Research on Calorimetry for Future Colliders

HighRR Lecture Week on Next Generation Particle Detectors

Bergen, NO, June 13, 2024

Felix Sefkow
DESY and Heidelberg

HighRR

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

DESY

Outline

From Basics to Future

Introduction: Challenges for Calorimetry

Requirements for Future e+e- Collider Detectors

Major Directions

- Dual Readout with Fibres and Crystals
- High Granularity with CALICE Technologies
- The Return of Liquid Argon

Outline

From Basics to Future

Introduction: Challenges for Calorimetry

Requirements for Future e+e- Collider Detectors

Major Directions

Dual Readout with Fibres and Crystals

High Granularity with CALICE Technologies

The Return of Liquid Argon

Thanks to everyone from whom
I have shamelessly stolen material

Role of Calorimeters

Detection of Neutral Particles

Only charged particles create signals

- ionisation
- scintillation
- Cherenkov light
- transition radiation

Calorimetry is a destructive measurement

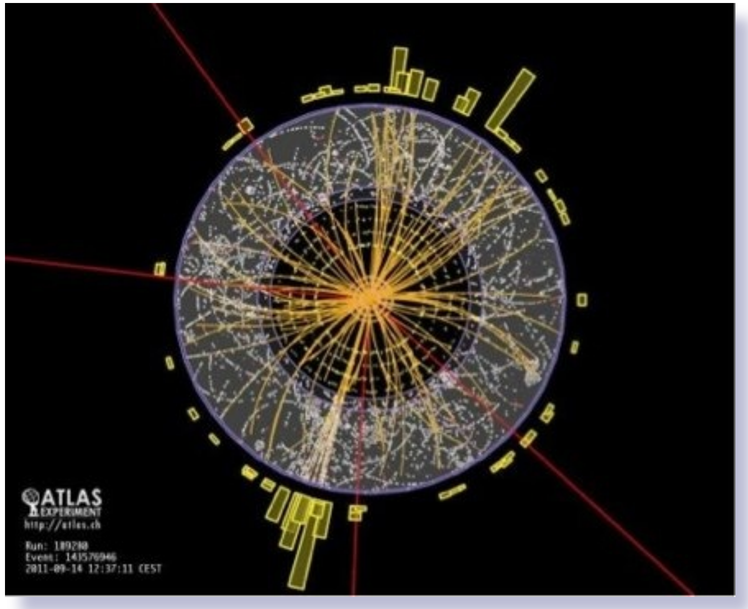
- transfer energy to charged particles
- rely on energy conservation
- obtain a total charged-particle signal proportional to the energy of the primary incident neutral

Statistical process

- resolution improves with energy
- in contrast to momentum measurements relying on curvature

The only detector which sees all particles

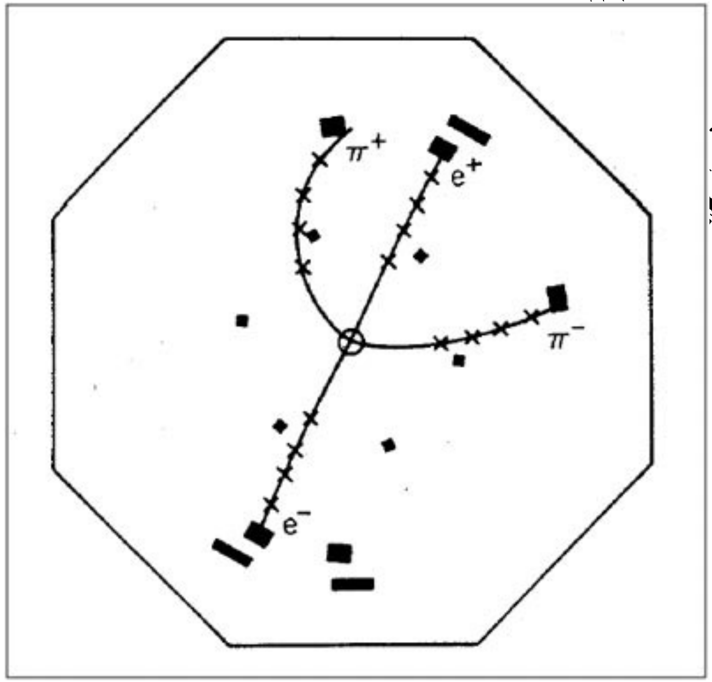
- indispensable for jets
- and for missing momentum signatures of, e.g., neutrinos

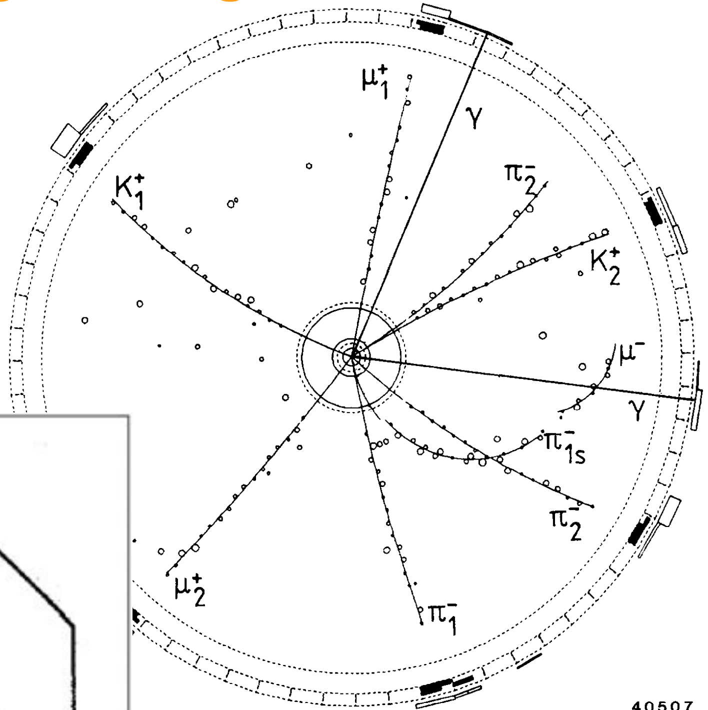


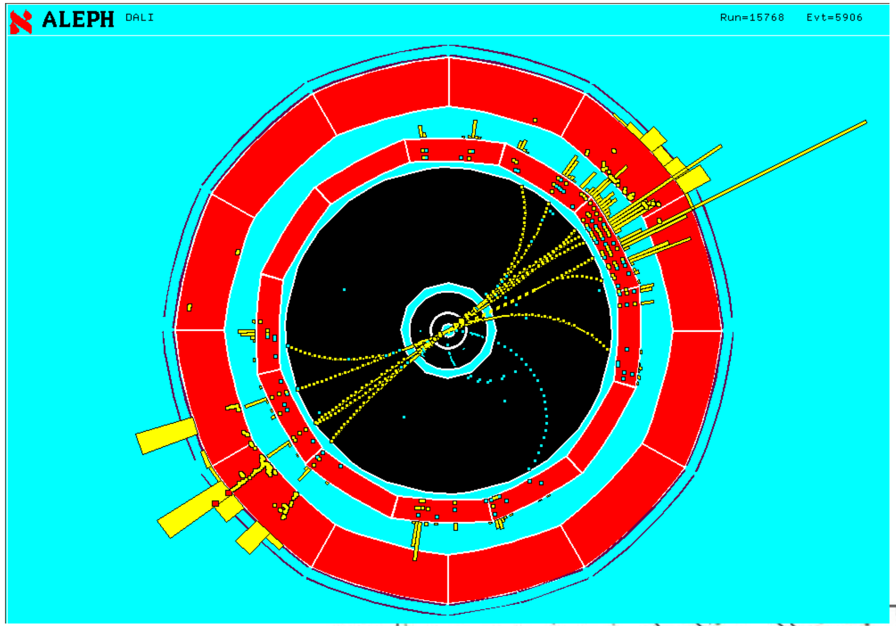
e+e- Events

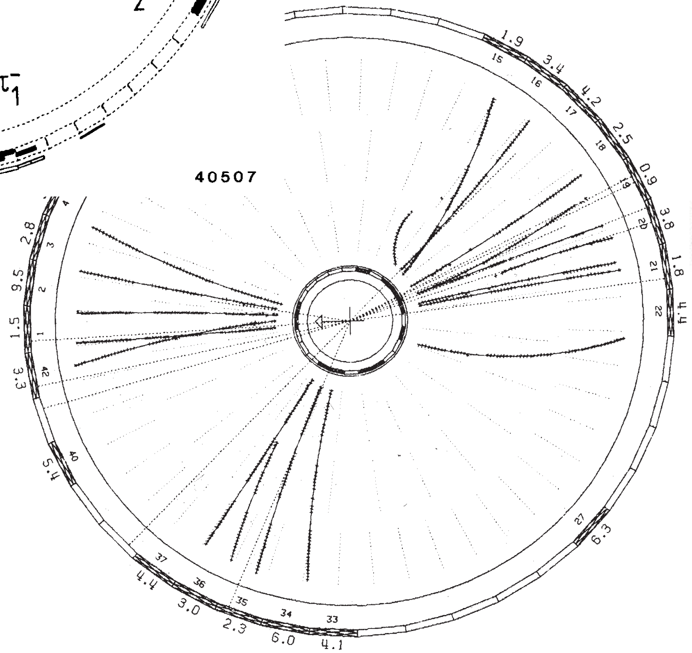
Calorimetry entering the stage

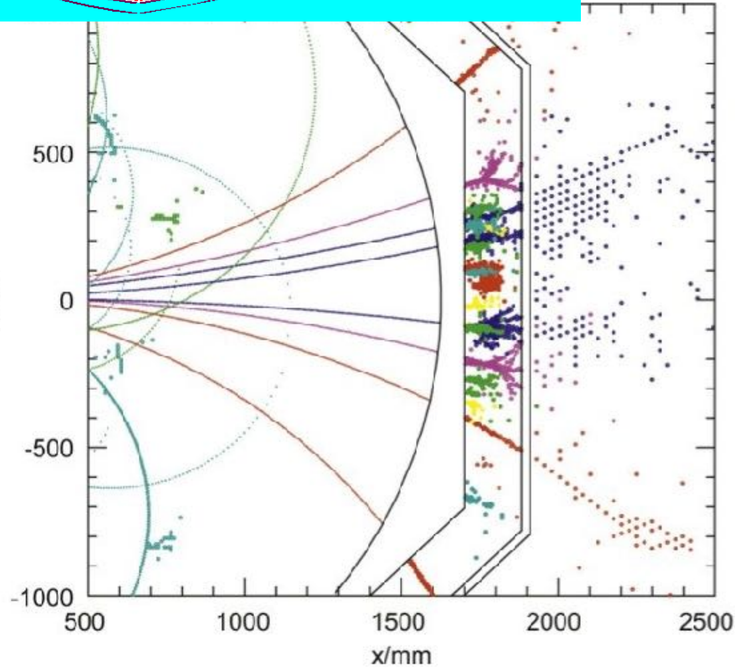
Mark I, ARGUS, JADE, ALEPH, ILD











Intrinsic Limitations of Hadron Calorimeters and Ways to Overcome or Get Around Them

Hadron Interactions

Complex and Diverse

Hard inelastic nuclear scattering:

- cross section ~ $\sigma_{pp} \cdot A^{2/3}$

Hadronic interaction length:

- $\lambda_{int} = 1 / \sigma n \sim A^{1/3}$
- mean free path

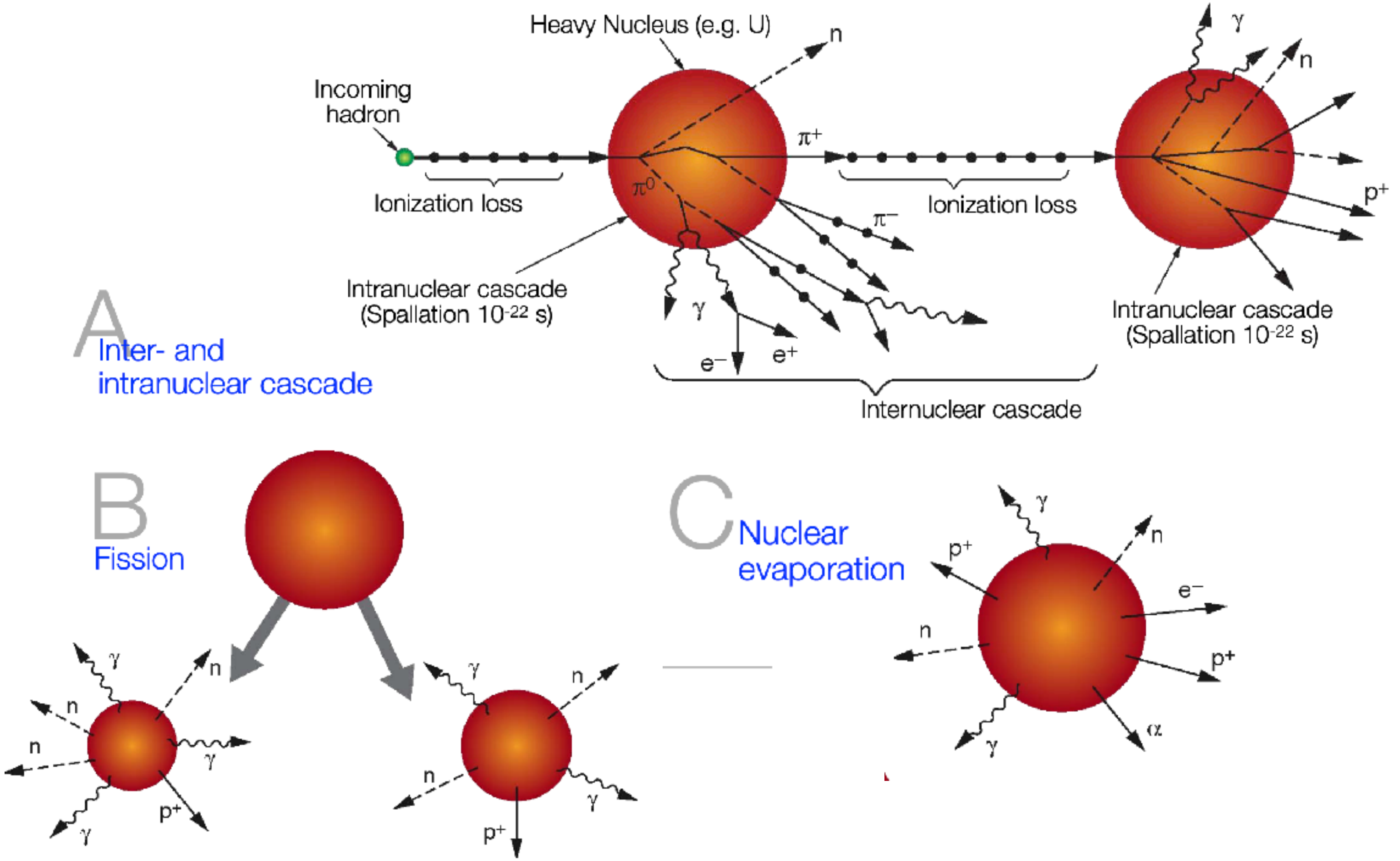
$$N(x) = N_0 \exp(-x/\lambda_{\mathrm{int}})$$

Shower dimension scale

- length 5-10 λ_{int}, radius ~ 1 λ_{int}

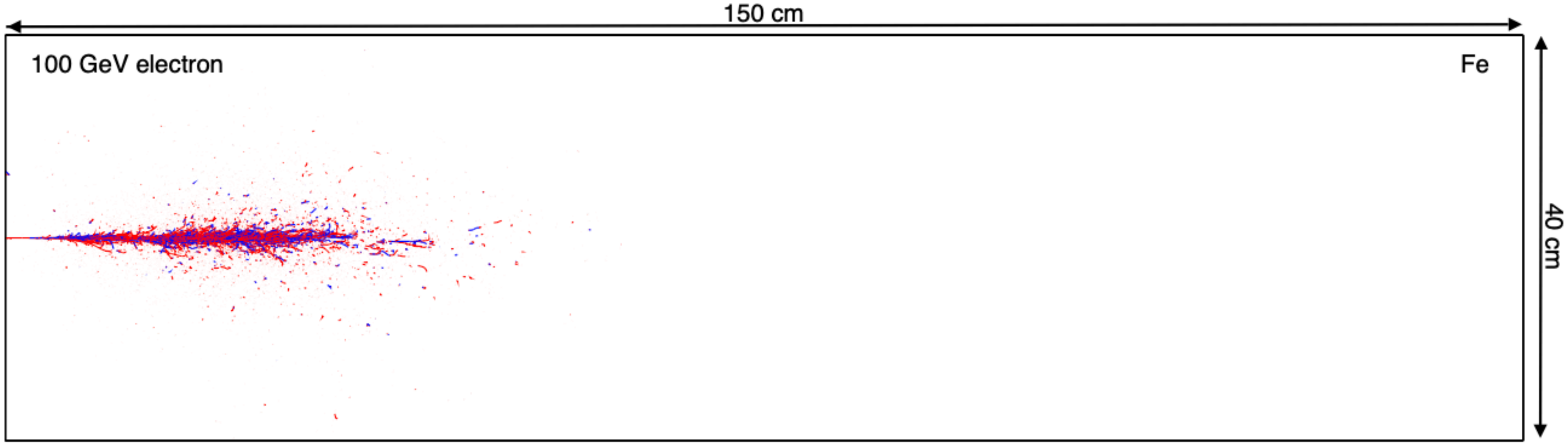
Hadronic cascade

- large variety of processes
- larger multiplicities at each step
- pion production threshold ~300 MeV
- sub-structure



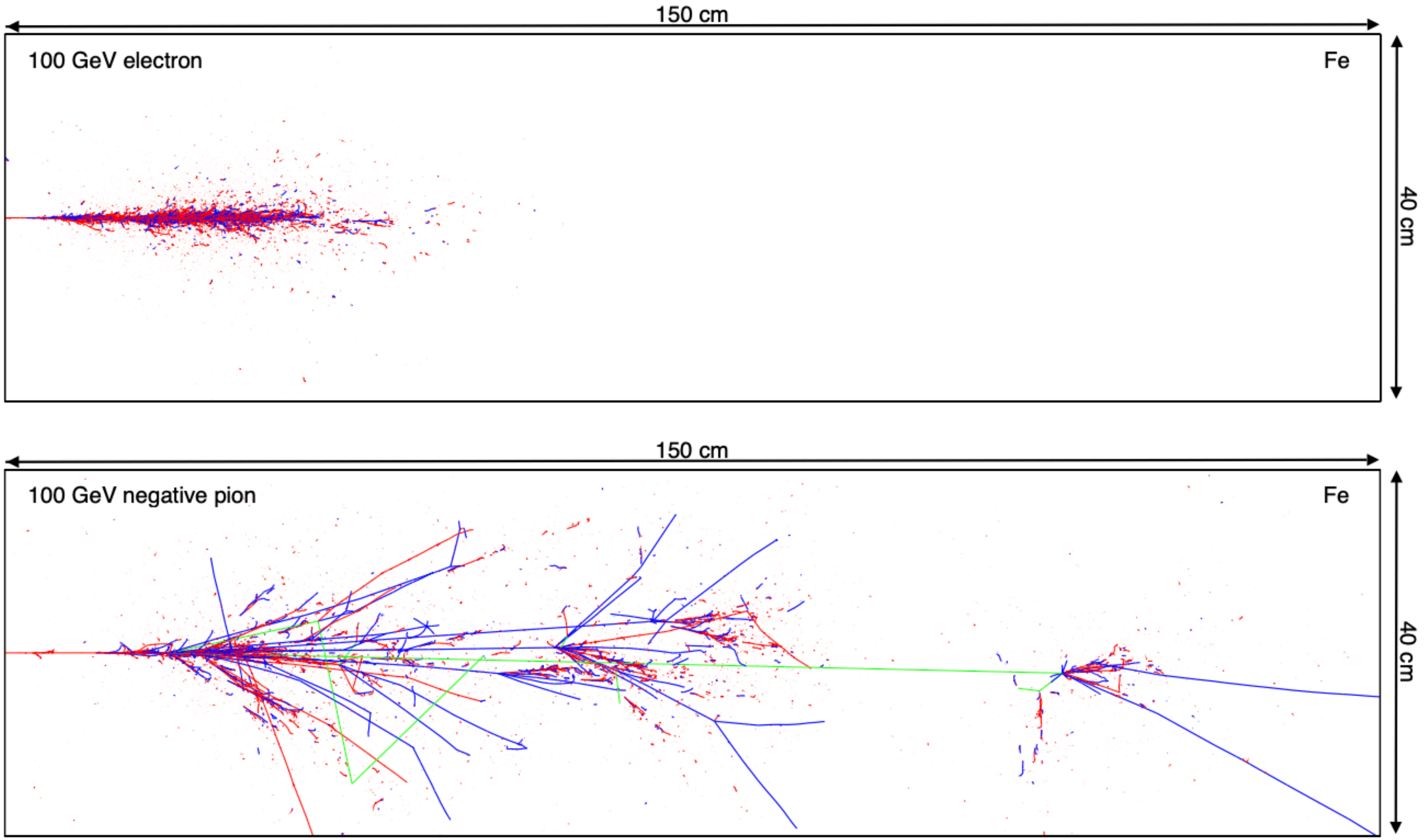
Electromagnetic and Hadronic Showers

Enjoy the Differences



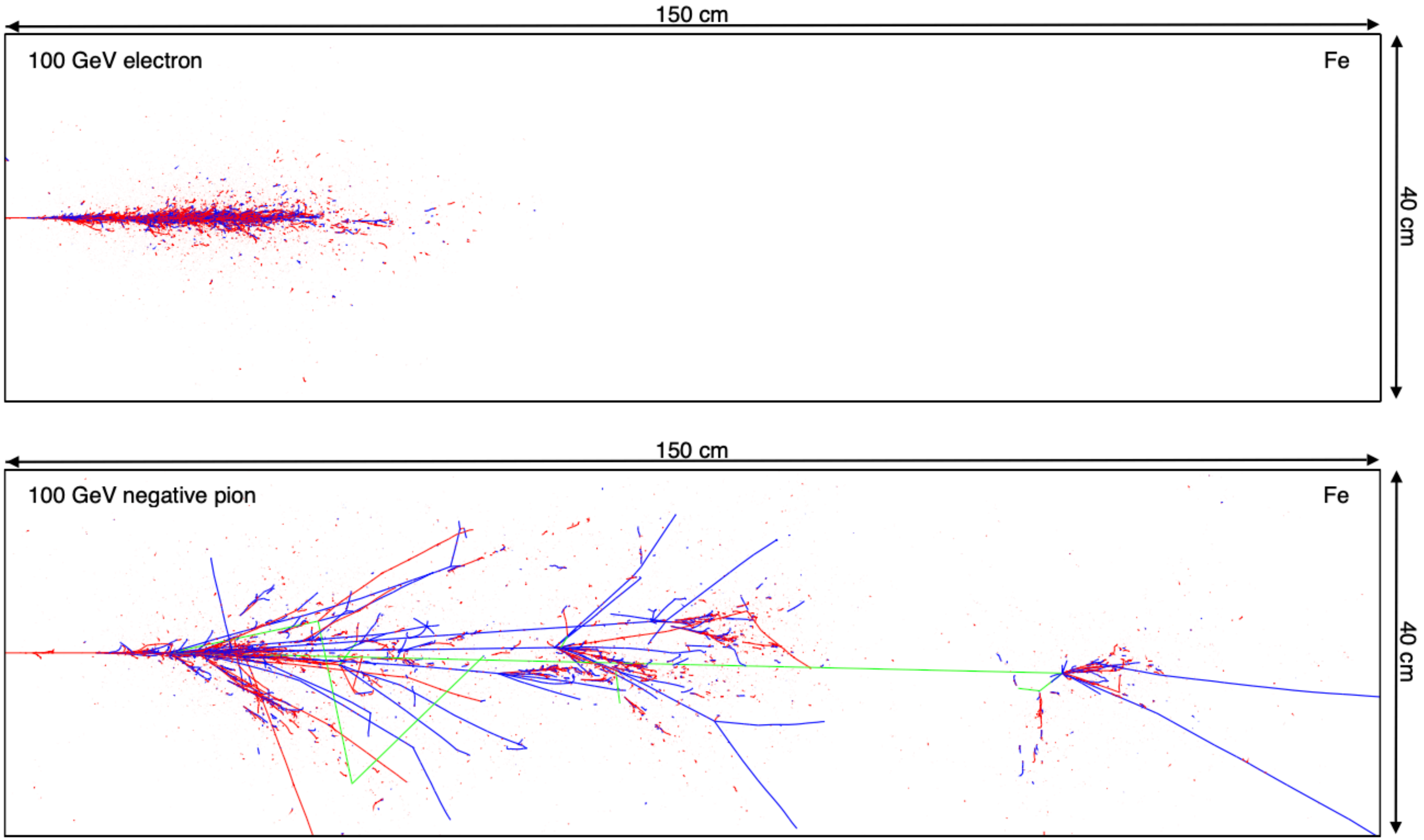
Electromagnetic and Hadronic Showers

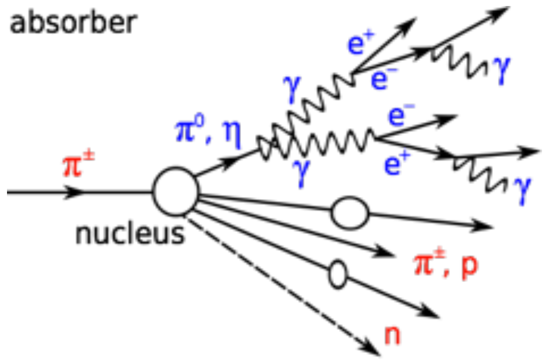
Enjoy the Differences



Electromagnetic and Hadronic Showers

Enjoy the Differences



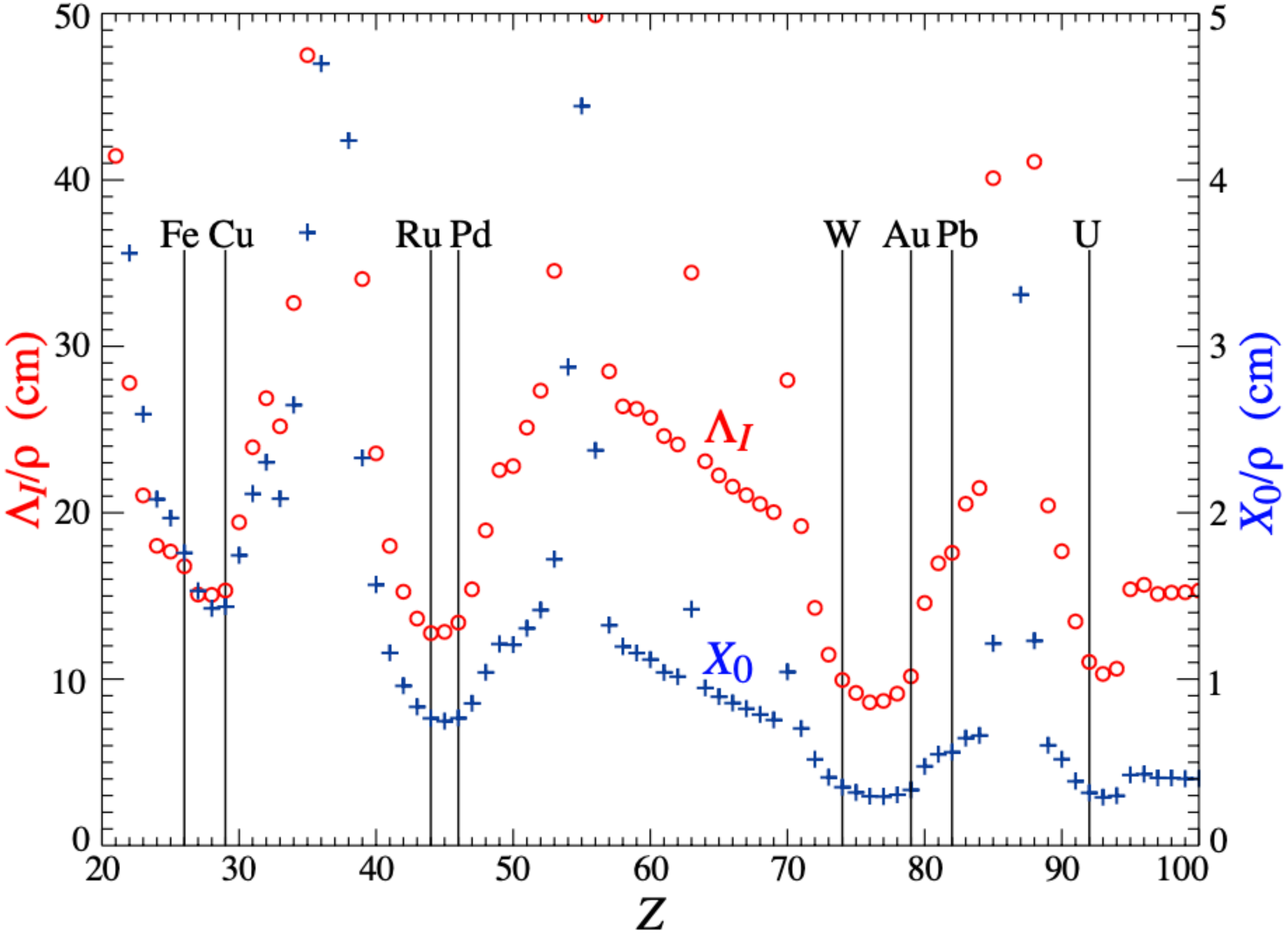


π^0 production (1/3 !) gives rise to electromagnetic sub-showers

- second scale X_0

Electromagnetic and Hadronic Shower Parameters

Calorimeter Absorber Materials

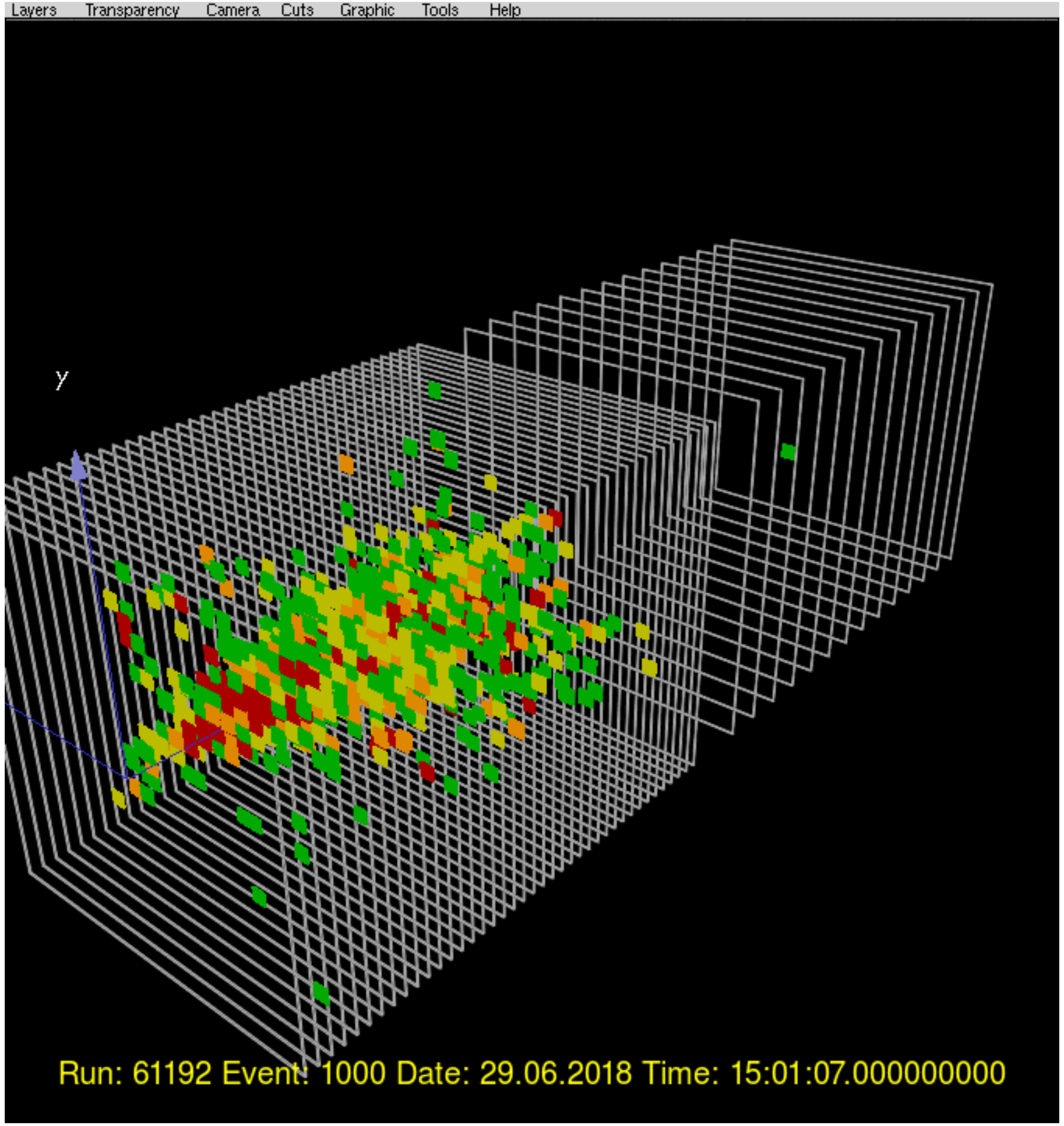


	λ_{int} [cm]	X_0 [cm]
Szint.	79,4	42,2
LAr	83,7	14
Fe	16,8	1,76
Pb	17,1	0,56
U	10,5	0,32
C	38,1	18,8

Fluctuations

Event to event

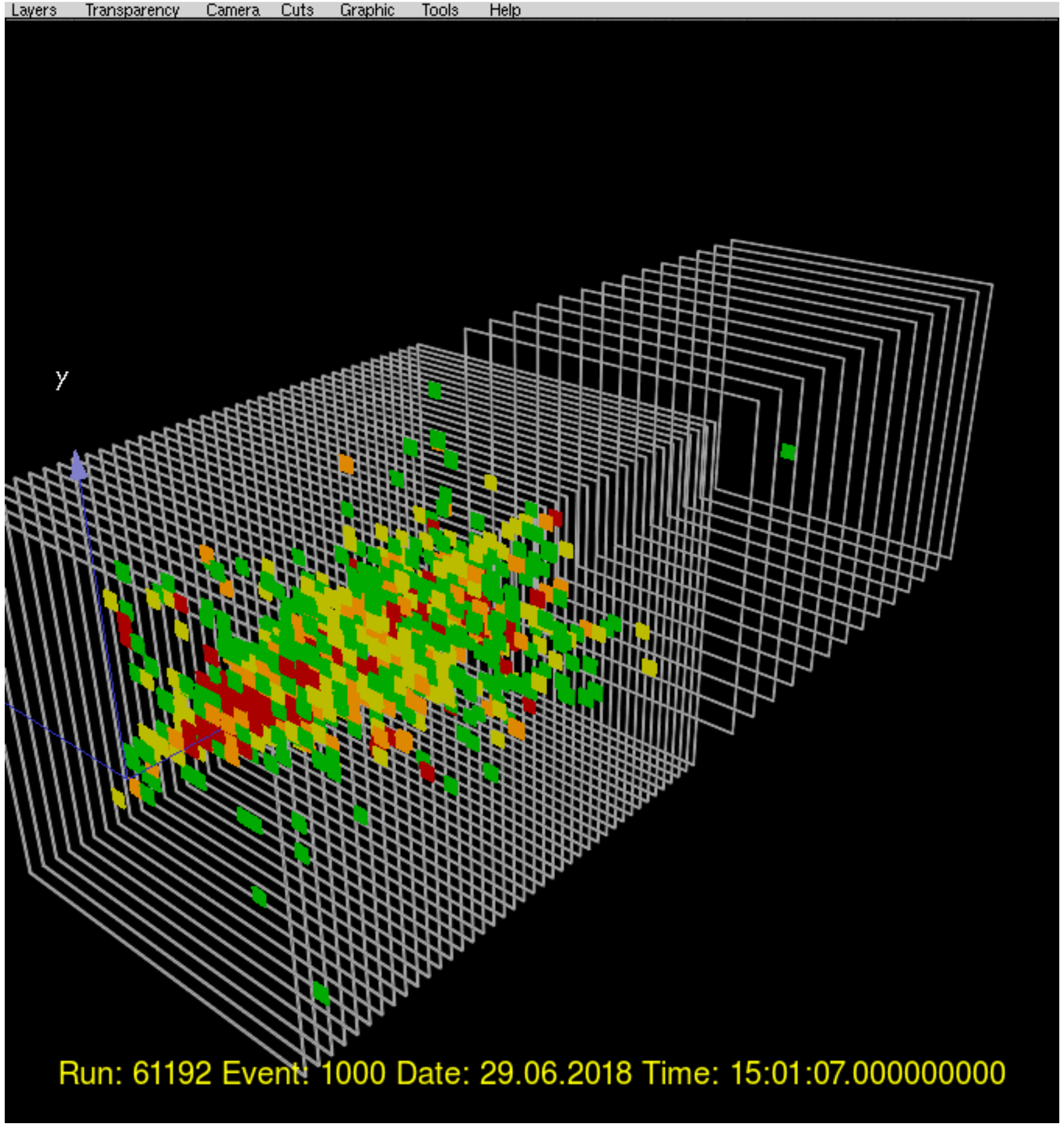
pions 50 GeV
in steel scintillator
CALICE AHCAL
testbeam at CERN



Fluctuations

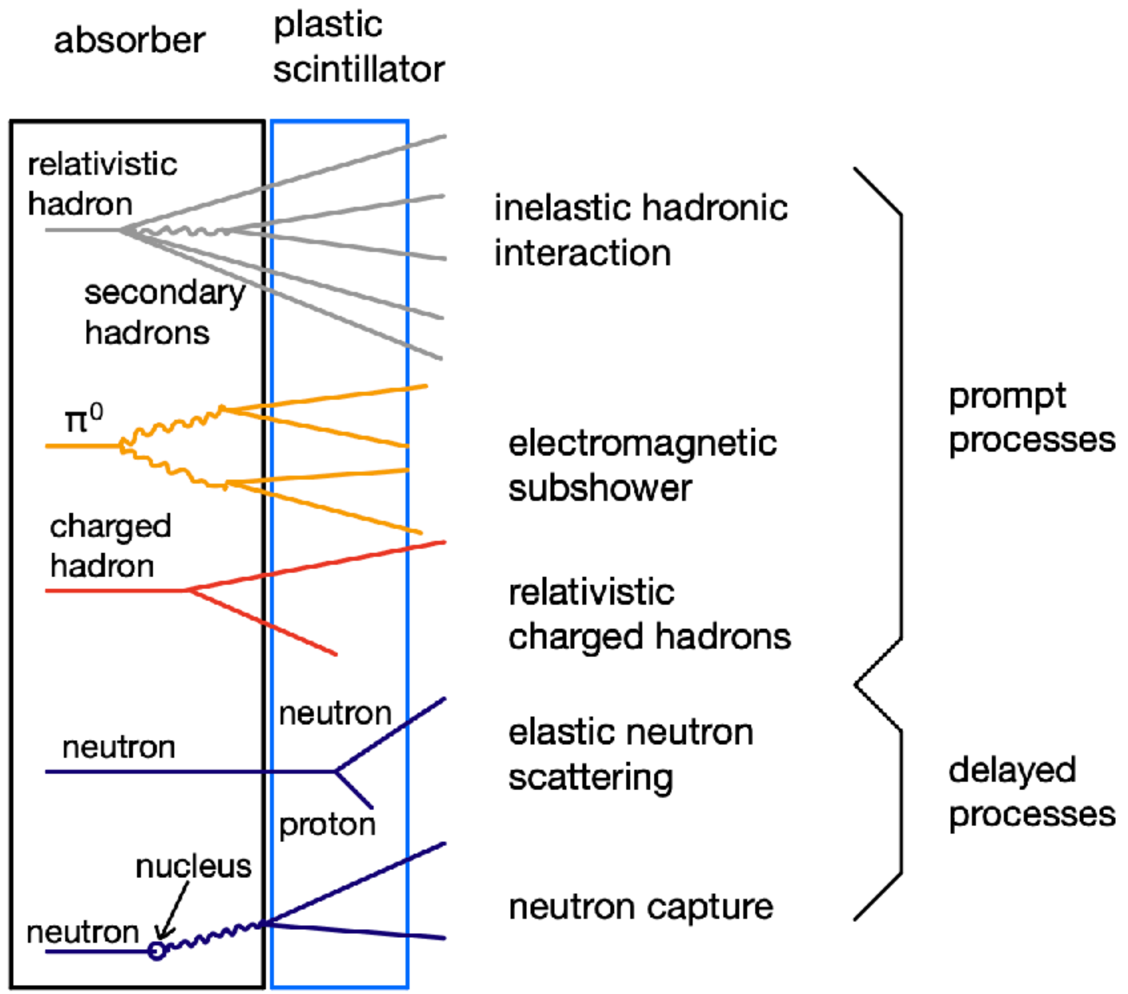
Event to event

pions 50 GeV
in steel scintillator
CALICE AHCAL
testbeam at CERN



Hadron Calorimeter Challenges

Complex Composition



Example: 5 GeV pion in Pb scintillator

Ionization energy of charged particles (p,π,μ)	1980 MeV [40%]
Electromagnetic shower (π^0,η^0,e)	760 MeV [15%]
Neutrons	520 MeV [10%]
Photons from nuclear de-excitation	310 MeV [6%]
Non-detectable energy (nuclear binding, neutrinos)	1430 MeV [29%]
	5000 MeV [100%]

Hadron Calorimeter Resolution

Intrinsically limited

In general: hadronic response < electrom. response

- due to invisible contributions

Electromagnetic fraction f_{em} increases with E: non-linear response

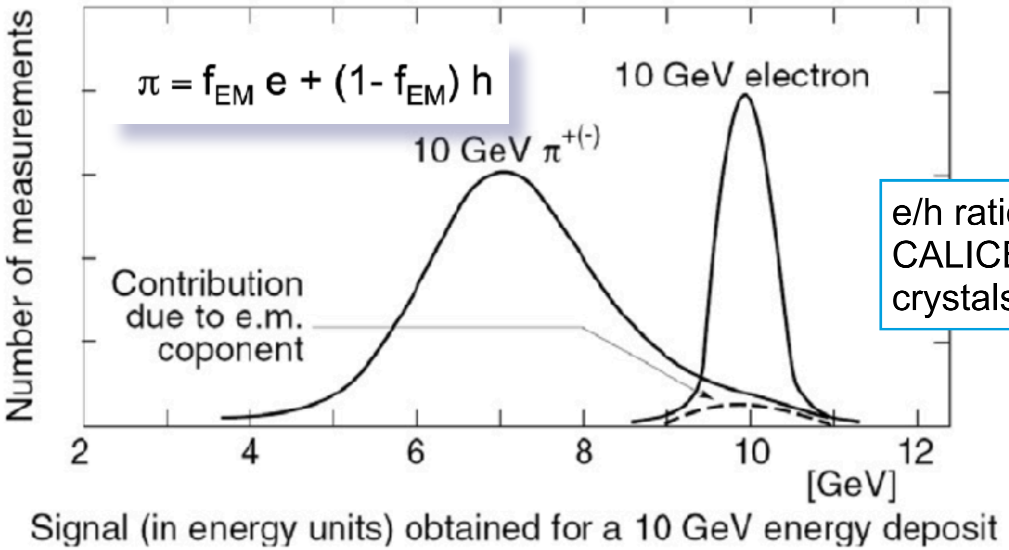
- non-linear response

f_{em} fluctuates strongly from event to event

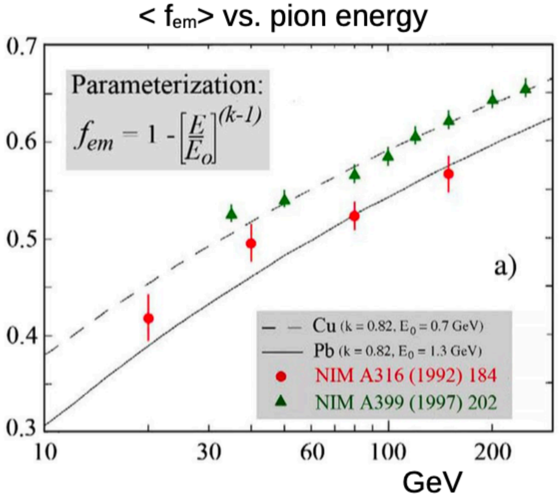
- from 0 to 1 (charge exchange, UHE air shower)
- Impact of f_{em} fluctuations depends on "compensation"

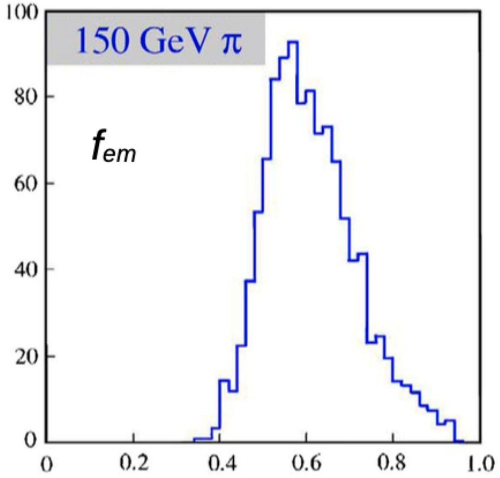
Invisible energy fraction f_{em} also fluctuates strongly from event to event

- irreducible contribution to resolution
- sampling fluctuations also strong: which is the dominant effect depends on design



e/h ratio:
CALICE AHCAL ~ 1.25
crystals ~ 2.5





Compensation

Achievements and Drawbacks

Restore e/h = 1

- suppress electromagnetic response
  - heavy absorber, shield soft components
- enhance hadronic response
  - heavy absorber, hydrogenous scintillator

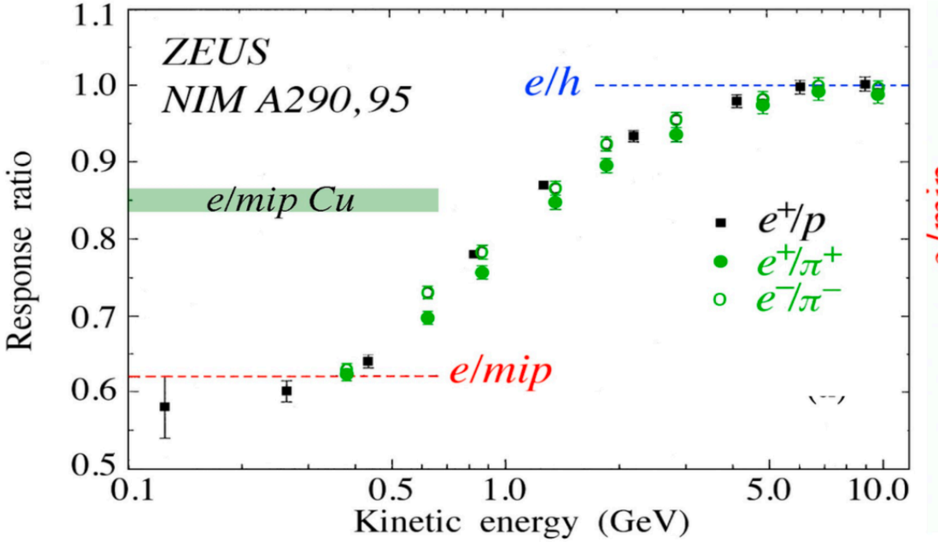
High-Z absorber, low sampling

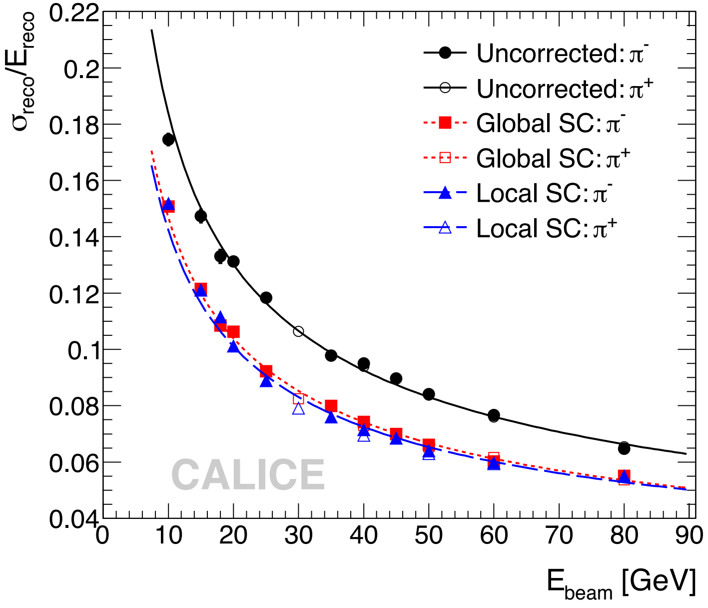
- sampling in X_0 reduced more than in λ
- good e.m. performance would require large sampling
- e.m. and jet performance mutually exclusive

Example CALICE AHCAL:

- 5 mm scintillator, 20 mm **Fe**: 58%/√E
  - h/e ~ 0.78: with software compensation: 45%/√E
- 5 mm scintillator, 10 mm **W**: 58%/√E
  - h/e ~ 1, no gain with software compensation

Low-energy response (compensating calorimeter!)

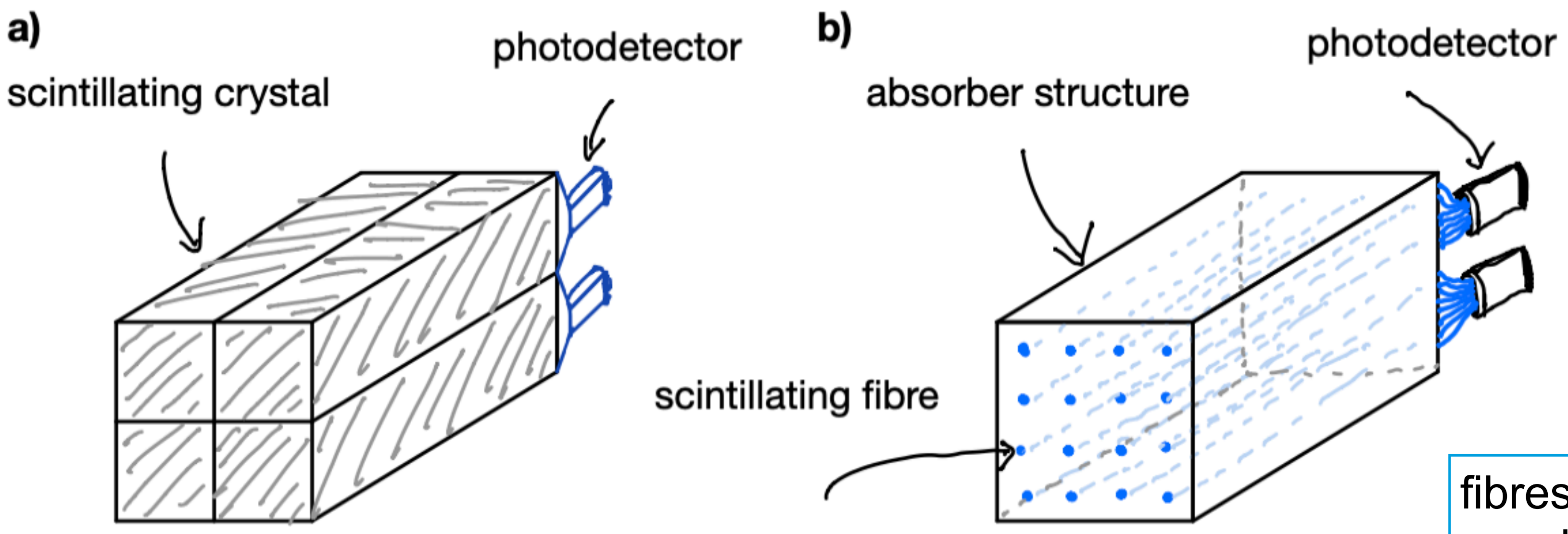




Calorimeter Types

Homogenous and Sampling Calorimeters

With Optical Readout



crystals

fibres: spaghetti

Homogenous calorimeter

- Absorber and active medium are the same
- crystals or glass (so far only electromagnetic)
- extreme example: Earth’s atmosphere

Sampling calorimeter

- separate materials
- active medium “samples" shower
- “visible energy”

Sandwich Geometries

Infinite Possibilities

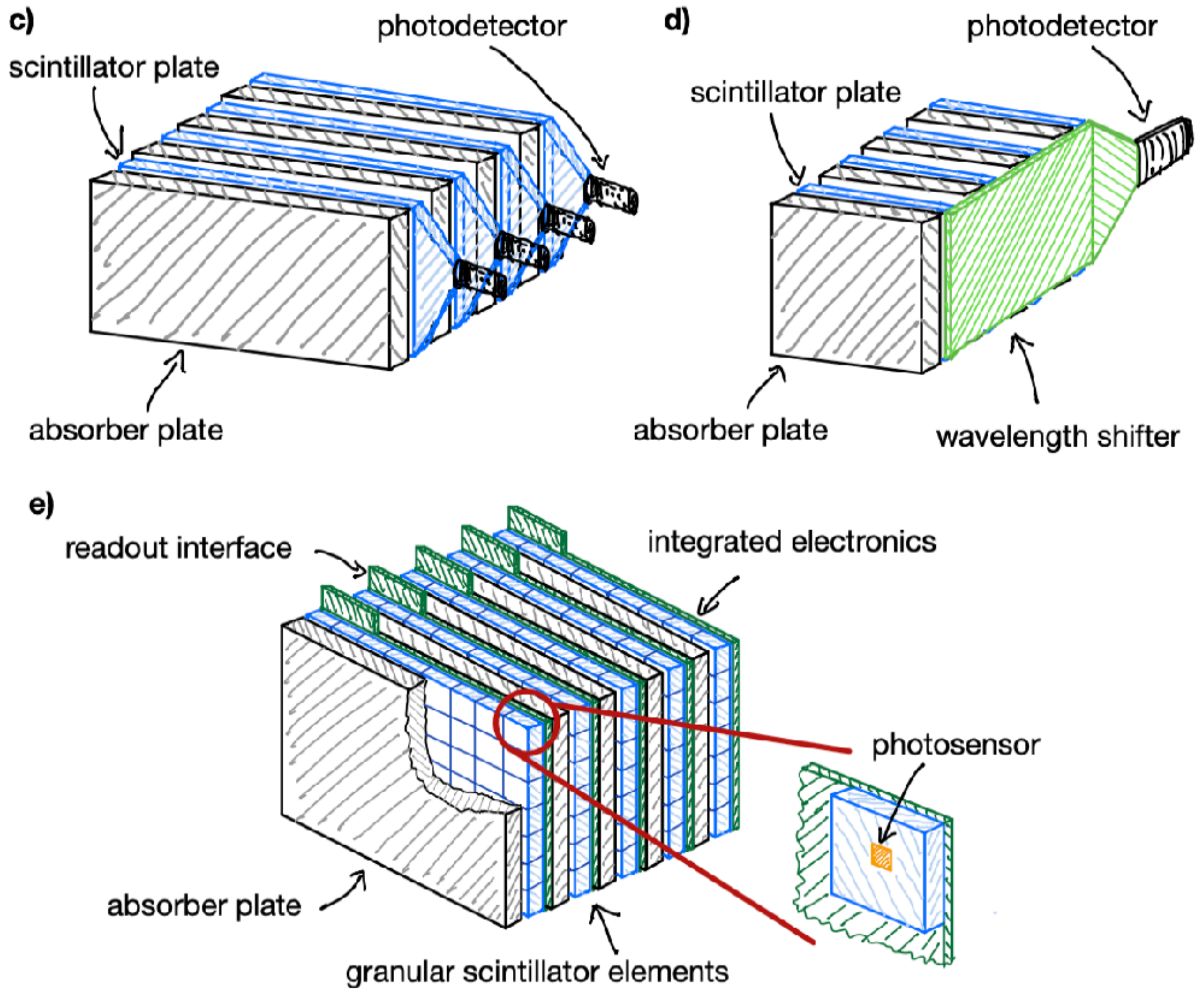
Basic choice for a cylindrical collider detector:

How to rout the signals out of the volume?

- radially
- axially
- tangentially

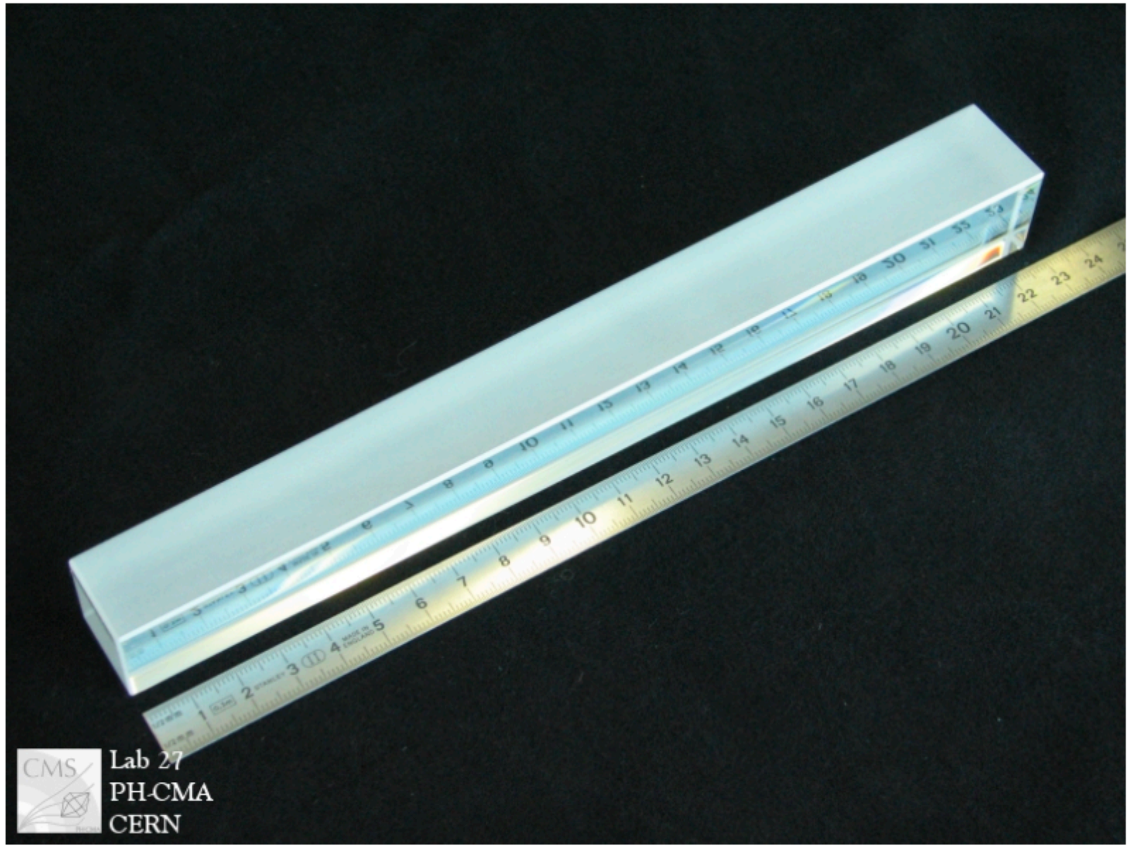
And where to place the interfaces?

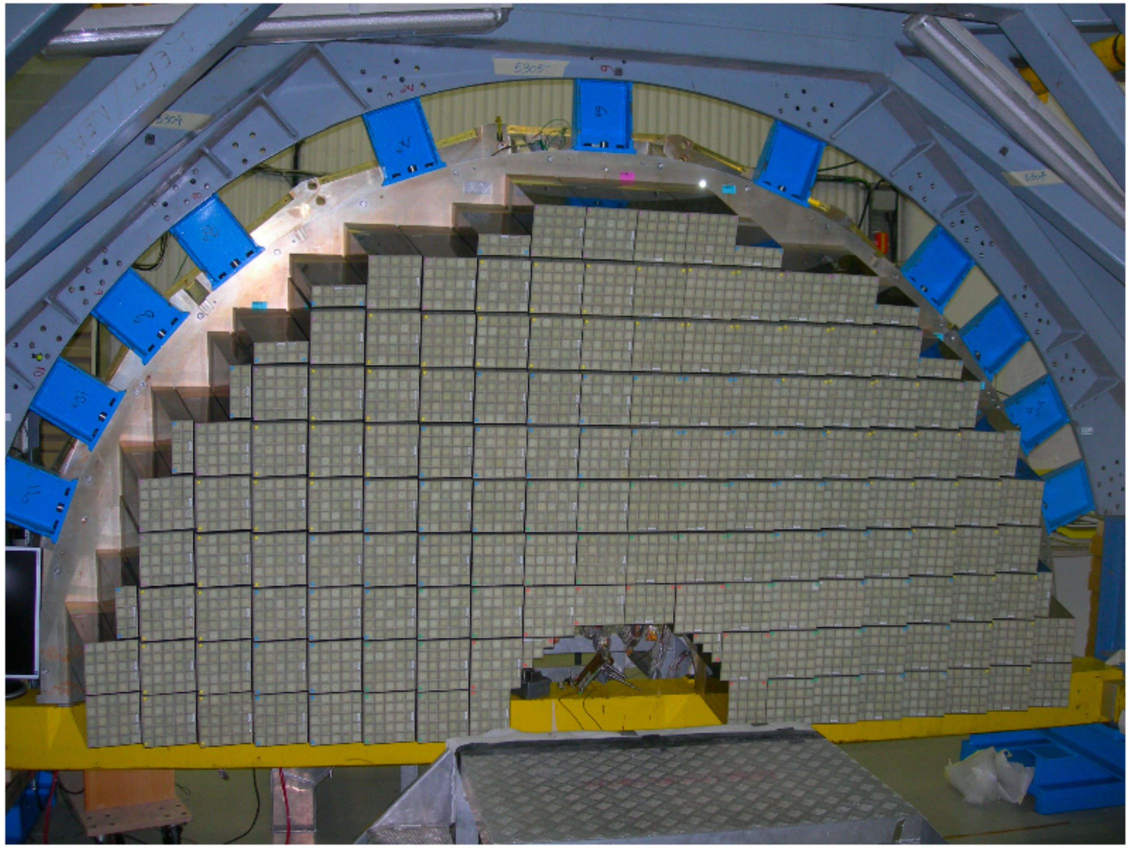
- on the barrel
  - outside ECAL, but in front of HCAL
- at the end face
  - creating a barrel endcap gap
- in certain barrel areas
  - elegant, but complex



ECAL Examples

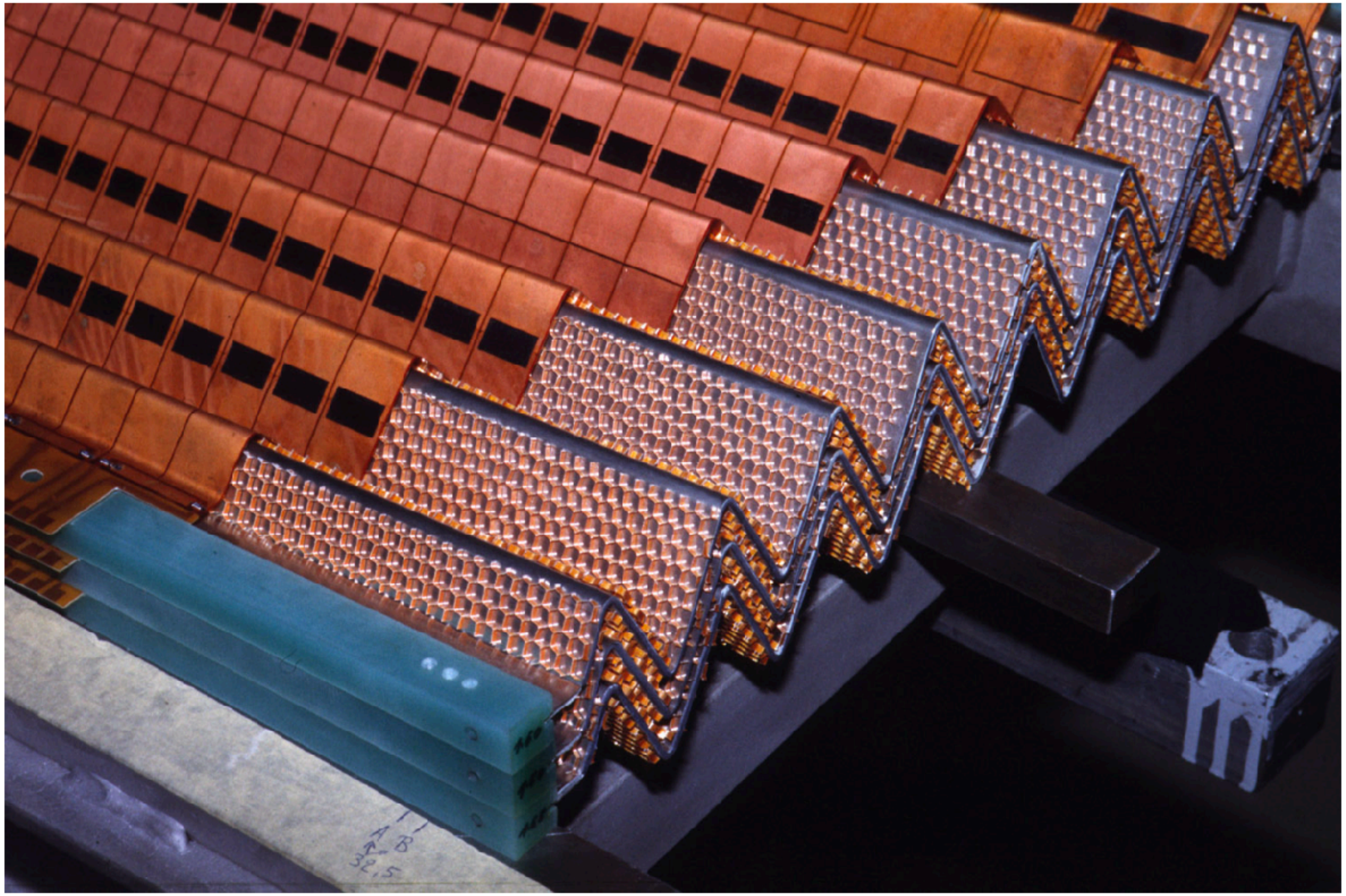
CMS Crystals





ECAL Examples

ATLAS LAr Akkordeon

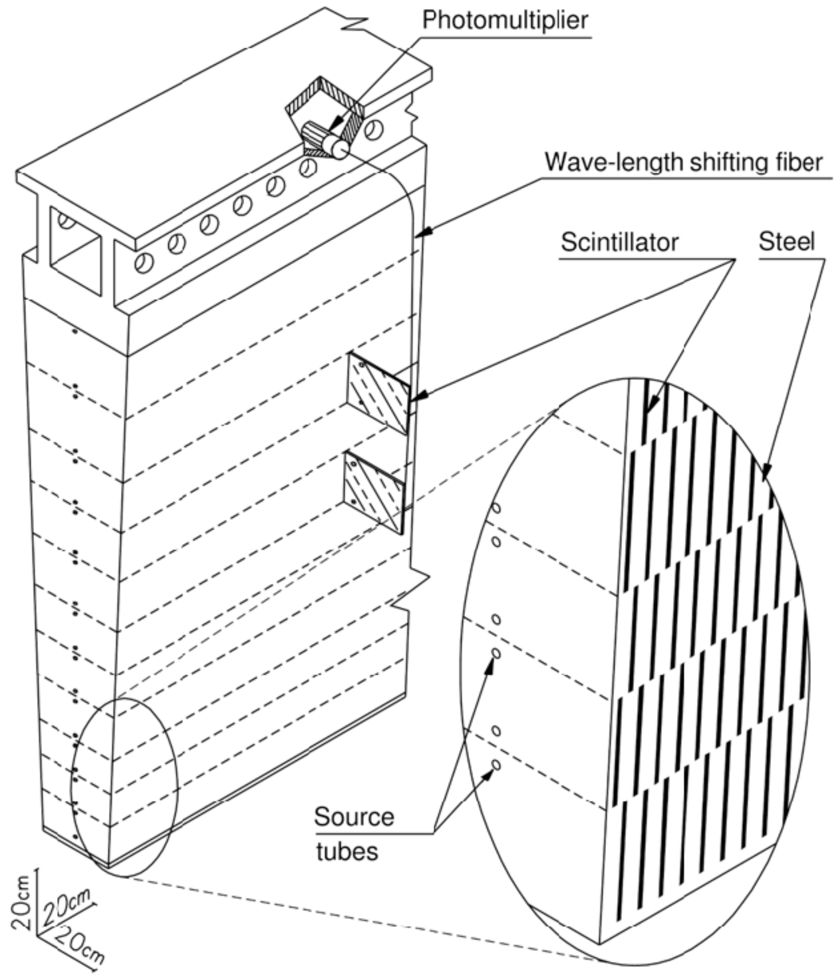


ECAL Performance

Selected Examples

experiment	technology	depth	e.m. energy resolution
	homogeneous calorimeters		
Belle	CsI(Ti)	16 X_0	1.7% for $E_\gamma > 3.5$ GeV
CMS	$PbWO_4$	26 X_0	$3.0\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$
	sampling calorimeters		
KLOE	Pb/scintillating fibres	15 X_0	$5.7\%/\sqrt{E} \oplus 0.1/E$
H1	Pb/LAr	20 – 30 X_0	$12.0\%/\sqrt{E} \oplus 1.0\%$
ZEUS	depleted U / plastic scintillator	20 - 30 X_0	$18\%/\sqrt{E}$
ATLAS	Pb/LAr	25 X_0	$10.0\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$

HCAL Example
ATLAS Tile HCAL

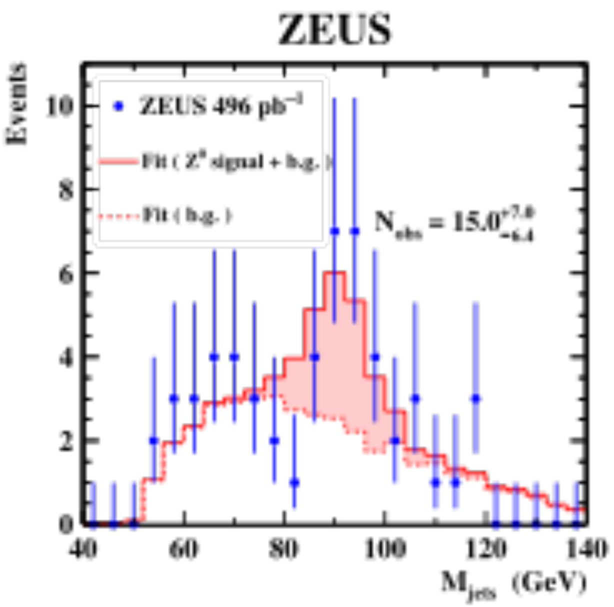


HCAL Performance

Topical Examples

experiment	technology (ECAL, HCAL)	combined hadronic energy resolution
H1	Pb/LAr, Steel / LAr	$46\%/\sqrt{E} \oplus 2.6\% \oplus 0.73/E$
ZEUS	depleted U / plastic scintillator	$35\%/\sqrt{E}$
ATLAS	Pb/LAr, Steel/plastic scintillator	$52\%/\sqrt{E} \oplus 3.0\% \oplus 1.6/E$
CMS	$PbWO_4$, brass/plastic scintillator	$84.7\%/\sqrt{E} \oplus 7.4\%$

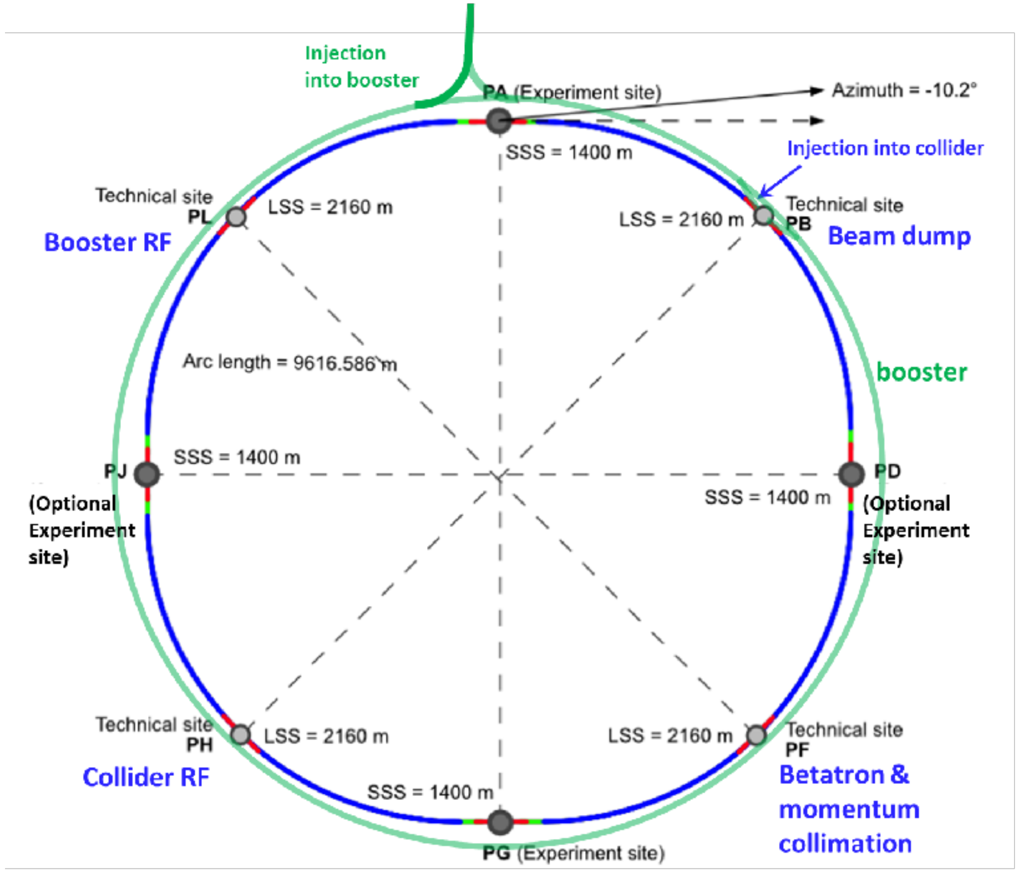
What counts is
ECAL HCAL combined performance
Often worse than HCAL alone:
ZEIS 60%, CMS 100%



Detector Requirements for the Next Large Collider

FCCee Parameters and Program

Challenges



FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	140	20	5.0	1.25
Bunch spacing	ns	25	160	680	5000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section	pb	70,000	30	10	8
Event rate	Hz	100,000	6	0.5	0.1
"Pile up" parameter [μ]	10^{-6}	2,500	1	1	1

ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$
$\bar{t}t$ threshold	$\sqrt{s}$ ~ 365 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	$\sqrt{s}$ = 125 GeV	5? years	~5000	$e^+e^- \to H_{125}$]

per IP

Detector Requirements from Physics

Ambitious

Higgs Factory Program
- 1.2M ZH events at √s = 240 GeV
- 75k WW→H events at $\sqrt{s}$ = 365 GeV
- Higgs Couplings
- Higgs self-couplings (2-4σ) via loop diagrams
- Unique: e+e- →H at $\sqrt{s}$ = 125 GeV

→

- **Momentum** Resolution $\frac{\sigma_{pT}}{p_T} \simeq 10^{-3}\ at\ p_T \sim 50\ \text{GeV}$.
- Jet **energy** resolution of 3-4% in multi-jet environment for Z/W separation
- **Impact** parameter resolution for *b, c* tagging

Precision EW and QCD Program
- 5 x 10^{12} Z and 10^8 WW events
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, m_W, Γ_W, …
- 10^6 tt events
  - m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics

→

- Absolute normalisation of **luminosity** to 10^{-4}.
- Relative normalisation to 10^{-5} (eg Γ_{had}/Γ_l)
- Momentum resolution, limited by **multiple scattering** → minimise material.
- Track angular resolution < 0.1 mrad
- Stability of **B-field** to 10^{-6}

Detector Requirements from Physics

Ambitious

Heavy Flavor Program
- 10^{12} bb, cc; 1.7 x 10^{11} $\tau\tau$ produced in a clean environment (10x Belle)
  - CKM matrix, CP measurements,
  - rare decays, CLFV searches, lepton universality

→

- Superior impact parameter resolution
  - Precisely dentify secondary vertices and measure **lifetimes**
- **ECAL** resolution at few $\%/\sqrt{E}$
- Excellent π^0/γ separation for **tau identification**
- **Particle ID**: K/π separation over a wide momentum range → e.g. by precision 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 lifetimes LLPs

→

- Sensitivity to **far detached vertices**
  - Tracking: more layers, “continuous" tracking
  - **Calorimeter**: granularity, tracking capability
- Large decay length → extended decay volume
- Precise **timing**
- **Hermeticity**

From Linear to Circular e+e- Detectors

Conceptual Adaptations

Lower energy jets and particles, less collimated jets:

- reduced calorimeter depth
- shift imaging vs. energy resolution balance towards the latter
  - jet assignment ambiguities: added value of $\pi^0 \rightarrow \gamma\gamma$ mass reconstruction
- tracking even more multiple-scattering dominated: increased pressure on material budget of vertex detector and main tracker
  - fresh air to gaseous tracking

Limitations on solenoidal field B < 2T, to preserve luminosity:

- recover momentum resolution with tracker radius
- on the other hand larger magnetic volume also more easily affordable (coil and yoke)

Main difference: no bunch trains; collisions every 20 ns (~ at LHC)

- no power pulsing, more data bandwidth: both imply larger powering and cooling needs
- adds material to the trackers and compromises calorimeter compactness - or reduce granularity, timing, speed
- implications strongly technology-dependent, interesting optimisation challenges
- **Trigger and DAQ re-enter the stage**

From Linear to Circular e+e- Detectors

Conceptual Adaptations

FCCee has many common challenges with ILC plus significant additional ones

Lower energy jets and particles, less collimated jets:

- reduced calorimeter depth
- shift imaging vs. energy resolution balance towards the latter
  - jet assignment ambiguities: added value of $\pi^0 \rightarrow \gamma\gamma$ mass reconstruction
- tracking even more multiple-scattering dominated: increased pressure on material budget of vertex detector and main tracker
  - fresh air to gaseous tracking

Limitations on solenoidal field B < 2T, to preserve luminosity:

- recover momentum resolution with tracker radius
- on the other hand larger magnetic volume also more easily affordable (coil and yoke)

Main difference: no bunch trains; collisions every 20 ns (~ at LHC)

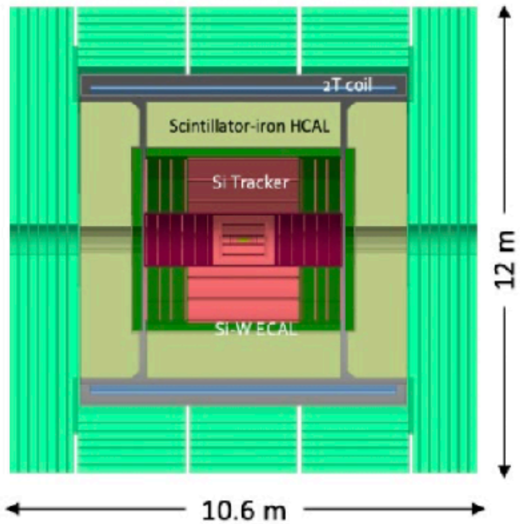
- no power pulsing, more data bandwidth: both imply larger powering and cooling needs
- adds material to the trackers and compromises calorimeter compactness - or reduce granularity, timing, speed
- implications strongly technology-dependent, interesting optimisation challenges
- **Trigger and DAQ re-enter the stage**

Detector Concepts and DRD Collaborations

FCCee Detector Concepts

Strawman Detector Benchmarks

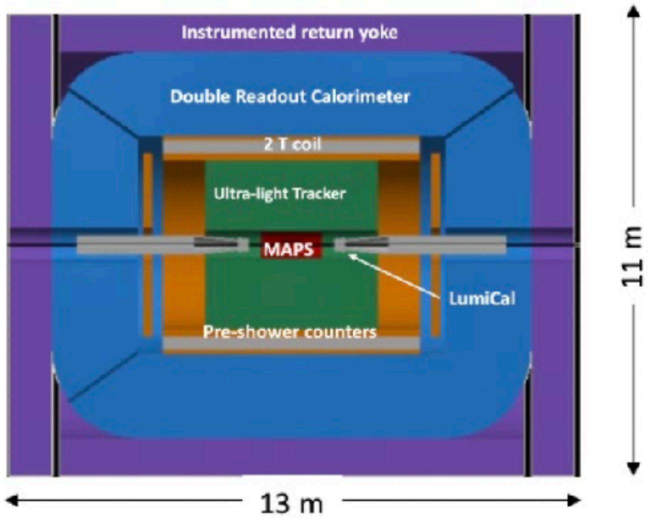
CLD



- 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
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

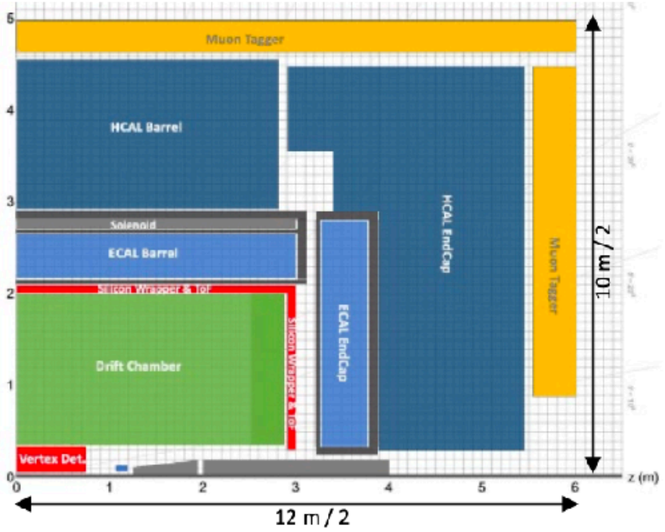
CDR

IDEA



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

ALLEGRO

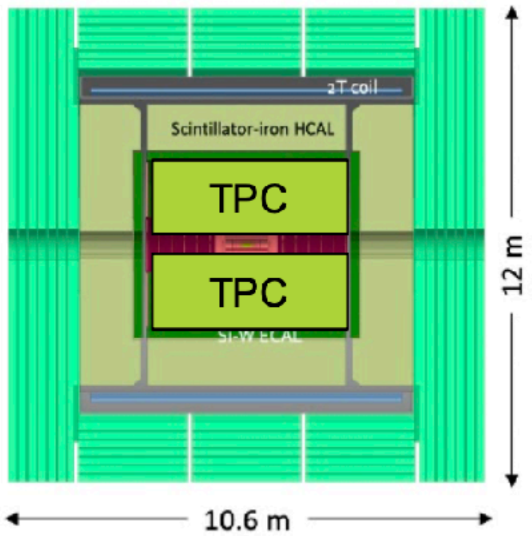


- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout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

FCCee Detector Concepts

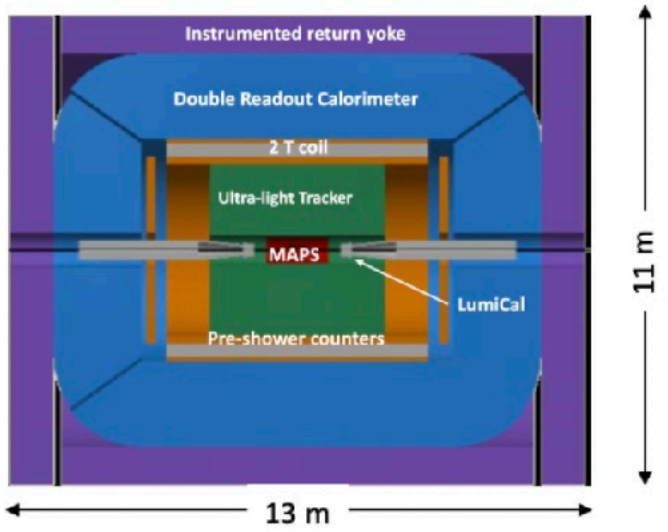
Strawman Detector Benchmarks

CLD/ILD'



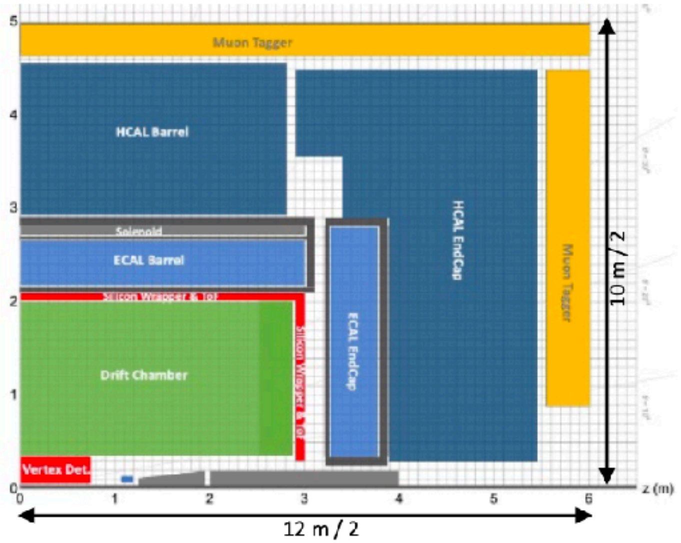
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker, study TPC option viability
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector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

IDEA



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

ALLEGRO

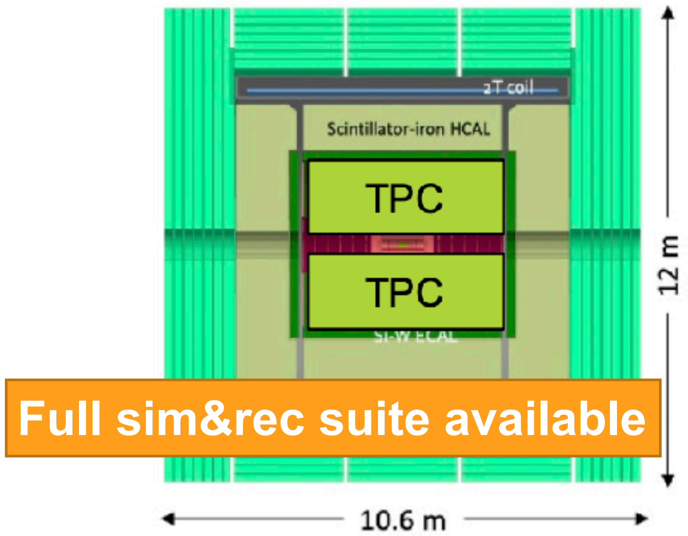


- The "new kid on the block"
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout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

FCCee Detector Concepts

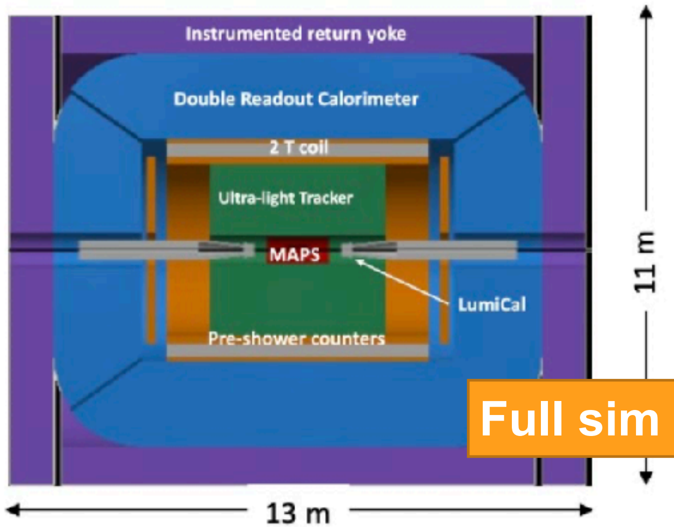
Strawman Detector Benchmarks

CLD/ILD'



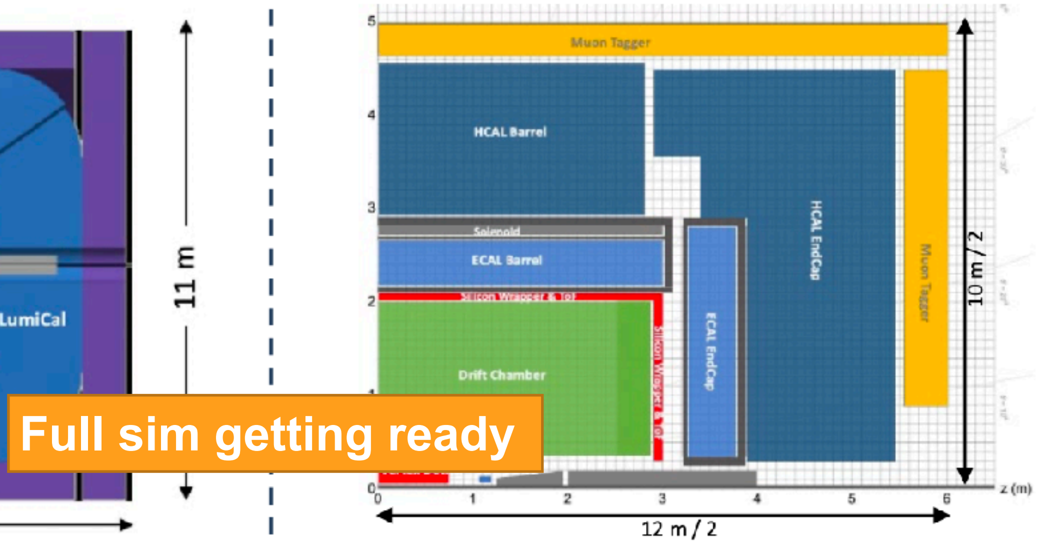
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker, study TPC option viability
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector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

IDEA



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

ALLEGRO



- The "new kid on the block"
- 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

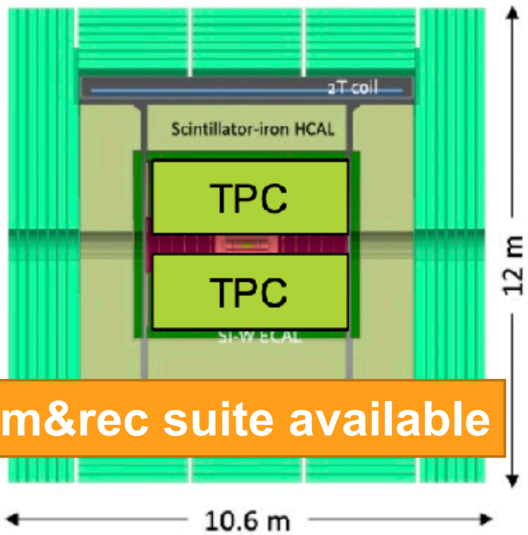
- CLD: https://arxiv.org/abs/1911.12230
- IDEA: https://pos.sissa.it/390/819
- ALLEGRO: Eur.Phys.J.Plus 136 (2021) 10, 1066, https://arxiv.org/abs/2109.00391

FCCee Detector Concepts

Strawman Detector Benchmarks

- 3 calorimeters
- 1-2 gaseous trackers
- 0-1 silicon tracker
- 1 vertex detector

CLD/ILD'

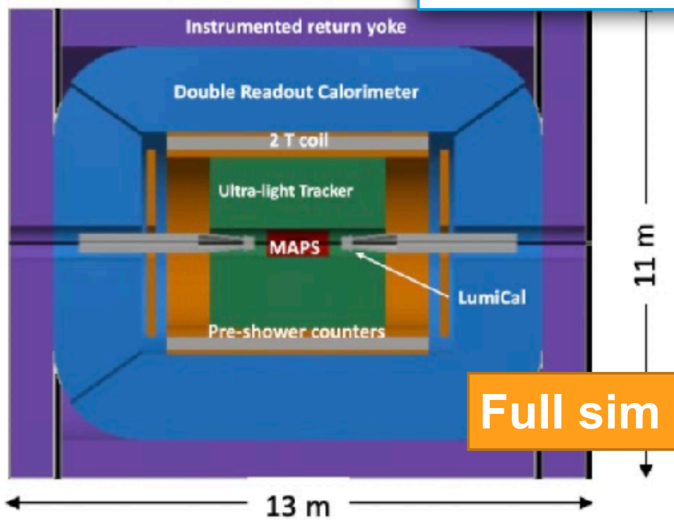


Full sim&rec suite available

CDR

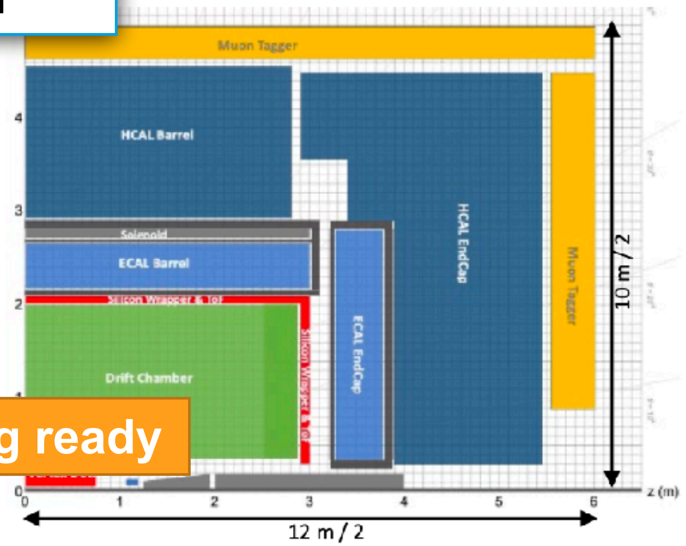
- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker, study TPC option viability
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector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

IDEA



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

ALLEGRO



Full sim getting ready

- The "new kid on the block"
- 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

- CLD: https://arxiv.org/abs/1911.12230
- IDEA: https://pos.sissa.it/390/819
- ALLEGRO: Eur.Phys.J.Plus 136 (2021) 10, 1066, https://arxiv.org/abs/2109.00391

Calorimeter Technologies

Main directions

All concepts aim at Particle Flow reconstruction

- with different emphasis on granularity, energy resolution, stability

Liquid Argon + tiles

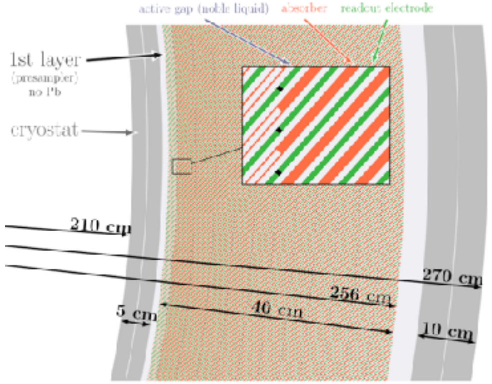
- finer longitudinal sampling wrt ATLAS (4→12)
- warm or cold electronics
- CALICE or ATLAS style scintillator tile HCAL

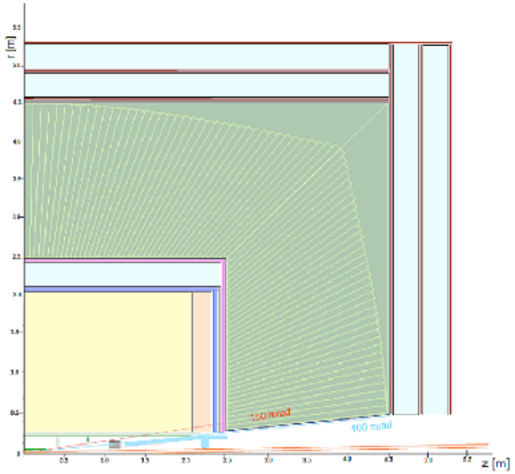
Fibre-based Dual Read-out with crystals in front

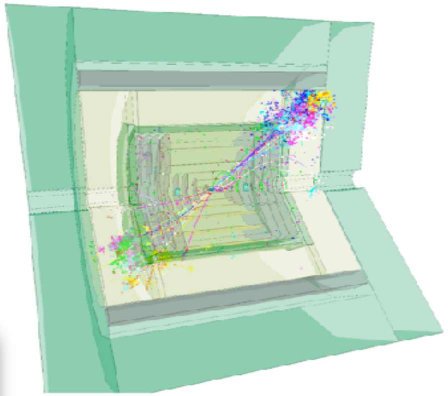
- copper or steel matrix, Cherenkov and scintillating fibres, SiPMs
- pointing geometry, superior PID
- longitudinal segmentation via timing

CALICE-style sandwich with embedded front-end electronics

- silicon (pads or MAPS) ECAL, SiPM-on-Tile HCAL
  - alternatives: strip ECAL, gas HCAL
- LC technology to be re-invented: no power-pulsing
- synergies with CMS HGCAL upgrade







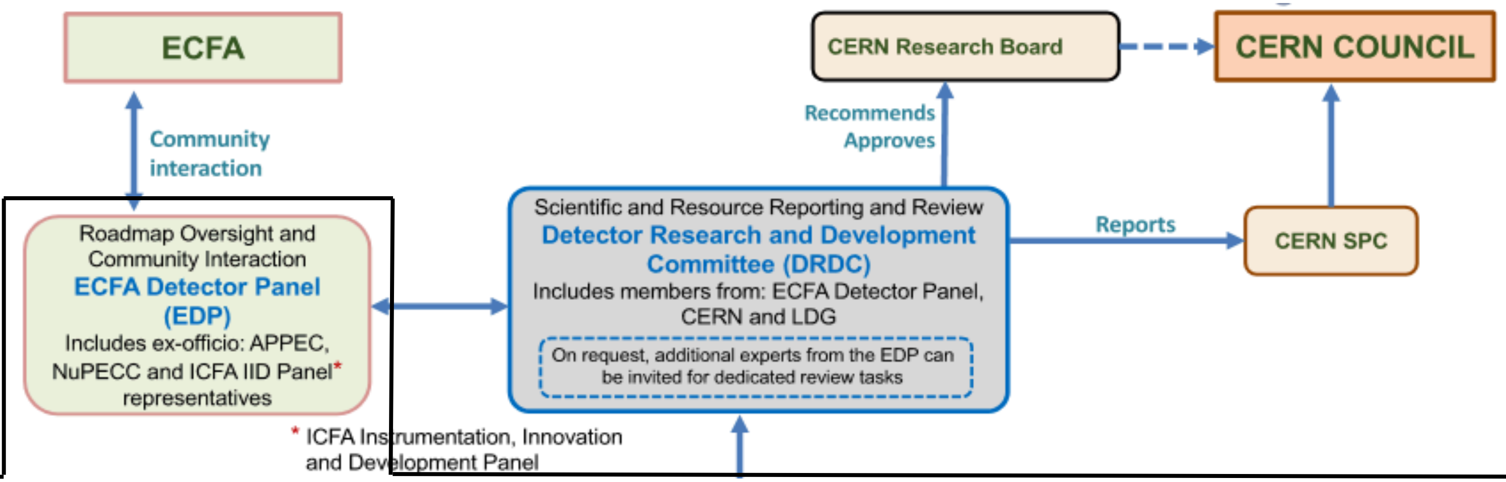
- Eur.Phys.J.Plus 136 (2021) 10, 1066, https://arxiv.org/abs/2109.00391

New DRD collaborations hosted at CERN (framework)

follows general conditions for execution of experiments at CERN

EDP web page
- contact point for the community

EDP/DRD Managers Forum
- common issues



DRD1 ✓	Gaseous Detector	M. Titov, E. Oliveri
DRD2 ✓	Liquid Detector	R. Guenette, J. Monroe
DRD3 ✓	Solid State Detector	G. Kramberger, G. Pellegrini
DRD4 ✓	Photon det. and PID	M.Fiorini, G. Wilkinson
DRD5 ✓	Quantum, emerging techno.	M. Demarteau, M. Doser
DRD6 ✓	Calorimetry	R. Poeschl, R. Ferrari
DRD7 ✓	Electronics on-detector processing	F. Simon, F. Vasey
DRD8 ✓	Mechanics and Integration	B. Schmidt, A. Mussgiller

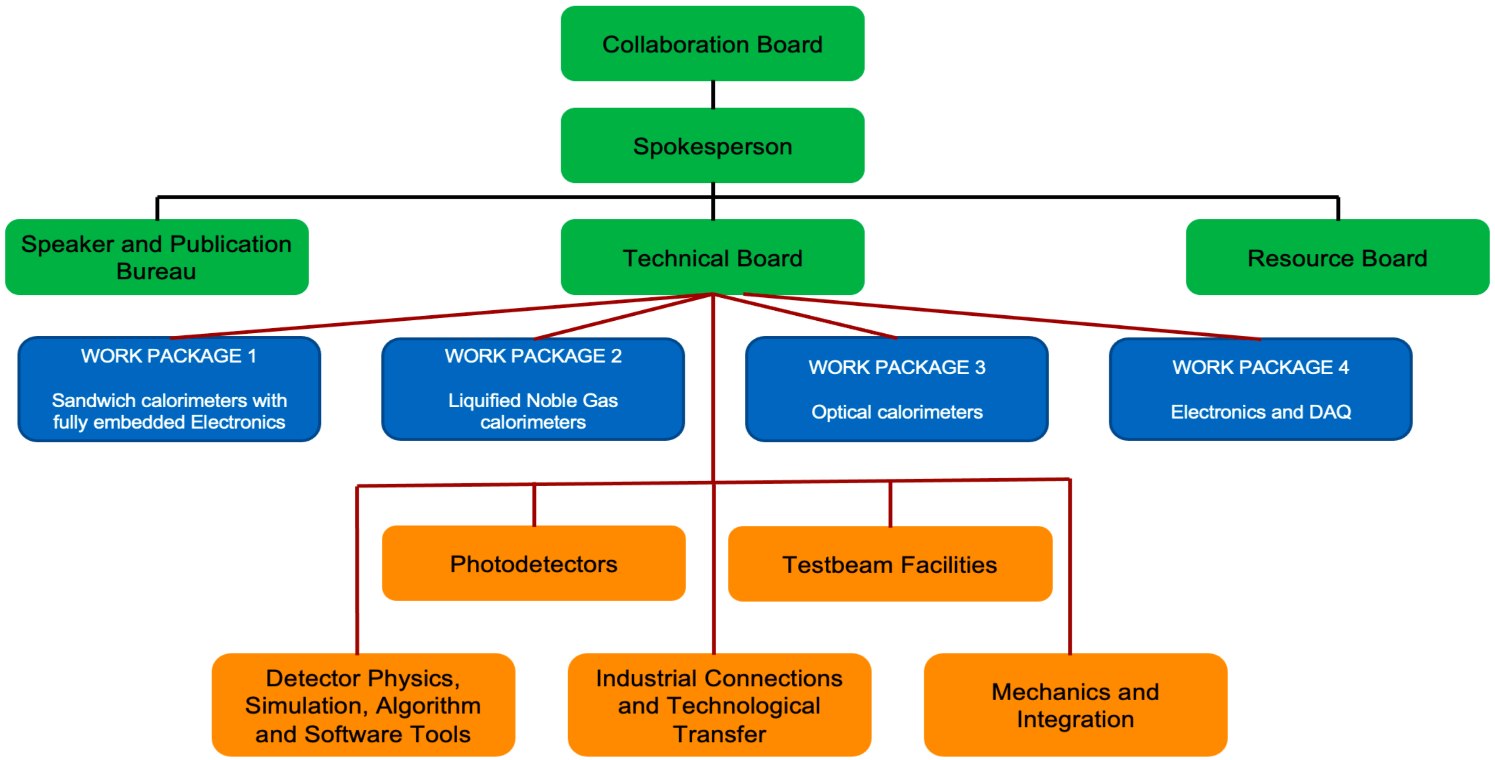
✓ Approved by CERN RB*, ✓ DRD8 LoI submitted to DRDC, proposal aims end-2024

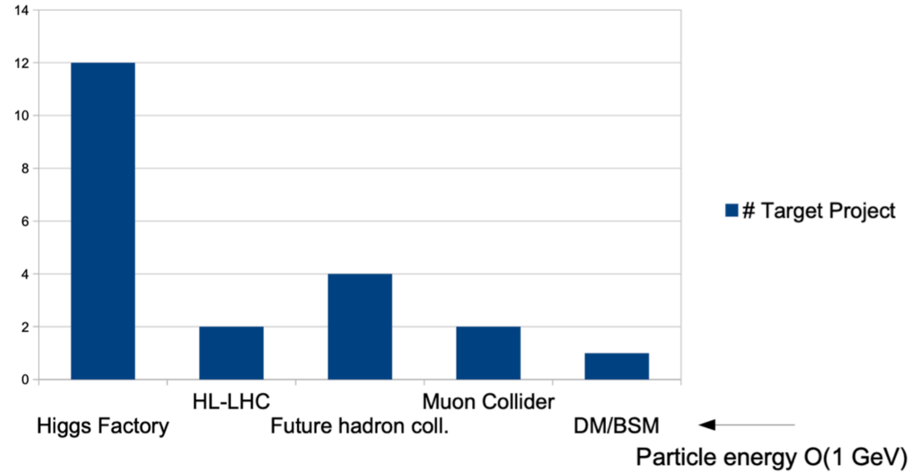
DRDC wep page and presentations of DRDs at open sessions

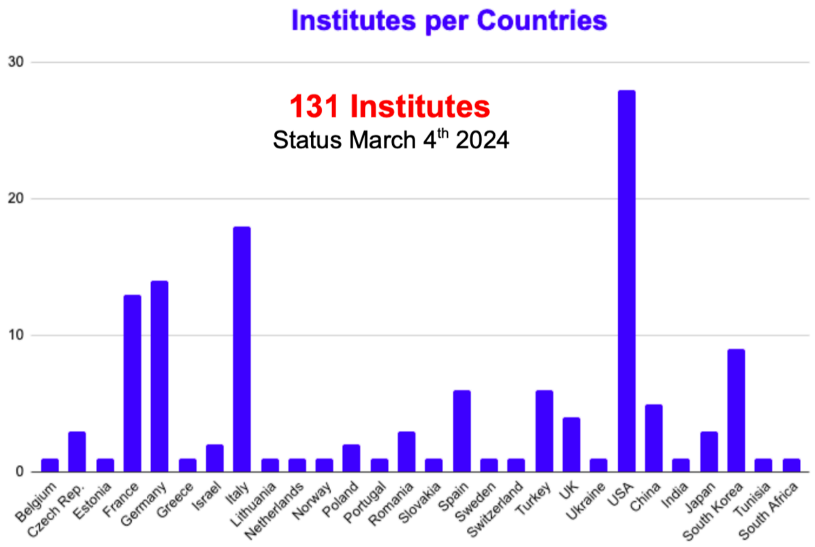
** approvals cover a period of three years – to be renewed*

DRD 6 - Calorimetry

Higgs Factory Driven

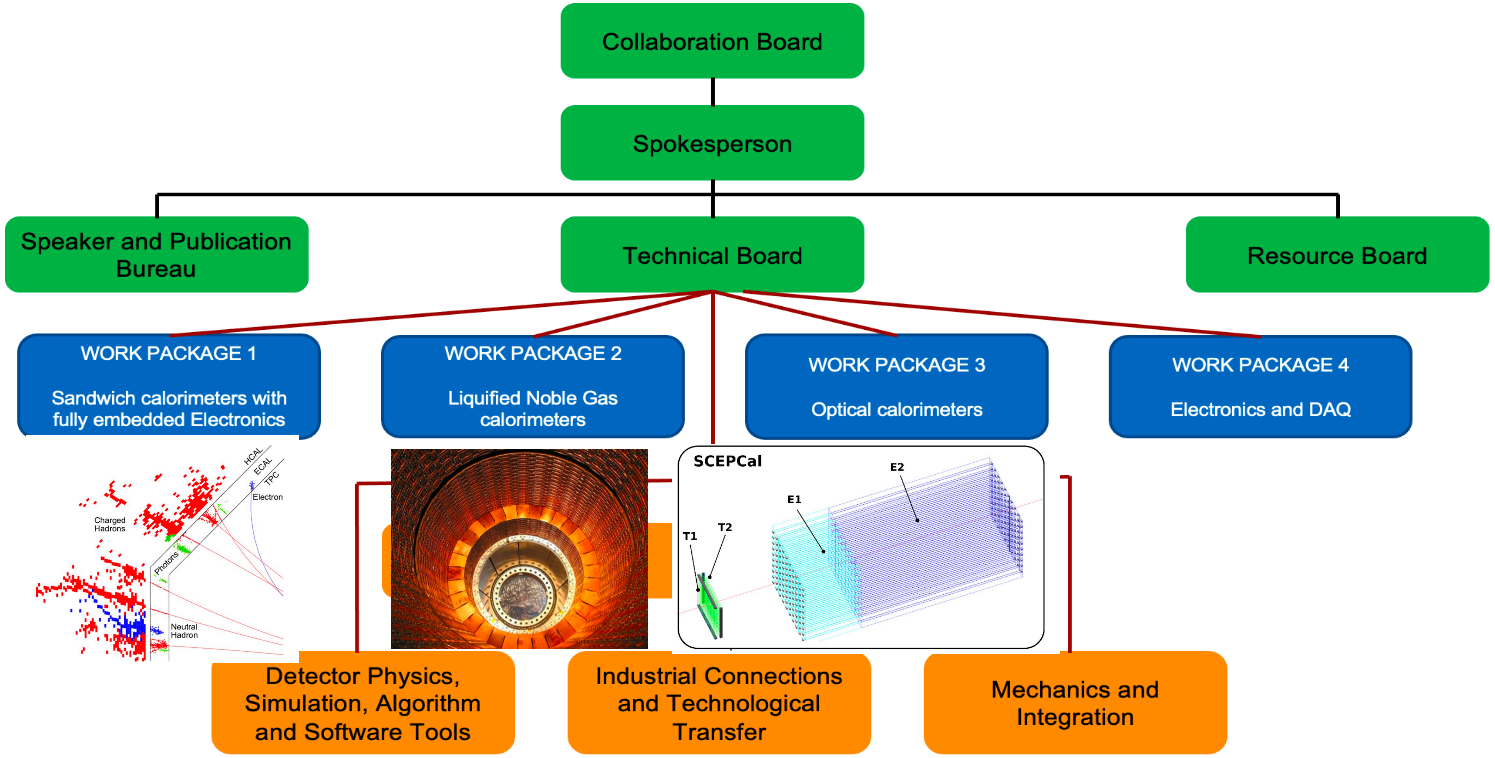


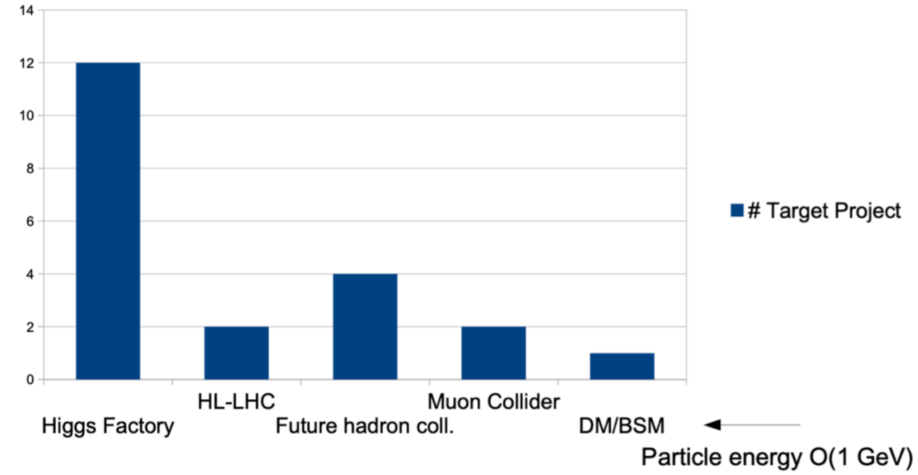


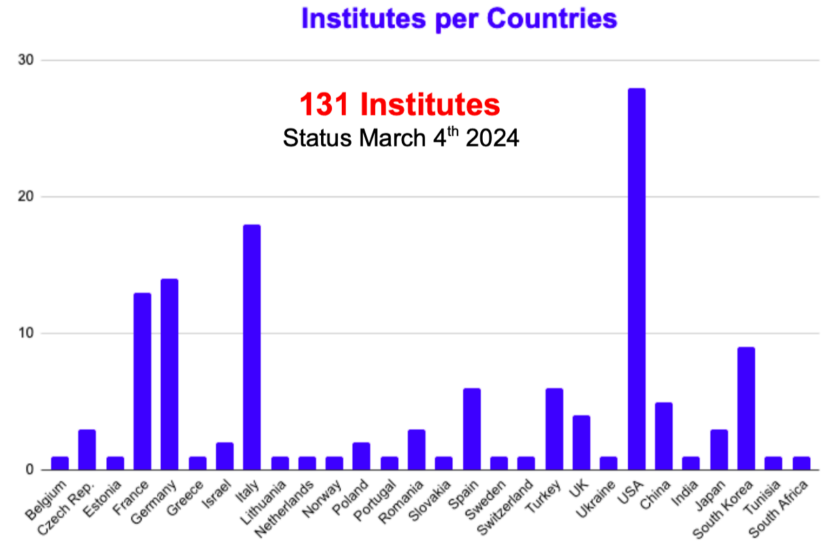


DRD 6 - Calorimetry

Higgs Factory Driven



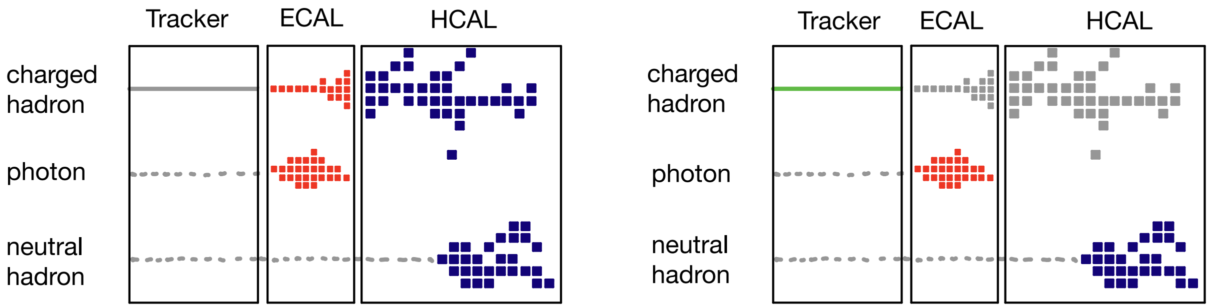


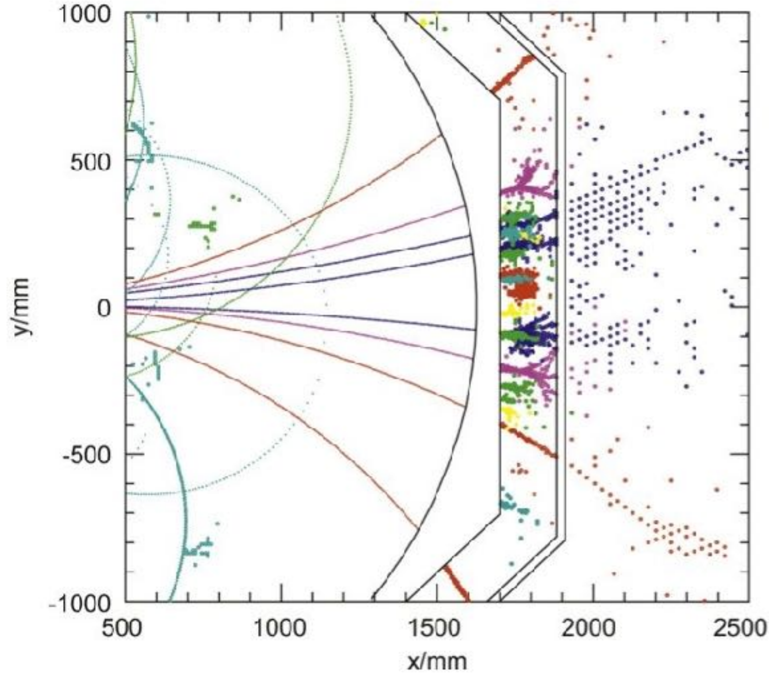


Particle Flow and High Granularity

Particle Flow Principle

CALICE and Followers





Typical jet: 60% charged, 10% neutral hadrons

- use tracker where possible
- used in ATLAS and CMS

Need to disentangle energy depositions, using topology <u>and</u> energy

- requires excellent imaging and decent energy performance
- even in ideal case the 10% neutral hadrons dominate the jet energy resolution

Requires excellent imaging capabilities

- 10’s or 100’s of millions of channels

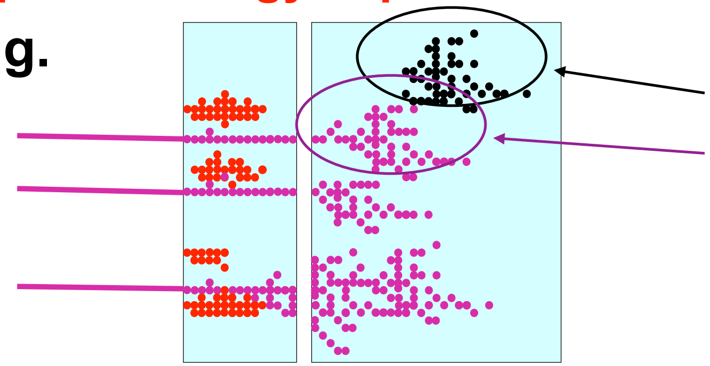
Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

e.g.

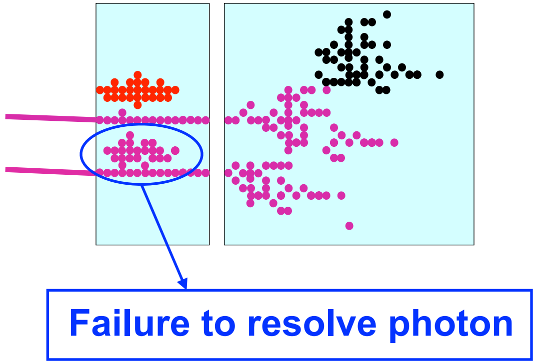


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

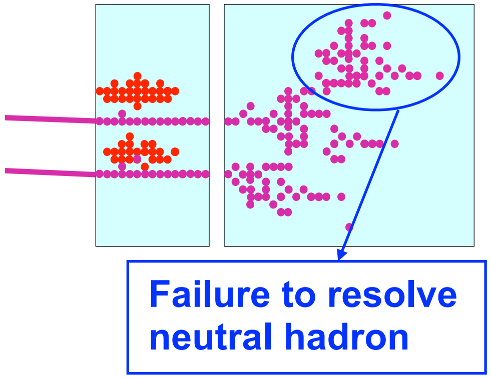
Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

Three types of confusion:

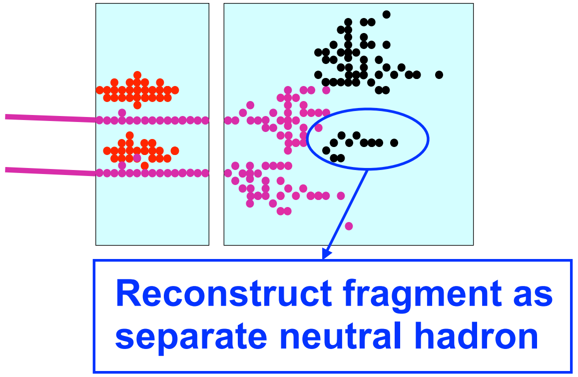
i) Photons



ii) Neutral Hadrons

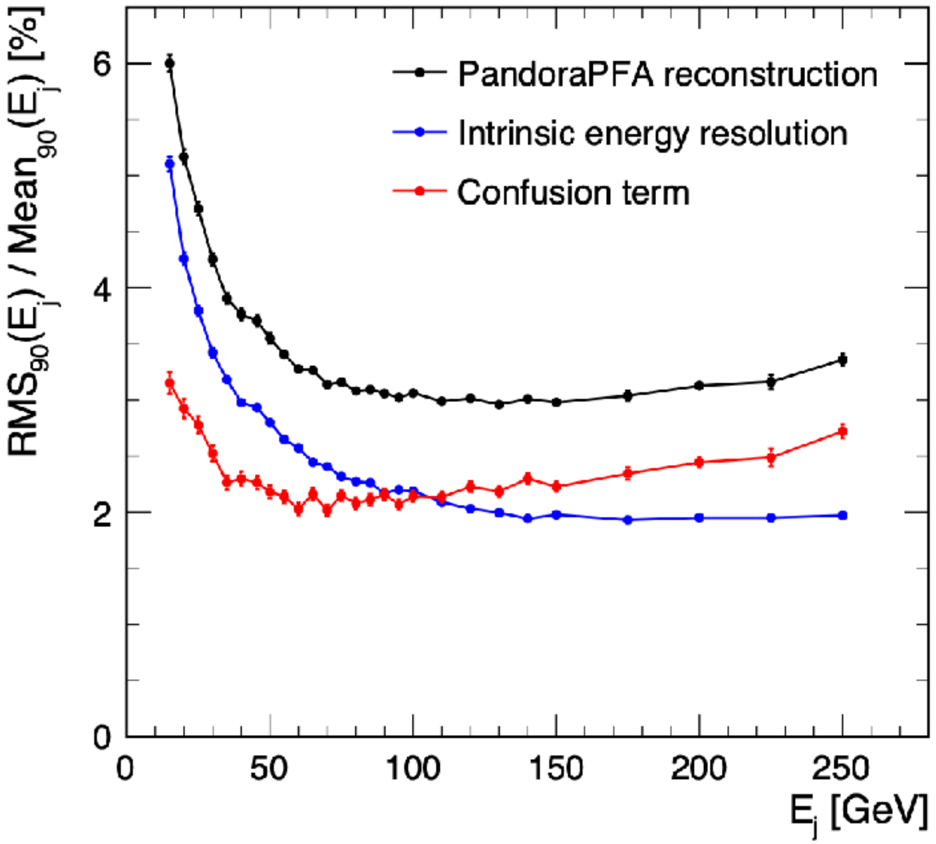


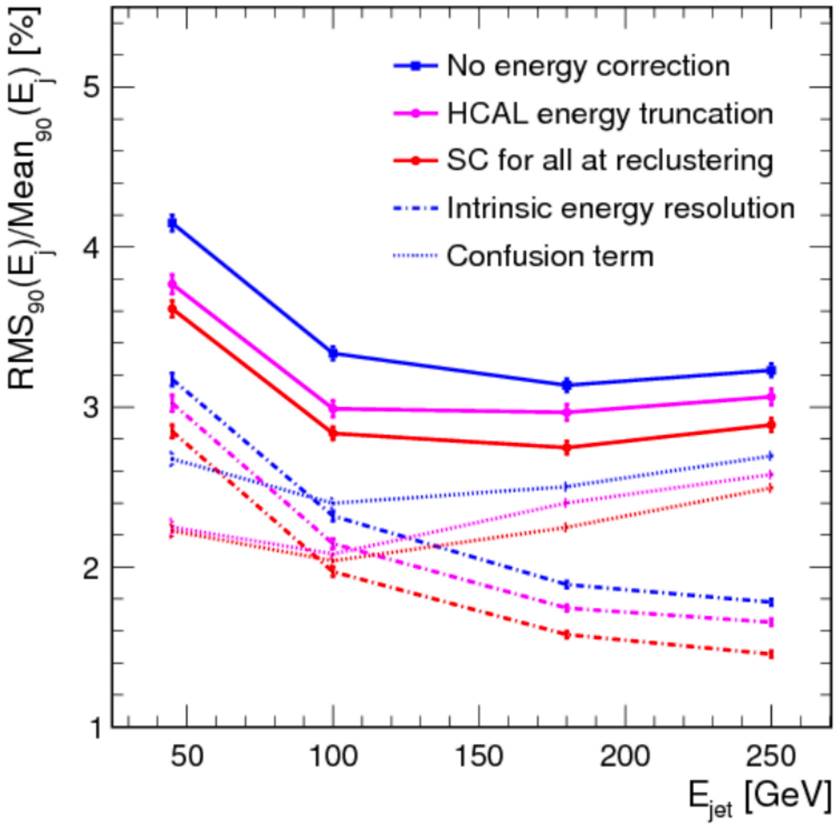
iii) Fragments



Particle Flow Performance

Realistically





Intrinsic energy resolution relevant at low **and** at high jet energies

High Granularity

Multiple Benefits

High granularity becomes possible thanks too advances in micro-electronics integration

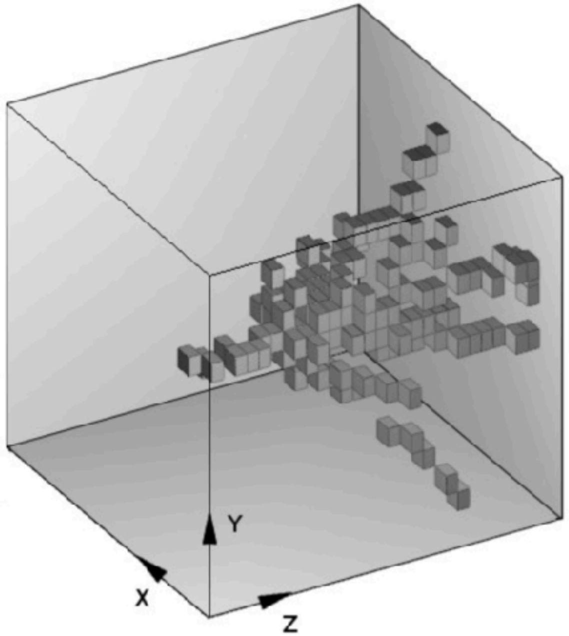
- cost of sandwich calorimeters scales with active area rather than channel count

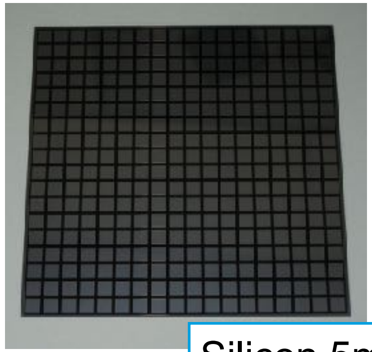
Benefits beyond particle flow

- imaging for particle ID
- software compensation
- pile-up rejection

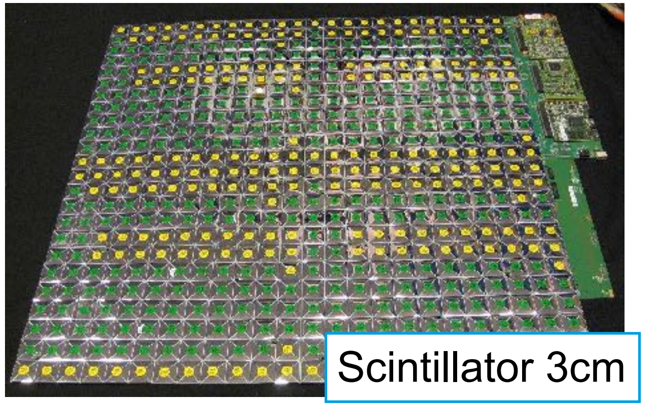
Signal over noise for small cells

- lower noise e.g. for silicon or LAr
- more signal from scintillators

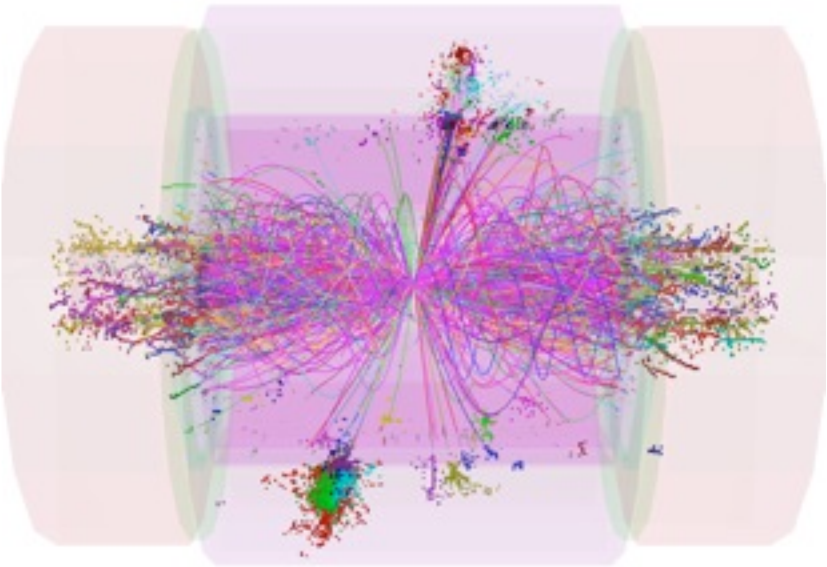




Silicon 5mm



Scintillator 3cm



High Granularity

Multiple Benefits

High granularity becomes possible thanks too advances in micro-electronics integration

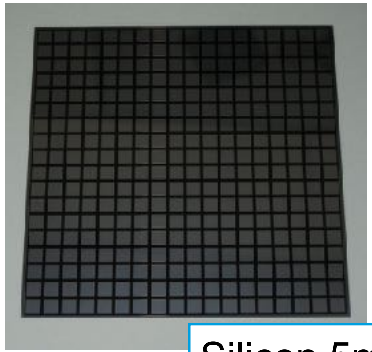
- cost of sandwich calorimeters scales with active area rather than channel count

Benefits beyond particle flow

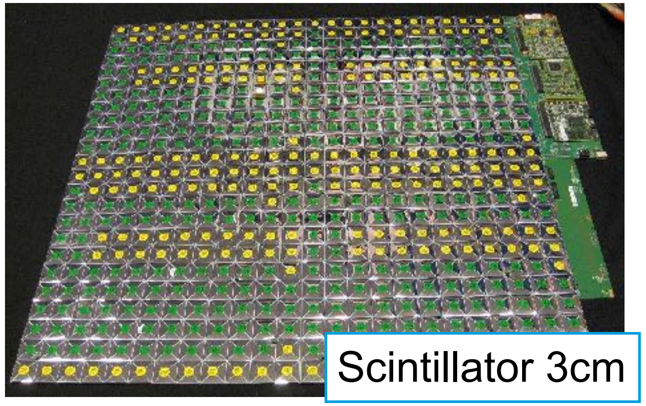
- imaging for particle ID
- software compensation
- pile-up rejection

Signal over noise for small cells

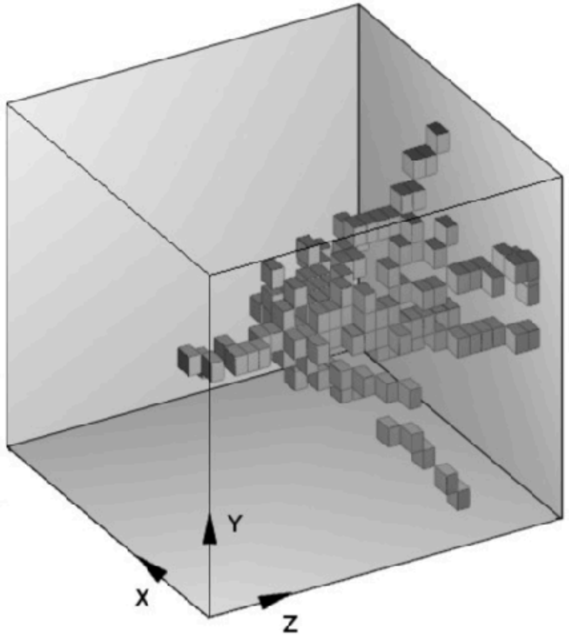
- lower noise e.g. for silicon or LAr
- more signal from scintillators

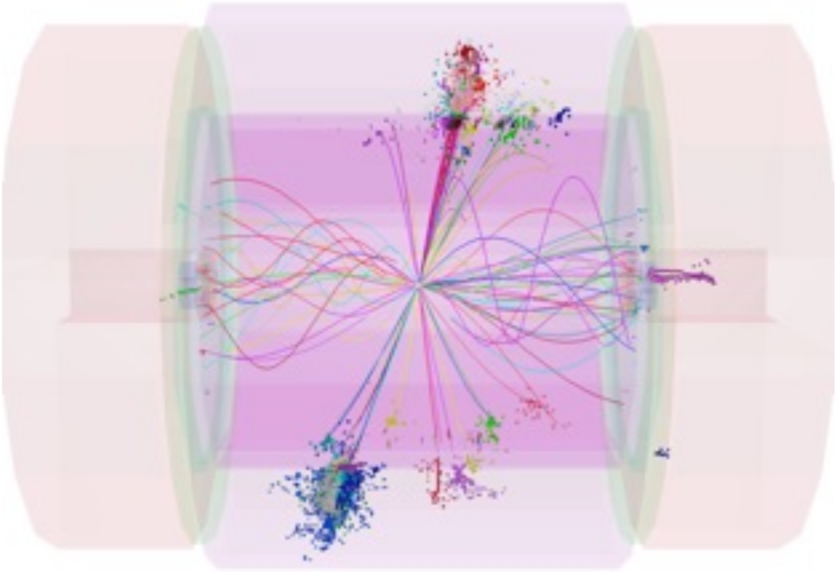


Silicon 5mm



Scintillator 3cm





CMS High Granularity Calorimeter

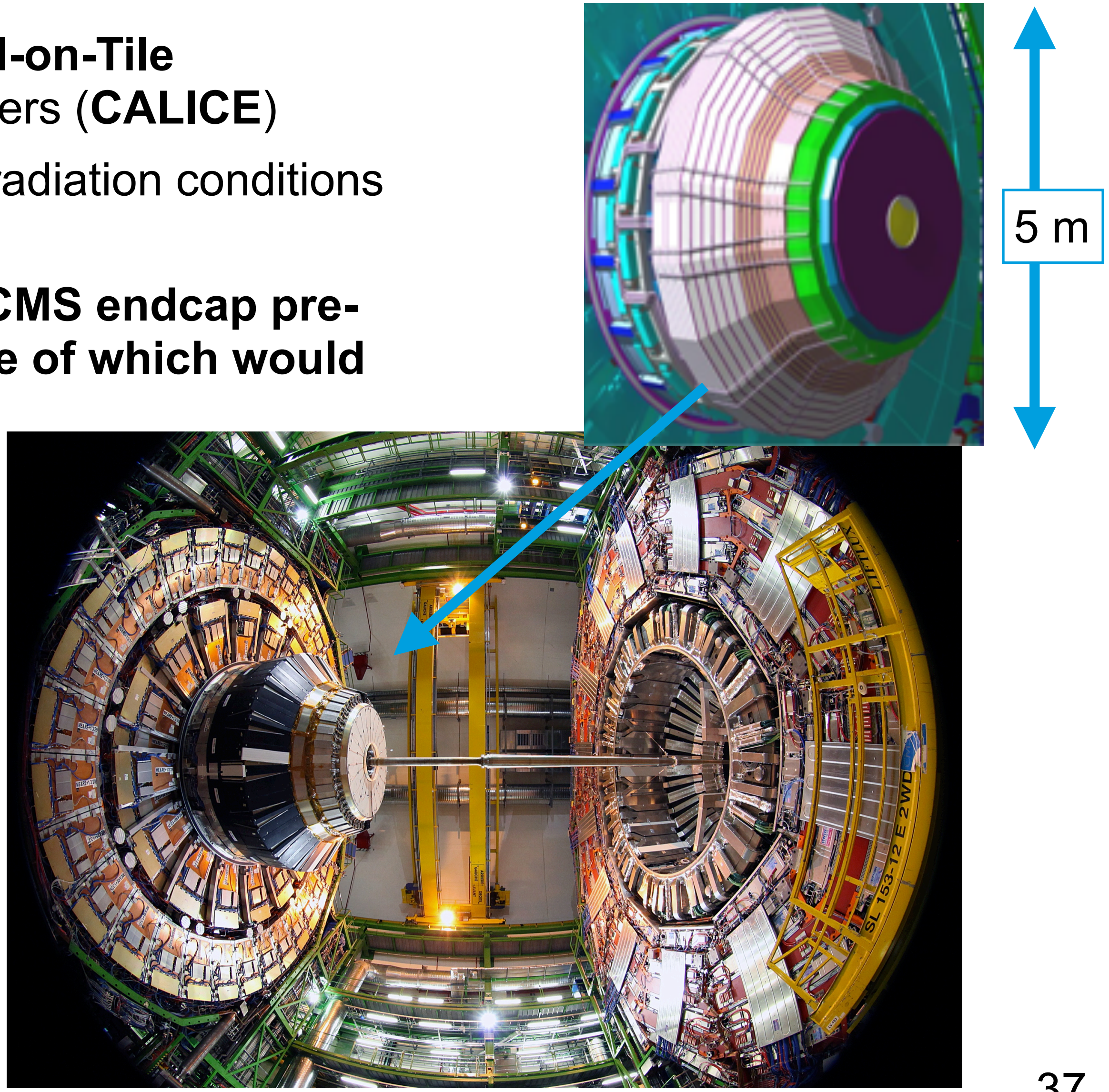
High Granularity for the High Luminosity LHC

CMS Phase 2 Upgrade

Highly granular calorimeters based on Silicon and SiPM-on-Tile technologies were originally developed for future e+e- colliders (**CALICE**)

They are also among the very few possible choices for the radiation conditions at the upgraded LHC.

High Granularity Calorimeter HGCAL: replace existing CMS endcap pre-shower, electromagnetic and hadronic calorimeter, none of which would remain performant at the HL-LHC.



Higher luminosity at the energy frontier AND better detectors - new physics capabilities

Emphasis moves to vector boson fusion initiated processes: **WW collider**

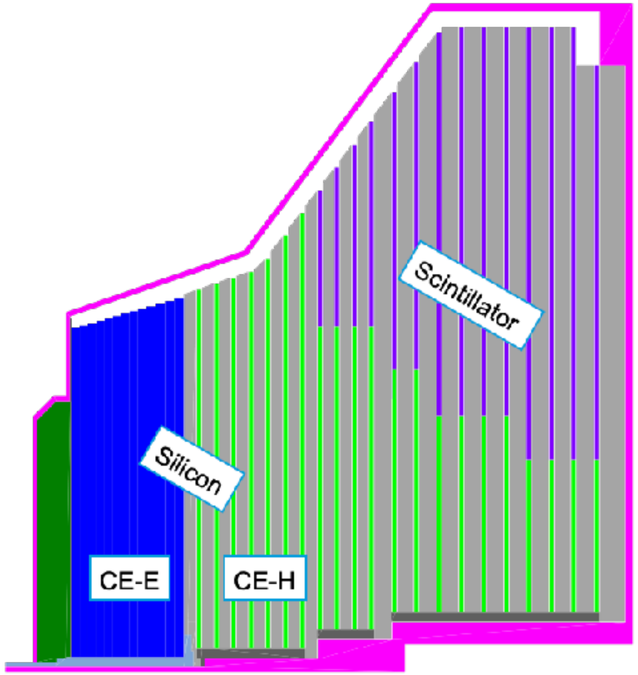
Narrow and merged jets

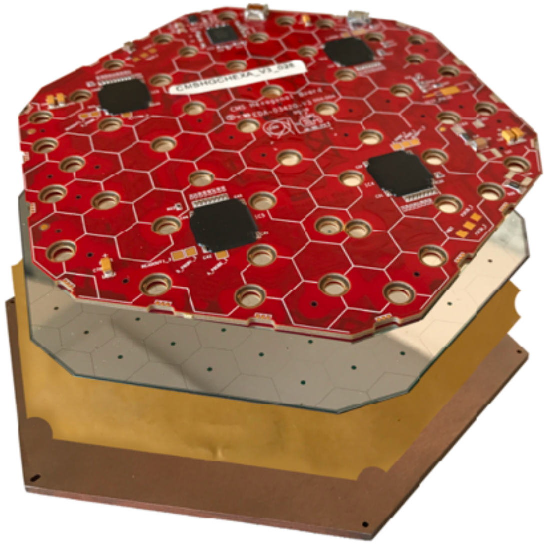
tagging quark jet in the endcap

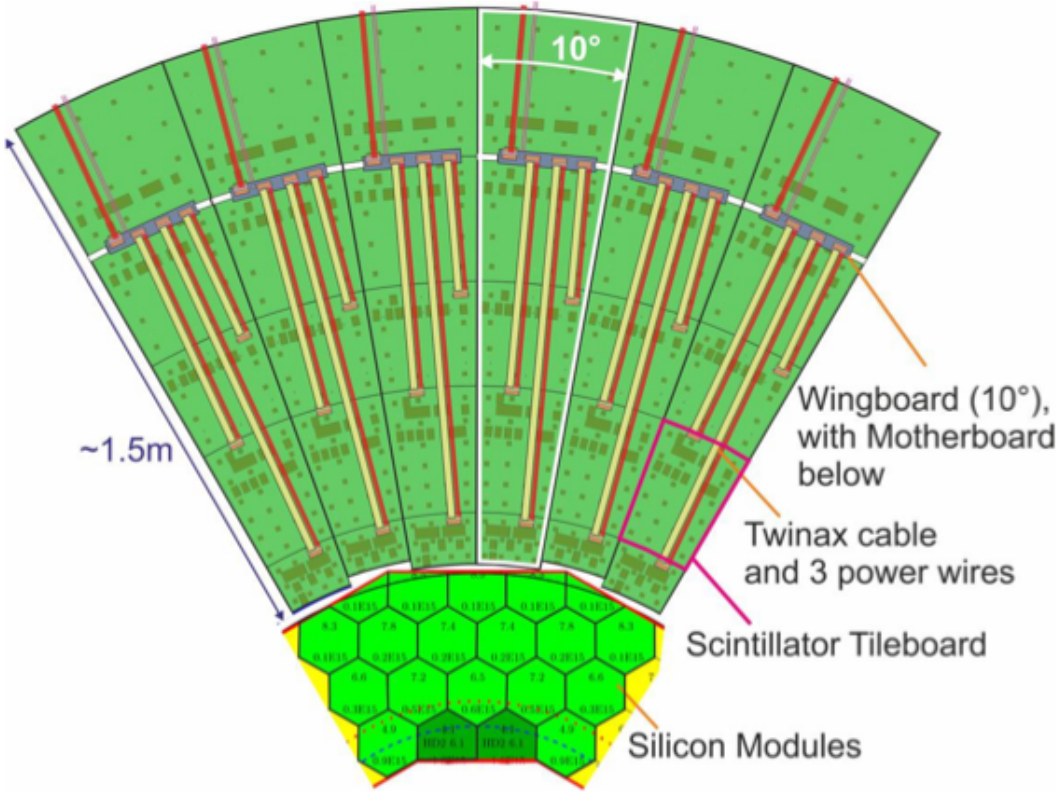
HGCAL shall see 90% of the total LHCs luminosity

SiPM-on-Tile System Overview

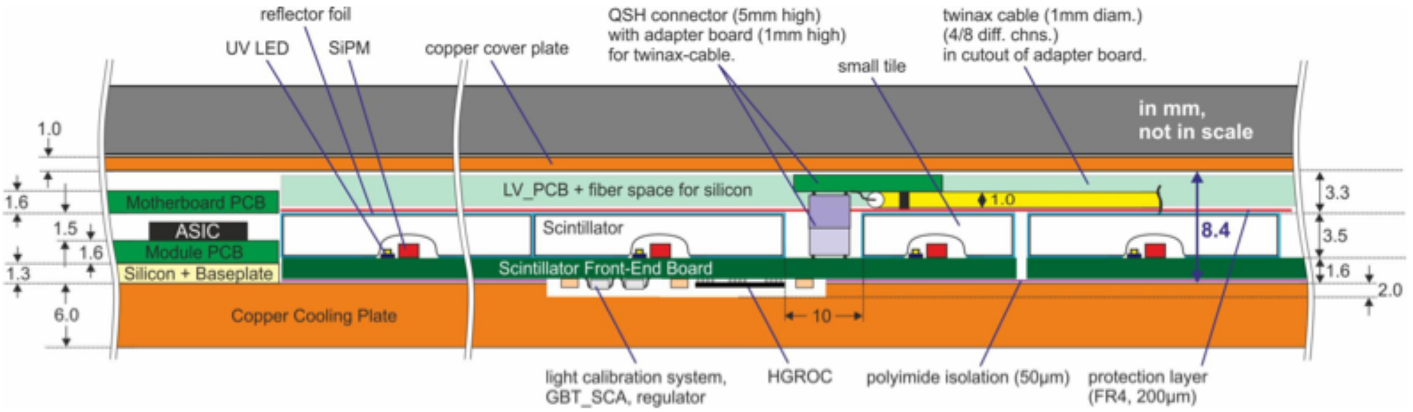
Main ingredients





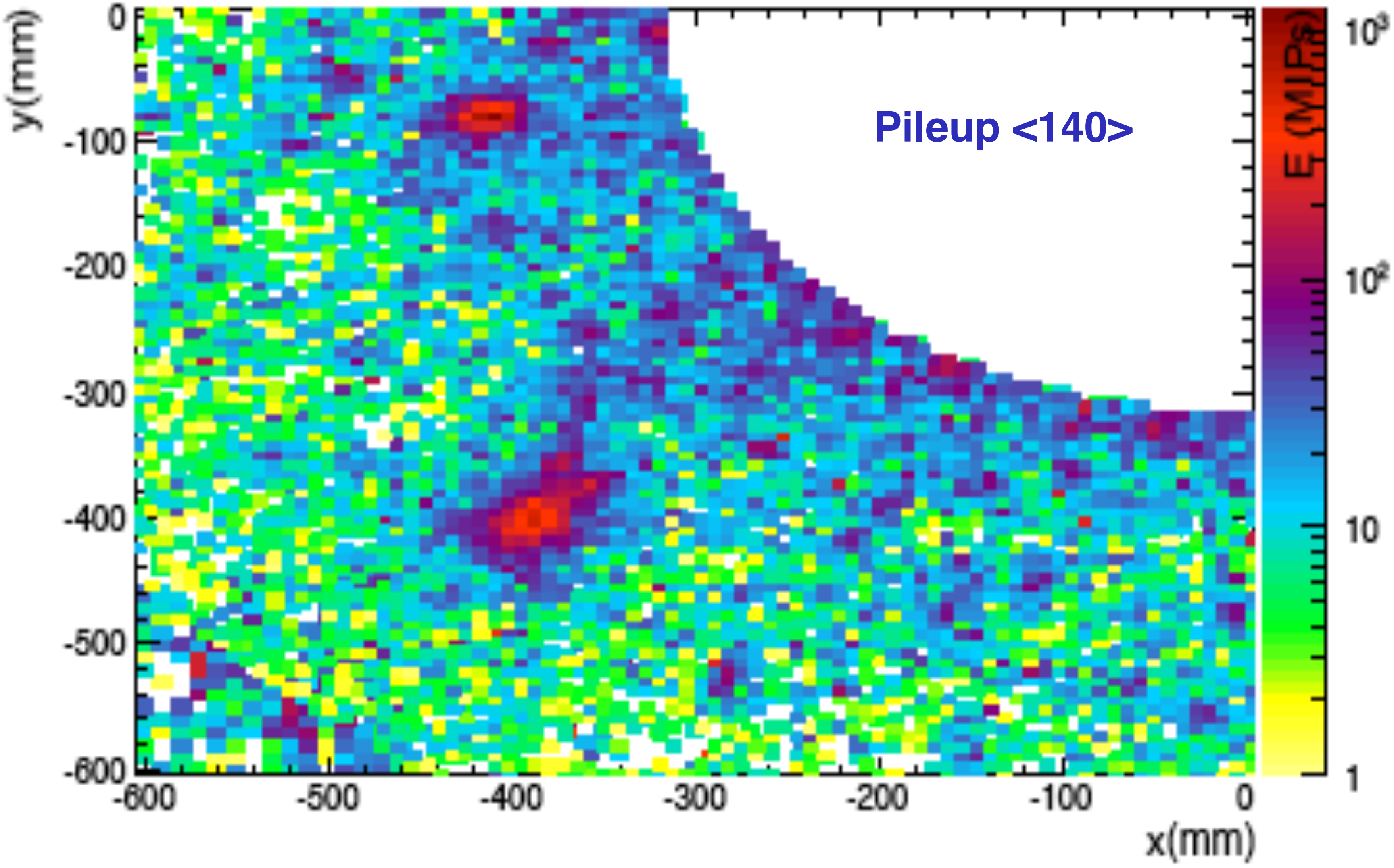


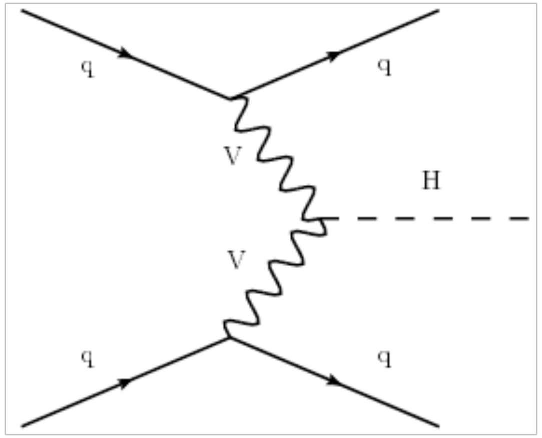
In addition to front-end electronics also data and power interfaces in detector volume



The Power of High Granularity at the LHC

VBF jets + H →γγ: 720 GeV jet, 175 GeV photon

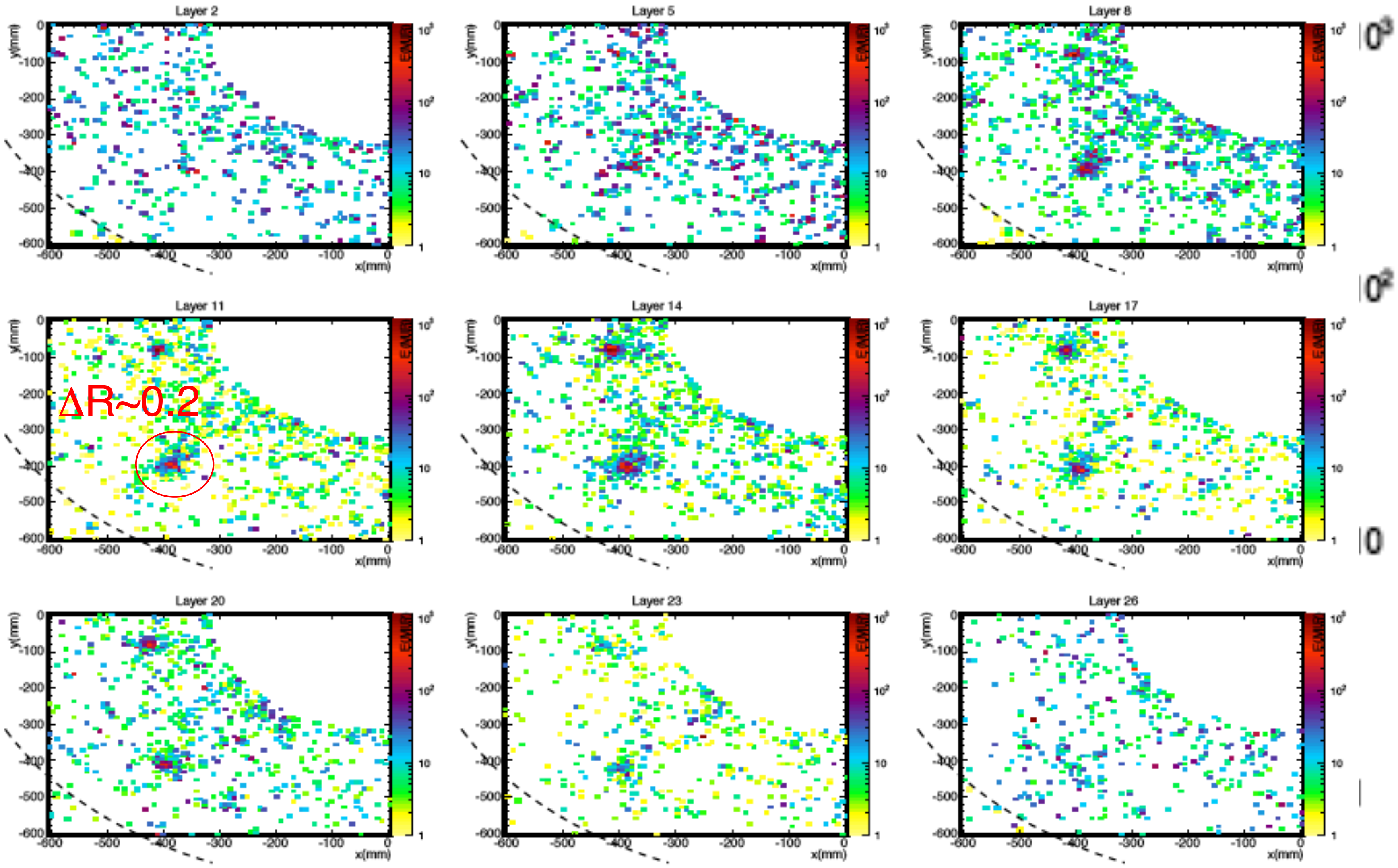


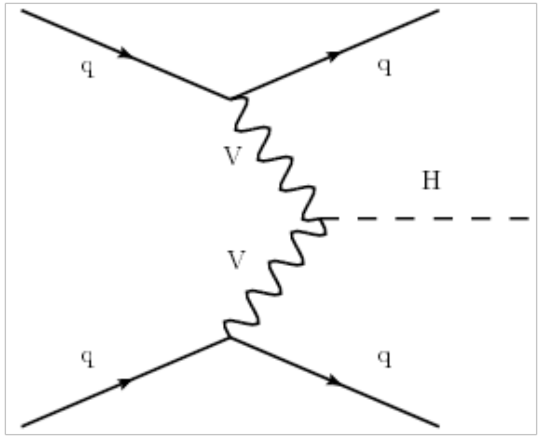


(Next slides) layer by layer development of showers. VBF jet carries 720 GeV (pT = 118 GeV) along with a photon with 175 GeV (pT = 22 GeV). Most of energy in the very narrow VBF jet carried by three particles (two charged pions and one photon) impacting the calorimeter within 1 cm of each other.

The Power of High Granularity at the LHC

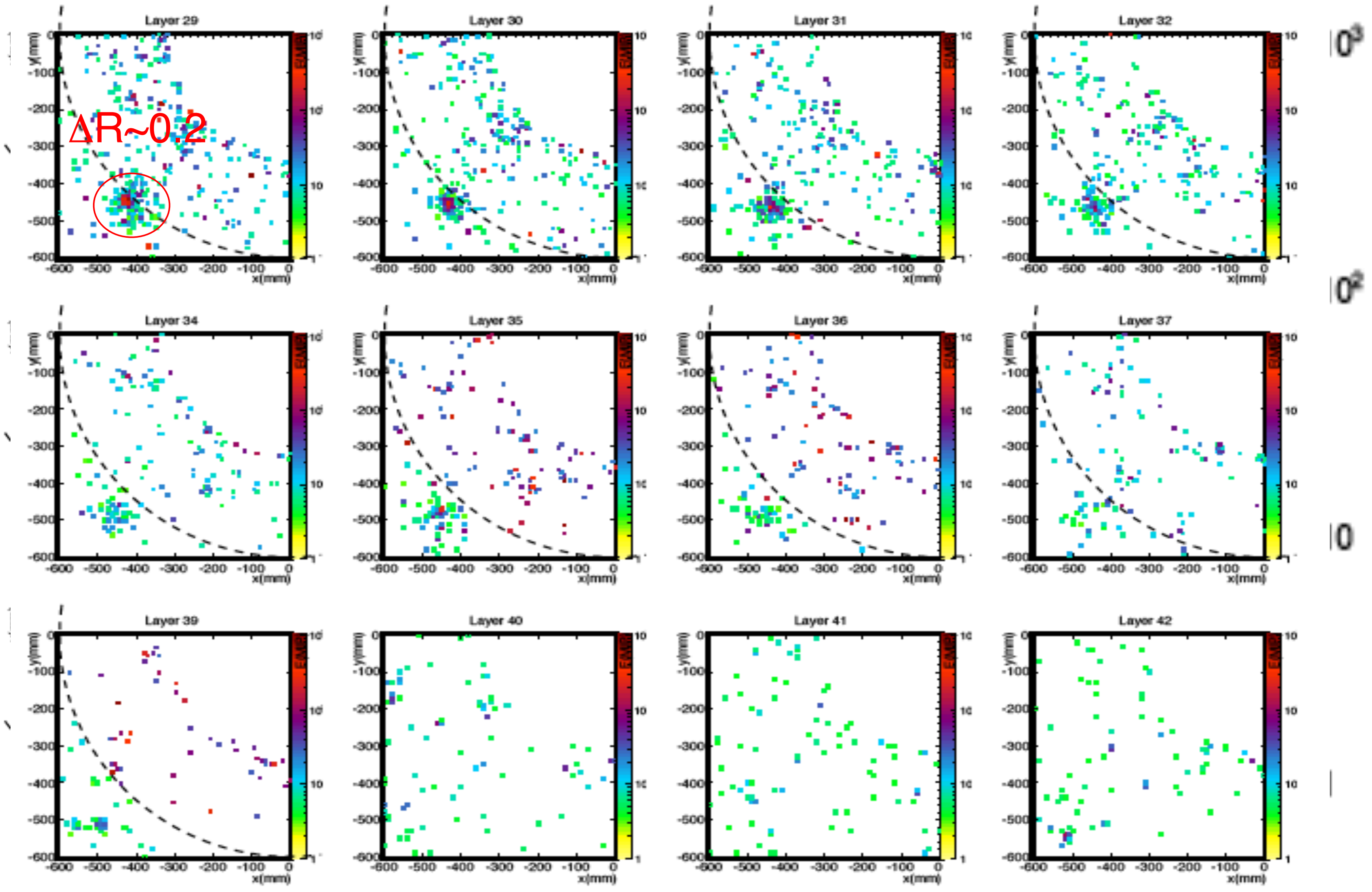
VBF jets + H →γγ: 720 GeV jet, 175 GeV photon

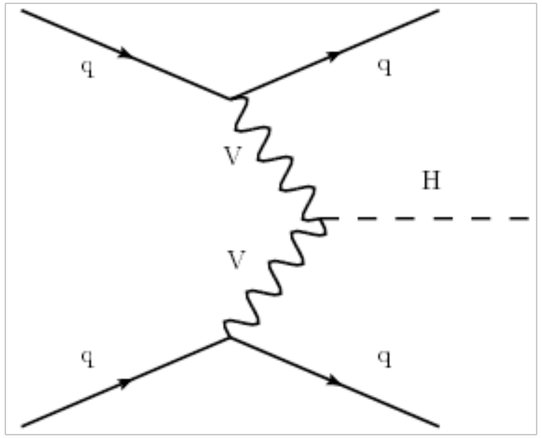




The Power of High Granularity at the LHC

VBF jets + H →γγ: 720 GeV jet, 175 GeV photon



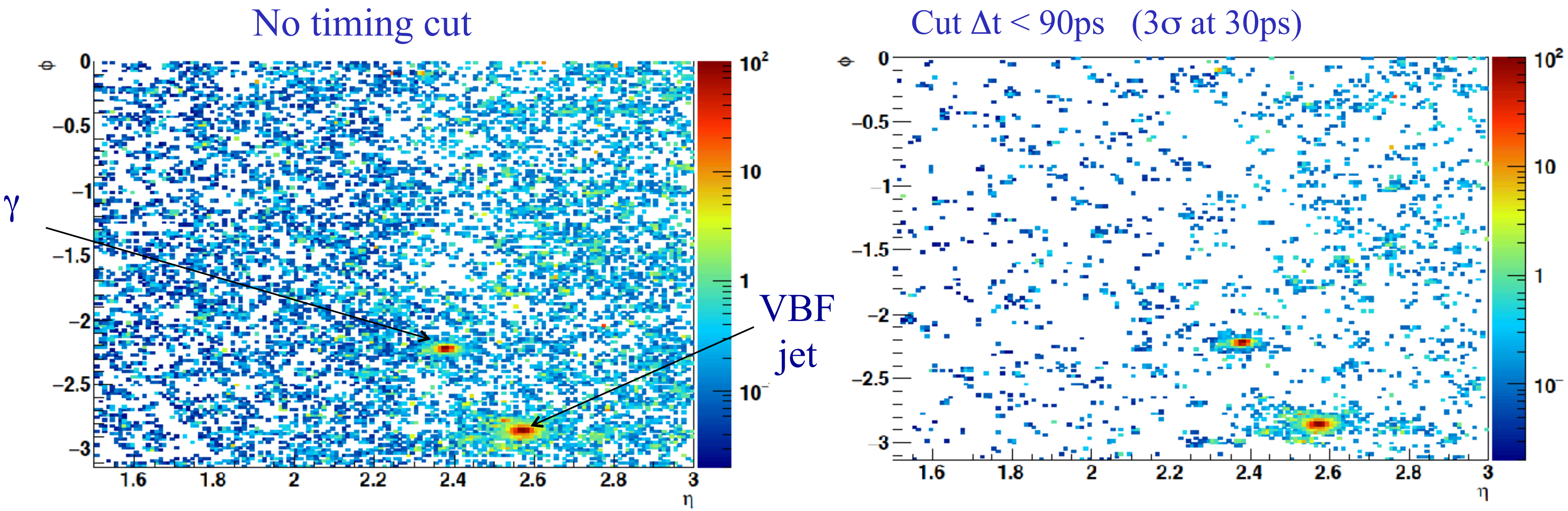


Pile-up rejection

Granularity and timing: a 5D detector

Made possible by HGCAL electronics design aimed at making use of fast silicon sensor response and multi-MIP energy deposits in showers

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,

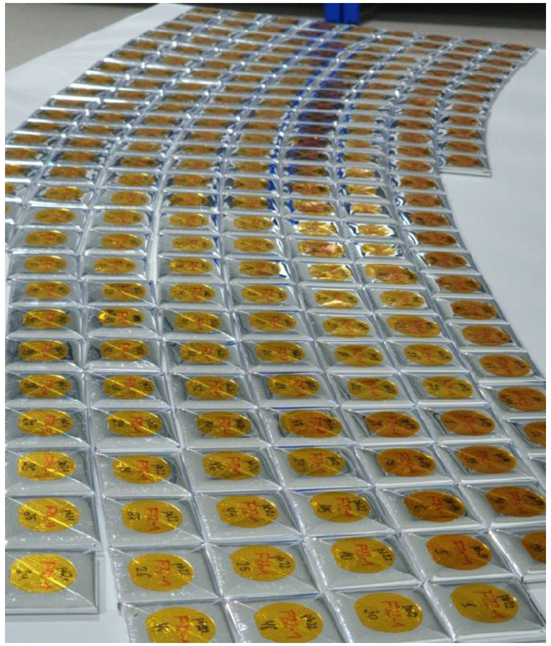


Plots show cells with Q > 12fC (~3.5 MIPs @300μm - threshold for timing measurement) projected to the front face of the endcap calorimeter.
Concept: identify high-energy clusters, then make timing cut to retain hits of interest

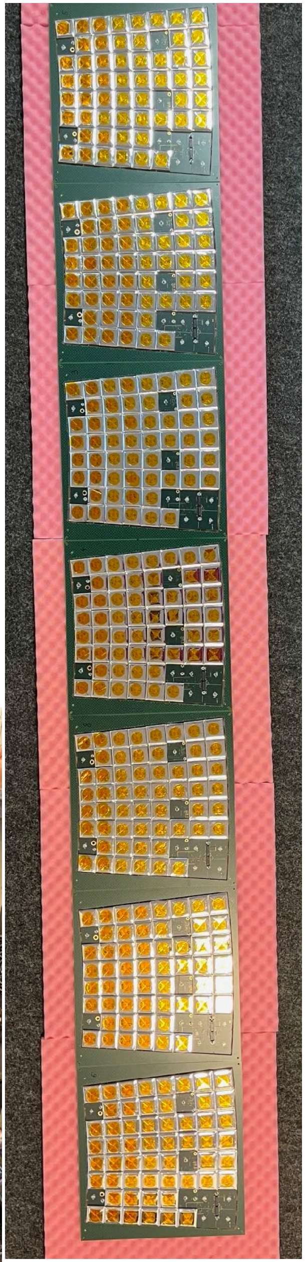
Automated Assembly

From Tiles to Modules

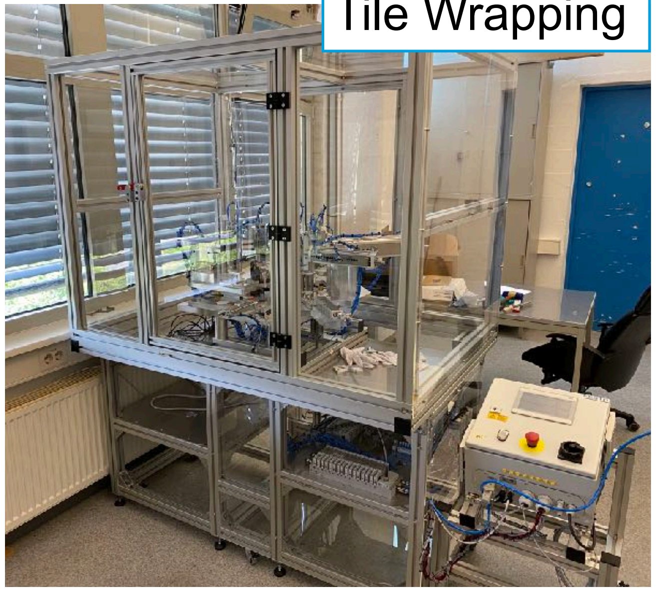
Injection Moulding



Electrical Assembly



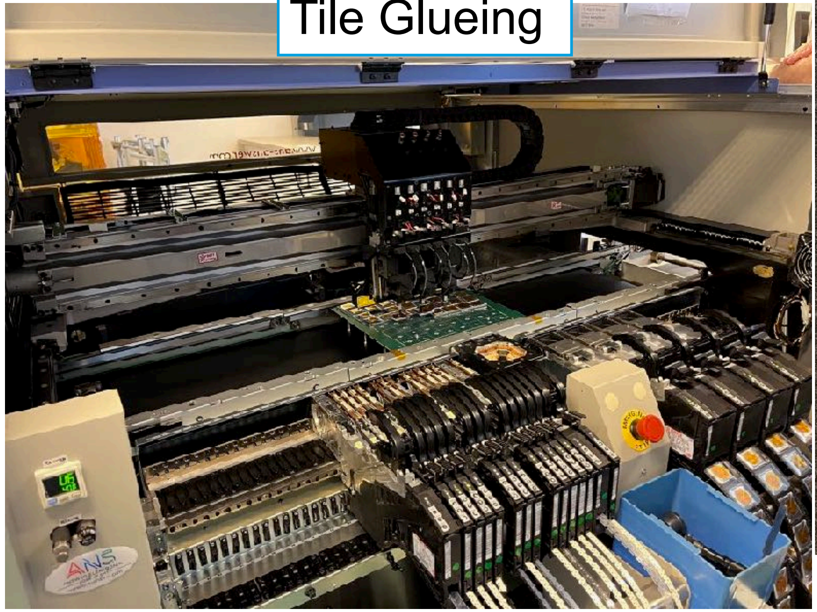
Tile Wrapping



https://indico.desy.de/event/36972/contributions/135046/attachments/80510/105260/Wrapping23-44s.mov

https://indico.desy.de/event/36972/contributions/135046/attachments/80510/105259/Tile_assembly_2020_cut2.mp4

Tile Glueing



Outlook

Production started…

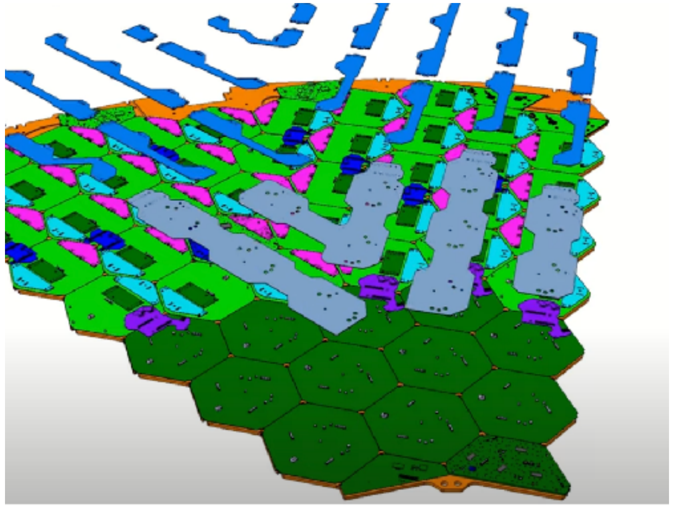
High Granularity presents tremendous engineering and integration challenges

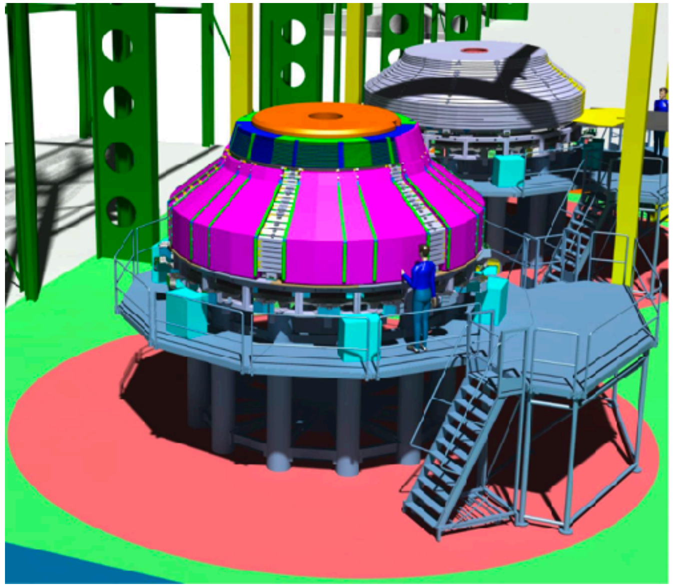
- high degree of industrialisation required
  - eg. modular and partially automated design of variants
  - automated production procedures
  - automated mass testing procedures
  - typically come with demands in reproducibility and accuracy of parts

The adventure of actually building it has just started

- so the rest is in animation only:

https://www.youtube.com/watch?v=QRCXi-V1fbg



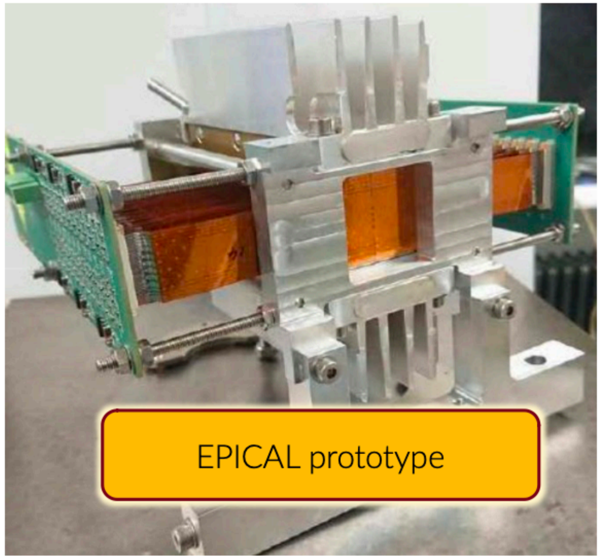


Developments: Ultrahigh granularity with MAPS

Integration of silicon sensor and electronics in CMOS (MAPS) has been successful for the ALICE inner tracker development

Two efforts ongoing to develop this concept for calorimetry purposes, with a goal to reach O(1 CHF/cm^2) for sensor and initial electronics

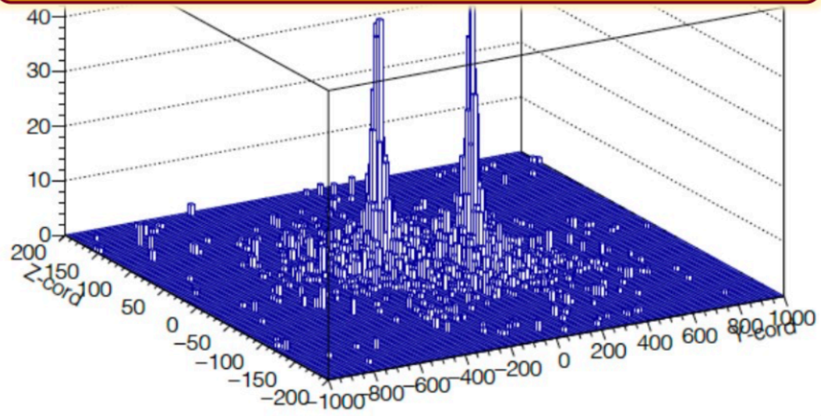
- Pixel dimensions in the range of 25 um –100 um
- In simulation, allows “easy” separation of showers as close as 5 mm

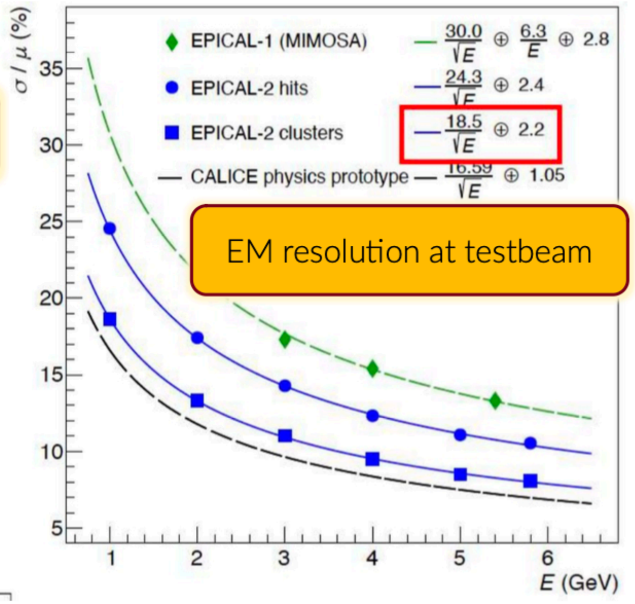


Challenges for the technology

- Cost-effective scaling to large systems (stitching)
- Power utilization/cooling in the context of a circular collider environment → impact on density

20 GeV showers separated by 1 cm (Oregon/SLAC)

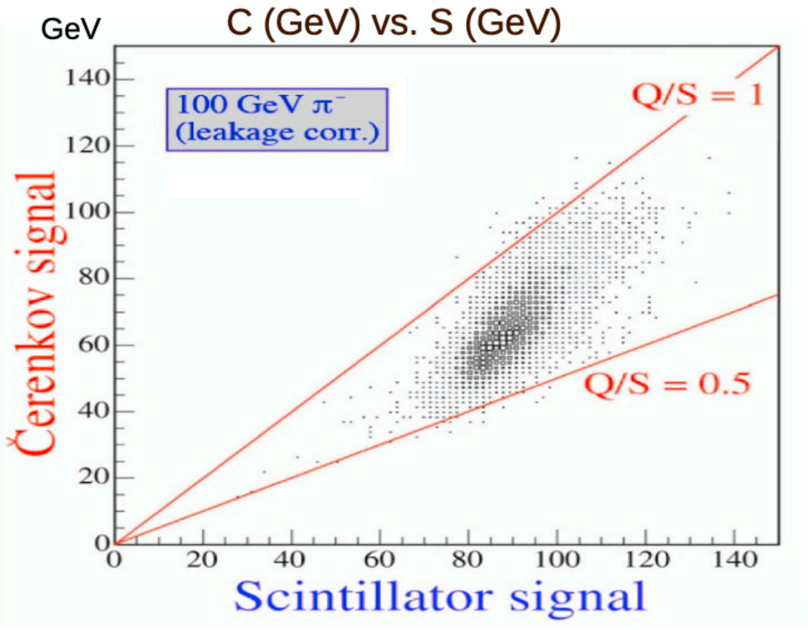


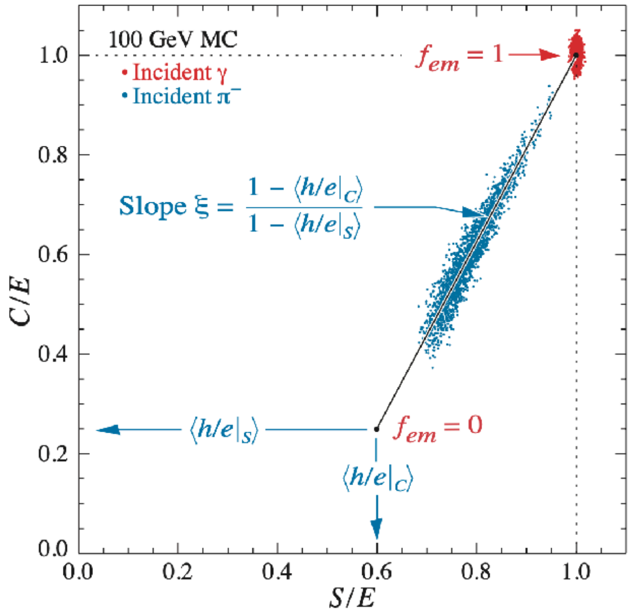


Dual Readout

Basic Idea

Relativistic and Total Energy





$$C = [f_{\rm em} + (h/e)_C(1 - f_{\rm em})]E\,,$$
$$S = [f_{\rm em} + (h/e)_S(1 - f_{\rm em})]E\,,$$
$$E = (\xi S - C)/(\xi - 1)\,,$$
$$\xi = [1 - (h/e)_C]/[1 - (h/e)_S]$$

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

$$\chi = 1/\xi$$

Read scintillator and Cherenkov light

- total and relativistic (mainly e.m.) part of shower
- solve for f_{em} and E: correct for e.m. fluctuation event by event

Mainly followed with fibre calorimeters

- other possibilities: wavelength, timing, direction
- “multi-messenger calorimetry"

Large hadronic prototype still to be built

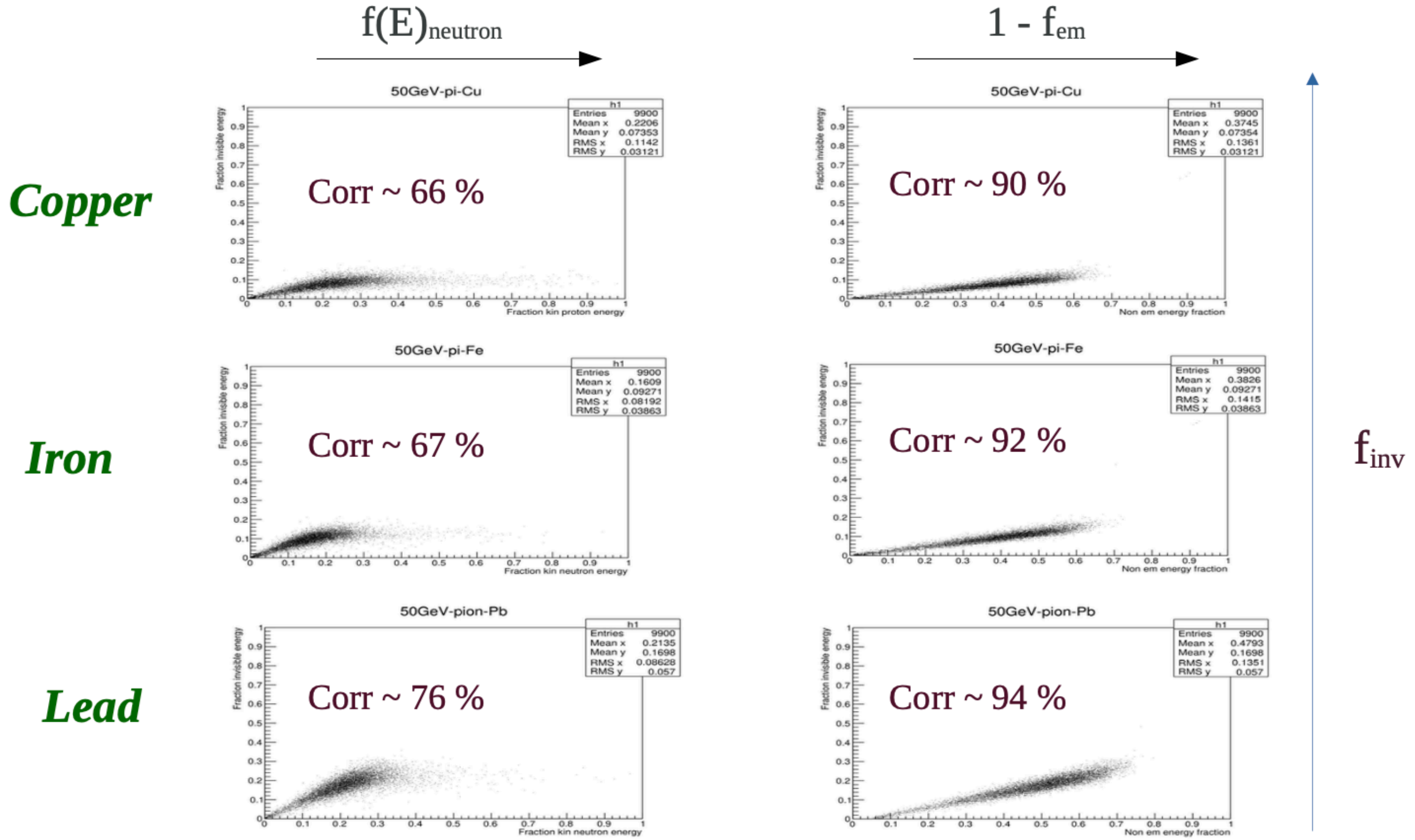
- 70% / √E measured, but with large leakage

Fibres require pointing geometry

- fine transverse segmentation: excelent PID (e - π)

Invisible Energy

Correlated with hadronic fraction

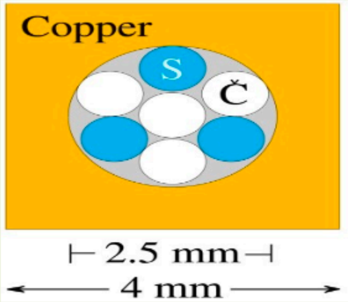


Roberto Ferrari
Seminar at CERN
7.6.2024

DREAM/RD52 dual-readout spaghetti prototypes

2003
DREAM

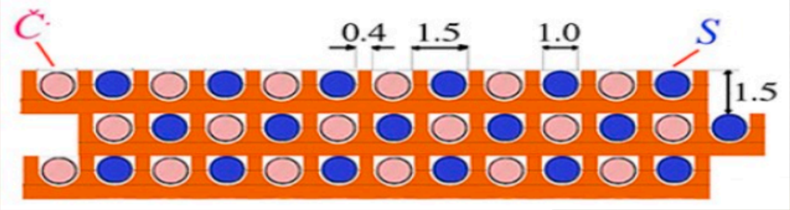
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}



Texas Tech Uni

2012
RD52

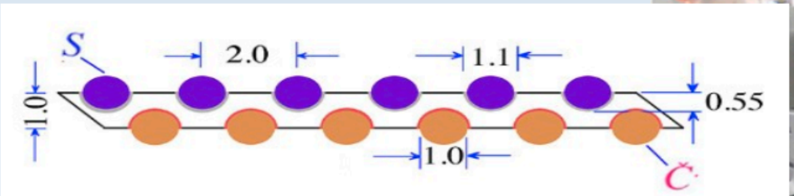
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

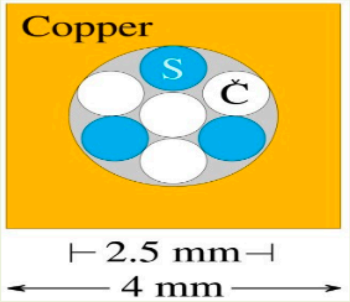


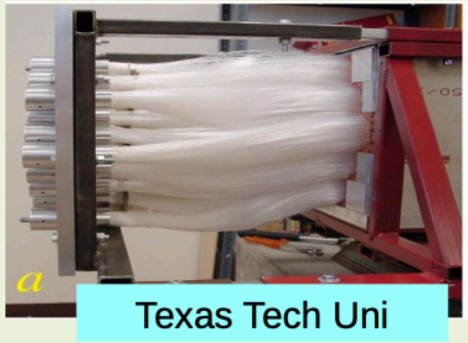

INFN Pavia

DREAM/RD52 dual-readout spaghetti prototypes

2003 DREAM

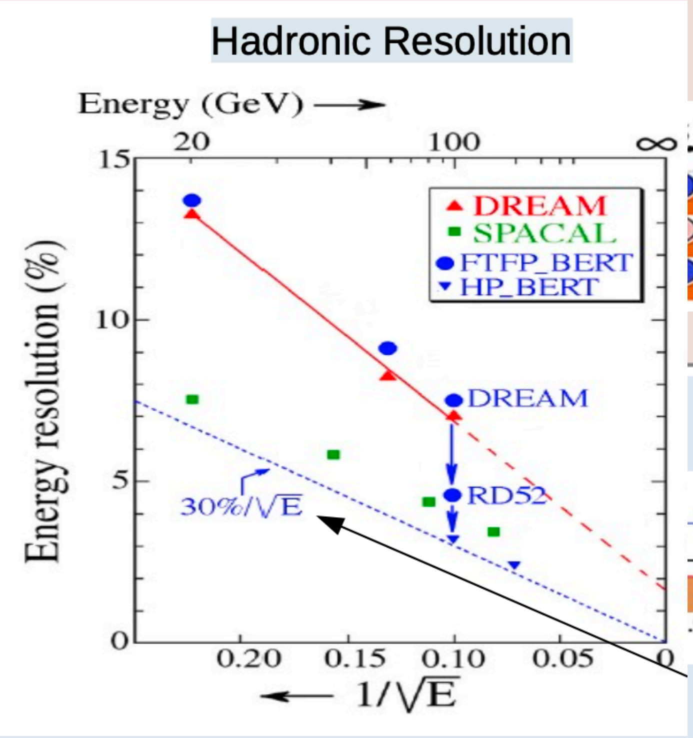
Cu: 19 towers, 2 PMT each
2 m long, 16.2 cm radius
Sampling fraction: 2%
Depth: ~10 λ_{int}





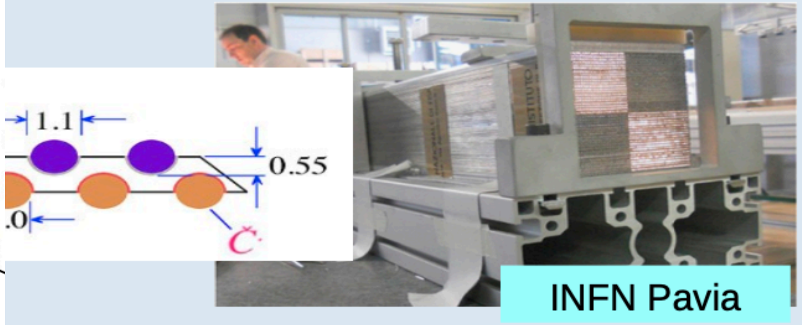
2012 RD52

Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



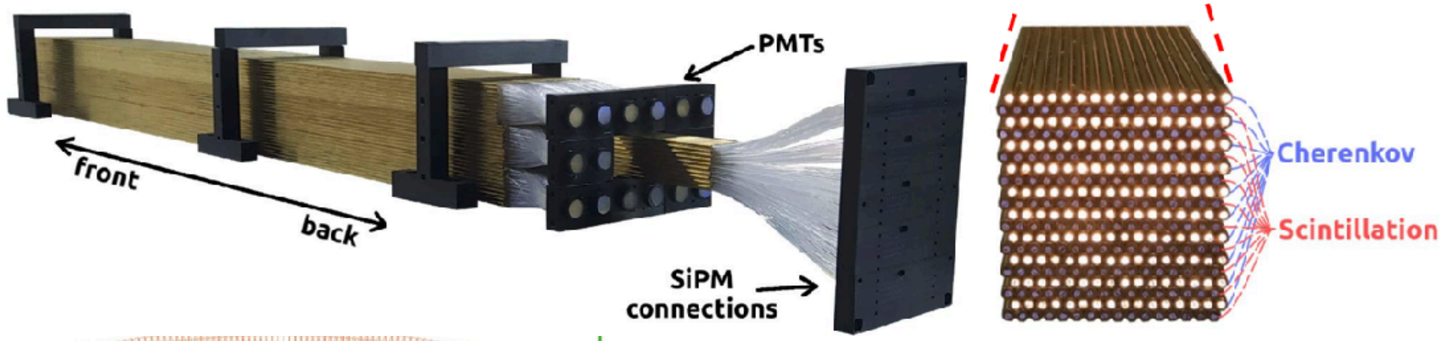
2012 RD52

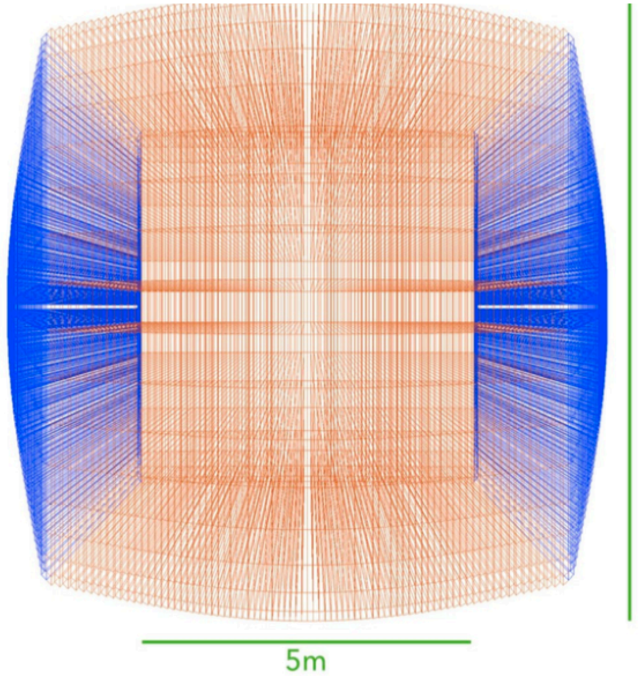
Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}

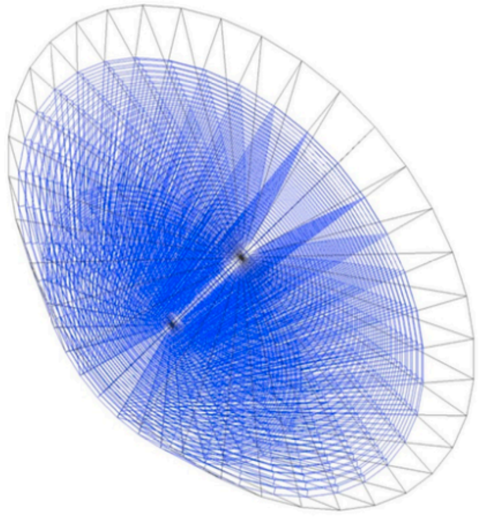


Dual Readout Goes Granular

Fibres individually readout by SiPMs







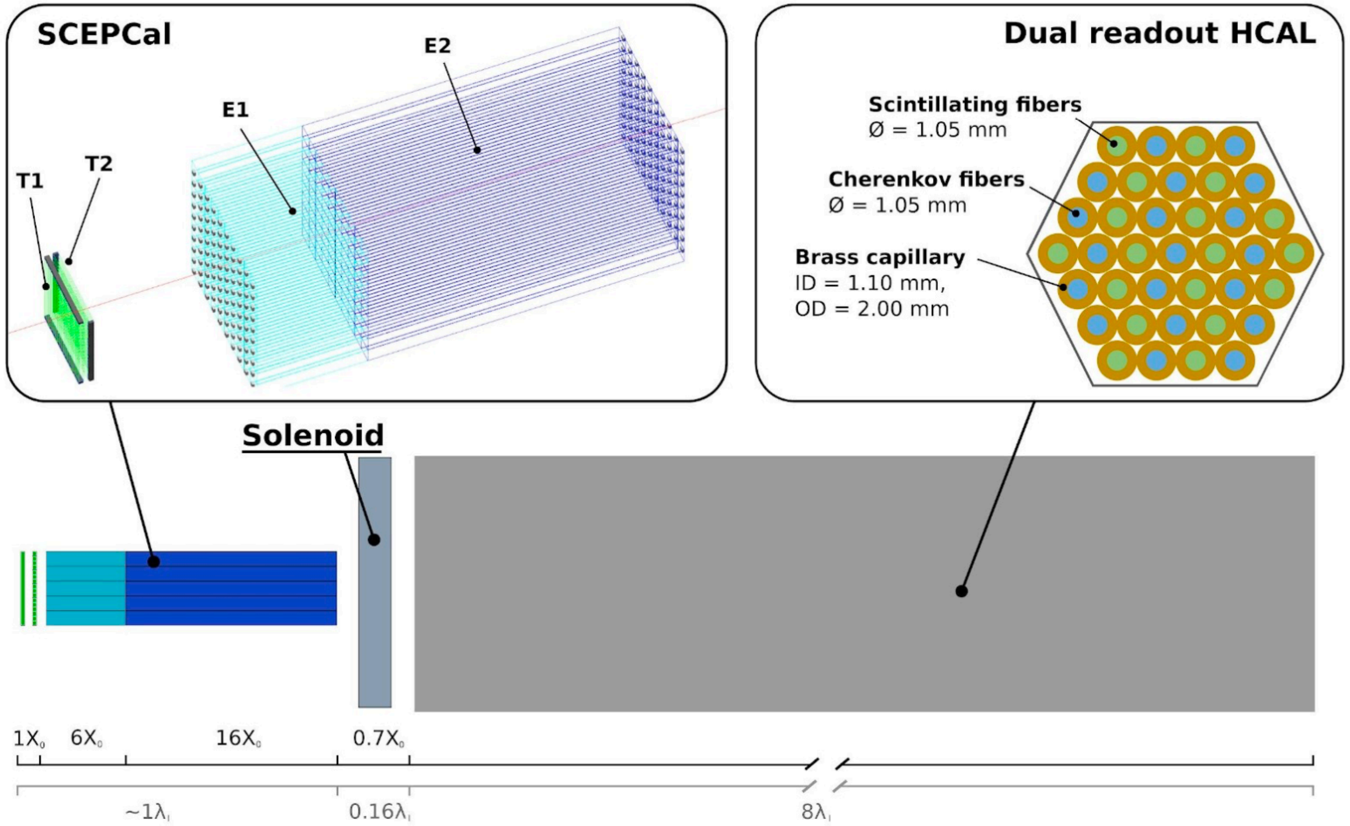
- DR fibre calorimeter
  - O(100 M) fibres
    - 1 mm ⌀, 1.5 mm pitch
  - copper absorber
  - 75 projective towers × 36 slices
    - $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
    - ϑ coverage: $|\vartheta| > 100$ mrad

Longitudinal “segmentation" with fast timing

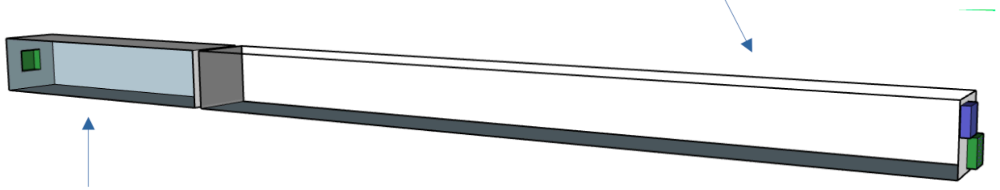
- 100 ps -> 5cm
- fast sampling and waveform analysis
- no system design yet

Dual Readout plus Crystals

And Dual Readout *with* Crystals



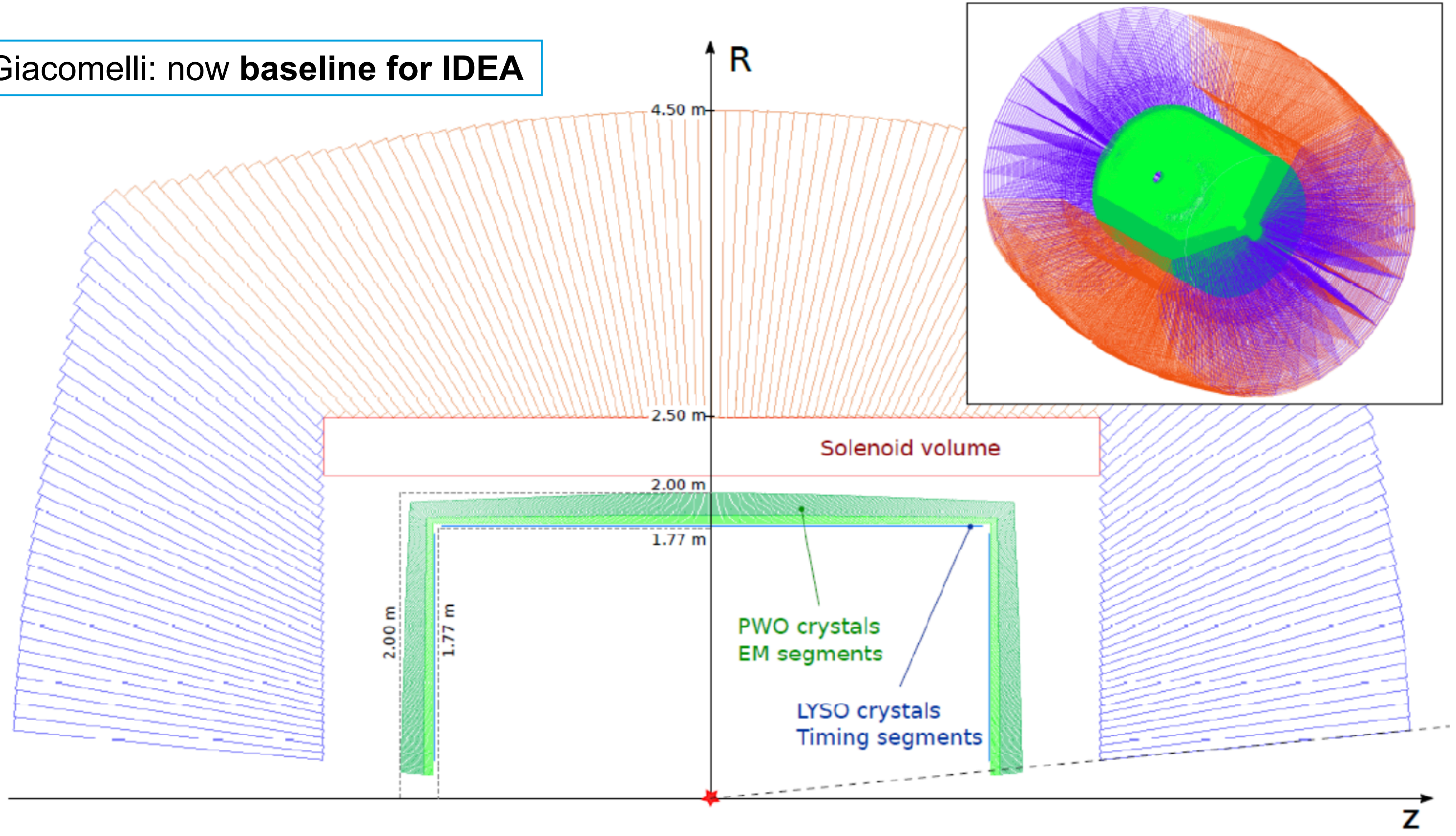
Rear crystal ECAL segment: two 4x4 mm² SiPMs with optical filters optimised for scintillation and Cherenkov detection



Front crystal ECAL segment: single 5x5 mm² SiPM per crystal optimised for scintillation light detection

Crystal option

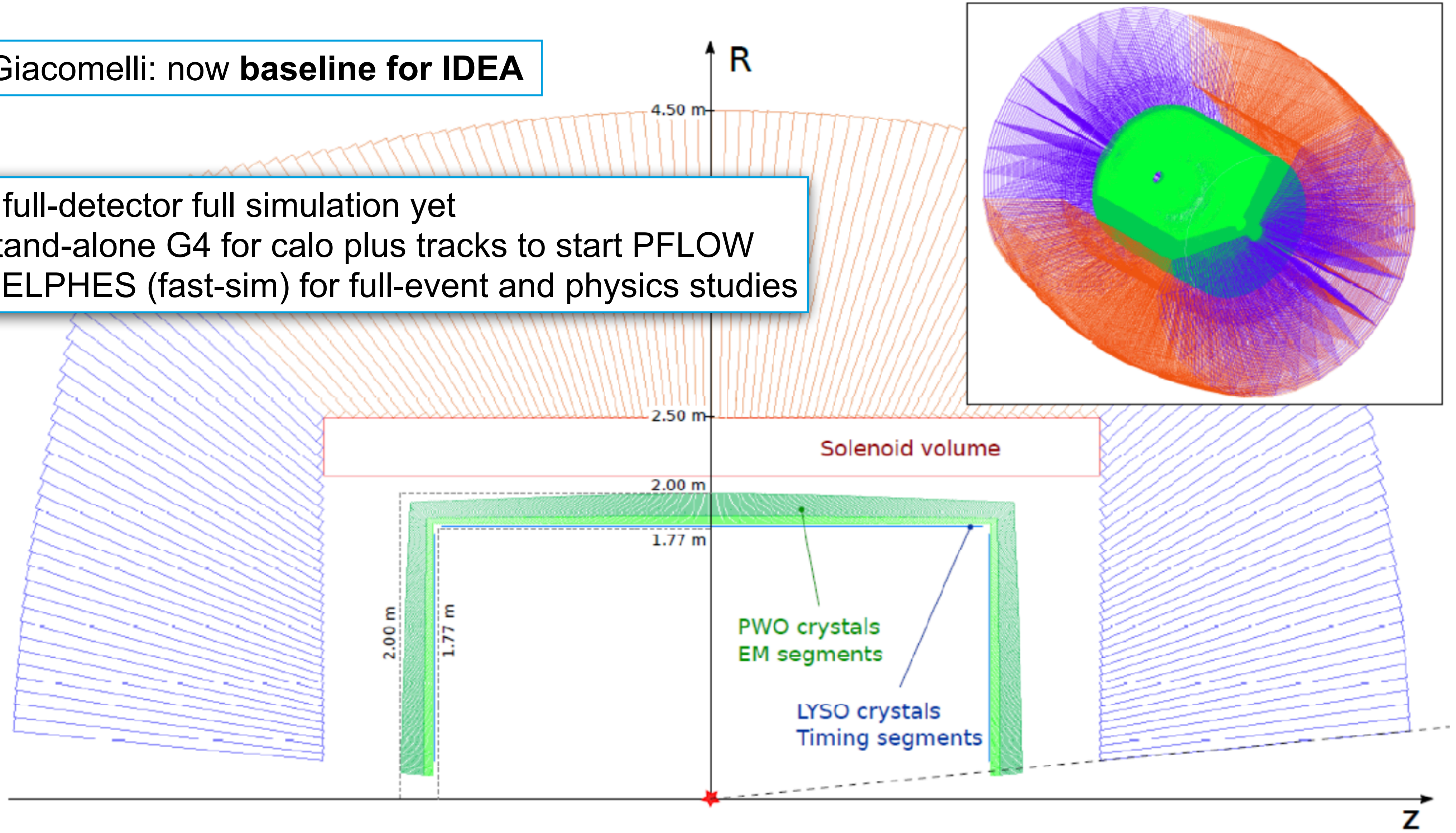
P. Giacomelli: now **baseline for IDEA**



Crystal option

P. Giacomelli: now **baseline for IDEA**

No full-detector full simulation yet
- stand-alone G4 for calo plus tracks to start PFLOW
- DELPHES (fast-sim) for full-event and physics studies

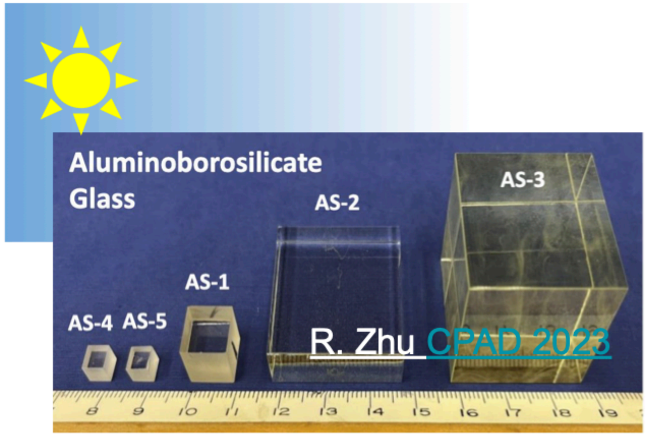


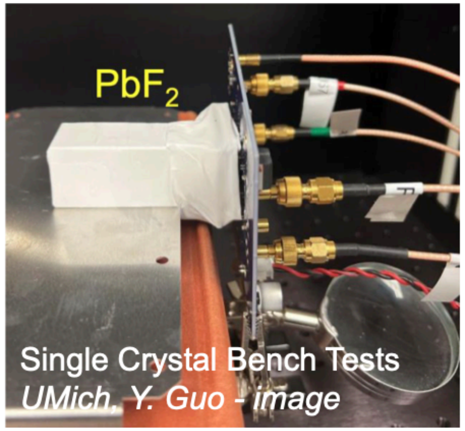
Heavy Glasses for
DR Fiber HCAL
Homogenous HCAL

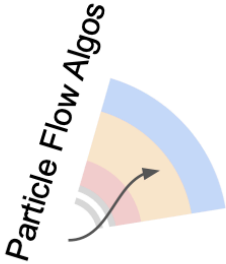
CalVision - Overview

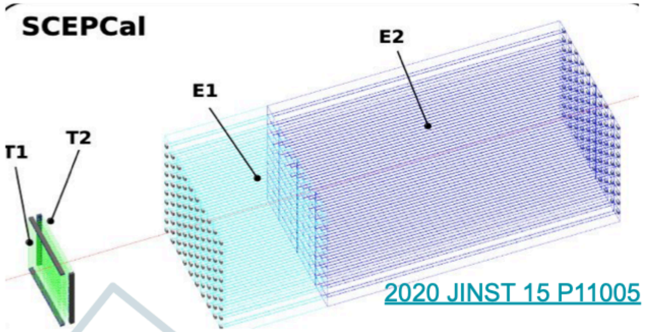
Joined w/ MaxiCC!

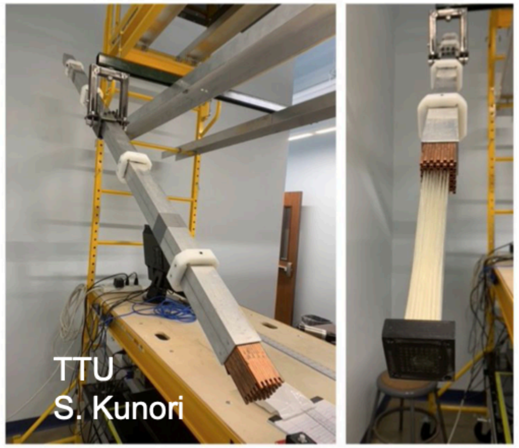
Technologies → Detector Implementation

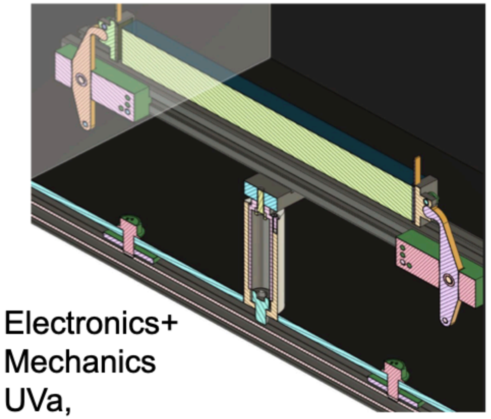




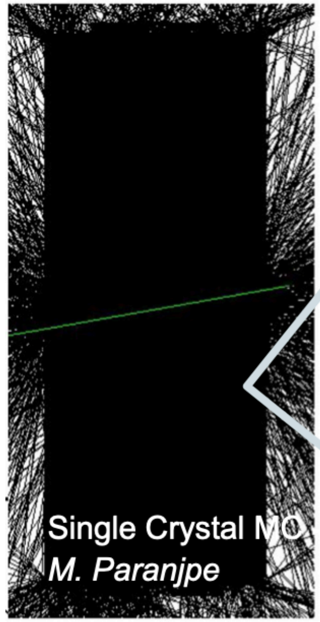




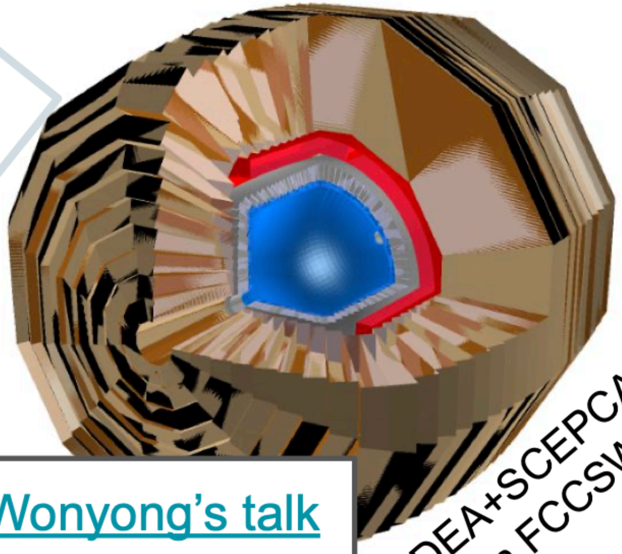




Electronics+
Mechanics
UVa,
E. Fernandez- image



Simulation Fundamentals-
See Sergei's talk

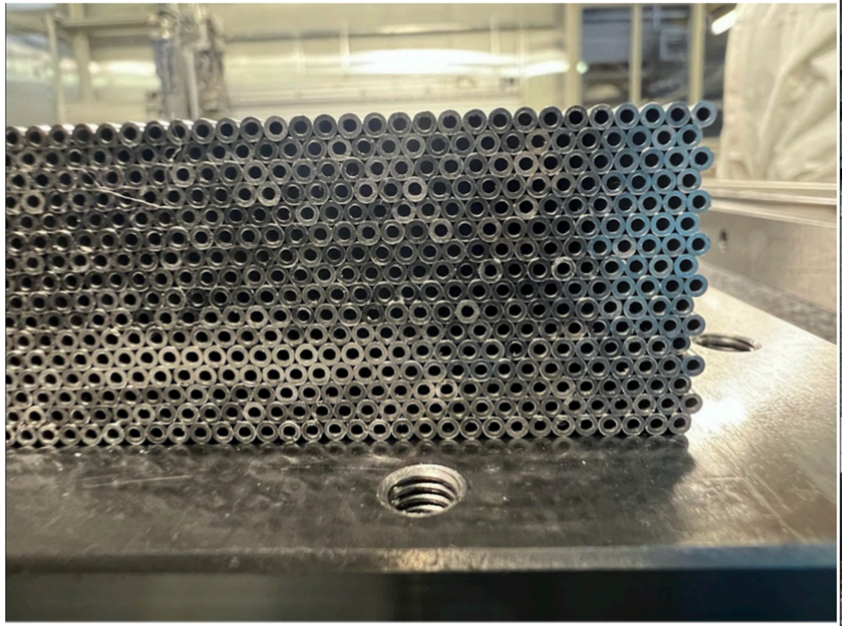


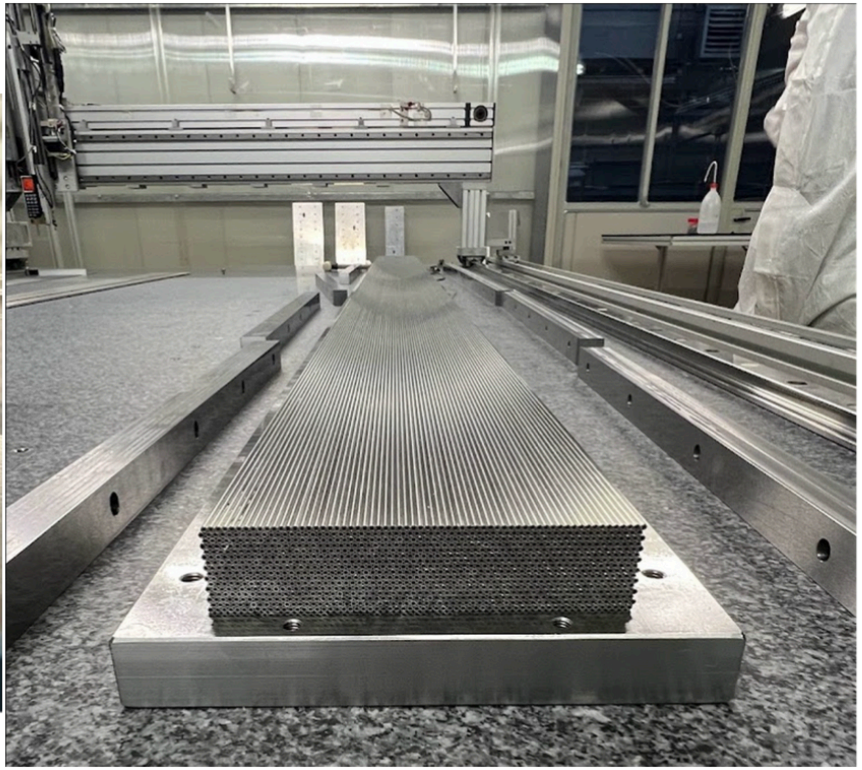
See Wonyong's talk

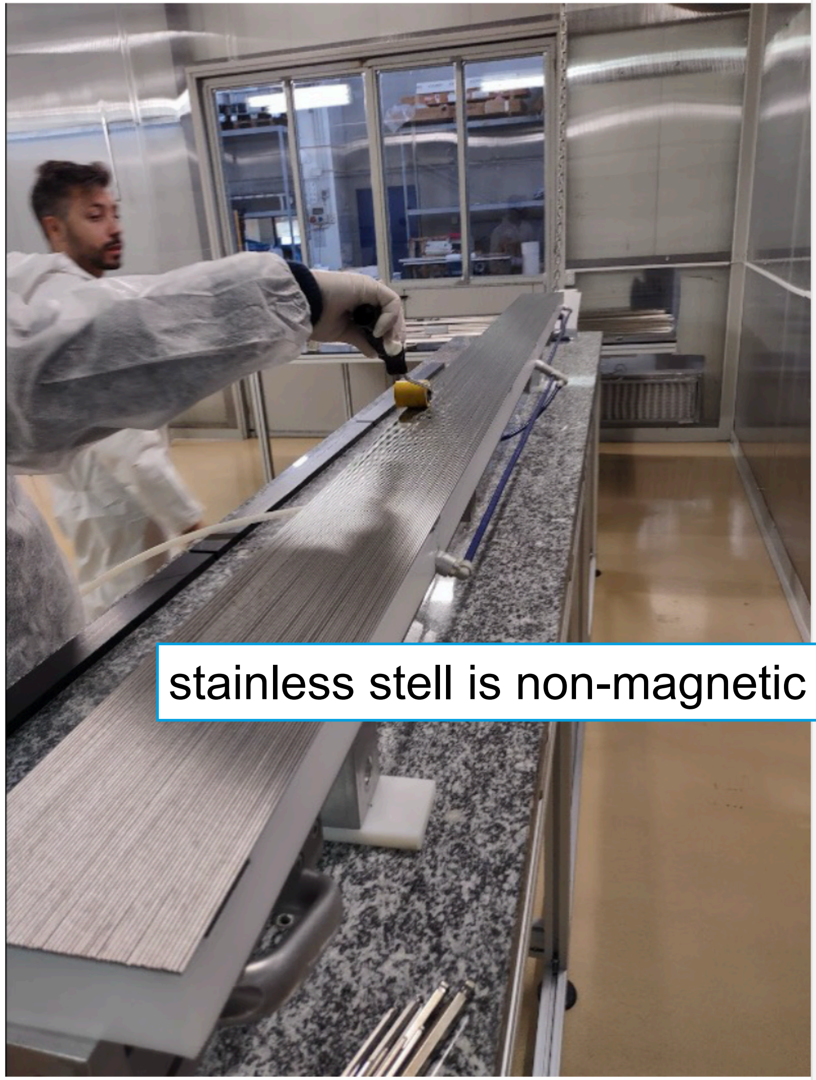
IDEA+SCEPCAL in FCCSW

DR calorimeter

- ❖ Full containment hadronic prototype in progress
  - ➢ Hidra2 call INFN CSN5







stainless stell is non-magnetic

Liquified Noble Gas Calorimeters

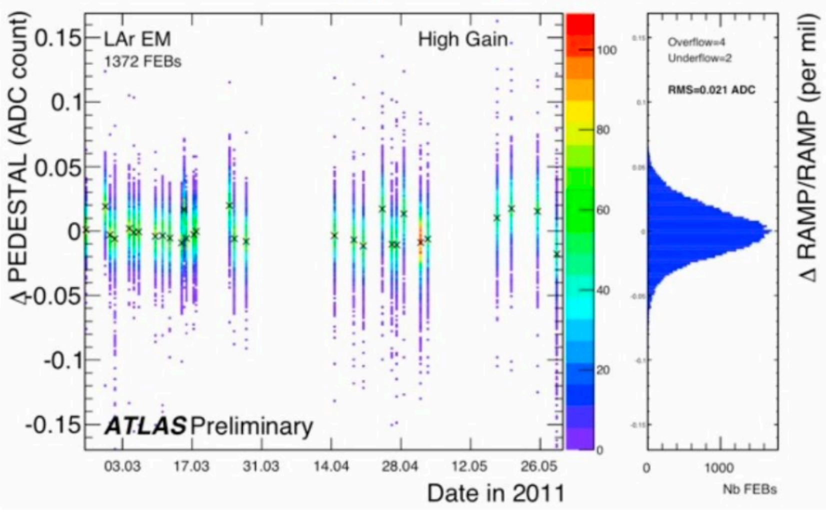
Example: Stability of ATLAS LAr Energy Scale

Noble-liquid calorimetry: High intrinsic stability

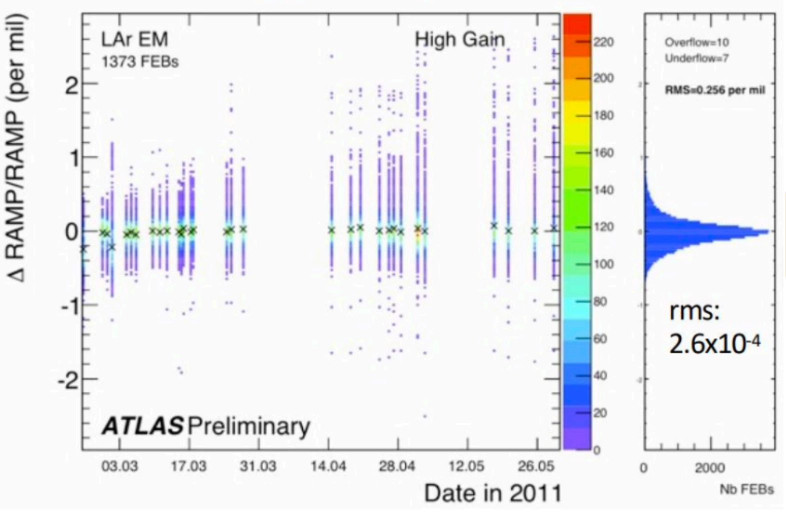
- Pedestal stability < 100 keV
- Gain stability 2.6×10^{-4}
- Parameters monitored in daily calibration runs
  - Changes in constants needed only about 1 / month

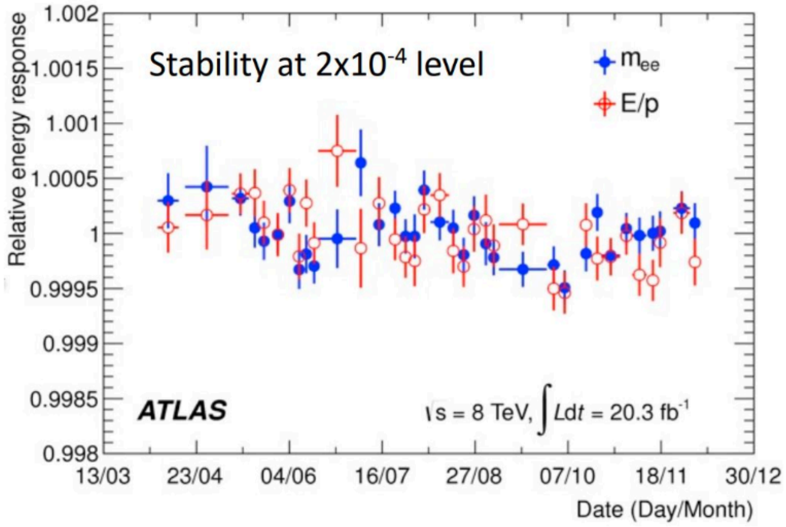
➢ Stability of the energy scale of 2×10^{-4}
  - Visible on Z→ee invariant mass and E/p

Pedestal (P) stability



Gain (R) stability





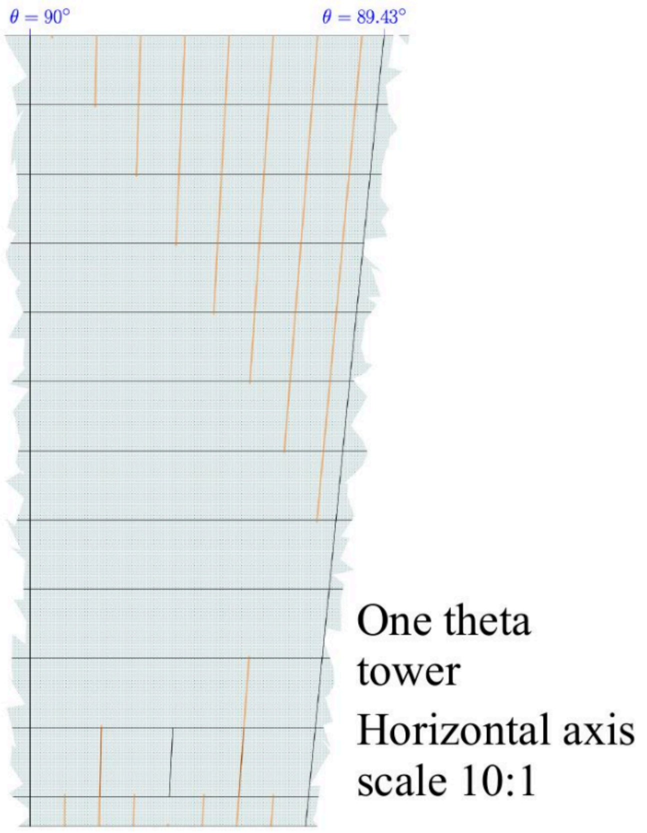
How to achieve high granularity ?

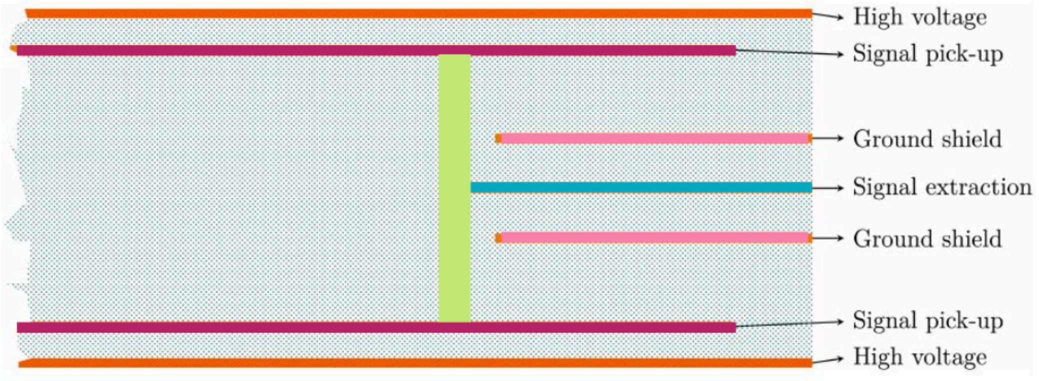
Aiming for ~ ×10 ATLAS granularity

- High granularity required for better PFlow performance (few million cells)
- >6 compartments to compensate LAr gap widening

Implementation: multi-layer PCBs

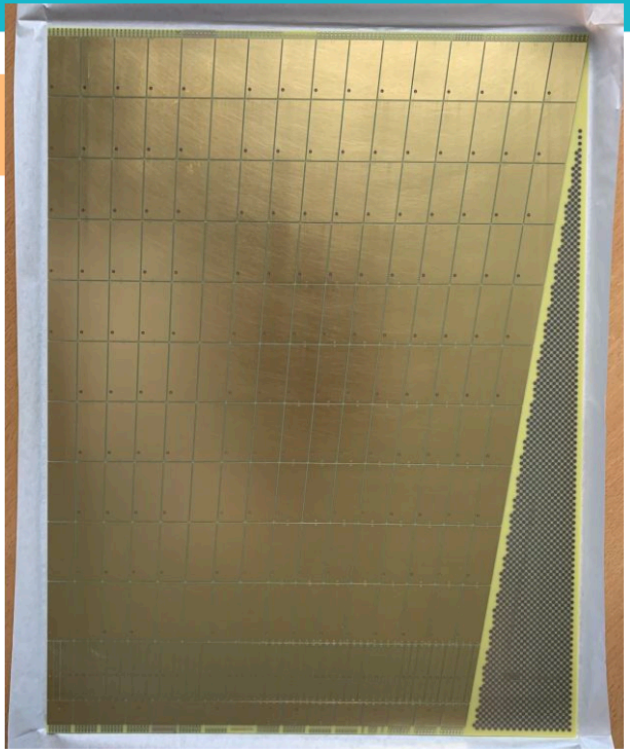
- 7-layer PCB
  - Signal collection on **readout planes**
  - Transmission through **via**
  - Signal extraction on **trace**
  - **Ground shields** to mitigate cross-talk
- Challenges
  - Trade-off capacitance (noise) / cross-talk
  - Maximum density of signal traces ?
- Studies on simulations and prototypes



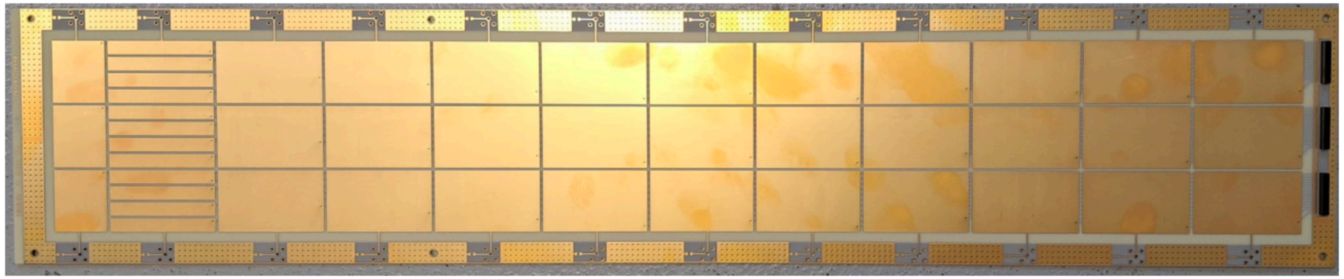


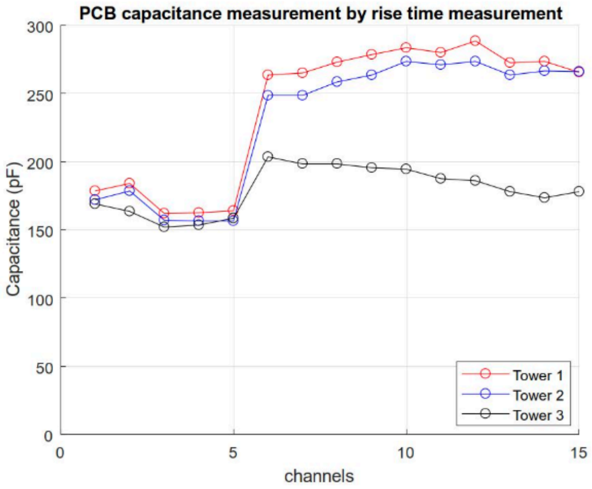
Electrodes prototypes

Explore tradeoffs: max granularity / capacitance (noise) / cross-talk



- **First large-scale prototype at CERN**
  - Explore many options for grounding, for shields
  - First layers readout at the front
  - Few per-mille cross-talk achievable with long shaping
- **Next prototype at IJCLab**
  - All layers readout at the back
    - Best for material budget, worse for noise and cross-talk
  - Use of connectors for easier measurements
  - New shielding ideas
  - Development of system for automated measurements

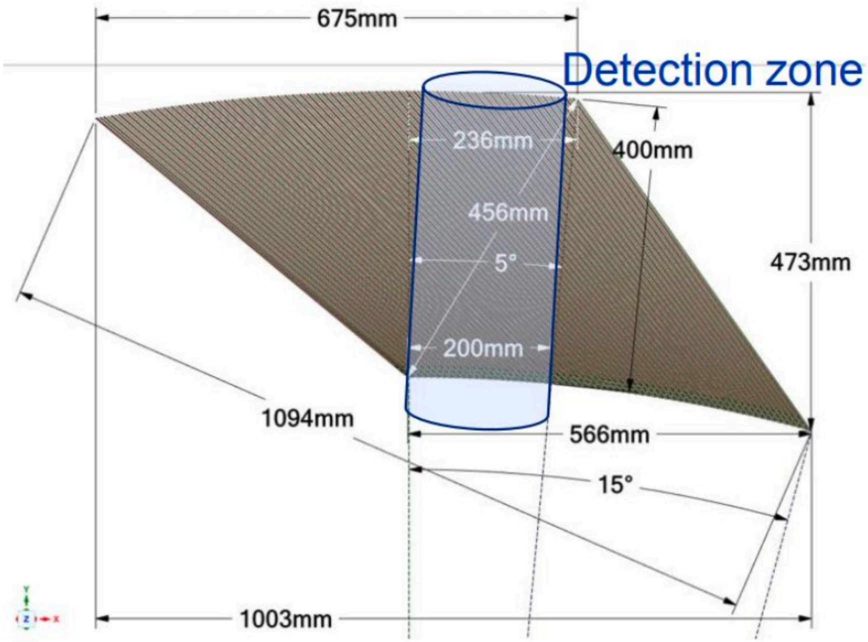




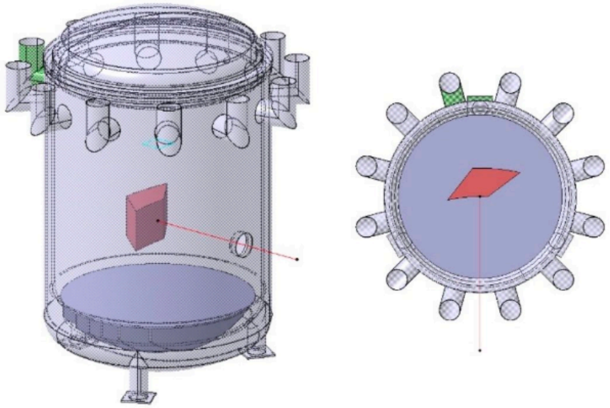
Towards a testbeam module

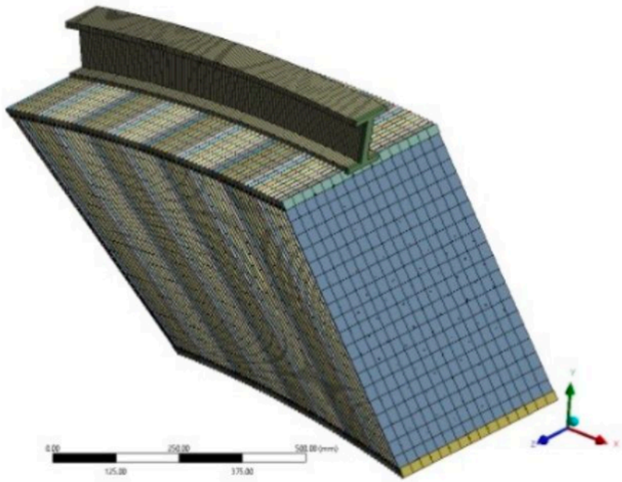
Plan to produce testmodule in the next four years

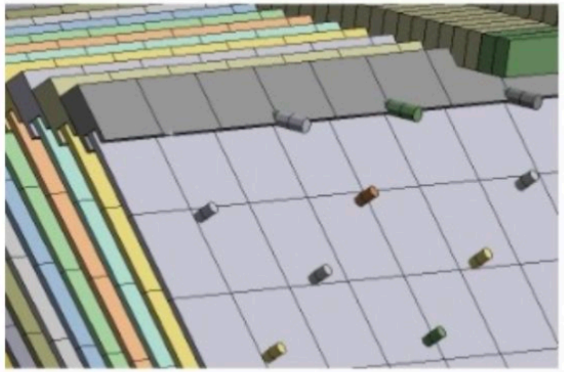
- Mechanical design of module (64 absorbers) has started
  - First finite element calculations performed
- Work on finding / adapting testbeam cryostat
- Common tools (e.g EUDAQ) should facilitate integration in testbeam facility



The cryostat available to make the test beam is the CRRP-00563.





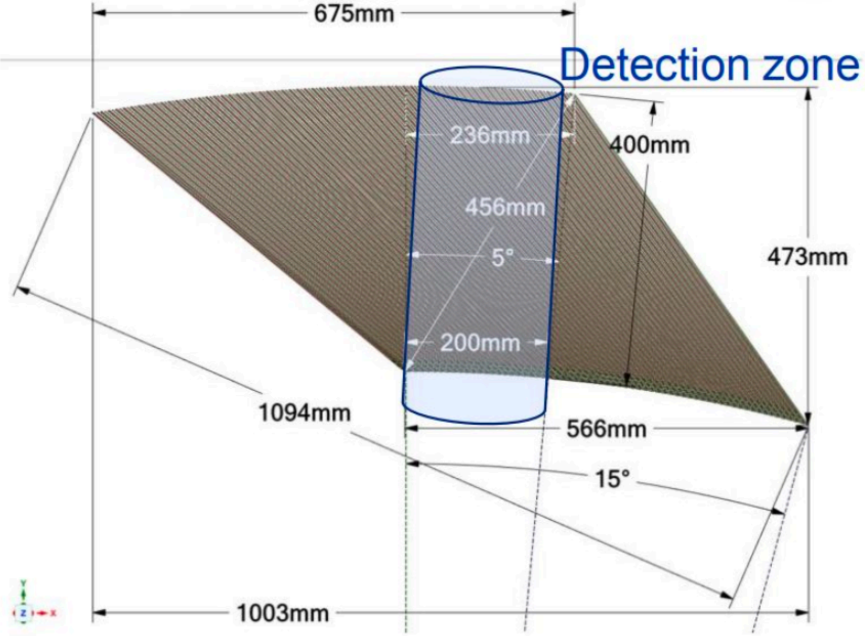


Towards a testbeam module

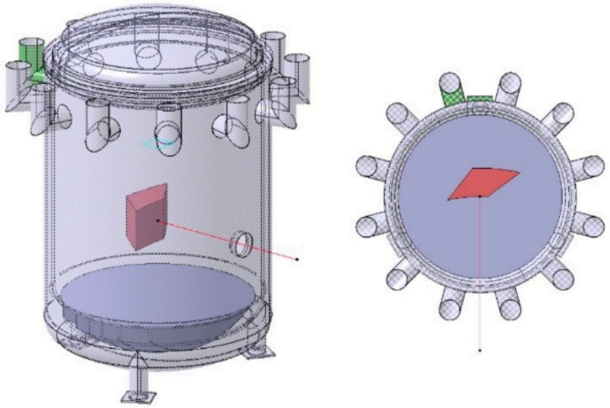
prototypes are small experiments!

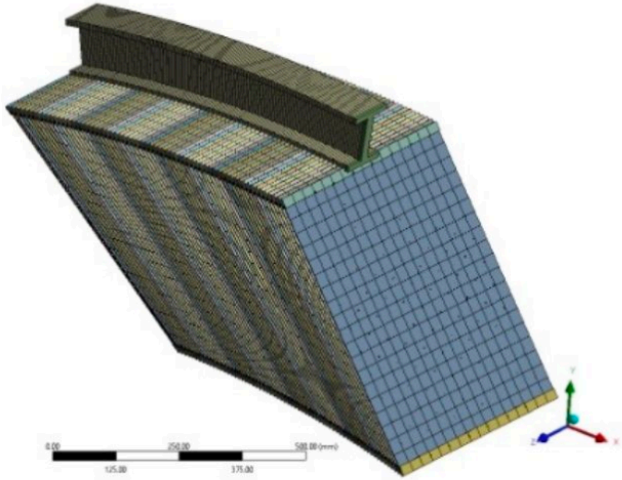
Plan to produce testmodule in the next four years

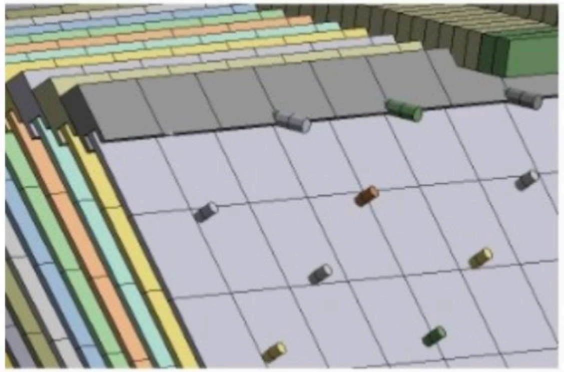
- Mechanical design of module (64 absorbers) has started
    - First finite element calculations performed
- Work on finding / adapting testbeam cryostat
- Common tools (e.g EUDAQ) should facilitate integration in testbeam facility



The cryostat available to make the test beam is the CRRP-00563.





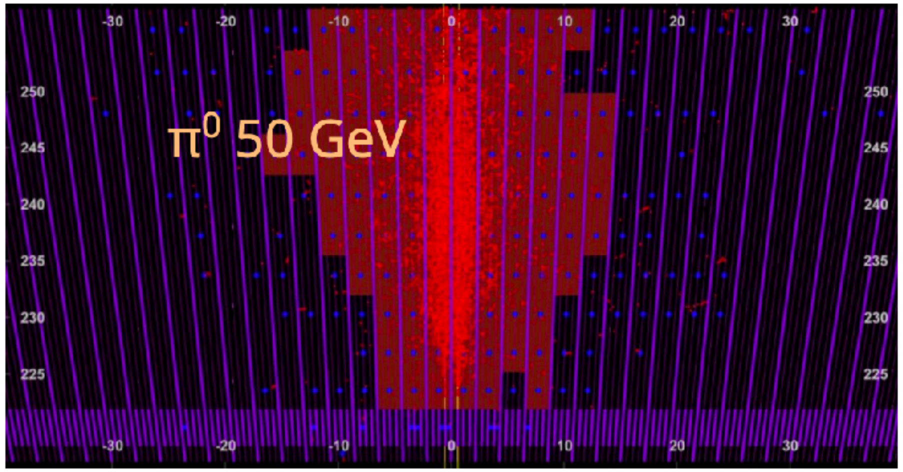


Status of ALLEGRO / LAr Simulations

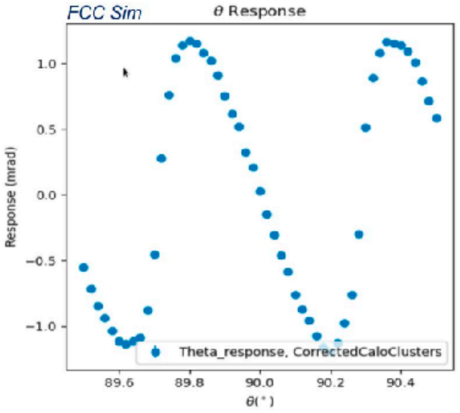
Active Development in Key4HEP

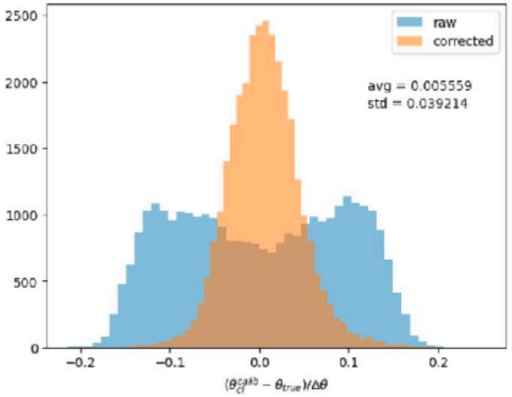
2023: important groundwork. ⇒ 2024: granularity optimisation studies possible

- Flexible geometry implemented in Full sim
  - Can study EM shower shapes
  - Benchmark: photon / π^0 separation
  - Ongoing: implementation of cross-talk effects



- Calibrations of reconstruction
  - Simple MVA energy regression of EM clusters
  - Cluster position calibration per layer
    - Allows pointing studies (⇒ ALPs)
- Particle Flow on its way
  - Using Pandora toolbox
  - For technical reasons, pioneered in detector sim with Allegro Ecal + CLD Tracker
  - Hope for first results in 2024 !





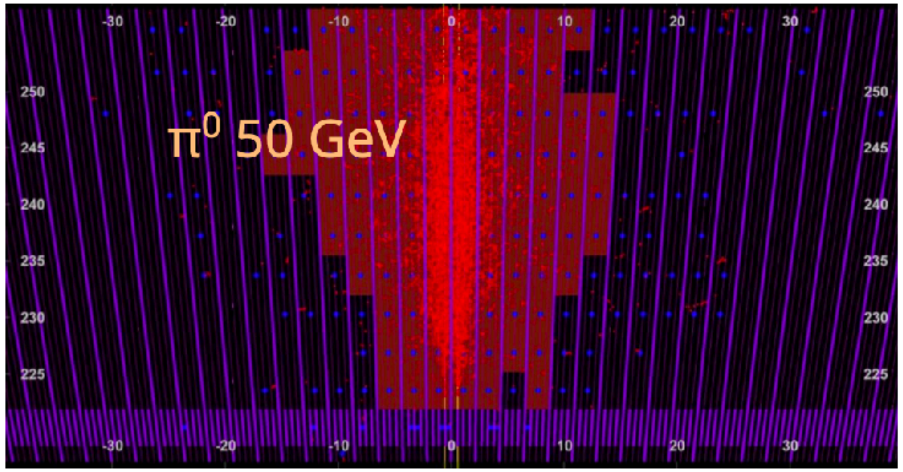
Status of ALLEGRO / LAr Simulations

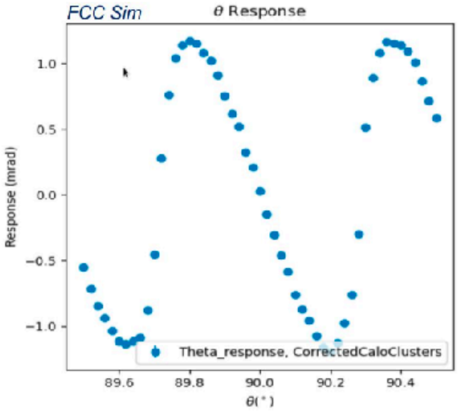
Active Development in Key4HEP

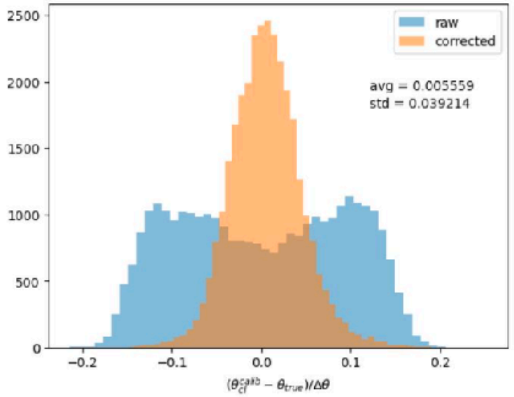
2023: important groundwork. ⇒ 2024: granularity optimisation studies possible

- **Flexible geometry implemented in Full sim**
  - Can study EM shower shapes
  - Benchmark: photon / π^0 separation
  - Ongoing: implementation of cross-talk effects
- **Calibrations of reconstruction**
  - Simple MVA energy regression of EM clusters
  - Cluster position calibration per layer
    - Allows pointing studies (⇒ ALPs)
- **Particle Flow on its way**
  - Using Pandora toolbox
  - For technical reasons, pioneered in detector sim with Allegro Ecal + CLD Tracker
  - Hope for first results in 2024 !

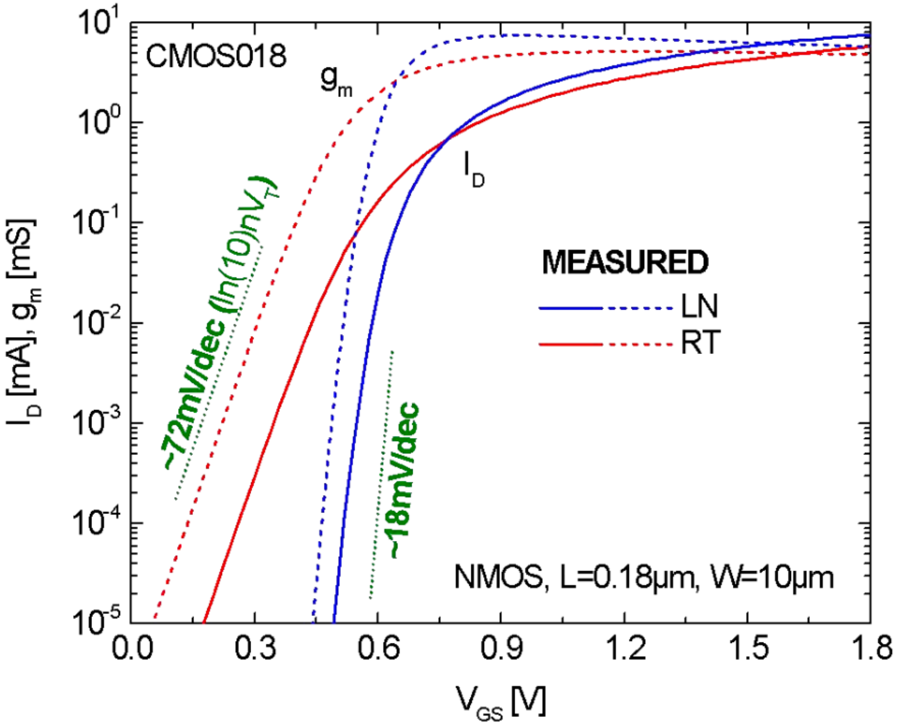
Plug & play →

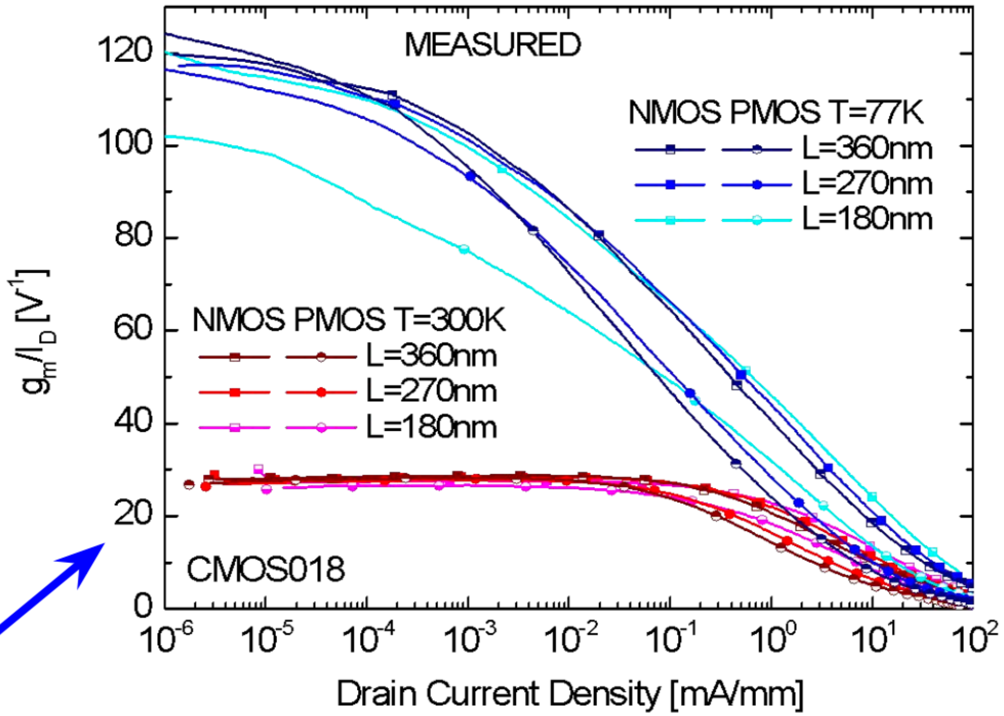






CMOS Transistors *Become Better* in LAr/LN2





Transconductance/ drain current

$$\frac{g_m}{I_D} \rightarrow \frac{q}{nk_BT} = \begin{cases} \sim 30 \quad at \quad T = 300K \\ \sim 116 \quad at \quad T = 77K \end{cases}$$

At 77-89K, charge carrier **mobility** in silicon increases, **thermal fluctuations** decrease with **kT/e**, resulting in a **higher gain**, **higher g_m / I_D**, **higher speed** and **lower noise**

Hucheng Chen, BNL

Further reading:

Nuclear Inst. and Methods in Physics Research, A 1045 (2023) 167571

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Cryogenic electronics for noble liquid neutrino detectors

Hucheng Chen *, Veljko Radeka

Brookhaven National Laboratory, Upton, NY, United States of America

ARTICLE INFO

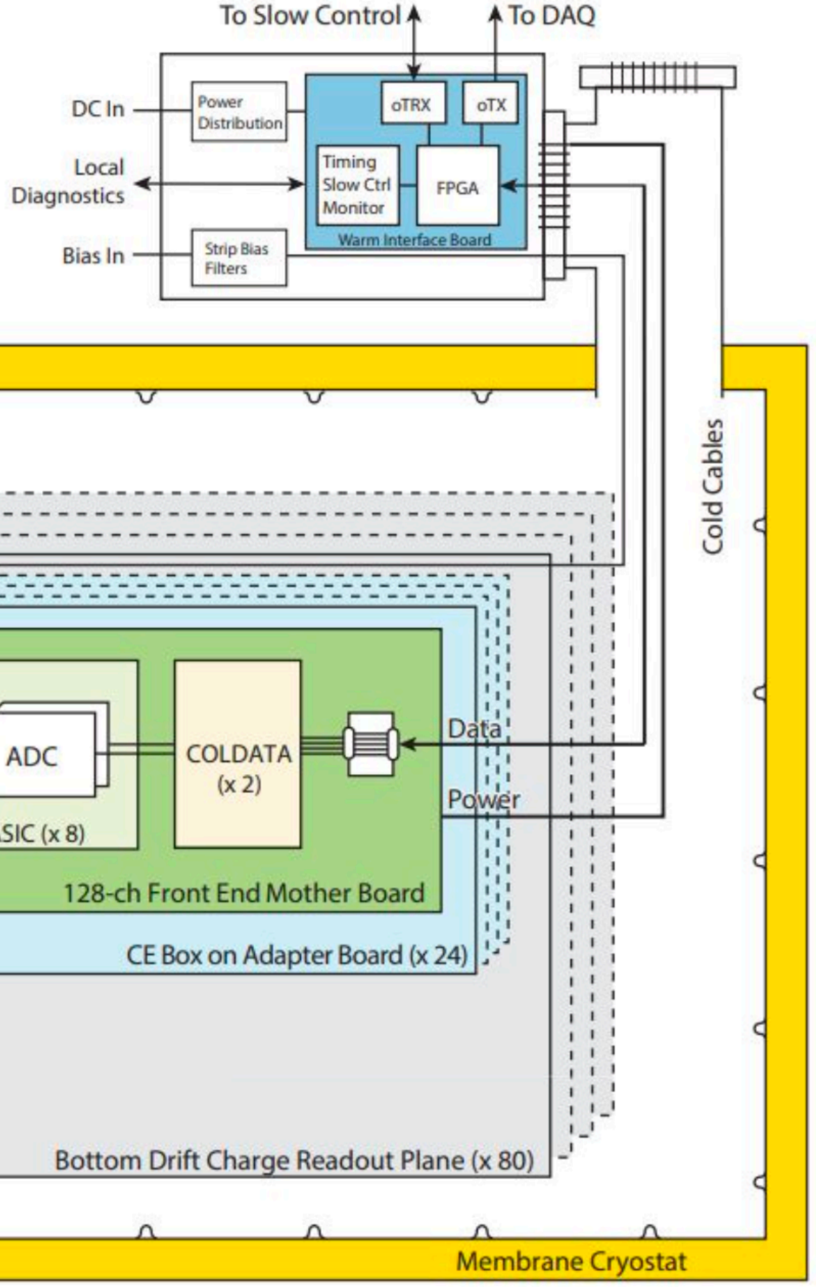
Keywords:
Cryogenic electronics
Application-specific integrated circuit (ASIC)
Noise
Front-end electronics for detector readout
Time projection chambers
Noble liquid detectors
Neutrino detectors

ABSTRACT

In this paper we present the general features of cryogenic (or "cold") electronics for noble liquid time projection chambers, with design principles and details for neutrino physics, a brief history of the technology and details of recent research and development that is driving the design of the detectors under construction. Finally, some comments on future R&D envisioned and the impact of this work on other fields is described. "Cold" in the context of this work applies to CMOS devices operated at 77 K and above, at liquids temperatures of LAr (89 K), LKr (125 K) and LXe (165 K), with most of the tests performed in, or at LN_2 (77 K). The paper is concentrated on the design of cold electronics for large liquid argon TPCs, those that have been successfully operated, MicroBooNE and ProtoDUNE, and those designed or under construction, such as SBND and DUNE first and second 10 kton modules. The high performance achieved with MicroBooNE and ProtoDUNE – a high signal-to-noise ratio combined with high stability of response – is mainly due to the integral approach to design and construction of sensing electrodes with cold readout electronics in a modular approach with the cryostat signal feed-throughs incorporating warm interface electronics into a Faraday cage with the cryostat. The integral concept is described in some detail in this paper.

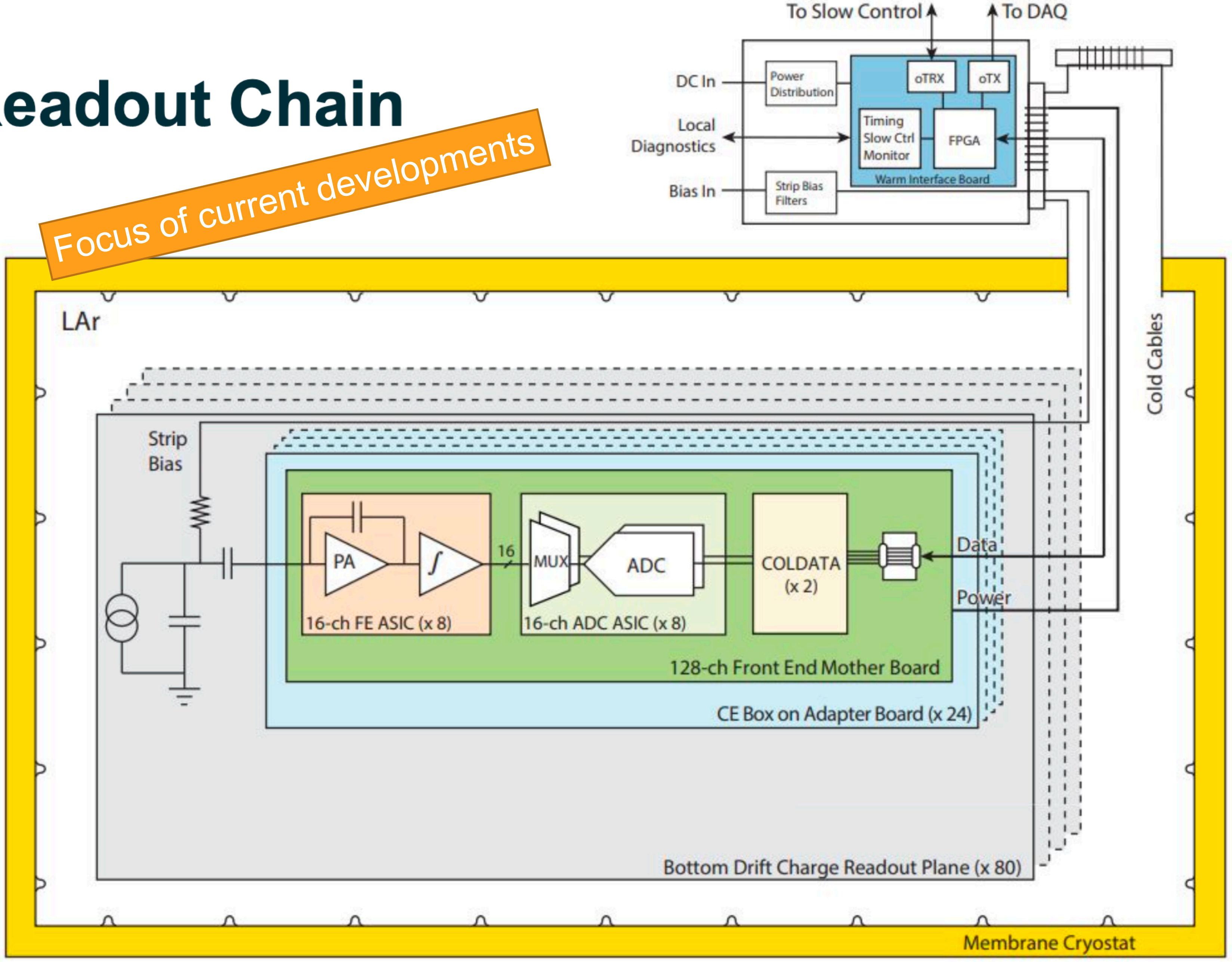
TPC Electronics Readout Chain

- Charge readout performed by 128-channel **front-end motherboards (FEMBs)** placed in close proximity to the sensing wires/strips
  - 3000 FEMBs for FD1
  - 1920 FEMBs for FD2
- Warm electronics provide power and digital control of the FEMBs, and provide the interface with the DAQ system
  - 4 FEMBs per warm interface board



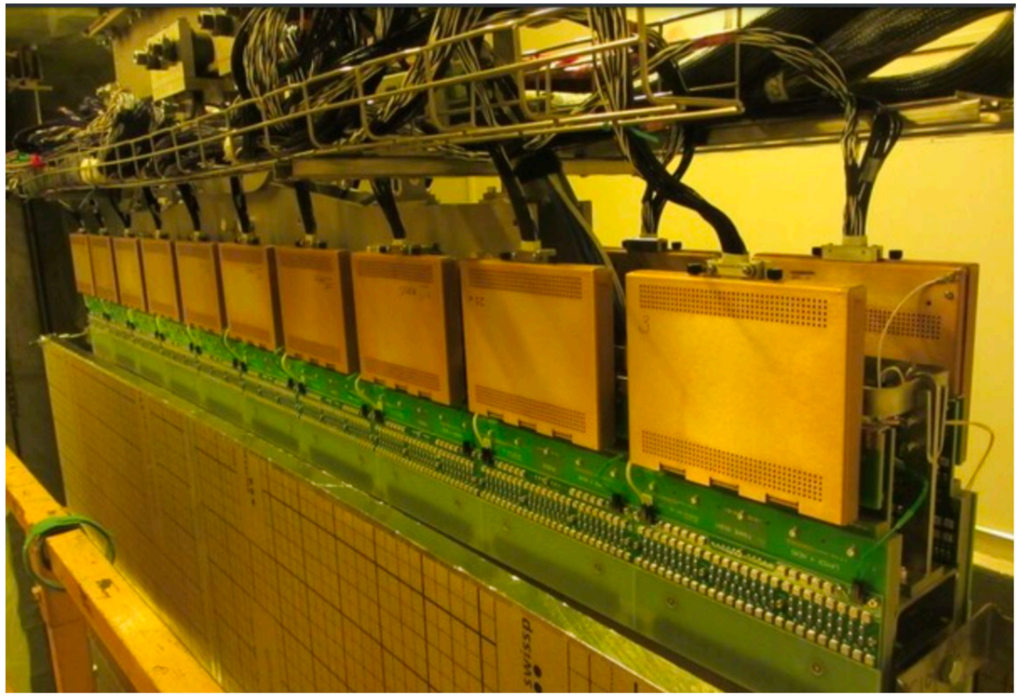
TPC Electronics Readout Chain

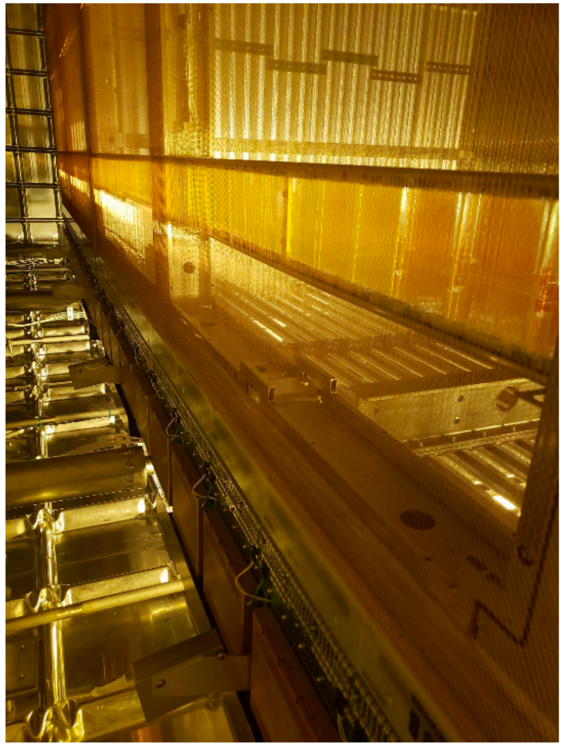
- Charge readout performed by 128-channel **front-end motherboards (FEMBs)** placed in close proximity to the sensing wires/strips
  - 3000 FEMBs for FD1
  - 1920 FEMBs for FD2
- Warm electronics provide power and digital control of the FEMBs, and provide the interface with the DAQ system
  - 4 FEMBs per warm interface board



ProtoDUNE-II-HD

- Cryostat will contain 2 drift volumes, read out by 4 APAs
- Each APA tested with all readout electronics in a **nitrogen gas coldbox** (down to ~160 K)





ProtoDUNE-II-HD

Experience presently gained at large scale

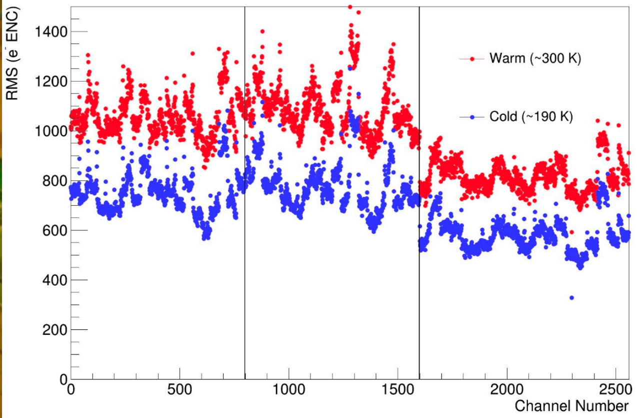
- Cryostat will contain 2 drift volumes, read out by 4 APAs
- Each APA tested with all readout electronics in a **nitrogen gas coldbox** (down to ~160 K)

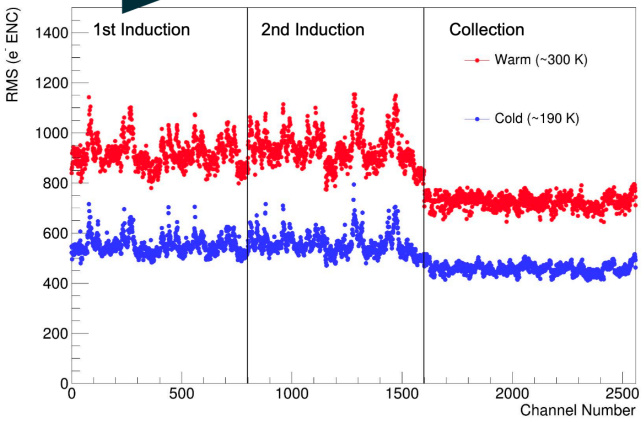
TPC Electronics Performance for ProtoDUNE-II-HD

General noise performance of electronics at cold is well below the desired ~1000 e^- equivalent noise charge (ENC) for DUNE

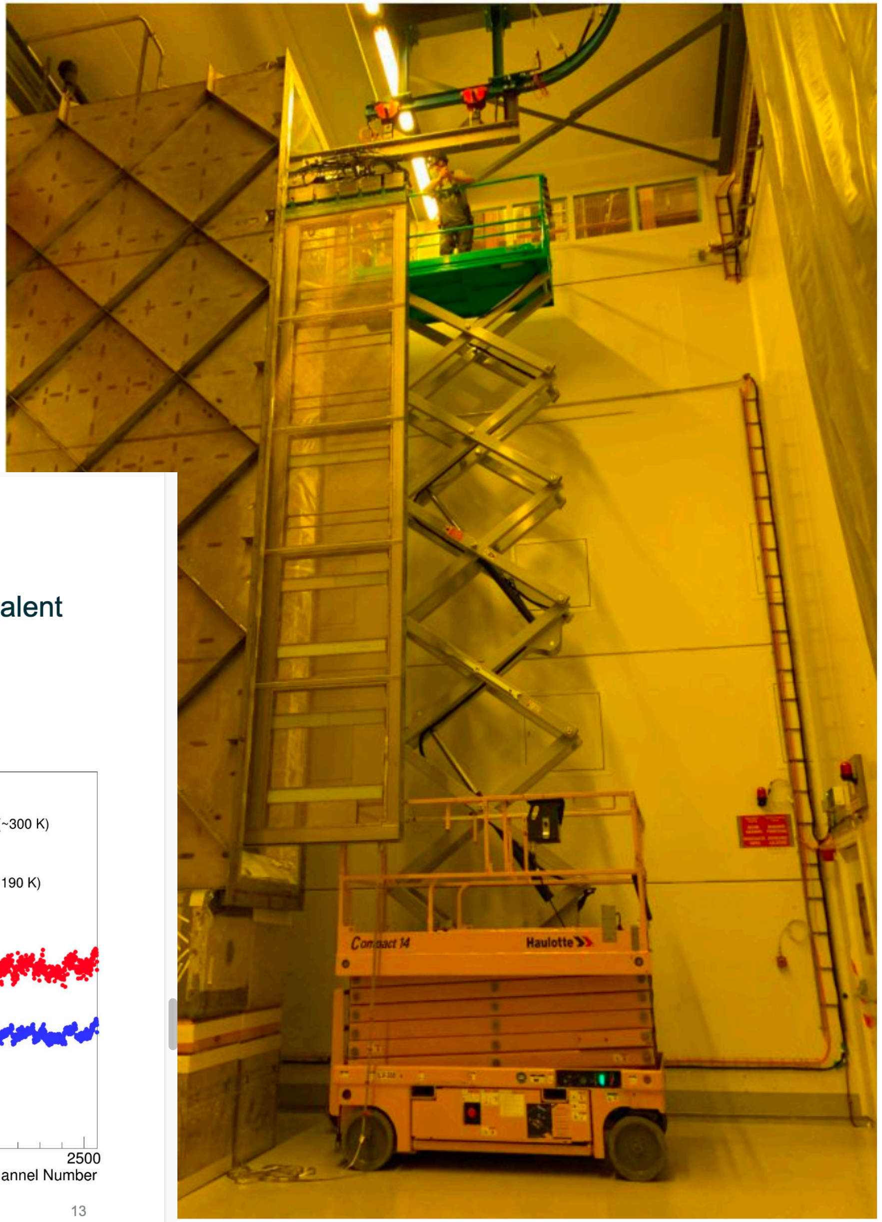
- Minimum-ionizing particle releases >10000 electrons onto each collection wire

APA1 Noise Performance without CNR **Coherent Noise Removal** → APA1 Noise Performance with CNR





10/05/2023 | TWEPP 2023, Calaserena, Italy 13



Summary

FCCee calorimeters represent exciting challenges

- radiation tolerance generally not an issue - but rate capability is, and in tension with ILC-like ambitions for precision and compactness

There is time and room for new ideas, concepts and technologies

- try them out: demonstrators are collider-agnostic

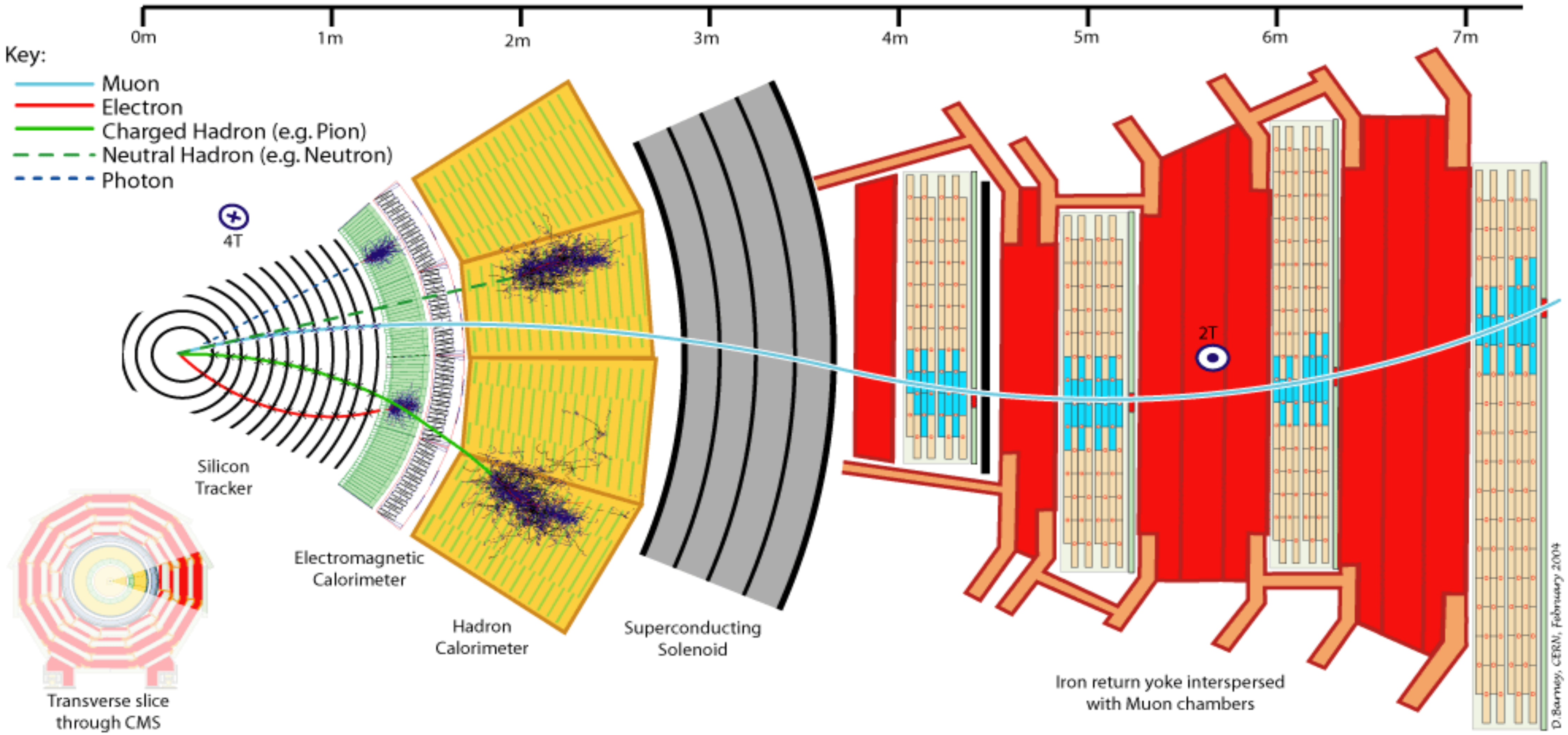
High Granularity everywhere

- but at different degrees of realism
- CALICE technologies to be adapted
- Dual readout towards prototyping and proof of principle; many system challenges
- LAr gaining momentum - and cold electronics opening up ambitious options

Back-up

Typical Collider Detector

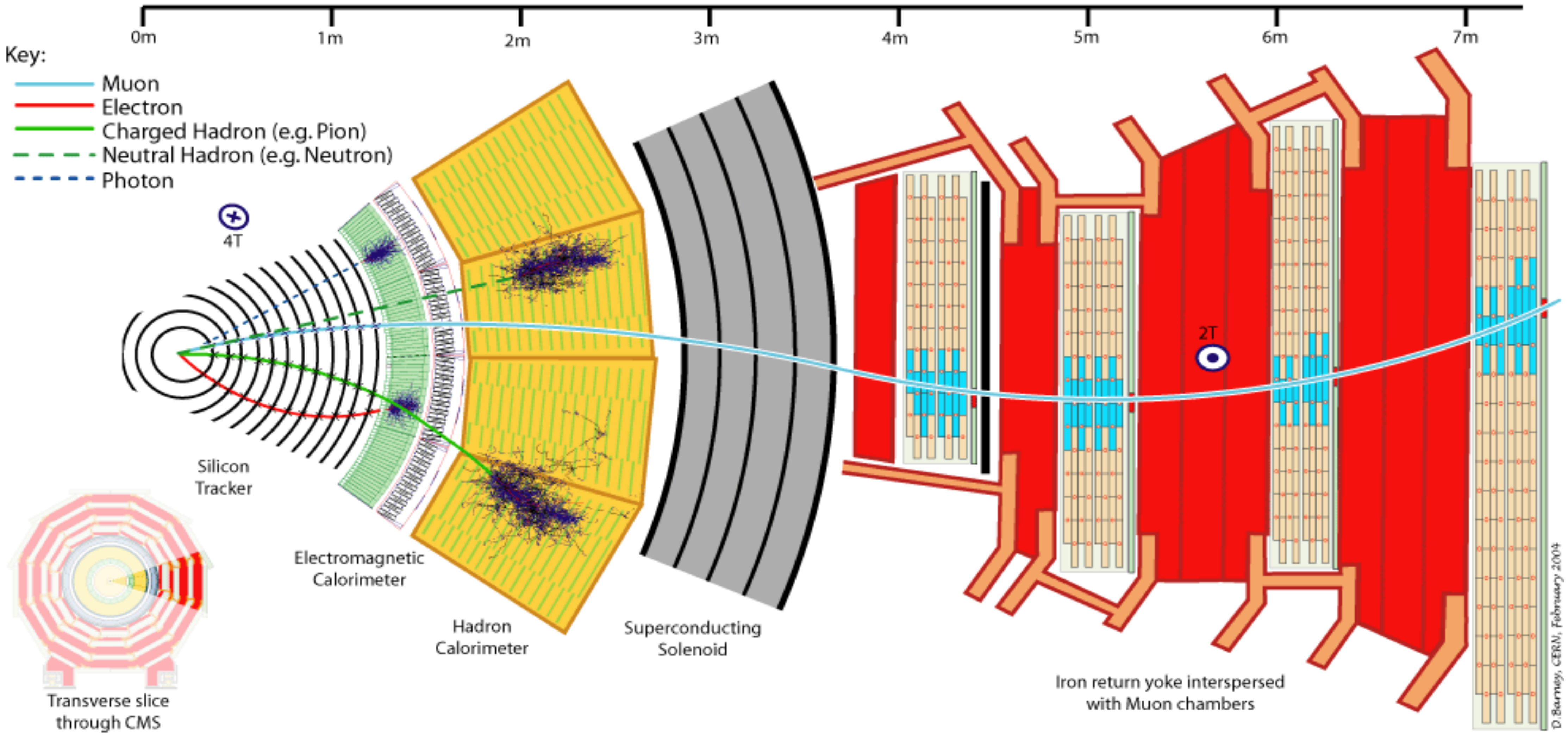
CMS



Typical Collider Detector

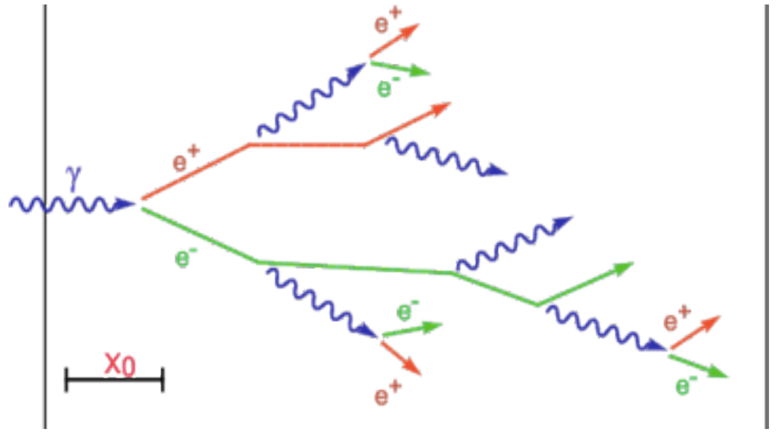
CMS

Two particle are shown with untypical signatures



Electromagnetic Showers

Electrons and Photons



Bremsstrahlung from electrons (and positrons)

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ln \frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0} \quad \rightarrow E = E_0 e^{-x/X_0}$$

- 1/e of energy left after 1 X_0

Pair creation from γ

- absorption length 7/9 X_0 (mean free path)
- 1/e of photons still there after 0.8 X_0

$$X_0 = \frac{180A}{Z^2} \frac{\text{g}}{\text{cm}^2}$$

Common scale X_0

- number of particles doubles every X_0
- until _E<E_c ionisation takes over
- total N = E / E_c particles
- length, depth of maximum ~ log E/E_c

Radial extension

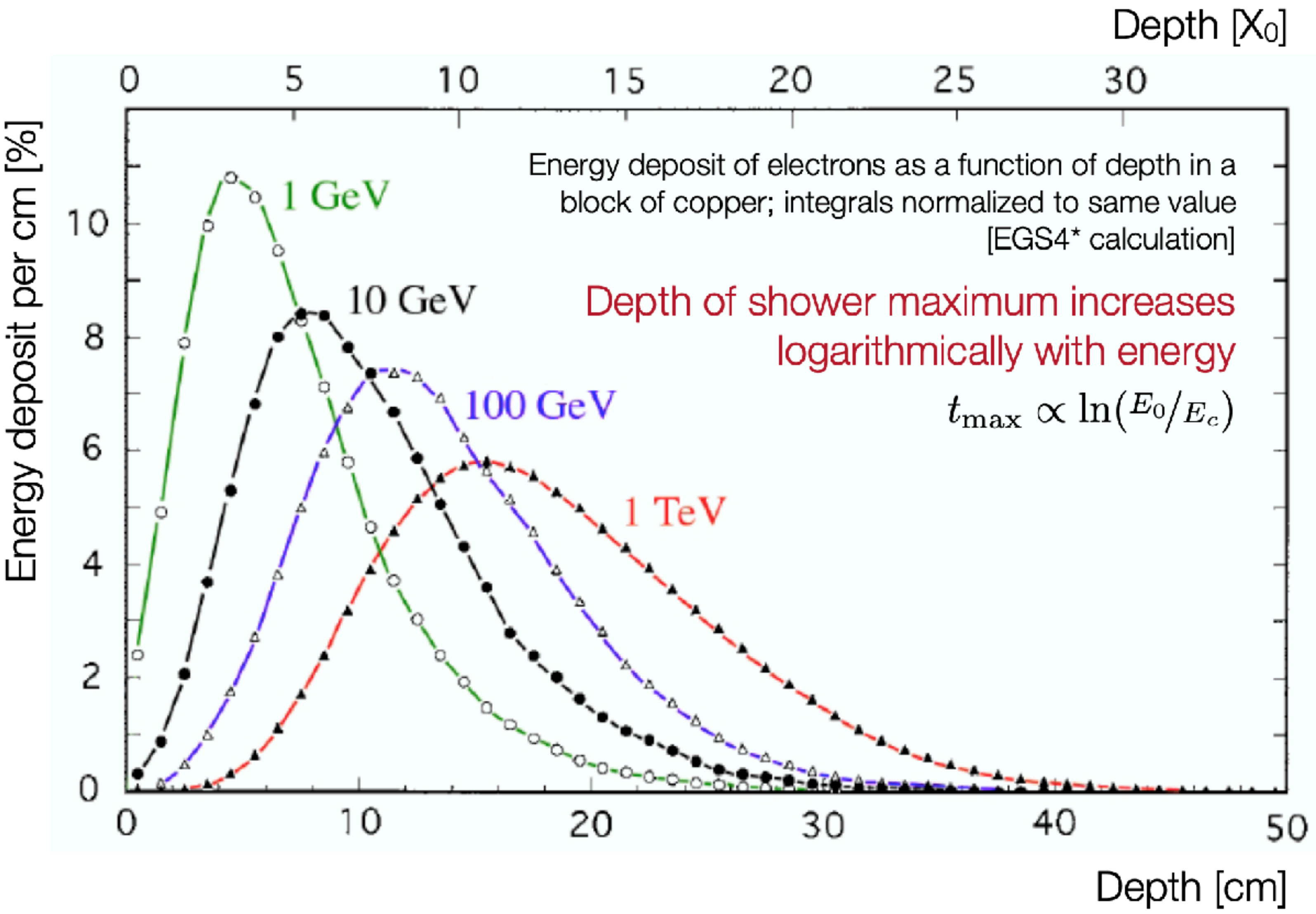
- Moliere radius R_M
  - contains 90% of energy
  - related to multiple scattering
- R_M decreases with Z

$$E_c = \frac{550 \text{ MeV}}{Z}$$

$$R_M = \frac{21 \text{ MeV}}{E_c} X_0$$

Longitudinal Evolution vs. Energy

Electromagnetic Showers



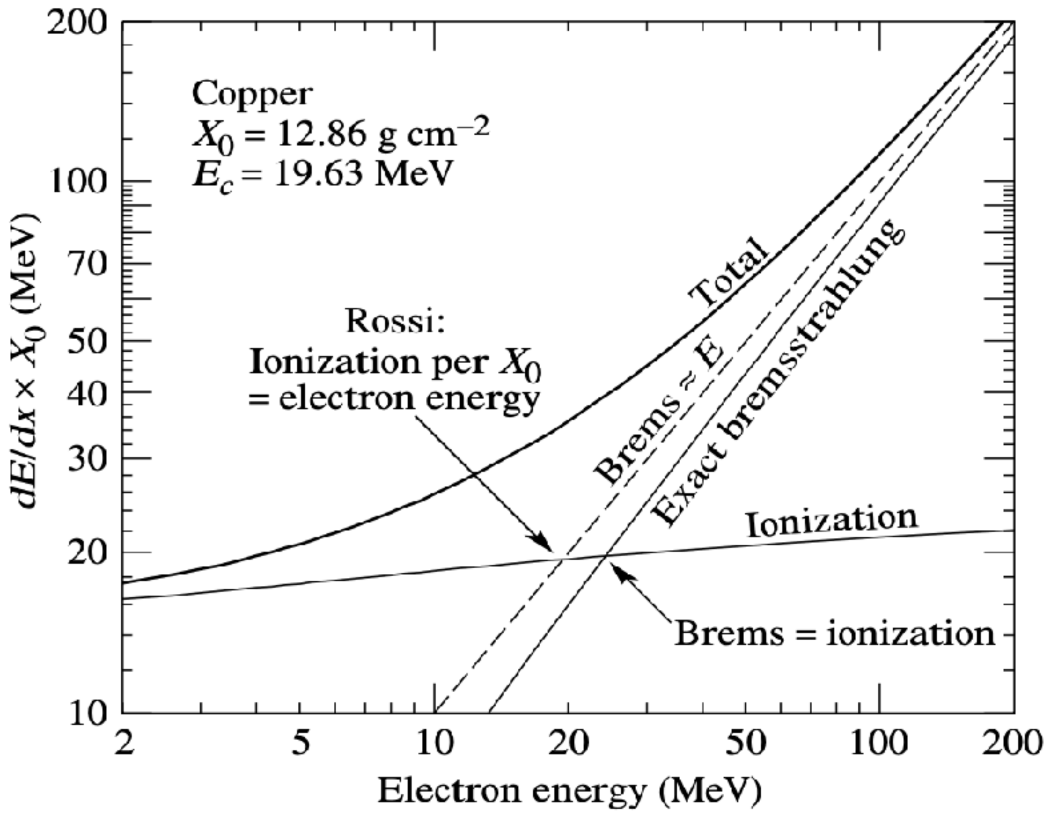
Critical Energy

End of electromagnetic showers

Approximations

$$E_c^{\mathrm{Gas}} = \frac{710\ \mathrm{MeV}}{Z + 0.92} \qquad \left[E_c^{\mathrm{Sol/Liq}} = \frac{610\ \mathrm{MeV}}{Z + 1.24} \right]$$

$$E_c = \frac{550\ \mathrm{MeV}}{Z}$$



Photons below pair threshold of 1 MeV

- Compton scattering
- photoelectric effect

Heavy absorbers - smaller E_c means

- more particles
- softer particles
- surface effects

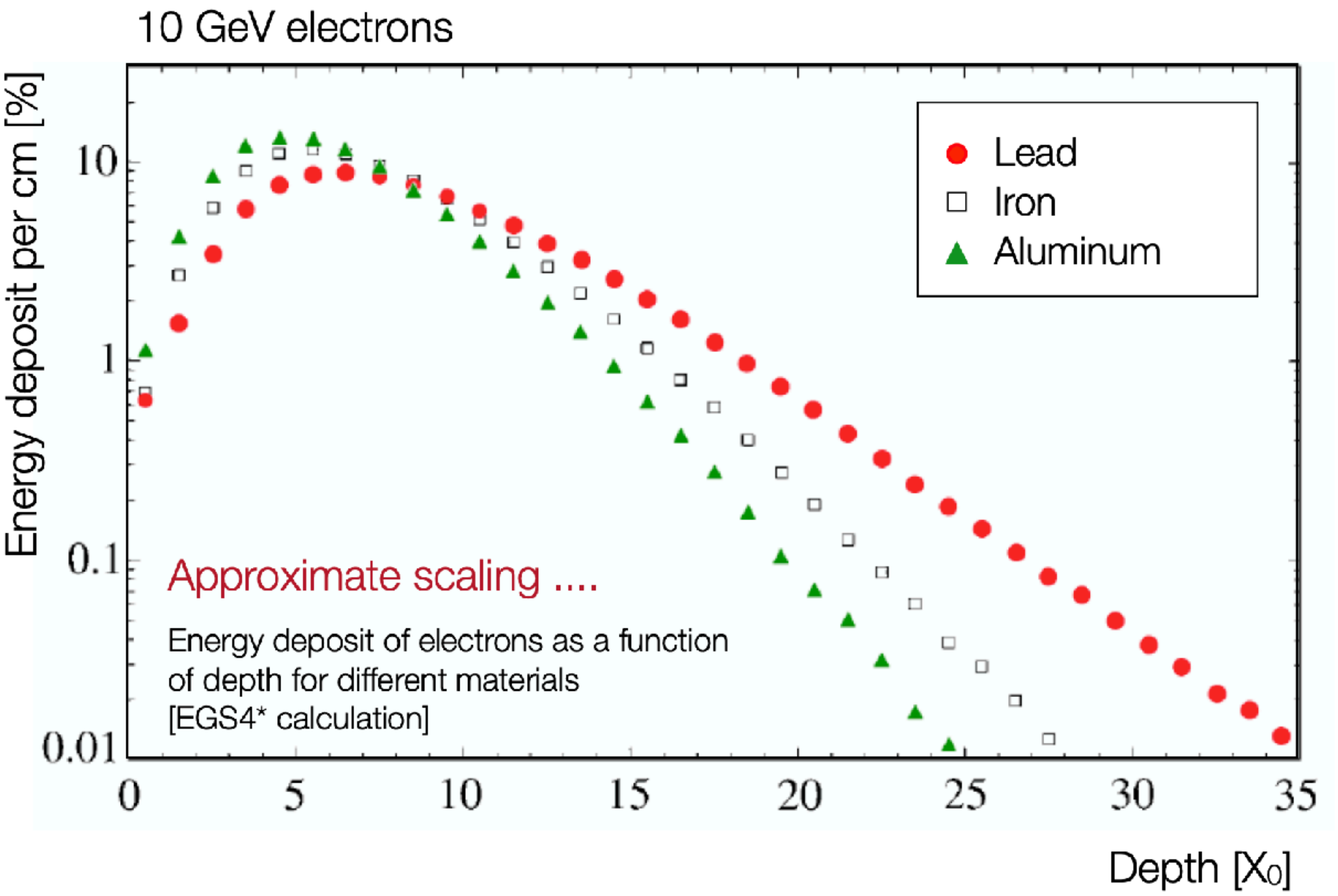
Electromagnetic Shower Parameters

Centimeters

	X_0 [cm]	E_c [MeV]	R_M [cm]
Pb	0,56	7,2	1,6
Scintillator (Sc)	34,7	80	9,1
Fe	1,76	21	1,8
Ar (liquid)	14	31	9,5
BGO	1,12	10,1	2,3
Sc/Pb	3,1	12,6	5,2
PB glass (SF5)	2,4	11,8	4,3

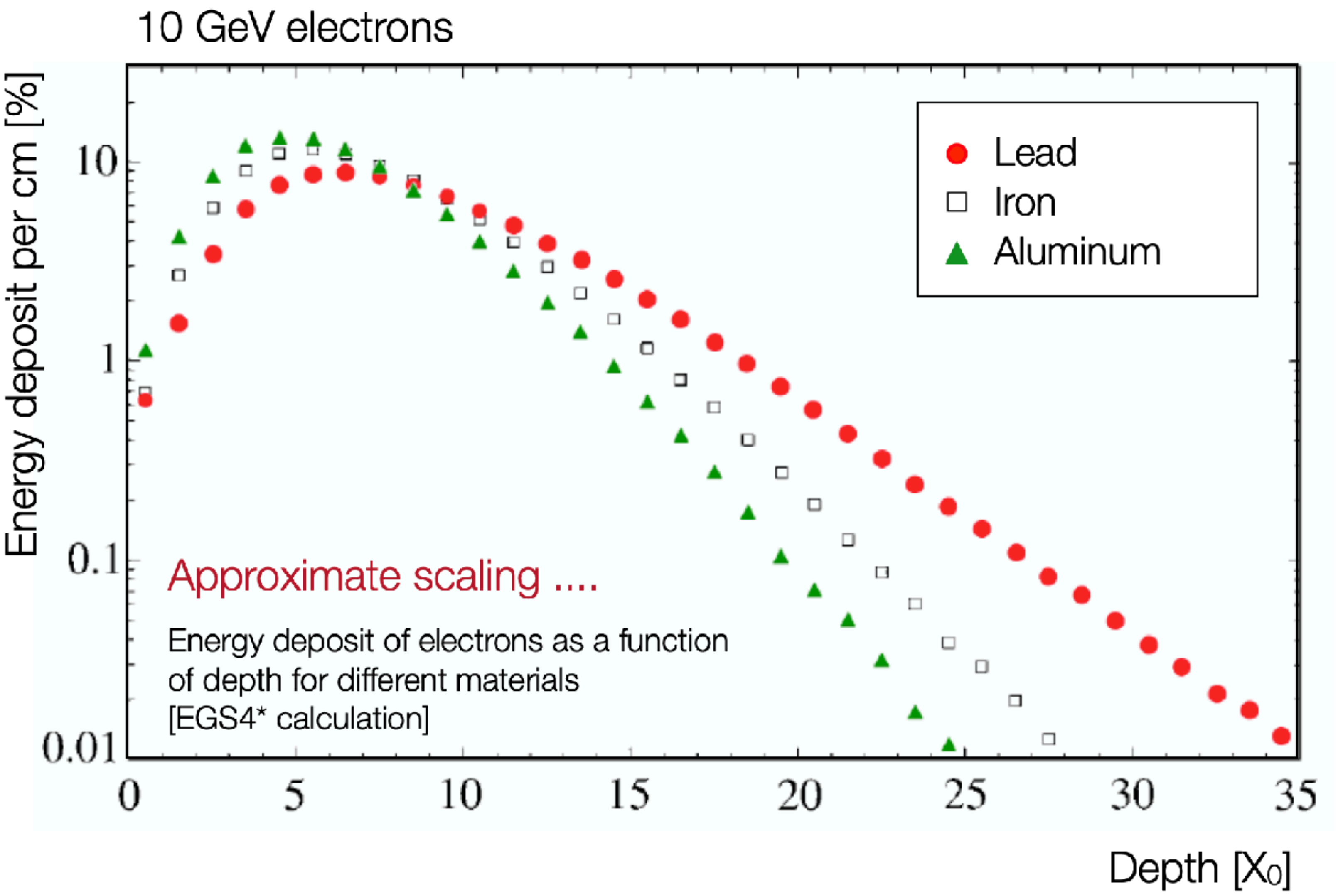
Longitudinal Evolution vs. Material

Electromagnetic Showers



Longitudinal Evolution vs. Material

Electromagnetic Showers



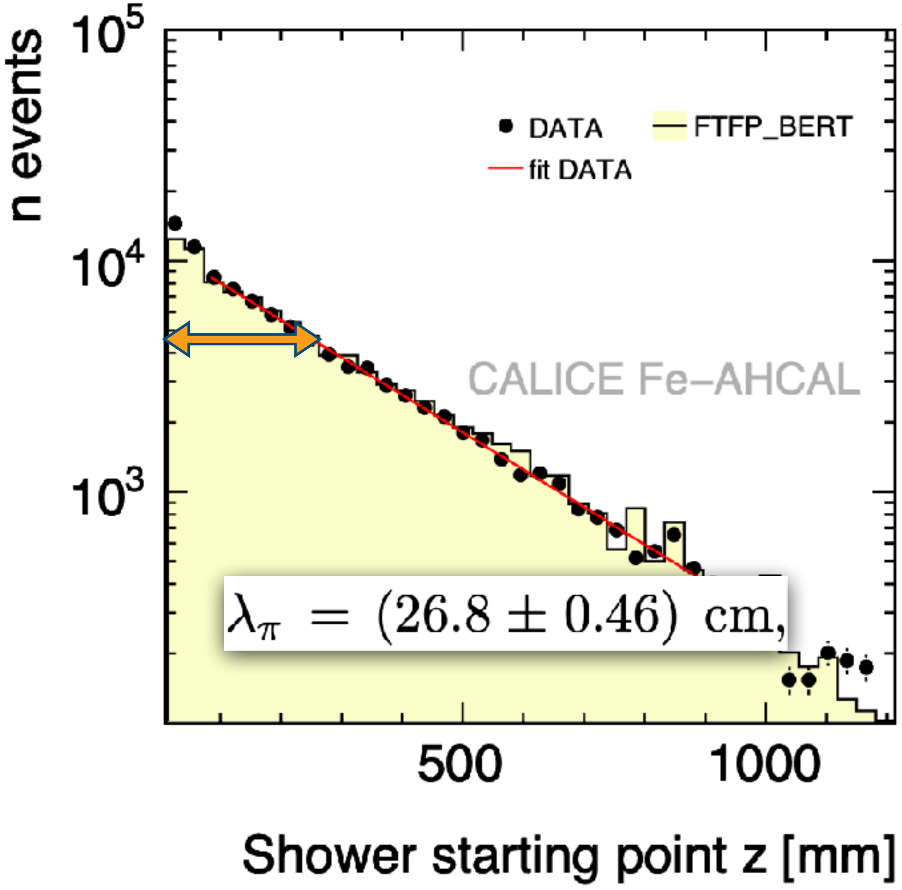
High Z materials:
many soft photons in tail

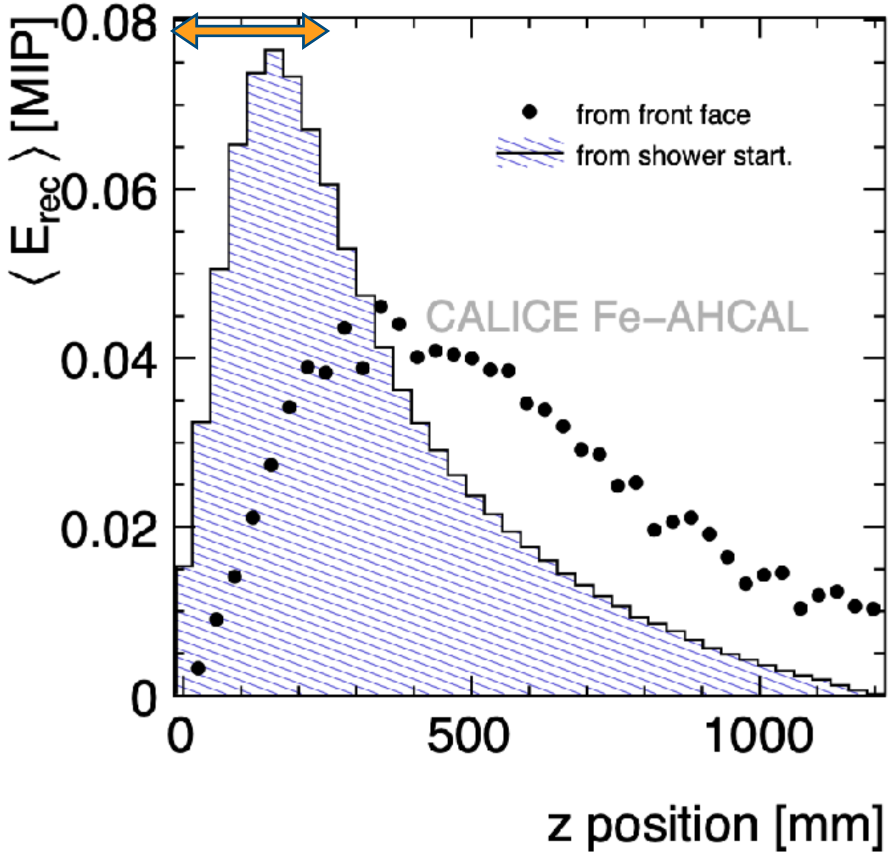
- surface effects
- response may depend on “age"

Shower profiles

Convolution

pions 45 GeV





Detector Concepts

In a Nutshell

Detector concepts form the link between performance requirements and technological capabilities

- thus **guide the R&D** and give **feedback on performance** impact of technical solutions

Two main ingredients:

- a full **simulation** model
  - enable validation of single particle performance with prototypes
  - realistic prediction of full-event performance: will also need higher-level reconstruction tools
- overall **engineering**
  - to act and respond in the design of the MDI
  - to guide the optimisation of the global structure and parameters

Collaboration forming at a later stage

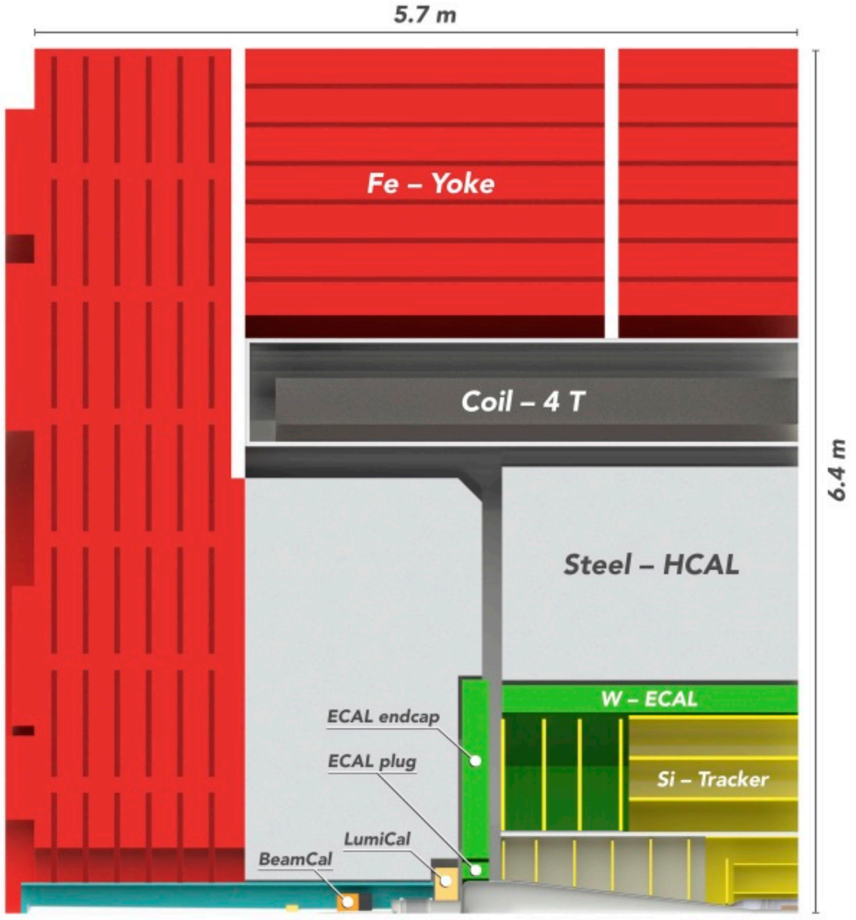
- maintain freedom to combine, e.g. tracking and calorimeter technologies ("plug & play")

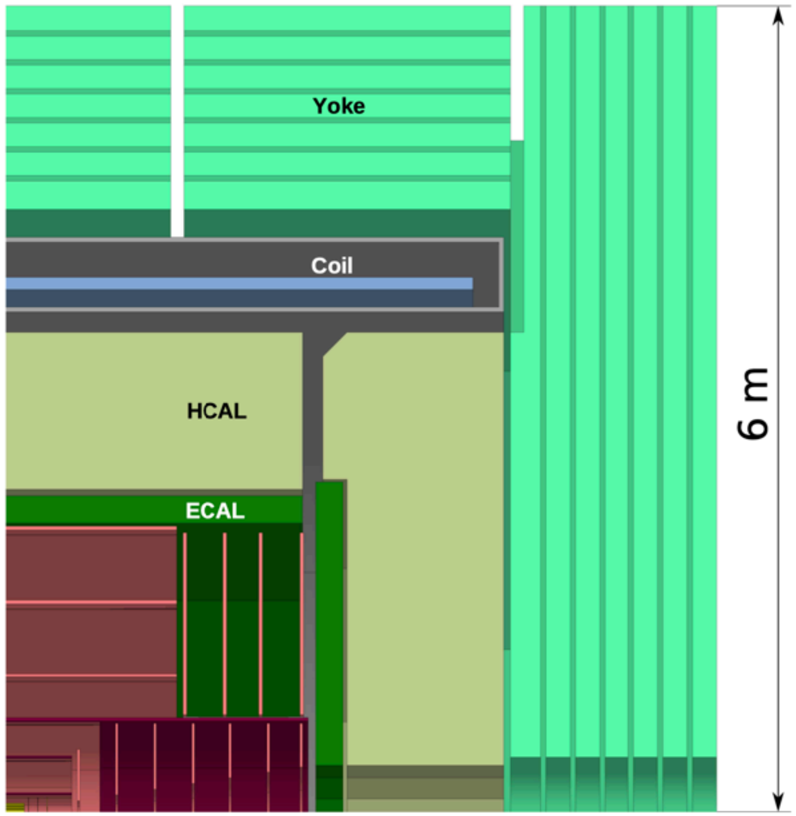
From LCs to FCCee

From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



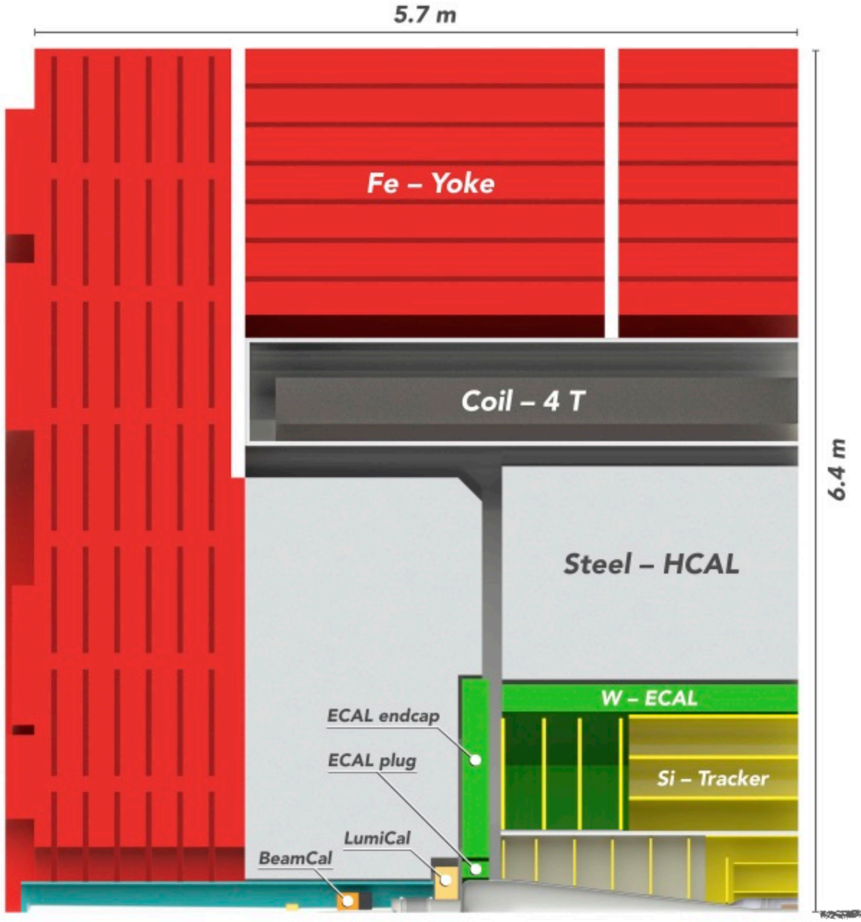


From LCs to FCCee

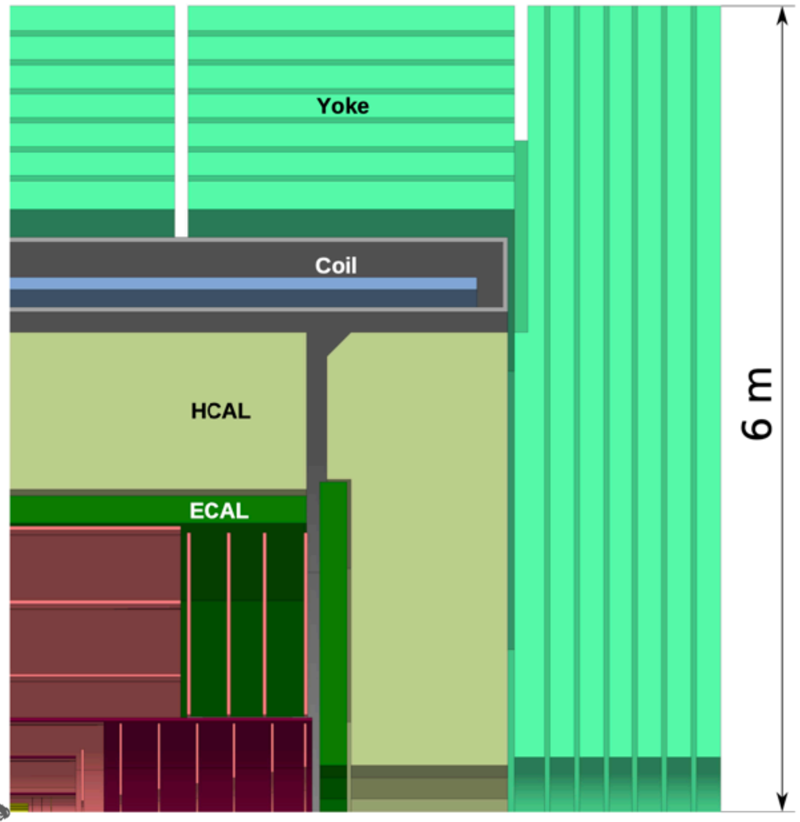
From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



smaller VTX radius: profit from lower backgrounds, compensate material

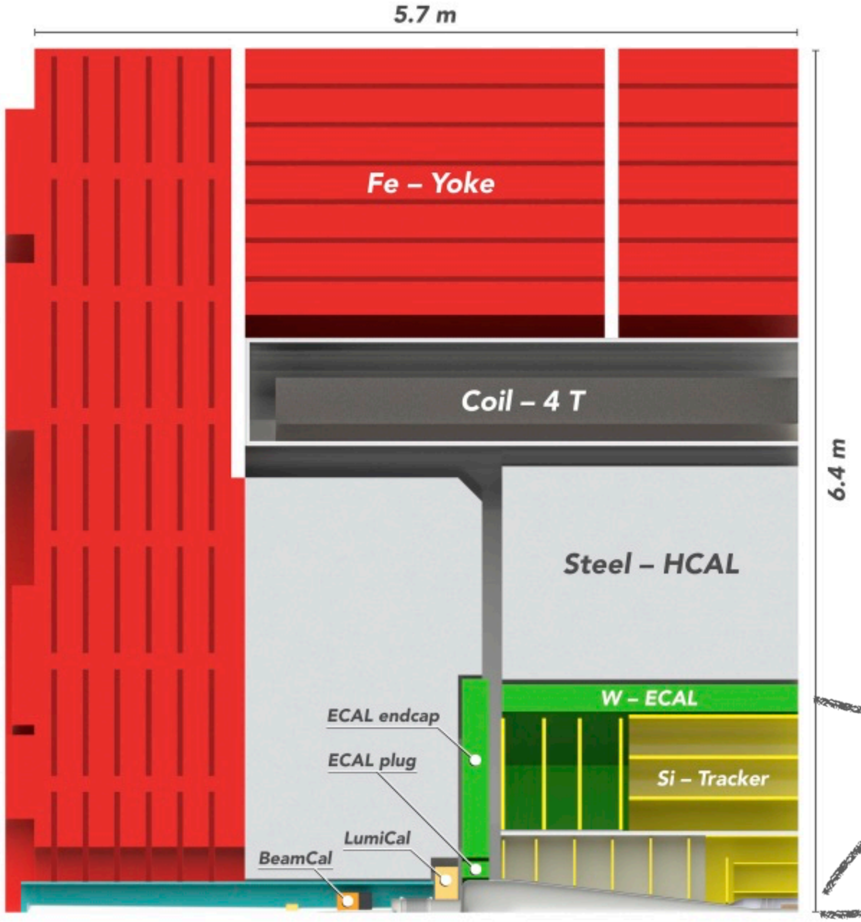


From LCs to FCCee

From CLICdet to CLD

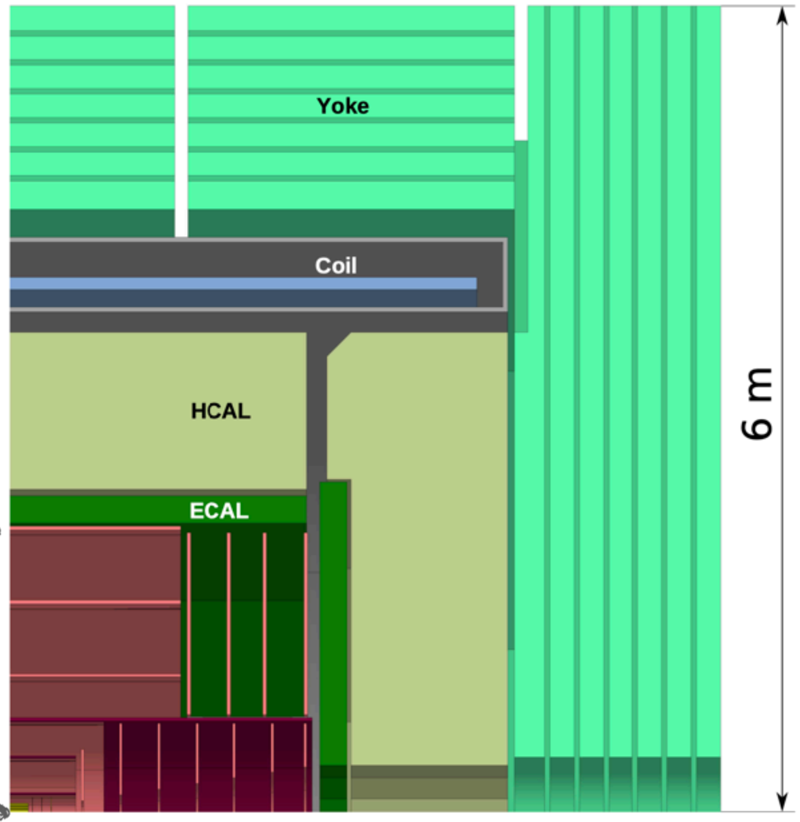
CLICdet = CLIC-SiD CLIC-ILD merger

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material



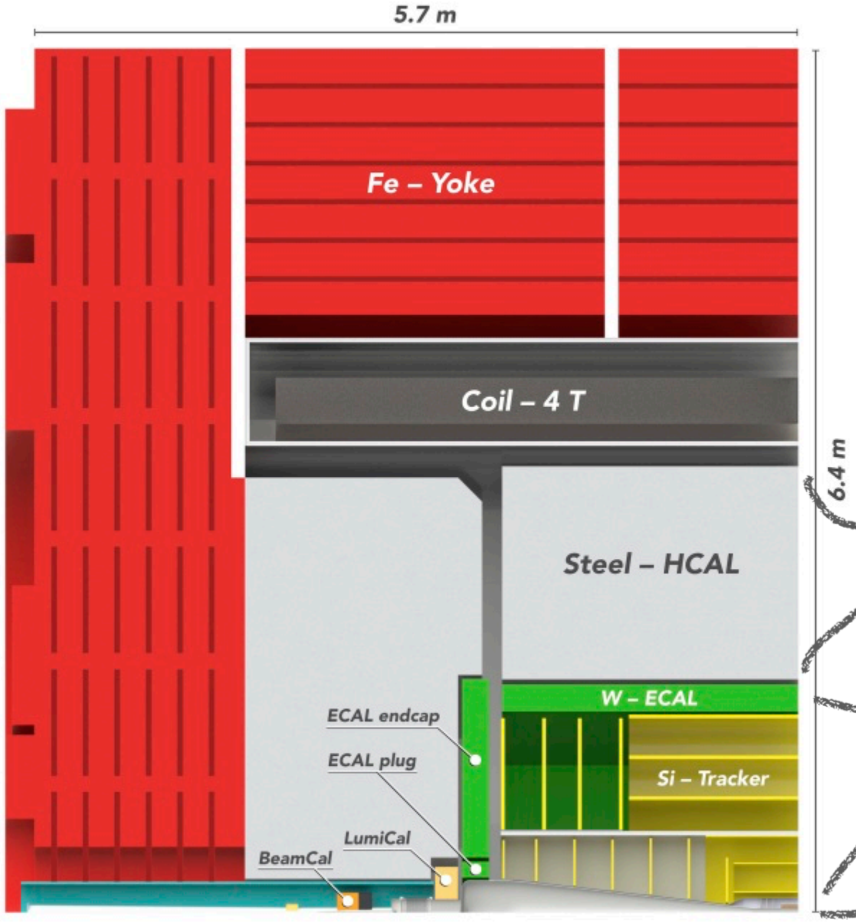
From LCs to FCCee

From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

MAX-PLANCK-INSTITUT FÜR PHYSIK

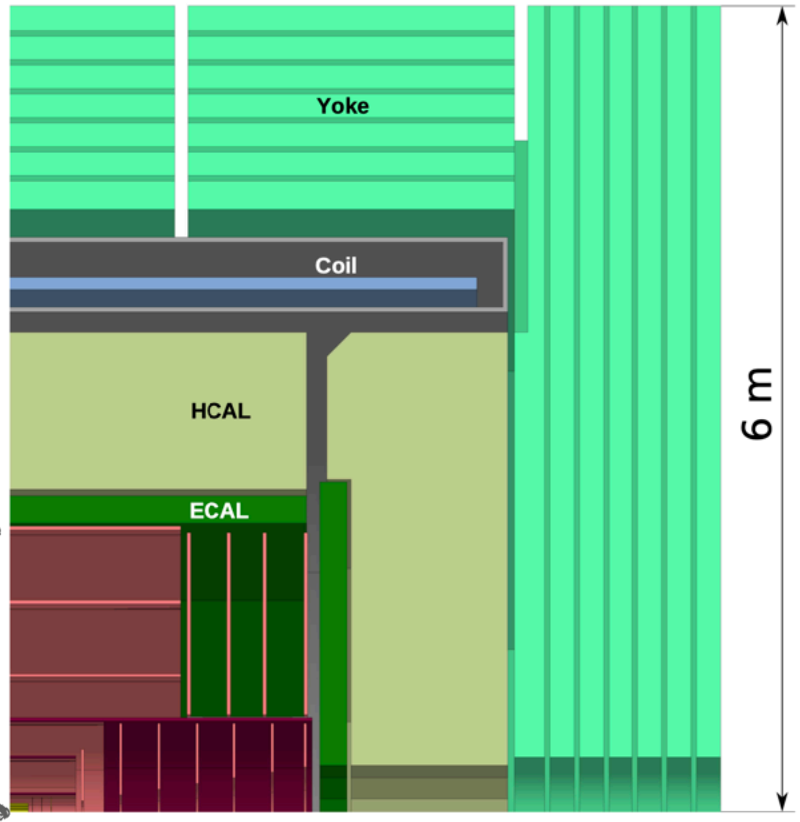
- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material

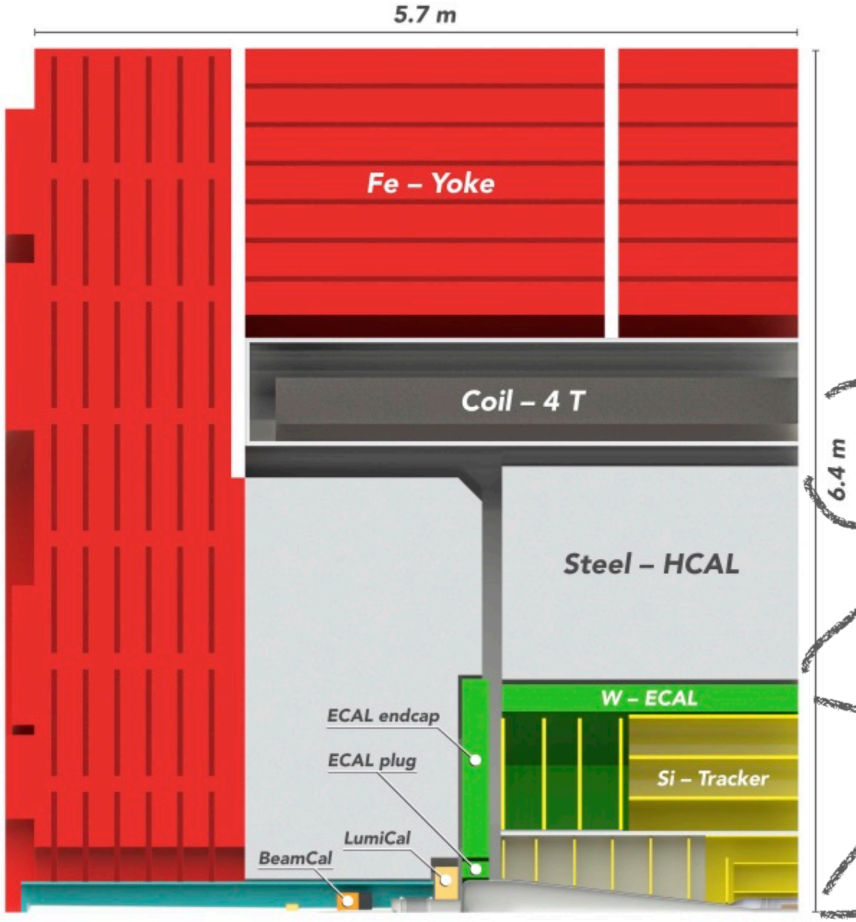


From LCs to FCCee

From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD

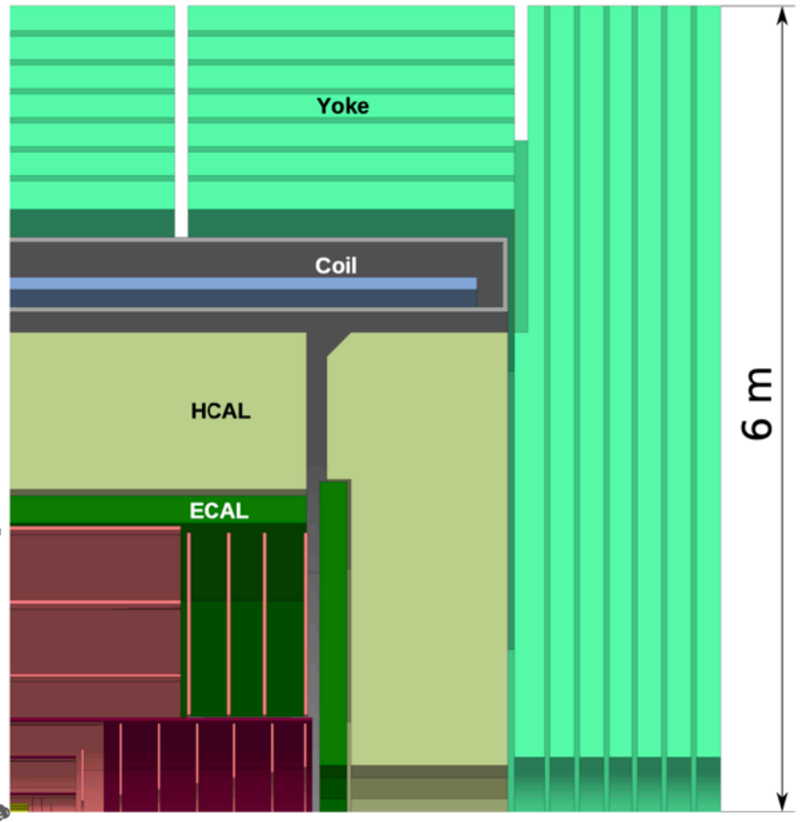


lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material

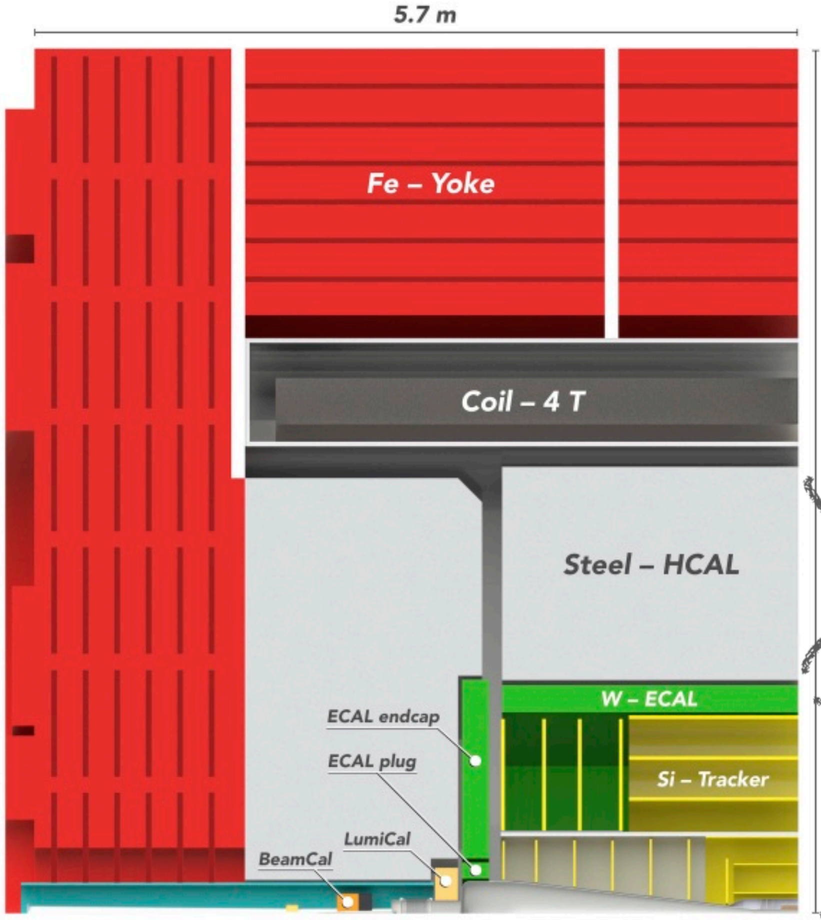


From LCs to FCCee

From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



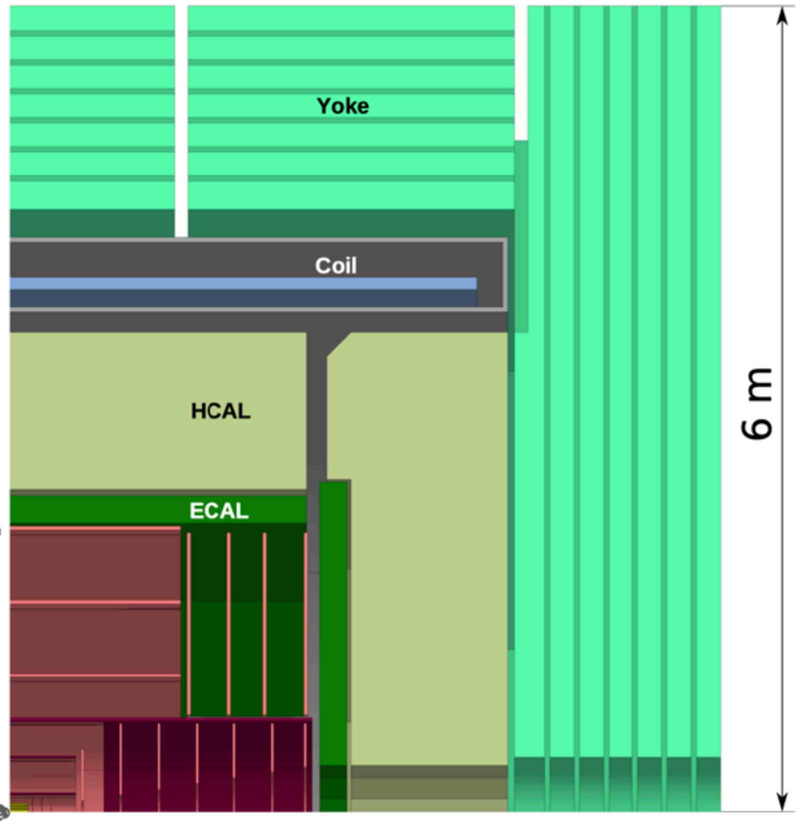
less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

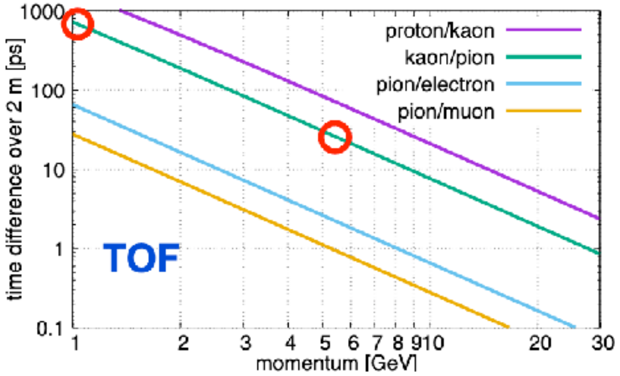
increase in tracker radius: retain p resolution

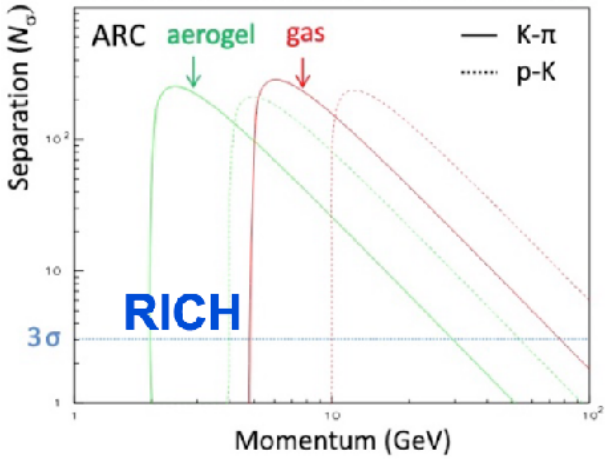
smaller VTX radius: profit from lower backgrounds, compensate material



CLD with RICH-based Particle ID

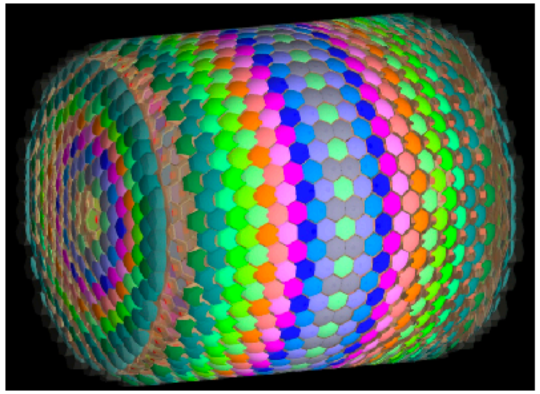
Up to high momenta

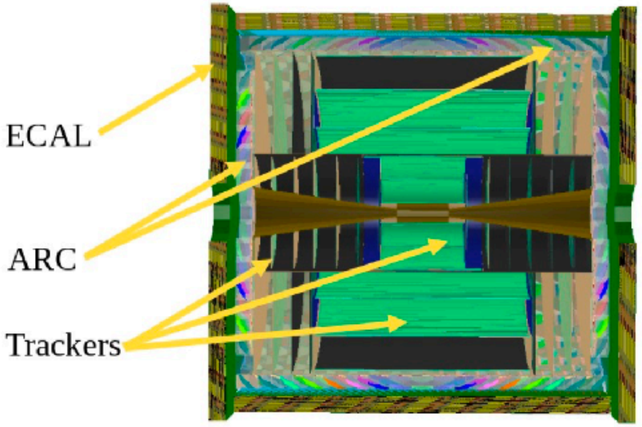




CLD option with ARC

- New option of CLD to accommodate ARC subdetector (A. Tolosa-Delgado) [link]
- Array of RICH Cells (ARC) is a Cerenkov-based detector
- RICH detectors are suitable for particle identification at high momentum
- Work in geometry optimization, digitization and reconstruction algorithms is ongoing

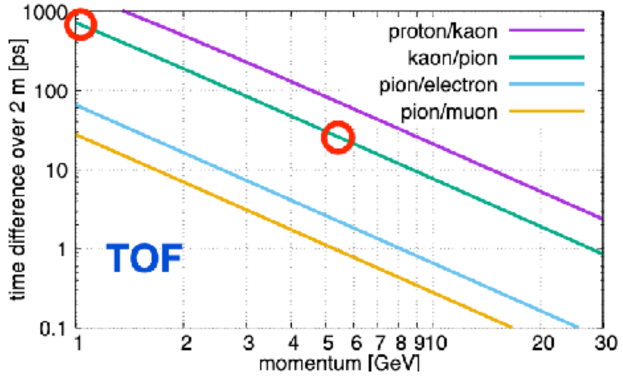


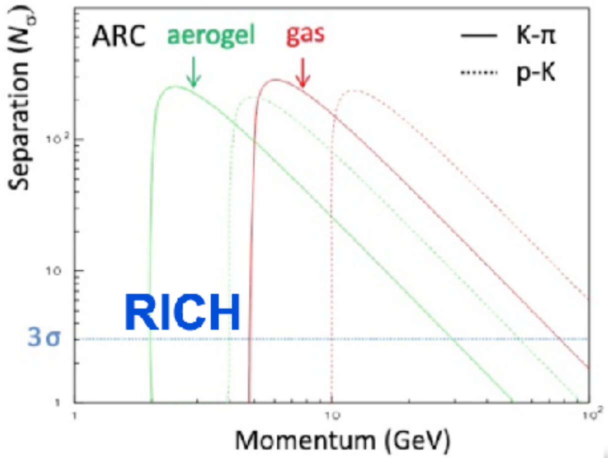


FCCee detector fullsim implementation alvaro.tolosa.delgado@cern.ch 8

CLD with RICH-based Particle ID

Up to high momenta

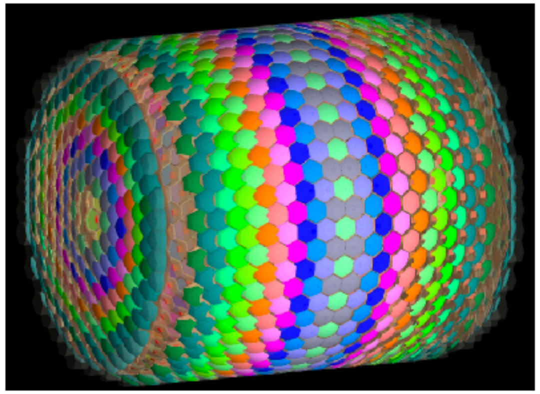


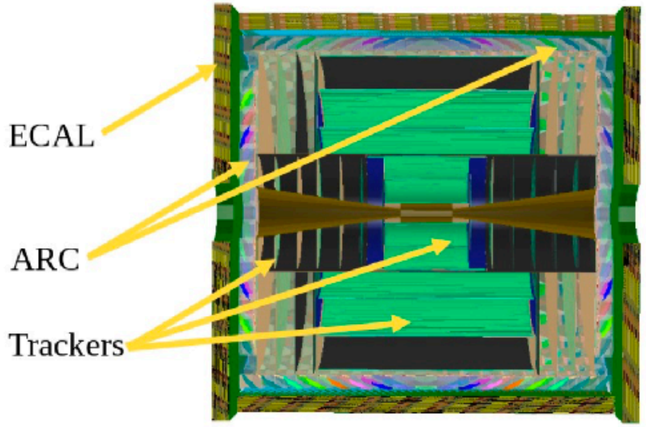


Tracking re-optimised
Particle flow to be studied next

CLD option with ARC

- New option of CLD to accommodate ARC subdetector (A. Tolosa-Delgado) [link]
- Array of RICH Cells (ARC) is a Cerenkov-based detector
- RICH detectors are suitable for particle identification at high momentum
- Work in geometry optimization, digitization and reconstruction algorithms is ongoing





FCCee detector fullsim implementation alvaro.tolosa.delgado@cern.ch 8

HGCAL System

Overview

Electromagnetic calorimeter (CE-E):

- Active elements: hexagonal silicon modules
- Cu & CuW & Pb absorbers, 26 layers, ~28 X_0

Hadronic calorimeter (CE-H):

- Si (as in CE-E) & scintillator tiles read by SiPMs
  - as radiation levels permit
- steel absorbers, 21 layers,10 λ (including CE-E)

Key Parameters:

- 620m2 Si sensors in ~26000 modules
- 6M Si channels, 0.5 or 1.2cm^2 cell size
- 370m2 of scintillators in ~3700 boards
- 280k scint. channels, 4-30cm^2 cell size
- 220 tonnes per endcap, full system at -30^{o}C
- up to 280kW, two phase CO2 cooling