ALICE upgrade

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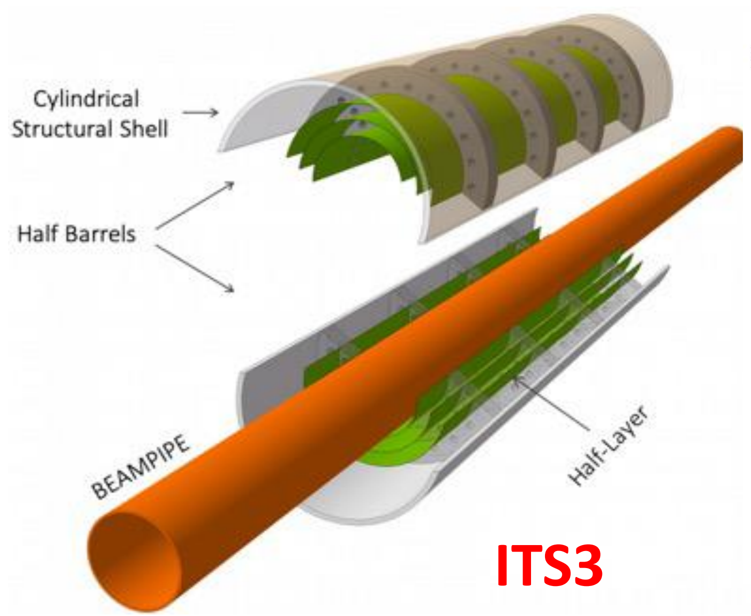
(for the ALICE China Team)

Central China Normal University

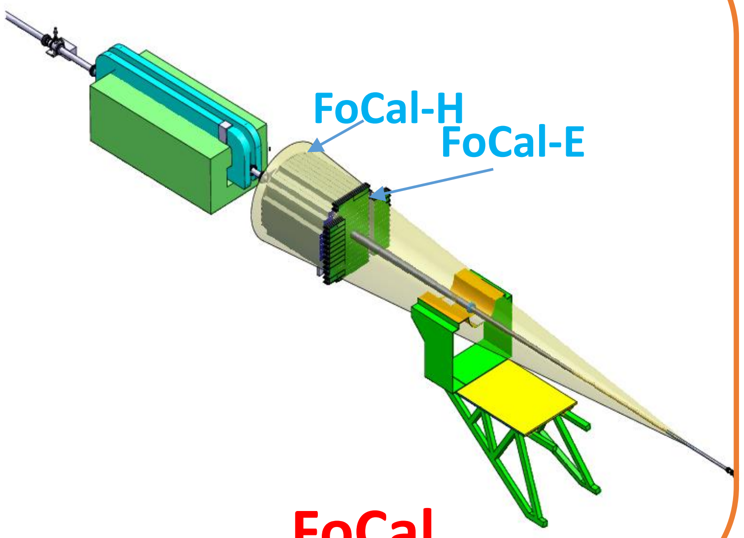
The 10th China LHC Physics Workshop, Nov. 14-17, 2024, Qingdao

ALICE upgrade programs

LS3 upgrades

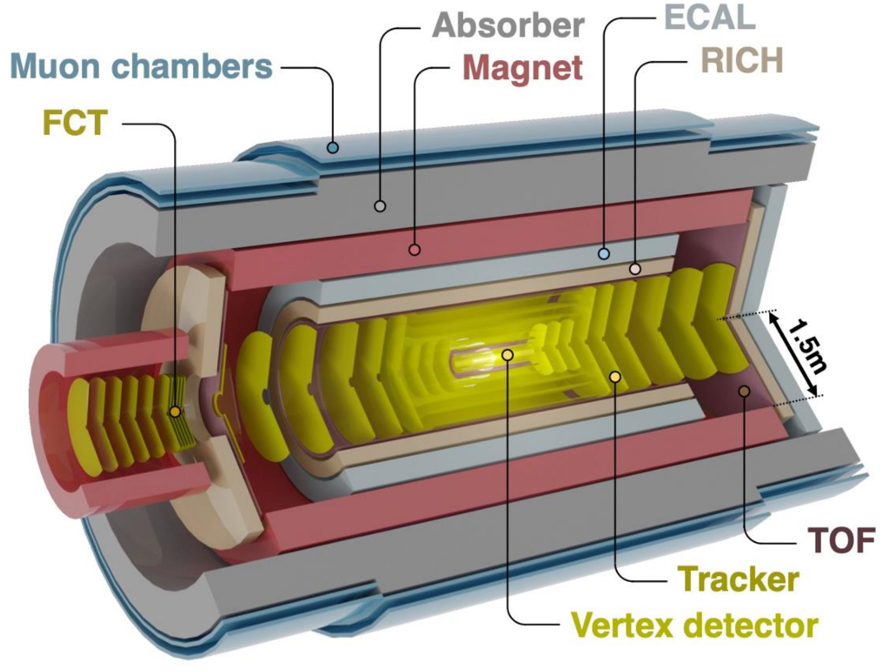


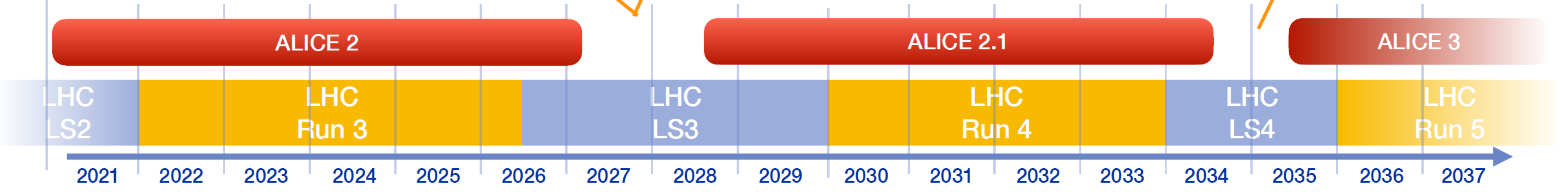
ITS3



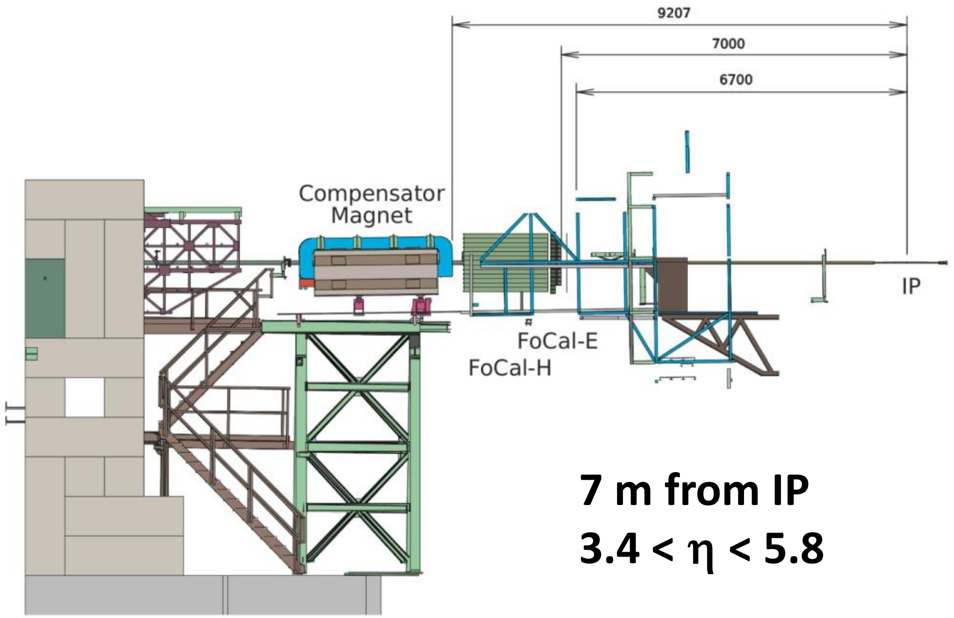
FoCal

LS4: ALICE3

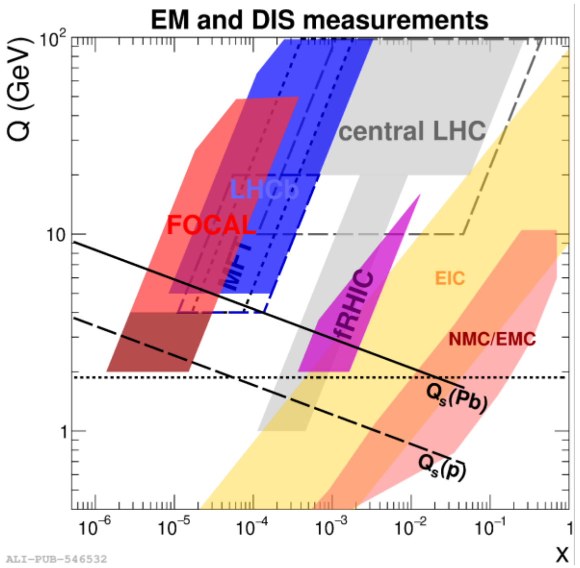


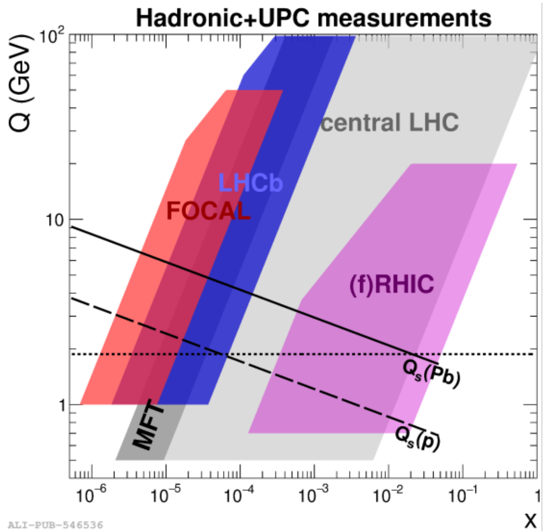


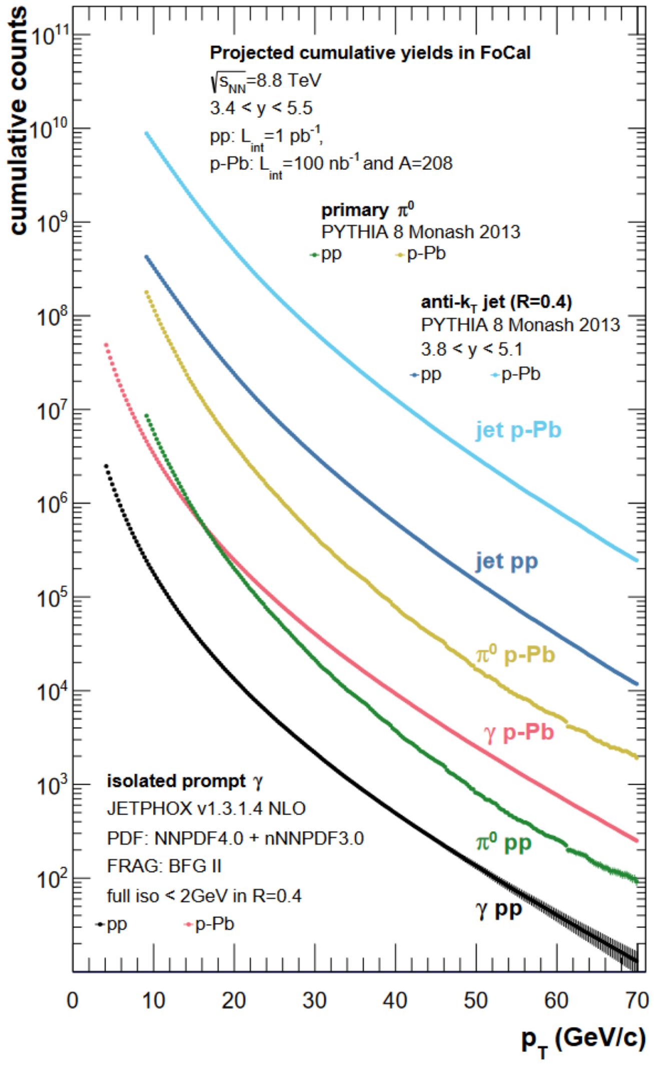
FoCal – Forward Calorimeter



7 m from IP
3.4 < η < 5.8





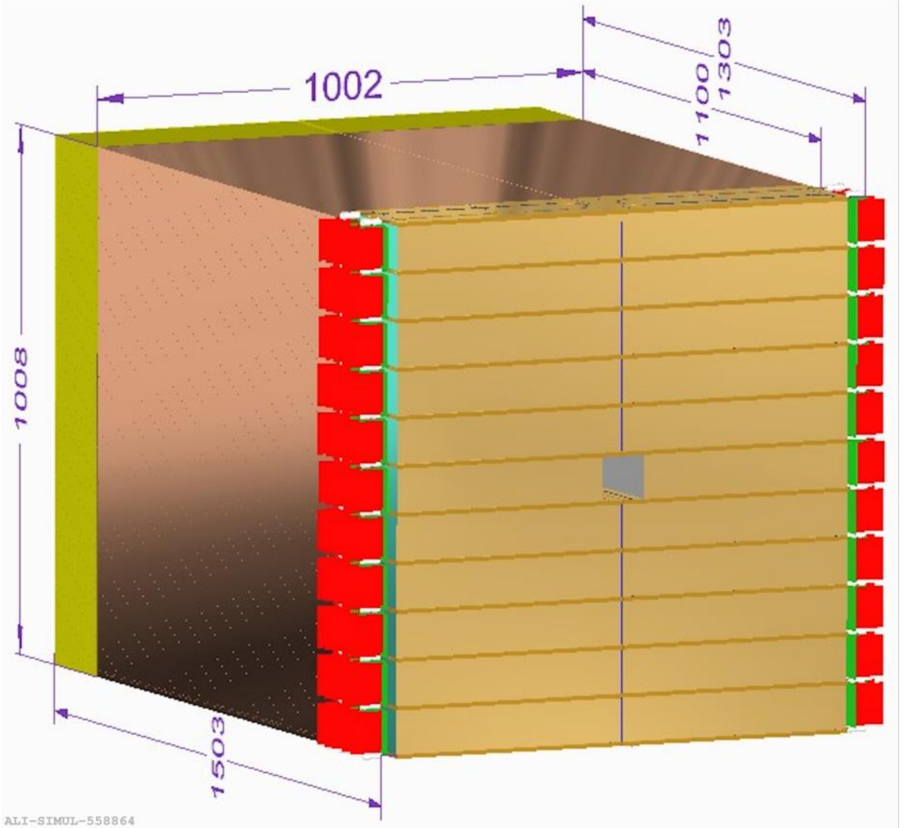


ALICE-PUBLIC-2023-001

Main goal:

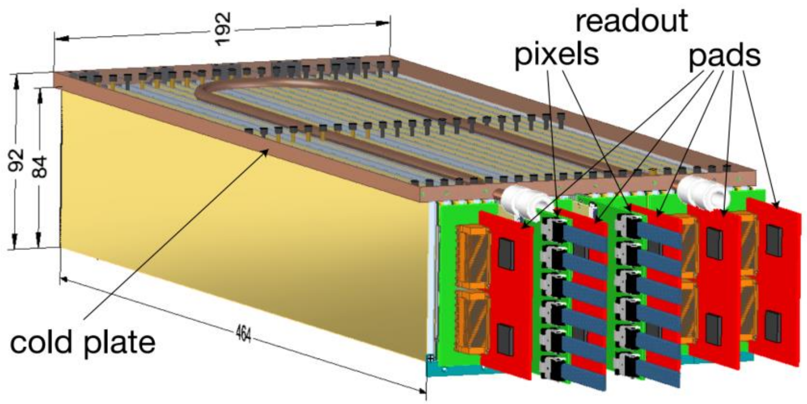
- measurement of **direct photon production at forward rapidity in pp and pPb** to probe gluon density at small x
- constrain gluon nuclear PDF at **small Bjorken-x ($x<10^{-4}$)**: structure of protons and nuclei not well constrained experimentally

FoCal detector



FoCal-E

Si-W calorimeter with effective granularity ≈ 1mm²



FoCal-E module

- **20 layers: W(3.5 mm ≈ 1X_0) + silicon sensors**
- **Two types: Pads (LG 1x1 cm²) and Pixels (HG, 27x29 μm²)**
  - **Pad layers provide shower profile**
  - **Pixel layers provide position resolution to resolve shower overlaps**
- **22 FoCal-E modules stacked vertically to form FoCal-E**

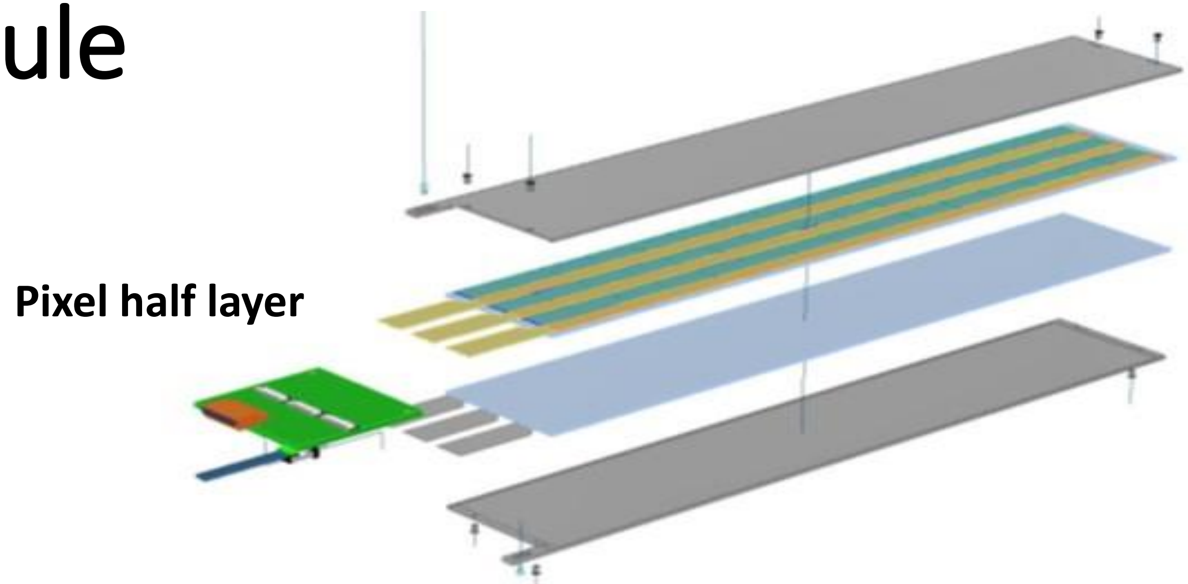
FoCal-H

Hadronic spaghetti calorimeter

- **Copper capillary tubes, length 110 cm ~ 7λ_I**
- **1 mm scintillating fibers inside 2.5 mm Cu tubes**
- **Bundle fibers readout with SiPM**

FoCal–H prototype, 9 x (6.5 x 6.5 x 110 cm³)

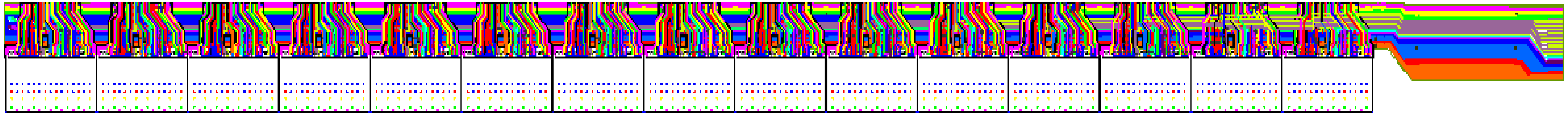
FoCal-E Pixel Layer Module



Structure of Pixel layer Module

Sketch

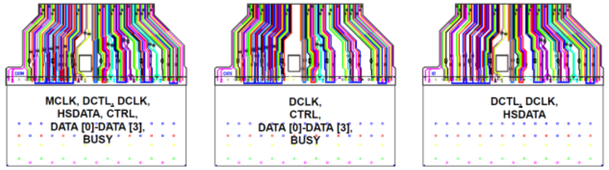
Total length of string ~50cm

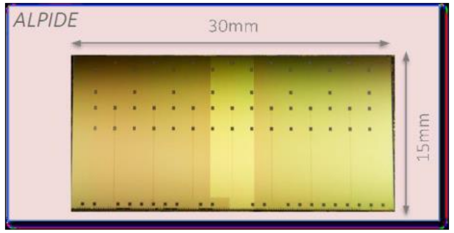


Length of active area ~45cm

- full area coverage with 2 x 3 strings of 15 ALPIDE sensors
- 90 ALPIDE sensors per pixel layer
- 44 pixel layers, 3960 ALPIDE sensors

Assembly procedure of pixel half layer

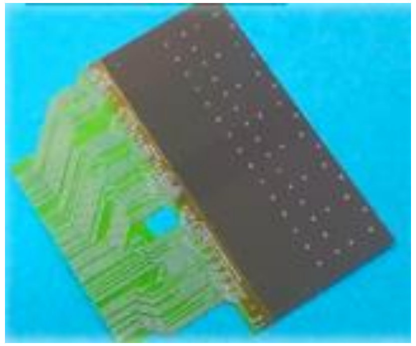


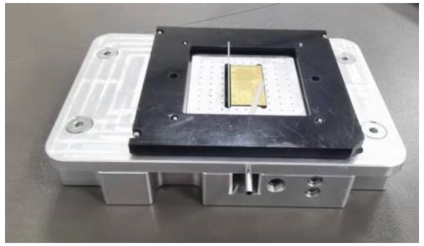


ALPIDE

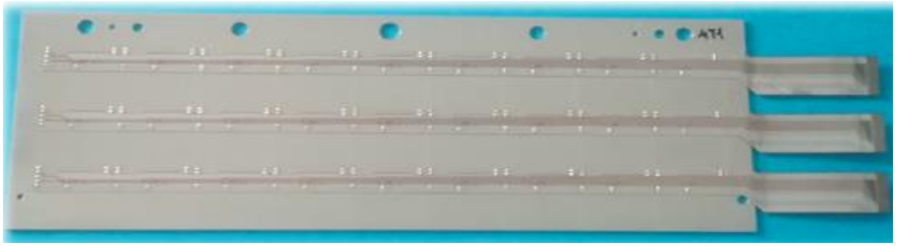
SpTAB

ALPIDE bond to chipcable



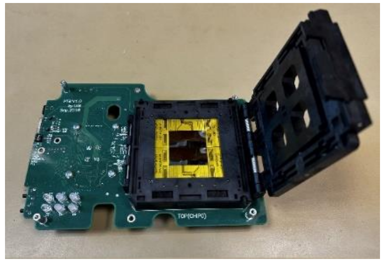


Single ALPIDE mounting jig



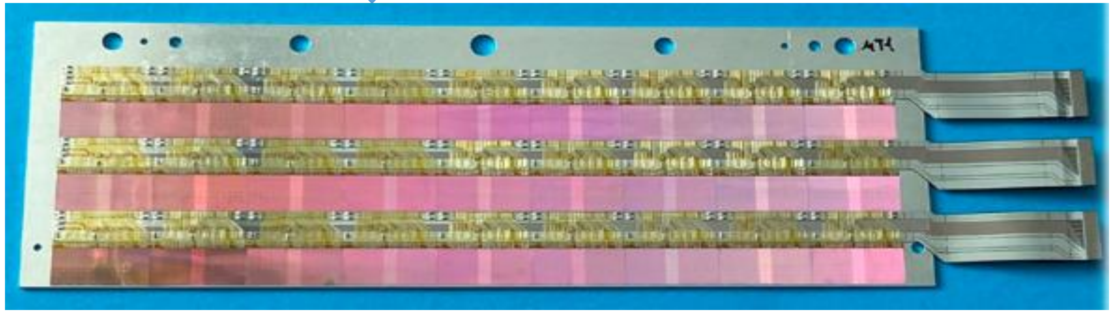
Carrier board with flex

SpTAB



Production test box

Pixel layer assembly jig

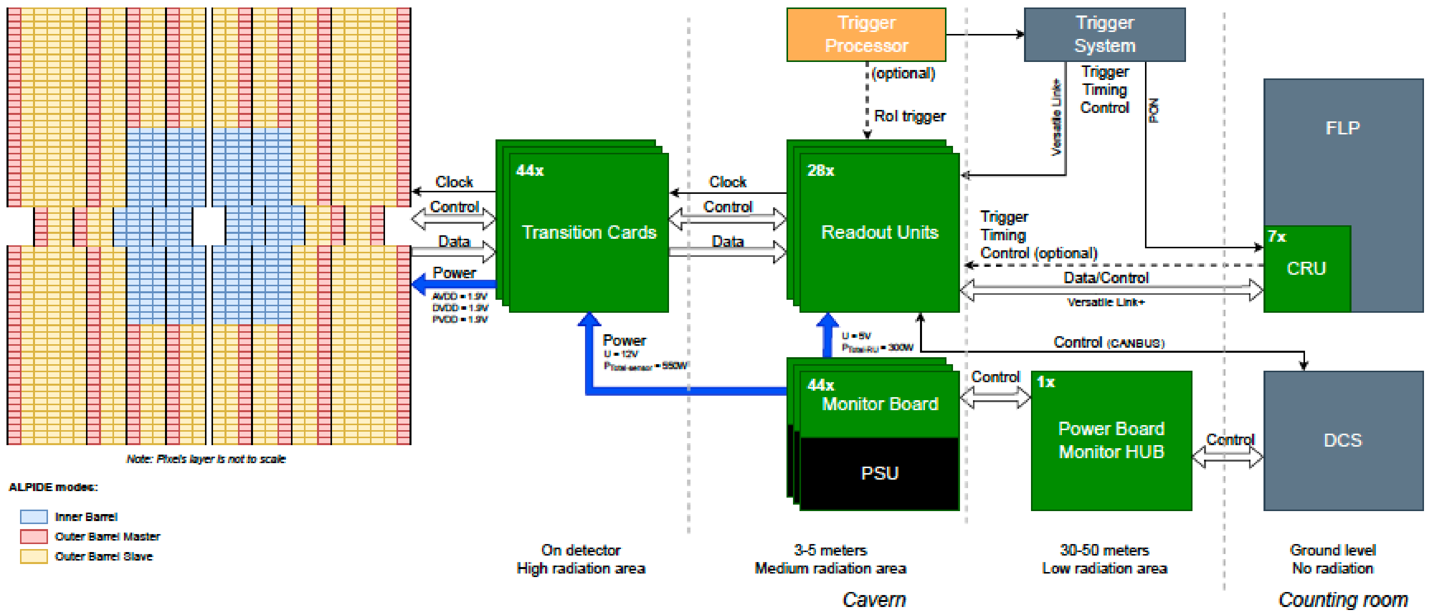


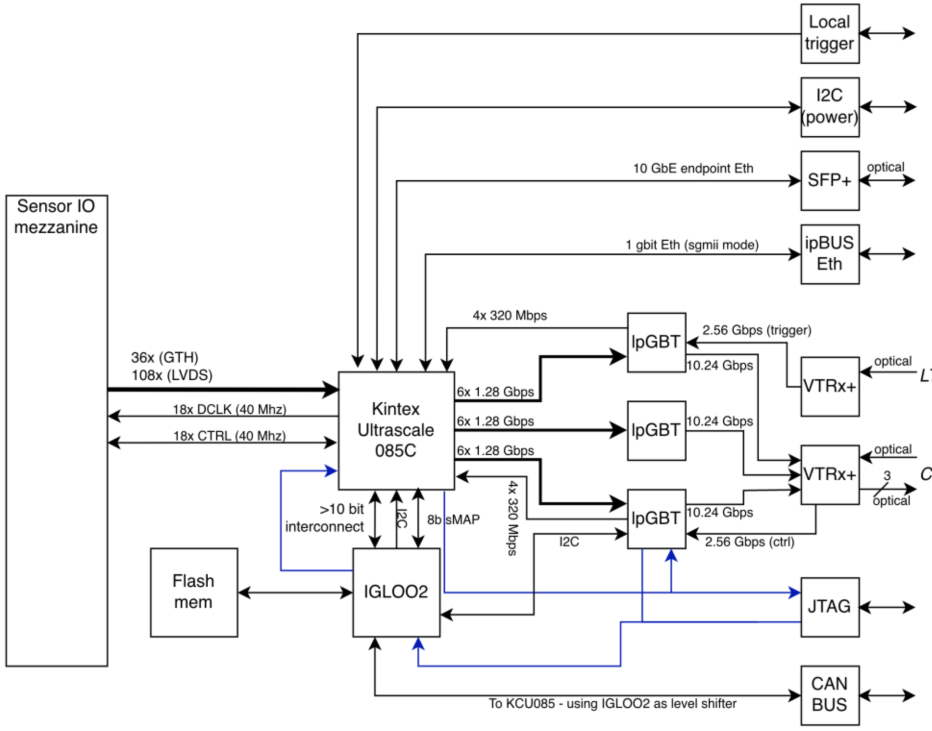
See Jun Liu's talk, Friday 14:00-14:15

Pixel Layer Readout Chain

See Poster by Shoulong Lin

Data rate (2 pixel layers): 65 - 320 Gbps



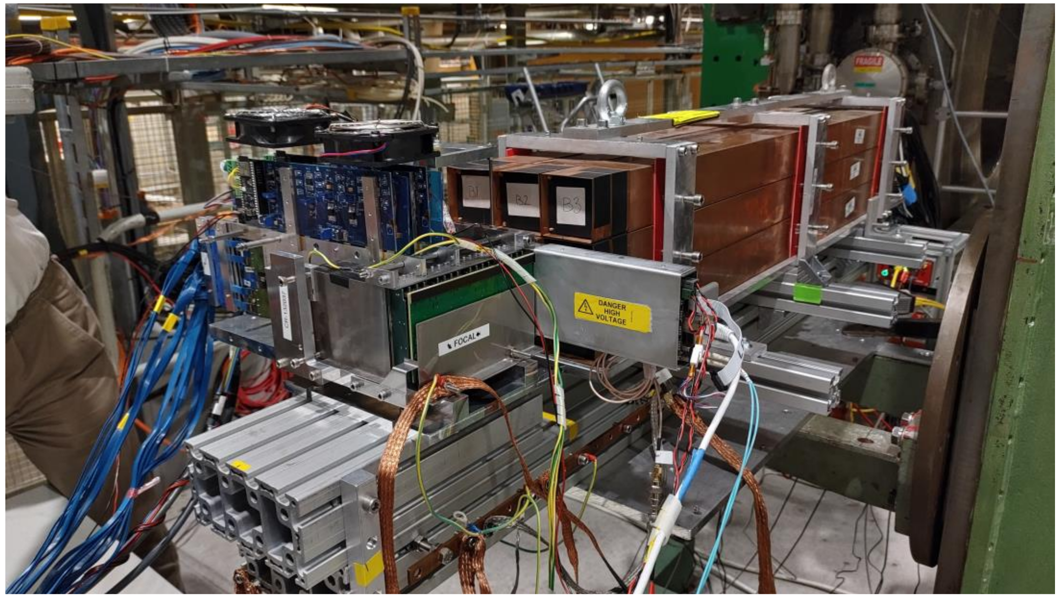


- Pixel layers have ALPIDE in IB (high data rate) mode and OB (low data rate) mode
- Similar readout structure to ITS2 readout system but different detector layout

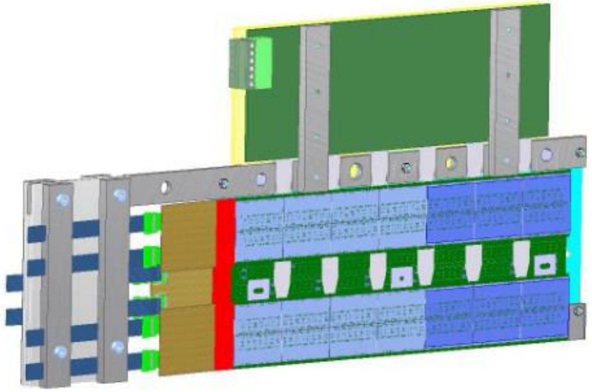
- The Radiation tolerant FPGA readout system
  - SRAM-based main Xilinx FPGA for readout
  - FLASH-based aux IGLOO2 FPGA for radiation mitigation
  - Triple Modular Redundancy and scrubbing at SRAM FPGA

FoCal beam test results

See Qian Tang's talk, Friday 14:15-14:30

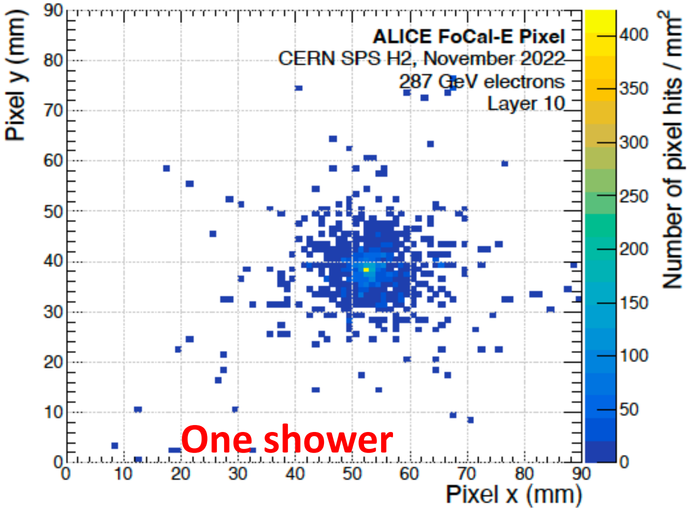


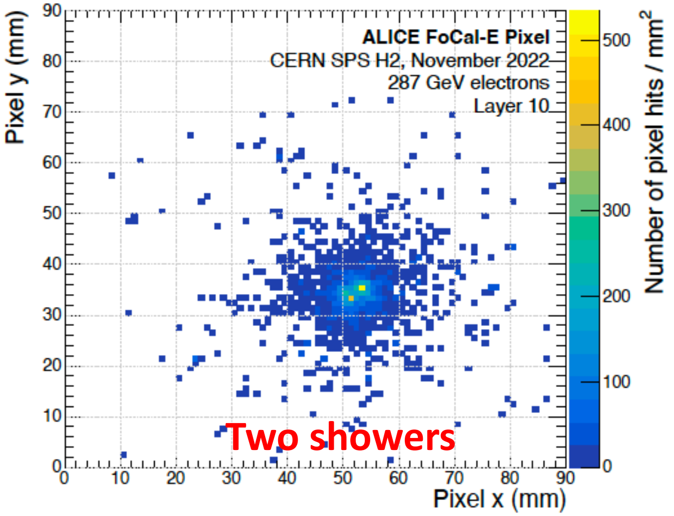
FoCal prototype

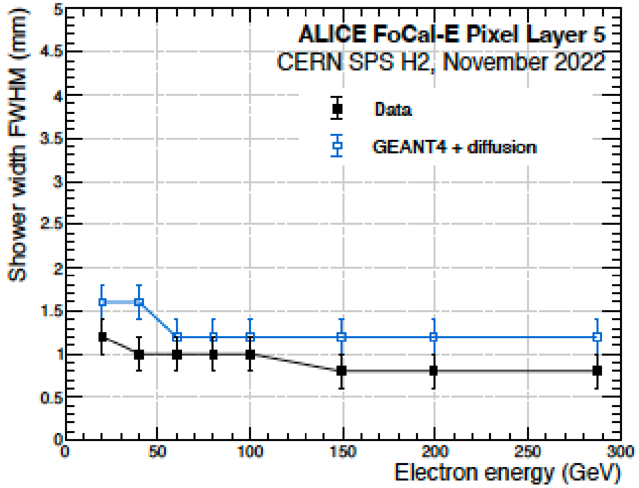


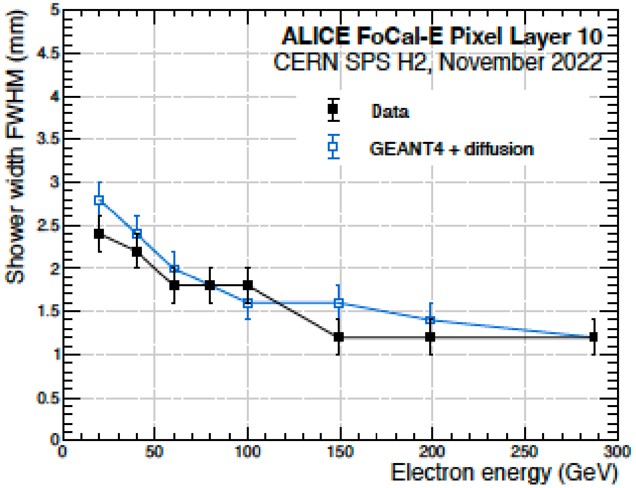
Pixel layer prototype

Shower profile in pixel layer









- **Shower width of 1 mm achieved**

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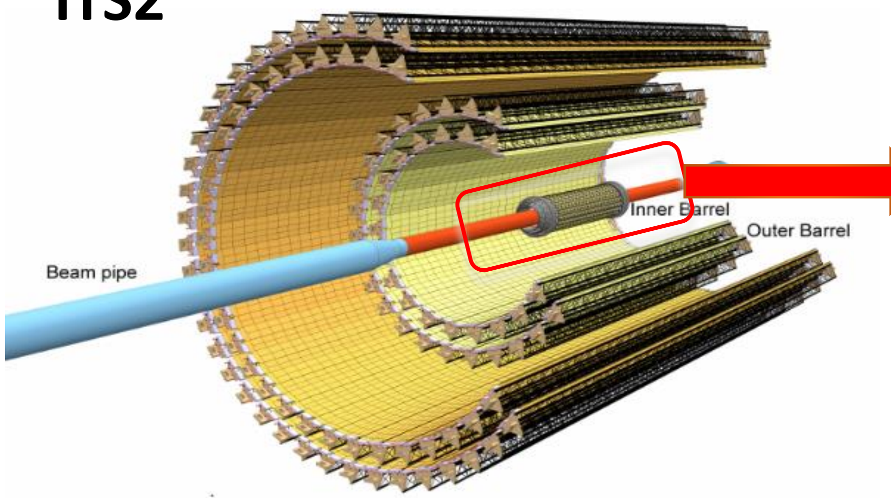
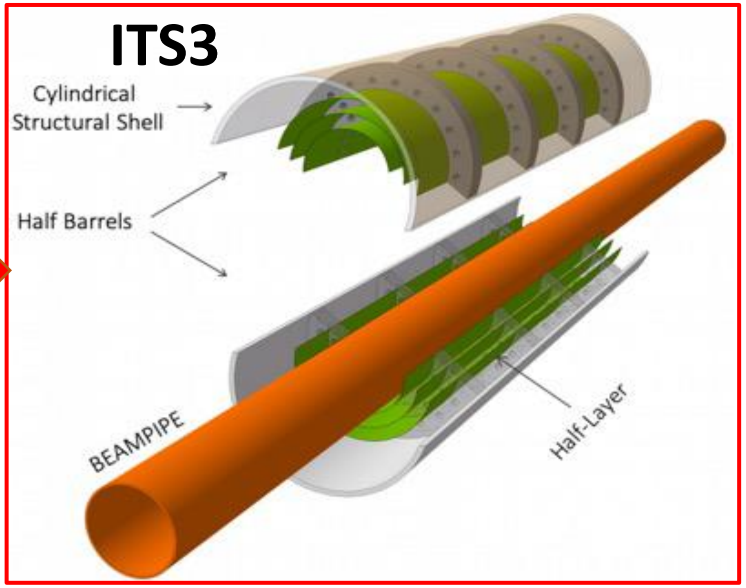
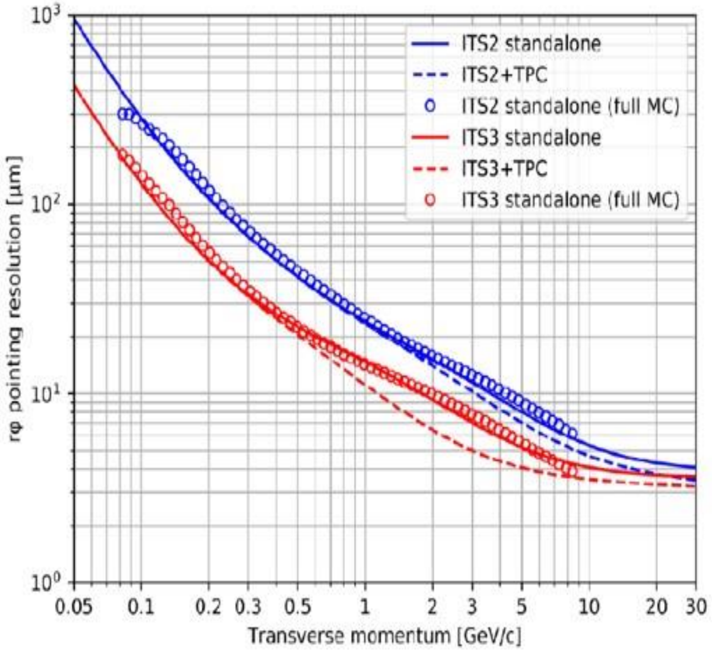
ITS3





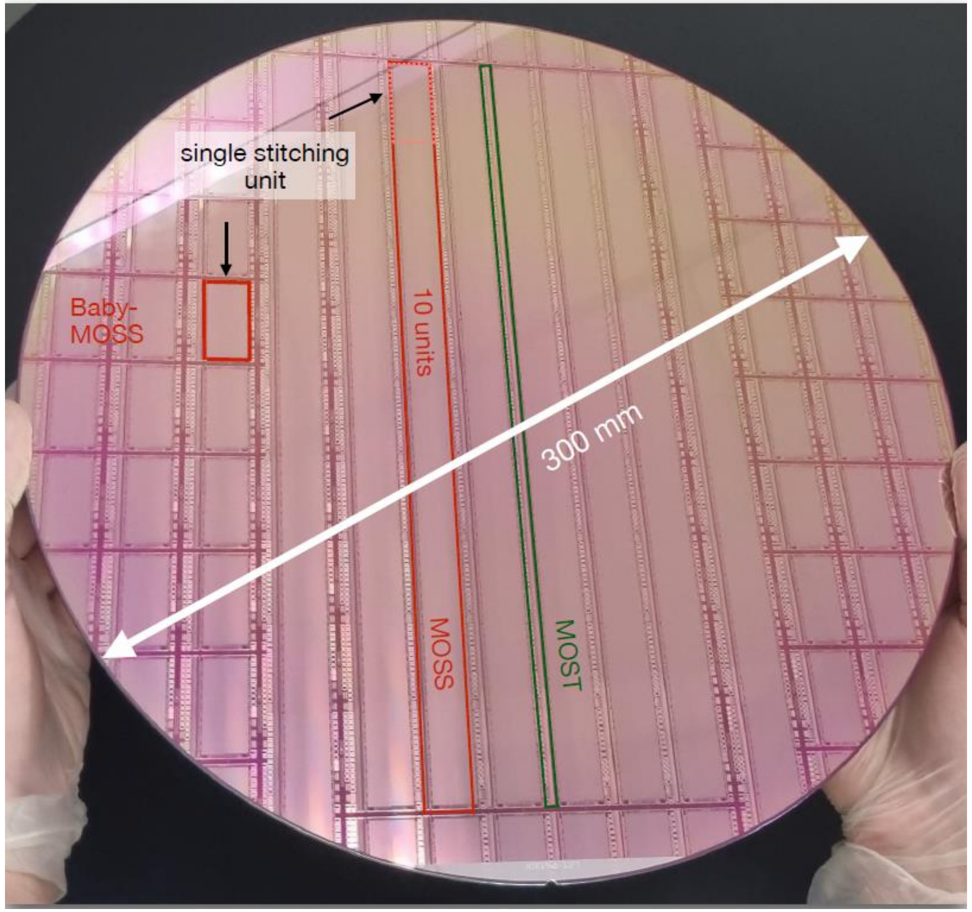


- 7 layers (3 IB + 4 OB) of pixel layers
  - ALPIDE MAPS
  - 12.5G pixels
  - 10 cm²
- 3 truly cylindrical pixel layers
  - 6 ultra-thin wafer-size curved sensors
  - Supported by carbon foam ribs
  - Air cooling
- Material budget reduced to **0.09%** X_0 instead of **0.36%** X_0 per layer
- Smaller radius of the innermost layer: **19 mm** instead of **23 mm**
- **Pointing resolution improved by a factor of two compared to ITS2 at p_T up to 5 GeV/c**

Status of R&D on ITS3

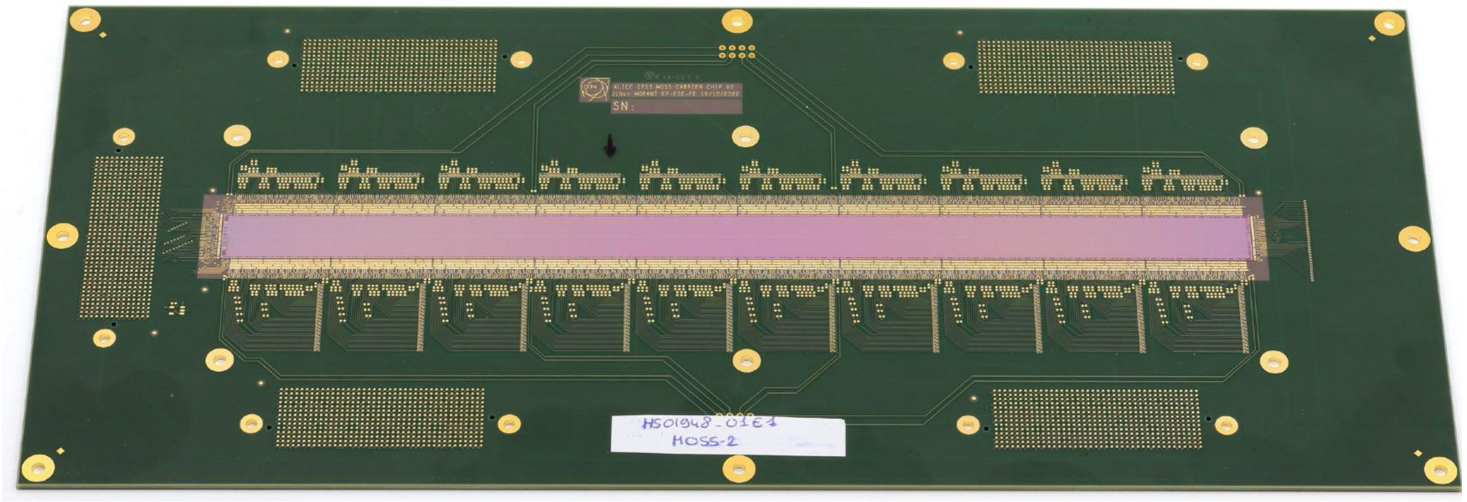
Stitched wafer-scale MAPS — Engineering Run 1 (ER-1)

- First MAPS for HEP using stitching
- one order of magnitude larger than previous chips
- based on TPSCo 65 nm technique
- "**MOSS**": 14 x 259 mm^2, 6.72M Pixels (22.5 x 22.5 and 18 x 18 μm^2)
- conservative design, different pitches
- "MOST": 2.5 x 259 mm^2, 0.9 M Pixels (18 x 18 μm^2)
- more dense design, different power granularity
- Baby-MOSS (single stitch ~ reticle-sized)
- Plenty of small chips (like MLR1)

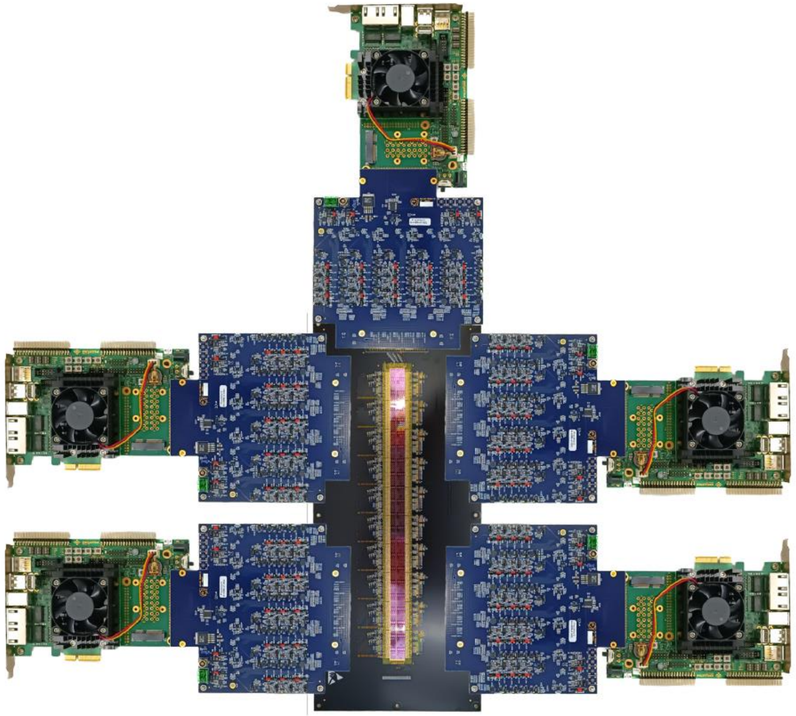


Engineering Run 1 wafer with various dies

MOSS characterization

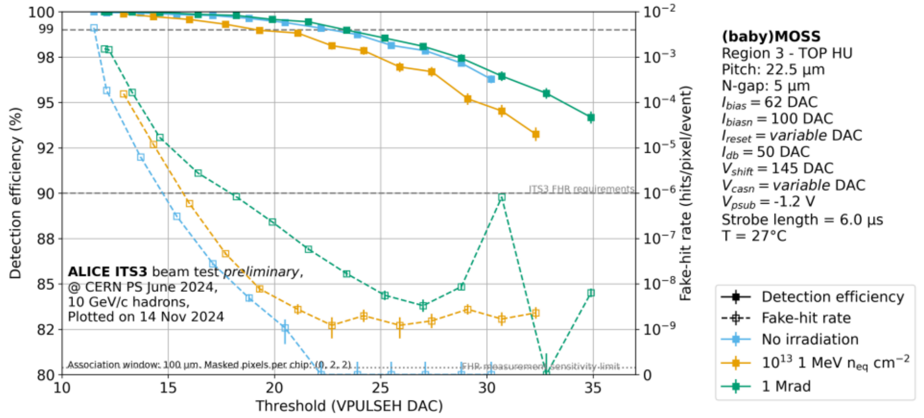


MOSS bonded to carrier board



Test system

- 10 Repeated Sensor Units (RSUs) stitched together: **259 mm x 14 mm** per **sensor**
- 2 pixel pitches (18 μm and 22.5 μm) and 5 front-end variants, a total of **6.72 M Pixels** per chip
- Chip is **operational** and reaches **full efficiency**
- Yield currently being studied in detail, main failure mechanism expected to be mitigated in the next submission



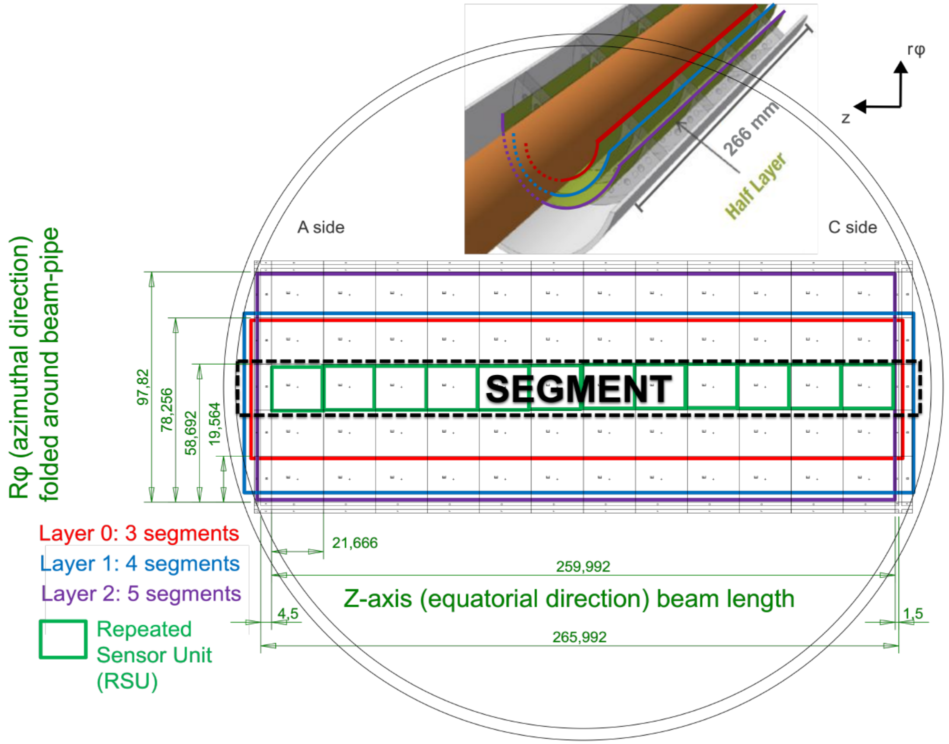
There is an operational margin after irradiation

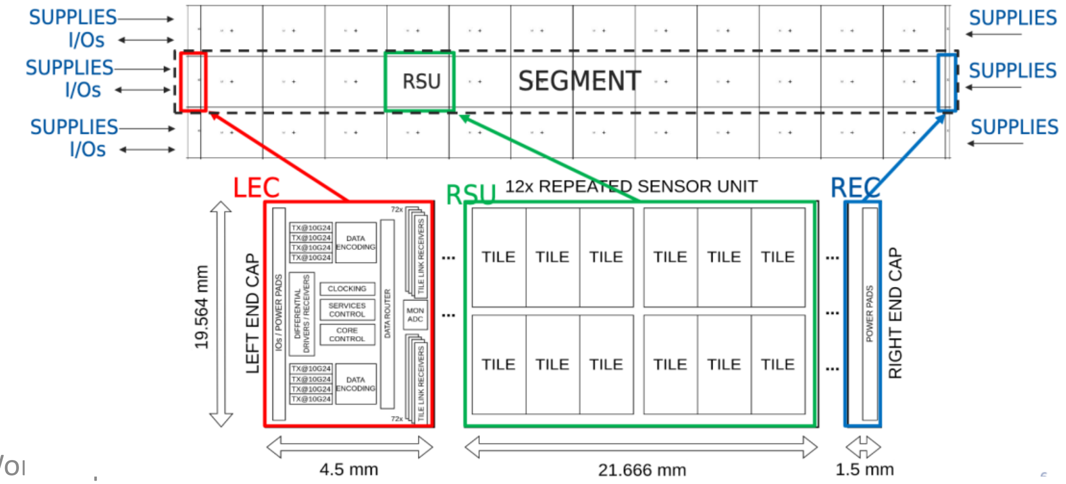
Stitched Wafer-Scale MAPS — MOSAIX

See Poster by Qiaomu Tong

Design of the final **full size, full functionality sensor** called MOSAIX is ongoing

- Modular design:
  - Sensor divided into 5 segments (allowing to use 3, 4 or 5 segments for layers 0, 1 and 2, respectively)
  - Each segment is constituted of **12** Repeated Sensor Units (RSUs)
  - Each RSU is divided in turn into **12** fully independent tiles (powering, control and readout)
- Interfacing from the Left End Cap (LEC) and Right End Cap (REC)
  - Powering from both sides
  - Control and readout from the LEC only
- Yield target: >98% of pixels active
- Submission to foundry planned for the end of 2024





Unique Physics goals of ALICE3

- **Access to temperature as function of time**

➟ high-precision di-electron mass spectra, p_T dependence, elliptic flow

- **Understanding thermalization in the QGP**

➟ direct access to charm diffusion: D-Dbar azimuthal correlations

➟ degree of thermalization of beauty: high-precision beauty measurements

➟ approach to chemical equilibrium: multi-charm hadrons

- **Fundamental aspects of the QCD phase transition**

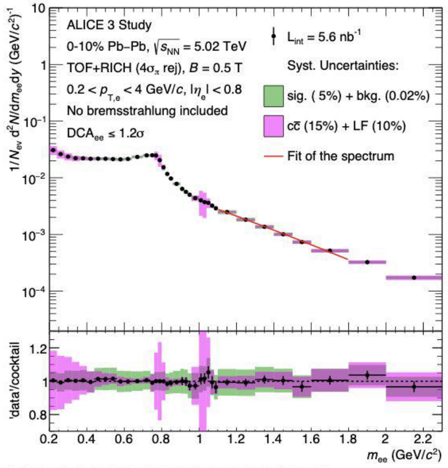
➟ net-baryon and net-charm fluctuations

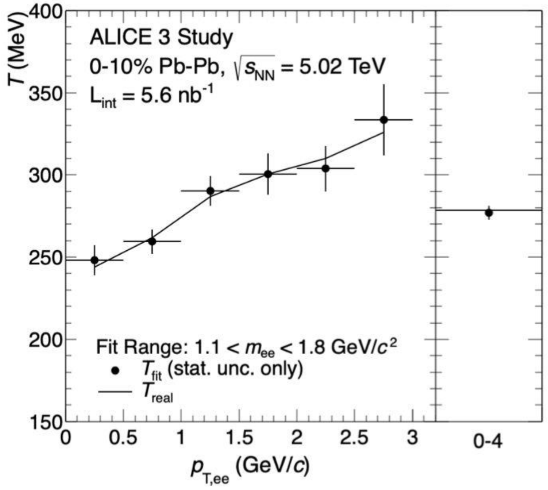
➟ mechanism of chiral symmetry restoration in the QGP: di-electron mass spectrum

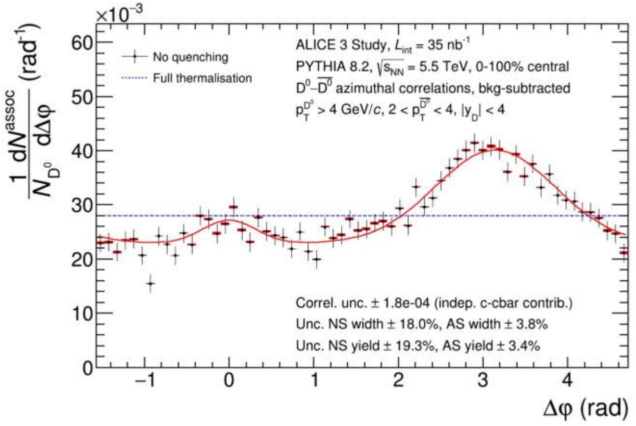
- **Laboratory for hadron physics**

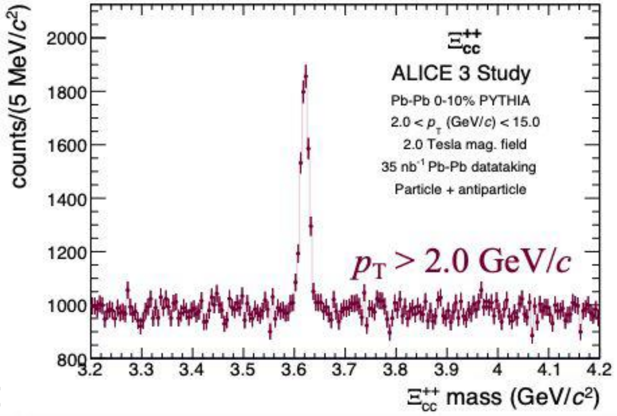
➟ hadron-hadron interaction potentials

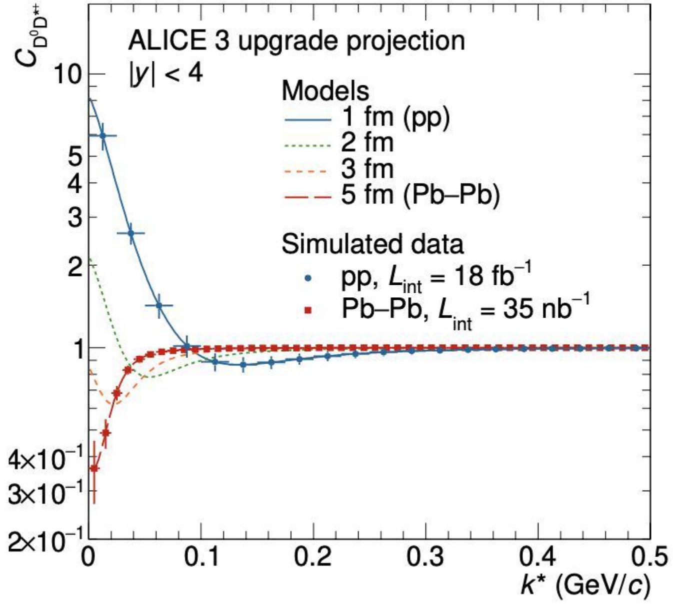
➟ explore nature of exotic hadrons (tetraquarks)





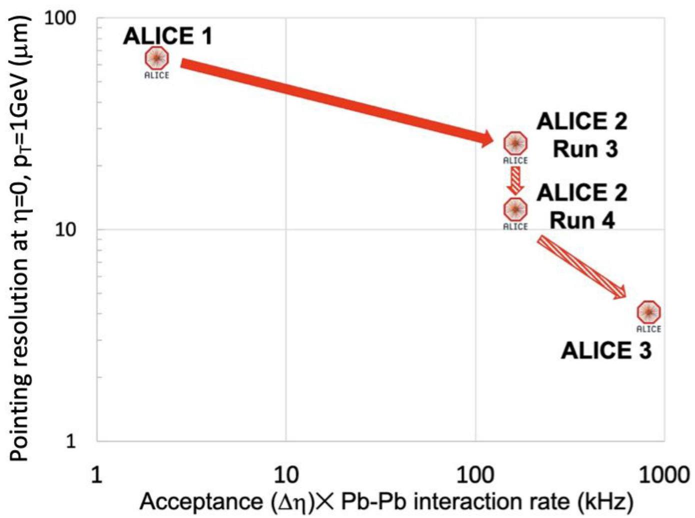




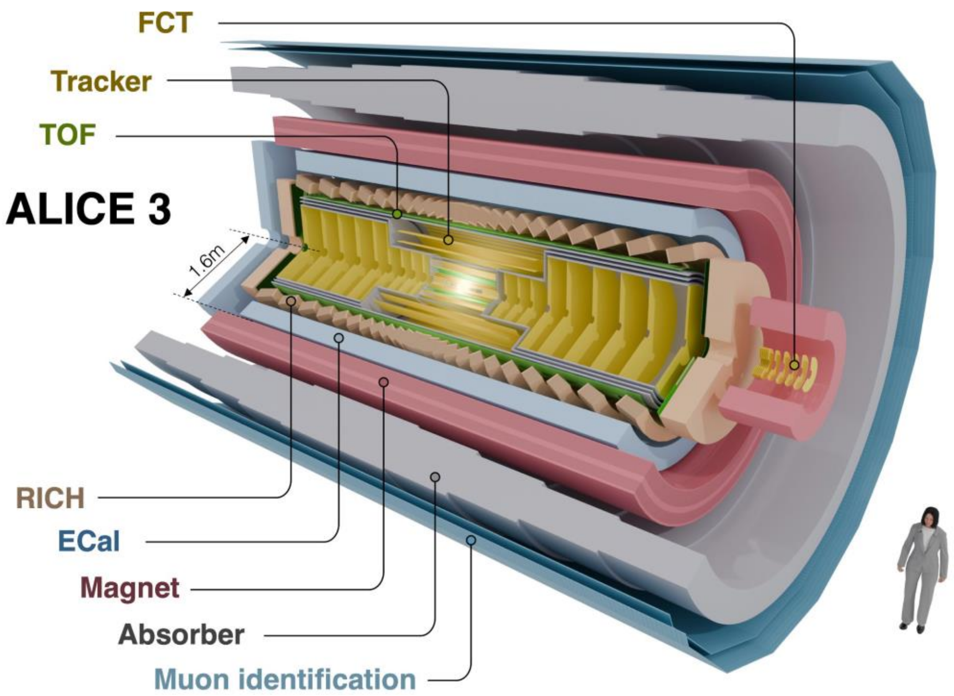


Charm pair strong interaction

ALICE3 strategy and detector concept

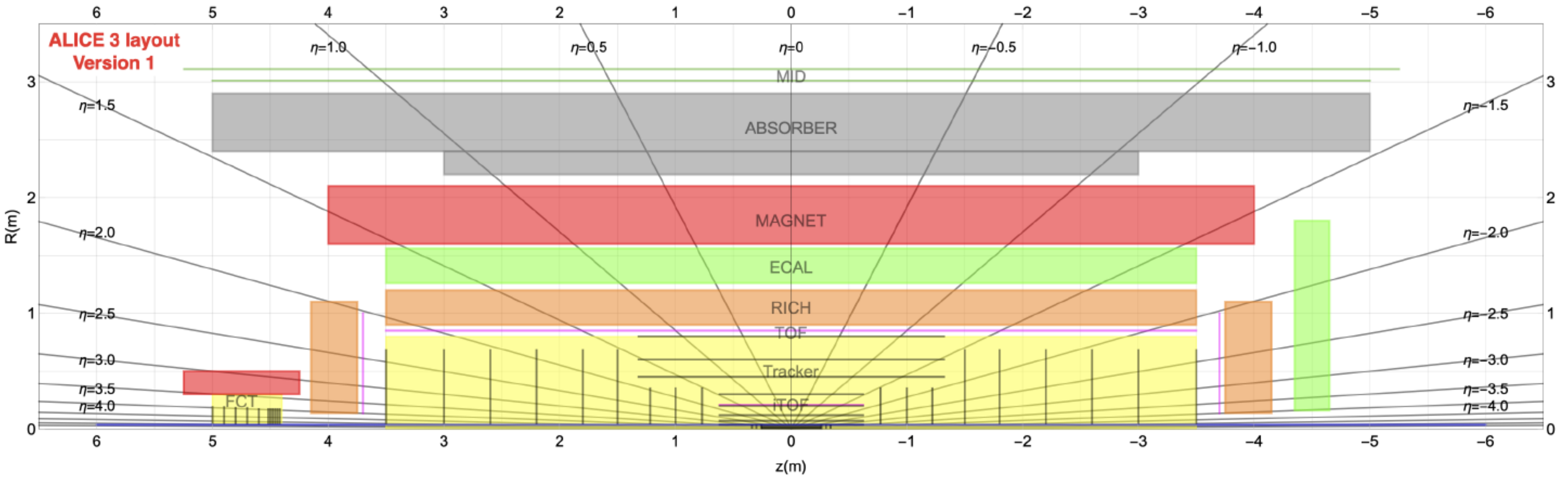


Improvement of pointing resolution and effective statistics

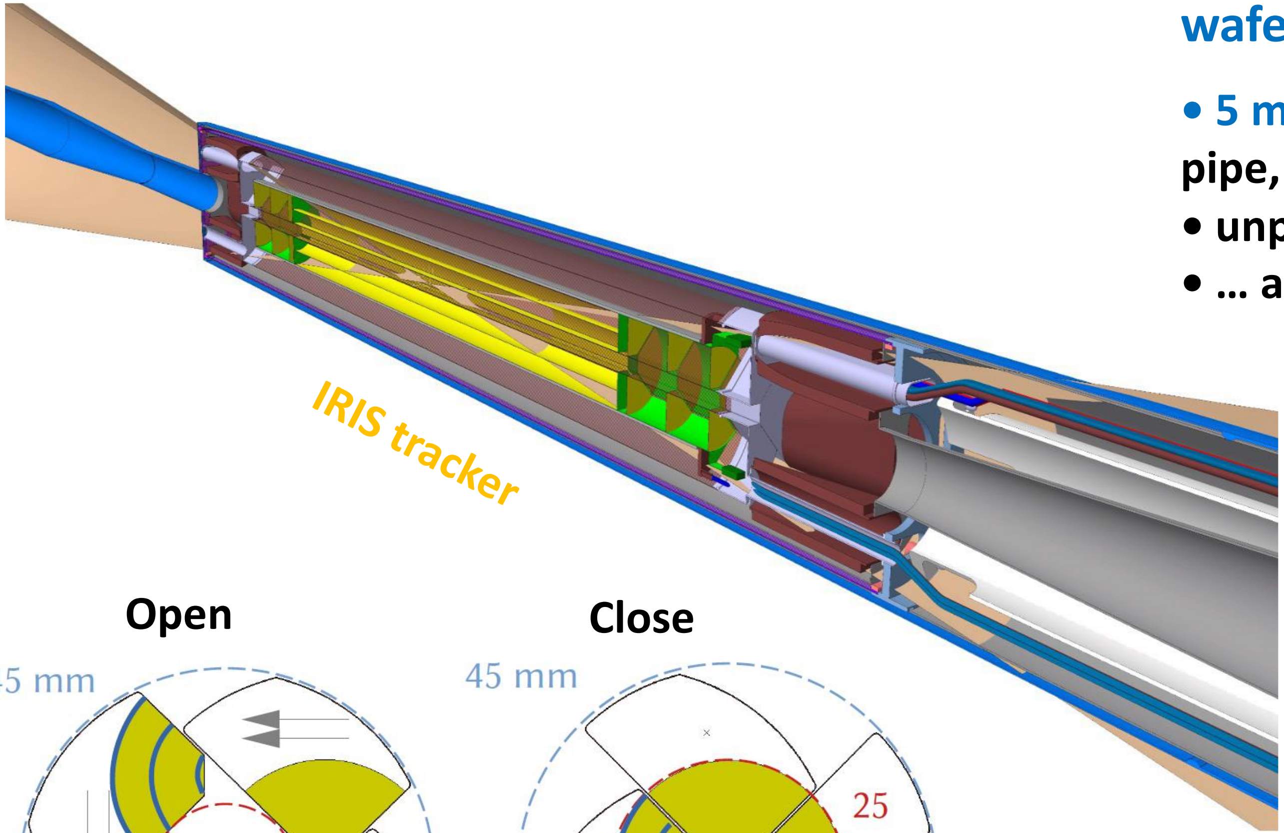


•Novel and innovative detector concept

- **Compact and lightweight all-silicon tracker**
- **Retractable vertex detector**
- **Extensive particle identification system (TOF, RICH, MID)**
- **Large acceptance**
- **Fast read-out and online processing**



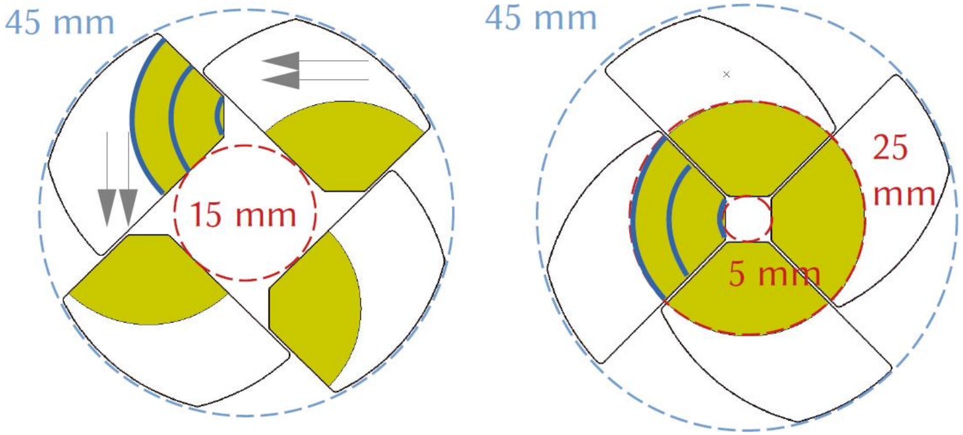
Tracker -Vertex detector

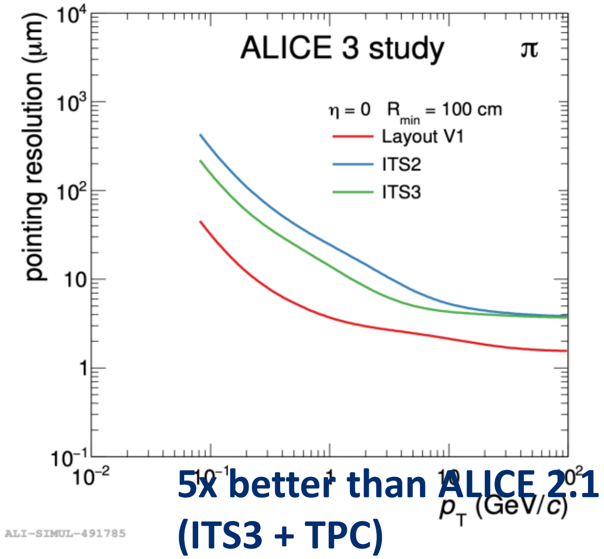


wafer-size, ultra-thin, curved, MAPS sensor

- **5 mm radial distance from interaction point (inside beam pipe, retractable configuration)**
- **unprecedented spatial resolution: $\sigma_{pos} \approx 2.5\ \mu m$**
- **… and material budget ≈ 0.1% X_0 / layer**

Open **Close**





5x better than ALICE 2.1 (ITS3 + TPC)

Radiation hardness: 10^{16} 1 MeV n_{eq}/cm^2

Vertex Detector R&D:

- Sensor design (China involvement)
- services integration
- study of protection between primary and secondary vacuum
- impact of vacuum on components, wire bonding, glued parts

Middle Layers of Inner Tracker

	Layer	Material thickness ($\%X_0$)	Intrinsic resolution (μm)	Barrel layers: Length Δz (cm)	Barrel layers: Radius (r) (cm)	Forward disks: Position ($\|z\|$) (cm)	Forward disks: R_{in} (cm)	Forward disks: R_{out} (cm)
VD	0	0.1	2.5	50	0.50	26	0.50	2.5
	1	0.1	2.5	50	1.20	30	0.50	2.5
	2	0.1	2.5	50	2.50	34	0.50	2.5
ML	3	1	10	124	3.75	77	5	35
	4	1	10	124	7	100	5	35
	5	1	10	124	12	122	5	35
	6	1	10	124	20			

R&D on Middle Layers:

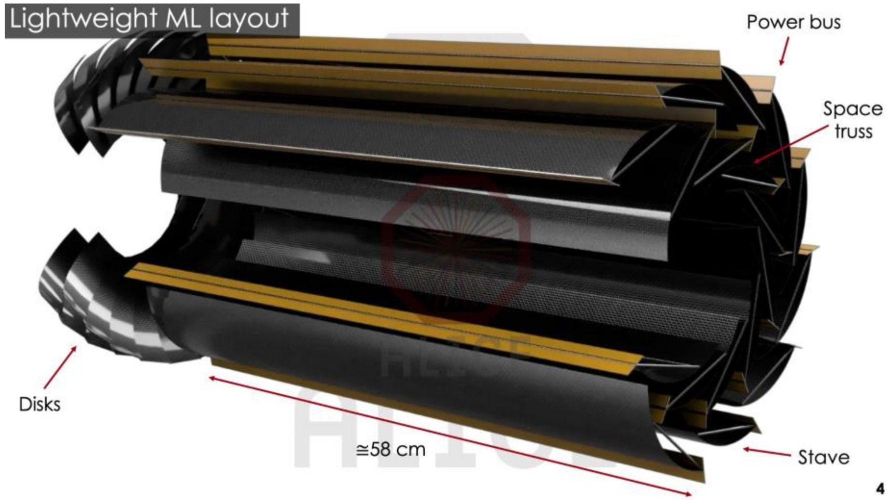
- studying various options for ultra-light layers, leveraging on ITS3 technology
- benefits on tracking of soft electrons and of charged hyperons (Ξ-, Ω-)

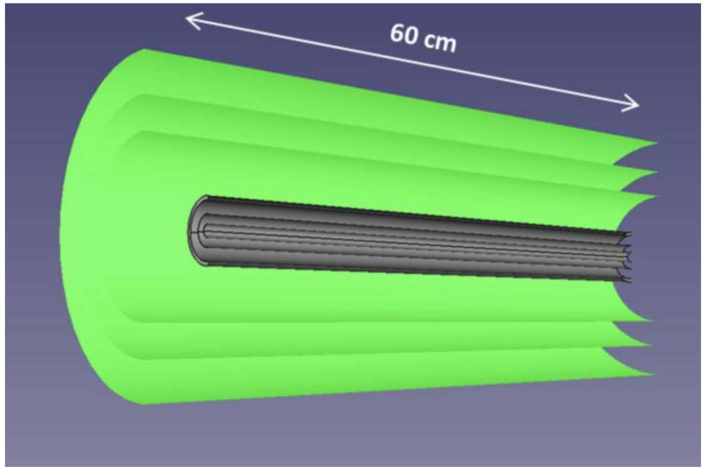
Options with ultra-light curved sensor layers:

ML:

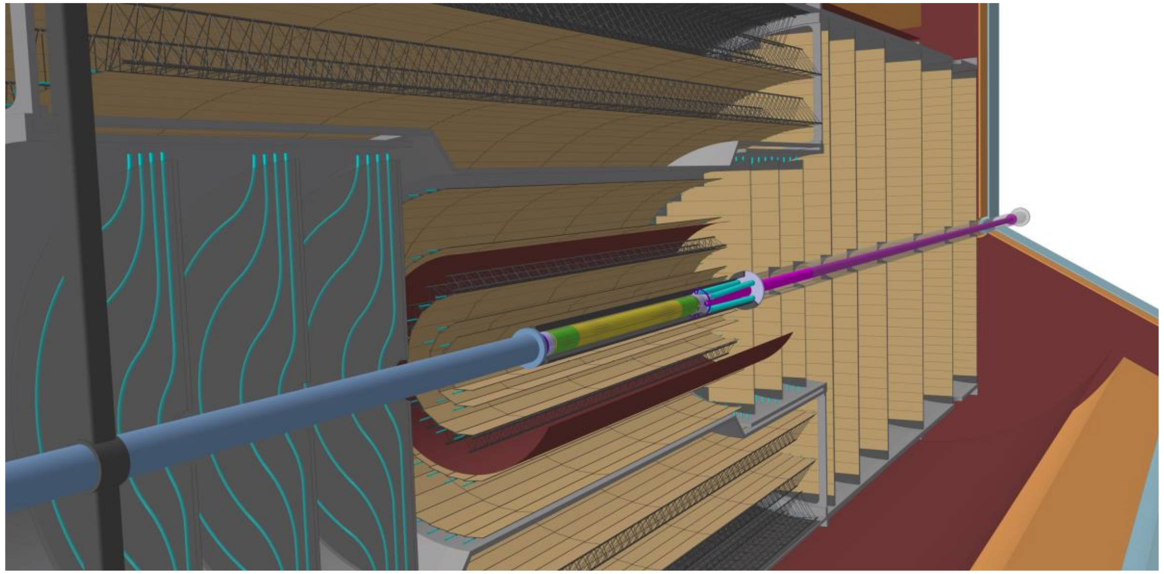
- Total surface to be covered: ~6.4 m^2
- Total sensor surface: ~6 m^2
- Baseline module size: ~ 25 cm^2
- 3650 modules

Radiation hardness: 2×10^{14} 1 MeV n_{eq}/cm^2





Tracker – Outer tracker



Layer	Det.	Material thickness ($\%X_0$)	Intrinsic resolution (μm)	Barrel layers Full length (Δz) (cm)	Barrel layers Radius (r) (cm)	Forward disks Position ($\|z\|$) (cm)	Forward disks R_{in}–R_{out} (cm)
6	IT/OT	1	10	1×124	20	150	5–68
7	OT	1	10	1×129	30	180	5–68
8	OT	1	10	2×129	45	220	5–68
9	OT	1	10	2×129	60	260	5–68
10	OT	1	10	2×129	80	300	5–68
11	OT	1	10			350	5–68

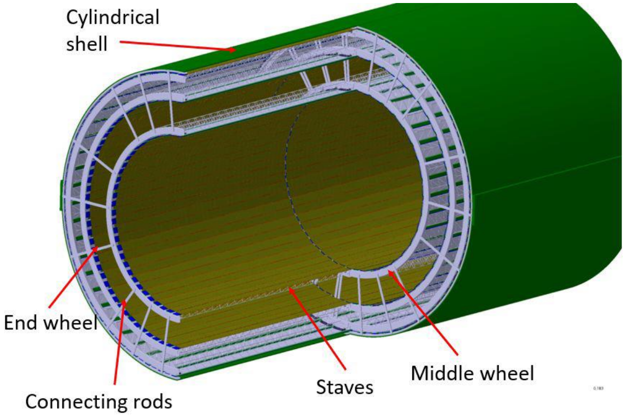
50 m² silicon pixel detector based on MAPS

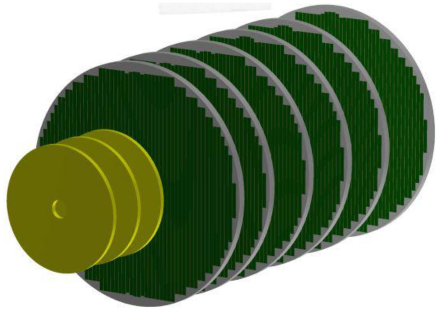
- **large pseudorapidity coverage: ±4**
- **compact: R_{out} ≈ 80 cm, z_{out} ≈ ±400 cm**
- **high-spatial resolution: σ_{pos} ≈ 5 μm (req. < 10 μm)**
- **very low material budget: $X/X_0 \lesssim 1\%$ per layer**
- **low power: ≈ 20 mW/cm²**

- Sensor size: ~3.2x2.5 cm²
- Module of 2x4 sensors: 12.88x5.04 cm²
- 8308 modules (10750 modules to be produced)

R&D focuses on

Module, stave and barrel design, air cooling system, module assembly for industrial production





Endcap disks: double-sided layout of sensor modules

Particle identification: TOF

	Inner TOF	Outer TOF	Forward TOF disks
Radius (m)	0.19	0.85	0.15 to 1.0
z range (m)	−0.62 to 0.62	−3.50 to 3.50	±3.70
Area (m^2)	1.5	37	6
Acceptance	$\|\eta\| < 1.9$	$\|\eta\| < 2$	$2 < \|\eta\| < 4$
Granularity (mm^2)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm^2)	200	15	280
Material thickness (% X_0)	1 to 3	1 to 3	1 to 3
Power density (mW/cm^2)	50	50	50
Time resolution (ps)	20	20	20

$\sigma_{TOF} \lesssim 20ps$

Barrel TOF ($|\eta| < 2$)

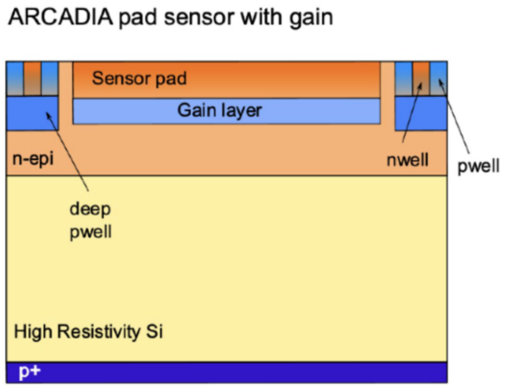
- **Outer TOF radius = 85 cm surface: 37 m^2, pitch: 5 mm**
- **Inner TOF, radius = 19 cm surface: 1.5 m^2, pitch: 1 mm**

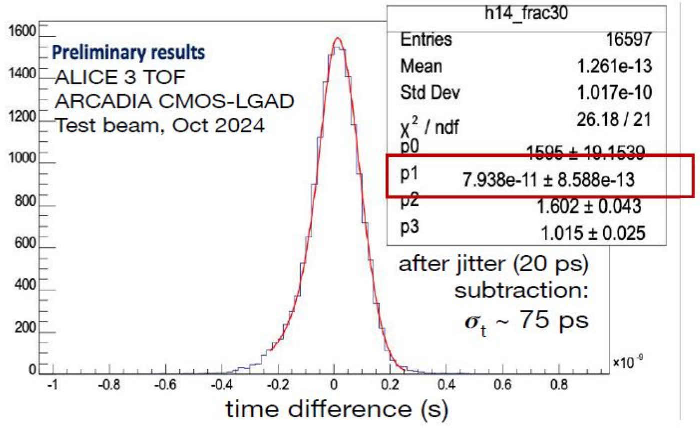
Forward TOF ($2 < |\eta| < 4$)

- **Inner radius = 15 cm**
- **Outer radius = 100 cm surface = 6 m^2, pitch = 1 mm to 5 mm**

Sensor technologies under study:

- **CMOS LGAD (baseline):**
  - **integration of sensor and readout in a single chip**
  - **easier system integration and significant cost reduction (save 11.5 MCHF)**
- **Conventional LGADs (fallback)**: R&D with very thin sensors shows a timing resolution of **22 ps** reachable
- **Silicon Photon Avalanche Diodes (SPADs):**
  - **A timing resolution of 20-25 ps measured**
  - **Pursued further only for outer TOF layers (radiation req.)**

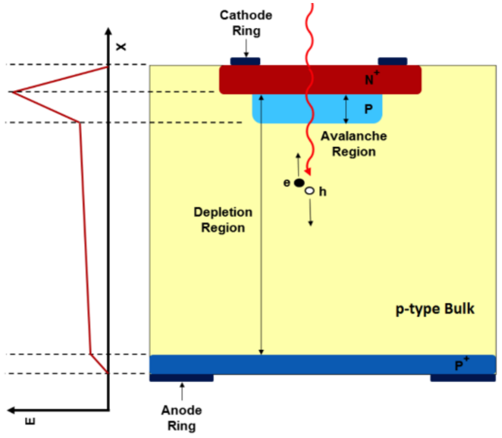




- **First prototype CMOS-LGAD with improved gain (~13), but still "thick" (50 μm)**
- Preliminary time resolution of 75 ps, consistent with expectation for this thickness
- Good prospects to reach ~20 ps with thinned versions in preparation (25 and 15 μm)

Plans of China Team for ALICE 3

- **Inner Tracker**
  - **R&D of sensors for VD and ML**
    - **Design and characterization**
  - **Mass production of ML HIC modules if it is possible to produce in labs**
  - **R&D of the readout electronics**
- **TOF**
  - **R&D of high timing resolution LGAD**
    - **Design and characterization**
  - **Mass production of TOF modules**
  - **R&D of the readout electronics**



Summary

- **Intermediate upgrade for the LS3 will allow higher precision measurements:**
  - **ITS3: better pointing resolution, R&D is ongoing according to schedule**
  - **FoCal: prototypes being tested, very good results from beam test data**
- **Novel and innovative ALICE3 detector proposed for Run 5 & 6 to give better insight of the microscopic dynamics of the QGP**
- **China ALICE team will contribute to ALICE3 IT and TOF**

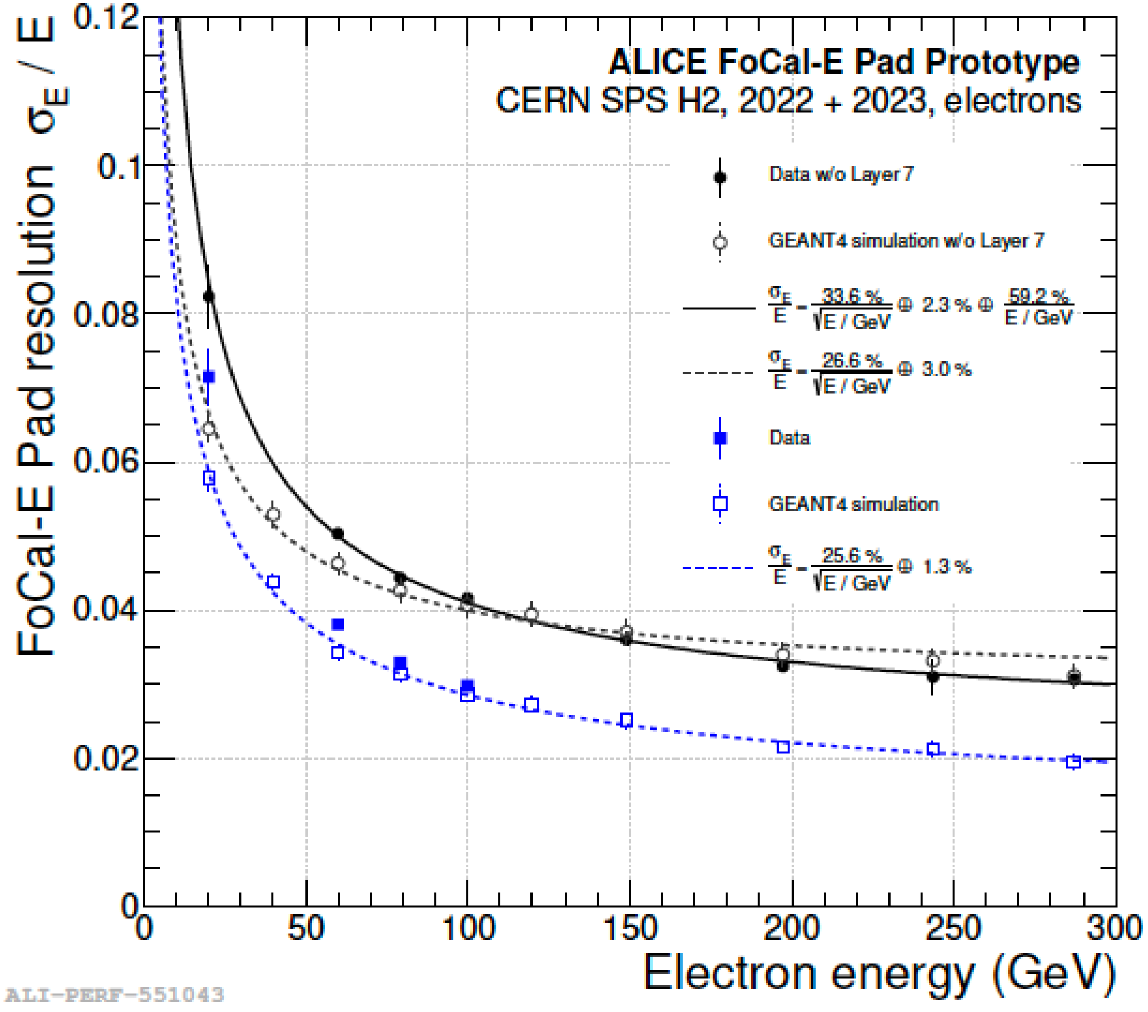
Thanks a lot for your attention!

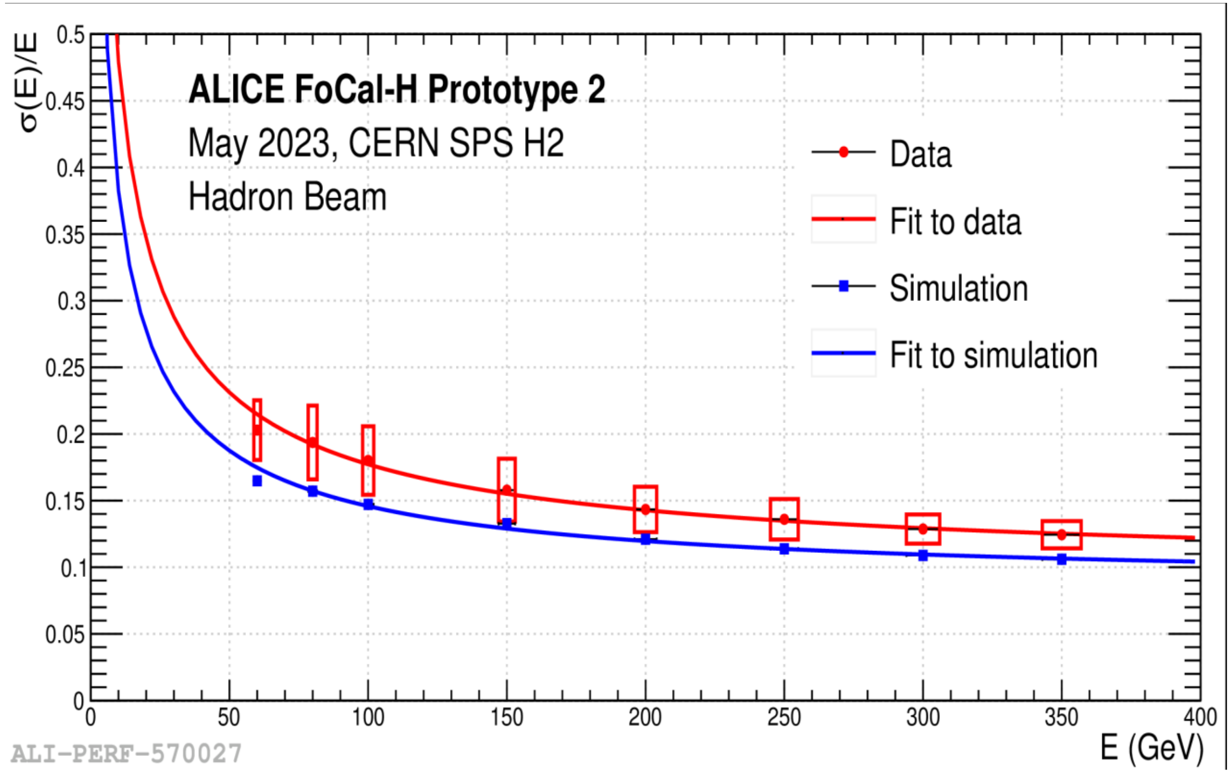
Backup

Stitched Wafer-Scale MAPS — MOSAIX — challenges

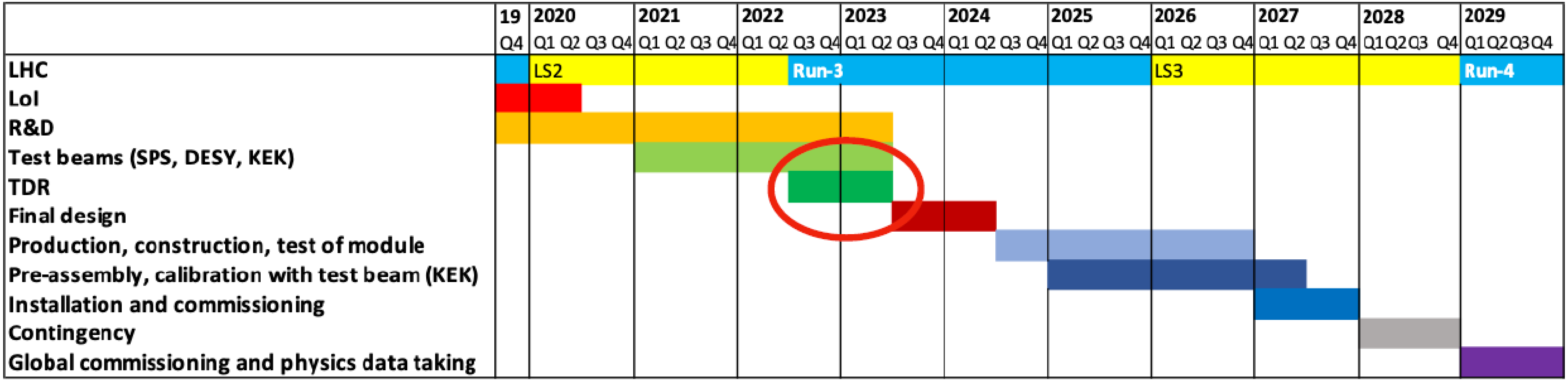
- Interdependencies and integration: ‘stave on a chip’
- Fill factor above 94% - 95%
  - No overlap zones (like in ‘conventional’ detectors)
  - Readout of data needs peripheral circuits, whose area and complexity increase with amount of data to move
- Power distribution
  - IR drops on the metals of the CMOS stack significant even with very low power
  - Complex segmentation in many independent domains that can be maintained off in case of short circuits
  - Switches and cross-domain signaling and protections
- Significant leakage
  - Large variations with process and temperature
  - Needed to devise mitigation techniques, e.g., library of low leakage standard cells
- Data transmission
  - Integrate 144 on-die transmission lines of 25 cm working at 160 Mb/s
  - High speed (10 Gb/s) wireline drivers for off-chip transmission

FoCal energy resolution



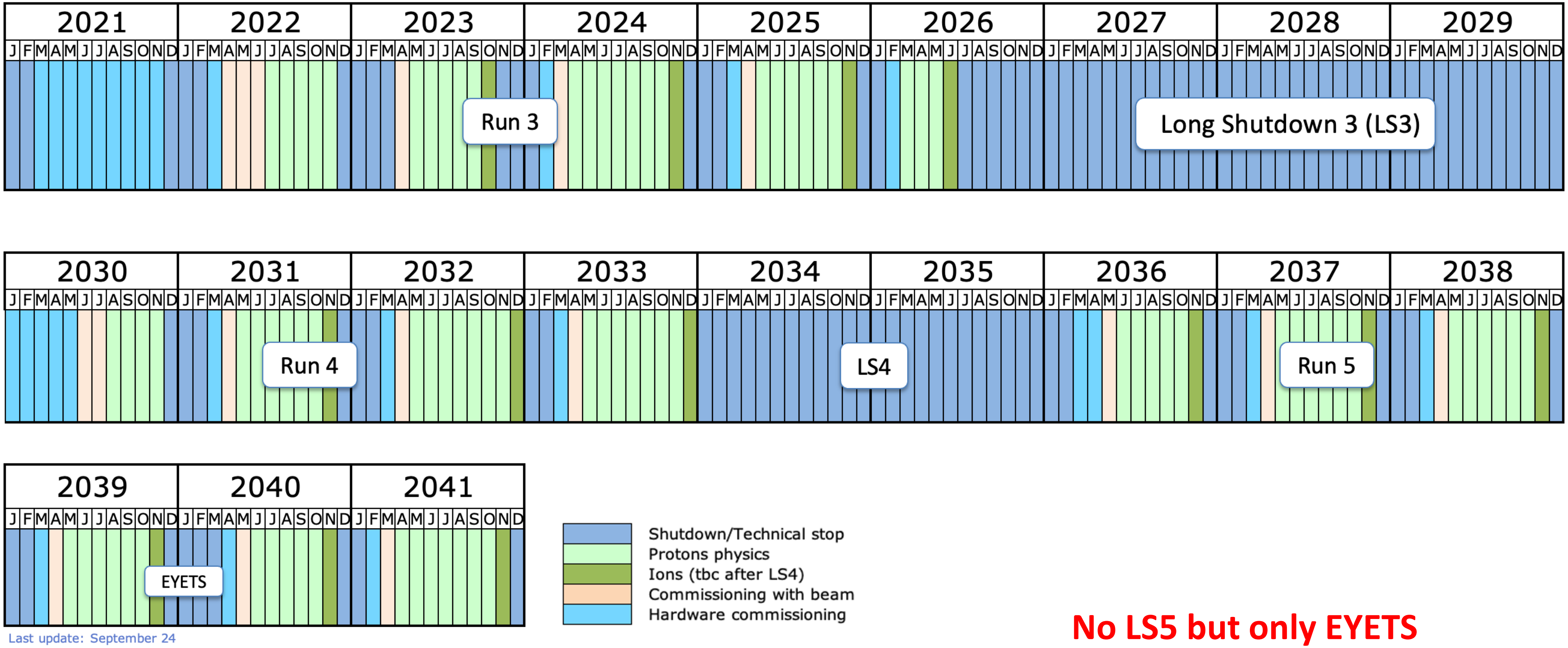


FoCal timeline

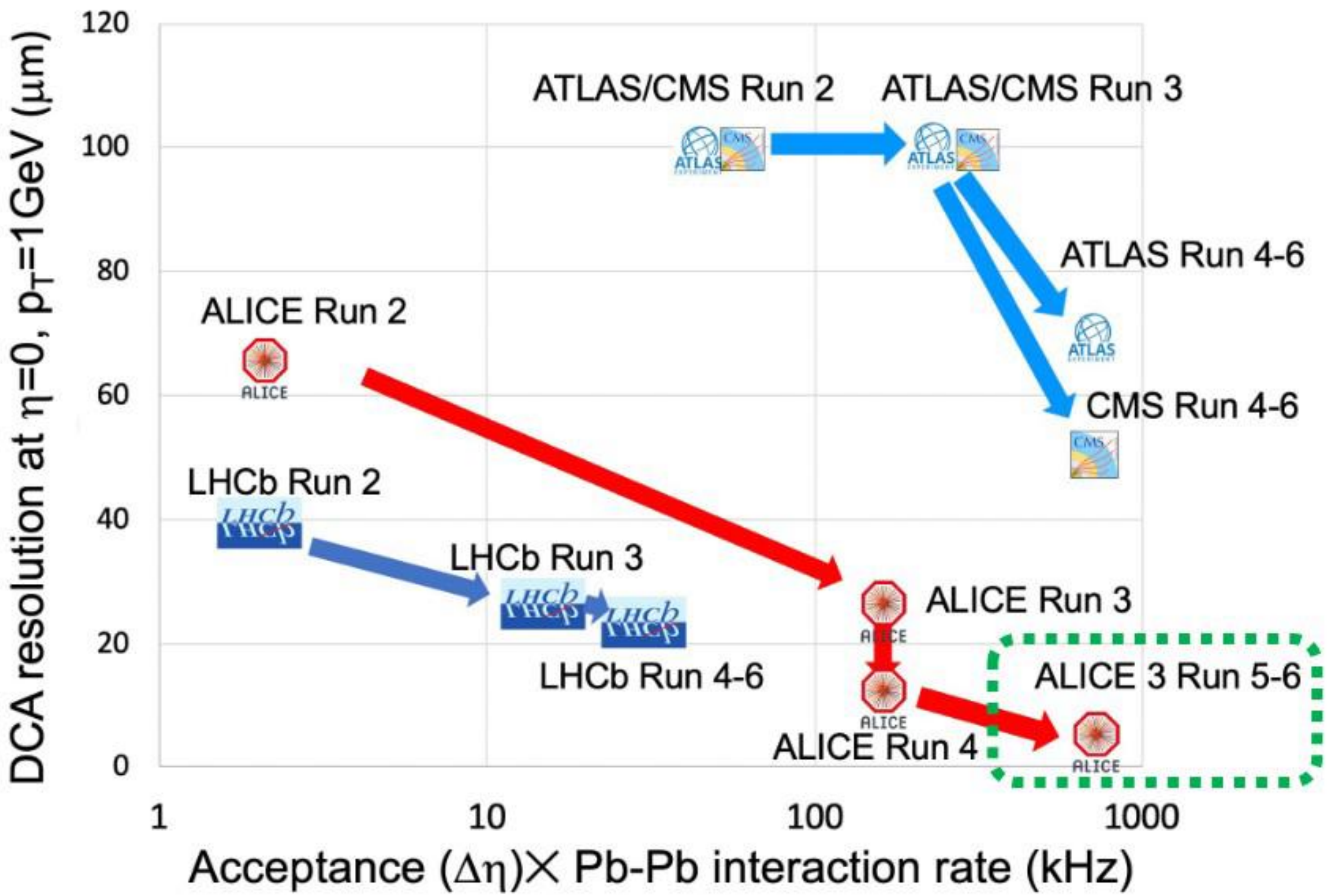


- **Schedule:**
  2023: TDR
  2023/2024: final design for production
  2024-2027: production and calibration in beam
  2027: installation

LHC run plan



No LS5 but only EYETS



DCA resolution at η=0, p_T=1GeV (μm)
120
100
80
60
40
20
0
1
10
100
1000
Acceptance (Δη)× Pb-Pb interaction rate (kHz)
ATLAS/CMS Run 2
ATLAS/CMS Run 3
ATLAS Run 4-6
CMS Run 4-6
ALICE Run 2
LHCb Run 2
LHCb Run 3
LHCb Run 4-6
ALICE Run 3
ALICE Run 4
ALICE 3 Run 5-6

Particle identification: RICH

	barrel RICH	forward RICH disks
Radius (m)	0.9 to 1.2	0.15 to 1.15
z range (m)	-3.50 to 3.50	$3.75 < \lvert z \rvert < 4.15$
Surface (m^2)	28	9
Acceptance	$\lvert \eta \rvert < 2$	$2 < \lvert \eta \rvert < 4$
Granularity (mm^2)	2×2	2×2

RICH specification: Cherenkov angle resolution < 6 mrad

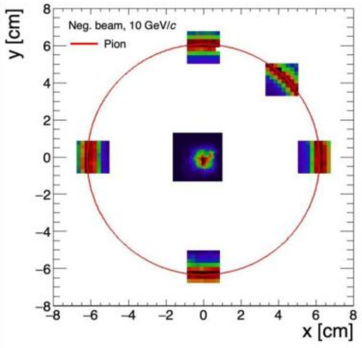
Ring-Imaging Cherenkov

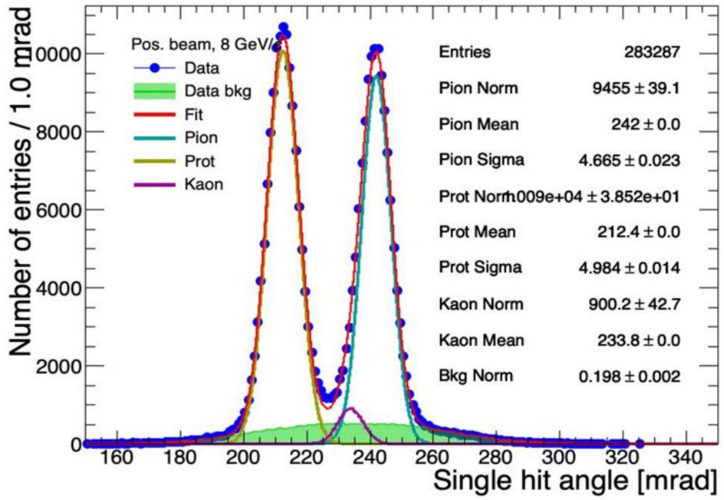
- **Extend PID reach of outer TOF to higher p_T**
- **aerogel radiator to ensure continuous coverage from TOF**

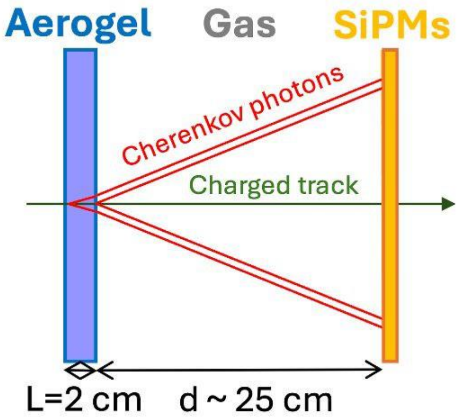
→ refractive index n = 1.03 (barrel)

→ refractive index n = 1.006 (forward)

- **silicon photon sensors**
- **R&D on monolithic photon sensors**

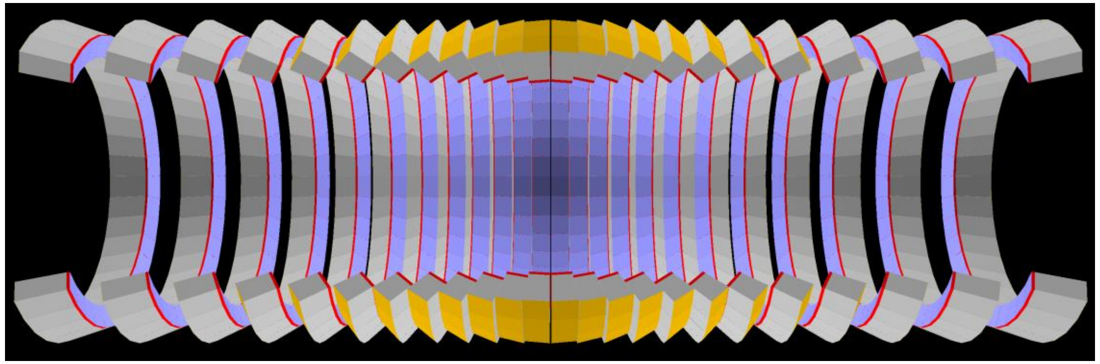






Proximity focusing RICH layout

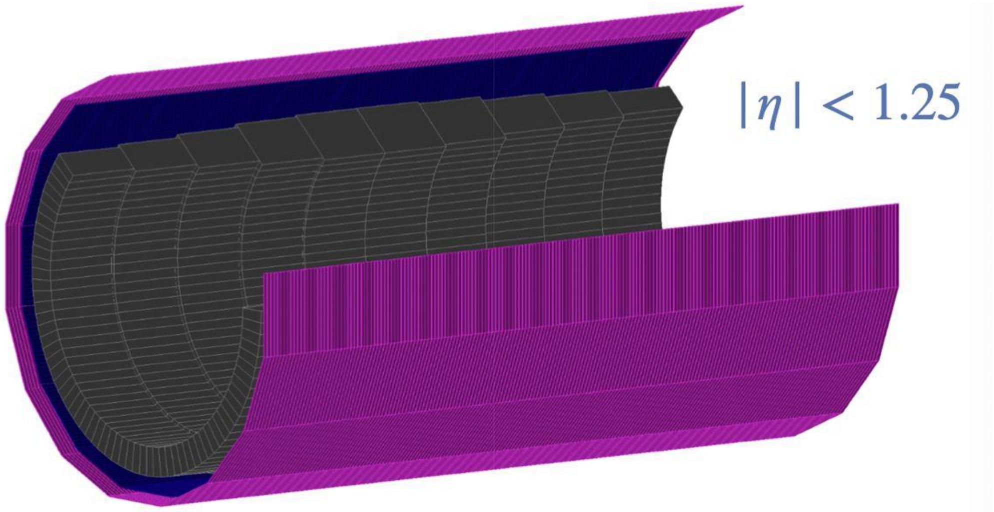
37 m^2 SiPM



Projective cylindrical bRICH layout

Cherenkov angle of pions and protons: 5 mrad single photon resolution

Muon ID detector

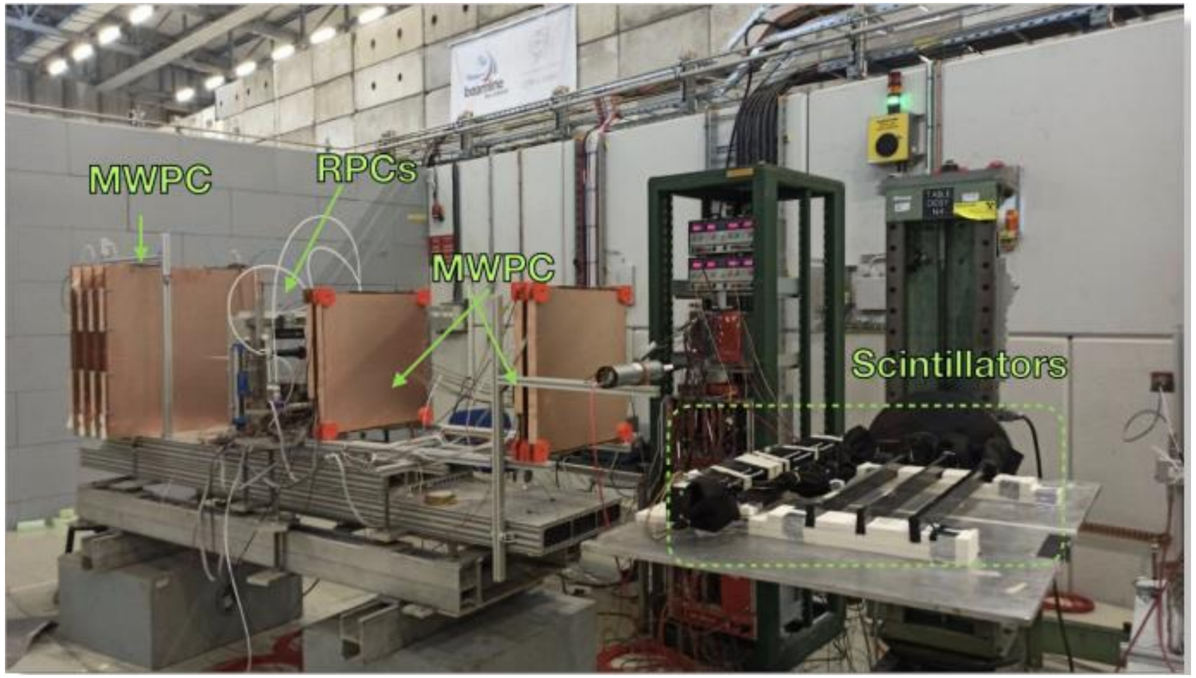


	Absorber	MID layer 1	MID layer 2
Inner radius (m)	2.20	3.01	3.11
Outer radius (m)	2.90	3.02	3.12
Total length (m)	10	10	10.5
No. of sectors in z	9	10	10
No. of sectors in φ	1	16	16
Scintillator bar length (cm)	–	99.8	123.5
Scintillator bar width (cm)	–	5.0	5.0
Scintillator bar thickness (cm)	–	1.0	1.0

MID specification: pion rejection >96%

Absorber: a standard magnetic steel with a thickness varying from 70 cm to 38 cm

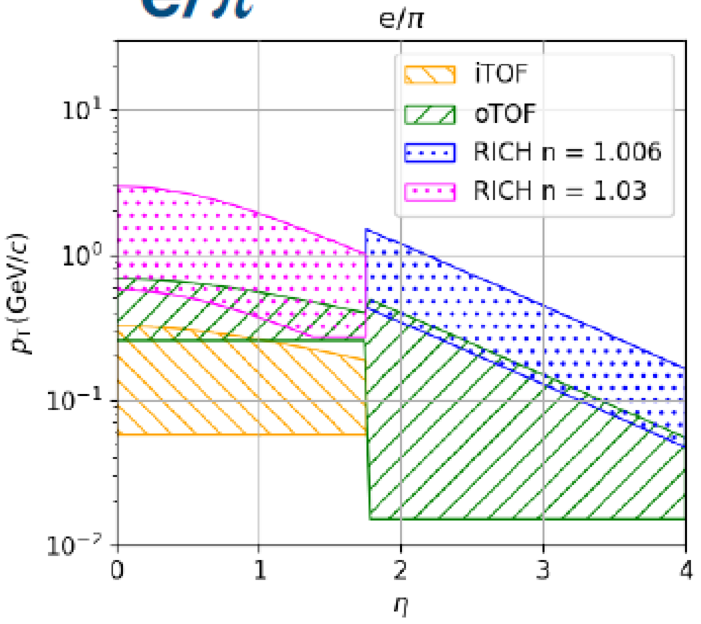
Baseline for charged particle detectors:
scintillator bars + wave-length shifting fibers + SiPM



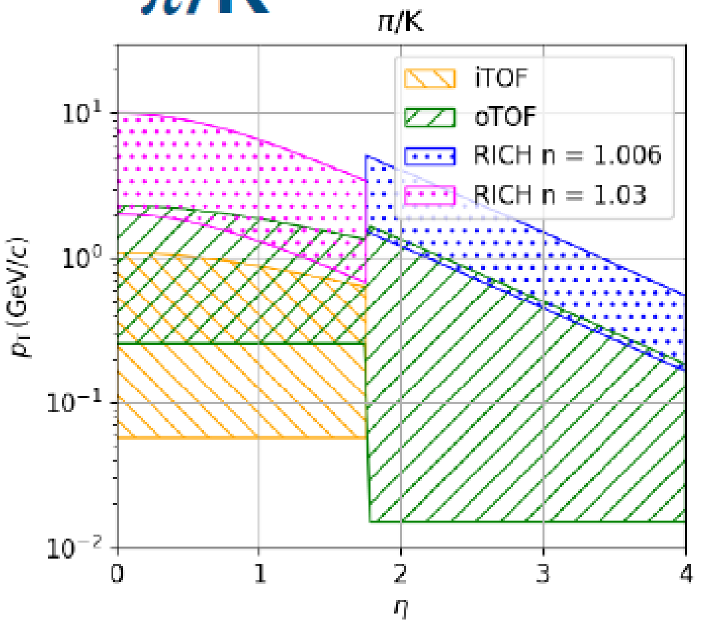
Technologies under study:

- scintillators + SiPM
- multi-wire chambers
- resistive plate chambers

e/π


e/π
iTOF
oTOF
RICH n = 1.006
RICH n = 1.03
p_T (GeV/c)
η

π/K


π/K
iTOF
oTOF
RICH n = 1.006
RICH n = 1.03
p_T (GeV/c)
η

ALICE3 core cost (without labor and contingency)

- **170.2 MCHF for the baseline**
- **Fair share for China team with 15 M&O members**
  - **2.7% compared to 1.5% core contribution up to now (ALICE1 & ALICE2)**
  - **4.5 MCHF (about 36 MCNY)**