A Survey of Detector R&D in China

Jianchun Wang (IHEP, CAS)

HSTD13, Dec 3-8, 2023, Vancouver

Detector R&D Planning

- The High Energy Physics (HEP) branch of Chinese Physics Society (CPS) holds annual meetings to discuss plans and issues, including detector R&D strategy.

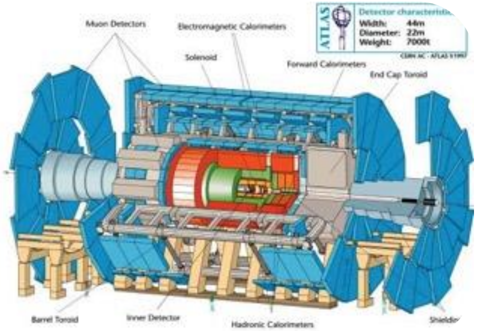
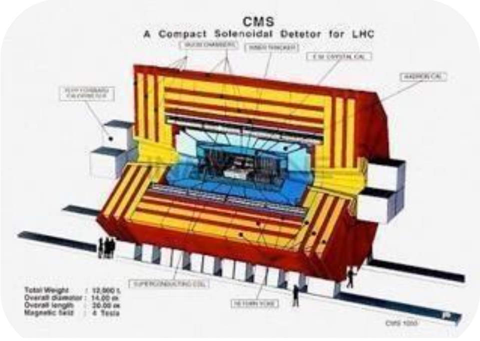
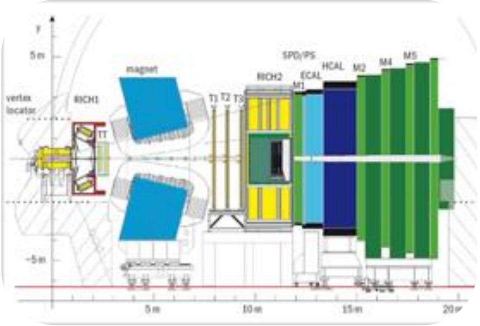
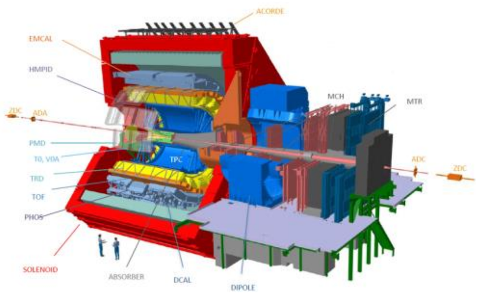
- There has not been sufficient efforts, like the ECFA DRD, to prioritize the development directions or distribute resources strategically. Although it is not rare to see such actions happening at the institute level.

- The detector R&Ds in China are more experiment-oriented, including major upgrades and new experiments.
  - Collider experiments: ATLAS, CMS, LHCb, ALICE, Belle-II, CEPC, STCF
  - Non-accelerator ground experiments: LHAASO, JUNO & TAO, Trident, Dark-Shine
  - Space particle experiments: AMS-02, HERD

- In recent years, the share of detector contributions to major international experiments increases significantly.

My apology to the on-going detector R&D activities that could not be covered

Upgrades of The LHC Experiments

ATLAS	CMS	LHCb	ALICE
			

2010 2011 2012 2013 2014 **2015** 2016 2017 2018 2019 **2020** 2021 2022 2023 2024 **2025** 2026 2027 2028 2029 **2030** 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041

Run 1 | LS 1 | Run 2 | LS 2 | Run 3 | LS 3 | Run 4 | LS 4 | Run 5 | LS5 | Run6

Contribution from Chinese groups

LS 2	
ATLAS	NSW
CMS	CPPF, CSC
LHCb	UT, SciFi
ALICE	ITS2, MFT

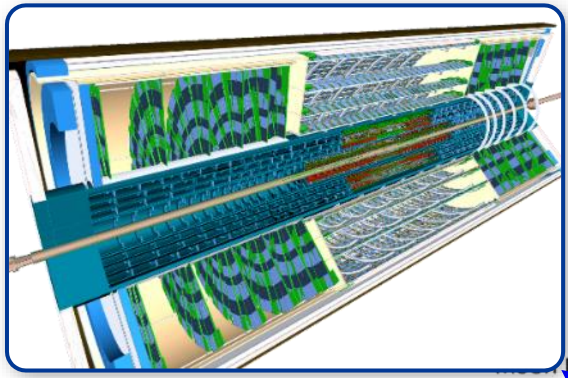
LS 3	
ATLAS	ITK, HGTD, Muon
CMS	HGCAL, MTD, Muon
LHCb	SPACAL ?
ALICE	ITS3, FoCal

LS 4	
ATLAS	?
CMS	?
LHCb	UT, SPACAL
ALICE	ITS4, TOF

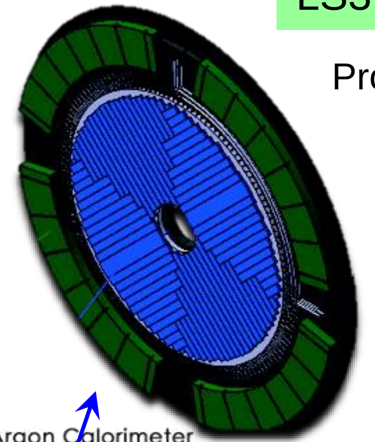
The ATLAS Upgrades

LS3: **ITk**

Produce SSD modules

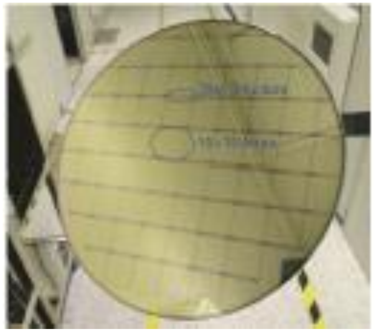


LS3: **HGTD**



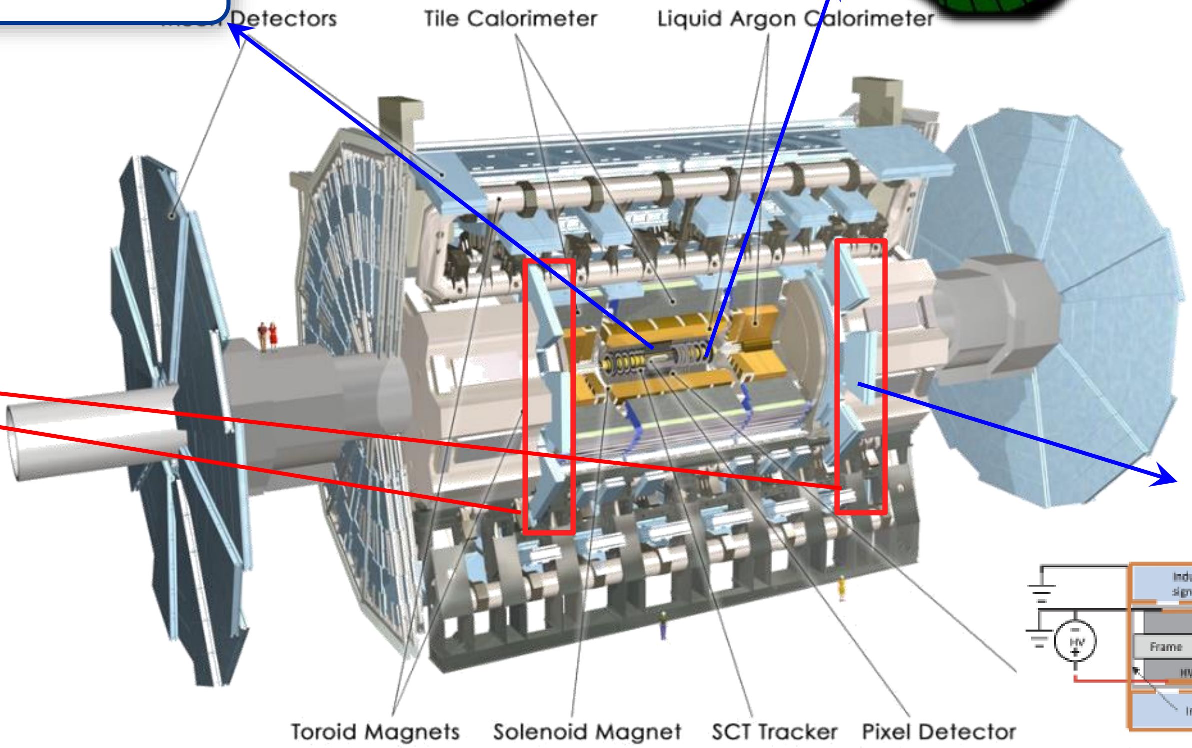
Produce rad-hard **LGAD in China**
(30-50 ps, $2.5\times10^{15}\ n_{eq}/cm^2$)

Design and produce detector



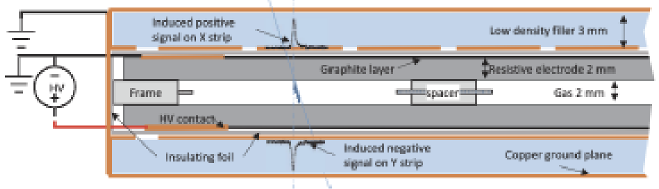
LS2: **NSW**

Small strip Thin Gap Chamber
Produce sTGC panels



LS3: **Muon**

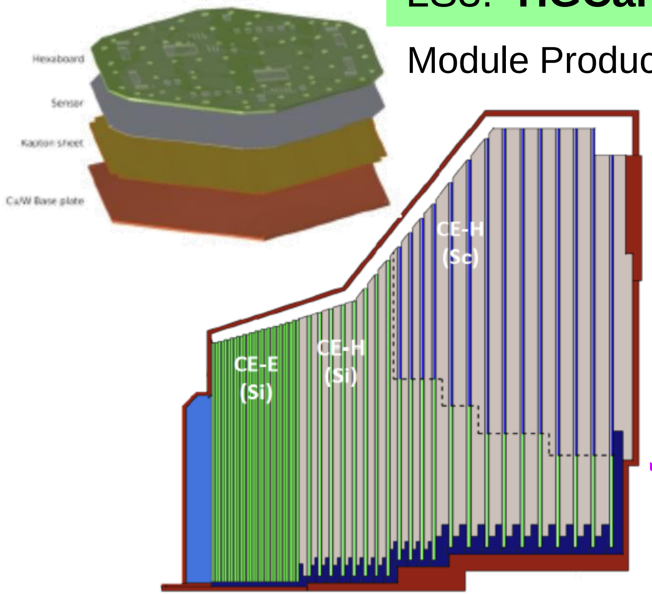
Produce RPC singlets



The CMS Upgrades

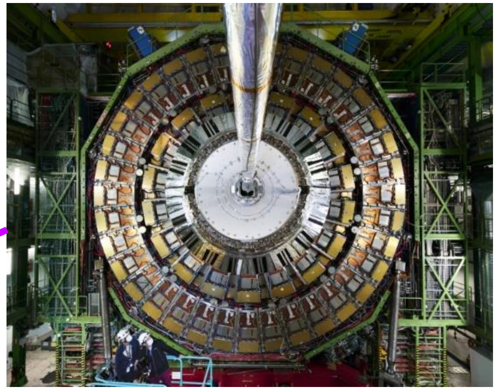
LS3: HGCal

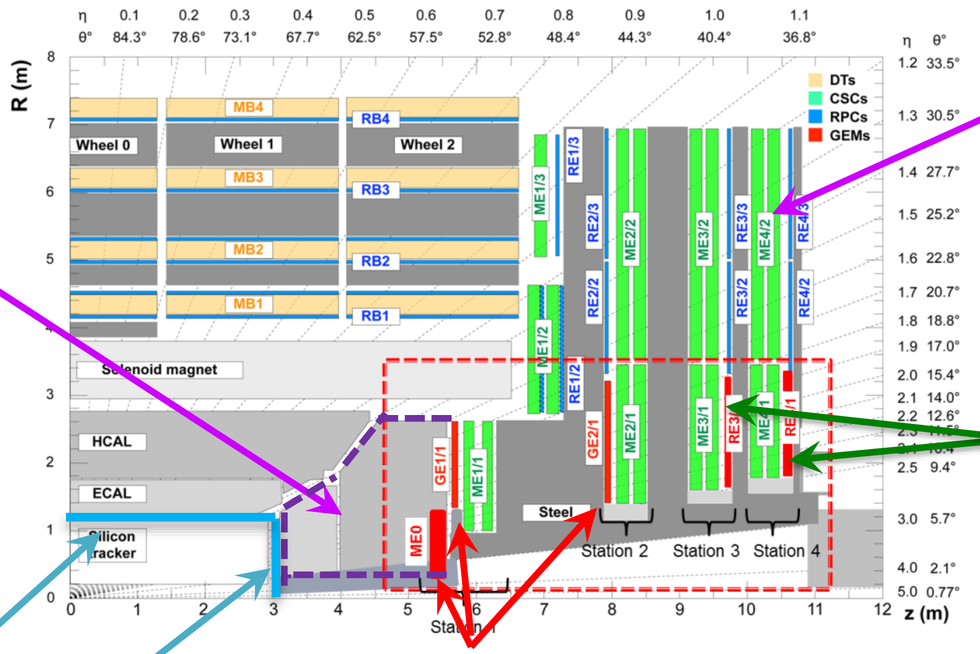
Module Production



LS2: Muon

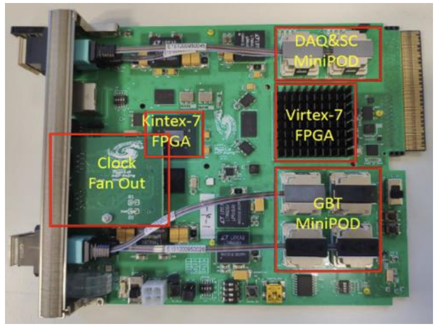
Cathode Strip Chamber
Muon L1 Trigger





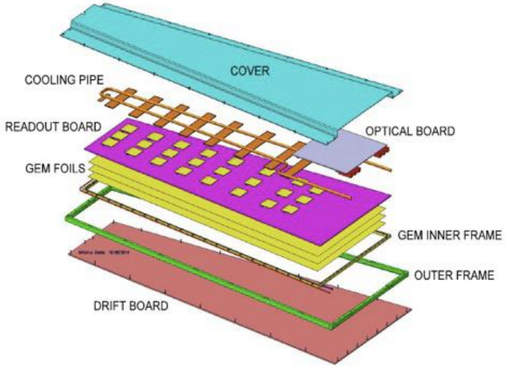
LS3: MIP Timing Detector

ETL: LGAD based
BTL: LYSO+SiPM
~30 ps / track



LS3: Endcap Muon

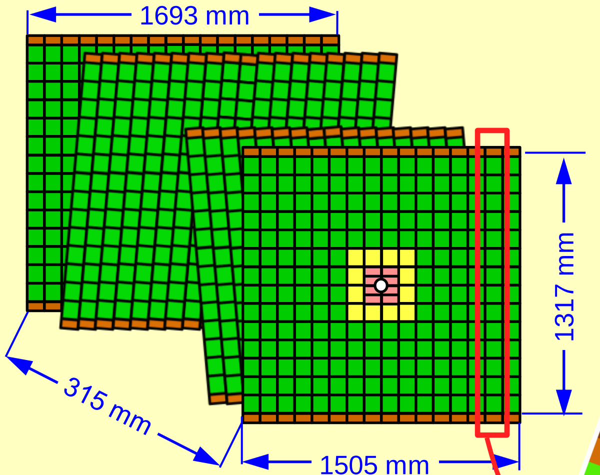
RPC/iRPC trigger backend

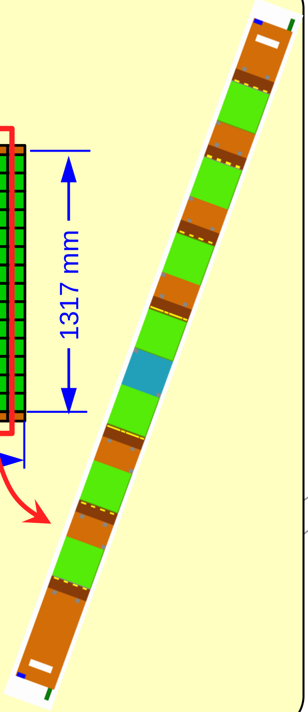


LS3: Endcap Muon

GEM ME0, GE1/1. GE2/1

The LHCb Upgrades



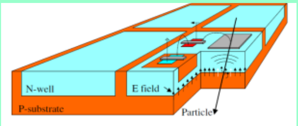


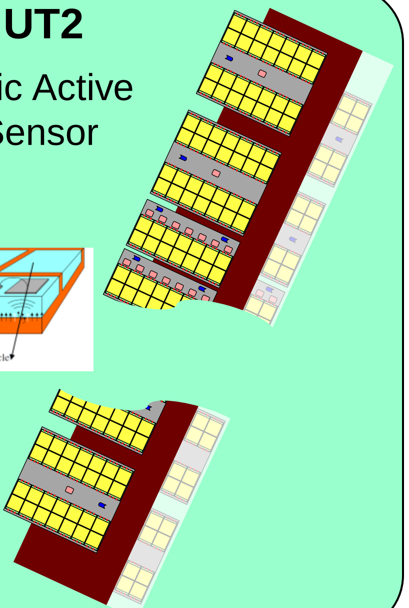
LS2: **UT**

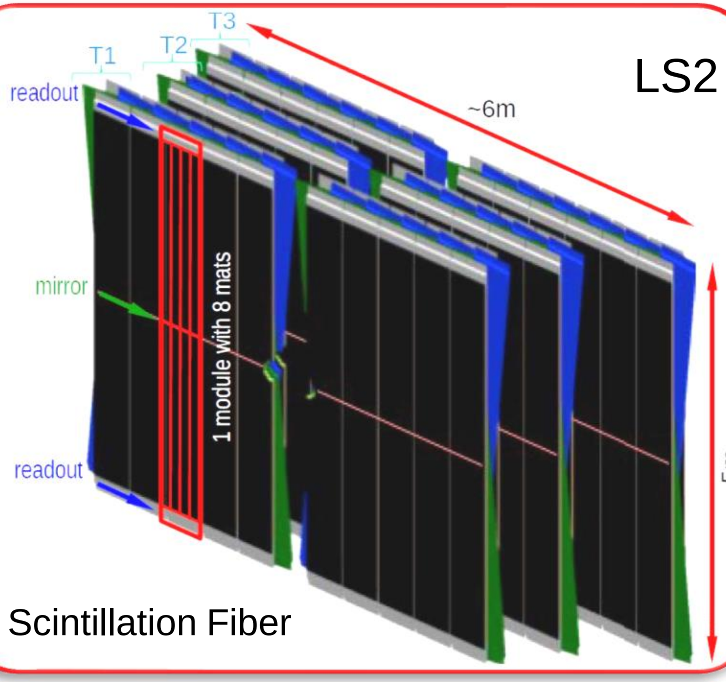
Si Strip Detector

LS4: **UT2**

Monolithic Active
Pixel Sensor

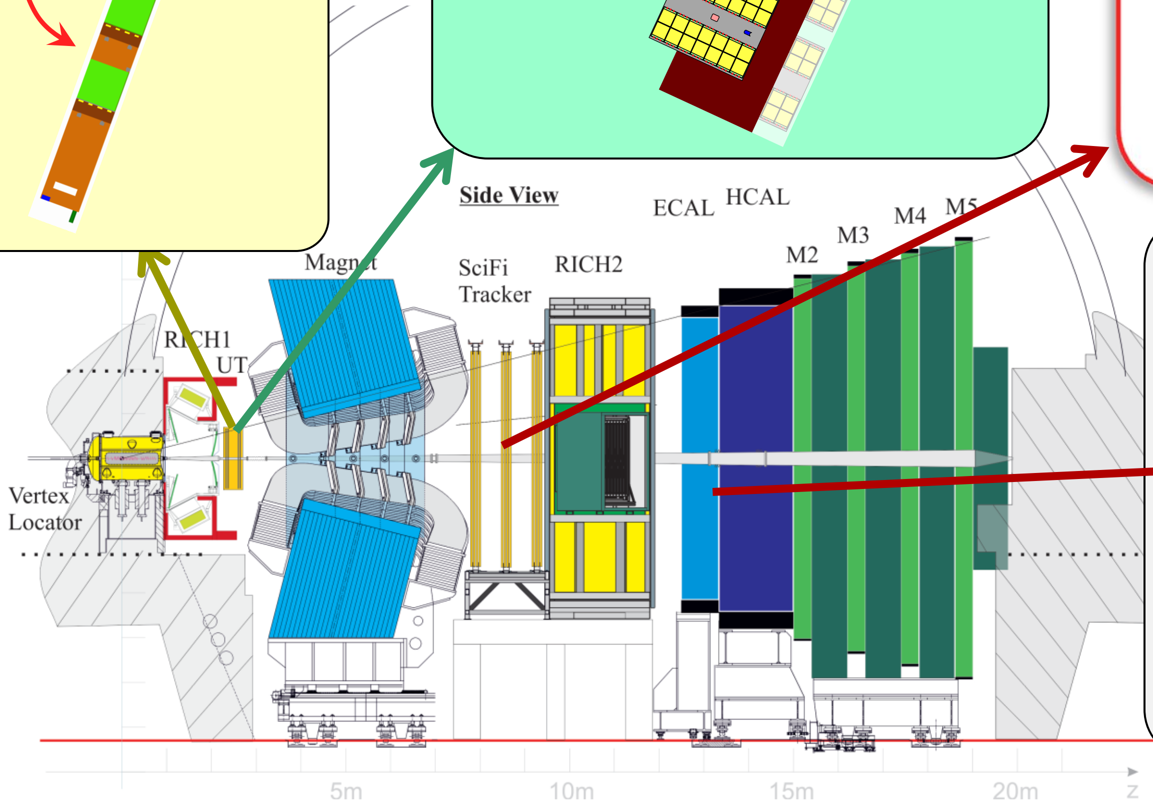


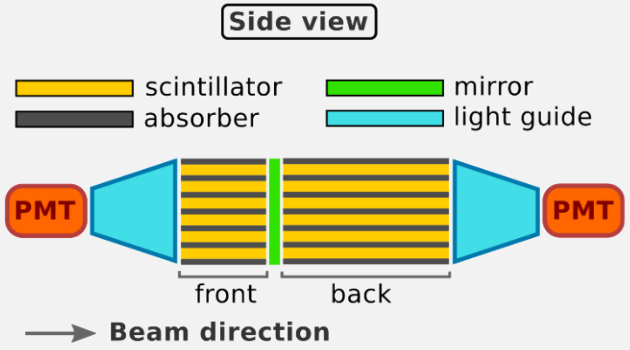




LS2

Scintillation Fiber





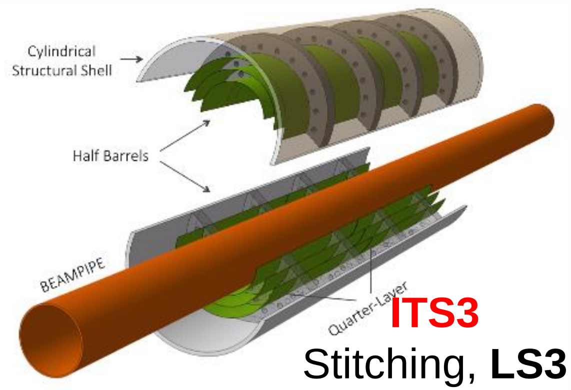
LS4 / 3

SPACAL
Spaghetti Cal

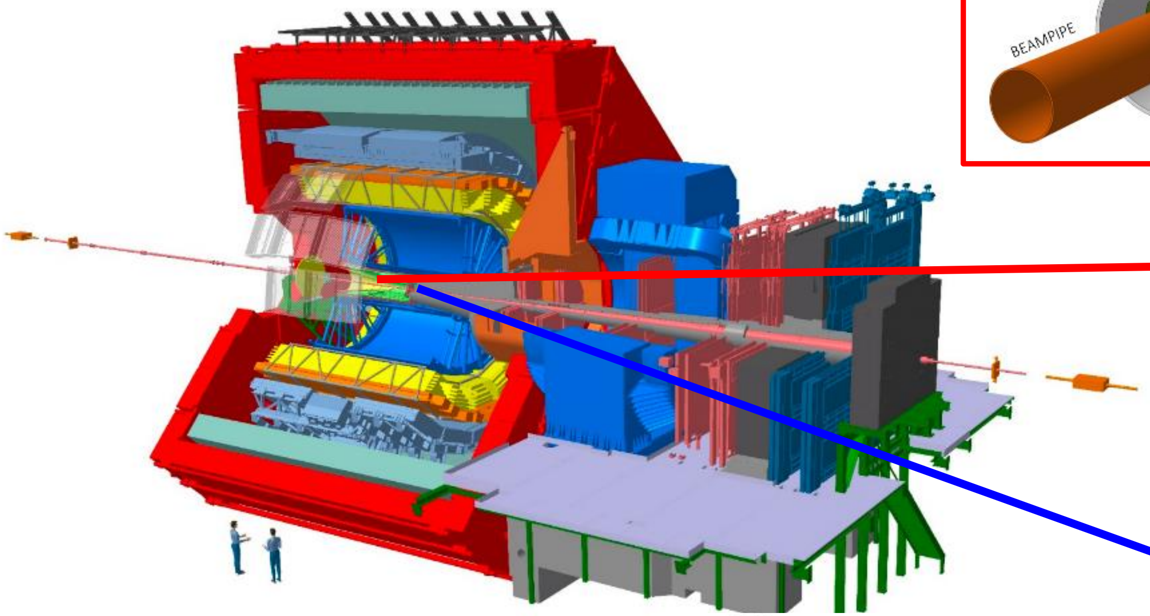
The ALICE Upgrades

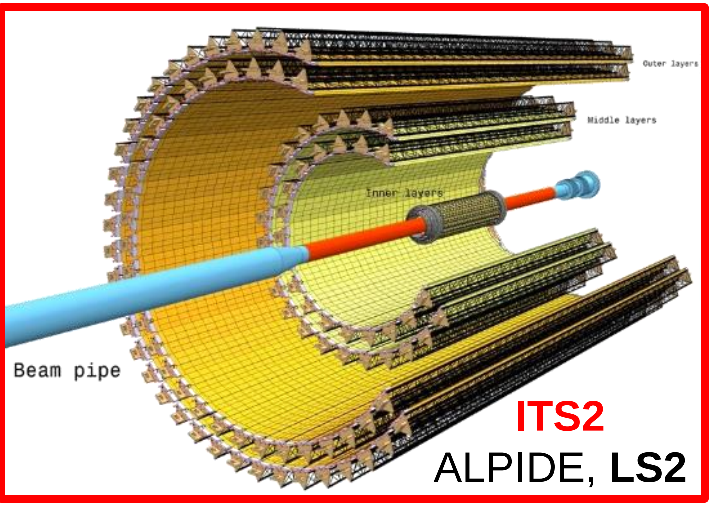
LS4: **ToF ?**
LGAD-based,
or LGAD with MAPS

LS4: **ITS4 ?**
Bigger area ALPIDE

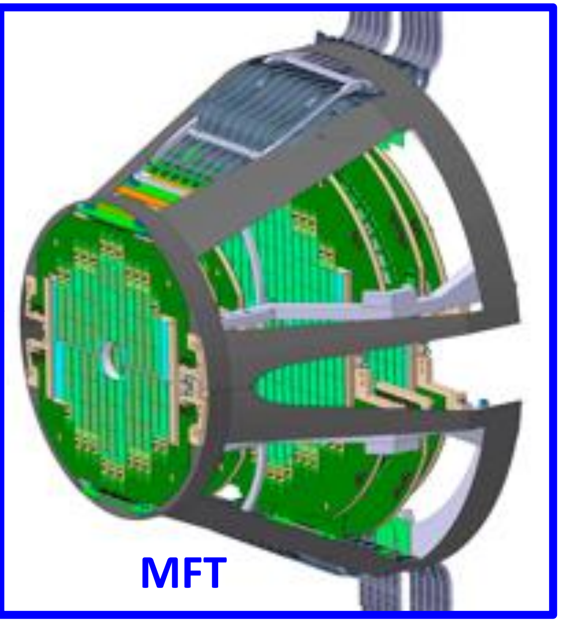


ITS3
Stitching, **LS3**





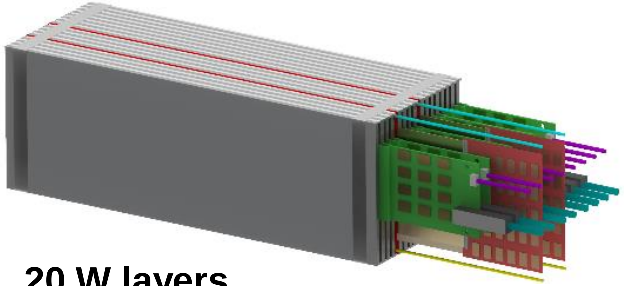
ITS2
ALPIDE, **LS2**



MFT

LS2
MFT discs

A full pixel layer with 3x15 ALPIDE chips



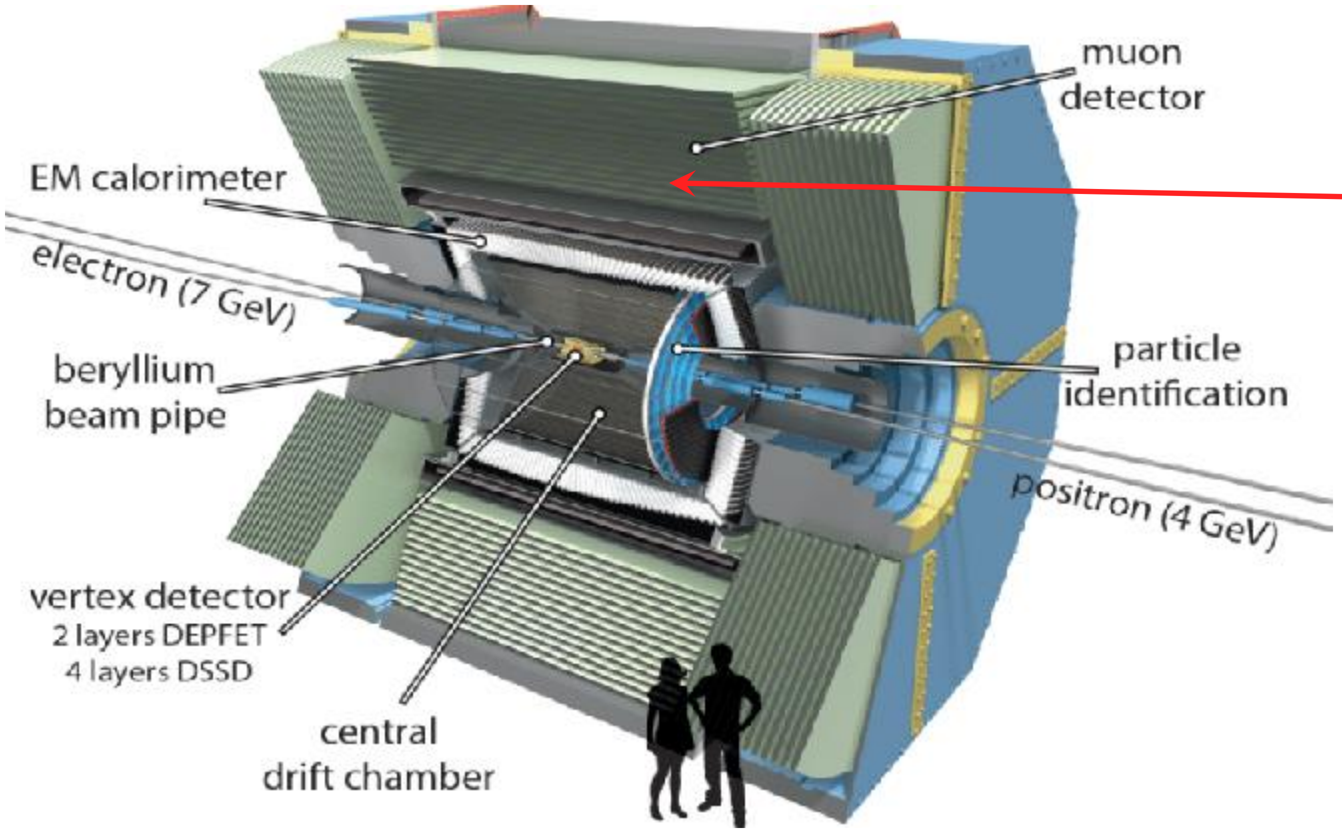
20 W layers
+ 18 pad sensors
+ 2 pixel layers

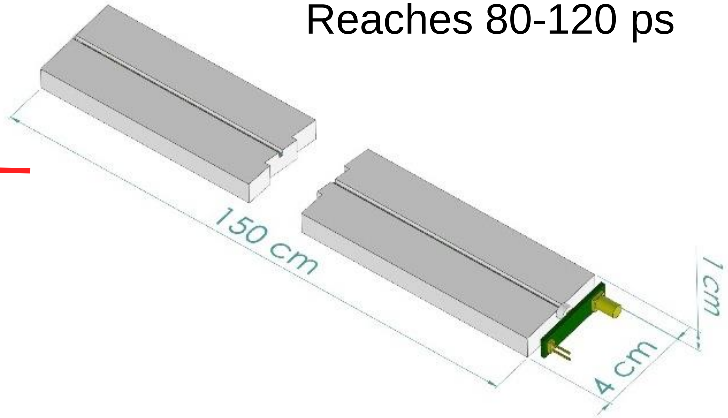
FoCal
LS3

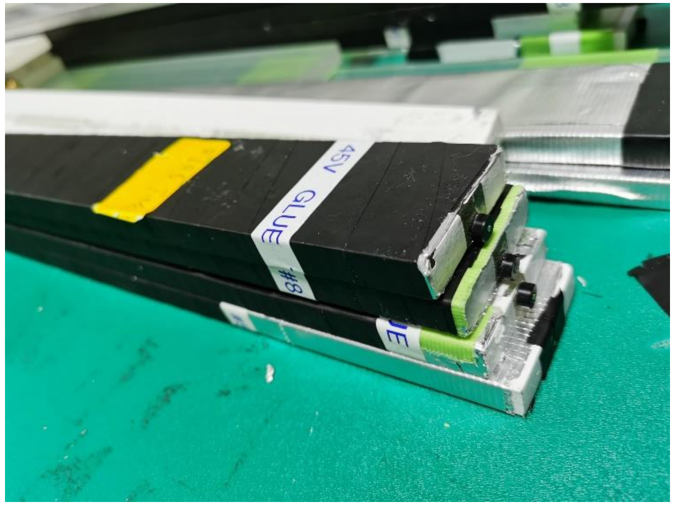
The Belle-II Upgrade

Upgrade in 2026: KLM

Scintillator + WLS fiber + SiPM
Reaches 80-120 ps



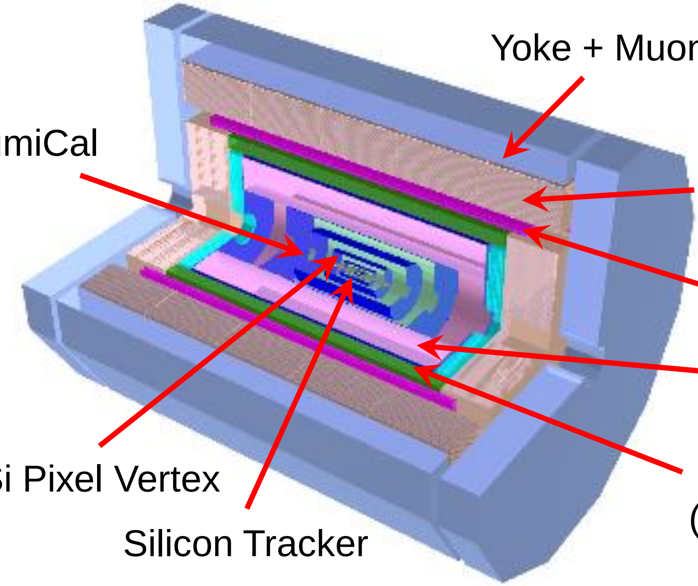


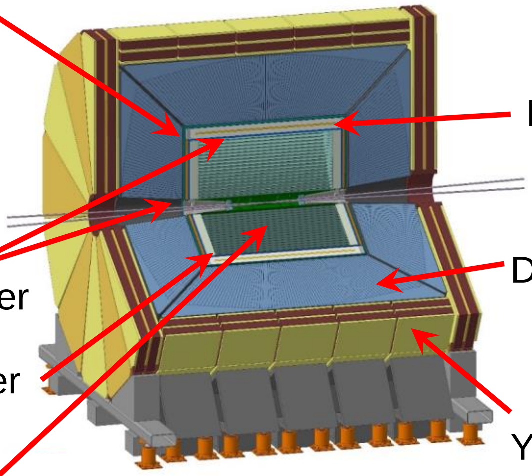


R&D Efforts for Future Higgs Factories

Det	Technology
Pixel Vertex	JadePix
	TaichuPix
	CPV(SOI)
	Stitching
	Arcadia
Tracker & PID	CEPCPix ←
	Silicon Strip
	TPC
	Drift chamber
	PID DC
	AC-LGAD ToF
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL
	Fast LumMoni
	CEPC SW

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
Misc	HTS / LTS Magnet
	MDI & Integration
	TDAQ scheme





A **CEPC Ref-TDR** in mid of 2025

CEPC Silicon Detectors

TaichuPix3-based Prototyping

Silicon Pixel Vertex

Goal:

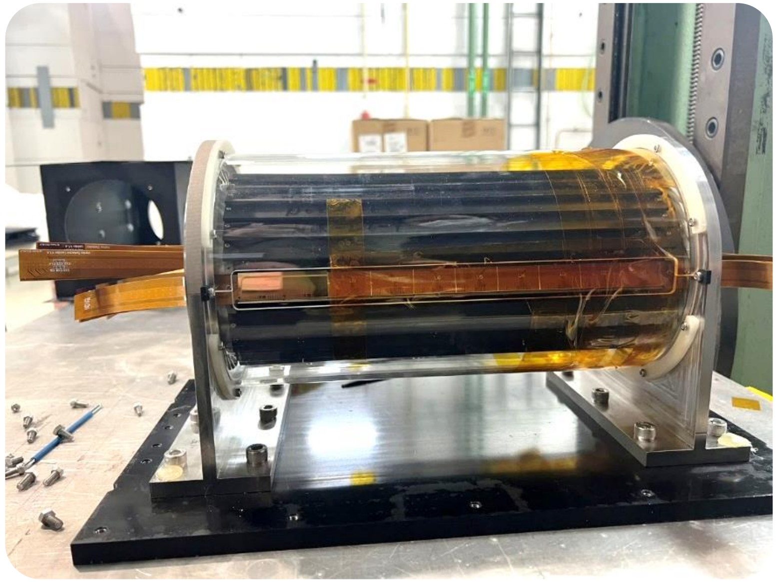
- σ(IP) ~ 5 μm for high P track.

Design specs:

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

Layout design:

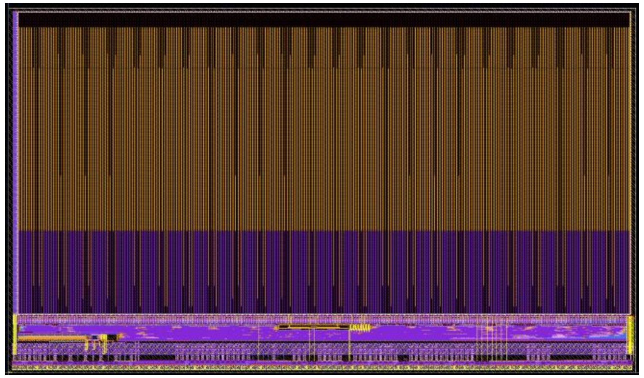
- 3 dual-layers, R_{in}~16mm



Silicon Pixel Tracker

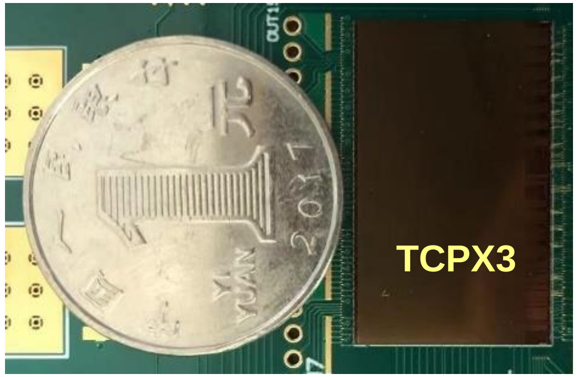
- ❑ Large area (70 or 140 m^2)
  ➔ Cost effectiveness
- ❑ Joint effort with KIT to explore SMIC 55 nm HV process
- ❑ May choose SPD inner tracker and SSD outer tracker

JadePix4 356×498 pixels, 20×29 μm^2

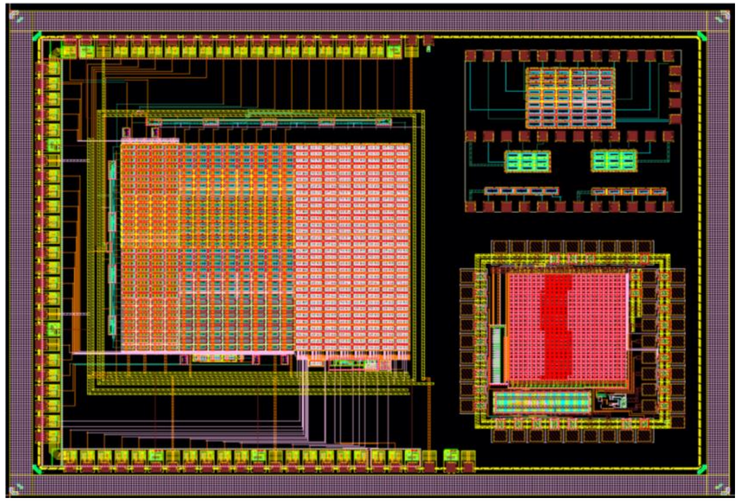


TowerJazz 180nm CIS process
$\sigma_{x/y}$ ~3-4 μm, σ_t ~1 μs, ~100 mW/cm^2

TaichuPix3 1024×512 pixels, 25×25 μm^2



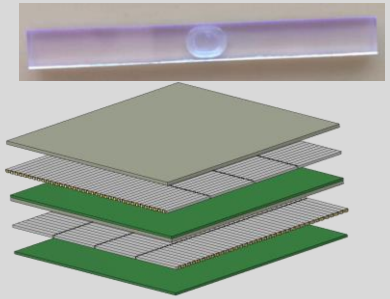
The 2nd design for **SMIC** 55nm HV HR process

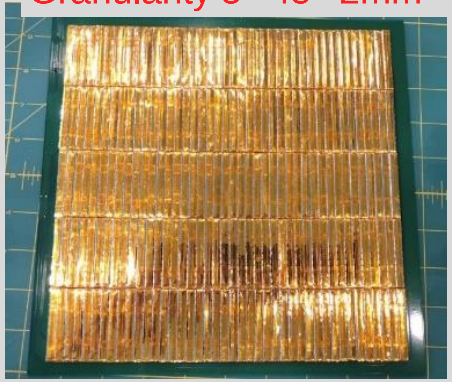


CEPC PFA Sampling Calorimeters

ECAL
Scin strip+SiPM, CuW

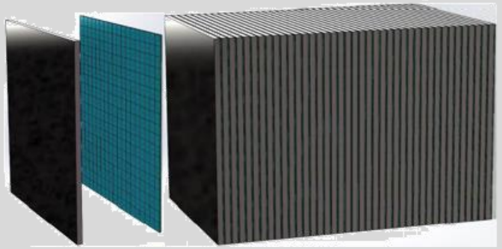
Granularity $5\times45\times2mm^3$

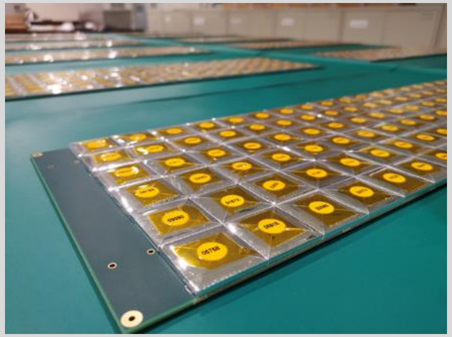




HCAL
Scint tile+SiPM, steel

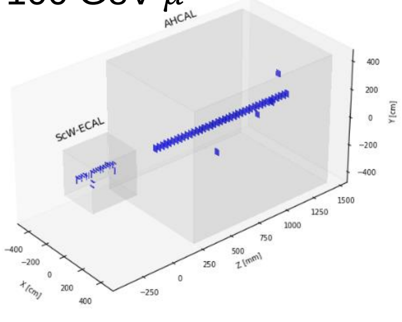
Granularity $40\times40\times2mm^3$



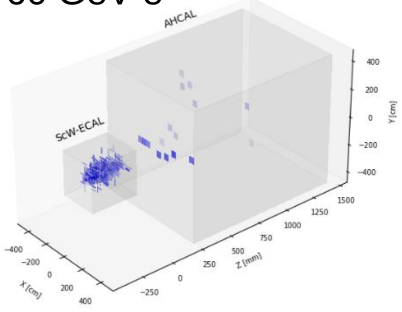


Prototypes developed within CALICE
Members from China, Japan, France & Israel

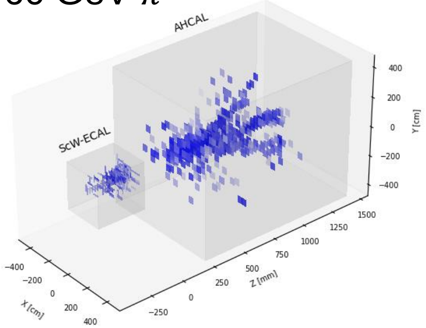
100 GeV μ^-



60 GeV e



60 GeV π^-

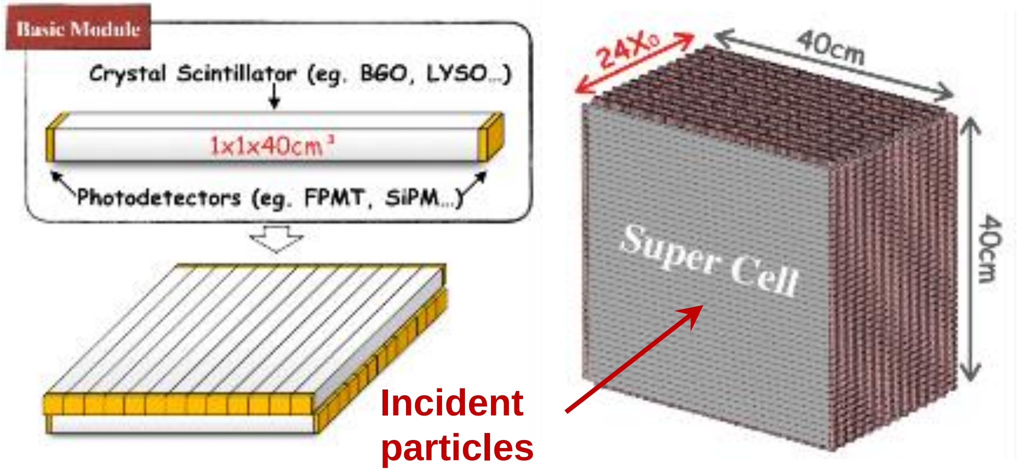


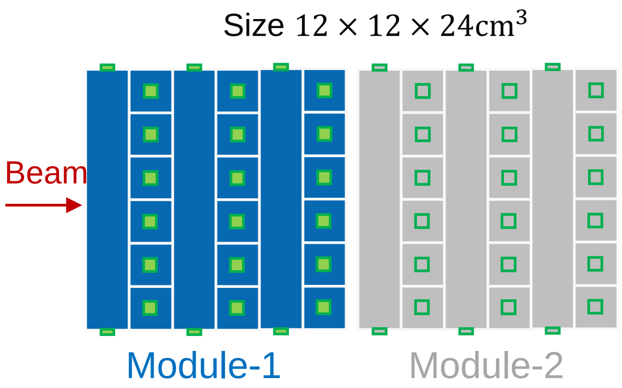
Validated in testbeams at CERN

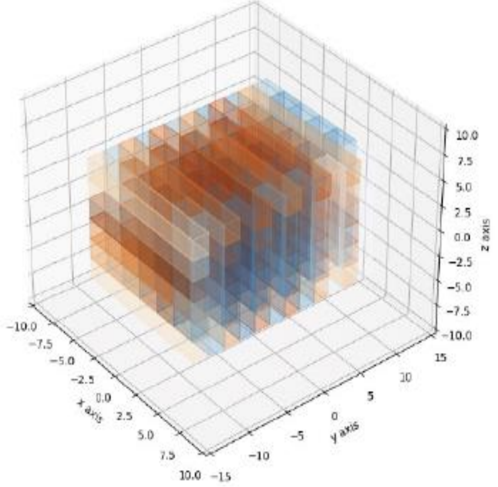
New Approaches in Calorimeters

PFA Crystal ECAL

Improve EM resolution by a factor of 5





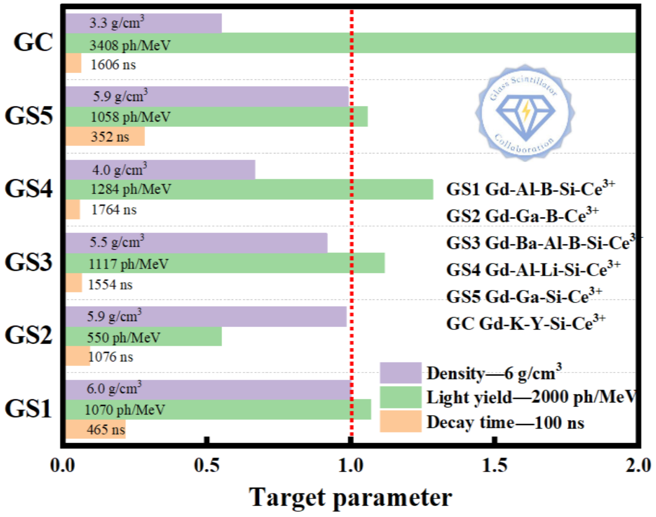


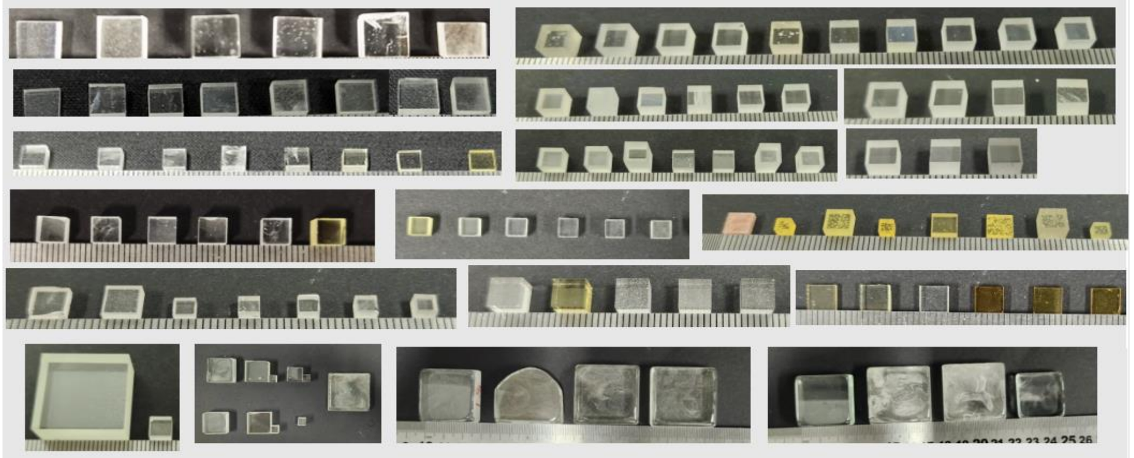
PFA Glass Scintillator HCAL

Replacing plastic scintillator with high density glass scintillator

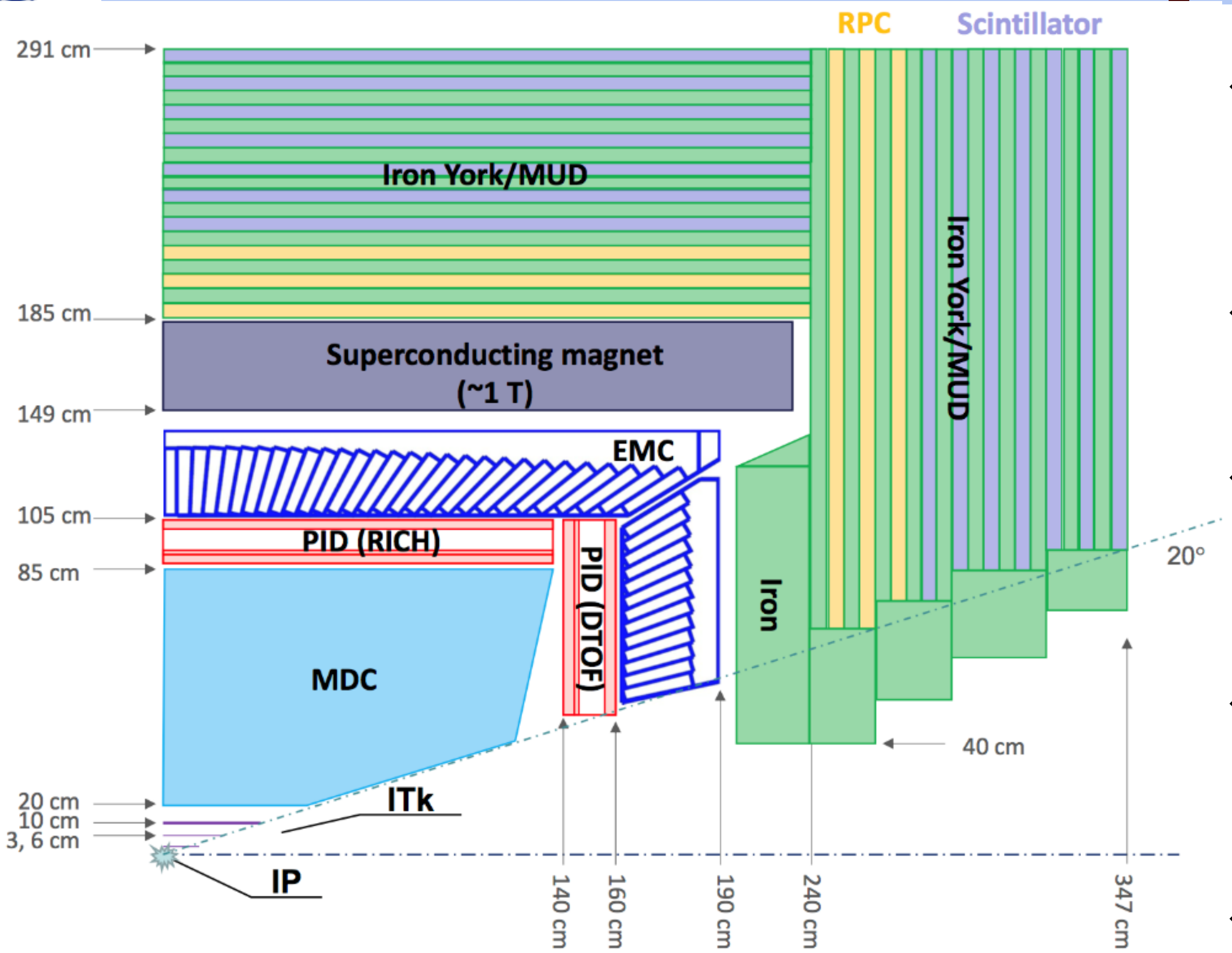
Specs of glass scintillator

- Light yield: 1000~2000 ph/MeV
- Density: 5~7 g/cm³
- Scintillation time: ~100 ns
- Low cost
- Tiles in cm scale





STCF Conceptual Detector



- Acceptance: 94%×4π
- σ_p/p ~ 0.5% @1GeV, σ_E/E ~ 2.5% @1GeV
- PID: π/K ~4σ @2GeV
- μ-ID: eff >98% & mis-ID <3% @1GeV

❖ Inner Tracker

- Gas option: cylindrical μ-RWELL
- Silicon option: low mass MAPS

❖ Central Tracker

- Small-cell drift chamber

❖ PID

- Barrel – RICH: MPGD-based photon detector
- Endcap – DIRC: super high time resolution

❖ EMC

- Pure CsI+APD: high rate, high energy resolution with timing capability

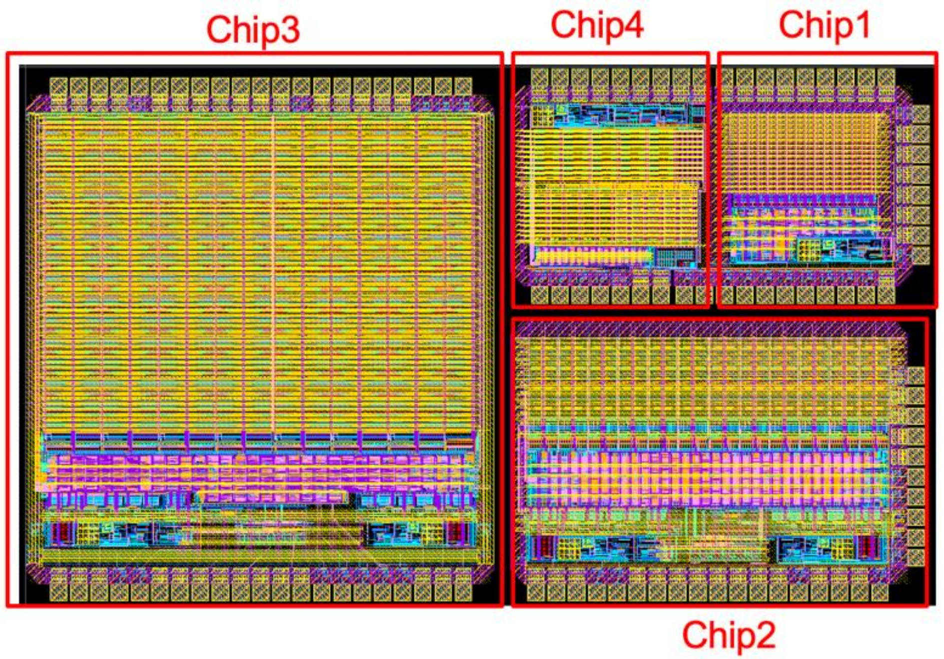
❖ MUD (hybrid design)

- Inner layers - High-rate RPC: insensitive to beam background
- Outer layers - Sci+SiPM: efficient for n and K_L

MAPS Inner Tracker

Challenges: spatial, timing & energy measurements with lower power consumption

Design based on TJ180nm technology



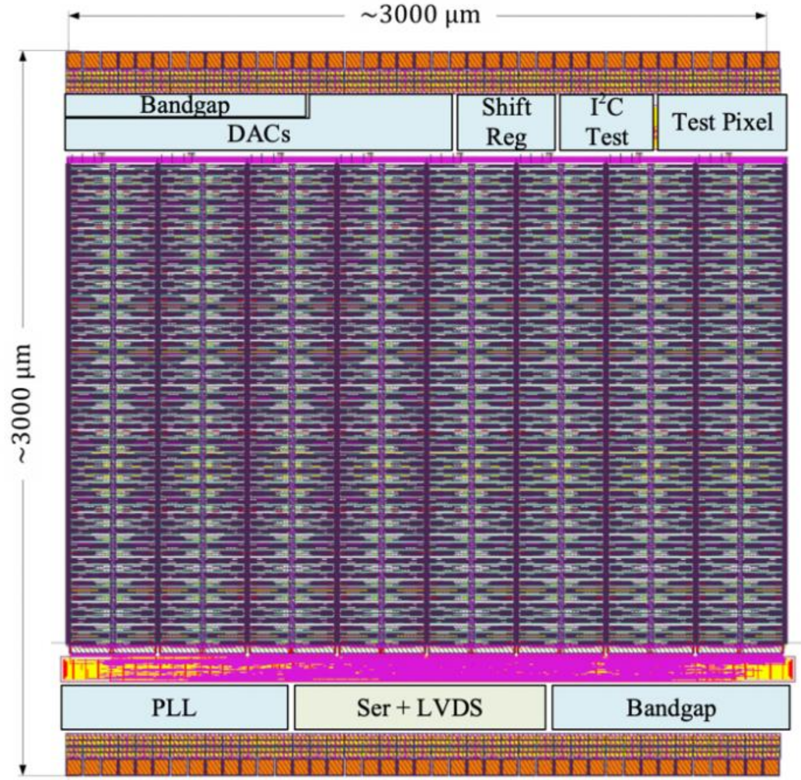
Chip 1: ALPIDE-like small pixel, digital readout

Chip 2: $60\mu m \times 90\mu m$ pixel size, TOA/TOT readout (pixel & strip-based)

Chip 3: $30\mu m \times 180\mu m$ pixel size, TOA/TOT readout (pixel & strip-based)

Chip 4: analog readout (all 5 different pixel matrix layouts)

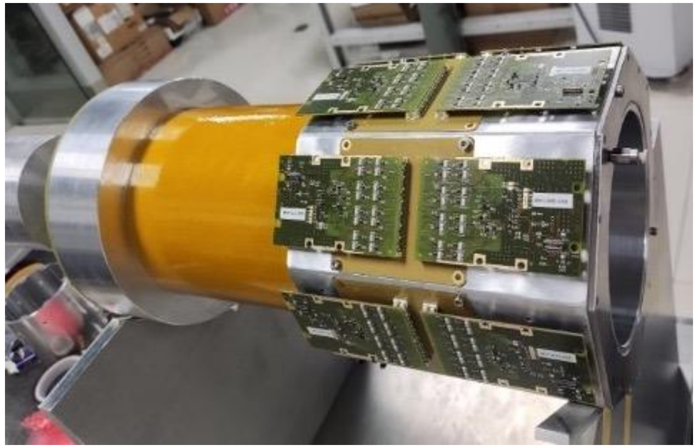
Domestic NexChip FCIS 90 nm technology



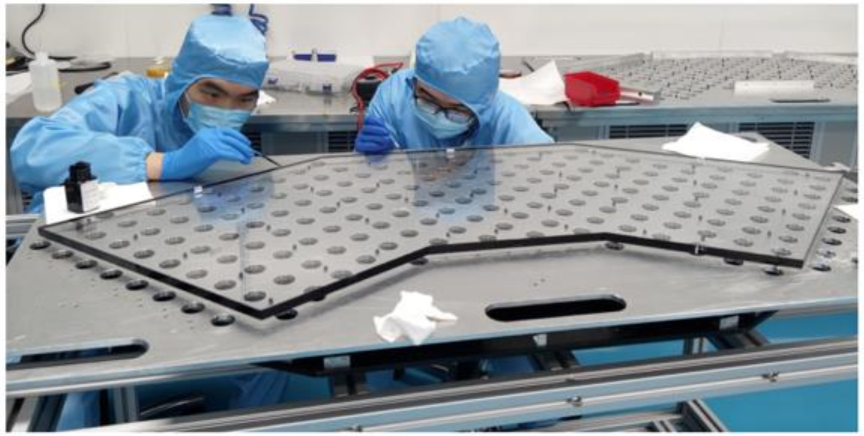
Both designs will be submitted in beginning of 2024

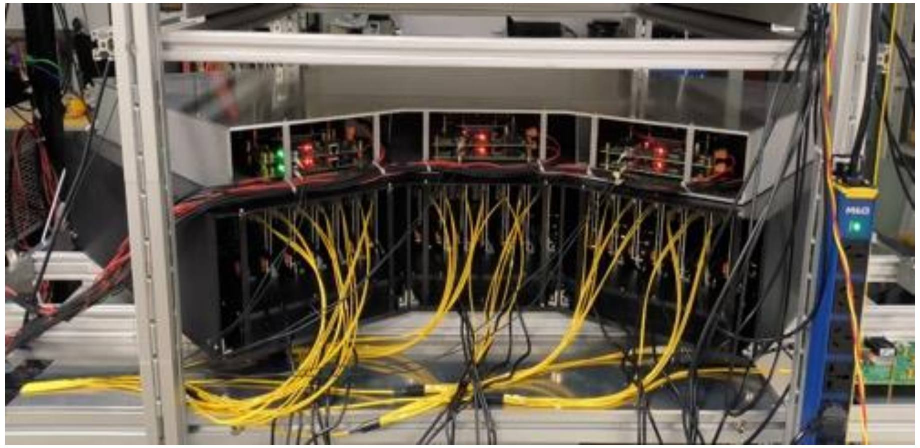
STCF R&D Highlights

Cylindrical MPGD engineering

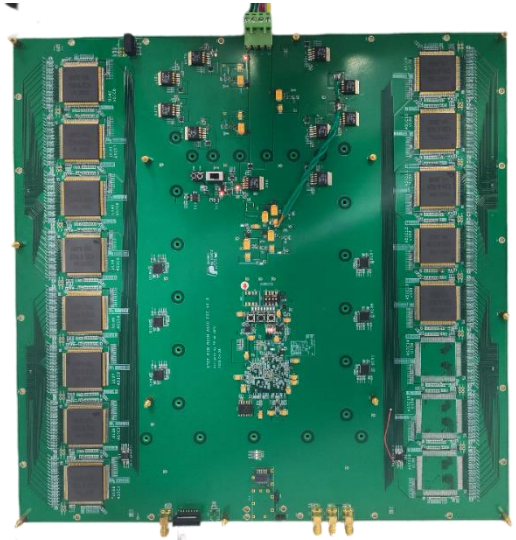


Large-size DIRC detector prototype with full readout



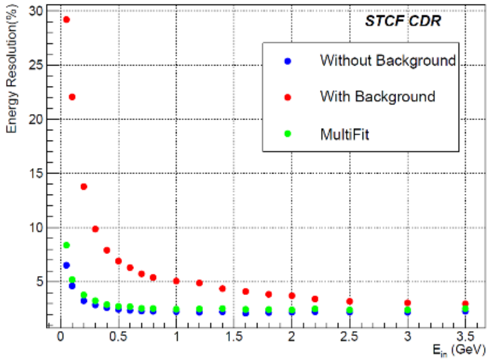


RICH readout ASIC development

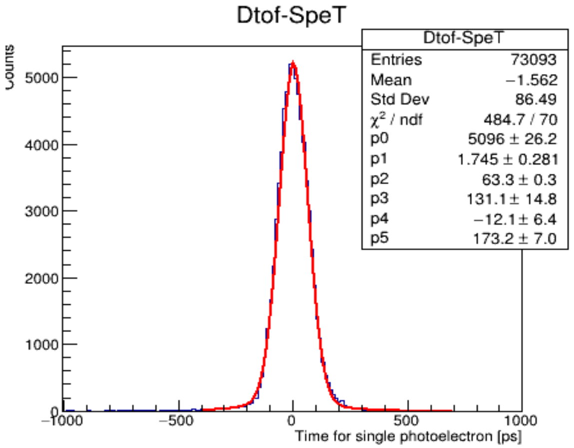


A novel approach to enhancing pCsI light yield (reaching 300 p.e./MeV)

Pile-up mitigation



DIRC time resolution ~20ps



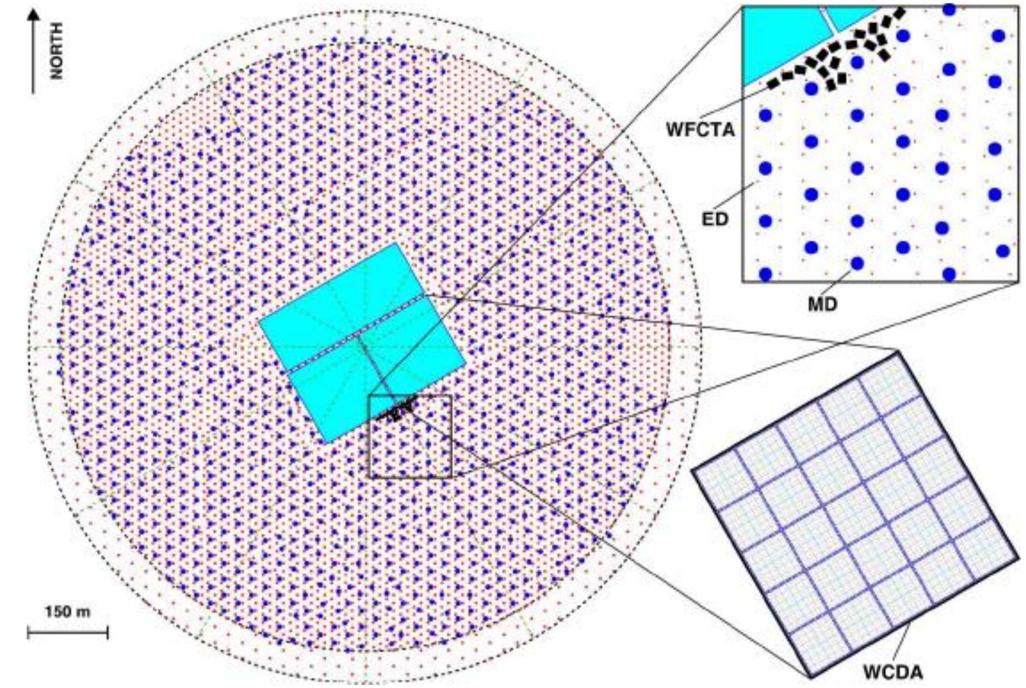
The LHAASO Upgrade

Large **H**igh **A**ltitude **A**ir **S**hower **O**bservatory

12 PeVatrons have been discovered !

KM2A (5216 EDs & 1188 MDs)
~1.3 km^2, 10 TeV – 10 PeV

WFCTA (18 WFCTs)
E: 10 TeV – 1 EeV



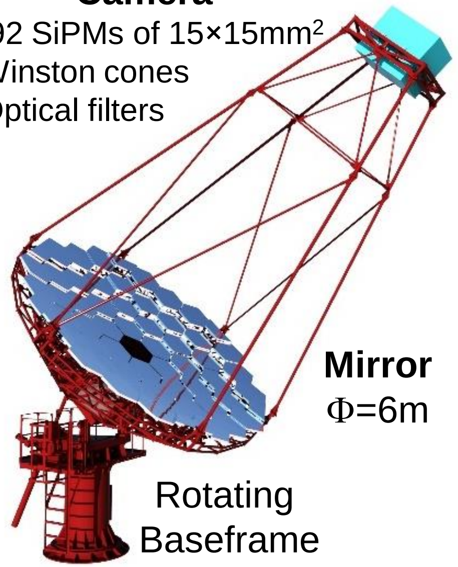
Altitude: 4410 m

WCDA (3120 WCDs)
78,000 m^2, 0.1 – 10 TeV

Large **A**rray of **C**herenkov **T**elescopes (LACT)

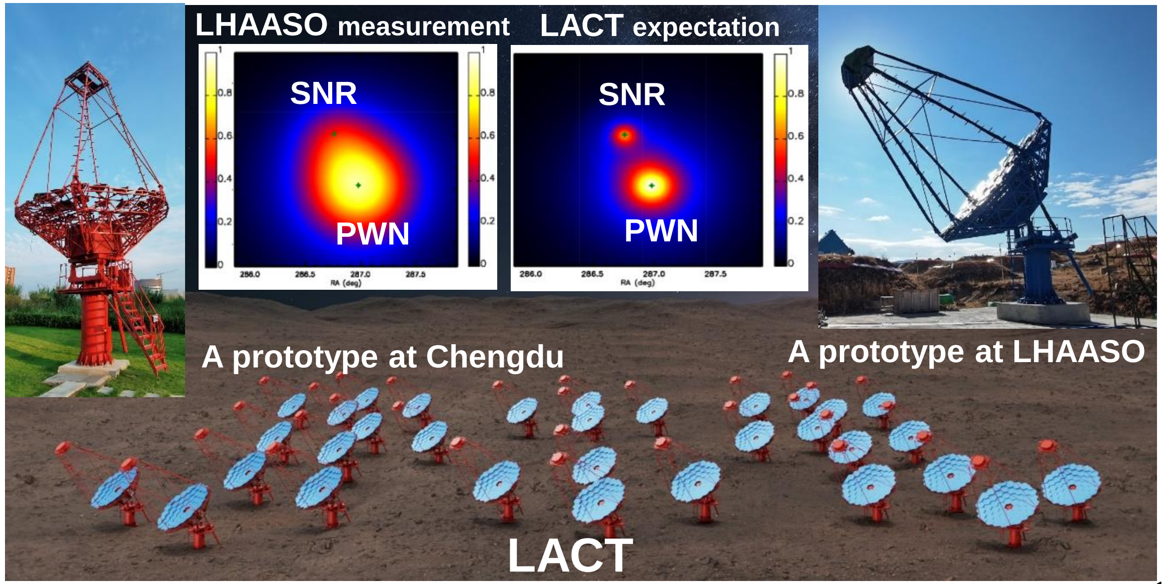
- Will add in total 32 telescopes. Two prototypes were built and will start operation in 2024
- Improve angular resolution ~0.3°@30 TeV ⇒ < 0.05°@>10 TeV
- Main scientific goal: morphology of PeVatrons and locating UHE γ-emitters

Camera
2192 SiPMs of 15×15mm^2
+ Winston cones
+ Optical filters



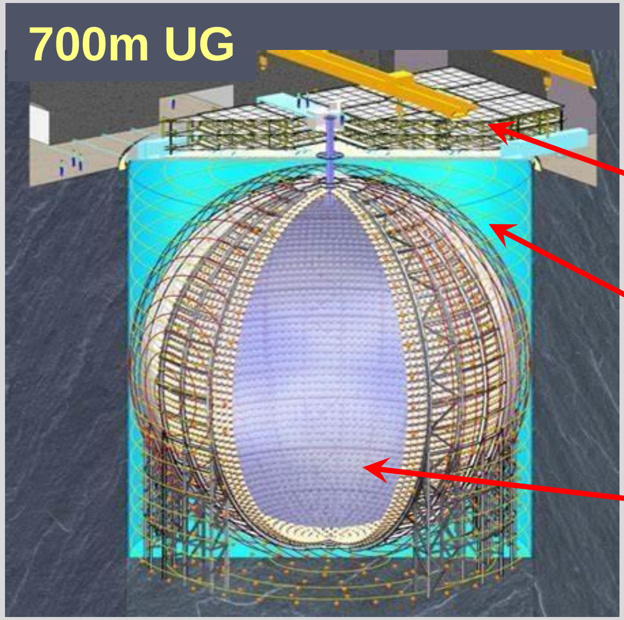
Mirror
Φ=6m

Rotating Baseframe



The JUNO & TAO Neutrino Experiments

JUNO & TAO Experiments

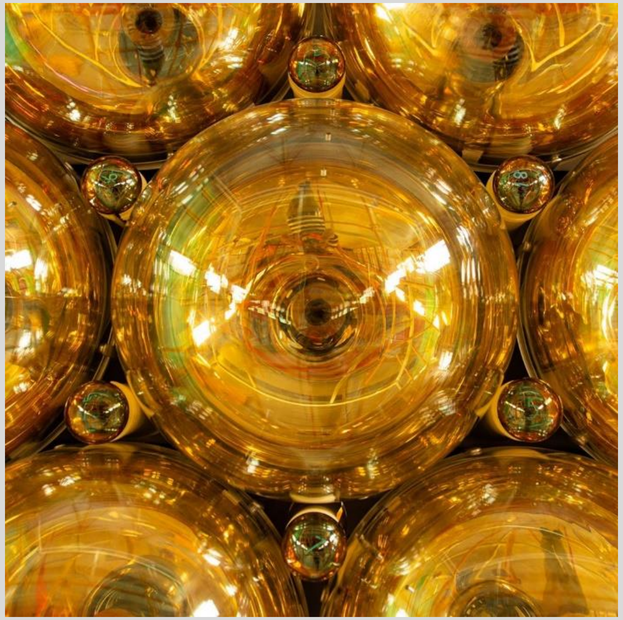


JUNO

Plastic Scintillator
Top Tracker

35 kton ultra pure water
Water Cherenkov Det

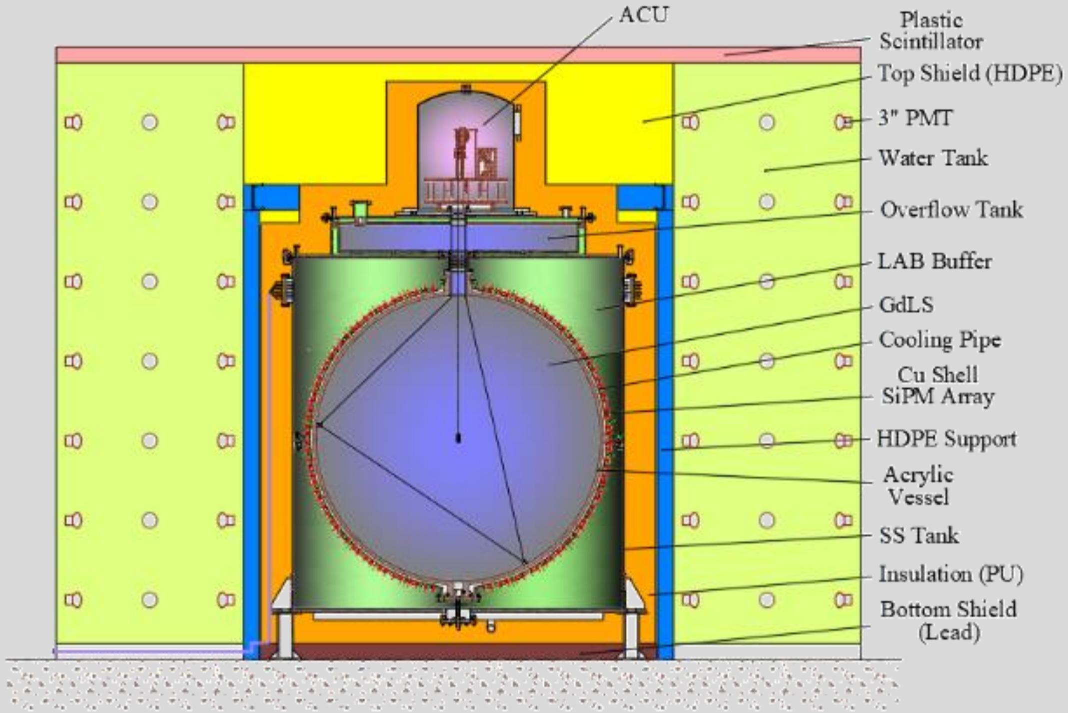
20 kton Liquid scint.
CD



20k 20” PMT
25k 3” PMT

expected to start operation by the end of 2024

TAO is a satellite experiment to JUNO, providing reference spectrum

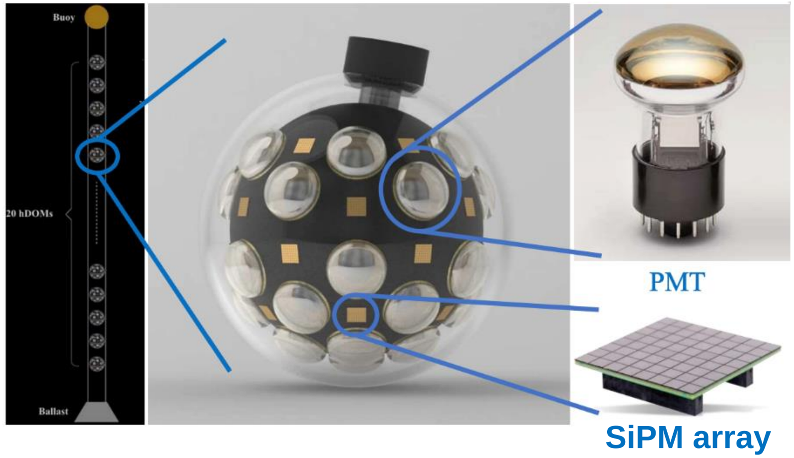


- Operated at -50 ℃,
- Low temperature 2.8 ton Gd-LS
- Full coverage of SiPMs (10 m^2) w/ PDE > 50%
- LY: ~4000 p.e./MeV, resolution: < 2% @1 MeV
- Under construction, online in 2024

The tRopIcal DEep-sea Neutrino Telescope (TRIDENT)

Next generation neutrino telescope at west Pacific ocean
Search for high energy astro-physical neutrino sources

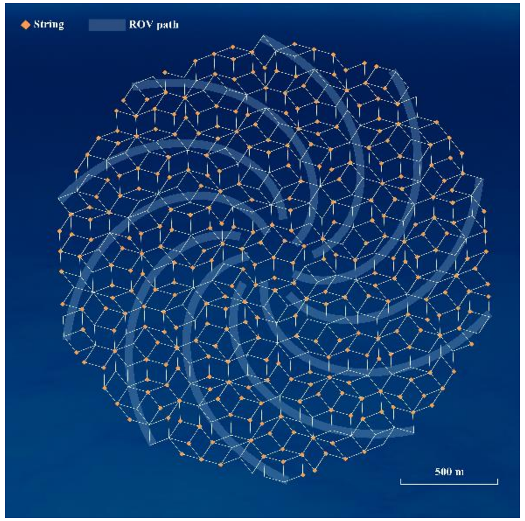
1200 strings, 20 hDOMs on each string, volume: ~ 8 km^3



Detector unit (**hDOM**) based on PMT+SiPM

Large light collection area + fast timing ~O(100) ps

Angular resolution: < 0.1^o @ E(ν_u)> 100 TeV



Penrose tiling:

Uneven inter-string spacing: 70m & 110m, expand energy window of sub TeV – EeV

10-string operation in **2026**

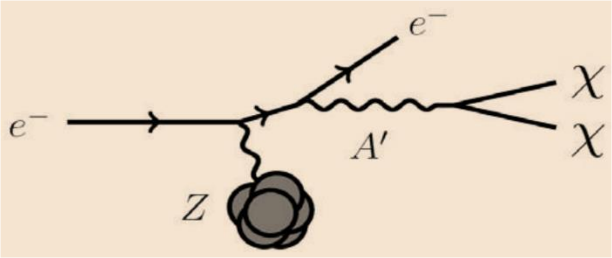
Full operation in ~2030

Electrical-optical network under sea (3500m) for power/data

Large data rate (~20Tb/s) → requires superior TDAQ system

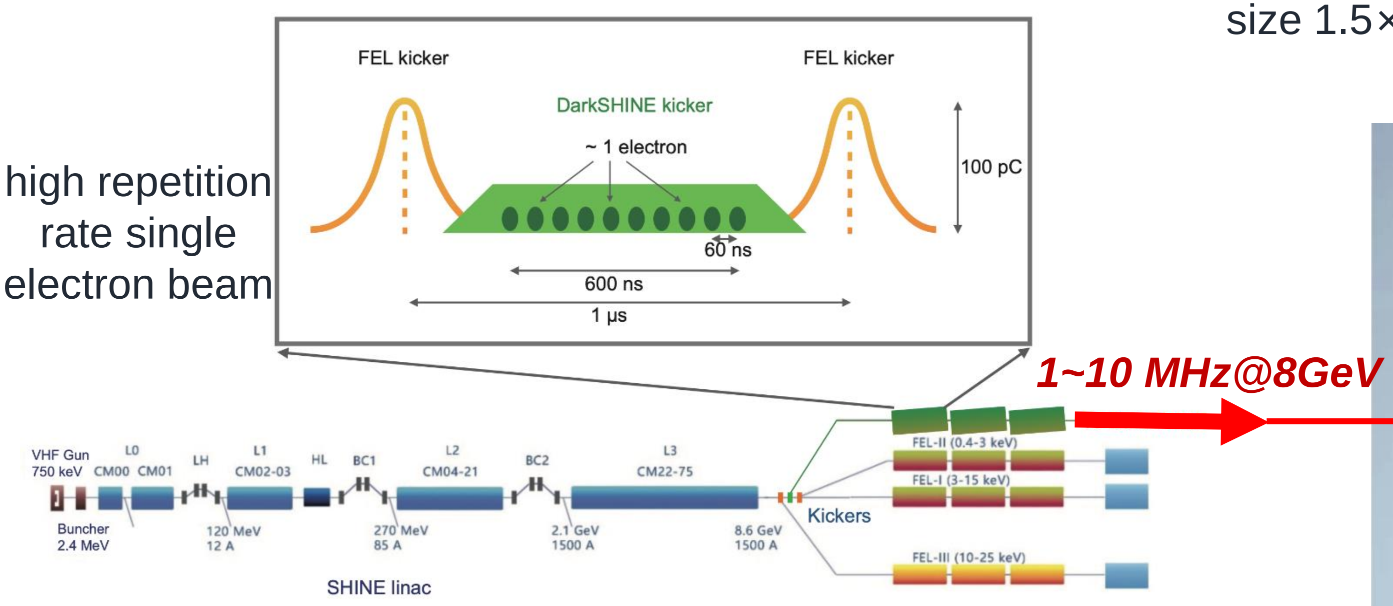
The DarkSHINE Experiment

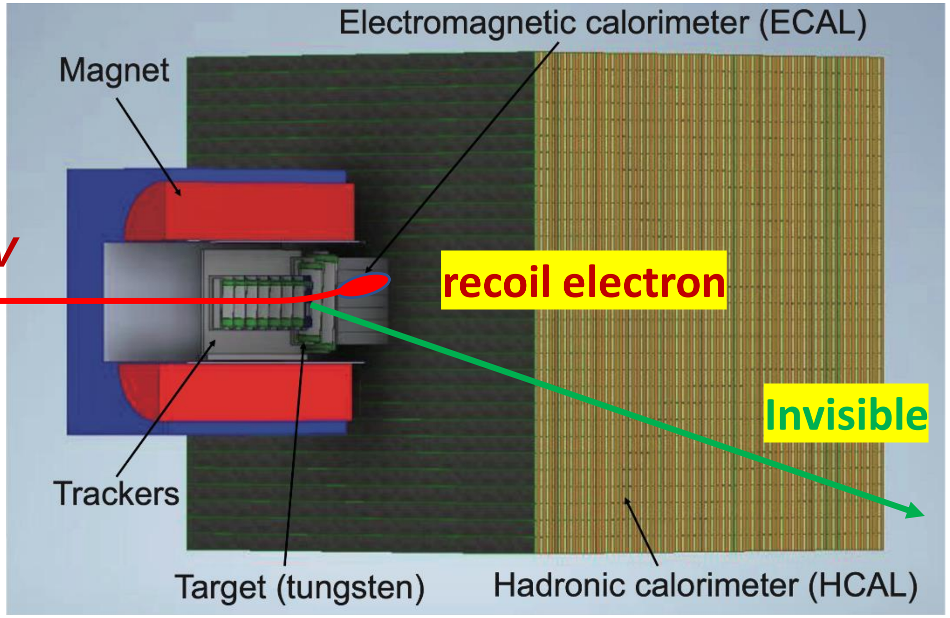
Hunting for 5th fundamental force: Dark Photon shining on the Dark Matter



- Tracker: Si strip detector, 7-layer tagging modules, and 6-layer recoil modules
- ECAL to measure Energy of recoil: LYSO+SiPM, crystal size 2.5×2.5×4 cm^3, total 20×20×11 crystals
- HCAL to reject n/μ backgroud: Fe+PS+WLS+SiPM, size 1.5×1.5×2.5 m^3, ~11λ

high repetition rate single electron beam

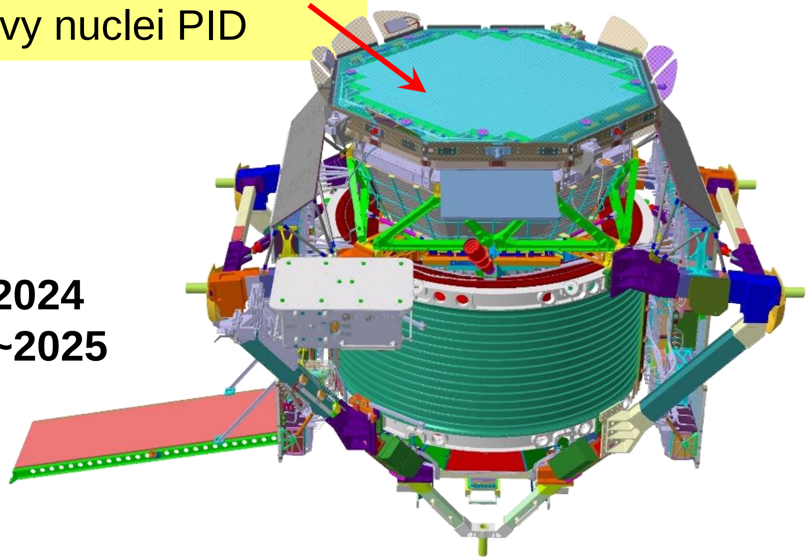


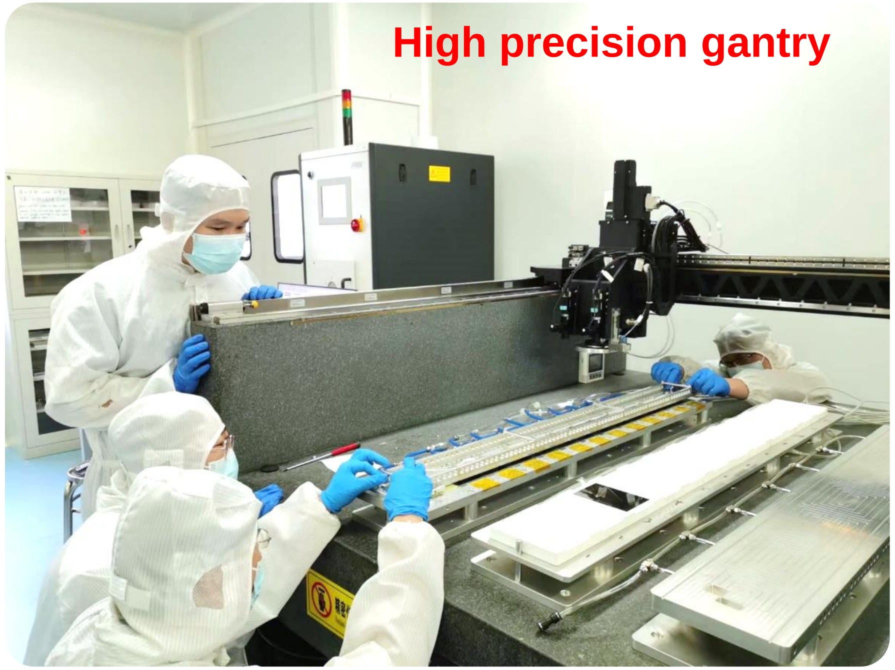


AMS L0 Tracker Upgrade

2x4 m^2 silicon strip detector
Increase x3 acceptance
Heavy nuclei PID

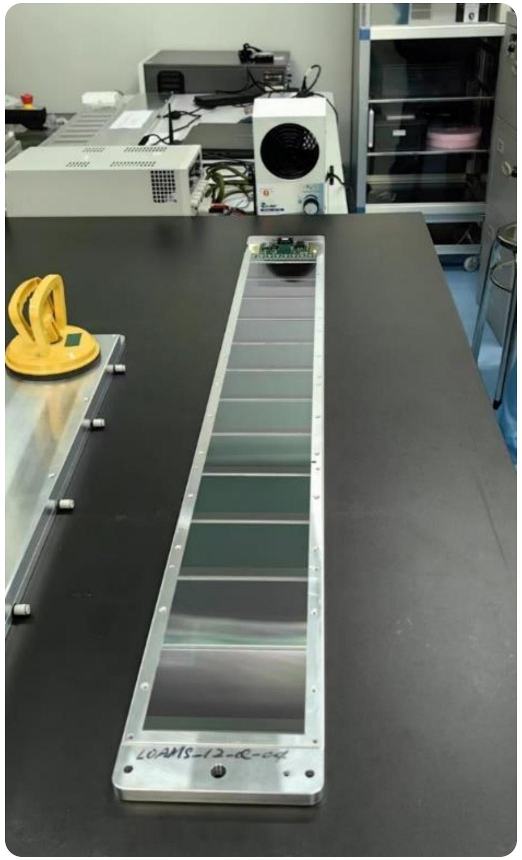
Ready in 2024
Launch in ~2025



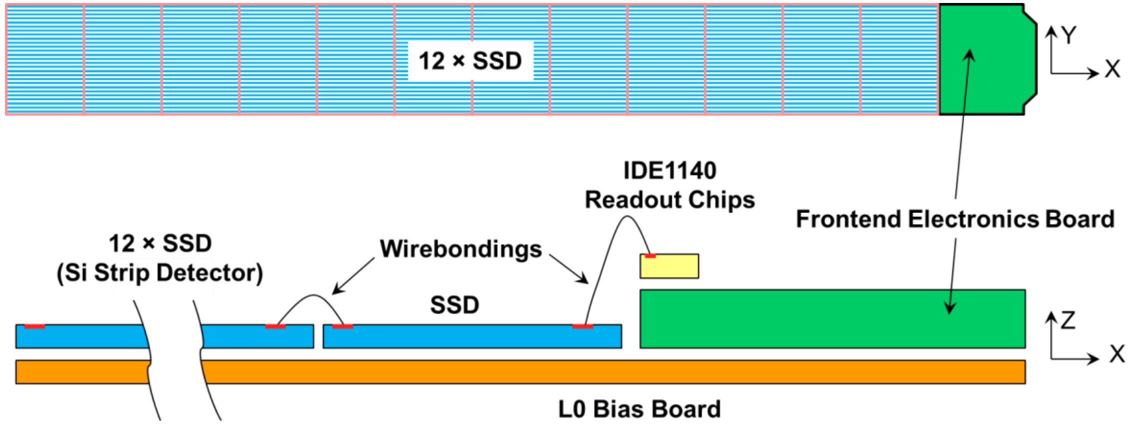


Prototype detectors

Achieved 4.1 μm precision from placement of SSDs



The longest SSD single unit ~ 1 m



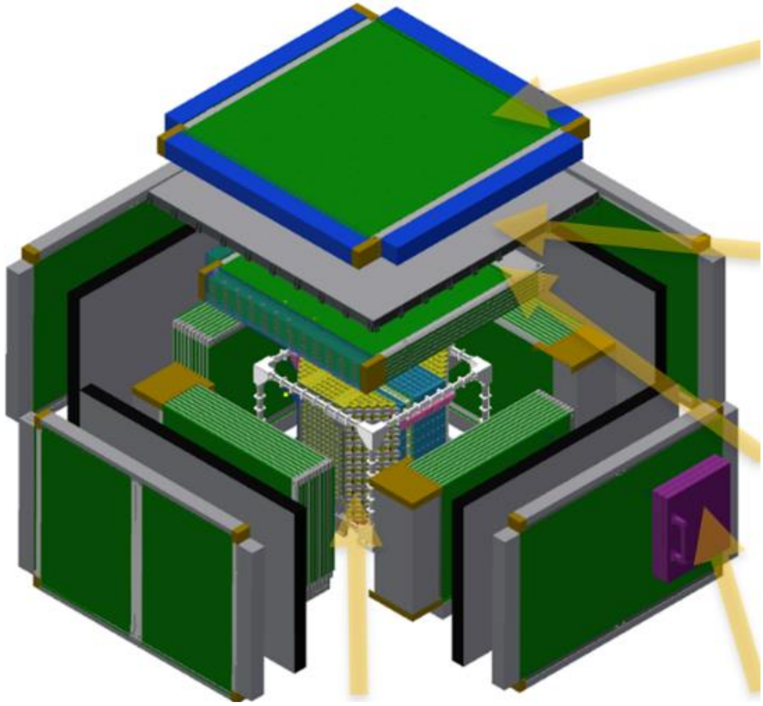
Challenges

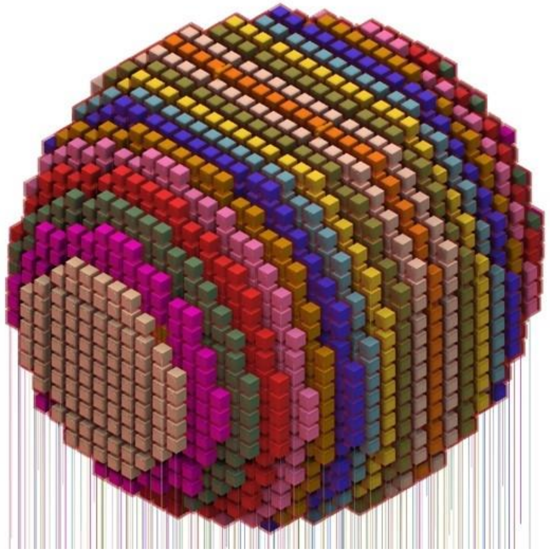
- Coupling and noise level due to long strips impose big challenges.
- Precise placement of SSDs on a ladder. Aim for a < 5 μm precision.
- Highly reliable wire-bonding (>12K wires per ladder).

High Energy Cosmic Radiation Detection (HERD)

Mount on the Chinese Space Station ~ 2027

To detect dark matter particle, study cosmic ray composition, and observe high energy gamma-ray

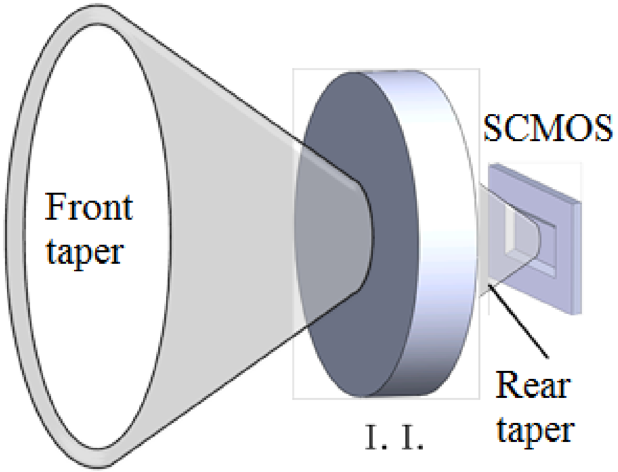




- LYSO CALO
- 7500 cubes of $(3cm)^3$
- 3D Imaging
- 5-face sensitive
- Large acceptance

- $4m^2Sr$

Fiber + Camara Read Out

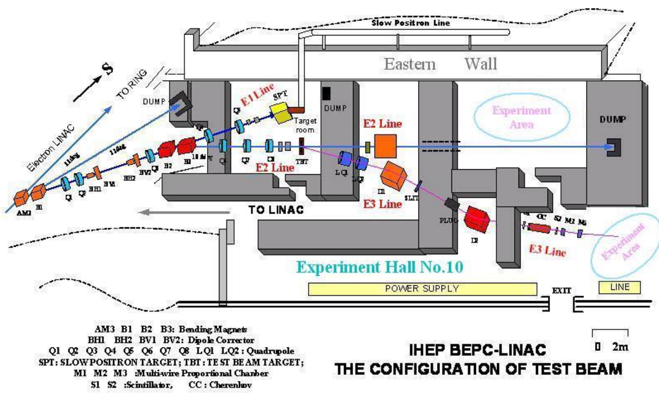


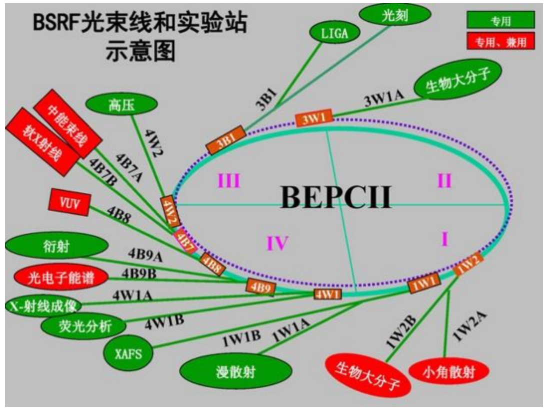
International Collaborative Efforts

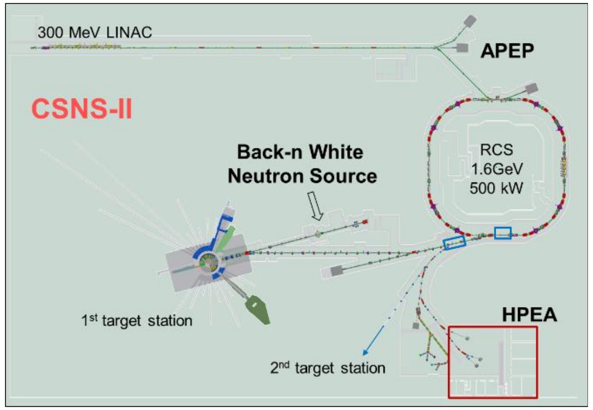
- Many R&D's are for major international experiments. A significant portion of others are also associated with interational detector R&D collaborations: CALICE, LCTPC & RD*
- From an incomplete survey, about 30 proposals from Chinese institutes were submitted to ECFA DRD.
- As a community, it is very important that we work together, share responsibilities, ideas and resources

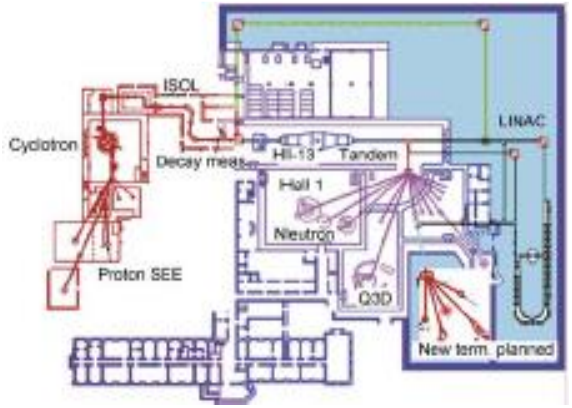
DRD Themes	Proposals	Institutes	People
1 Gaseous detectors	7	IHEP, USTC, SJTU, JLU, SIAT, THU, WHU	46
2 Liquid detectors	2	IHEP	7
3 Solid state detectors	4	SCNU, SDU, SJTU, THU	10
4 PID and photo detectors	3	IHEP, Henan NU, SDU	11
5 Quantum & emerging tech	2	SDU, THU	7
6 Calorimetry	6	IHEP, SDU, SCNU, PKU	37
7 Electronics	3	IHEP, SDU, SJTU	5
8 Integration	3	IHEP	8
Total	**30**	**11 institutes**	**131**

Selected Testbeam Facilities in China

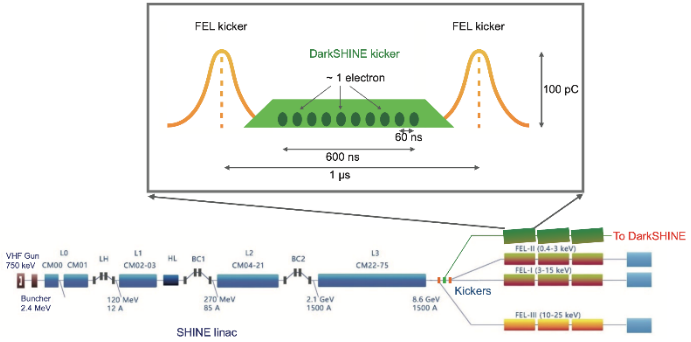








Facility	Particle		Intensity	Comments
BTBF, IHEP	e	0.3-1.1 GeV	~ few Hz	Closed for other studies
BSRF, IHEP	e	1-2 GeV	~ kHz	Energy and direction are not well controlled
APEP, CSNS	p	< 80 MeV	$10^7 – 10^{10}$ /s	Max ~ 300 MeV by 2028
HPEA, CSNS	p, π	0.8-1.6 GeV	10 kHz – 2 MHz	Available ~ **2028**
BRIF, CIAE	p	100 MeV	$10^7 – 10^{10}$ /s	
HI13, CIAE	Ions	11 MV	~ 2 kHz	Li - Au
SHINE	e	8 GeV	kHZ - MHz	Available ~ **2026**



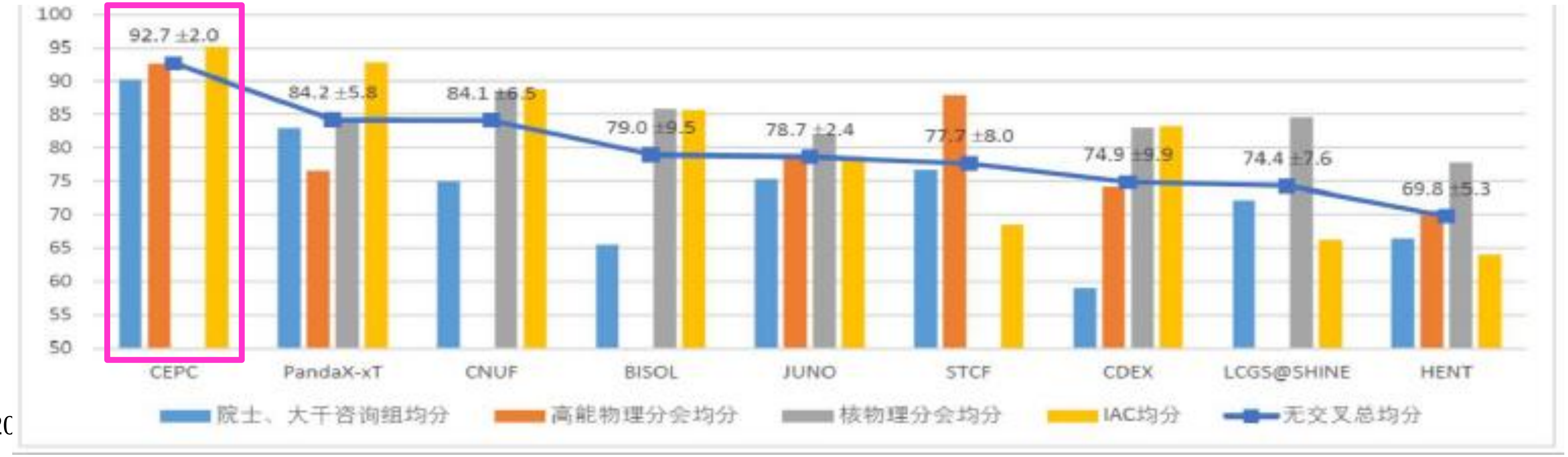
Support of R&D Projects

- Potential funding sources: MOST, NSFC, CAS or the equivalents, local governments, institutes or universities, companies, ….
- Generally, MOST eyes more on the results, whereas NSFC more on the research itself. Thus a blue-sky R&D would have a better chance with a NSFC support. The national labs typically have their own "tolerance" on risky projects, to cultivate great ideas.
- At the beginning of a funding cycle, e.g. the national 5-year plan, the funding agency releases the "Project Application Guidelines". These guidelines were drafted by a committee of experts in the domain, with many inputs and feedbacks from the community.
- The proposal application and approval procedures are similar. The guideline & corresponding proposals typically have quantized specification that could be evaluated properly.
- For a project of a reasonable size, a scientific committee is required to review the project yearly and provide feedback, sometimes can be extremely helpful.
- Besides of annual reports, there are also mid-term review and final review, to ensure that the research follows the requirements properly.

Disclaim: These are just my humble personal view. I am in a learning curve, and the system evolutes continuously.

Strategic Supports

- The funding agencies choose carefully the “flagship” projects. Special “pilot project” funding may be awarded to those of big potential. For example, CEPC has received such supports from CAS.
- CAS is planning for the 15th 5-year plan for large science projects. A steering committee has been established, chaired by the president of CAS.
- High energy physics and nuclear physics, as one of the 8 groups, worked for a year.
  - Set up rules and the standards, established domestic and international advisory committees
  - Collected 15 proposals and selected 9, based on the standard (scientific and technological merits, strategic value and feasibility, R&D status, team and capabilities, etc.)
  - Evaluations and ranking by committees after oral presentations by each project
- CEPC is ranked No. 1, with the smallest uncertainties, by every committee
- A final report has been submitted to CAS for consideration Longer-term mechanisms to support strategic R&D towards future facilities and experiments



Summary

- The detector R&D activities in China started late and slow than in many other places, especially Europe, US, & Japan, also not as well-organized. But the situation improves
- In recent year, the share of detector contributions to major international experiments increases significantly. Participation in collaborative detector R&Ds also grows rapidly.
- These provide more opportunities to the rising detector physicists, and also help more experiments, including the home-grown ones.
- There are facilities in China that are helpful to detector R&D. We are happy to share them with the international collaborators, especially those supplementary in functionalities or availabilities.

Thank you !

Thanks to the colleagues for useful discussions and materials, especially:

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Xiaolong Wang, Liangjian Wen, Zhongbao Yin, Shoushan Zhang, …