Detector concepts for FCC-ee

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INFN Bologna

3rd FCC-France workshop
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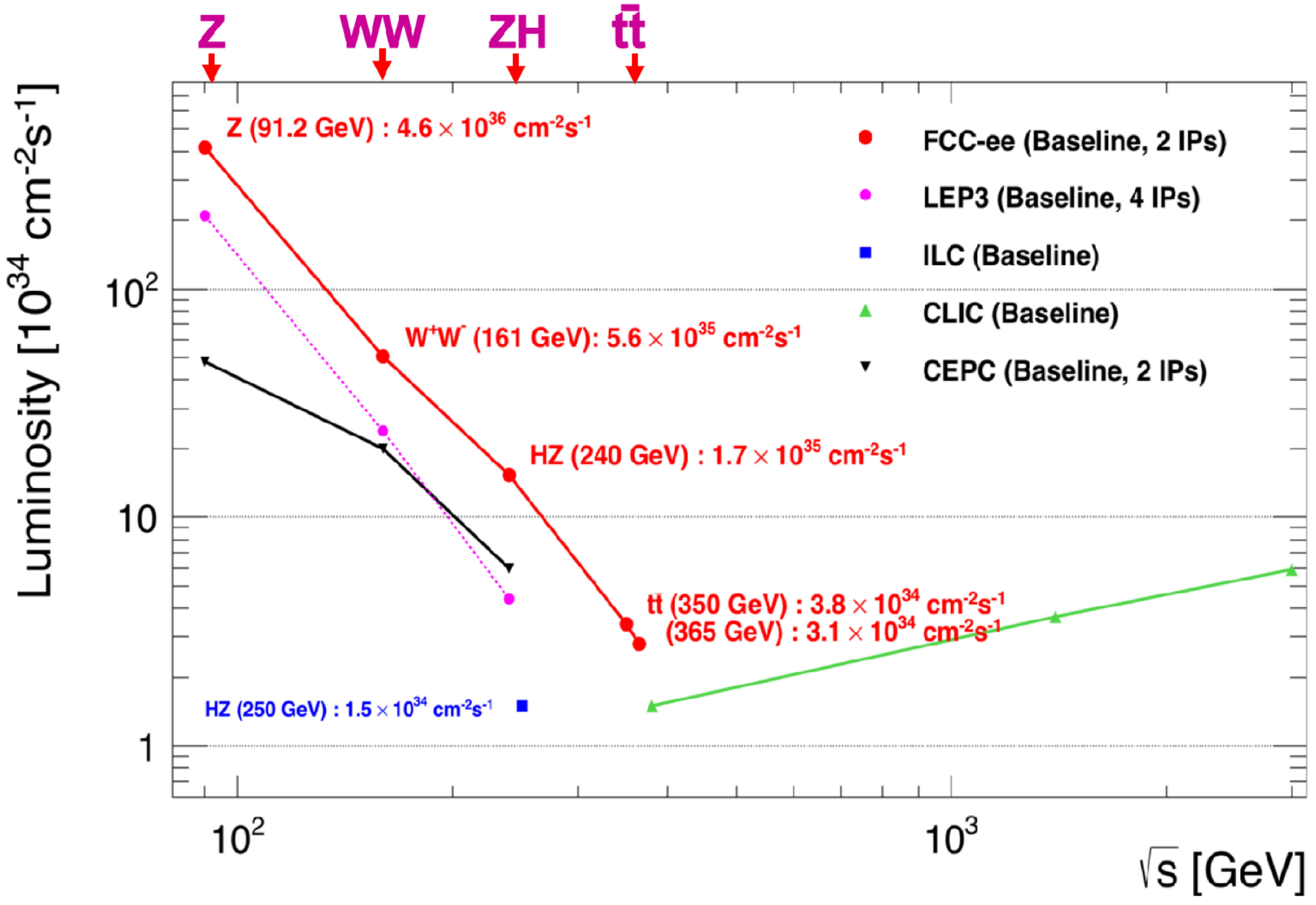
Photo J. Wenninger

FCC-ee conditions



Event statistics

5×10^{12} $e^+e^- \rightarrow Z$

10^8 $e^+e^- \rightarrow W^+W^-$

10^6 $e^+e^- \rightarrow HZ$

10^6 $e^+e^- \rightarrow tt$

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**230**	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8.4	1	0.1
"Pile up" parameter [μ]	**10^{-6}**	1,800	1	1	1

Experimentally, Z pole most challenging

- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 19.6 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- No pileup, no underlying event, …
  - …well, pileup of 2 x 10^{-3} at Z pole

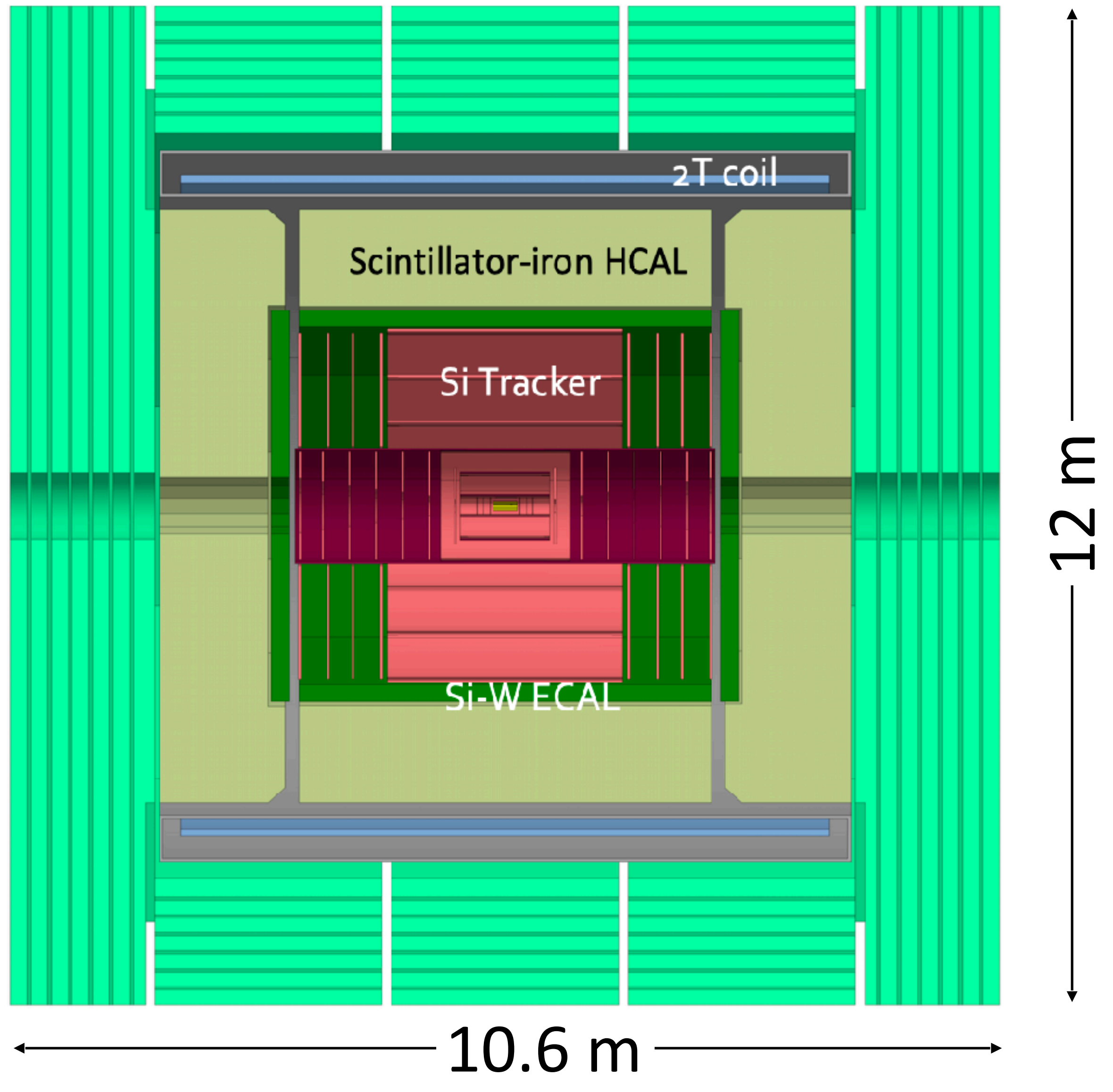
Mogens Dam

CDR: 2 Detector concepts

”Proof of principle concepts”

- Not necessarily matching (all) detector requirements, which are still being spelled out

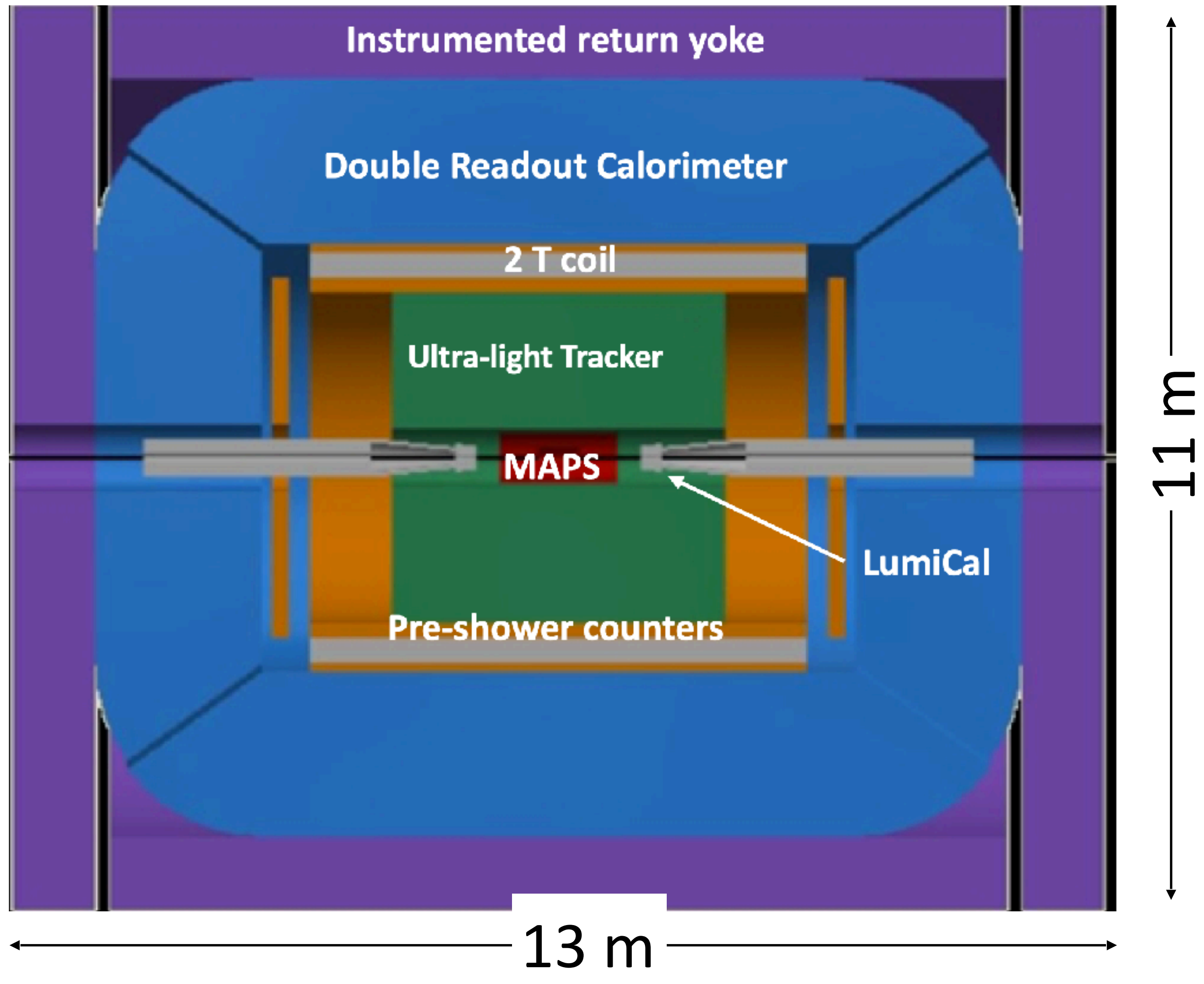
CLD



- Based on CLICdet detector design; profits from technology developments carried out for LCs
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system
  - Muon system made of RPC layers embedded in the iron yoke

https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520

IDEA



- New, innovative, possibly more cost-effective concept
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil *inside* calorimeter system
  - Muon system made of 3 layers of μRWell detectors in the return yoke

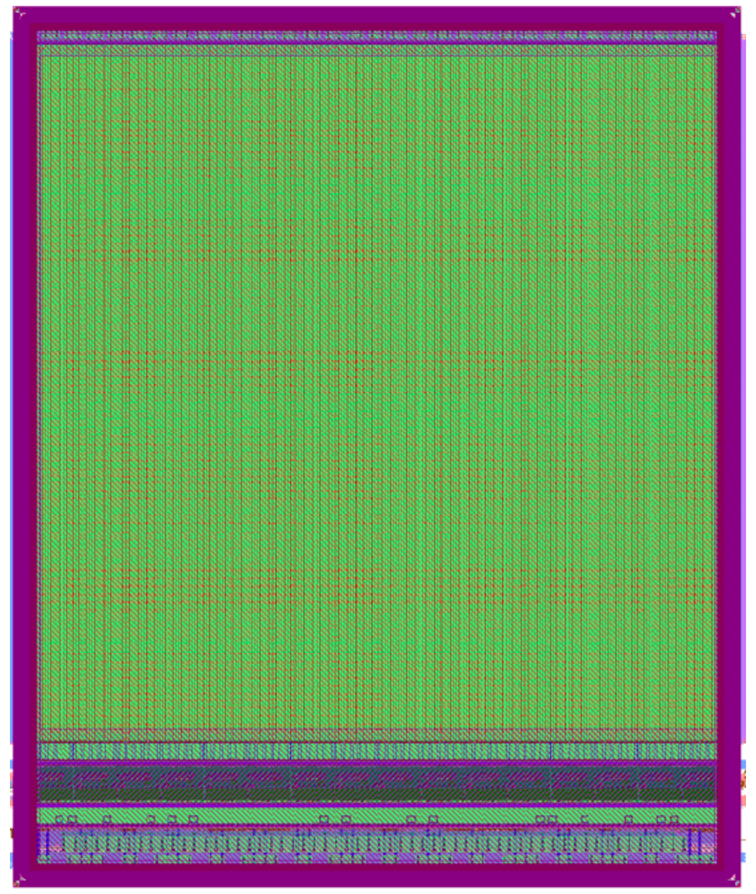
https://pos.sissa.it/390/

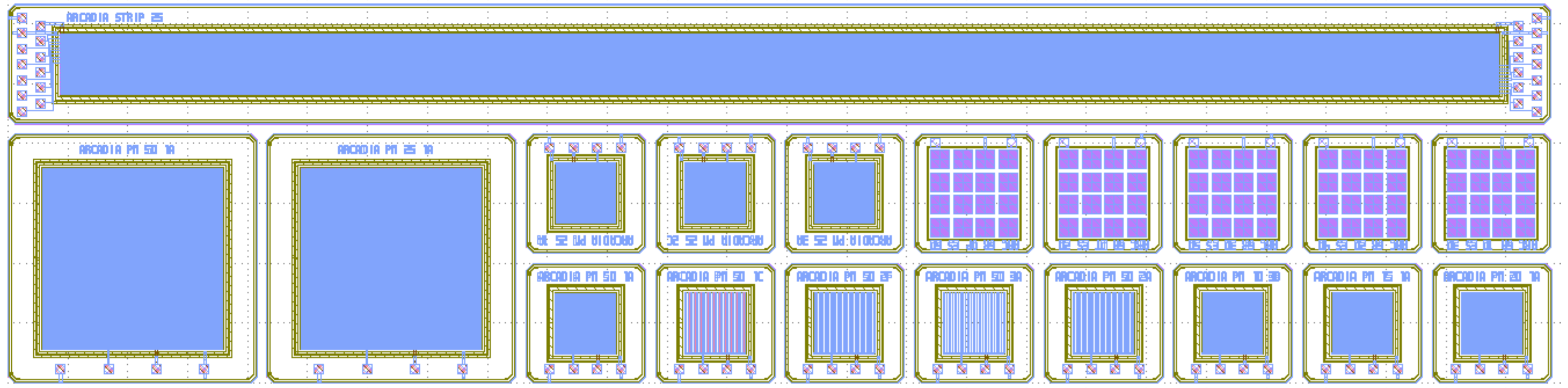
Vertex detector: IDEA

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

- Pixels 25 × 25 μm² (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





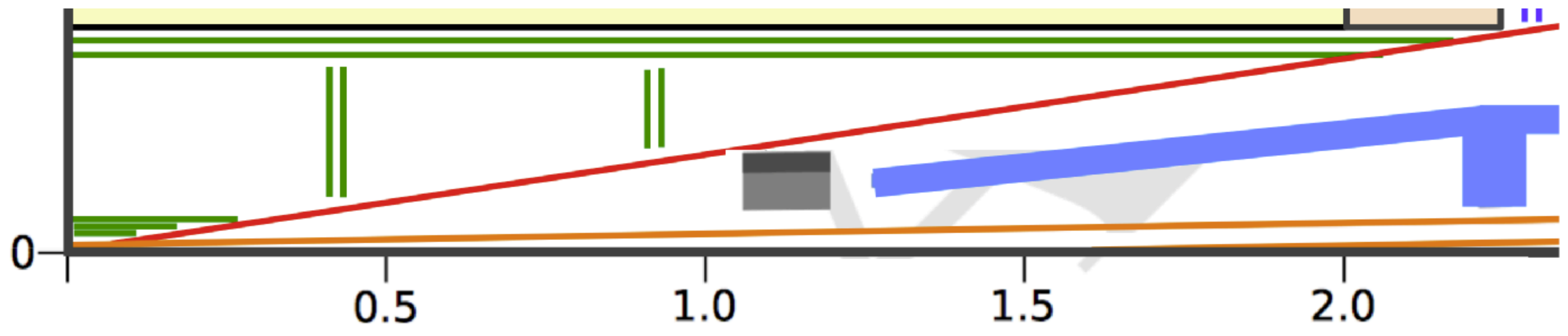
5 MAPS layers:

R = 1.7 - 2.3 - 3.1 cm

Pixel size: 20 x 20 μm²

R = 32 - 34 cm

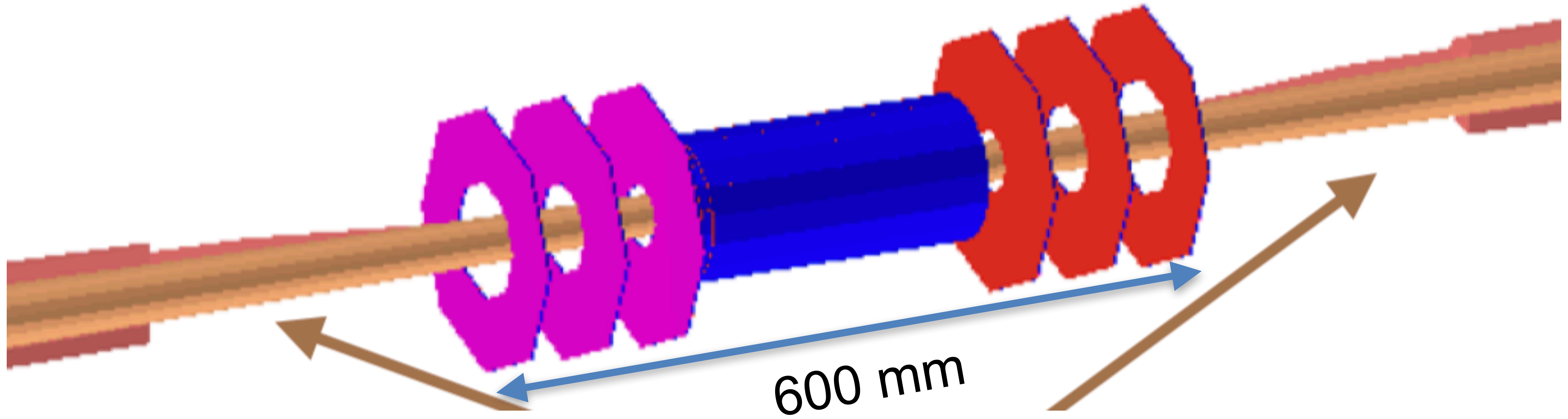
Pixel size: 50 x 100 μm²



Vertex detector: CLD

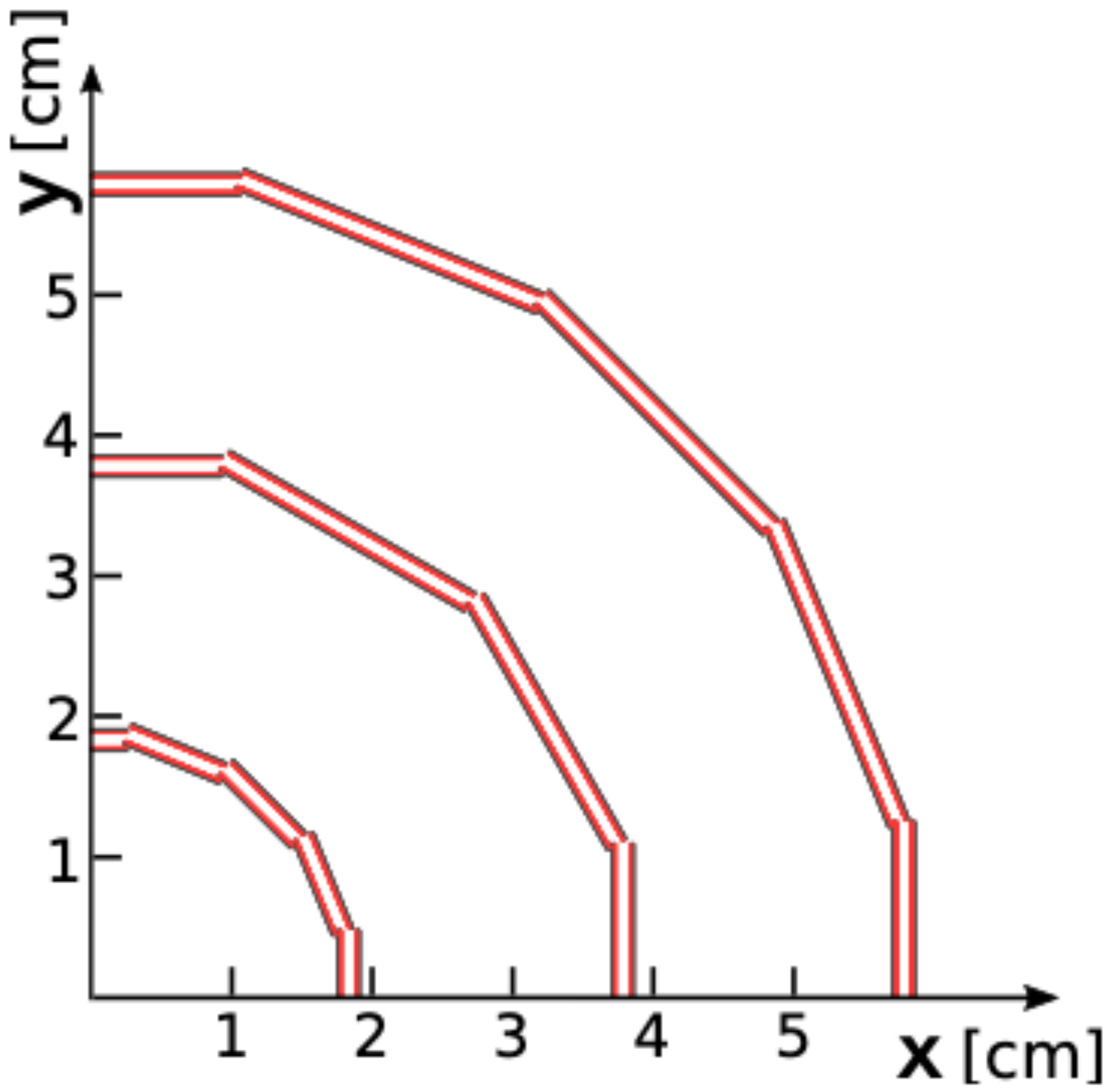
CLD is the all-silicon-tracker detector concept developed for FCC-ee

- 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

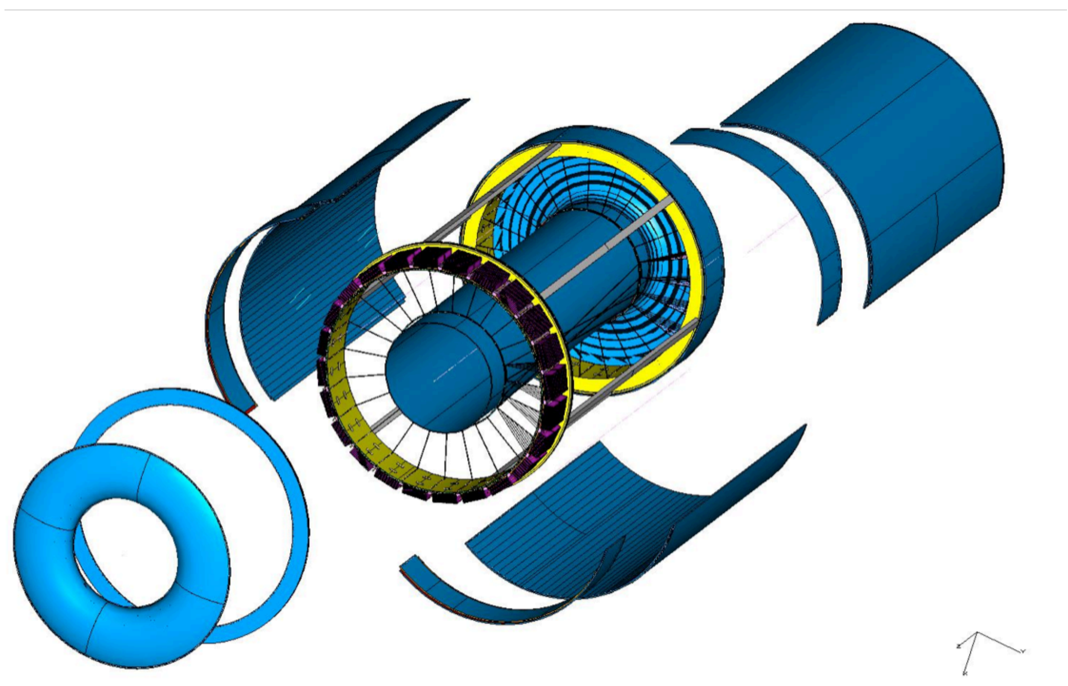


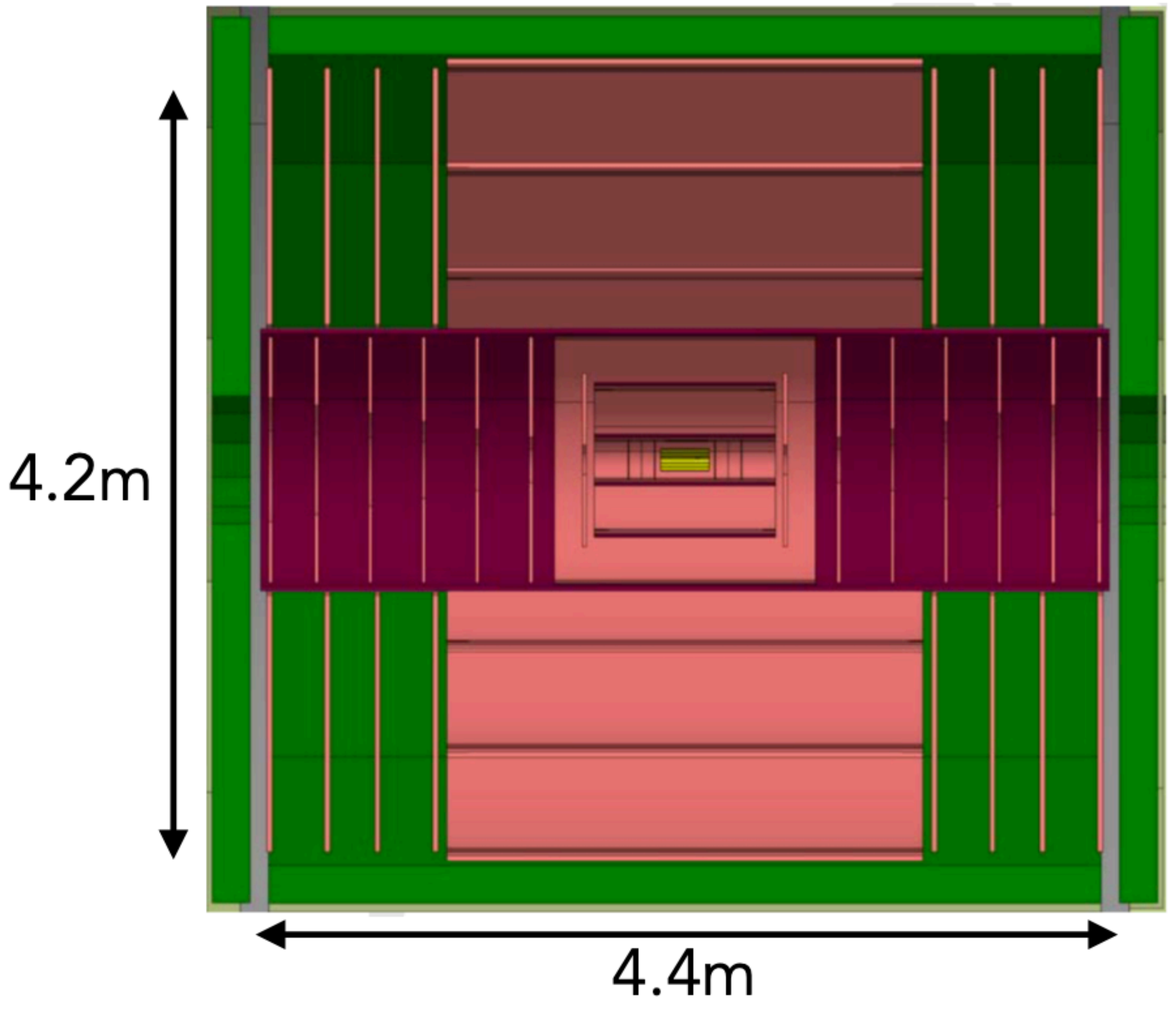
Central tracker

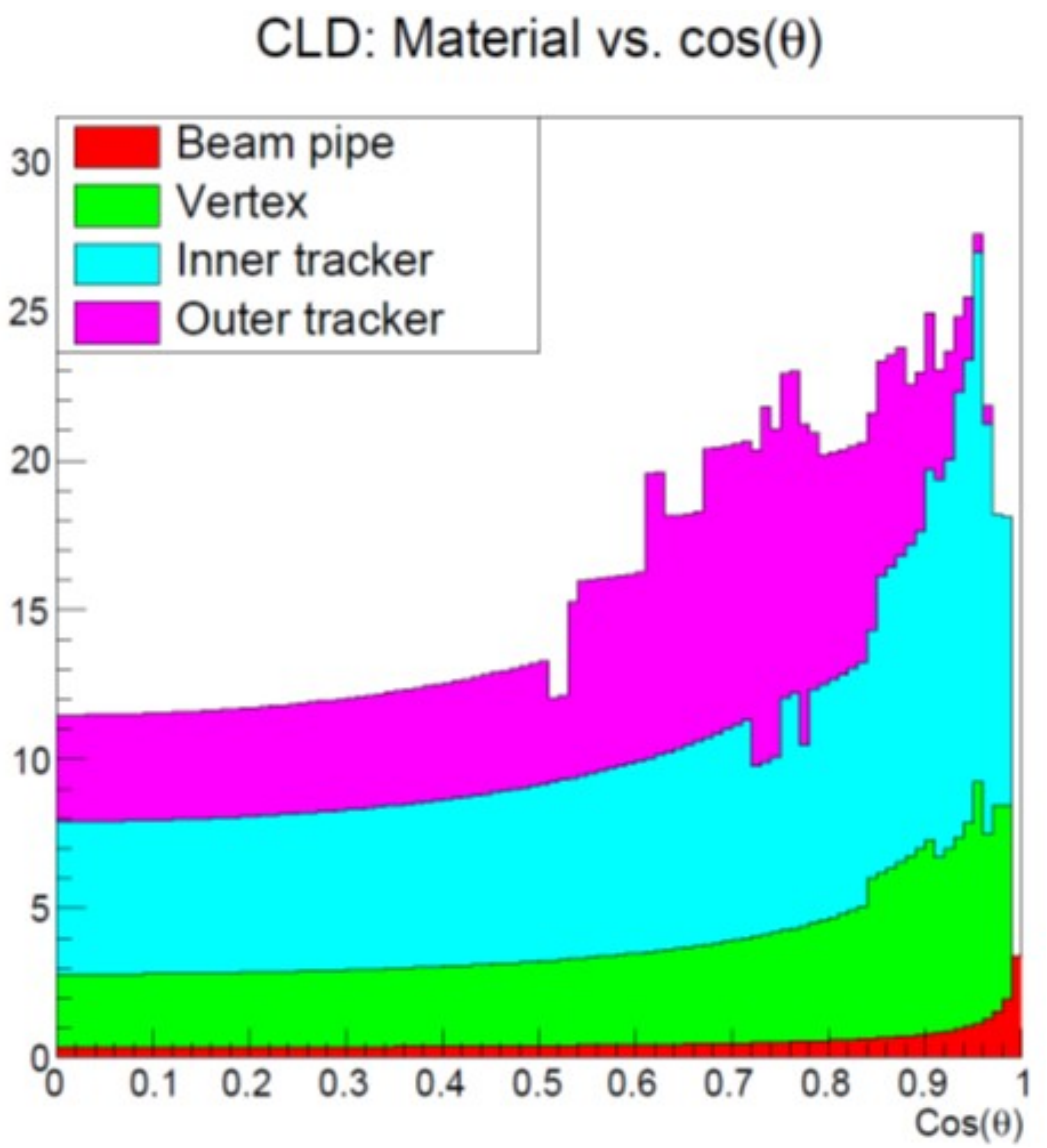
Two solutions under study

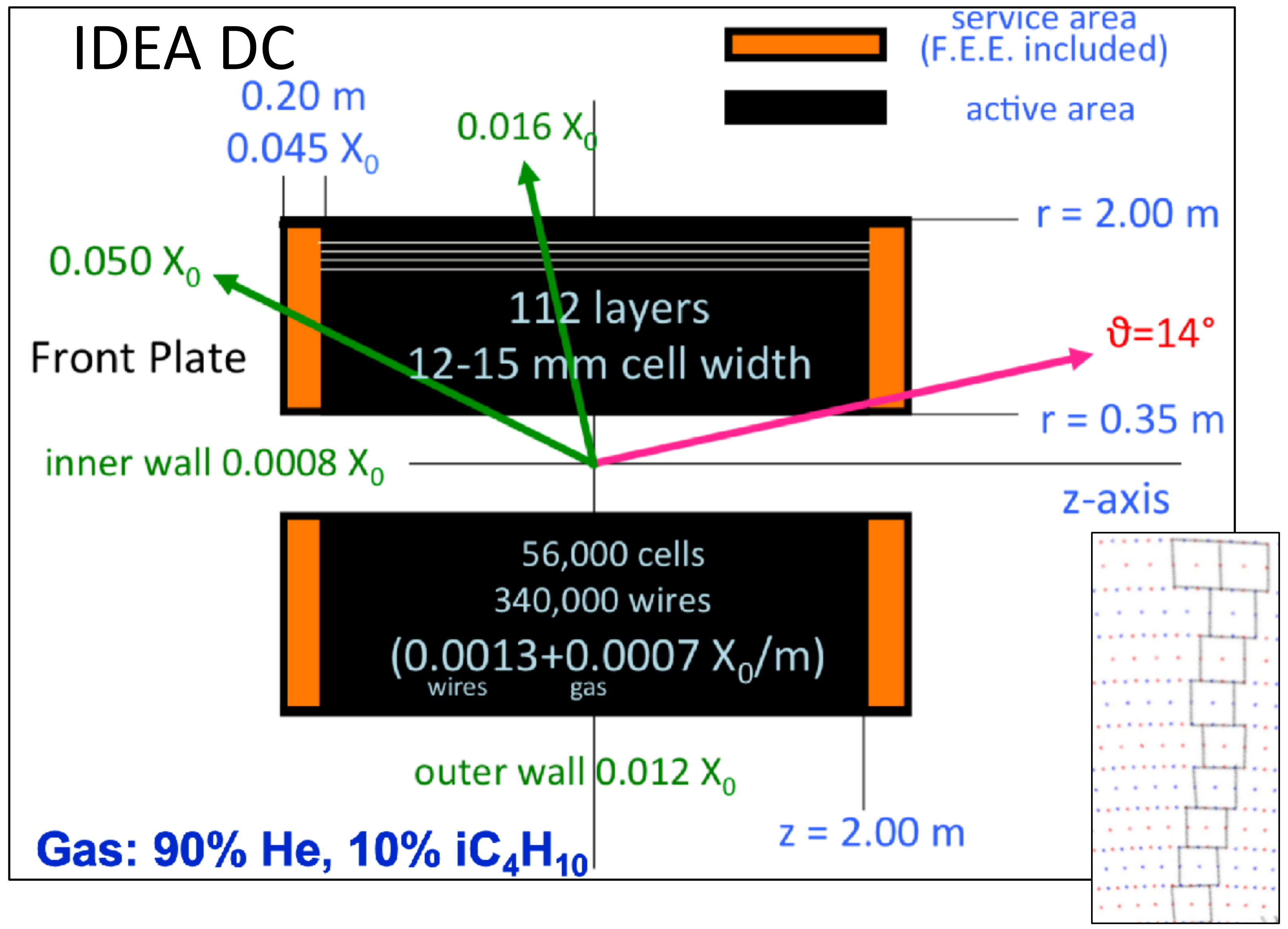
- CLD: All silicon pixel (innermost) + strips
  - ❑ Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - ❑ Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - ❑ Separated by support tube (2.5% X_0)

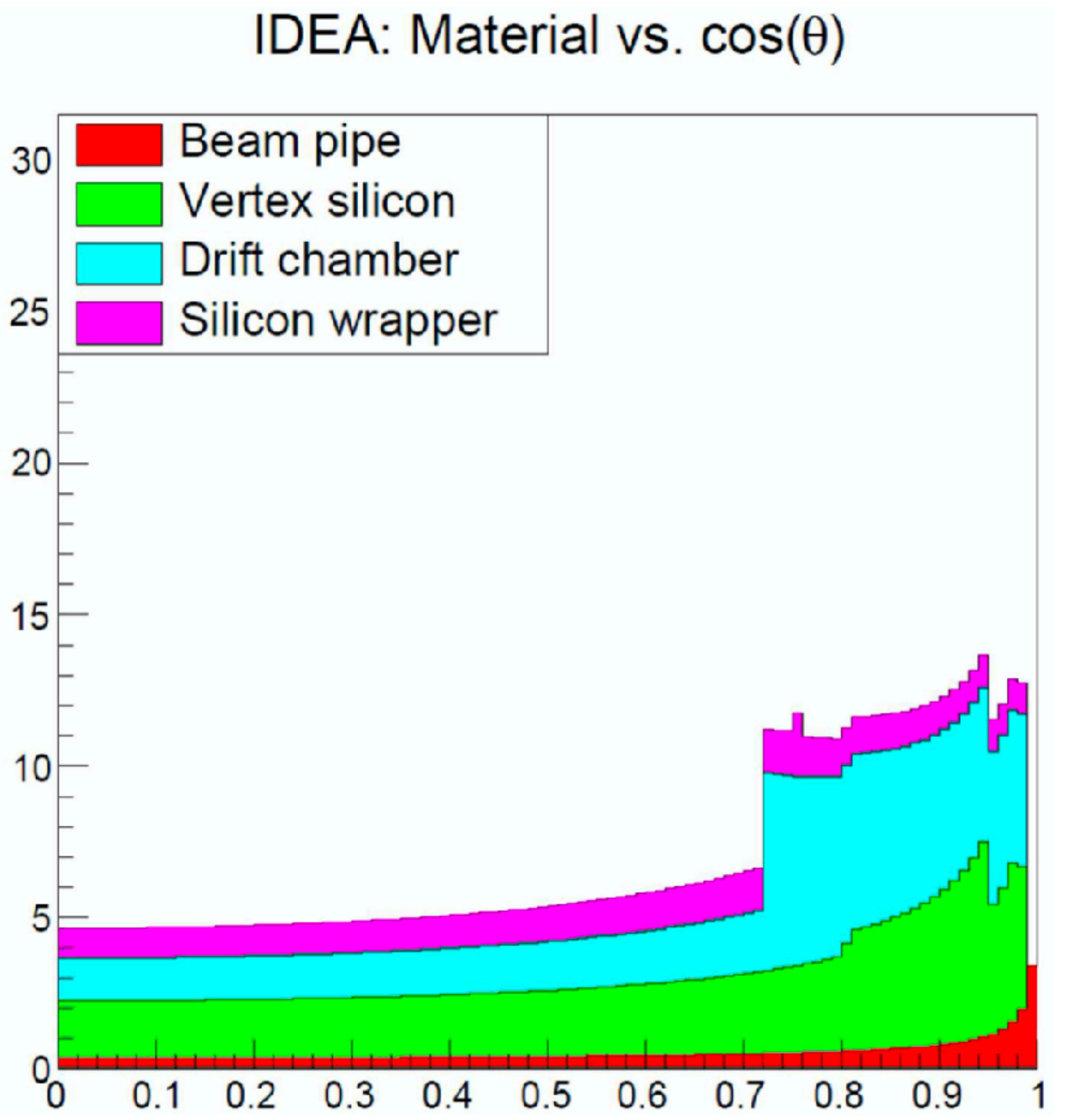
- IDEA: Extremely transparent Drift Chamber
  - ❑ GAS: 90% He – 10% iC_4H_{10}
  - ❑ Radius 0.35 – 2.00 m
  - ❑ Total thickness: 1.6% of X_0 at 90°
    - ❖ Tungsten wires dominant contribution
  - ❑ Full system includes Si VXT and Si "wrapper"







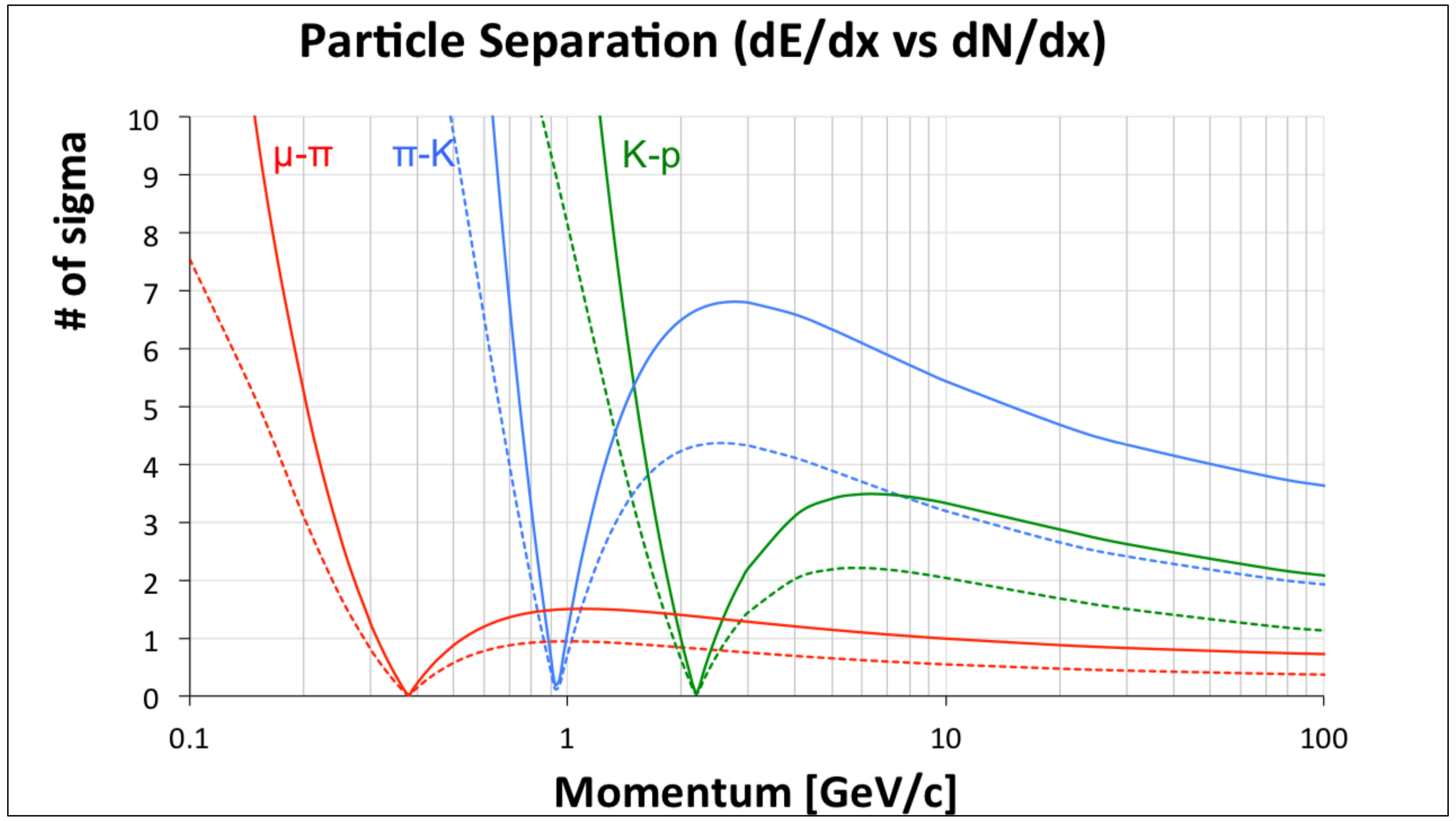


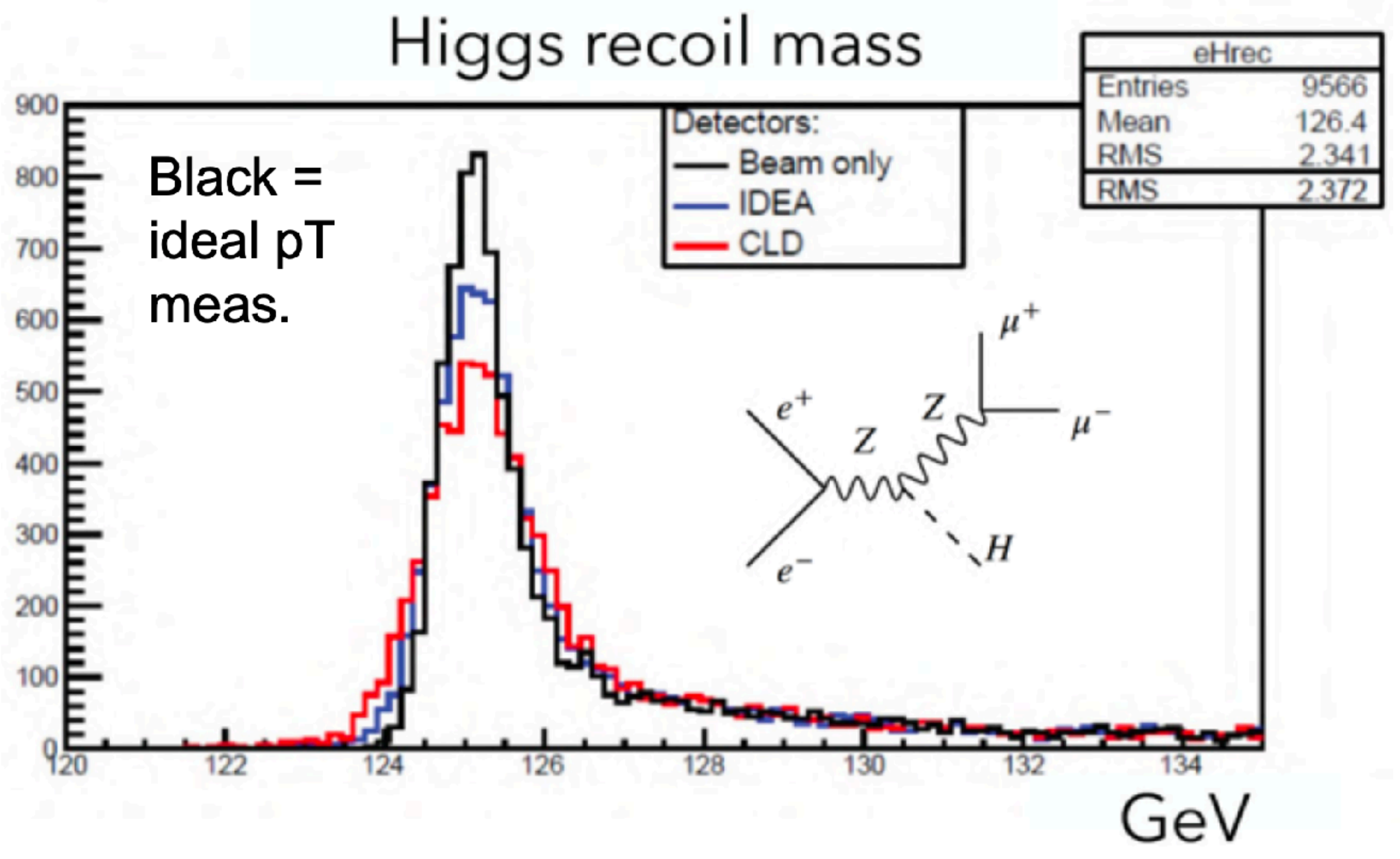


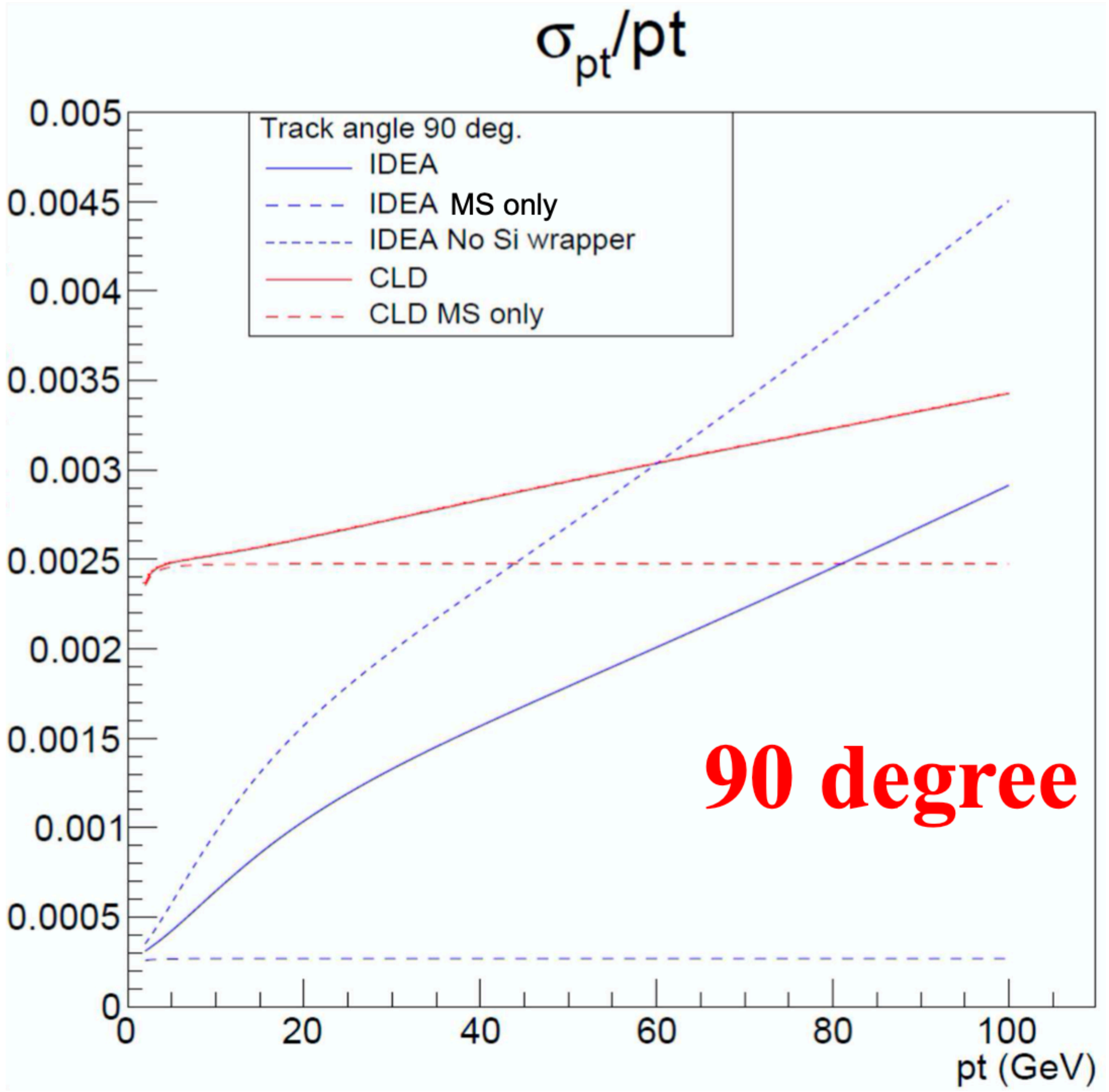
Drift chamber

- 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, Λ, 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,

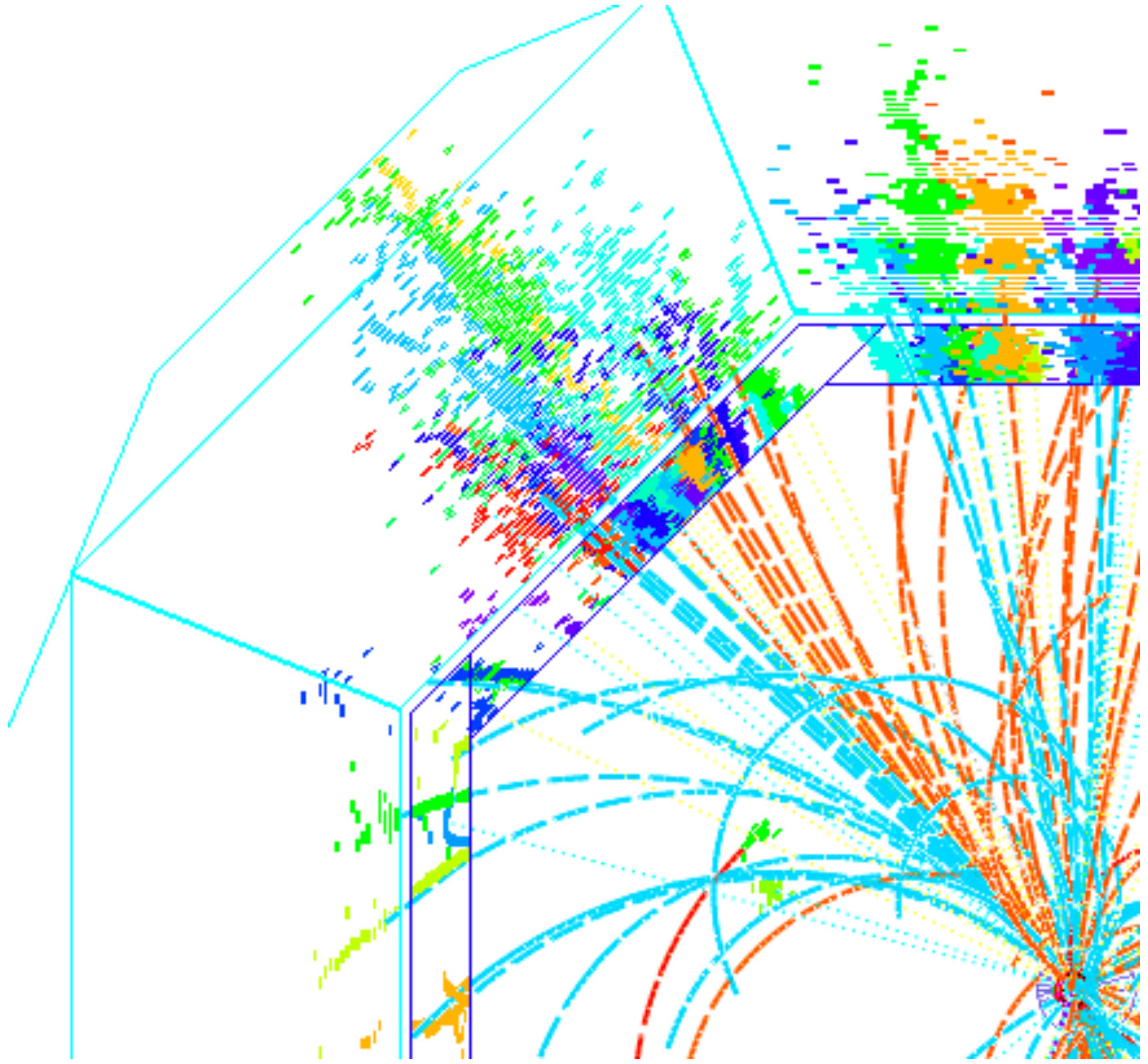
cell size: 5 x 5 mm^2

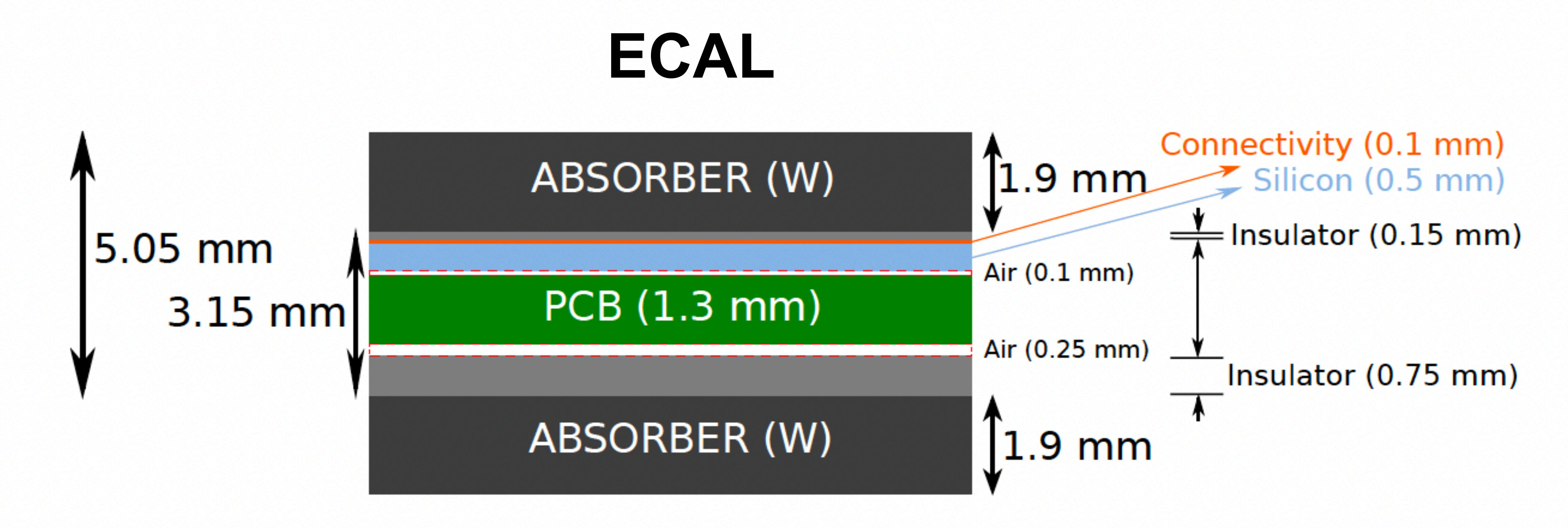
40 layers (1.9 mm thick W plates), 22-23 X_0 total, 20 cm thick

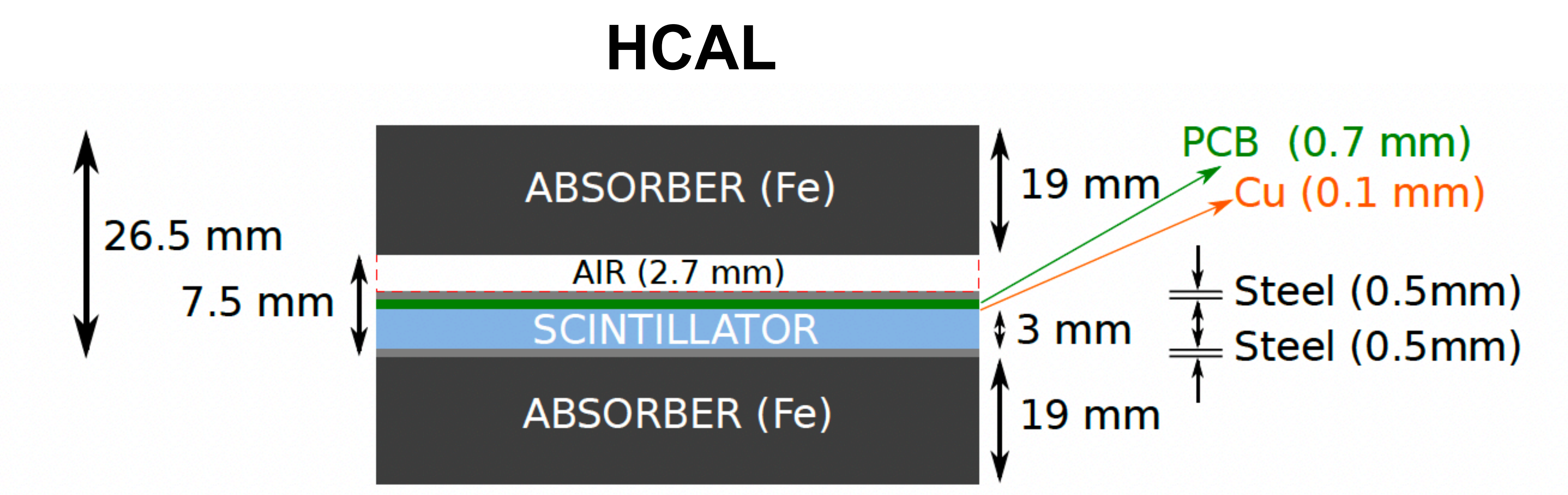
- Scintillator-steel sampling HCAL,

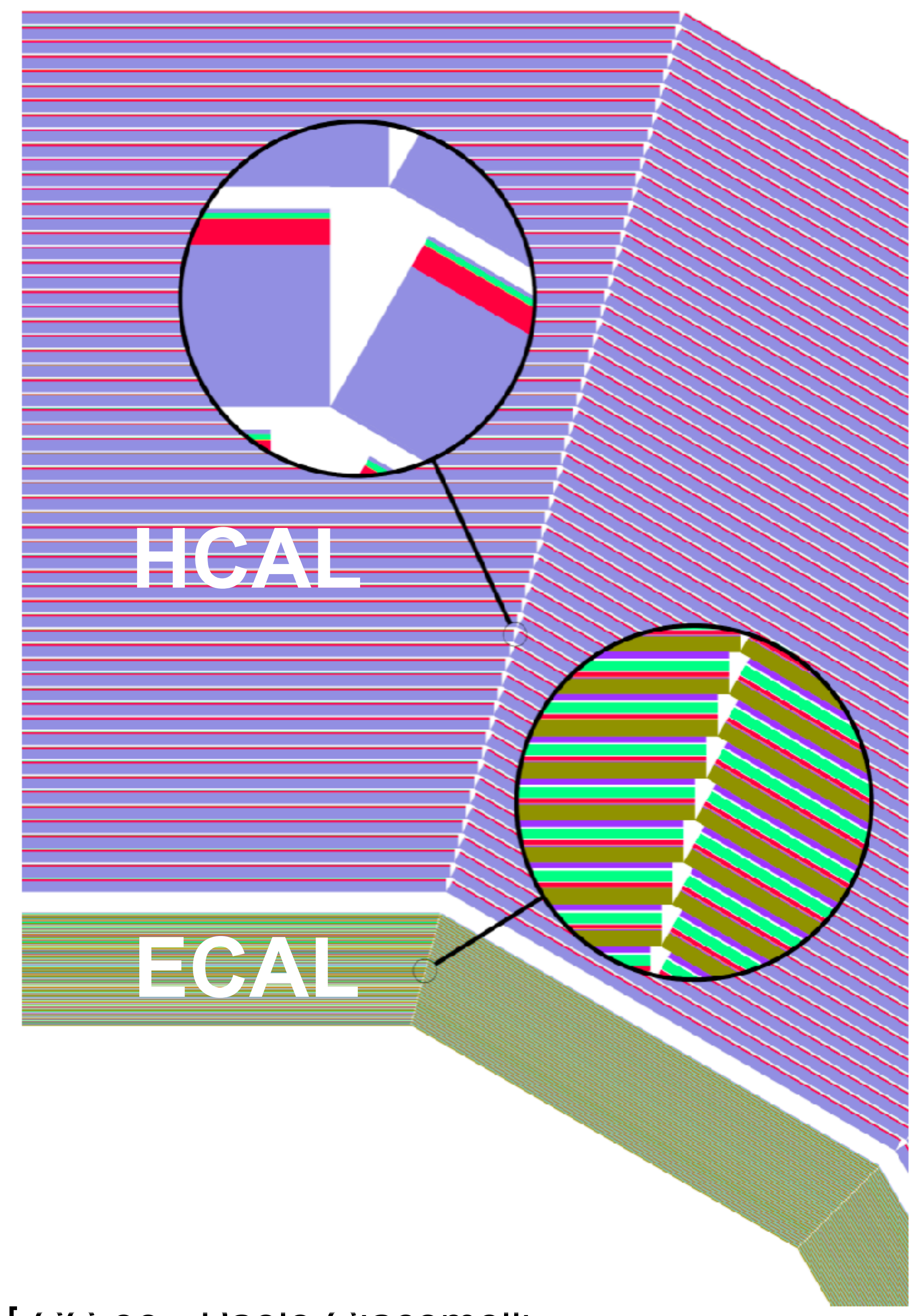
cell size: 30 x 30 mm^2

44 layers (1.9 mm steel plates), 5.5 Λ total, 117 cm thick

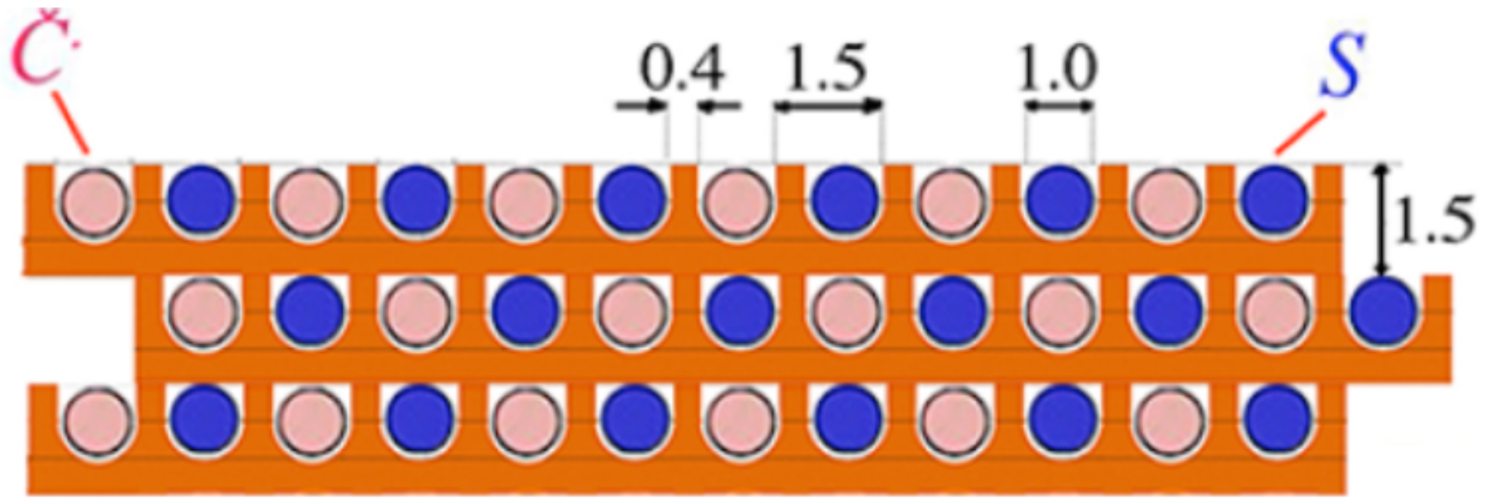






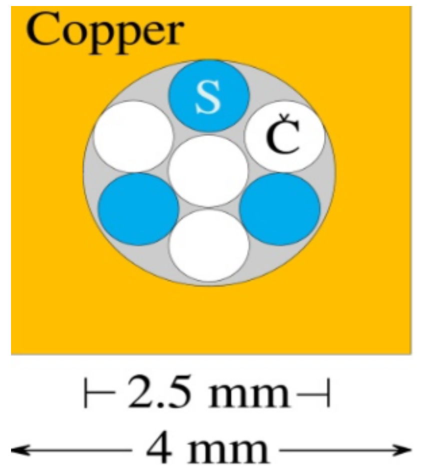


Calorimetry: IDEA



Dual Readout calorimetry

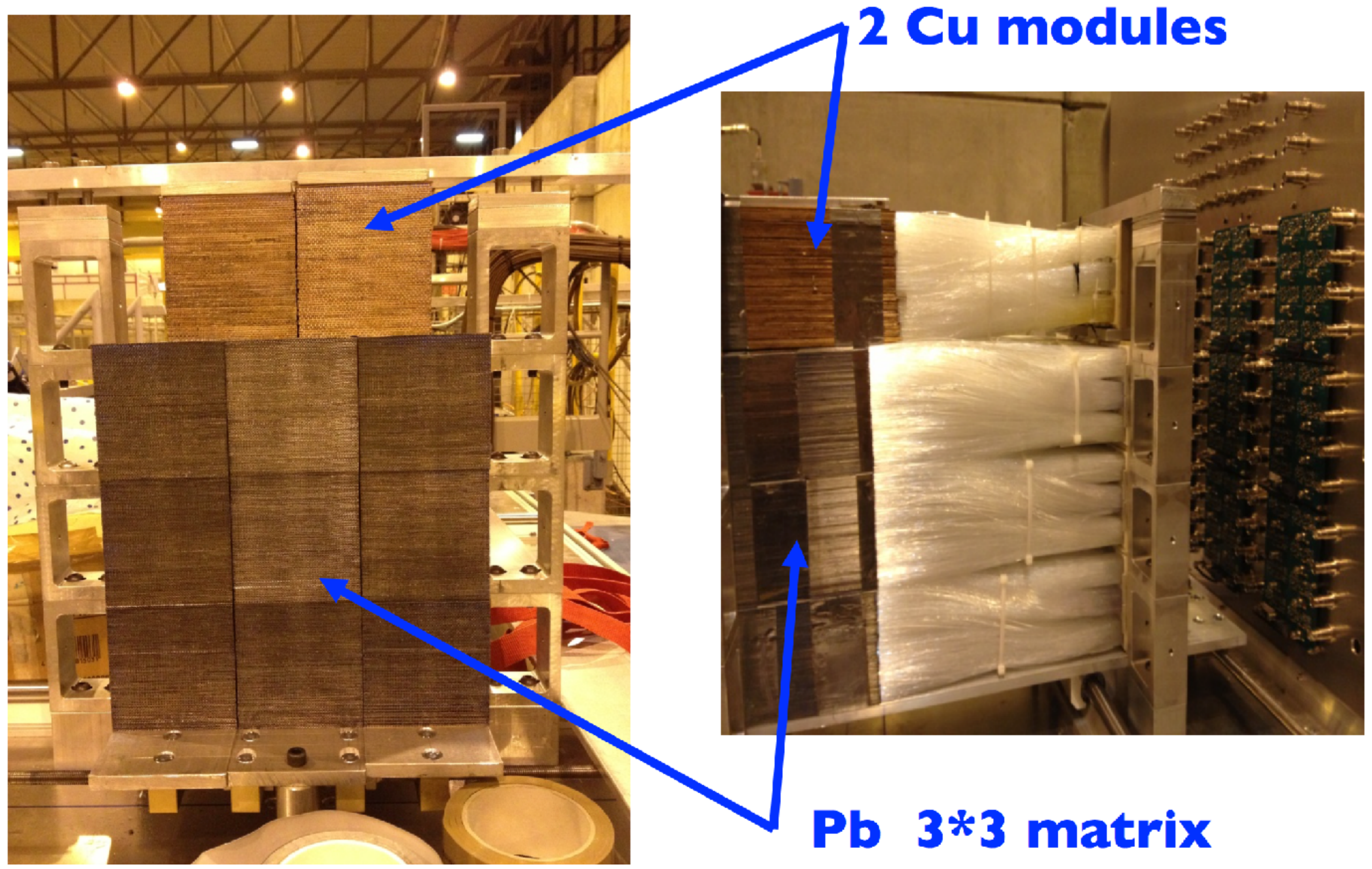
Alternate
Cherenkov fibers
Scintillating fibers



“Building block” of the DREAM calorimeter

2m long (10 λ_{int}) [5130 blocks, ≈ 16 cm radius]
R $_{\text{Molière}}$ = 20.4 mm

A Dual Readout calorimeter prototype (looks like a spaghetti calorimeter)



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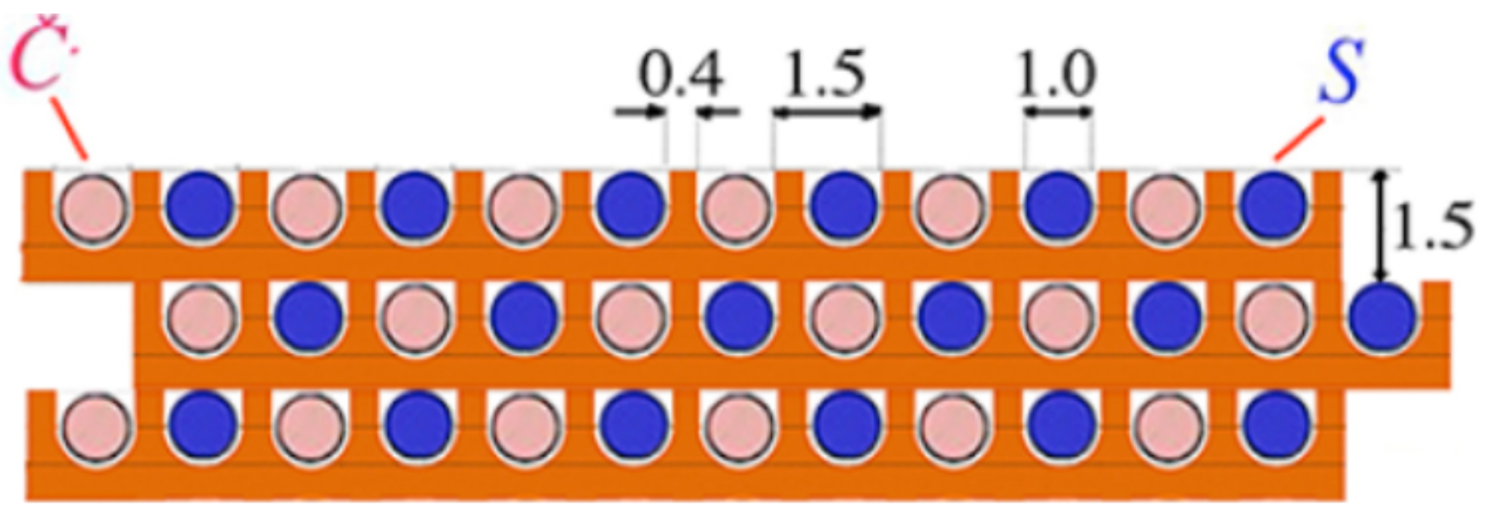

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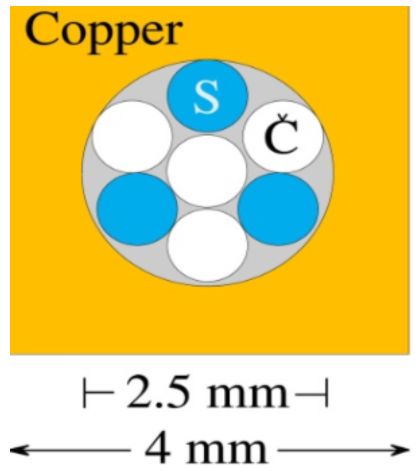

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- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)

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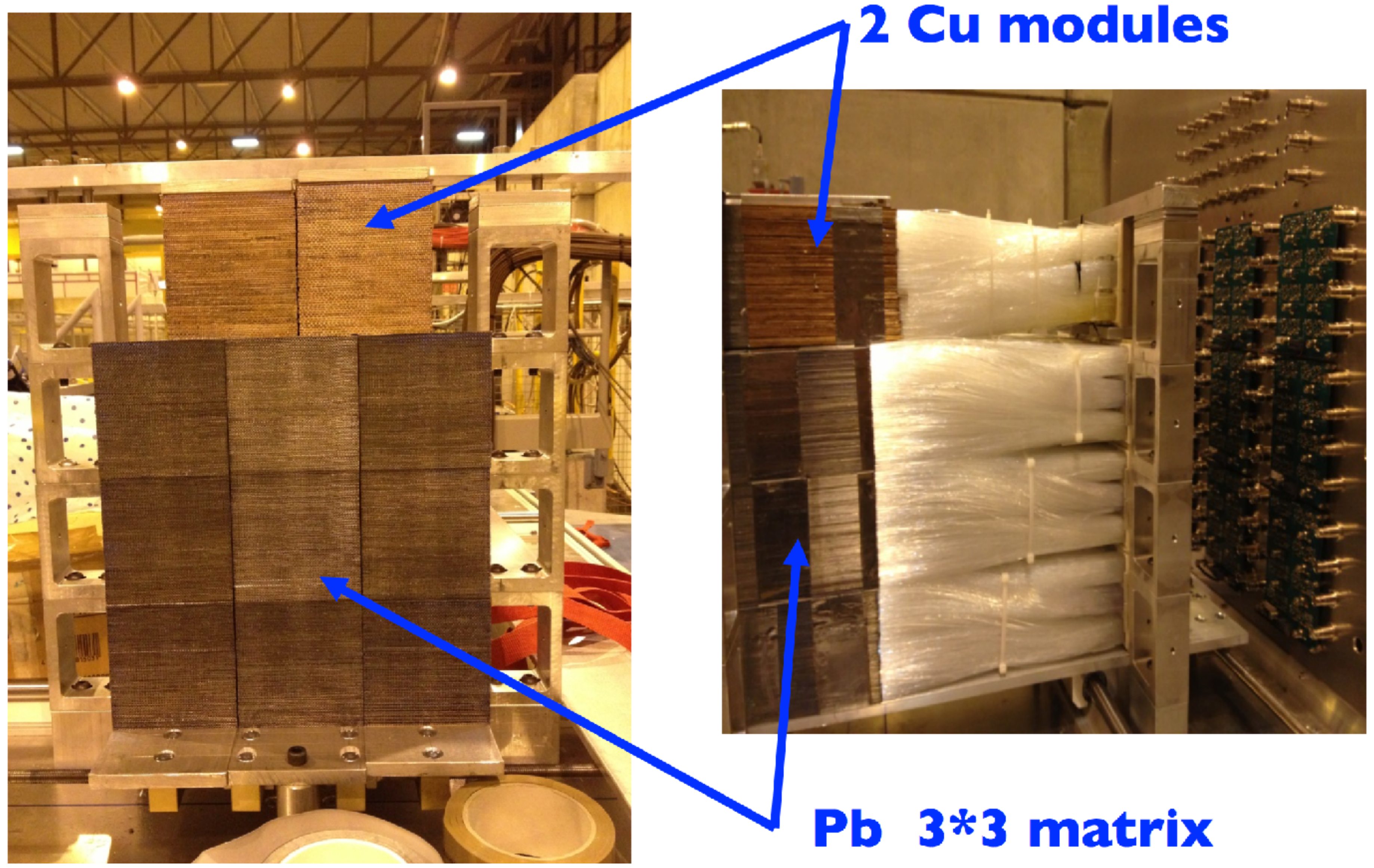
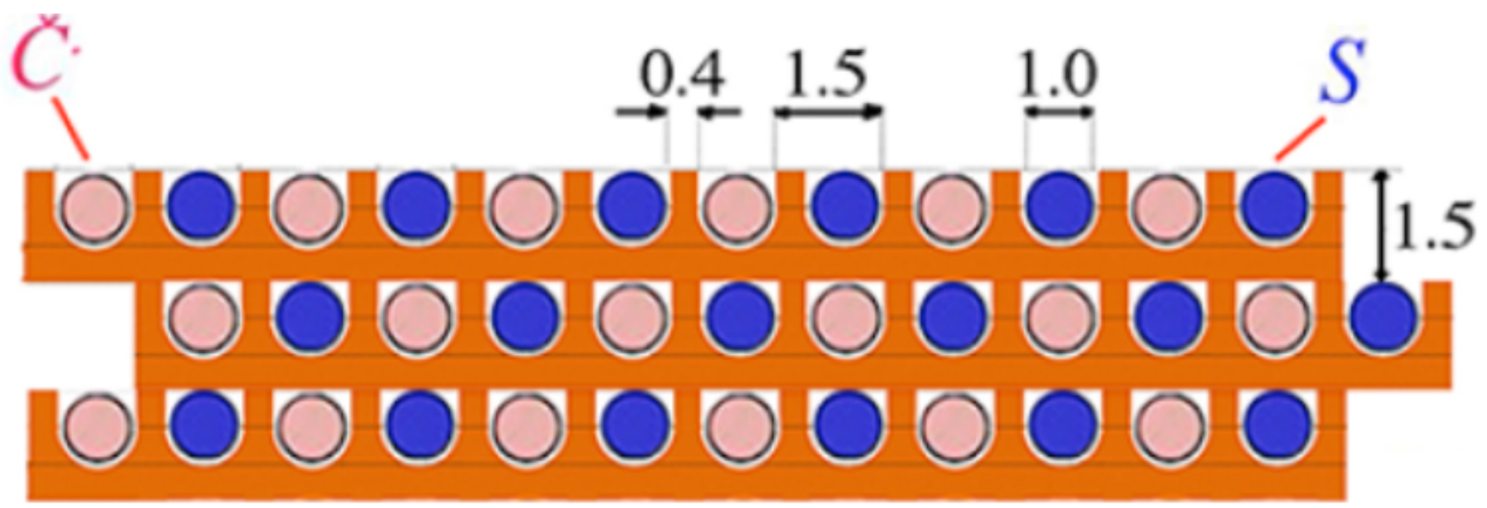


2 Cu modules

Pb 3*3 matrix

Calorimetry: IDEA



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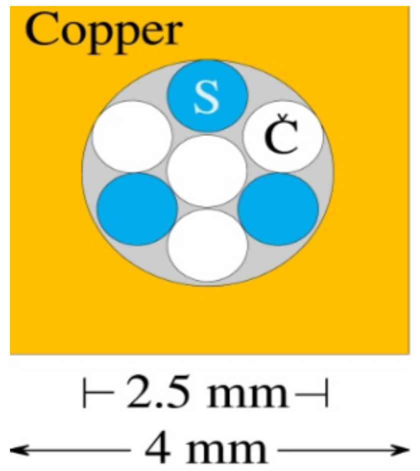

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- Calibrate both signals with e^-

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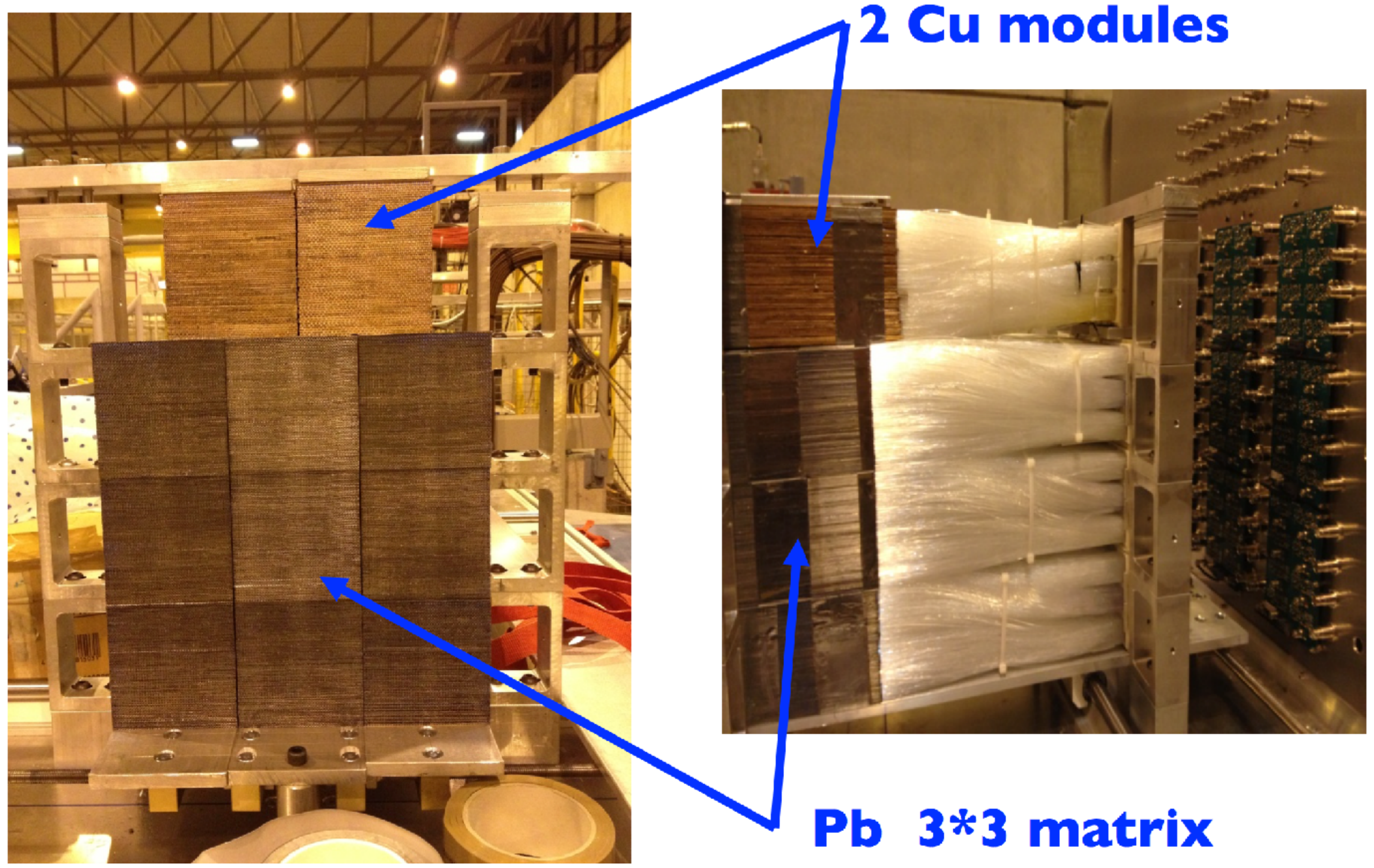

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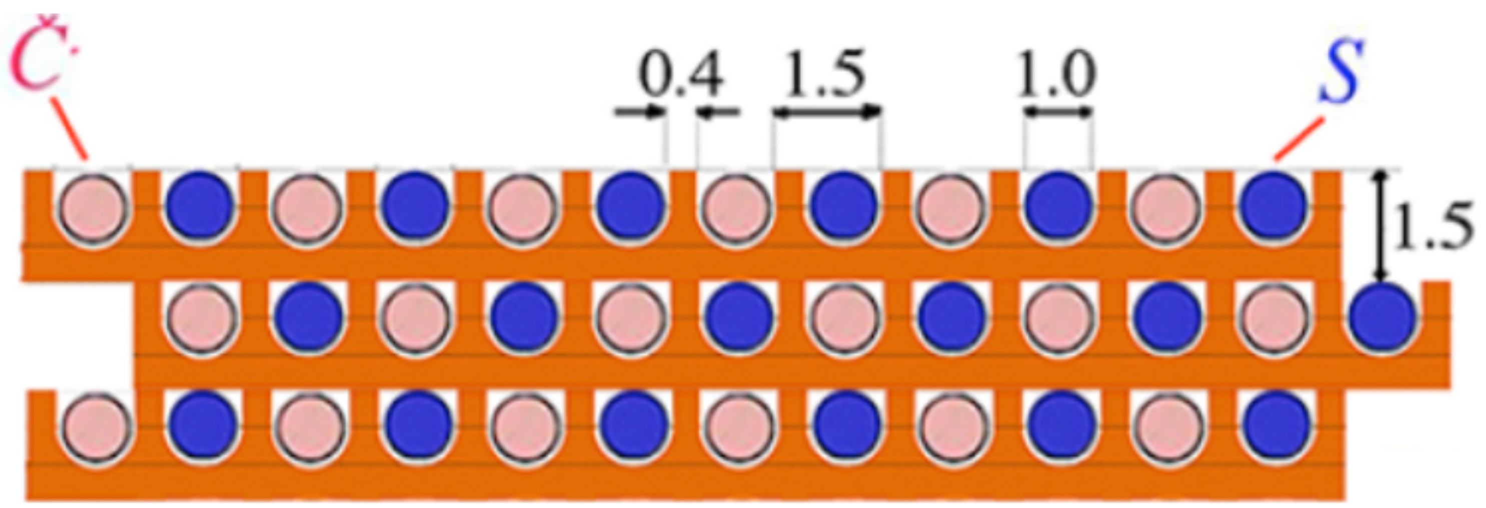

Dual Readout calorimetry

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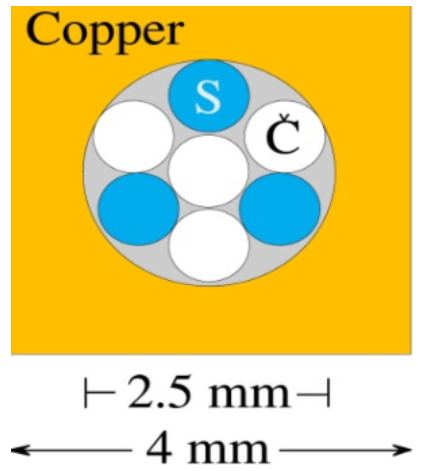
Cherenkov fibers
Scintillating fibers



"Building block" of the DREAM calorimeter

2m long (10 λ_{int}) [5130 blocks, ≈ 16 cm radius]
R $_{Molière}$ = 20.4 mm

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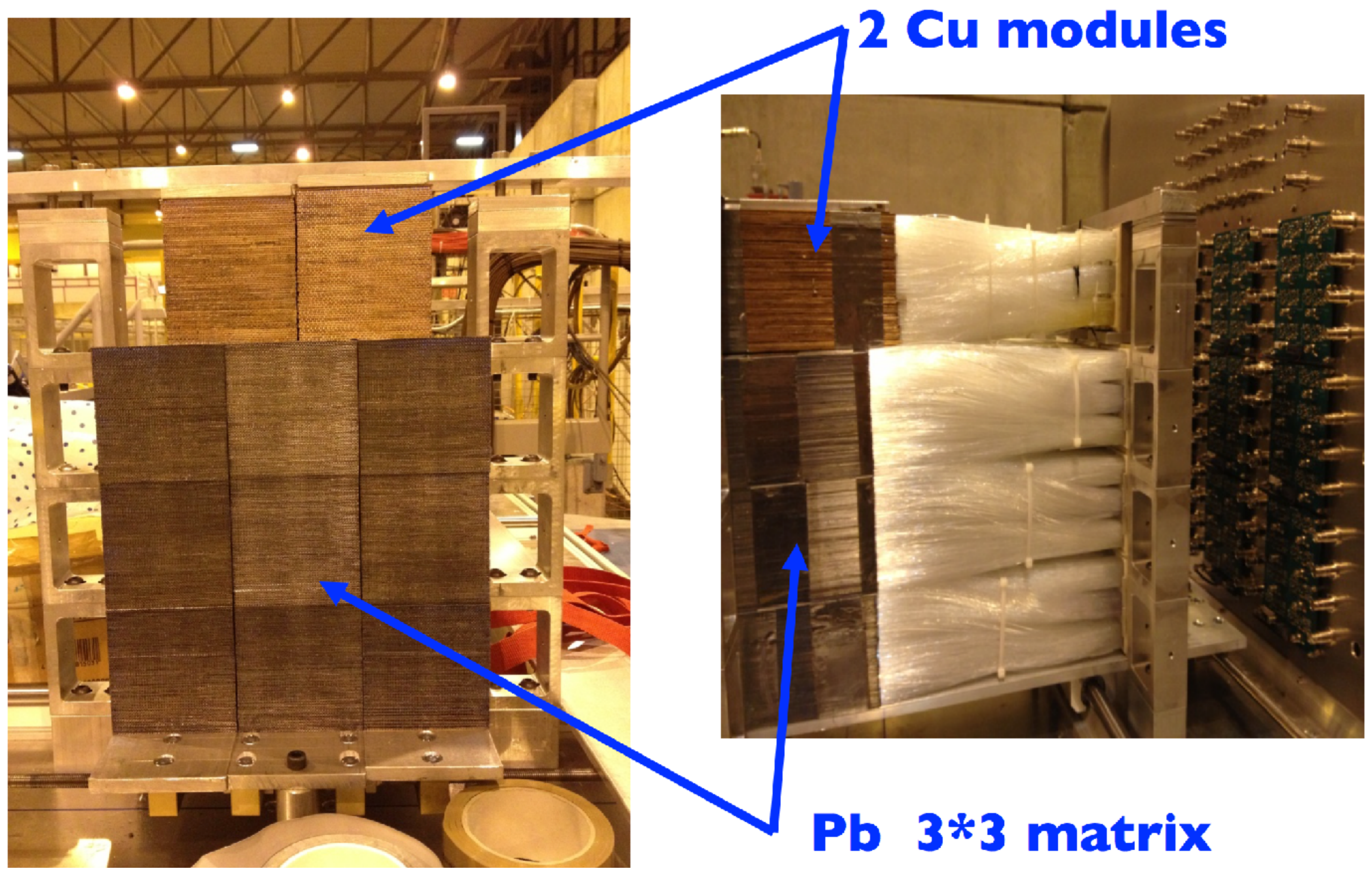
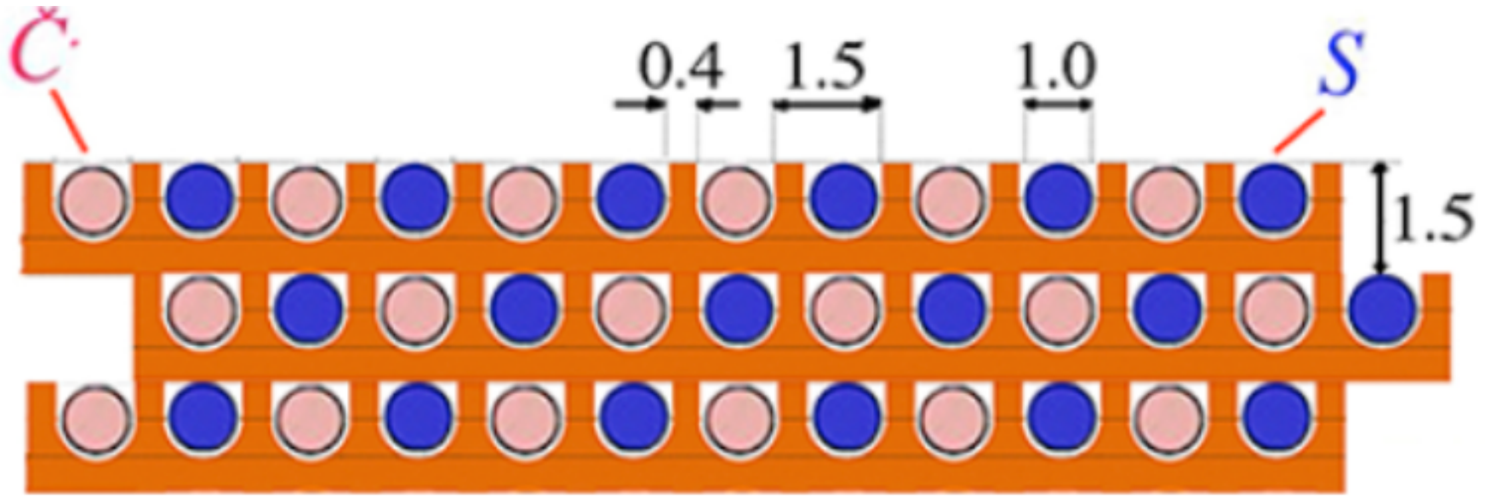
  - Cherenkov signal (Q)
- Calibrate both signals with e$^-$
- Unfold event by event f_{em} to obtain corrected energy

A Dual Readout calorimeter prototype (looks like a spaghetti calorimeter)



Calorimetry: IDEA



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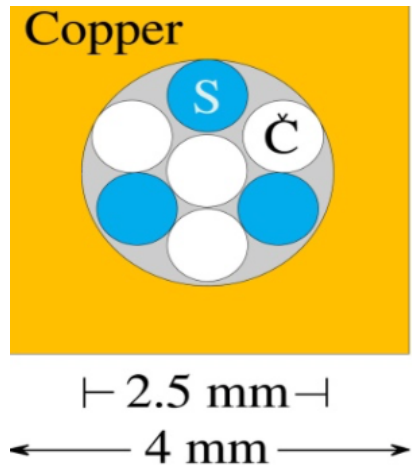

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- Measure simultaneously:
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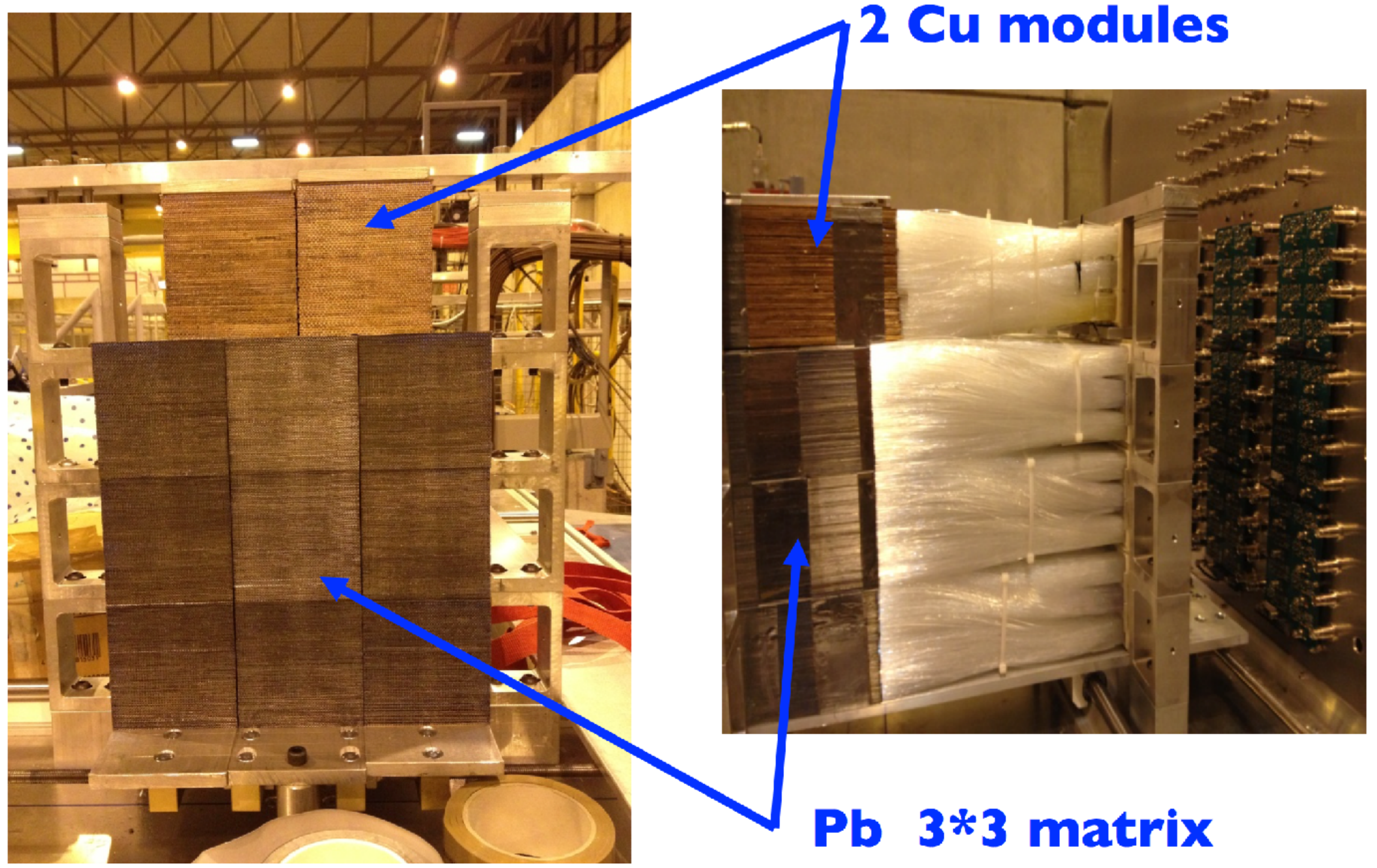
  - Cherenkov signal (Q)
- Calibrate both signals with e-
- Unfold event by event f_{em} to obtain corrected energy

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

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

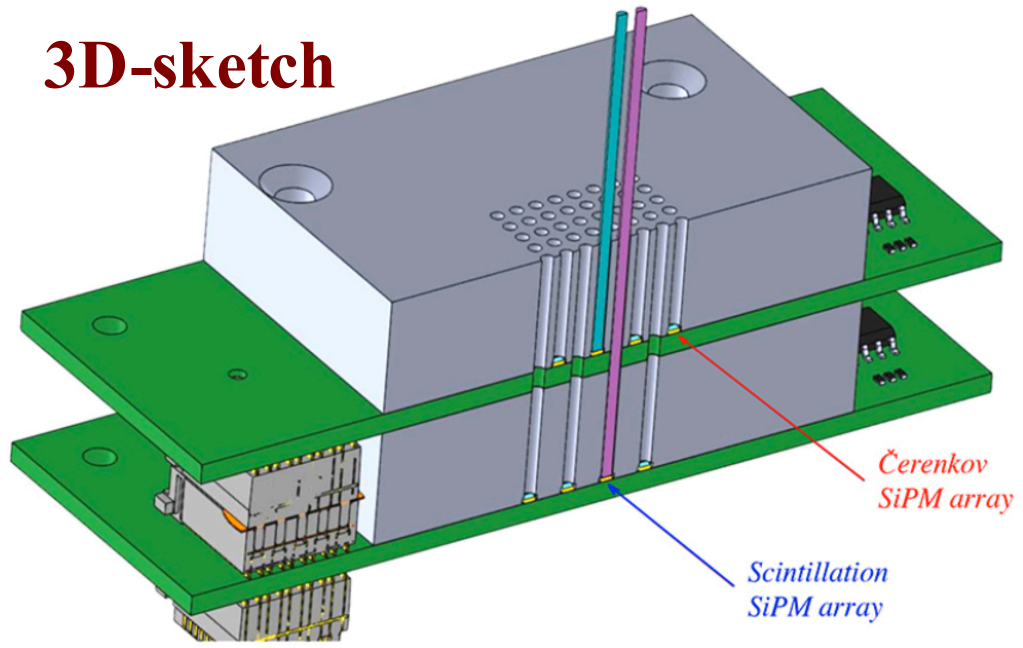
$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

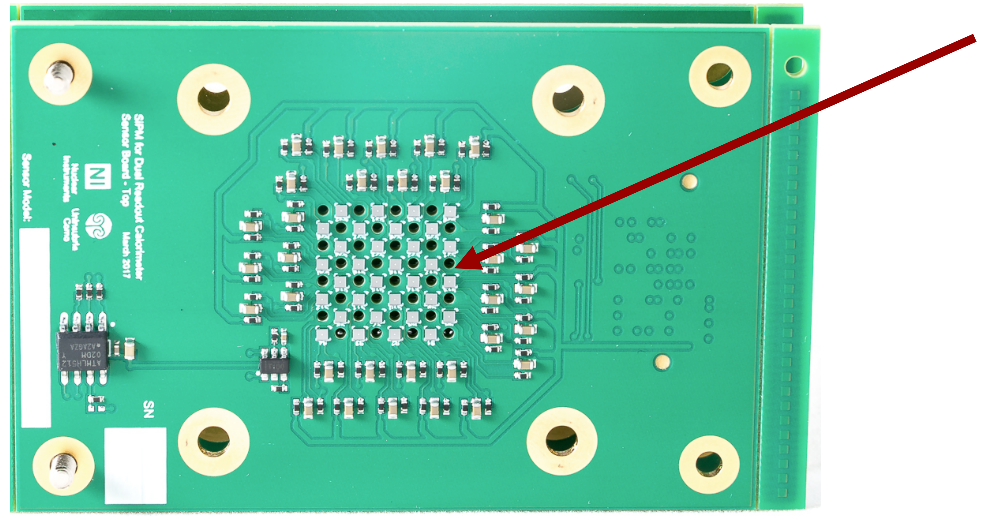
A Dual Readout calorimeter prototype (looks like a spaghetti calorimeter)

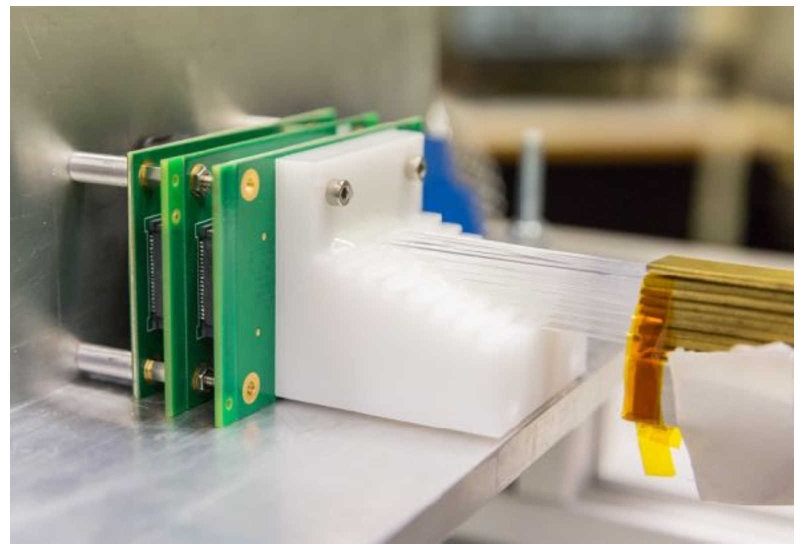


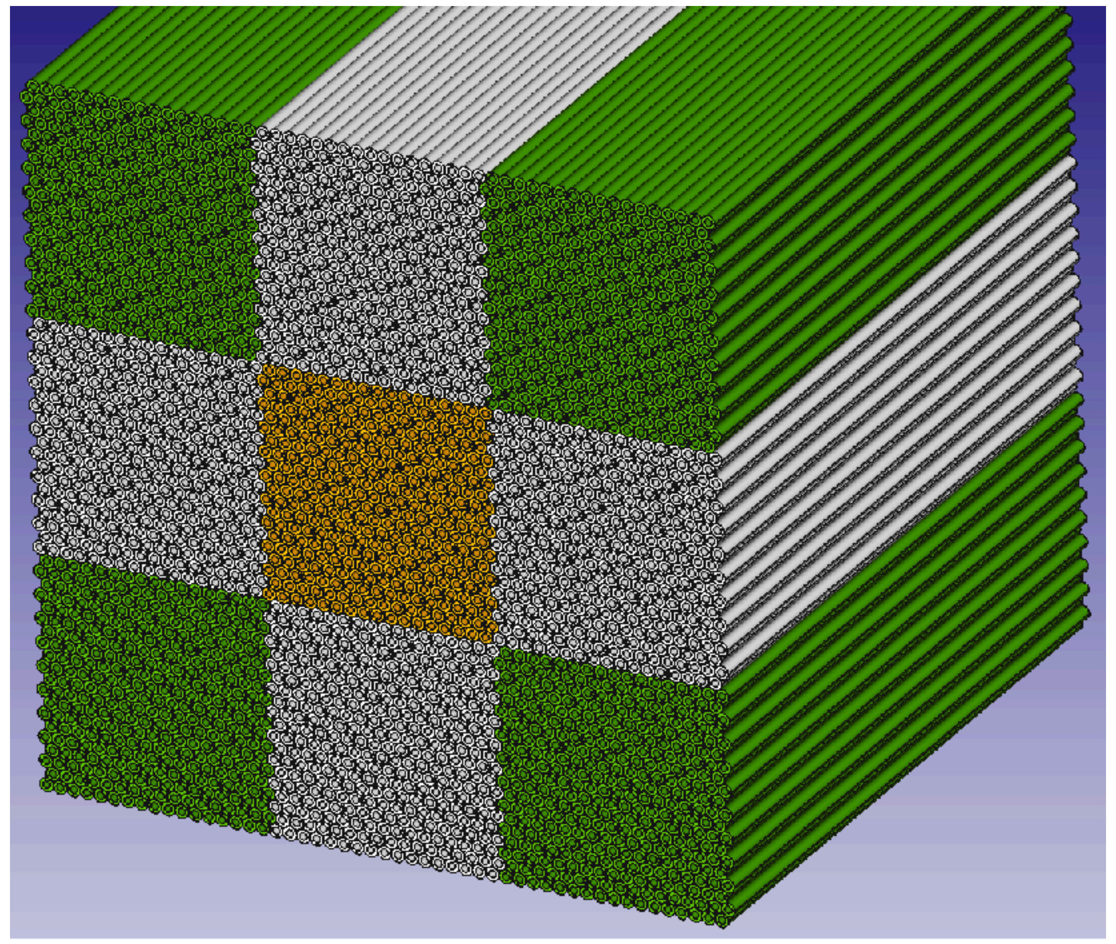
Calorimetry: IDEA

3D-sketch

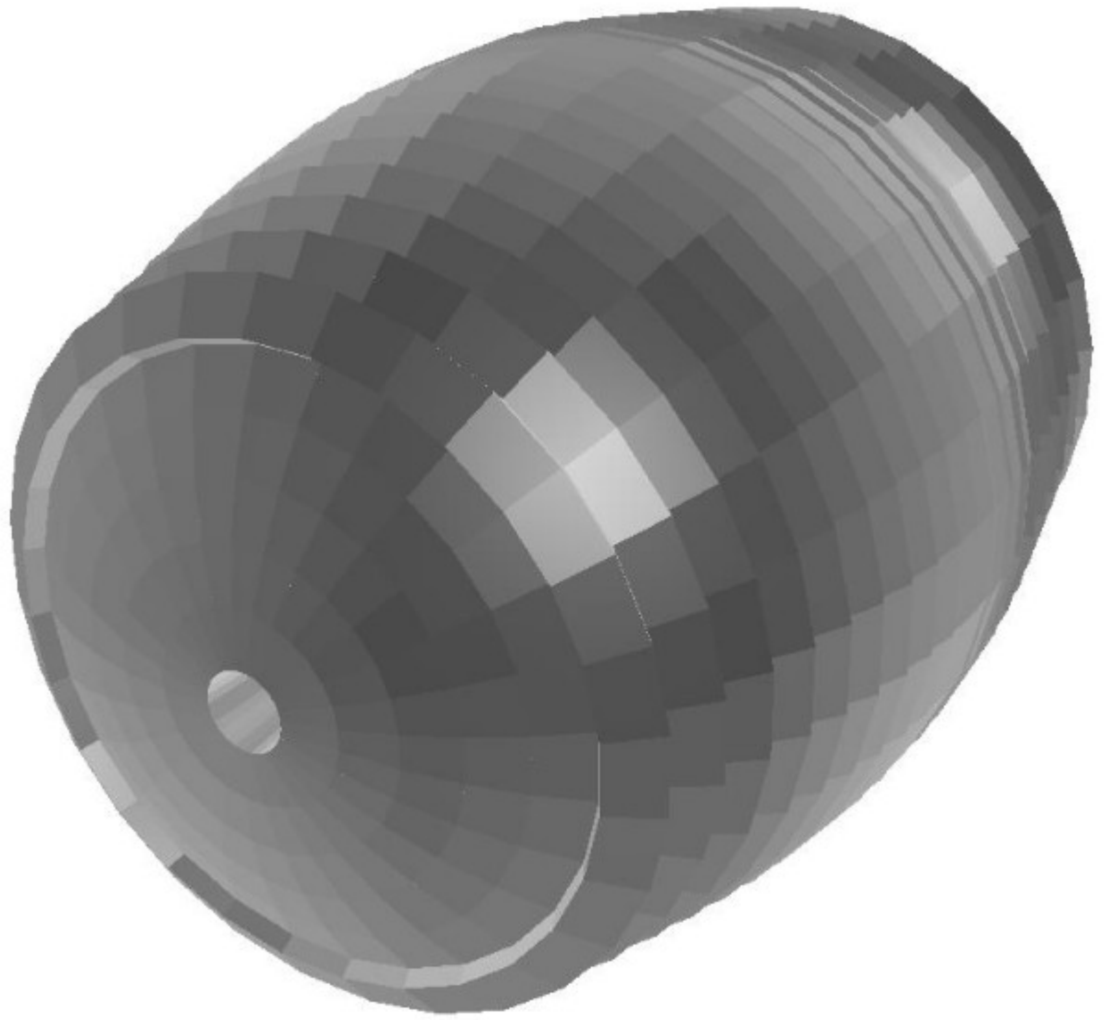


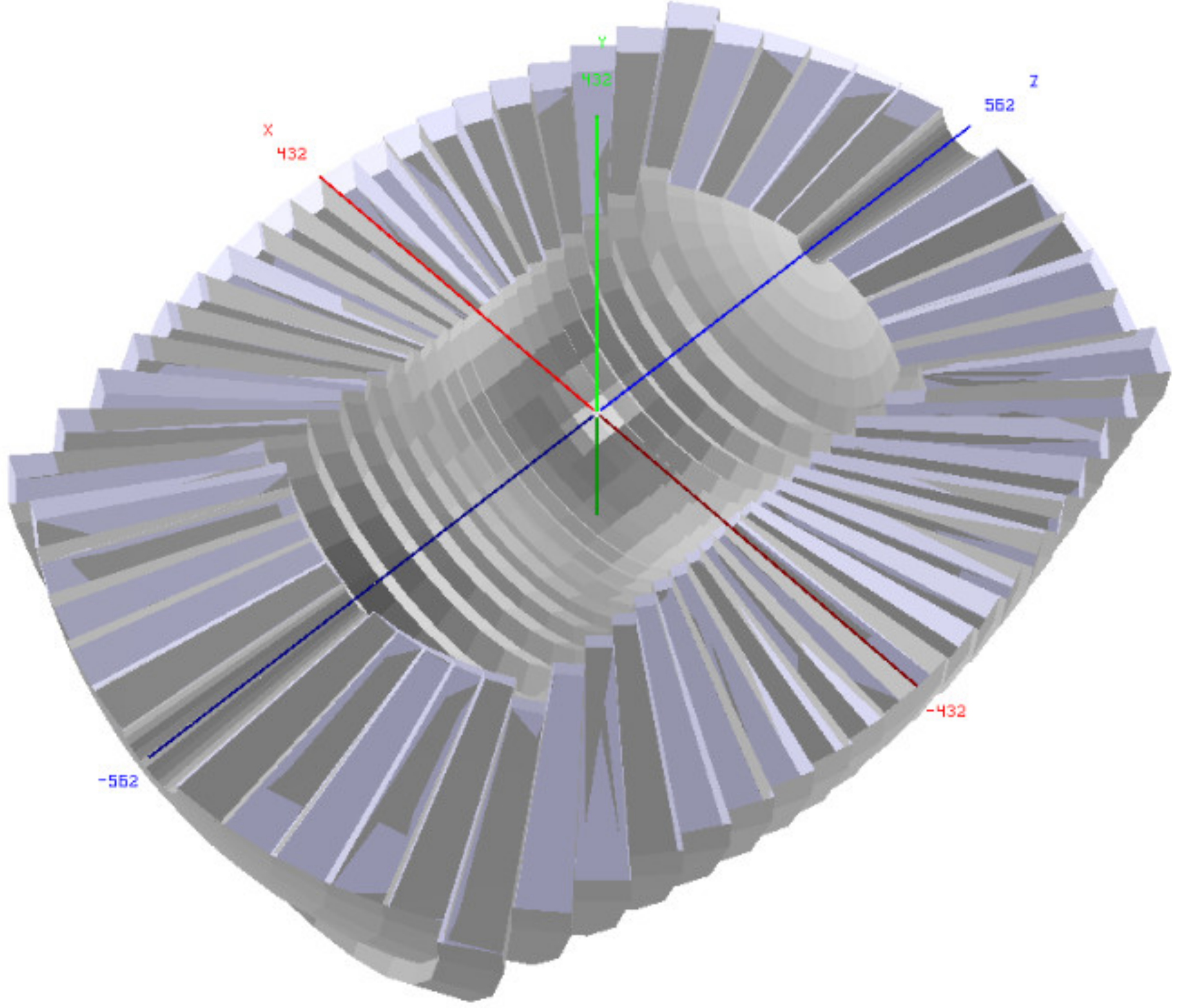


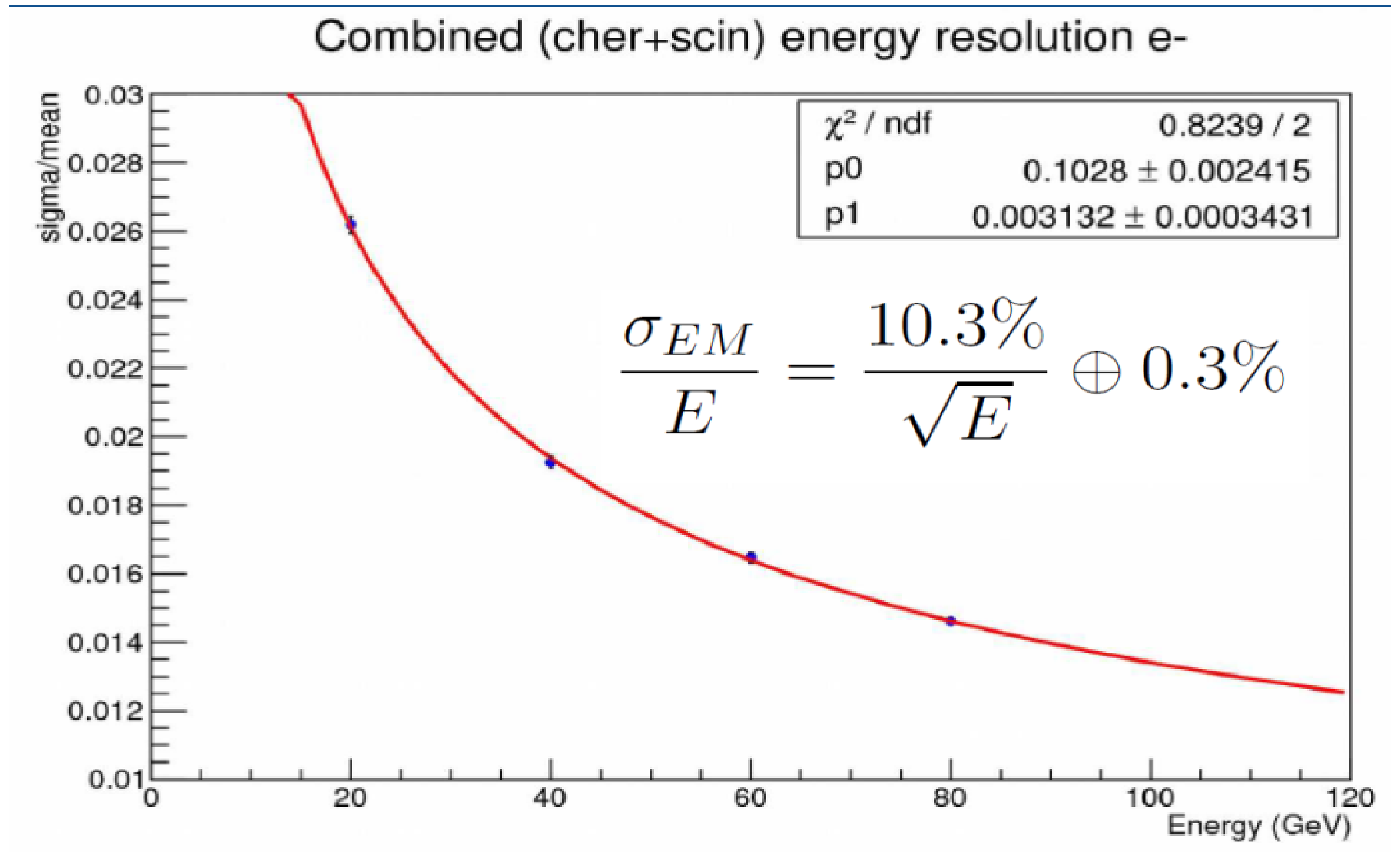


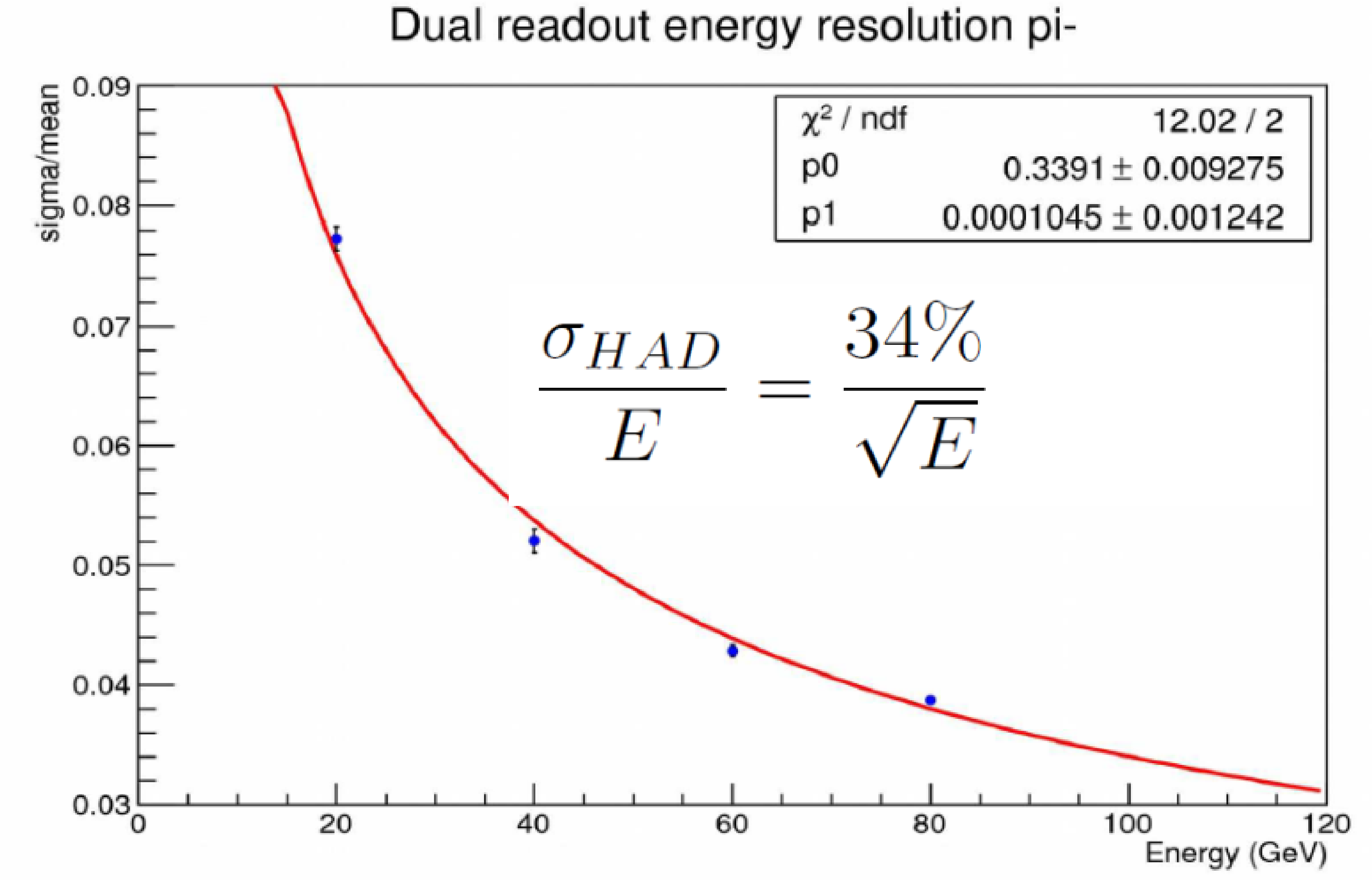


Full GEANT4 implementation of the DR calorimeter







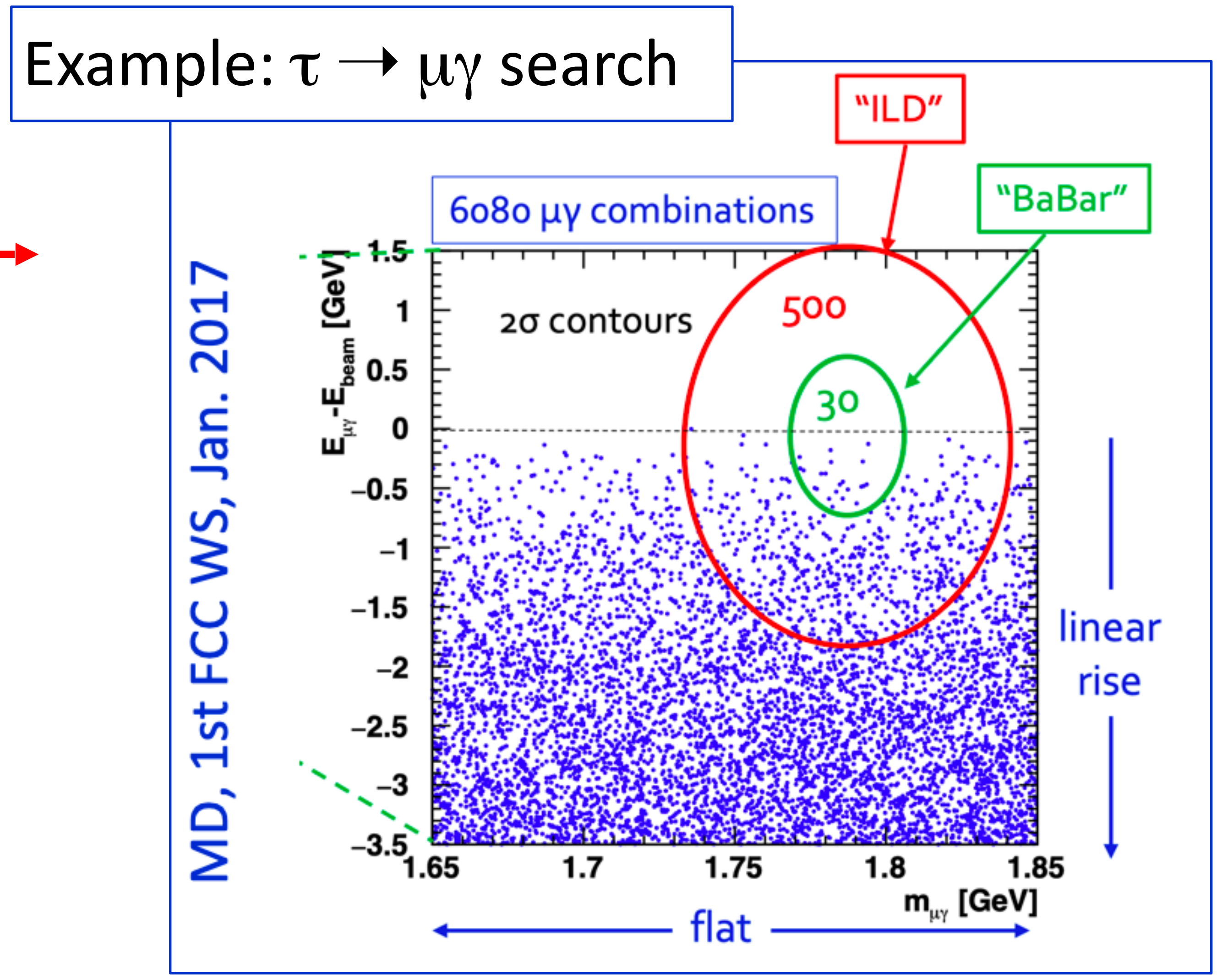


Calorimetry

- Several technologies being considered

Technology	ECAL	HCAL
CLD / CALICE-like	W/Si W/scint + SiPM	Steel/scint + SiPM Steel/glass RPC
IDEA / Dual Readout	Brass (lead, iron) / parallel scint + PMMA (C) fibres, SiPM	
Noble Liquid	Fine grained LAr (LKr) / Pb (W)	CALICE-like ?
Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber?

- Jet energy and angular resolutions via Particle Flow algorithm
  - Possibly augmented via Dual Readout
- Fine segmentation for PF algorithm and powerful γ/π^0 separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed
  - 15%/√E → 8%/√E → 3%/√E
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …



Example: τ → μγ search

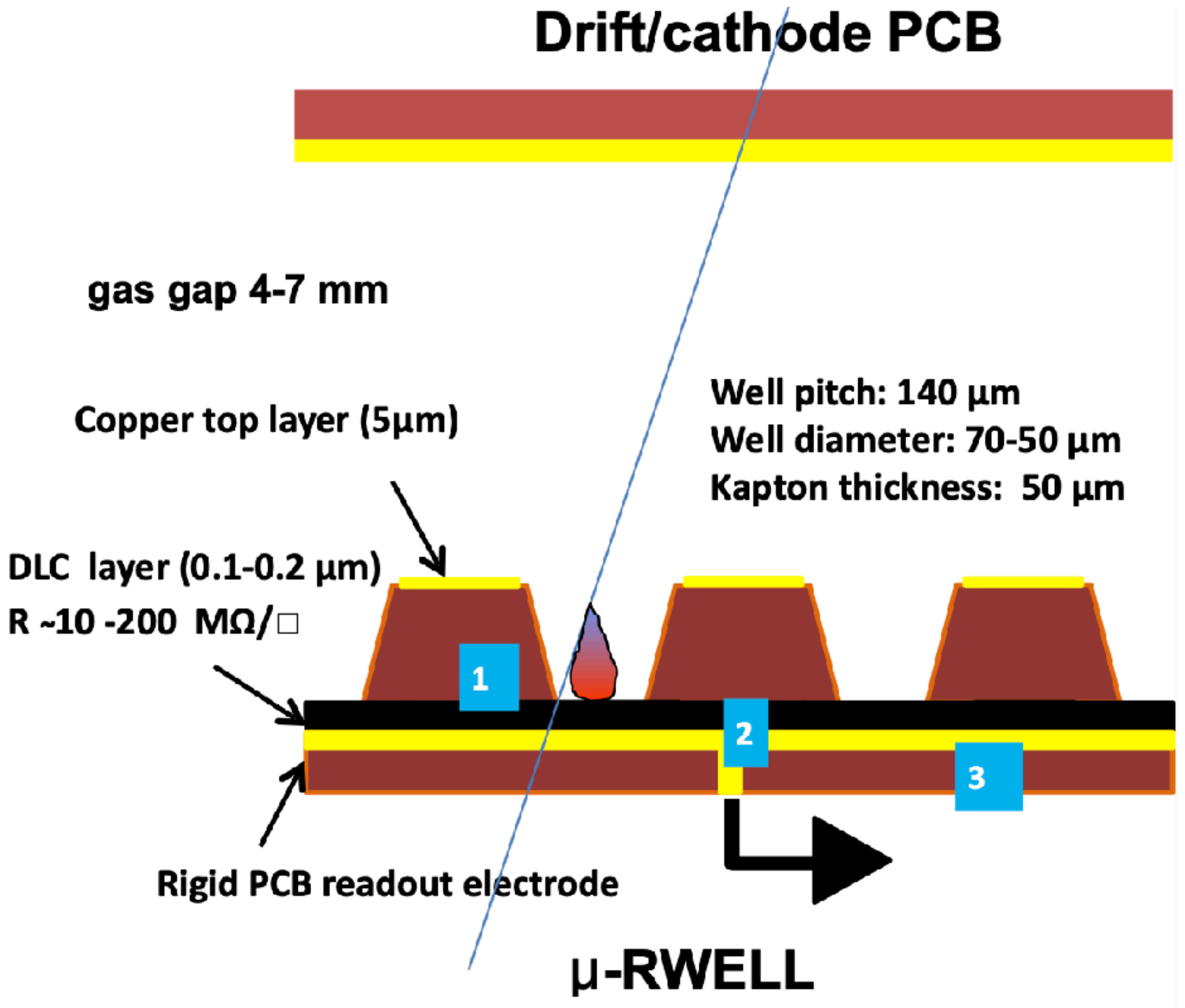
Muon detector

Muon system in instrumented return yoke

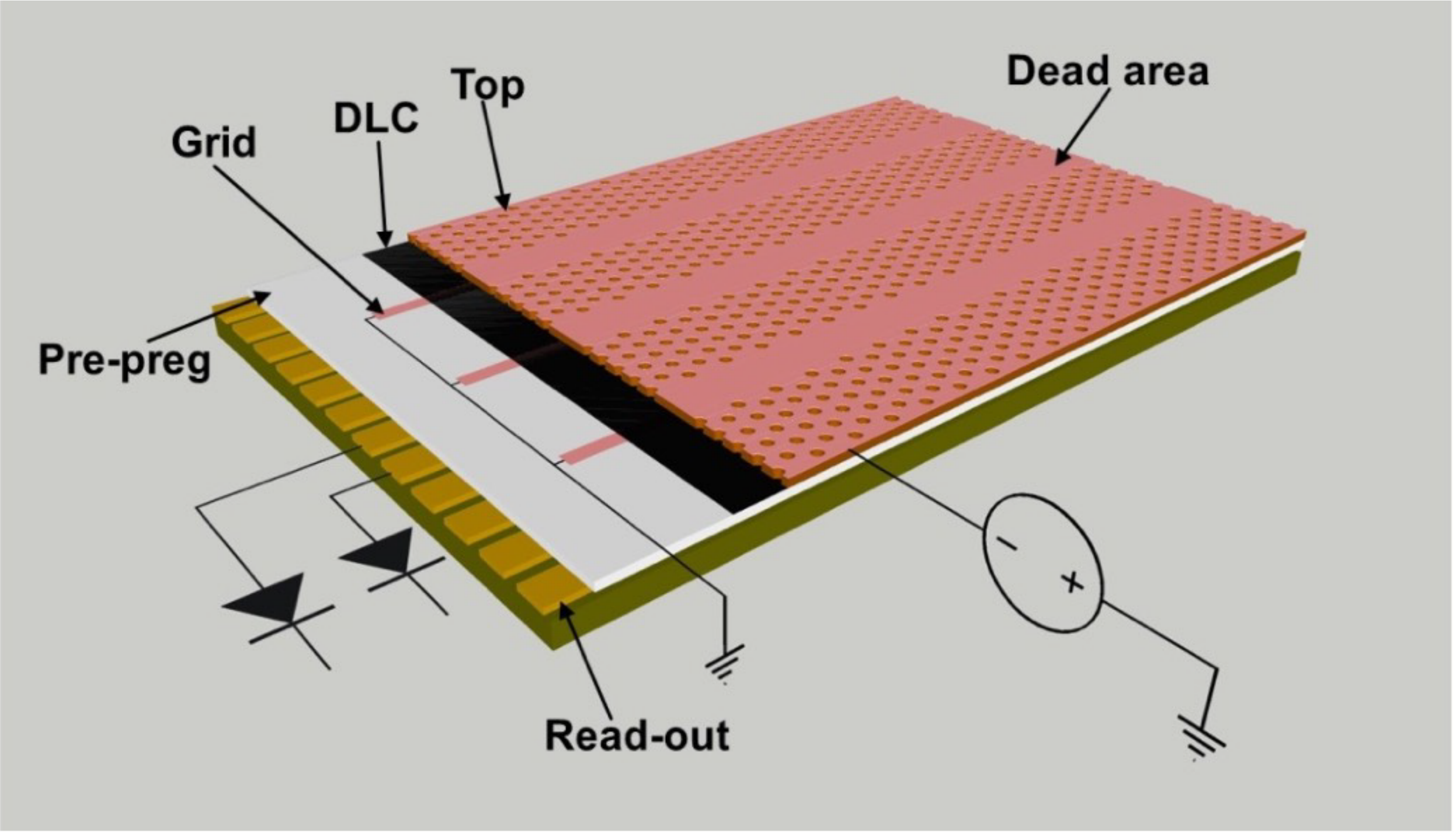
- 3-7 layers being considered: 3000-6000 m^2
- Proposed technologies
  - RPC (30 × 30 mm^2 cells)
  - Crossed scintillator bars
  - µRWell chambers (1.5 × 500 mm^2 cells)
    - Also for IDEA pre-shower detector
    - Ongoing R&D work

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

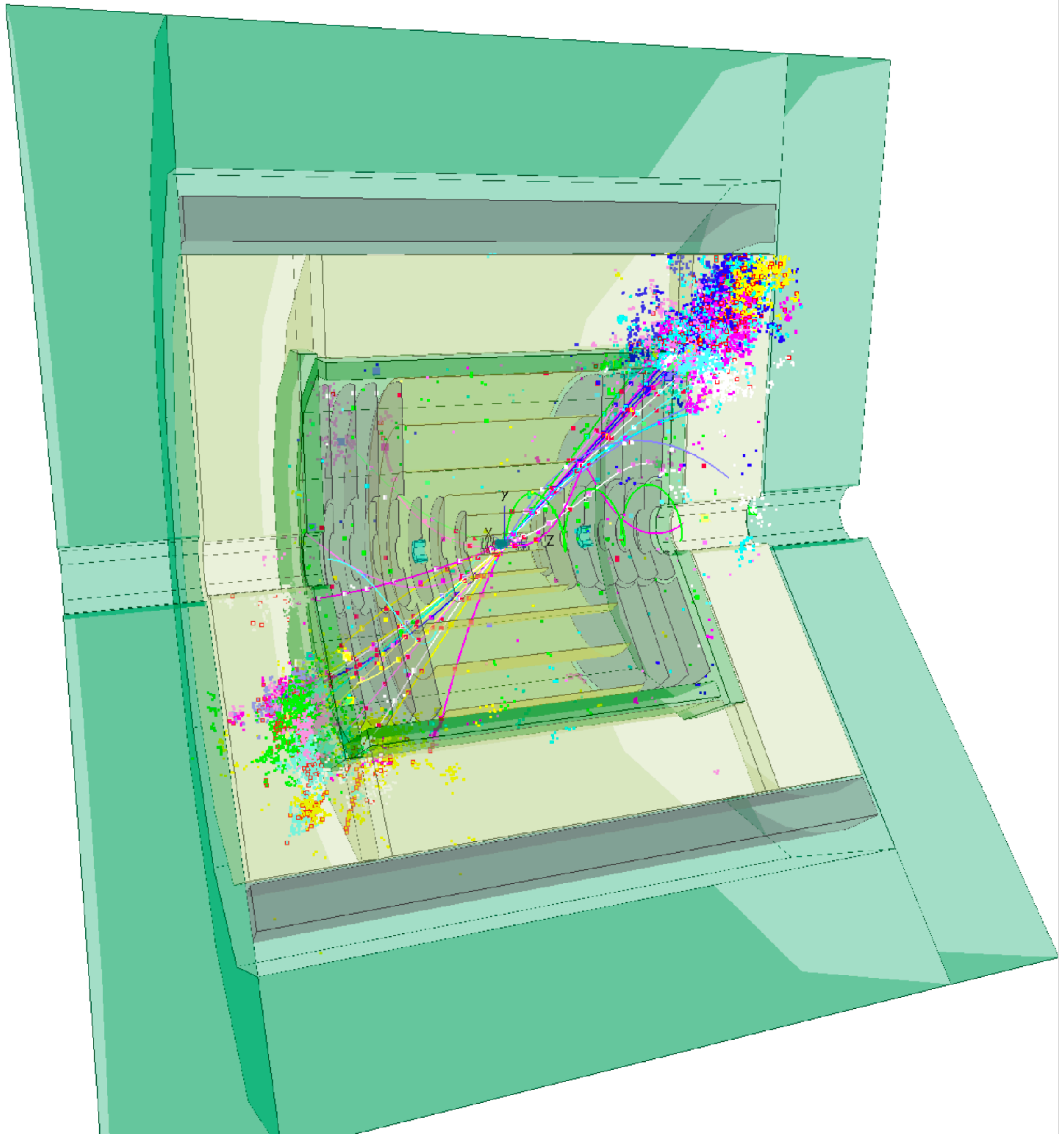


IDEA Muon system

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

Physics performance studies: CLD

CLD comes with a full software suite for simulation and is completely integrated in **Key4HEP**



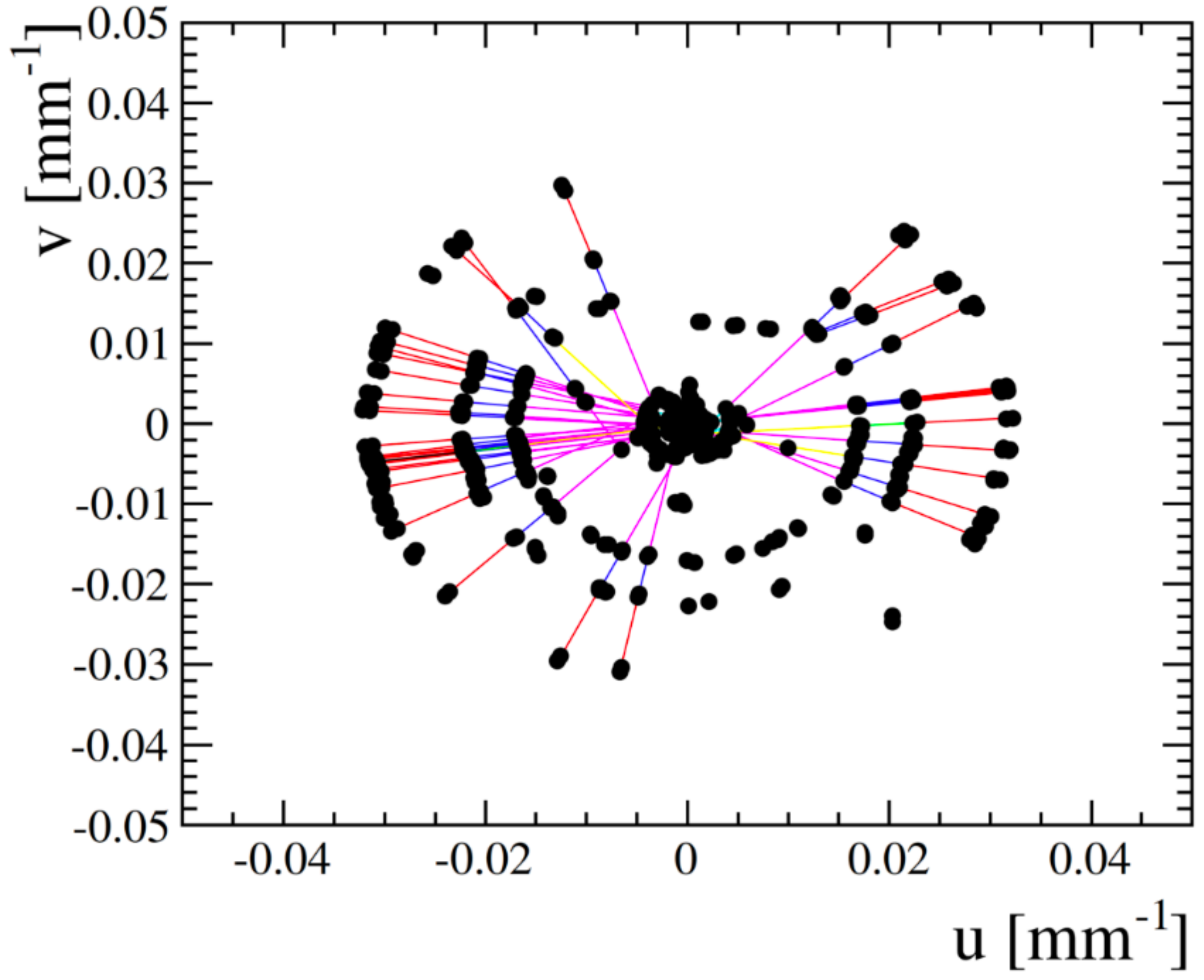
$e^+e^- \rightarrow qq$ event at $\sqrt{s}$ = 365 GeV in CLD (full detector simulation)

Detector geometries: DD4hep

Event reconstruction framework: Marlin

Key event reconstruction steps:

- “Conformal tracking”: cellular automaton in conformal space for track finding



$u = x / (x^2 + y^2)$

$v = y / (x^2 + y^2)$

Nucl. Inst. Meth. A 956, 163304 (2020)

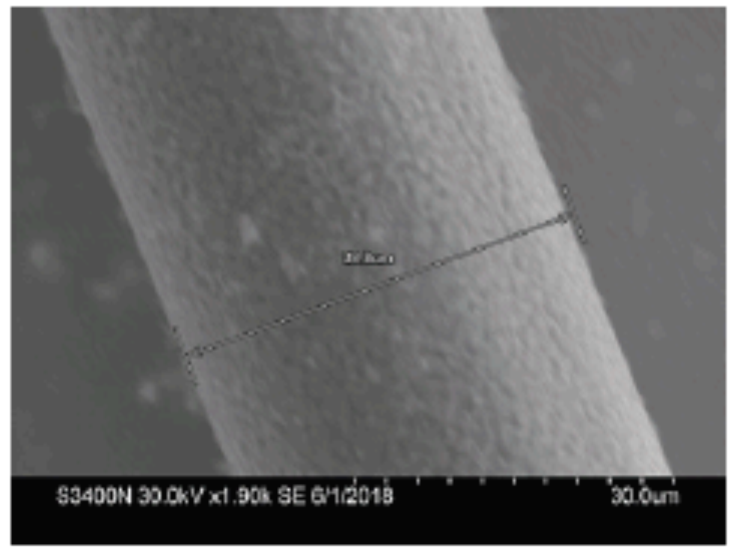
- Calorimeter clustering and particle flow analysis: PandoraPFA
- Flavour tagging: LCFIPlus

Ongoing R&D

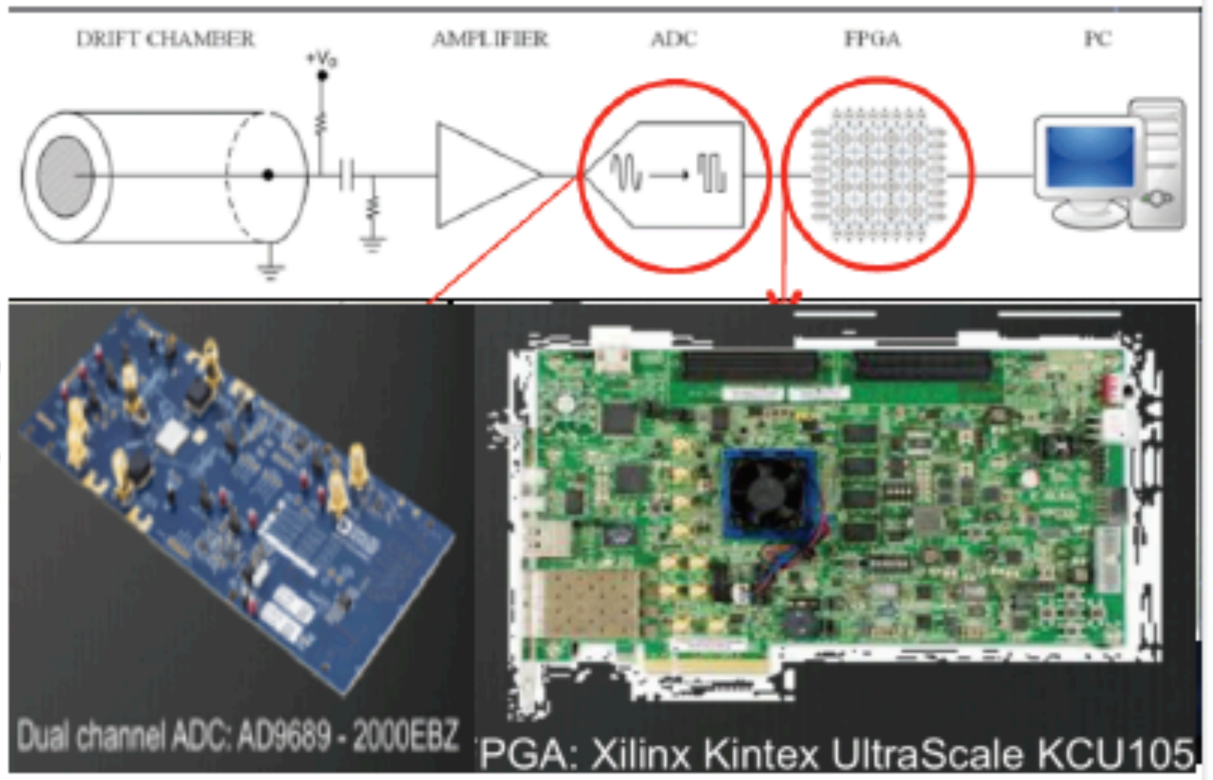
IDEA Drift chamber: R&D program

- Studies on new materials for DCH wires → metal coated Carbon monofilaments to operate with safer wire tensions far away from the elastic limit (e.g. : a tension $T_c \geq 250$ N needs to be applied to 35μm C monofilament, but elastic limit is 830 N)

35 μm C wire – Cu coated



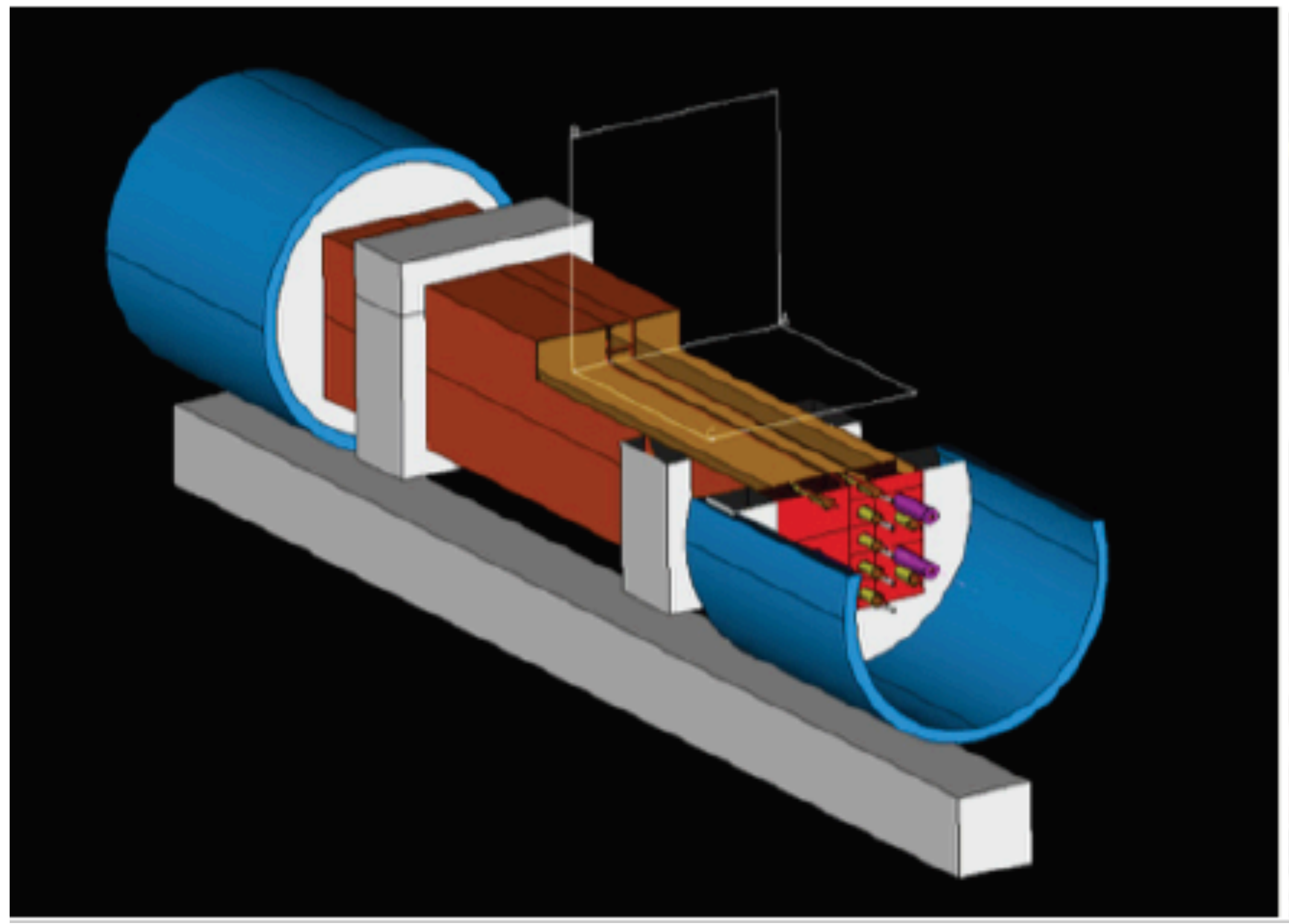
- Studies on new polymeric fibers for DCH envelopes → (e.g. conductive polymeric matrices) to strongly reduce gas permeability (Helium), to enhance electrical conductivity for electrostatic and radiofrequency shielding, to improve the transparency
- Front-end, DAQ and pre-processing electronics for cluster counting → FEE: wideband (1 GHz) amplifier (25 dB) low mass, low power, low noise, multichannel (×8) ASIC, 12 bit & 2 GSa/s digitizers, multi-channel (16/32) FPGA for filtering and data reduction

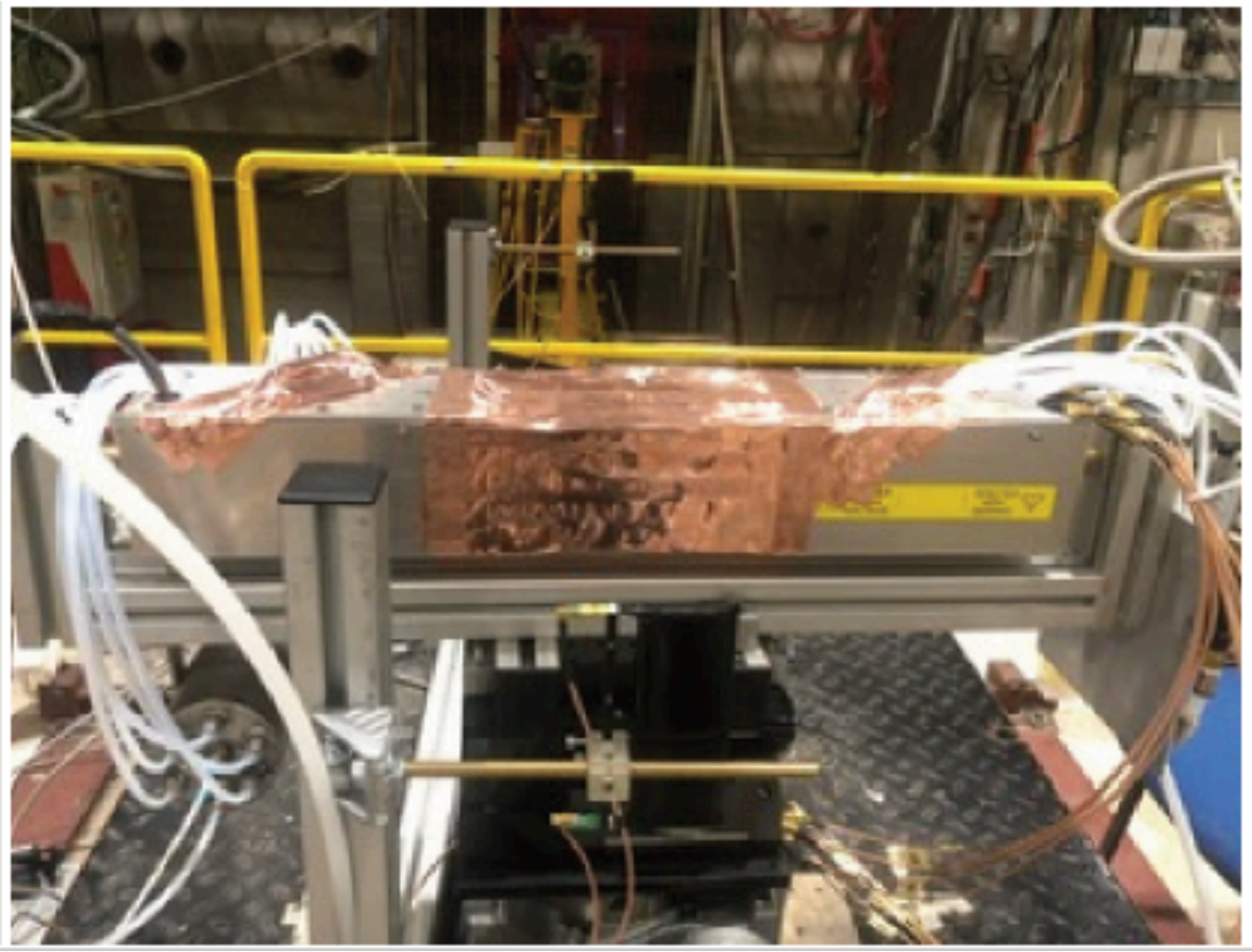


- Construction of scale 1:1 prototypes → to test the proposed innovative solutions for new materials
- Test beam facilities with identified beams of *e/μ/π/K/p* in the range 1-50 GeV/c → to experimentally determine the particle identification capabilities in the relativistic range

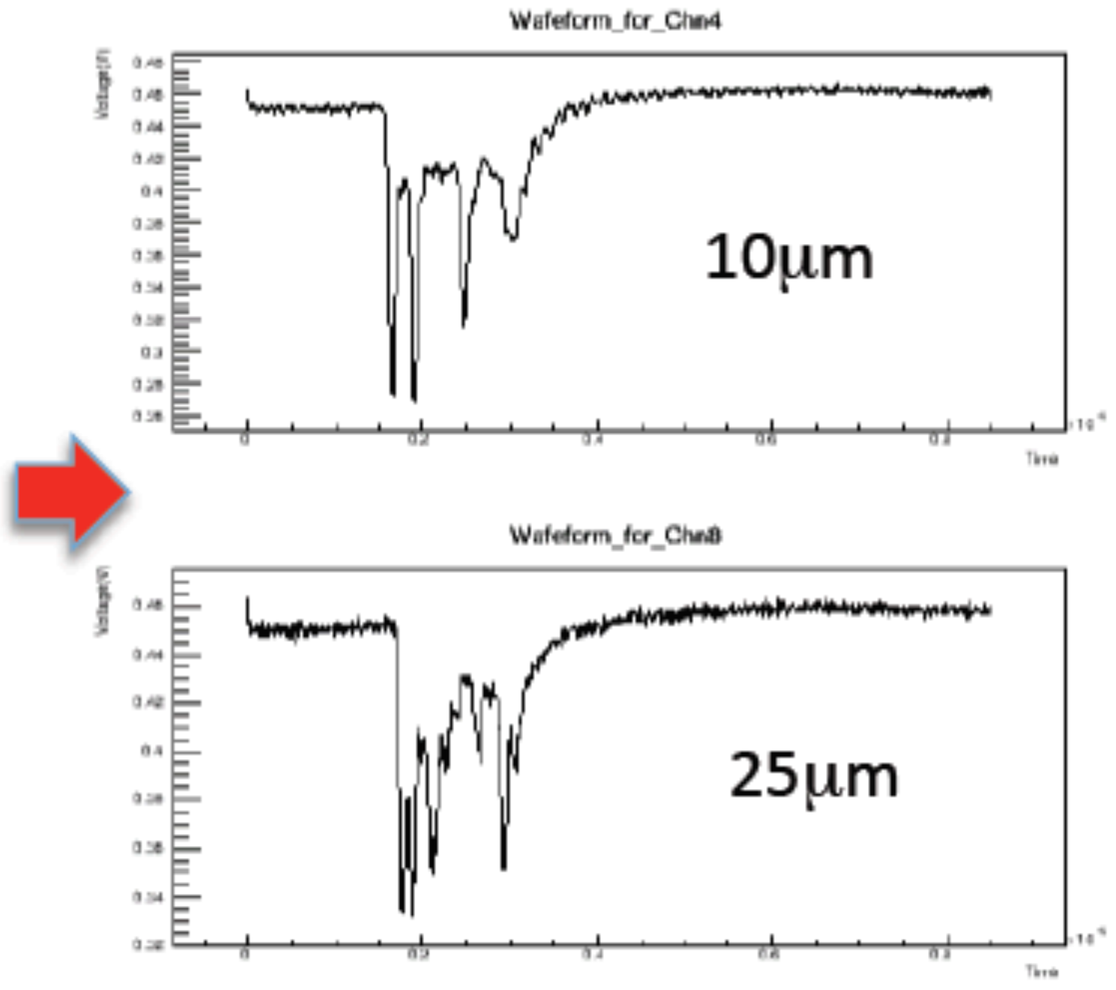
IDEA Drift chamber: R&D program

- Beam test in parasitic mode (we could be main user in spring 2022) now ongoing at CERN (H8) with drift tubes :
  - @fixed muon momentum → N_{cl} versus cell size (1x1cm^2, 2x2cm^2, 3x3cm^2), gas mixture (90/10 to 75/25 He/iC_4H_{10}), gas gain (1x10^5 to 5x10^5), sense wire diameters (15, 20, 25, 30 μm), angle between track and wire (0°, 30°, 45°, 60°) → **measure counting efficiency vs cluster density, estimate cluster size distribution, study number of clusters versus space charge effects**
  - @muon momentum scan (few GeV/c to about 250 GeV/c, $\beta\gamma = 40 \div 1800$) and having chosen optimal conditions (gas mixture, gain, sense wire diameter, etc.) → **measure relativistic rise** both for dE/dx and dN_{cl}/dx and use the experimental results to fine tune simulation for flavor physics and for jet flavor tagging (both in fast and in full simulation)
  - test and optimize counting algorithms

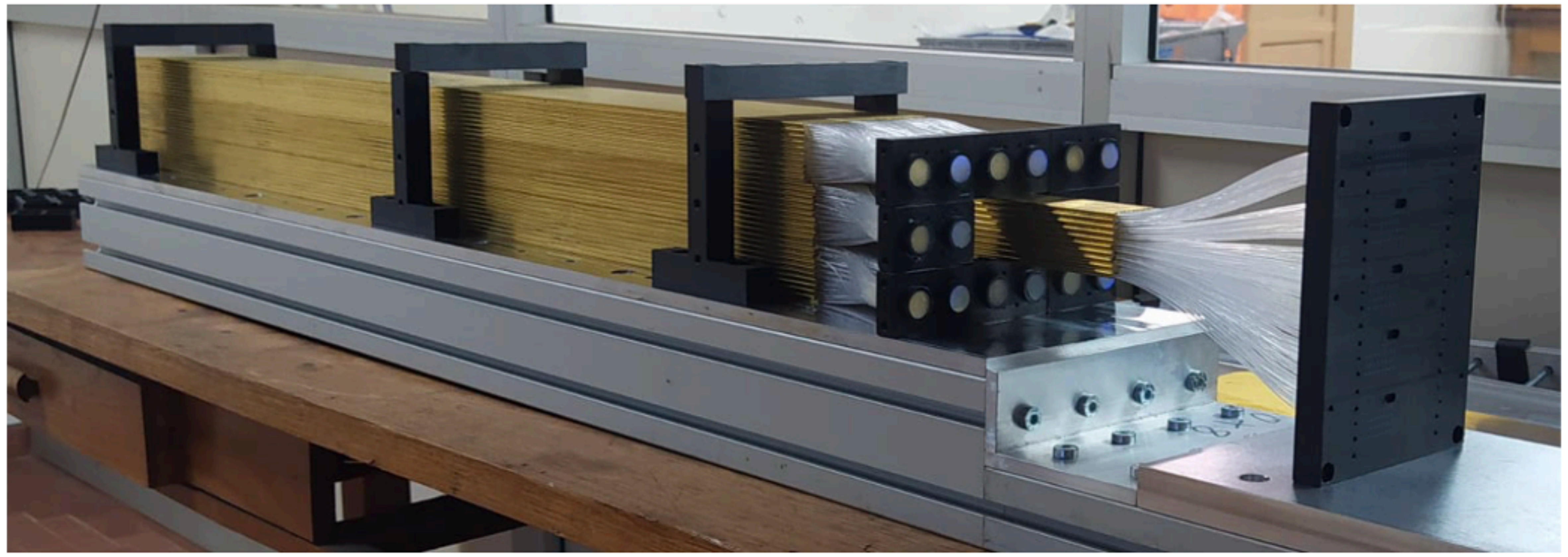




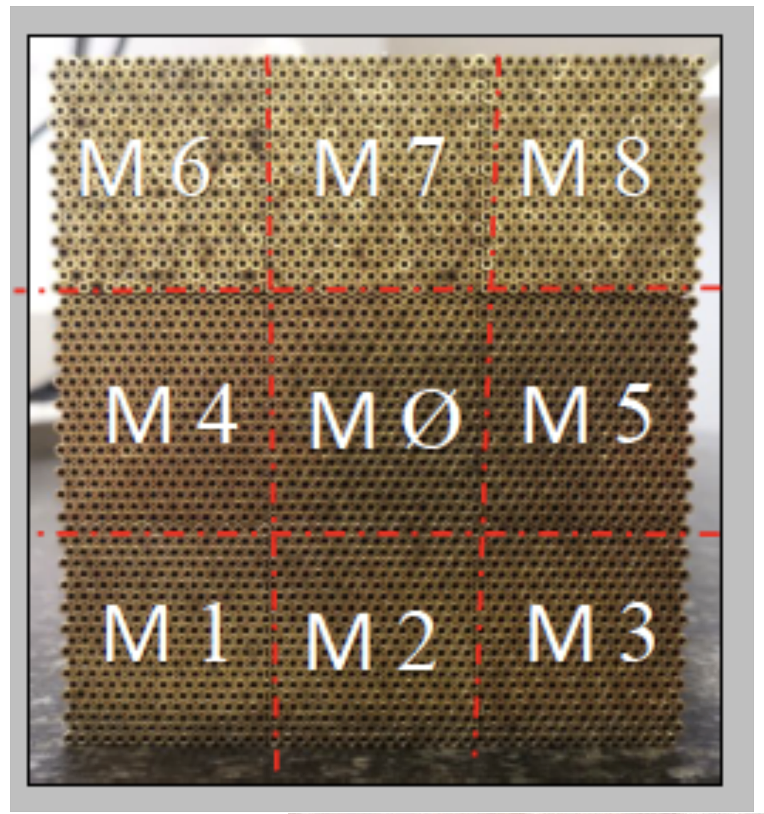
1x1cm^2



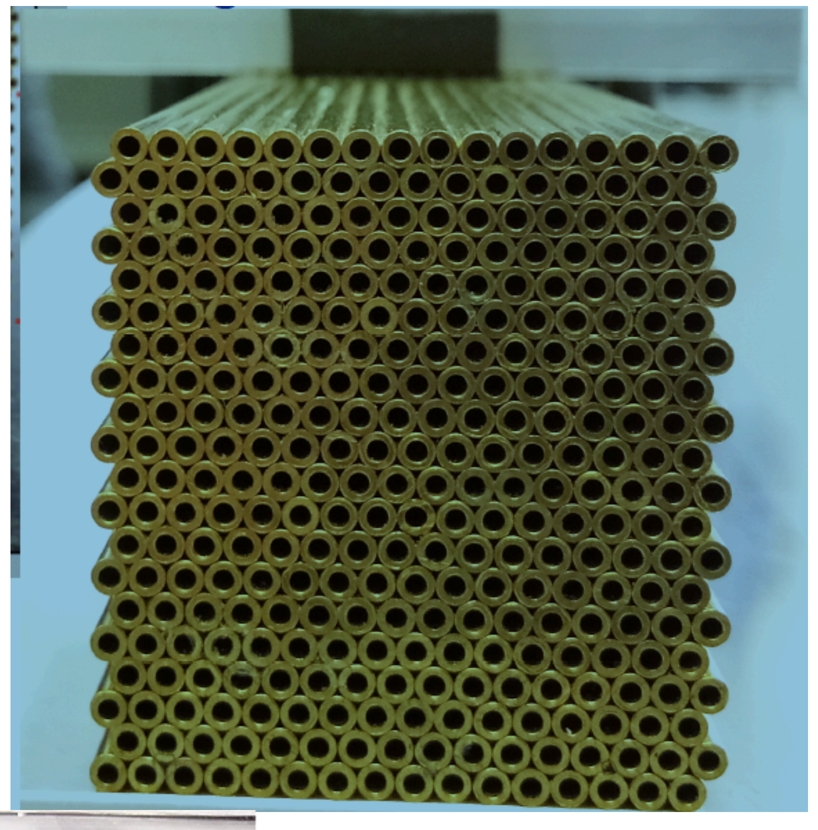
2020 Dual Readout prototype



Full prototype - 9 towers



Single tower



Electromagnetic dimensions of 10x10x100 cm^3

9 towers containing 16x20 capillaries (160 C and 160 S)

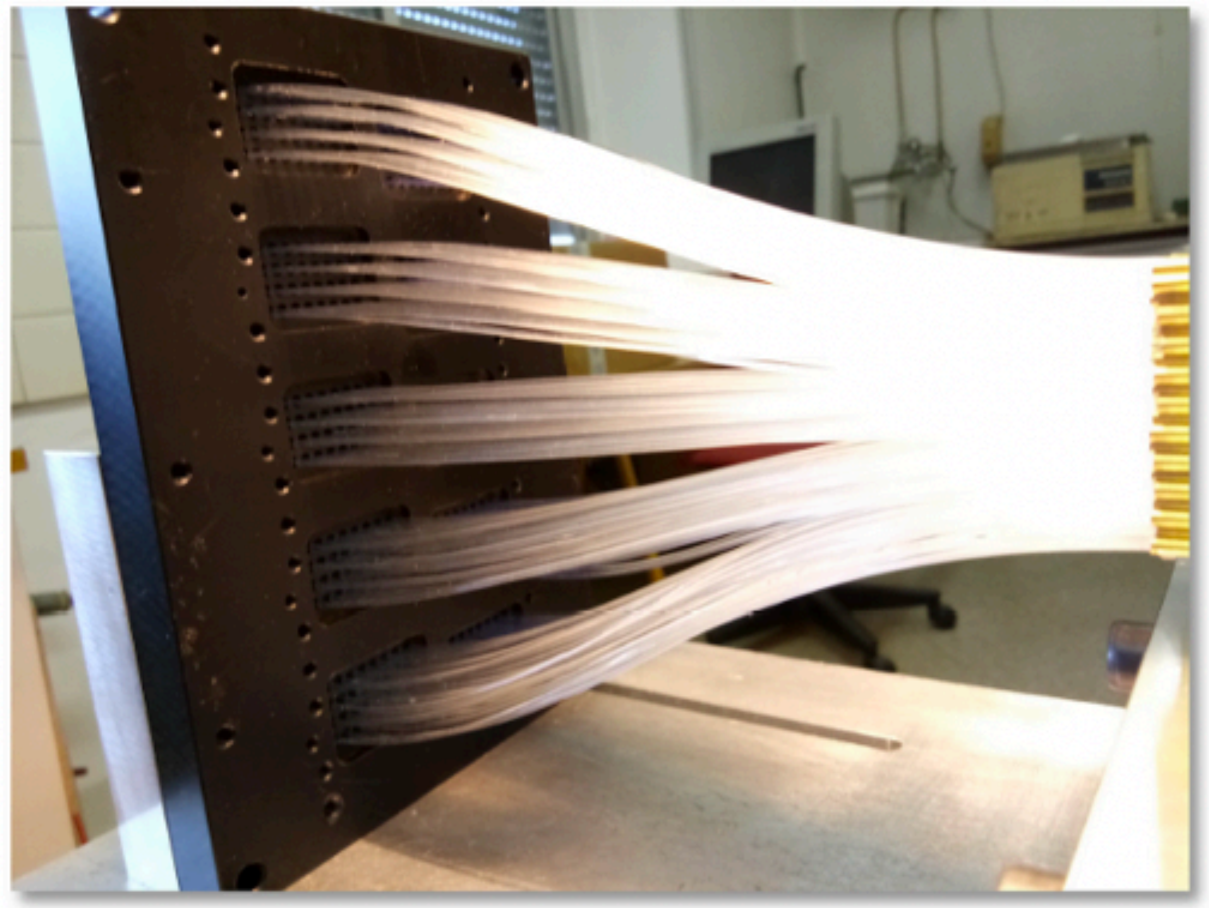
Capillary tube with outer diameter of 2 mm and inner diameter of 1.1 mm

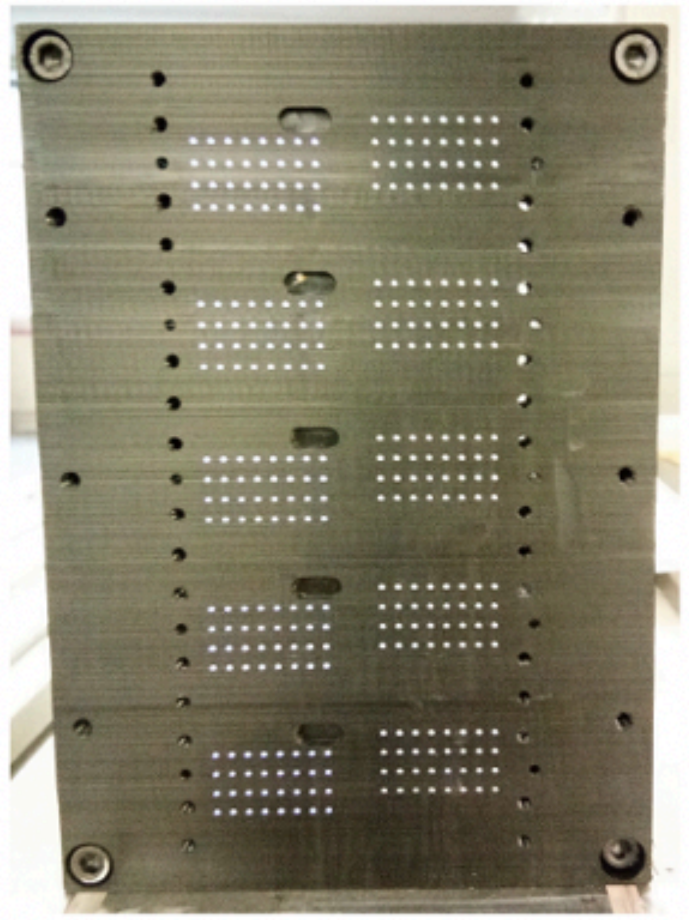
1-mm-thick fibers

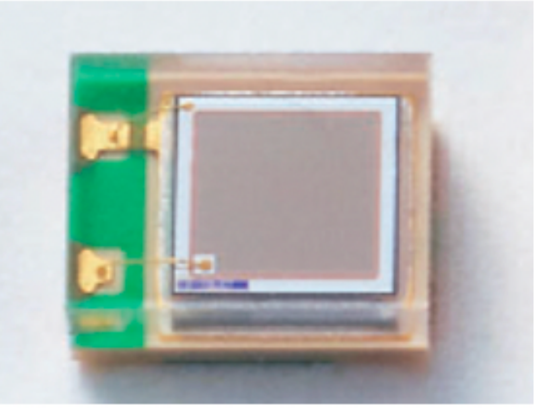
“Bucatini calorimeter”

Front end board housing 64 SiPM

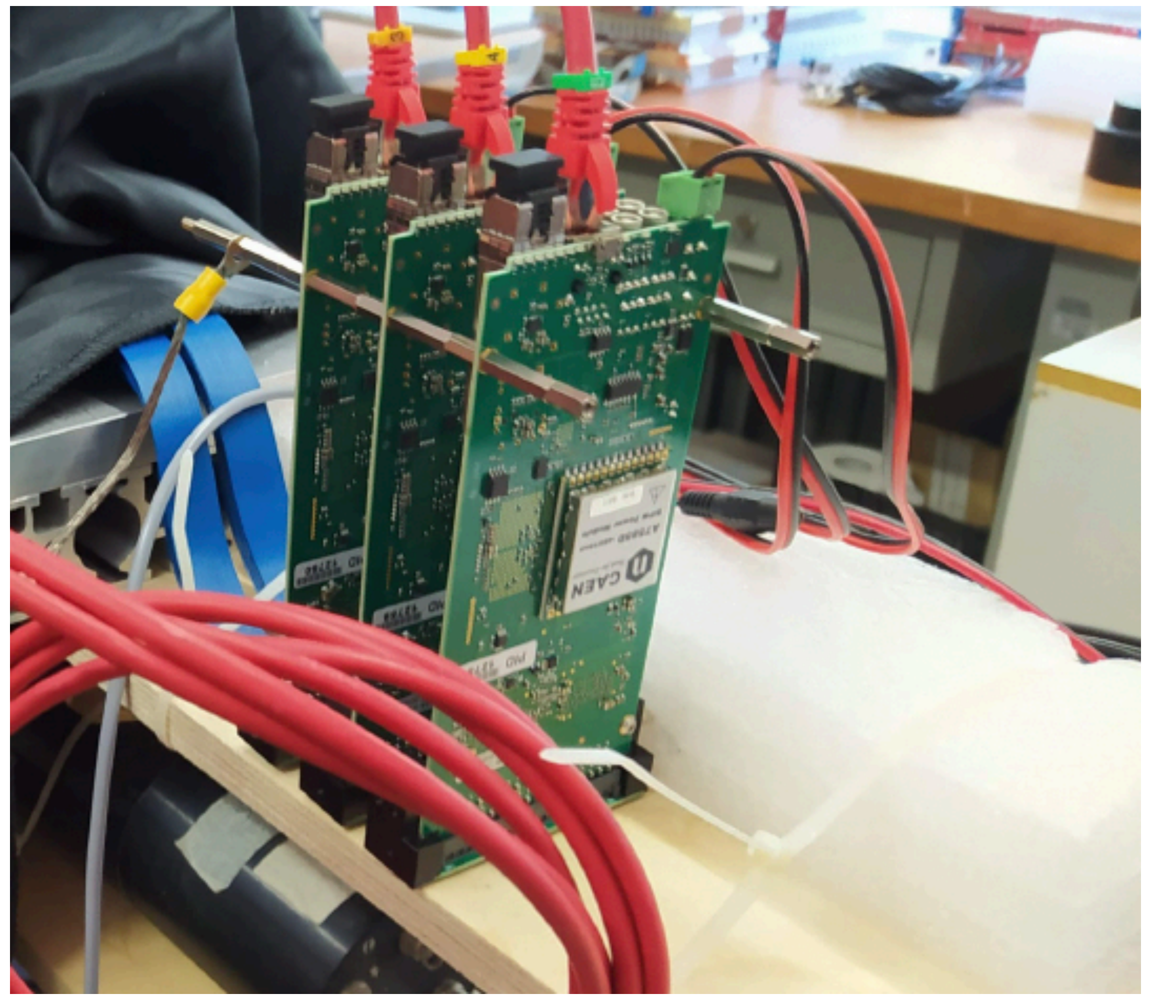
Fiber guiding system







Hamamatsu SiPM: S14160-1315 PS Cell size: 15 μm

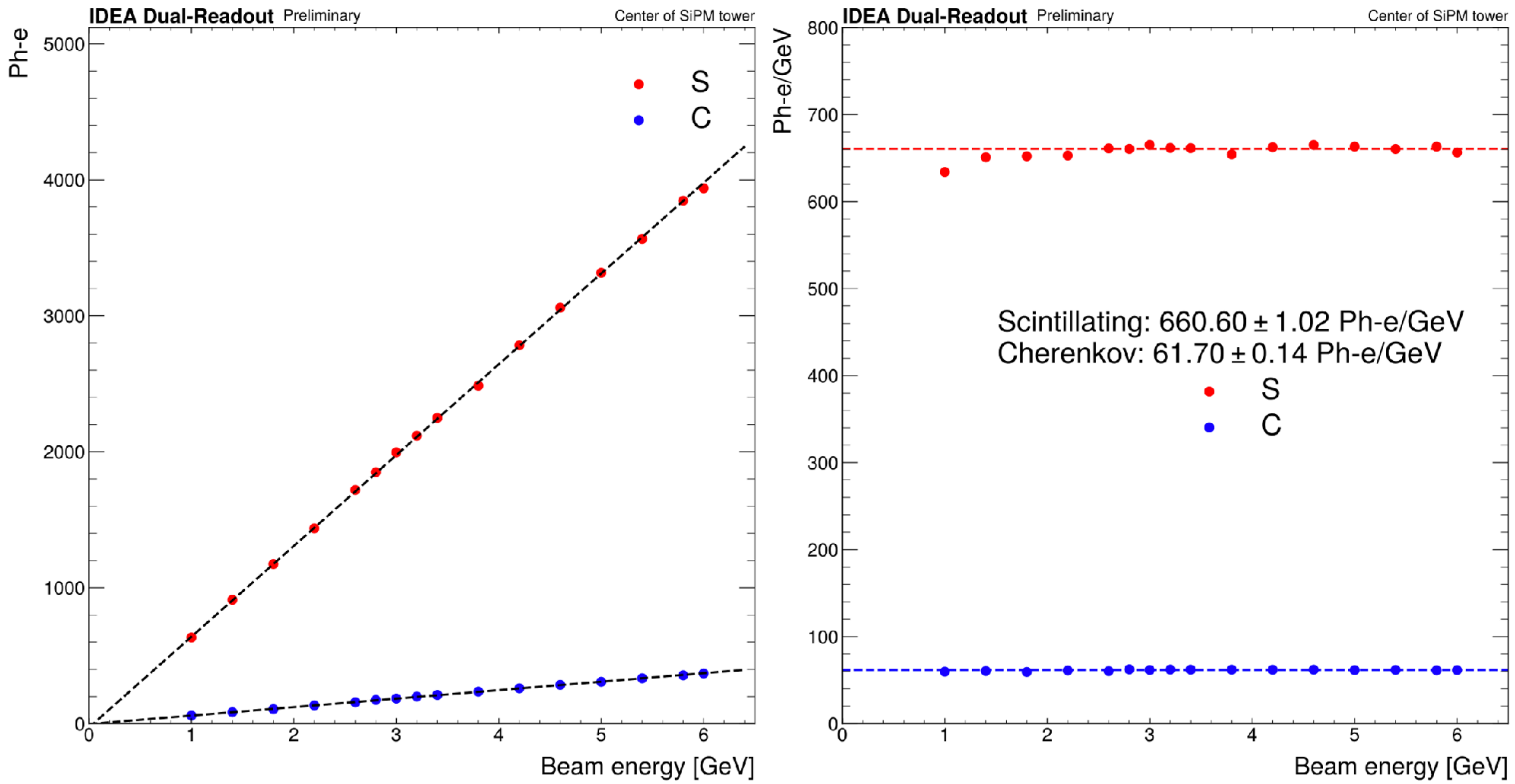


Readout Boards CAEN A5202

2020 Dual Readout prototype

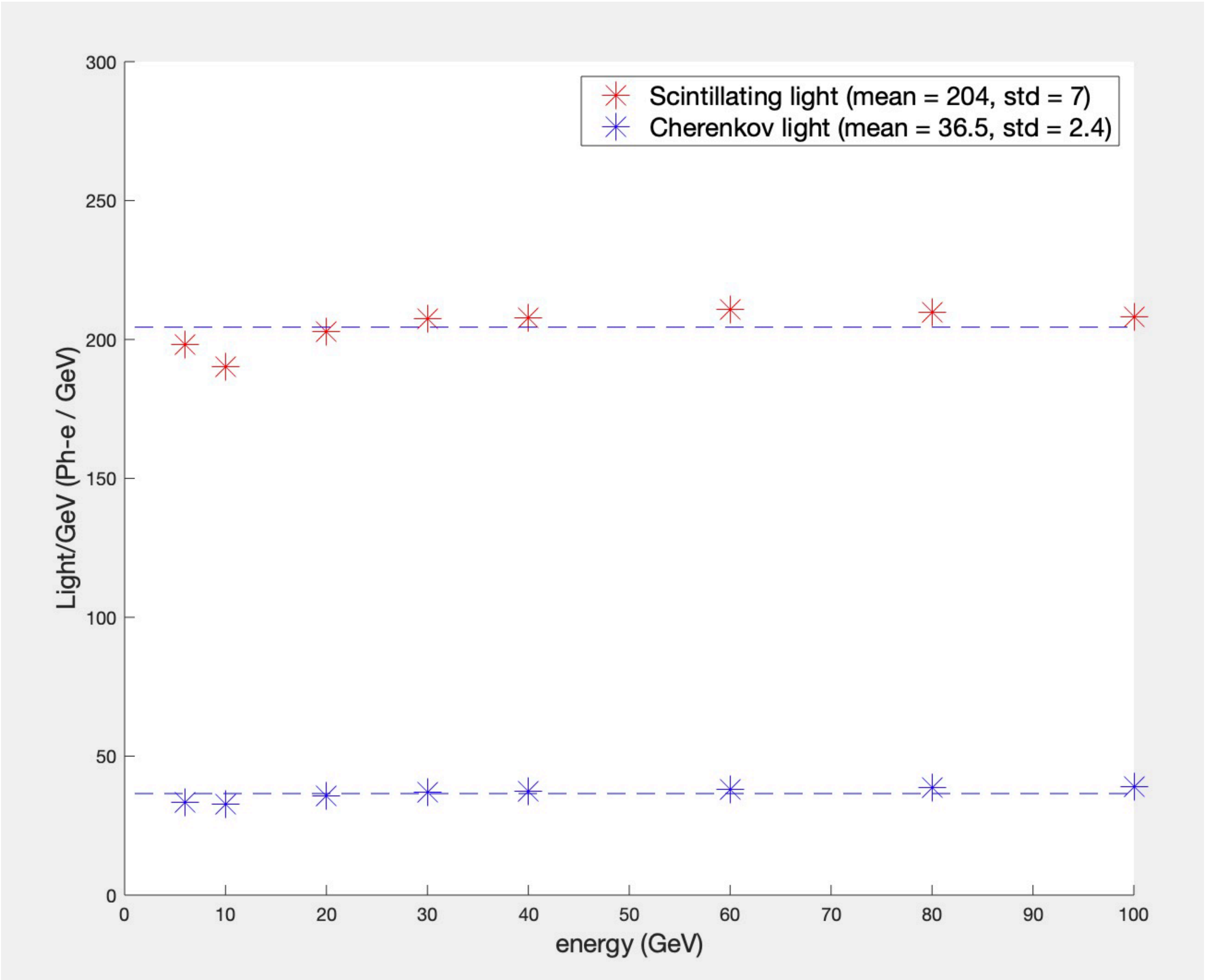
Two test beams in 2021: DESY and CERN

DESY with e^- 1-6 GeV



Preliminary - no filters used

SPS with e^+ 10-125 GeV

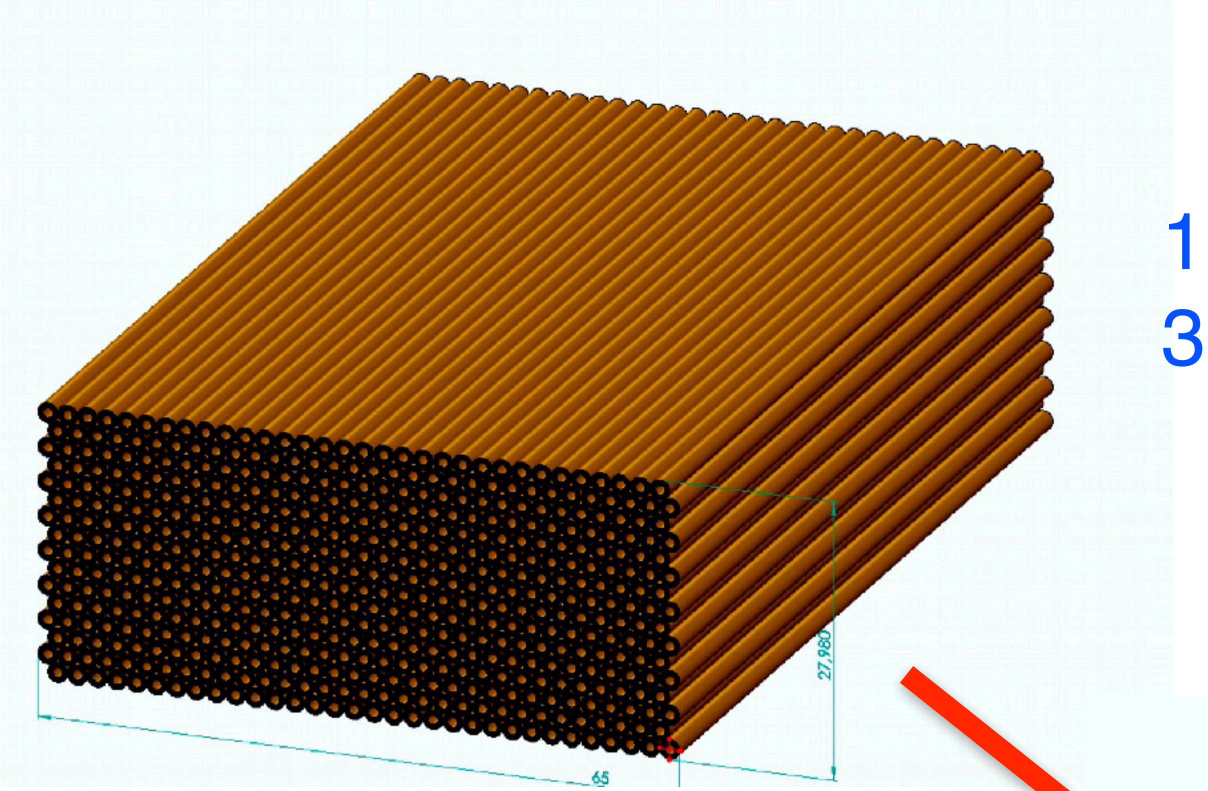


Preliminary

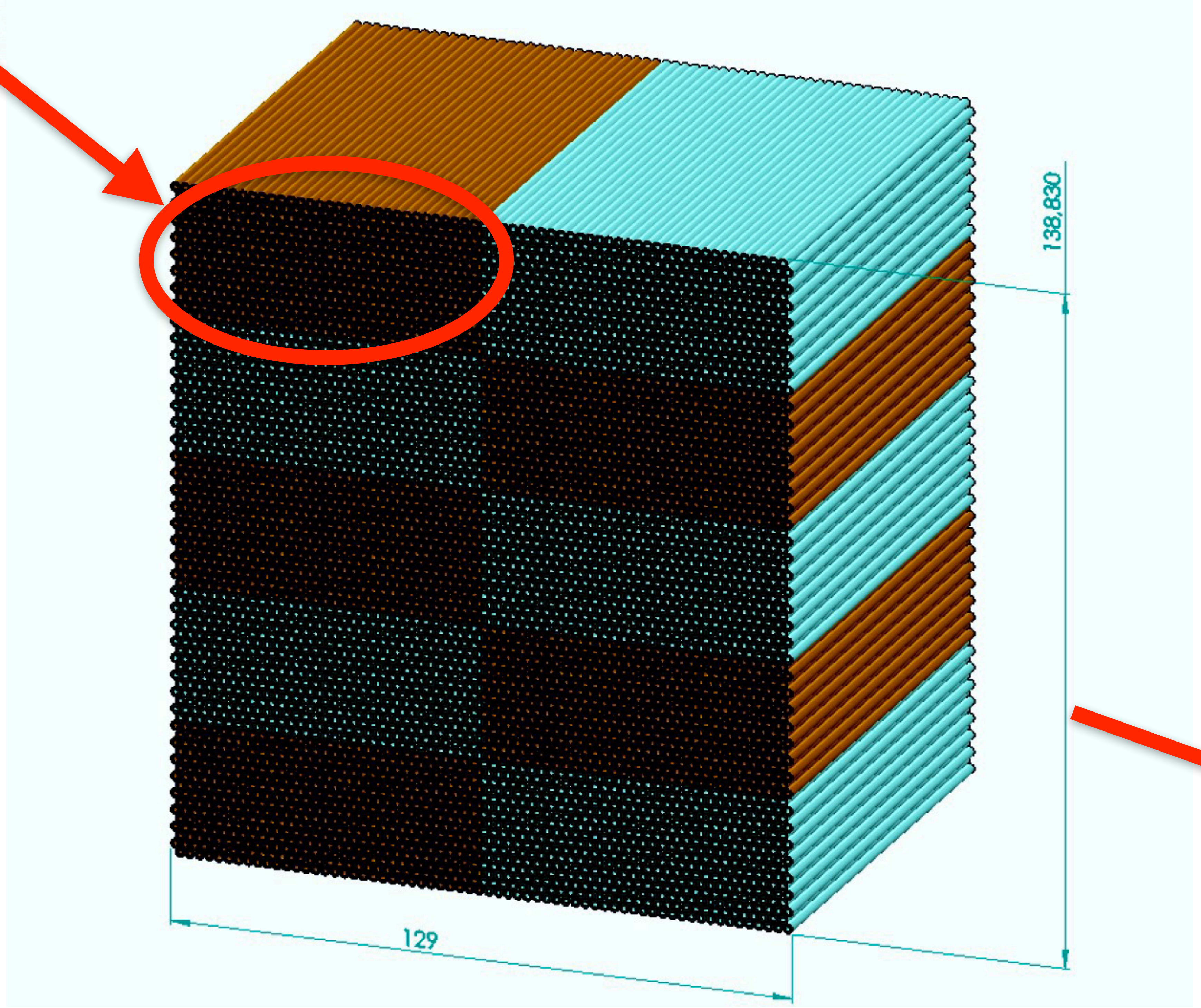
yellow filters used over scintillating fibers, neutral filters used over clear fibers

DR future prototypes

HiDRa2



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

Full hadronic shower containment calorimeter

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

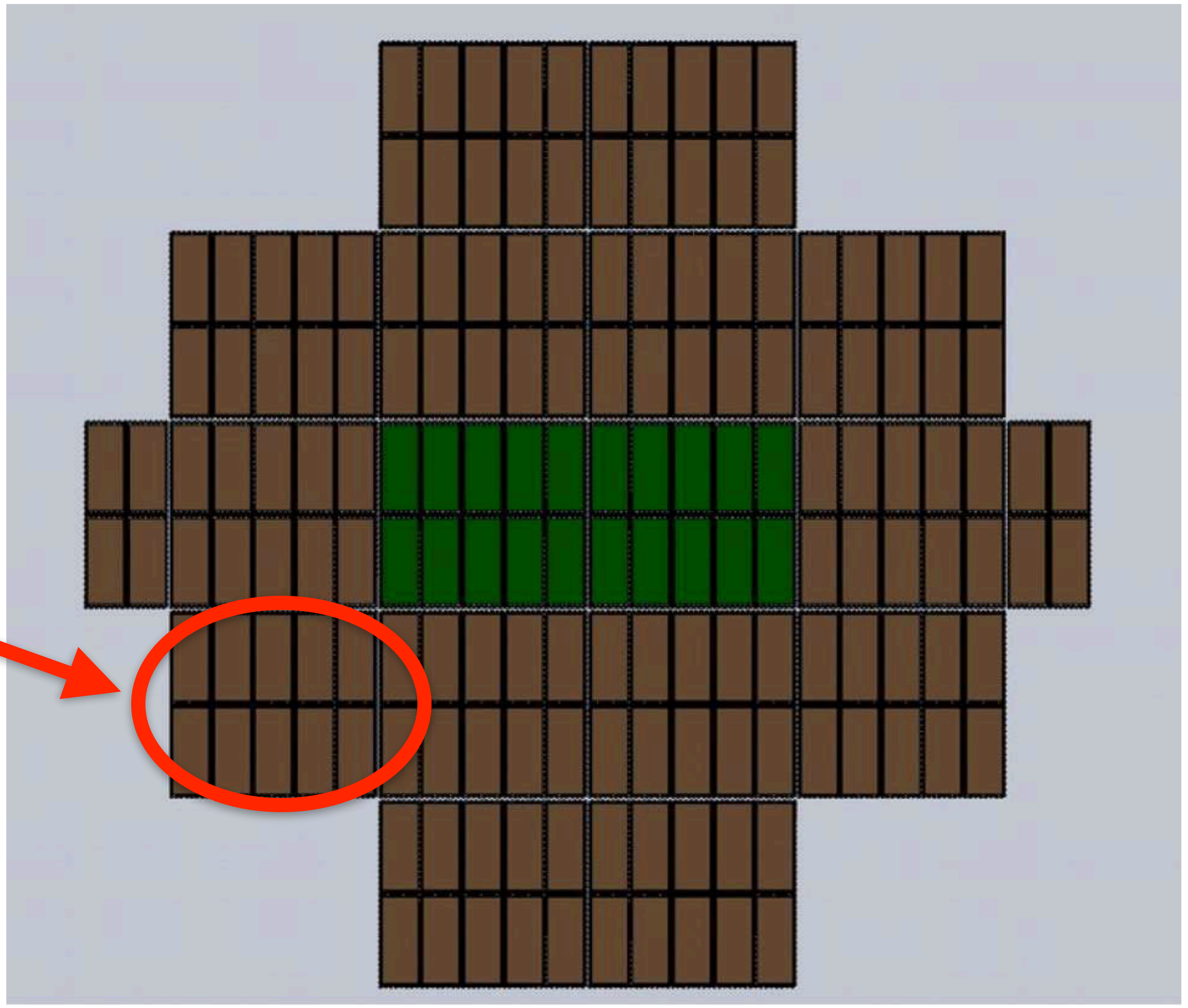
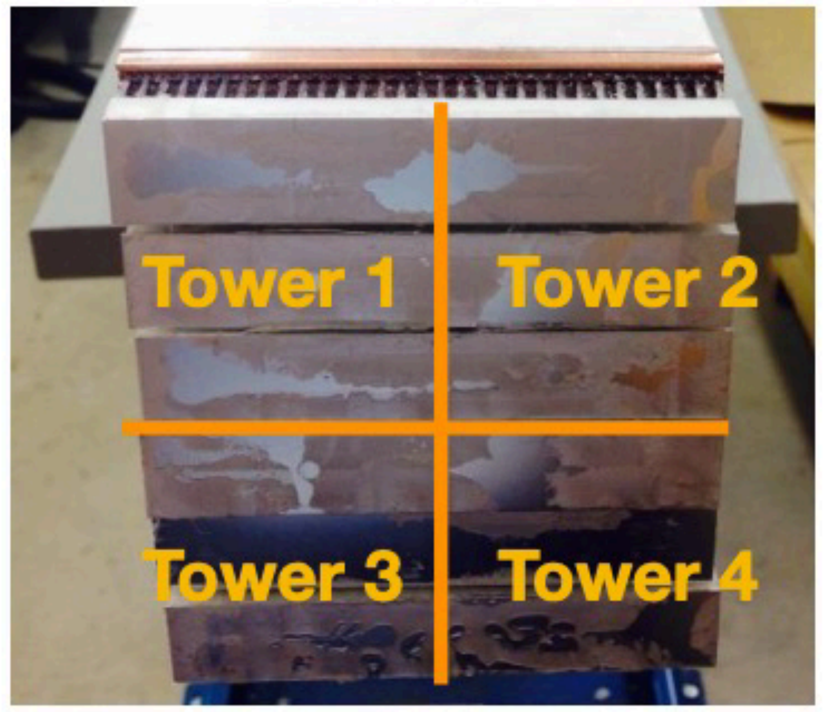
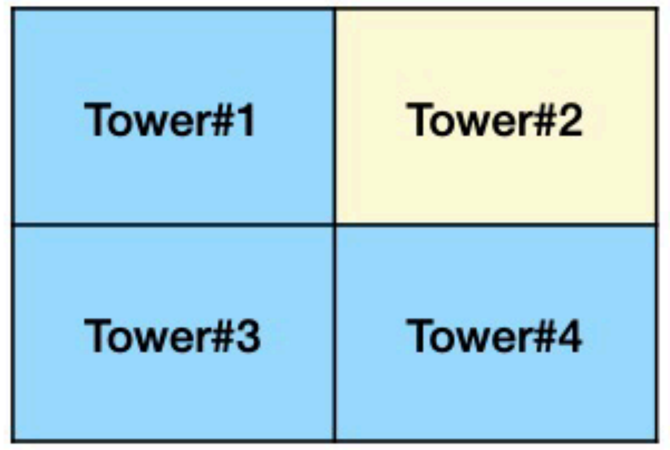


Plate based + 3D printing calo (Korea)

"Short-term plan"

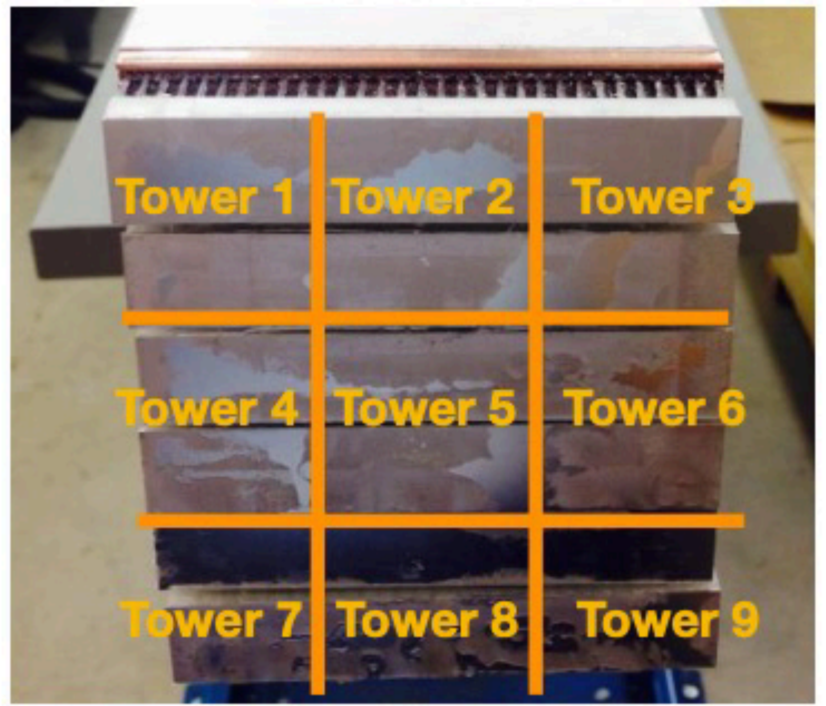
Module #1 (2x2)

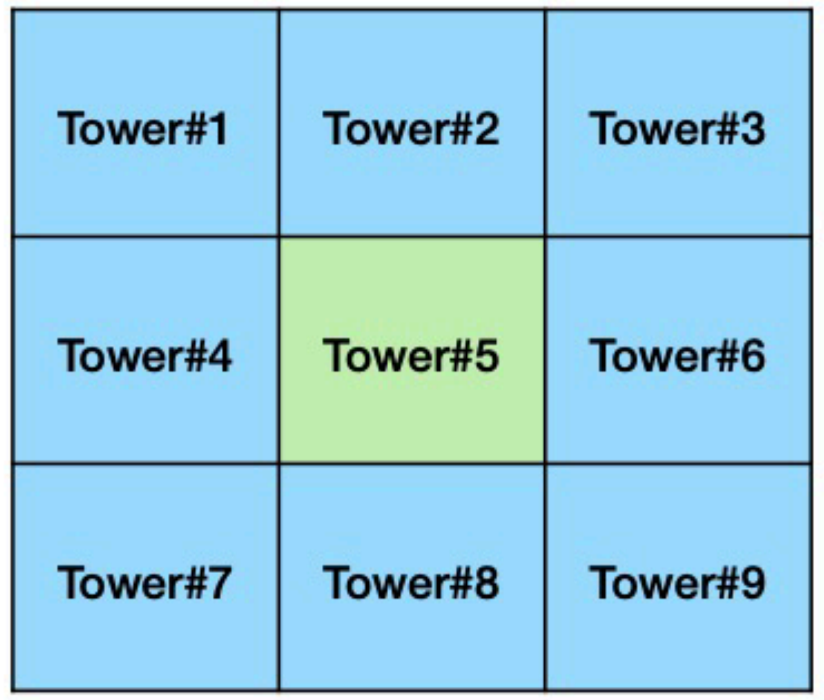




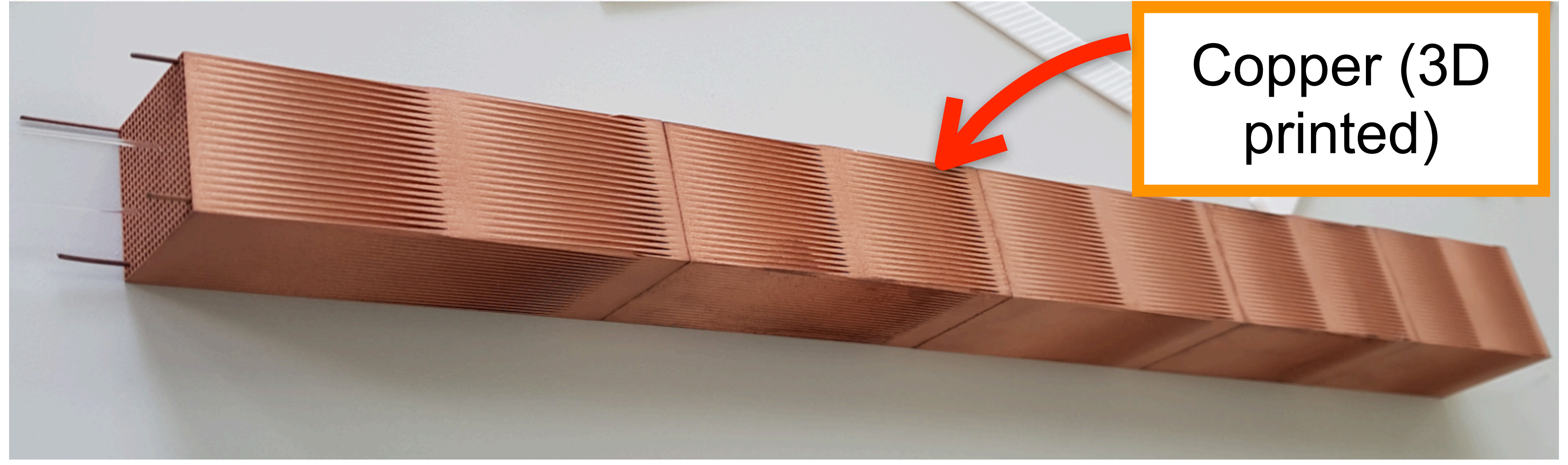
Tower#1	Tower#2
Tower#3	Tower#4

Module #2 (3x3)



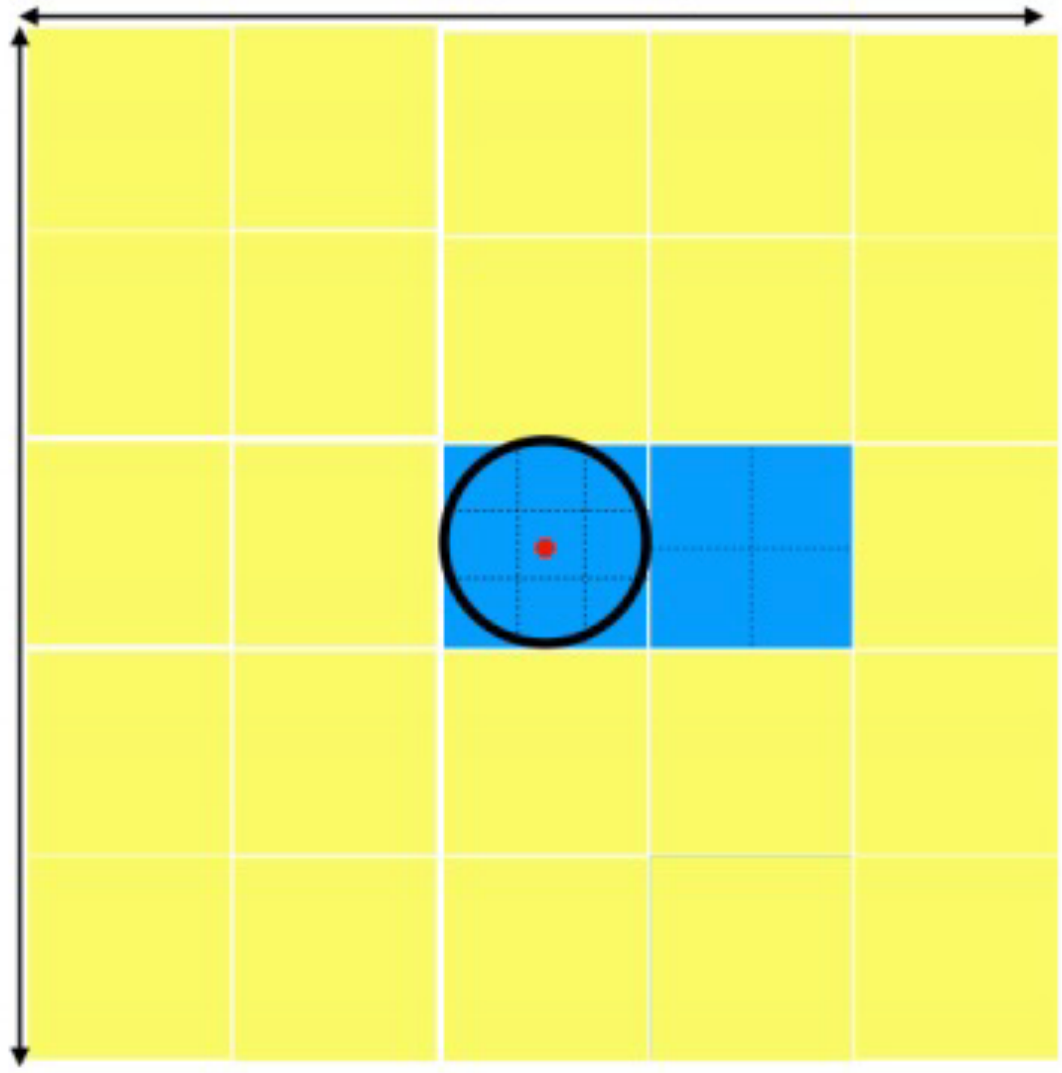


Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9



Prototype Detector (2021)

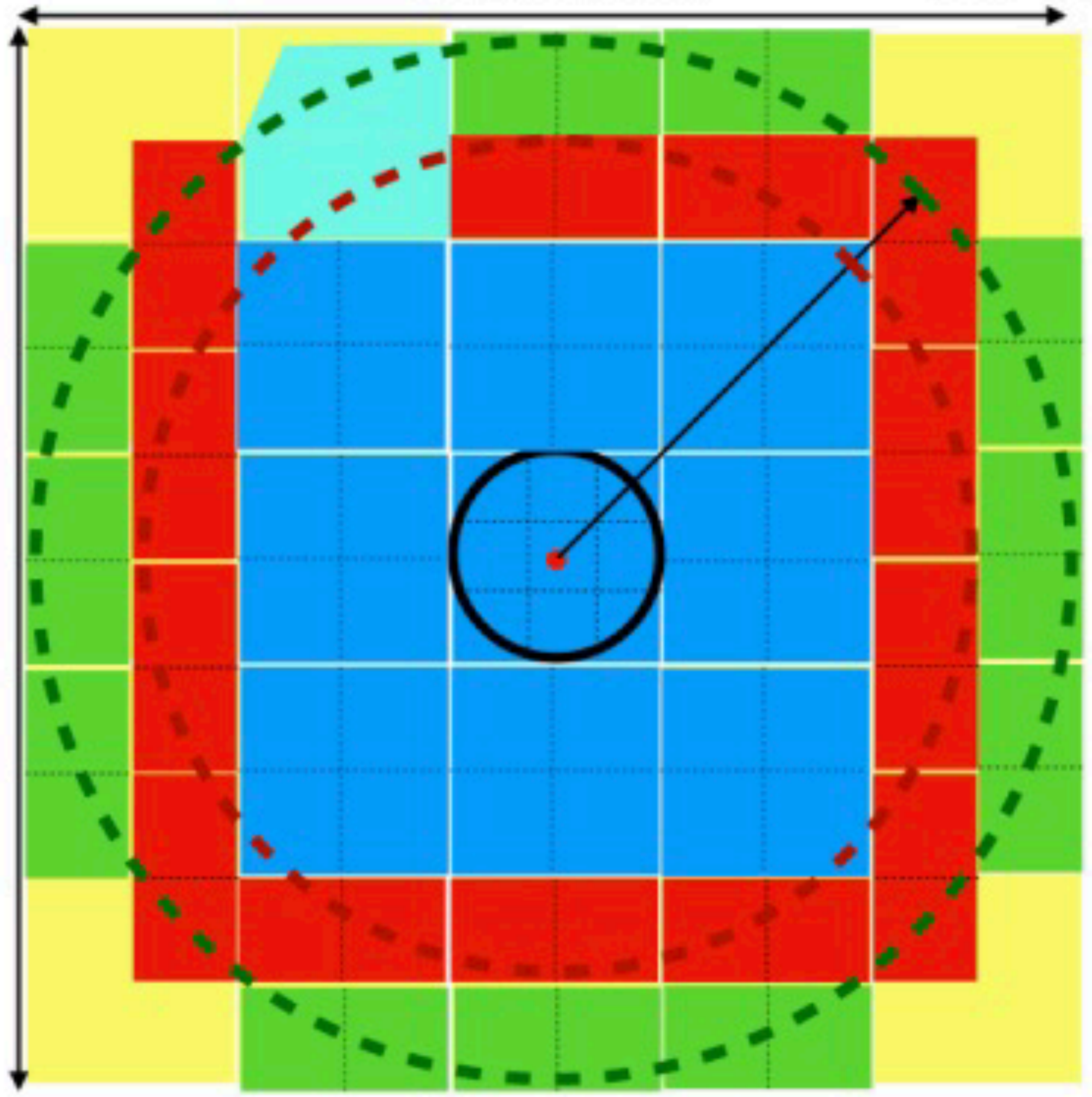
5x5 (460 mm)



"Mid-term plan"

Prototype Detector (2025)

5x5 (460 mm) **TBD (budget is**



- 🟨 Mechanical supporter
- 🟦 3D-printing module
- 🟦 9.2x9.2cm modules: 9
- 🟥 1/2 modules: 13 (Opt1)
- 🟩 1/2 modules: 11 (Opt2)

Building more and more modules 2022-2025

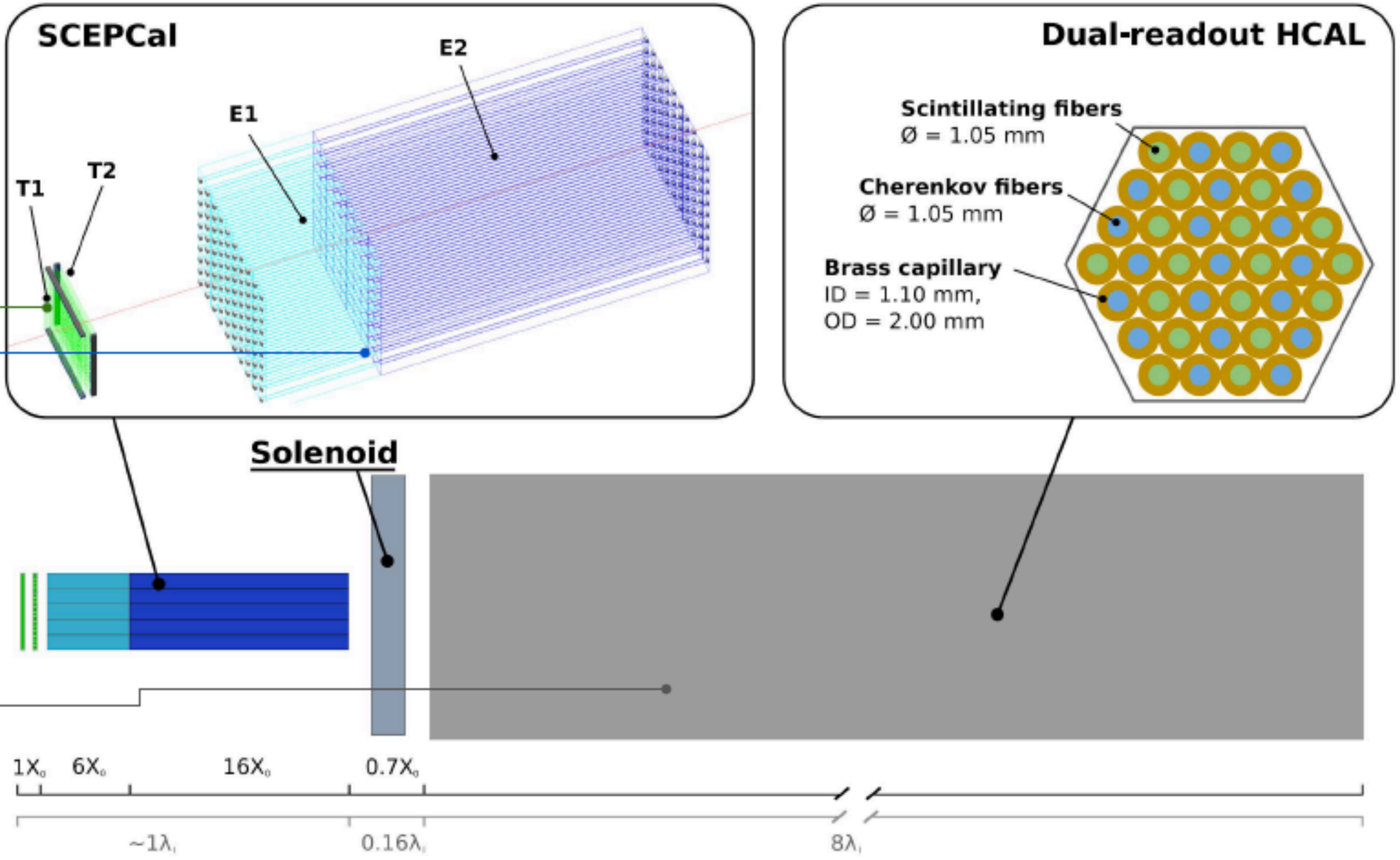
Strong collaboration on DR calorimetry between INFN, Korea and USA

Crystal ECAL with IDEA's DR calorimeter

Layout overview

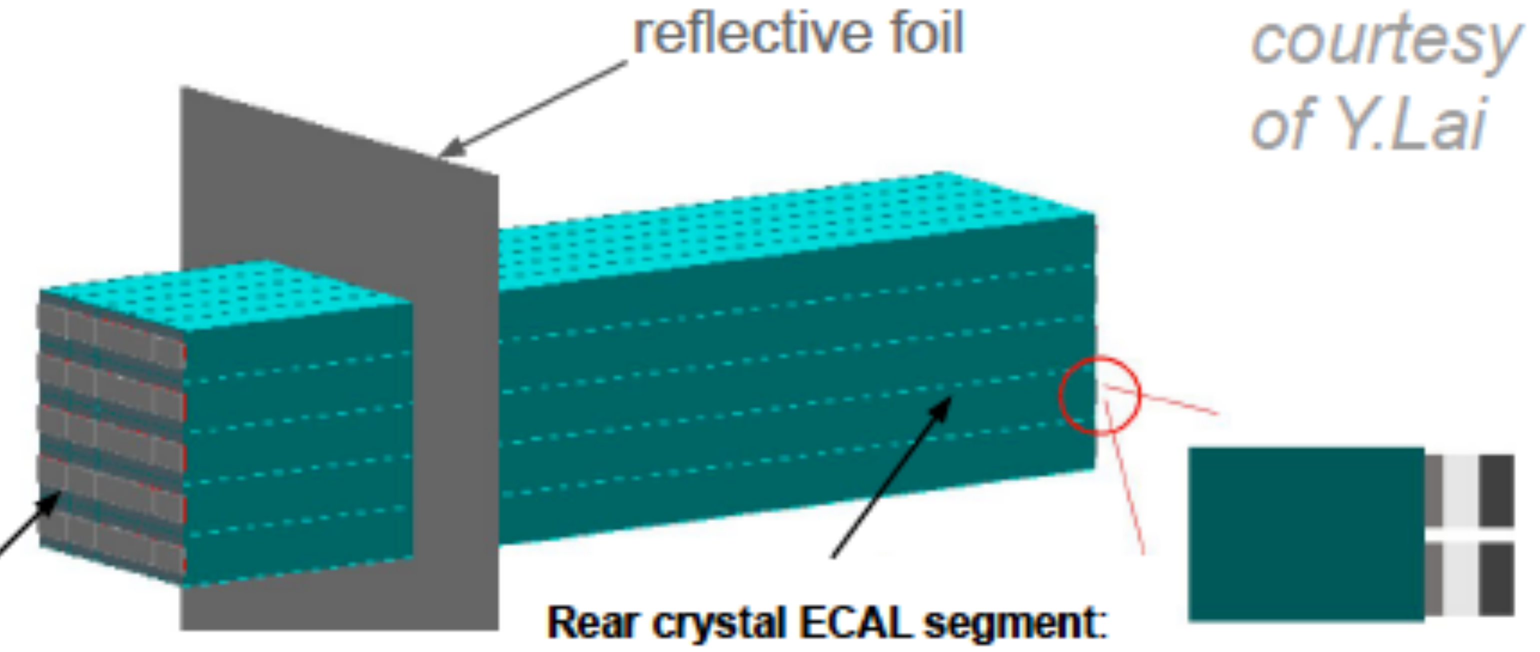
- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **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 IDEA's DR calorimeter



reflective foil

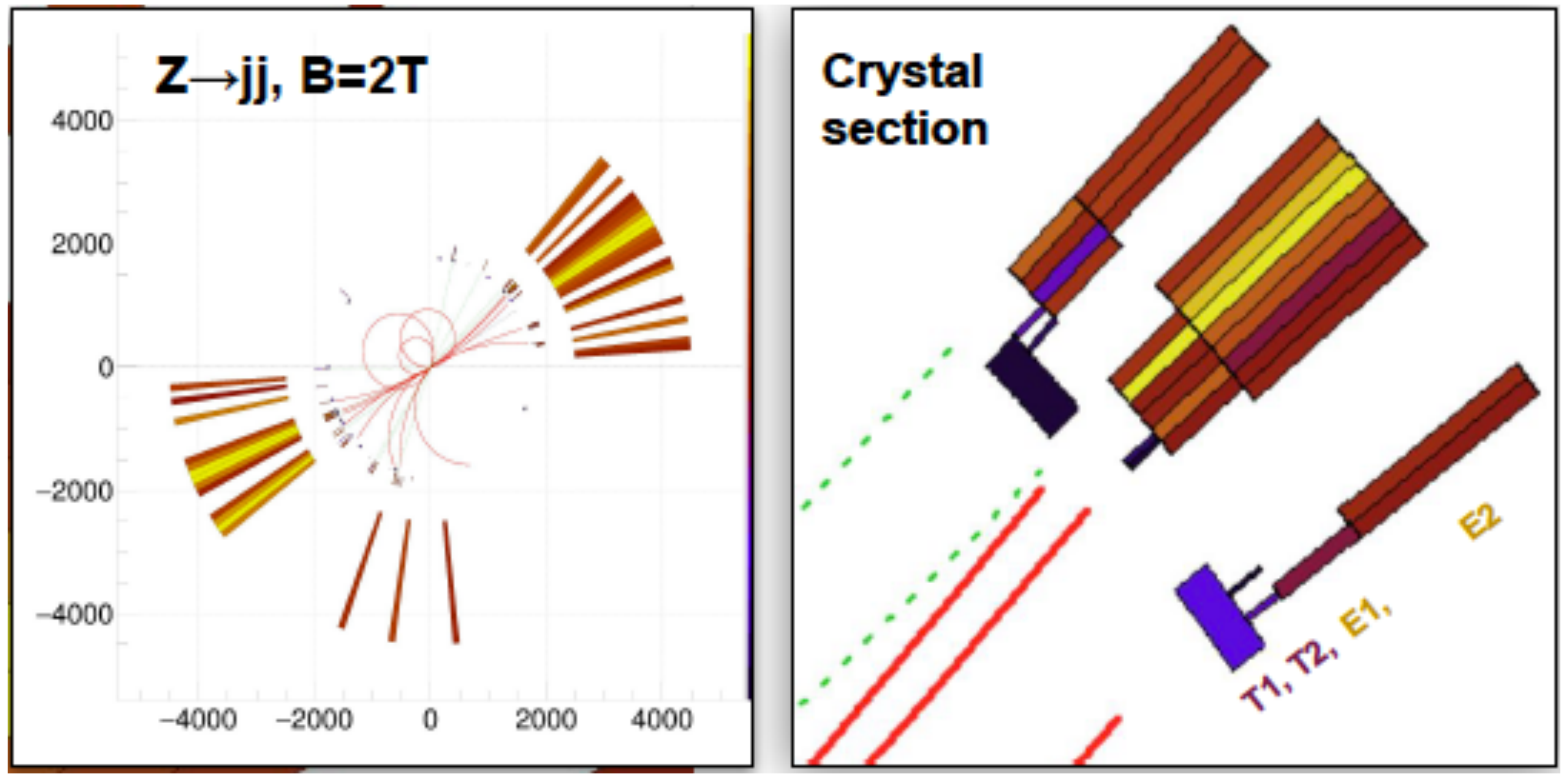
courtesy of Y.Lai

Front crystal ECAL segment:
Single 5x5 mm² SiPM per crystal optimized for scintillation light detection

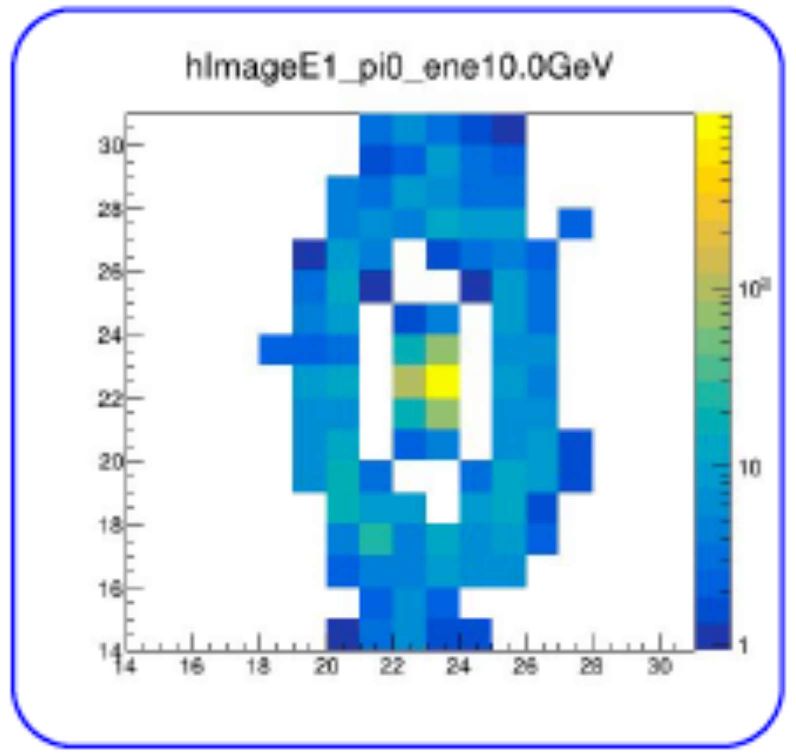
Rear crystal ECAL segment:
2 SiPMs with optical filters optimized for scintillation and cherenkov detection resp.

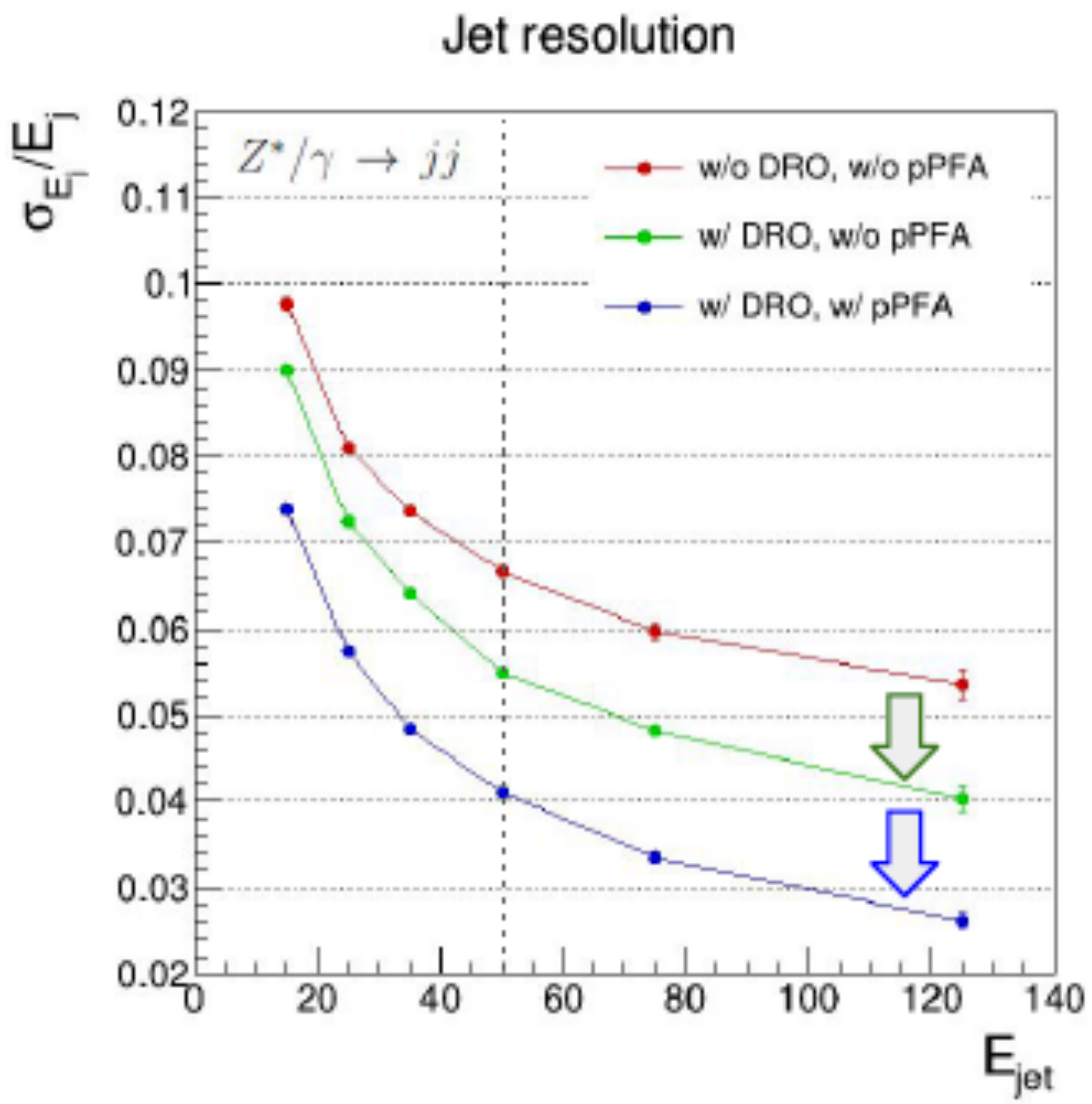
2 SiPMs

Event display



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





crystals + IDEA w/o DRO

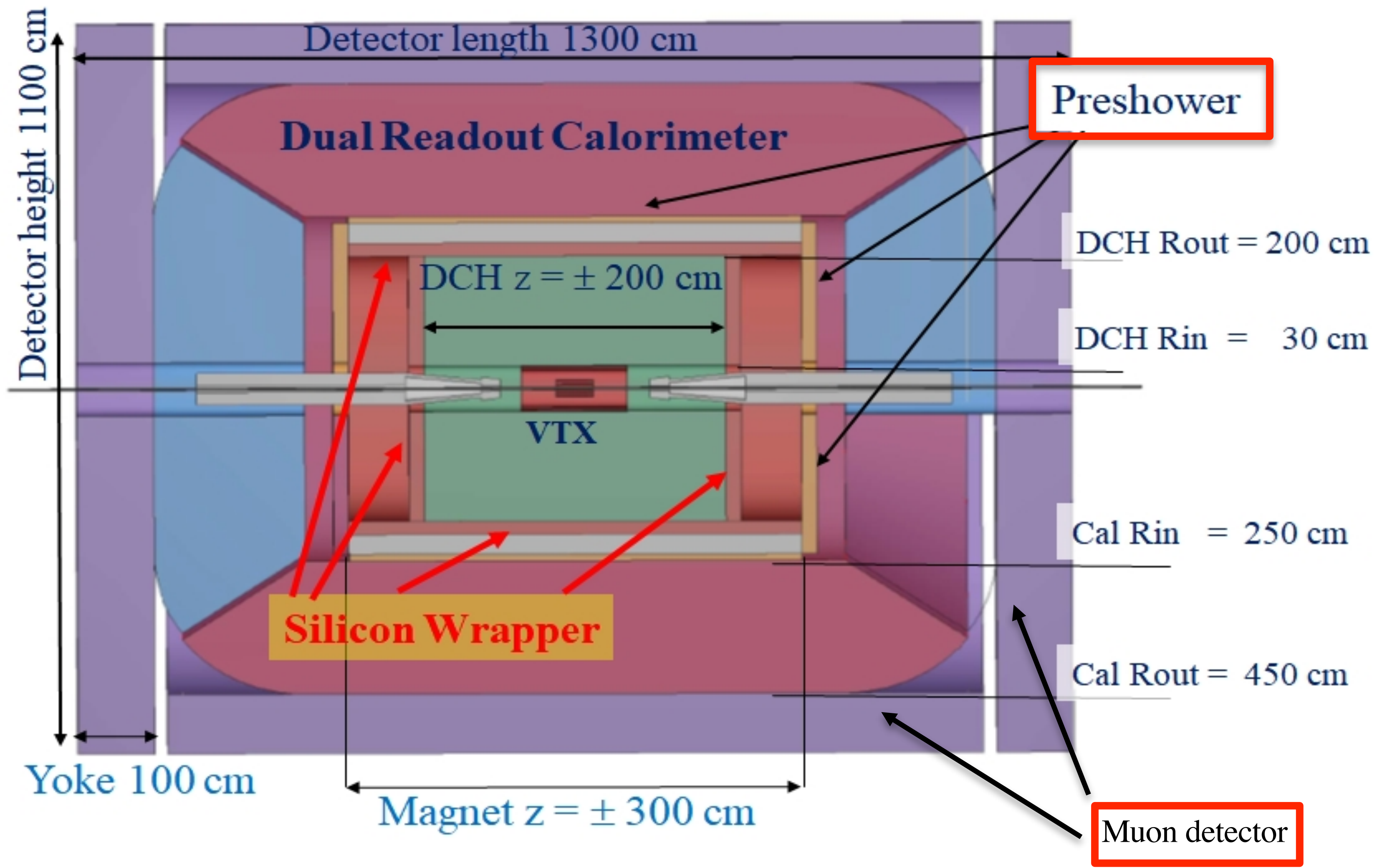
crystals + IDEA w/ DRO

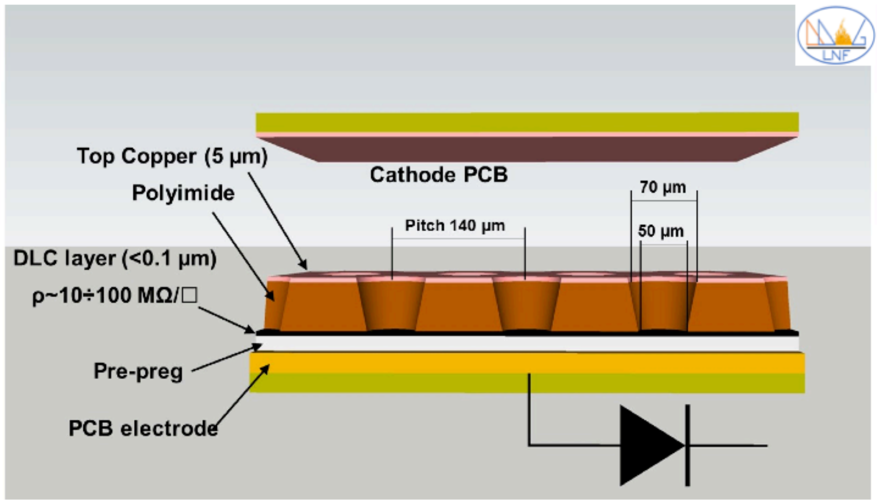
crystals + IDEA w/ DRO + pPFA

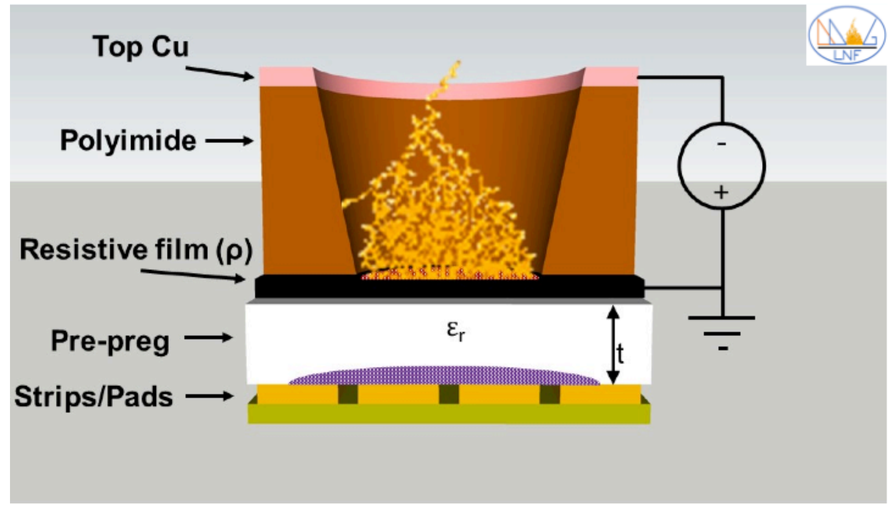
Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

M. Lucchini

µRWELL-based detectors

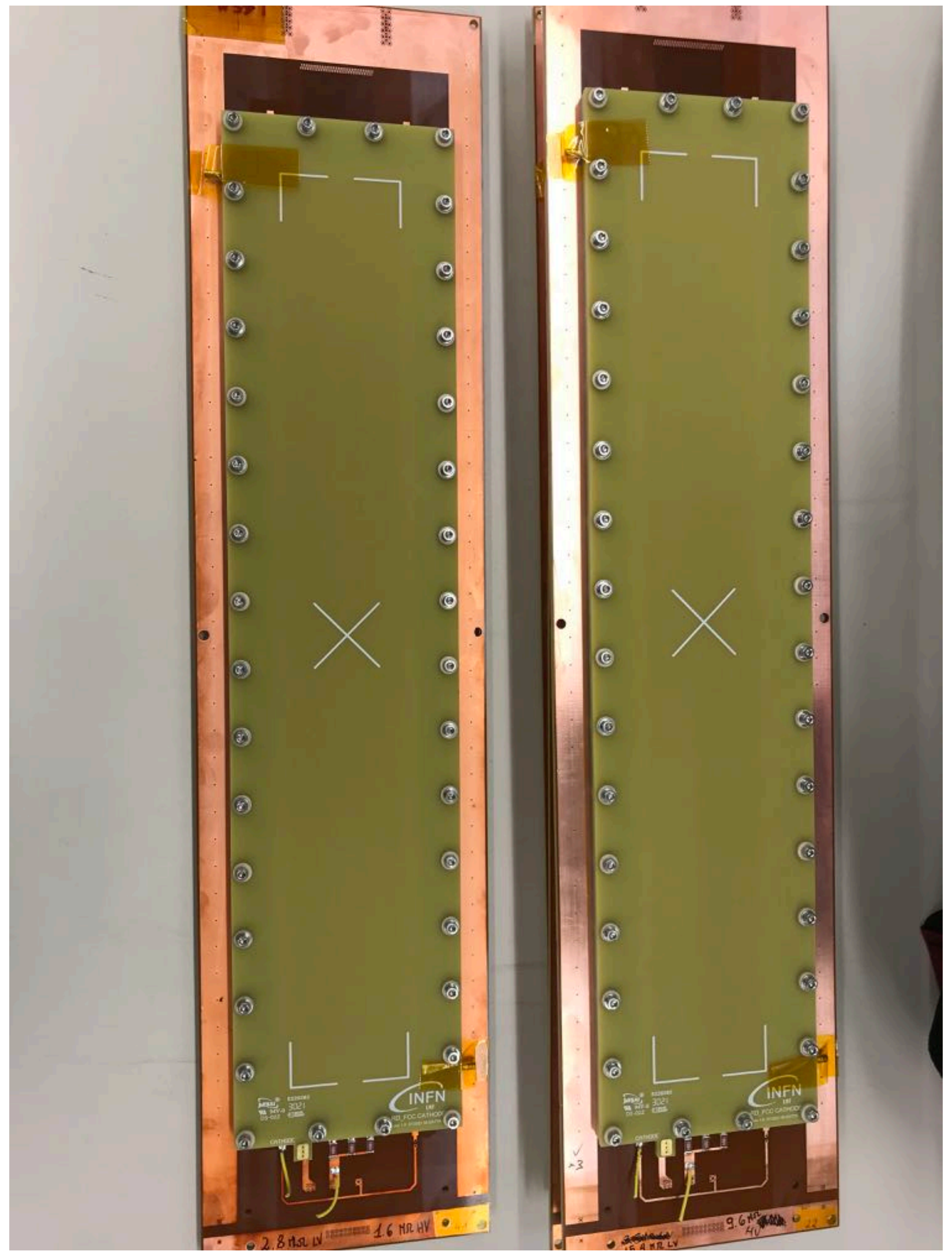


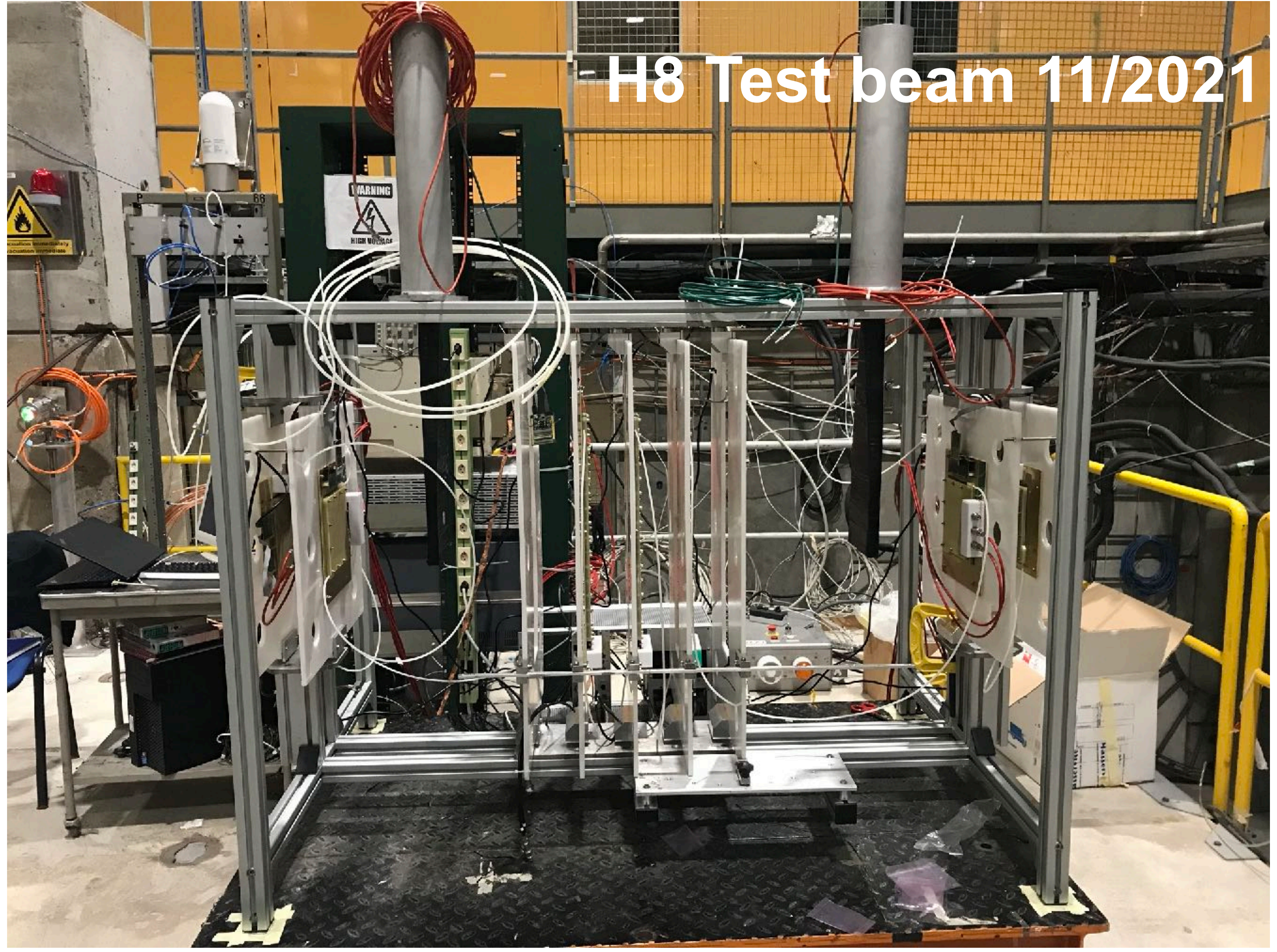


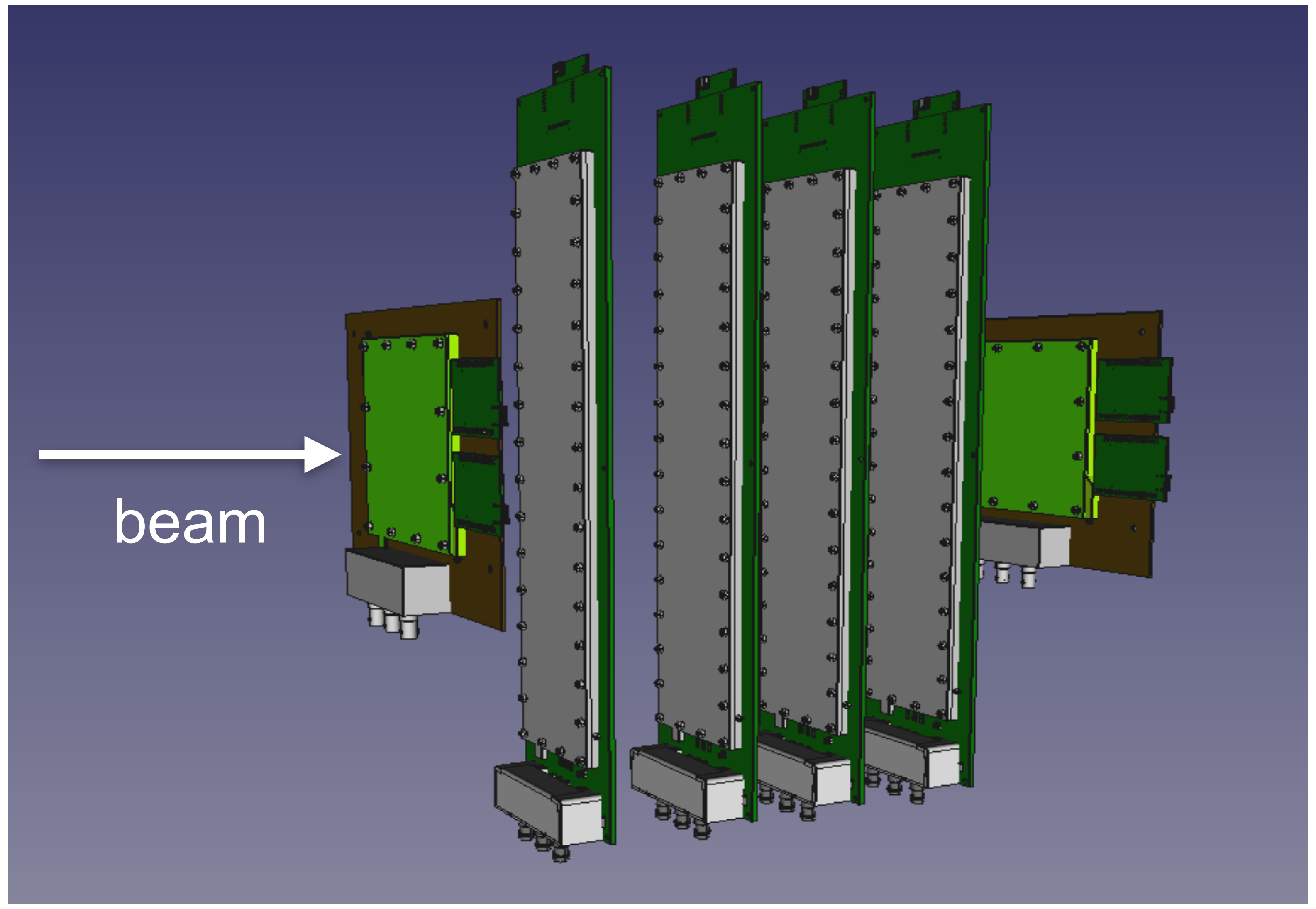


New µRWELL prototypes with 50cm long strips

strips







7 µRWELL prototypes with resistivity varying between 10 and 80 MOhm/☐

Will allow to define best resistivity for final 50x50 cm^2 detector

Common R&D

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Why not use the good example of **key4HEP** and take advantage and exploit the synergies between R&D plans for **FCC-ee**, **ILC**, **CLIC**, **CEPC**?

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  - These concepts should include also engineering solutions
- Should be ready for the next **ESU** foreseen around 2026-2027

Backup

Experimental challenges

Mogens Dam

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- Extremely high luminosities
  - ❑ Large statistics (high statistical precision) – control of systematics down to 10^{-5} level
  - ❑ Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics

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- Physics events at 100 kHz
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - Material budget: minimise mass of electronics, cables, cooling, …
  - Requirement of 10^{-5} level relative normalisation of physics channels

Mogens Dam

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  - Requirement of 10^{-5} level relative normalisation of physics channels
- ”Continuous” beams (no bunch trains); bunch spacing at 19.6 ns
  - Power management and cooling (no power pulsing)

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Experimental challenges

- Extremely high luminosities
  - Large statistics (high statistical precision) – control of systematics down to 10^{-5} level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics
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  - Very complex MDI (Machine Detector Interface)
- More physics challenges
  - Luminosity measurement to 10^{-4} – luminometer acceptance to 1 μm level
  - Detector acceptance to ~10^{-5} – acceptance definition to few 10s of μm, hermeticity (no cracks!)
  - Stability of momentum measurement – stability of magnetic field wrt. E_{cm} (10^{-6})
  - b/c/g jets separation – primary importance for Higgs decays; flavour and τ physics: vertex detector precision
  - Particle identification (π/K/p) without ruining detector hermeticity – flavour and τ physics (and rare processes)

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FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

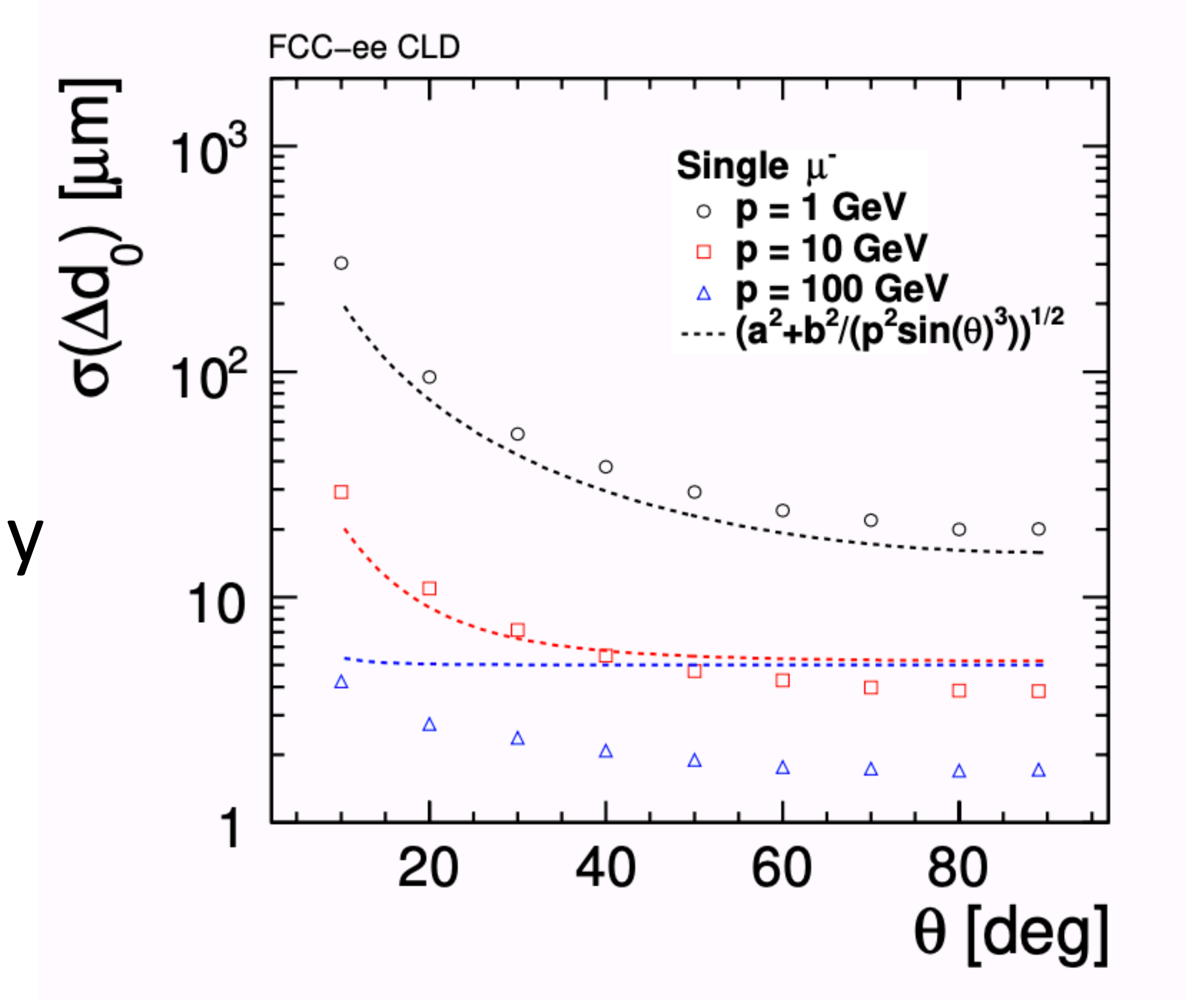
Impact parameter resolution

Design goal…

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m GeV}$$

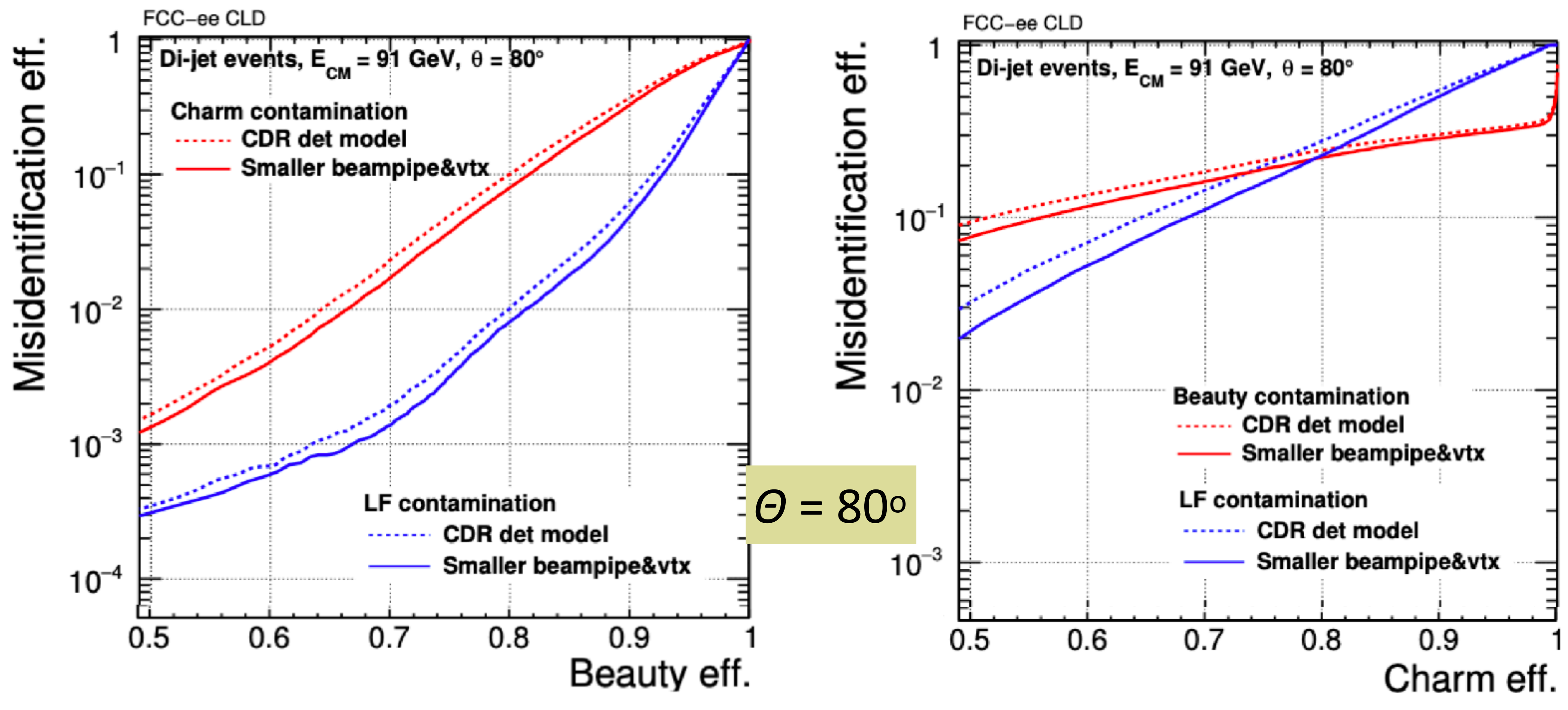
…satisfied in CLD full simulation study



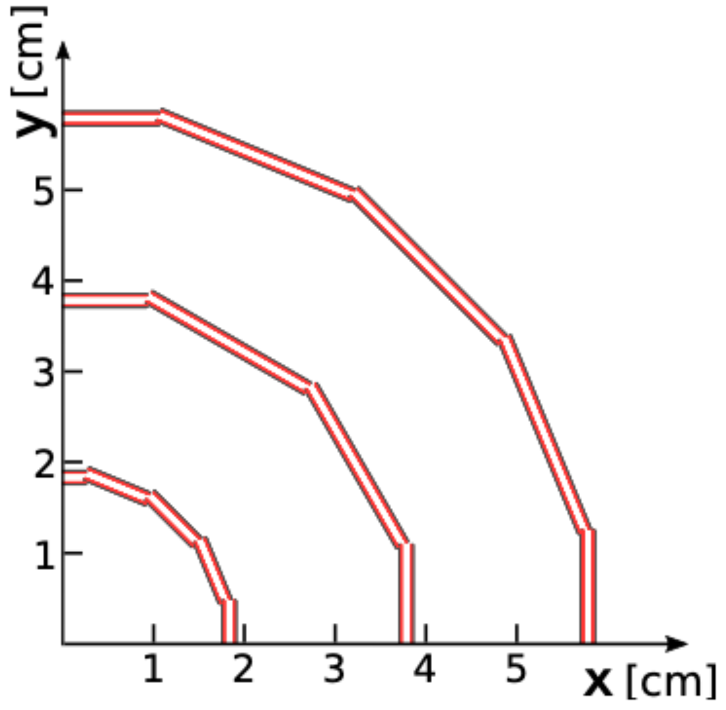
CLD flavour tagging

arXiv:1911.12230

b-tagging **c-tagging**



- Single point accuracy of 3 μm
- Three very thin double sensor layers (50 μm Si) at radii 18, 37, 57 mm
  - 0.6% of X_0 for each double layer
- Beryllium, water cooled beam pipe at r=15 mm (possibility to go down to r=10 mm)
  - 0.5% of X_0



Strong development:

- Lighter, more precise, closer
- 10 mm beam pipe under investigation

Accelerator	a (μm)	b ($\mu m \cdot GeV/c$)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILD	< 5	< 10

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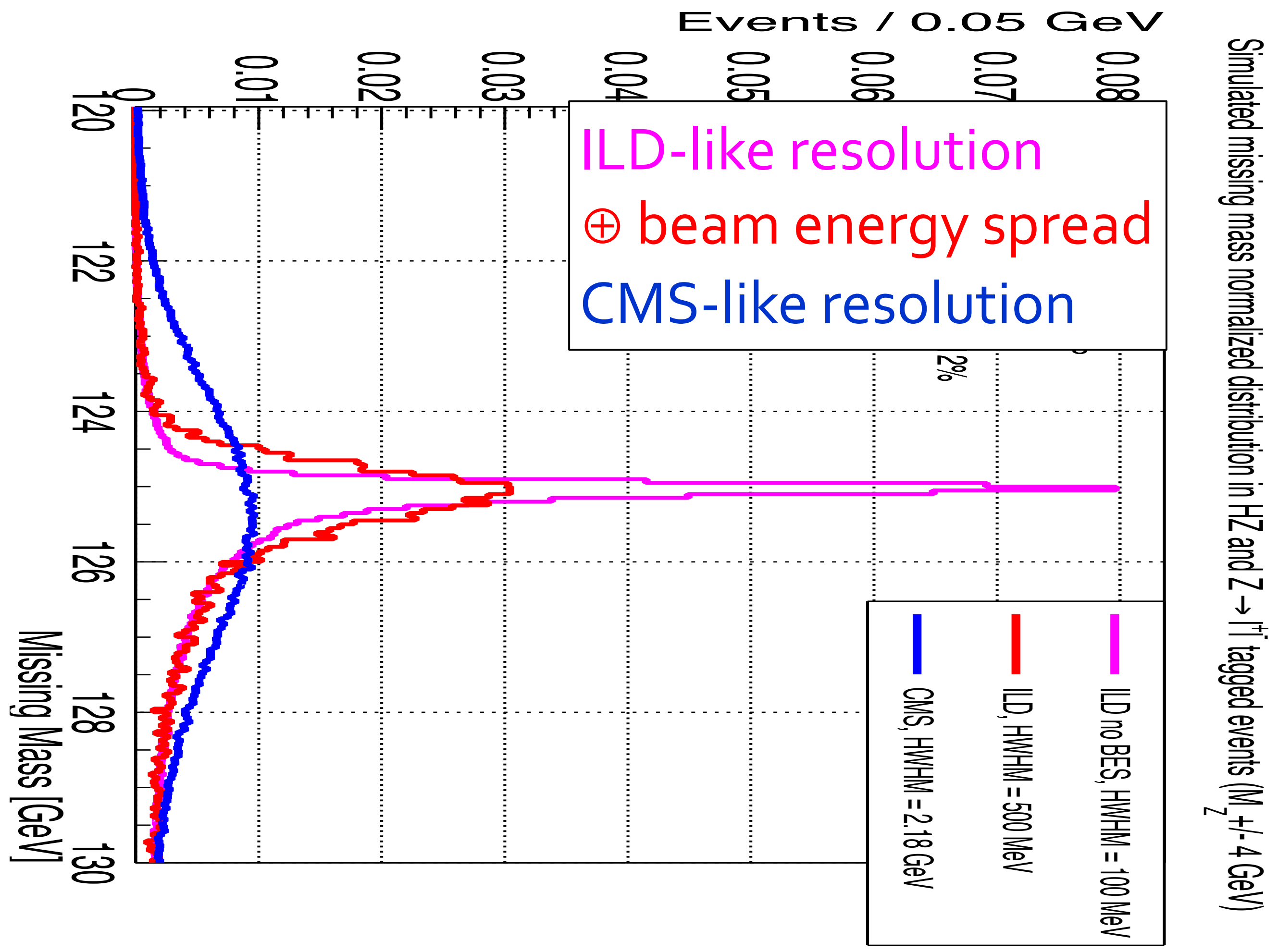
Momentum resolution

Often, the "canonical" requirement is expressed as

$$\boxed{\sigma_{p_T}/p_T^2 \simeq 2\times10^{-5}\,\mathrm{GeV}^{-1}}$$

⇒ Mass reconstruction from lepton pairs

in Higgs production



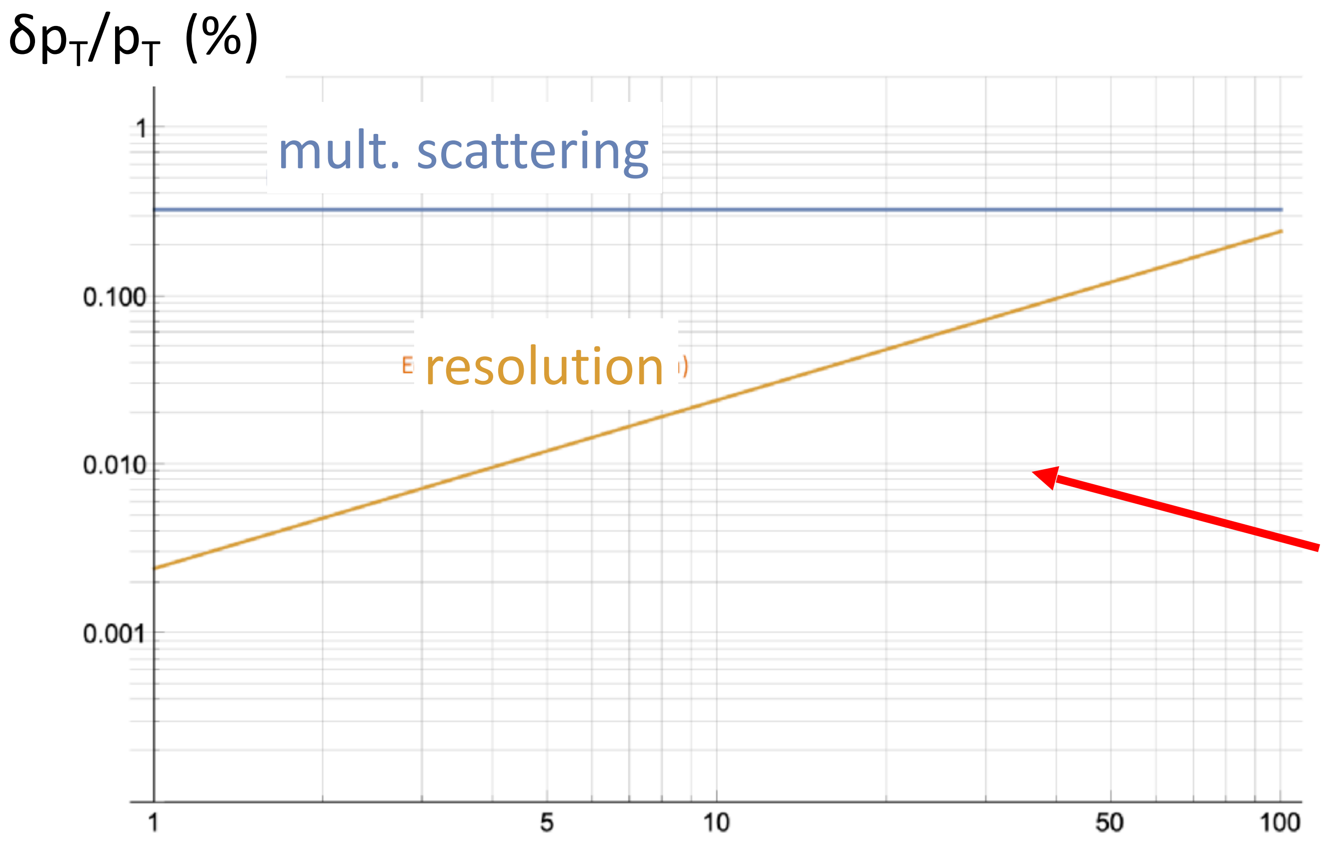
Eur.Phys.J. C77 (2017) no.2, 116

For FCC-ee, this matches well the beam energy spread of $\delta E/E \simeq 1\text{-}2\times10^{-3}$

In reality, there is of course a resolution term (*a*) and a multiple scattering term (*b*)

$$\boxed{\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}}$$

For "standard" ultra-light detectors (e.g. full Si), multiple scattering dominates up to p_T of ~100 GeV



Here illustrated for the CLD detector at 90°:
Total material budget = 11% of X_0

From analytic expressions for track parameter resolutions.

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}} \qquad \left.\frac{\Delta p_T}{p_T}\right|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

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Momentum resolution

At FCC-ee, very few tracks with $p_T > 100$ GeV. Momentum measurements will be multiple scattering limited

- Possible to reduce multiple scattering contribution?

Reduce to a minimum the amount of material seen by the traversing particles

- Very light gas tracker

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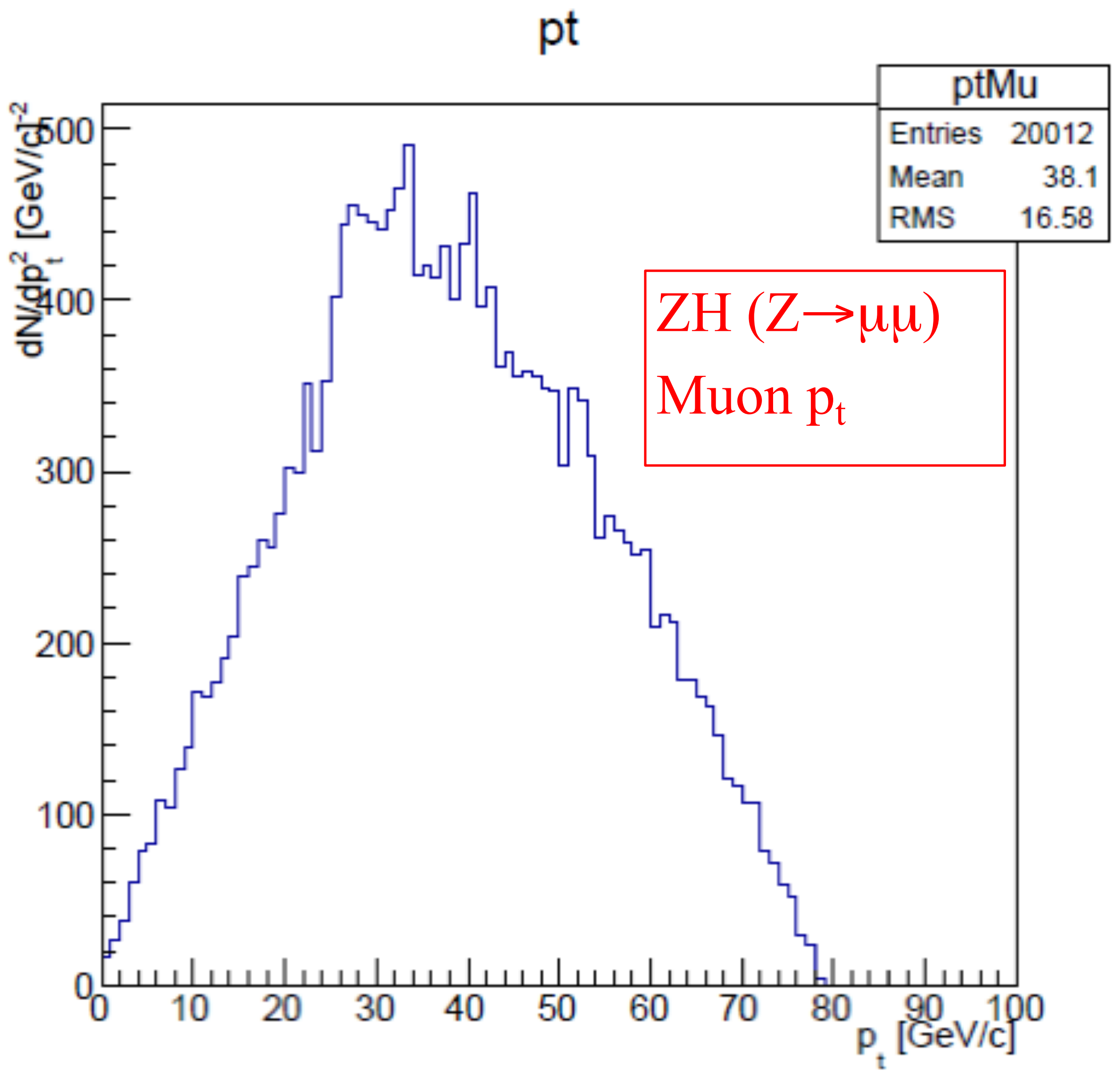

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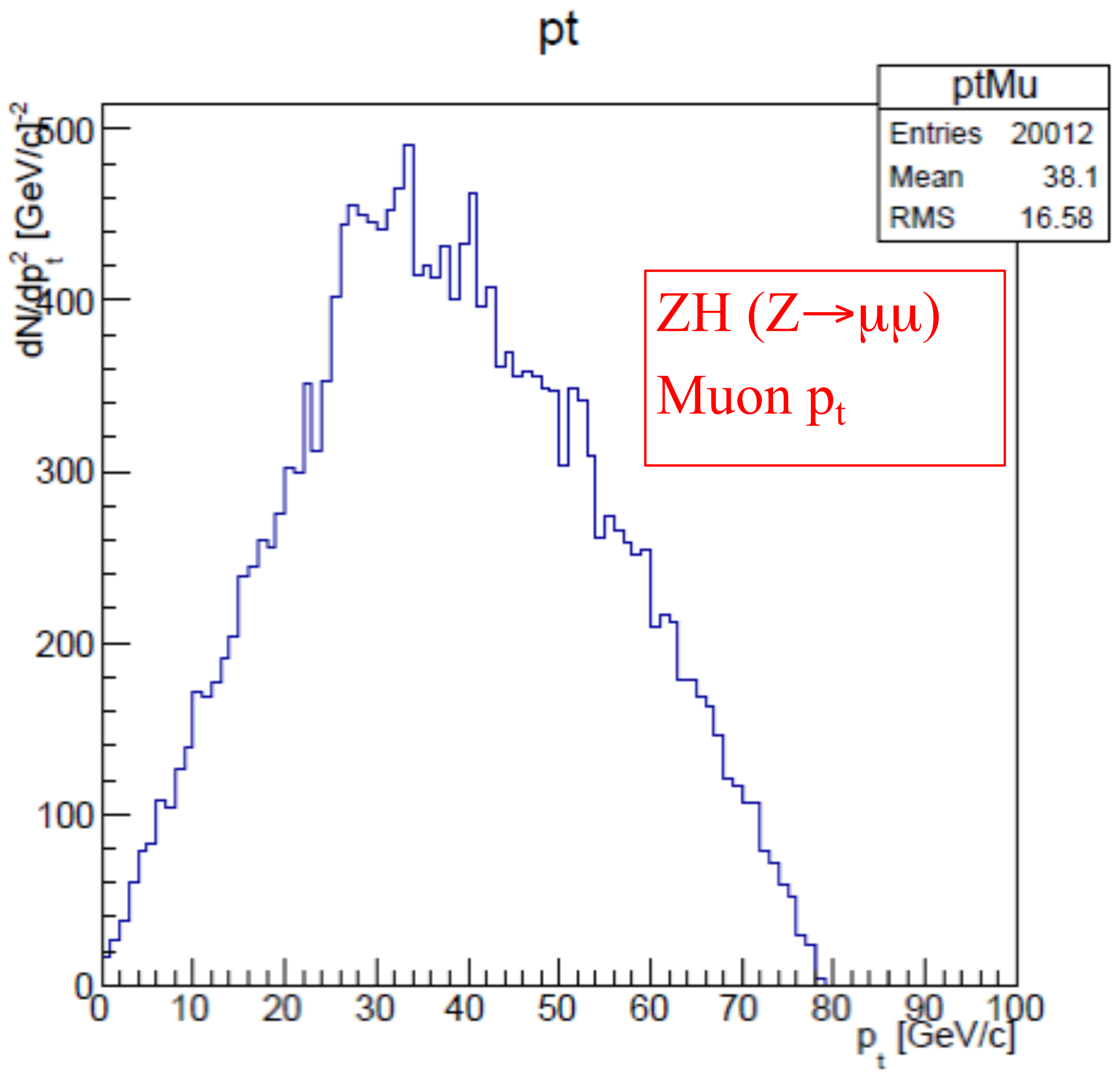

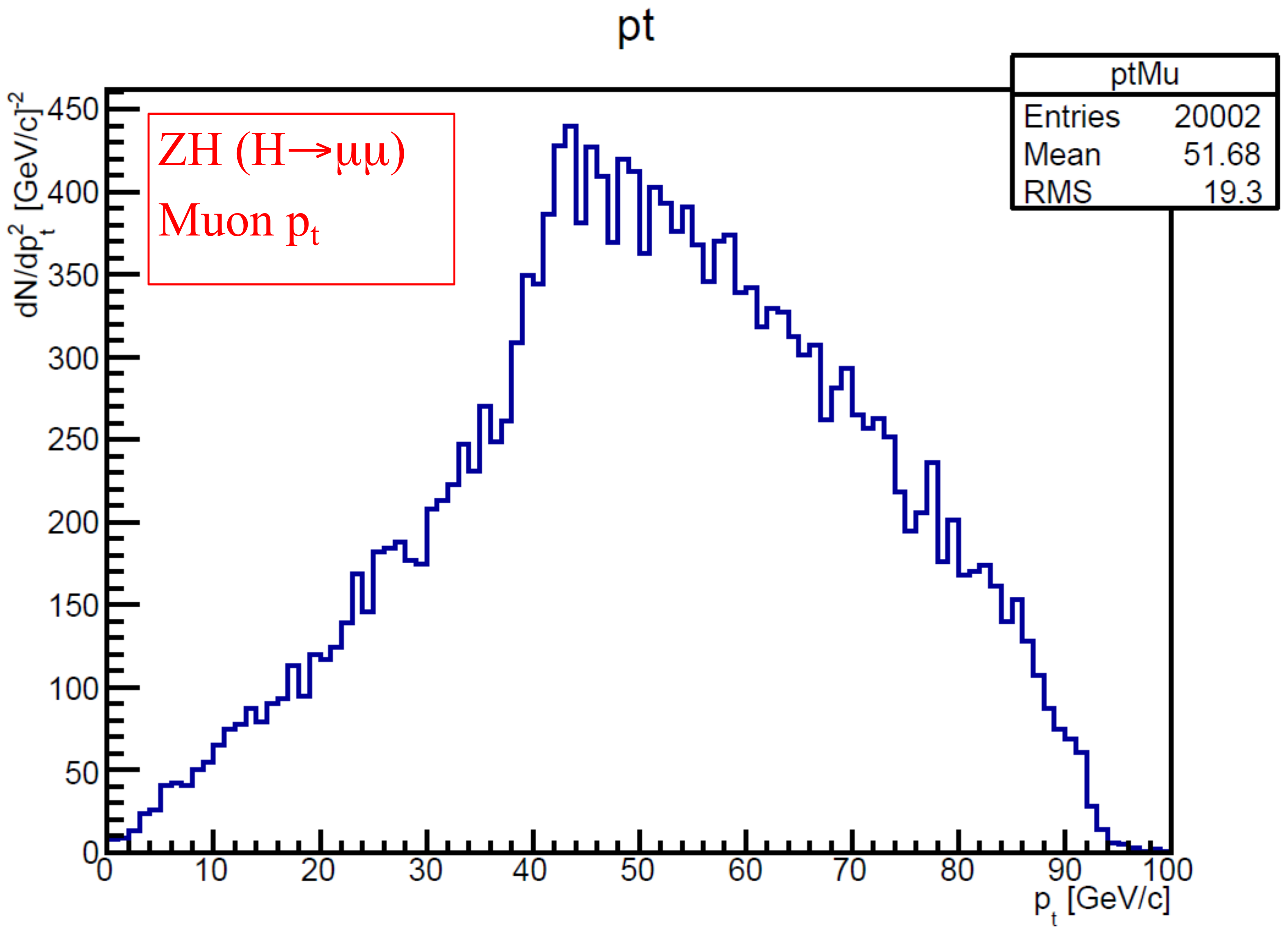

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Calorimetry - Jet energy resolution

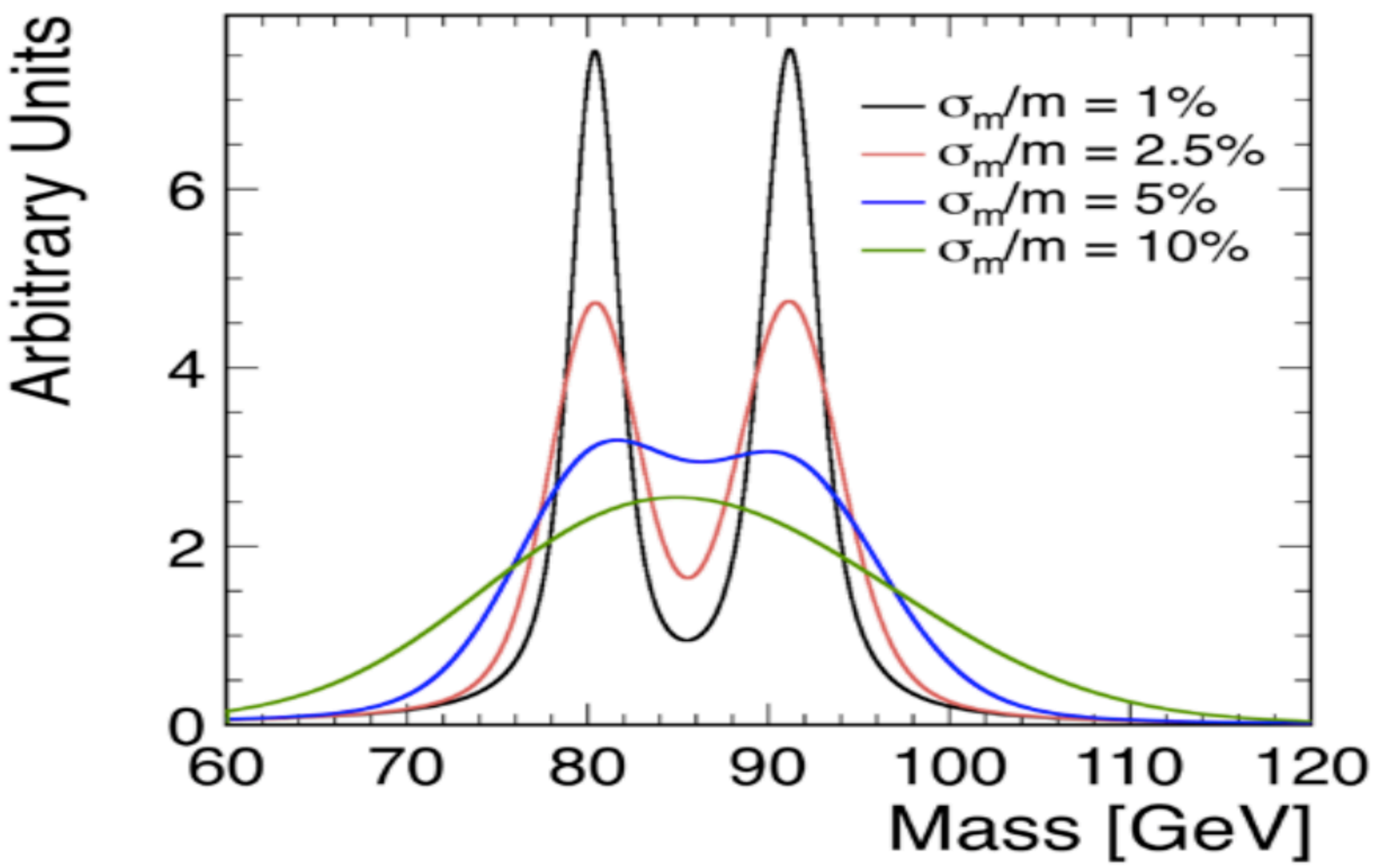
Energy coverage < 300 GeV : $22\ X_0$, 7λ

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ Mass reconstruction from jet pairs

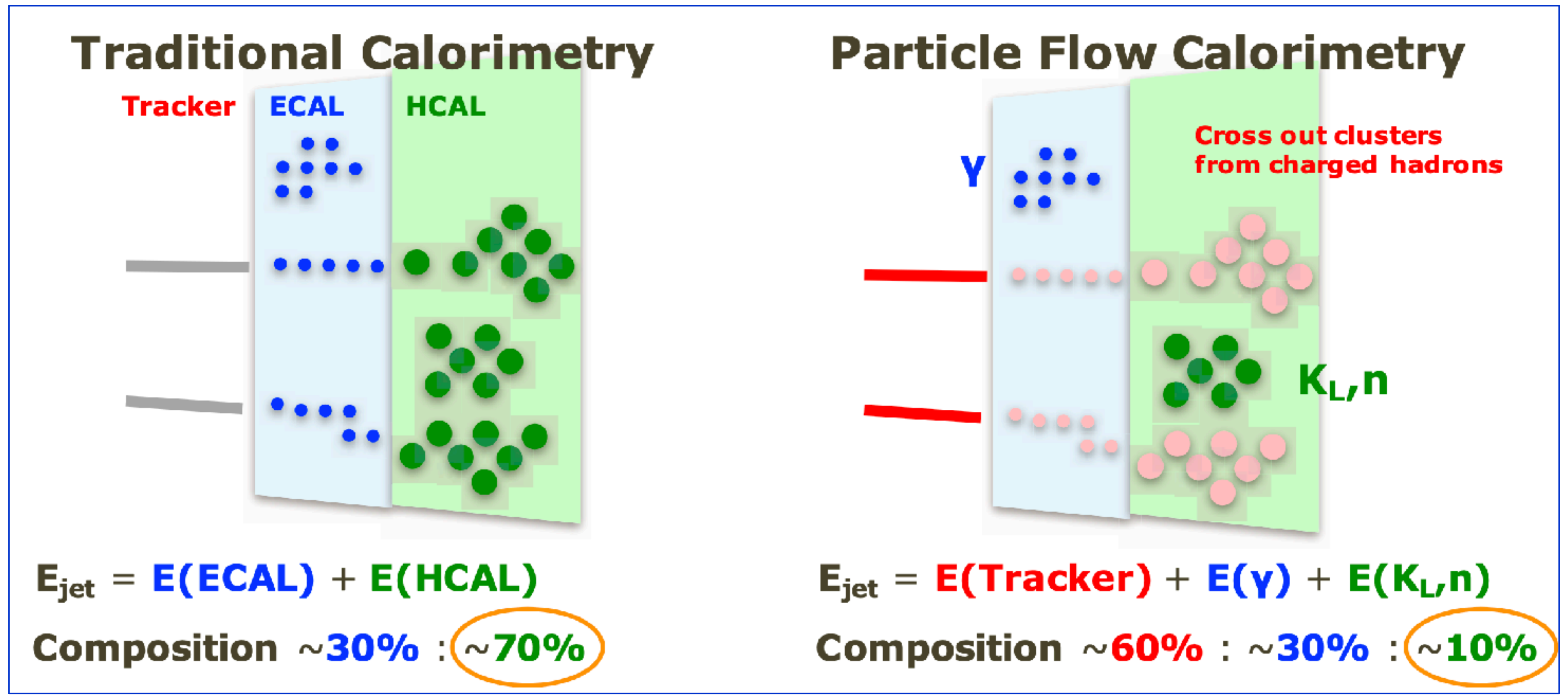
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, tt events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



To reach jet energy resolutions of ~3%, detectors employ

- **highly granular calorimeters**
- **Particle Flow Analysis techniques**



Technologies being pursued

a) **CALICE** like (ILC, CLIC, CLD)
  - ECAL: W/Si or W/scintillator+SiPM
  - HCAL: steel/scintillator+SiPM or steel/glass RPC

b) Parallel fiber **Dual Readout** calorimeter (IDEA)
  - Fine transverse, but no (weak) longitudinal segmentation

c) **Liquid Argon** ECAL + **Scintillating Tile** HCAL (ATLAS like)
  - Very fine segmentation, $\delta E_{EM}/E_{EM} \lesssim$ 8-9%

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Calorimetry - ECAL

ECAL energy resolution parametrised as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

with typically

technology	*a*	*b*	*c*
CALICE	15%	-	1%
Fiber DR	10%	-	1%
Lar	9%	-	-
Crystal	3-5%	-	0.5%

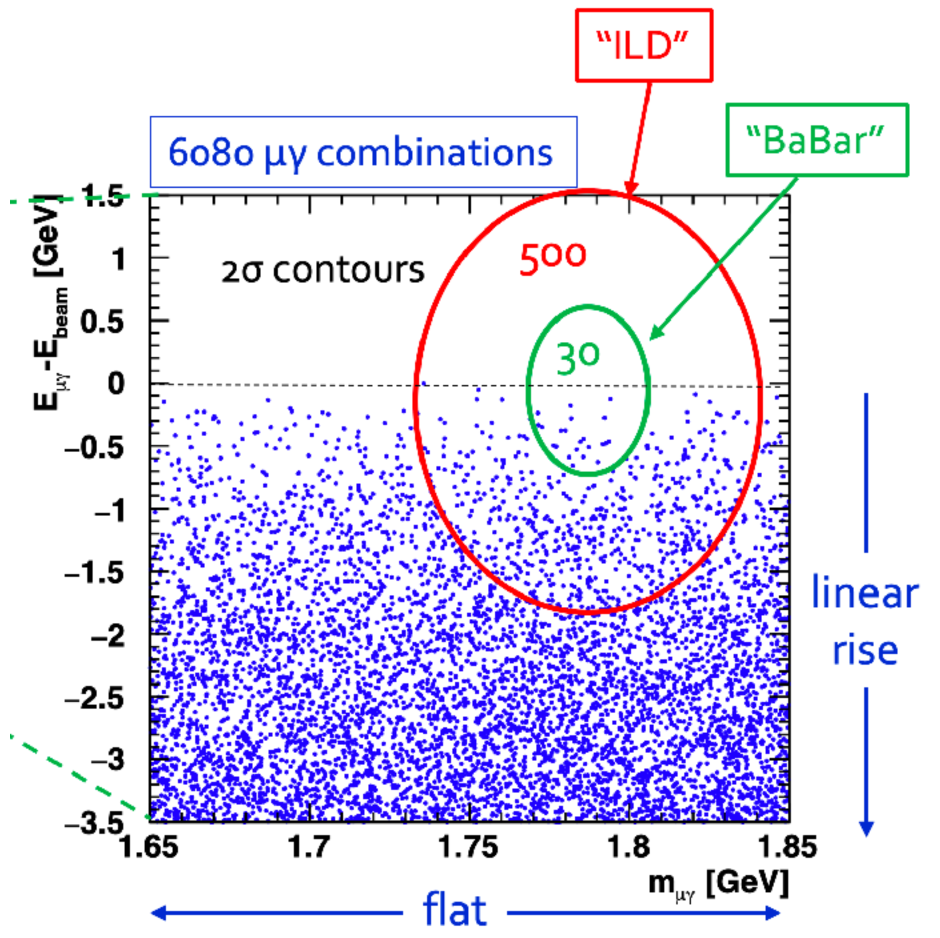
- CALICE-like resolution regarded sufficient at linear colliders with main emphasis on physics at 250-500 GeV
- An improved resolution may be advantageous for the 90-160 GeV FCC-ee programme

Finely segmented ECAL (transverse and longitudinal) is important for the precise identification of γ's and π^0's in dense topologies, e.g. τ and other heavy flavour physics

Examples:

a) Much improved search limits for rare decays involving γ's

- Here LFV decay τ → μγ



MD, 1st FCC WS, Jan. 2017

e/γ:
resolution : ~3%√E and granularity (transverse and longitudinal)
Low X0 detector before the ECAL

b) Much improved b-physics reach by making accessible exclusive channels with π^0's

c) More precise jet definition in multijet events

2008.00338

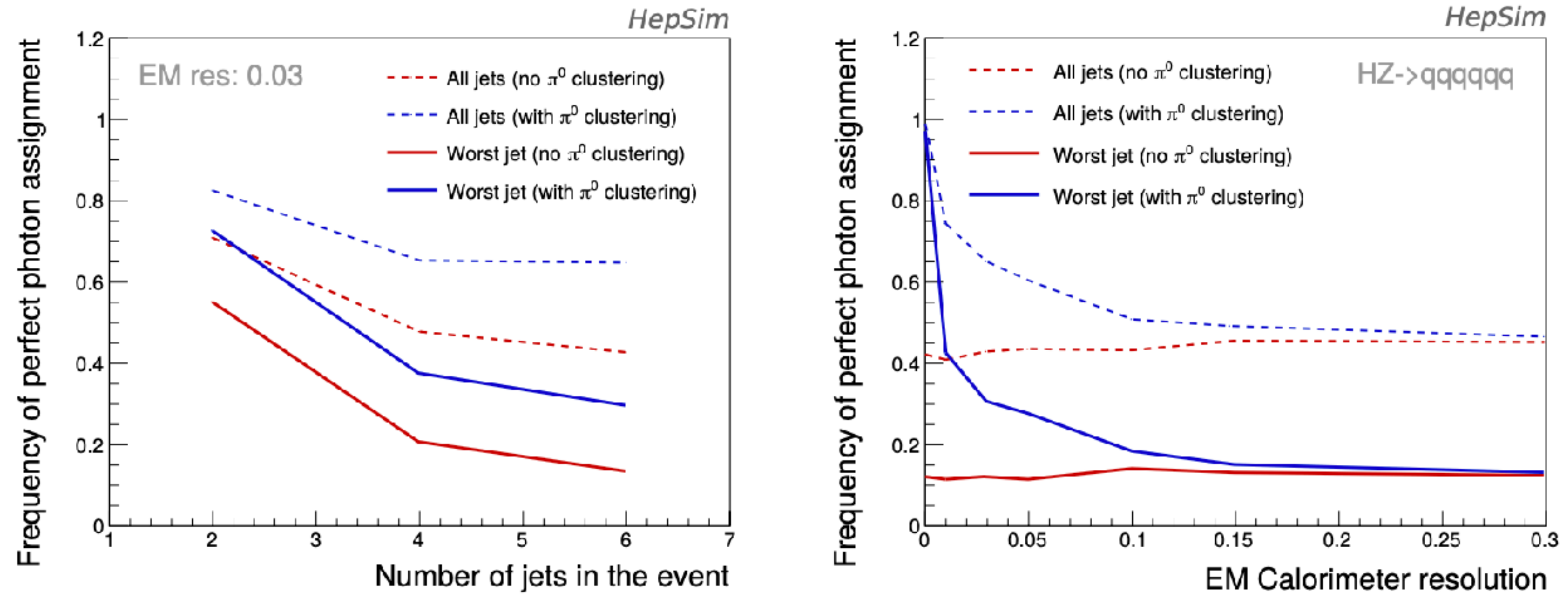


Figure 10. Frequency of events where photons are perfectly assigned to the corresponding jet as a function of the number of jets in the event, assuming a calorimeter resolution of $3\%/\sqrt{E}$ (left), and as a function of calorimeter EM resolution in the case of the $HZ \to q\bar{q}q\bar{q}q\bar{q}$ sample (right).

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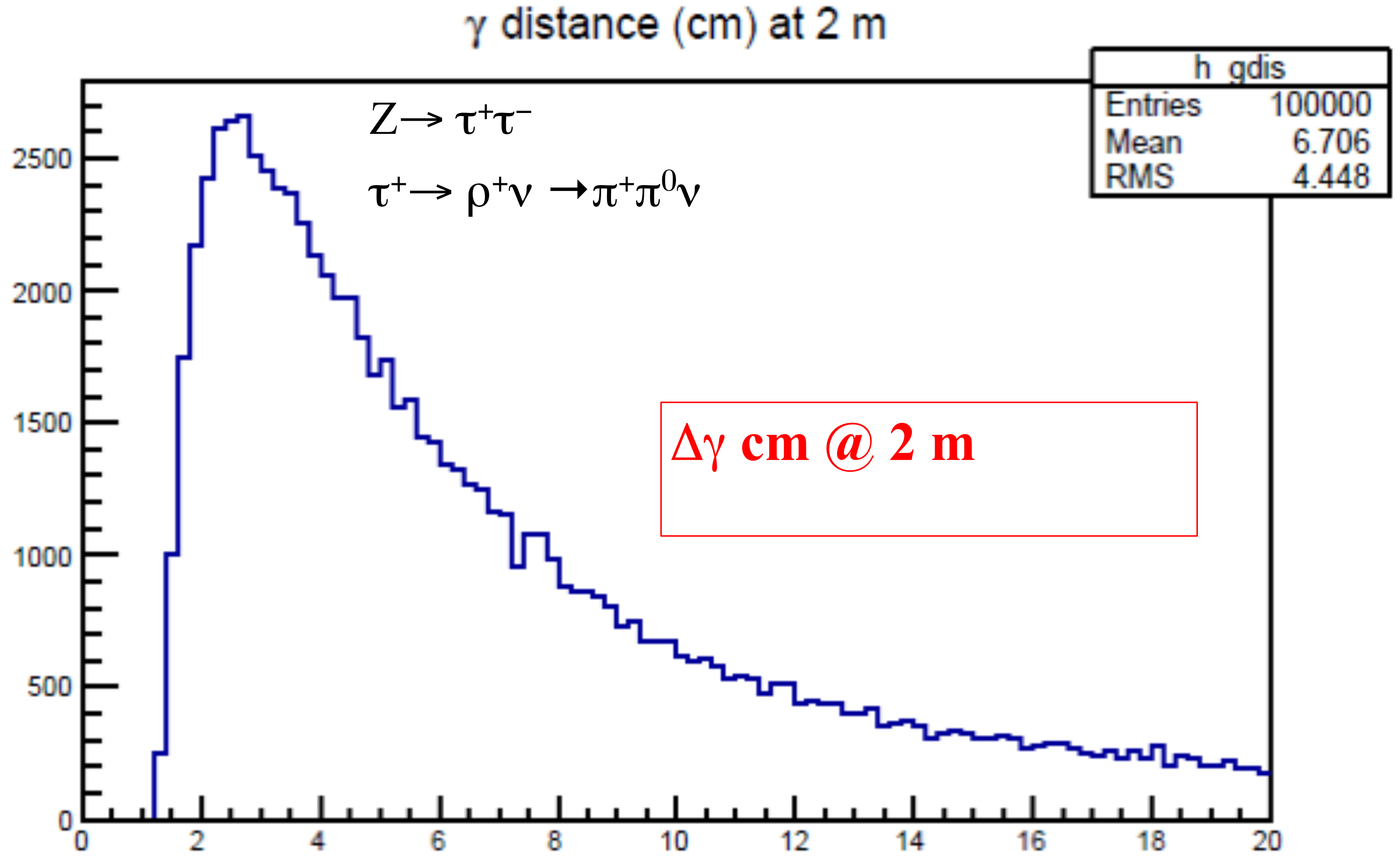
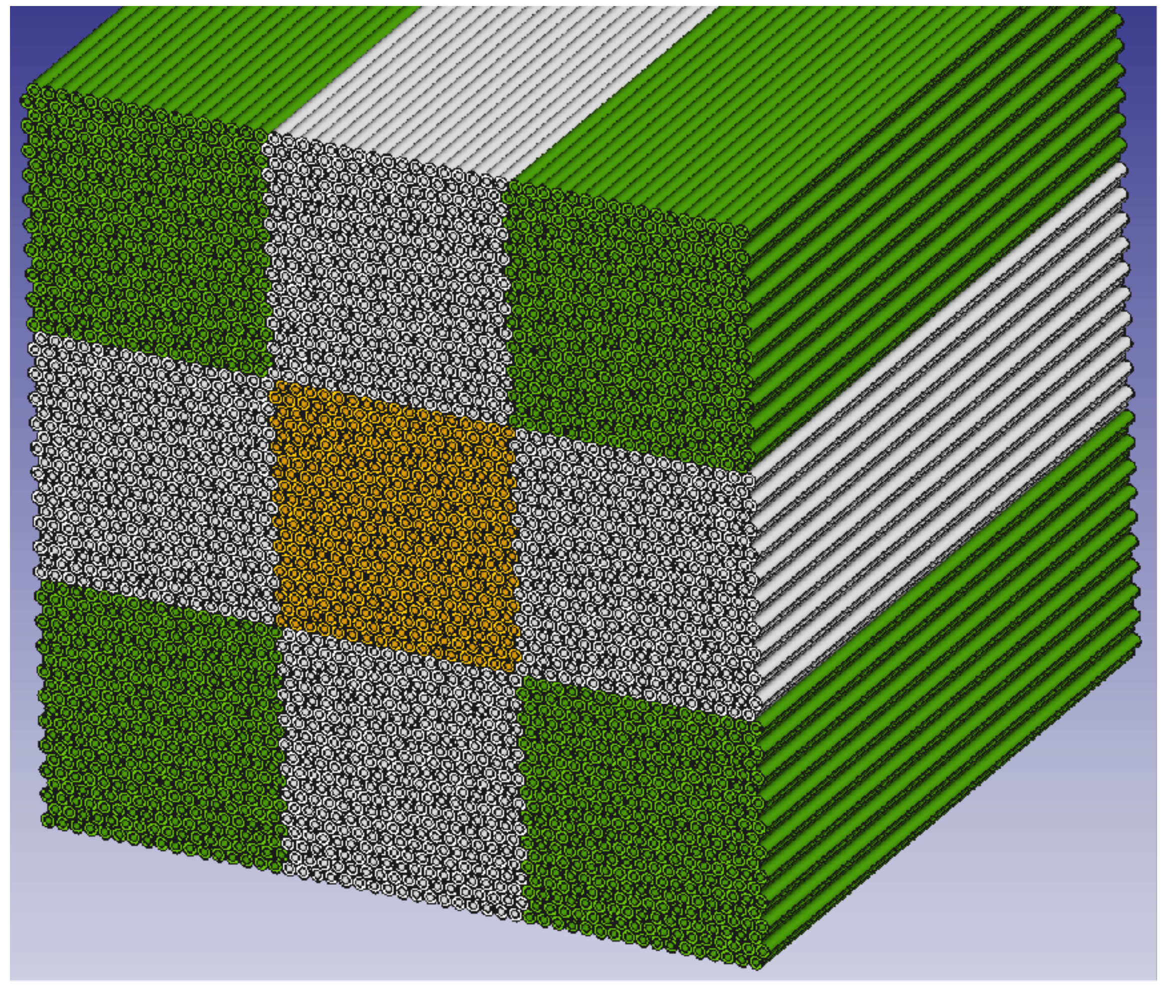
Calorimeter separation

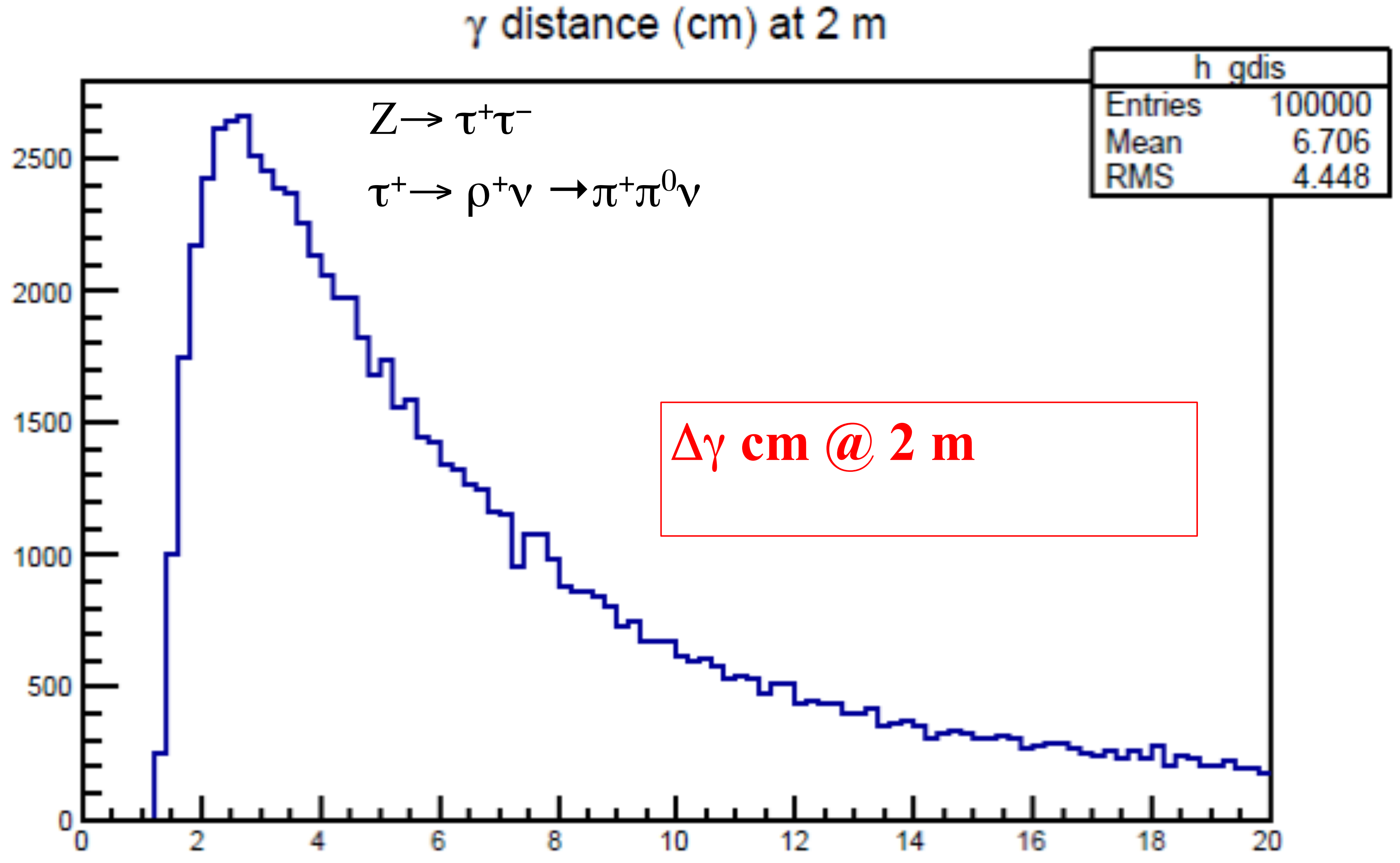


- Transcribe granularity below 1 cm seems adequate
- Extreme granularity achievable with the DR
  - At a cost...

IDEA DR calorimeter



Calorimeter separation



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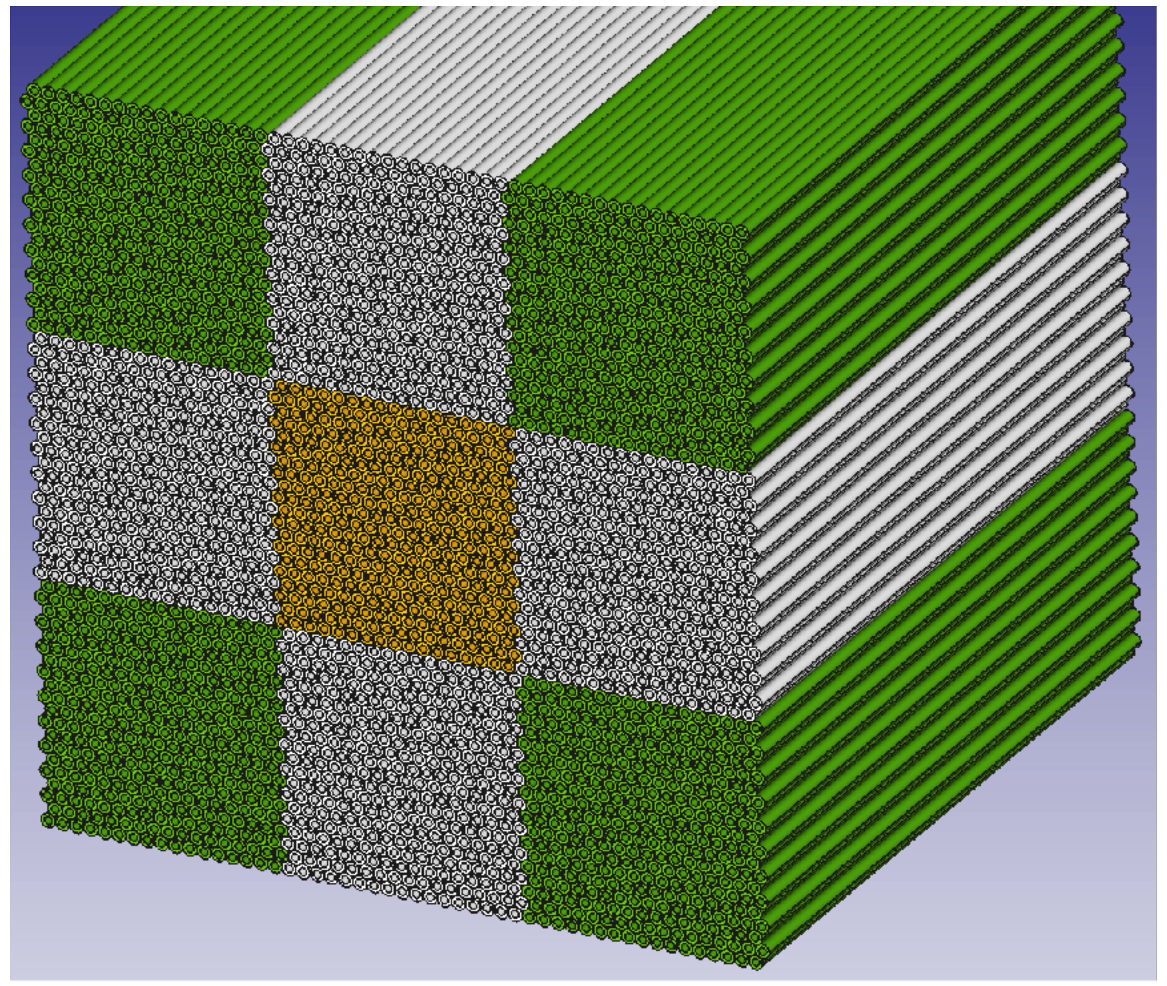
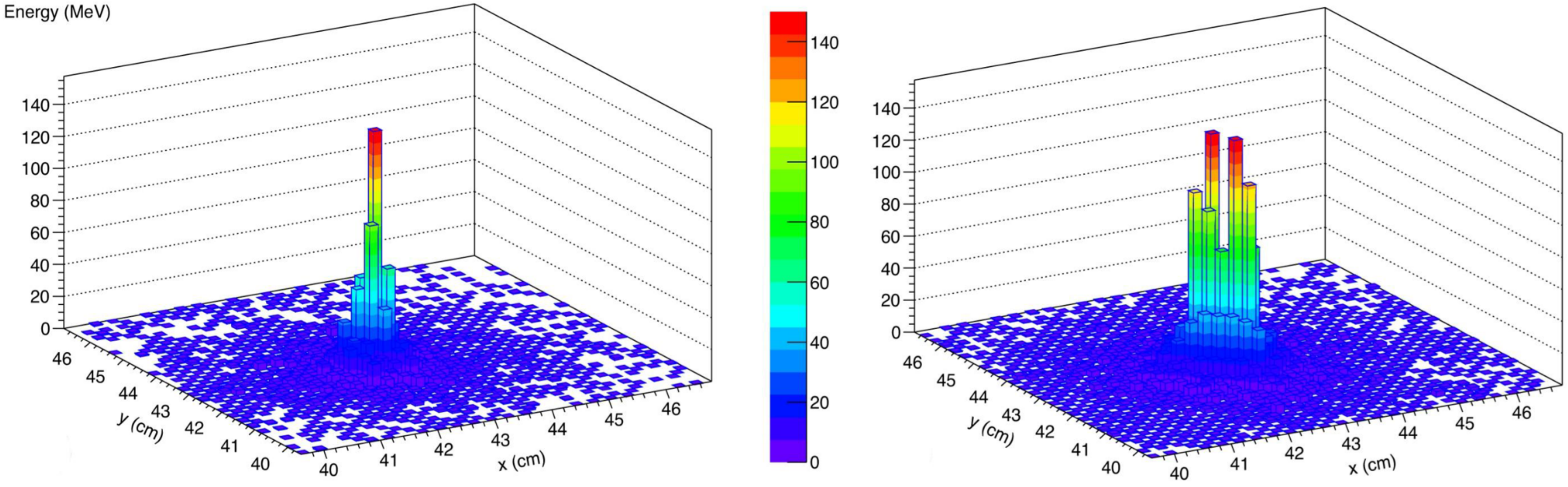
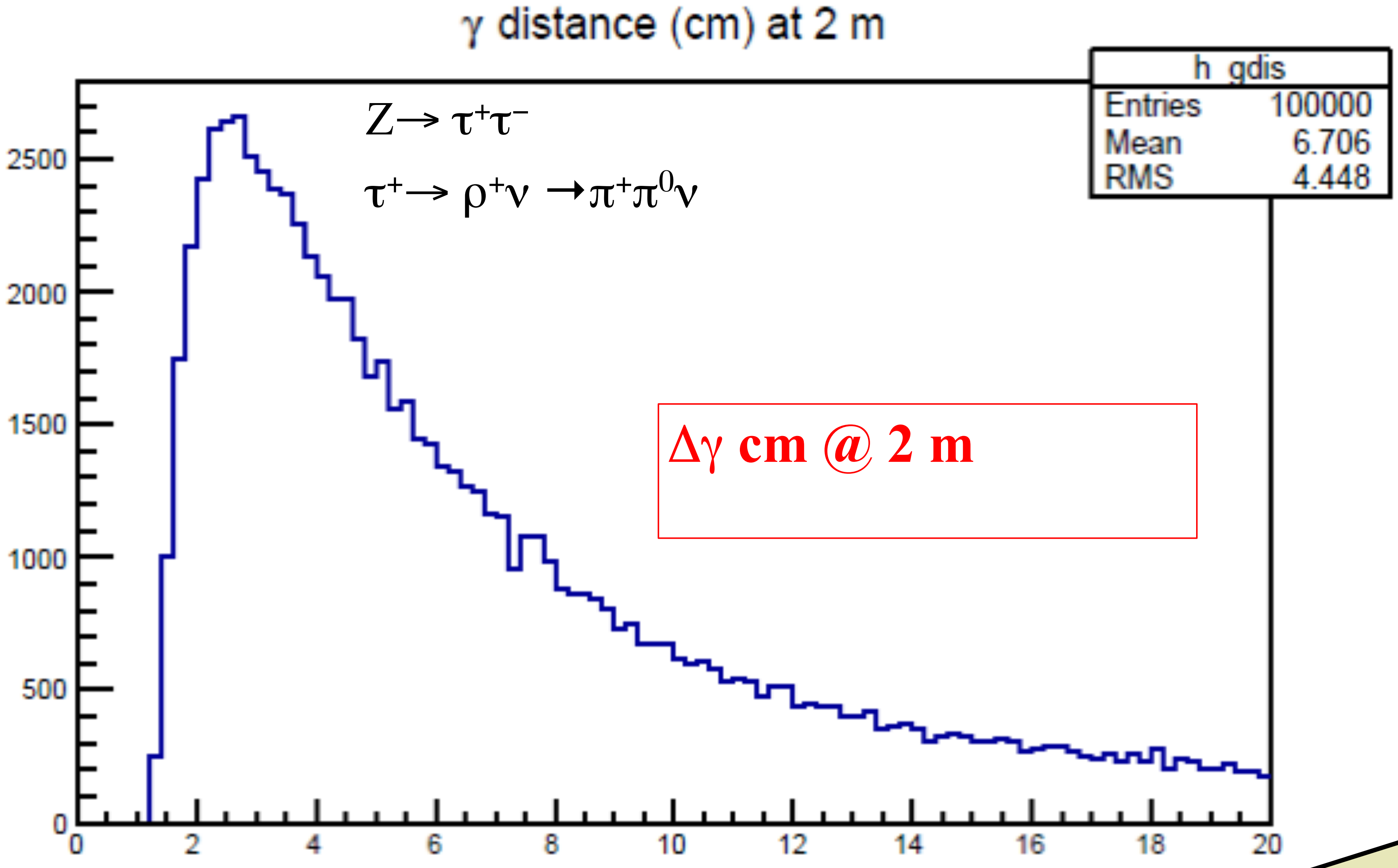


50 GeV electrons

100 GeV π^0



Calorimeter separation



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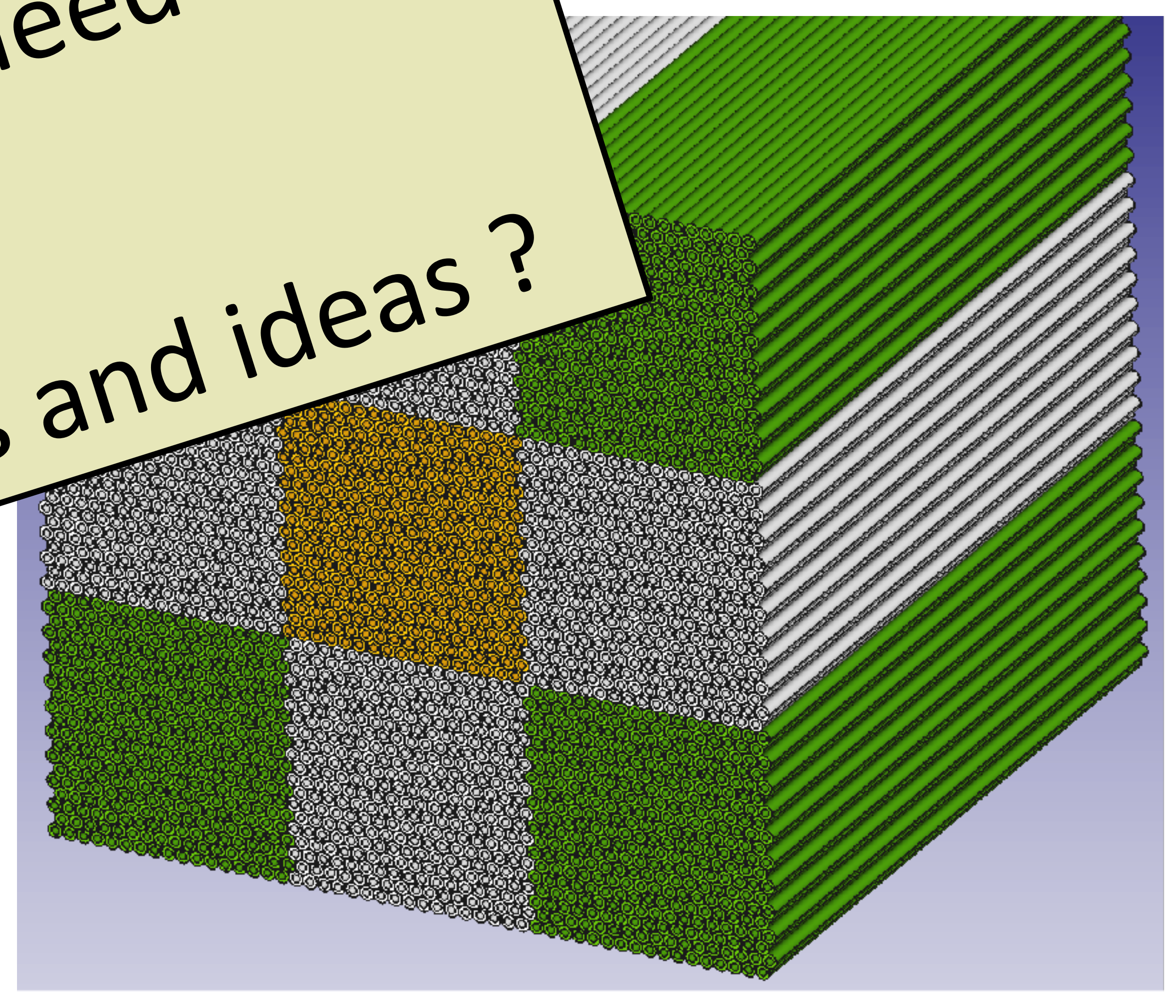
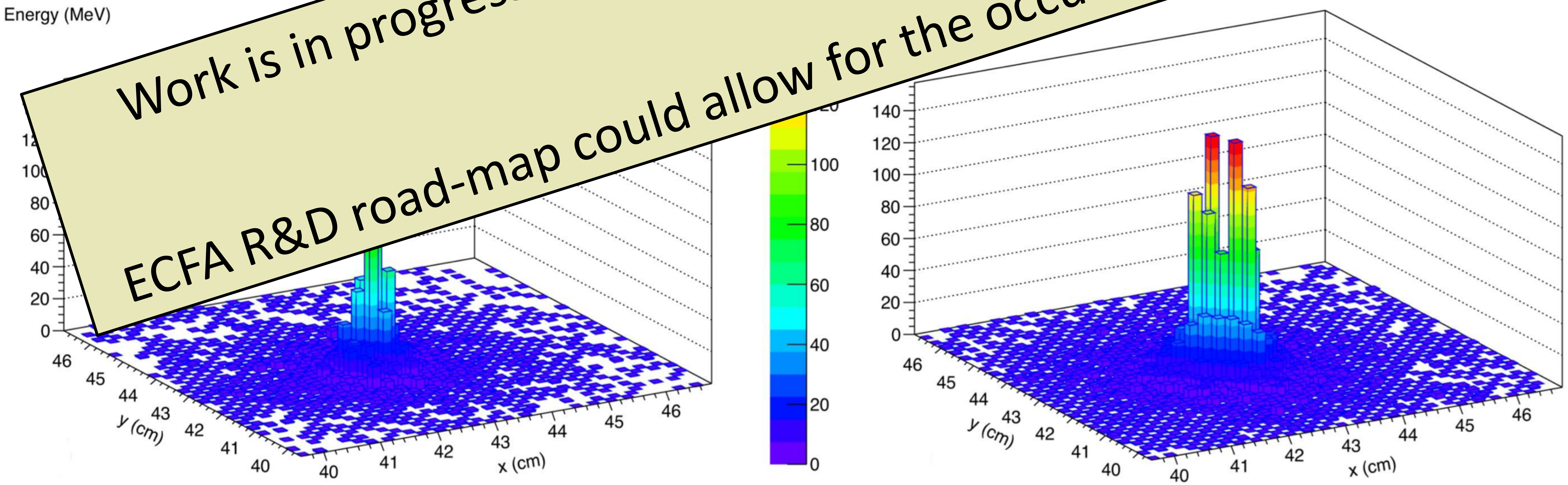
calorimeter



50 GeV electron

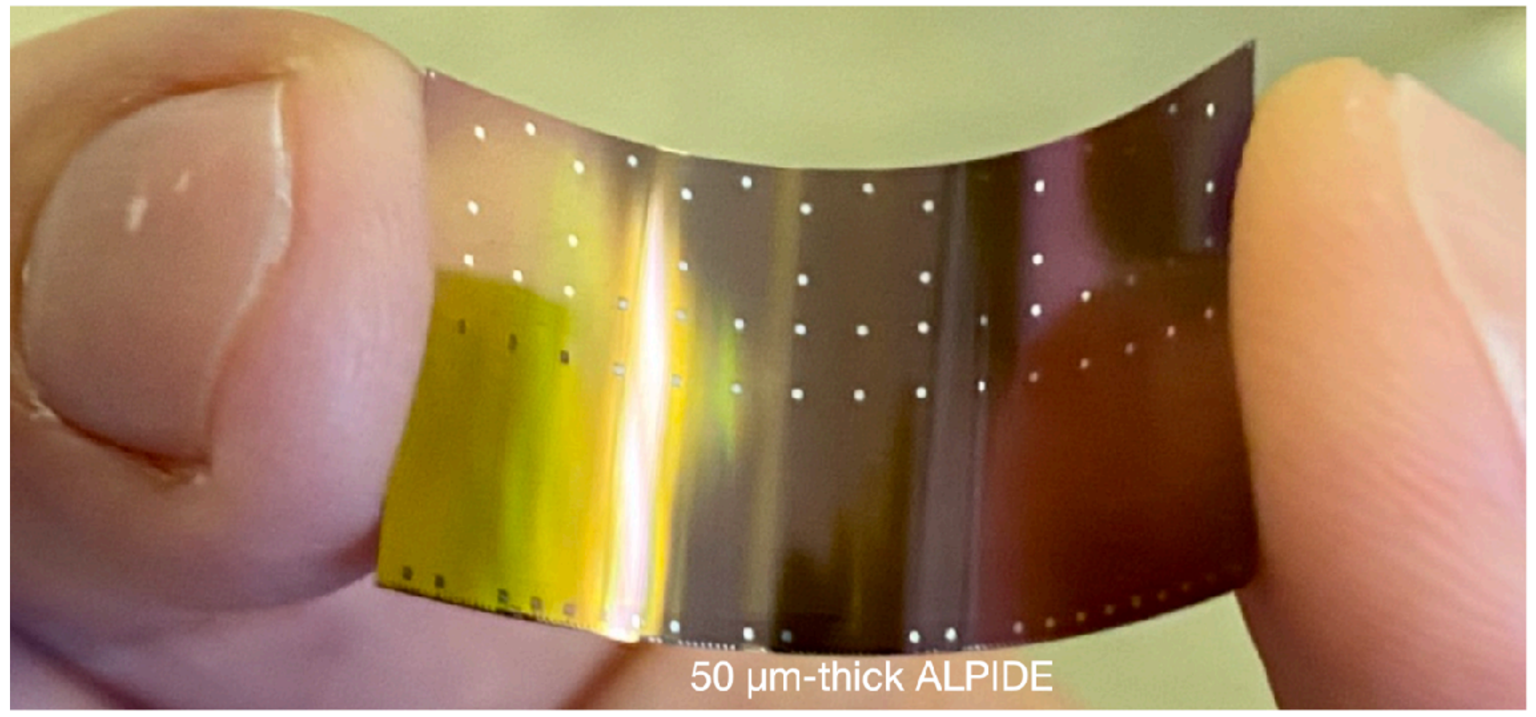


Work is in progress to refine the current requirements and study the need for additional ones.

ECFA R&D road-map could allow for the occurrence of new challenges and ideas ?

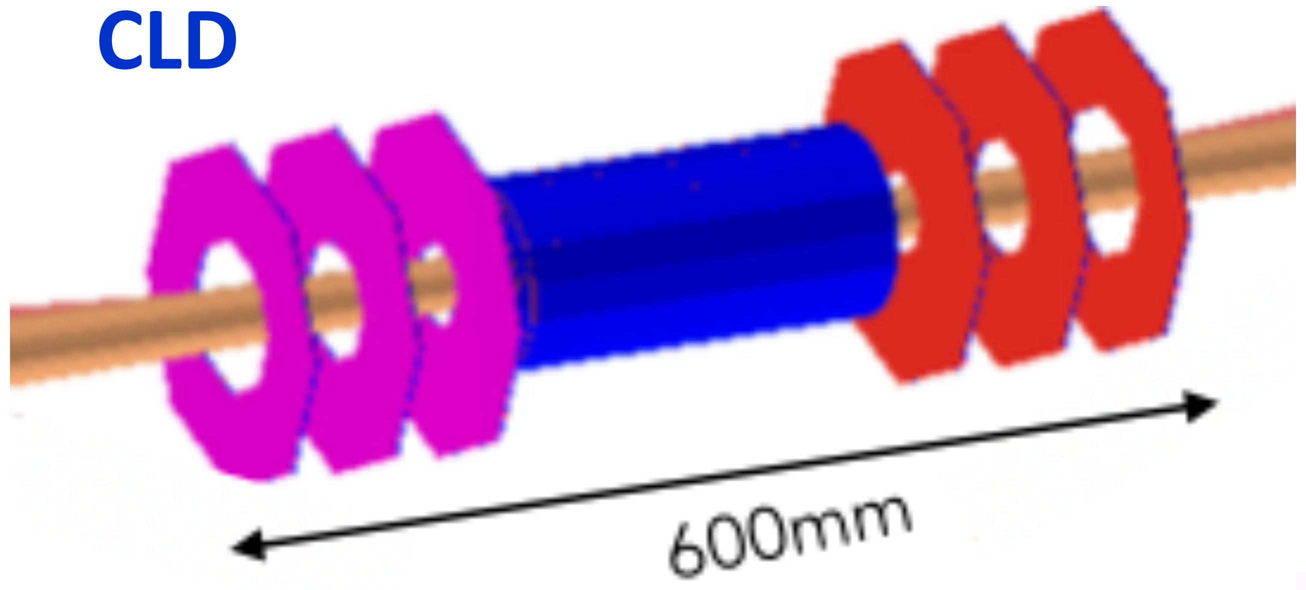
Vertex detector: CLD

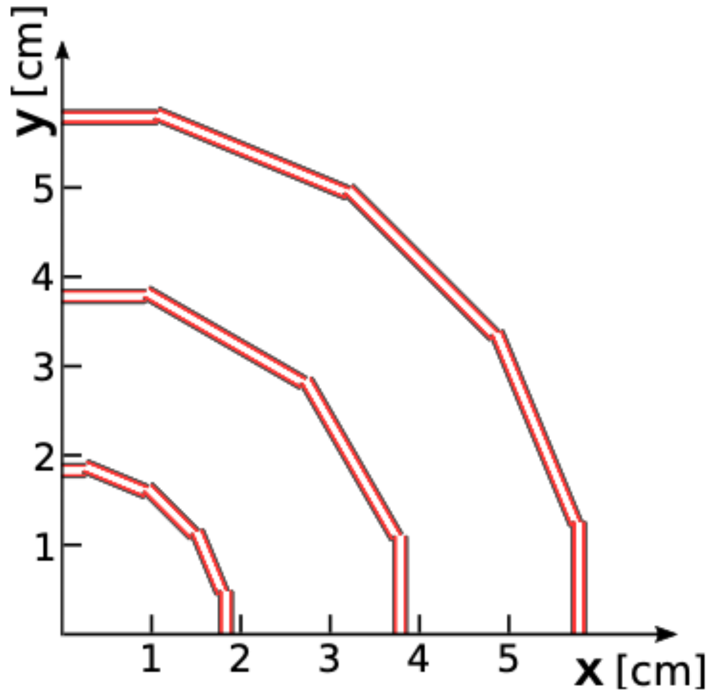
- Beam pipe radius:
  - 15 mm base line → 10 mm
- Thanks to collimators and effective beam-pipe shielding, beam backgrounds are in general negligible
  - Example: max rate of 10^{-5} hits / mm^2 / BX @ $\sqrt{s}$ = 91.2 GeV
  - This and other simulation results from CLD full simulation
- Following ongoing rapid technological development
  - Lighter, more precise, closer, less power

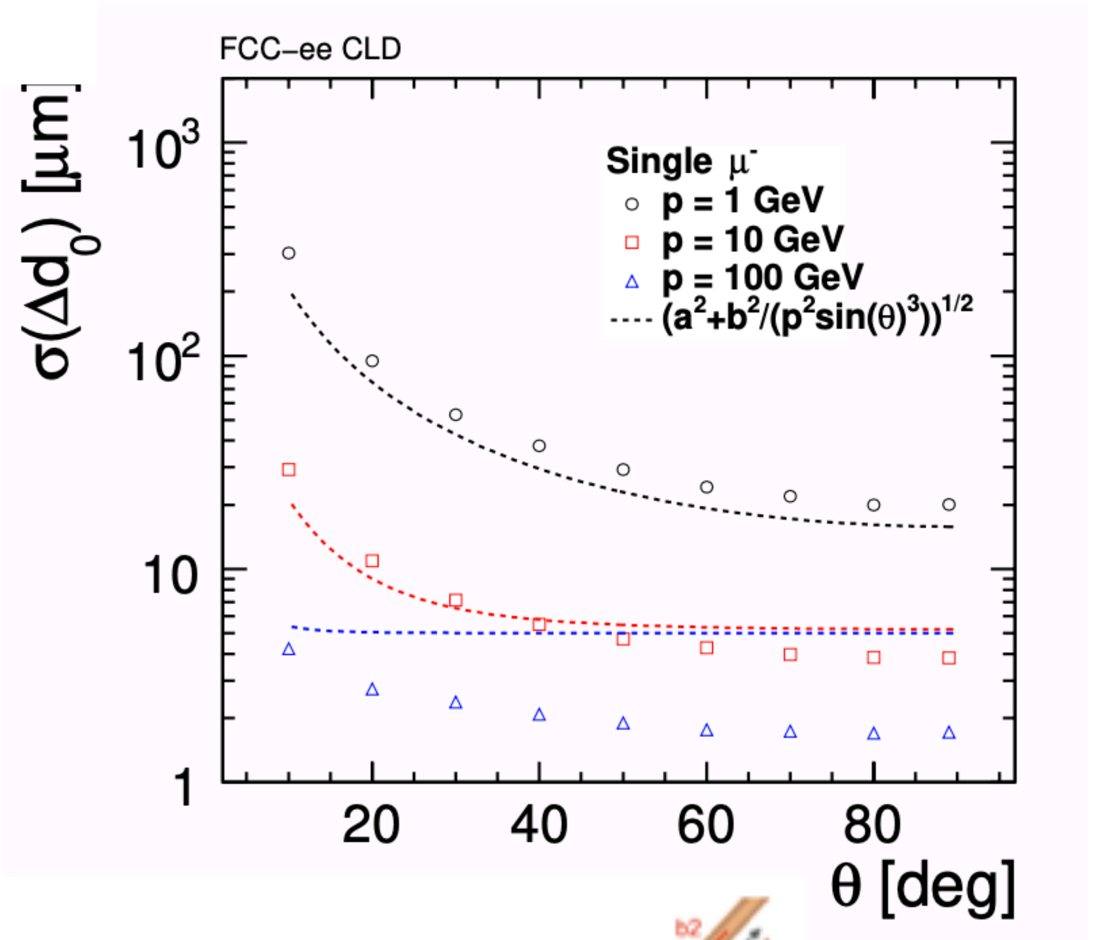


- Extreme alignment-precision needs for life-time measurements
  - Ex.: τ lifetime to ≲ 10^{-4} relative precision ⇒ ≲ 0.2 µm on flight distance

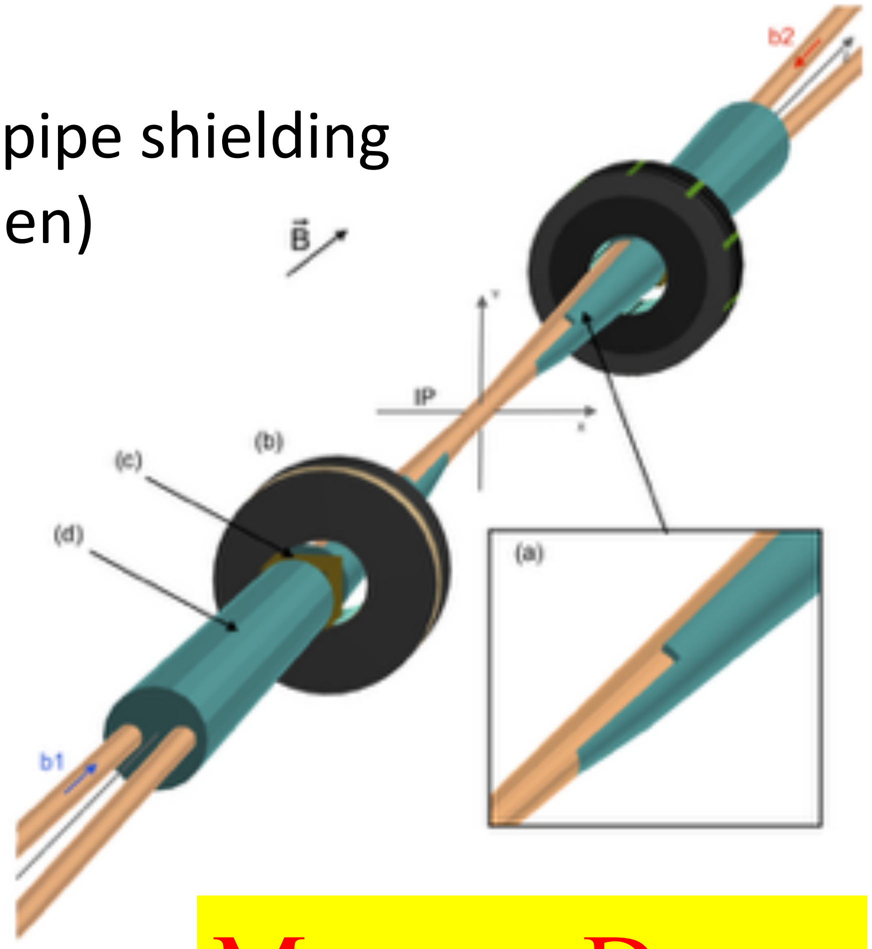
CLD







Beam pipe shielding (in green)



@91.2 GeV: max 10^{-5} hits / mm^2 / BX

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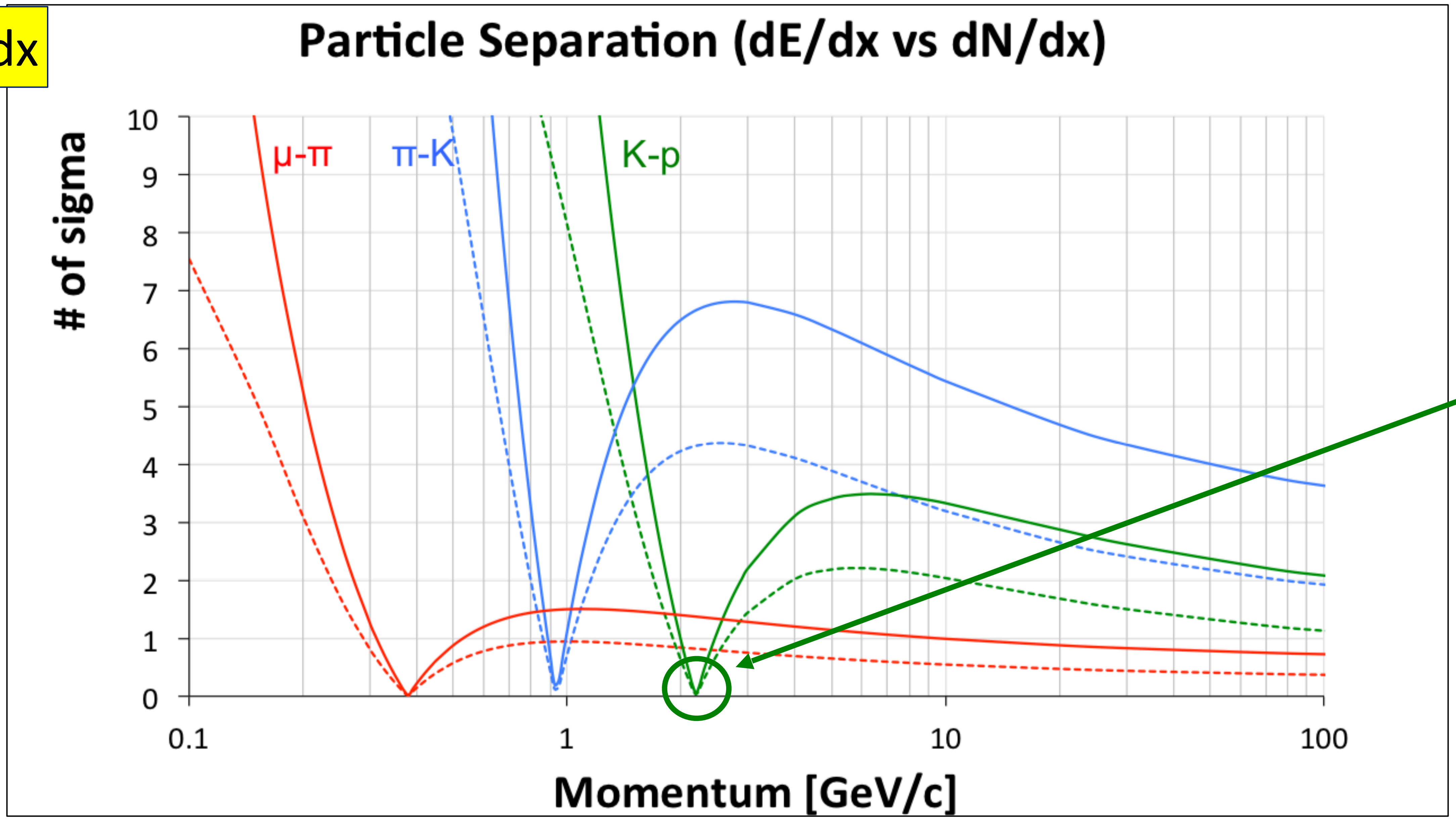
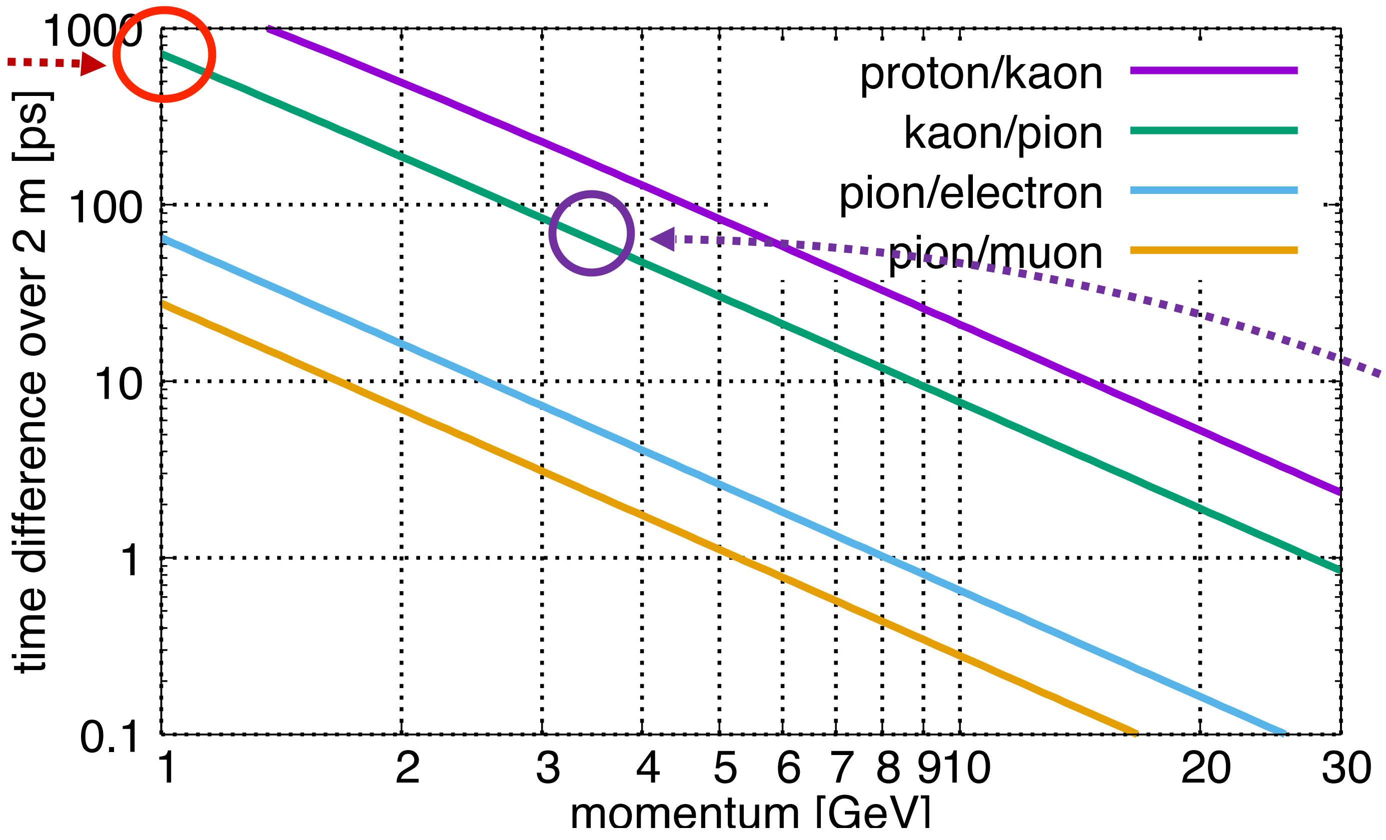
PID possibilities

- The IDEA Drift Chamber provides very powerful PID. Improved considerably by the use of *cluster counting*
  - ❑ Standard truncated mean dE/dx : σ ≃ **4.2%**
  - ❑ Cluster counting : σ ≃ **2.5%**

dE/dx



- ❑ >3σ π/K separation all the way up to several tens of GeV
  - ❖ Except for cross-over window at ~1 GeV.



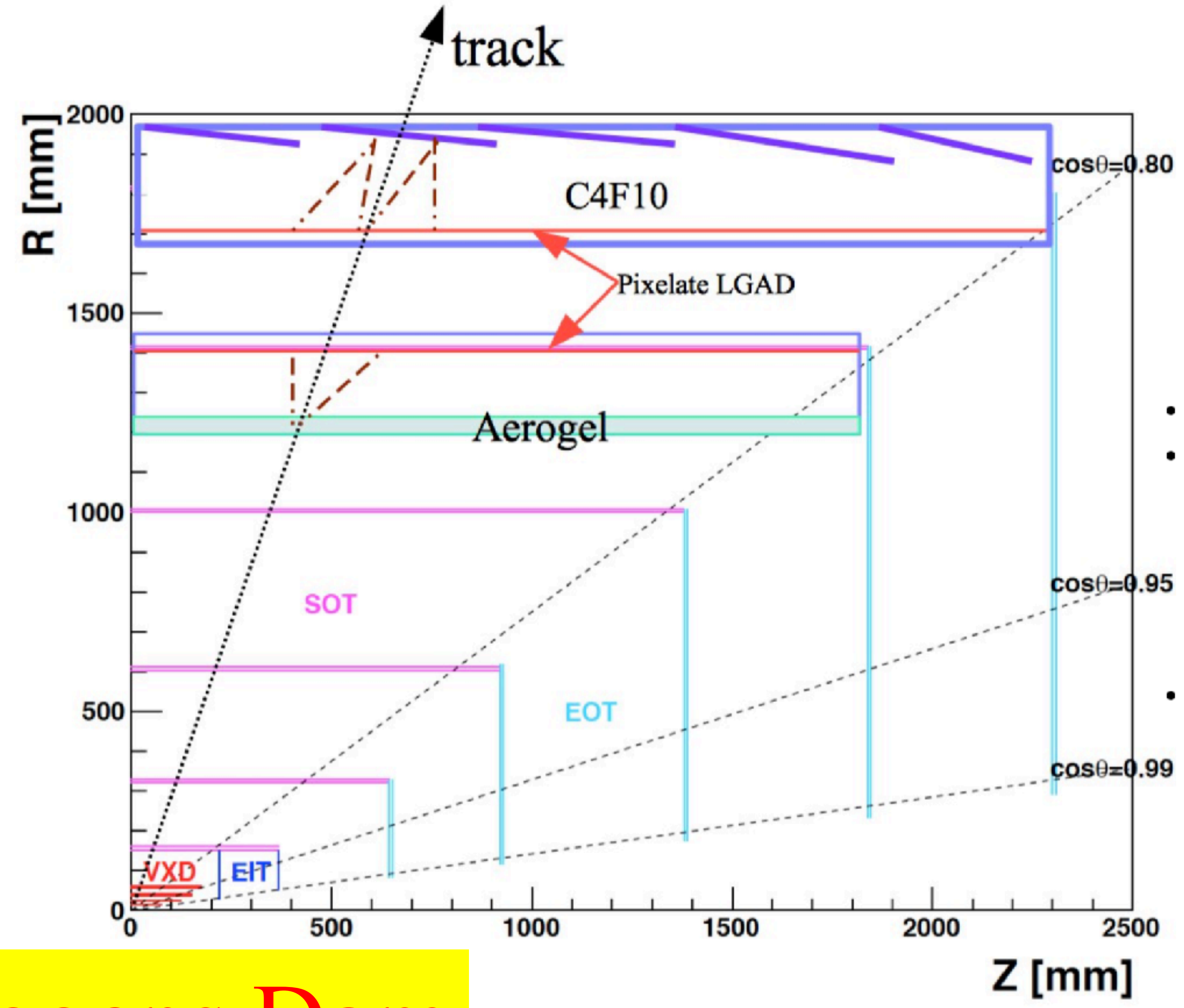
TOF

- ❑ Narrow dE/dx cross-over window at ~1 GeV, can be alleviated by unchallenging TOF measurement at r=2m of δT ≲ 0.5 ns
- ❑ TOF *alone* could give 3σ π/K separation up to a 3.5 GeV if measurement precision would be δT ~ 20 ps (LGAD, TORCH)

Cherenkov

Study of RICH counter for CEPC Full Silicon Detector

Also TORCH (LHCb) and TOP (BelleII): Essentially precise TOF devices: ~20 ps.



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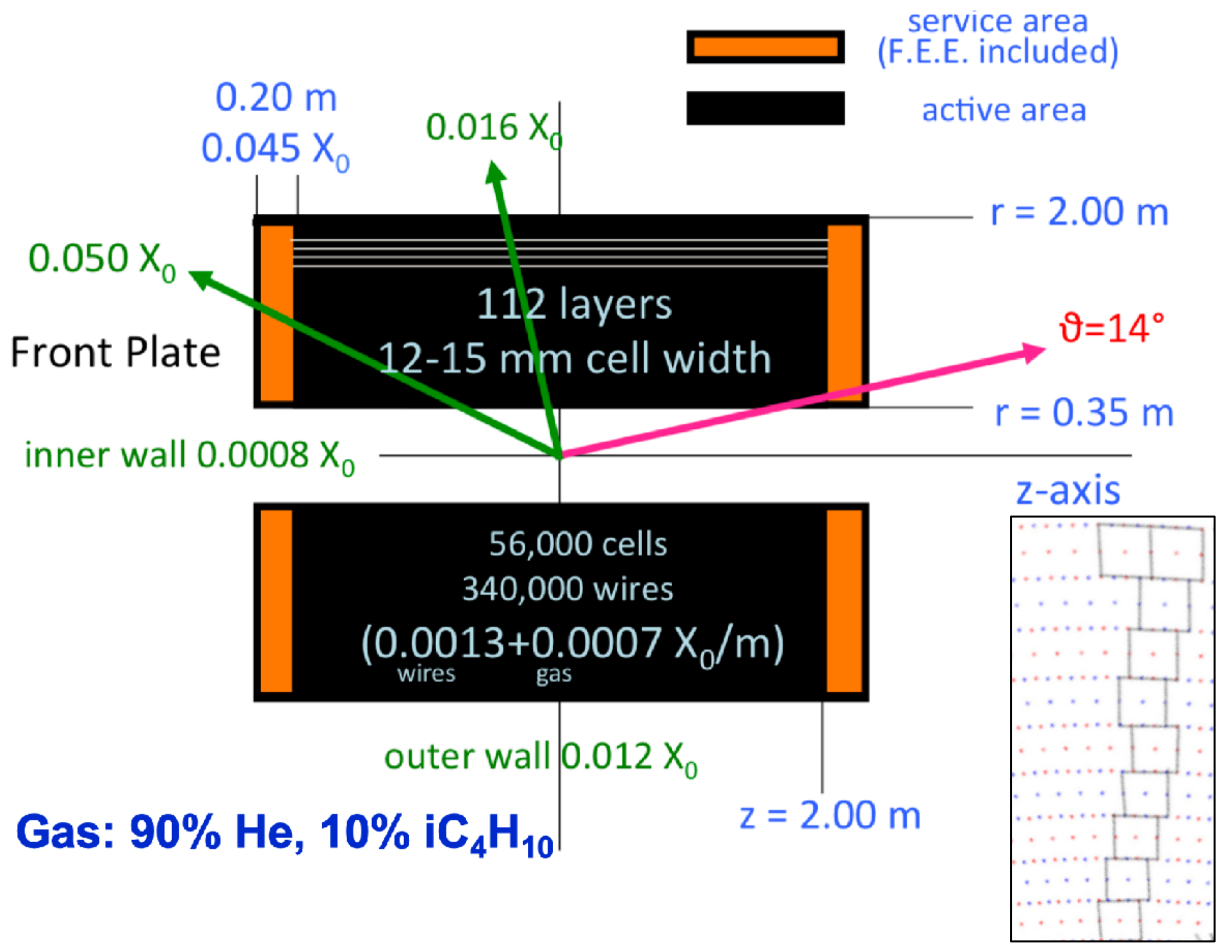
Momentum resolution

At FCC-ee, very few tracks with $p_T > 100$ GeV. Momentum measurements will be multiple scattering limited

- Possible to reduce multiple scattering contribution?

IDEA 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 to material
- Full tracker system includes Si VTX and Si “wrapper”



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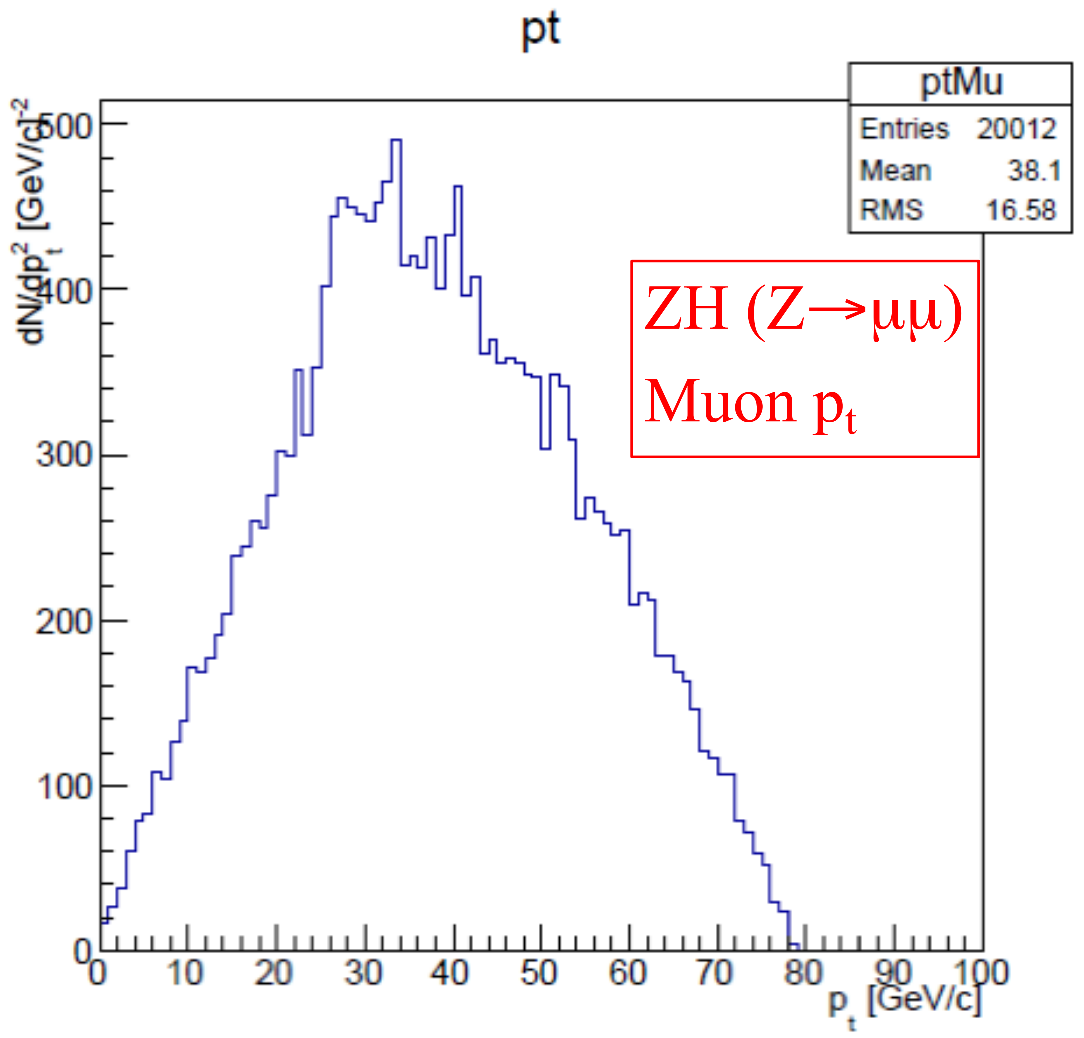

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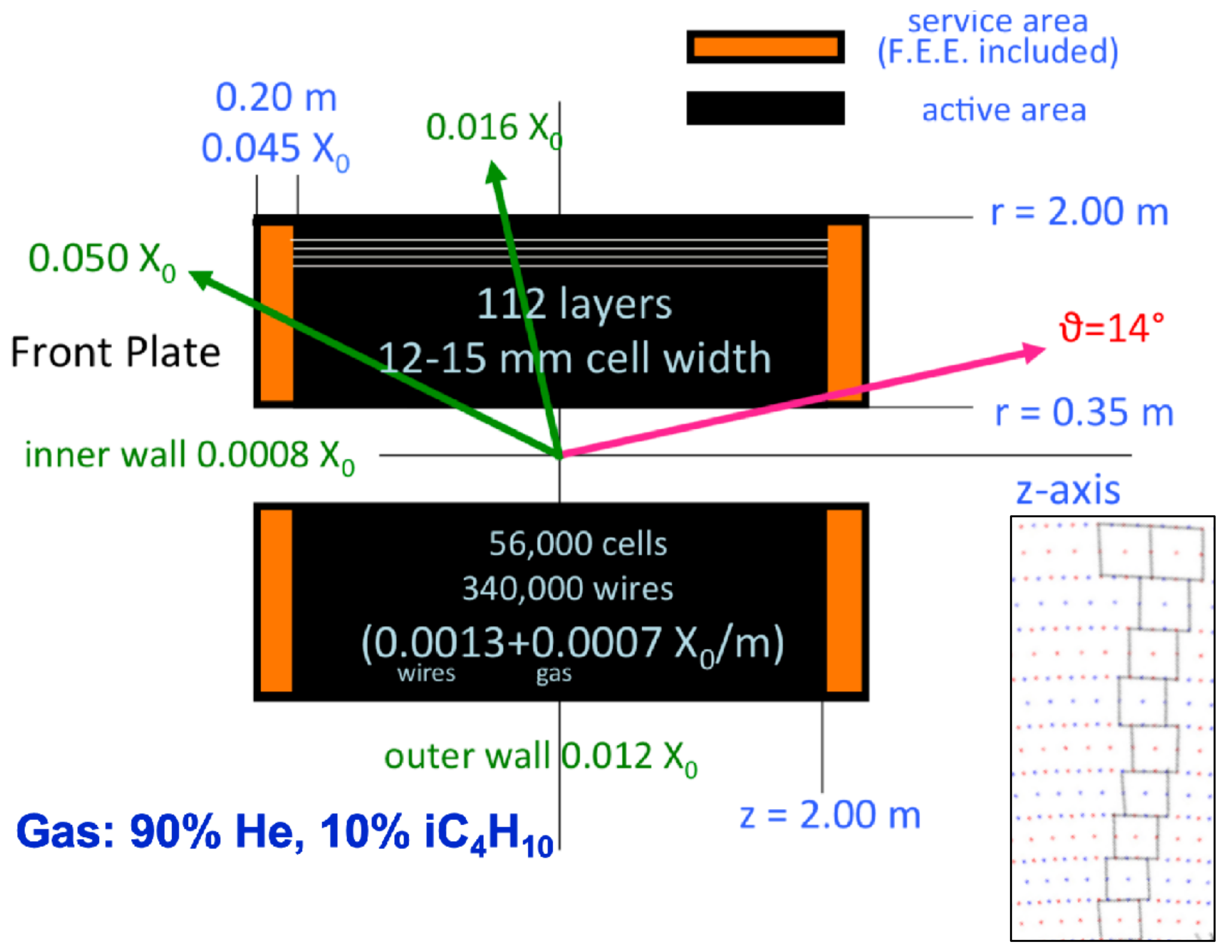

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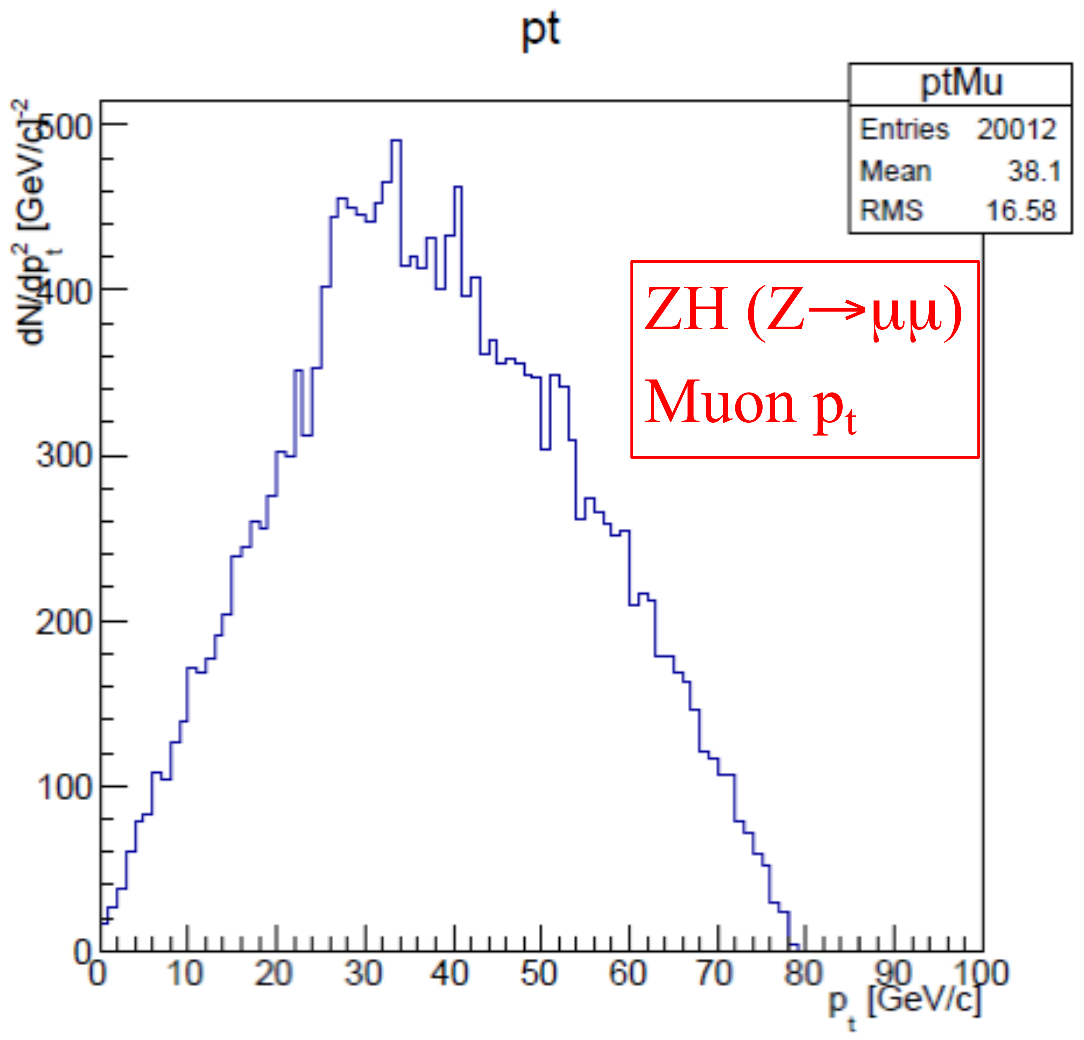

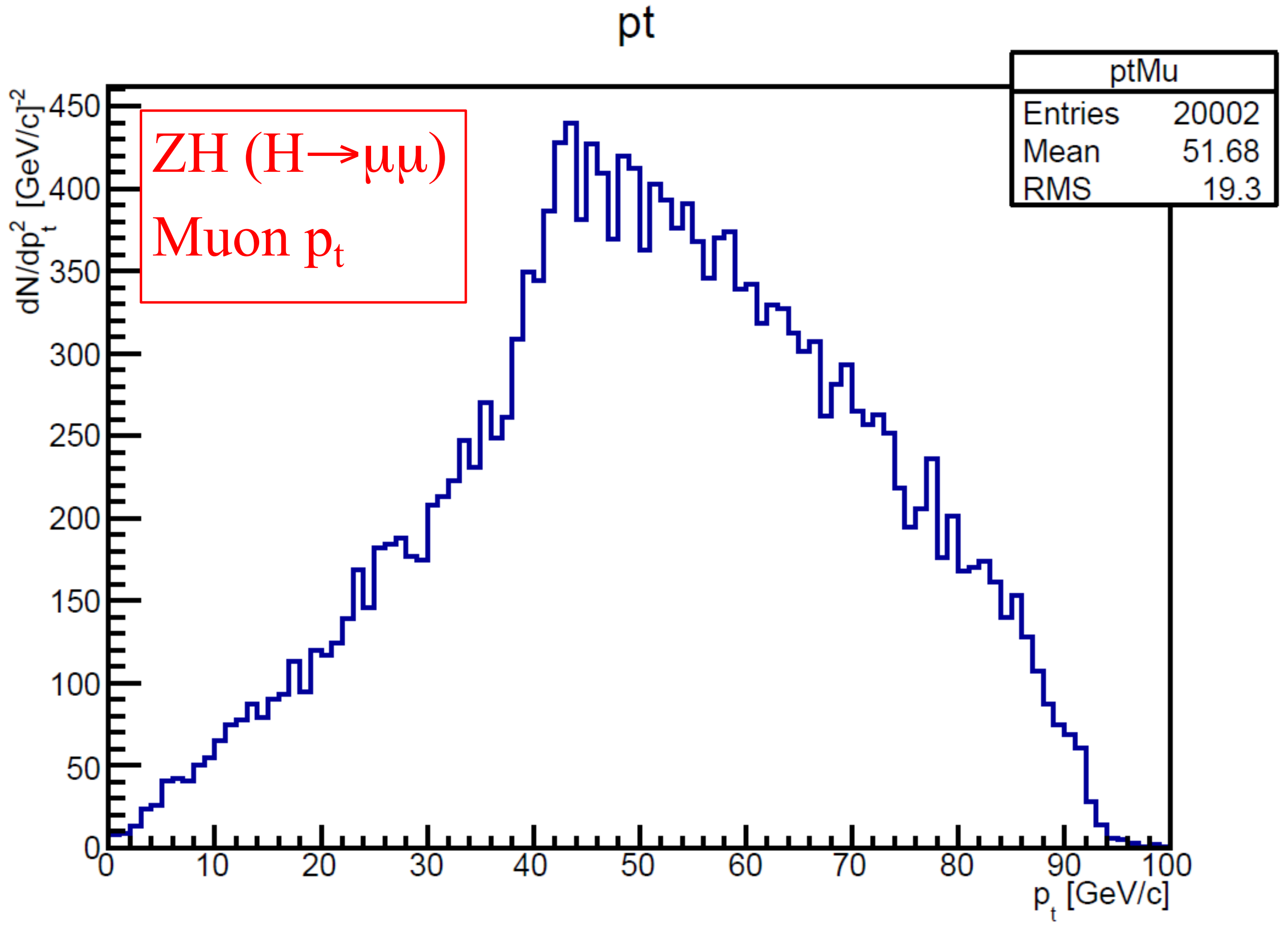

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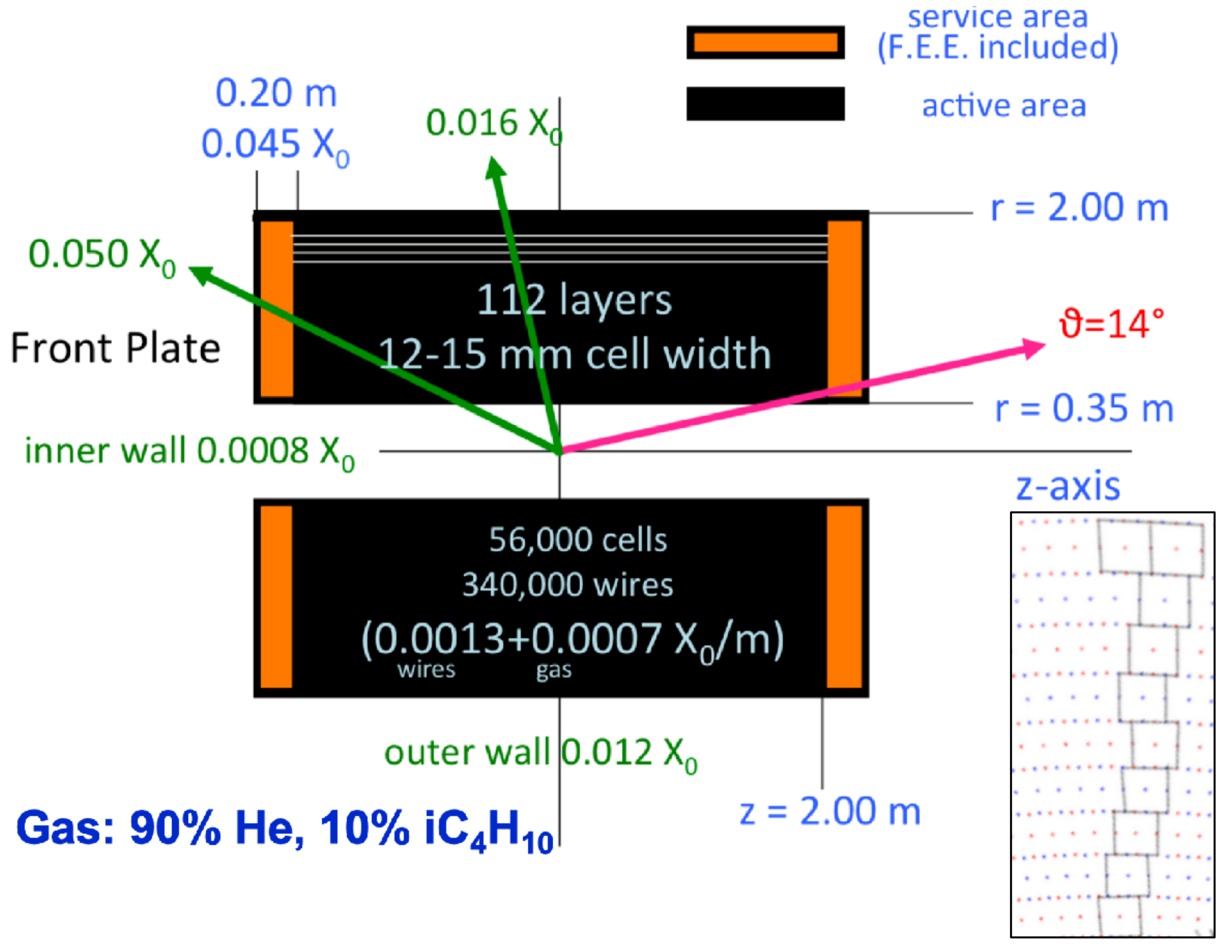

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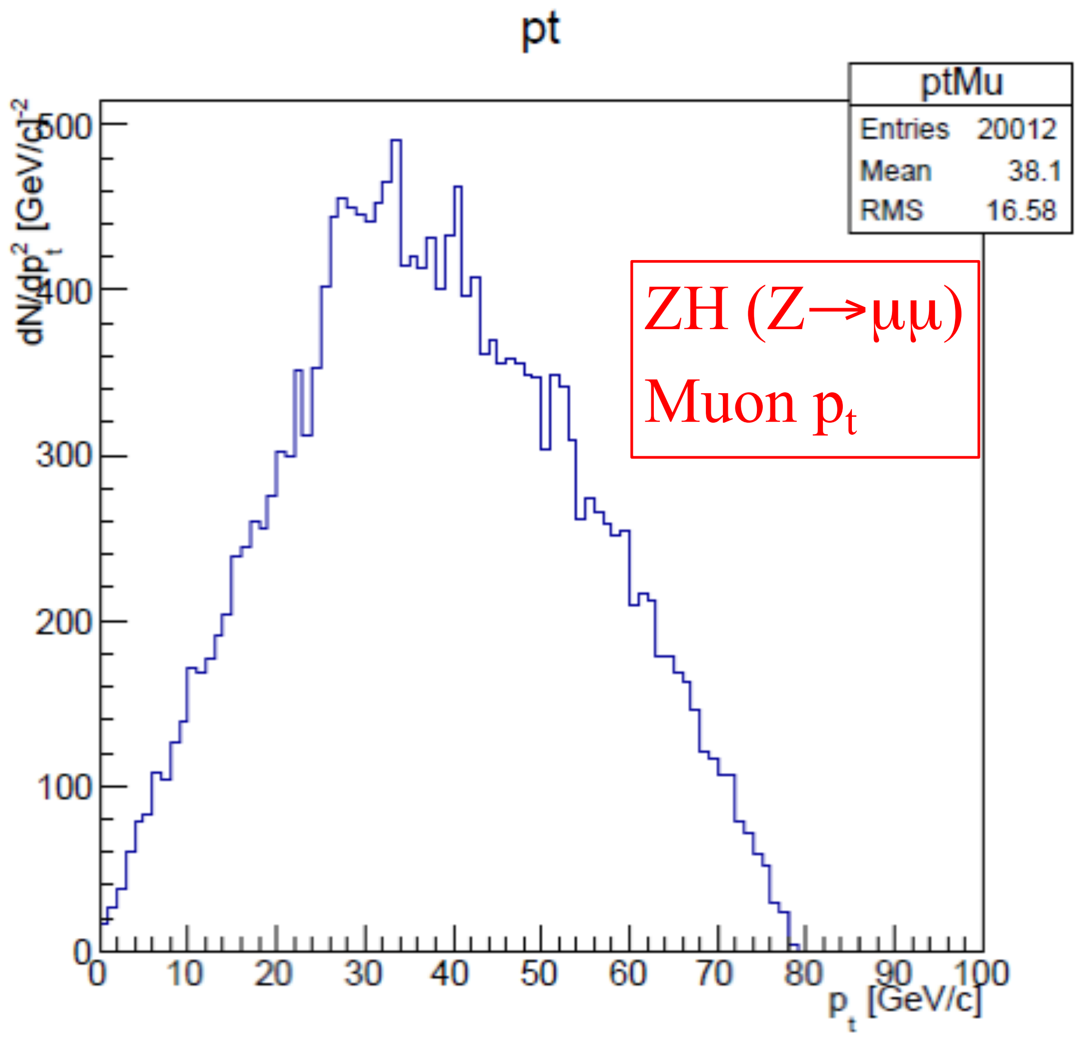

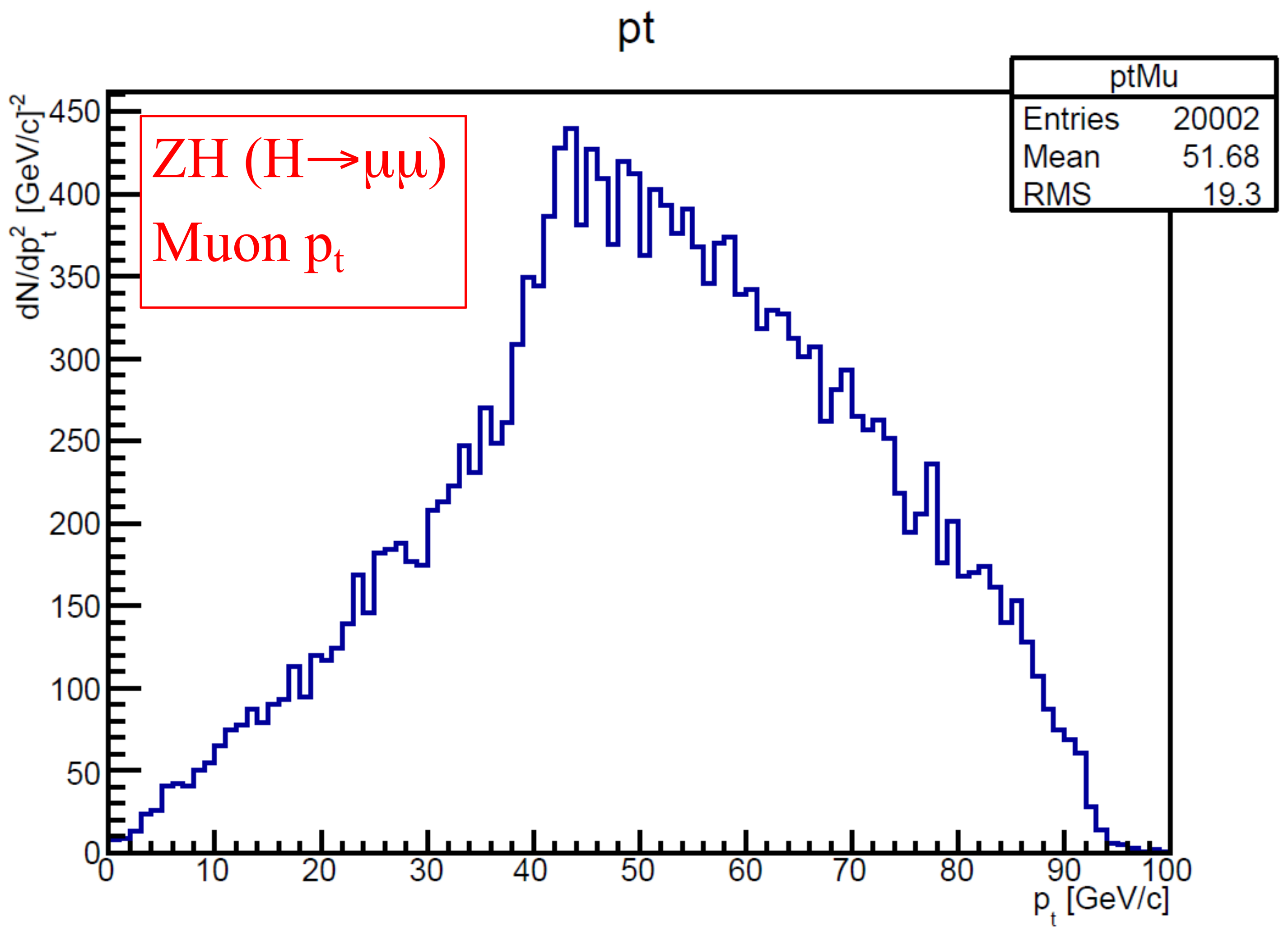

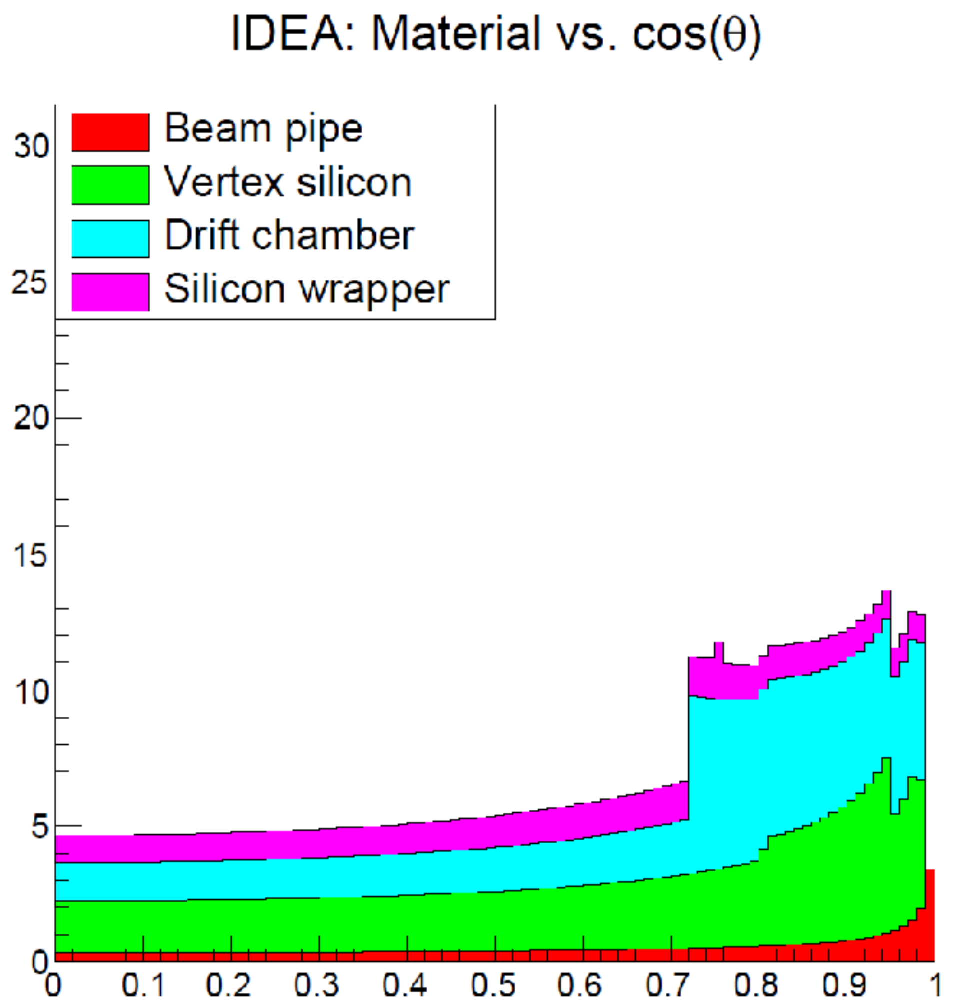

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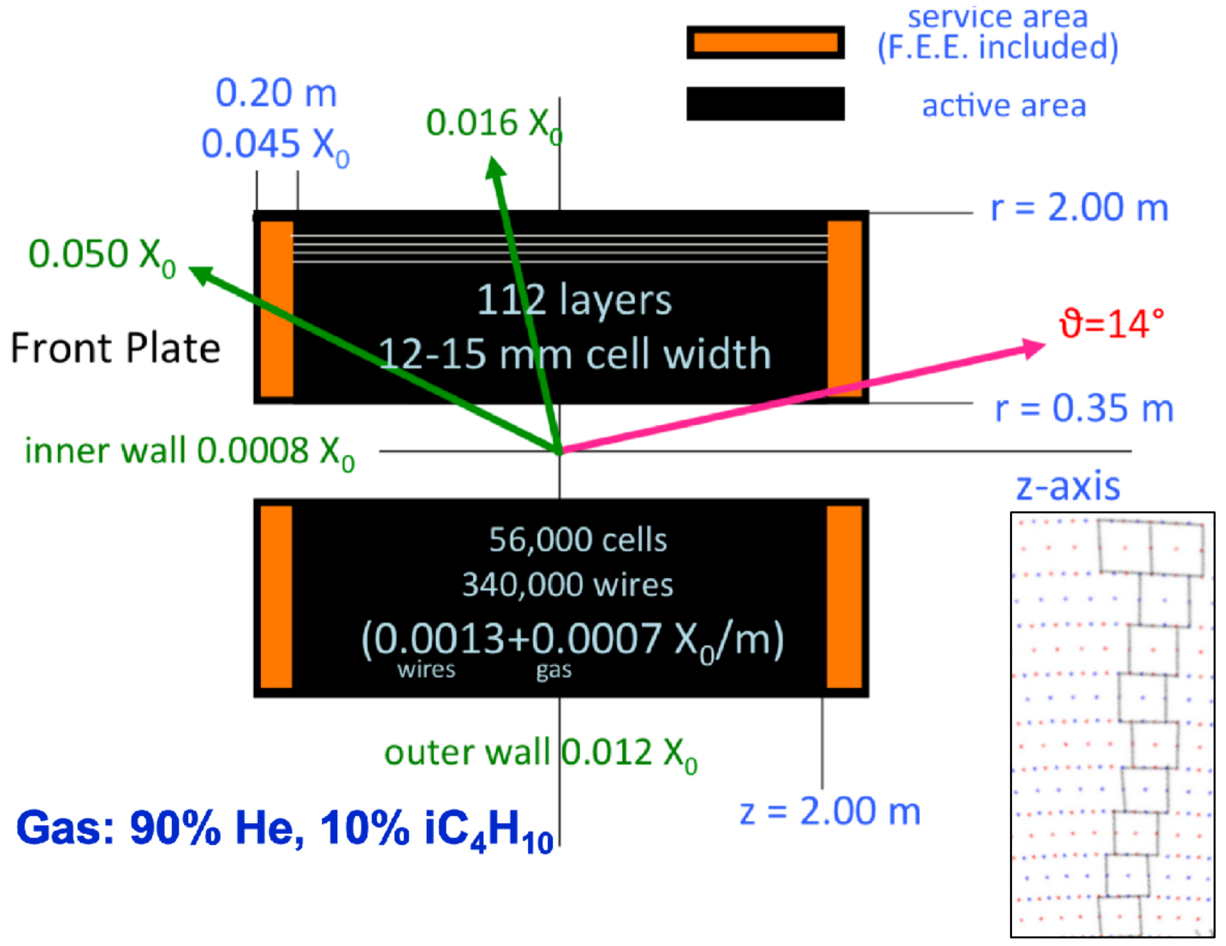

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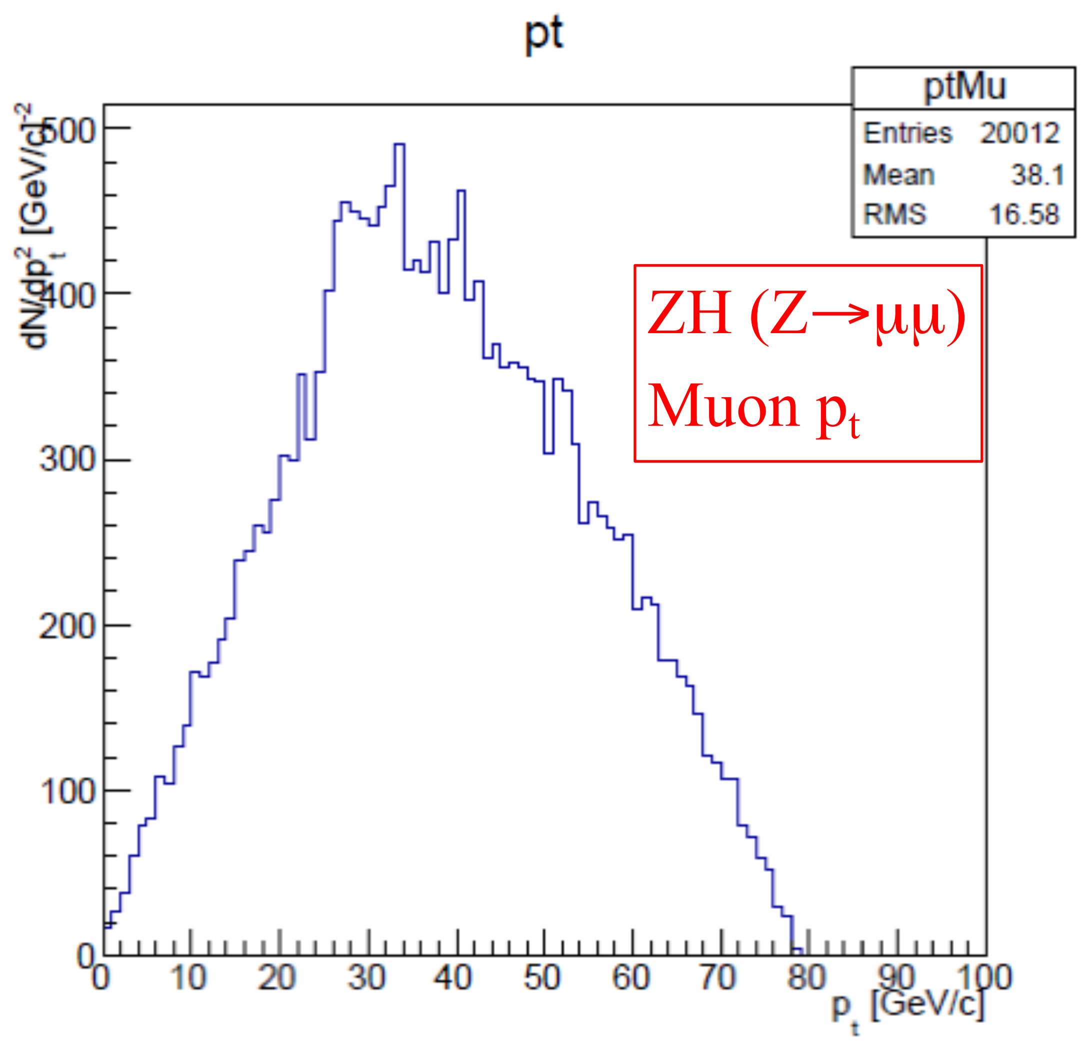
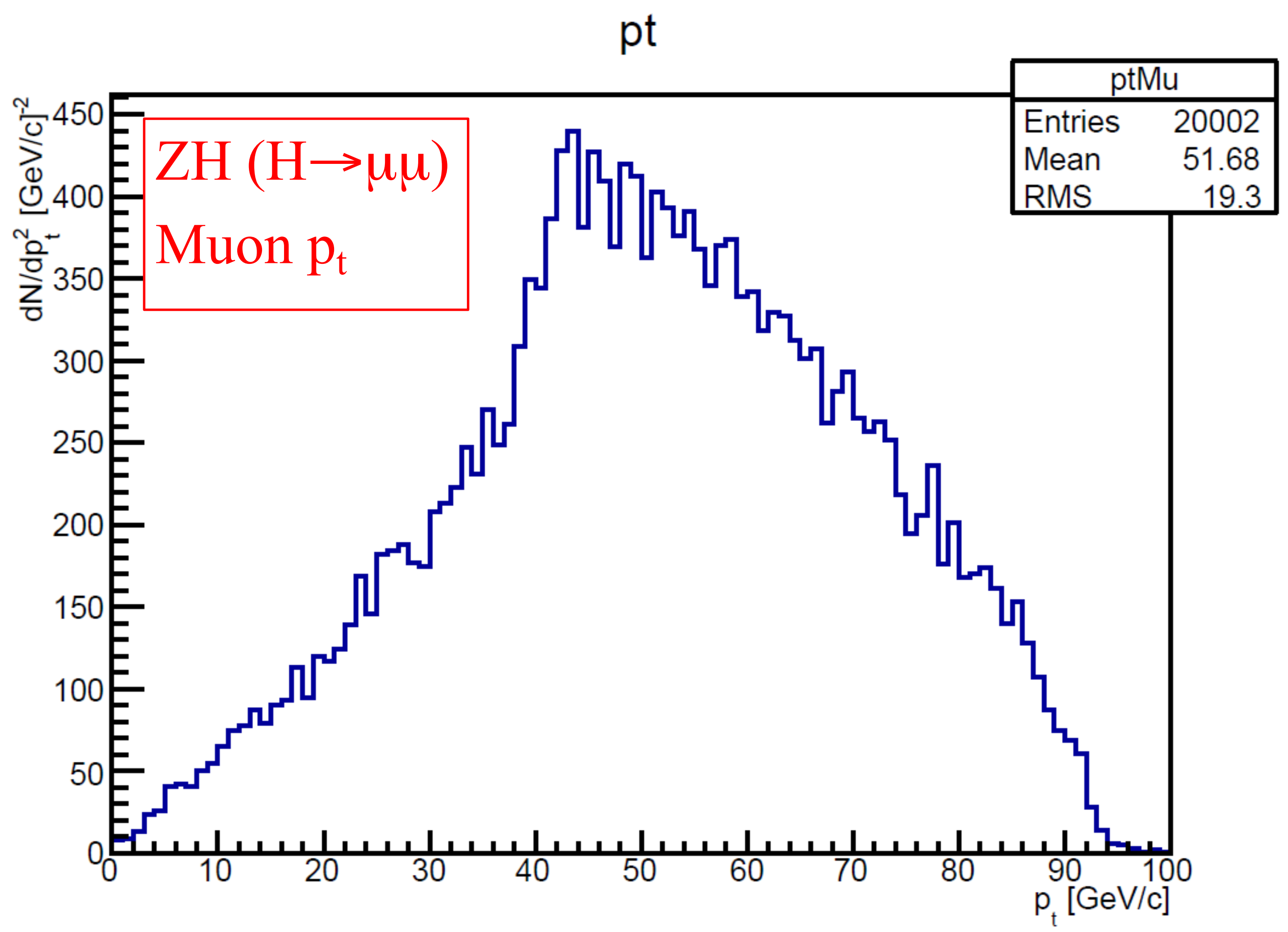
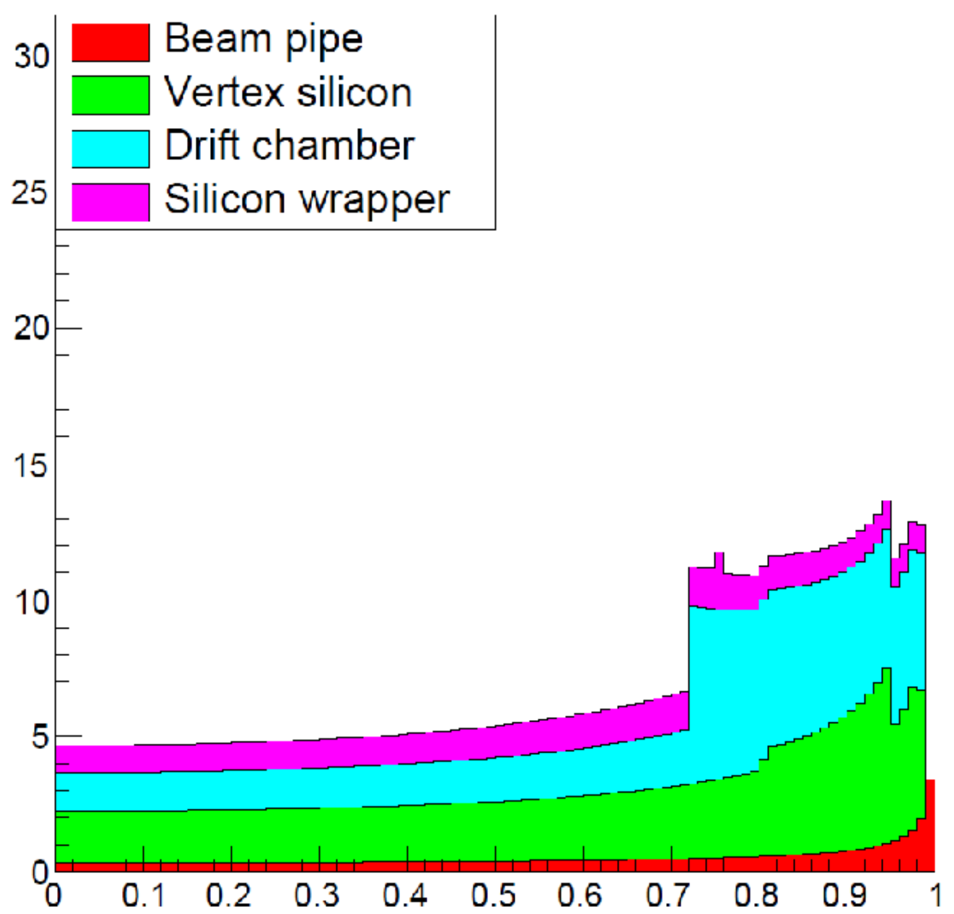


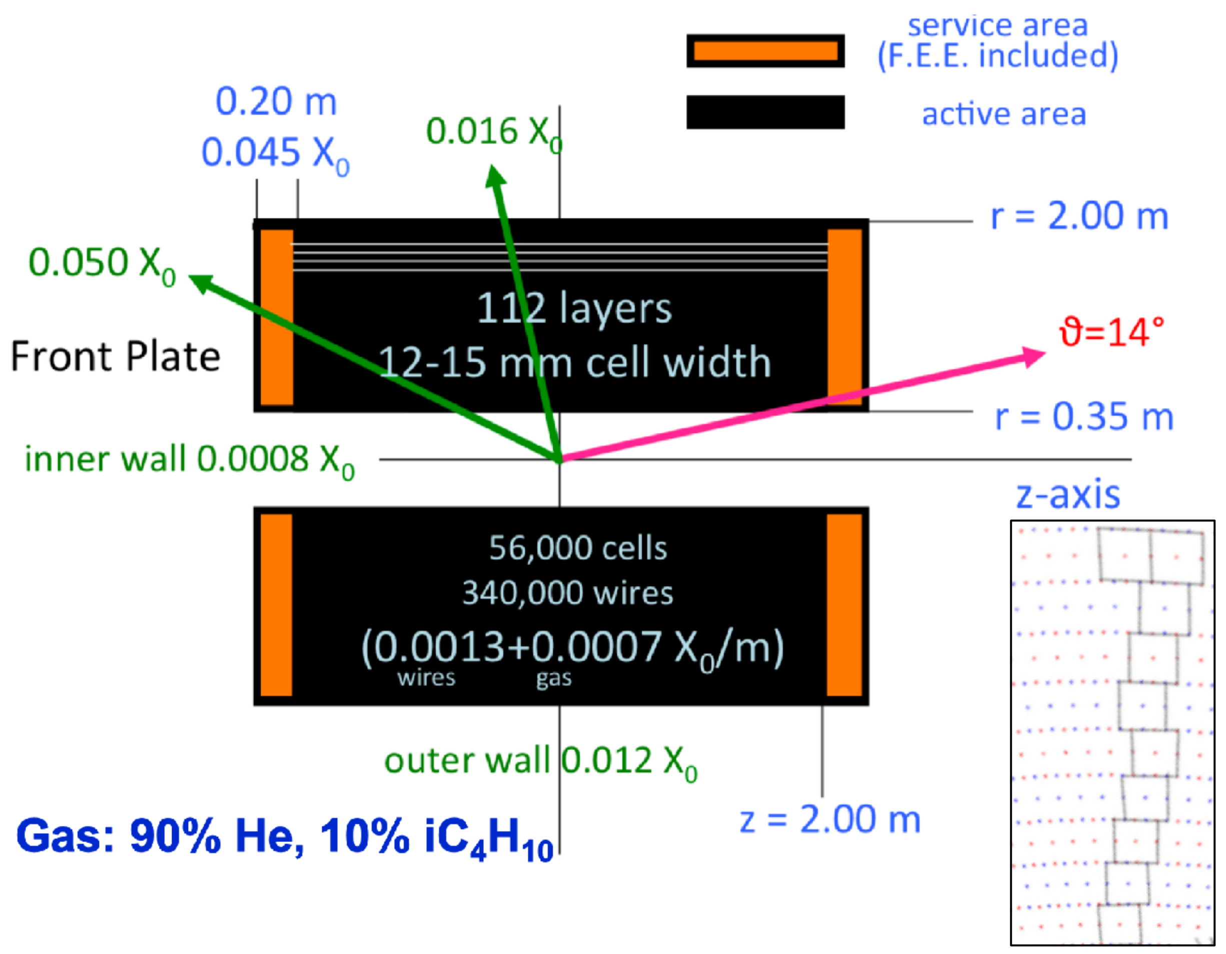


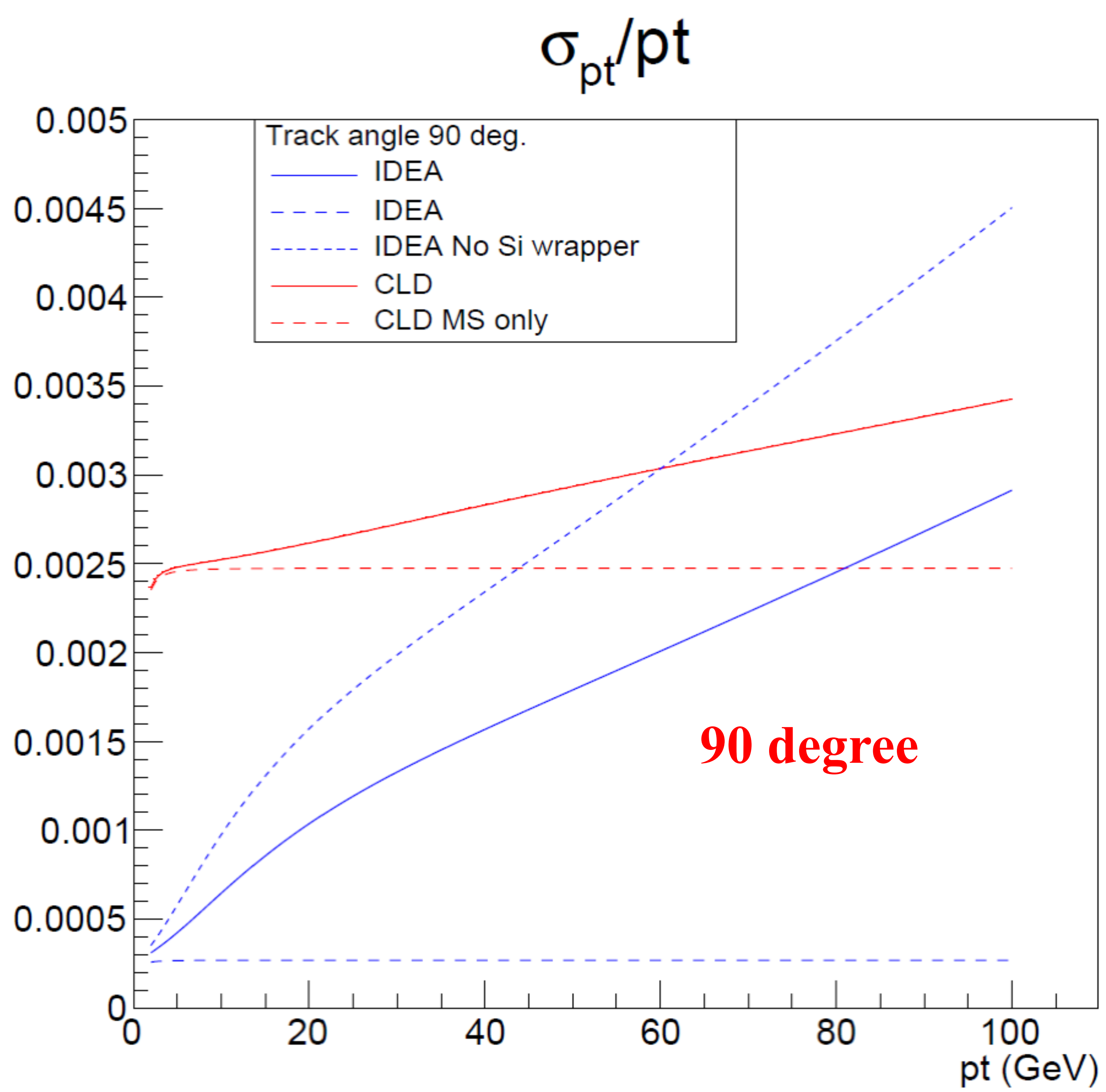
IDEA: Material vs. cos(θ)



IDEA Drift Chamber

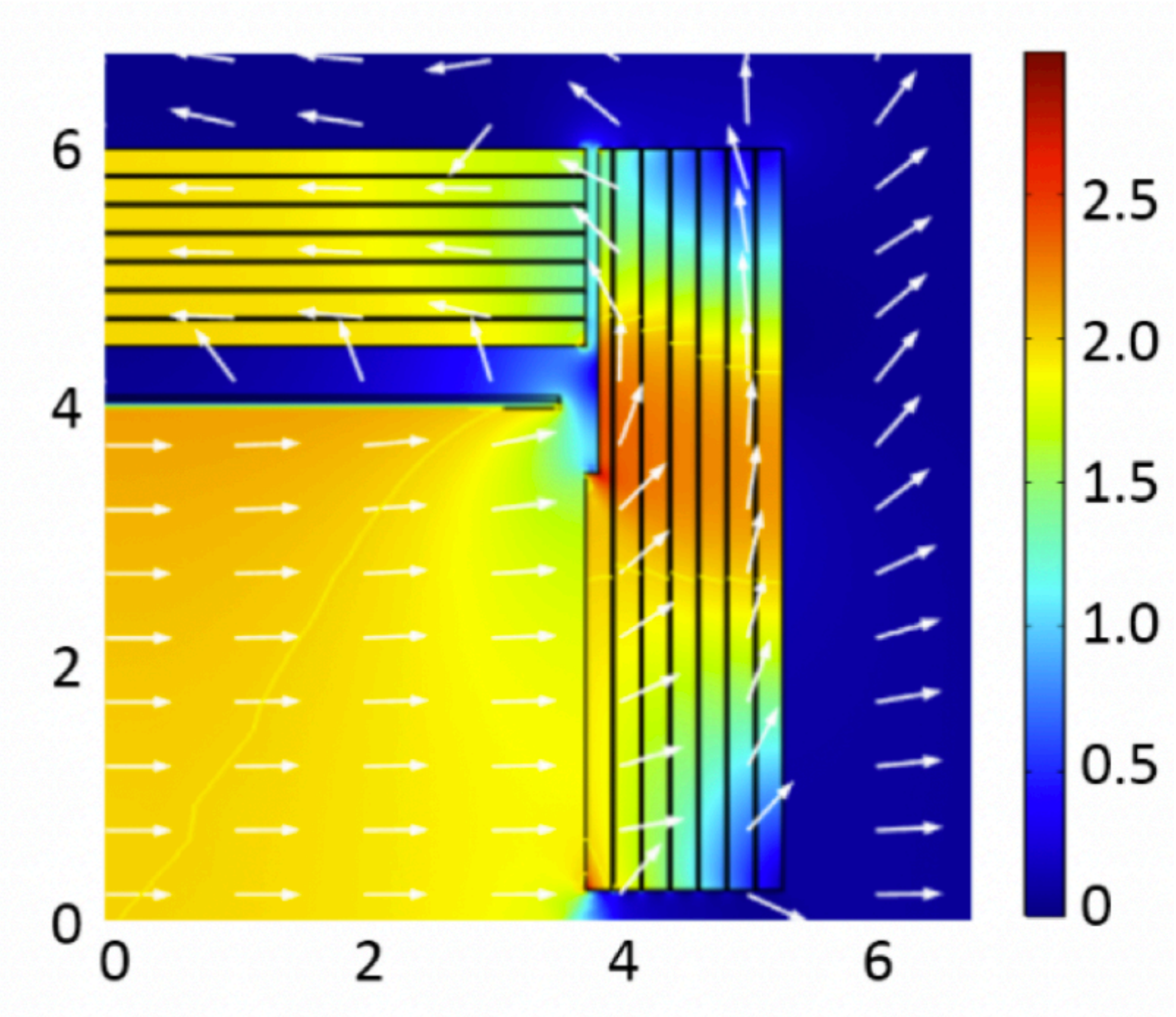
- GAS: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00 m
- Total thickness: 1.6% (!) of X_0 at 90º
  - Tungsten wires dominant contribution to material
- Full tracker system includes Si VTX and Si “wrapper”





Solenoid magnet

Large solenoid outside calorimeter system (**CLD**)



Thin solenoid inside calorimeter system (**IDEA** & LAr)

Must be **thin** and very **transparent**

- R&D ongoing

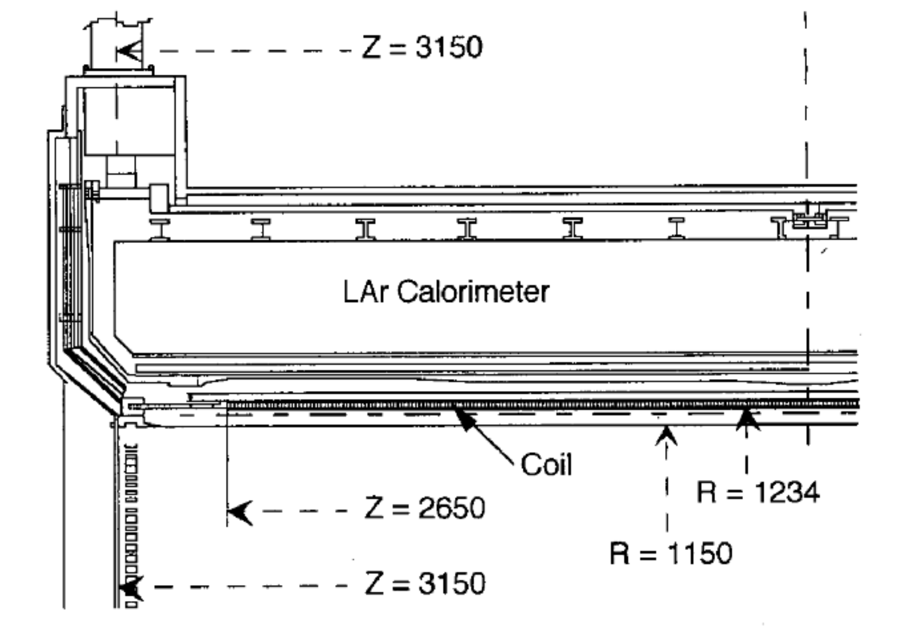
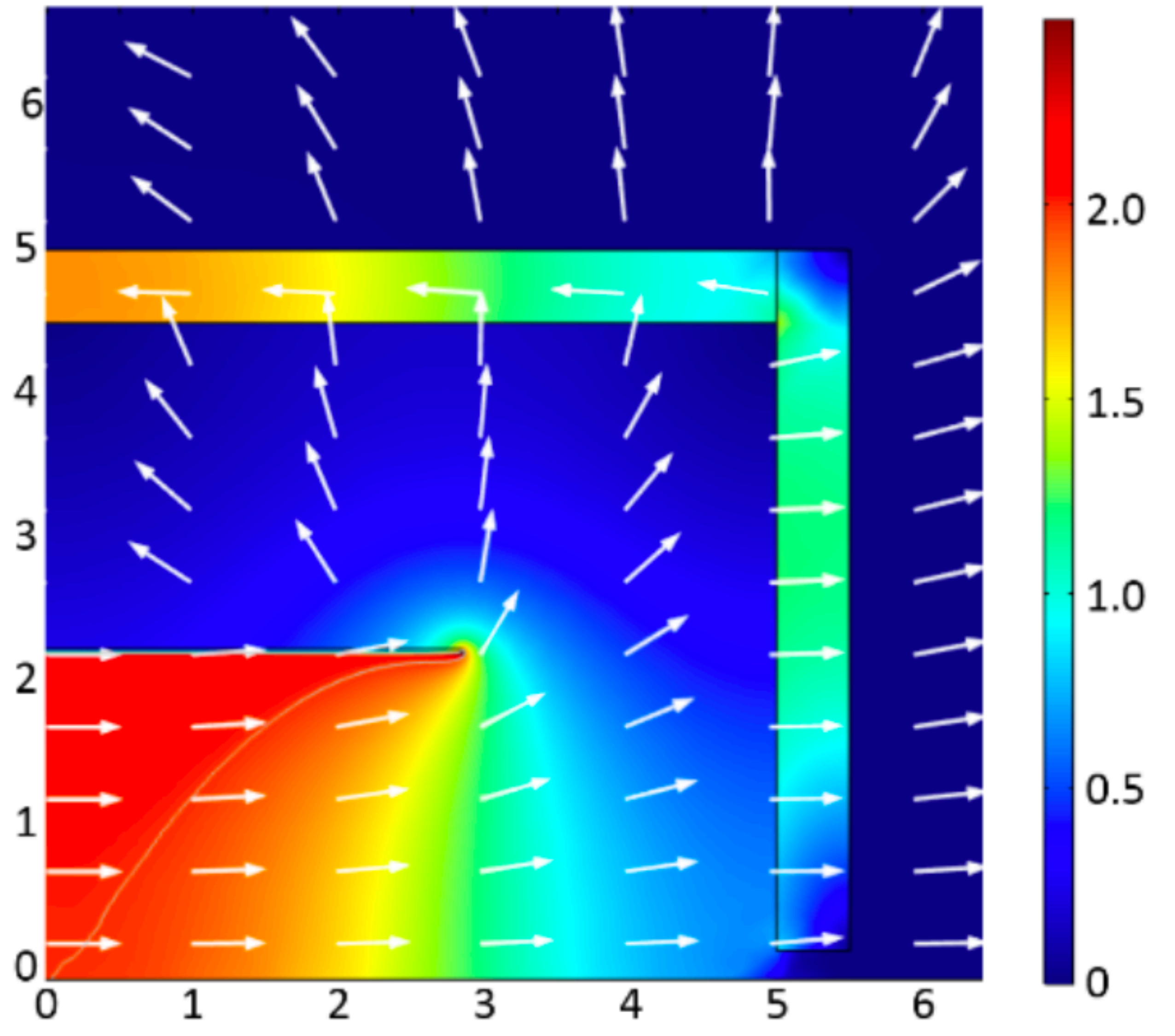


Fig. 2. Cross section of the coil, LAr calorimeter, and the common cryostat.

LAr: Calorimeter and
coil in same cryostat (ATLAS style)



R&D programs of interest for FCC-ee

WP5: Depleted Monolithic Active Pixel Sensors

- **High granularity DMAPS** for e^+e^- colliders
  - Low mass, low power: ALICE, BelleII, **Higgs and EW factories**

WP7: Gaseous Detectors

- **MPGDs, industrialisation**
  - μ**RWell** technology
- **Large gaseous detectors**
  - Cluster-counting electronics for ultra-light **drift chambers**

WP8: Calorimeters and Particle Identification Detectors

- **High granularity**
  - **integration aspects Si, SiPM, compact interfaces and structures**
  - **LAr read-out PCB prototyping**
- **Dual readout** fibre calorimeter, read-out system
- **Crystal ECAL** with **IDEA's DR calorimeter**

WP11: Microelectronics

- **ASIC network for MPW runs**
  - μ**RWell**, Si, SiPM, cold LAr readout

WP12: Software for future detectors

- **Turnkey software stack (key4HEP)**
- **Machine learning** for fast simulation
- **Tracking** algorithms
- **Particle flow** reconstruction

And other WPs (**Test beams and irradiation**, **Advanced Mechanics**, **Cooling**) are also of interest for FCC-ee...

Other R&D programs of interest to FCC

ECFA R&D Roadmap initiative

Roadmap document should be ready by the end of July

CALICE: R&D for high performance e.m. and hadronic calorimeters

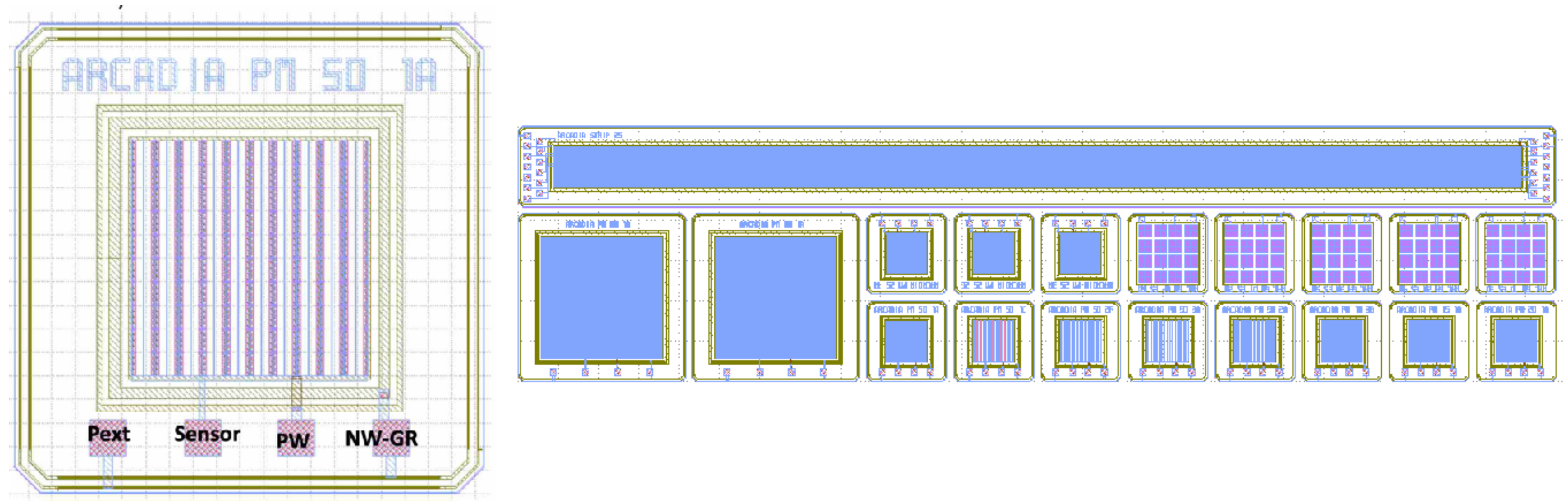
- SCECAL
- SiW ECAL
- MAPS ECAL
- AHCAL
- DHCAL
- TCMT

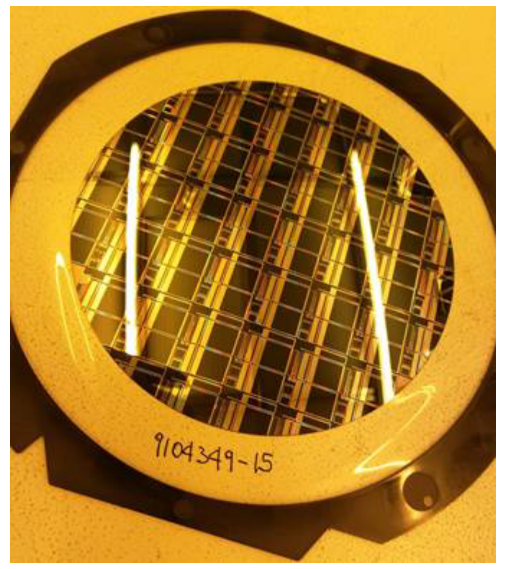
Some national programs

ARCADIA: INFN Advanced R&D on DMAPS

. others

.





DR calorimeter

Dual-readout fiber-sampling calorimeter

- Longitudinally unsegmented fiber-sampling calorimeter
  → measure both EM & hadronic components simultaneously
  → fine unit structure with a high granularity
- Projective geometry with a uniform sampling fraction
  → more fibers in the rear than the front

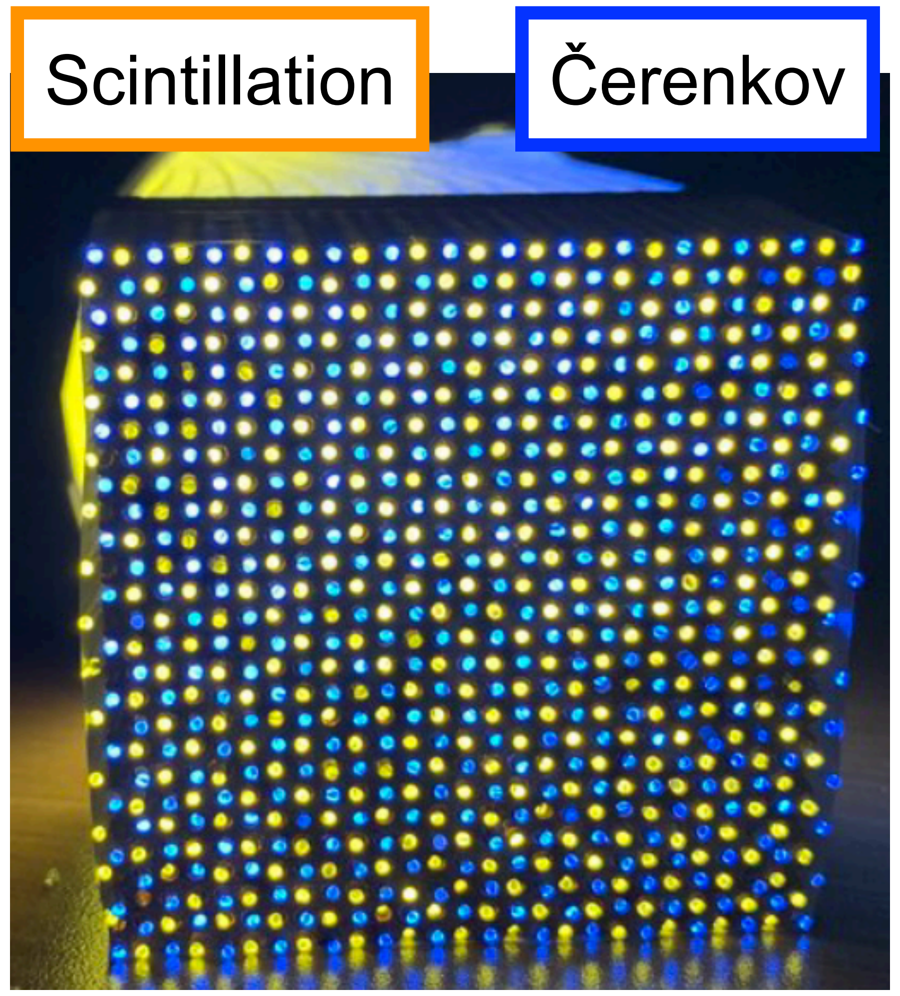
$$S = E\left[f_{em} + \left(\frac{h}{e}\right)_s (1 - f_{em})\right],$$

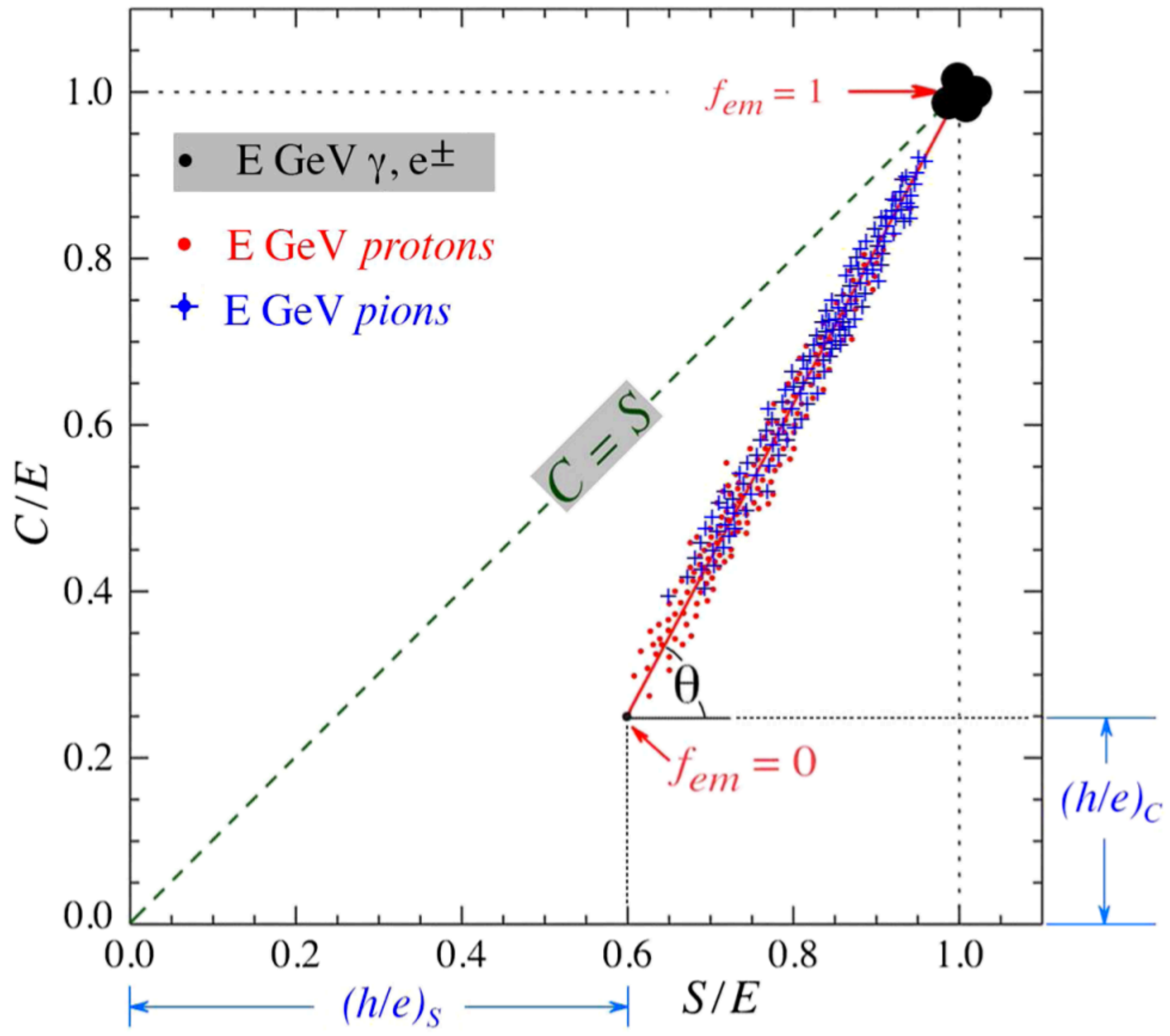
$$C = E\left[f_{em} + \left(\frac{h}{e}\right)_c (1 - f_{em})\right]$$

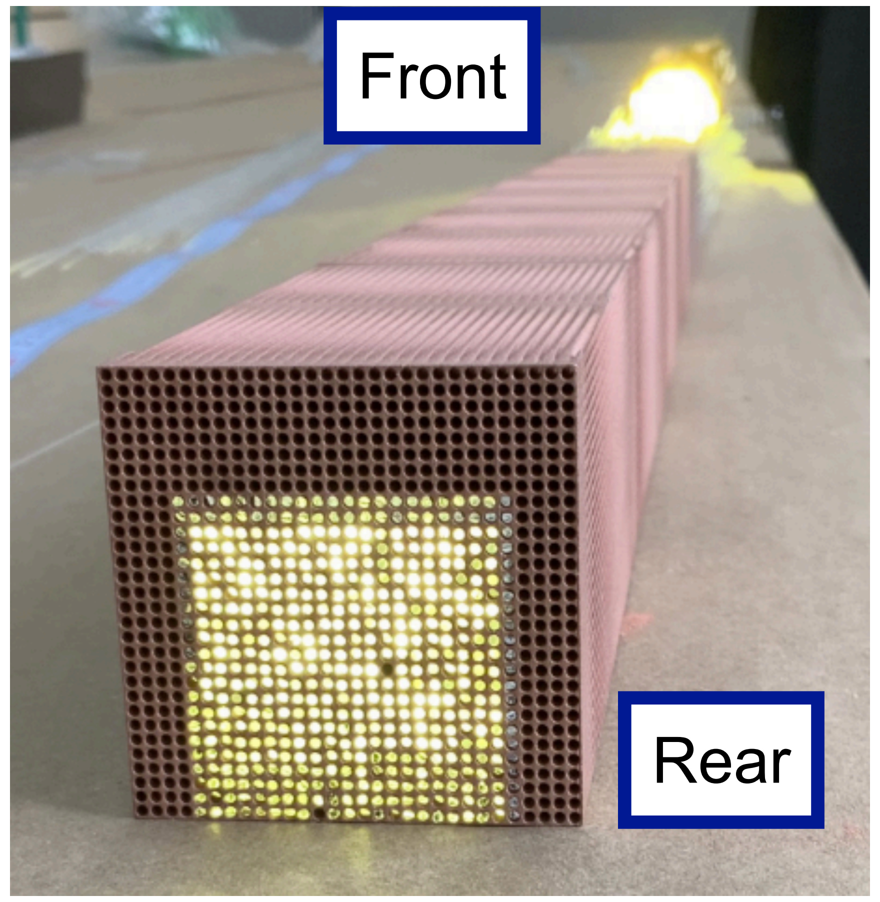
$$f_{em} = \frac{(h/e)_c - (C/S)(h/e)_s}{(C/S)[1-(h/e)_s] - [1-(h/e)_c]}$$

$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} \equiv \chi,$$

$$E = \frac{S - \chi C}{1 - \chi}$$







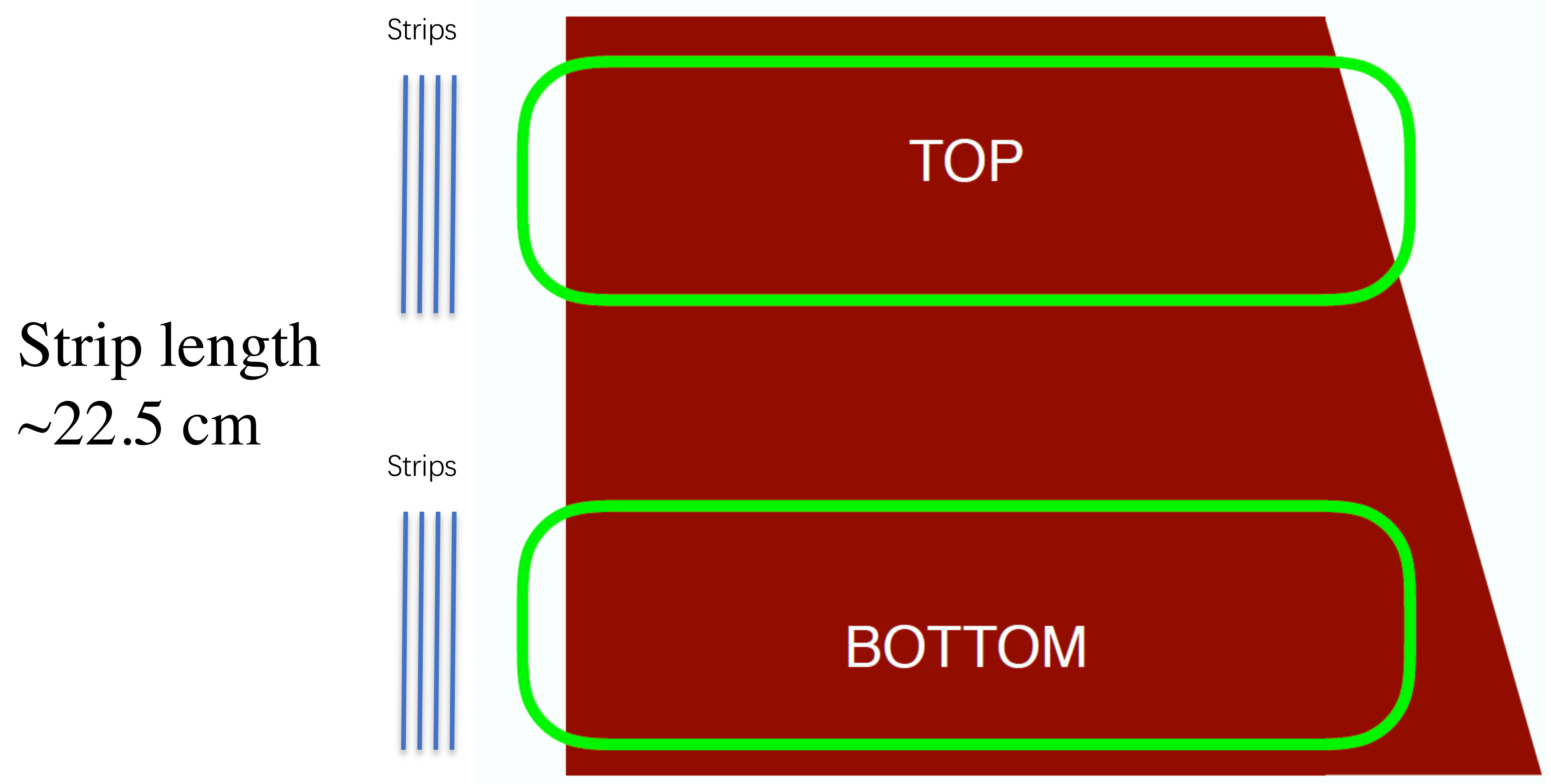
µRWELL-based detectors

2022-2024 R&D program

- ➢ Define the best resistivity of the DLC for both μRWELL fundamental tiles and build the 50×50 cm^2 prototypes for the pre-shower and muon systems.
- ➢ Optimize the engineering mass construction process together with the ELTOS industry.
- ➢ Develop a custom-made ASIC for the μRWELL with the experience obtained from the TIGER chip and to test the μRWELL prototypes.
- ➢ Develop a new reconstruction algorithm, ML-based, to improve the resolution of μRWELL.
- ➢ Simulation of the CEPC decay channels of interest to optimize the detector design with special emphasis on Long Lived Particles to show the impact of a performing tracked in the muon system instead of a tagger.

M4-right

x-coordinate scan in 2 y-coordinated positions



M4 right homogeneity scan

Development of a new ASIC

- ➢ Two large microRWell chambers M4 in Bologna;
- ➢ Ferrara has procured the Tiger electronics;
- ➢ Plan to start equipping the M4s with the TIGER next spring;
- ➢ Use a cosmic telescope to characterize the detector and the electronics and later to expose the chamber with the TIGER electronics to a test beam;
- ➢ Funding received to develop a new ASIC starting from the experience of the TIGER.