Calorimeter R&D for Higgs Factories - Inspiration for LHC Upgrades

Frank Simon

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Karlsruher Institut für Technologie

KSETA Plenary Workshop, March 2023

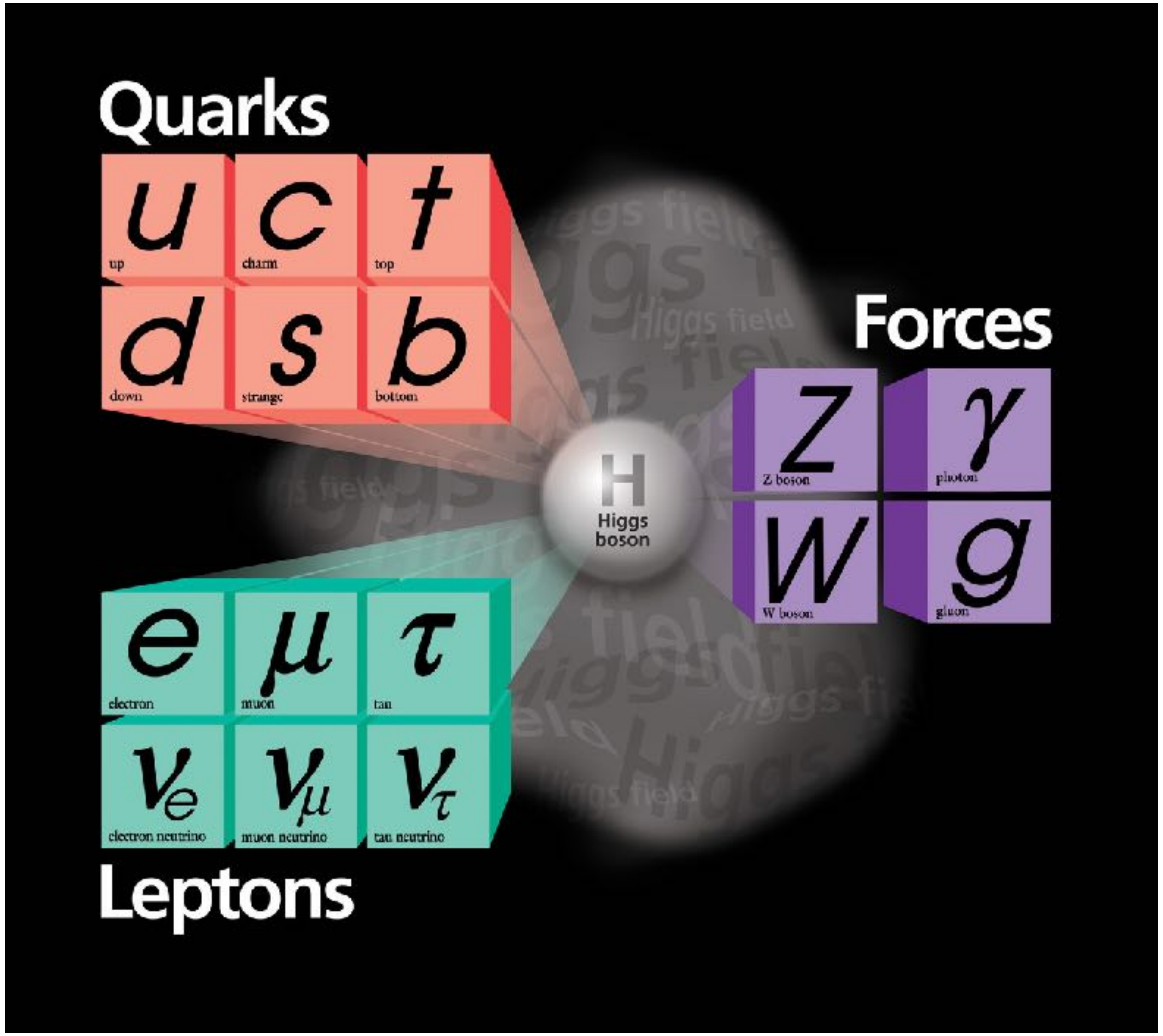
Outline

- Higgs Factories
- Event Reconstruction in Future Experiments
- Highly Granular Calorimeters - from a hadronic perspective
- Highly Granular Calorimeters for LHC
- Summary

Higgs Factories

The next large Collider

- Starting from what we know today:



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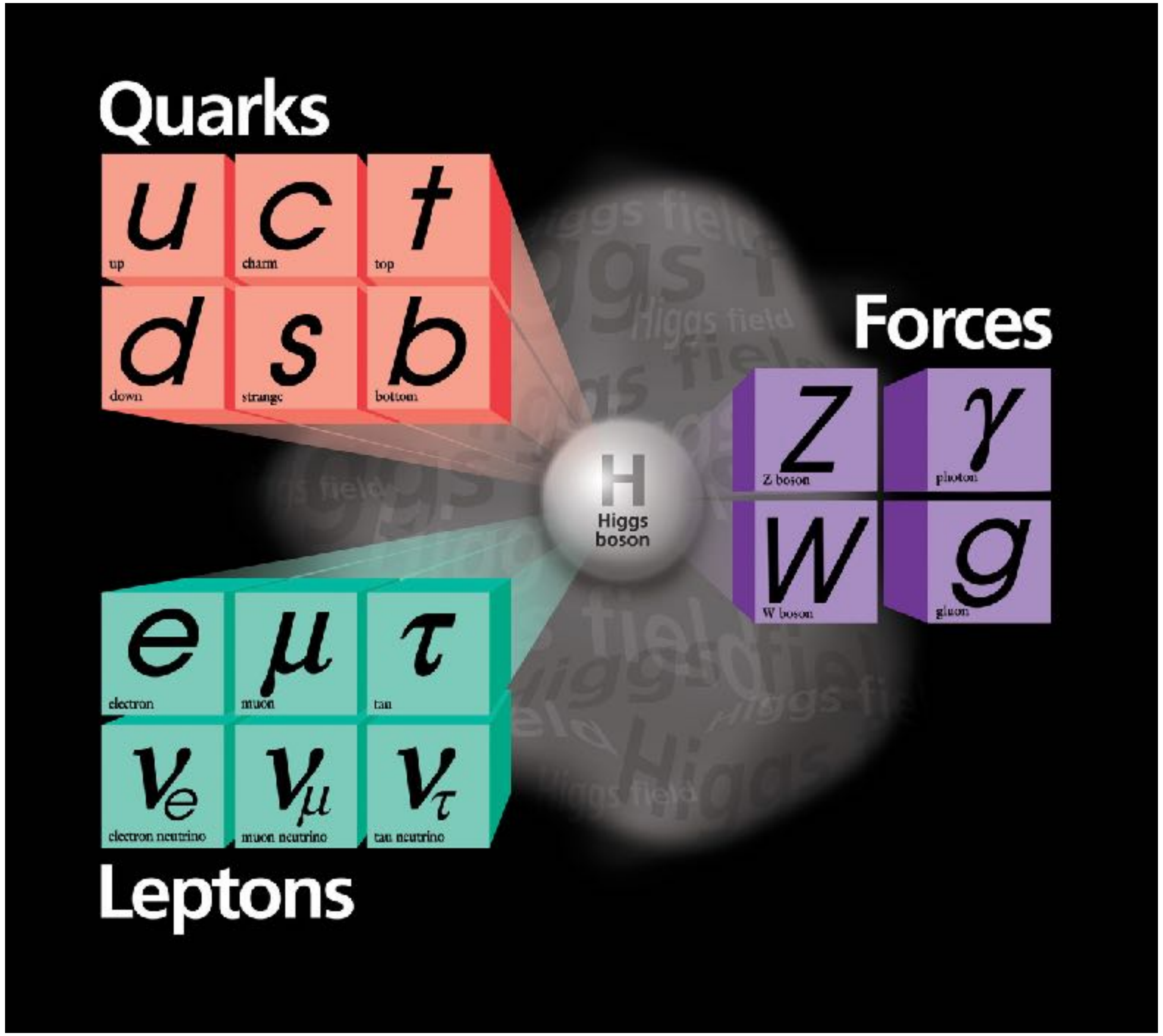

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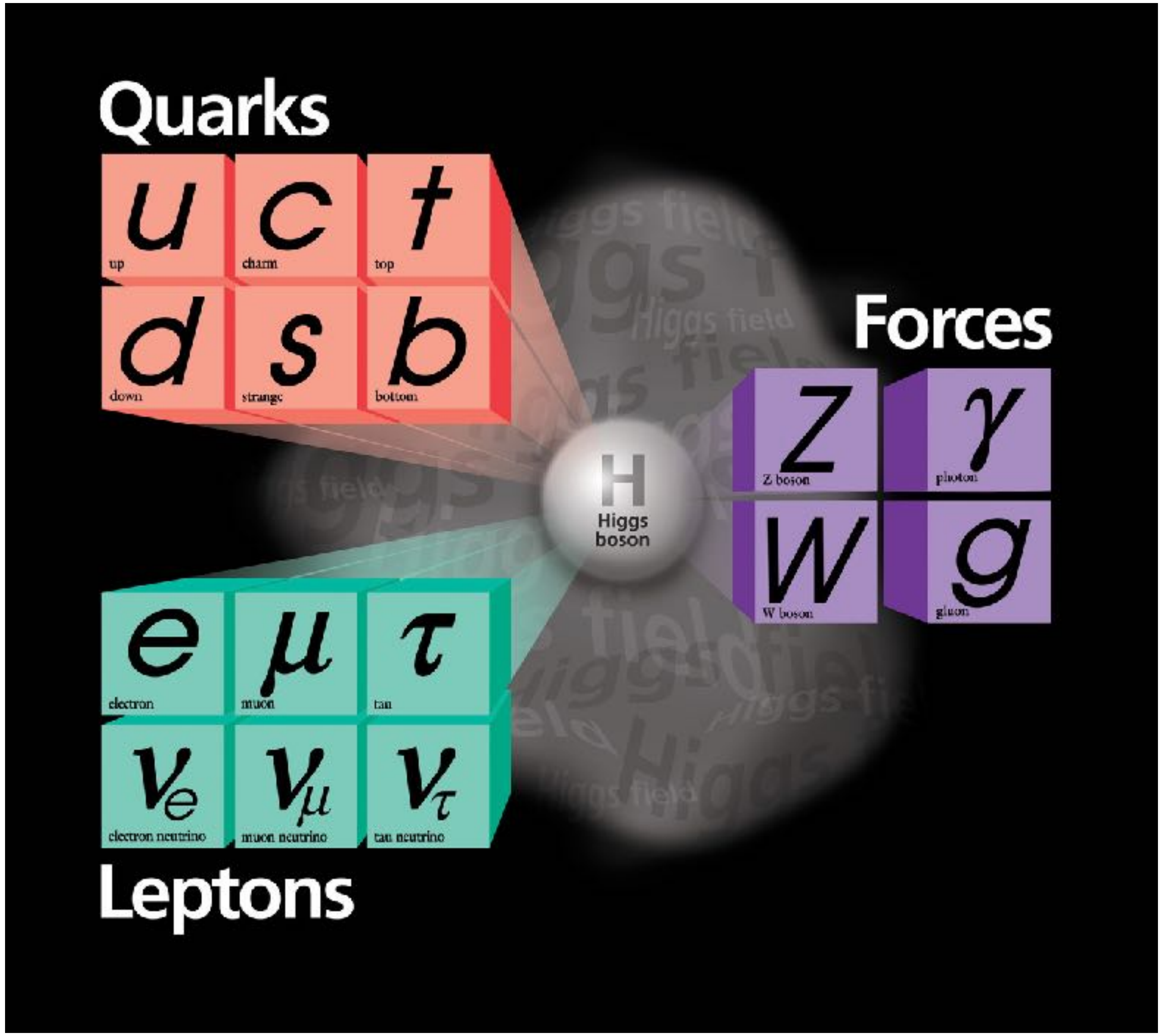

Where do we go next?

The way charted by the European Strategy:

Precision!

The Higgs Boson

model-independent study
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The Top Quark

a precise measurement of its properties.
A possible window to new physics due to its high mass!

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push down the uncertainties on all electroweak measurements to push the SM to (hopefully beyond) its breaking point

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New Particles

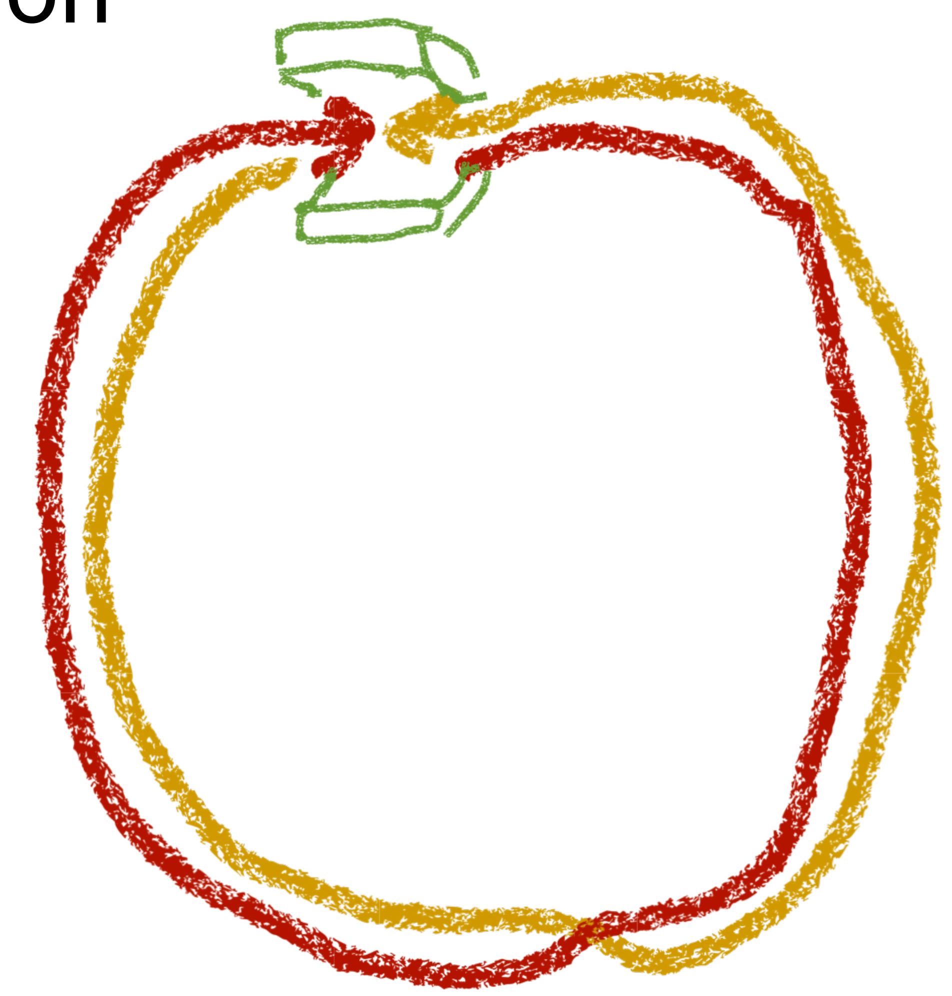
searches for weakly coupled new particles with high luminosity / high energy in a clean environment

Higgs Factories

Collider types

Circular Colliders:

Collision of two particle beams on circular orbits in opposite direction



Re-use of non-collided particles in future turns, acceleration can proceed over many revolutions. Need for bending magnets to keep particles on track.

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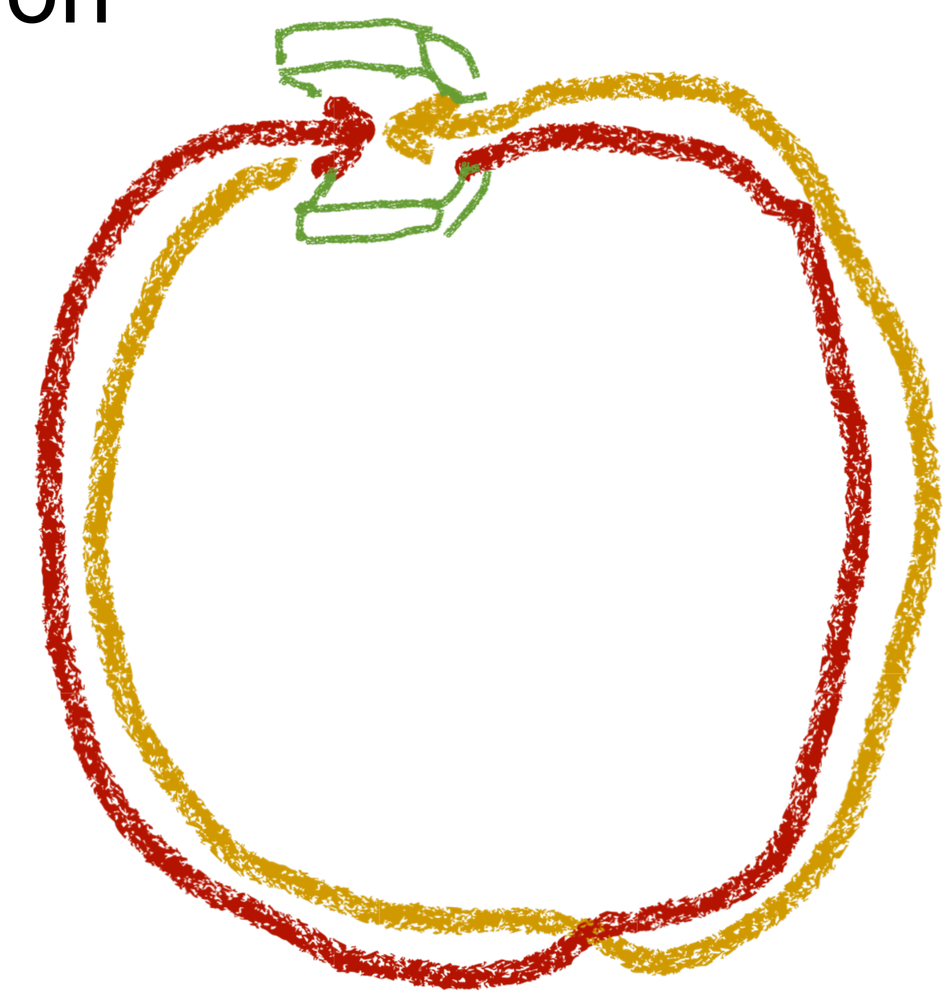

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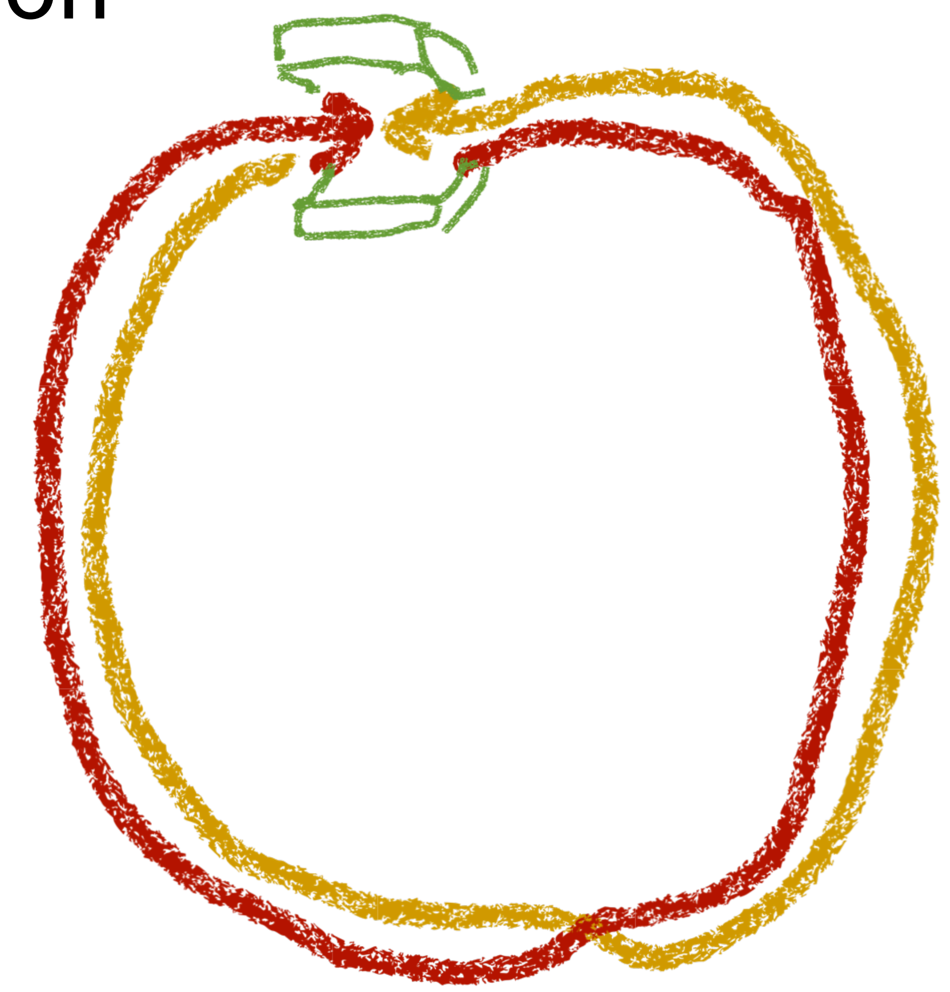

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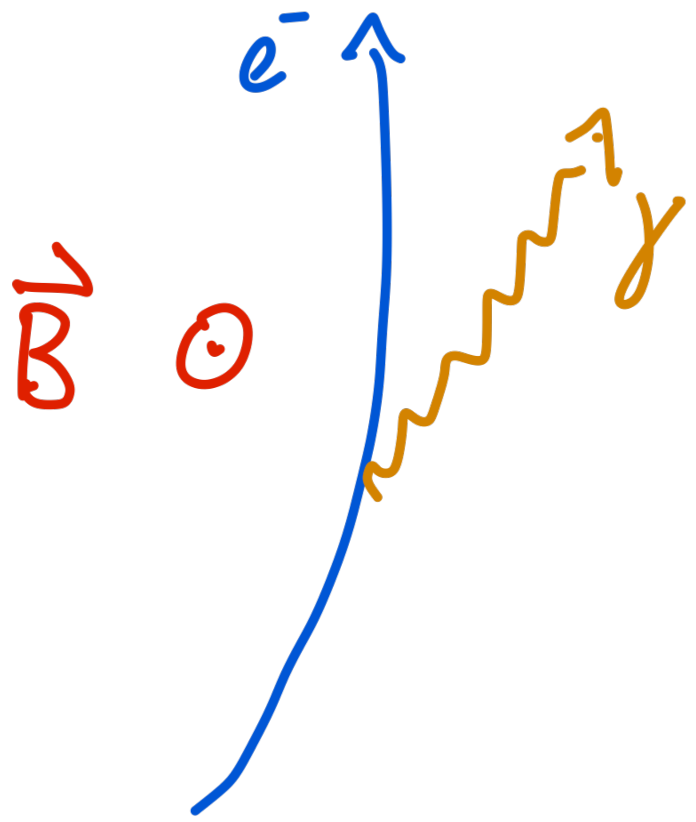

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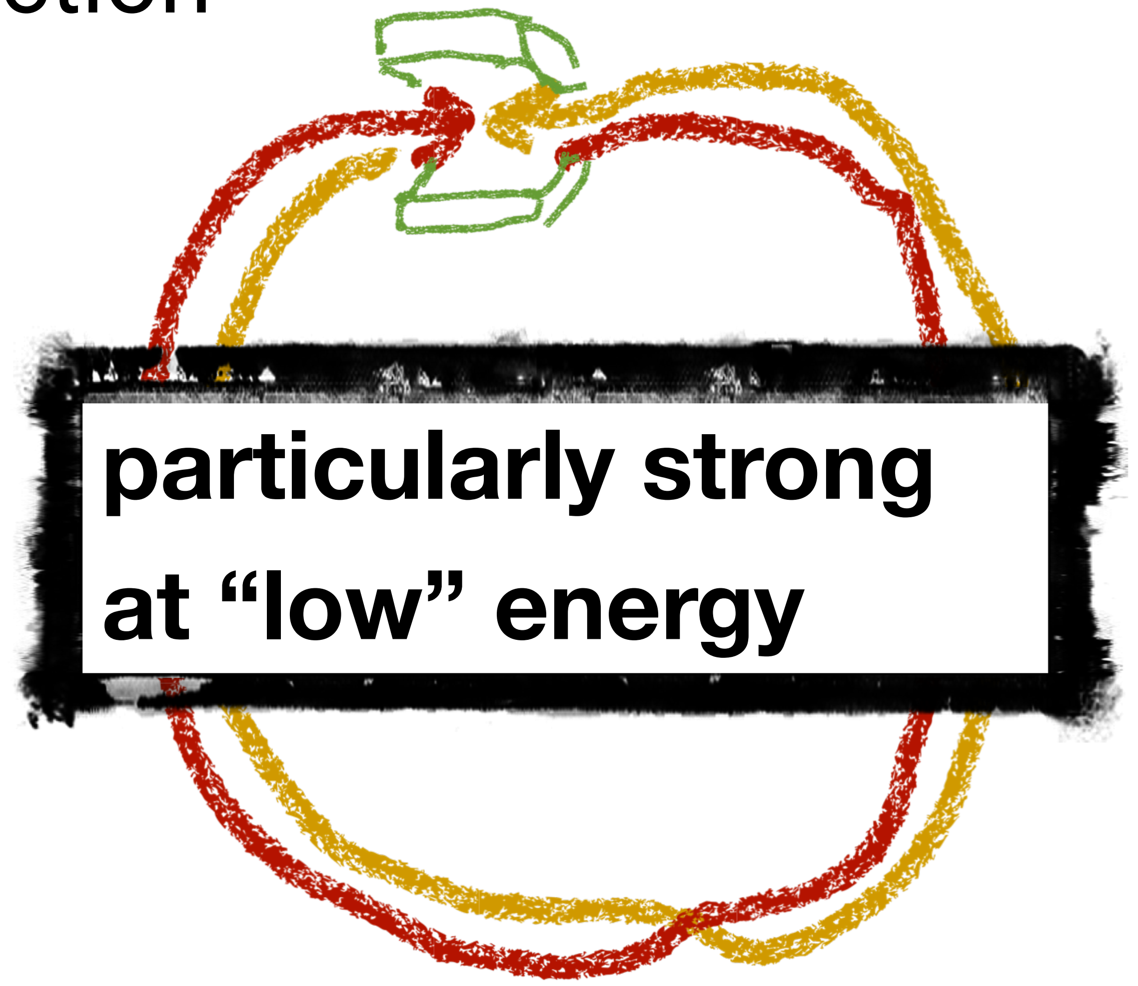

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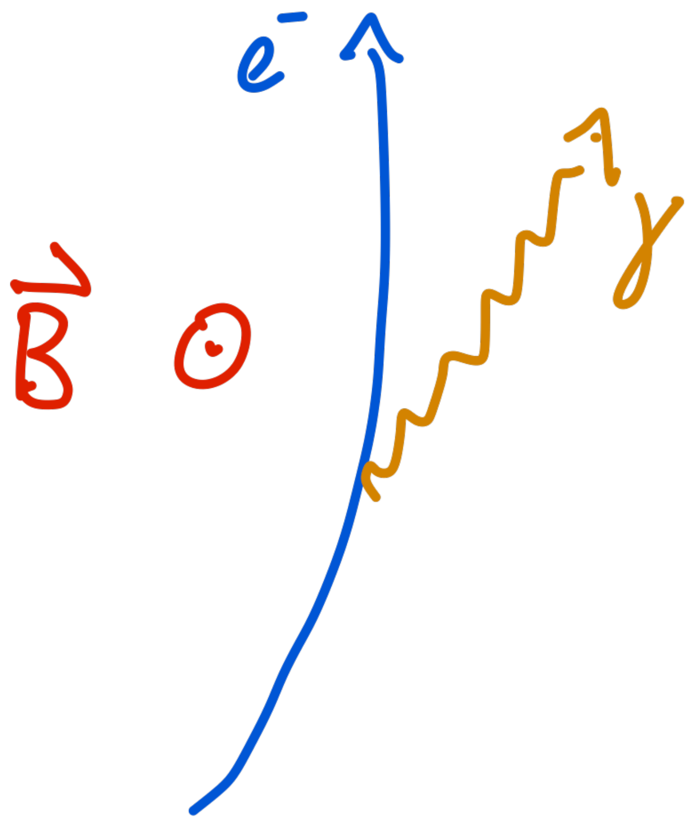

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Event Reconstruction in Future Experiments

Ideas in broad strokes - for Higgs Factories

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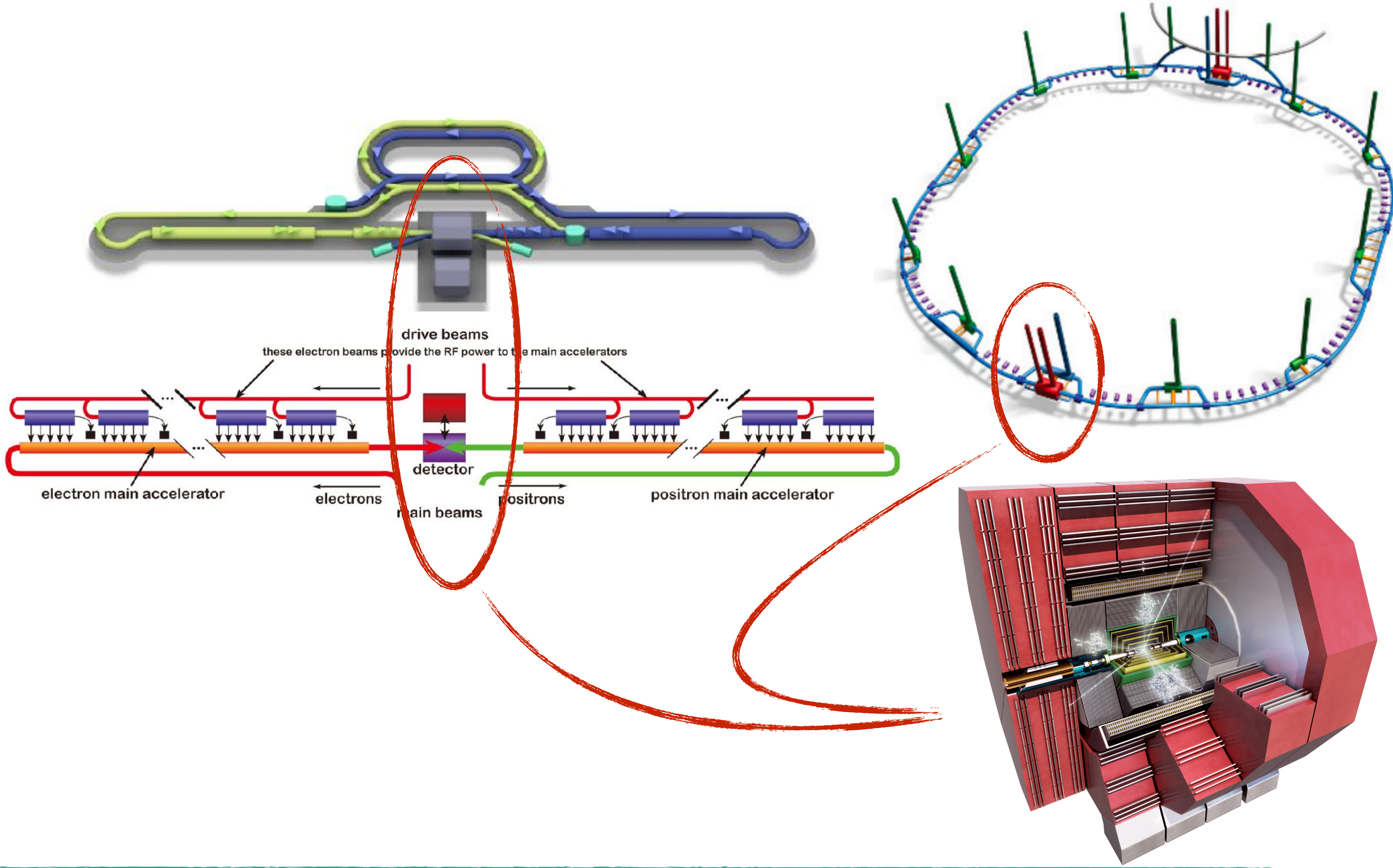
Japan:

- **ILC**: 250 GeV (500 GeV - 1 TeV with upgrade)

CERN Future:

- **FCCee**: Circular collider, 90 GeV - 365 GeV
- **CLIC**: Staged machine, 380 GeV - 3 TeV



Detector Performance Requirements

What we should be able to do

- Typical final states:
  Involves H, W, Z - all decay predominantly into hadrons

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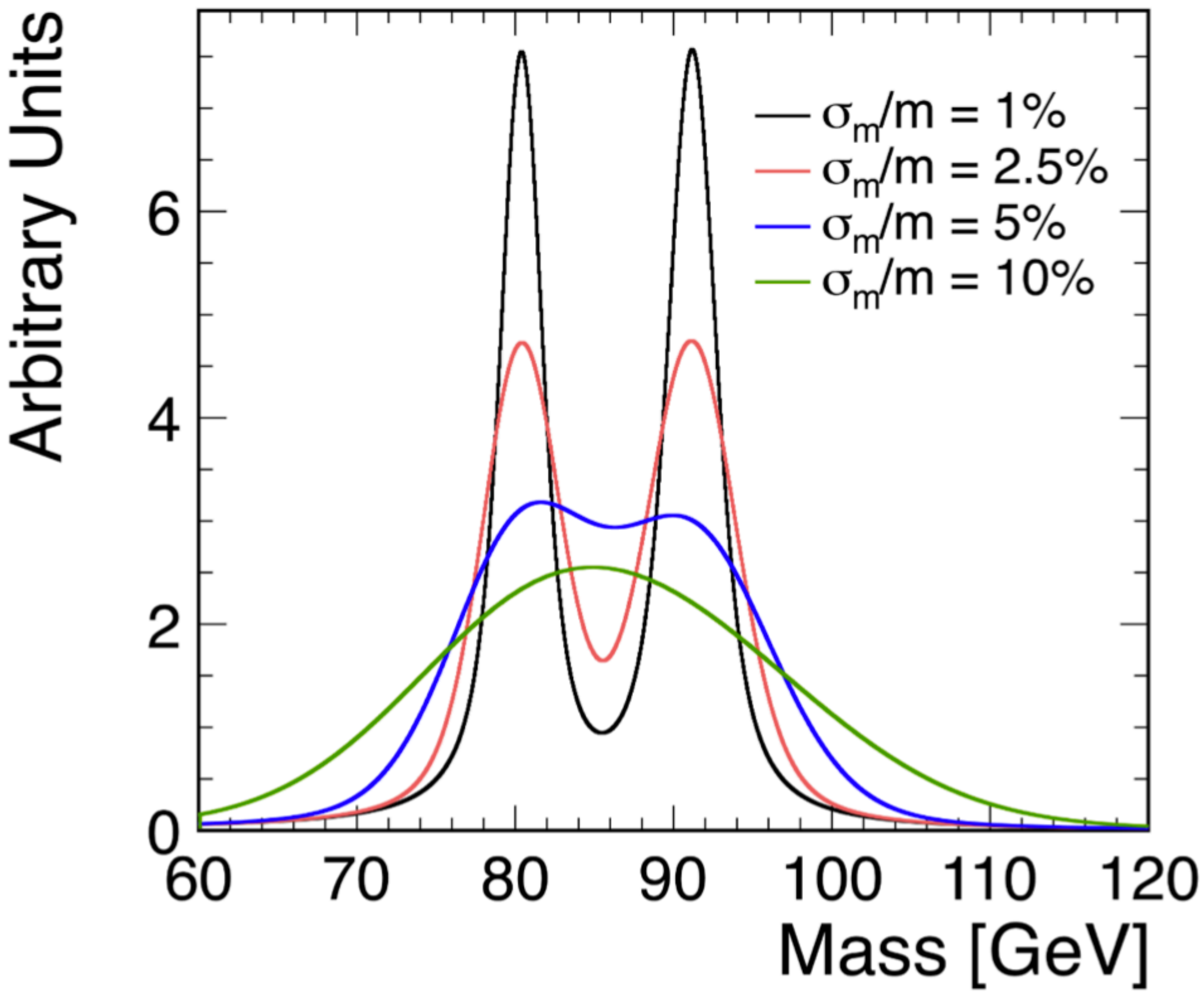
  Need a jet energy resolution of **3%** (- 5%)



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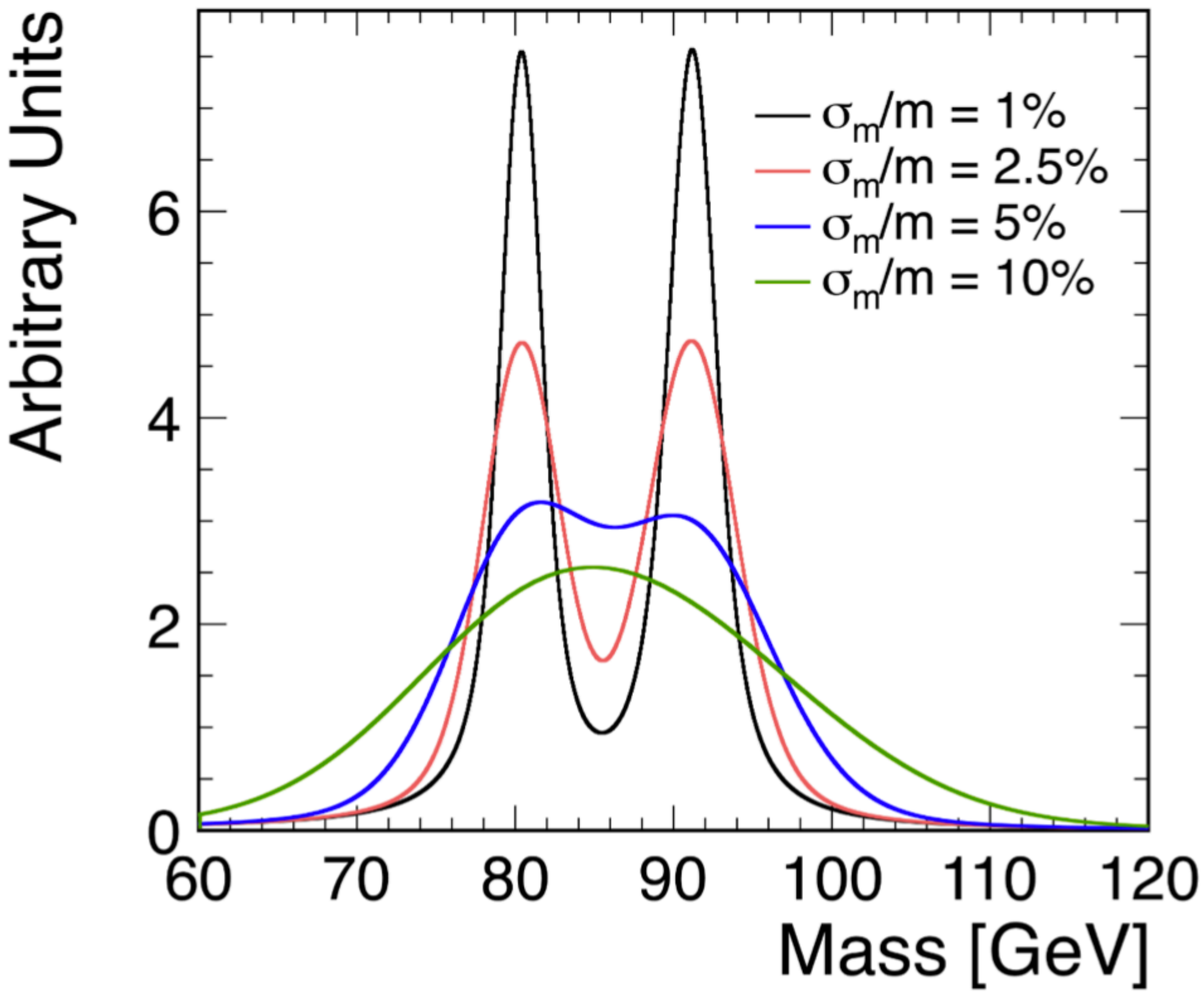
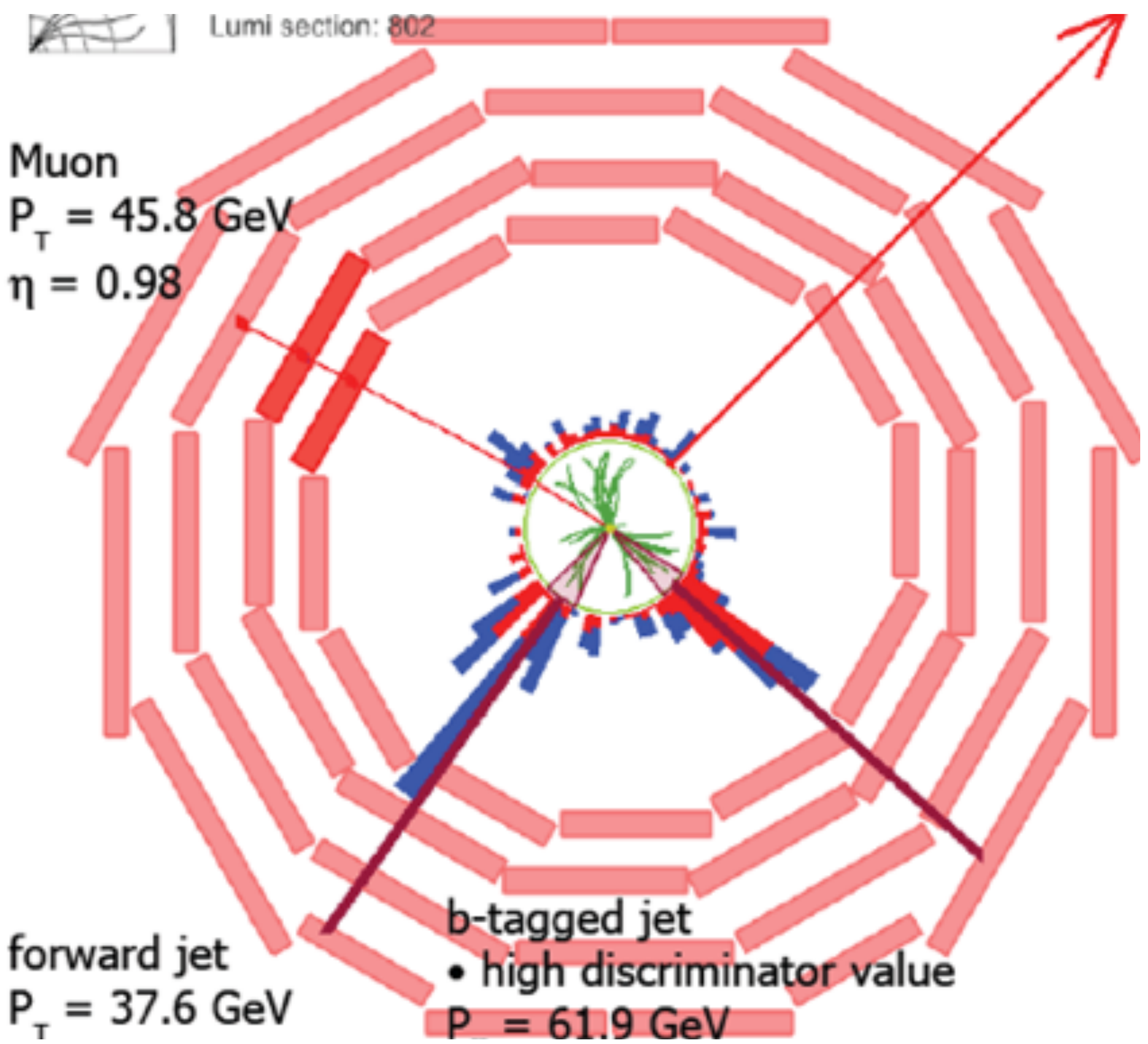
  N.B.: This is *hard!*
  x2 (or more) better than LHC experiments
  corresponds to ~ 30%/Sqrt(E) or better in relevant energy range

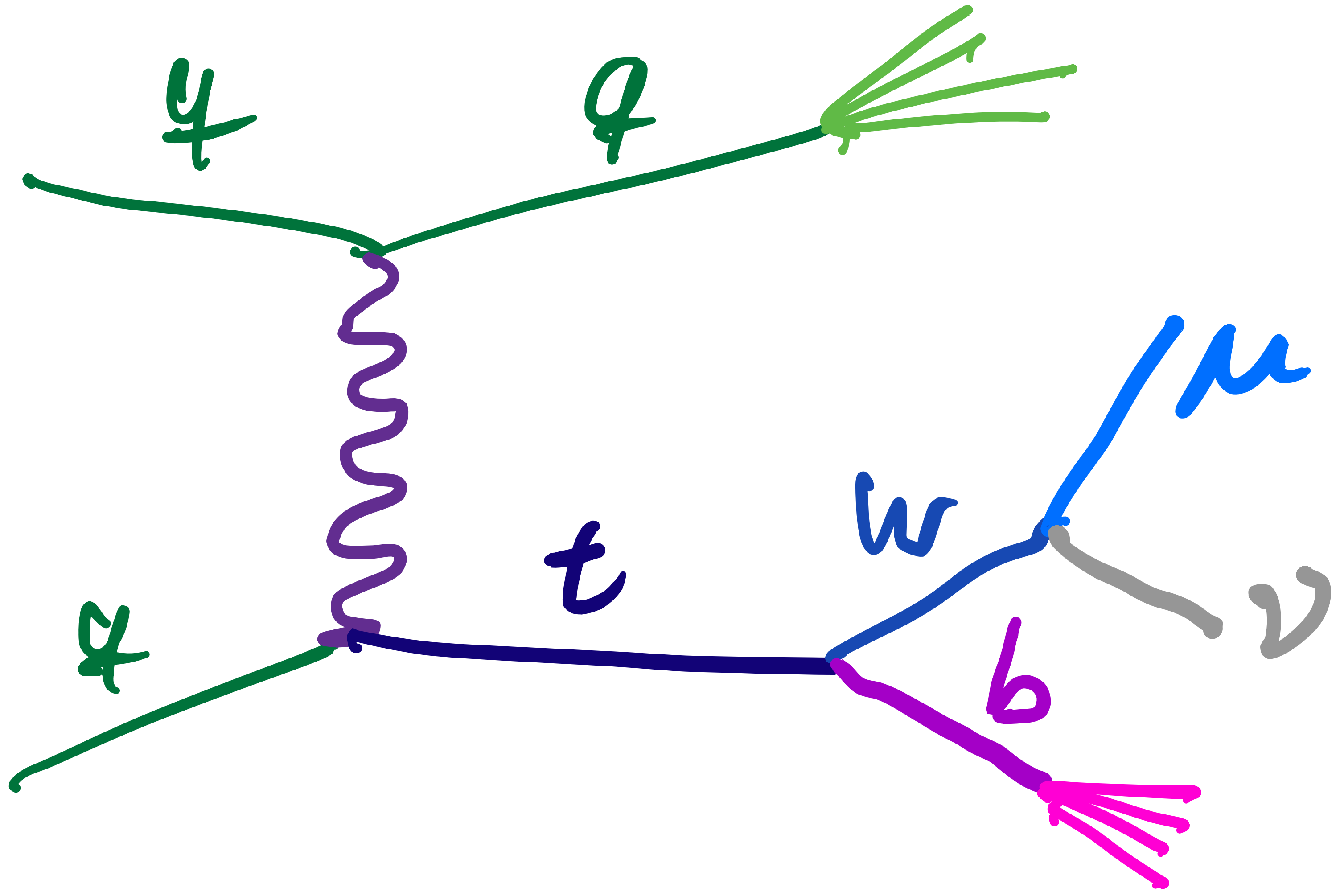


Event Reconstruction at Future Colliders

Dreams…

- For *hadronic* (and all other) final states, we want to solve this problem:





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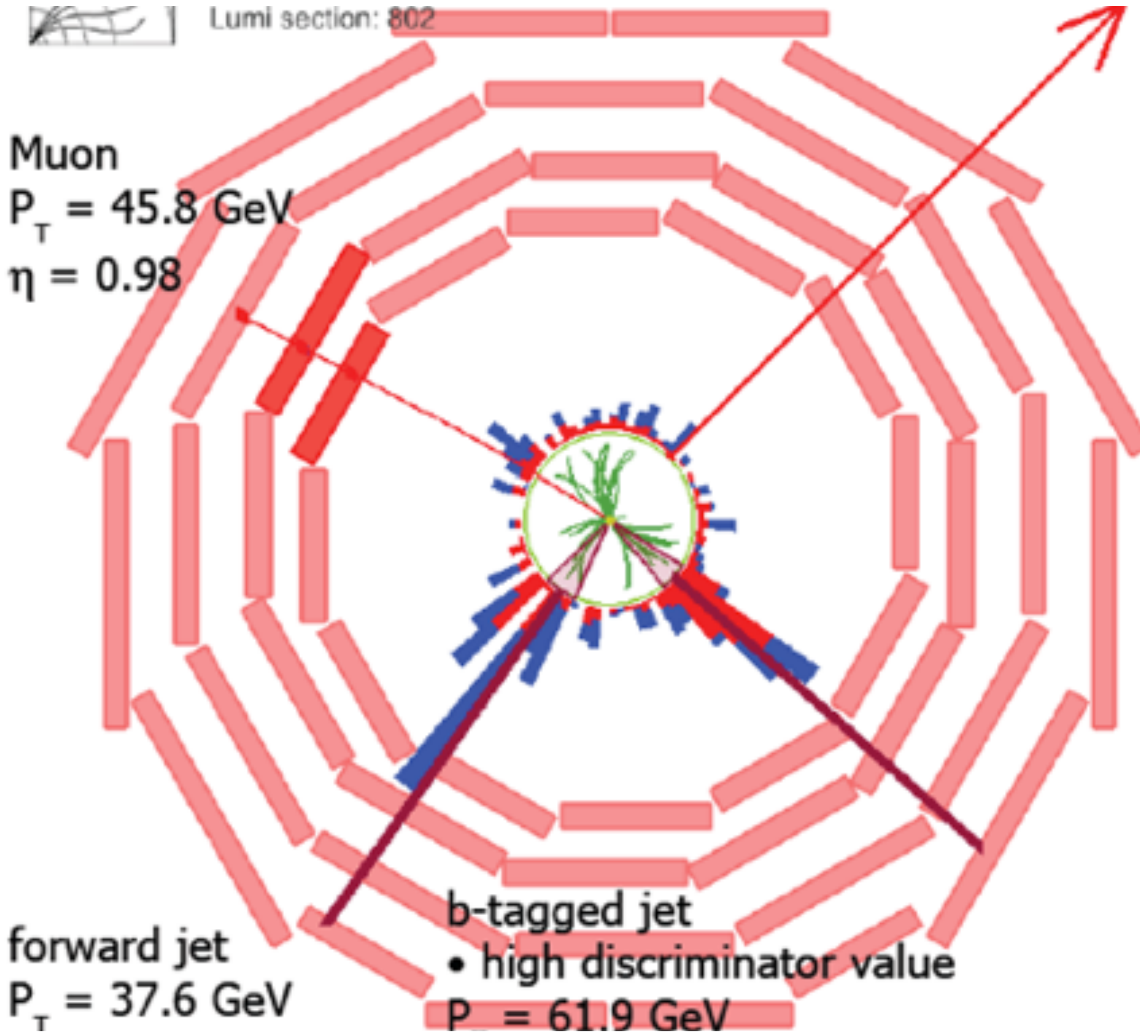
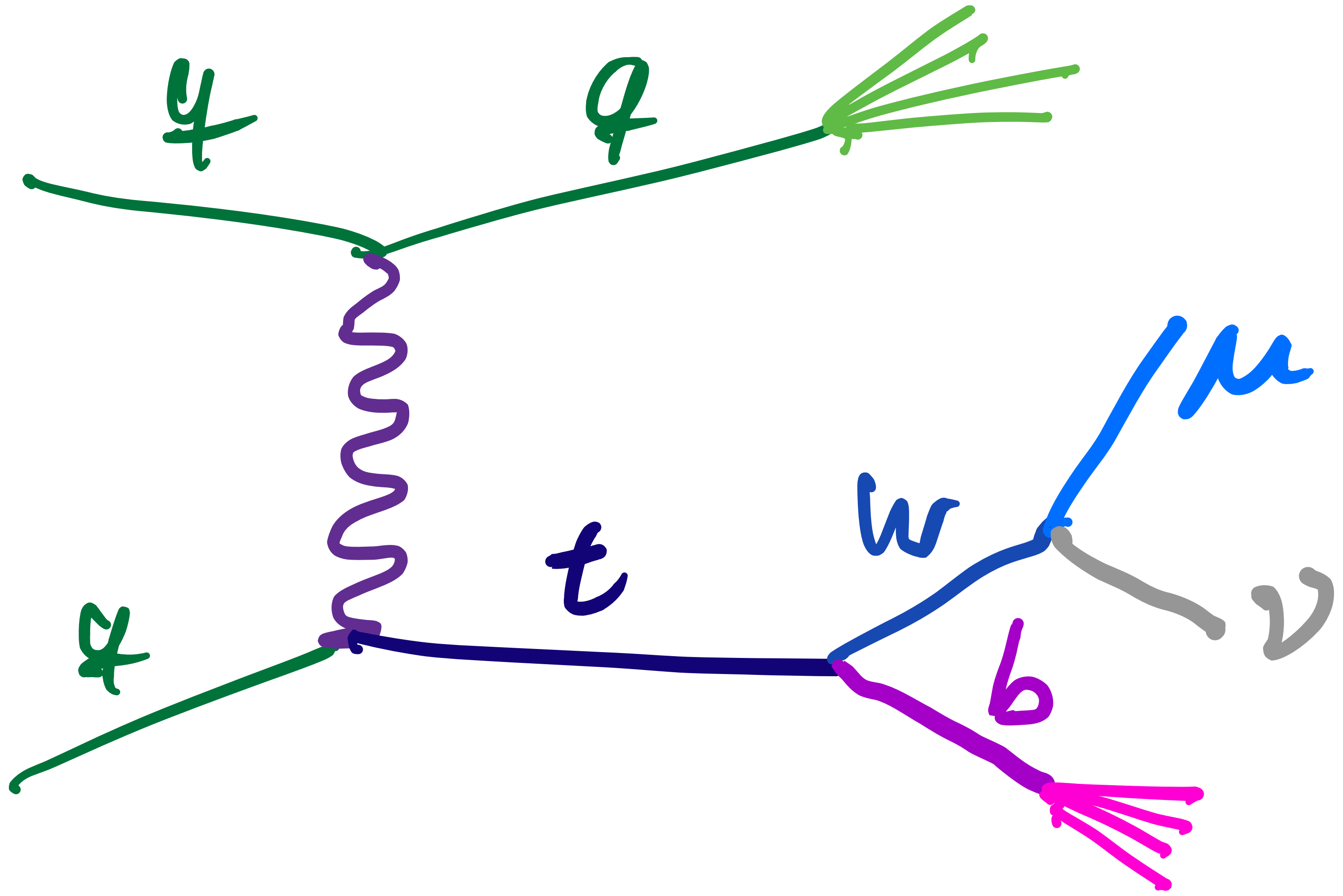
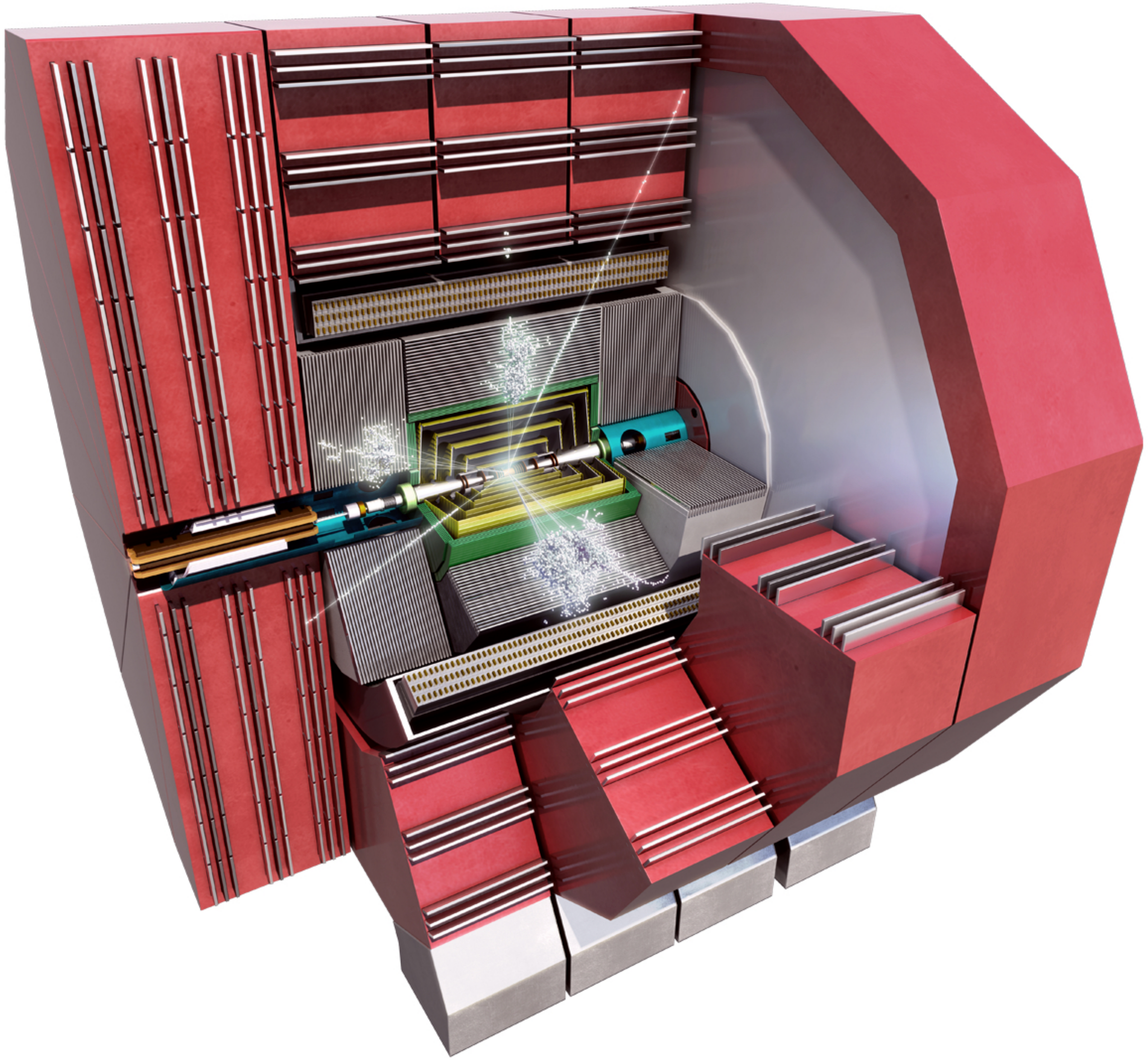




Ideally: reconstruct every single particle in the event -

not just leptons + "cones of energy"



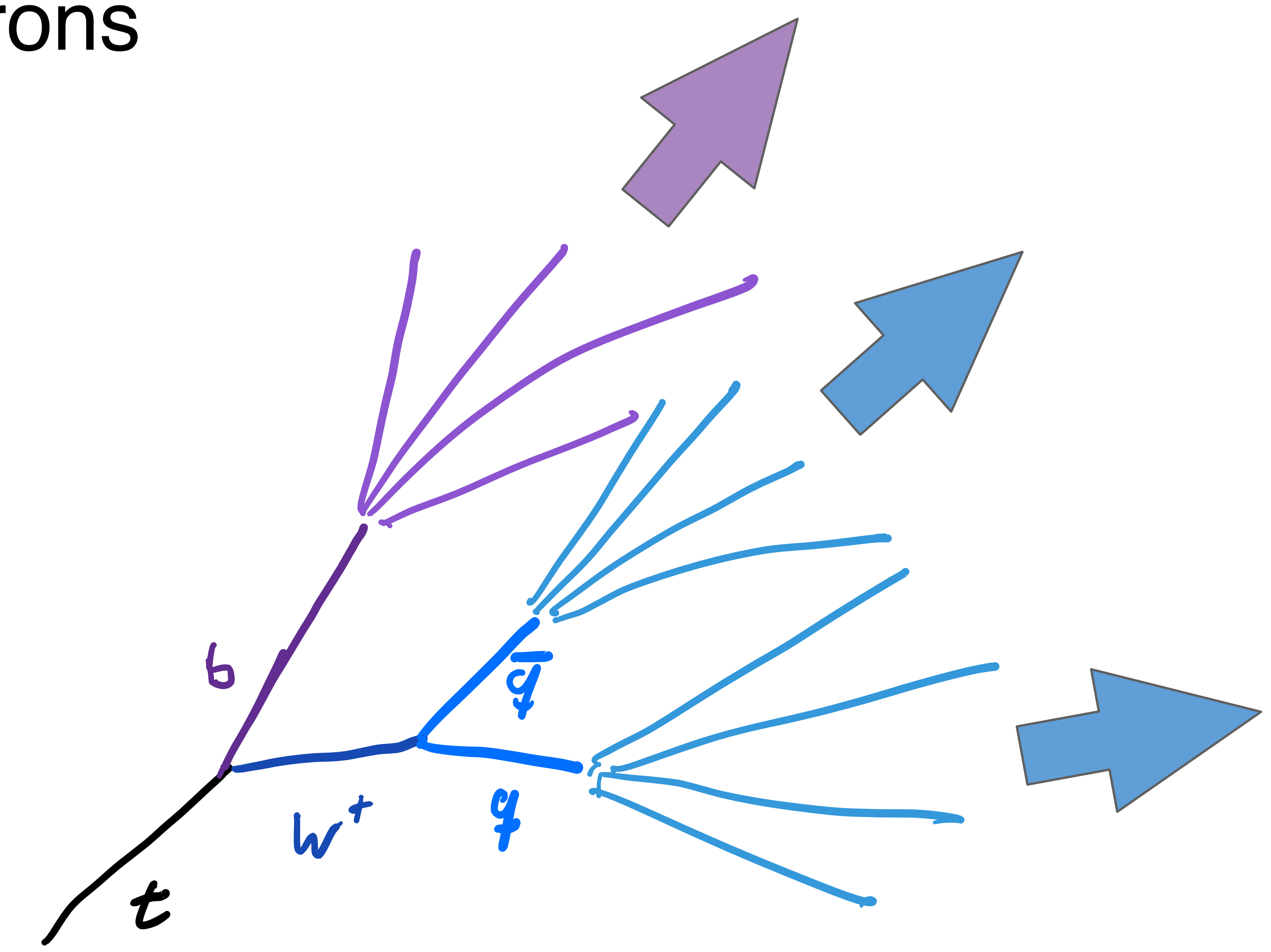
- The hardware to work with: A Collider Detector
  - ***Vertex detectors*** to identify heavy quarks and leptons
  - ***Tracking system*** to measure the momentum of charged particles via curvature in magnetic field
  - ***Calorimeter systems*** to measure energy of neutral and charged particles via total absorption
  - ***Muon system*** to identify muons, improve momentum measurement

Event Reconstruction at Future Colliders

… and Algorithms

- Particles decaying into quarks lead to jets: Multiple hadrons originating from final-state quarks

➯ Parton four-vector only accessible via reconstruction of final hadrons



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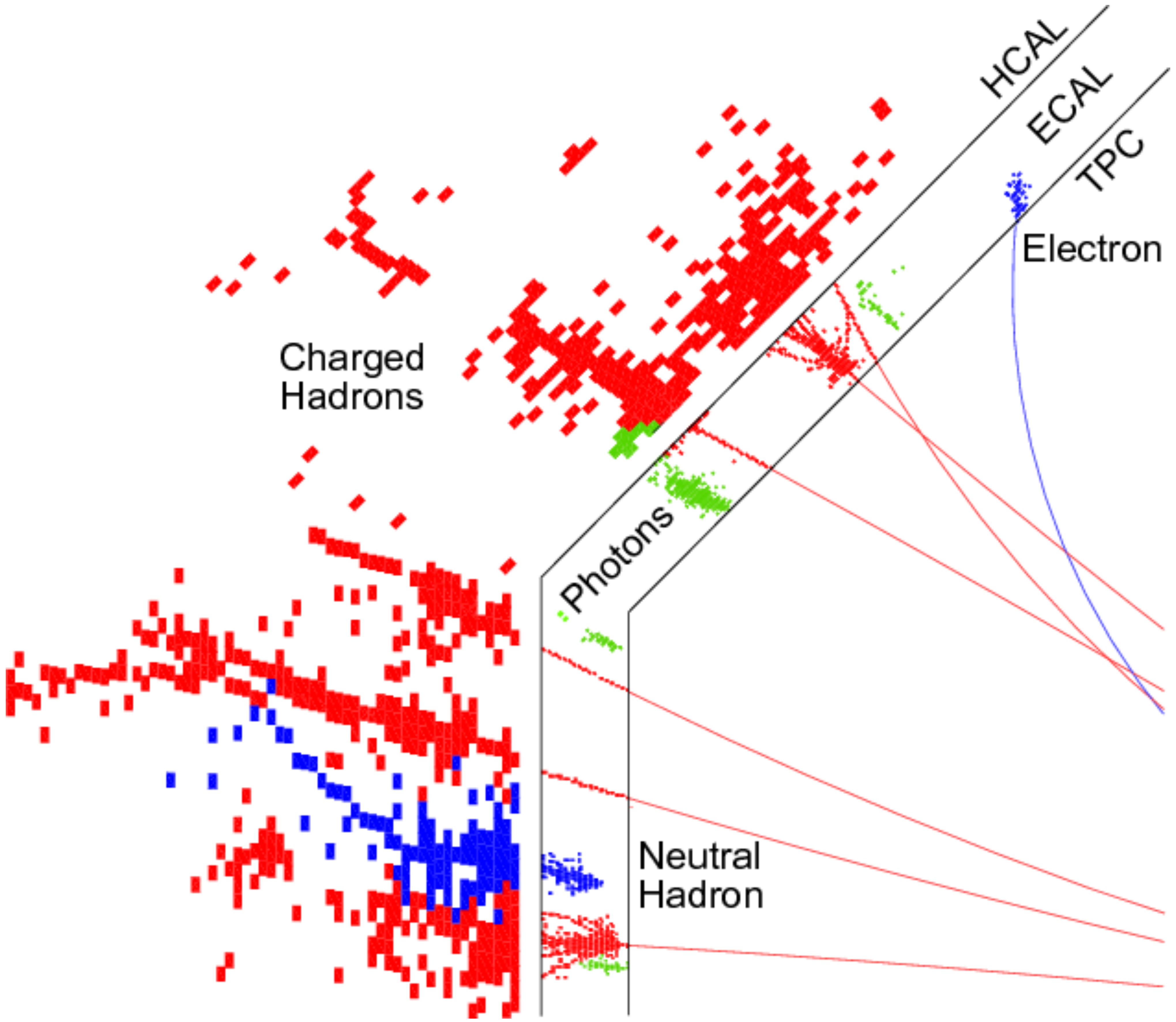
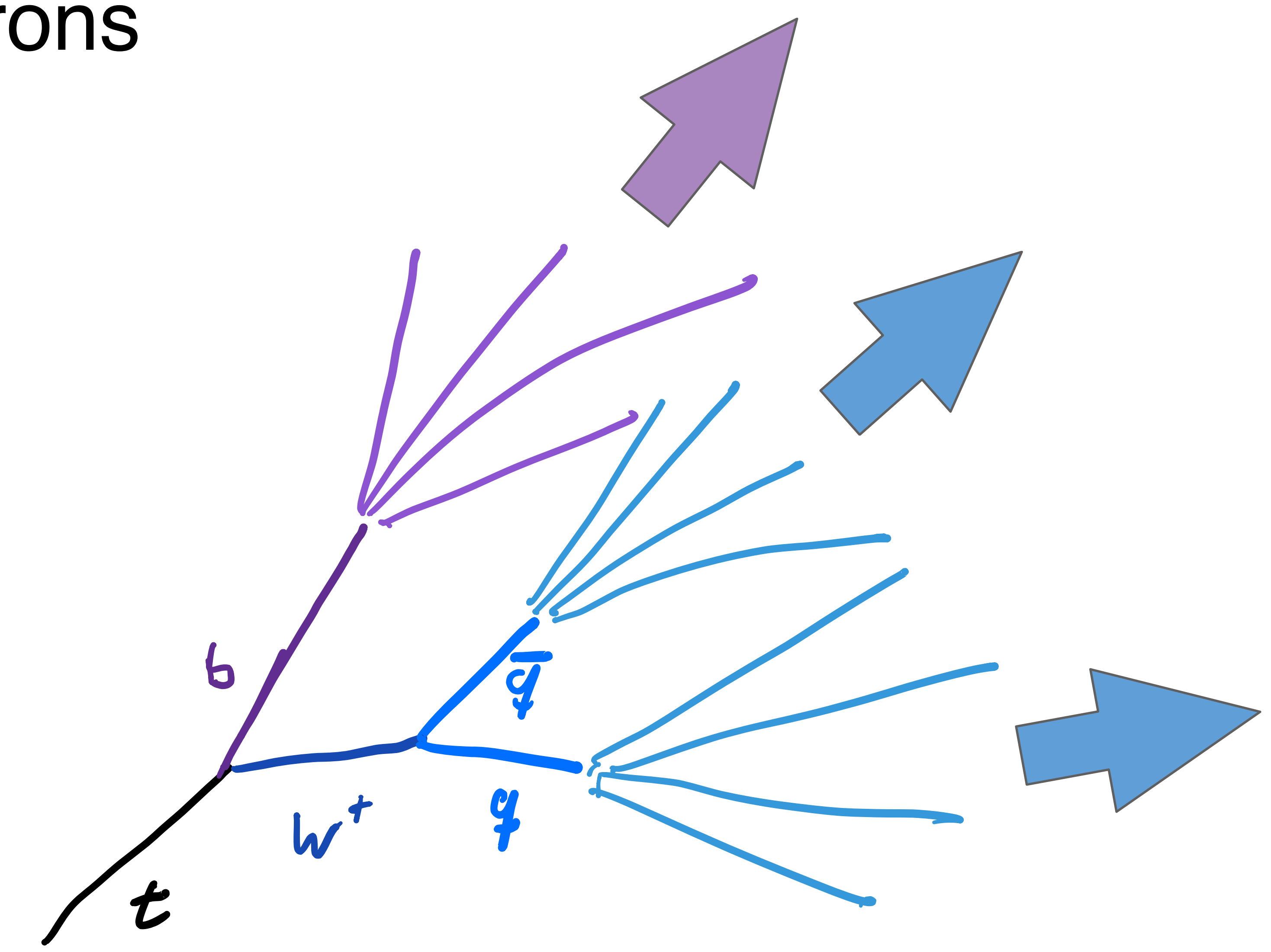




- Requires measuring the energies of different particle types
  - Charged hadrons ($\pi^{+/-}$, …)
  - Electromagnetic particles (γ, $e^{+/-}$)
  - Neutral hadrons (K_L, n, …)

The Particle Flow Paradigm

In a Nutshell

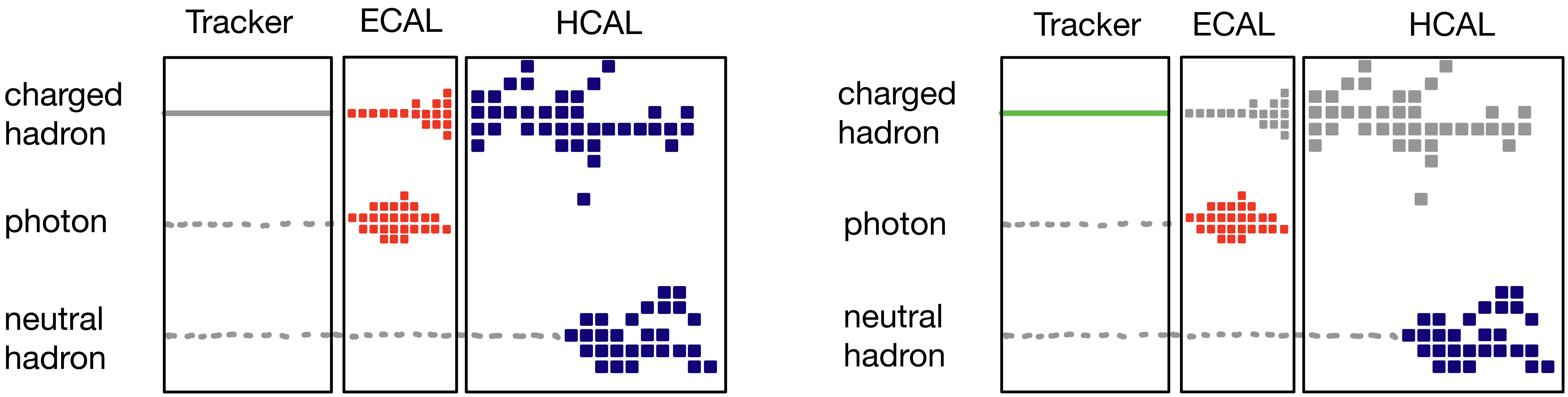
- The typical jet composition:
  - 60% charged (primarily $\pi^{+/-}$)
  - 30% photons (from π^0 decay)
  - 10% neutral hadrons (n, K_L)

Jet reconstruction with *Particle Flow*

excellent measurement in tracker, negligible resolution

~ 10% - 20% / Sqrt(E)

~ 60% - 100+% / Sqrt(E)



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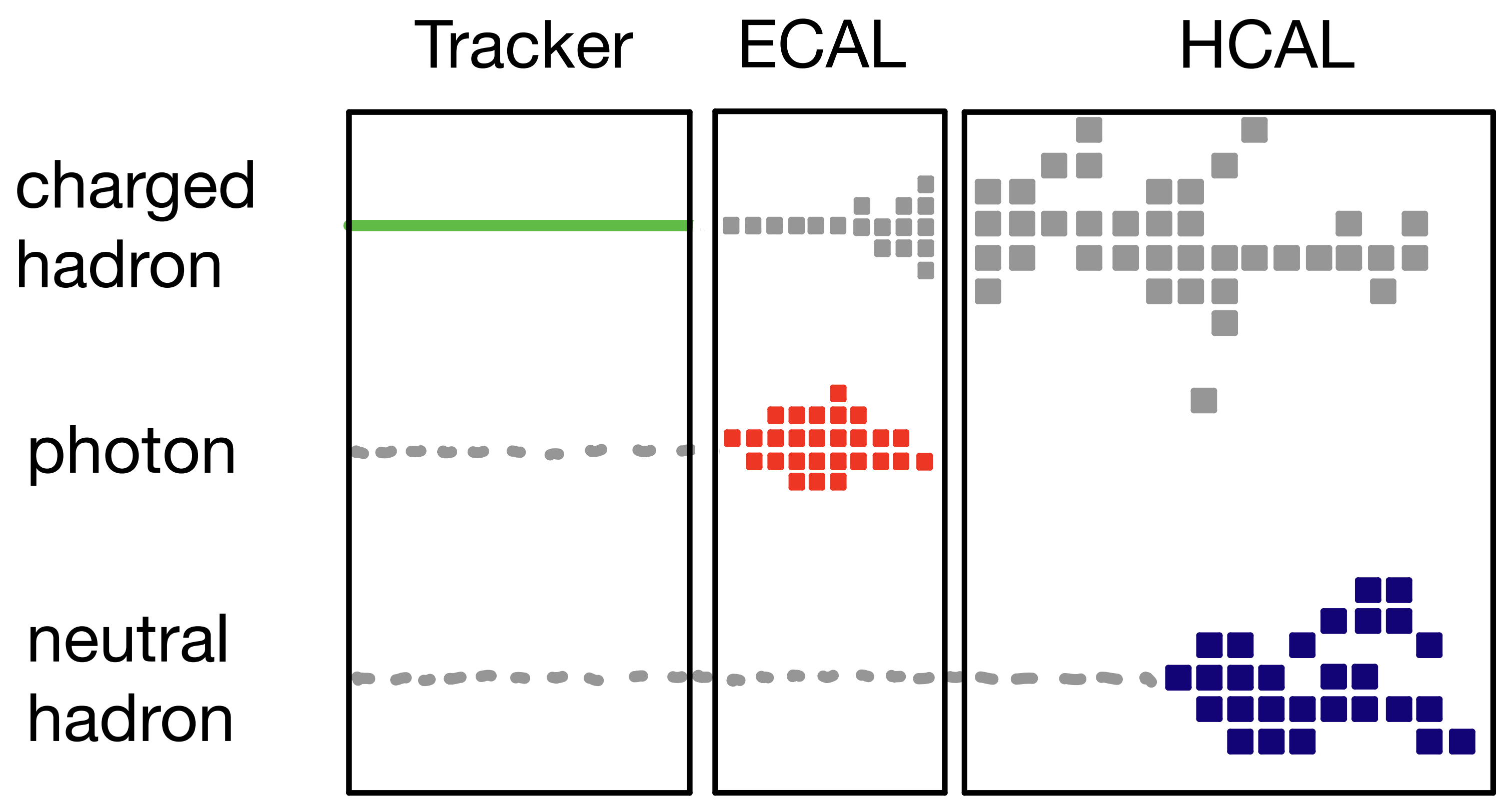

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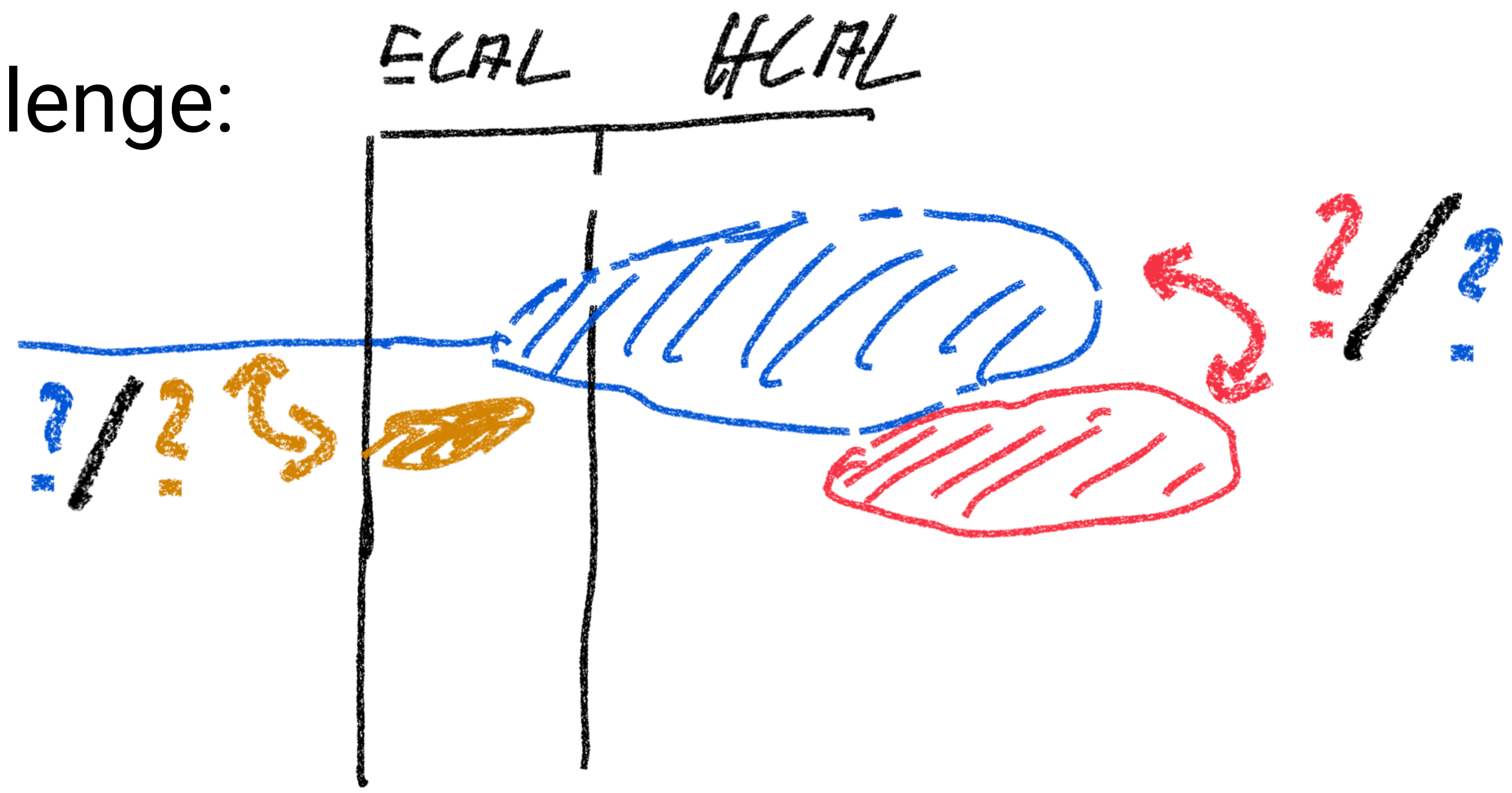
Confusion



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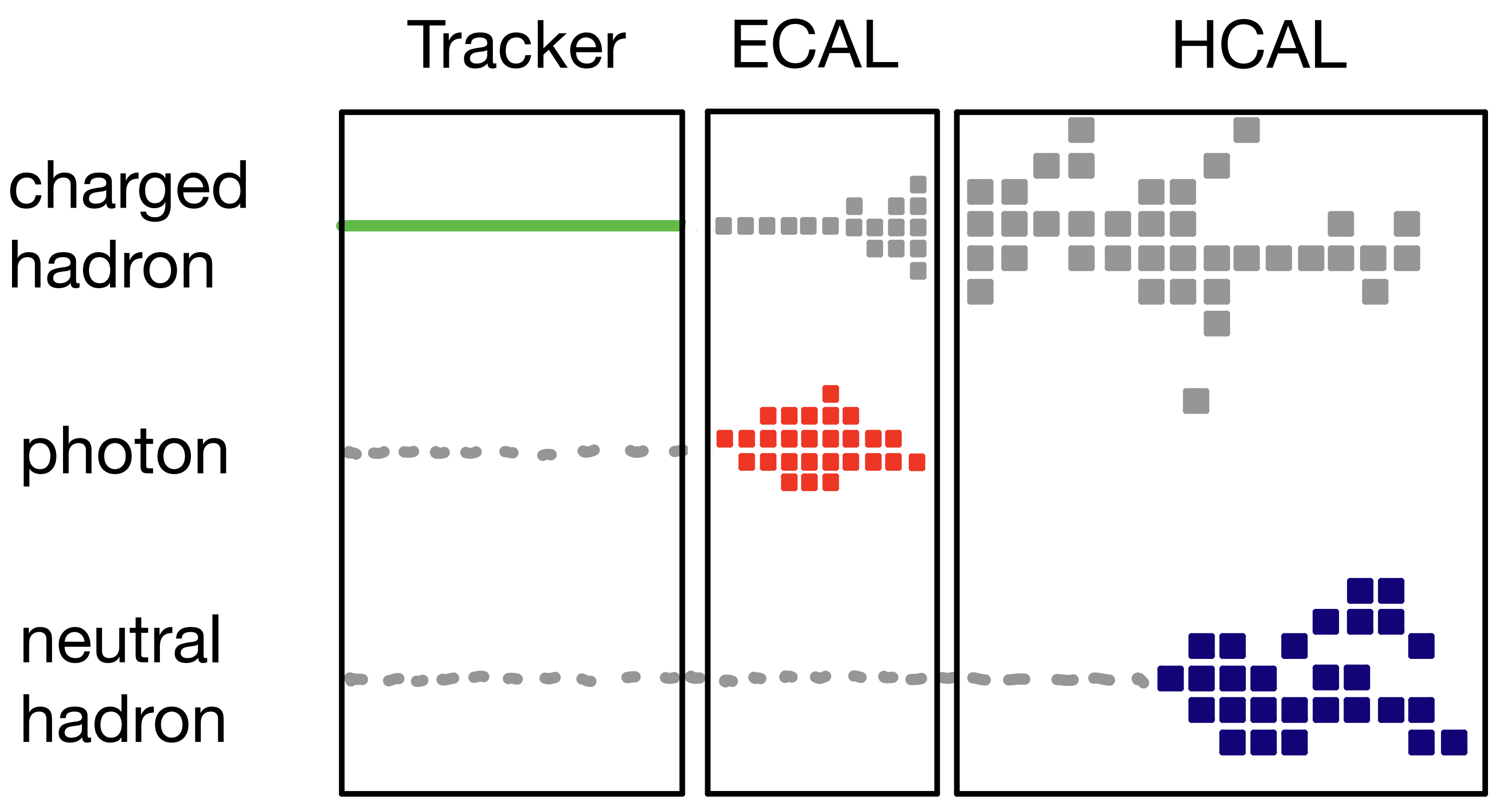

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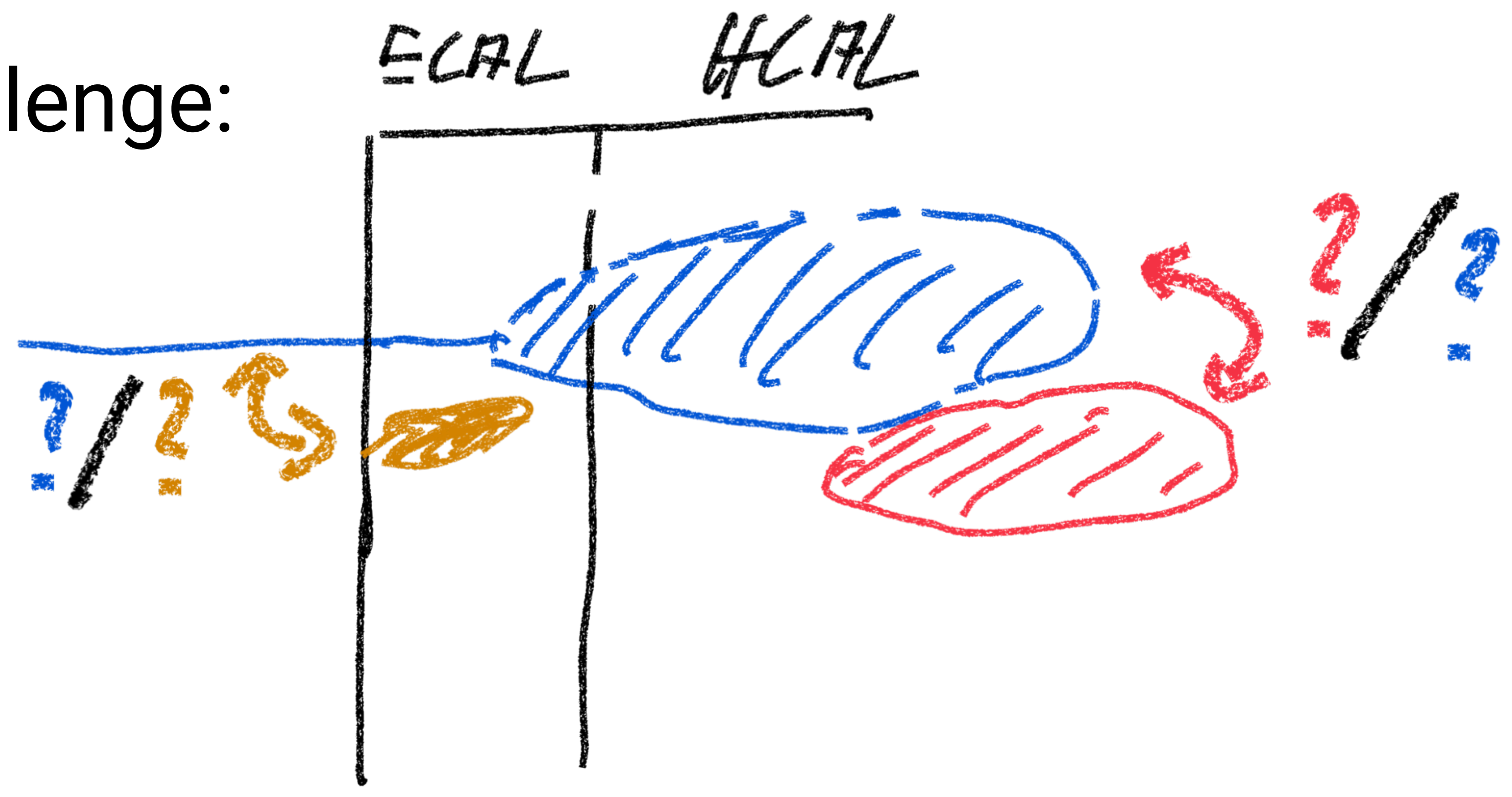

Highly granular (imaging) calorimeters

- Segmentation finer than typical shower structure (X_0, ρ_M)
- High-density materials, minimal gaps - in particular in ECAL: compact showers for improved separation

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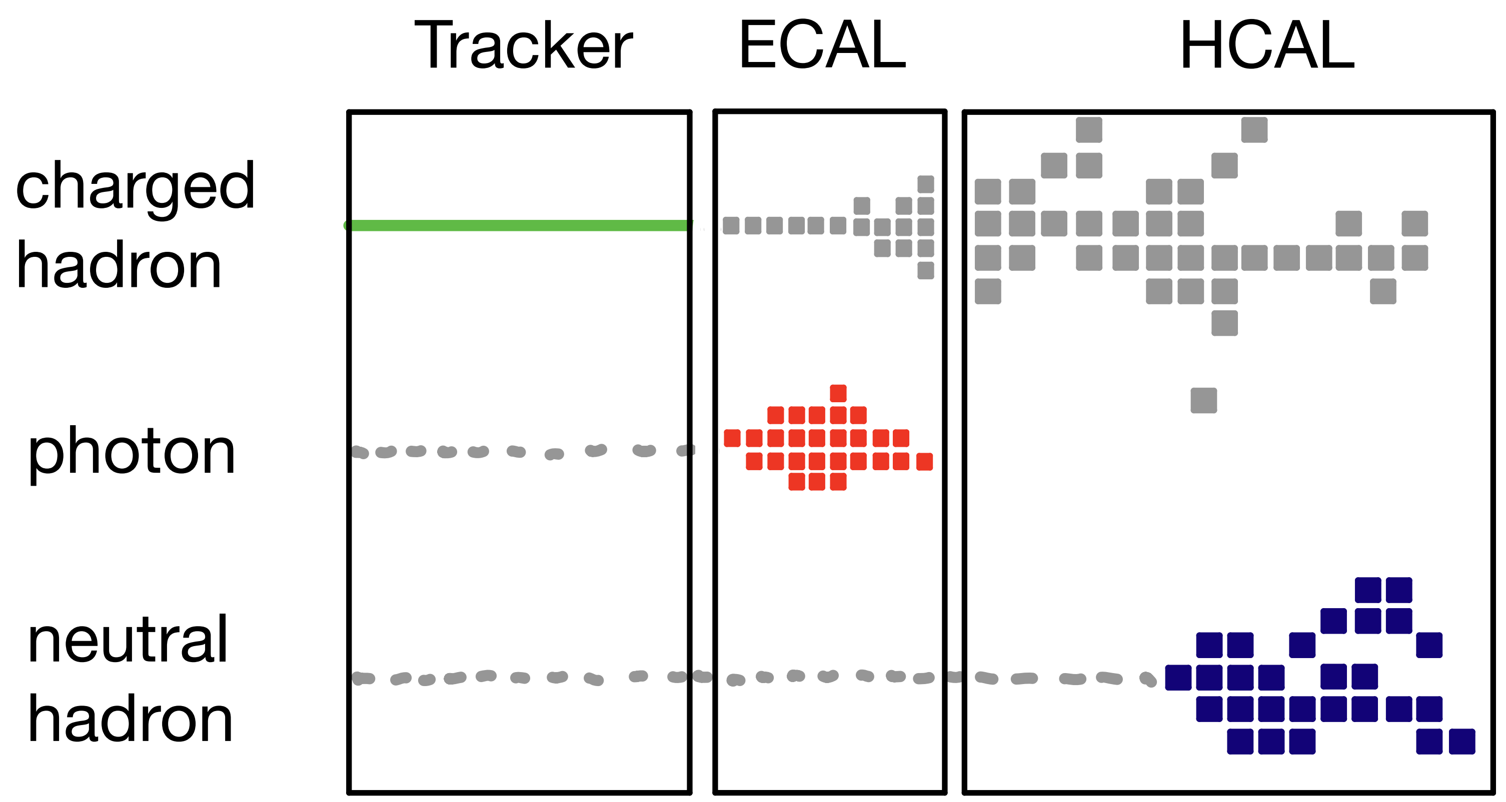

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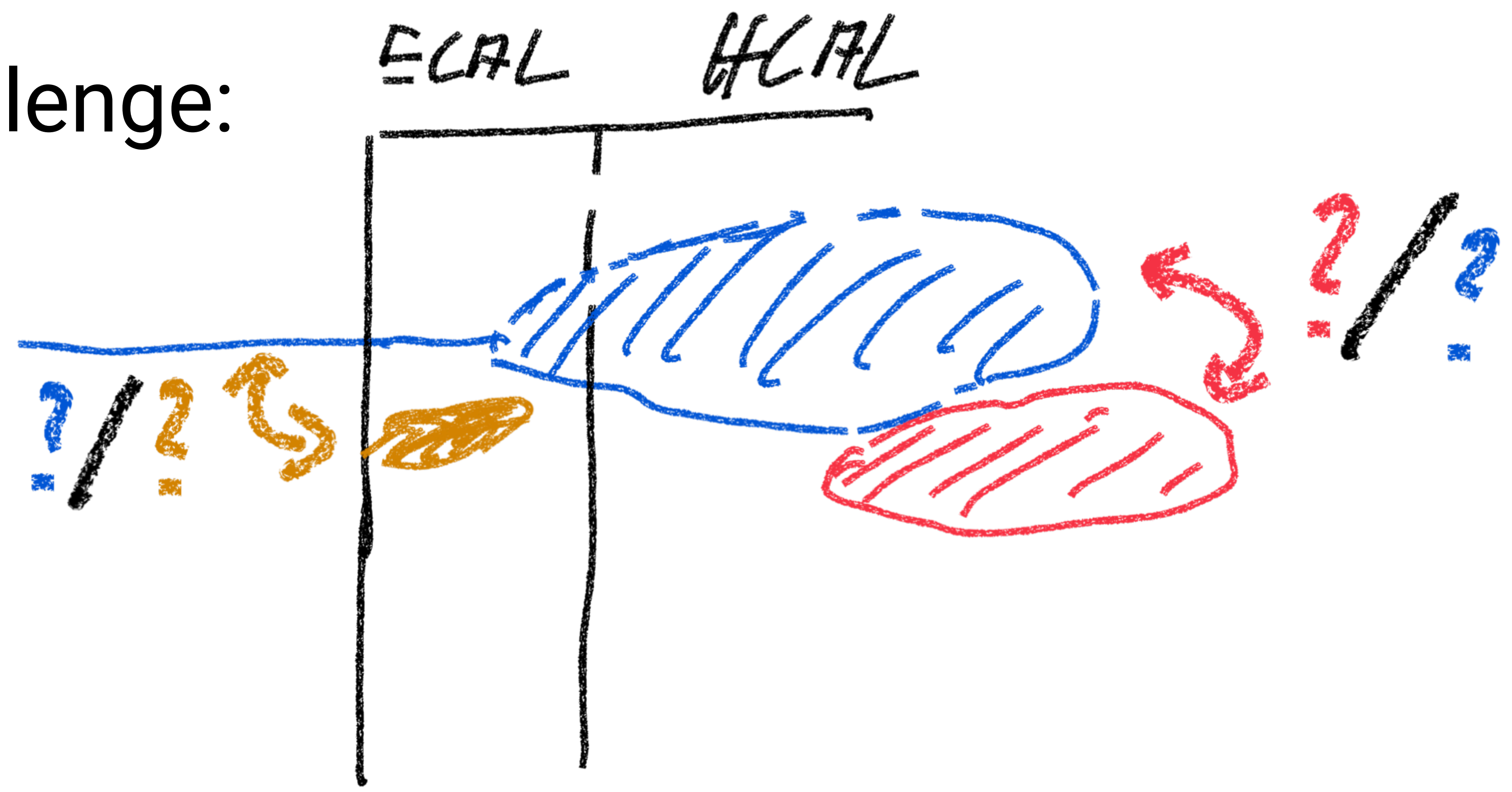

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Putting concrete numbers:

- Fe: $X_0 \sim 20$ mm, $\rho_M \sim 30$ mm
- W: $X_0 \sim 3$ mm, $\rho_M \sim 9$ mm

Separation in ECAL particularly critical: **W as absorber**!

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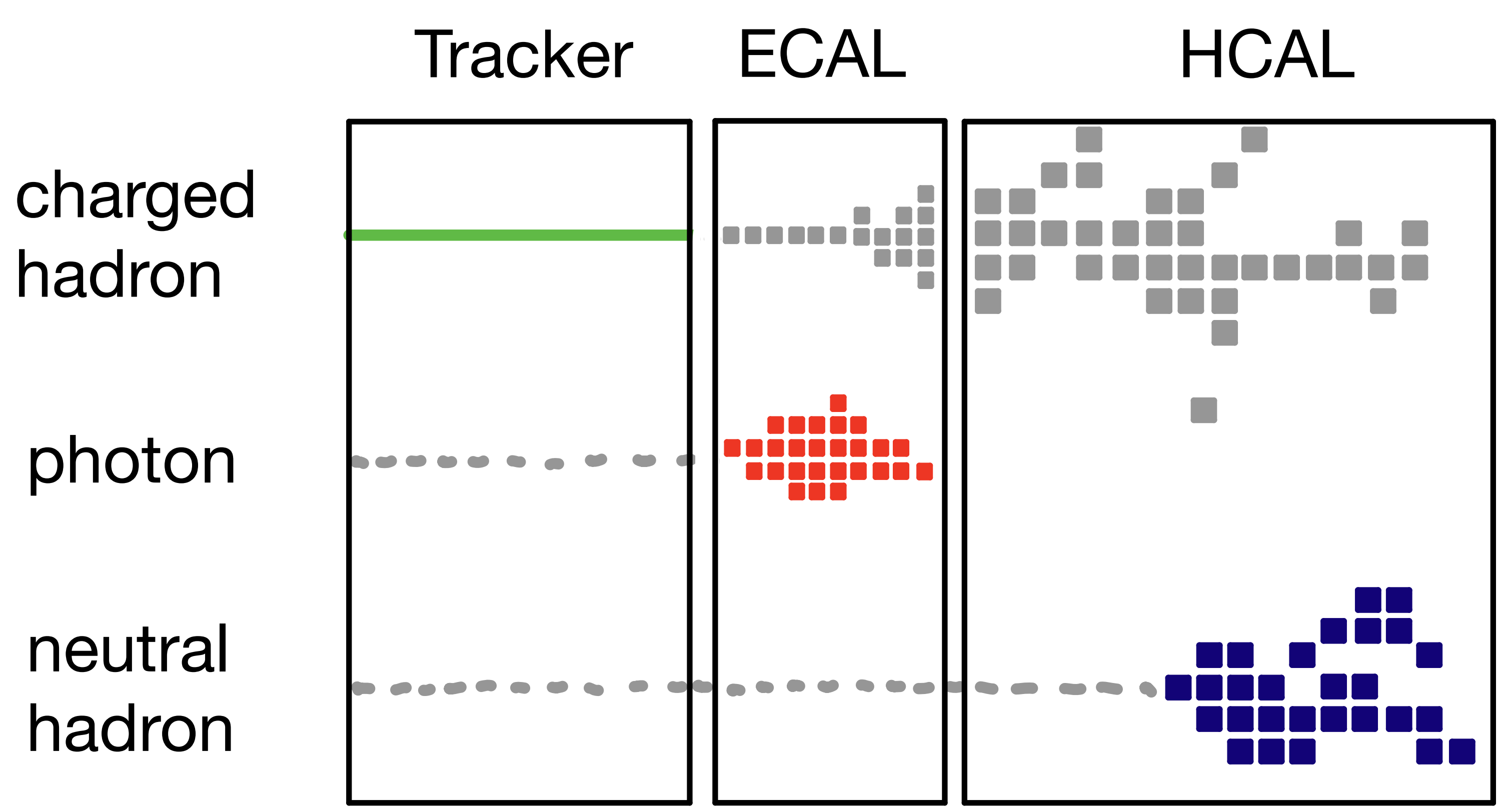

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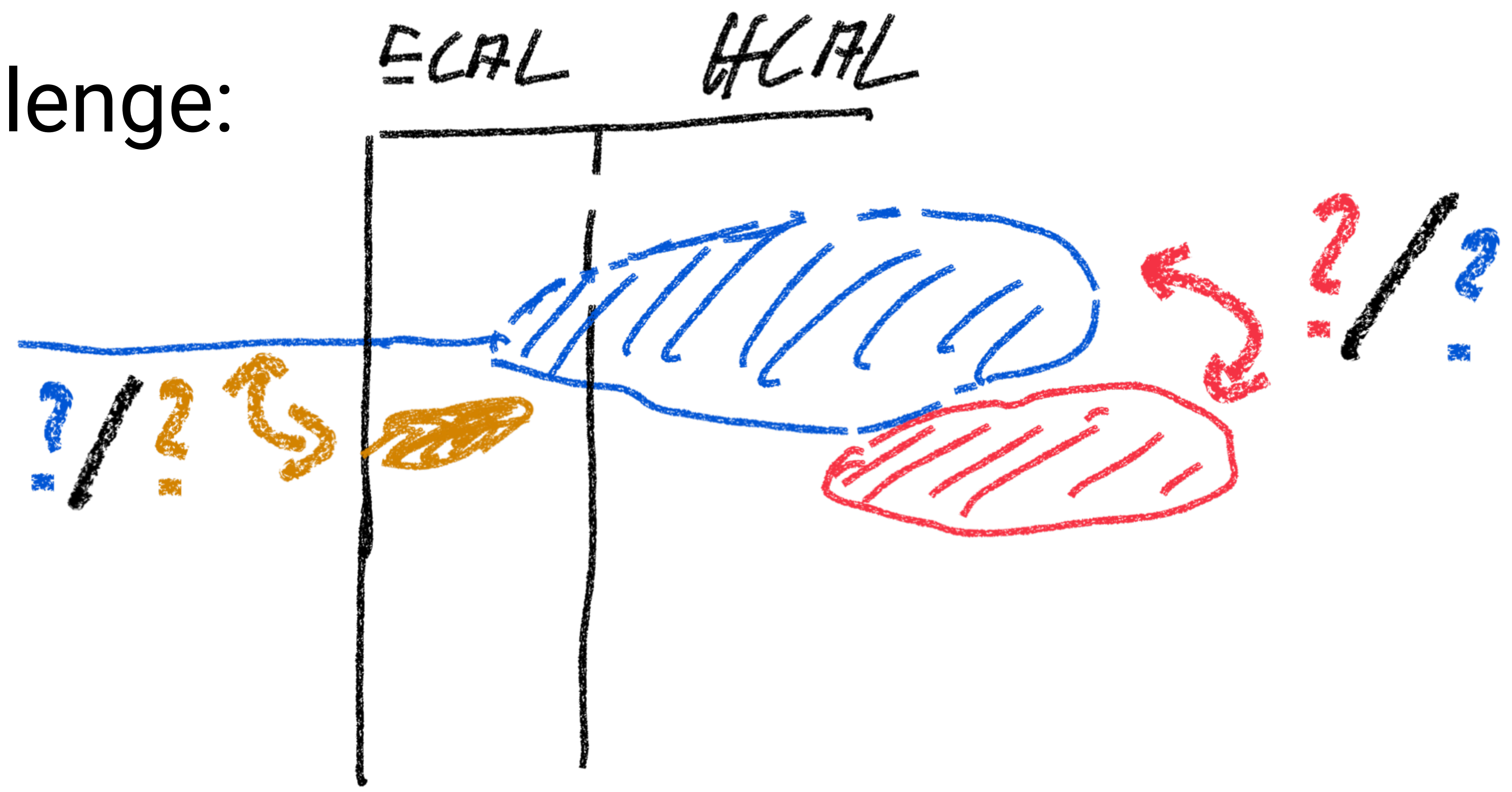

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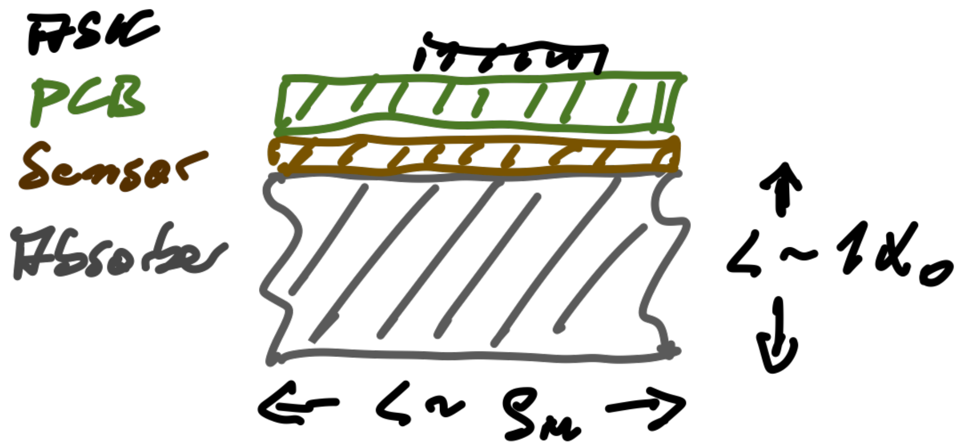


When adding active elements:
$\sim 0.5\ \mathrm{cm}^3$ in ECAL, $\sim 25\ \mathrm{cm}^3$ in HCAL

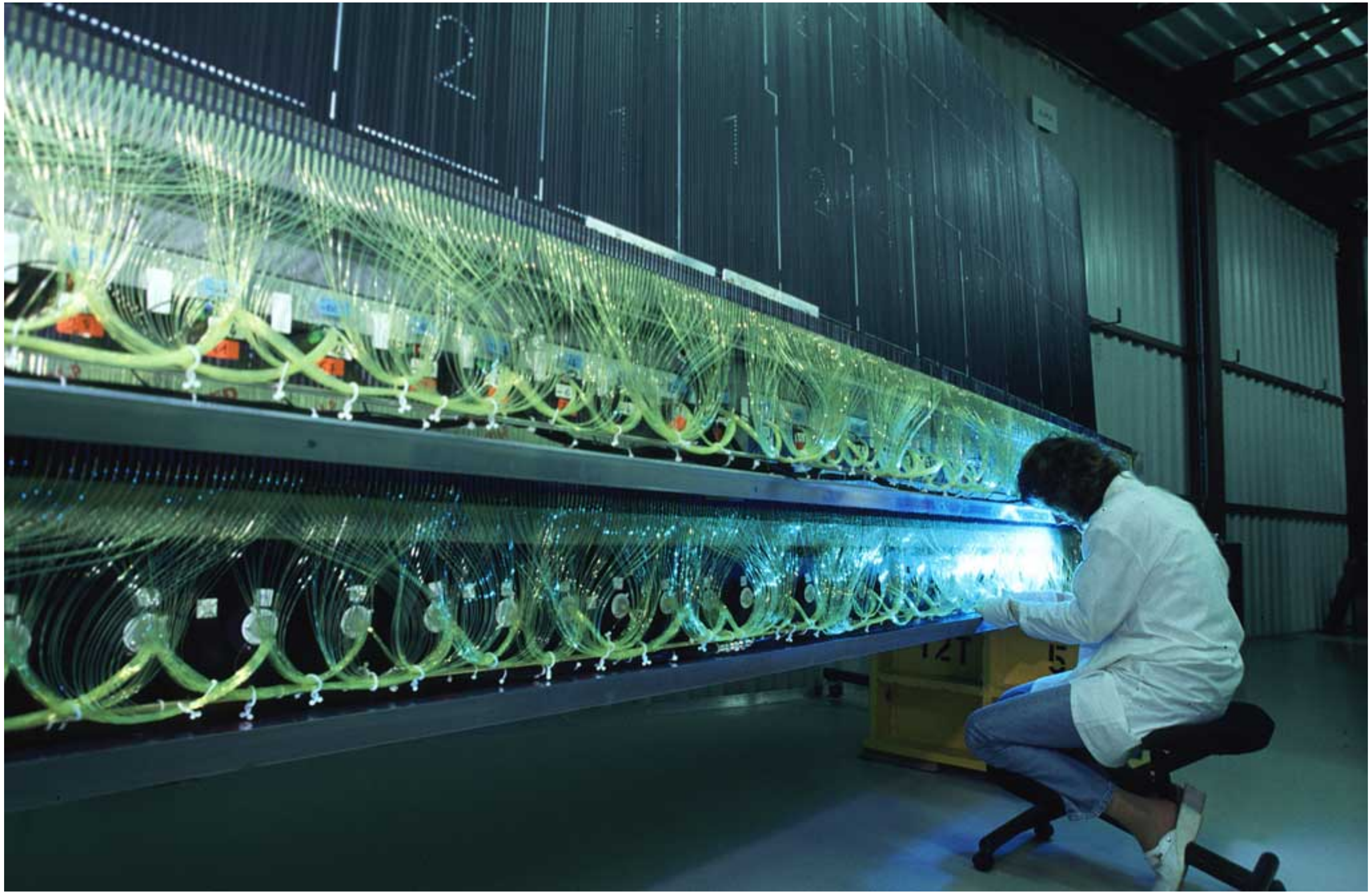
Highly Granular Calorimeters

An enabling technology - From a hadronic perspective

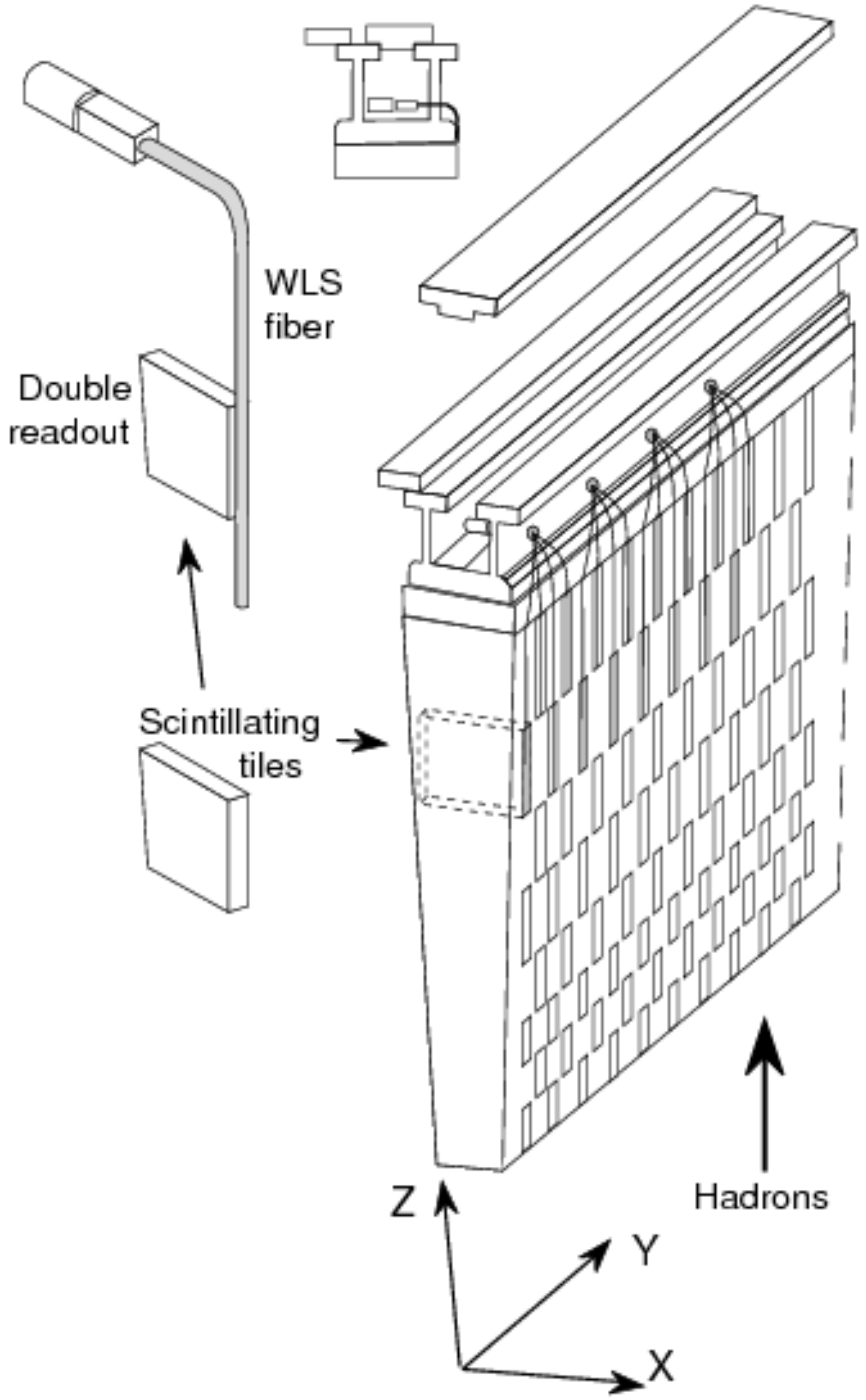
- SiPMs and microelectronics as game changers
- Real-world challenges

Hadronic Calorimeters

Classical Solutions



- Light collected over large volumes, brought by fibers to PMTs in magnetically shielded volumes



Silicon Photomultipliers

The Revolution

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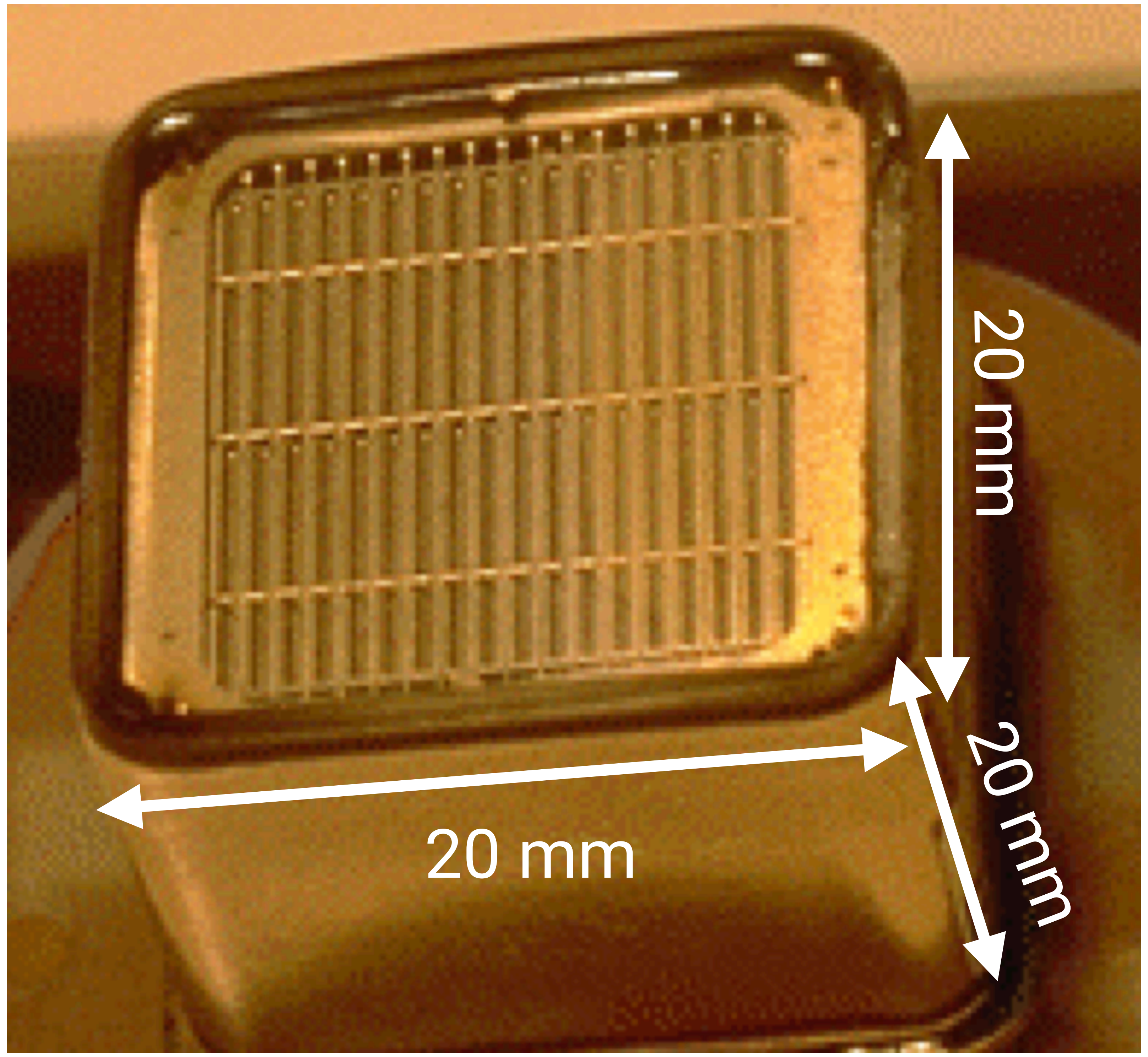

ATLAS TileCal PMT HPK R5900

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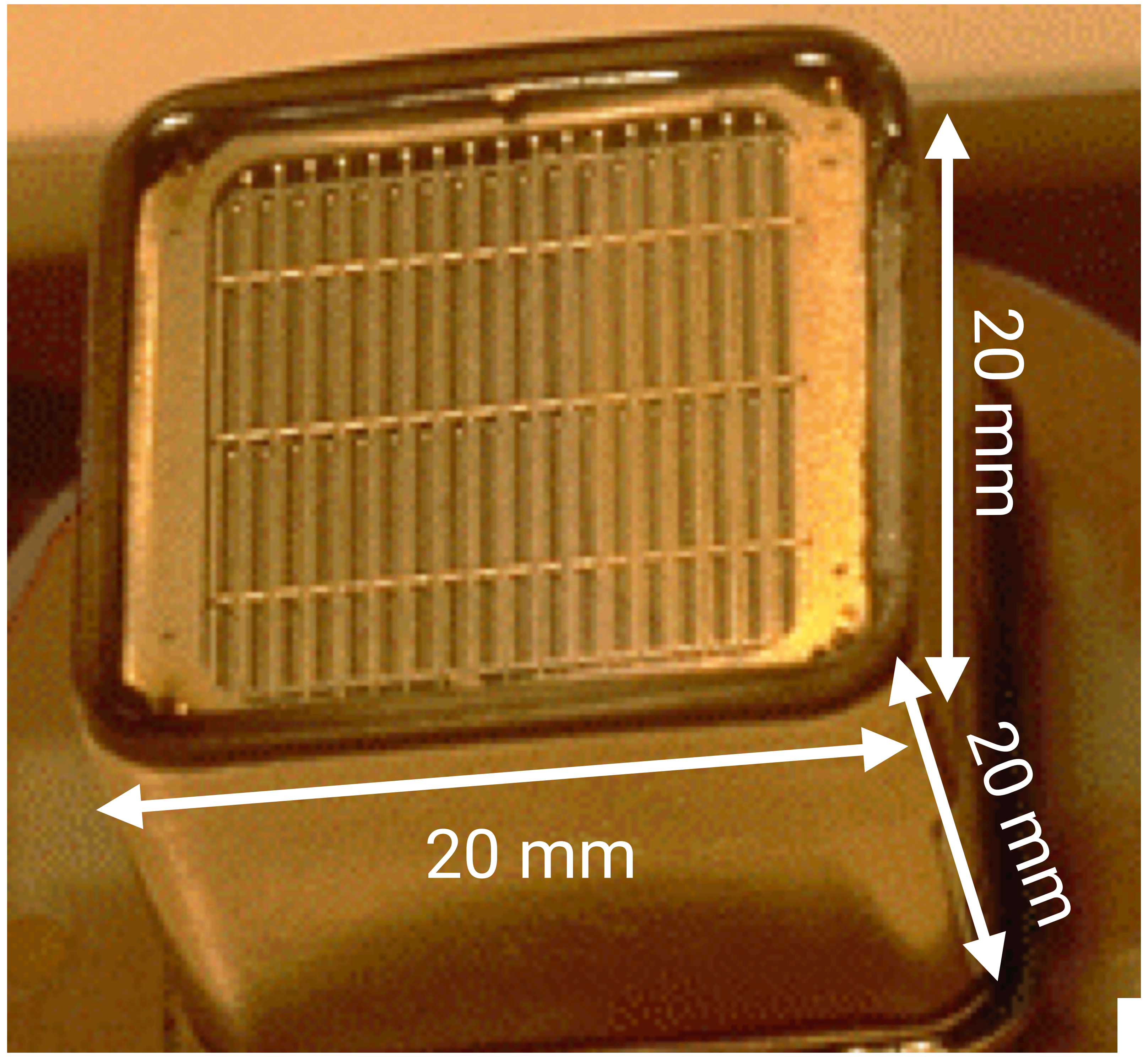

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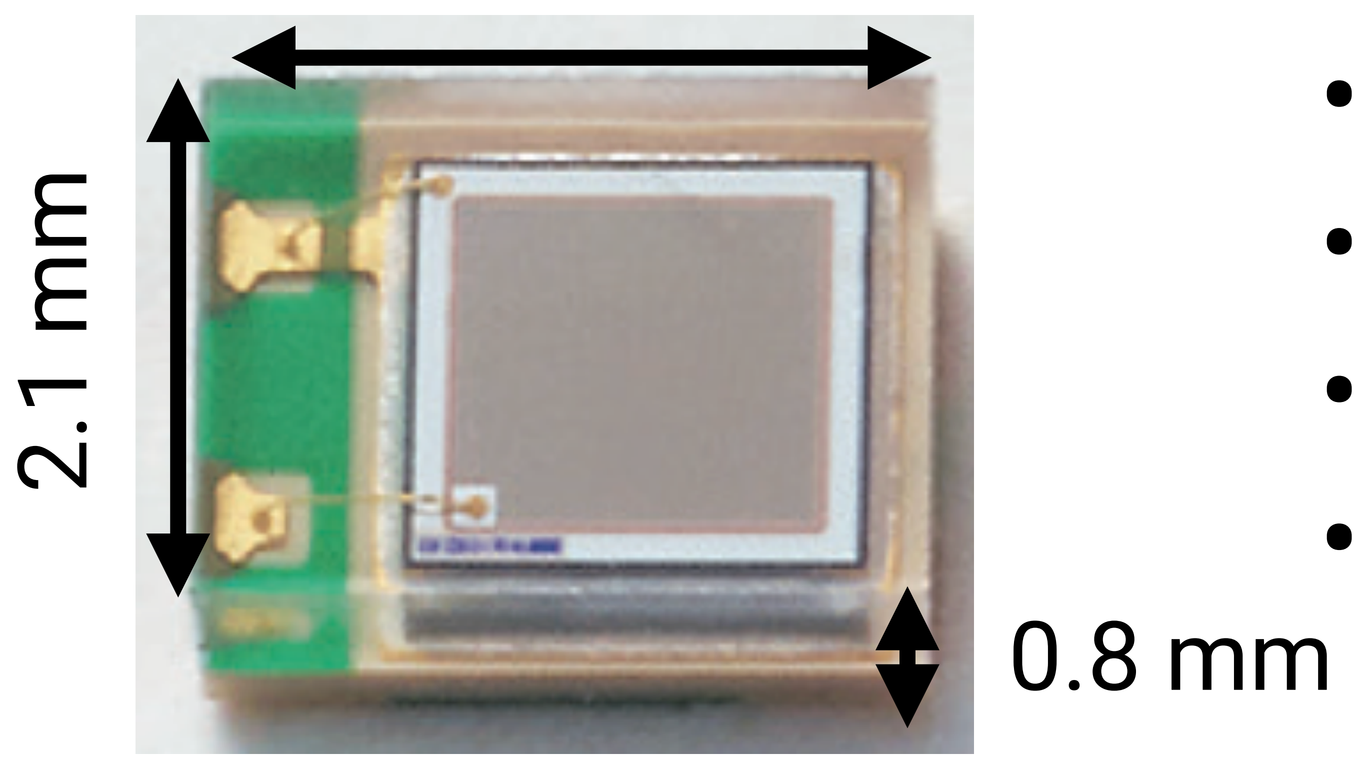
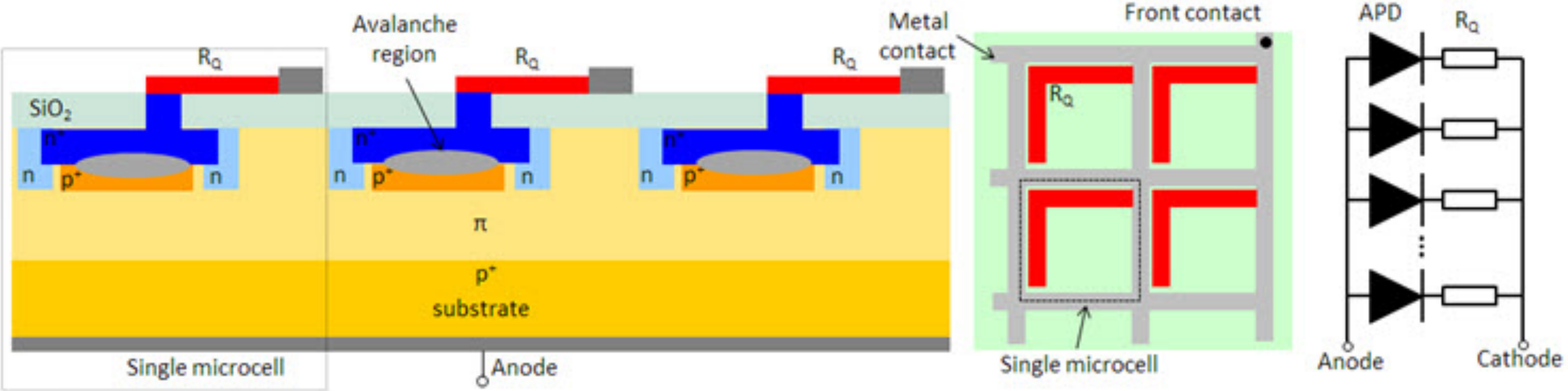


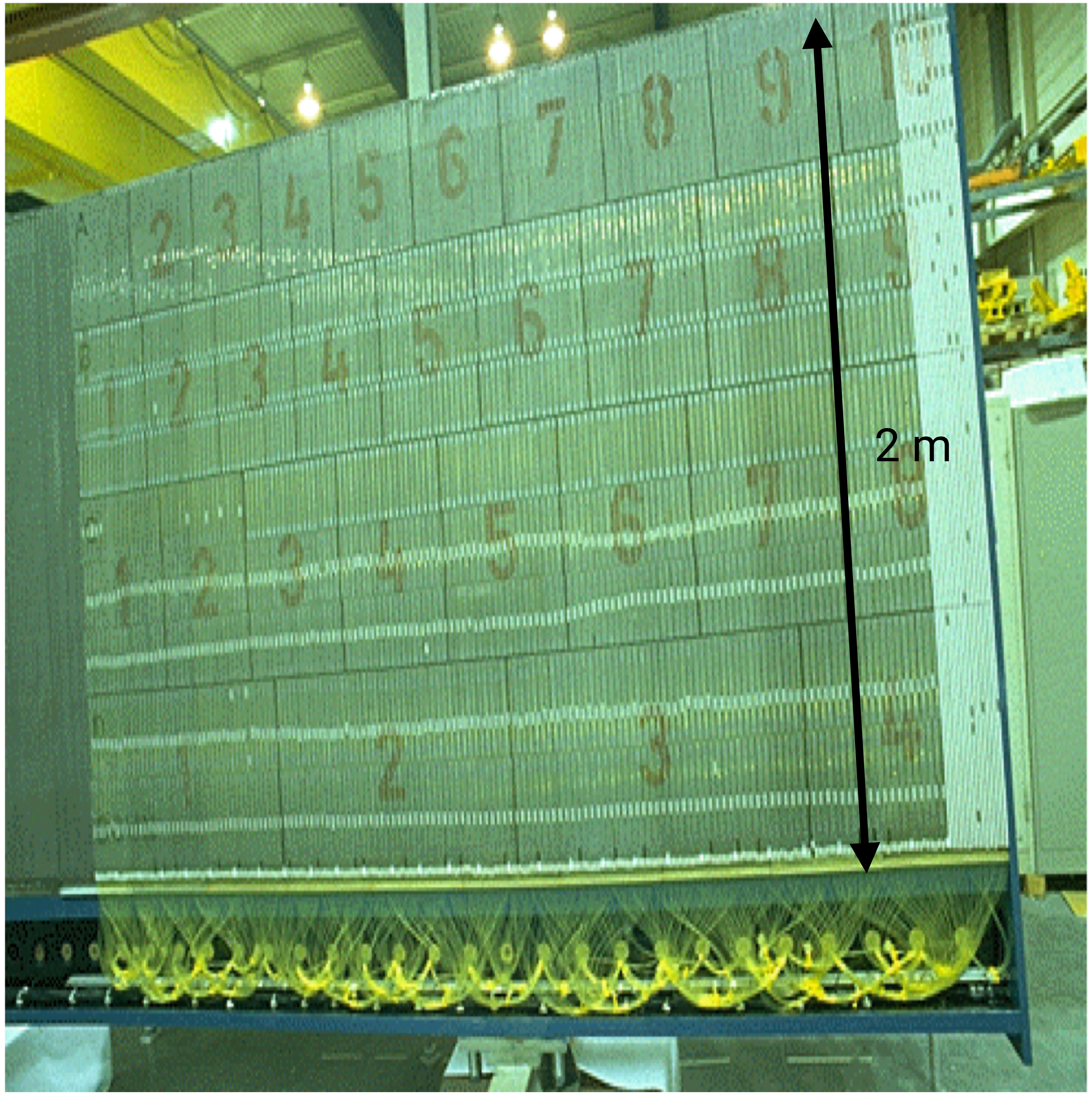
Silicon Photomultipliers (SiPMs)

- high gain: ~ 10^6
- insensitive to B fields
- good PDE
- dynamic range given by N_{pix}



SiPMs: A Game Changer for Calorimetry

Enabling unprecedented granularity



ATLAS tile calorimeter half barrel module: 23 “cells”

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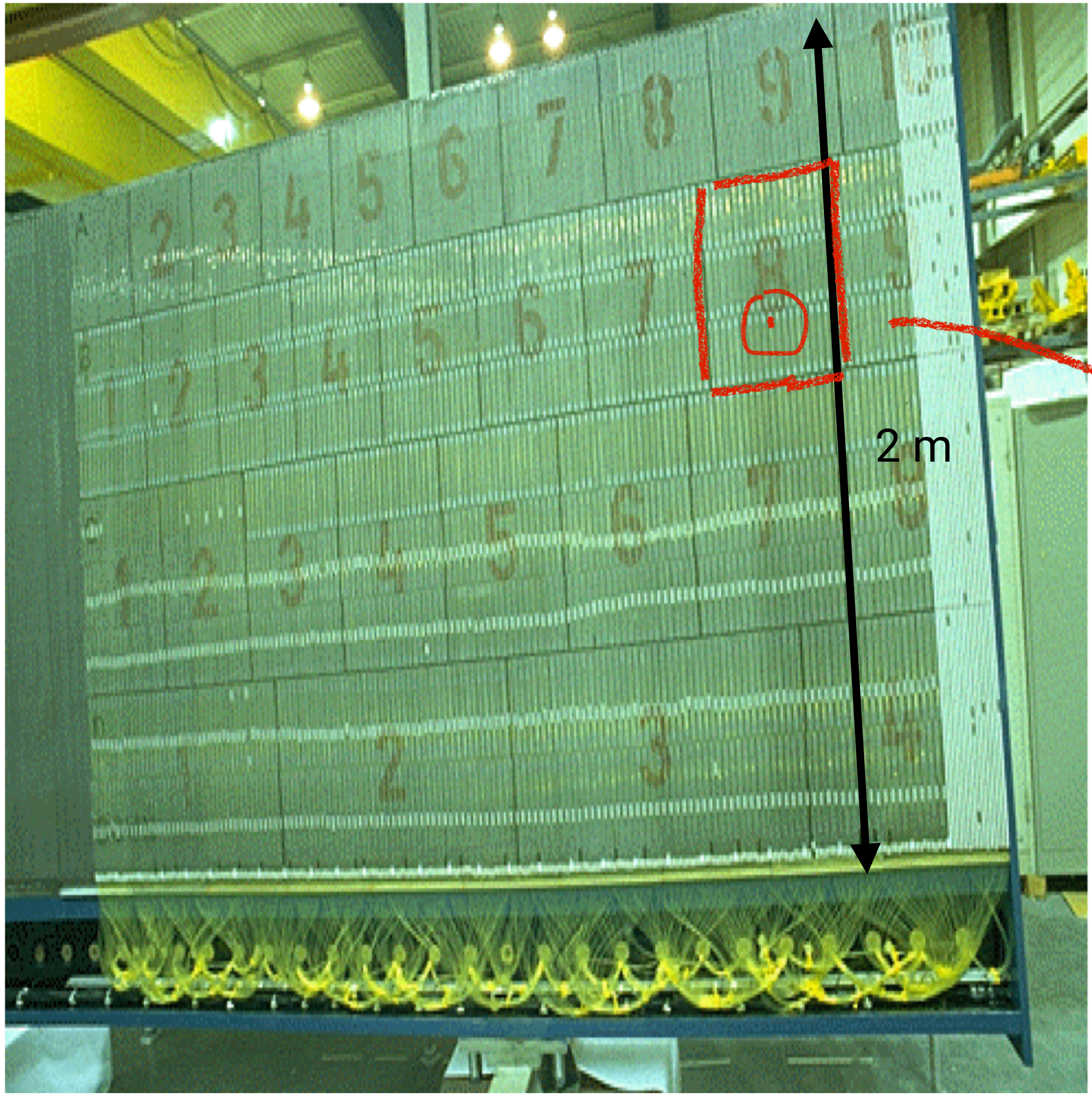

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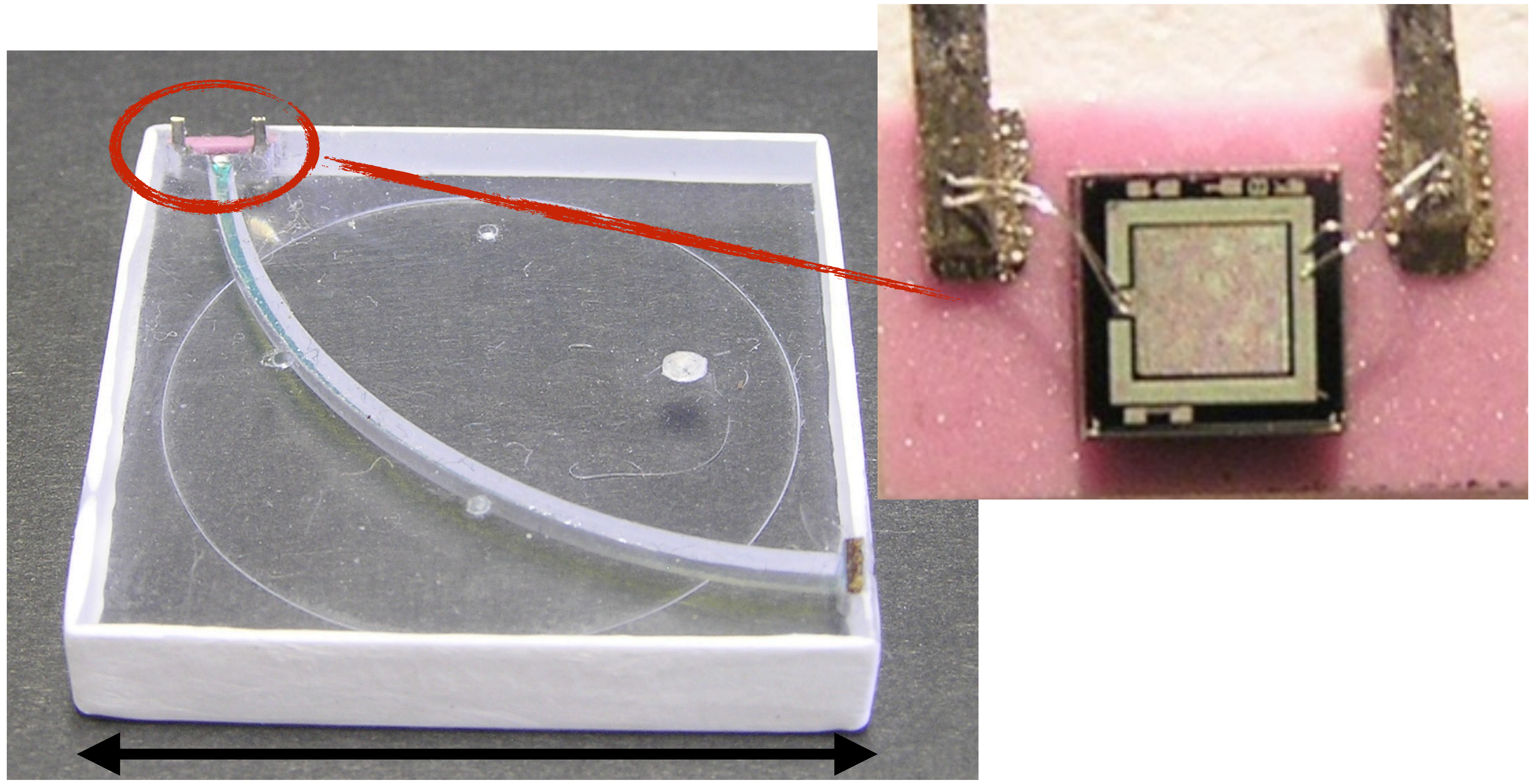

3 cm

- Scaling up the channel density (= spatial granularity) by 3 orders of magnitude

The CALICE Physics Prototype

A proof of principle

- "*Imaging calorimeters*": A new type of calorimeters
  - 3D (4D with amplitude, 5D with timing) images of particle showers
    ~ x1000 higher channel density as current detectors

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Different technologies:
Si / **Scint+SiPMs** / gas

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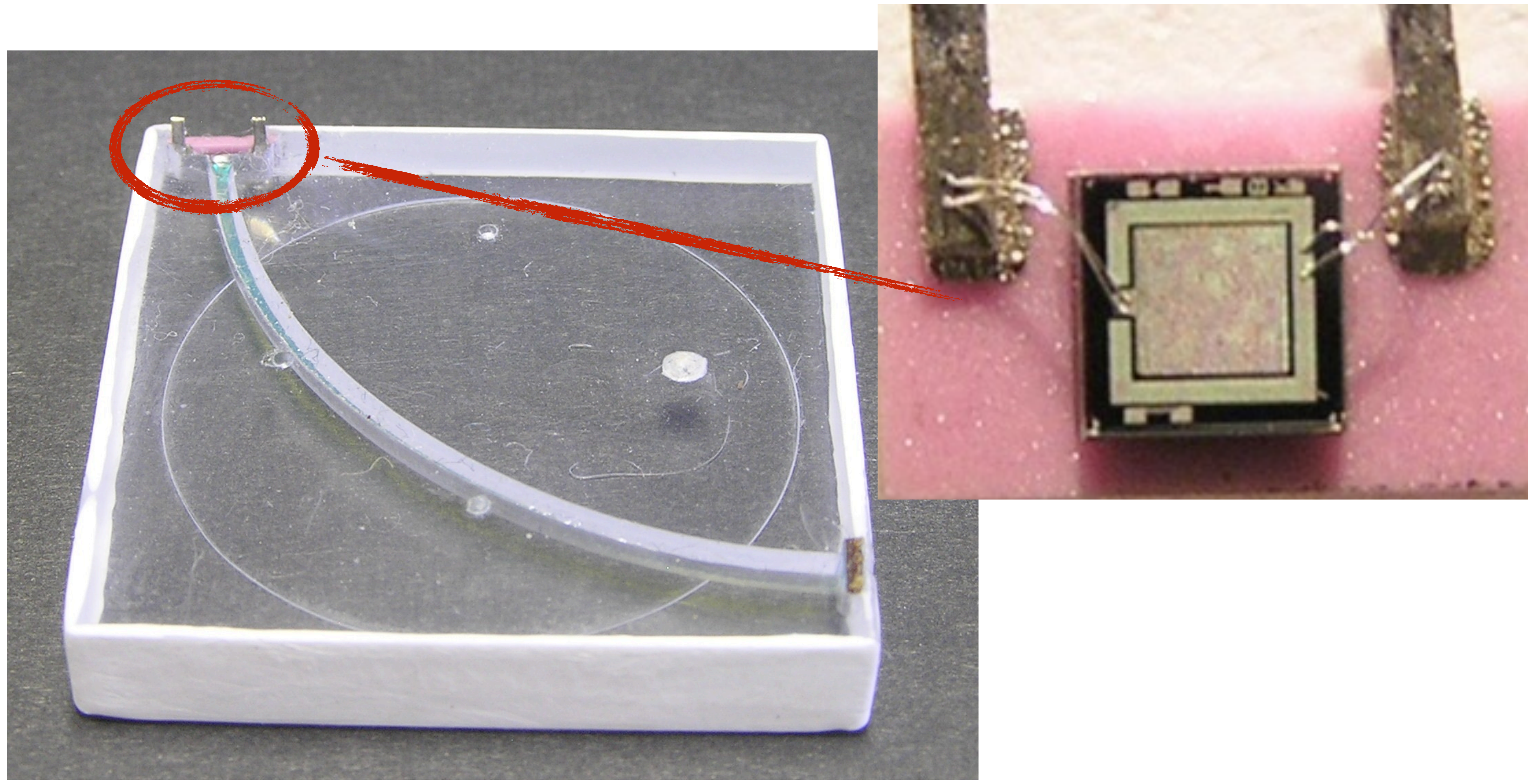

The focus today: The SiPM-based
Analog Hadron Calorimeter

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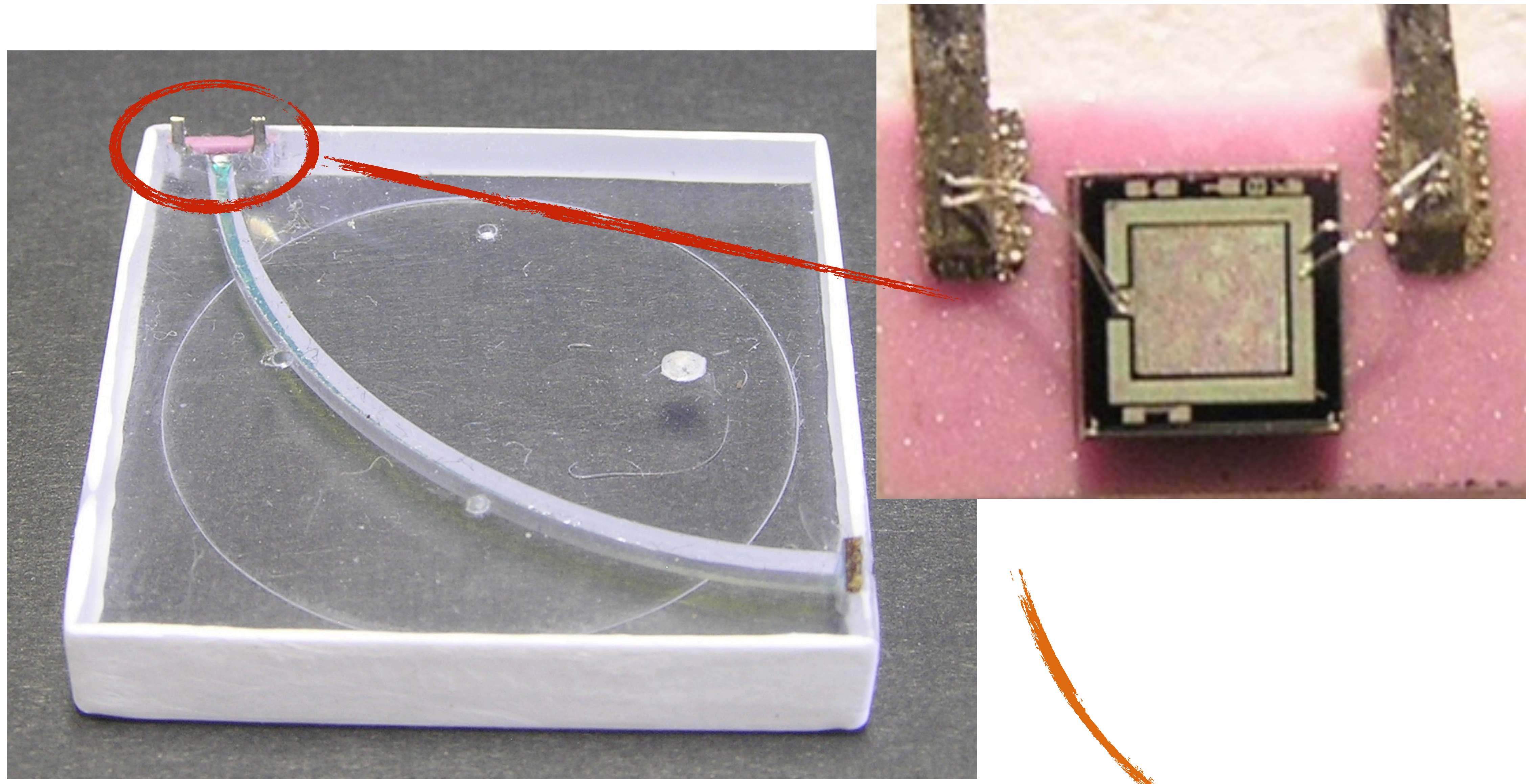

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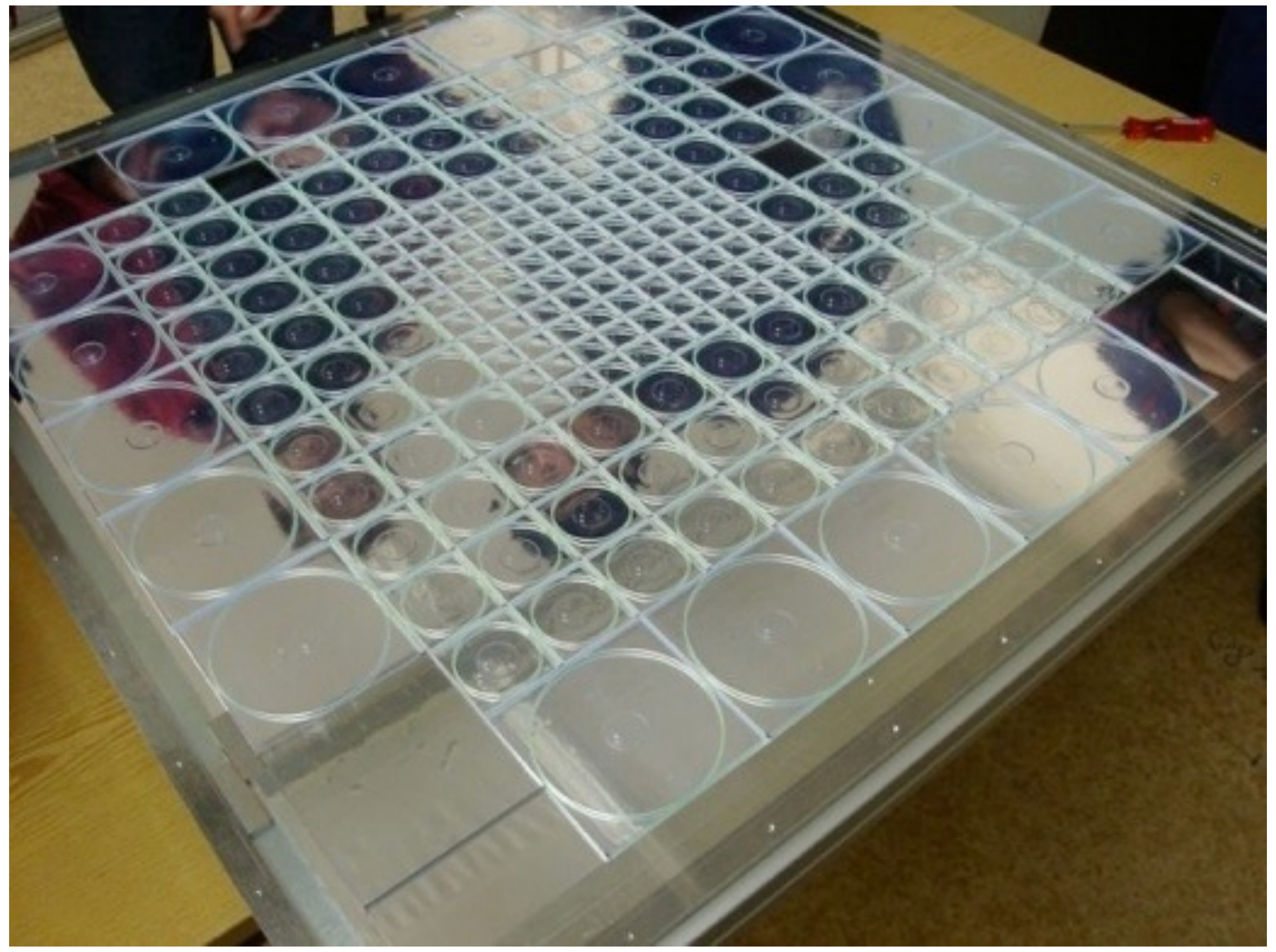
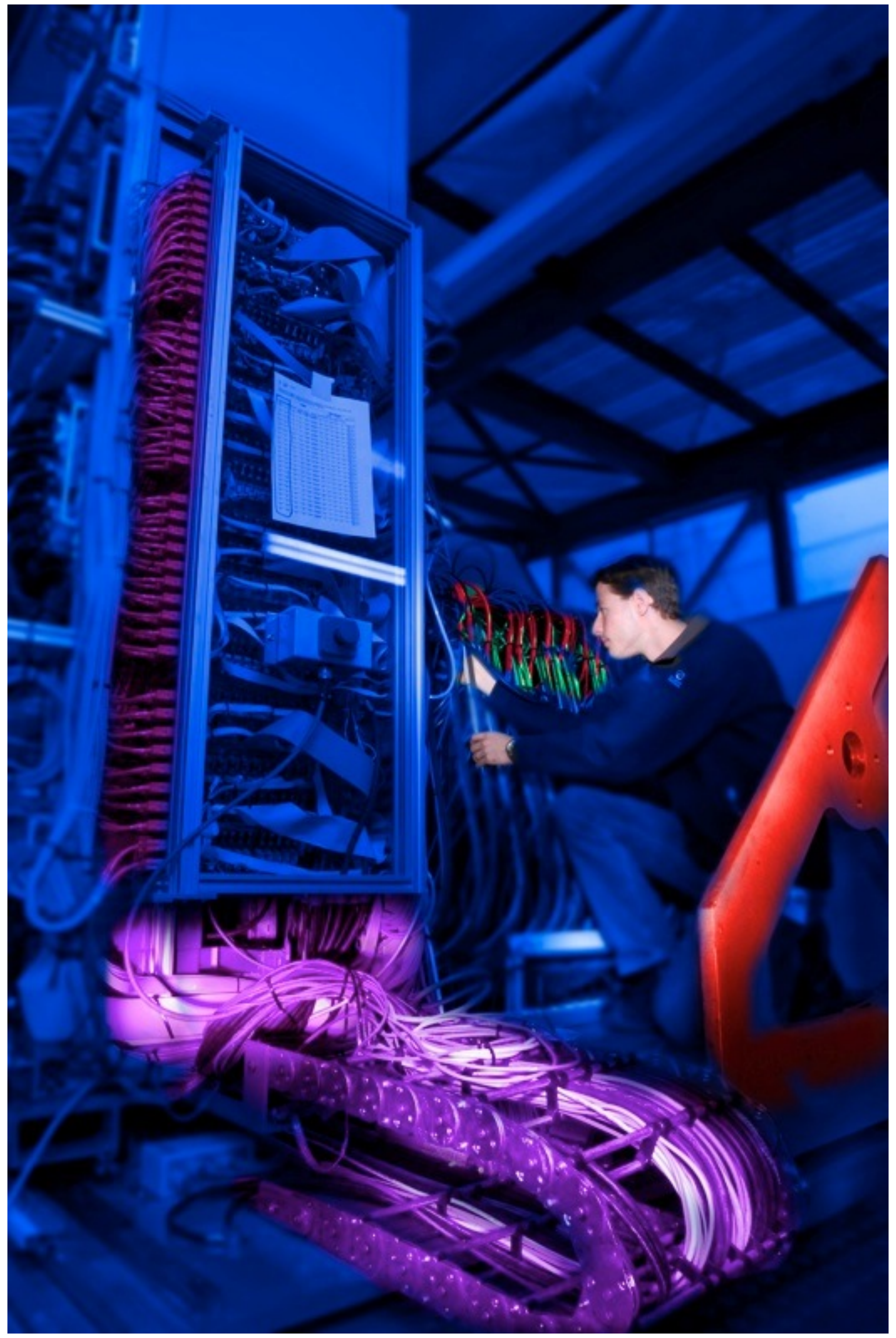
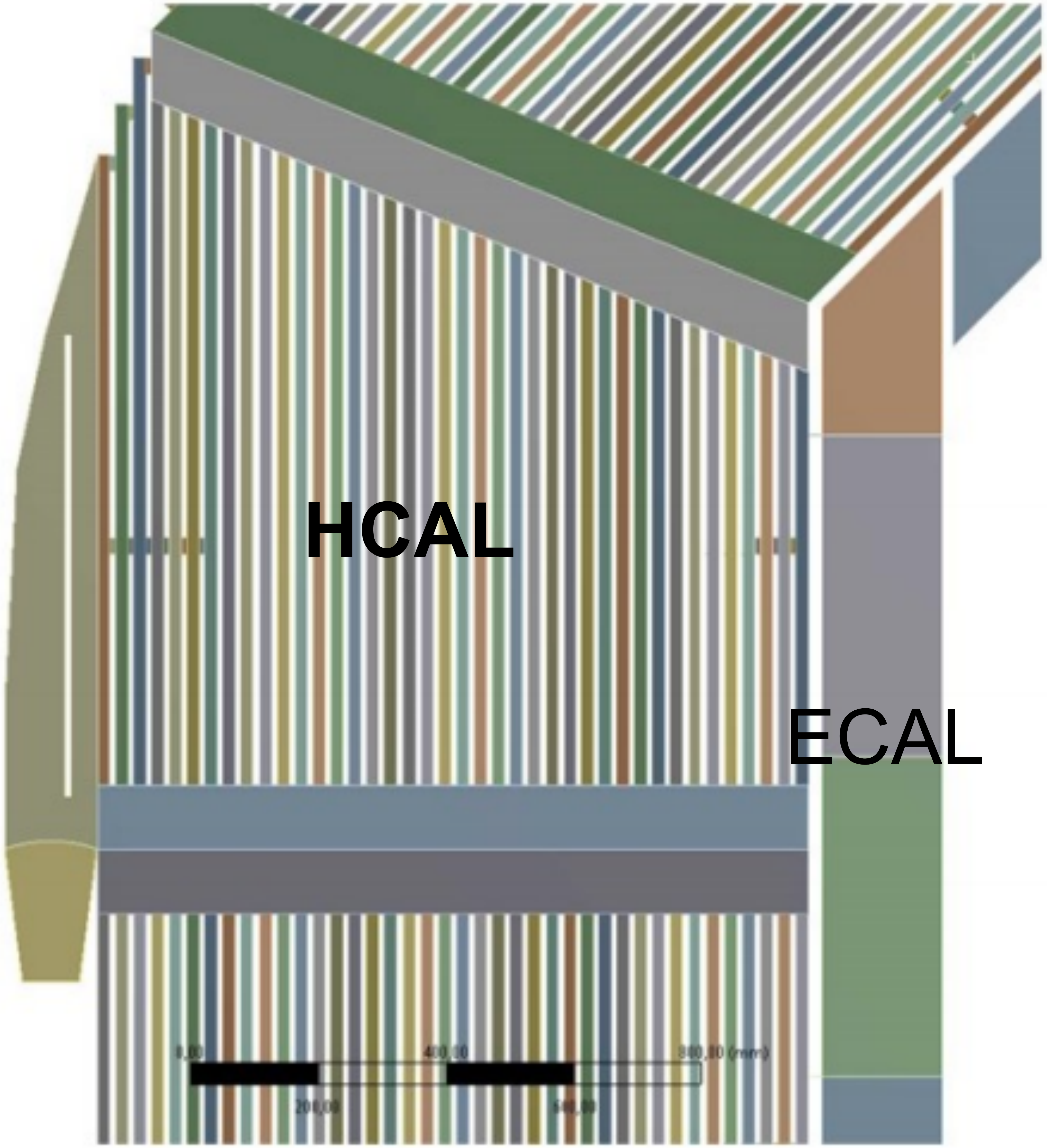


A first full prototype
1 m^3, 8000 channels (2007)



Interlude: What do we need?

Integration requirements of large detector systems



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minimal tolerances

no / minimal cracks

10 - 100 M channels
10 000 m^2 active elements

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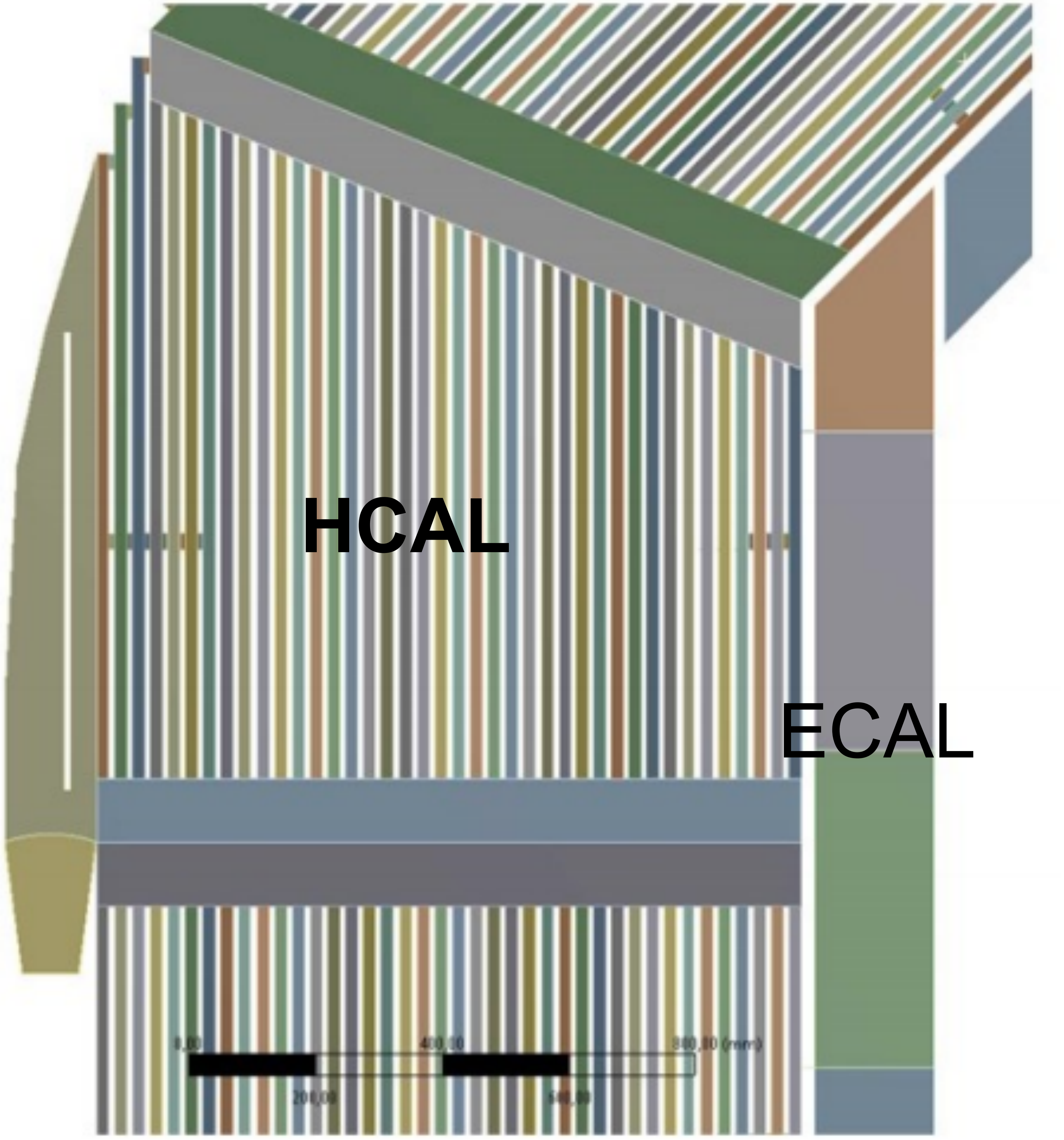

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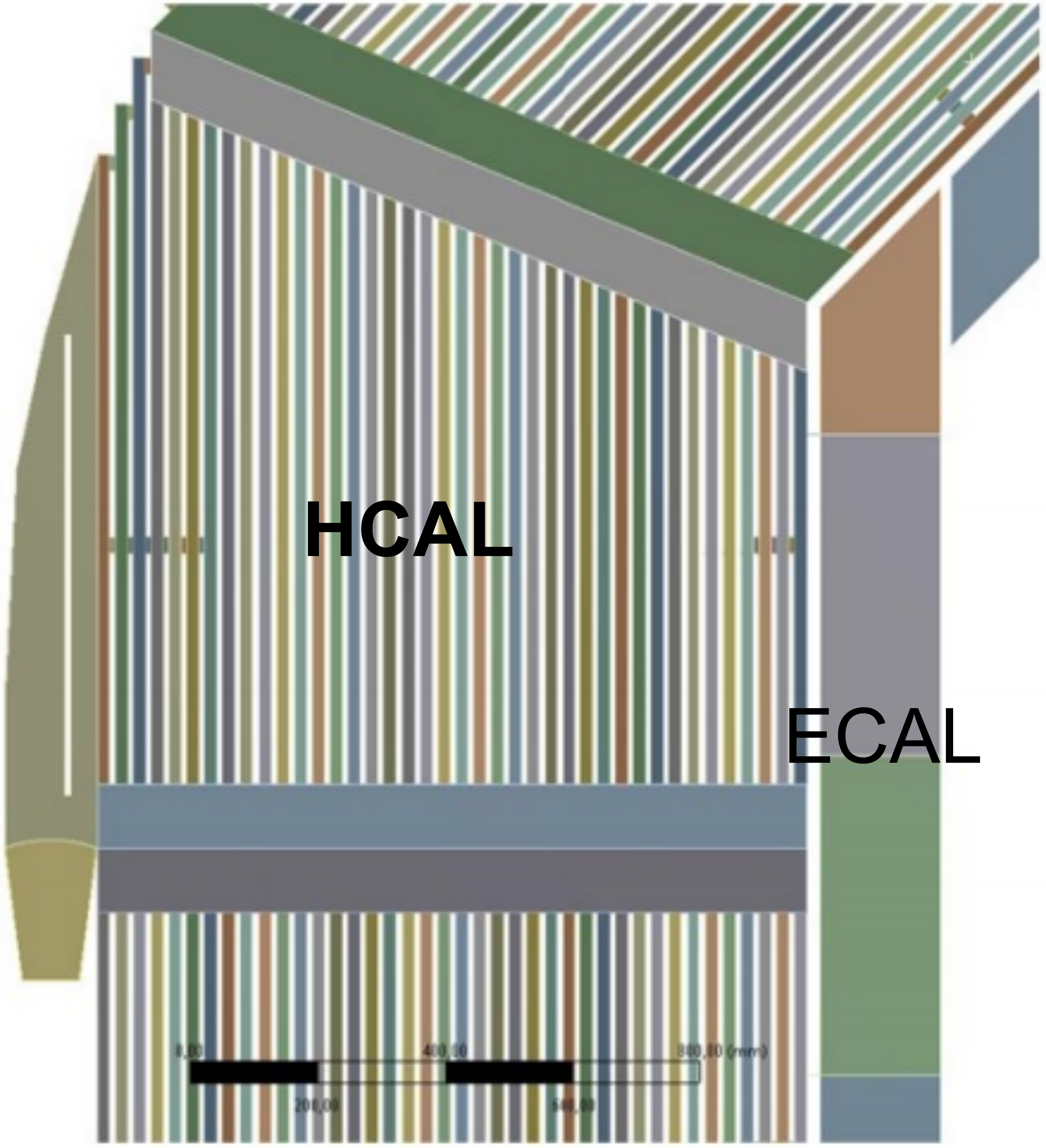

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scalability & mass production

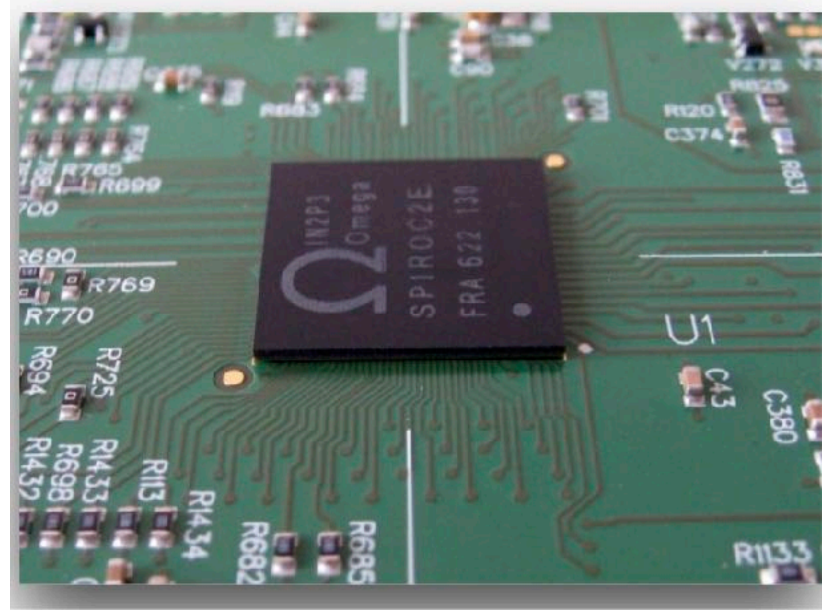
device-to-device uniformity

Technical Realisation

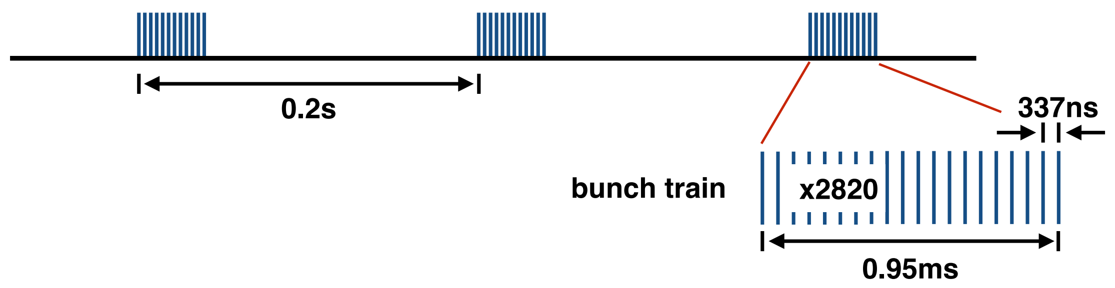
Addressing real-world constraints with new prototypes

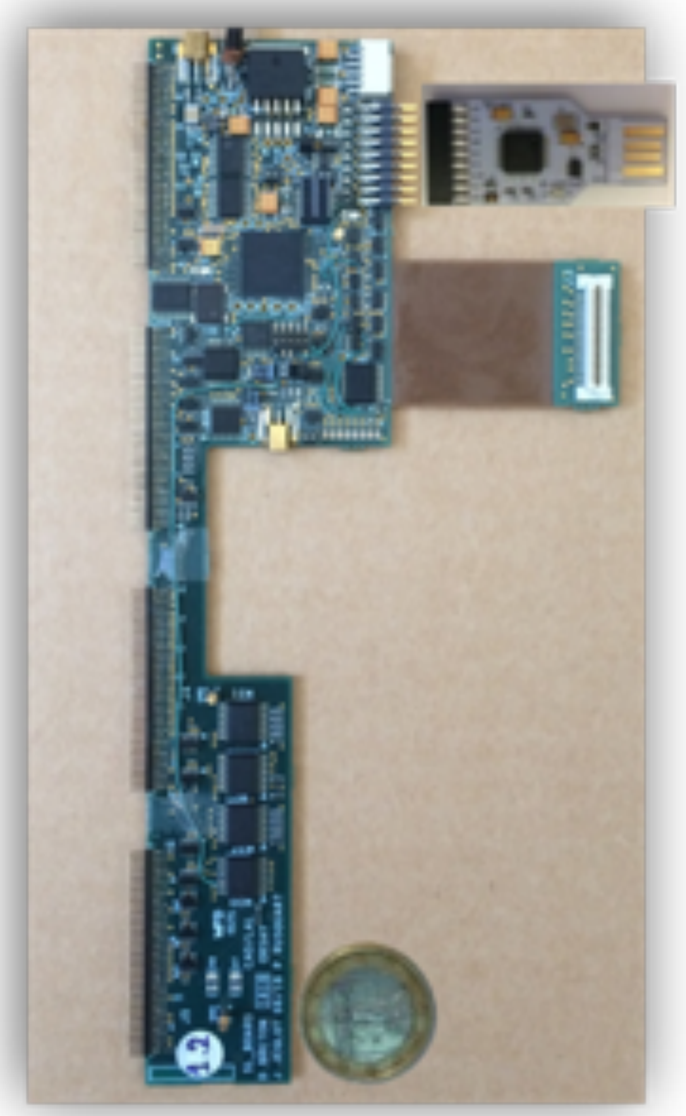
Physics prototypes

integration



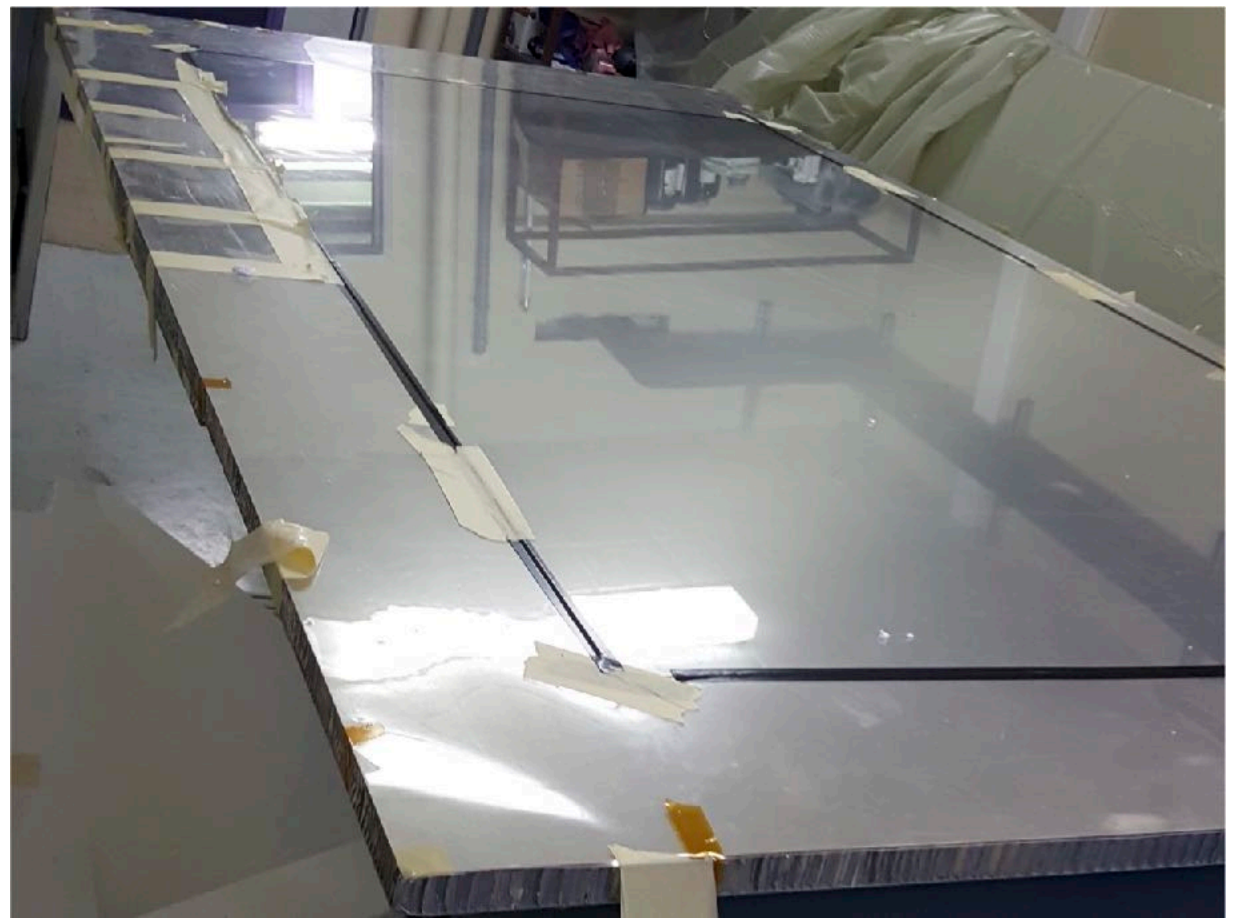
- Embedded electronics, power pulsing, compact interfaces

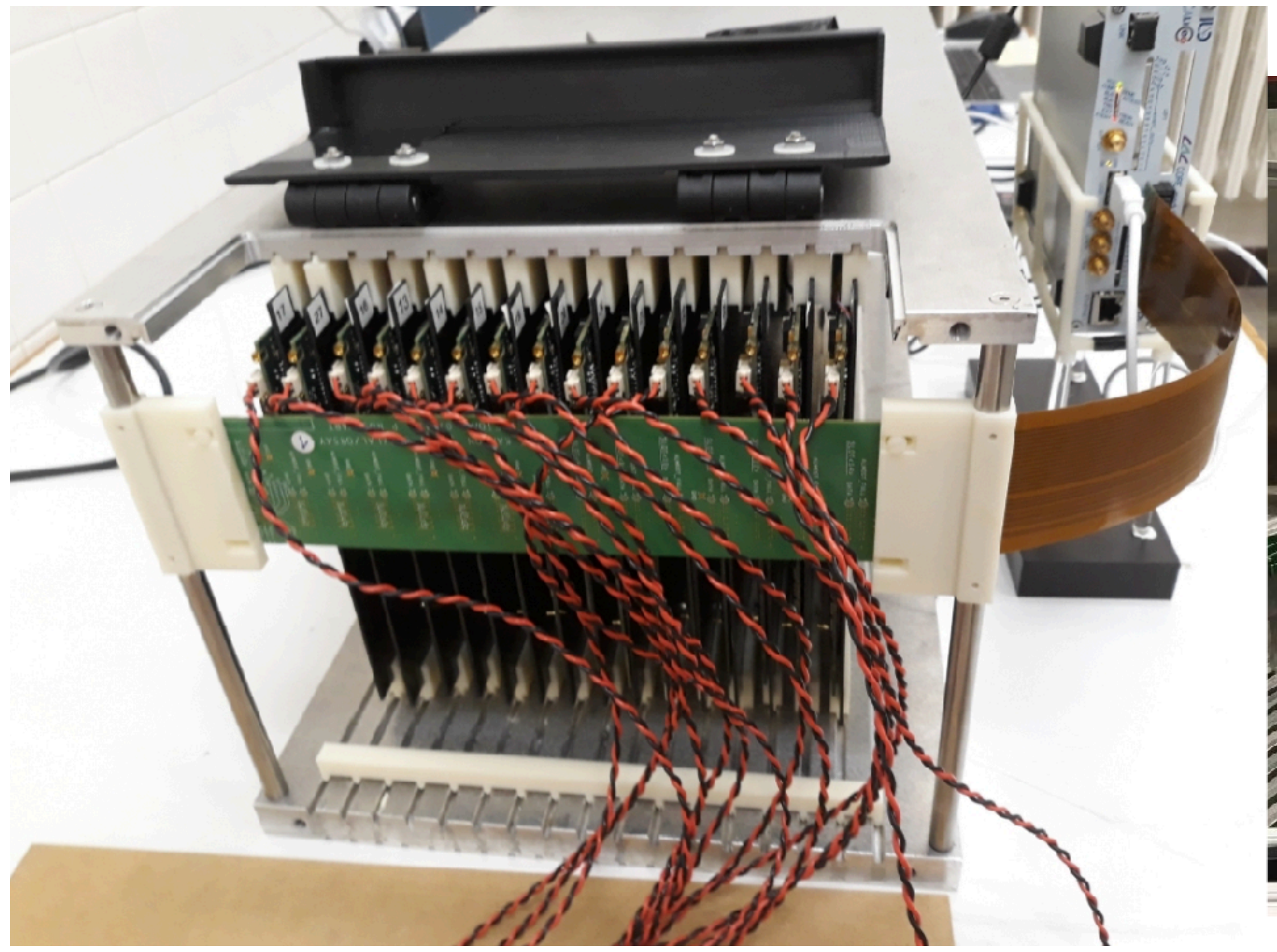




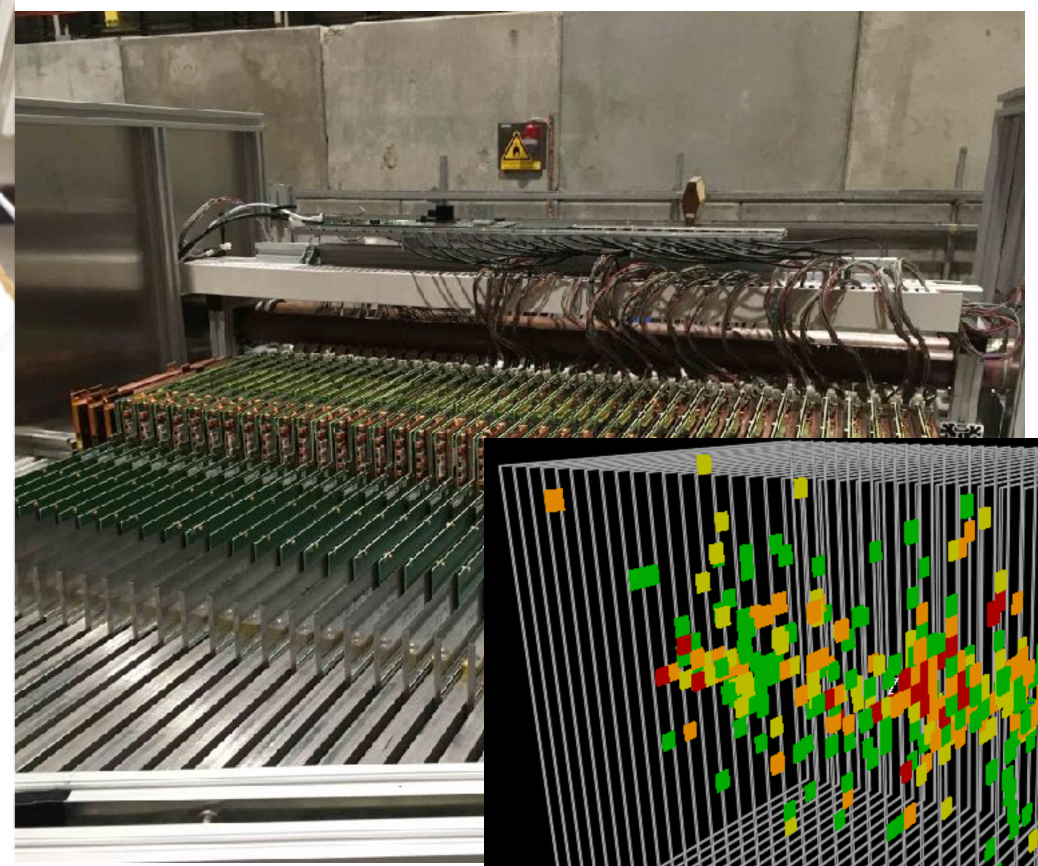
scalability to large areas, automatisation

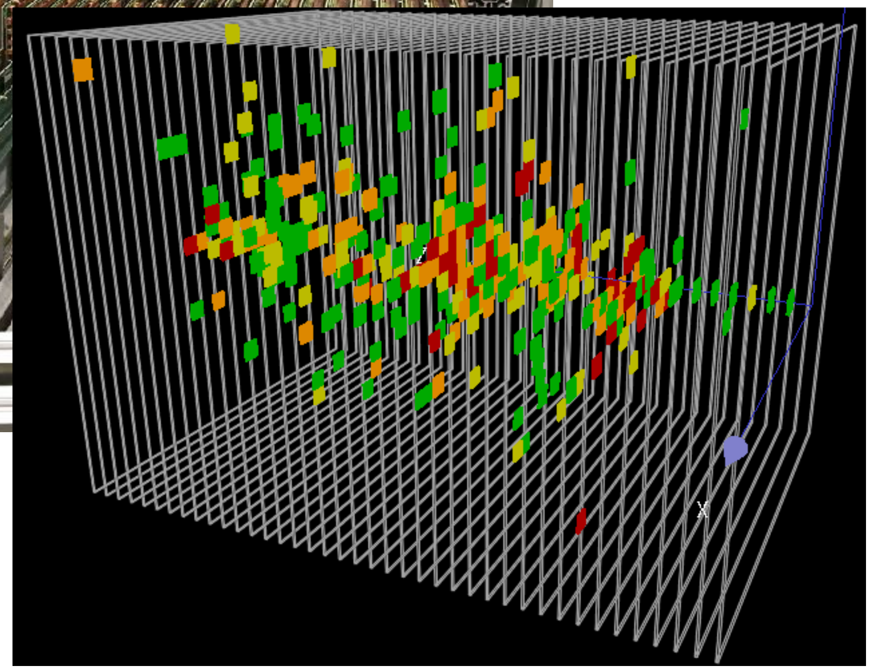
Large RPCs
SDHCAL prototype





SiW ECAL prototype

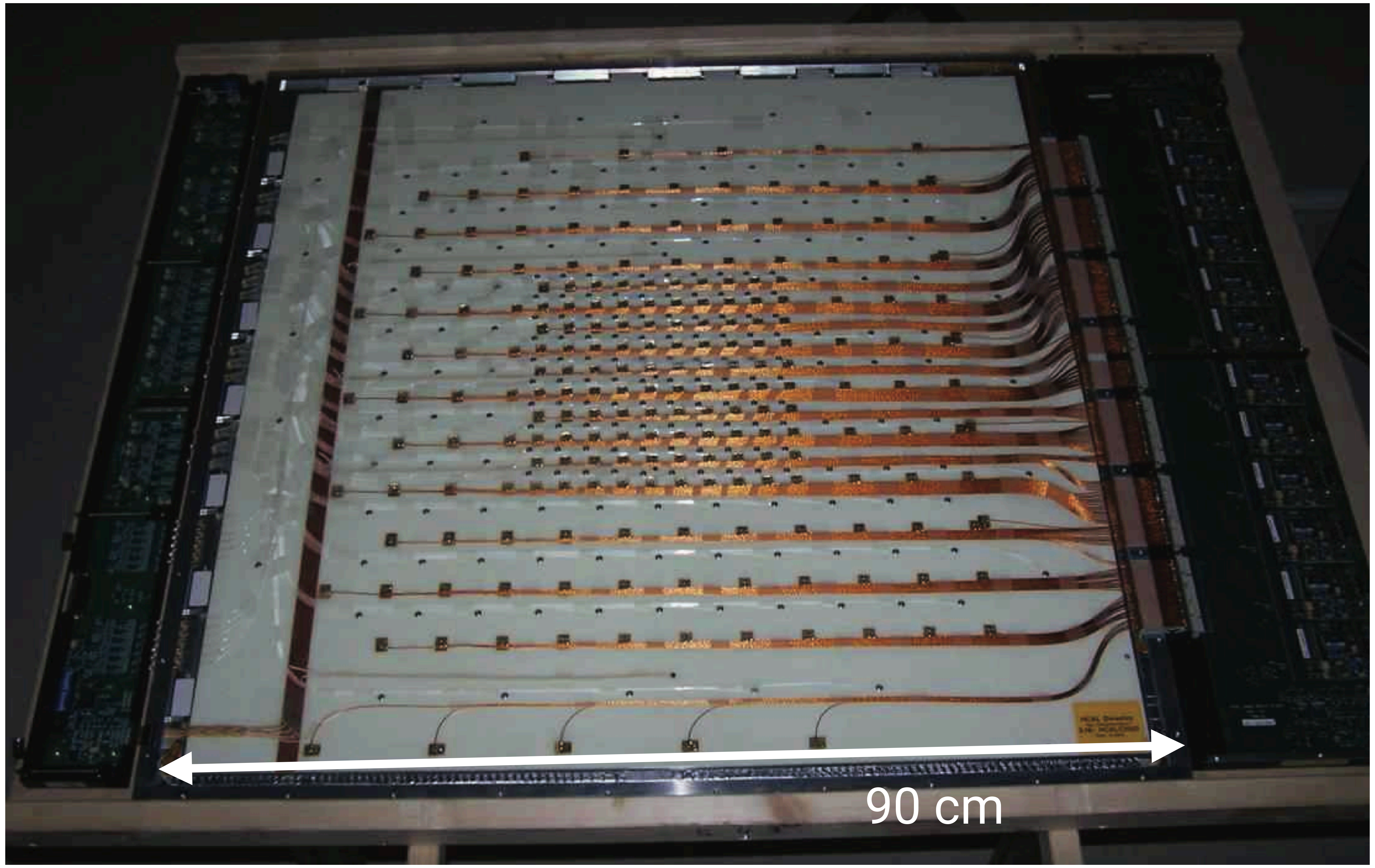




AHCAL prototype

Front-ends and Interfaces

Key elements to meet requirements



Physics prototype: front-end electronics, calibration / power interfaces outside of active volume

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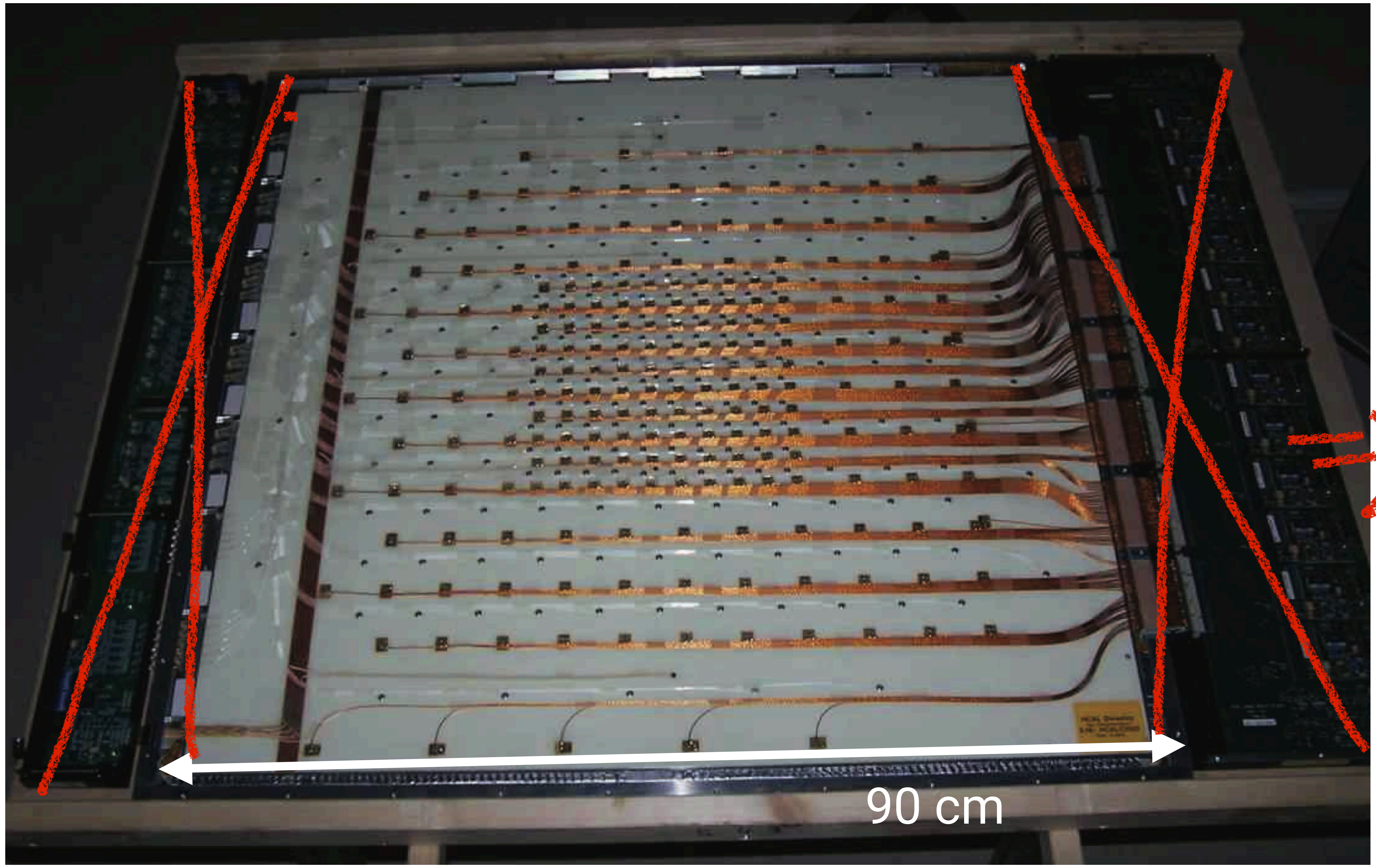
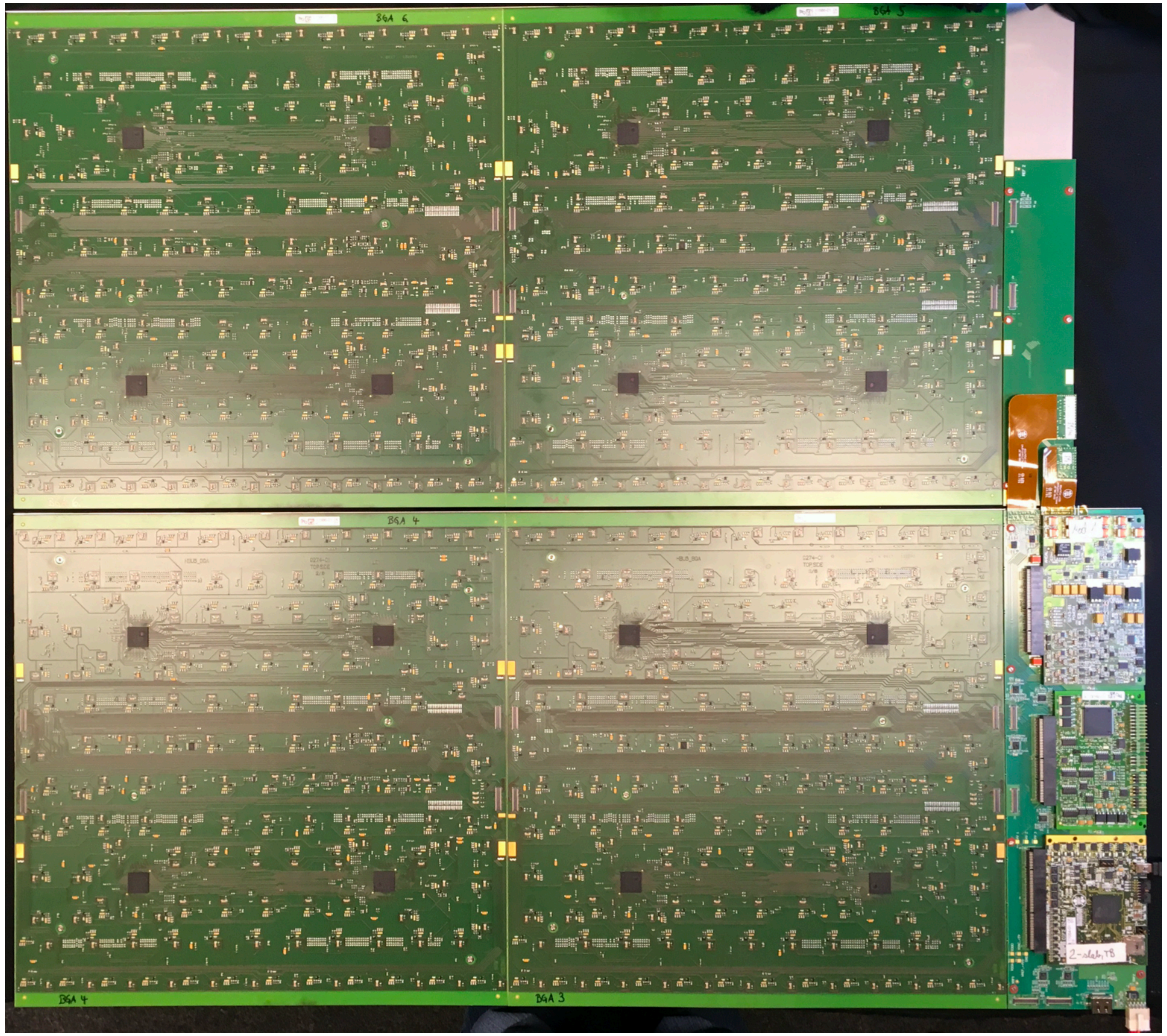


Physics prototype: front-end electronics, calibration / power interfaces outside of active volume

Technological prototype / final design: fully integrated front-end, compact interfaces



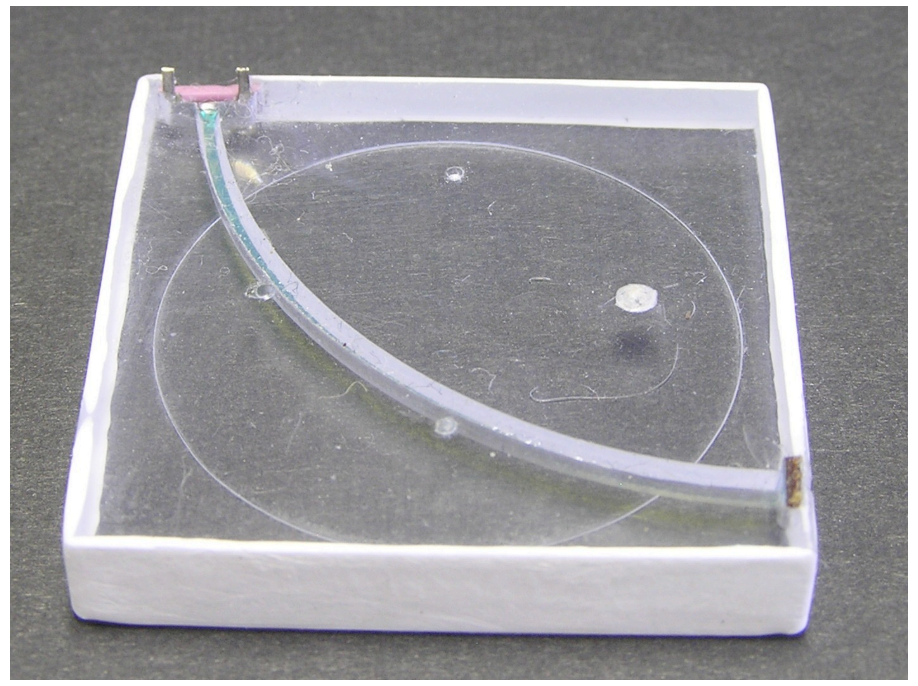
Up to 6 x 3 HBUs controlled by single interface

Towards a viable Solution

Improving the original technology, ensuring scalability

- From the first large-scale application of SiPMs to the "***SiPM-on-tile***" technology

2008 - 2016



Physics Prototype

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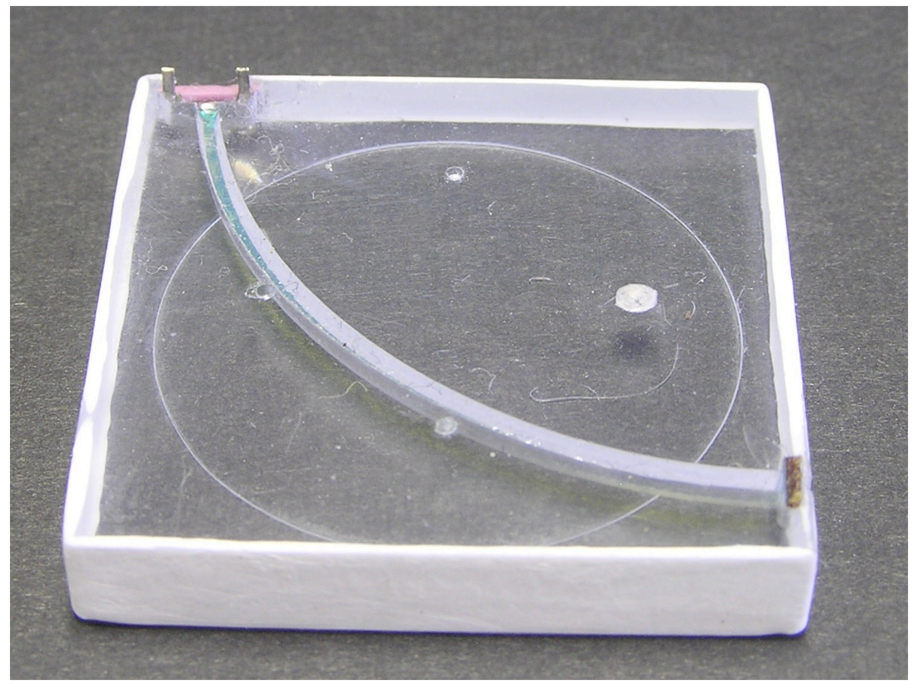

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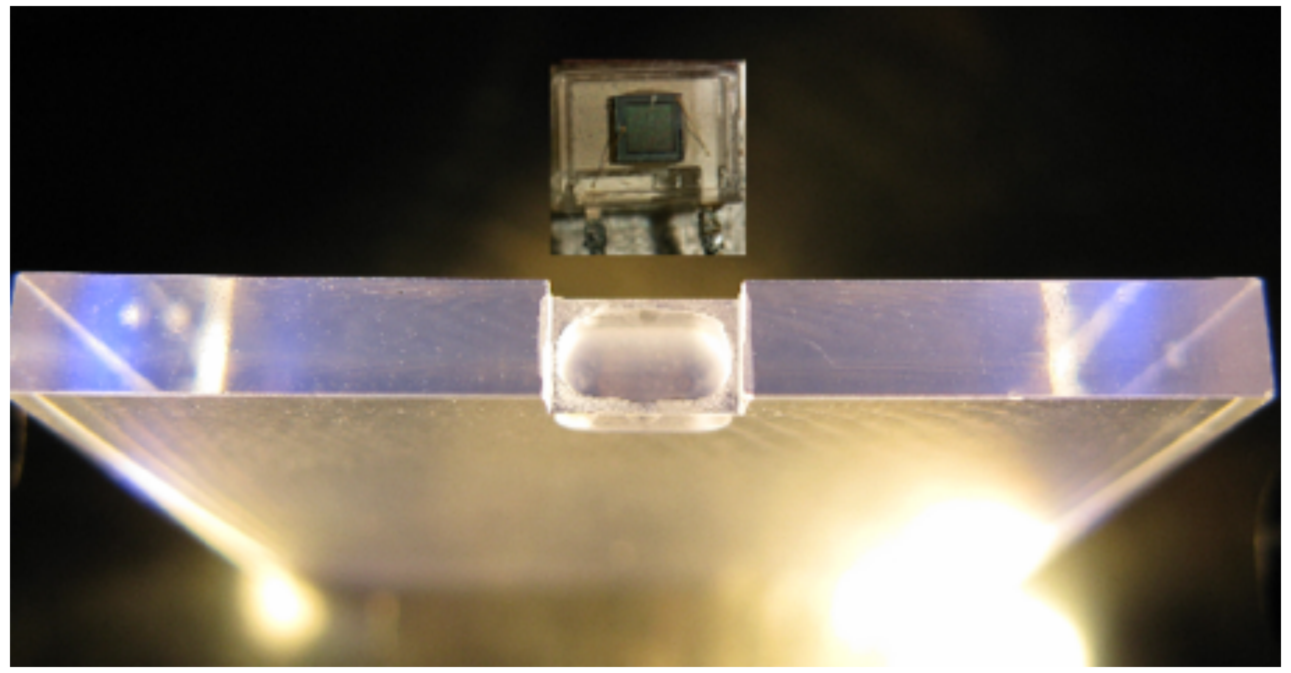

Direct coupling of tiles and photon sensors

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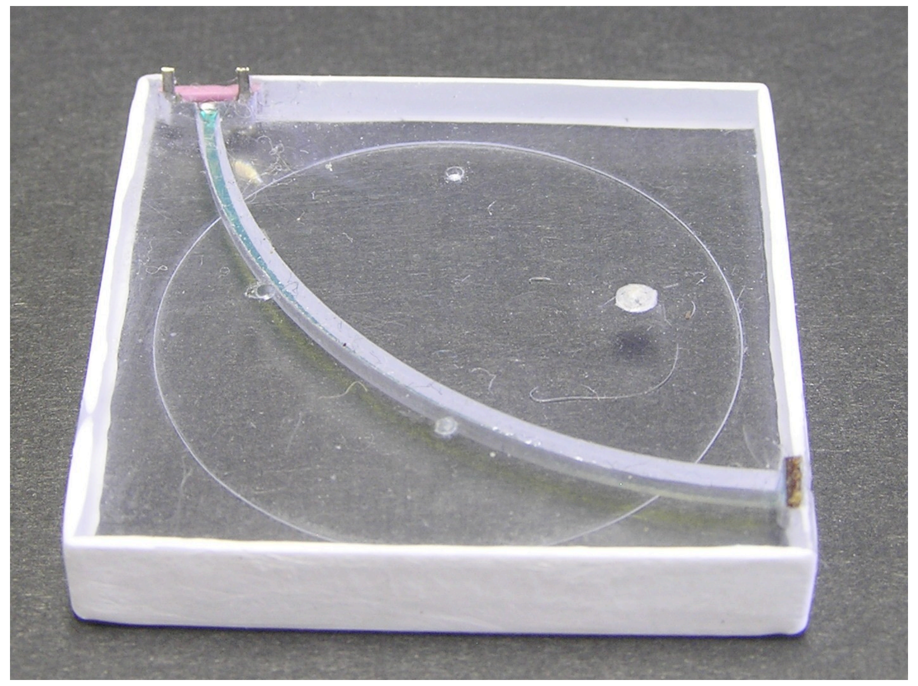

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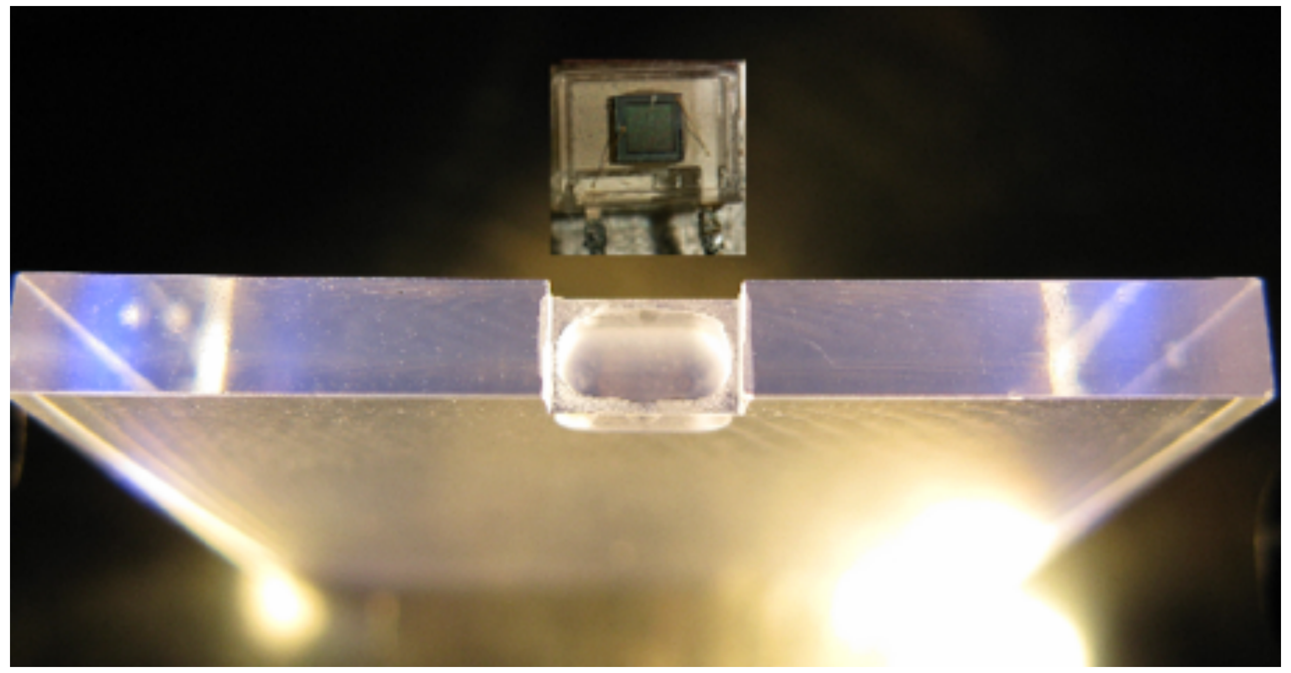

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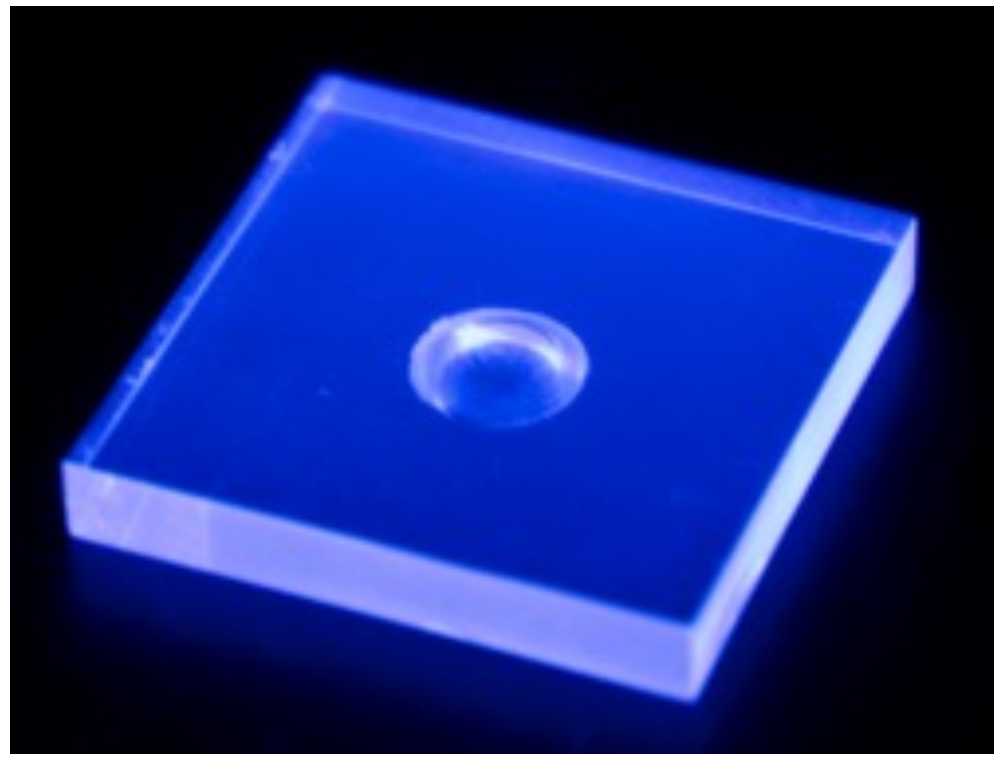

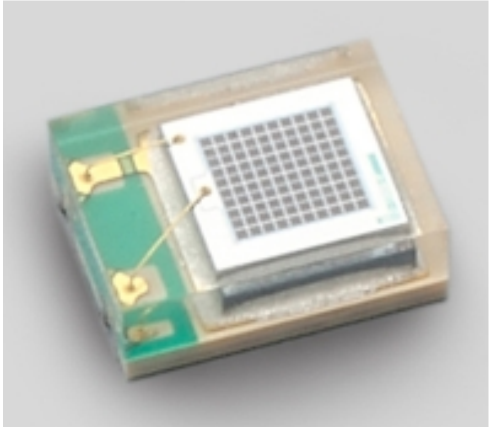

SMD SiPMs, modification of direct coupling

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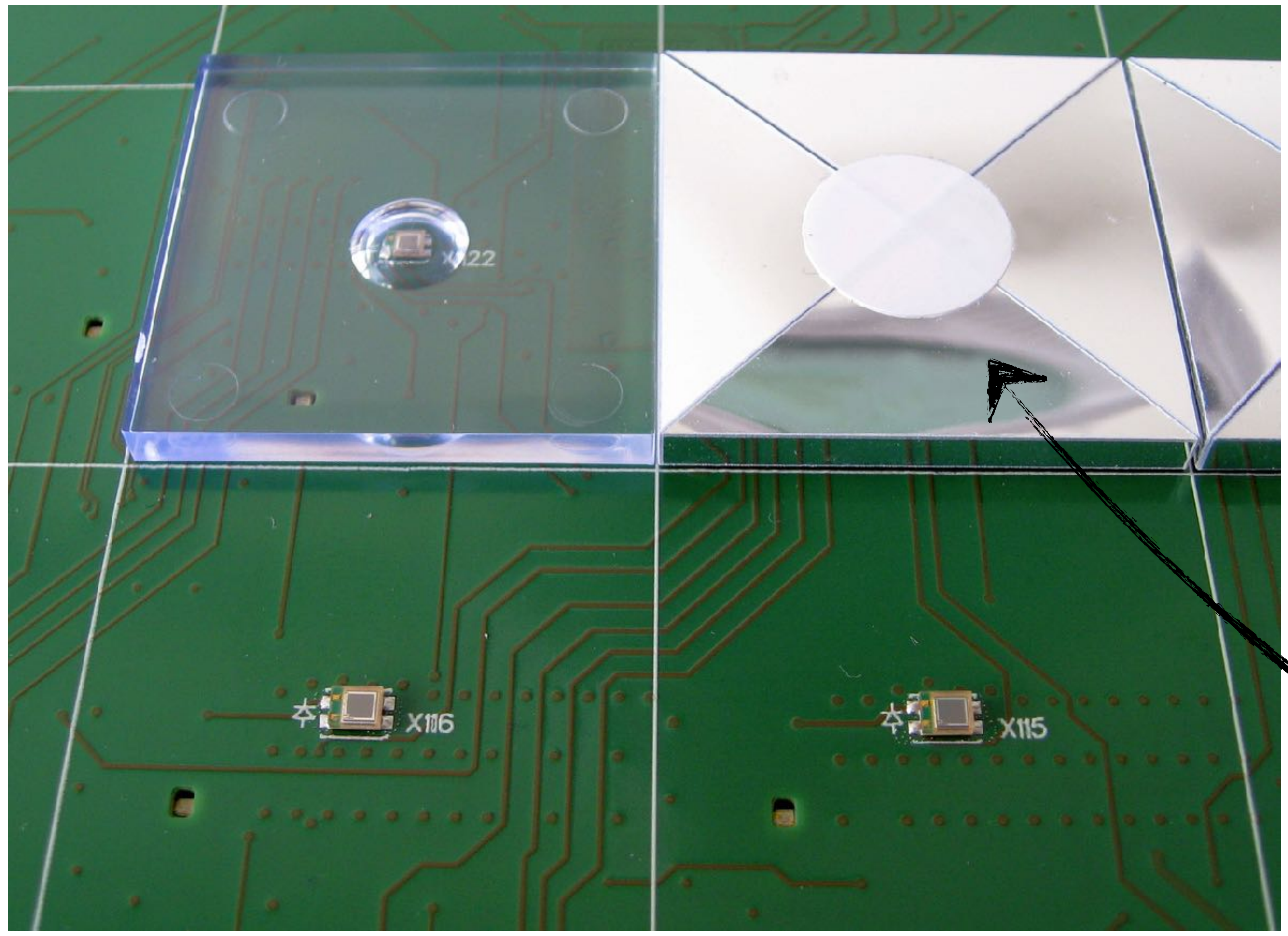

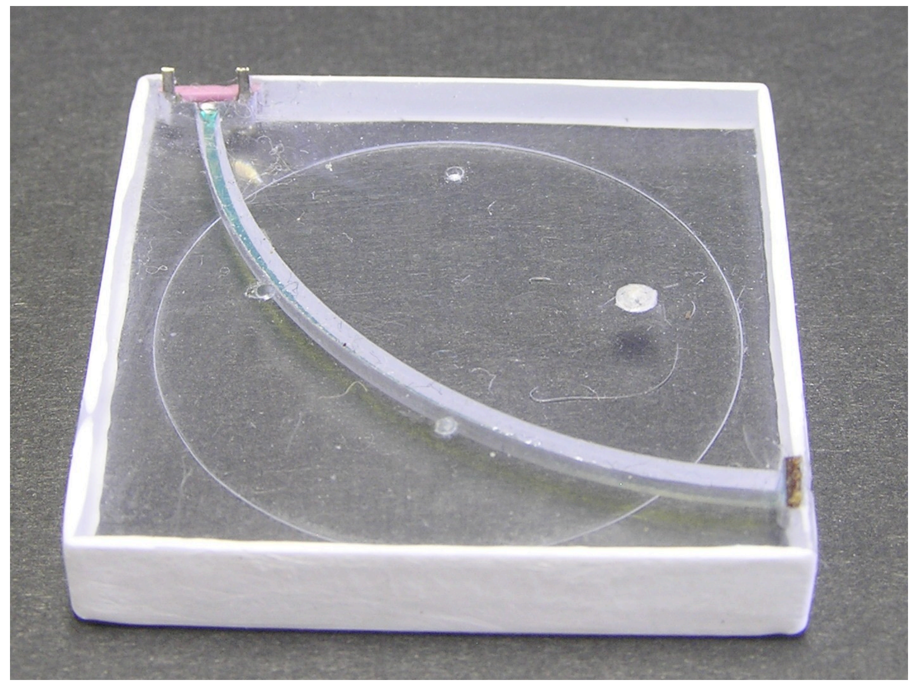

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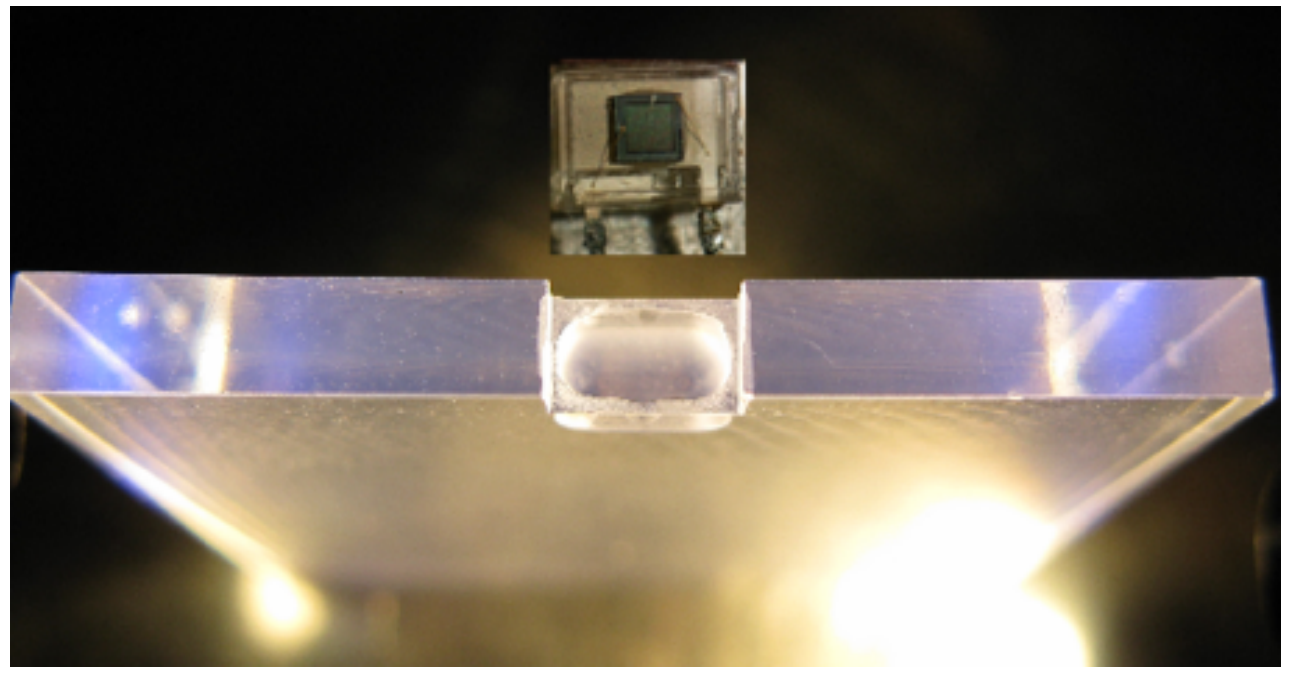

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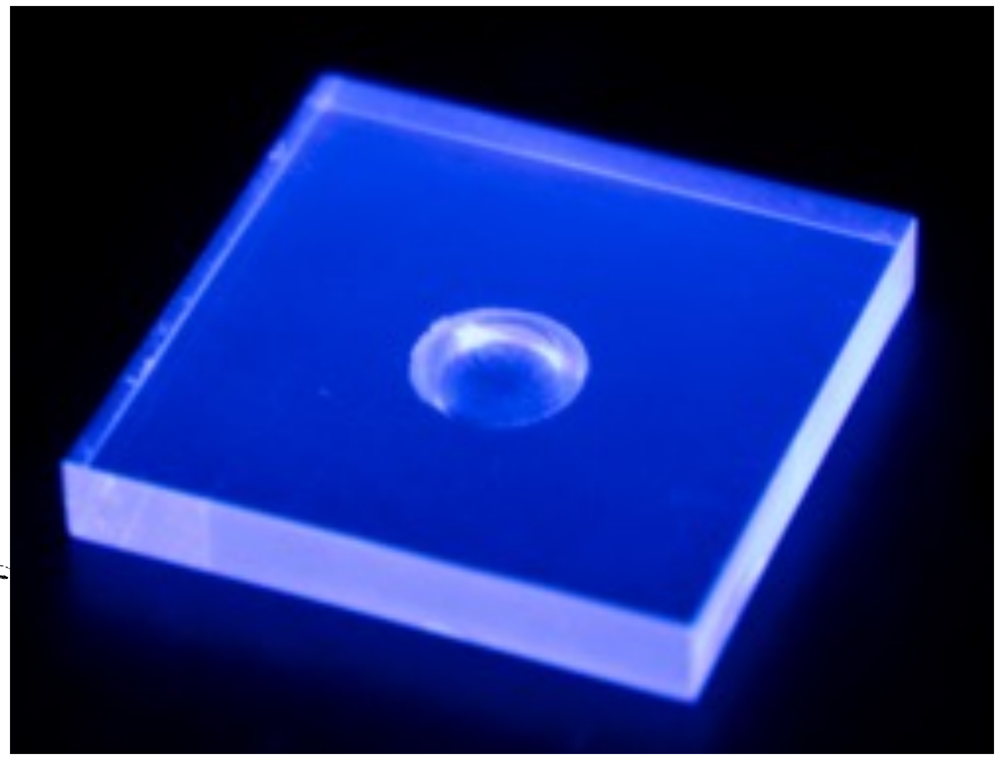

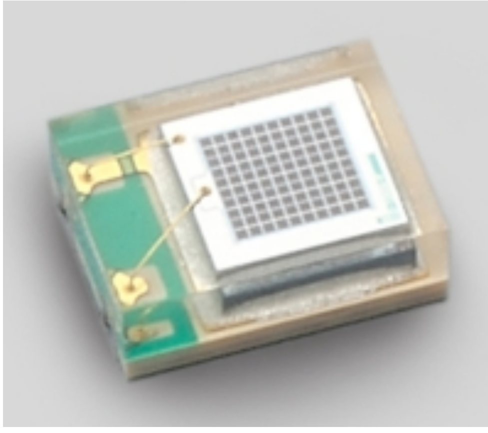

SMD SiPMs, modification of direct coupling

Fully integrated concept with embedded front-end electronics, calibration system

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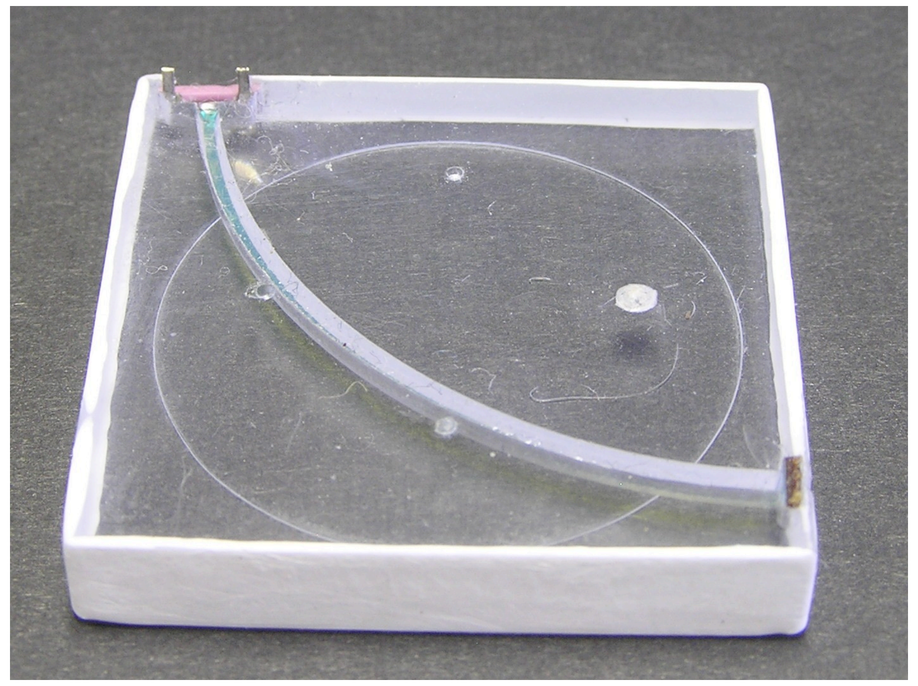

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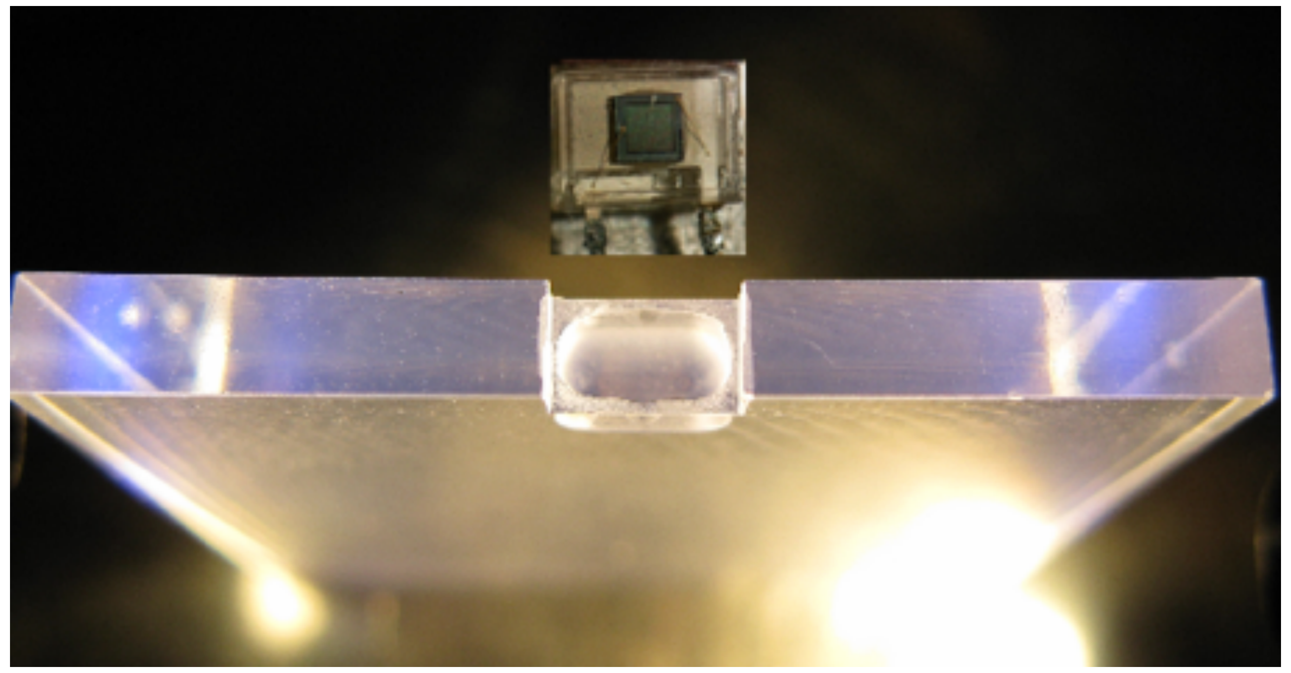

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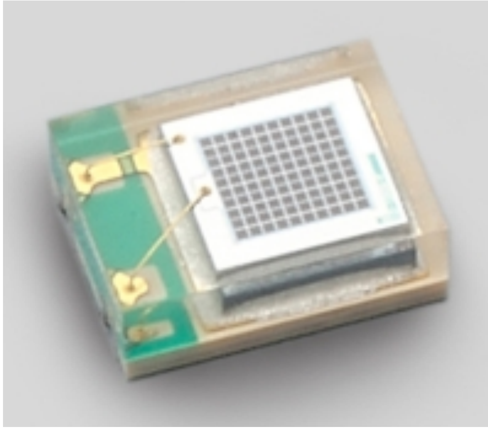

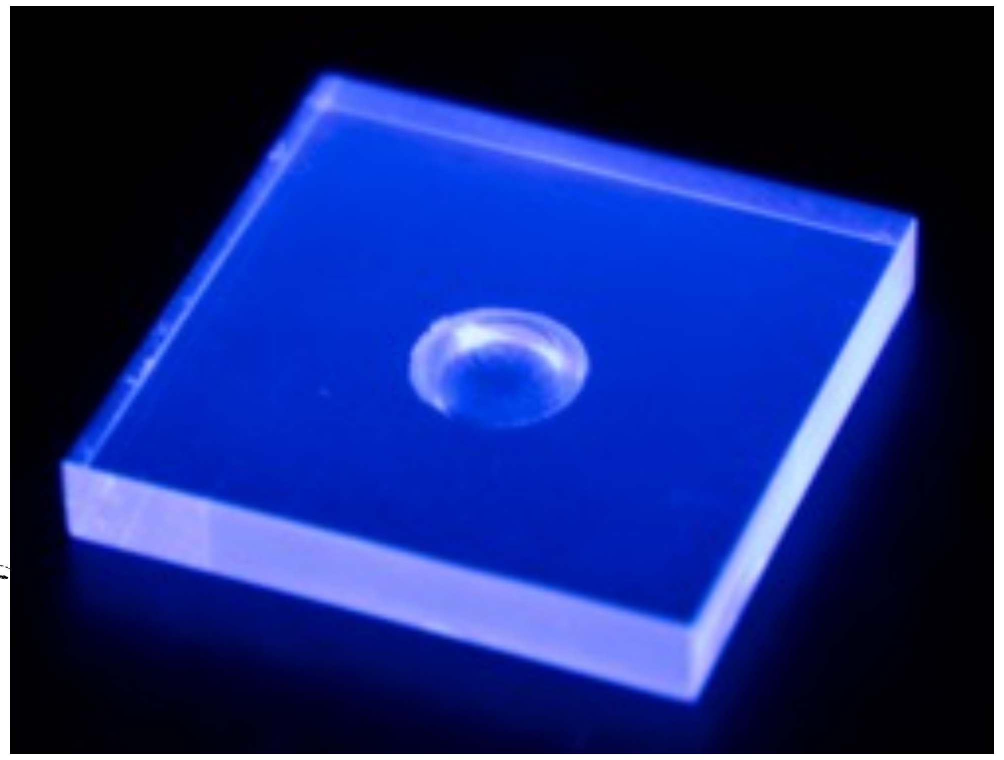

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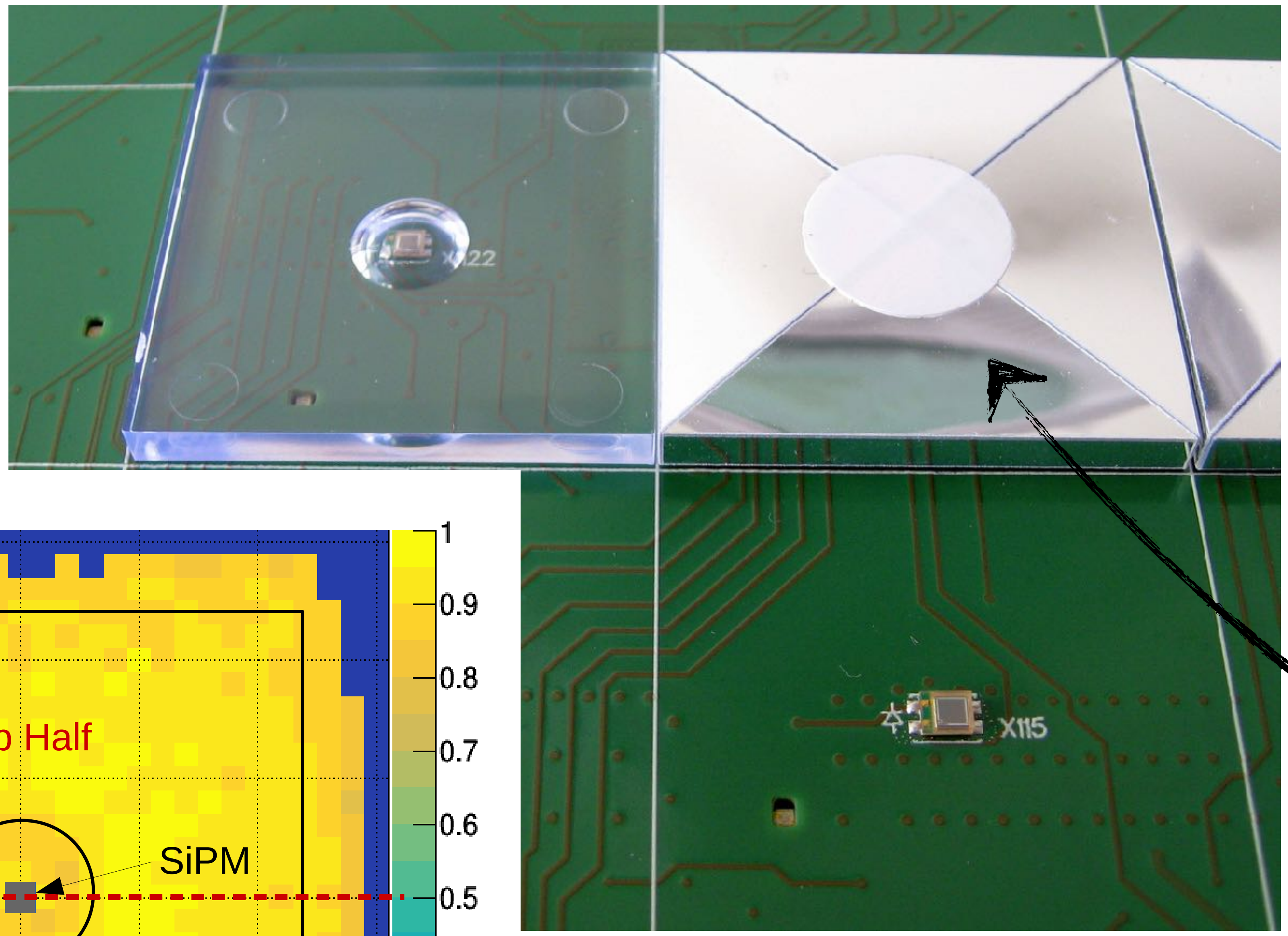

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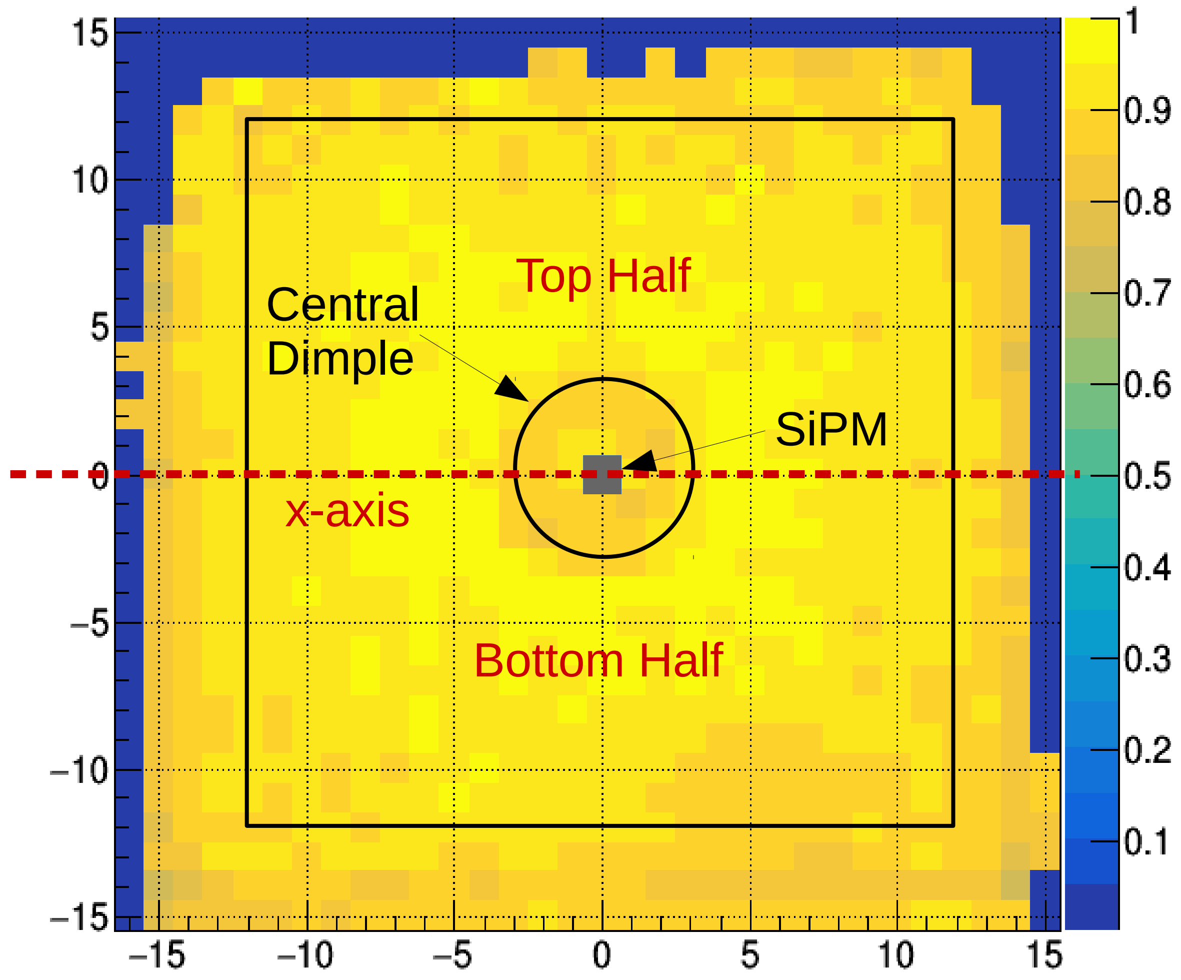
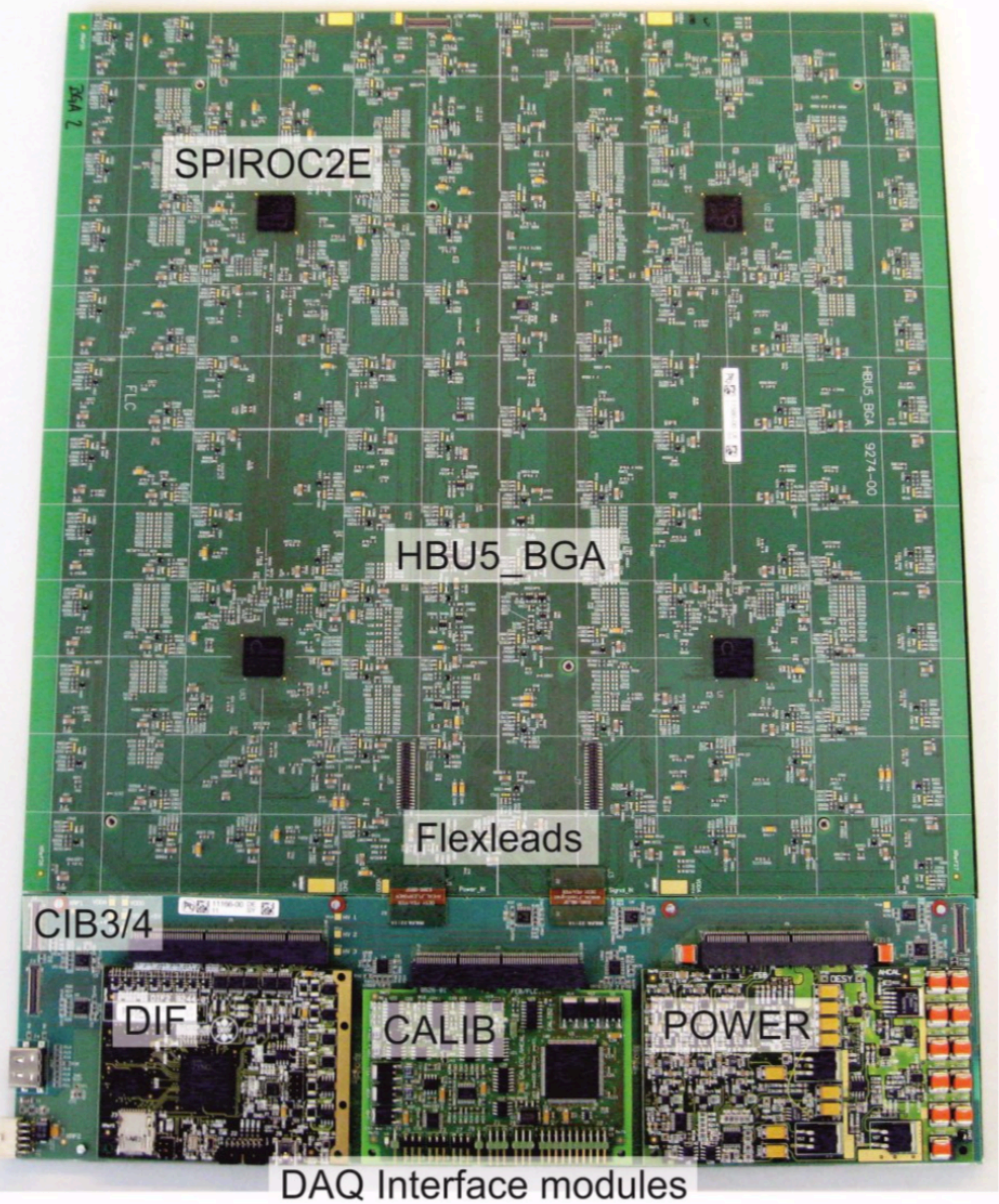


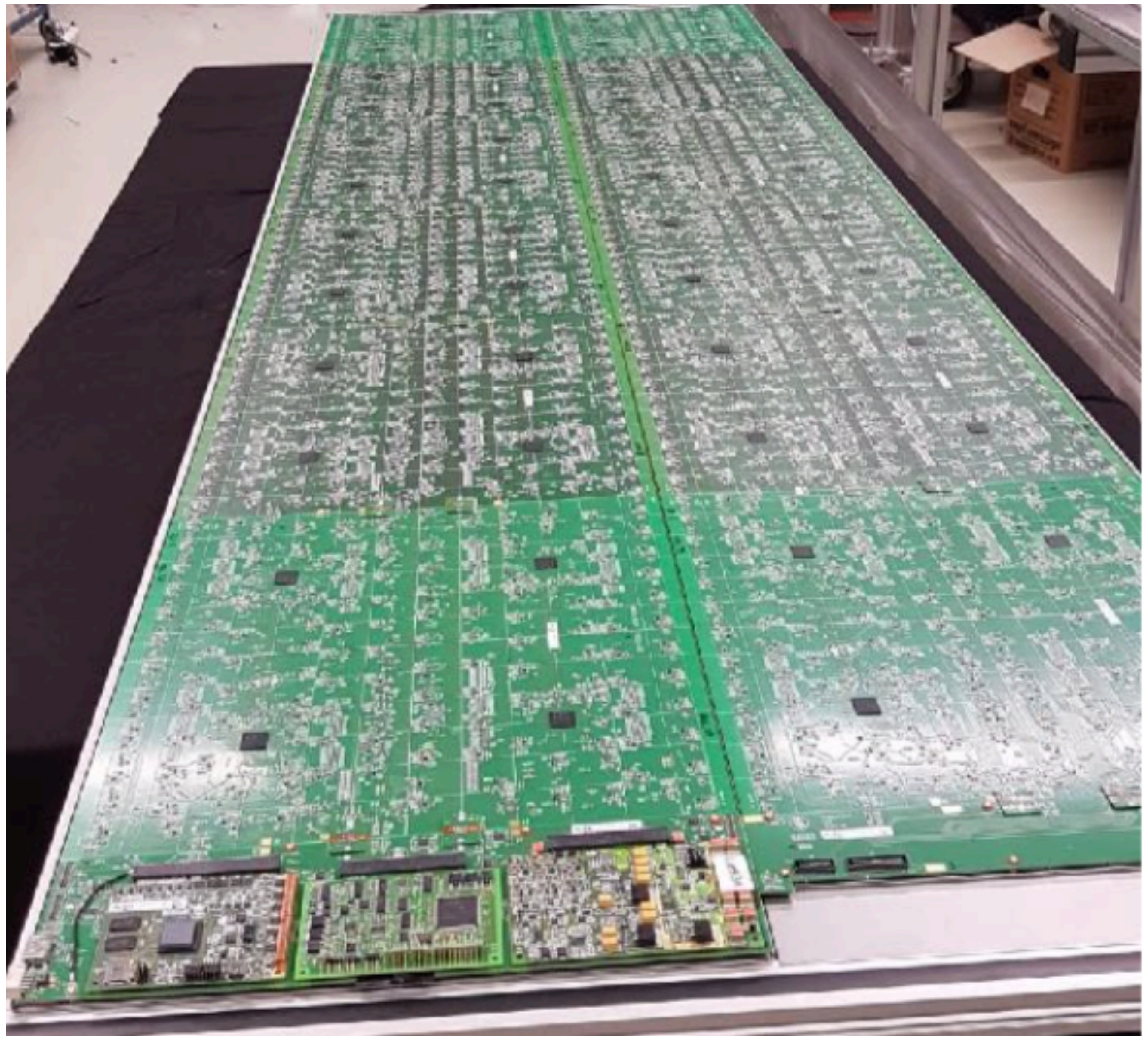
Validation of element performance

The Full Concept: The CALICE AHCAL Technological Prototype

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies



- Fully integrated electronics, with HBU “base units” combinable to larger areas, compact control & services



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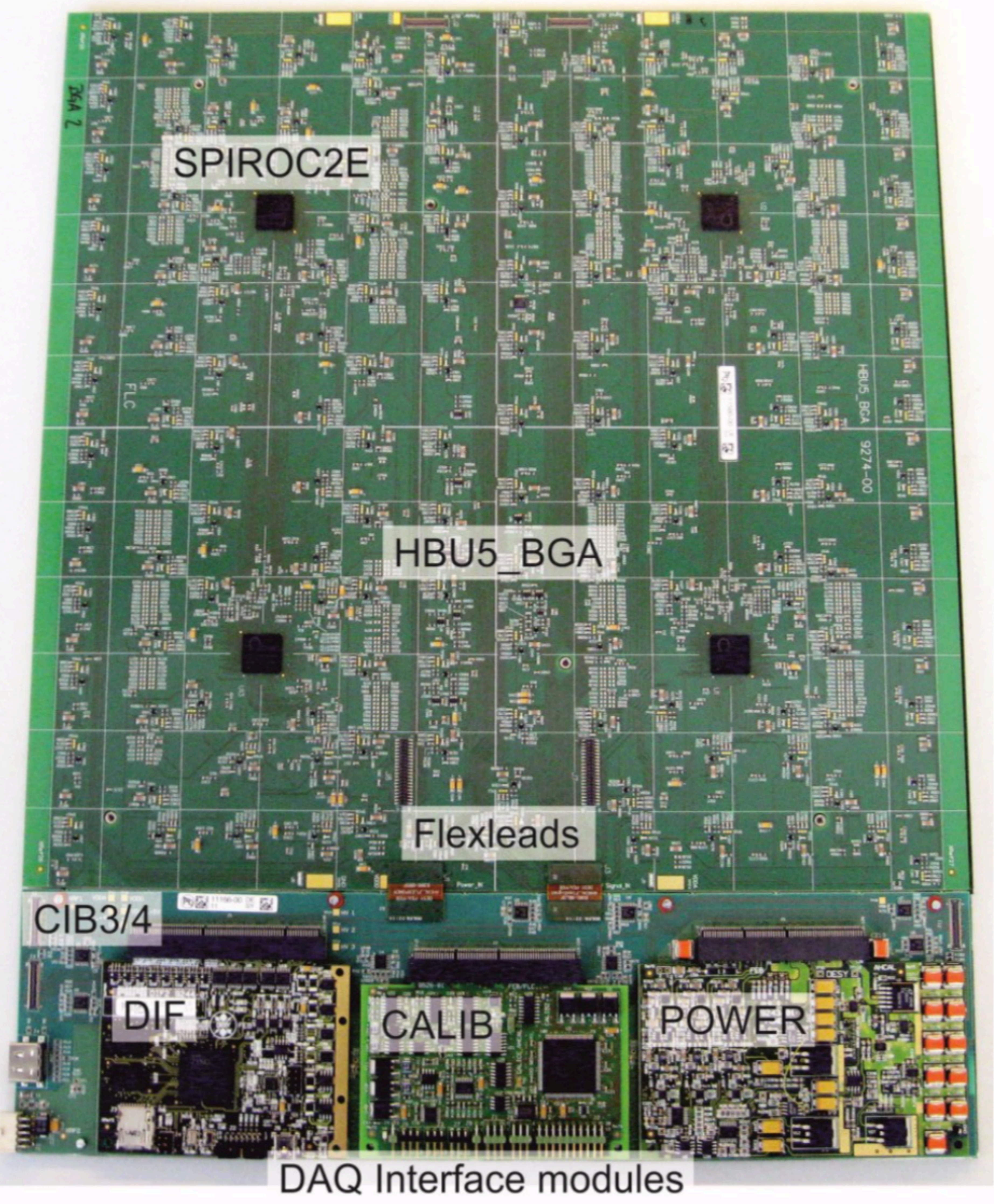

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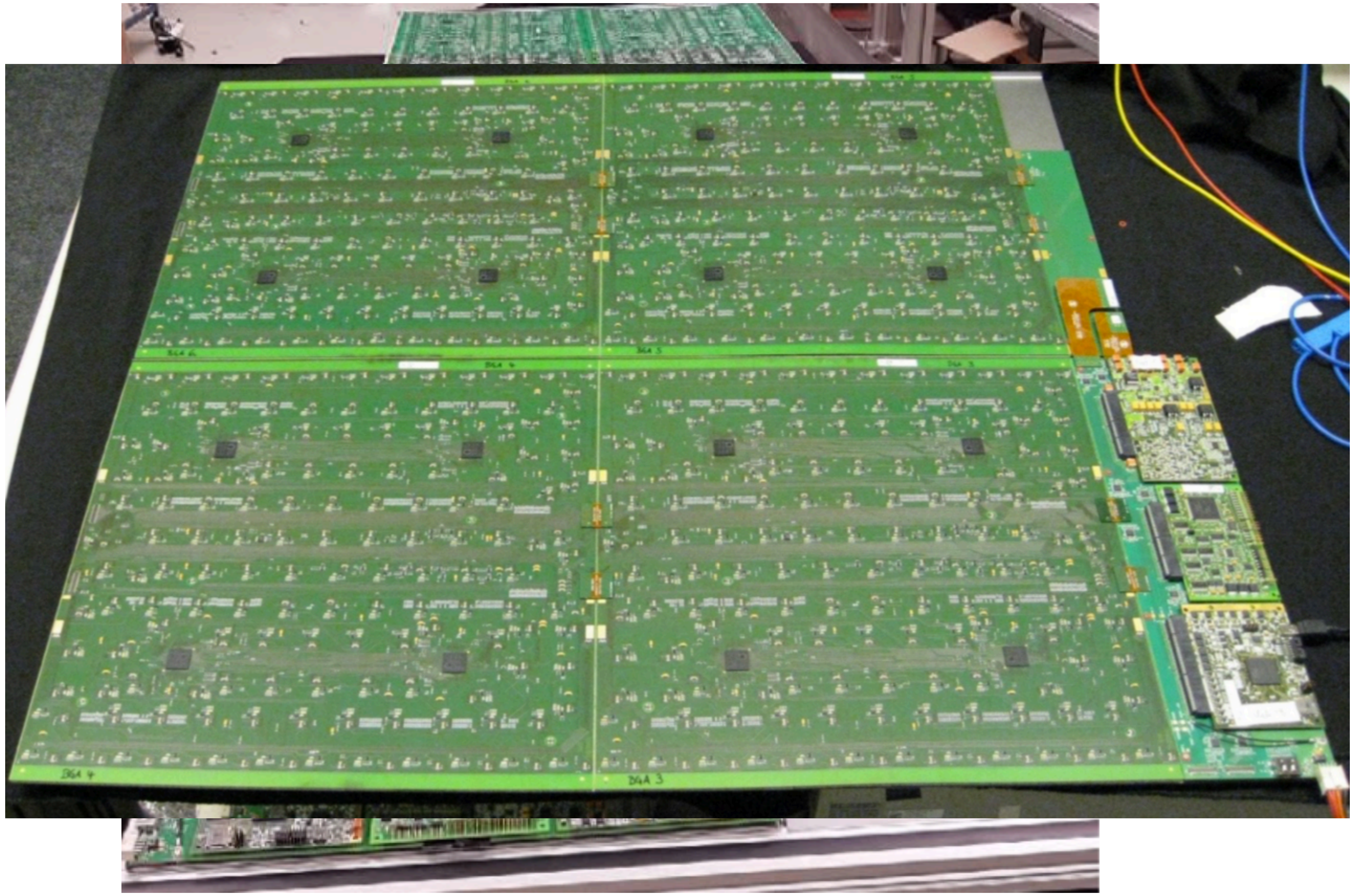

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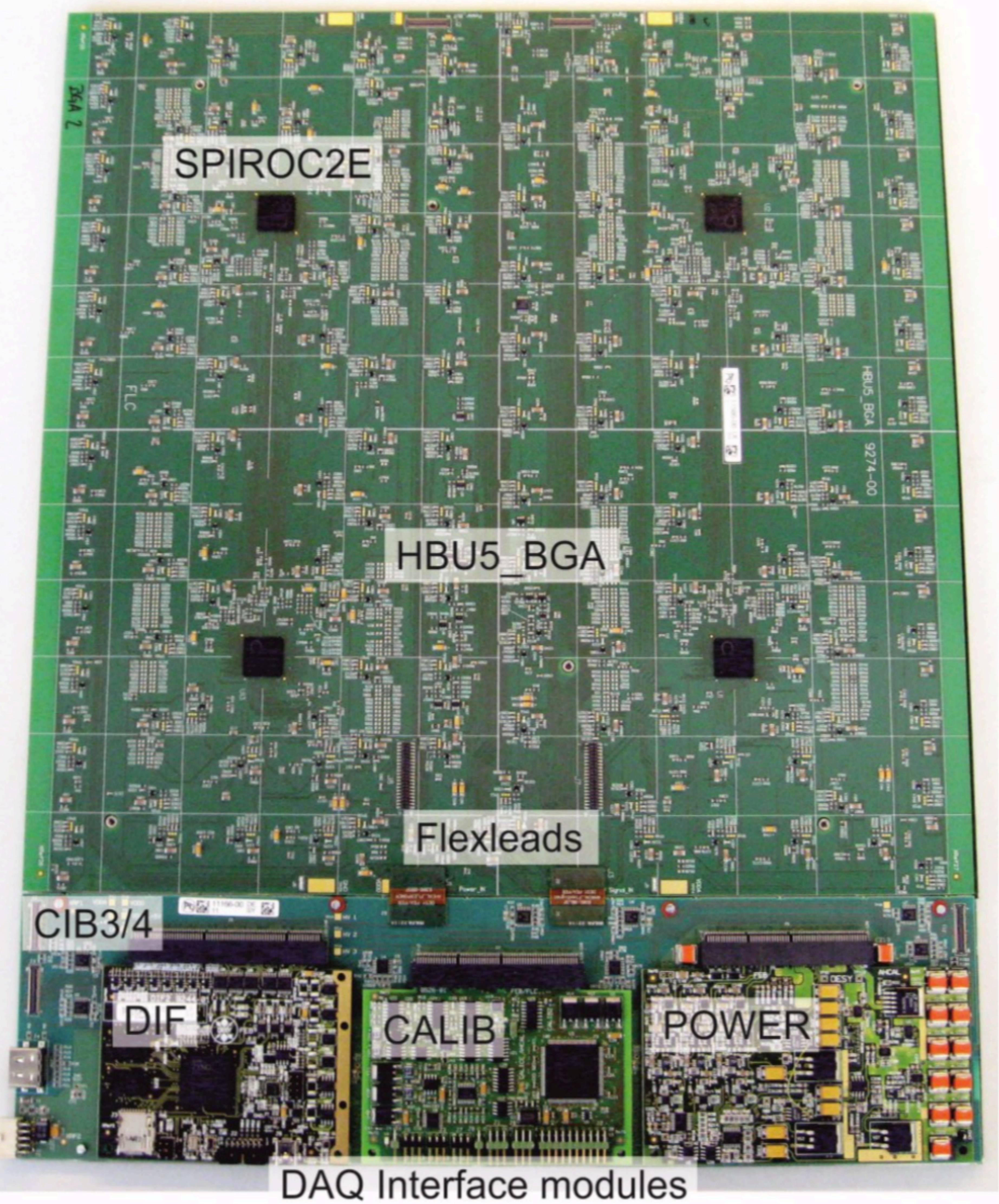

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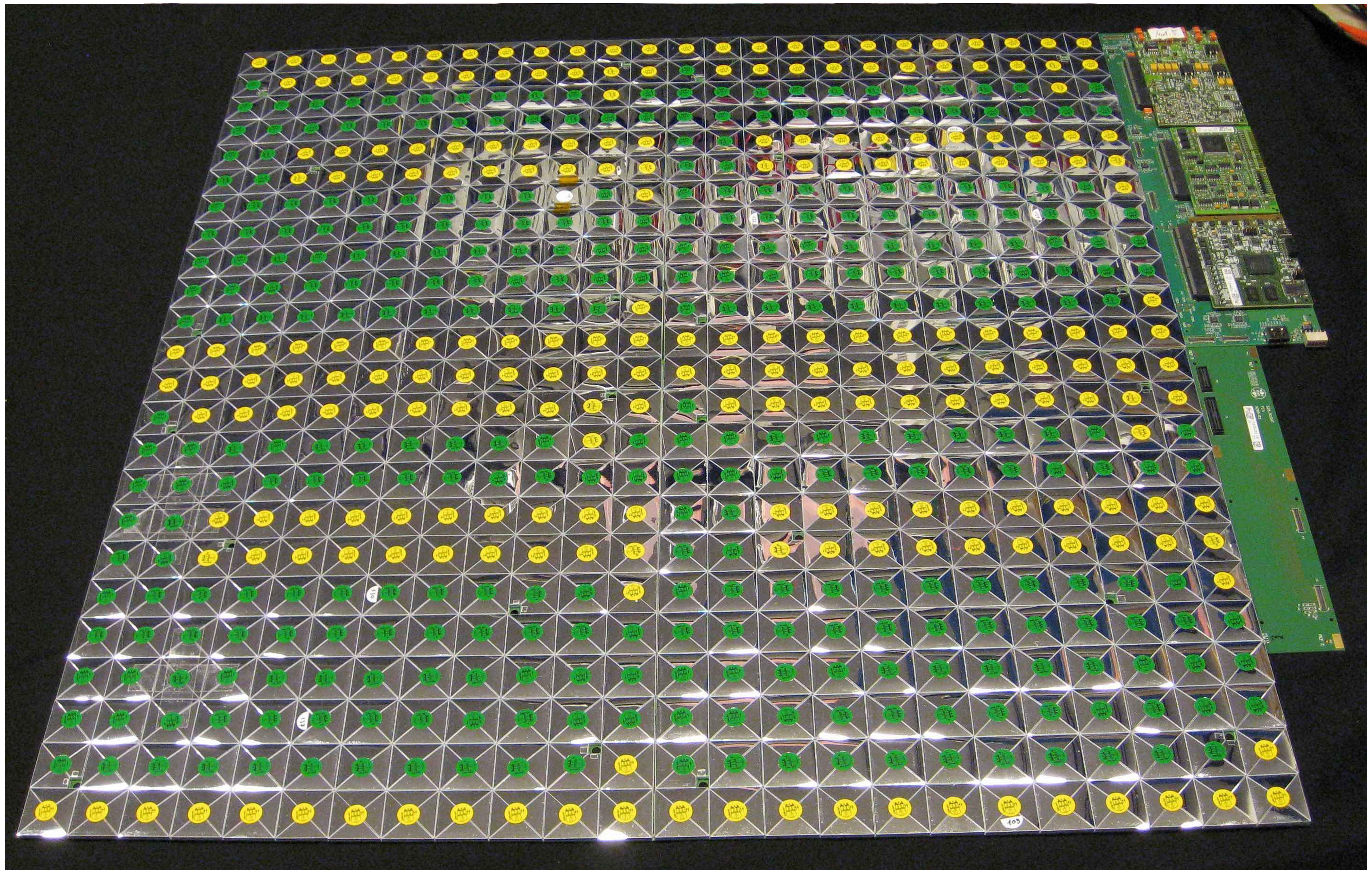
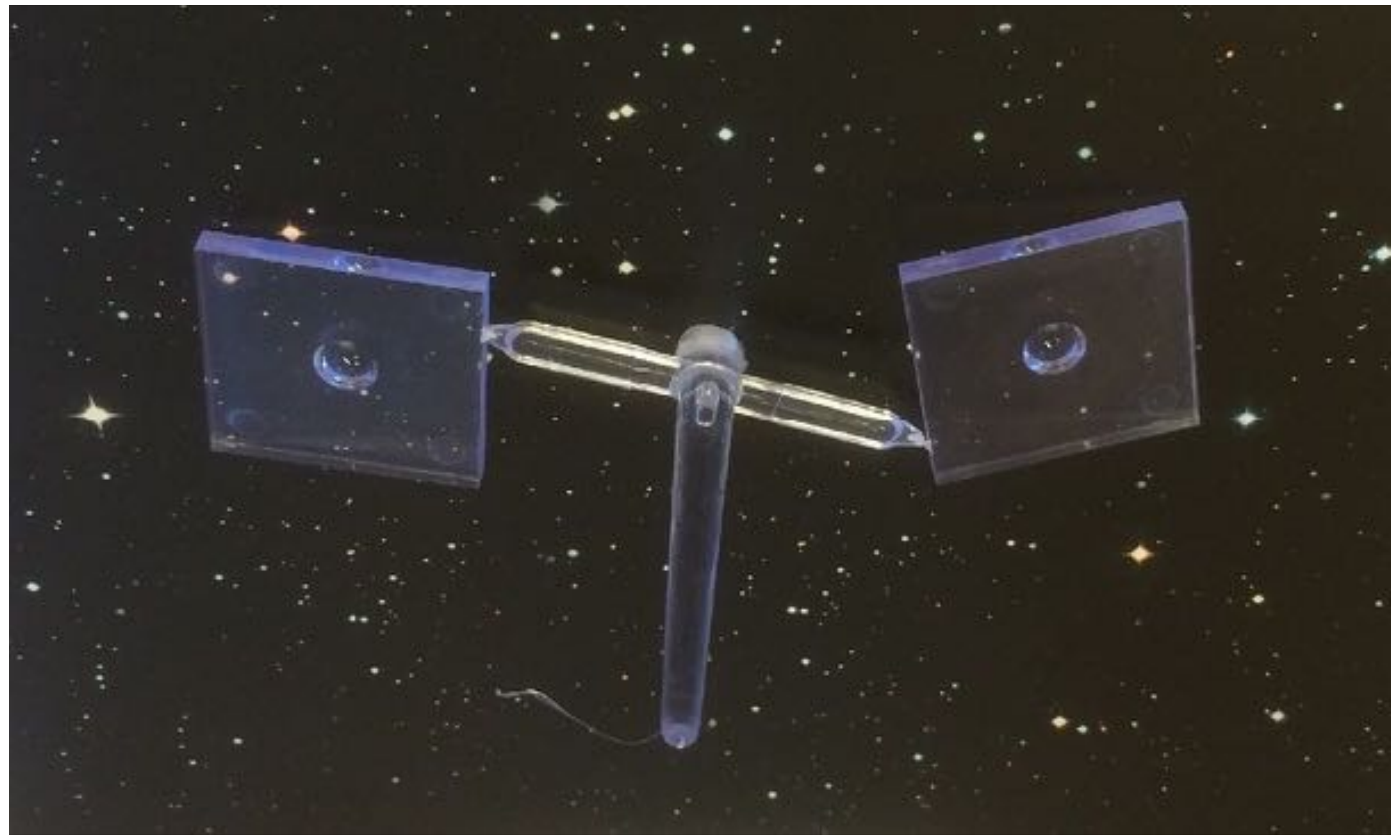
SiPMs / scintillators on other side of board



Construction of the AHCAL Prototype

Exercising scalability

- Mass production for a new 0.5 m^3, 22k channel prototype
  - 24k tiles produced & wrapped



injection molding of PS based scintillator tiles

09/2017

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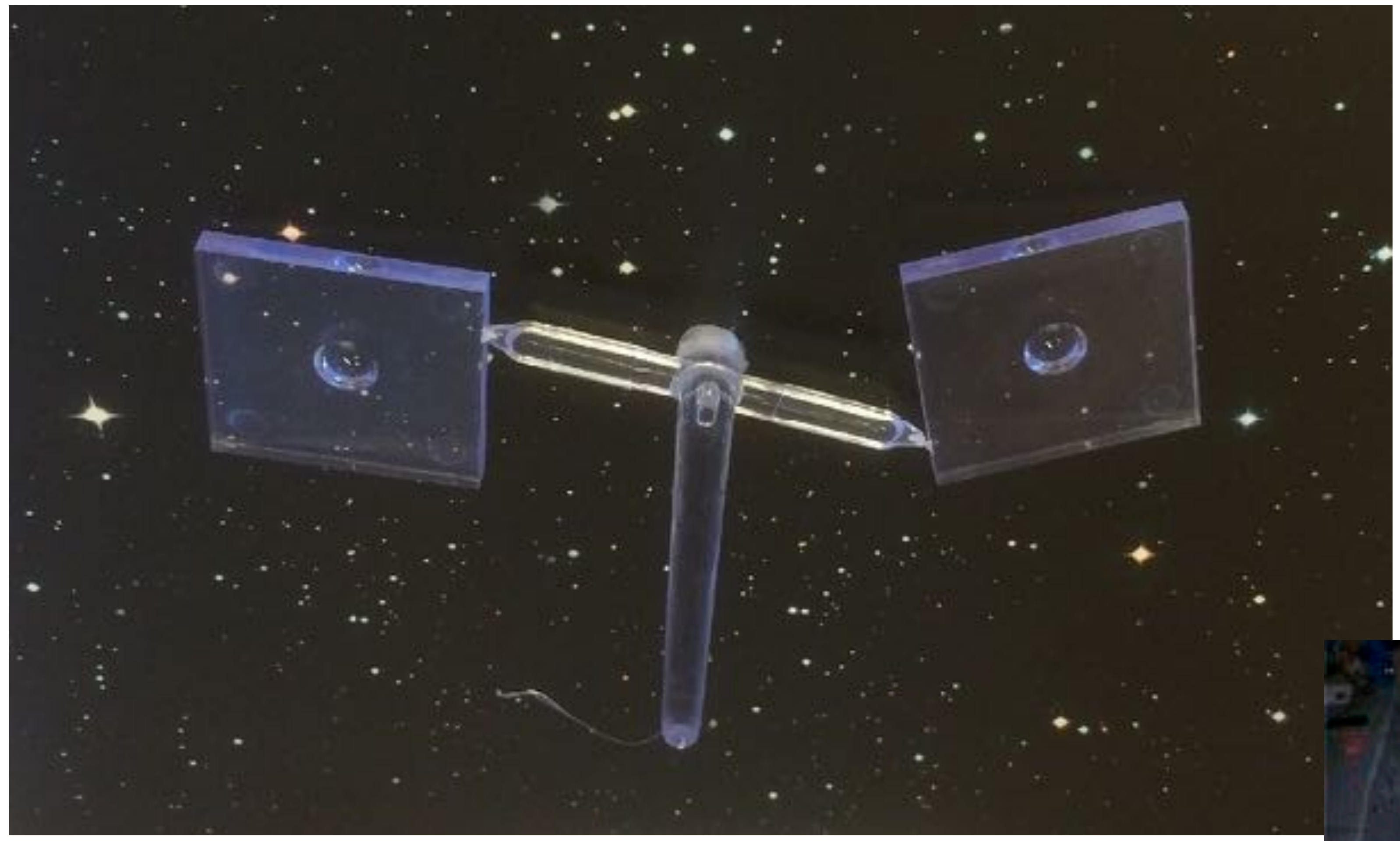

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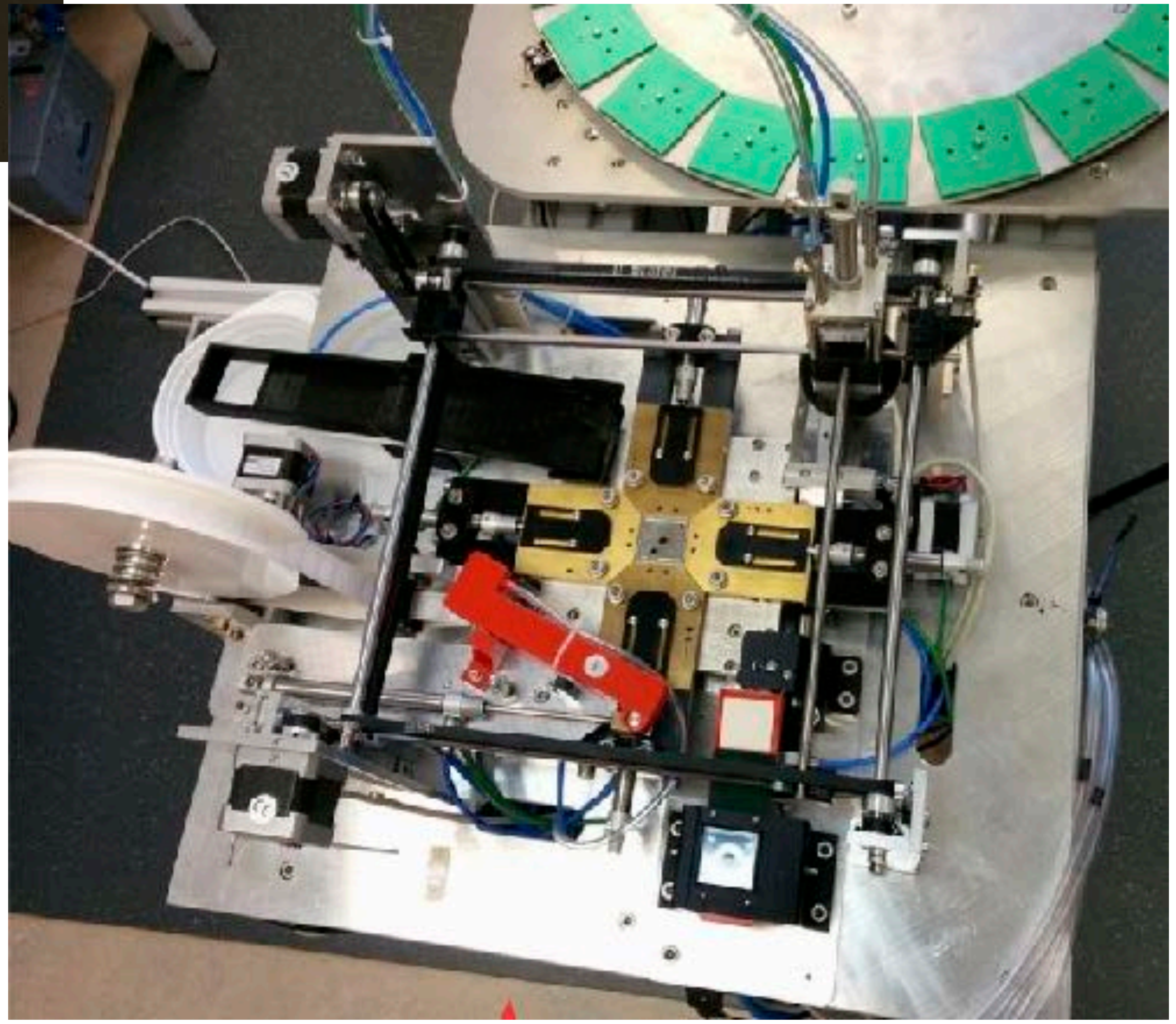

10/2017 - 01/2018

semi-automatic wrapping of scintillator tiles

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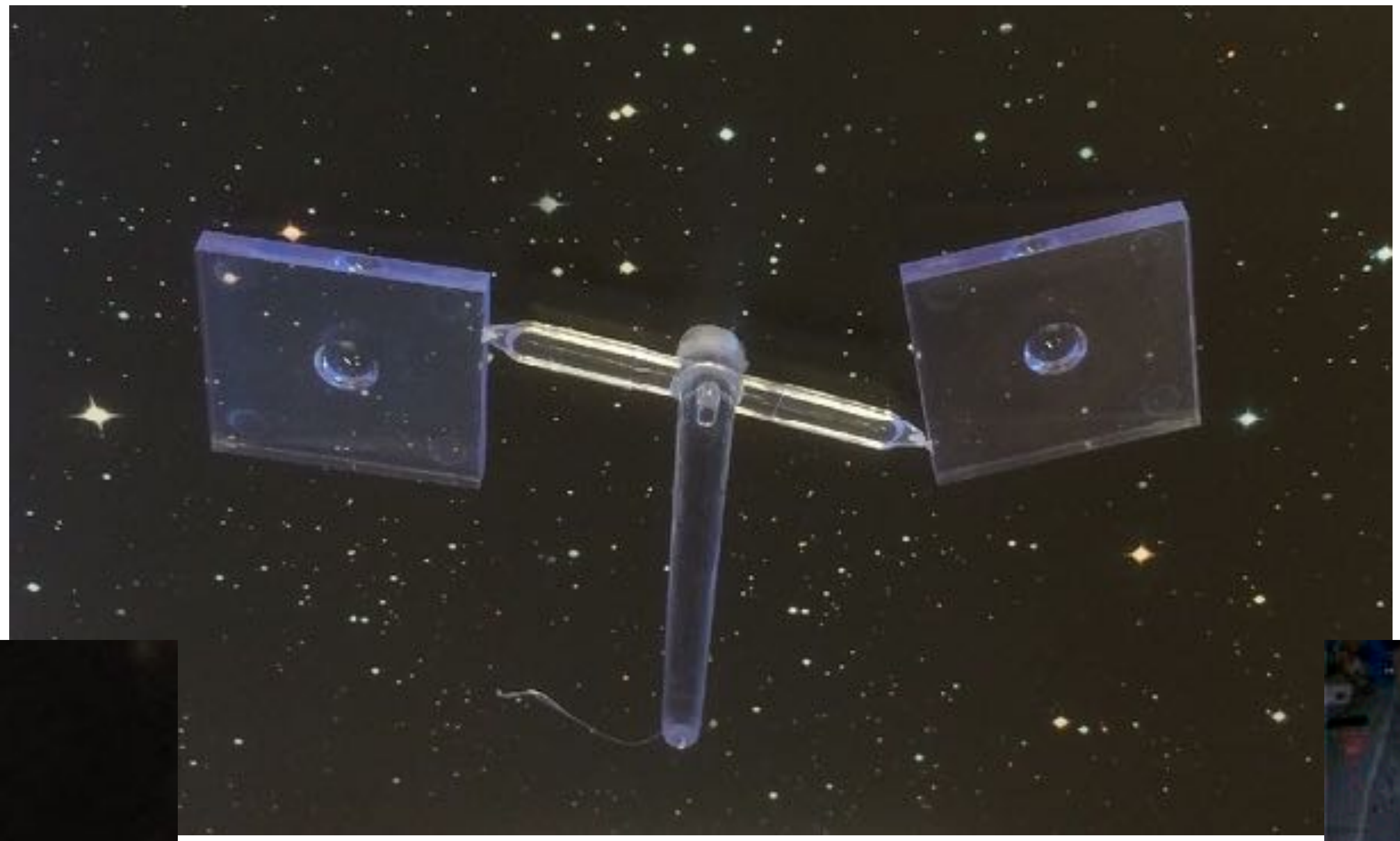

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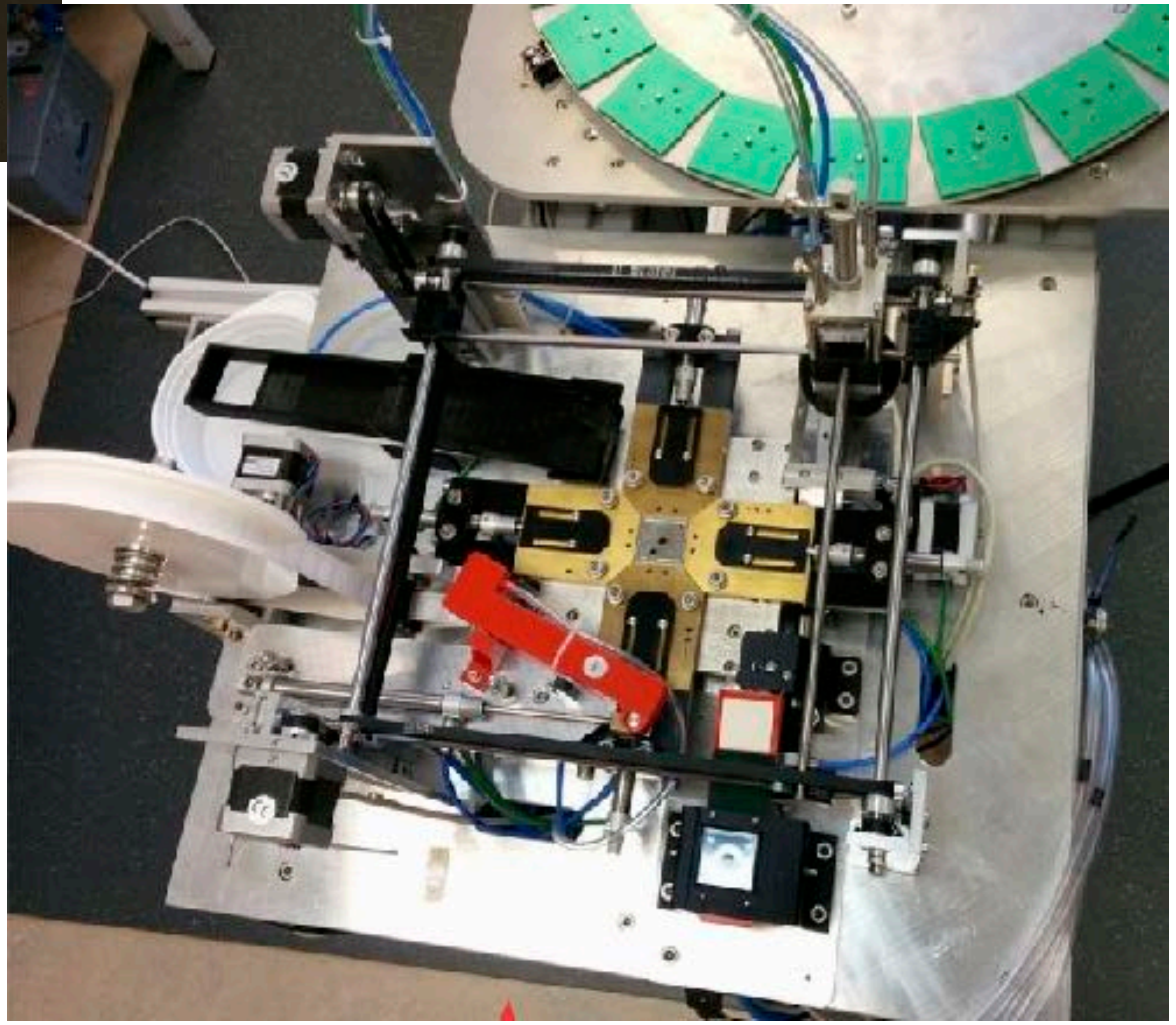


semi-automatic wrapping of scintillator tiles

10/2017 - 01/2018

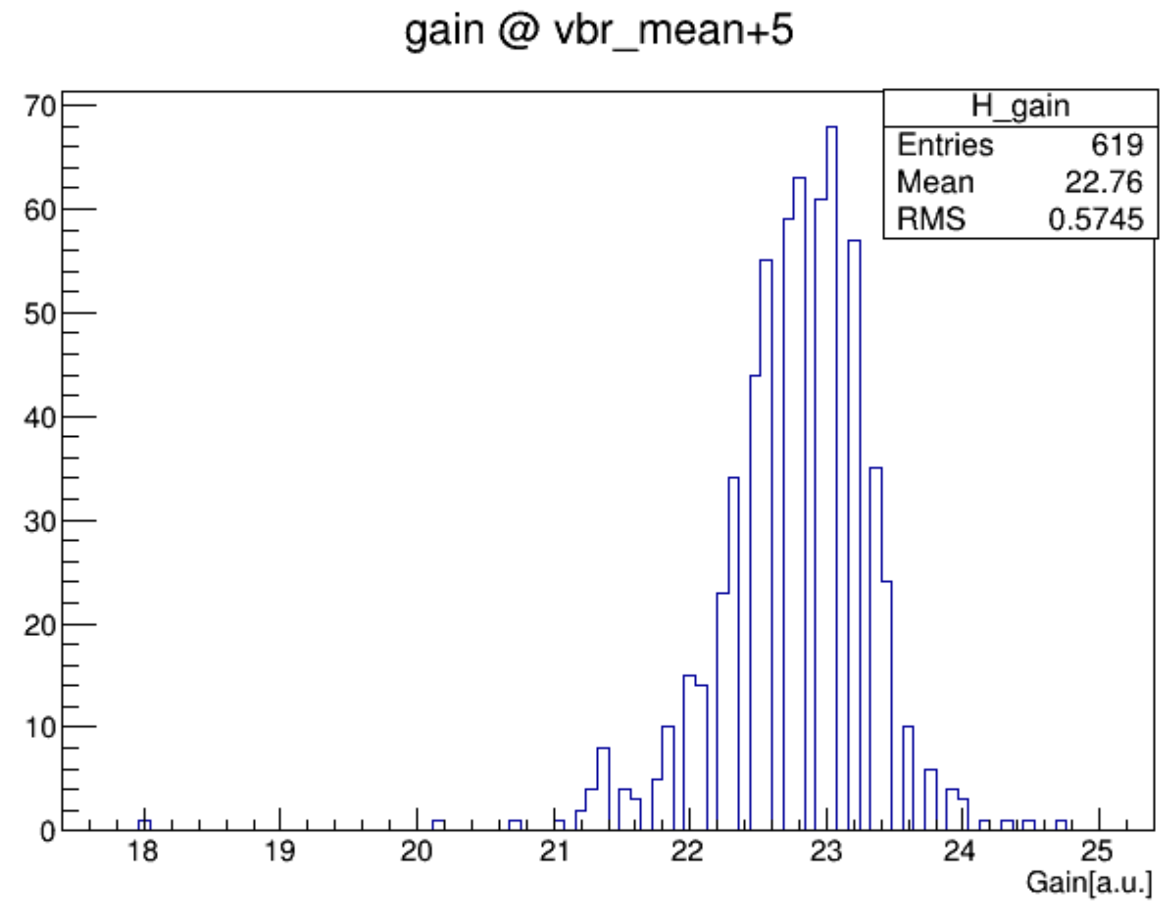
automatic placement of tiles on electronics board (HBU), fully assembled with SiPMs and ASICs

11/2017 - 02/2018

Construction of the AHCAL Prototype

Exercising scalability

- A multi-step QA procedure



spot testing of few % of 22k SiPMs, acceptance of 600 pc batches according to pre-defined criteria - all batches accepted

Construction of the AHCAL Prototype

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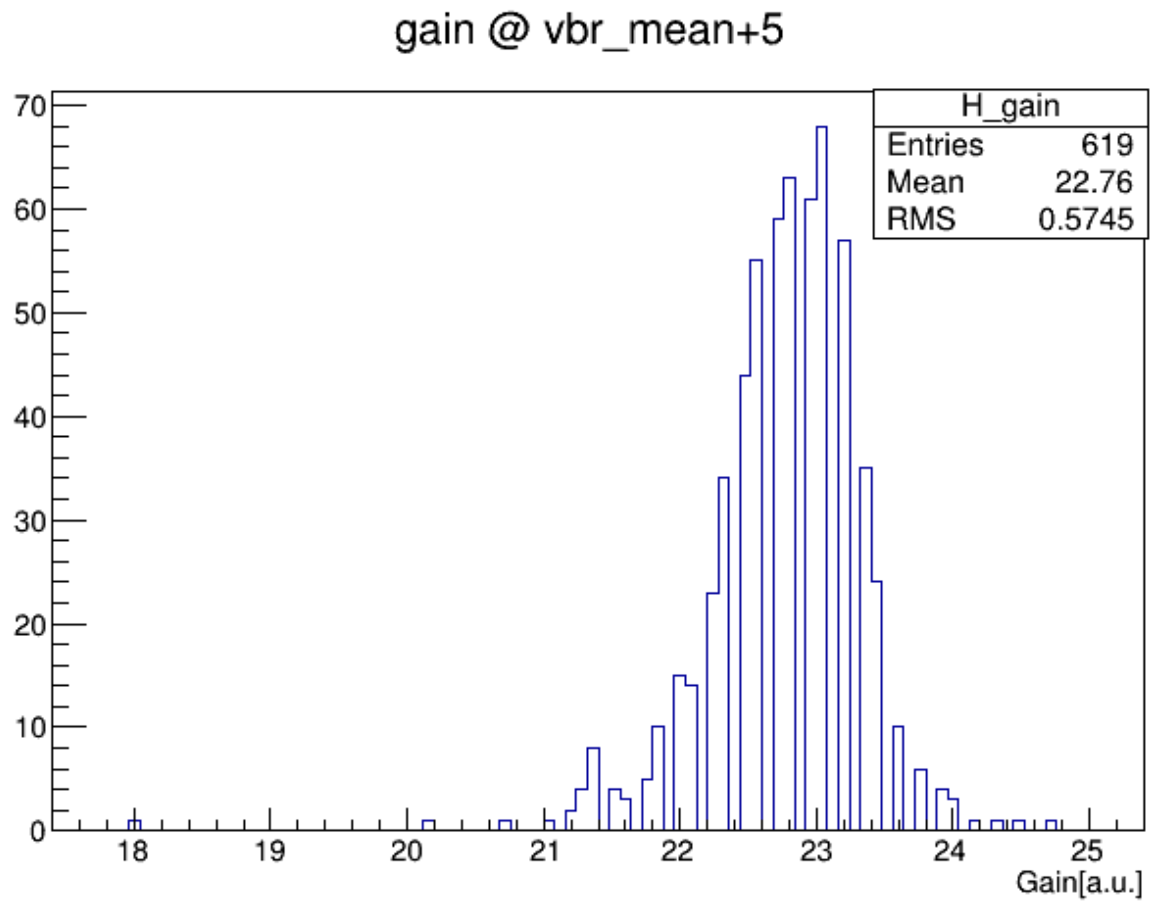

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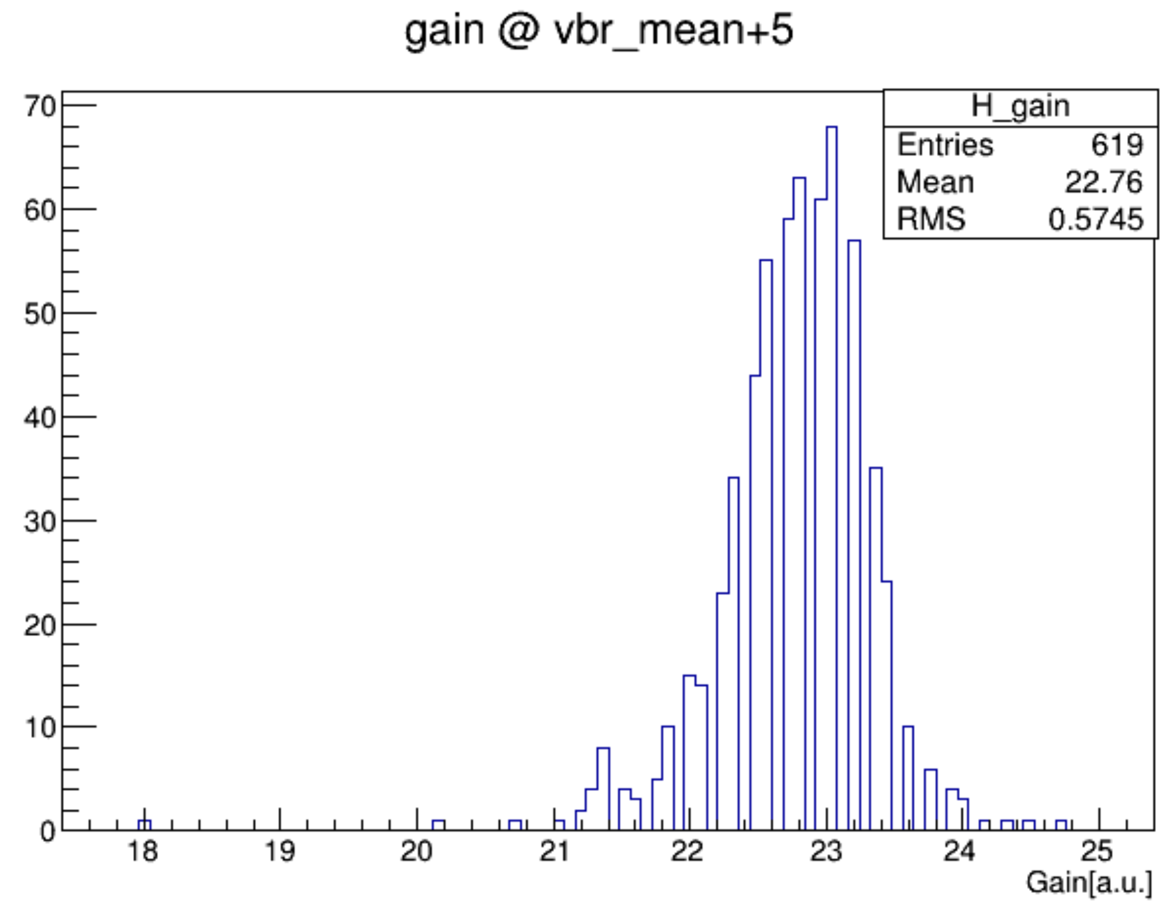

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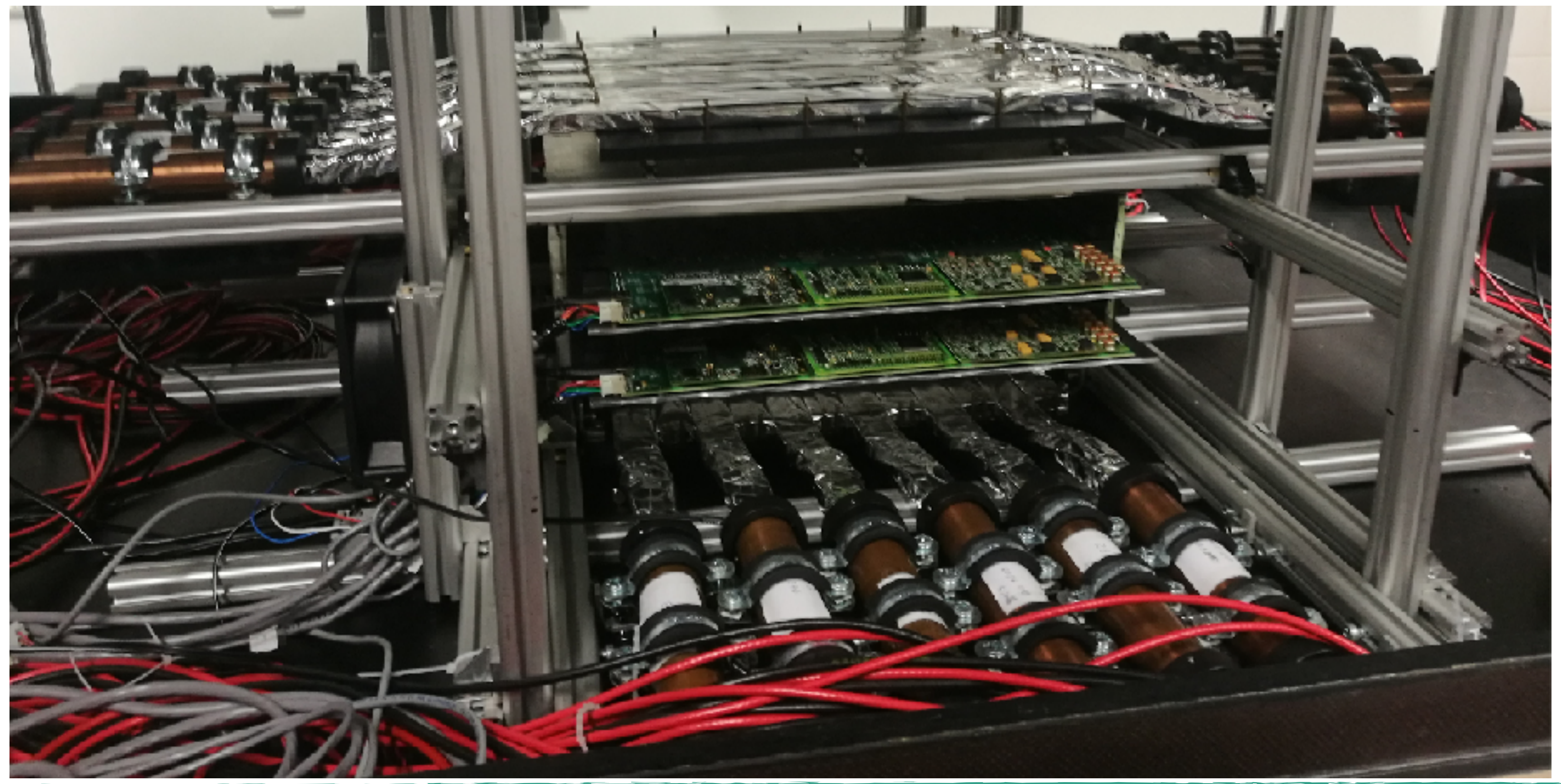

test and calibration of all channels with cosmics

Construction of the AHCAL Prototype

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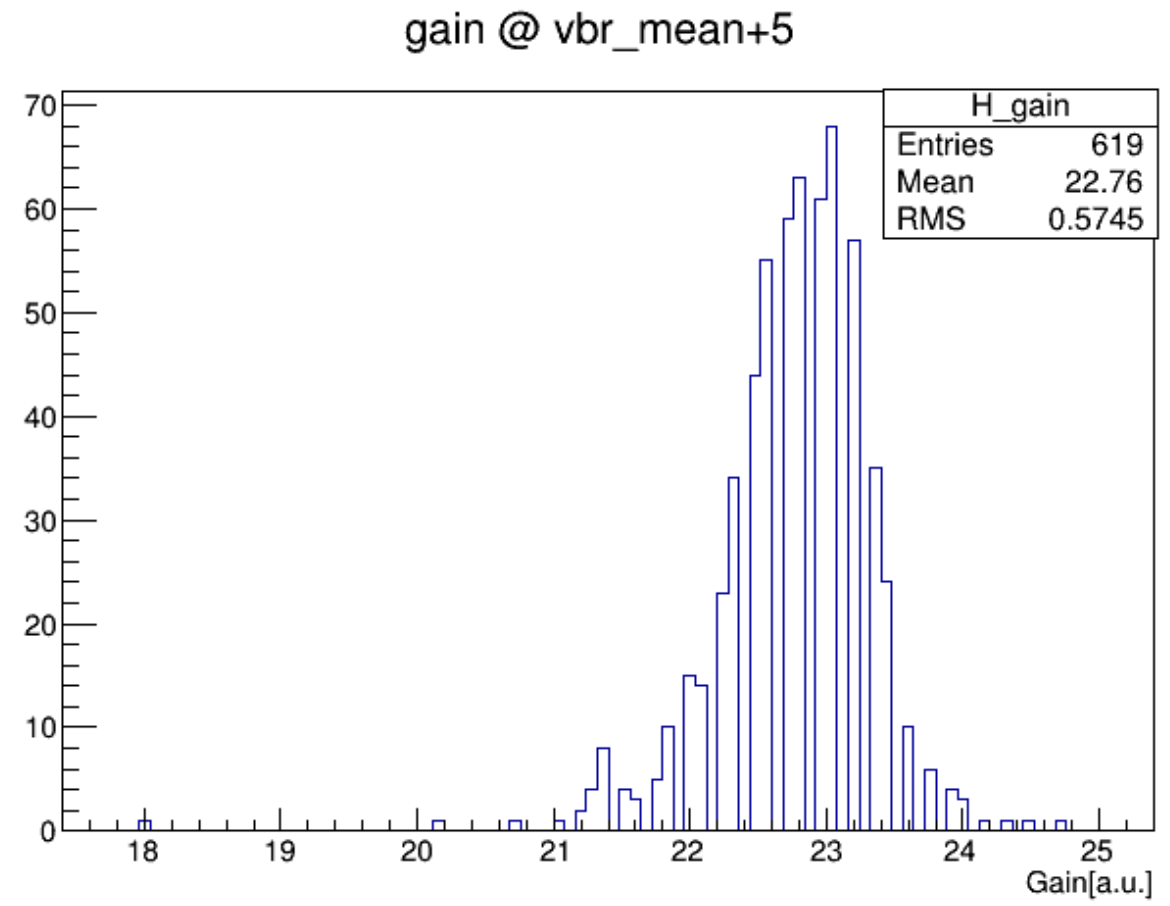

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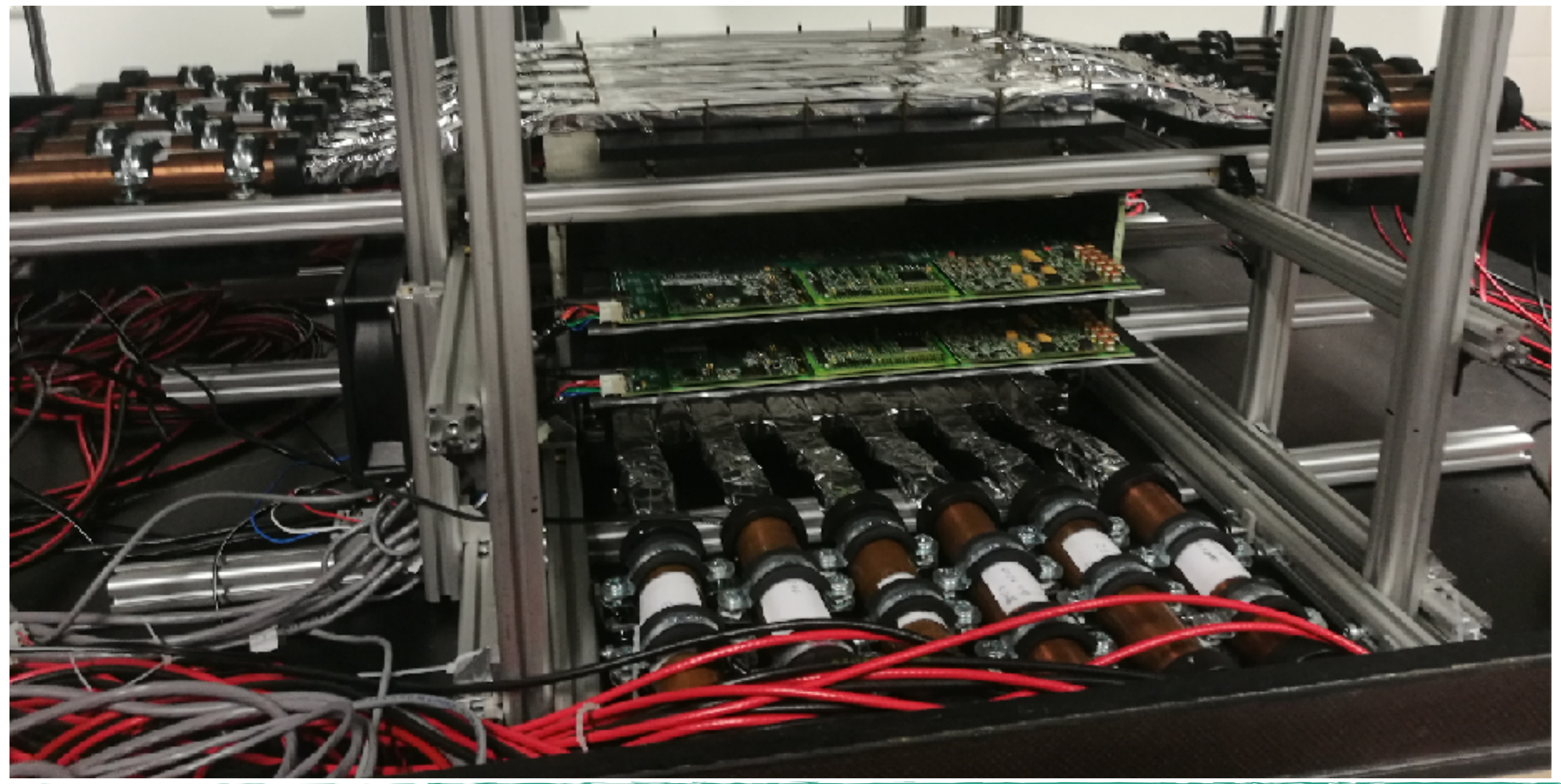
integration of layers & interfaces, test in beam at DESY



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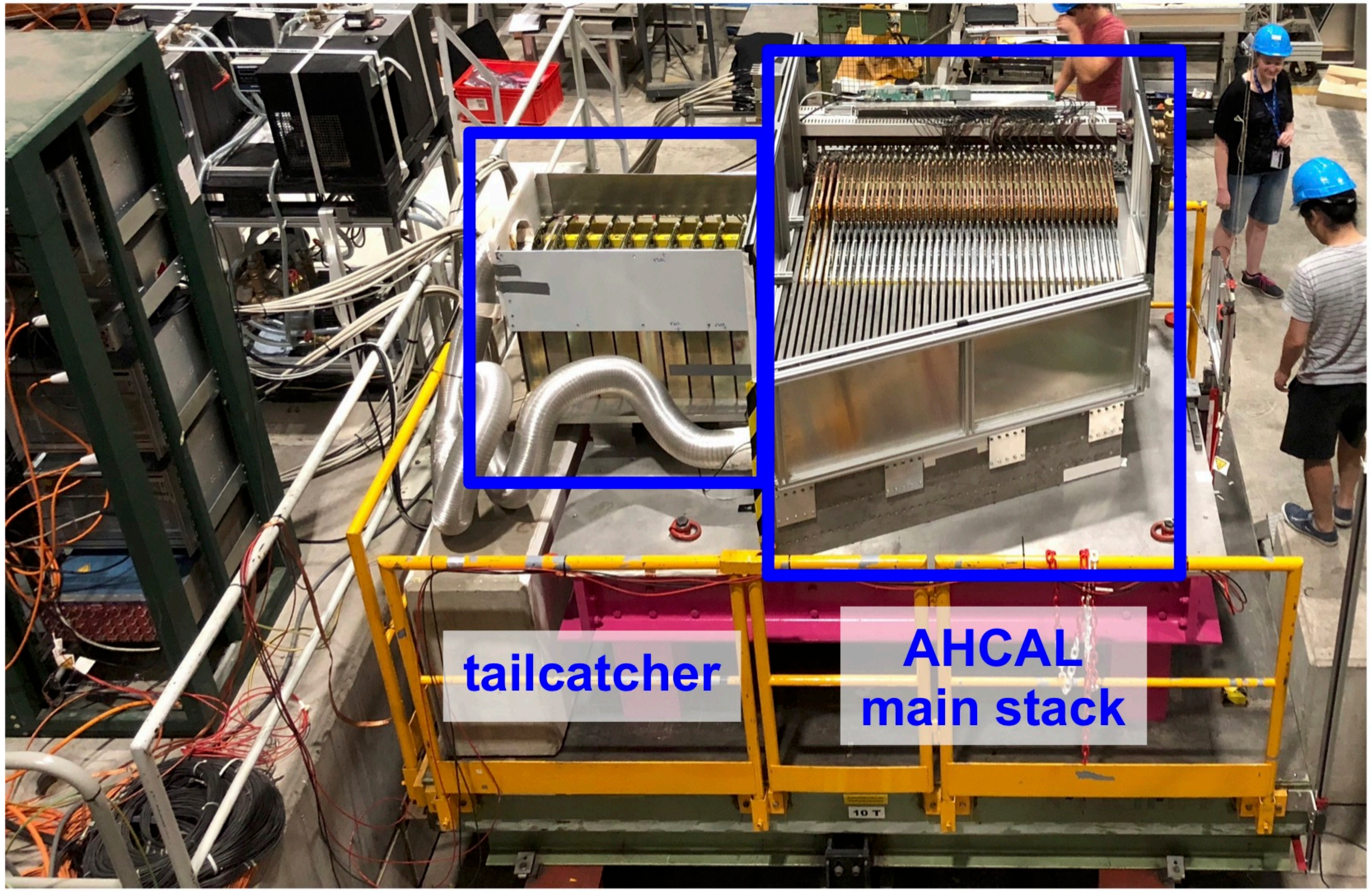
Full Prototype in Particle Beams

Demonstration of Performance

- Test beam at CERN SPS - the smoothest CALICE test beams ever.



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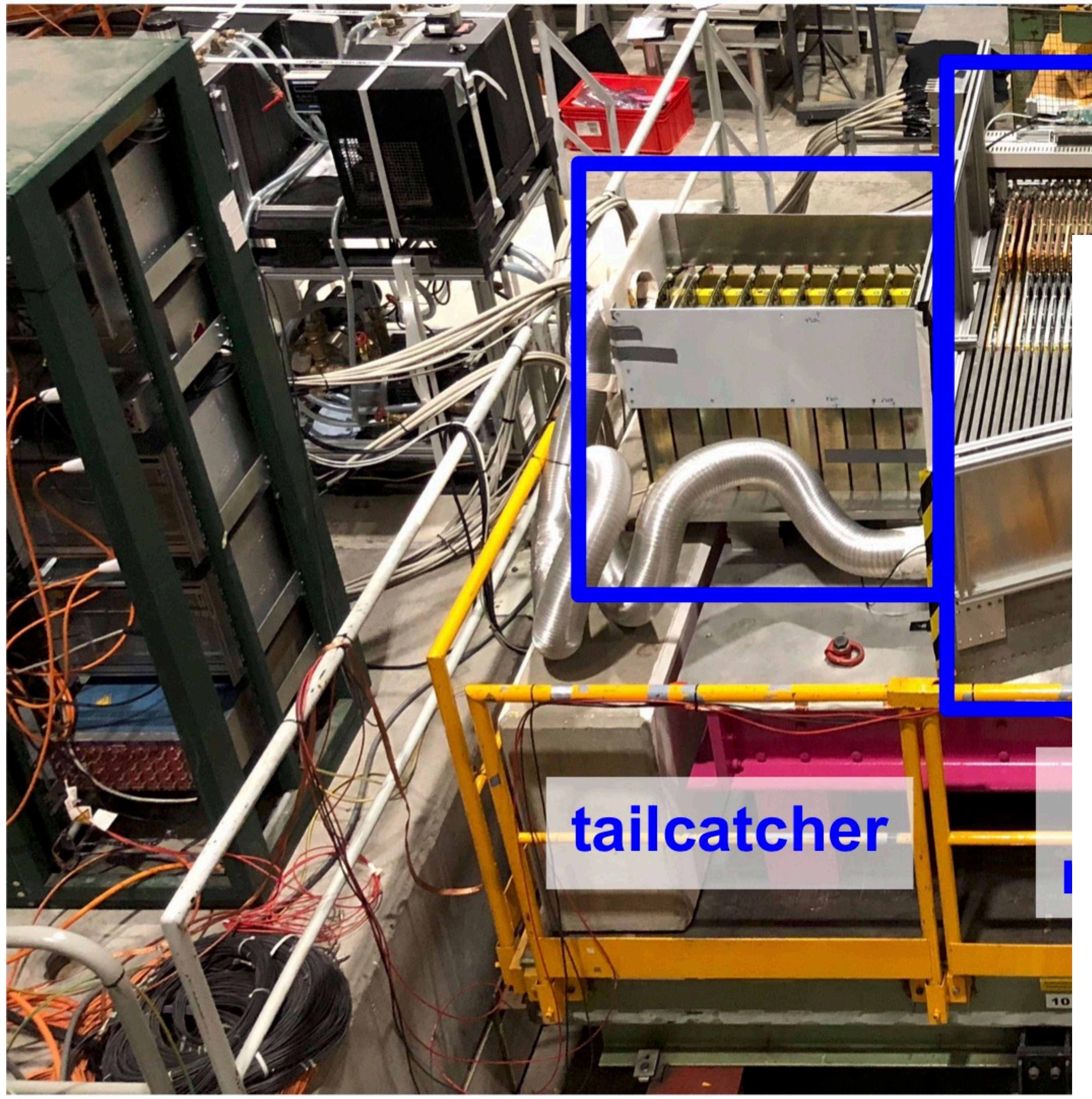
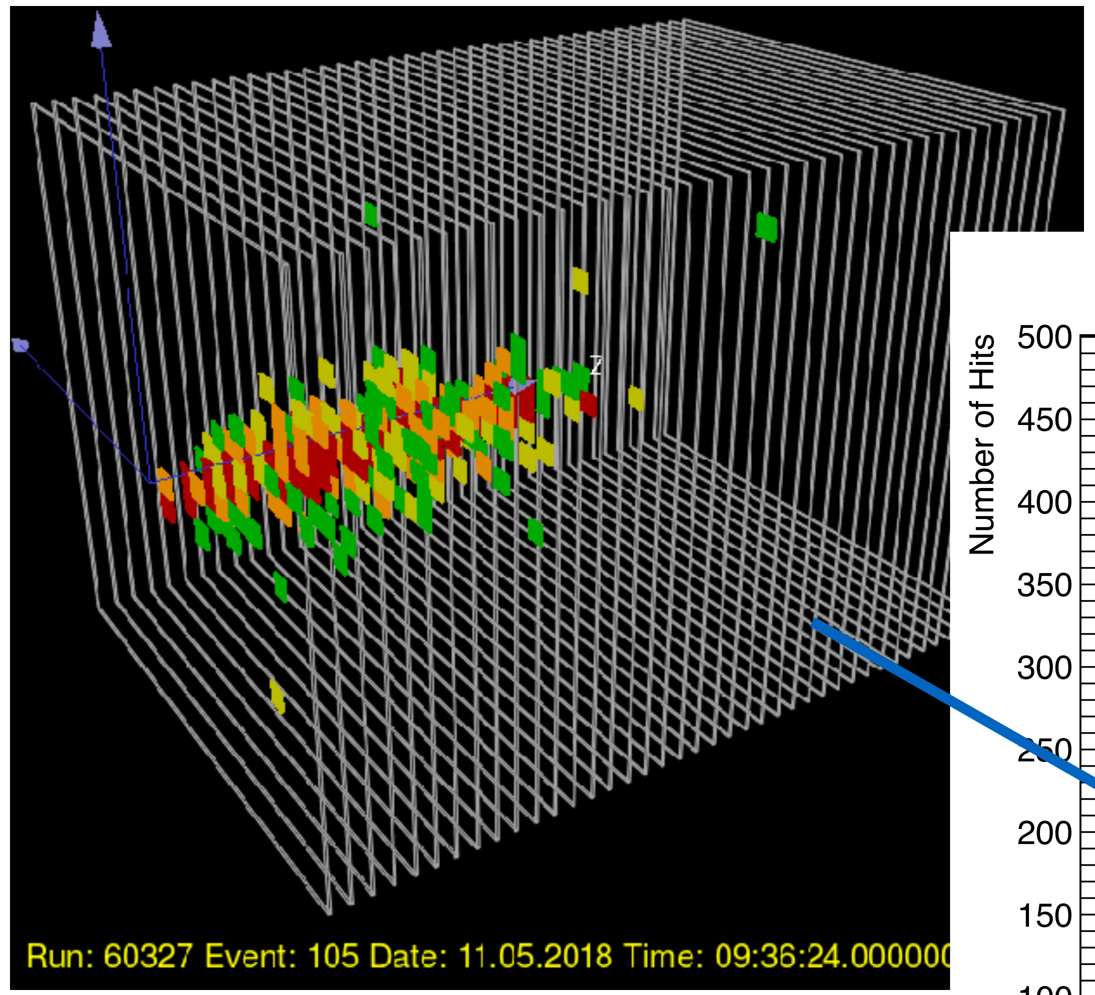
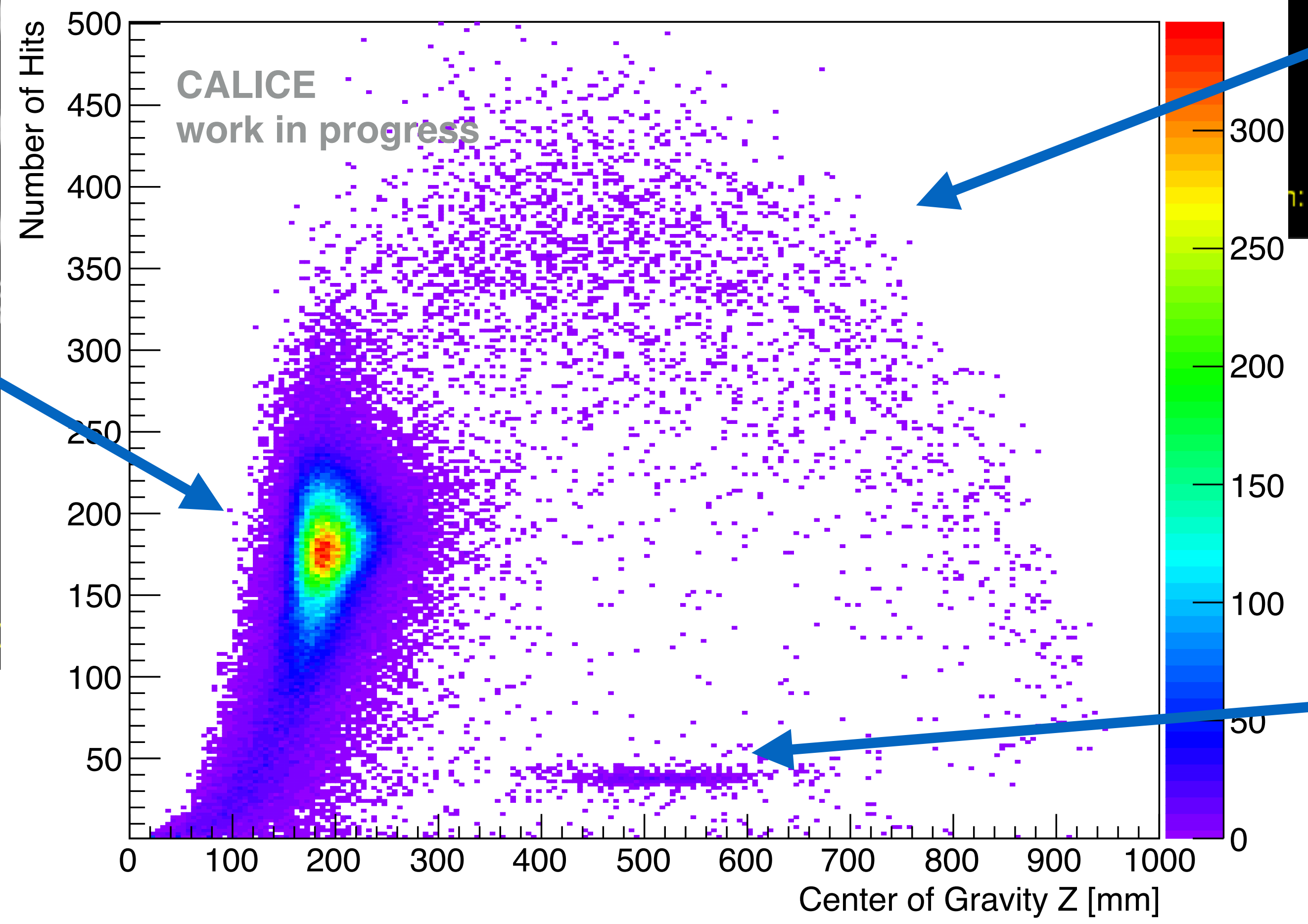


electron shower

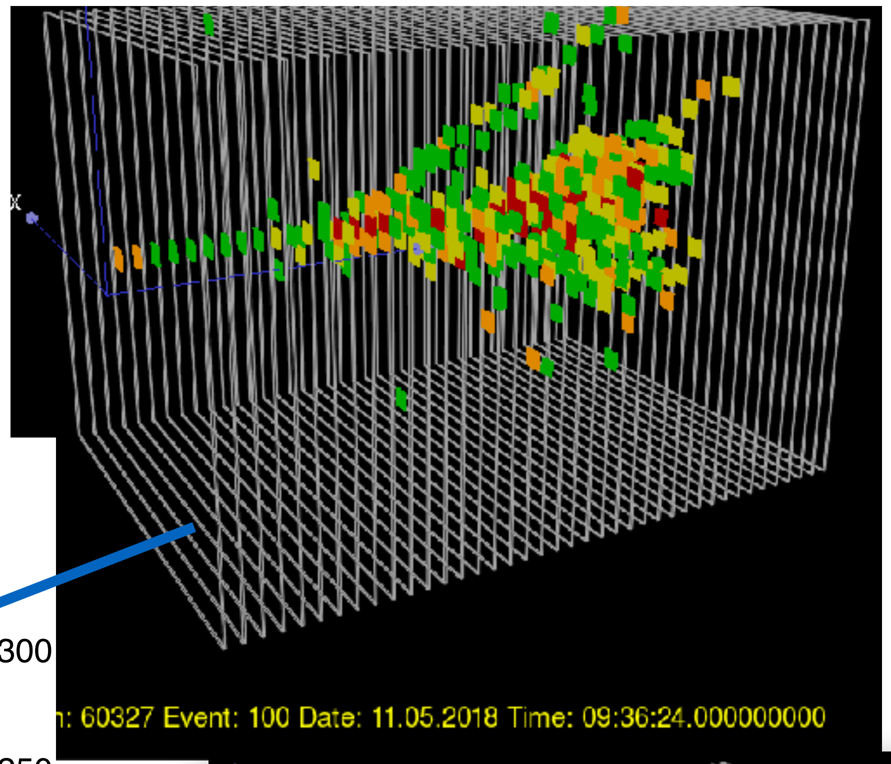


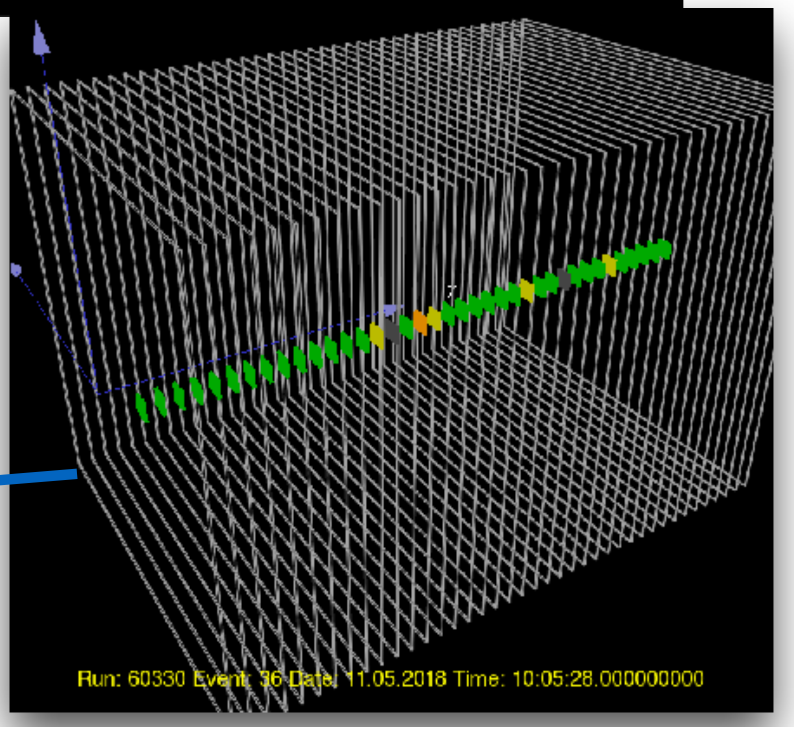
online data

50 GeV electron beam with pion and muon contamination



pion shower



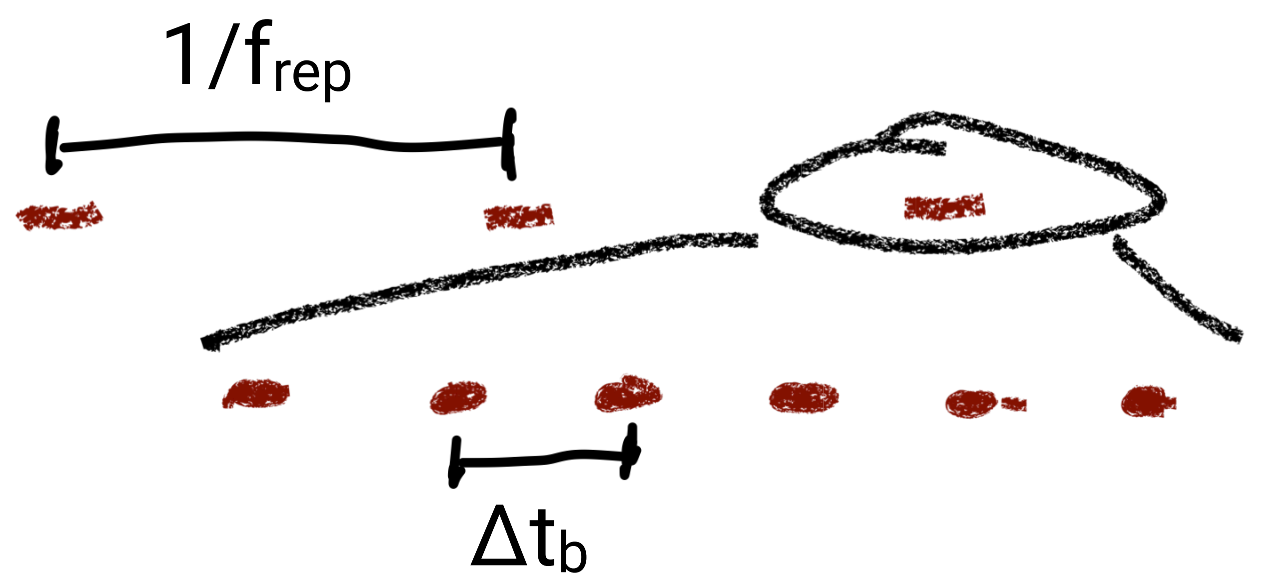


muon track

Developing the Technology Further

In the Context of Higgs Factories

- Electronics and thermal design currently optimised for linear colliders:



- at CLIC: **Δt_b = 0.5 ns**; f_{rep} = 50 Hz
- at ILC: Δt_b = 554 ns; f_{rep} = 5 Hz

⇨ power pulsing possible:
most of the electronics off for 99% of the time

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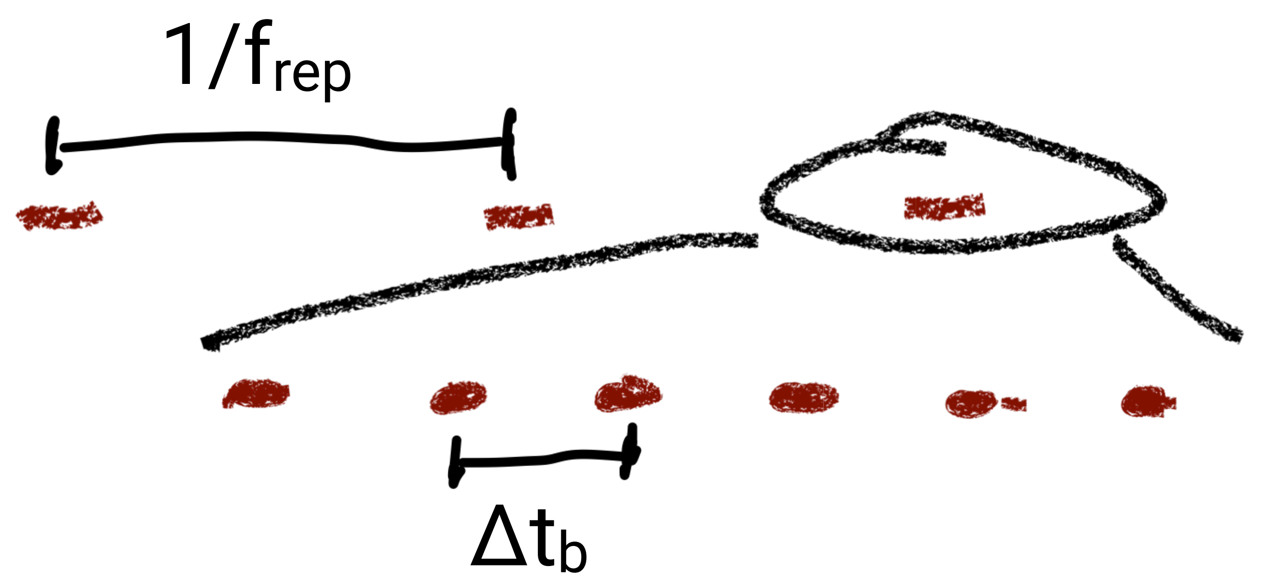

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- At circular colliders (FCC-ee): Continuous collisions - toughest conditions at the Z pole:
  Δt_b = 20 ns, physics rate ~ 100 kHz

➯ Need continuous readout
-> No power pulsing possible, potentially significant increase in power

Consequences for cooling?

Advances in power efficiency?

➯ Significantly higher data rates: more sophisticated data concentration and transmission

Highly Granular Calorimetry at LHC

Pushing the Technology to its Limits?

Highly Granular Calorimetry at LHC

Pushing the Technology to its Limits?

Seoul, ca. 2013:

Dave Barney, CERN

Cool technology. Would that work at the LHC?

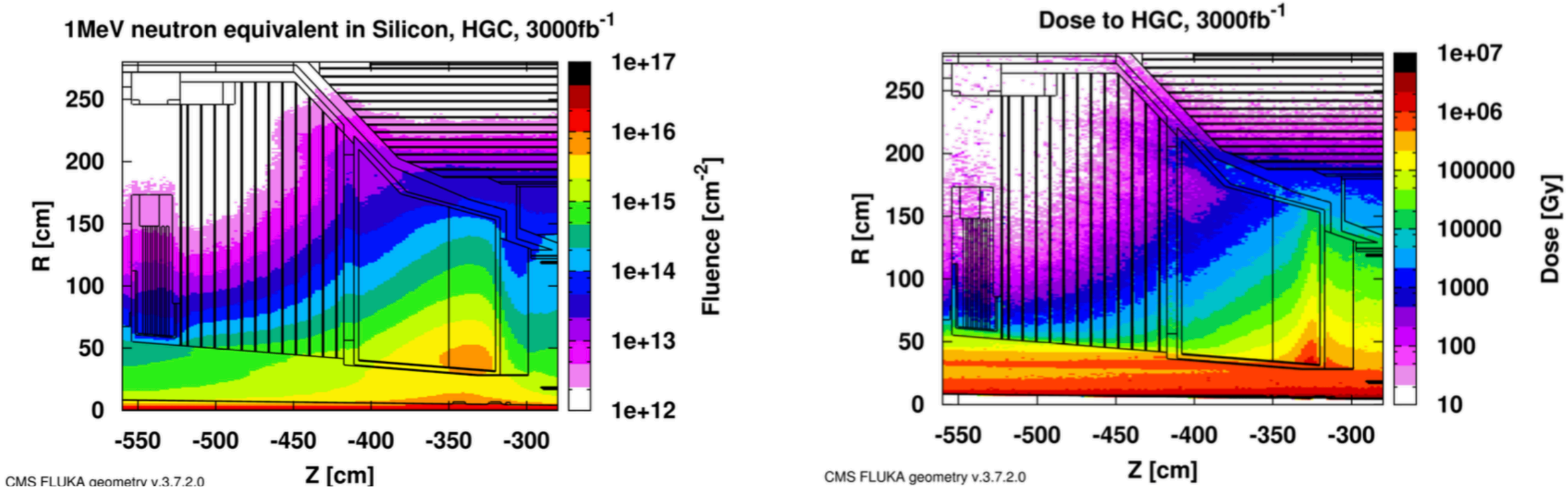
Doubt it… Not rad-hard enough, too much data, need cooling - can't be compact enough…

FS

The Conditions at the HL-LHC

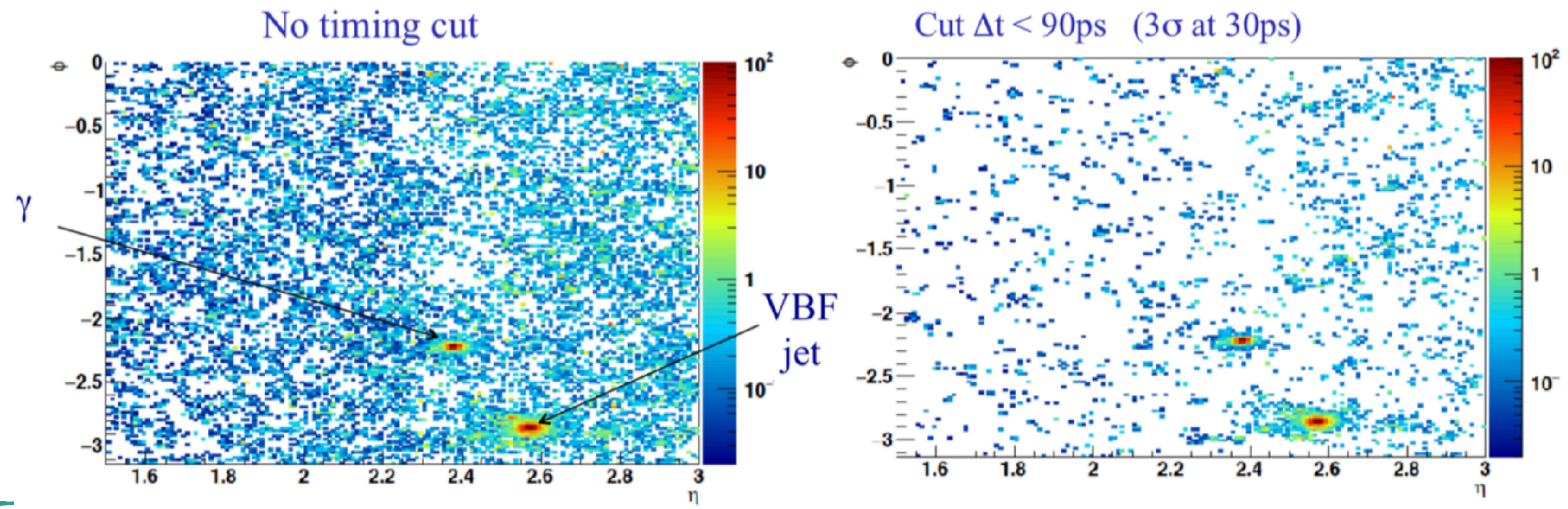
The CMS Endcap Calorimeter

- Extreme radiation:



- High particle density:

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



Timing and granularity as a way to cope with pileup!

A High Granularity Calorimeter for LHC

What we need to make it work

- It has to survive!
  - ➾ Use silicon as active element!

A High Granularity Calorimeter for LHC

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  The key: Ensuring sufficient light yield and S/N.

  Two main elements to this:

  - Radiation hardness of SiPMs
  - Radiation hardness of scintillator

A High Granularity Calorimeter for LHC

What we need to make it work

Karlsruher Institut für Technologie

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operation “in the cold”: -30 C via CO_2 cooling

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operation “in the cold”: -30 C via CO_2 cooling

profit from SiPM advances in last decade: “trenches”, lower DCR

use high-quality machined scintillator in critical areas

A High Granularity Calorimeter for LHC

What we need to make it work

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- It has to survive!
  - ➫ Use silicon as active element!
- You have to be able to pay for it!
  - ➫ Use SiPM-on-Tile wherever allowed by radiation.

The key: Ensuring sufficient light yield and S/N.

Two main elements to this:

- Radiation hardness of SiPMs
- Radiation hardness of scintillator

operation "in the cold": -30 C via CO_2 cooling

profit from SiPM advances in last decade: "trenches", lower DCR

use high-quality machined scintillator in critical areas

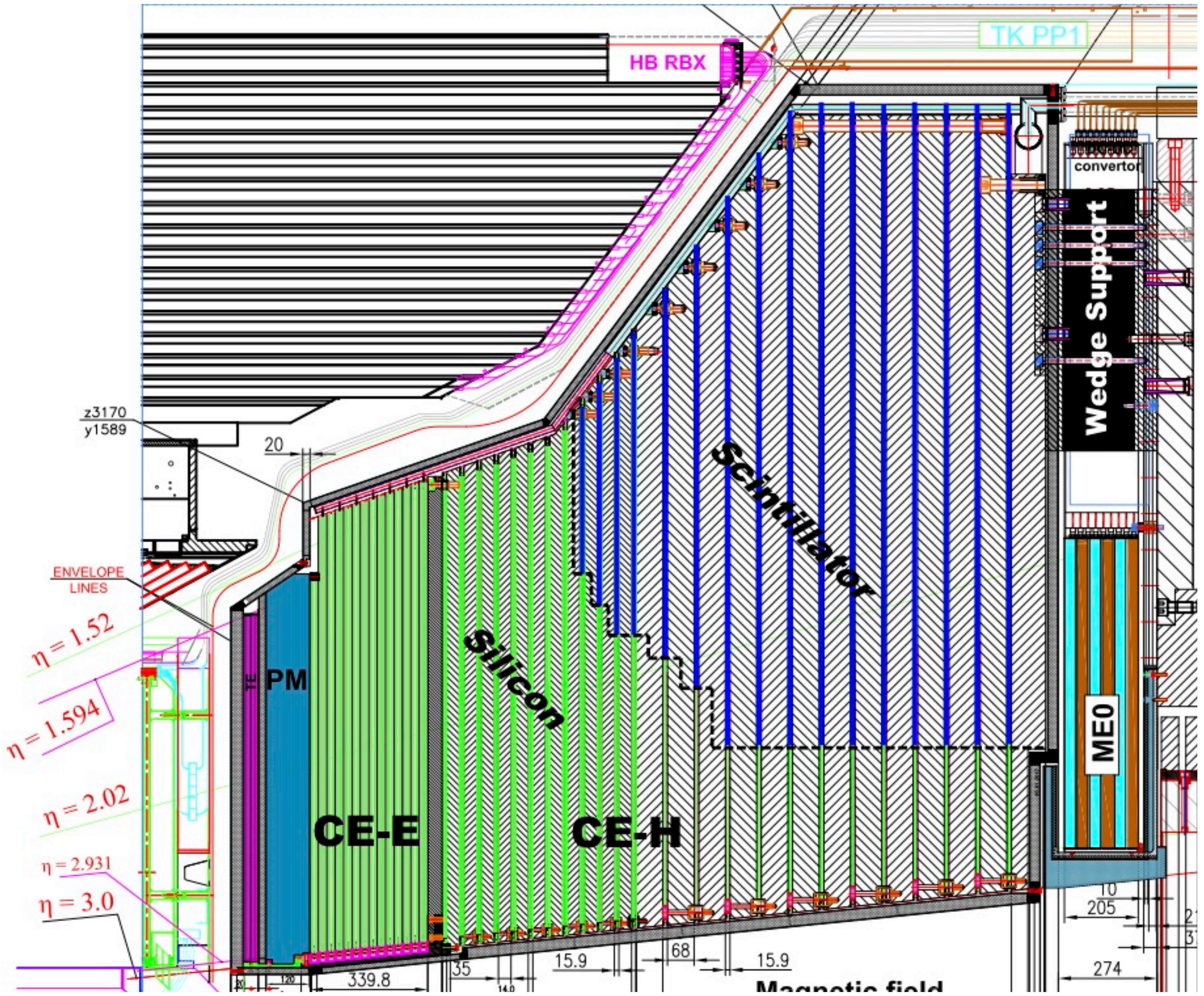
- You need to be able to get the data out!
  - ➫ Data concentrators within the detector volume

From CALICE to CMS

The HGCAL - Technology Transfer & further Development

- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

Most prominent: The CMS Endcap Calorimeter Upgrade HGCal



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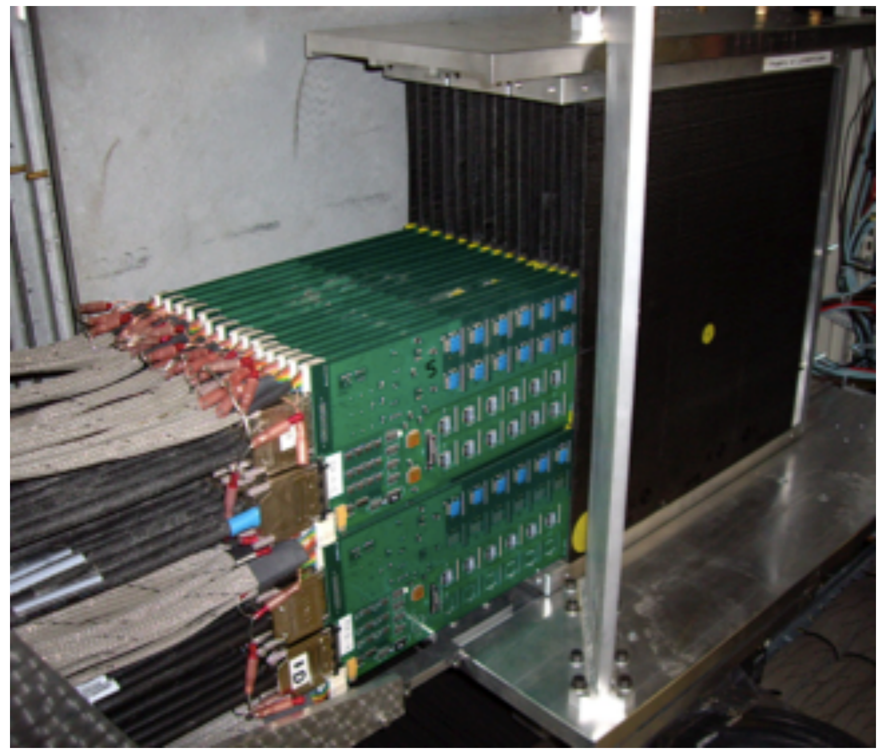

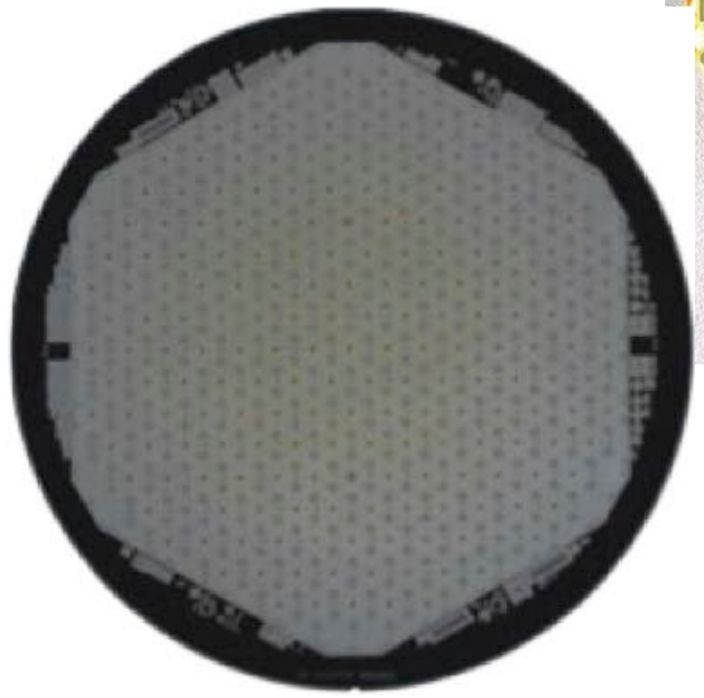

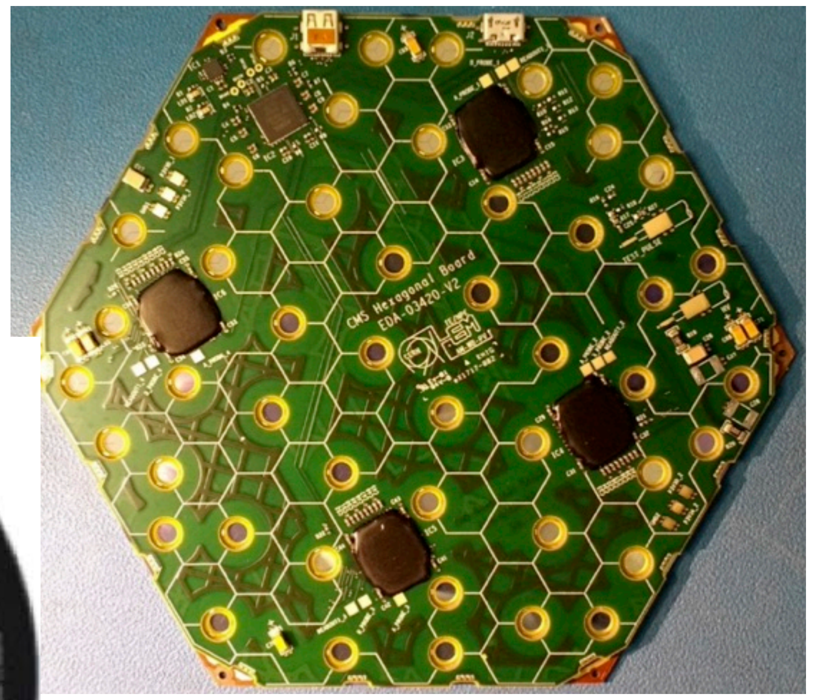

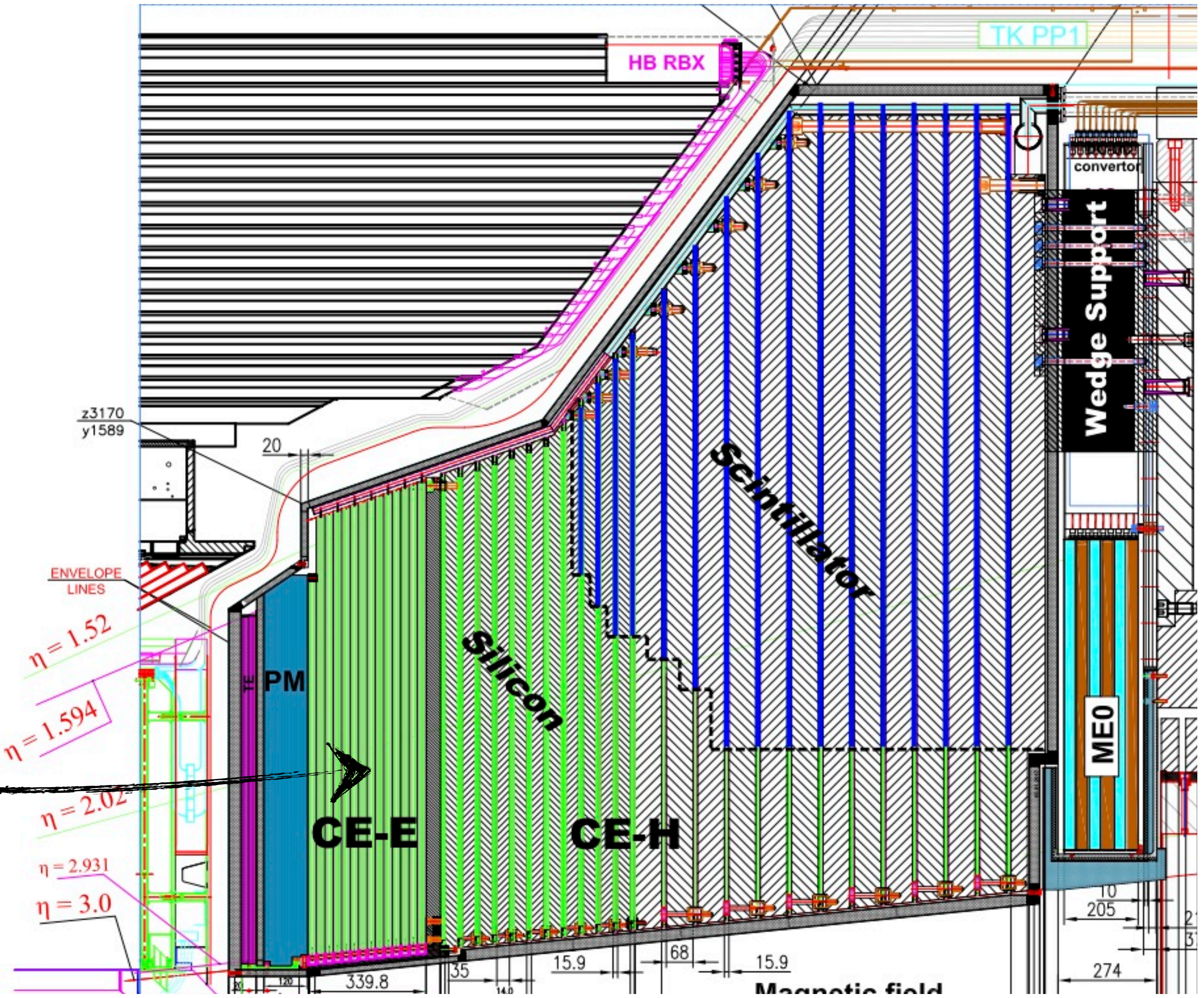

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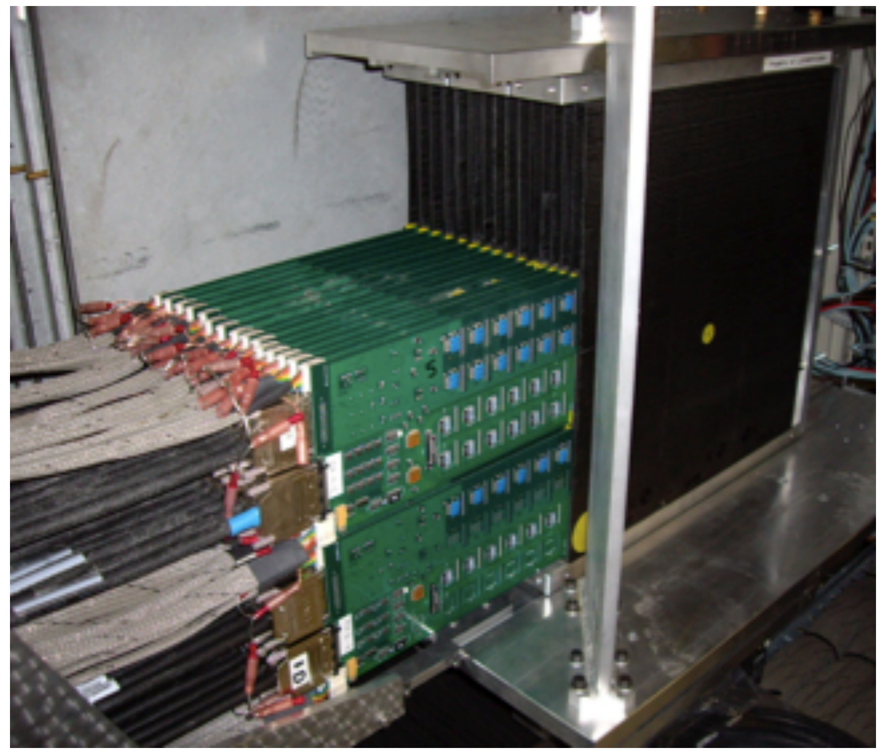
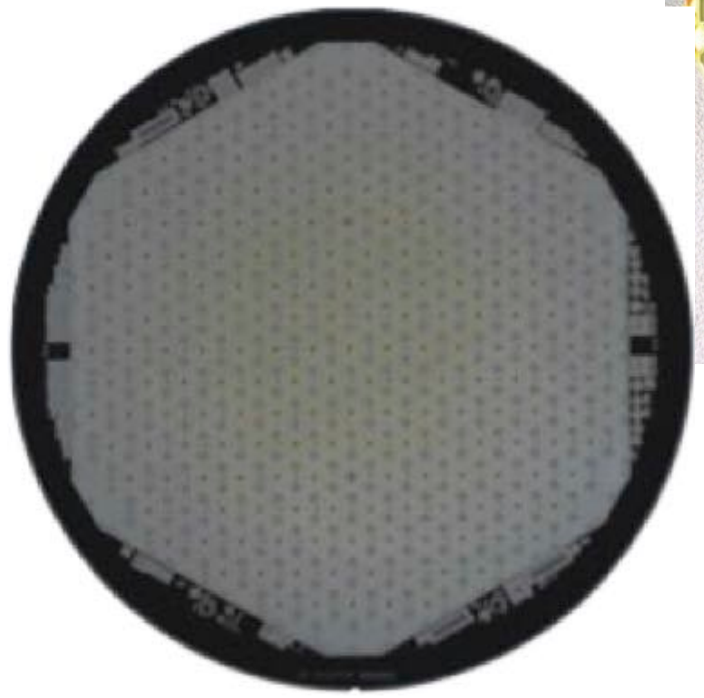
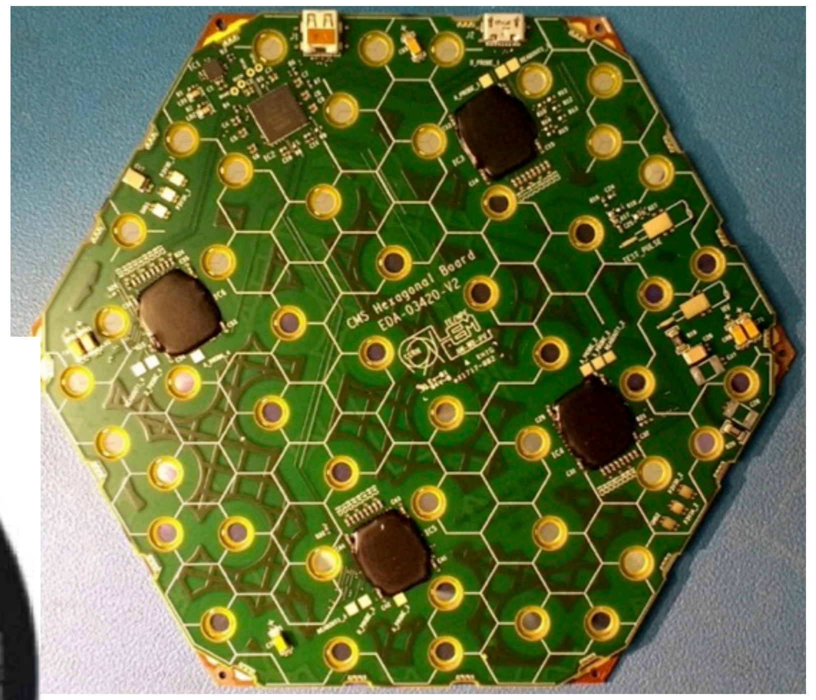
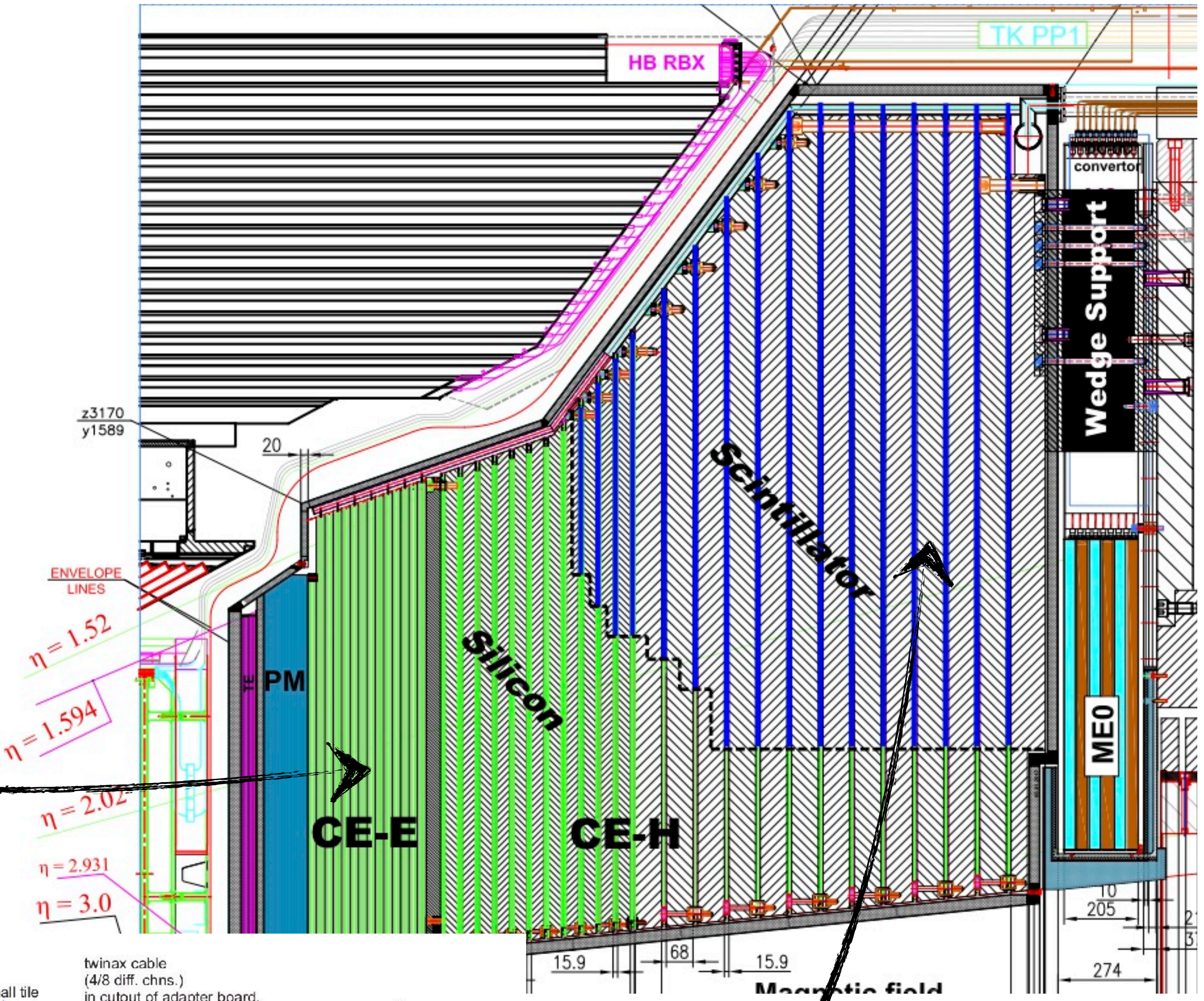
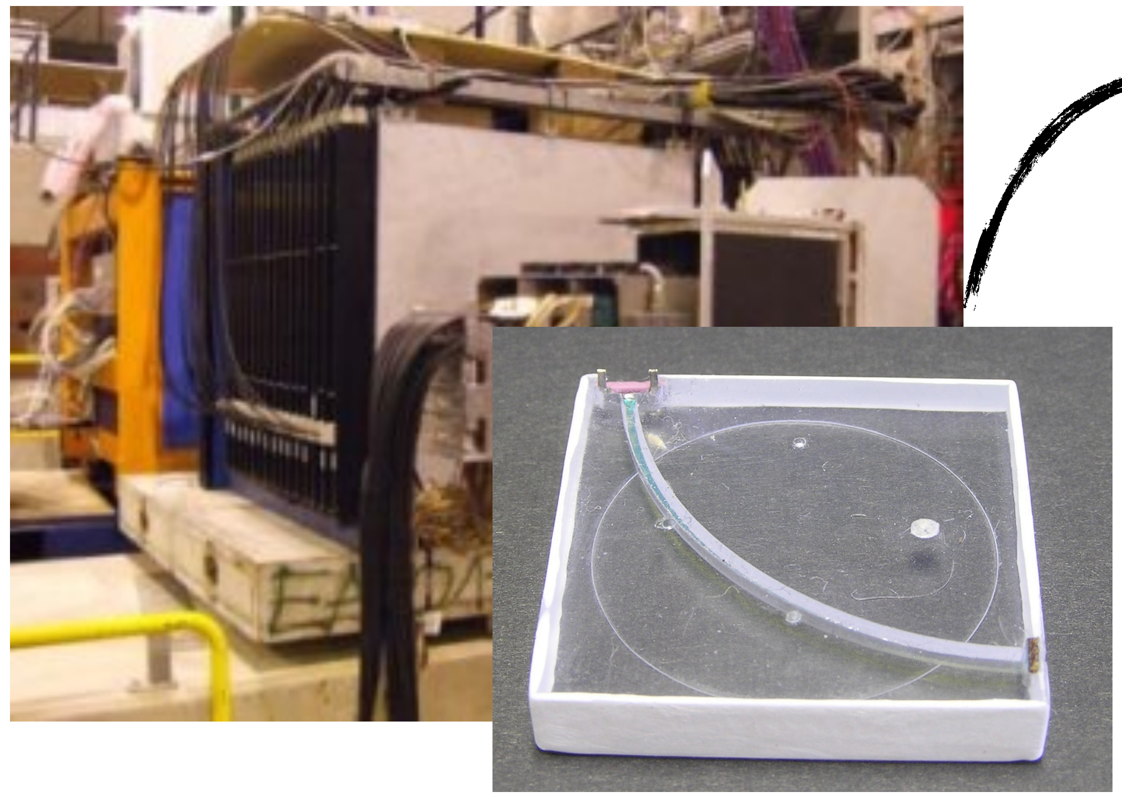
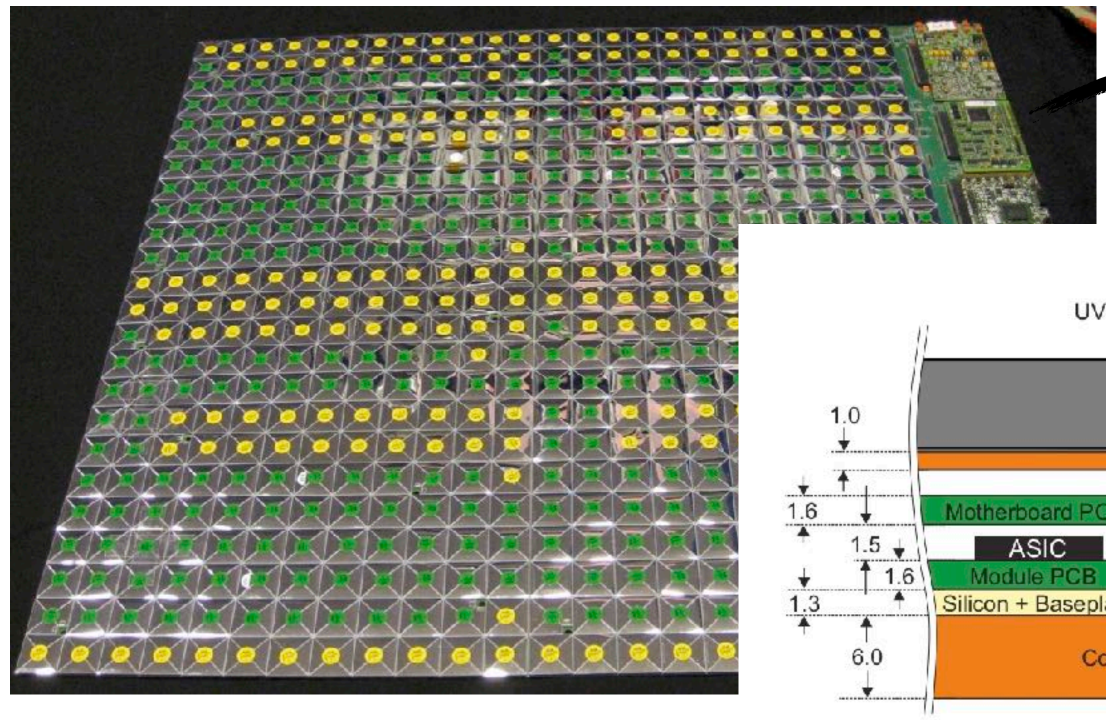


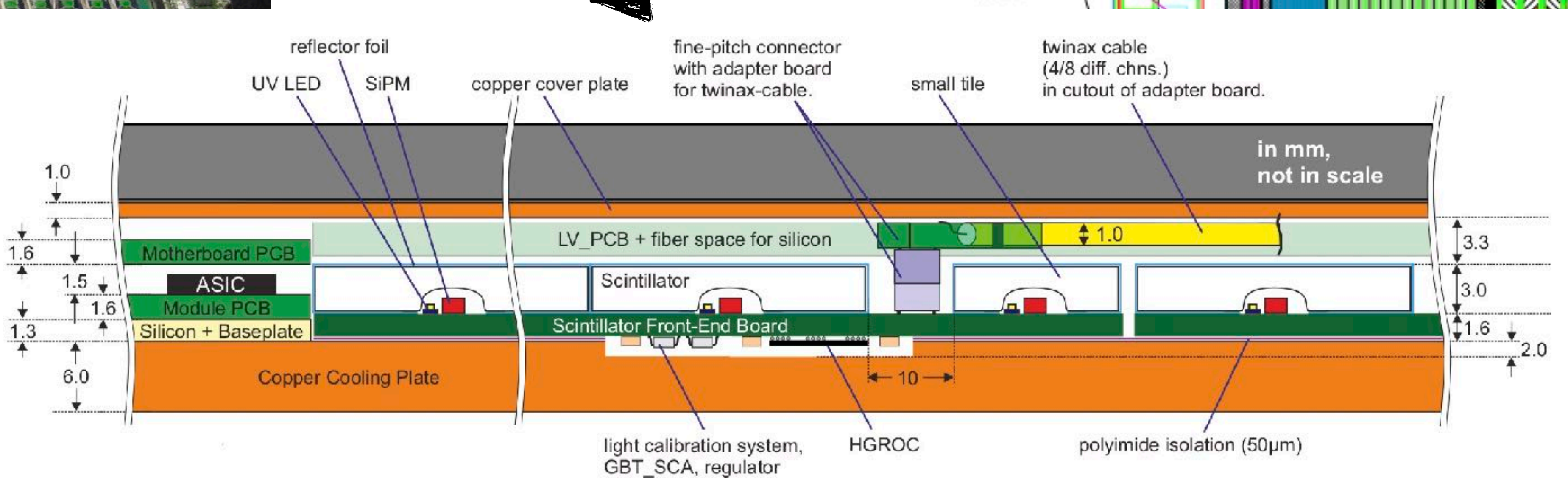










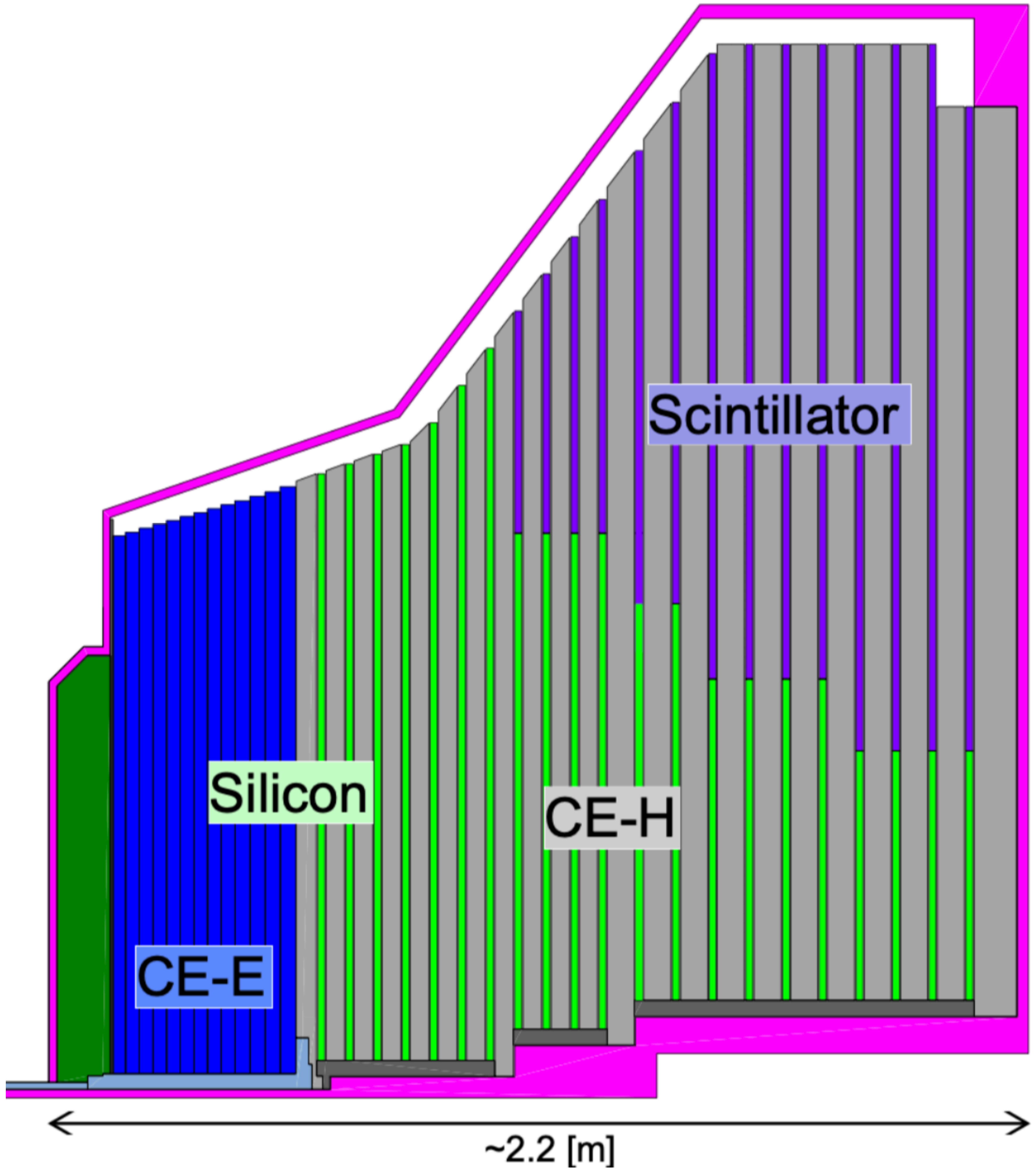


The CMS HGCAL

Pushing current limits on many fronts

Both Endcaps	Silicon	Scintillator
Area	~620 m^2	~370 m^2
Channel Size	0.5 - 1.2 cm^2	4 - 30 cm^2
# Channels	~6 M	~240 k
# Modules	~27000	~4000
Op. Temp.	-30 C	-30 C

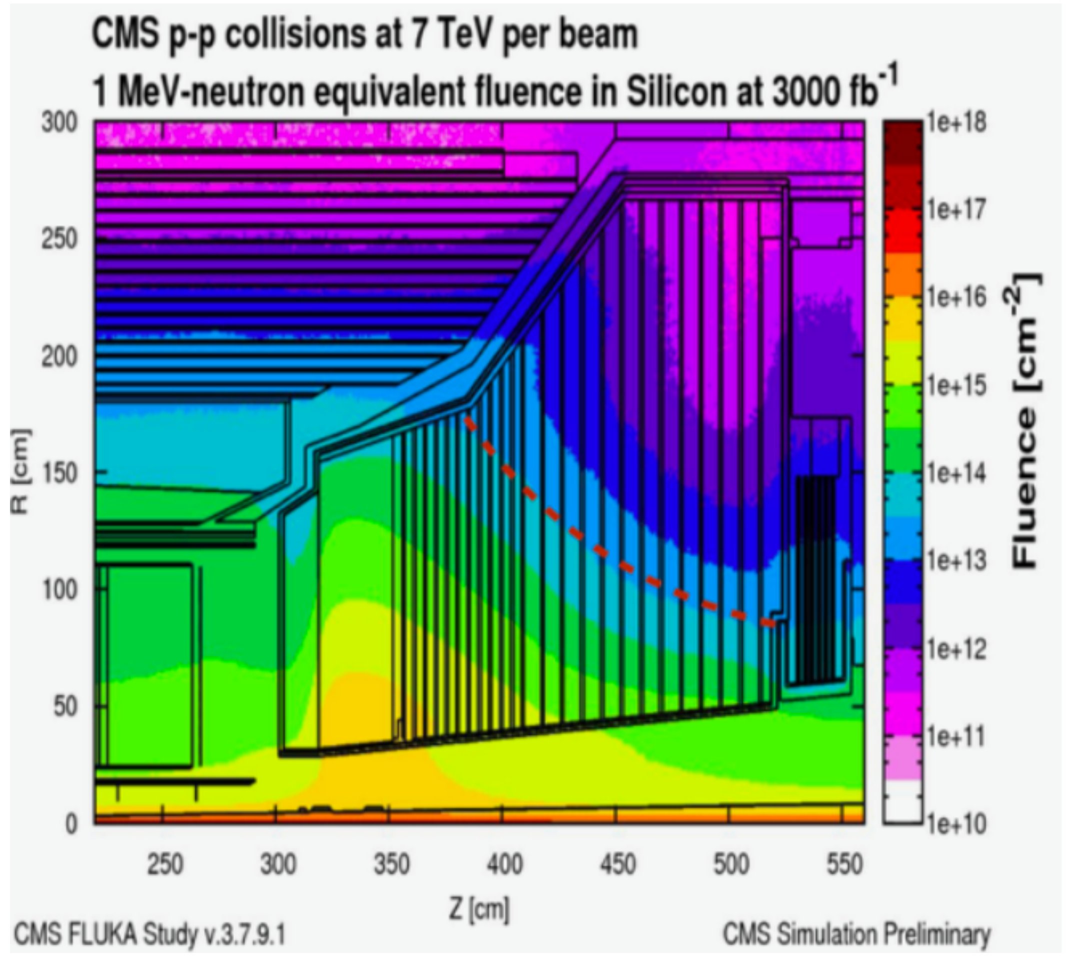
Per Endcap	CE-E	CE-H Si	CE-H Si+Scint
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10 λ	
Layers	26	7	14
Weight	23 t	205 t	



~ 250 kW of power; CO_2 cooling at ~ -30 C

Silicon & SiPM-on-Tile + HGCROC

The HGCAL Sensors & Front-end



Silicon & SiPM-on-Tile + HGCROC

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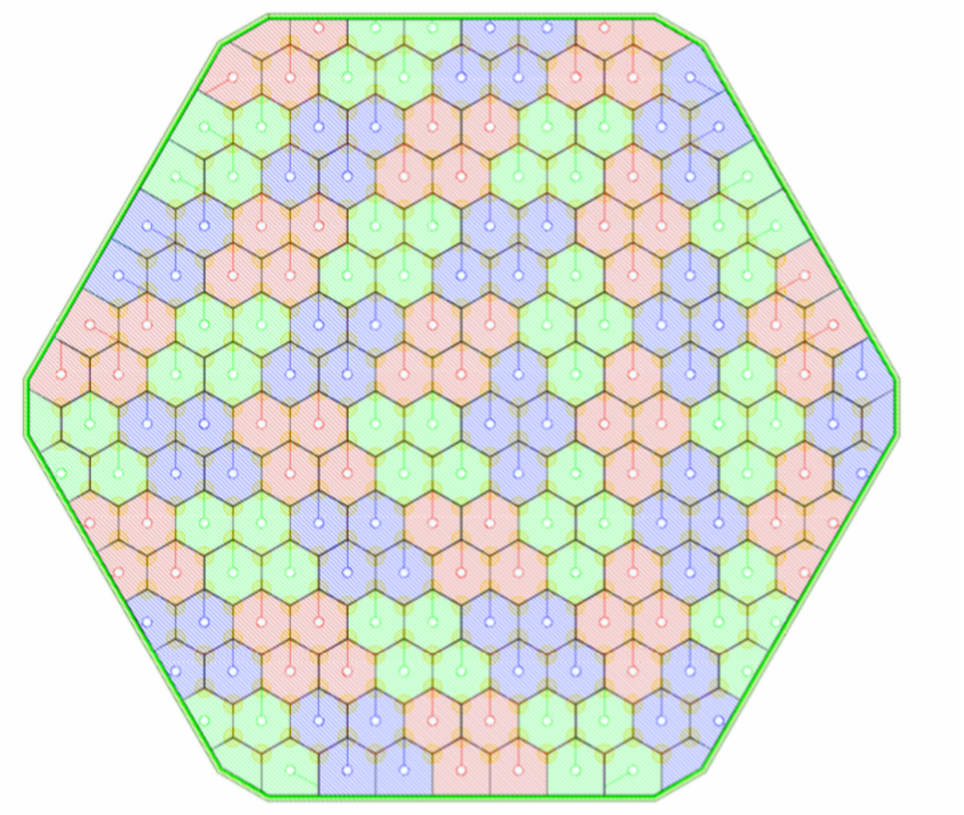
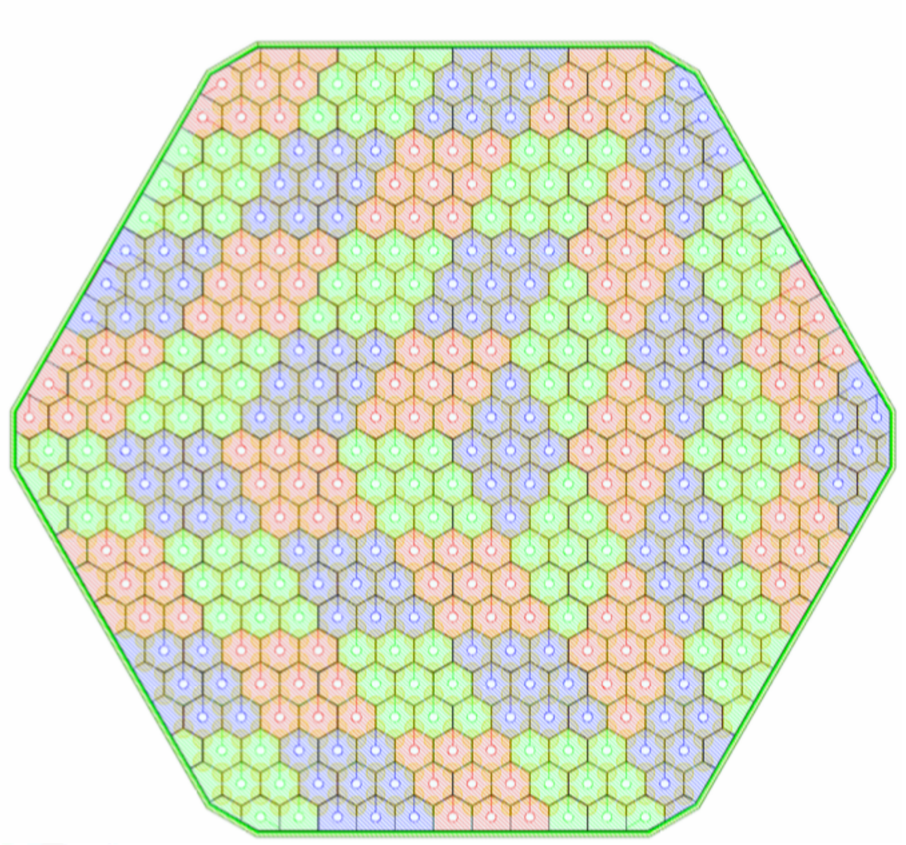
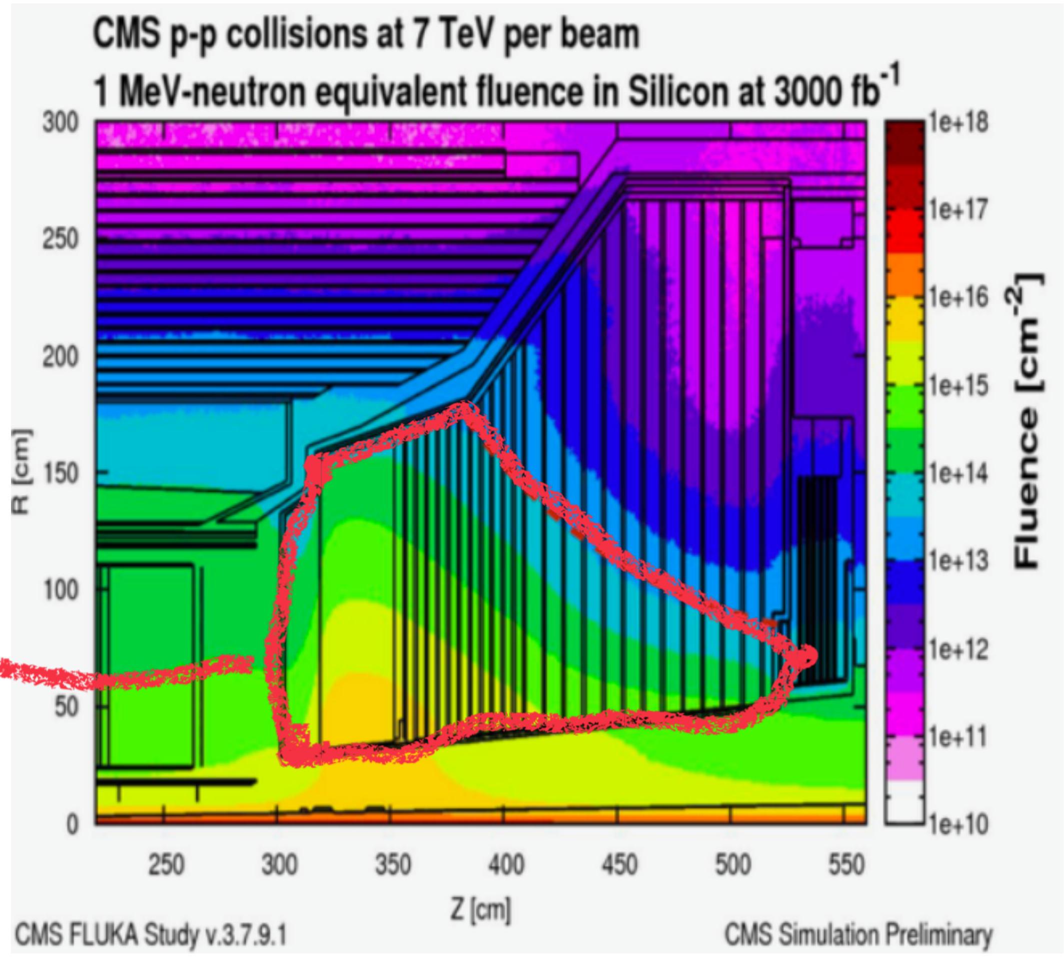
LD: ~200 cells of 1.2cm²
300um & 200um thickness

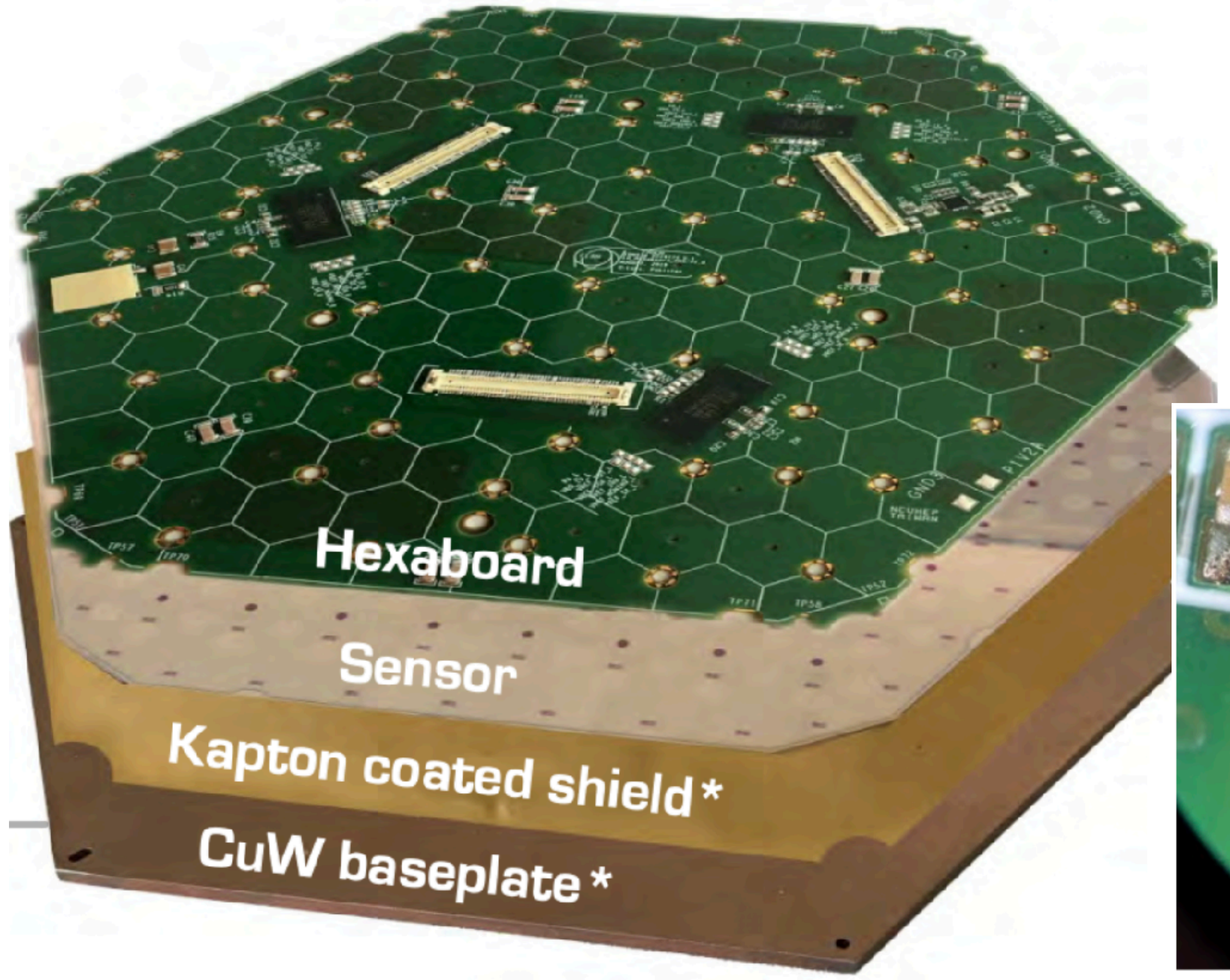


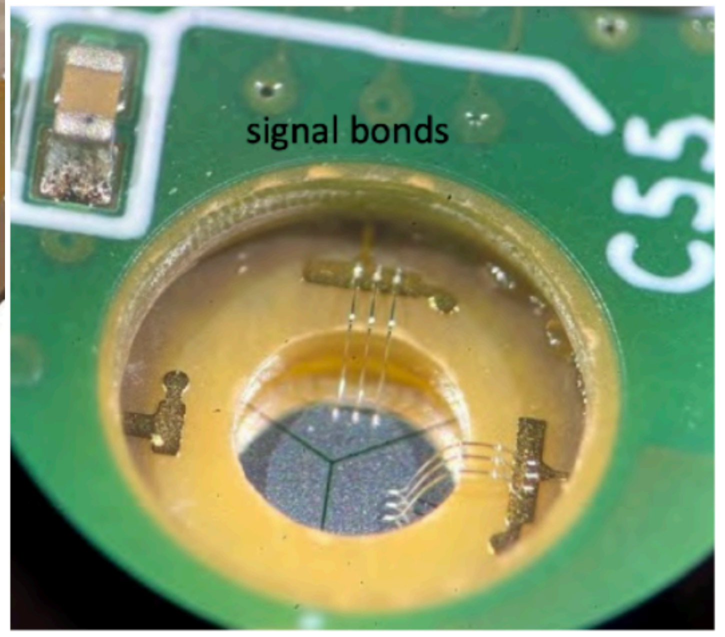
HD: ~450 cells of 0.5cm²
120um active thickness



planar, p-type
sensors on 8” wafers







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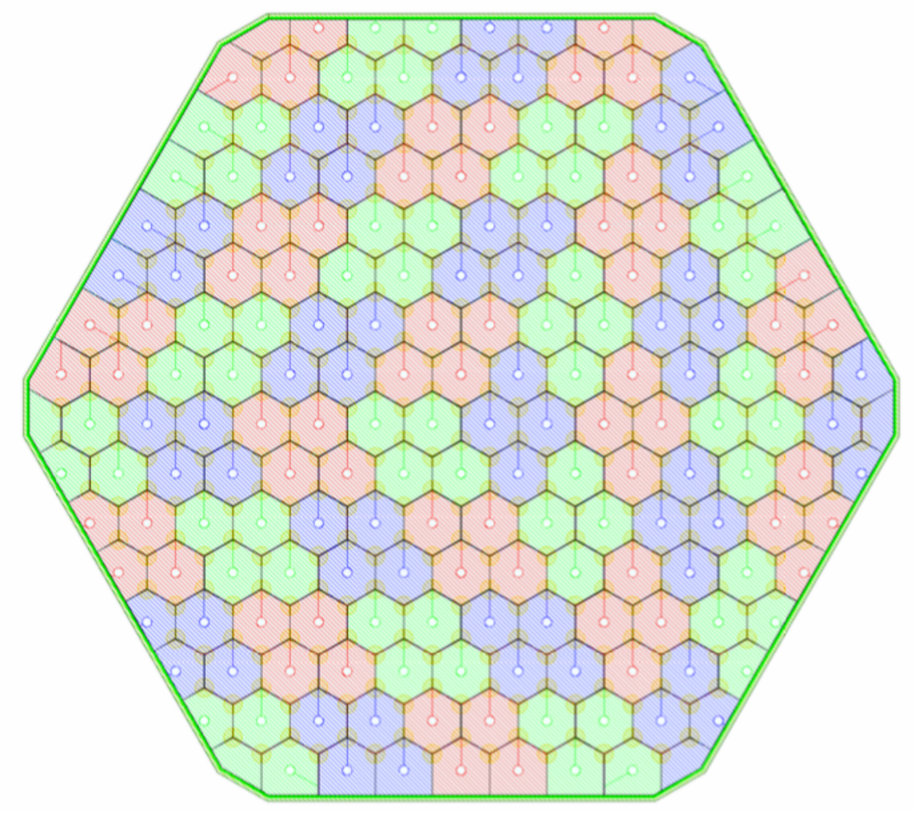

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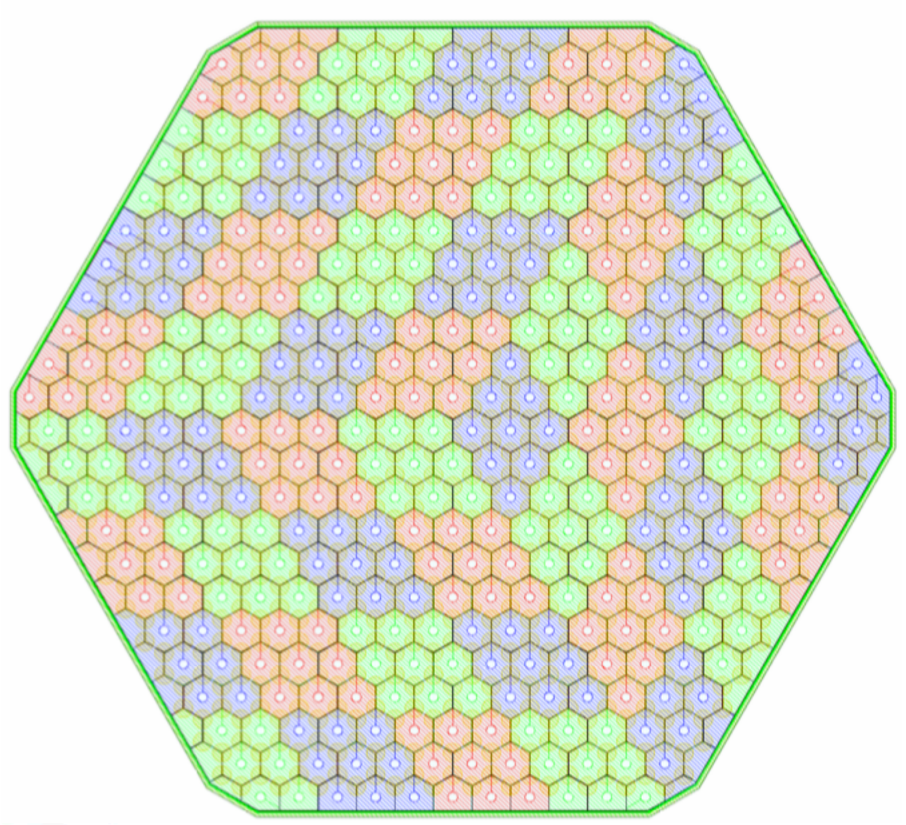

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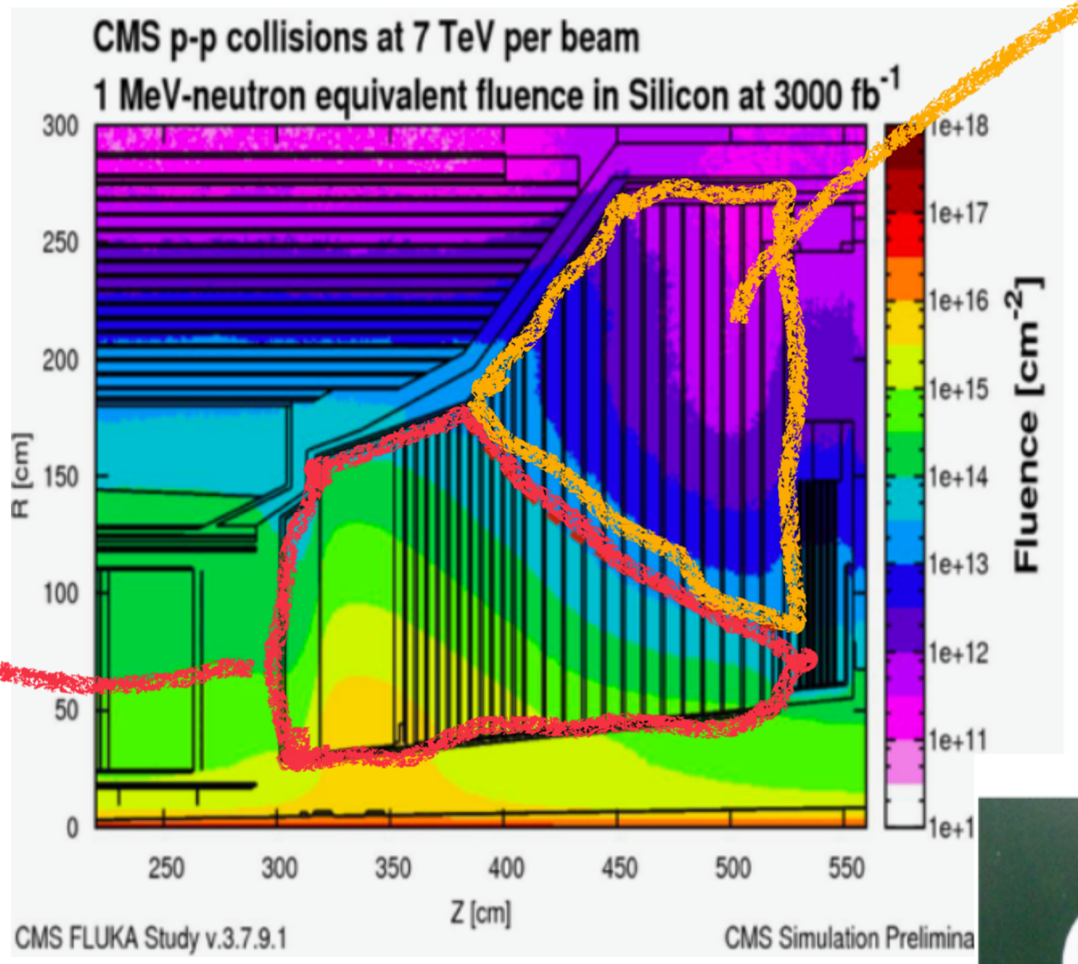

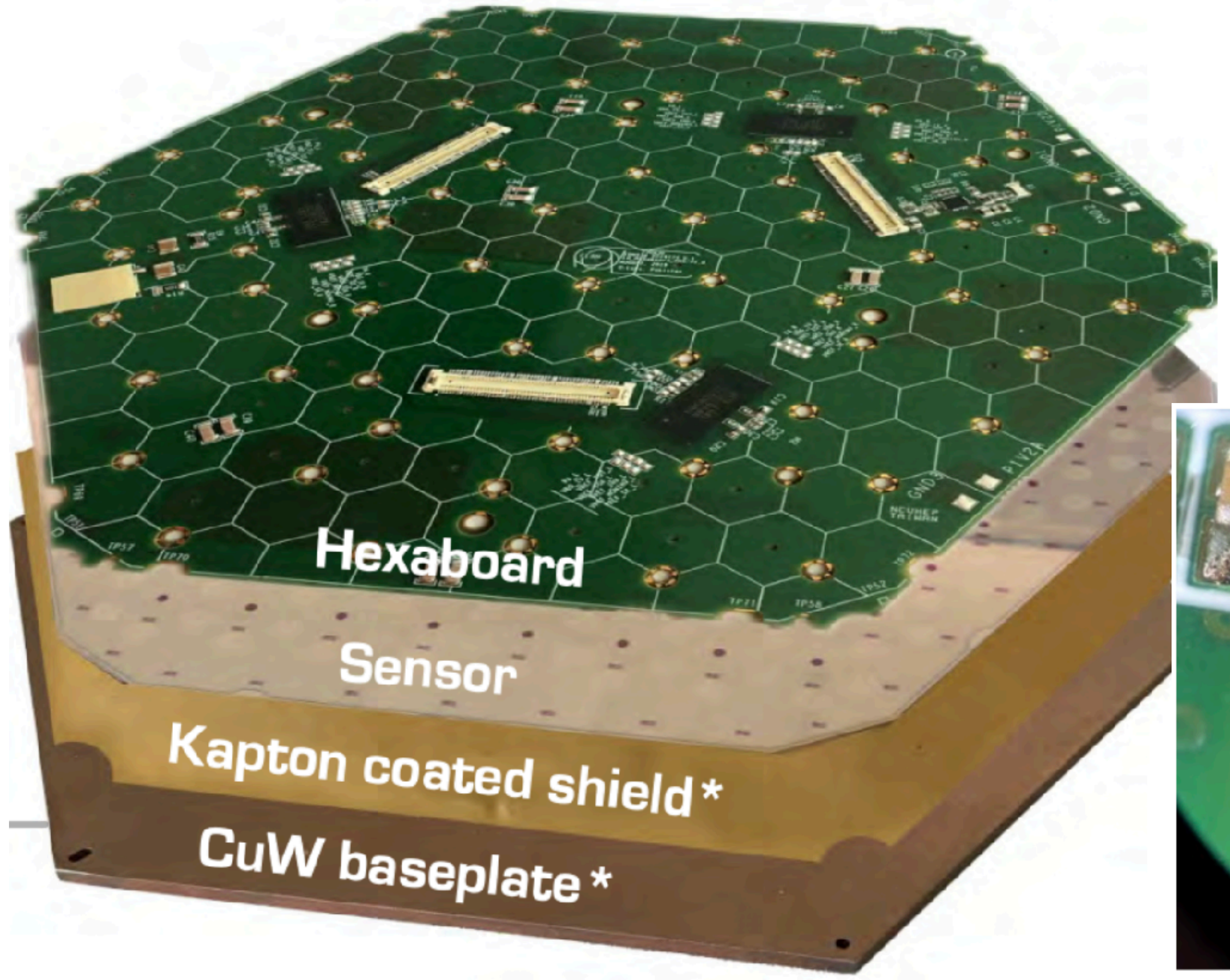

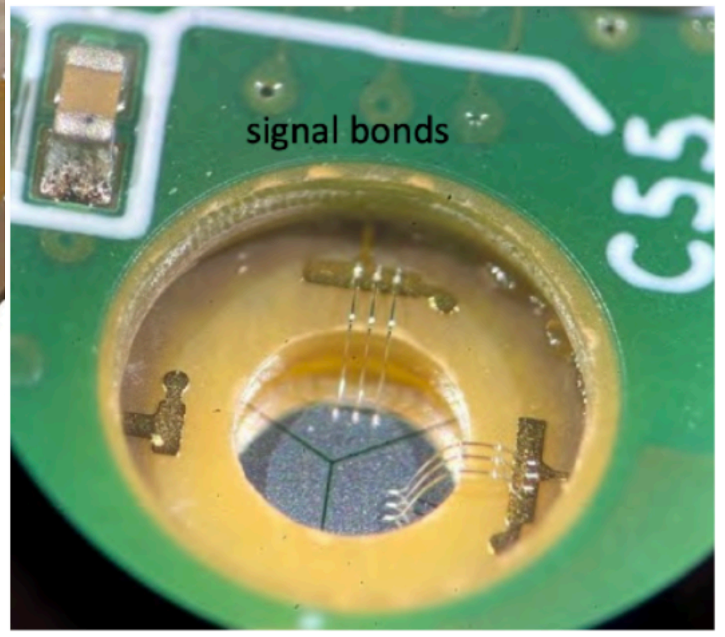

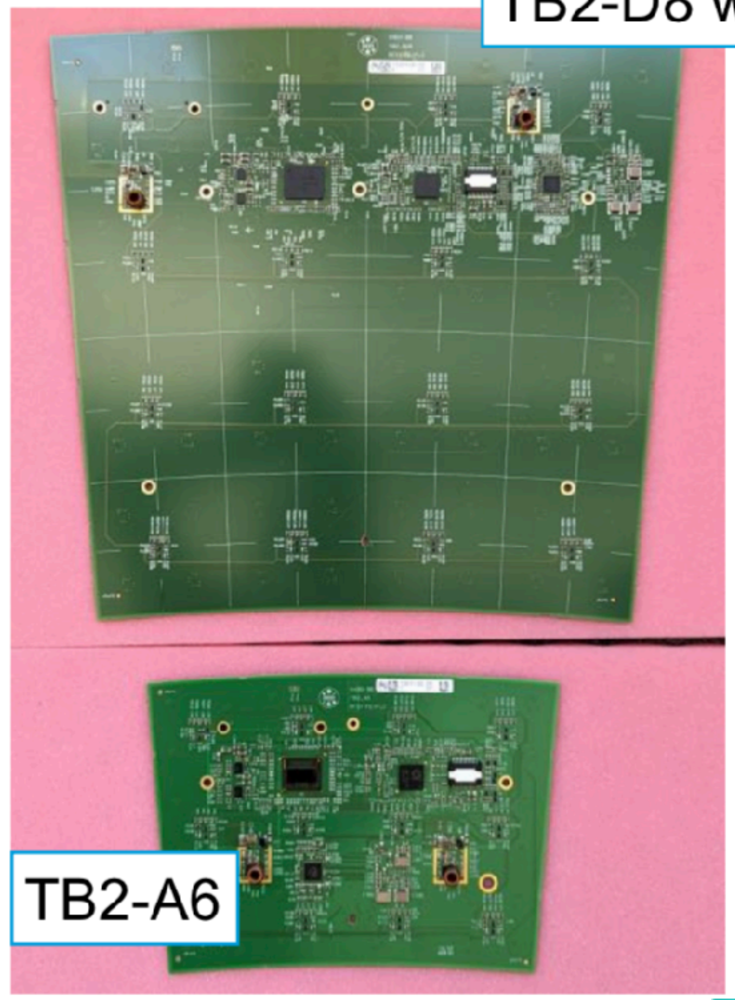

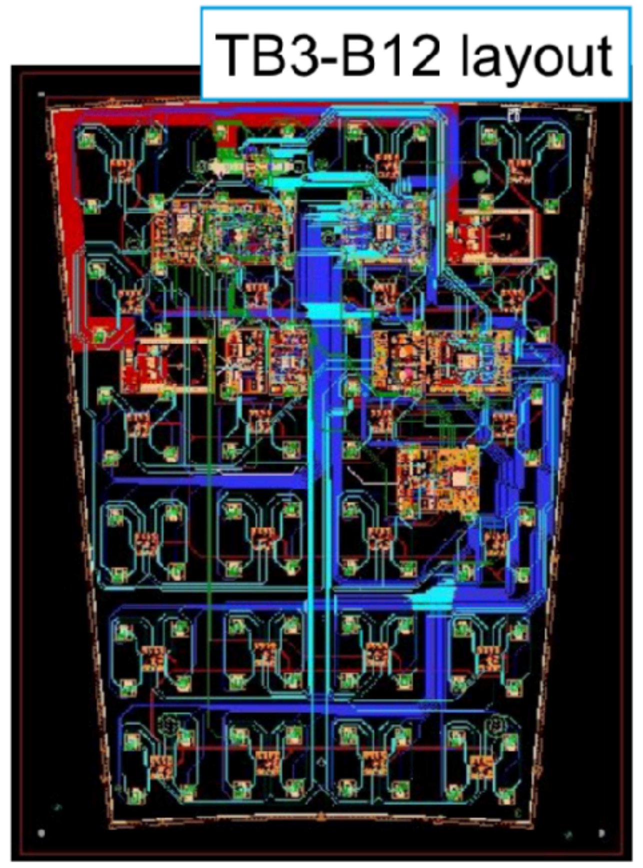

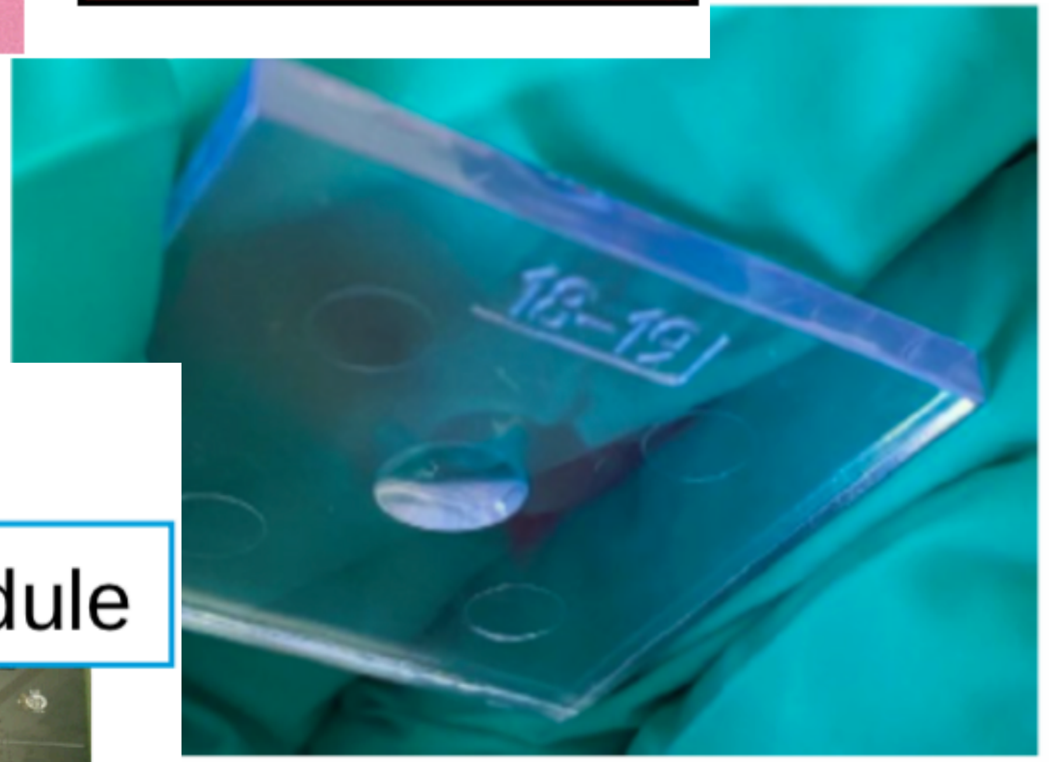

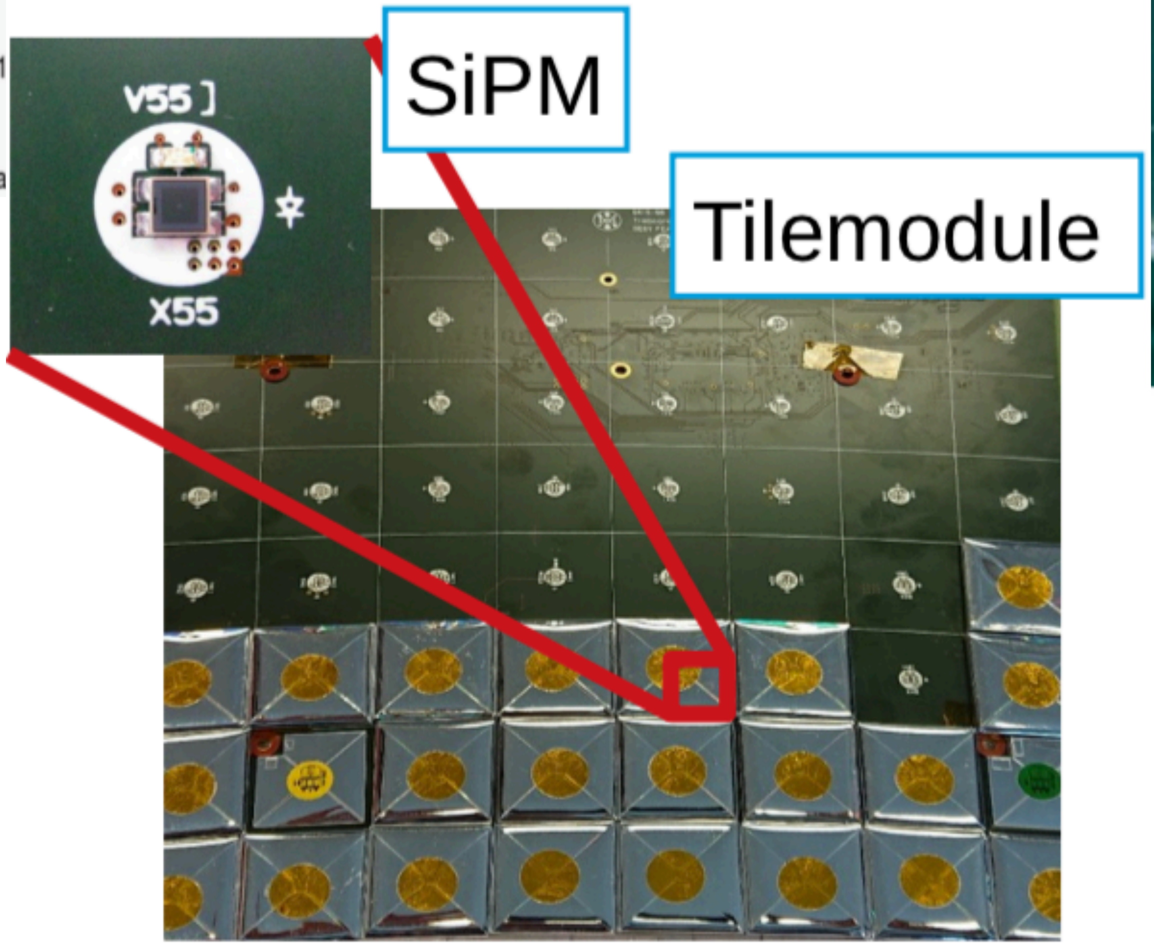

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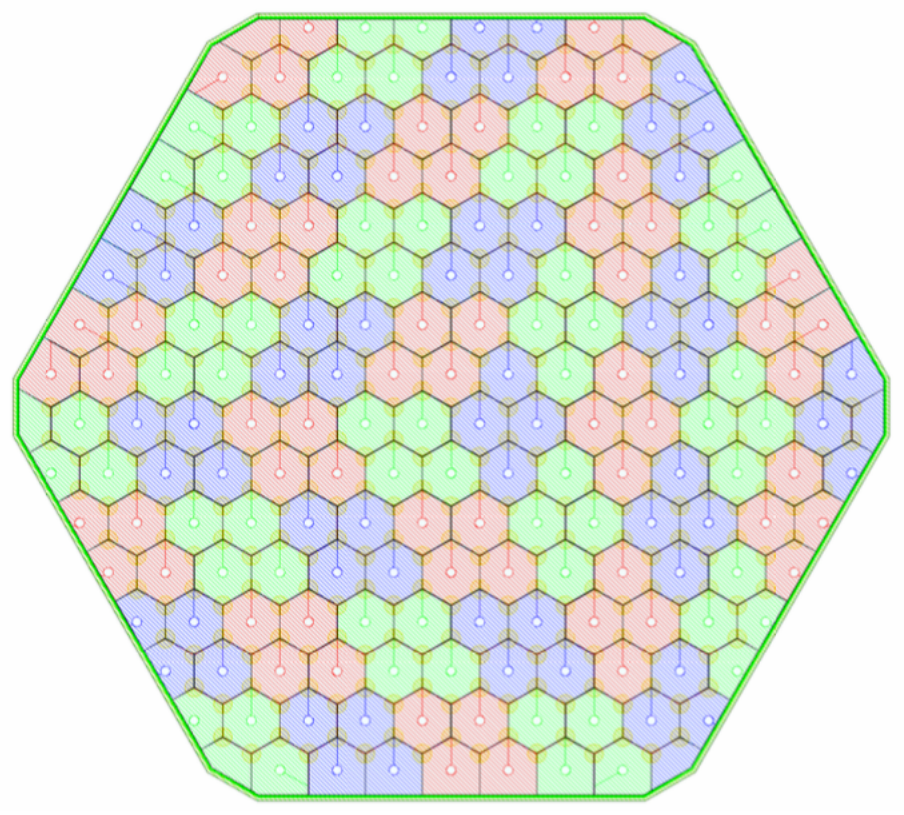

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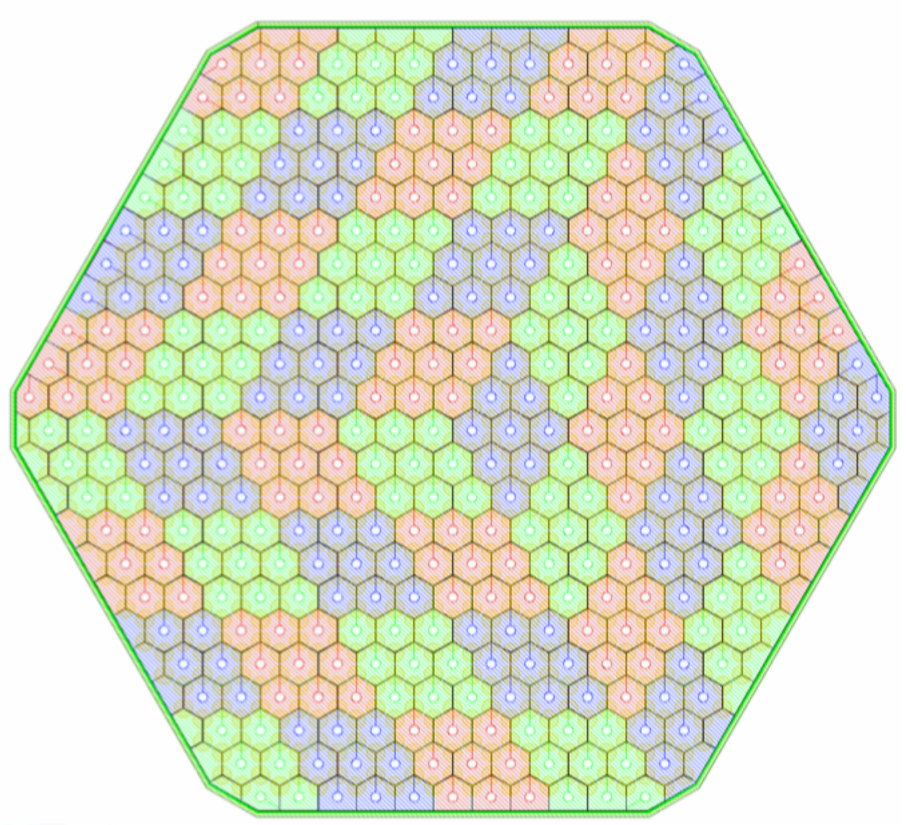

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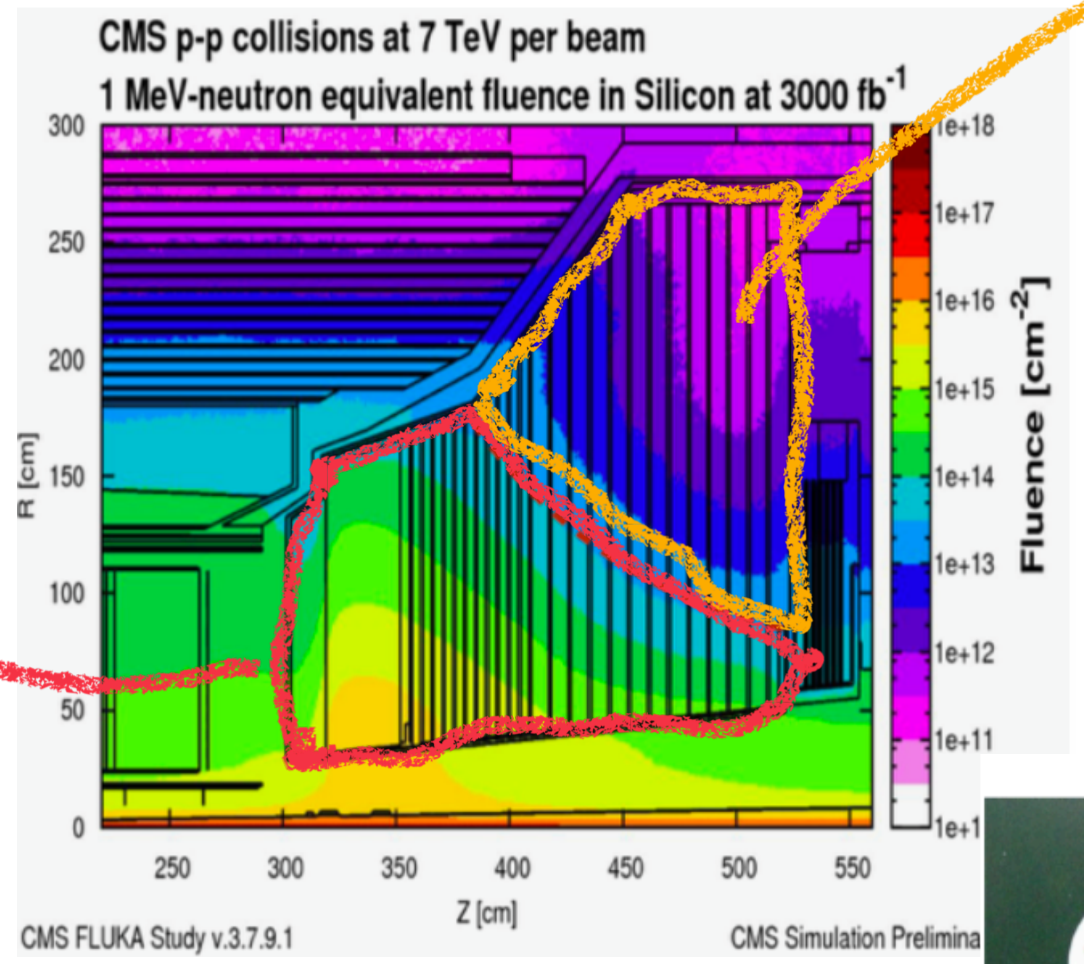
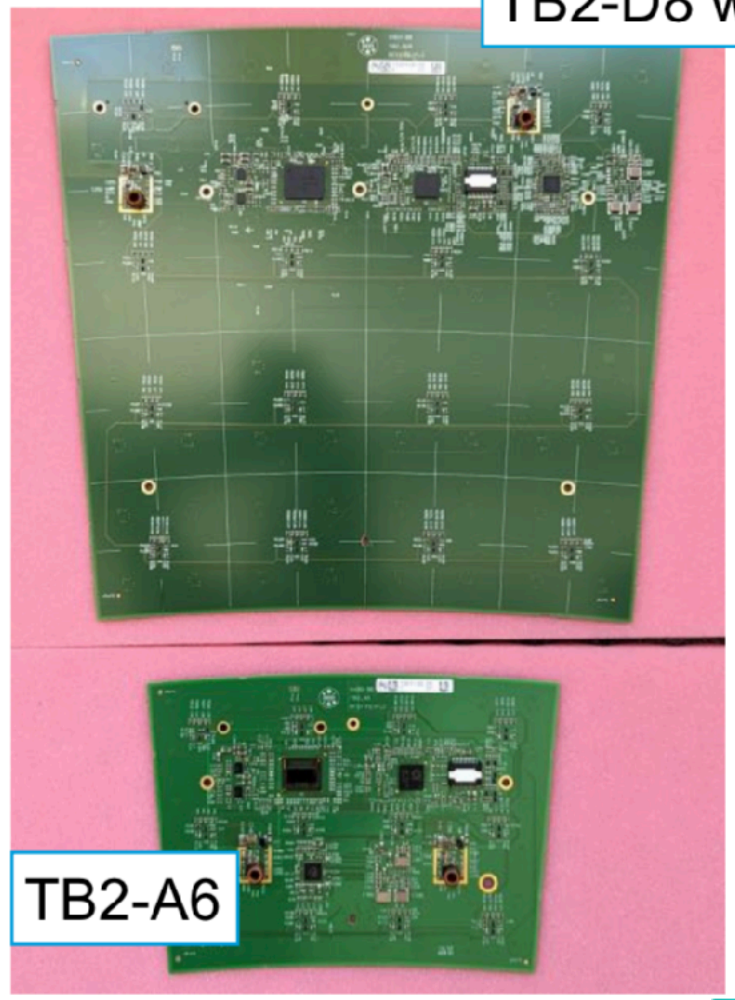
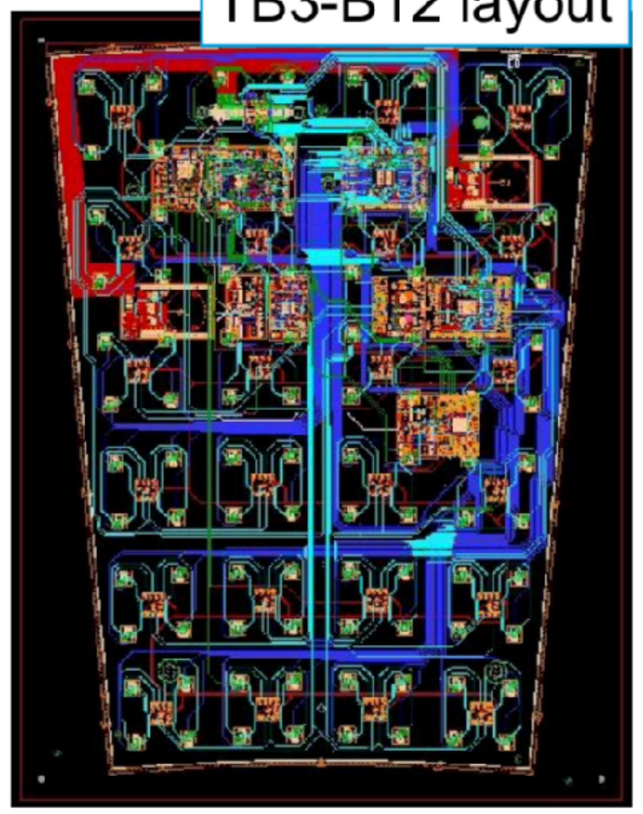
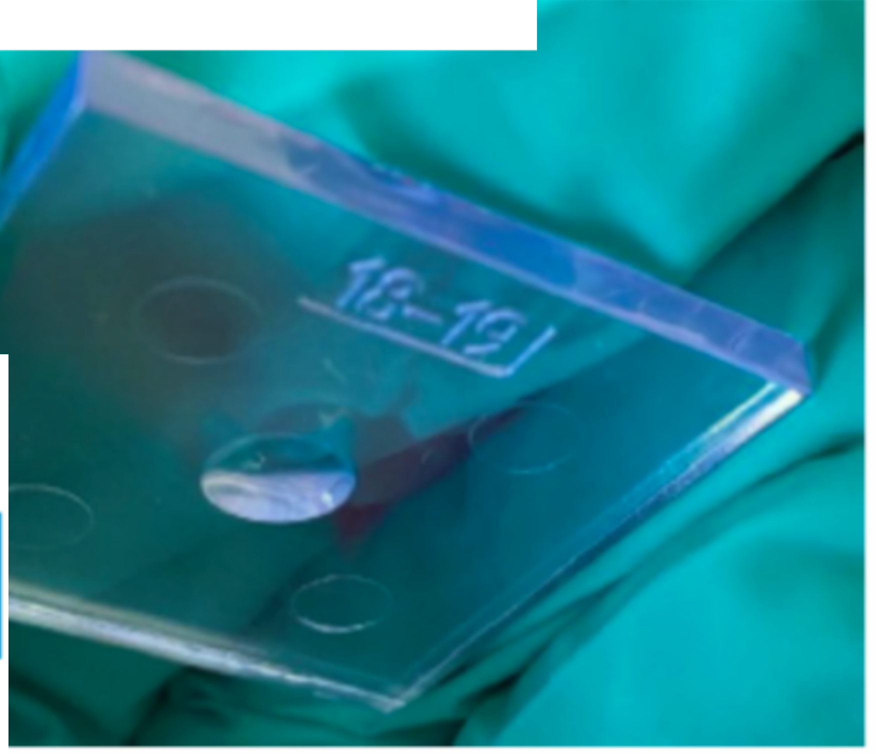
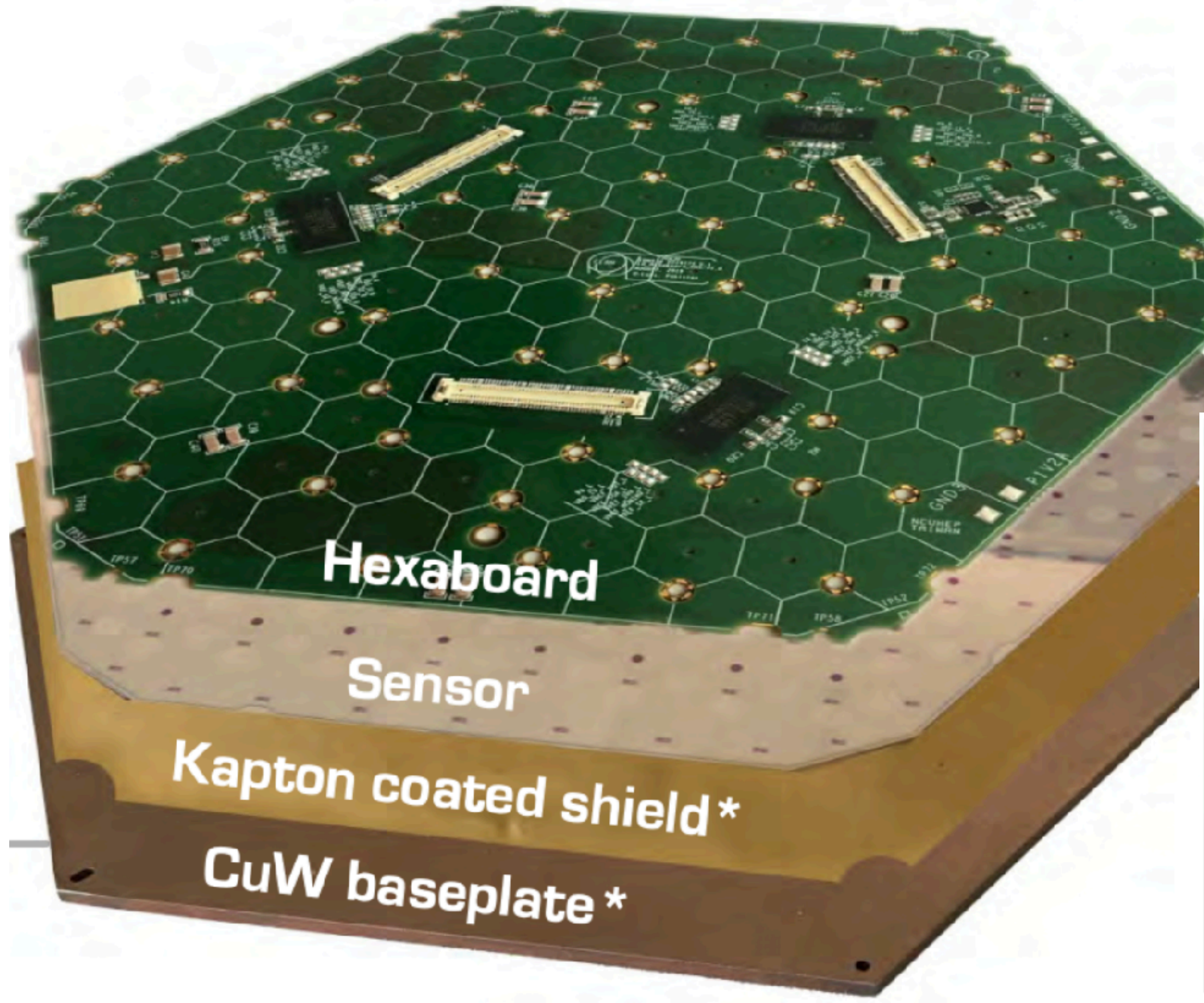
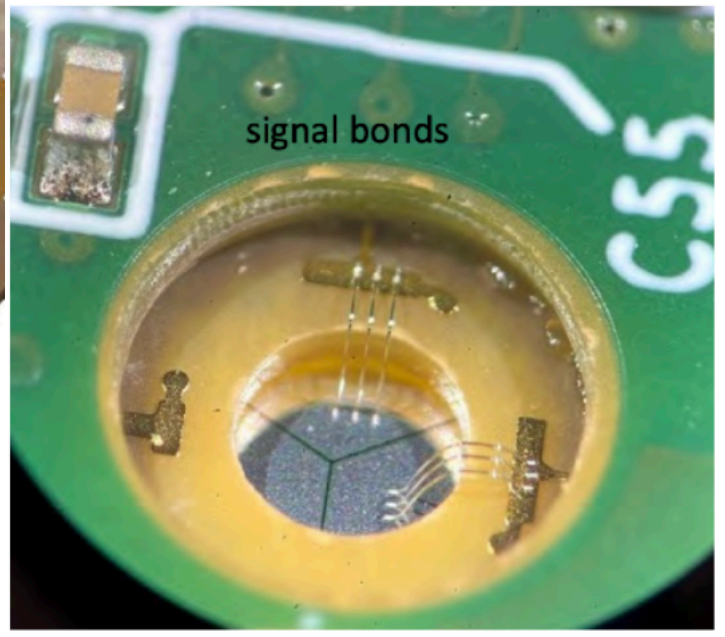




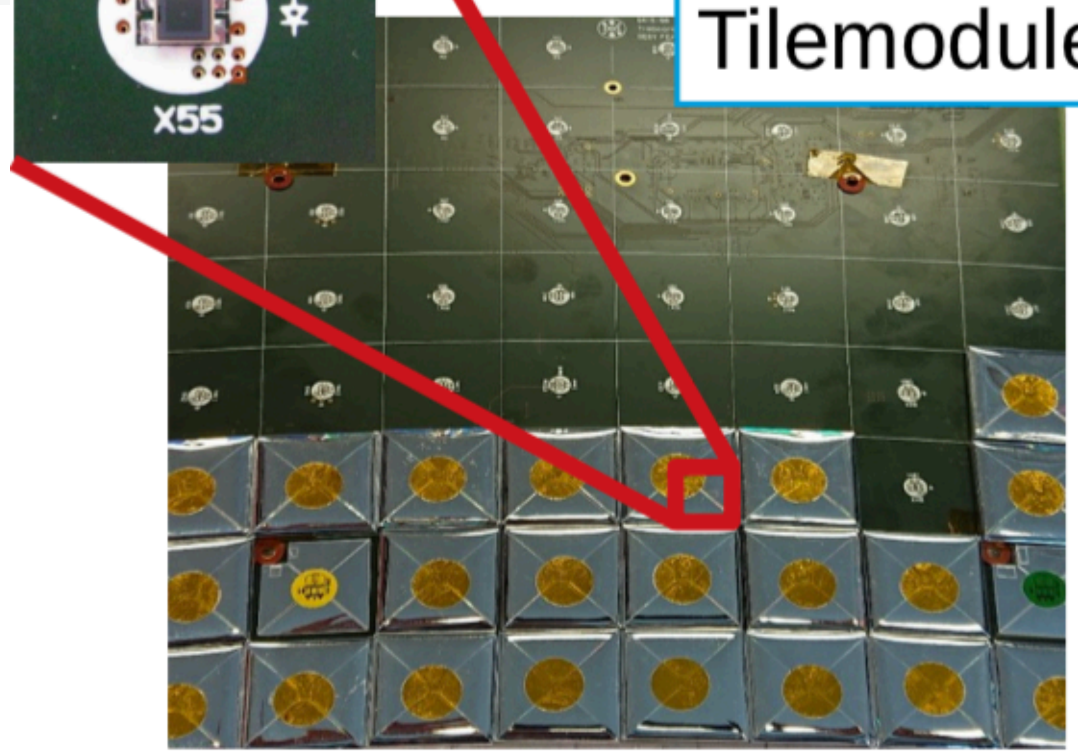




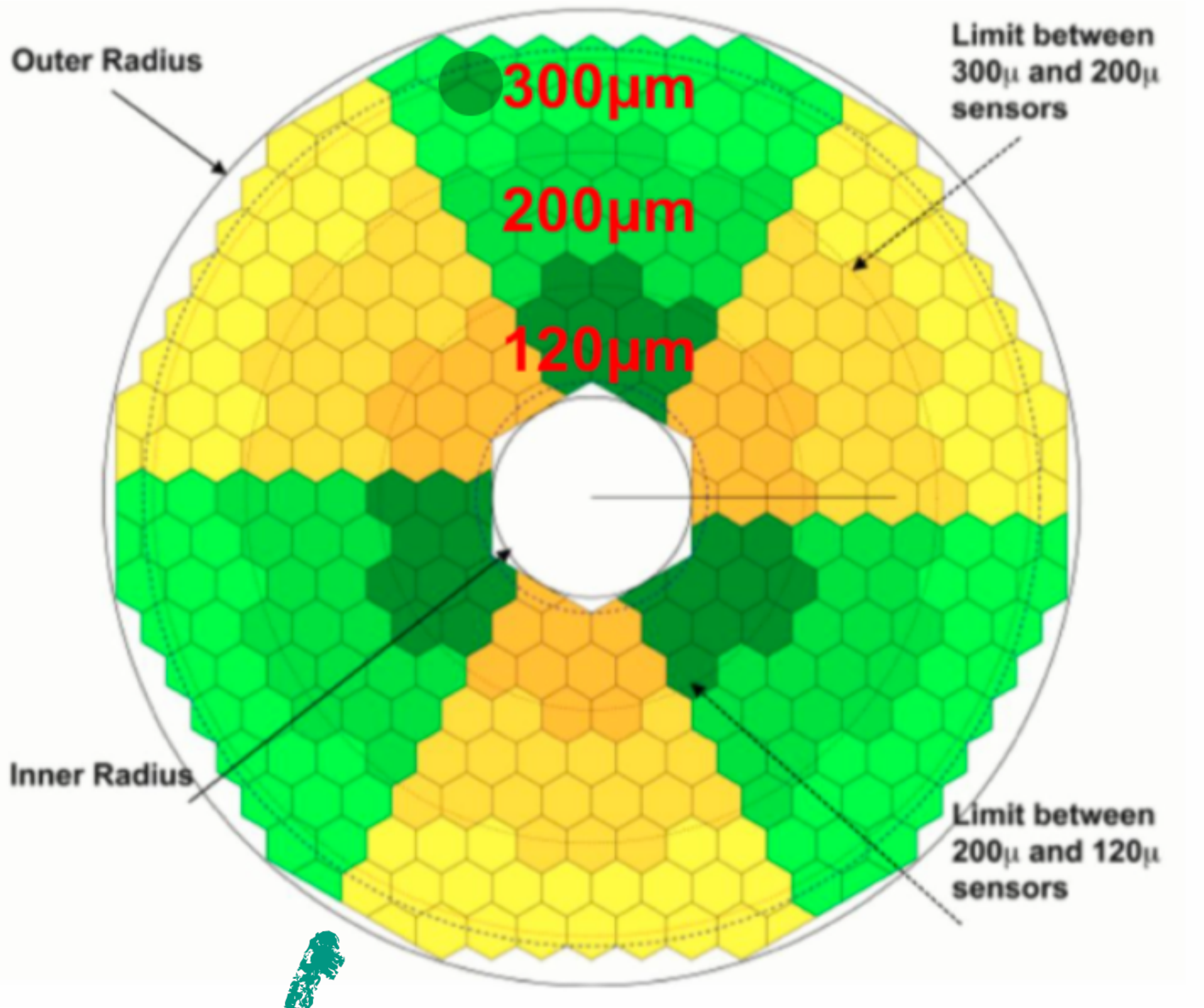


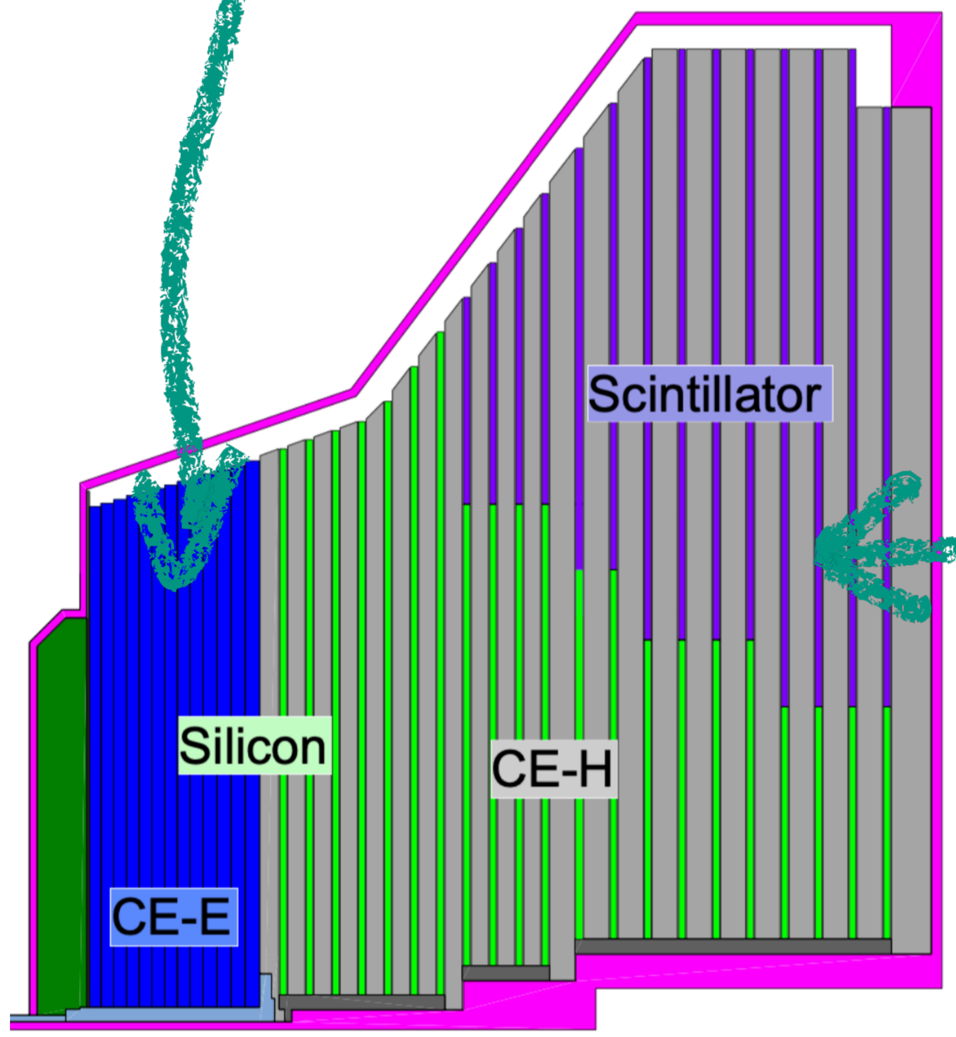


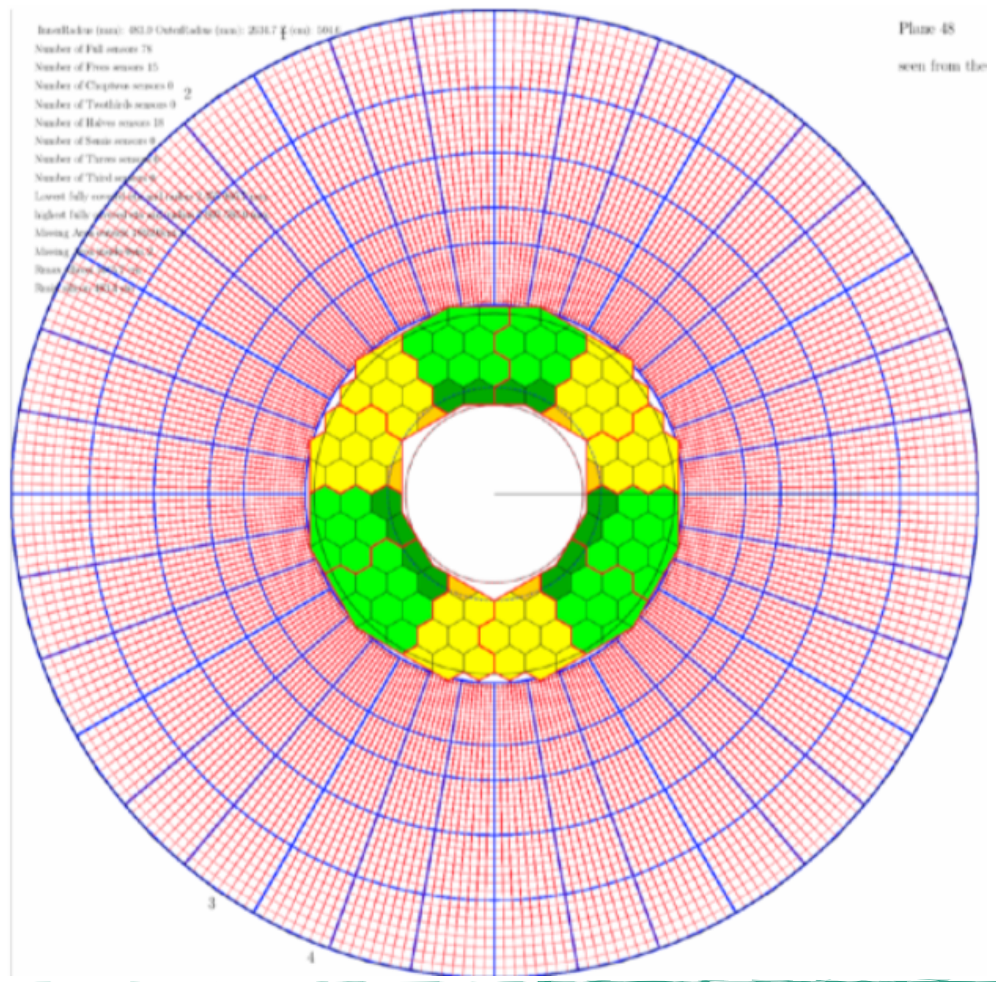
HGCROC:
common FE ASIC
for both - based on
CALICE ASICs



Cassettes: All-Si or mixed



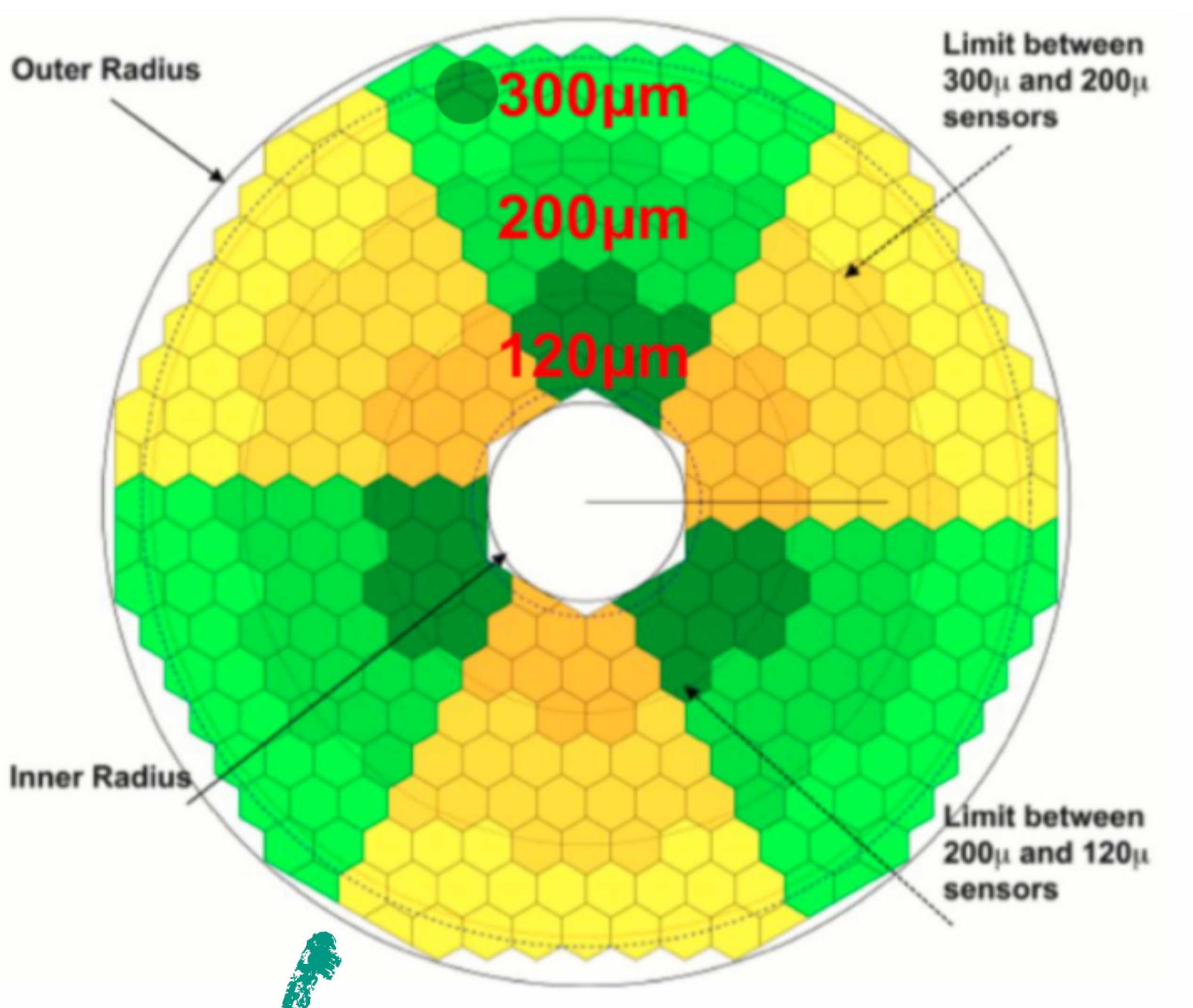


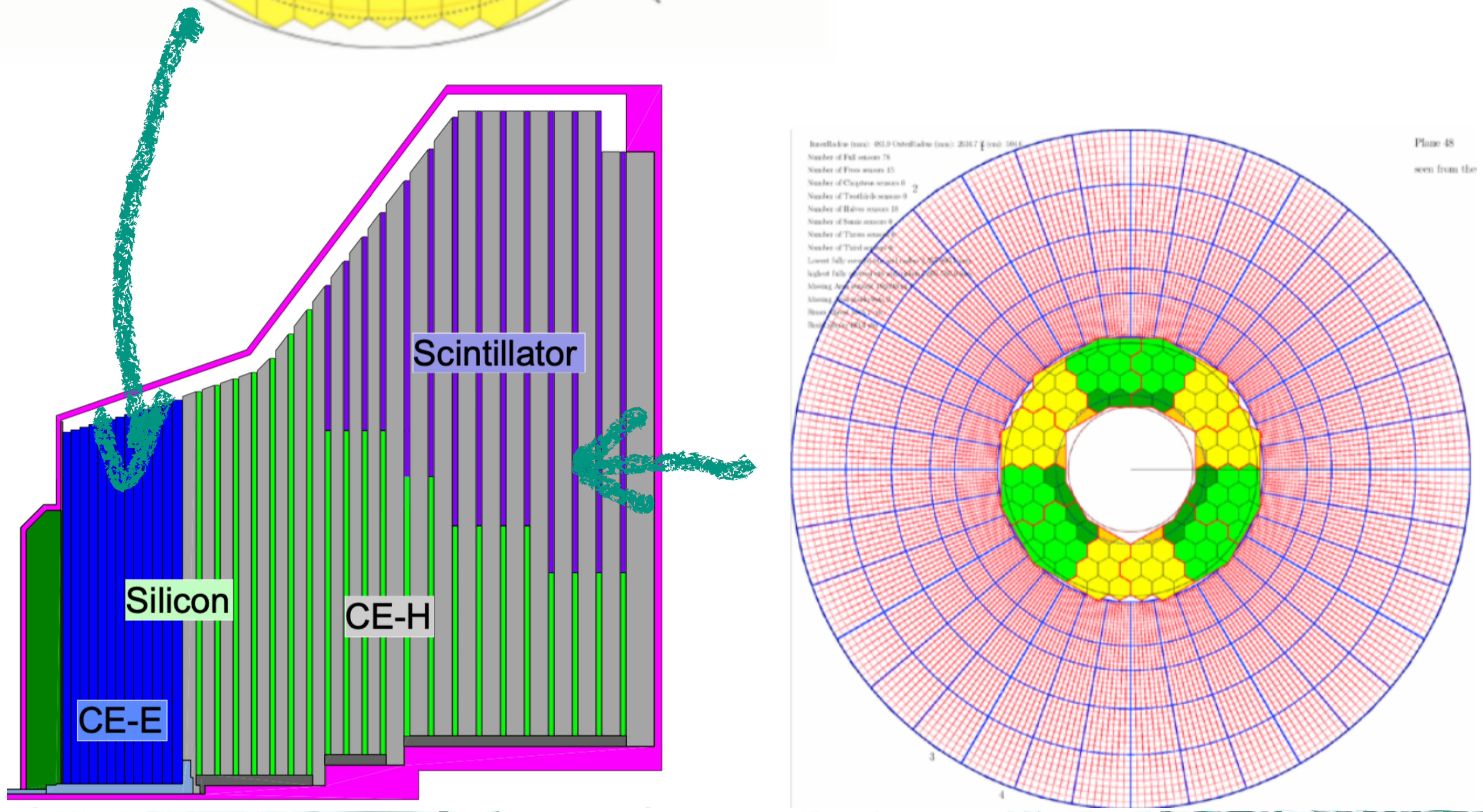


Modules & Readout

Turning it into a system

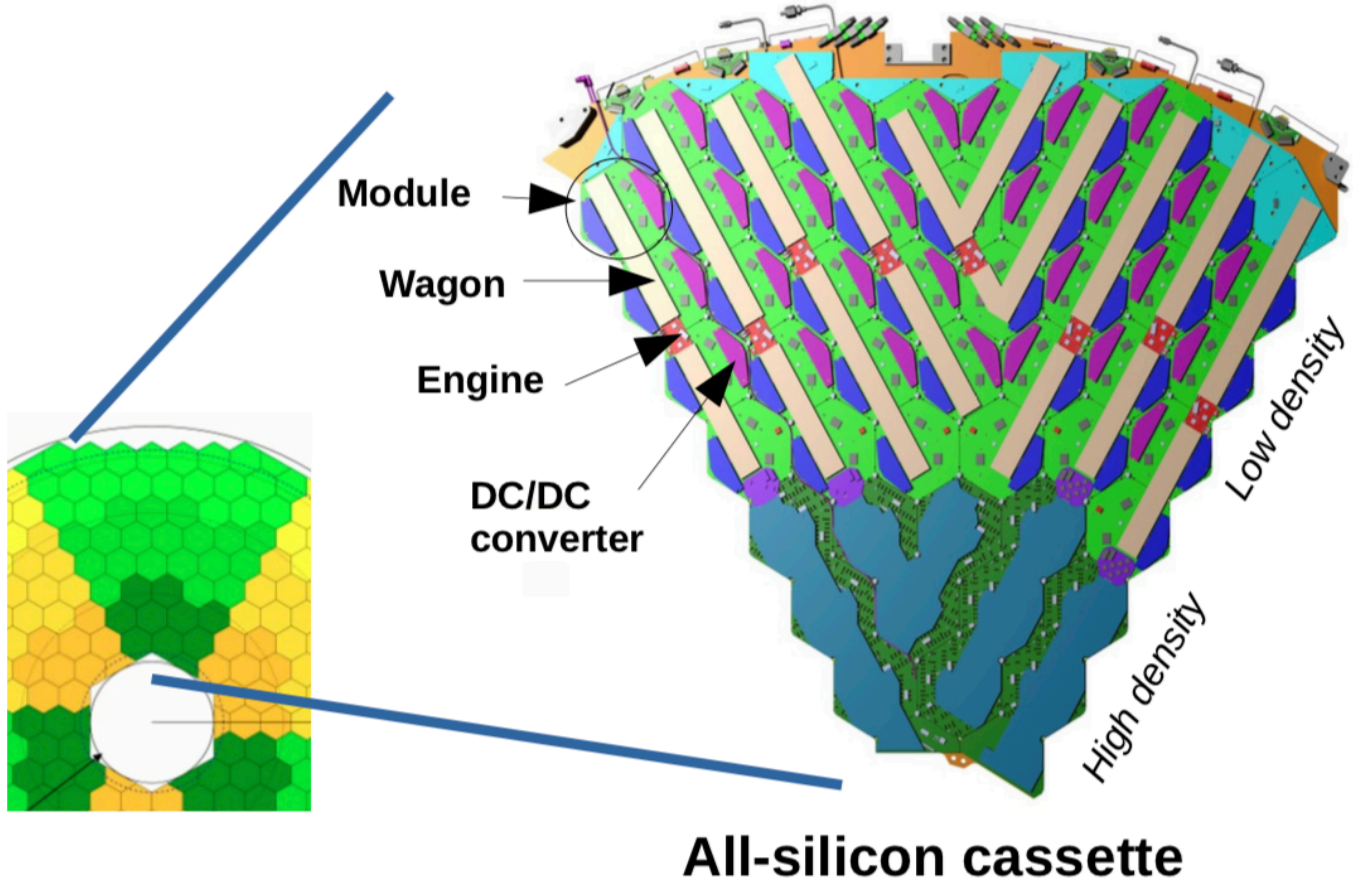
Cassettes: All-Si or mixed





Getting the data out:

- FE + Concentrators (ECON) on modules
- Transmission on "Wagons", going optical on "Engines"



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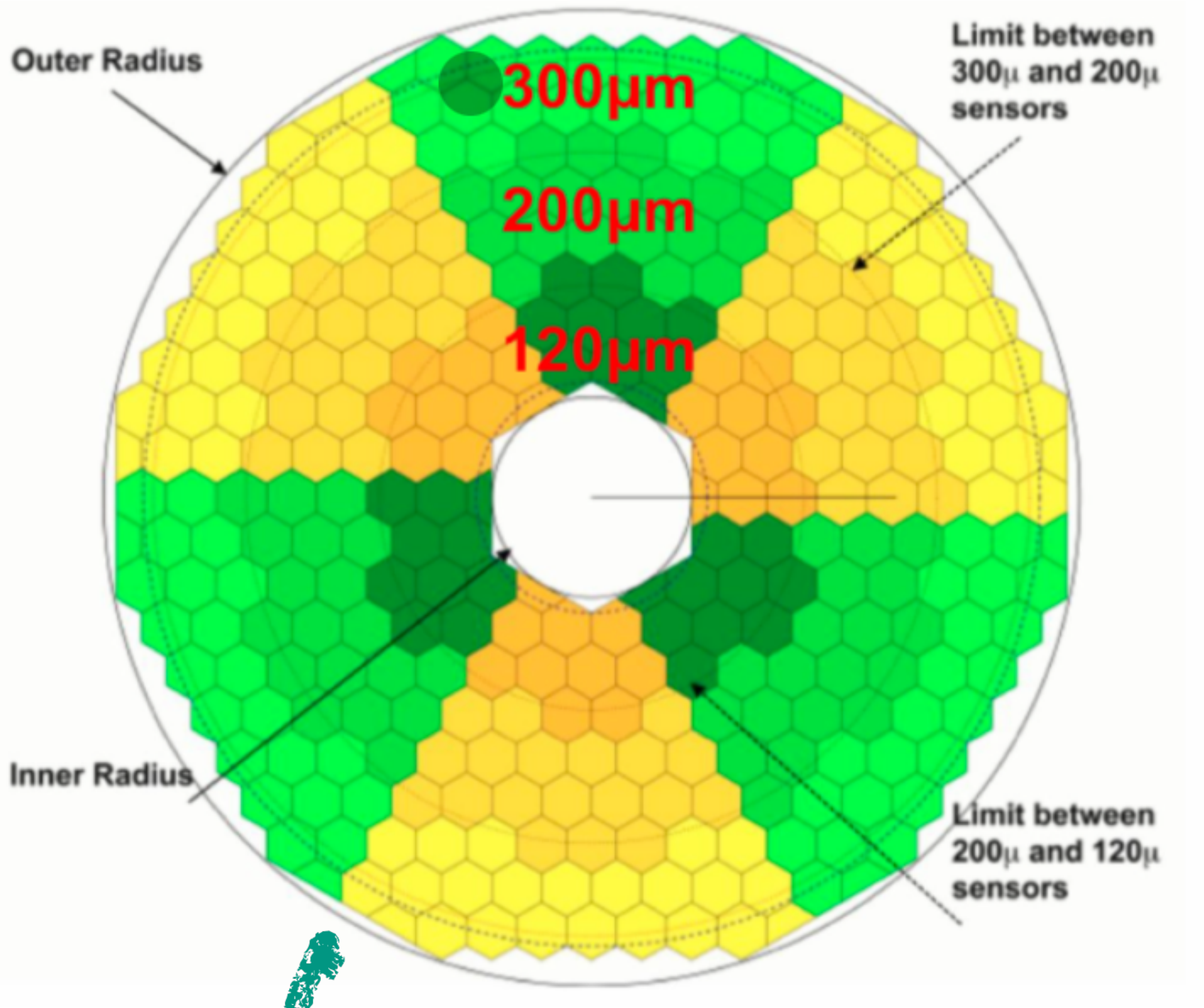

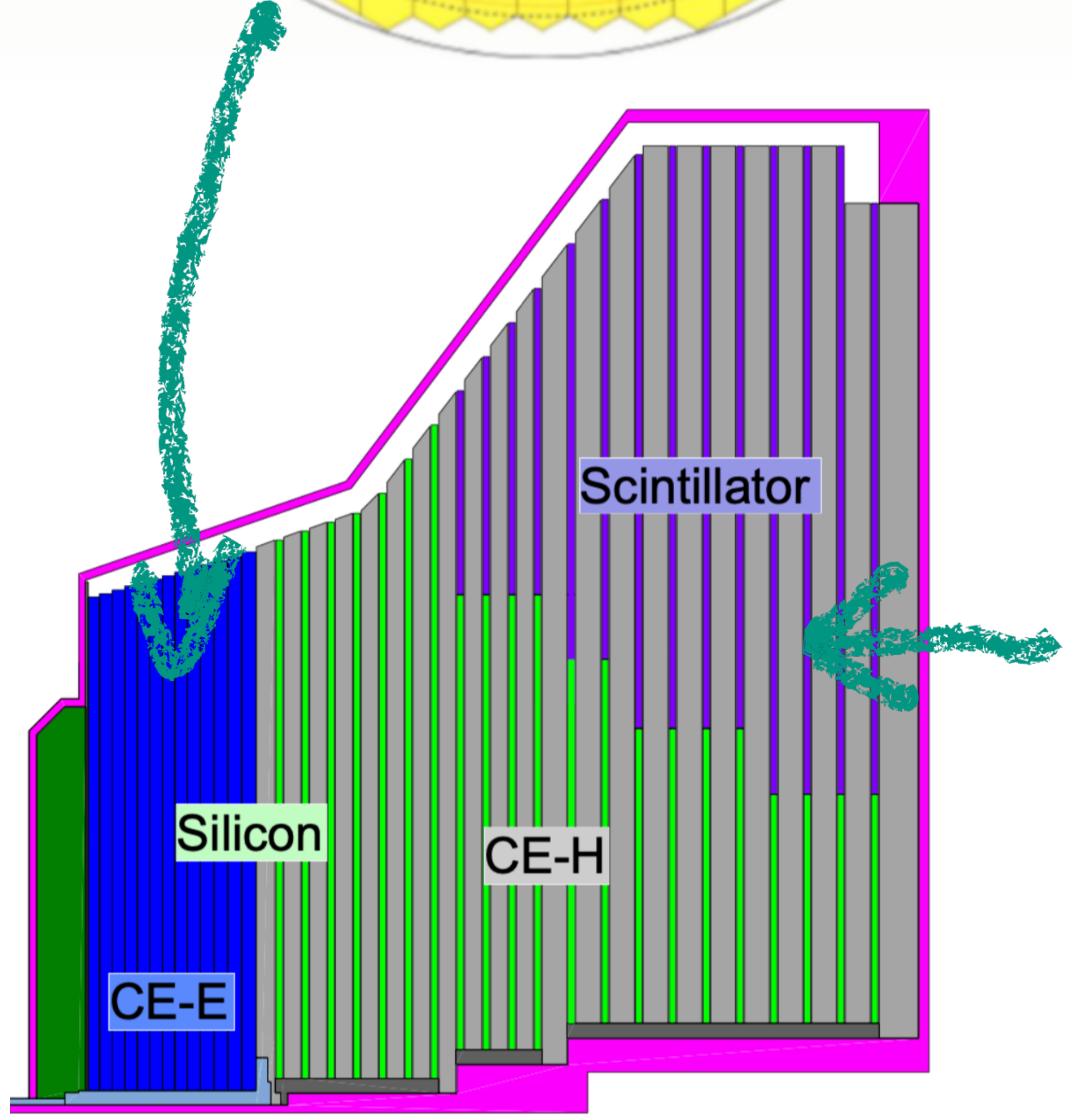

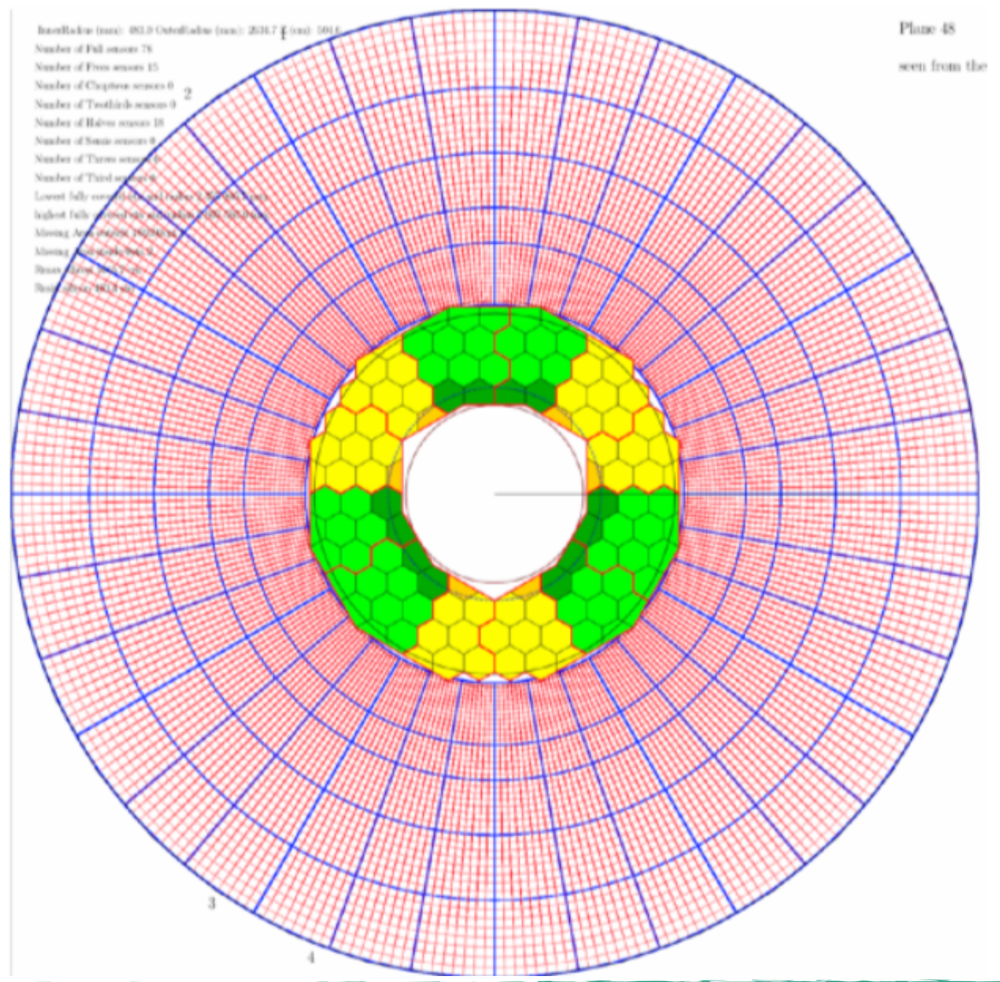

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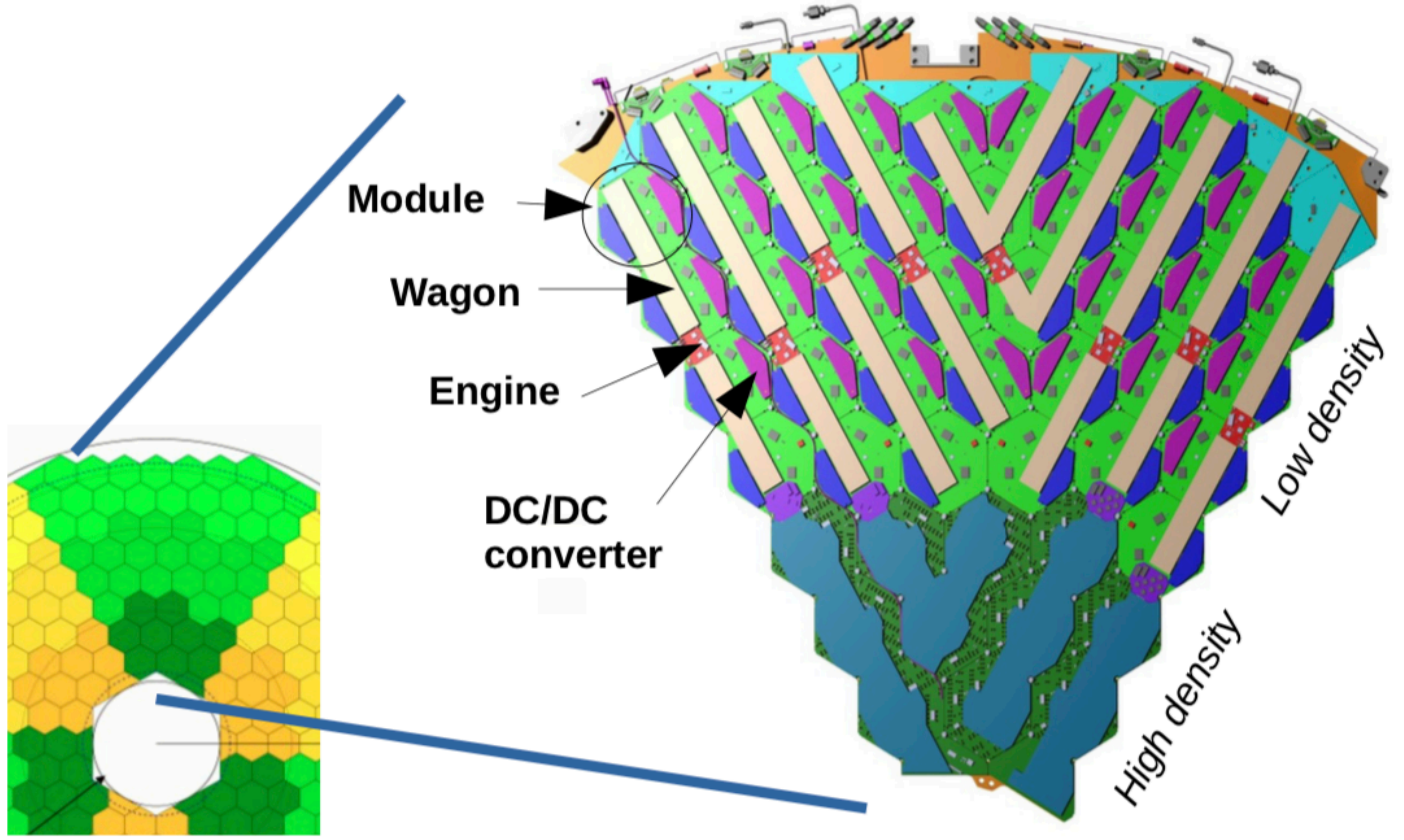


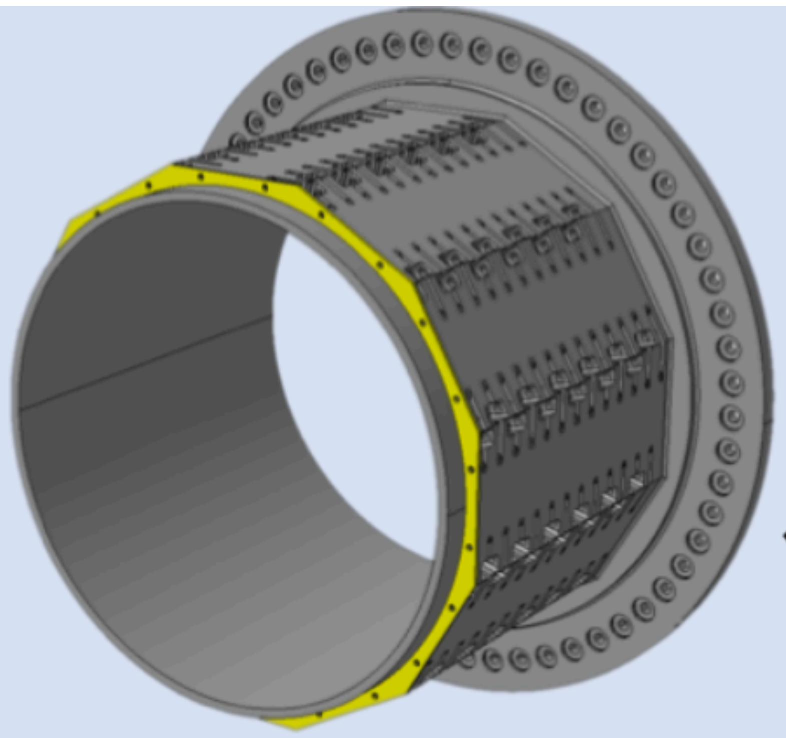
All-silicon cassette

Backend based on Serenity boards

- DAQ & Trigger
- Trigger based on trigger cells: groups on a layer
  ~ 10 000 10 Gbps links to trigger system
  - no layer-to-layer connection within detector volume:
    - ➯ all trigger data selection uses local information only
    - ➯ all sophistication pushed to backend

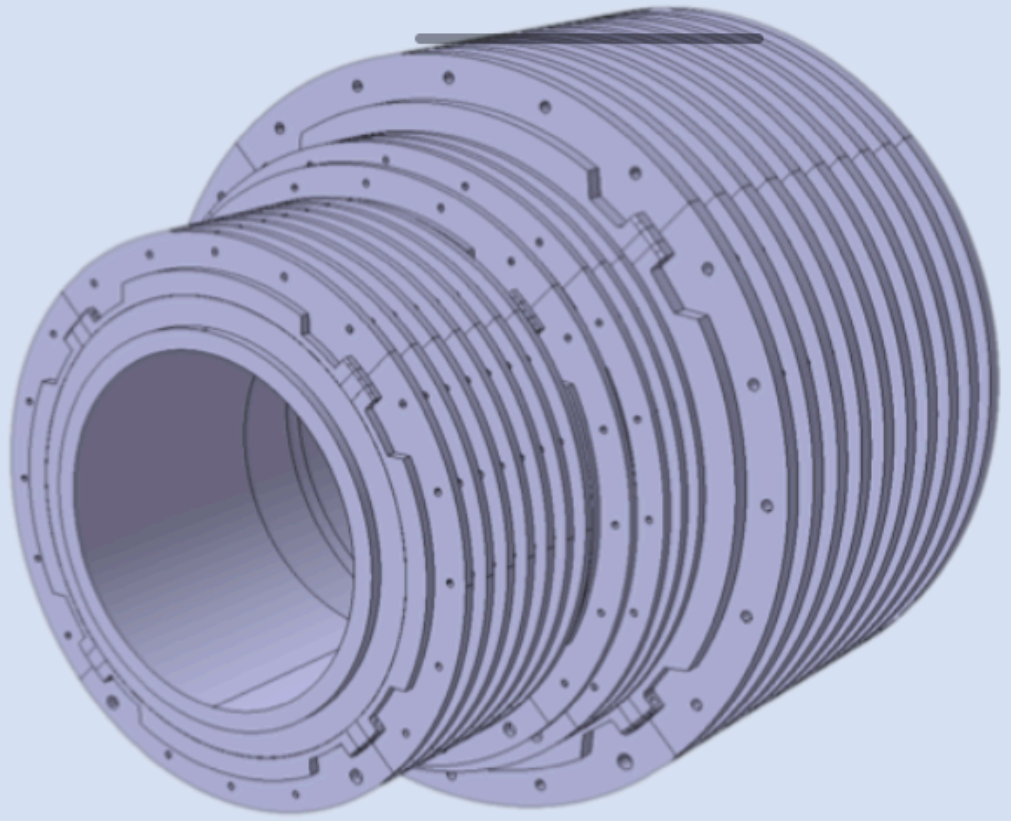
Absorber and Mechanics

Holding it together



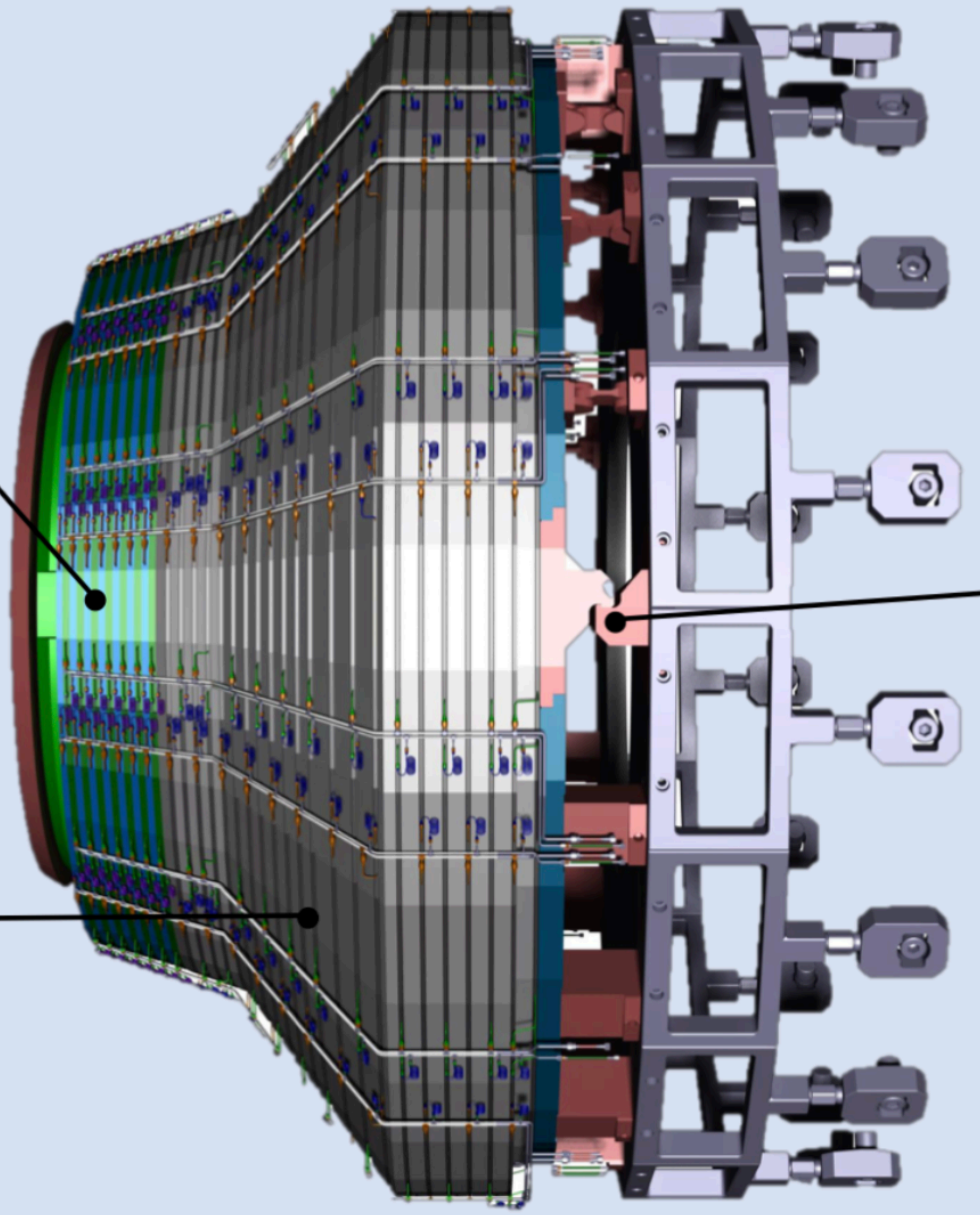
CE-E support:

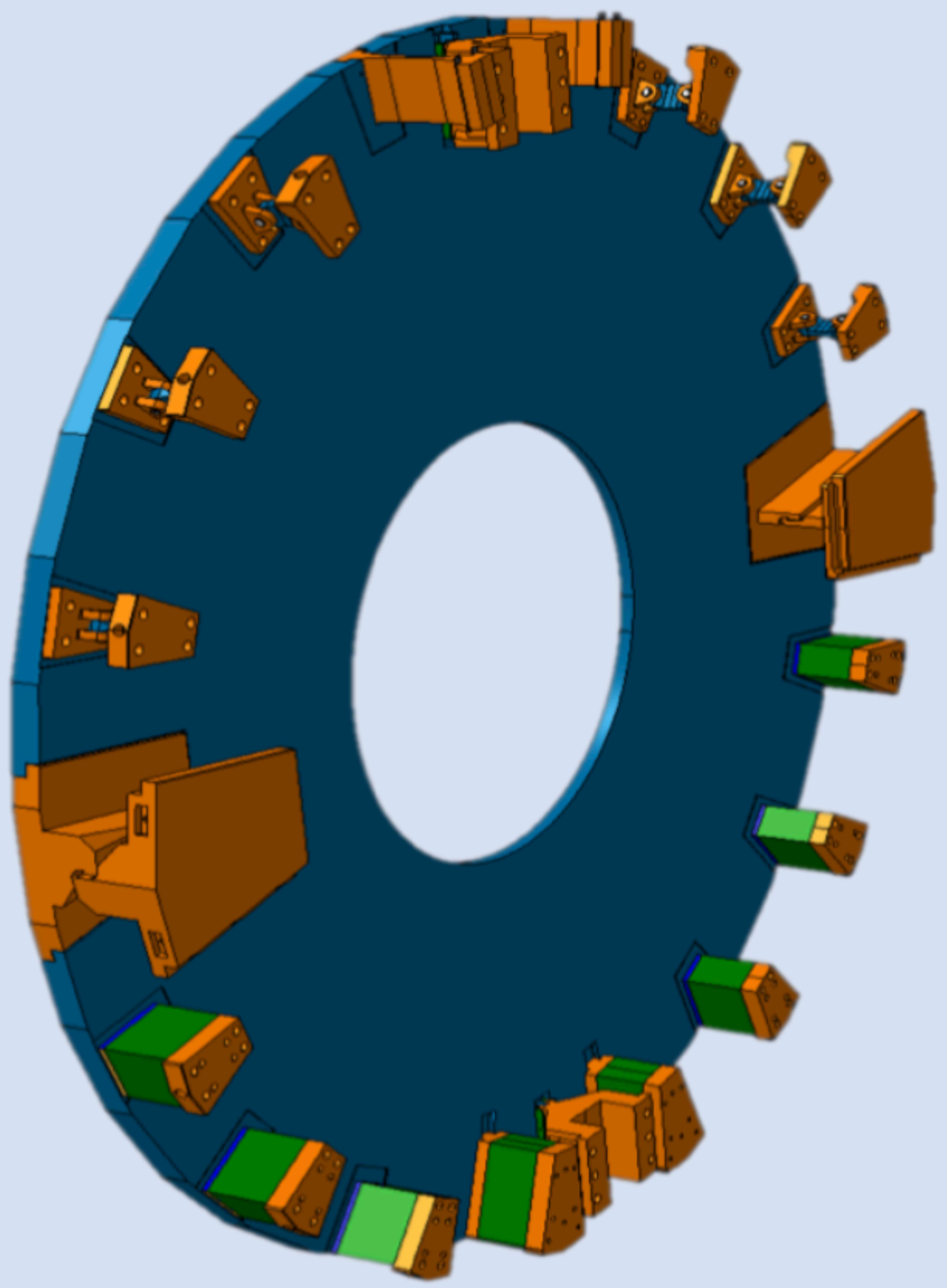
Forged aluminium support machined from a single solid piece of metal



CE-H support:

Stainless steel support assembly designed to take the weight of the Hadronic cassettes and stainless steel absorbers





Sliding wedges:

Stainless steel supports designed to take the total detector weight. Sliding feature will allow to cope with a thermal contraction as one end of the wedges will be at -35°C while the other end will be at 18°C

Summary & Outlook

The Role of KIT

Calorimeter R&D & CMS

Karlsruher Institut für Technologie

- Strategic detector R&D - implementation of the ECFA detector R&D roadmap
  A new collaboration for calorimeter R&D is being formed - active in coordination.
  Key technological contributions:
  - Solving the circular Higgs Factory challenge: Electronics systems, data concentration, DAQ
  - Advanced algorithms - from CPUs to FPGAs; applications of ML/AI

- The HGCAL - an opportunity to expand the KIT role in CMS
  - Mechanics & services (CuW Baseplates, Cooling manifolds, …)
  - The backend system - DAQ and trigger based on Serenity boards:
    Hardware & algorithms

Summary

and Outlook

- Highly granular calorimeters are central components for future Higgs factory detectors
  - Enabled by silicon photomultipliers and capable ASICs
  - Require ultra-compact interfaces and low power, scalable technologies suitable for mass production
- Key elements demonstrated by the CALICE collaboration - but challenging (and interesting!) developments remain
- The CALICE technology has been adopted by CMS for the Phase II HGCAL upgrade - and is being pushed to a whole new level:
  - Extreme radiation, enormous data volumes
- This project is happening now - and it has to succeed! KIT will make decisive contributions.

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Karlsruher Institut für Technologie

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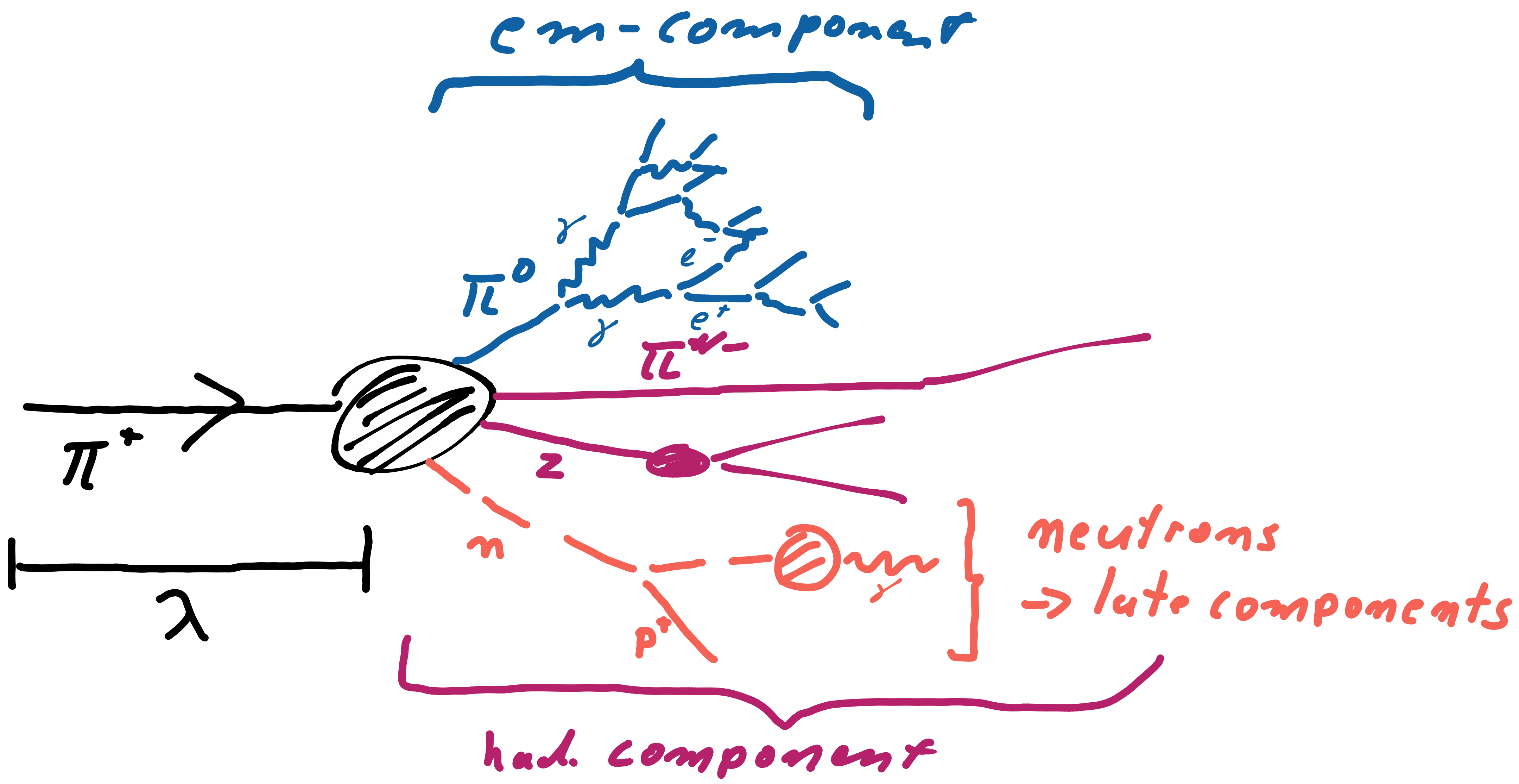
~ 25 years from initial ideas to first full-scale application with HL-LHC startup.

And: the blueprint for future calorimeters in HEP.

Extras

Reconstructing Energy

Using granular information



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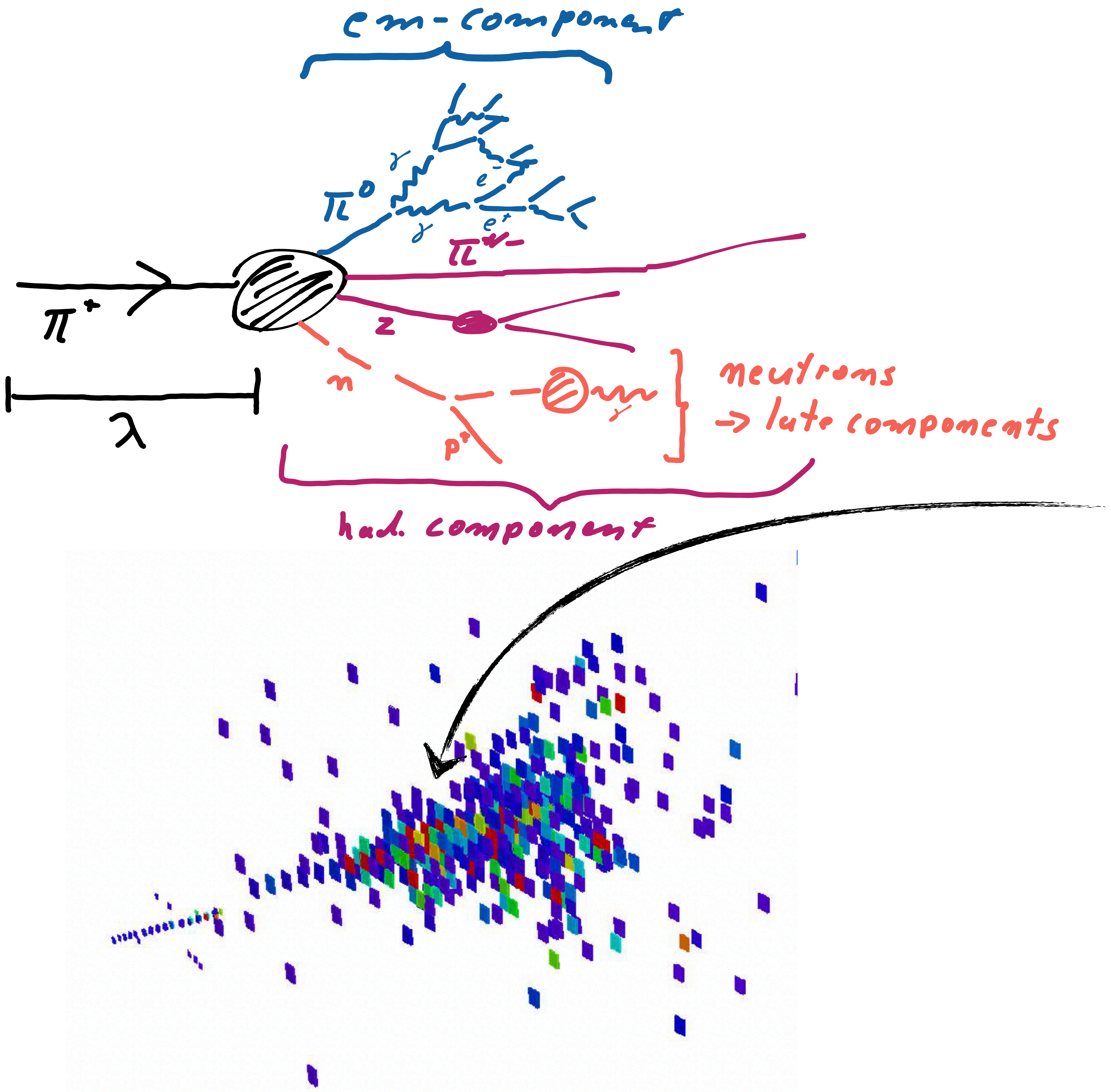

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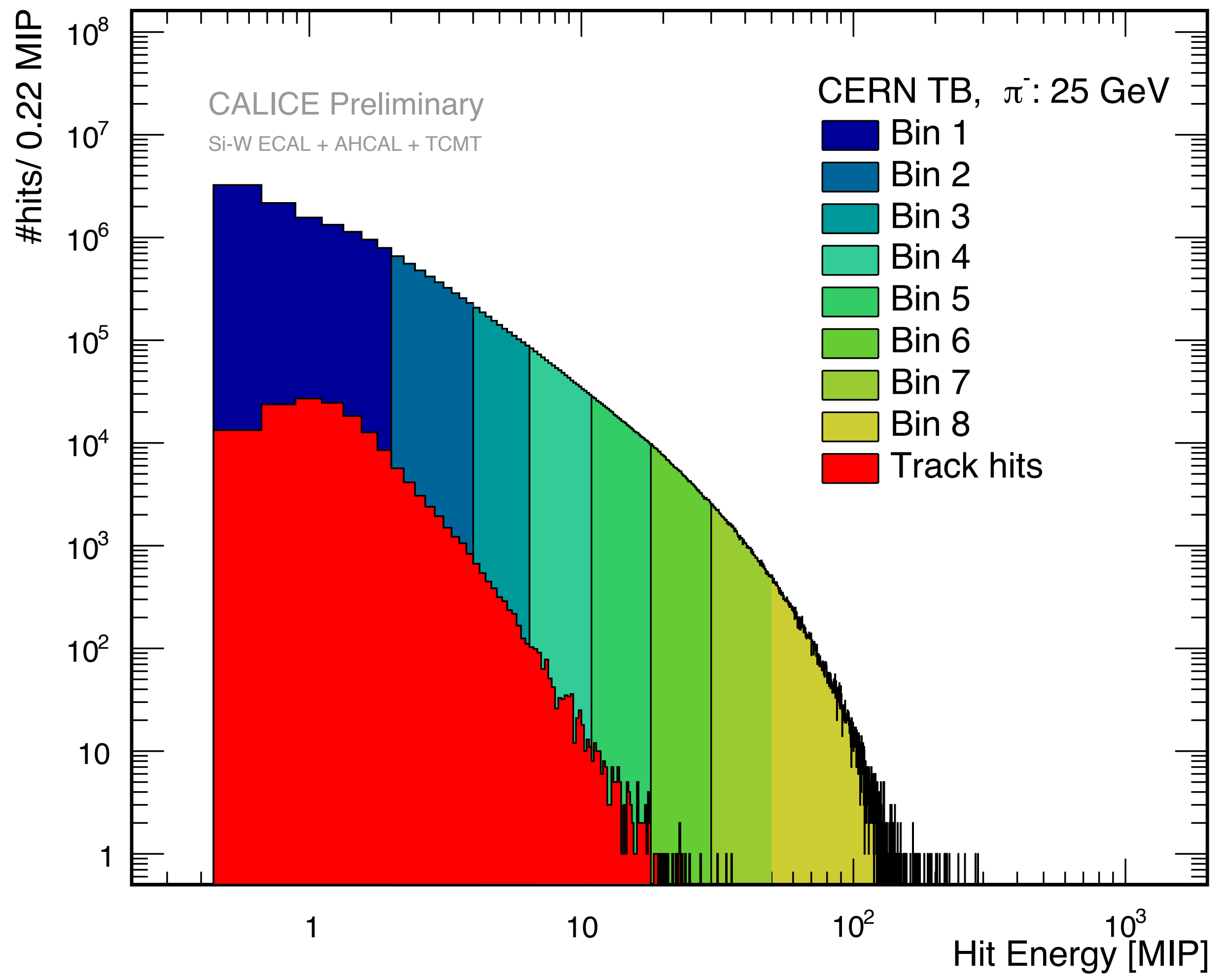
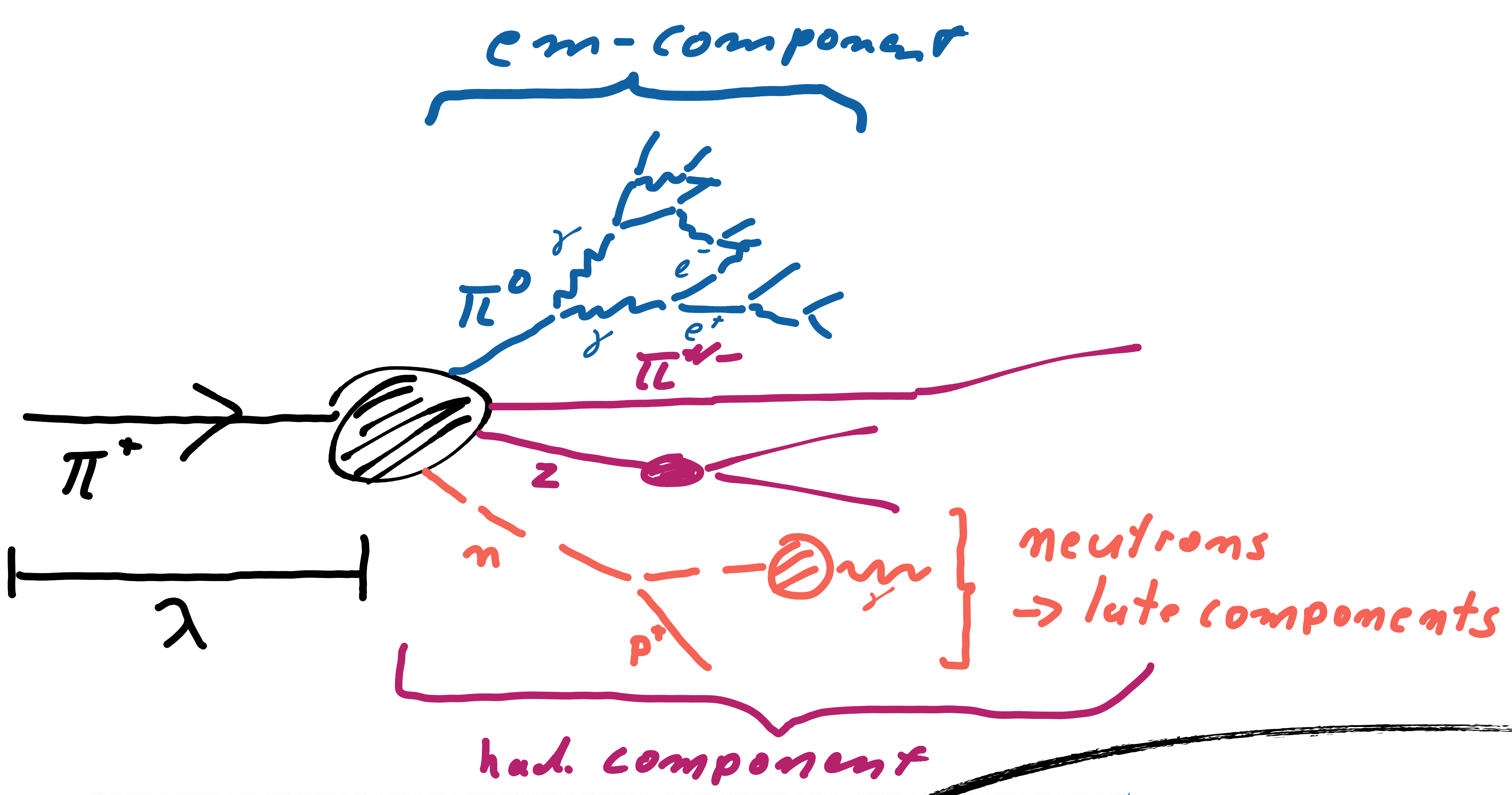
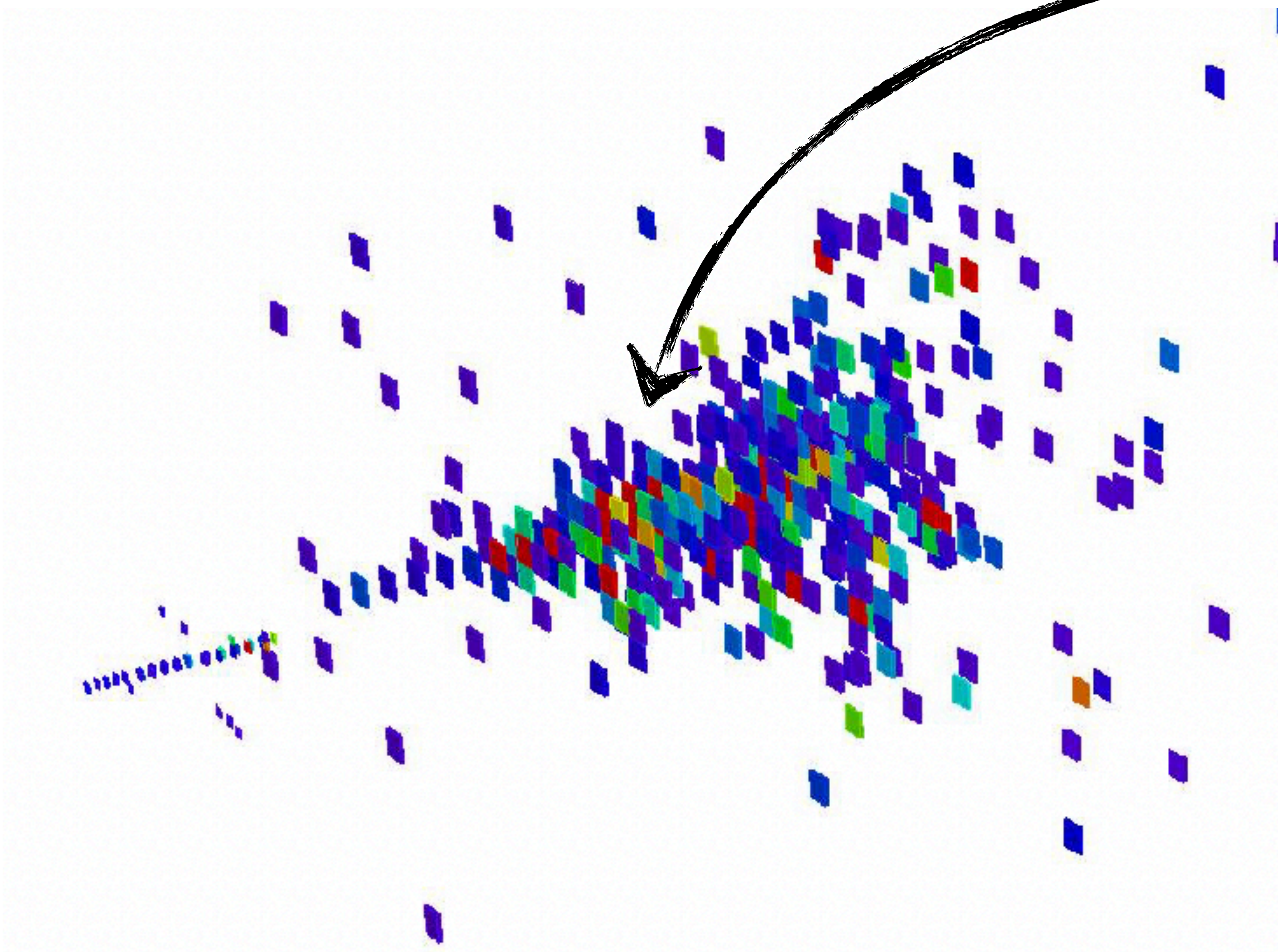


Reconstructing Energy

Using granular information

Karlsruher Institut für Technologie





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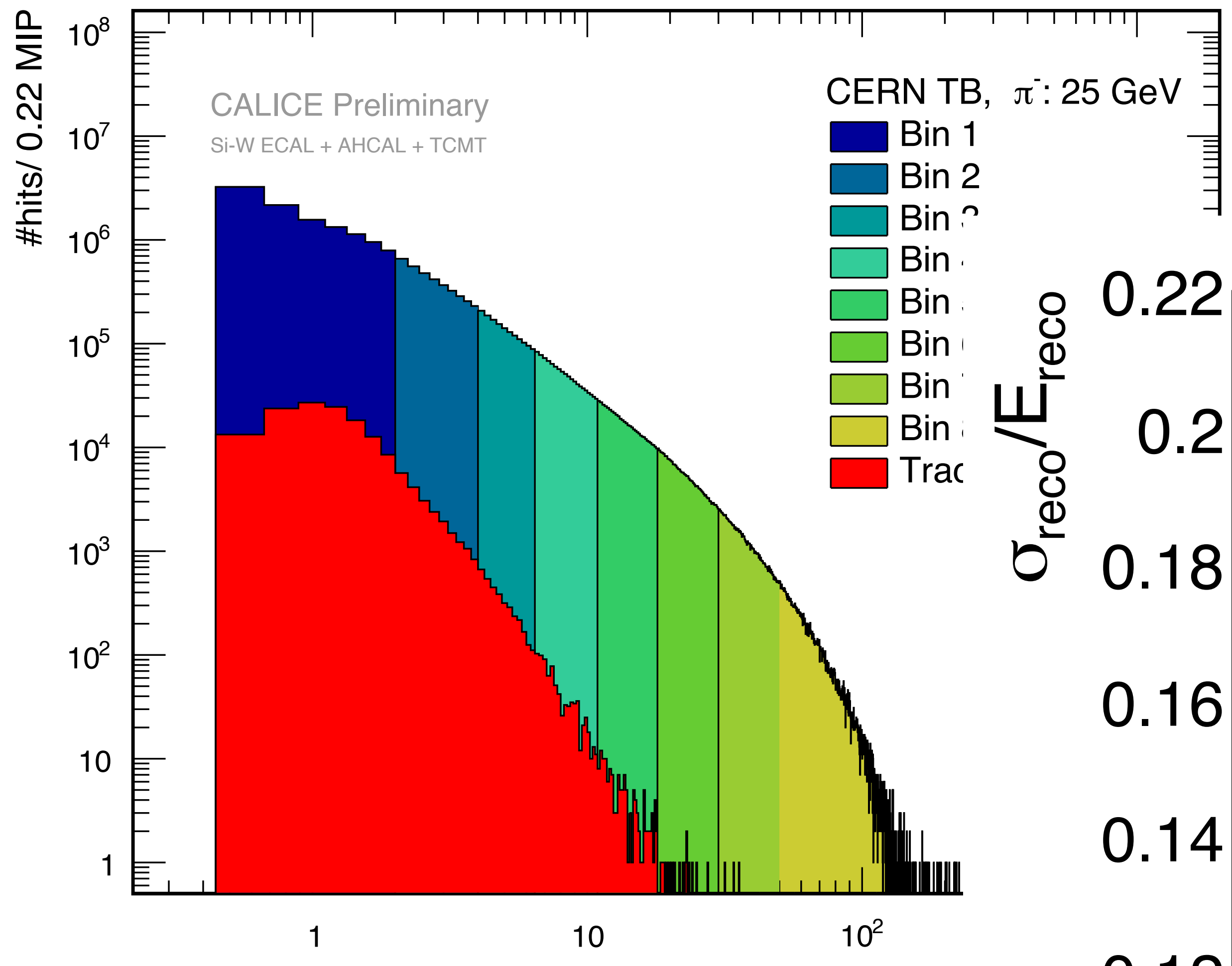
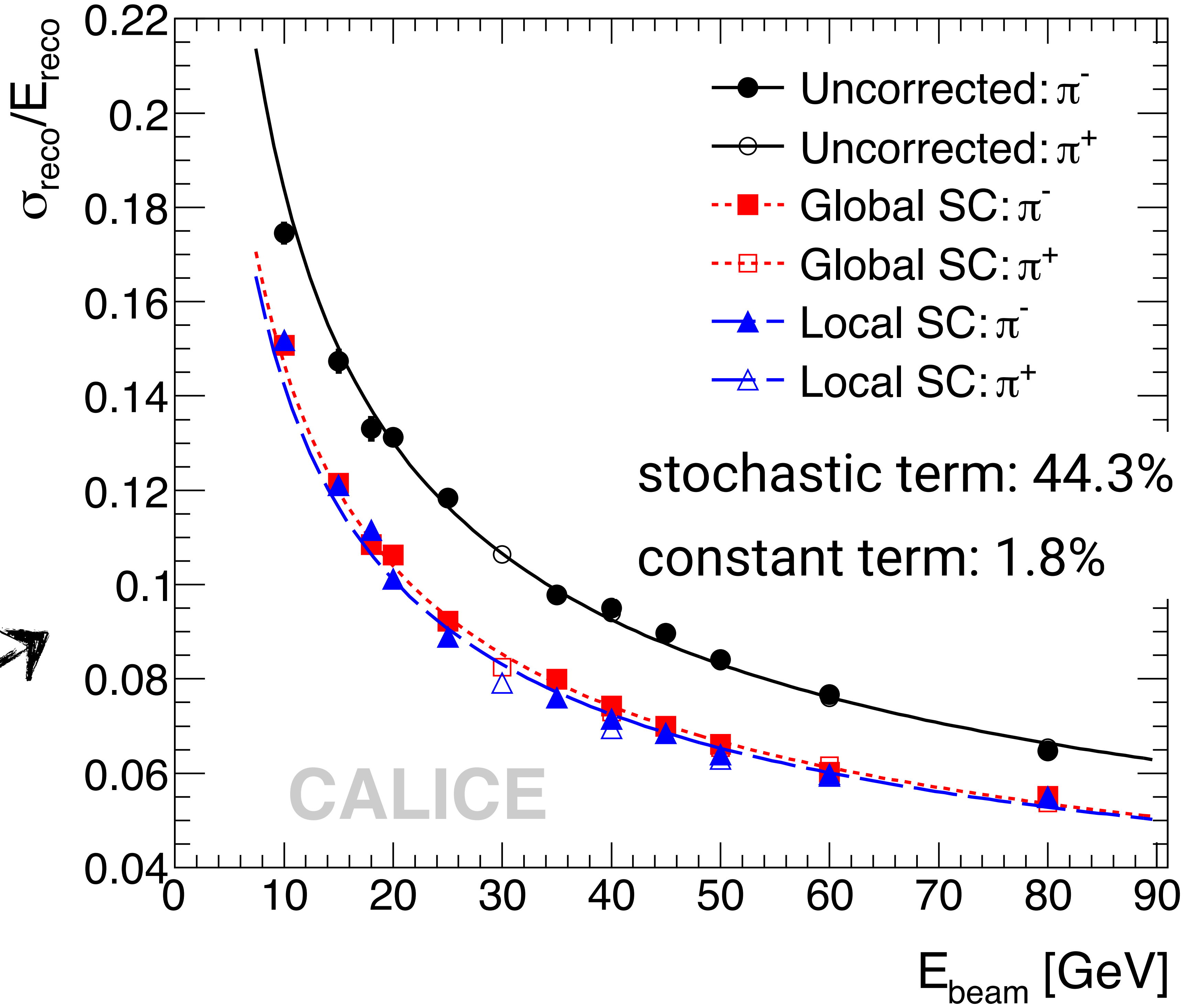
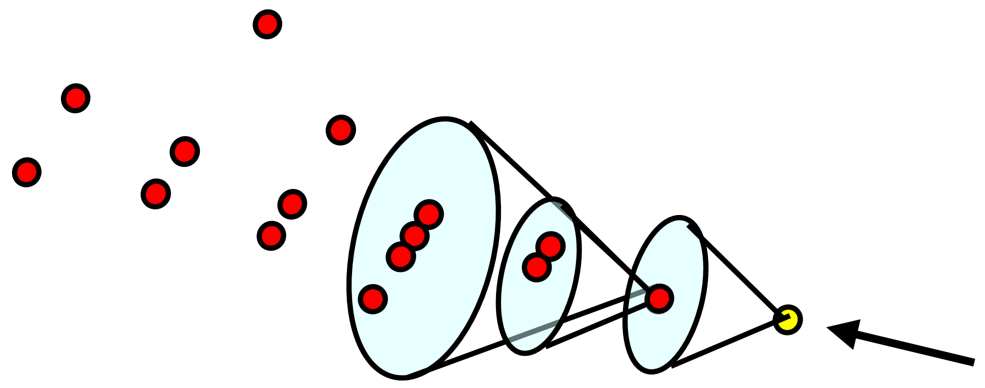


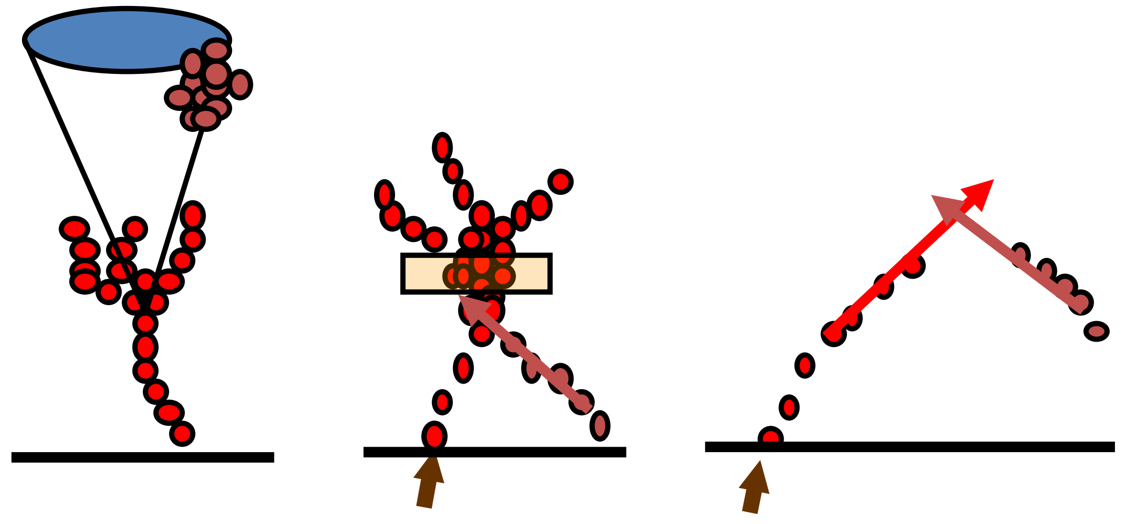


- hits weighted according to amplitude

Particle Flow Algorithms

Under the hood

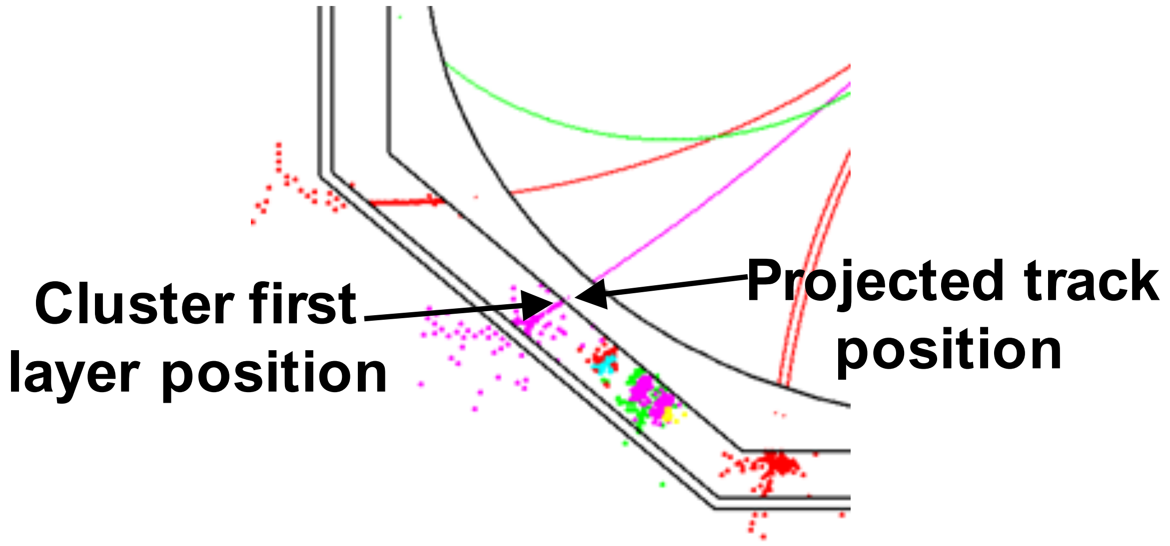




Cone associations | Back-scattered tracks | Looping tracks

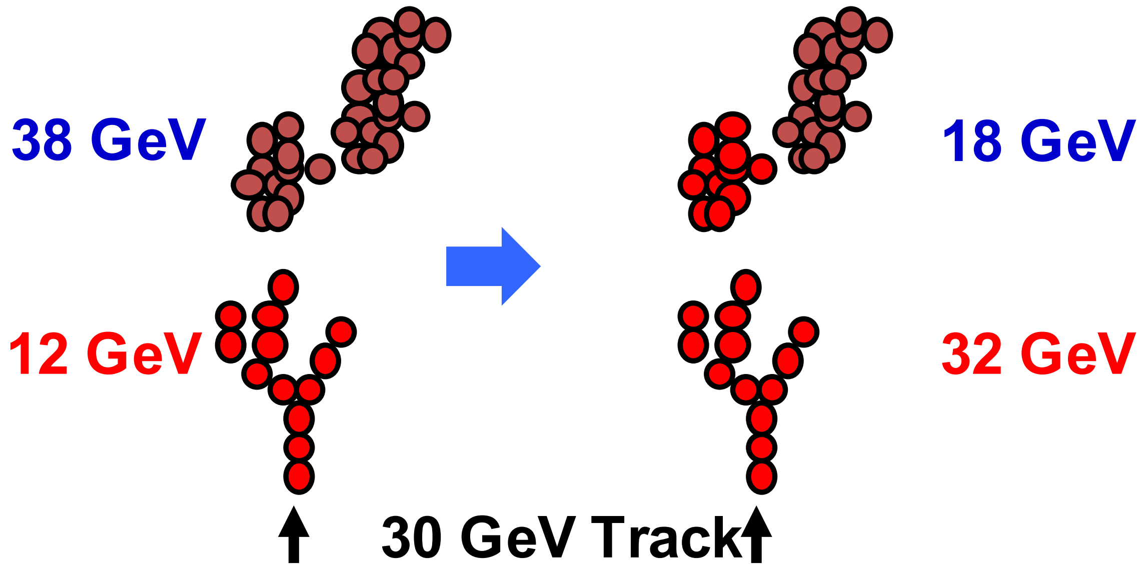
ConeClustering Algorithm

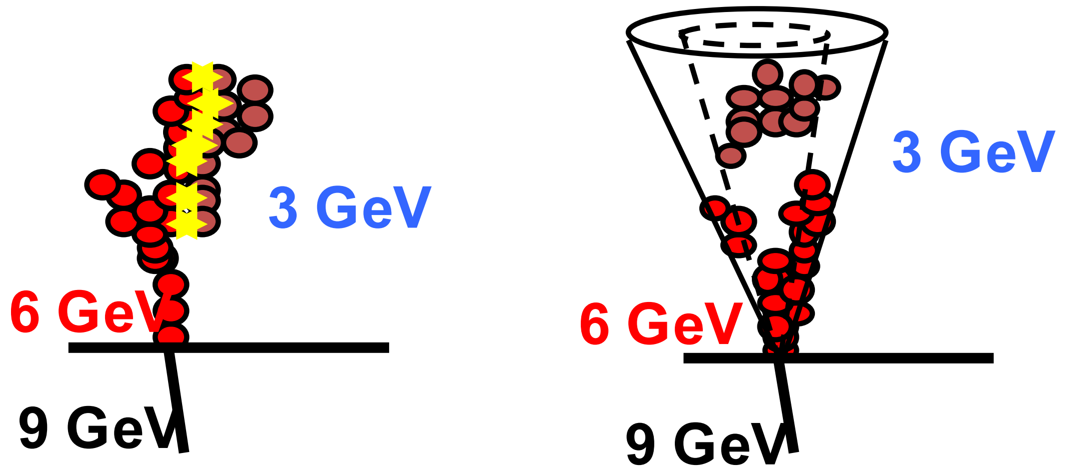
Topological Association Algorithms



Track-Cluster Association Algorithms

Reclustering Algorithms

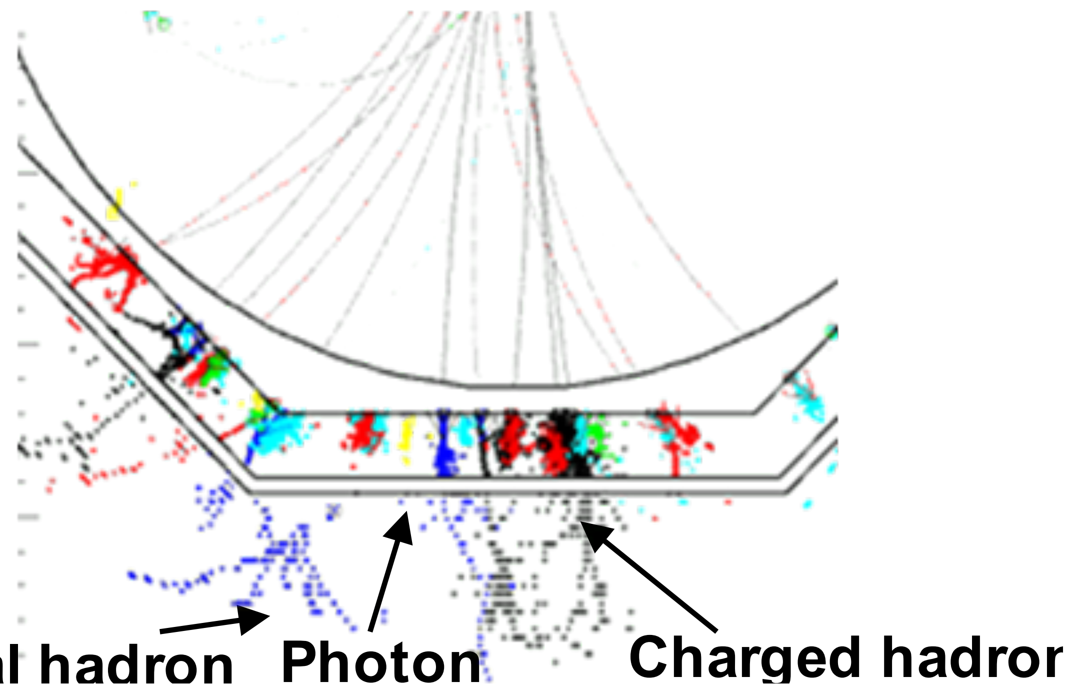




Layers in close contact | Fraction of energy in cone

Fragment Removal Algorithms

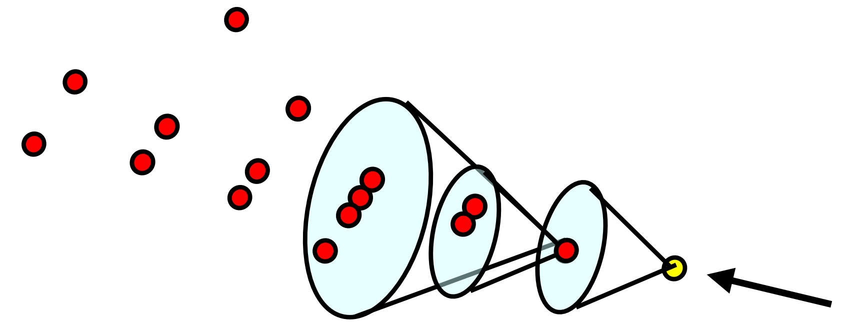
PFO Construction Algorithms



M. Thomson, NIM A61, 24 (2009)

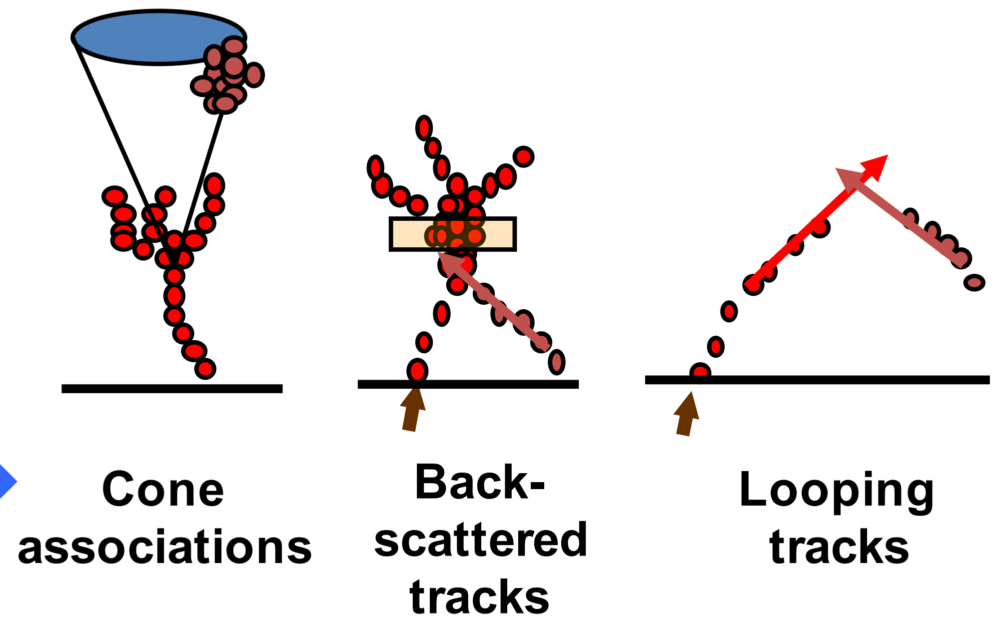
Particle Flow Algorithms

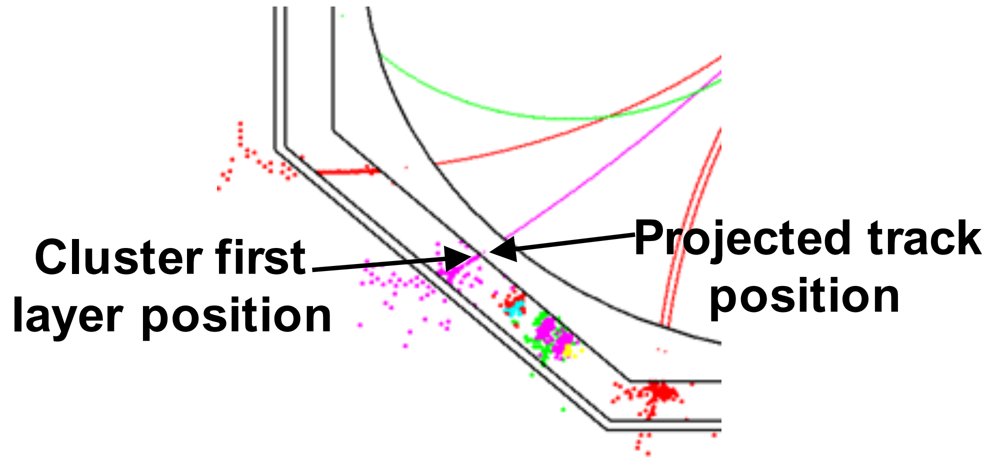
Under the hood



ConeClustering Algorithm

Topological Association Algorithms





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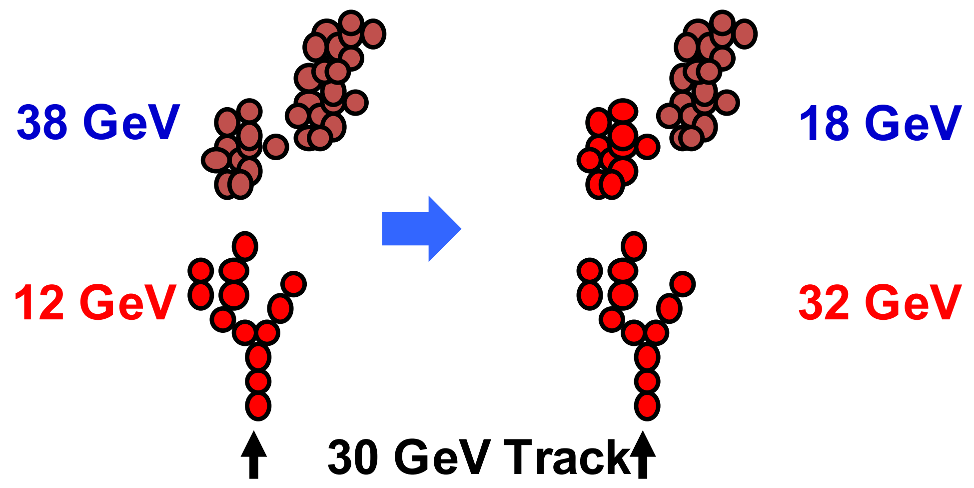

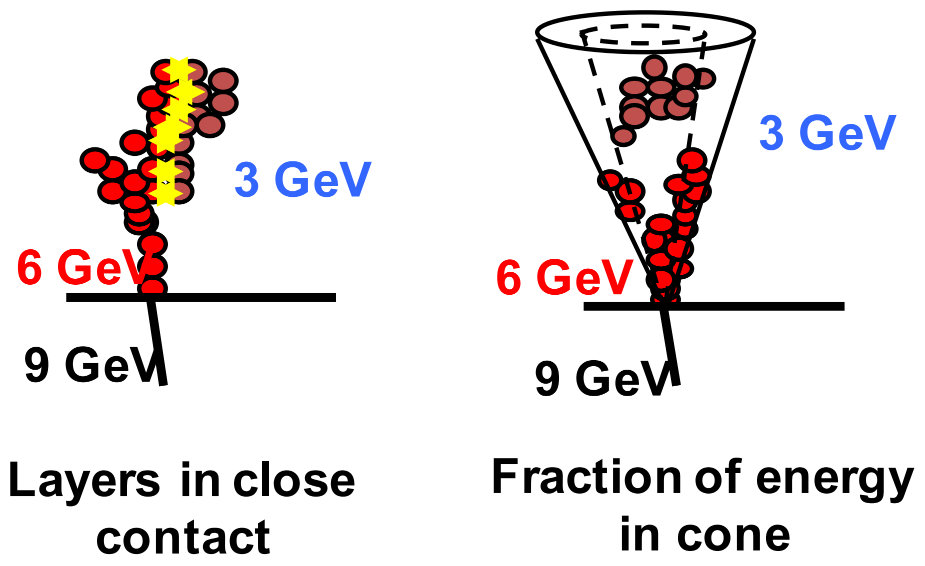

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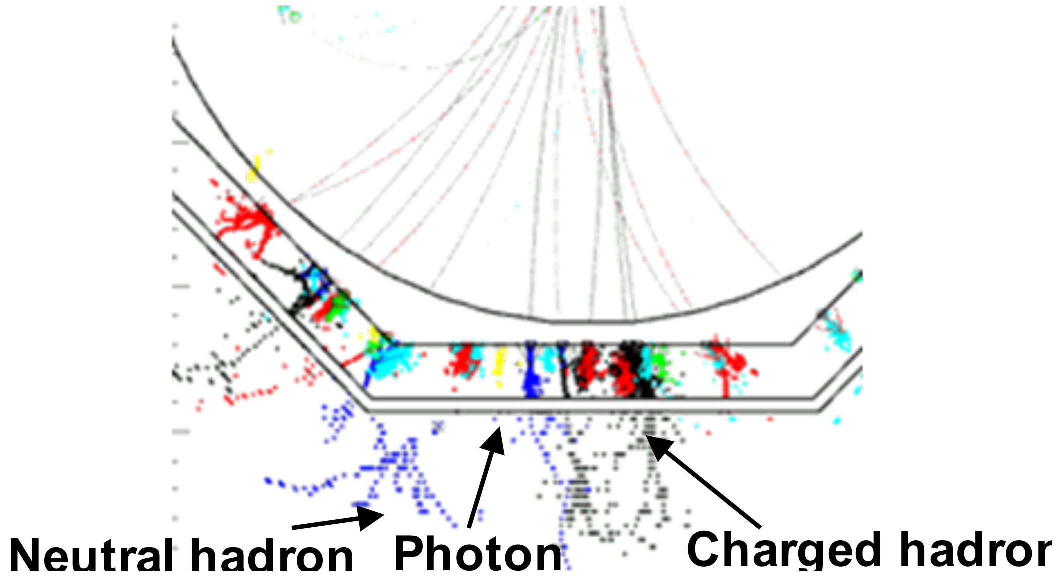
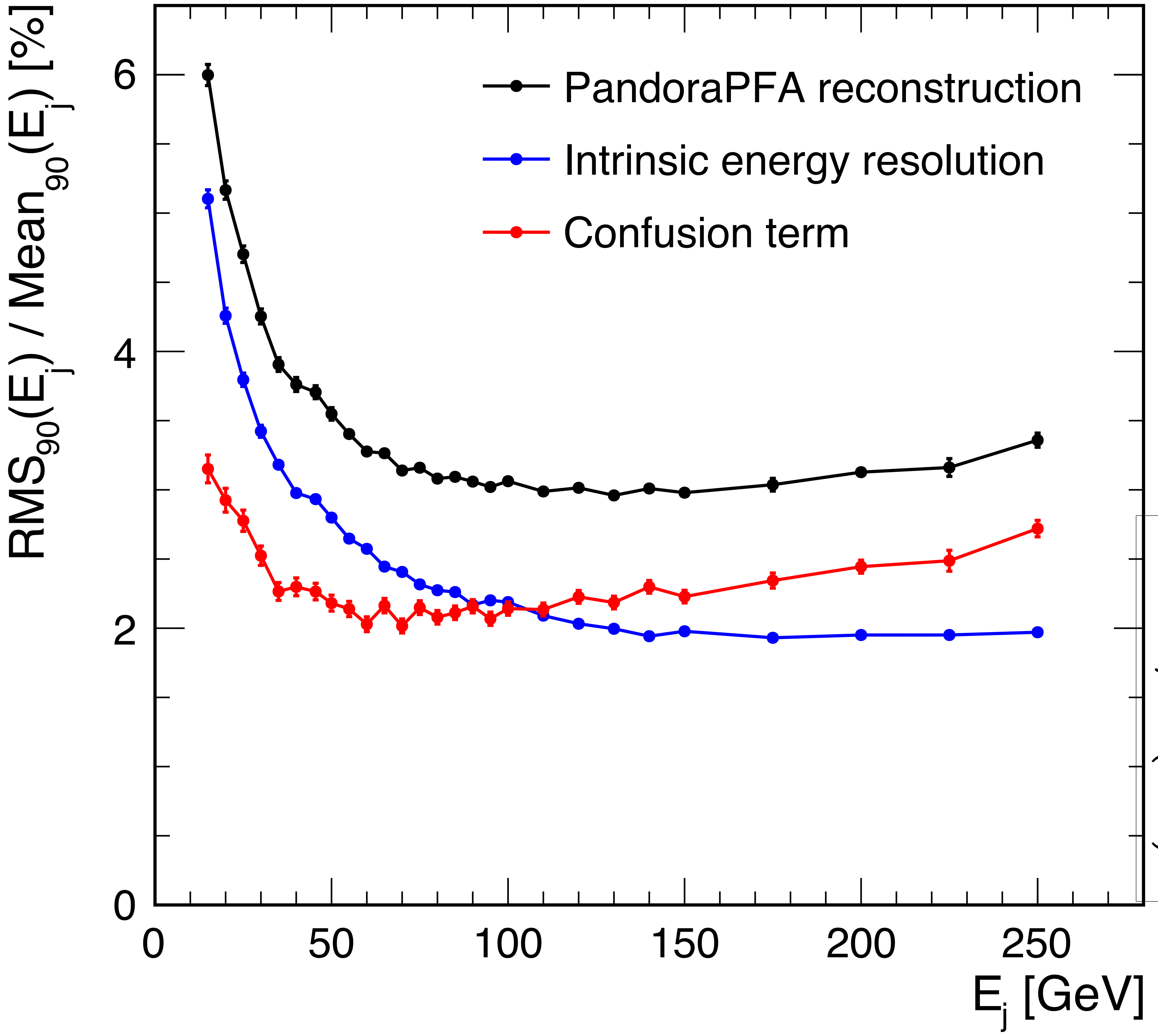


M. Thomson, NIM A61, 24 (2009)

Performance drivers

- *intrinsic energy resolution*: primarily neutrals
- *confusion*: mistakes in track - calorimeter assignments

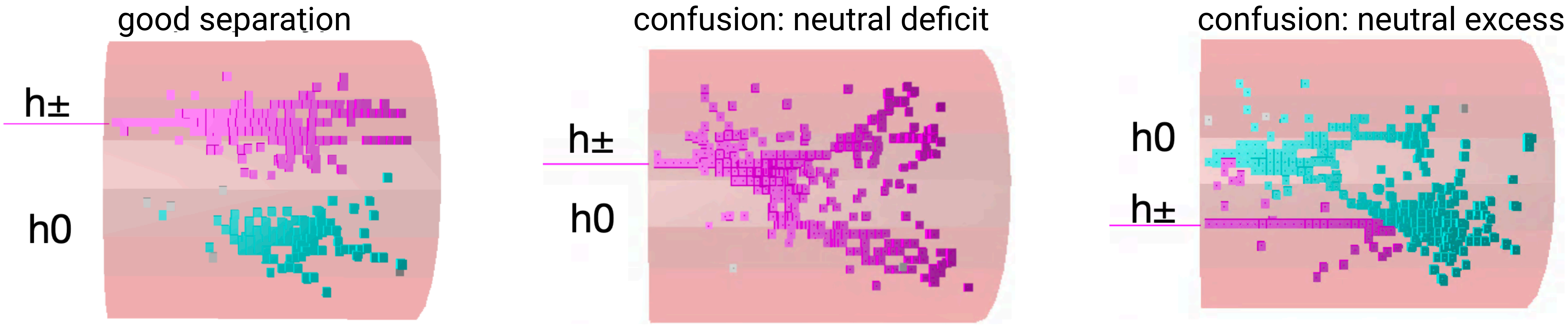


EPJ C77, 698 (2017)

Validating PFA Performance

Using test beam data

- Using the CALICE prototype data to validate key aspects of PFA: Shower separation / confusion



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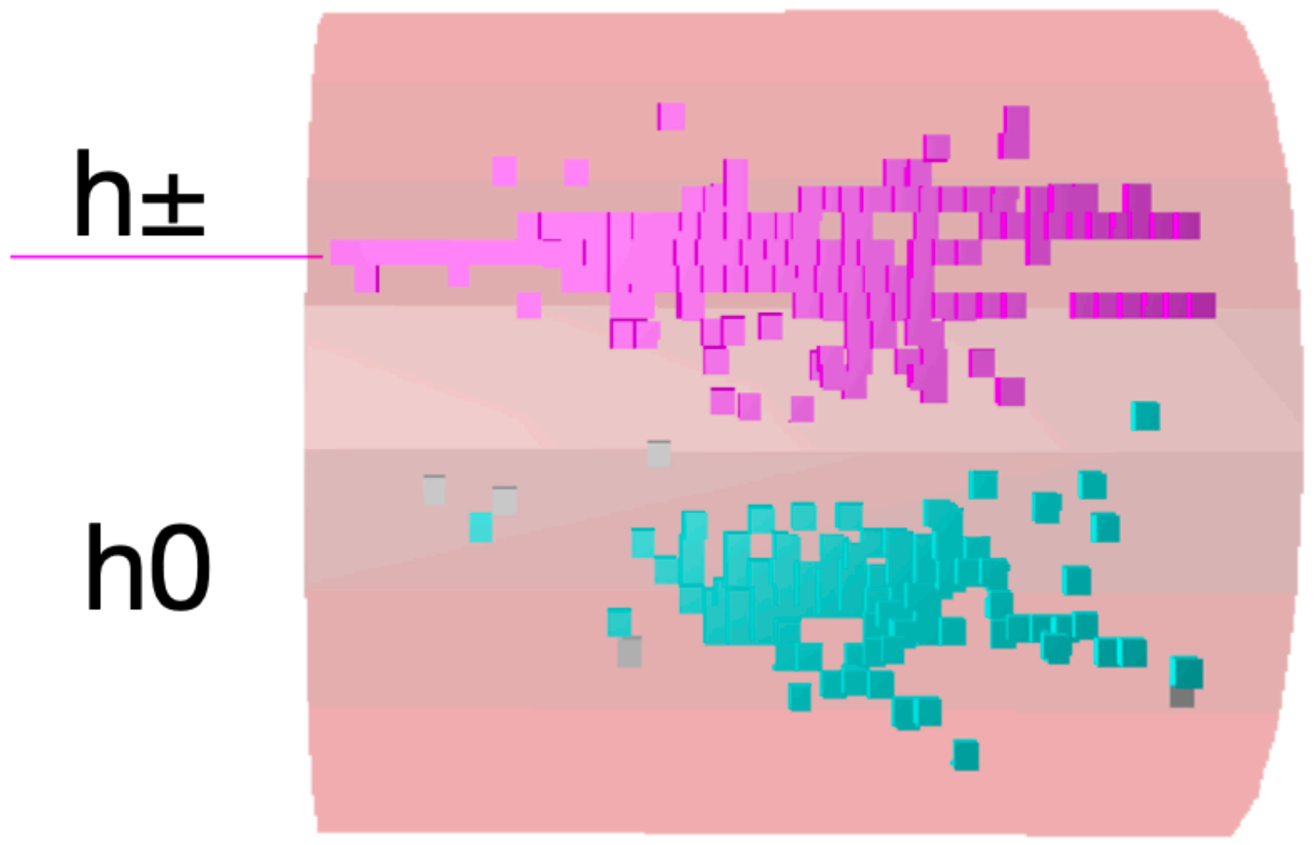
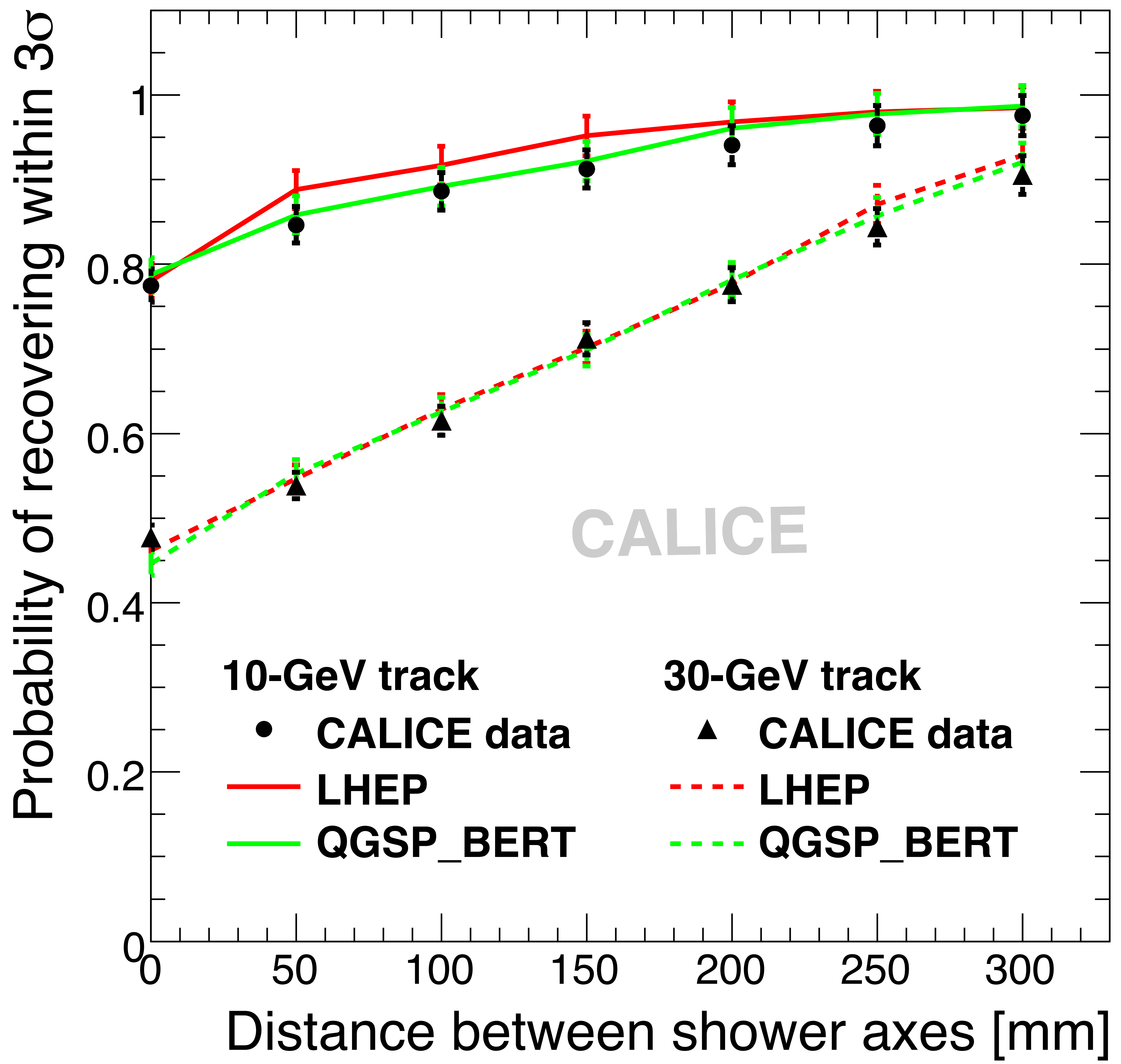
good separation





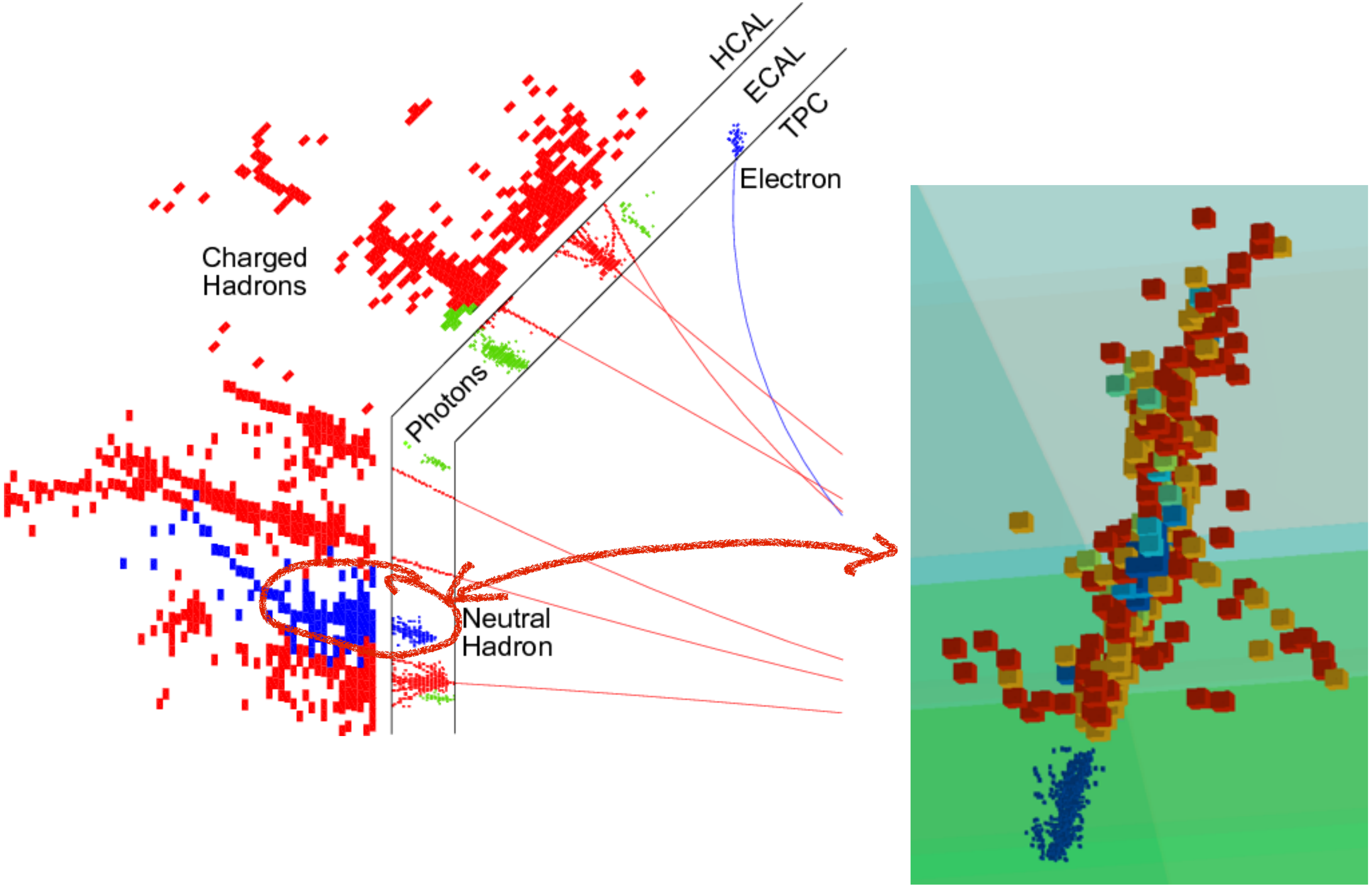
- Important for confidence in full PFA studies (simulations only!): Validation of simulation

Studies with latest algorithm improvements in progress

JINST 6, P07005 (2011)

Extending PFA Performance

Combination with advanced energy reconstruction



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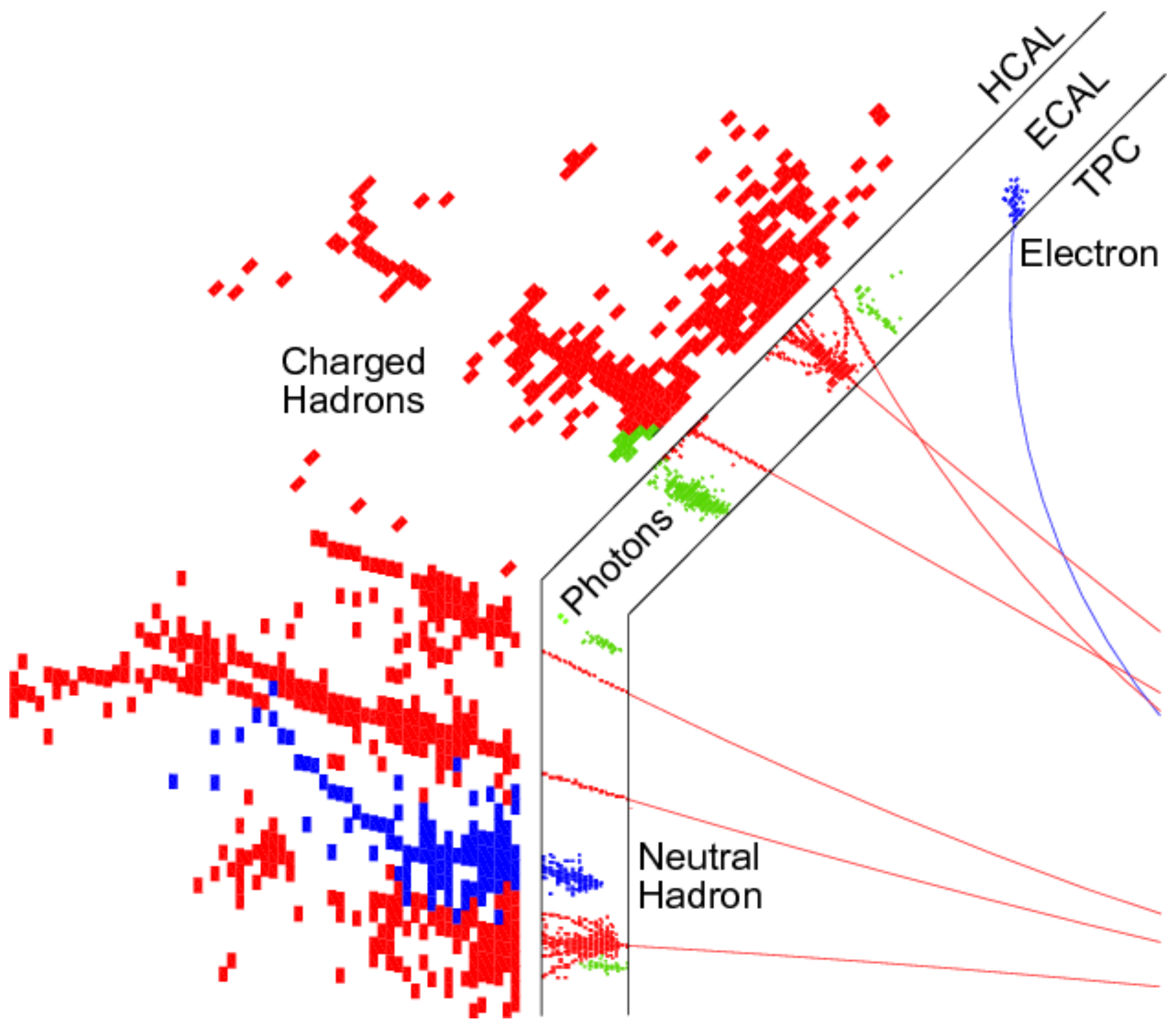

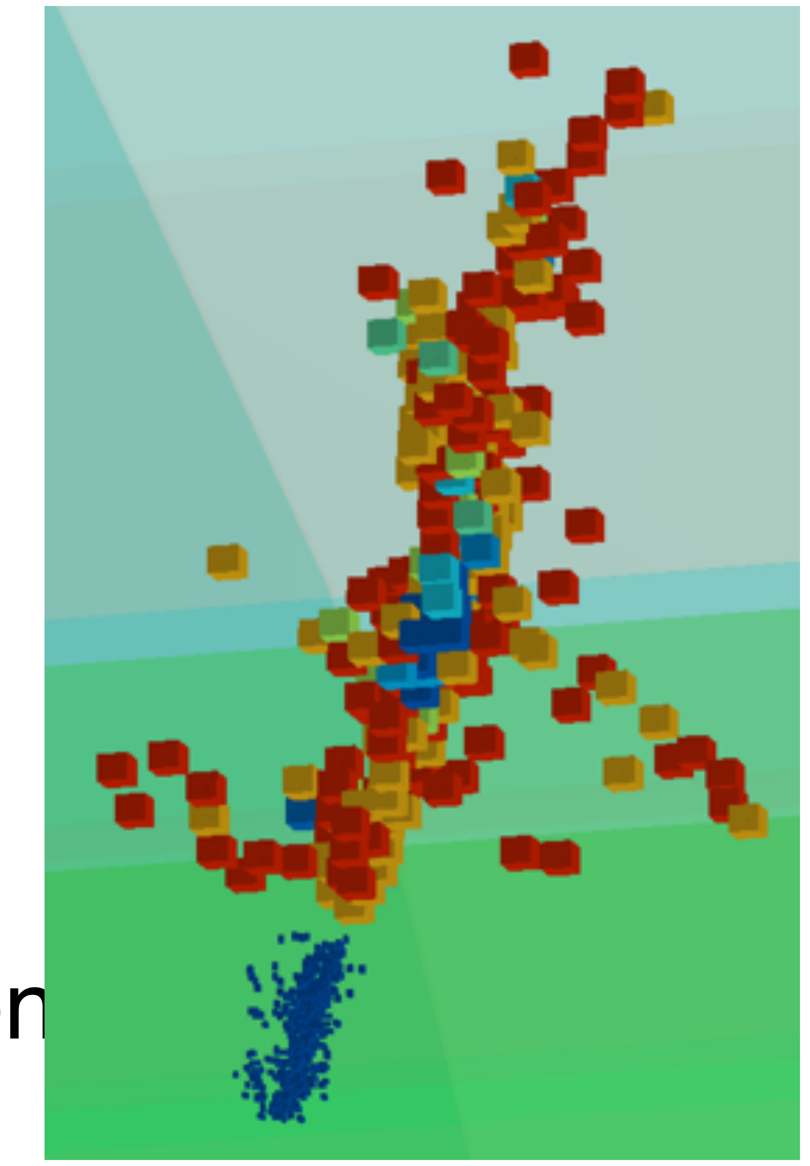

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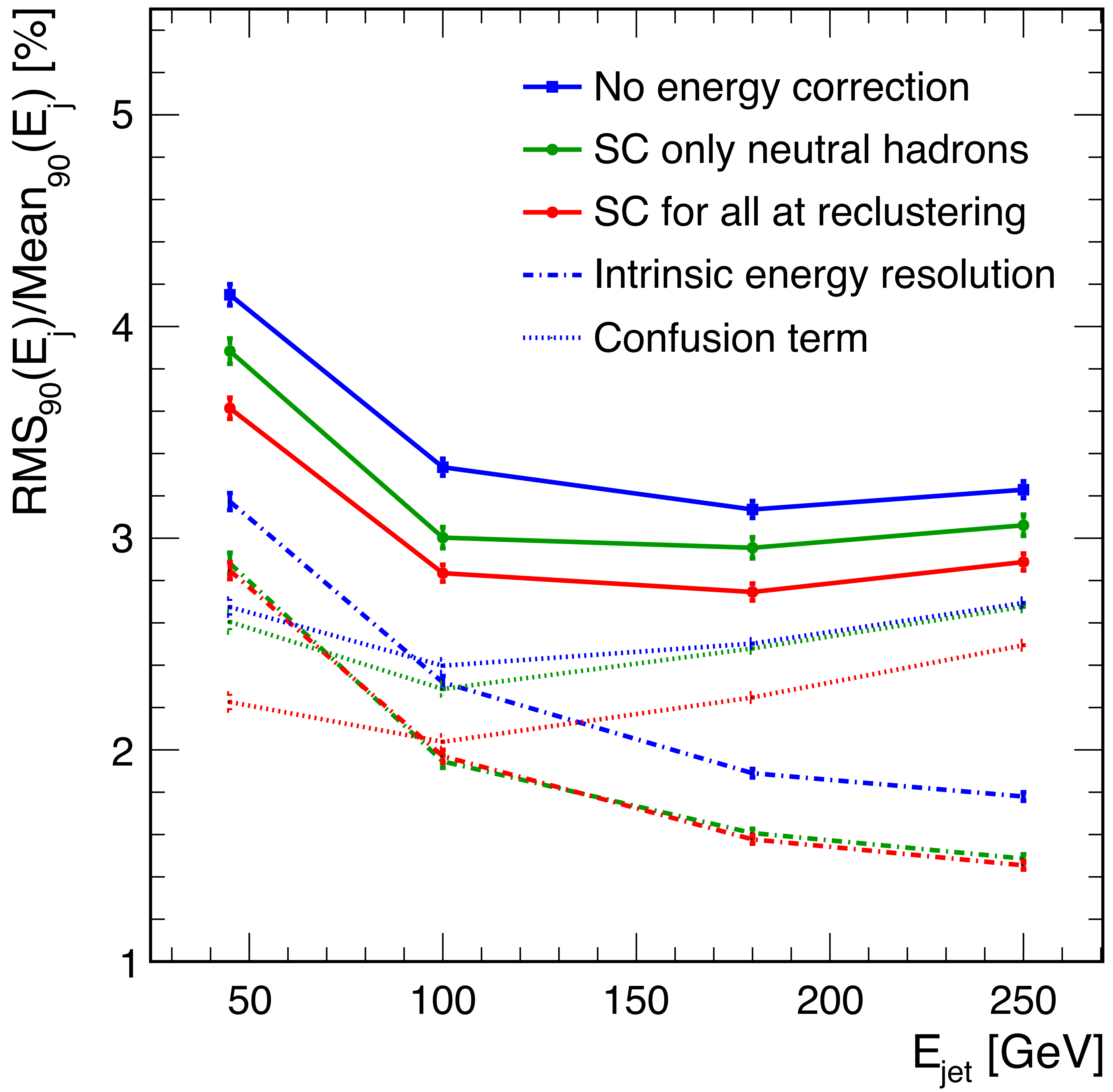

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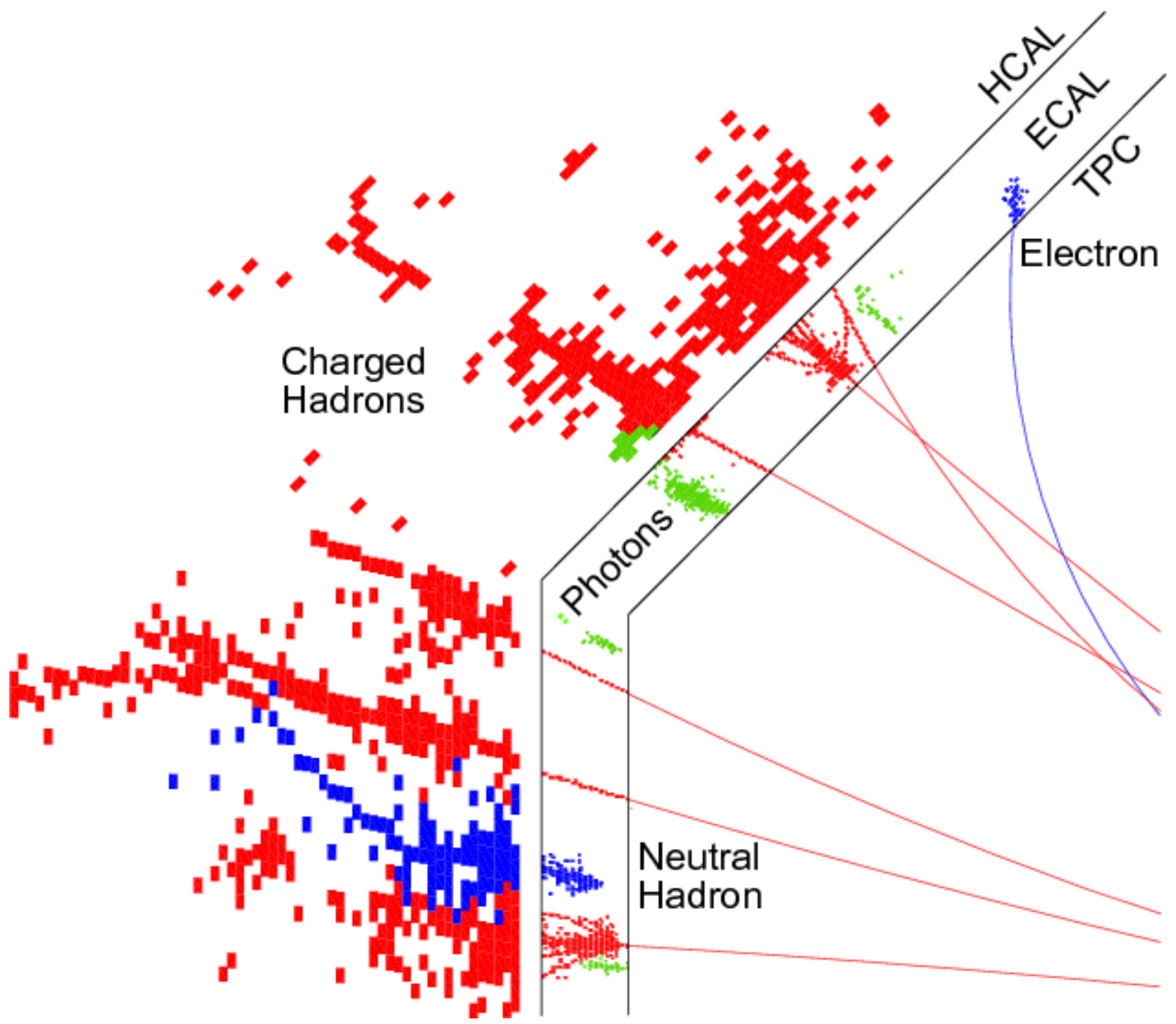

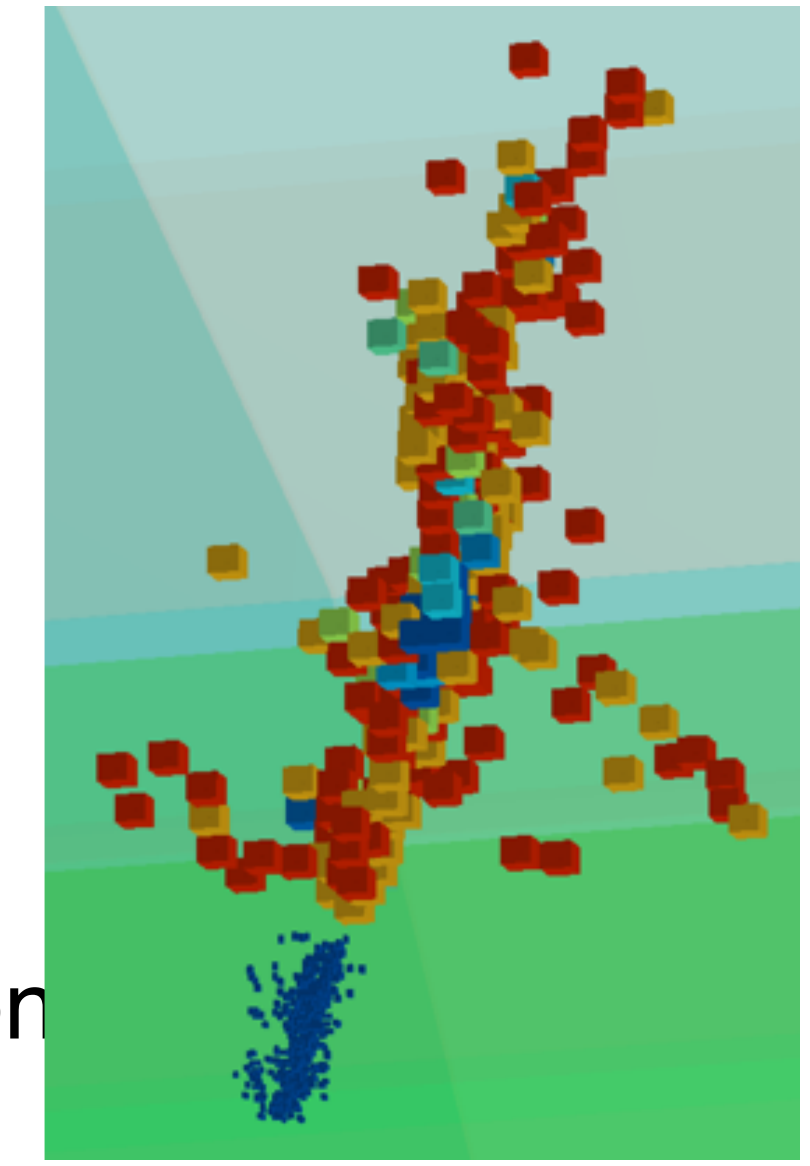

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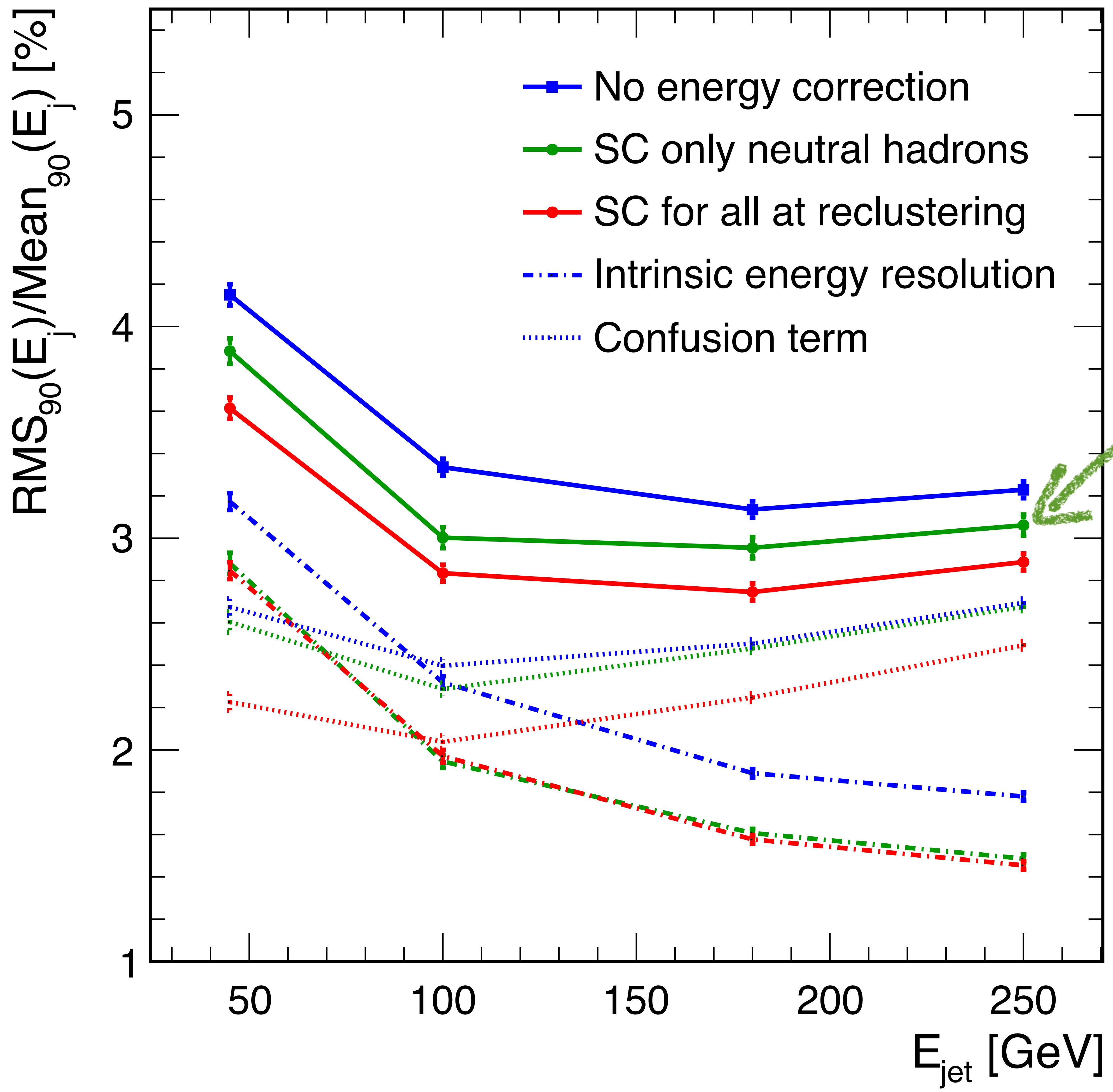

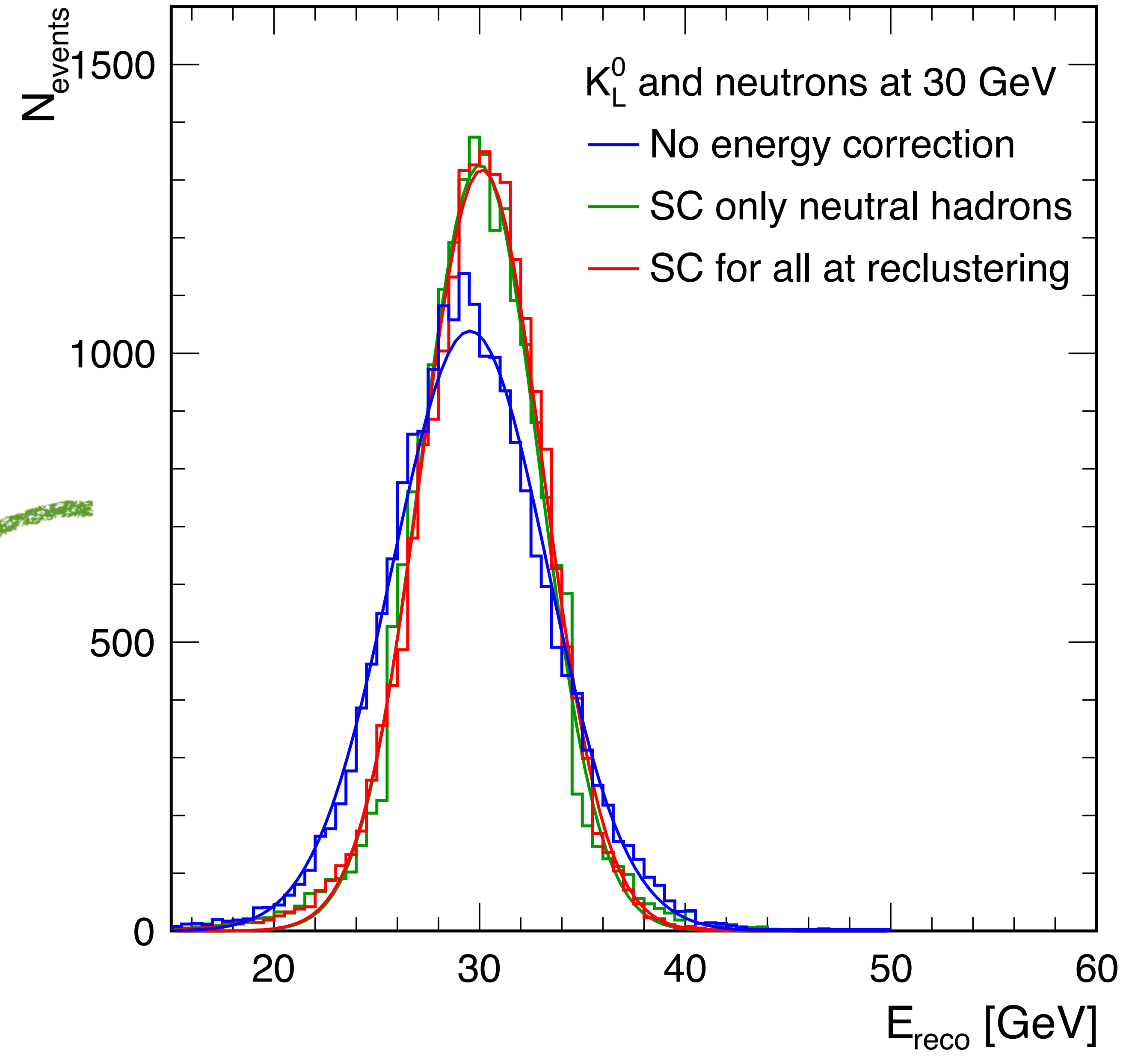

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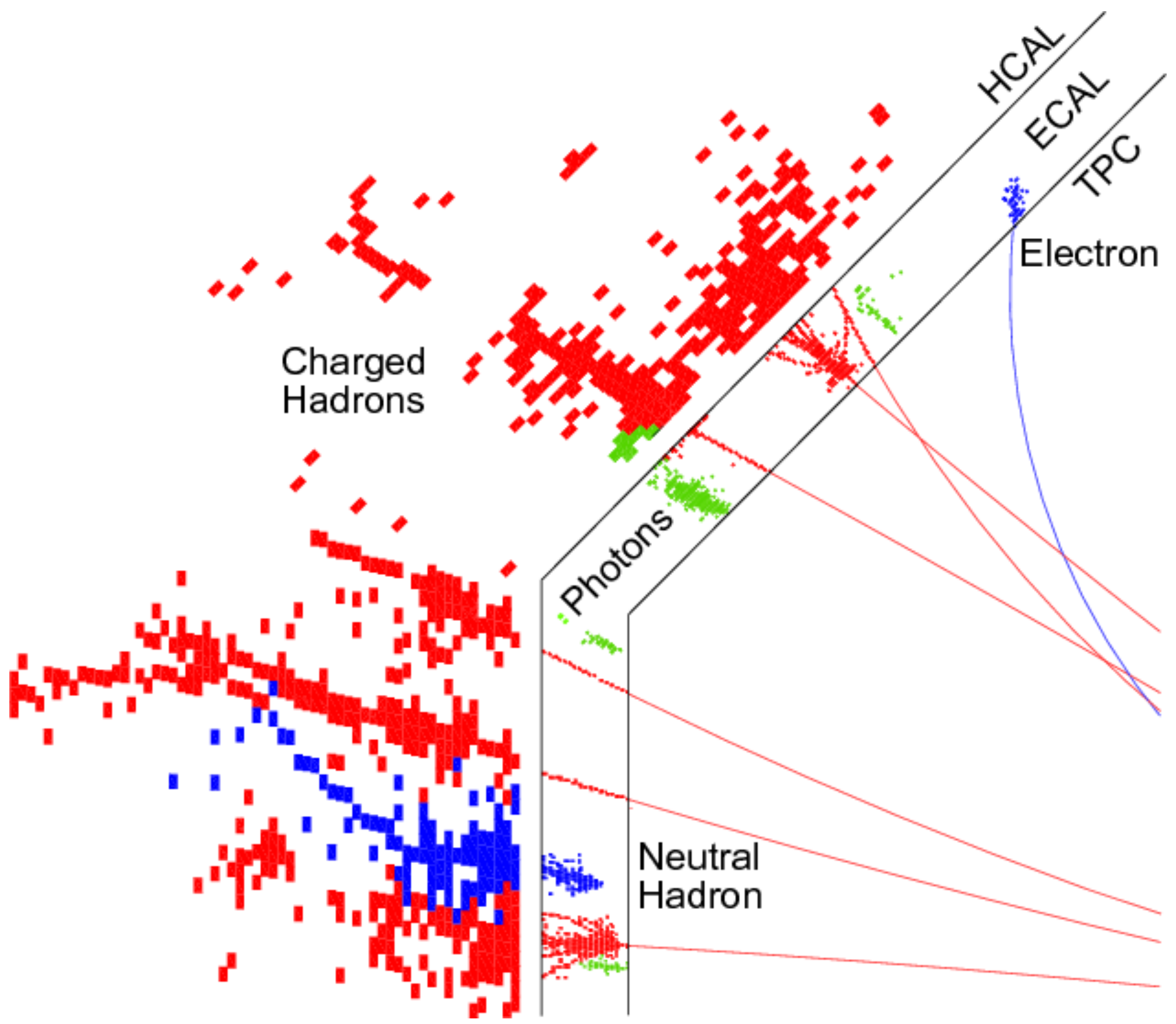

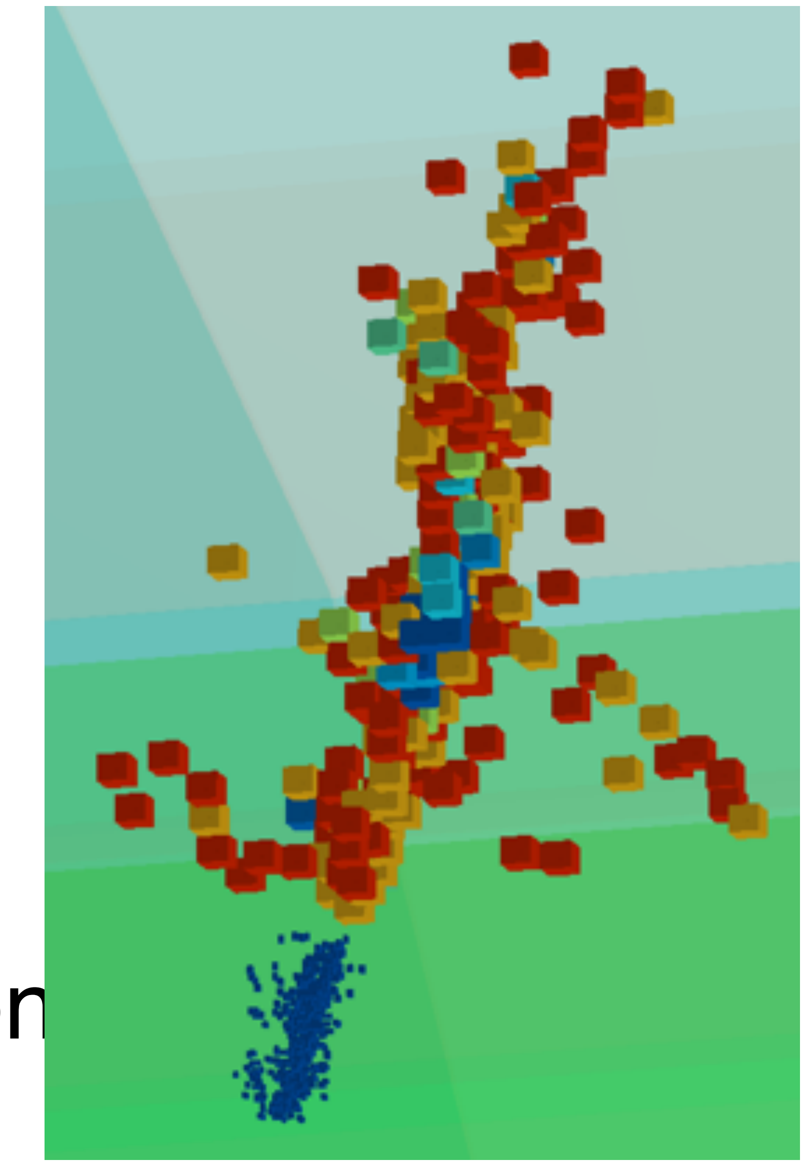

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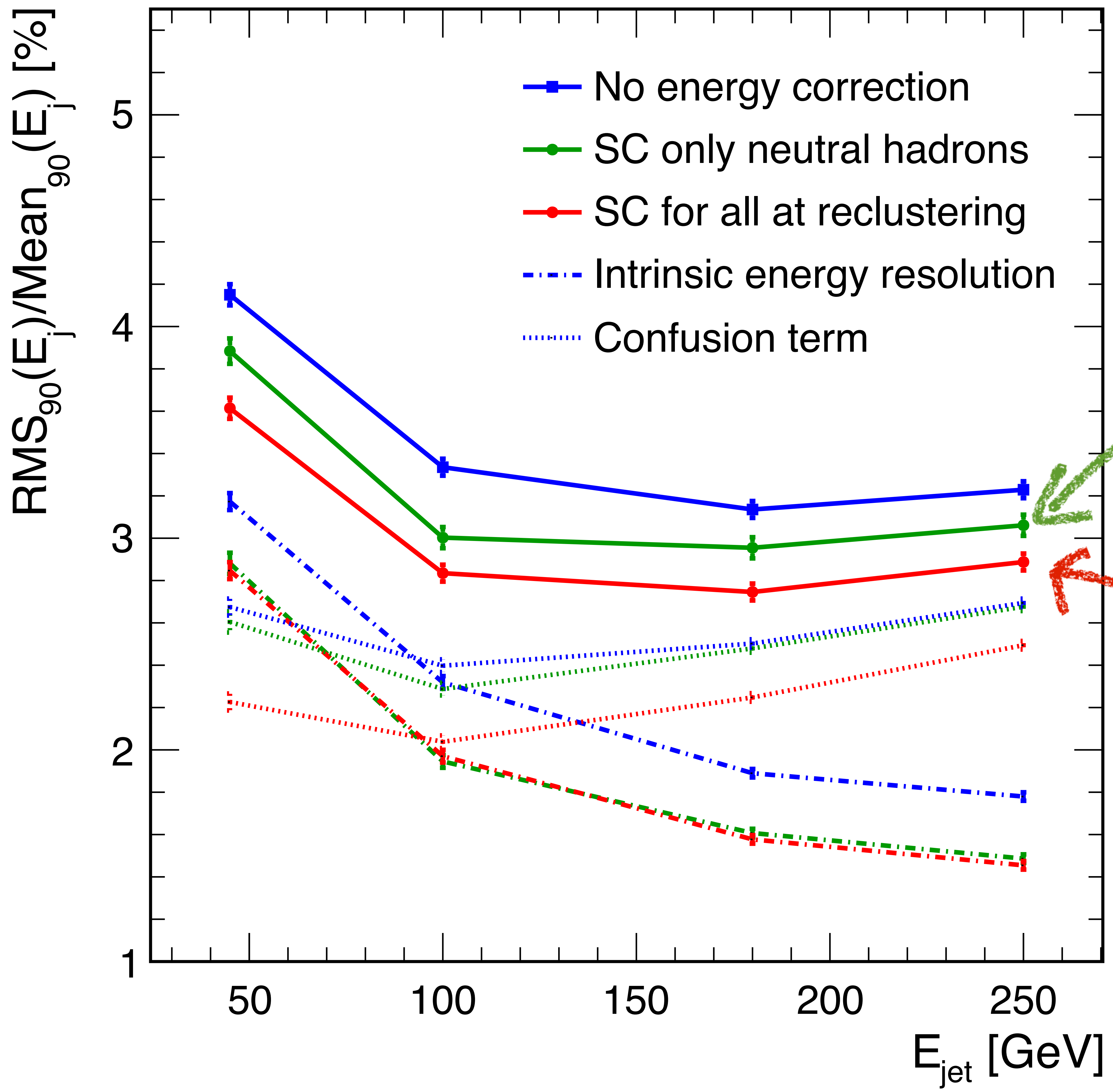
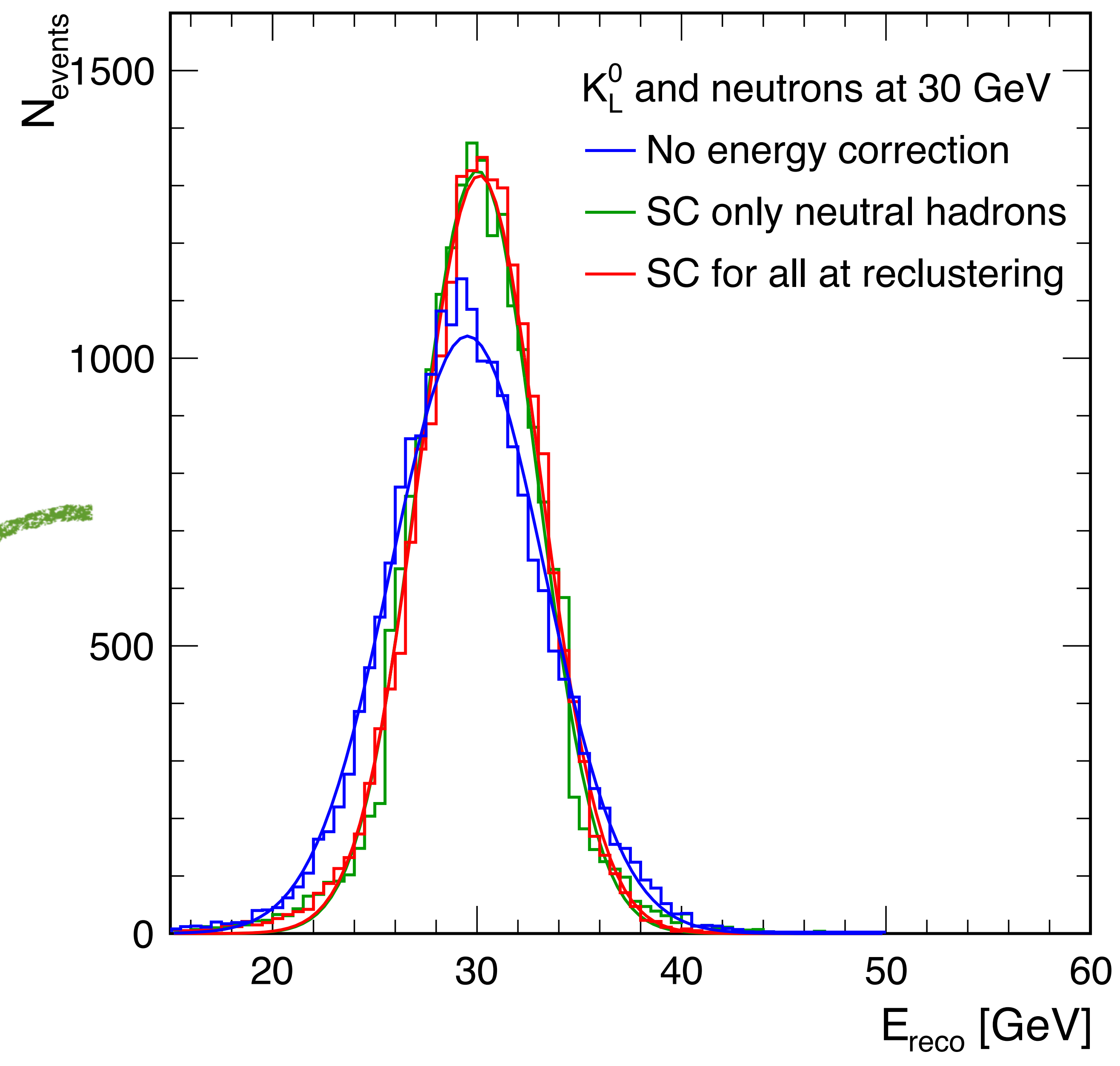
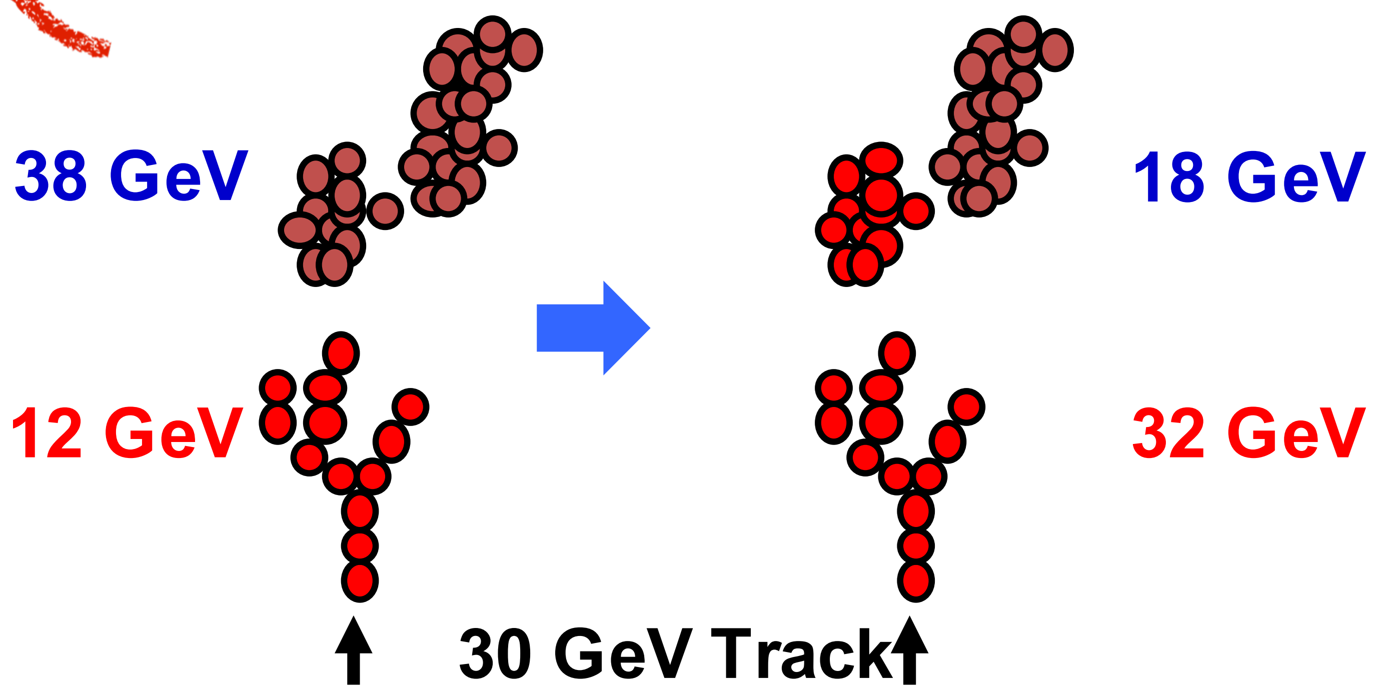
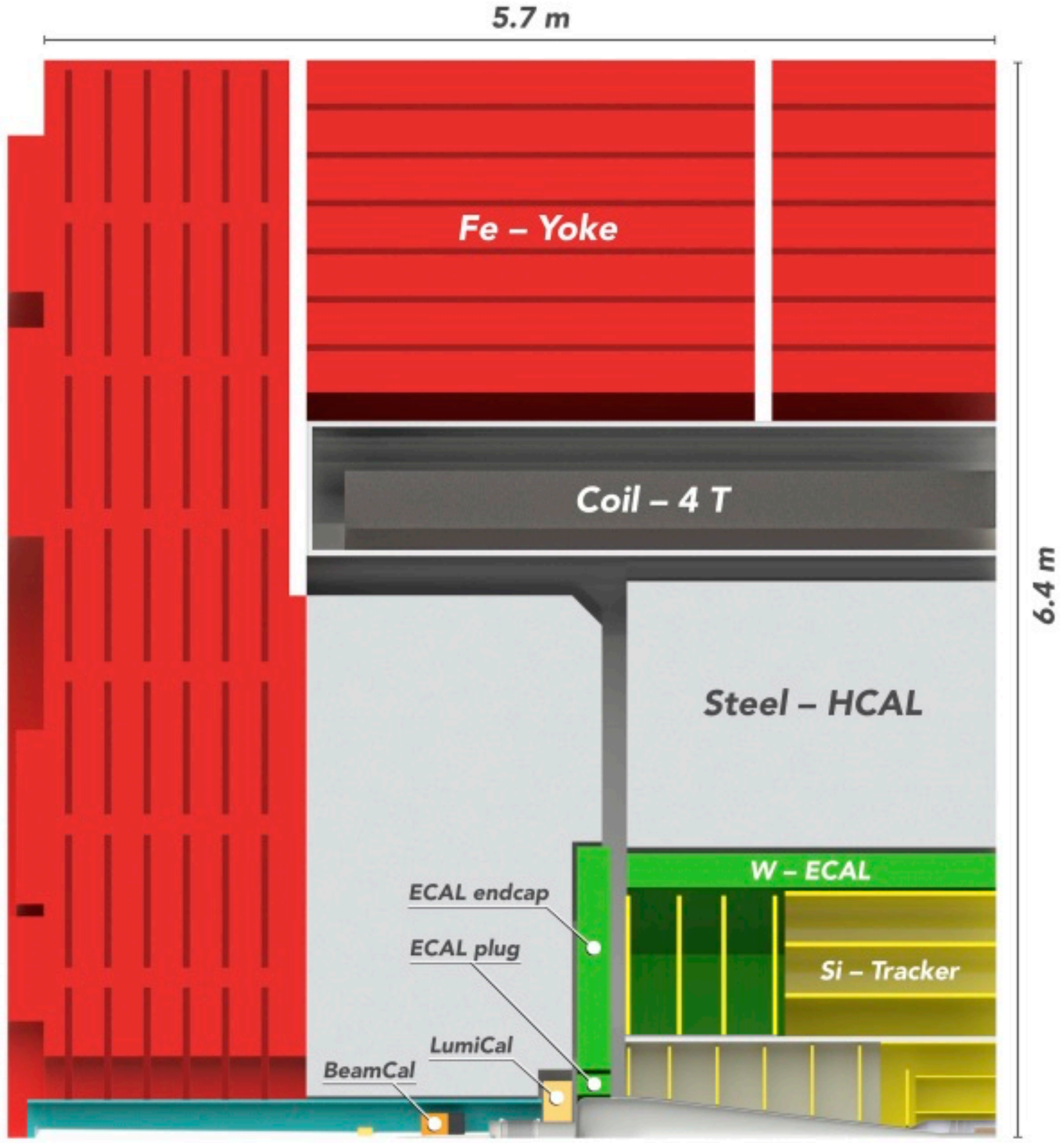






Optimising Detectors for Higgs Factories

Using simulations, validated with test beams



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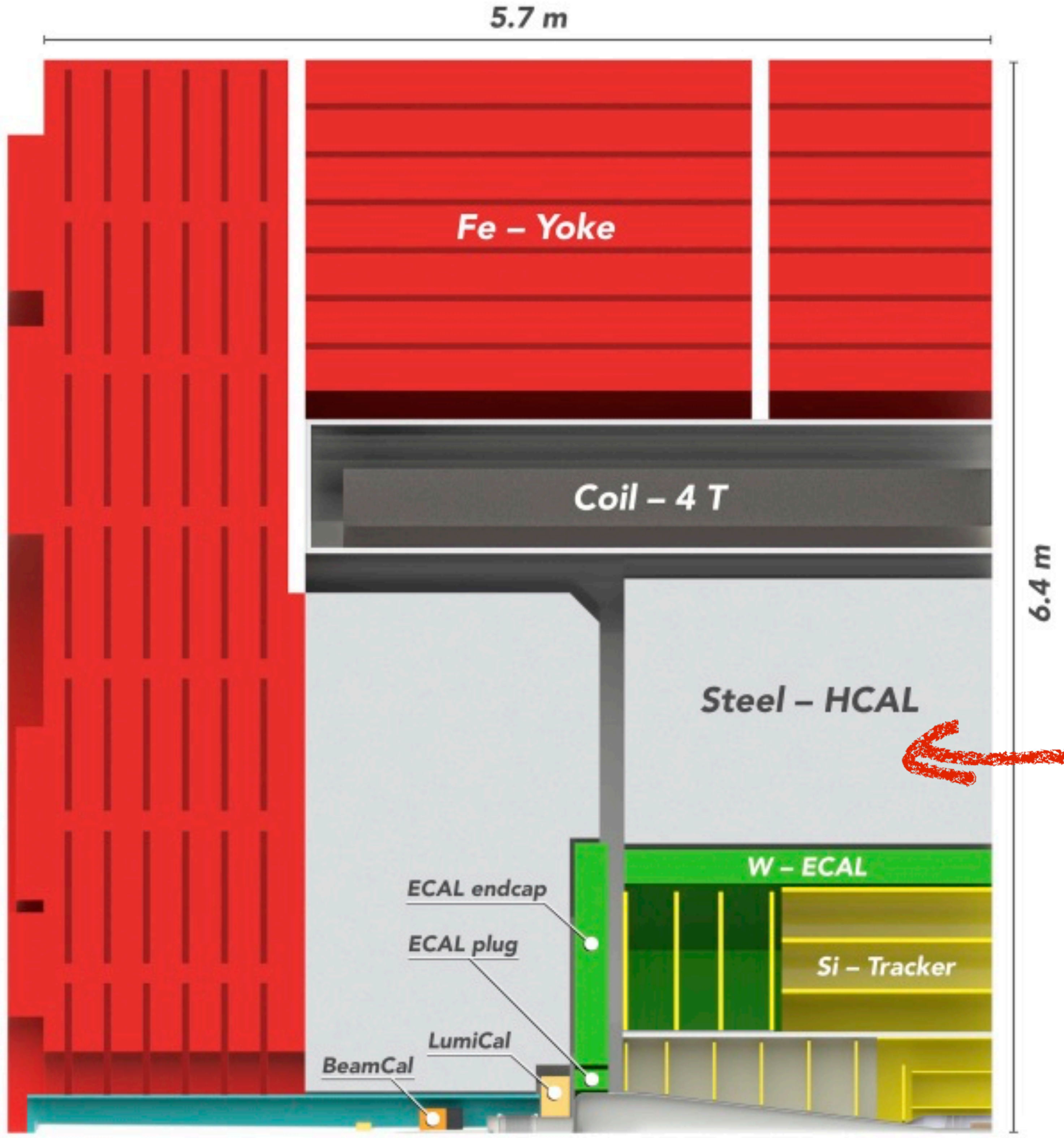

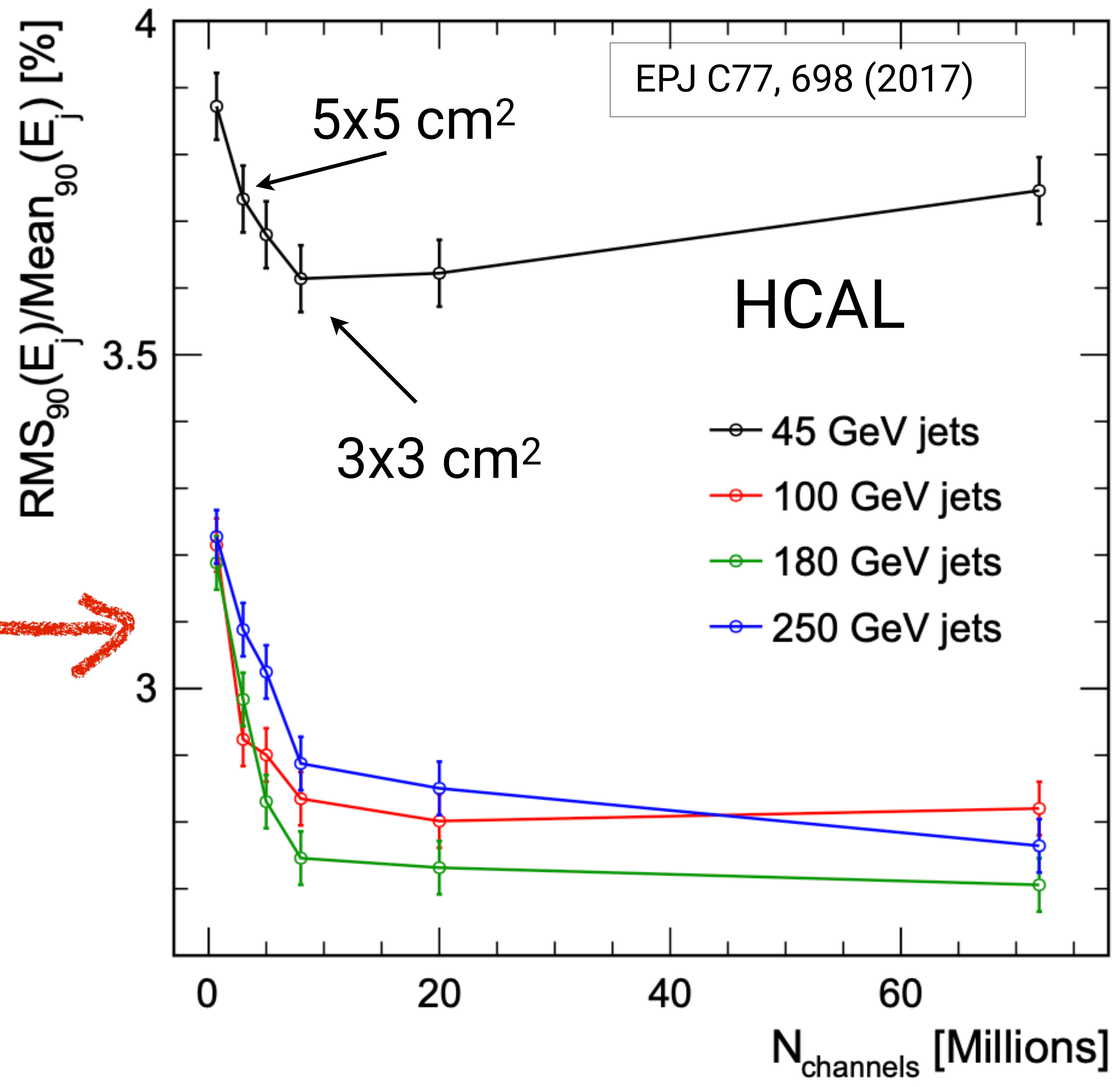

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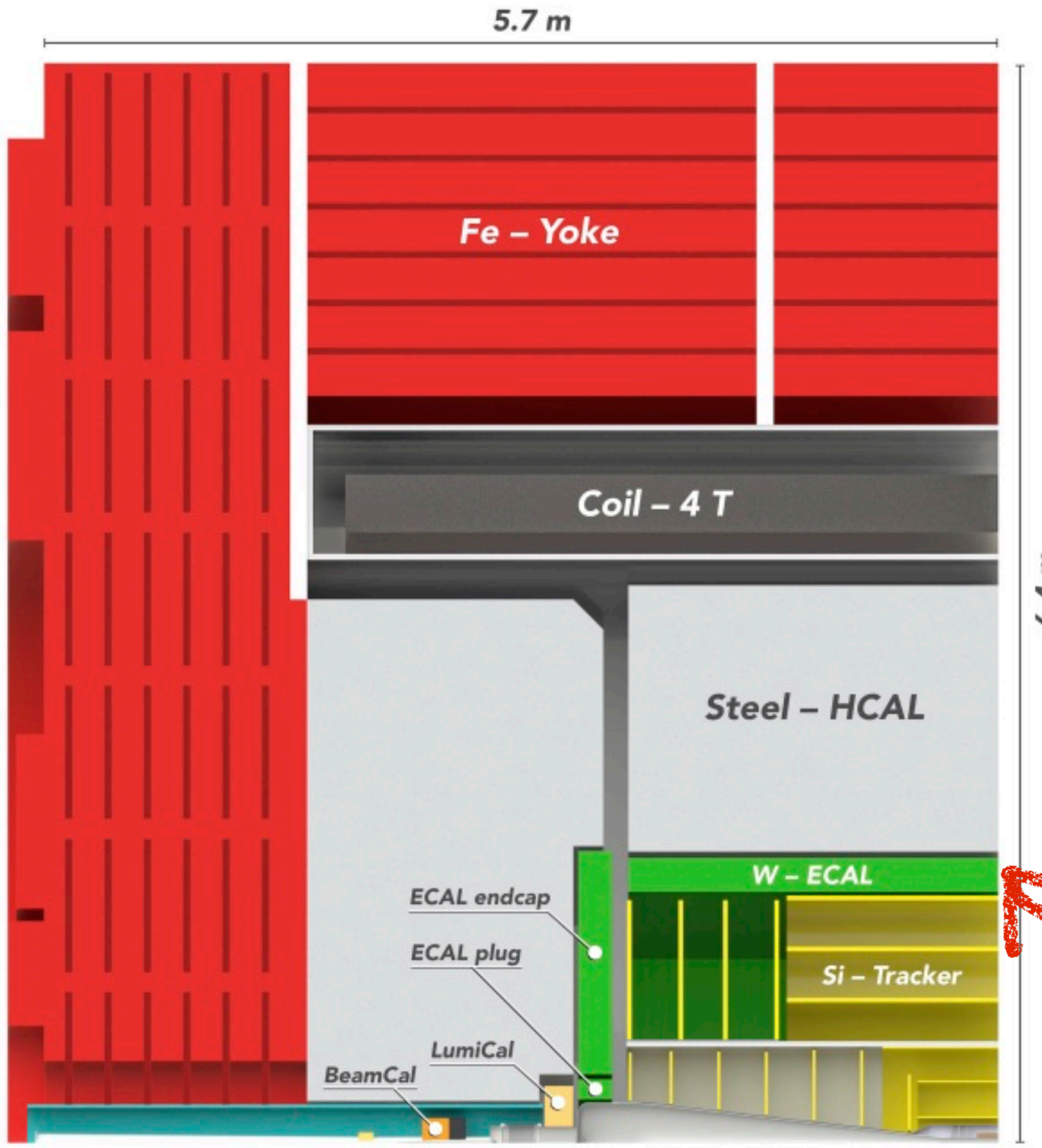

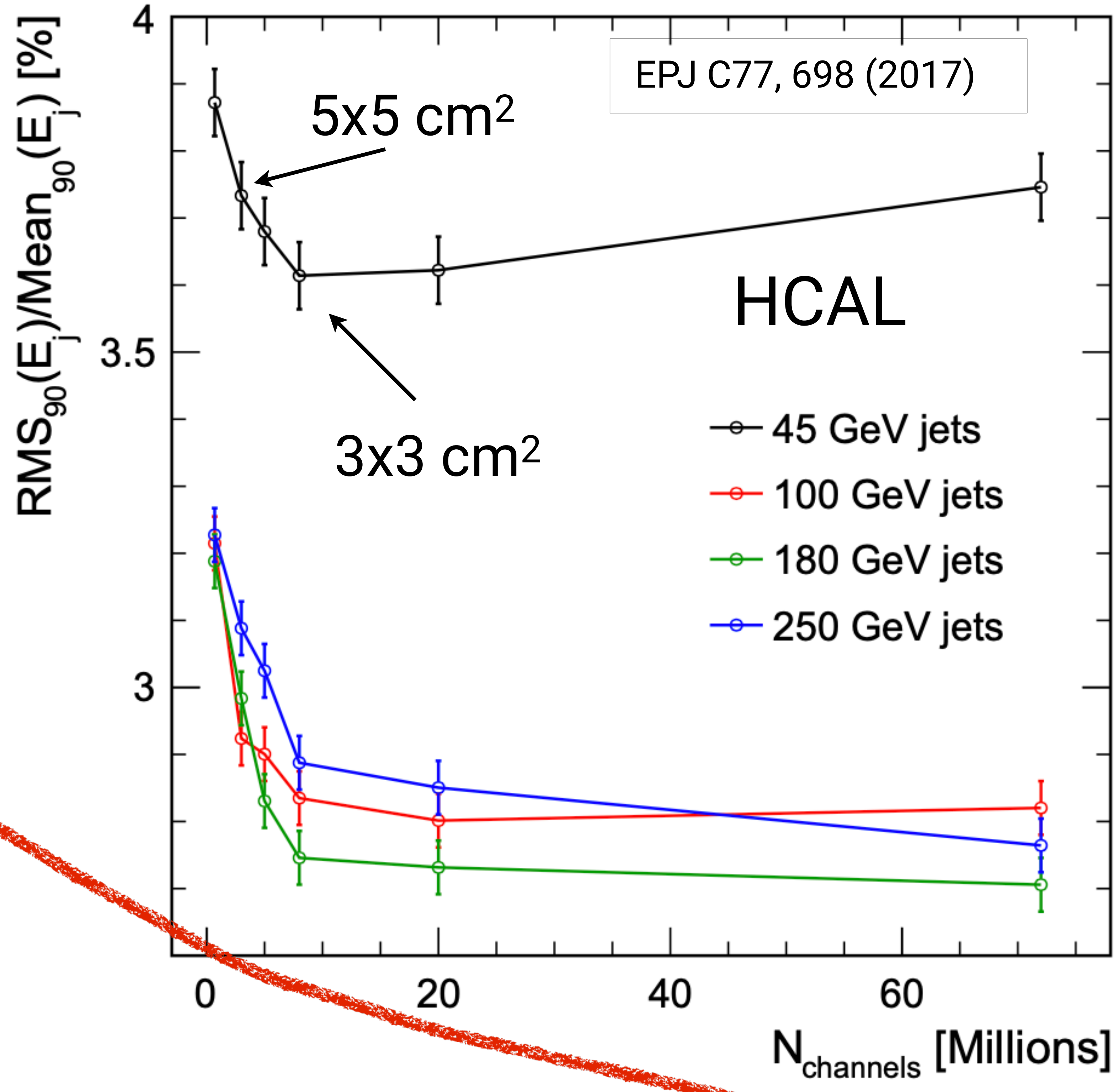

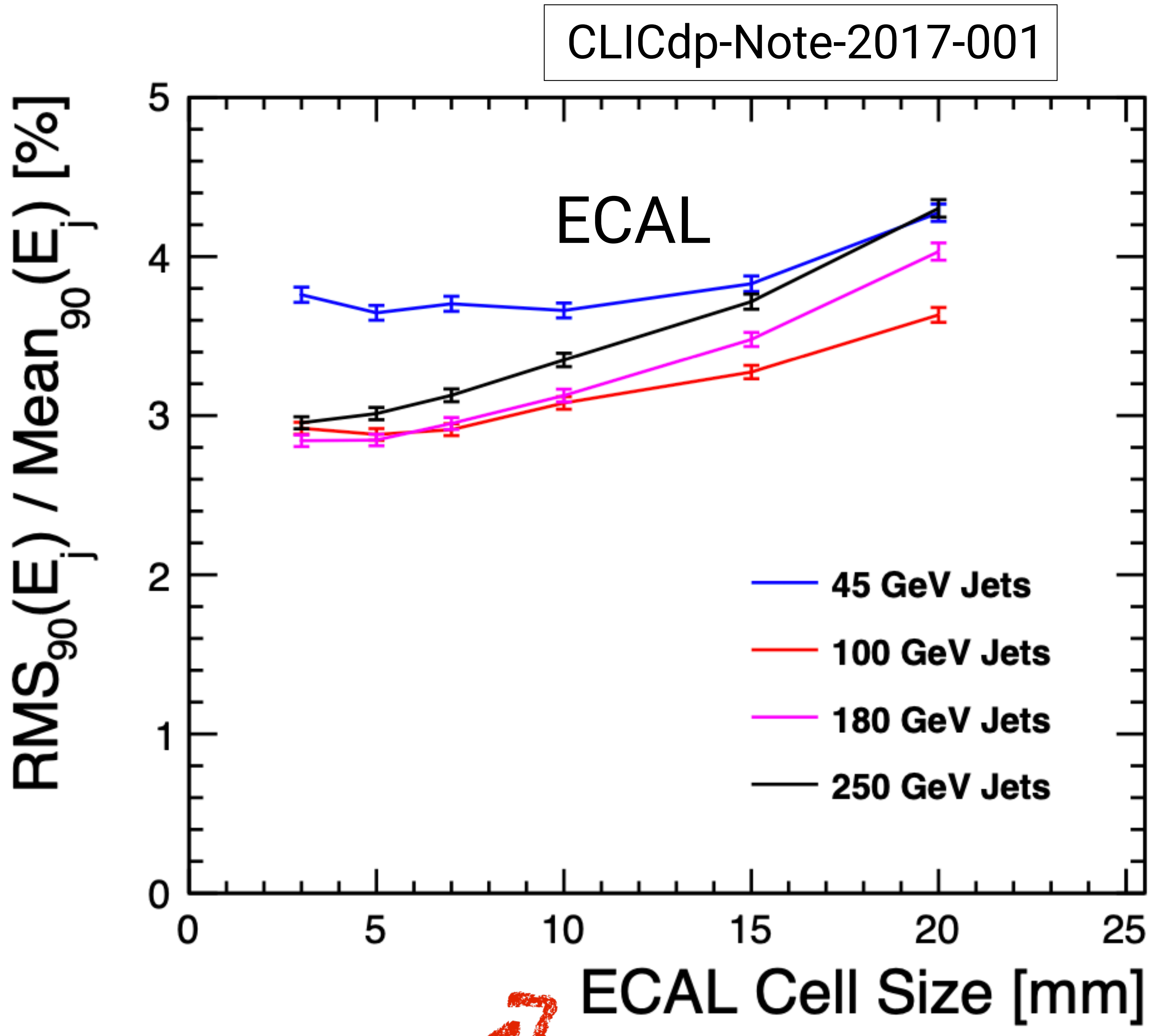

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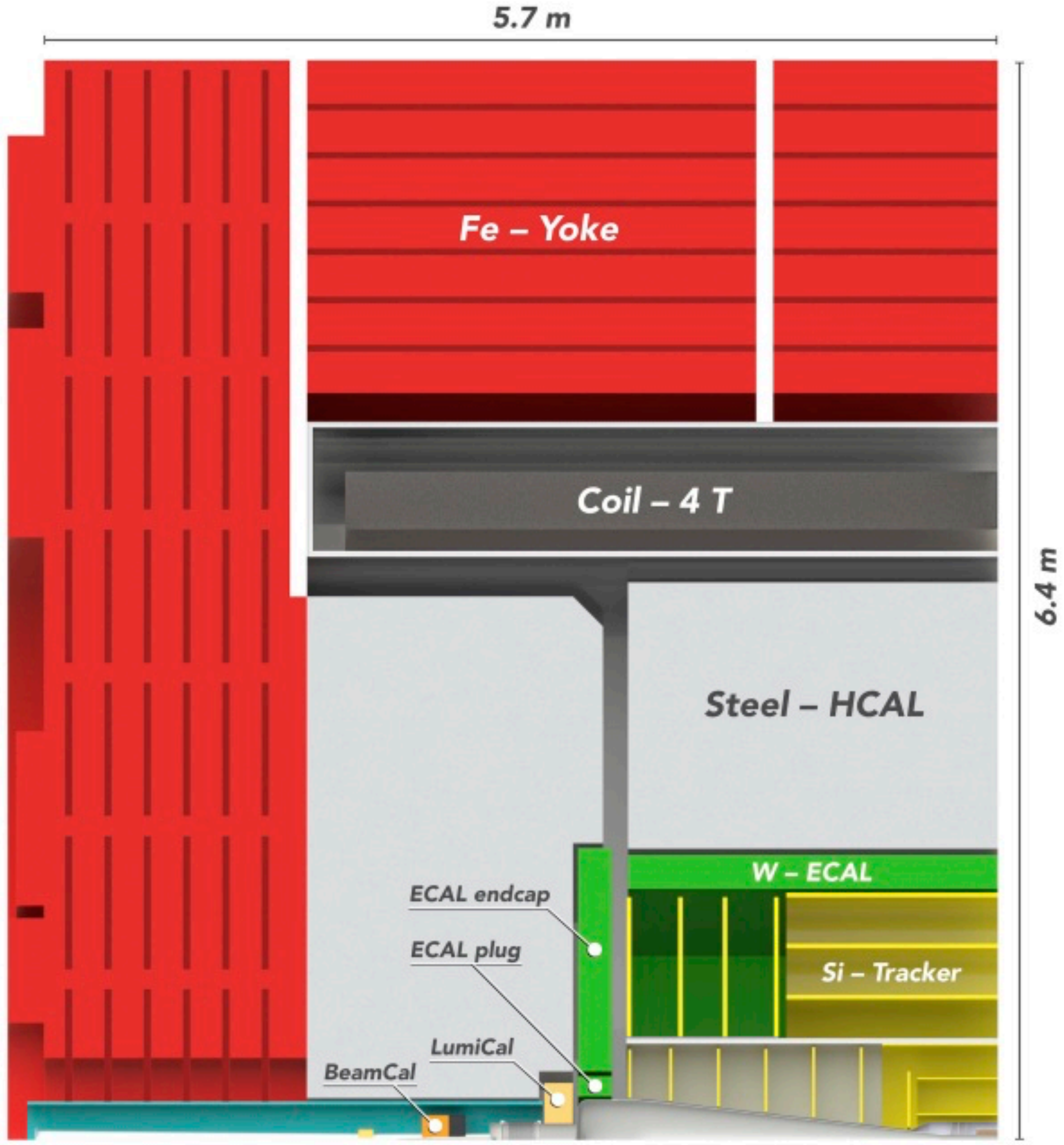

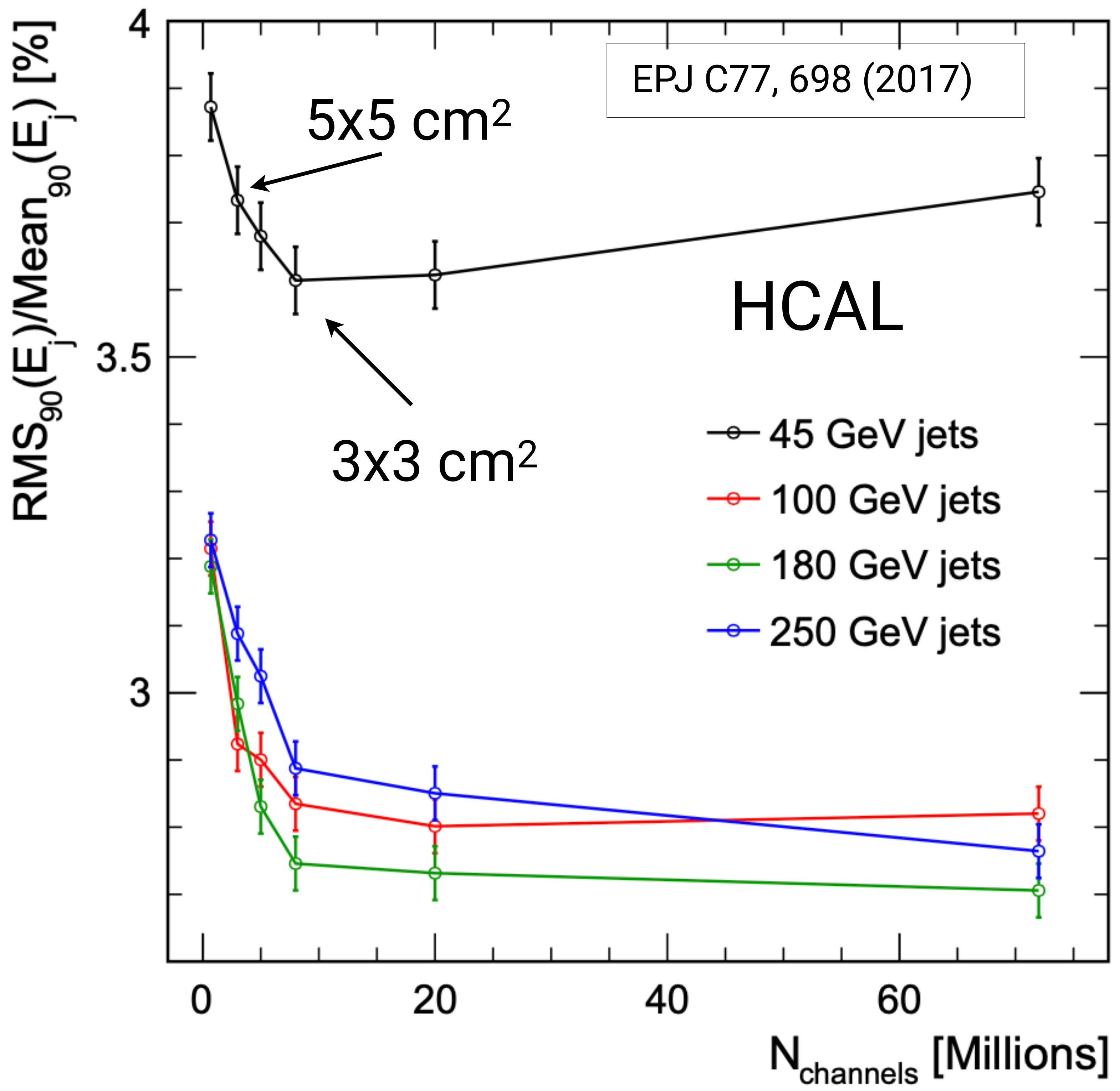

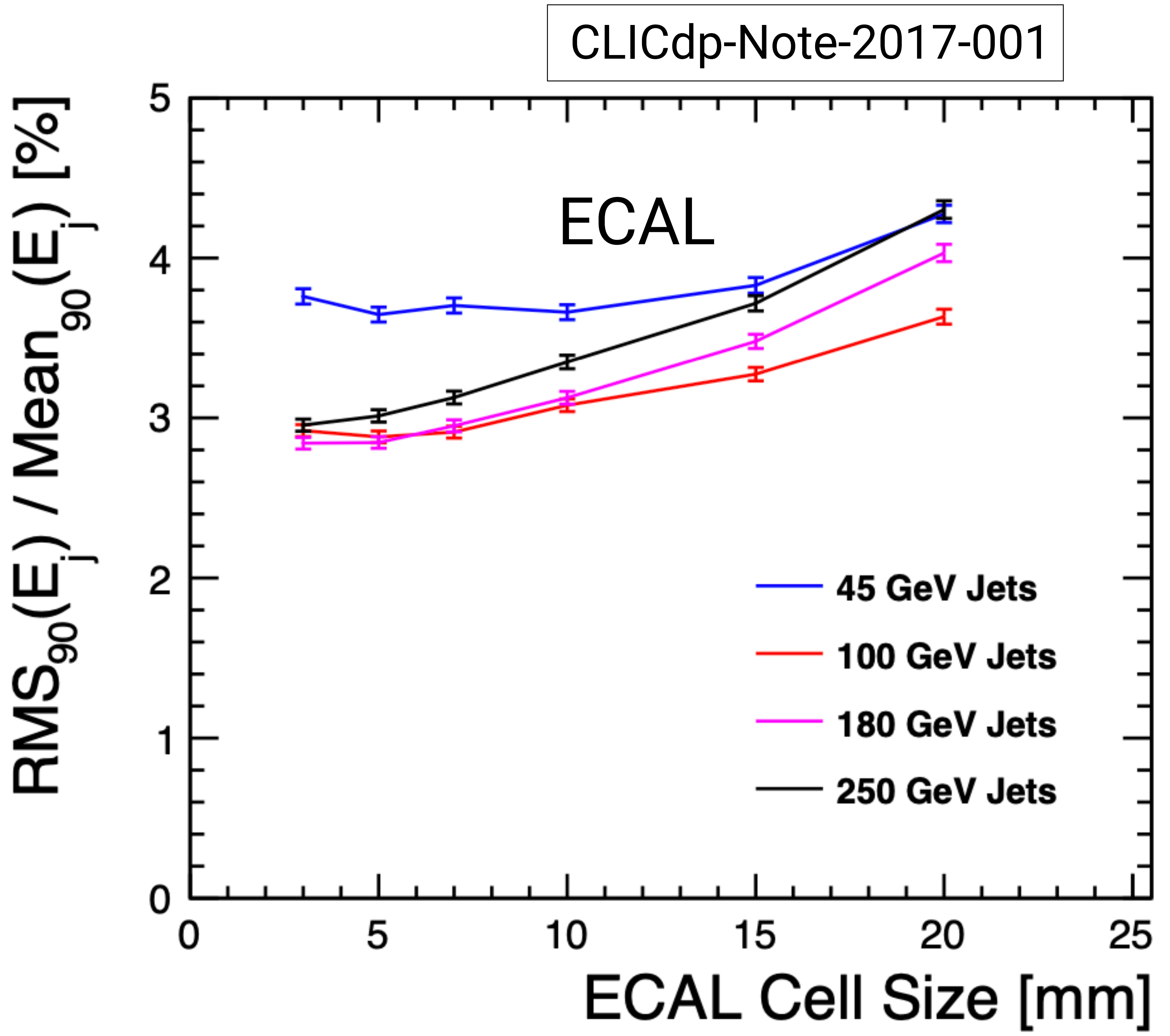

- In combination with many other parameters:
  - radius, resolution of tracker; magnetic field, …

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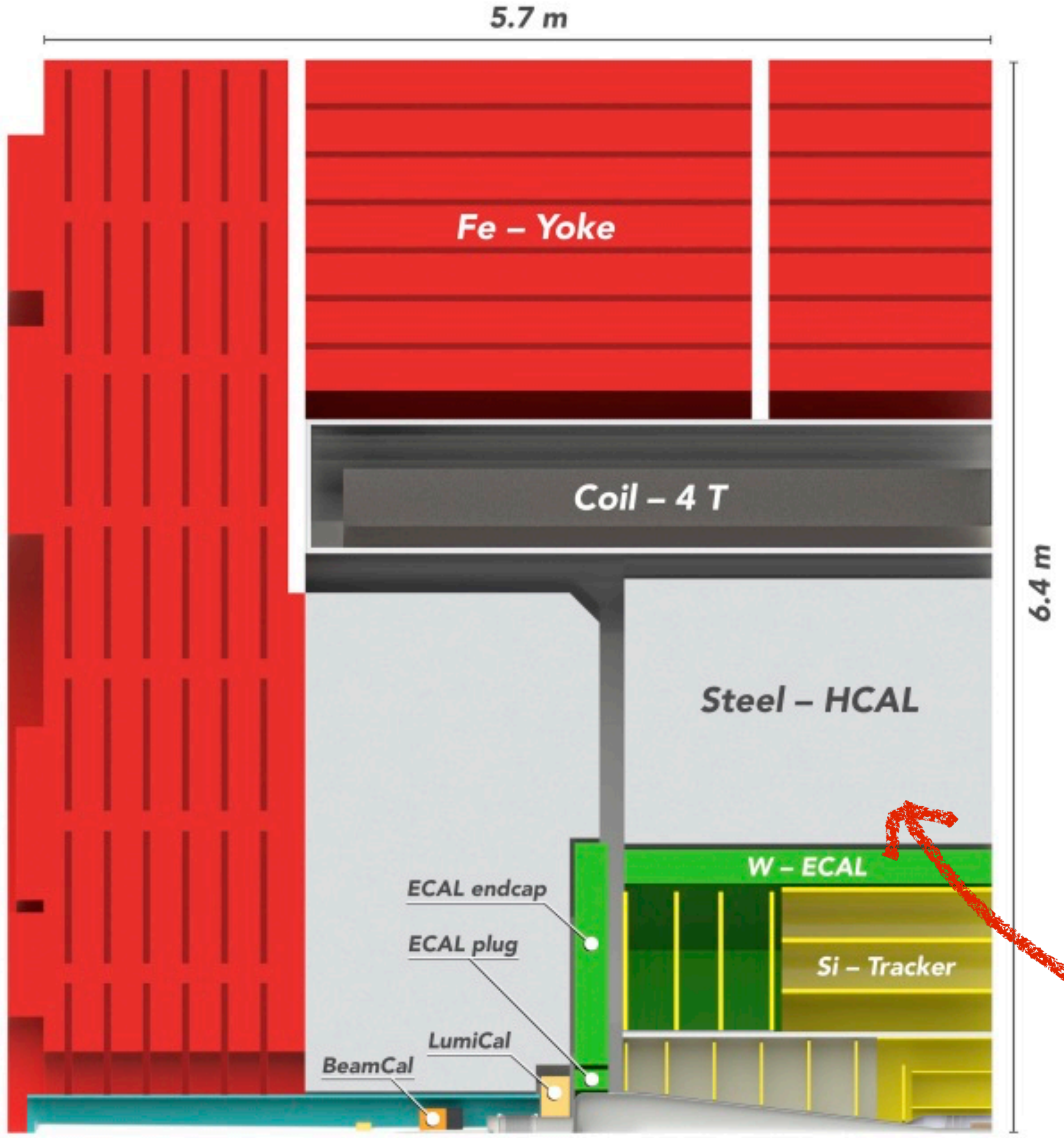
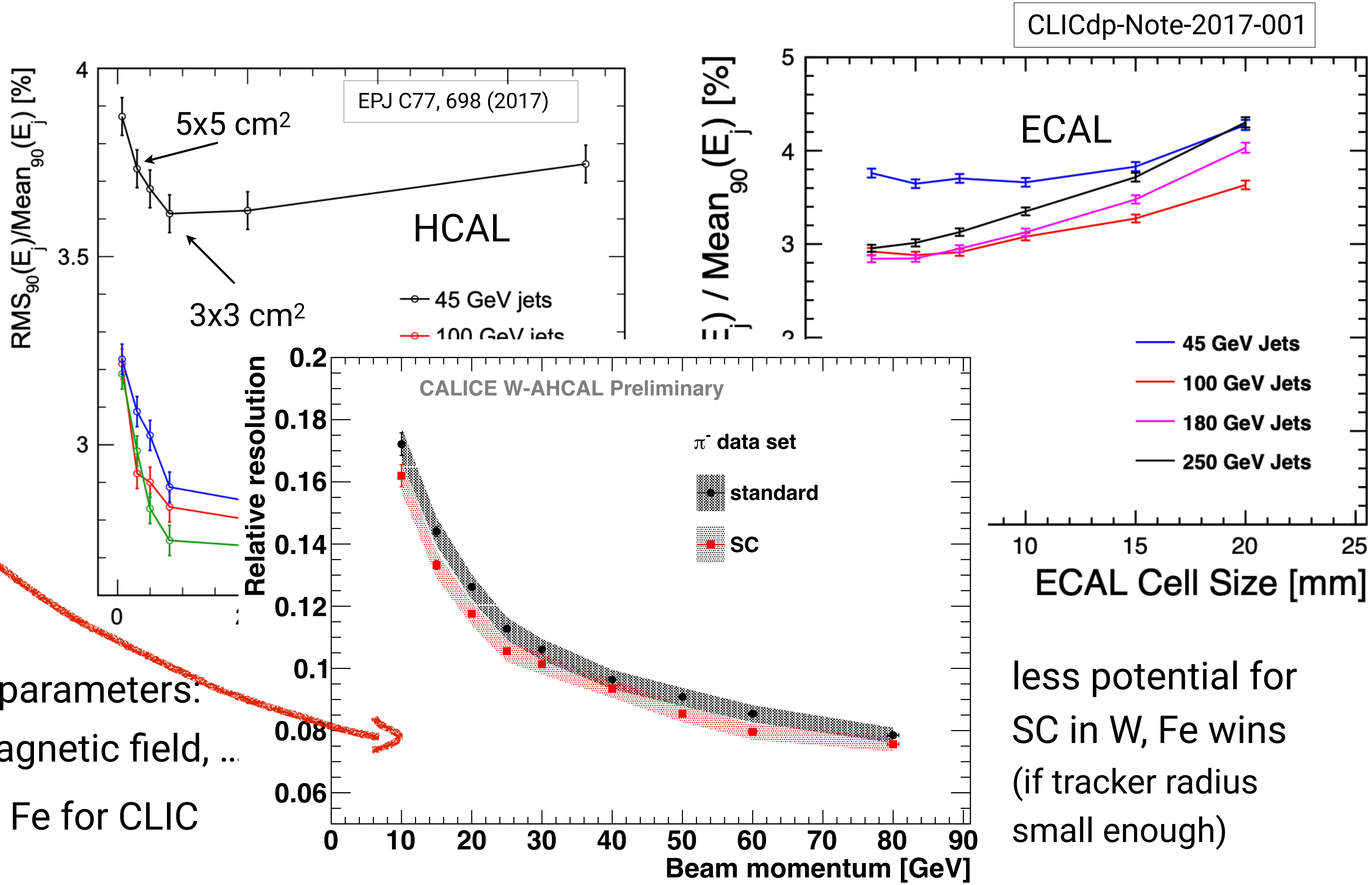


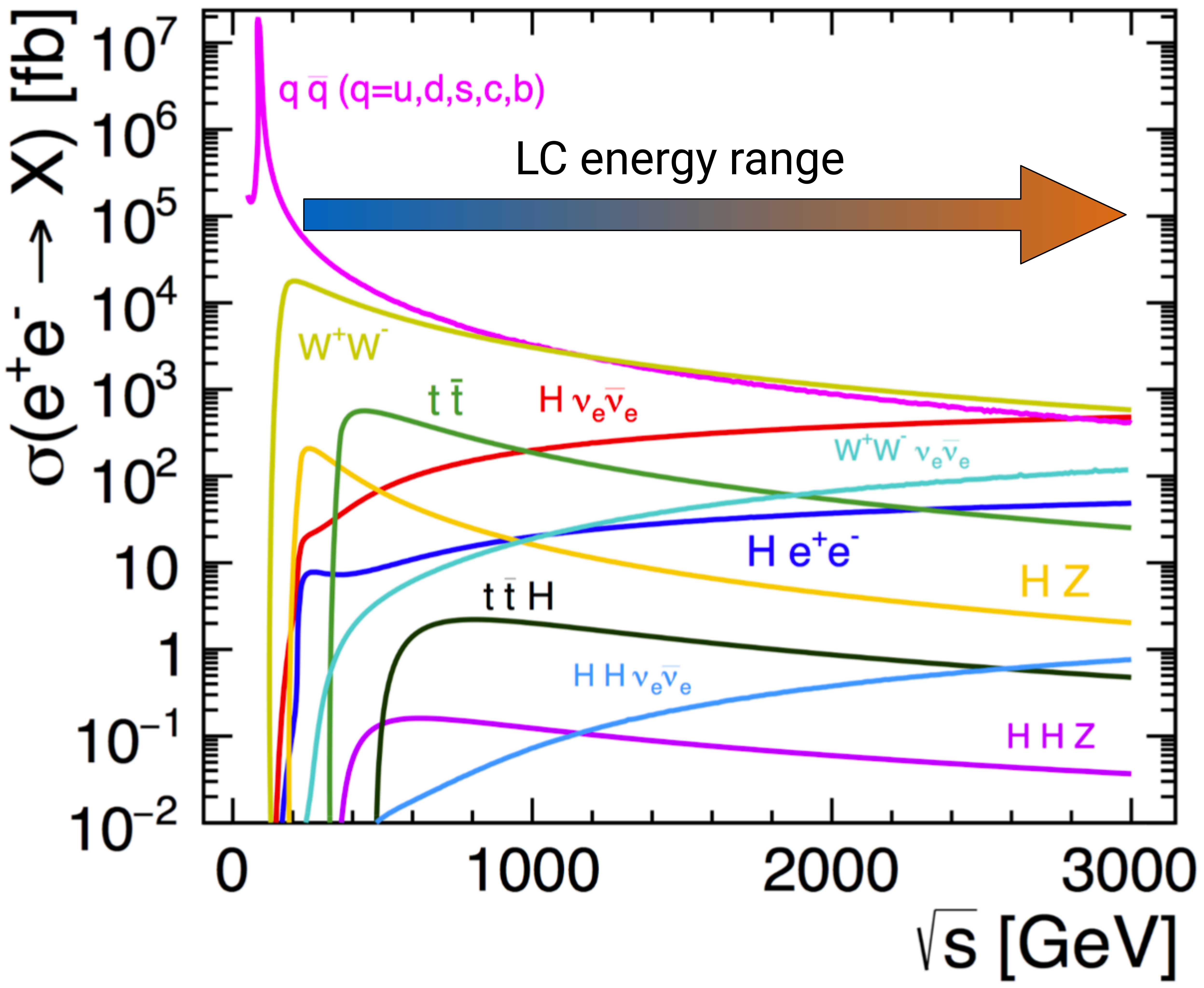


- In combination with many other parameters:
  - radius, resolution of tracker; magnetic field, ...
- Also: calorimeter absorber: W vs Fe for CLIC

less potential for SC in W, Fe wins (if tracker radius small enough)

Physics Cross Sections & Signatures

General drivers



Collision Energy

- ILC: 250 GeV - 500 GeV - 1+ TeV
- CLIC: 380 GeV - 1.5 TeV - 3 TeV
  - ➡ Leptons, jets, from a few 10 to many 100 GeV, heavy bosons / complex final states

Physics Drivers

- Physics cross sections low: rates, radiation damage moderate in most regions of the detector
  - ➡ Statistics is precious: Excellent reconstruction of all final states
  - ➡ Requires high luminosity - achievable with very small beams: Beamstrahlung (Luminosity spectrum, backgrounds)

Detector Performance Goals - Tracking

Motivated by key physics signatures

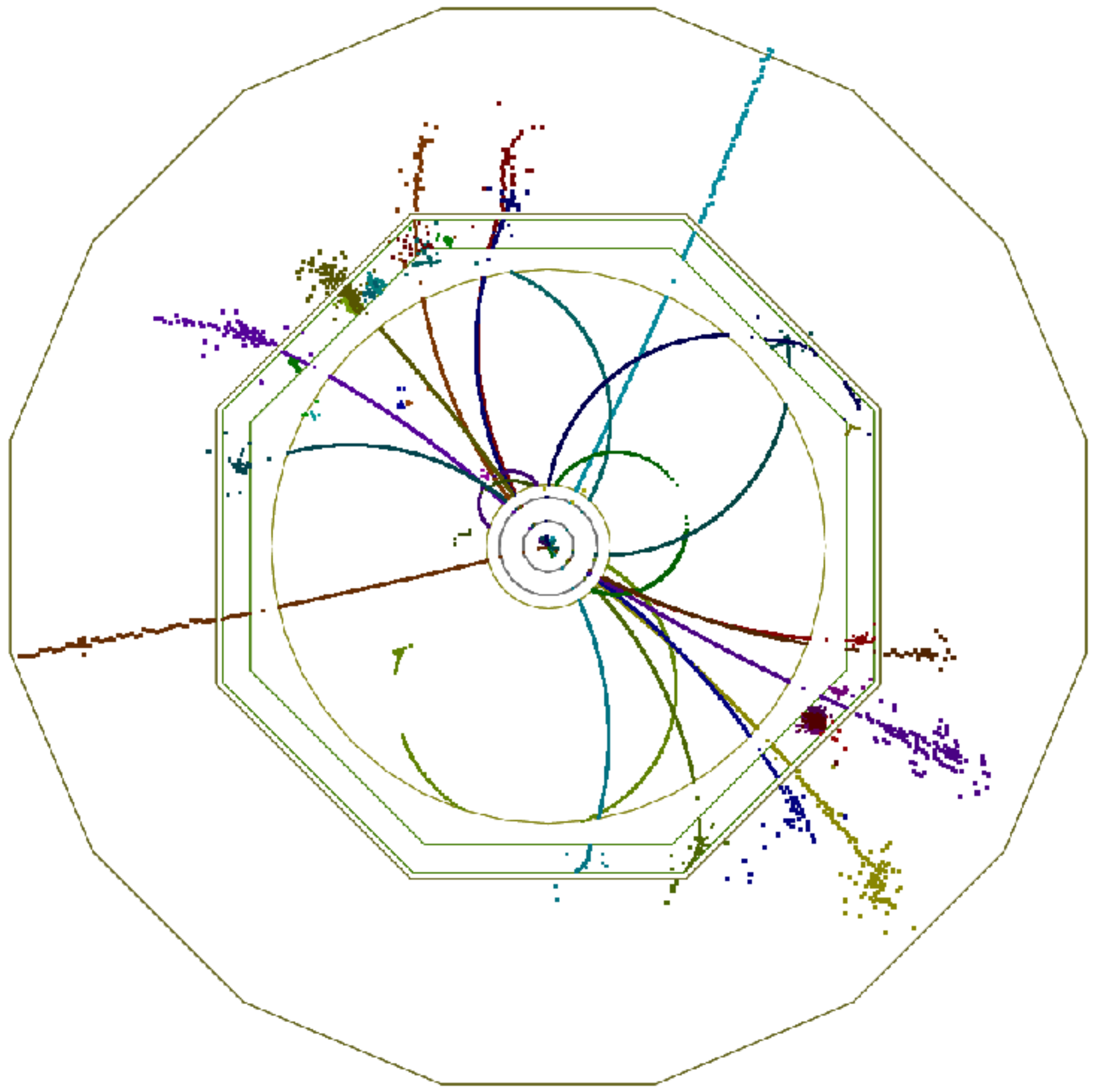
- ***Momentum resolution***

  Higgs recoil measurement, H -> $\mu\mu$,
  BSM decays with leptons

  $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ / GeV

  precise and highly efficient tracking, extending to 100+ GeV

low mass, good resolution:
for Si tracker ~ 1-2% X_0 per layer, 7 µm point resolution



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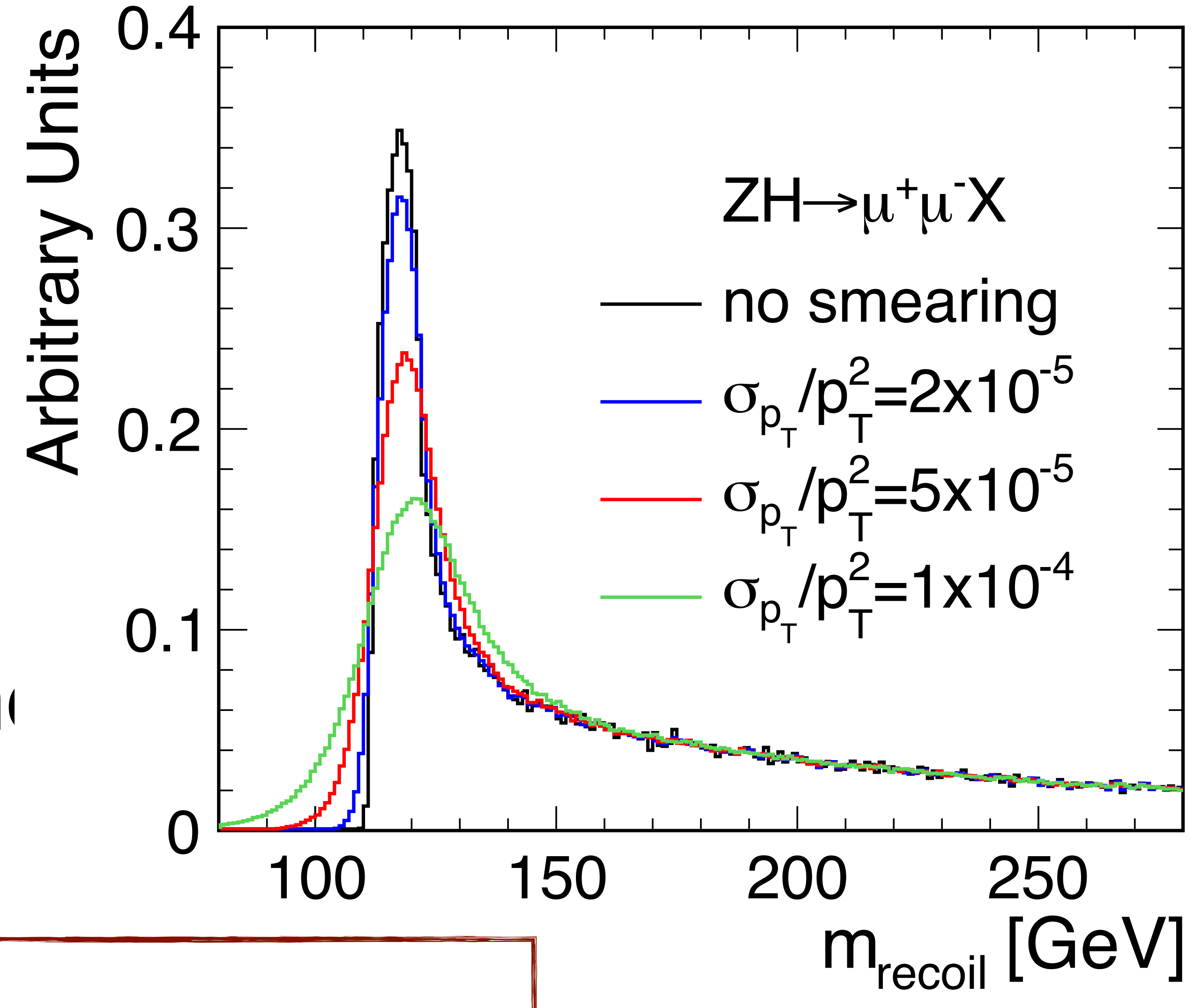

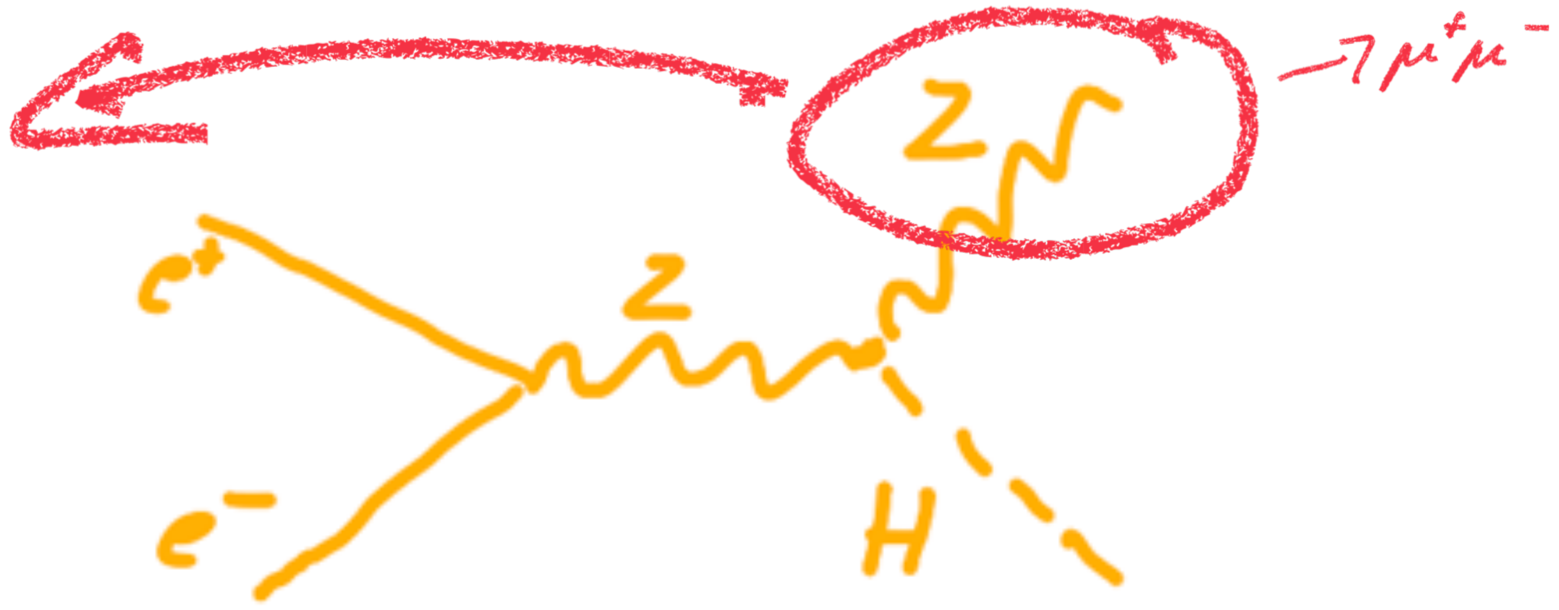

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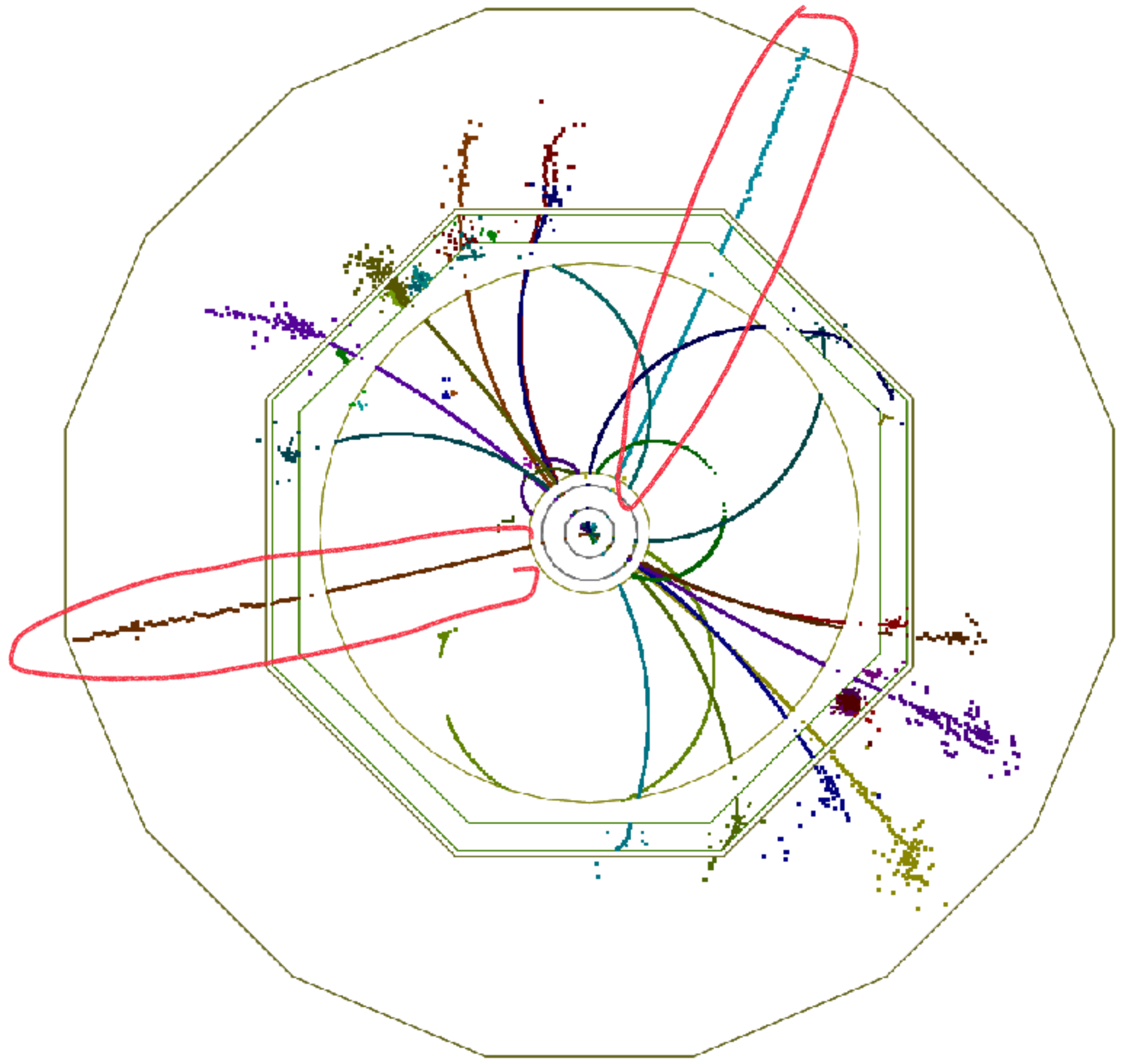

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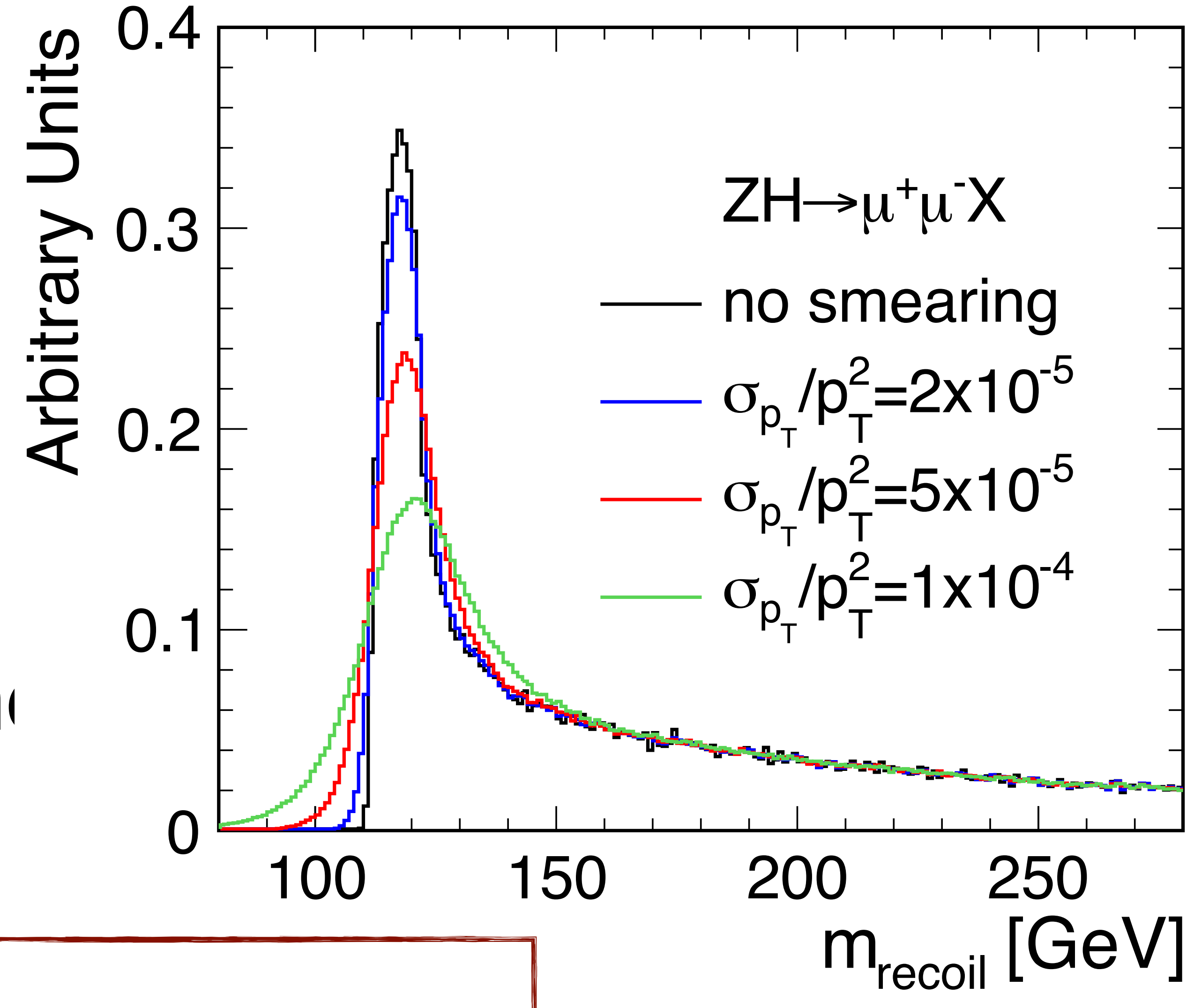

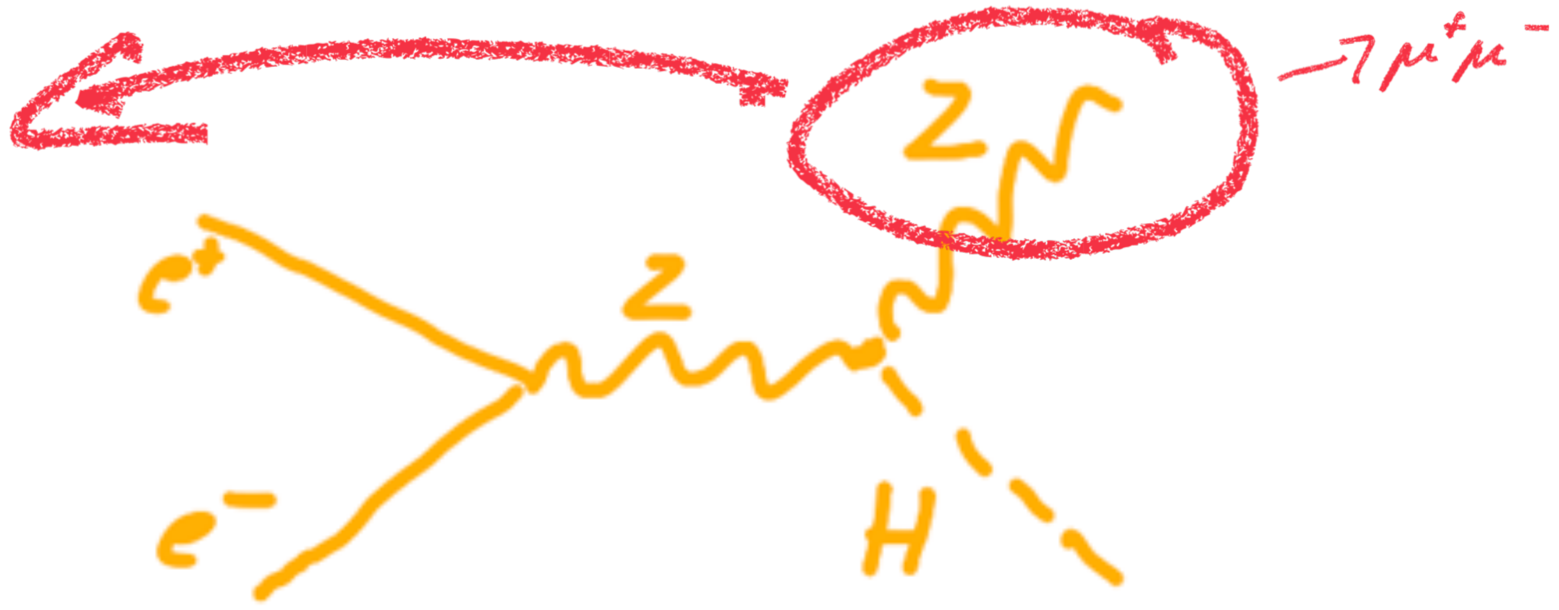

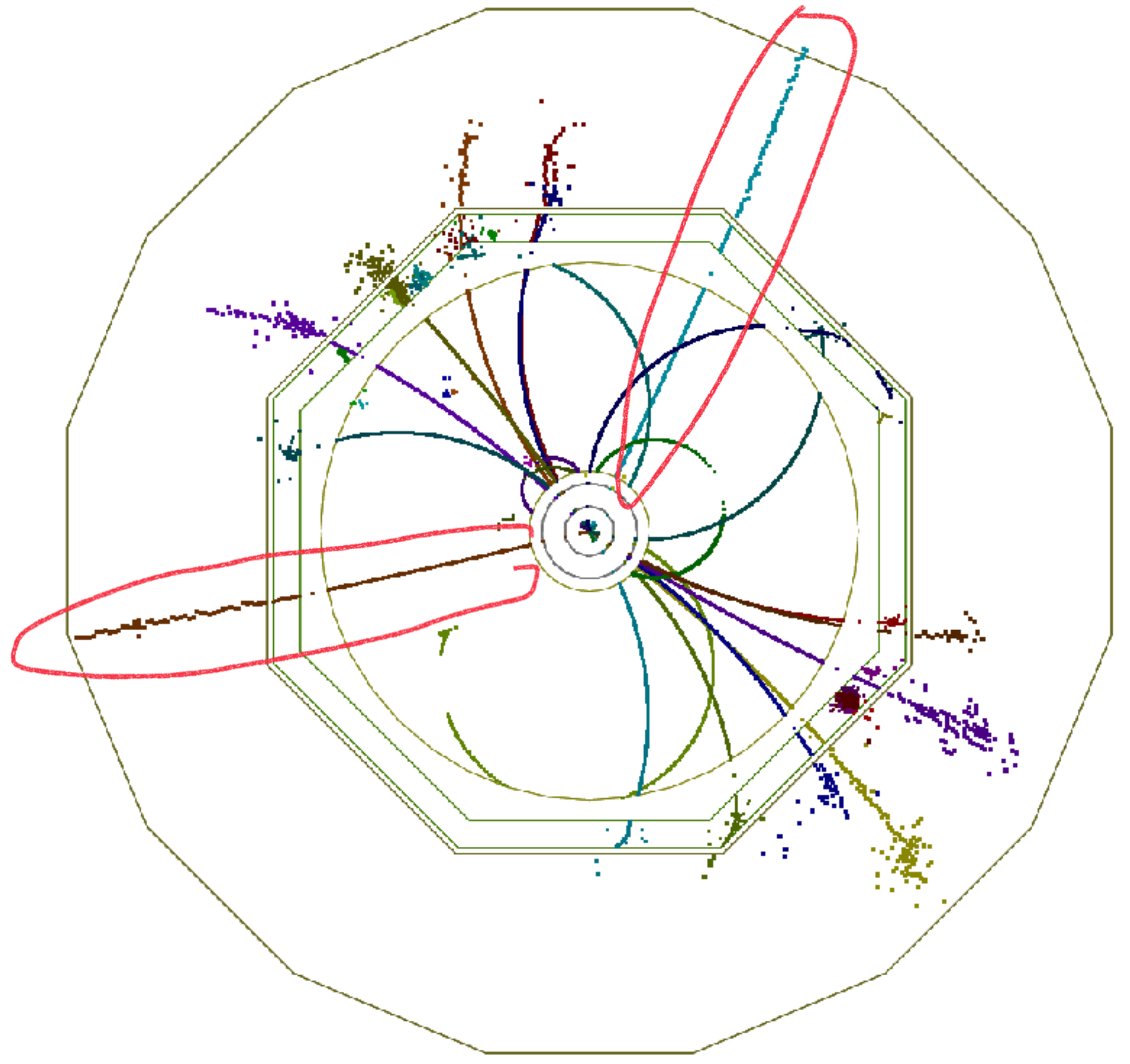

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- ***Impact parameter resolution,*** *vertex charge*

  Flavour tagging: b/c/light tagging in Higgs decays, top physics, …

  $$\sigma(d_0) \sim [5 \oplus (10 - 15)/p\sin^{3/2}\theta]\ \mu m$$

single point resolution in vertex detector ~3 µm
< 0.2 X_0 per layer

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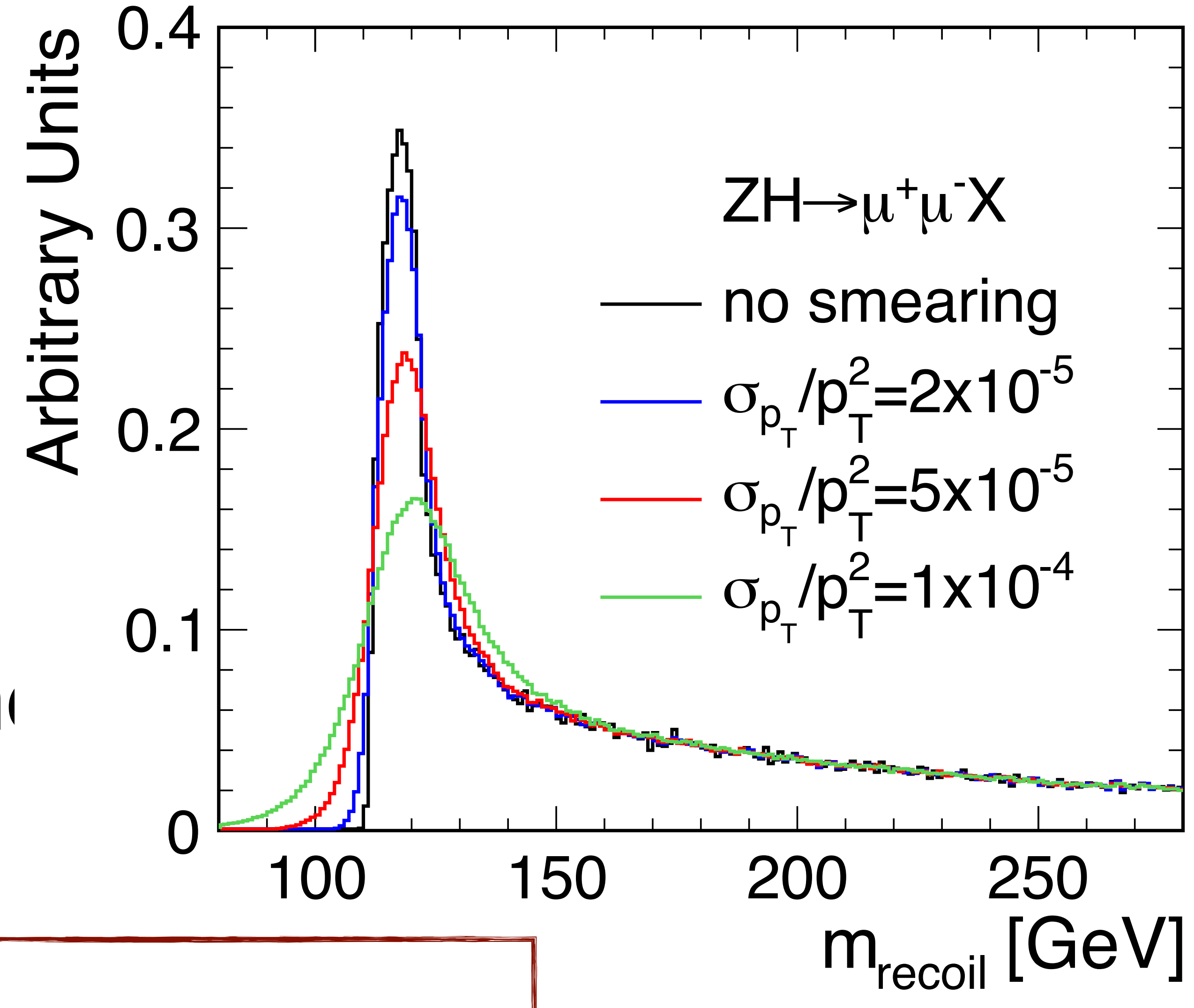

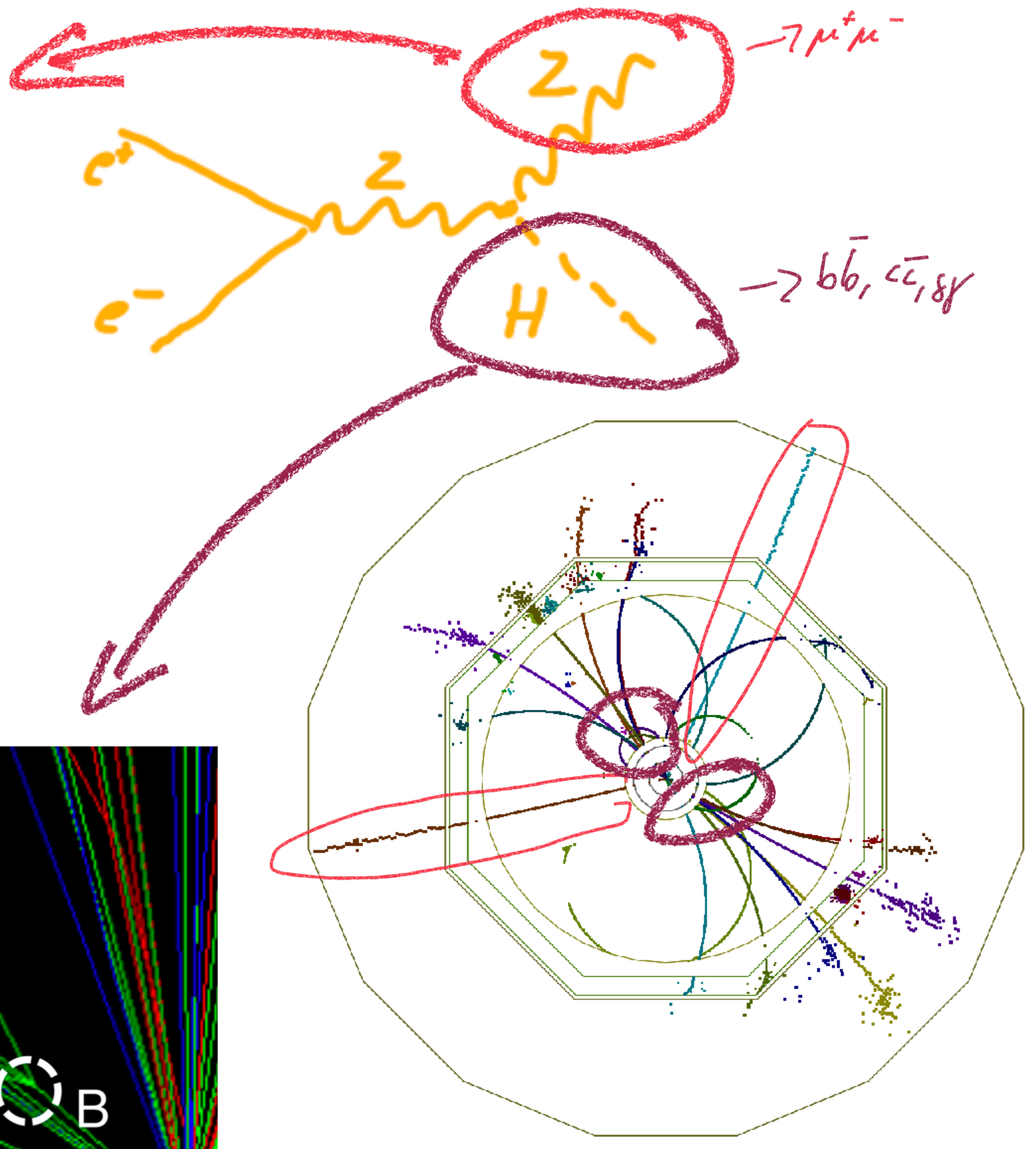

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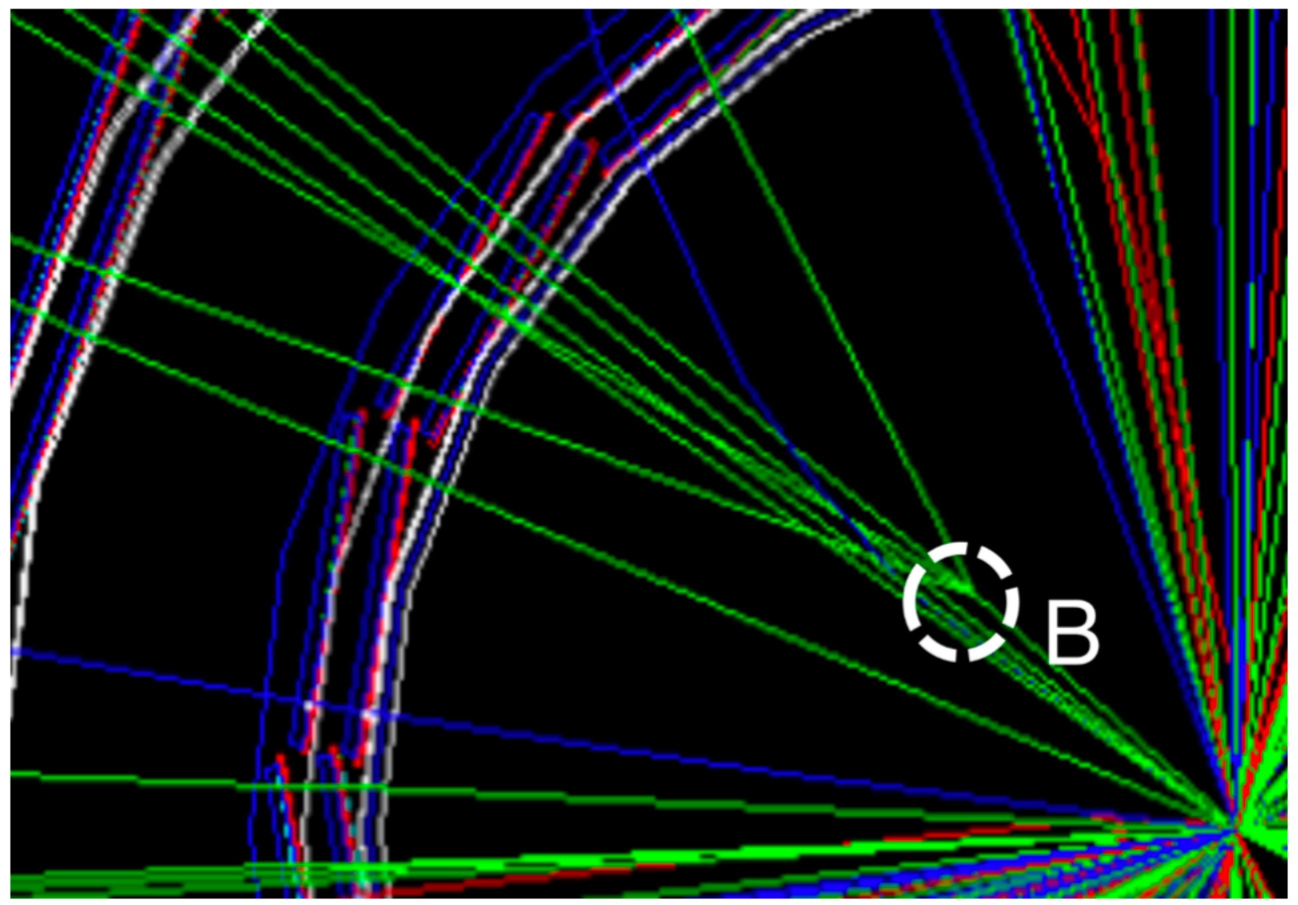

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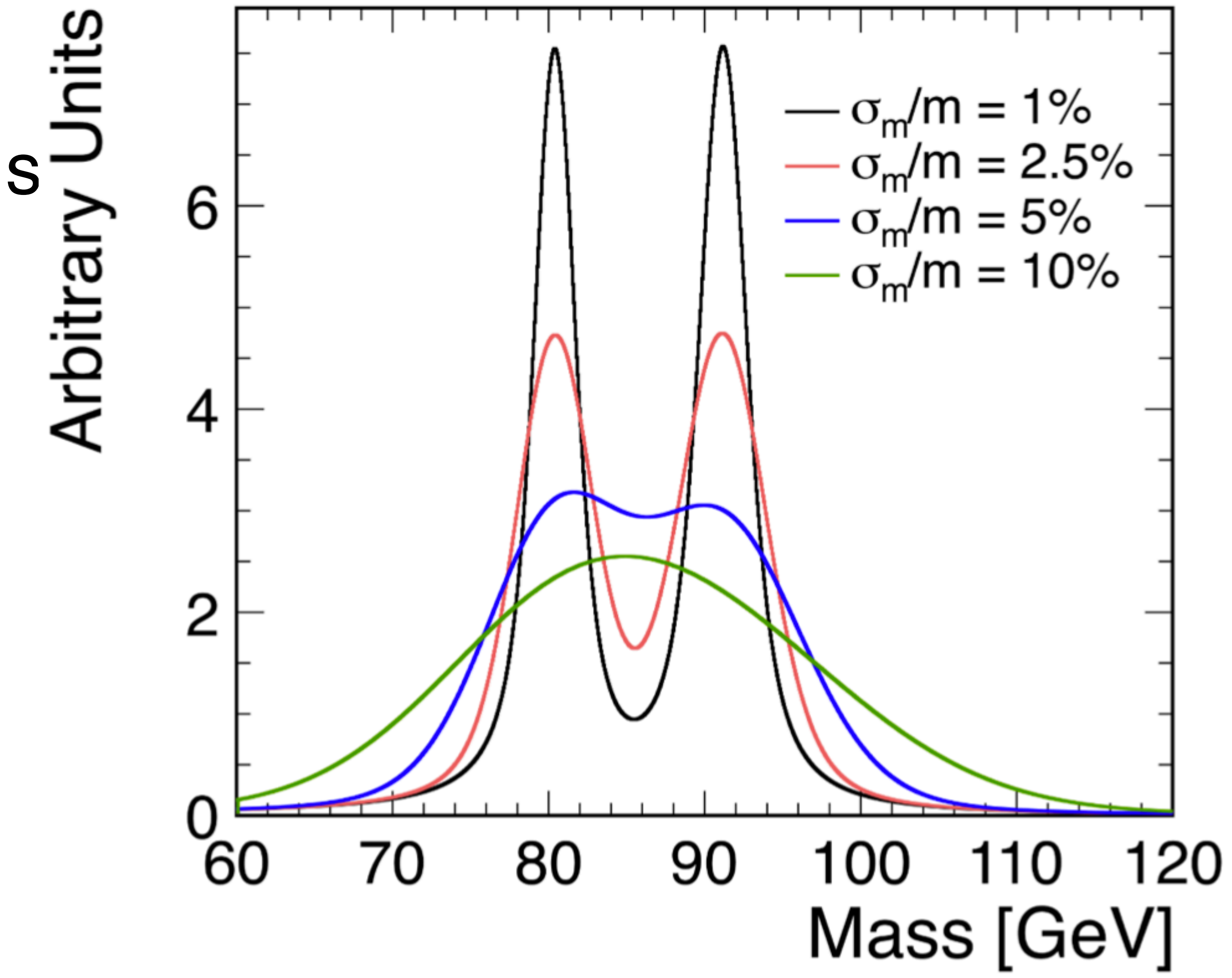
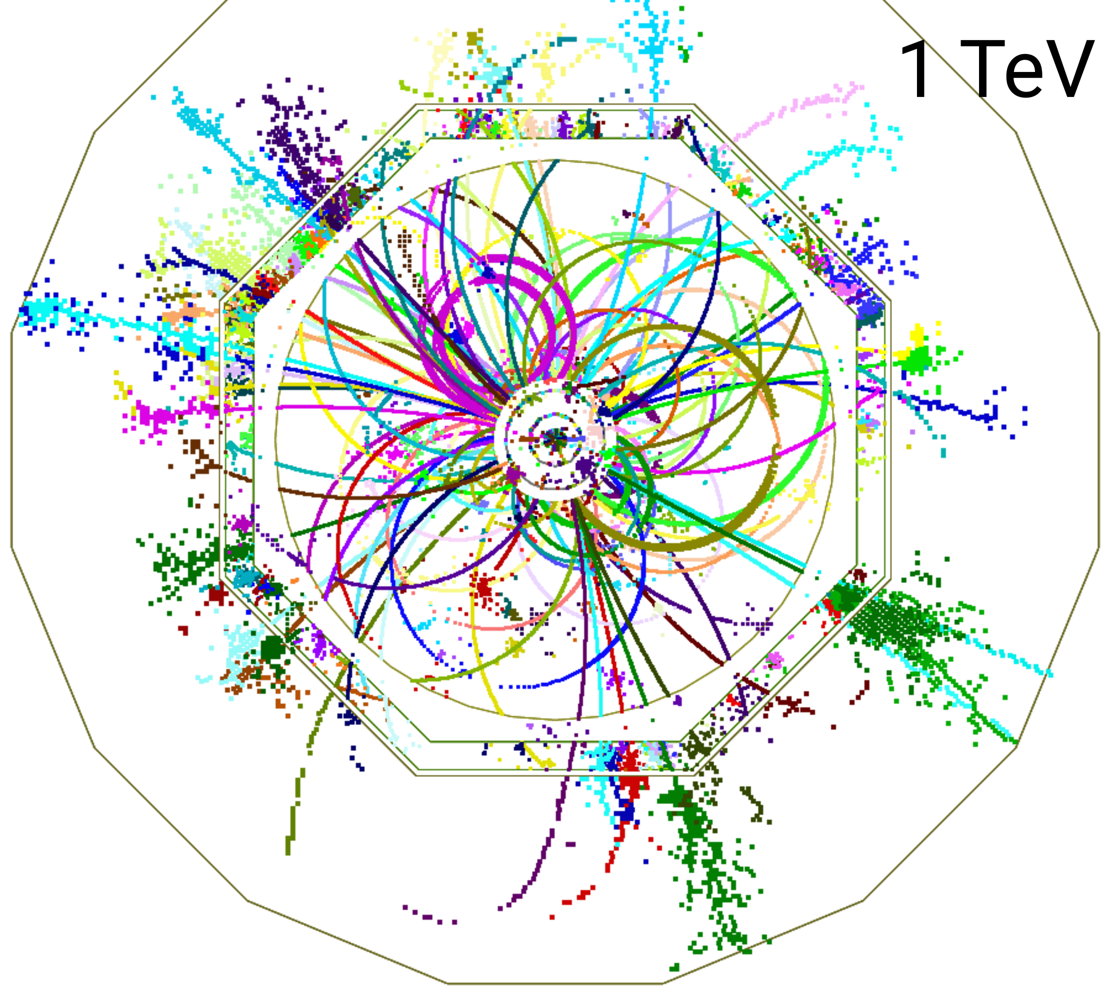
Detector Performance Goals - Jets, Photons, PID

Motivated by key physics signatures

- ***Jet energy resolution***
  Recoil measurements with hadronic Z decays, s
  $\sigma(E_{jet}) / E_{jet}$ ~ 3% - 5% **for E_{jet} > 45 GeV**
  reconstruction of complex multi-jet final states.



$e^+e^- \to ttH \to q\bar{q}b\,q\bar{q}\bar{b}\,b\bar{b}$



- ***Photons***
  Resolution not in the focus: ~ 15 - 20%/√E
  Worth another look ?
  Coverage to 100s of GeV important

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Karlsruher Institut für Technologie

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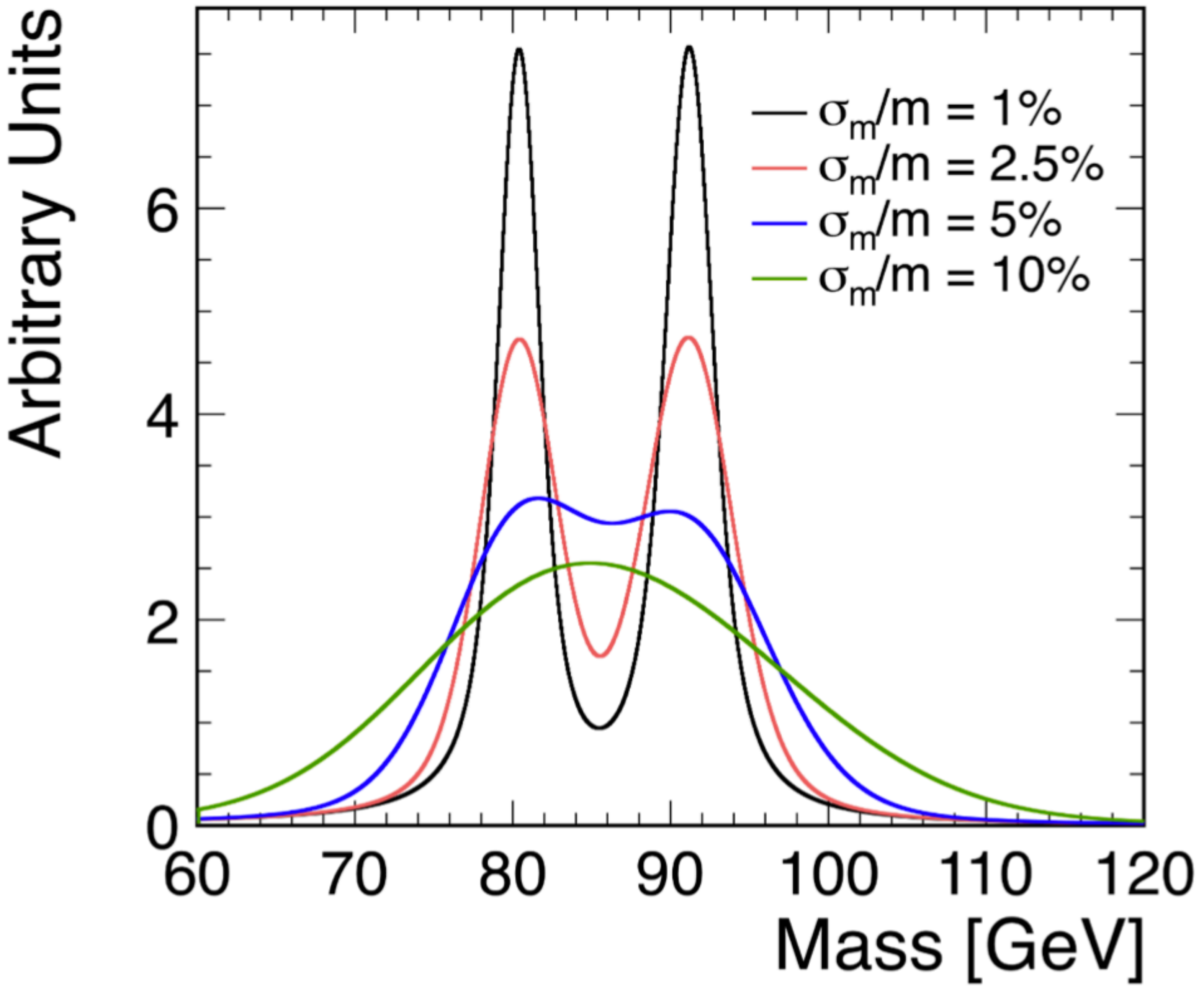

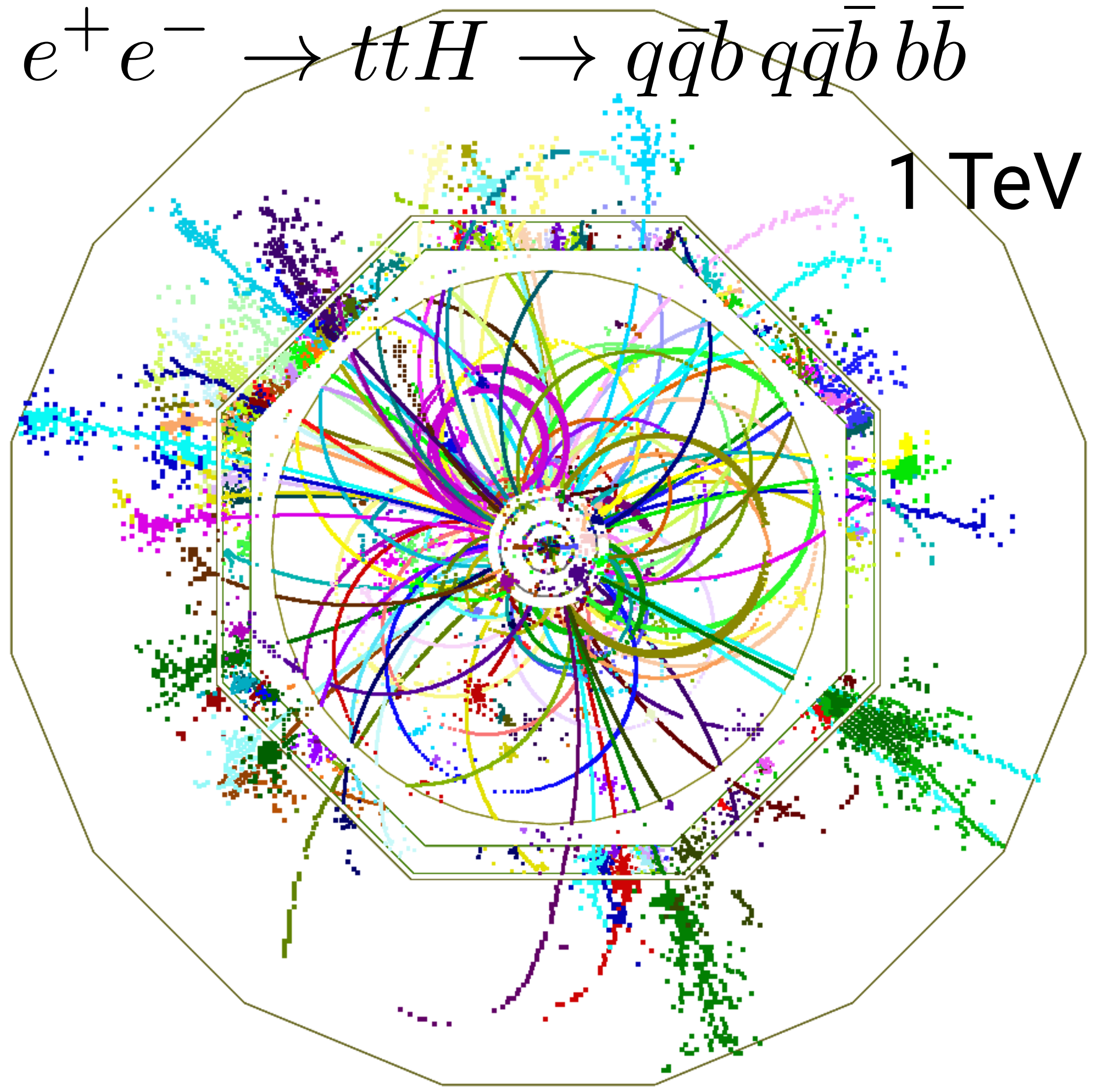

- ***Particle ID***
  Clean identification of e, μ up to highest energies
- PID of hadrons to improve tagging, jets,…

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- ***Particle ID***

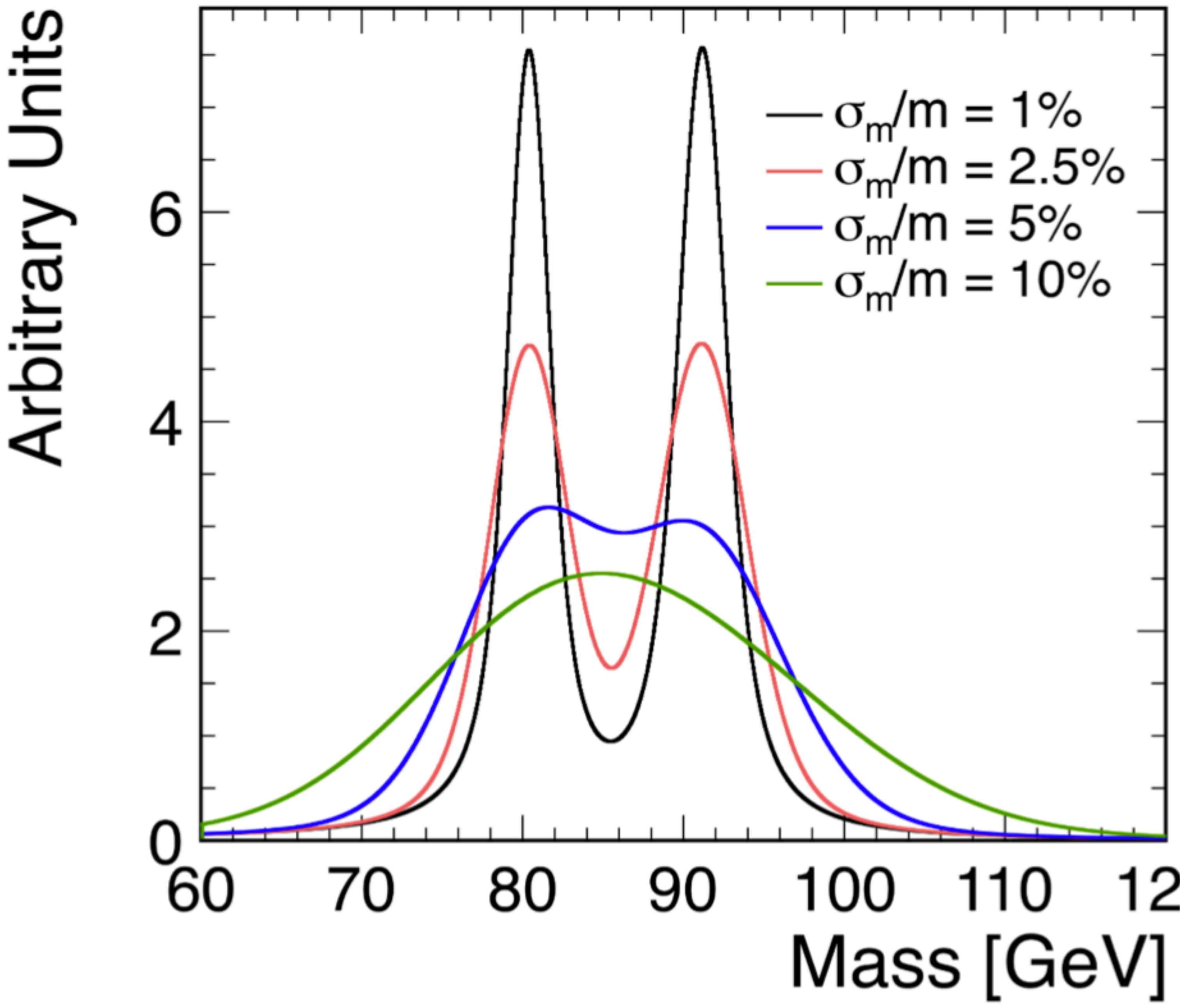
  Clean identification of e, μ up to highest energies

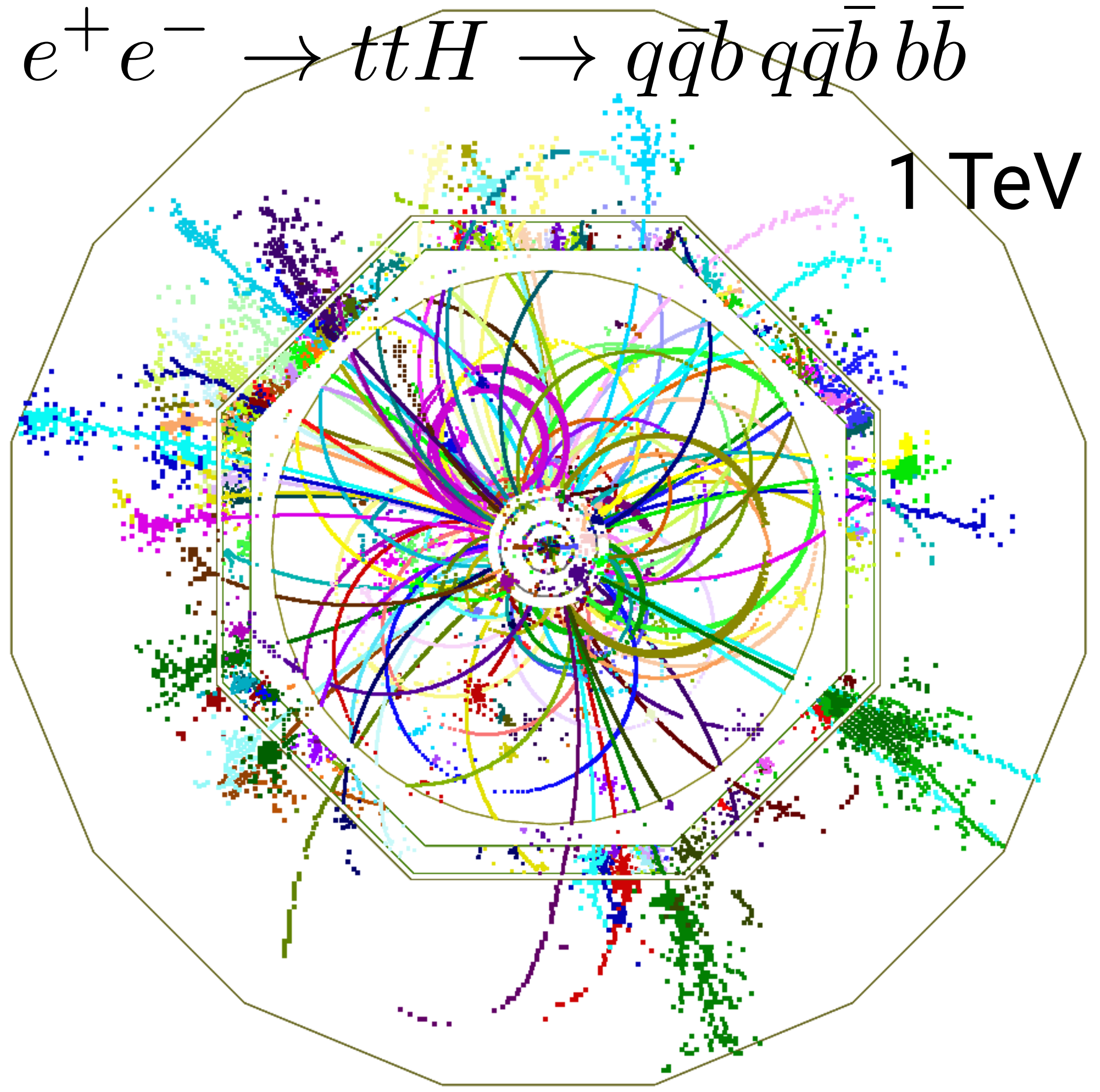
- PID of hadrons to improve tagging, jets,…

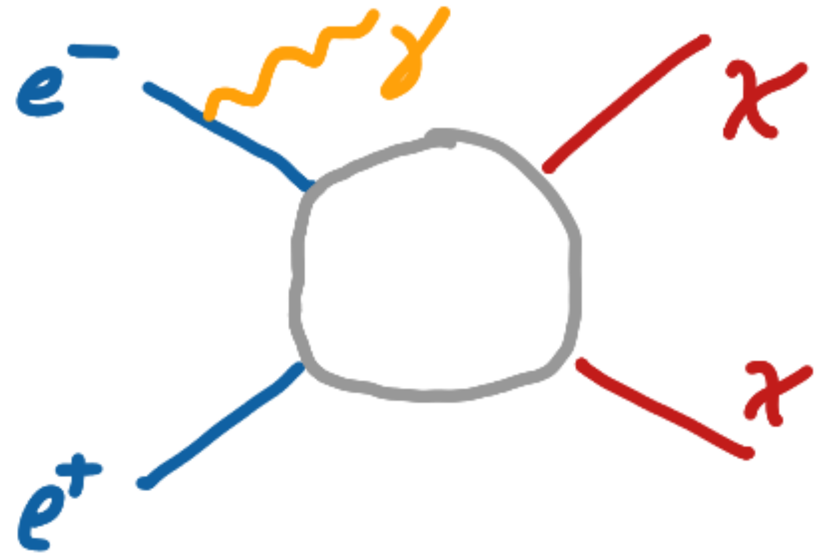
- ***Hermetic coverage***

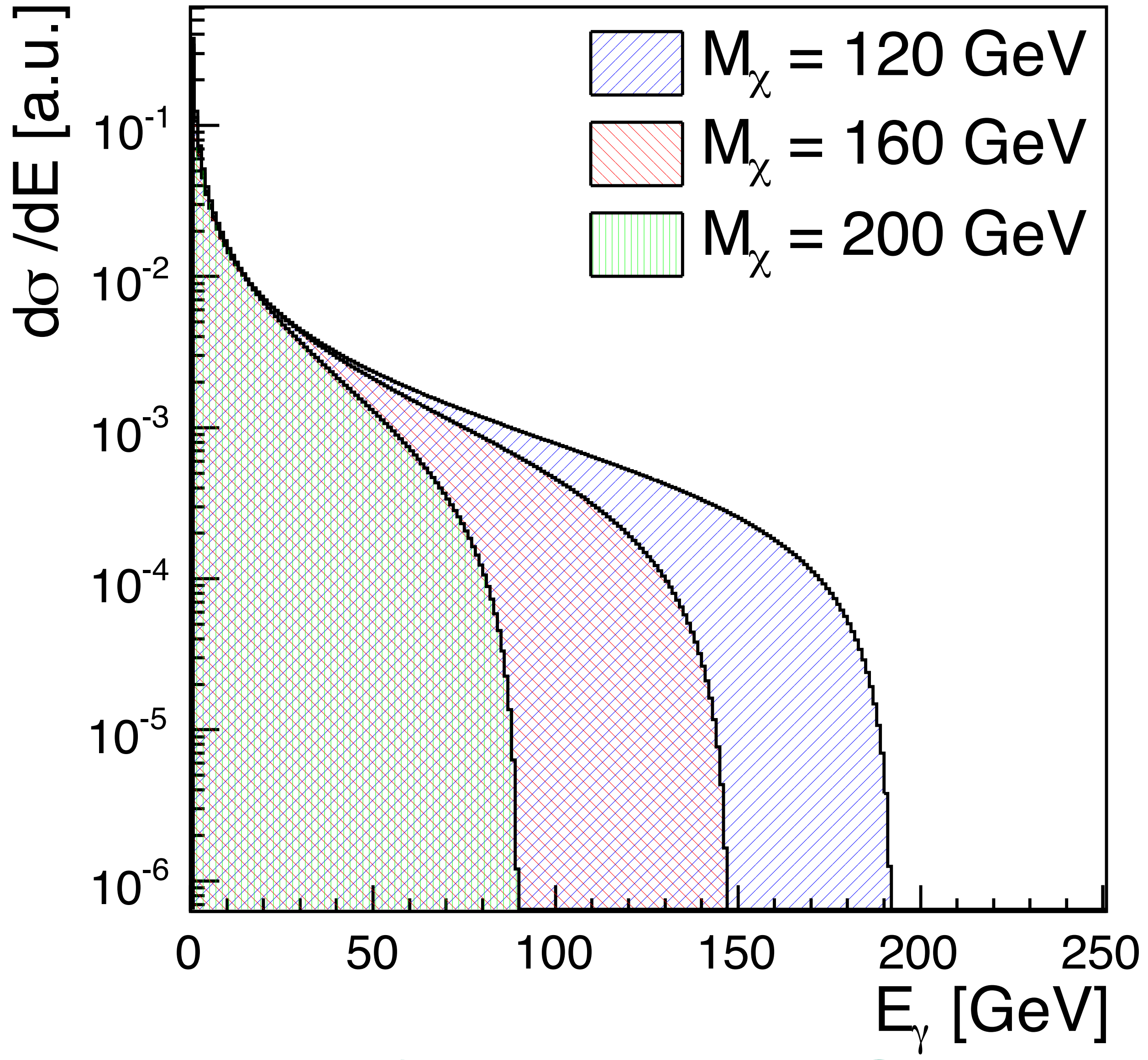
  Dark matter searches in mono-photon events, …

  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$



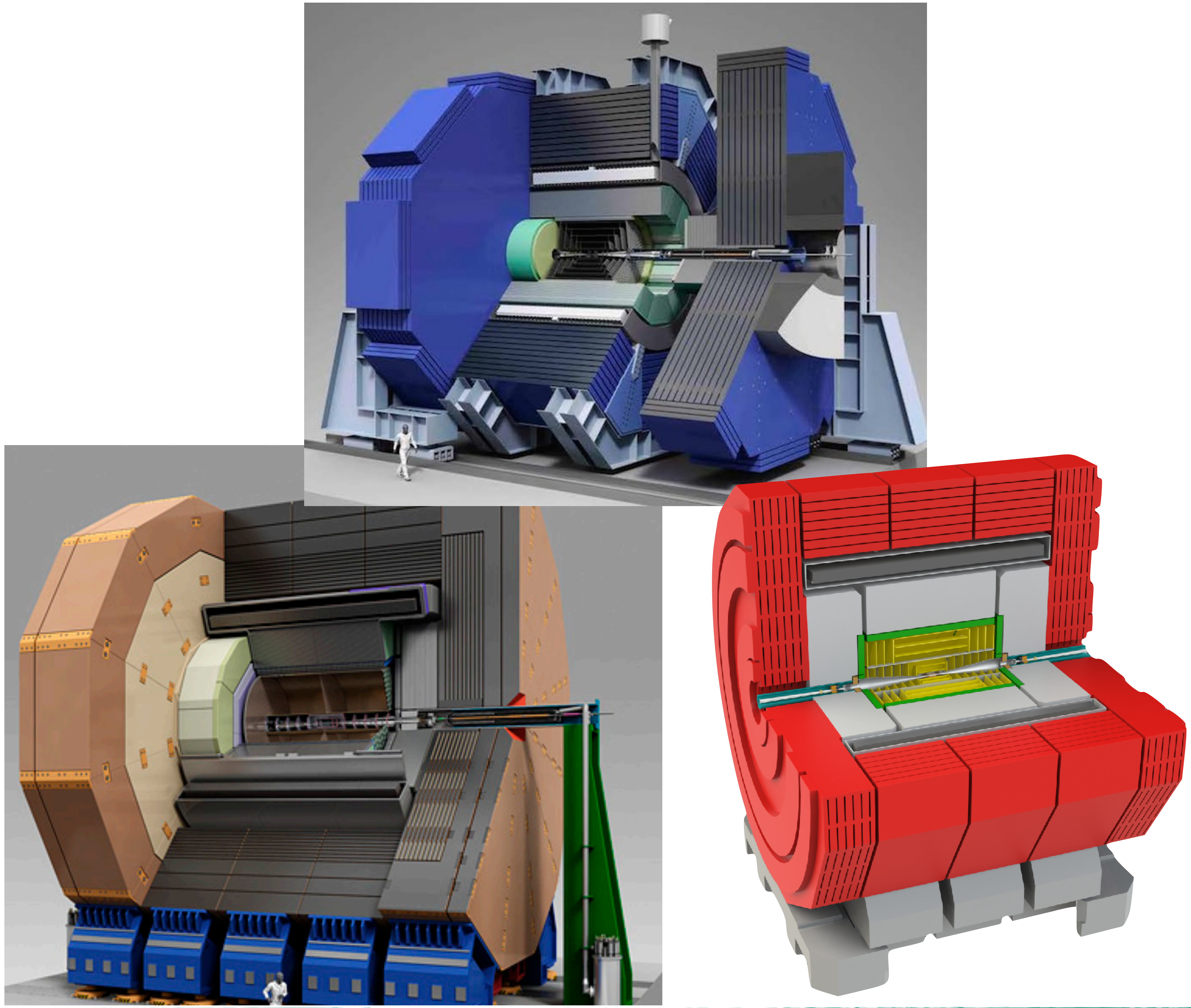






The Linear Collider Detector Design - Main Features

Focusing on general aspects

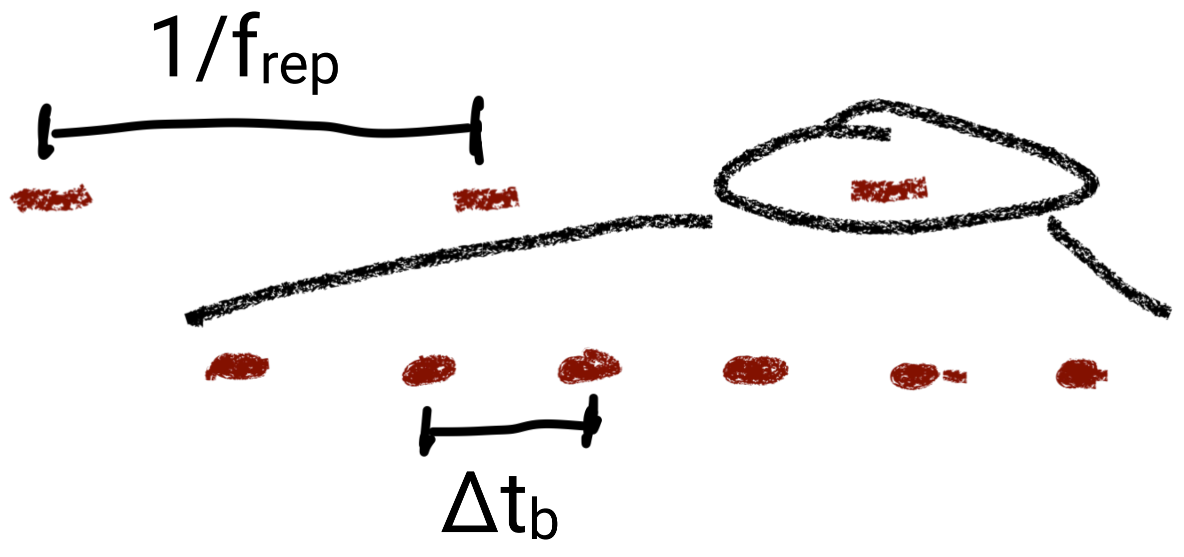


- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

Linear Collider Conditions

… and the consequences for the detector design

- Linear Colliders operate in bunch trains:



  - at CLIC: **Δt_b = 0.5 ns**; f_{rep} = 50 Hz
  - at ILC: Δt_b = 554 ns; f_{rep} = 5 Hz

⇰ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

- ⇰ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

Linear Collider Conditions

… and the consequences for the detector design

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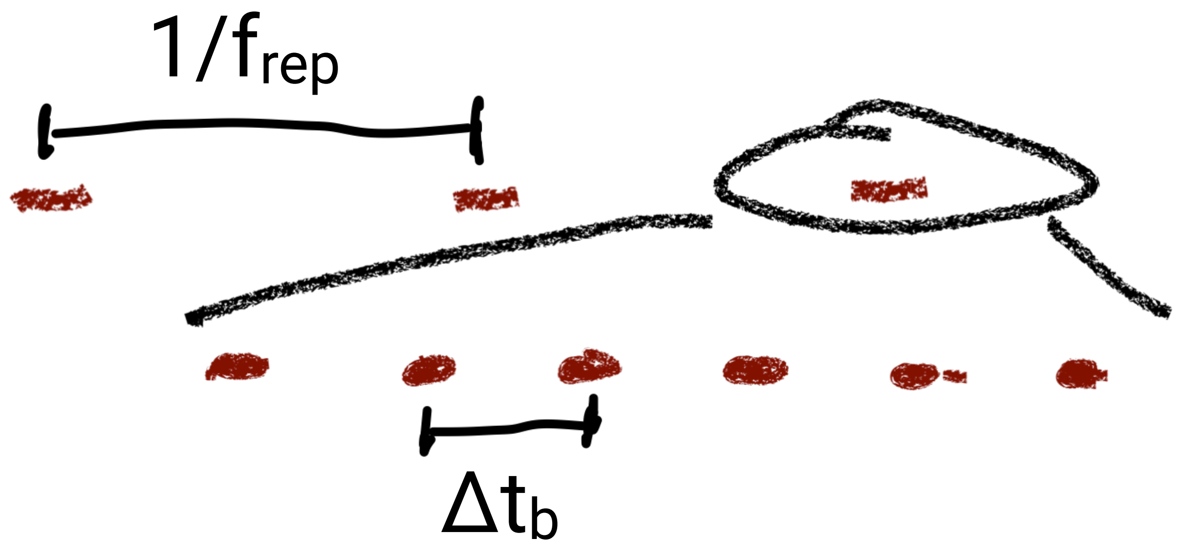

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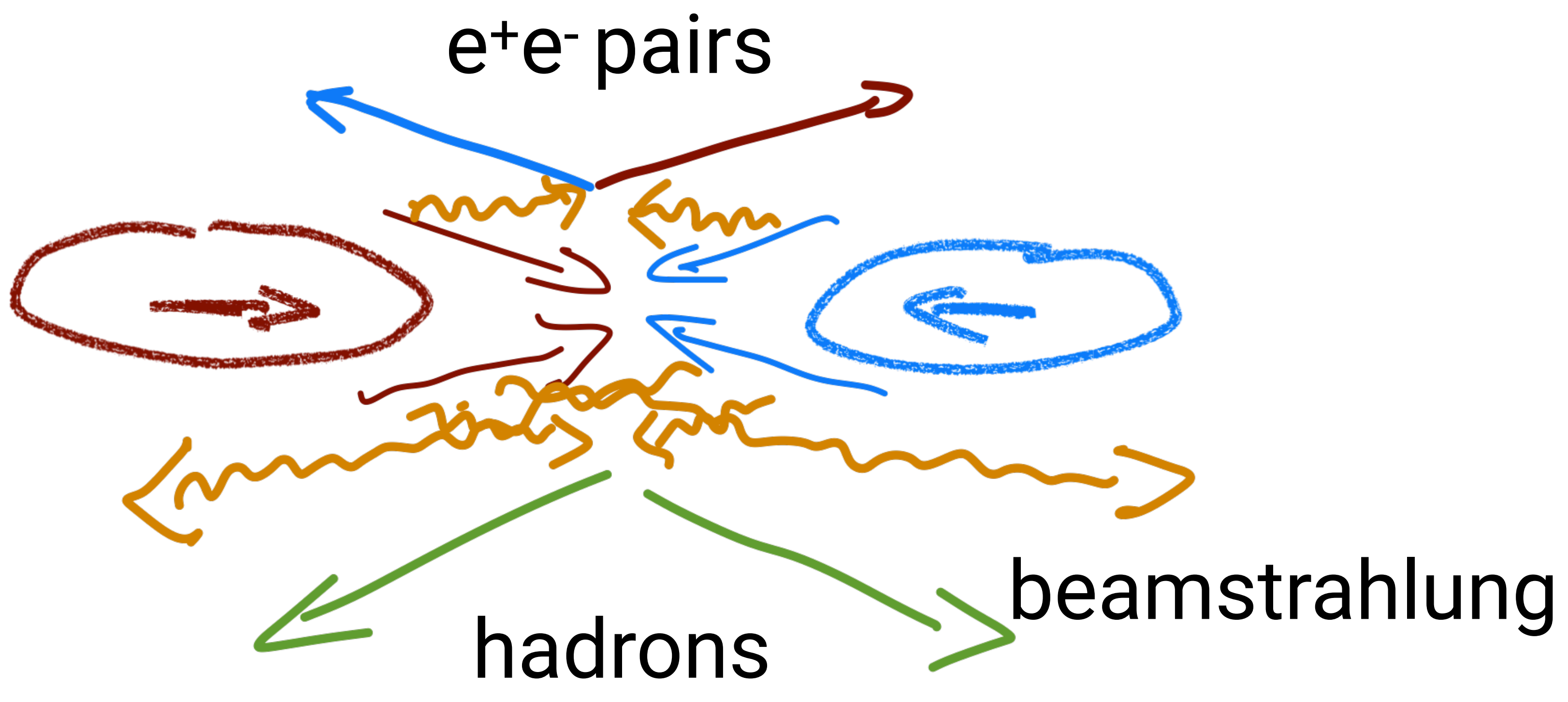
  ➩ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

- … and require extreme focusing to achieve high luminosity



➩ Significant beam-induced backgrounds

  ➩ Constraints on beam pipe geometry, crossing angle and vertex detector radius

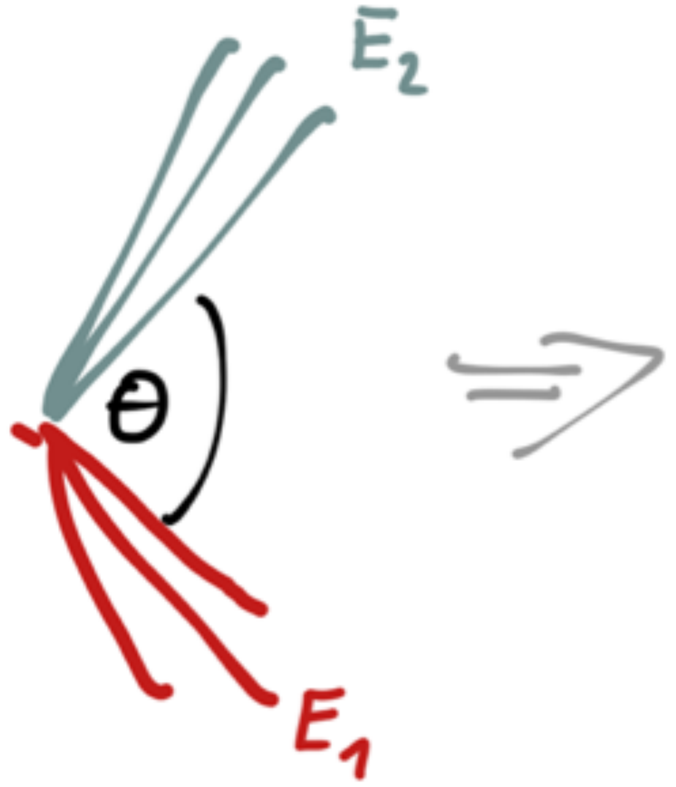
  ➩ In-time pile-up of hadronic background: **sufficient granularity for topological rejection**

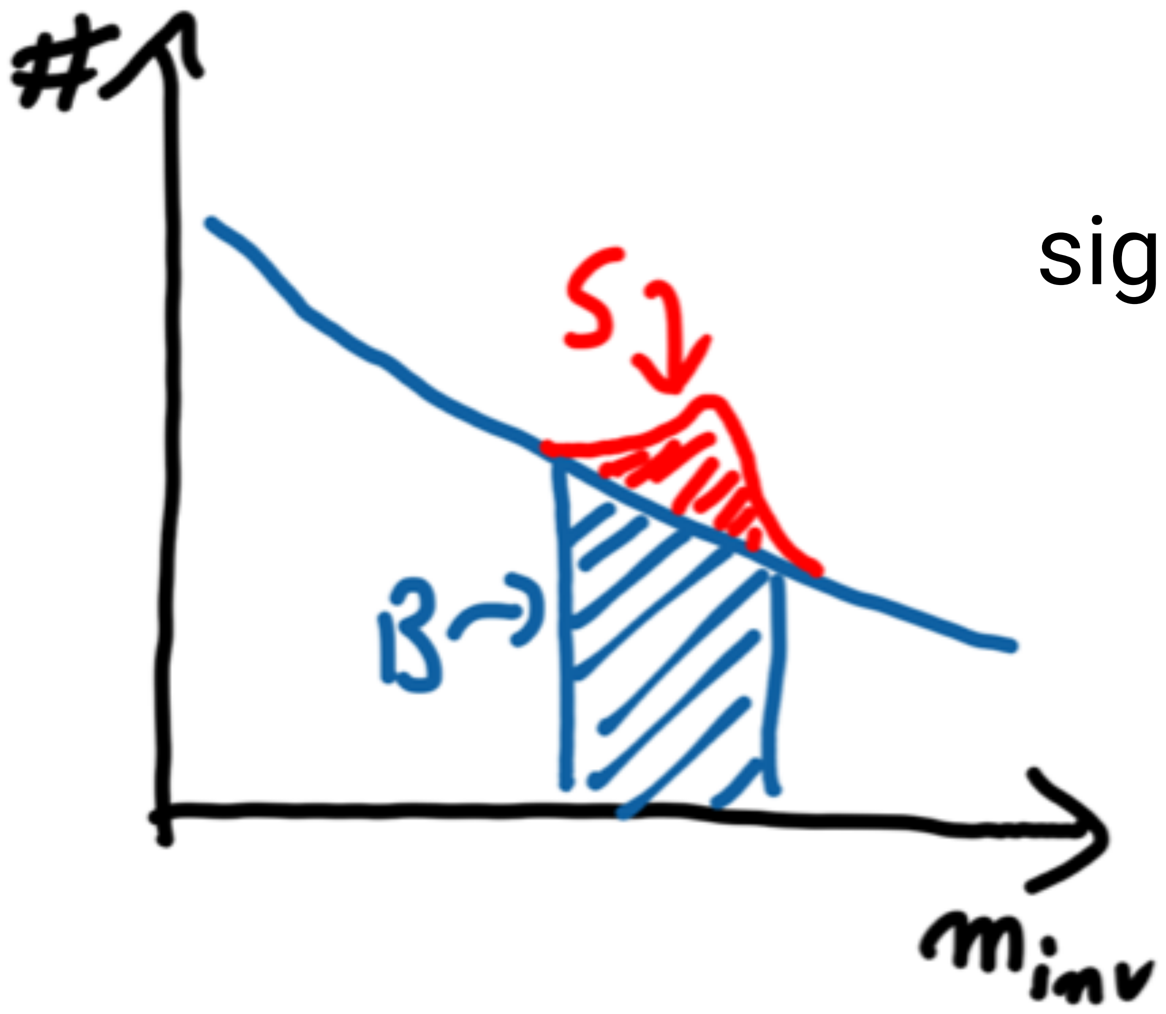
  ➩ At CLIC: small Δt_b also results in out-of-time pile-up: **ns-level timing** in many detector systems

Event Reconstruction at Future Colliders

The goals of PFA

- More practically:

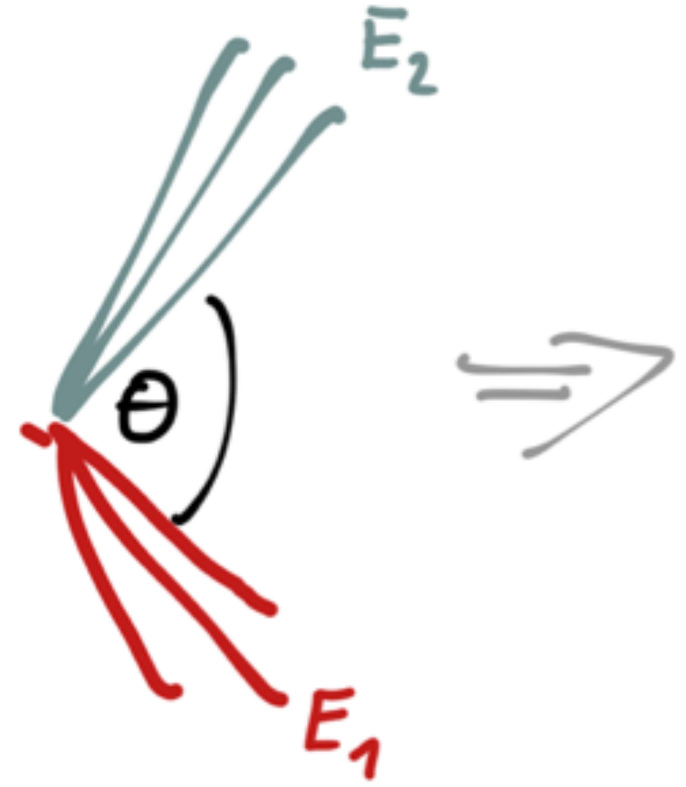


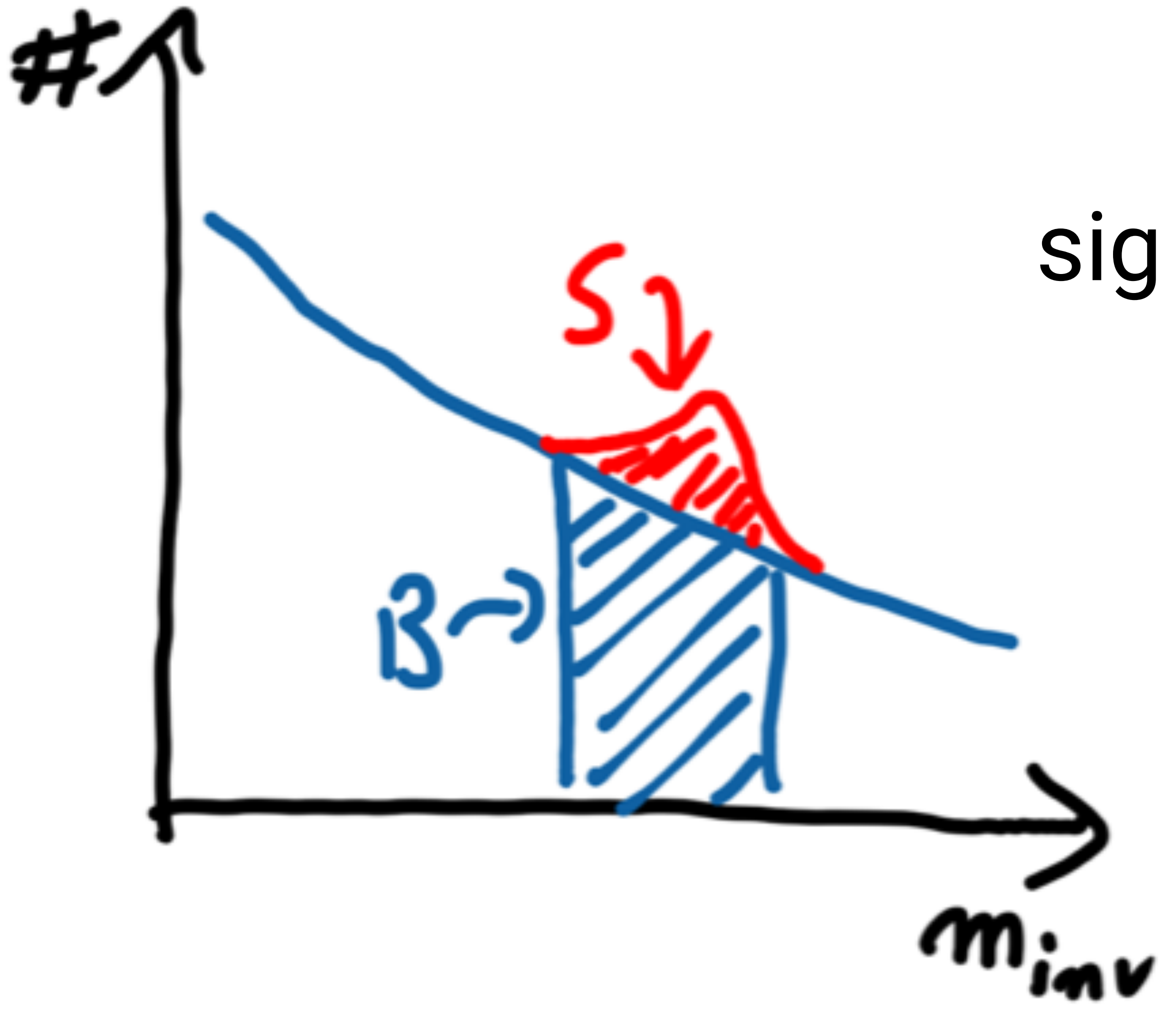


significance: $$\frac{S}{\sqrt{S+B}}$$

directly depends on mass resolution

- More practically:





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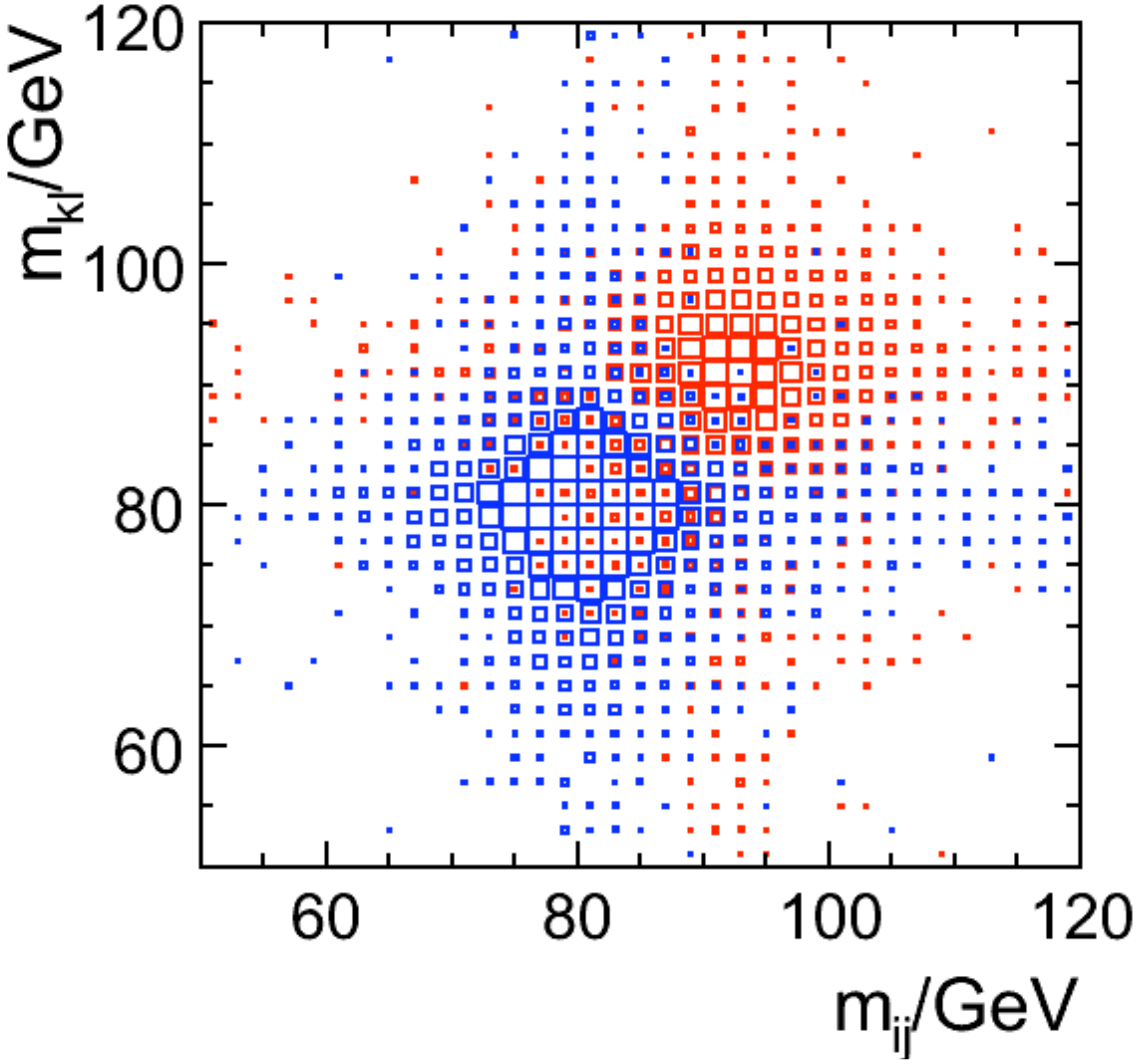

The typical "PR" example:

Separation of hadronic final states of heavy bosons: Requires jet energy resolution of ~ 3.5% over a wide energy range