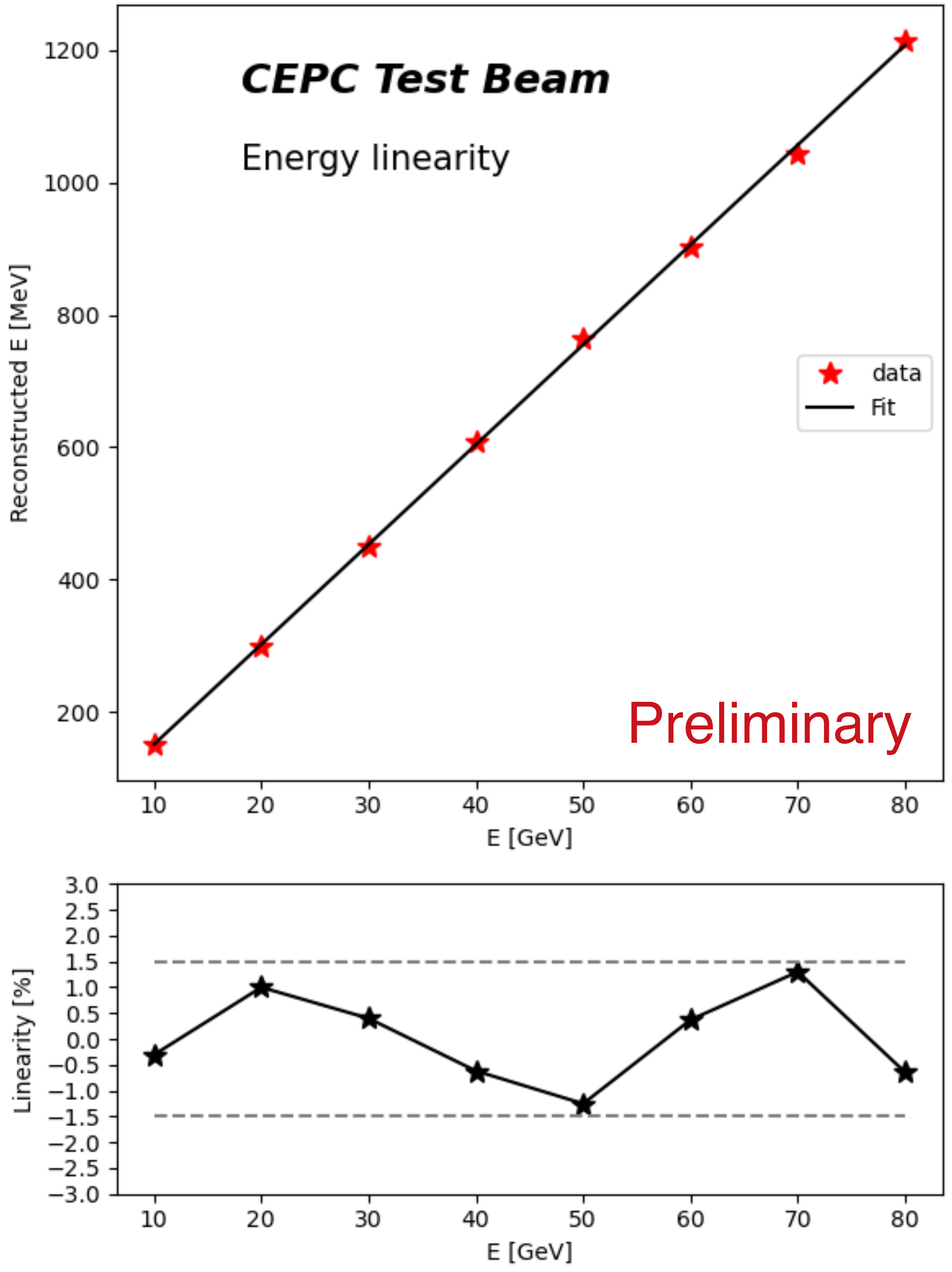
Maximum pion beam energy of existing testbeam facilities

General impressions: much better purity of electron and pion beams than data taken at H8 in 2022

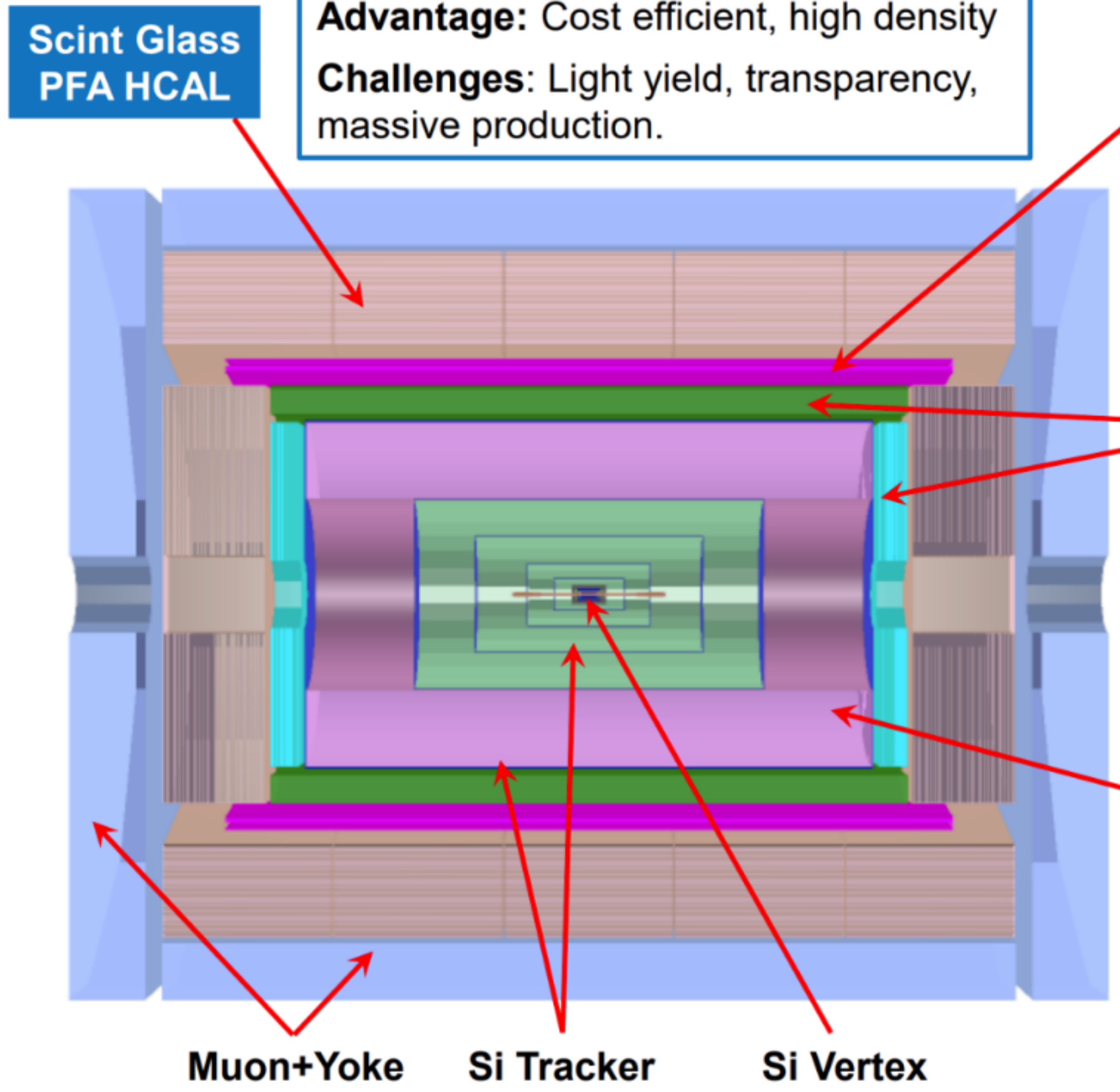
Key calorimeter performance

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





High-granularity calorimetry: new concepts



Advantage: Cost efficient, high density
Challenges: Light yield, transparency, massive production.

Solenoid Magnet (3T / 2T) Between HCAL & ECAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.
Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

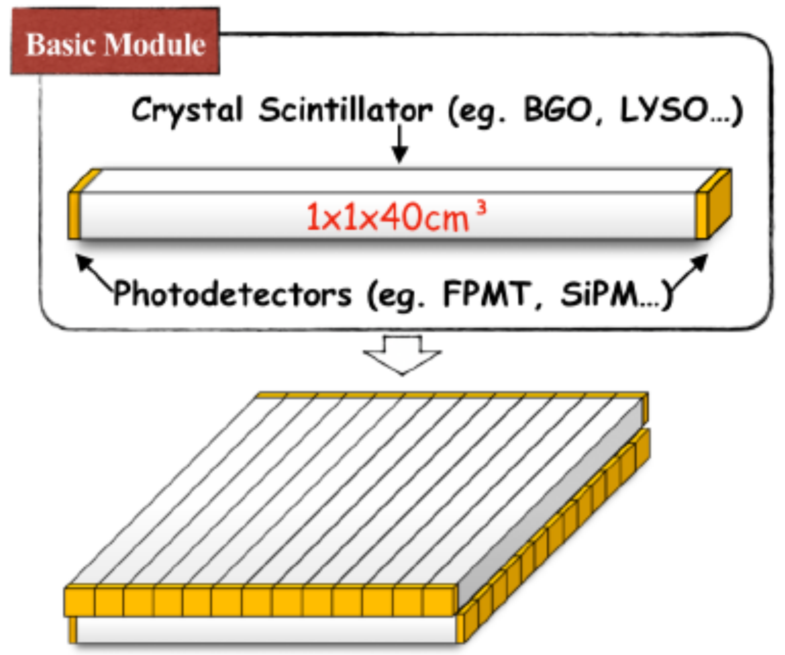
Advantage: better π^0/γ reconstruction.
Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

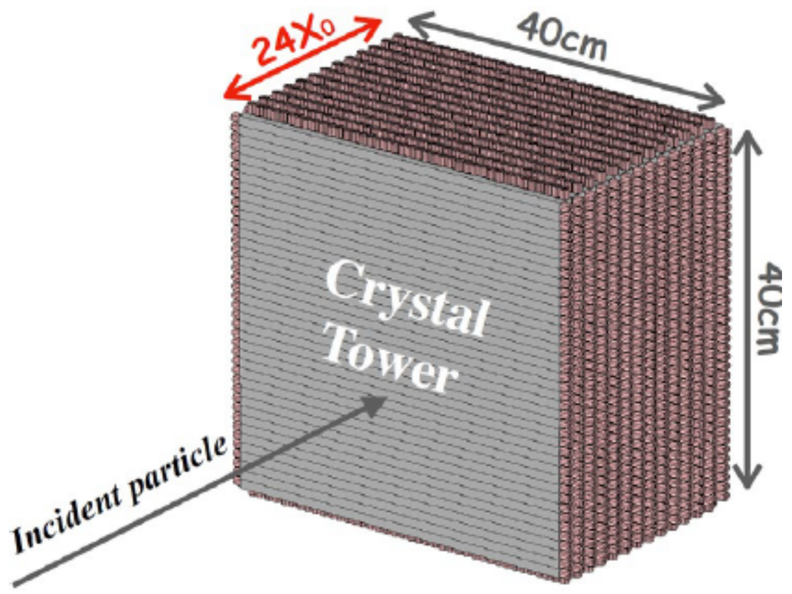
A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs
Challenges: sufficient PID power; thin enough not to affect the moment resolution.

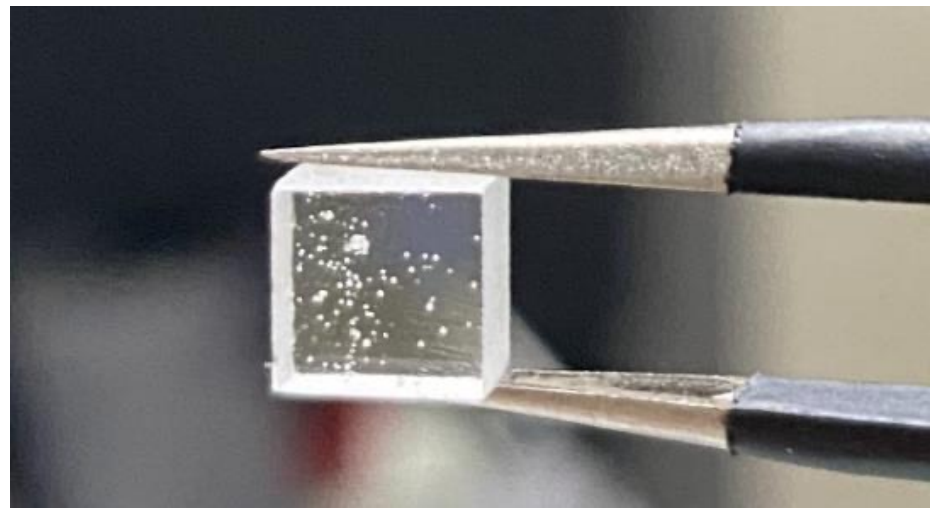
CALICE prototypes EM/hadronic resolutions, $\sim 14\%/\sqrt{E(GeV)}$ and $\sim 58\%/\sqrt{E(GeV)}$; new concepts expected to further improve performance

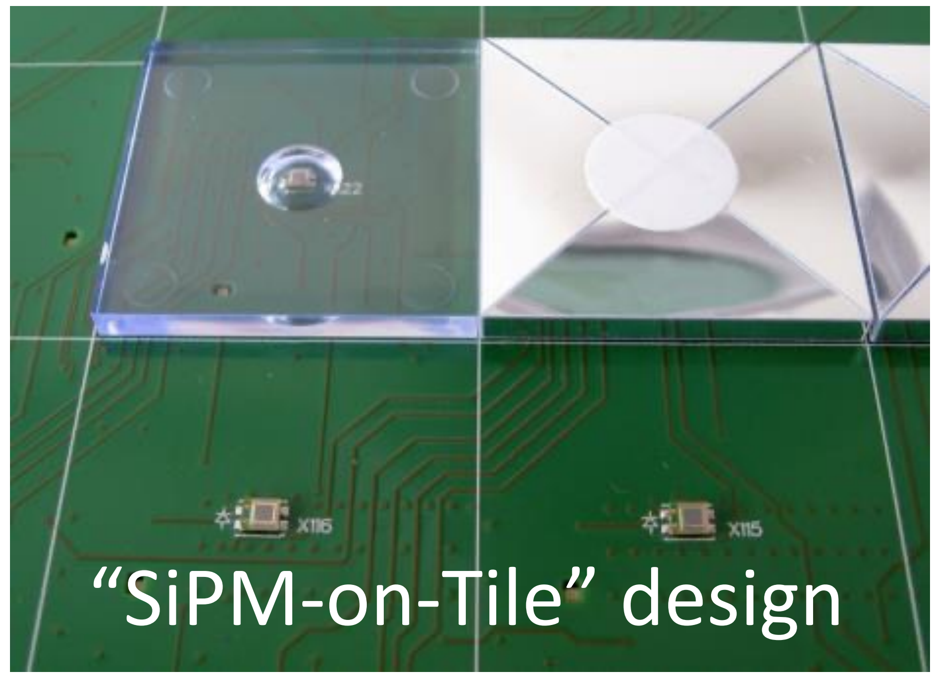
4D crystal calorimeter





Glass scintillator sampling calorimeter





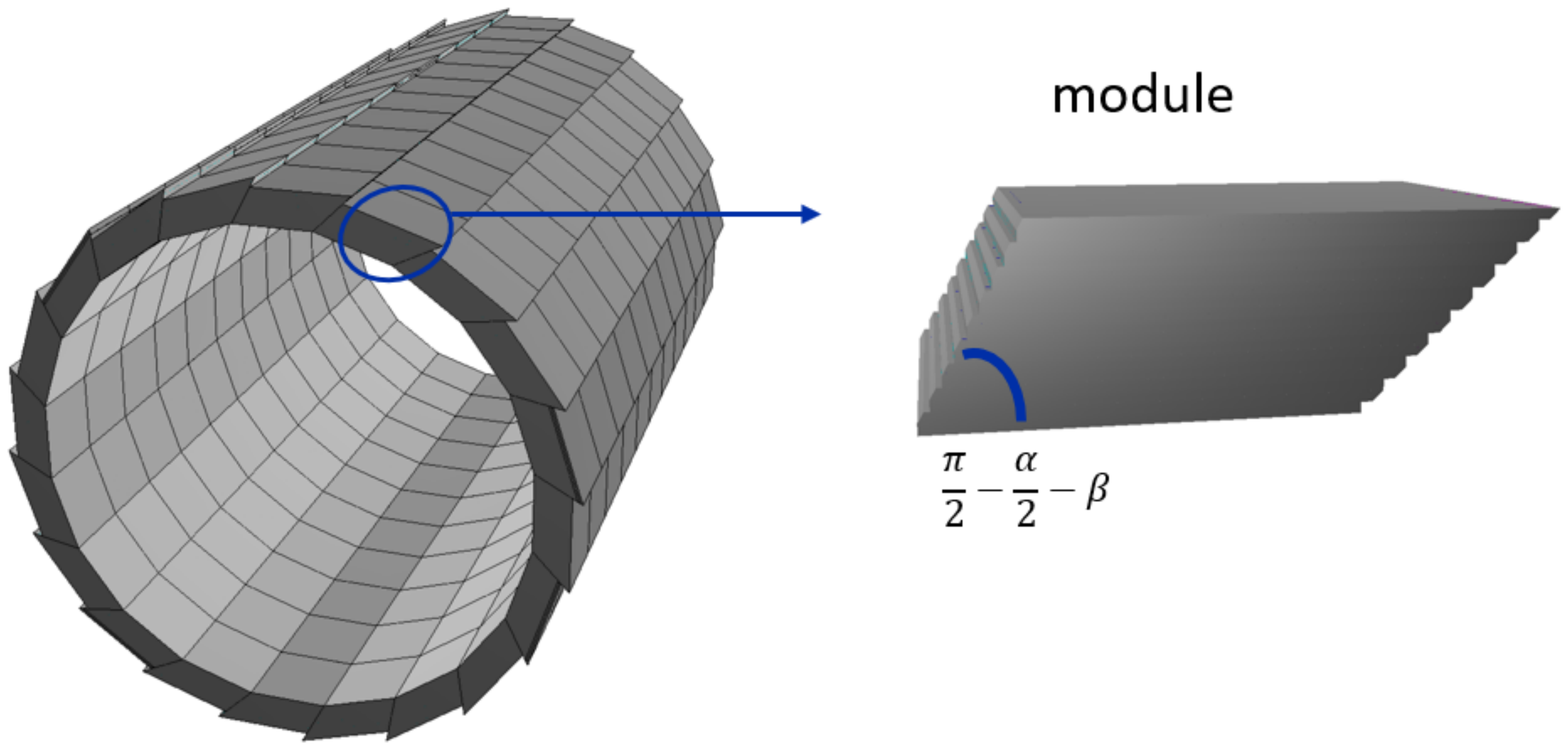
a la CALICE-AHCAL, but with glass tiles

- CEPC 4th Concept Detector: new calorimeters
  - 4D crystal calorimeter: high granularity, EM resolution $\leq 3\%/\sqrt{E(GeV)}$
  - Glass scintillator calorimeter: high granularity, hadronic resolution $\leq 40\%/\sqrt{E(GeV)}$

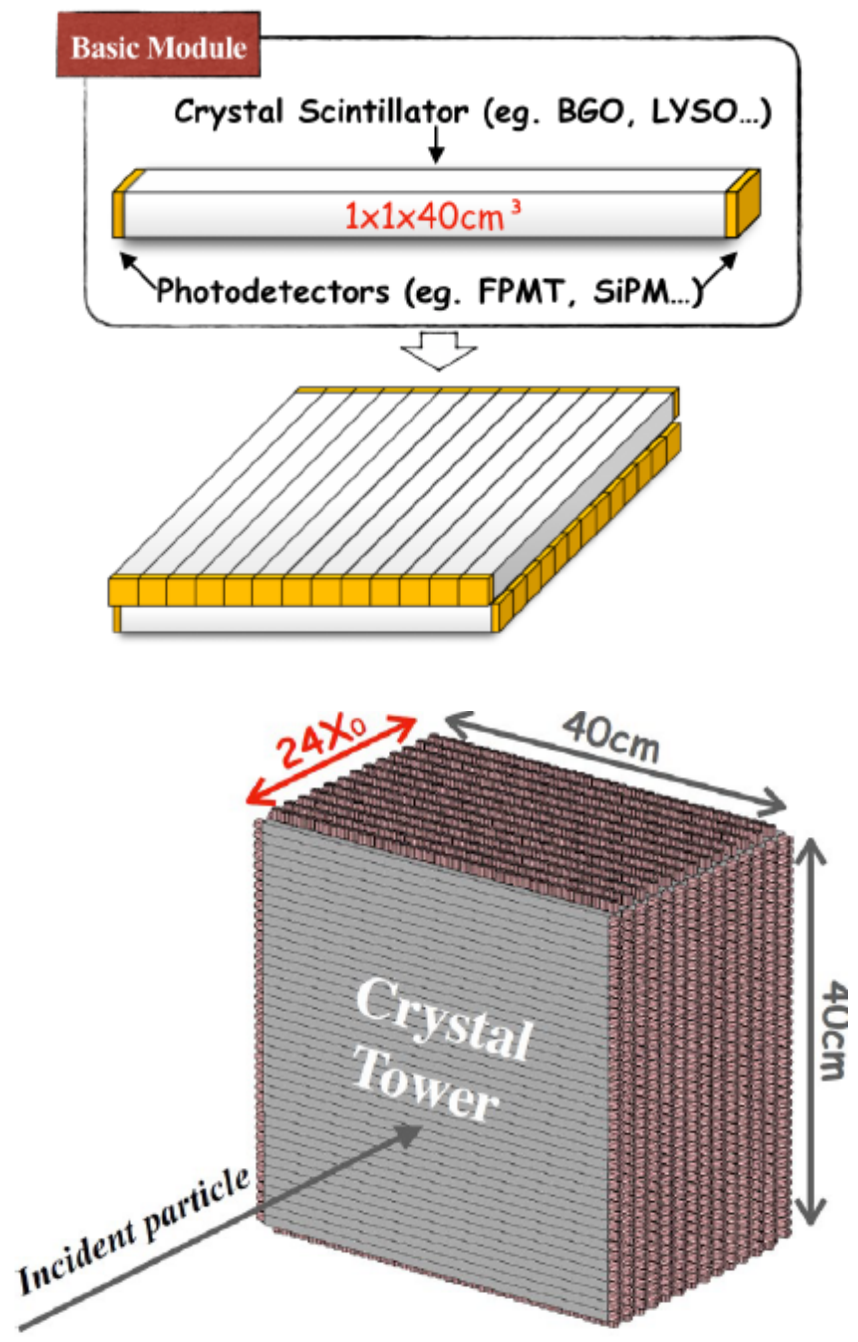
Replacing plastic scintillator in the PFA HCAL with high light yield, high density, low cost scintillating glass

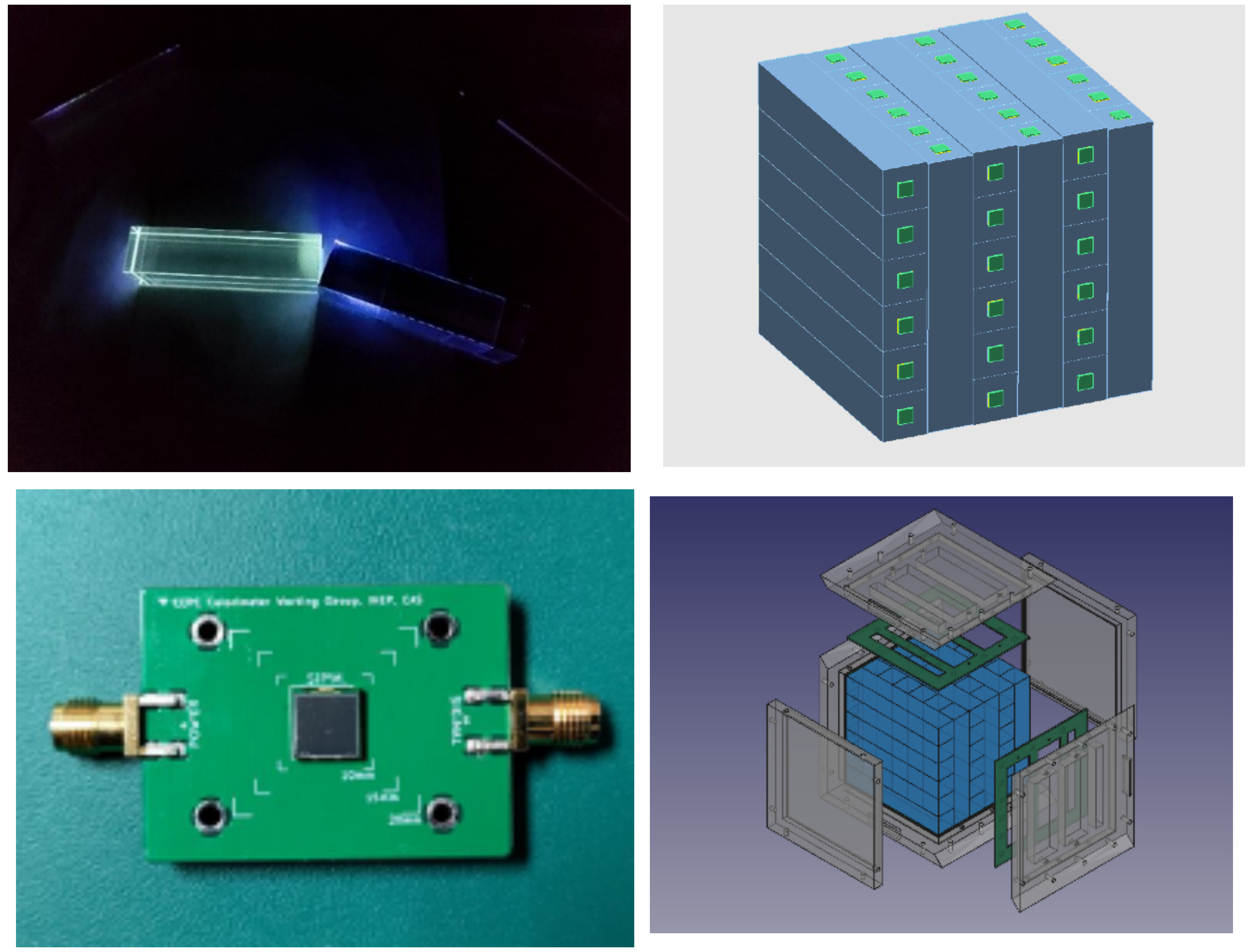
4D crystal calorimeter

- Design specifications
  - Granularity $1 \times 1\mathrm{cm}^2$, EM resolution $\leq 3\%/\sqrt{E(GeV)}$
  - Timing resolution: ~100 ps @MIP signal
  - Single photon detection capability
  - Low energy threshold: ~0.5 MeV
  - Wide dynamic range: single photon – 100k photons

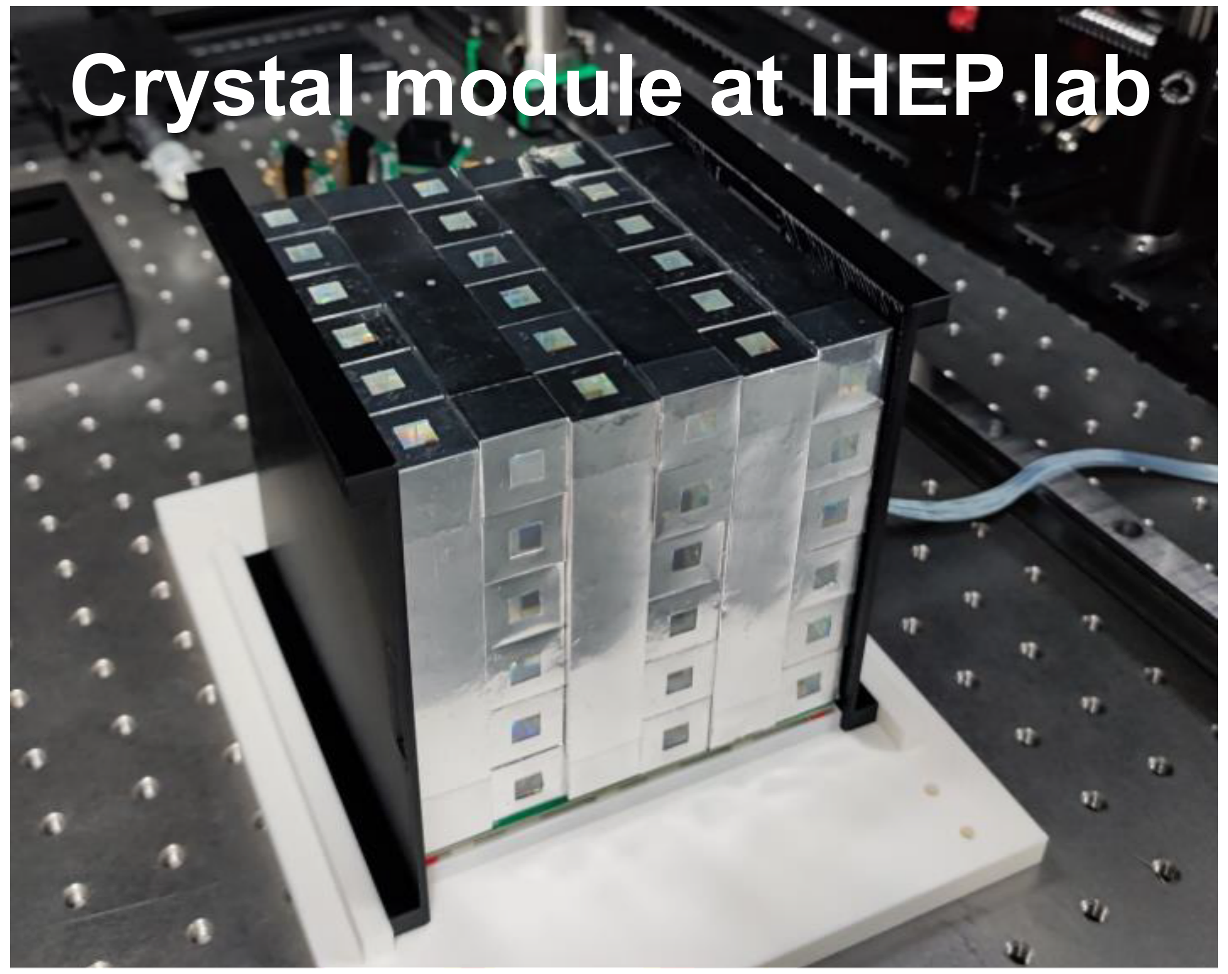


cylindrical crystal ECAL





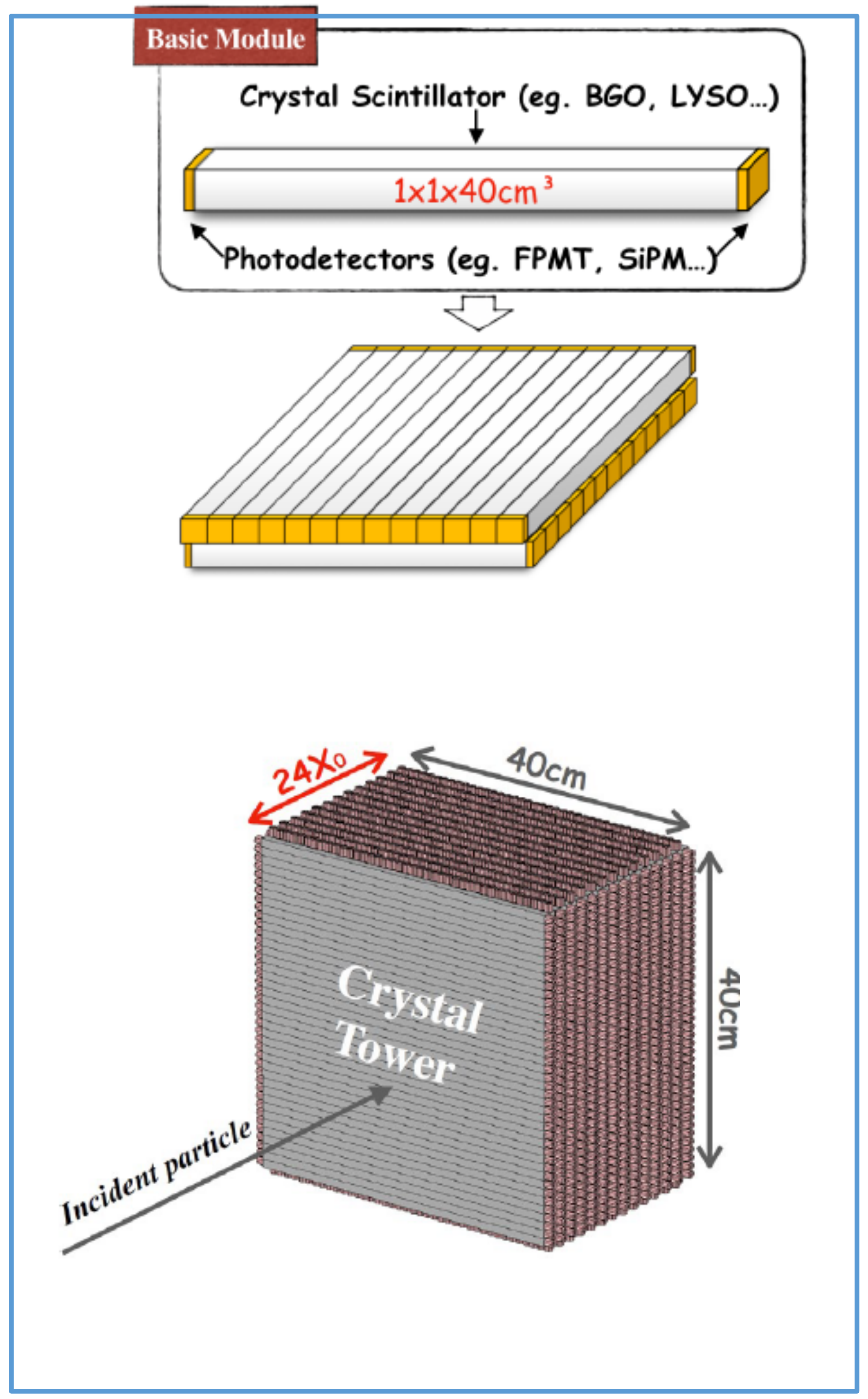
Scintillating crystal + SiPM

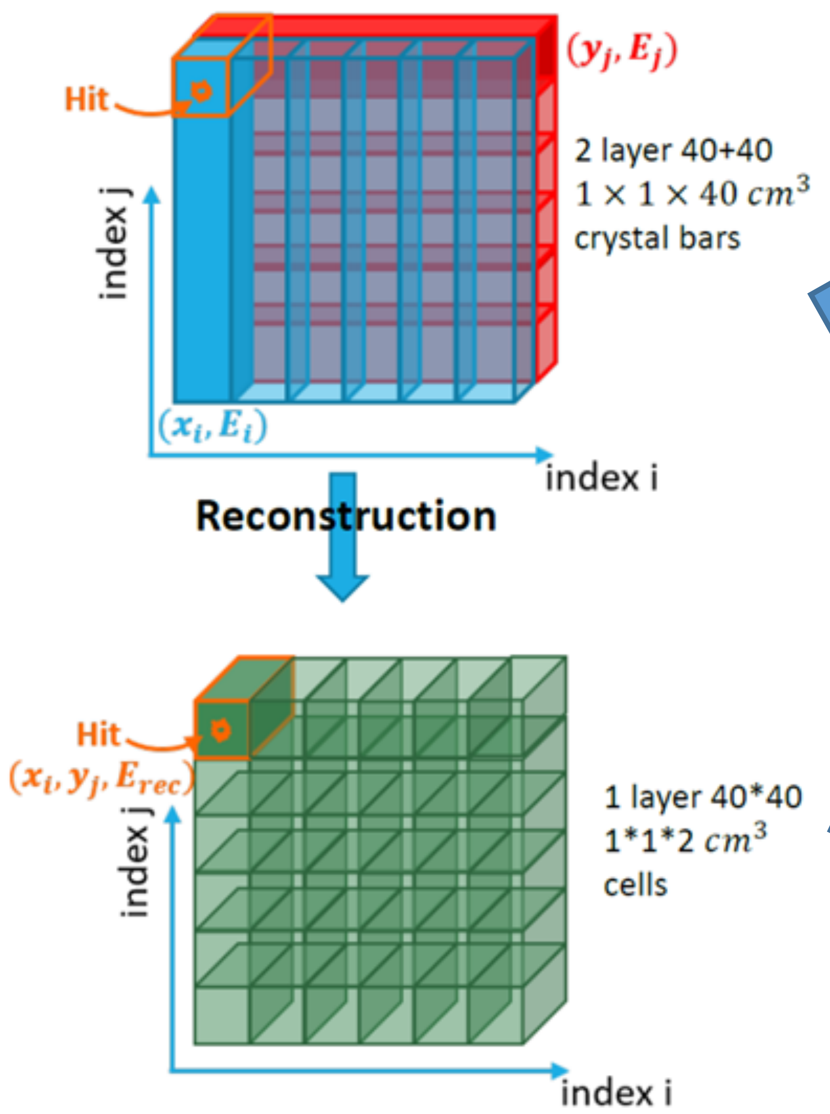


Proposal inputs to the 2021 US Snowmass (IF) and ongoing ECFA DRD6 (Calorimetry)

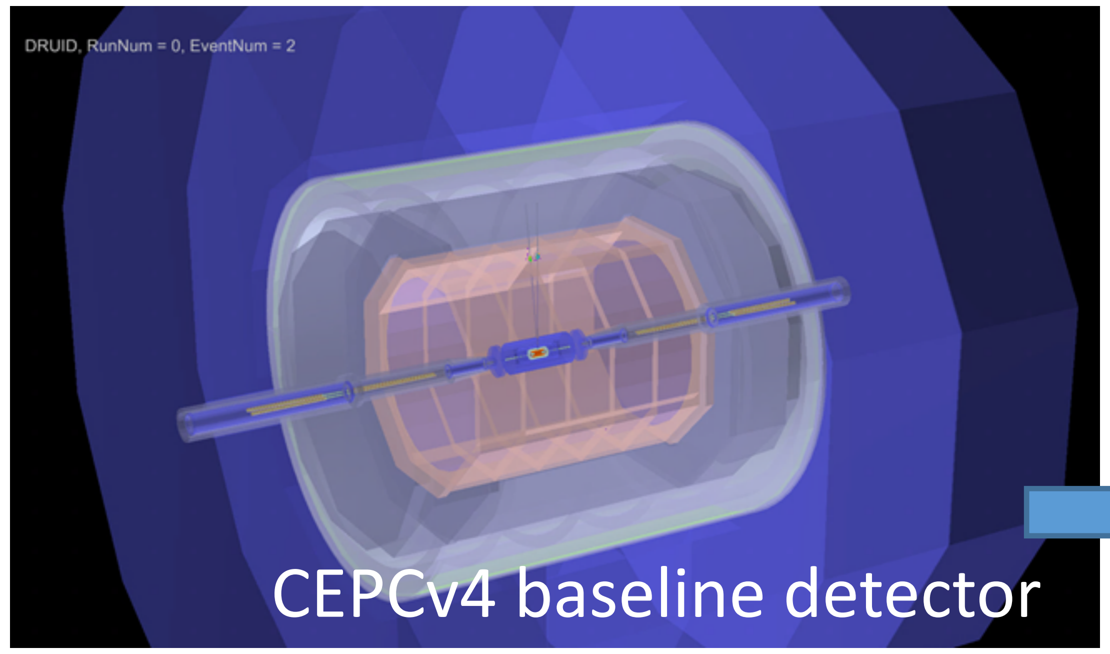
4D crystal calorimeter: R&D overview

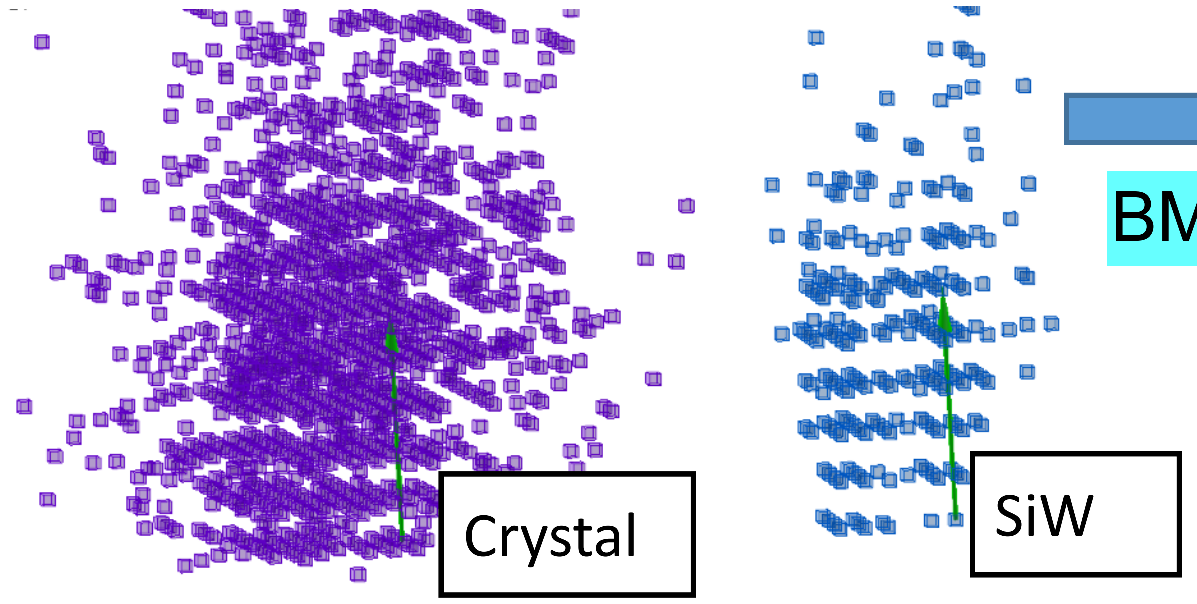
Collaborations within teams on hardware, software and PFA/physics



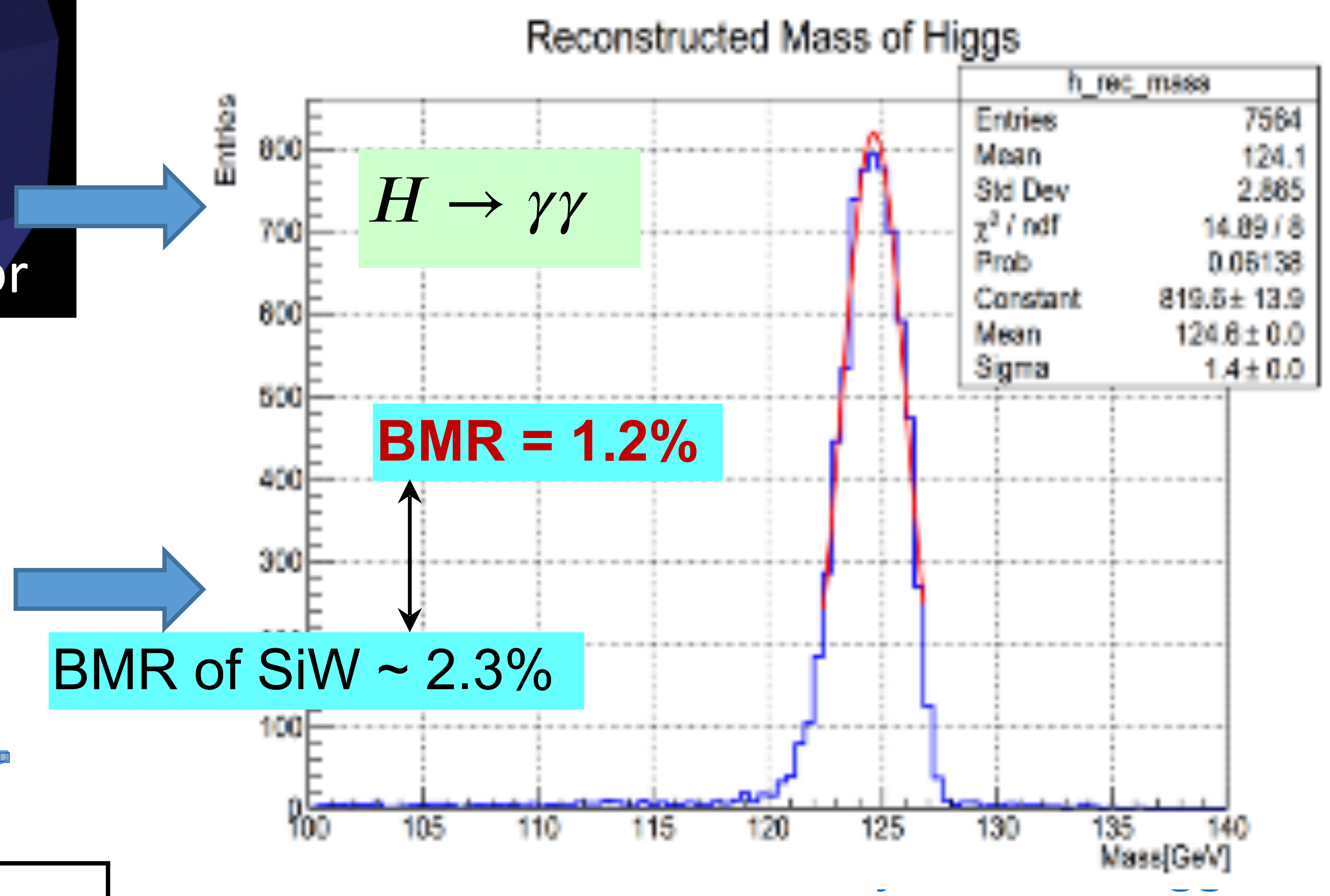


Crossed long bar design: $1\times1\times2$ cm^3 granularity after digitization





Event display: crystal compared to SiW: significant increase of #hit



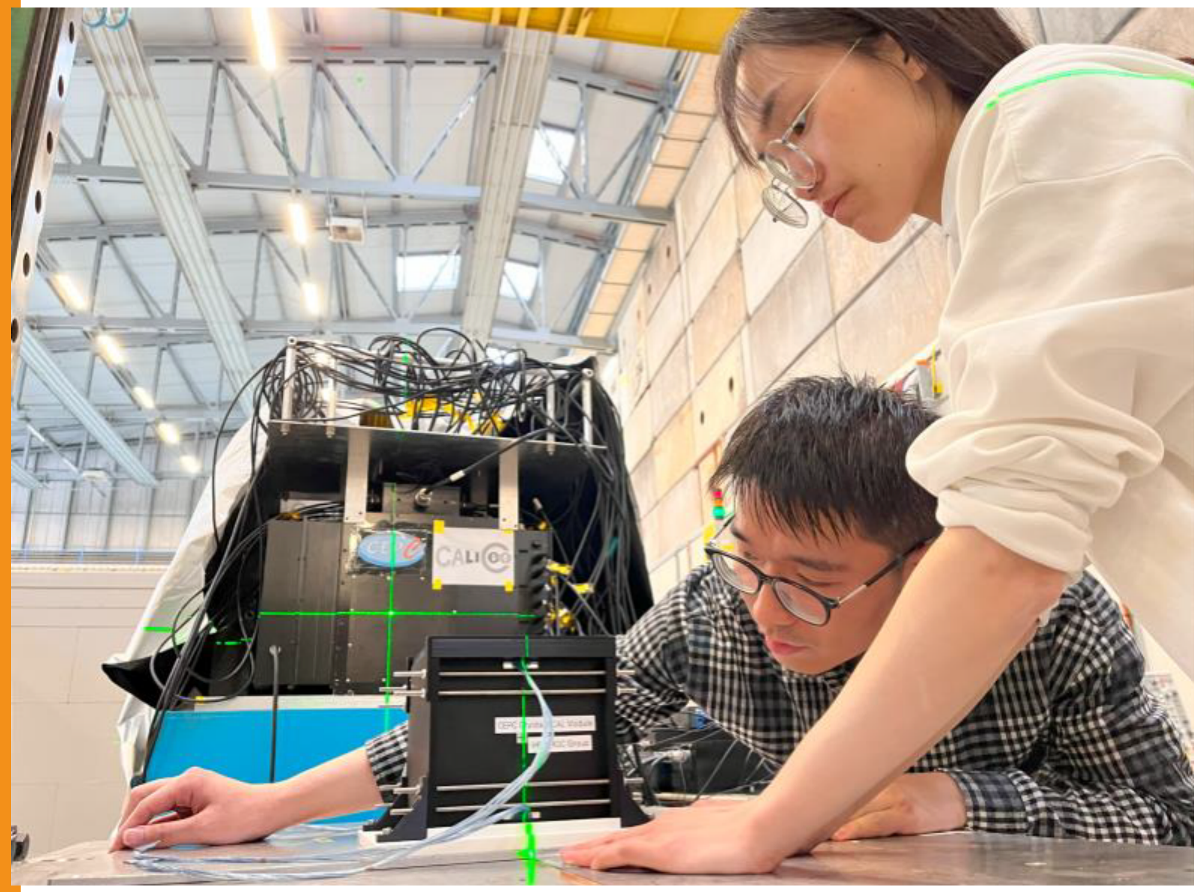
Hardware development: key questions and specs

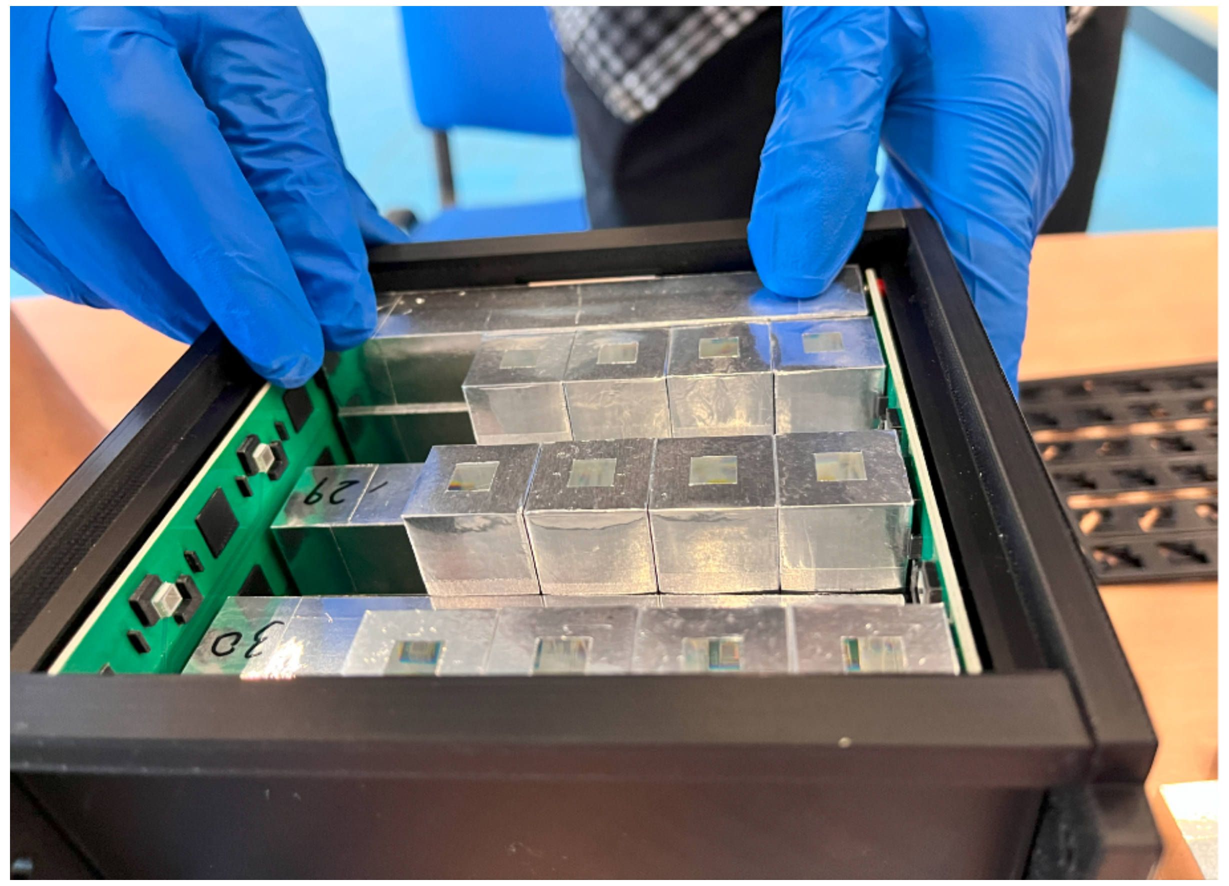
- New reconstruction software for long bars
- Arbor-PFA optimization for crystal ECAL

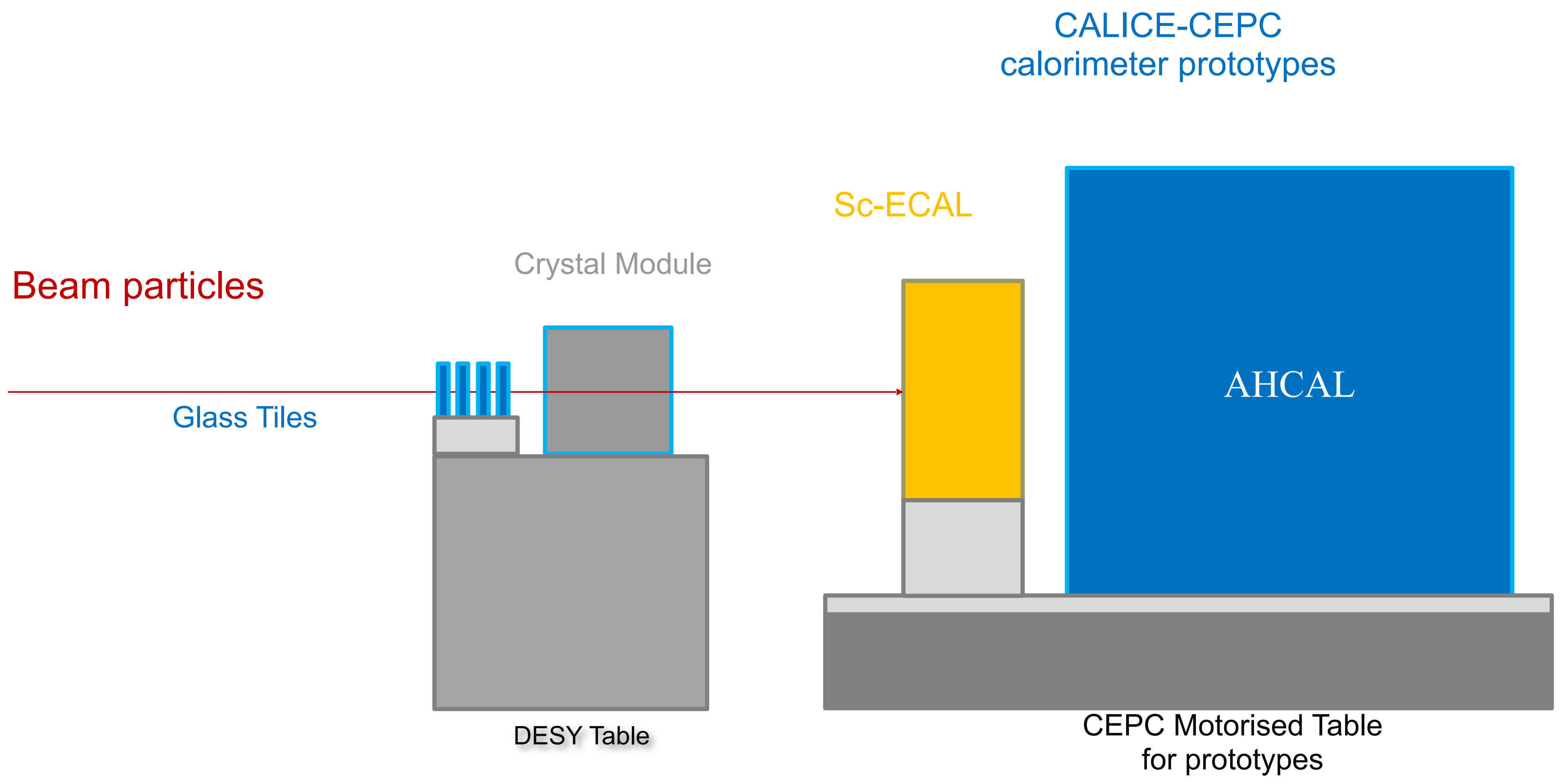
Physics performance evaluation: Higgs benchmarks (+ flavor physics)

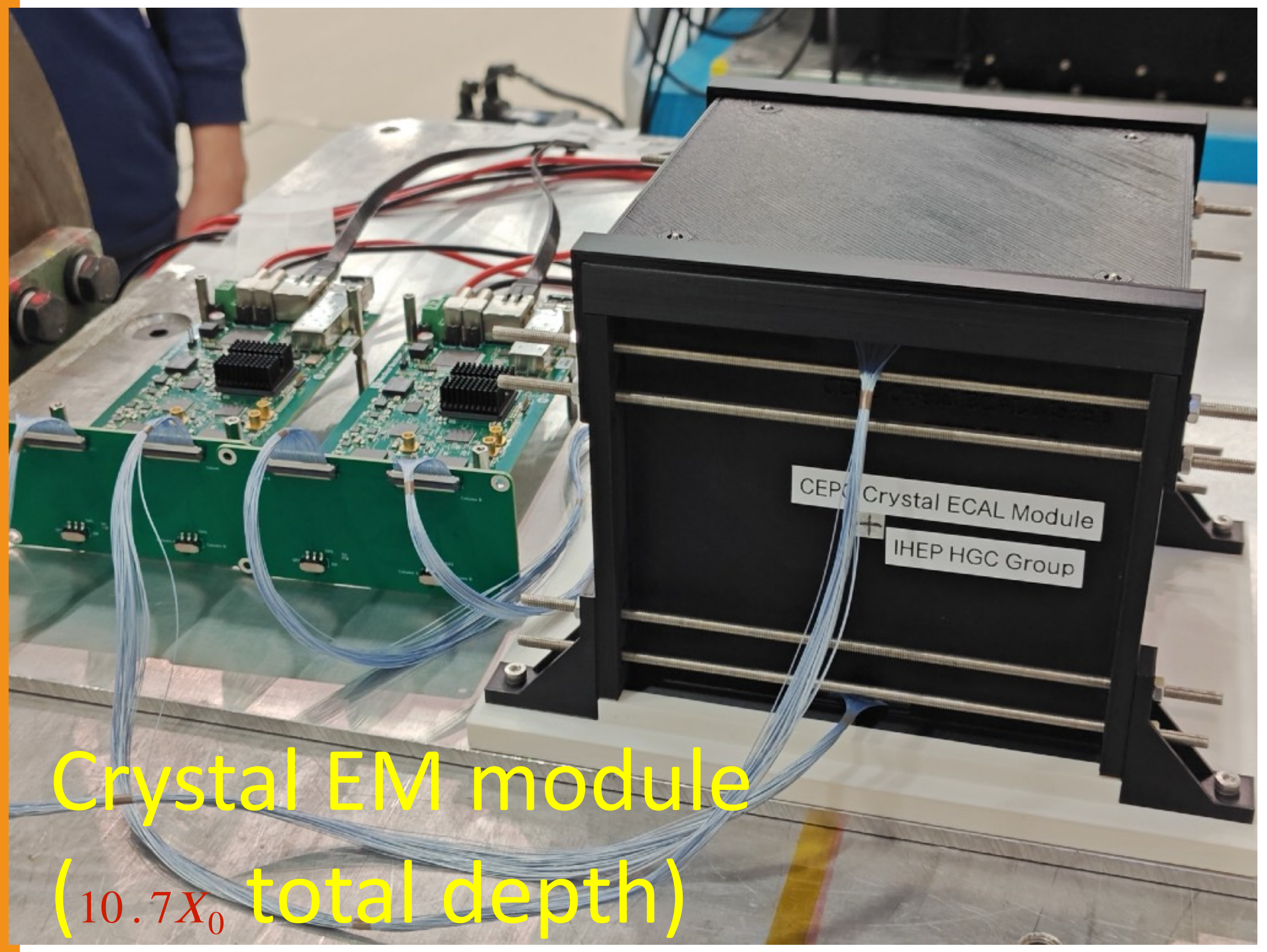
Crystal modules: beamtest at CERN in 2023

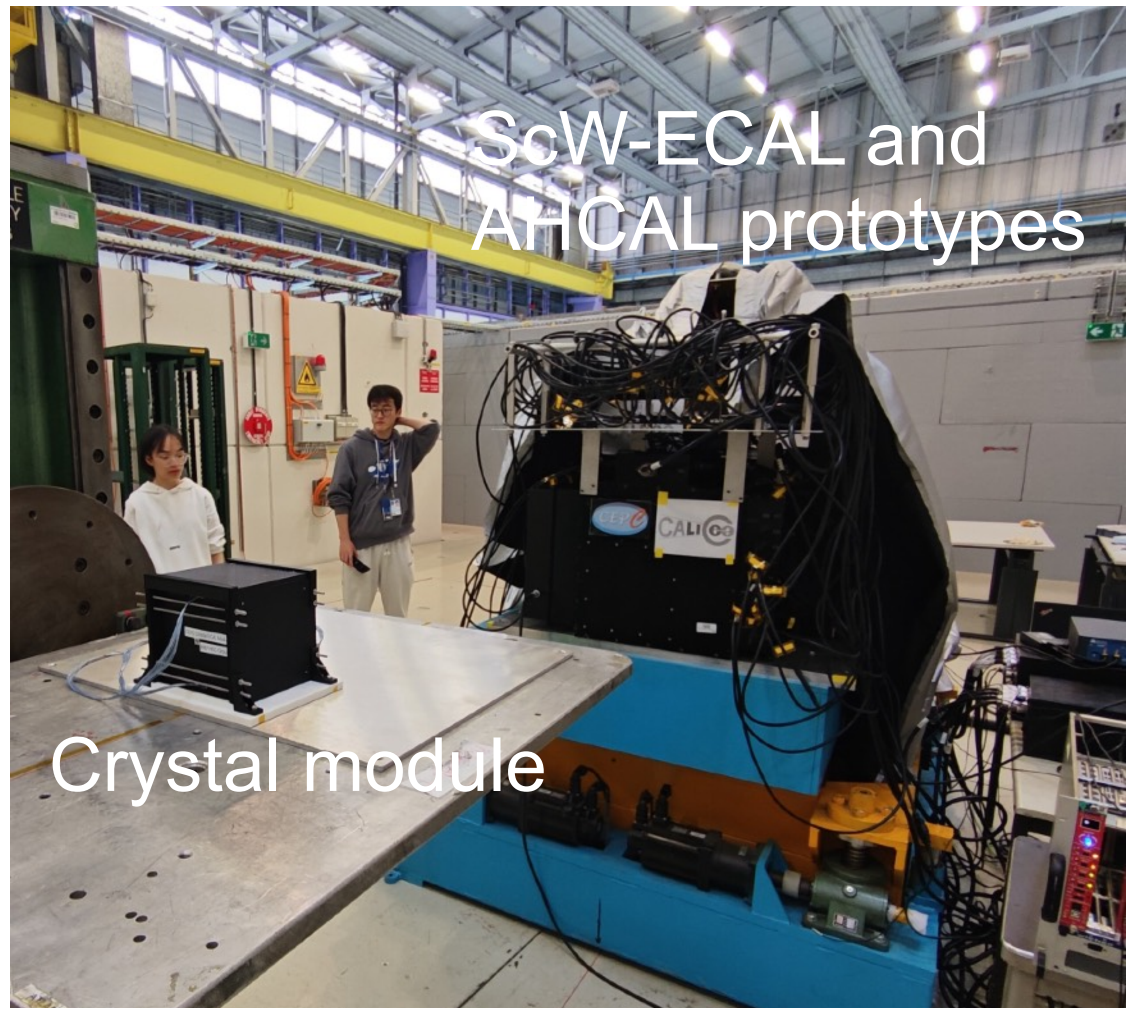
- Successful CERN beamtest: parasitic runs at PS-T9 (May 16-23, 2023)







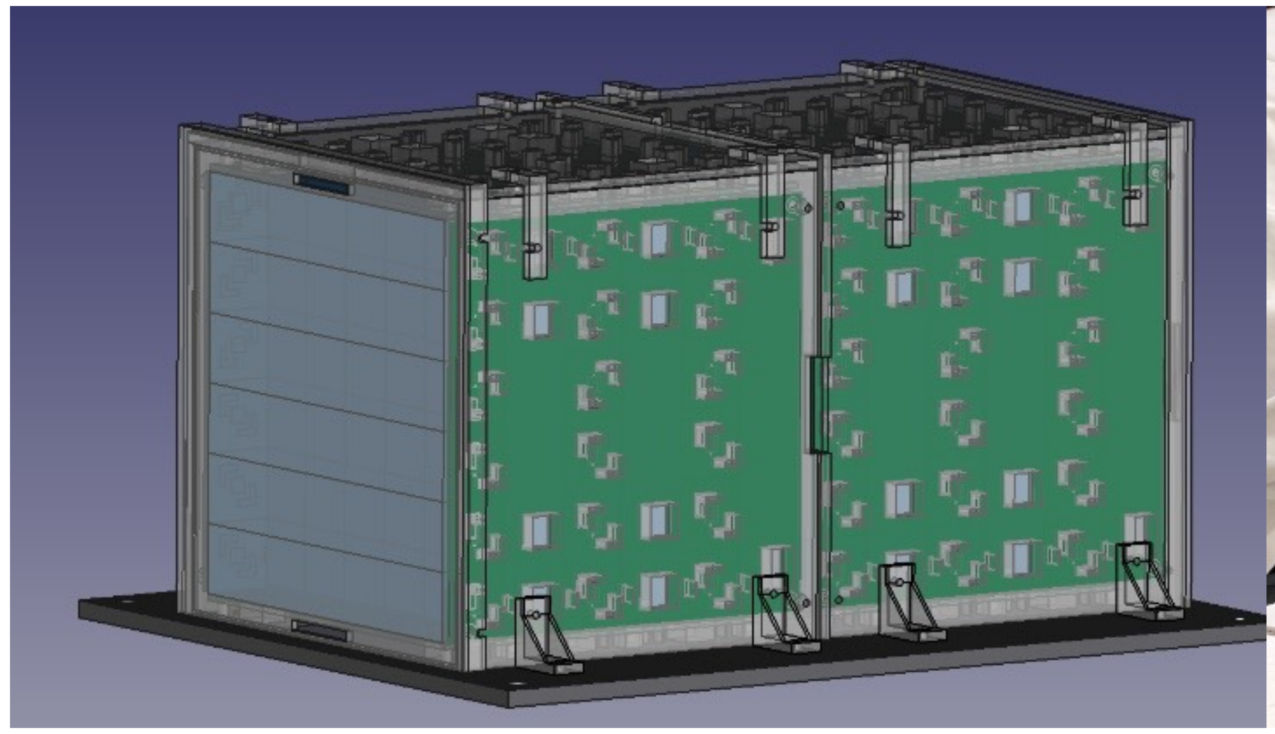
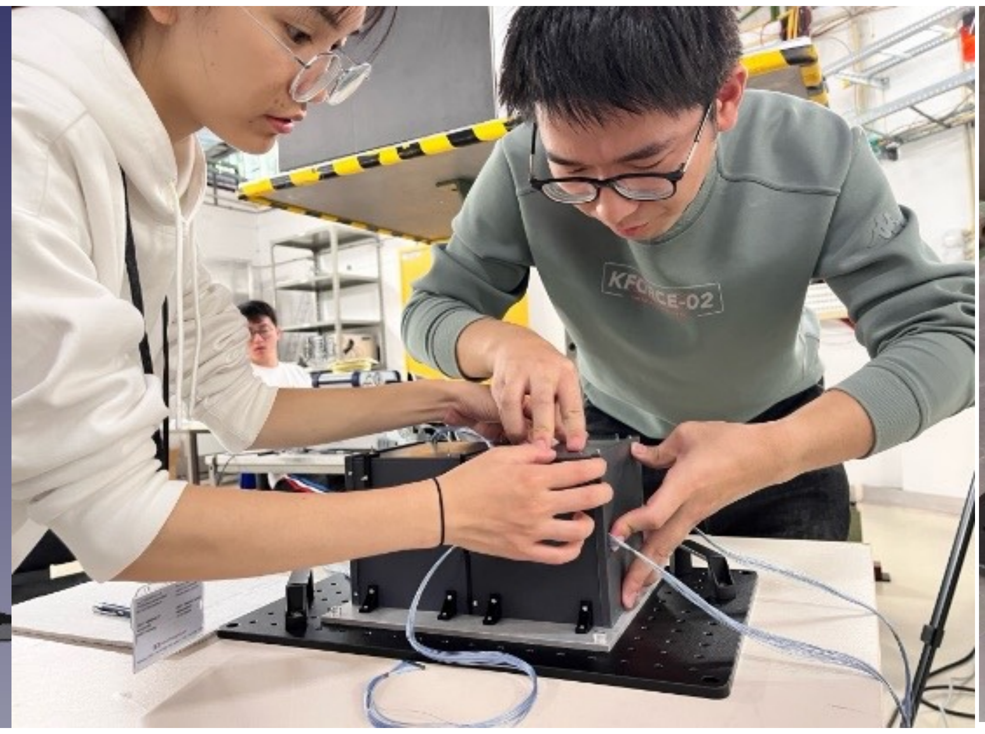


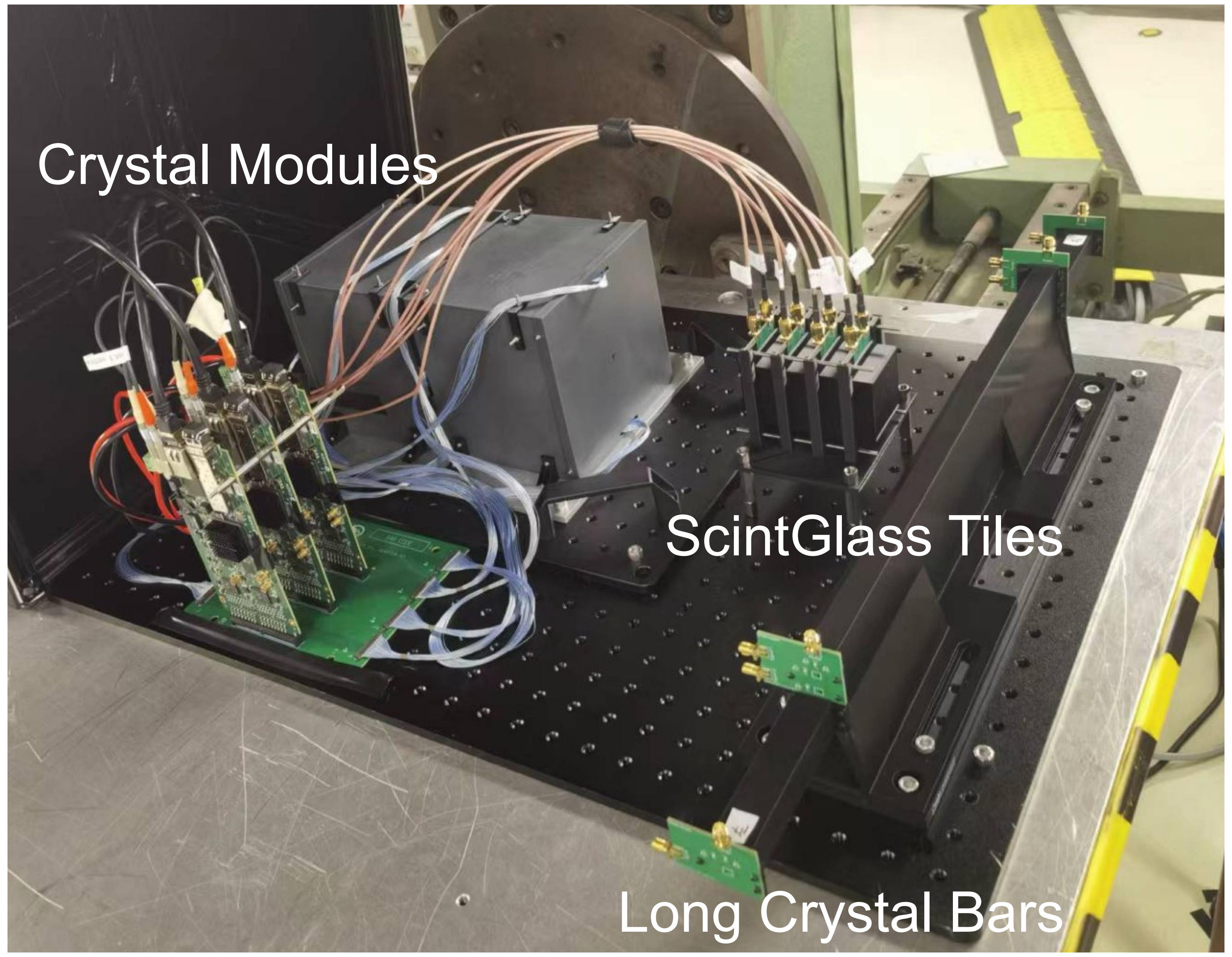


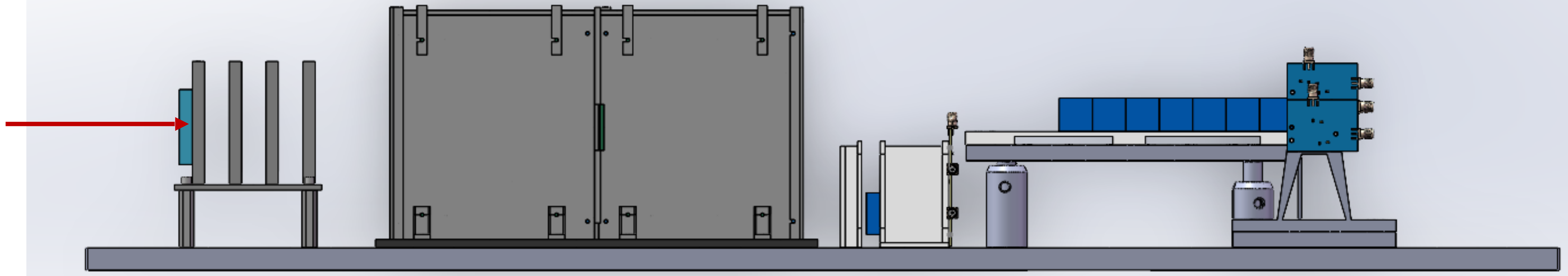
- Achieved major goals
  - Commissioning of the first crystal module
  - Validation of simulation and digitization

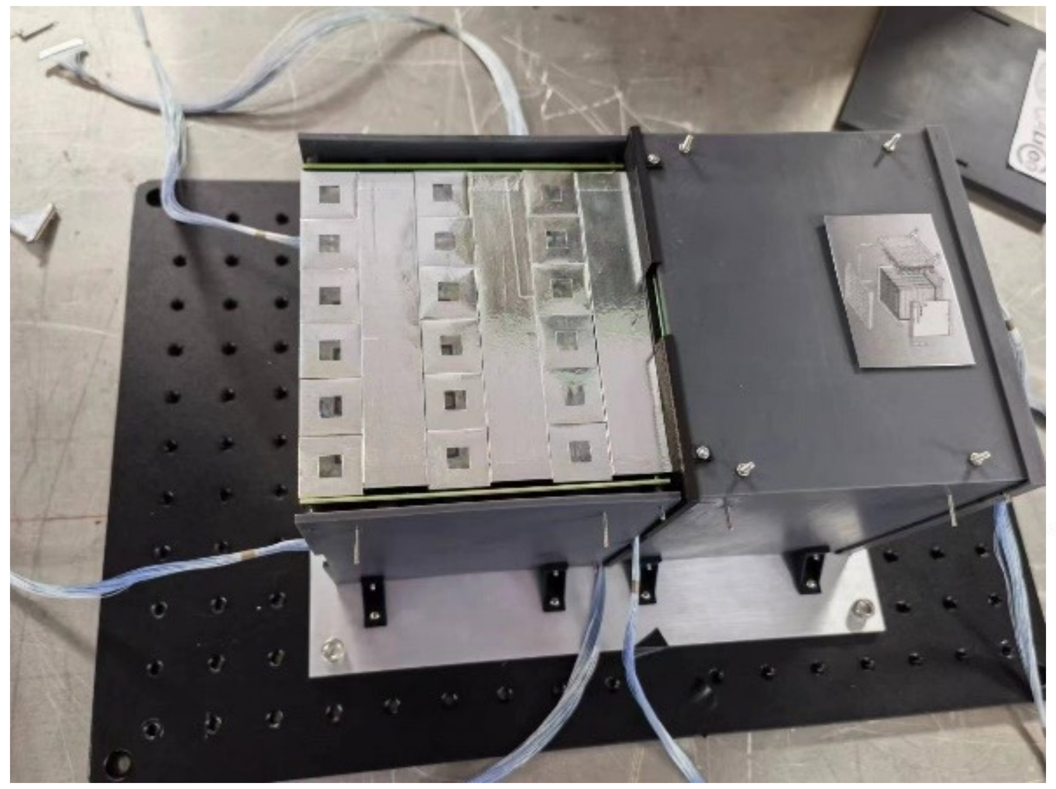
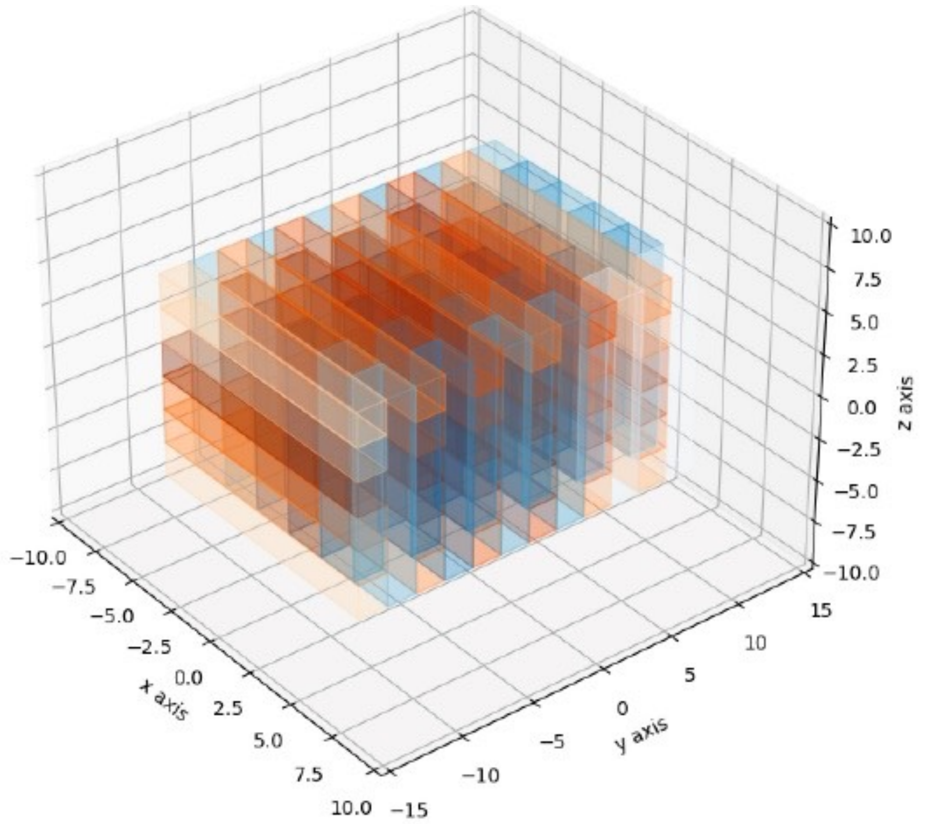
Crystal modules: beamtests in 2023

- DESY beamtest at TB22 (Oct. 2-15, 2023)
  - Successful data taking, ongoing analysis



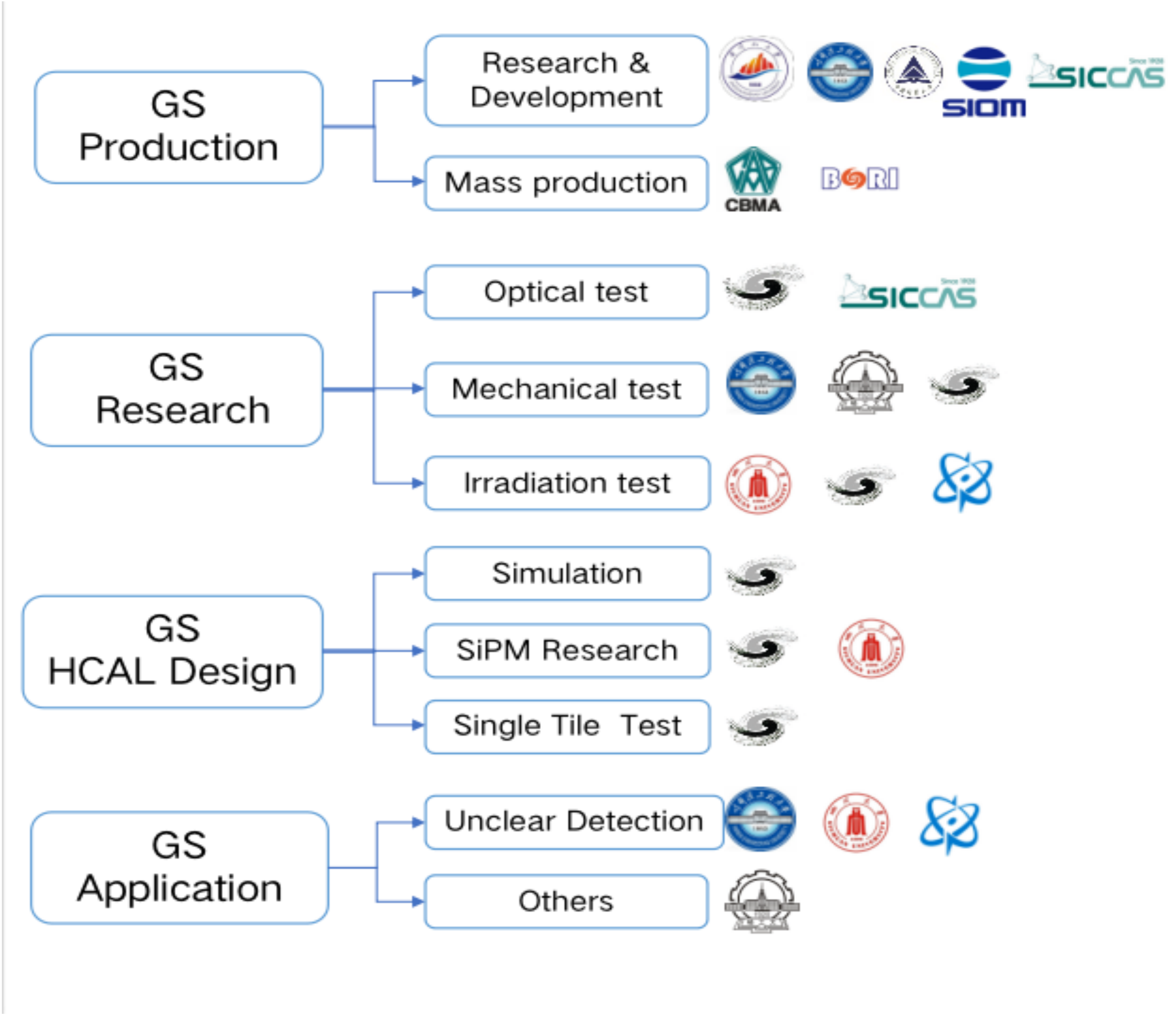


CEPC calorimetry: international collaborations

- **CALICE collaboration**
  - International community to explore technology options of high-granularity calorimetry
  - Technical Board Members: Jianbei Liu (USTC), Yong Liu (IHEP)
  - Institutional Board Members: J. Liu (USTC), Y. Liu (IHEP), Haijun Yang (SJTU)
- **ECFA Detector R&D (DRD) collaboration**
  - Implementations of ECFA detector research and development roadmap
  - Actively involved with DRD6 formation for future calorimetry
  - Three input R&D proposals submitted to DRD6
    - crystal calorimeter (HGCC), glass scintillator calorimeter (ScintGlassHcal), ScW-ECAL
- **US Snowmass 2021**
  - Two input R&D proposals to PFA-oriented calorimetry with high granularity
    - Report of the Topical Group on Calorimetry [arXiv:2208.12861]
    - Particle Flow Calorimetry [arXiv:2203.15138]

The Large Area Glass Scintillator Collaboration



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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 Mechan
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

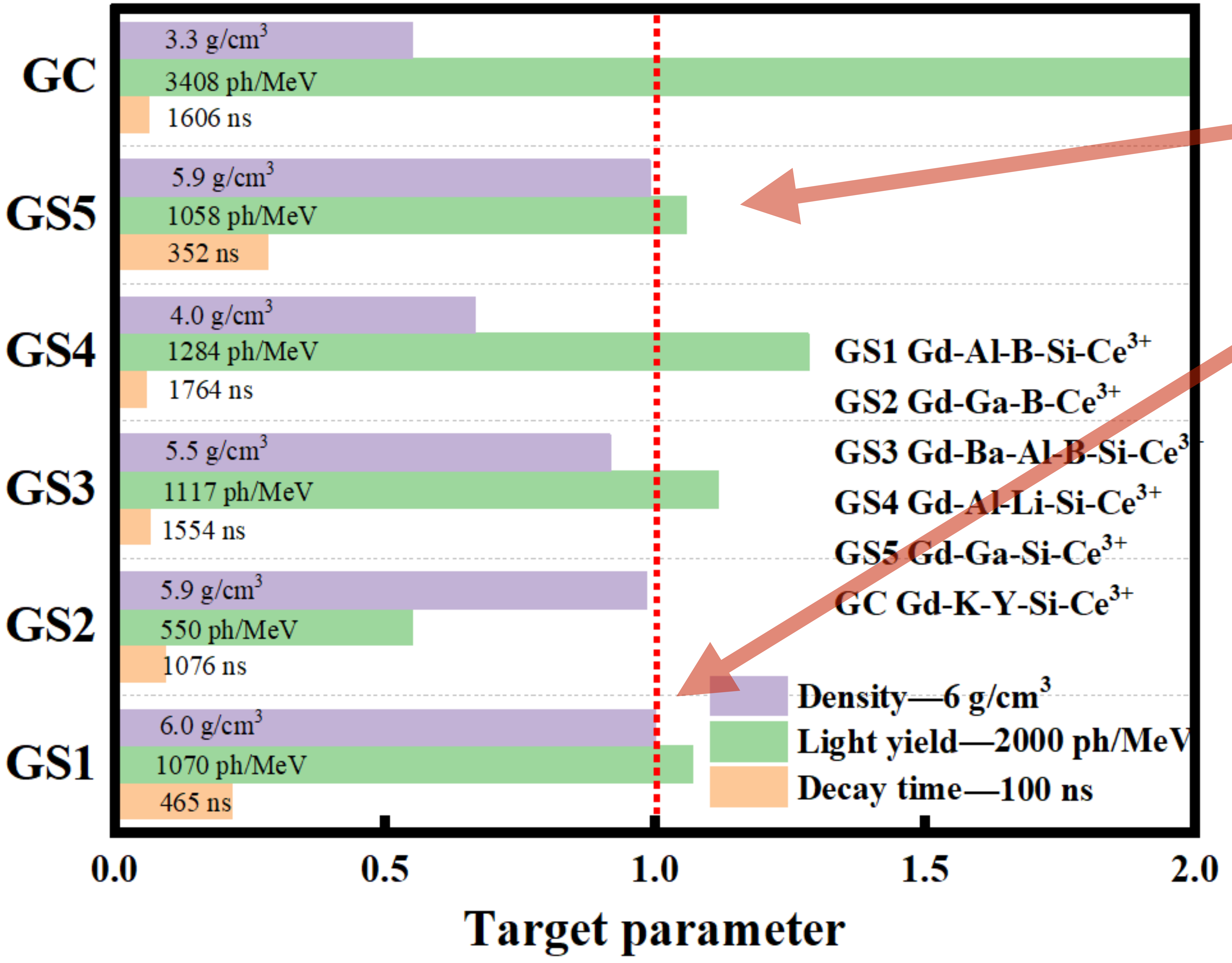
Glass Scintillator Collaboration

闪烁玻璃合作组
Glass Scintillator Collaboration

-- The Glass Scintillator Collaboration Group established in Oct.2021

-- There are 3 institutes of CAS, 5 universities, 3 factories join us for the R&D of GS;

The Progress of the R&D of GS



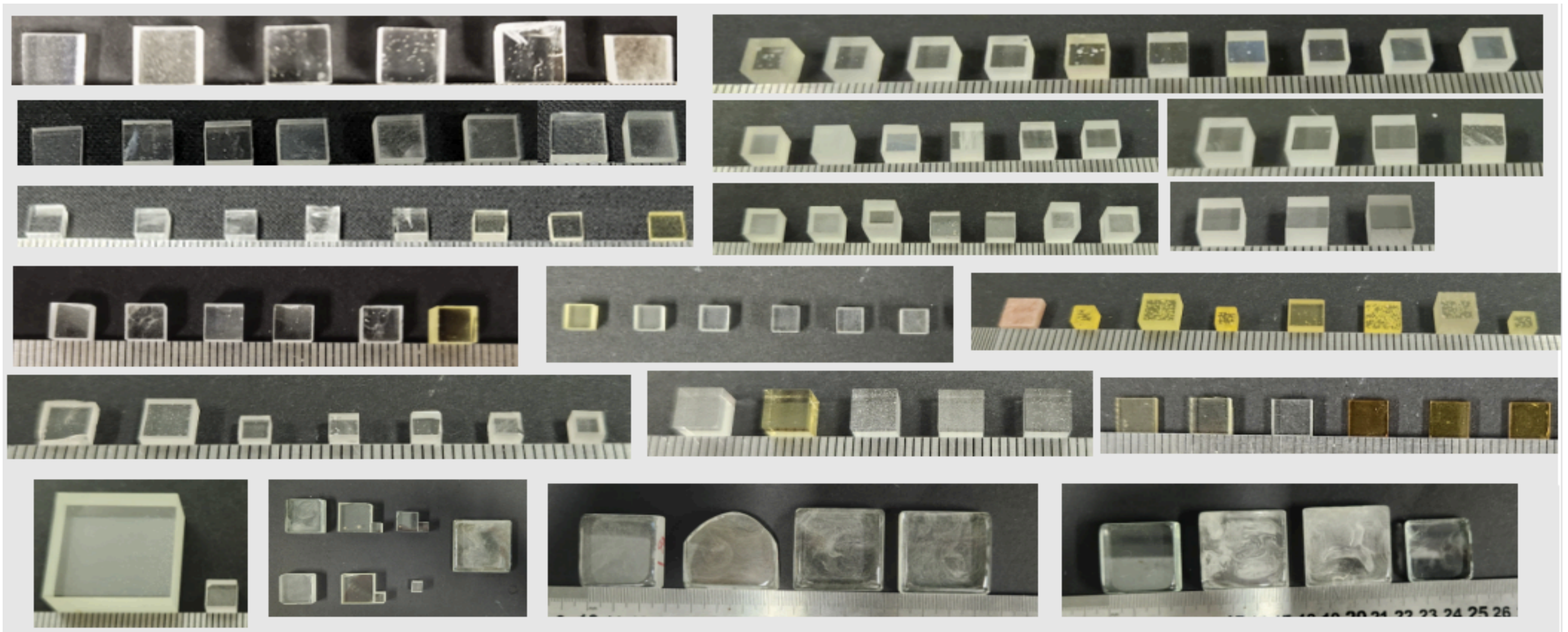
Glass scintillator of high density and light yield

- **GS5: Gd-Ga-Si-Ce^{3+} glasses：(Silicate glass)**

5.9 g/cm³ & 1060 ph/MeV with 23.7%@662keV & 352 ns

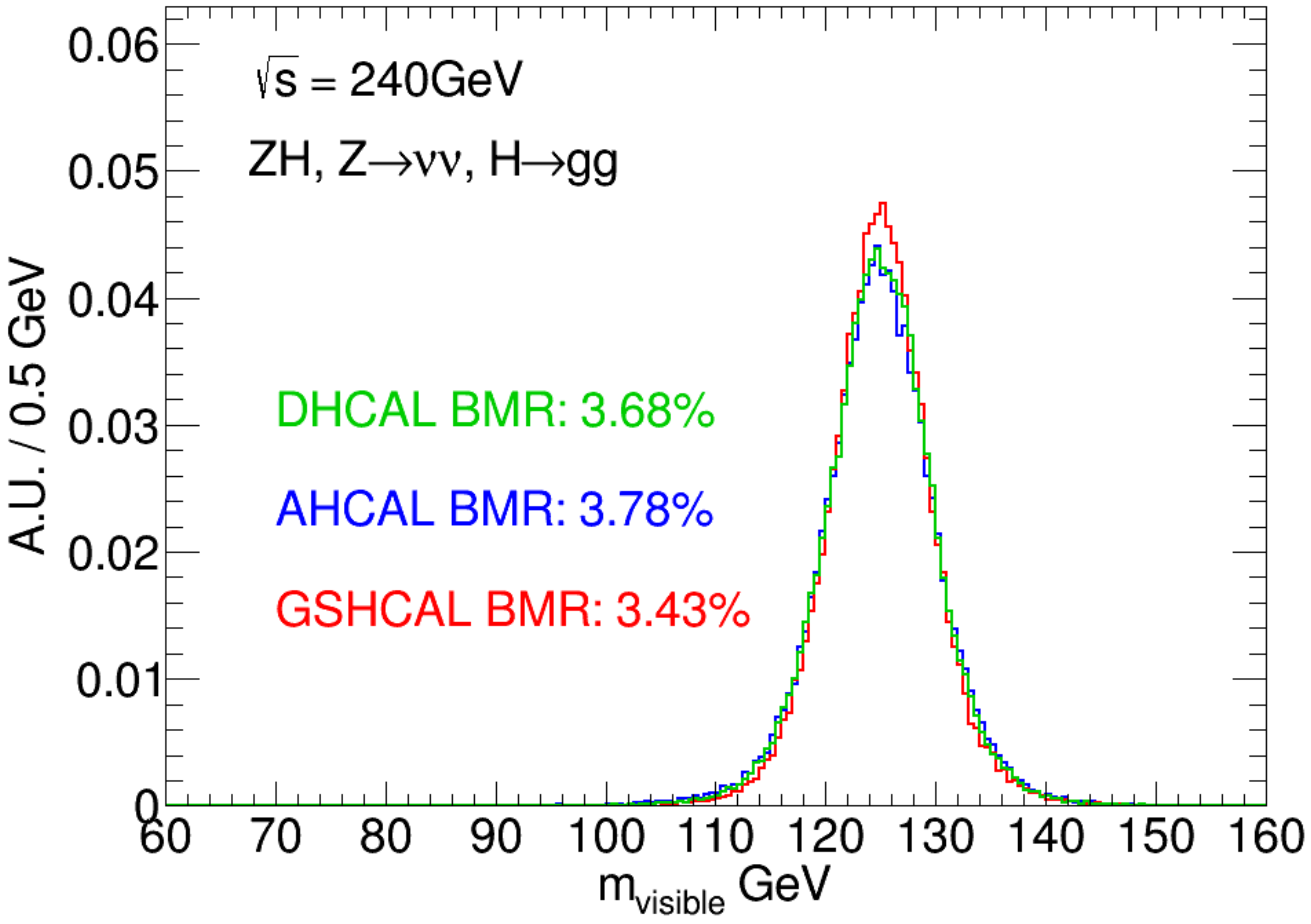
- **GS1: Gd-Al-B-Si-Ce^{3+} glasses：(Borosilicate Glass)**

6.0 g/cm³ & 1070 ph/MeV with 24.4%@662keV & 460 ns



The Progress of the PFA of the GS-HCAL

Comparing baseline AHCAL with glass HCAL



Next steps:

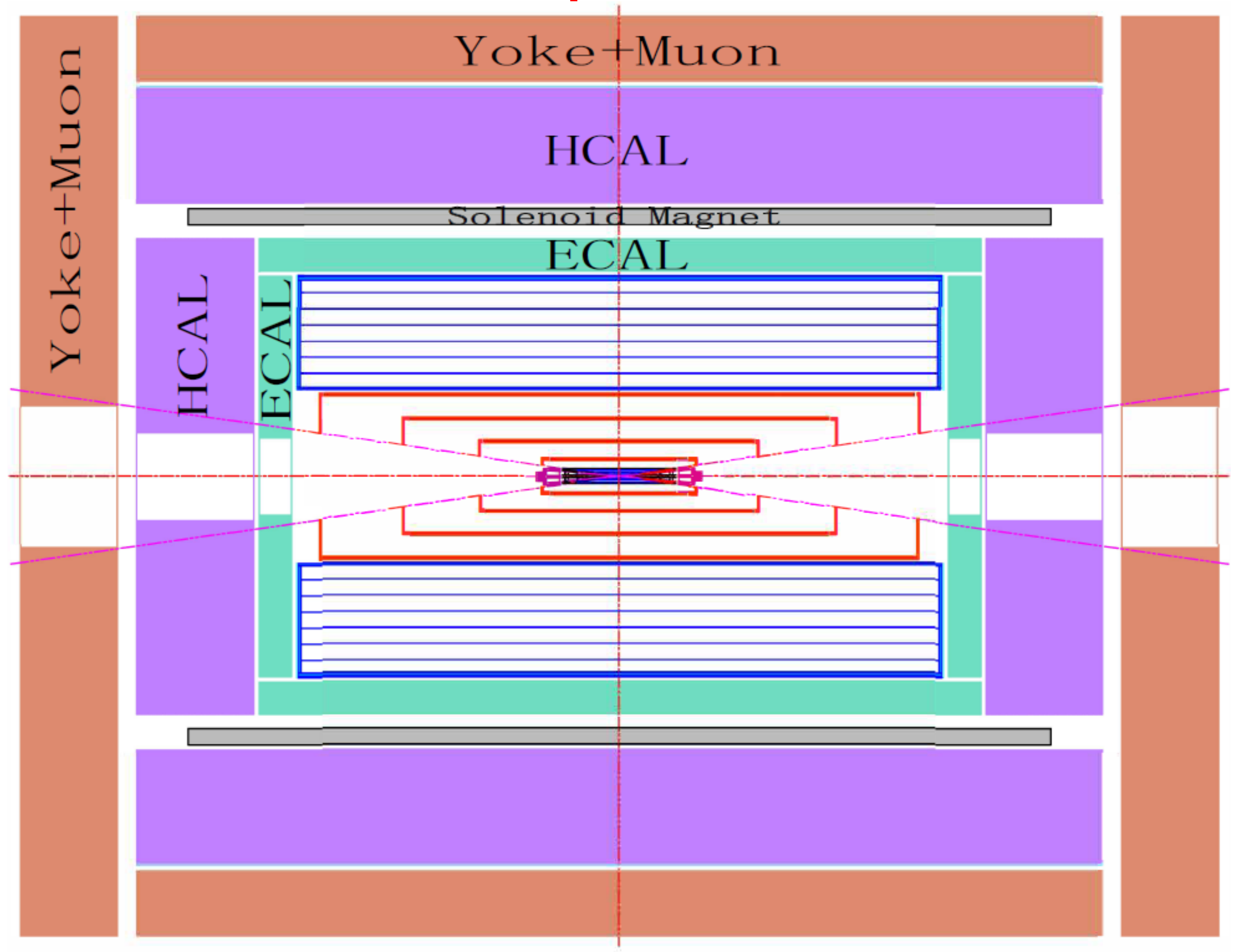
- Study the Glass Scintillator HCAL on test beam
- Optimize the design and mechanics of the GS-HCAL, to improve the BMR to ~3.0% ;
- **Main:** Continue R&D of large-size glass tiles featuring high density, high light yield and short decay time

High Temperature Superconducting Detector Solenoid

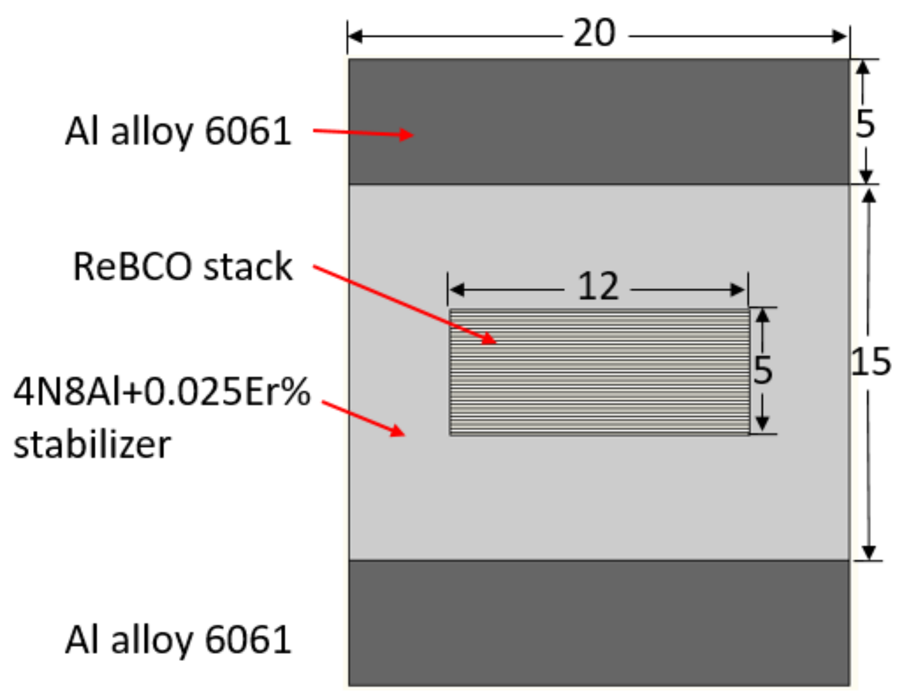
CEPC HTS detector magnet

The 4th Conceptual Detector Design: The solenoid magnet locates between Hcal and Ecal.

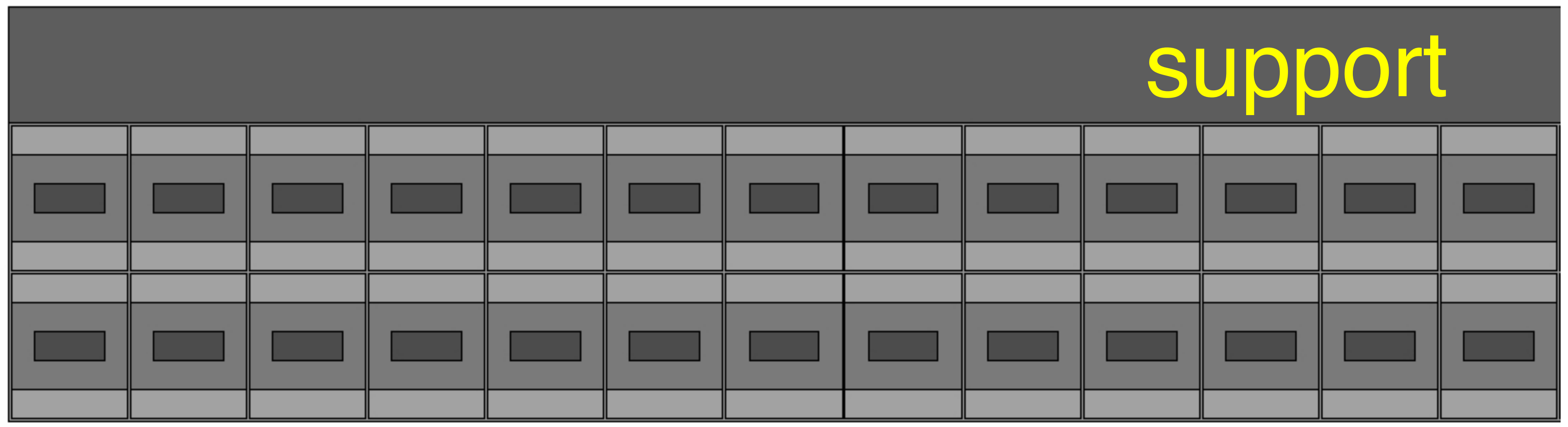
A large ultra-thin & transparent HTS solenoid magnet:

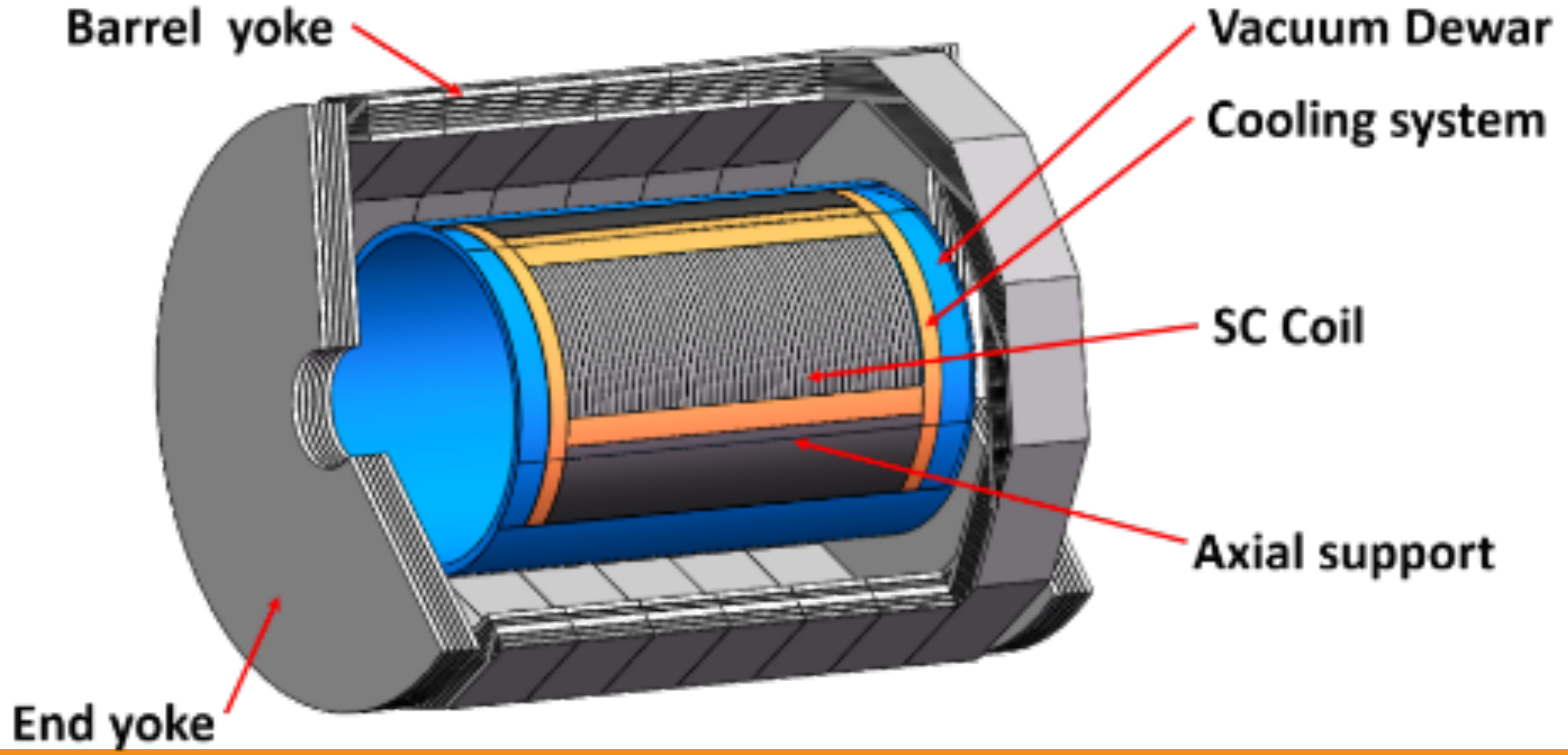


HTS cable



Coil layout



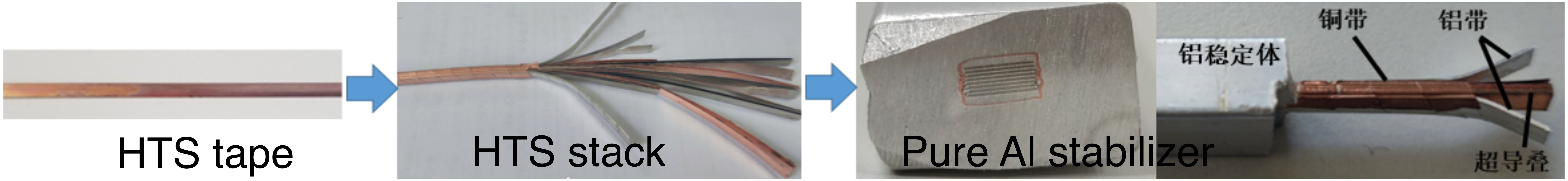


Magnetic field	3 T	Current	28000 A
Inner diameter	4660 mm	Inductance	1.27 H
Outer diameter	4960 mm	Stored energy	500 MJ
Magnet thickness	**150 mm**	Cold mass	27 ton
Length	8000 mm	HTS cable length	10.7 km
Total weight	48 ton	ASTC weight	16.6 ton

HTS cable development

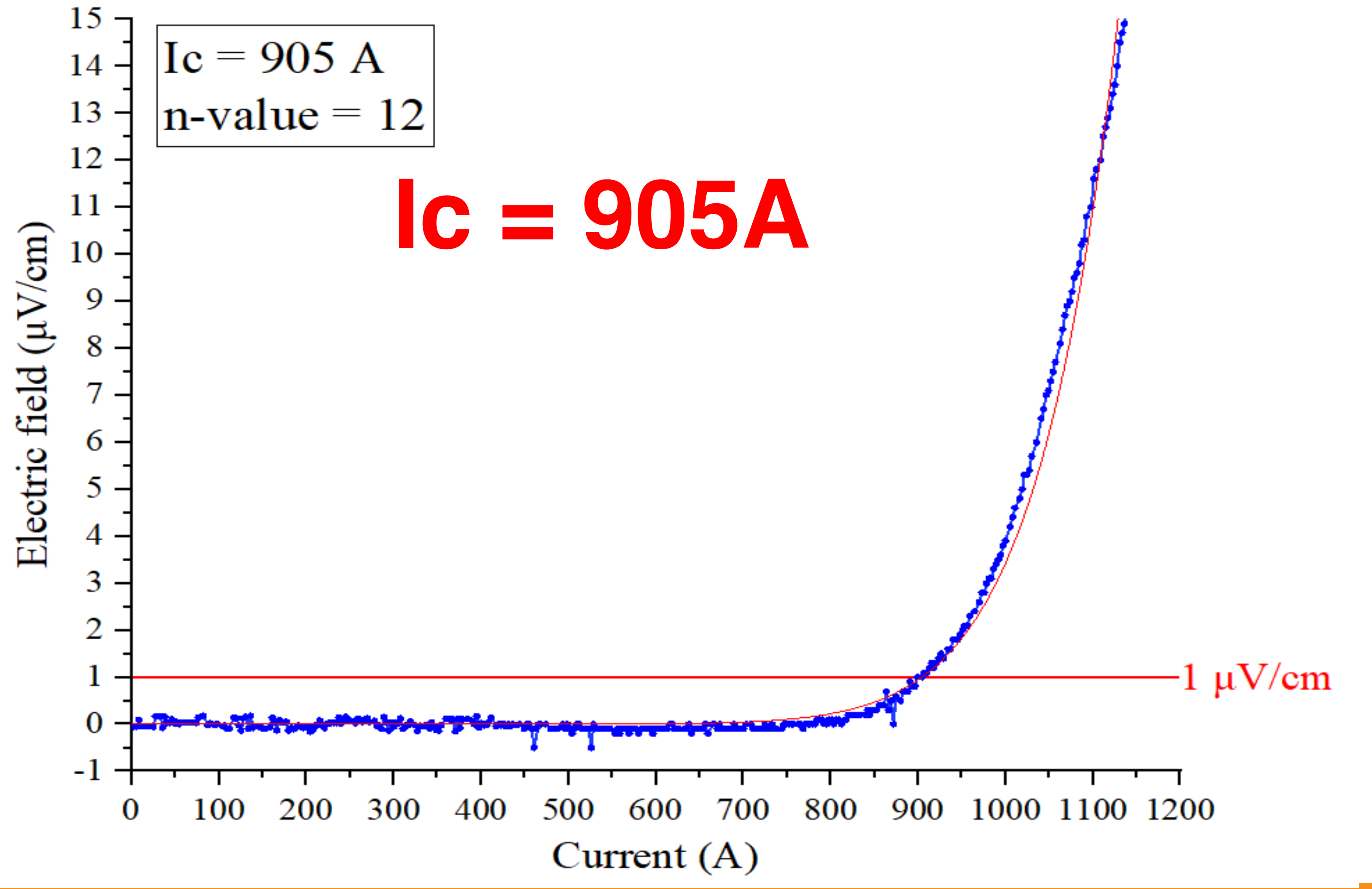
ASTC(Al stabilized HTS Stacked Tape Conductor) cable development

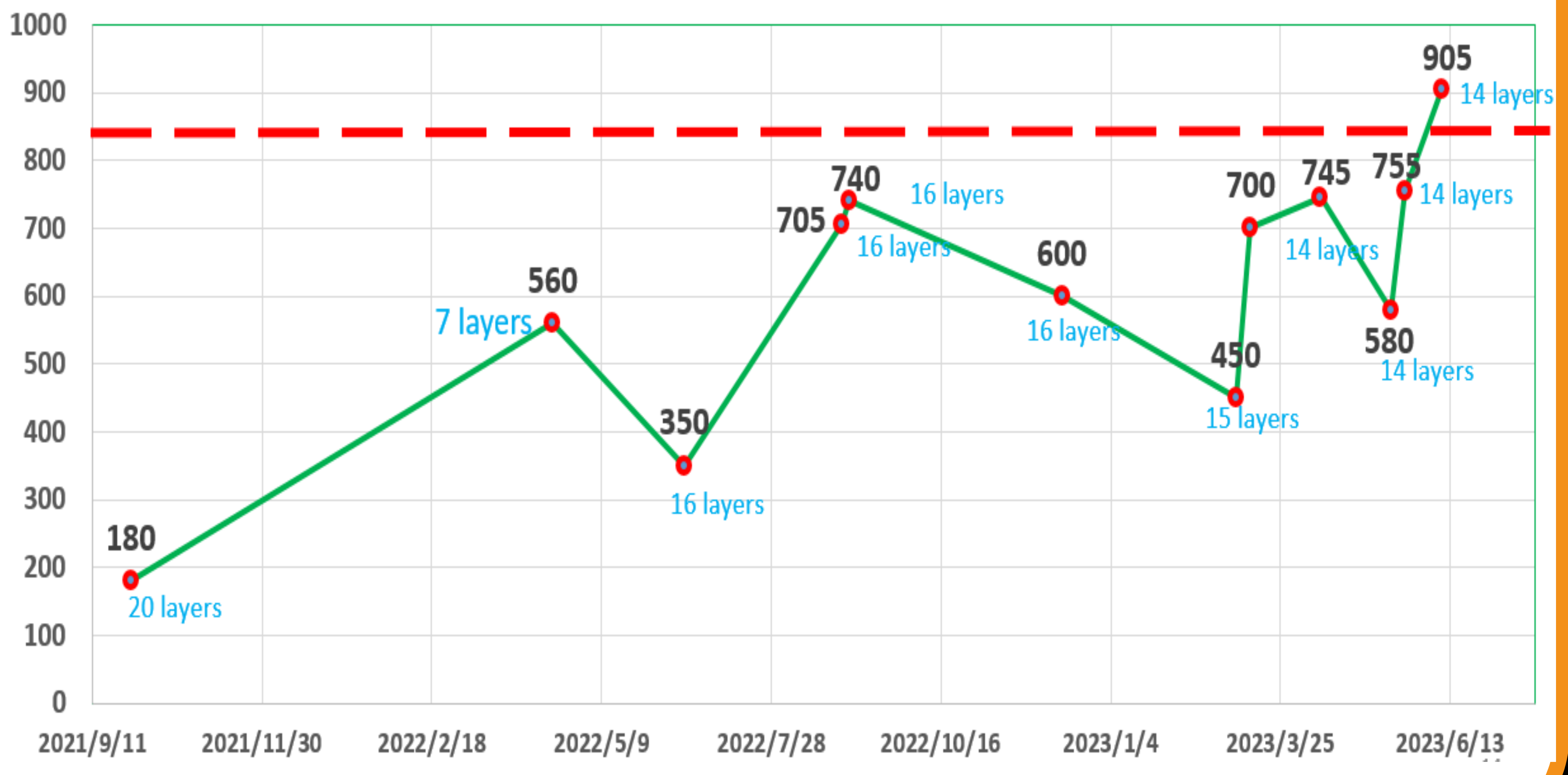
Small size cable: 15*10mm² , Tape Width: 4 mm, tape thickness: 80 µm, tape Ic > 120A@77K;



Significant progress has been made in the development of HTS cable.

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



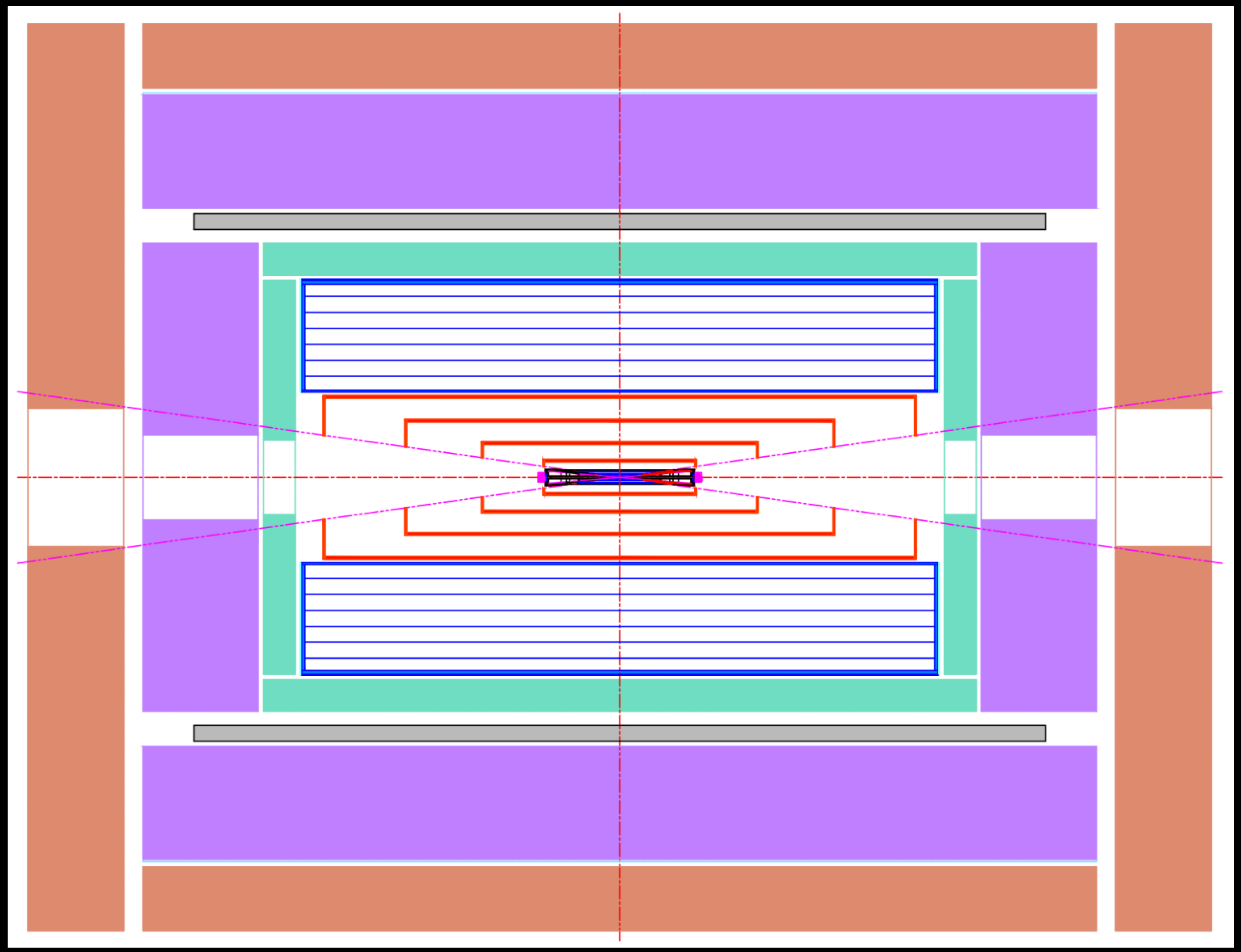


Mechanical Design

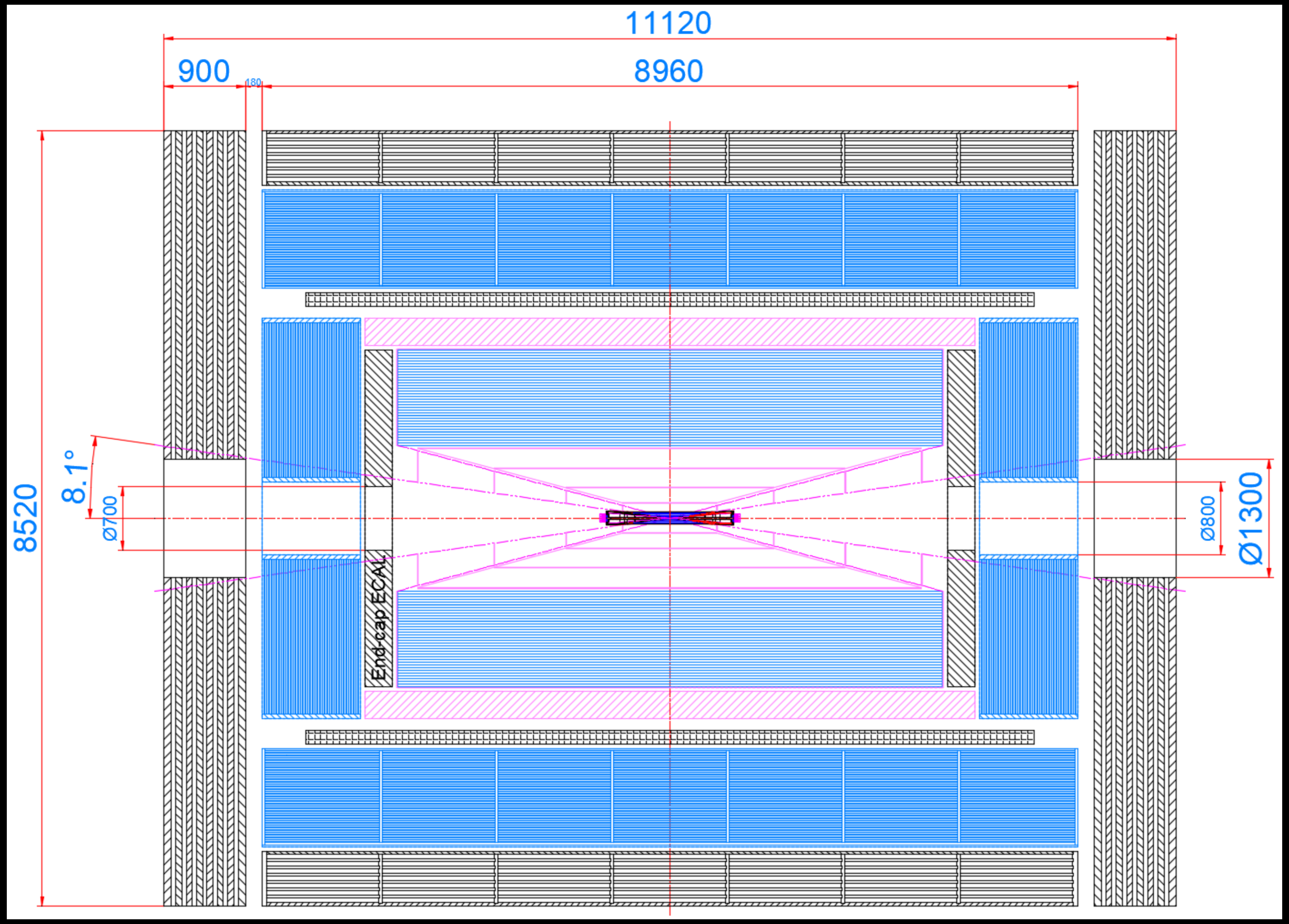
Progress in the mechanical design of the CPEC

Moving towards engineering design:

CEPC Detector diagram



Detector conceptual design transferred to draft of engineering drawing



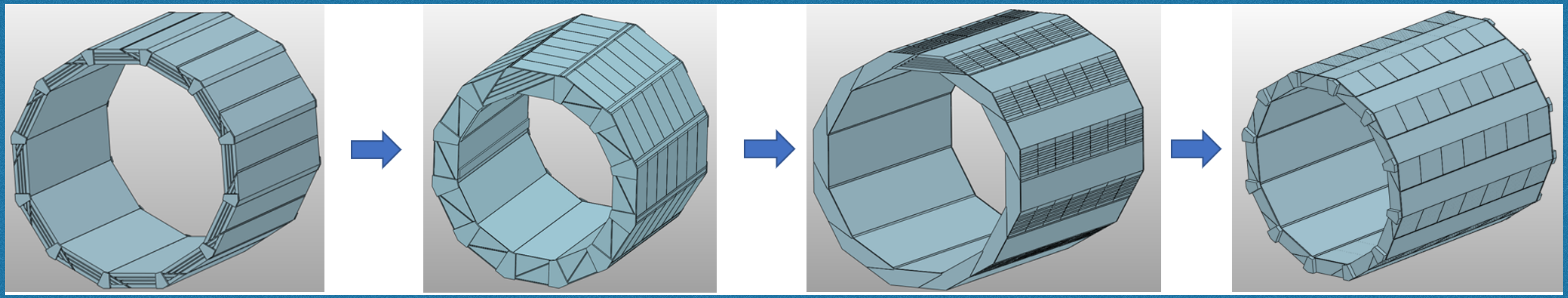
Comparison of the several schemes of engineering design for each sub-detector has been carried out

Progress in the mechanical design of the CPEC

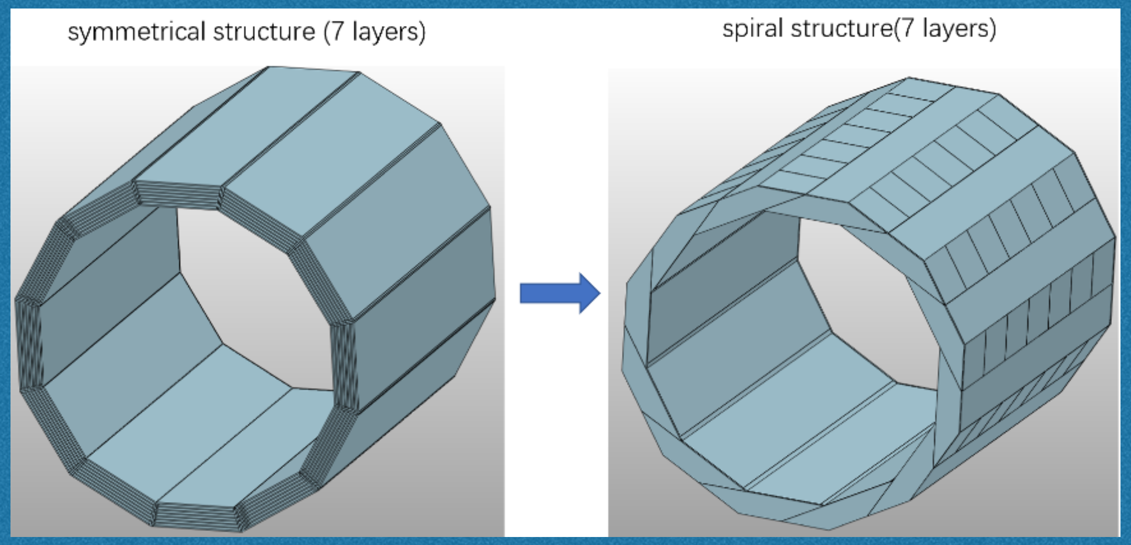
Progress in Yokes, superconducting magnets, EM Calorimeter and beam tubes

Yoke

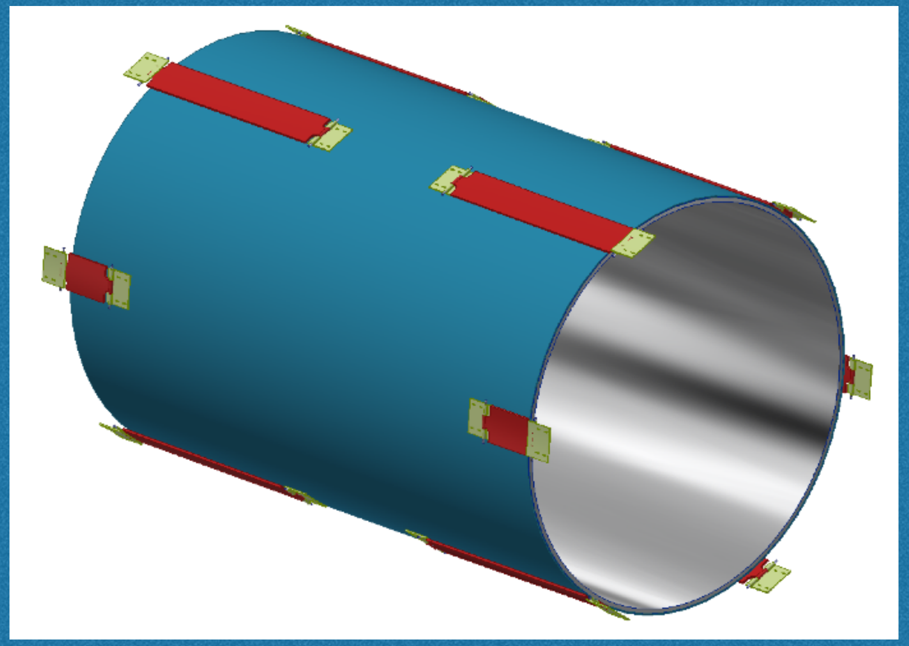
Structural analysis of different yoke layers (4, 5, 6, 7)
with minimum deformation: approx. 0.5 mm



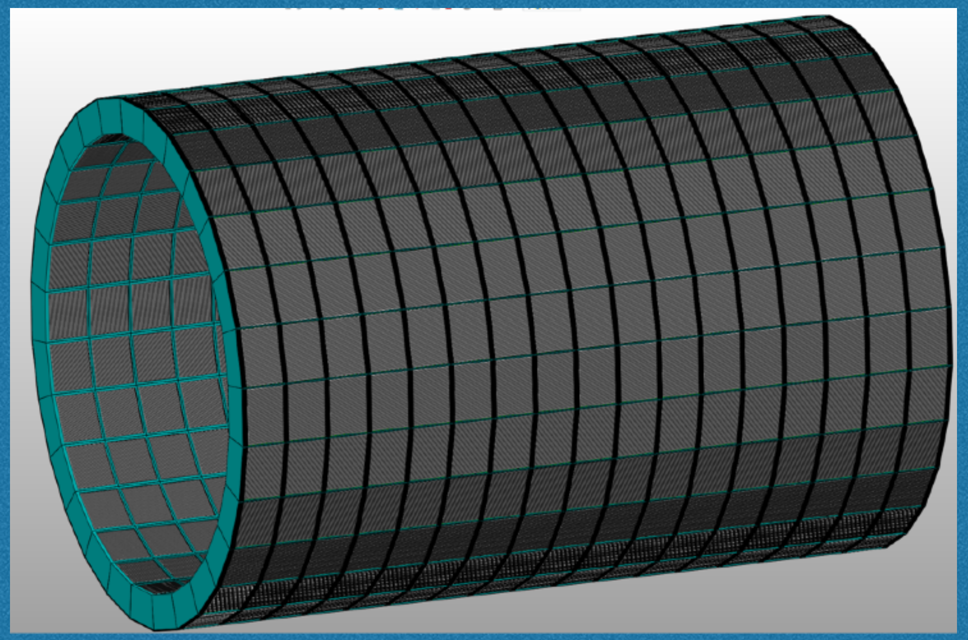
Different structures
(symmetrical vs. spiral)
(minimum deformation: 2.5mm)



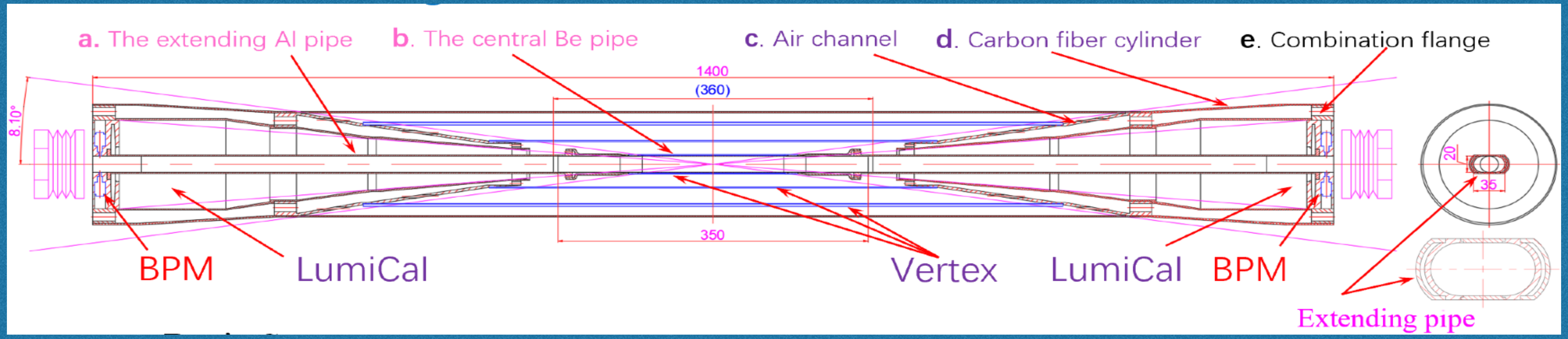
Superconducting magnet



EM Calorimeter



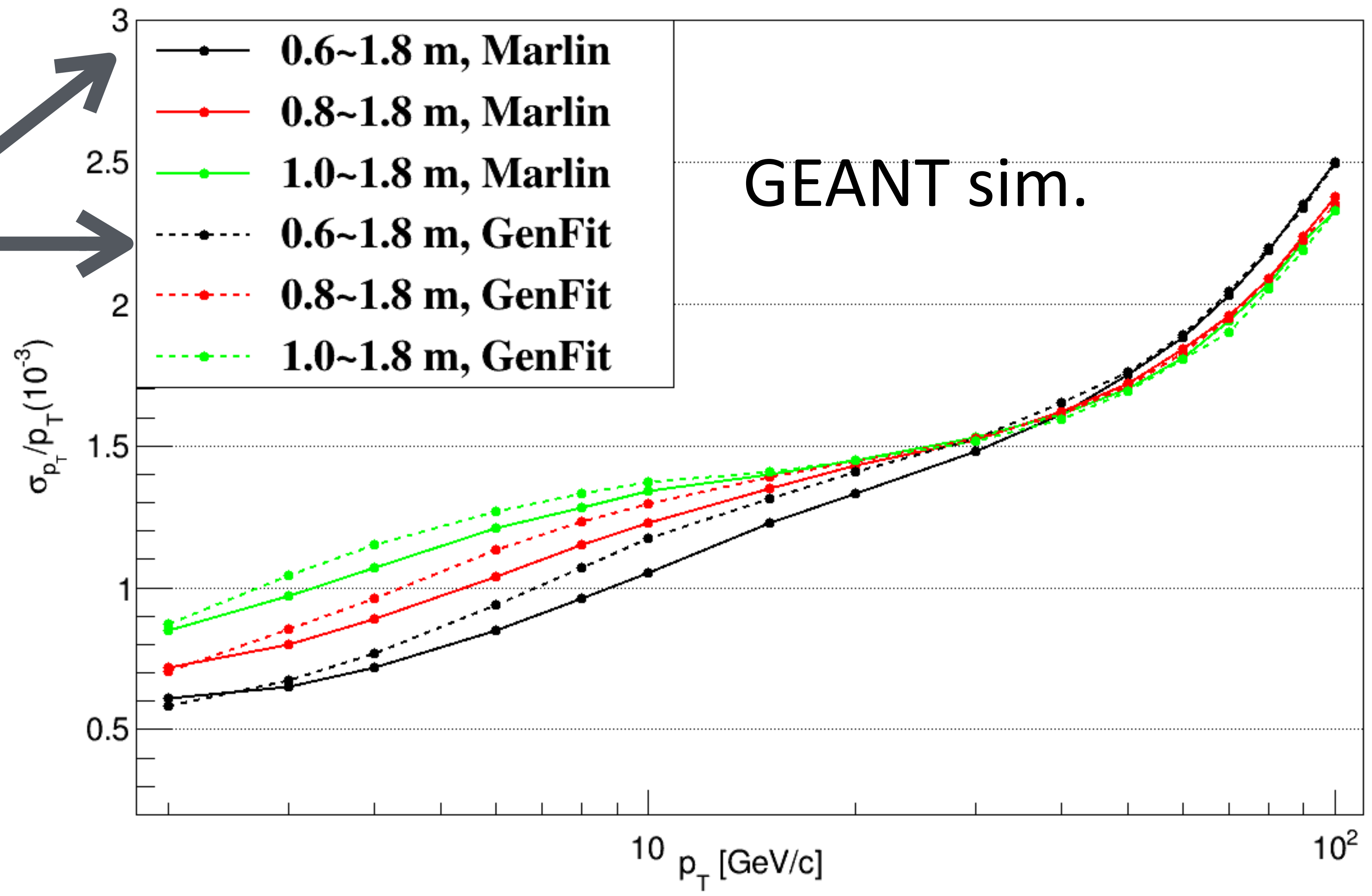
MDI design



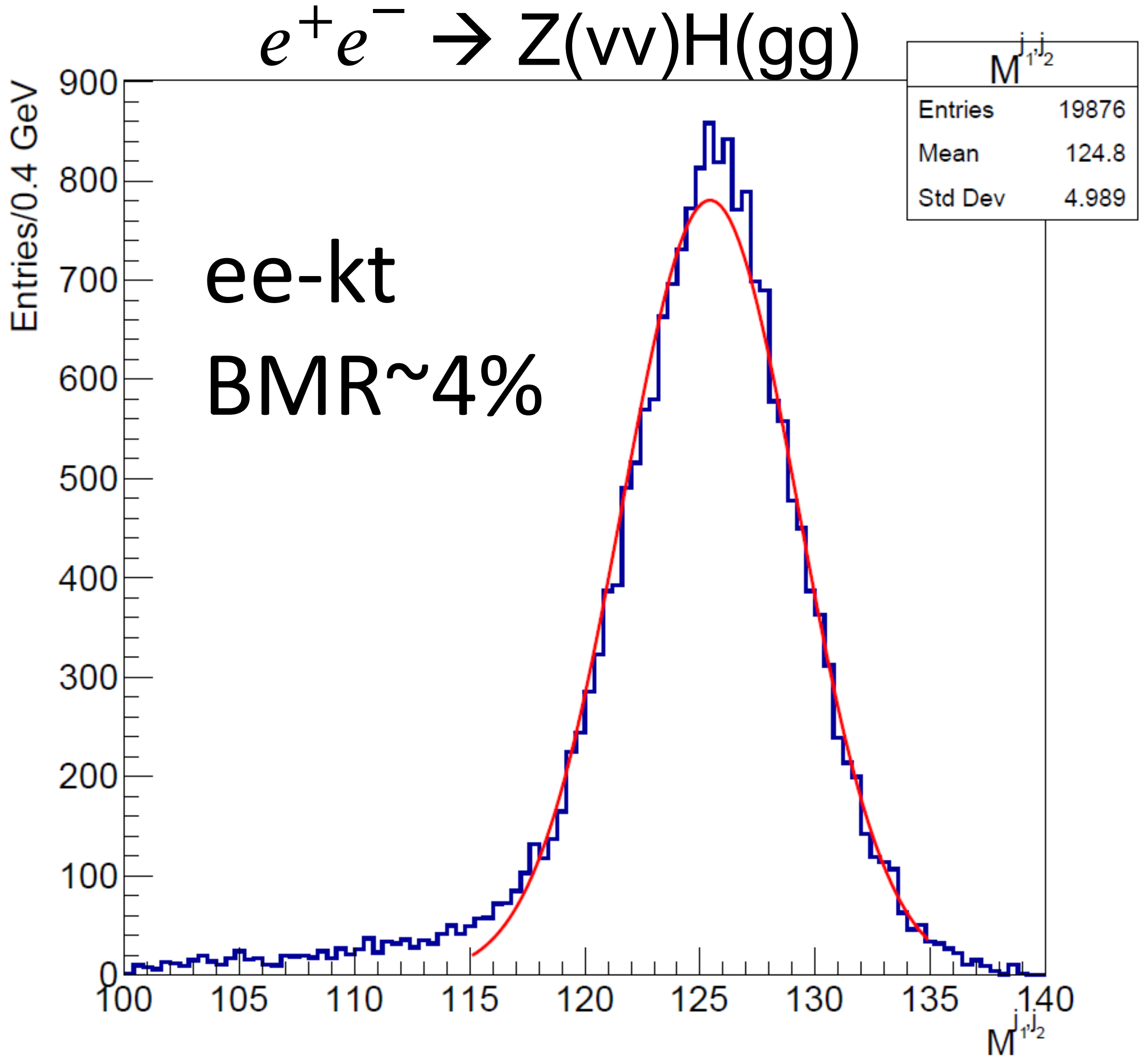
Fast simulation optimization of 4^{th} concept detector

Optimization of 4th Conceptual Detector using Fast Simulation

- **Tracker layout optimization on-going using diverse tools:**
  - A Drift Chamber starting at smaller radius is favored
  - Significant better momentum resolution for low pt tracks when DC adopted



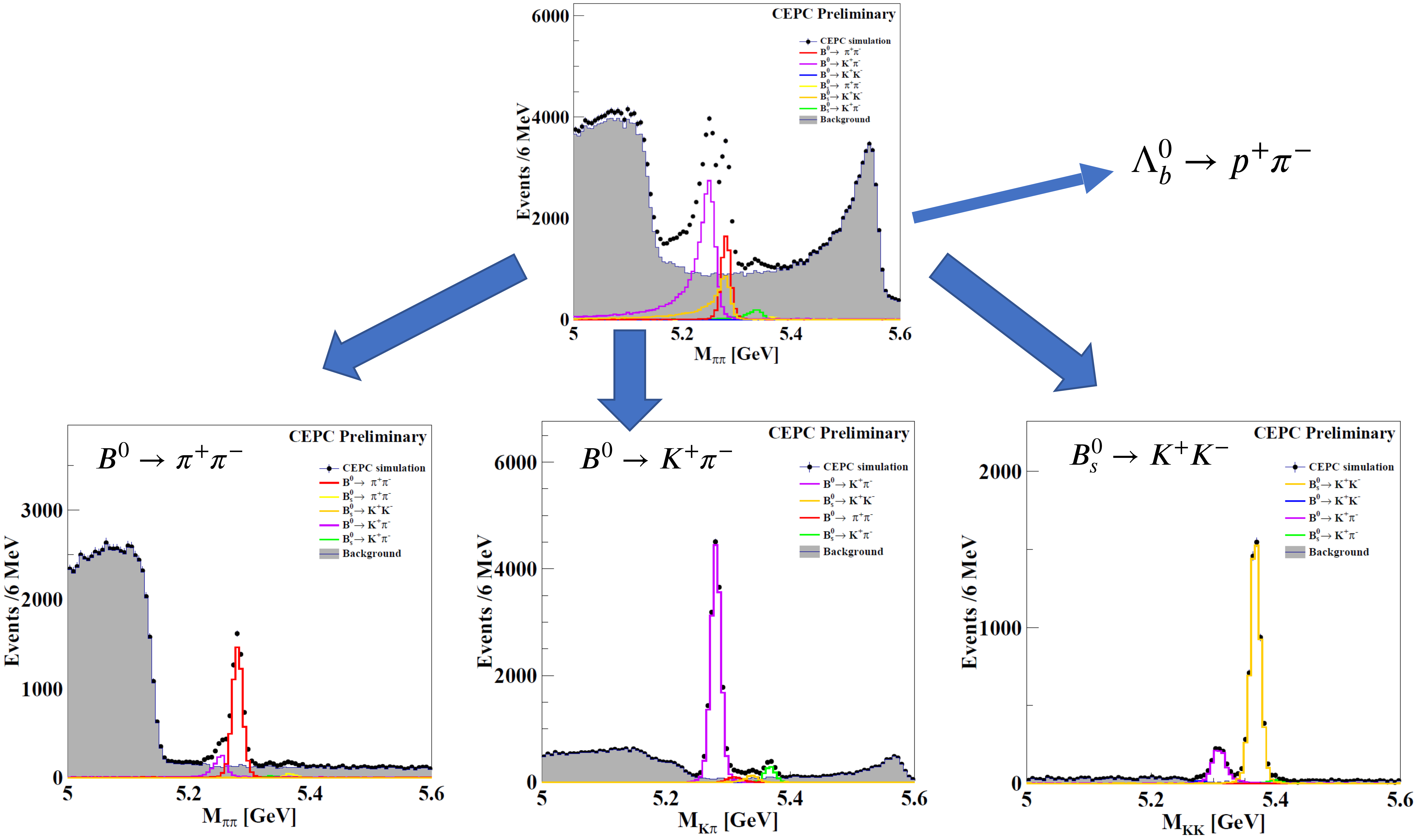
- **DELPHES simulation implemented for 4th conceptual detector (tracker, calorimeter, etc…)**
  - Full covariance of tracks
  - Some code developed for the **PID** and jet-clustering functions
  - Ready for physics study after careful validations
  - Keep updating according to detector design and optimization



Significance of PID with DELPHES simulation

W/o PID

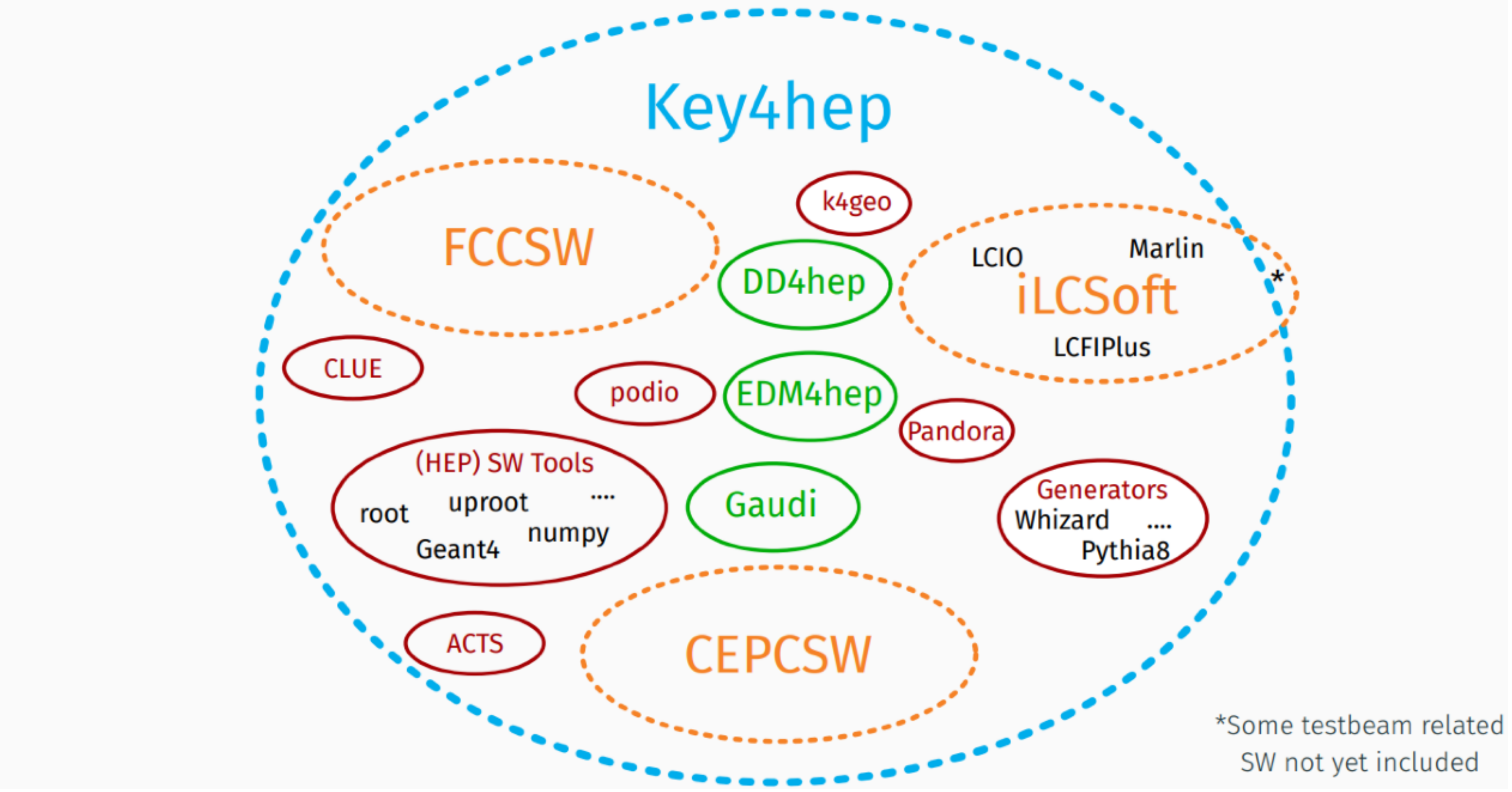
W/ PID



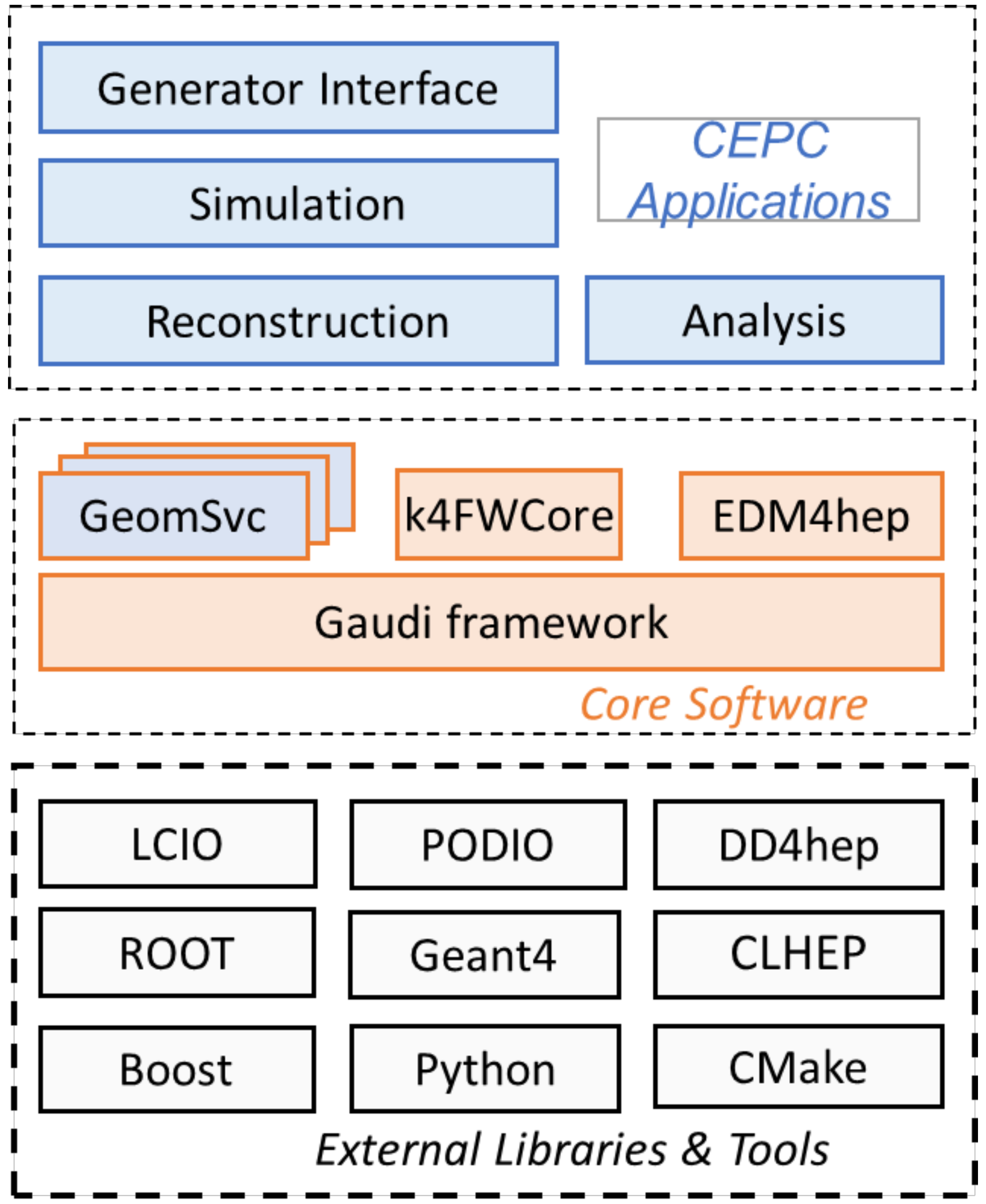
Software

CEPCSW (CEPC Software)

- **A consensus among CEPC, CLIC, FCC, ILC and other future experiments was reached at the Bologna workshop in 2019**
  - Develop a Common Turnkey Software Stack (Key4hep) for future collider experiments
  - Maximize the sharing of software components among different experiment

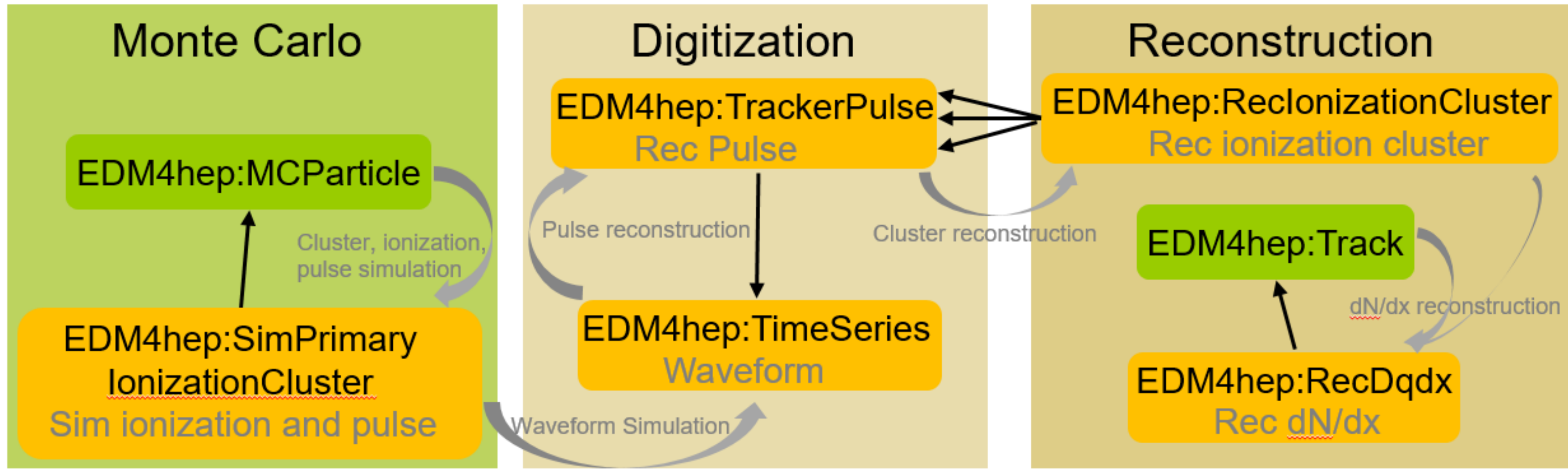


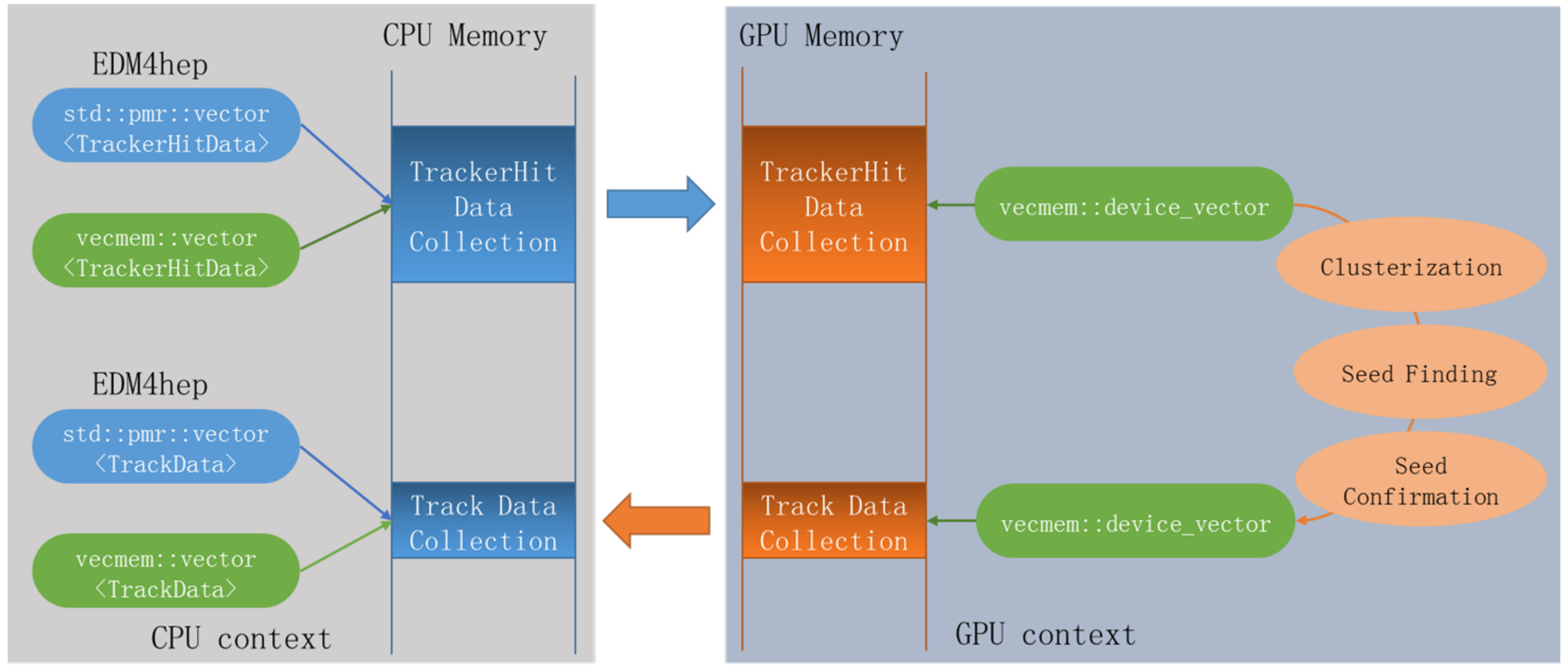
- The development of **CEPCSW is based on Key4hep** and the developers have a close collaboration with Key4hep members at CERN and DESY
- CEPCSW is organized as a multi-layer structure and the key components include:
  - Gaudi/Gaudi: defines interfaces to all software components
  - Edm4hep: generic event data model
  - k4FWCore: management of event data objects
  - DD4hep: detector geometry description

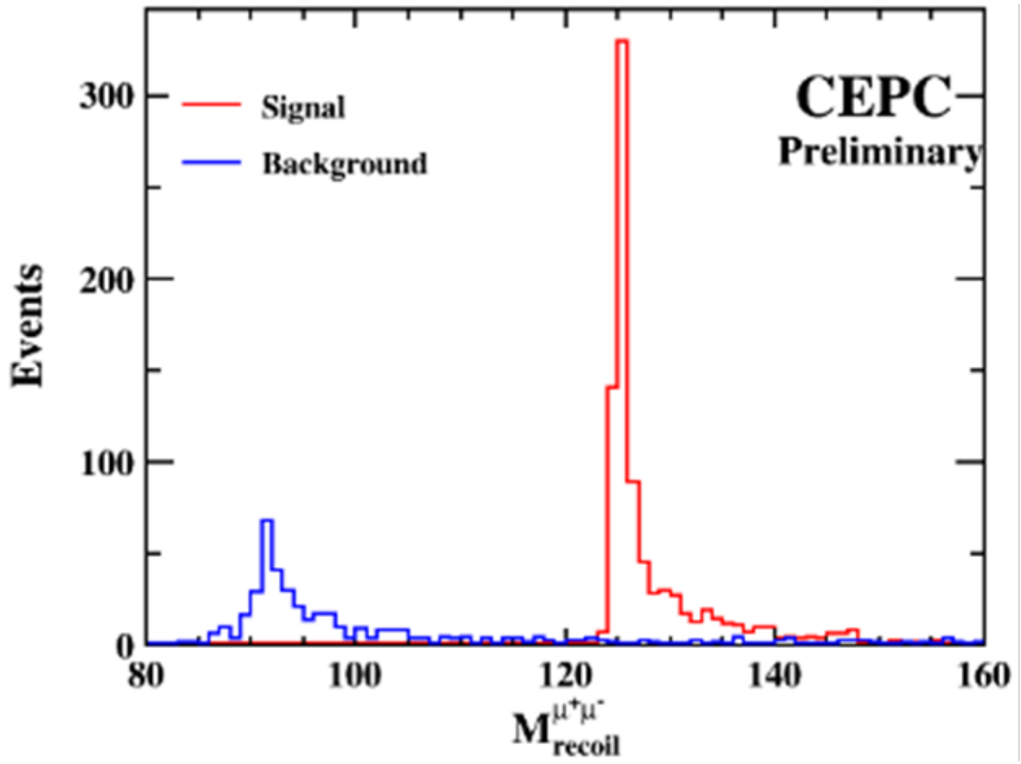


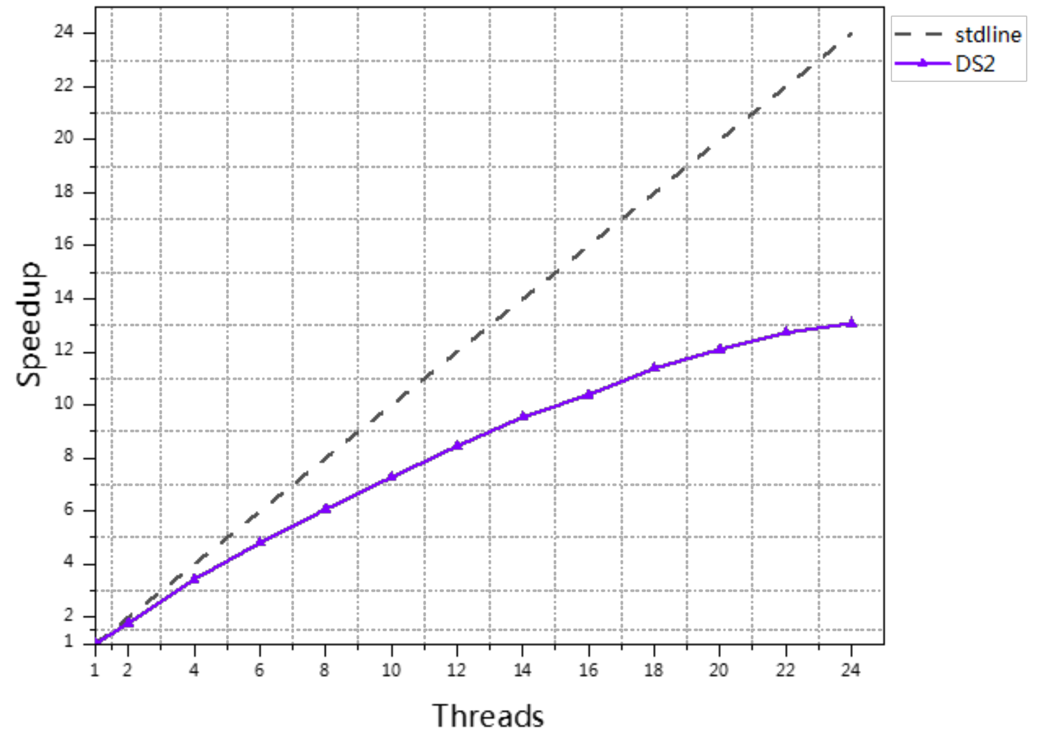
Progress: Core Software (1)

- Extended Edm4hep to accommodate the requirements raised by the simulation of primary ionizations in the drift chamber
- Heterogeneous computing
  - ACTS's seeding algorithm (SYCL version) was imported to CEPCSW and optimization of data communication between CPU and GPU is in progress
- RDataFrame-based analysis framework development
  - Integrated Marlin Kinefit and JetClustering algorithms to RDataframe
  - Completed multi-threading performance studies with e+e- -> H(2jet)μμ events
- Migration to Gaussino-based simulation framework is ongoing





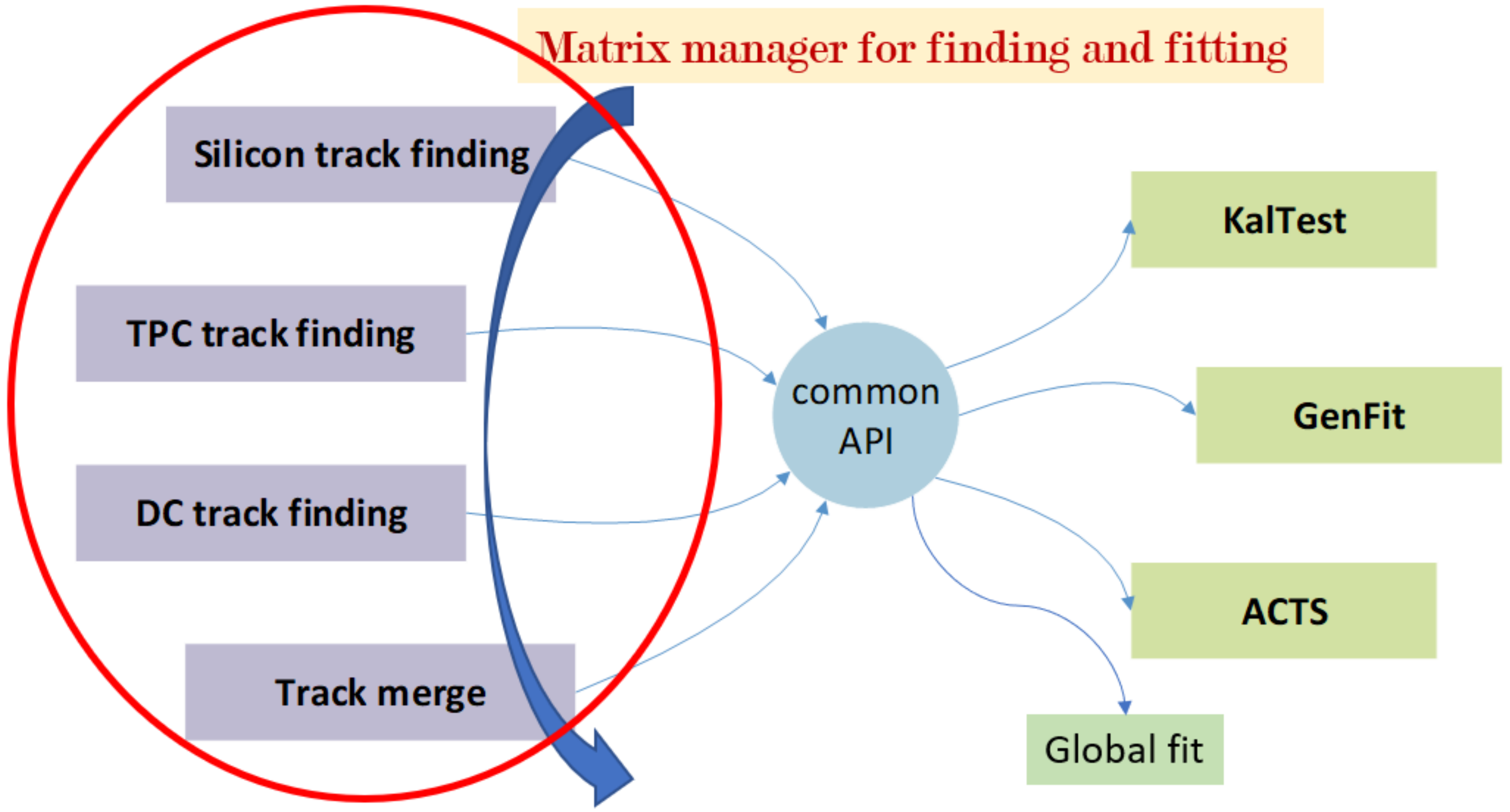




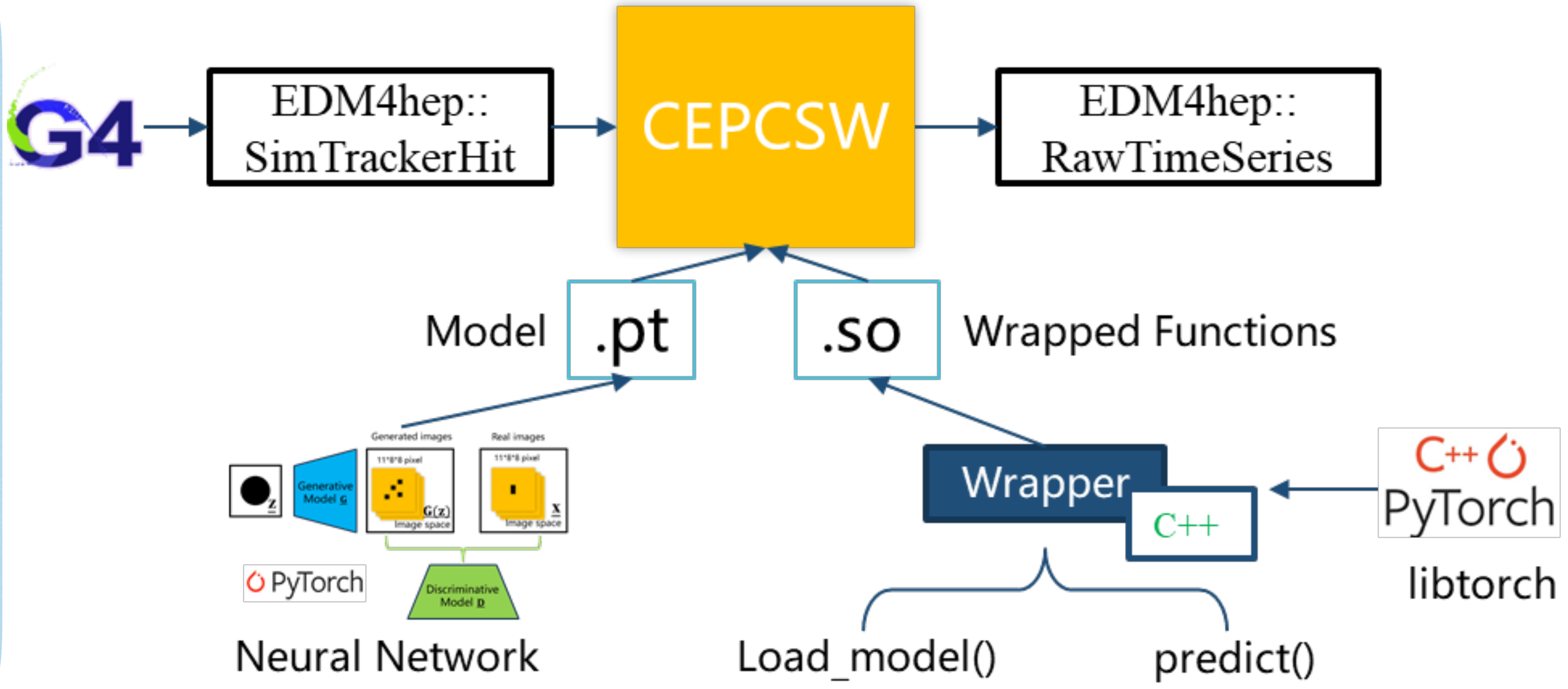
Progress: CEPC reconstruction software and Distributed Computing

Many reconstruction algorithms were developed:

- A common API for different track fitting algorithms
- Silicon vertex detector machine leaning based digitization algorithm
- Drift Chamber track finding software
- Crystal-bar ECAL Software reconstruction

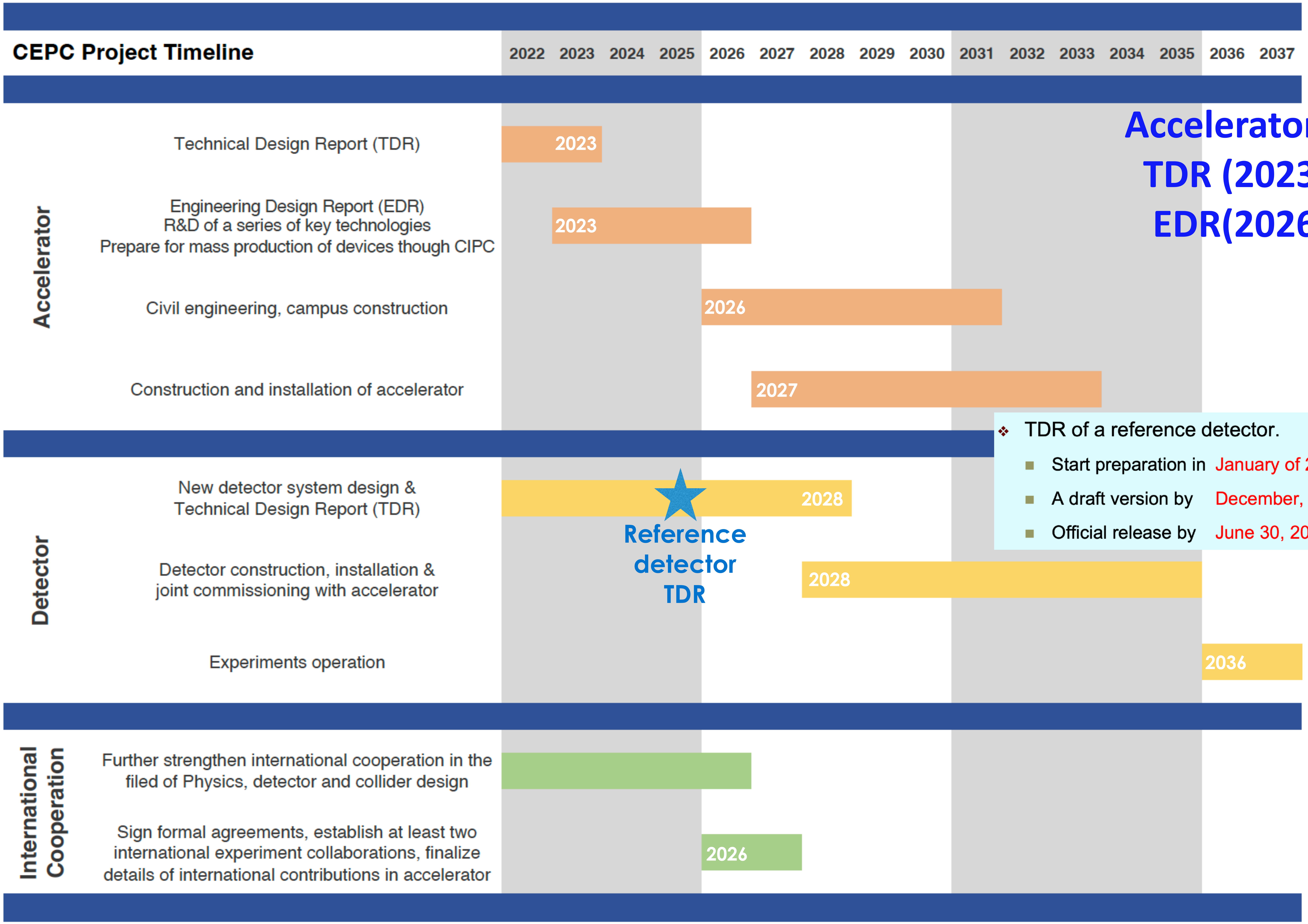


- **The CEPC distributed computing platform for detector R&D was established based on DIRAC and WLCG middleware**
  - **The platform is able to integrate heterogeneous and distributed resources, including cloud, grid, cluster resources**
  - **~4600 cores from IHEP, UK and other Chinese universities**



Timescale

CEPC Project timeline



Accelerator:
TDR (2023)
EDR(2026)

- TDR of a reference detector.
  - Start preparation in January of 2024
  - A draft version by December, 2024
  - Official release by June 30, 2025.

TDR Timescale

What is the proper timescale from TDR to first beam?

Detectors will be complex but not as large **and** complex **as the LHC detectors**

- **BABAR Timescale**
  - 1989: First physics workshop
  - 1993: PEP-II CDR released
  - 1994: BABAR Letter of Intent released
  - 1995: BABAR TDR released
  - 1998: The BABAR Physics Book
  - May 1999: First collisions in BABAR in May 1999
  - 2001: BABAR first physics paper

6 years from TDR to first paper
4 years to collisions

Final remarks

Some CEPC R&D detector projects reaching a successful conclusion

e.g. Silicon Vertex Detector, Scintillator HCAL and ECAL

Although these are likely not what we will ultimately build, they provide invaluable information for the future and demonstrate that the targets get be achieved

New ideas have emerged and they are being put to prototyping quickly

e.g. Crystal calorimeter, scintillating glass calorimeter

No identifiable showstoppers in detector R&D

International collaboration continues to be a main goal of the CEPC

Explore the CEPC and FCC-ee R&D synergies

Acknowledgements

Thank you to all that provided material for this talk, in particular, Hongbo Zhu, Yiming Li, Zhijun Liang, Yong Liu, Feipeng Ning, Zhao Mei, Huirong Qi,

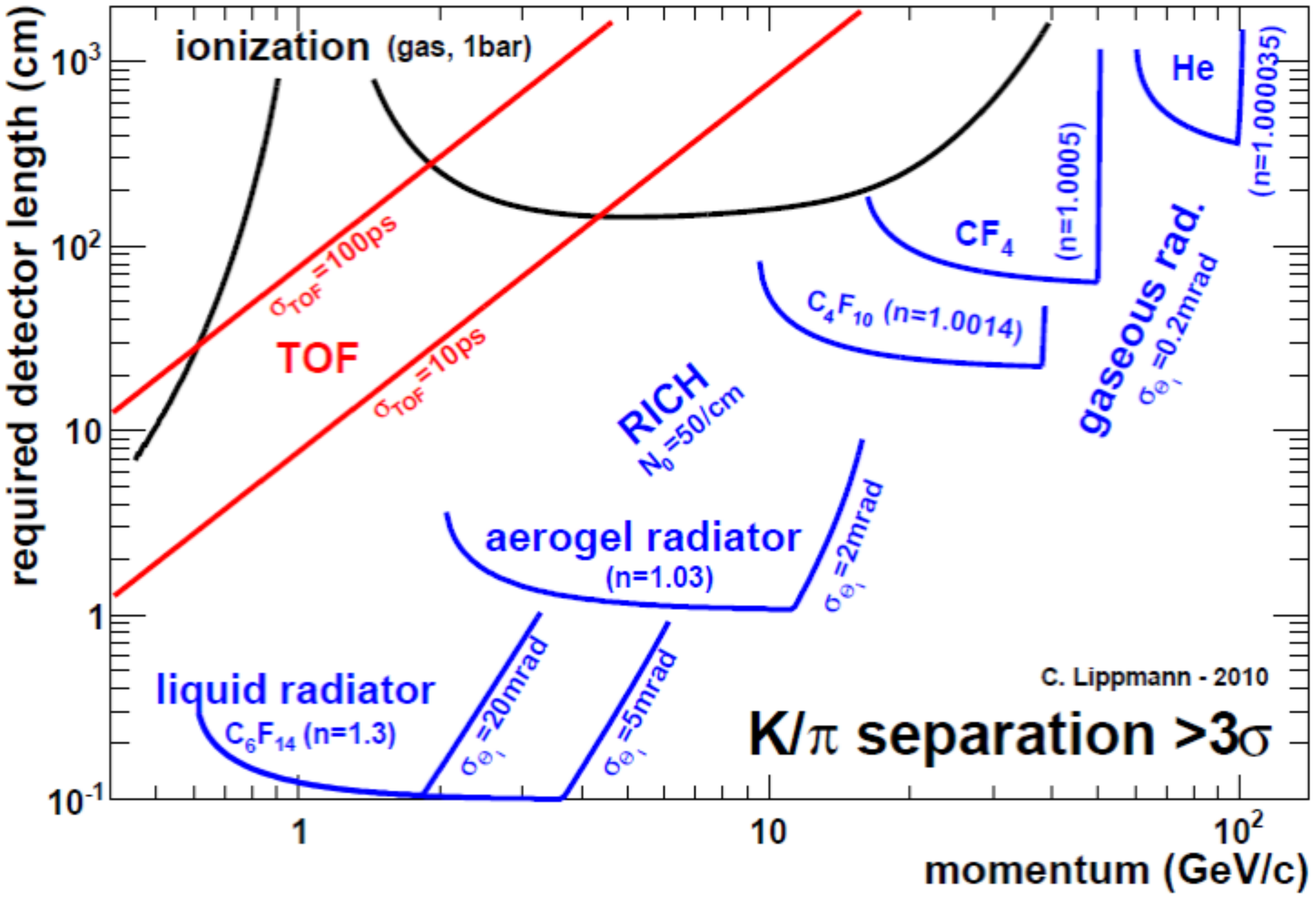
The End

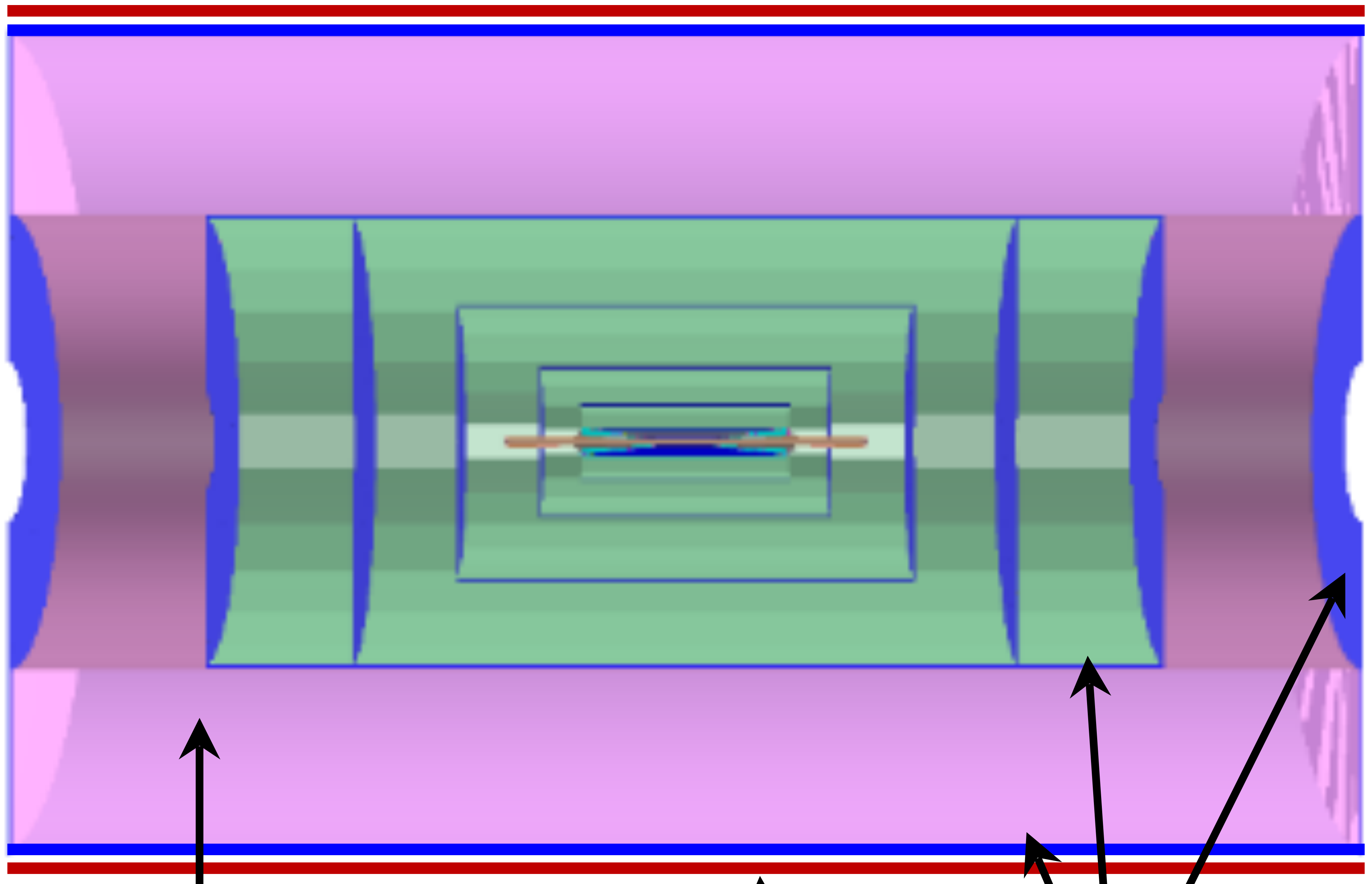
Challenges

Particle Identification in case of no TPC

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

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





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

Full silicon trackers

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

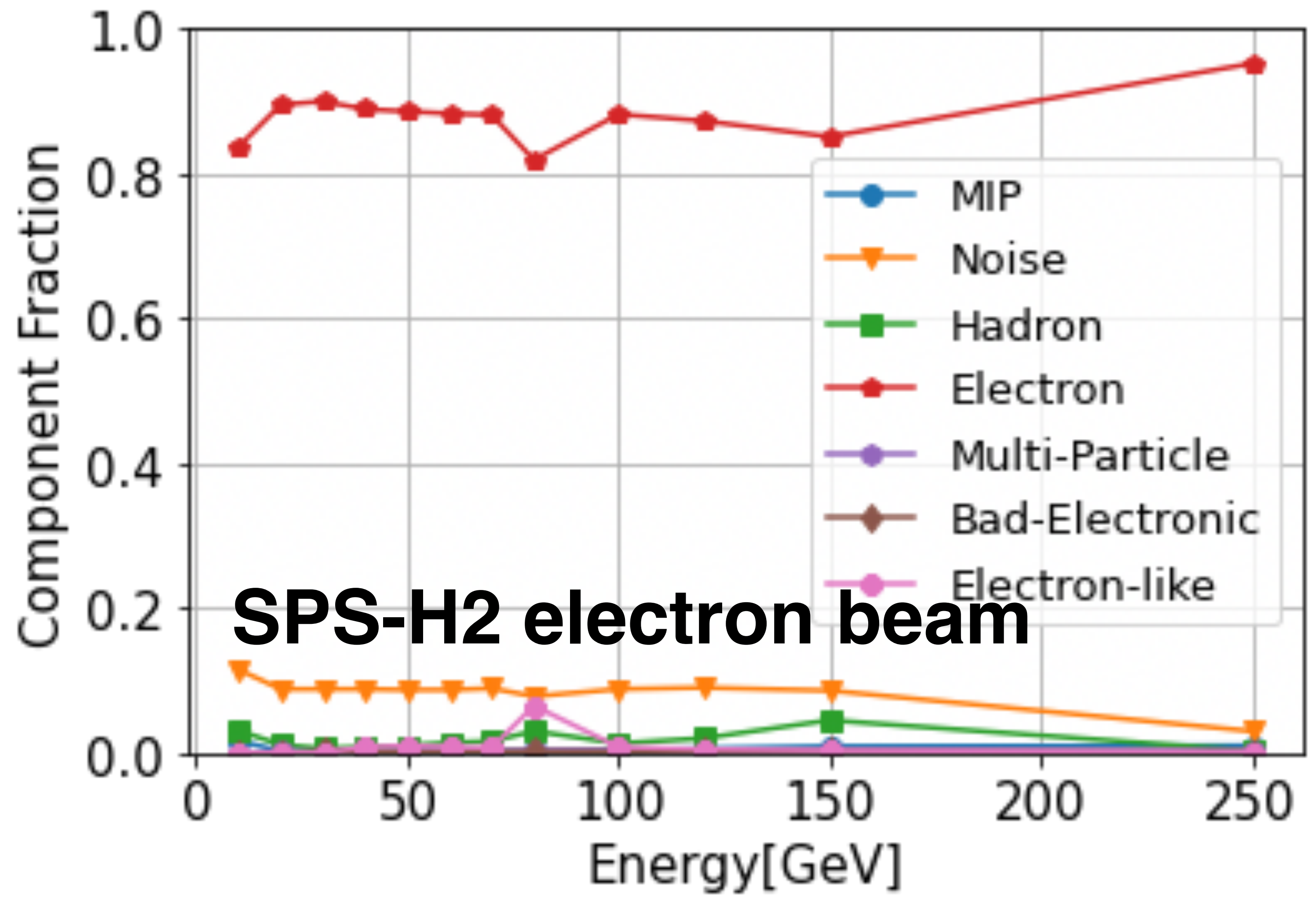
A Quest of Silicon Pixel Vertex Detector

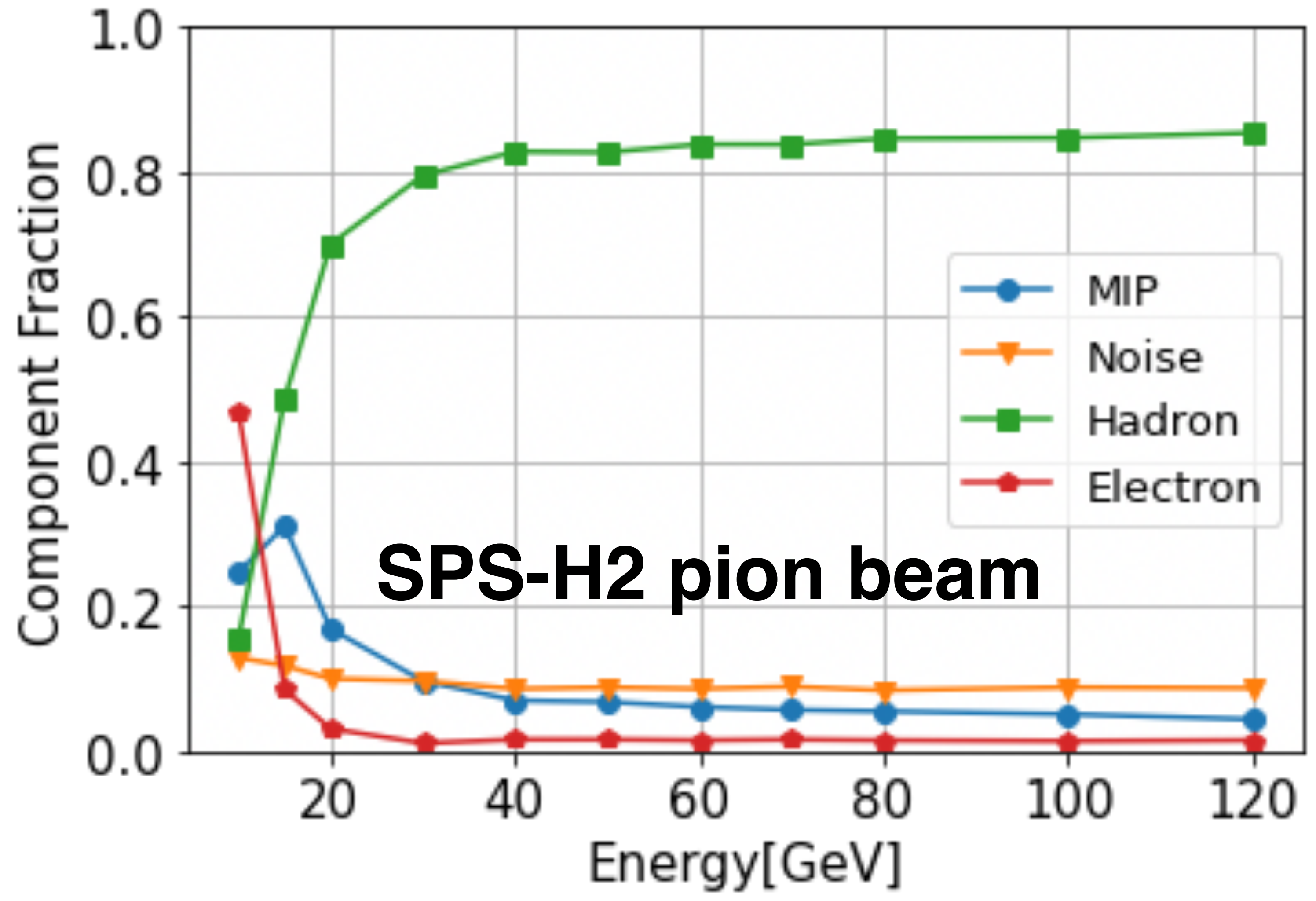
	JadePix	TaichuPix	*MOST3*	CDR
Spatial resolution	2.7-5 μm for JadePix-3 Worse for JadePix-4	4.5 μm for single chip 4.9 μm for ladder	3 μm	3 μm
IP resolution	-	~5-6 μm for P= 4-6 GeV		
Power dissipation	72 mW/cm^2 for JadePix-3	60 mW/cm^2 @ 17.5 MHz ?? @ 40 MHz	100 mW/cm^2	
Time resolution	100 μs for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

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

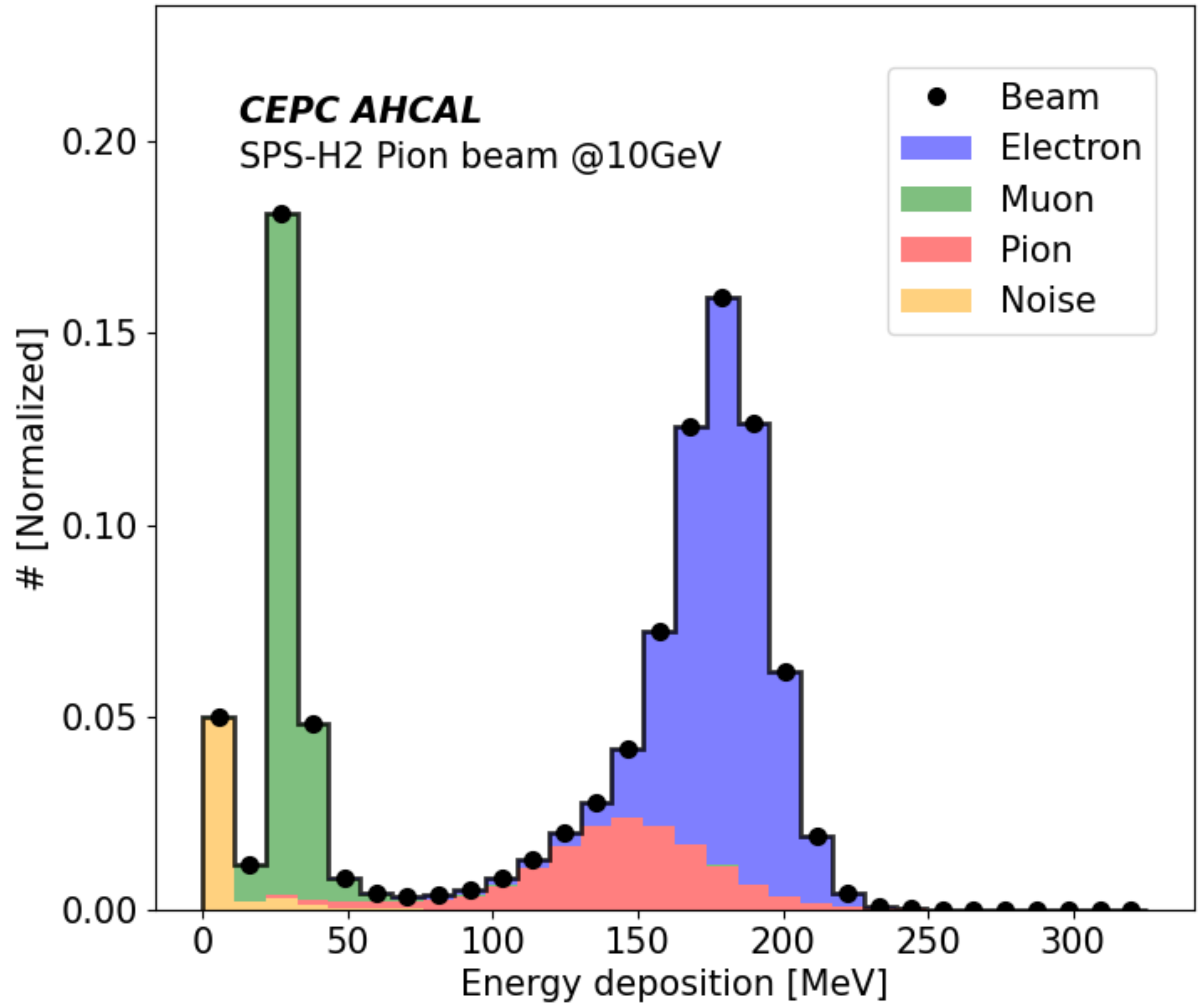
PID studies on beam compositions

Calorimeter PID based on Fractal Dimension

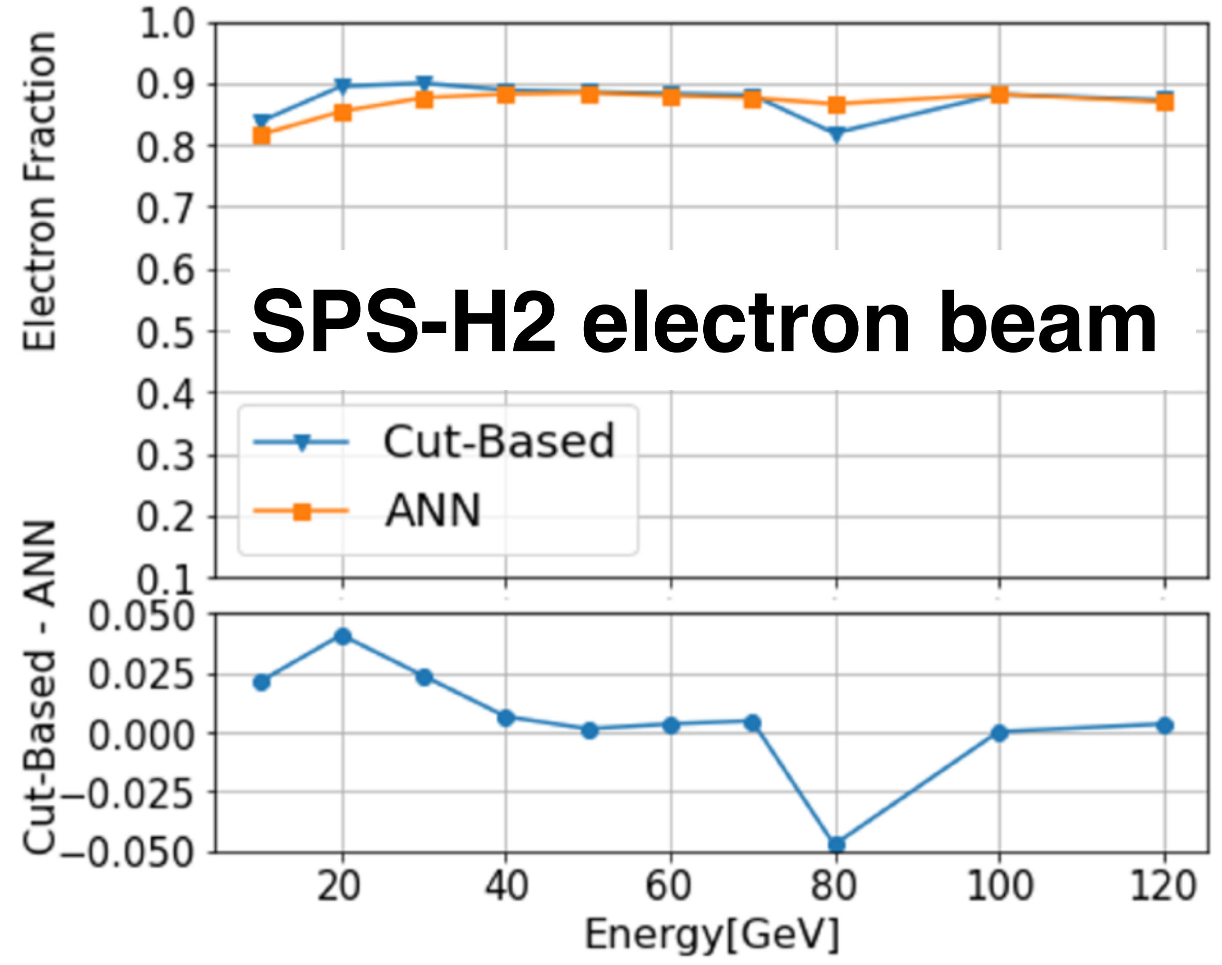


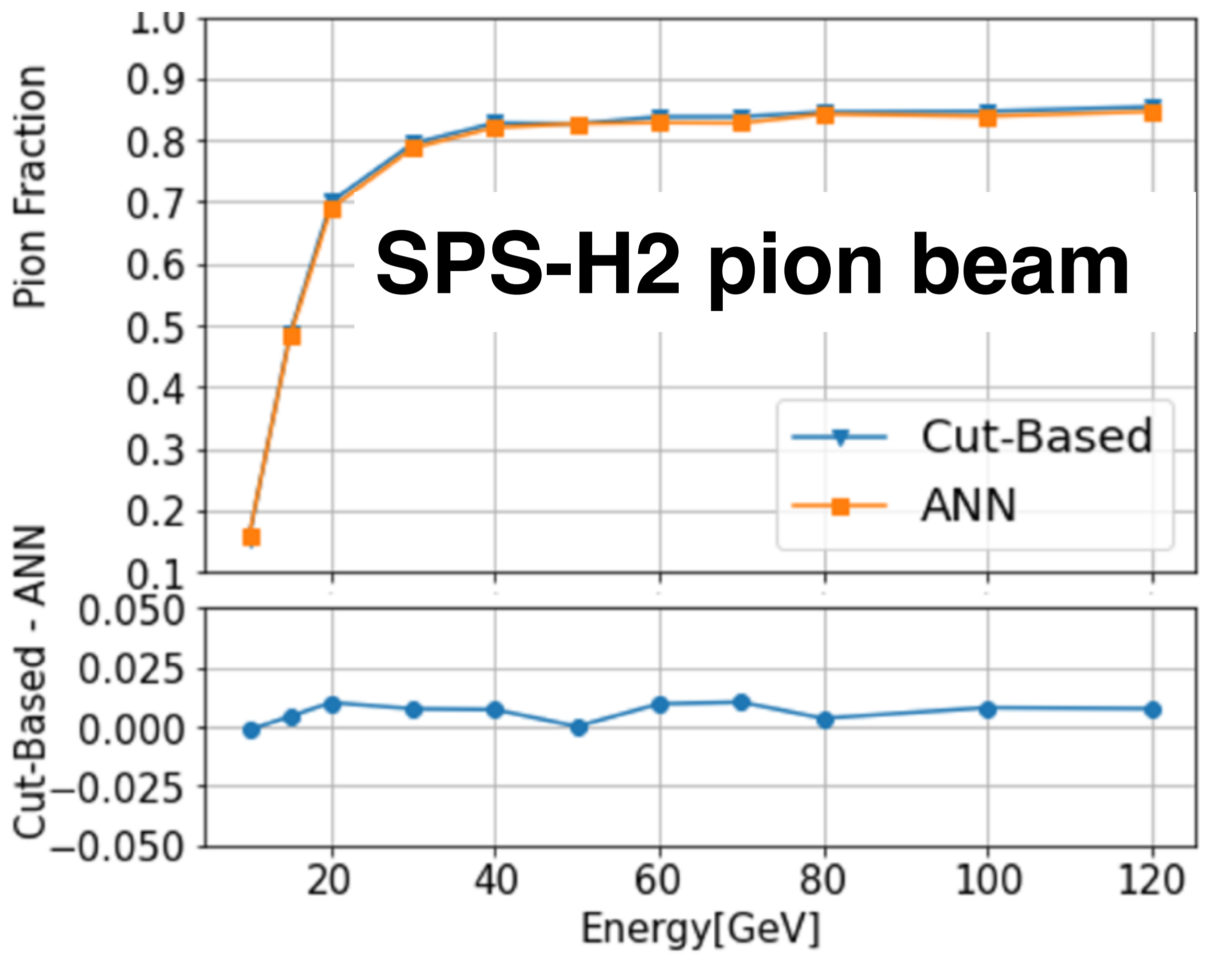


Energy depositions with 10 GeV hadron beam (various compositions)



PID comparison: ANN versus Fractal Dimension (cut-based)





By Feipeng Ning/Ling Zhao

Al-stabilized superconducting technology research

- Coextrusion line has been established at Wuxi Toly Co.
- Al-stabilized NbTi superconductor with lengths greater than 1 kilometer has been produced(4.7mm*15mm) , and samples by a second coextrusion are in the process of testing(56mm*22mm).
- Al-stabilized HTS cable have been successfully developed, and the critical current of the cable has a degradation of less than 10%.
- R&D of High Strength and High RRR Aluminum- Stabilizer for Superconducting Cable get a good results: Yield strength > 74 MPa at room temperature, RRR value > 400.

统力电工 TOLY ELECTRIC

Al-stabilized superconductor

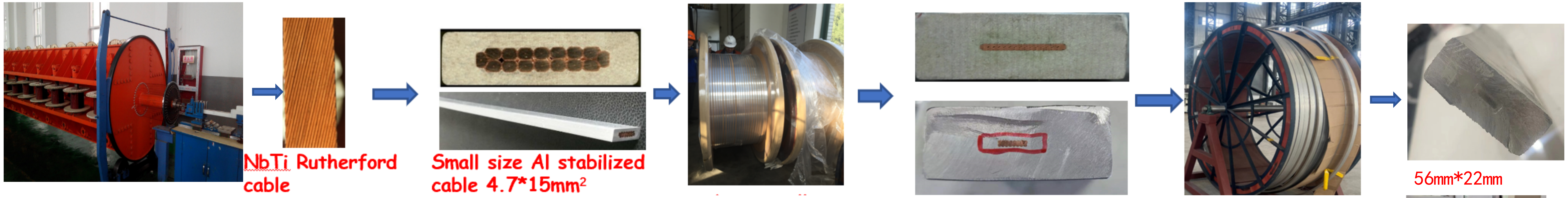
Pre-processing equipment

Extrusion machine

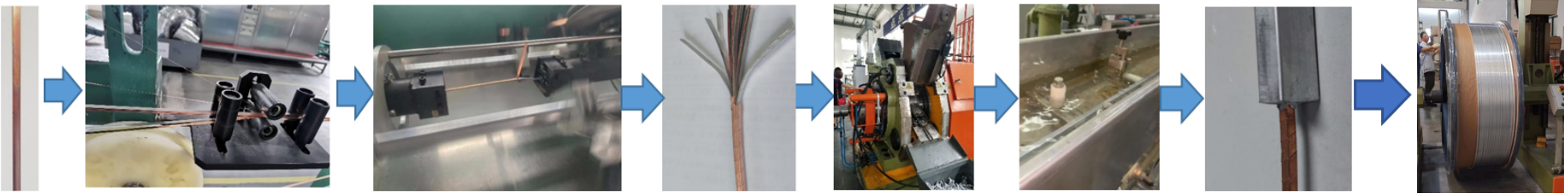
Parameter	Extrusion wheel diameter/mm	Rod diameter/mm	Cable thickness/mm	Cable width/mm
Value	400	2*9.5~12	3.0~30.0	10.0~70.0

8

LTS

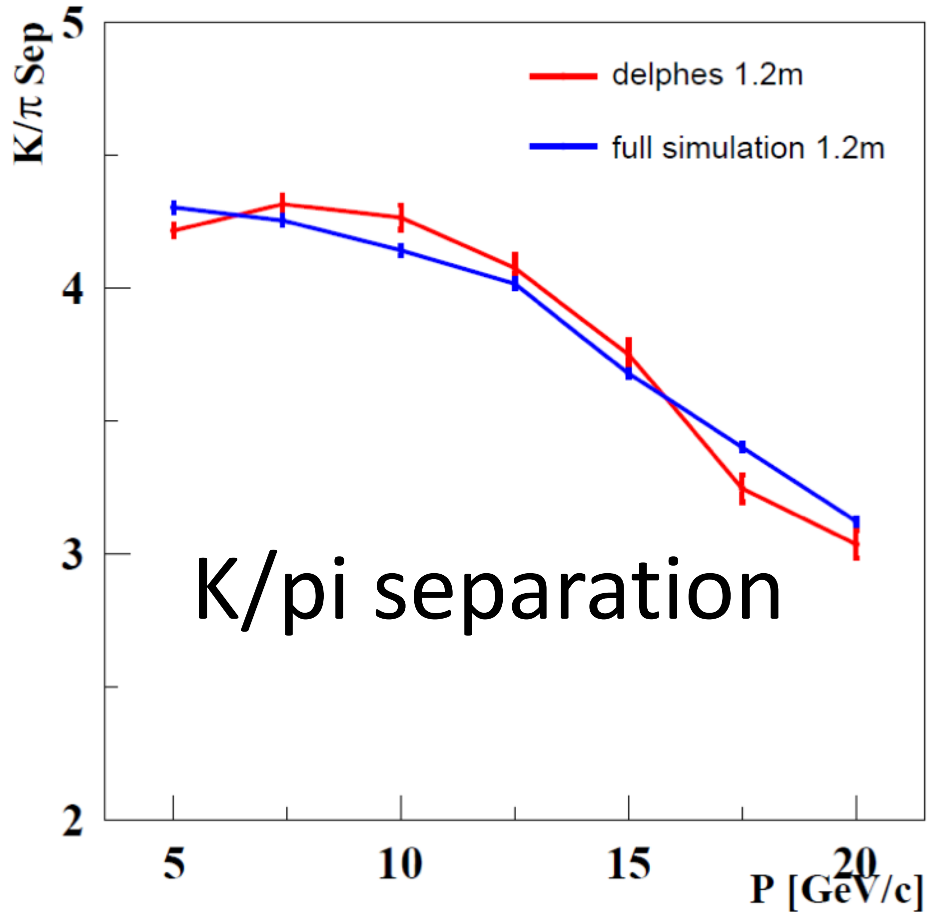


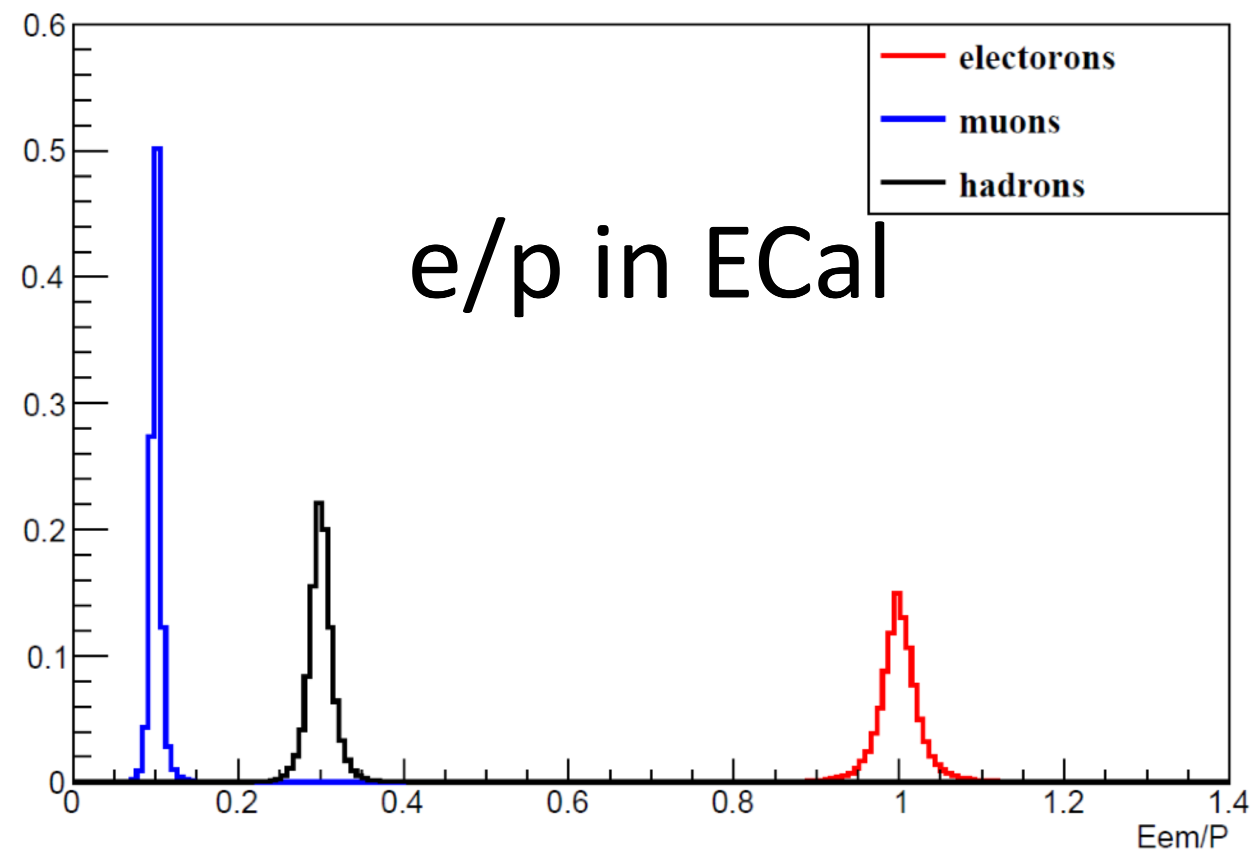
HTS

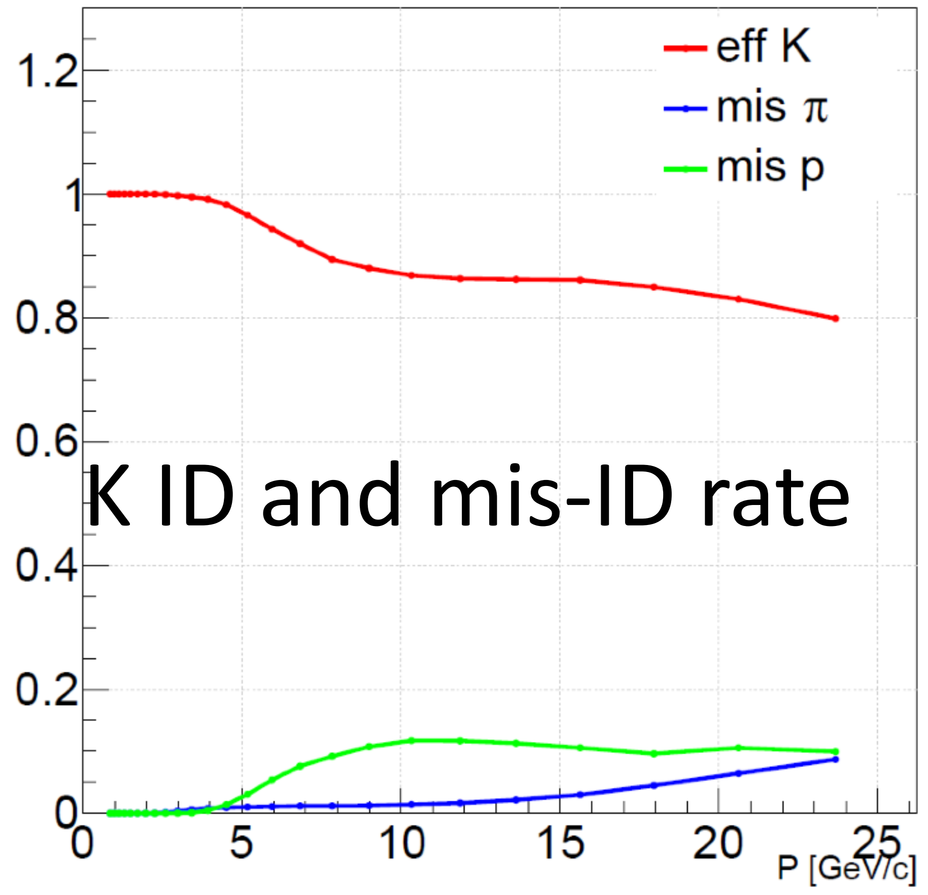


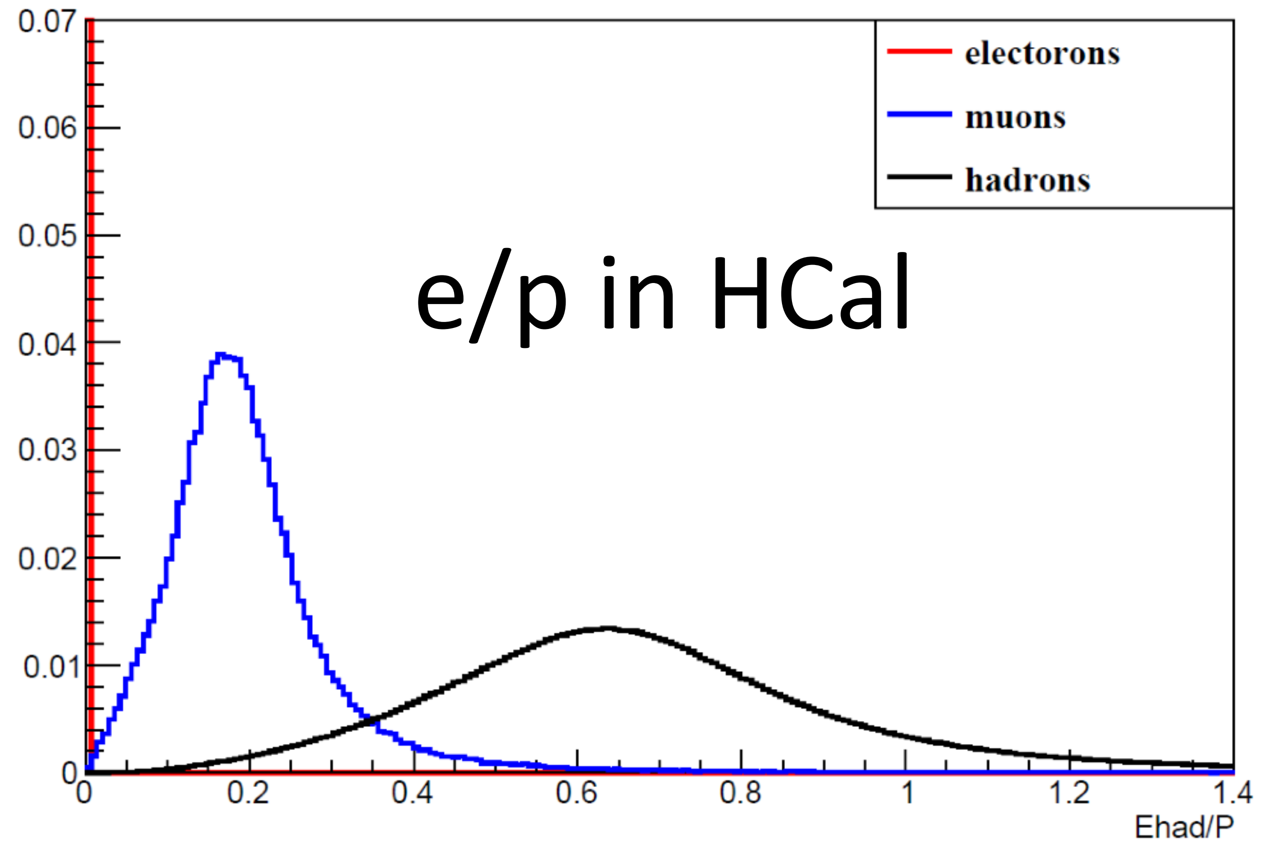
Fast simulation of the 4th conceptual detector design with DEPHES

- Implement tracker, calorimeter, … , into a DELPHES card; full covariance of tracks
- Some code development for the PID and jet-clustering functions
- Ready for physics study after careful validations
- Keep updating according to detector design and optimization

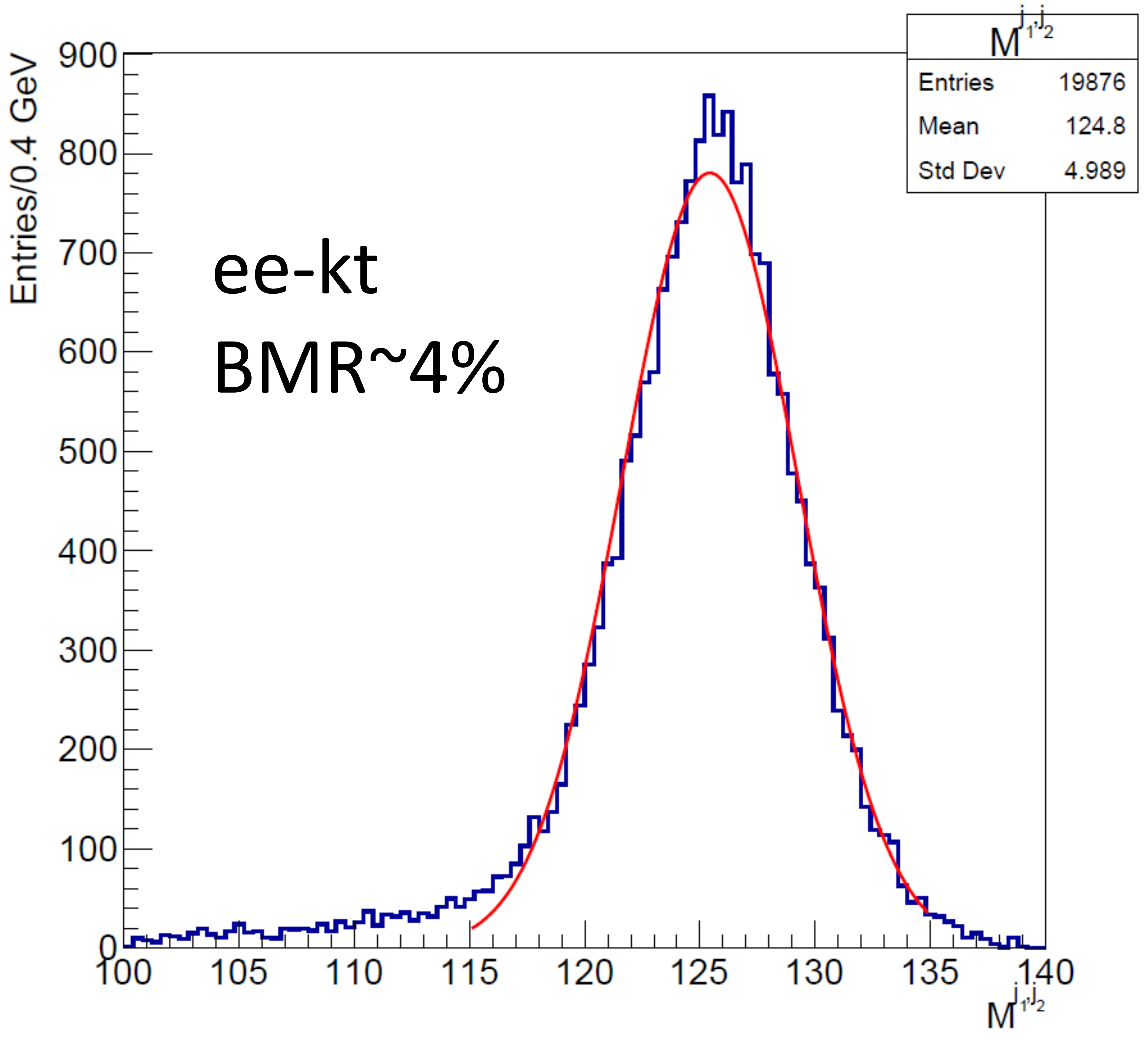








$e^+e^- \rightarrow Z(\nu\nu)H(gg)$



To be checked

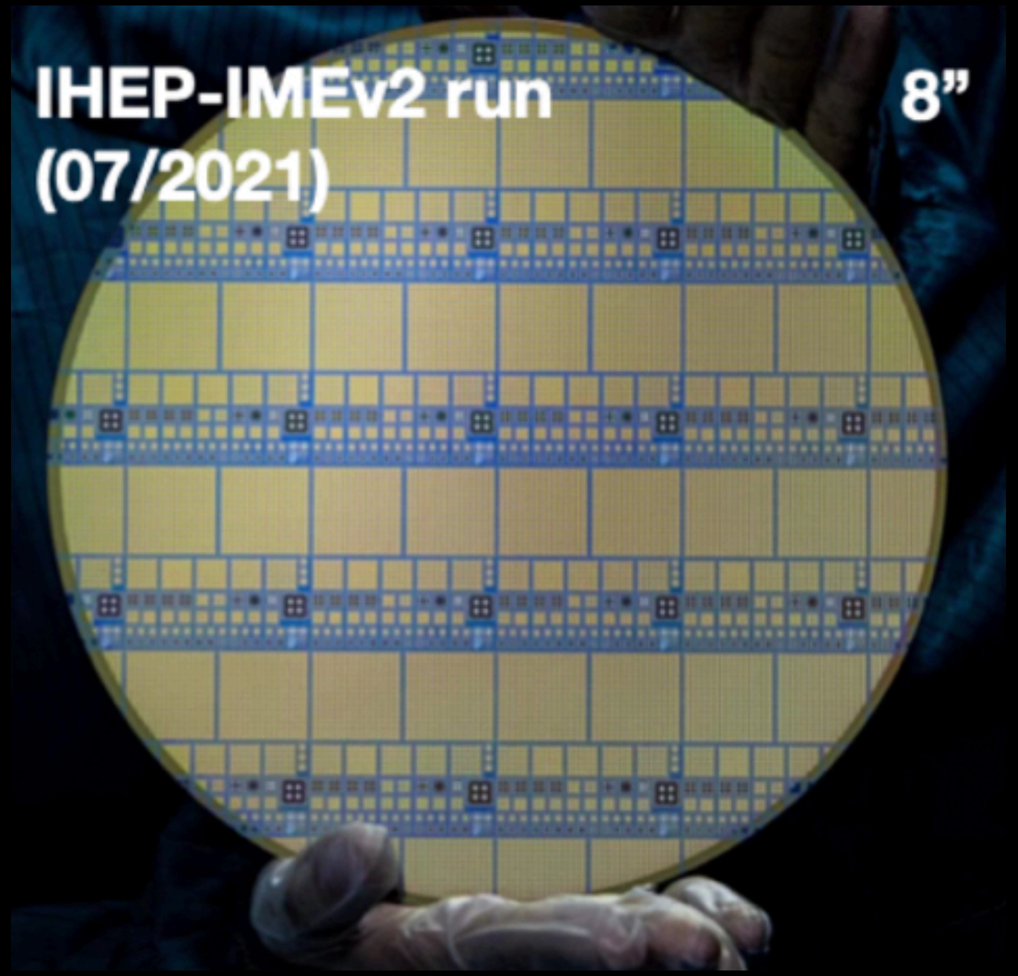
Tracker Optimization

The End

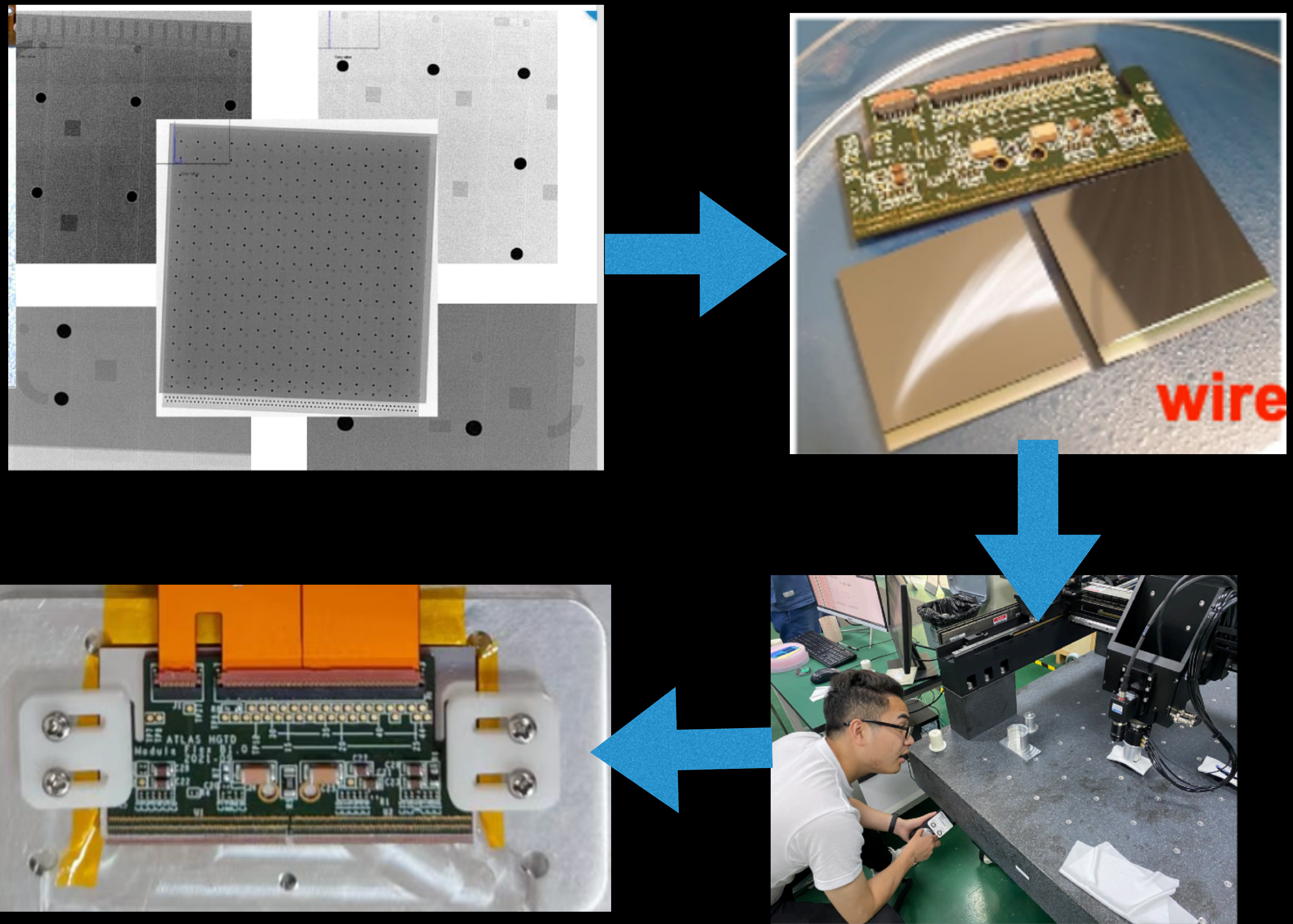
ATLAS Timing Detector (HGTD)

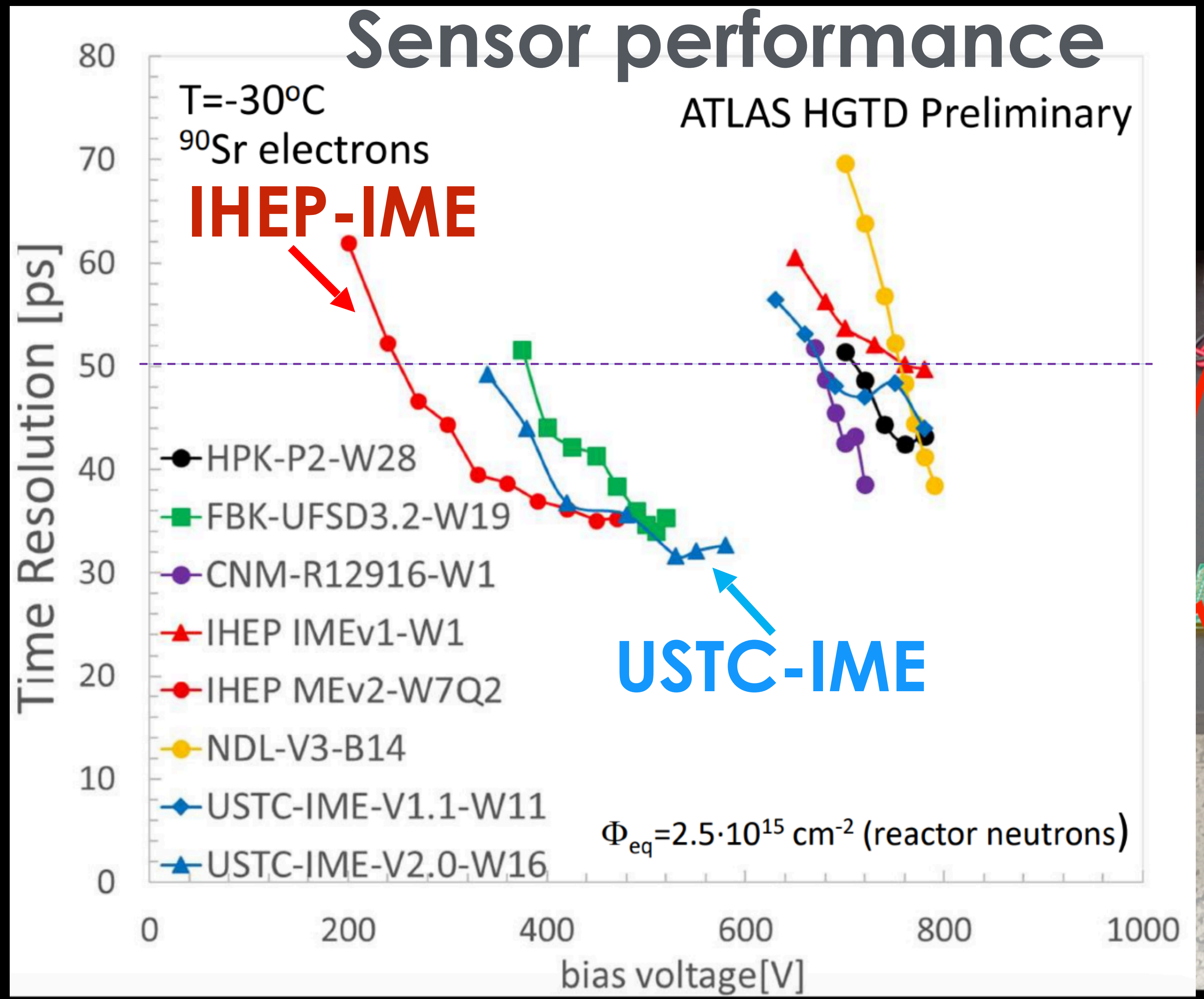
China is taking a leadership role in HGTD (IHEP, USTC, Nanjing, Shandong, Shanghai)

- 34% of LGAD sensors (IHEP-IME, USTC-IME)
- 100% module flex electronics
- 50% module hybridization
- 44% module assembly
- 50% module supports
- 33% flex cables
- 67% design/100% production peripheral electronics
- Low voltages power supplies

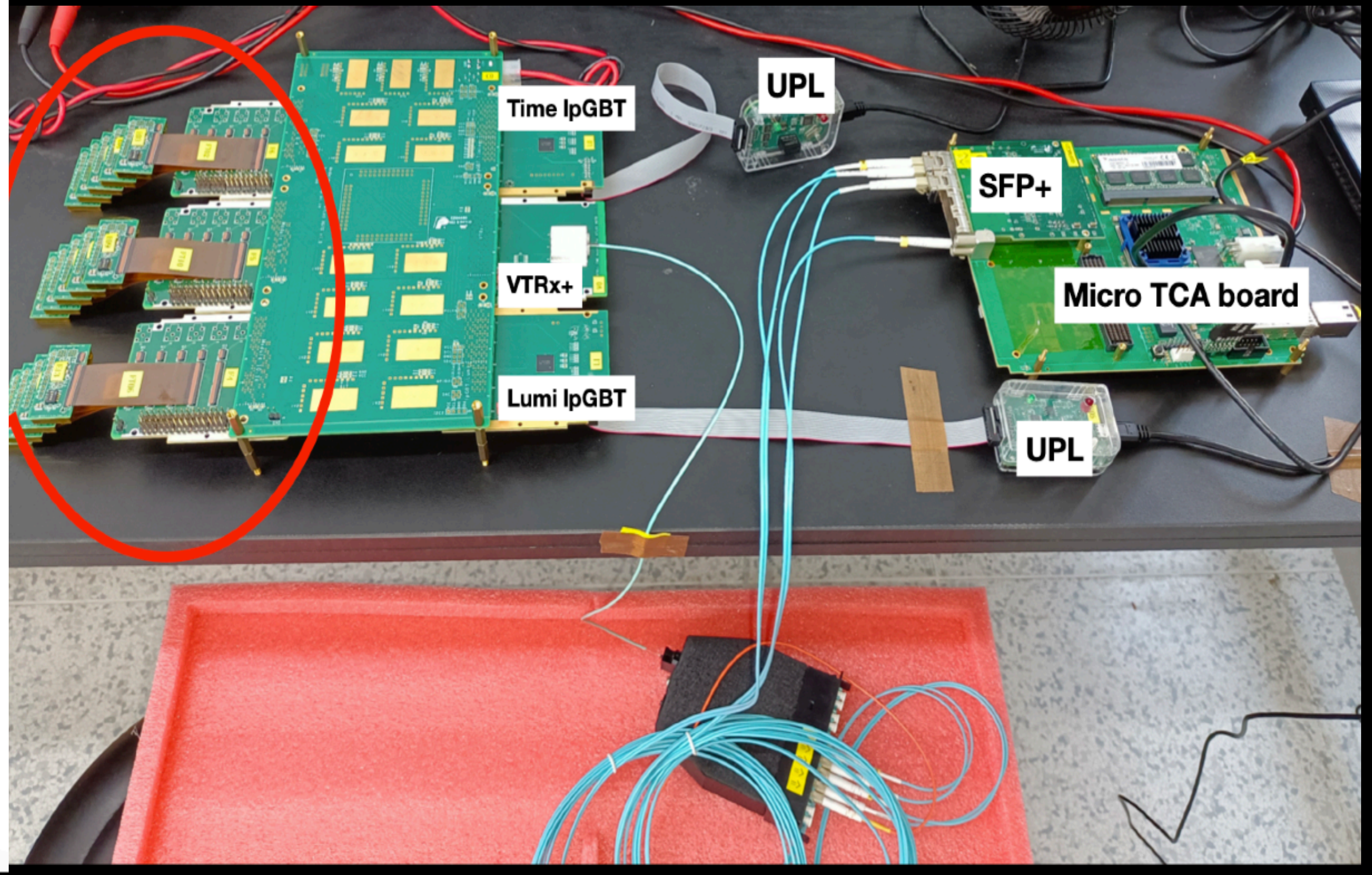


- Project leader
- HGTD risk and schedule coordinator
- L2 Sensors coordinator
- L2 Module coordinator
- L3 Module flex coordinator
- L2 software coordinator
- L3 Peripheral electronics coordinator
- L3 High Voltage coordinator
- HGTD Speakers committee Chair





Peripheral electronics testing



CEPC International Detector R&D Review Committee (IDRC)

Committee proposed by CEPC IAC

Initial Charge and Goals

Evaluate International proposals for detector R&D relevant to the CEPC

Independent organ to evaluate the importance and suitability of worldwide detector R&D proposals for CEPC and produce short report with findings.

Reviews and endorses the Detector R&D proposals from the international community, such that international participants can apply for funds from their funding agencies and make effective and sustained contributions

Later, this committee is expected to evolve to evaluate the Letters of Intent for the CEPC Detectors submitted by the proponents of the International Detector Collaborations

CEPC International Detector R&D Review Committee (IDRC)

Goals for original meeting, provided to committee:

Provide an overview of the on-going detector R&D linked to the CEPC

Solicit input regarding the directions one should take in the near future

Suggest: Short report with the opinion of the committee regarding the current R&D program and future directions

Outcome of original review: Report with main recommendation to produce:

1) Document with a coherent list of the on-going of R&D activities, such that the presence of gaps and overlaps can be determined and addressed — DONE
2) Updated CDR document within 12-18 months
3) A conservative full-detector concept, potentially deliverable on an aggressive time scale, should be specified by the CEPC Management and adopted as the baseline for the CDR update

We, the CEPC management and IAC, didn't agree with the production of another "CDR" document in this timescale, due to the large amount of resources required. Instead, the decision was to move forward with the R&D for a 4th detector

Key previous steps:

- IDRC expressed concern that the schedule presented to them (with detector TDRs in 2023) was not realistic and prompted the problematic recommendations
- Follow-up IDRC meeting in 2020, planned for Marseille, was cancelled due to COVID
- A document with the summary of on-going R&D activities was produced and sent to the IDRC chair, as requested by the IDRC

- Since the last IAC meeting in 2021:
  - An updated version of the document with the summary of R&D activities was produced and sent to the IDRC
  - Two attempts to organize a meeting in 2022 were made by the IDRC chair, but unfortunately it was not possible to secure the presence of enough committee members
  - Given the current international situation, the chair has suggested a modification to the committee charge that we would like to discuss

Document with summary of on-going R&D activities updated in early 2022

Contents

Suggestions and next steps:

Discussion with IDRC chair → suggestions on how to proceed

- Concern that, given the current international situation, effectively there are no proposals from international community specifically to work at CEPC and it is difficult to imagine such proposals will materialize in the near future, therefore, the charge to this committee is not actionable
  - Observation: This might not be exactly correct since most detector R&D work for FCC-ee directly applies to CEPC. It is possible that, for certain communities, getting the support of this International Committee would be advantageous — this seems to be the situation with our Italian colleagues

- Suggest to change the charge of the committee to become more technical covering a technical evaluation of all detector R&D being done towards the CEPC — hence, closer to the International Accelerator Review Committee charge

- Re-evaluate the committee membership in light of this new, more technical, charge, and in particular, investigate the availability of the current committee members to still serve in such committee

Given that this committee was created following an IAC recommendation, we would like to discuss these possible changes with you

Suggestions for a new charge:

- The IDRC will advise on matters related to the CEPC detector R&D, including the Machine-Detector Interface, and the compatibility of the detector technologies proposed with the high-luminosity operation of the accelerator at the Z, WW, ZH, and tt-bar production threshold energies.
- The IDRC will evaluate international proposals for detector R&D relevant to the CEPC, and produce a short report with its findings.
- The IDRC reports to the Project Director.
- Later, this committee is expected to evolve into an experimental committee (similar to LHCC) to evaluate the Letters of Intent for the CEPC Detectors submitted by the proponents of the International Detector Collaborations
- The committee should have external members including 2-3 IAC members.
- The committee should meet at least once a year and a report should be provided at the IAC meeting.

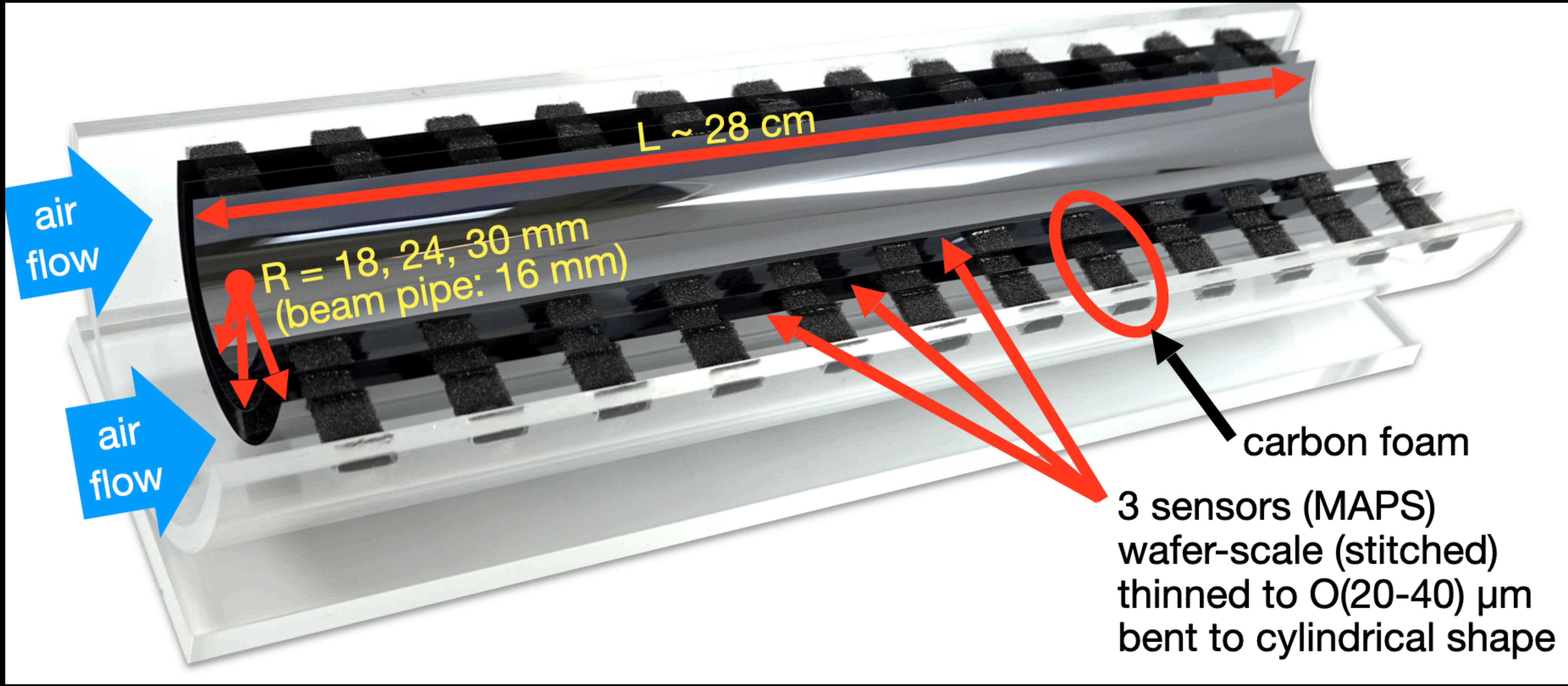
Current committee membership:

Dave Newbold, UK, RAL (chair)
Jim Brau, USA, Oregon
Brian Foster, UK, Oxford
Liang Han, China, USTC
Andreas Schopper, CERN, CERN
Steinar Stapnes, CERN, CERN
Hitoshi Yamamoto, Japan, Tohoku
Valter Bonvicini, Italy, Trieste
Ariella Cattai, CERN, CERN
Cristinel Diaconu, France, Marseille
Abe Seiden, USA, UCSC
Laurent Serin, France, LAL
Roberto Tenchini, Italy, INFN
Ivan Villa Alvarez, Spain, Santader
Harvey Newman, USA, Caltech
Marcel Stanitzki, Germany, DESY

Key R&D Issues Moving Forward

Some key R&D topics moving forward

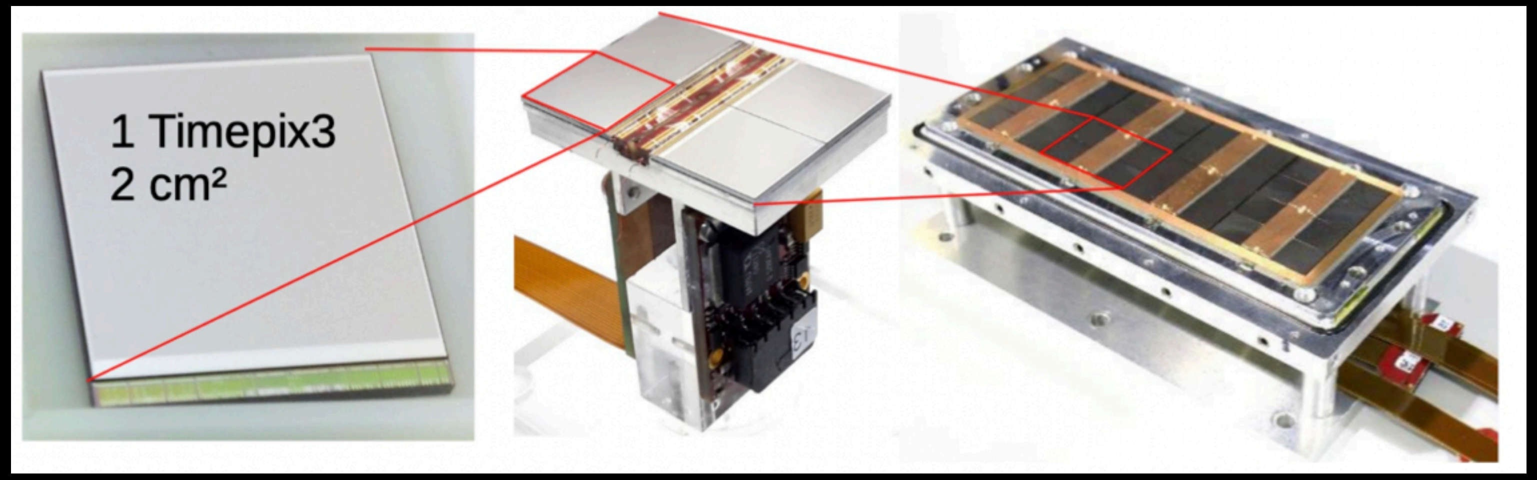
- **Machine Detector Interface**
- **Luminosity meter (LumiCal)** - continue integration in beampipe development
- **Silicon Vertex**
  - Continue to explore low-material budget solutions, cooling integration and performance optimization
  - Major issue: Sensor technology and availability in China
  - Curved silicon, as in ALICE ITS3, should be considered but it has lots of challenges that would need to be solved in a tight timescale



Some key R&D topics moving forward

Trade off: Transparency <—> reliability/resolution

- Tracker
  - Time Projection Chamber
    - Evaluate the Pixel TPC possibility



  - Drift Chamber
    - Demonstrate it can cope with the high increased rates at the Z pole? Enough resolution?
    - Demonstrate PID capabilities with cluster counting
    - Continue mechanical design and stability analysis
  - Full silicon tracker → still need manpower increase to exploit this option
    - Continue Silicon Tracker prototype collaboration
    - Need to add detector for particle identification — drift chamber is an option
    - Consider adding timing Silicon layer
      - AC-Coupled Resistive Silicon Detector (RSD)
      - Trench-isolated LGAD (TI-LGAD)

Some key R&D topics moving forward

- Calorimetry
  - Cost versus physics performance
  - ECAL
    - Finalize evaluation of the crystal calorimeter option
    - Cooling of PFA calorimeter versus performance
  - HCAL
    - Finalize evaluation of Scintillator Steel option
    - Study glass hadronic calorimeter has an alternative
    - Cooling and mechanics studies
  - Dual Readout
    - Demonstration using full size prototype

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- Muon System optimization
  - Optimize number of layers
  - Optimize design for industrialization and cost

Optimization of detectors

Not an easy task without definite detectors/collaborations target

- Use a mixture of fast simulation and full simulation
- Need to consider engineering aspects
- Need to consider costing issues
  - balance between performance and eventual total detector cost