Experimental Opportunities at a Future Collider at CERN

Max Planck Institute for Physics, Munich, January 14, 2025

Felix Sefkow

DESY

Menu

Sequence of Courses

Project overview and Timeline

Detector Requirements from Physics

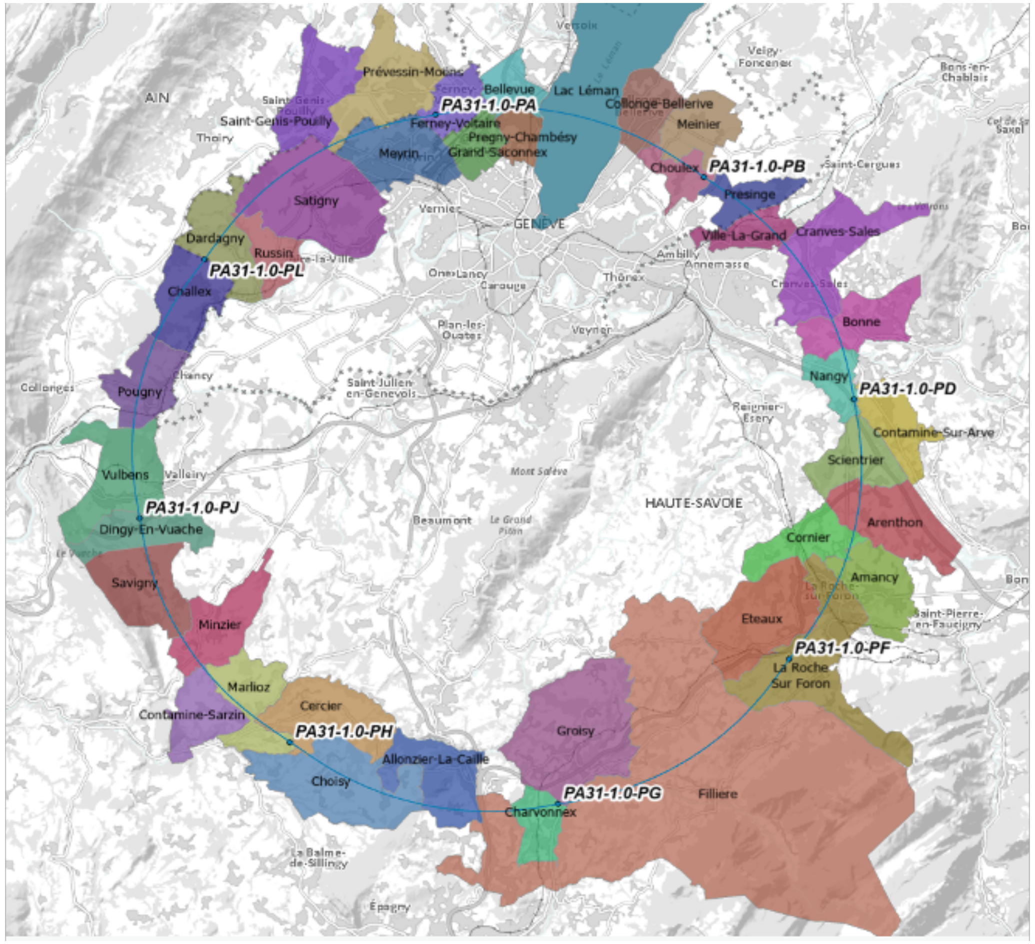
Detector concepts

- linear and circular colliders

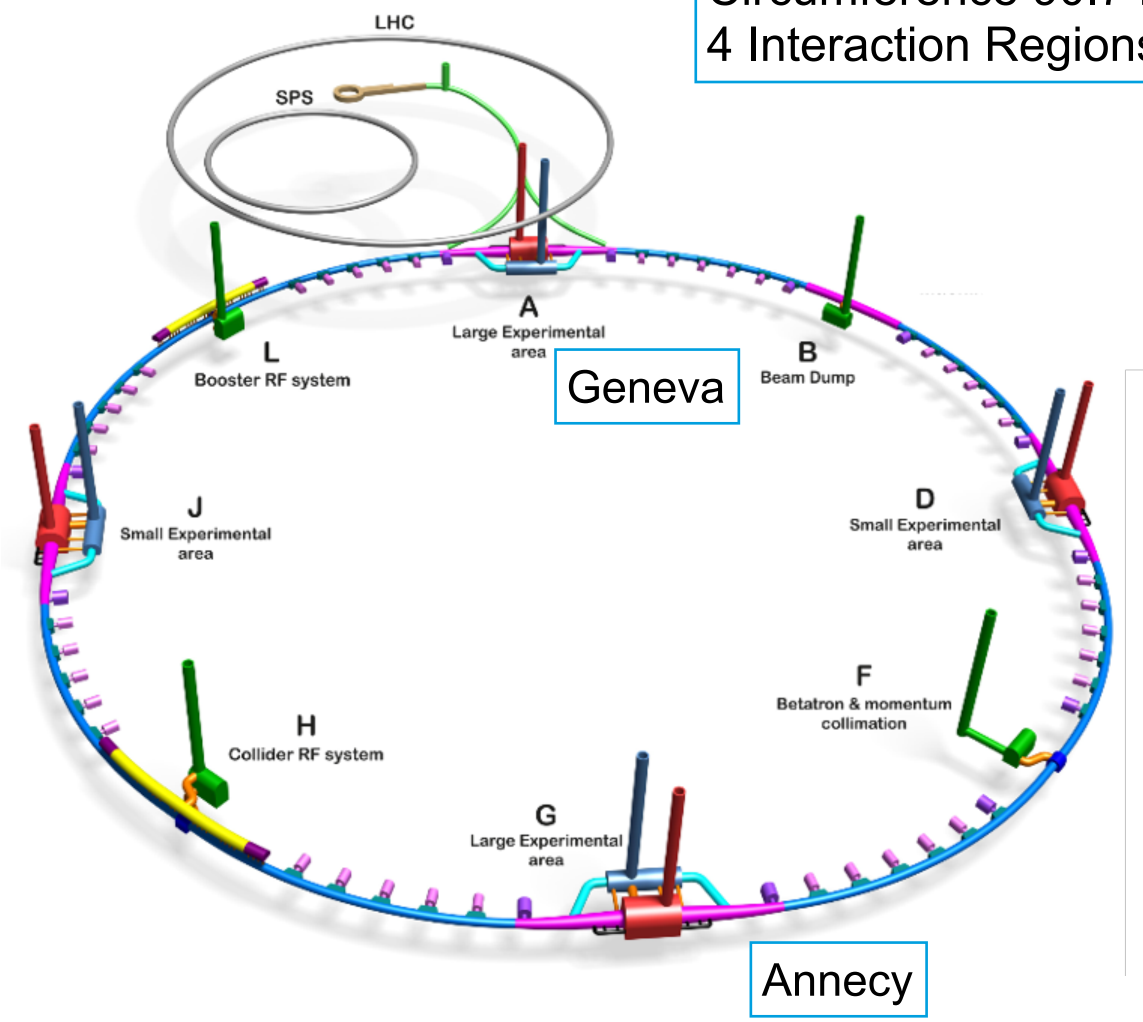
Selected detector systems and technologies

The Future Circular Collider

Proposed Next Flagship Project at CERN

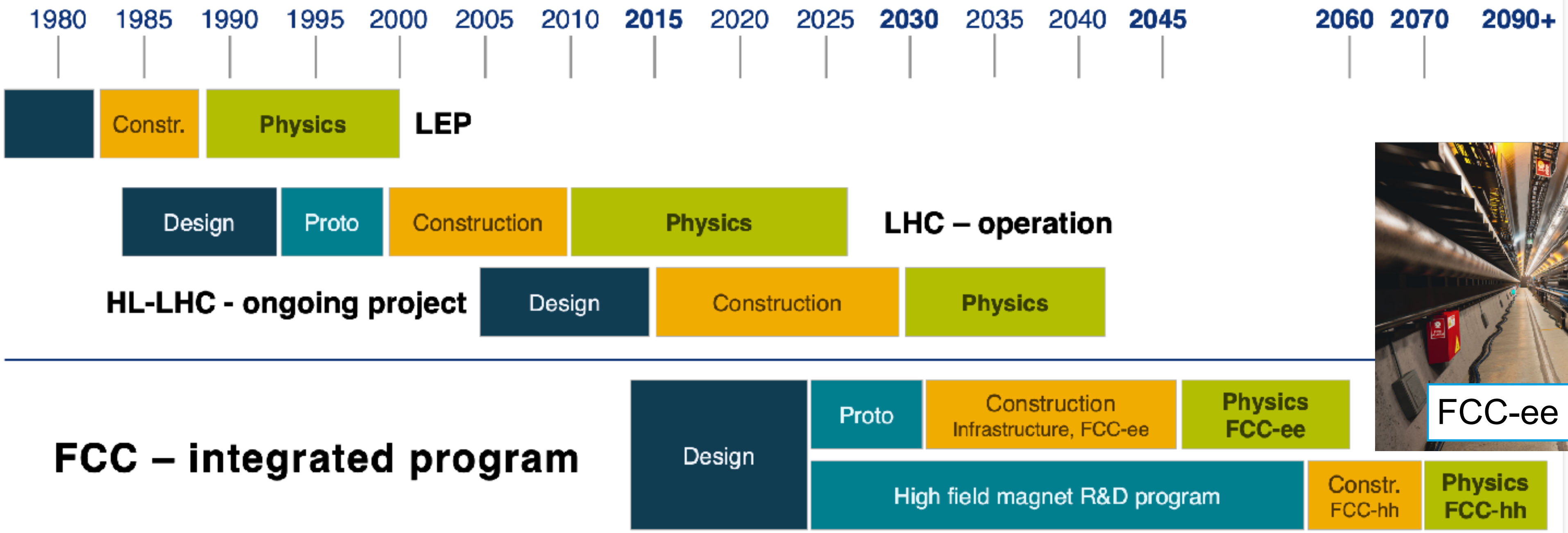


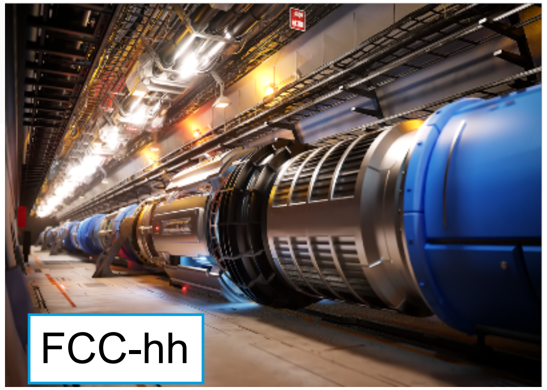
Circumference 90.7 km
4 Interaction Regions



High-Level Timeline

Circular Colliders at CERN





1. Stage: e+e-: Higgs El.weak and top factory (Z, WW, ZH, tt)

2. Stage: hh: pp physics at the energy frontier (~100 TeV)

How Much Time Do We Need?

"Random" Examples - and NOT from the start of the R&D

Nuclear Instruments and Methods in Physics Research A309 (1991) 438–449
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

t0 -17y

Performance of a liquid argon electromagnetic calorimeter with an "accordion" geometry

RD3 Collaboration

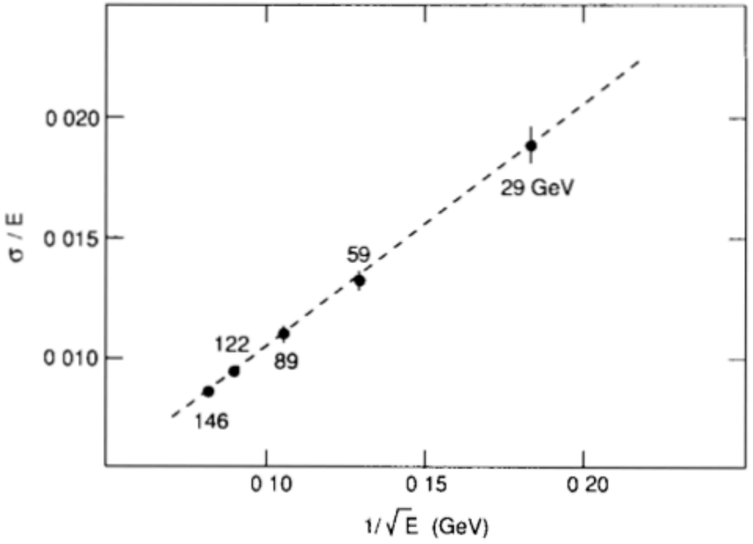


Fig. 6. Energy resolution of the prototype at different electron energies. The dashed line is a linear fit to the experimental points.

CMS

CERN-LHCC-2015-10
LHCC-P-008
CMS-TDR-15-02
ISBN 978-92-9083-417-5
1 June 2015

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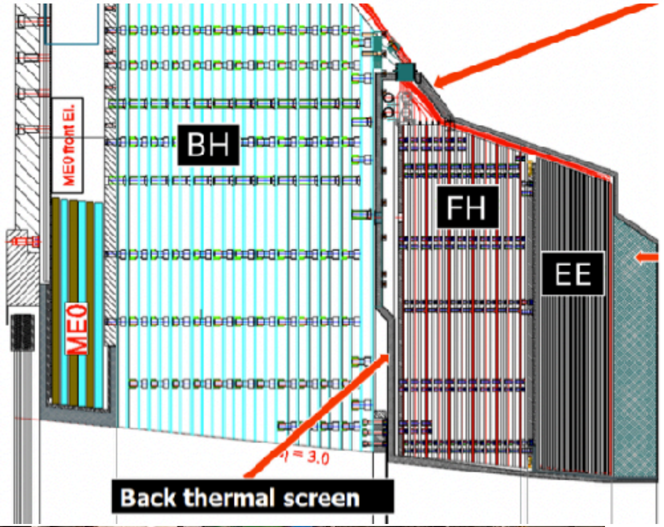
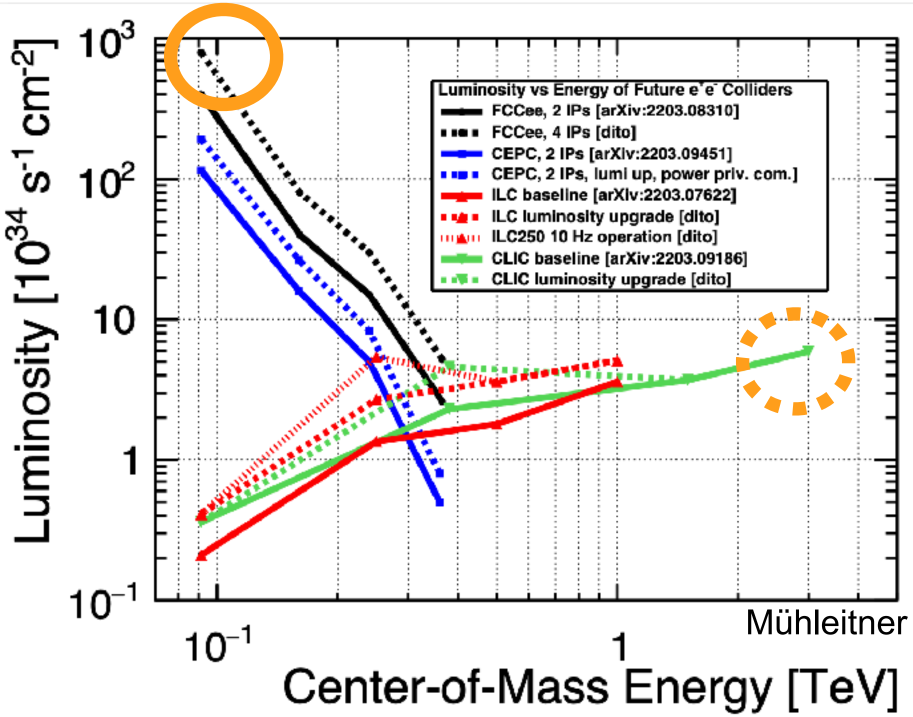


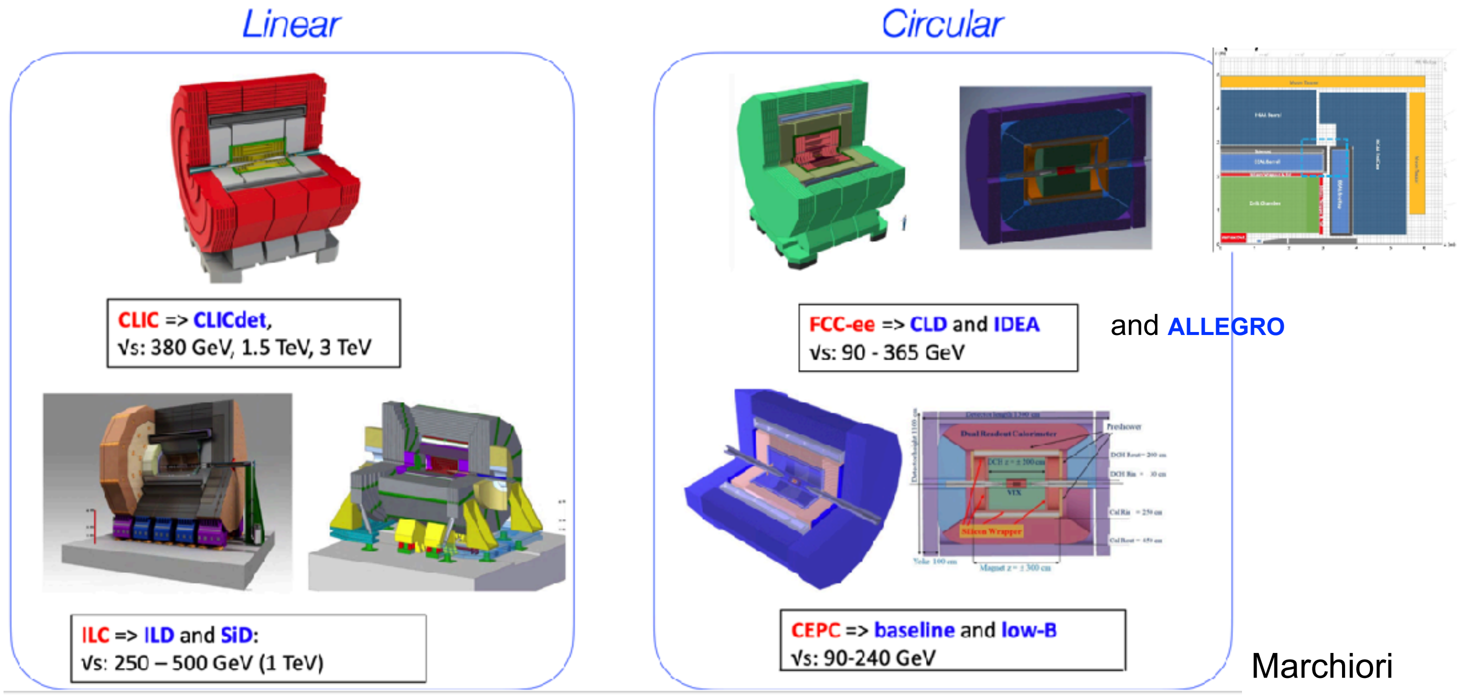
CALICE 2006-2018

Higgs Factory Energies, Luminosities, Experiments

And Detector Requirements



Mühleitner



Marchiori

Particle and jet energies vary only logarithmically with collider energy

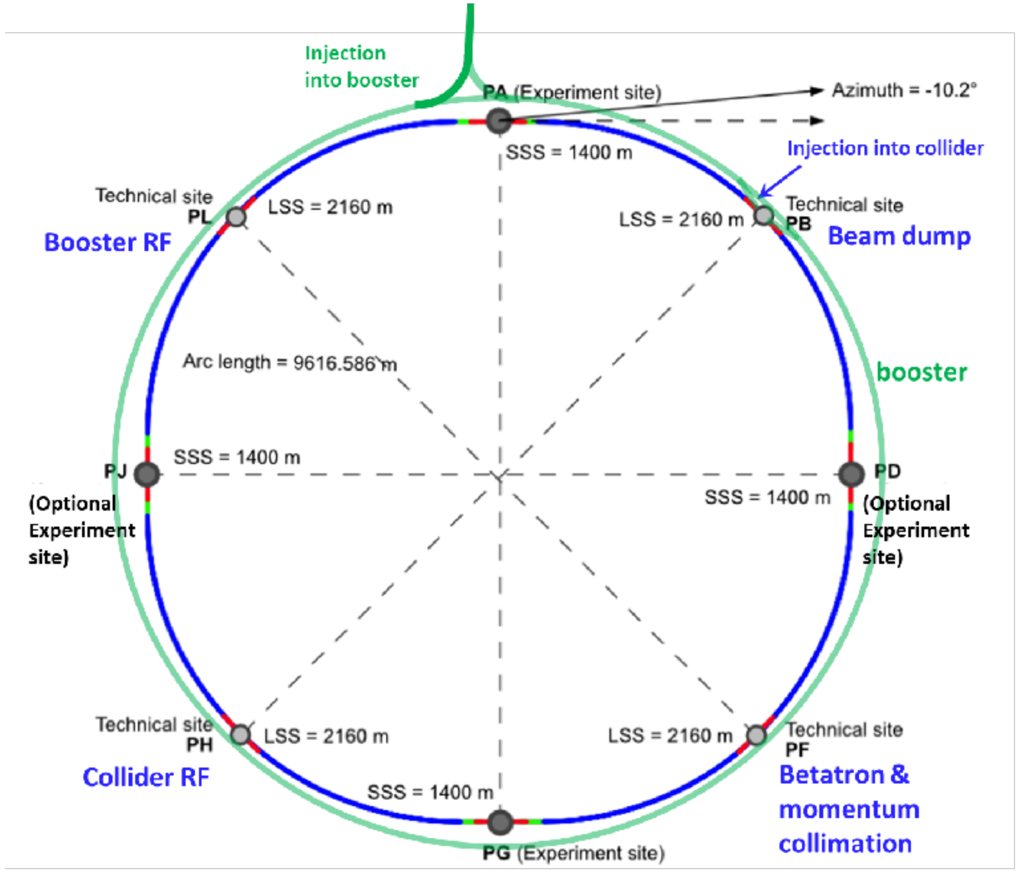
- detector concepts have been evolving adiabatically from one collider to the other

Two extreme points:

- CLICdet at high energy extensively studied 2010-2020: 0.5 ns pile-up of hadronic γγ background manageable
- **Tera-Z at FCCee poses most extreme challenges still to be tackled**

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}	143	20	7.5	1.38
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

Z peak	√s ~ 88, 91, 94 GeV	4 yrs	~200 ab^{-1}	6.10[12] $e^+e^- \to Z$
WW threshold	√s ~ 157.5, 162.5 GeV	2 yrs	~10 ab^{-1}	10[8] $e^+e^- \to WW$
ZH maximum	√s ~ 240 GeV	3 yrs	~10 ab^{-1}	2.10[6] $e^+e^- \to ZH$
[s-channel H option	*√s ~ 125 GeV*	*5? yrs*		*~5000 $e^+e^- \to H$*
Top threshold	√s ~ 345 – 365 GeV	5 yrs	~3 ab^{-1}	2.10[6] $e^+e^- \to t\bar{t}$

per IP

Detector Requirements from Physics

Ambitious

Higgs Factory Program
- 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 $\frac{\sigma_{pT}}{p_T} \simeq 10^{-3}$ $at\ p_T \sim 50$ 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
- 6 x 10^{12} Z and 10^8 WW events
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, m_W, Γ_W, …
- 2 x 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**
- **Heremeticity**

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 matter: 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 reduces granularity, timing, speed
- implications strongly technology-dependent, interesting optimisation challenges
- **DAQ (and possibly trigger) re-enter the stage, trigger-less read-out challenged**

From Linear to Circular e+e- Detectors

Conceptual Adaptations

FCCee has many common challenges with ILC plus significant additional ones

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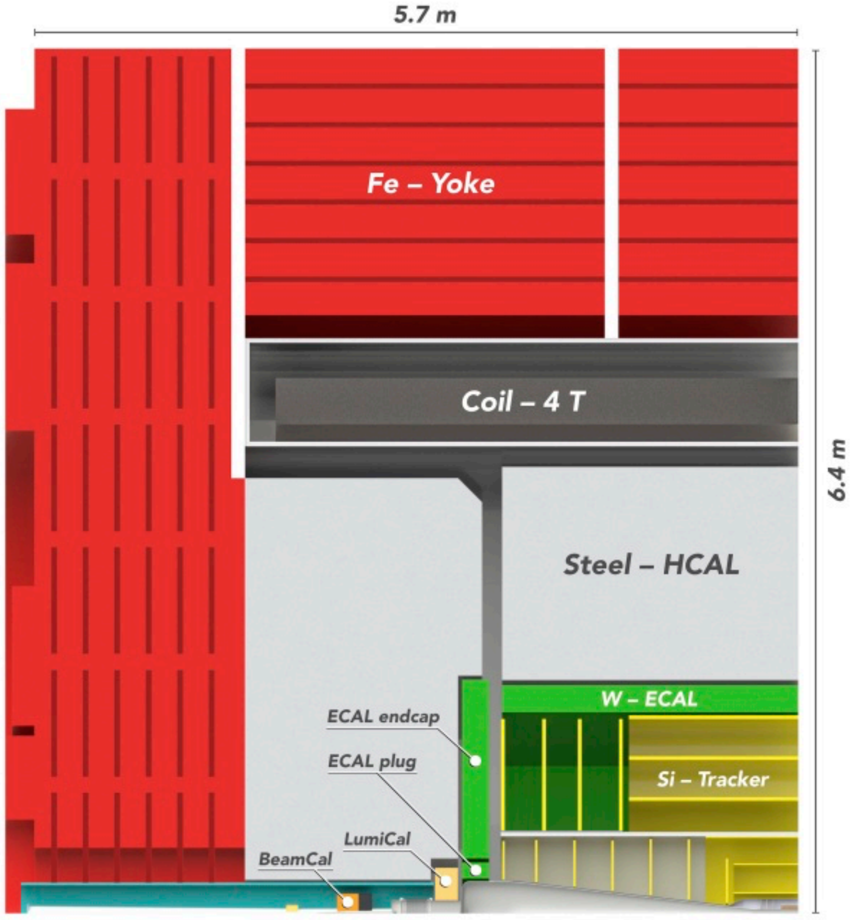
Detector Concepts

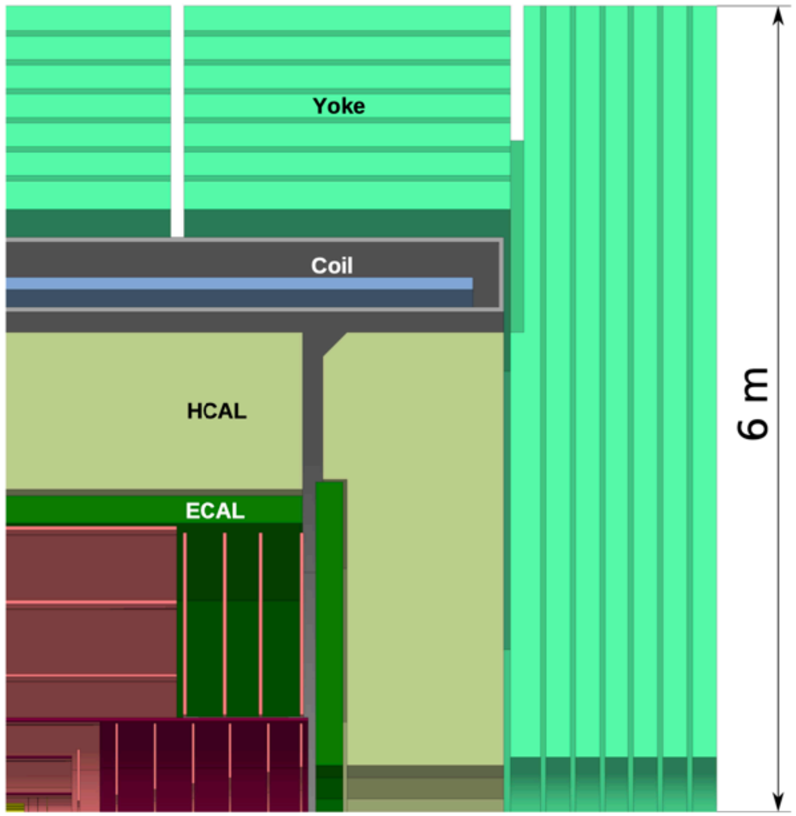
From LCs to FCCee

From CLICdet to CLD

CLICdet = CLIC-SiD CLIC-ILD merger

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





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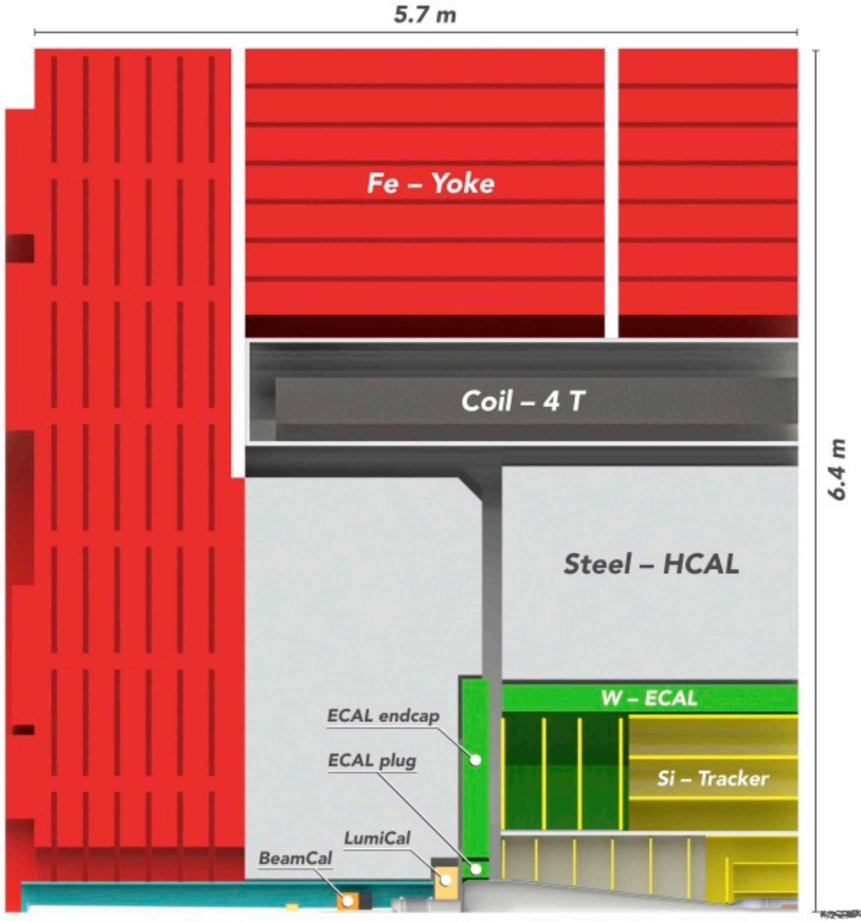
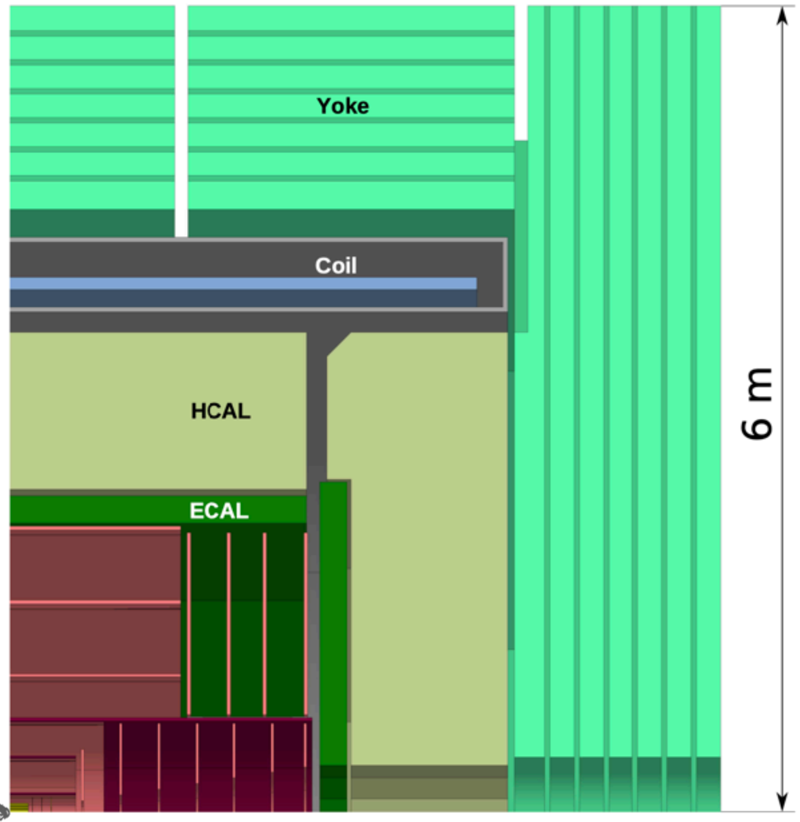


smaller VTX radius: profit from lower backgrounds, compensate material



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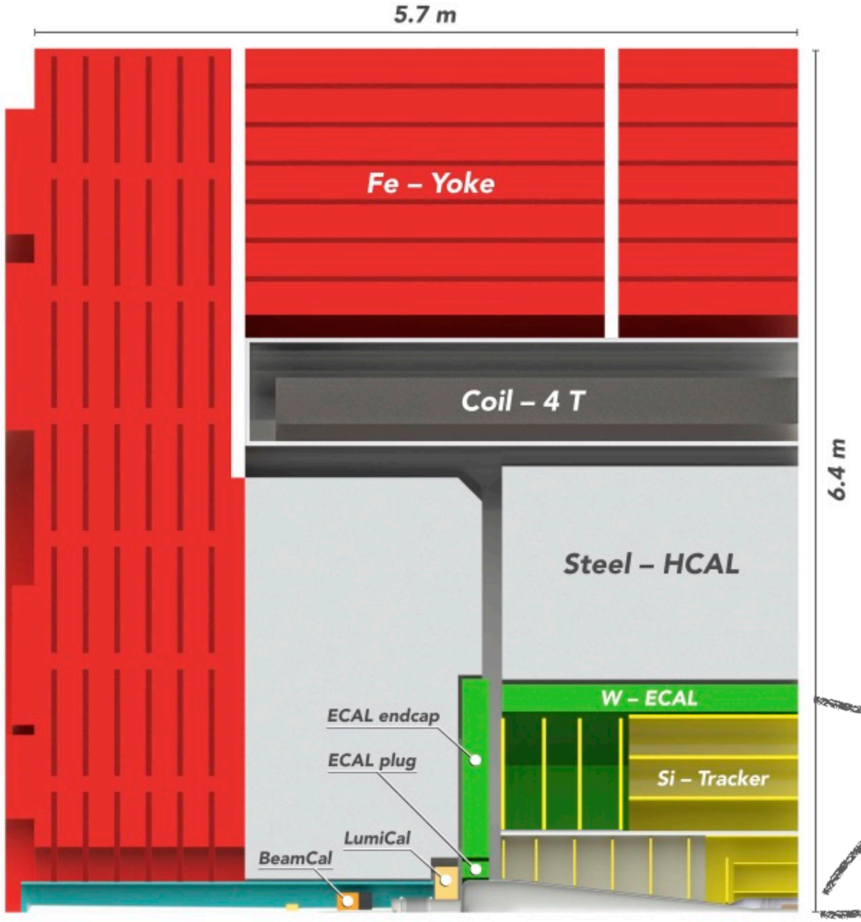
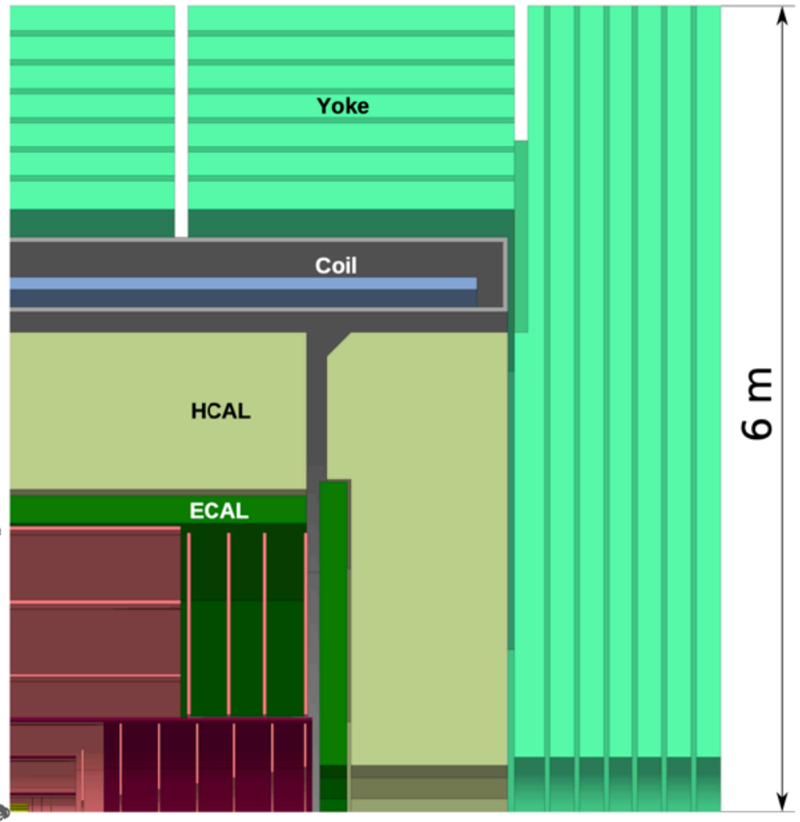


increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material



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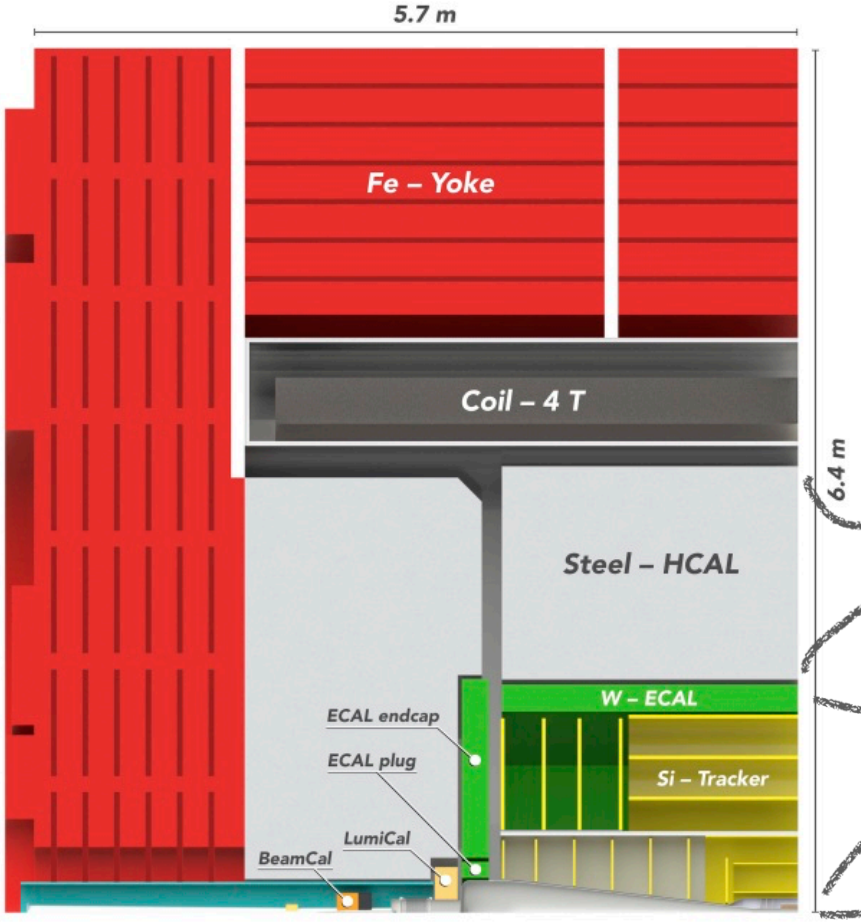
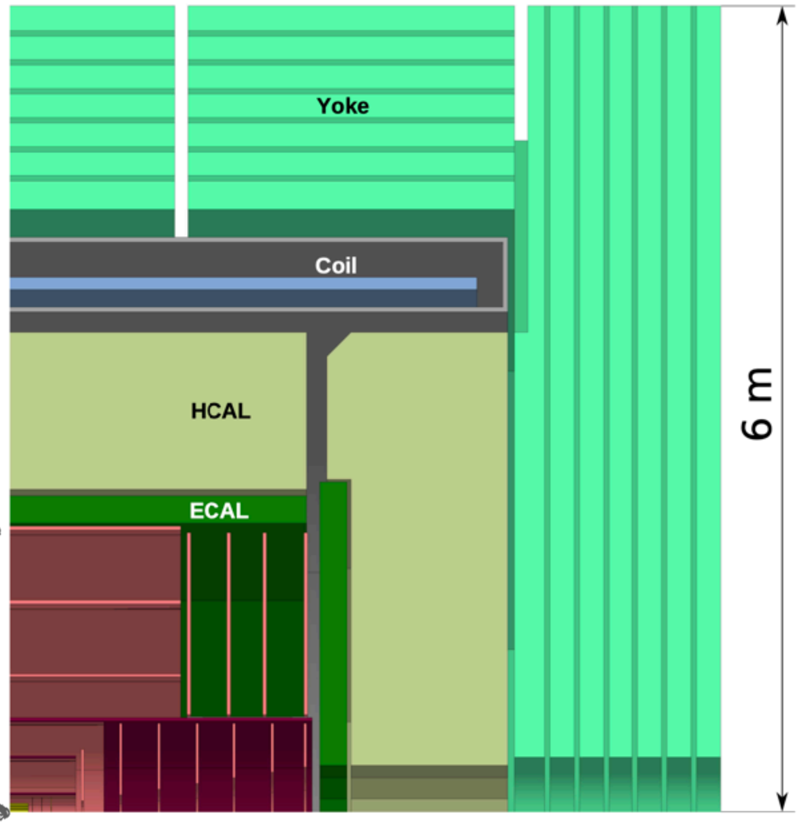


reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material



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MAX-PLANCK-INSTITUT FÜR PHYSIK

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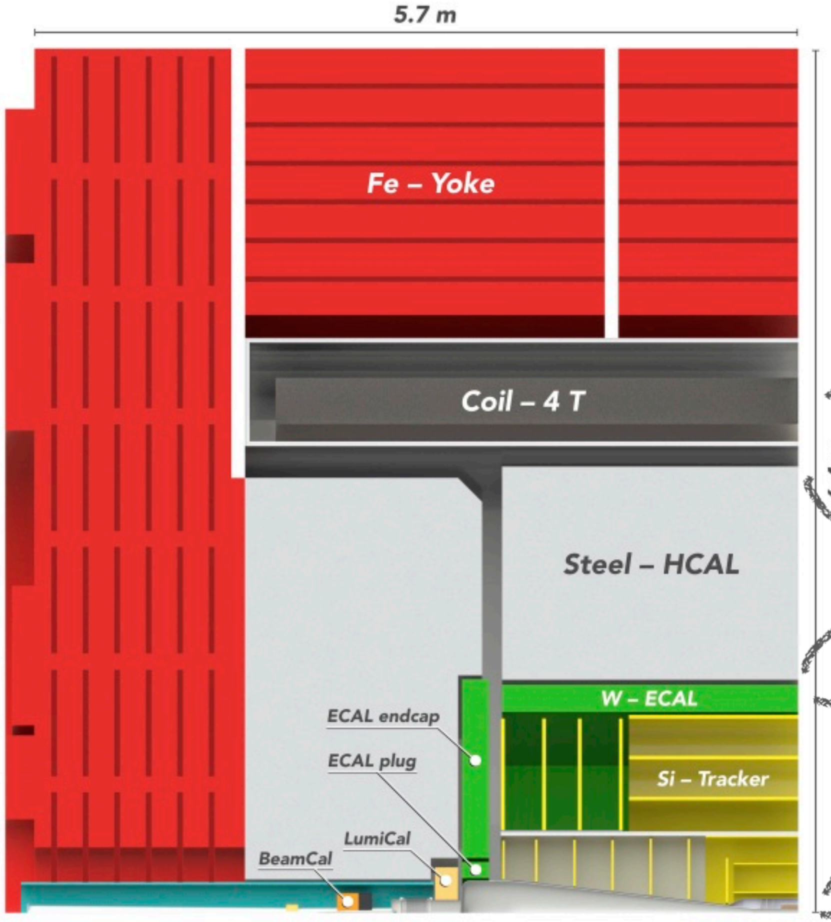

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

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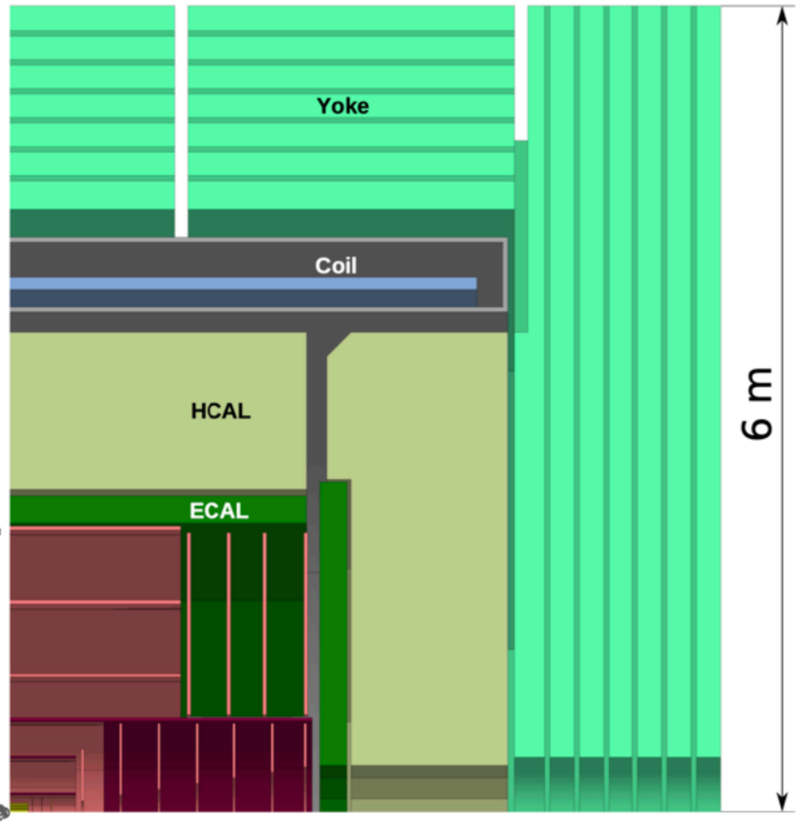

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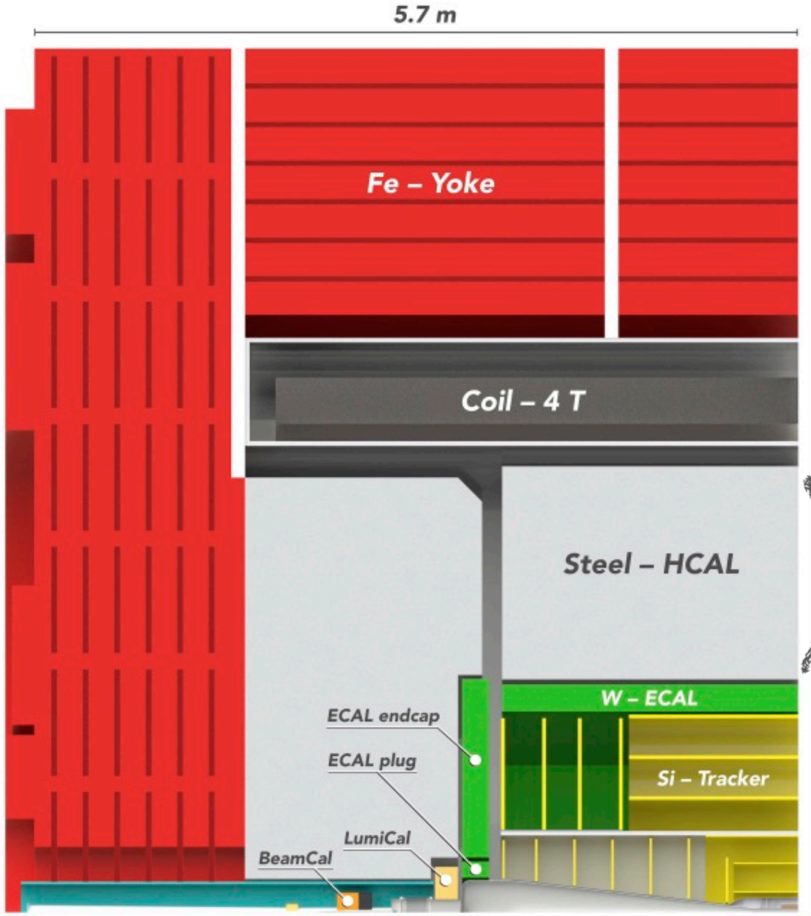

less steel: lower field allows reduced yoke thickness

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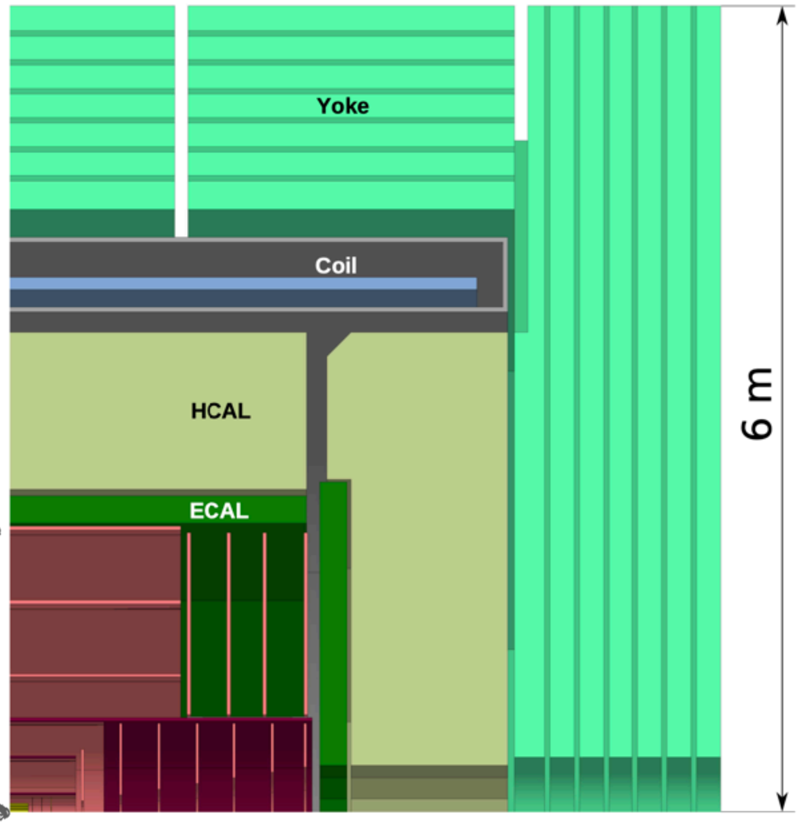
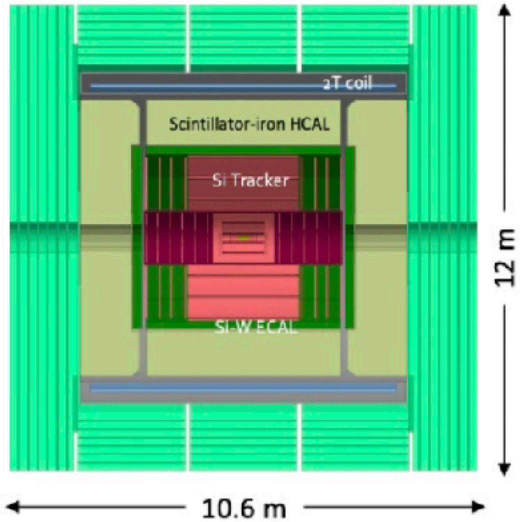


FCCee Detector Concepts

Strawman Detector Benchmarks

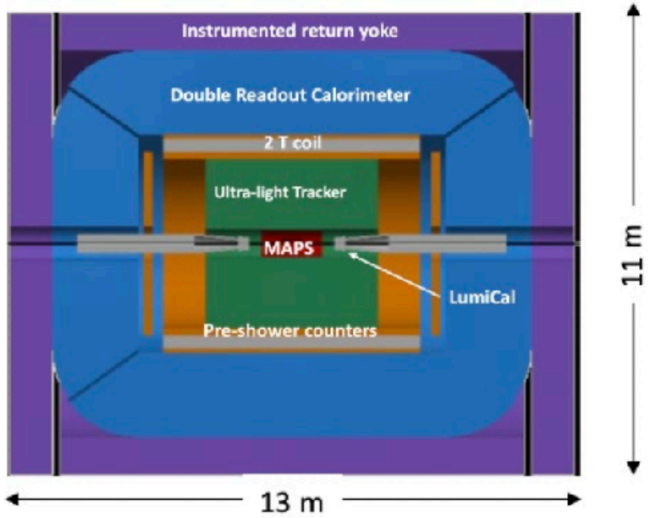
CLD



- 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)?

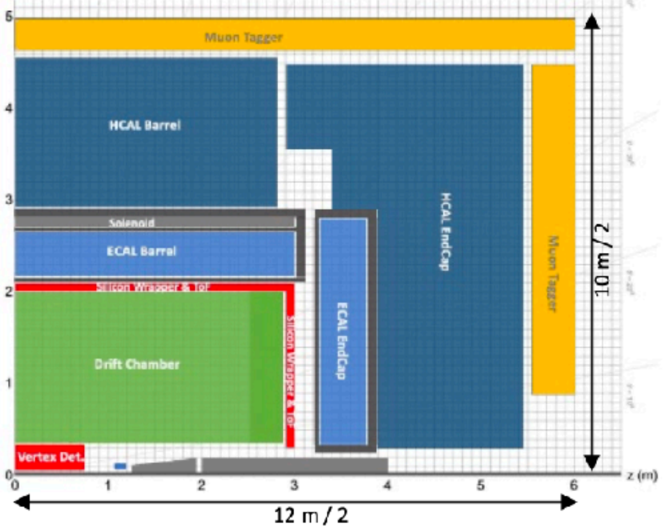
CDR

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



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- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
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FCCee Detector Concepts

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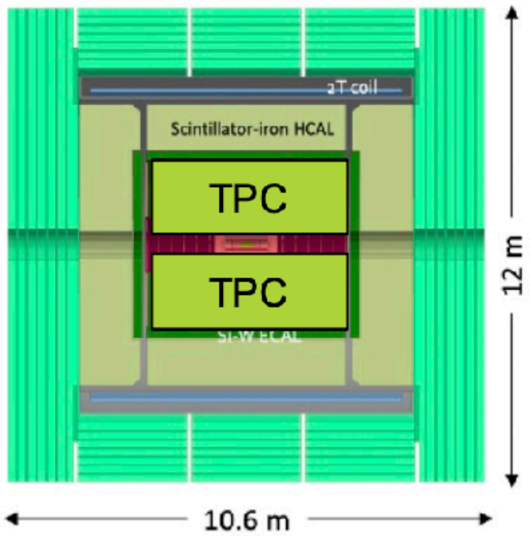
CLD/ILD'



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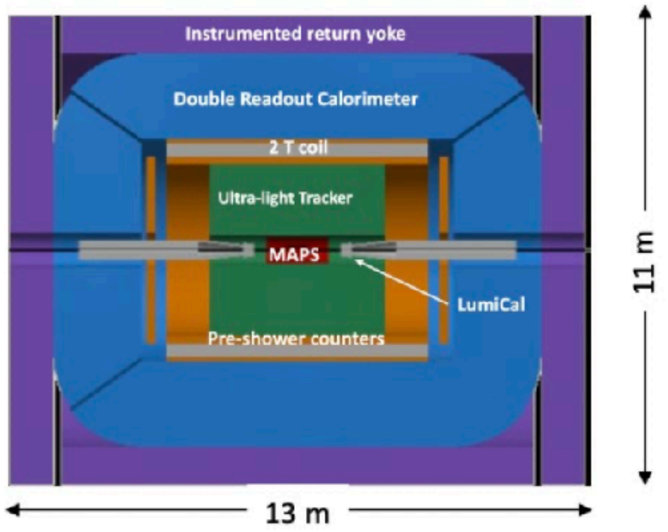

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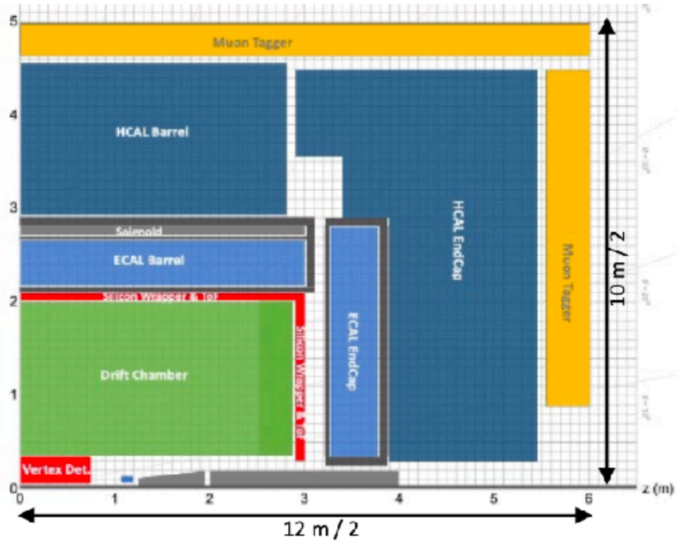

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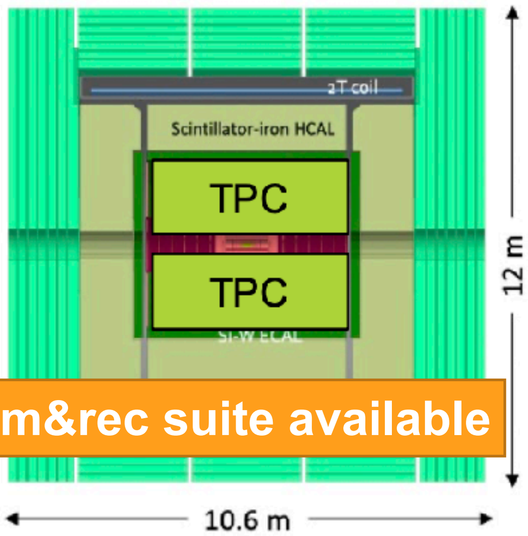

Full sim&rec suite available

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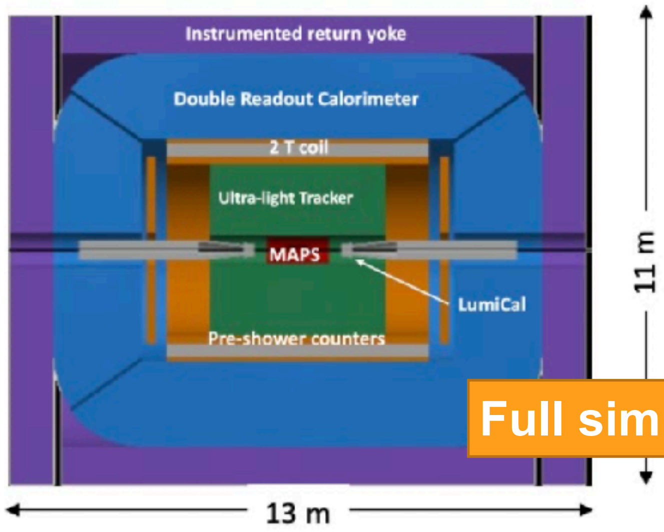

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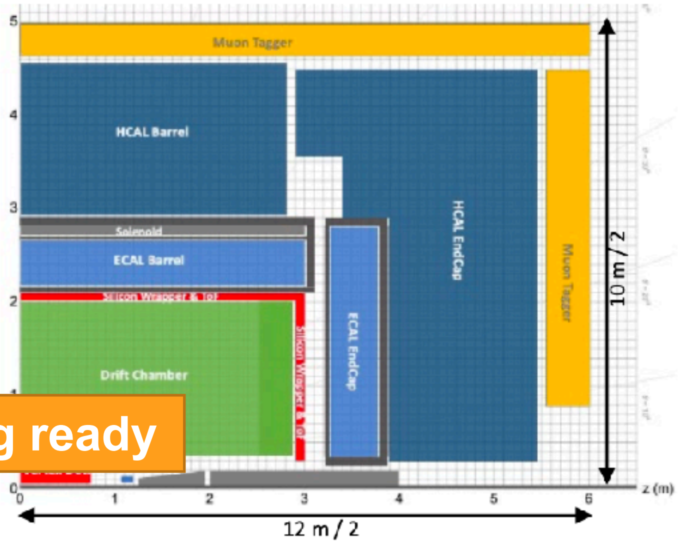
ALLEGRO



Full sim getting ready

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- 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

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

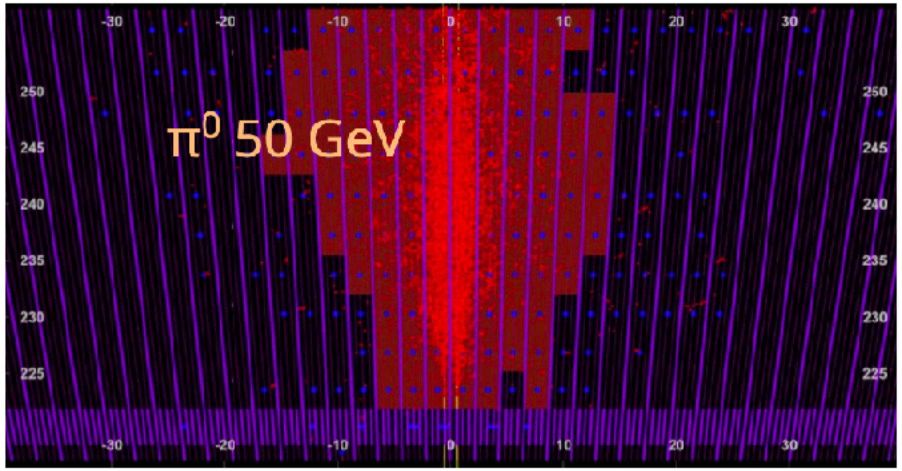
- maintain freedom to combine, e.g. tracking and calorimeter technologies ("plug & play")

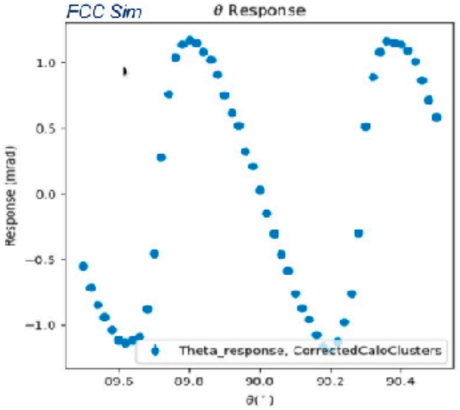
Status of ALLEGRO / LAr Simulations

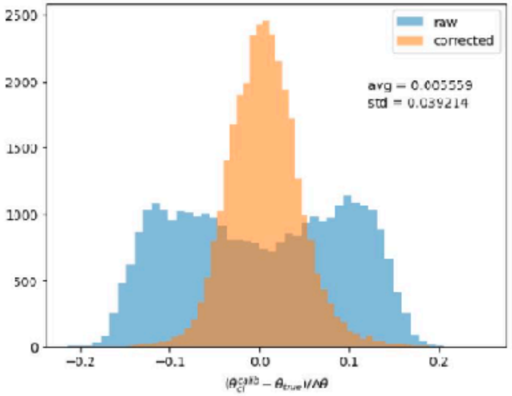
Active Development in Key4HEP

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 !







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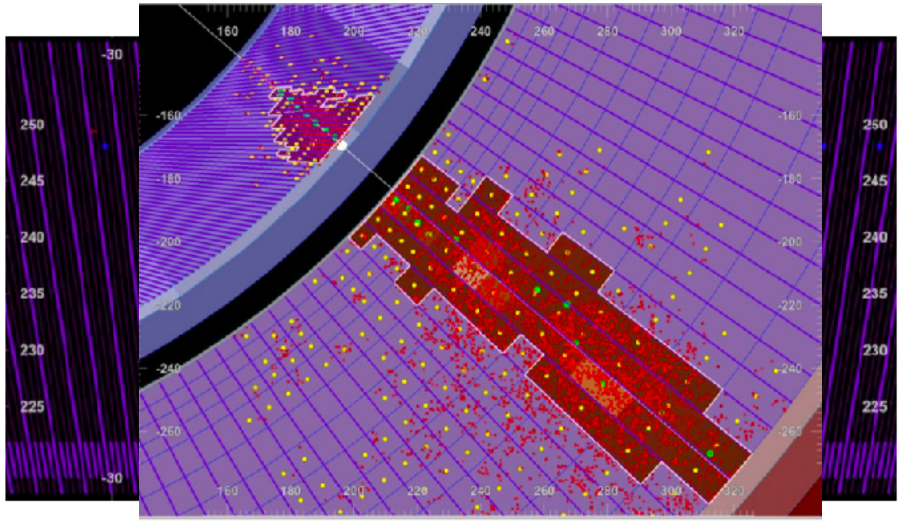
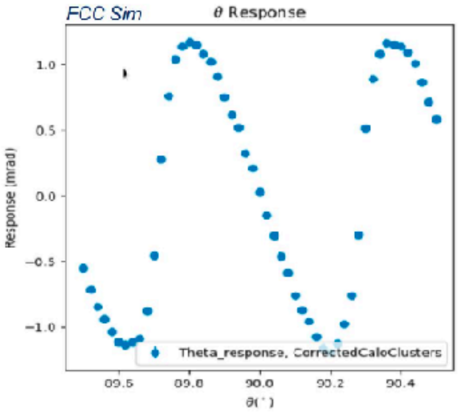
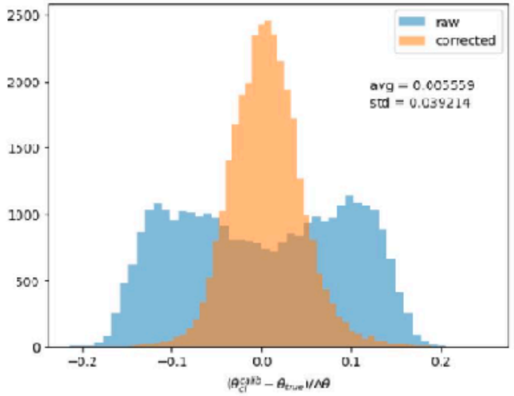






Status of ALLEGRO / LAr Simulations

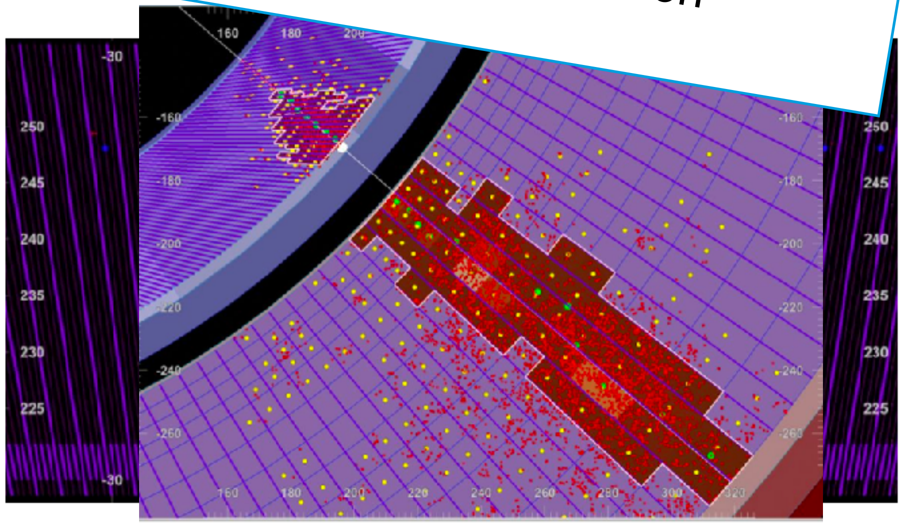
Active Development in Key4HEP

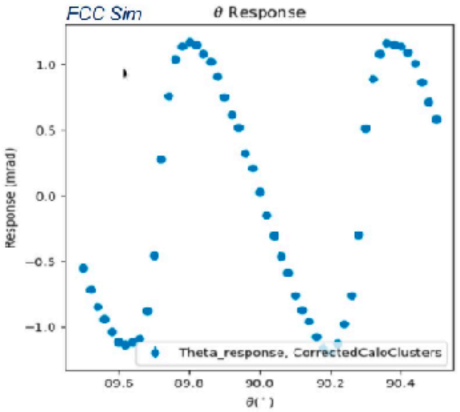
Optimisation of overall geometry, granularity, ECAL HCAL and HCAL TC transition still to be done

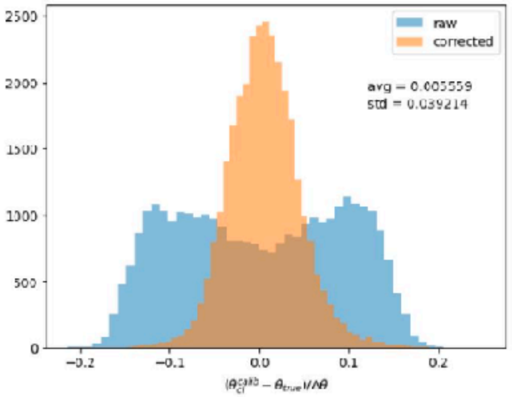
2023: important groundwork. ⇒ 2024: granularity o

- 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 →







Detector Subsystems and Technologies

Status of DRD collaborations

DRD Meetings:
https://indico.cern.ch/category/6805/

Proposals (search for DRDC public)
https://cds.cern.ch/?ln=en

DRD1	DRD2	DRD4	DRD6	DRD3	DRD5	DRD7	DRD8
Gaseous	Liquid	PID and Photon	Calorimetry	Solid state	Quantum	Electronics	Integration
Ex RD51				Ex RD50, RD42			

DRD1, DRD2, DRD4, DRD6: Fully approved for 3 years by CERN Research Board in **December 2023**

DRD3, DRD5, DRD7: Fully approved for 3 years by CERN Research Board in **June 2024**

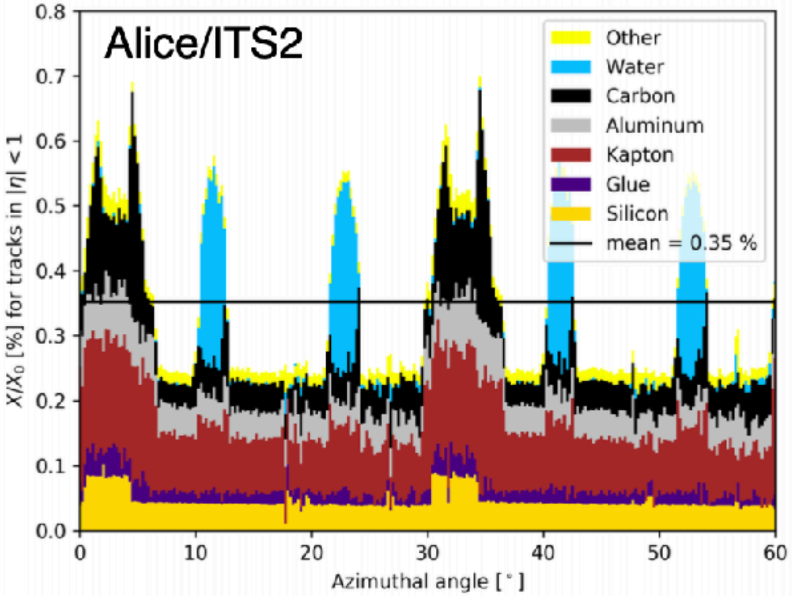
DRD8: Fully approved for 3 years in November 2024

Silicon Vertex Detector and Main Tracker

Sensors technology requirements for Vertex Detector

Several technologies are being studied to meet the physics performance

CERN-LHCC-2019-018



- Sensor's contribution to the total material budget is 15-30%
  - Services cables + cooling + support make up most of the detector mass
- Sensors will have to be less than 75 μm thick with at least 3-5 μm hit resolution (17-25 μm pitch) and low power consumption
- Beam-background suppression
  - ILC/C^3 - evolve time stamping towards O(1-100) ns (bunch-tagging)
  - FCC, continuous r/o integrated over ~10μs with O(1) ns timing resolution for beam background suppression

Physics driven requirements	Running constraints	Sensor specifications	
σ $< 3\ \mu m$		Small Pixel	~15μm
Material budget $0.1\% X_0$/layer		Thinning to	50 μm
	Cooling	Low Power	20-50 mW/cm^2
r of the Inner most layer 12-14 mm	Beam-background	Fast Readout	~1-10 μs
	Radiation damage	Radiation Tolerance	10 MRad, $10^{14}\ n_{eq}$ / /cm^2

Time resolution vs. power

O(ns) time resolution for beam-background suppression requires dedicated optimizations

Current designs that can achieve ns or sub-ns time resolutions compensate with higher power consumption

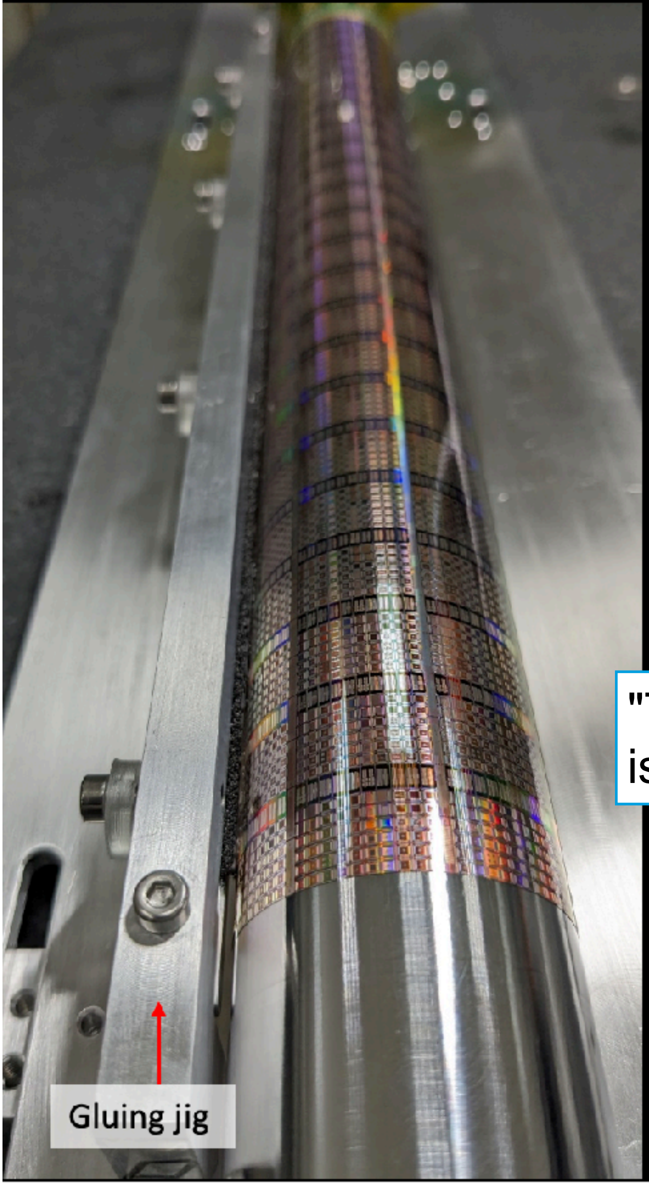
- Target power consumption is less than 20 mW/cm^2

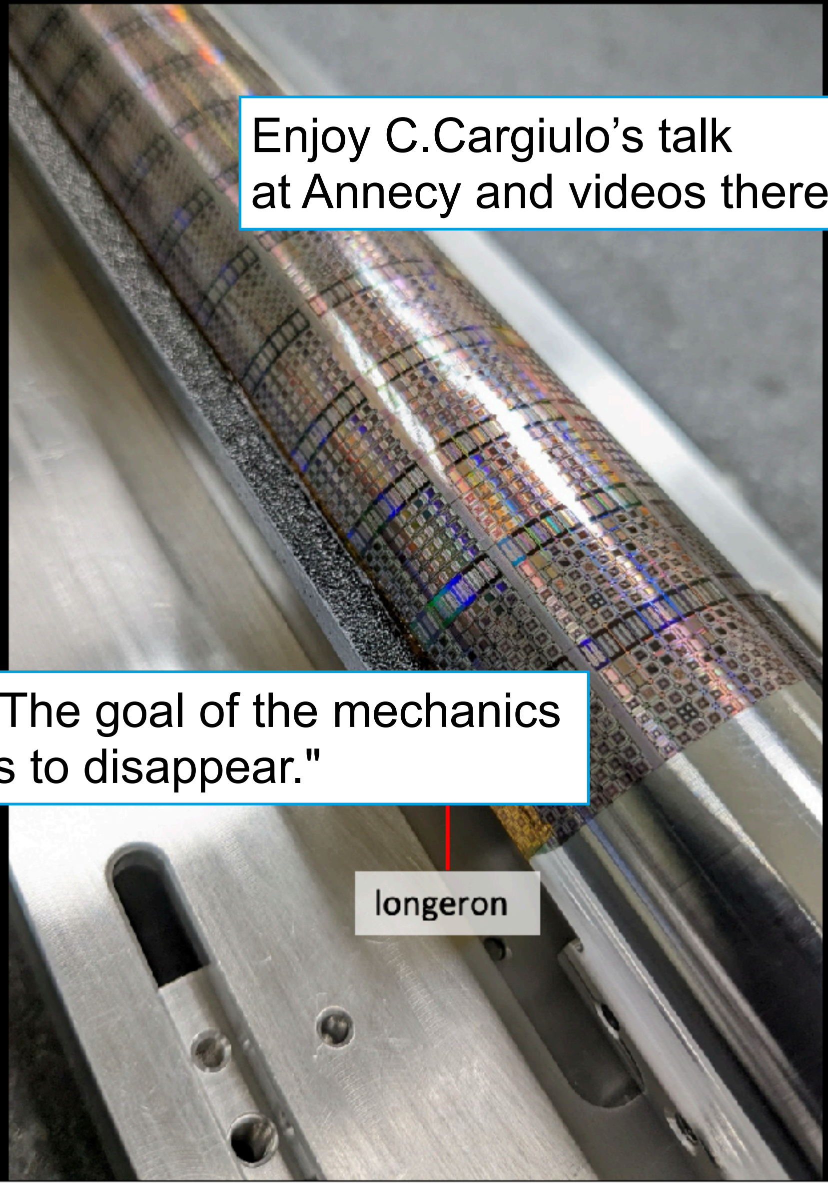
Chip name	Experiment	Subsystem	Technology	Pixel pitch [μm]	Time resolution [ns]	Power Density [mW/cm^2]
ALPIDE	ALICE-ITS2	Vtx, Trk	Tower 180 nm	28	< 2000	5
Mosaic	ALICE-ITS3	Vtx	Tower 65 nm	25x100	100-2000	<40
FastPix	HL-LHC		Tower 180 nm	10 - 20	0.122 – 0.135	>1500
DPTS	ALICE-ITS3		Tower 65 nm	15	6.3	112
NAPA	SiD	Trk, Calo	Tower 65 nm	25x100	<1	< 20
Cactus	FCC/EIC	Timing	LF 150 nm	1000	0.1-0.5	145
MiniCactus	FCC/EIC	Timing	LF 150 nm	1000	0.088	300
Monolith	FCC/Idea	Trk	IHP SiGe 130 nm	100	0.077 – 0.02	40 - 2700
Arcadia	FCC/Idea	Trk	LF 110 nm	25	-	30

Dedicated ongoing effort to target O(ns) resolution with MAPS (slides)
First prototype (Napa-p1) produced in TJ 65 nm process 5x5 mm^2, 25 µm pitch

Assembly of a half-layer

Gluing of the longerons

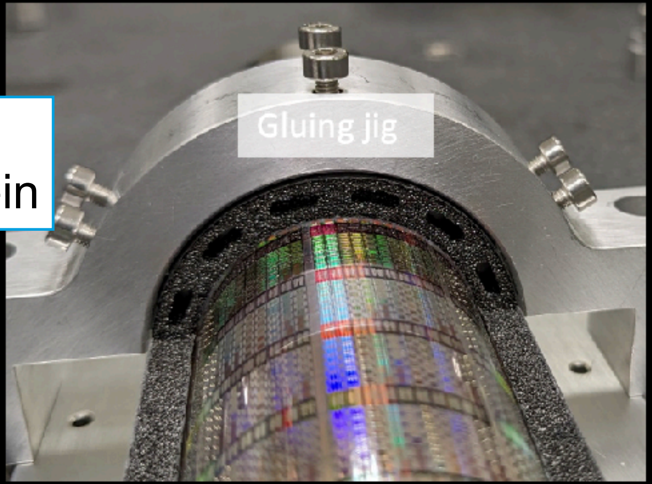


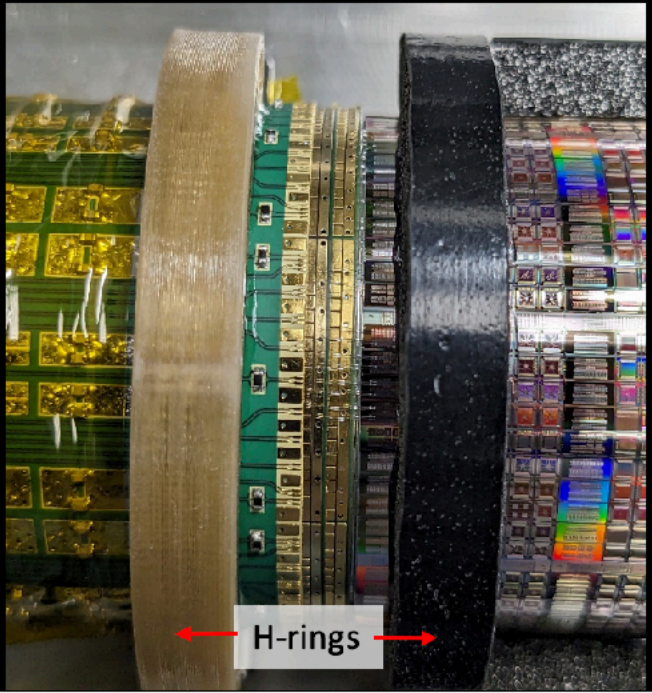


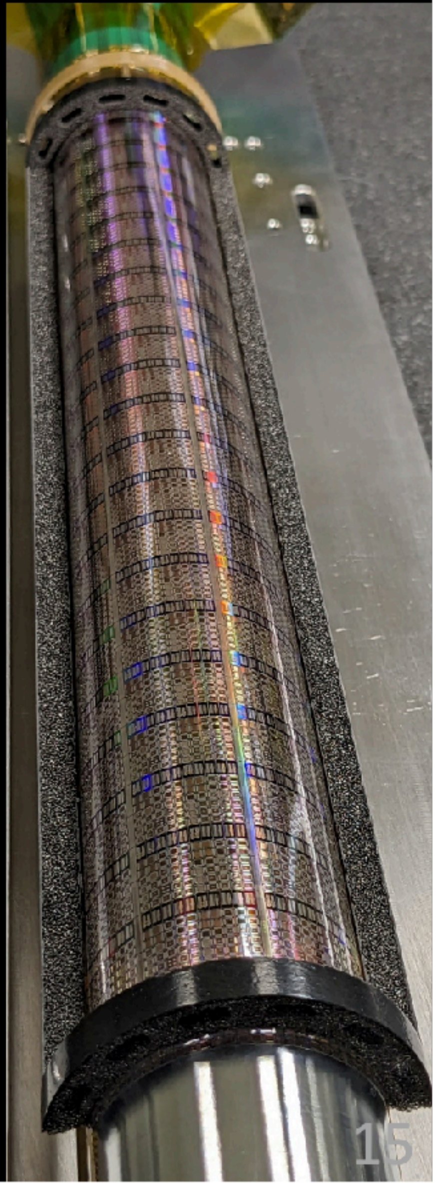
Enjoy C.Cargiulo’s talk
at Annecy and videos therein

"The goal of the mechanics
is to disappear."

Gluing of the H-rings







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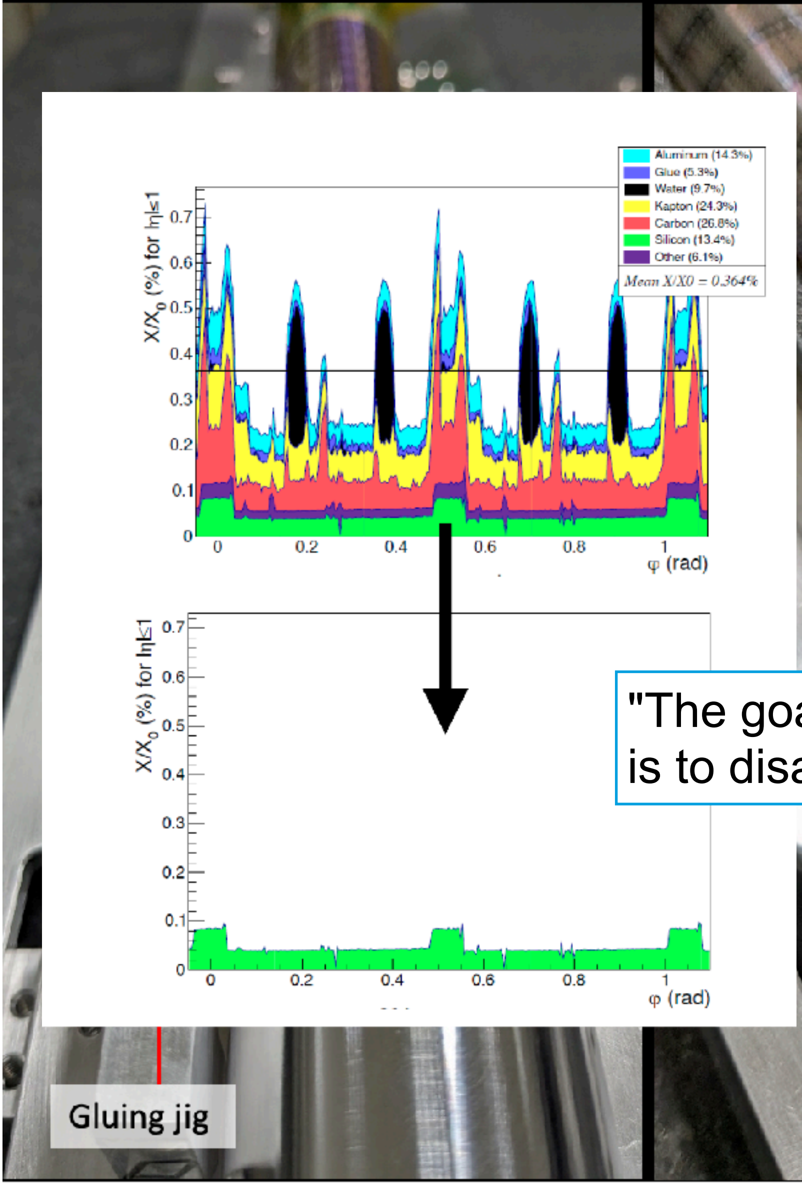

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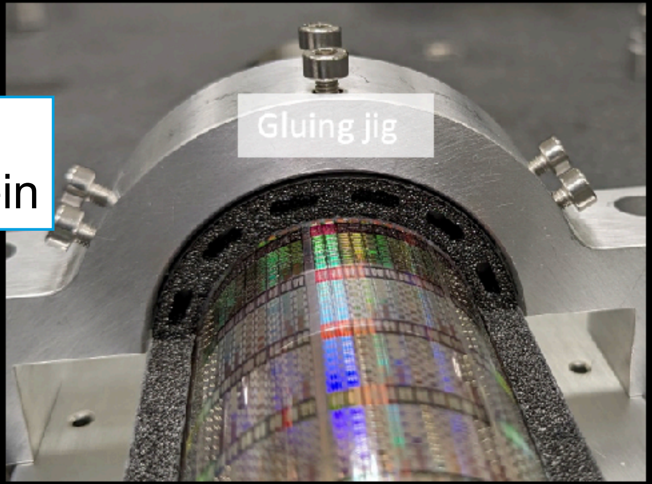
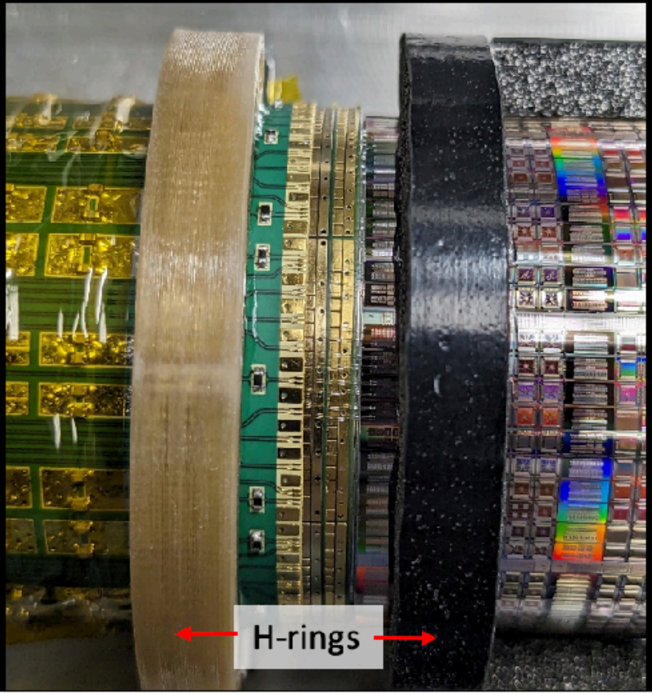
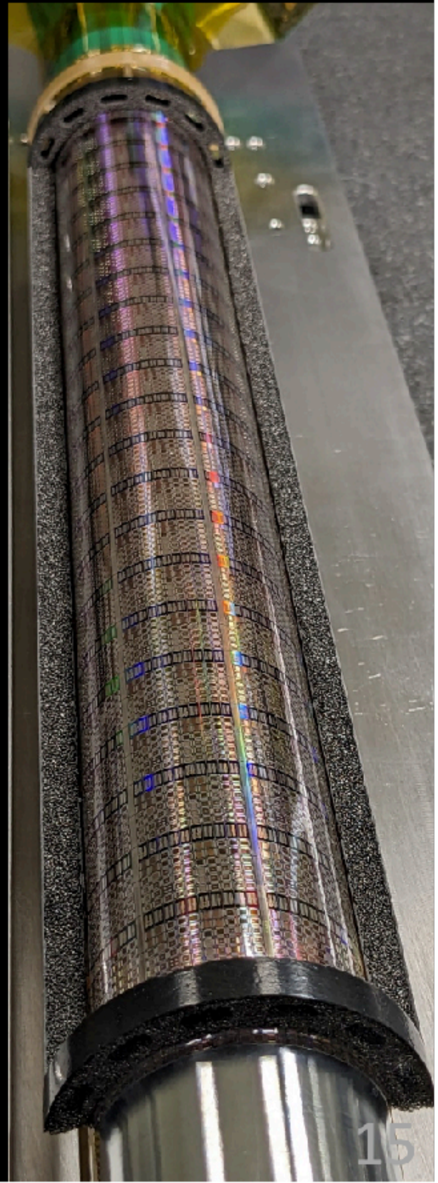
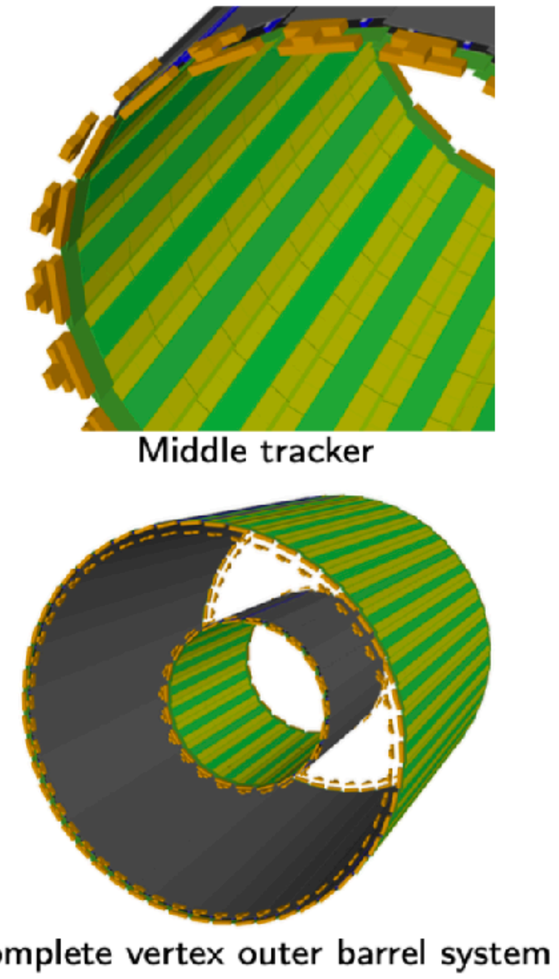


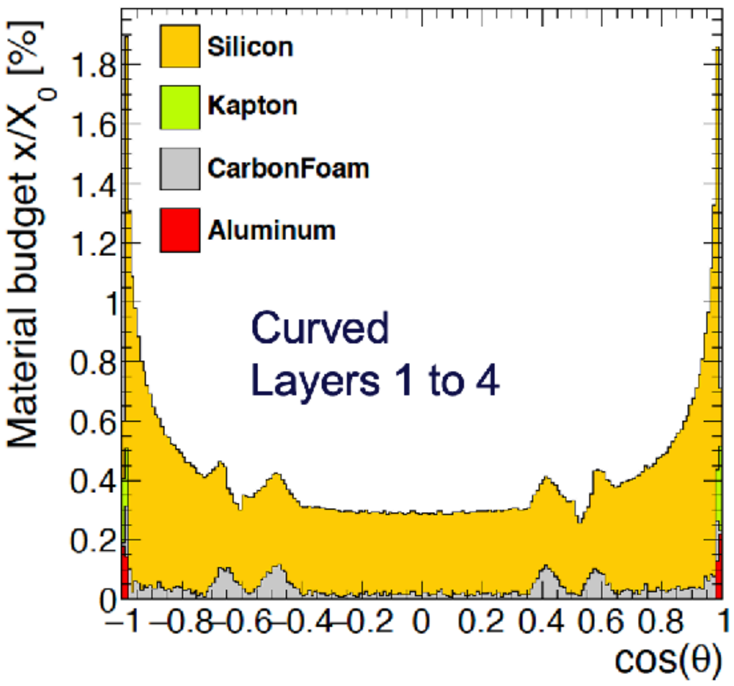


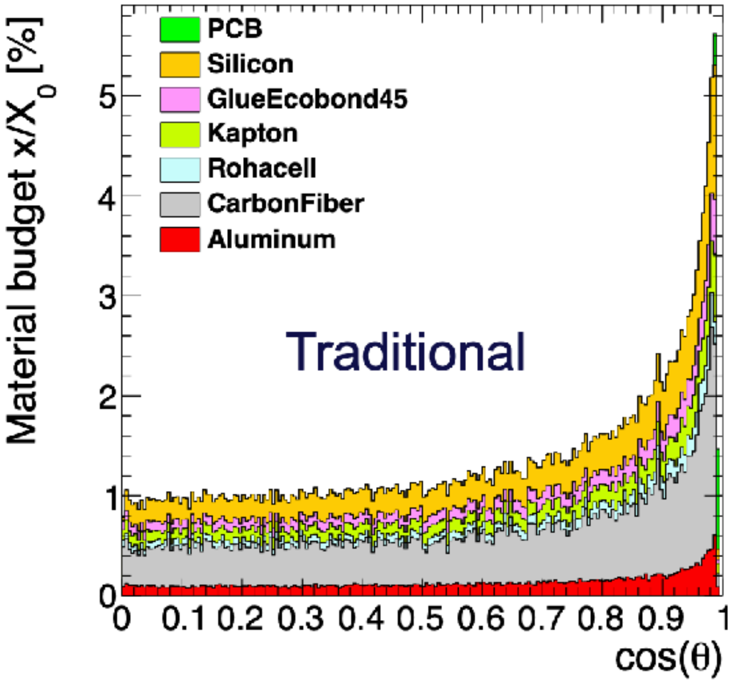


Detailed Full Simulations

Realistic Material Budgets







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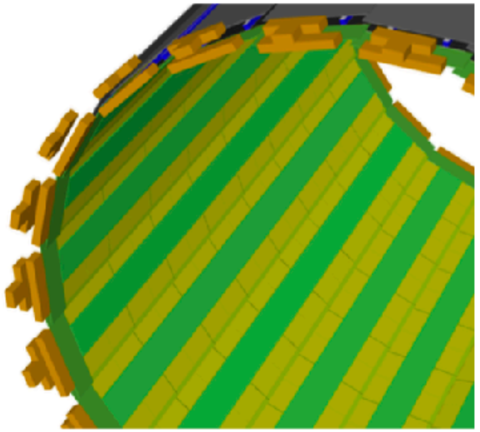
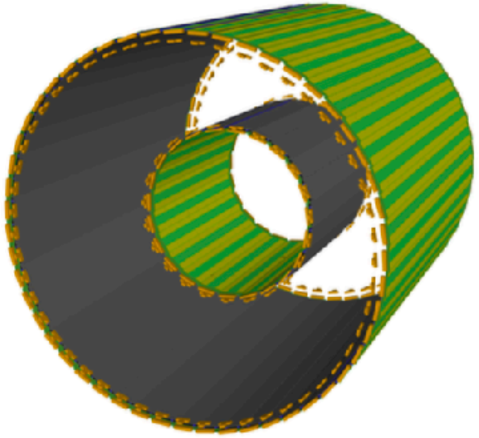
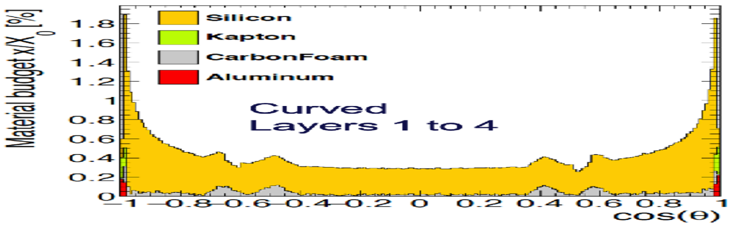
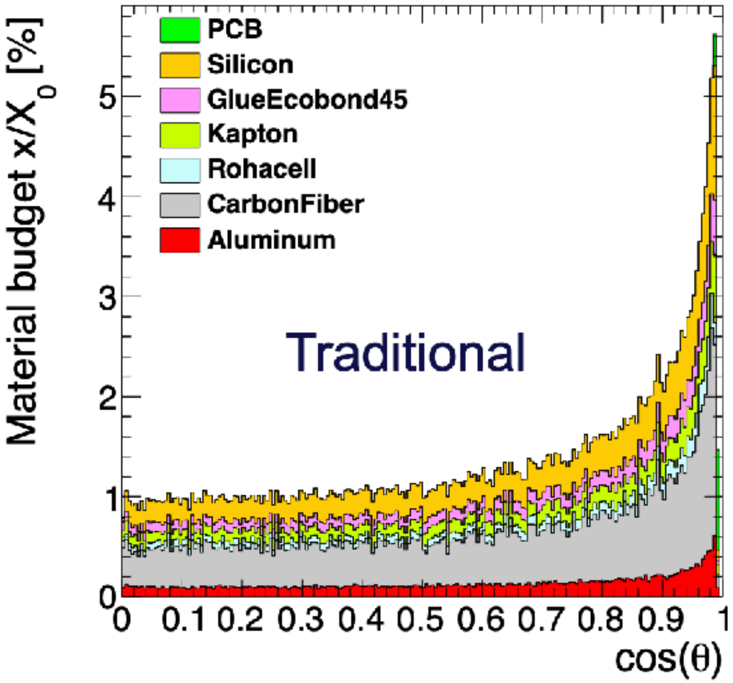


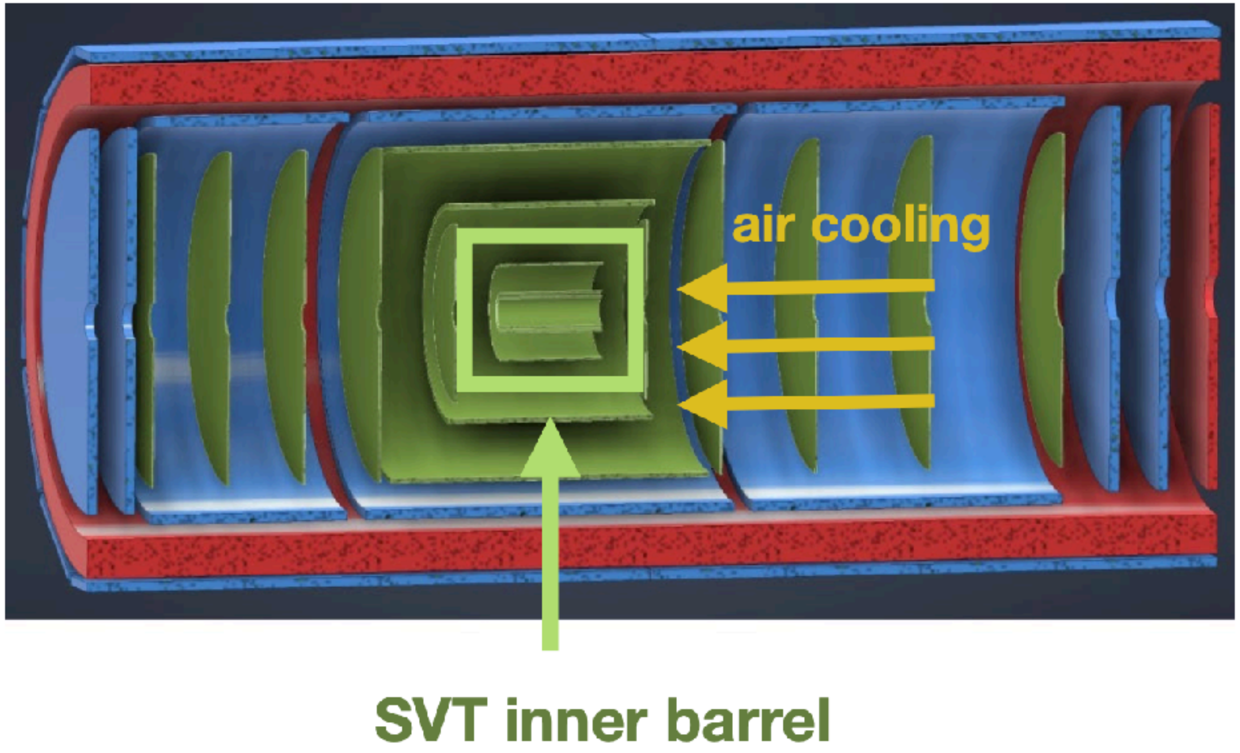






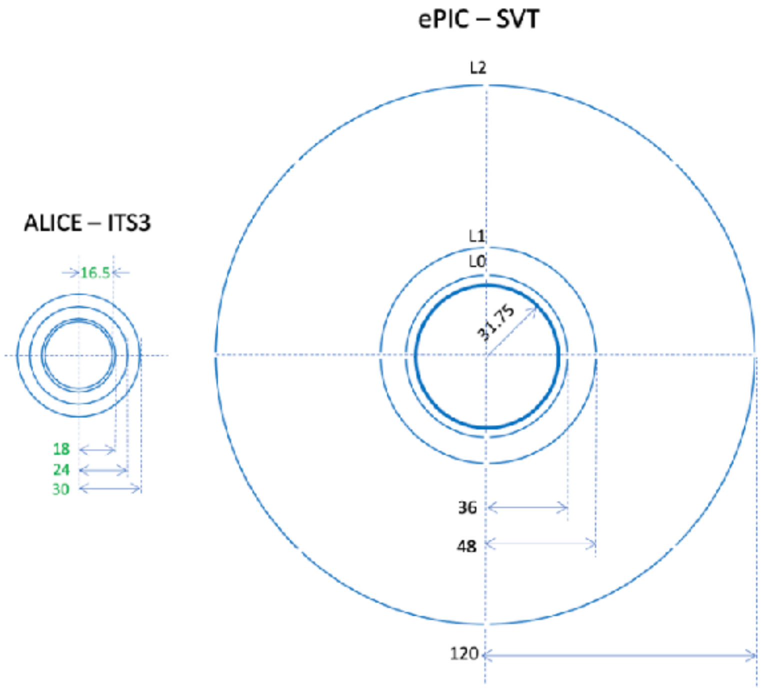
The SVT inner barrel ("bent" layers 0, 1, 2)

Innocenti
https://indico.mit.edu/event/876/contributions/2981/attachments/1070/1762/20240326_SVTInnocenti.pdf



- built with **bent ITS3 wafer-size sensors**
- minimal support structure (carbon foam)
- air cooling (~ few m/s)

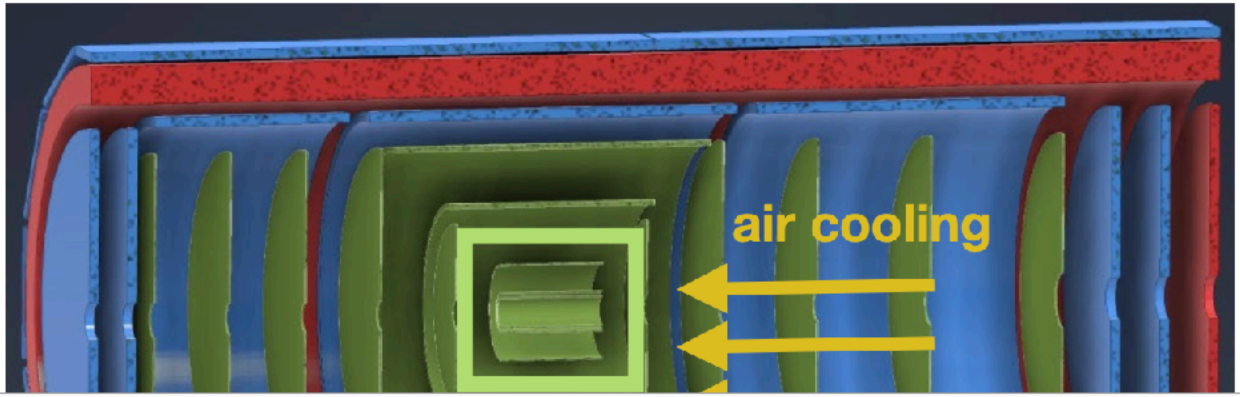
- **Radii = 3.6, 4.8, 12 cm**
- **Lengths = 27 cm**



ePIC specific needs:
- reduce services at forward/backward
- mechanical stability in the presence of a R=12 cm layer (R_{ITS3}^{max} is < 4 cm!)
- air cooling strategy is more challenging due to the presence of the disks

The SVT inner barrel ("bent" layers 0, 1, 2)

Innocenti
https://indico.mit.edu/event/876/contributions/2981/attachments/1070/1762/20240326_SVTInnocenti.pdf



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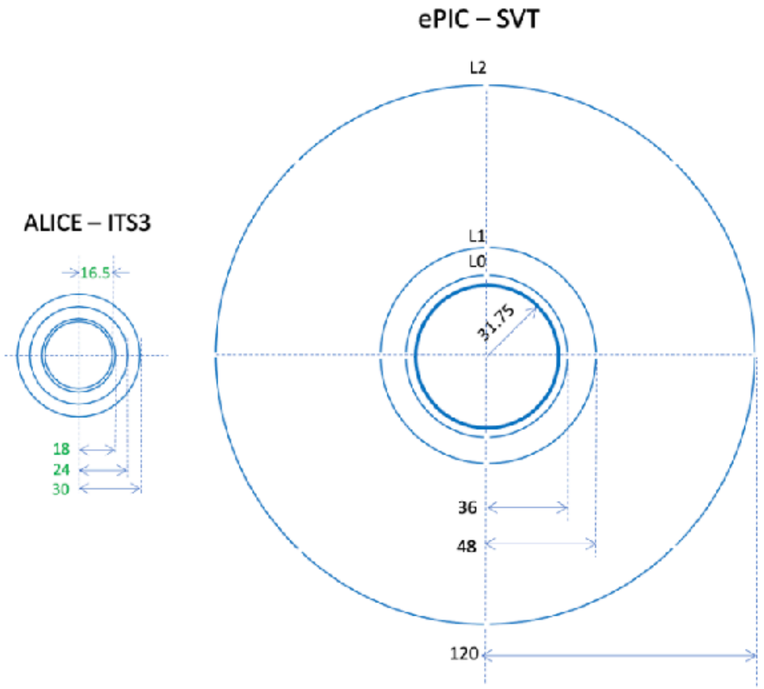
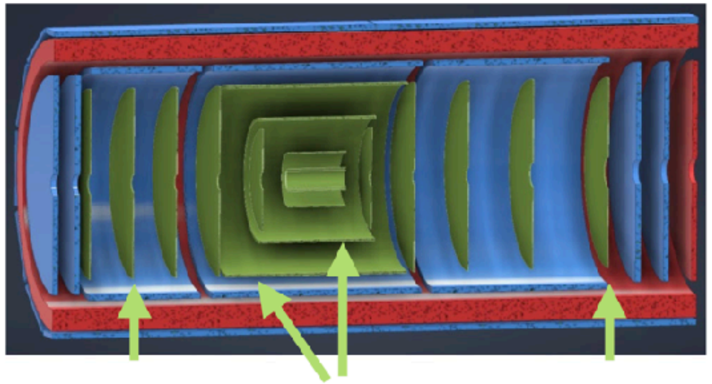


The SVT outer barrel (layers 3, 4) and disks



"Flat" Large Area Sensors (LASs) derived from ITS3 optimised for covering large surfaces

- **traditional staved** structure (not bent)
- carbon fibre support
- integrated cooling (liquid or air)

Challenges:
- preserve the low material budget in the presence of carbon fiber supports and services
- disk geometry can obstruct air cooling for the inner barrel

→ **SVT for ePIC** as the most advanced application of stitched MAPS sensors for large-area wide-acceptance detectors
→ **unique benchmark for a future MAPS-based FCC tracker**

Gaseous Tracking

Gaseous Main Trackers

Strong Case

Transparency wins over single point resolution

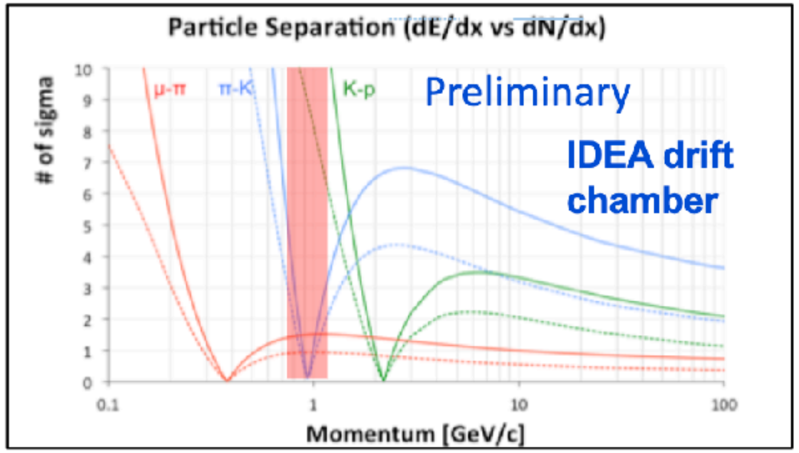
- over most of relevant momentum range

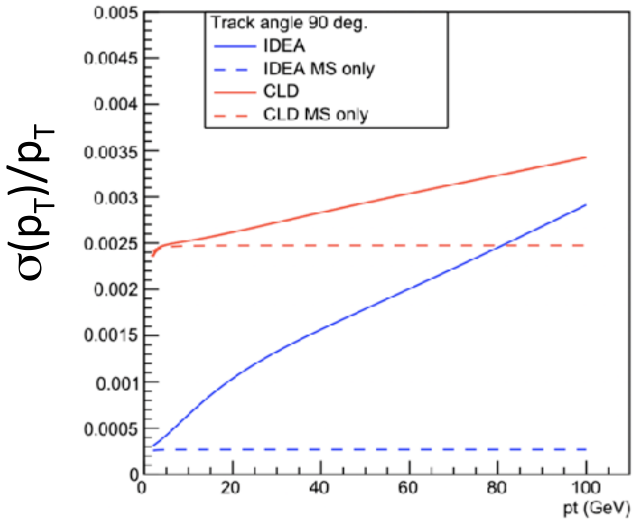
Particle ID via dcdx or dN/dx (cluster counting)

- complement ToF

Continuous tracking

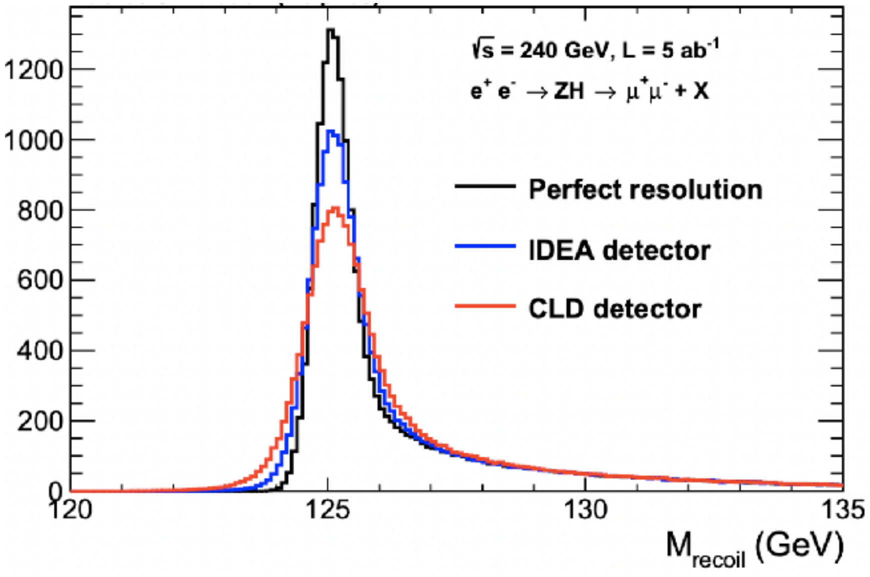
- for long-lived particle vertices





CLID
- All Si Tracker
- total material budget 11%

IDEA
- Drift Chamber
- Material budget is < 2%



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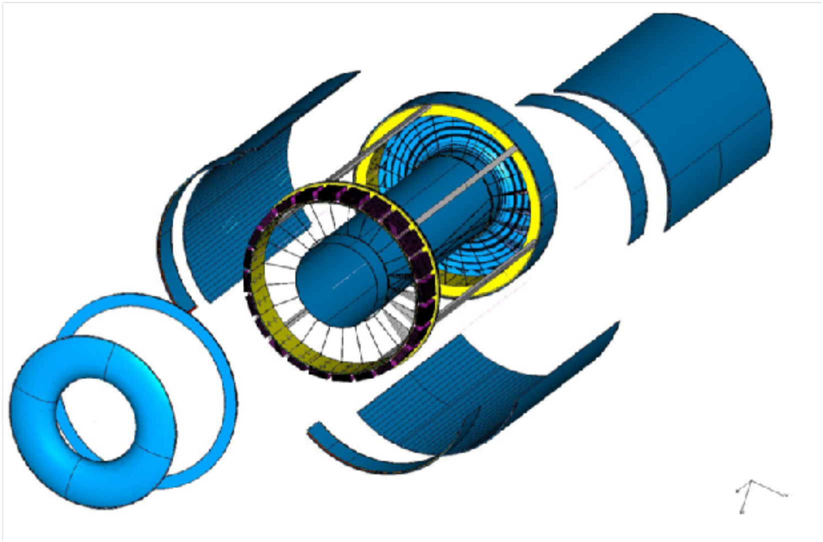

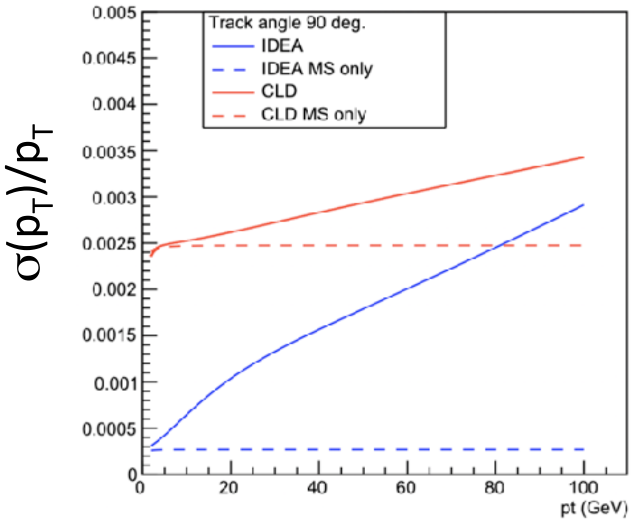

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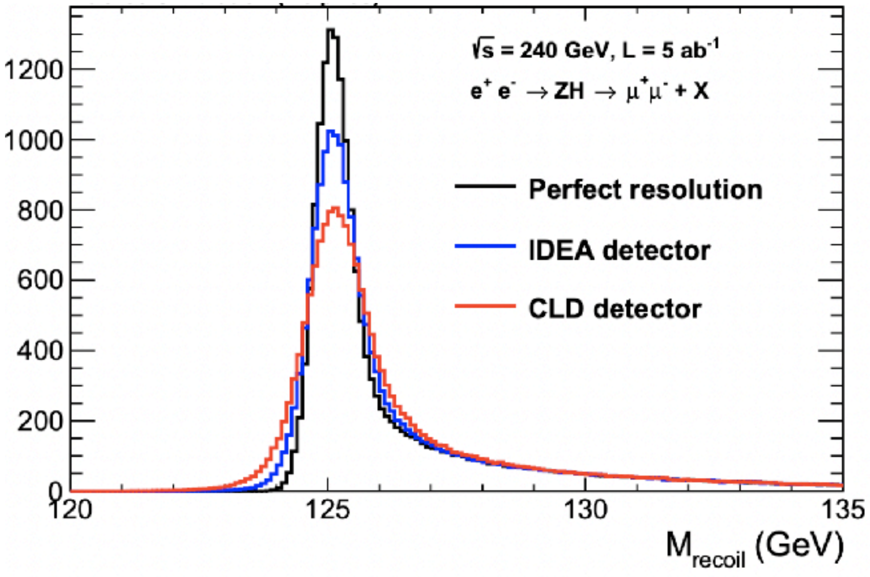

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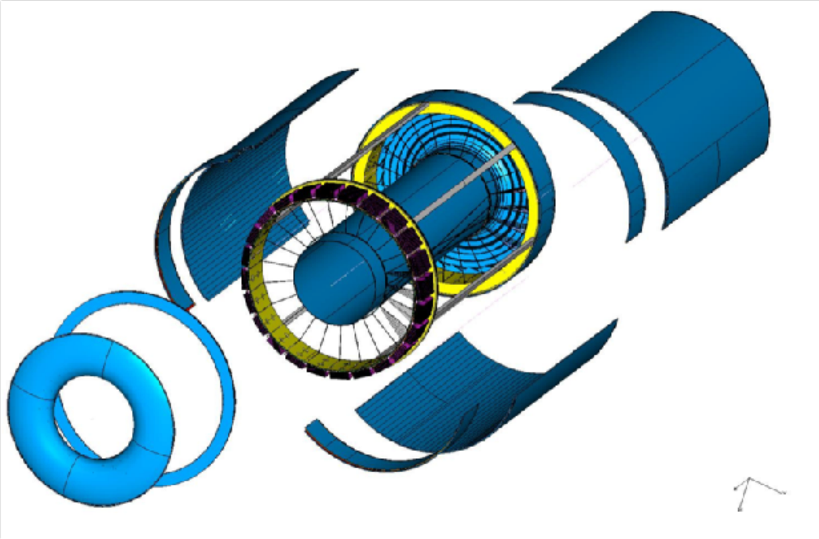

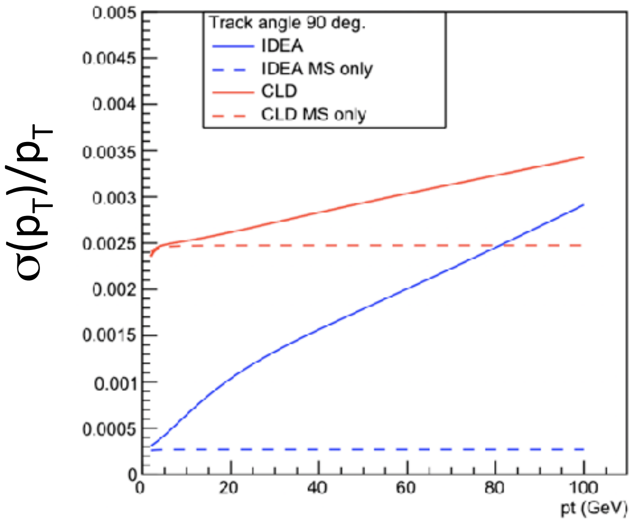

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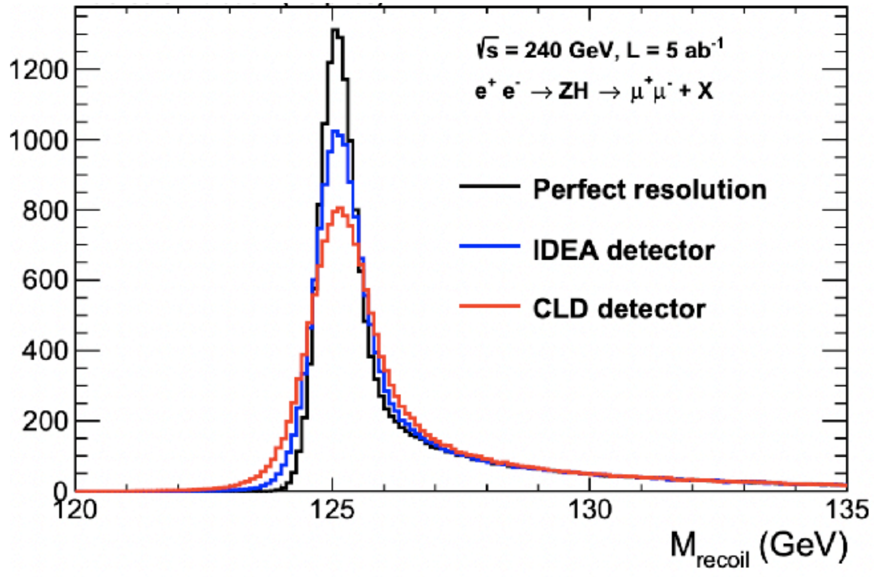
this will evolve!

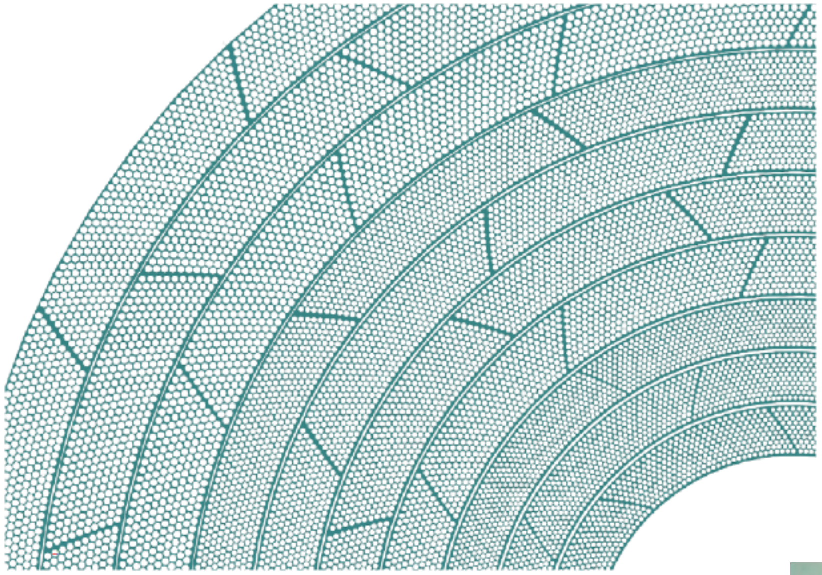


Straw Tube Tracker

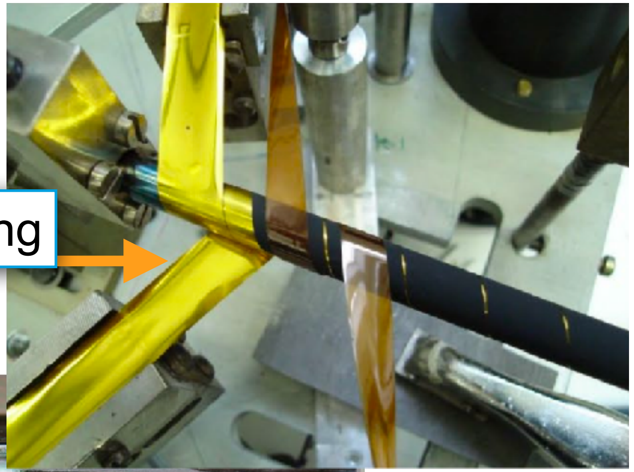
More Recently Gaining Momentum

Re-discover rationale

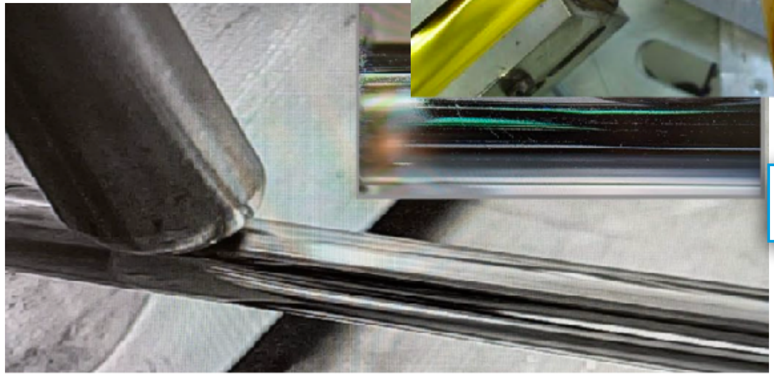
- robustness against single wire failures
- reduced mechanical stress
- different gas choices possible
- flexibility in **combination with silicon**



Workshop
U Michigan



winding



welding

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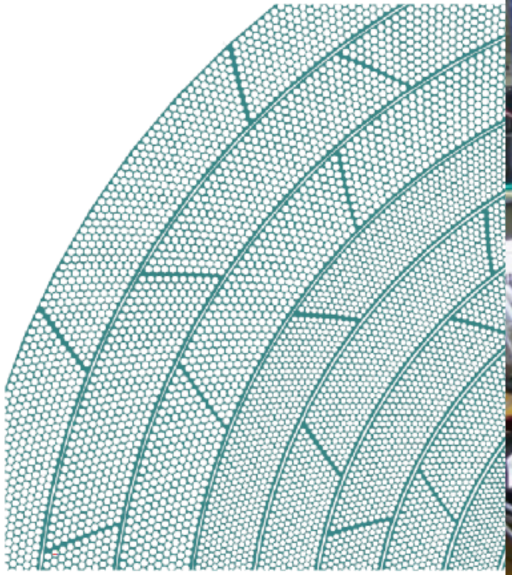

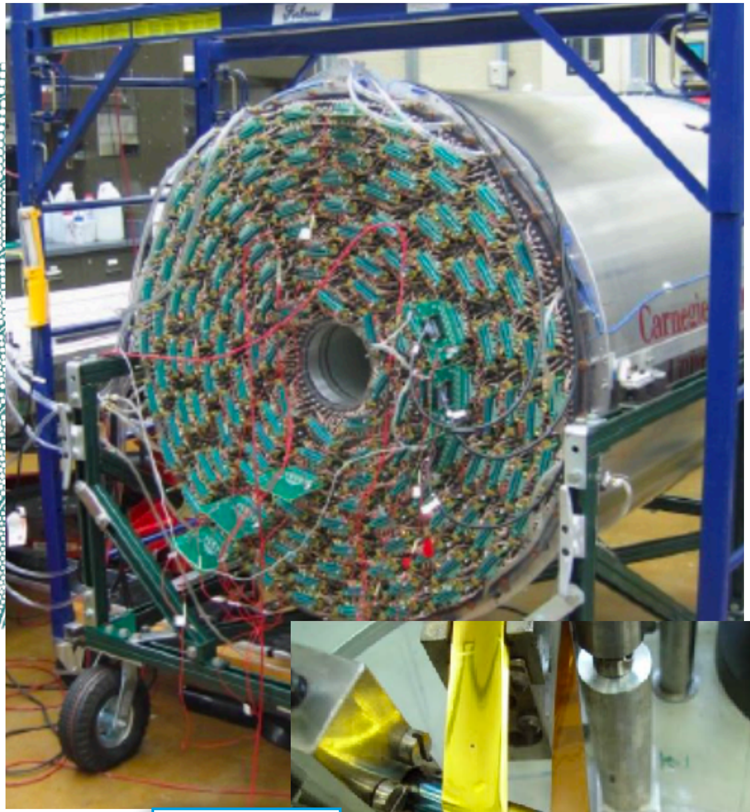

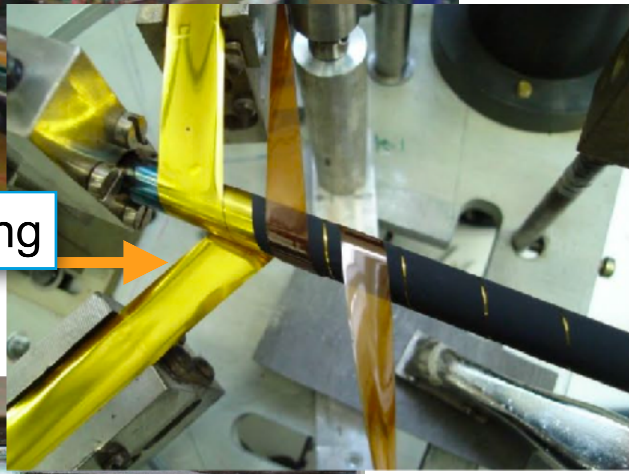

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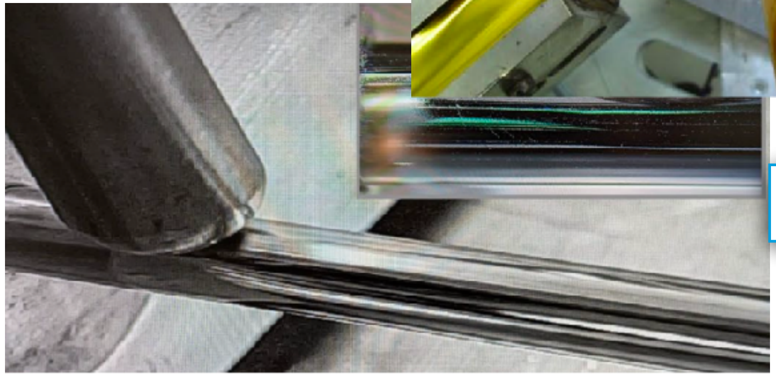


welding

Workshop
U Michigan

Calorimetry

Calorimeter Technologies

Already Introduced

All concepts aim at Particle Flow reconstruction

- with different emphasis on granularity, energy resolution, stability

Liquid Argon + tiles

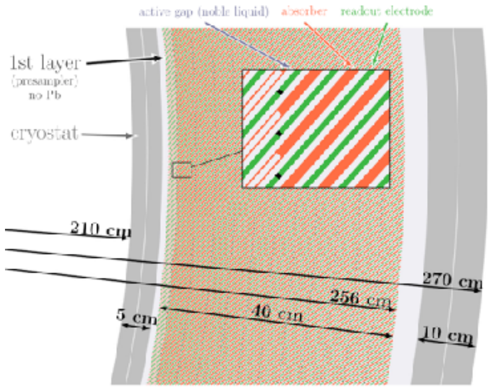
- finer longitudinal sampling wrt ATLAS (4→12)
- warm or cold electronics
- CALICE or ATLAS style scintillator tile HCAL

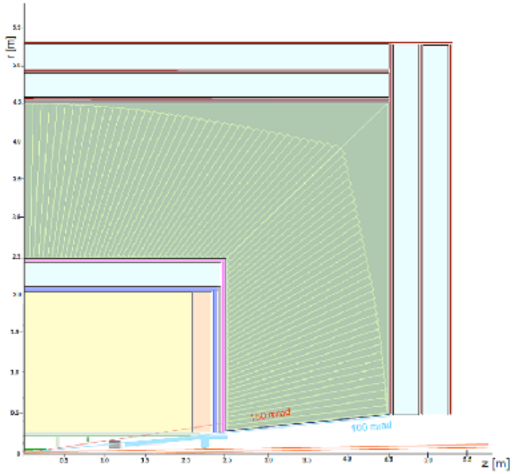
Fibre-based Dual Read-out with crystals in front

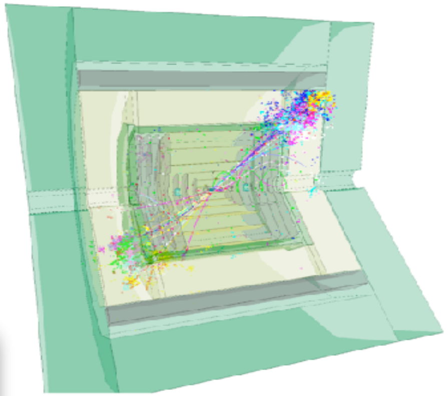
- copper or steel matrix, Cherenkov and scintillating fibres, SiPMs
- pointing geometry, superior PID
- longitudinal segmentation via timing

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

Scaling up - Step by Step

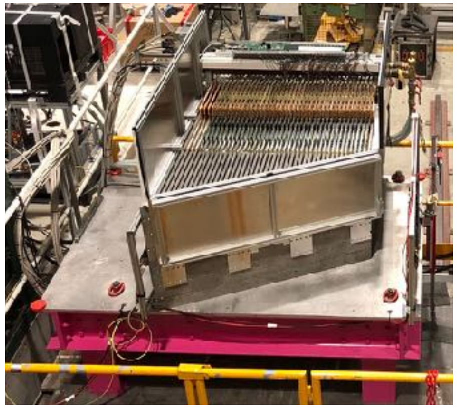
Orders of Magnitude

High channel count of highly granular calorimeters remains a challenge on all levels

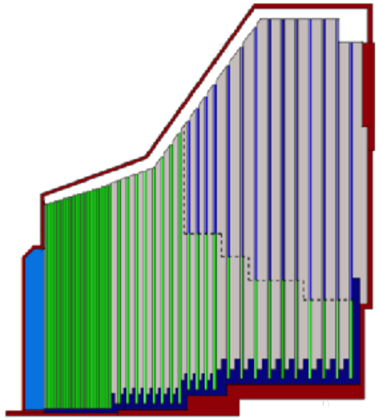
- production, test, calibration, software, management
- each step in size requires higher degrees of automation
  - e.g. mega-tiles

Full imaging power requires both ECAL and HCAL inside the solenoid

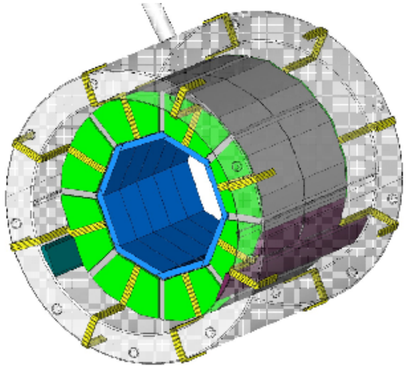
- continuous read-out: no power pulsing and much higher bandwidth than at linear colliders
- much higher demands on compactness than in the CMS endcap
- re-optimisation of sampling including cooling and services / dead spaces
- NB: all alternatives have peripheral electronics



CALICE AHCAL prototype
22’000 SiPMs



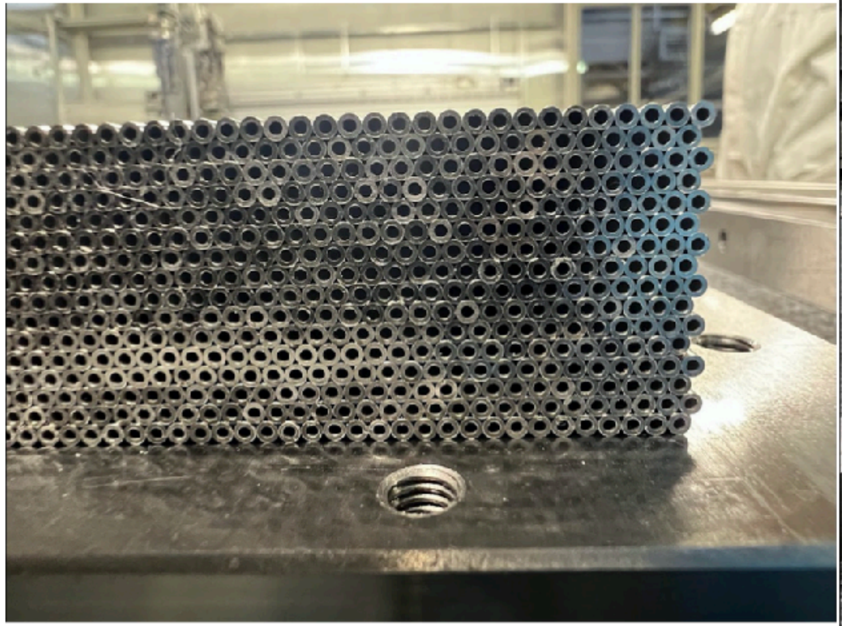
CMS HGCAL (2 end-caps)
280'000 SiPMs

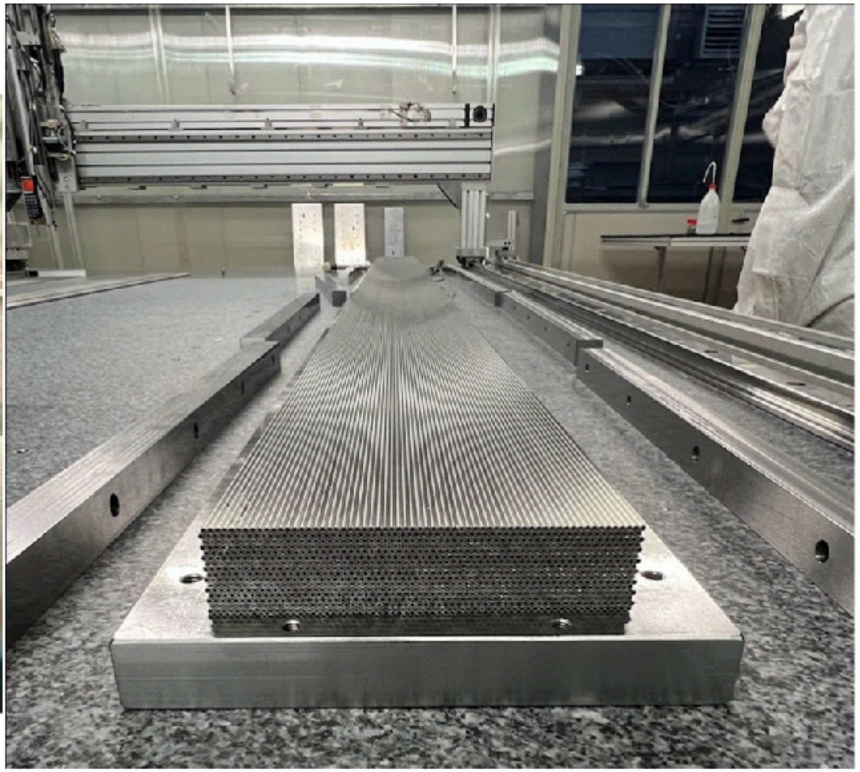


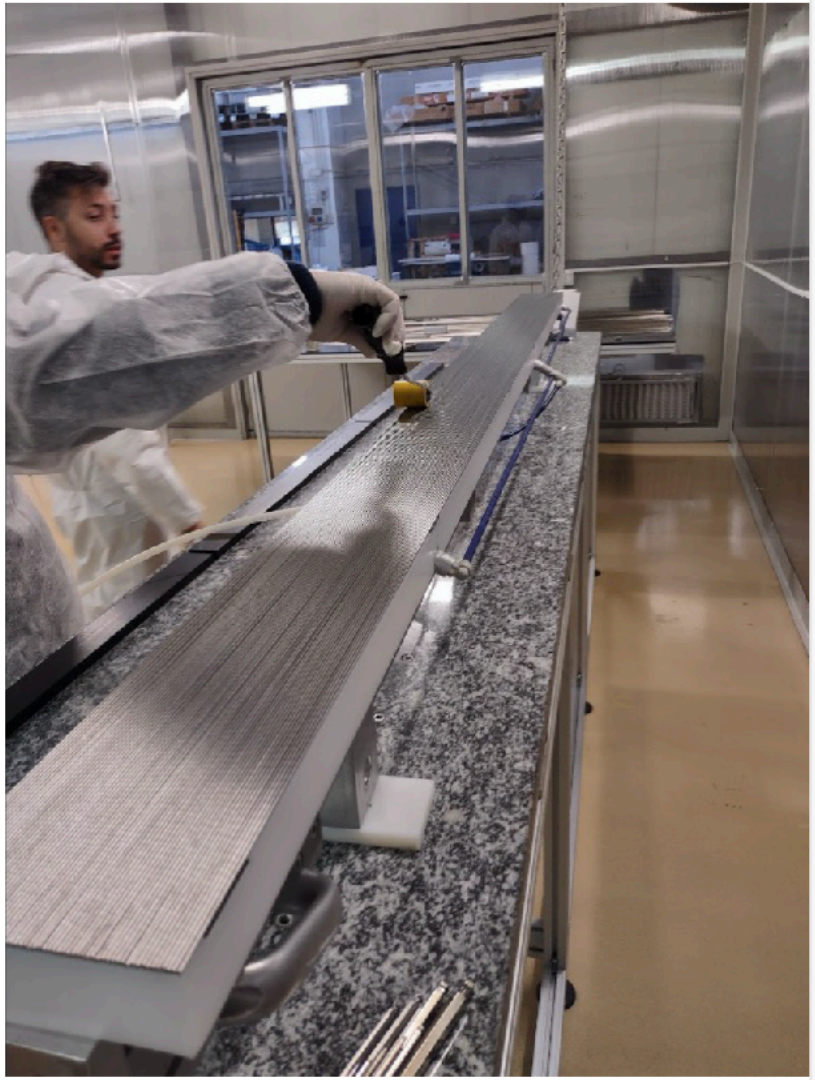
CLD / ILD HCAL barrel only
4’000’000 SiPMs

DR calorimeter

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







DR calorimeter

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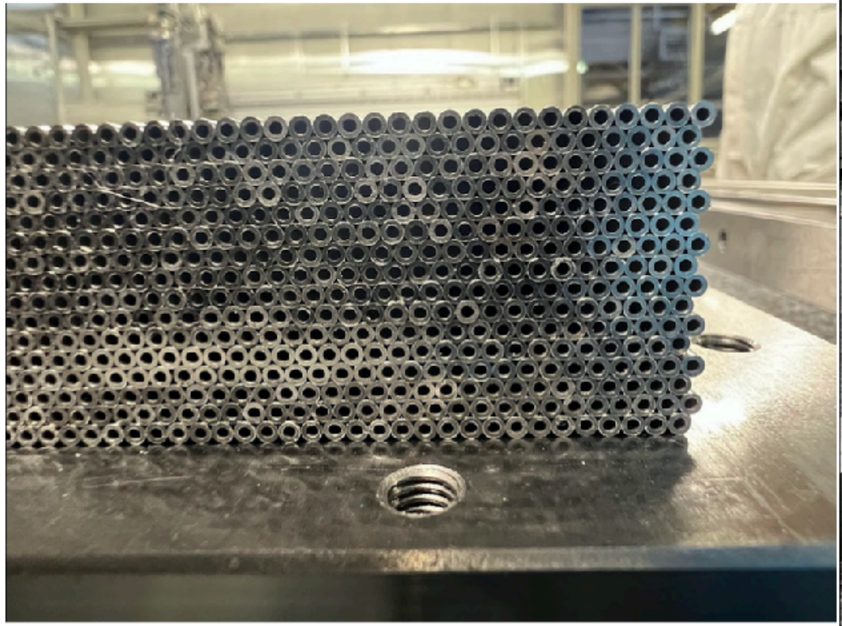
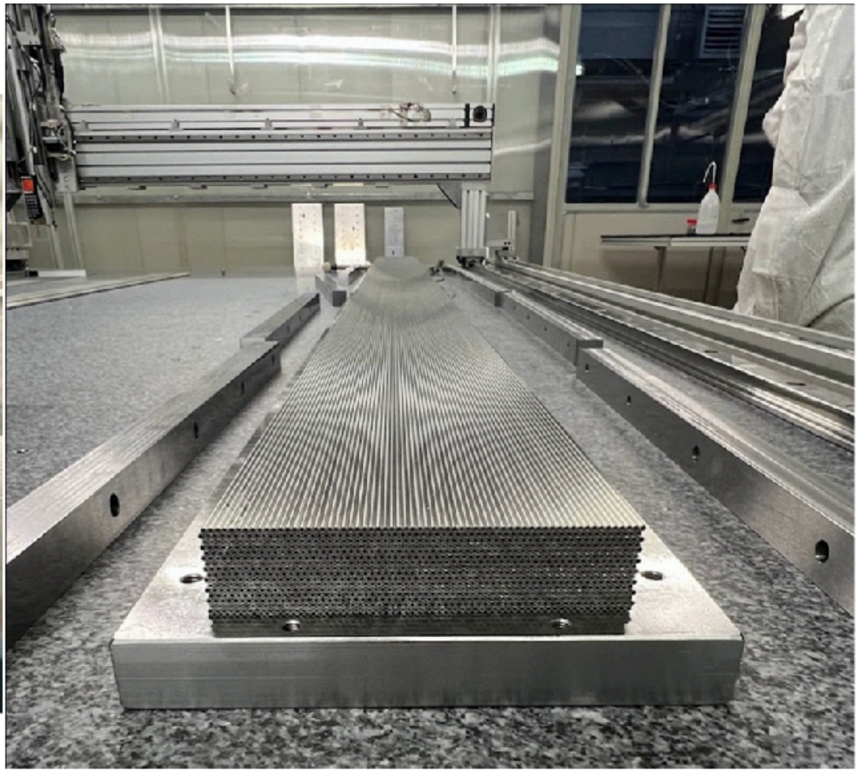
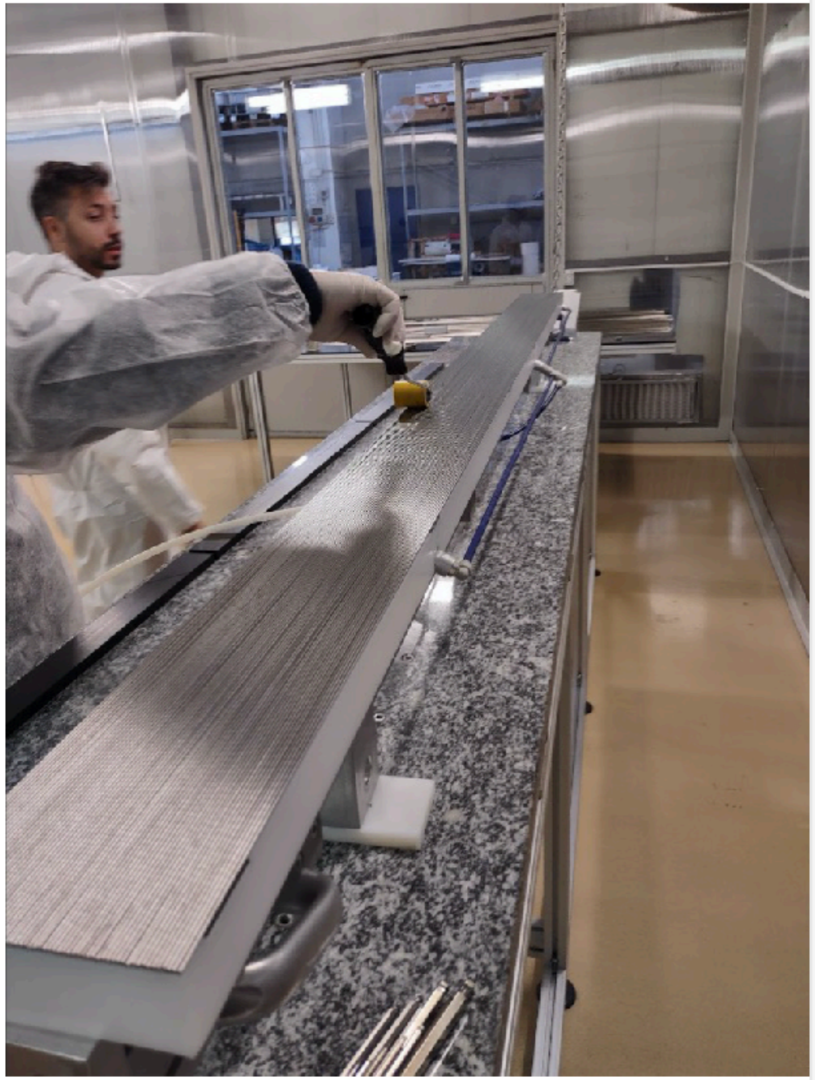
  - Hidra2 call INFN CSN5

first DR prototype with containment







FUTURE CIRCULAR COLLIDER

DR calorimeter

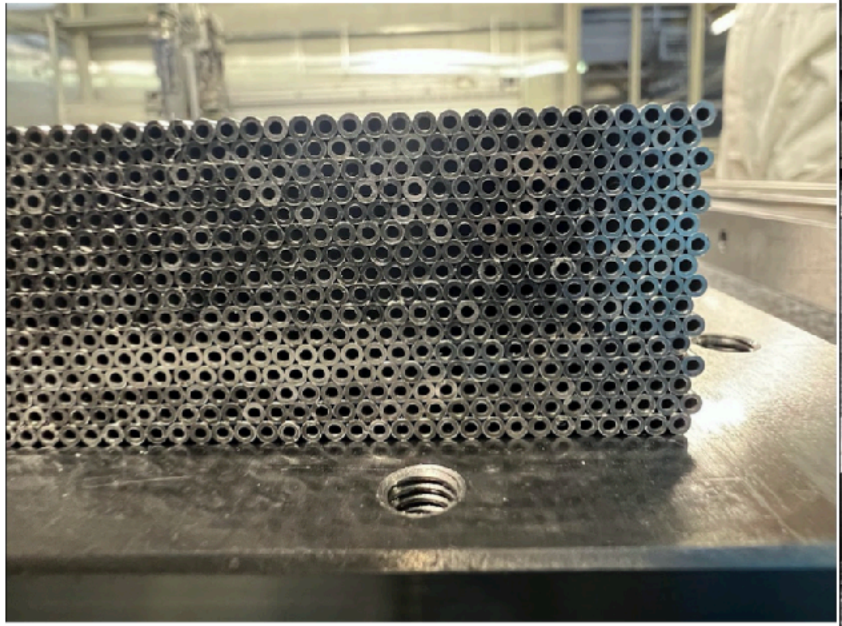
INFN Istituto Nazionale di Fisica Nucleare

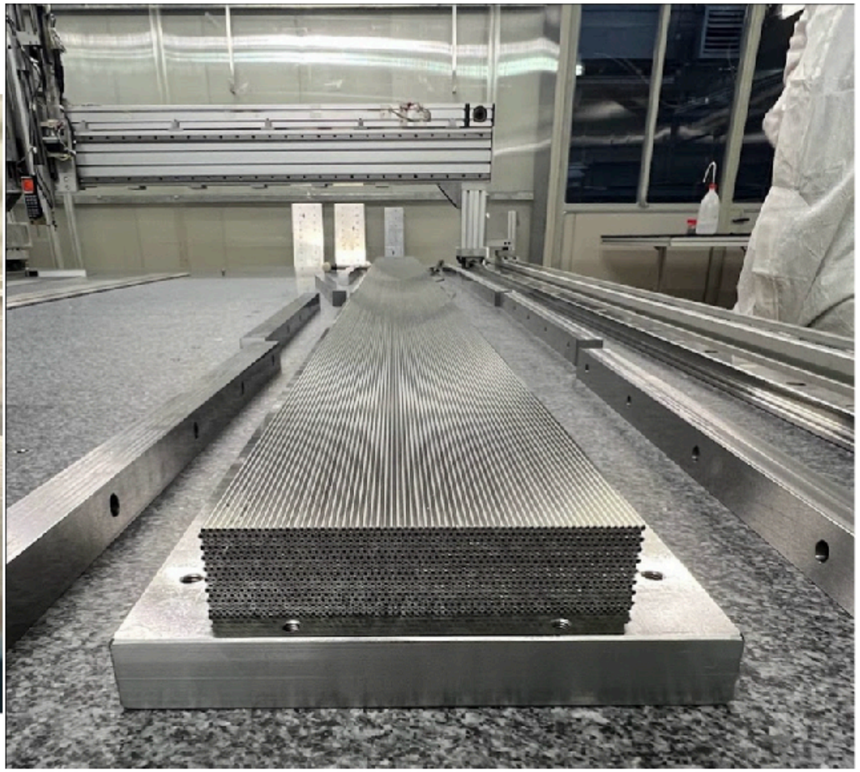
❖ Full containment hadronic prototype in progress

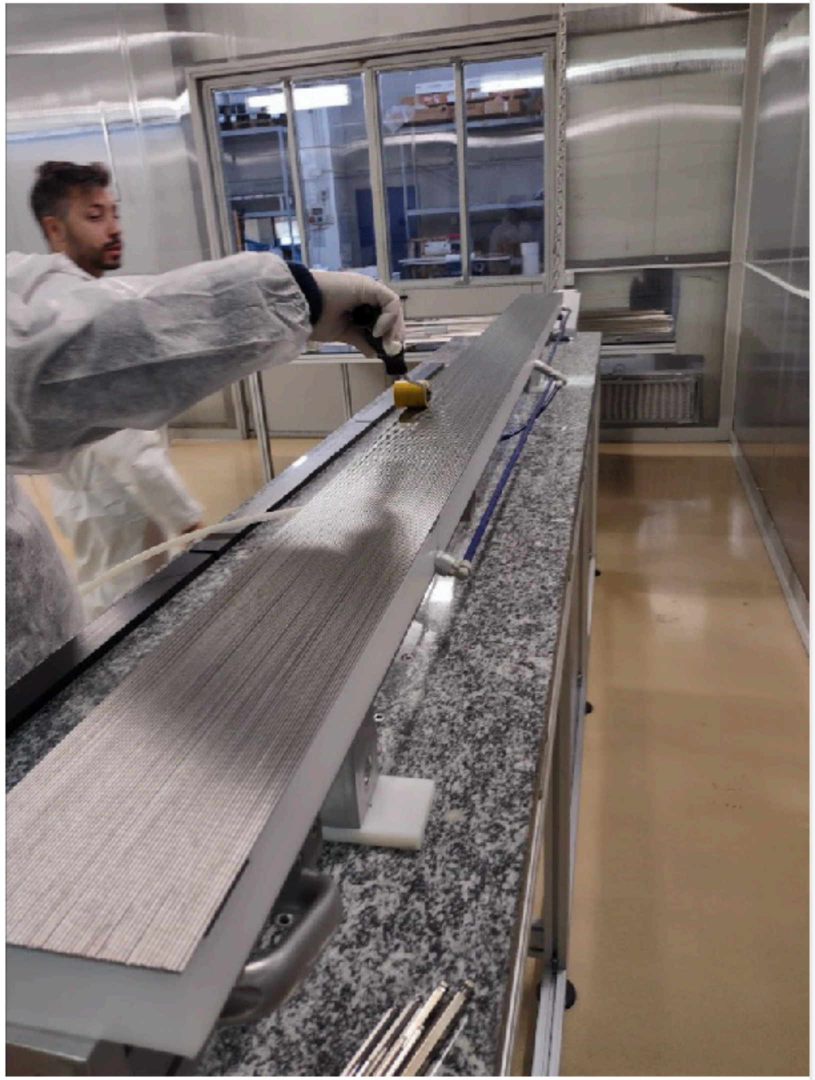
➢ Hidra2 call INFN CSN5

first DR prototype with containment

stainless steel is non-magnetic







Liquid Argon Goes Granular

Towards Finer 3D Segmentation

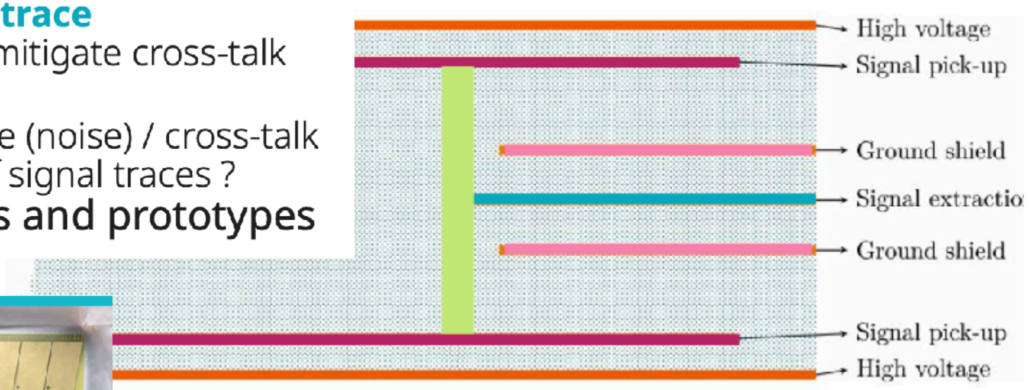
Aiming at 10x ATLAS granularity

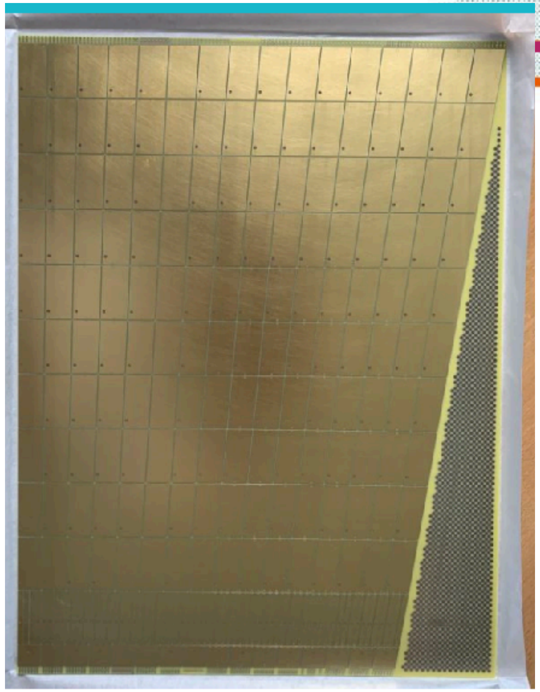
- few million channels
- multi-layer PCBs
- high-density feed-throughs

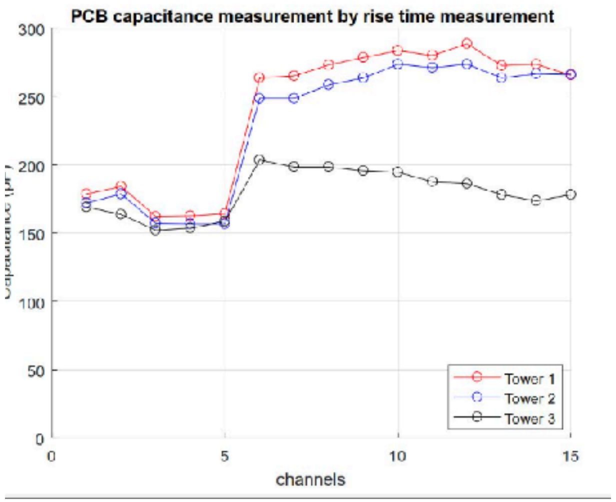
Prototypes made and under test

- optimise noise, granularity, capacitance
- study trade-offs on test bench and in simulations

- 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



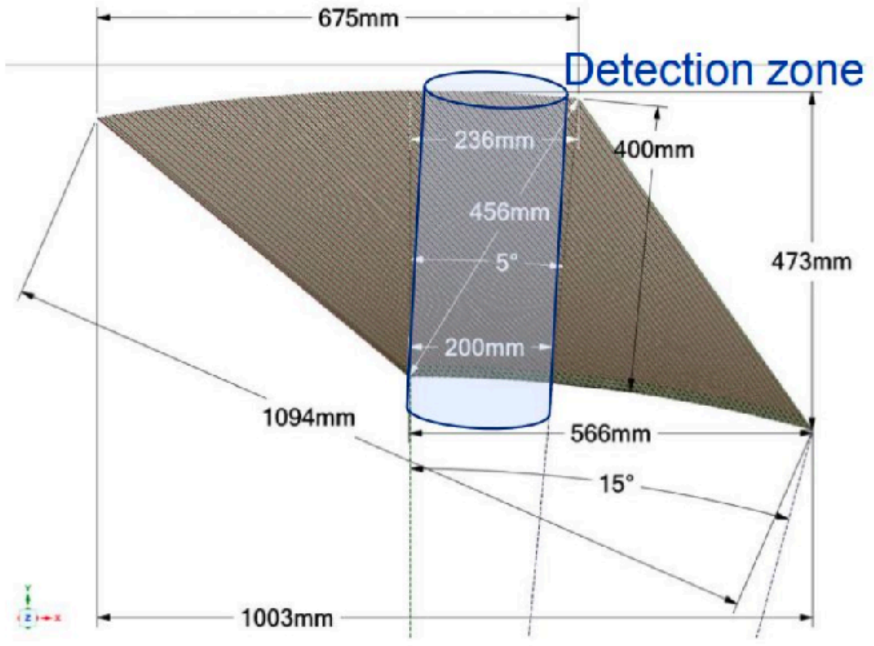




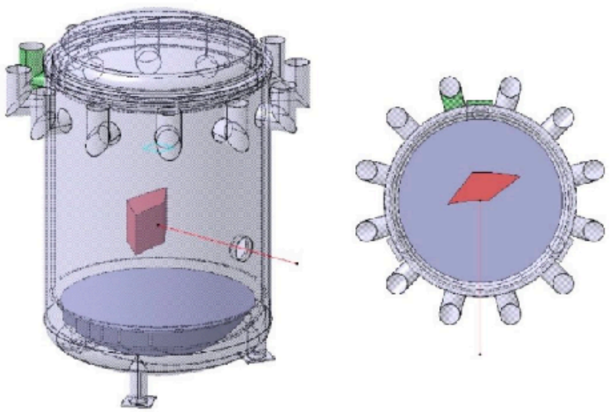
Towards a testbeam module

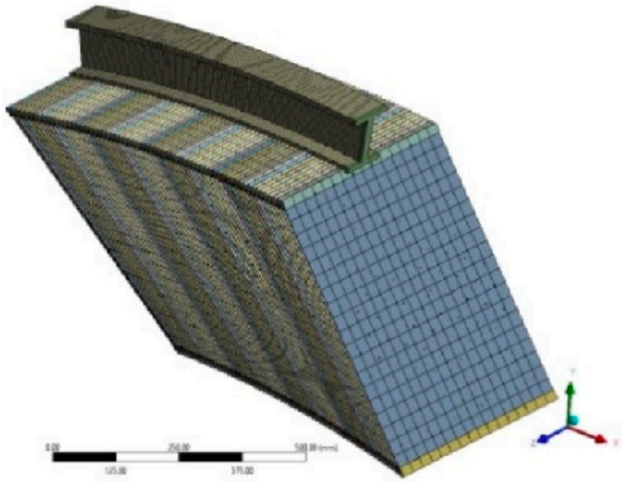
Plan to produce testmodule in the next four years

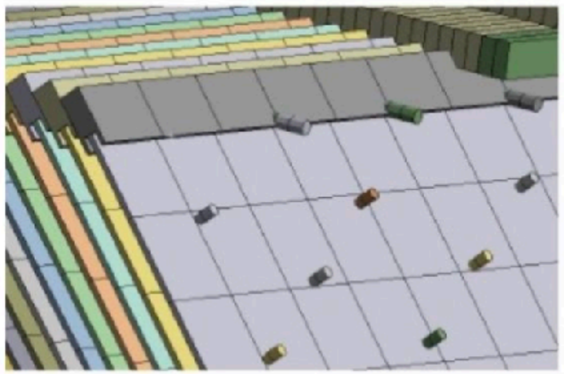
- Mechanical design of module (64 absorbers) has started
  - First finite element calculations performed
- Work on finding / adapting testbeam cryostat
- Common tools (e.g EUDAQ) should facilitate integration in testbeam facility



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







Towards a testbeam module

prototypes are small experiments!
update at this workshop

Plan to produce testmodule in the next four years

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- Work on f
- Common integratic

The cryostat available t
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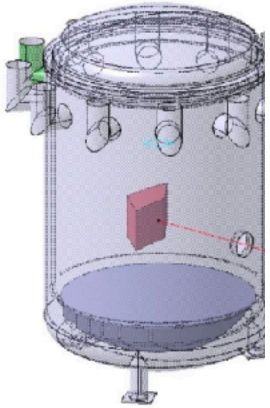
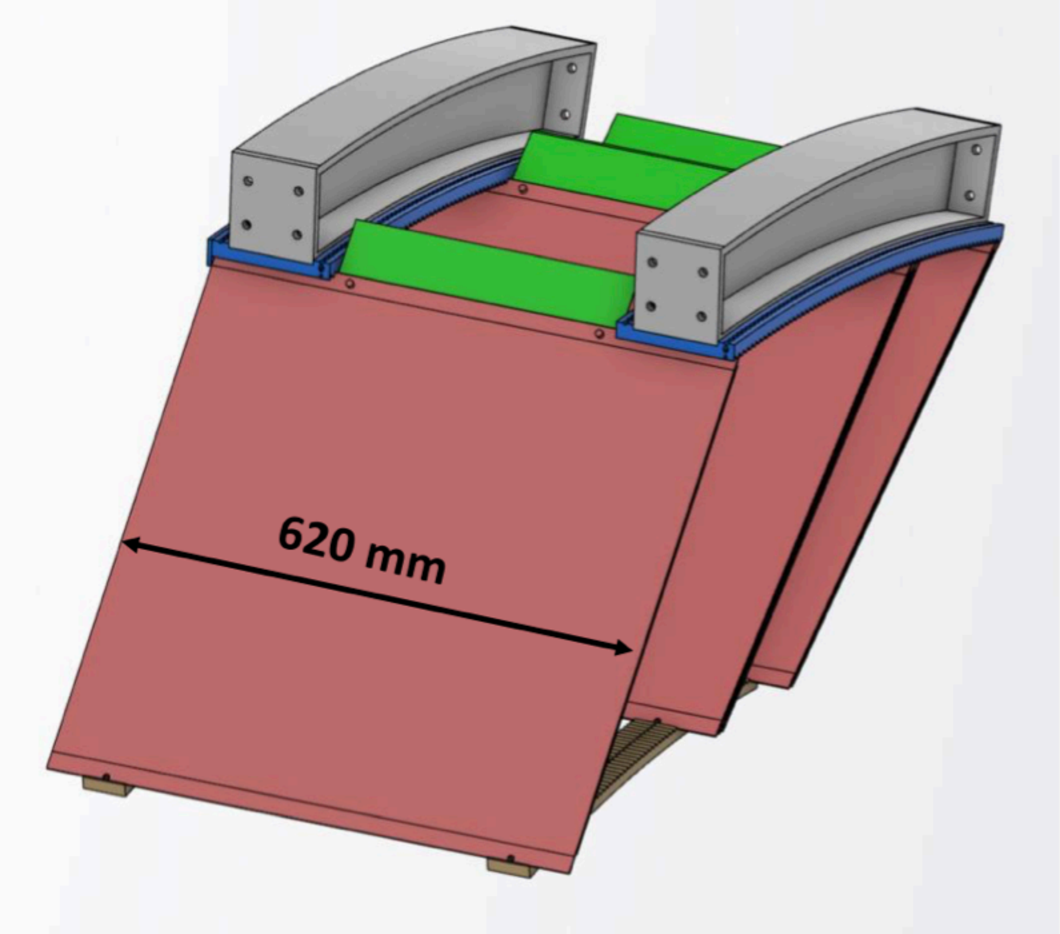
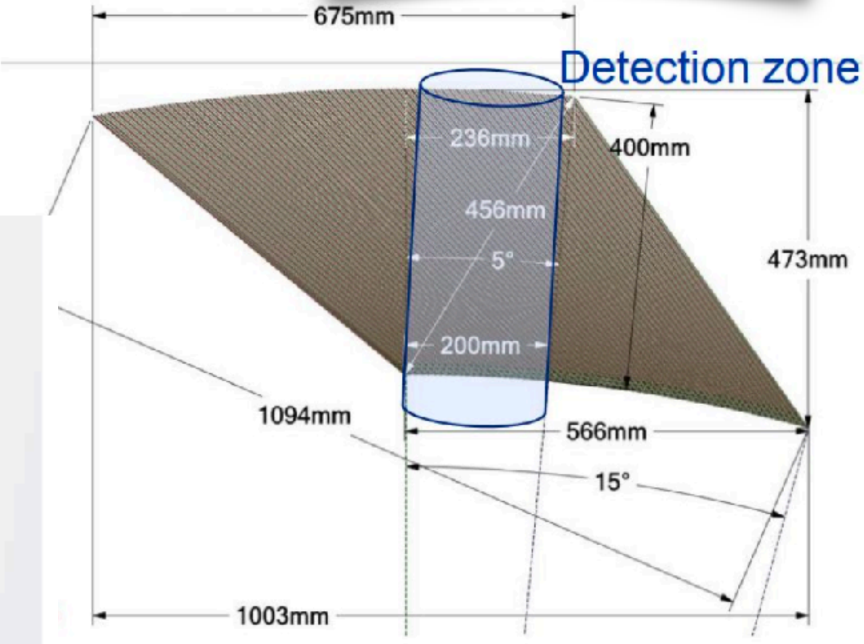
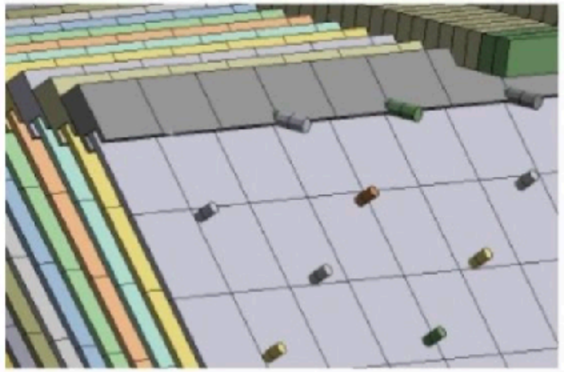
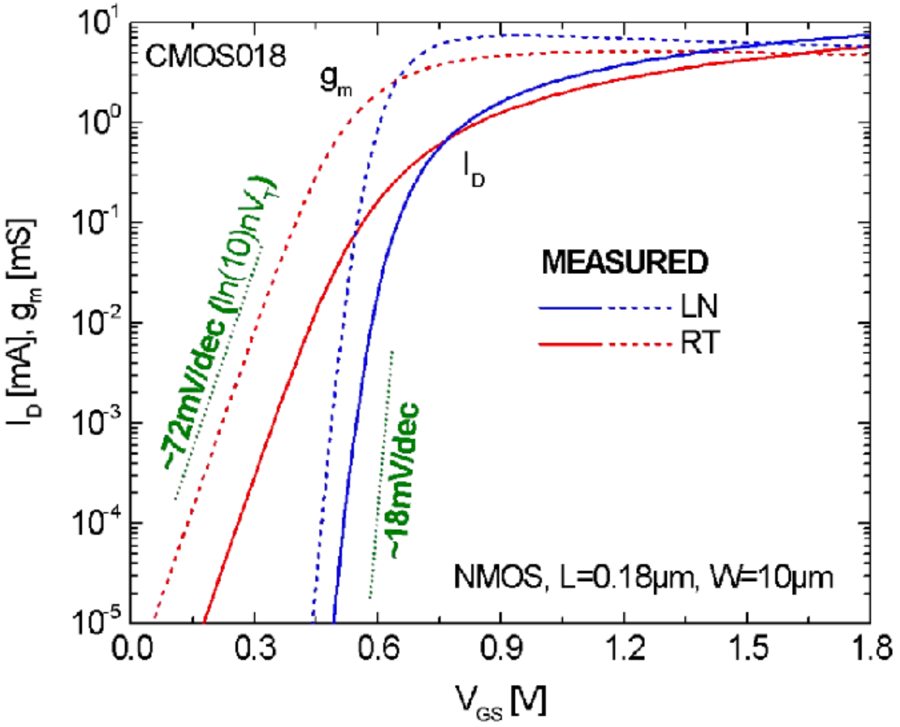


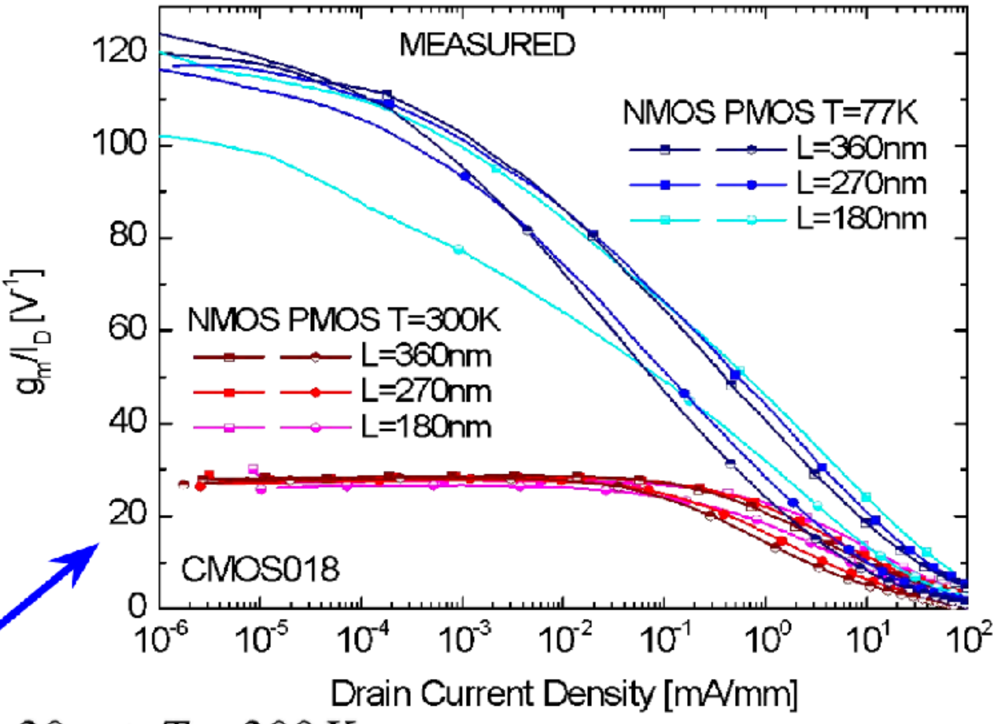






CMOS Transistors *Become Better* in LAr/LN2





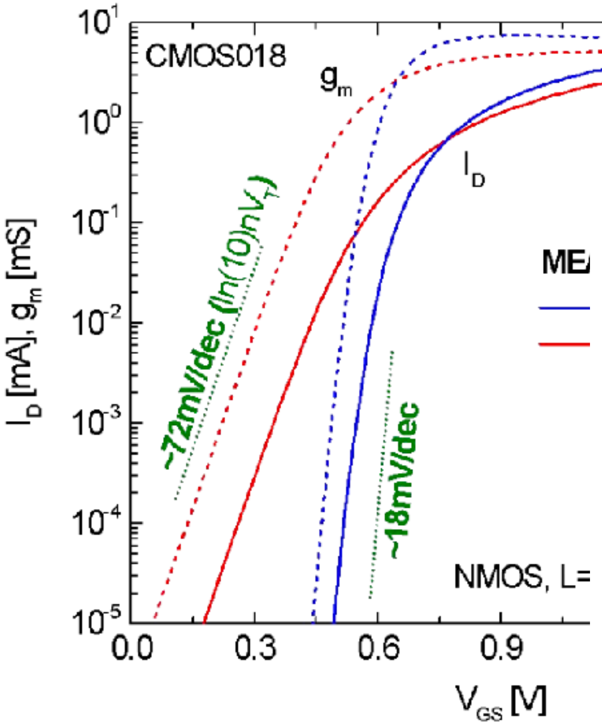
Transconductance/ drain current

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

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

CMOS Transistors *Become Better* in LAr/LN2



Transconductance/ drain current

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decrease with **kT/e**, re
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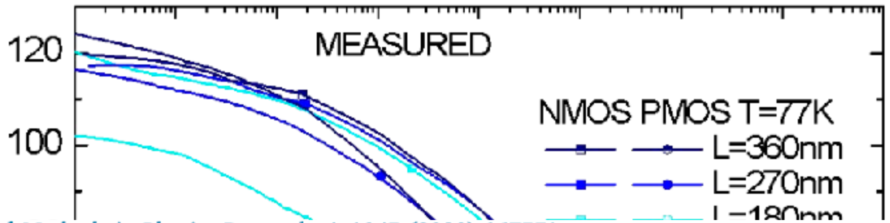

Further reading:

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

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ARTICLE INFO

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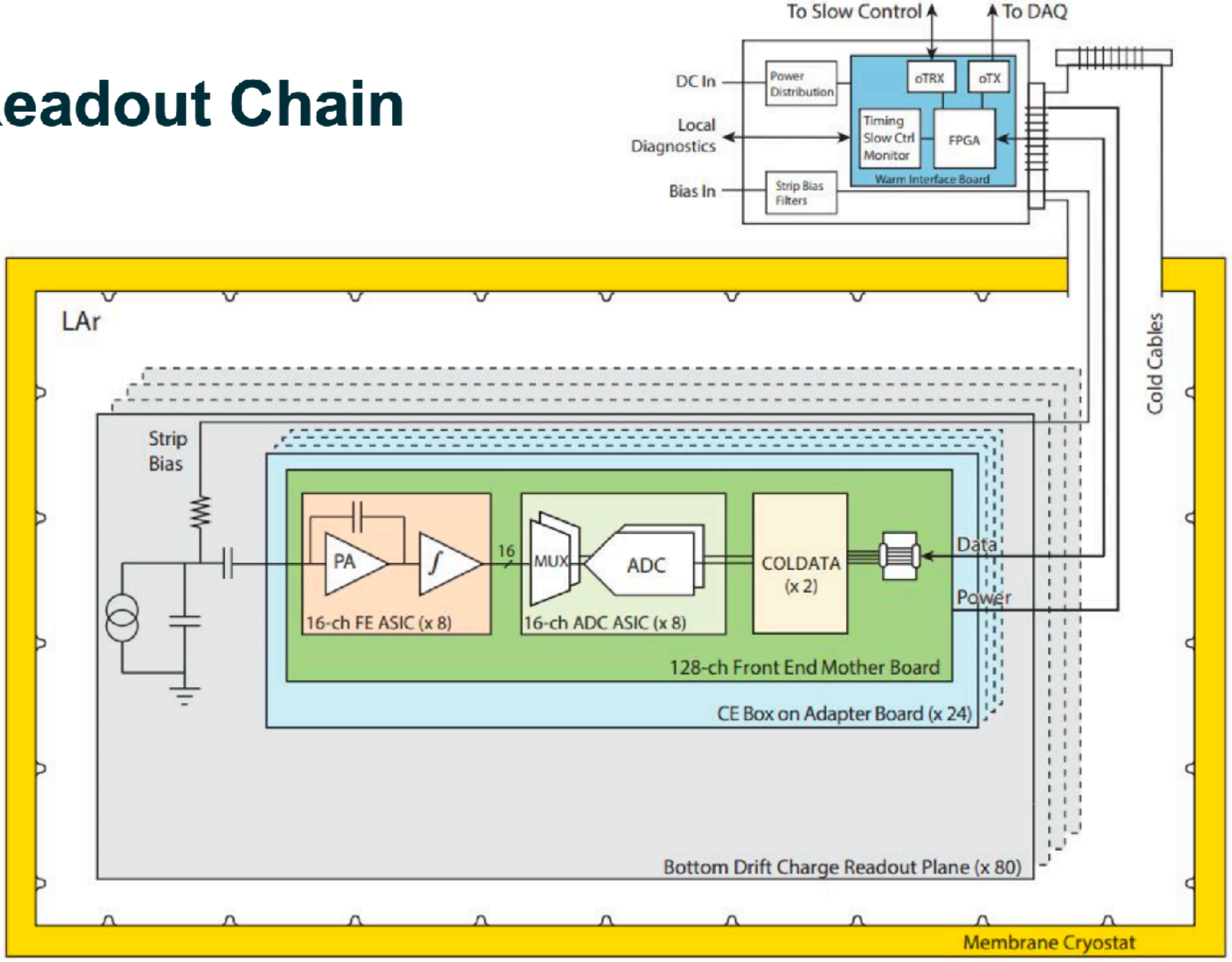
Application-specific integrated circuit (ASIC)
Noise
Front-end electronics for detector readout
Time projection chambers
Noble liquid detectors
Neutrino detectors

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



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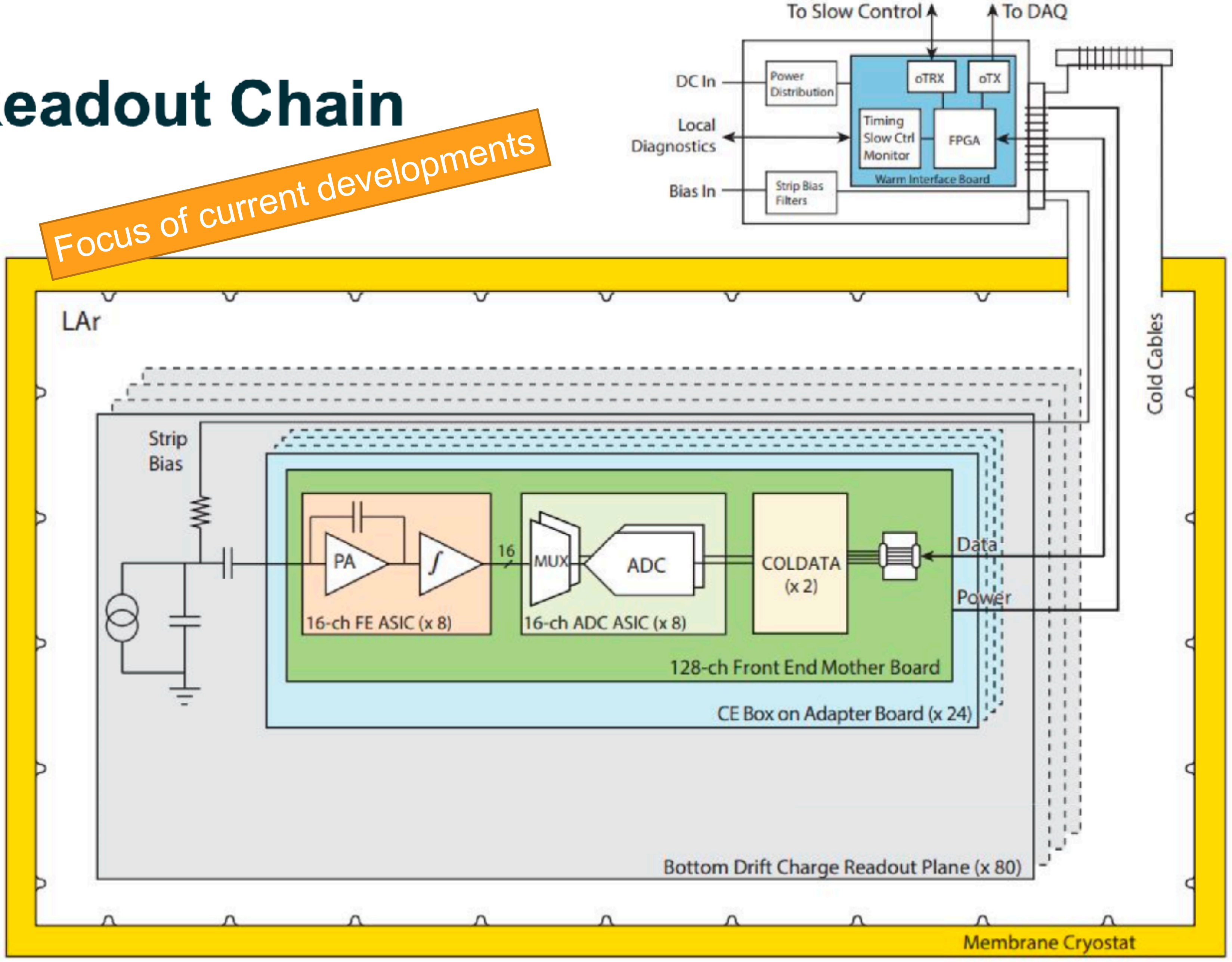
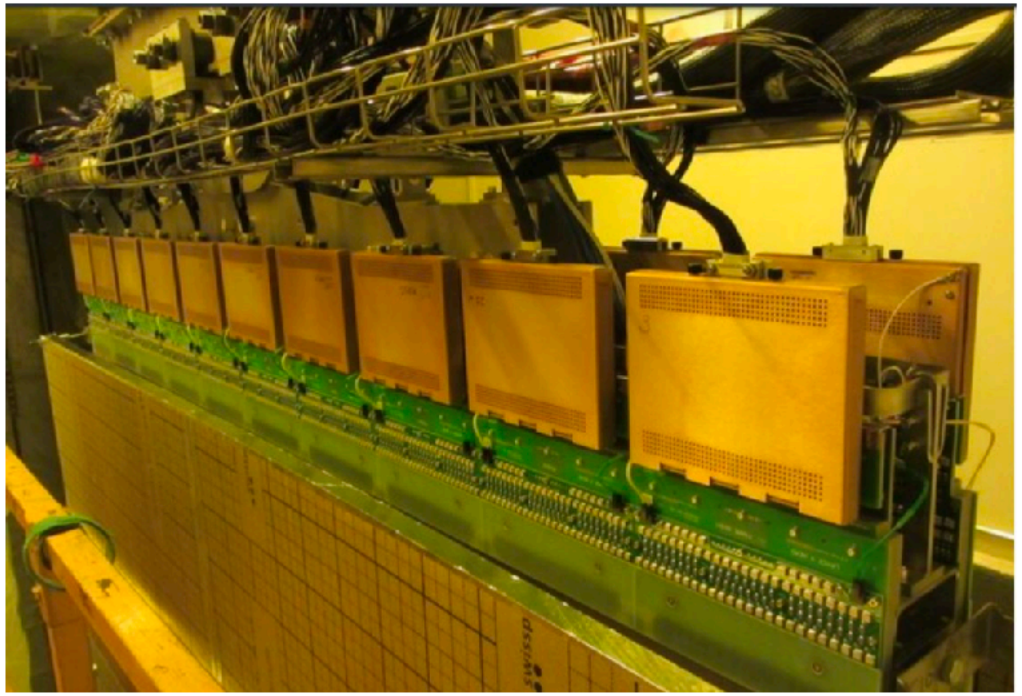
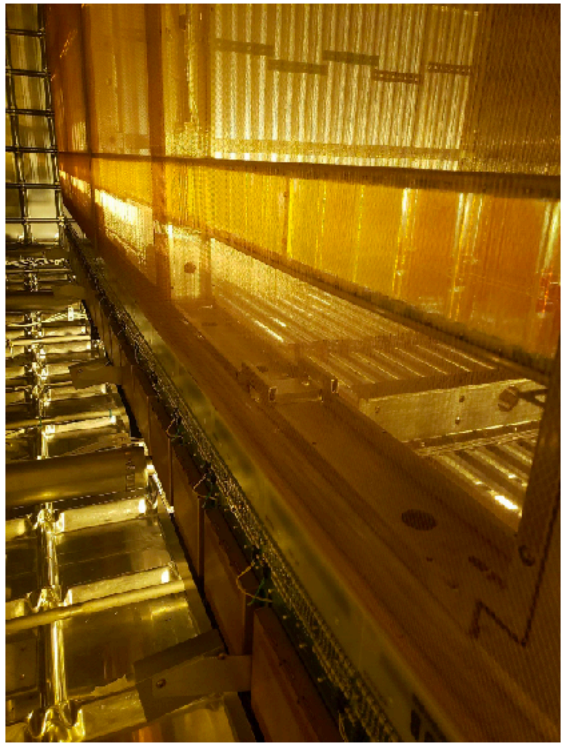
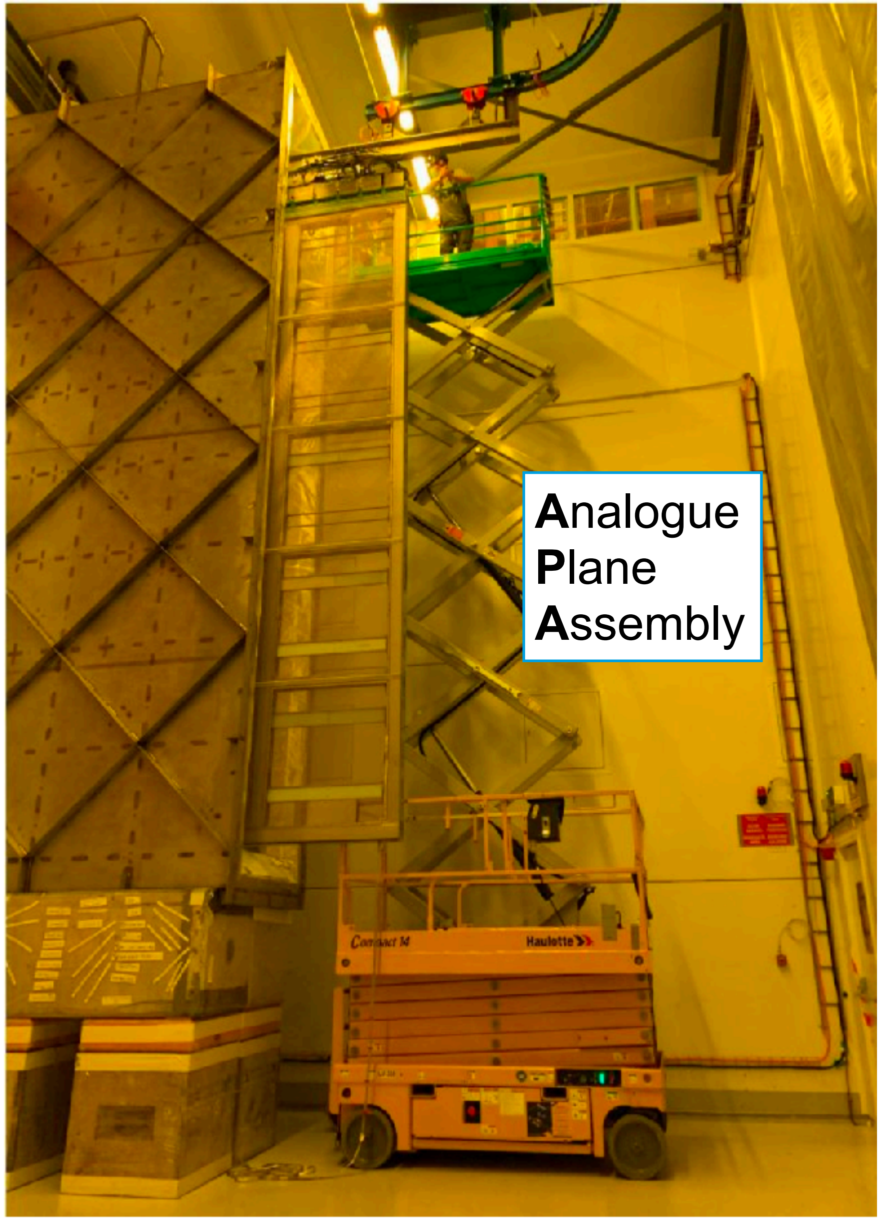


ProtoDUNE-II-HD

- 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
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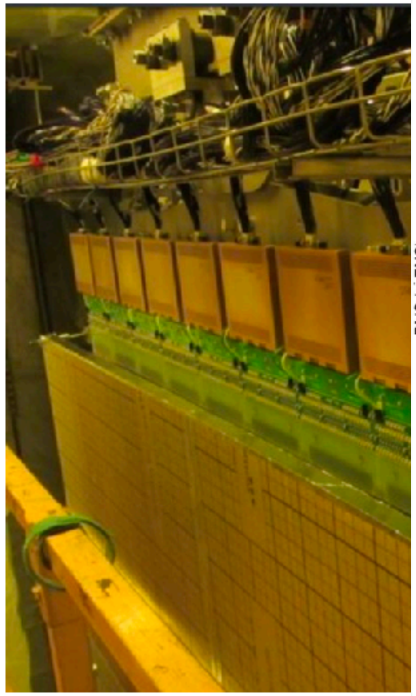
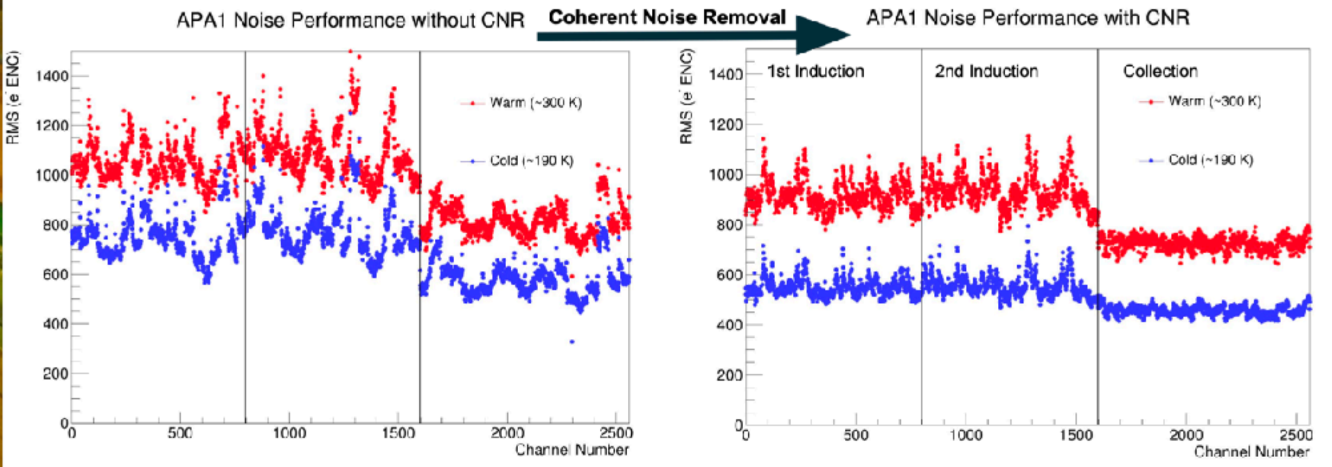


TPC Electronics Performance for ProtoDUNE-II-HD

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



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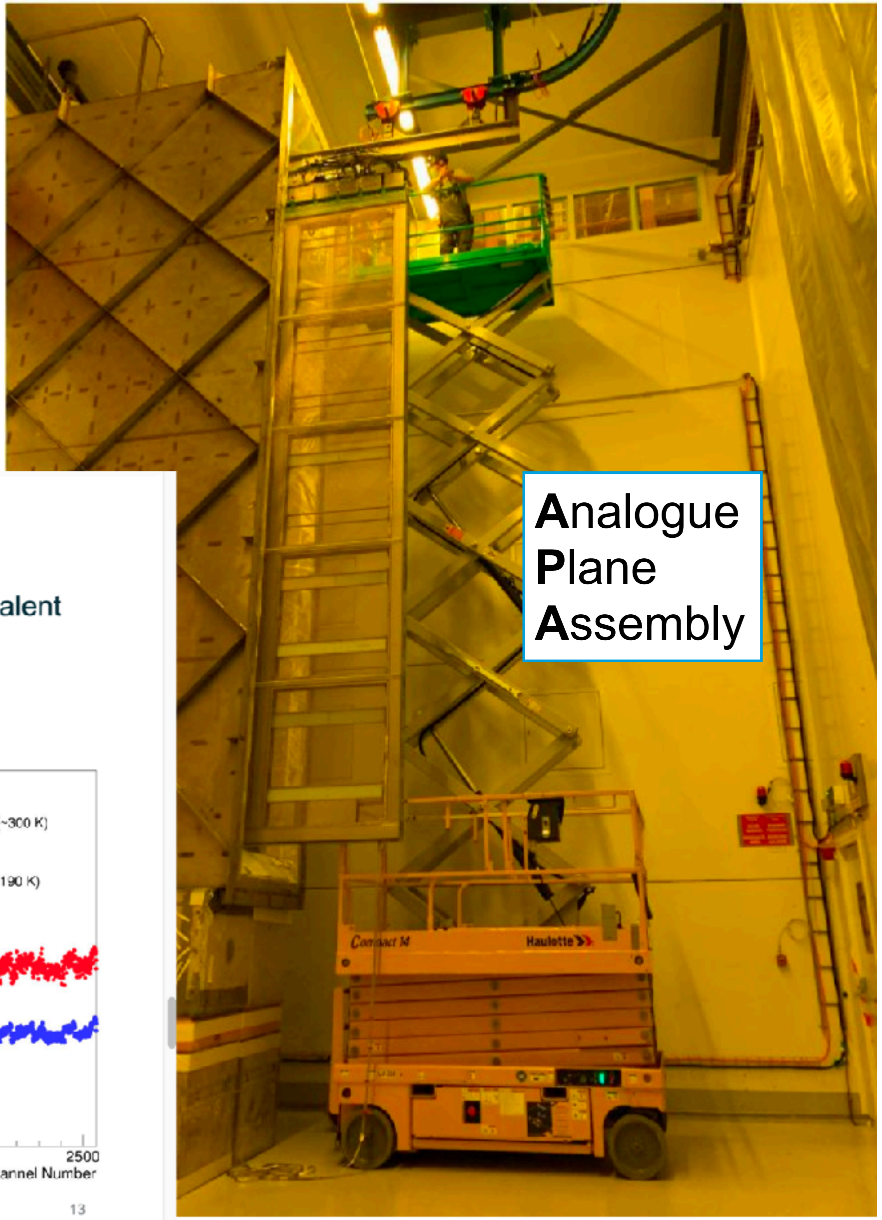
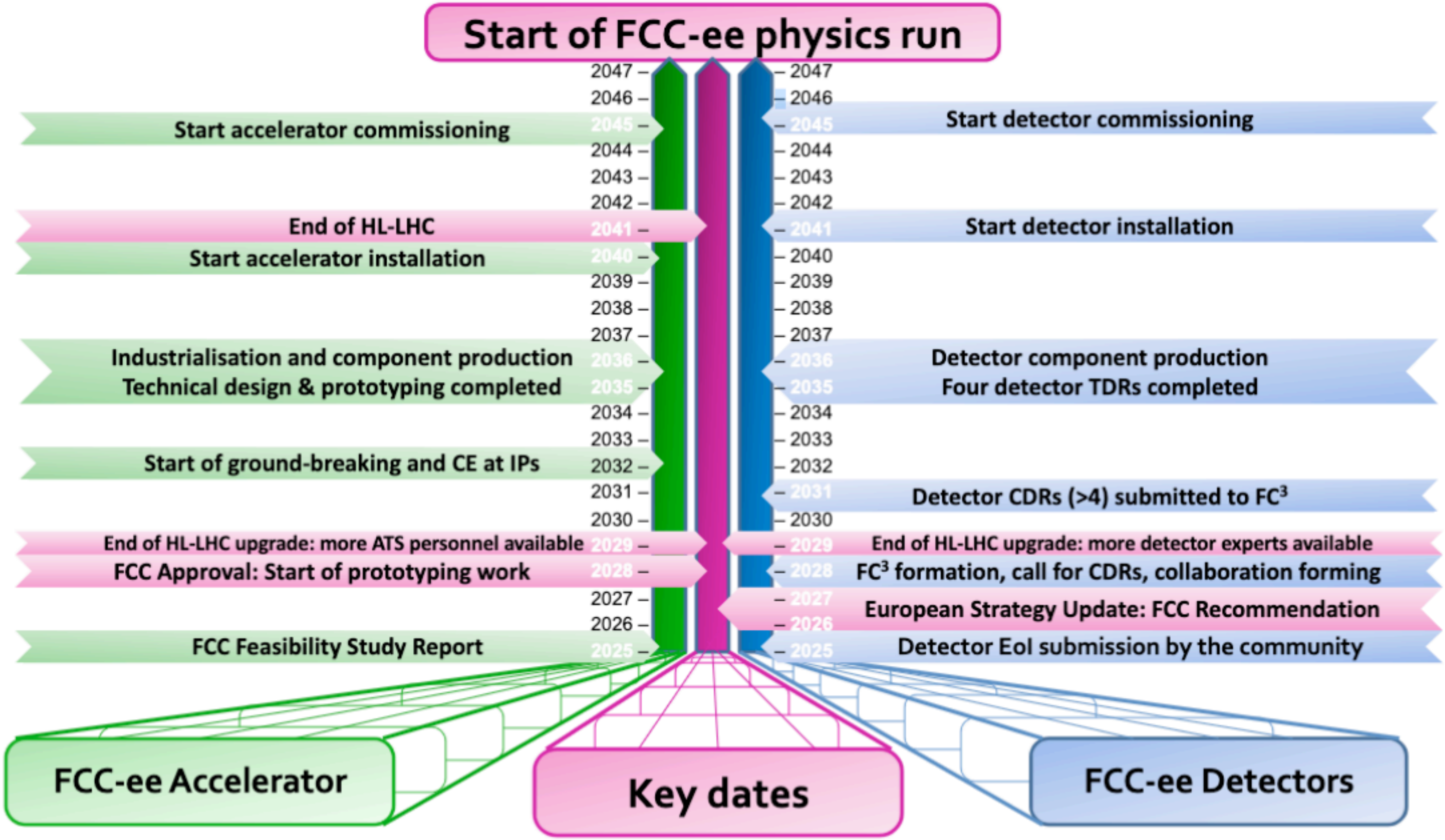


Timeline for the FCCee

Working Hypothesis

all HF projects similar, except maybe CEPC



Timeline for the FCCee

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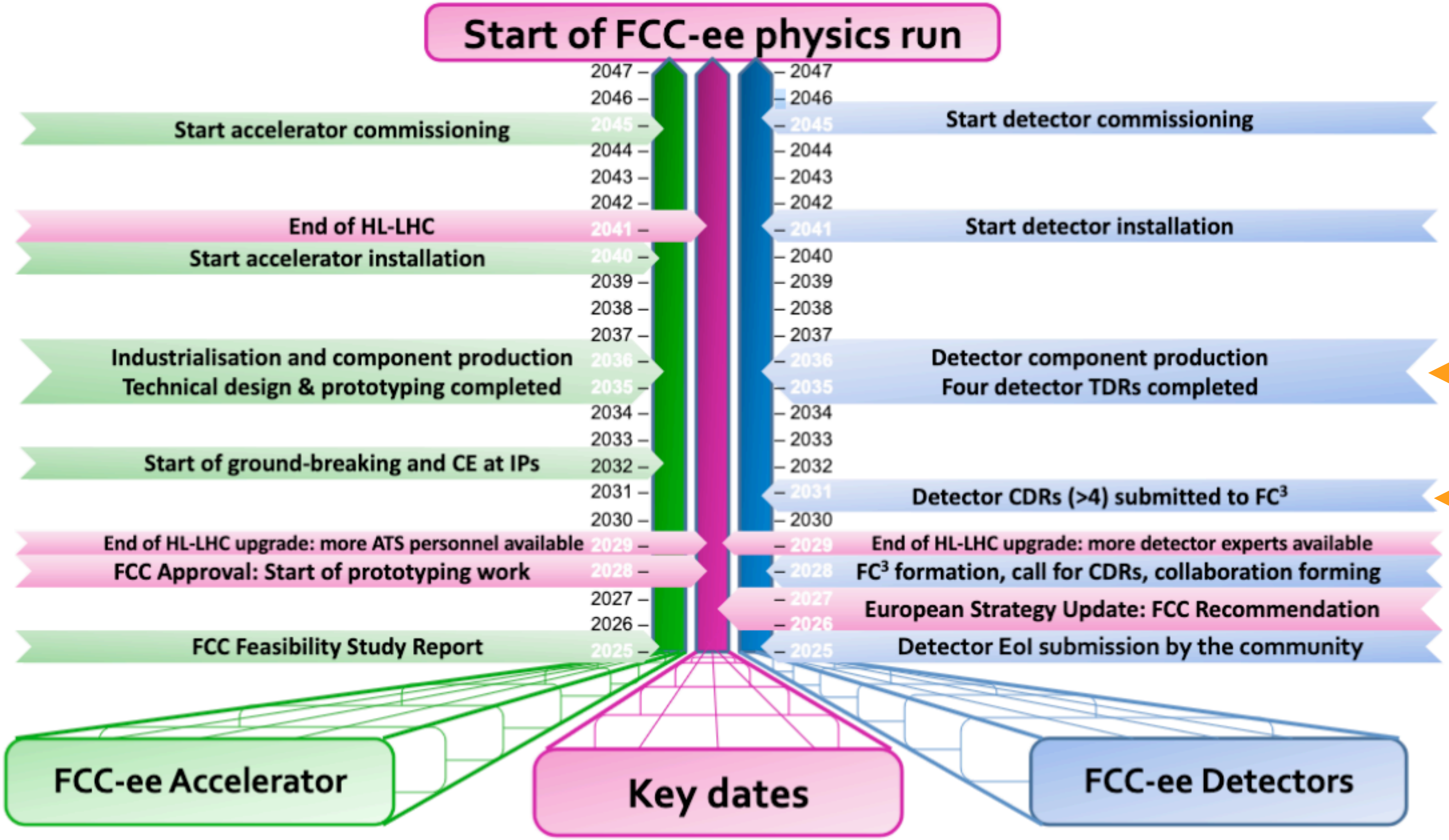


all HF projects similar, except maybe CEPC

2030-33
- scalable prototypes

2027-30
- system demonstrators

2024-27
- optimisation
- component R&D

Summary

Take-home

FCCee detectors represent exciting challenges

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

There is time and room for new ideas, concepts and technologies - see this workshop!

- try them out: demonstrators are largely collider-agnostic

Gradual and moderate ramp-up in resources in some places (only)

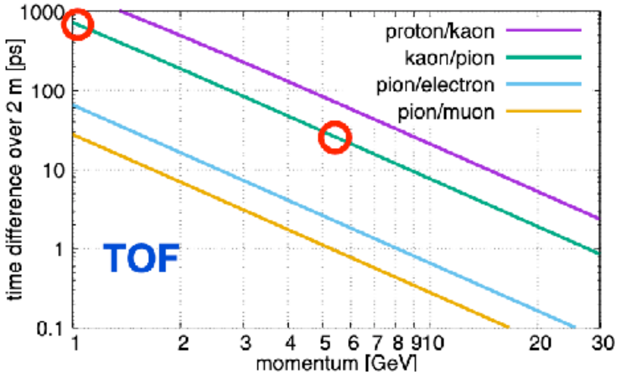
- but real (scalable) prototypes will soon have to meet TDAQ electronics specs and will require some engineering - to address system aspects from the beginning

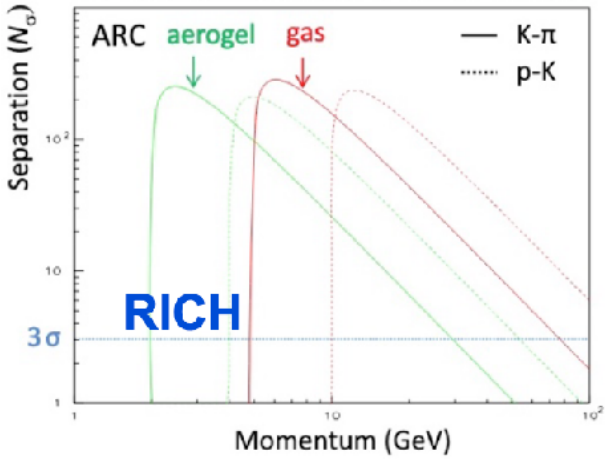
FCC PED is inviting sub-detector groups to form

Back-up

CLD with RICH-based Particle ID

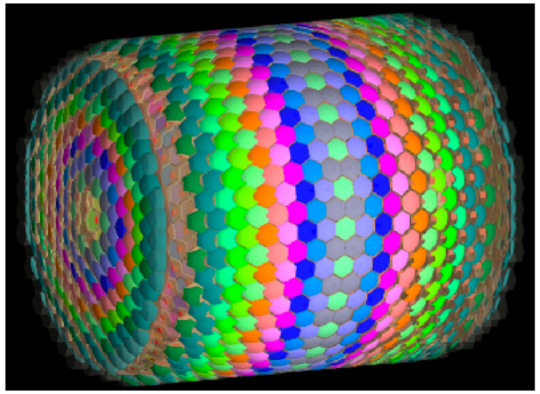
Up to high momenta

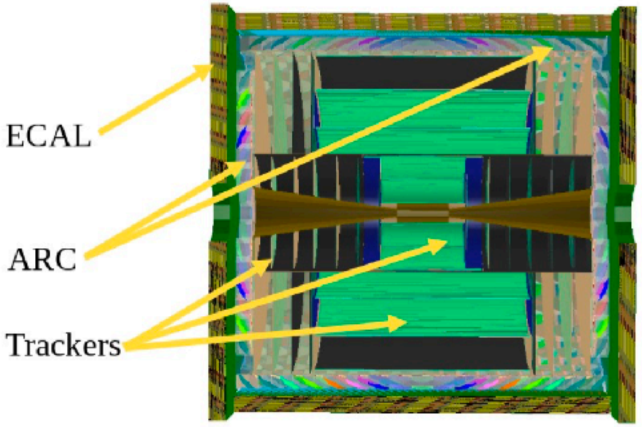




CLD option with ARC

- 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

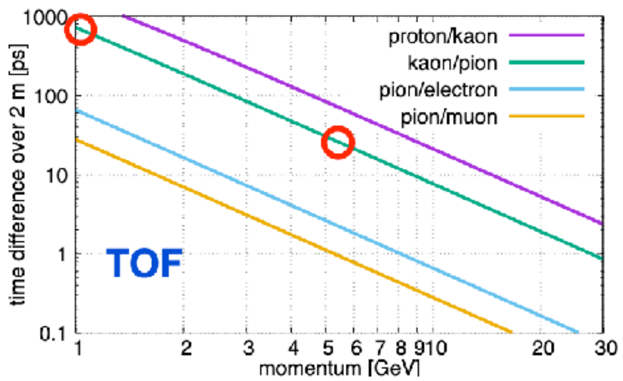


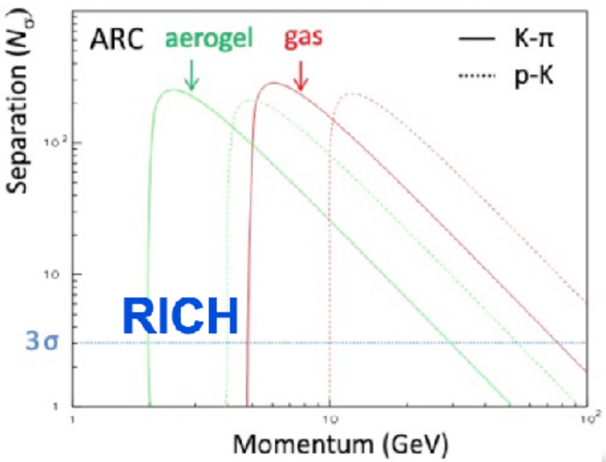


FCCee detector fullsim implementation alvaro.tolosa.delgado@cern.ch 8

CLD with RICH-based Particle ID

Up to high momenta





Tracking re-optimised
Particle flow to be studied next

CLD option with ARC

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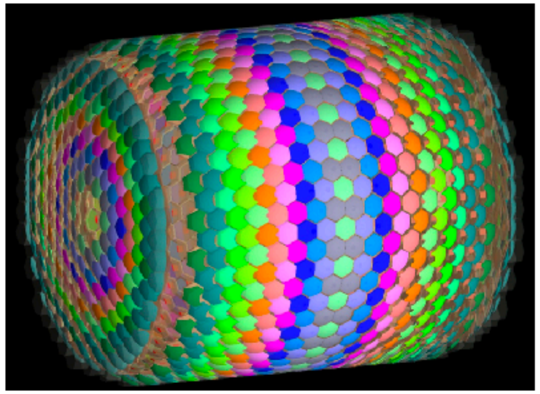
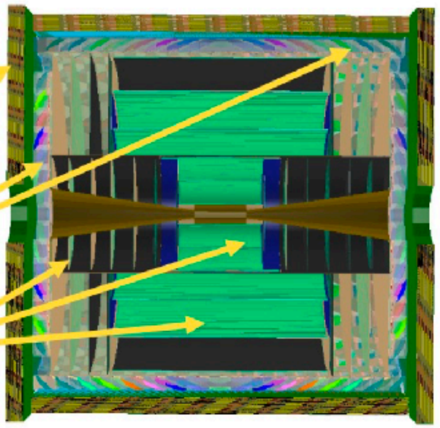
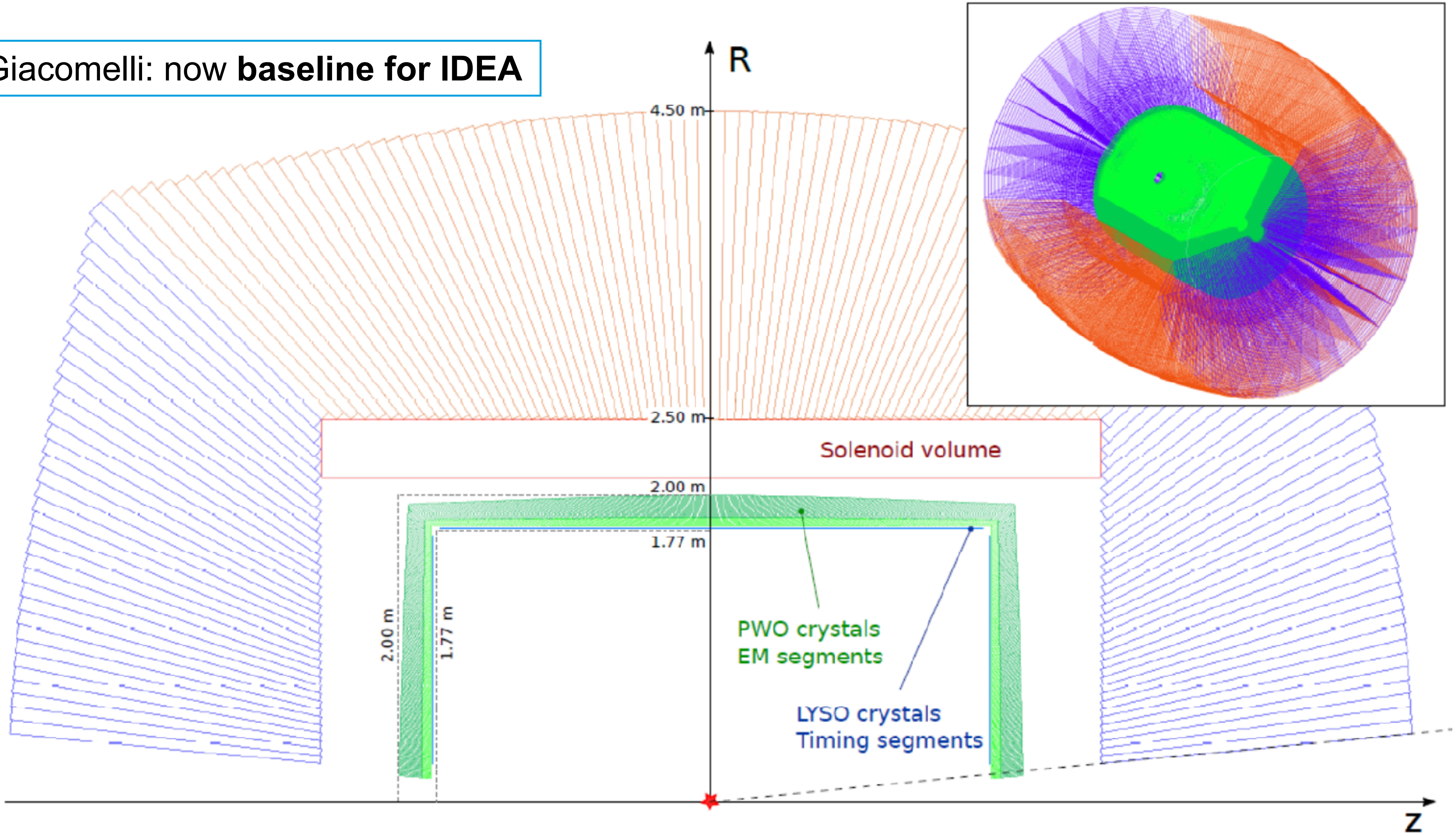




FCCee detector fullsim implementation alvaro.tolosa.delgado@cern.ch 8

Crystal option

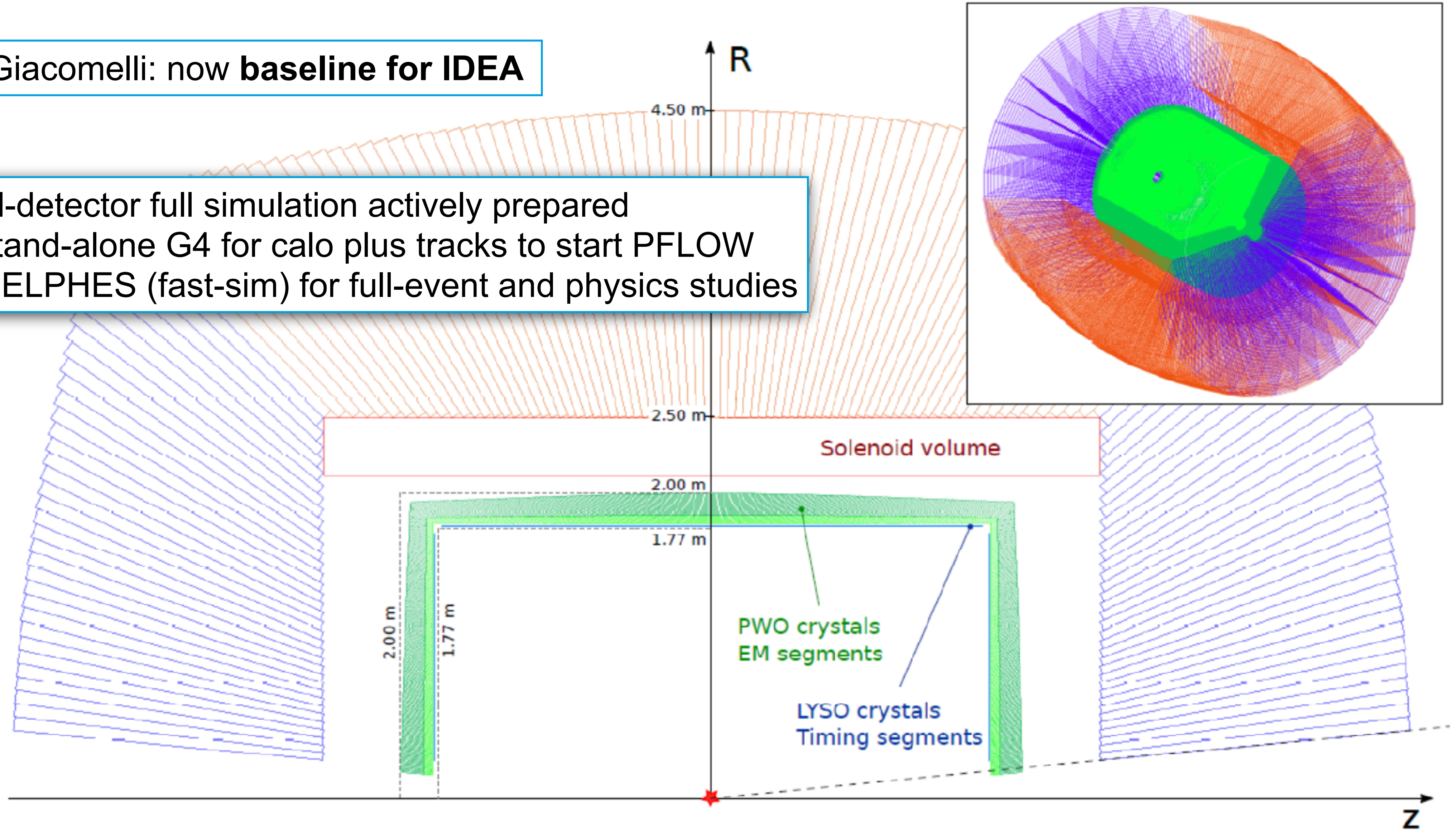
P. Giacomelli: now **baseline for IDEA**



Crystal option

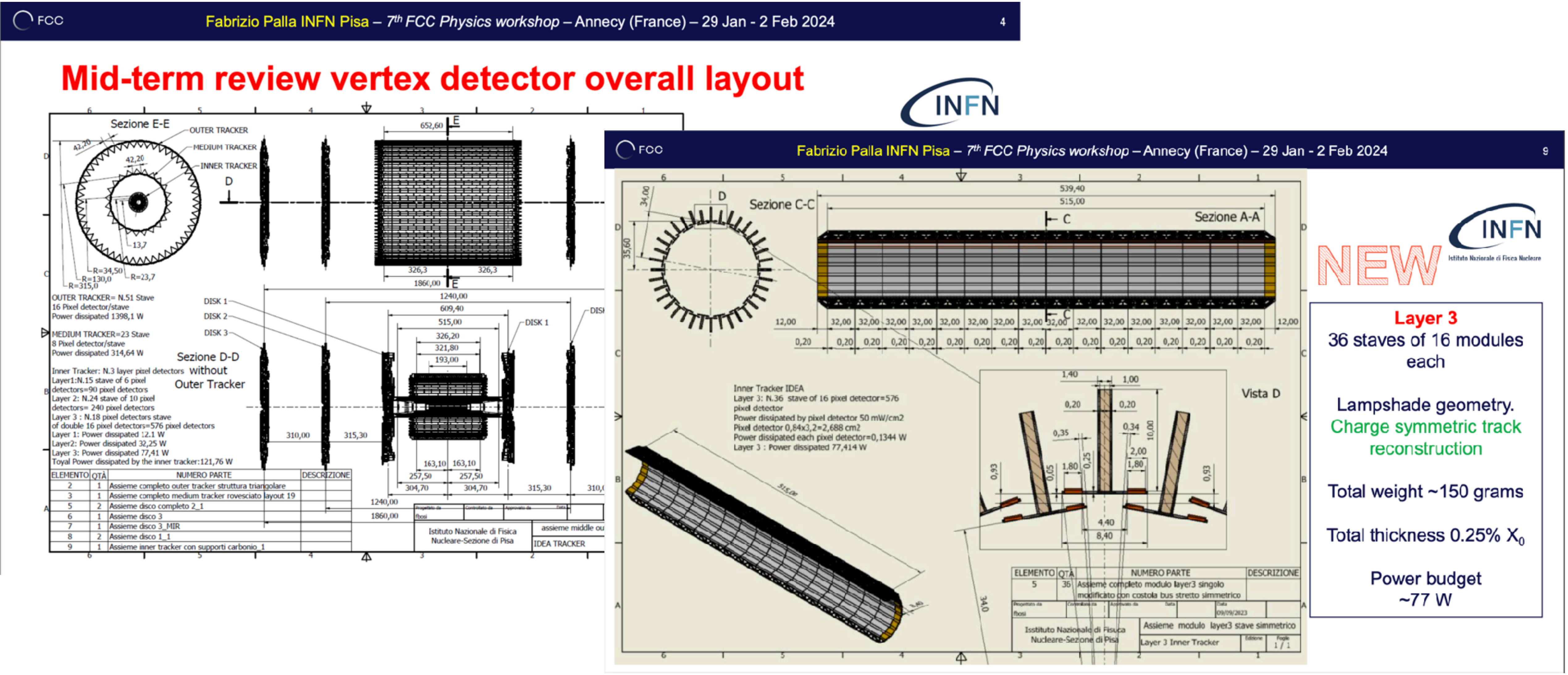
P. Giacomelli: now **baseline for IDEA**

Full-detector full simulation actively prepared
- stand-alone G4 for calo plus tracks to start PFLOW
- DELPHES (fast-sim) for full-event and physics studies



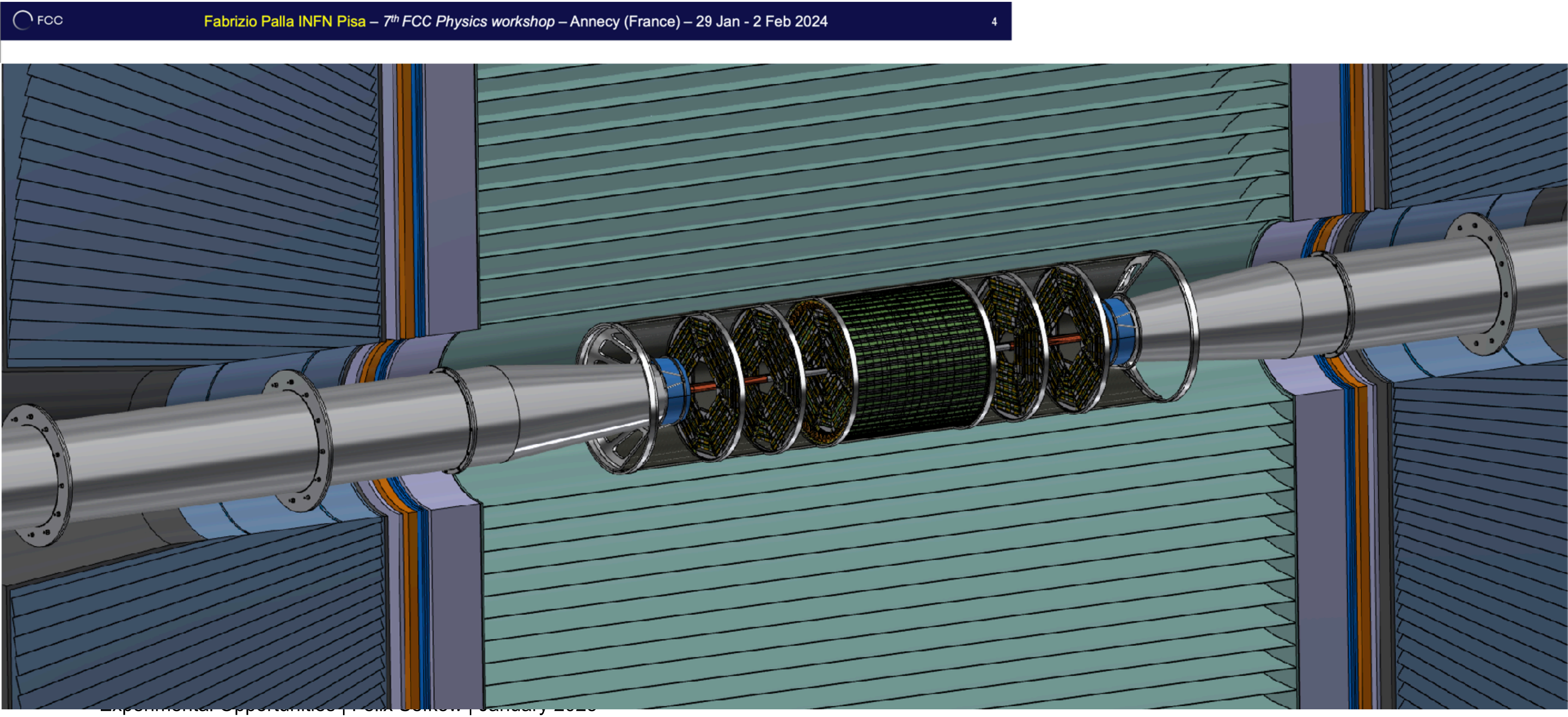
Vertex Detector & Interaction Region

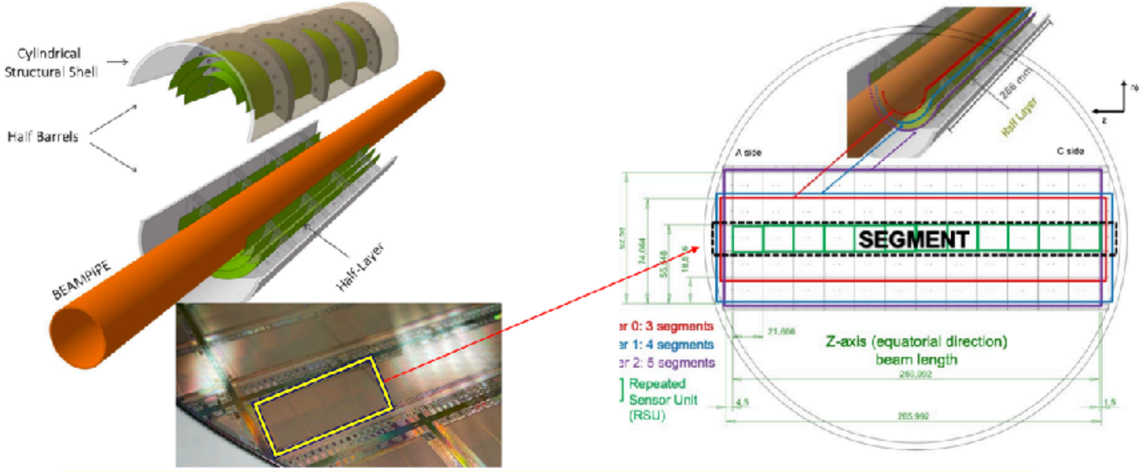
Detailed Engineering



Vertex Detector & Interaction Region

Detailed Engineering



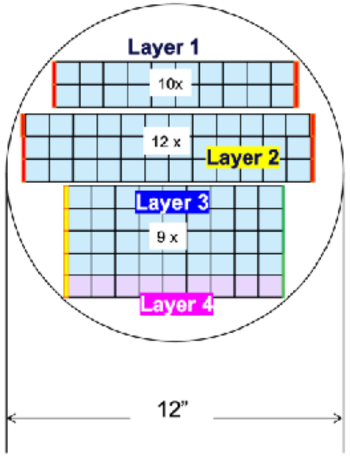


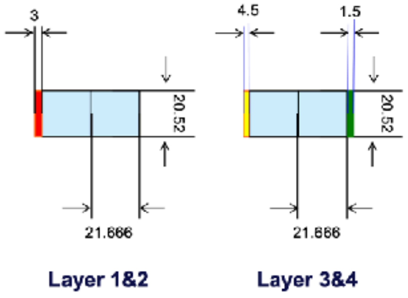
Proposed layout using an ALICE ITS3 inspired design

(~0.05 % X/X_0 material budget per layer – 5 times less than the Mid-Term one)

*After fruitful discussions with **C. Gargiulo, A. Junique, G. Aglieri Rinella, W. Snoeys***

Same reticle for all layers





Layer	Radius (mm)
1	13.7
2	20.23
3	26.76
4	33.3

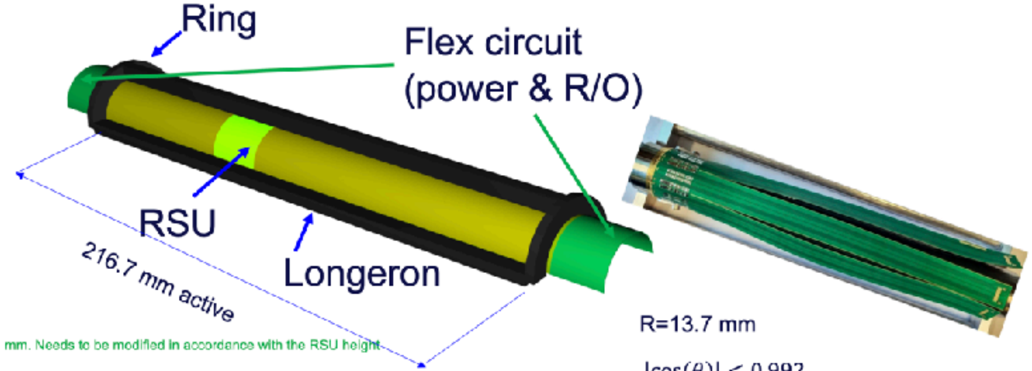
	Power density [mW cm^{-2}] Expected 25 °C	Max 25 °C	Max 45 °C
Left End Cap (LEC)		791	
Active area (RSU)	28	44	62
Pixel matrix	15	32	51
Biasing	168	168	168
Readout peripheries	432	457	496
Data backbone	719	719	719

Power dissipation in ITS3
(not necessarily the same for FCC-ee)

- RSU~ 50 mW/cm² (depends on Temp.)
- LEC ~ 700 mW/cm²

Layer 1

- 10 RSU + 2 EC (same size) long per half layer
  - Readout and power from both sides (reduces transmission off-detector and limits power dissipation in the endcaps)
- Leaves two ~2 mm* insensitive gaps in R-phi, to account for assembly tolerances

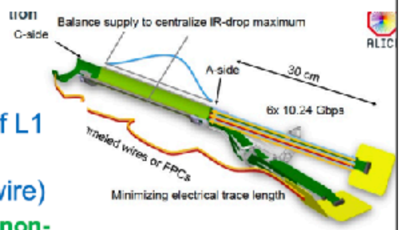


R=13.7 mm

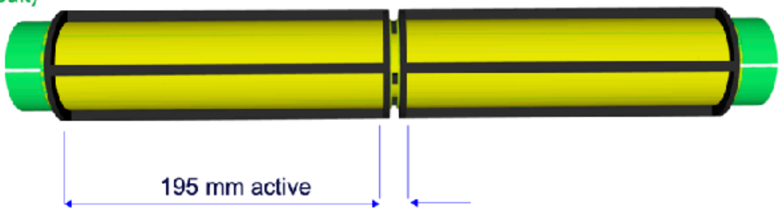
$|\cos(\theta)| < 0.992$

* In ITS3 is 1 mm. Needs to be modified in accordance with the RSU height

Layers 3 & 4



- Four "quarter" layers of 9 RSU to allow same angular coverage of L1
- Layer 4 has the same length of Layer 3 but higher radius
- Quarter readout only on one side. The other side only for power (wire)
  - Gap of ~ 2xO(10 mm) at z=0: can be mitigated by having **quarters with non-symmetric layout** (e.g. left quarter with 10 RSU and right one with 8 RSU, and swapped for L4) **or with (slightly) twisted wrap** (complicated wire bonding of the flex circuit)



Layer 3
R=26.76 mm
$|\cos(\theta)| < 0.992$

Layer 4
R=33.3 mm
$|\cos(\theta)| < 0.987$

2x few mm

Estimate Distortions in a TPC

Full simulation study in ILD

Combine ILD and CLD elements

- ILD geometry and TPC
- CLD: MDI and inner Si tracker
- lower B field

Primary ions (no backflow)

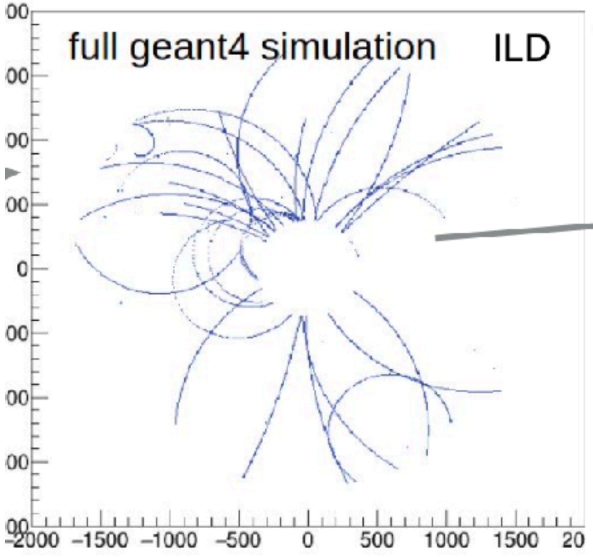
- 1e10 from physics,
- 1e12 from background

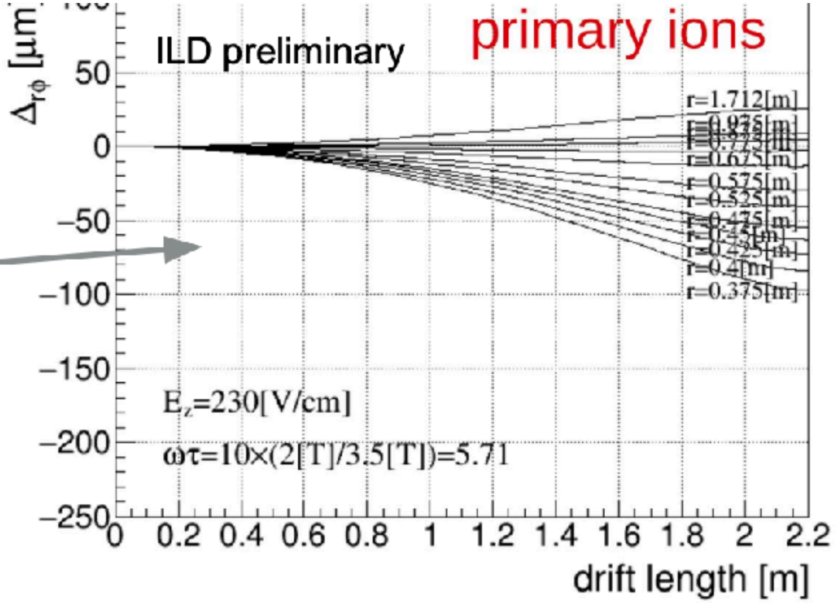
Distortions up to 20 mm

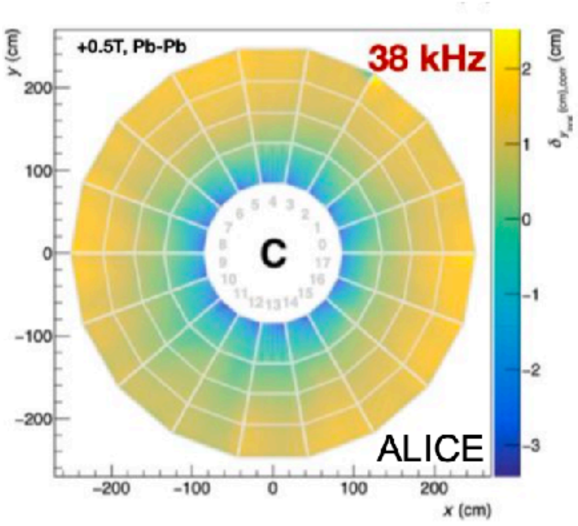
- comparable to ALICE TPC

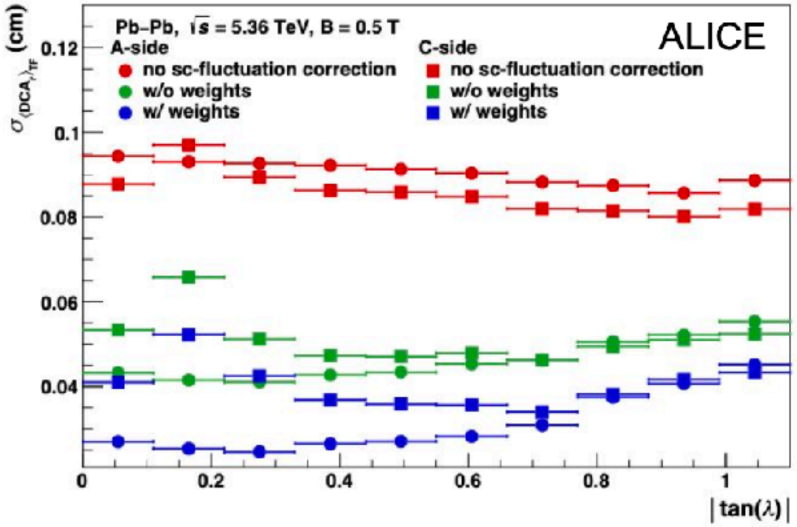
ALICE: data-driven corrections

- comparable to ALICE TPC
- residuals after correction up to 0.6mm
- work ongoing









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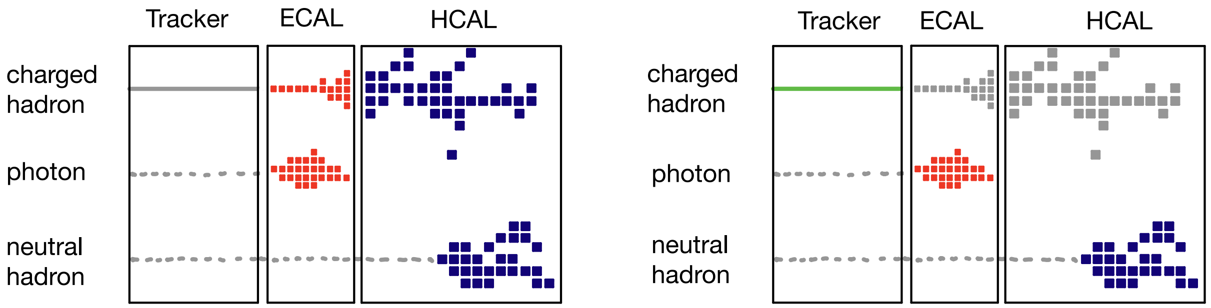
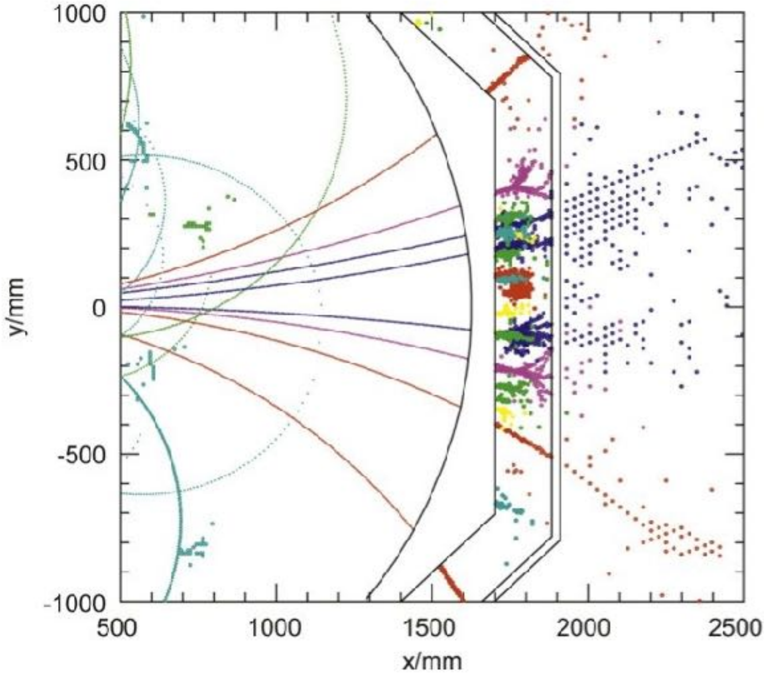
Particle Flow and High Granularity

Particle Flow Principle

CALICE and Followers





Typical jet: 60% charged, 10% neutral hadrons

- use tracker where possible
- applied in ATLAS and CMS

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

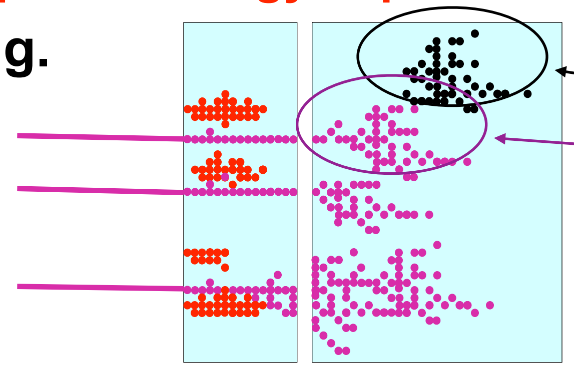
- requires excellent imaging and good energy performance
- 10’s or 100’s of millions of channel

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.

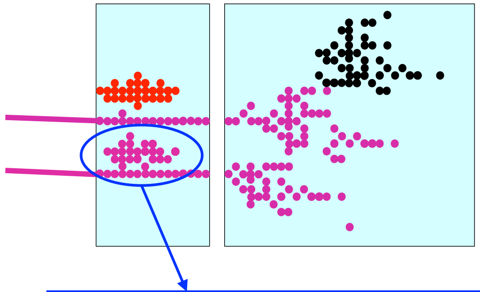


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

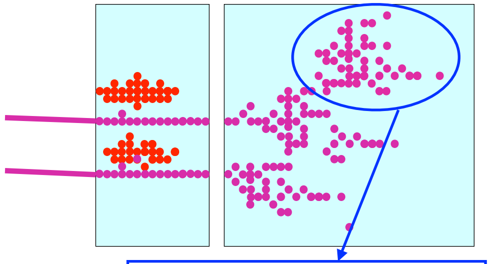
Three types of confusion:

i) Photons



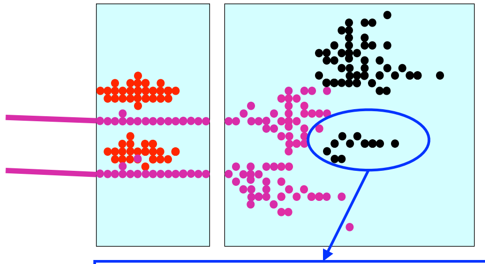
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

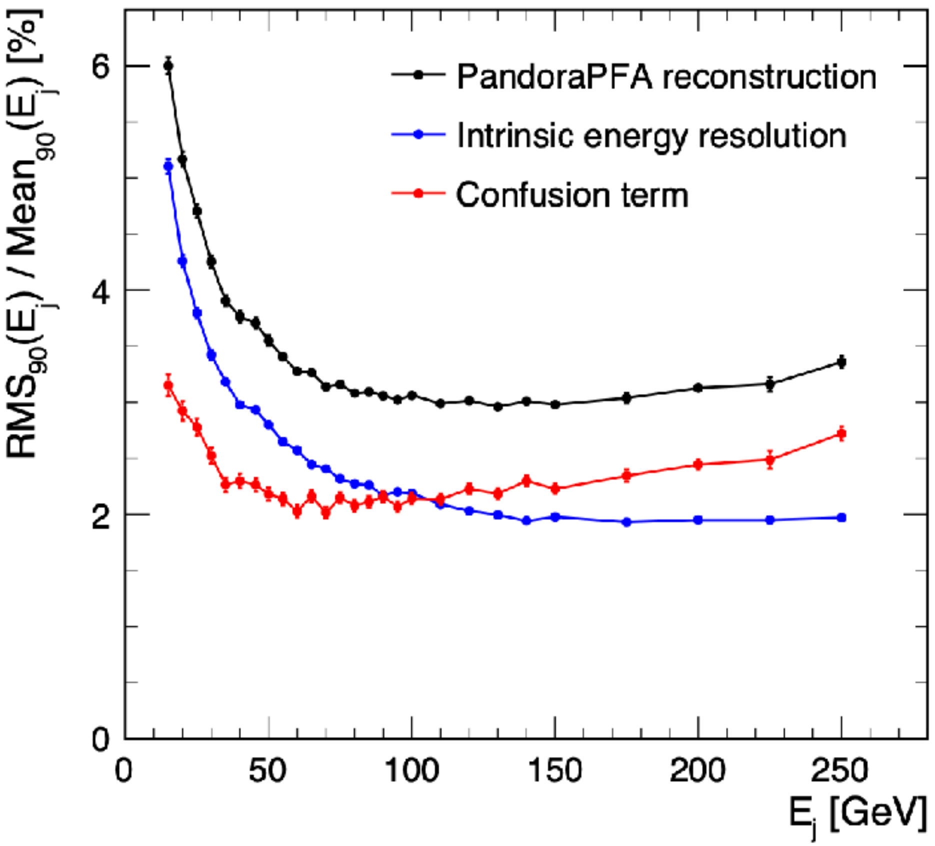
iii) Fragments

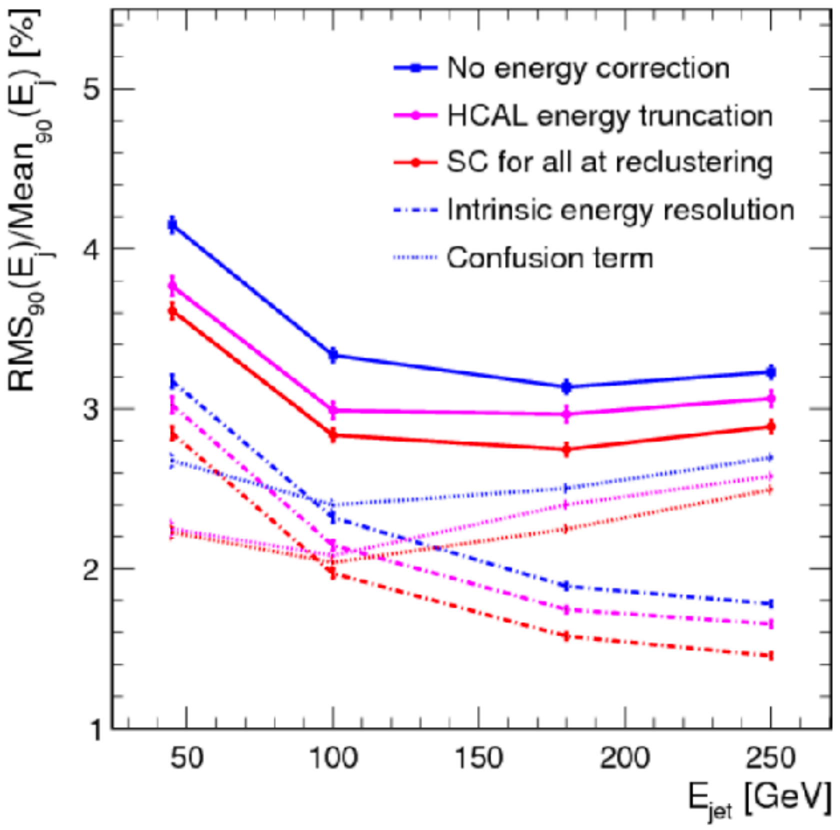


Reconstruct fragment as separate neutral hadron

Particle Flow Performance

Realistically





Need to disentangle energy depositions, using topology **and** energy

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

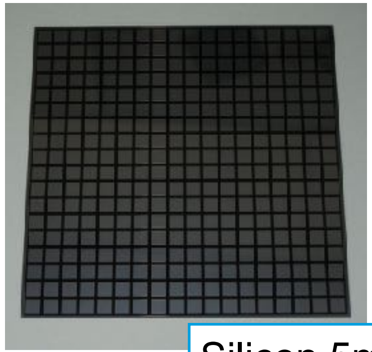
- cost of sandwich calorimeters scales with active area rather than channel count

Benefits beyond particle flow

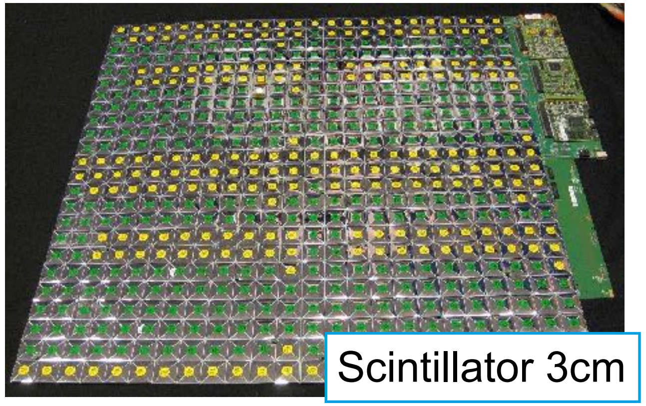
- imaging for particle ID
- software compensation
- pile-up rejection

Signal over noise for small cells

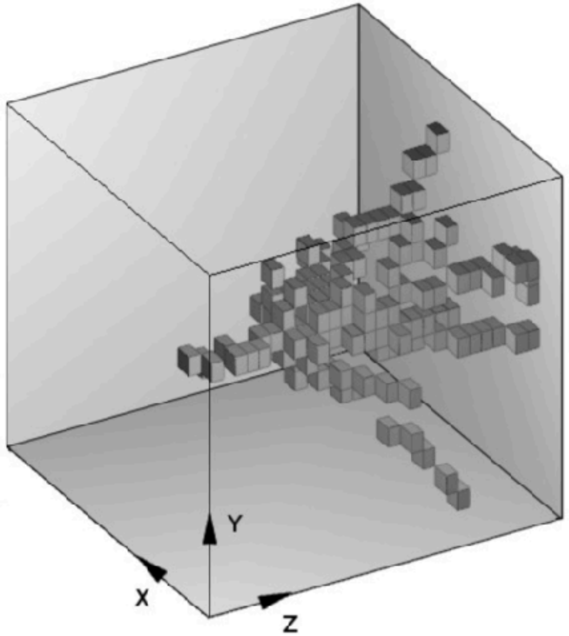
- lower noise e.g. for silicon or LAr
- more signal from scintillators

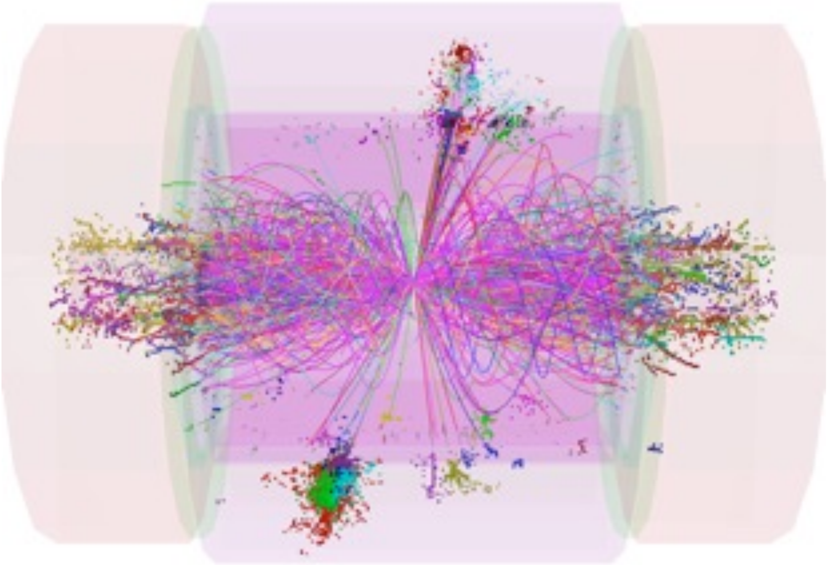


Silicon 5mm



Scintillator 3cm





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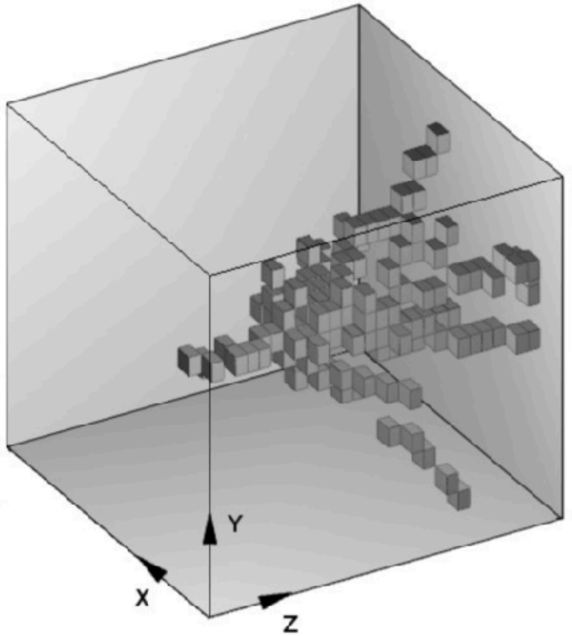
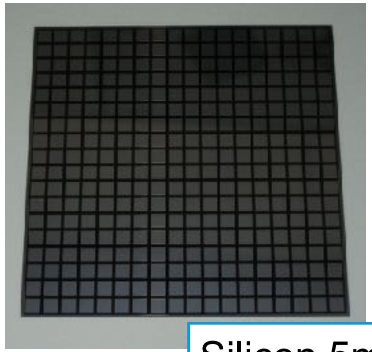
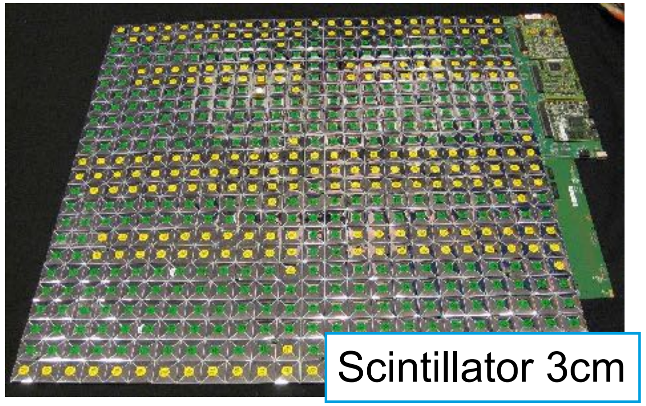




Silicon 5mm



Scintillator 3cm