6th EUROPEAN NUCLEAR PHYSICS CONFERENCE (EuNPC25)
Caen, France, 22-26 September 2025

ALICE upgrades for LHC Run 4 and beyond

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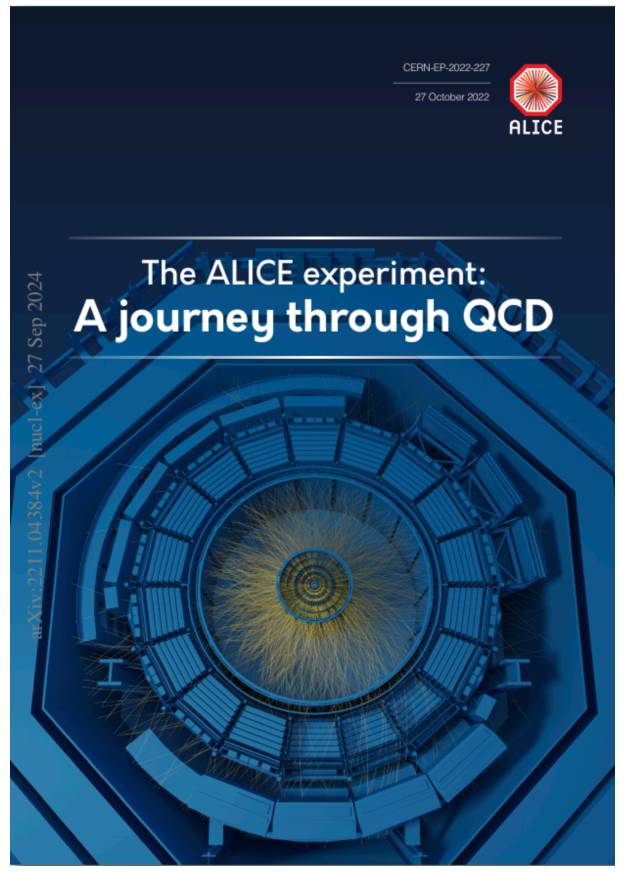
University and INFN Bari
on behalf of
ALICE Collaboration

A journey through QCD

High luminosity for ions | HL-LHC | Higher luminosities for ions

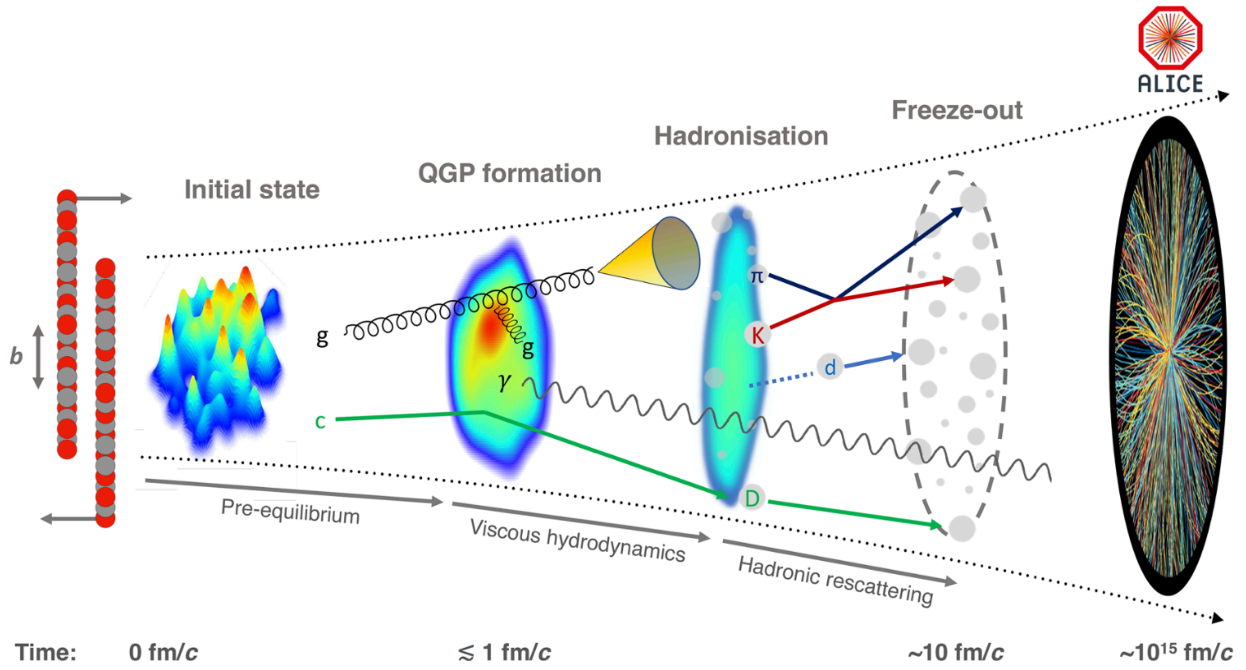
Run 1	Run 2	Run 3	Run 4	Run 5
2009 - 2013	2015 - 2018	2022 - 2025	2030 - 2033	2036 - 2041
ALICE 1		ALICE 2	ALICE 2.1 upgrade	ALICE 3 upgrade



"The ALICE experiment: a journey through QCD"
Eur. Phys. J. C (2024) 84:813

List of key scientific questions concerning QGP/QCD:

A. What are the thermodynamic properties of the QGP?
B. What are the hydrodynamic and transport properties of the QGP?
C. How does the QGP affect the formation of hadrons?
D. How does the QGP affect the propagation of energetic partons?
E. How does deconfinement in the QGP affect the QCD force?
F. Can the QGP lead to discovery of novel QCD effects?
G. What are the minimal conditions of QGP formation?
H. What is the nature of the initial state of heavy-ion collisions?
I. What is the nature of hadron–hadron interactions?



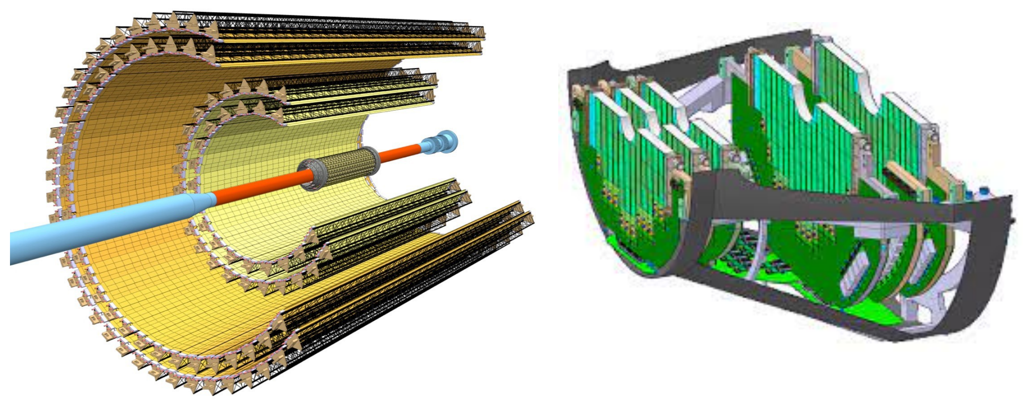
Evolution of a heavy-ion collision

A journey through QCD - ALICE R&D roadmap

High luminosity for ions — HL-LHC — Higher luminosities for ions

Run 1	Run 2	Run 3	Run 4	Run 5
2009 - 2013	2015 - 2018	2022 - 2025	2030 - 2033	2036 - 2041
ALICE 1		**ALICE 2**	**ALICE 2.1 upgrade**	**ALICE 3 upgrade**

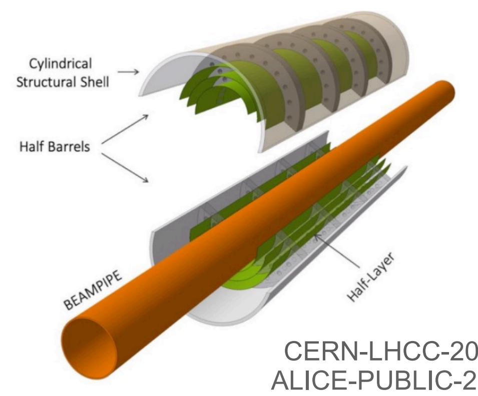
LS2 upgrades



ITS2+MFT
Largest MAPS based tracker/vertexer

2024 JINST 19 P05062

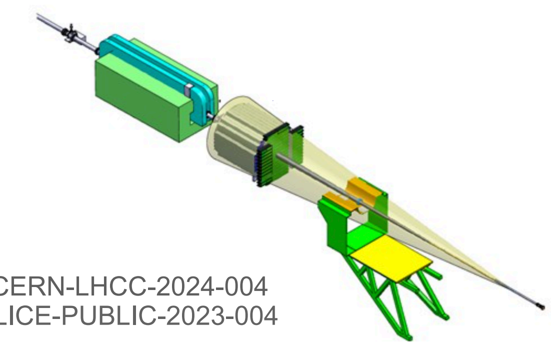
LS3 upgrades



CERN-LHCC-2024-003
ALICE-PUBLIC-2023-002

ITS3
First wafer-size bent MAPS with ultra-light support structures

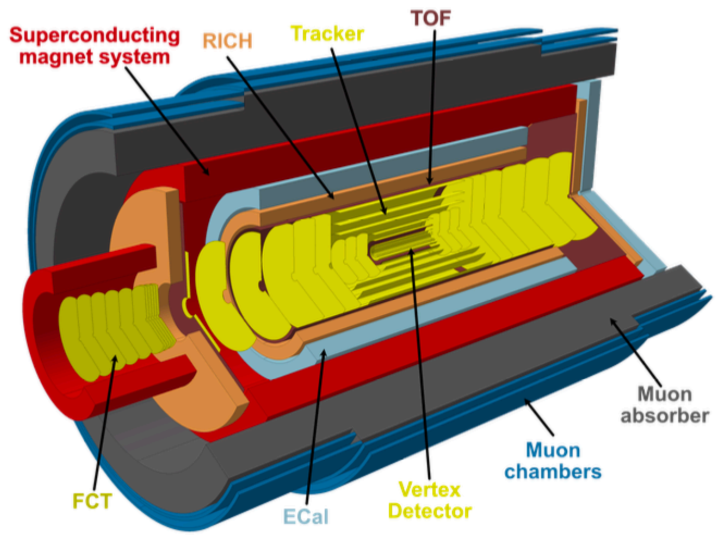
FoCal
First MAPS based electromagnetic calorimeter



CERN-LHCC-2024-004
ALICE-PUBLIC-2023-004

Paola La Rocca, Monday 22/9, 17:20:
"ITS3 in ALICE: pioneering bendable wafer-scale sensors for LHC Run 4"

LS4 upgrades



ALICE 3
All-silicon nearly massless detector

CERN-LHCC-2022-009 CERN-LHCC-2025-02

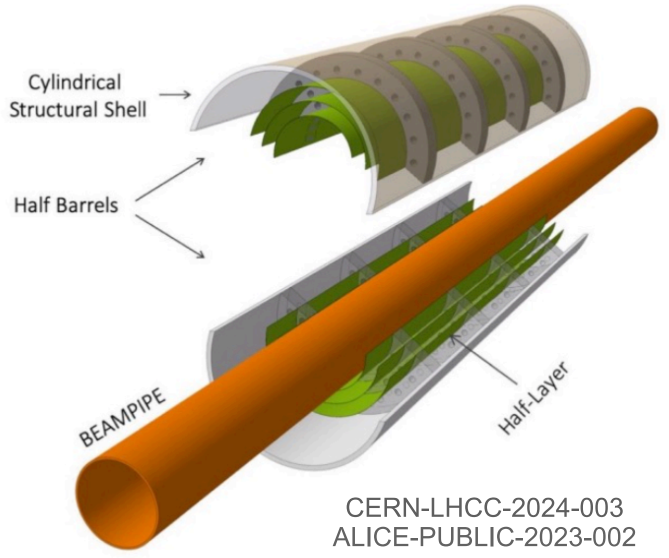
David Chinellato, Thursday 25/9, 9:00:
"Future physics programme and facilities for relativistic heavy-ion collisions"

A long R&D journey toward a compact detector featuring a very low-mass, all-silicon tracker with excellent low-p_T performance, while also advancing innovative technologies relevant to future accelerator experiments (e.g., FCC).

Physics motivations

ITS3

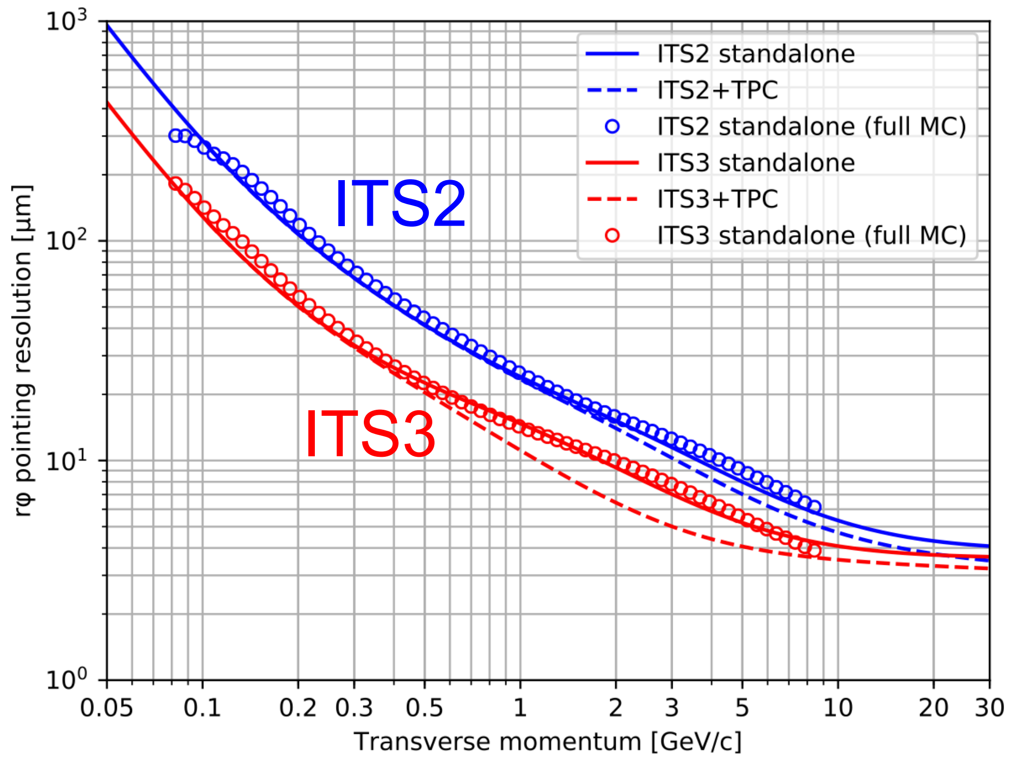
Truly cylindrical, wafer-size sensors for homogeneous inner tracker with ultra-low material budget

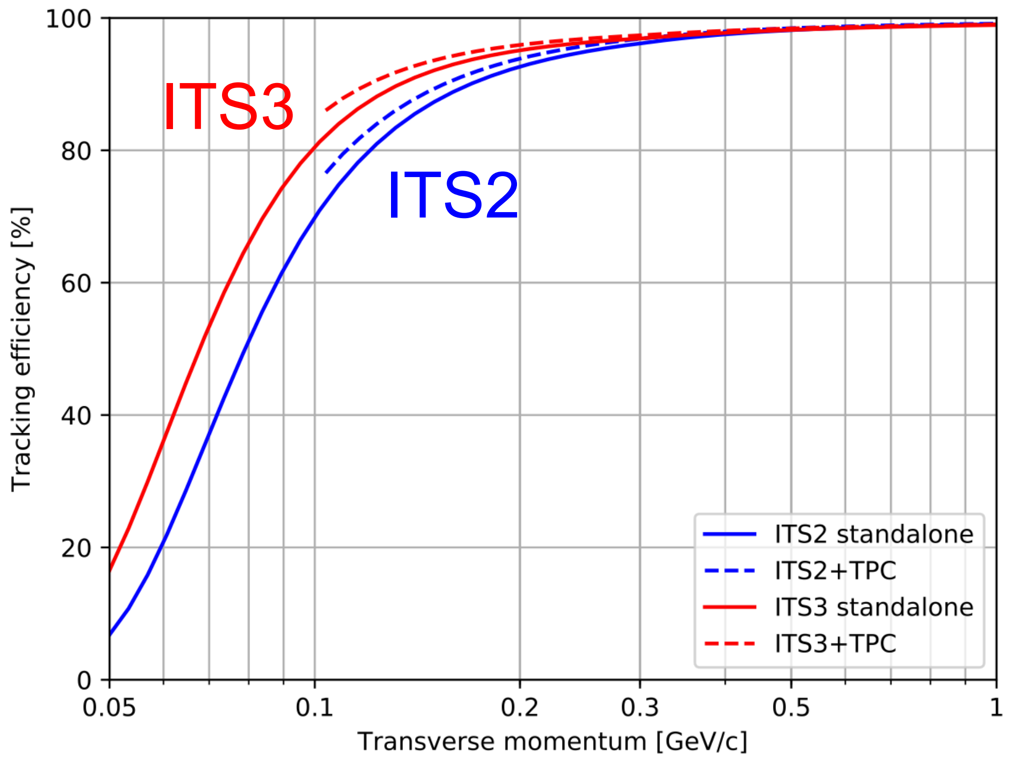


CERN-LHCC-2024-003
ALICE-PUBLIC-2023-002

Main goals

- Significantly extend the range of physics channels that can be measured in ALICE, especially at **very low transverse momentum**.
  - → heavy-quark hadrons (Λ_c^+, Ξ_c^+, Λ_b^0, B_s^0)
  - → strangeness tracking, boosting identification of Ω_c^0 and Ξ_c
  - → hypernuclei, c-deuteron
  - → dielectrons

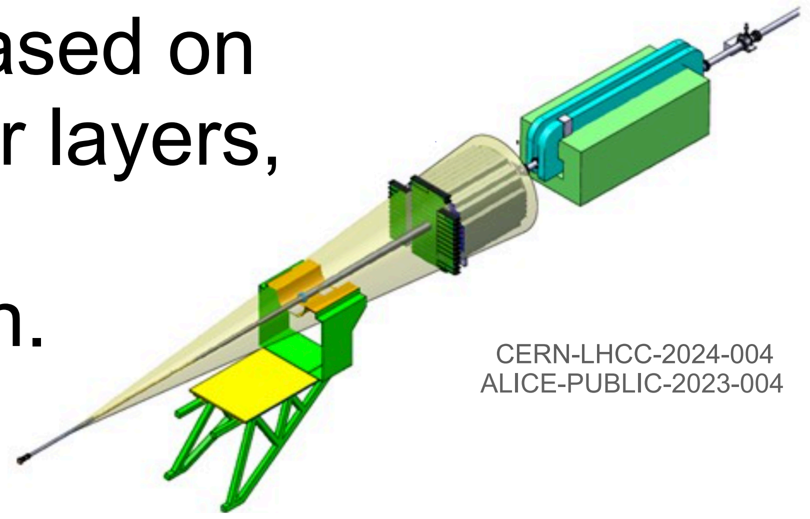




Paola La Rocca, Monday 22/9, 17:20:
"ITS3 in ALICE: pioneering bendable wafer-scale sensors for LHC Run 4"

Forward Calorimeter (FoCal)

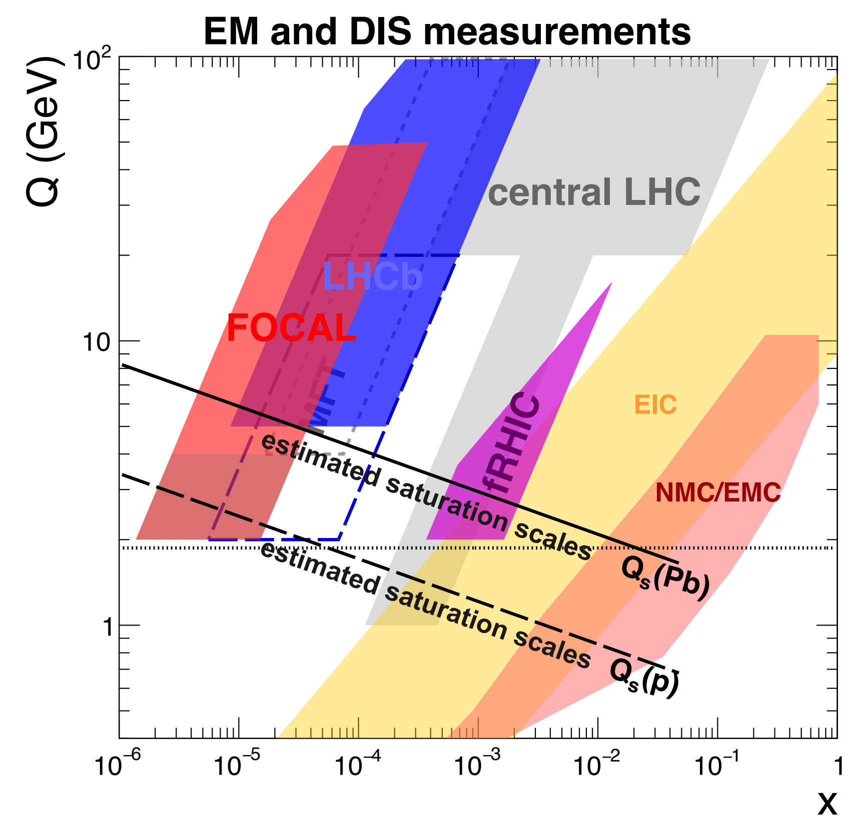
Highly compact sampling calorimeter based on extremely high-granularity silicon sensor layers, designed to provide precise shower reconstruction in the very forward region.



CERN-LHCC-2024-004
ALICE-PUBLIC-2023-004

Main goals

- Constrain gluon nuclear PDF at small Bjorken-x
  - → Isolated photons at forward rapidity
- Investigate non-linear QCD evolution
  - → Azimuthal π^0–π^0 correlations and isolated γ–π^0 correlations
- Quantify parton energy loss at forward rapidity
  - → High-p_T neutral pion production



Approximate (x,Q) coverage of various experiments for regions probed by deep inelastic scattering measurements

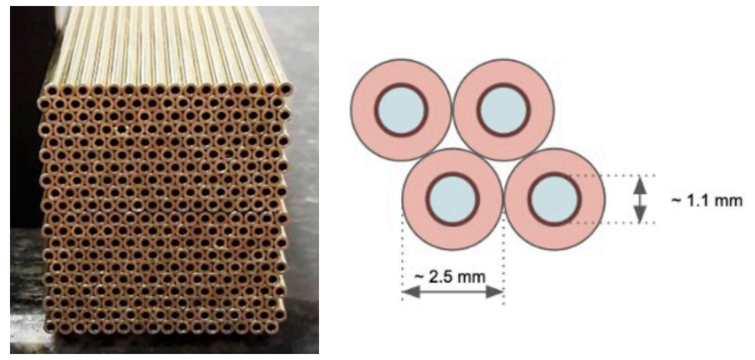
ALICE 2.1

Forward Calorimeter (FoCal)

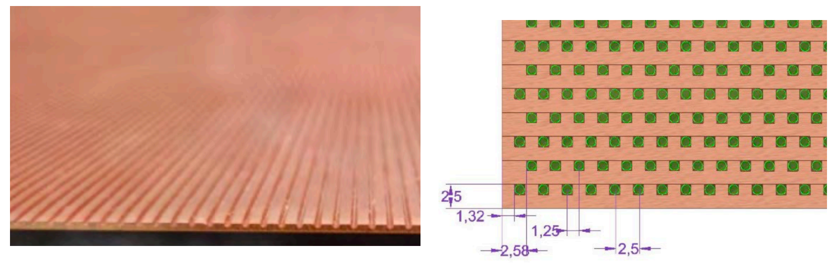
FoCal-H - Conventional metal-scintillator sampling hadronic calorimeter

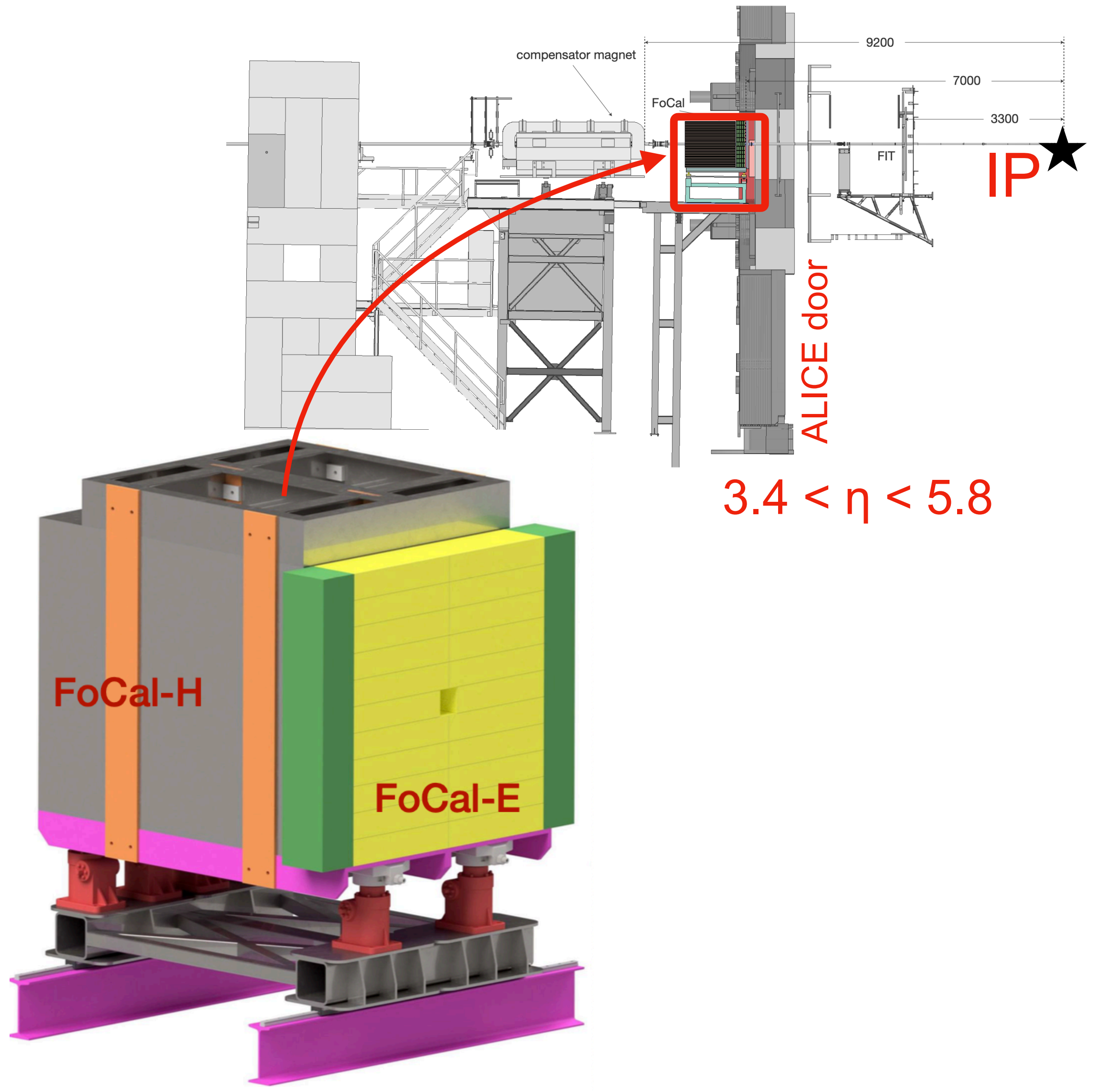
Two designs under evaluation:

A) Cu capillary-tubes enclosing BCF scintillating fibers

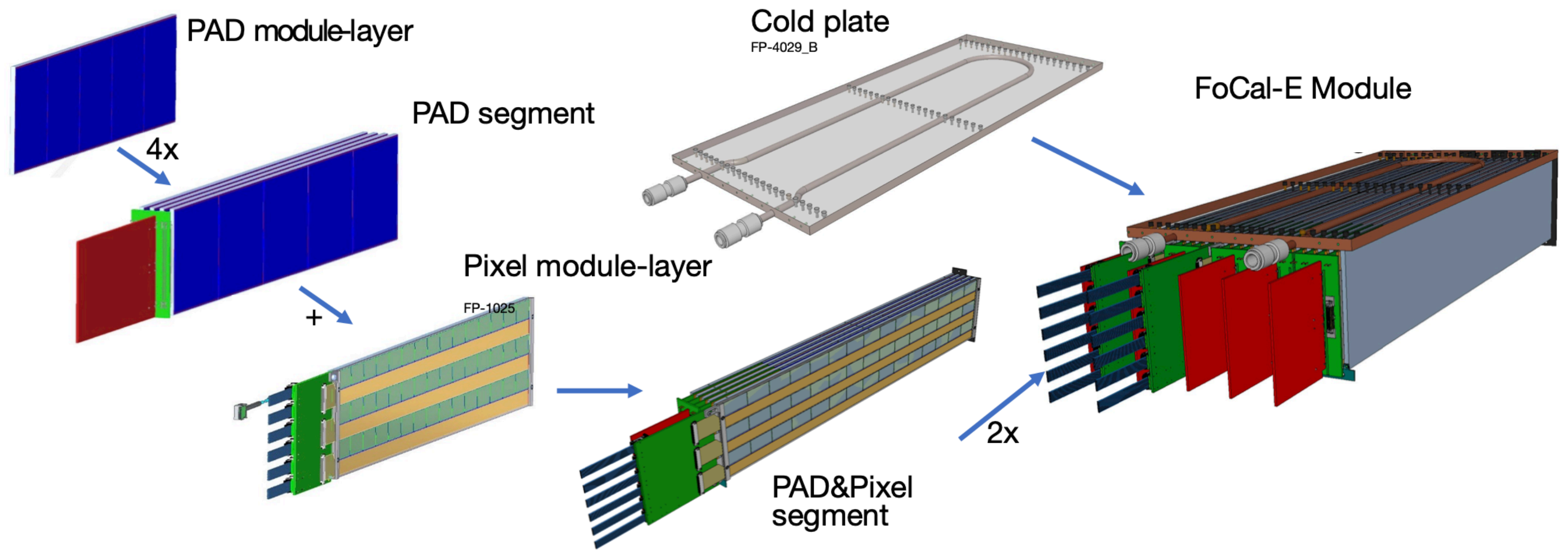


B) Cu grooved plates enclosing BCF scintillating fibers

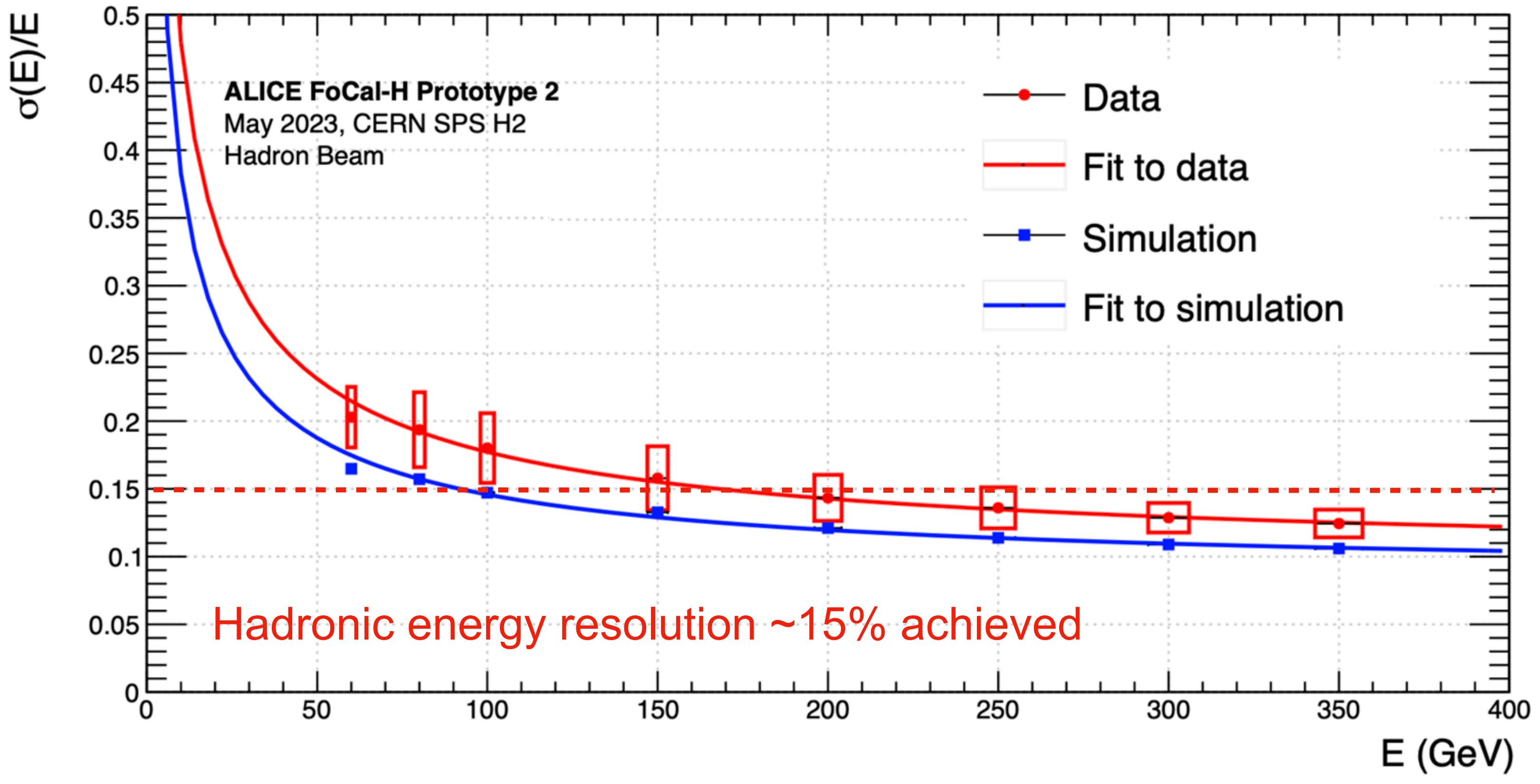




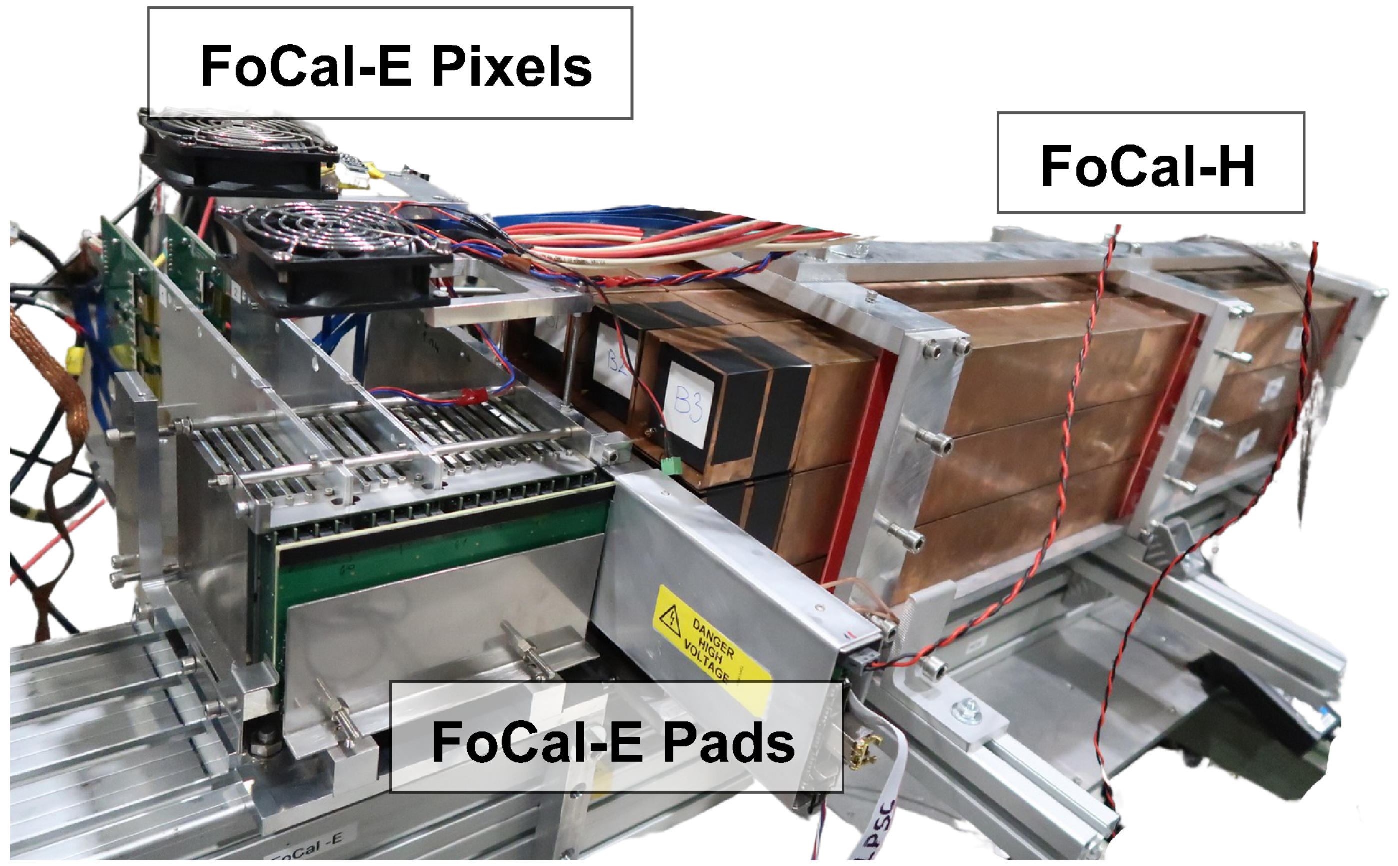
FoCal-E - High granularity Si-W sampling electromagnetic calorimeter

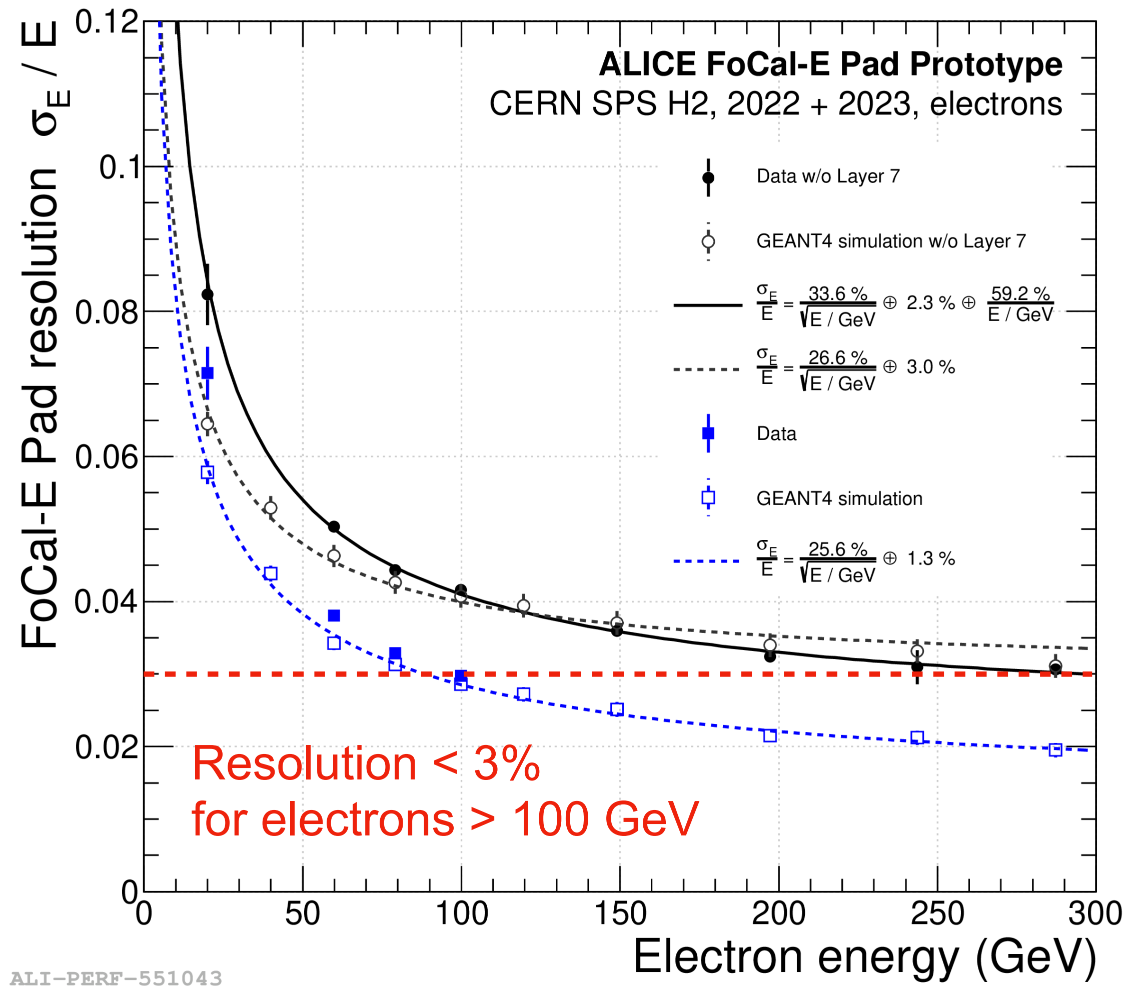


Longitudinally segmented in low granularity analog PAD layers and high granularity digital MAPS layers



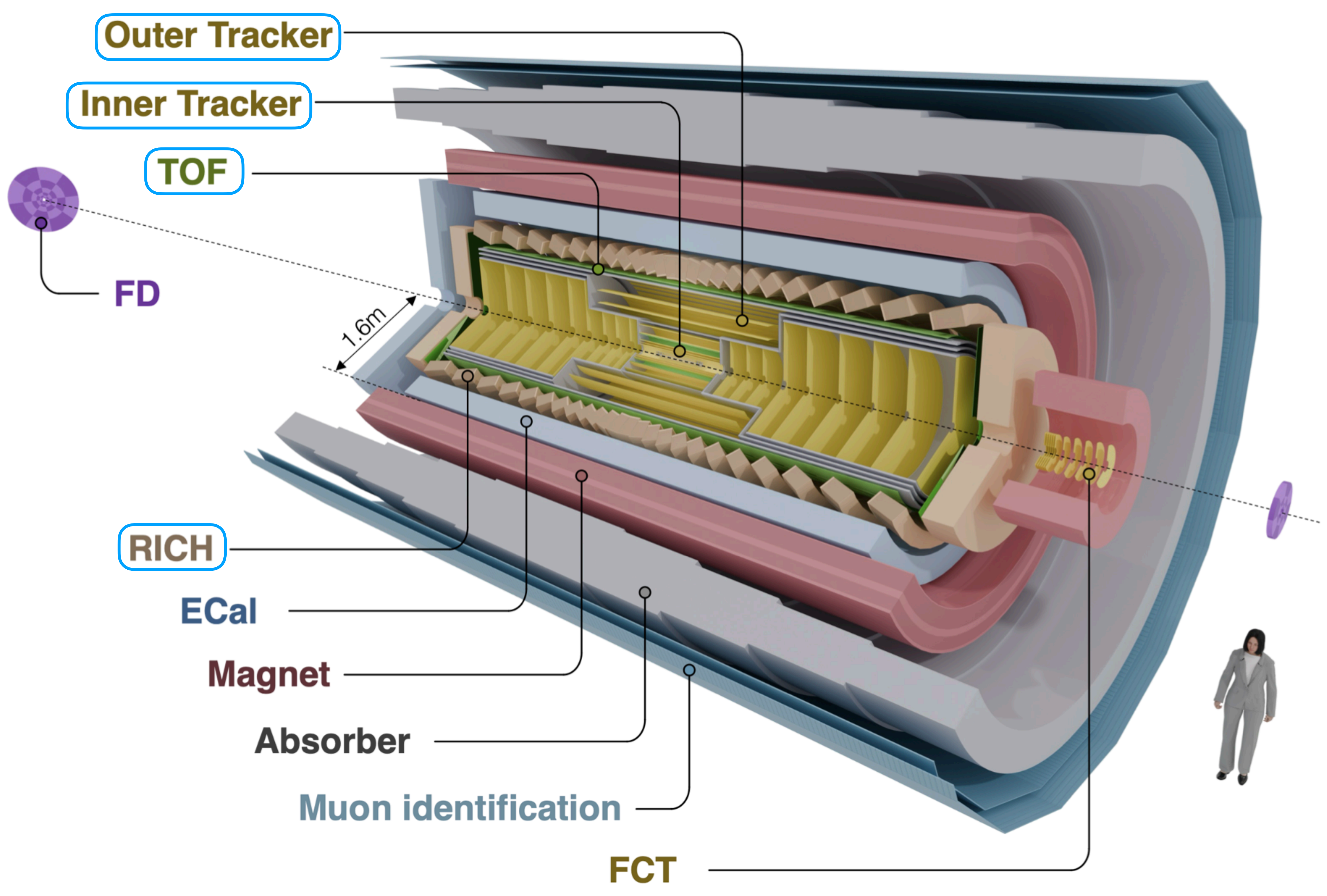
FoCal Test Beam setup at H2 (May 2023)





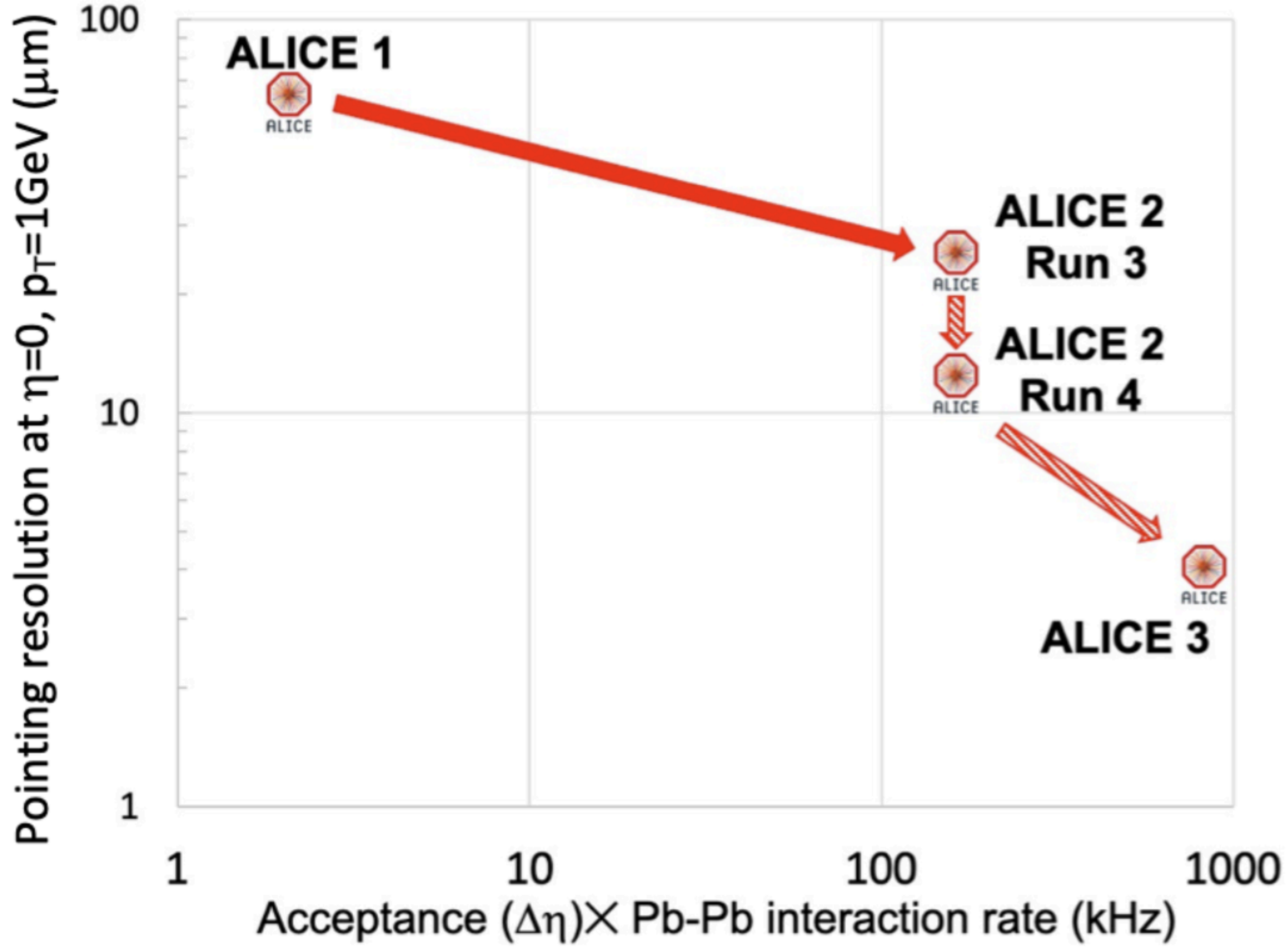
ALICE 3

Detector concept



Key features

- Compact **all-silicon tracker** with **high-resolution** retractable vertex detector
- Superconducting solenoidal magnet system at 2 T
- **Particle Identification** over large acceptance: muons, electrons, hadrons, photons
- Large acceptance: η < 4
- **Fast read-out** and online processing



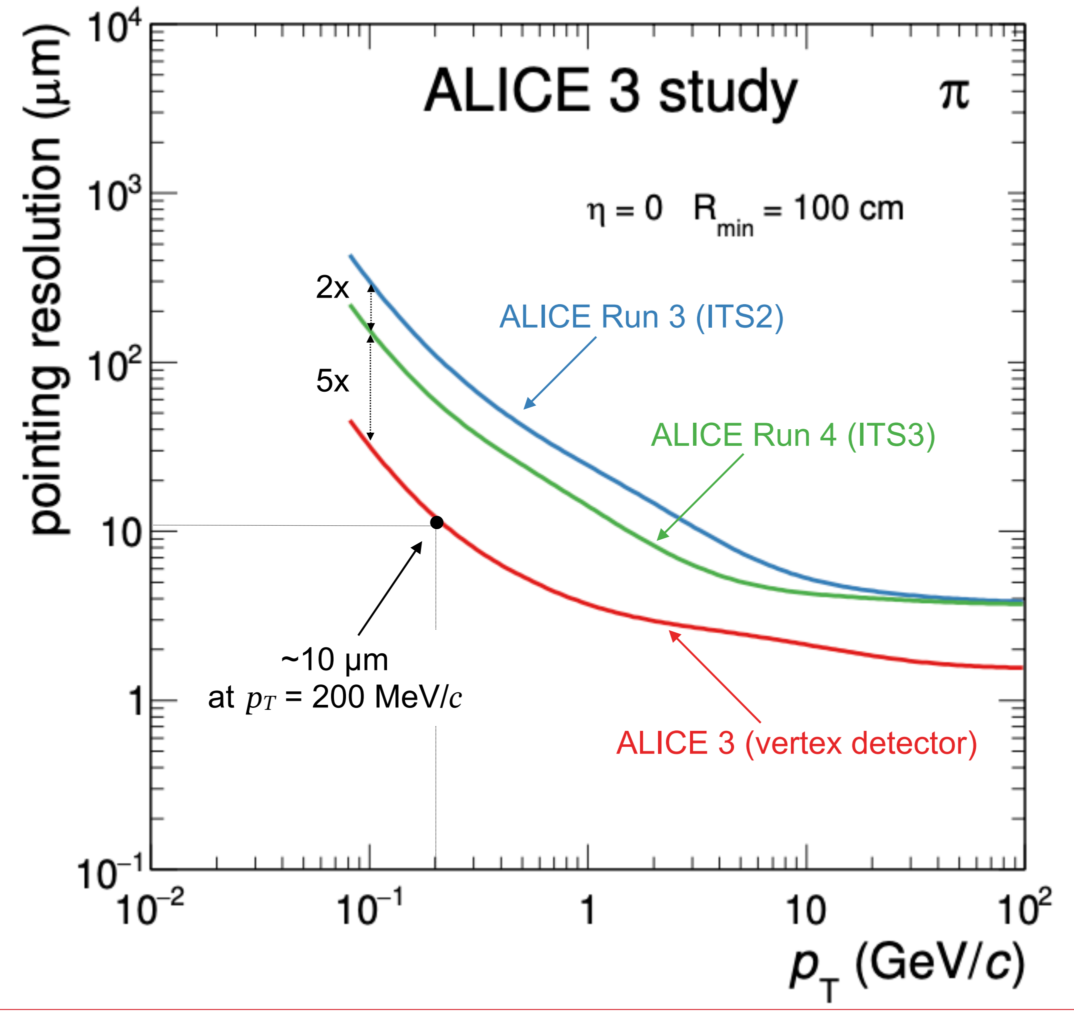
ALICE 3
Vertex detector

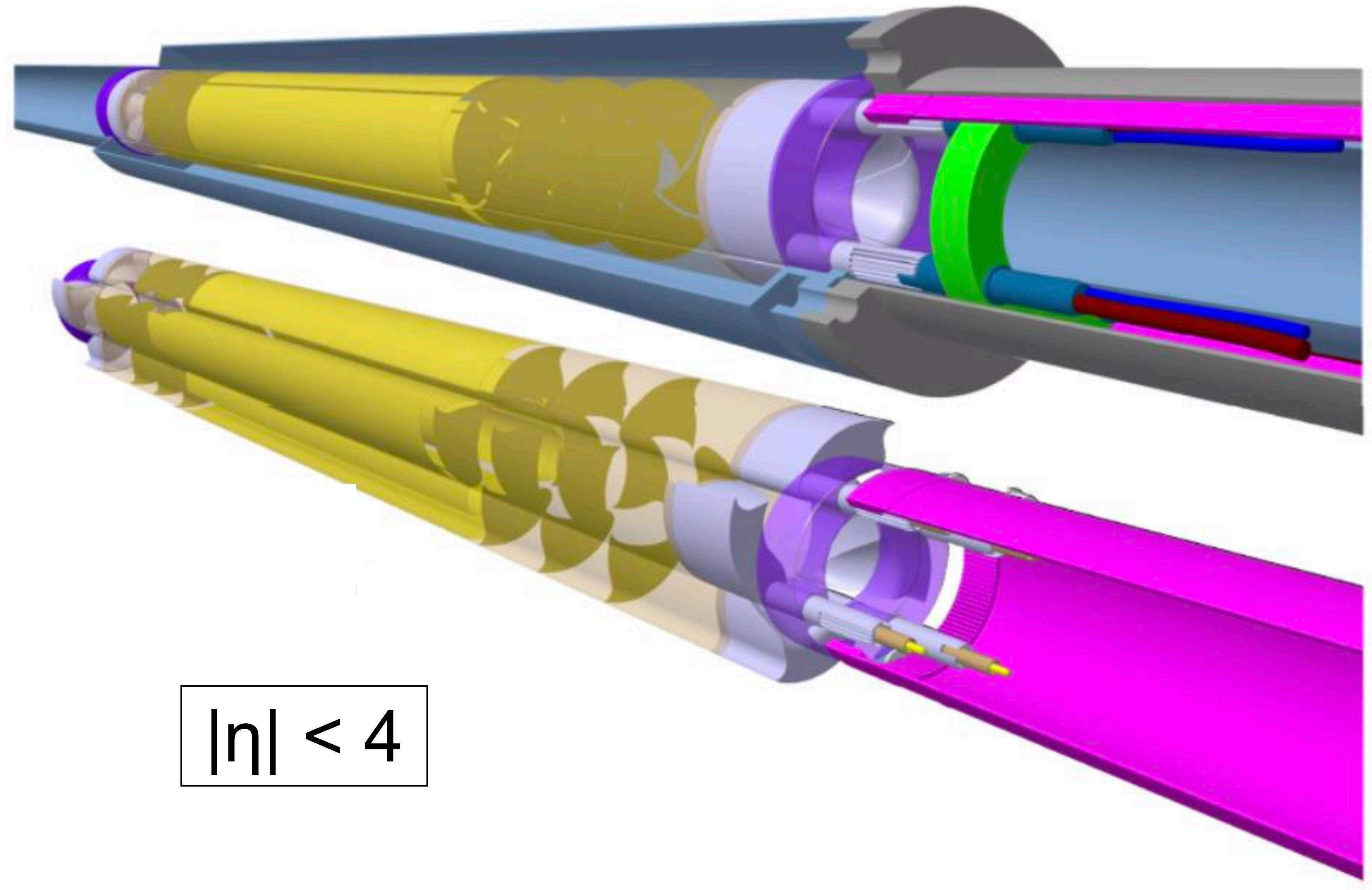
Requirements
- Pointing resolution
  - ~10 μm @ p_T = 200 MeV/c
  - $\propto r_0 \cdot X/X_0 \rightarrow r_0$ = 5 mm & X/X_0 ~ 0.1% / layer
- Spatial resolution 2.5 μm → 10 μm pixel pitch
- Time resolution ~100 ns

Implementation
- Wafer-sized, bent MAPS (leveraging ITS3 R&D)
- Retractable detector: 3 (barrel) + 3·2(disk) layers in secondary vacuum within the beam pipe

Challenges
- Mechanics
- Integration in vacuum
- Radiation tolerance

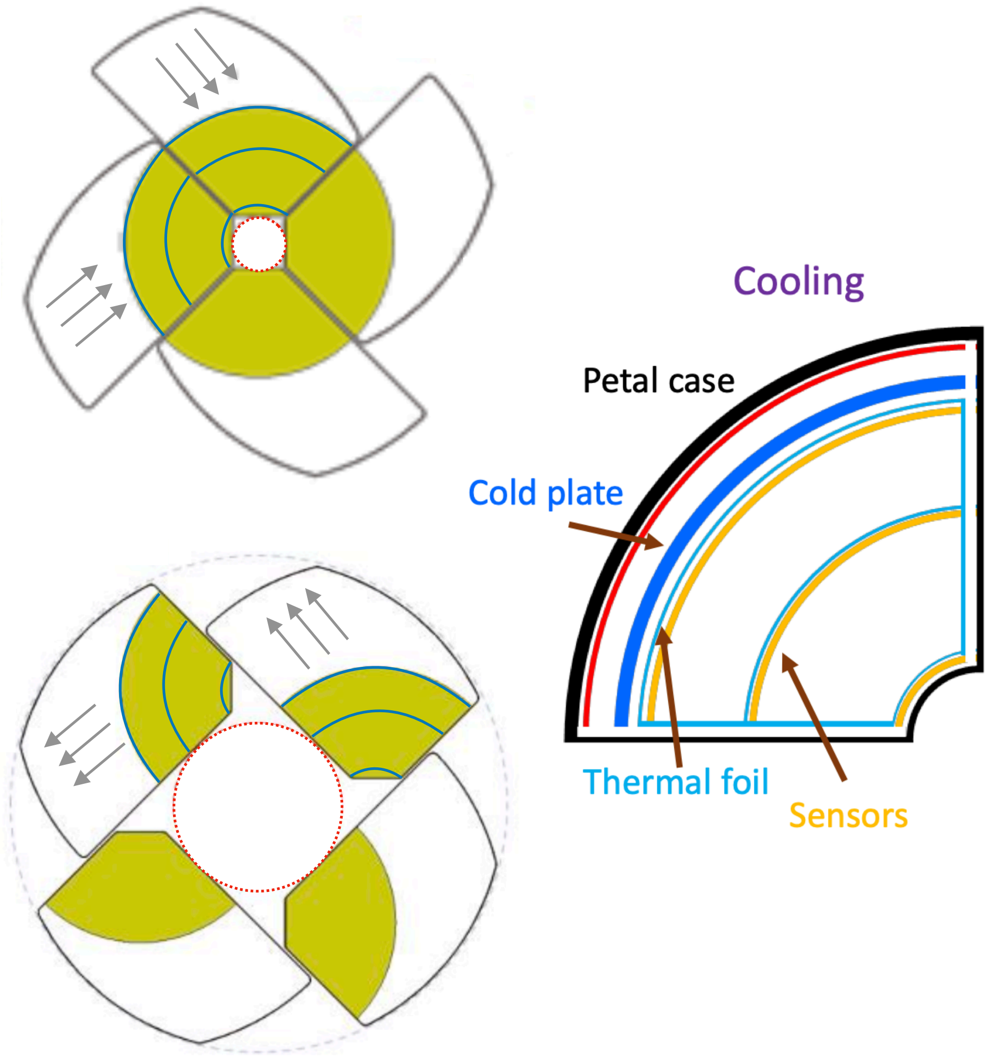
NIEL (MeV n_{eq}/cm^2)	TID (Mrad)
10^{16}	300

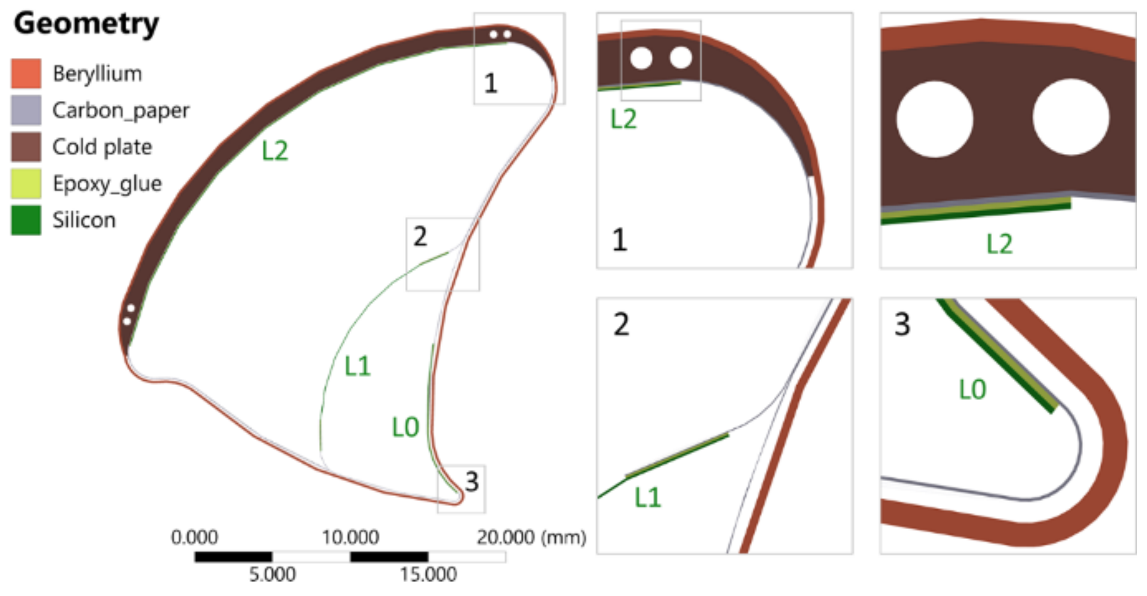


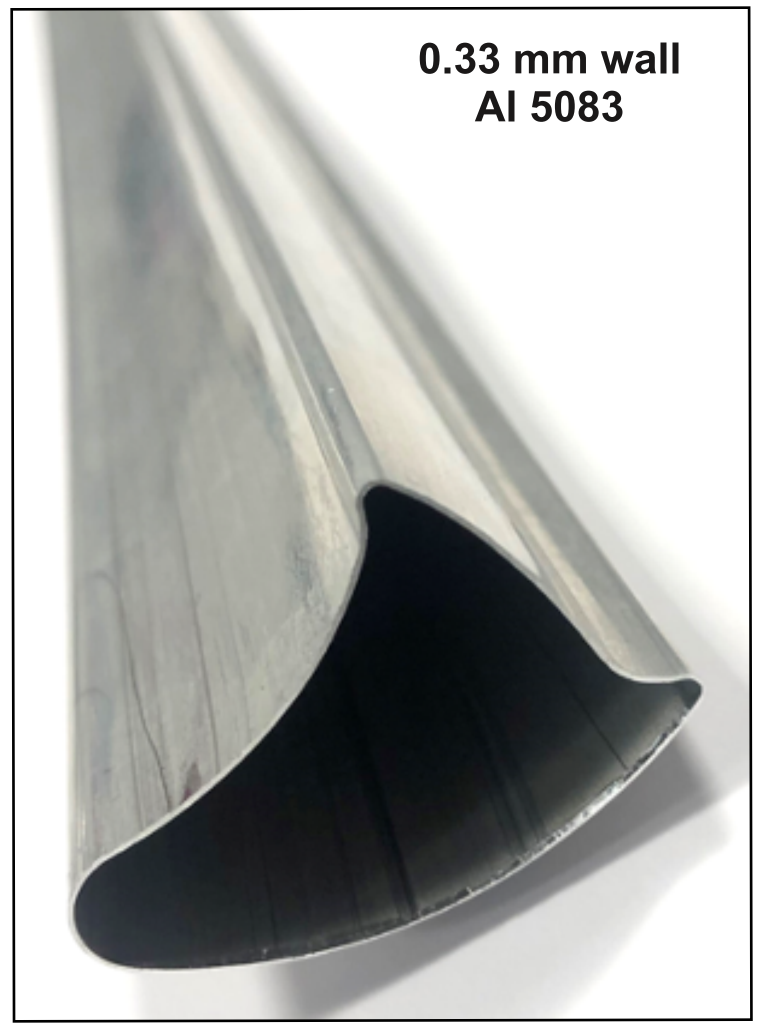


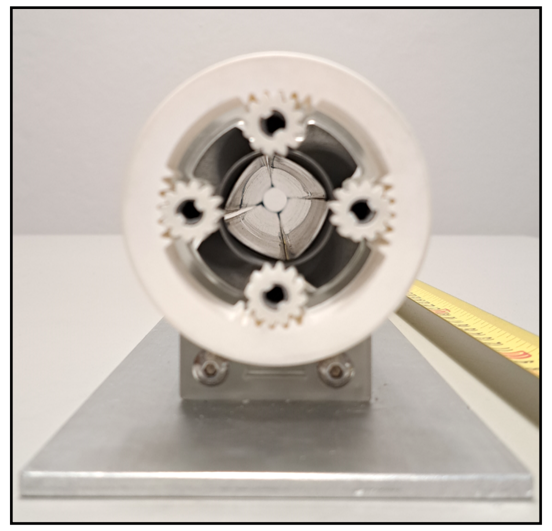
Stable beam → Closed petals (5 mm)

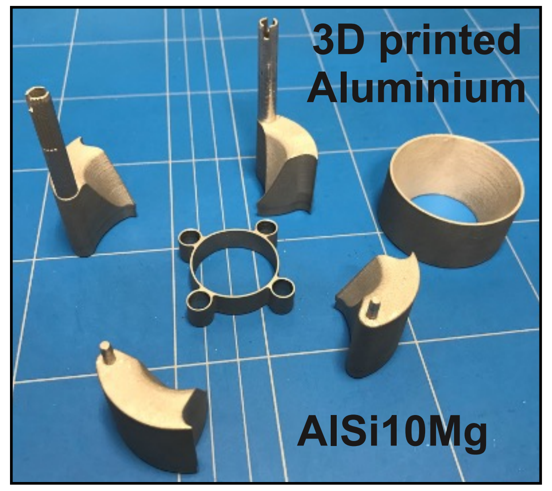
Beam injection → Open petals









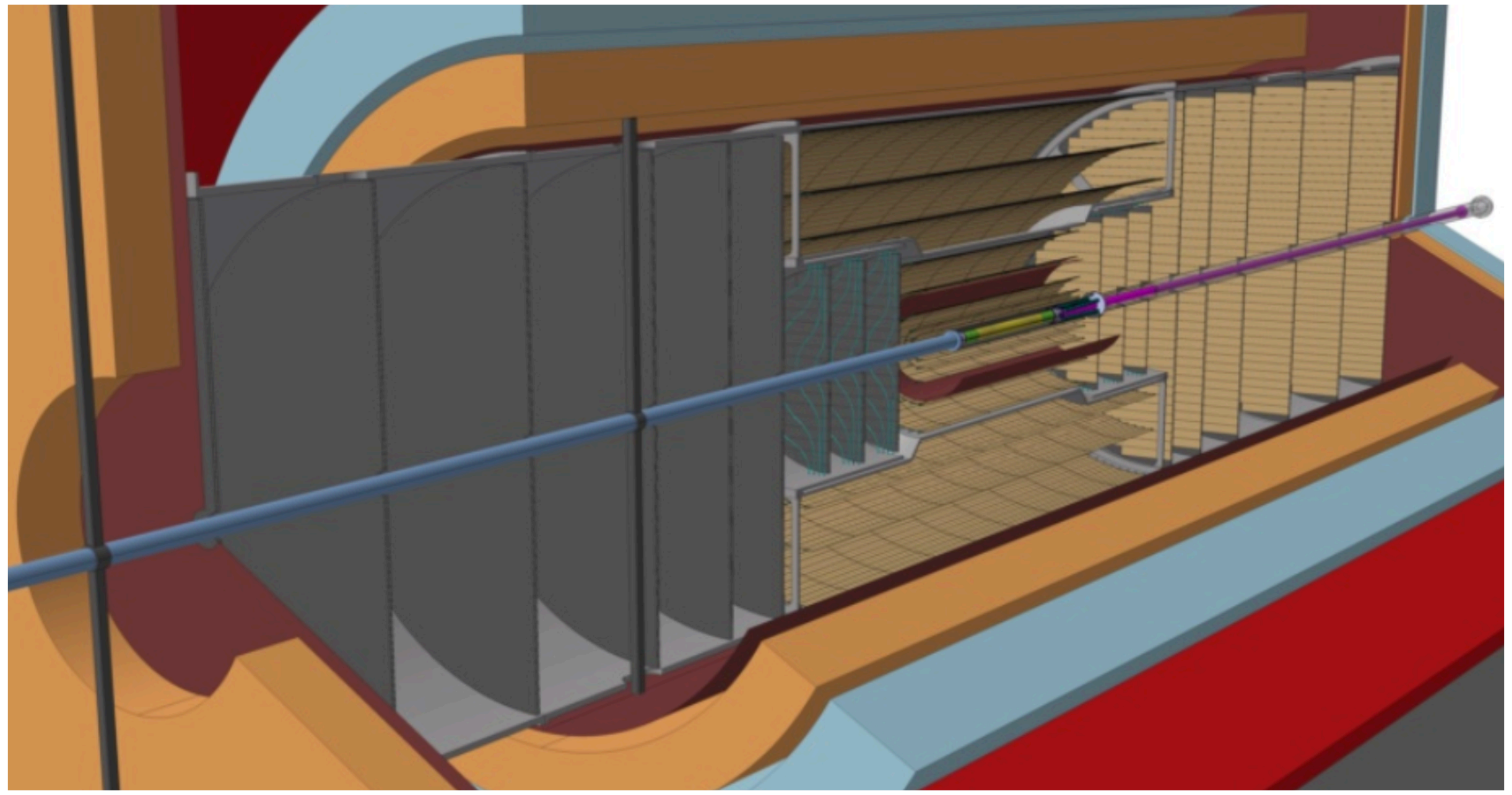


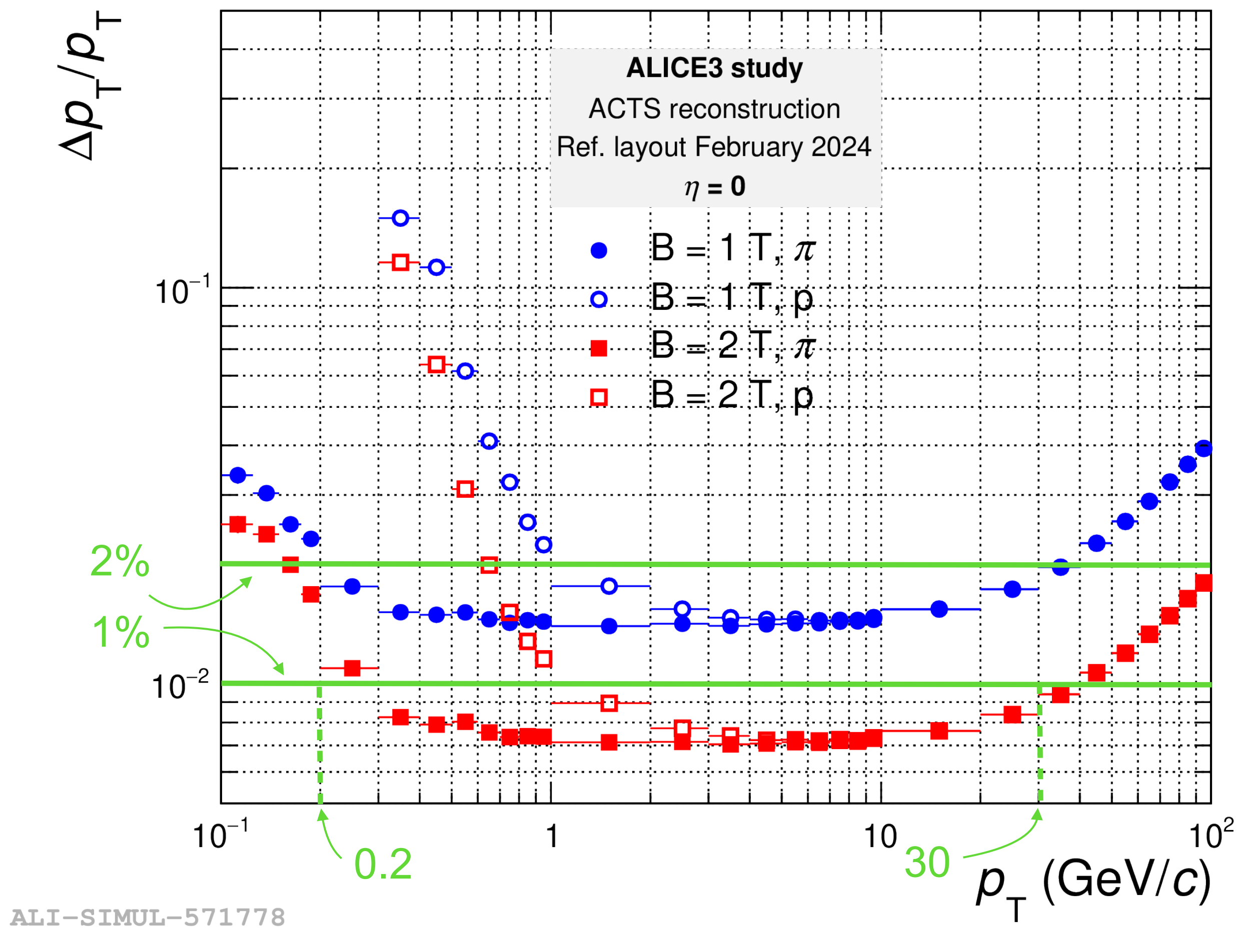
Tracker middle and outer layers

Requirements
- Transverse momentum resolution
  - ~1% up to |η| = 4
  - ∝ $X/X_0 \rightarrow X/X_0$ ~ 1% / layer
- Position resolution ~10 μm → 50 μm pitch
- Time resolution ~100 ns

Implementation
- MAPS ~60 m² active area
- 8 (barrel) + 9·2 (disk) layers
- R_{out} ~ 80 cm, z_{disc} < 3.5 m

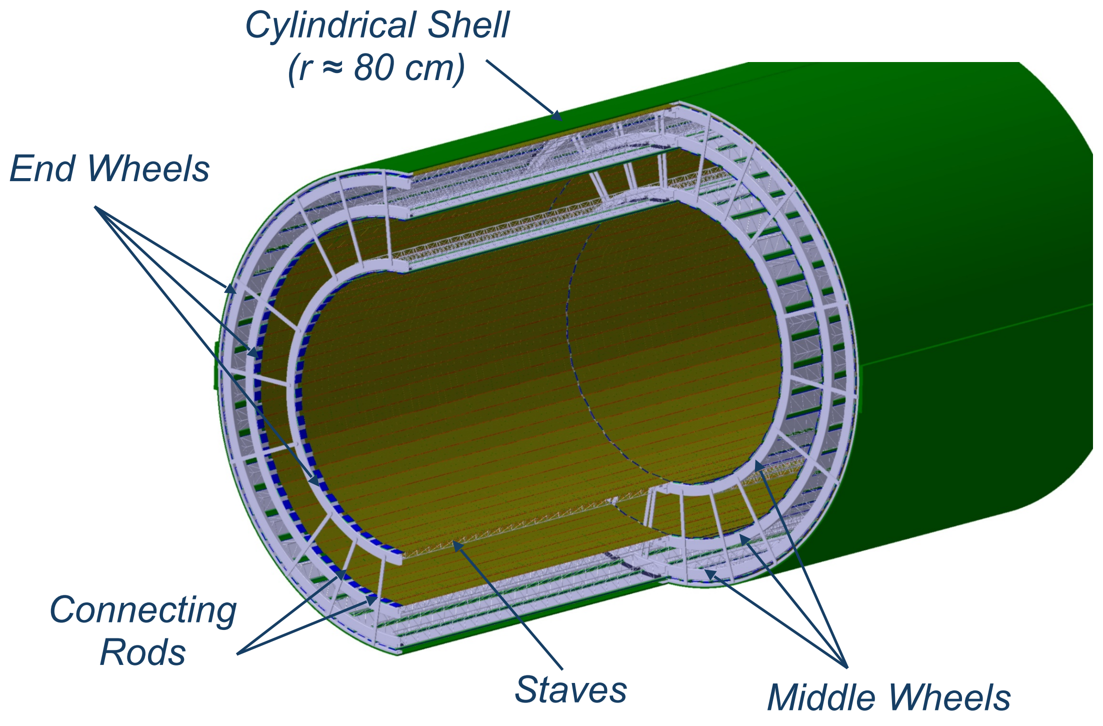
Challenges
- Industrialization of the module assembly
- power consumption



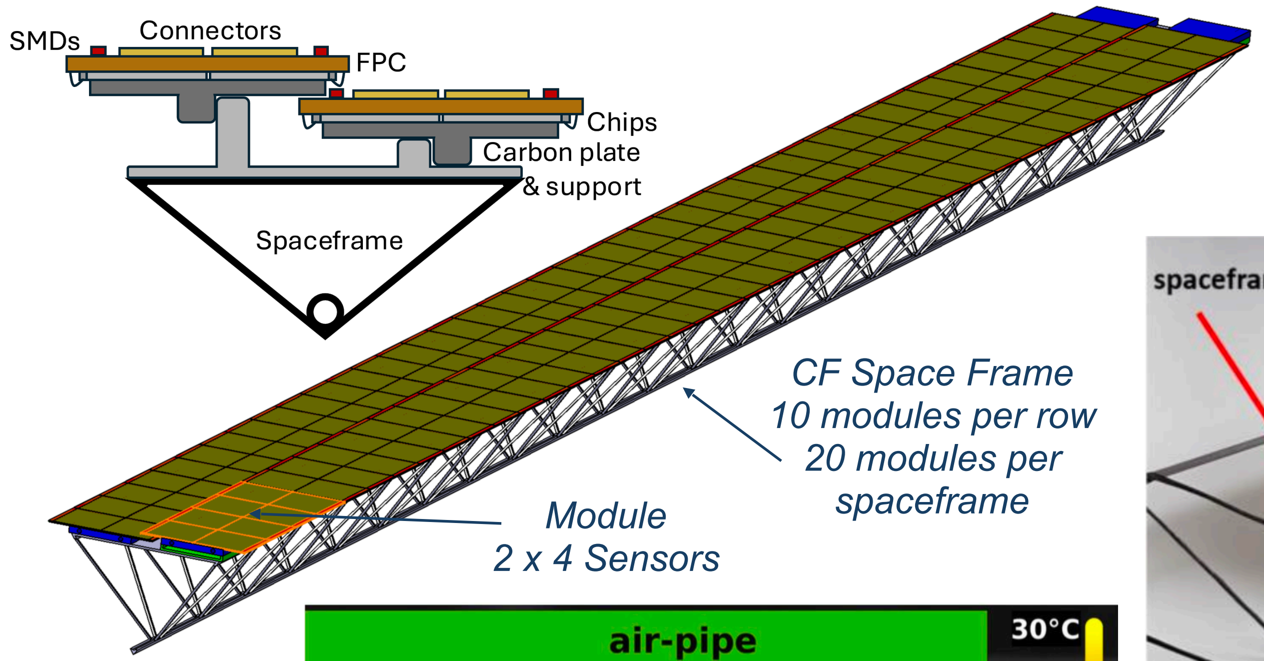


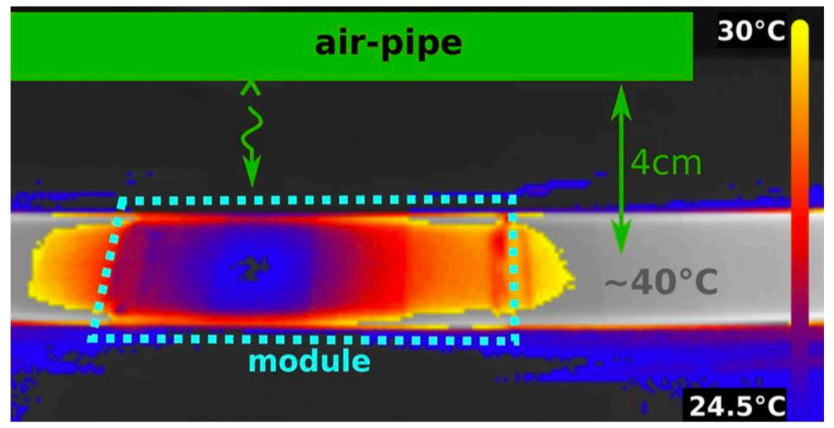
p_T resolution < 2% for mid-rapidity in the pion p_T range [0.2; 30] GeV/c

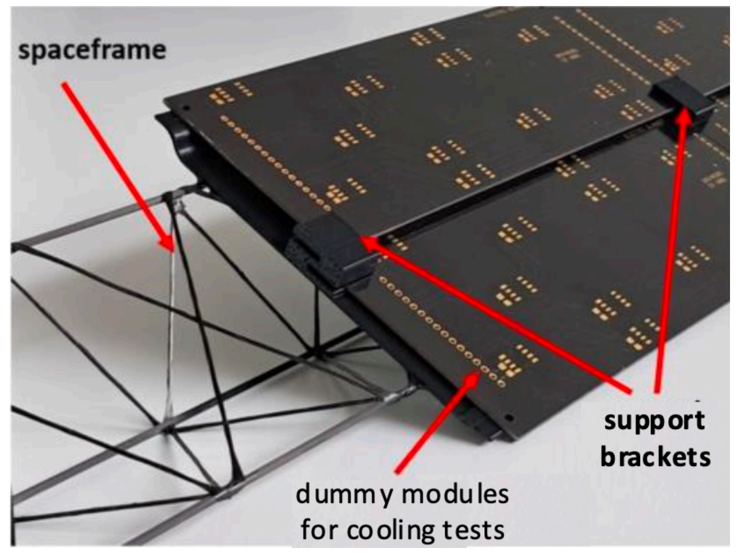
Outer layers



Stave based layers, cooled by air-flow

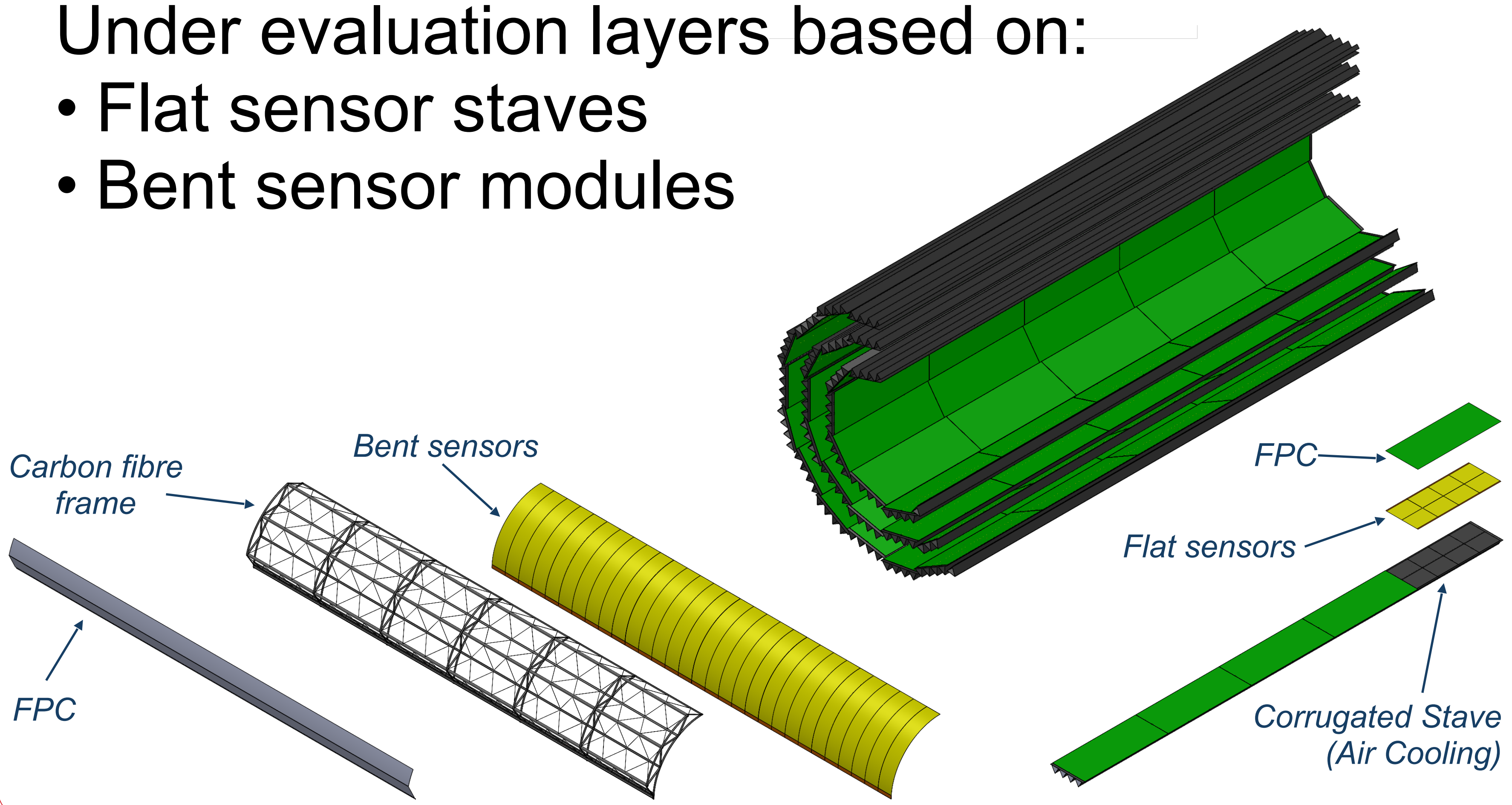






Middle layers

Under evaluation layers based on:
- Flat sensor staves
- Bent sensor modules



Particle Identification - Time Of Flight (TOF)

Requirements

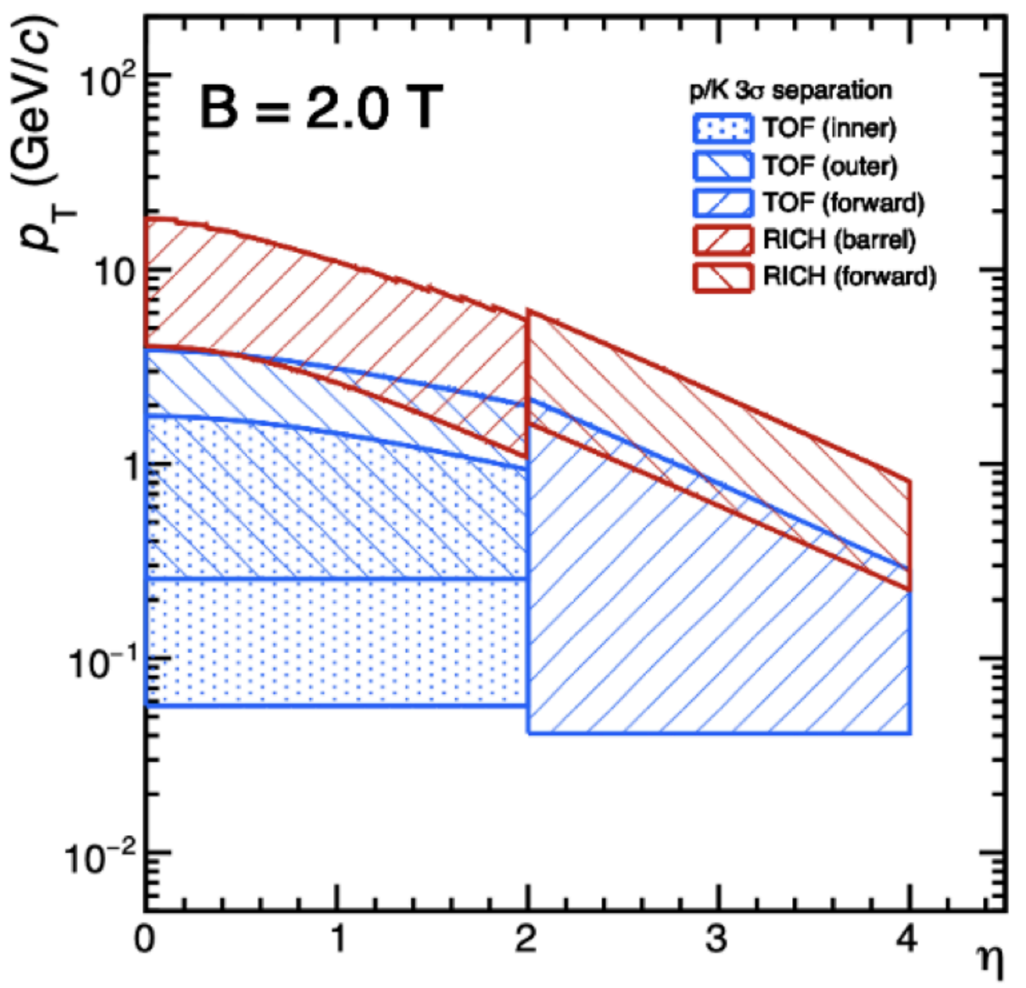
- e/π, π/K and K/p separation up to ~0.5, 2 and 4 GeV/c, respectively
  - ~1% up to |η| = 4
  - ∝ L/σ_{TOF} → σ_{TOF} ~ 20 ps

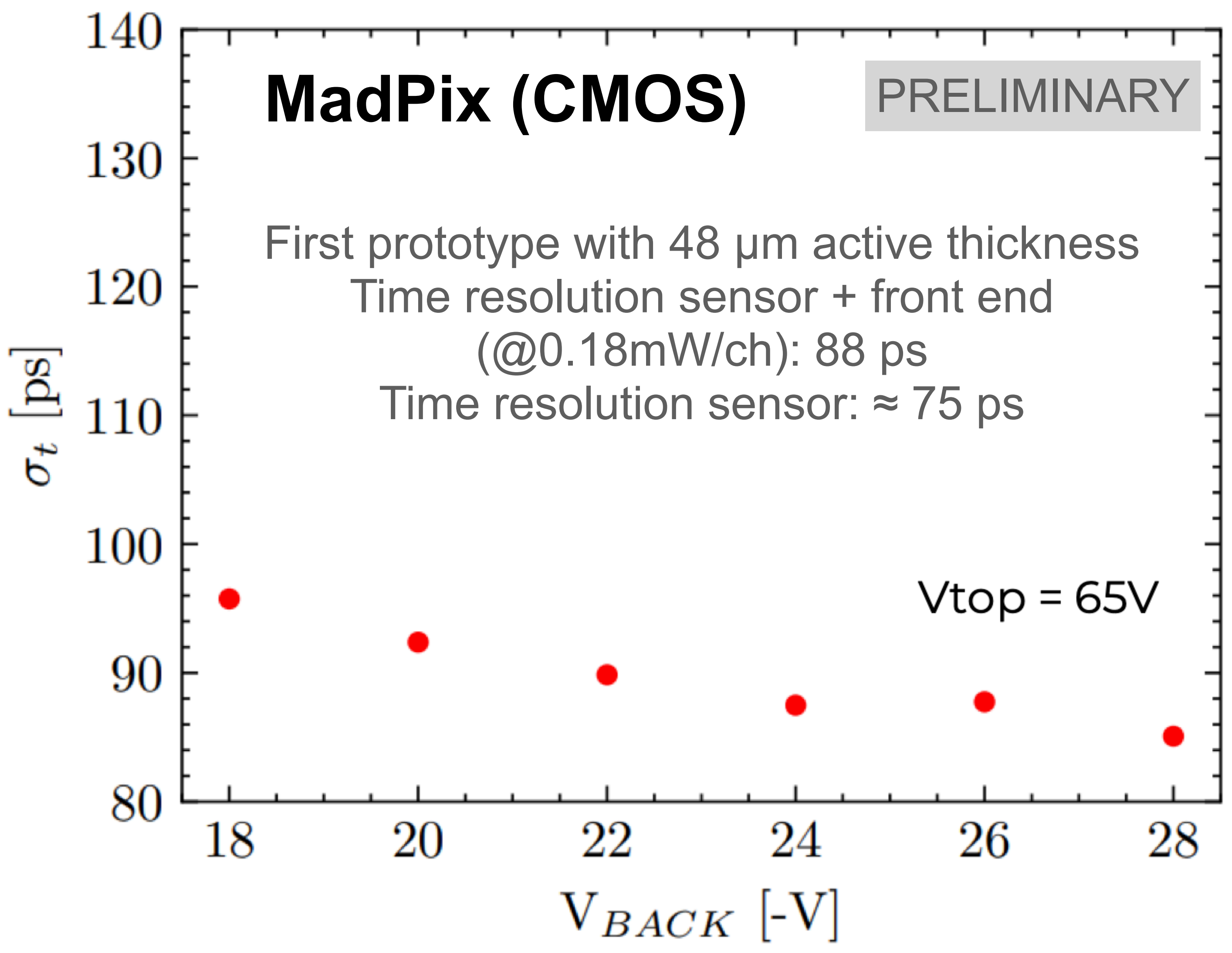
Implementation

- 2 barrel + 1 forward layers, 45 m^2

Challenges

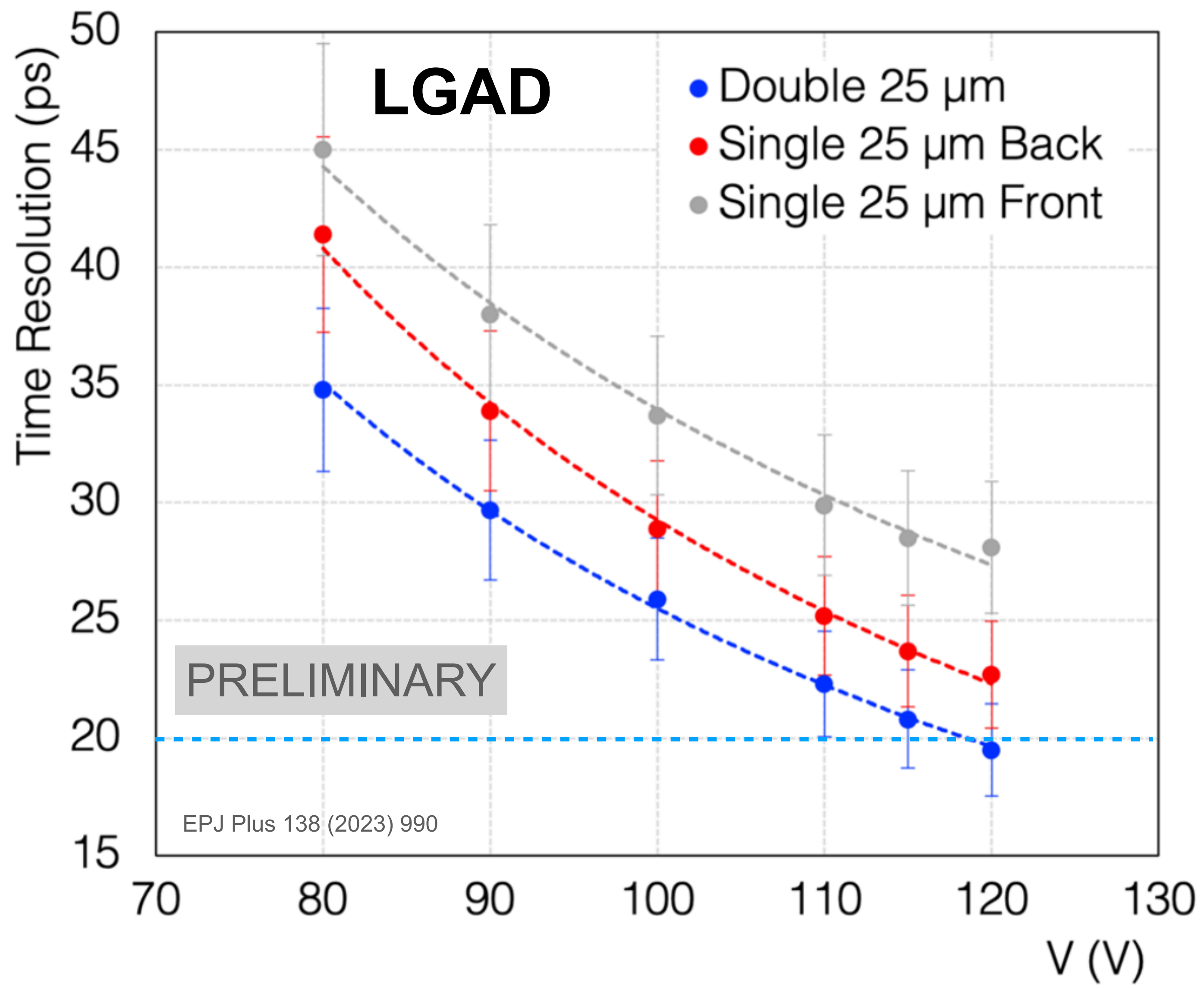
- Achievement of the target 20 ps time resolution at “full-system” level

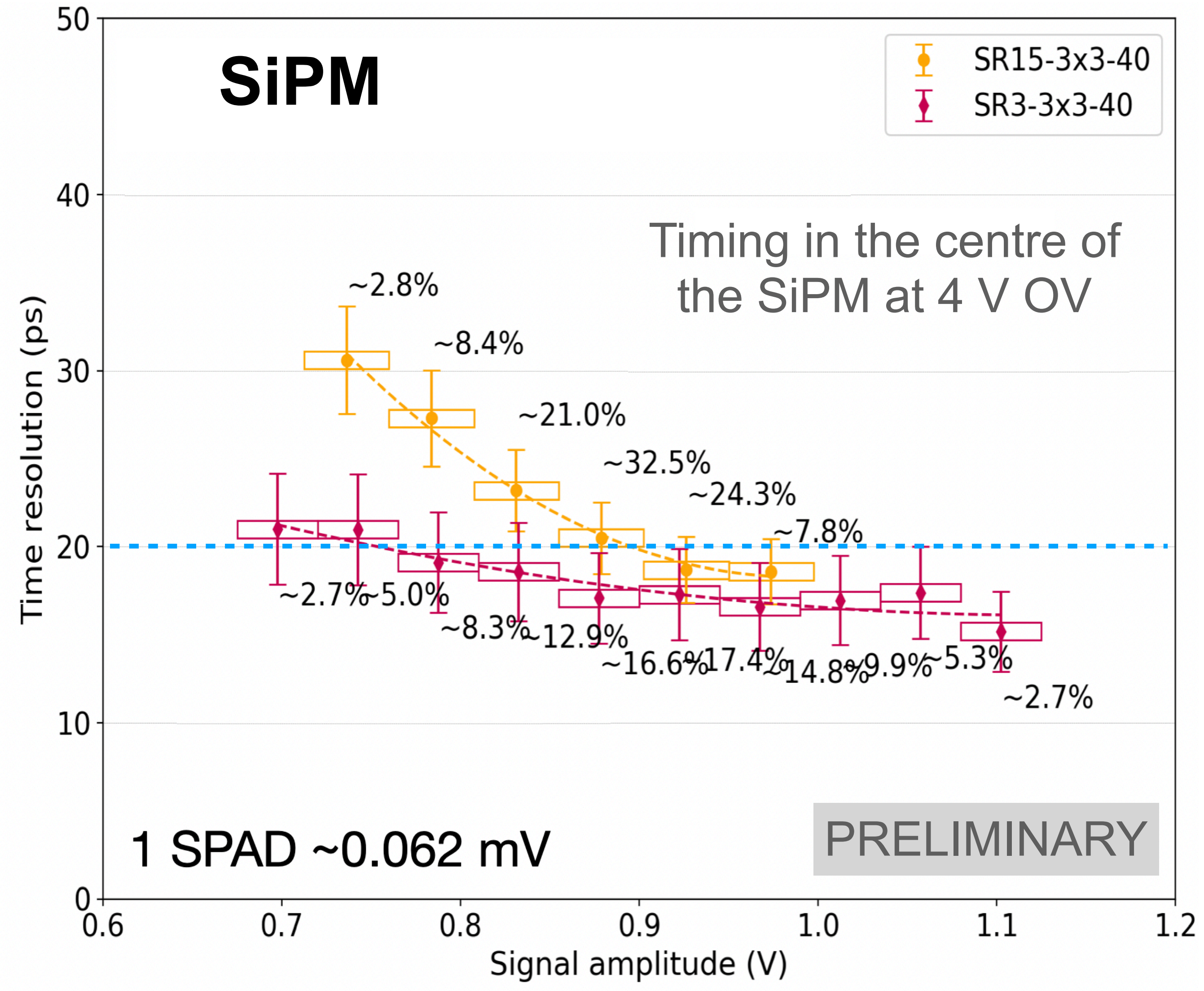




Three technology options

- **CMOS**: promising 20-ps prospects with:
  - new sensor layout (with final gain)
  - thinning to 15 µm
- **LGAD**: double-LGAD with signals of both layers sum up using a *single* front-end amplifier shown consistent improvement
- **SiPM**: direct response to charged particles due to Cherenkov light firing up to 4-5 SPADs → Large number of firing SPADs improves significantly σ_t



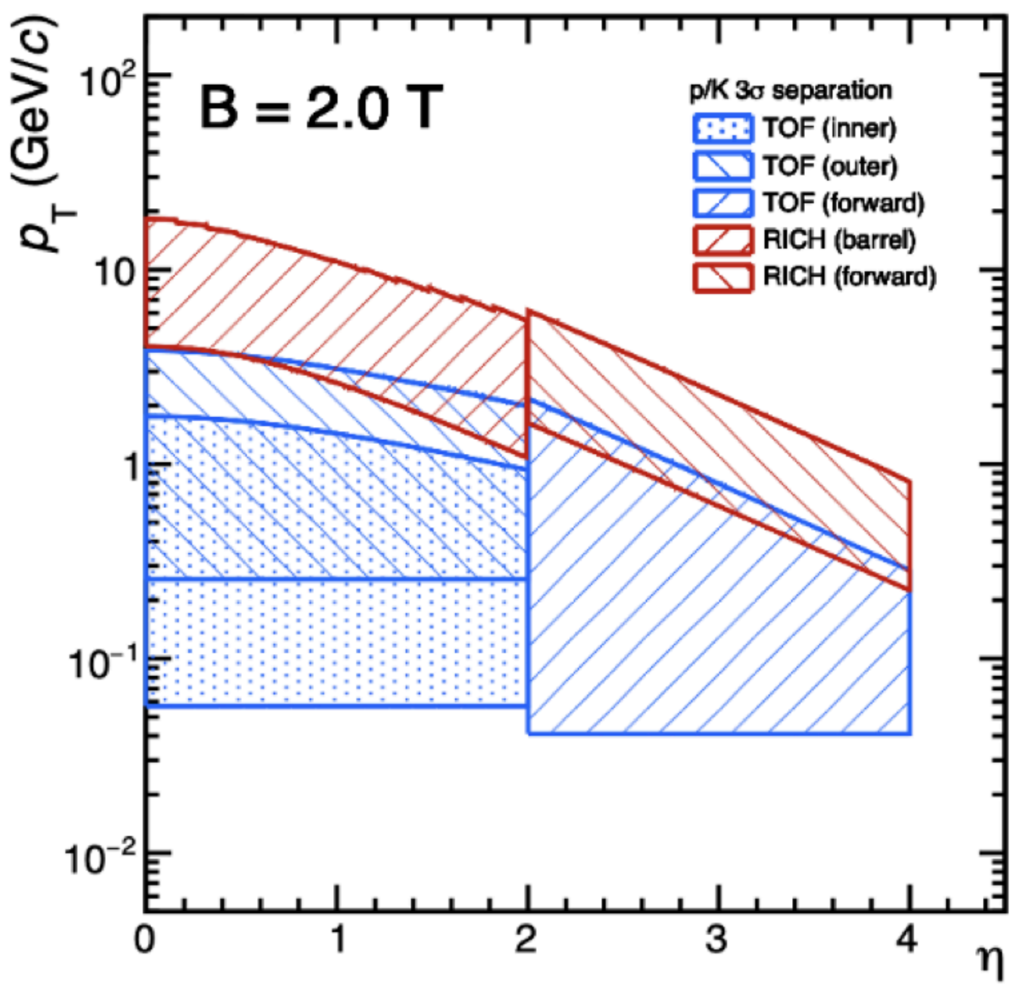


Particle Identification - Ring Imaging Cherenkov (RICH)

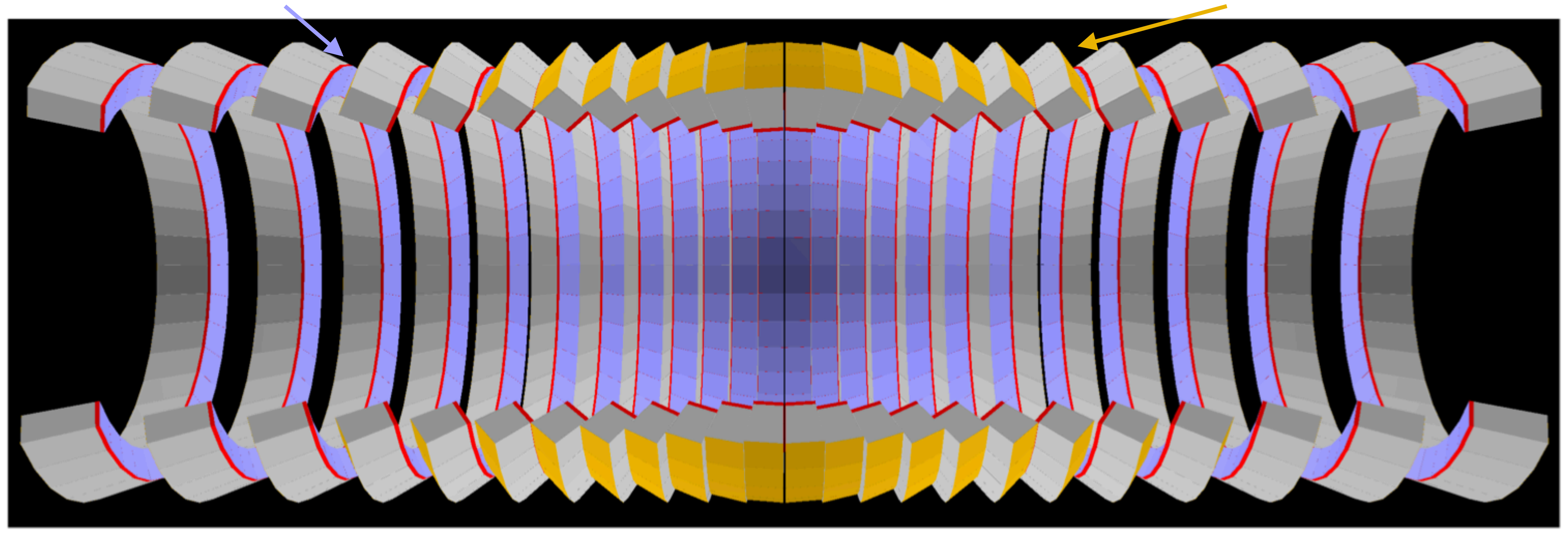
<u>Requirements</u>
- Extended PID beyond TOF limits
  - e/π, π/K and K/p separation up to ~2, 10 and 16 GeV/c, respectively
- σ_{RICH} ~1.5 grad at saturation

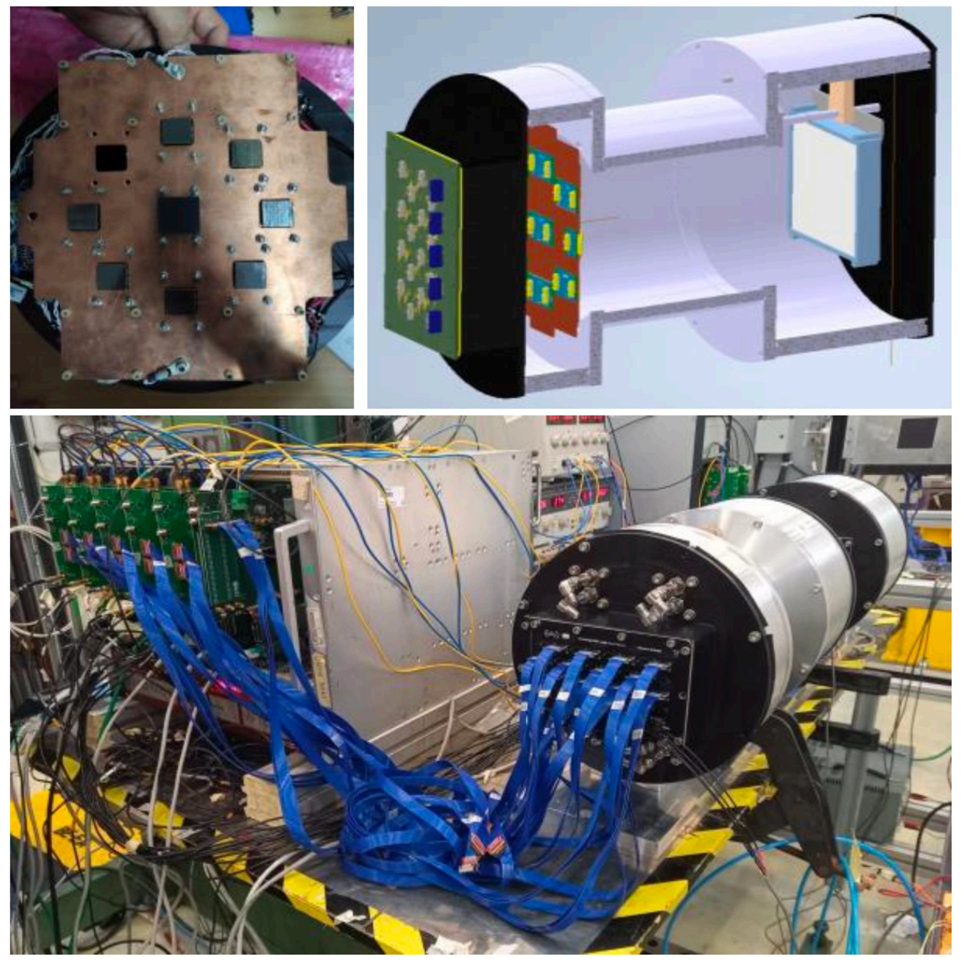
<u>Implementation</u>
- bRICH:
  Aerogel (n=1.03) + SiPMs (~30 m²)
- fRICH:
  Aerogel (n=1.015) + HRPPDs (~8 m²)

<u>Challenges</u>
- SiPM radiation tolerance and DCR mitigation with cooling + annealing

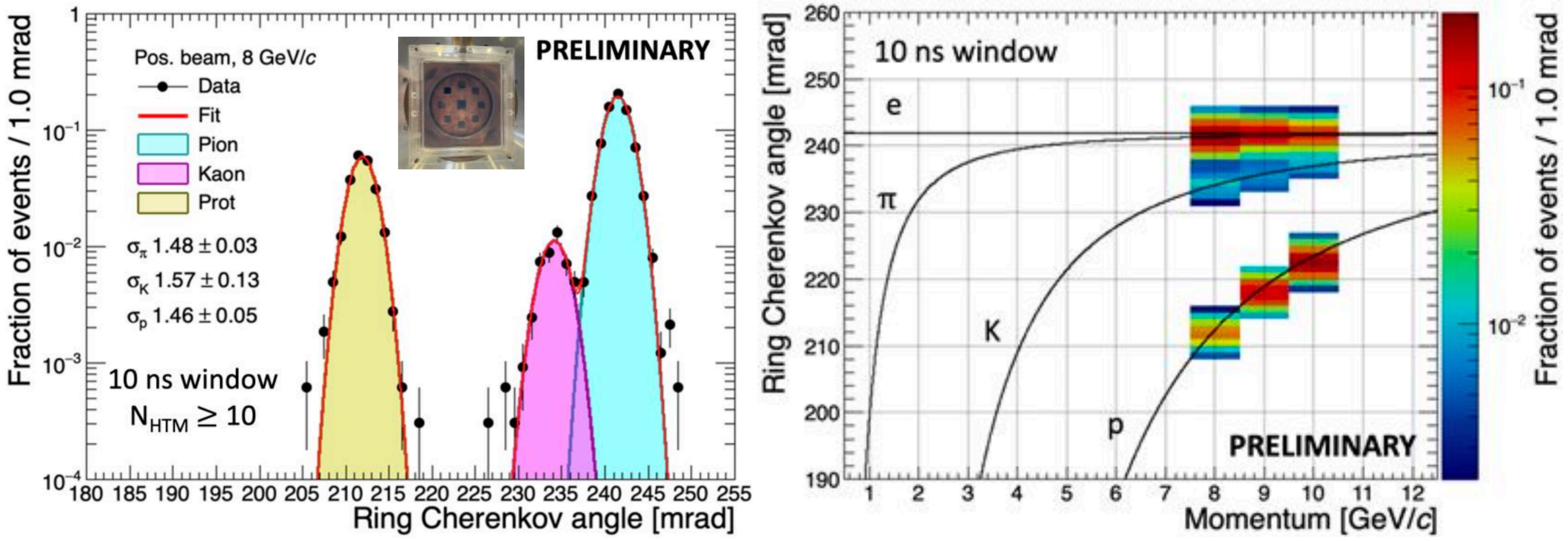


Projective bRICH layout





2024 beam test results using Radioroc + PicoTDC



CONCLUSIONS

- The **ALICE experiment** was conceived to determine the properties of the quark–gluon plasma (QGP) and is preparing to further investigate in the coming years how these properties emerge from the fundamental interactions described by quantum chromodynamics.

- The upgrade to **ALICE 2.1** is extending the present capabilities of the experiment, especially at very low transverse momentum, and is paving the technology for the future vertexes.

- The substantial **R&D** effort is advancing the state of the art in detector technologies, aiming at unprecedented spatial and temporal resolution while maintaining an exceptionally low material budget.

- The **ALICE 3** schedule foresees the selection of technologies during 2025–2026, followed by the production of large-scale prototypes and the preparation of the Technical Design Reports in 2026–2027.

CONCLUSIONS

ITS3 and ALICE 3 trackers have similar requirements as the FCC-ee tracker

	ITS3	ALICE 3 VTX	ALICE 3 TRK	ePIC	FCC-ee
Single-point res. (μm)	5	2.5	10	5	3
Time res. (ns RMS)	2000	100	100	2000	20
In-pixel hit rate (Hz)	54	96	42		few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	10^{-7}		
Power cons. (mW / cm^2)	35	70	20	<40	50
Hit density (MHz/cm^2)	8.5	96	0.6		200
NIEL (1 MeV n_{eq}/cm^2)	$4 \cdot 10^{12}$	$1 \cdot 10^{16}$	$2 \cdot 10^{14}$	few 10^{12}	10^{14} (/year)
TID (Mrad)	0.3	300	5	few 0.1	10 (/year)
Material budget (X_0/layer)	0.09%	0.1%	1%	0.05%	˜0.3%
Pixel size (μm)	20	10	50	20	15-20

Input to ESPP2026 ”Frontier sensor R&D for the ALICE 3 apparatus”:
https://indico.cern.ch/event/1439855/contributions/6461481/

ALICE R&D is really a stepping stone toward the future experiments

Backup