ALFA

Advanced, **L**ightweight and **F**ine-grained **A**pparatus

for e^+e^- physics

History and status

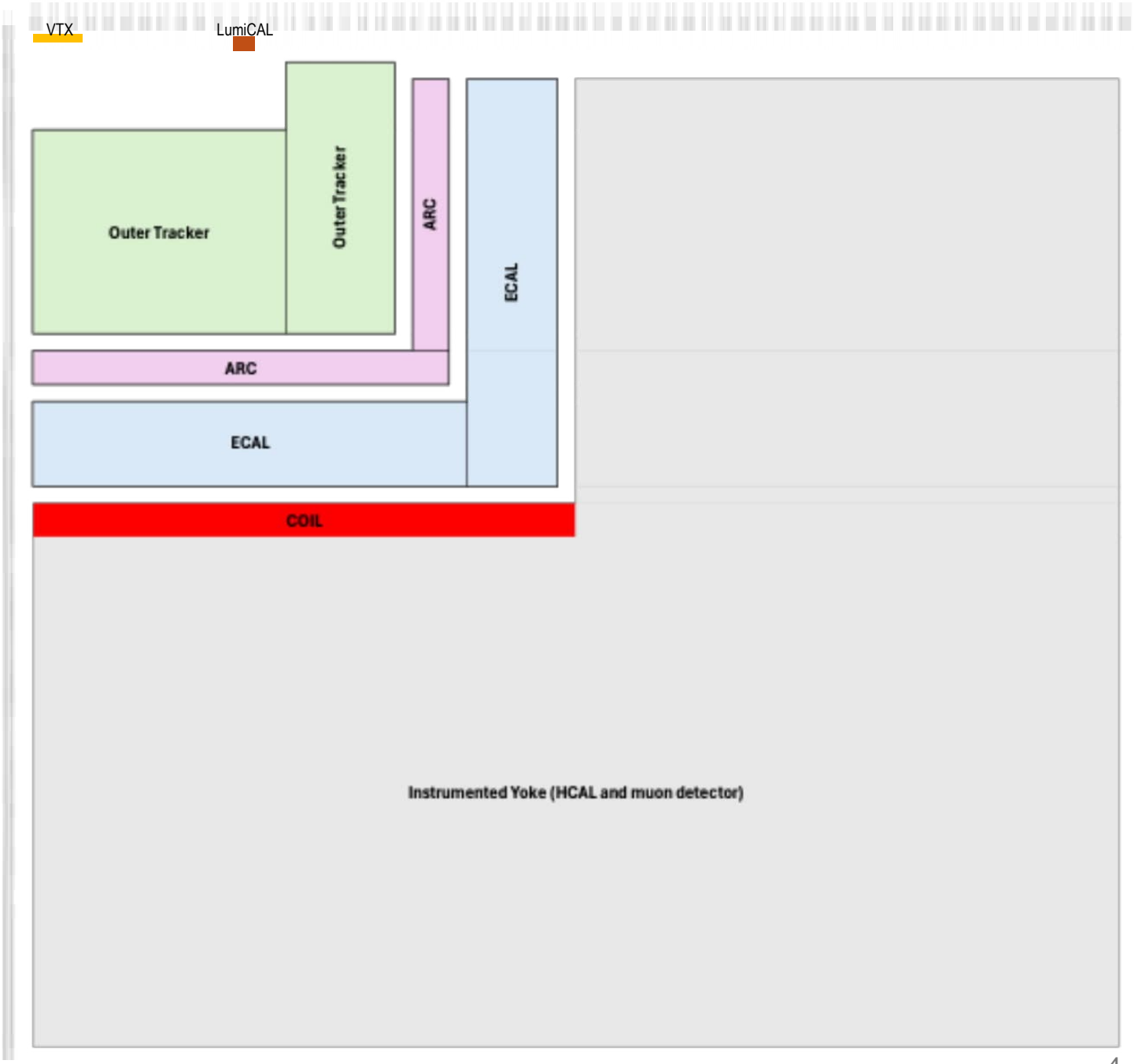
- A young project: started from scratch in Summer 2025
- High-level goal: develop a detector design that will become a proposal for one of the four FCC-ee detectors
- **Problem-driven approach: optimize performance**
- Adopt state-of-the-art (… **but not futuristic**) detector technologies, and technical solutions for system design
- Make sure the detector is realistic and affordable
- Minimize complexity and M&O cost
  - **Minimal number of different detector technologies**
  - Robust detector design, requiring minimal/no maintenance to the extent possible

Objective

- Establish and document a **reference design** by Q1 2008
  - Complete conceptual design of all detector subsystems, demonstrating technical feasibility
    - Including services (power distribution, readout electronics, cooling), mechanical structures, and system integration
  - Based on existing or credible near-term technologies (e.g. solutions currently under development for the LS4 upgrades of the LHC experiments)
  - Enabling a bottom-up assessment of the achievable detector performance, replacing the current top-down "performance targets"
  - Enabling a credible estimate of the detector cost and construction effort
  - Identify the assumptions underlying the detector design and the critical developments required for the final detector
  - Define the preliminary specifications of key components (e.g. readout ASICs)
- **R&D on alternative solutions is welcome** throughout the Reference Design phase and beyond
- The Reference Design is a realistic conceptual design, developed to a level of maturity that supports credible performance, cost, schedule, and integration assessments, and that **could be taken forward towards construction**
- It will serve as the **project's baseline design** and as the **benchmark** against which future

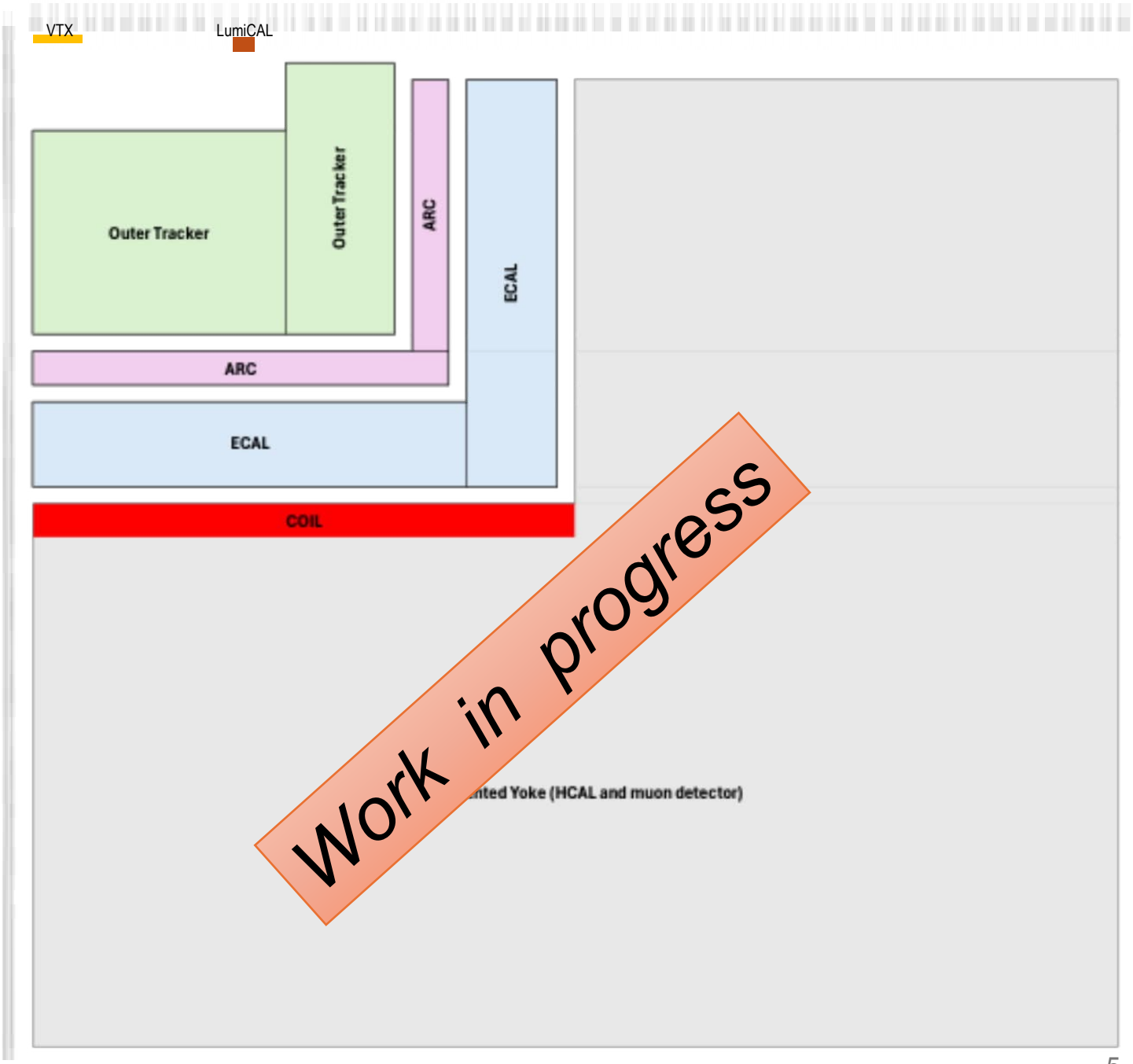
The ALFA detector

- High-performance all-MAPS Tracker
- Si-W Luminosity Calorimeter (LumiCAL) also based on MAPS
- ARC (**A**rray of **R**ICH **C**ells)
  - Good particle ID over large momentum range
- ECAL based on GRAiNITA
  - Excellent energy and position resolution with a cost-effective technology
- Coil for 3T field
  - Might operate at lower field for the Z run
- Instrumented yoke serving as HCAL and muon detector
  - Based on SiPM-on-tile design, with scintillating tiles



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The **all-MAPS Tracker** for the **ALFA detector**

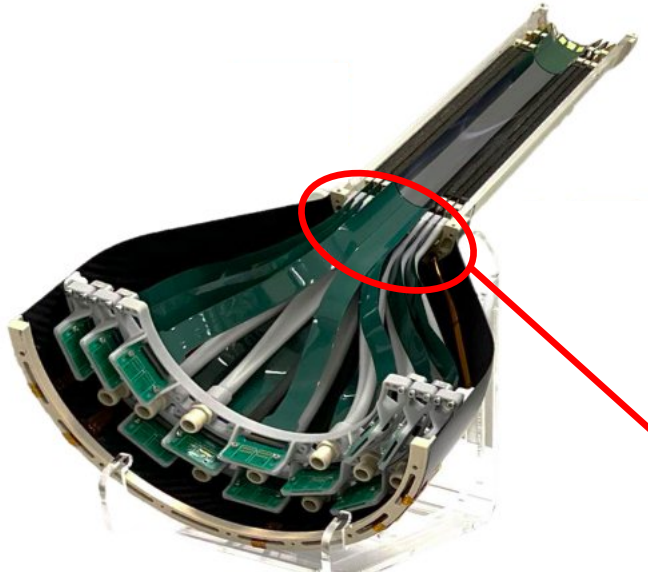
A full-MAPS Tracker

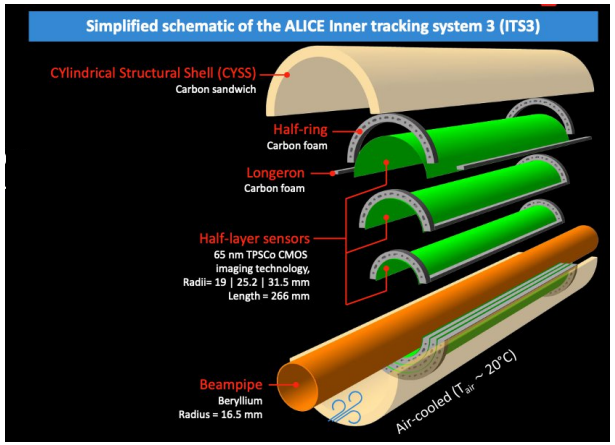
- All aspects must be optimized for minimal mass
  - ⟶ **Detector concept and layout**
  - ⟶ **Mechanics**
  - ⟶ **Electronics system design**

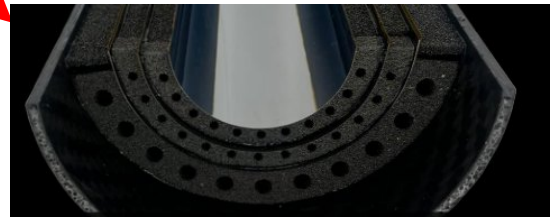
- **Tentative MAPS specs** (inspired by the ALICE developments)
  - 10 μm pixels in all layers (specs for the ALICE3 Tracker)
  - Time resolution of $\lesssim$ 1 μs for the VTX layers, with $\lesssim$ 40 mW/cm^2 of power density
    - Air cooling
  - Time resolution of ~ 5 μs for the OT layers, with < 20 mW/cm^2 of power density
    - Lower power density ⟶ lower mass

Vertex detector: curved MAPS

- Curved MAPS ***with air cooling*** are the compelling choice for the Vertex Detector
  - Best resolution with lowest material budget
- Under development for the ALICE ITS3

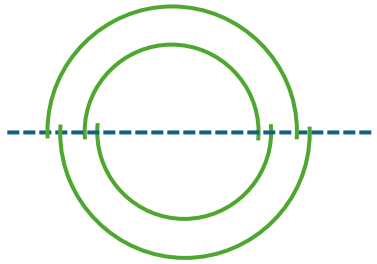




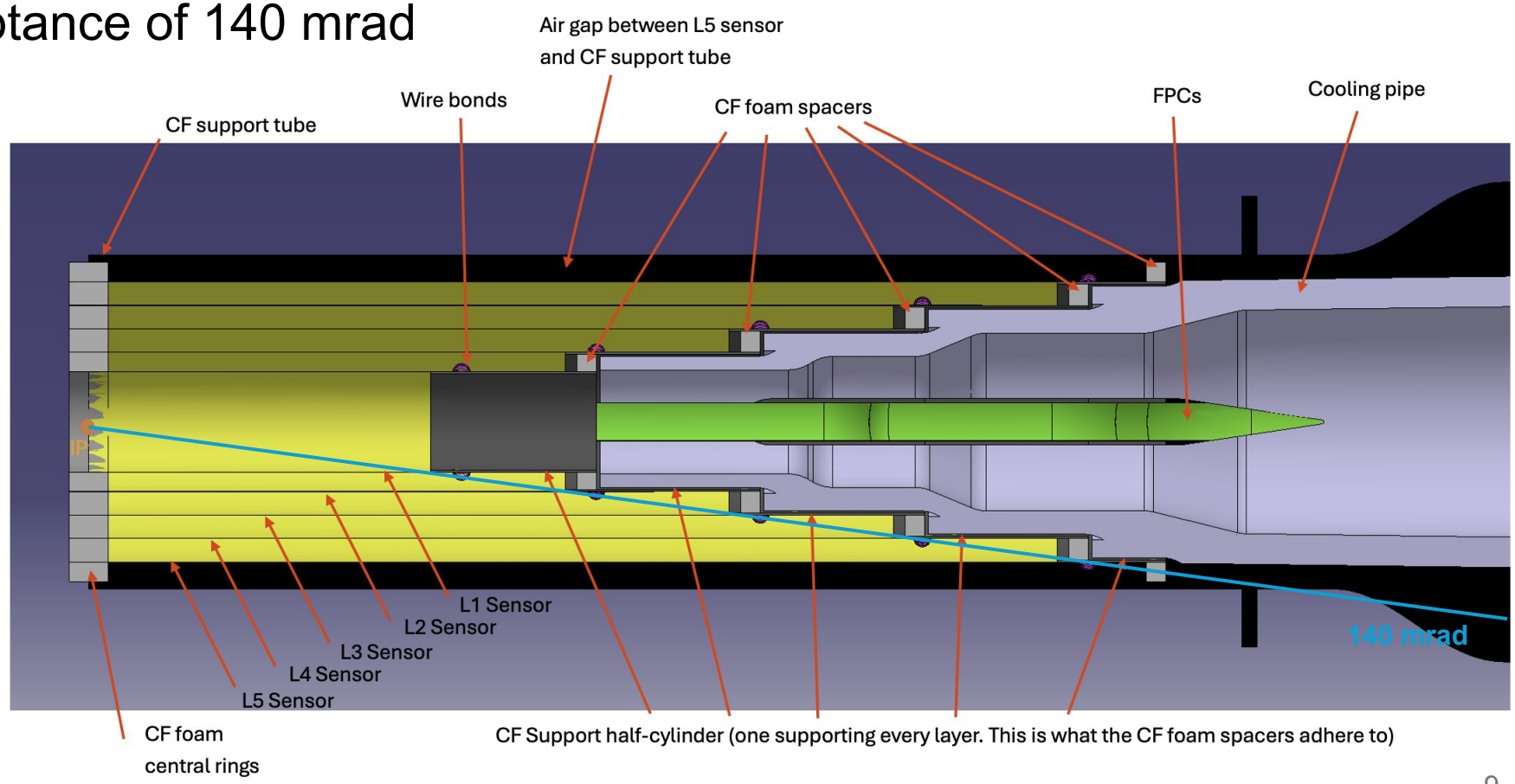


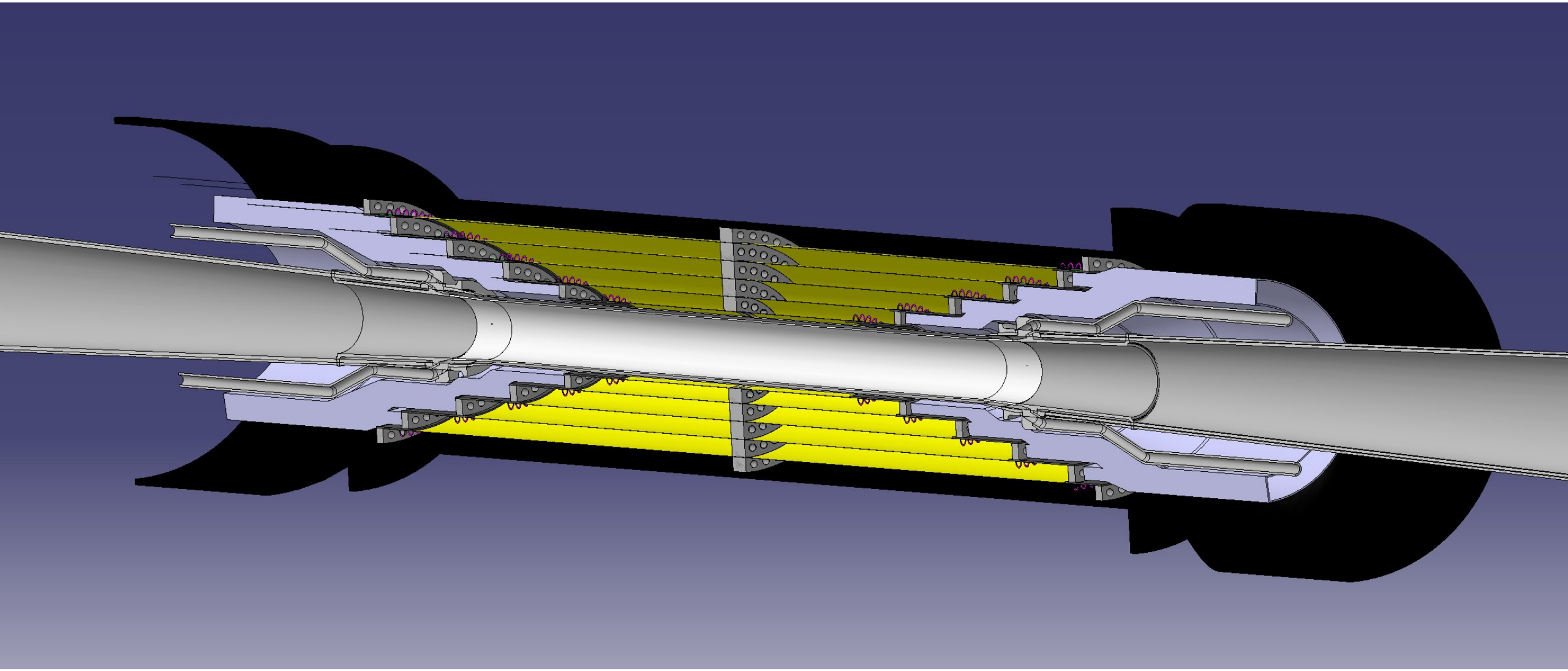
Vertex detector: curved MAPS

- Geometry with 5 layers developed (almost complete)
  - Includes air ducts, support structures and electrical services
  - Current version: acceptance of 140 mrad



Overlap between the two halves

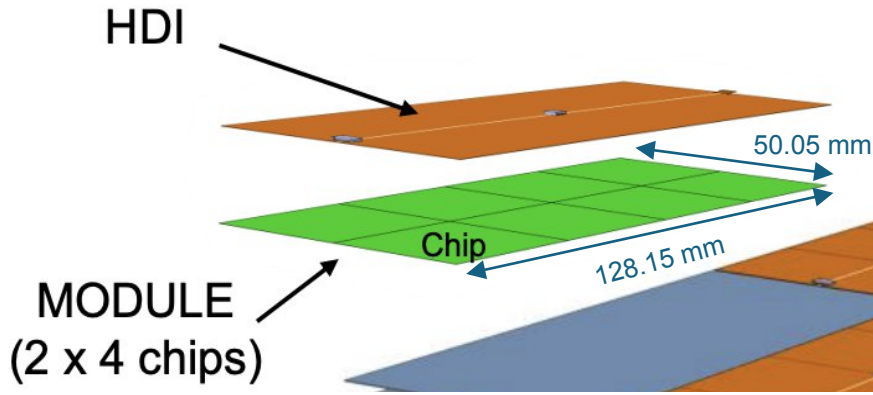




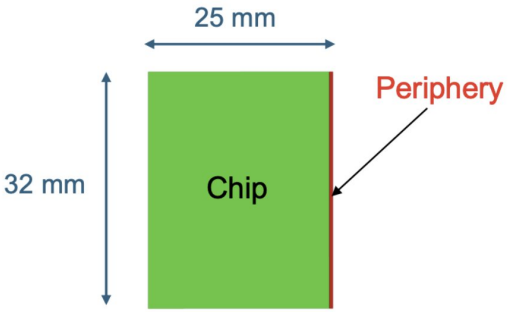
Outer Tracker system concept

- Reticle-size MAPS, bump-bonded onto a **H**igh-**D**ensity **I**nterconnect circuit

- 25×32 mm^2 MAPS ⟶ 50×128 mm^2 module
- Building block of the barrel staves

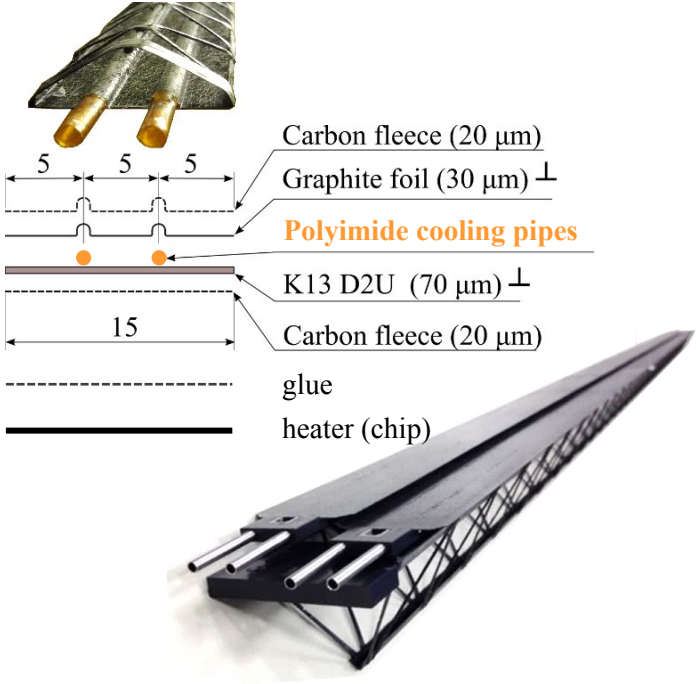


- Industrial flip-chip process for module construction
- Cope with MAPS process yield



- Chip peripheries are located side by side in the center of the module

Mechanics for the Outer Tracker



- Starting point is the “cold plate” invented for the ALICE ITS2

[Corrado Gargiulo & Massimo Angeletti]

  - Extremely light and efficient thermal interface

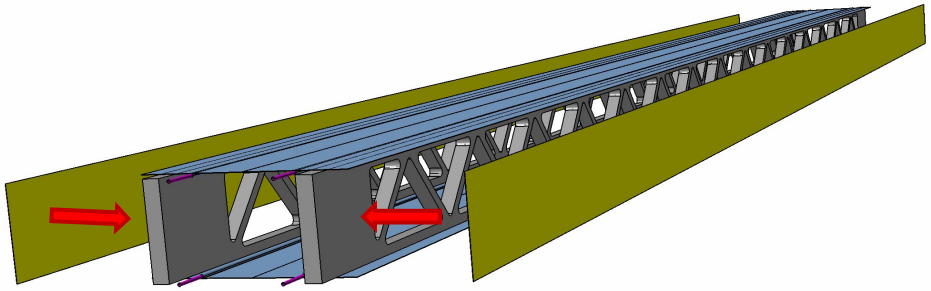
- Deploy with larger size, couple two plates with thick foam structures in between

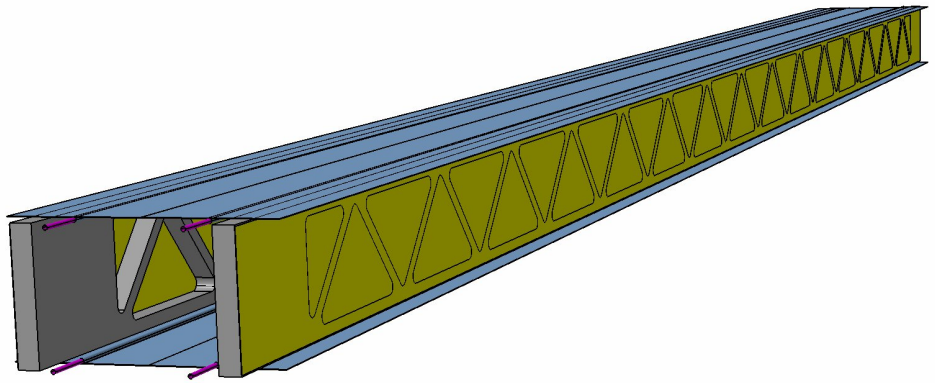
- Box-beam structure, lightweight and stiff, supported from ends

~ 10 cm (width) x **5 cm** (height) x **268.8 cm** (length)

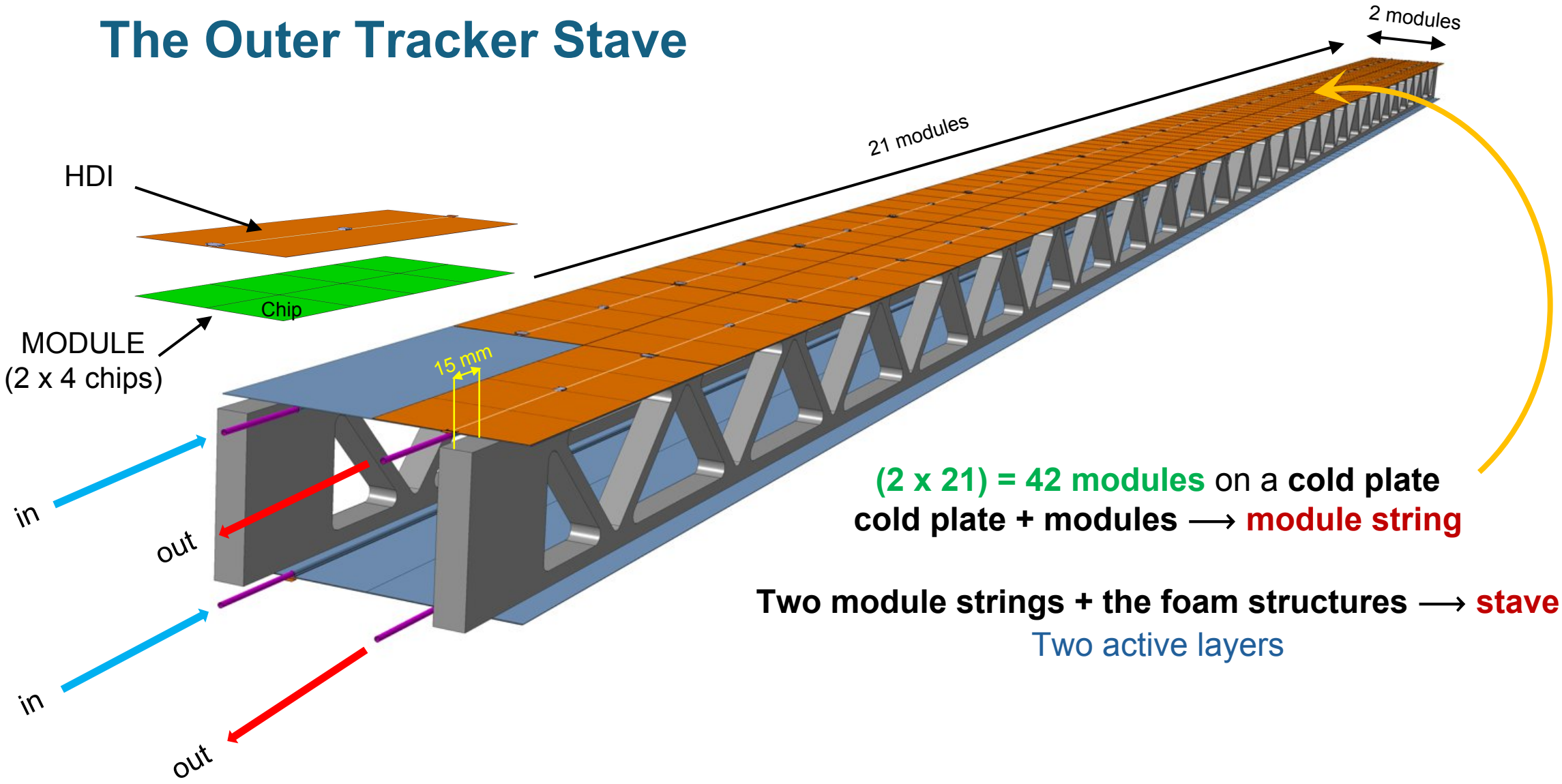
~ 0.19 kg (mass)







The Outer Tracker Stave



(2 x 21) = 42 modules on a **cold plate**

cold plate + modules ⟶ module string

Two module strings + the foam structures ⟶ stave

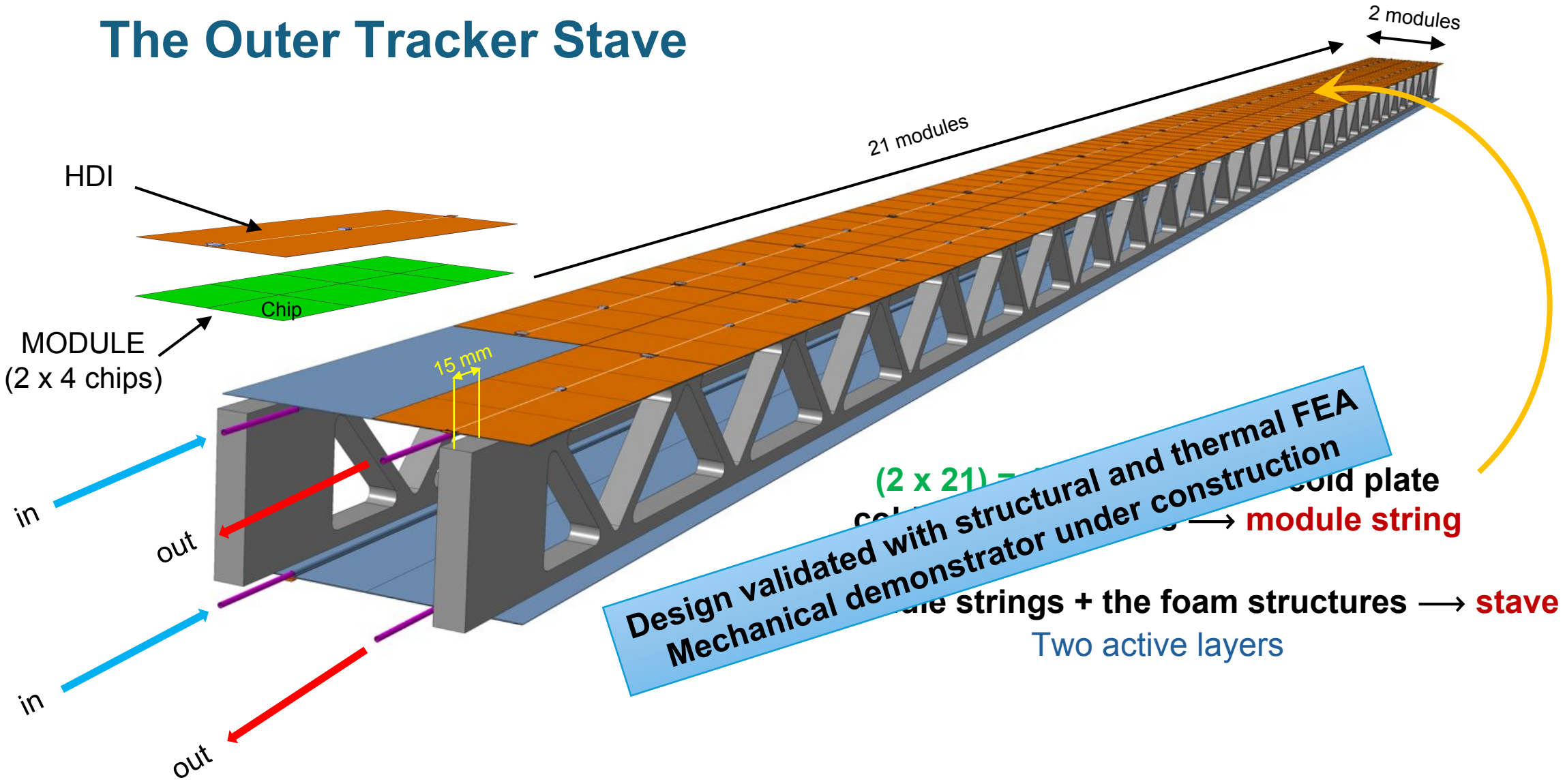
Two active layers

➢ **Opteon™ SF10** eco-friendly fluid used for electronics immersion cooling

- Pipe internal diameter: **ID = 1.6 mm**
- Fluid in-out difference temperature: **ΔT ~ 5°C**

⟹ **Pressure drop ~ 1.2 bar**

The Outer Tracker Stave



(2 x 21) = [illegible] cold plate
[illegible] ⟶ module string

Design validated with structural and thermal FEA
Mechanical demonstrator under construction

[illegible]ule strings + the foam structures ⟶ stave
Two active layers

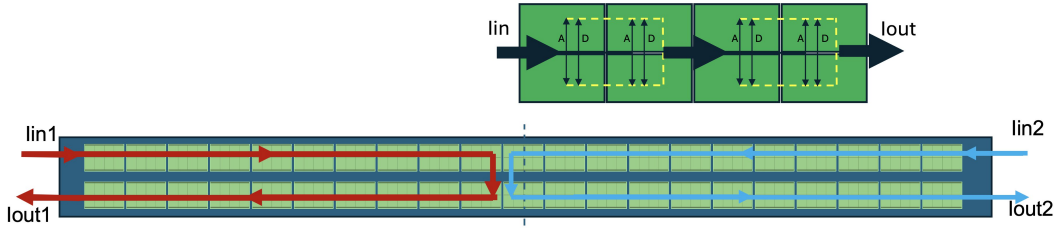
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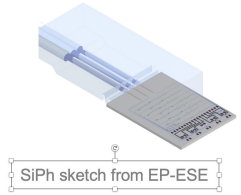
⟹ **Pressure drop ~ 1.2 bar**

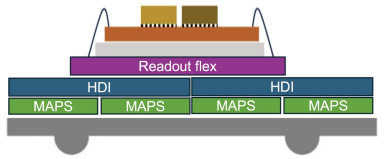
Outer Tracker Stave: electronics system

Key technologies:



- **Serial powering** for delivering the required power to the modules
- **Data merging and command sharing** across multiple chips
- **Ultra-thin aluminium** interconnets realized with **Physical Vapour Deposition**
- **Silicon photonics readout**

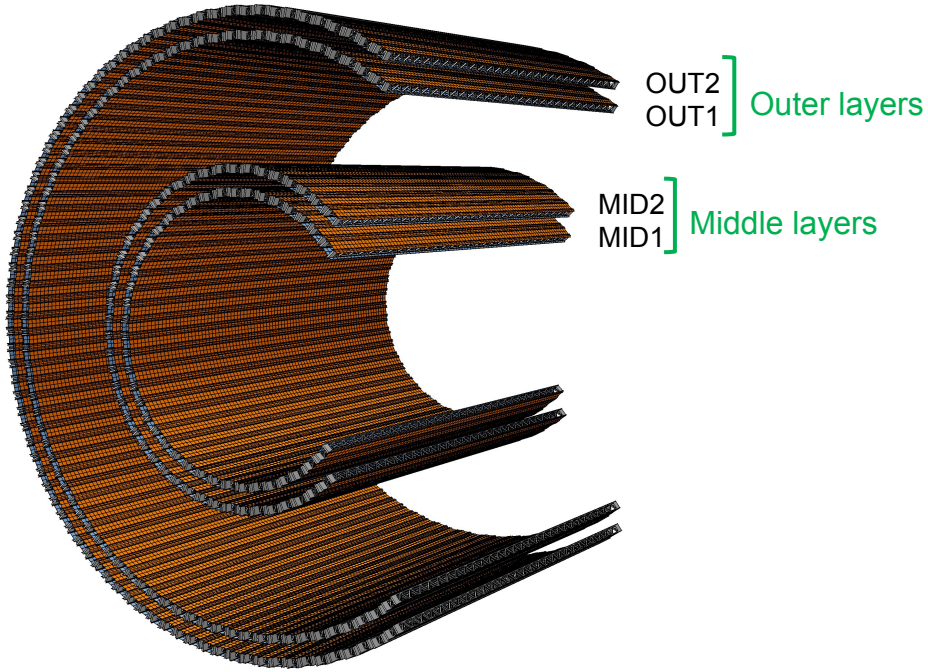




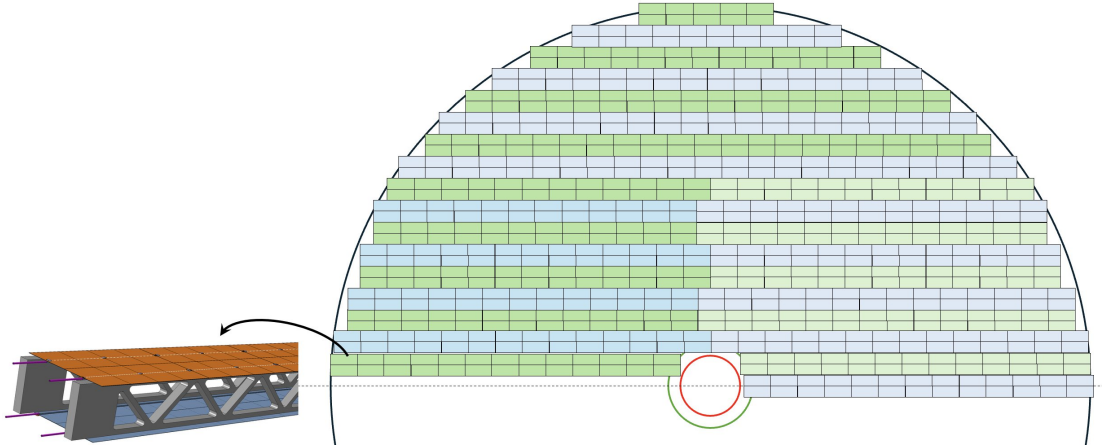
Sketch (not to scale) of silicon photonics mezzanine wire-bonded to the readout flex

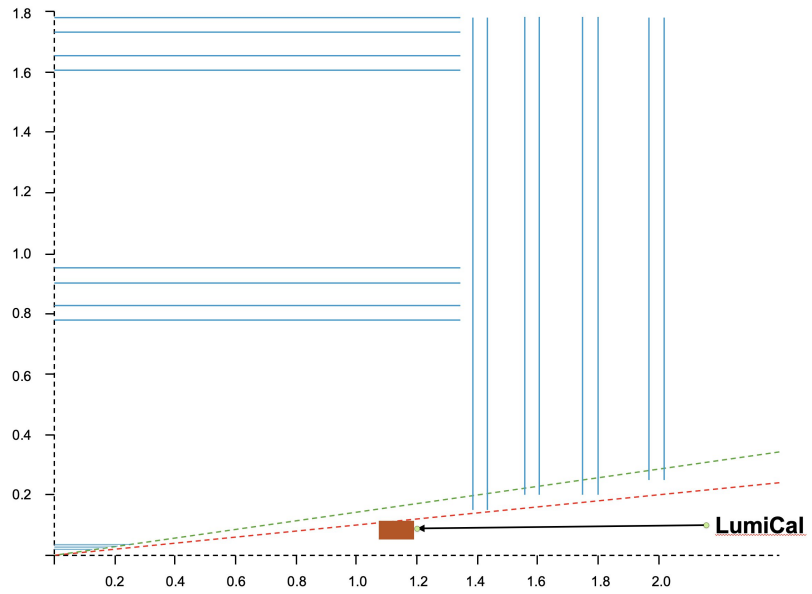
Outer Tracker layout

	N. of staves	N. of modules	Silicon active surface (m^2)	Power (kW)
MID1	52	4.368	27,96	5,59
MID2	60	5.040	32,26	6,45
OUT1	104	8.736	55,91	11,18
OUT2	112	9.408	60,21	12,04
Total	**328**	**27.552**	**176,34**	**35,27**



Endcaps made of “module strings” similar to the barrel
Installed on ~5 cm thick foam structures
Engineering design started





Mass estimates

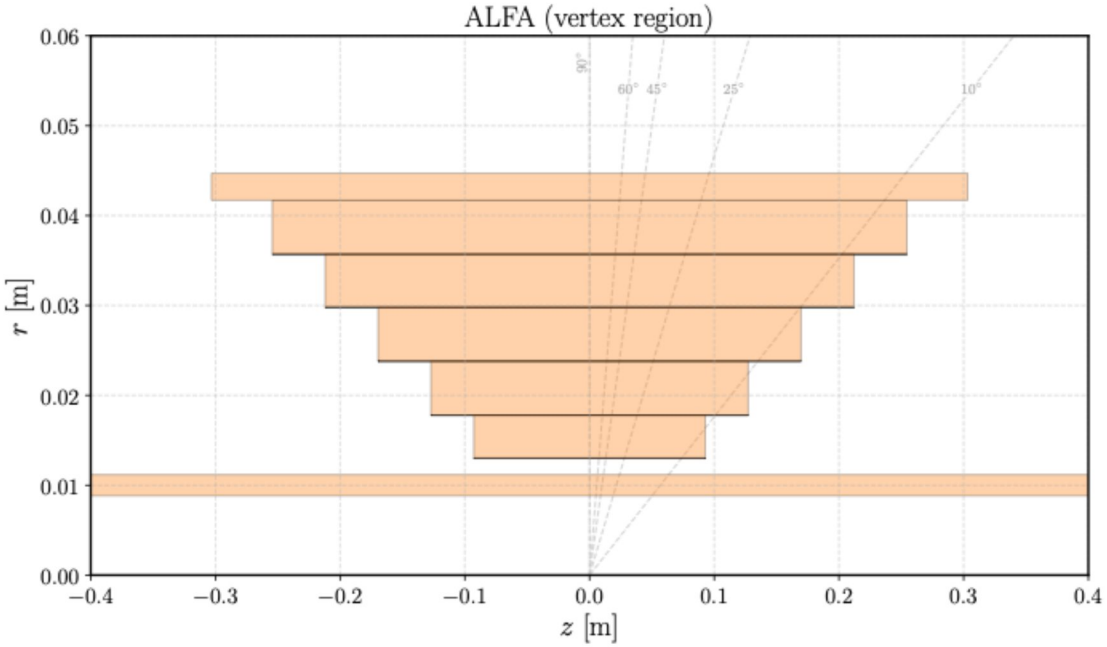
Silicon Module		Avg X/X_0 (%)
MAPS	Si	0.0534
	Cu	0.0139
Bumps	Sn95Ag5	0.0009
HDI	Coverlay	0.0103
	Al	0.0022
	HDI prepreg	0.0281
	Decoupling cap	0.0071
Connector power	LCP	0.0003
	Cu	0.0006
Connector data	LCP	0.0006
	Cu	0.0015
Total		**0.1190**

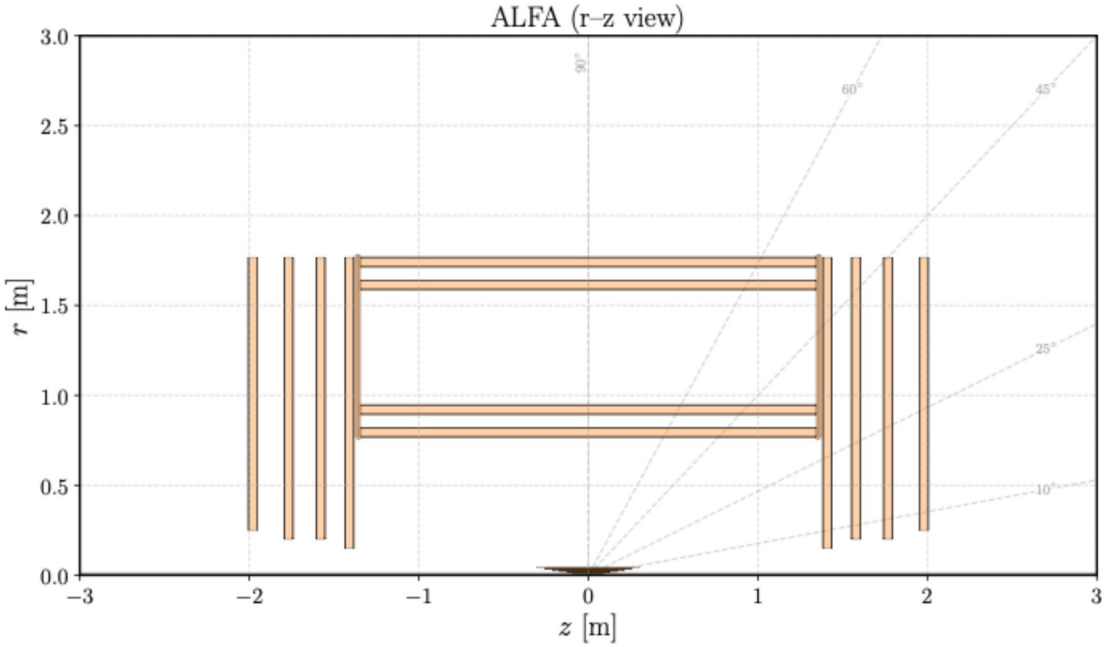
Stave		Avg X/X_0 (%)
Cold plates	C paper	0.0225
	C fleece	0.0112
	K13D2U	0.0577
Foam structures	FR-3703	0.0196
Pipes	Kapton	0.0224
Coolant	Opteon SF10	0.1302
FPC	Kapton	0.0175
	Coverlay	0.0103
	Al	0.0539
	Epoxy	0.0118
Side plates	C fleece	0.0037
	K13D2U	0.0282
Total		**0.3891**

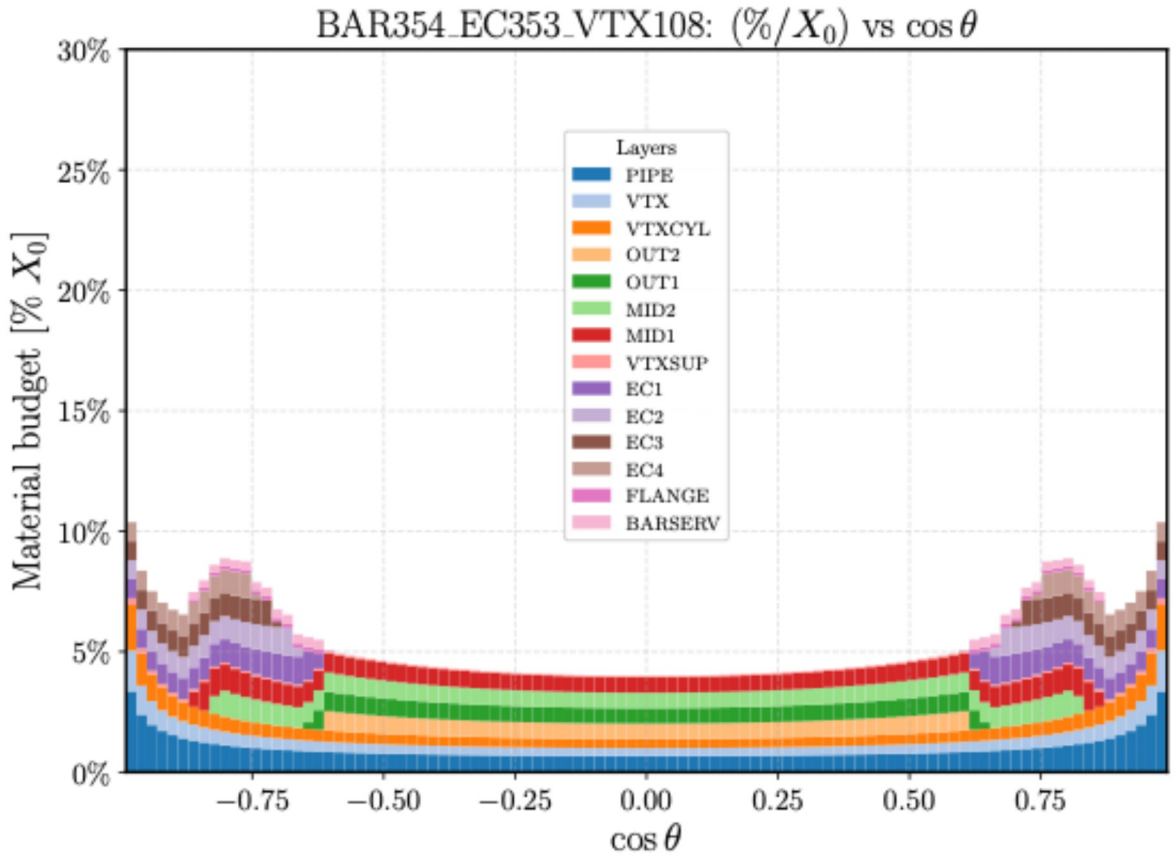
	N of staves in phi	Avg X/X_0 modules (%)	Avg X/X_0 staves (%)
OUT2	**112**	**0.12**	**0.39**
		0.12	
OUT1	**104**	**0.12**	**0.39**
		0.12	
MID2	**60**	**0.12**	**0.39**
		0.13	
MID1	**52**	**0.12**	**0.39**
		0.13	

0.32% X/X_0 per active layer!

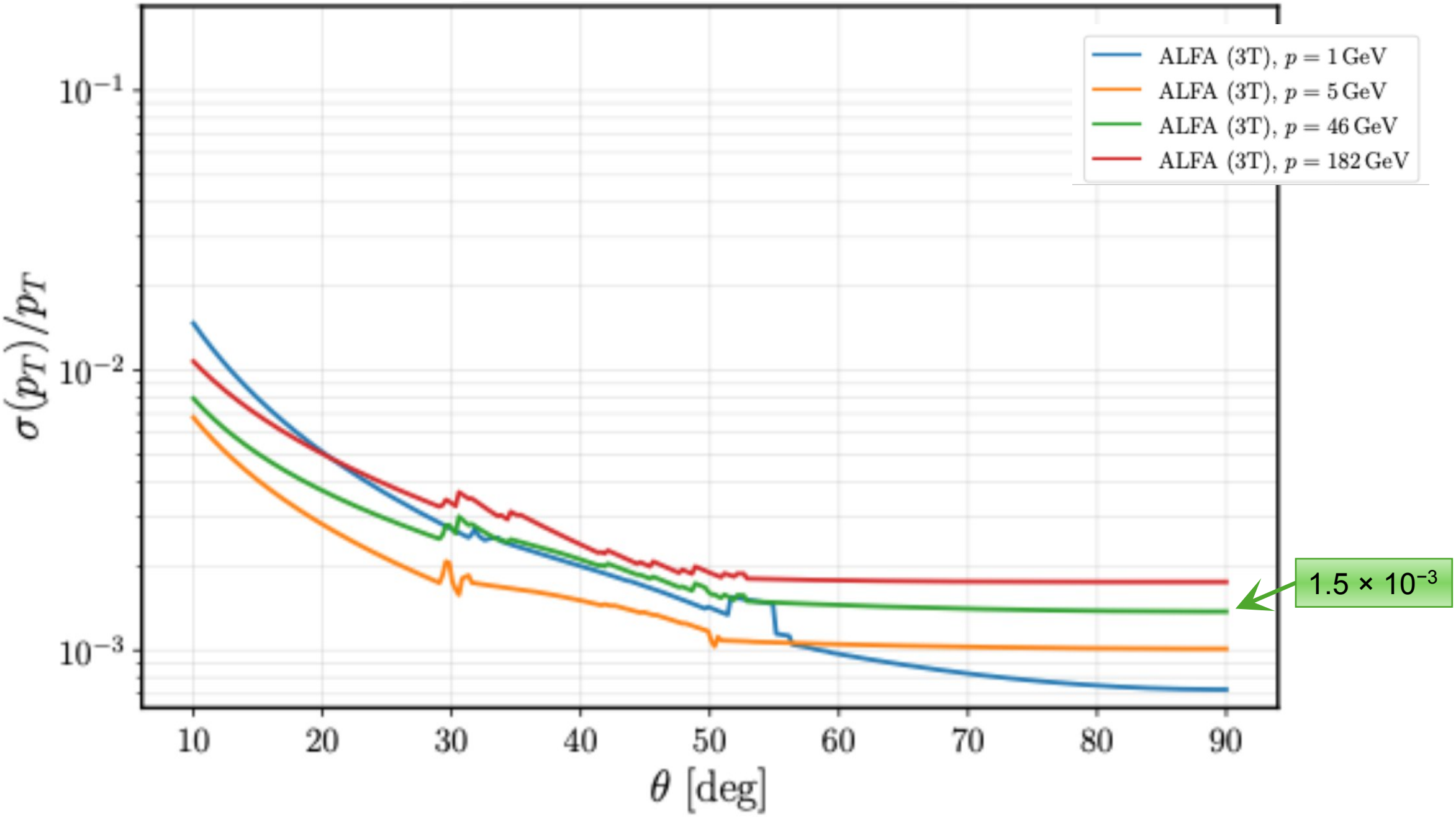
Performance – from DELPHES

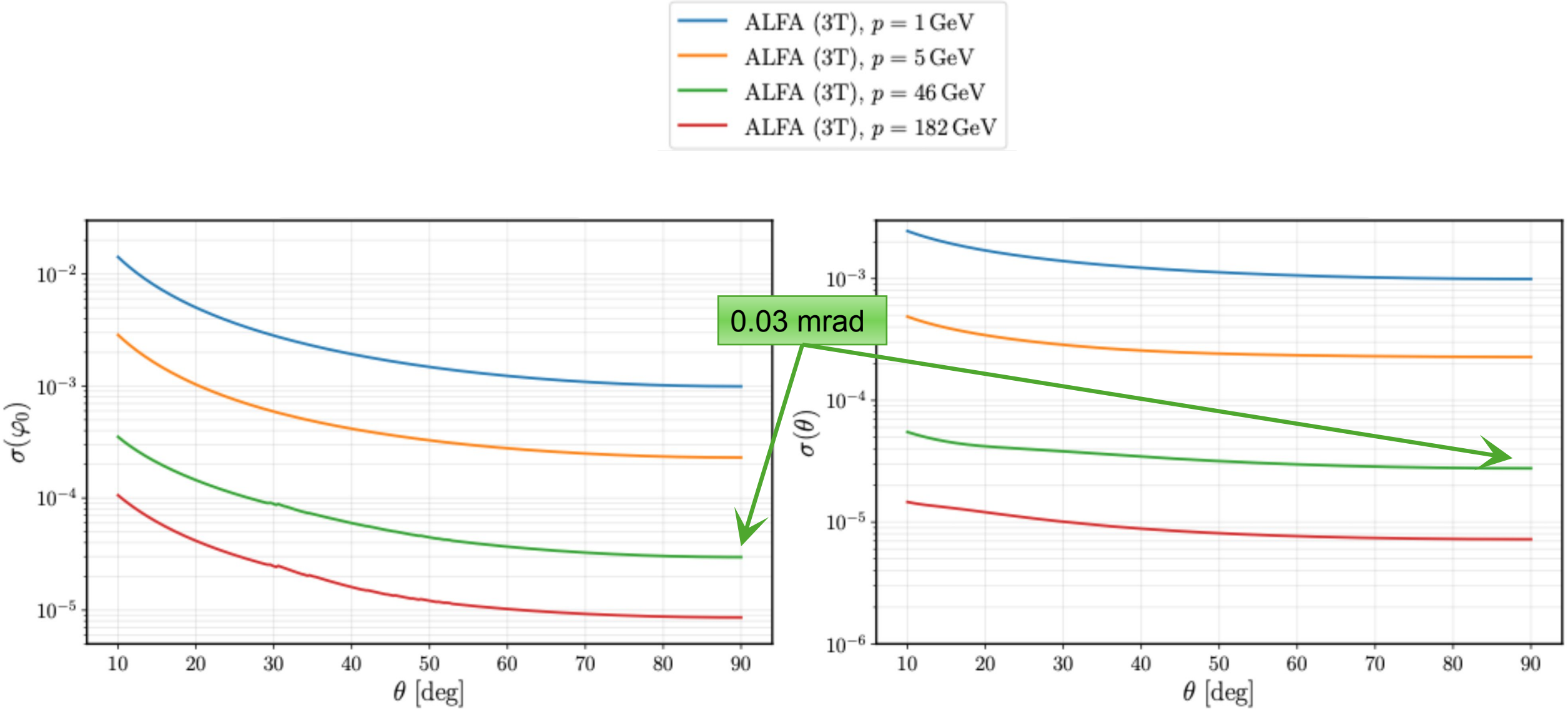


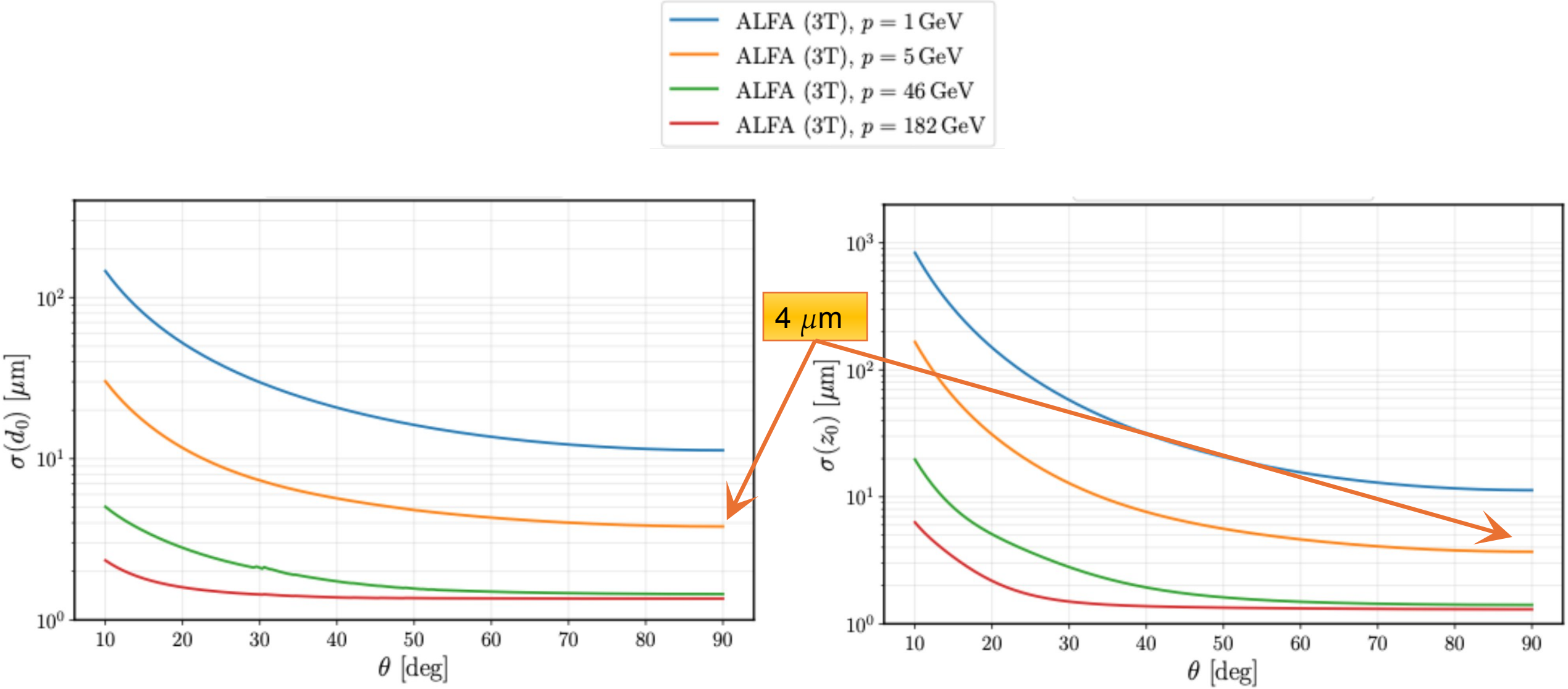


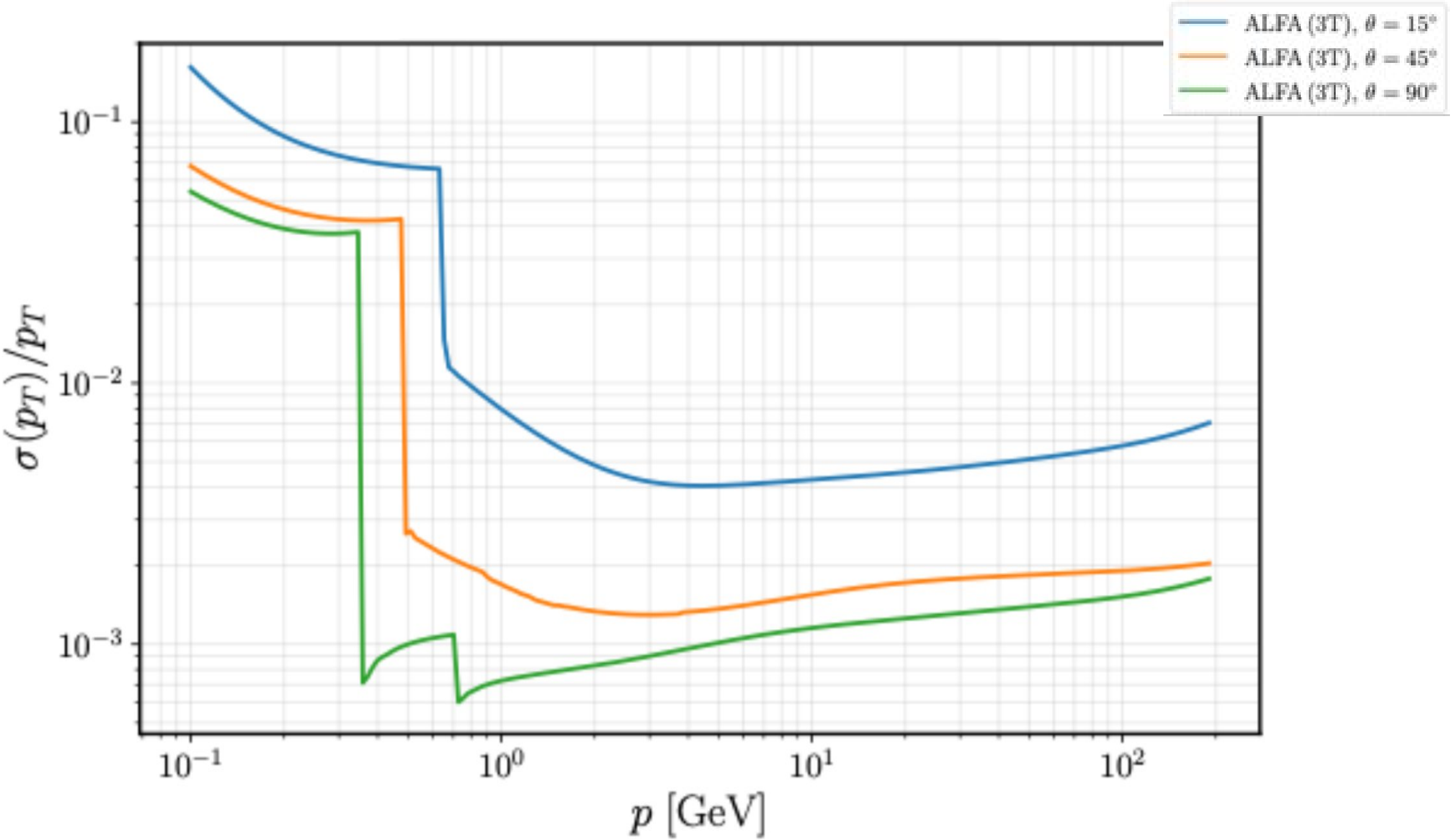


Using binary resolution for now – exceedingly conservative!


ALFA (3T), $p = 1\,\mathrm{GeV}$
ALFA (3T), $p = 5\,\mathrm{GeV}$
ALFA (3T), $p = 46\,\mathrm{GeV}$
ALFA (3T), $p = 182\,\mathrm{GeV}$
10^{-1}
10^{-2}
10^{-3}
$\sigma(p_T)/p_T$
10
20
30
40
50
60
70
80
90
θ [deg]
1.5×10^{-3}

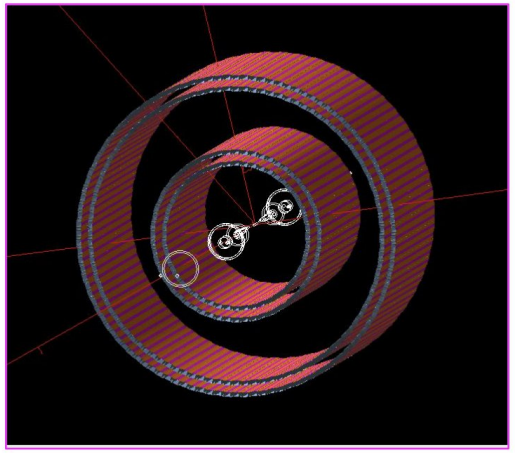

ALFA (3T), $p = 1\,\mathrm{GeV}$
ALFA (3T), $p = 5\,\mathrm{GeV}$
ALFA (3T), $p = 46\,\mathrm{GeV}$
ALFA (3T), $p = 182\,\mathrm{GeV}$
$\sigma(\varphi_0)$
θ [deg]
$\sigma(\theta)$
θ [deg]
0.03 mrad

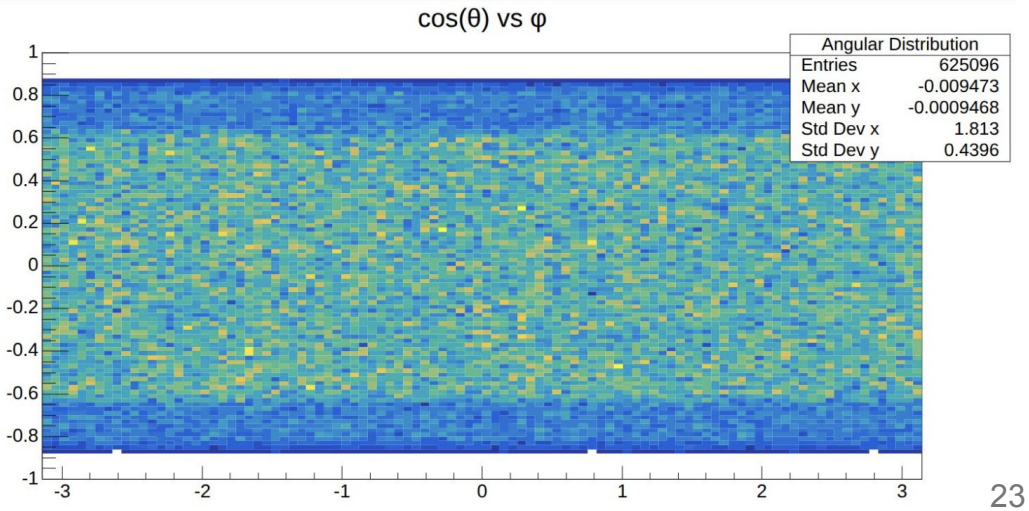

ALFA (3T), $p = 1\,\mathrm{GeV}$
ALFA (3T), $p = 5\,\mathrm{GeV}$
ALFA (3T), $p = 46\,\mathrm{GeV}$
ALFA (3T), $p = 182\,\mathrm{GeV}$
$\sigma(d_0)$ [μm]
θ [deg]
$\sigma(z_0)$ [μm]
θ [deg]
4 μm


ALFA (3T), $\theta = 15°$
ALFA (3T), $\theta = 45°$
ALFA (3T), $\theta = 90°$
$\sigma(p_T)/p_T$
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^{0}
10^{1}
10^{2}
p [GeV]

Tracker Outlook

- Build VTX mock-ups (CERN+Strasbourg)
- Assemble and validate OT stave demonstrator (parts available)
- Full simulation and tracking progressing rapidly!





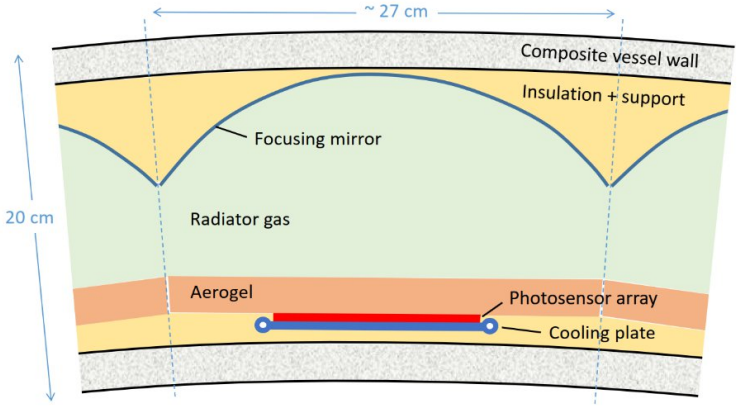
The ARC for the ALFA detector

Development started in 2021

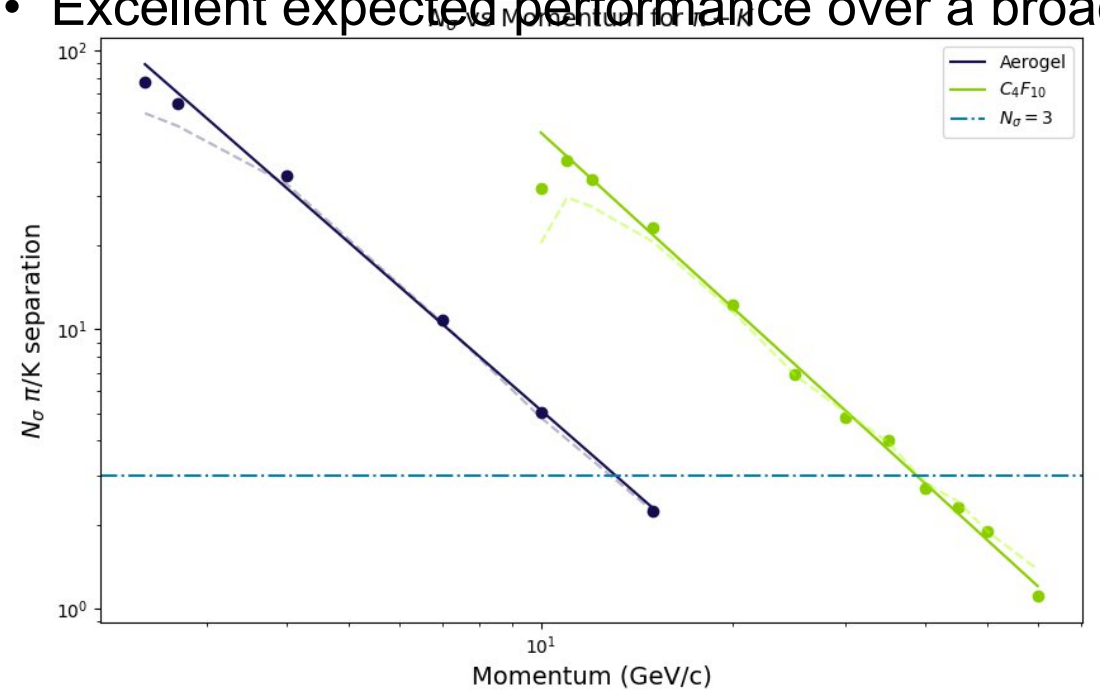
Roberta Cardinale[1], Serena Pezzulo[1], Roger Forty[2],
Sneha Malde[3], Todd Slater[3], Alvaro Tolosa Delgado[2], Guy Wilkinson[3]

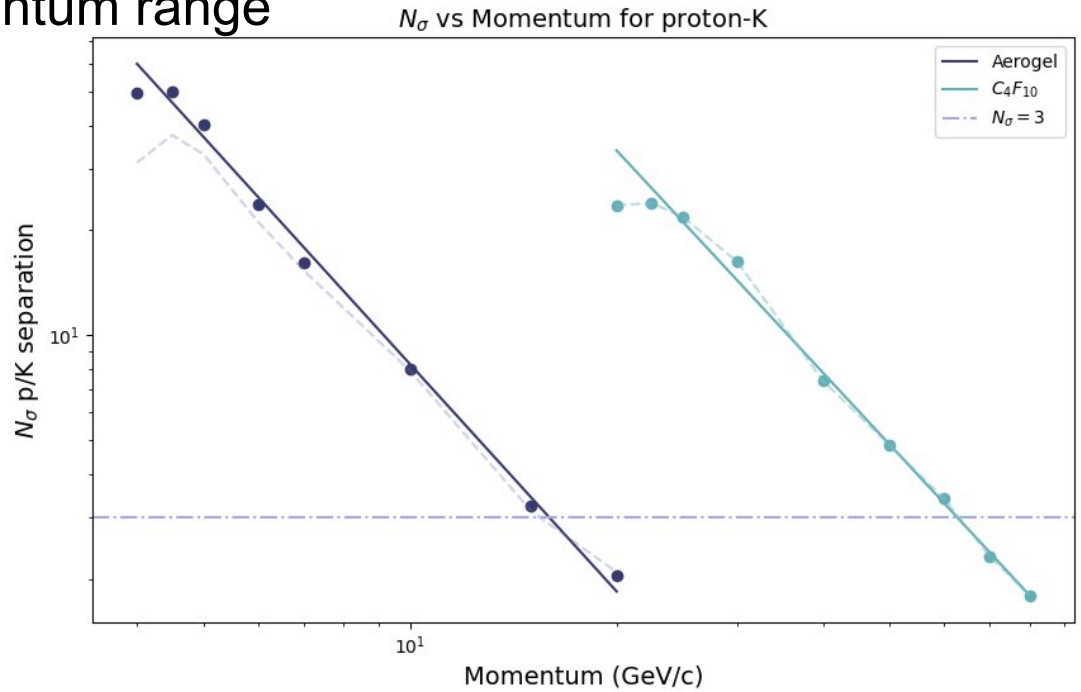
[1]INFN and University of Genova [2]CERN [3]University of Oxford

ARC (Array of RICH Cells)



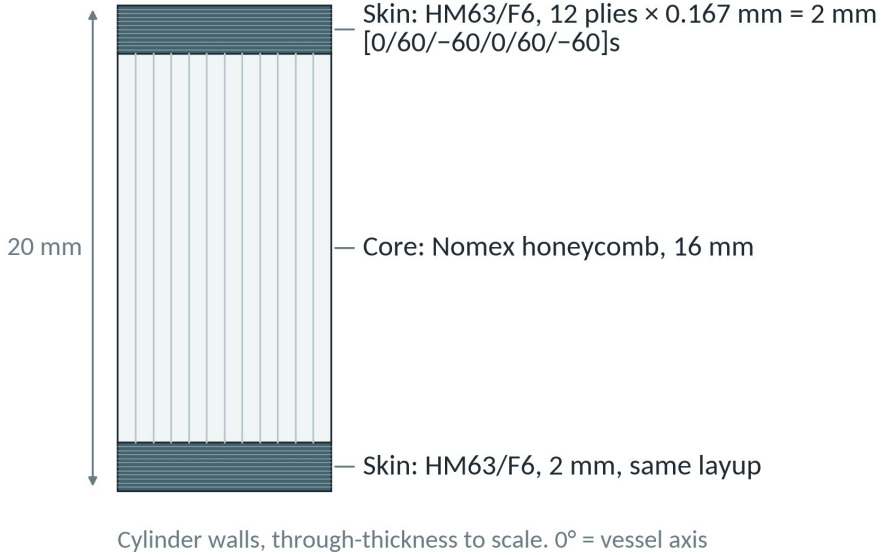
- Lightweight and compact solution for particle ID
  - Target: 20 cm radial depth, 10% X_0
- Cellular design
- Two radiators (gas + aerogel) to cover the full momentum range of interest
- Silicon Photomultiplier array mounted on a cold plate
- Excellent expected performance over a broad momentum range



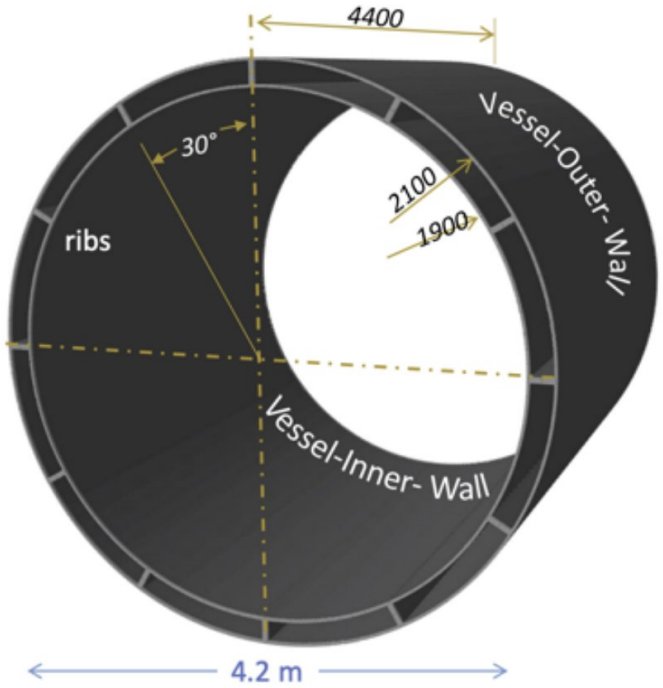


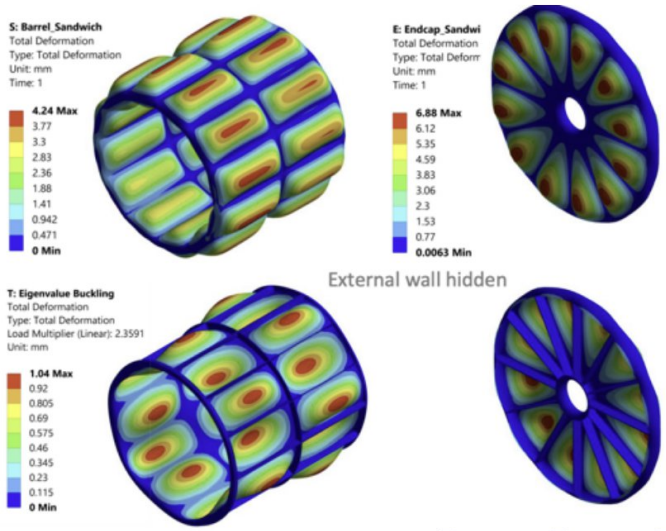
Integration in ALFA

- Carbon fiber pressure vessel to operate at ~2 bar with Xenon



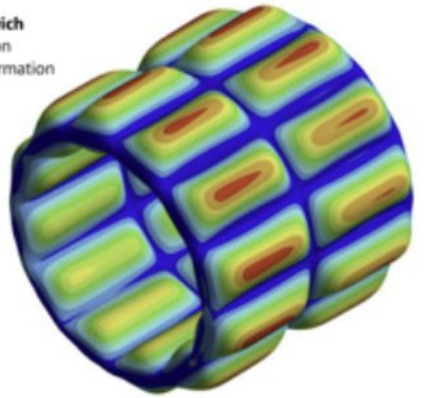
Cylinder walls, through-thickness to scale. 0° = vessel axis

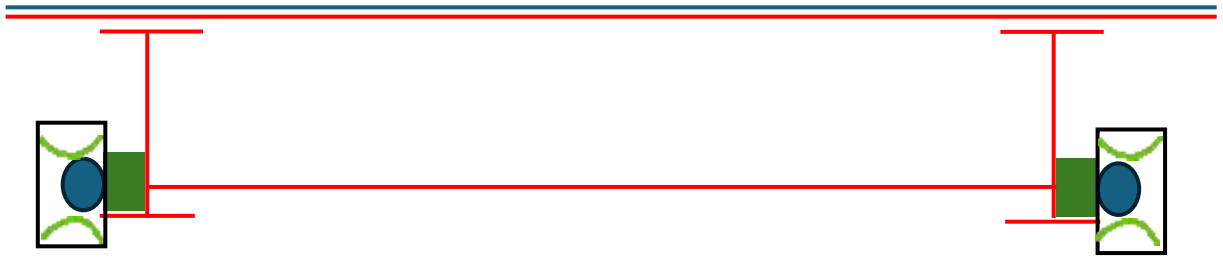




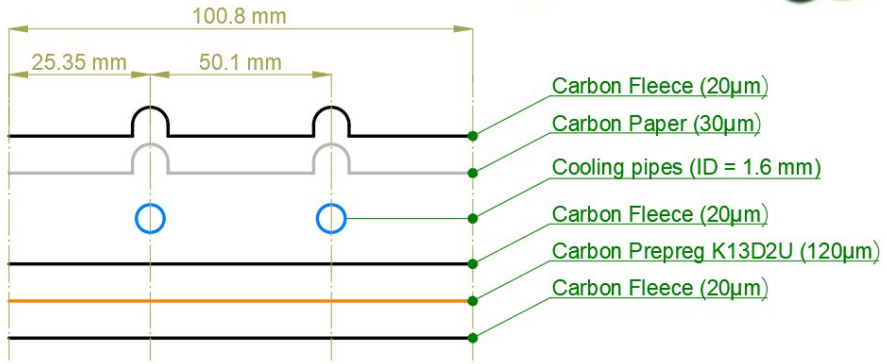
Stiff structures based on CF I-beams

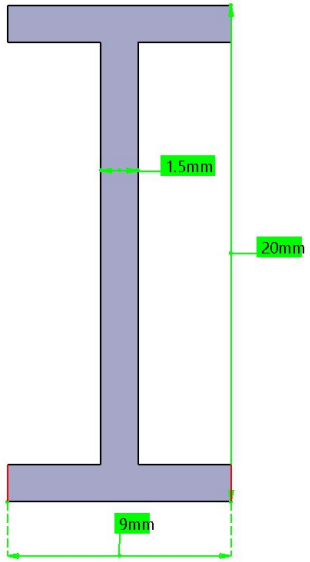
Fixed to the vessel only at z=0 and z=max, where there are ~ no deformations
From structural analysis expected sag <1 mm

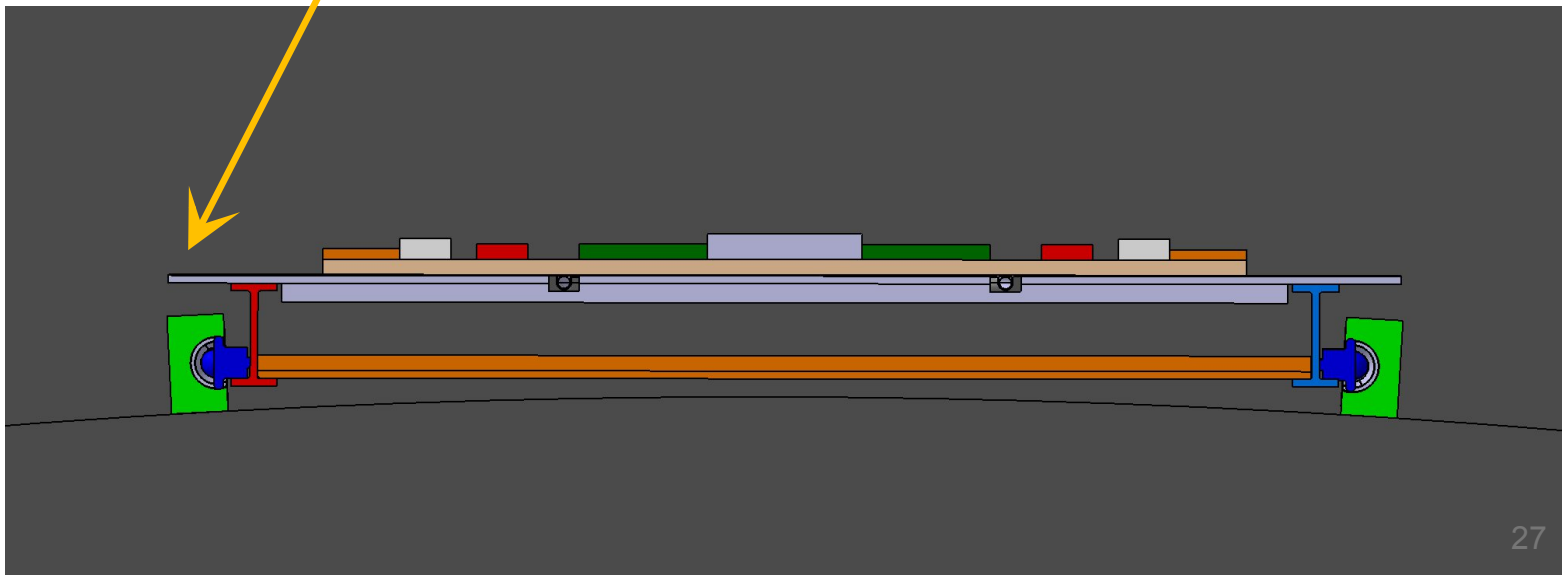




Cold plate similar to the Outer Tracker

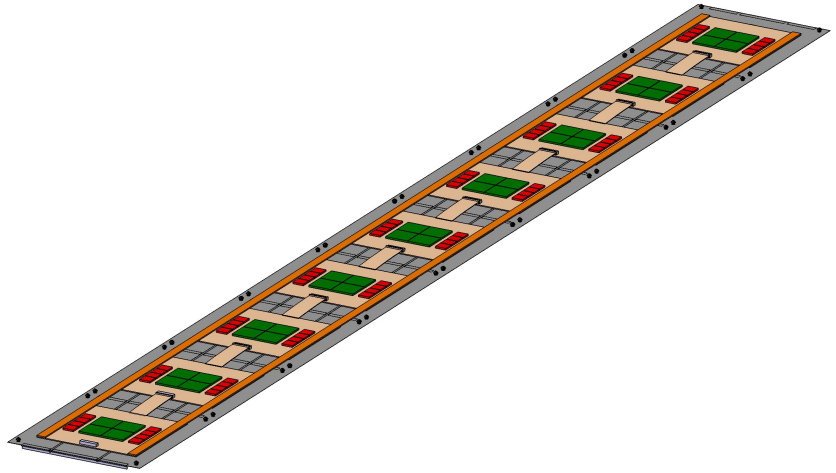


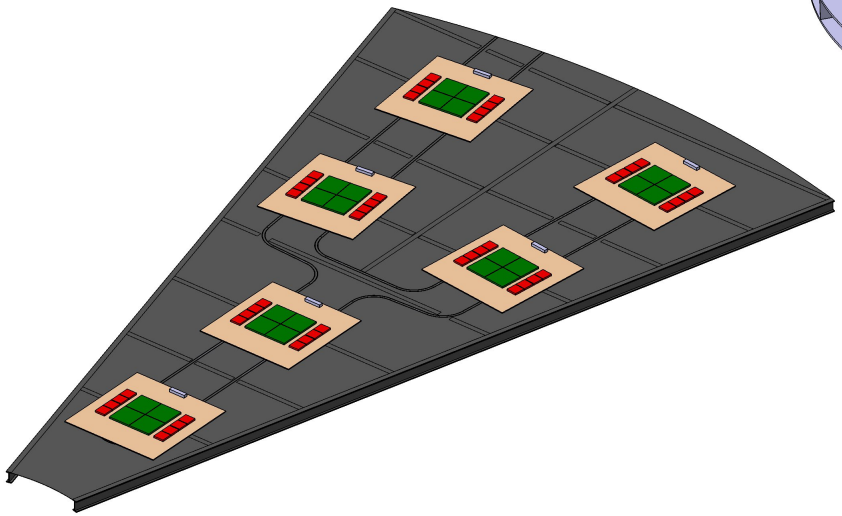


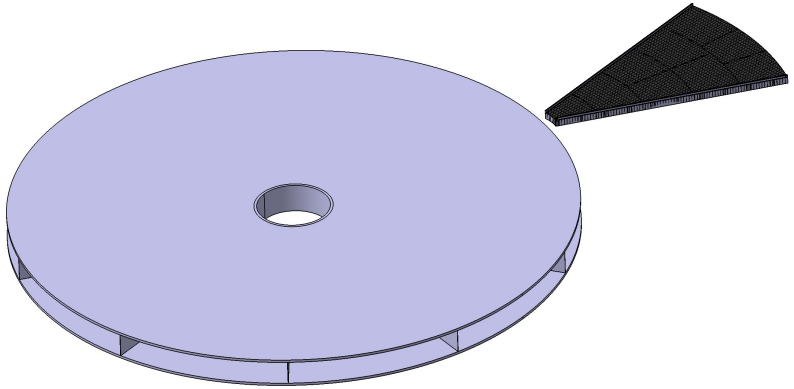


I-beams produced with the pultrusion process

Same concept applied to the endcaps





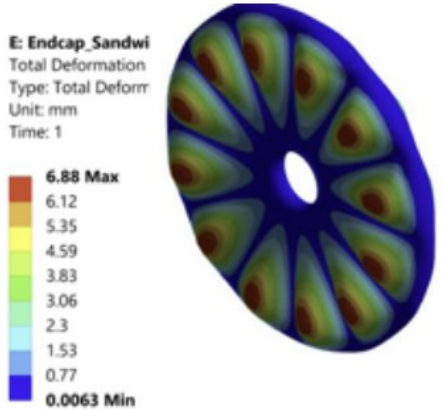


Barrel tray

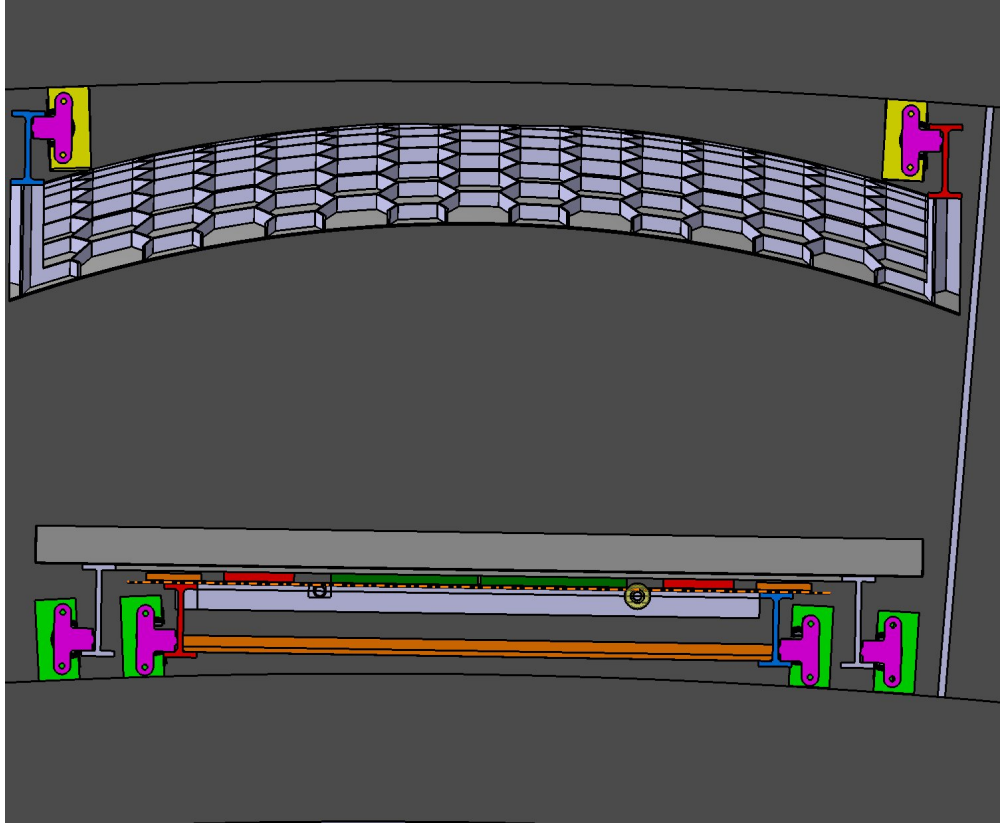
Length ≈ 2.4 m
Width ≈ 25 cm
One row of 9 cells

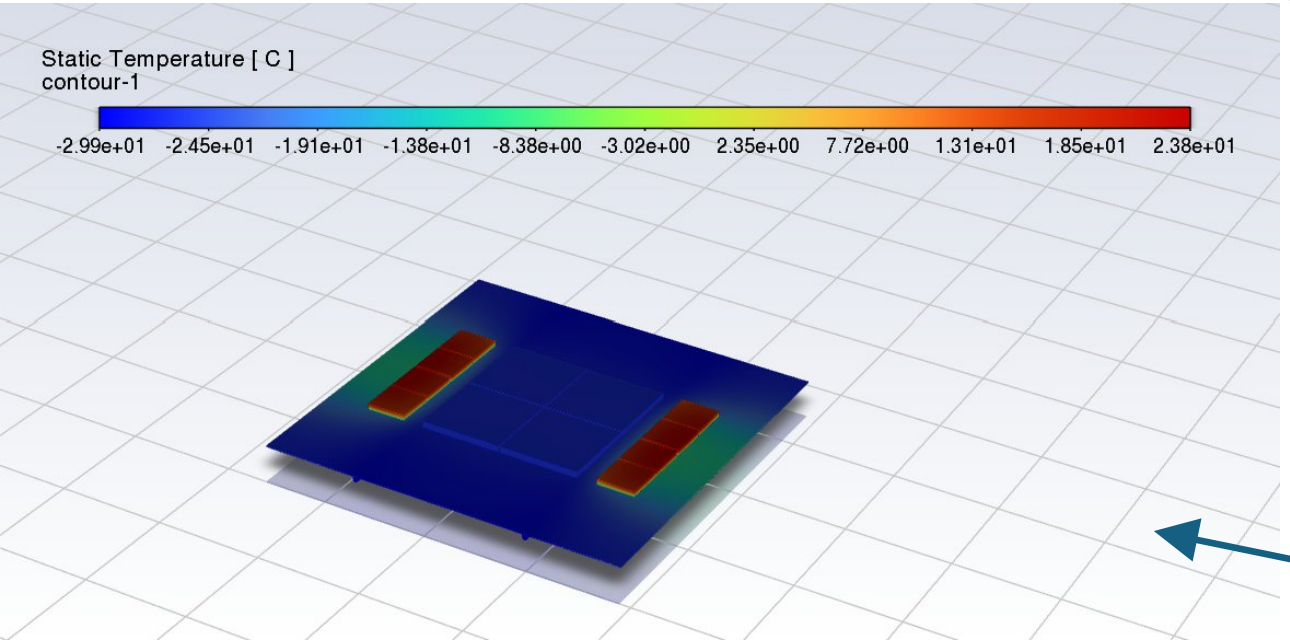
Endcap petal

Length ≈ 1.465 m
Maximum width ≈ 0.900 m
6 cells per petal



Similar structures for aerogel tiles and mirrors on the outer surface (three independent structures)





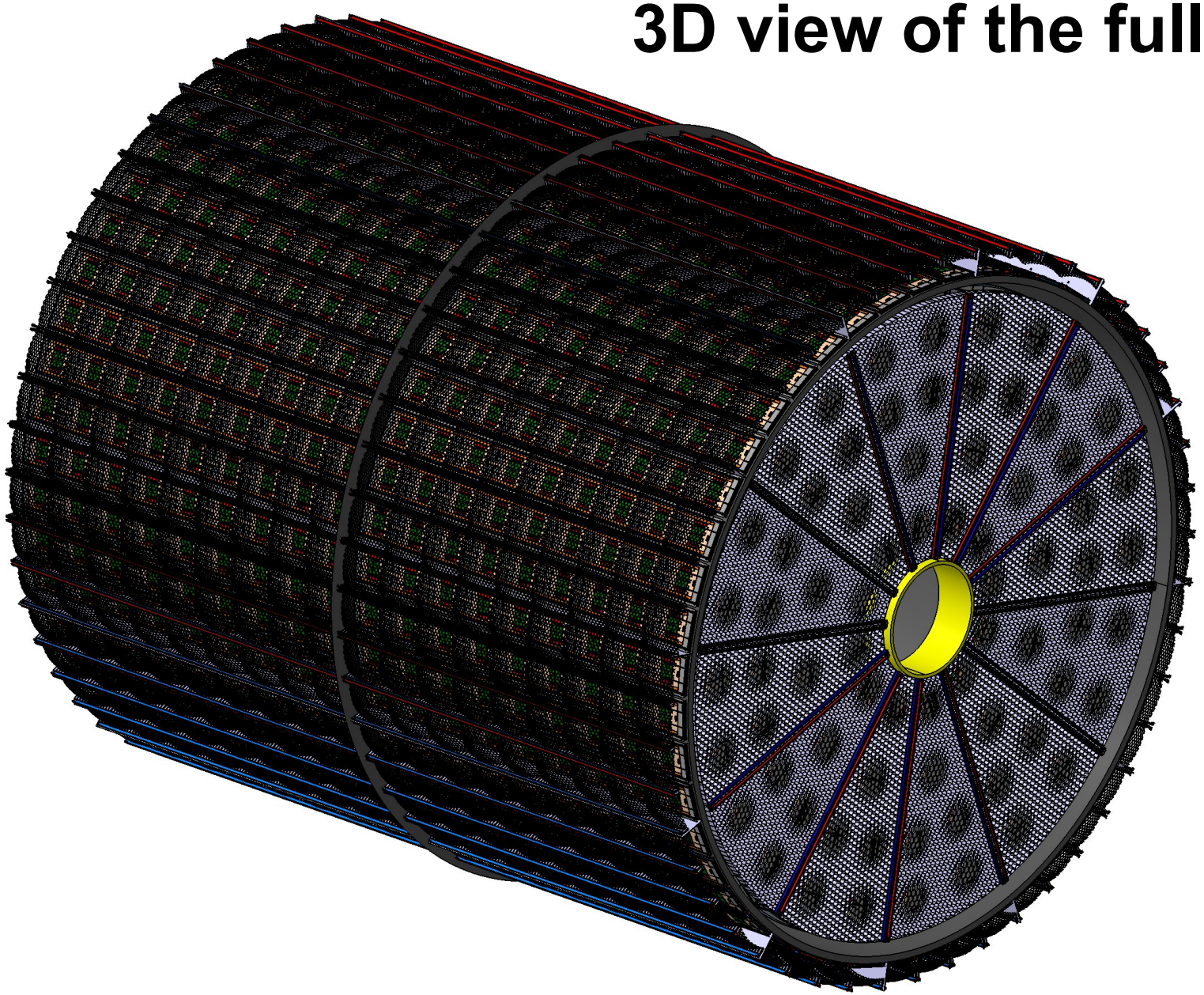
First results from thermal FEA very encouraging

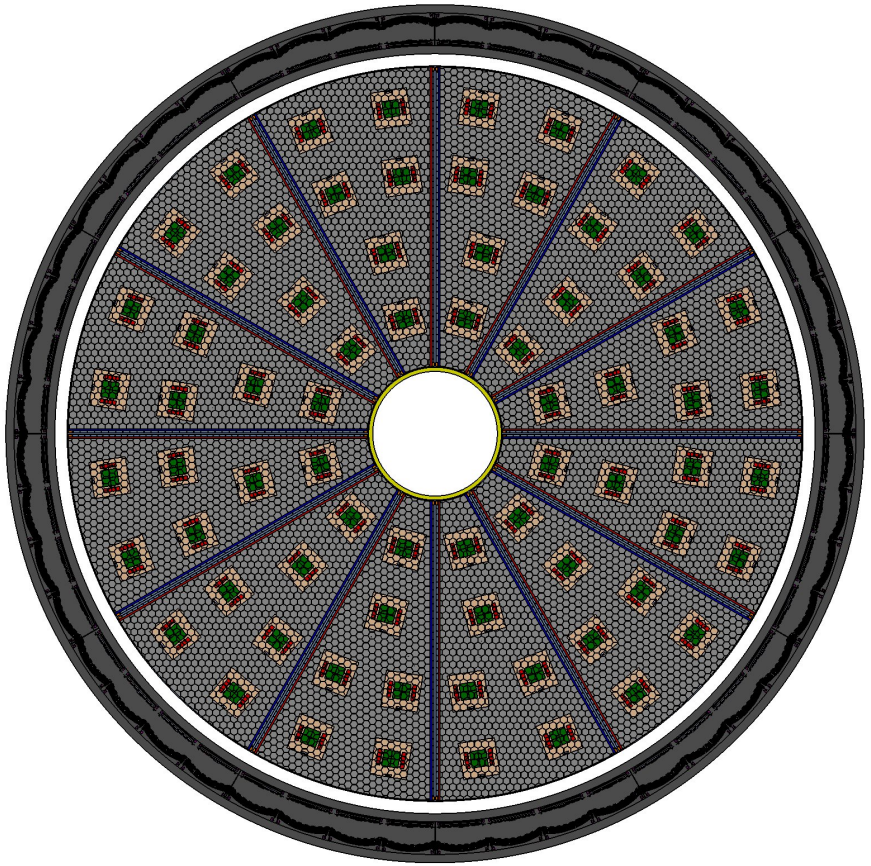
(Chip power is an initial guess)

Each support structure contributes ~0.4% X_0 to the material budget ⟶ very good

Radial depth might increase by a few cm compared to initial target

3D view of the full ARC detector





Shape of the mirrors, positions and shape of mirrors and photodetectors still to be optimized

ARC Outlook

- Design and construction of an early cell demonstrator based on existing hardware
  - With DRD4
- Implementation in full simulation
- Optimization of geometry
- Develop integration details (e.g. services)

The ECAL for the ALFA detector



Based on the **GRAiNITA** development:

IJCLab: S. Barsuk, I. Boyarintseva, D. Breton, G. Hull, J. Lefrançois, J. Maalmi, MH.Schune

ISMA: A. Boyarintsev, I. Tupitsyna

LPClermont: H. Chanal, Y. Hou, M. Magne, S. Monteil, D. Picard, M. Yeresko

TSNUK: O. Bezshyyko, A. Dubovik, D. Klekots, A. Kotenko, N. Semkiv

The GRAiNITA concept

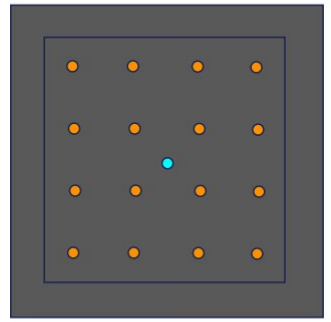
- Crystal grains ($ZnWO_4$) immersed in a heavy transparent liquid (sodium-tungstate water solution)
  - Mass fraction 80% $ZnWO_4$, 20% heavy liquid
- Light emitted by the crystal grains is collected by WLS fibres, spaced by 7 mm, + SiPM
- Excellent energy and position resolution
- Grains produced with the flux method, cost-effective compared to homogenous crystals

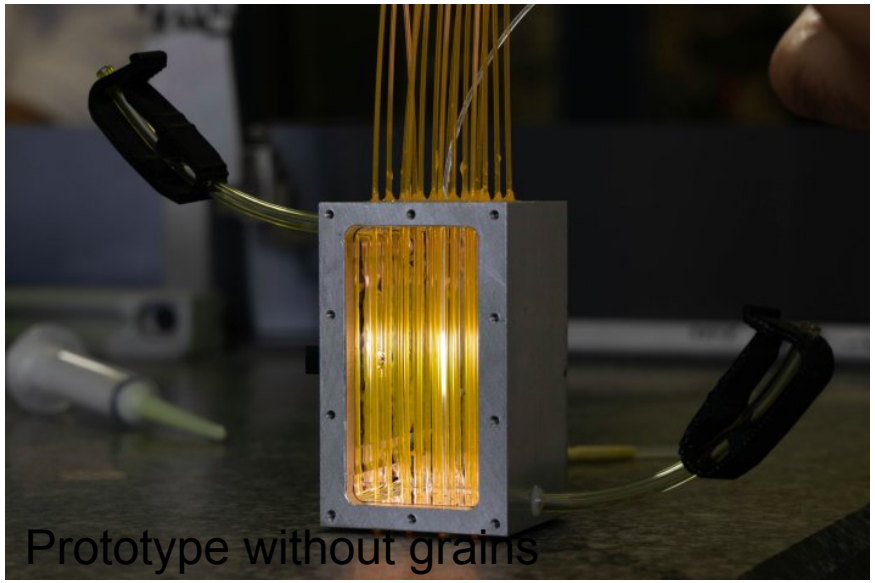


~1 mm scintillator grains (solid)
in high-density transparent liquid

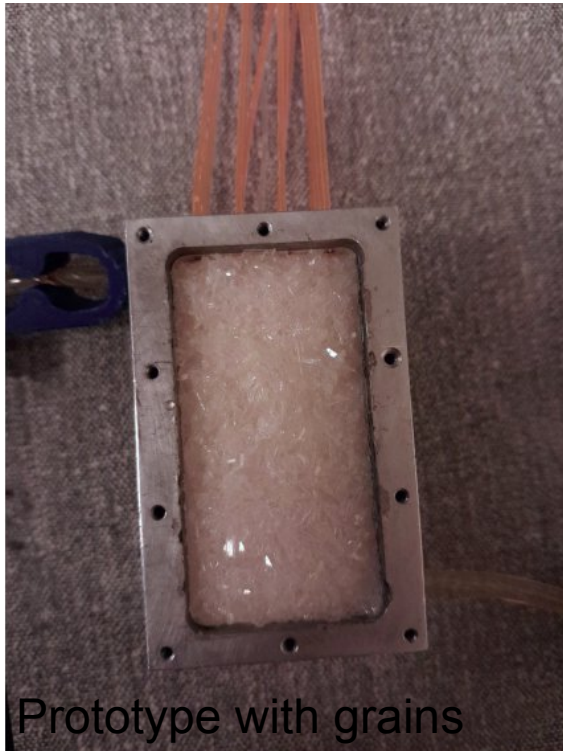
GRAiNITA: the first prototype

- 28 x 28 x 55 mm^3 active volume
- ~200 grams of $ZnWO_4$ and heavy liquid
- 4 x 4 WLS fibres, spaced by 7 mm
- Clear fibre at the center, for light injection

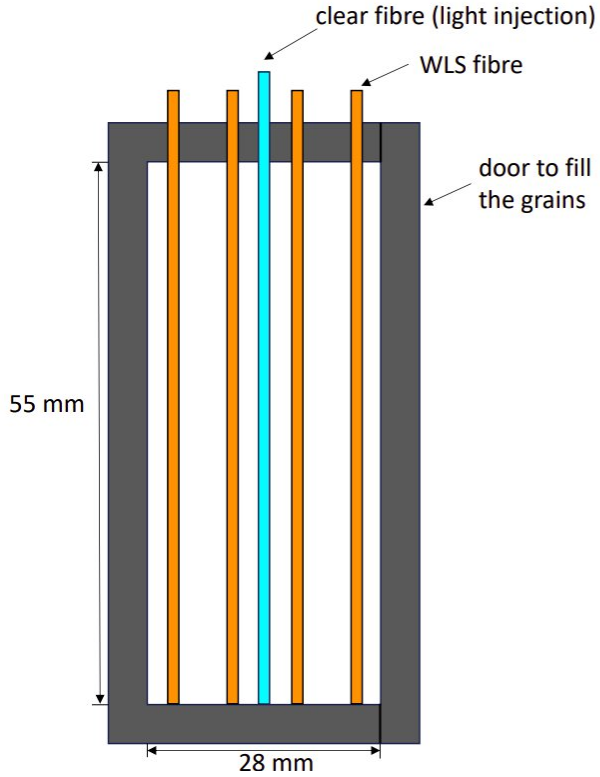




Prototype without grains

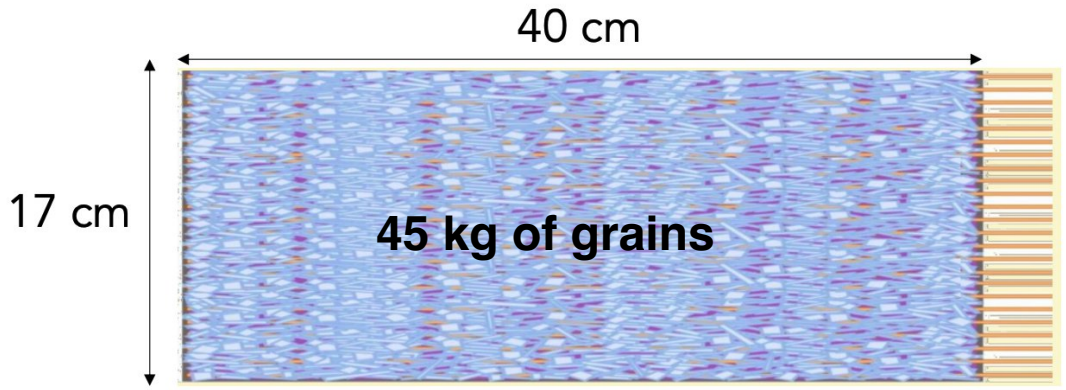


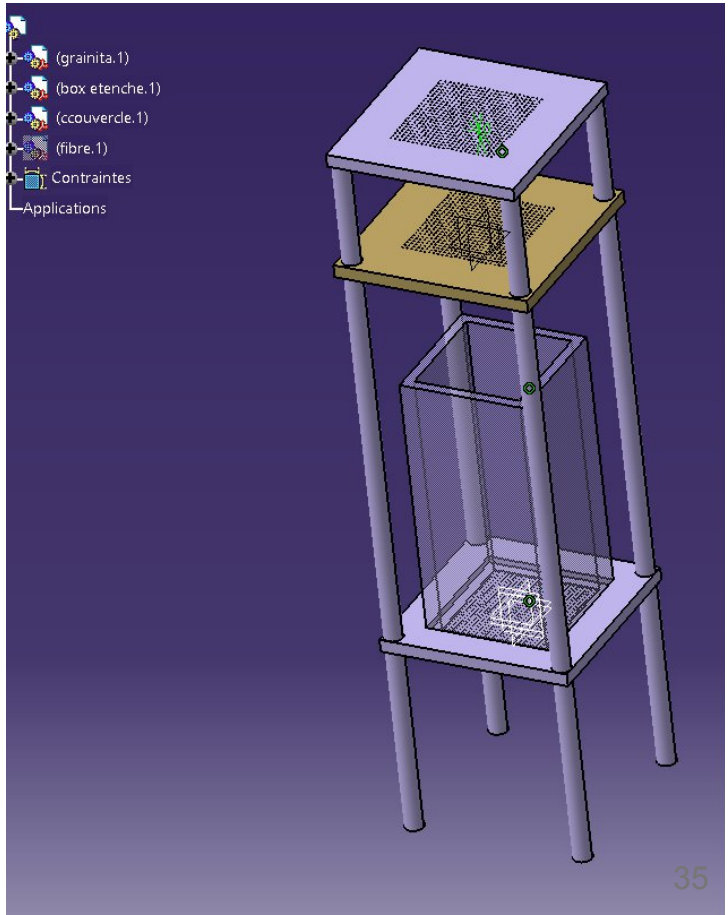
Prototype with grains



GRAiNITA: status and next steps

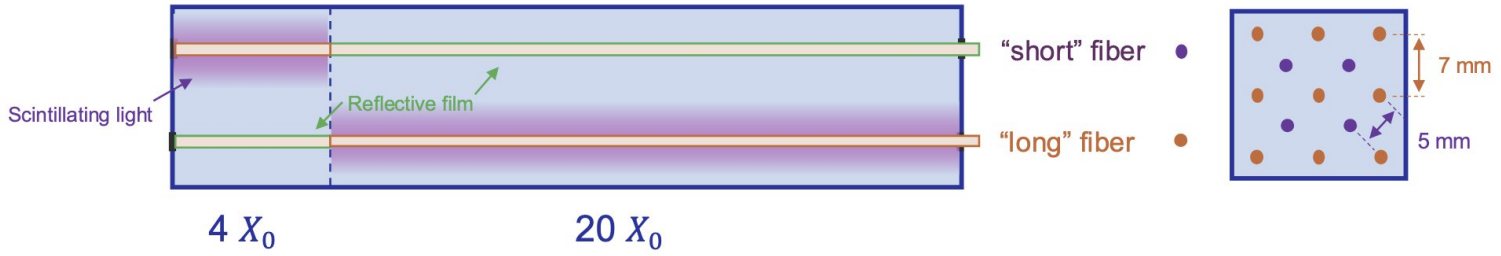
- **Based on results from the prototype, a stochastic term of < 2% and a constant term of < 1% seem realistic**
- A full-size module demonstrator (17 × 17 × 40 cm^3) is under construction
  - 25 X_0 in depth to contain 25 GeV photons
  - Lateral size adequate for extensive measurements of uniformity
  - Quantitative assessment of all components of the resolution





In parallel: studies to improve hadron energy measurement

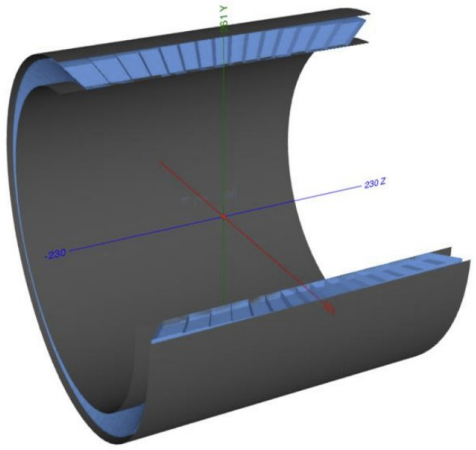
- **Improved hadron energy measurement**
  - **Pulse shape discrimination (baseline)**
    - Exploits differences in the light emission time profiles for different particle types
    - Requires precise reconstruction of the pulse shape
    - Recent CYRCE beam-test data with 10 and 25 MeV protons support this approach
      - Data analysis ongoing
  - **Measurement of Cherenkov light (alternative or complement)**
    - A small but detectable amount of Cherenkov light is produced in the grains
    - Requires fast sampling in the beginning of the signal
- **Longitudinal segmentation into two sections**
  - **Possible implementation by doubling the number of fibers**
    -

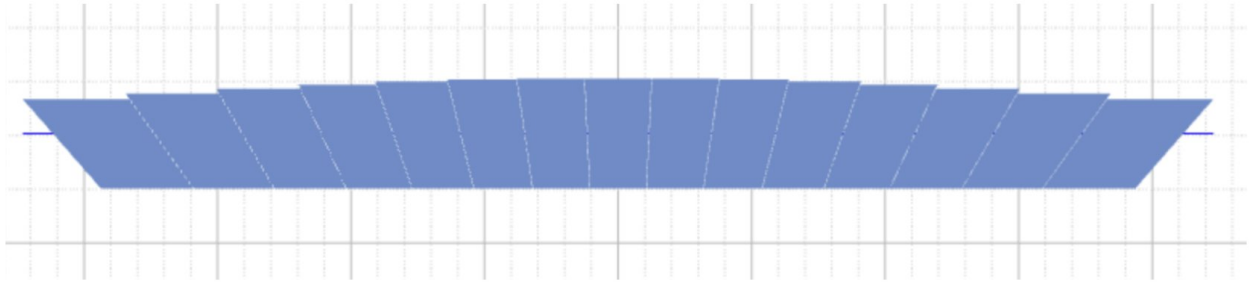


reflective aluminium coating

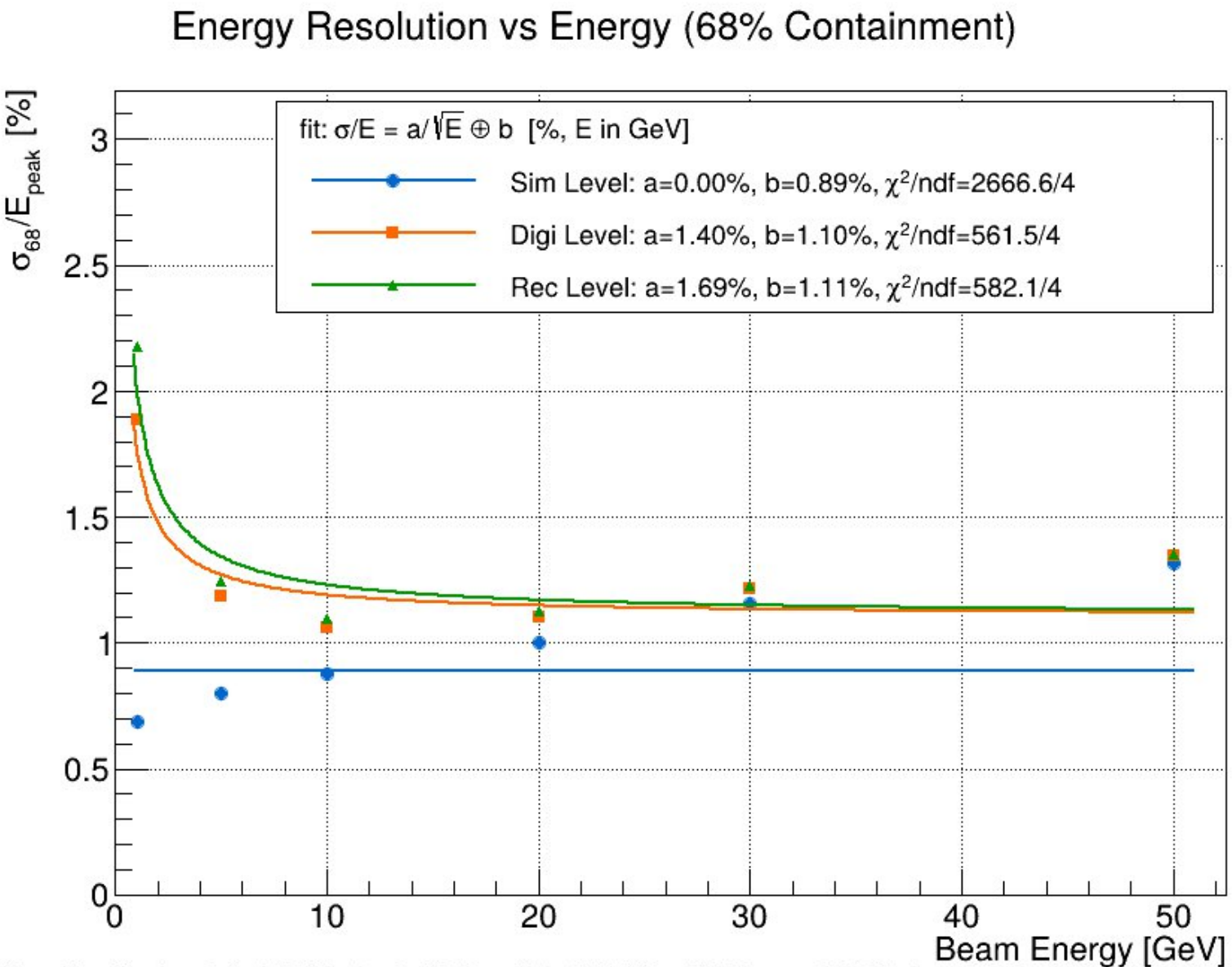
Grainita ECAL barrel in full sim

- ECAL barrel geometry, with $\mathbf{R_{in} = 2.2\ m}$, $\mathbf{R_{out} = 2.6\ m}$, $\mathbf{Z\ length = 4.6\ m}$
- Total thickness 443 mm = 10 mm (inner support) + **405 mm (ZnWO4+liquid mixture, 24.3 X_0)** + 18 mm (air, space for SiPM, cable, cooling etc.) + 10 mm (outer support).
- Module segmentation: $72(\phi) \times 15(\theta)$, with 5 mm carbon fiber walls between modules
- 2 longitudinal layers: ~5 X_0 and ~20 X_0.
- Particle gun: single photon, 1-50 GeV, $\theta \in [60°, 120°]$, $\phi \in [0°, 360°]$.
  - Sim-level: Geant-4 dE/dx, no Grainita light response model.

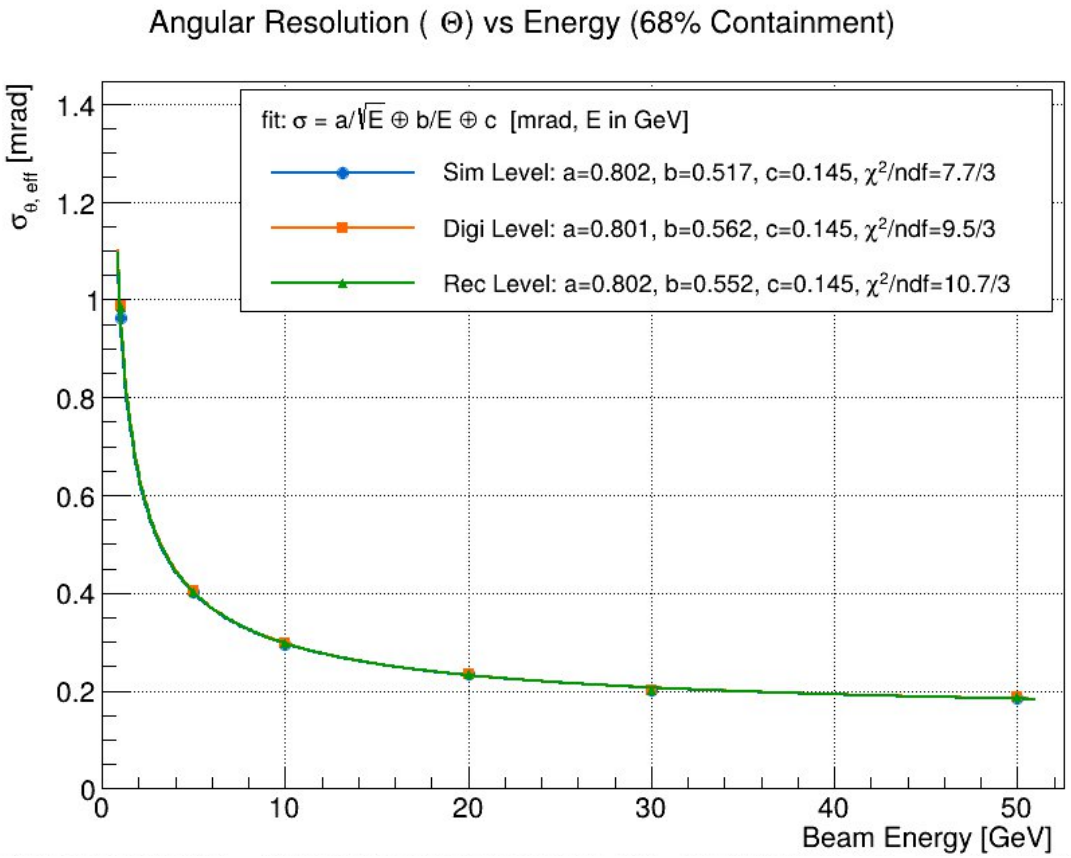


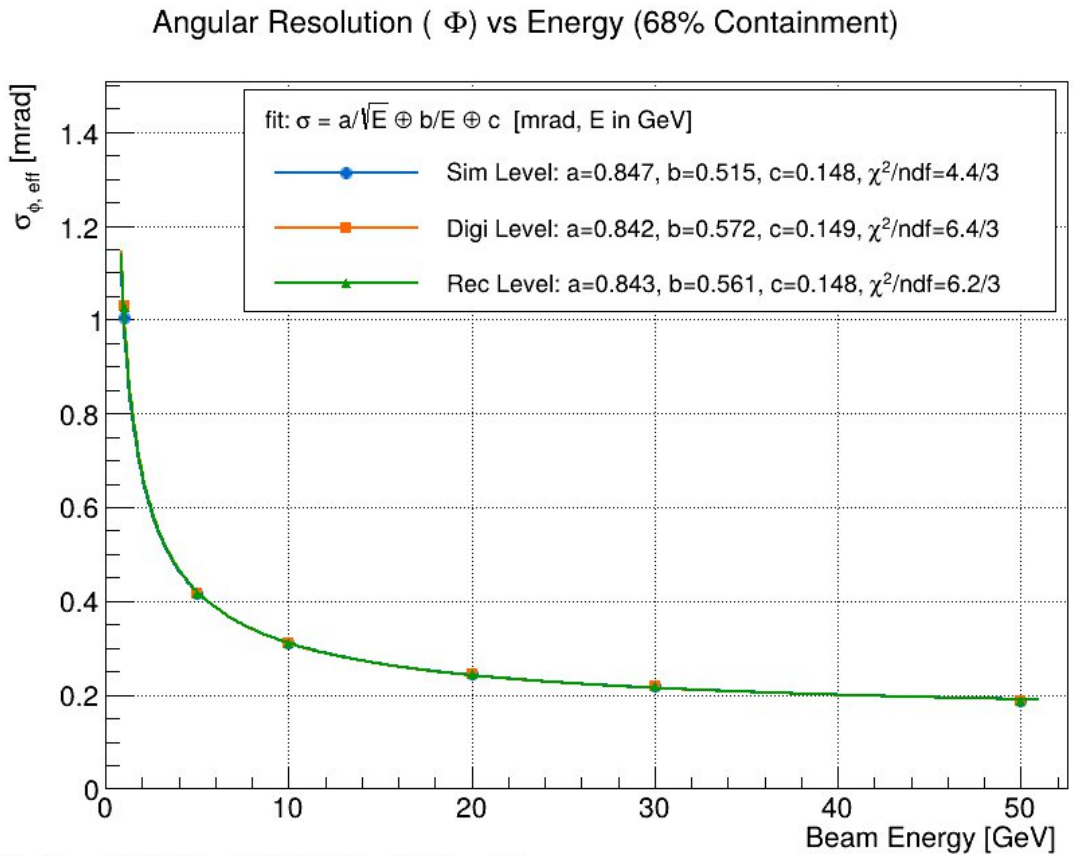


Grainita ECAL performance



Grainita ECAL performance





CFR CMS ECAL resolution: ~1 mrad

ECAL Outlook

- Simulations ahead of engineering design
- Launch design and prototyping of a module optimized for integration in a large-size calorimeter
- Design of overall supporting mechanics
- Evolve simulations accordingly
- Endcaps…

The **Instrumented Yoke** for the **ALFA detector**

The Concept

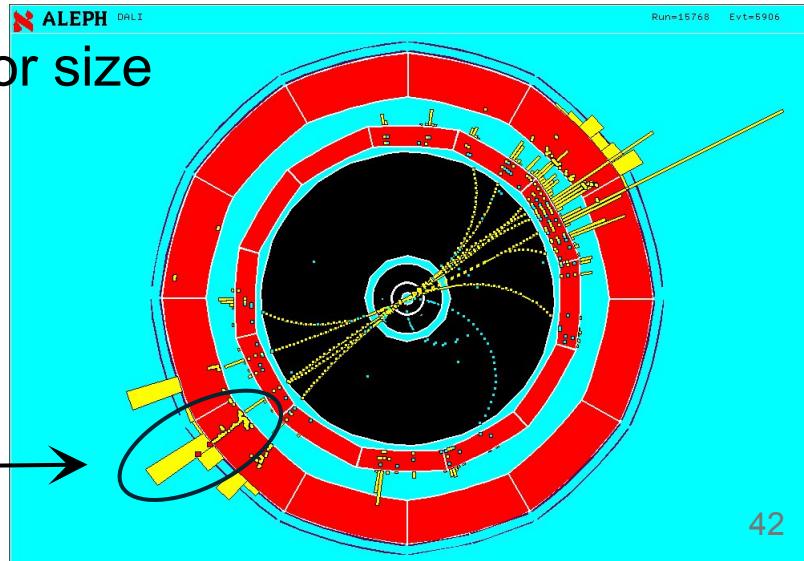
- Yoke instrumented with layers of plastic scintillator tiles read out by SiPMs

- Flexible and cost-effective detector concept
  - Sufficiently fine sampling enables good hadron energy measurement
  - Sampling density can be tuned as a function of depth
  - Optimize design taking into account physics performance, cost, complexity and mechanical requirements

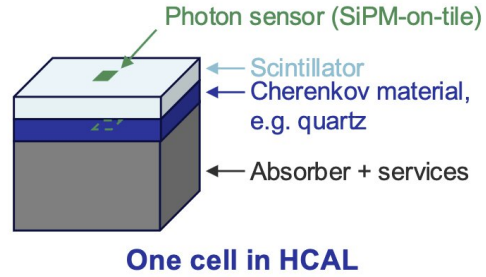
    ⟶ **The yoke is the main support structure of ALFA**

- Using the yoke as the HCAL absorber helps limit the overall detector size

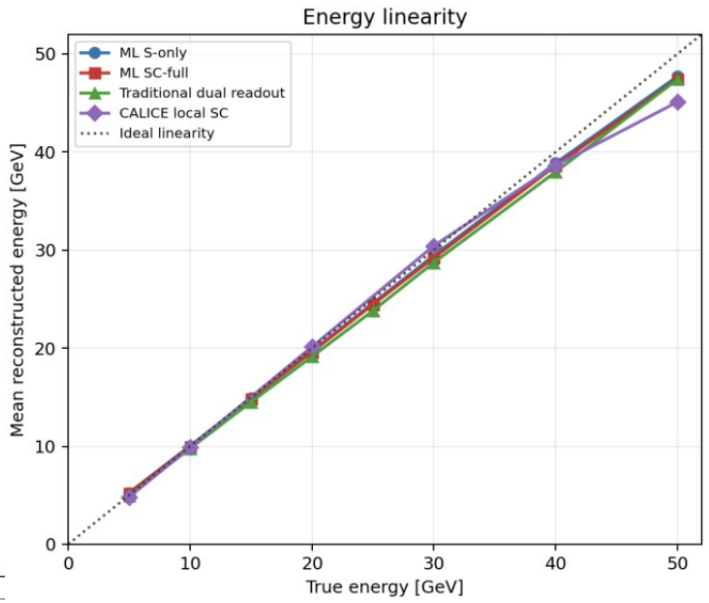
- Also provides muon tagging in the back part

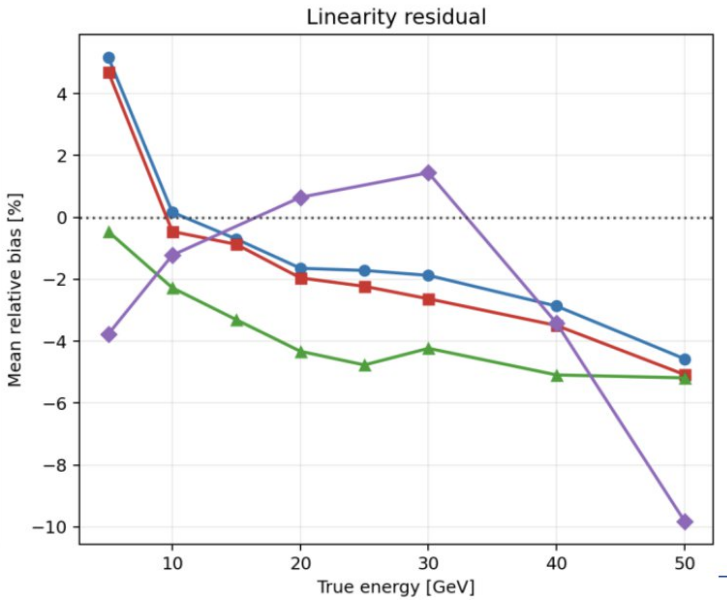


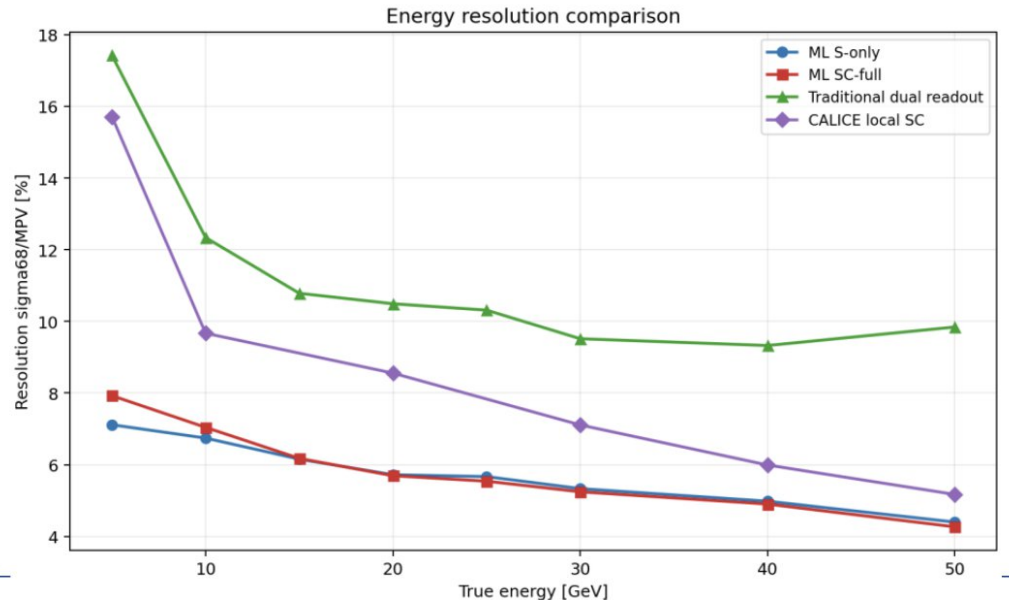
Standalone simulation studies



- Cube of dimensions 1.8×1.8×1.8 m^3
- Cell of 3×3×3 cm^3
- 2 cm steel absorber + 0.5 cm plastic scintillator + (optional) 0.5 cm sapphire material

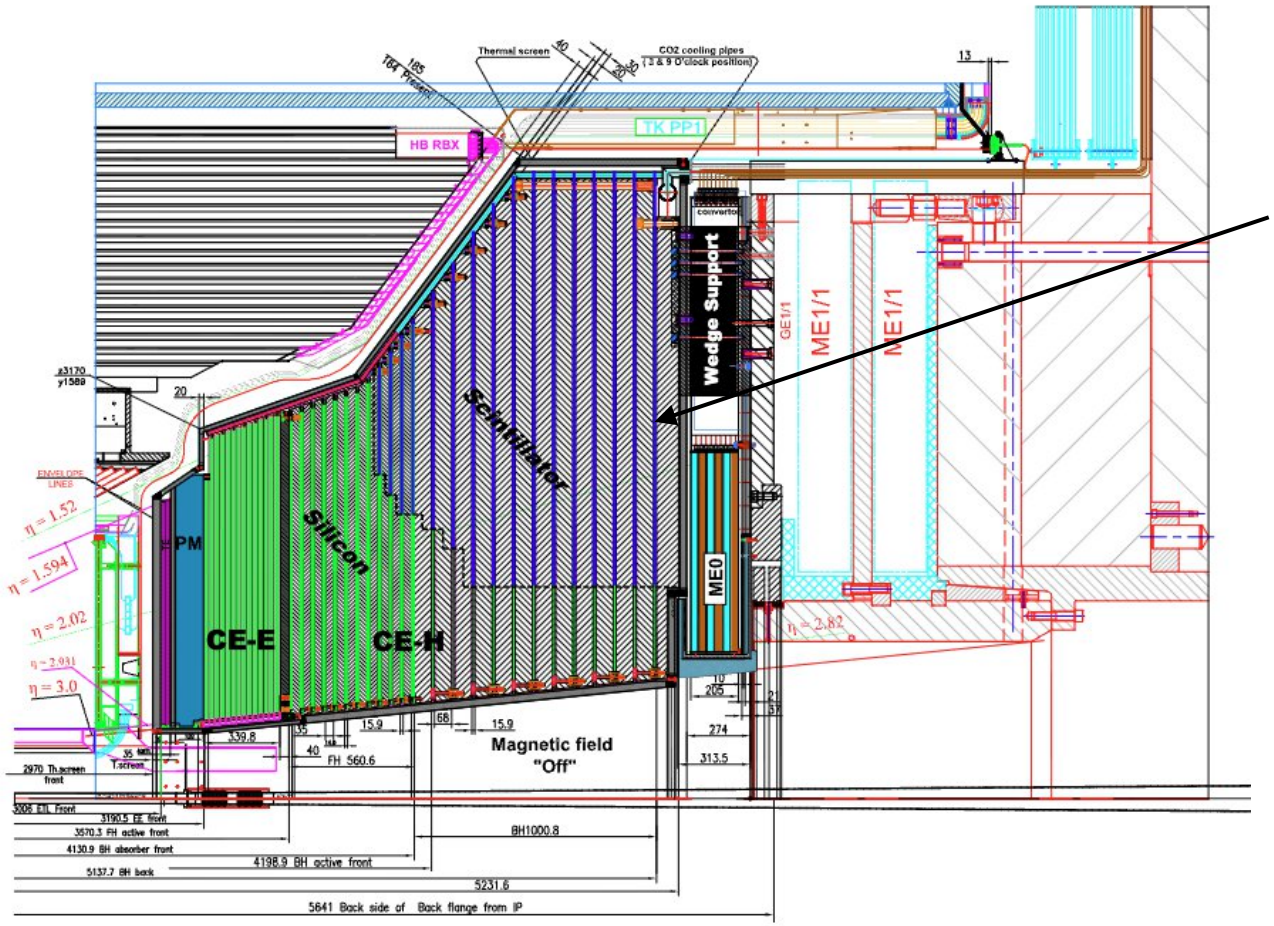


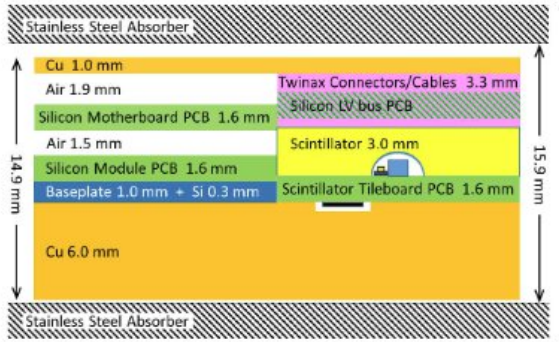


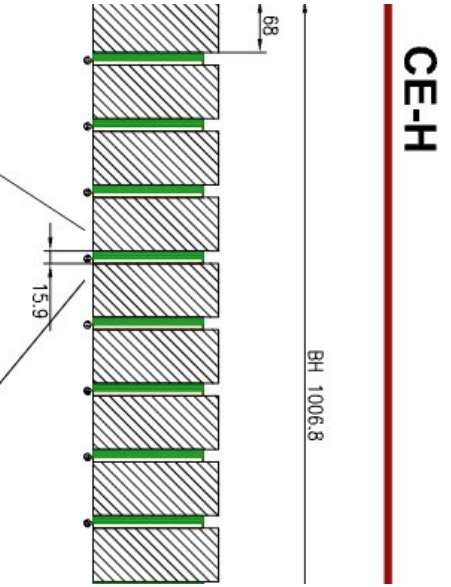


- Additional “Cherenkov” layer appears to bring modest benefit
- Baseline defined as a scintillating tiles / steel sampling calorimeter

Detector model







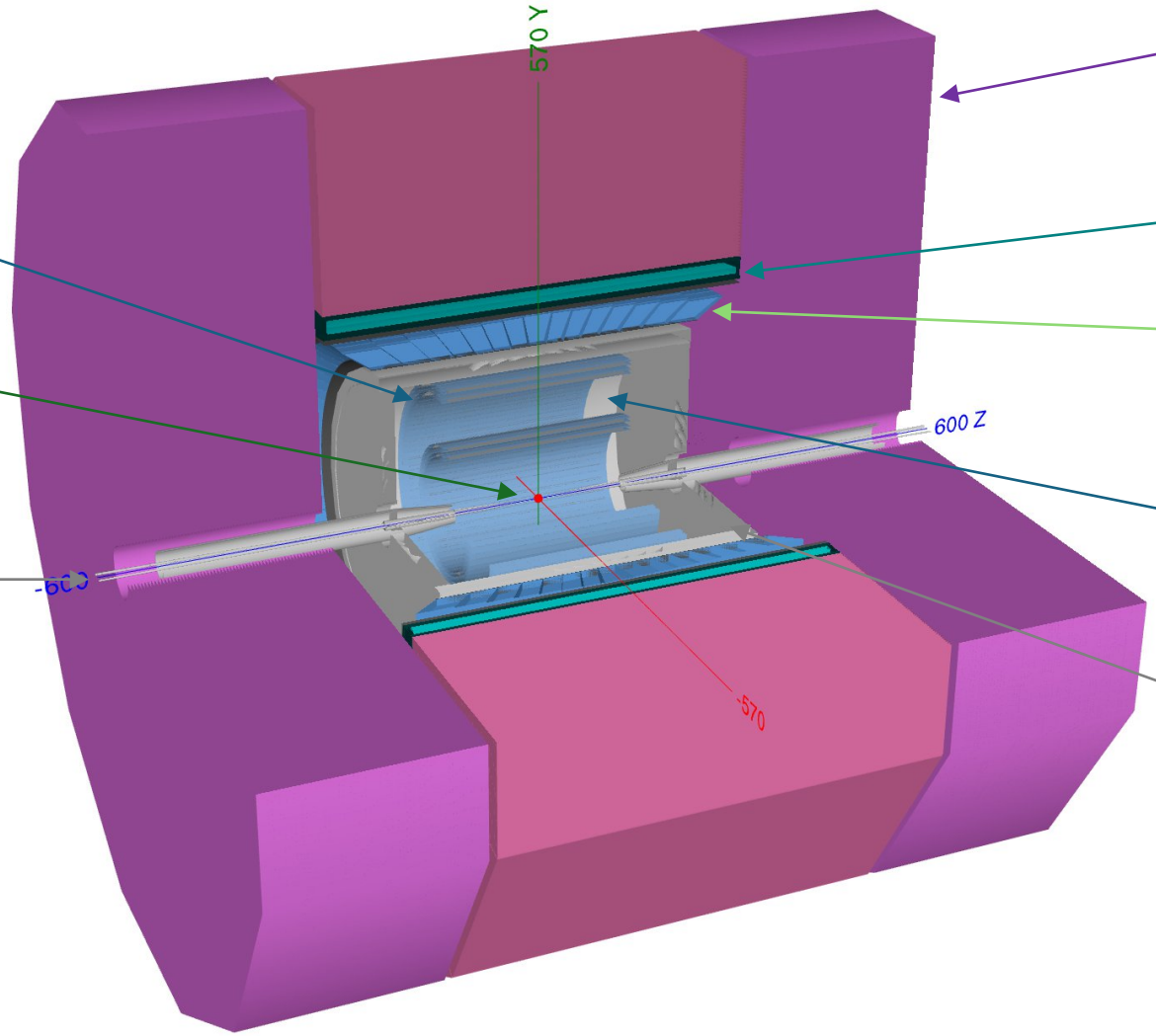
Use HGCAL as template, with finer sampling

Engineering design of the yoke on the starting blocks!

Instrumented Yoke Outlook

- Develop an engineering design of the Yoke (starting)
- Develop an initial design of the detector planes based on the HGCAL back part
- Implement in fullsim and evaluate performance as hadron calorimeter
- Evaluate performance as muon detector
  - Consider possible improvements, if appropriate

ALFA taking shape in fullsim!



HCAL / Yoke (place holder)

Outer tracker barrel

Solenoid (place holder)

Grainita ECAL barrel

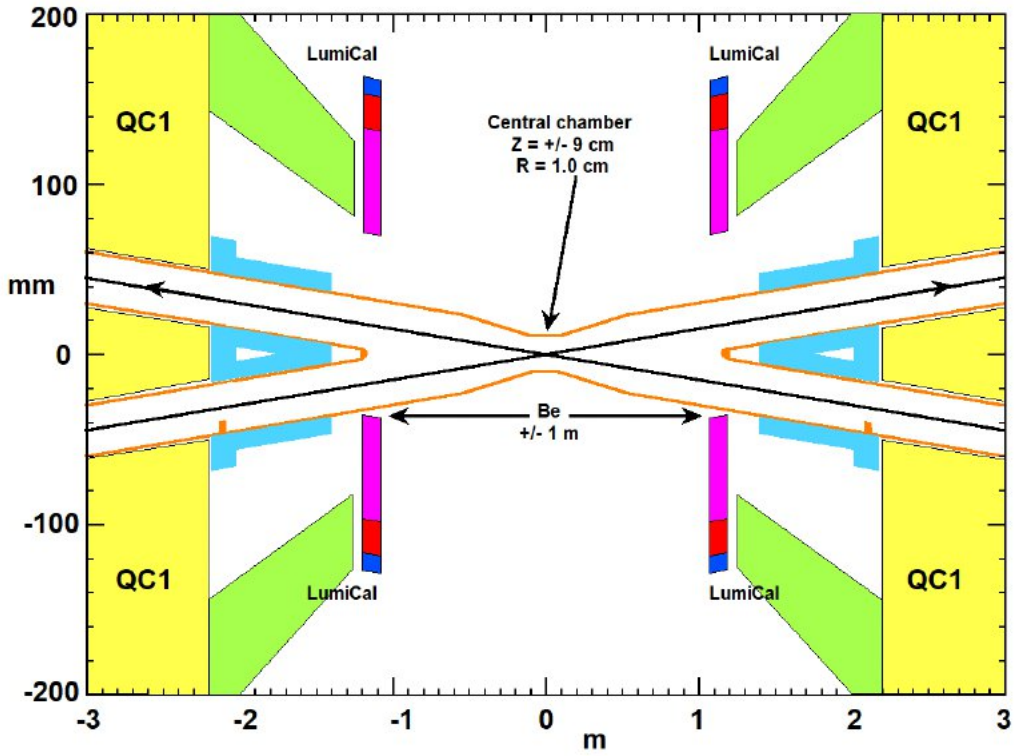
Vertex detector (place holder)

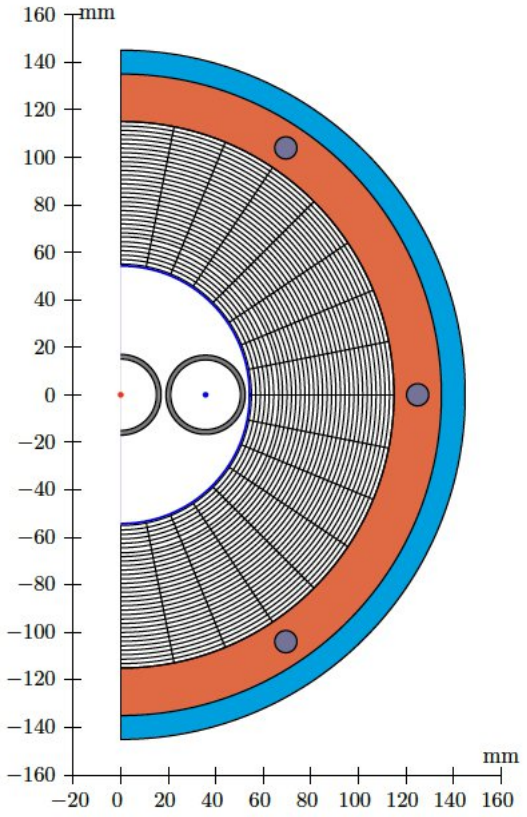
Outer tracker endcap…
will come later!

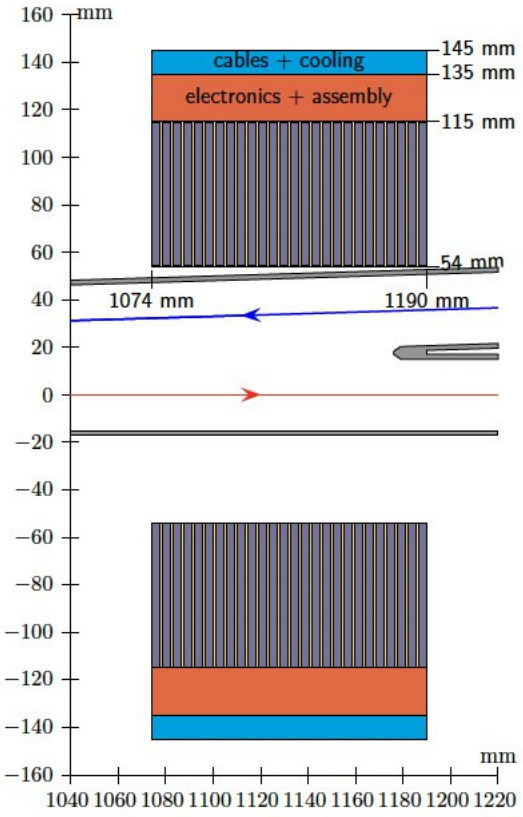
MDI (place holder)

ARC (place holder)

One more subdetector: the luminometer

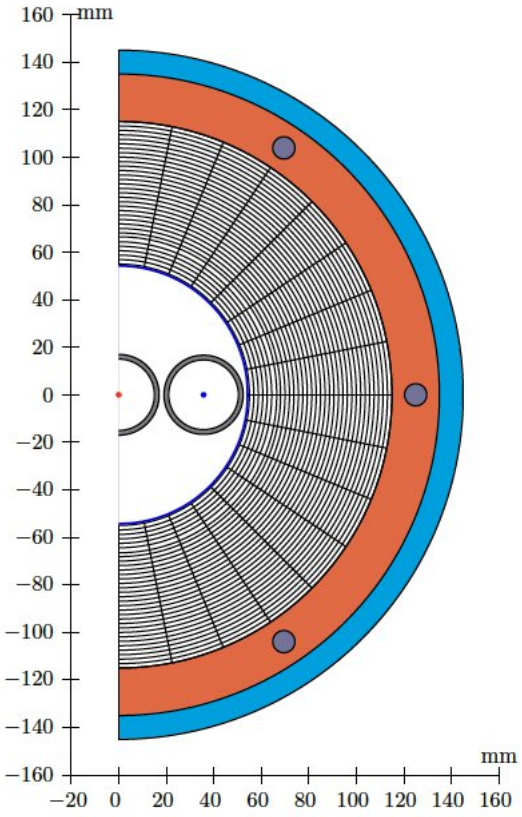


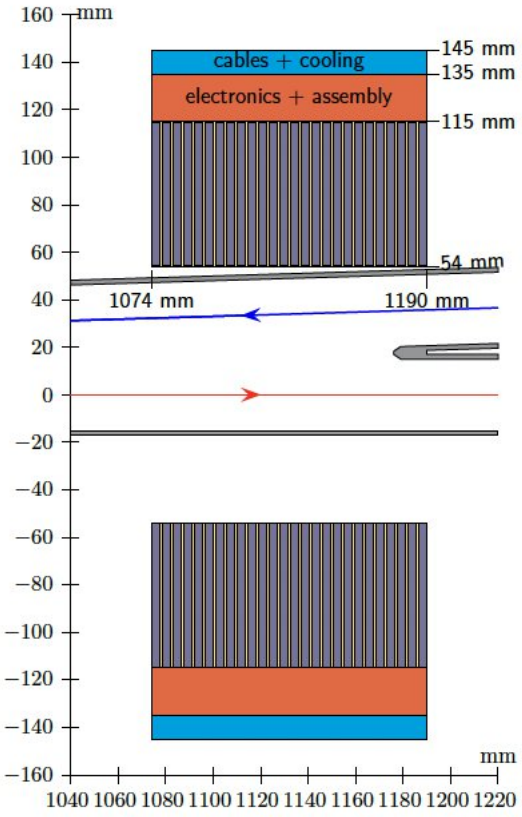




One more subdetector: the luminometer

- One existing concept made of W and Si-strip layers
  - Inspired by the OPAL luminosity calorimeter

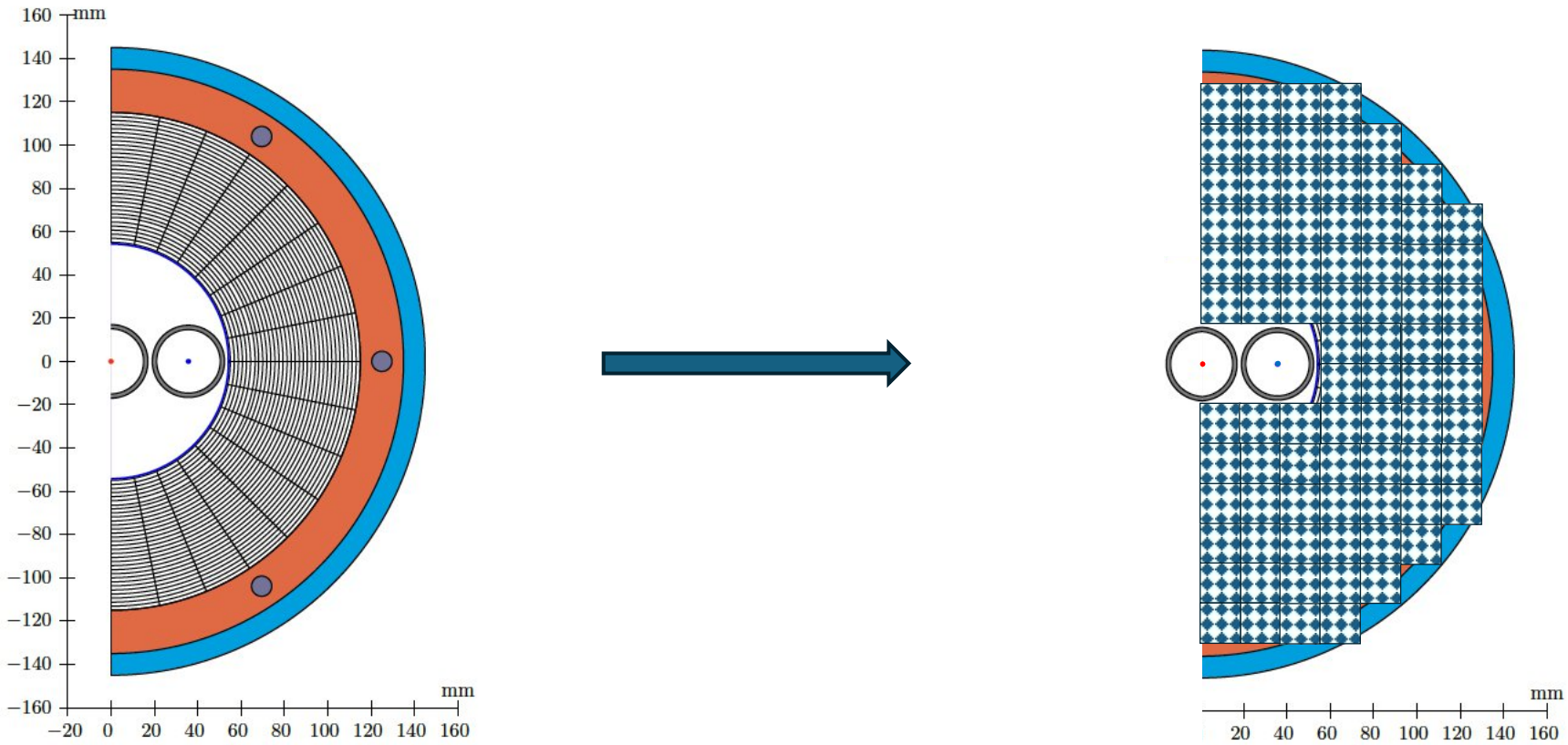




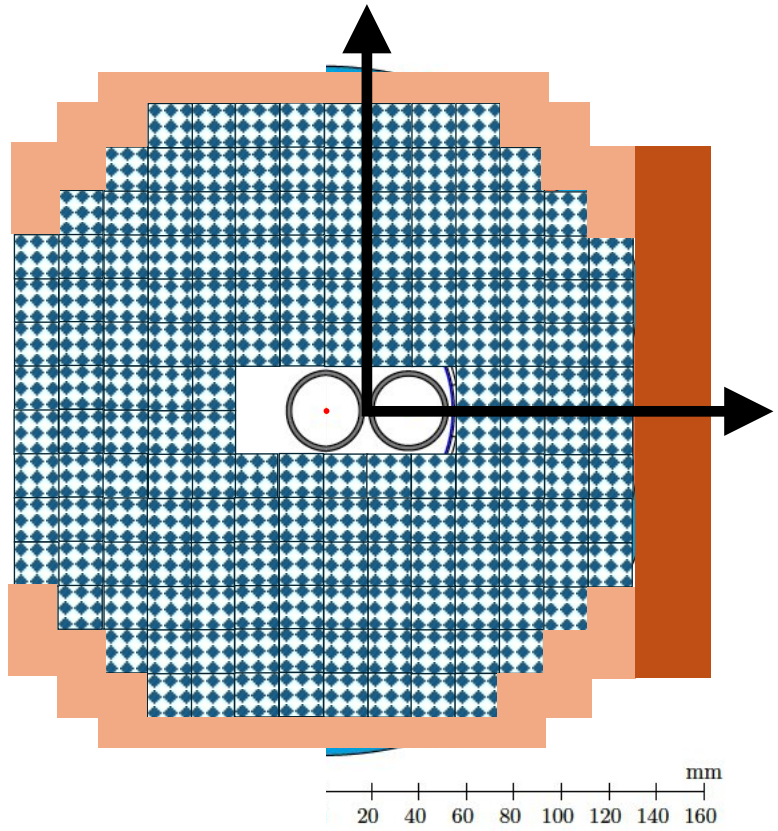
- Acceptance needs to be defined *a posteriori* using physics constraints
  - Like the alignment for the Tracker

Basic idea:

- Replace Si strips with MAPS positioned as close as possible around the beam pipe(s)



Why MAPS?



- ❖ Penalty in geometry because of rectangular units
- ➢ Minimal circuitry needed on the periphery of the sensor
  - Probably compensates the disadvantage
- ➢ Highest granularity ⟶ best possible “image” of the shower
- ➢ Sensors are (routinely) thinned down to 50 μm
  - Could reduce gap between W slabs, and/or implement two active layers for redundancy
- ➢ Sensors could be glued directly on the W surface, with cooling contacts on the periphery of the W slabs

✓ **Concept to be developed**

Meetings and EOIs

There are two series of ALFA-related meetings:

- **ALFA general meetings – biweekly**
  - https://indico.cern.ch/category/21437/
  - Working meetings: present progress and new ideas, keep the community informed, obtain feedback
  - fcc-ped-detectorconcepts-alfa
- **Round-table among developers, with no agenda – weekly**
  - https://indico.cern.ch/category/20354/
  - Mostly intended for discussion among developers… but everybody is welcome!
  - ep-fcc-alfa-design

Recently invited to express interest in ALFA

- Google sheet

Thanks for your attention

Questions?



Backup

ARC acceptance at low momentum

