
# FCC detector concepts

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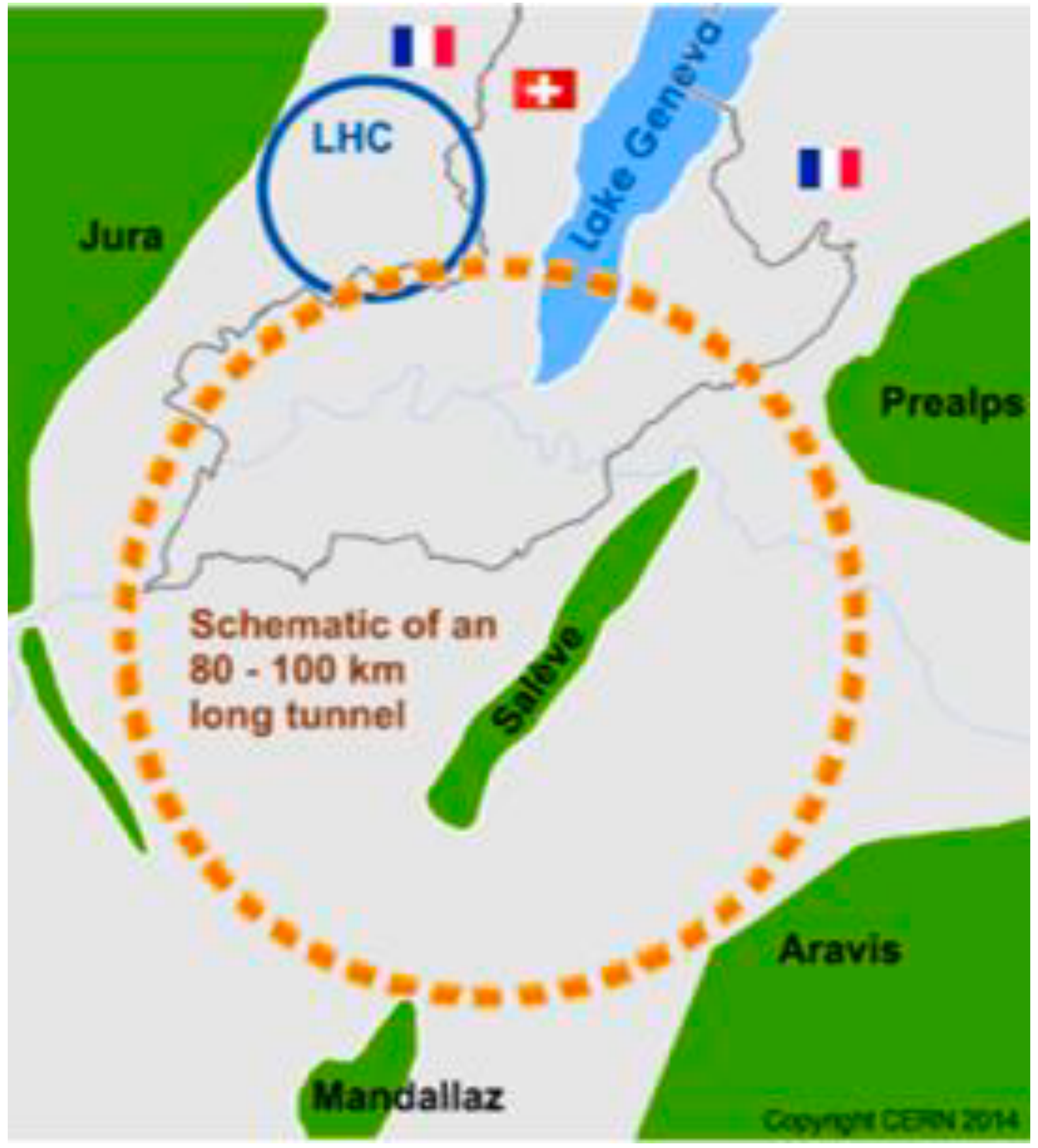
**INFN Bologna**

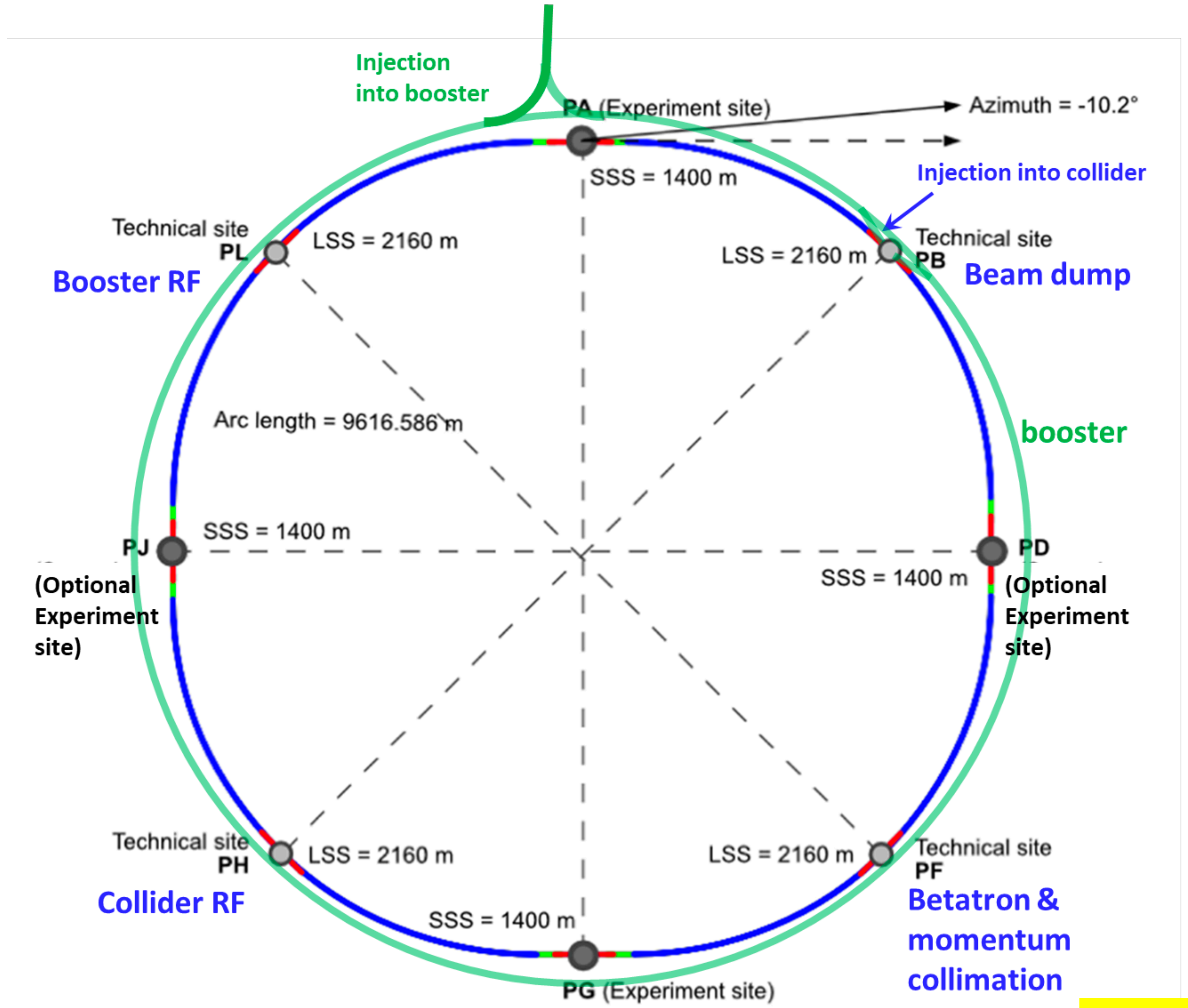
# FCC integrated program

**Comprehensive long-term program maximizing physics opportunities**

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier with pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders

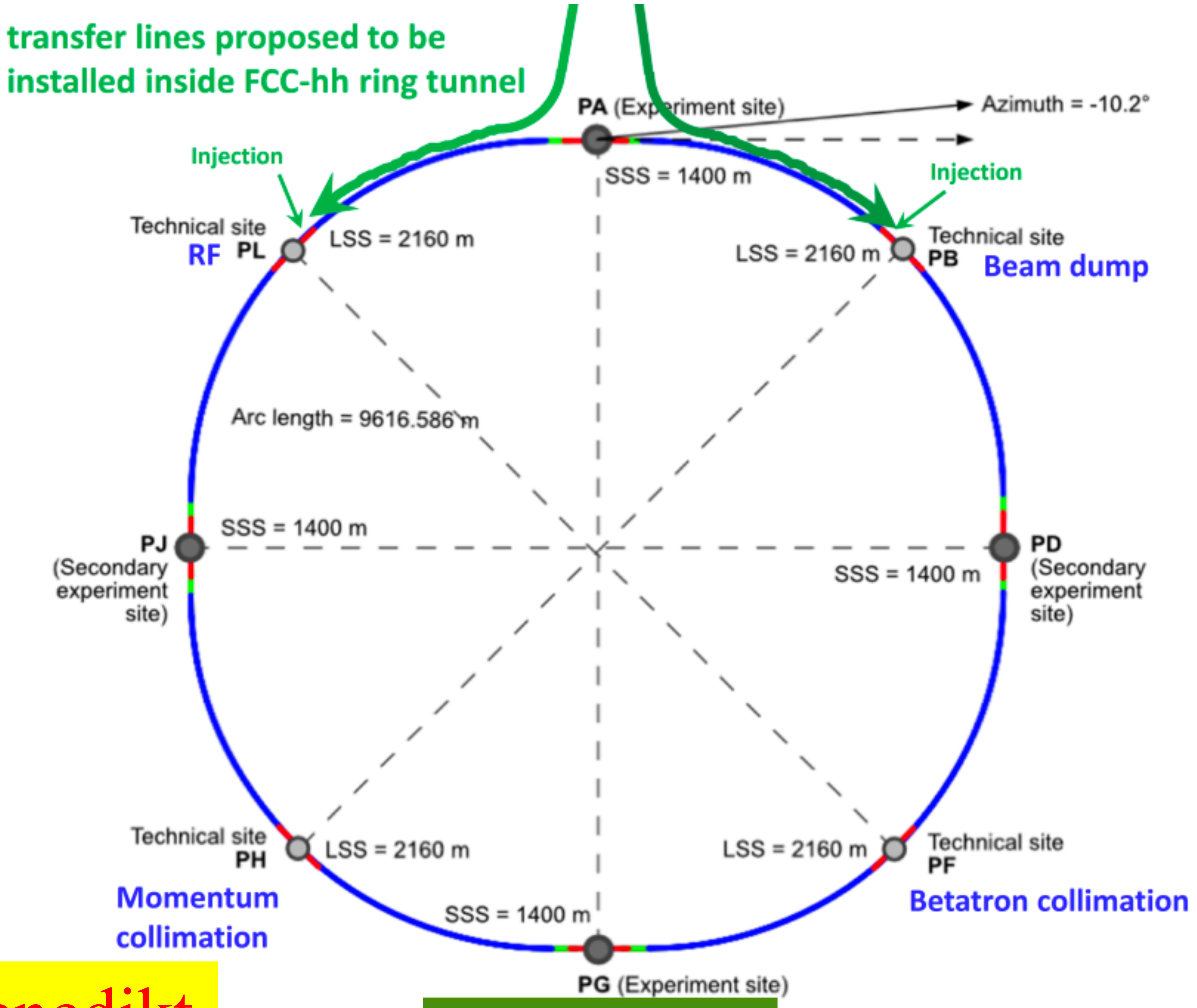



2020 - 2040




2045 - 2063

M. Benedikt




2070 - 2095

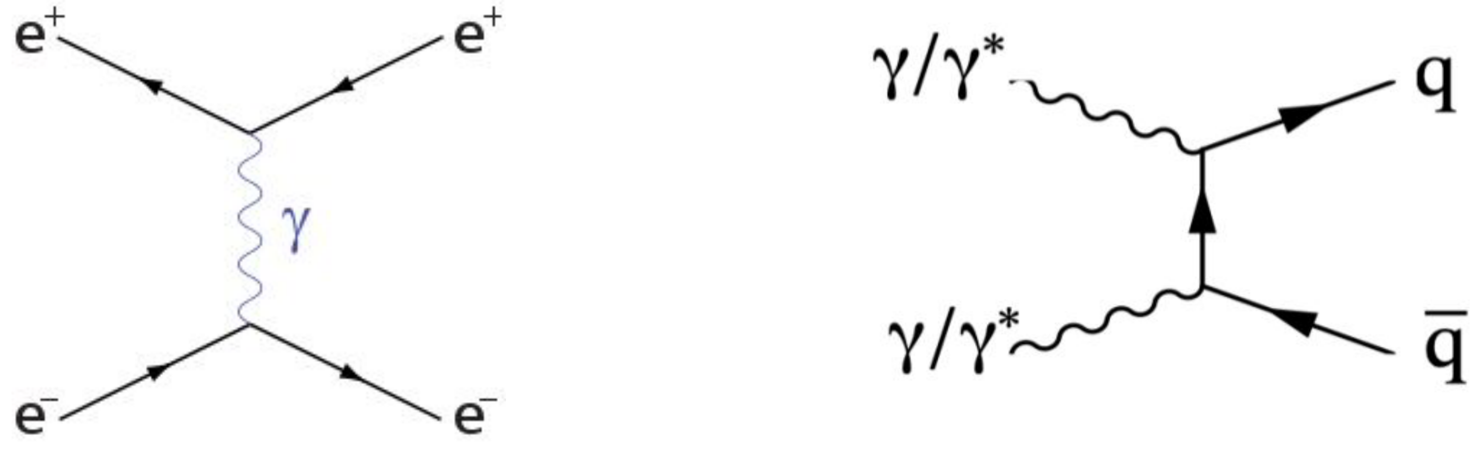
# Detector requirements for FCC-ee

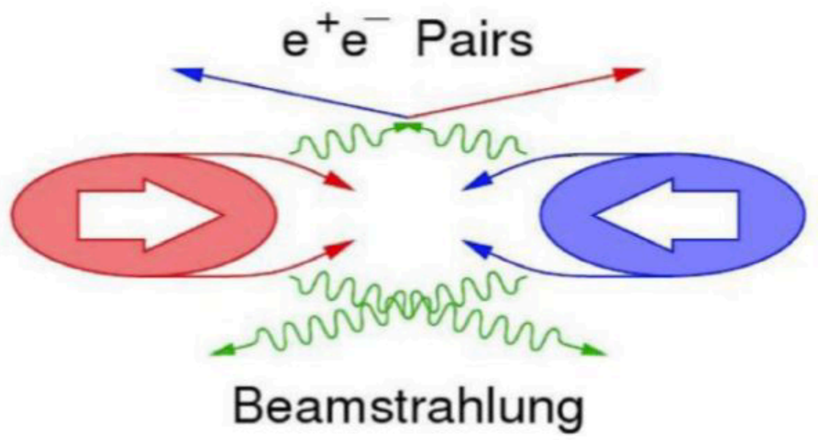


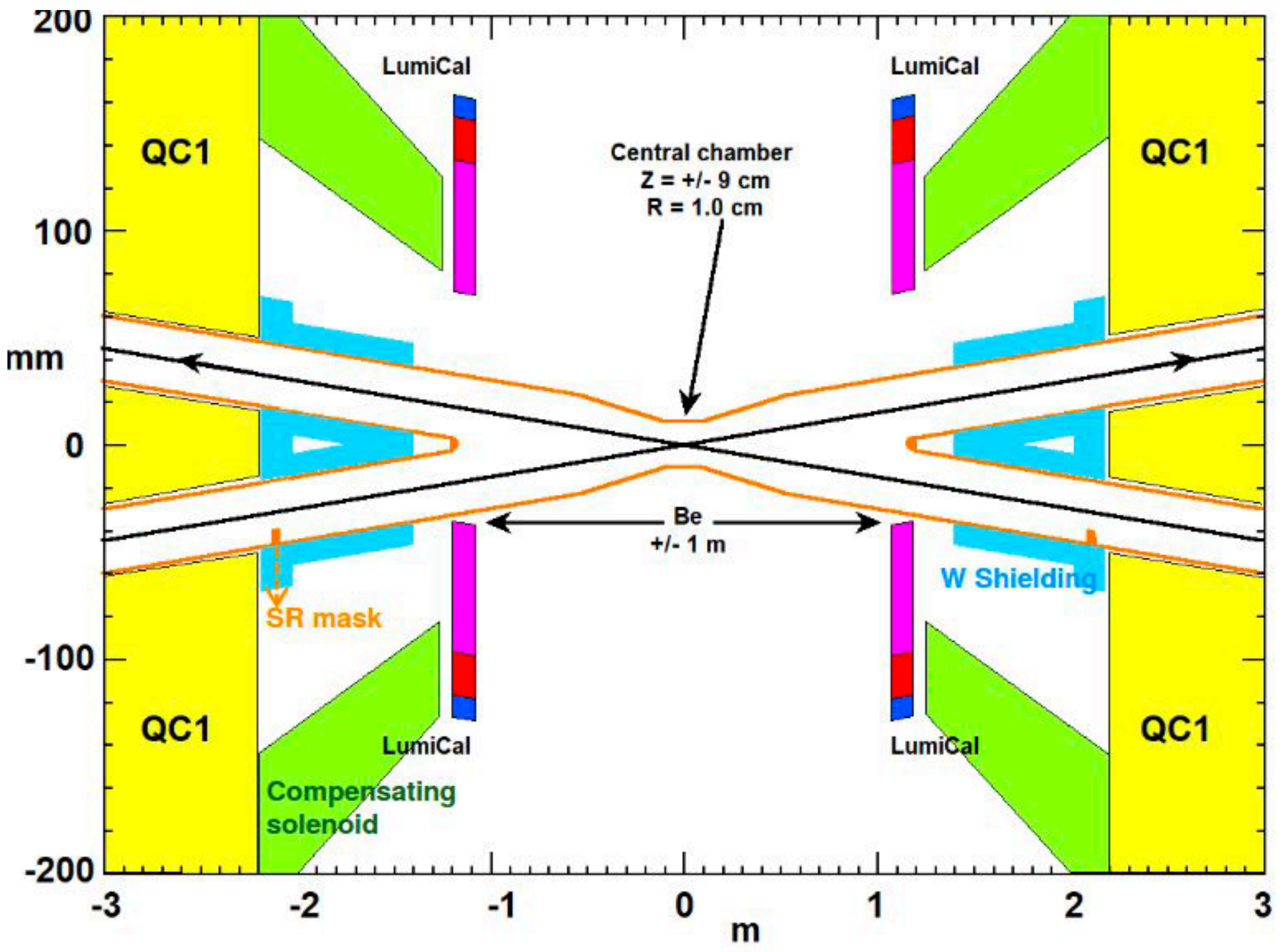
- Requirements for Higgs and above have been studied to some extent by LC:
  - have to be revised by FCC-ee
  - we want a detector that is able to withstand a large dynamic range:
    - in energy ($\sqrt{s}$ = 90 - 365 GeV)
    - in luminosity (L = $10^{34}$ - $10^{36}$ $cm^2/s$)

- most of the machine induced limitations are imposed by the Z pole run:
  - large collision rates ~ 33 MHz and continuous beams
    - no power pulsing possible
  - large event rates ~ 100 kHz
    - fast detector response / triggerless design challenging (but rewarding)
    - high occupancy in the inner layers/forward region (Bhabha scattering/γγ hadrons)
  - beamstrahlung

- complex MDI: last focusing quadrupole is ~ 2.2m from the IP
  - magnetic field limited to B = 2T at the Z peak (to avoid disrupting vertical emittance/inst. Lumi via SR)
    - limits the achievable track momentum resolution
  - "anti"-solenoid
    - limits the acceptance to ~ 100 mrad



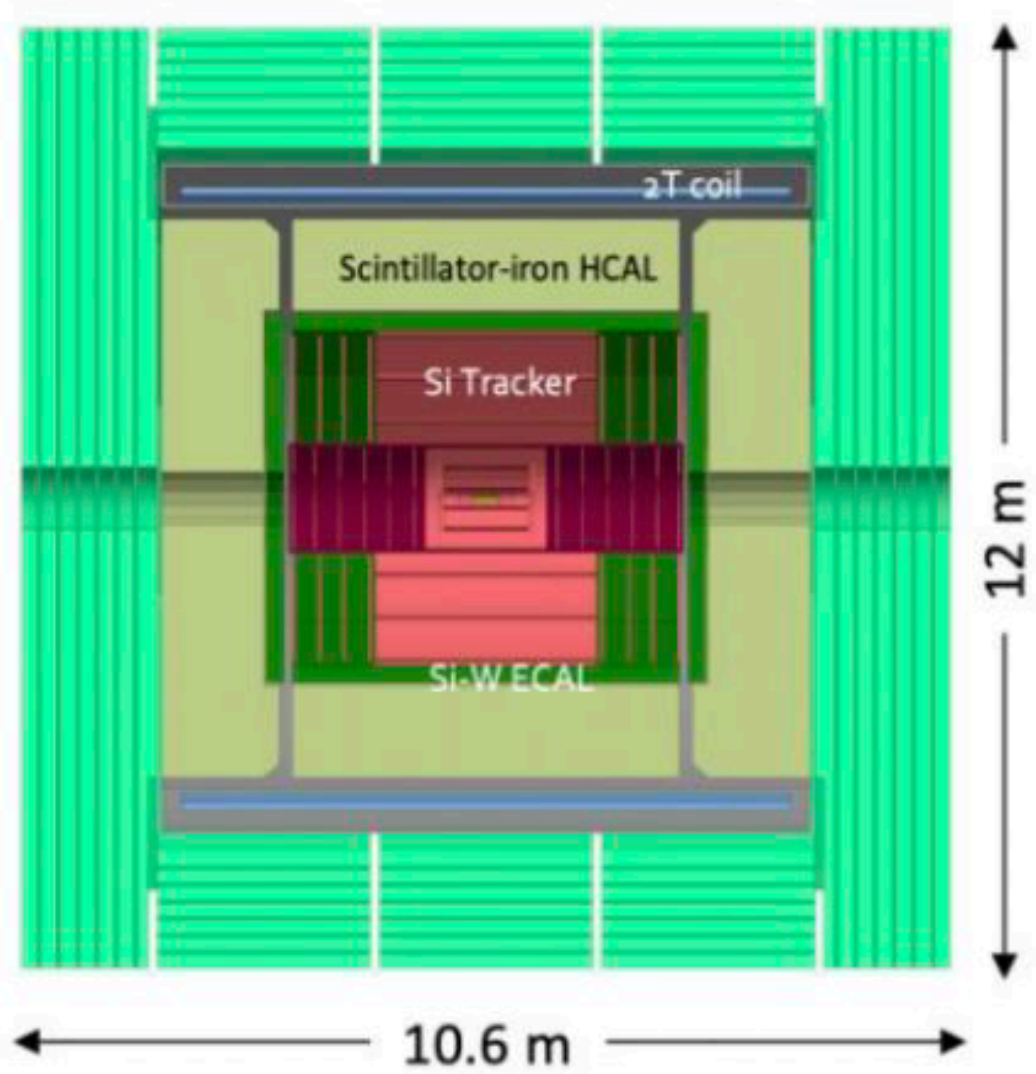

M. Selvaggi

FUTURE CIRCULAR COLLIDER

# Detector concepts fast overview

INFN Istituto Nazionale di Fisica Nucleare

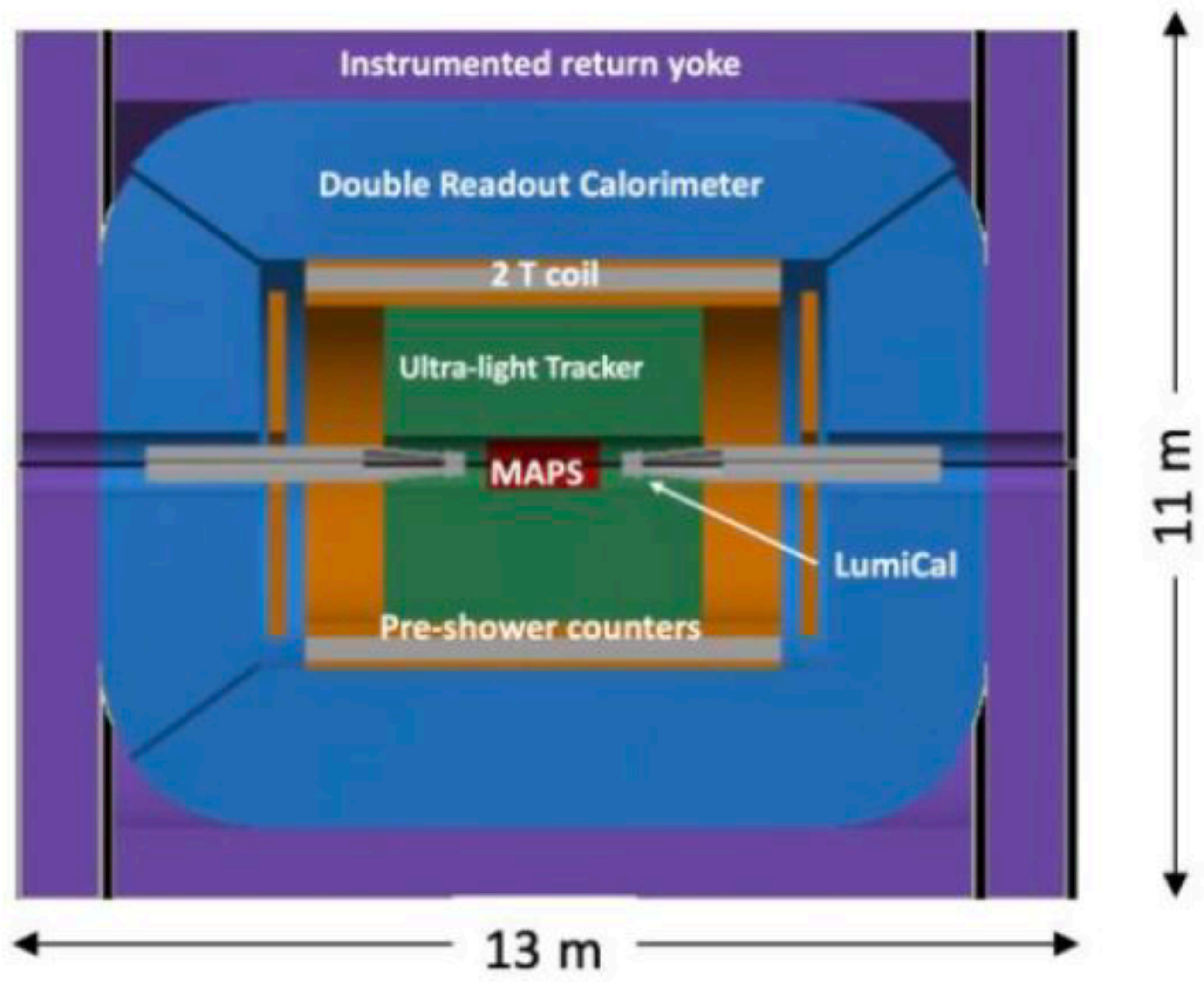
## CLD




- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - $\sigma_p/p$, $\sigma_E/E$
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

CDR

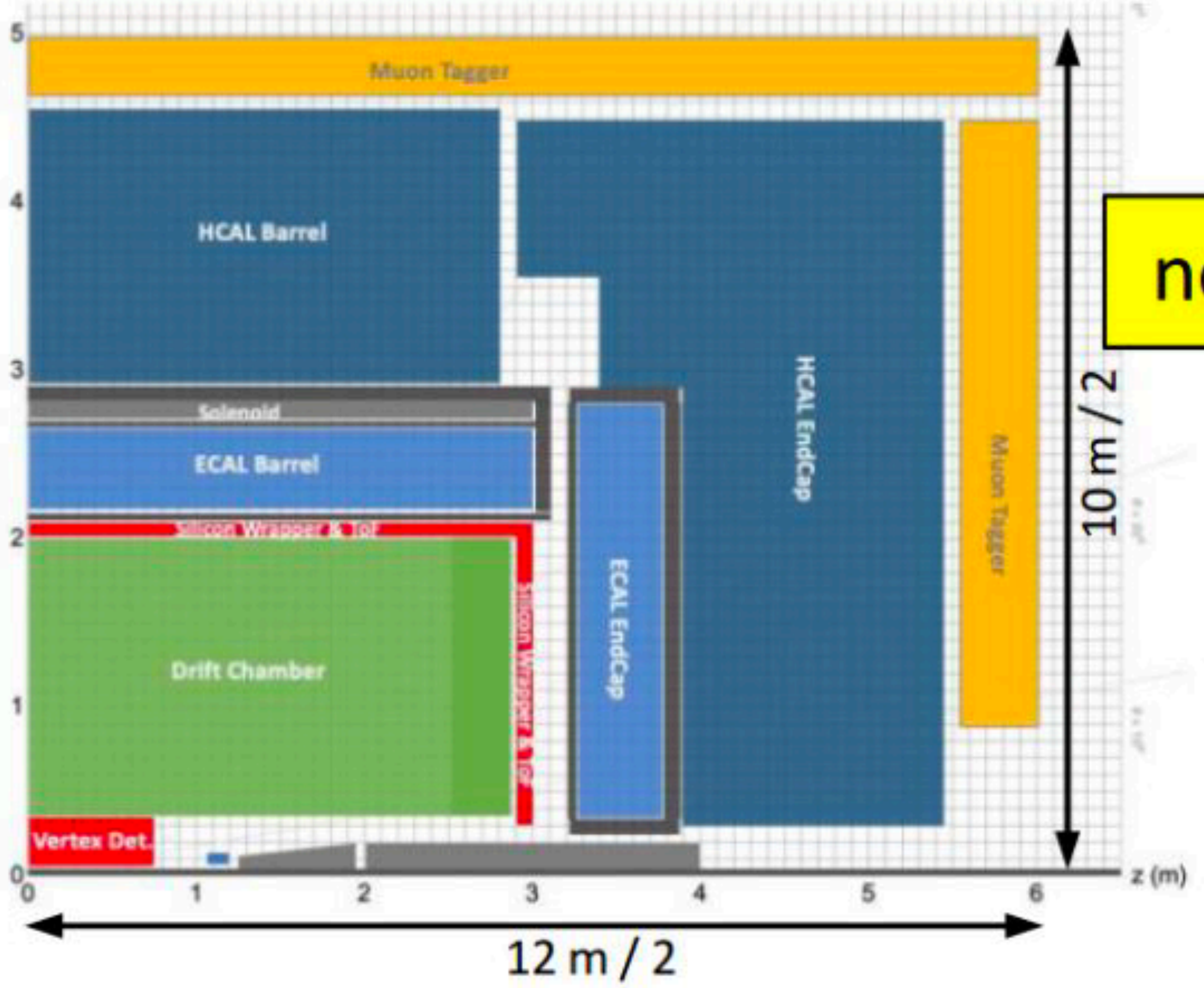
## IDEA




- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

## Noble Liquid ECAL based

new

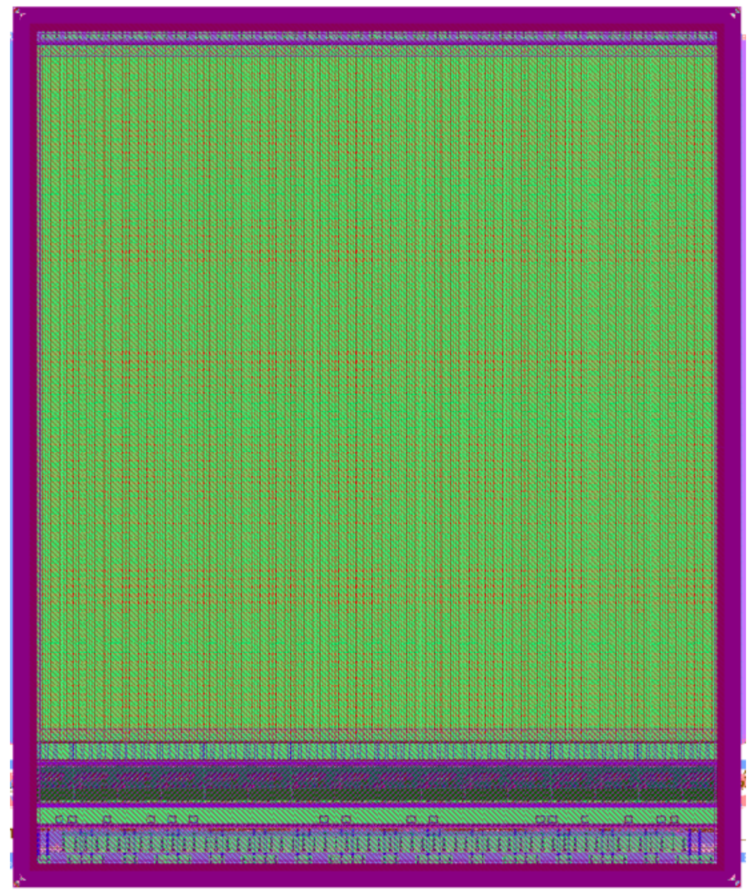



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520 https://pos.sissa.it/390/

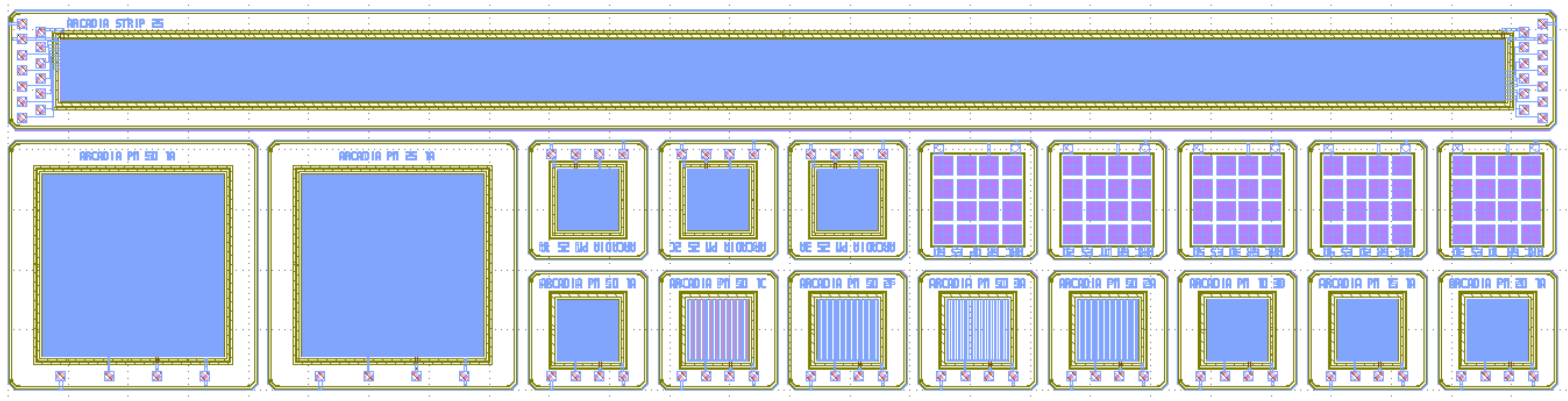
# Vertex detector: IDEA



Inspired by ALICE ITS based on MAPS technology, using the ARCADIA R&D program

- ❑ Pixels 25 × 25 μm$^2$ (with developments to even smaller pixels)

- Light
  - ❑ Inner layers: 0.3% of $X_0$ / layer
  - ❑ Outer layers: 1% of $X_0$ / layer
- Performance:
  - ❑ Point resolution of ~3 μm
  - ❑ Efficiency of ~100%
  - ❑ Extremely low fake rate hit rate



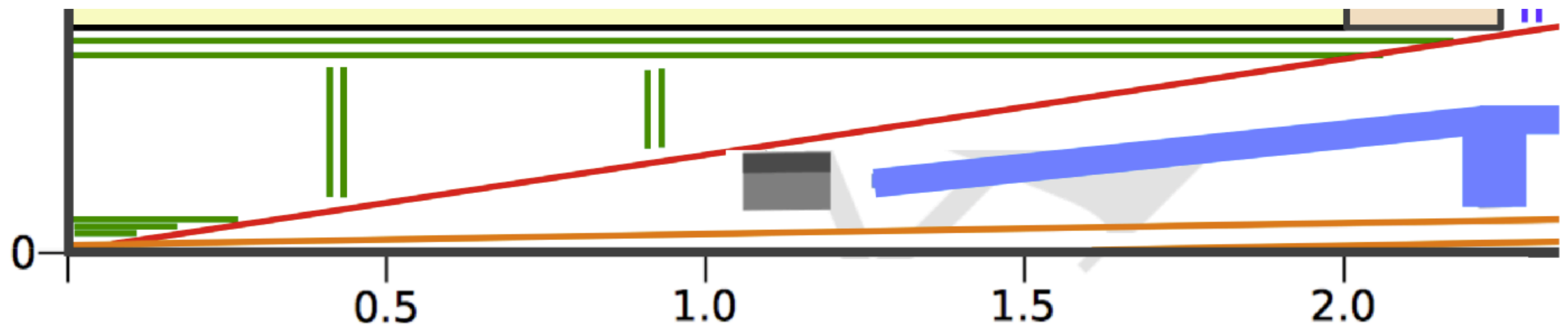
***5 MAPS*** layers:

R = 1.7 - 2.3 - 3.1 cm

Pixel size: 20 x 20 μm$^2$

R = 32 - 34 cm

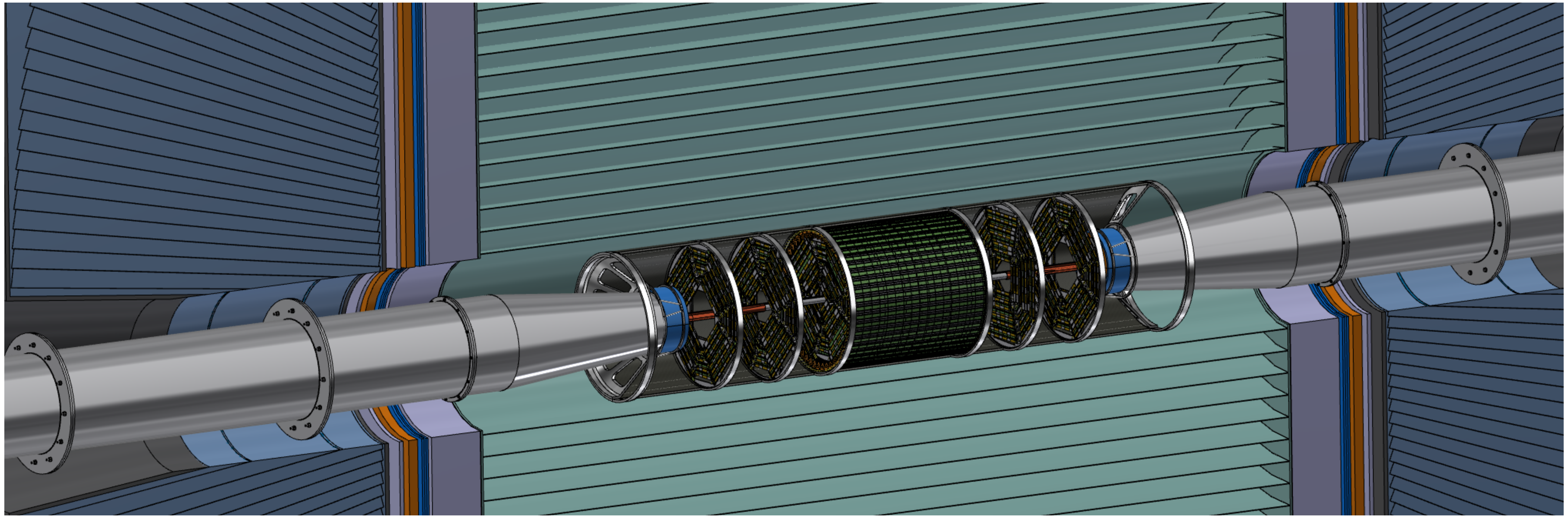
Pixel size: 50 x 100 μm$^2$



# IDEA: integration of vertex detector



## Inner and outer vertex trackers



See talk by F. Fransesini for the interaction region layout

Inside the same volume of the support tube that holds also the LumiCal

- Inner vertex detector supported by the beam pipe
- Outer vertex detector (2 barrel and 6 disks) fixed to the support tube

Minimal number of detector module variants

- One module type only for the Vertex
- One module type only for the Outer barrel and disks

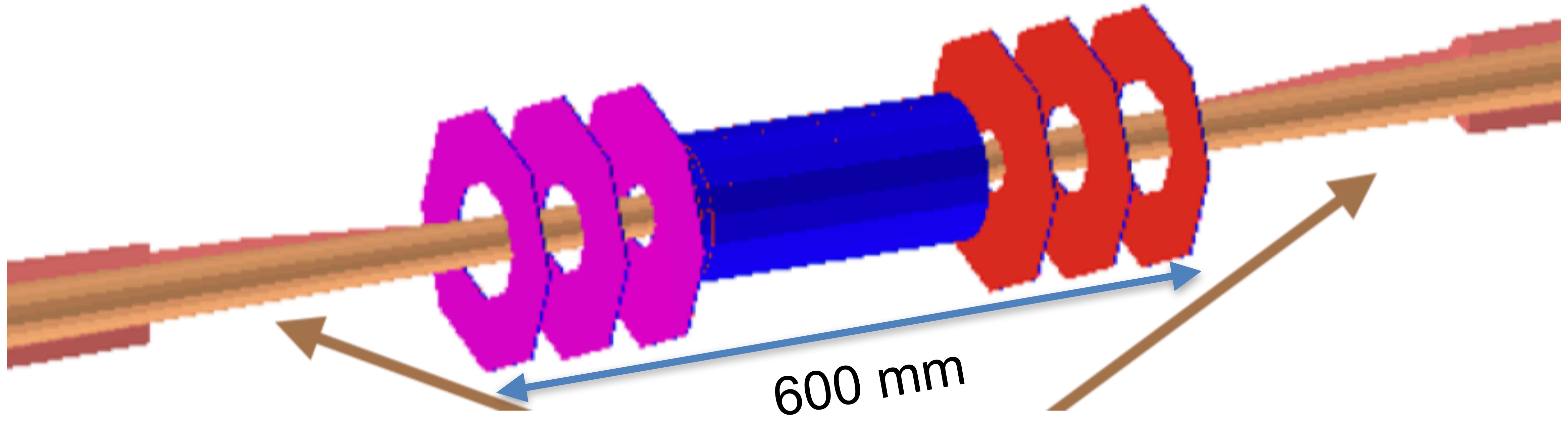
F. Palla

# Vertex detector: CLD



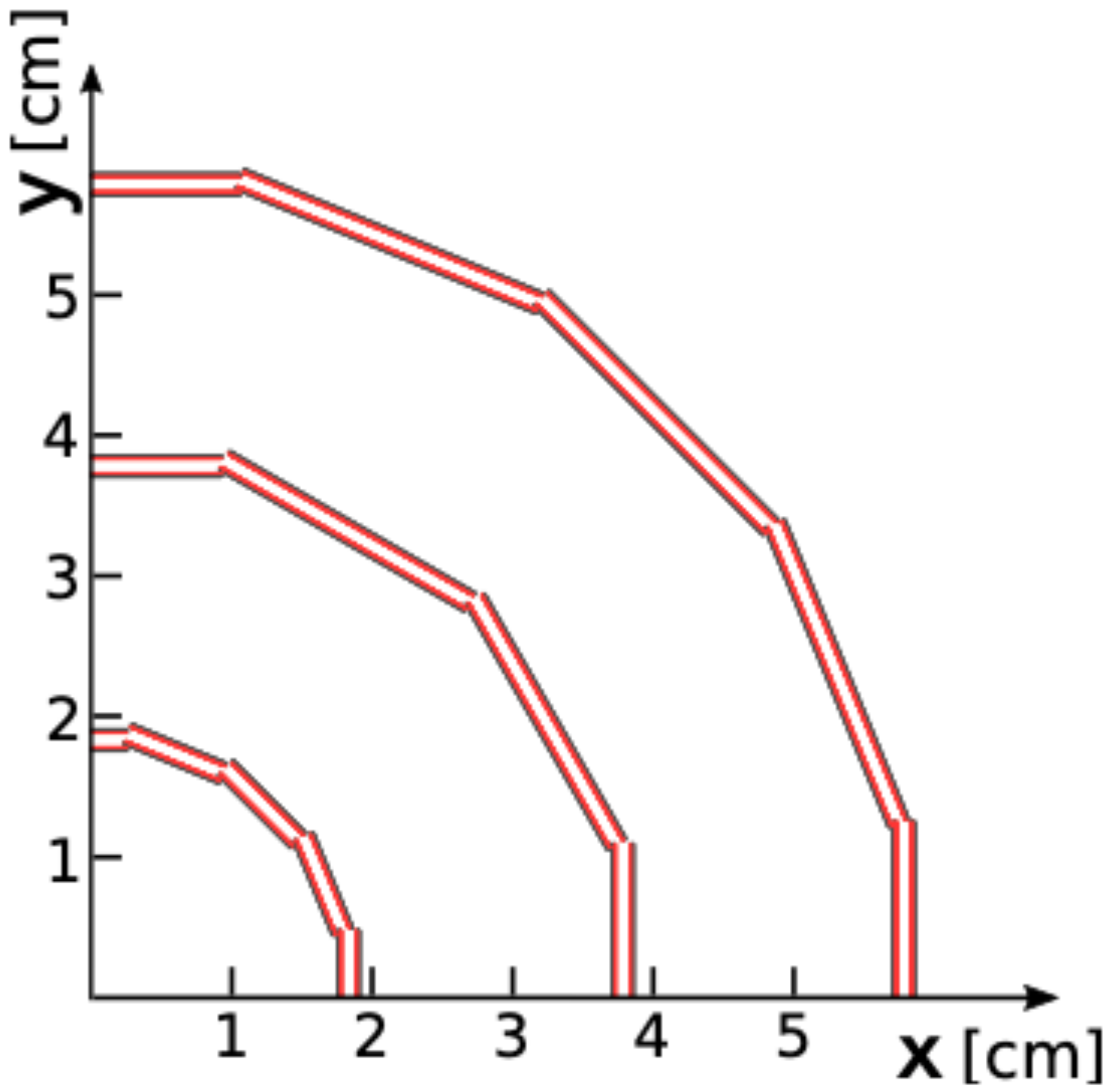
CLD is the all-silicon-tracker detector concept developed for FCC-ee

- adapted to B=2T, driven by 30 mrad beam crossing angle and vertical emittance
  - respecting 150 mrad forward cone reserved for MDI elements
  - built upon a 15 mm radius beam pipe




3 double barrel layers + 3 double-layer disks per side

- radius of innermost layer = 17 mm
- ➡ as low material budget as possible
- ➡ sensitive thickness: 50 μm per layer
- ➡ 0.6% X0 per double layer
- ➡ pixel size 25 x 25 μm2
- ➡ total sensitive area = 0.35 m2

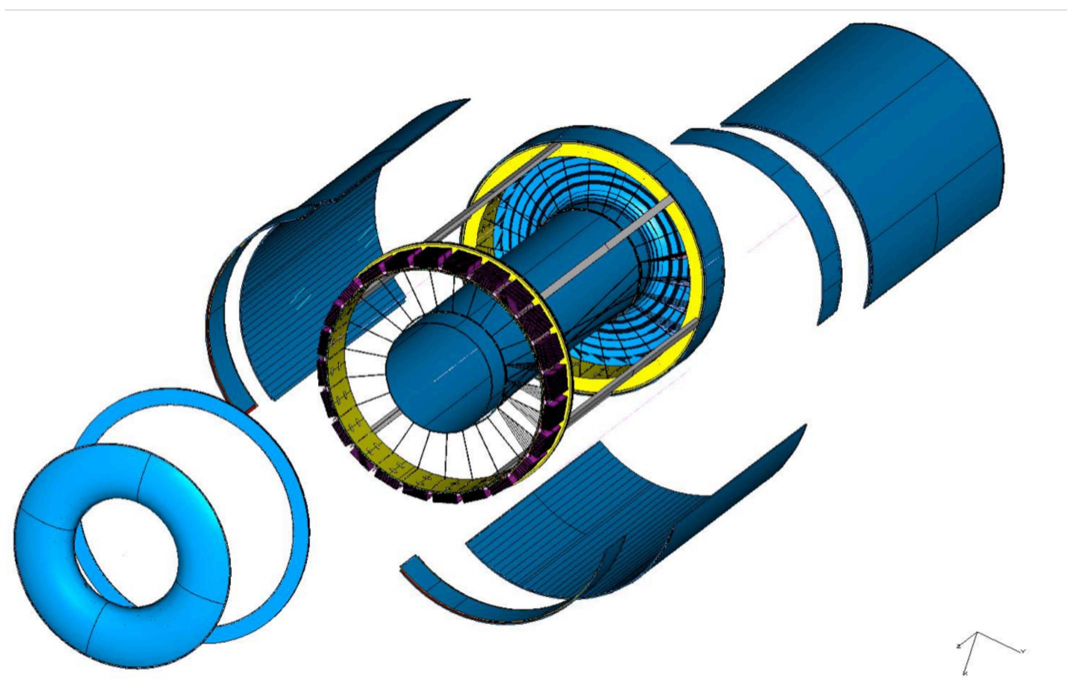


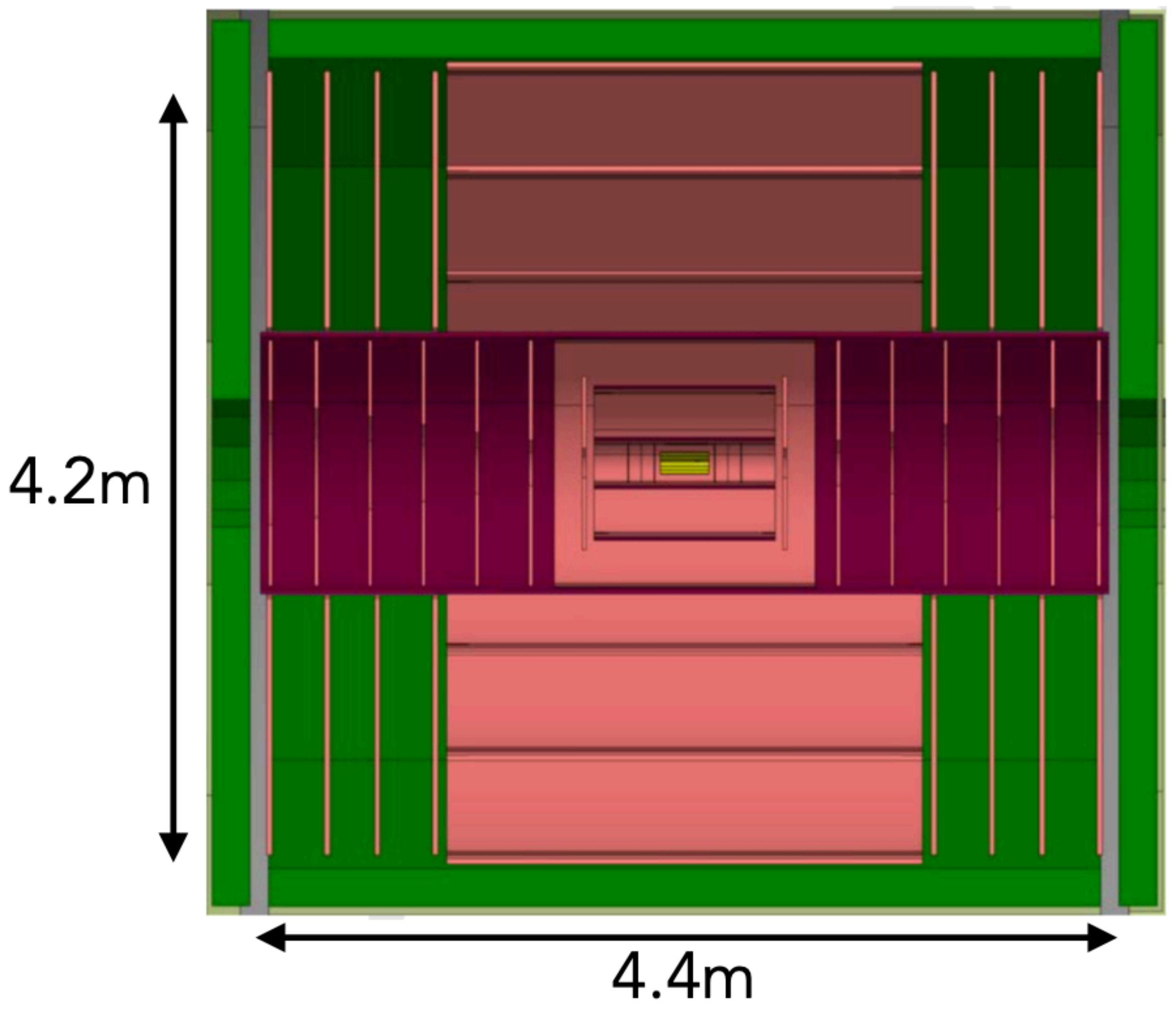
# Central tracker

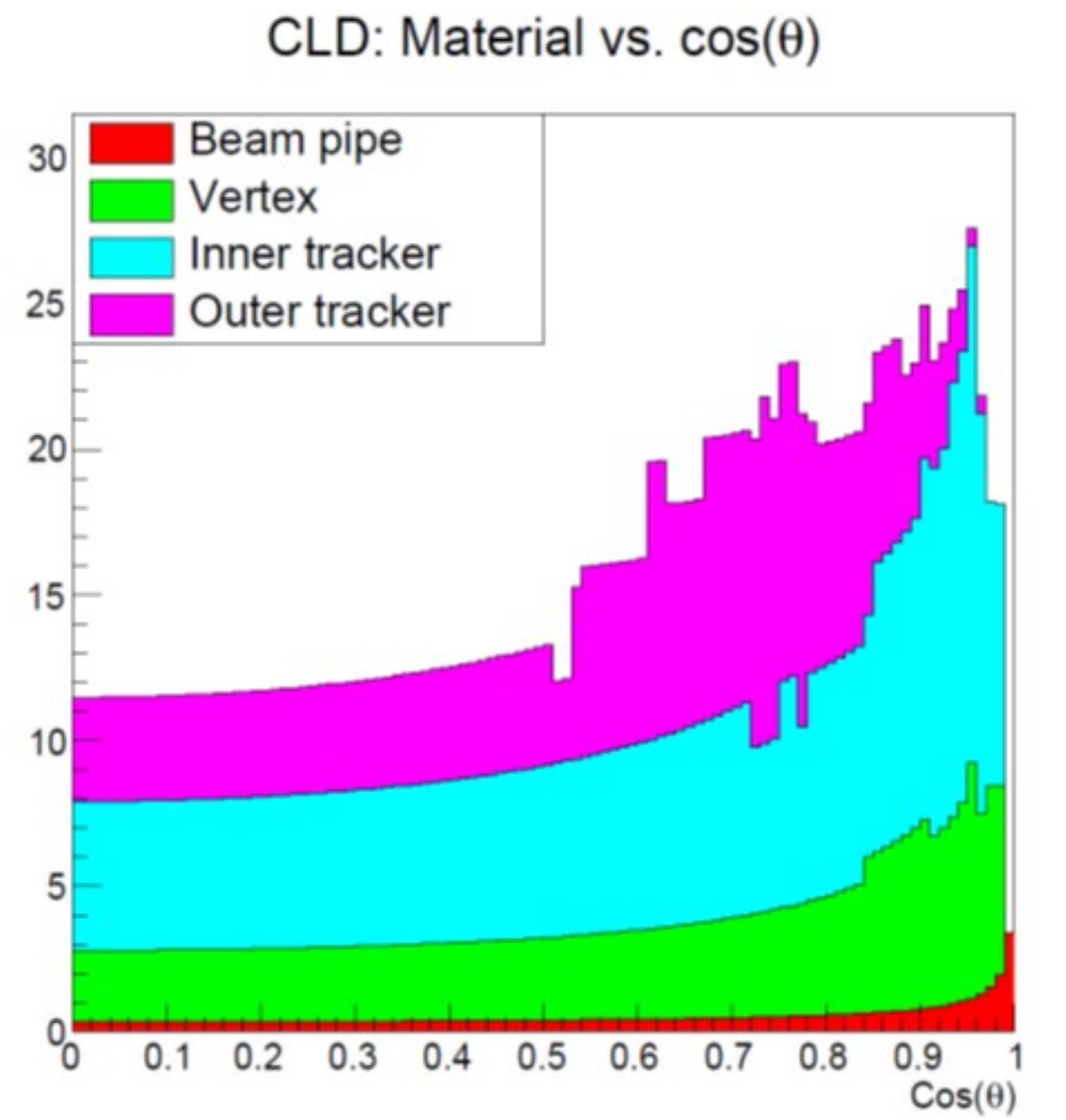
Two solutions under study

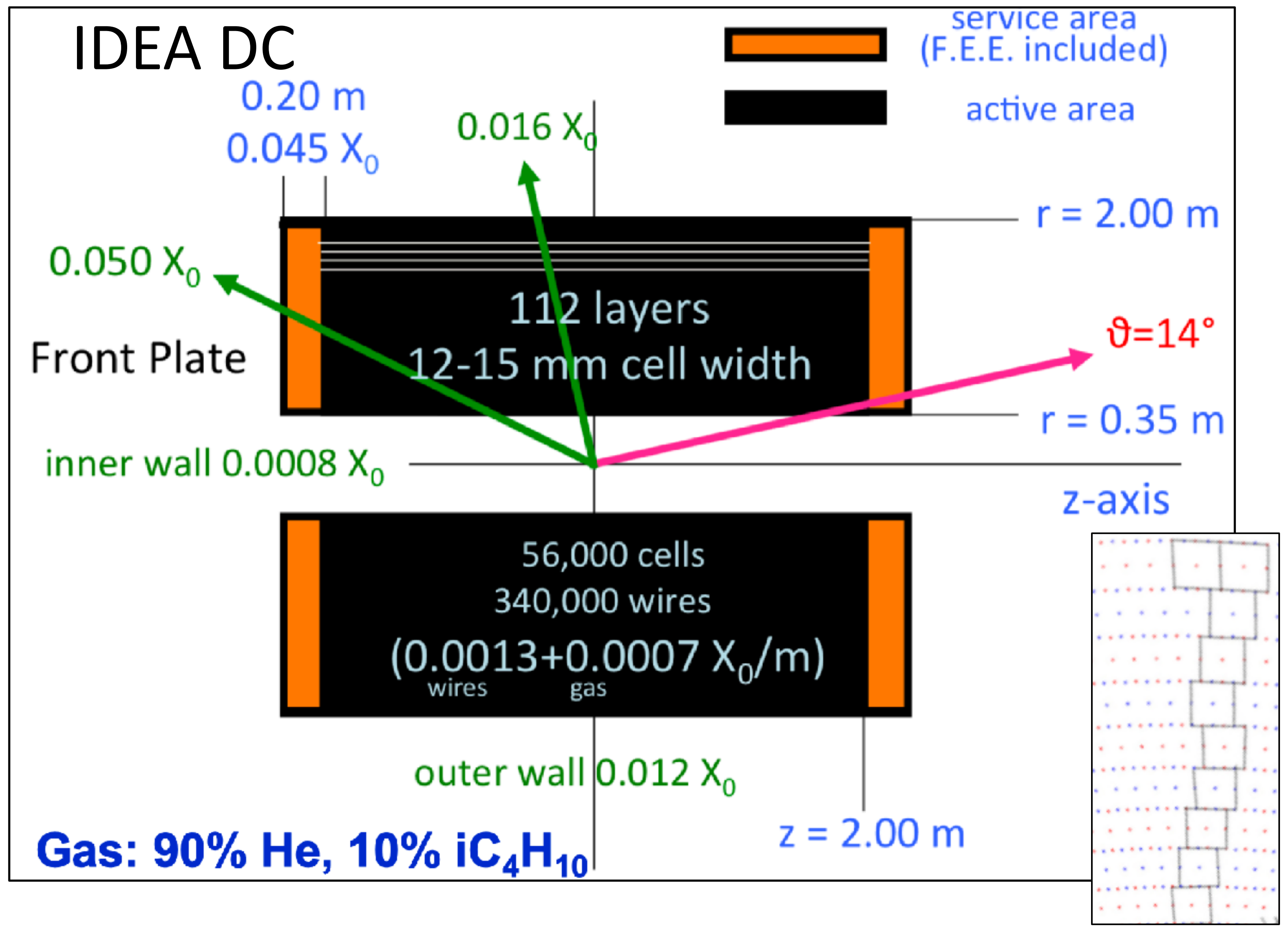
- CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% $X_0$ each)
  - Outer: 3 (4) barrel (fwd) layers (1% $X_0$ each)
  - Separated by support tube (2.5% $X_0$)

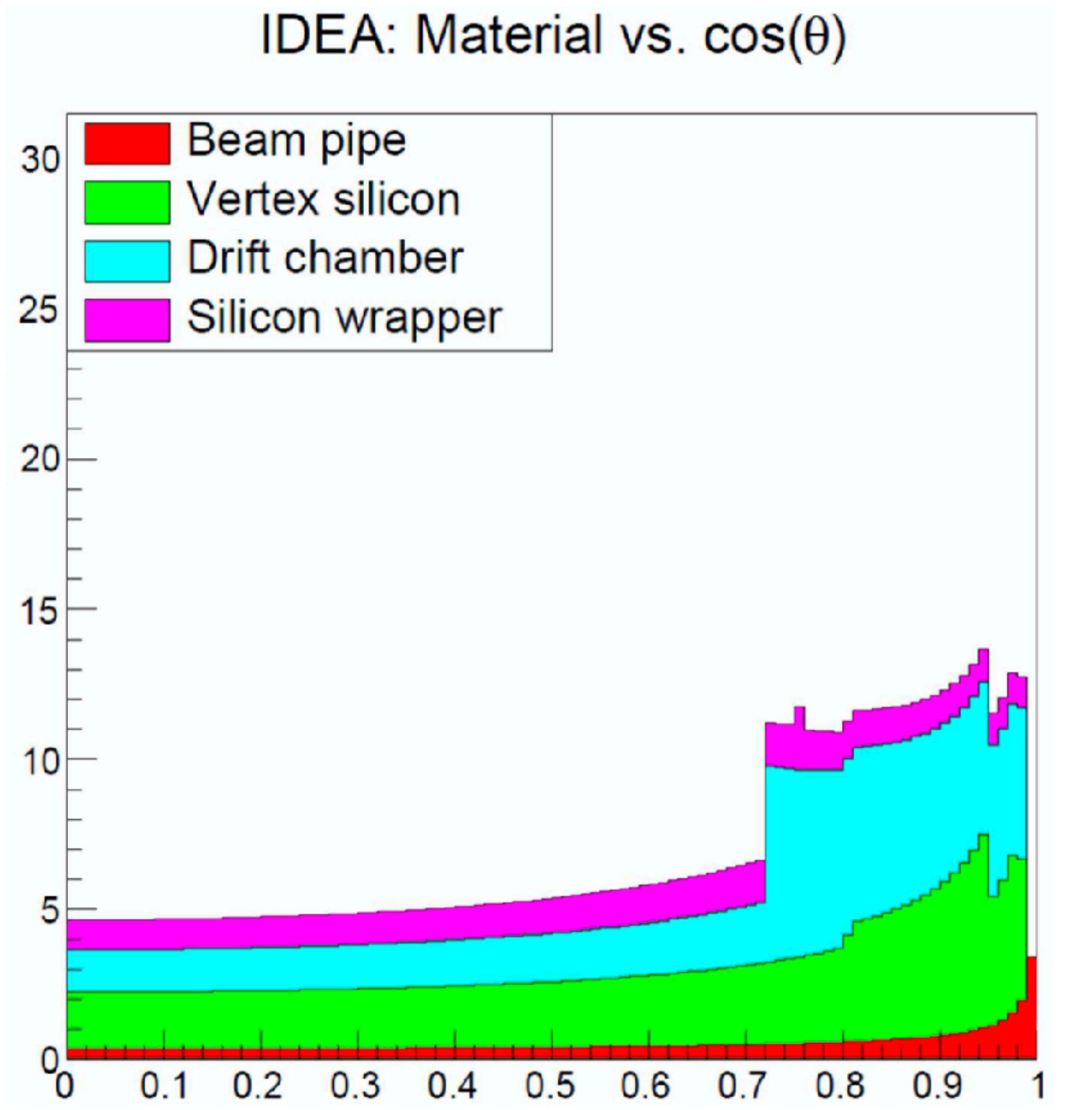
- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% $iC_4H_{10}$
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of $X_0$ at 90º
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"





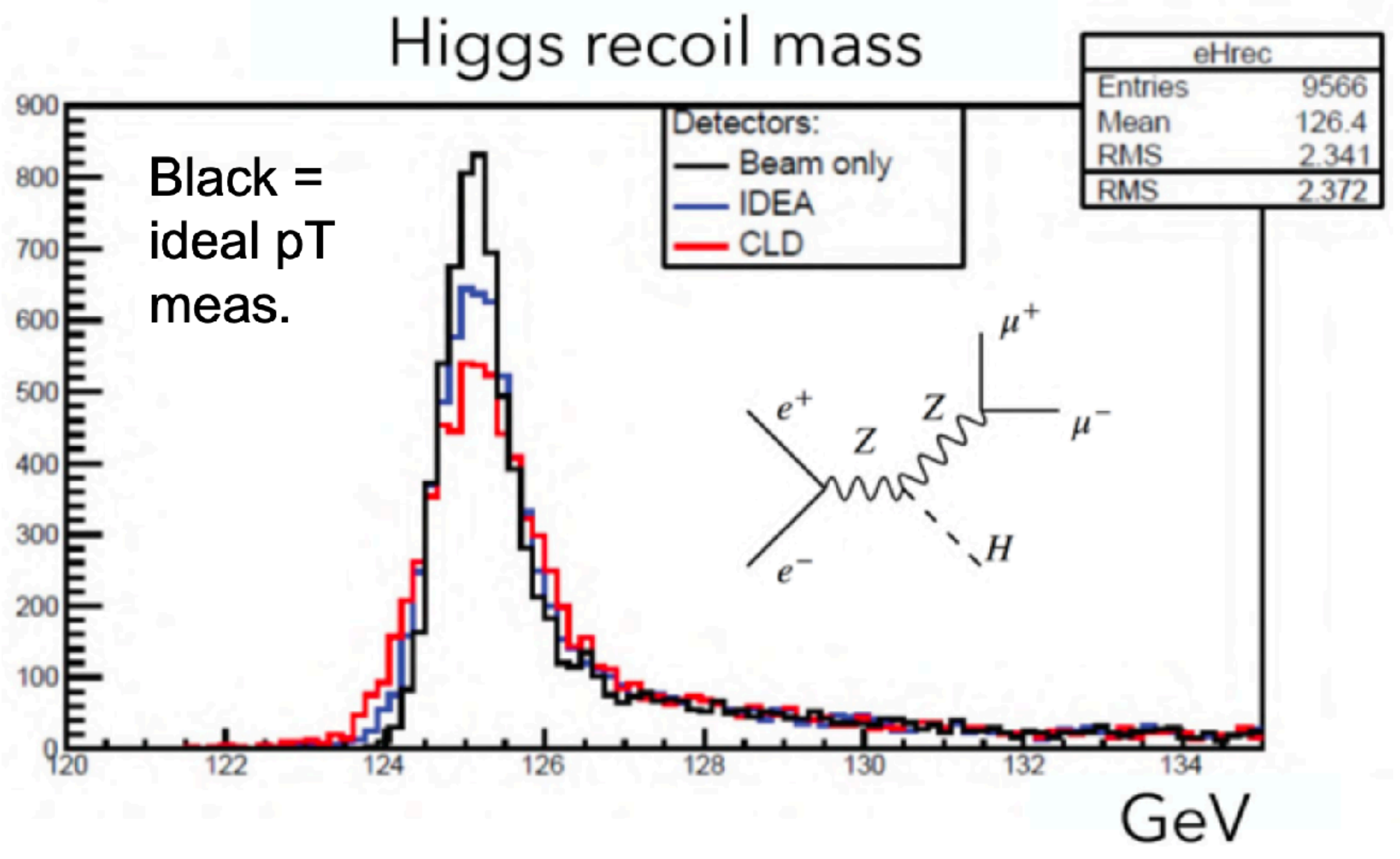



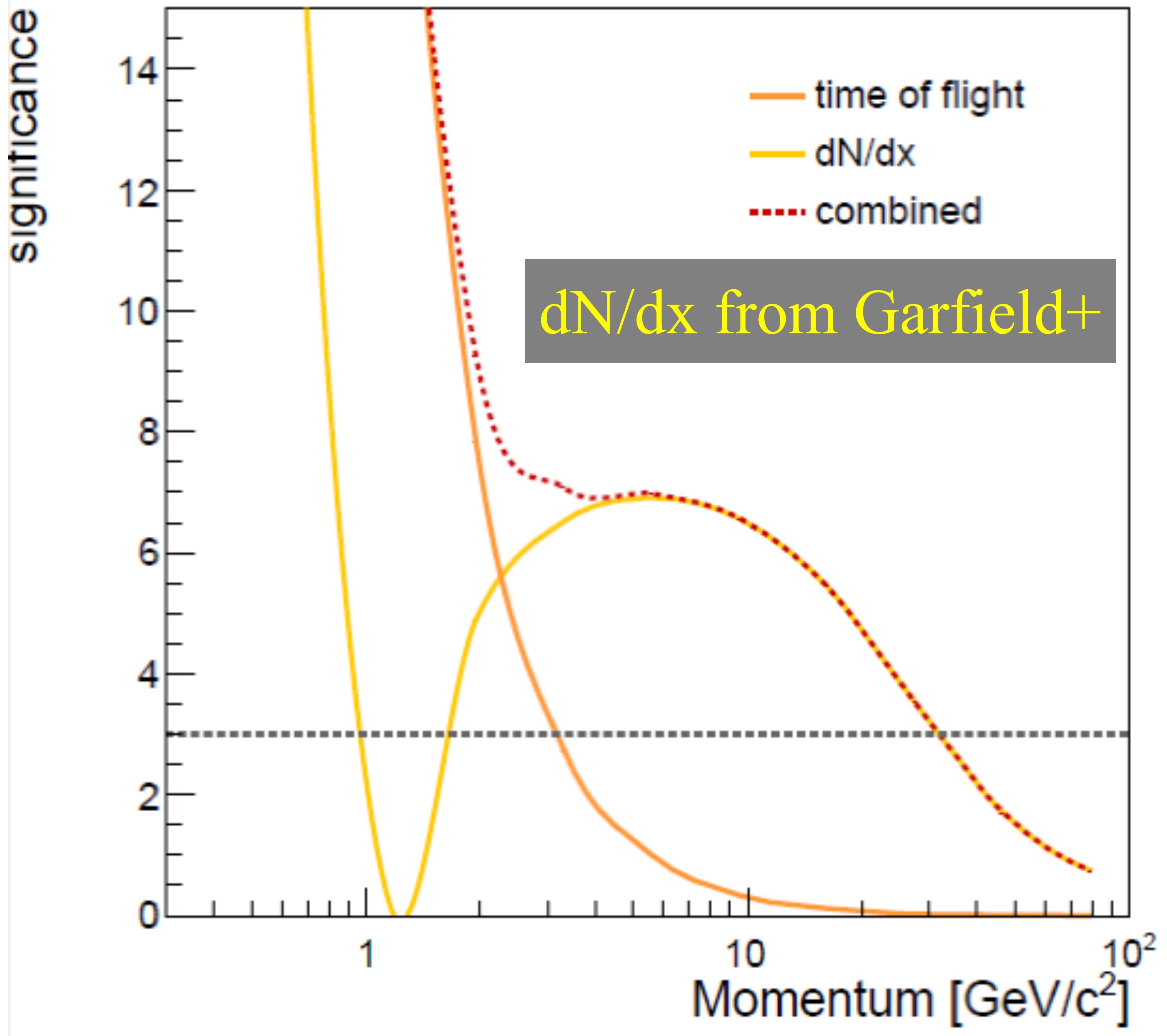



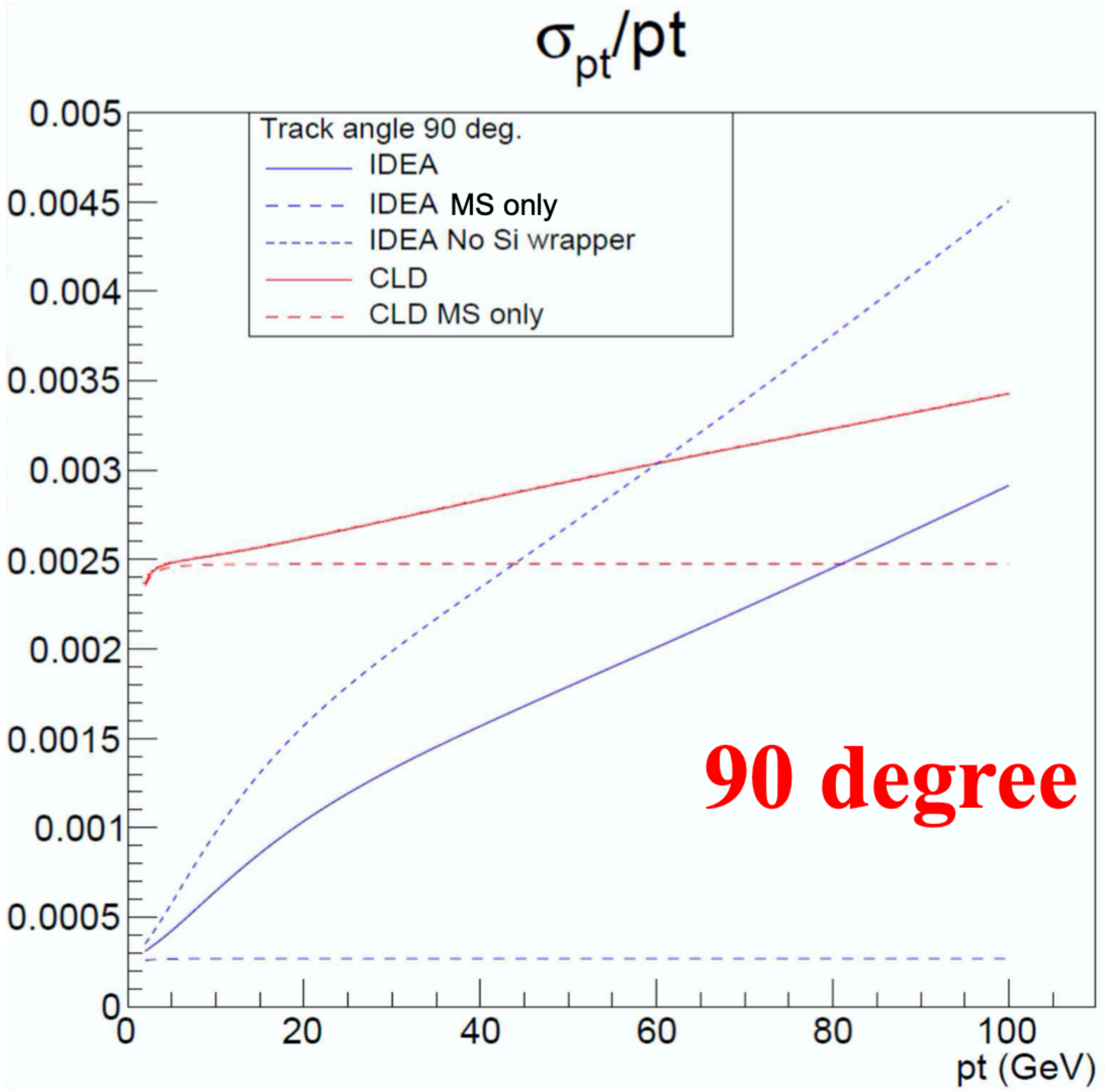
# Drift chamber

- For Higgs recoil mass analysis, both proposed tracker designs match well resolution from beam energy spread
- However, in general, tracks have rather low momenta ($p_T \lesssim 50$ GeV)
  - Transparency more relevant than asymptotic resolution

- Drift chamber (gaseous tracker) advantages
  - Extremely transparent: minimal multiple scattering and secondary interactions
  - Continuous tracking: reconstruction of far-detached vertices ($K^0_S$, $\Lambda$, BSM, LLPs)
  - Particle separation via dE/dx or cluster counting (dN/dx)
    - dE/dx much exploited in LEP analyses



# Calorimetry: CLD



## Particle flow calorimetry (inspired by CALICE)

**CLD**:

- Si-W sampling ECAL,

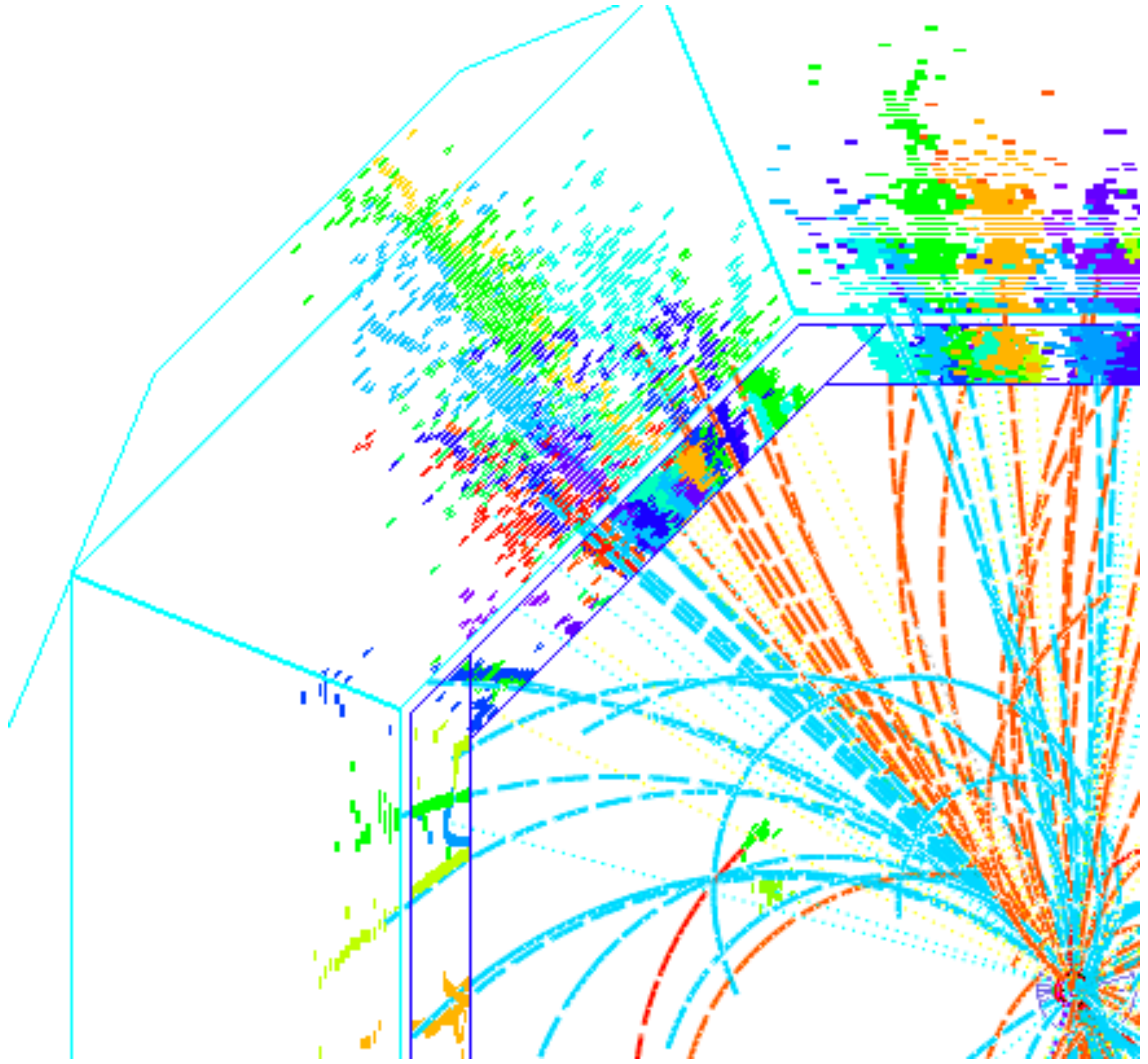
cell size: 5 x 5 mm²

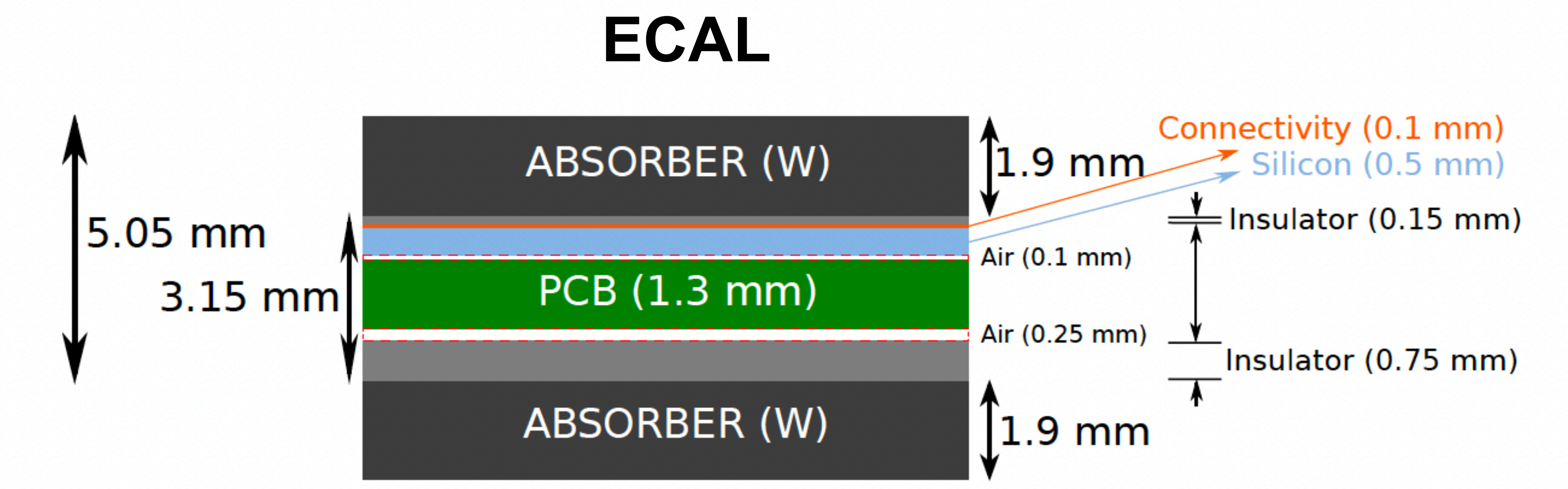
40 layers (1.9 mm thick W plates), 22-23 $X_0$ total, 20 cm thick

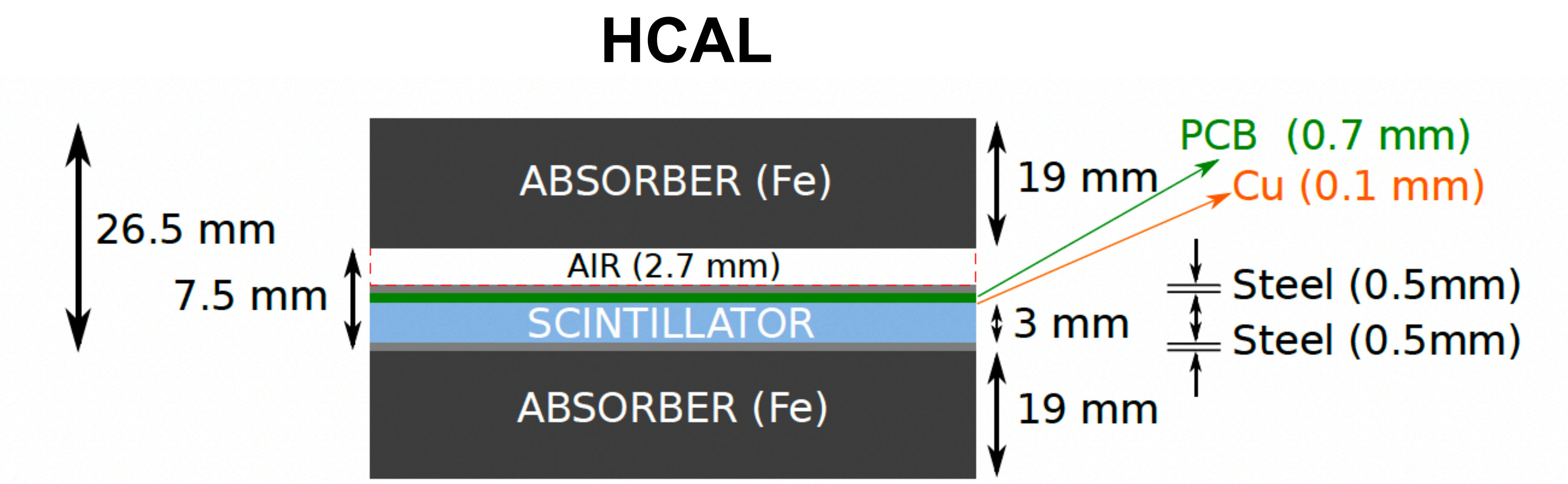
- Scintillator-steel sampling HCAL,

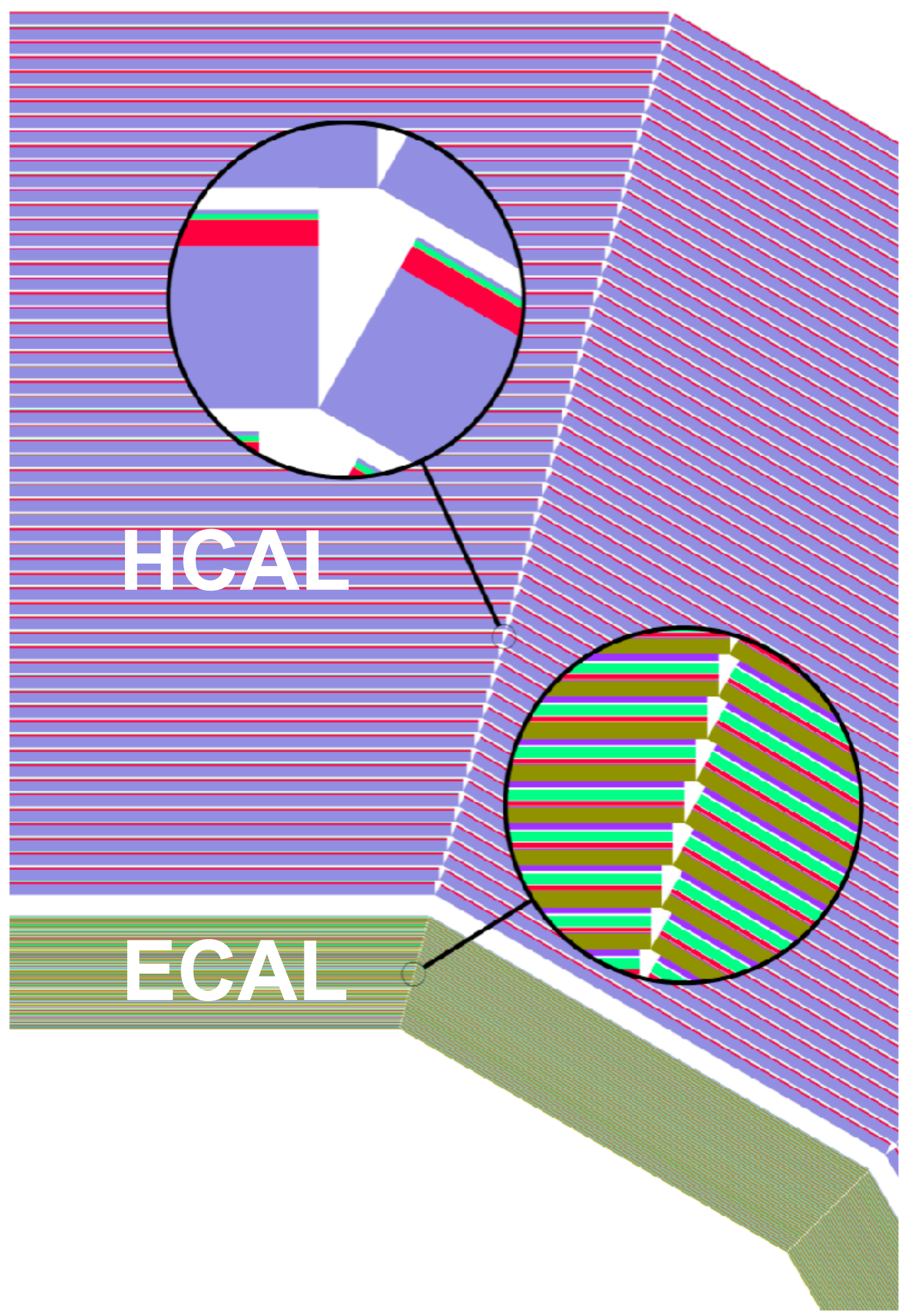
cell size: 30 x 30 mm²

44 layers (1.9 mm steel plates), 5.5 $\Lambda$ total, 117 cm thick





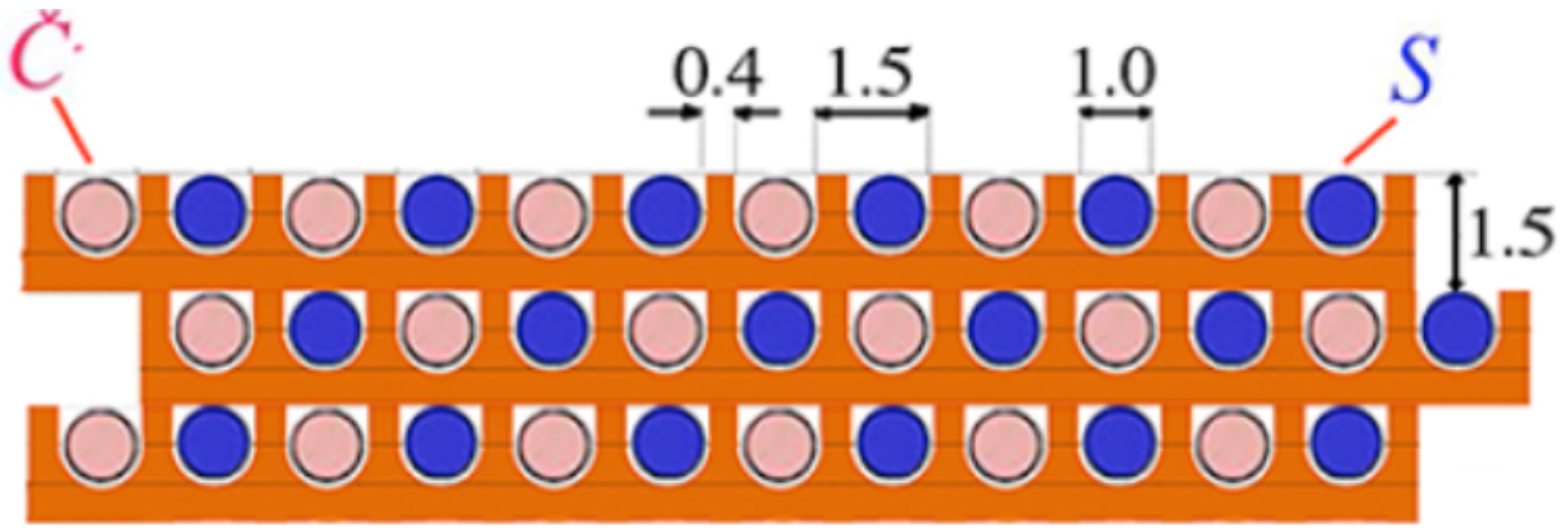




HCAL has been prototyped and tested by CALICE
*J. Phys. Conf. Ser.* 1162 (2019) 1, 012012 and https://arxiv.org/abs/2209.15327 and *JINST 18 (2023)* 08, P08014

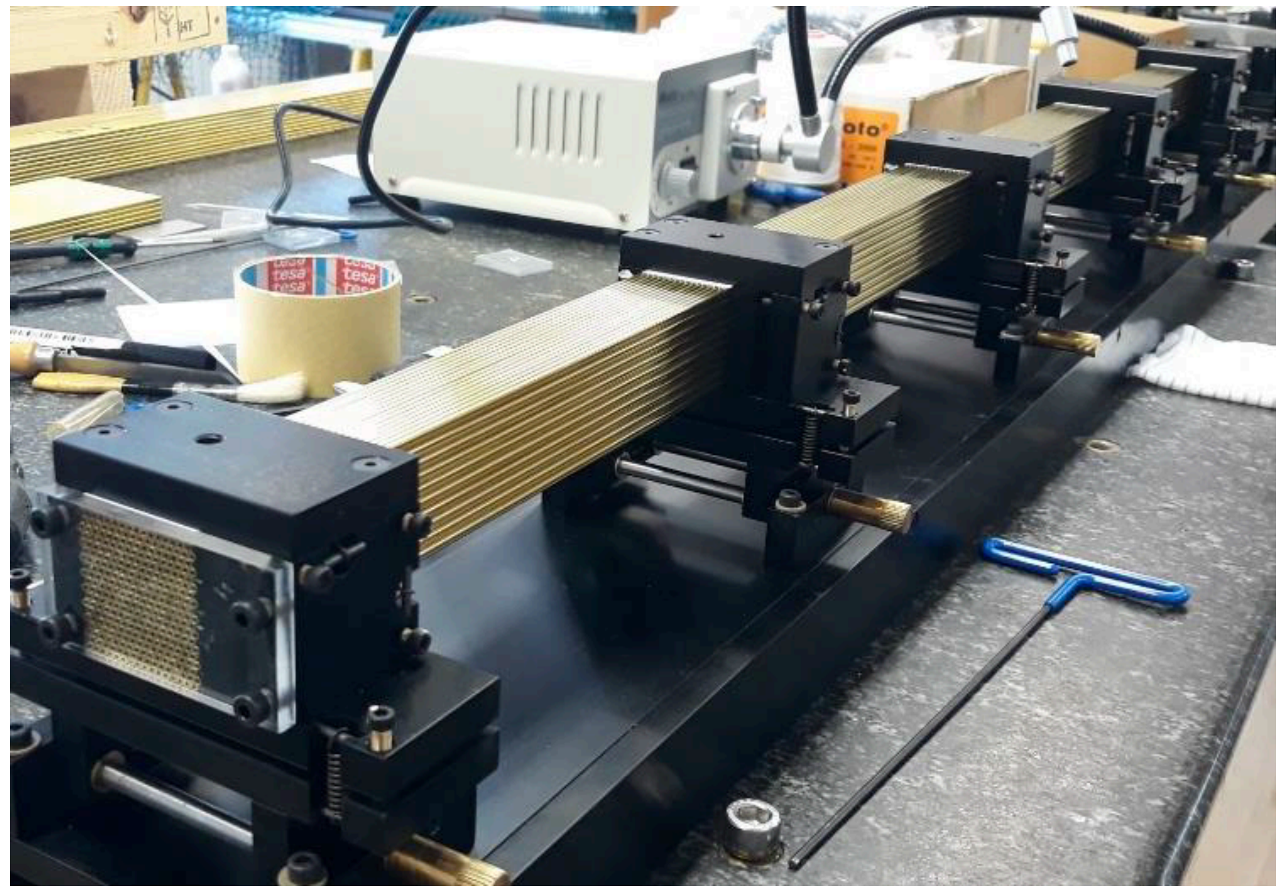
ECAL and HCAL technologies have inspired the CMS HGCAL

# Calorimetry: IDEA

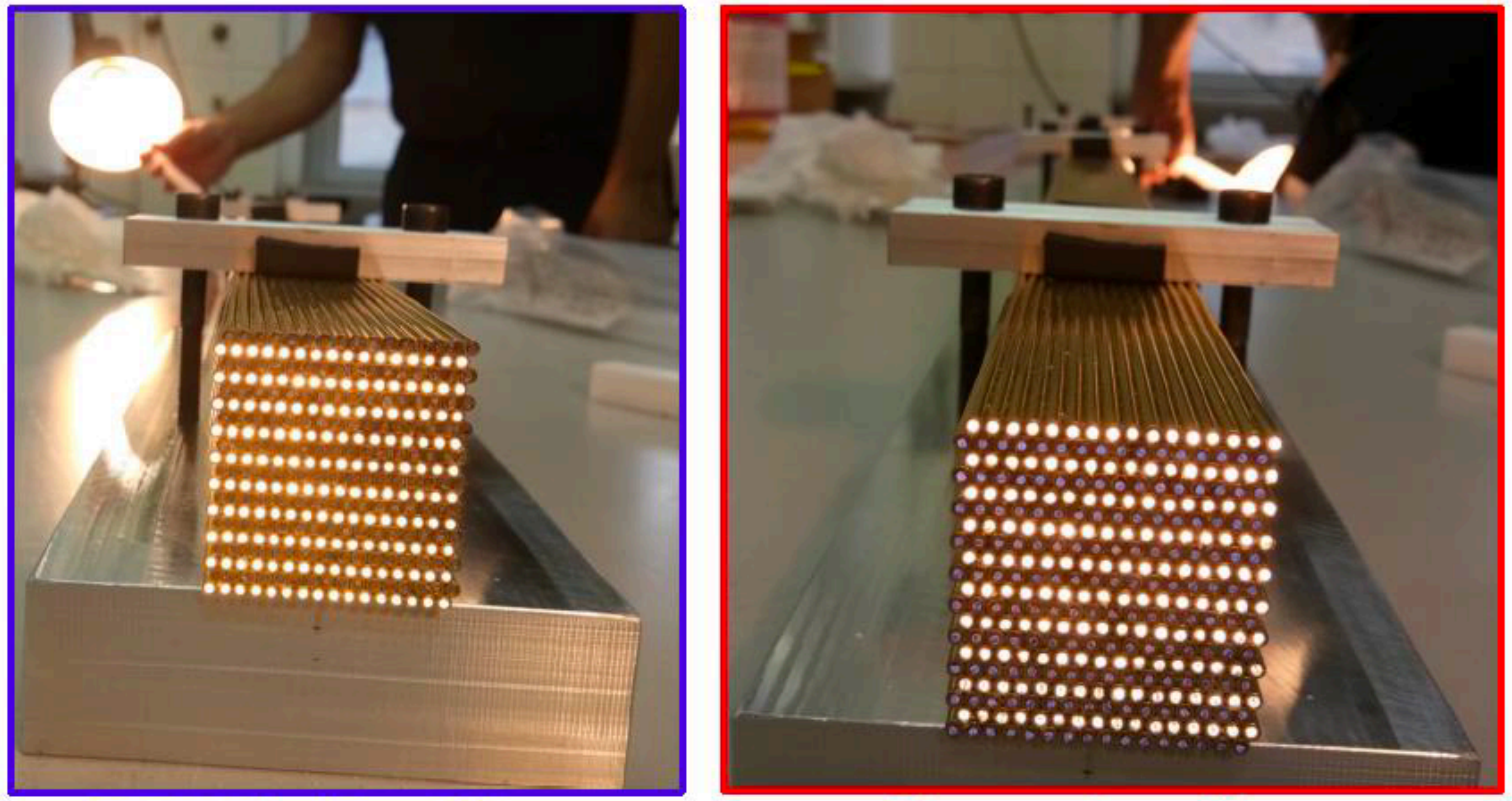



Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



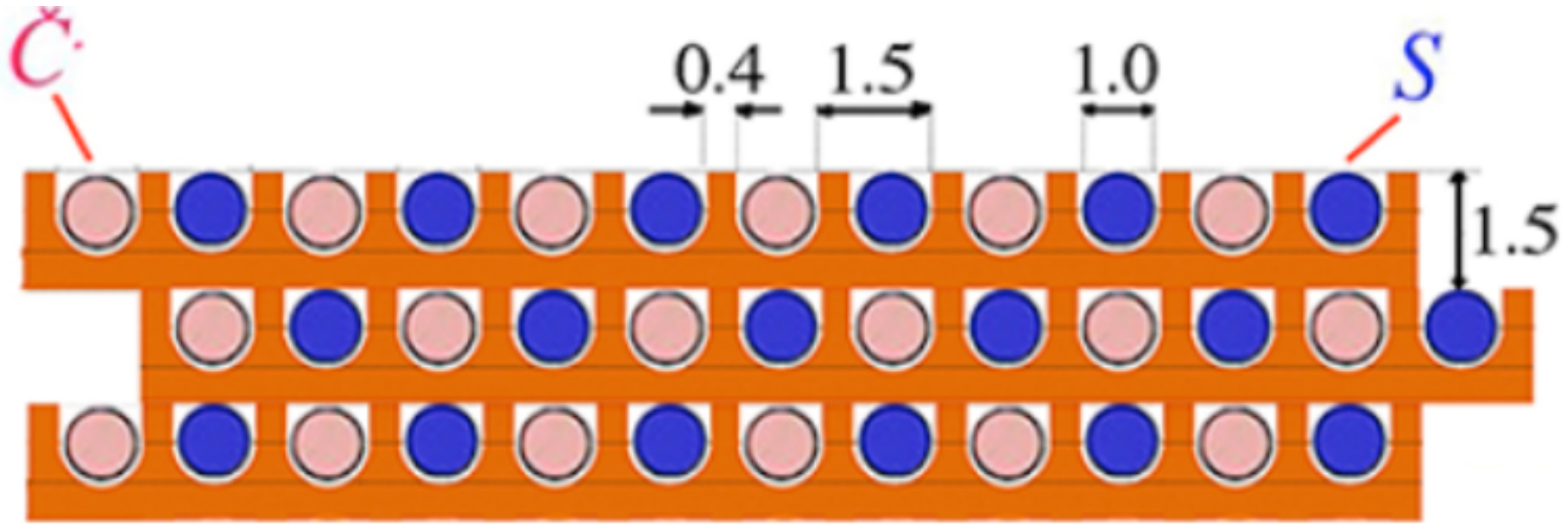
Newer DR calorimeter
( bucatini calorimeter)



Scintillation fibers

Cherenkov fibers

# Calorimetry: IDEA




Alternate
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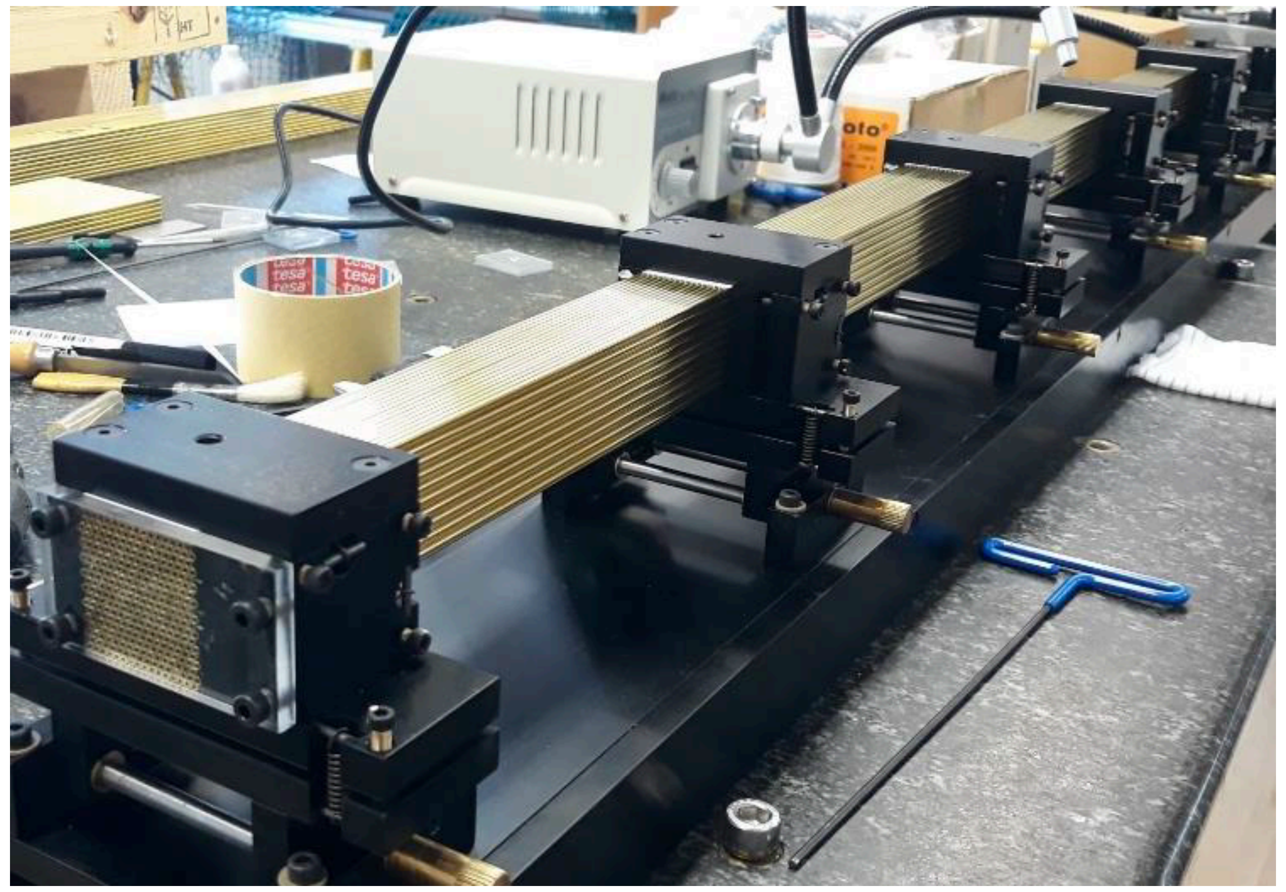
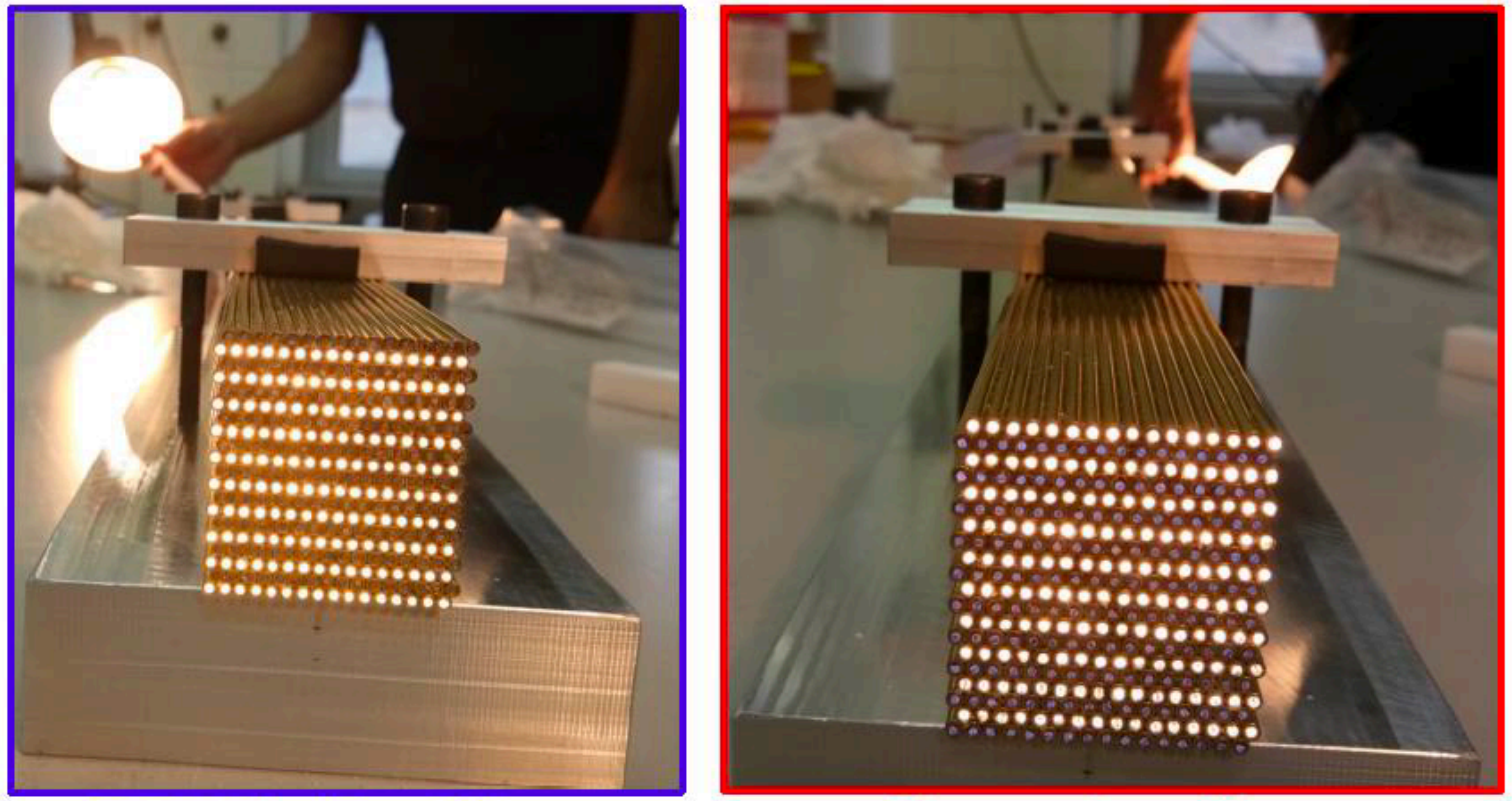


- ❖ Measure simultaneously:
  - ➢ Scintillation signal (S)
  - ➢ Cherenkov signal (Q)

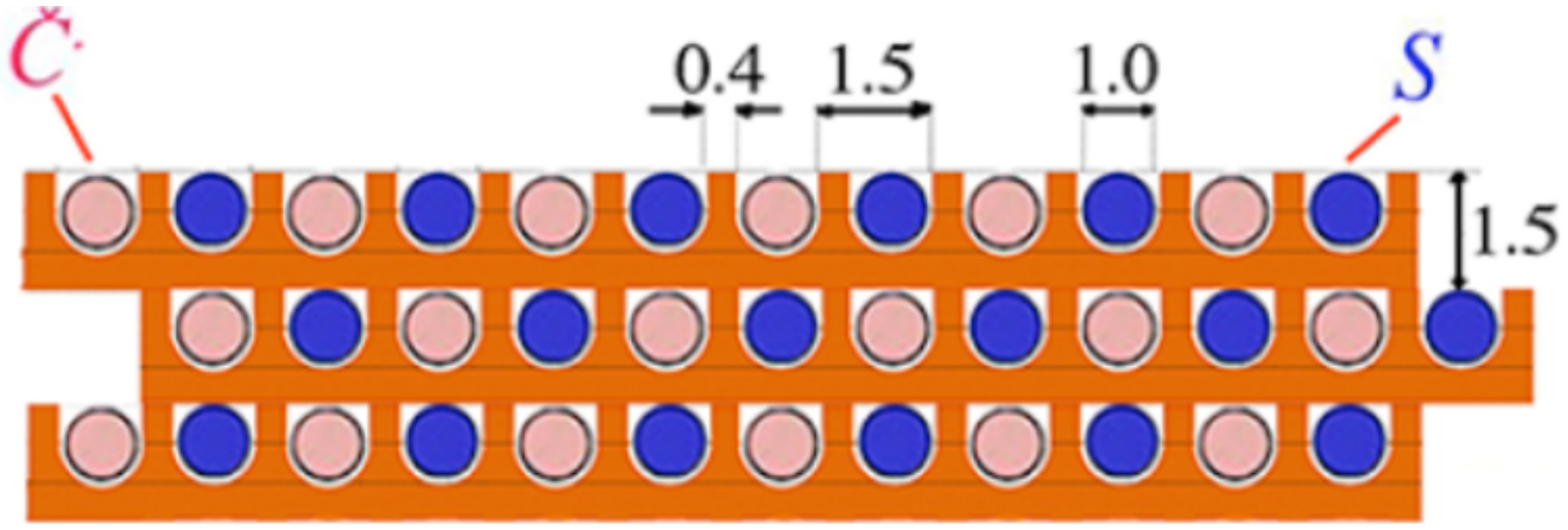
Newer DR calorimeter
( bucatini calorimeter)



Scintillation fibers  Cherenkov fibers

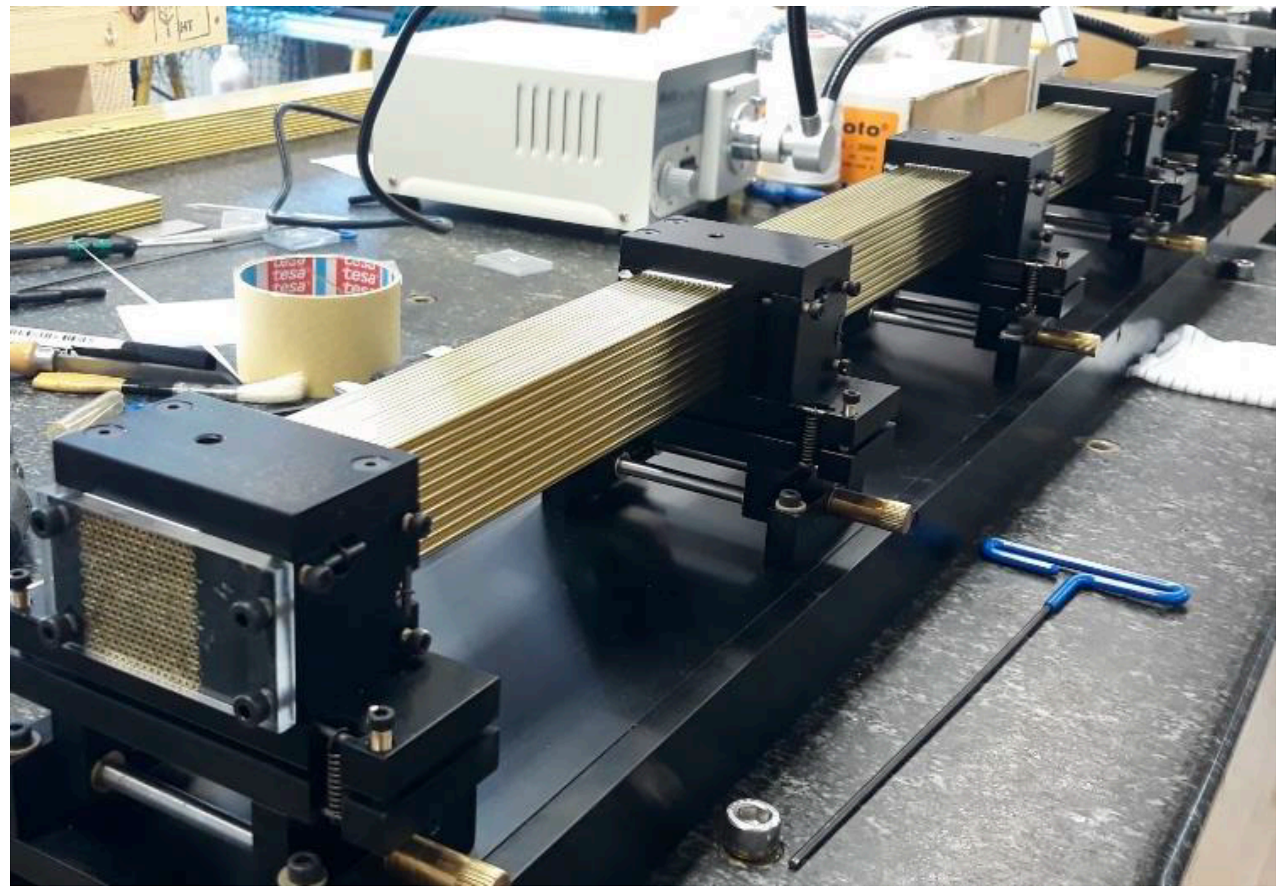
# Calorimetry: IDEA






Alternate
Cherenkov fibers
Scintillating fibers

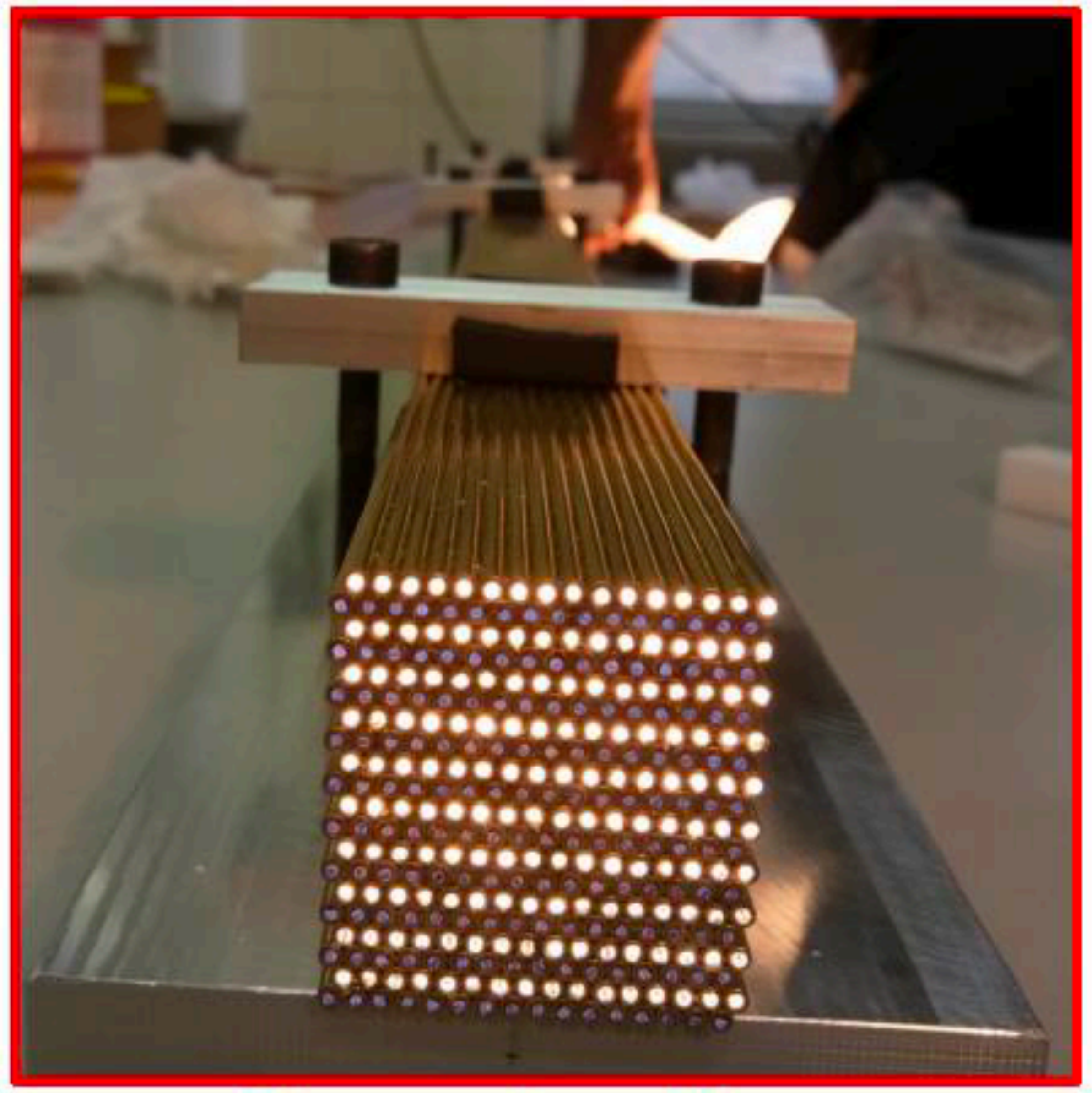
~2m long capillaries



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

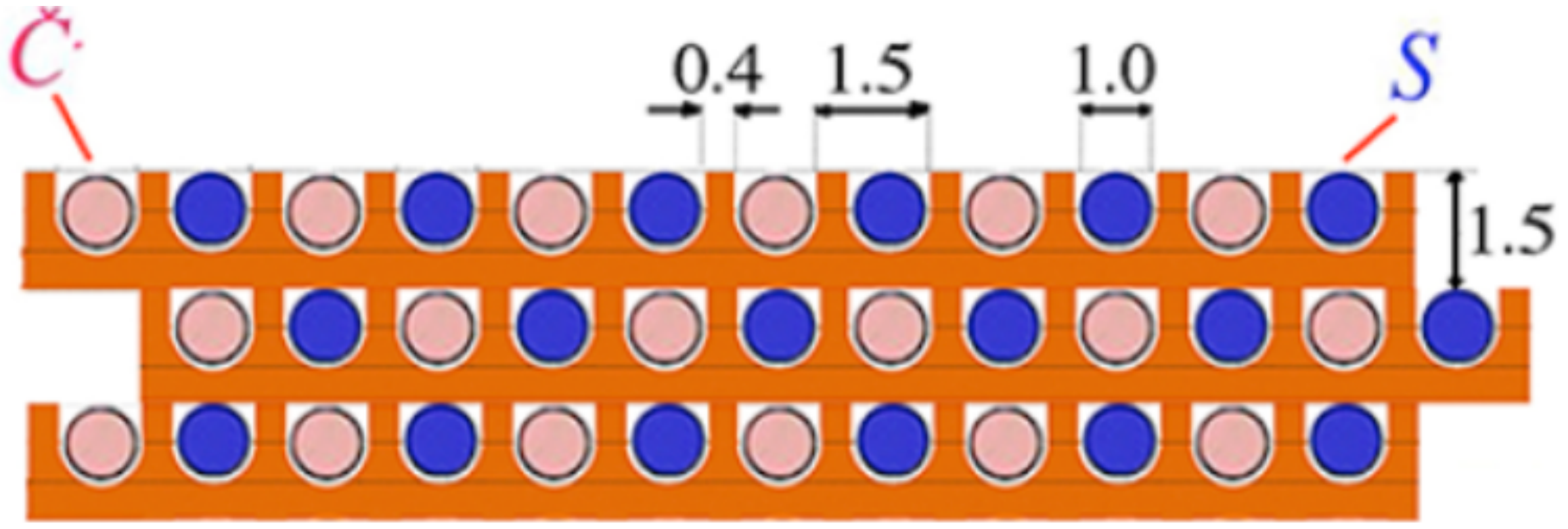
Newer DR calorimeter
( bucatini calorimeter)

Scintillation fibers



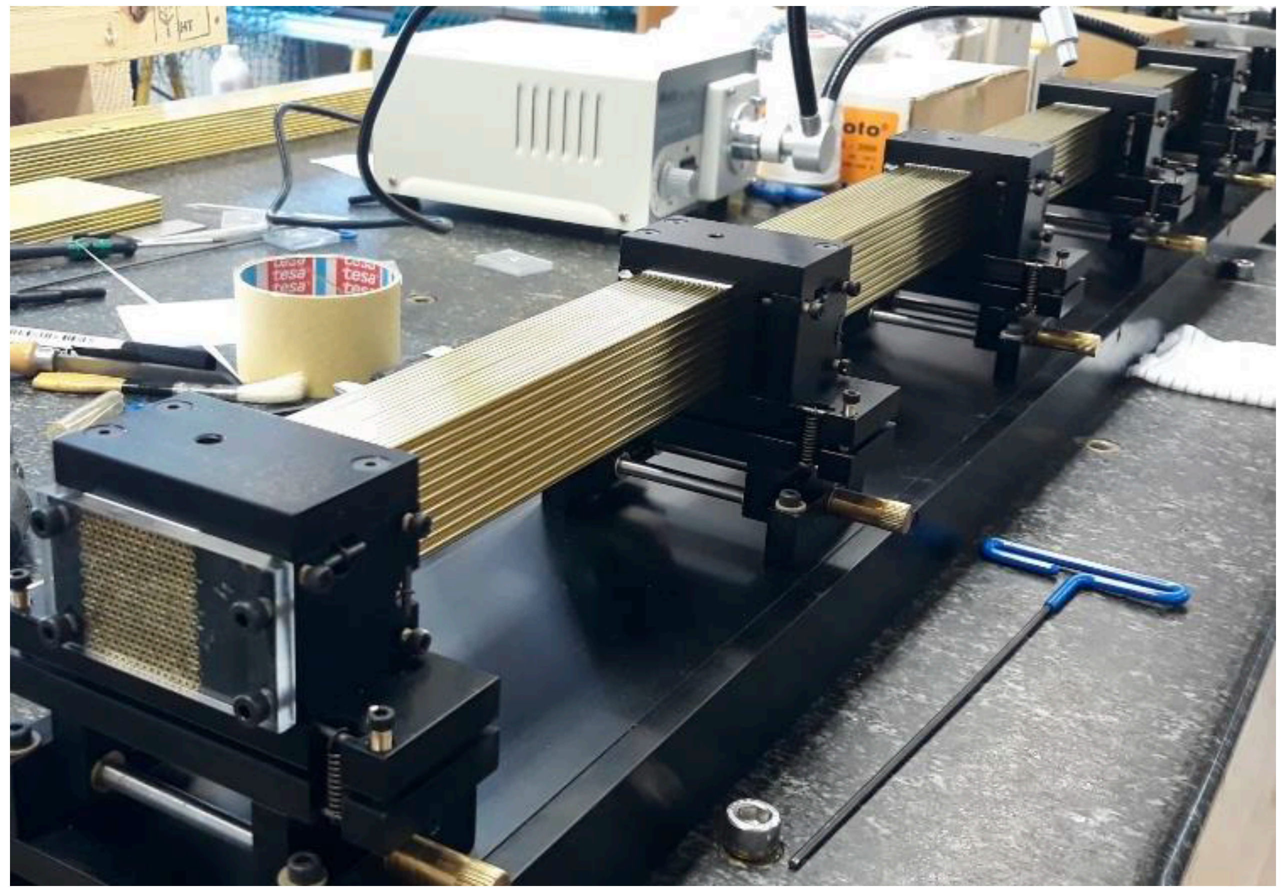
Cherenkov fibers

# Calorimetry: IDEA




Alternate
Cherenkov fibers
Scintillating fibers

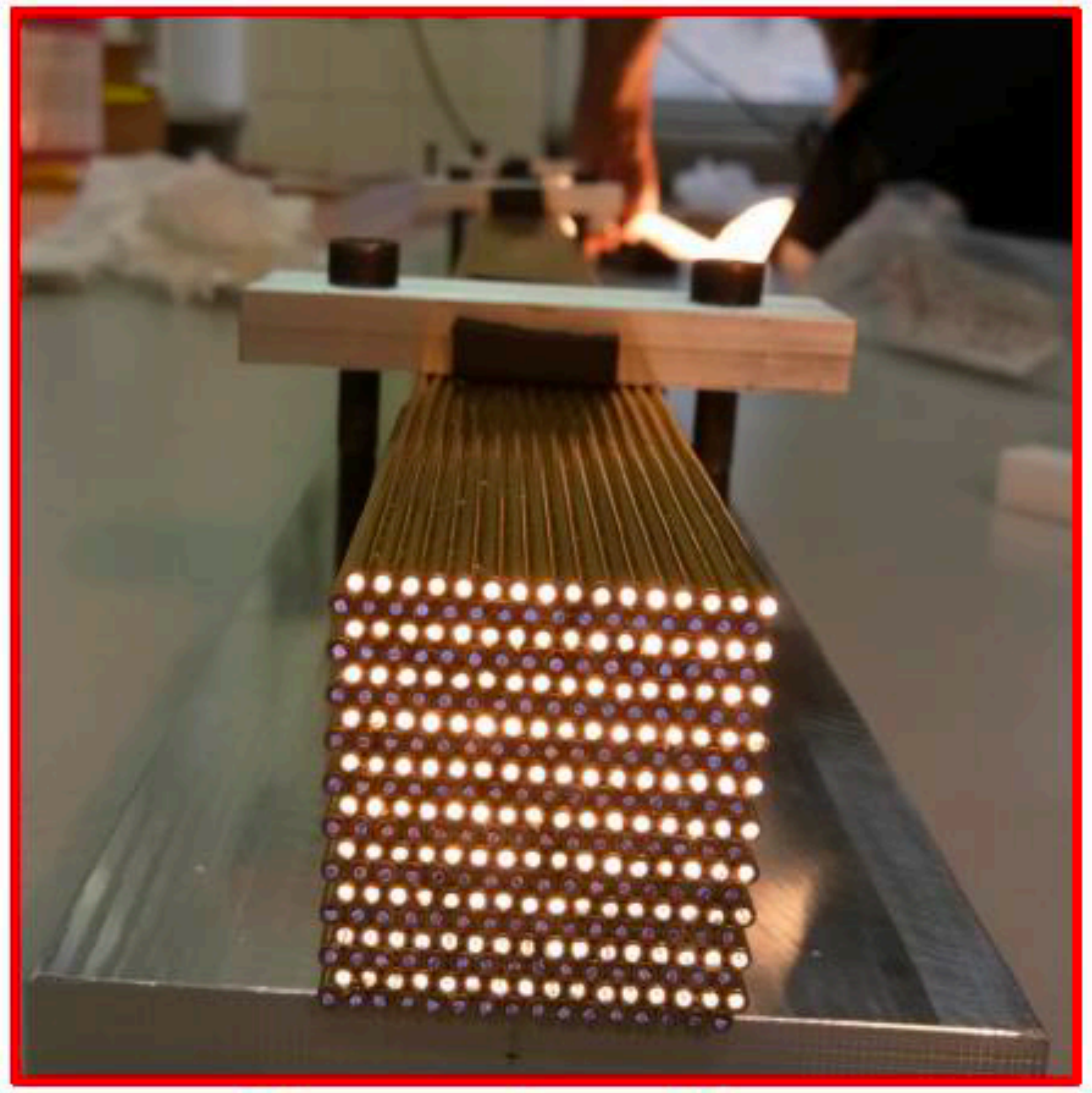
~2m long capillaries



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

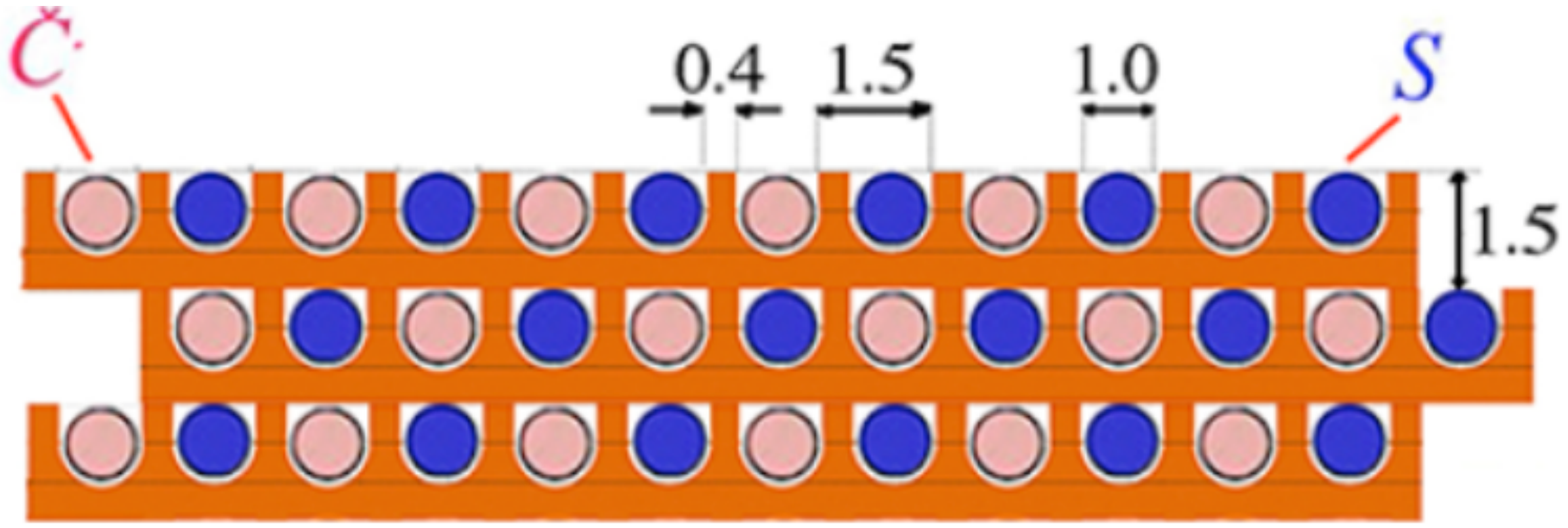
Newer DR calorimeter
( bucatini calorimeter)

Scintillation fibers



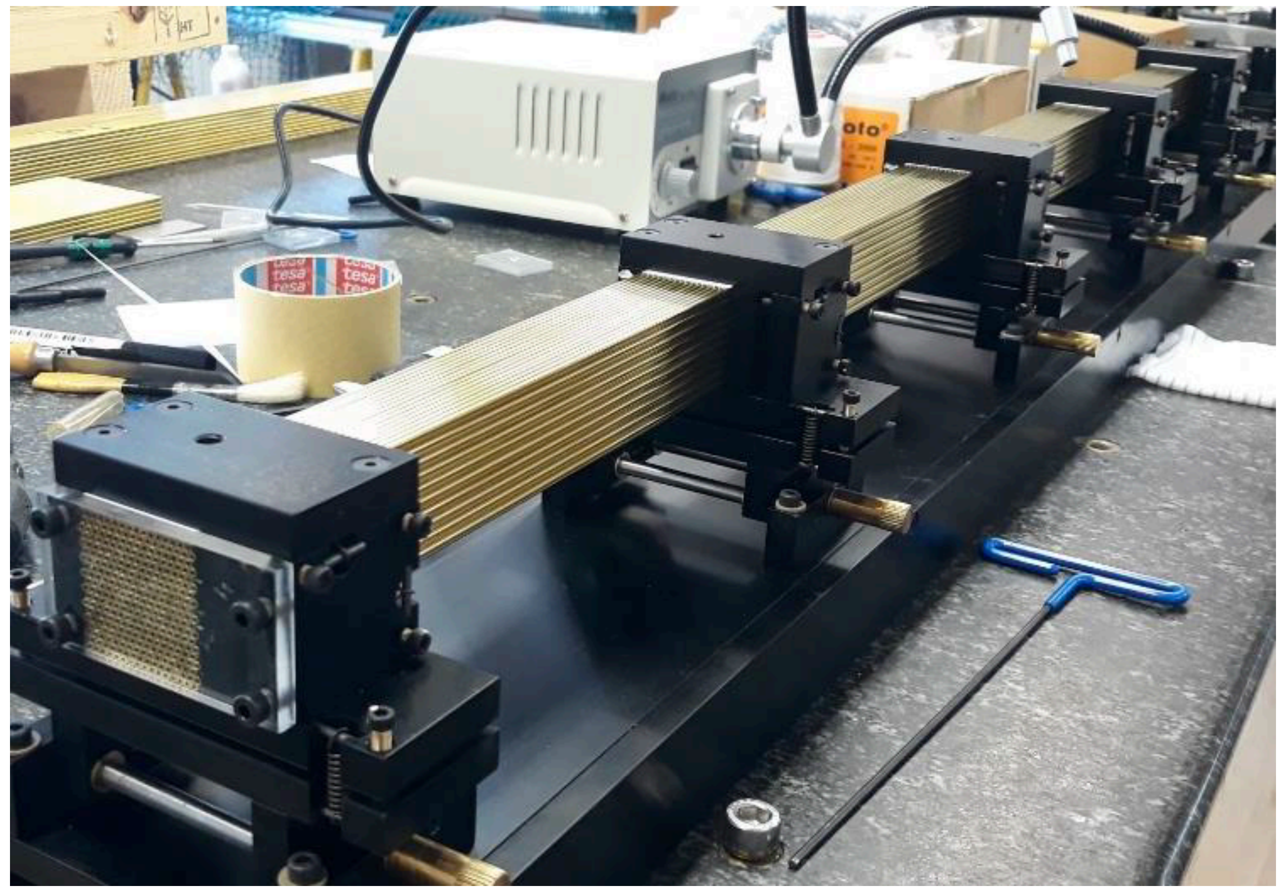
Cherenkov fibers

# Calorimetry: IDEA




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

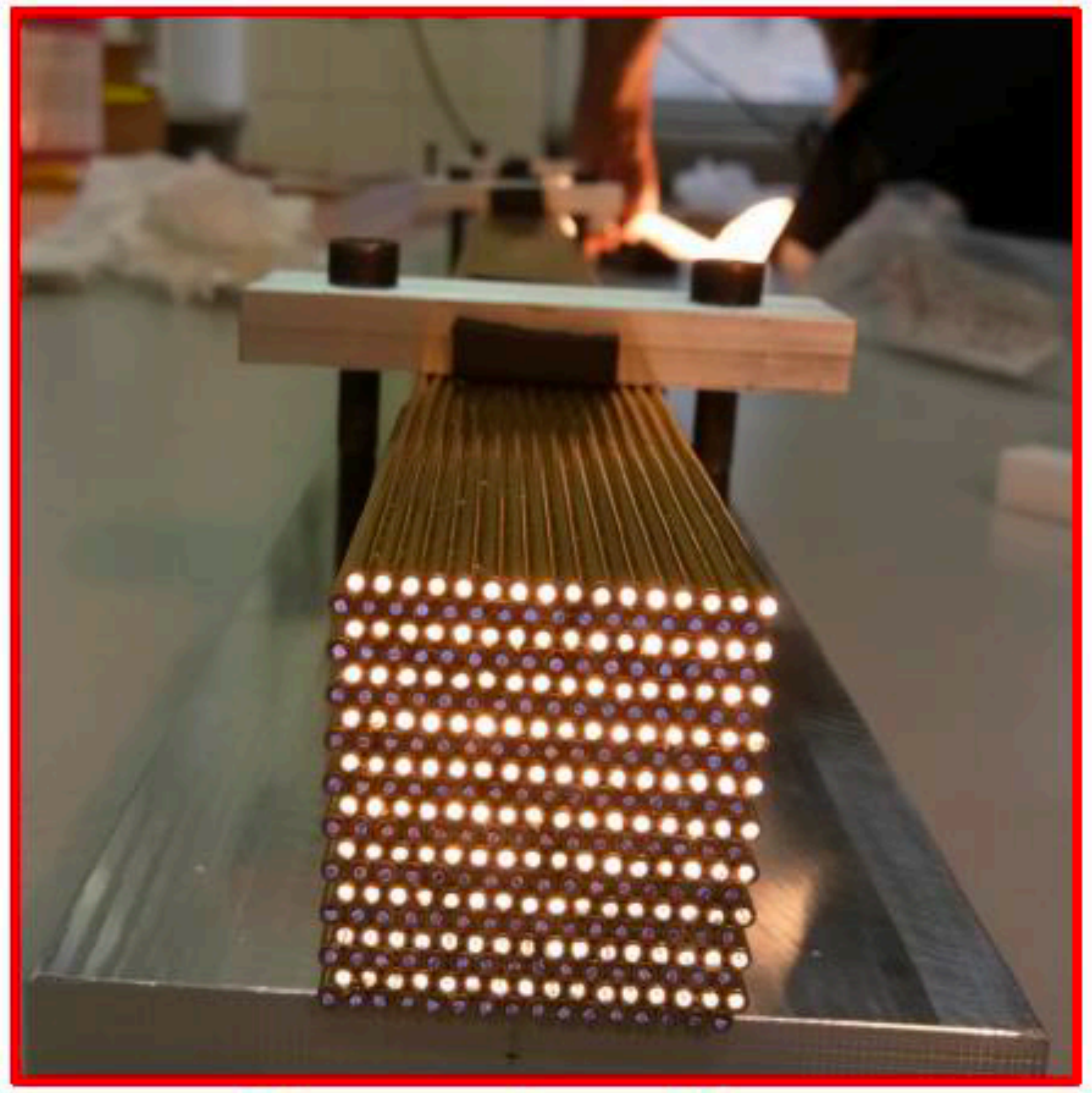
$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

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

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

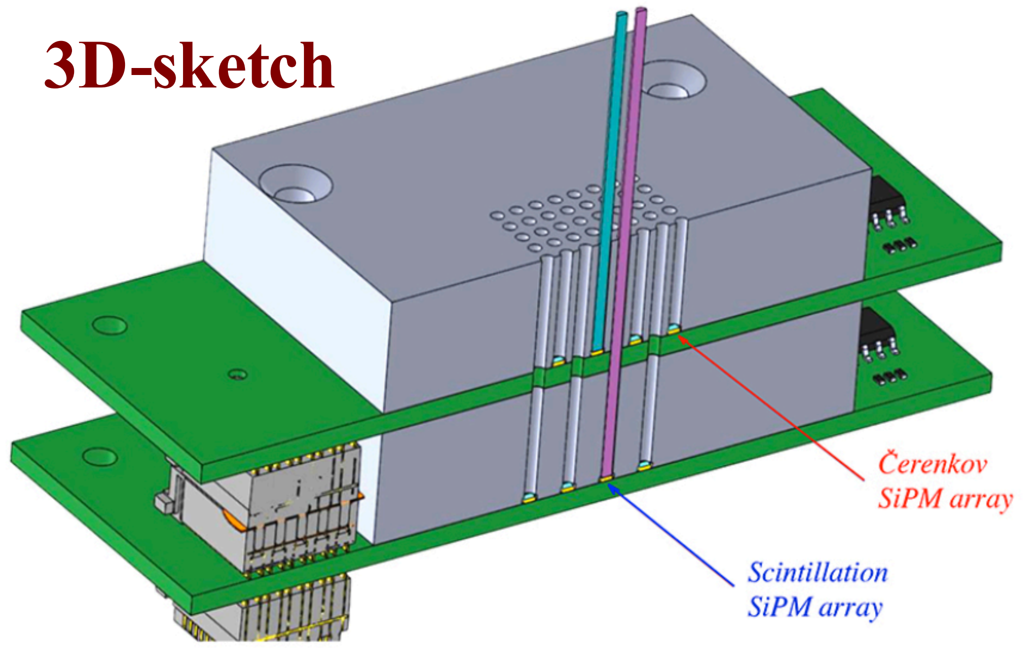
Newer DR calorimeter
( bucatini calorimeter)

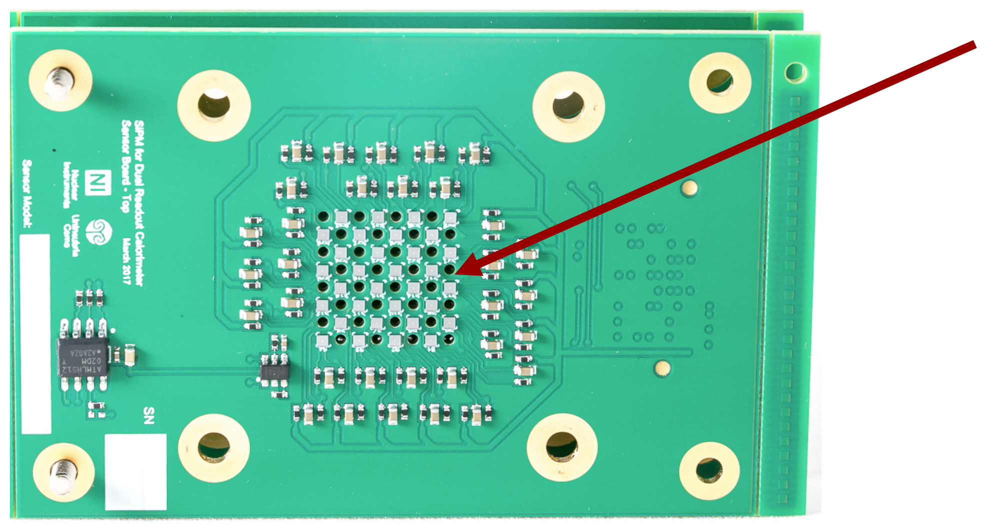
Scintillation fibers

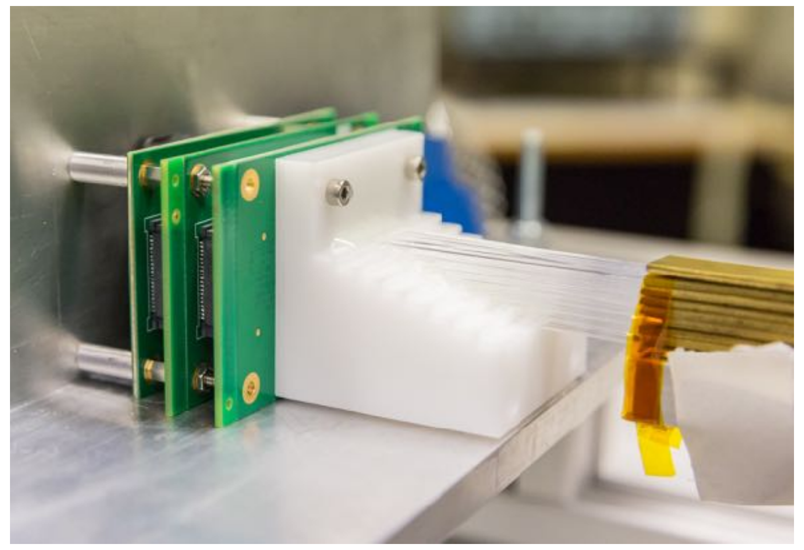


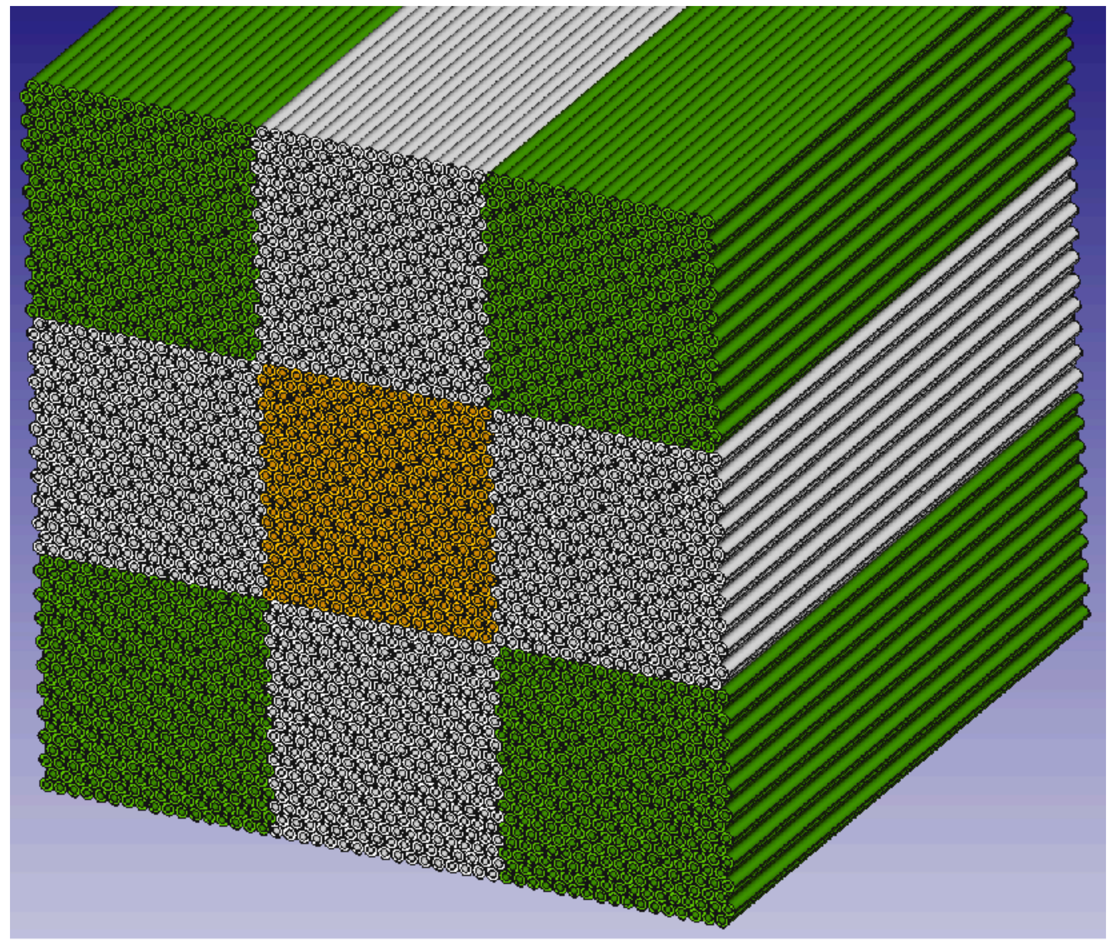
Cherenkov fibers

# Calorimetry: IDEA

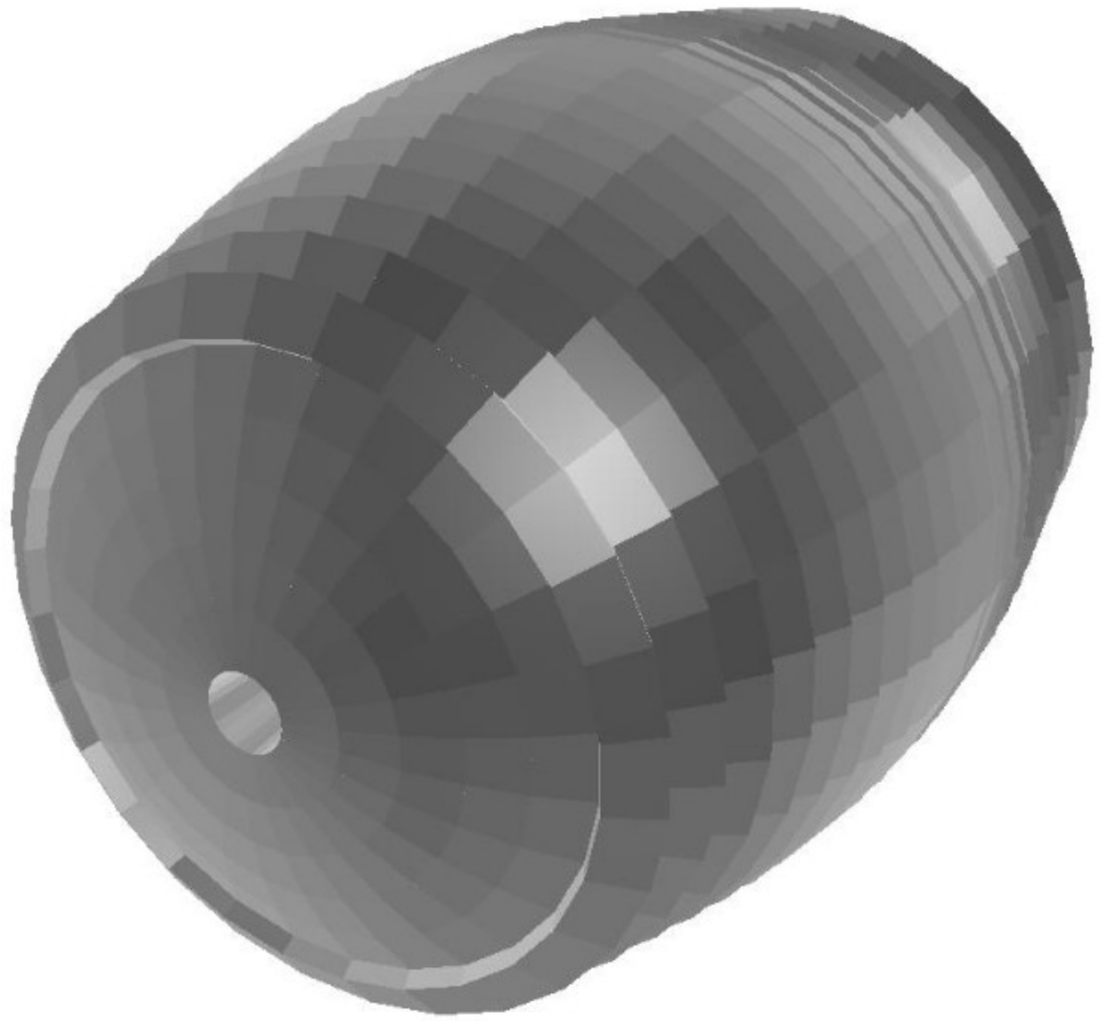


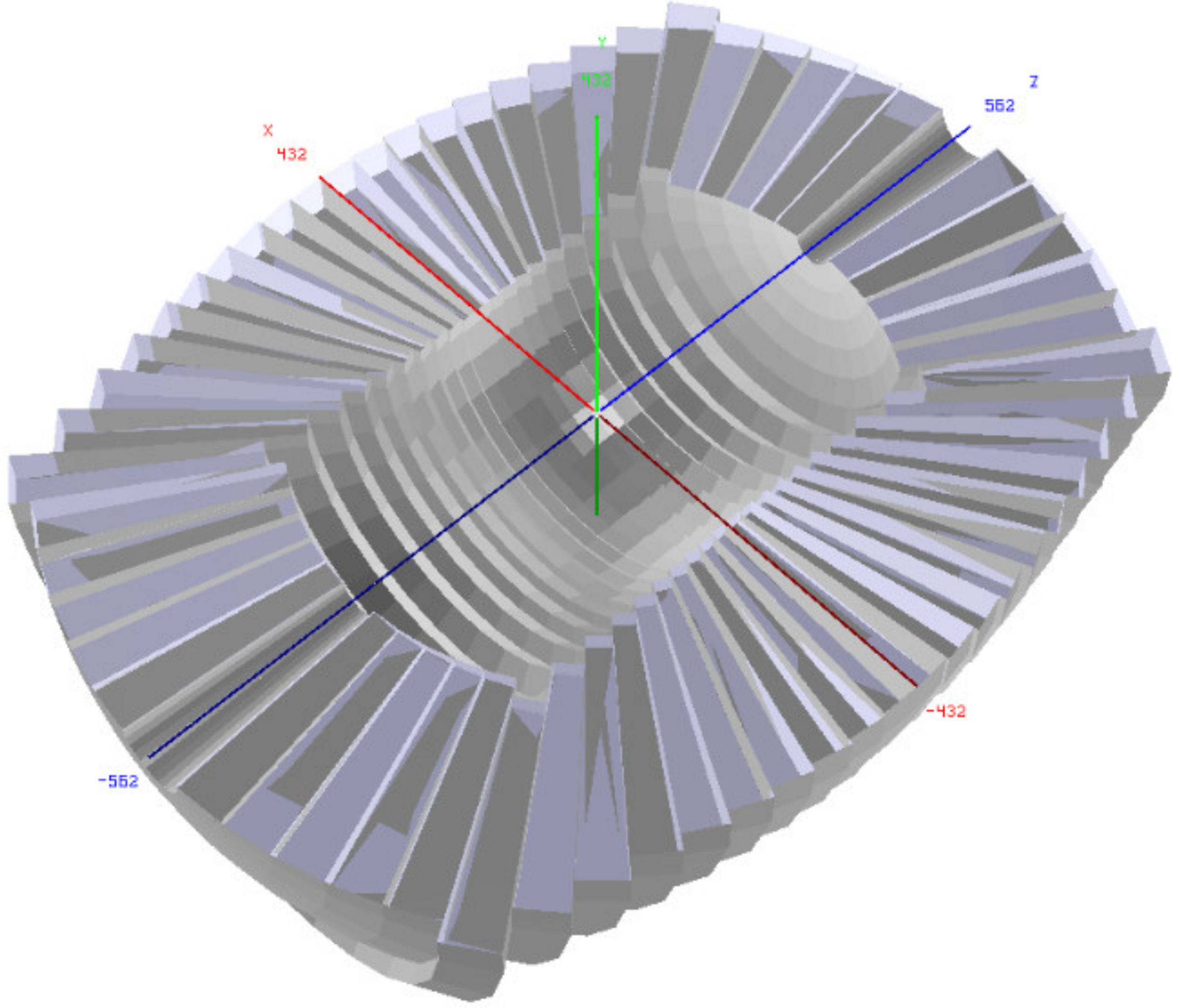



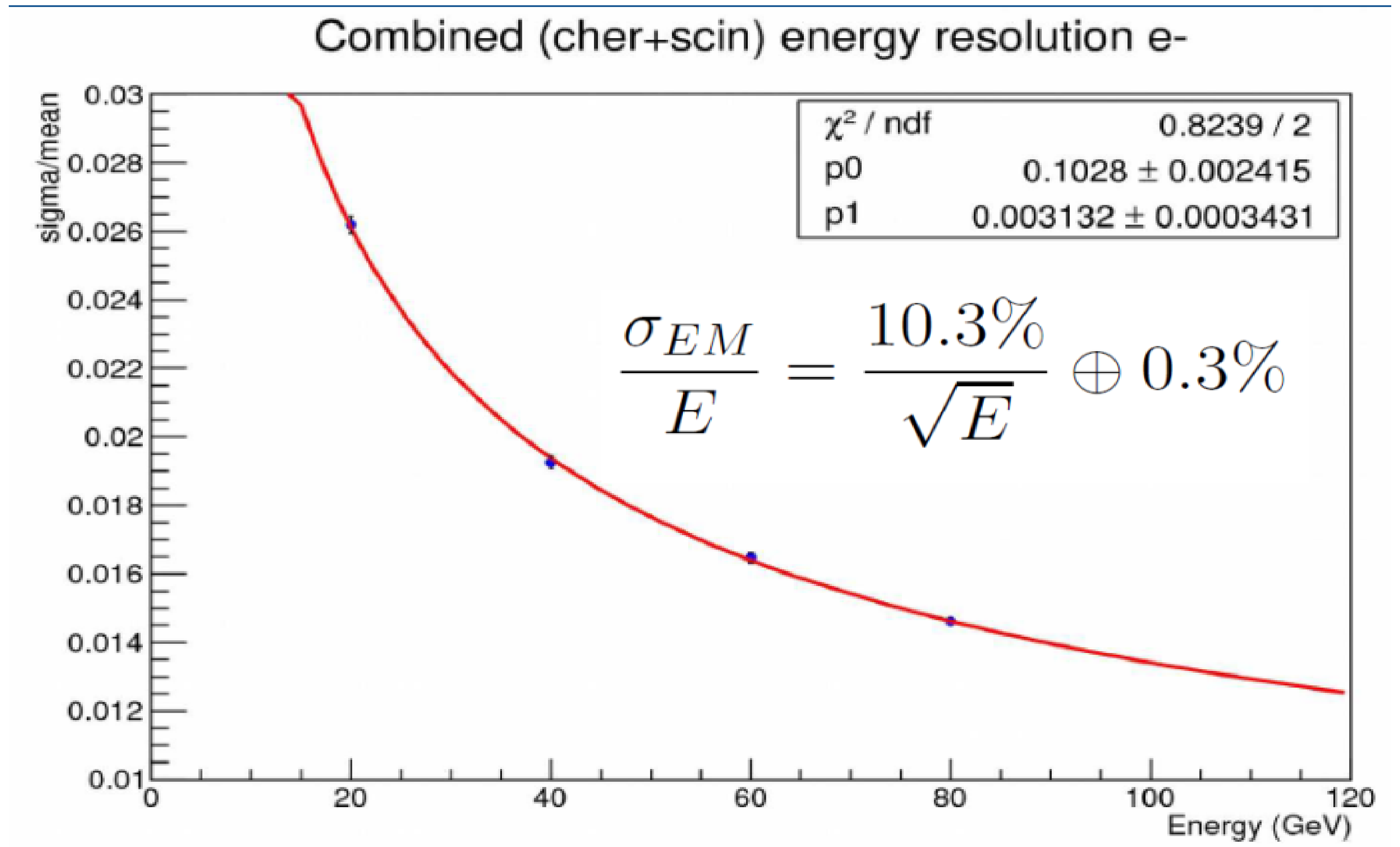


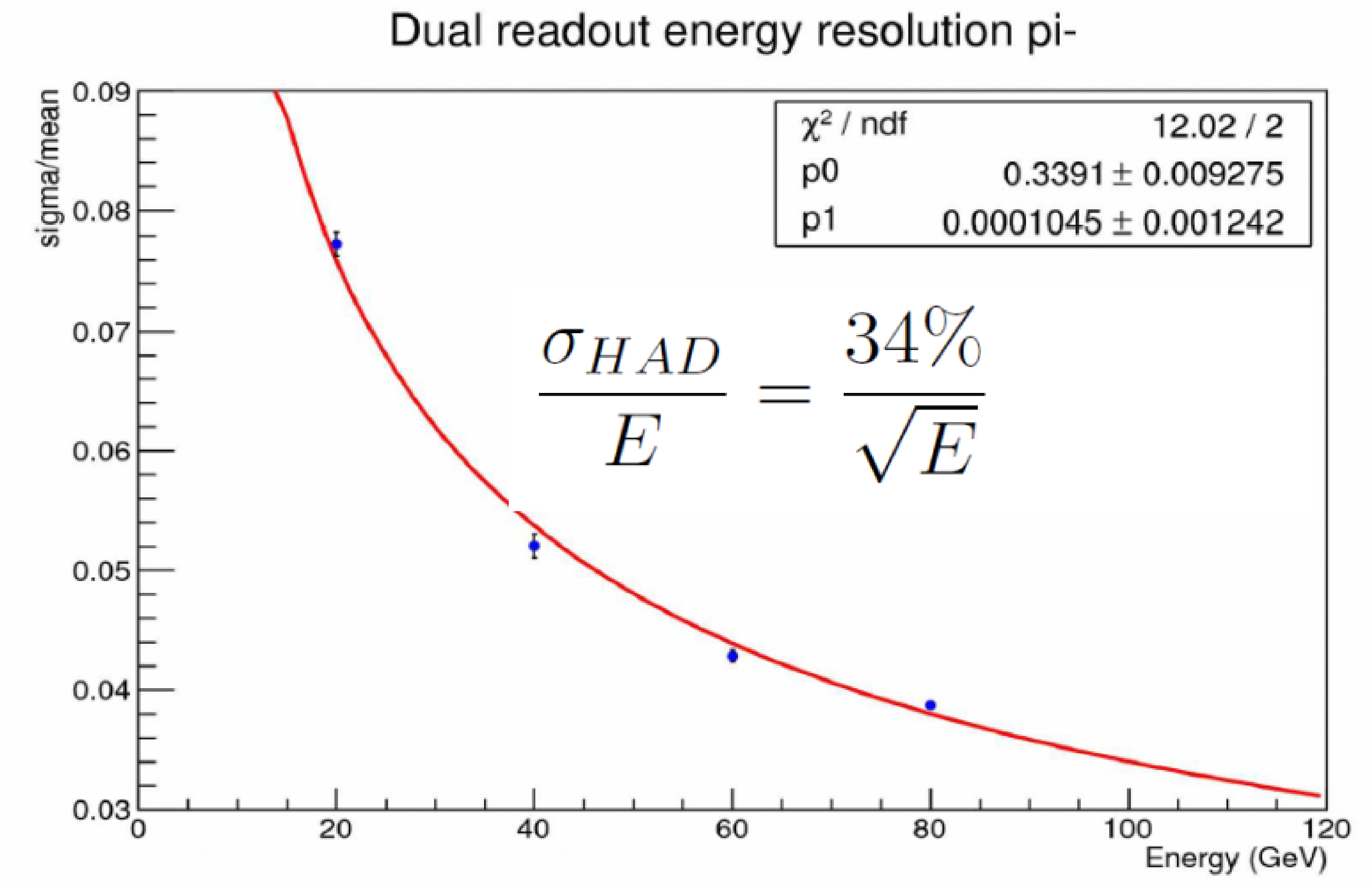


## Full GEANT4 implementation of the DR calorimeter





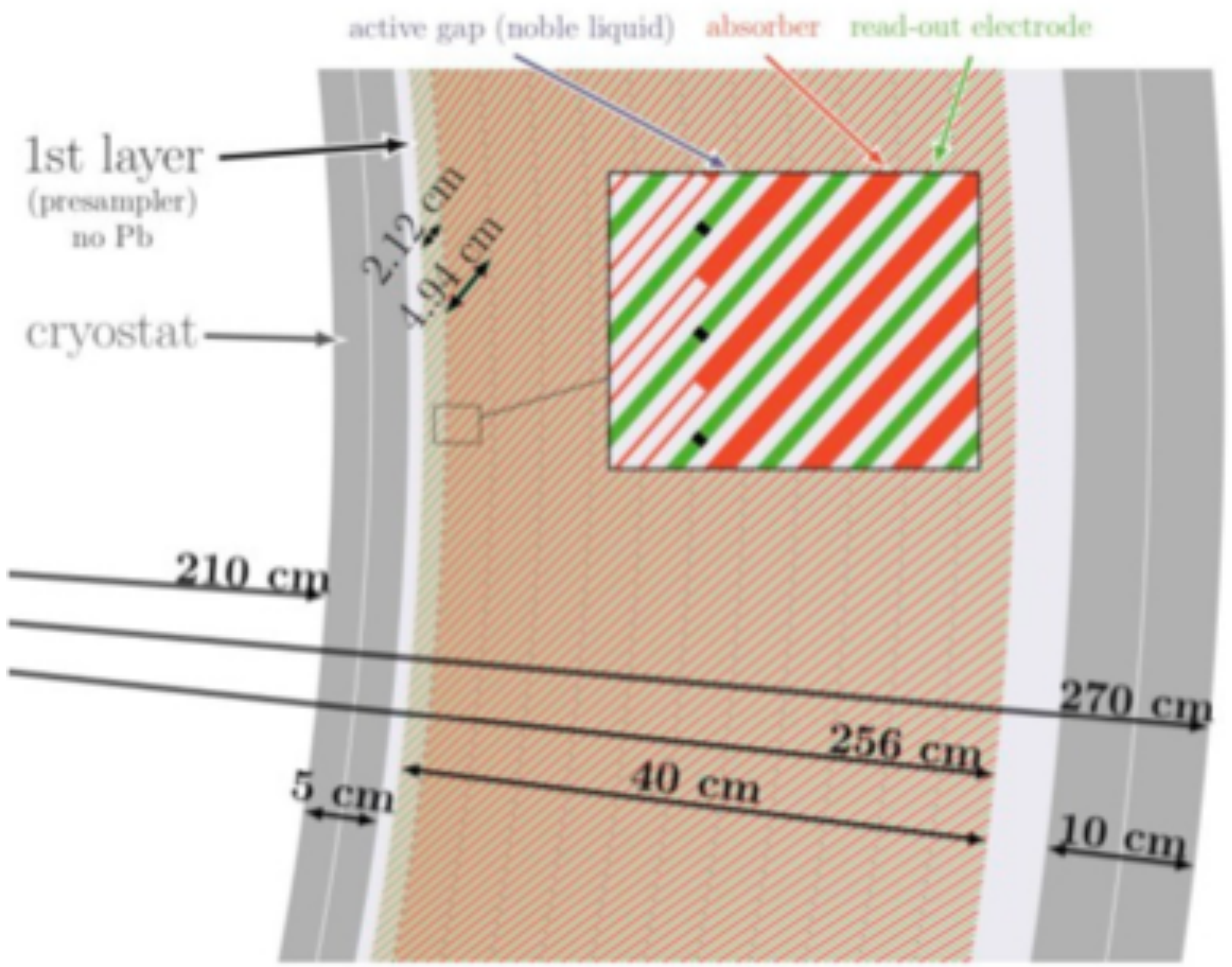


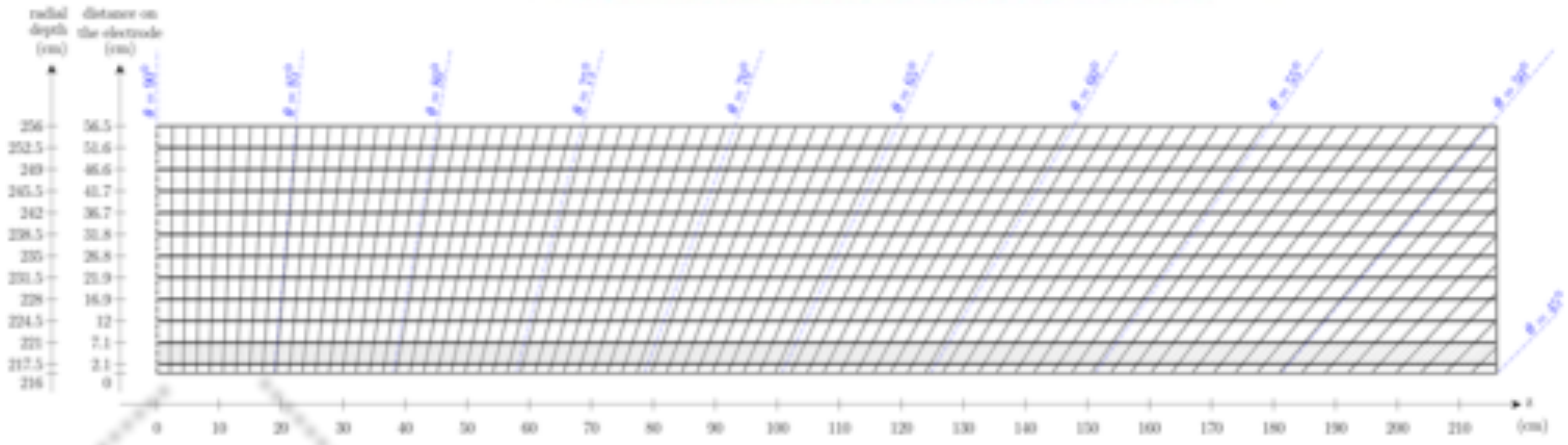



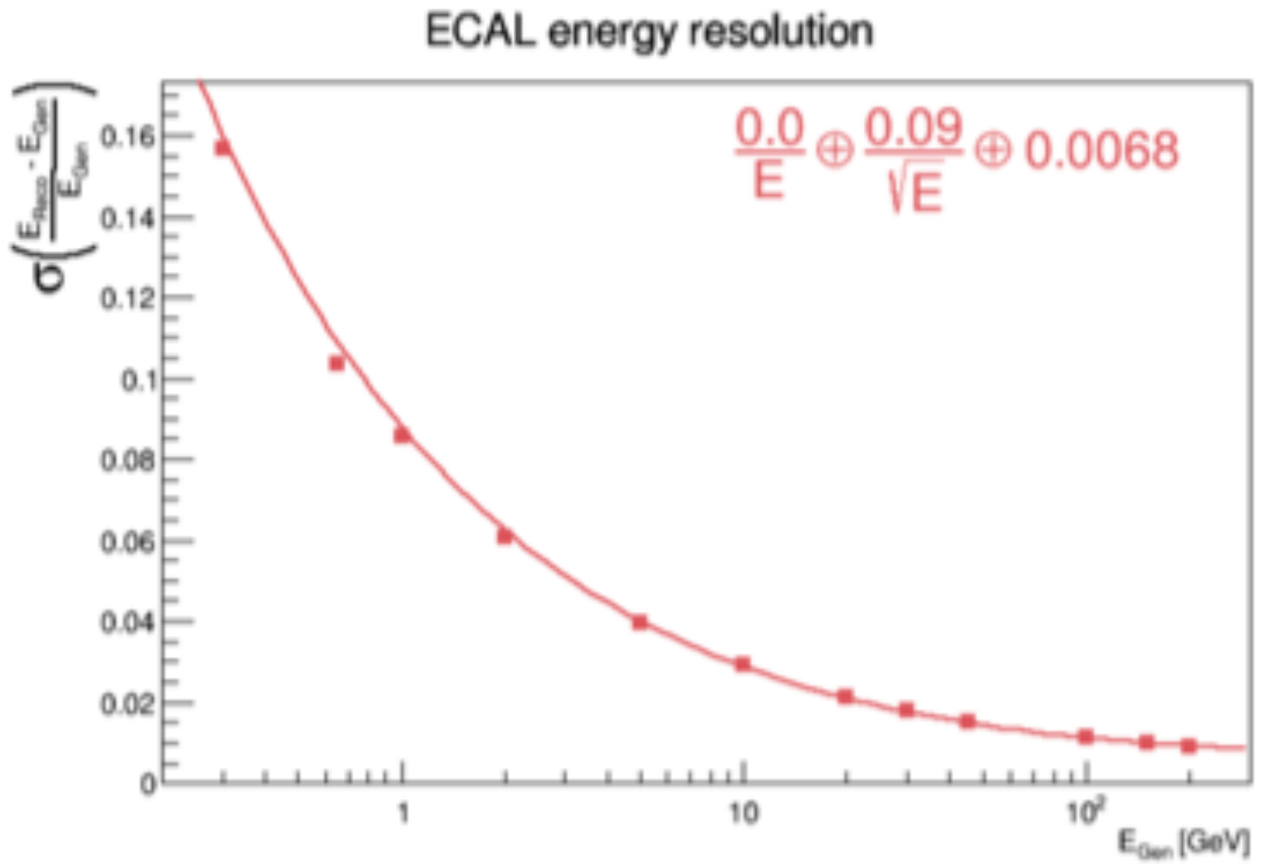
# Calorimetry: LAr ECAL

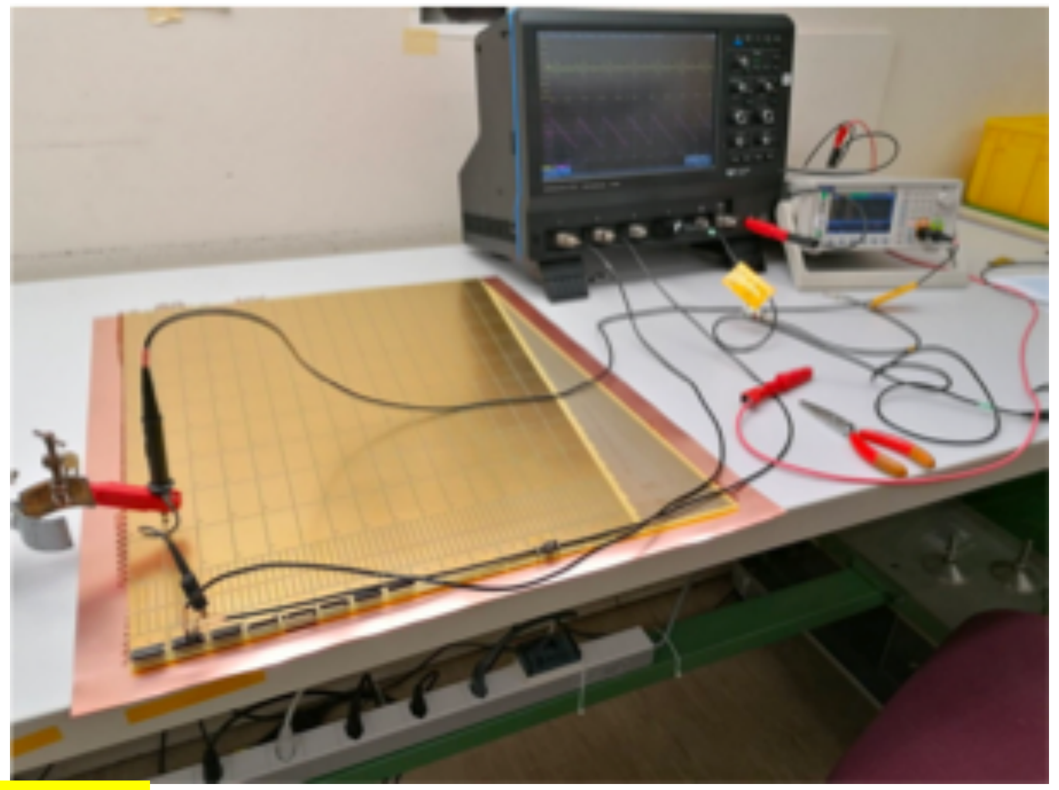


- Good experience with noble liquid ECALs in a number of experiments, e.g. D., H1, NA48/62, ATLAS
  - Good energy resolution, $\sigma_{EM} \sim 10\%/\sqrt{E}$
  - Linearity, uniformity, stability of response
    - Low systematics
- Baseline design for FCC-ee detector
  - 1536 straight inclined ($50.4_o$) 1.8mm Pb absorber plates, 22 $X_0$
  - Multi-layer PCBs as readout electrodes. Segmentation:
    - 11 longitudinal compartments
    - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
    - $\Delta\Phi$ = 8 mrad
  - Implemented in FCC-SW Fullsim
    - 11 longitudinal compartments
    - $\sigma_{EM} \sim 9\%/\sqrt{E}$
  - Definition of end-cap geometry ongoing
  - ECAL shares cryostat with coil (as in ATLAS)
    - Coil outside ECAL
  - Possible options, R&D ongoing
    - LKr or Lar actives; W or Pb absorber
    - Al or carbon fibre cryostat
    - Warm or cold electronics



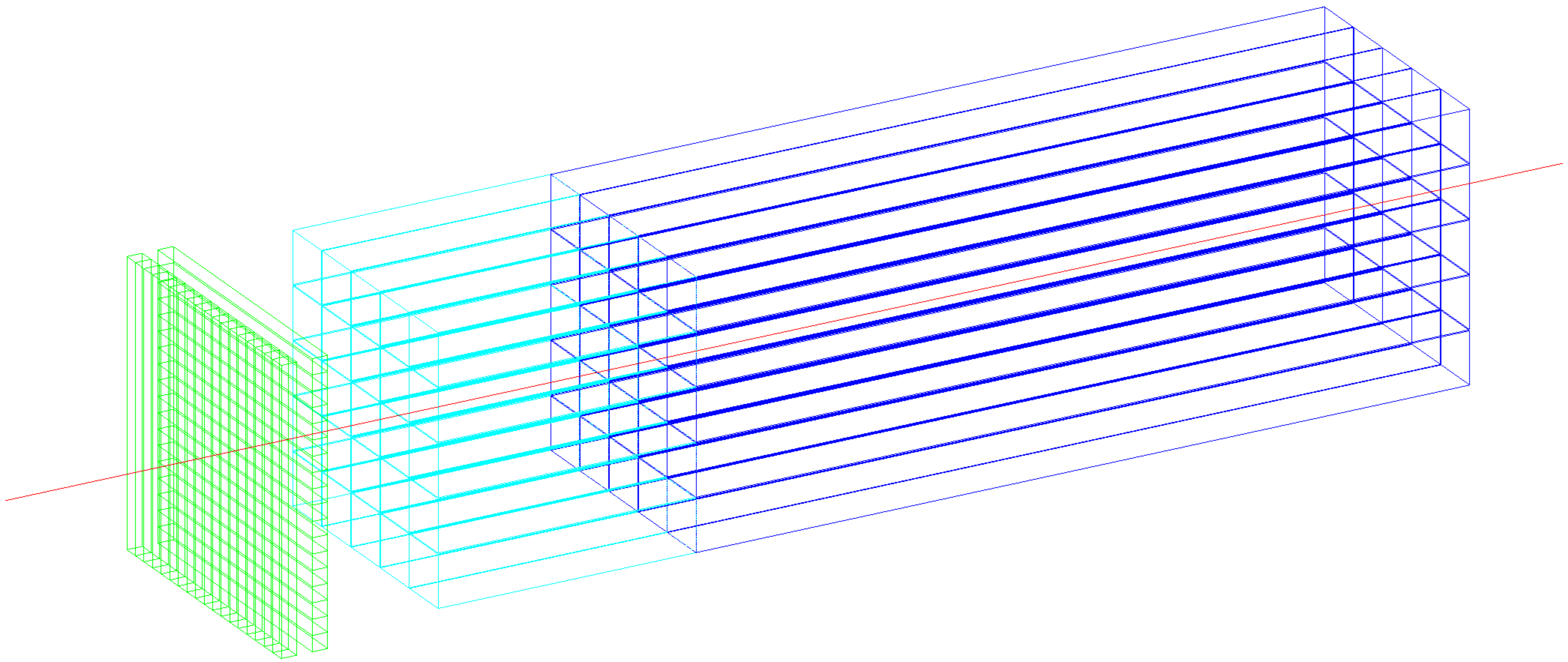


M. Dam

# Crystal option





- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4 $X_0$)
  - rear segment for core shower
  - (15 cm ~16.3 $X_0$)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)

1x1x5 cm³ PbWO

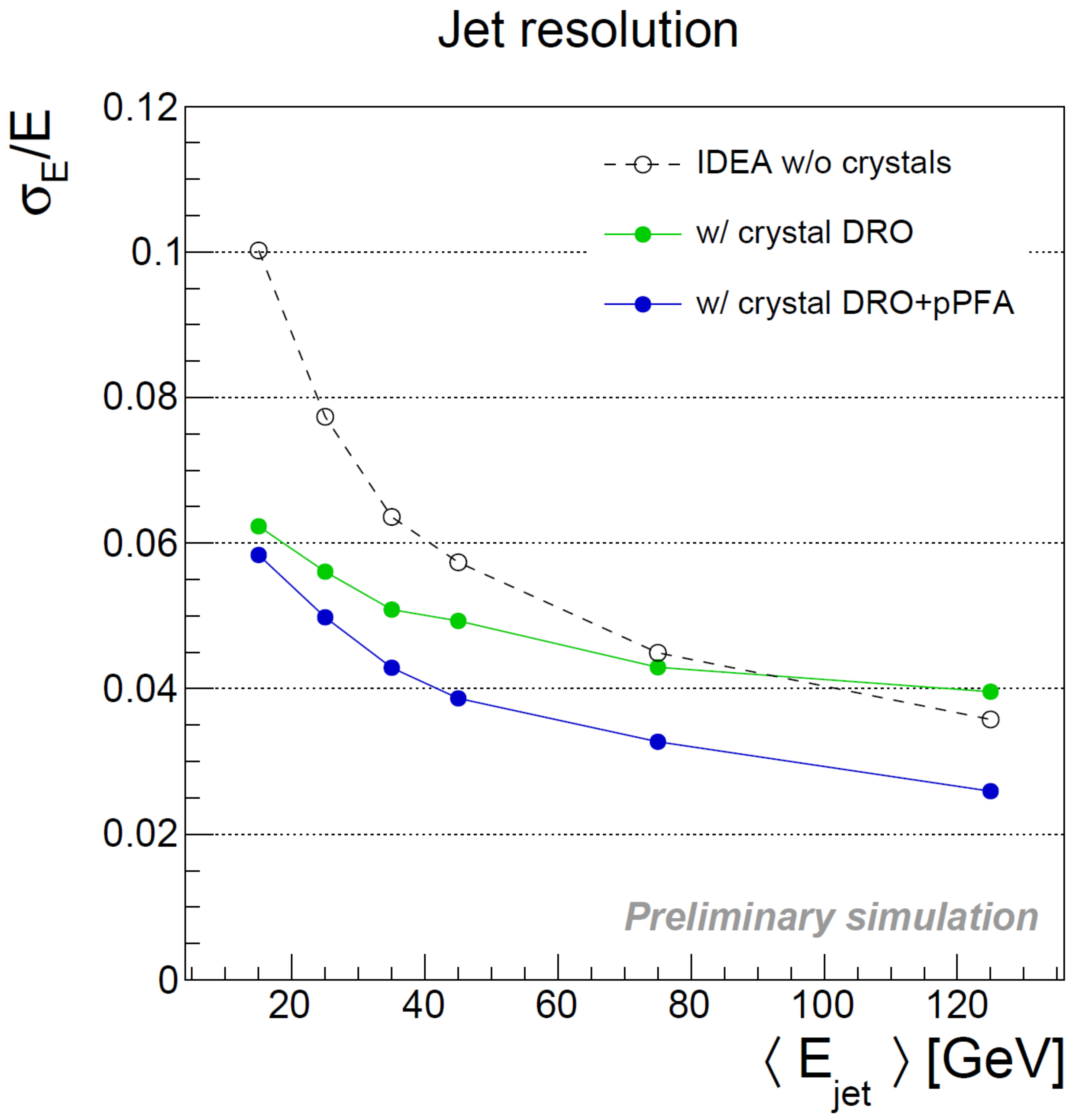
1x1x15 cm³ PbWO

# Crystal option



- ~20 cm $PbWO_4$
- $\sigma_{EM} \approx 3\%/\sqrt{E}$
- DR w. filters
- Timing layer
  - LYSO 20-30 ps

- PF for jets



# Calorimetry



| Detector technology (ECAL & HCAL) | E.m. energy res. stochastic term | E.m. energy res. constant term | ECAL & HCAL had. energy resolution (stoch. term for single had.) | ECAL & HCAL had. energy resolution (for 50 GeV jets) | Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets) |
|---|---|---|---|---|---|
| Highly granular Si/W based ECAL & Scintillator based HCAL | 15 – 17 % [12,20] | 1 % [12,20] | 45 – 50 % [45,20] | ≈ 6 % ? | 4 % [20] |
| Highly granular Noble liquid based ECAL & Scintillator based HCAL | 8 – 10 % [24,27,46] | < 1 % [24,27,47] | ≈ 40 % [27,28] | ≈ 6 % ? | 3 – 4 % ? |
| Dual-readout Fibre calorimeter | 11 % [48] | < 1 % [48] | ≈ 30 % [48] | 4 – 5 % [49] | 3 – 4 % ? |
| Hybrid crystal and Dual-readout calorimeter | 3 % [30] | < 1 % [30] | ≈ 26 % [30] | 5 – 6 % [30,50] | 3 – 4 % [50] |

**Table 1.** Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

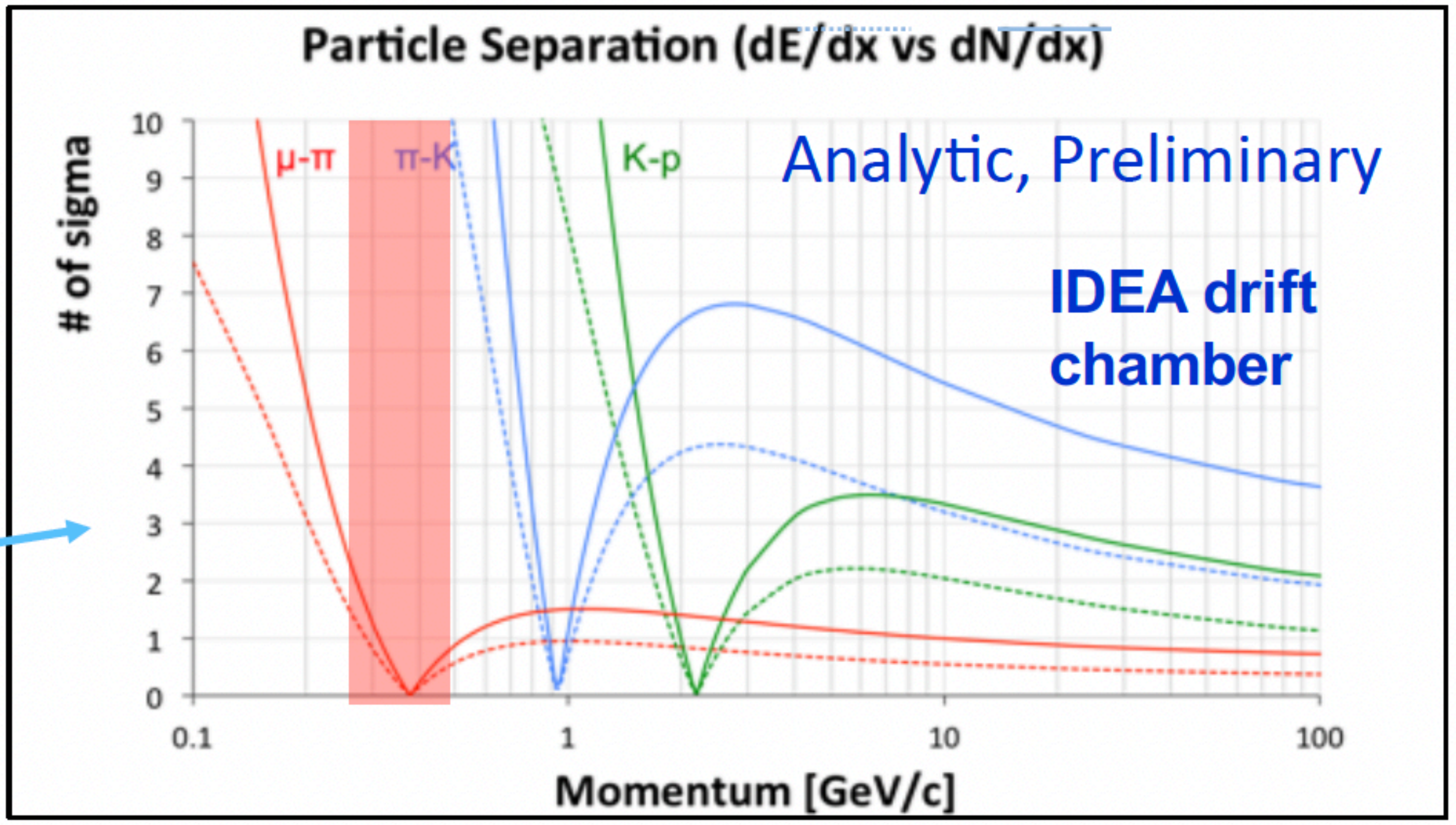
- **Excellent Jet resolution:** ≈ 30-40 %/√E
- **ECAL resolution:** Higgs physics ≈ 15%/√E; but for heavy flavour programme better resolution beneficial → 8%/√E → 3%/√E
- **Fine segmentation for PF algorithm** and powerful **γ/π⁰ separation** and measurement
- **Other concerns:** Operational stability, cost, …
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, …

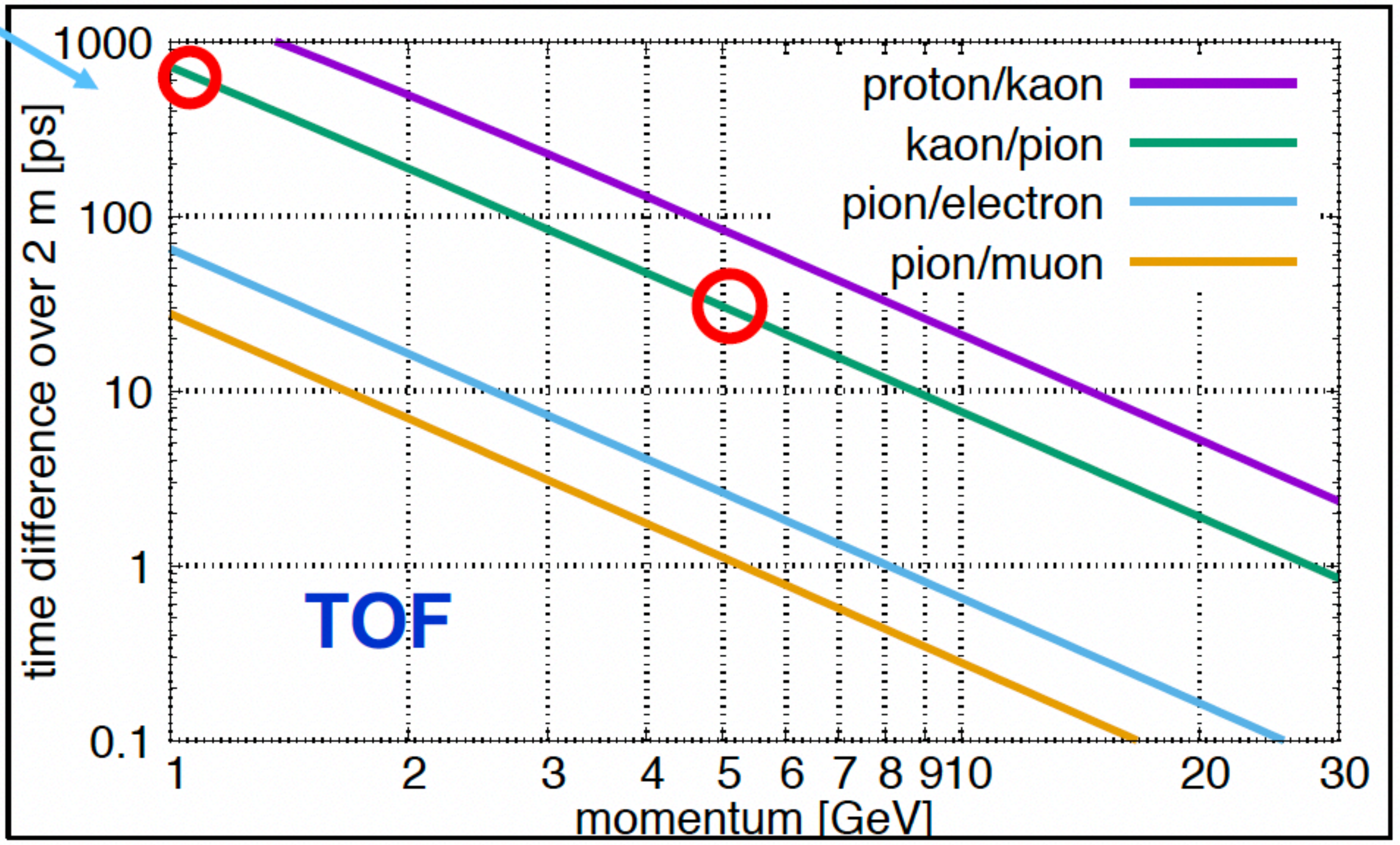
M. Dam

# Particle identification

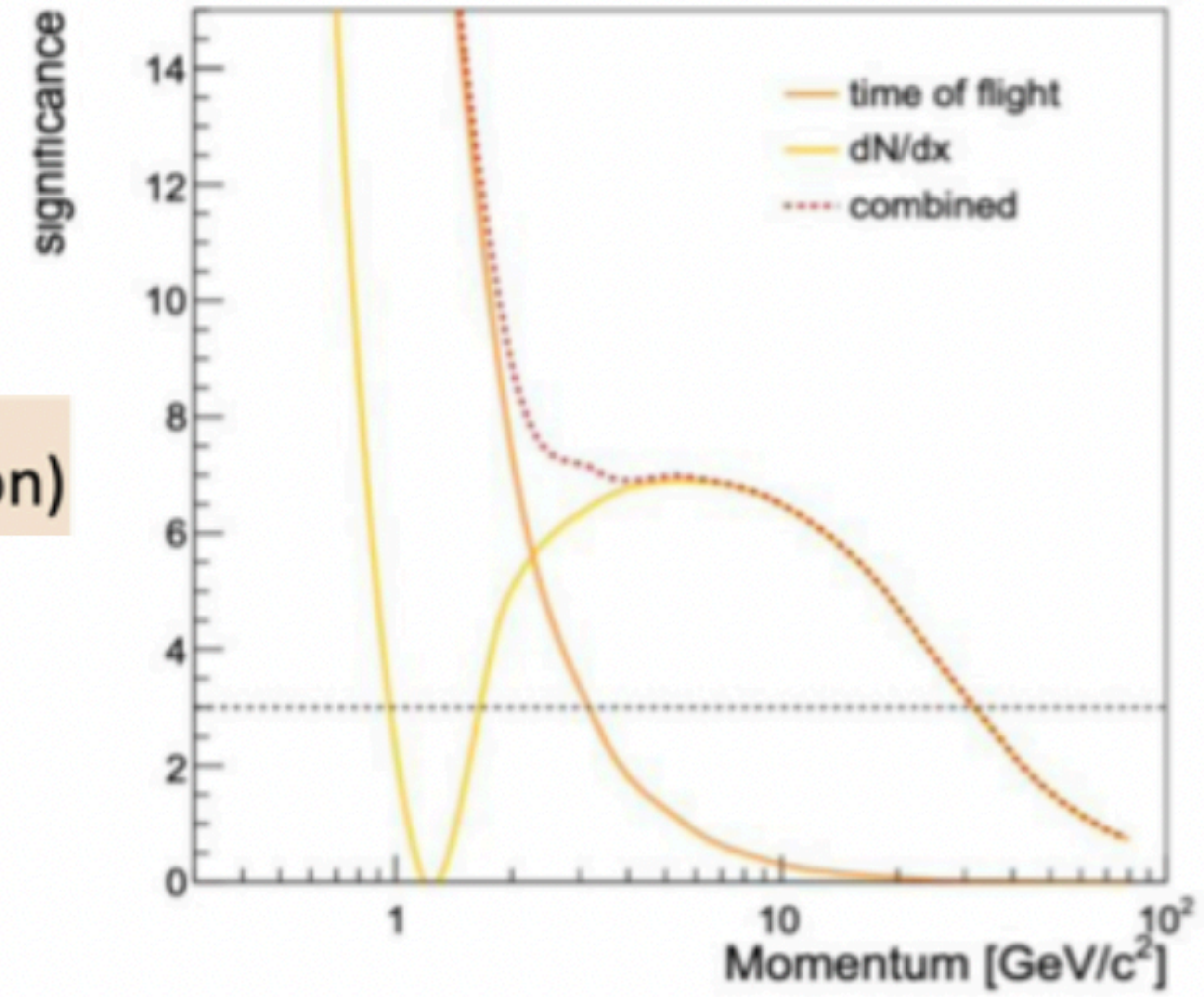


- Separation of π/K, K/p, over a wide momentum range
  - Prime importance for heavy flavour physics
  - Also provides important (invaluable!) independent means for e/π, π/μ separation
- Gaseous trackers: powerfull separation via ionisation measurement, **dE/dx** or **dN/dx**
  - Example, IDEA Drift Chamber
  - Cross-over window at 1 GeV can be alleviated by unchallenging TOF measurement $\delta T \lesssim 0.5$ ns
- **Time of flight (TOF) alone** $\delta T$ of ~10 ps over 2 m (LGAD, TORCH)
  - could give 3σ π/K separation up to ~5 GeV




*dN/dx* + TOF (IDEA simulation)

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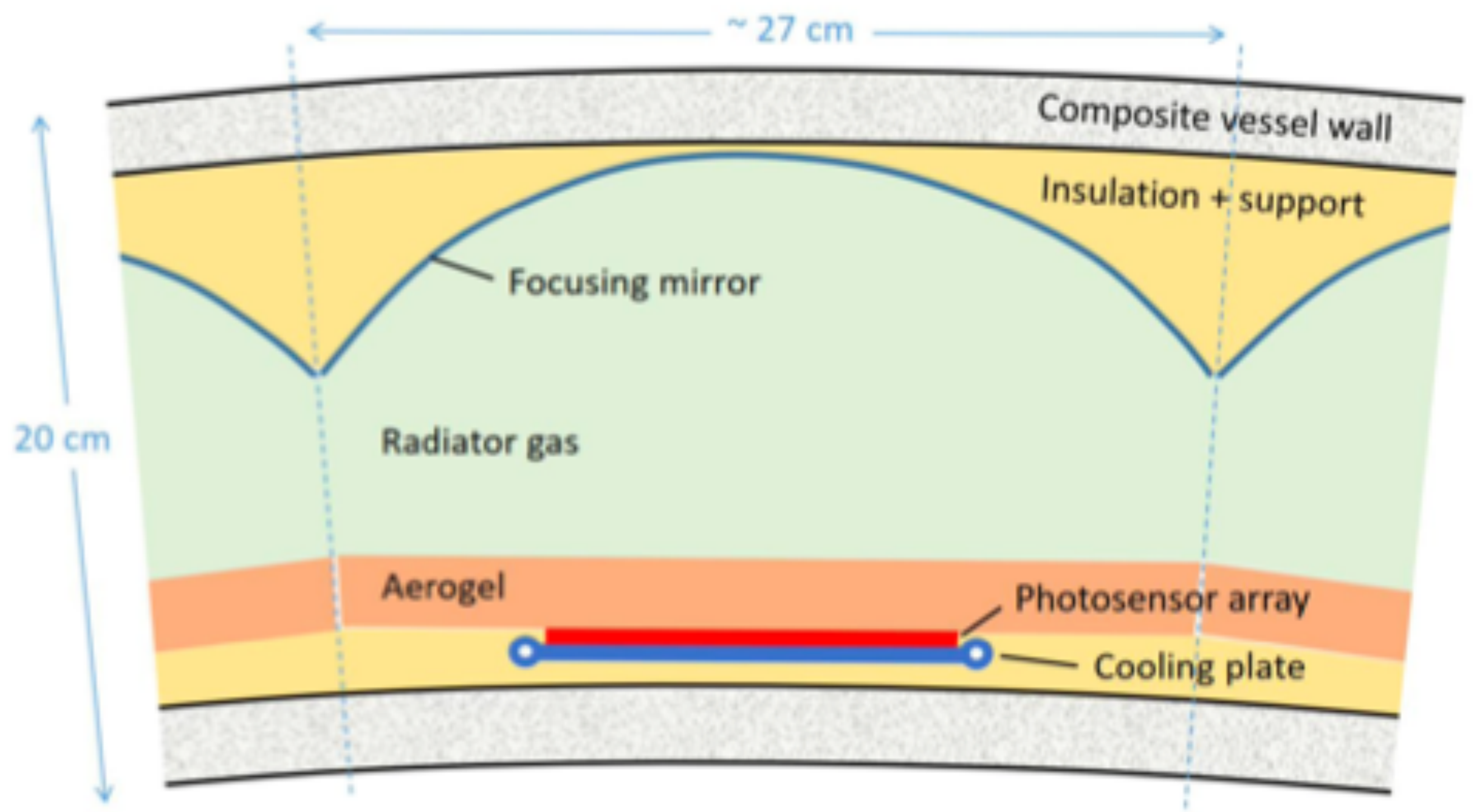
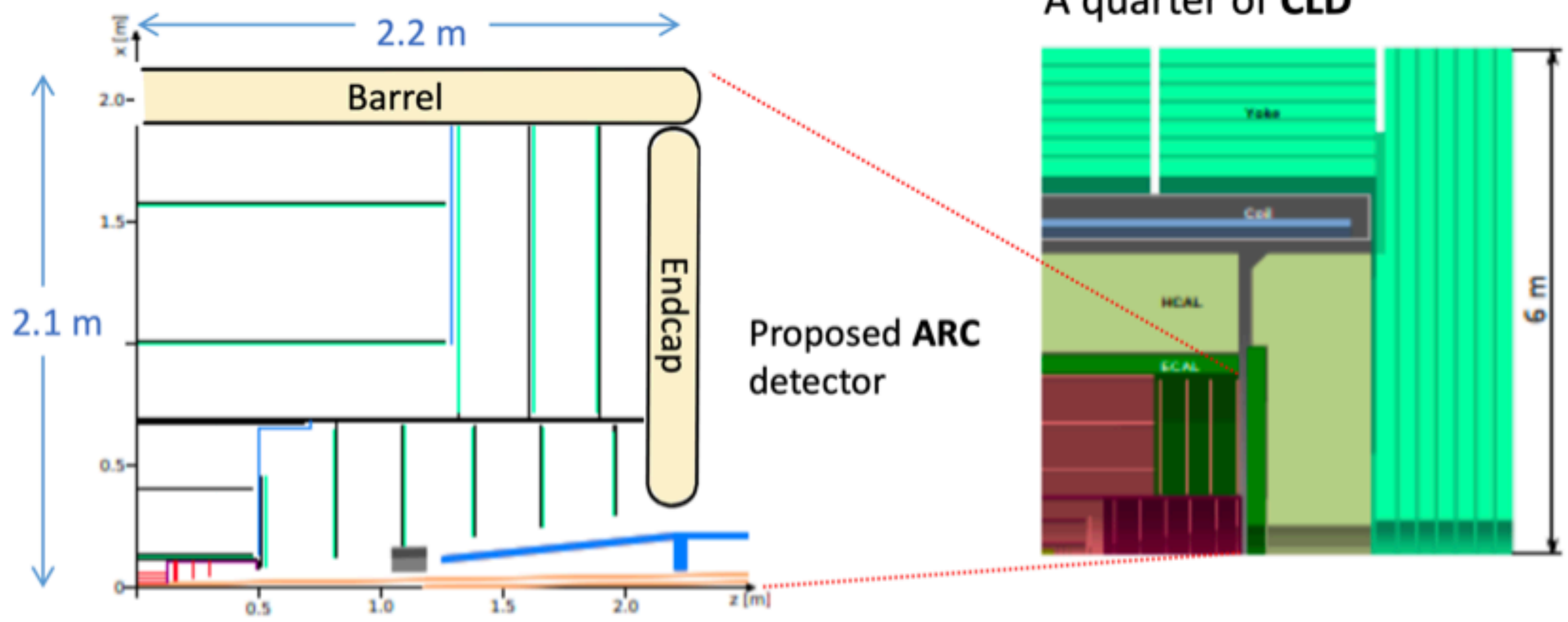
# Particle identification: compact RICH



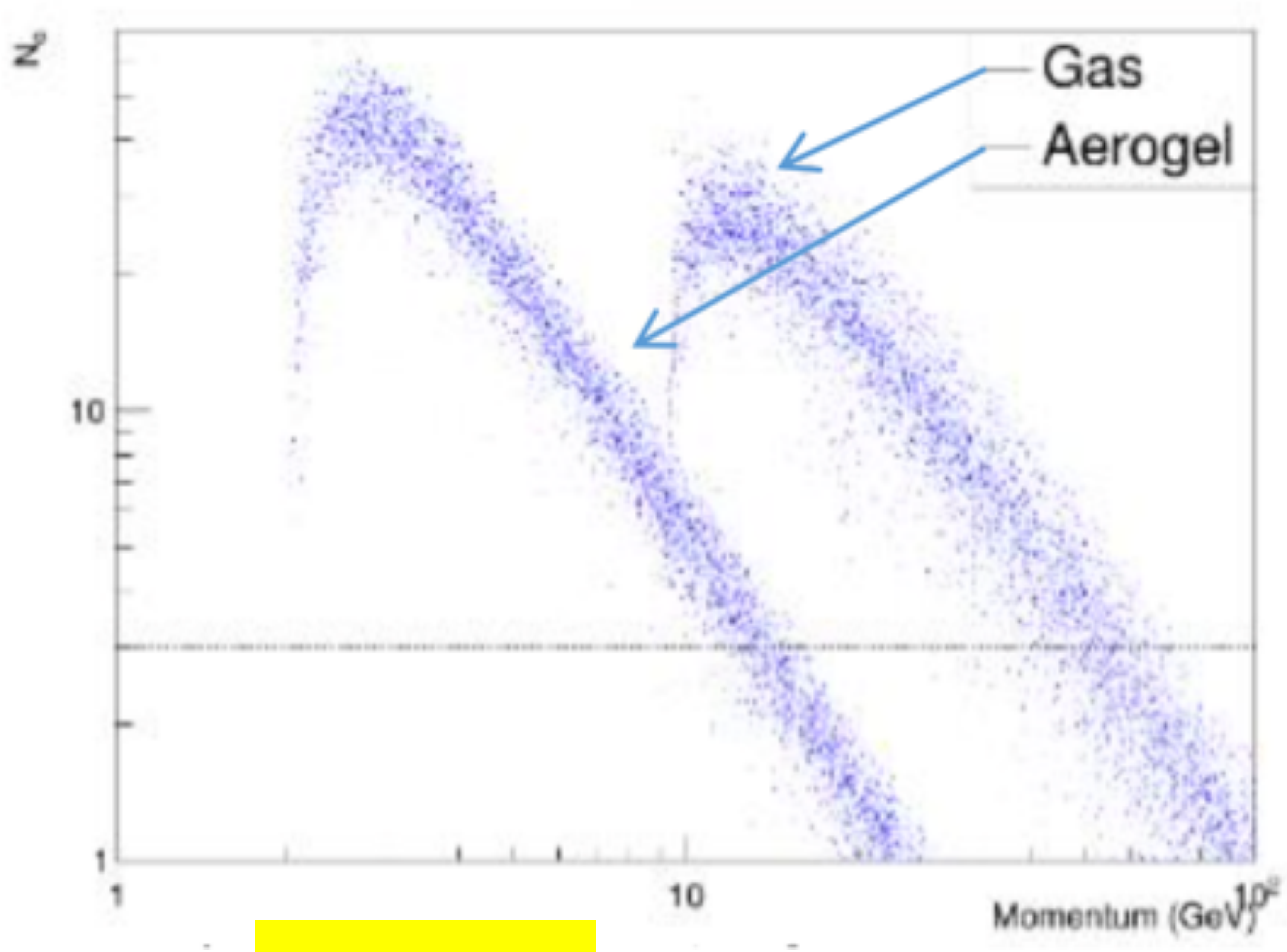
- Design goal: Compact design, max 20 cm depth, few % $X_0$
- Use spherical focussing mirrows, $r$ = 30 cm, for radiator thickness of 15 cm
- Two radiators
  - Aerogel
  - Gas
    - Unpressurised $C_4F_{10}$ gives good momentum range for K-π separation, with acceptable photon yield
    - Pressurised Xenon may provide similar performance if fluorocarbons unacceptable



**ARC detector** (one cell)




K-π separation



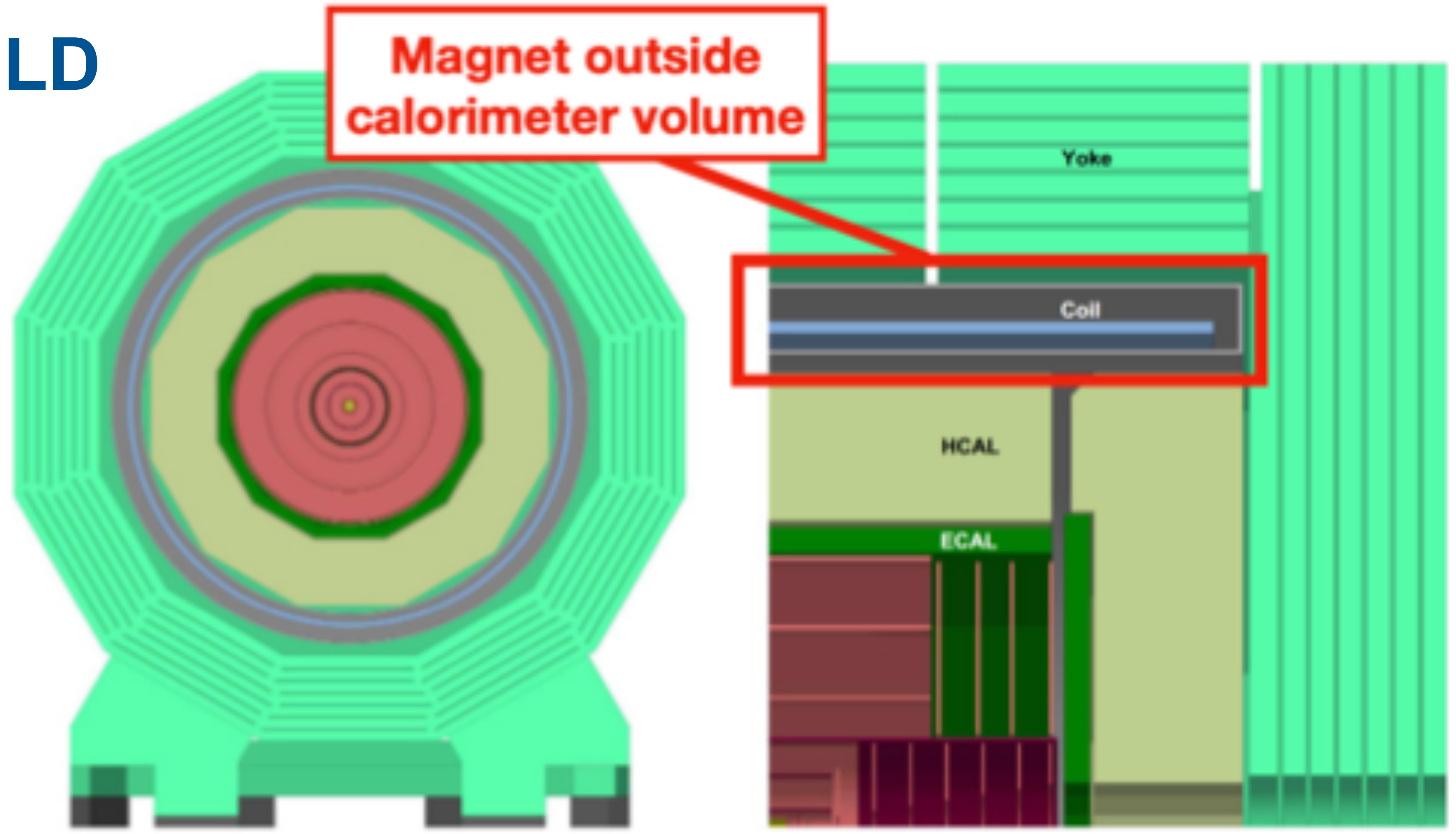

R. Forty

# Solenoidal magnet

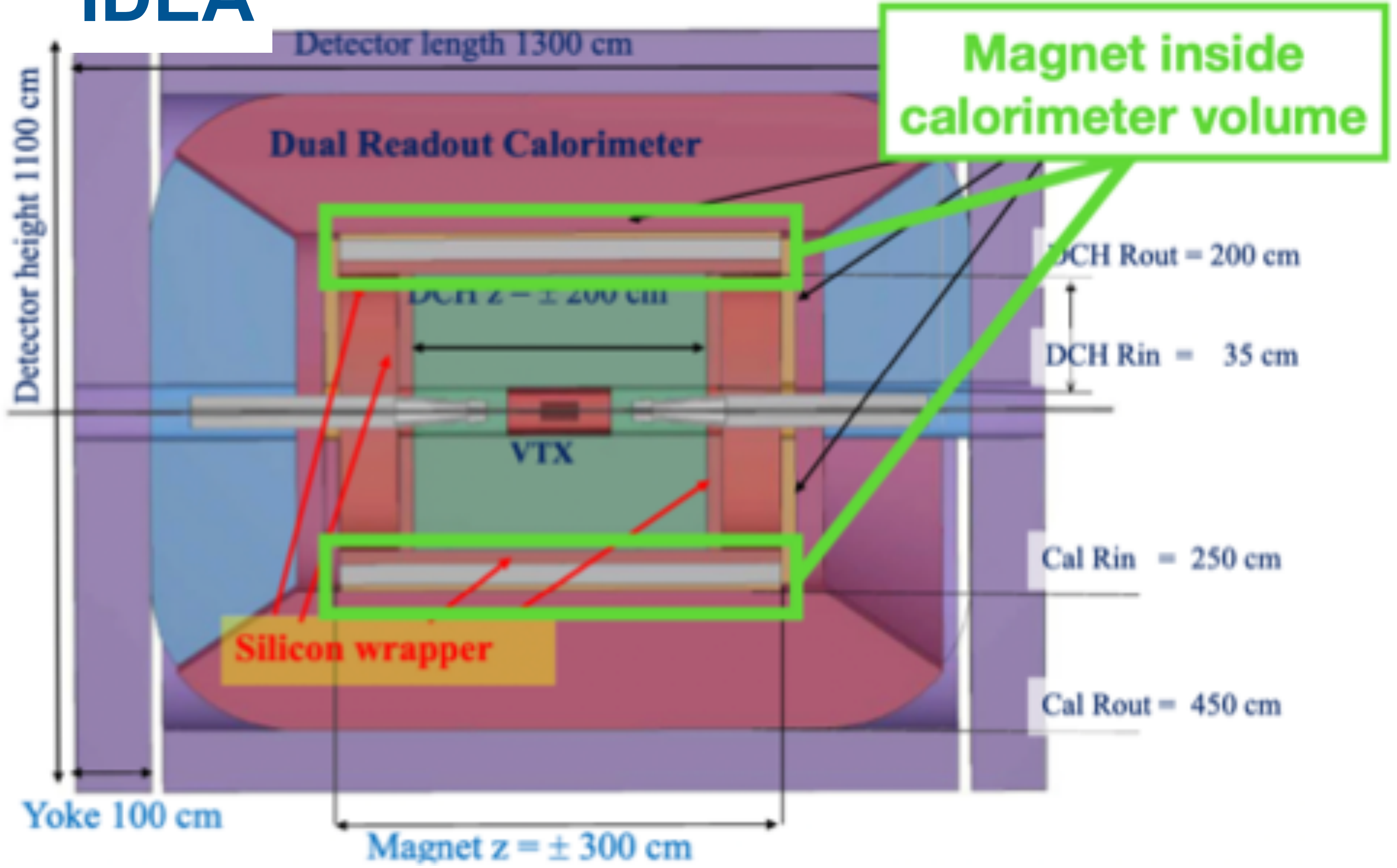


- ✦ Placement of coil different for different detector concepts

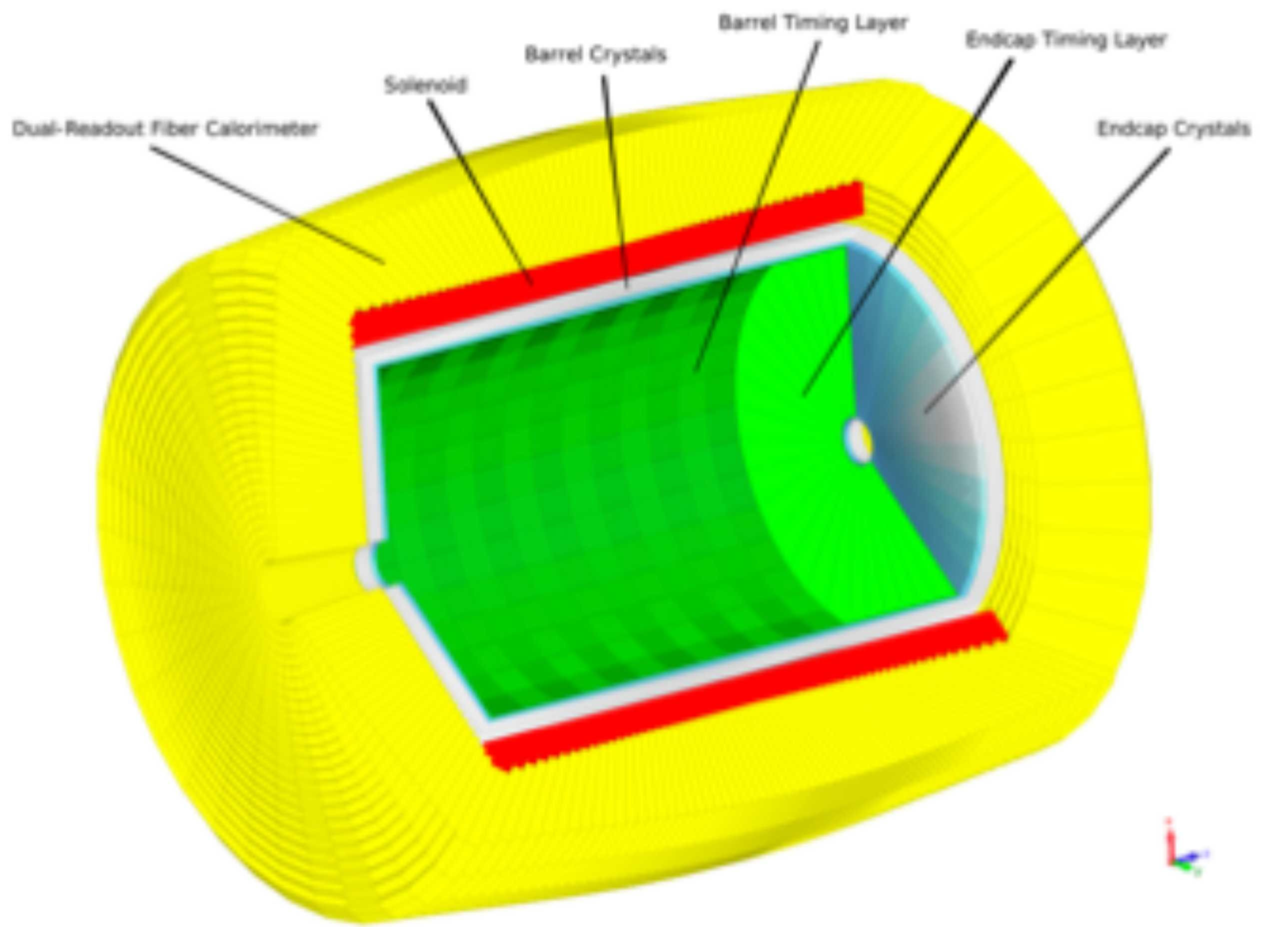
**CLD**



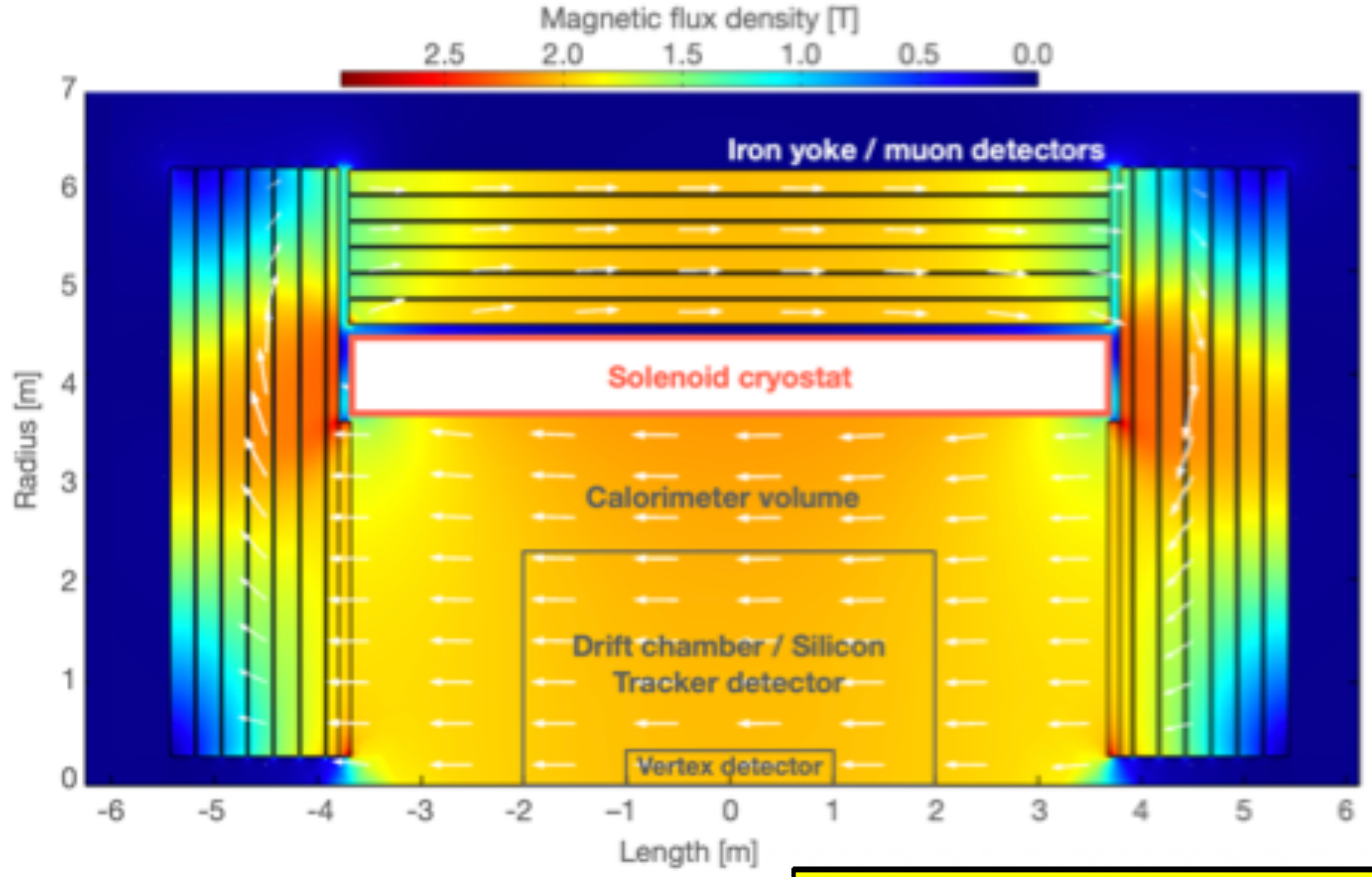

**IDEA**

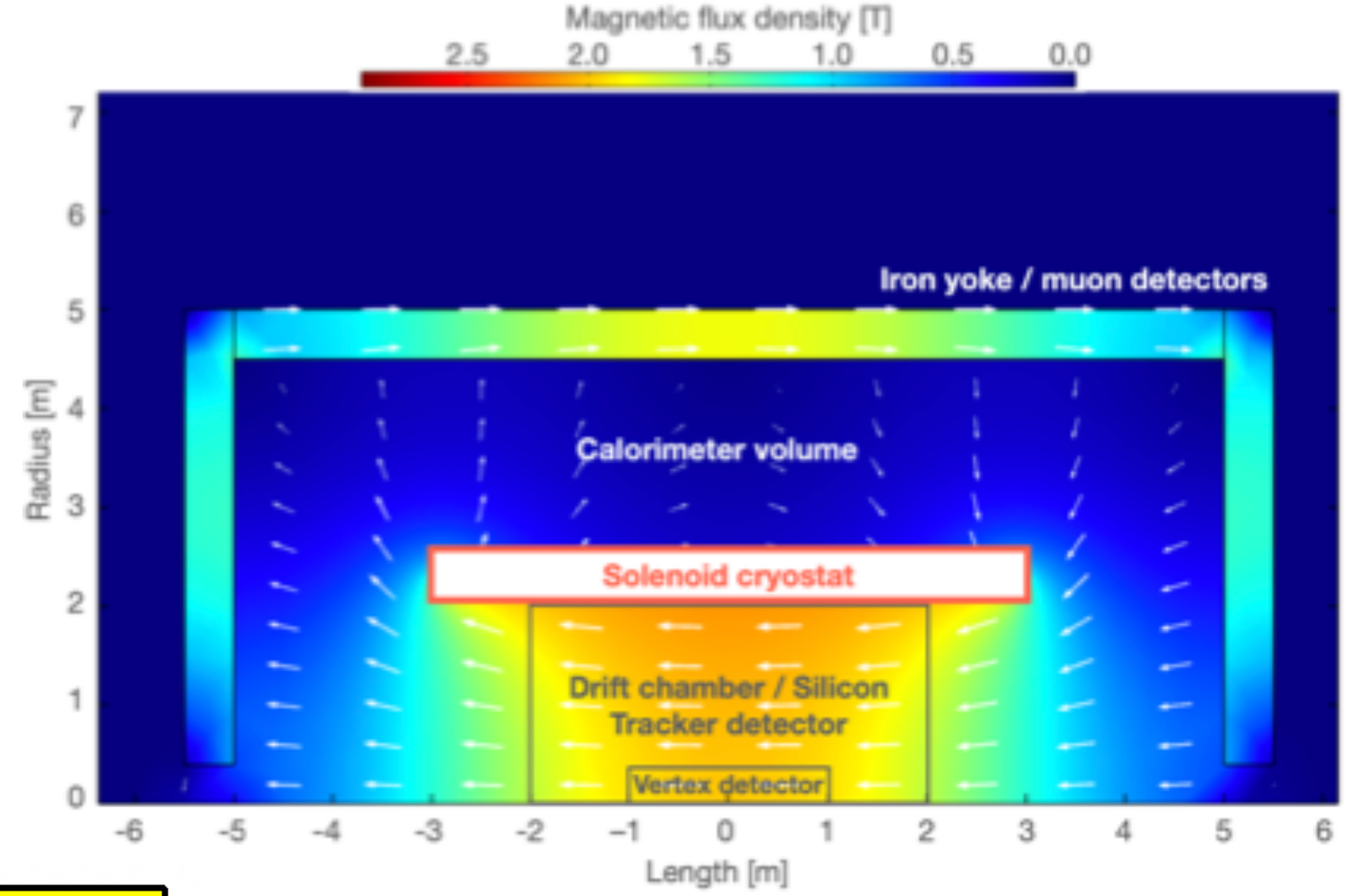



- ✦ For Noble Liquid concept and for IDEA with crystal option, coil *between* ECAL and HCAL
  - ✳ As Aleph and Delphi at LEP




IDEA w crystal ECAL+ DR fiber HCAL



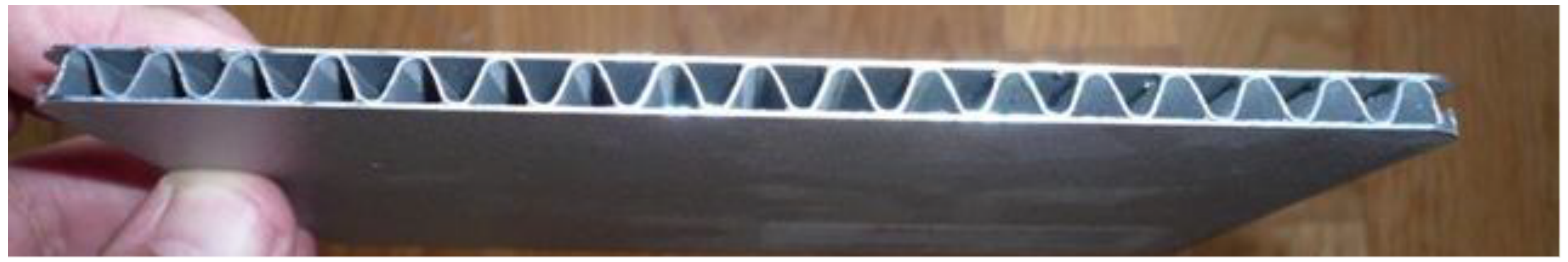

Nikkie Deelen,, 6th FCC Workshop, Feb. 2023

- ✦ Detailed simulation studies needed to understand pros and cons of the different placements

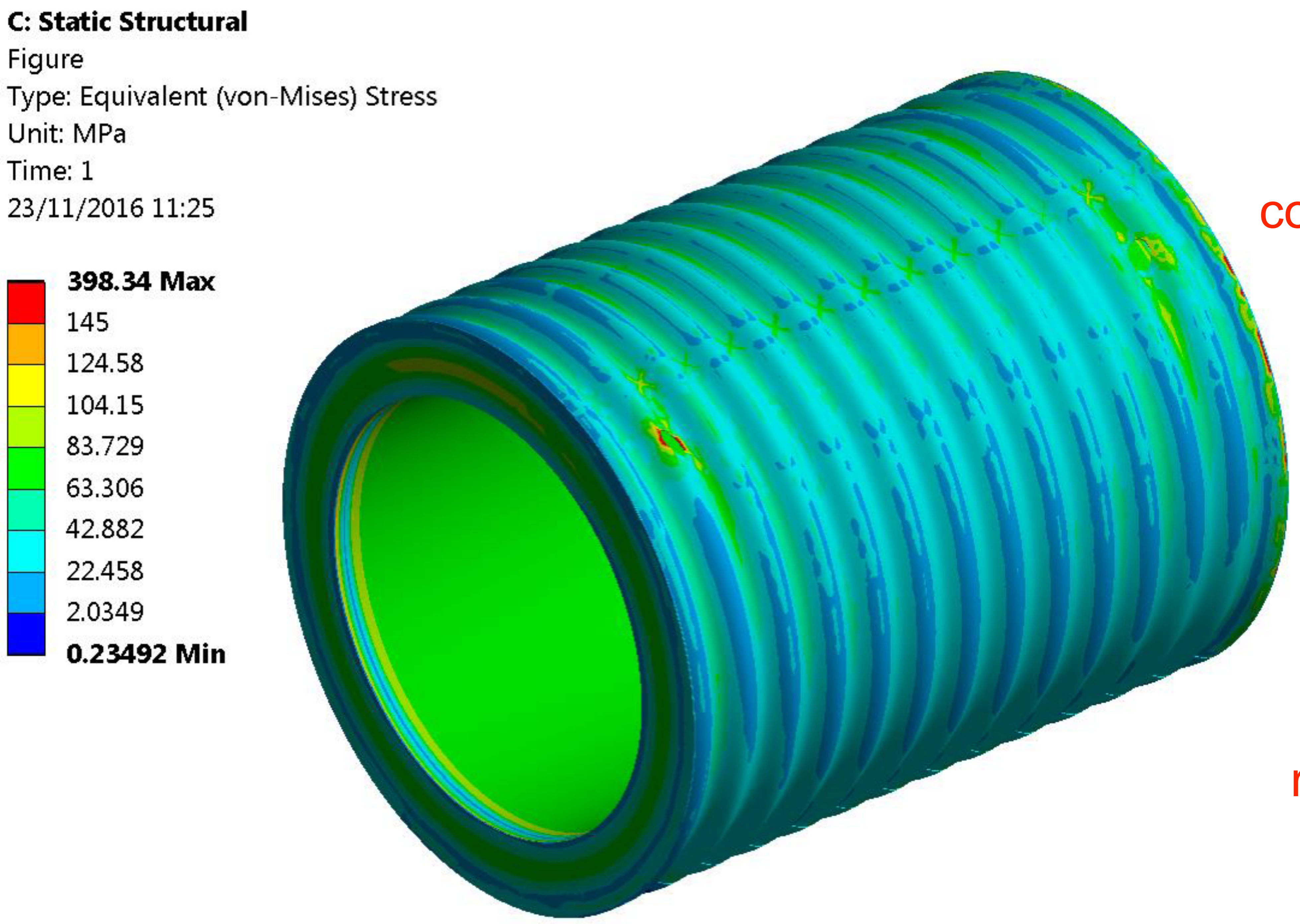
M. Dam

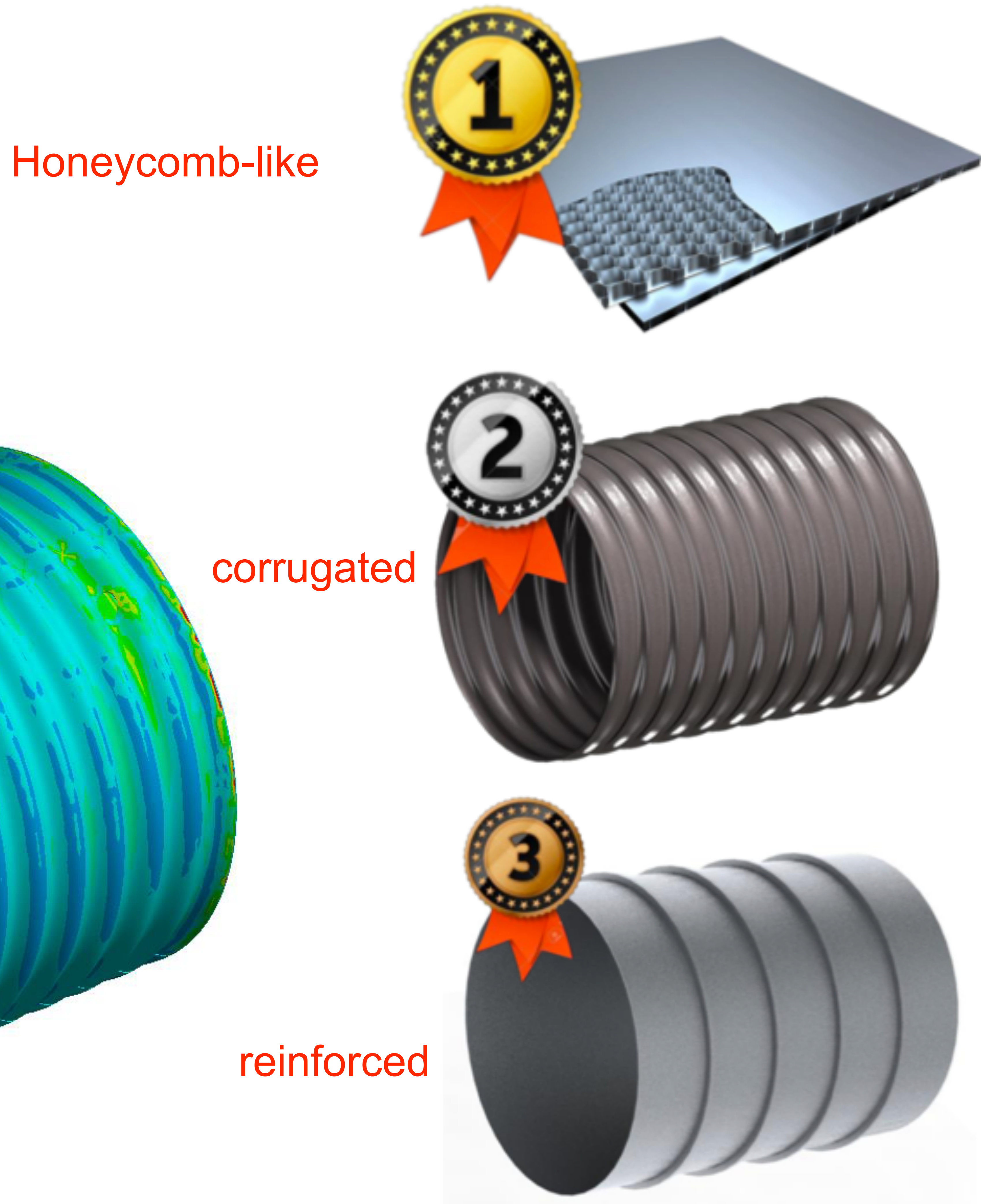
# Superconducting solenoid

- Ultra light 2 T solenoid:
  - Radial envelope 30 cm
  - Single layer self-supporting winding (20 kA)
    - Cold mass: $X_0 = 0.46$, $\lambda = 0.09$
  - Vacuum vessel (25 mm Al): $X_0 = 0.28$
    - Can improve with new technology
      - Corrugated plate: $X_0 = 0.11$
      - Honeycomb: $X_0 = 0.04$



Courtesy of H. Ten Kate



# Muon detector

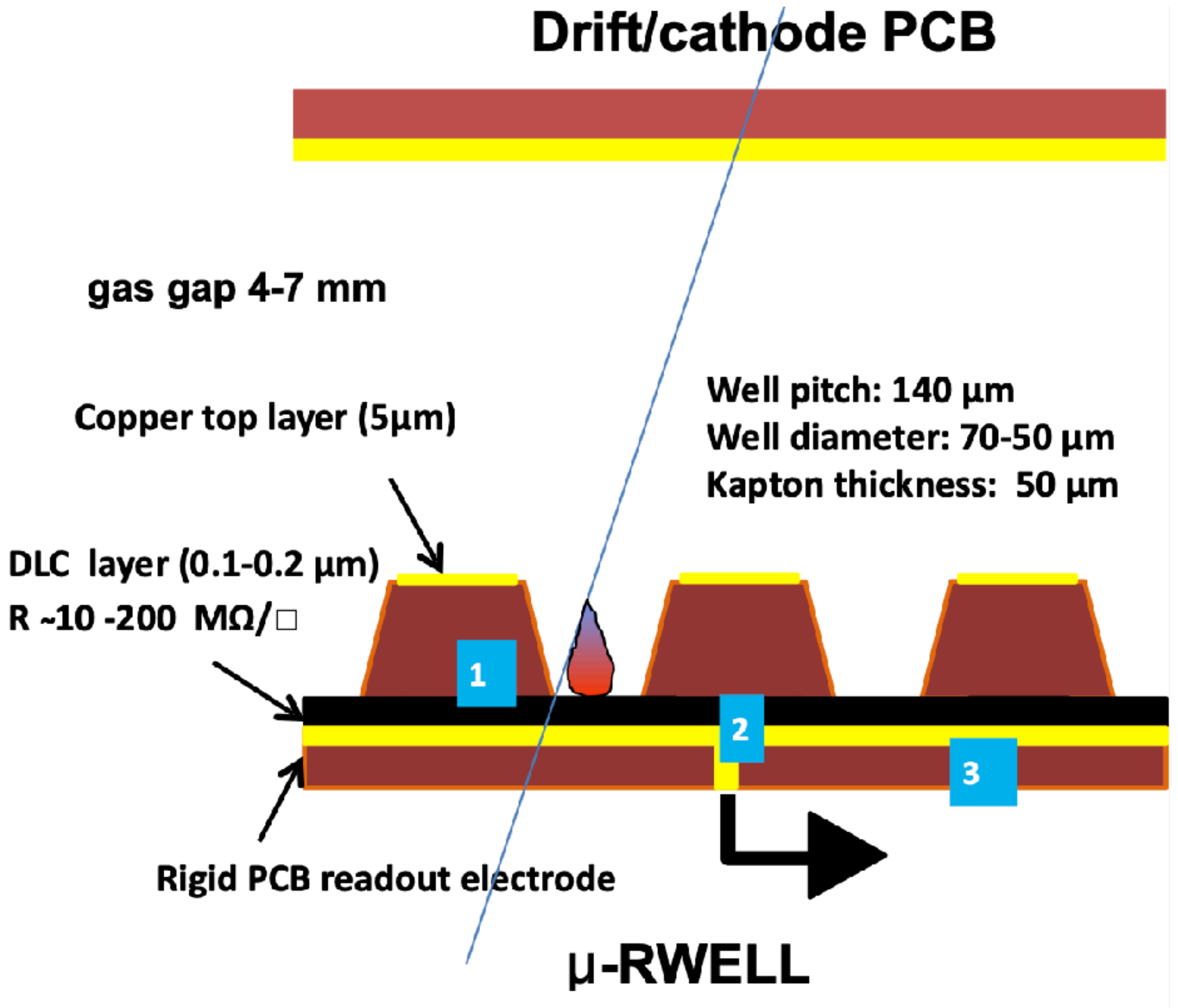


Muon system in instrumented return yoke

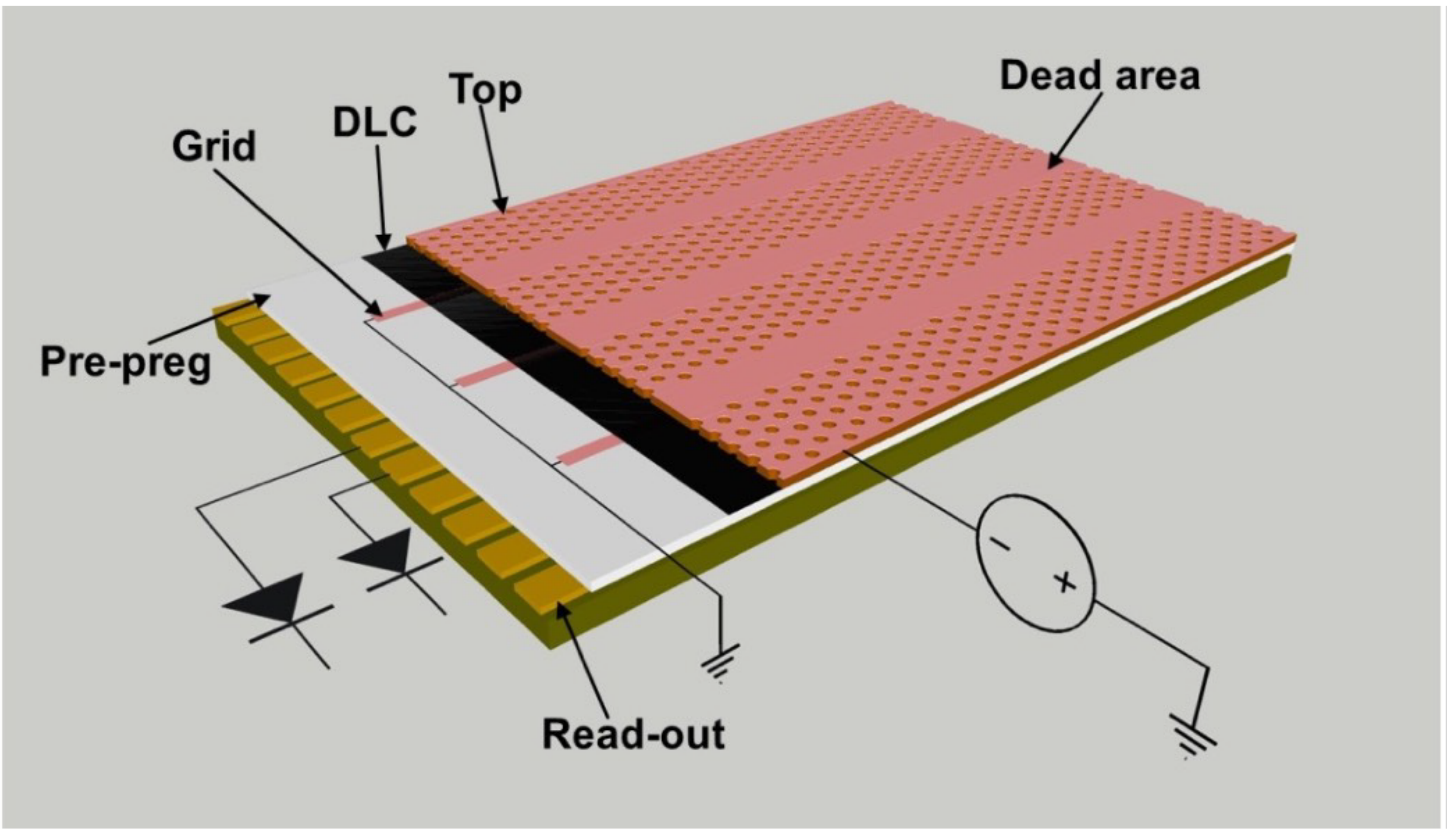
- 3-7 layers being considered: 1500-6000 m$^2$
- Proposed technologies
  - RPC (30 × 30 mm$^2$ cells) (CLD)
  - Crossed scintillator bars {CLD)
  - µRWell chambers (1.5 × 500 mm$^2$ cells) (IDEA)
    - Also for IDEA pre-shower detector
    - Ongoing R&D work

**CLD Muon system**

- 6 layers of RPC muon chambers inside yoke
  - Cell size: 30 × 30 mm$^2$




G. Bencivenni et al., 2015_JINST_10_P02008




**IDEA Muon system**

- 3 layers of µRWell chambers inside yoke
  - Cell size: 1.5 × 500 mm$^2$
  - Detector size: 500 x 500 mm$^2$

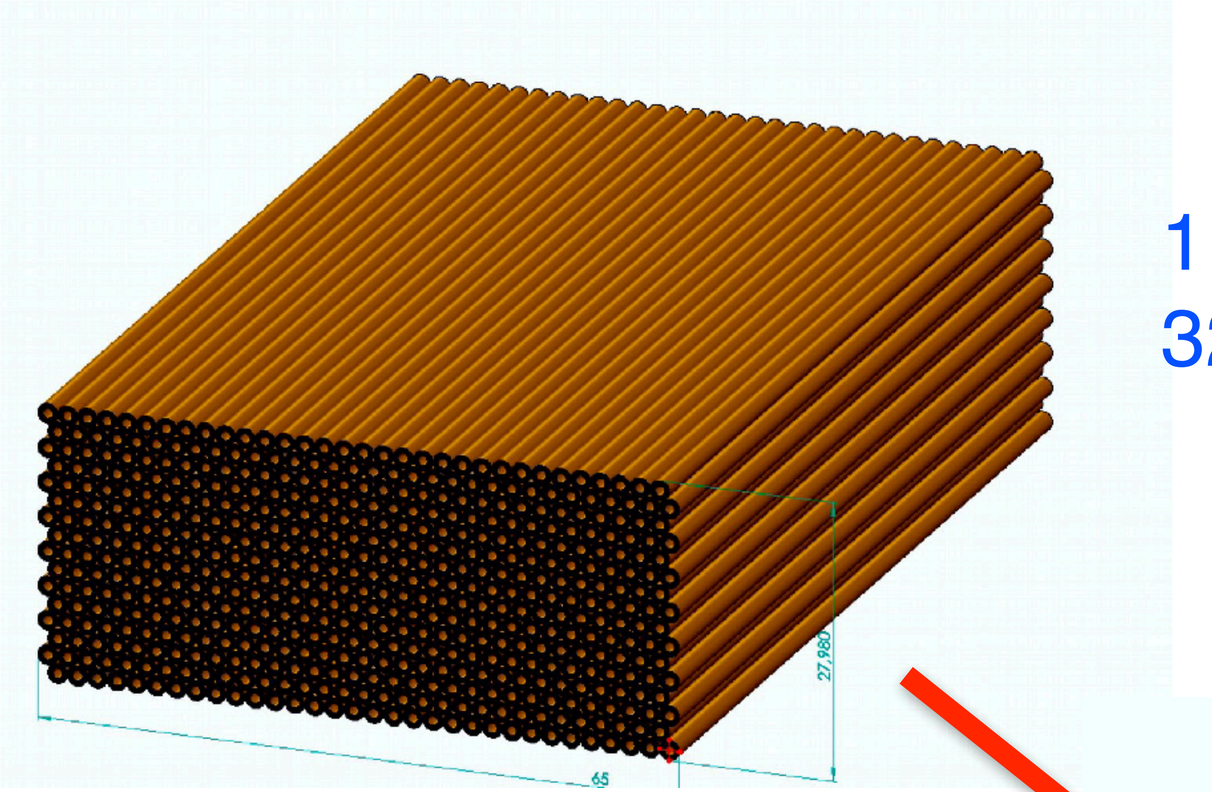
# Some of the ongoing R&D

# DR future prototypes

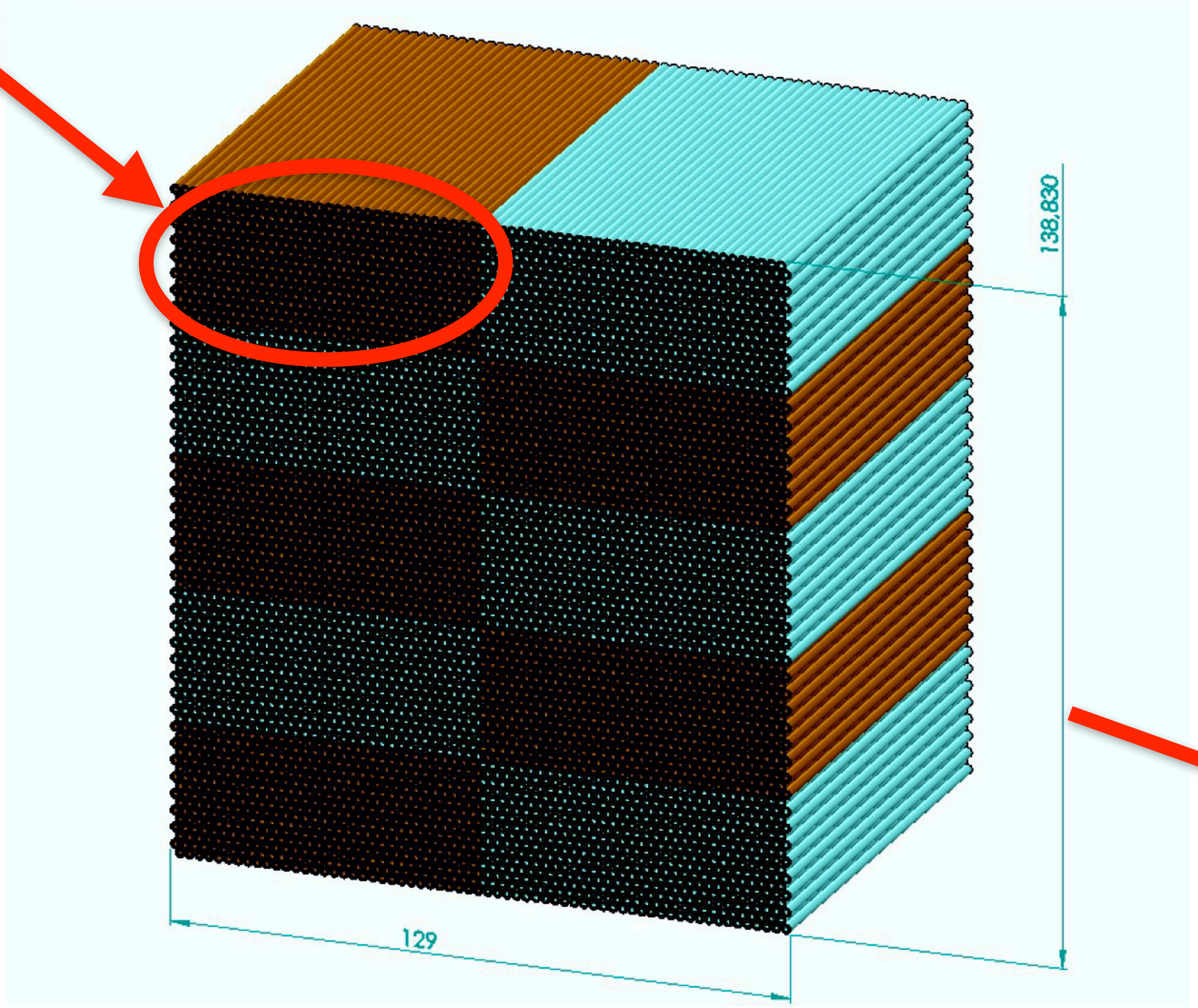


## HiDRa2

**Full hadronic shower containment calorimeter**




1 Mini-Module (MM):
32 x 16 channel ( 512 ch )

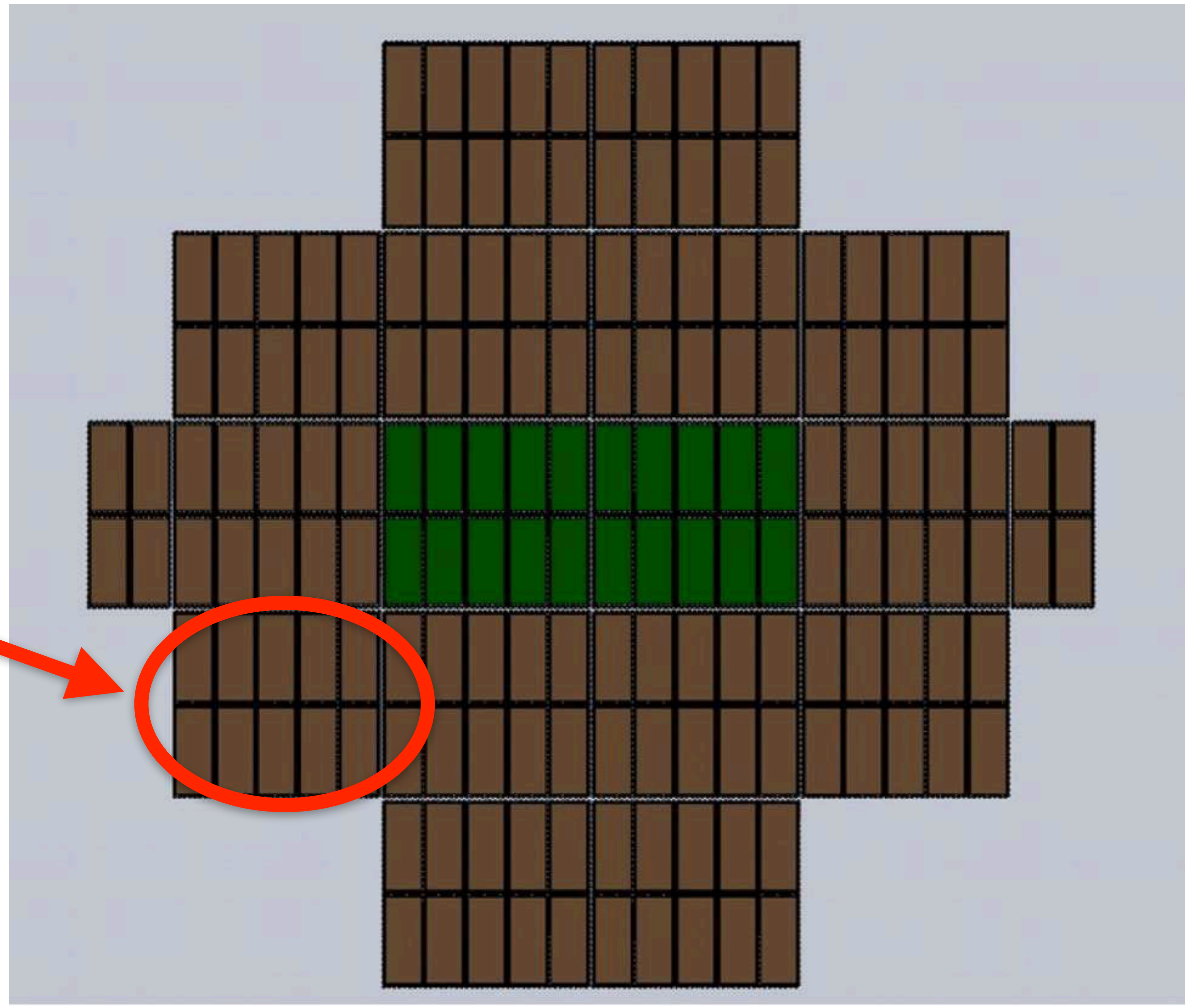



1 Module:

2 x 5 MMs
→ 10 FEE boards
(8-channel grouping)
~ 13 x13 x 200 cm$^3$

17 modules, ~ 65 x 65 x 200 cm$^3$

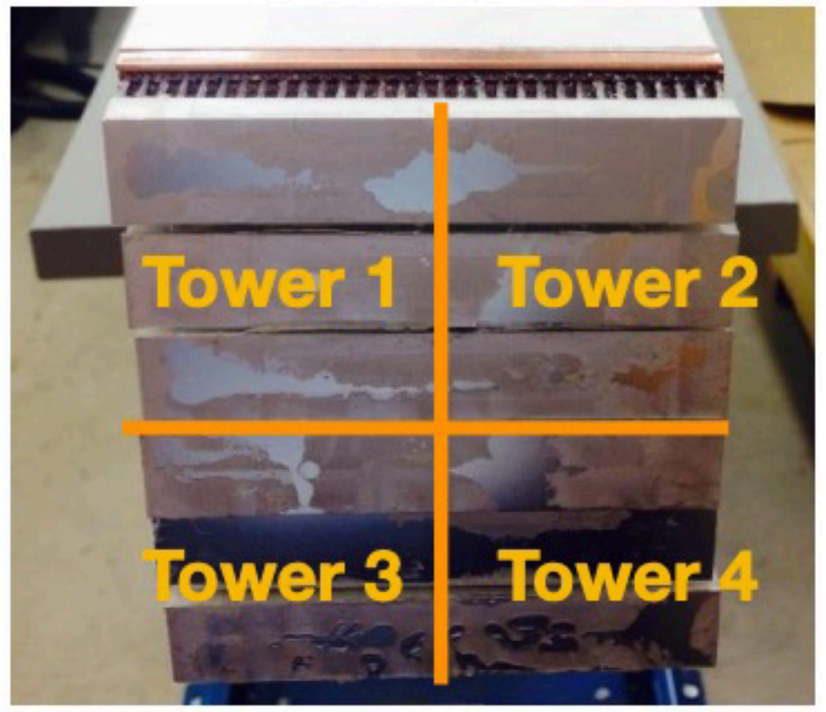
- 2 central modules with SiPMs
→ ~ 10 k SiPMs, ~ 20 FEE boards
- all others with PMTs
→ ~ 150 PMTs



# Plate based + 3D printing calo (Korea)

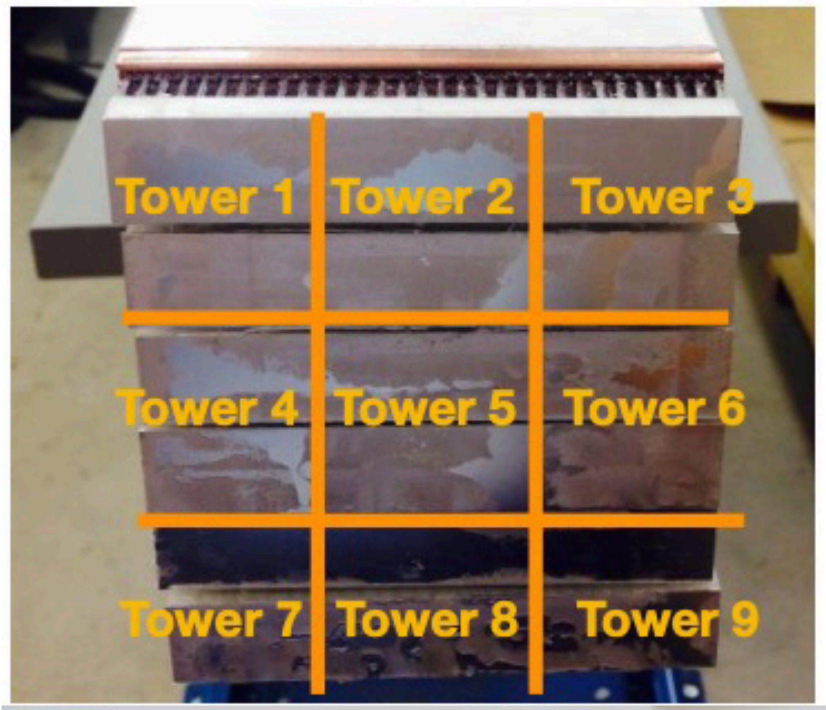
## "Short-term plan"

### Module #1 (2x2)

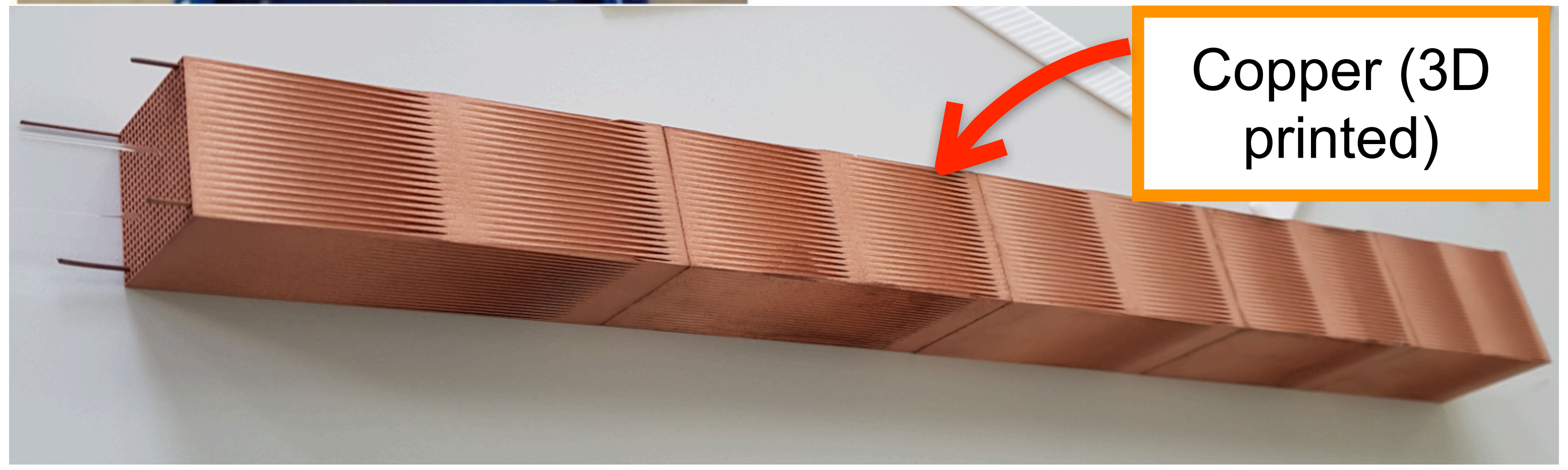


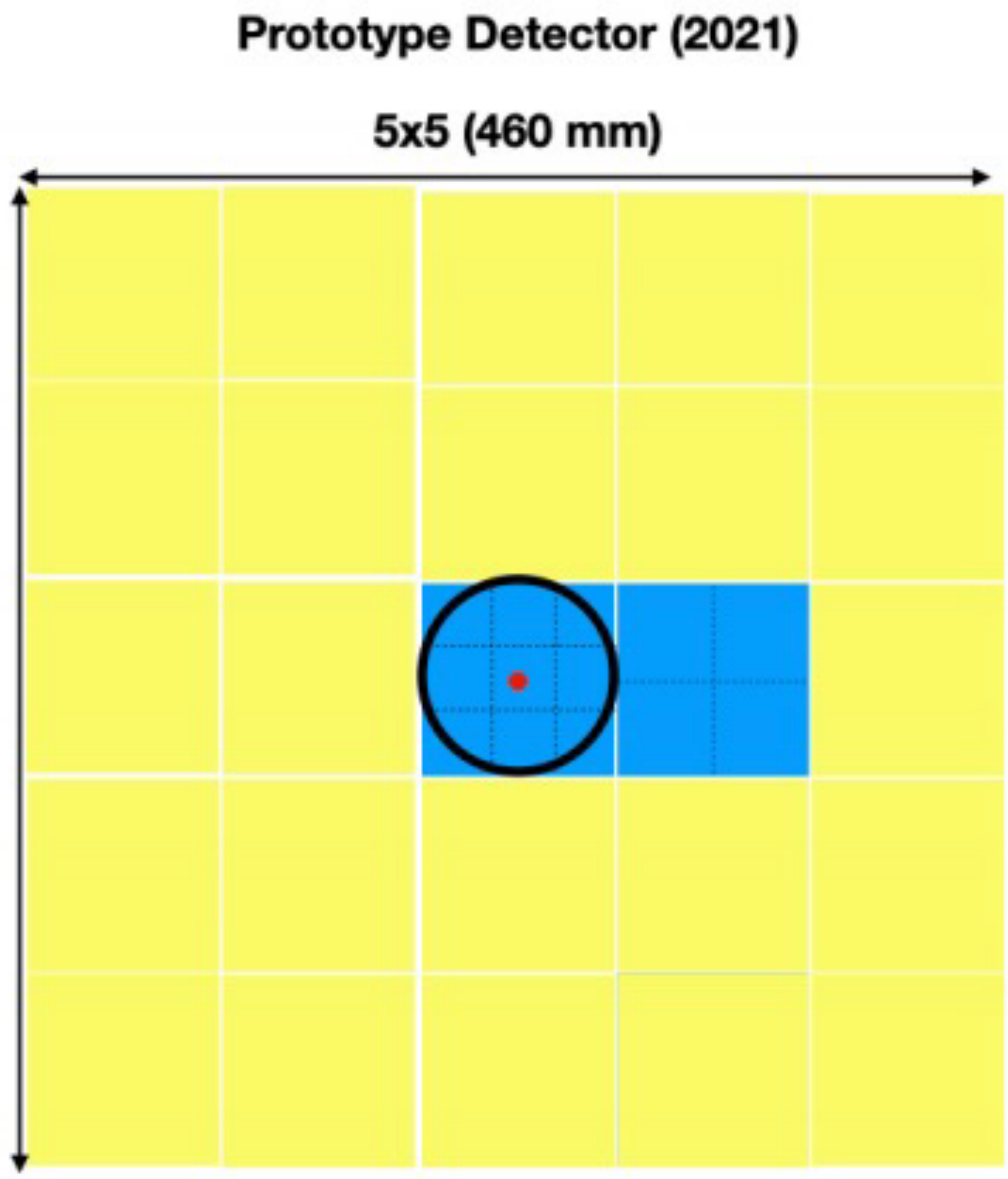

| | |
|---|---|
| Tower#1 | Tower#2 |
| Tower#3 | Tower#4 |

### Module #2 (3x3)

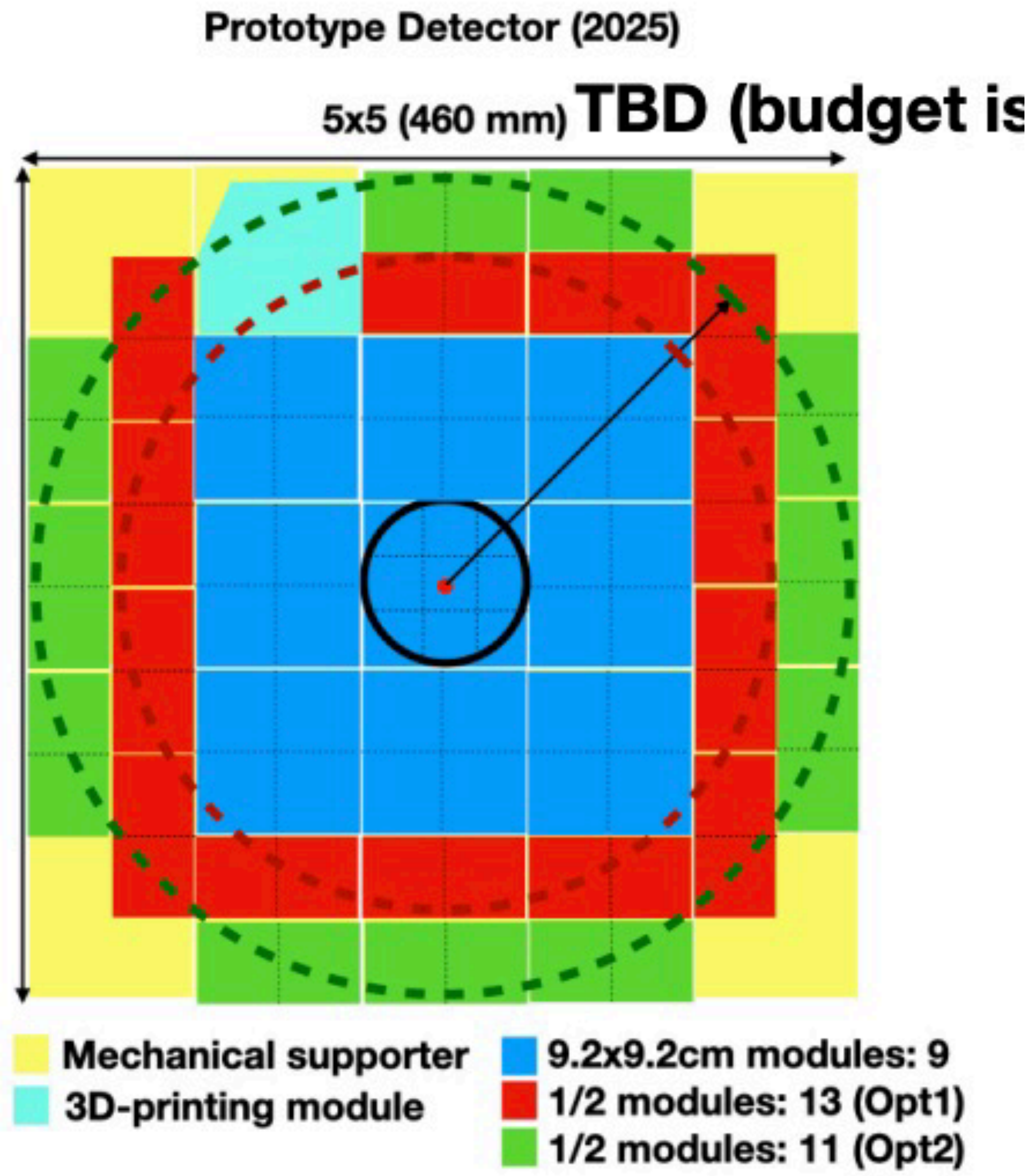



| | | |
|---|---|---|
| Tower#1 | Tower#2 | Tower#3 |
| Tower#4 | Tower#5 | Tower#6 |
| Tower#7 | Tower#8 | Tower#9 |




## "Mid-term plan"




Building more and more modules 2022-2025

**Strong collaboration on DR calorimetry between INFN, Korea and USA**

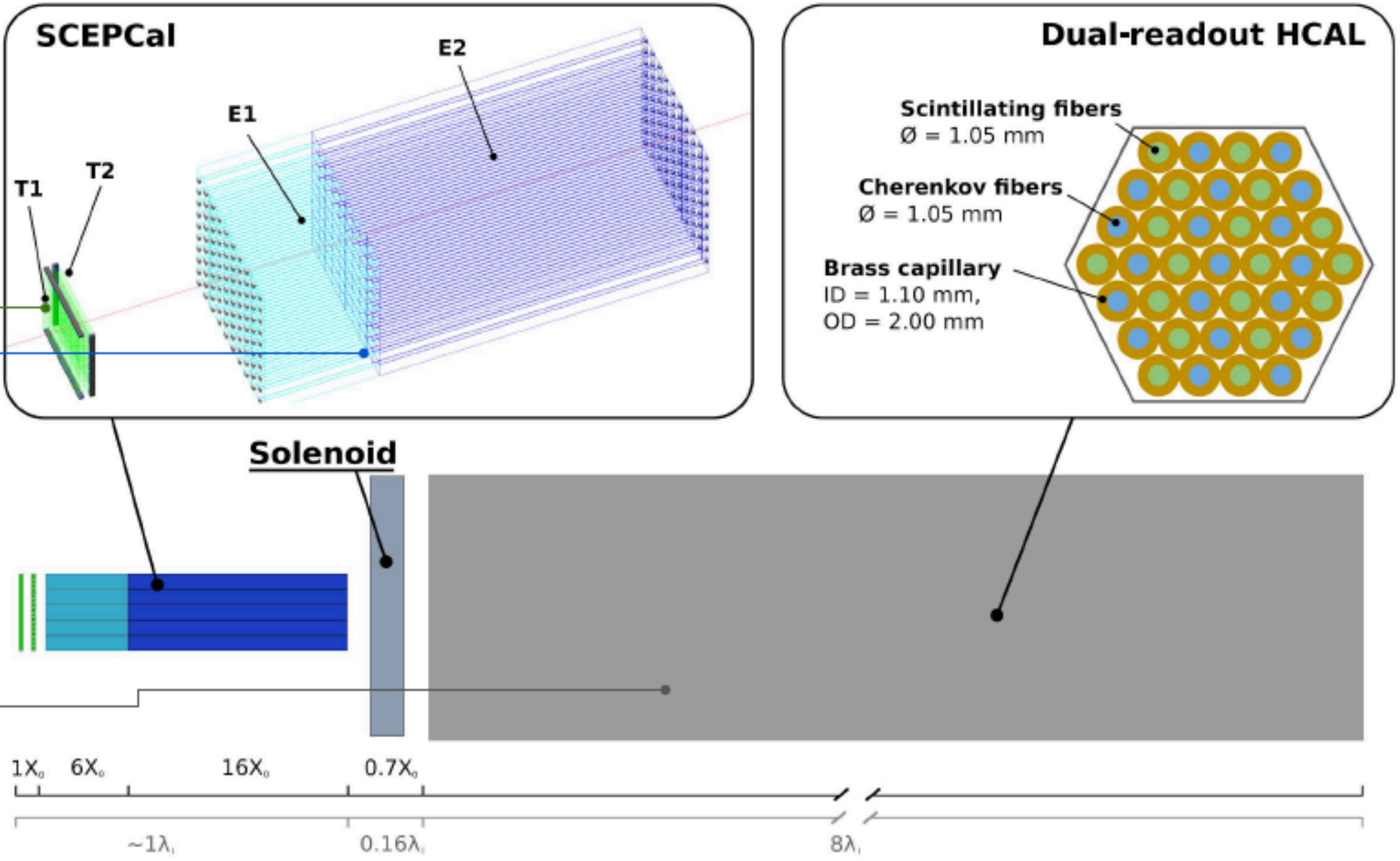
# Crystal ECAL with DR calorimeter



## Layout overview

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

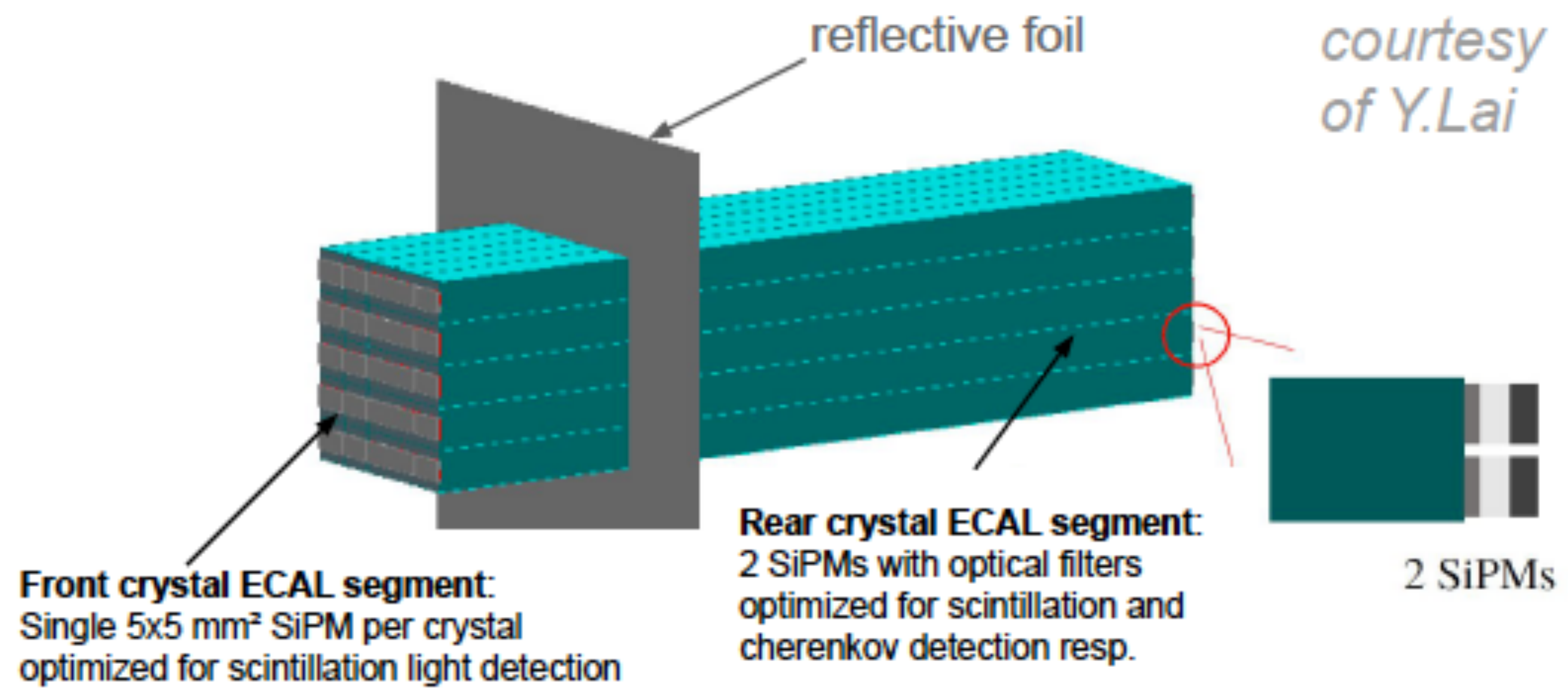
- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  -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



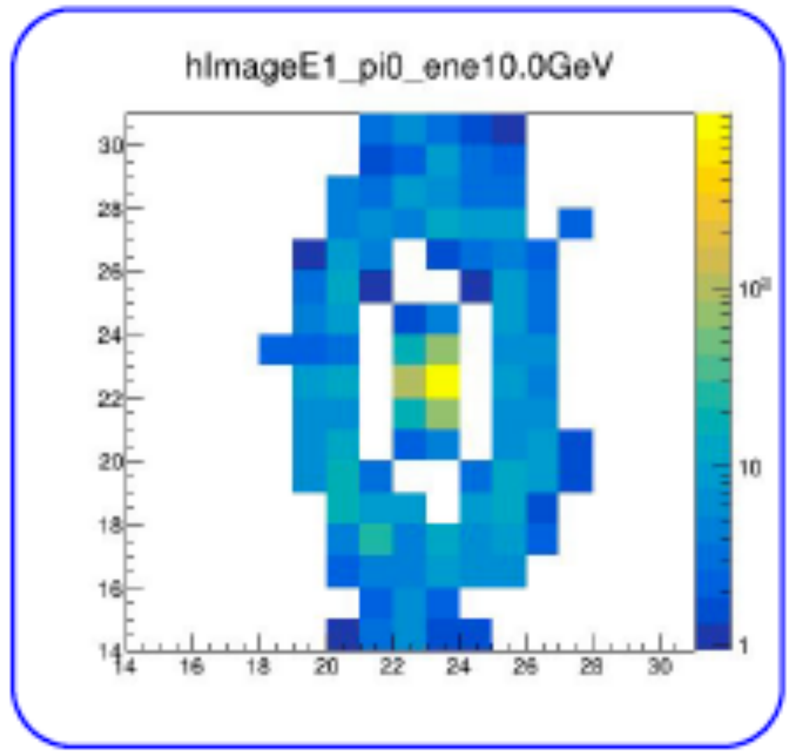

M. Lucchini

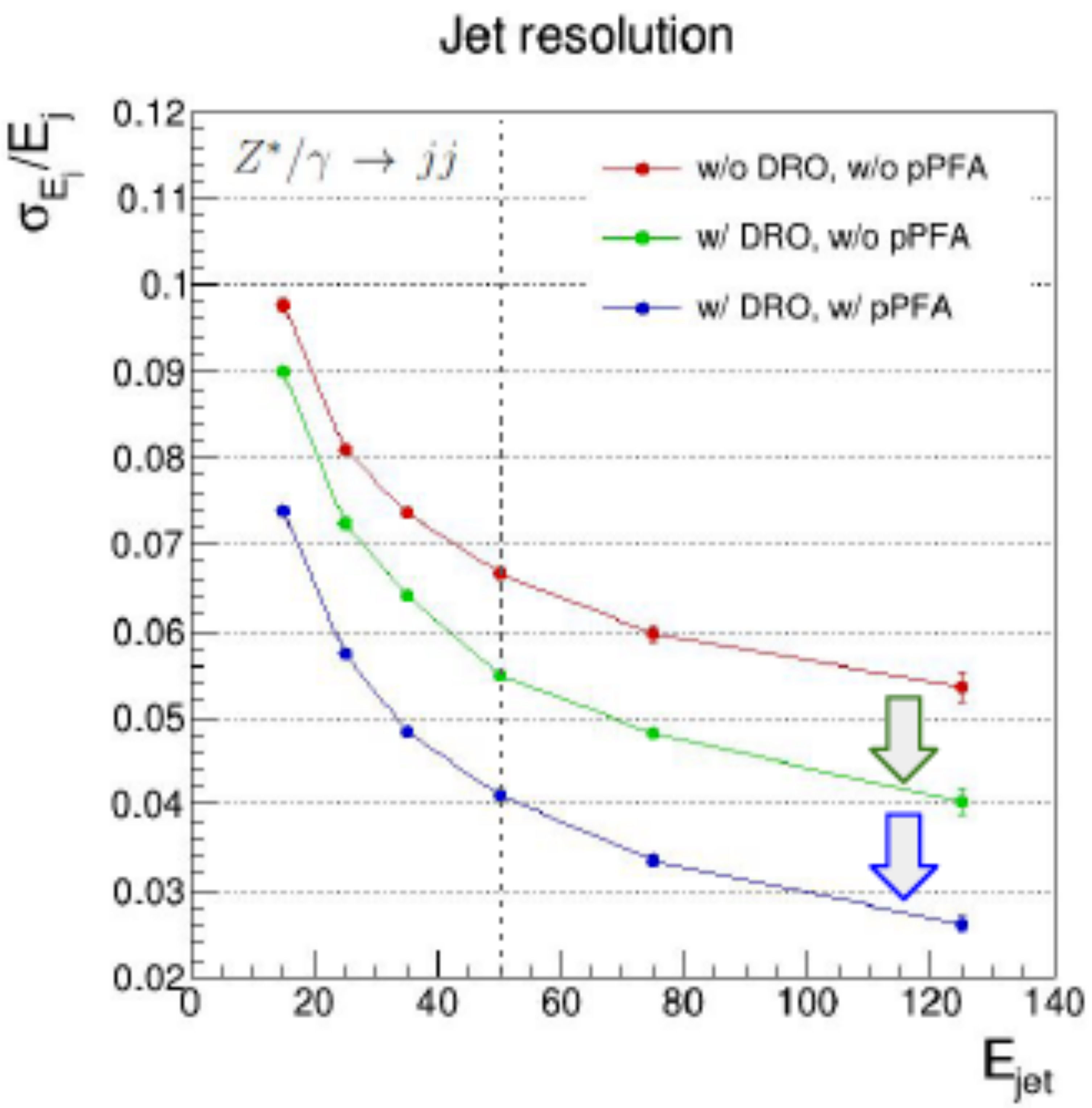
# Crystal ECAL with DR calorimeter






$\pi^0 \to \gamma\gamma$ events



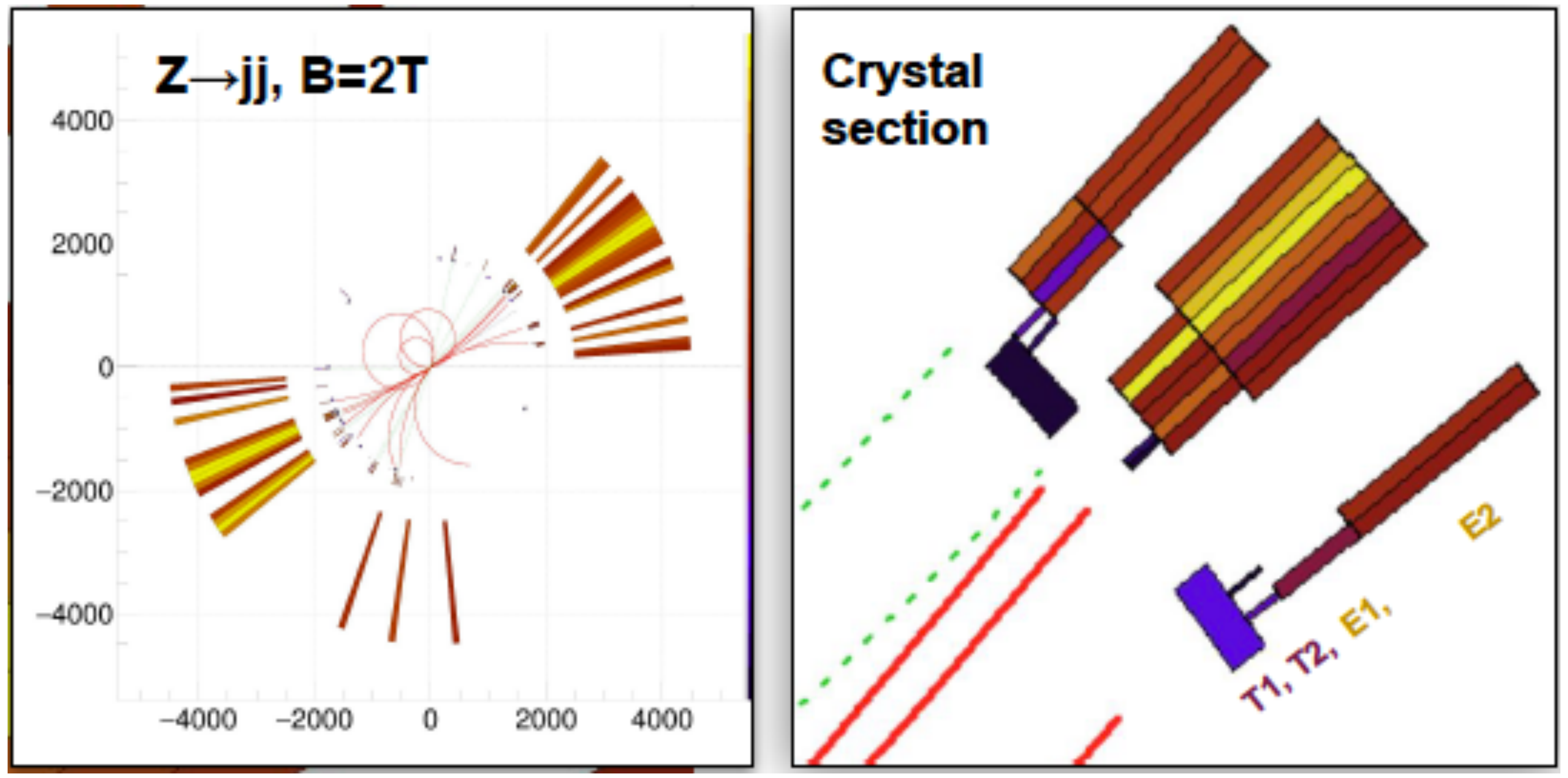




crystals + IDEA w/o DRO

crystals + IDEA w/ DRO

crystals + IDEA w/ DRO + pPFA

**Event display**

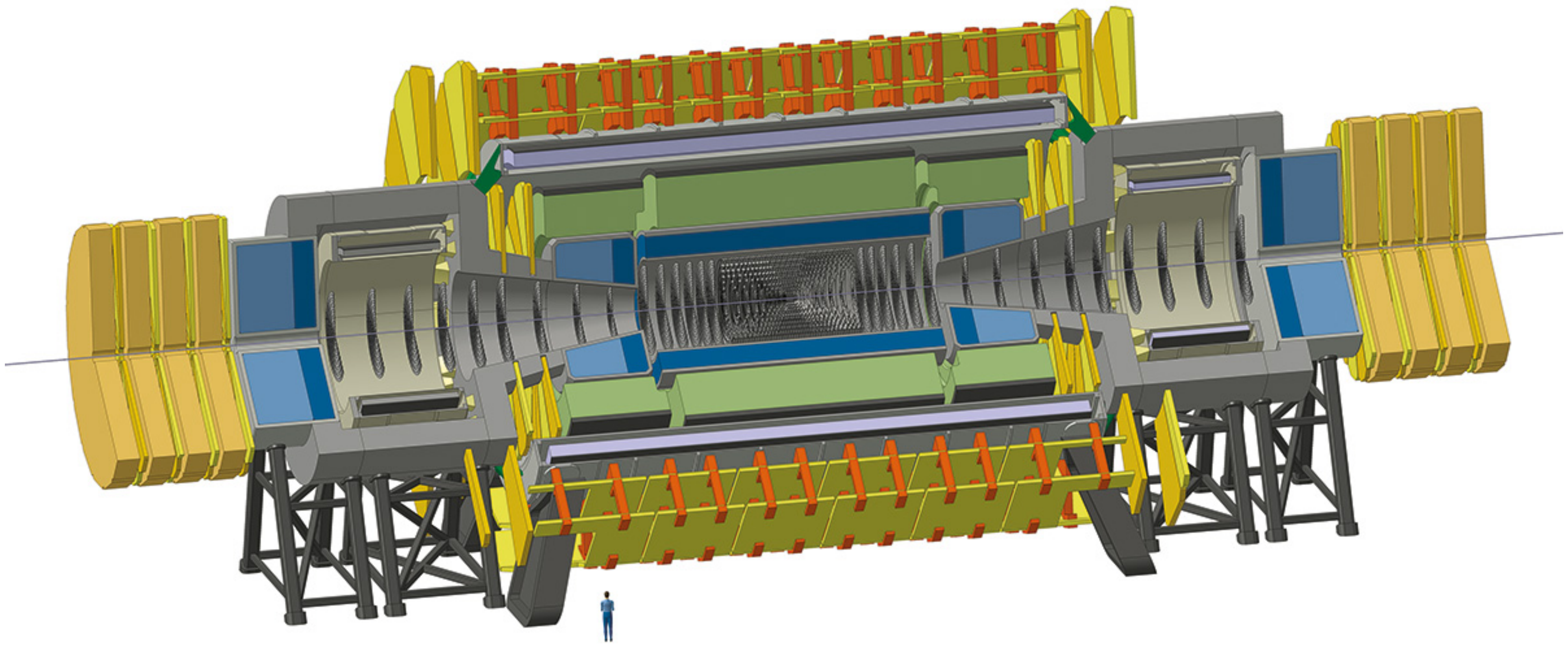


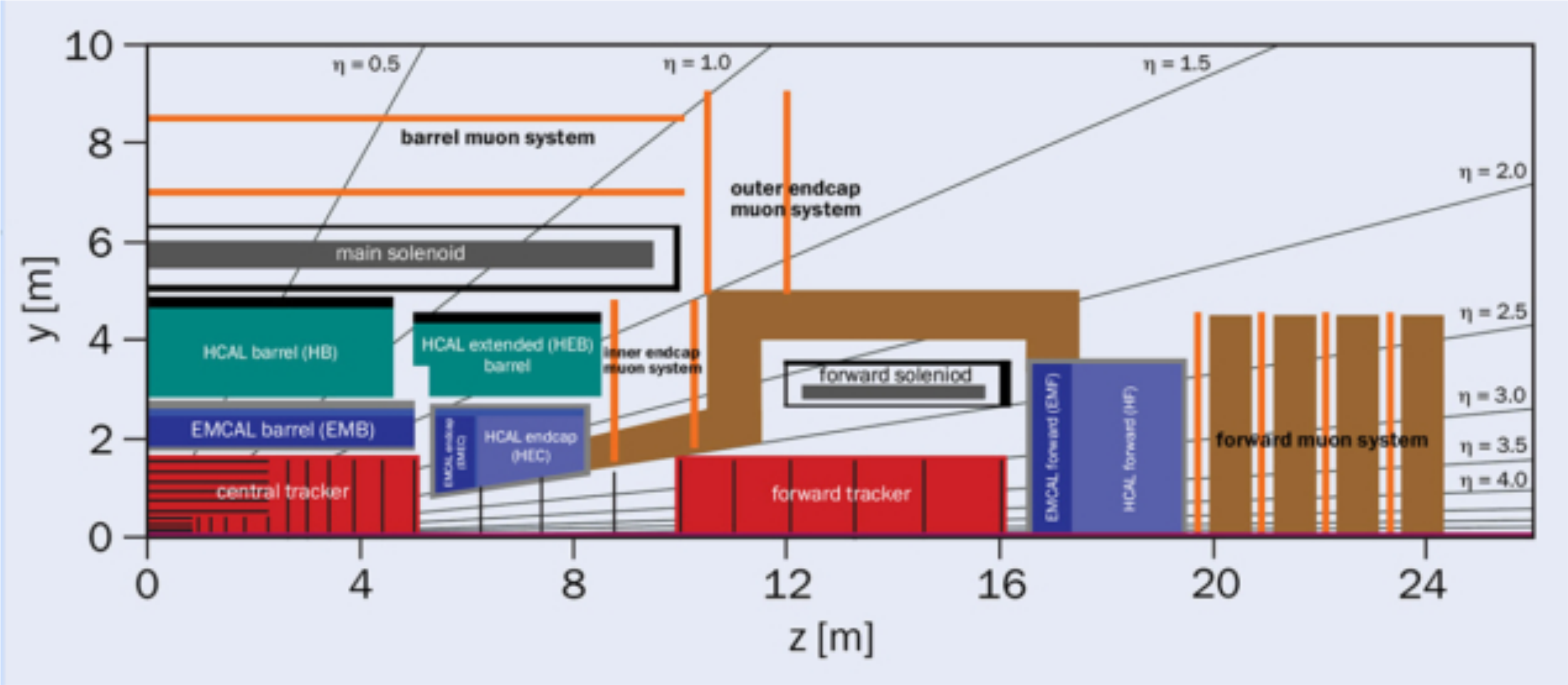

**Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV**

**M. Lucchini**

# 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





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FUTURE CIRCULAR COLLIDER

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INFN
Istituto Nazionale di Fisica Nucleare

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- **FCC-hh** will provide the highest $\sqrt{s}$ and open a large window for new physics
  - **A very preliminary detector concept has been proposed**
- Lots of possibilities for more International colleagues to join FCC and help on all these developments!!

# Backup

# μ-RWELL technology

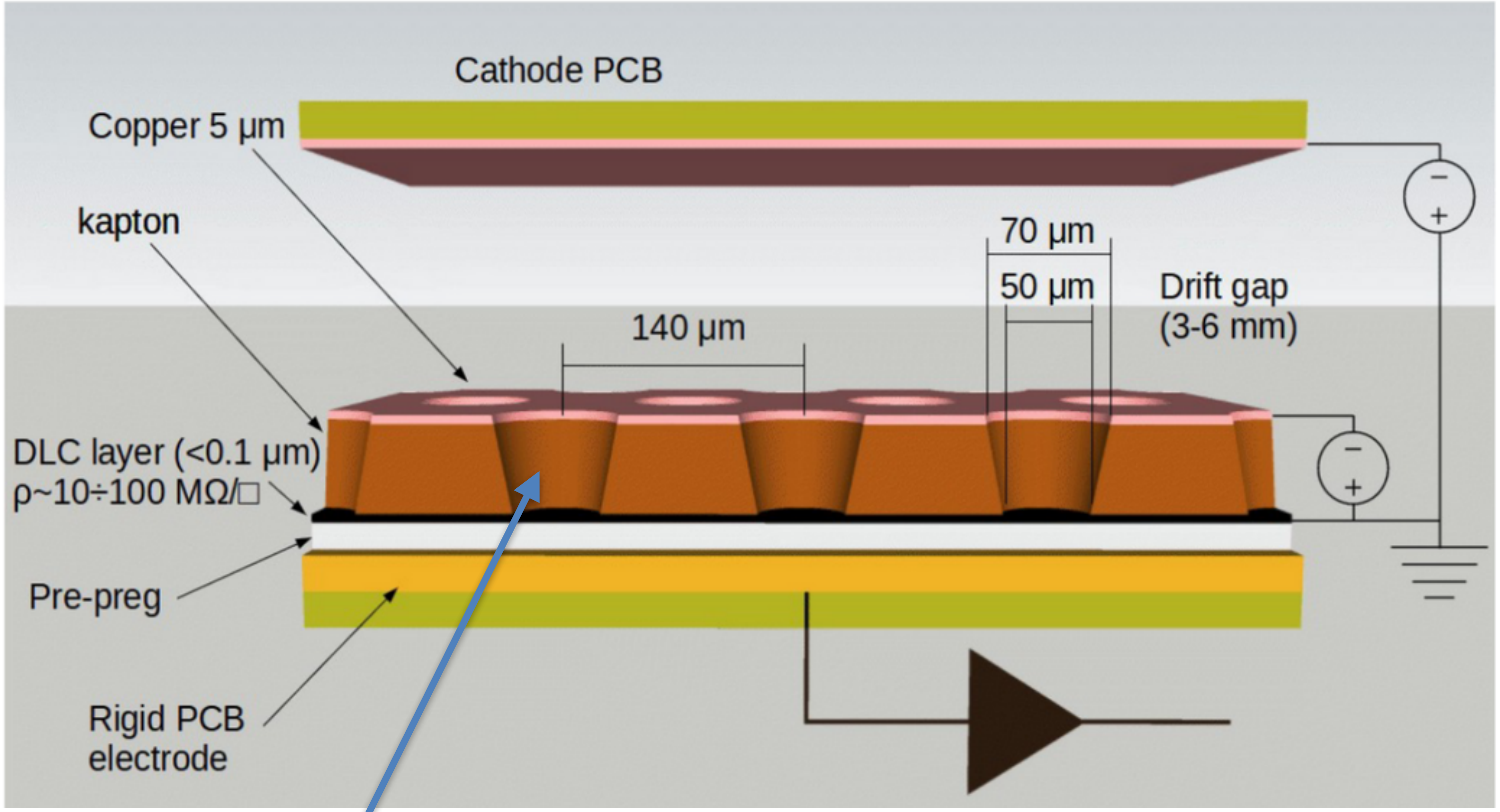
The μ-RWELL is composed of only two elements:

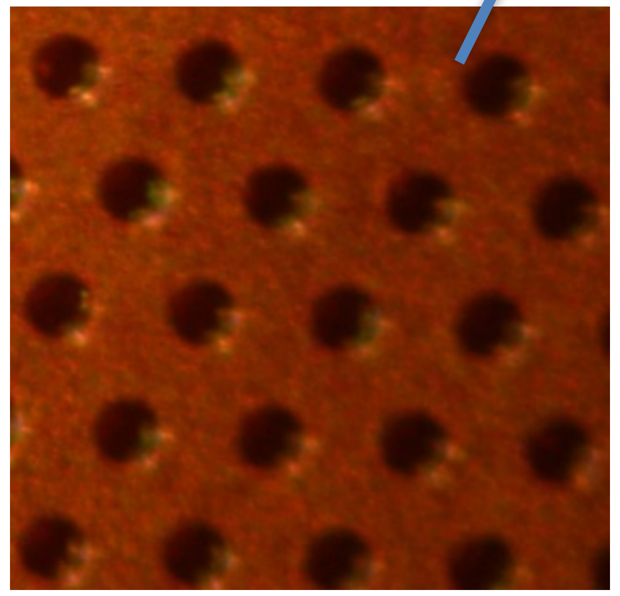
- μ-RWELL_PCB
- drift/cathode PCB defining the gas gap

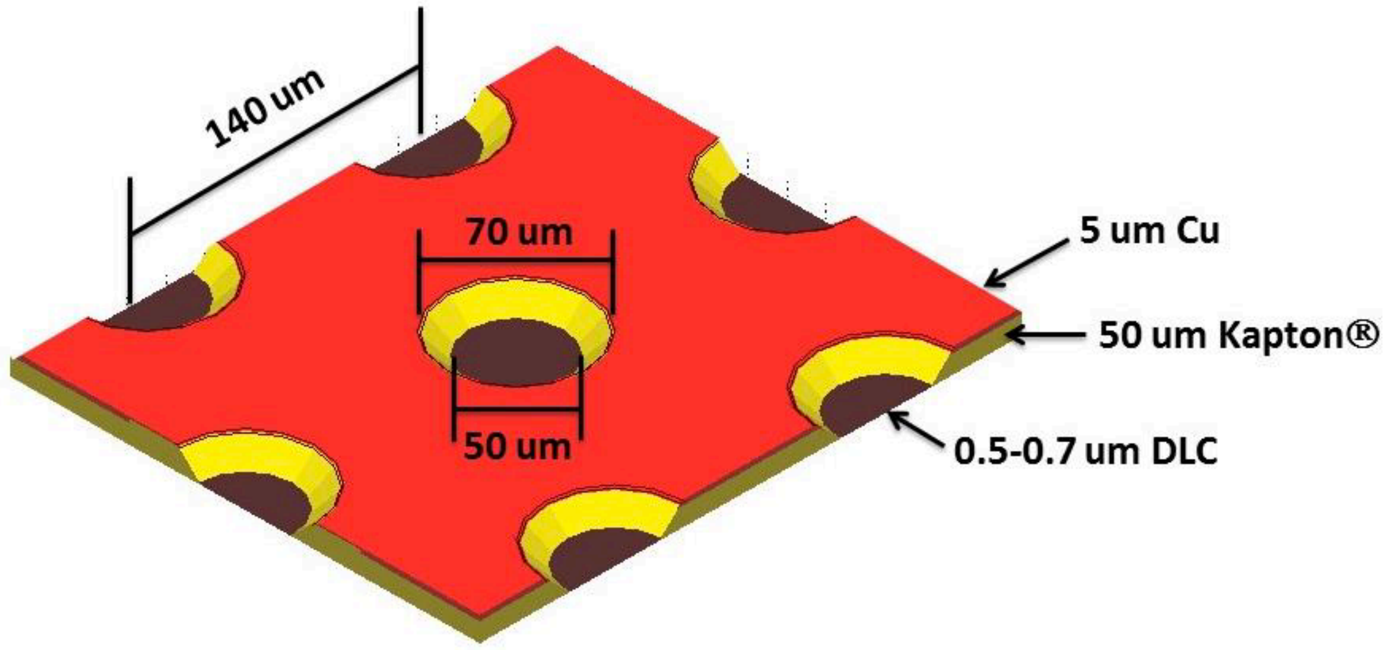
μ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

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






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

# IDEA: Preshower and muon detector

## Preshower Detector

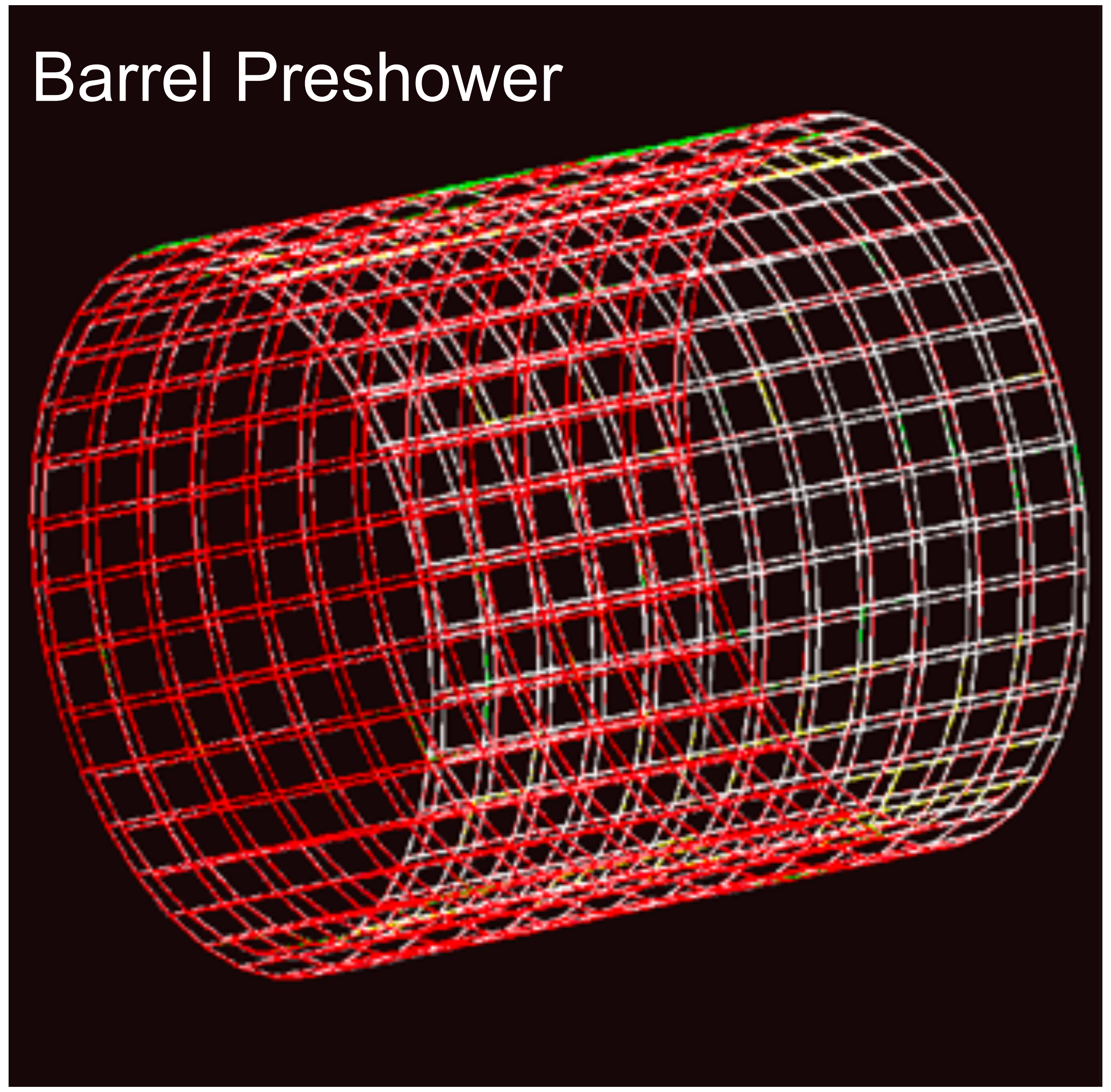
High resolution before the magnet
to improve cluster reconstruction

Efficiency > 98%
Space Resolution < 100 μm
Mass production
Optimization of FEE channels/cost

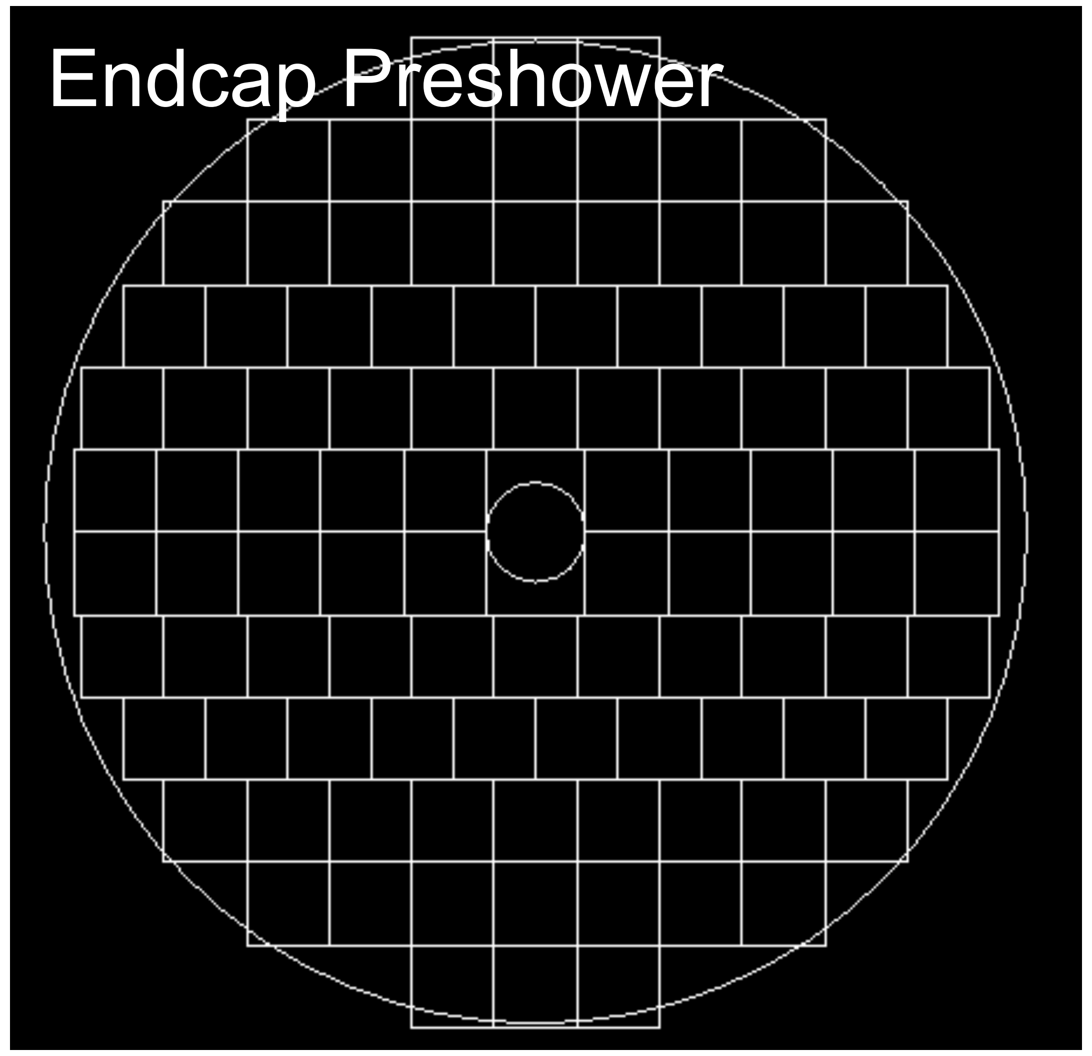
## Muon Detector

Identify muons and search for LLPs

Efficiency > 98%
Space Resolution < 400 μm
Mass production
Optimization of FEE channels/cost




Similar design for the Muon detector




Similar design for the Muon detector

**Detector technology: μ-RWELL**

50x50 $cm^2$ 2D tiles to cover more than 1500 $m^2$

| Preshower | Muon |
| --- | --- |
| pitch = 0.4 mm | pitch = 1.5 mm |
| FEE capacitance = 70 pF | FEE capacitance = 270 pF |
| 1.5 million channels | 5 million channels |