FCC workshop
Bologna, October 14th, 2025

FCC and Italian activities

Paolo Giacomelli
INFN Bologna

Physics requirements

Higgs Factory Programme

- At $\sqrt{s}$=240 and $\sqrt{s}$=365 GeV collect 2.6M HZ and 150k WW→ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \to$ H at 125 GeV

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim$ 50 GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6 × 10^{12} Z and 2 × 10^8 WW events
- × 500 improvement of statistical precision on EWPO: m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2 × 10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to $\lesssim 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2 × 10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/$\sqrt{E}$**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

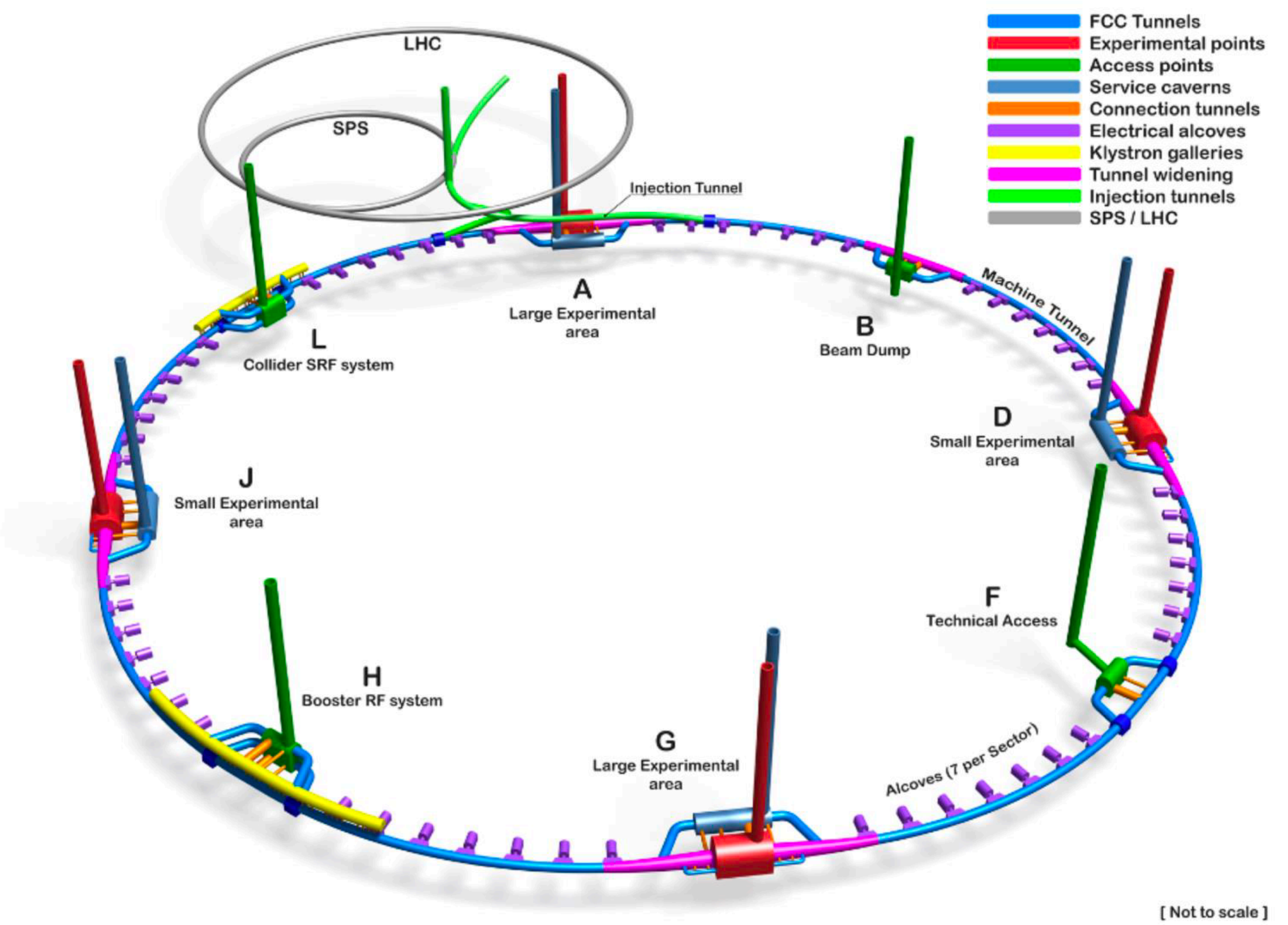
- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

M. Dam

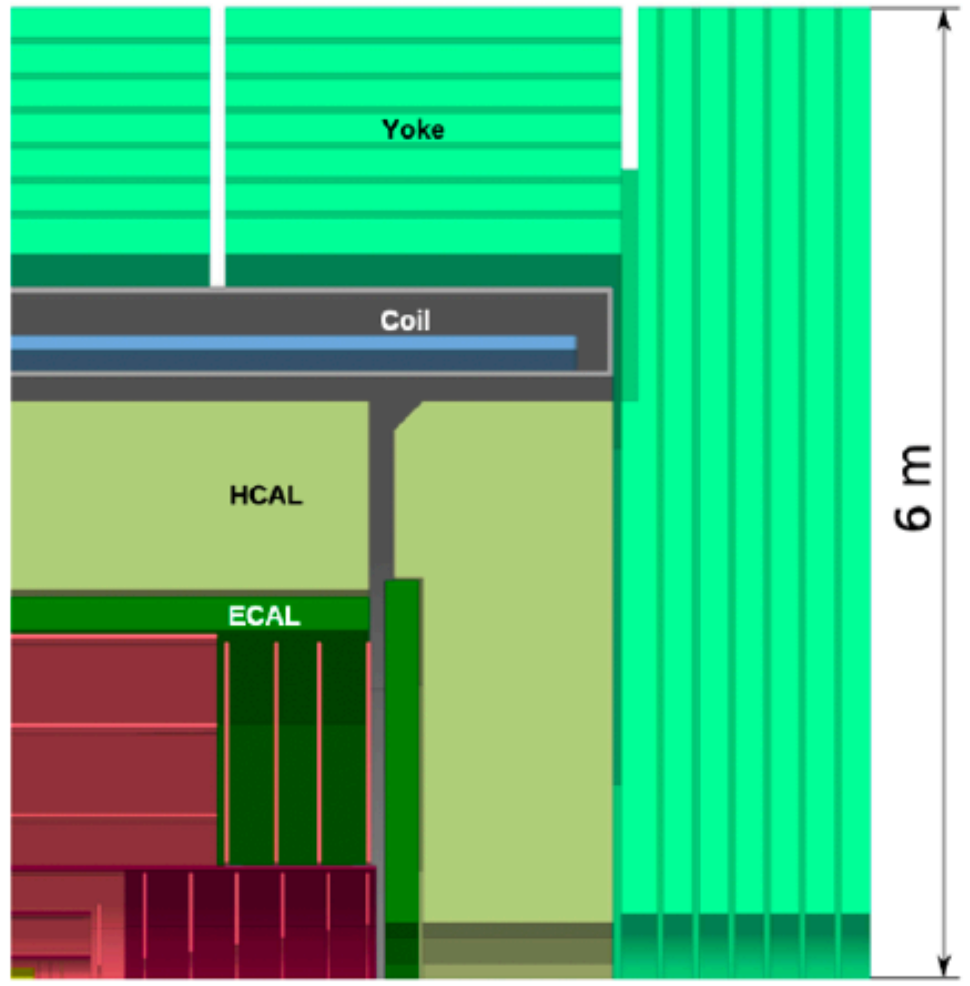
FCC-ee layout

4 experimental areas
(4 experiments)
Point A
Point D
Point G
Point J



FCC-ee Detector concepts

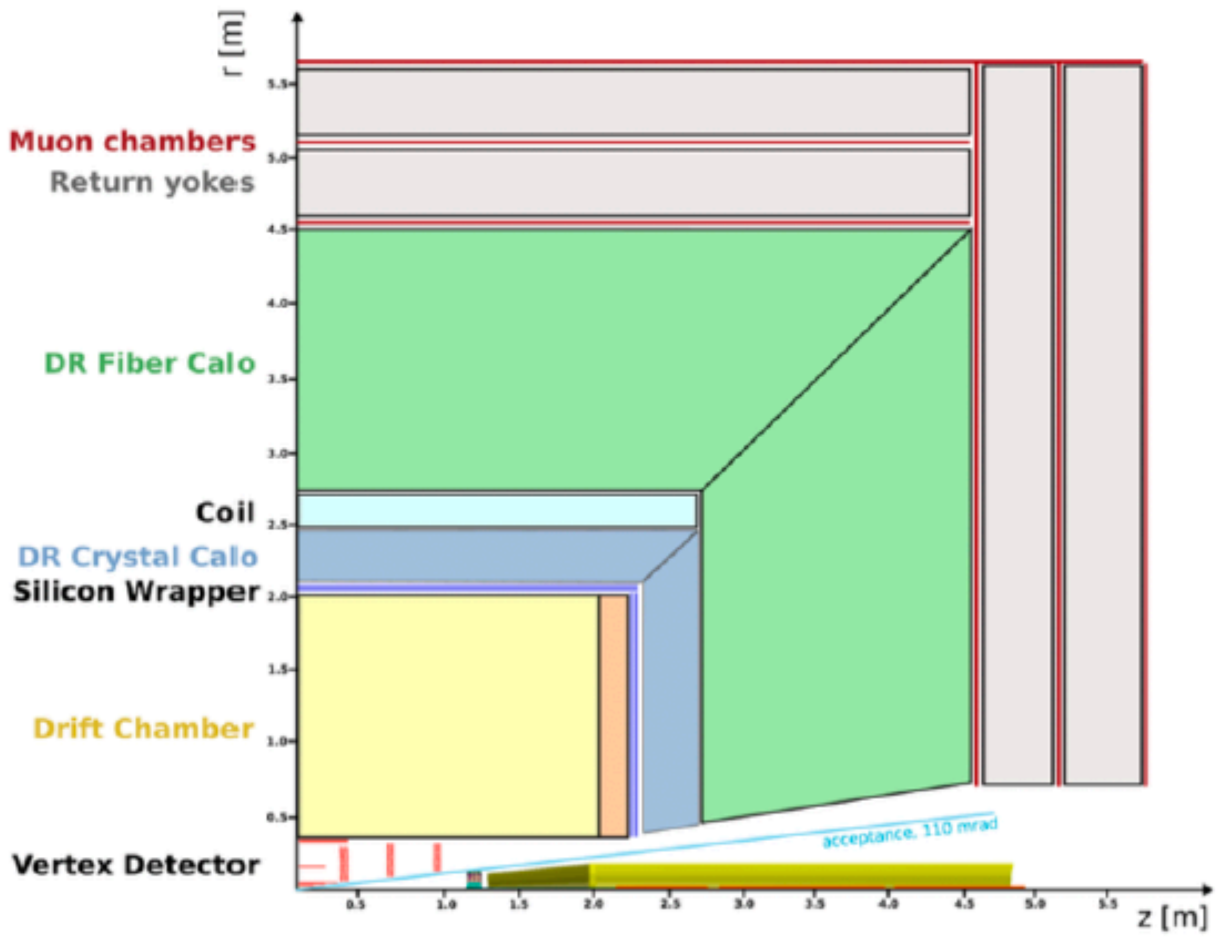
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

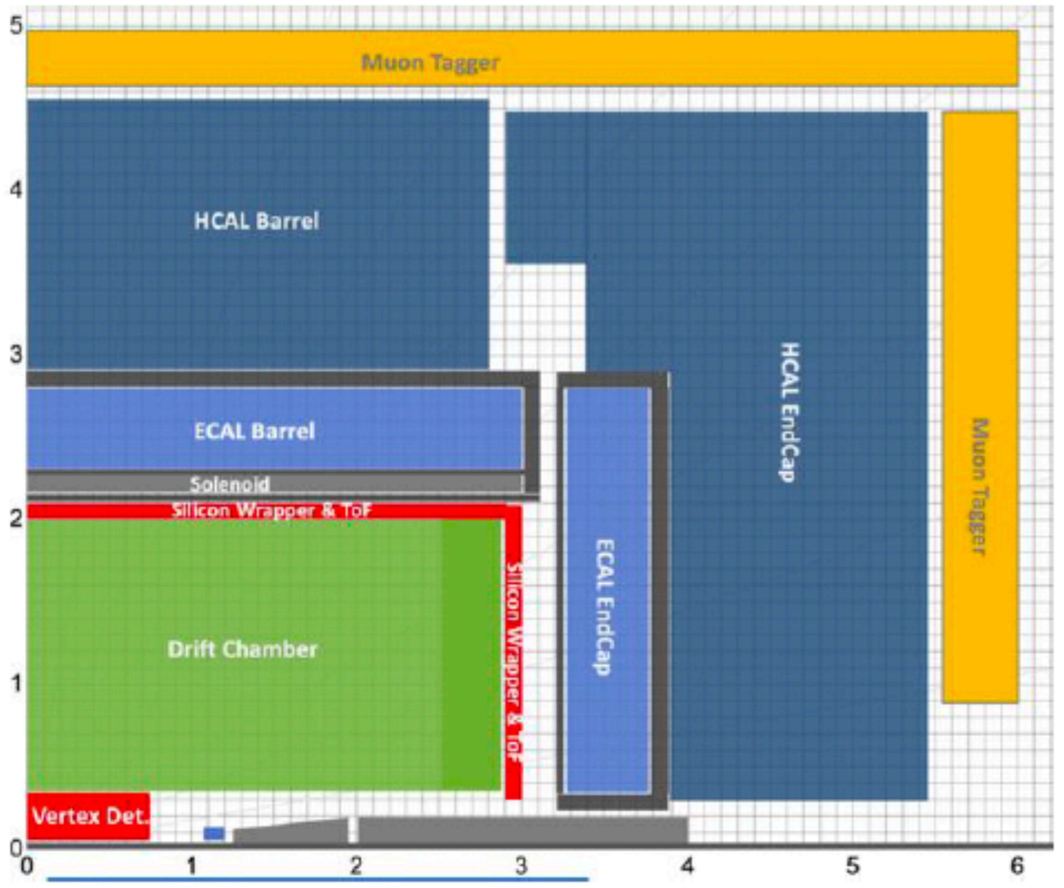
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

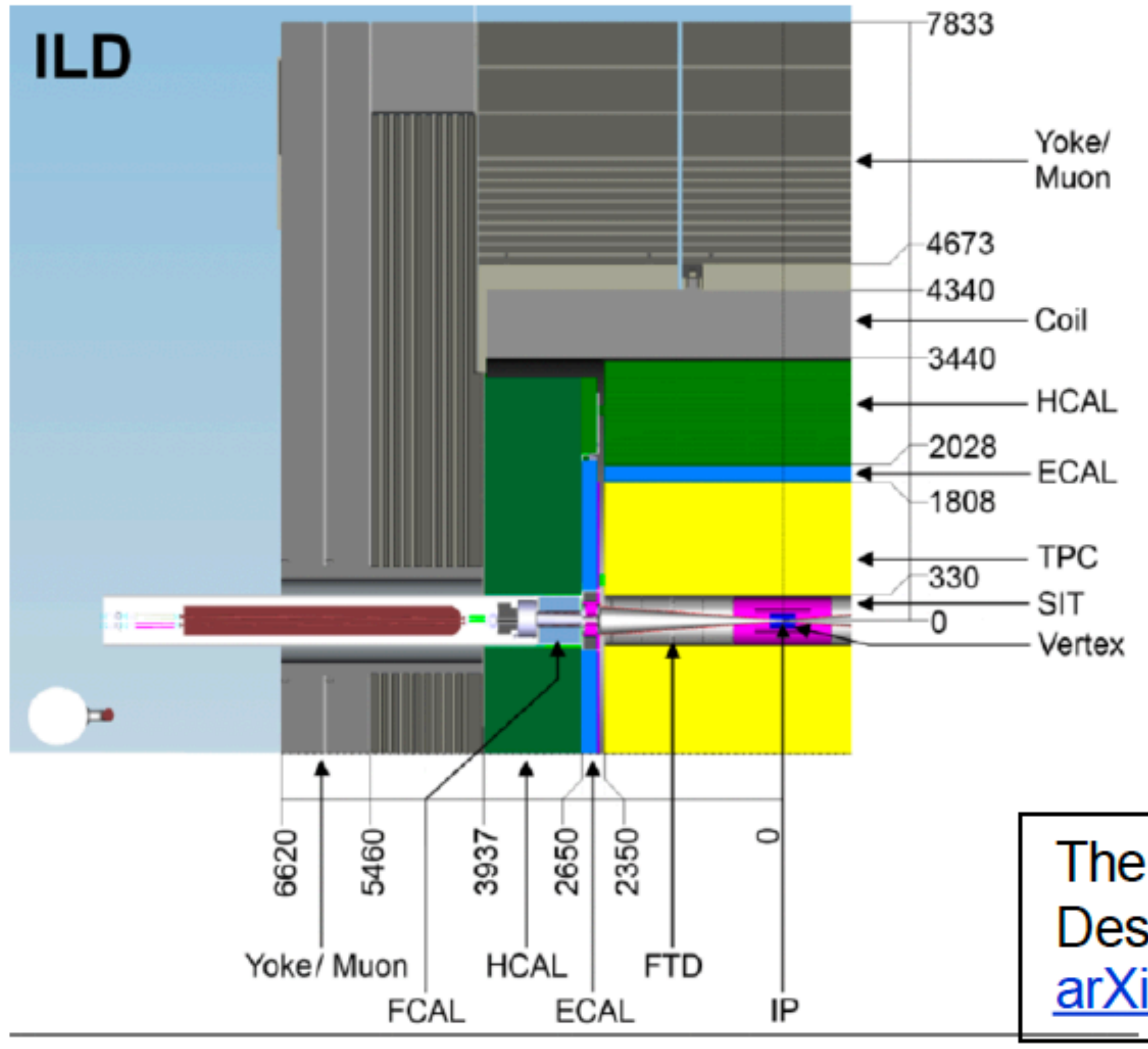
https://doi.org/10.48550/arXiv.2502.21223

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

M. Dam

IDEA Detector concept

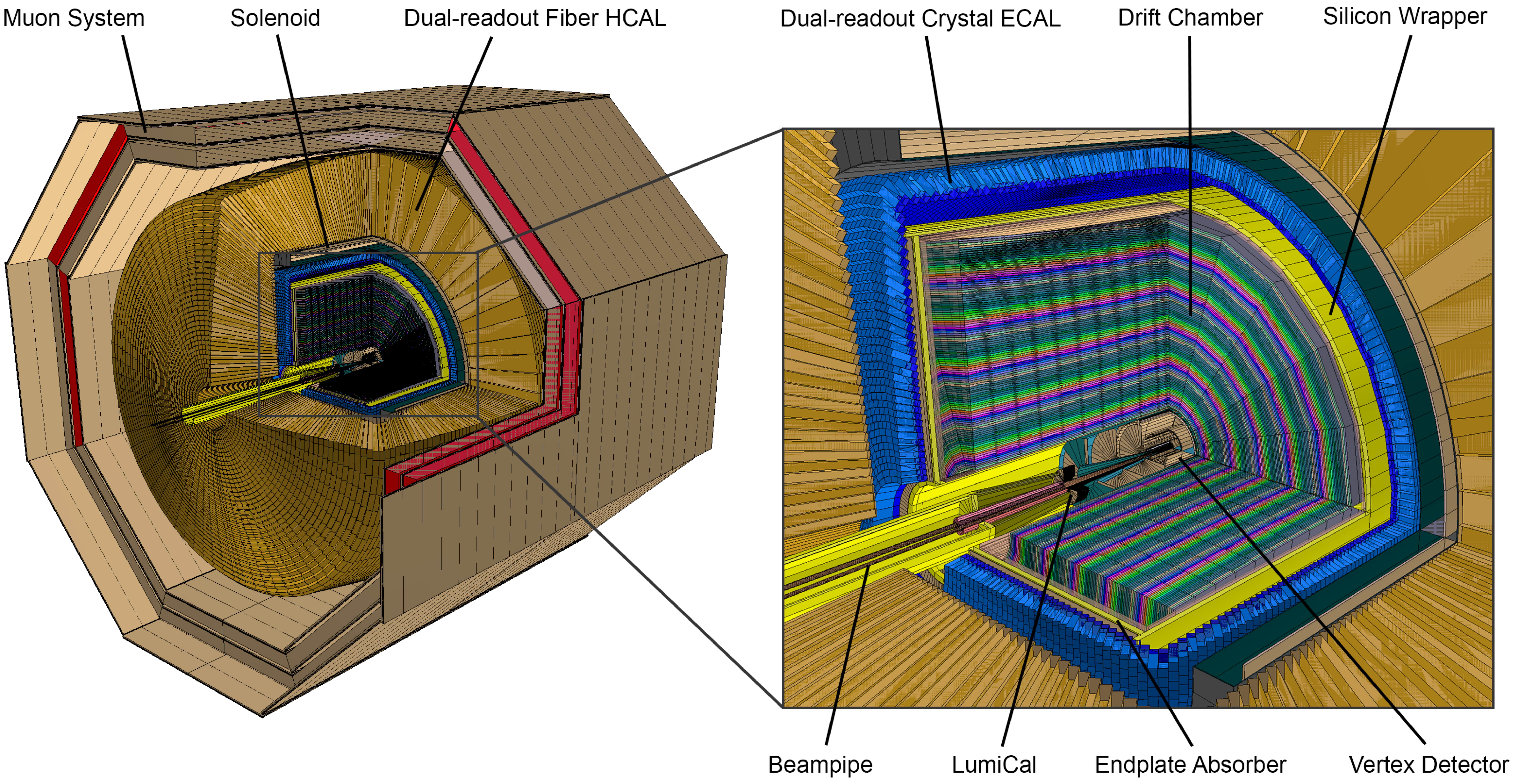
- Many sections of INFN teamed up and proposed the IDEA detector concept several years ago
- IDEA was designed to fulfil all the physics and detector requirements foreseen for FCC-ee
  - Provide outstanding performances at all FCC-ee centre-of-mass energy points
    - Z^0 peak
    - W^+W^- threshold
    - HZ peak production
    - ttbar threshold
  - It is an innovative and highly challenging detector concept with beyond the state-of-the-art technologies

Innovative Detector for E$^+$e$^-$ Accelerator (IDEA)

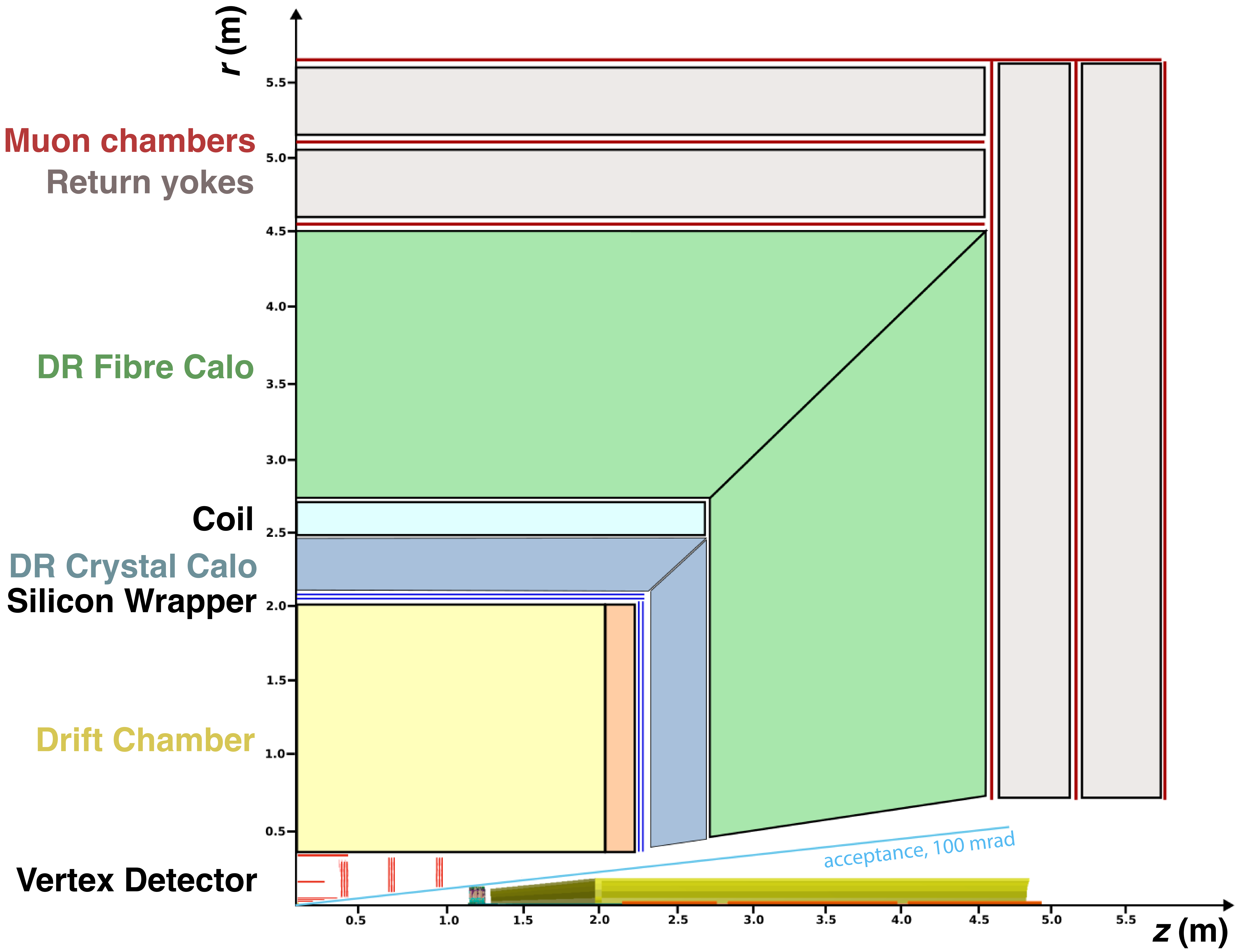
IDEA was proposed some years ago by several INFN researchers.

It was the first detector conceived specifically for FCC-ee.

It is probably the most ambitious of all 4 detector concepts.

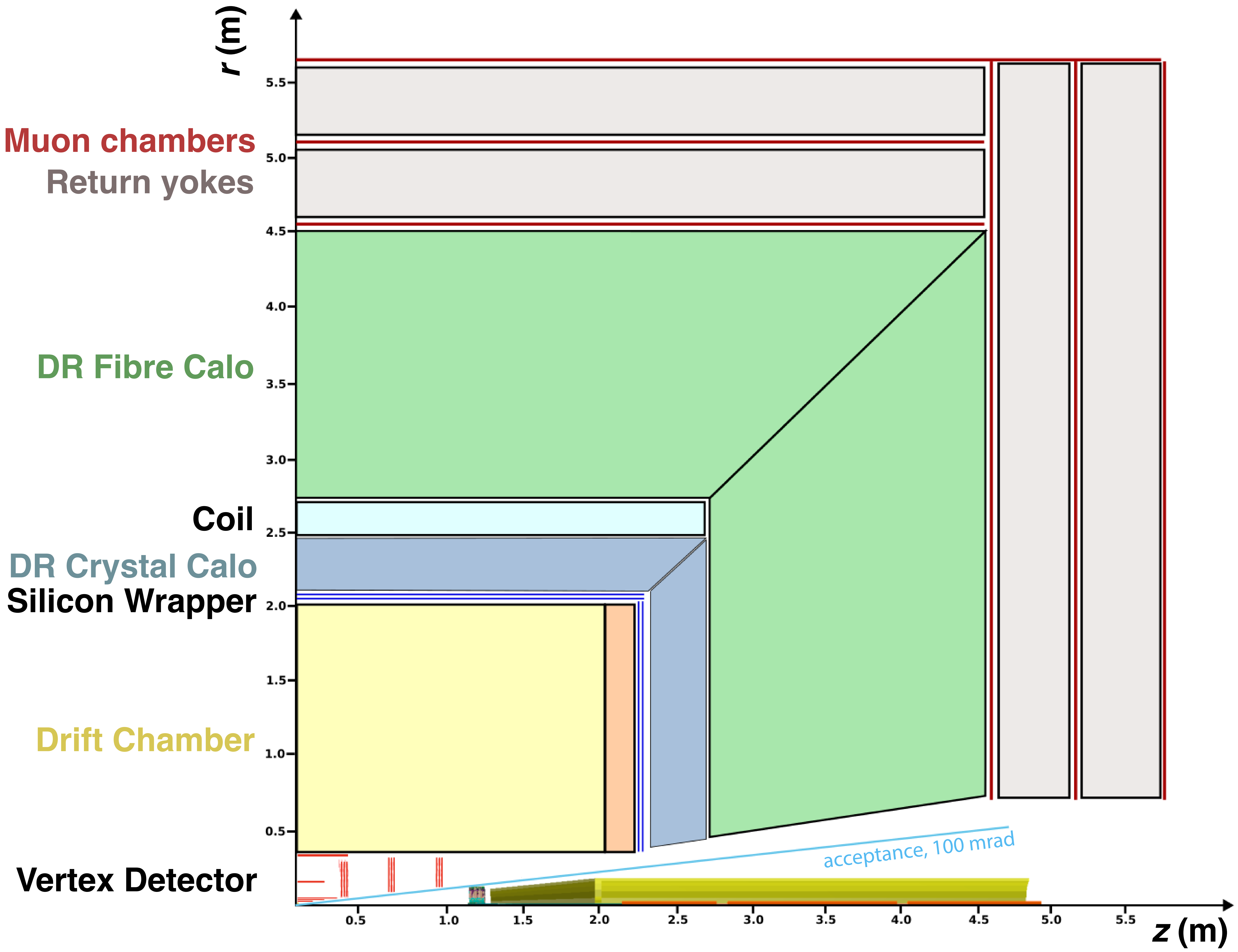


IDEA detector new baseline layout



IDEA detector new baseline layout

Beam pipe: R~1.0 cm



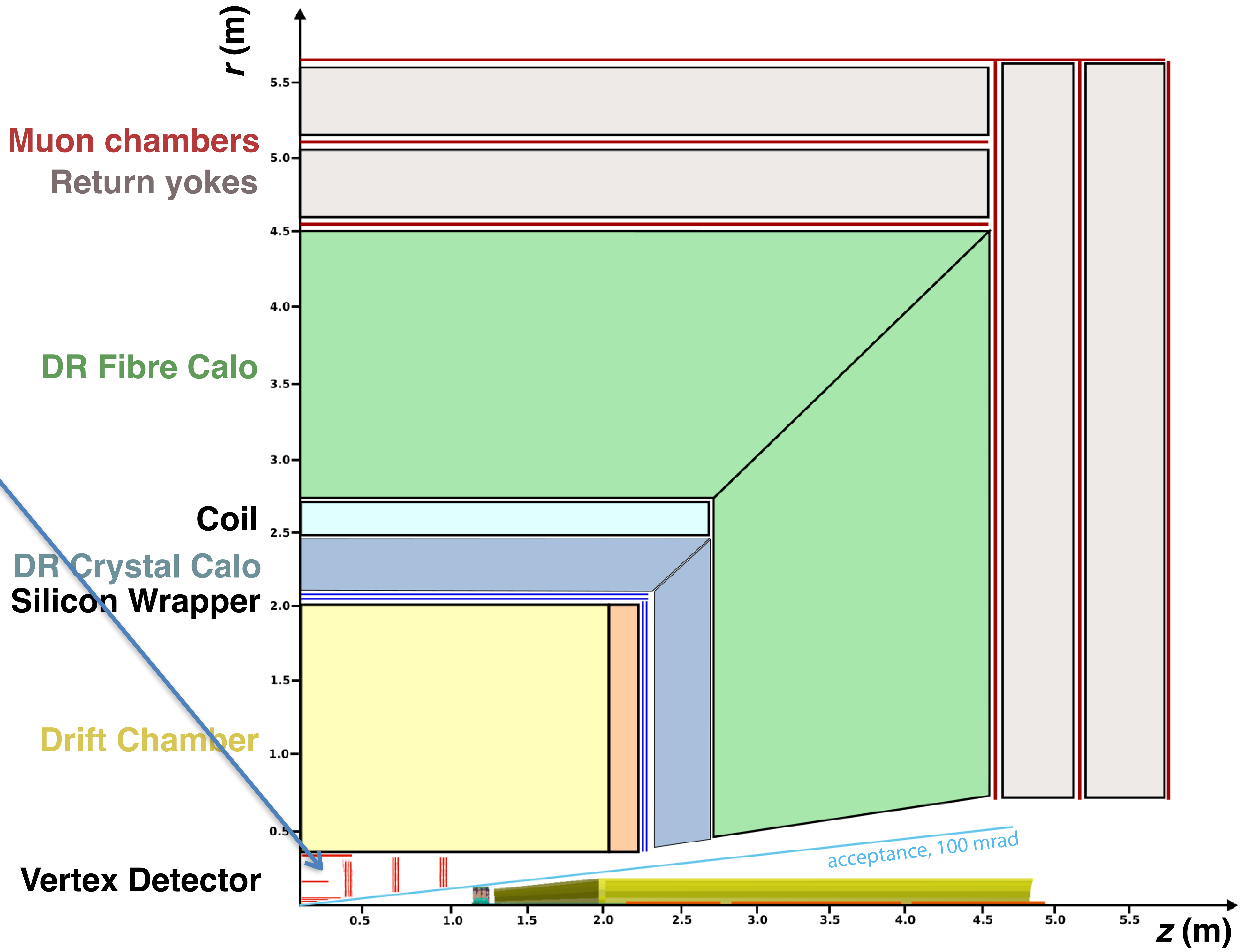
IDEA detector new baseline layout

Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

R = 1.37-31.5 cm



IDEA detector new baseline layout

Beam pipe: R~1.0 cm

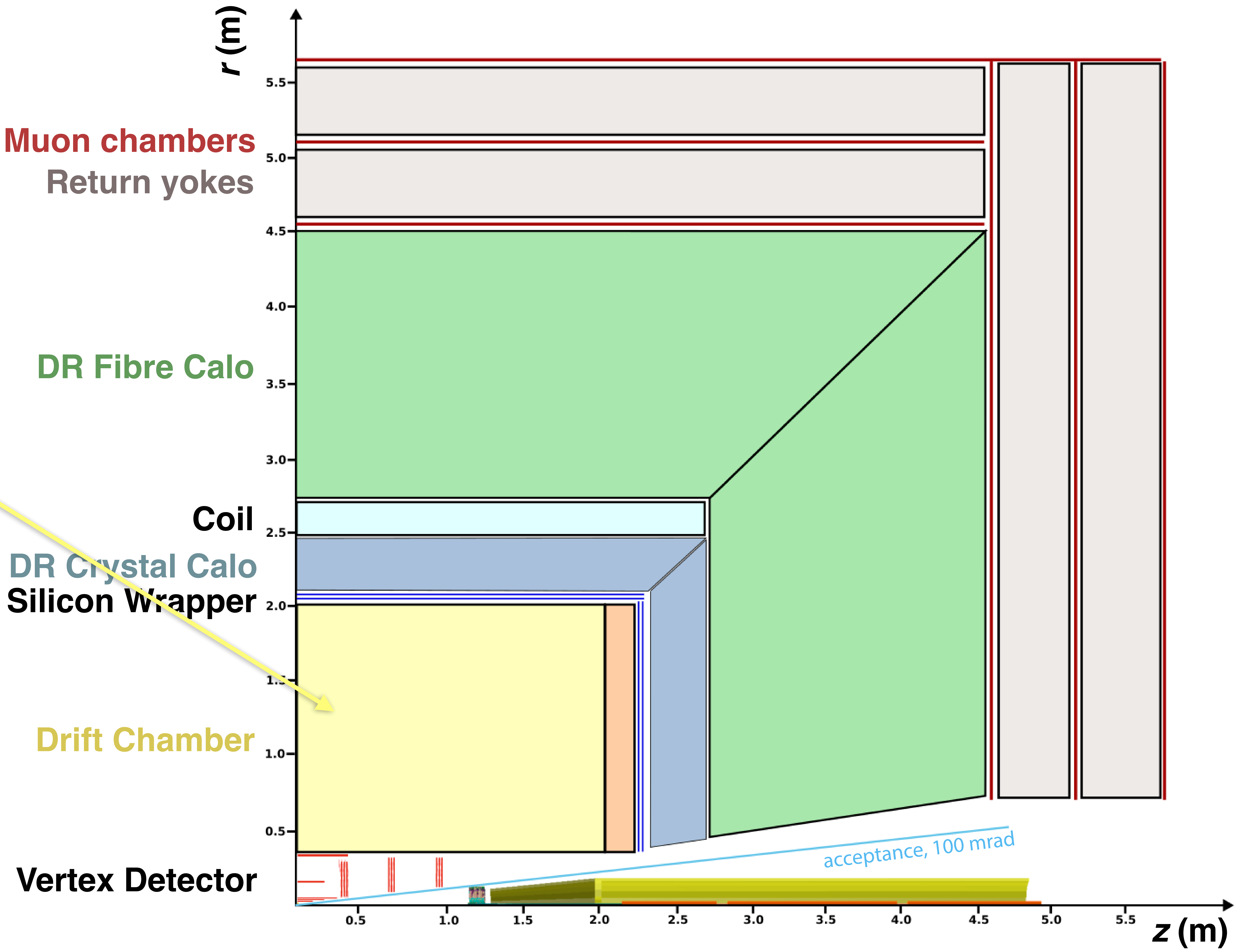
Vertex:

5 MAPS layers

R = 1.37-31.5 cm

Drift Chamber: 112 layers

4 m long, R = 35-200 cm



IDEA detector new baseline layout

Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

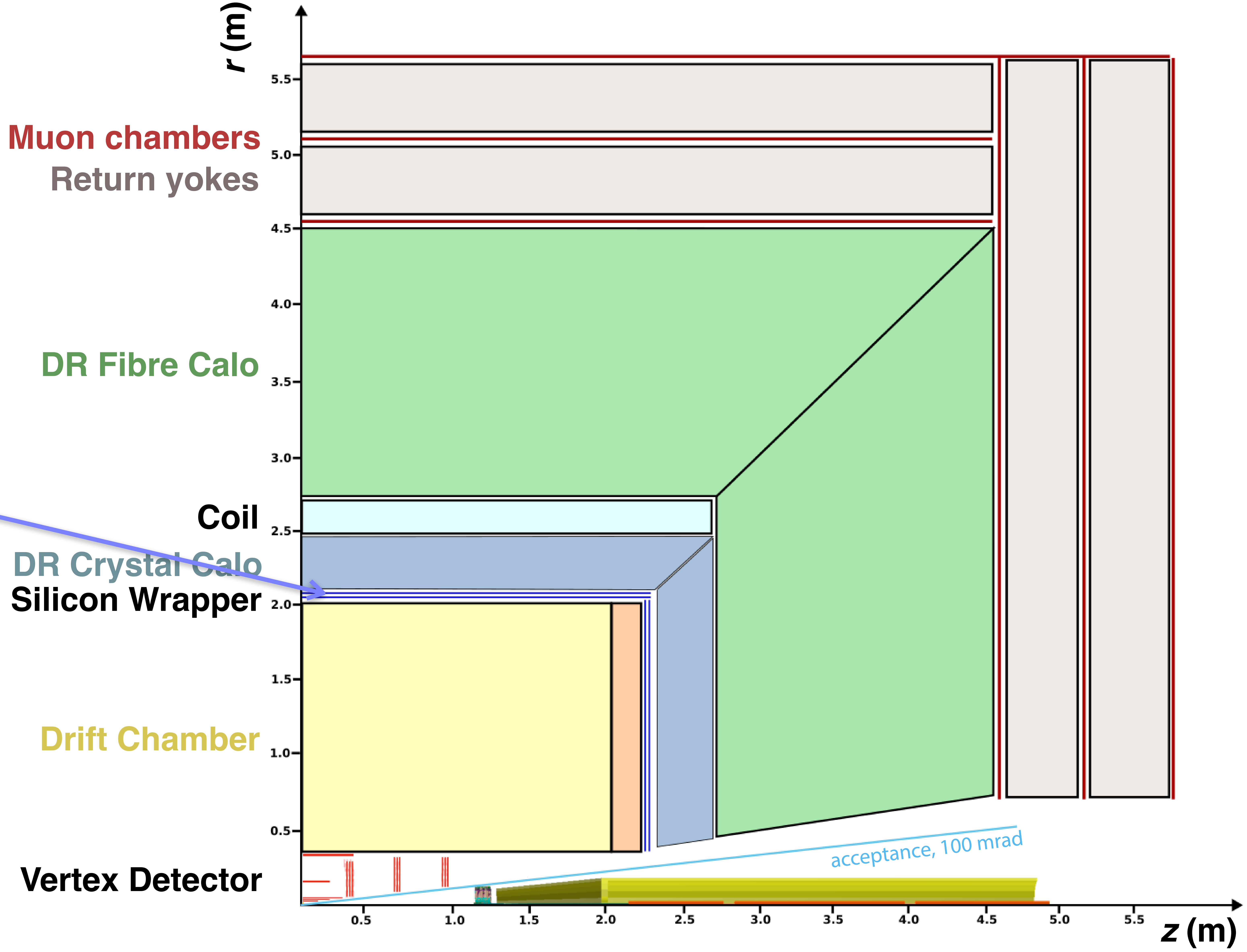
R = 1.37-31.5 cm

Drift Chamber: 112 layers

4 m long, R = 35-200 cm

Outer Silicon wrapper:

R = 200-215 cm



IDEA detector new baseline layout

Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

R = 1.37-31.5 cm

Drift Chamber: 112 layers

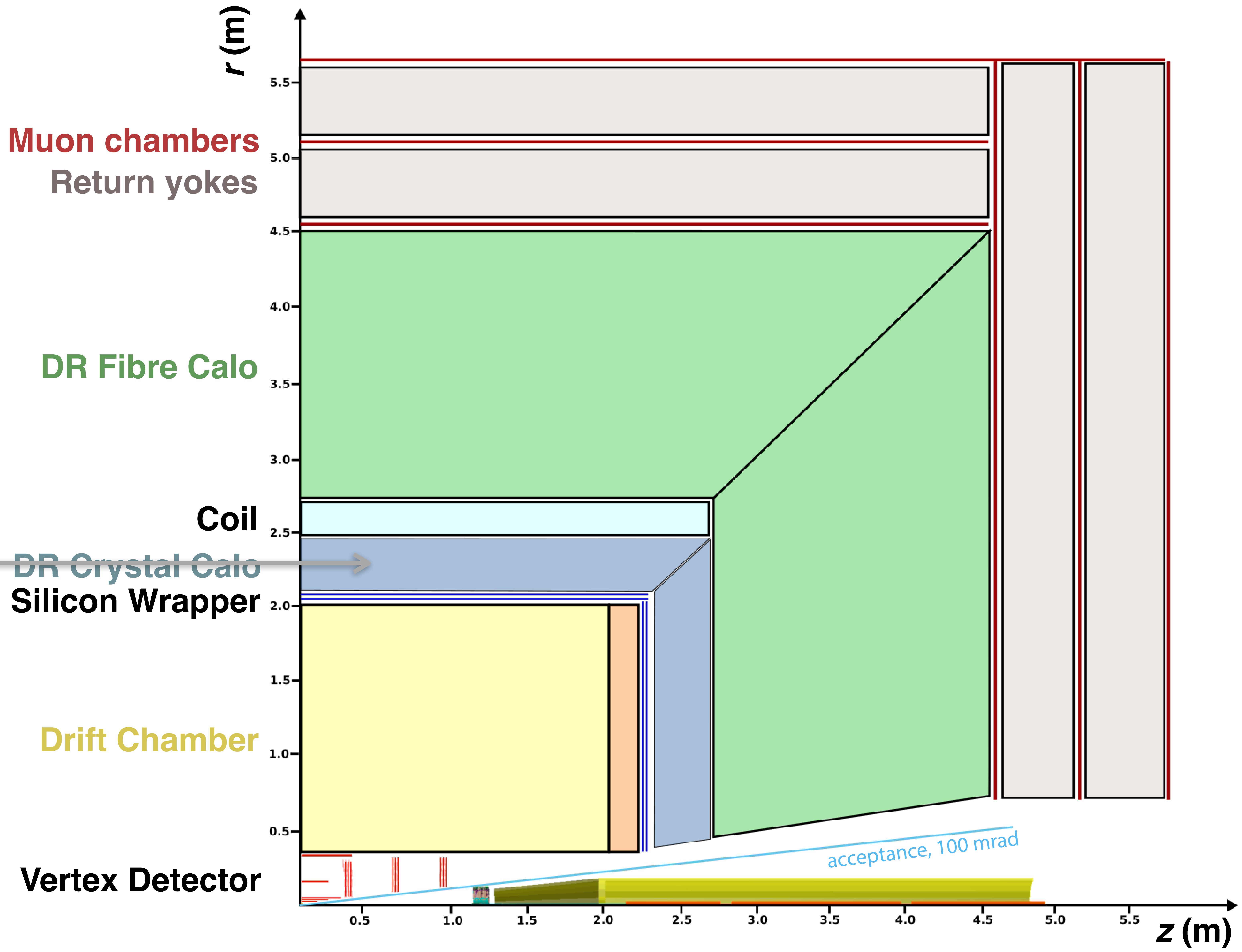
4 m long, R = 35-200 cm

Outer Silicon wrapper:

R = 200-215 cm

DR crystal ecal: ~ 22 X_0

R = 215-250 cm



IDEA detector new baseline layout

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Outer Silicon wrapper:

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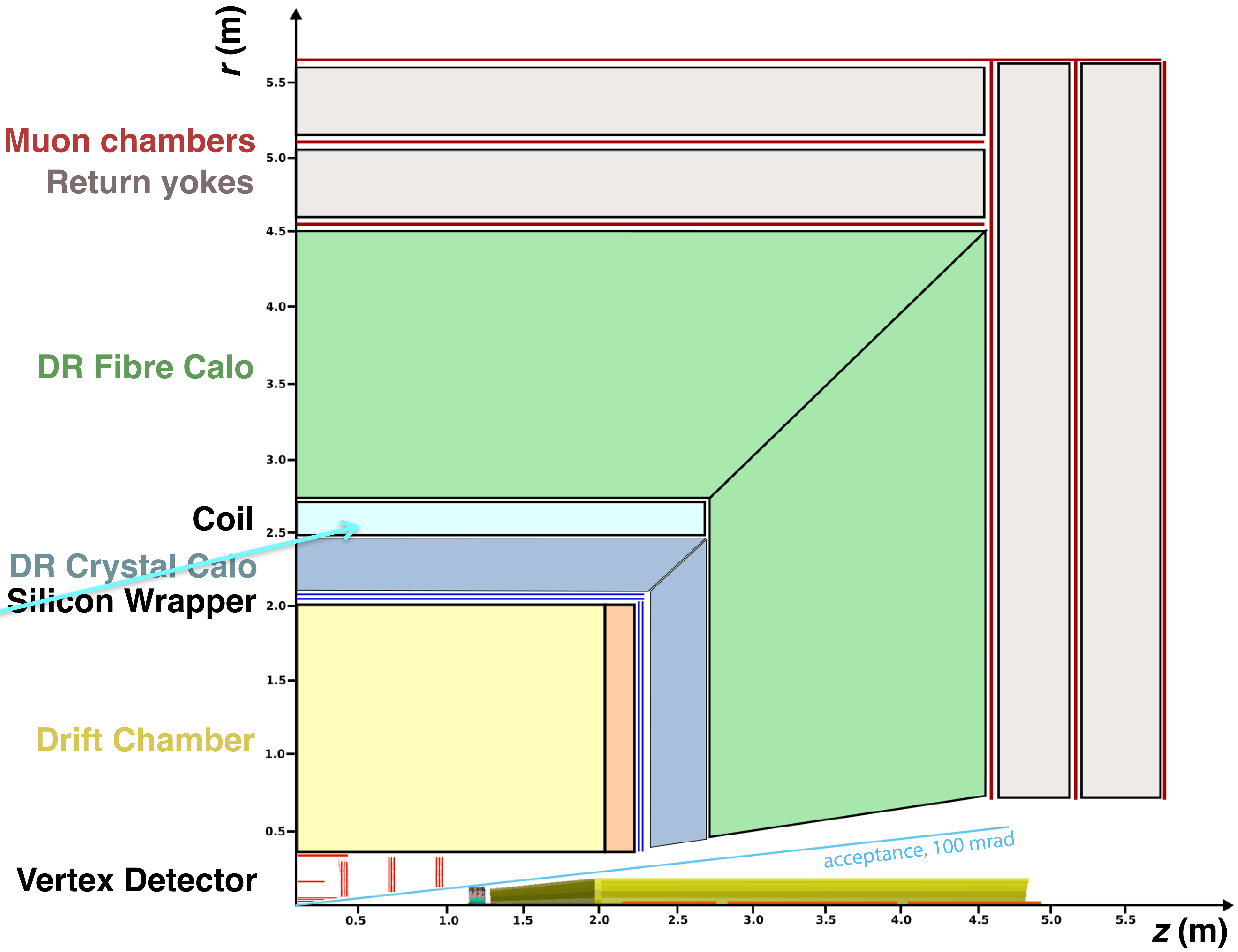
DR crystal ecal: ~ 22 X_0

R = 215-250 cm

Superconducting solenoid coil:

3 T, R ~ 2.5-2.8 m



IDEA detector new baseline layout

Beam pipe: R~1.0 cm

Vertex:
- 5 MAPS layers
- R = 1.37-31.5 cm

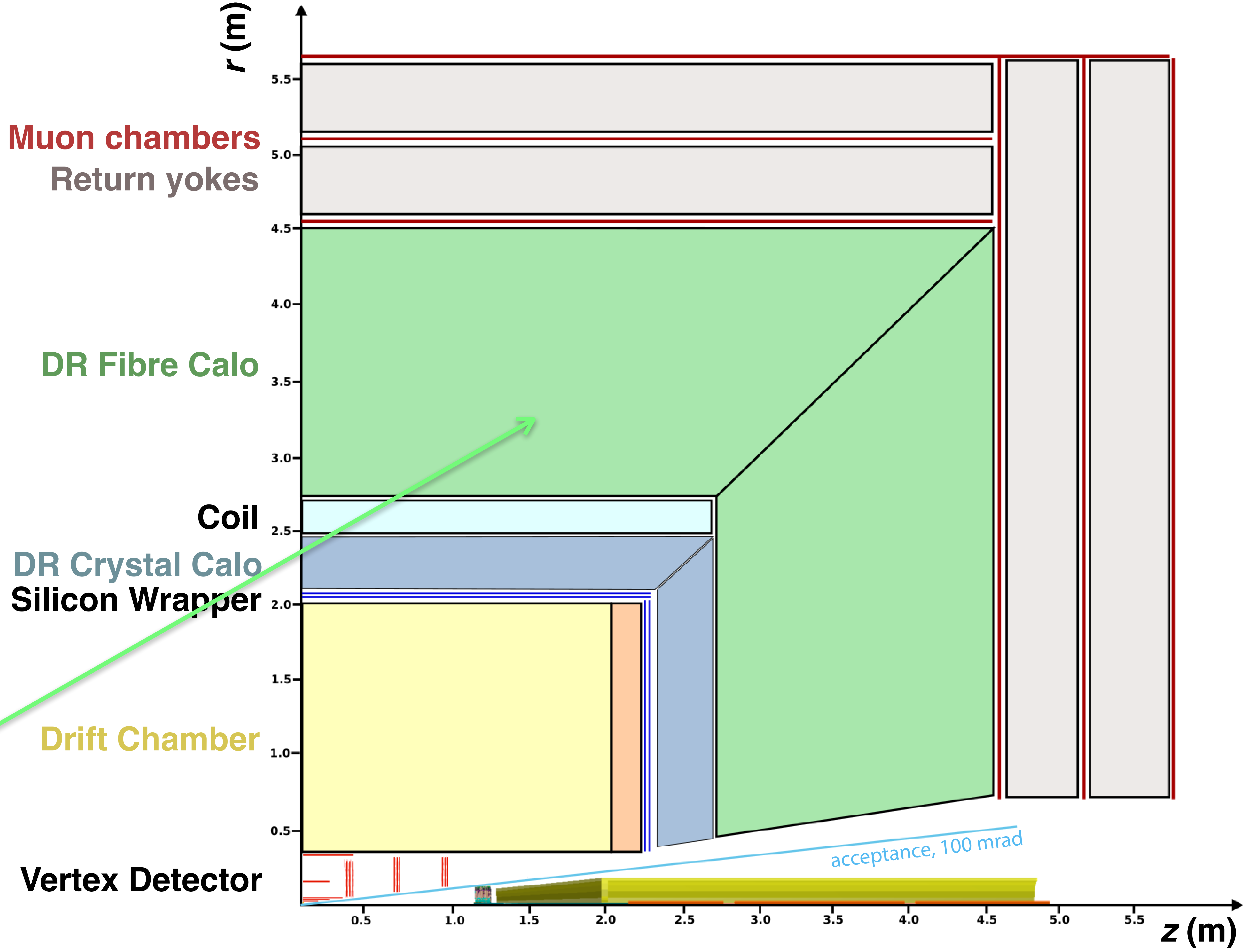
Drift Chamber: 112 layers
- 4 m long, R = 35-200 cm

Outer Silicon wrapper:
- R = 200-215 cm

DR crystal ecal: ~ 22 X_0
- R = 215-250 cm

Superconducting solenoid coil:
- 3 T, R ~ 2.5-2.8 m

Dual-Readout Calorimeter:
- R = 280-460 cm



IDEA detector new baseline layout

Beam pipe: R~1.0 cm

Vertex:

5 MAPS layers

R = 1.37-31.5 cm

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4 m long, R = 35-200 cm

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Superconducting solenoid coil:

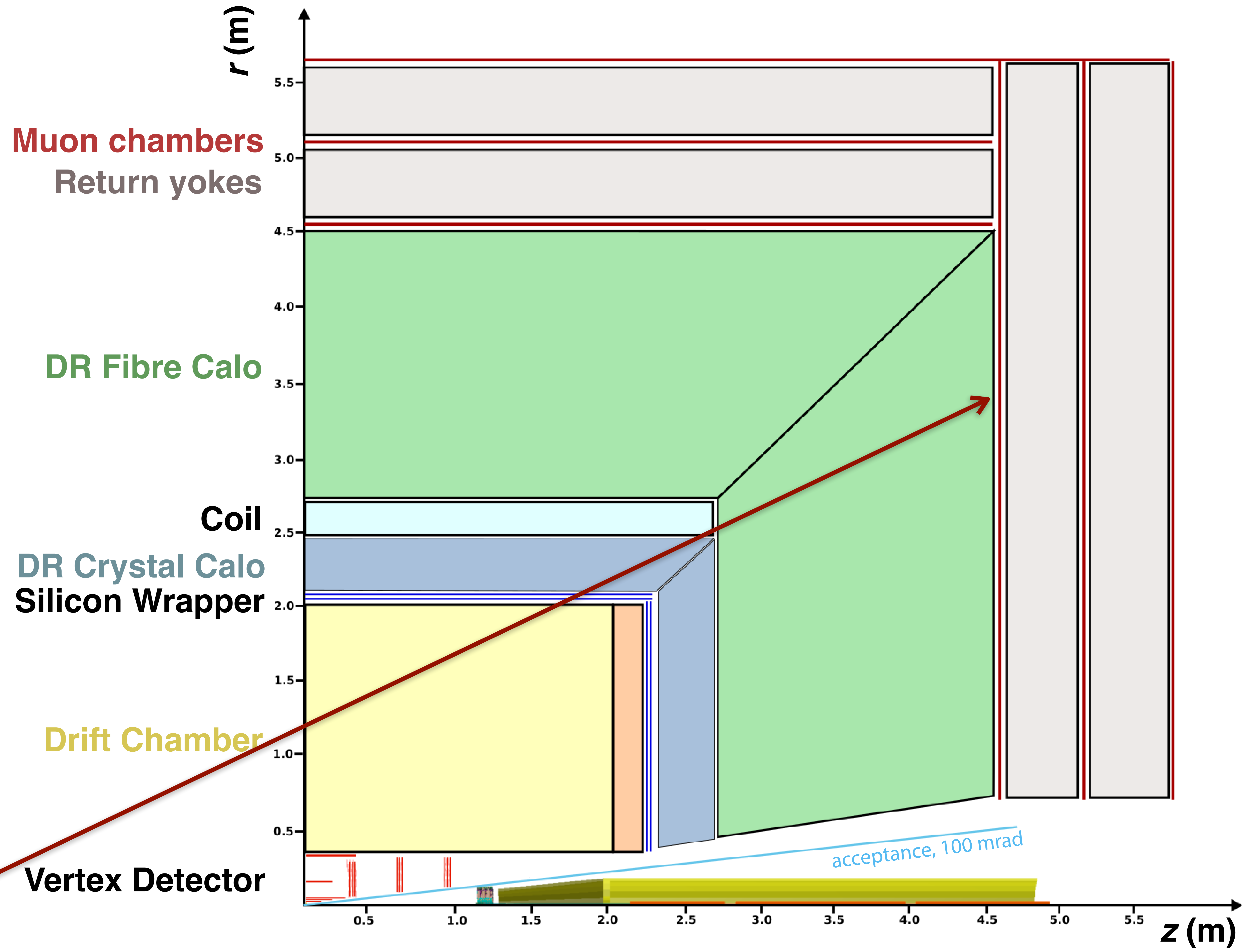
3 T, R ~ 2.5-2.8 m

Dual-Readout Calorimeter:

R = 280-460 cm

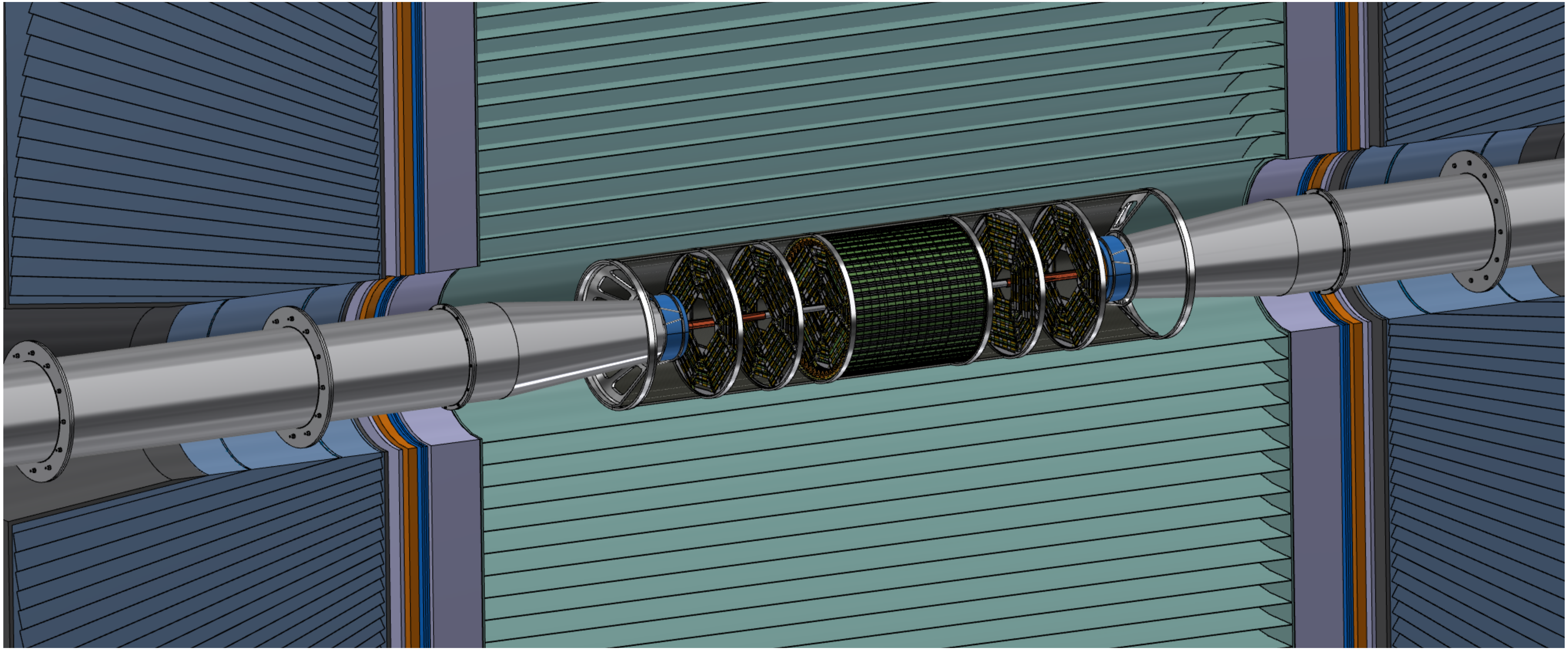
Yoke + Muon chambers

R = 460-570 cm



Vertex detector: IDEA

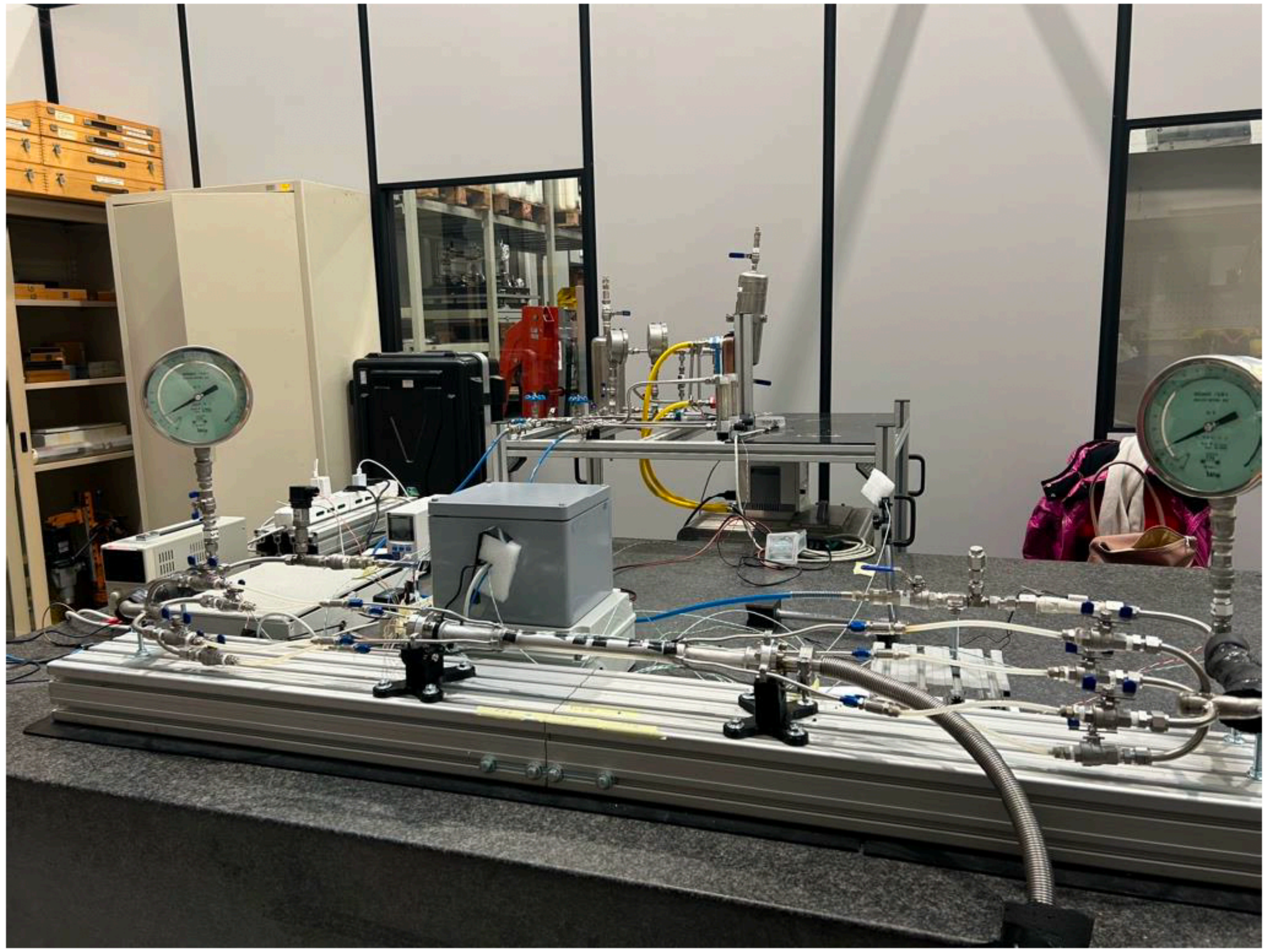
General integration

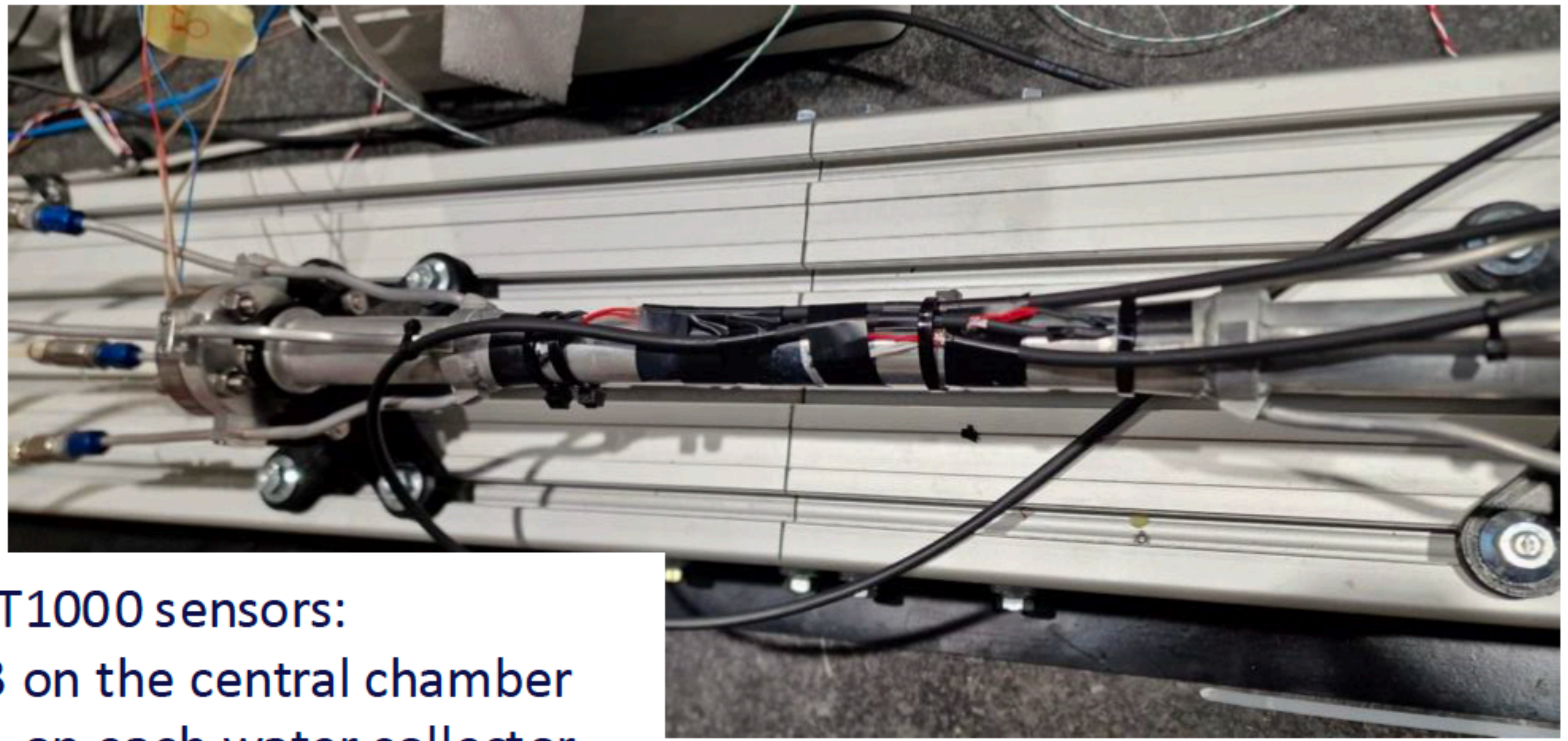


F. Palla

Italian Accelerator activities

Measurement set-up in Frascati





PT1000 sensors:
- 3 on the central chamber
- 1 on each water collector
- 1 environment

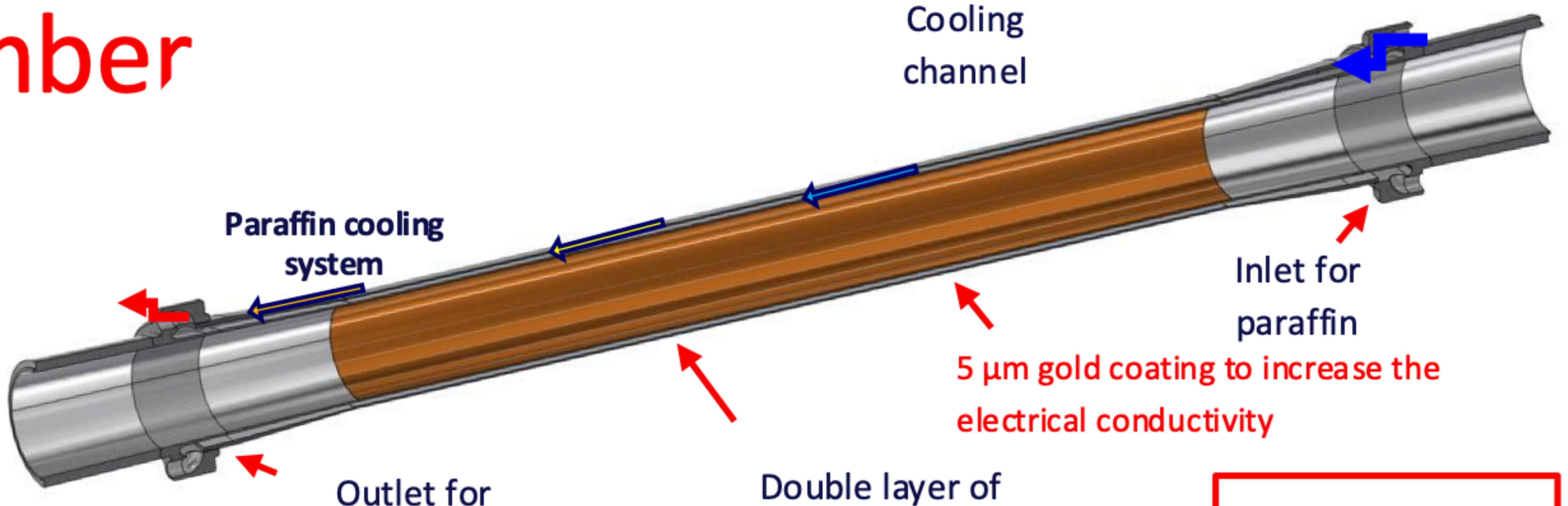
An internal ohmic heater inside the vacuum chamber simulates the beam heat load on the pipe during the beam passage.
A variable power supply controls the power deposited on the chamber.

Italian Accelerator activities

FCC-ee IR central chamber

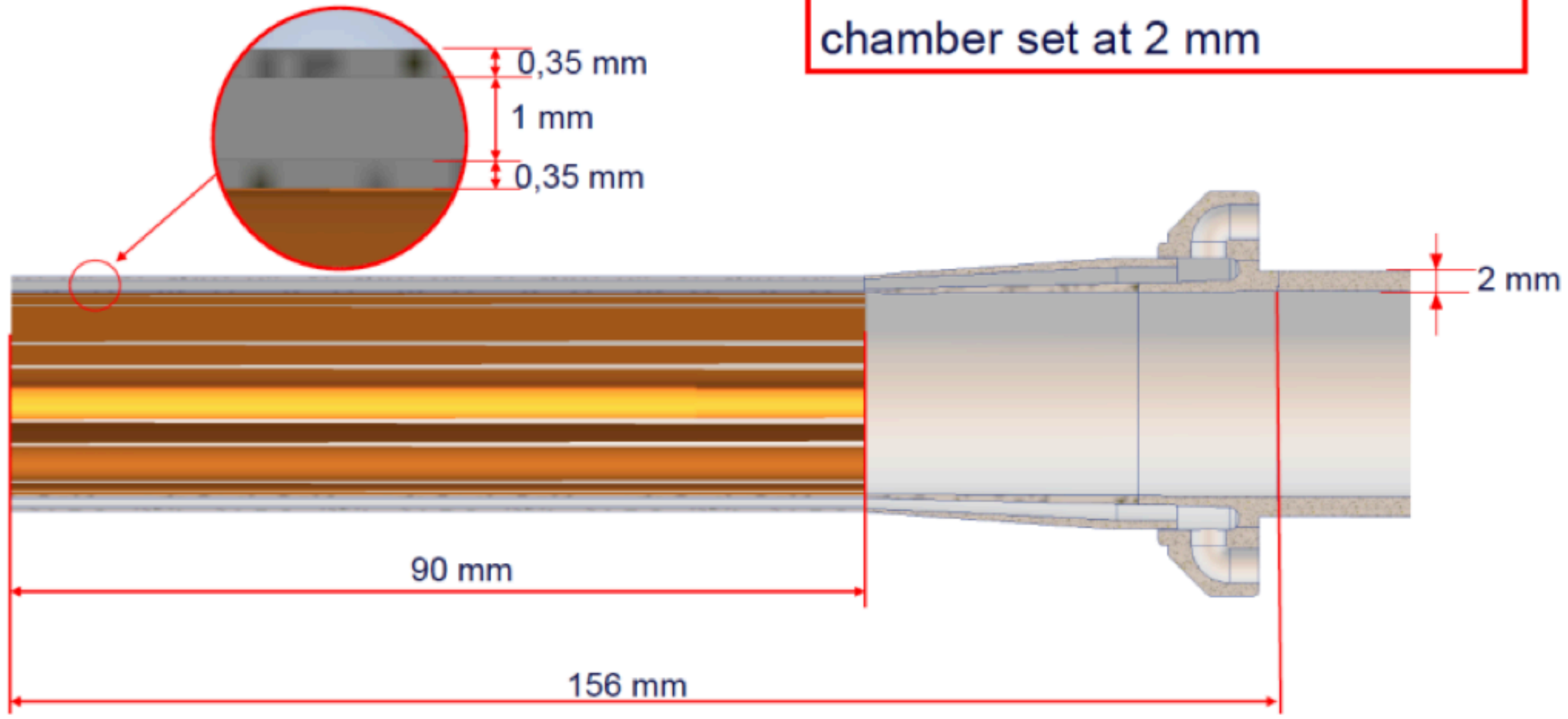
- AlBeMet 162 (62% Be, 38% Al)
- 180 mm long centered at the IP

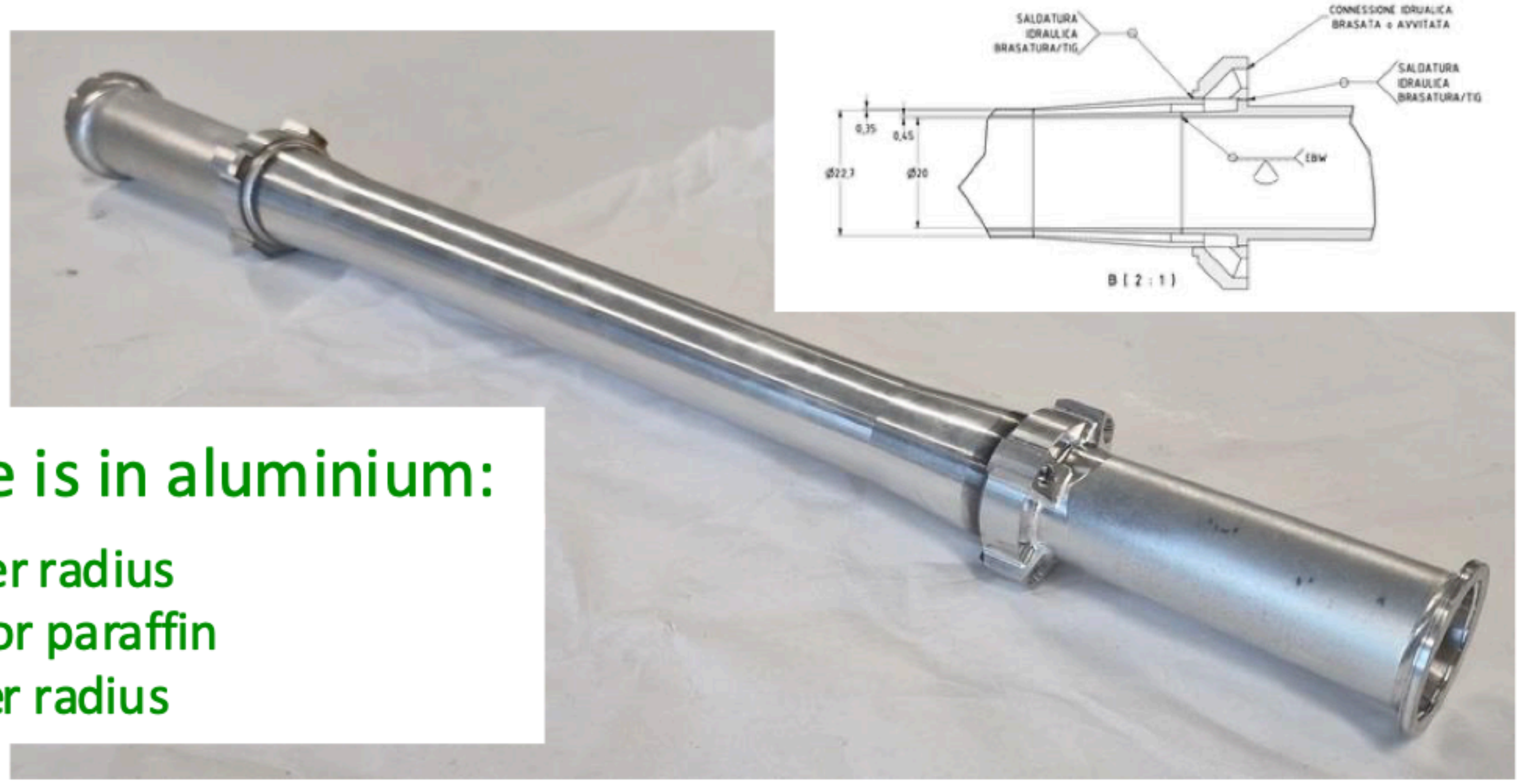
- **0.35 mm** outer radius AlBeMet162
- **1 mm gap** for paraffin
- **0.35 mm** inner radius AlBeMet162



Thickness of the chamber

Uniform thickness of the conical chamber set at 2 mm

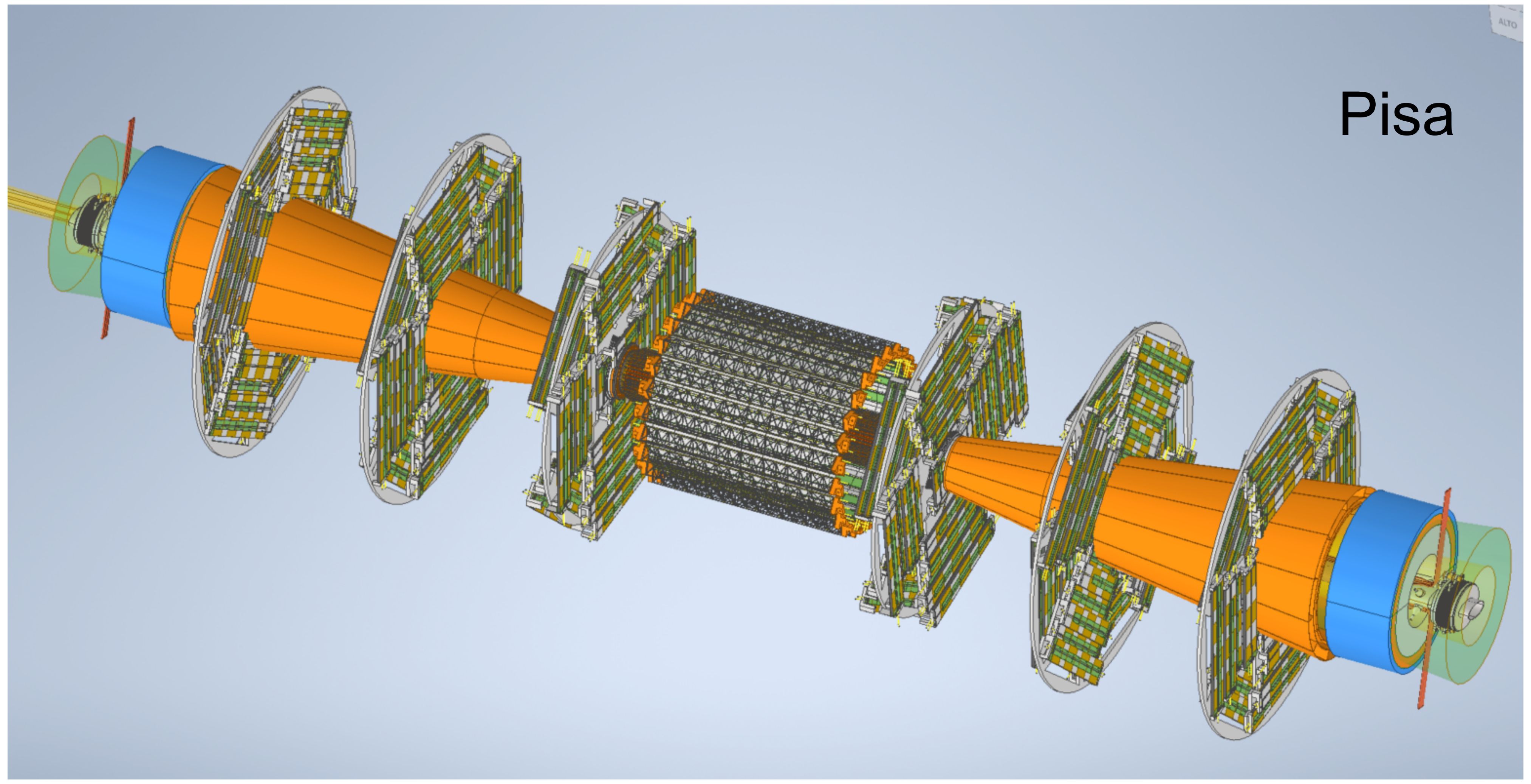


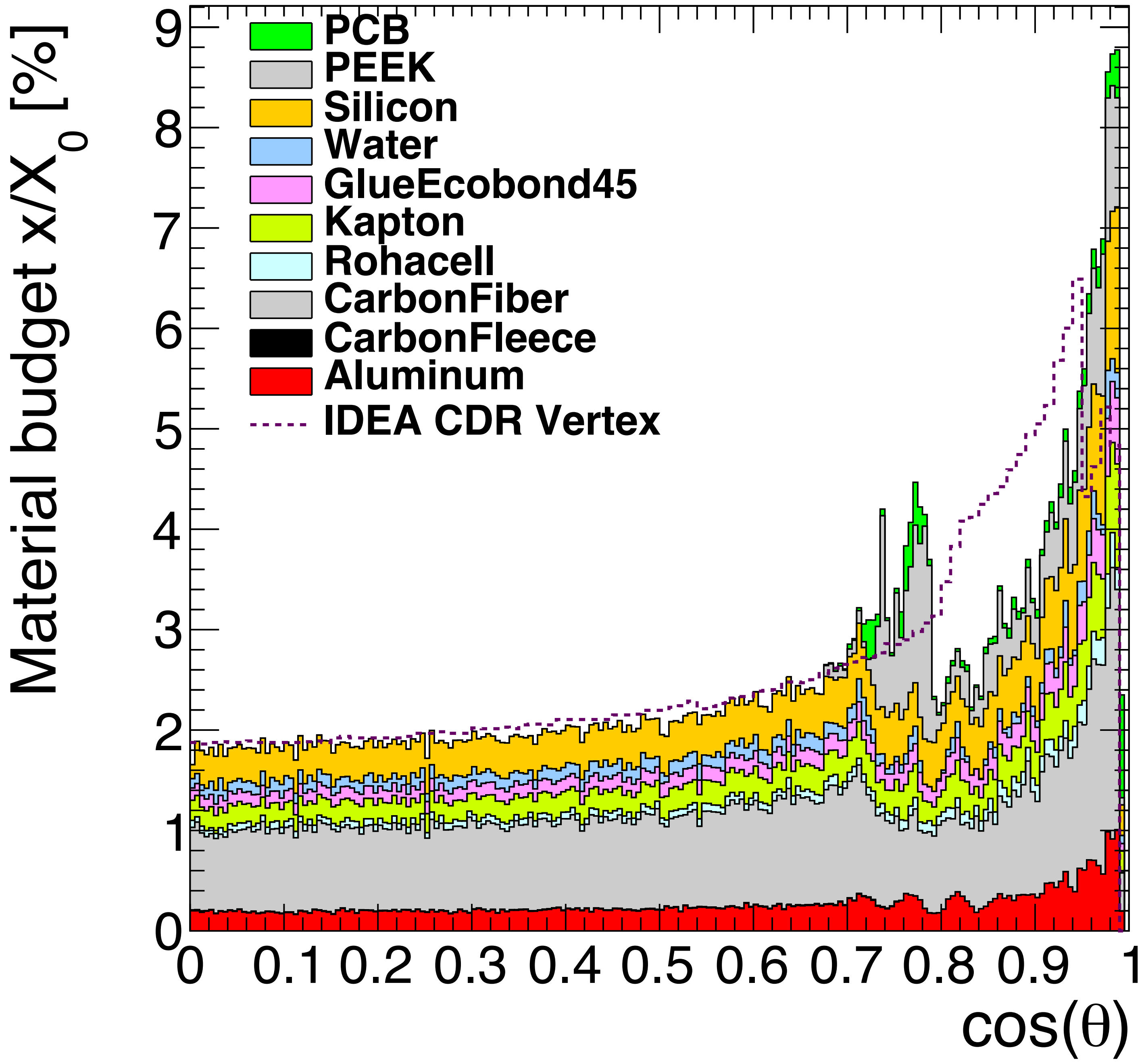


The prototype is in aluminium:

- **0.35 mm** outer radius
- **0.9 mm gap** for paraffin
- **0.45 mm** inner radius

Silicon tracker



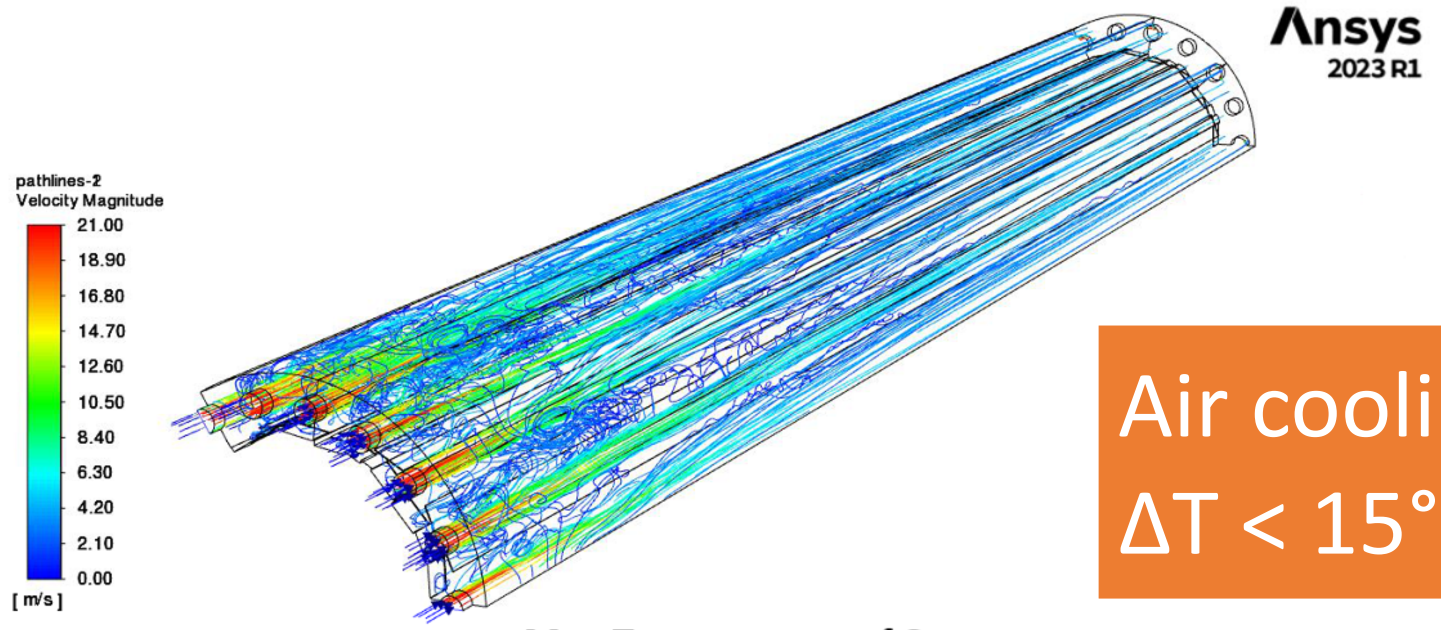


Outer vertex tracker:
ATLASPix3 based (Milano)

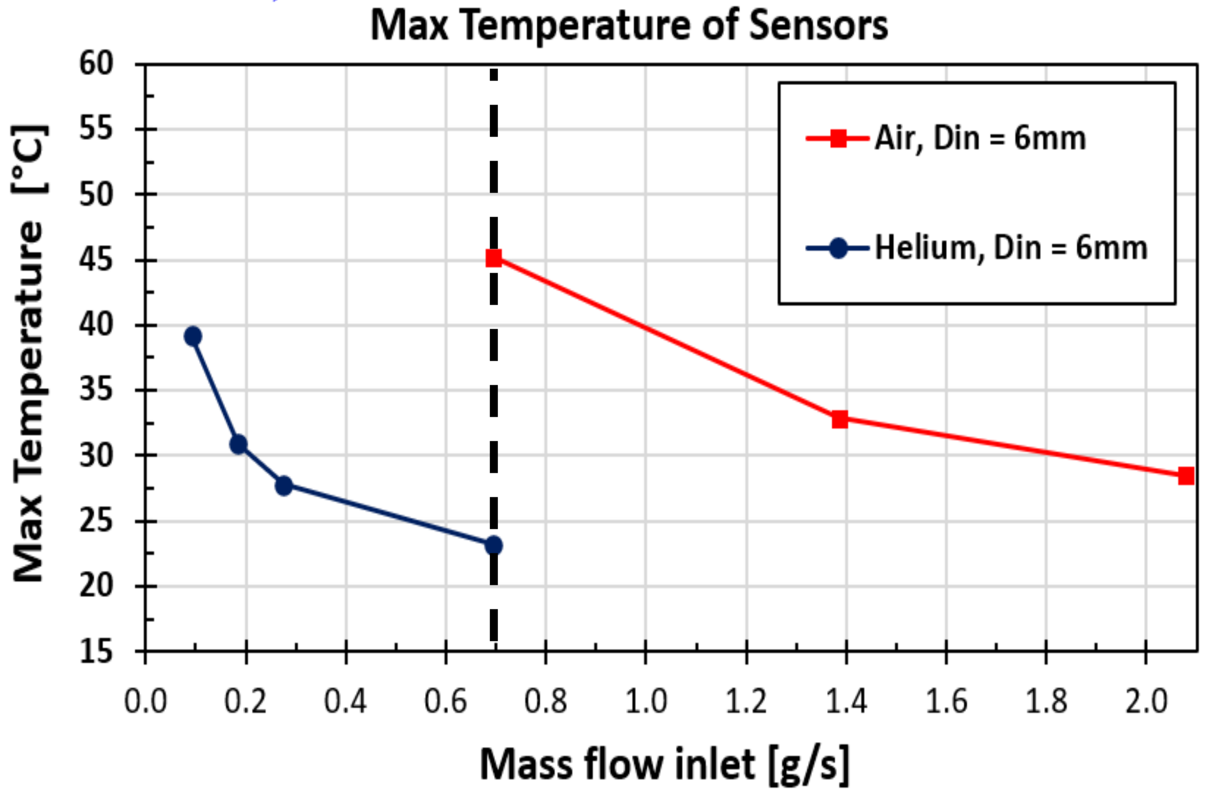
Modules of $50 \times 150\ \mu m^2$pixel

Inner Vertex detector:
ARCADIA based (Torino, Milano, Padova, Pisa, Perugia)

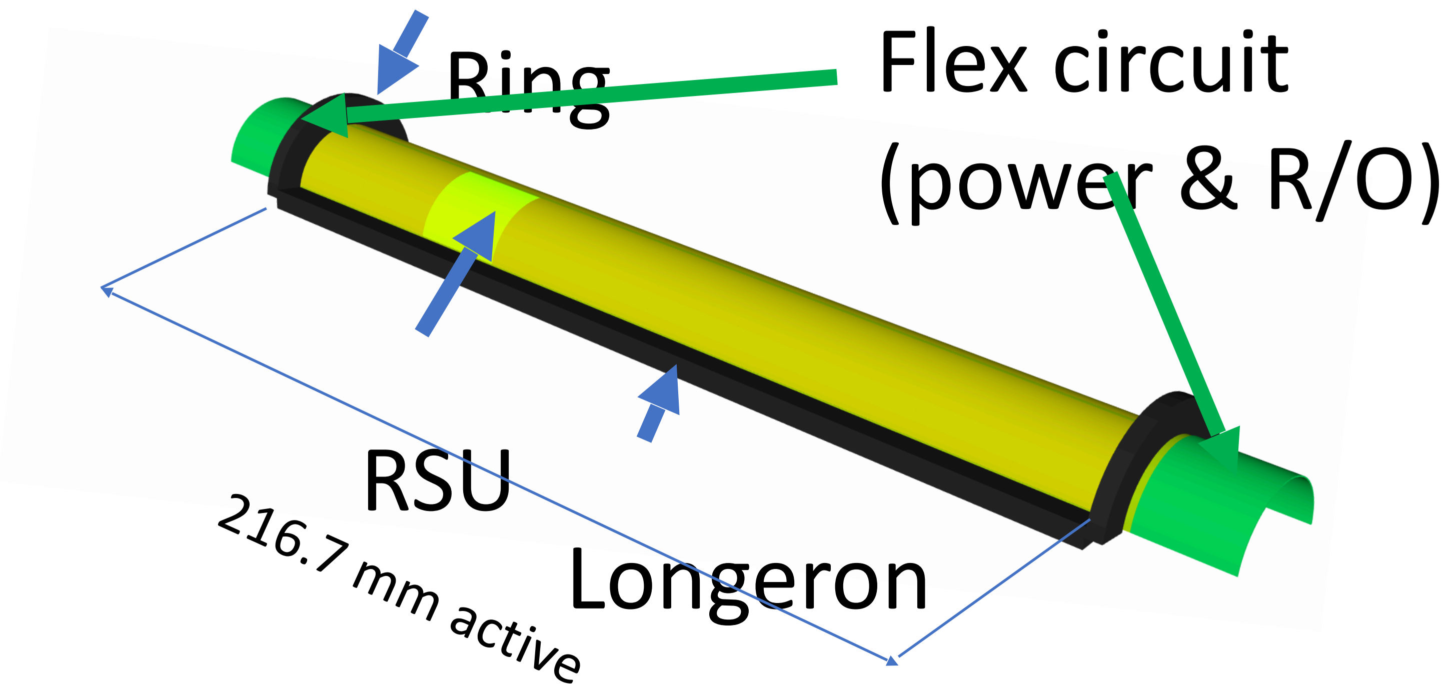
Modules of $25 \times 25\ \mu m^2$pixel size

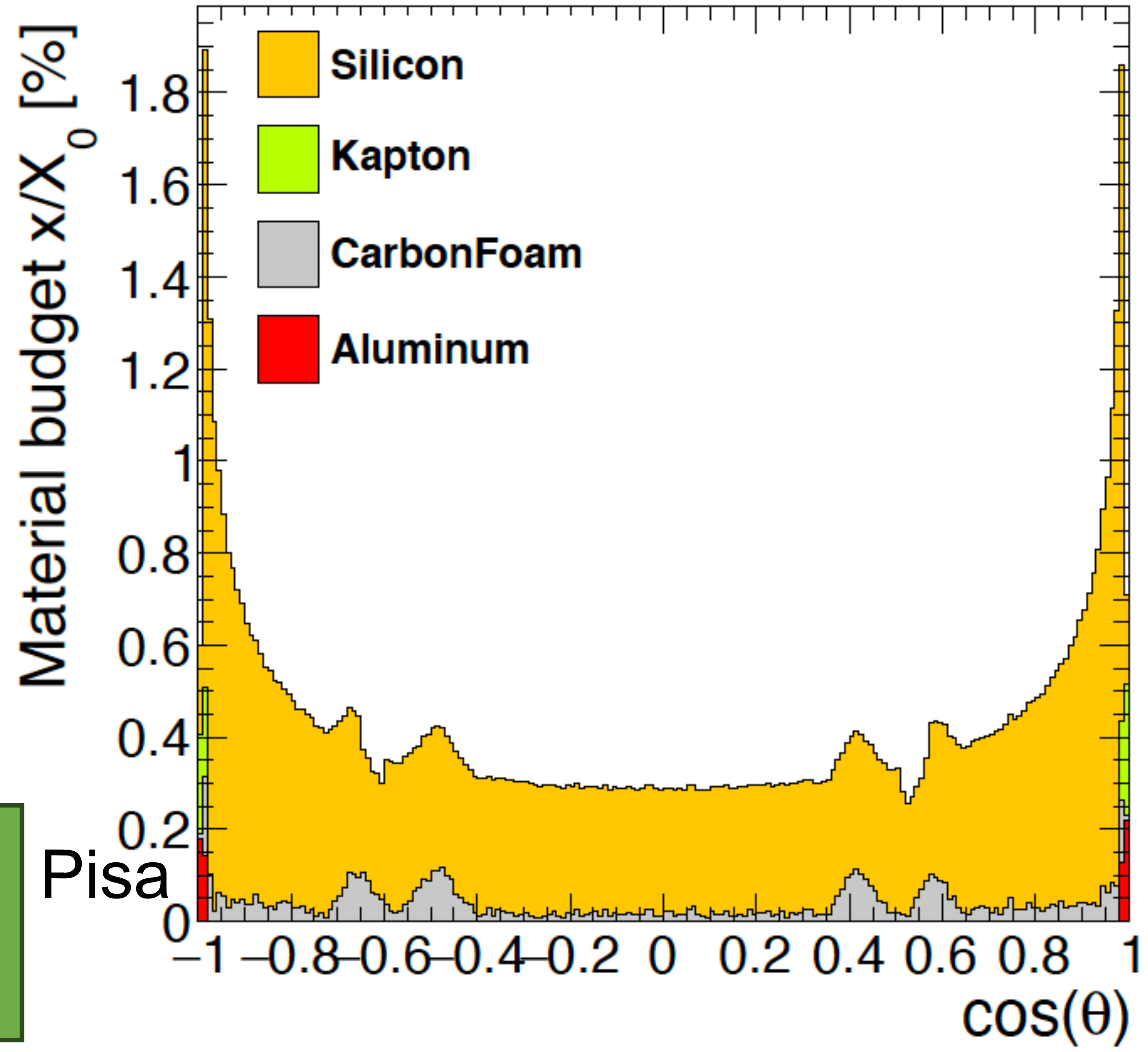


Air cooling studies:
ΔT < 15°C



Perugia

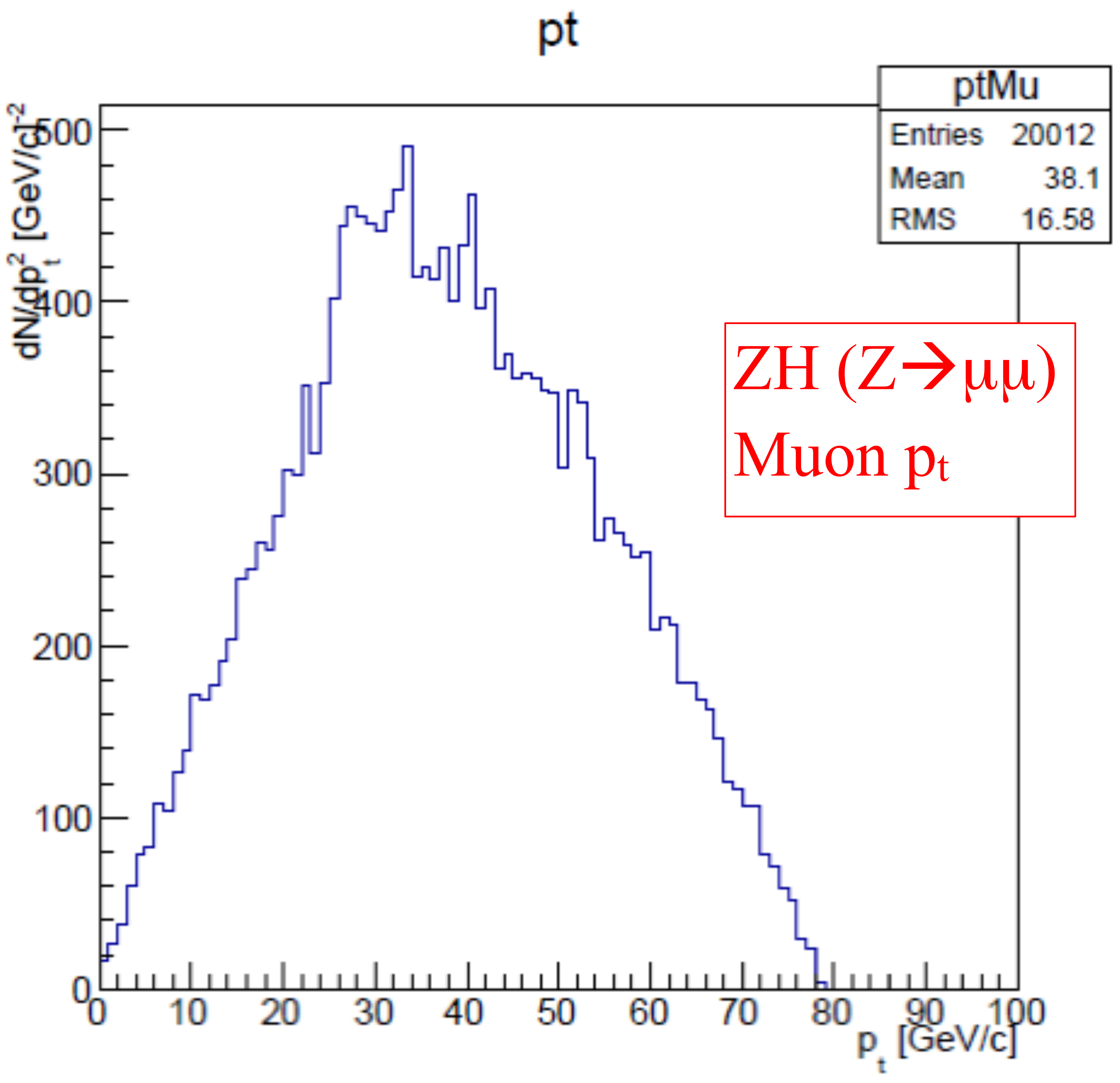


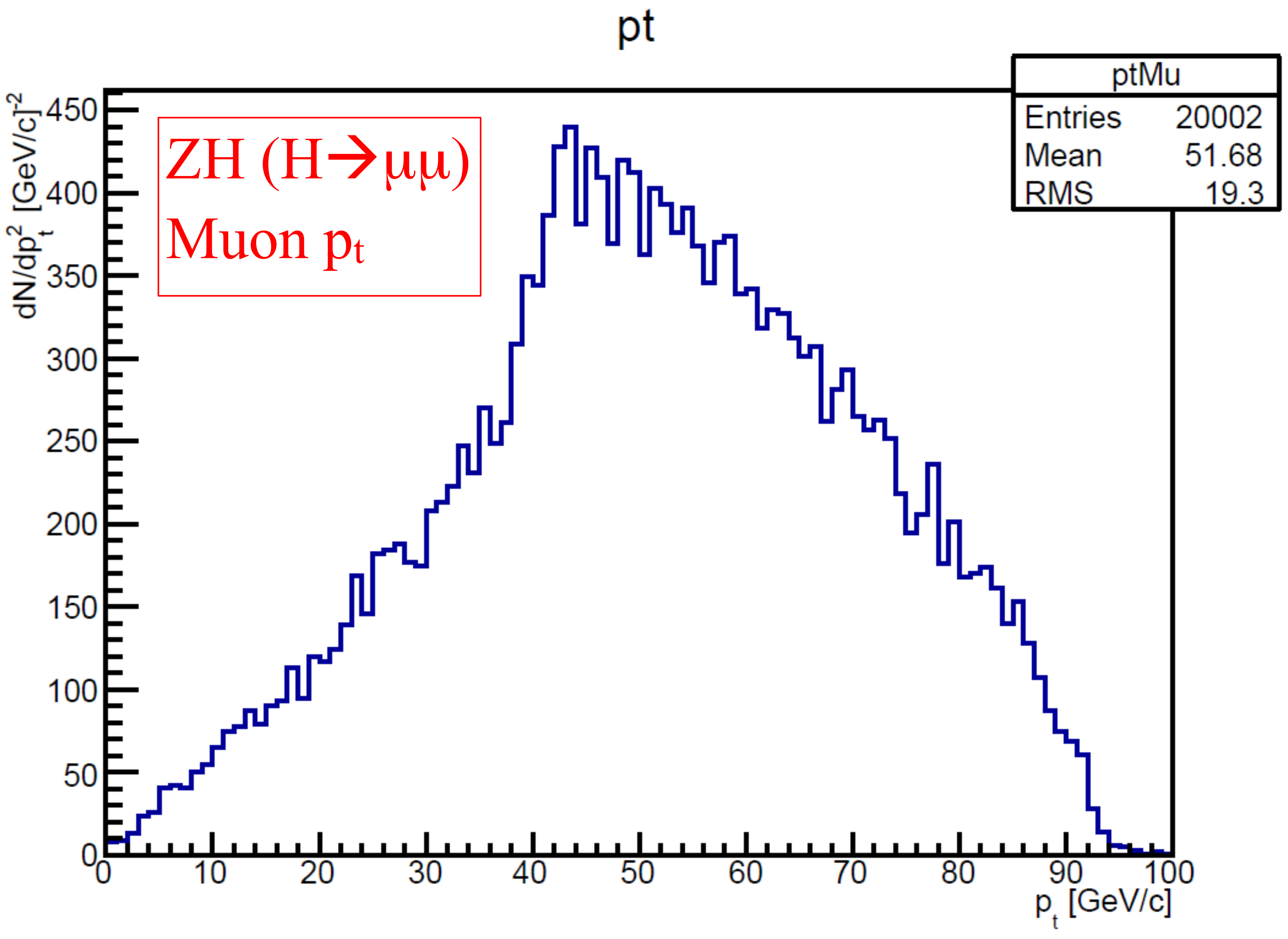


Pisa

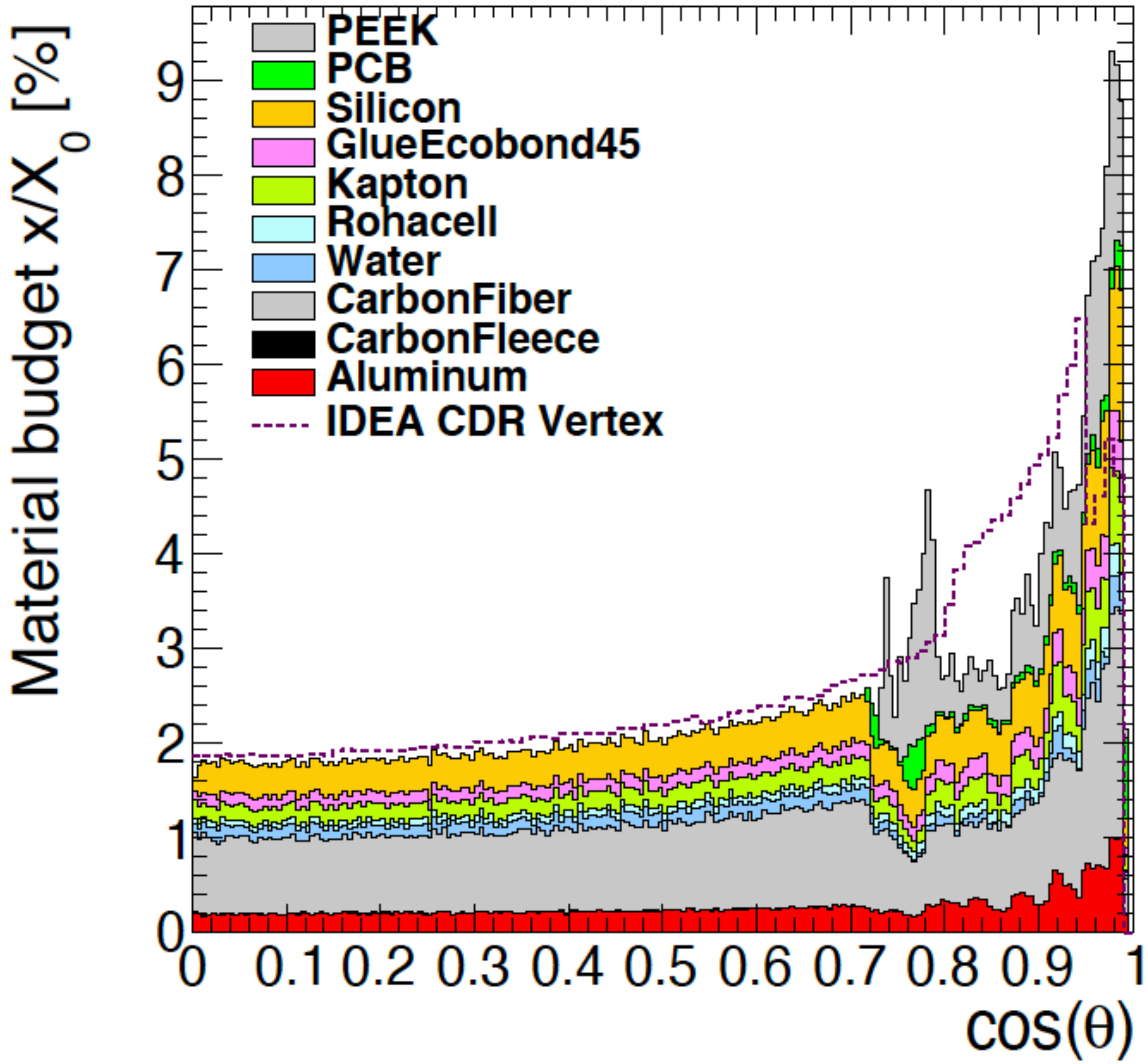
Also studying curved Silicon layout (ITS3 like)
~4 smaller material budget for inner vertex

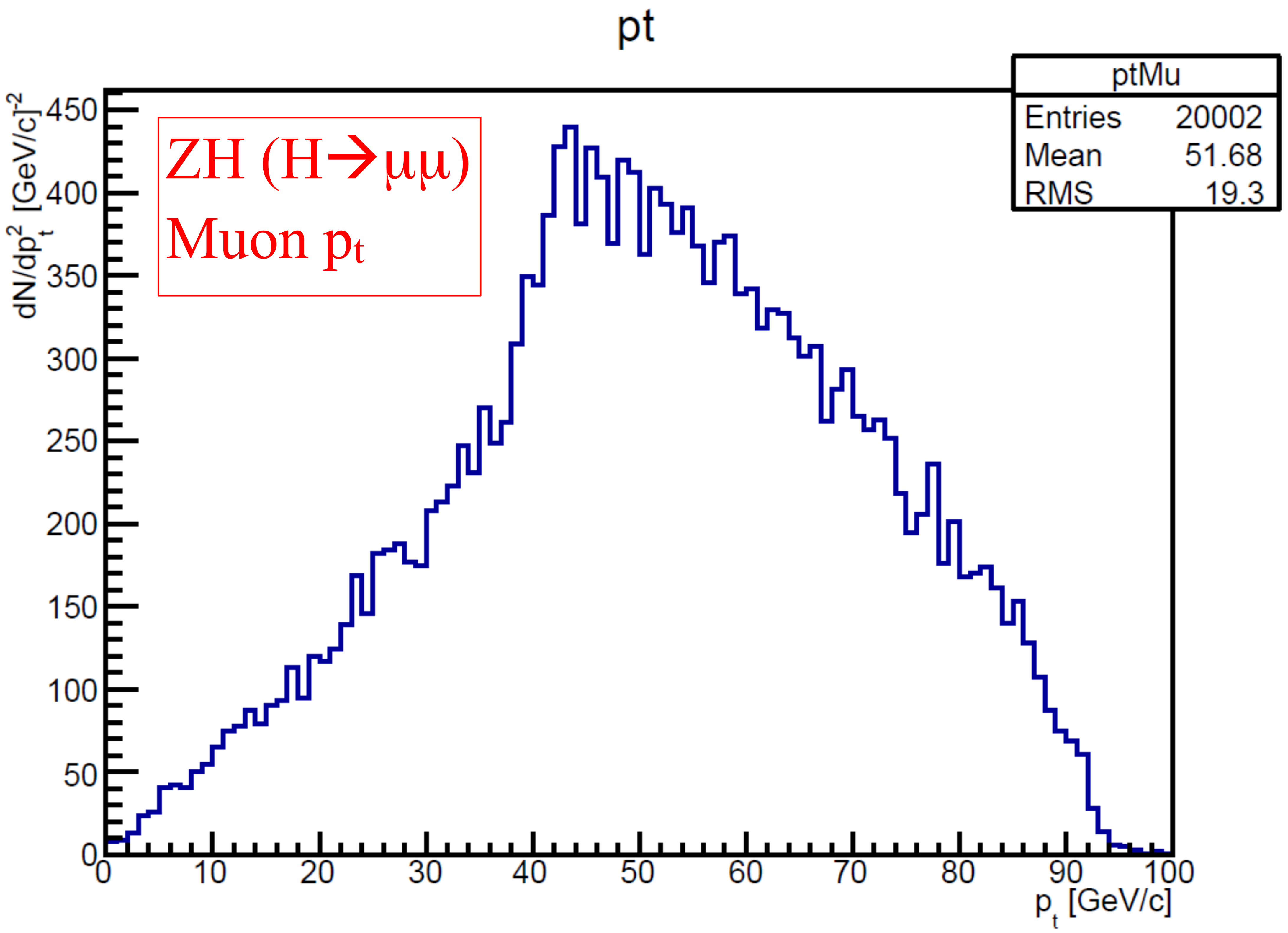
Momentum measurement





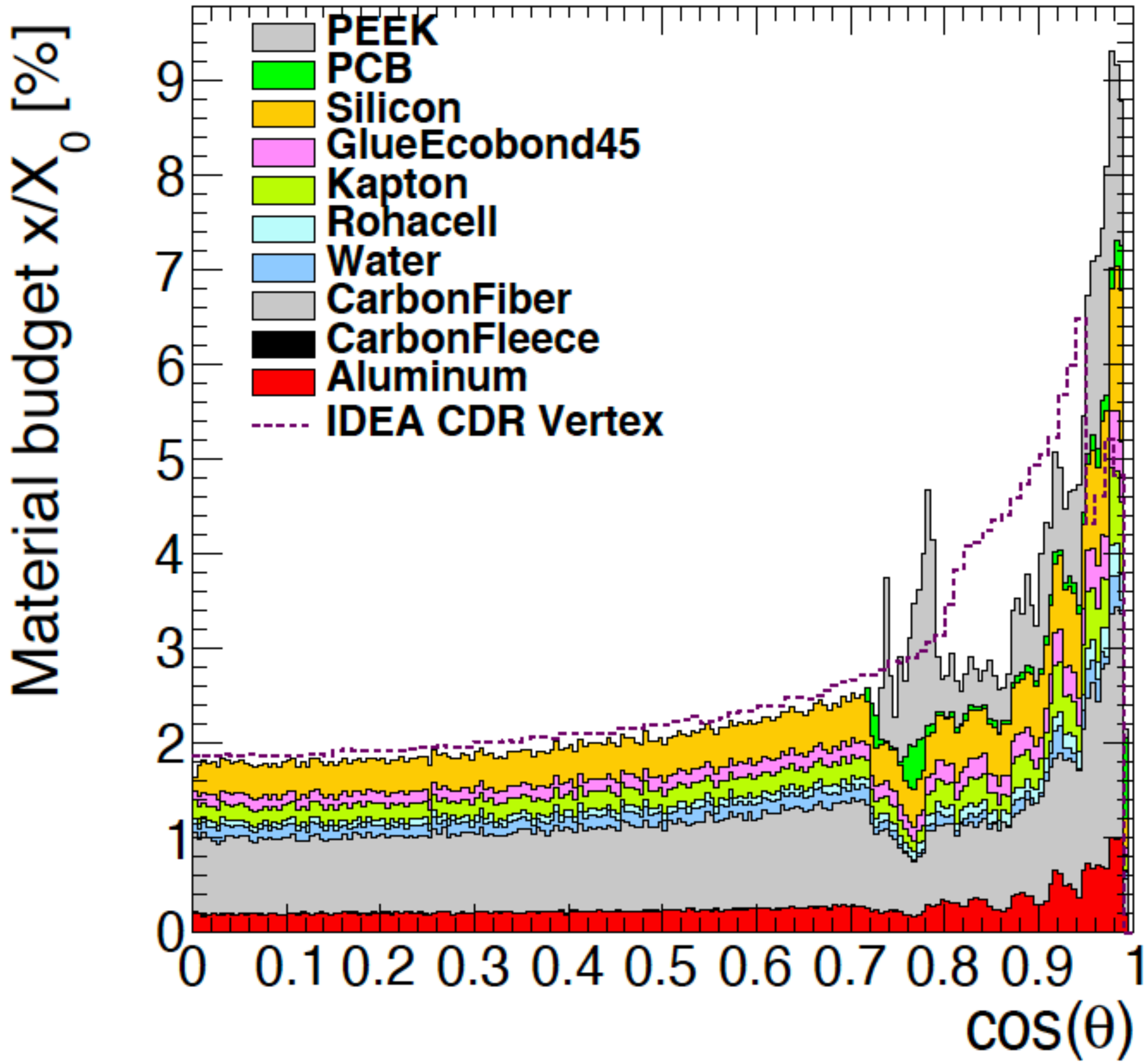
Momentum measurement

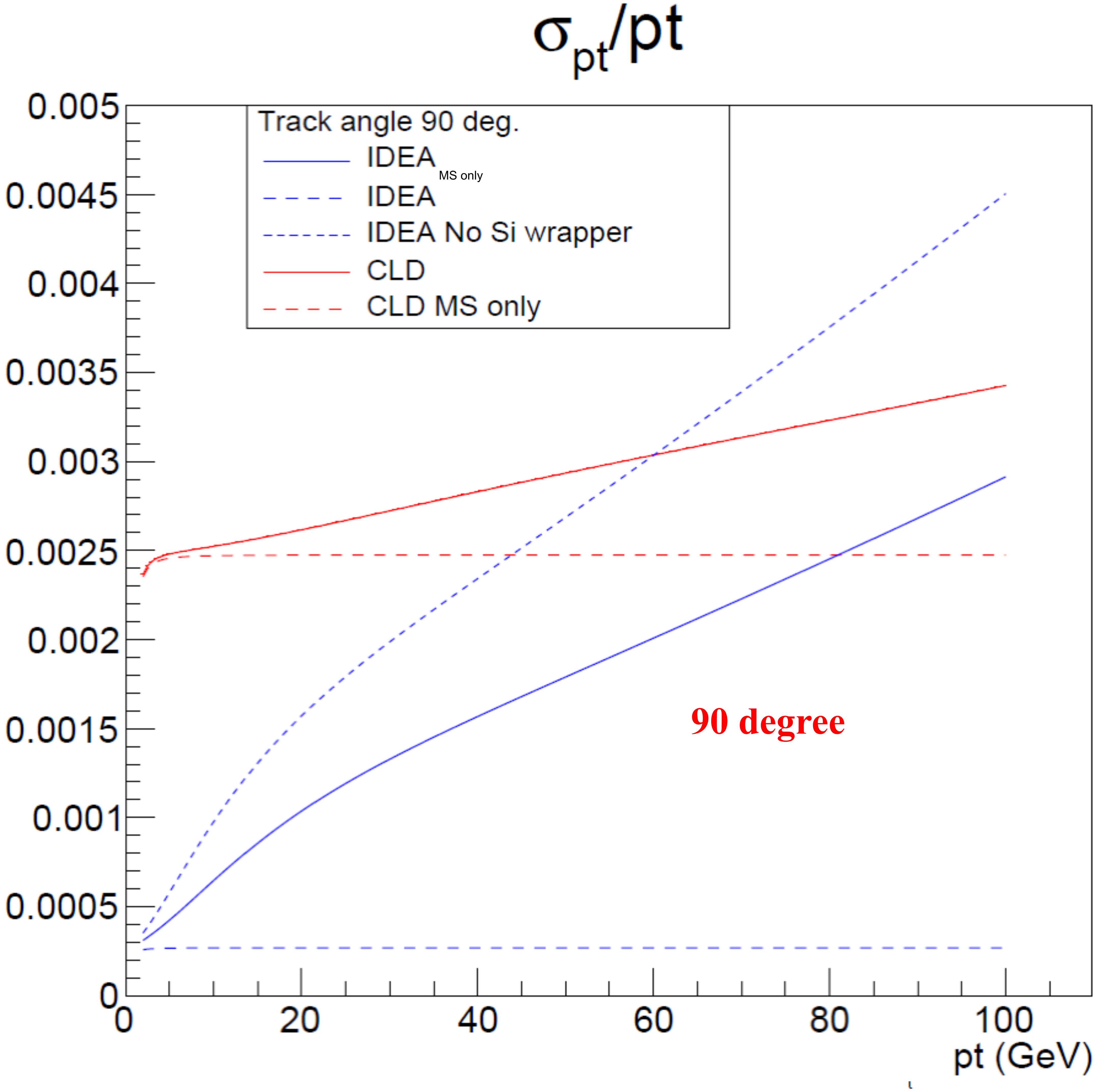




Momentum measurement

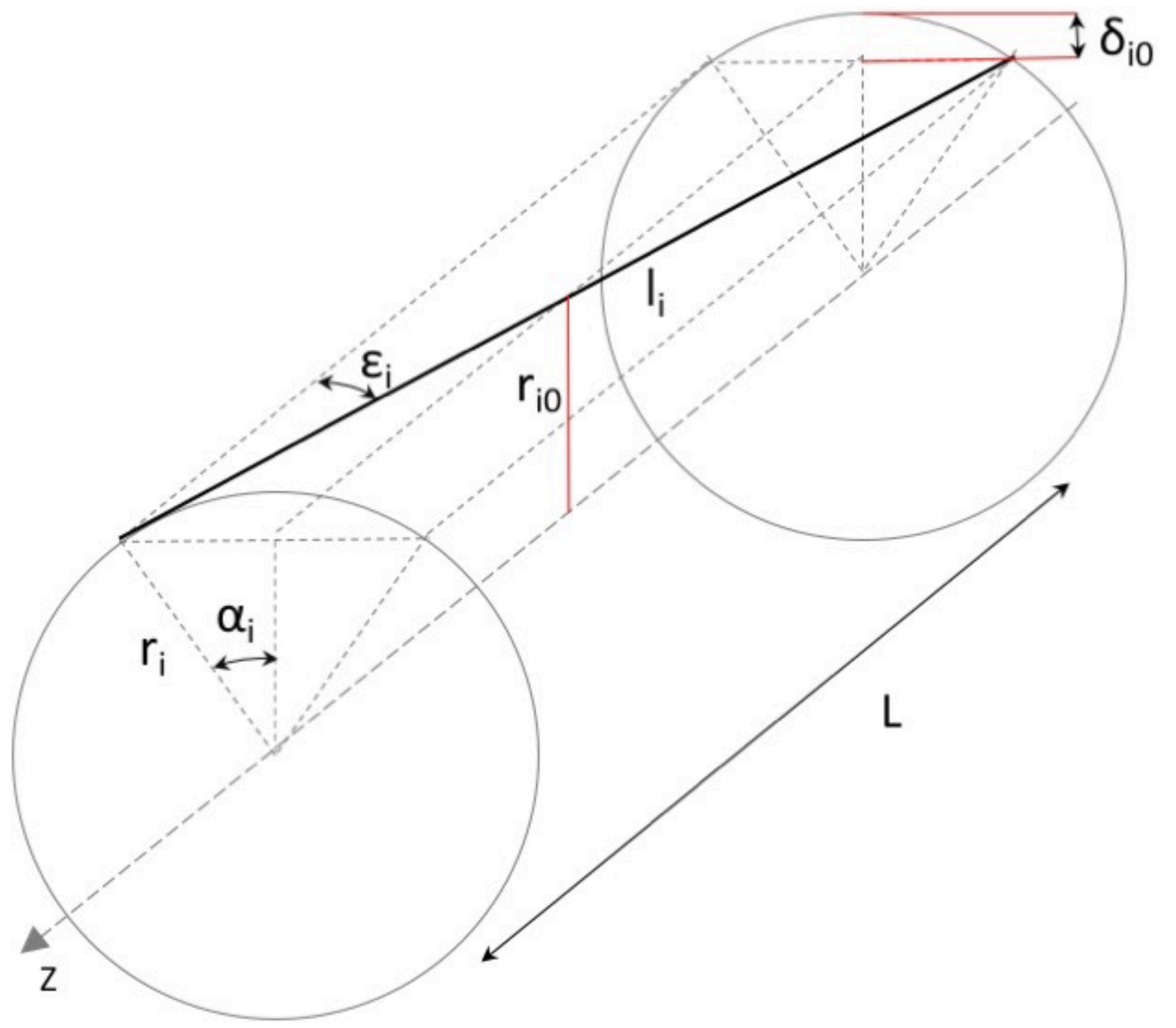
- Z or H decay muons in ZH events have rather low p_t
  - Transparency more important than asymptotic resolution



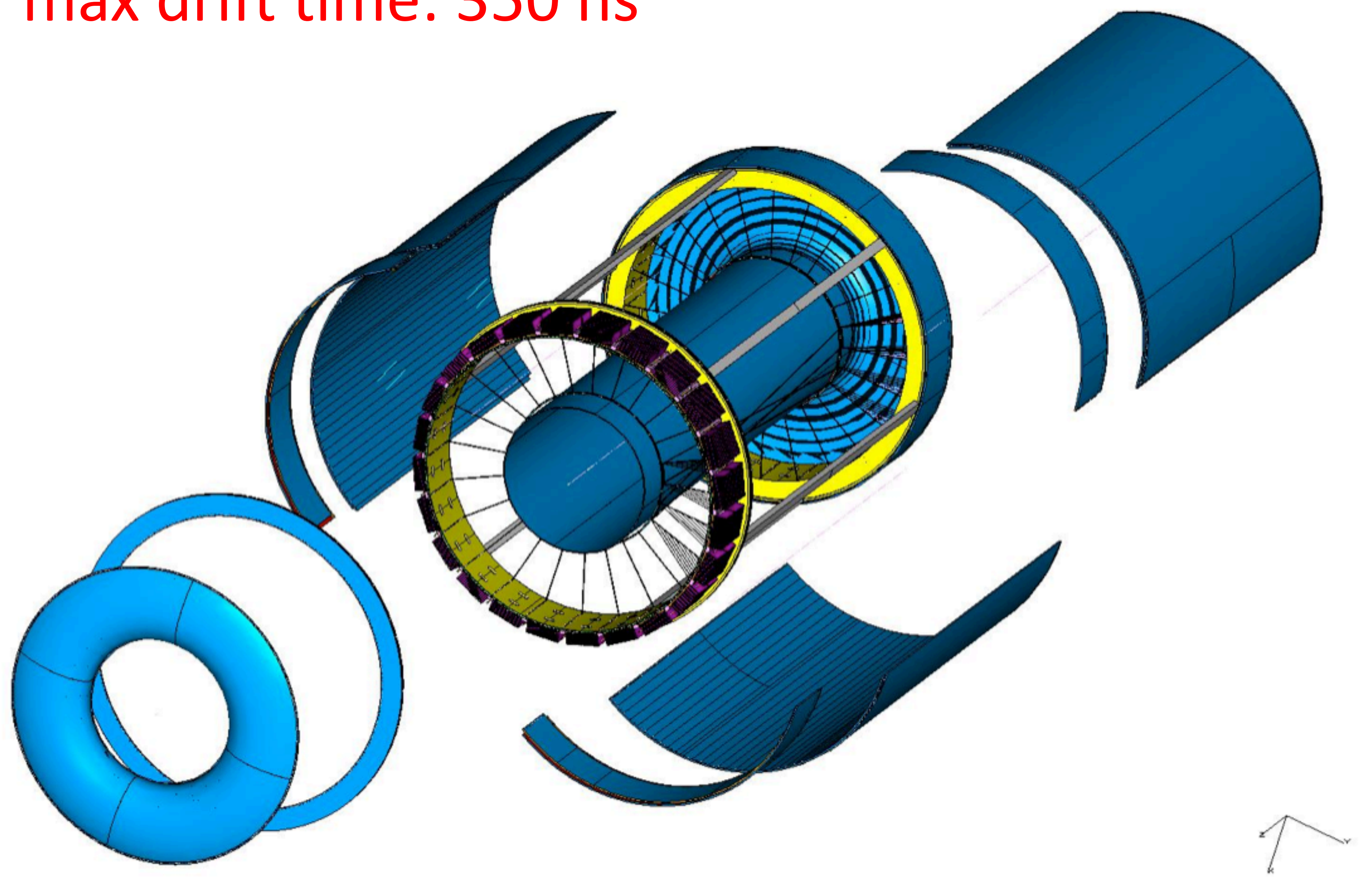


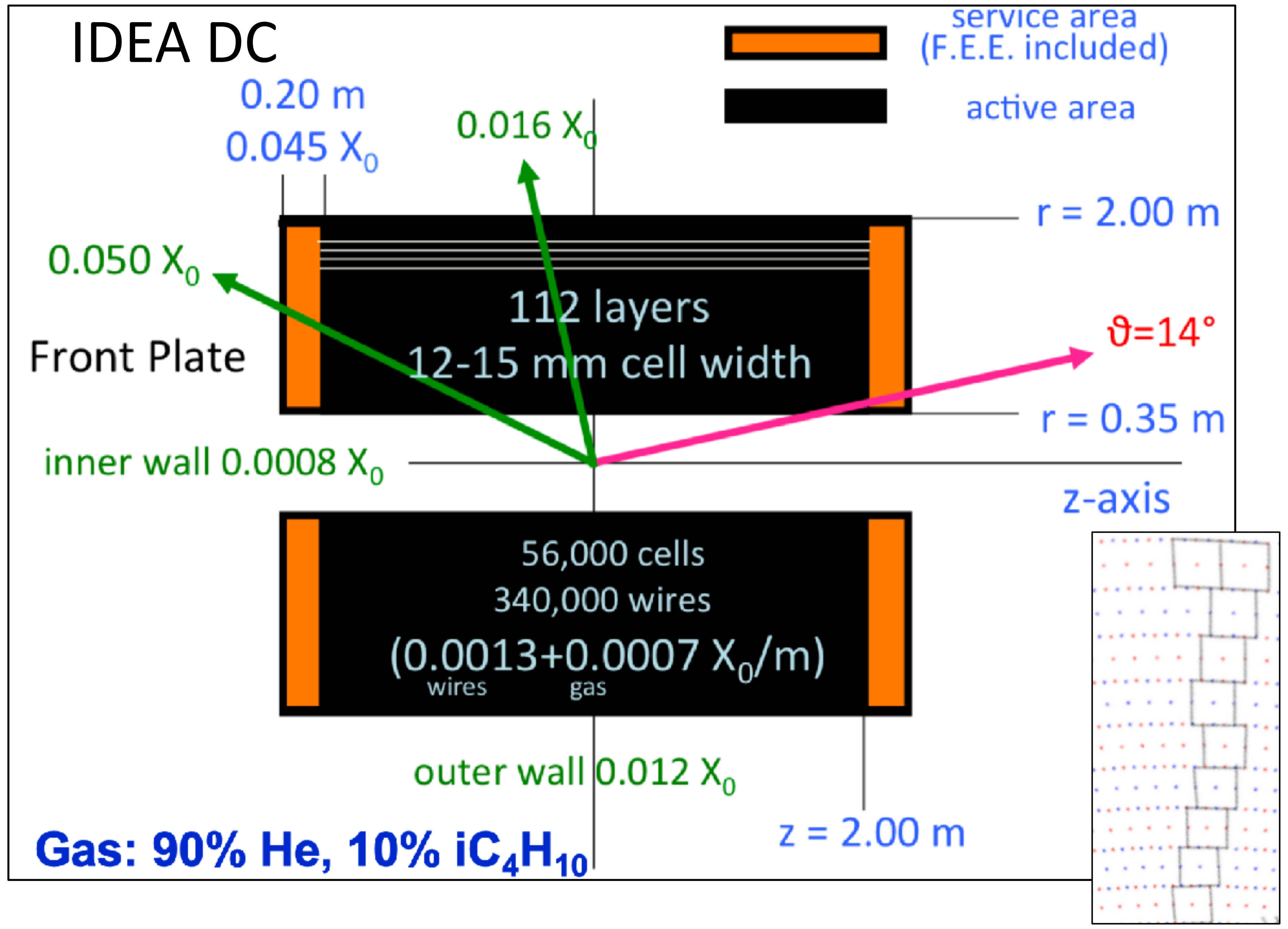
Drift chamber

- IDEA: Extremely transparent Drift Chamber
  - Gas: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
  - All stereo wires (56448 cells, 343968 wires)
    - Tungsten wires dominant contribution
  - 112 layers for each 15° azimuthal sector
  - max drift time: 350 ns



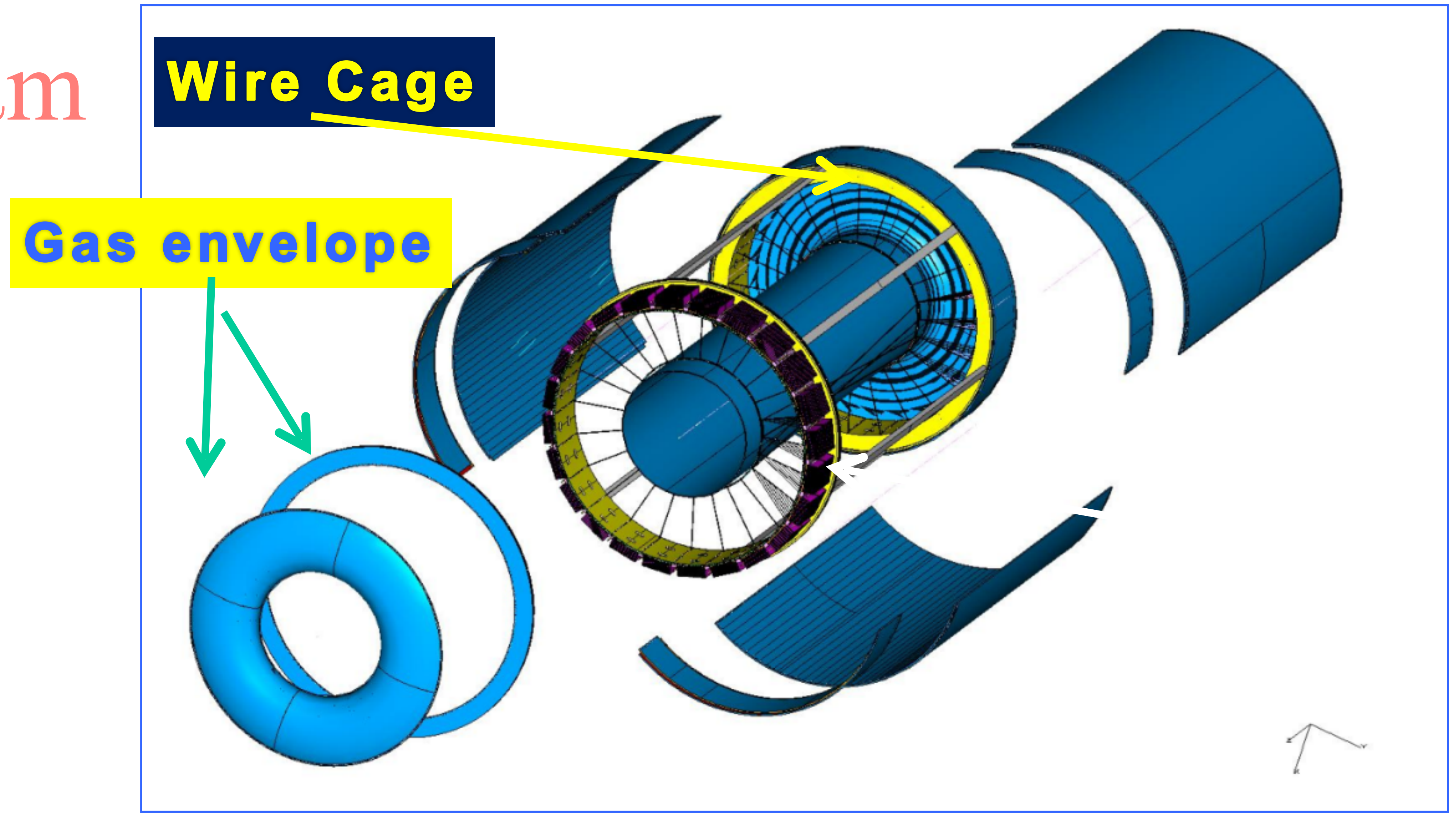
L = 4m

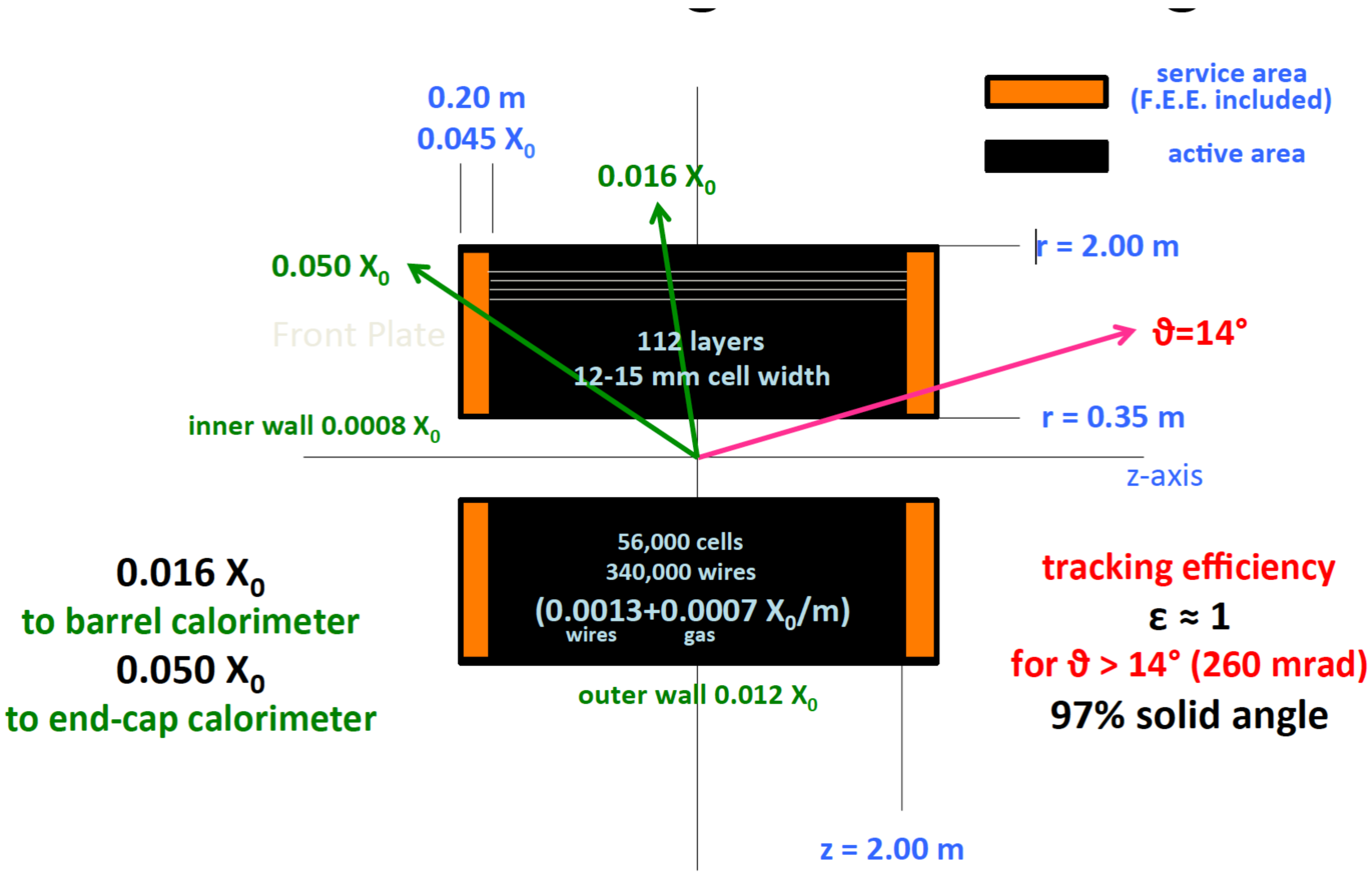


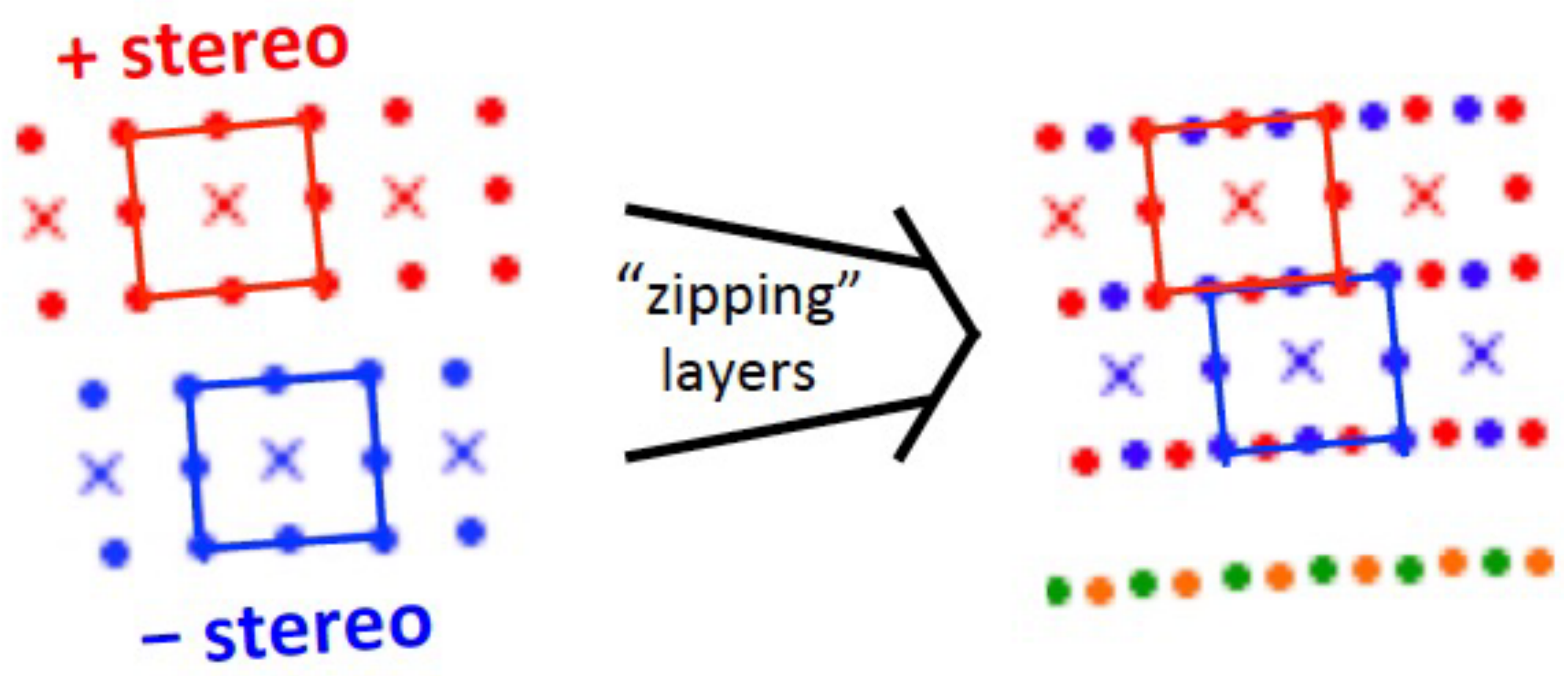


Drift chamber

- 90% He - 10% C_4H_{10} – All stereo – σ ~ 100 μm
- Small cells, max drift time ~ 350 ns

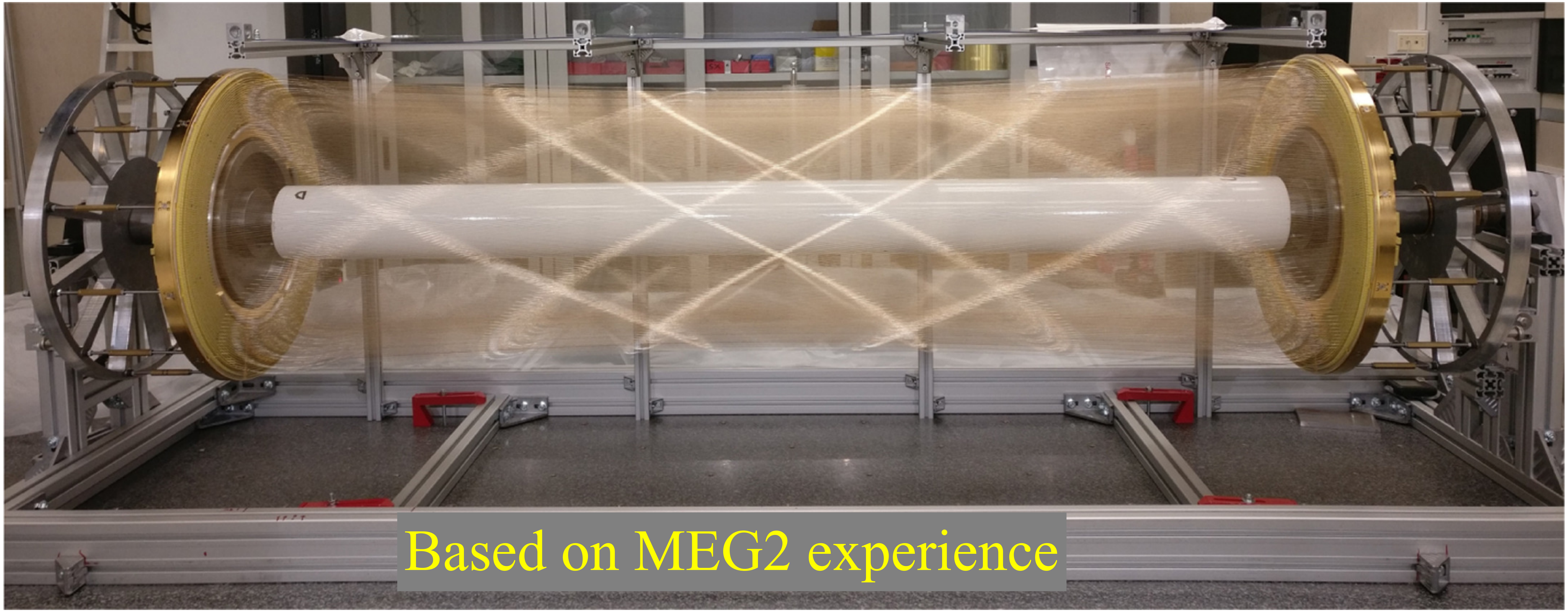




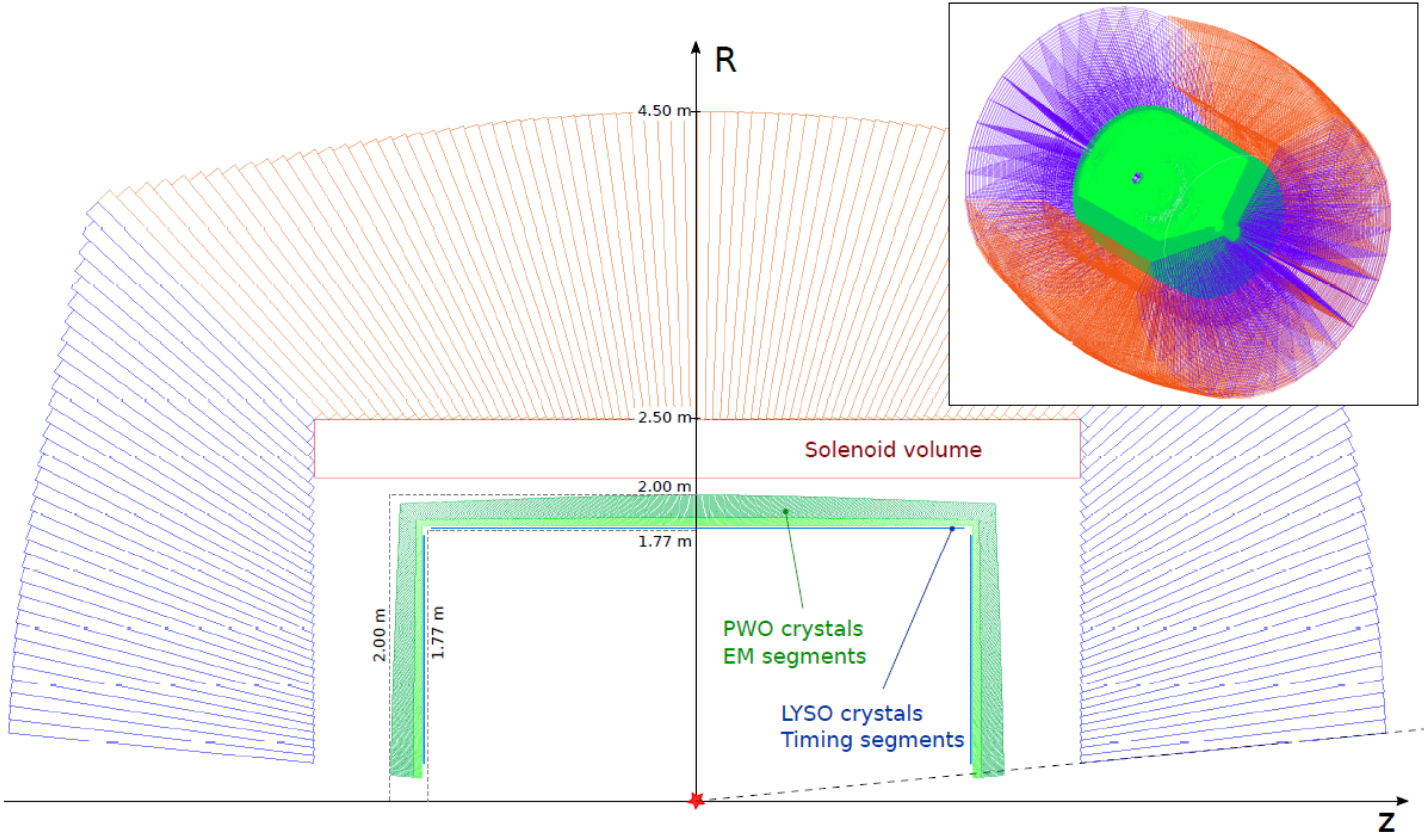


Drift chamber

- 90% He - 10% C_4H_{10} – All stereo – $\sigma \sim 100\ \mu m$
- Small cells, max drift time ~ 350 ns



Crystal DR calorimeter

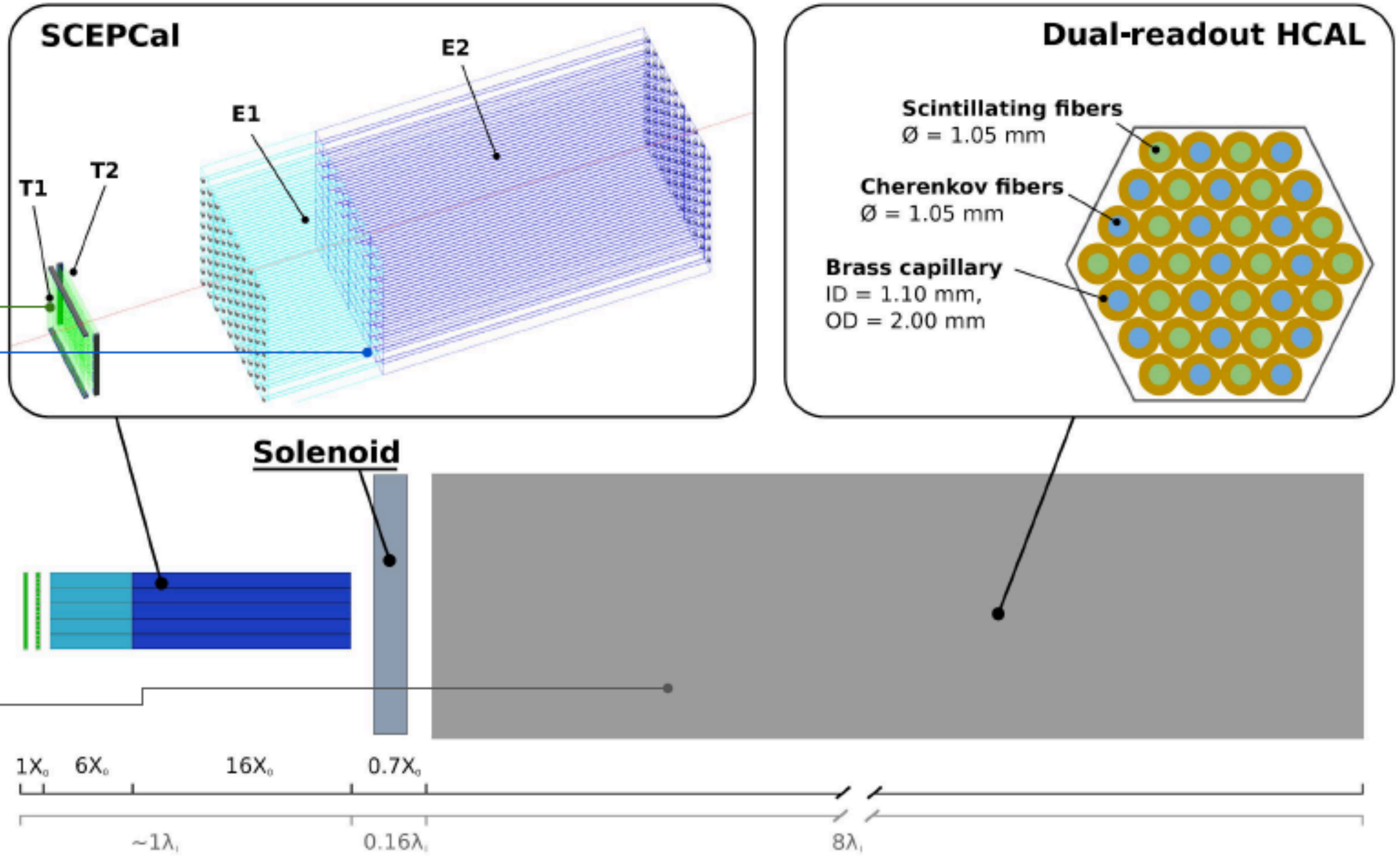


Crystal ECAL with DR calorimeter

Layout overview

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

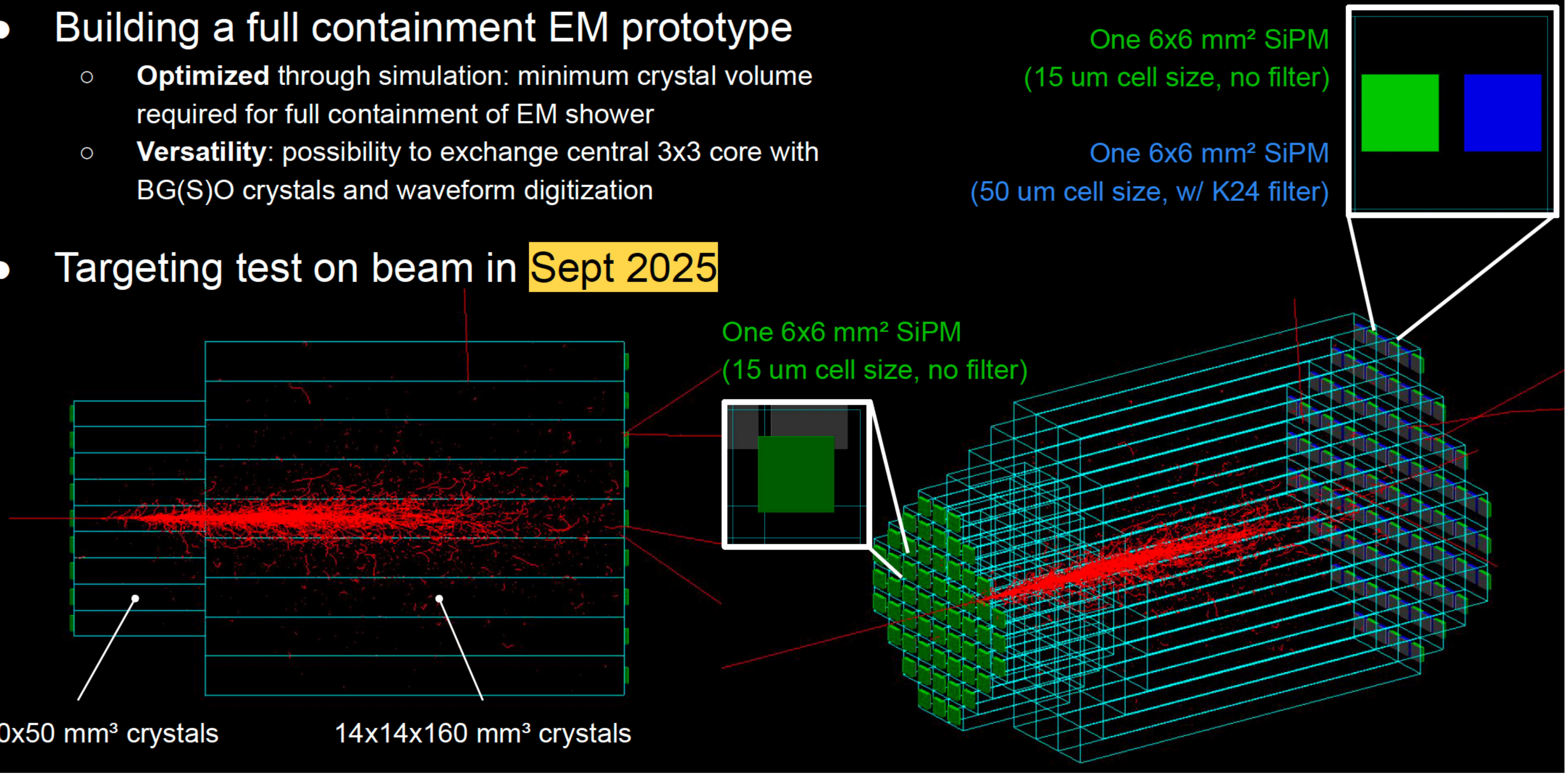


M. Lucchini

ECAL crystal calorimeter

Prototype design

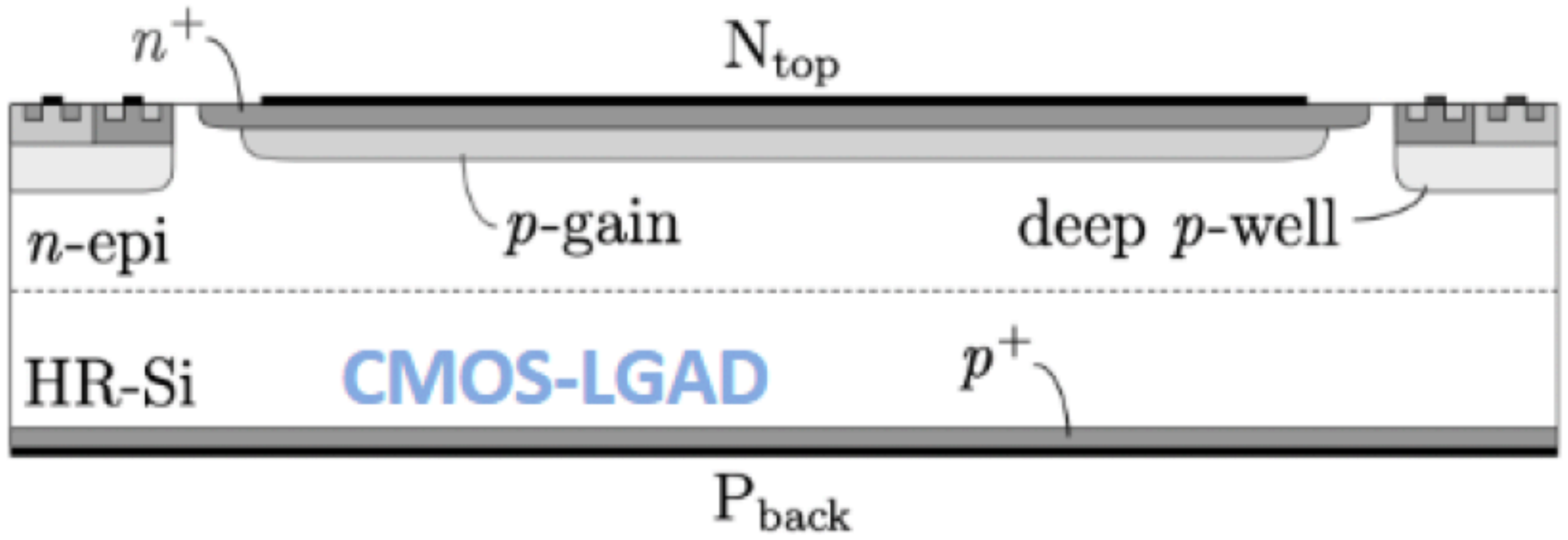
- Building a full containment EM prototype
  - **Optimized** through simulation: minimum crystal volume required for full containment of EM shower
  - **Versatility**: possibility to exchange central 3x3 core with BG(S)O crystals and waveform digitization
- Targeting test on beam in Sept 2025



RSD developments

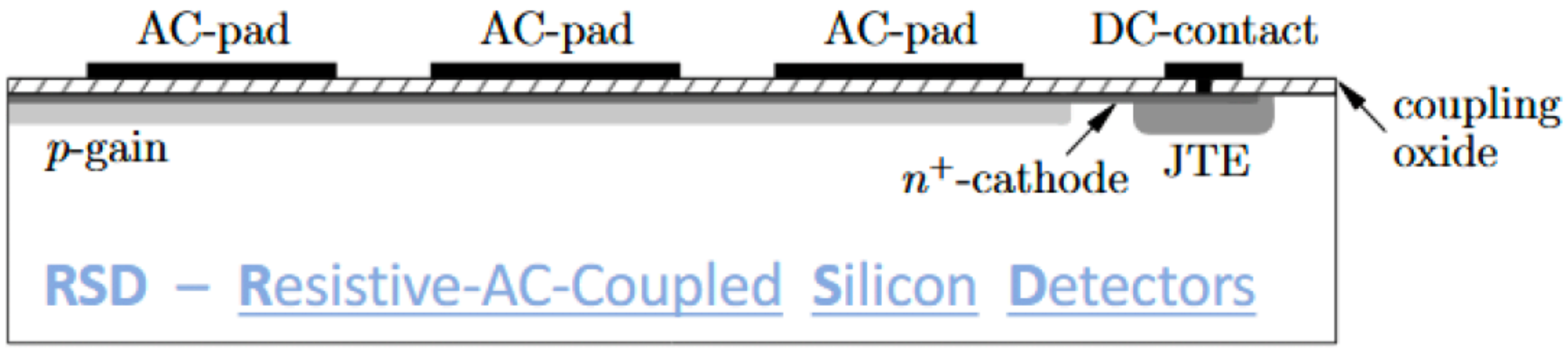
M. Mandurrino
FCC-ee Tracking WS

CMOS integration of the **LGAD technology** already demonstrated (in LF11is)



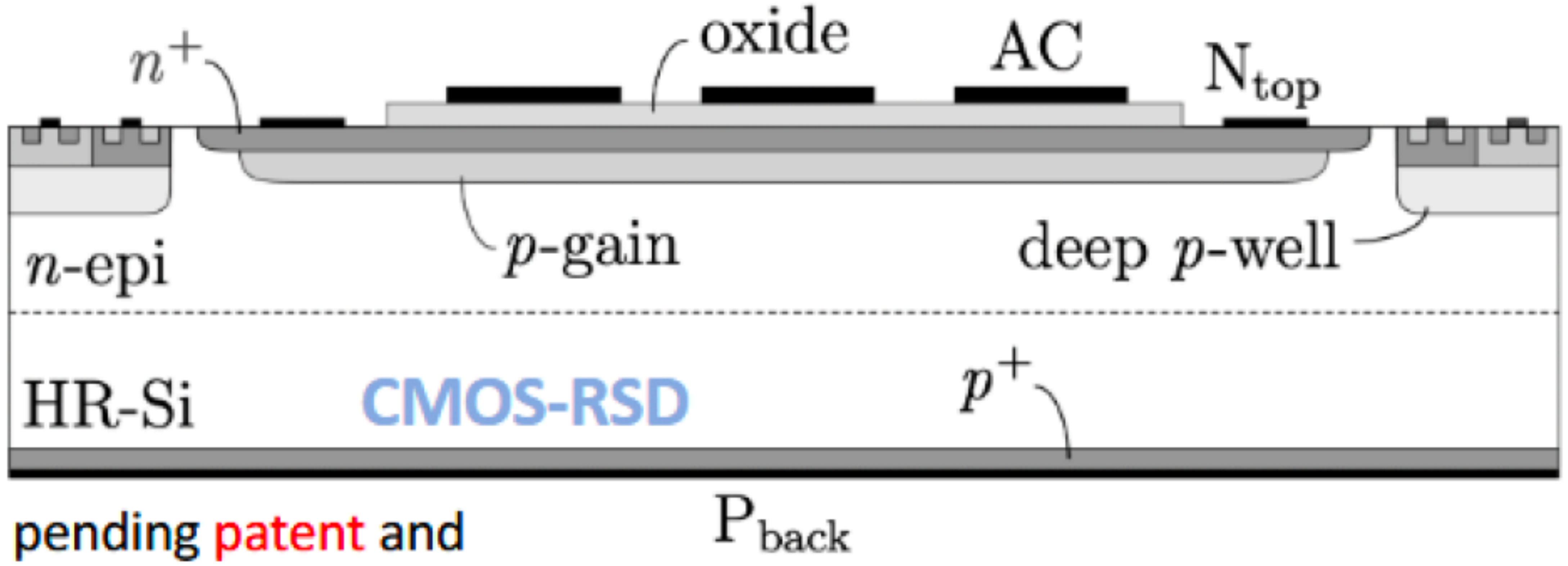
Spatial resolution **~3% of sensor pitch** (allowing to relax the channel density)

Time resolution similar to standard LGADs: **30-40 ps**



Plausible concurrent targets:

- **σ_t = 10-20 ps**
- **µm-level σ_x**
- **100% FF**



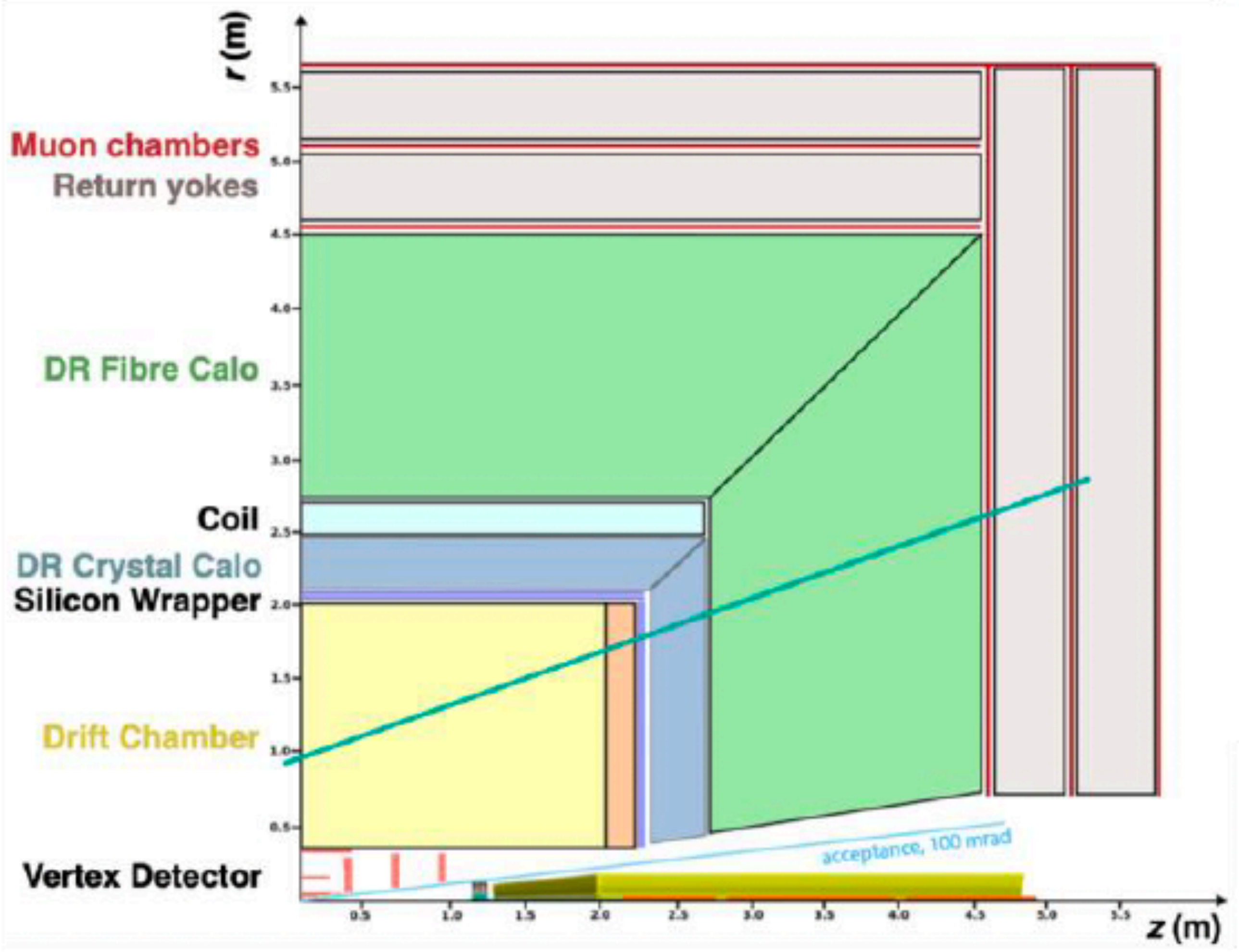
pending patent and extent of protection

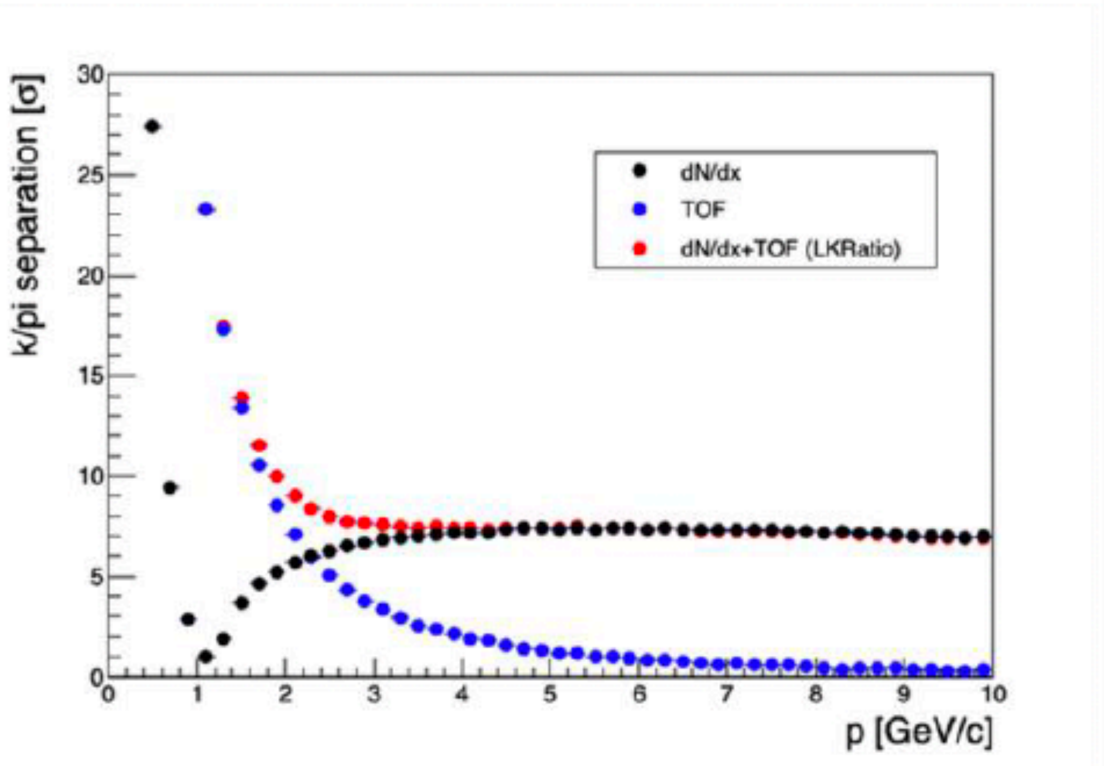
Detector layout and process flow design activities are ongoing

First prototypes in next silicon production runs (std. CMOS process)

RSD for Silicon Wrapper

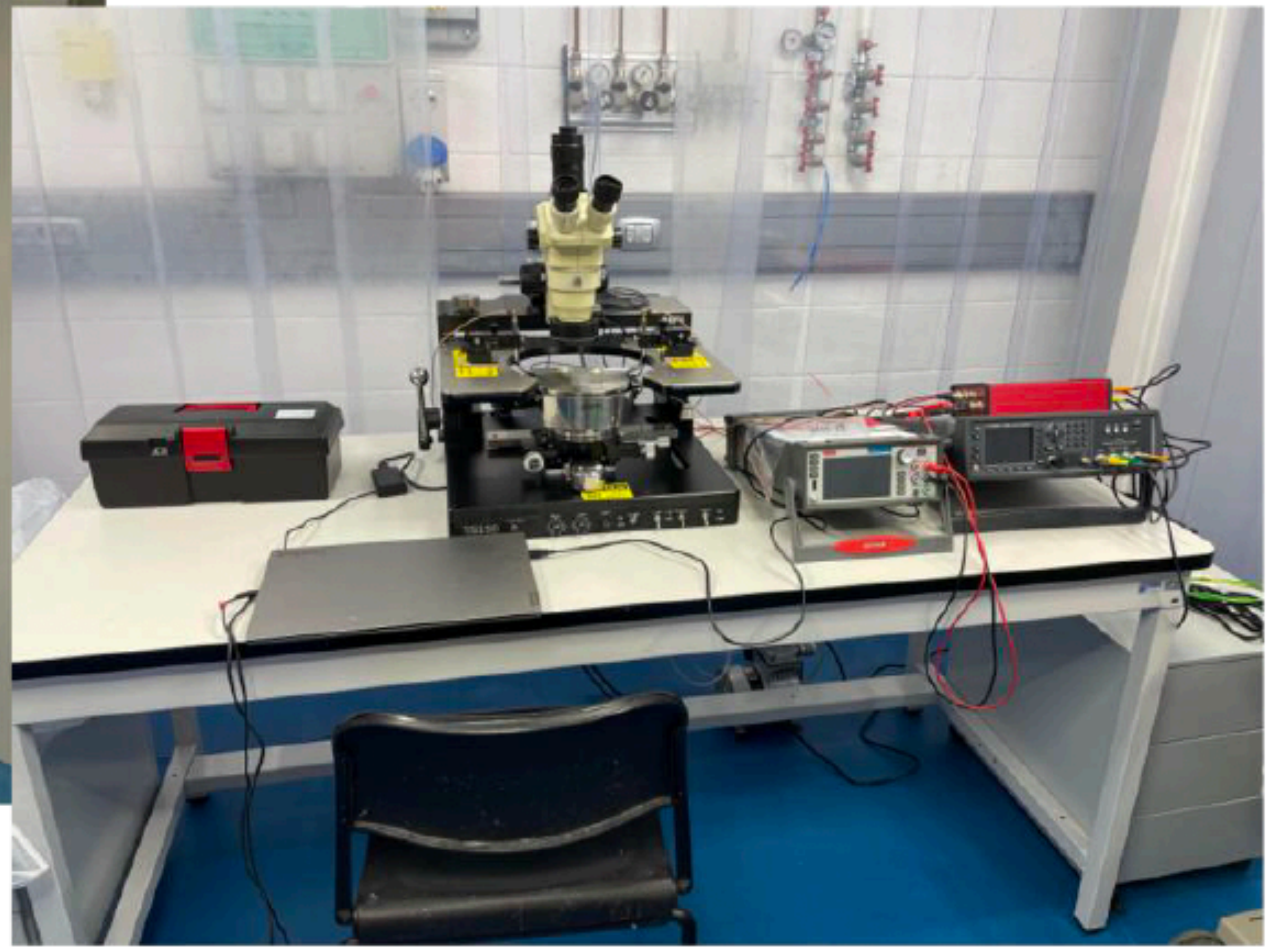
Genova





Set-up per caratterizzazione di sensori al silicio (in particolare RSD)

- Sistema con nuova probe station installato in camera “soft-wall” dedicata
- Sistema laser TCT pronto



Studi di simulazione su granularità silicon wrapper e introduzione misura di tempo

- Impatto in funzione di η

Possibili studi su nuovi canali di benchmark per l’utilizzo del TOF nella separazione K/π

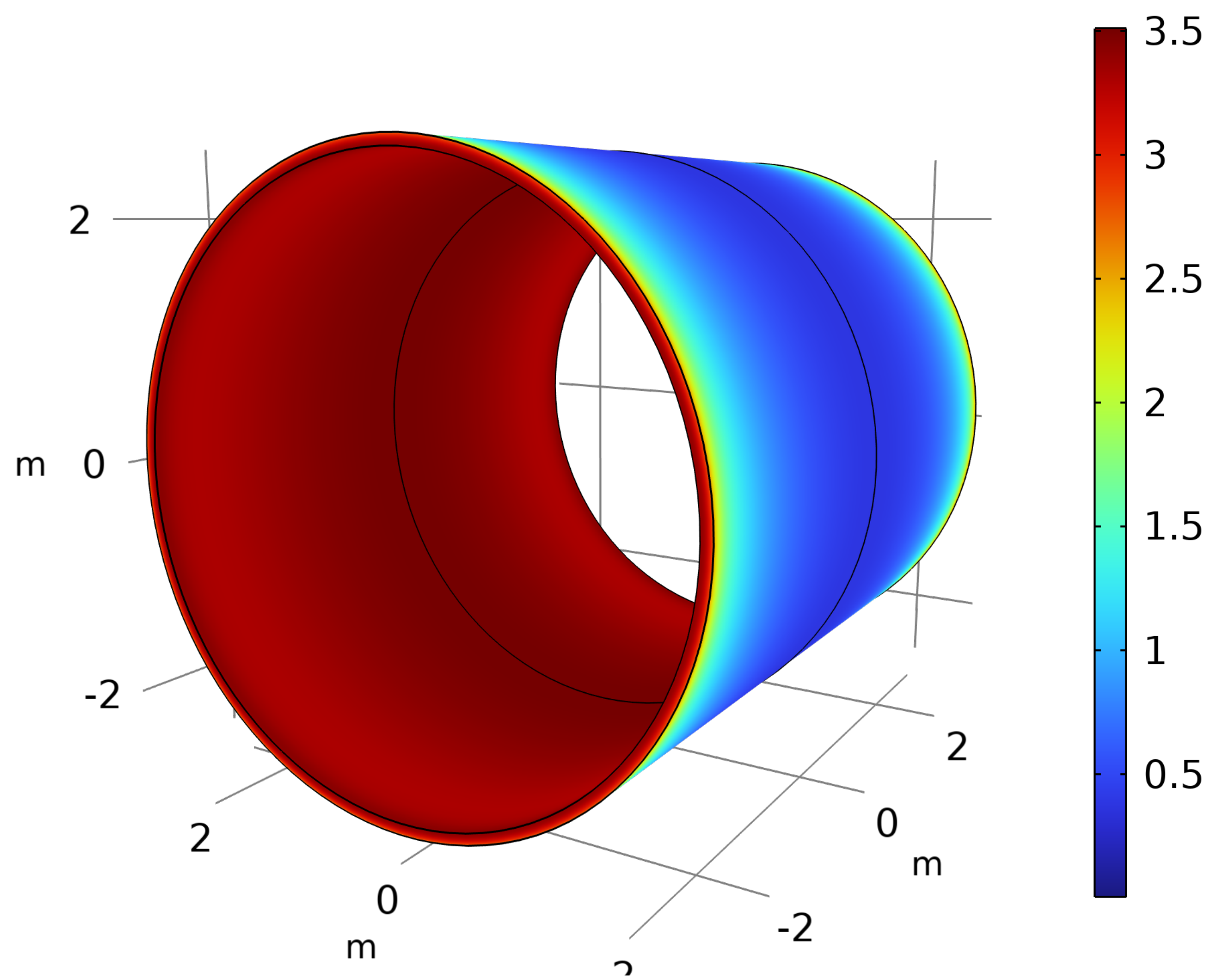
High temperature superconducting magnet

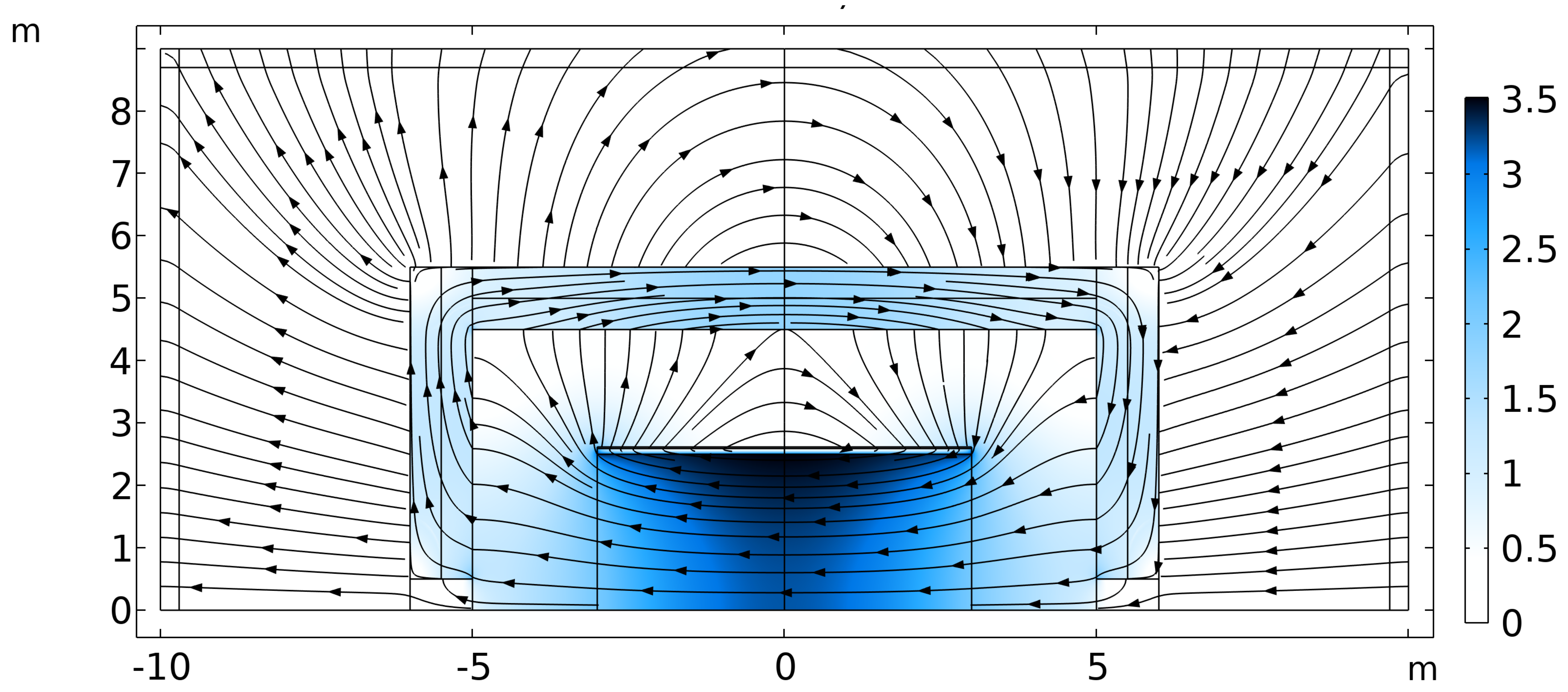
From analytical evaluations:

- B= 3 T, R_i=2.5 m e L=6 m → **18.65 MA-turns**

Peak field on the conductor equal to **3.5 T**
2D Rotational Symmetry Simulation in COMSOL

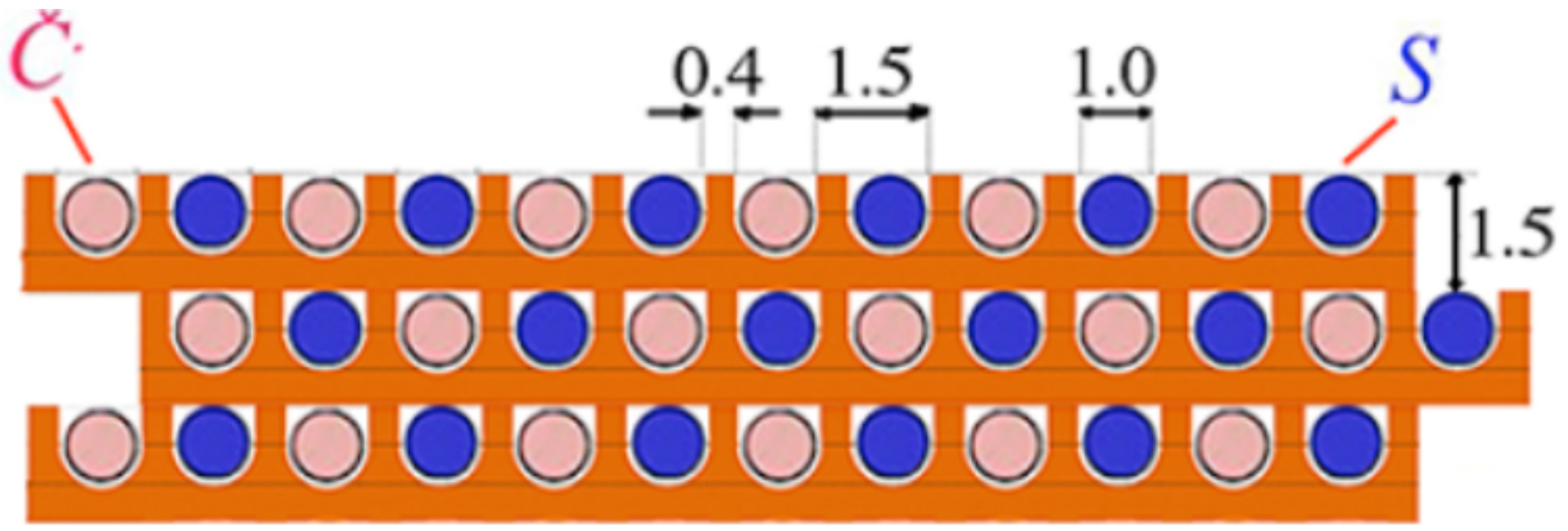
- Iron Yoke BH Curve still to be defined
- Internal radius increased to allow for EM Calorimeter
  - Still to be discussed coil transparency requirements
- Coil thickness limited stress on conductor (100 MPa)
- Dual readout HCal is ferromagnetic → **to be implemented in the computation model!**





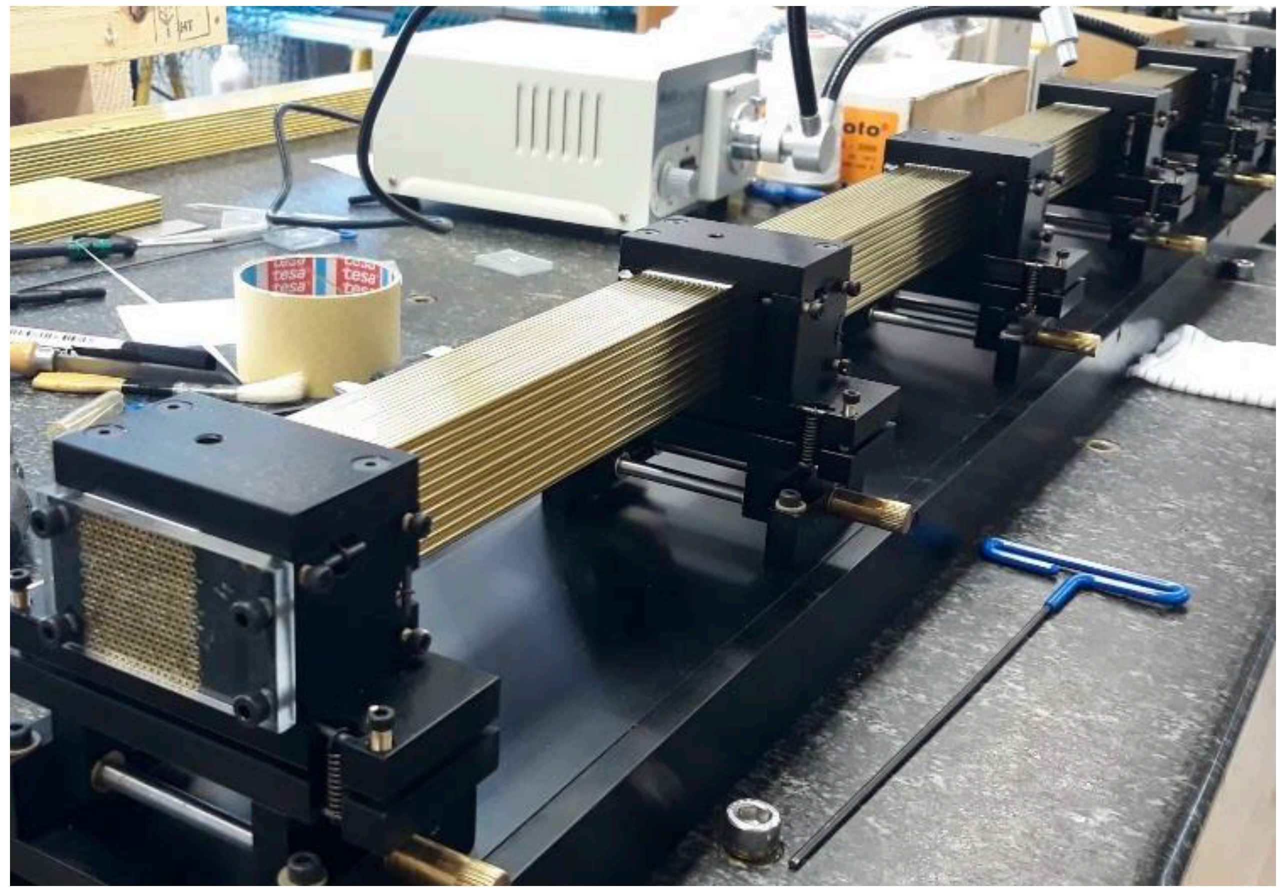
Parameter	Value
Bore Field	
	9323 [A]
Coil Thickness	92.3 [mm]
Turns	250x8
Inductance	**13 [H]**
Stored Energy	556 [MJ] - 28.2 [kJ/kg]
Operating Temperature	**20 [K]**

Dual Readout Calorimetry

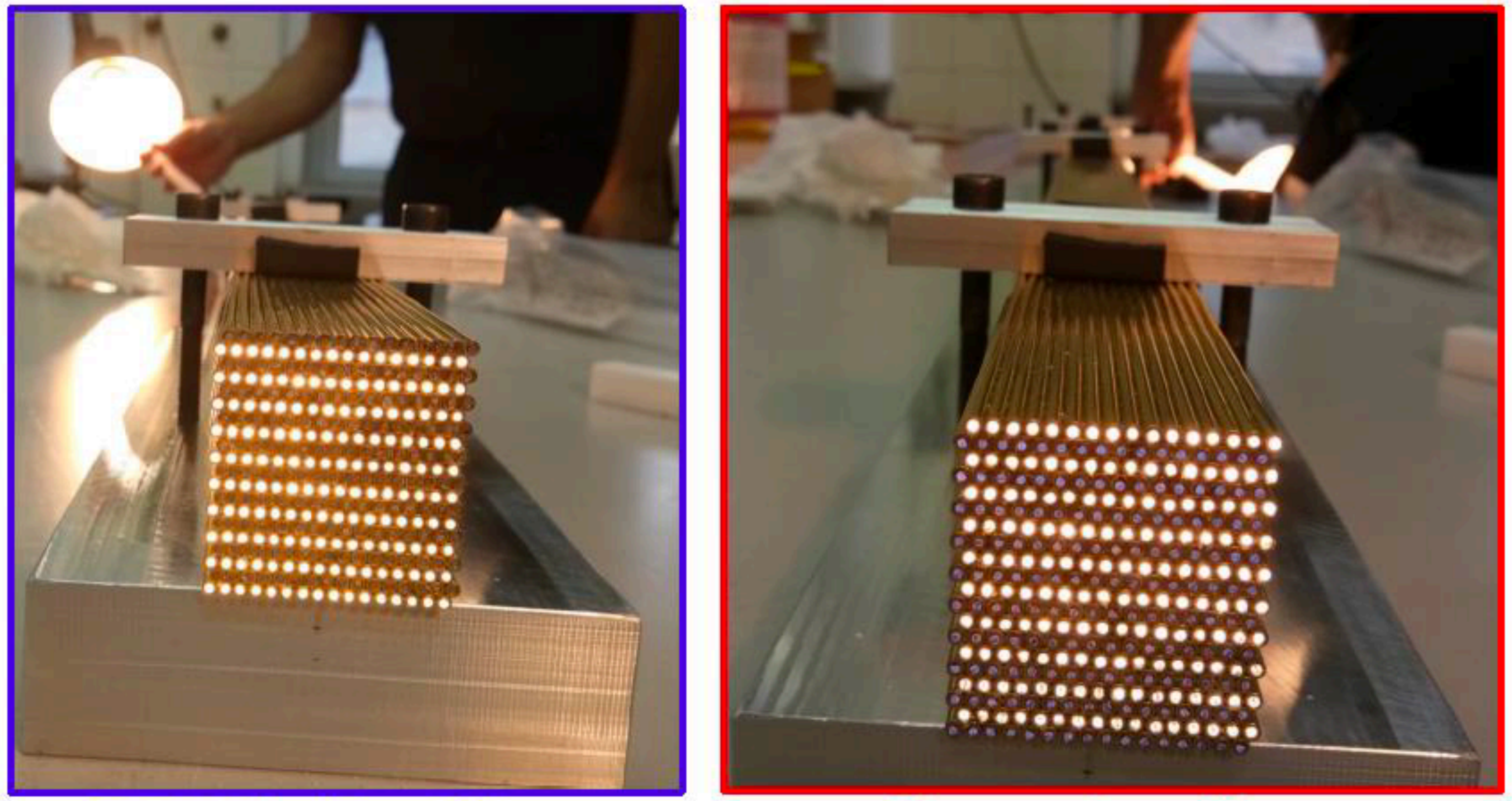


Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



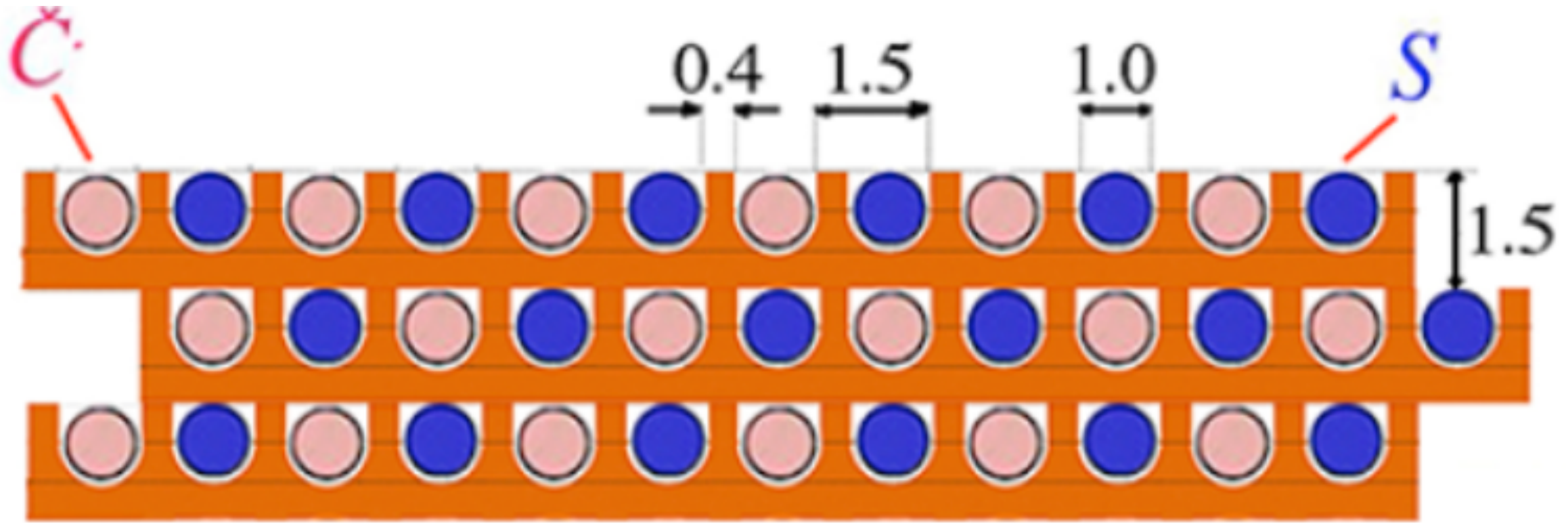
Newer DR calorimeter
(bucatini calorimeter)



Scintillation fibers

Cherenkov fibers

Dual Readout Calorimetry



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Cherenkov fibers
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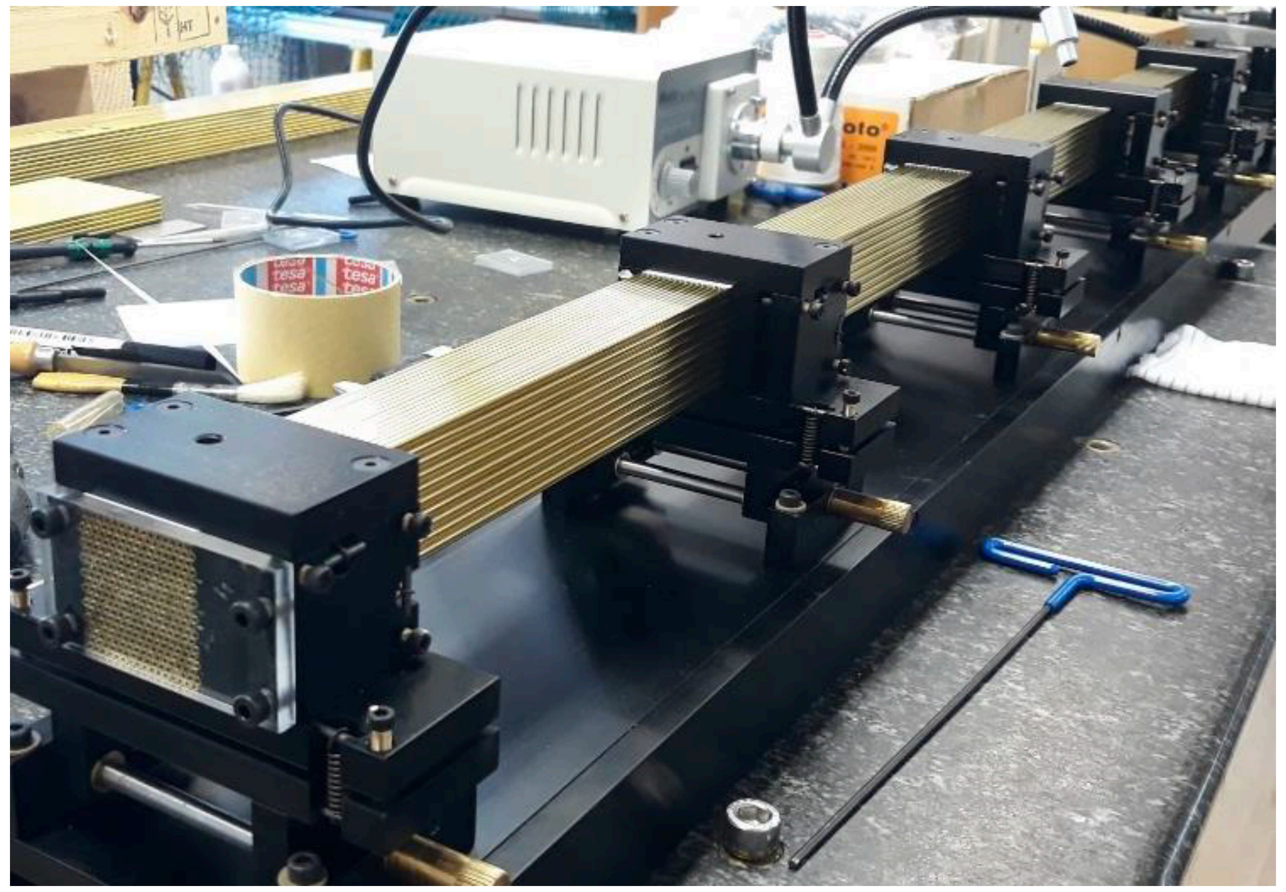
~2m long capillaries



Newer DR calorimeter
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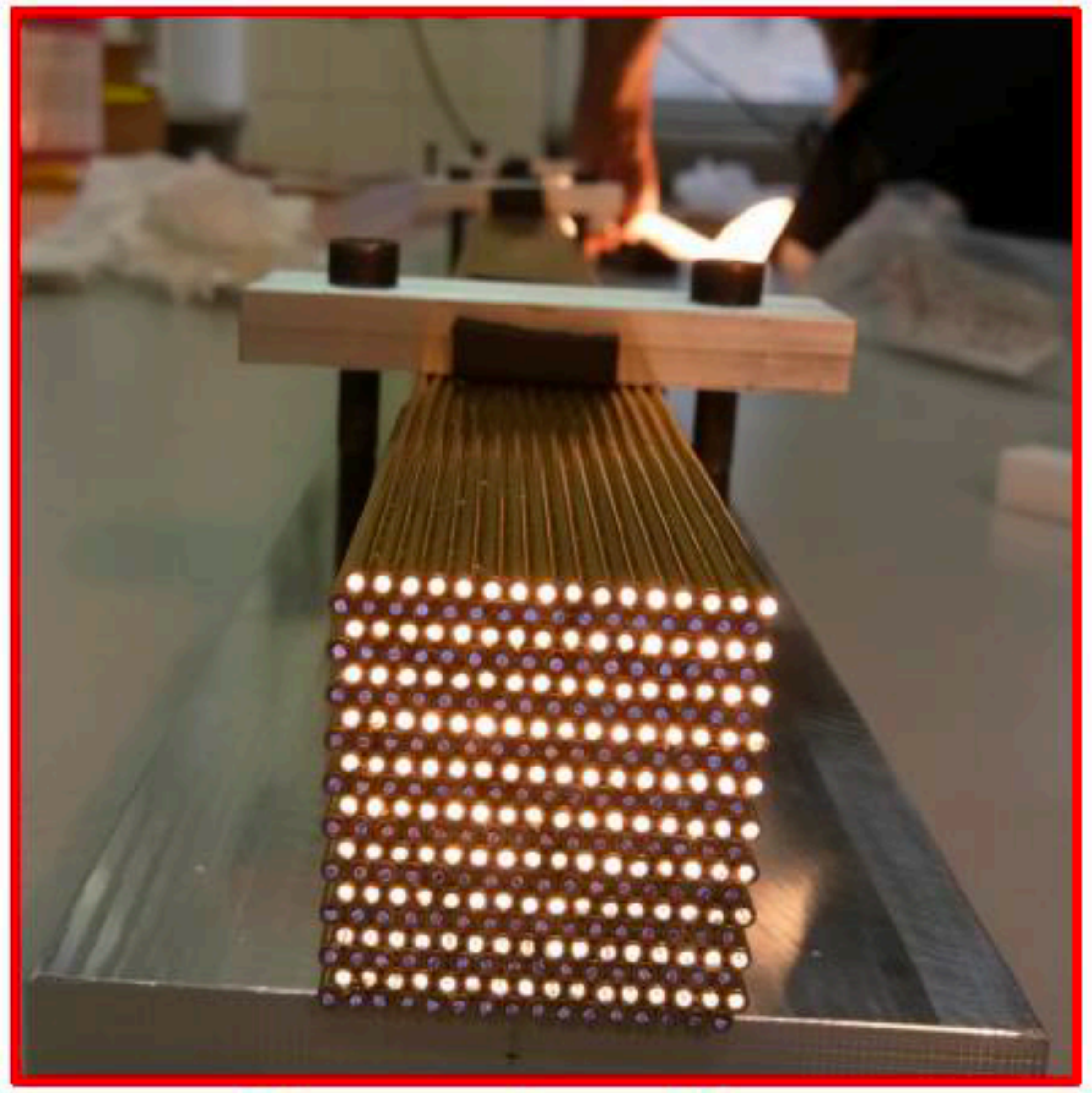
Scintillation fibers



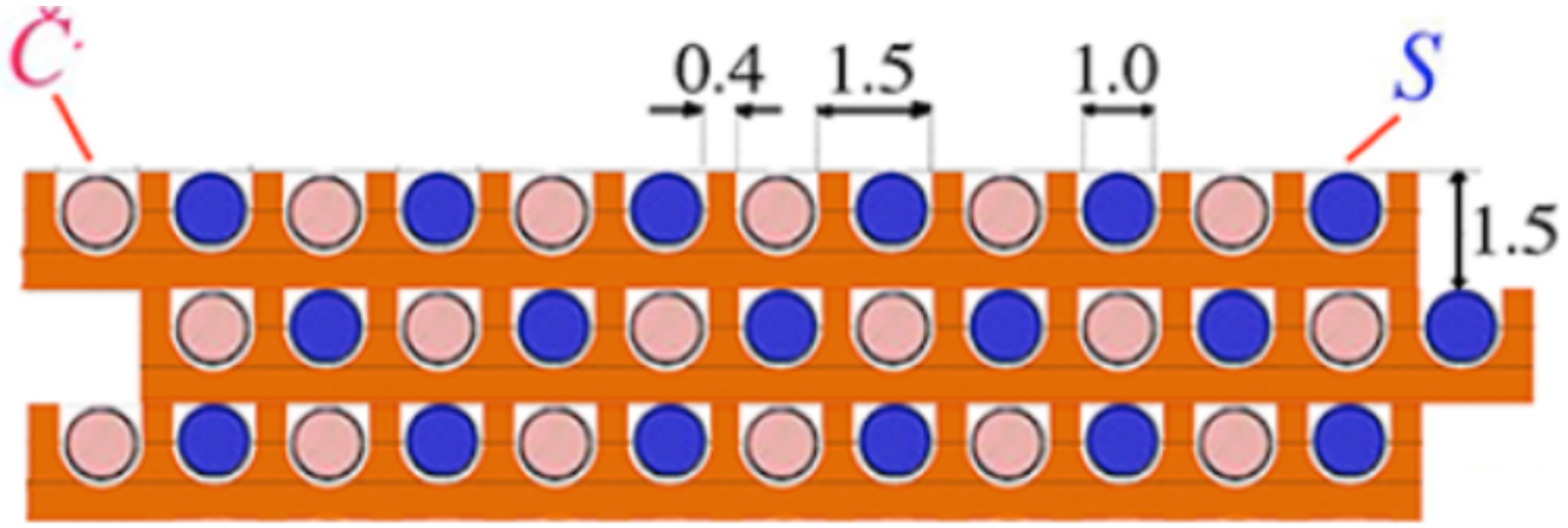
Cherenkov fibers

$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E\left[f_{em} + (h/e)_C(1 - f_{em})\right]$$

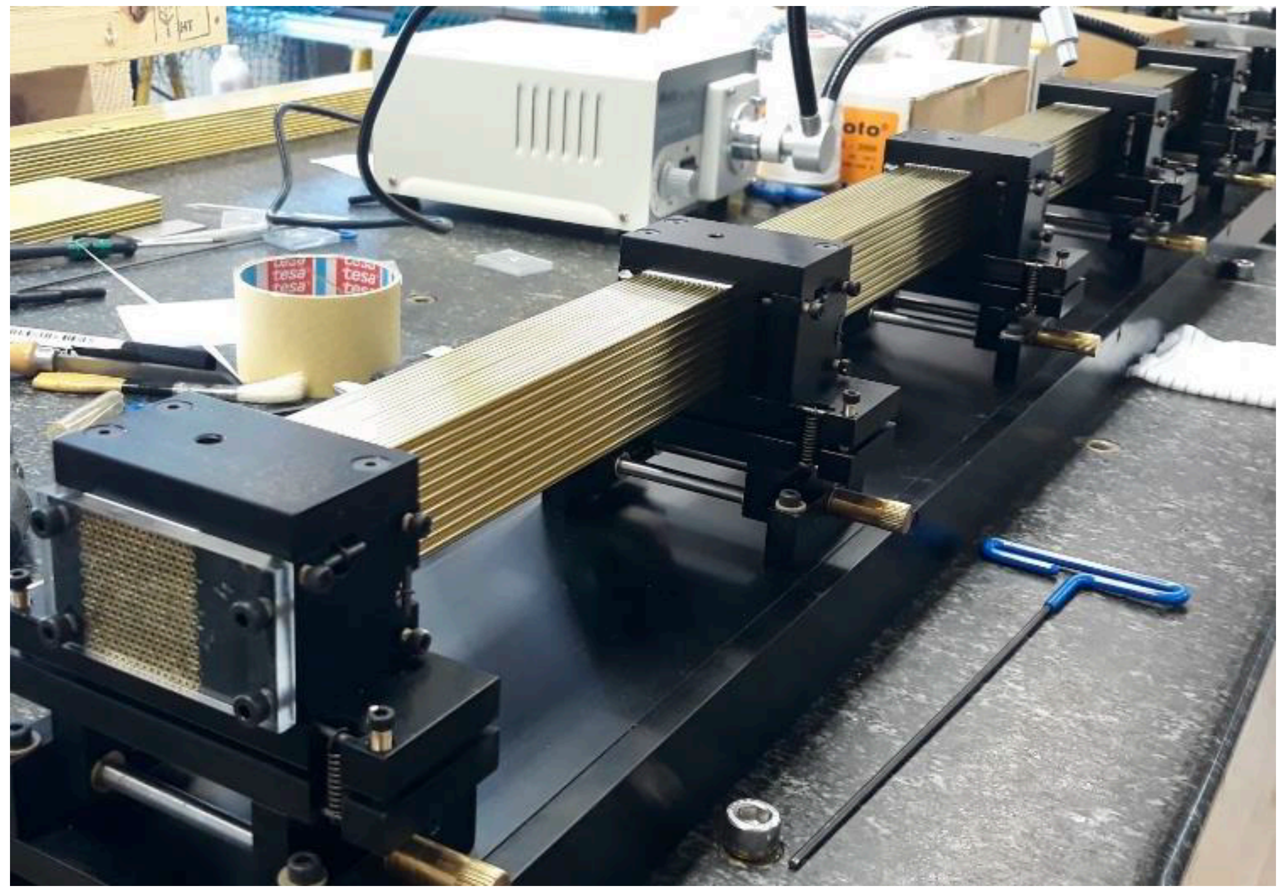
$$E = \frac{S - \chi C}{1 - \chi} \qquad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

Dual Readout Calorimetry



Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)

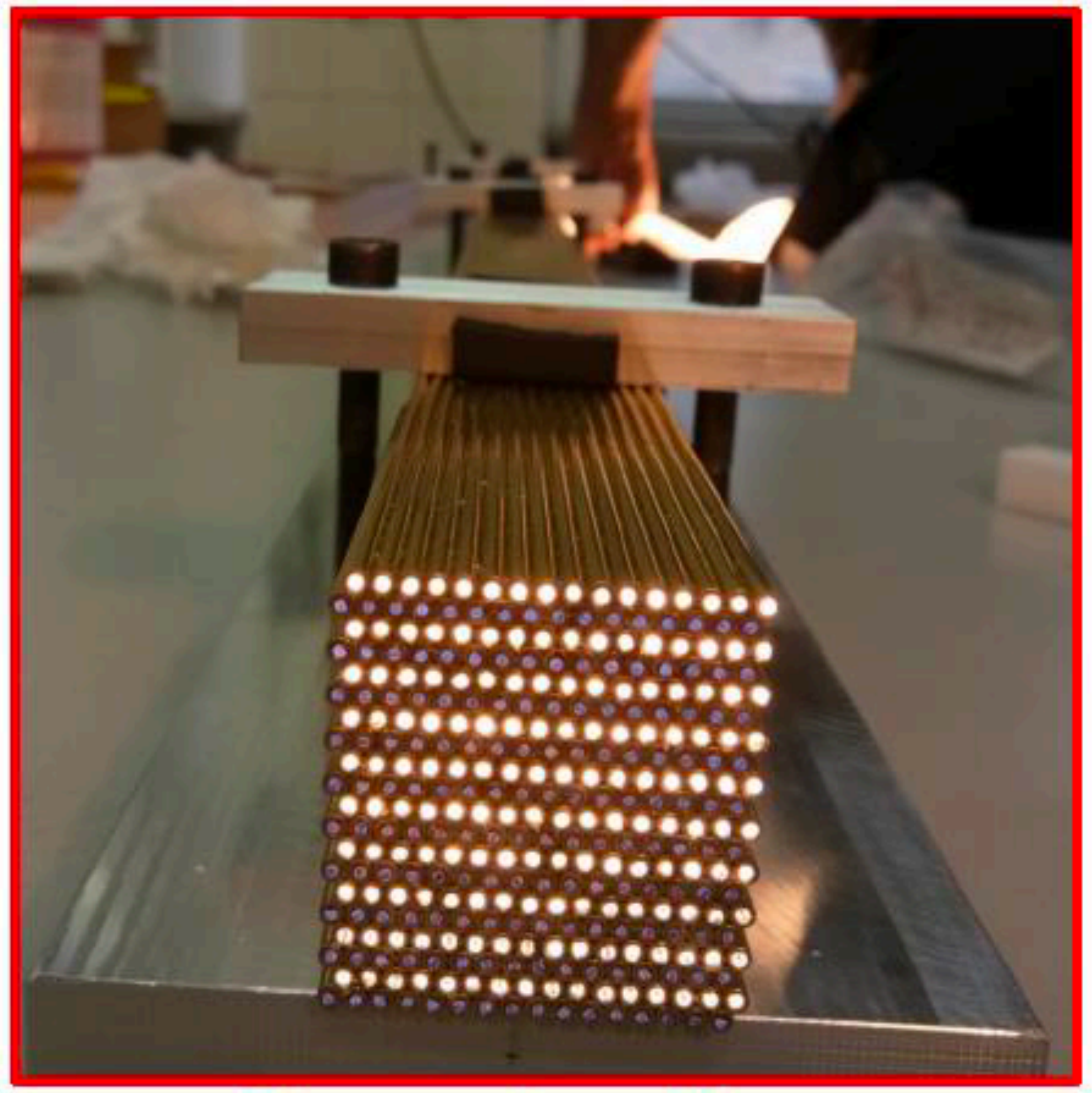
$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E\left[f_{em} + (h/e)_C(1 - f_{em})\right]$$

$$E = \frac{S - \chi C}{1 - \chi} \qquad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

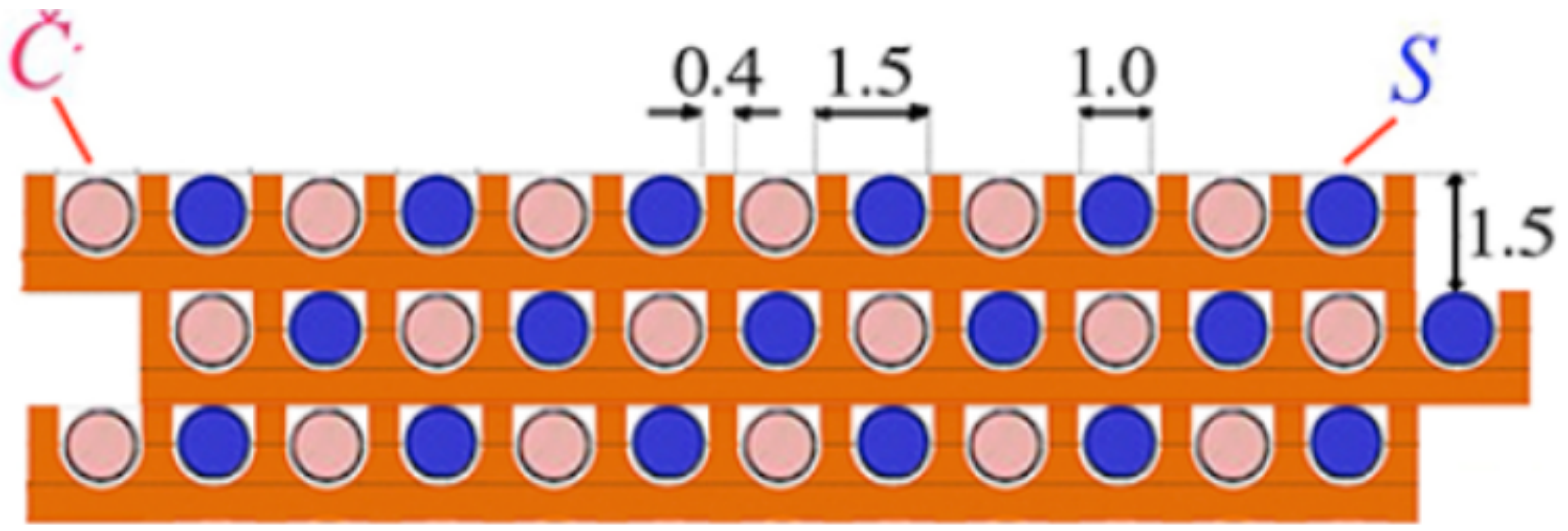
Newer DR calorimeter
(bucatini calorimeter)

Scintillation fibers



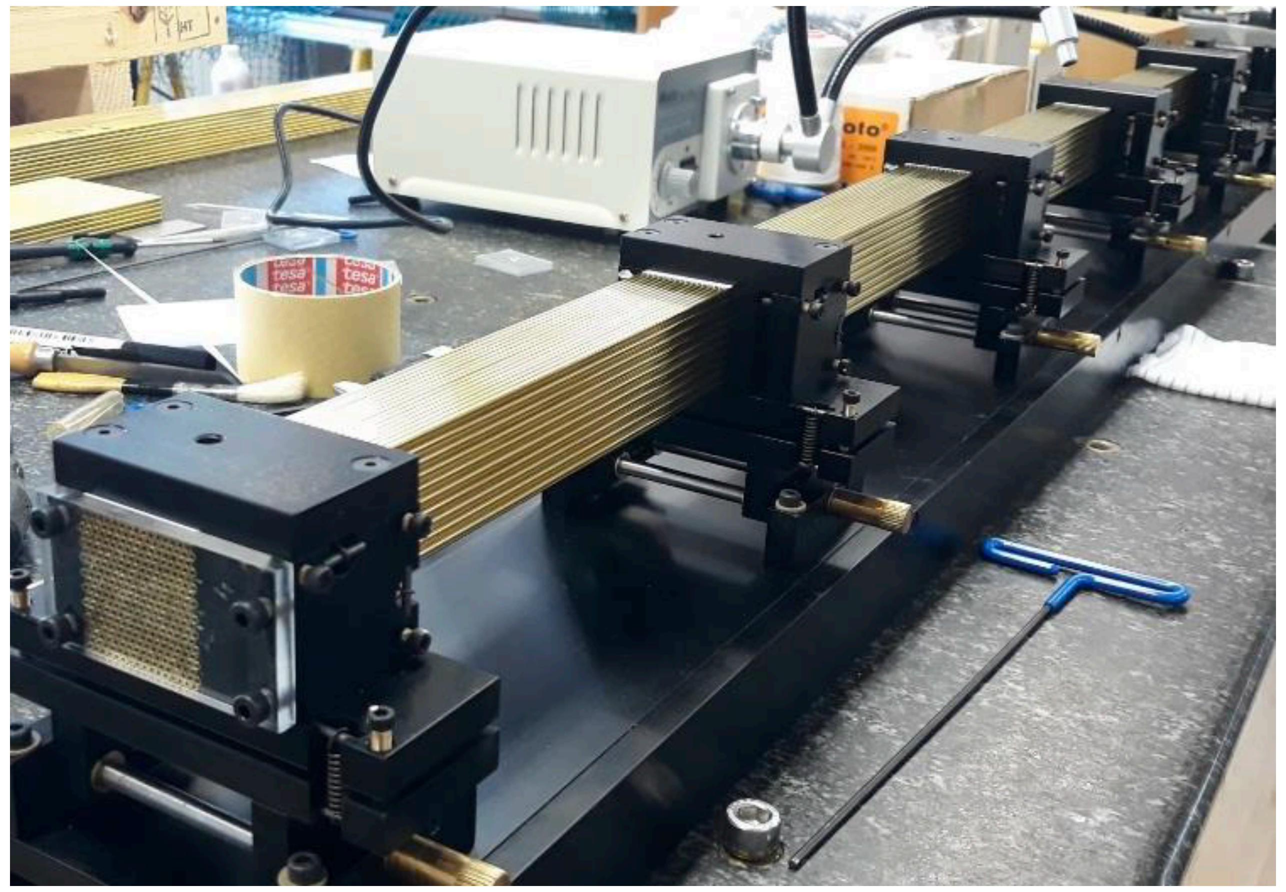
Cherenkov fibers

Dual Readout Calorimetry



Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with e-

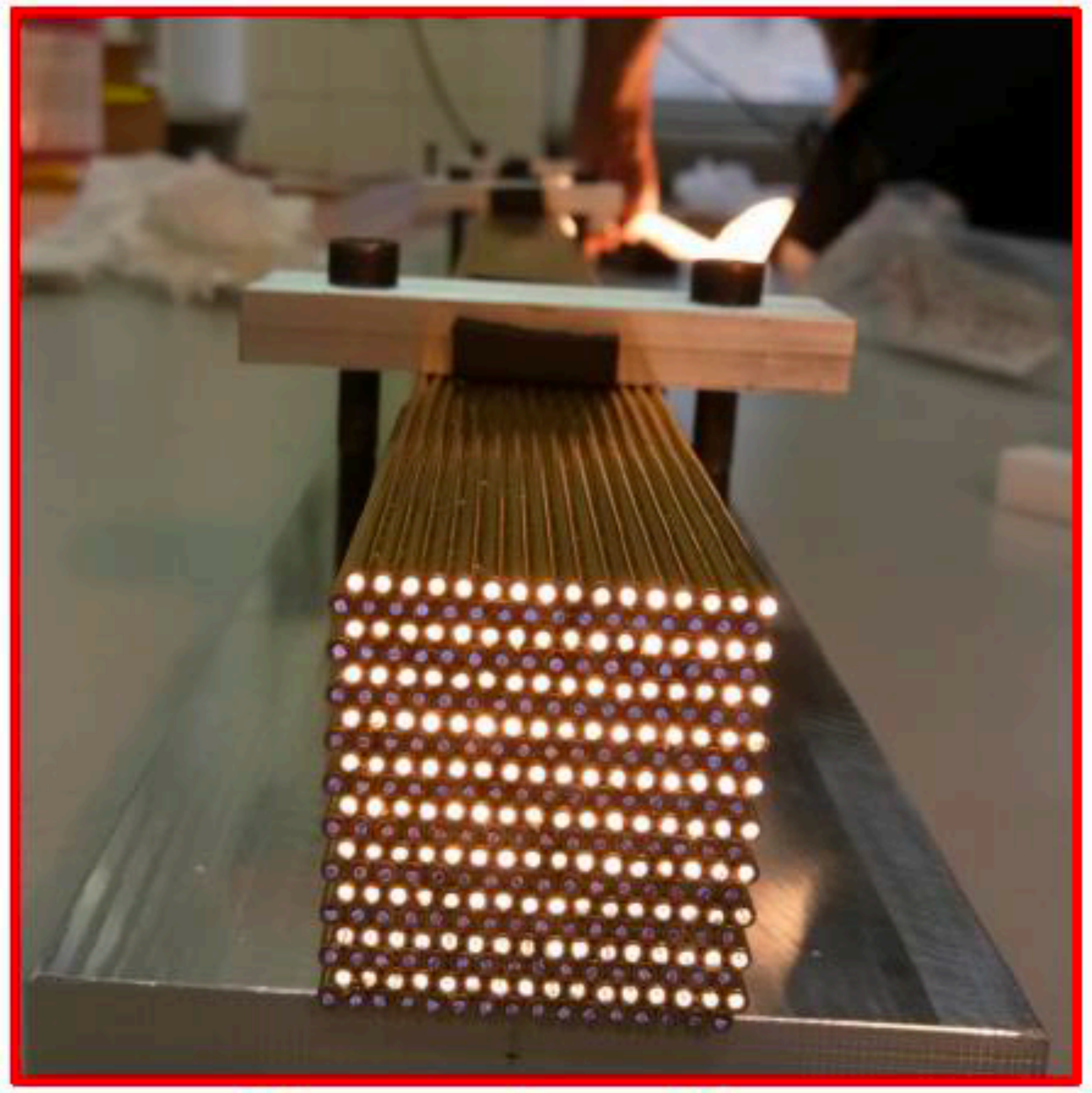
$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E\left[f_{em} + (h/e)_C(1 - f_{em})\right]$$

$$E = \frac{S - \chi C}{1 - \chi} \qquad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

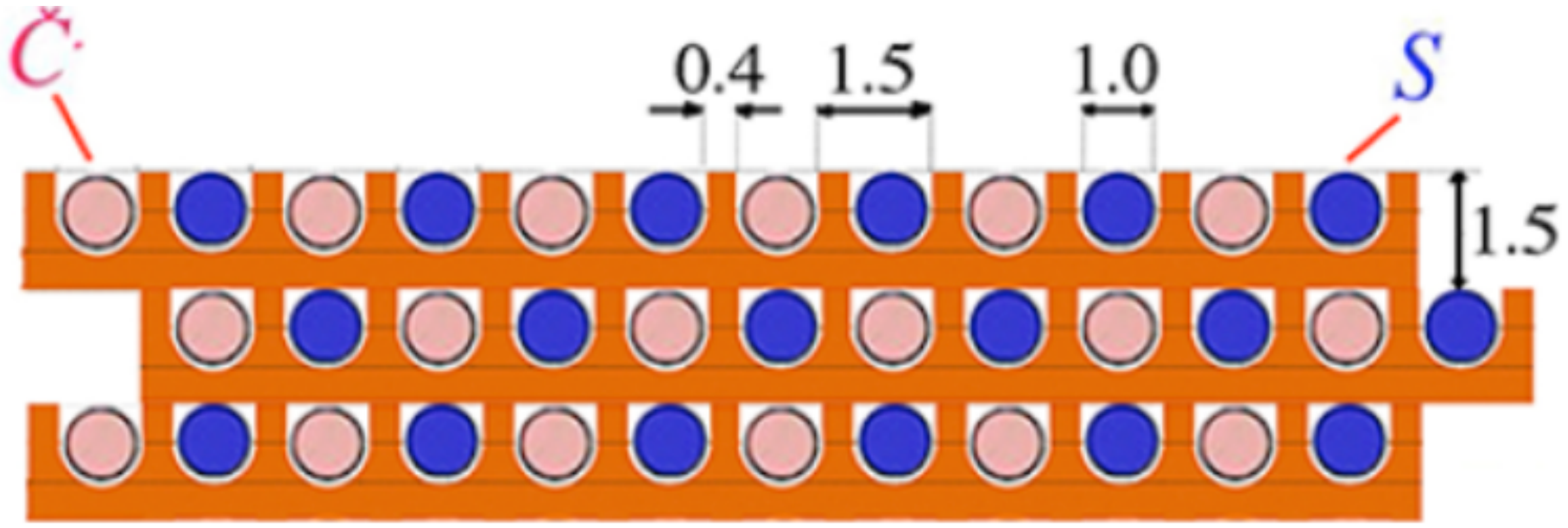
Newer DR calorimeter
(bucatini calorimeter)

Scintillation fibers



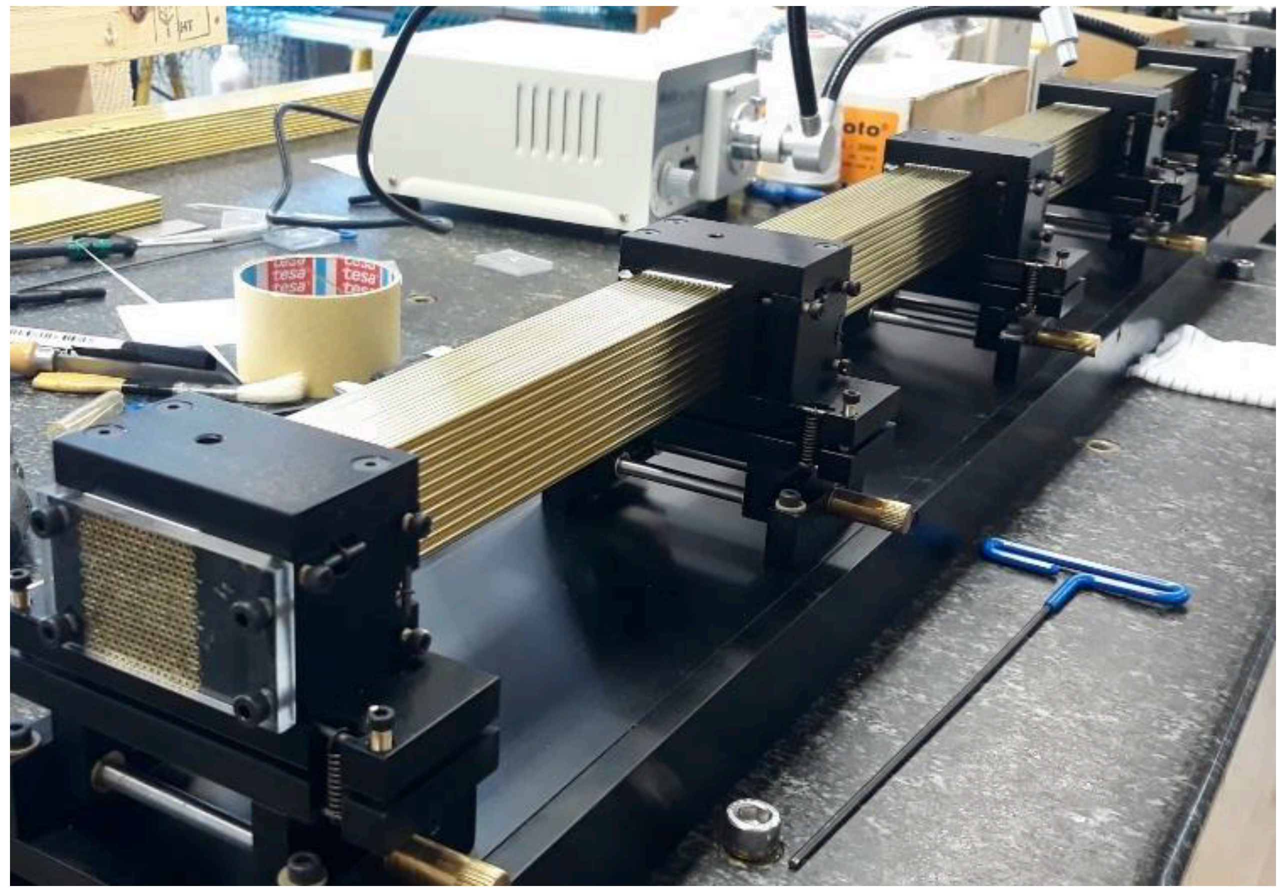
Cherenkov fibers

Dual Readout Calorimetry



Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



- ❖ Measure simultaneously:
  - ➢ Scintillation signal (S)
  - ➢ Cherenkov signal (Q)
- ❖ Calibrate both signals with e$^-$
- ❖ Unfold event by event f_{em} to obtain corrected energy

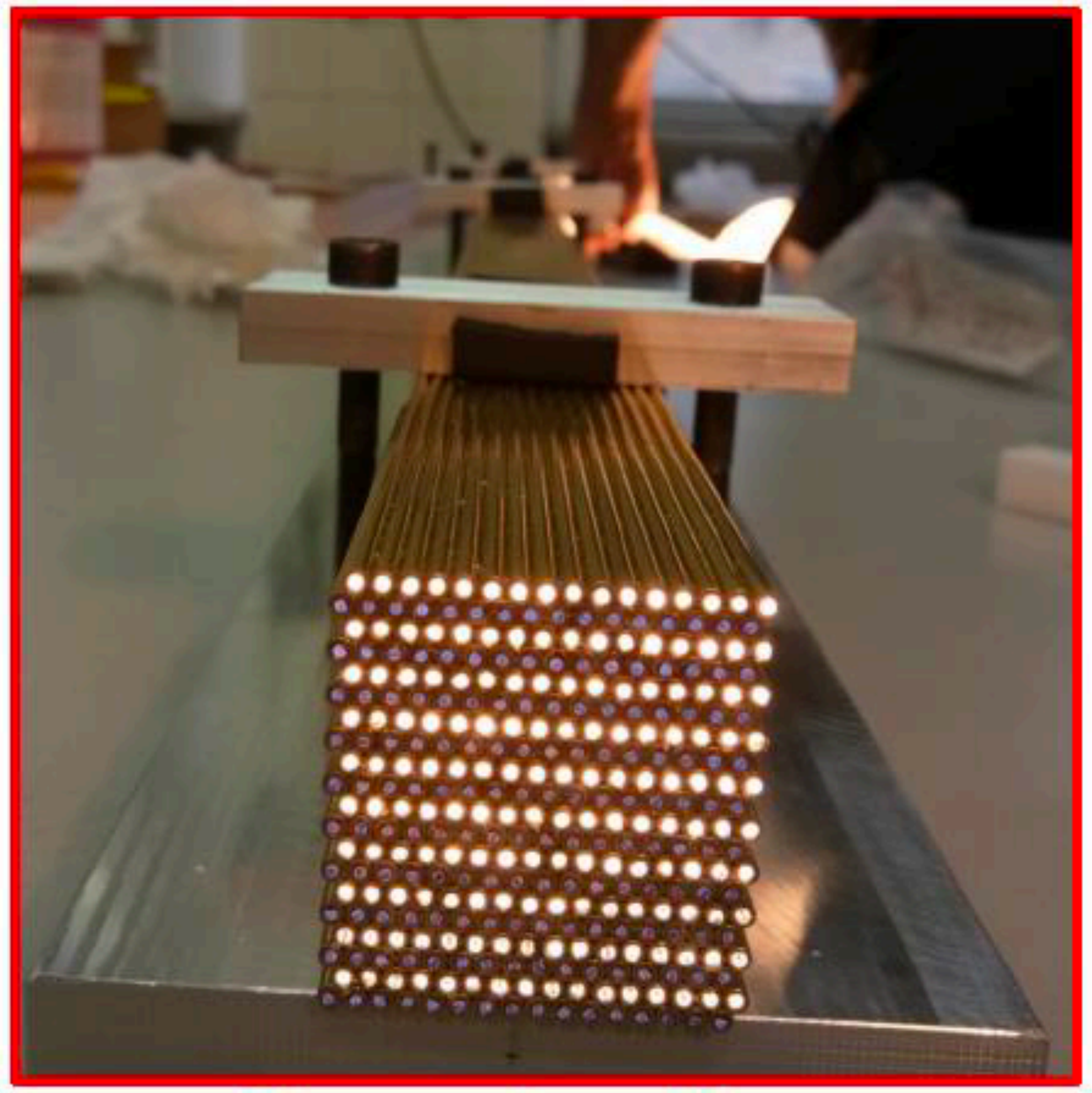
$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E\left[f_{em} + (h/e)_C(1 - f_{em})\right]$$

$$E = \frac{S - \chi C}{1 - \chi} \qquad \text{with:} \qquad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

Newer DR calorimeter
(bucatini calorimeter)

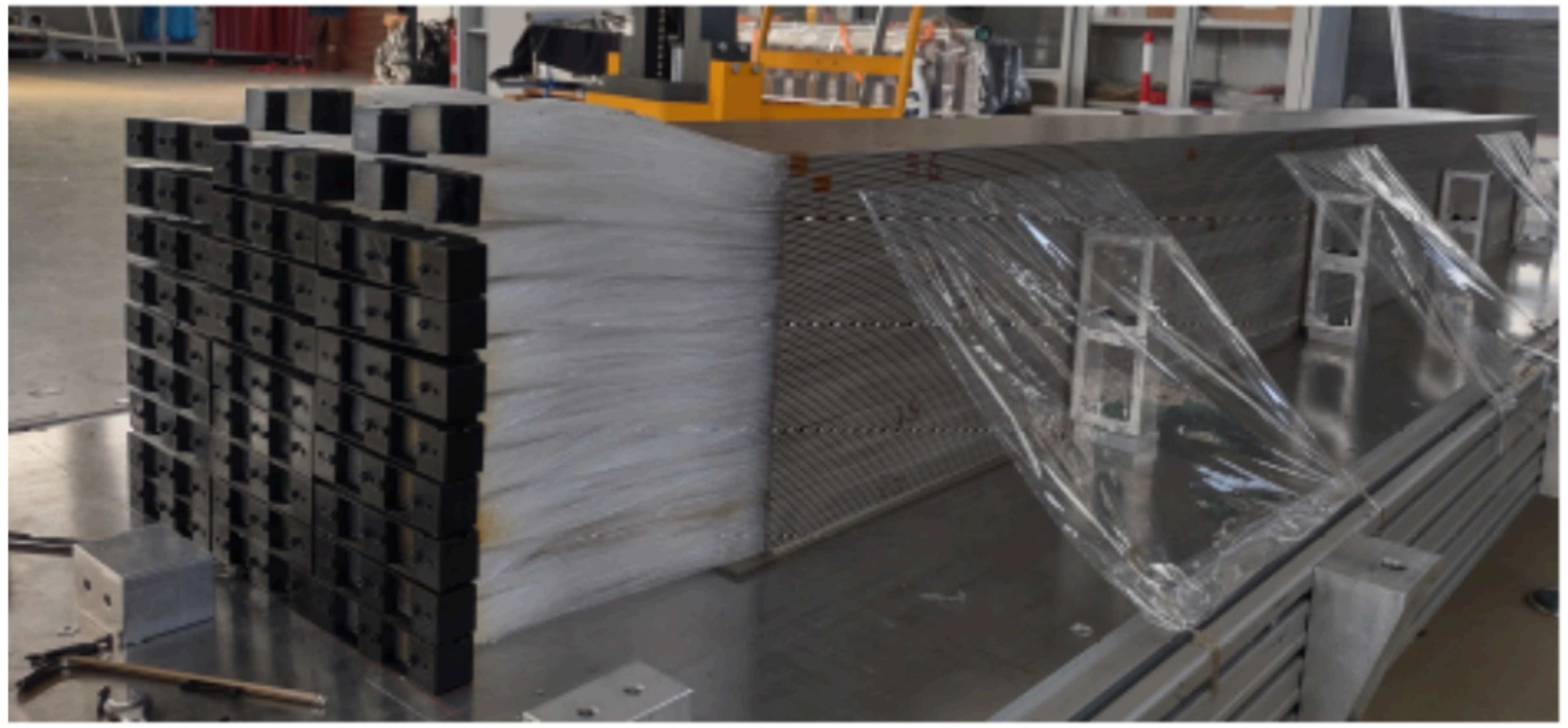
Scintillation fibers



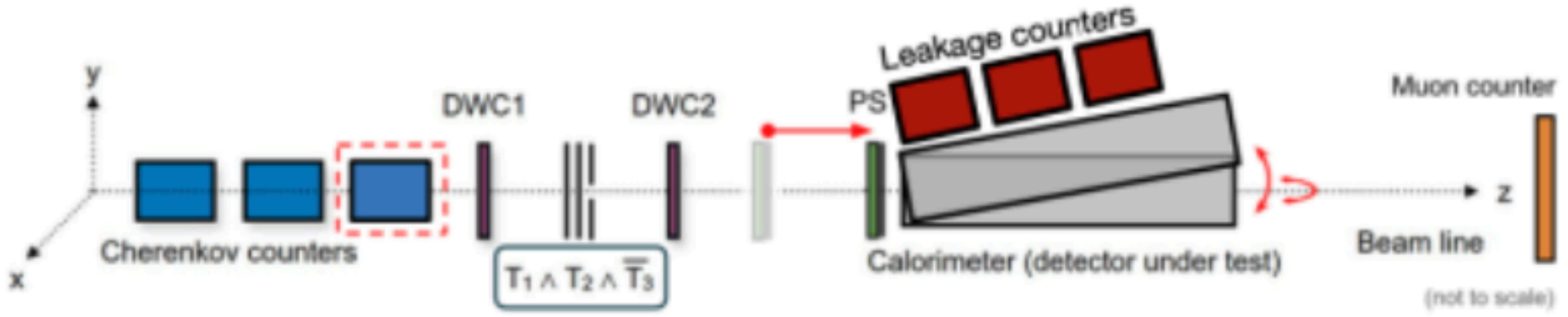
Cherenkov fibers

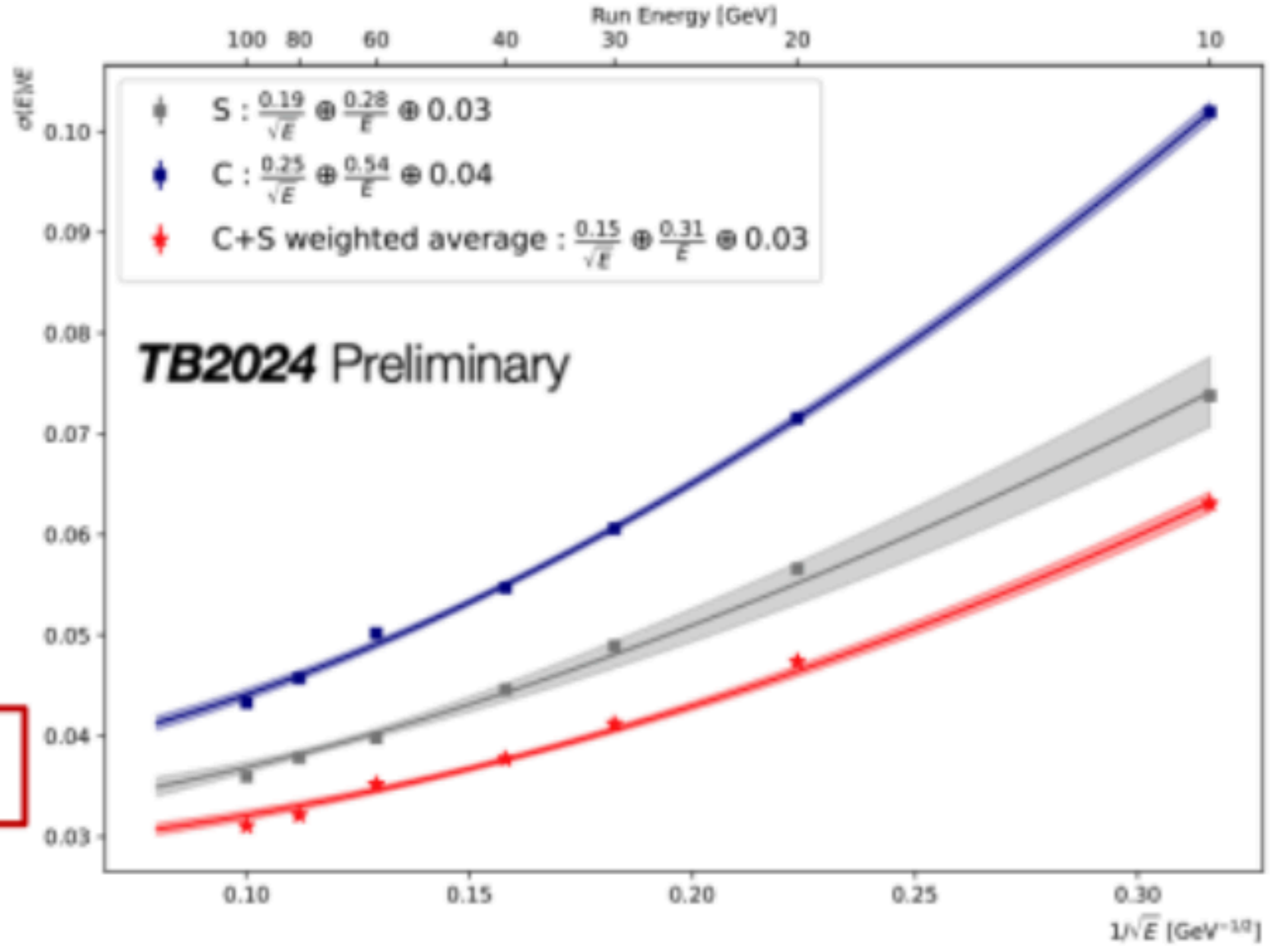
DR fibre calorimeter

2024 beam test



- Low-Granular modules qualification on beam:
  - 36 HiDRa minimodules, 3 columns × 12 rows: 39 × 39 × 250 cm^3
  - Nominal beam-axis angle of 2.5° wrt both X and Y axes
  - PMT-readout only

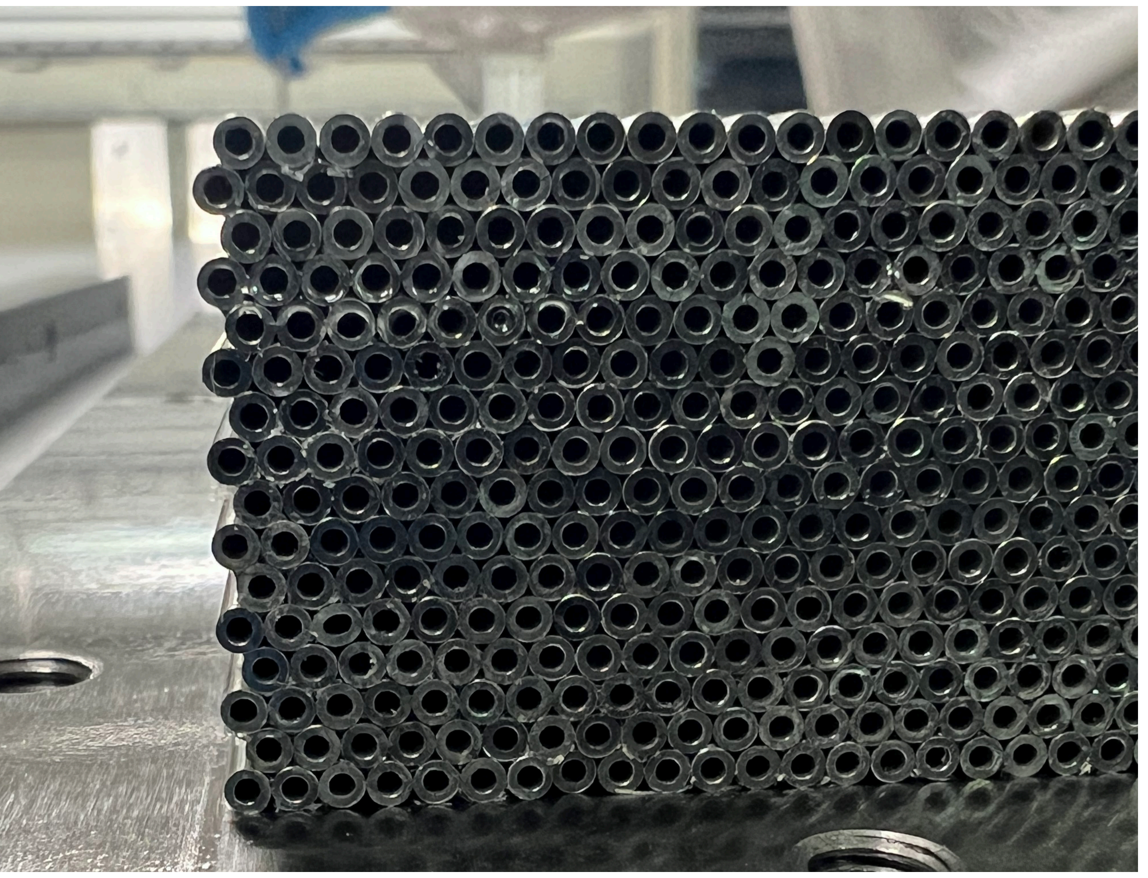


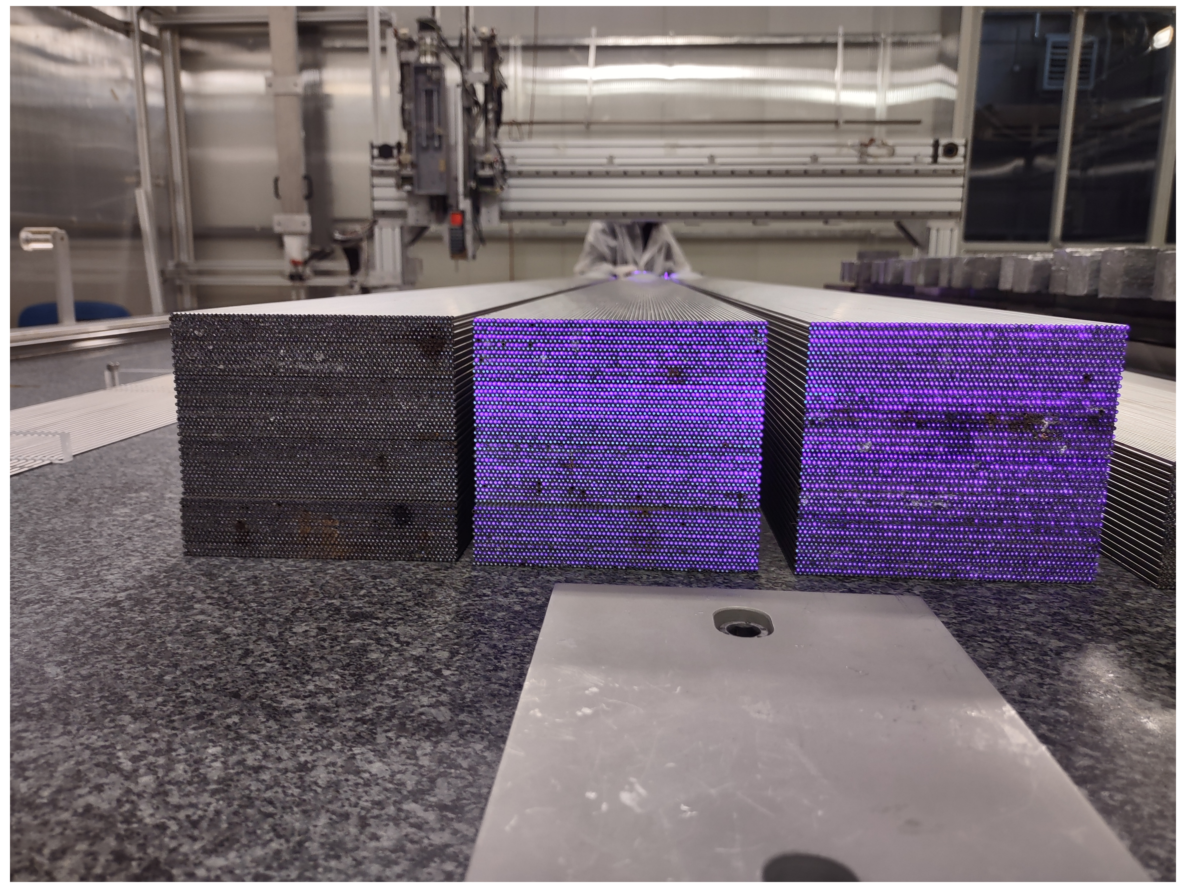
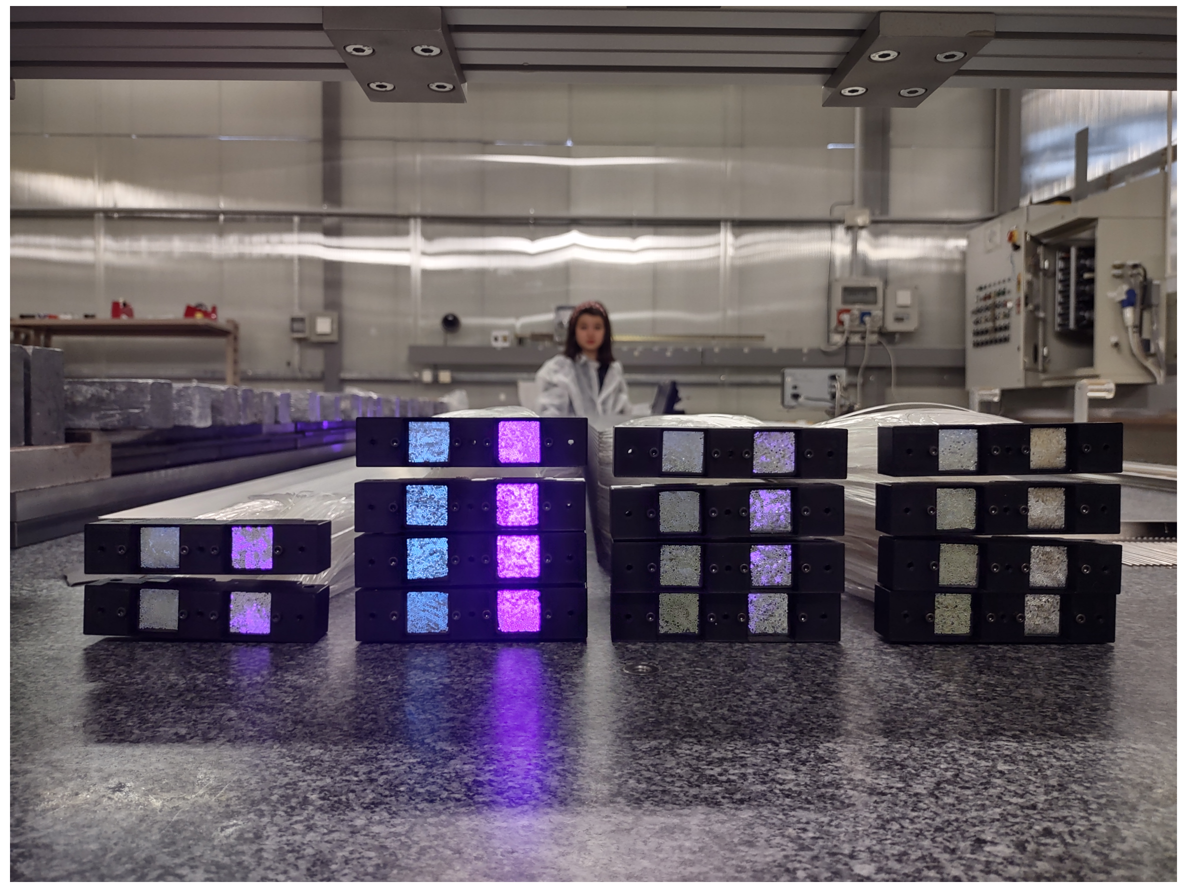


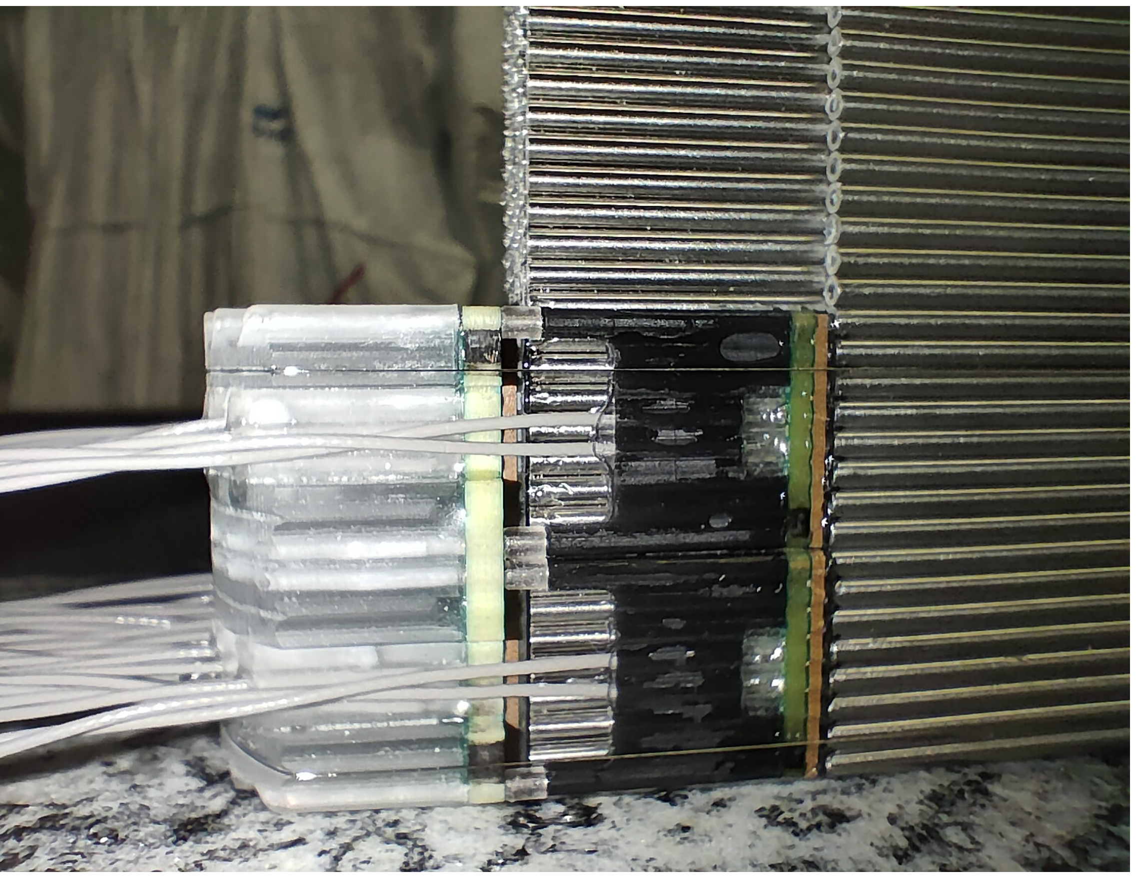
L. Nasella @ VCI2025

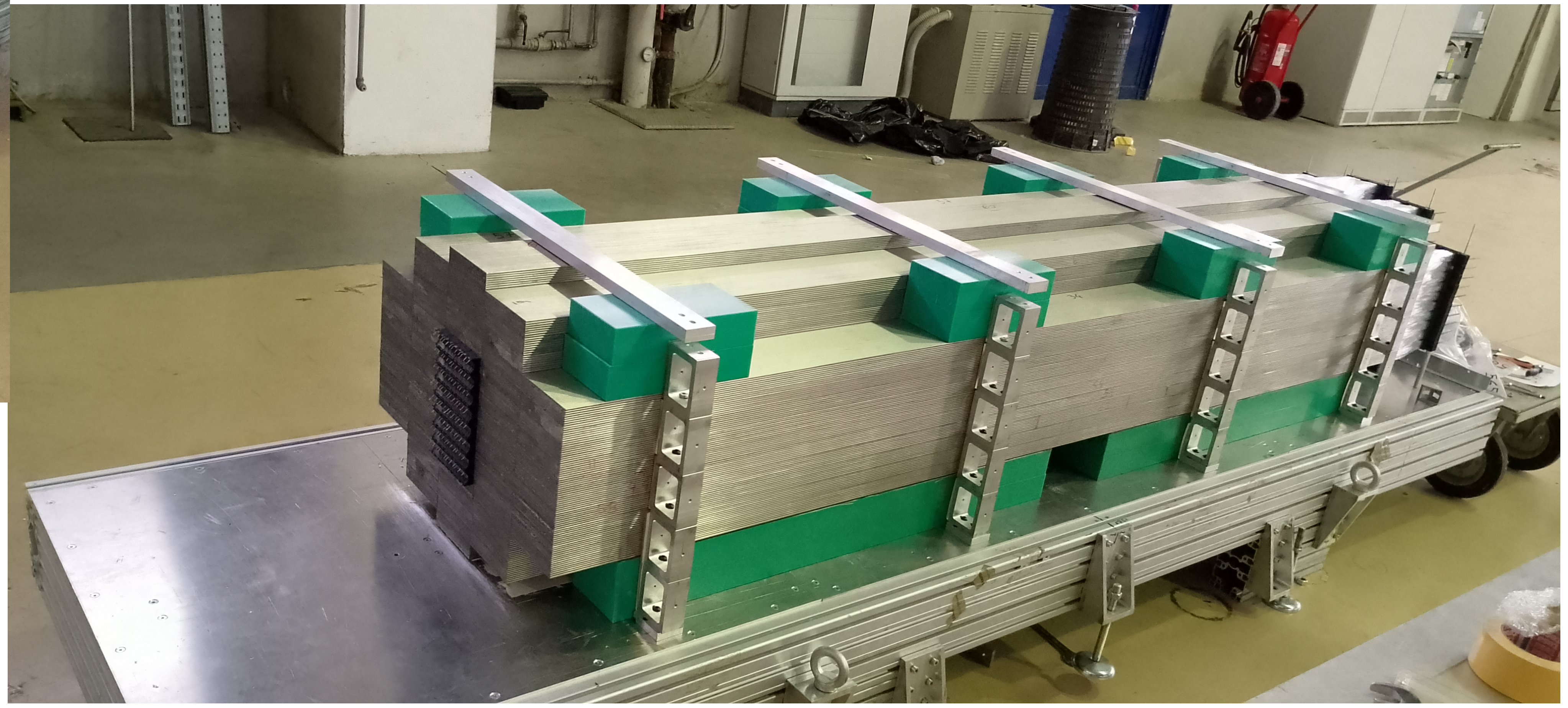
FUTURE CIRCULAR COLLIDER

DR fibre calorimeter: mechanical integration

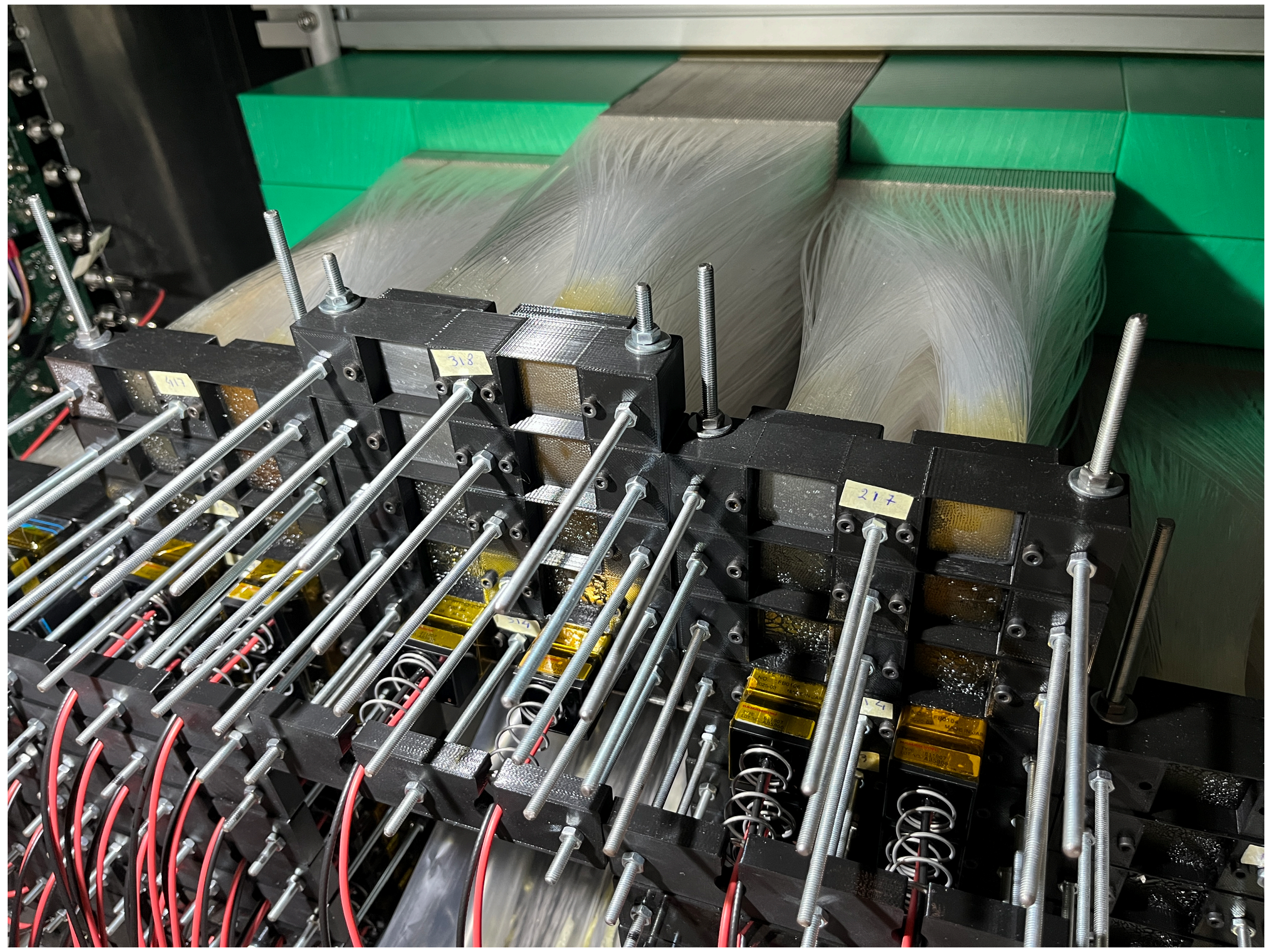


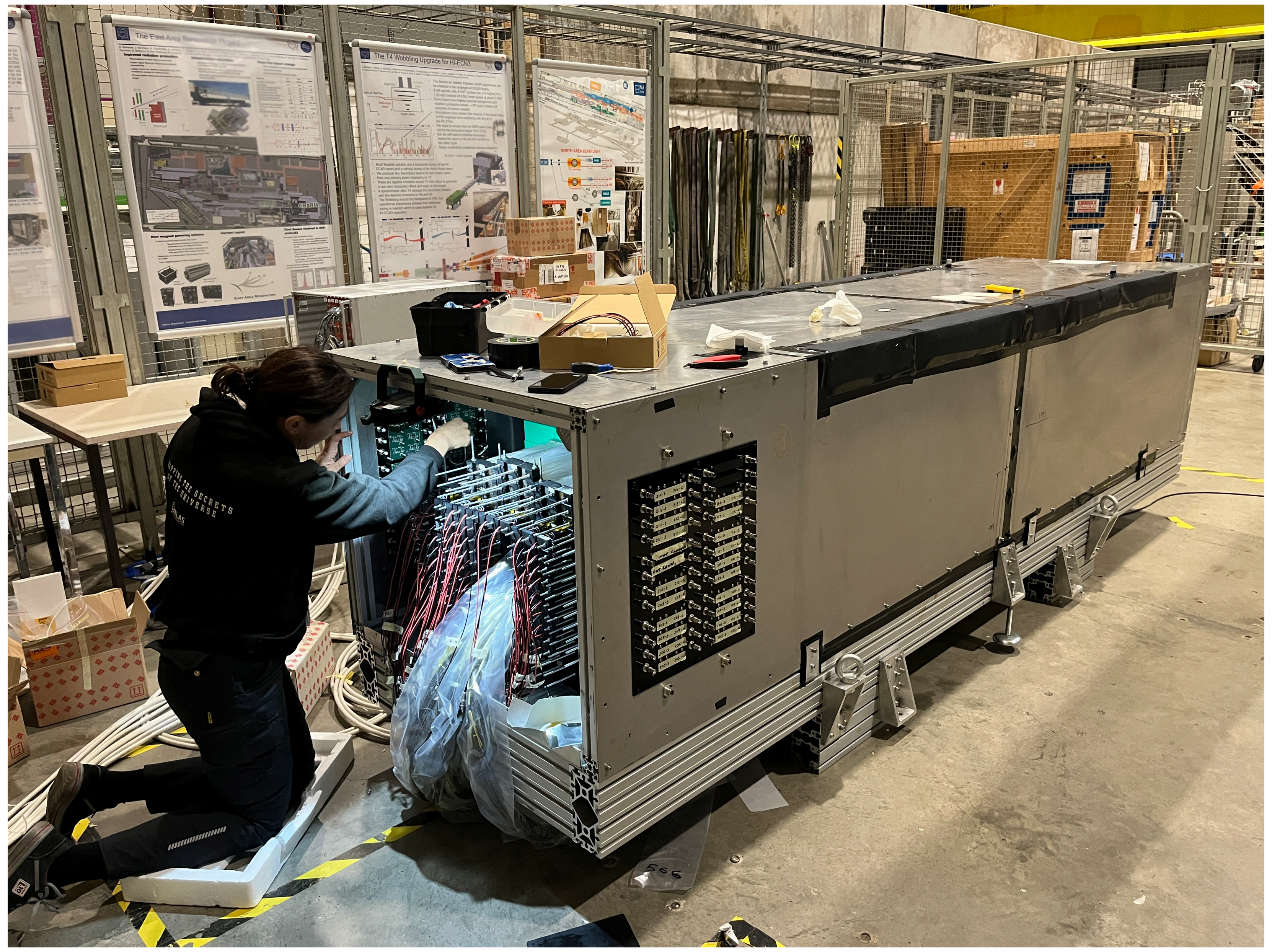



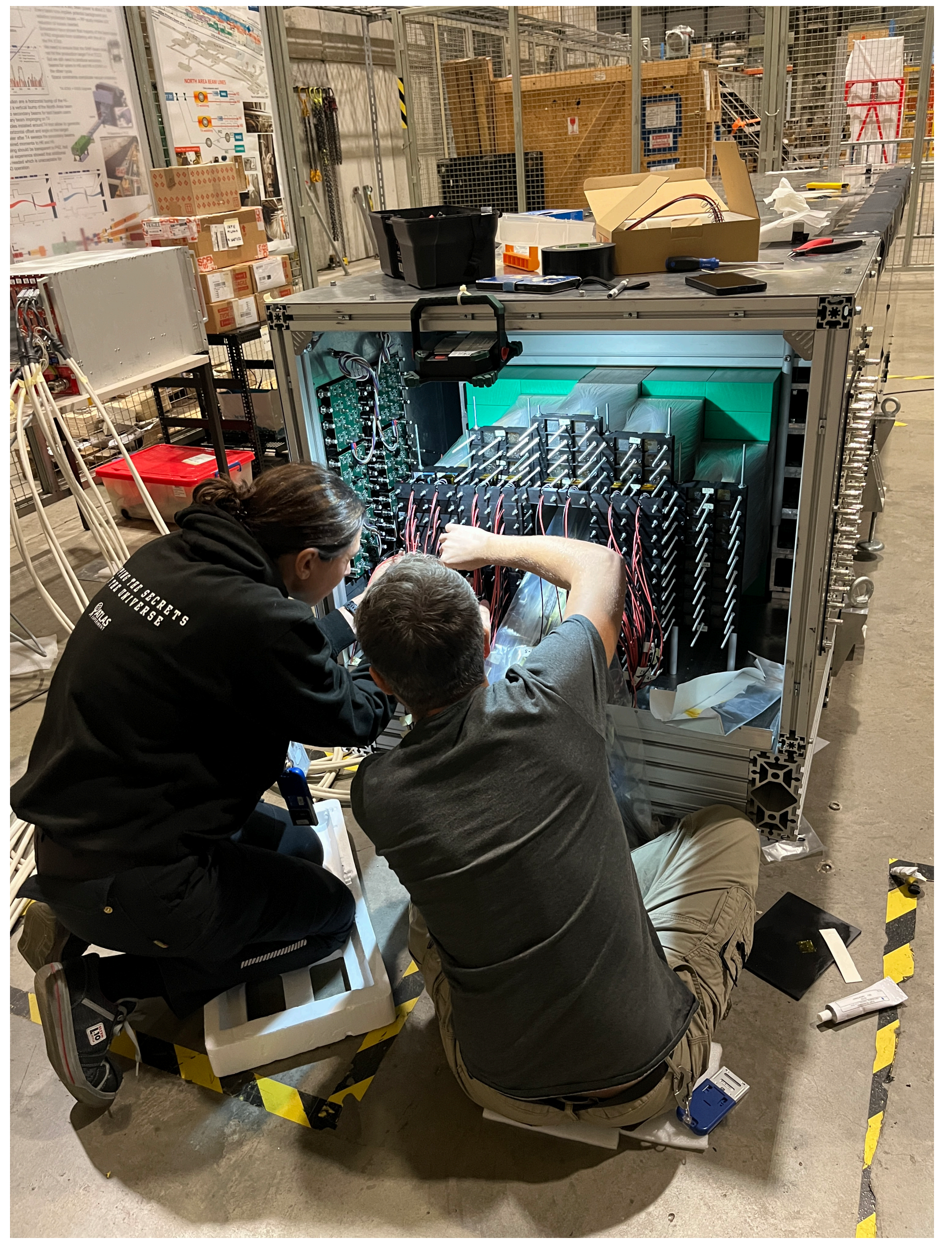




DR fibre calorimeter 2025 test beam





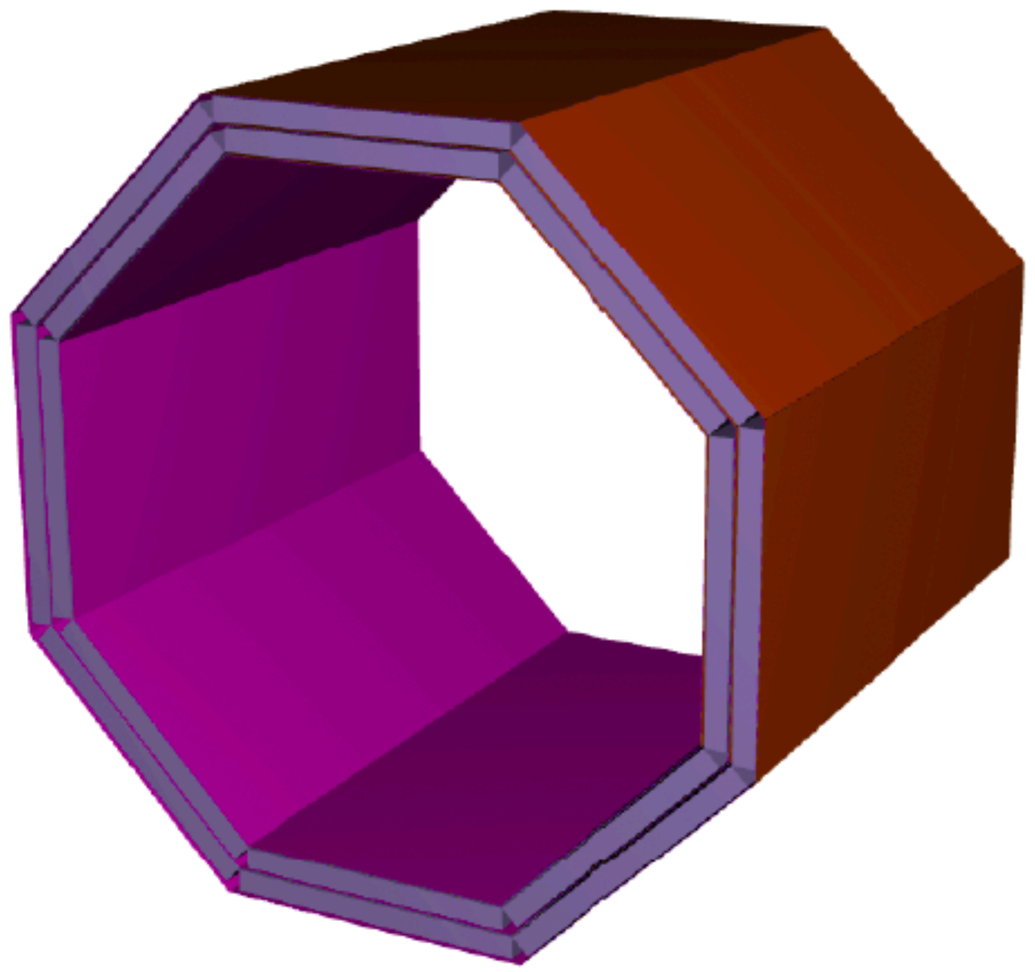


μ-RWELL muon detector

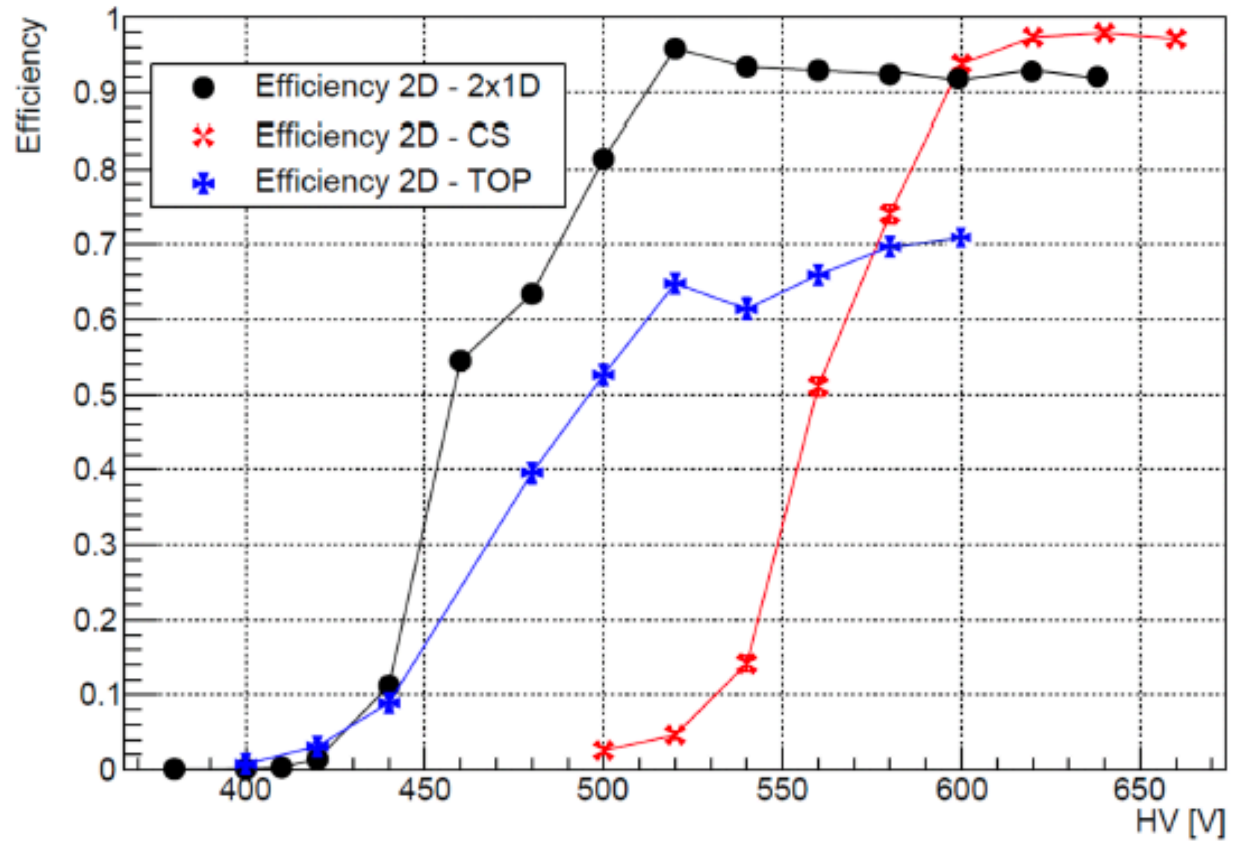
- $\sigma_p(\mu)$ driven by tracker, but...
  - → need high-purity and efficient identification
  - → need to catch hadronic shower tails not contained in HCAL
- Independent μ tracking could, however, be relevant for LLP searches!
  - Not part of IDEA: Proposal to instrument cavern walls

IDEA muon detector design

- Barrel and endcaps, ≥ 3 layers
- μ-RWELL tiles of $50 \times 50\,\text{cm}^2$, overlap to avoid dead areas

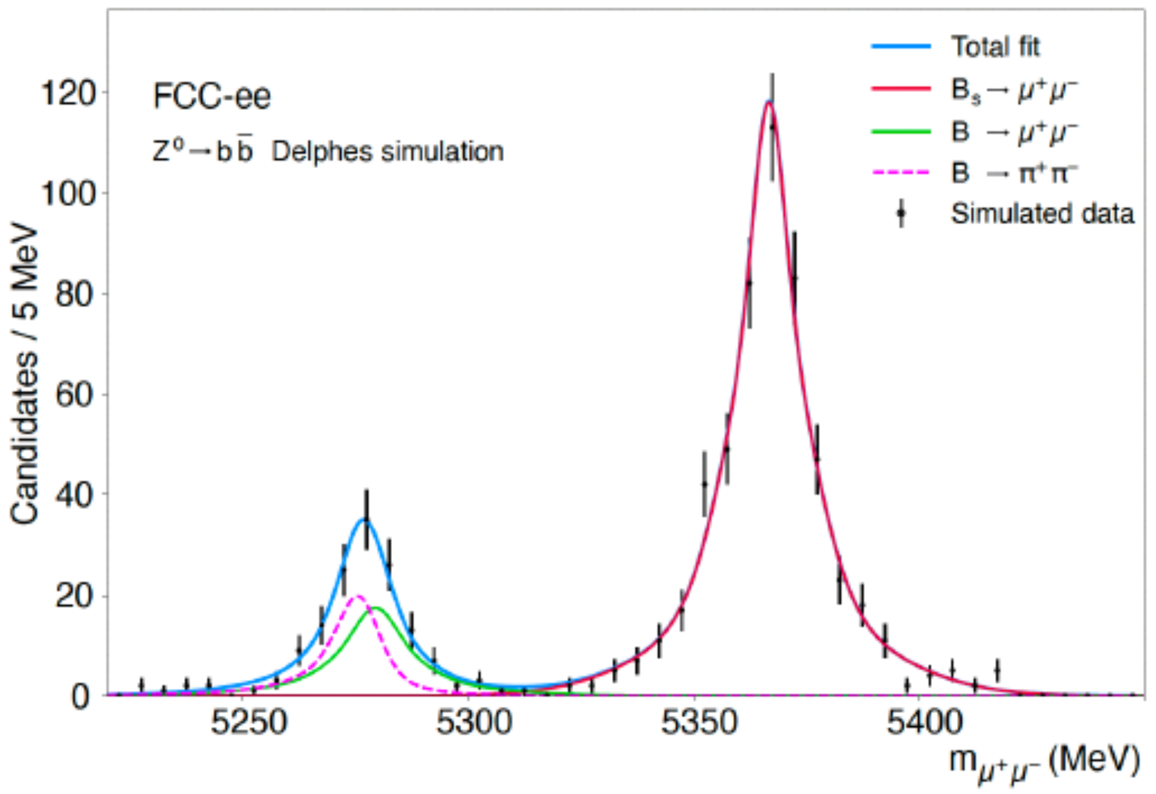


IDEA muon barrel in DD4hep full simulation [12]

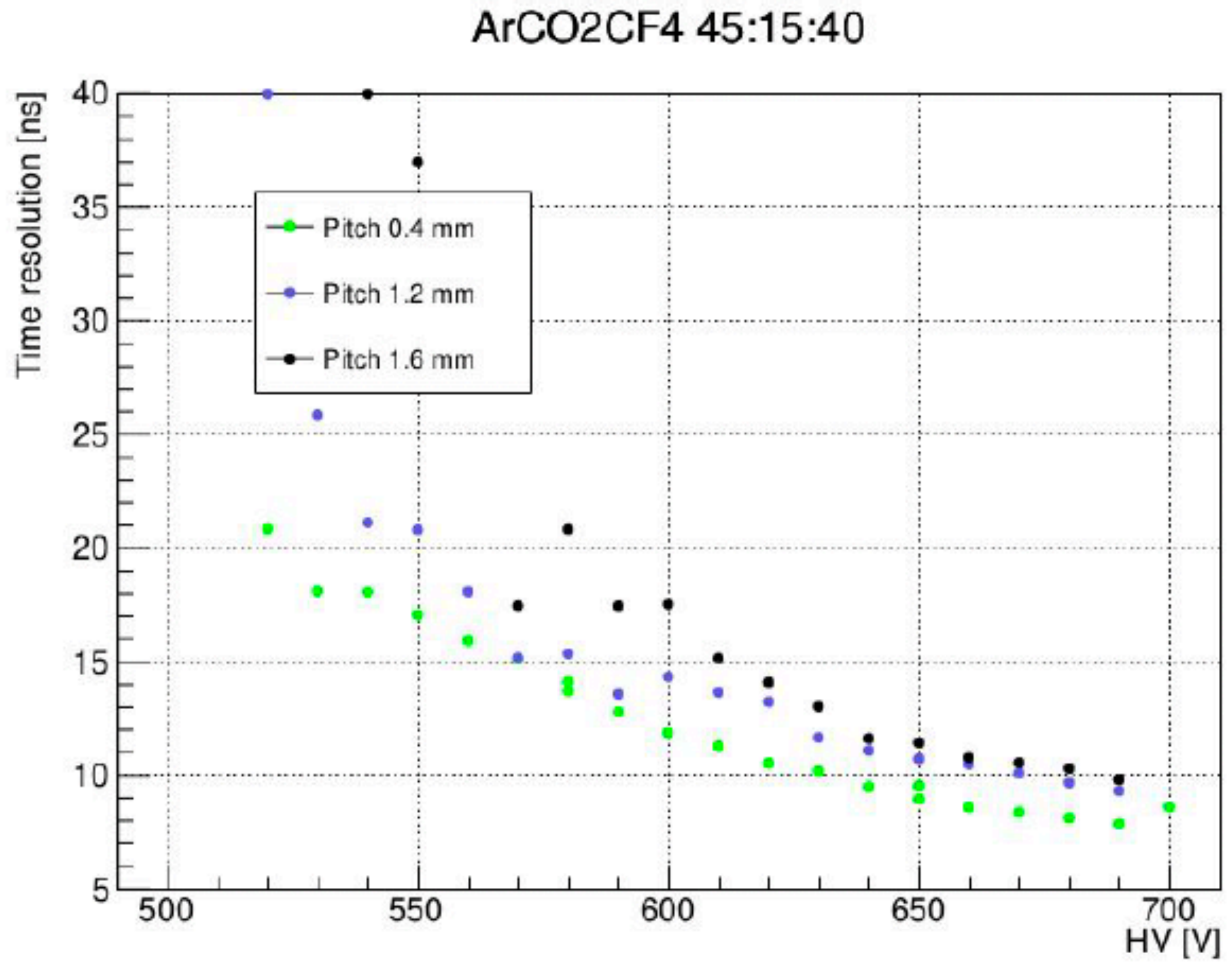


A. Ilg

2D layouts comparison. CS: capacitiy sharing anode [21], TOP: 1D R&O + strip-patterned top electrode. [12]



Impact of misidentified pions in $B/B_s \to \mu^+\mu^-$ [2]



Timing performance in TB with TIGER front-end. Courtesy of R. Farinelli

μ-RWELL technology

The μ-RWELL is composed of only two elements:

- μ-RWELL_PCB
- drift/cathode PCB defining the gas gap

μ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

μ-RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the μ-RWELL_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field

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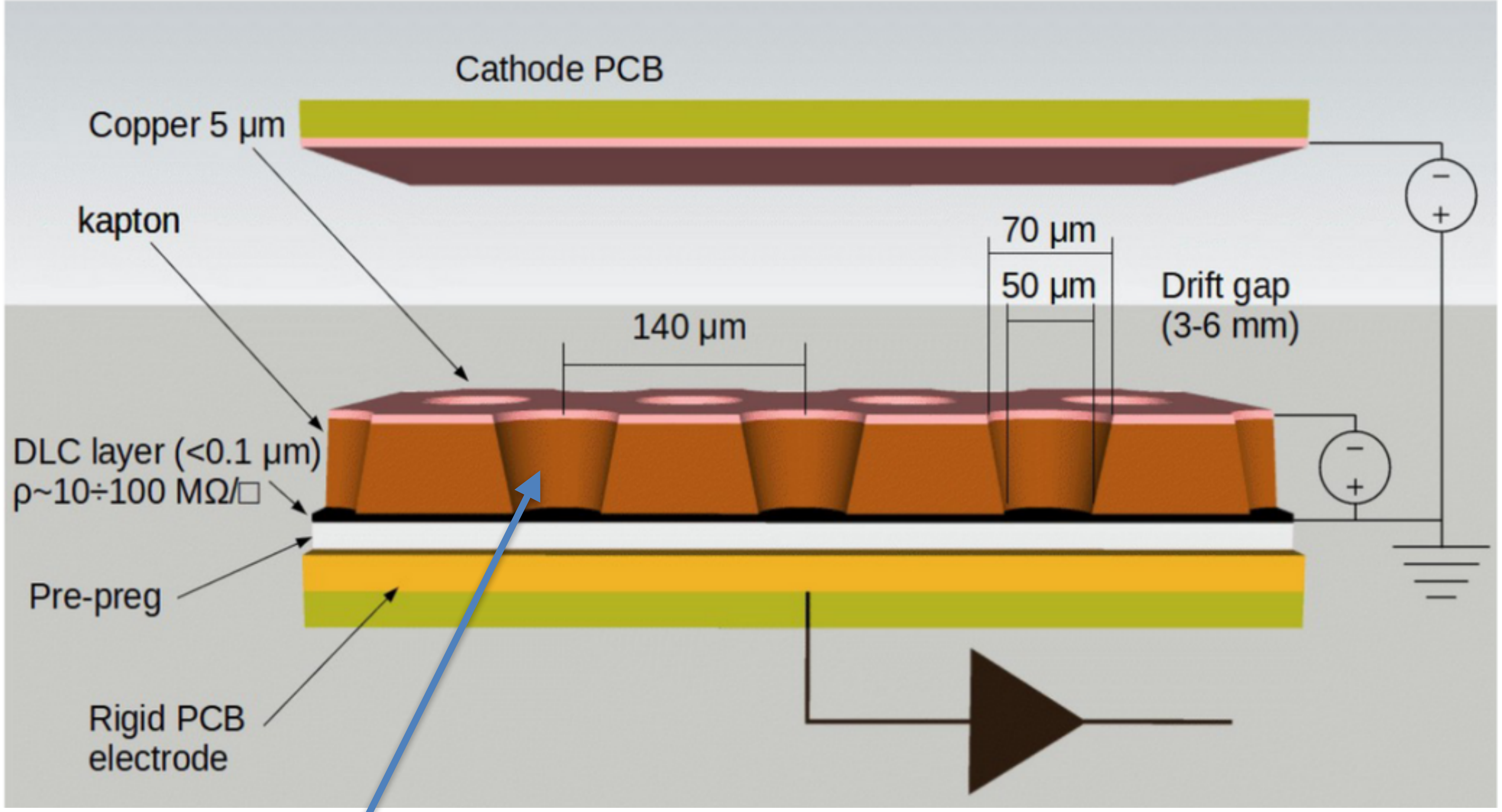
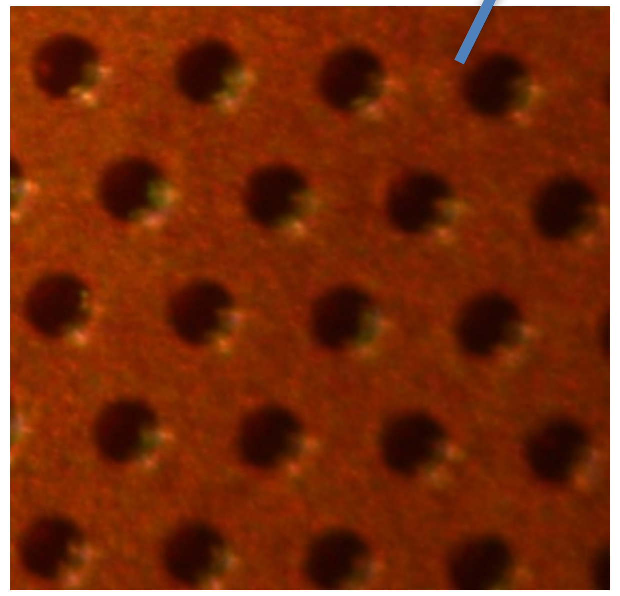
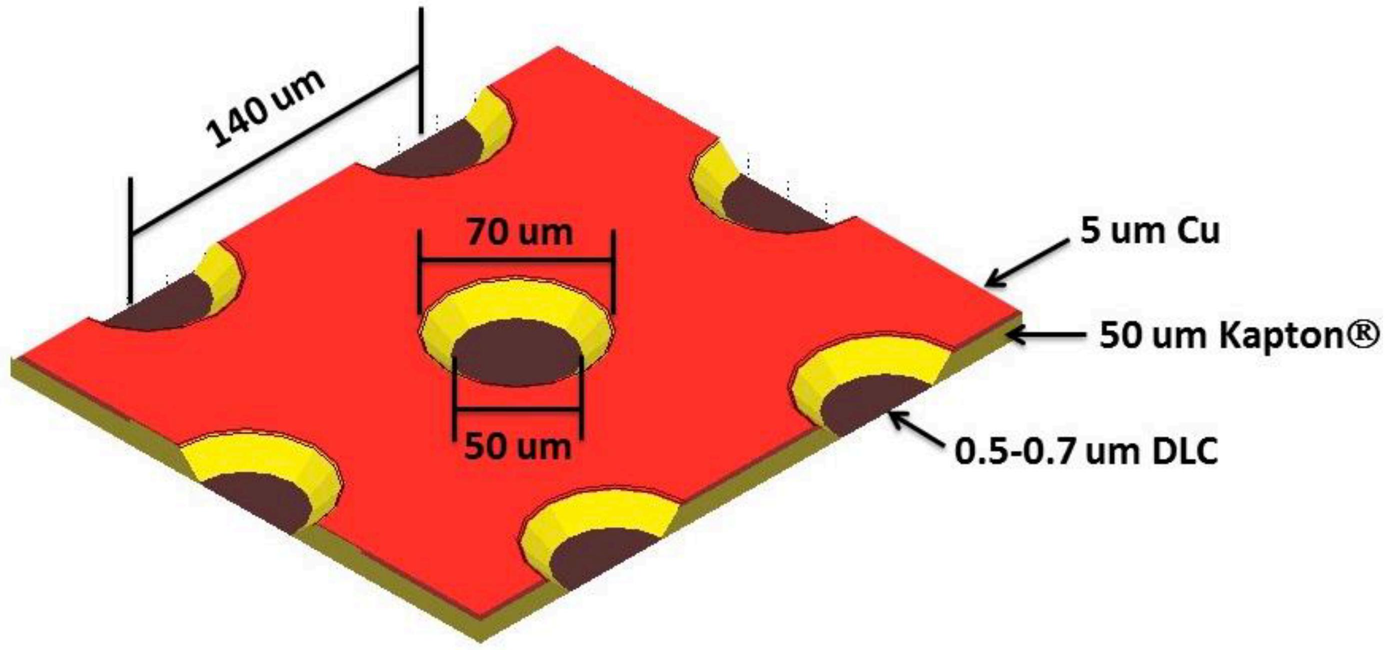
FERRARA
TORINO







(*) G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015_JINST_10_P02008)

HTS R&D for the FCC-ee project

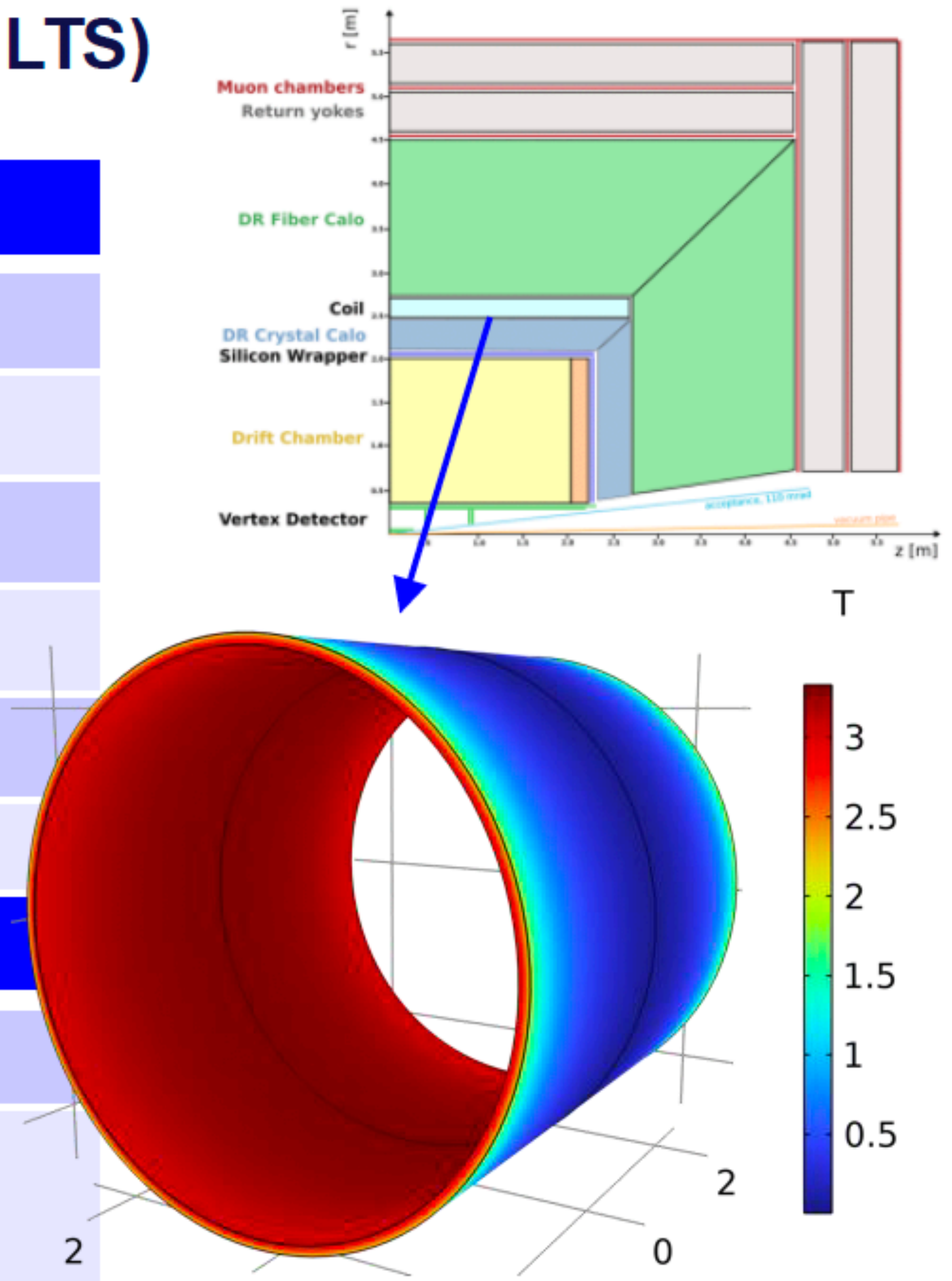
INFN LASA

3 T HTS solenoid for the IDEA detector project

Aluminium stabilized high current HTS cable (Al2.0wtNi)

- **$T_{op} = 20\ K$ for reduced power consumption**
- **Reduced Helium Inventory**
- **Increased margin (wrt. LTS)**

Design Parameters	
Bore Field	3 T
Current	8168 A
Peak Field	3.27 T
Coil Length	5.3 m
Coil Radius	2.5 m
Stored Energy	412 MJ
T Margin	**15 K**
Max Strain	0.18%
Hot Spot T	160 K (10 s T_{det})

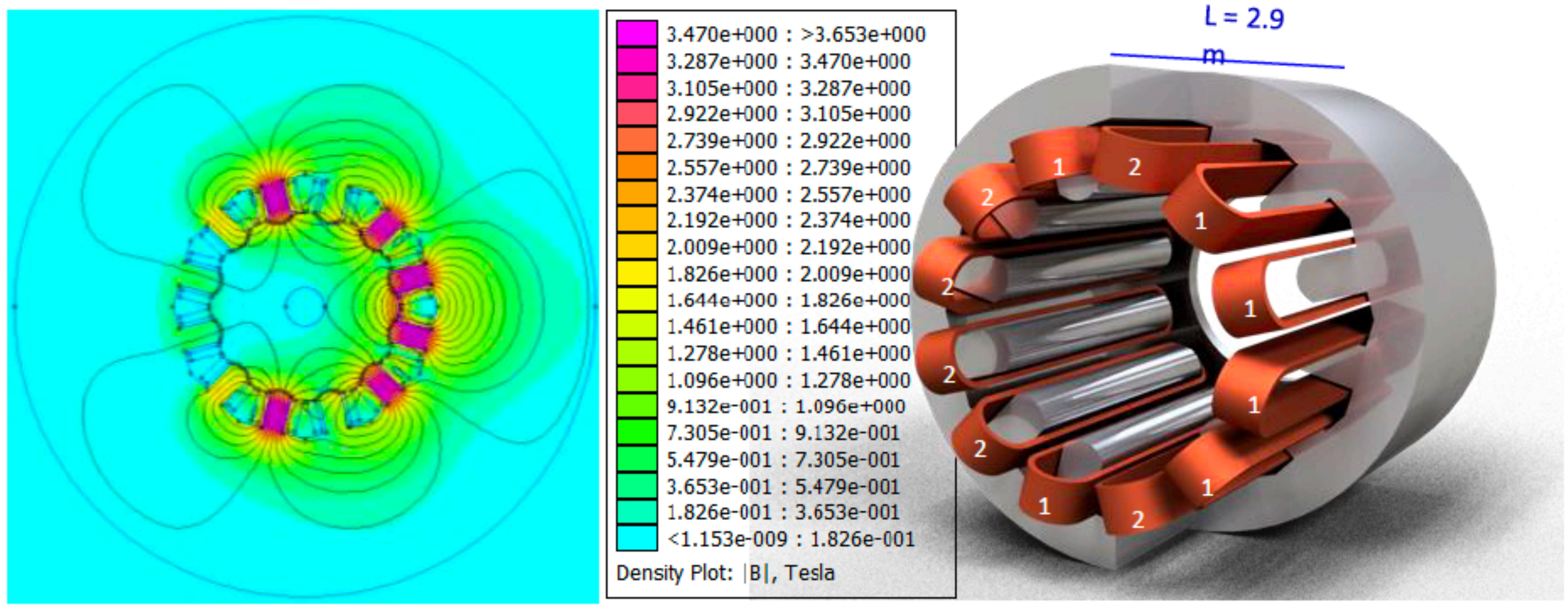


Combined function Quad/Sext for FCC-ee main ring

Superferric HTS Dodecapole magnet design

- **Increased dipole filling factor (-10% power synch. rad)**
- **Inheritance of HO magnets development (HL-LHC)**
- **Flat racetrack coils with independent power supplies**

T_{op}	Max Current [A]	G [T/m]	S [T/m^2]	B dipole [T]
20 K	447.15	11.863	880	-0.0022
30 K	341.27	11.8596	880	0.0113



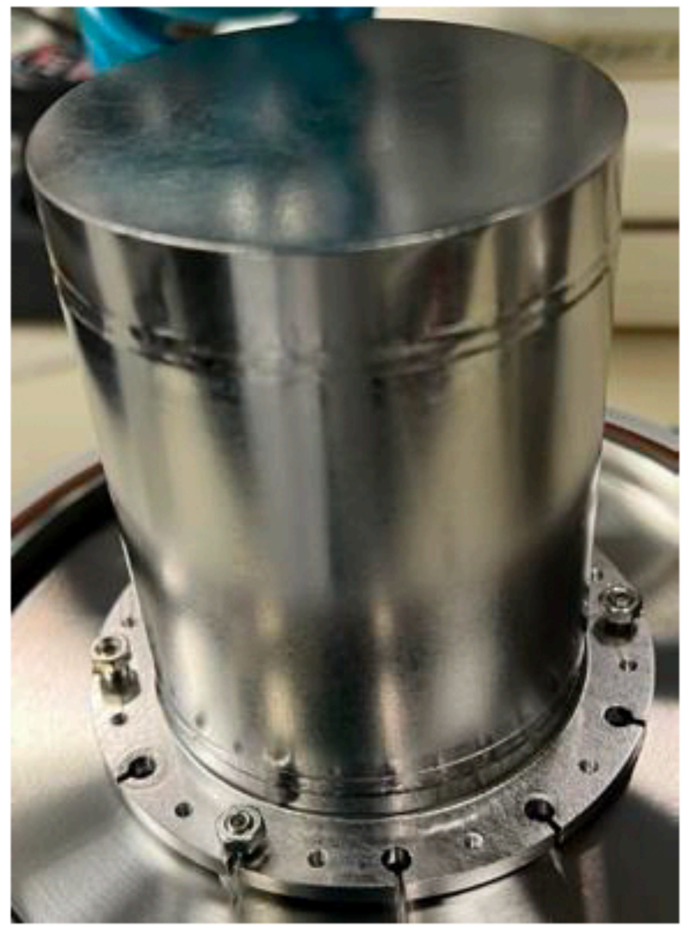
RD_FCC @ LNL – Activity Jan-Jun 2025

The LNL activity in RD_FCC is in synergy with the ESPP SRF experiment (SRF R&D for FCC-ee).
The experiment is focused on the development of Nb3Sn coatings (WP1) and copper substrate surface treatment via Plasma Electrolytic Polishing – PEP (WP2) for the SRF elliptical cavities of FCC-ee.

WP1 - Coating Nb_3Sn

- PVD system installation for 1.3 GHz cavity including rectangular magnetron
- New QPR coated with Nb3Sn and shipped to HZB for RF testing

Rectangular Magnetrons for Nb_3Sn 1.3 GHz coating system



QPR coated with Nb_3Sn ready for RF testing at HZB

WP2 – PEP

- Started collaboration with CERN and KEK for PEP validation on 1.3GHz cavity
- First 1.3 GHz cavity prepared with PEP and shipped to CERN. Waiting for Nb coating and RF testing (by September 2025).

1.3 GHz cavity treated by Plasma Electrolytic Polishing at LNL

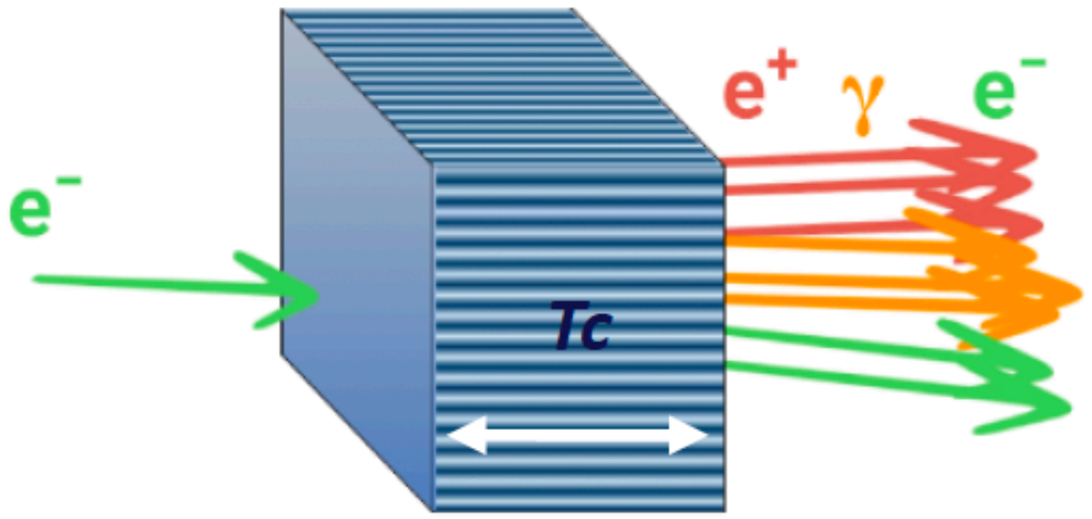
Italian Accelerator activities

Crystal-based positron source for FCC-ee Ongoing Activity 2025

Collaboration with the **FCC-ee Injector Studies Group** (I. Chaikovska, IJCLab)

FCC-ee injector full chain simulation: e+ yield before the dumping ring

F. Alharty et al, NIM A (2025)

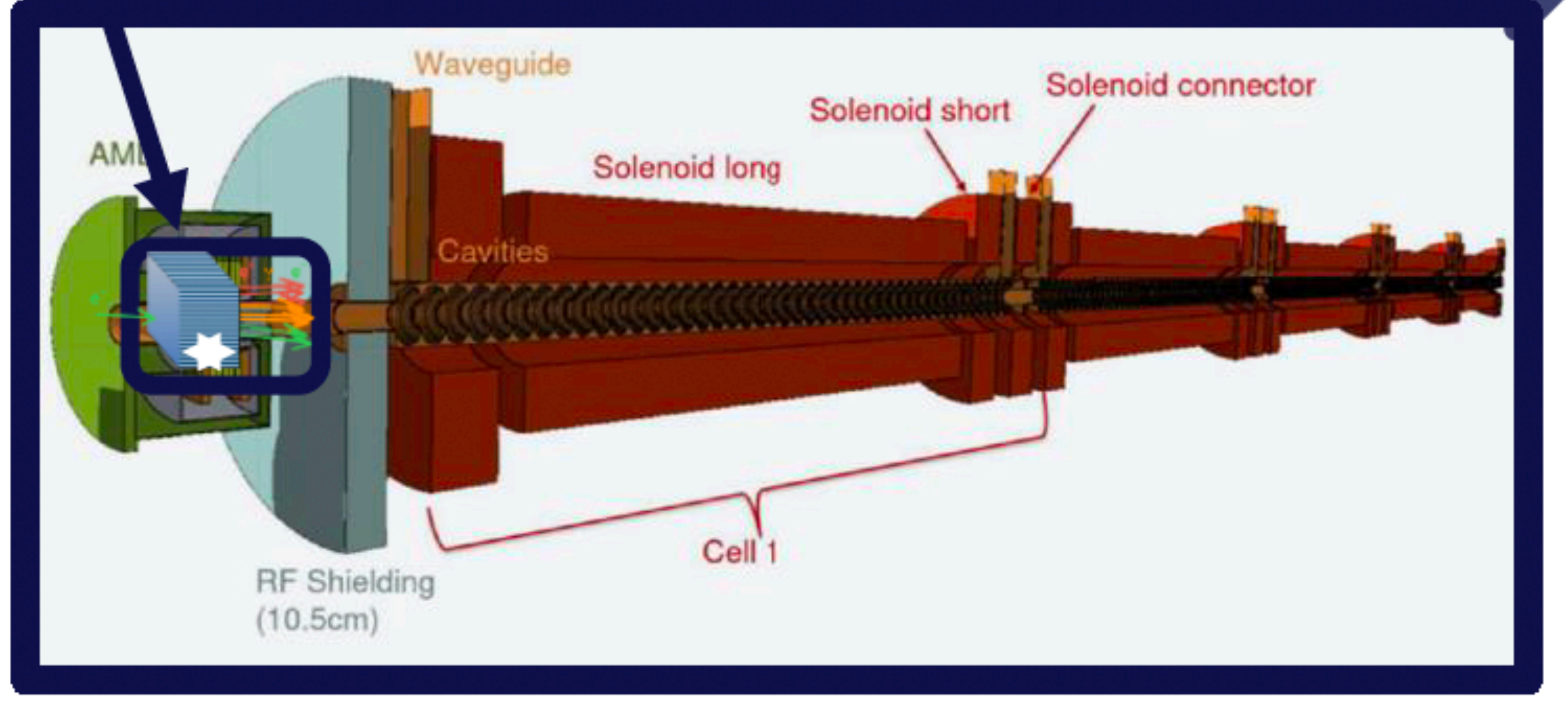


Collaboration with the **FCC-ee Injector Studies Group** (I. Chaikovska, IJCLab)
MoU signed between in INFN Ferrara and IJLab in Sept. 2022

The **whole crystal-based positron source** setup was simulated through Geant4 toolkit taking advantage of **GeantG4ChannelingFastSimModel**

A. Sytov, L. Bandiera et al. JKPS 83 (2023)

GEANT
European Commission
Trillion



After the positron source, the pair is captured in the injector system.

The simulation stages are simulated with the framwerok ***RF-Tracking***

- Adiabatic Matching Device (AMD)
- RF cavity
- Positron Linac

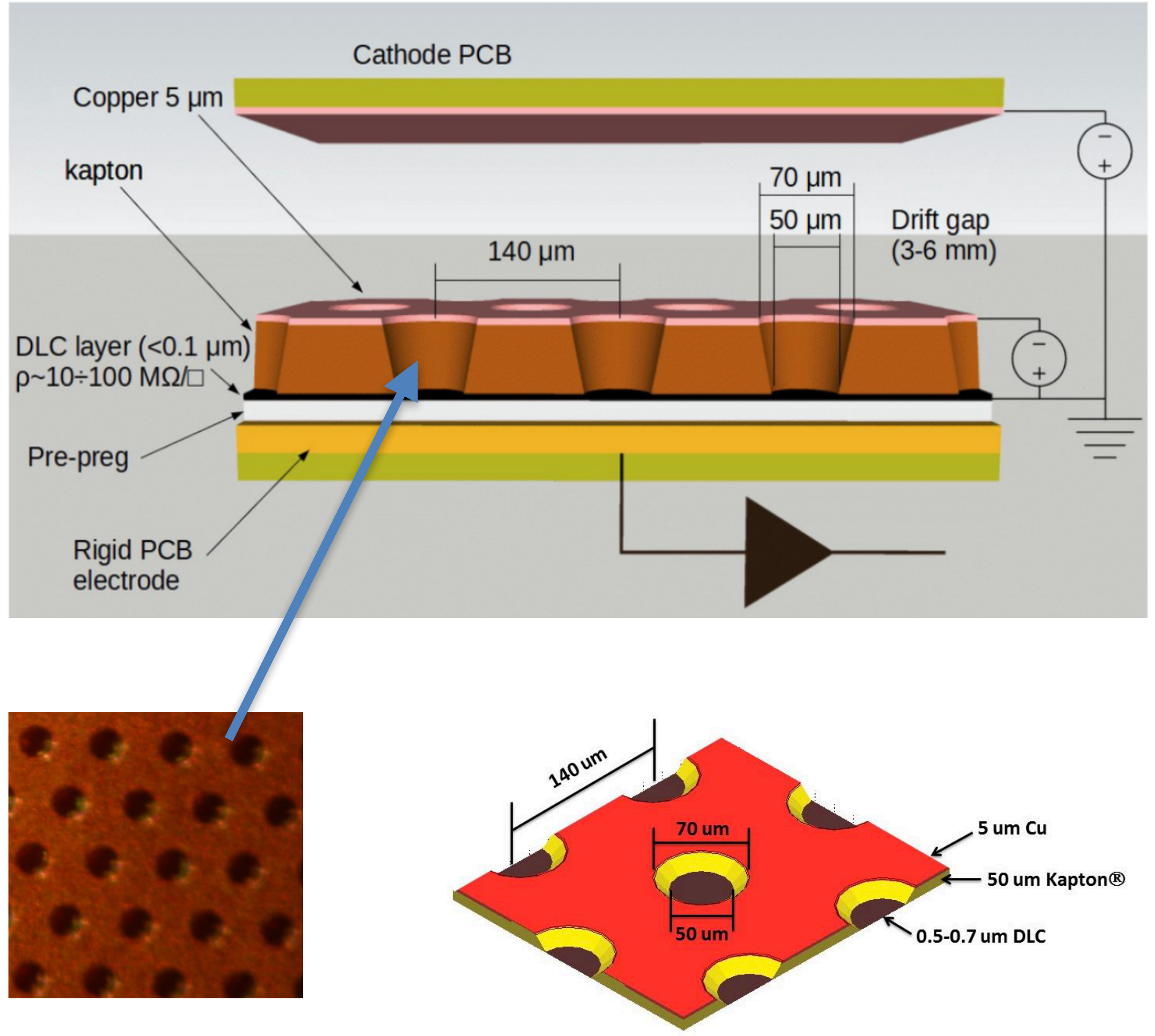
Contribution from INFN Ferrara, LNL, MiB and Naple (people cofinanced by the e+BOOST PRIN2022-2022Y87K7X)

Funded by the European Union NextGenerationEU

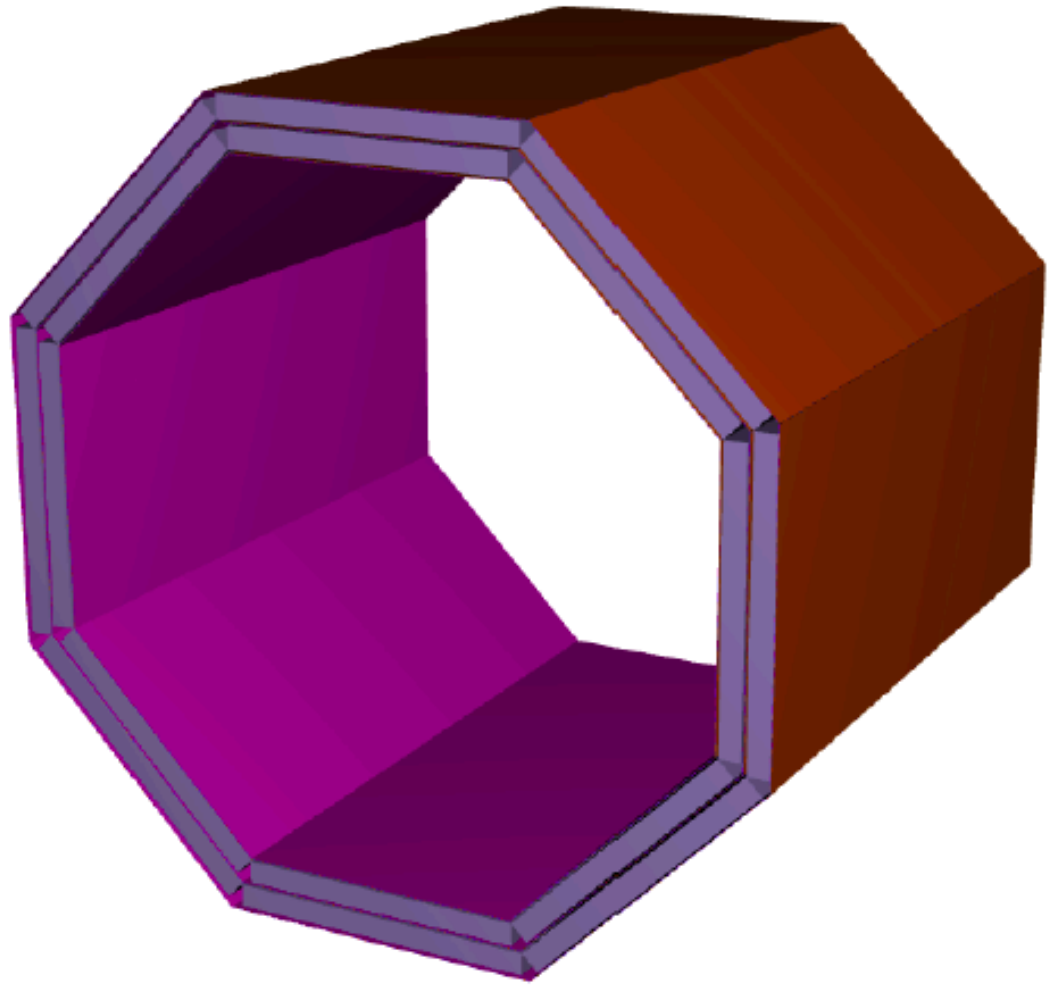
Activities in Bologna

DR fibre calorimeter

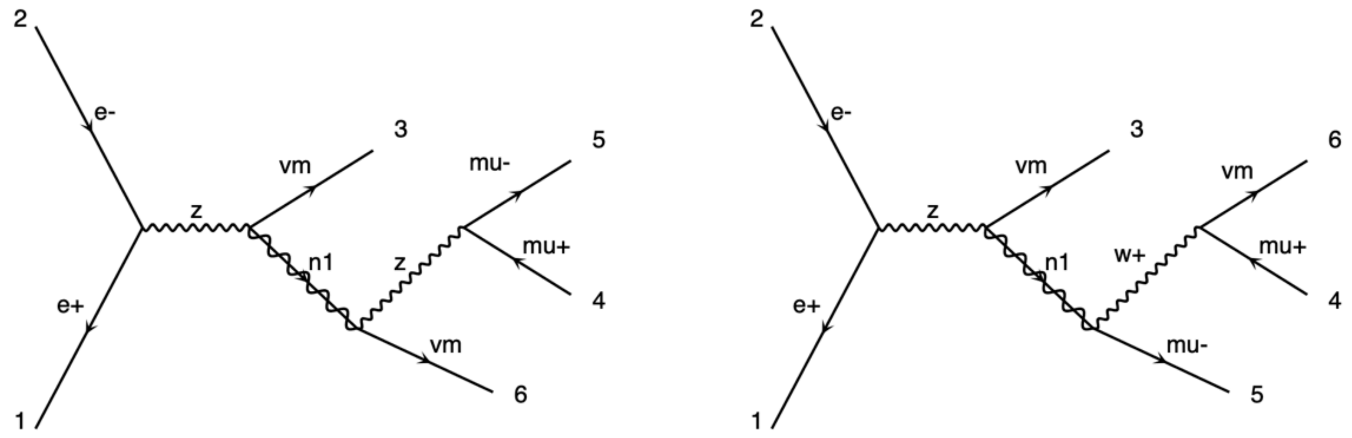
µ-RWELL



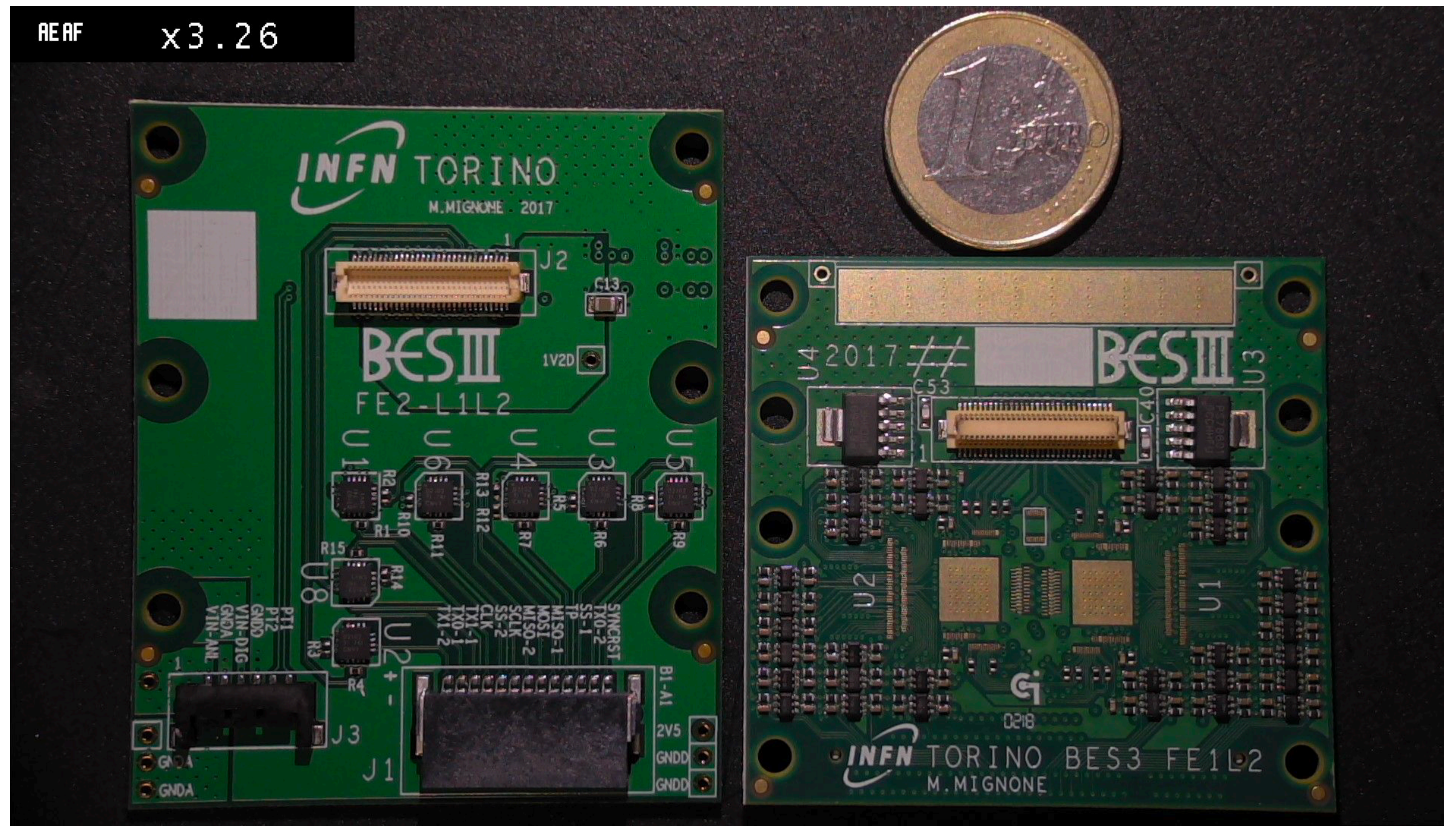
Simulations



Physics analyses



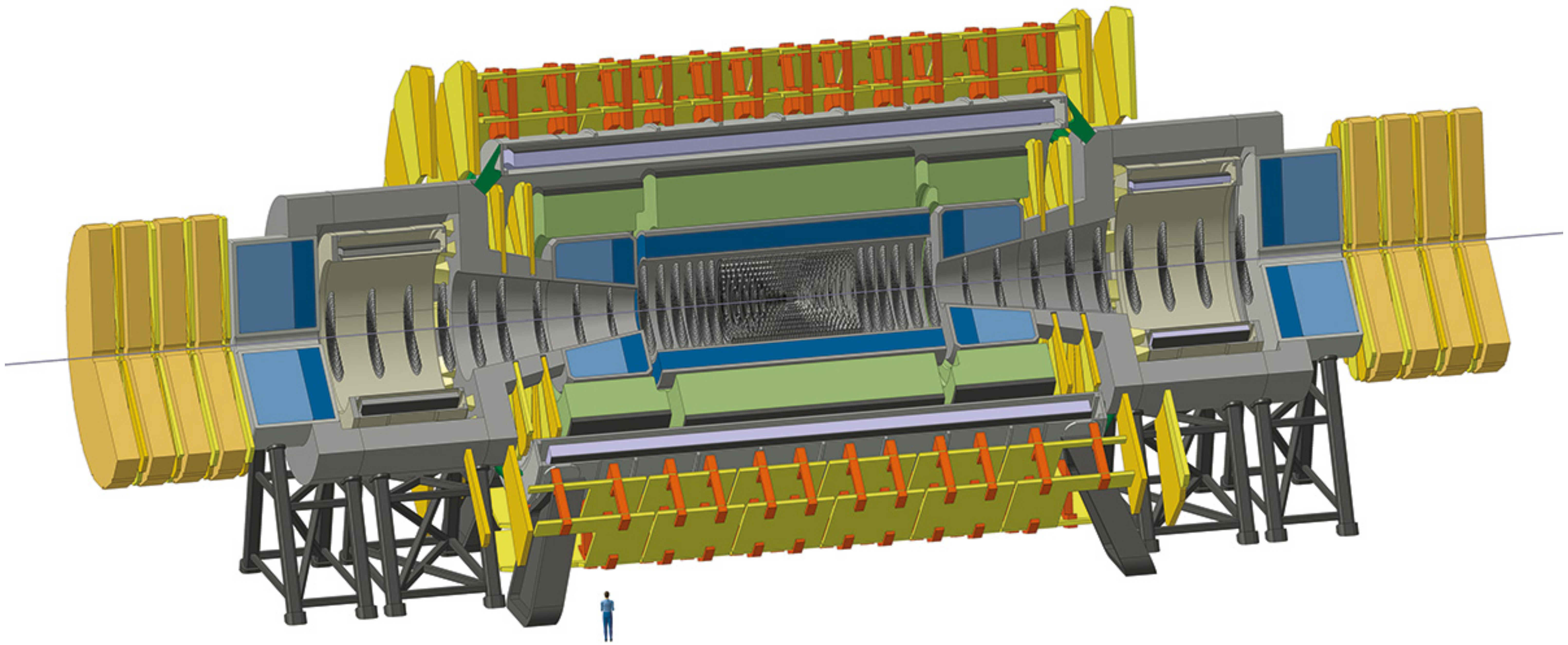
Electronics



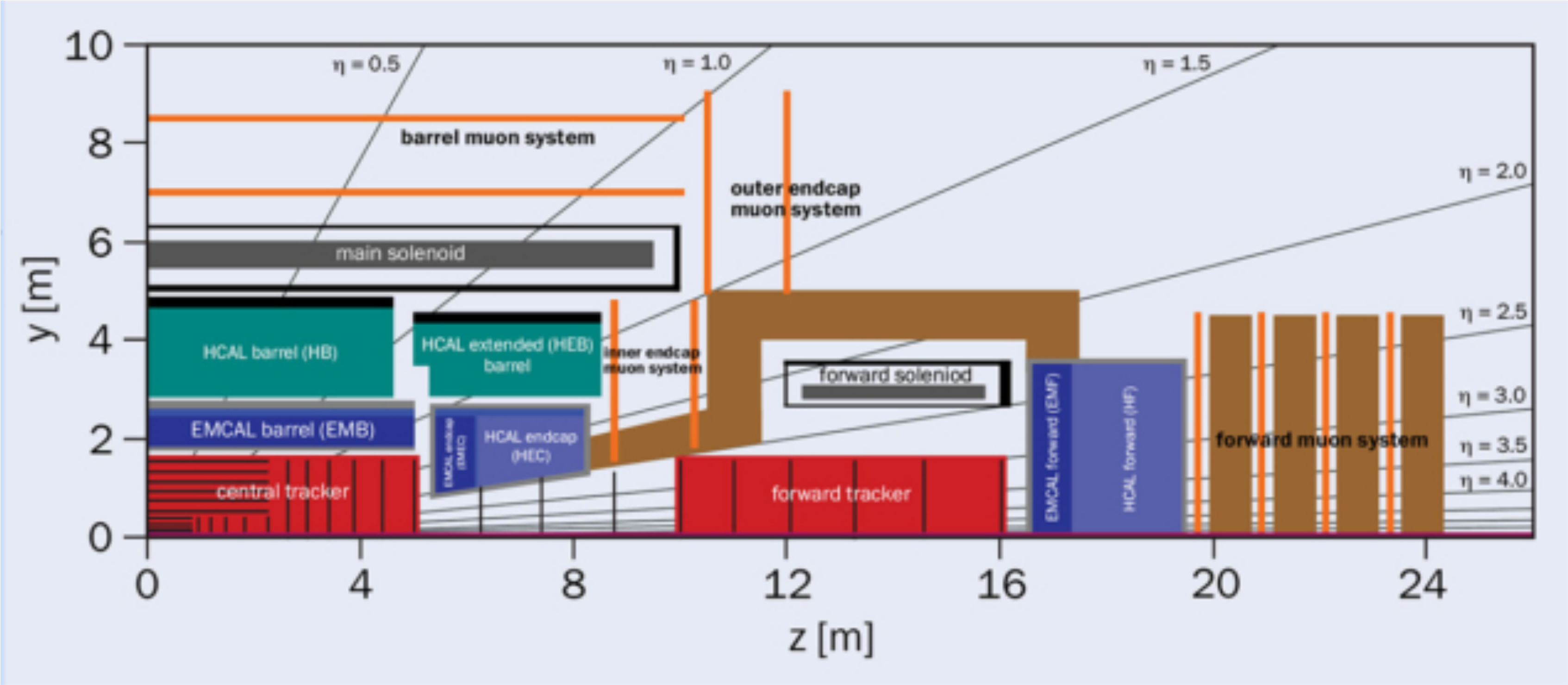
And more (accelerator, phenomenology, etc.)

FCC-hh detector concept

- pp collisions at $\sqrt{s}$ > 100 TeV, luminosity up to 3 x 10^{35} cm^{-2} s^{-1} (up to 1000 pileup events)
- Central detector houses tracking, e.m. and hadron calorimetry inside a 4T solenoid with a free bore of 10 m diameter
- Forward parts are displaced by 10m from the interaction point, with two forward magnet coils
- The muon system is placed outside the magnet coils
- Overall length ~50m, diameter ~20m



→ No field return yoke for FCC-hh reference detector



Conclusions

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- The FCC integrated program provides a fantastic future scientific program for particle physics for the next 60-70 years

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  - In the first phase, FCC-ee, electron-positron collisions will be studied

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- Lots of possibilities for new students to join FCC-ee and IDEA and contribute to all these developments!!

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