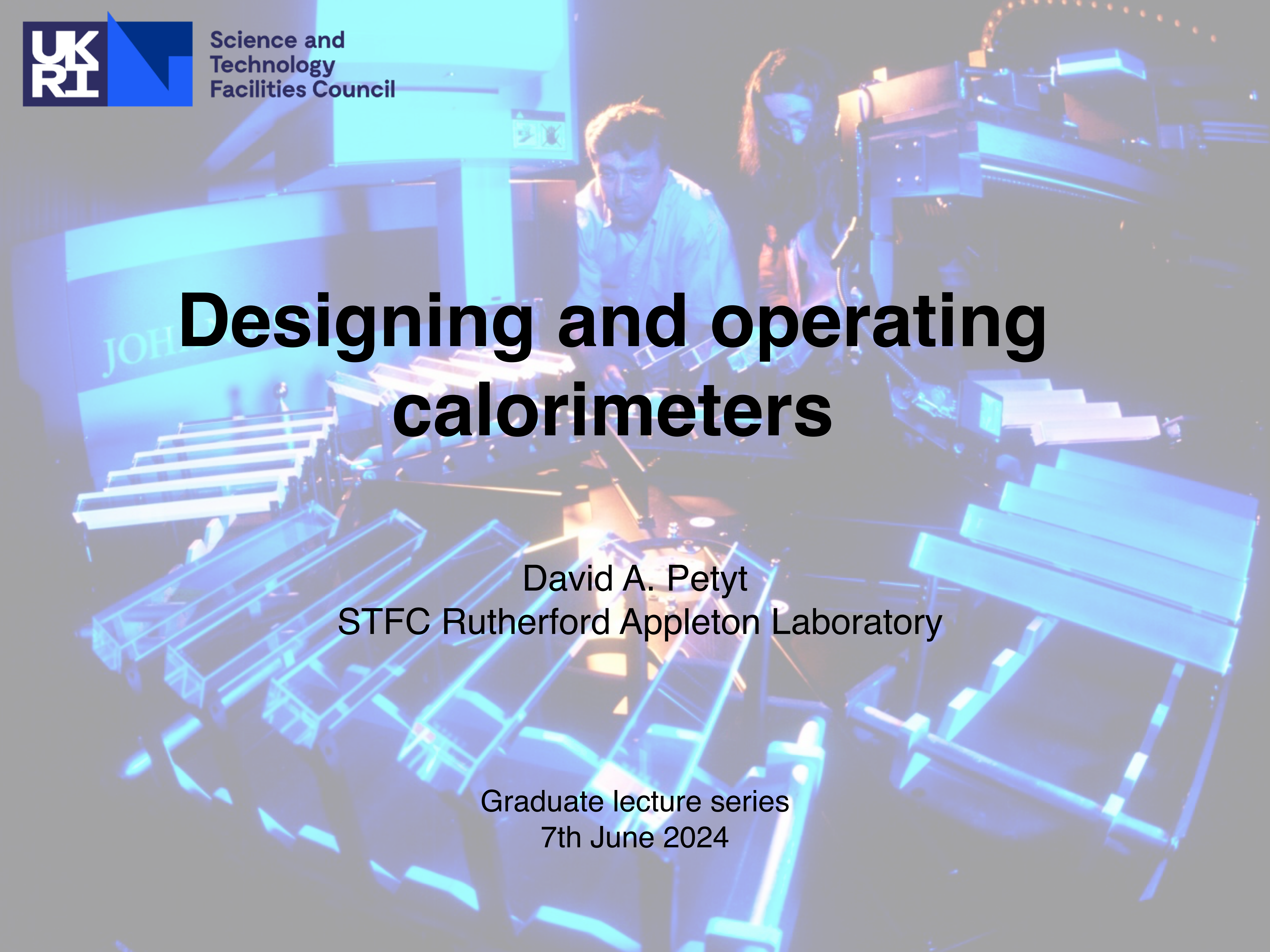

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Designing and operating calorimeters

David A. Petyt
STFC Rutherford Appleton Laboratory

Graduate lecture series
7th June 2024

Outline

- **What is a calorimeter?**
  - what types of calorimeter are there?
  - what physics measurements are calorimeters used for?
- **Calorimeter 101**
  - passage of particles through matter - reminder
  - calorimeter properties and design considerations
  - examples of electromagnetic and hadronic calorimeters
  - calorimeter energy resolution, calibration and performance
- **Operating calorimeters**
  - CMS ECAL example - operational aspects and challenges
- **Calorimeters in the future**
  - to meet the challenges of HL-LHC and beyond

What is a calorimeter?

calorimeter noun
ˌkæləˈrɪmɪtə(r)

An experimental apparatus for measuring the **total amount of heat** involved in a chemical reaction or other process

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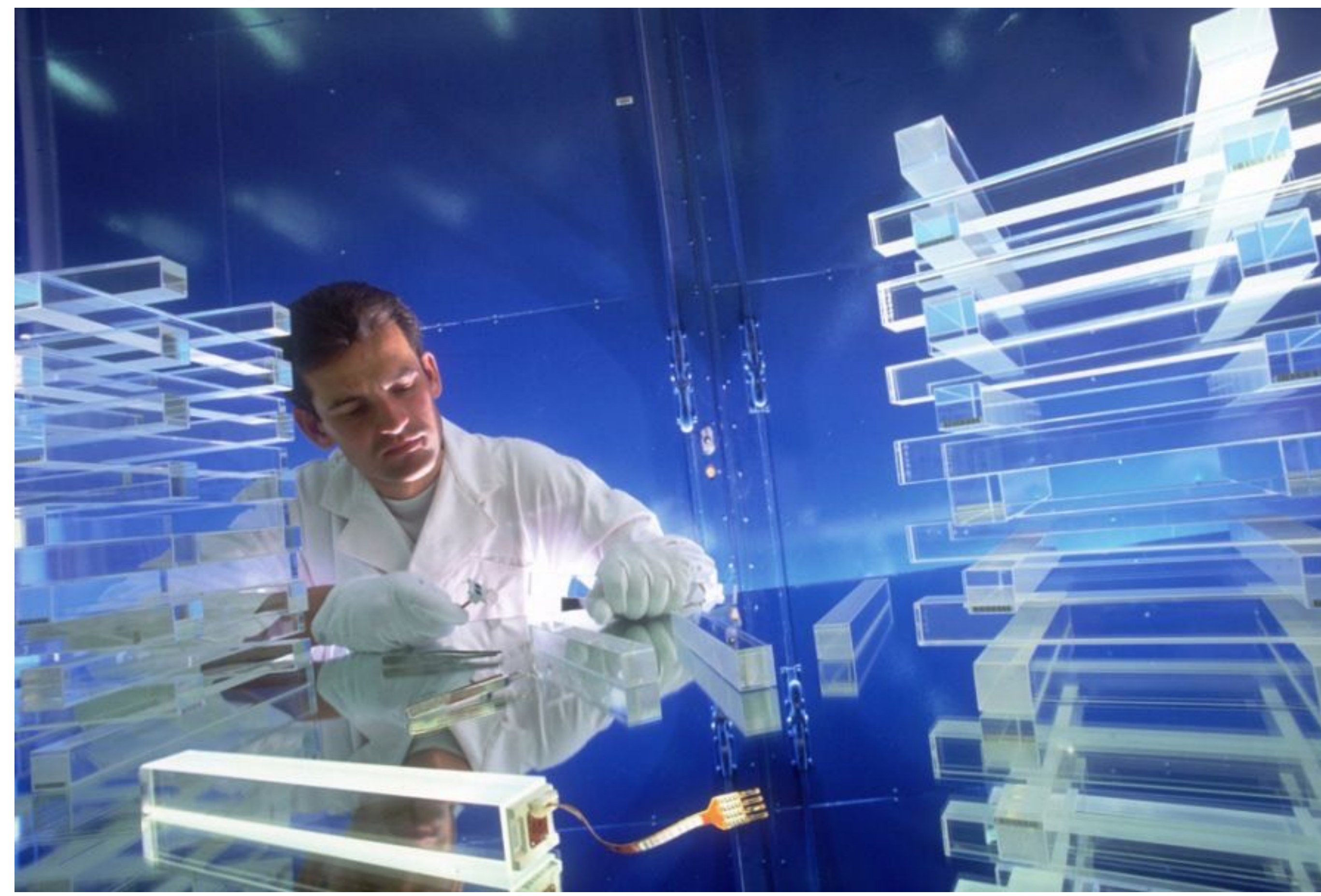
What is a particle physics calorimeter?

calorimeter noun
ˌkæləˈrɪmɪtə(r)

An experimental apparatus for measuring the **total energy of a particle** passing through the device



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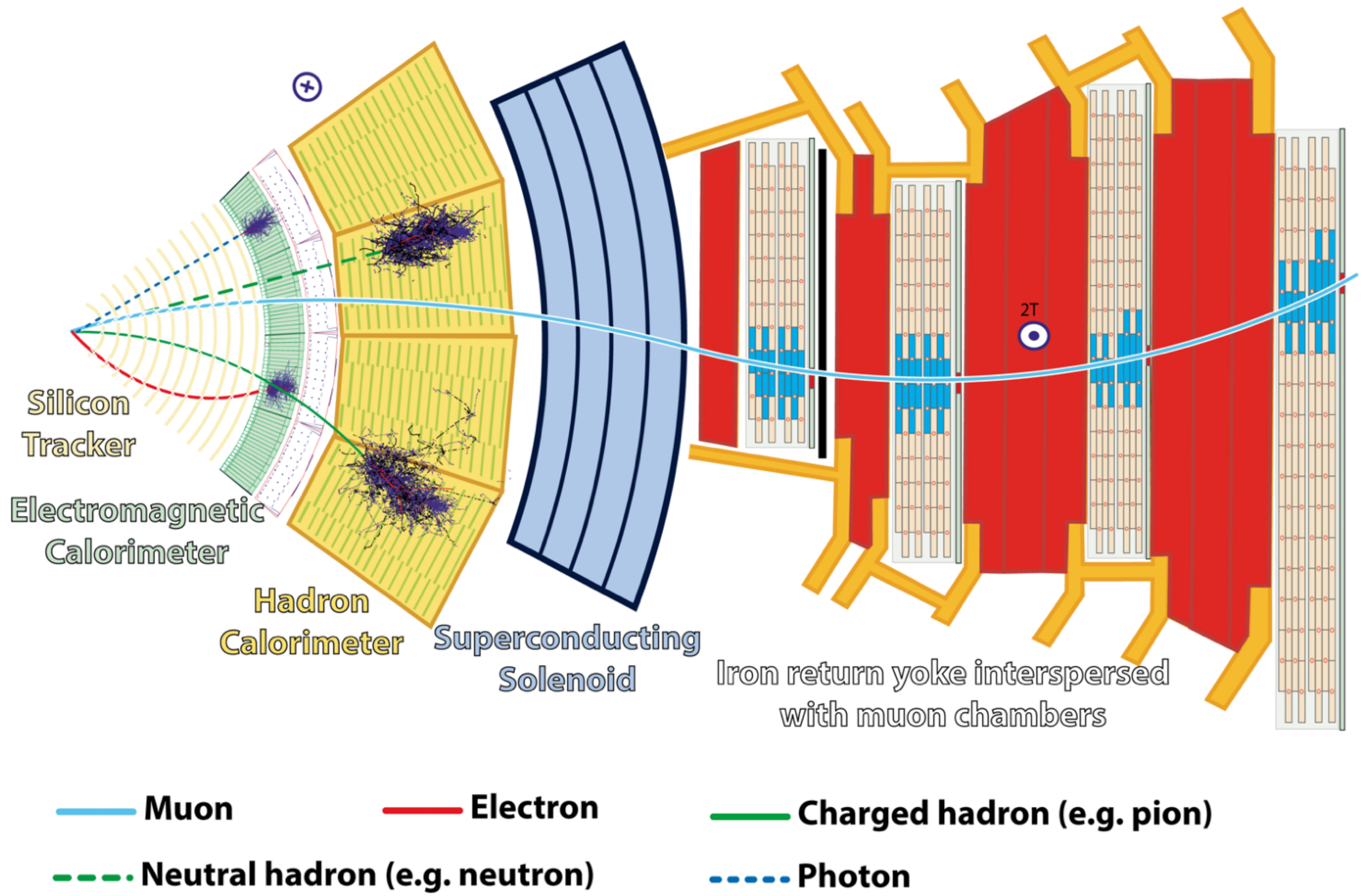
What is a particle physics calorimeter?

CMS example



<u>The objective of a particle physics calorimeter is to absorb the total energy of the particle that passes through it</u>

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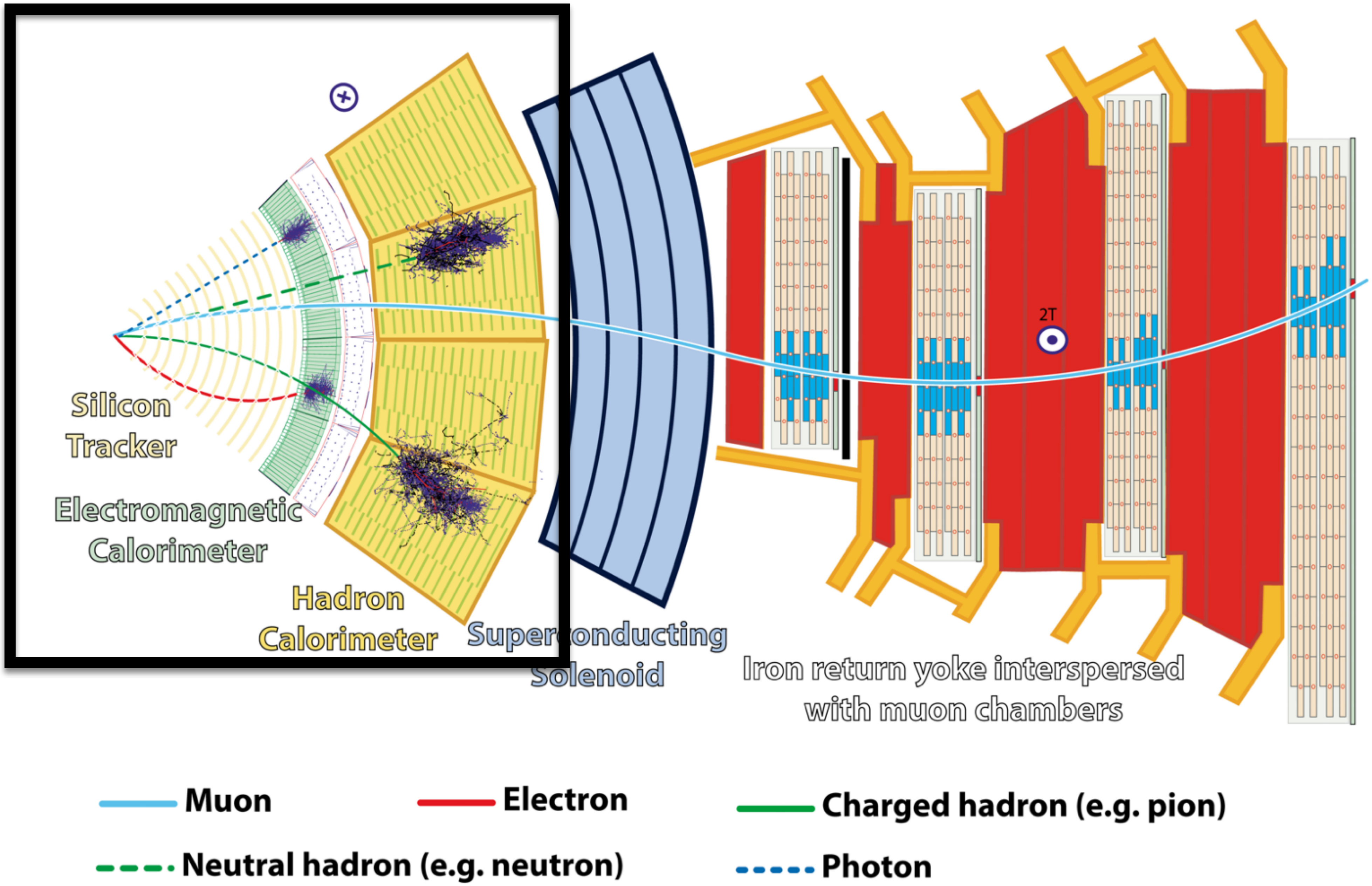
What is a particle physics calorimeter?

CMS example



<u>The objective of a particle physics calorimeter is to absorb the total energy of the particle that passes through it</u>

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What is a particle physics calorimeter?

Typically divided into dedicated electromagnetic and hadronic calorimeters

Electromagnetic calorimeter

electrons/positrons and photons

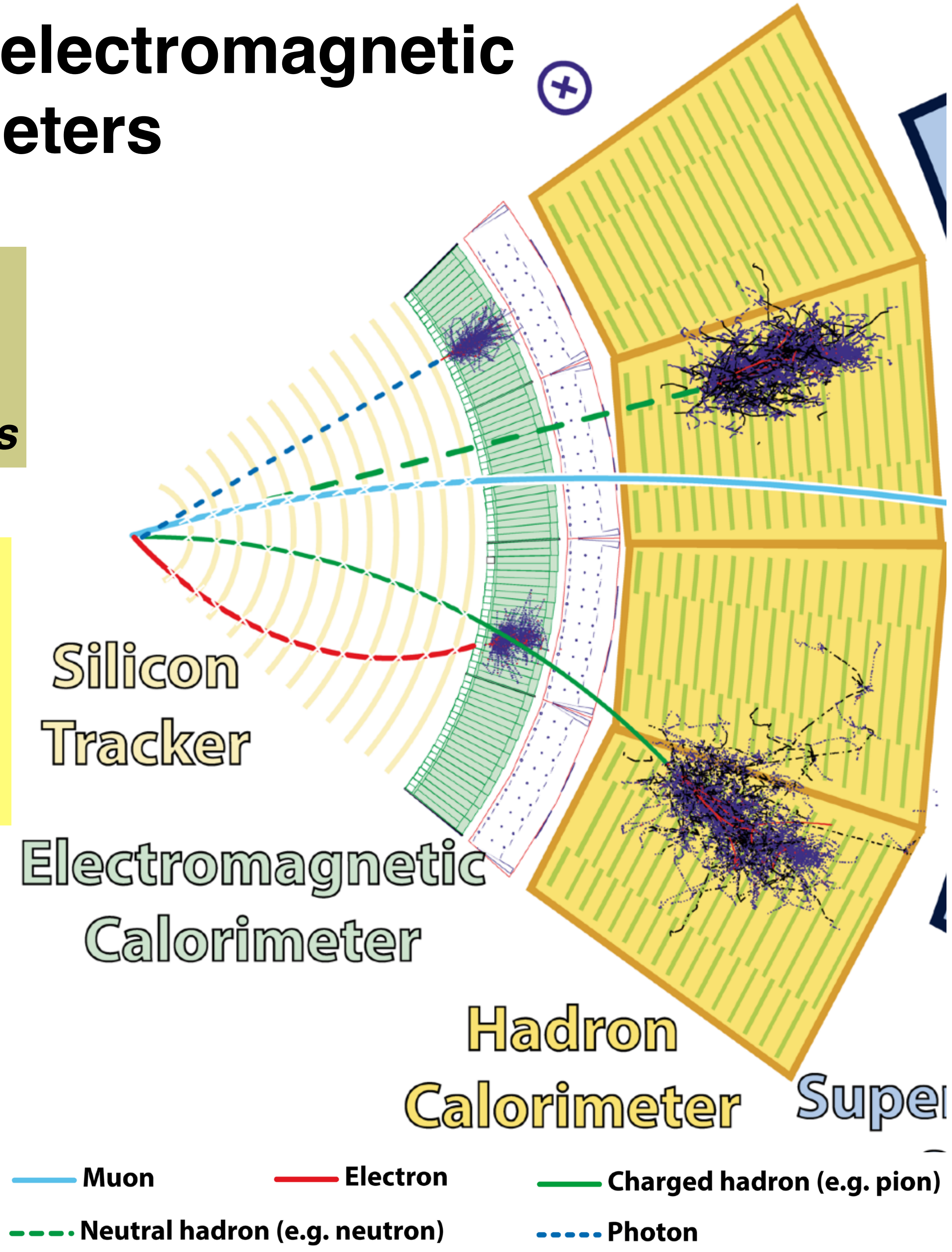
electrons and positrons can be matched to tracks

Hadron calorimeter

charged hadrons: $\pi^{\pm}$, $K^{\pm}$, p

neutral hadrons: neutron, K^0_L

charged hadrons can also be matched to tracks



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What is a particle physics calorimeter?

Typically divided into dedicated electromagnetic and hadronic calorimeters

Particle energy

particle energy E absorbed in calorimeter

is converted to electrical signal S

E is proportional to S

Particle type

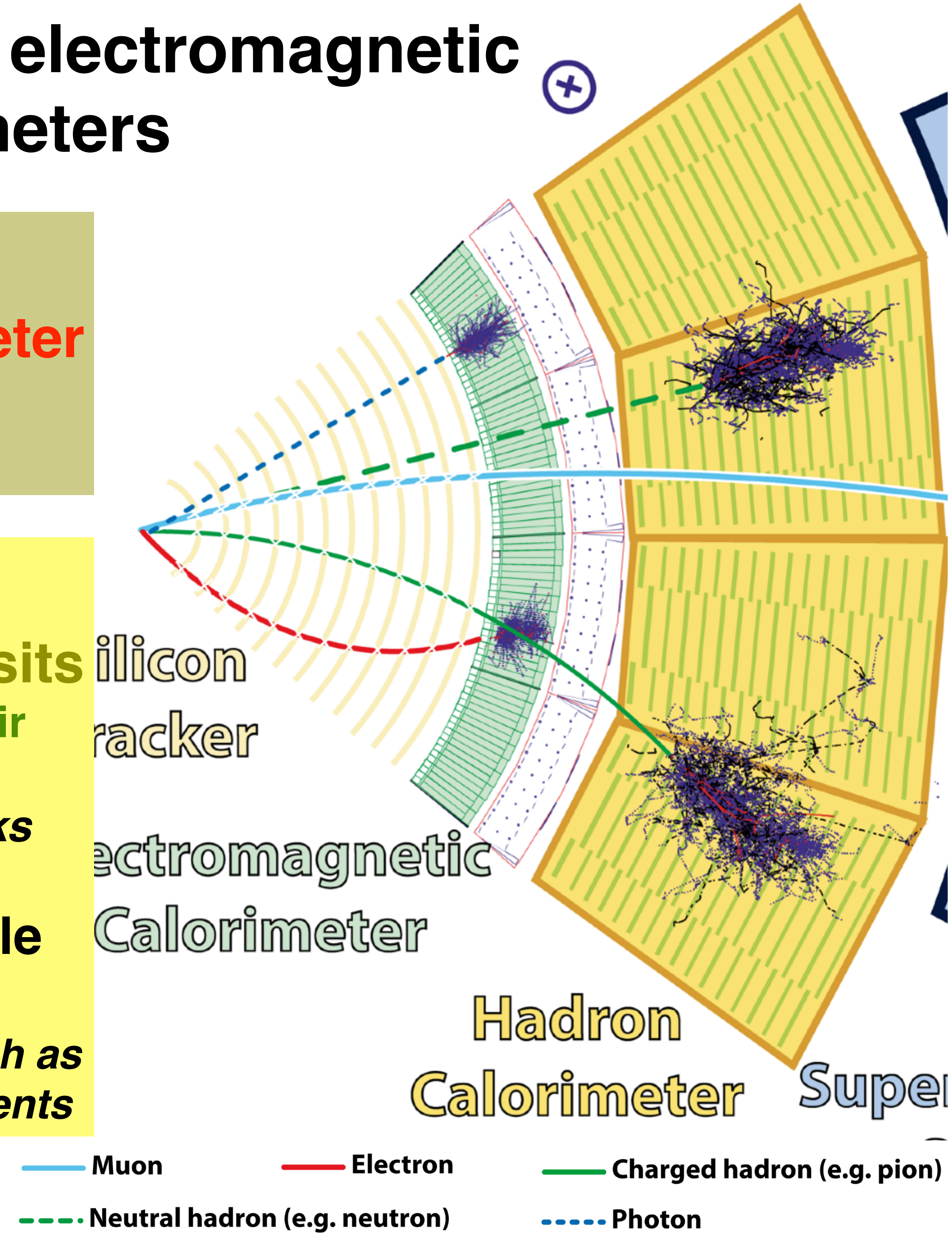
determined by pattern of energy deposits

EM and hadronic particles deposit most of their energies in their respective calorimeters

charged particles can also be matched to tracks

These criteria are heavily used in Particle Flow reconstruction techniques

including reconstruction of compound objects, such as jets, which contain both EM and hadronic components



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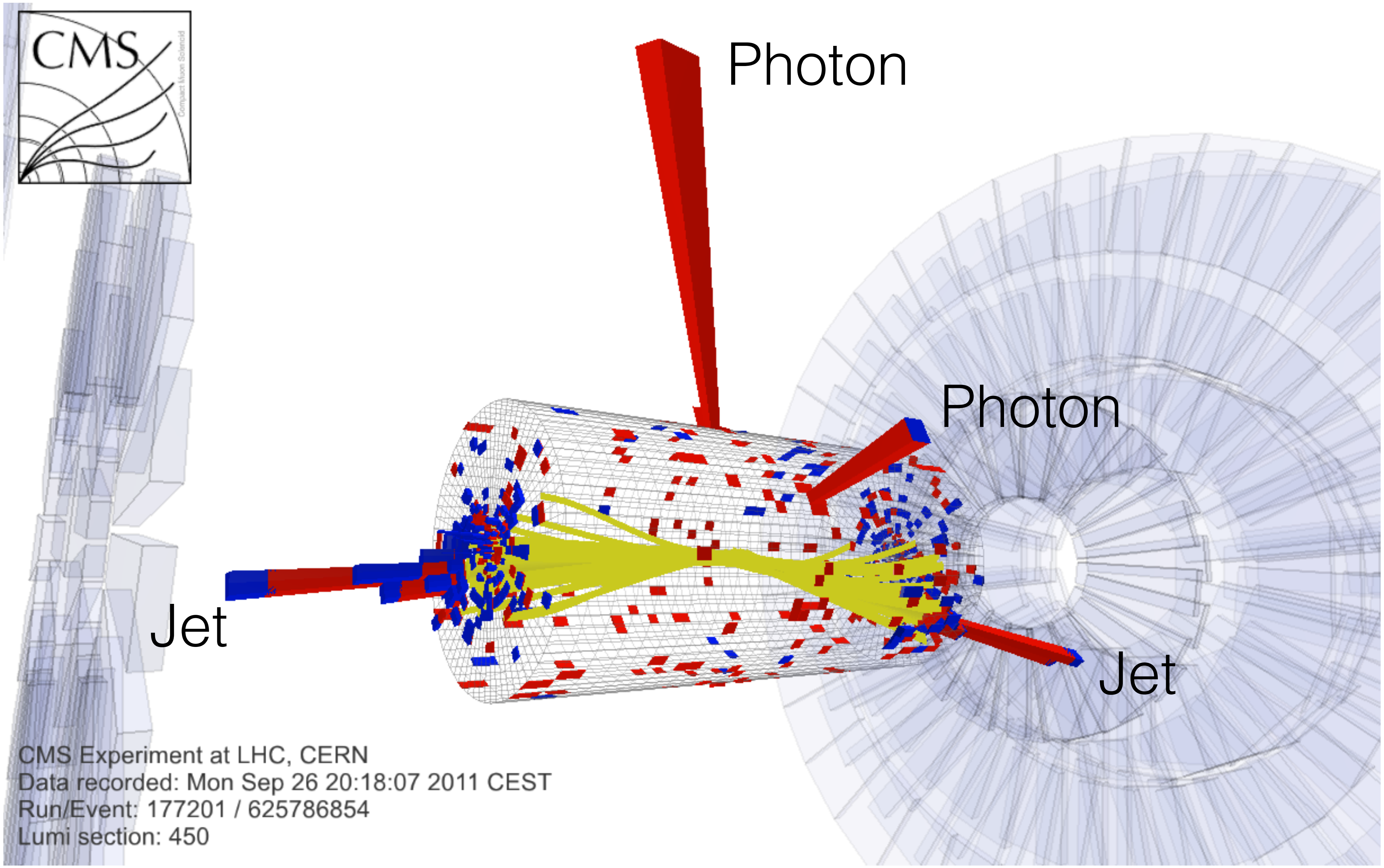
Calorimeter event displays

Candidate Higgs particle decaying to two photons, with two forward jets in CMS



ECAL energy in **RED**
HCAL energy in **BLUE**

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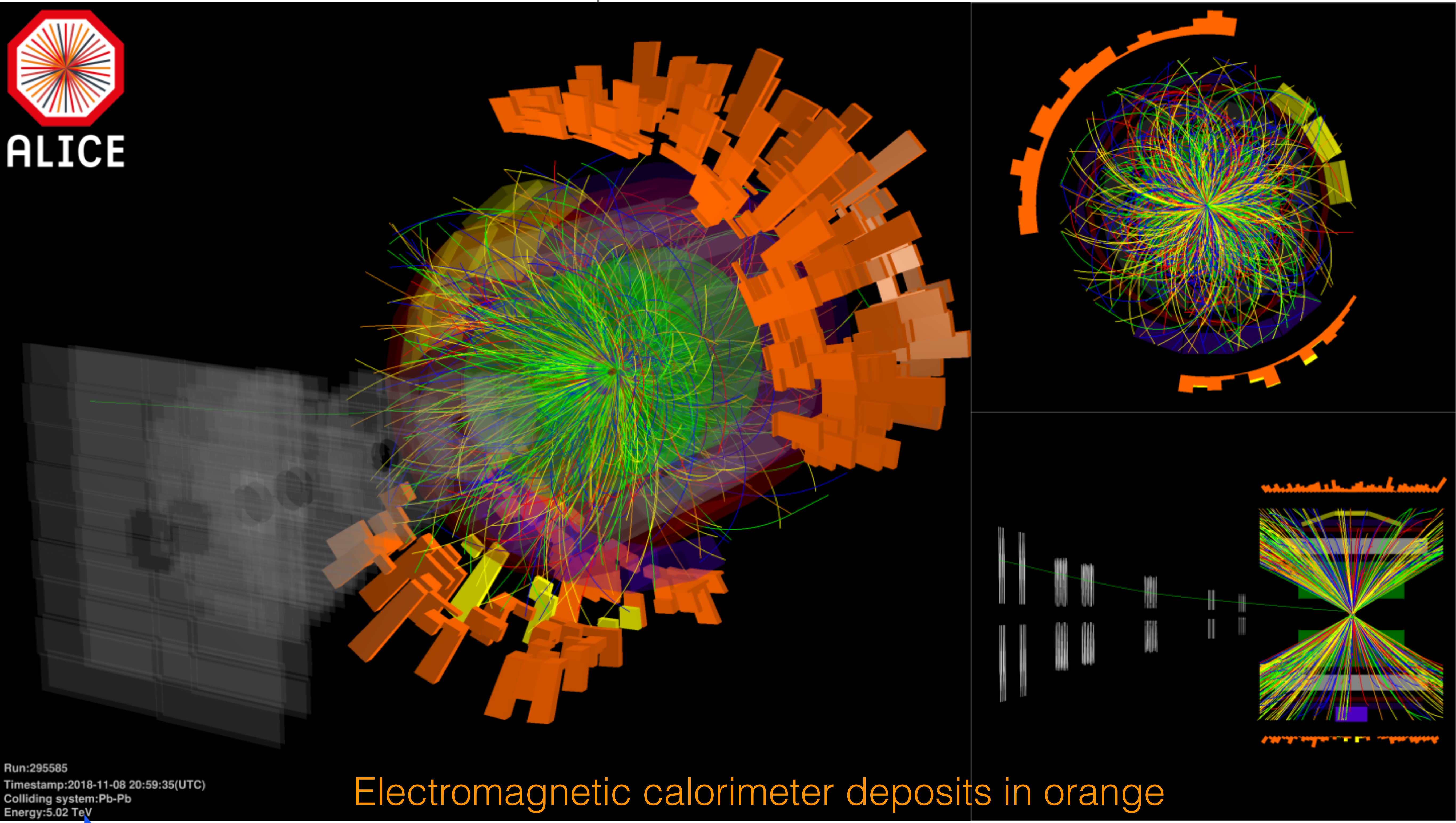
Calorimeter event displays

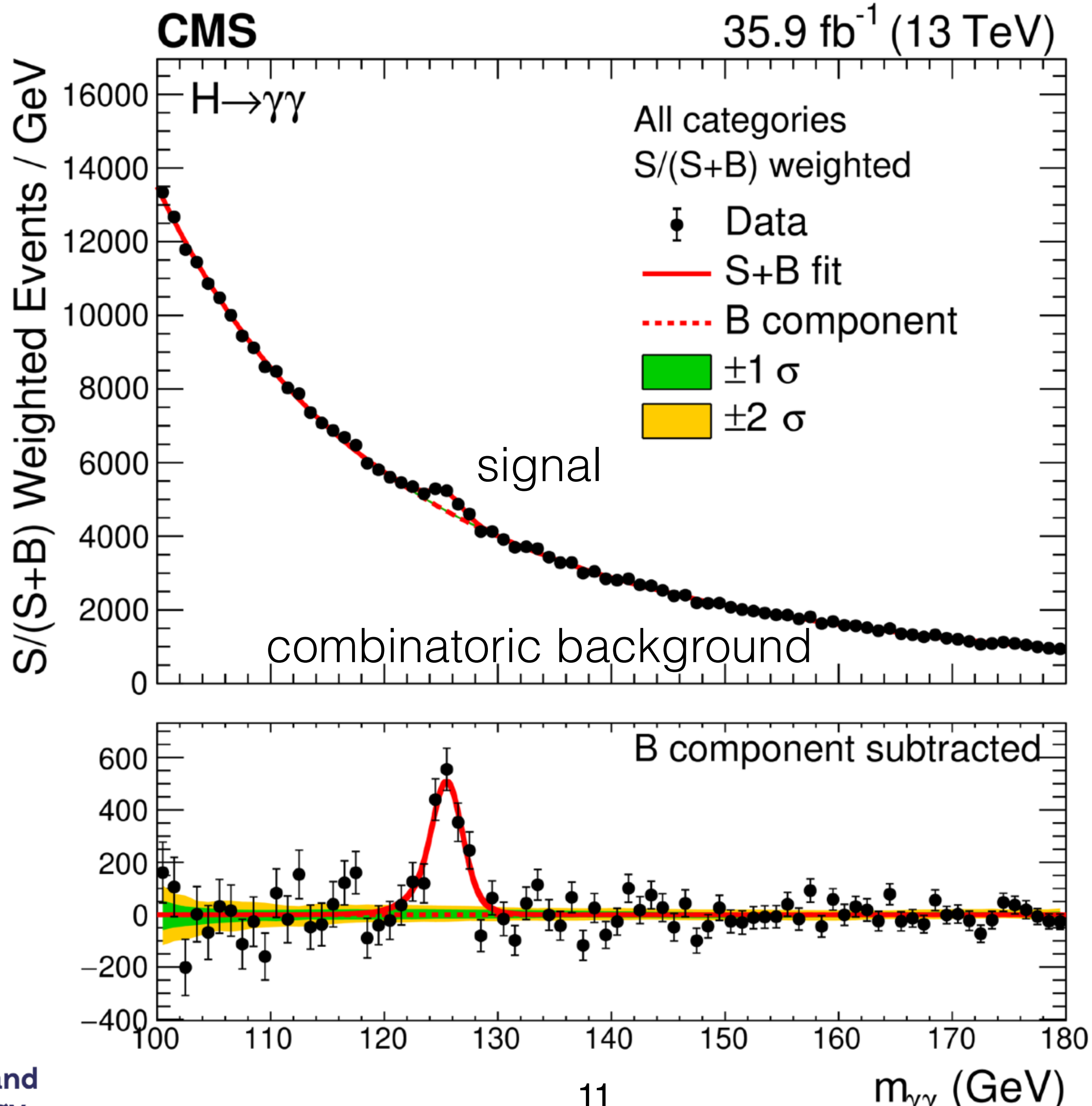
Pb on Pb particle collision in ALICE



Electromagnetic calorimeter deposits in orange

Physics with calorimeters

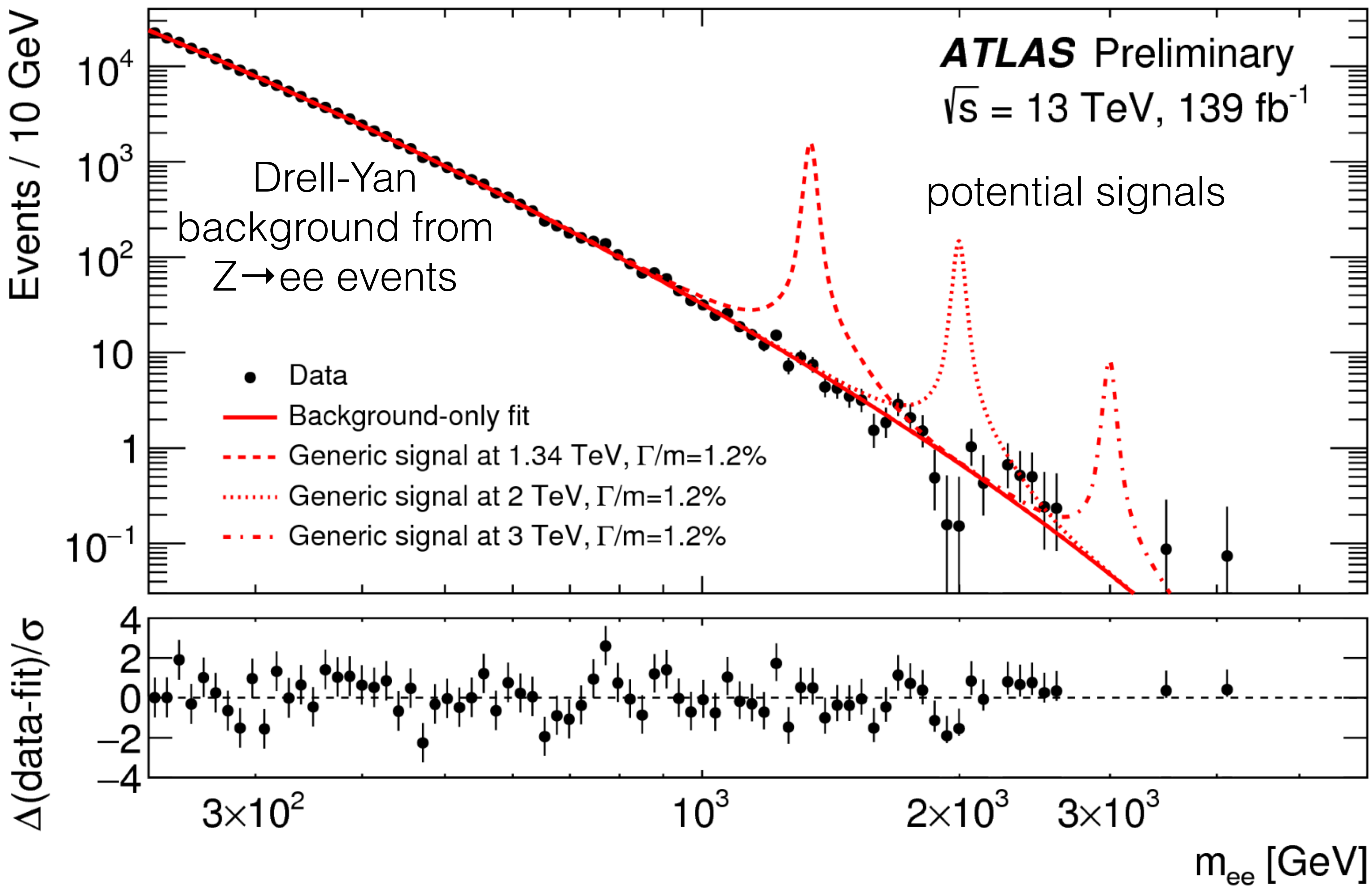
Observation of Higgs decaying to two photons in CMS



Excellent energy resolution required

Physics with calorimeters

Search for beyond the standard model Z' decaying to 2 electrons in ATLAS



Excellent energy response/ linearity up to several TeV required

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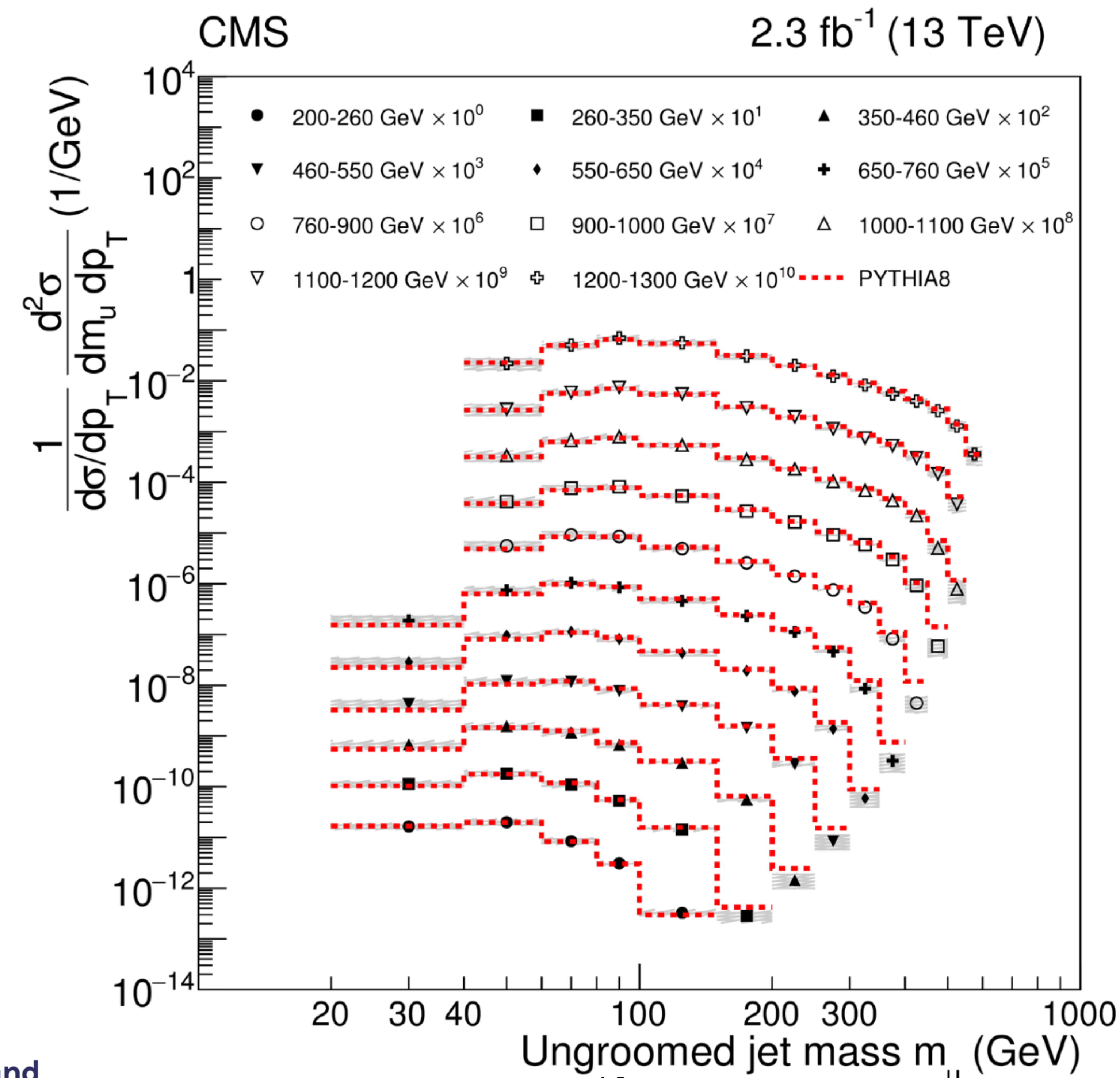
Physics with calorimeters

Jet cross section measurements in CMS and comparison with theory



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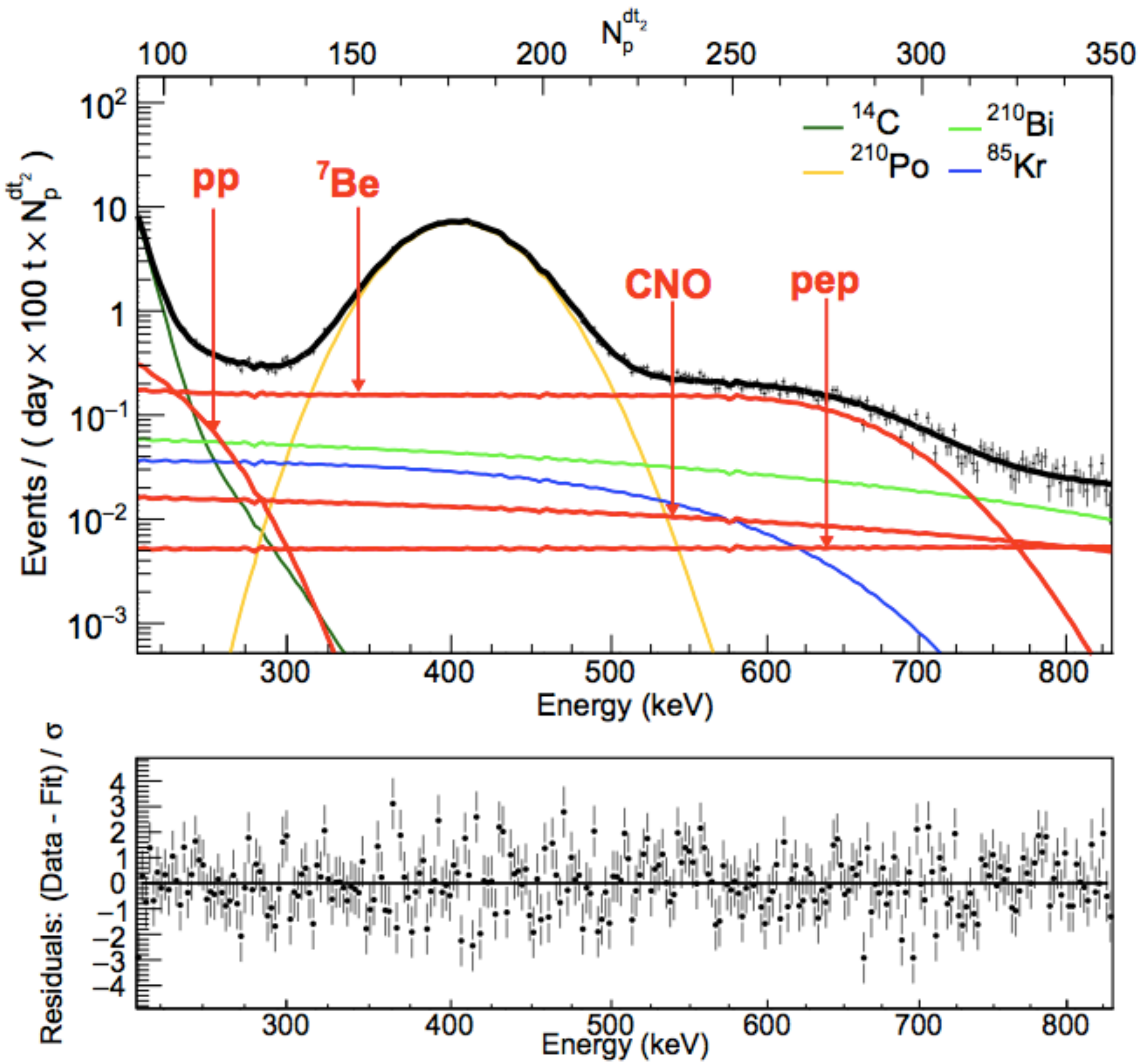
Physics with calorimeters

Measurement of components of solar neutrino flux in Borexino



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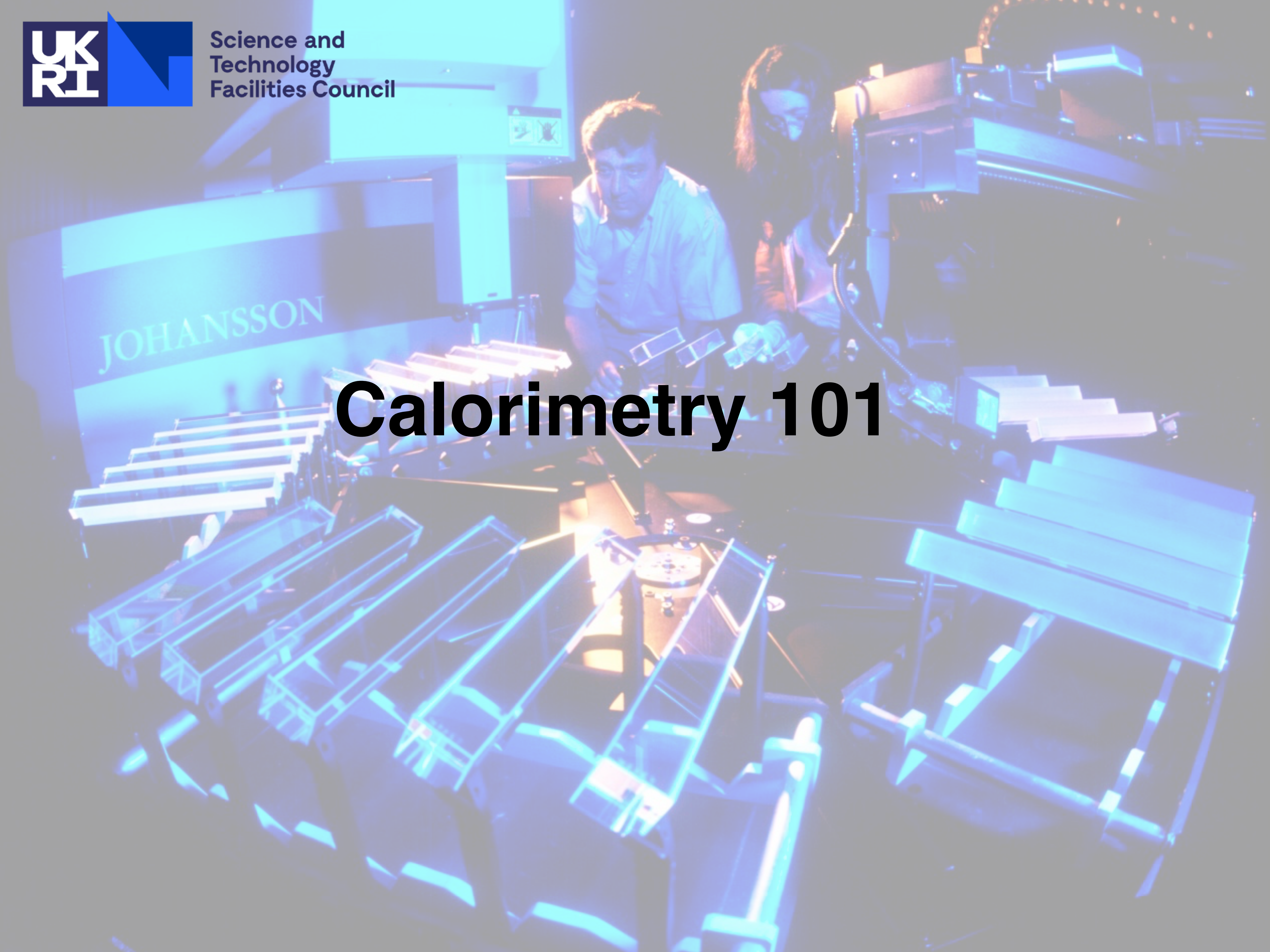
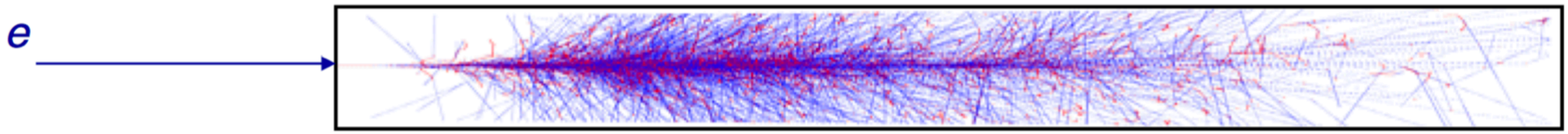
Calorimetry 101



Passage of particles through matter

Electromagnetic shower

$PbW0_4$ CMS, X_0=0.89 cm



Energy loss mechanisms:

Above critical energy E_c

electron bremsstrahlung

$e^{\pm} \rightarrow \gamma$

photon pair production

$\gamma \rightarrow e^{+} + e^{-}$

Below critical energy E_c

ionization

photoelectric effect

Compton scattering

$$E_c = \frac{610\ \text{MeV}}{Z + 1.24}$$

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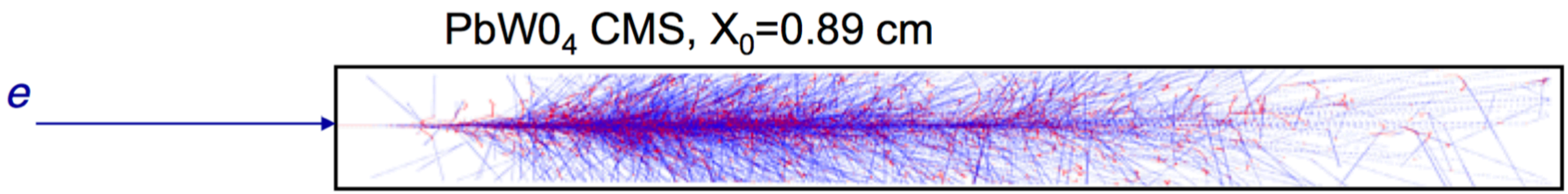
Passage of particles through matter

Electromagnetic shower



Energy loss mechanisms:

<u>Above critical energy E_c</u>

electron bremsstrahlung

$e^{\pm} \rightarrow \gamma$

photon pair production

$\gamma \rightarrow e^{+} + e^{-}$

Both processes controlled by <u>radiation length</u> **X_0** of the detector medium

X_0: thickness of material that reduces mean energy of electron by a factor e

$$E = E_0 e^{-x/X_0}$$

$$X_0 \propto \frac{1}{Z^2}$$

→ compact calorimeters require dense detector media

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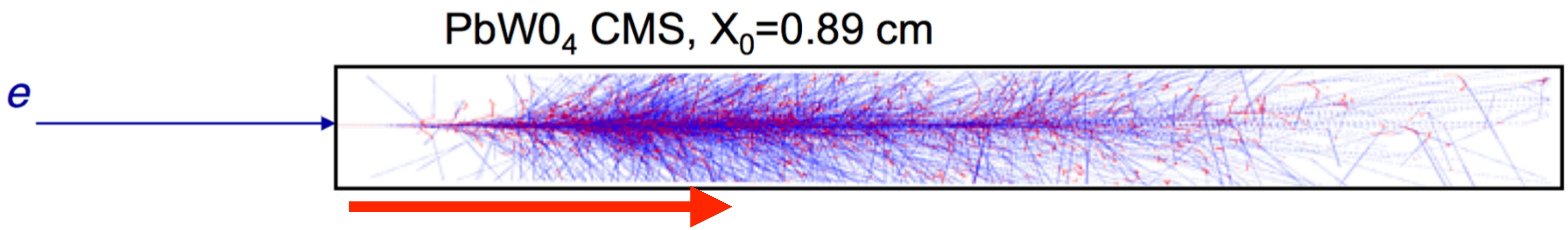
Passage of particles through matter

Electromagnetic shower



Above critical energy E_c

electrons lose energy via bremsstrahlung
with characteristic path length X_0

photons convert to lower energy electrons via pair production
with characteristic path length $9/7*X_0$

shower multiplication and development

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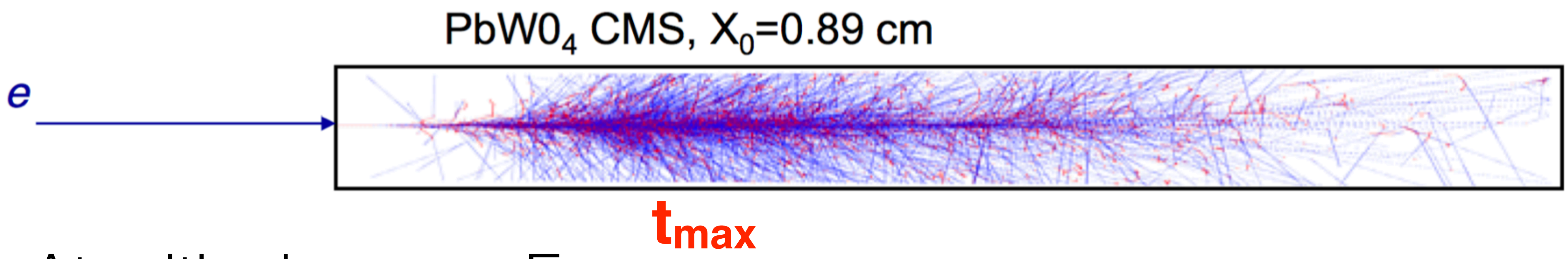
Passage of particles through matter

Electromagnetic shower



At critical energy E_c

average particle energy ~ E_C

ionisation losses are equal to bremstrahlung and pair production

peak particle multiplicity reached

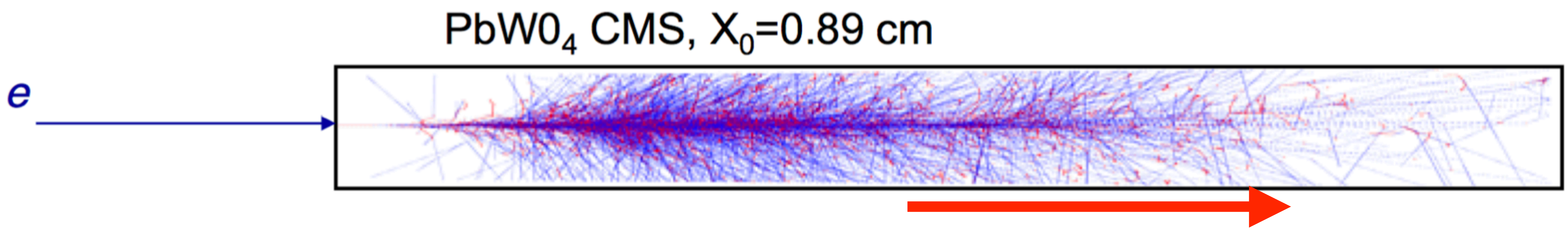
position of shower maximum: t_{max}

t_{max} depends logarithmically on incident particle energy

approximately 5 X_0 for a 10 GeV electron in $PbWO_4$ crystal

Passage of particles through matter

Electromagnetic shower



Below critical energy E_c

ionisation losses are larger than bremstrahlung and pair production

slow decrease in number of particles in the shower
electrons and positrons range out

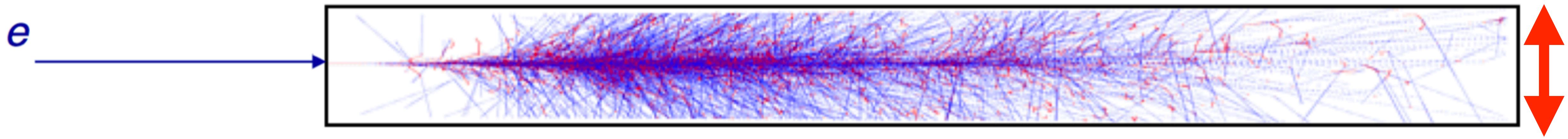
Shower containment depends on energy

100 GeV electron in $PbWO_4$ crystal contained within around 20*X_0

Passage of particles through matter

Electromagnetic shower

PbW0$_4$ CMS, X_0=0.89 cm



Lateral shower development

defined by Moliere radius R_M

95% of shower is contained in a cylinder of radius 2*R_M

mainly caused by electron multiple coulomb scattering within detector medium

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

CMS example ($PbWO_4$ crystals)

longitudinal dimensions of 23cm (25*X_0)
lateral dimensions of 2.2cm (1*R_M)

minimises leakage from back of crystal

maximises transverse granularity

lateral leakage minimised by summing energy over 3x3 matrix of crystals

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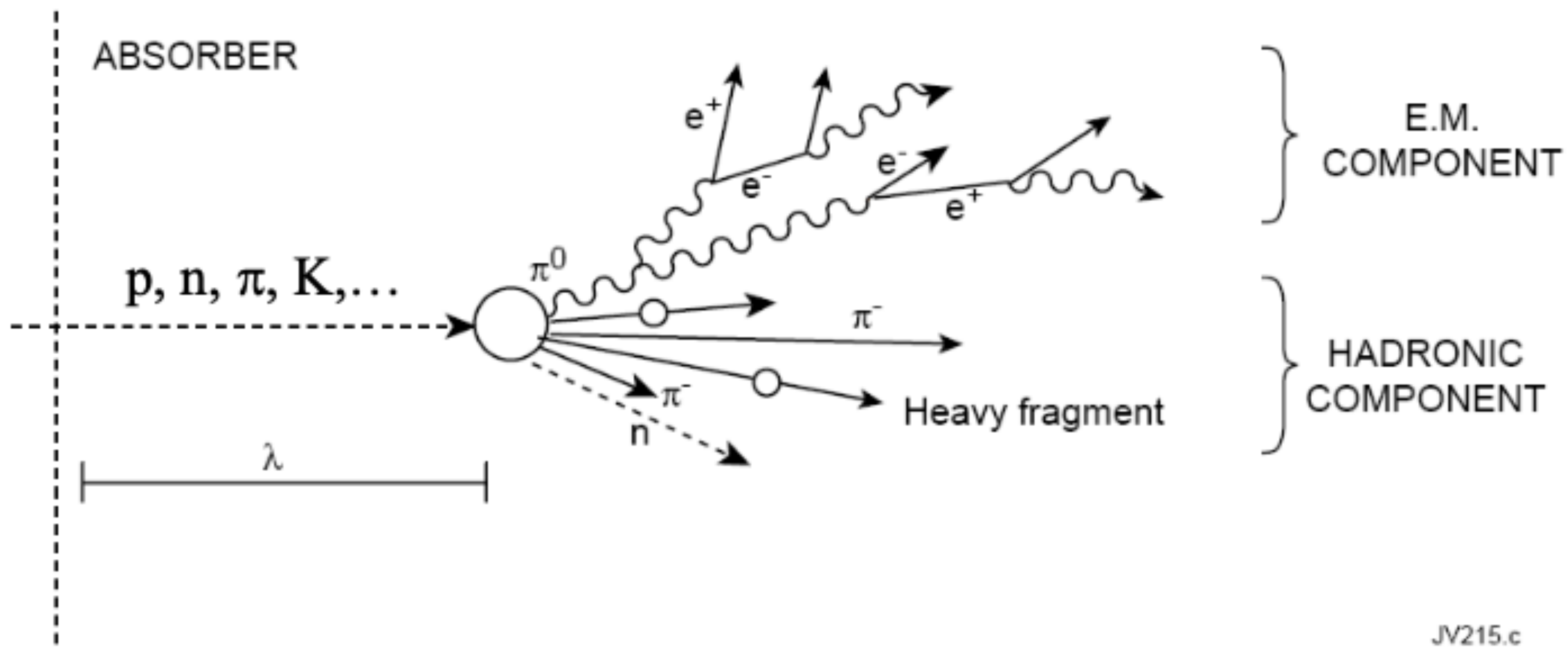
Passage of particles through matter

Hadron shower



Shower development determined by by <u>interaction length</u> $\boldsymbol{\lambda_I}$ of the detector medium

λ_I - mean free path between inelastic collisions: 16.7 cm in Lead

multparticle production

$\pi^{\pm}, \pi^0, K$

nuclear breakup

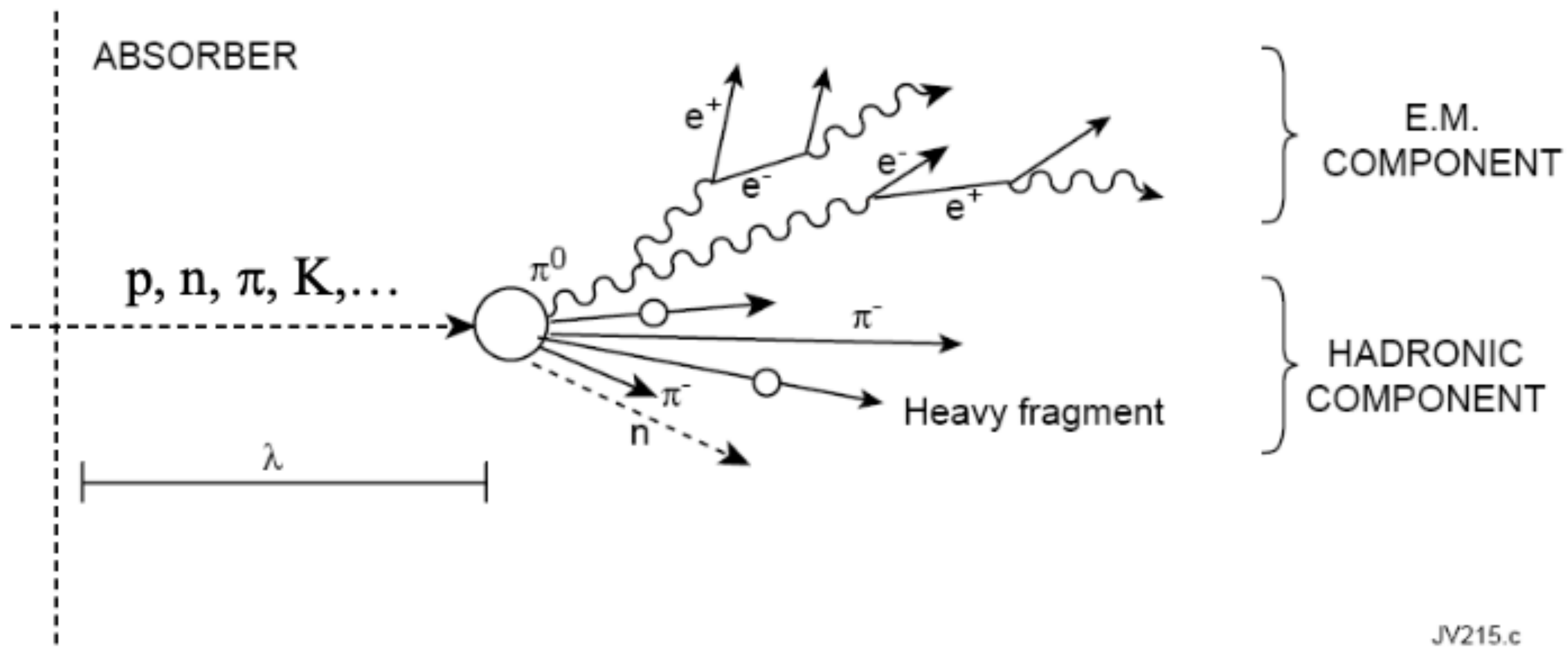
spallation neutrons, protons

electromagnetic component

$\pi^0 \rightarrow \gamma\gamma$

Passage of particles through matter

Hadron shower



Longitudinal containment: 95% of hadronic shower from 100 GeV pion contained in ~ 10$\boldsymbol{\lambda}_{\mathbf{I}}$ (1.7m of lead)

peak in shower profile at ~1 $\boldsymbol{\lambda}_{\mathbf{I}}$ with exponential fall-off

EM component more pronounced at start of shower

Lateral containment: 95% containment of hadronic shower from 100 GeV pion contained in ~ 1$\boldsymbol{\lambda}_{\mathbf{I}}$ (17cm of lead)

Hadron showers are larger and broader than EM showers
→ reflected in larger dimensions of hadron calorimeters

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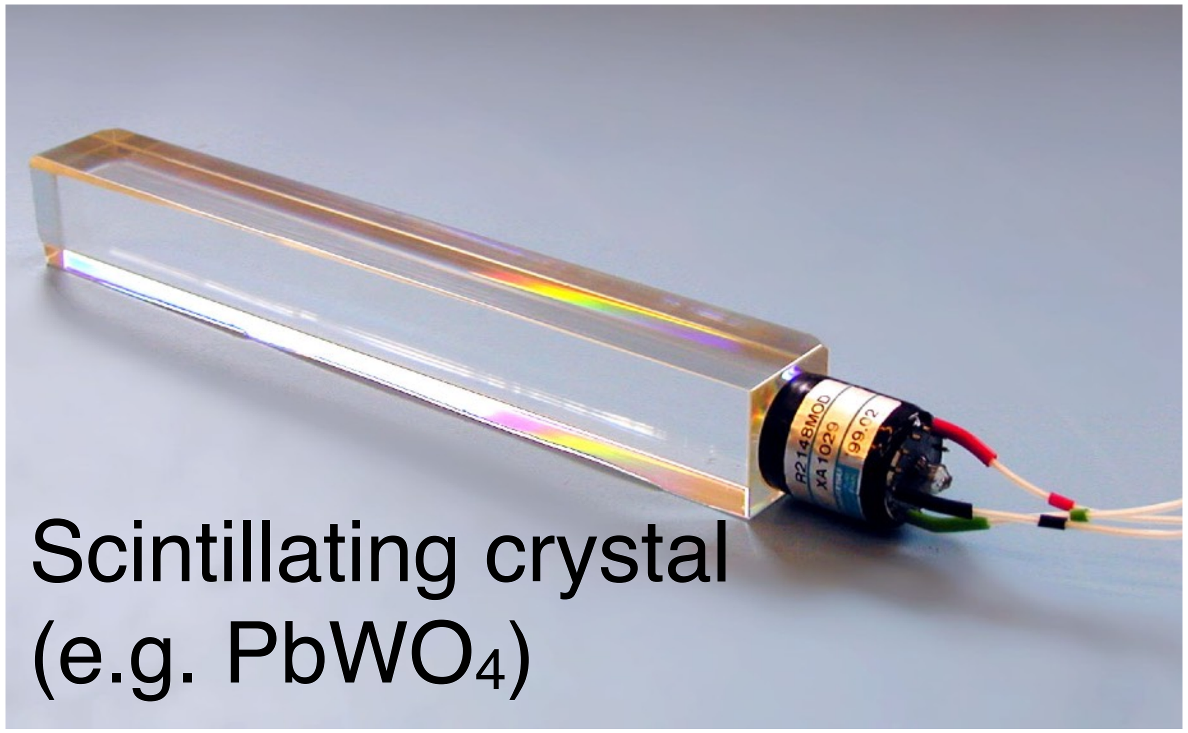
Homogenous vs sampling calorimeters

Homogenous



Single medium for absorber and detector

Liquefied noble gases (Kr,Xe,Ar)
Organic liquid scintillators
Dense organic crystals

Most often used for EM calorimetry
(premium on high resolution)
records full EM shower
(smaller stochastic term)

Sampling

Layers of passive absorber and detector material

Lead, Tungsten, Copper absorbers
Scintillator/Si/Ar active medium

Used for EM and hadron calorimetry
(usually more cost effective)
samples EM and hadron shower
(transverse and longitudinal segmentation)

Calorimeter energy resolution

- **EM energy resolution:**

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: Stochastic term:
photostatistics,
photodetector gain
sampling fraction
lateral shower containment

b: Noise term:
electronic noise
event pile-up

c: Constant term:
temperature/HV stability
accuracy of inter-calibration constants
non-uniformity of longitudinal light collection

dominates at high energy

statistical term: fluctuations in number of detected particles

$$\frac{\sigma_E}{E} \propto \frac{\sqrt{N}}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E}}$$

sampling fluctuations: event to event fluctuations in fraction of energy deposited in active detector medium

Homogenous vs sampling calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous

Sampling

Homogenous calorimeters have smaller stochastic term

Similar constant terms

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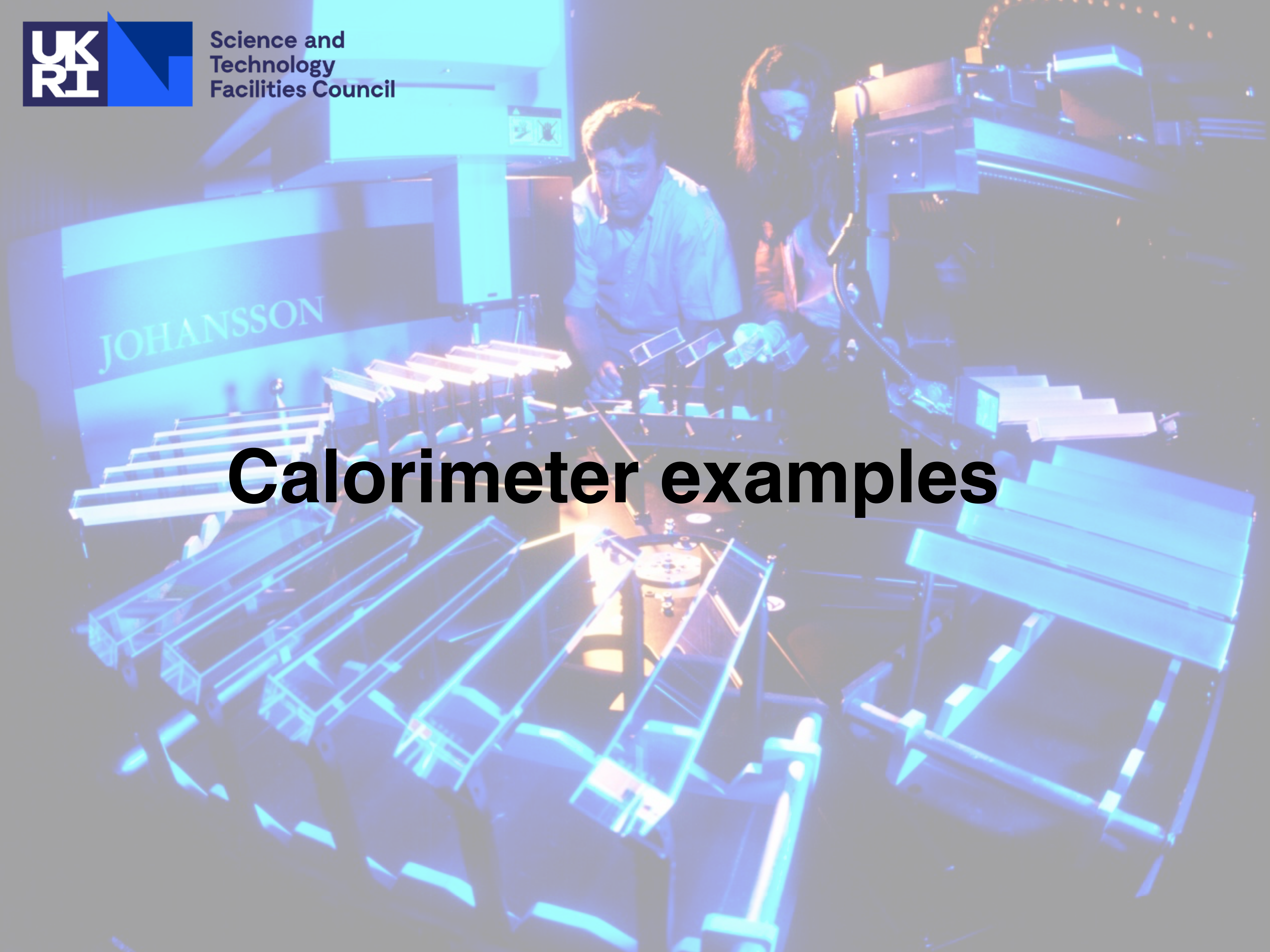
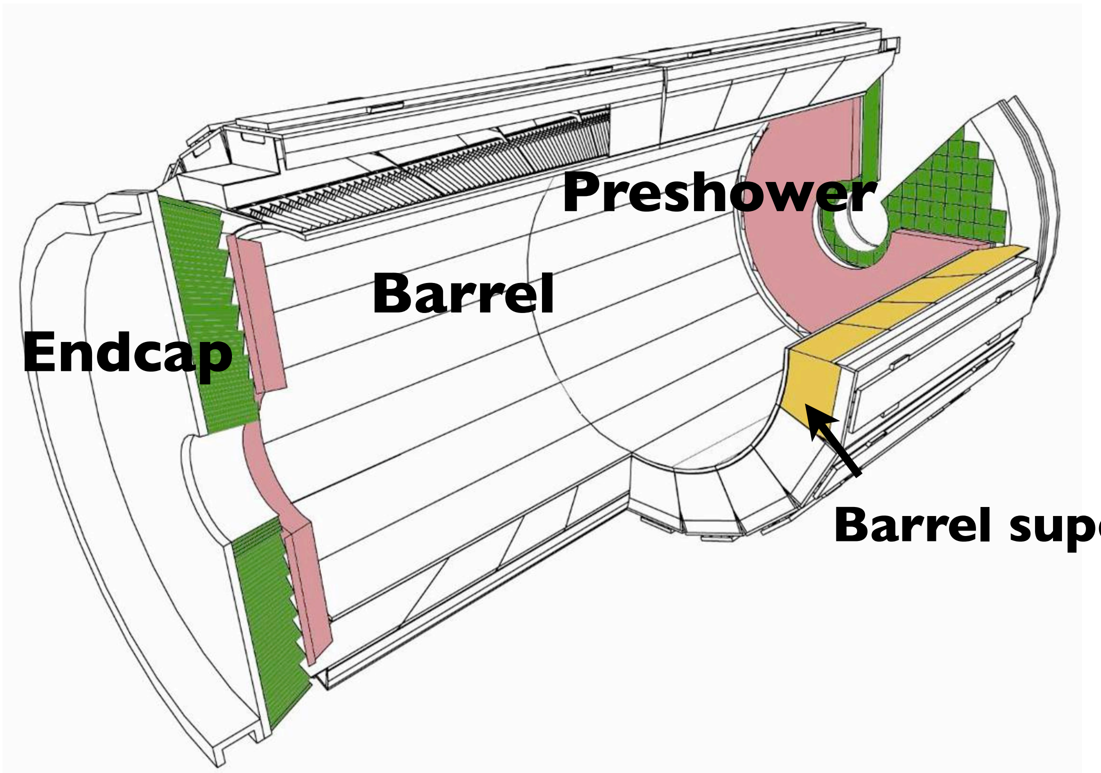
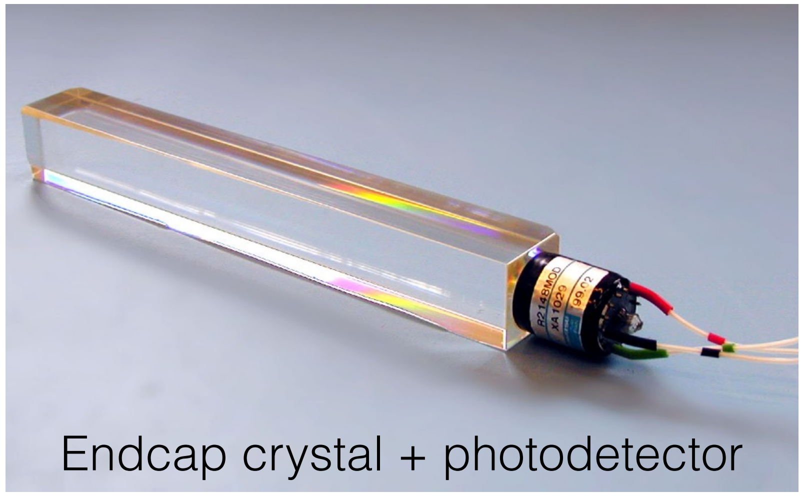


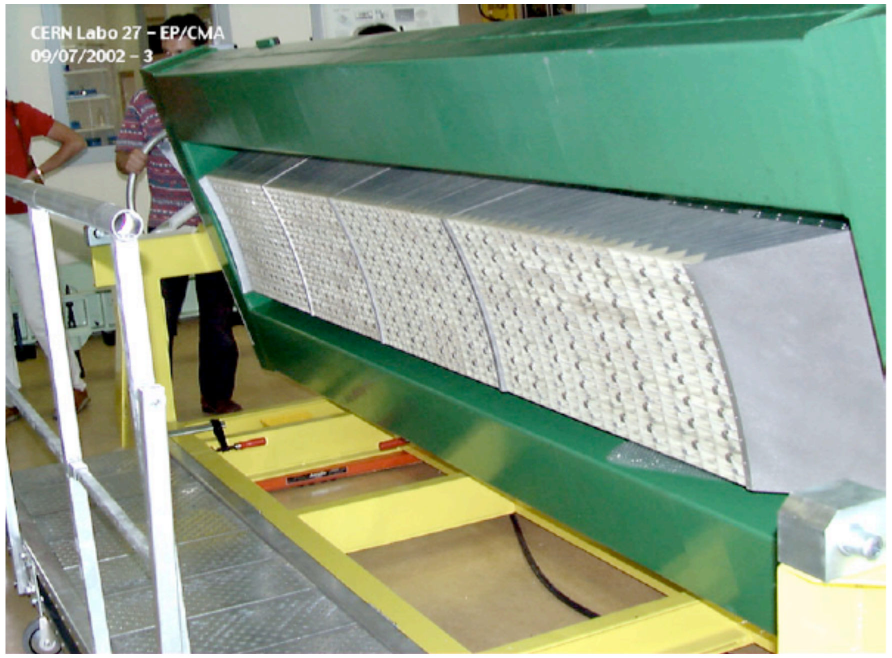
Calorimeter examples

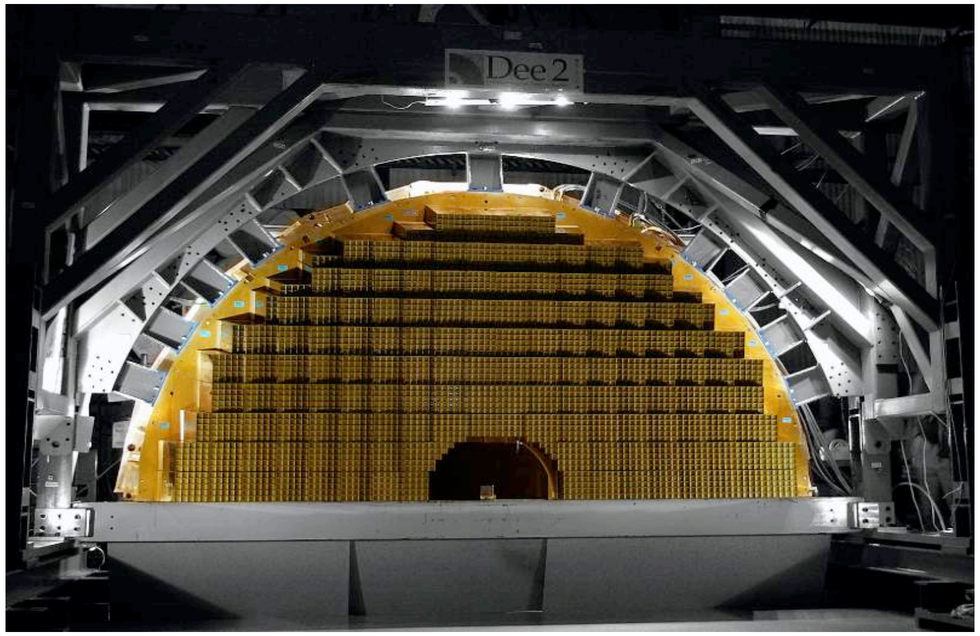
The CMS Electromagnetic calorimeter

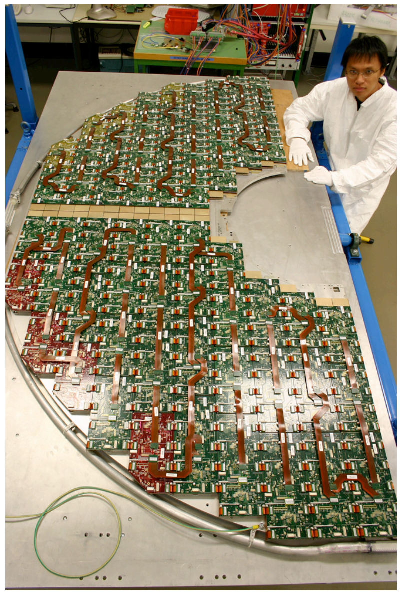


Crystal Barrel & Endcaps
(Lead tungstate $PbWO_4$ crystals) + Pb/Si Preshower









Barrel (EB)

36 supermodules (1700 crystals)
Total of 61200 $PbWO_4$ crystals
coverage: $|\eta|<1.48$

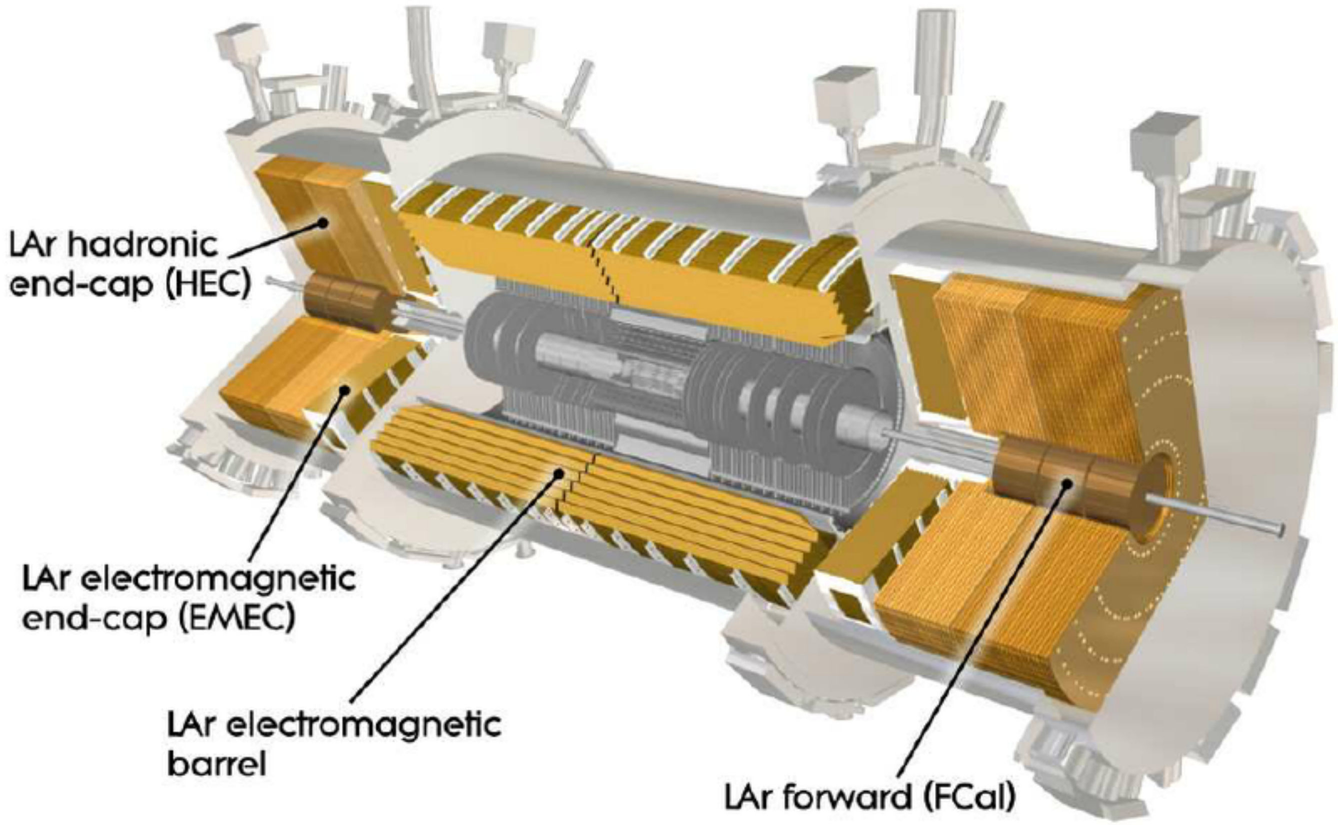
Endcap (EE)

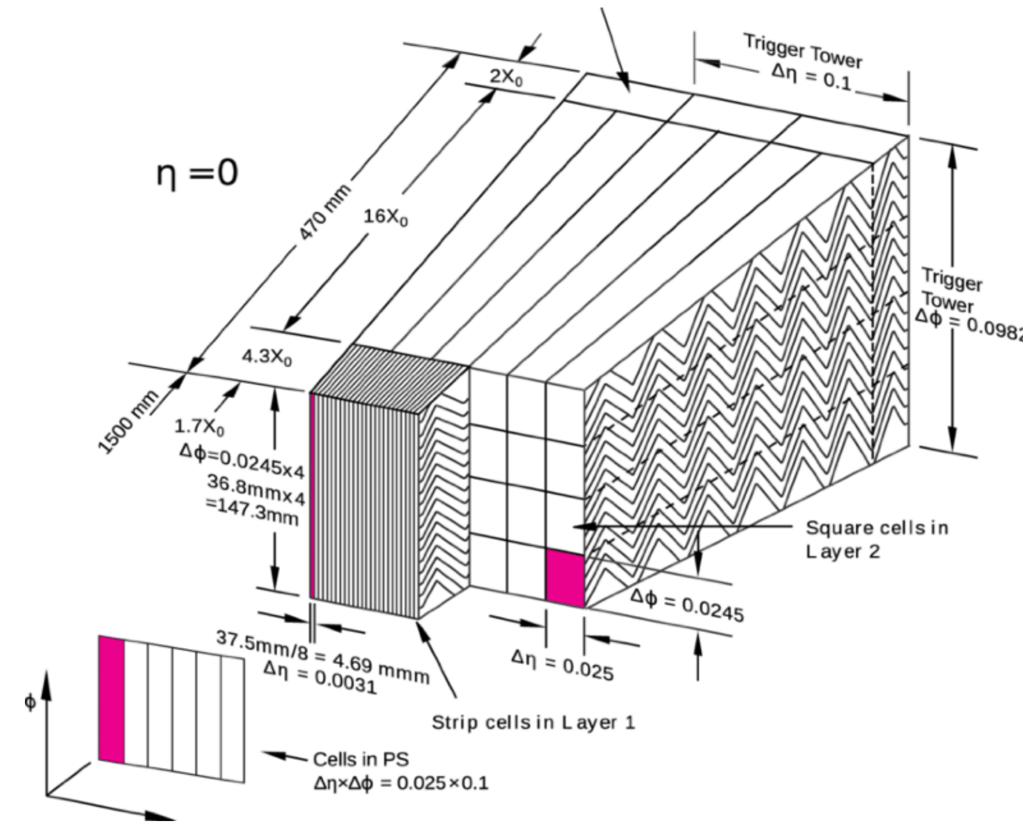
4 half-disk Dees (3662 xtals)
Total of 14648 $PbWO_4$ crystals
coverage: $1.48<|\eta|<3.0$

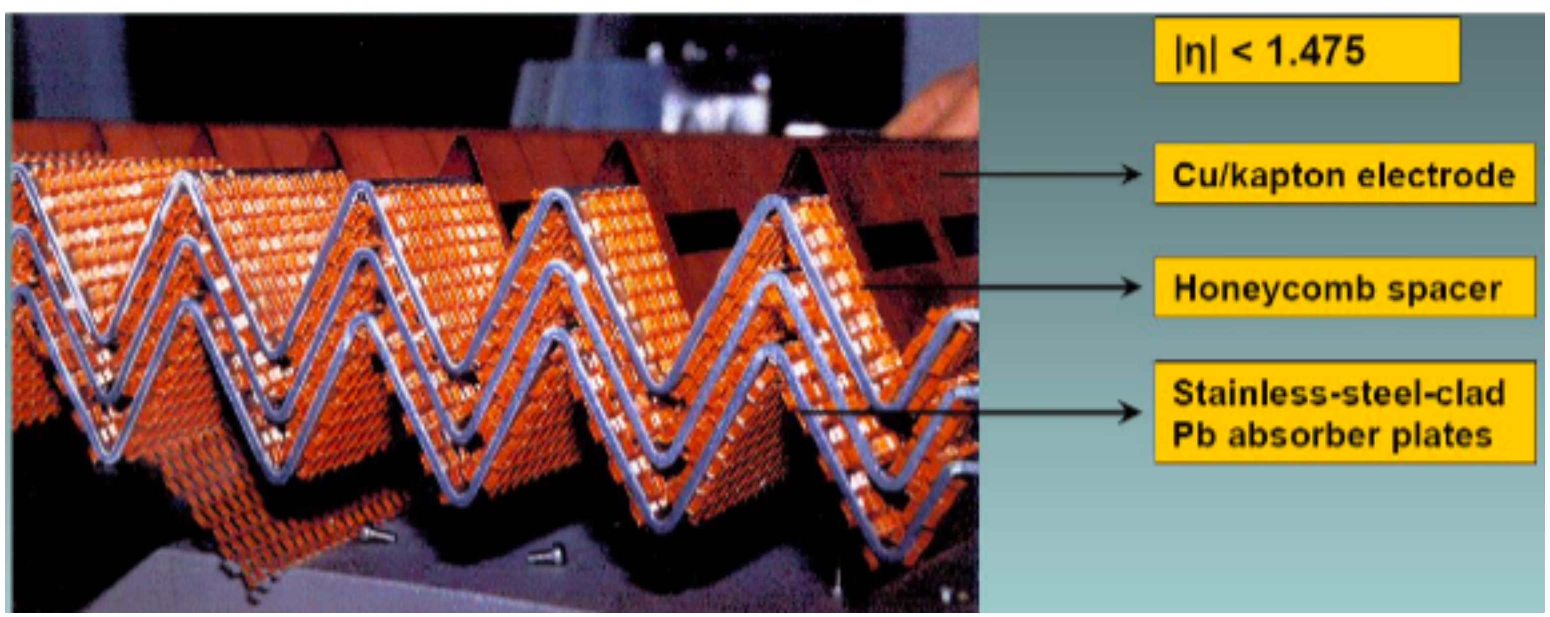
Preshower (ES)

4 half-disk Dees
Two Lead/Si planes
Total of 137216 Si strips ($1.8x61mm^2$)

The ATLAS Electromagnetic calorimeter







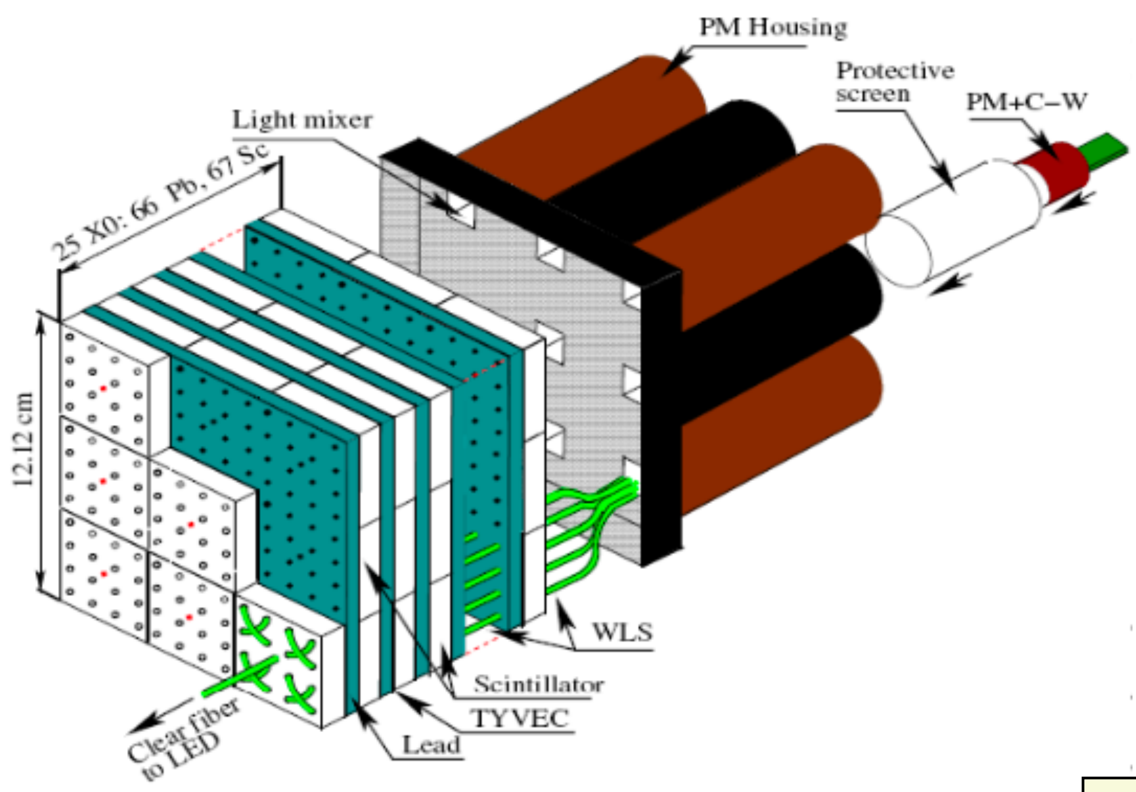
Liquid Argon active medium (90°K)
1-2mm lead absorbers in accordion geometry
Cu/kapton electrodes

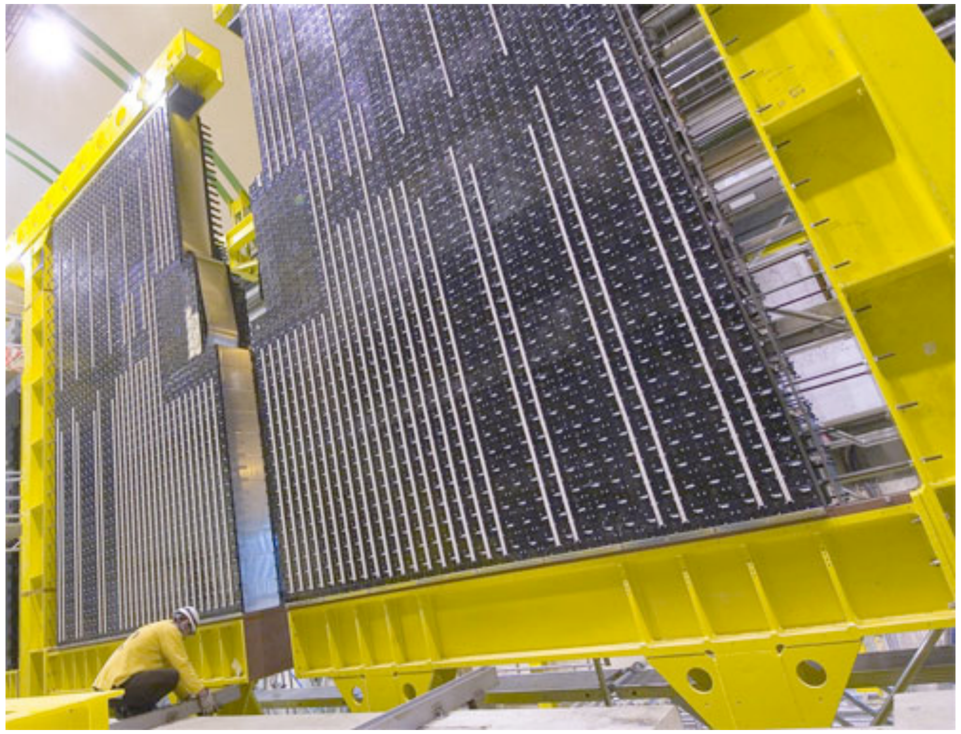
Barrel
101760 readout channels
3 longitudinal depths

Endcap
62208 readout channels
2 or 3 longitudinal depths

Presampler
9344 readout channels
one longitudinal depth

The LHCb Electromagnetic calorimeter



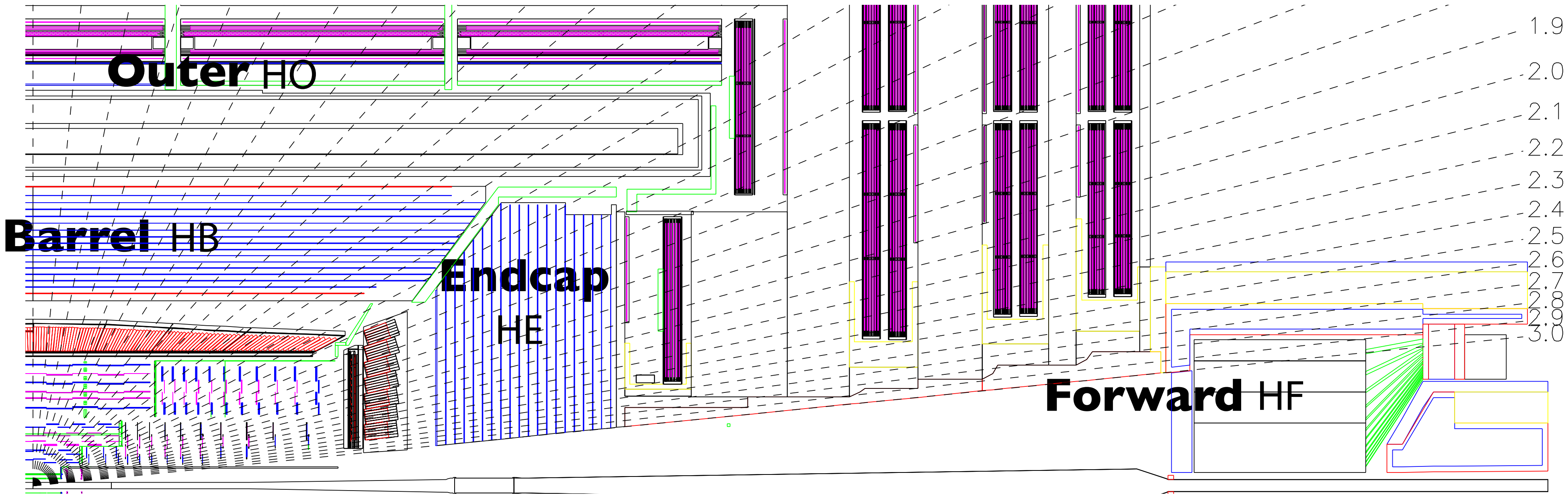


Sampling geometry with 3312 detector modules consist of lead absorbers and plastic scintillator active media
read out by PMTs via wavelength shifting fibres

Each module:

66 lead plates (2mm thick)
67 plastic scintillator plates (4mm thick)
1,4 or 9 readout channels based on proximity to beam

The CMS Hadron Calorimeter



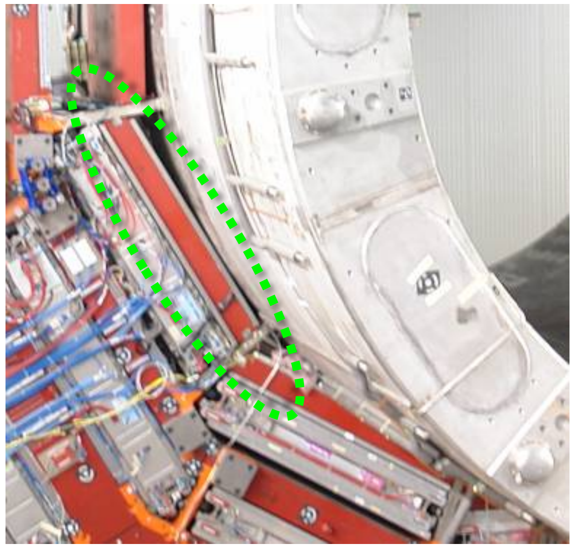
Sampling geometry with brass absorber and plastic scintillator active media
Read out by Silicon PMTs vis wavelength shifting fibres

Barrel (HB)

36 brass/scintillator wedges
17 longitudinal layers
5cm brass + 3.7mm scint
coverage: |η|<1.3

Endcap (HE)

Two brass endcap discs
19 longitudinal layers
8cm brass + 3.7mm scint
coverage: 1.3<|η|<3.0



Outer (HO)

scintillator tiles outside yoke
1 or 2 longitudinal layers
10mm scint
coverage: |η|<1.3

Forward (HF)

Steel absorber, in 20 deg wedges
Quartz fibre active element (~1000km)
coverage: 3<|η|<5.0

The ATLAS Hadron Calorimeter

Tile Calorimeter

Steel/scintillator sampling calorimeter
scintillating tiles read out by PMTs at both ends, via wavelength-shifting fibres
3 depth segments
9852 readout channels
coverage: $|\eta|<1.7$

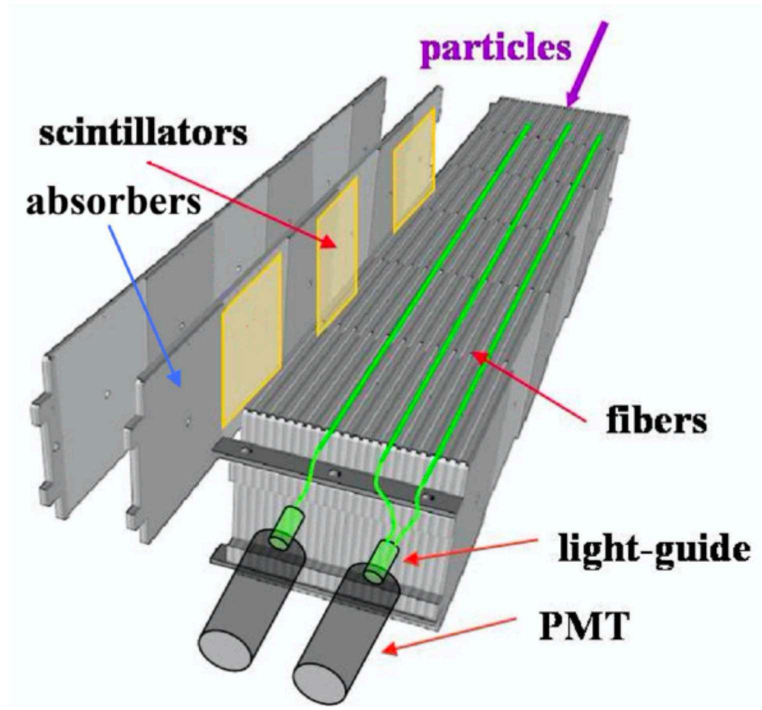
LAr Hadron endcap

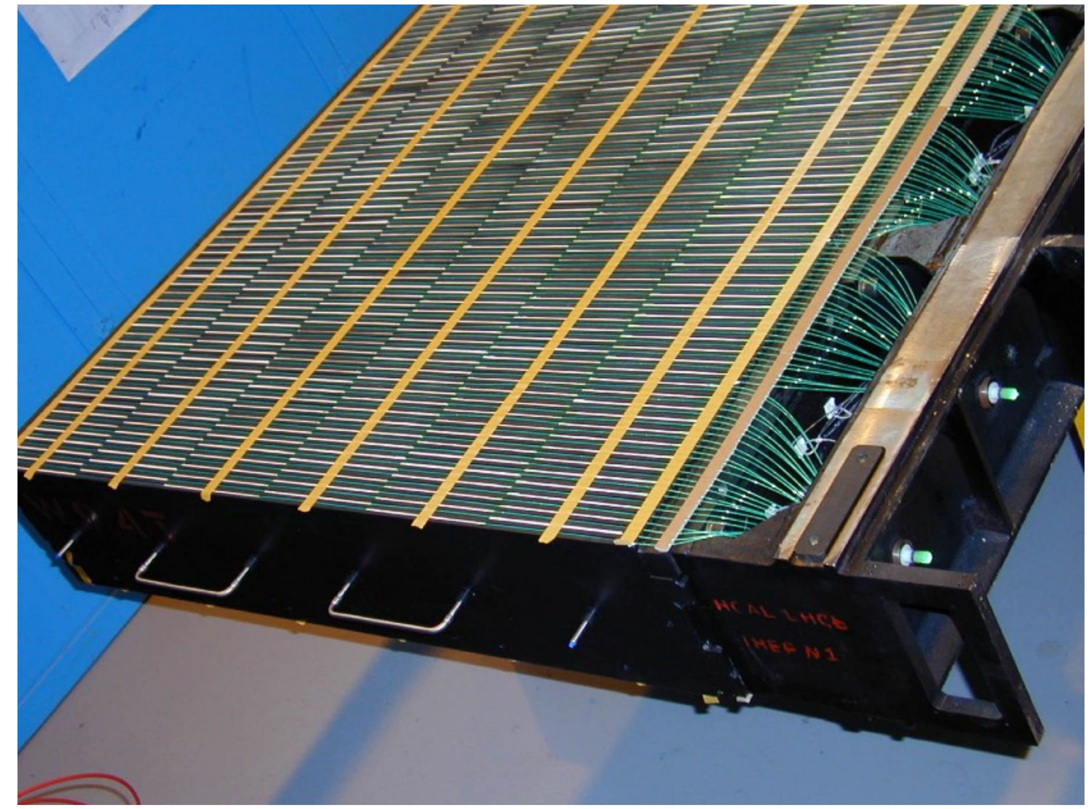
Cu absorbers/LAr active media
24 Cu plates (25mm thick) + 8.5 mm LAr gap (front)
16 Cu plates (50mm thick) + 8.5 mm LAr gap (rear)
4 depth segments
5632 readout channels
coverage: $1.5<|\eta|<3.2$

LAr forward calorimeter

Cu and W absorbers/LAr active media
3 depth segments
3524 readout channels
coverage: $3.1<|\eta|<4.9$

The LHCb Hadron Calorimeter





Sampling geometry with iron absorber and scintillator tile active media oriented parallel to beam
Read out by PMTs vis wavelength shifting fibres

52 horizontally stacked modules
- 1488 cells (608 outer, 880 inner)
- alternating rows of 4mm iron and 3mm scintillator plates

WLS fibres running along top/bottom edges of scintillator plates

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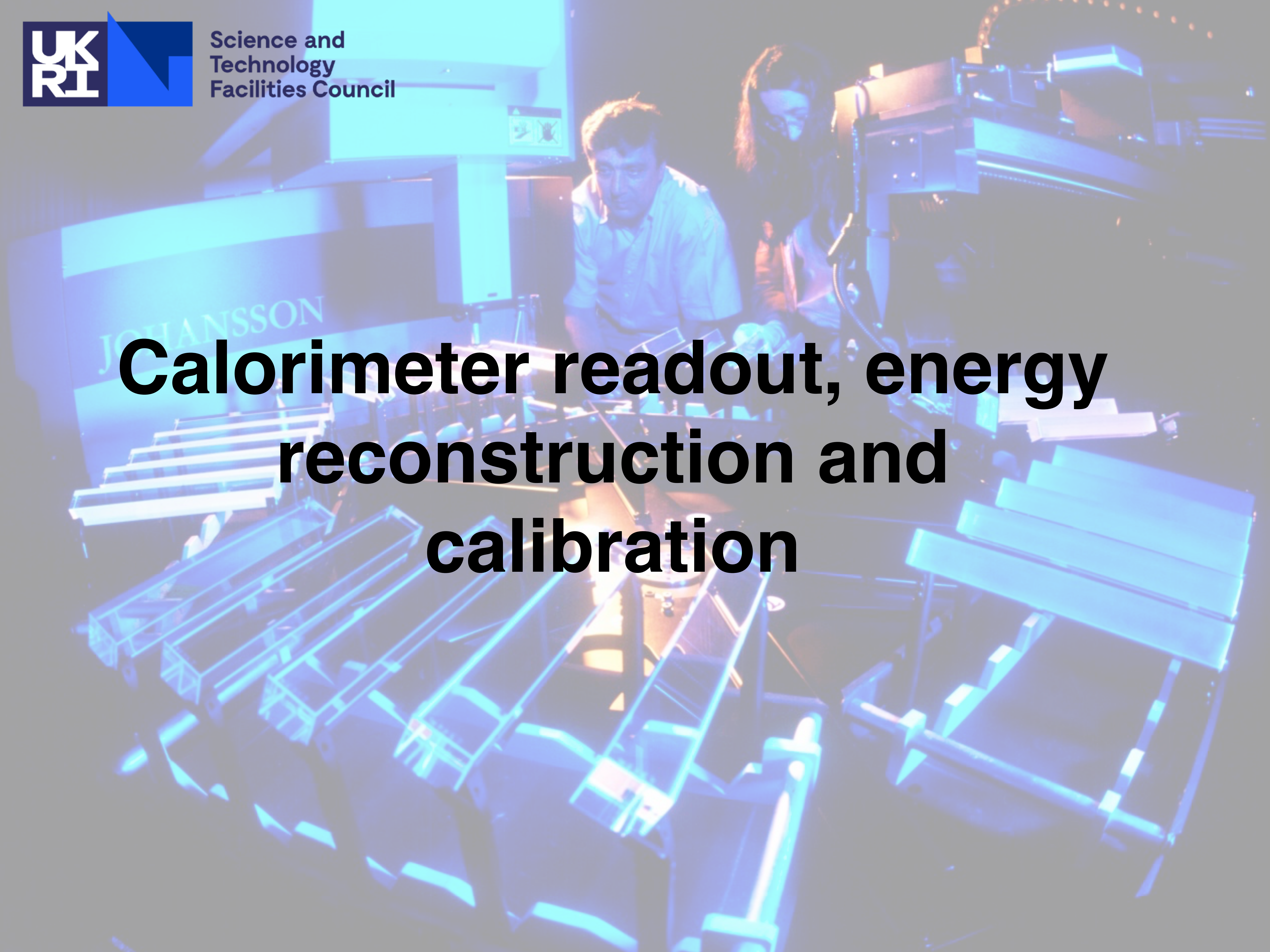
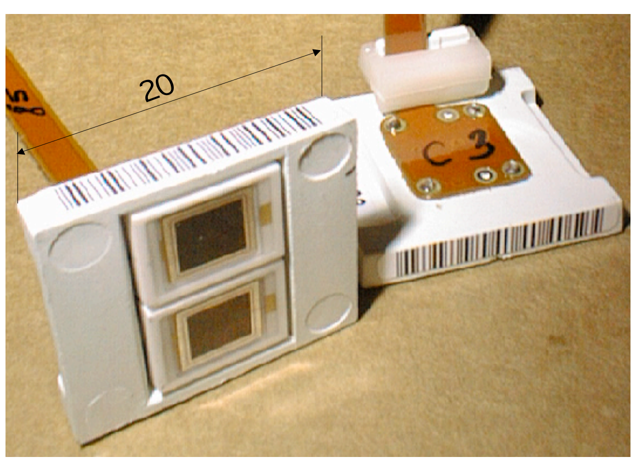


Calorimeter readout, energy reconstruction and calibration

Calorimeter readout

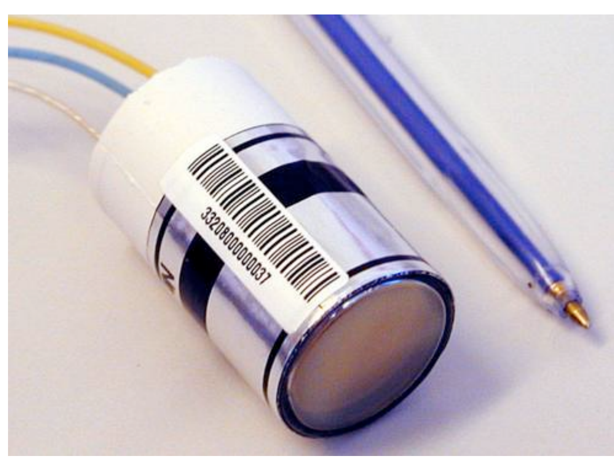
- **<u>Custom</u> photodetectors to readout scintillation light from calorimeters**
- **Key requirements**
  - **fast** (consistent with 25ns LHC collision rate)
  - **radiation tolerant** (to survive in harsh LHC irradiation environment)
  - **magnetic field tolerant** (CMS photodetectors must operate in 3.8T field)

CMS ECAL Barrel



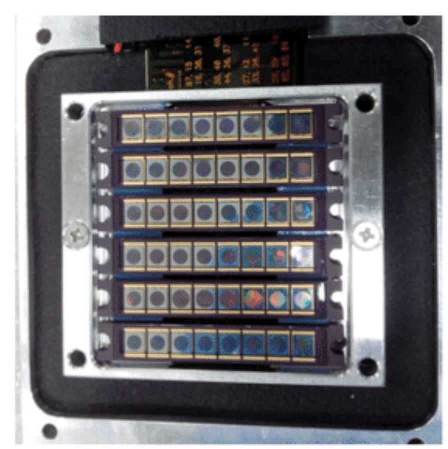
APD: Avalanche PhotoDiodes

CMS ECAL Endcaps



VPT: Vacuum PhotoTriodes

CMS HCAL



SiPM: Silicon PhotoMultipliers

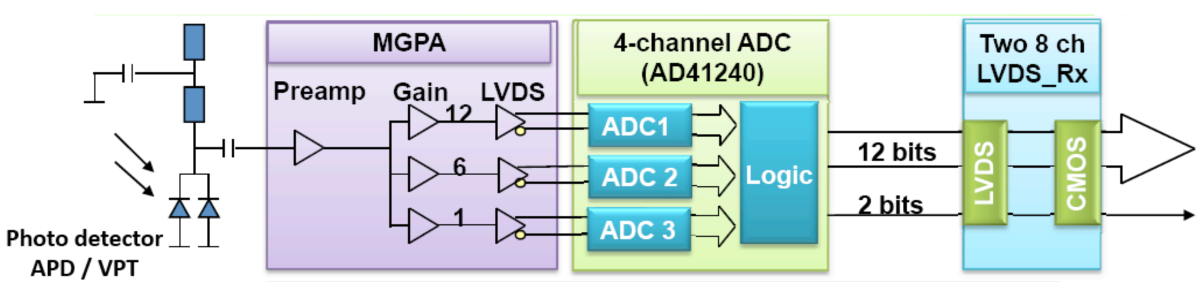
LHCb ECAL

PMT: Photo Multiplier Tubes

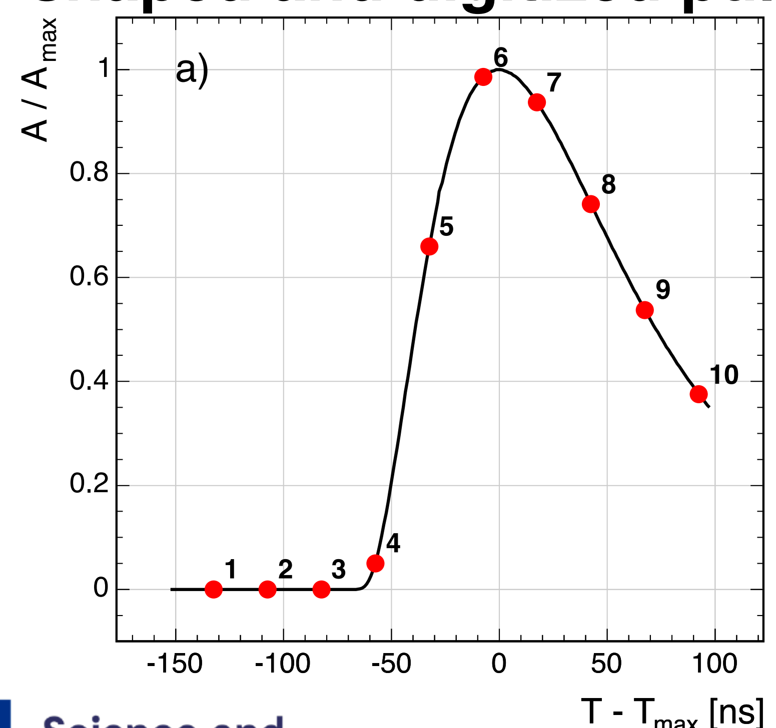
Calorimeter front-end electronics

- **Amplify and digitize signal pulses from calorimeter cells**
- **Perform fast energy sums (for trigger), data formatting/ buffering and readout to DAQ system**

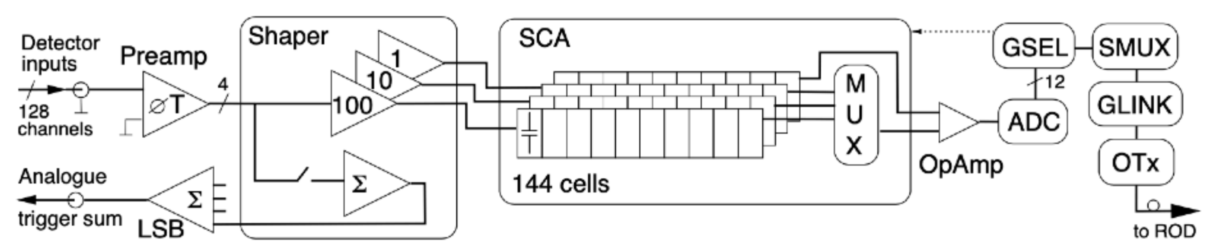
CMS ECAL



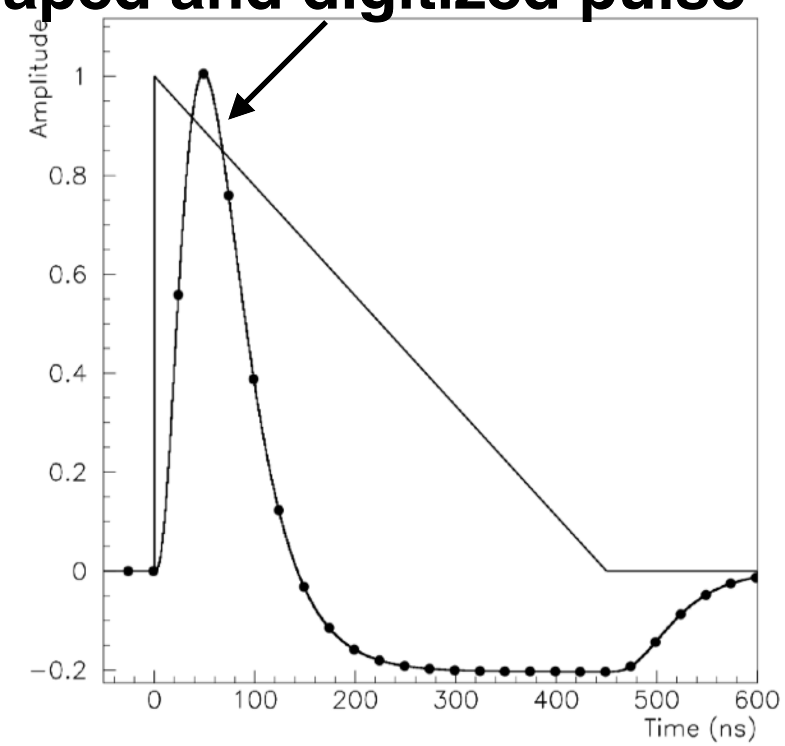
shaped and digitized pulse



ATLAS ECAL

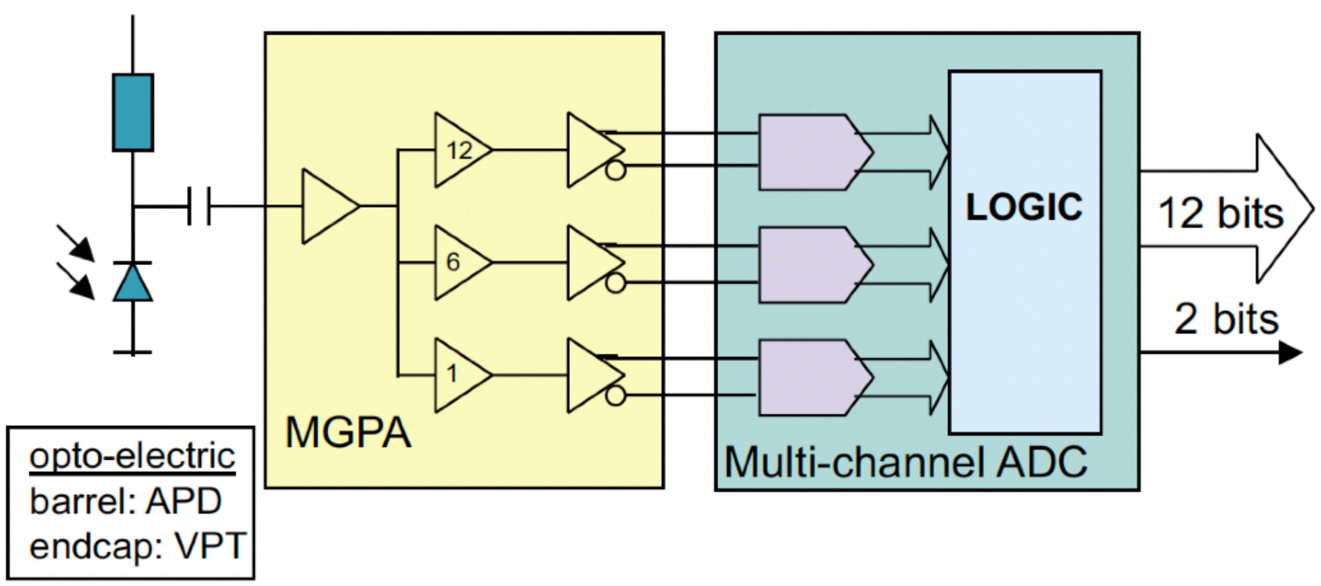


shaped and digitized pulse

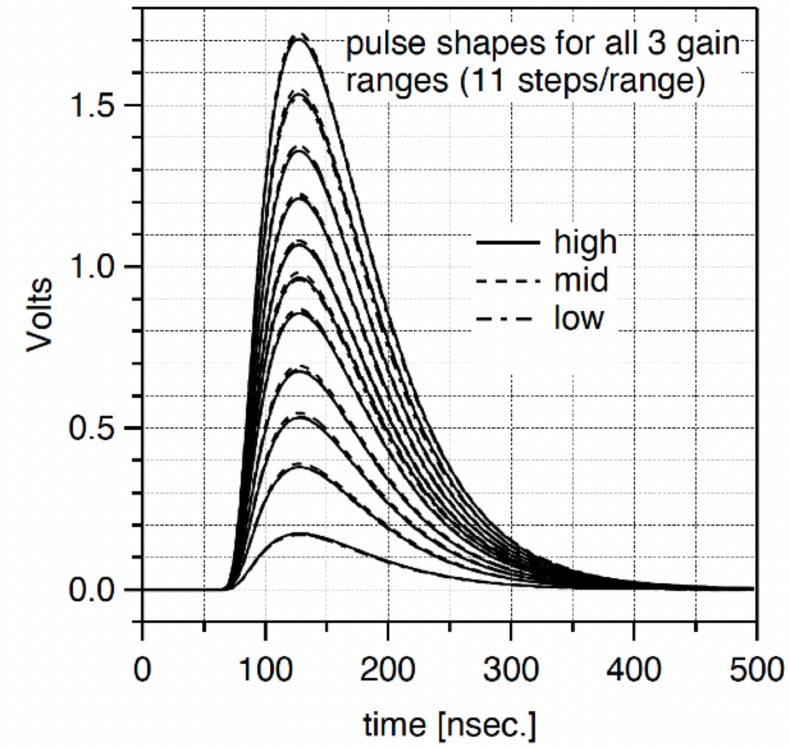


Digitization details

- **Calorimeter readout at LHC uses radiation tolerant ASICs for signal amplification, shaping and digitization**
  - **Stringent requirements on amplifiers with low noise, linear response and stable pulse shaping over a wide dynamic range**
    - typically between a few tens of MeV and several TeV for LHC calorimeters
  - **Pulse digitization uses ADCs (Analogue to Digital Converters)**
    - radiation tolerant examples usually have 12 bit precision
    - multiple ADCs with different amplifier gains are often needed to cover full dynamic range of the signal



Multi-gain amplifier and ADC architecture

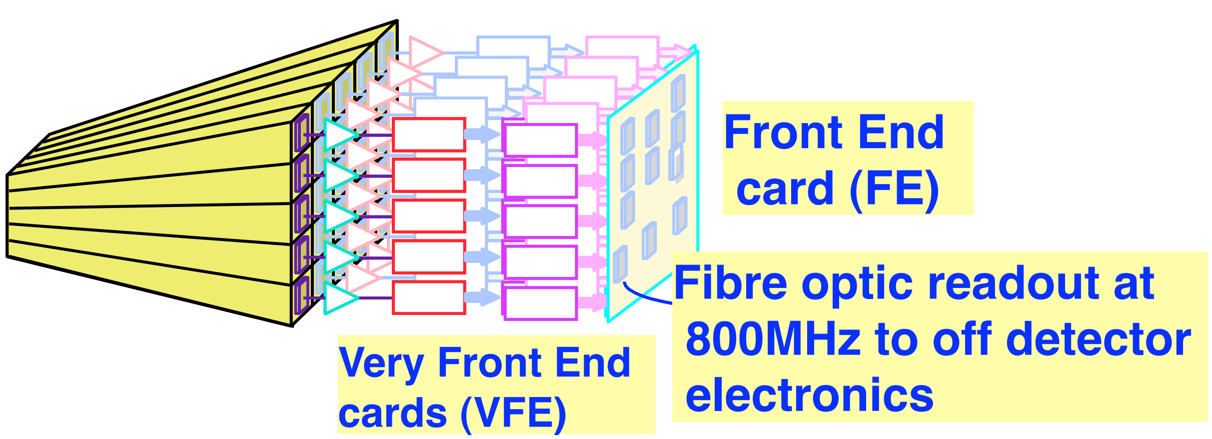


Pulse shape stability vs signal size

Calorimeter trigger sums

- **Fast energy sums sent every 25ns to first level trigger**
  - identify interesting events from calorimeter energy deposits
- **Computed from sums of calorimeter cells in ECAL and HCAL**
  - termed Trigger Towers
  - combined to form electron/photon, tau, jet candidates

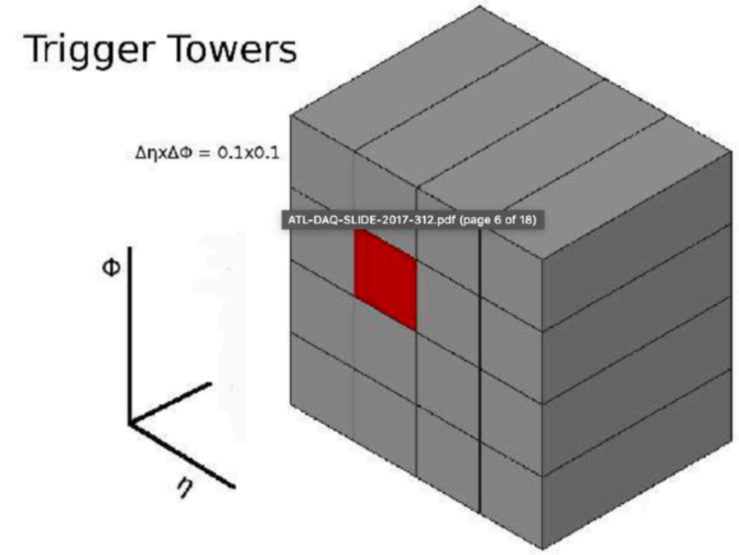
CMS ECAL trigger tower



5x5 crystal matrix

$\Delta\eta \times \Delta\phi = 0.087 \times 0.087$

ATLAS ECAL trigger tower



Single depth super-cell

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

Energy Reconstruction

For electron/photon object:

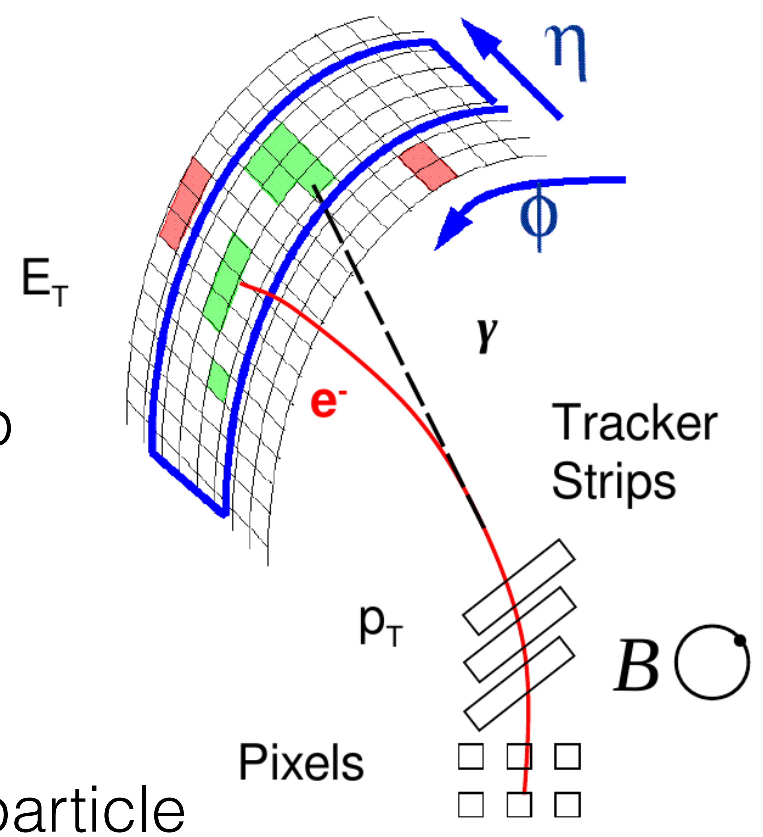
Pulse Amplitude — intercalibration — cluster corrections

$$E_{e,\gamma} = \sum_i [A_i \times S_i(t) \times c_i] \times G(\eta) \times F_{e,\gamma}$$

time-dependent response corrections: laser monitoring system — Global scale

intercalibration takes into account differing response of scintillator and photodetectors

Clustering:



Superclusters: dynamic sized clusters to gather energy radiated in phi (field bending direction) and mimimise pileup contamination

Cluster corrections: improve energy determination by applying energy corrections that depend on the type of particle (electron/photon), showering/non-showering, proximity to dead regions/cracks etc.

Energy calibration methods

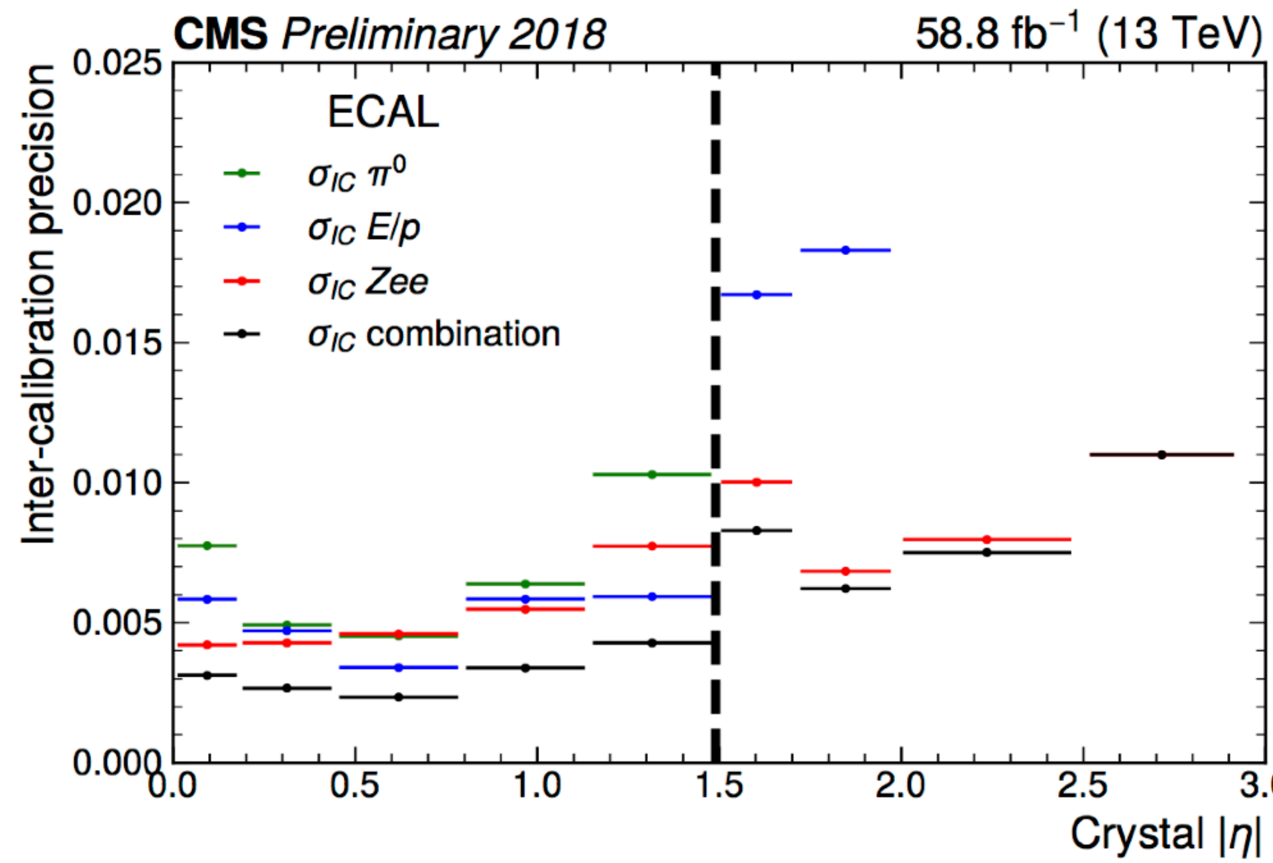
intercalibration sources

physics data are used to equalise the response of each channel in the detector

method	time needed
ϕ-symmetry	few days
$\pi^0/\eta \rightarrow \gamma\gamma$	1 month
electron E/p	20 fb^{-1}
Z→ee mass	20 fb^{-1}

Dedicated calibration streams (with limited event content) are used to collect enough stats.

intercalibration precision



Can achieve precision of better than 0.5% with a combination of calibration methods

Intercalibration is crucial to maintain energy resolution performance

Use of multiple methods

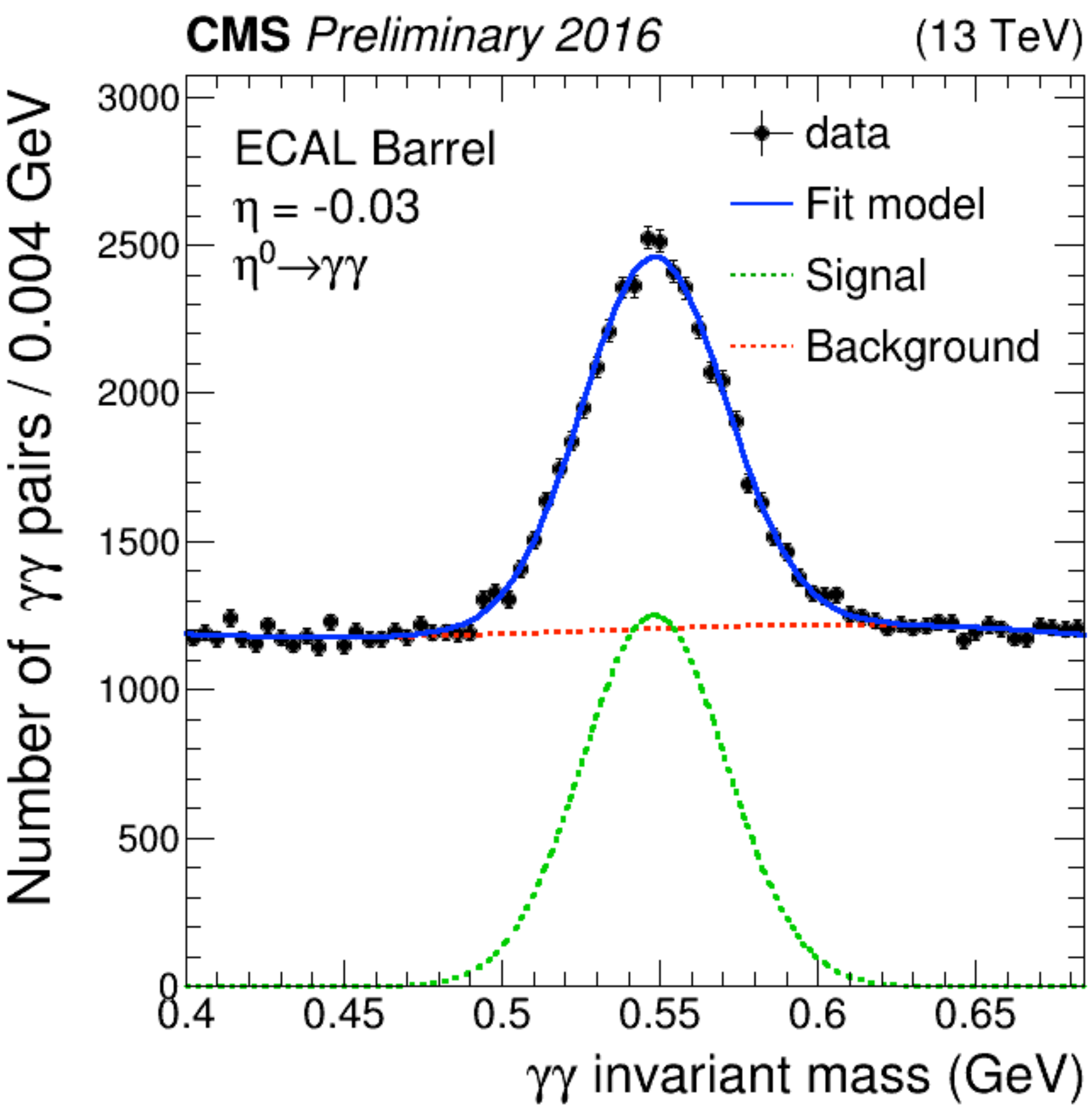
$\pi^0/\eta^0 \rightarrow \gamma\gamma$ and Z→ee - use invariant mass constraint to equalise response per channel

phi-symmetry (minimum bias events) and E/p ratio from W→ev can provide relative calibrations

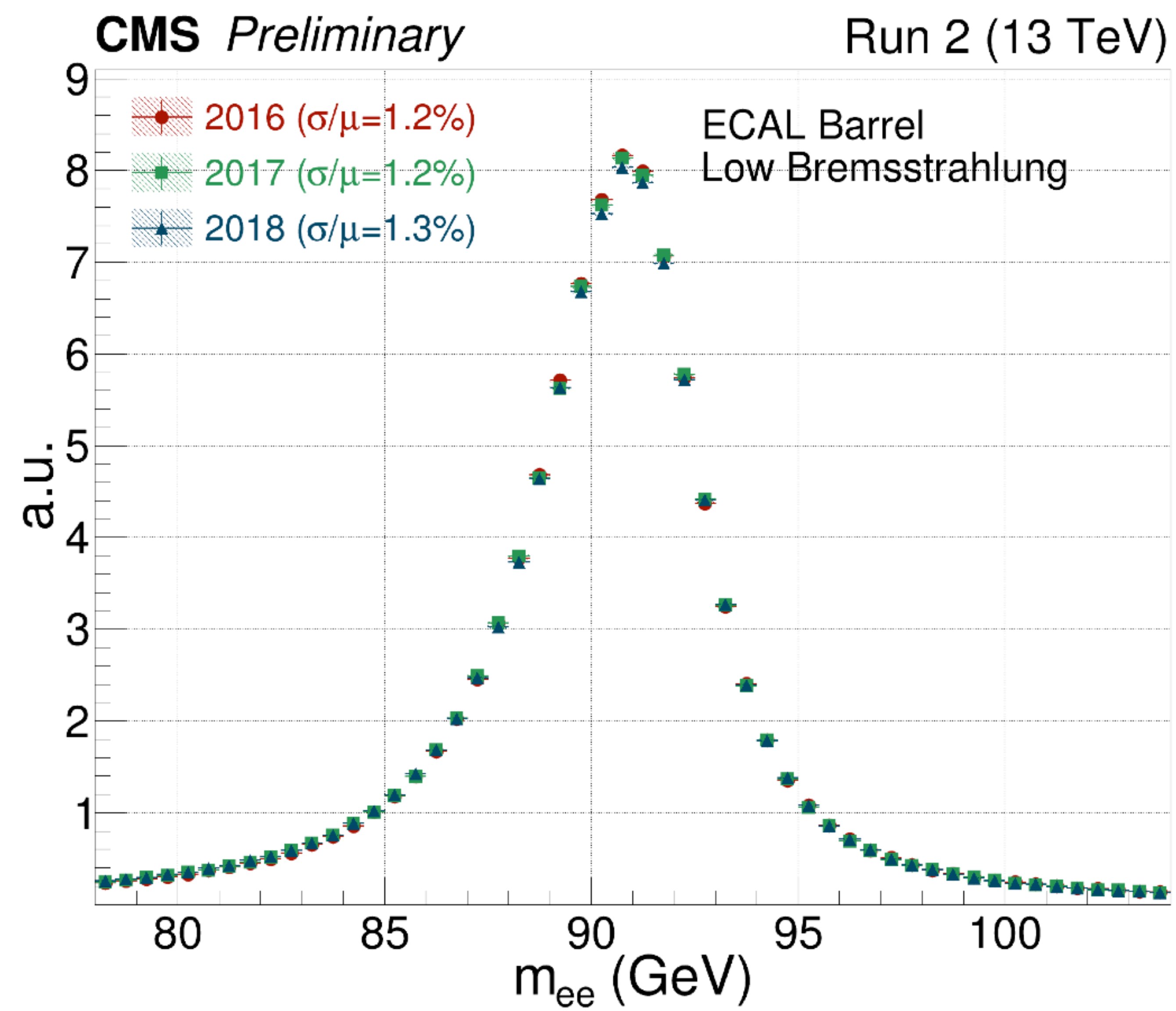
Z→ee fixes absolute energy scale

Energy calibration methods

Example of a $\eta^0 \rightarrow \gamma\gamma$ invariant mass fit in CMS



$Z^0 \rightarrow ee$ invariant mass distributions in CMS for LHC Run 2



advantages: high statistics, can provide calibrations with high time and spatial granularity
disadvantages: large backgrounds, more sensitive pileup and noise

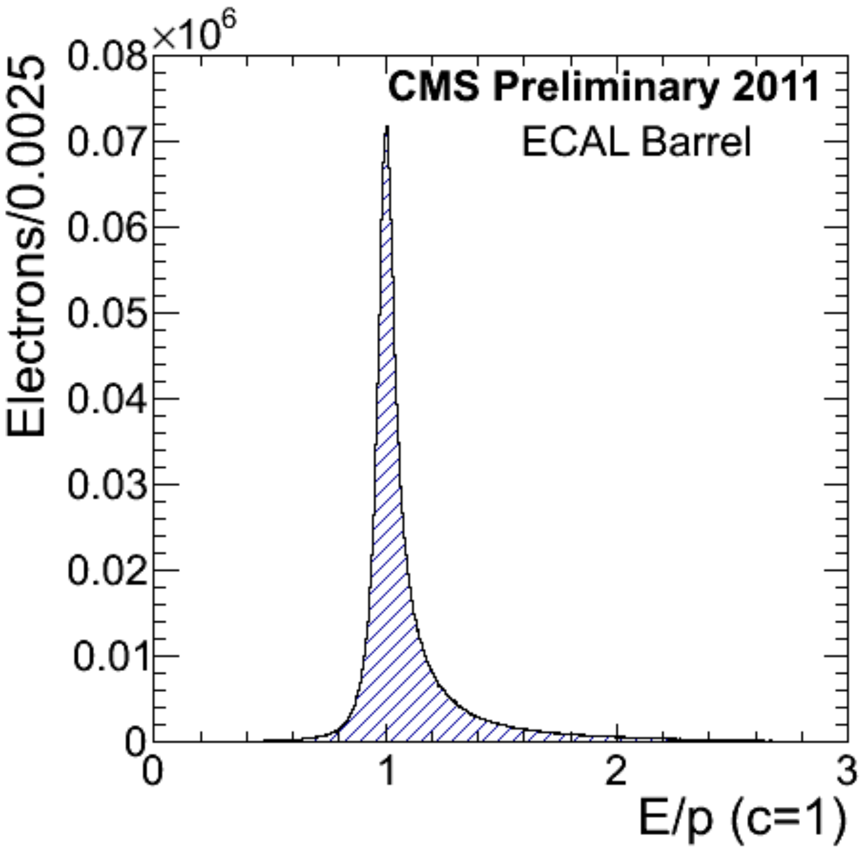
advantages: low background and small systematic errors, provides calibrations at relevant energies for $H \rightarrow \gamma\gamma$ decays

disadvantages: relatively low stats

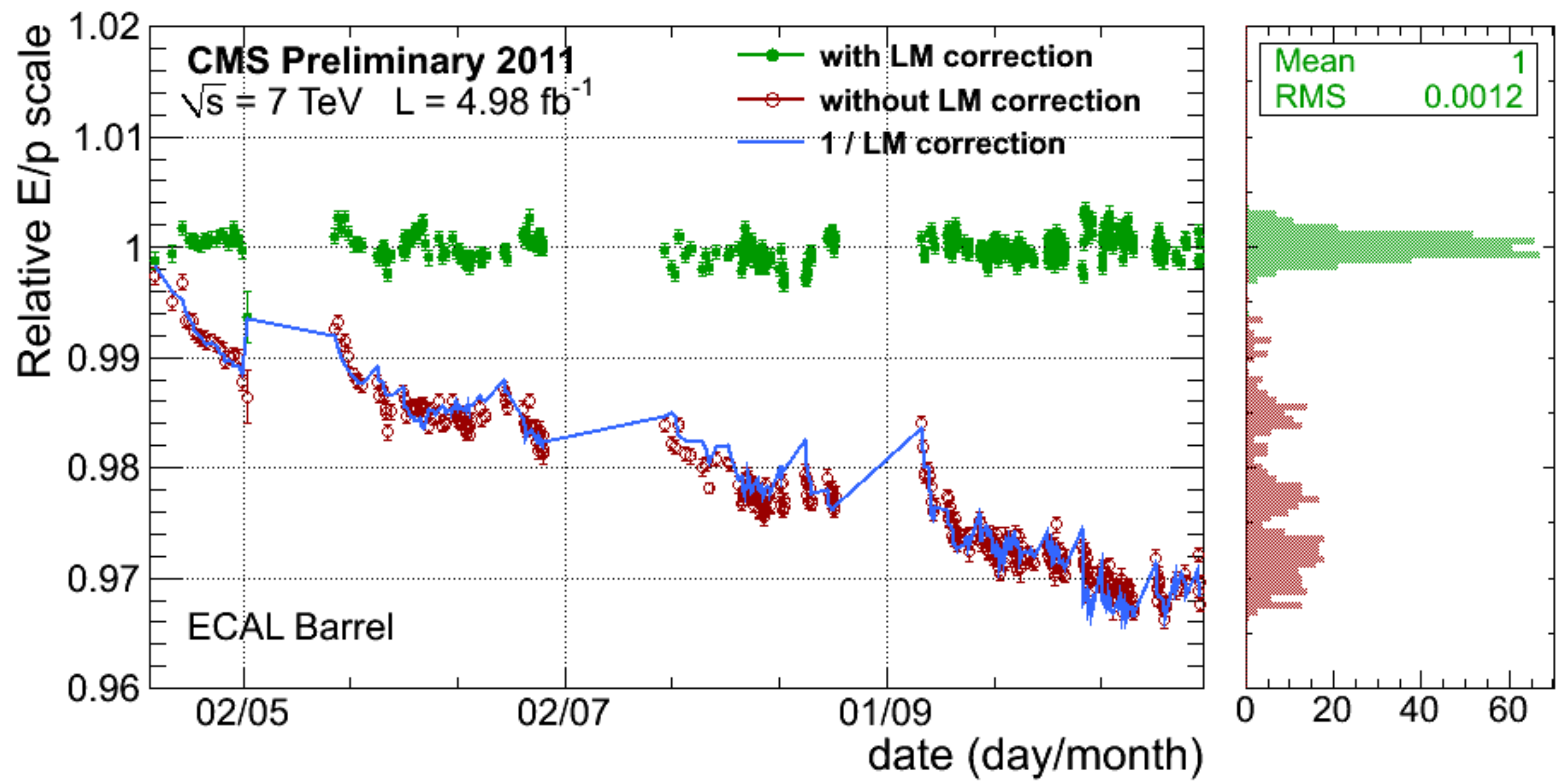
Energy calibration methods

E/p ratio of electrons from W→eν is a powerful calibration source

Energy scale
(relative to tracker)



Relative energy scale vs time
(assess energy scale stability + quality of response corrections)

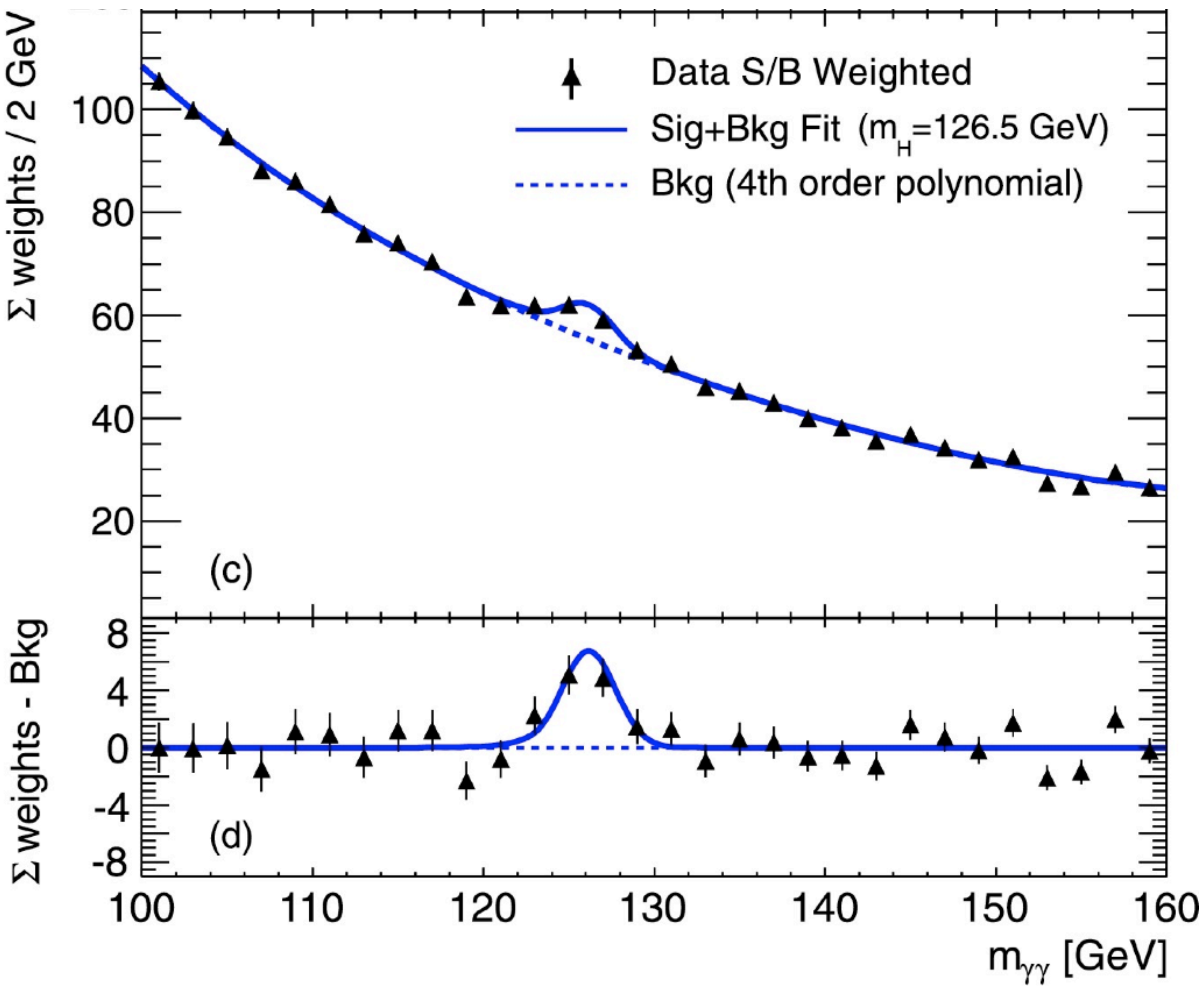


advantages: high statistics (5-6x more events than Z→ee): can provide energy scale measurements and calibrations with higher time and spatial granularity. Use of independent tracker momentum provides a normalising factor - can probe a large range of electron p_T

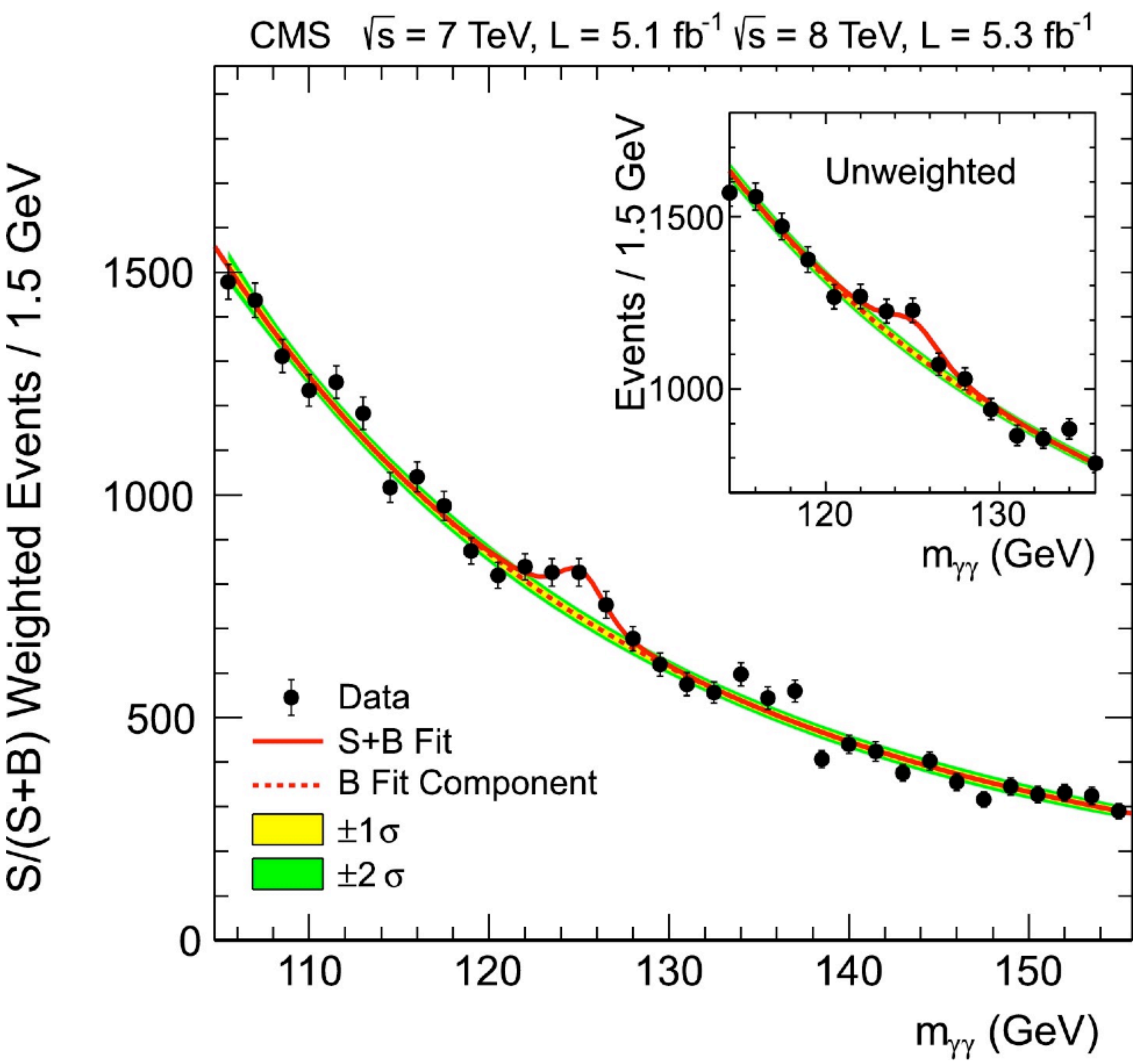
disadvantages: relies on the assumption that track p_T is well-calibrated - sensitive to issues and biases in track momentum measurement

H→$\gamma\gamma$ observation (2012)

ATLAS



CMS

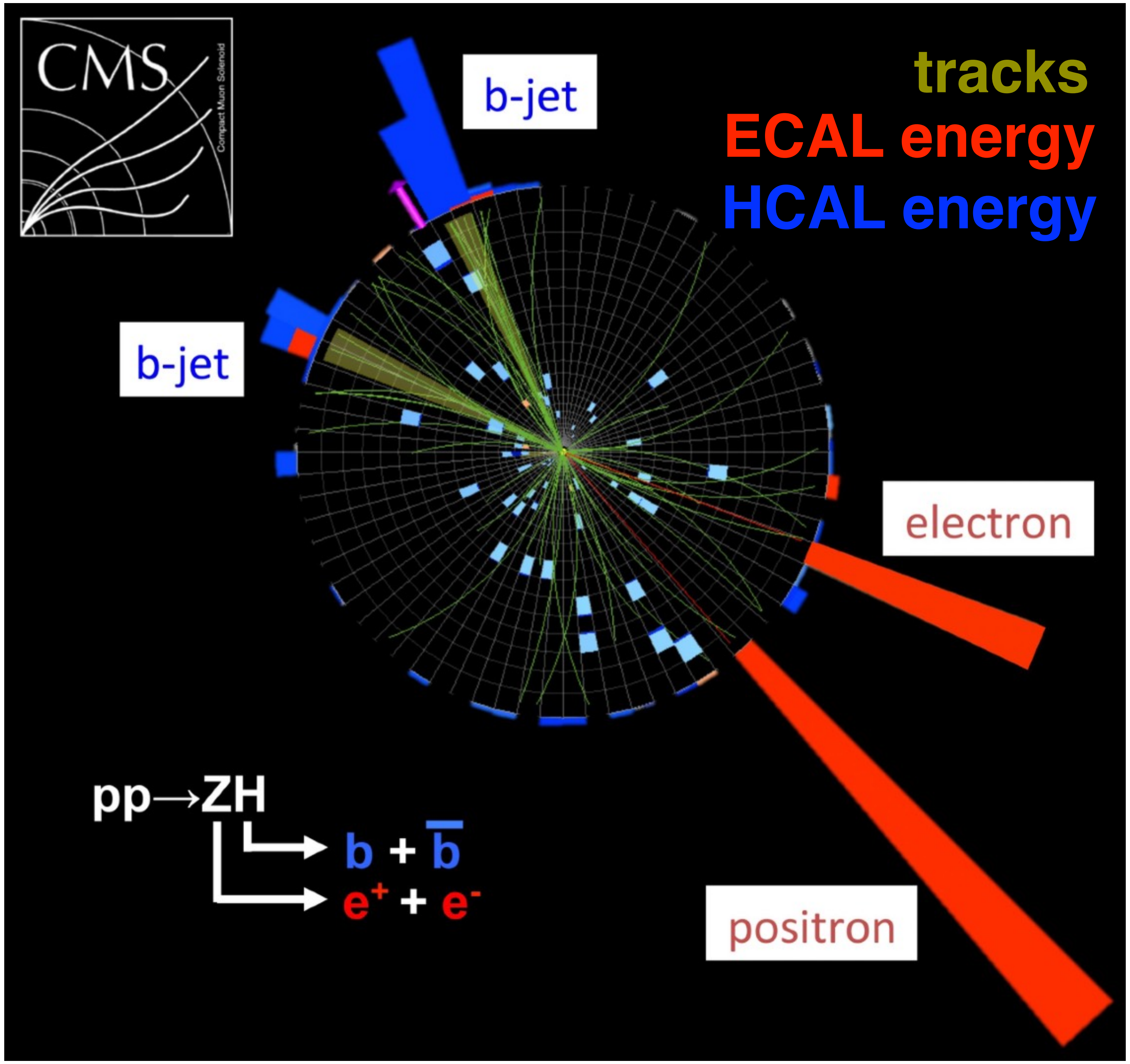


Energy resolution: crucial to observe small signal on large, exponentially falling background

Energy calibration: crucial for correct Higgs mass measurement

Electron/photon and jet reconstruction

- **Particle ID**
  - pattern of deposits in tracker, ECAL, HCAL determines particle type
    - **electrons**: ECAL energy matched to tracks, no HCAL energy
    - **jets**: multiple tracks associated with ECAL+HCAL deposits
- **Charge and momentum measurement**
  - from bending of tracks in magnetic field
- **Energy measurement**
  - from clustered deposits in ECAL and HCAL



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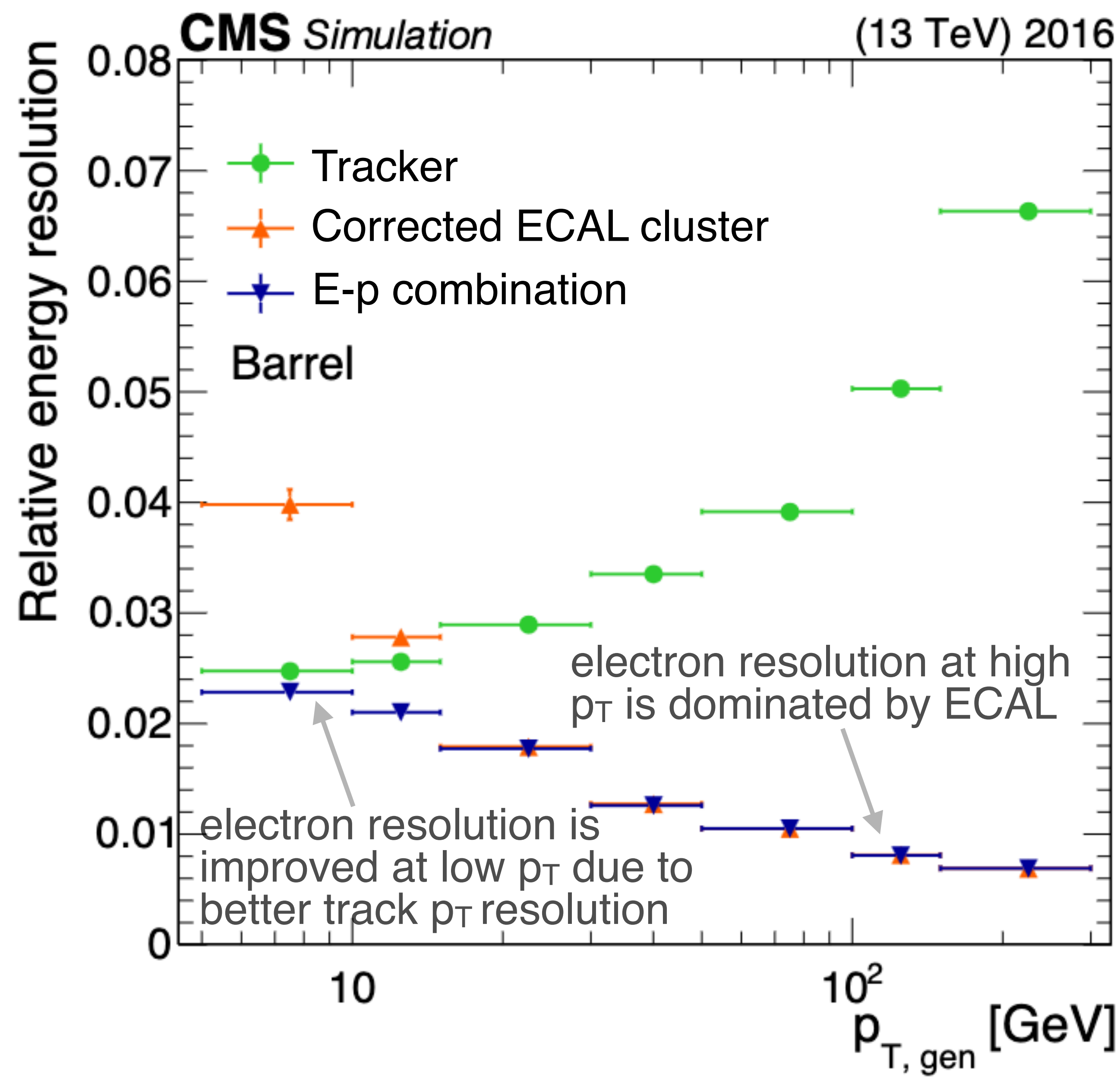
Electron track matching and E-p combination

- **Electron-track matching**
  - geometric matching of a **charged track** (in inner tracker) with an **equivalent** energy deposit in the ECAL.
    - **matching criteria depends on:**
      - uncertainty in the track extrapolation to the ECAL
      - the relative alignment of the ECAL and inner tracker
      - the spatial resolution of the ECAL cluster "seed"

- **Energy combination**
  - the ECAL cluster energy and tracker momentum can be combined
    - providing the two measurements are consistent (E/p matching)

$$E^{\rm reco}_{\rm combined} = \frac{E_{\rm ECAL}/\sigma_E^2 + p_{\rm tracker}/\sigma_p^2}{1/\sigma_E^2 + 1/\sigma_p^2},$$



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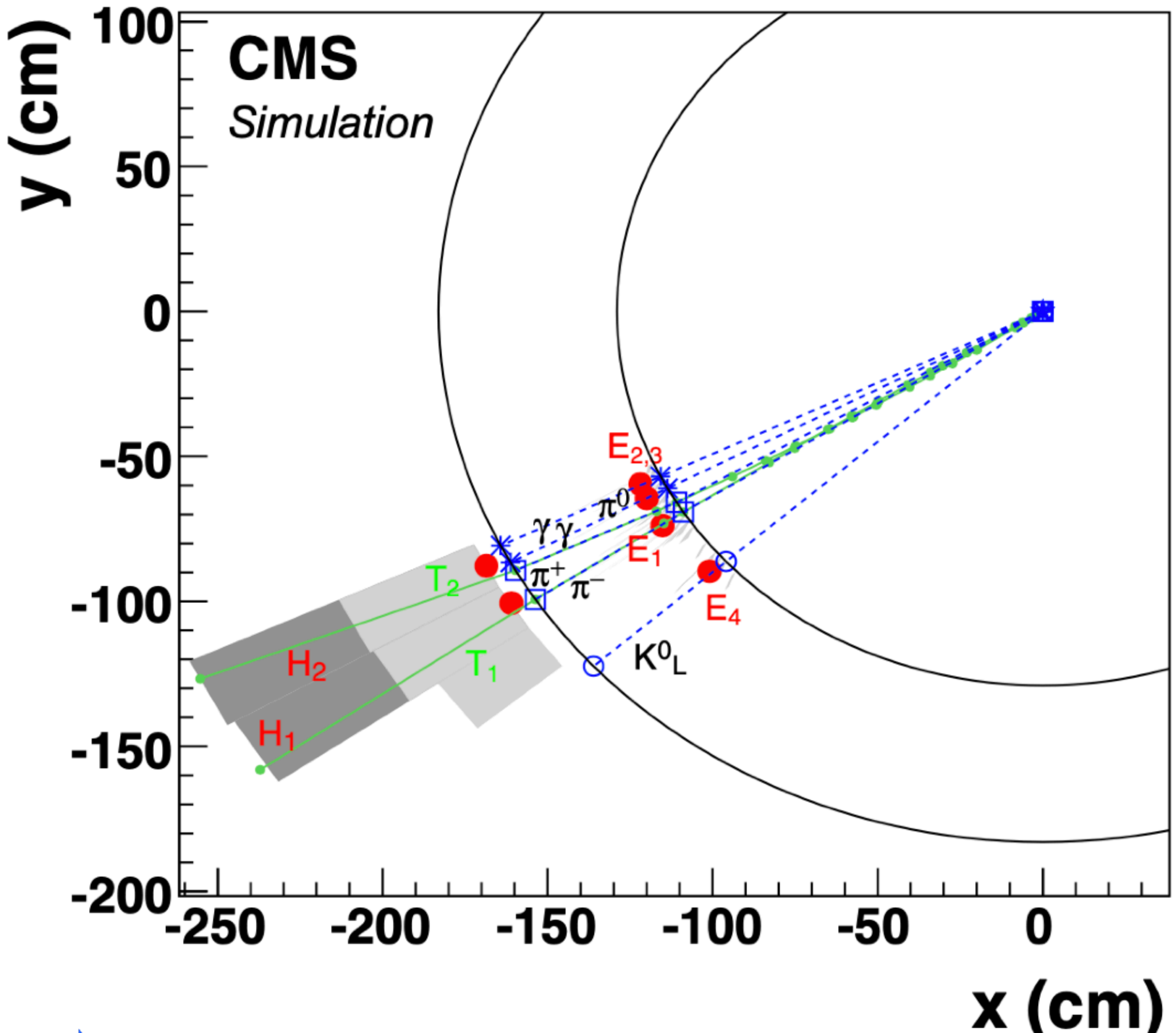
Particle flow reconstruction

- **Takes things one step further:**
  - attempts to classify individual particles by geometric association of tracks and calorimeter energy deposits



x,y view of particle jet

tracks, ECAL deposits and HCAL deposits indicated

inferred particle trajectories and particle IDs are shown in blue

can improve response and resolution by having dedicated energy corrections by particle type (compensate for different e/h response of HCAL)

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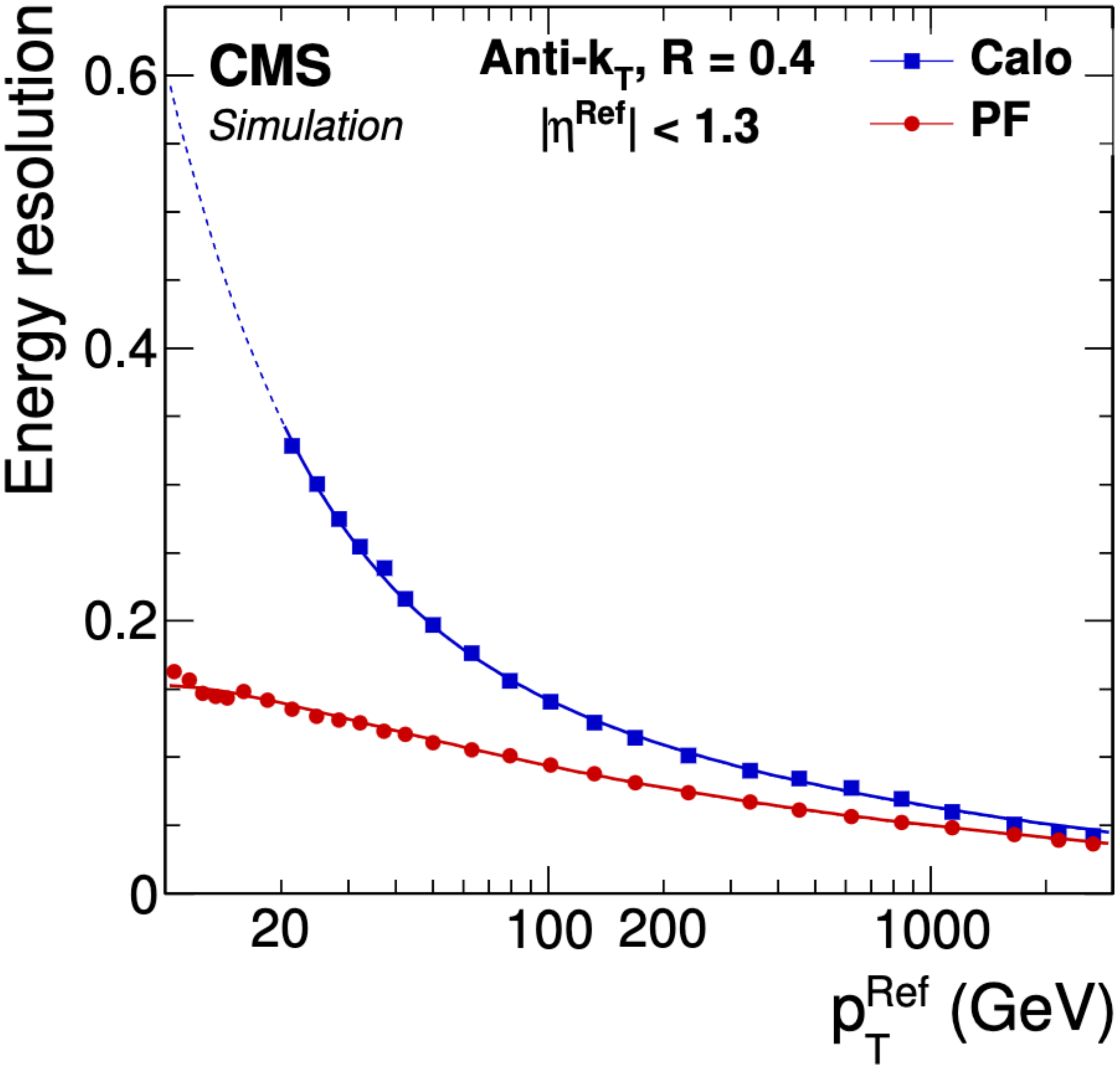
Particle flow: jet energy resolution



can improve response and resolution by having dedicated energy corrections by particle type (compensate for different e/h response of HCAL)

This plot demonstrates the potential of the particle flow approach: substantial improvements at low jet p_T over purely calorimetric approach

Particle flow: jet energy resolution

Particle flow relies on:

1) excellent tracking detector for precise measurement of charged particle trajectories

2) excellent EM calorimeter with fine transverse granularity for track-cluster association, and optional depth segmentation

3) hermetic hadronic calorimeter with optional depth segmentation (to isolate EM component of jets)

<u>not enough just to design a good ECAL or HCAL</u>

Need to consider both tracking and calorimetry together

calorimetric approach

Calorimeter design checklist

- **High resolution**
  - especially for ECAL - Higgs and rare decay measurements
- **High granularity**
  - for particle ID and position measurement, and particle flow reconstruction
- **Compact and hermetic**
  - with dimensions informed by R_M, X_0, λ_I
  - relative dimensions of ECAL/HCAL key to aid particle ID
  - hermeticity crucial to measure all visible particle decays
- **Fast response**
  - to satisfy high rates (e.g. of LHC collisions) and contribute to trigger decisions
- **Radiation tolerant**
  - to maintain performance over time in harsh radiation environment

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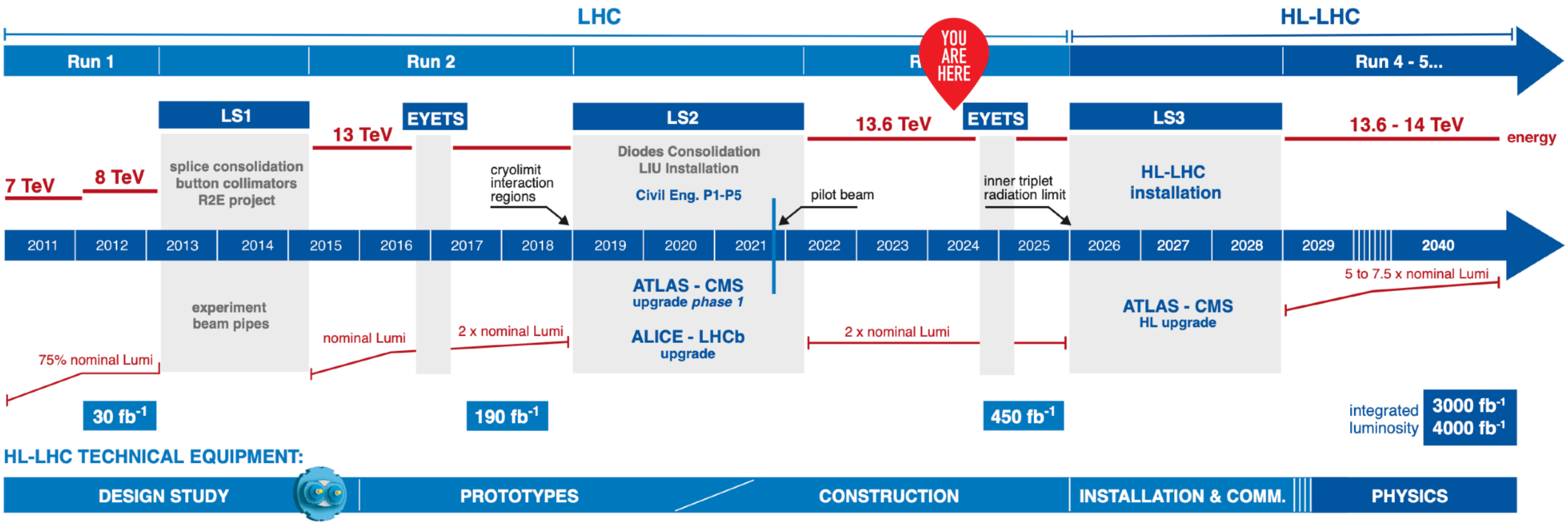
Calorimeter operating challenges

CMS example

LHC environment is challenging



LHC: delivers high luminosity proton-proton collisions (up to 14 TeV c.m. energy) to experiments

collides two bunches of 1e11 protons every 25ns

design luminosity: 1×10^{34} cm^{-2} s^{-1} already exceeded by a factor of 2 in 2017,2018

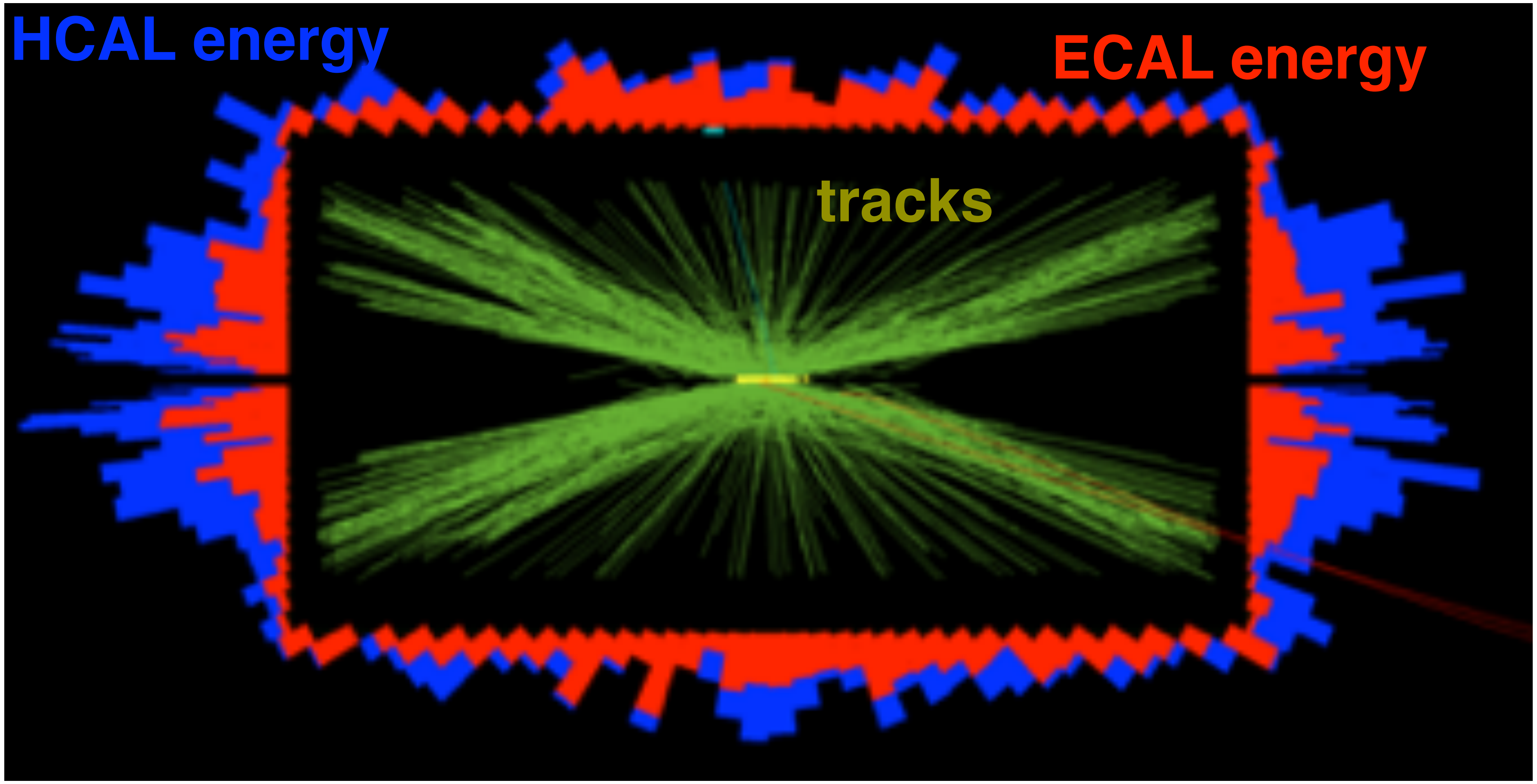
integrated luminosity (size of physics dataset) increased by a factor of 6 in Run 2 (2015+)

Consequences:

large instantaneous luminosities: *busy events with multiple overlapping collisions products (pileup) -> pattern recognition and reconstruction challenge*

large integrated luminosities: *increased detector ageing -> calibration and performance optimisation challenge*

A high pileup event in CMS



78 simultaneous interactions from one LHC collisions event

a significant challenge to pattern recognition and event reconstruction algorithms

Run 1 average: 10-20, Run 2 average: 40, Run 3 average: 60

Calorimeters must cope large radiation doses and high event pileup and maintain performance

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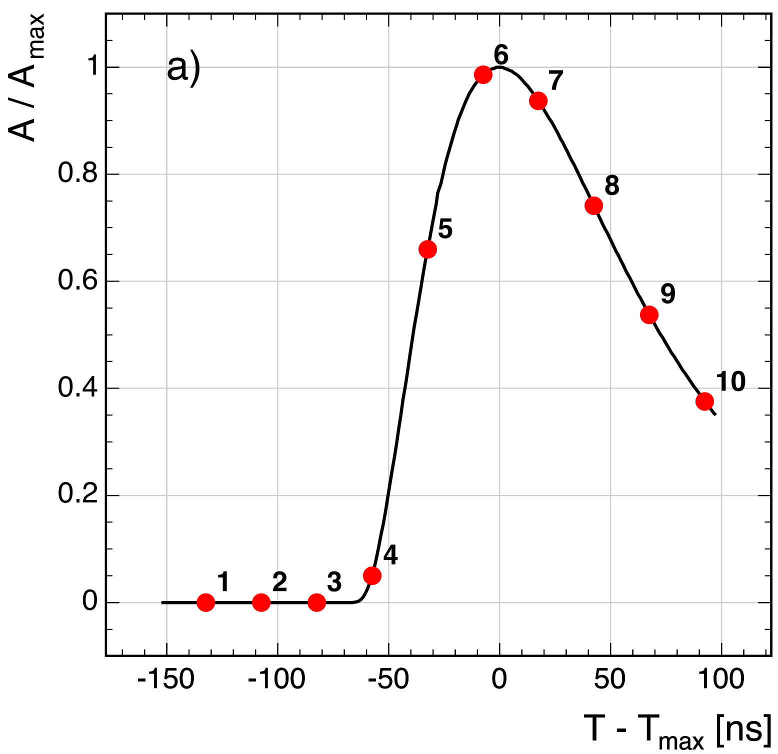
Pulse reconstruction methods

template fits to suppress out-of-time (OOT) pileup

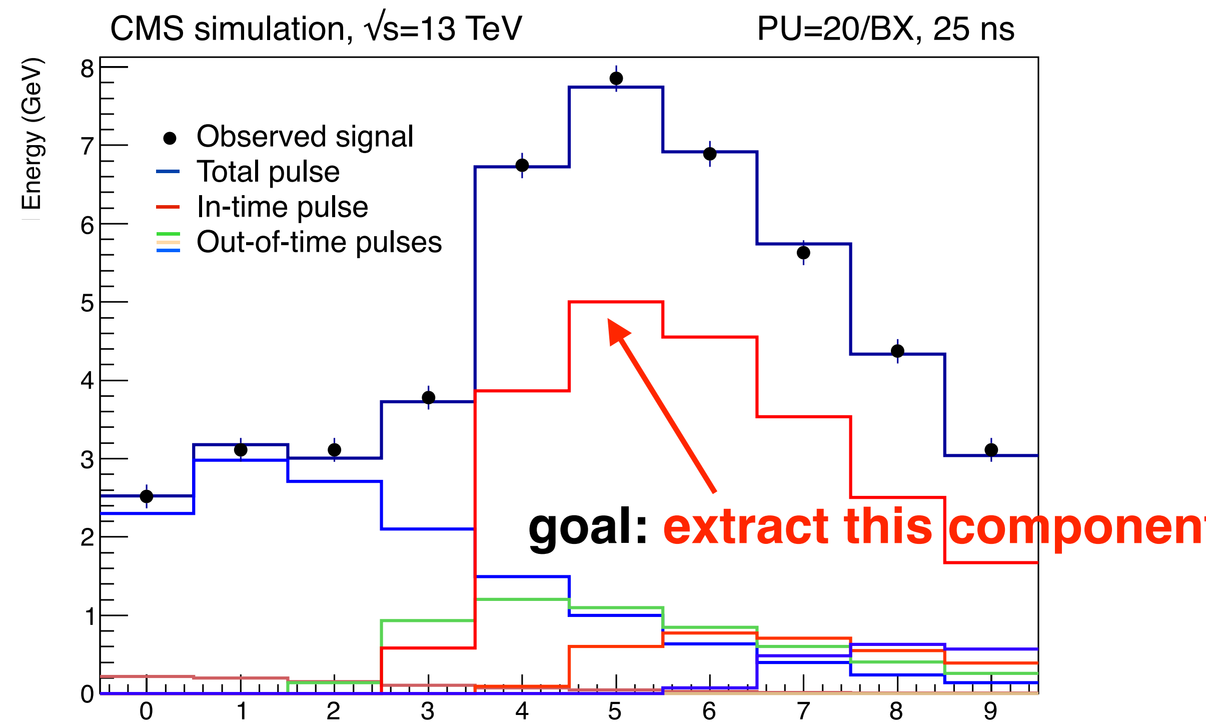
ECAL digitized pulse

no pileup



ECAL digitized pulse

with pileup



<u>Adnavced pulse reconstruction algorithms developed to mitigate OOT PU</u>

template fit(*) -> subtracts out-of-time pulses that overlap with in-time signal

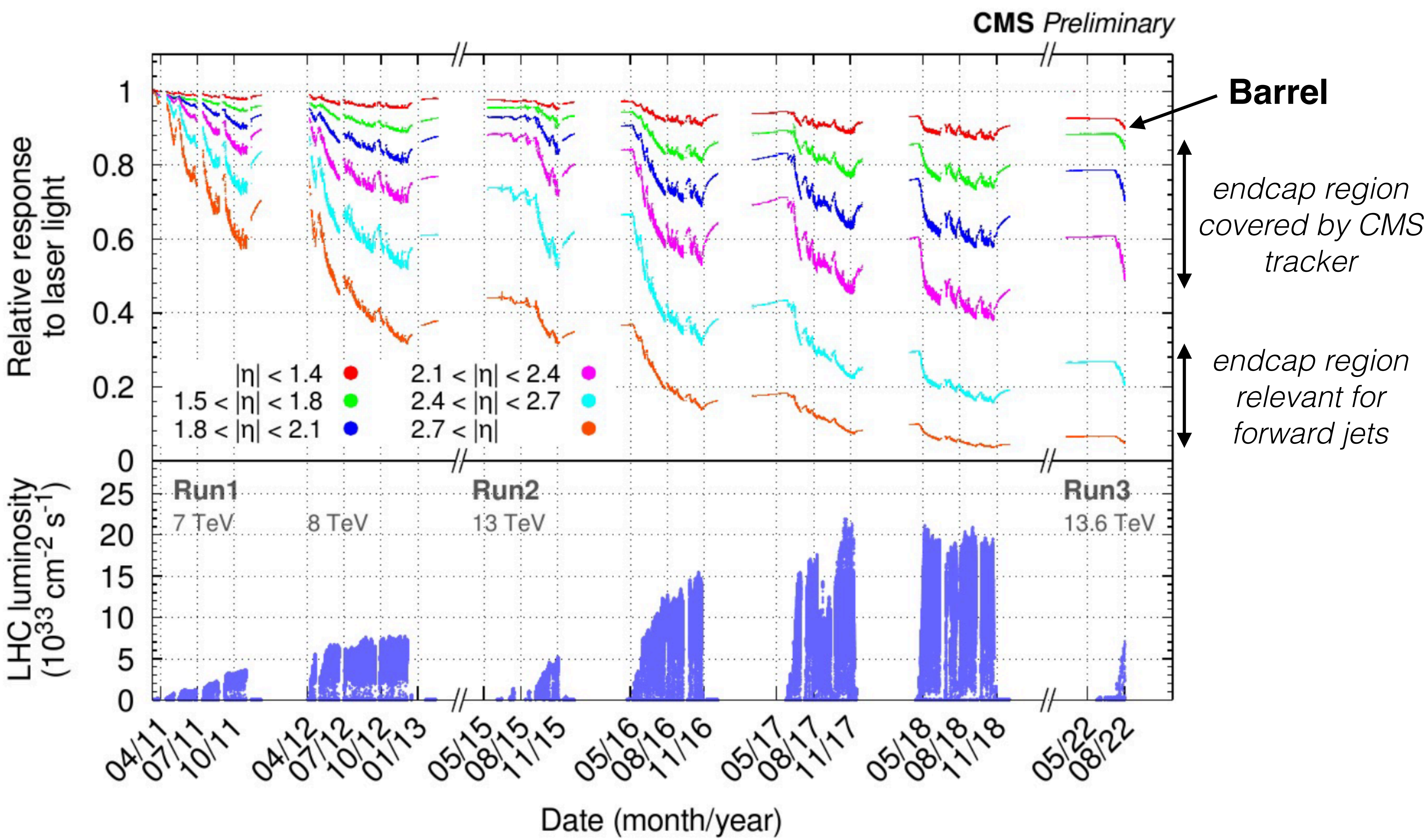
Large improvements in low energy e/γ and jet response are obtained

A similar algorithm has also been developed and deployed for CMS HCAL during LHC Run 2

(*) allows up to 9 out-of-time pulses

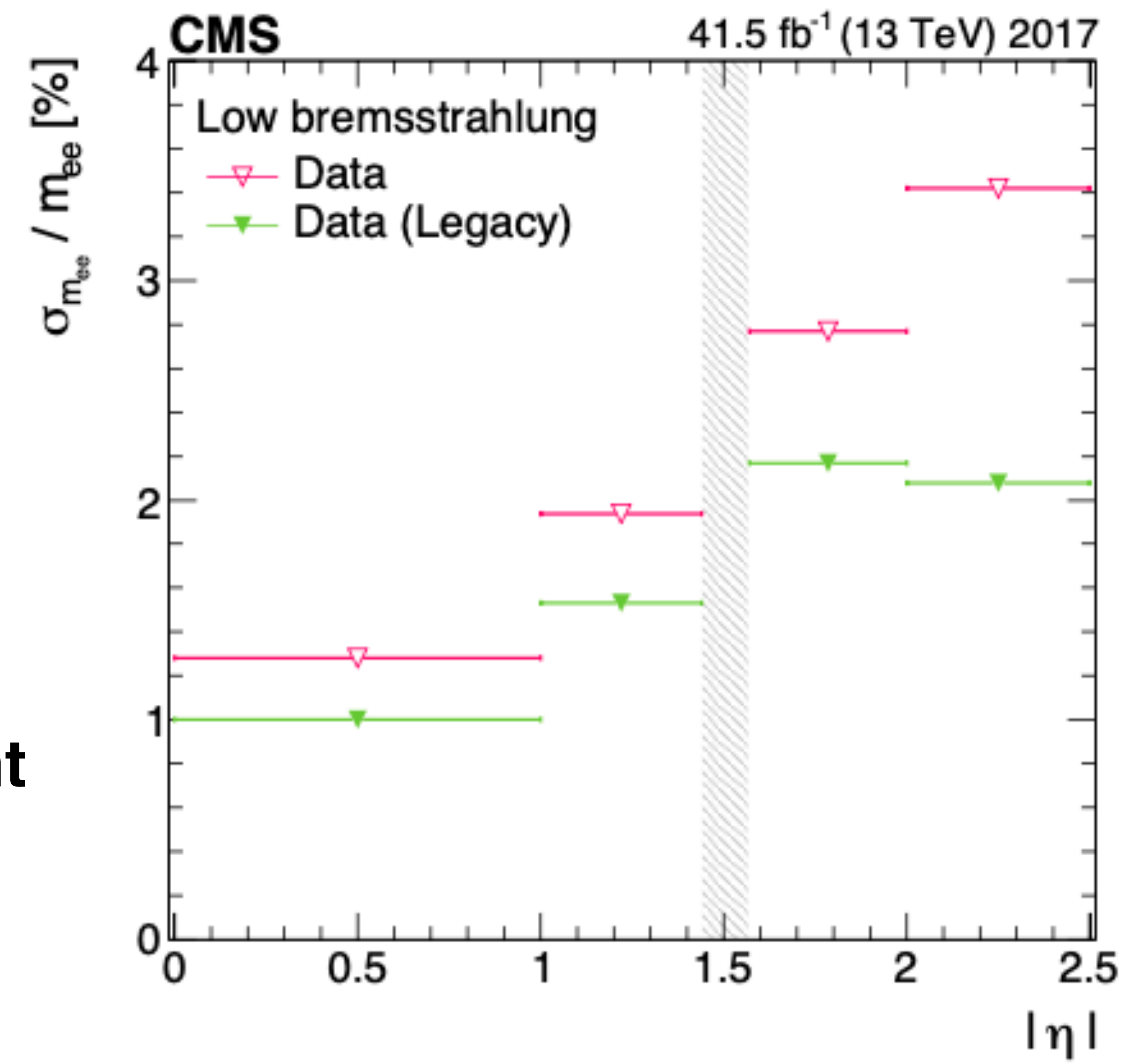
Calibration challenges - CMS ECAL

- **Significant response changes (crystal + photodetector) due to LHC irradiation**
- **Need for both short term and long term corrections**
  - via dedicated laser monitoring system (corrections within 48h)
  - **special attention must be devoted to high eta region to prevent biases in jets and MET**



Importance of recalibration

- **Refined physics-based calibrations using full dataset are derived at the end of each running year**
  - **these are required to obtain optimal energy resolution in all regions of the detector**
    - **they correct for time-dependent drifts/imperfections in calibrations**



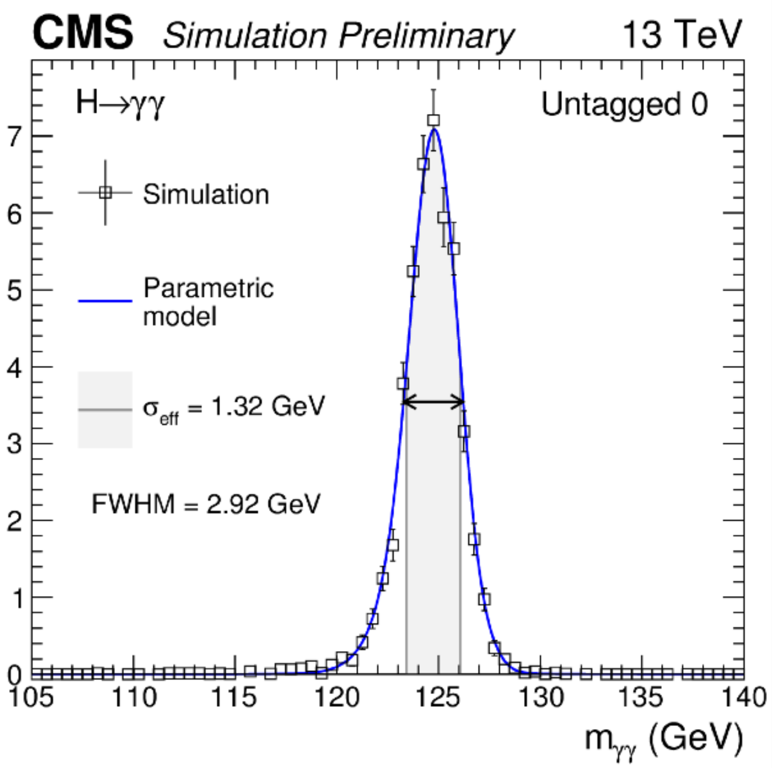
Di-electron Z mass resolution before and after end-year recalibration

Resolution vs eta follows distribution of upstream tracker material:

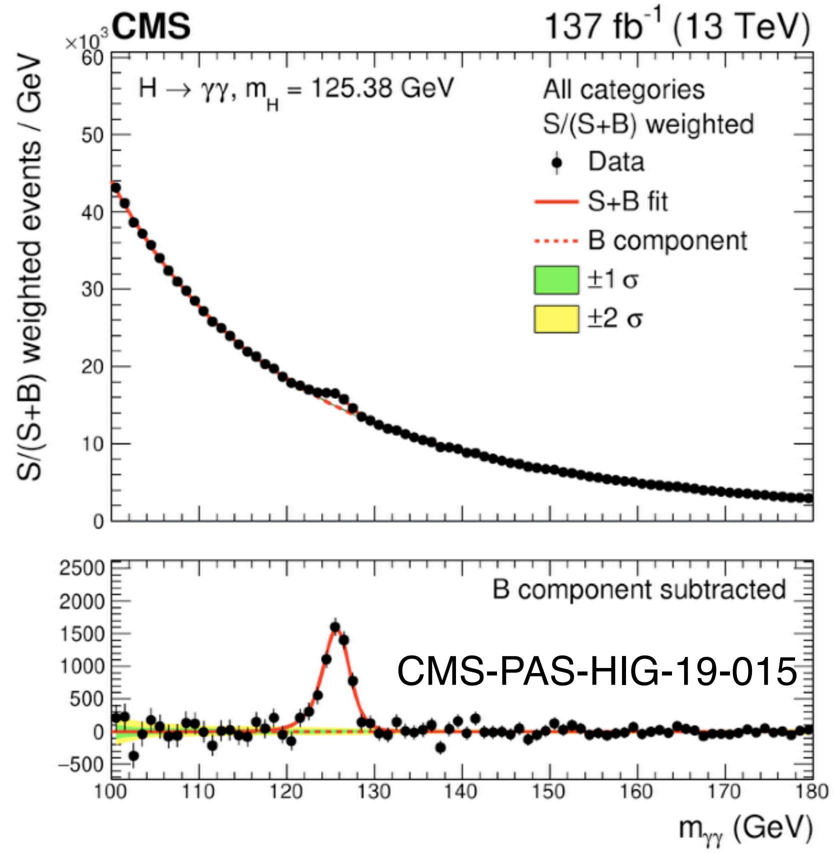
need to minimise this in future detector designs to preserve intrinsic ECAL resolution

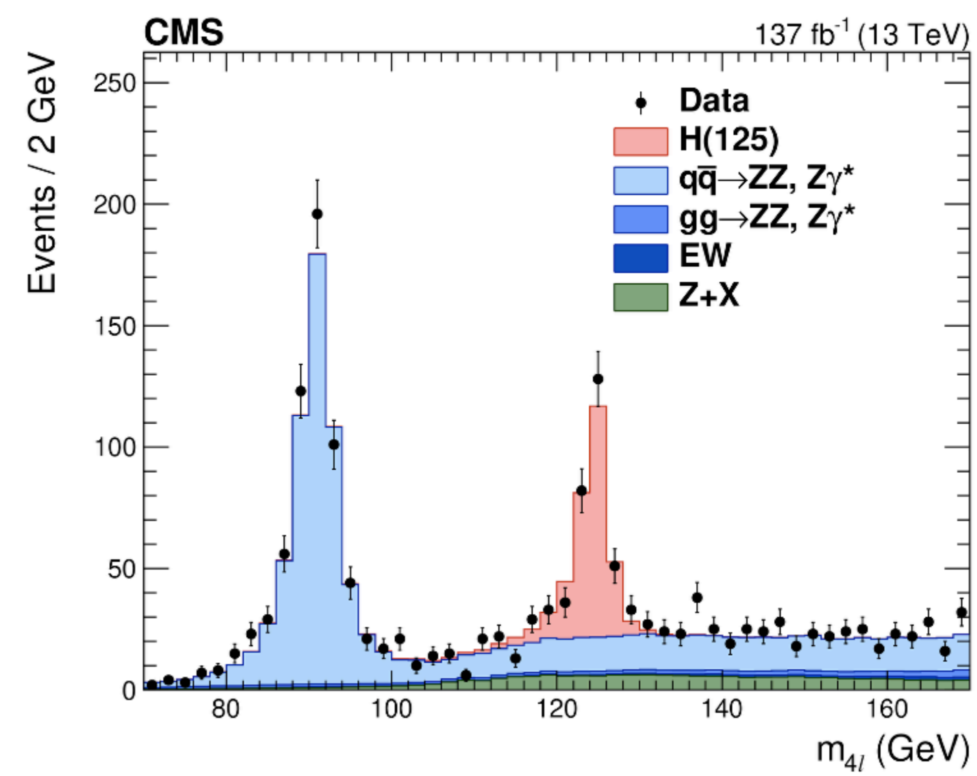
Despite the challenges:

$H \to \gamma\gamma$ | $H \to ZZ \to 4l$



Mass resolution in best category ~1%





… it was all worth it

The excellent resolution and electron/photon ID of the CMS and ATLAS calorimeters was crucial in the discovery and subsequent characterisation of the 125 GeV Higgs Boson

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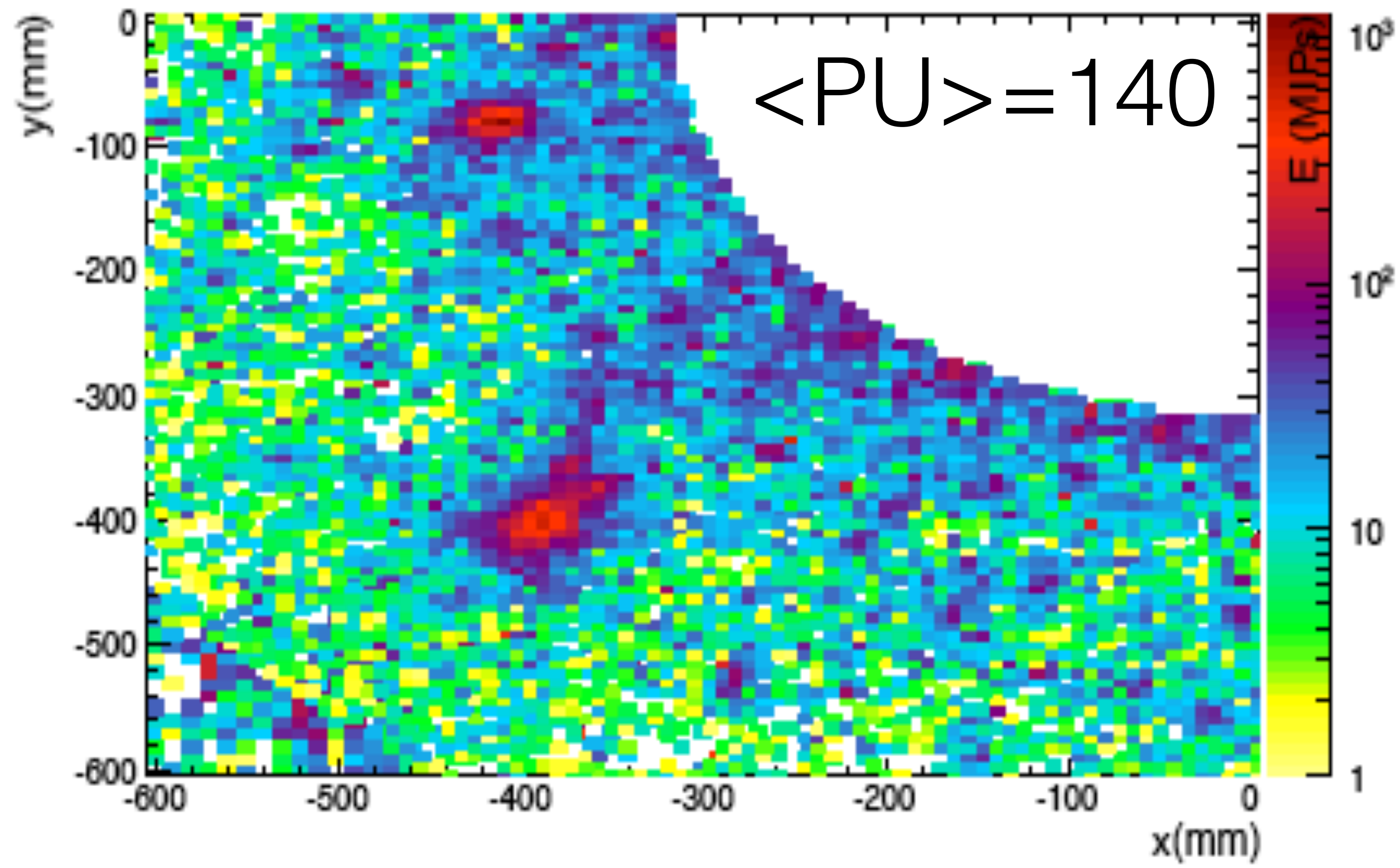
Upgrades

Challenges for forward calorimetry at HL-LHC

- **Expect LHC to deliver very high luminosity beams: <pileup> ~ 140-200 interactions per bunch crossing**
- Disentangling event properties at such high particle densities requires **good transverse and longitudinal segmentation**, and **advanced reconstruction** methods
- **Need highly granular radiation-hard detectors** to meet the challenges of **high beam intensity and event pileup**

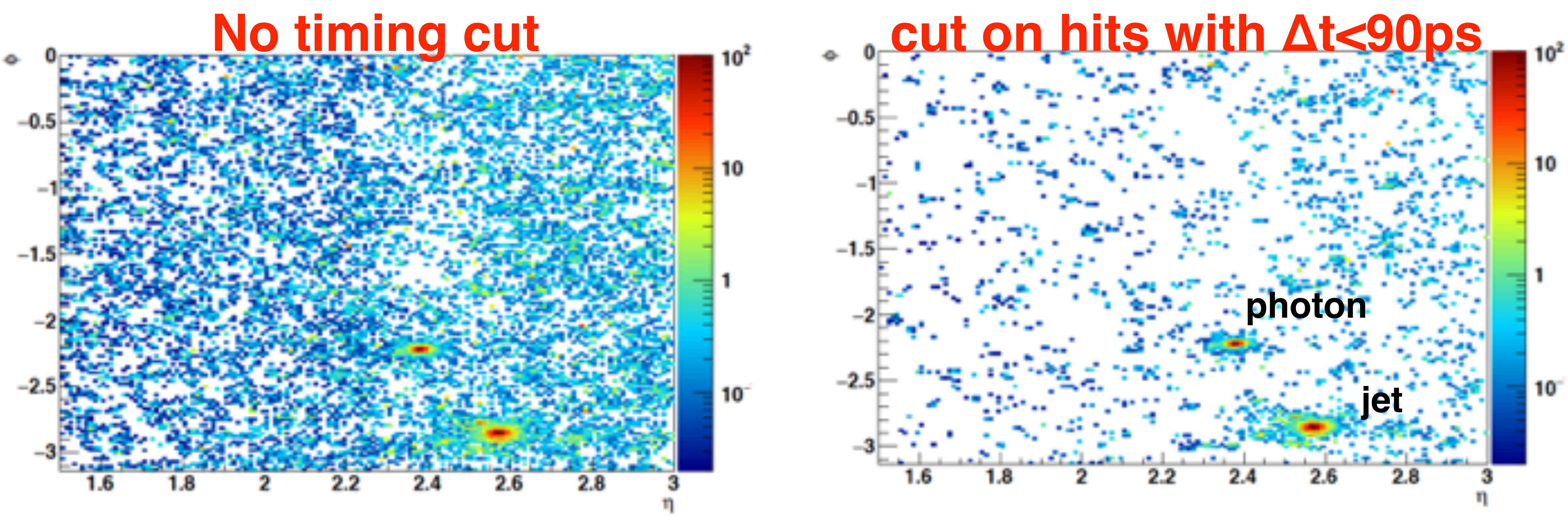


Event display of VBF jets (H->gg)

Impact of precise timing

- **Reconstruction at 200 PU is a significant challenge**
  - pattern recognition techniques and vertex identification struggle in dense environment

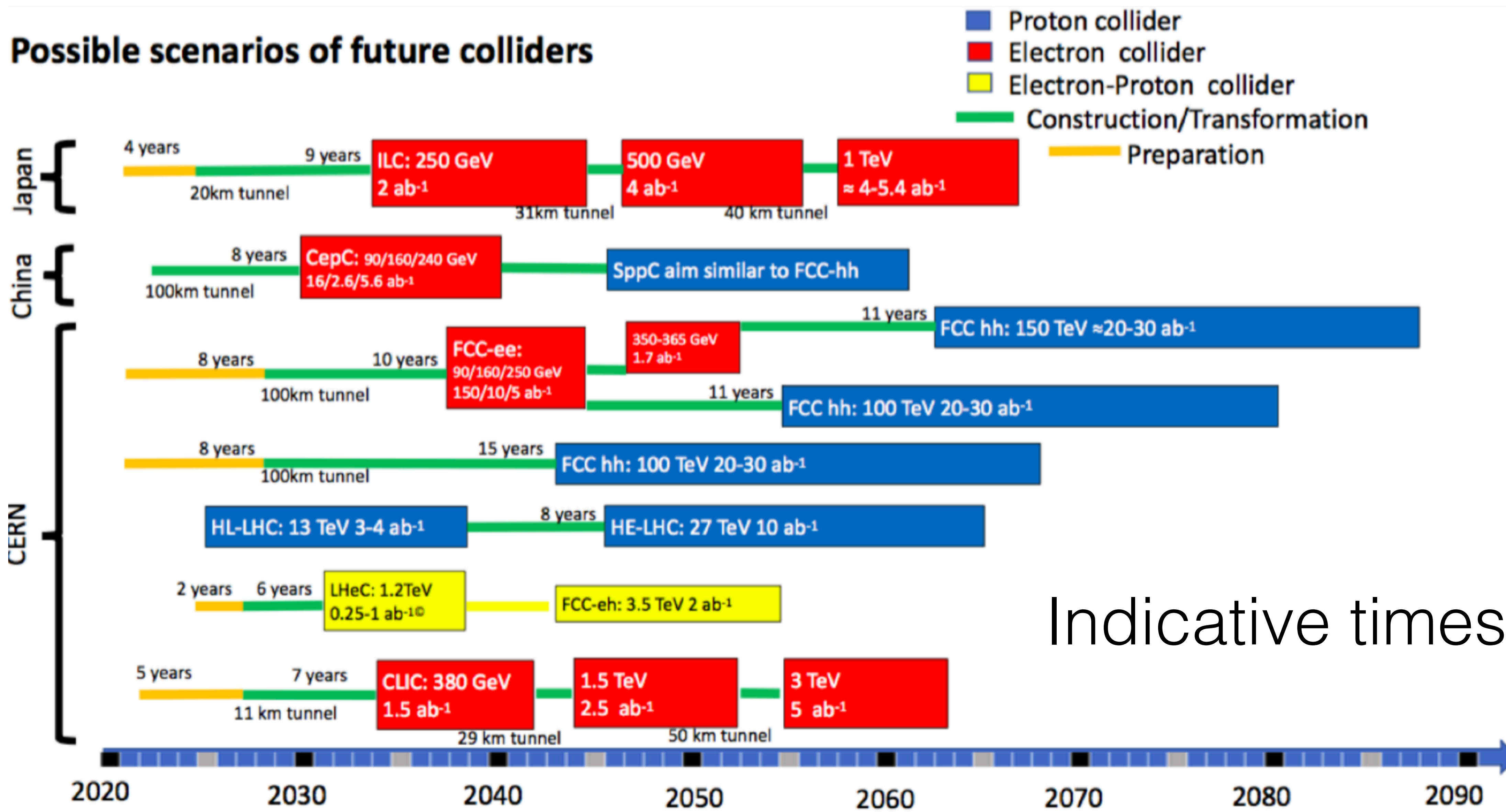
VBF H→γγ with forward jet



- **Improved vertex localisation and pileup suppression possible with precise timing capability (σ_t~30ps)**
  - precise timing a critical feature of CMS and ATLAS HL-LHC upgrades

The show must go on

- **Particle Physics community currently developing roadmap of future colliders/experiments**
  - **includes both precision Higgs physics facilities (linear/circular e+e- colliders) and higher energy (100 TeV) pp discovery machines**



Indicative timescales

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Calorimeters will be a key element of future collider experiments

Detector requirements from future experiments

From the Detector R&D requirements ECFA February session

Strong interaction experiments

- Measure low energy photons (down to 10 MeV)
- Photon pointing resolution
- Target energy resolution ~2%√E

'No-collider' experiments

- High-intensity and radiation conditions
- Energy resolution, segmentation and timing
- Low energy particles
- Crystal purity

Hadron colliders

- Pileup mitigation through precision timing and granularity
- Radiation tolerance (up 30 MGy for FCC-hh → ~30x HL-LHC)
- Target energy resolution ~10%√E

$\mu^+\mu^-$ colliders

- Mitigation of beam induced background (BIB) through precision timing and granularity
- Target energy resolution ~10%√E

e^+e^- colliders

- Improve Z→ee recoil mass resolution
- Clustering of π^0 photons
- Heavy flavor program (low energy photons)
- Target energy resolution ~3%√E

high granularity, excellent energy resolution, precise timing in focus

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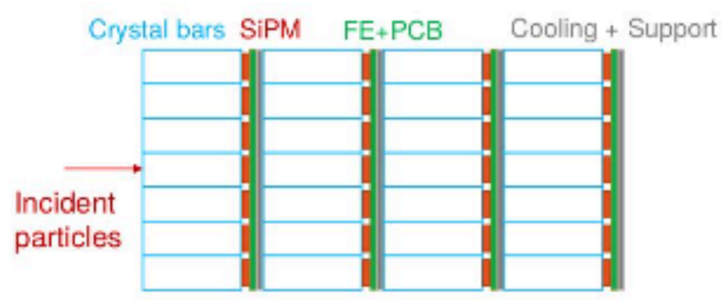
Example designs - electron colliders

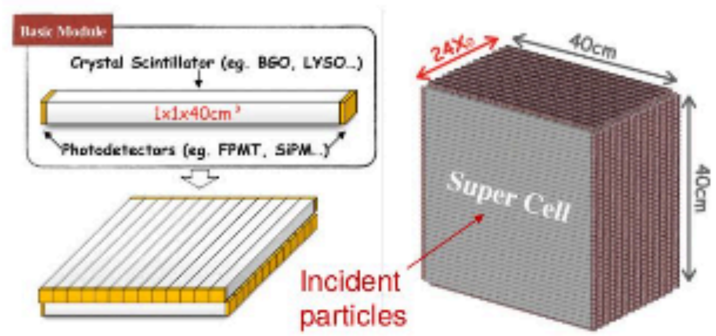
High granularity crystal calorimeter for CEPC

Y.Liu, Detector concept with crystal calorimeter @IAS Conference 2021

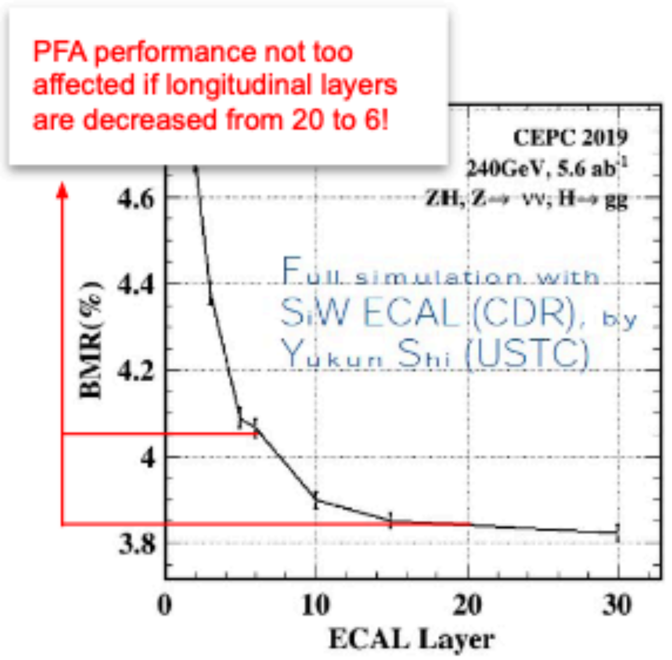
Design 1

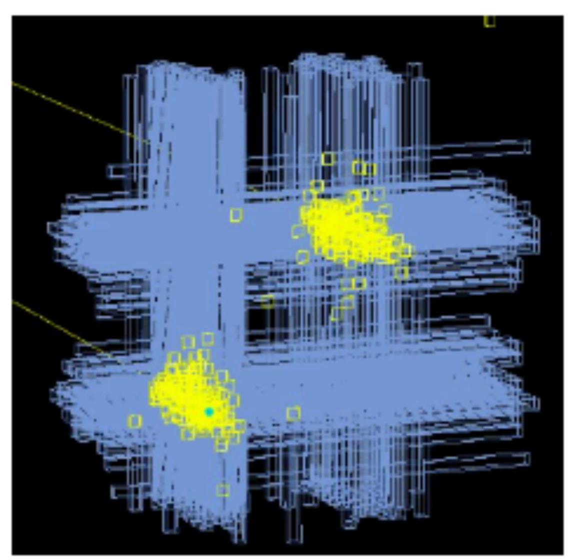


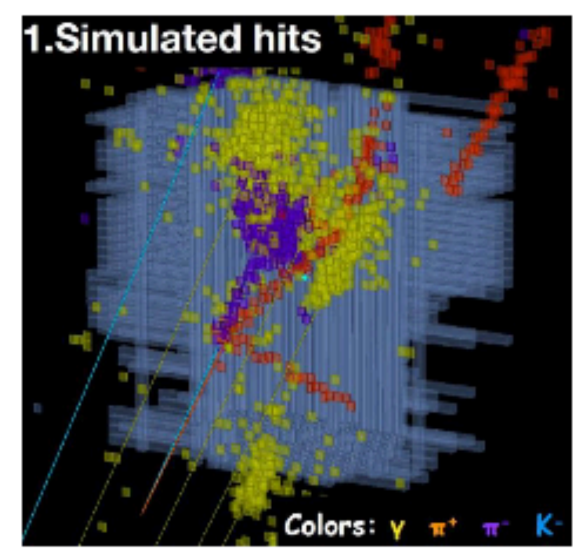
Design 2



Evaluating optimal crystal configuration for granular 3D imaging







Developing precision particle flow optimized for crystal calorimetry

Merging high granularity and high energy resolution for precision physics at e^+e^- colliders

23

Focus on energy resolution and segmentation for Particle Flow Reconstruction

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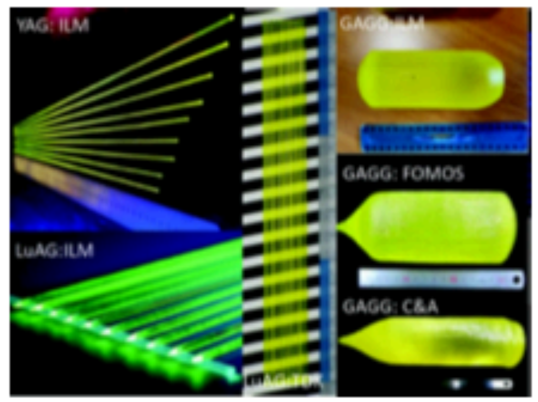
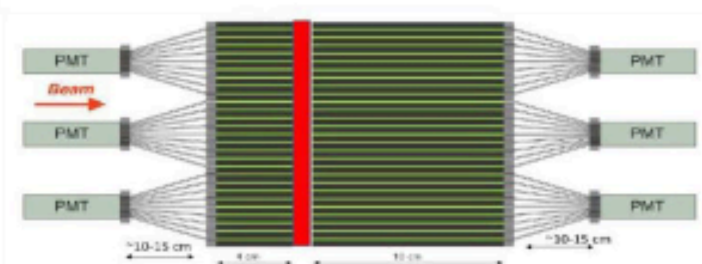
Example designs - hadron colliders

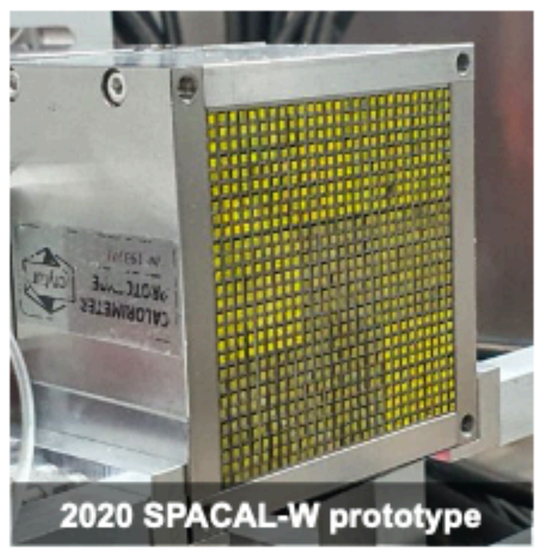
Radiation tolerant sampling crystal calorimeters

Spaghetti calorimeter (candidate for the LHCb phase II upgrade)

- Crystal fibers inside an absorber ‘groove’ (more details here)
- Co-doped garnet crystals (GAGG, YAG, GYAGG)
- **Possibility to mix different type of fibers** (e.g. Cerenkov, neutron sensitive)
- Targets: $\sigma_E/E \sim 10\%/\sqrt{E}$, $\sigma_t \sim O(10)$ps

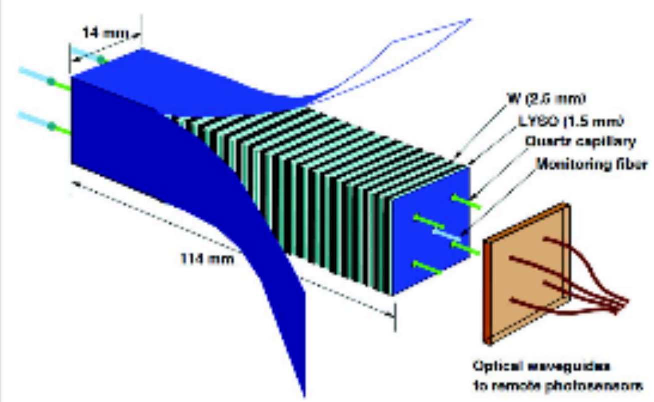





2020 SPACAL-W prototype

Shashlik calorimeter (was candidate for CMS phase II upgrade)

- Crystal slabs interleaved with tungsten slabs and read out with wavelength shifting fibers
- UV-emitting crystals (LYSO, CeF_3)
- SiO2:Ce or LuAG:Ce fibers as WLS
- Targets: $10\%/\sqrt{E}$, $\sigma_t \sim O(10)$ps
- Ongoing R&D targeting FCC-hh applications with the ***RADiCAL*** detector concept (CPAD 2021)



Combining tungsten with radiation tolerant crystals for compact calorimeters at hadron colliders

21

radiation tolerance is key for pp collider calorimeters

Example designs - hadron colliders

Radiation tolerant sampling crystal calorimeters

Lots of new ideas on calorimeters for future hadron and lepton colliders

See recent Calorimeter Detector R&D (DRD6) workshop at CERN:
https://indico.cern.ch/event/1246381/

Very interesting time ***to get involved in Calorimeter R&D, bench tests, test beams and simulations for the future generation of calorimeter detectors***

Combining tungsten with radiation tolerant crystals for compact calorimeters at hadron colliders 21

radiation tolerance is key for pp collider calorimeters

Summary and outlook

Summary

- **Calorimeters are a crucial element of HEP detectors**
  - provide total energy measurements of electrons/photons and jets
  - optimised for high spatial and energy resolution, often in challenging radiation environments
- **Calibration and monitoring are crucial to maintain optimal performance**
  - to minimise variations in energy response between channels and over time due to detector irradiation
- **Several different design choices have been implemented at LHC**
  - this complementary is essential - no “right” or “wrong” choices
  - physics output of LHC experiments is testament to the success of the designs
  - increased spatial and timing granularity in focus for HL-LHC upgrades to maintain performance in more challenging detector environment
  - **Thanks for listening and enjoy the remainder of the lectures!**

Q1: Energy scale uncertainty

CMS and ATLAS both claim to be able to measure the Higgs mass to around 0.1%, using events from $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ decays.

Assume that we calibrate their respective ECAL detectors using electrons from $Z \to ee$ (invariant mass) and $W \to e\nu$ (E/p ratio) events.

How can we know that the energy scale measured using Z/W events is also valid for the energy range relevant for photons from a 125 GeV Higgs boson decay?

How can we verify that measurements and calibrations using electrons (from Z/W) are also valid for photons from $H \to \gamma\gamma$ decays? Is there a way of testing the validity of the photon corrections using specific categories of electron events (i.e. how could you select a subset of electrons that look like photons)

How would you go about proving how well we measure the energy scale for TeV-scale electrons (e.g from hypothesised $Z' \to ee$ decays)? What type of events could we use for this?

Q2: Detector design

What are the main factors relevant for defining the transverse size of segmented ECAL detectors? Divide this into "physics" and "practical" considerations.

What are the advantages of longitudinal segmentation for a) electromagnetic and b) hadronic calorimeters? What are the potential negatives?

If you had the opportunity to design the ultimate particle flow calorimeter (money being no object) what should its main characteristics be?

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References

CMS letter of intent

https://cds.cern.ch/record/290808/files/cern-lhcc-92-003.pdf

ECAL and HCAL TDRs

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=2713

https://cds.cern.ch/record/357153/

CMS detector paper

http://iopscience.iop.org/article/10.1088/1748-0221/3/08/S08004/

ECAL Run 1 performance

https://cds.cern.ch/record/1554142

HCAL Phase 1 TDR

https://cds.cern.ch/record/1481837/

Phase 2 Technical proposal (see ch 3)

https://cds.cern.ch/record/2020886

LEGO® CMS Model

https://build-your-own-particle-detector.org/models/cms-lego-model

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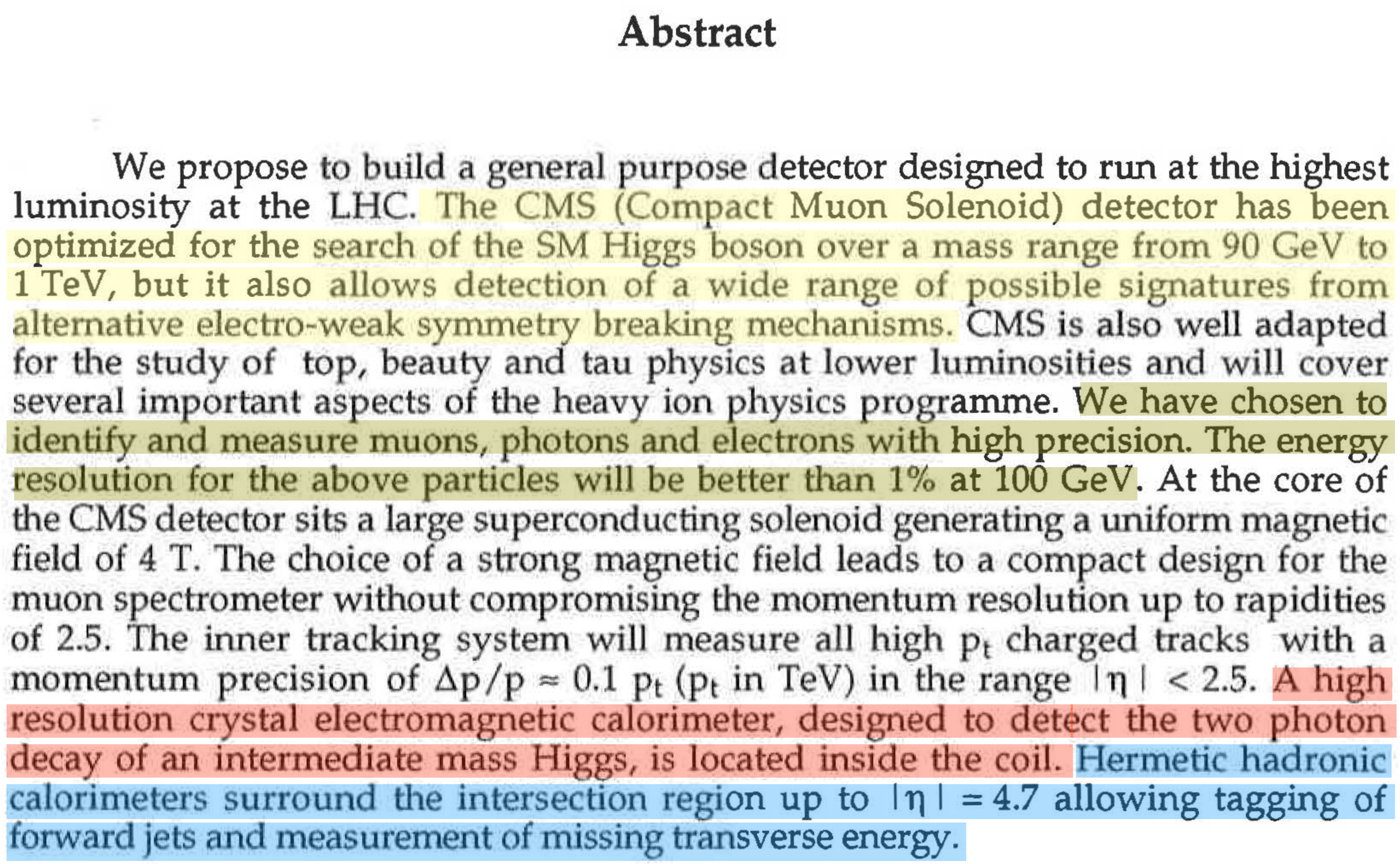
Designing and Operating calorimeters

CMS example, from design to construction to operation

1992: CMS Letter of intent

https://cds.cern.ch/record/290808/files/cern-lhcc-92-003.pdf



Abstract

We propose to build a general purpose detector designed to run at the highest luminosity at the LHC. The CMS (Compact Muon Solenoid) detector has been optimized for the search of the SM Higgs boson over a mass range from 90 GeV to 1 TeV, but it also allows detection of a wide range of possible signatures from alternative electro-weak symmetry breaking mechanisms. CMS is also well adapted for the study of top, beauty and tau physics at lower luminosities and will cover several important aspects of the heavy ion physics programme. We have chosen to identify and measure muons, photons and electrons with high precision. The energy resolution for the above particles will be better than 1% at 100 GeV. At the core of the CMS detector sits a large superconducting solenoid generating a uniform magnetic field of 4 T. The choice of a strong magnetic field leads to a compact design for the muon spectrometer without compromising the momentum resolution up to rapidities of 2.5. The inner tracking system will measure all high p_t charged tracks with a momentum precision of $\Delta p/p \approx 0.1\, p_t$ (p_t in TeV) in the range $|\eta| < 2.5$. A high resolution crystal electromagnetic calorimeter, designed to detect the two photon decay of an intermediate mass Higgs, is located inside the coil. Hermetic hadronic calorimeters surround the intersection region up to $|\eta| = 4.7$ allowing tagging of forward jets and measurement of missing transverse energy.

- **high resolution EM calorimetry for Higgs detection, located inside coil**
- **large rapidity coverage for jets/MET**

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The goals of calorimetry in CMS

- **CMS optimised for discovery of SM Higgs boson**
  - in mass range 90 GeV - 1 TeV
- **CMS ECAL optimised for golden discovery channels**
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$
  - Focus on excellent photon/electron efficiency and resolution
    - better than 1% energy resolution at 100 GeV
- **CMS HCAL optimised for excellent jet identification**
  - over a wide pseudorapidity range
  - excellent hermeticity a must for MET determination, for SM and BSM studies
  - combined HCAL and ECAL information essential for good electron/ photon ID and tau ID

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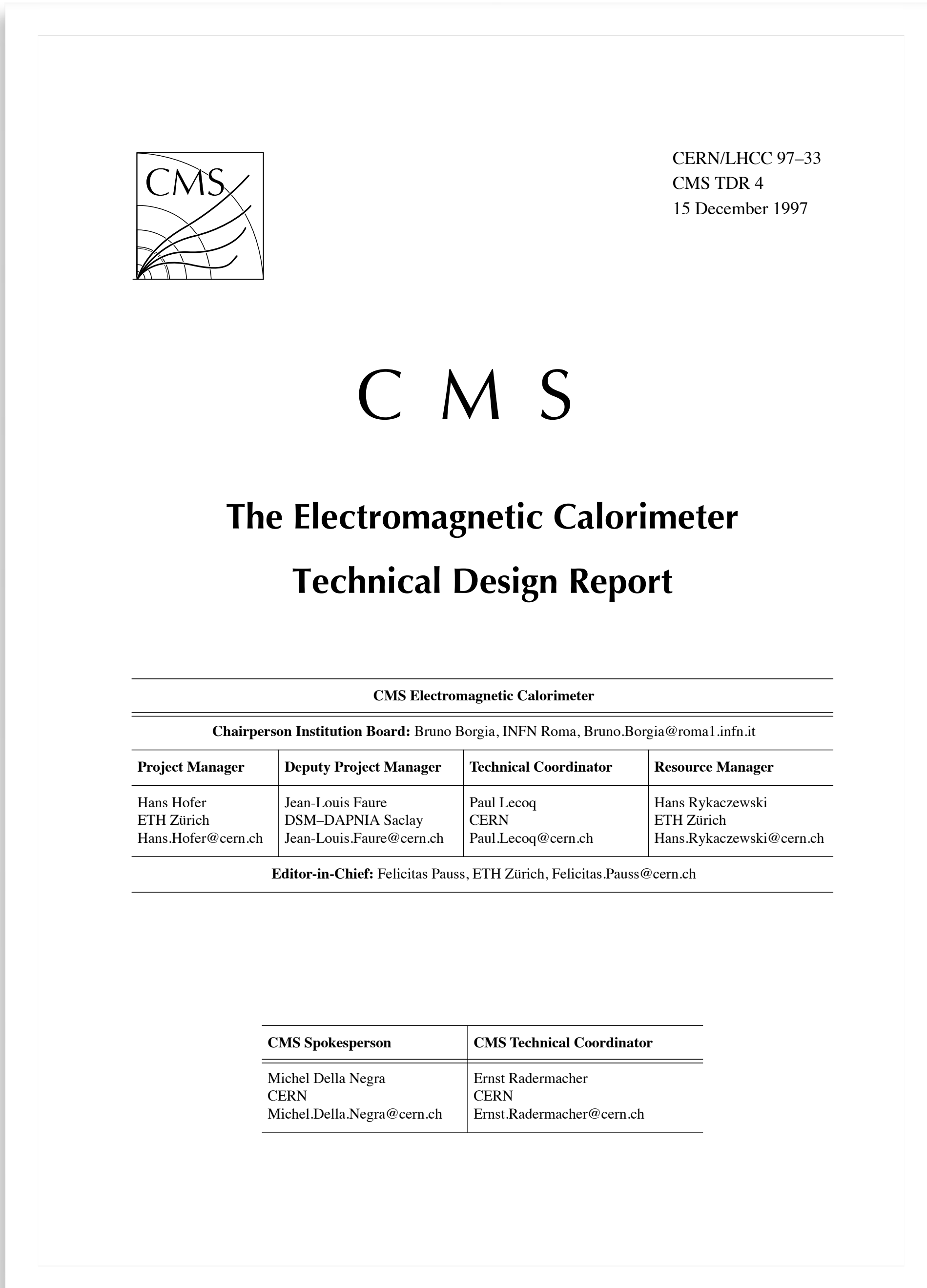
1997: ECAL and HCAL TDRs



CERN/LHCC 97–33
CMS TDR 4
15 December 1997

C M S

The Electromagnetic Calorimeter

Technical Design Report

CMS Electromagnetic Calorimeter			
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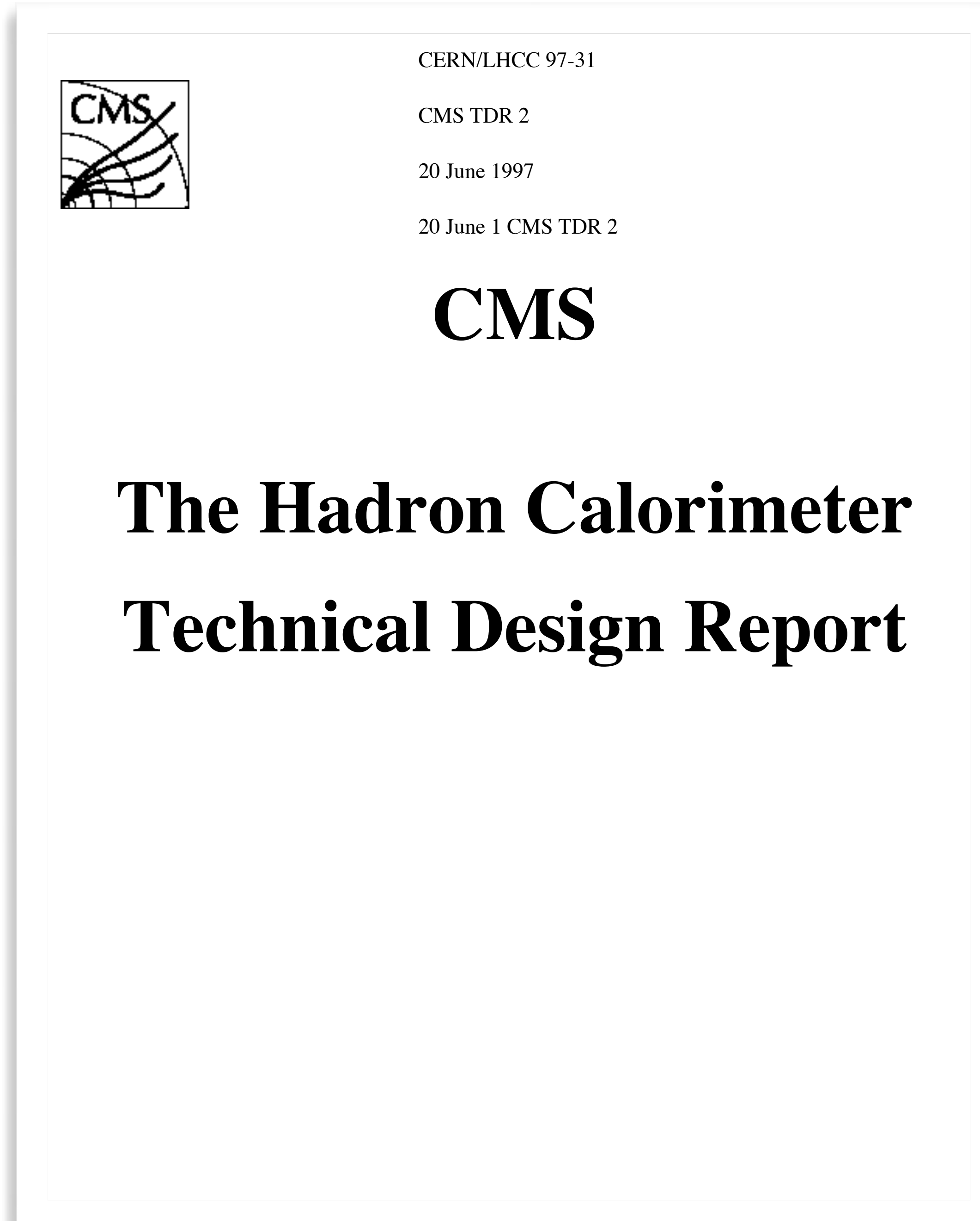


CERN/LHCC 97-31

CMS TDR 2

20 June 1997

20 June 1 CMS TDR 2

CMS

The Hadron Calorimeter

Technical Design Report

https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=2713

https://cds.cern.ch/record/357153/

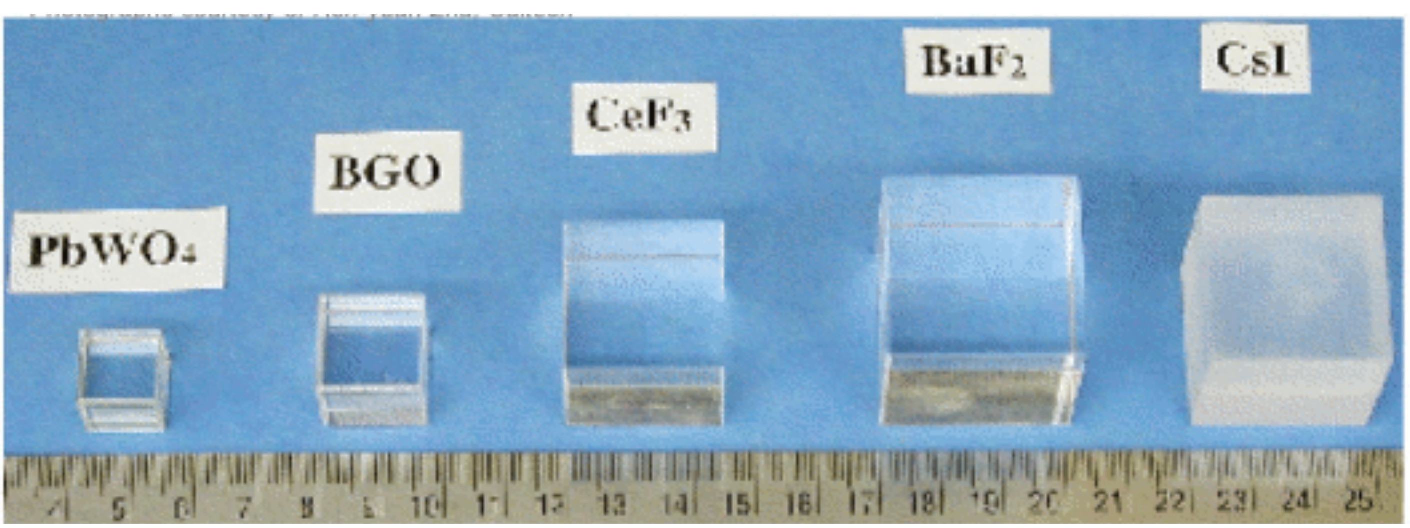
Lead tungstate crystals

	Sampling	Homogeneous scintillators		
Property	Pb/plastic Shashlik	Liquid Xenon	CeF_3 crystals	$PbWO_4$ crystals
Density (g cm^{-3})	4.5	3.06	6.16	**8.28**
Radiation length X_0 (cm)	1.7	2.77	1.68	**0.85**
Molière radius R_M (cm)	3.4	4.1	3.39	**2.19**
Wavelength peak (nm)	500	175	300	**440**
Fast decay constant (ns)	<10	2.2	5	**<10**
Light yield (γ per MeV)	13	~5 x 10^4	4000	**100**

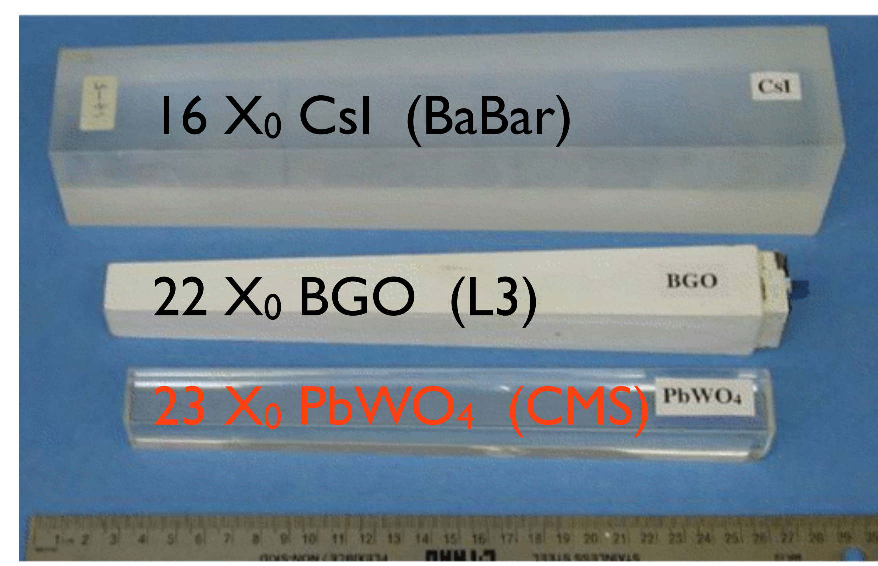
$PbWO_4$ is used for CMS:
fast, **dense** and **radiation-hard**

Low relative light-yield mitigated by use of high-QE/large area photodetectors with internal gain

light yield: -2%/deg C
requires stable temperature operation, within 0.05 deg C, to maintain resolution target



1.5 X_0 cubes of different xtal materials



compactness is crucial to allow both ECAL and HCAL to be situated within CMS solenoid

ECAL performance targets

- The CMS ECAL must be **fast** and **radiation tolerant** to survive in the LHC environment, and must possess **excellent energy resolution**
- Benchmark physics process: **H→γγ**
- Energy resolution target:
  - **0.5% for unconverted photons**

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

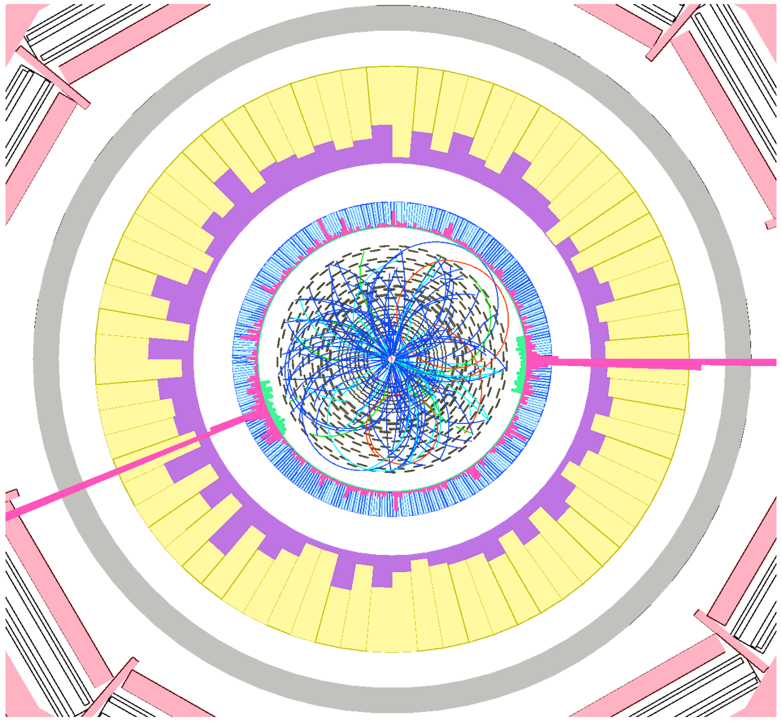
EM energy resolution

a: Stochastic term: lateral shower containment photostatistics, photo-detector gain

b: Noise term: electronic noise event pile-up

c: Constant term: temperature/HV stability accuracy of inter-calibration constants non-uniformity of longitudinal light collection

dominates at high energy



A **H** → γ γ event in CMS with M_H=120GeV

Performance measured for ECAL Barrel in CERN H4 test beam (20-250 GeV electrons):

a=2.8%	b=41.5 MeV	c=0.3%
stochastic term	noise term	constant term

P.Adzic et. al. *"Energy resolution of the barrel of the CMS Electromagnetic Calorimeter"*, JINST 2 P0400 (2007)

Performance in test beam

ECAL

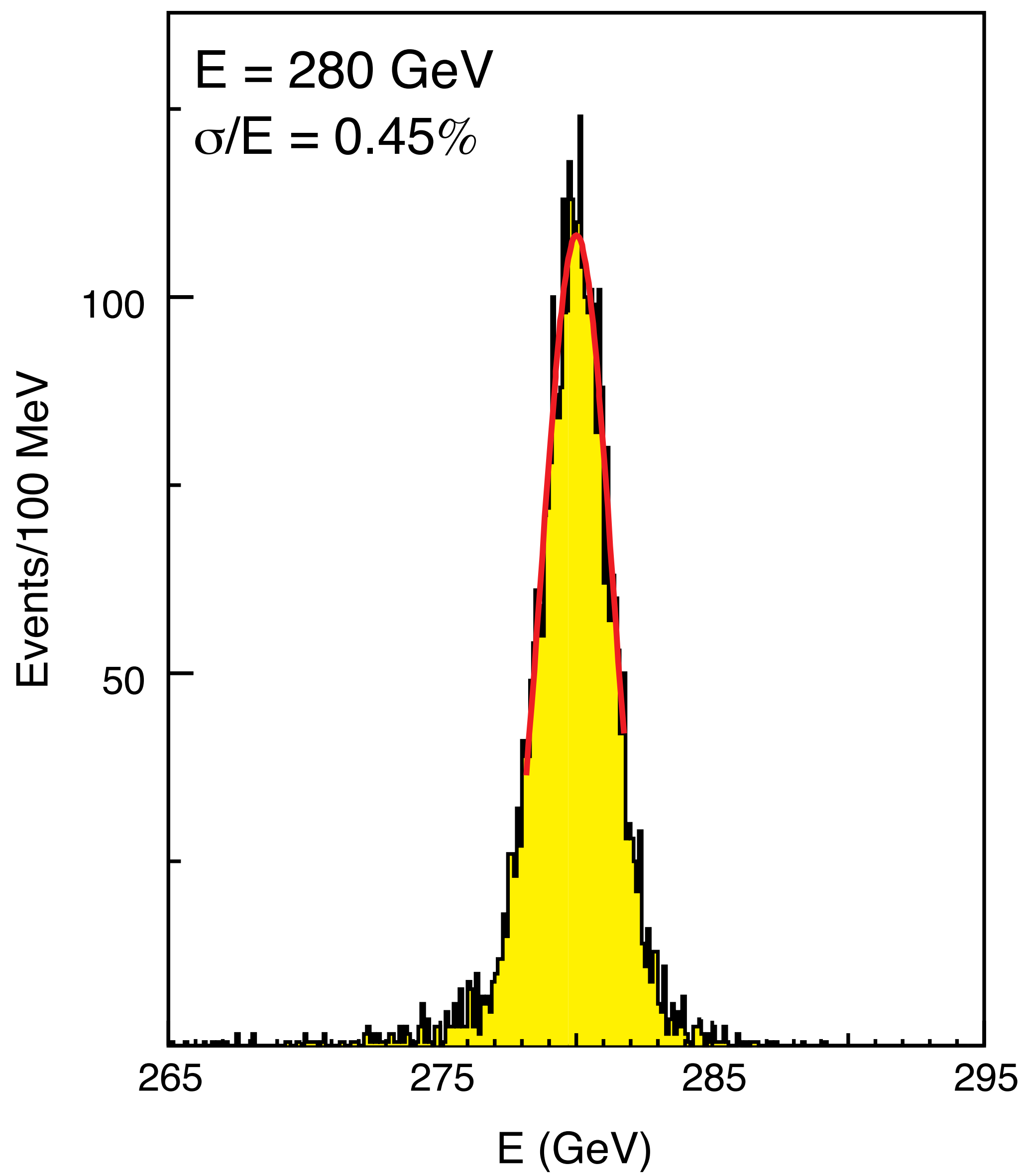
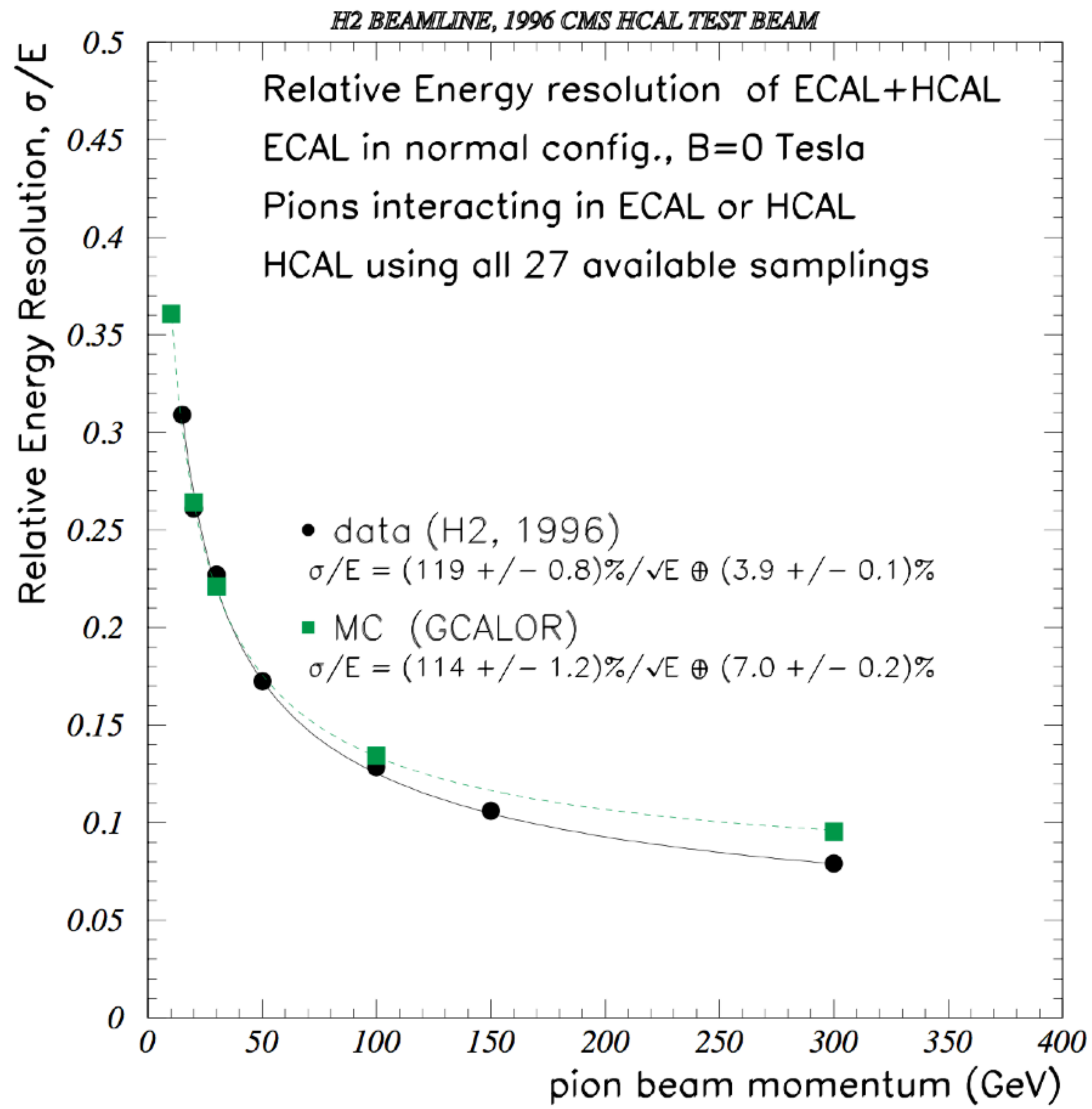


Fig. 1.15: Energy reconstructed in 3 × 3 crystals with 280 GeV electrons.

ECAL+HCAL



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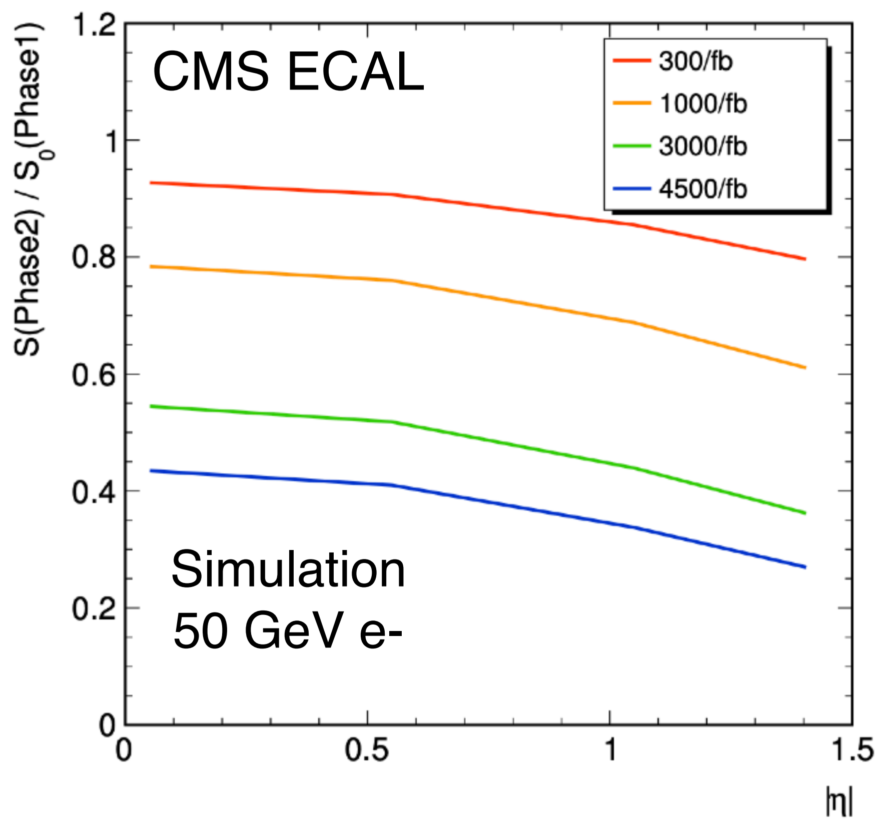
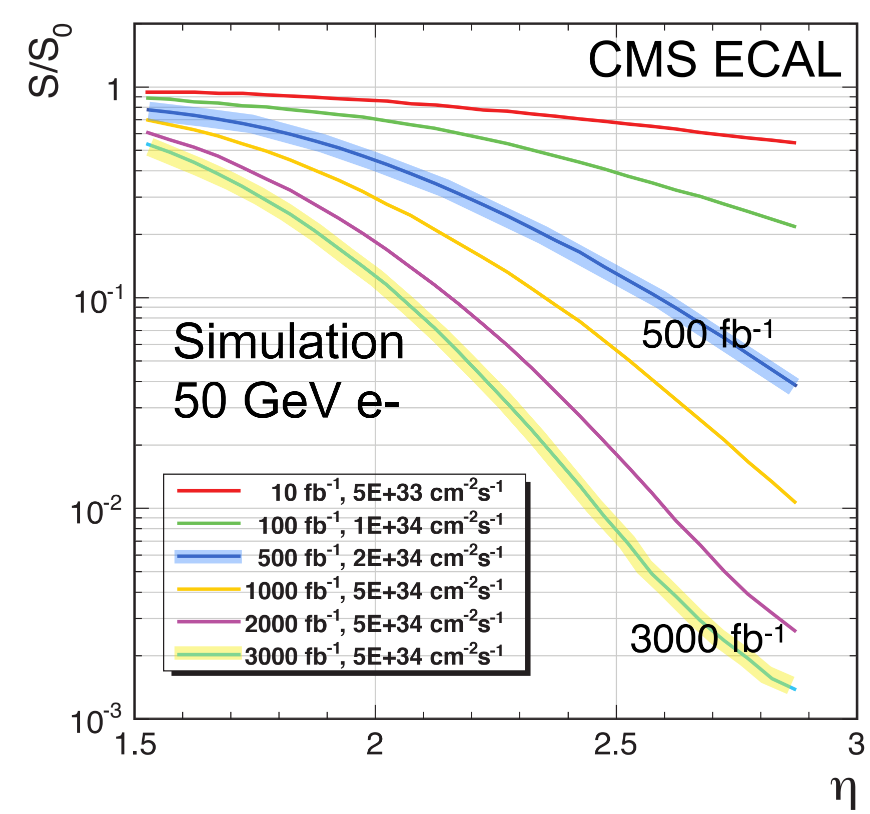
Detector longevity

- ECAL and HCAL barrel (|η|<1.48) will retain significant light output and will be **retained for HL-LHC operation**
- ECAL and HCAL endcaps (|η|>1.48) will suffer significant radiation damage after 500fb^{-1} and **will need to be replaced during LS3**
  - loss of light transmission in $PbWO_4$ crystals caused by hadron irradiation.
  - loss of signal response from plastic scintillator tiles + WLS fibre



Predicted ECAL Barrel signal response versus integrated luminosity and η



Predicted ECAL Endcap signal response versus integrated luminosity and η

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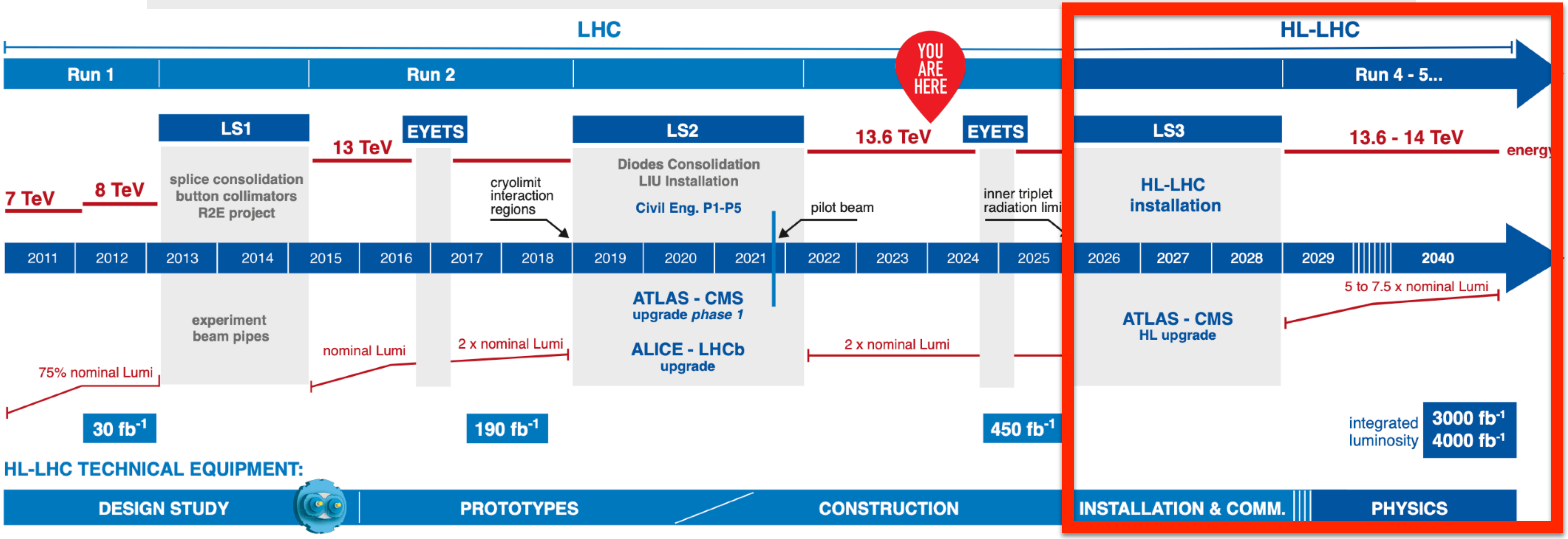
High Luminosity LHC



HL-LHC: major upgrade to accelerator complex during Long Shutdown 3 (2026-8)

will provide **10x** larger dataset for physics compared to LHC run ($4000fb^{-1}$)

4x higher instantaneous luminosity compared to peak LHC value

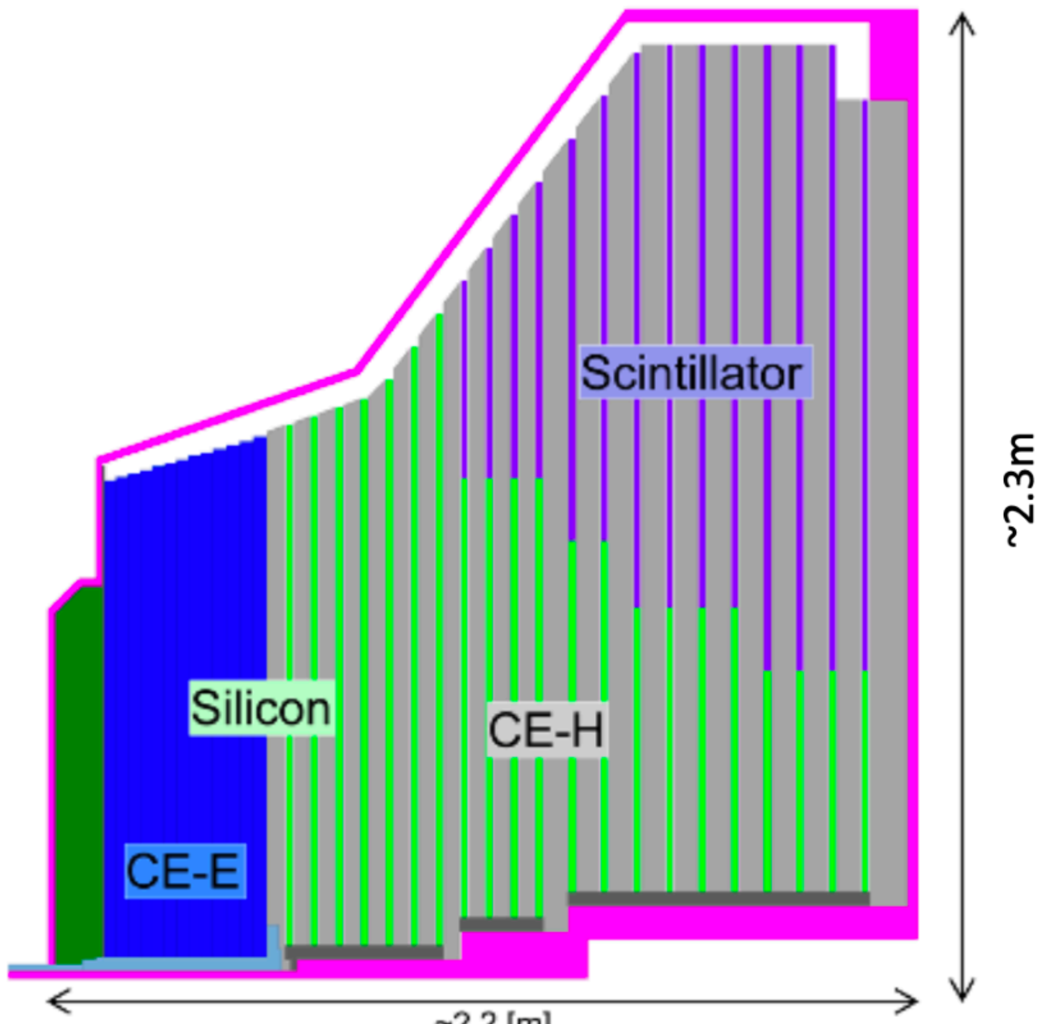
Consequences:

Run 2 challenges, pileup and detector ageing, are amplified

New and upgraded detectors are needed after 2025:

Focus on increased detector **granularity** and **precise timing** capability (for pileup mitigation), and increased **radiation tolerance**.

Endcap Calorimeter layout



- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

- **Full system maintained at -30°C**
  - **~620m²** of silicon sensors
  - **~370m²** of scintillators
- **6 Million Si channels**, 0.5 or 1.2 cm² cell size
  - ~26000 Si modules

Electromagnetic calorimeter (CE-E): **Si,** Cu/CuW/Pb absorbers, 26 layers, 27.7 X_0
Hadronic calorimeter (CE-H): **Si** + **scintillator**, steel absorbers, 21 layers, 10.0 λ_I

Complete replacement for CMS ECAL and HCAL endcaps

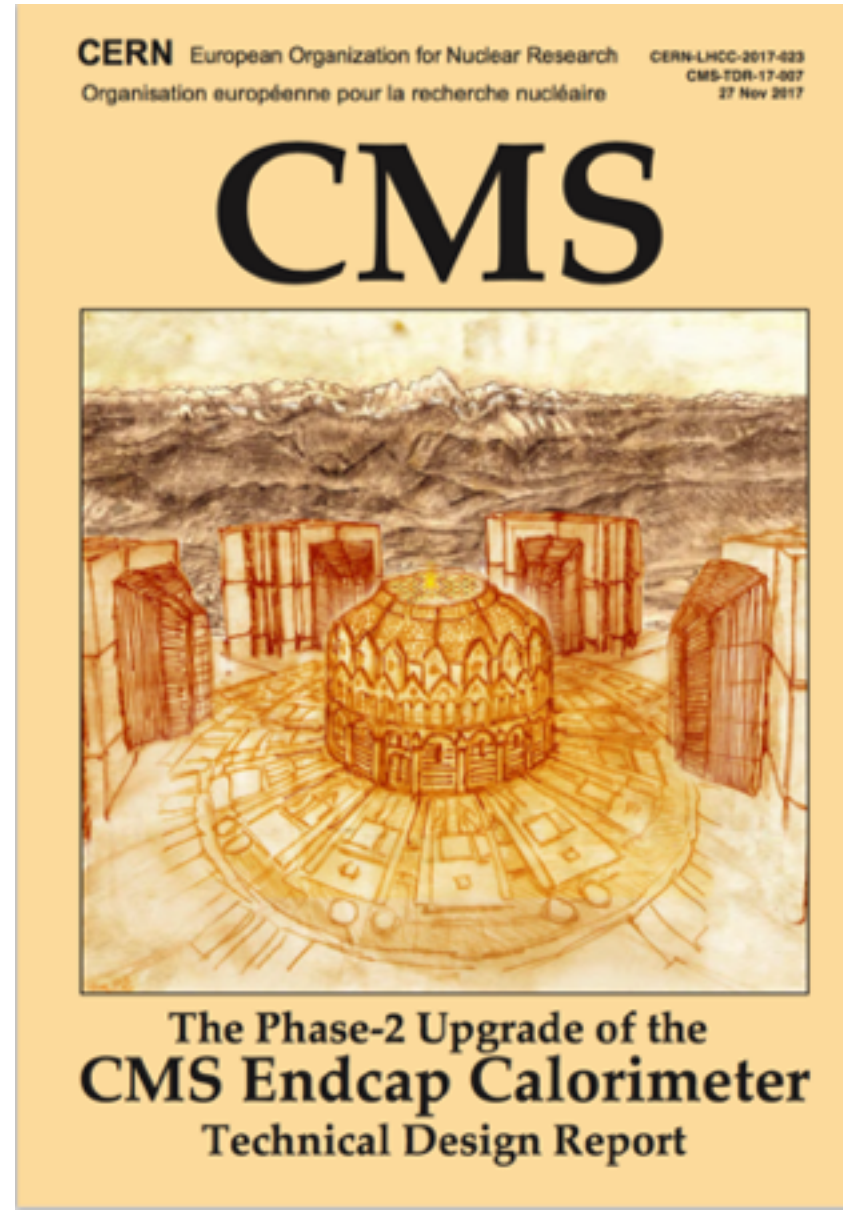
Sampling calorimeter with fine transverse granularity

silicon sensors in CE-E and inner CE-H region: intrinsically rad-hard

must operate at -30 degC to limit Si leakage current

Coming full circle

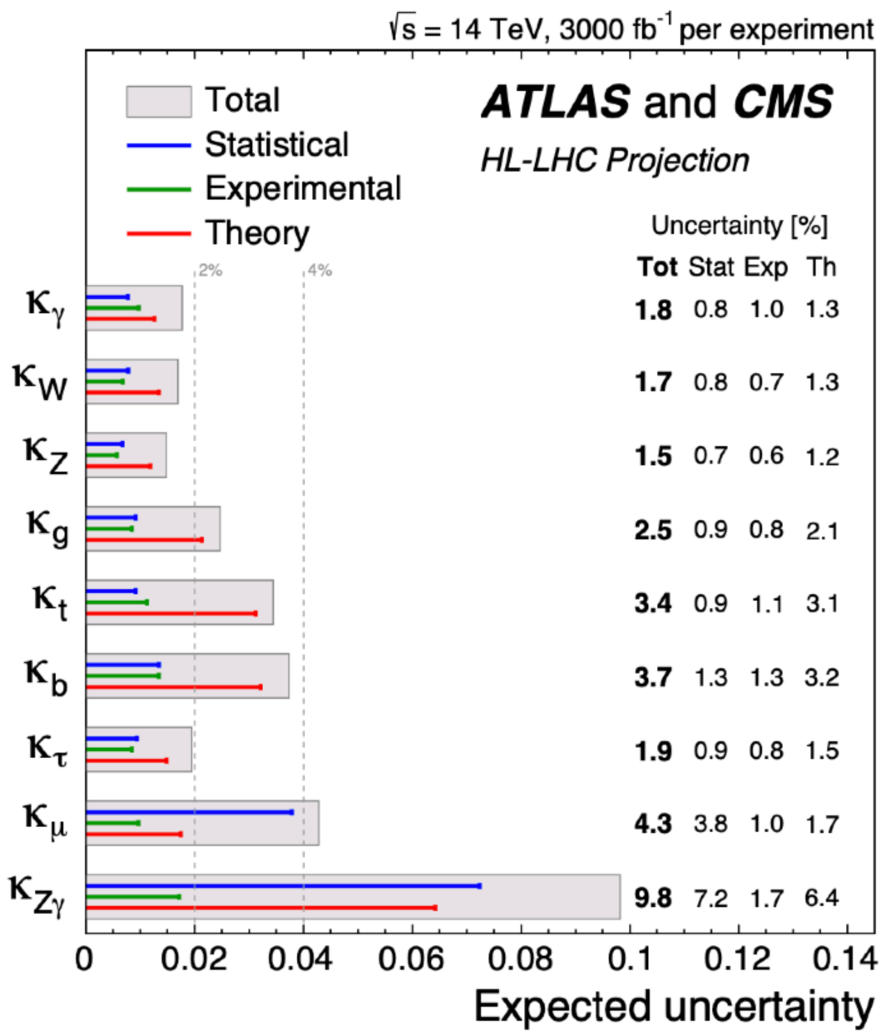
- **HL-LHC TDRs: released 20 years after the original versions**



https://cds.cern.ch/record/2283187/ https://cds.cern.ch/record/2293646/

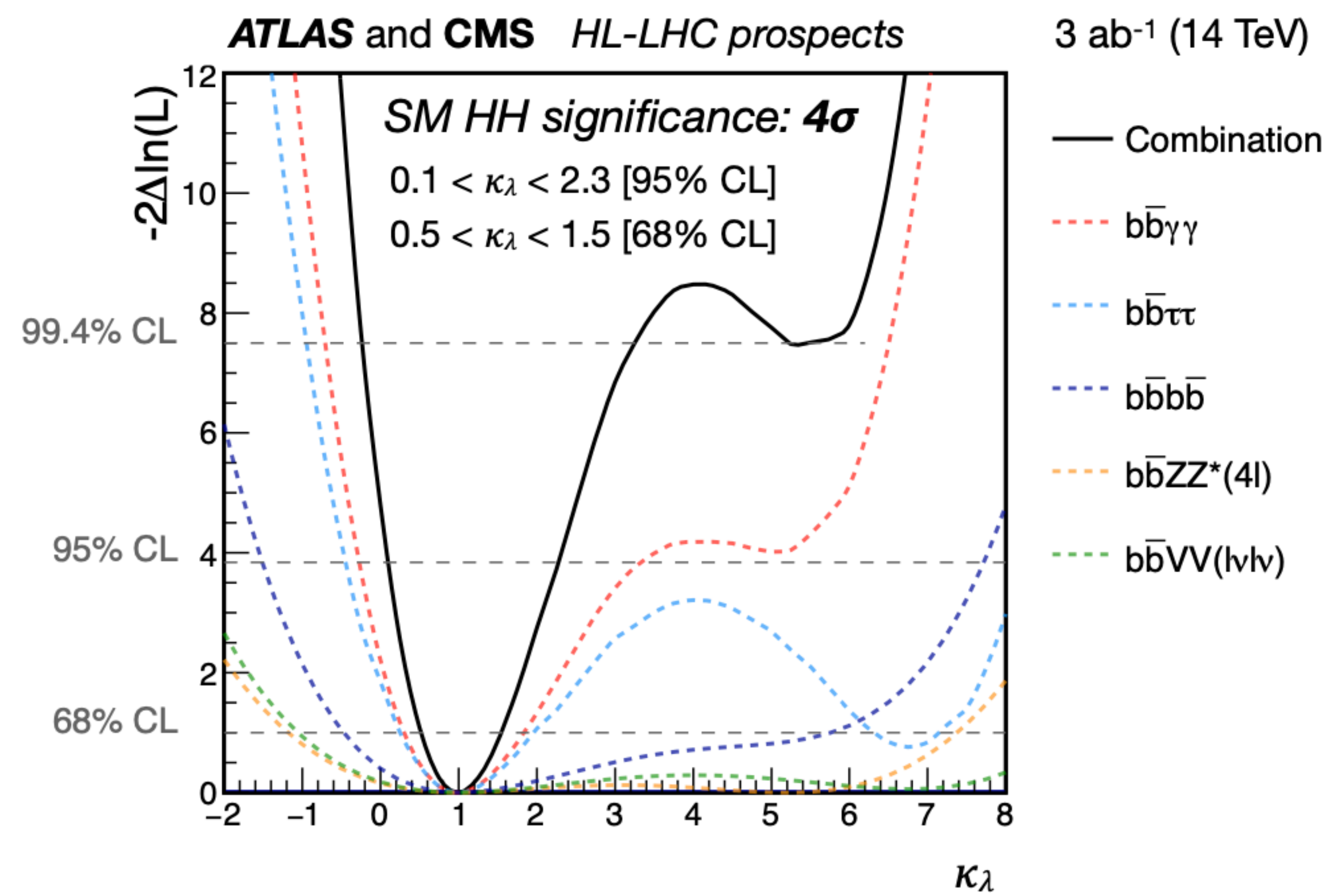
Physics capabilities of ATLAS+CMS at HL-LHC

- **Precision measurements of Higgs properties**



Precise (%-level) measurements of Higgs couplings

search for hints of BSM physics



4σ measurement of Higgs self-coupling

provide constraints on the shape of the Higgs potential close to the minimum and would allow to verify the electroweak symmetry breaking mechanism of the SM

HH→ bbγγ most sensitive channel

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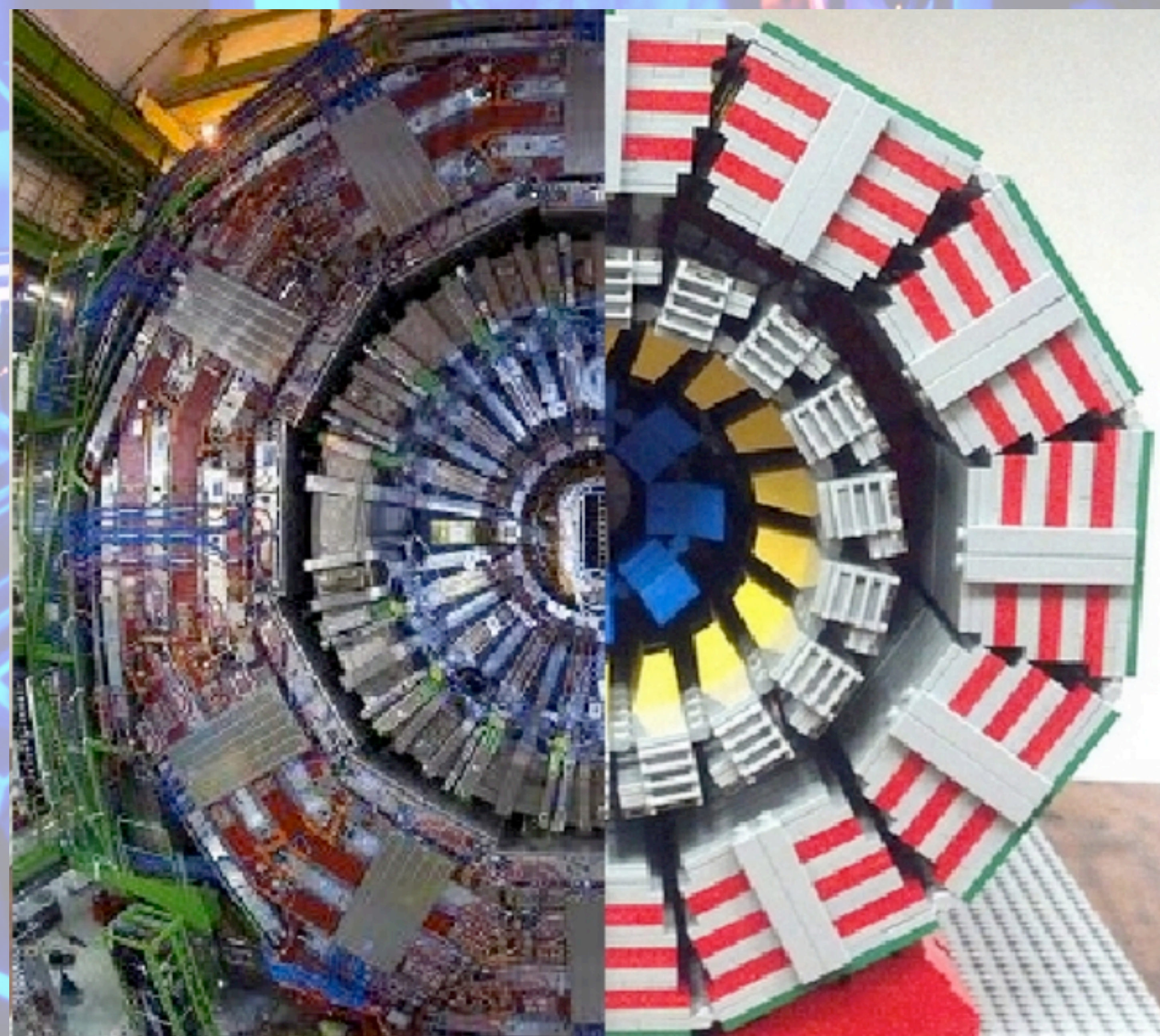
CMS Calorimeters as built

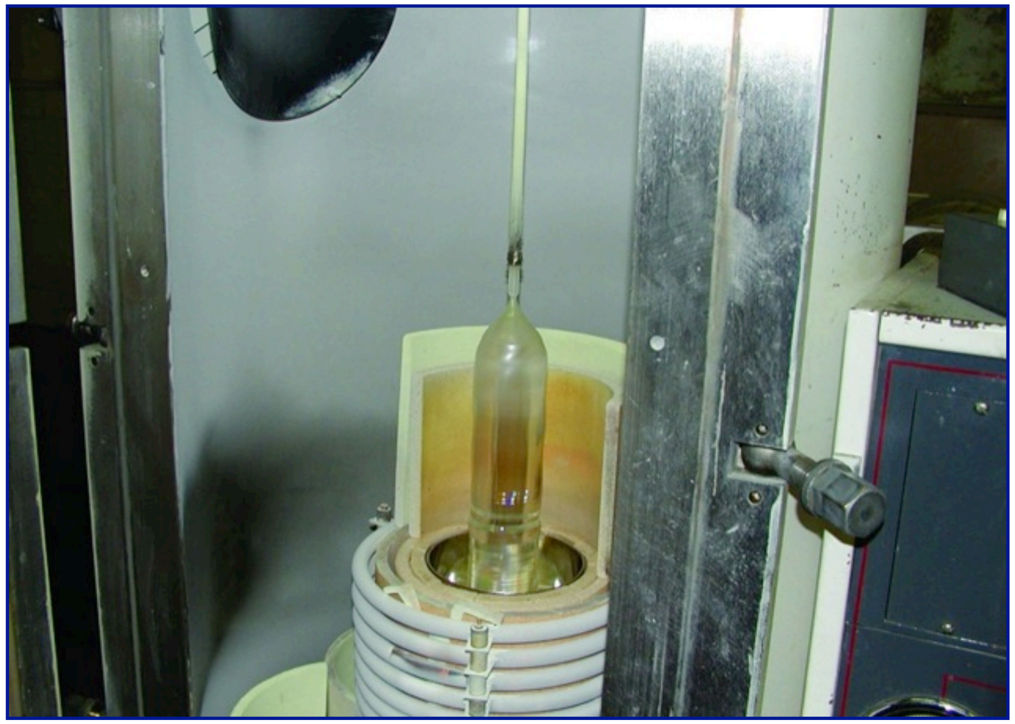


model credit: University of Maryland HEP group

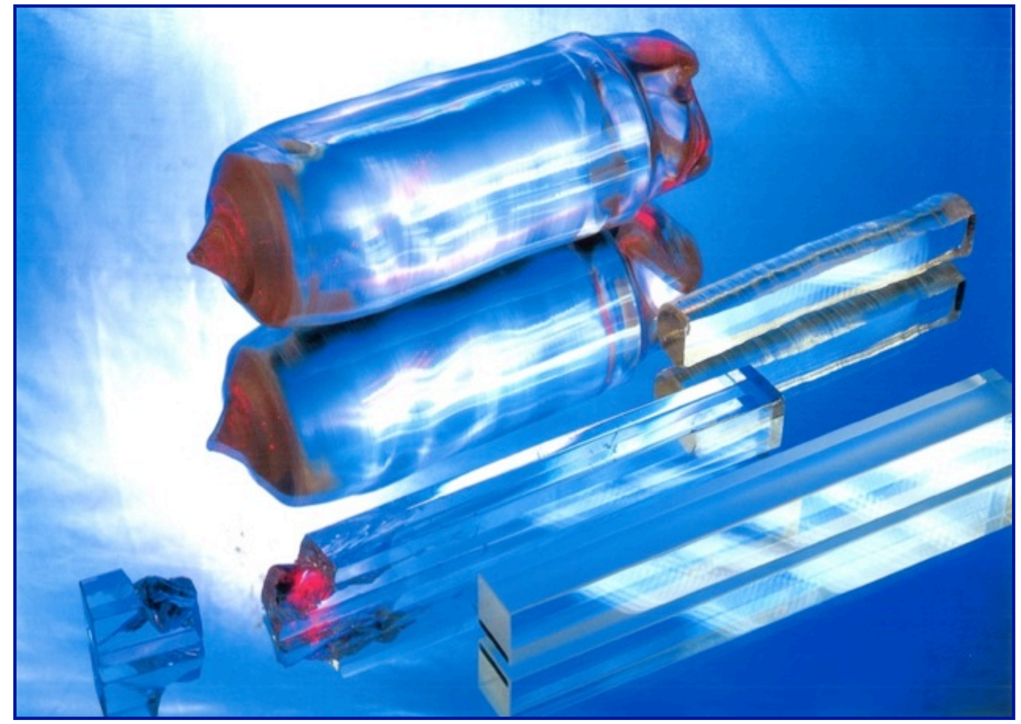
ECAL $PbWO_4$ crystals

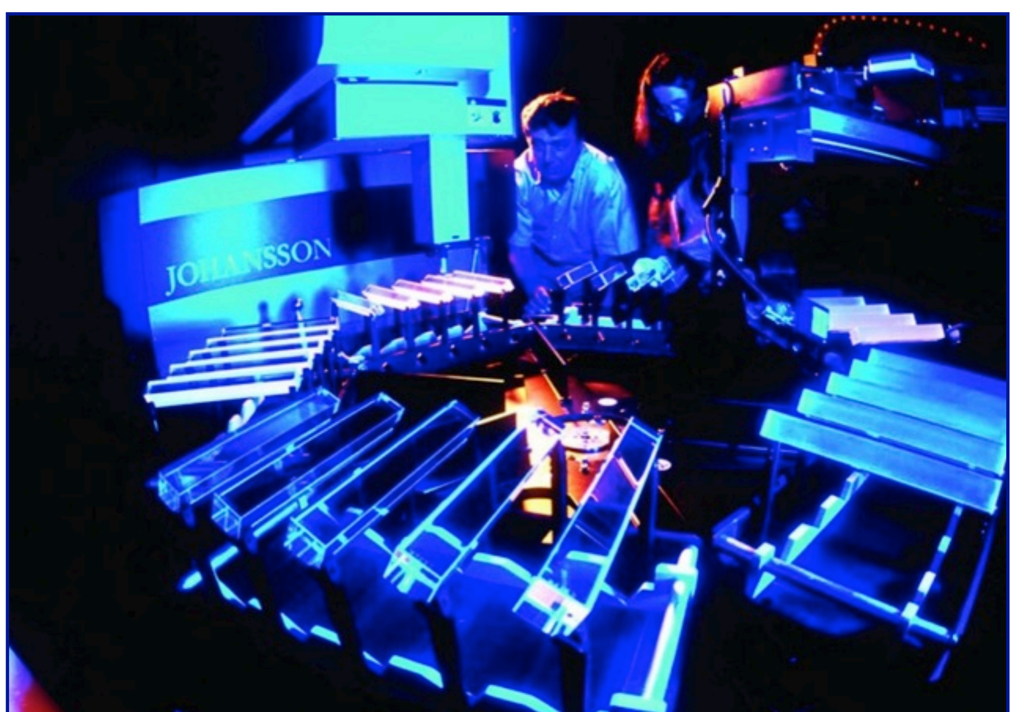
Two crystal producers: BTCP (Russia), SIC (China)

Crystal "growing"

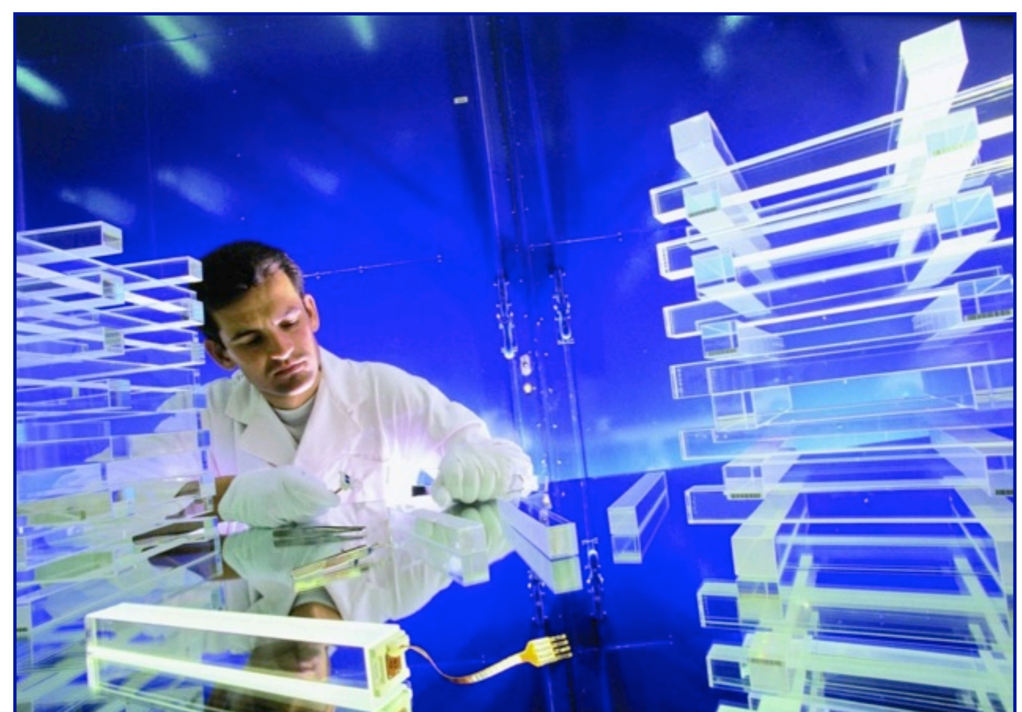


Raw crystal "boule" and cut crystals



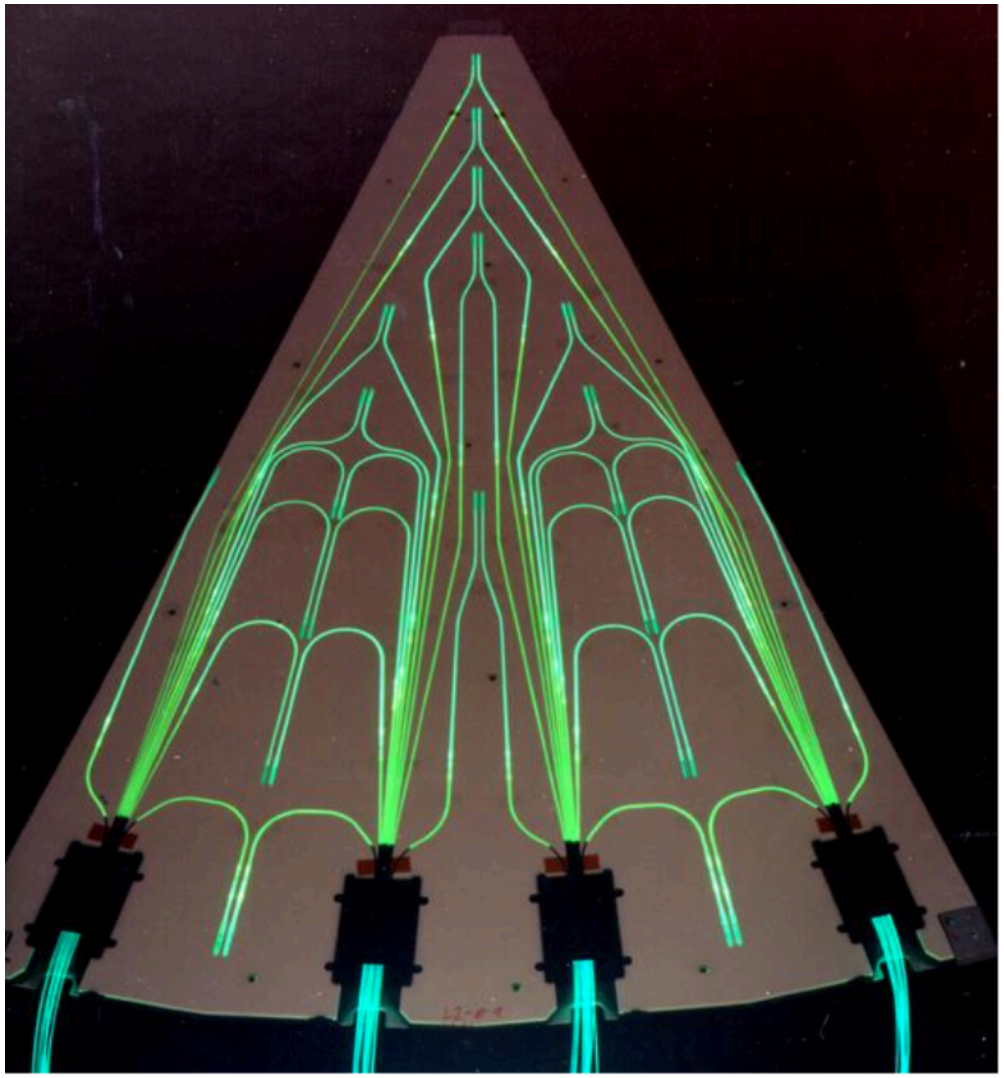


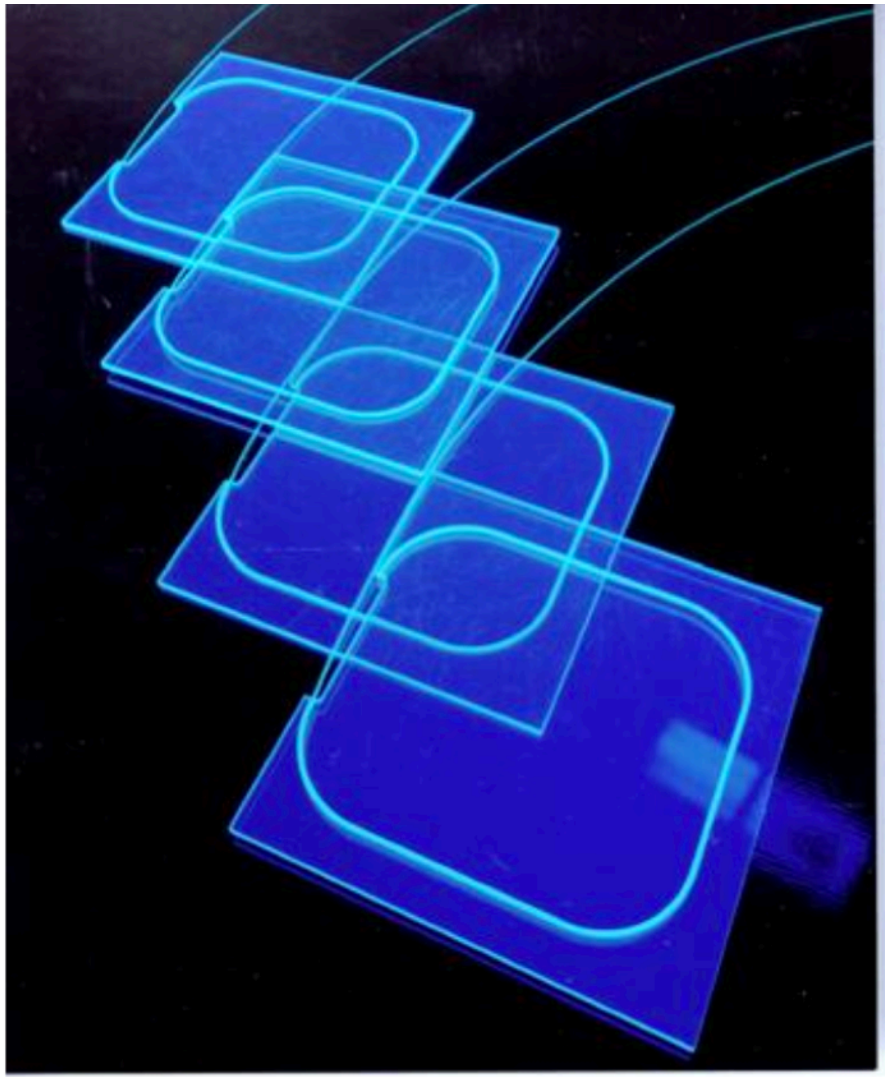
Crystal characterisation



APD gluing

HB/HE active elements



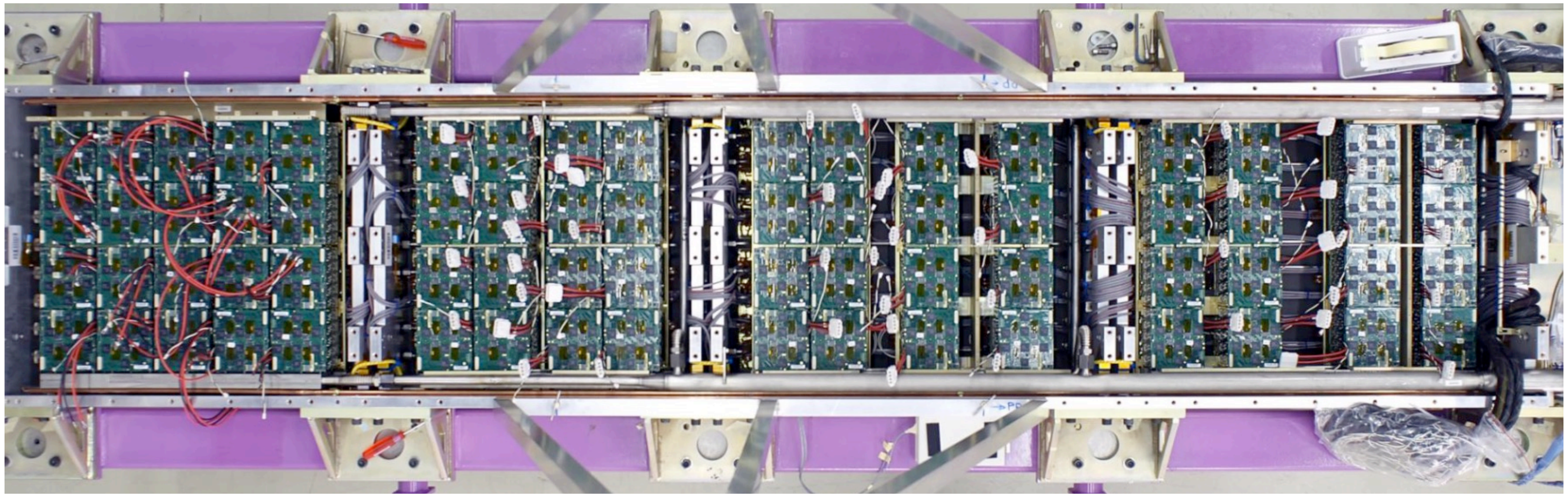


Scintillator tile, wavelength shifter and fibre-optic readout

ECAL Barrel construction

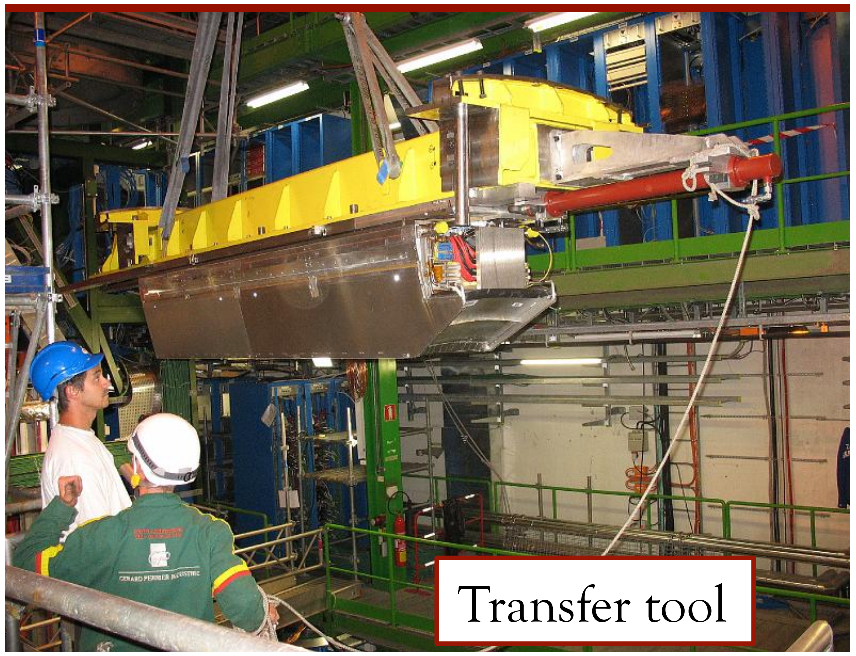
Electronics installation

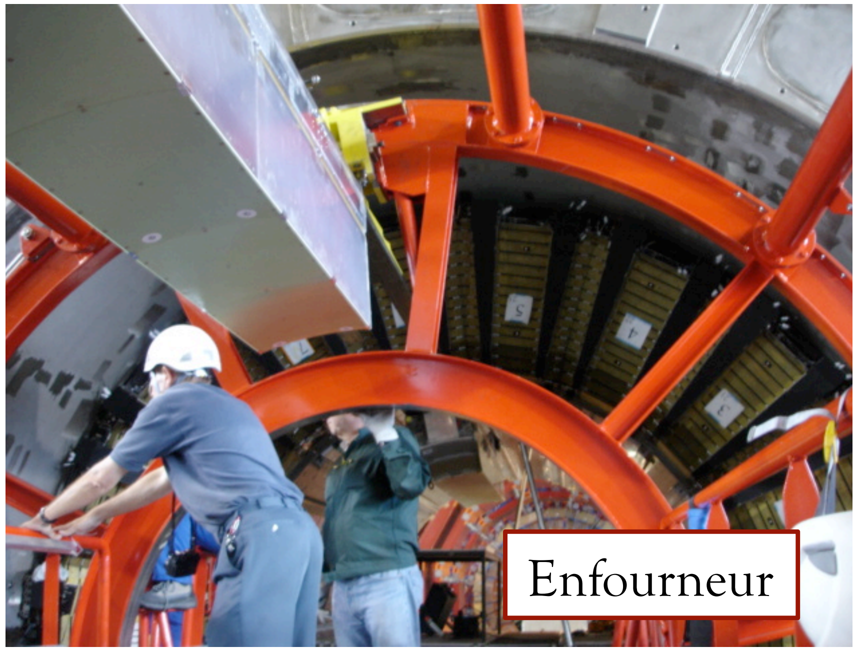
Supermodule integration/test stands @ Prevessin

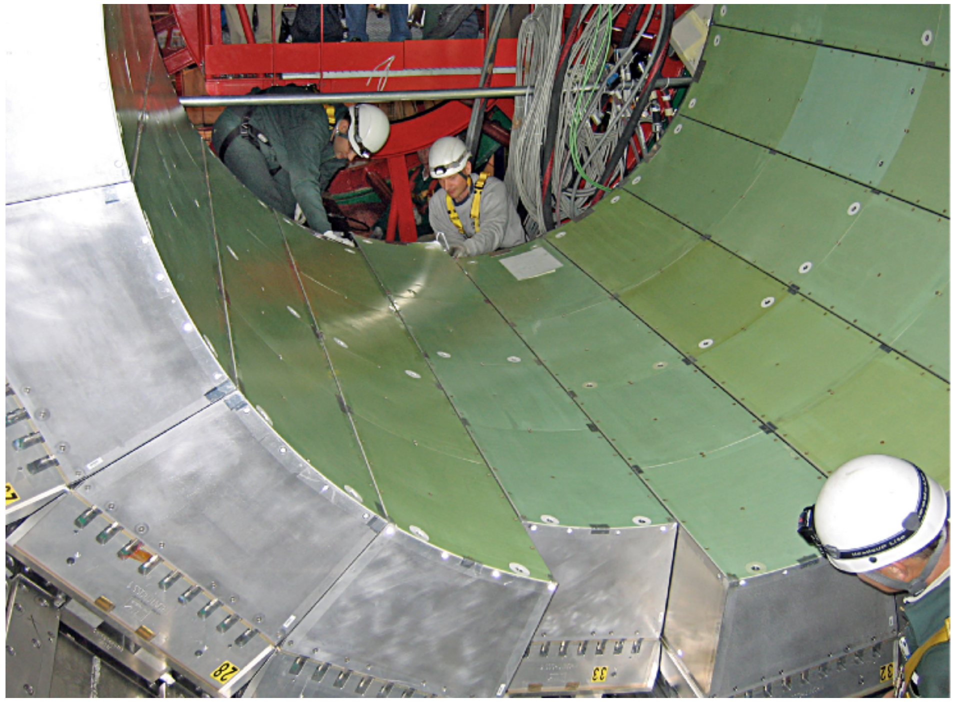


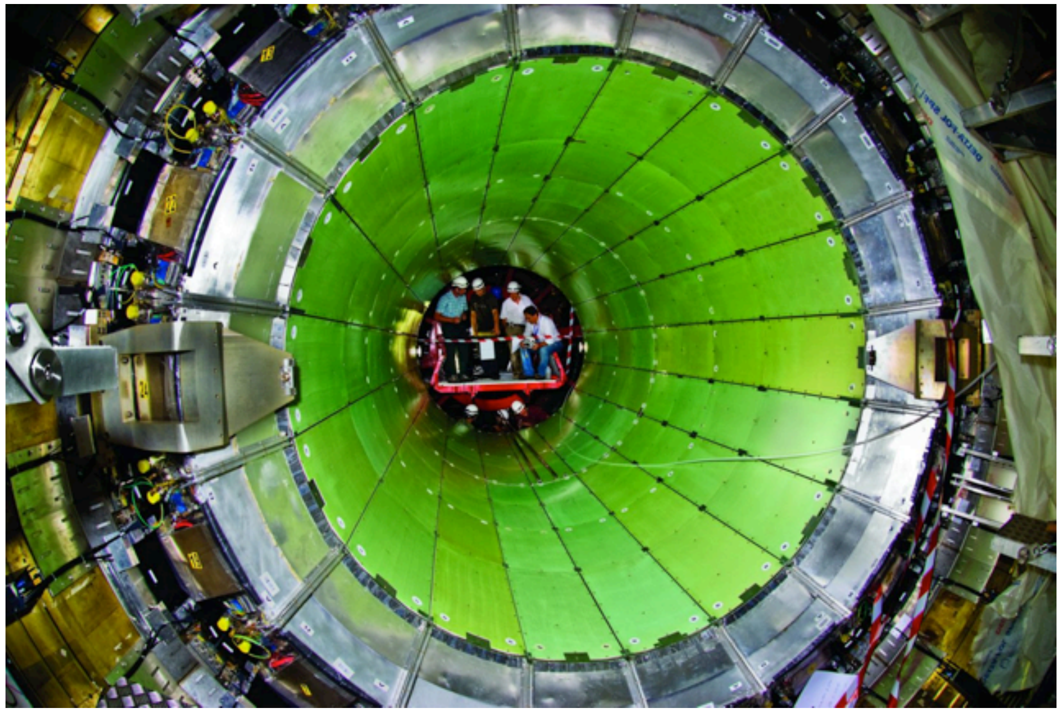
Supermodule in the process of electronics integration

ECAL Barrel installation









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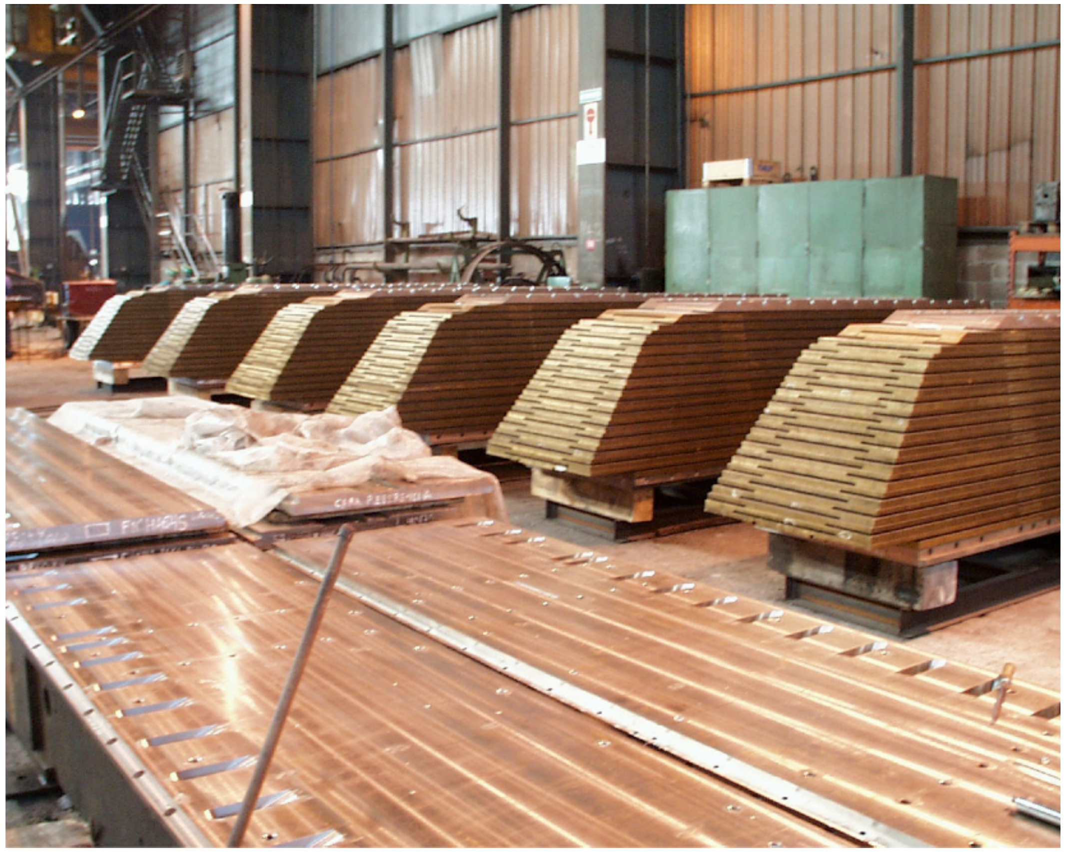
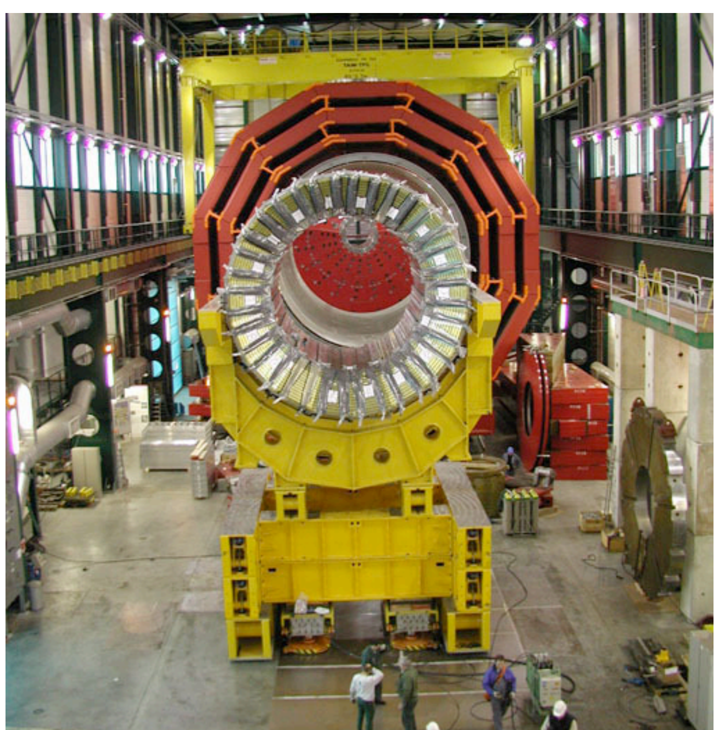
HB construction and installation

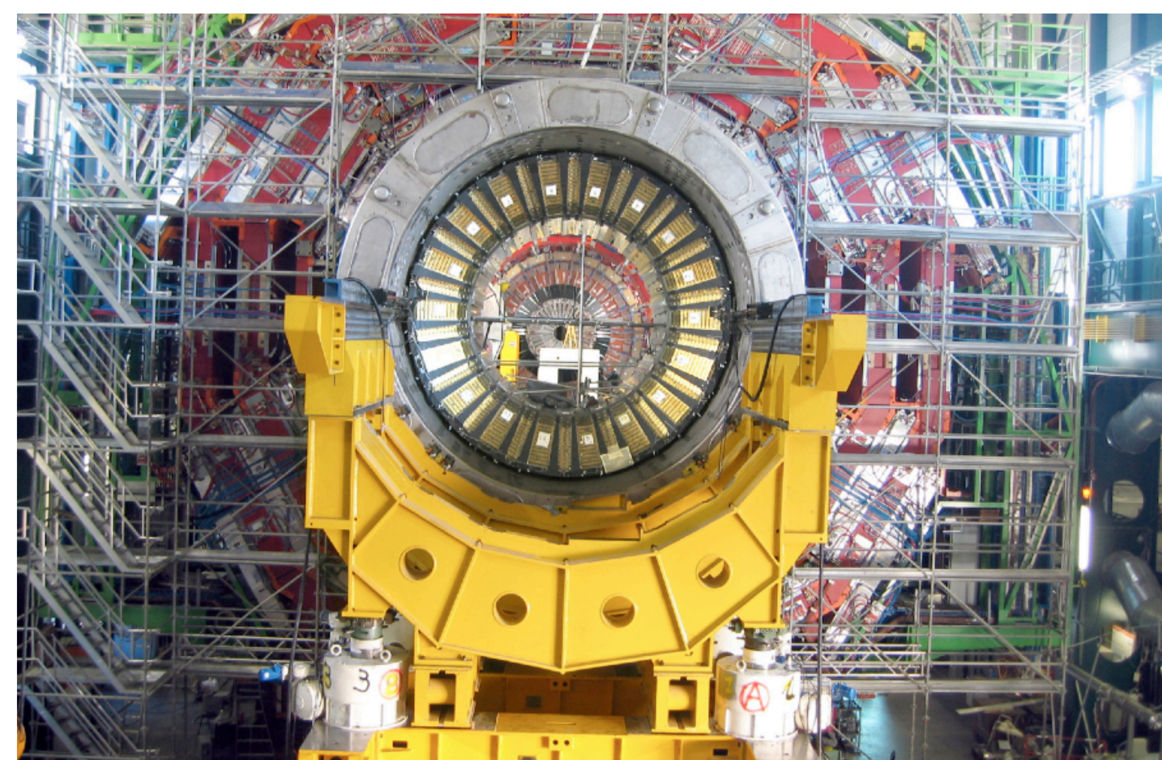


HB brass wedges

HB construction

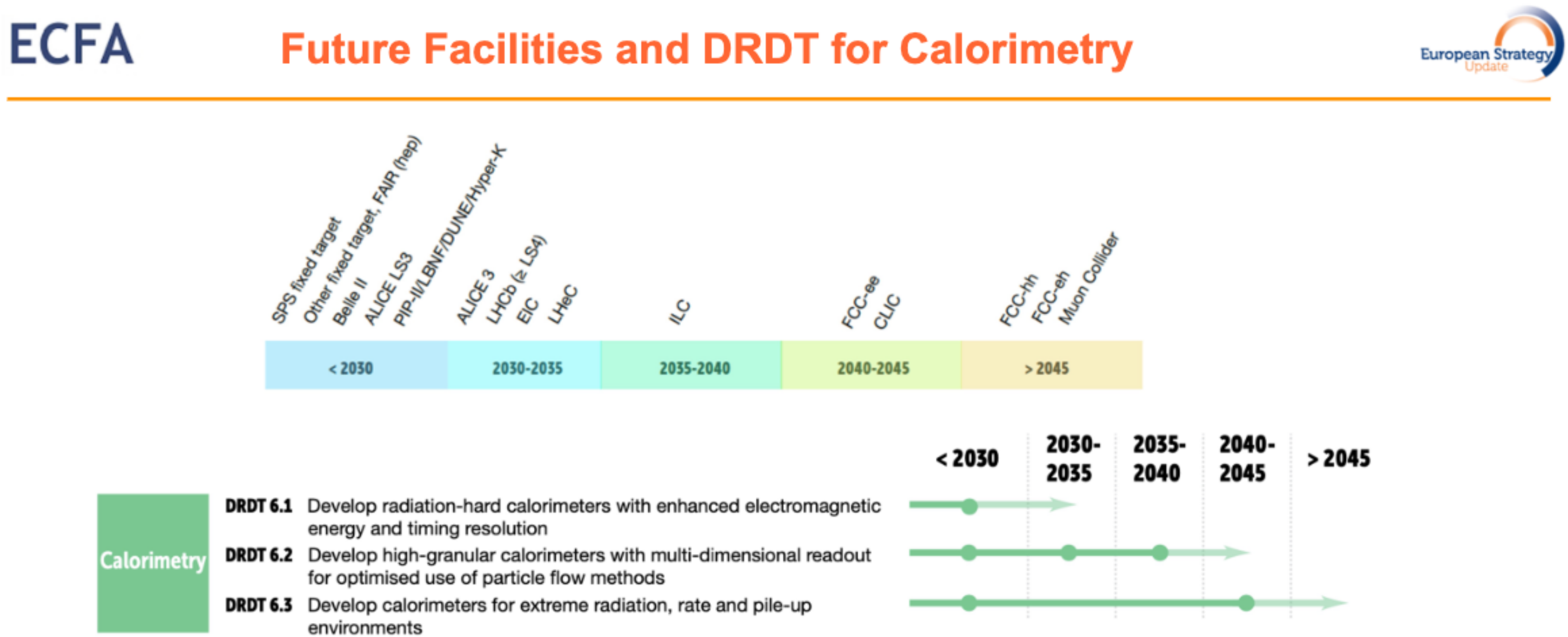


completed HB section ready to enter yoke



HB section inside yoke

ECFA DRD6 Calorimetry



ECFA DRD6 Calorimetry

ECFA Keyword: 5D calorimeters

European Strategy Update

- Calorimeters in no longer a detector to measure only Energy (1D)
- High granularity is recurrent topic in all the proposals (+ 3D)
  - 2D-segmentation
  - 3rd dimensions achieved either by physical segmentation or by timing information
- Timing is also additional "dimension" of the calorimeter (+1D)
  - pile-up rejection (μ-collider, FCC-hh, ...)
  - better track/particle matching
  - **tens of ps** is the current paradigm for timing application

ECFA DRD6 Calorimetry

ECFA Identified Key Technologies and R&D Tasks

European Strategy Update

Key technologies and requirements are identified in Roadmap

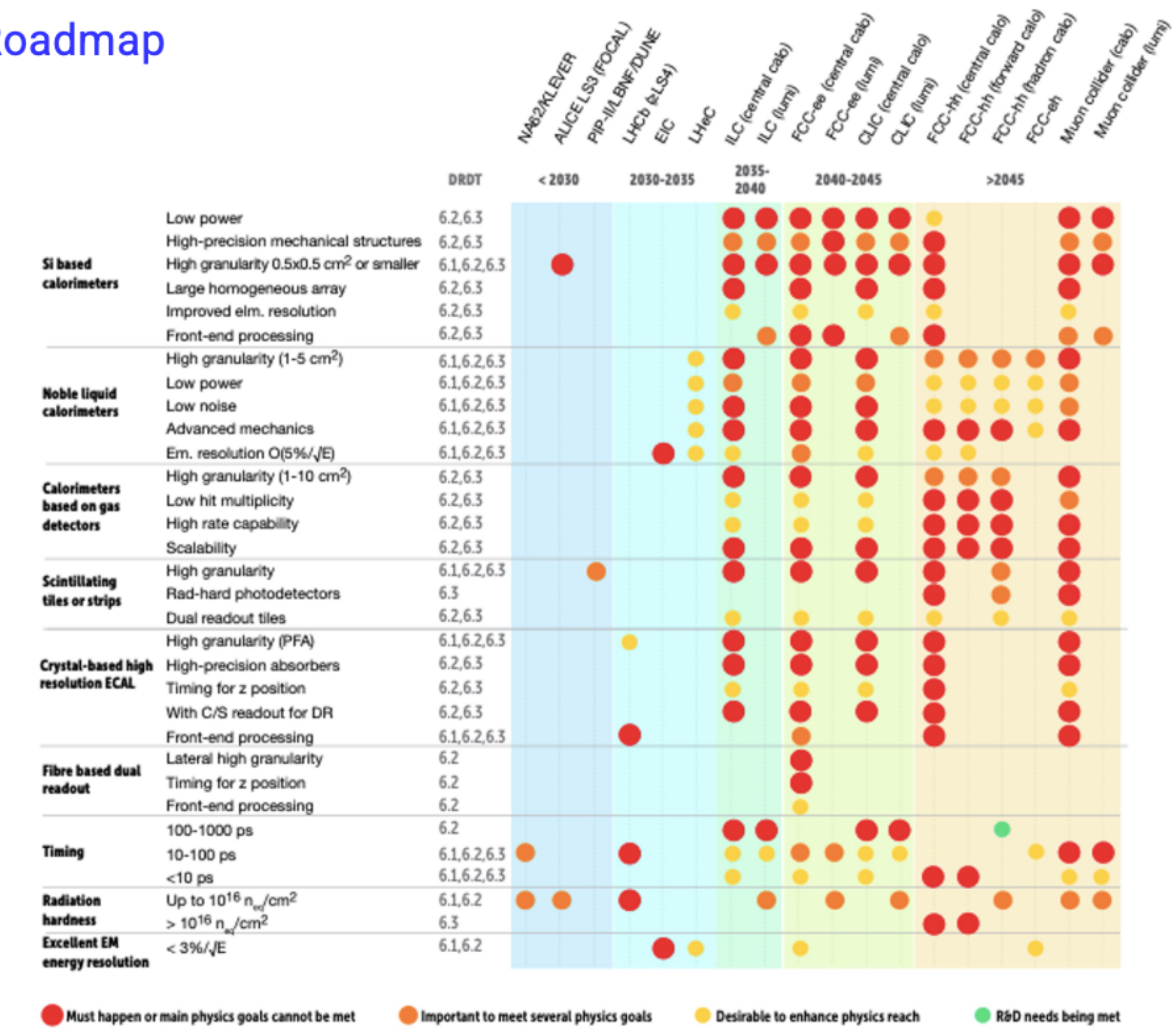
- Si based Calorimeters
- Noble Liquid Calorimeters
- Calorimeters based on gas detectors
- Scintillating tiles and strips
- Crystal based high-resolution ECALs
- Fibre based dual readout

R&D should in particular enable

- Precision timing
- Radiation hardness

R&D Tasks are grouped into

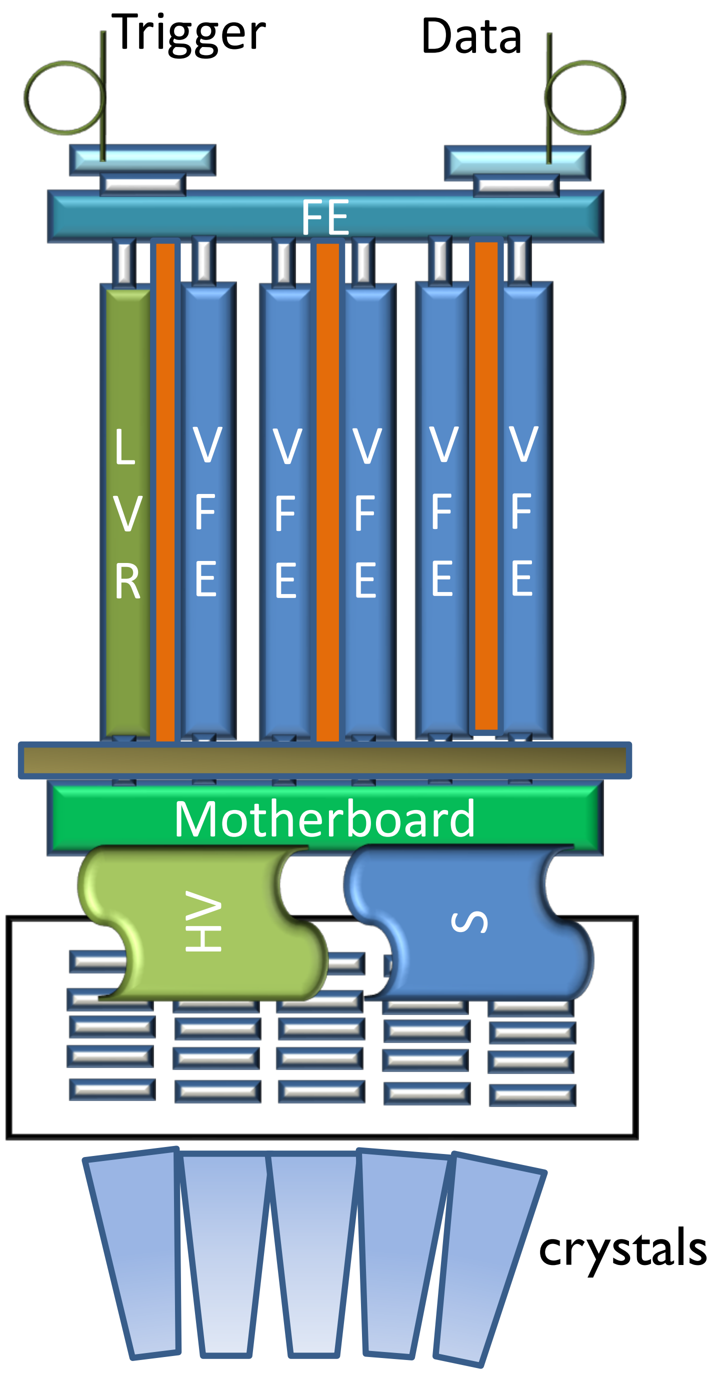
- Must happen
- Important
- Desirable
- Already met



2nd Calorimetry Community Meeting – 20.4.2023

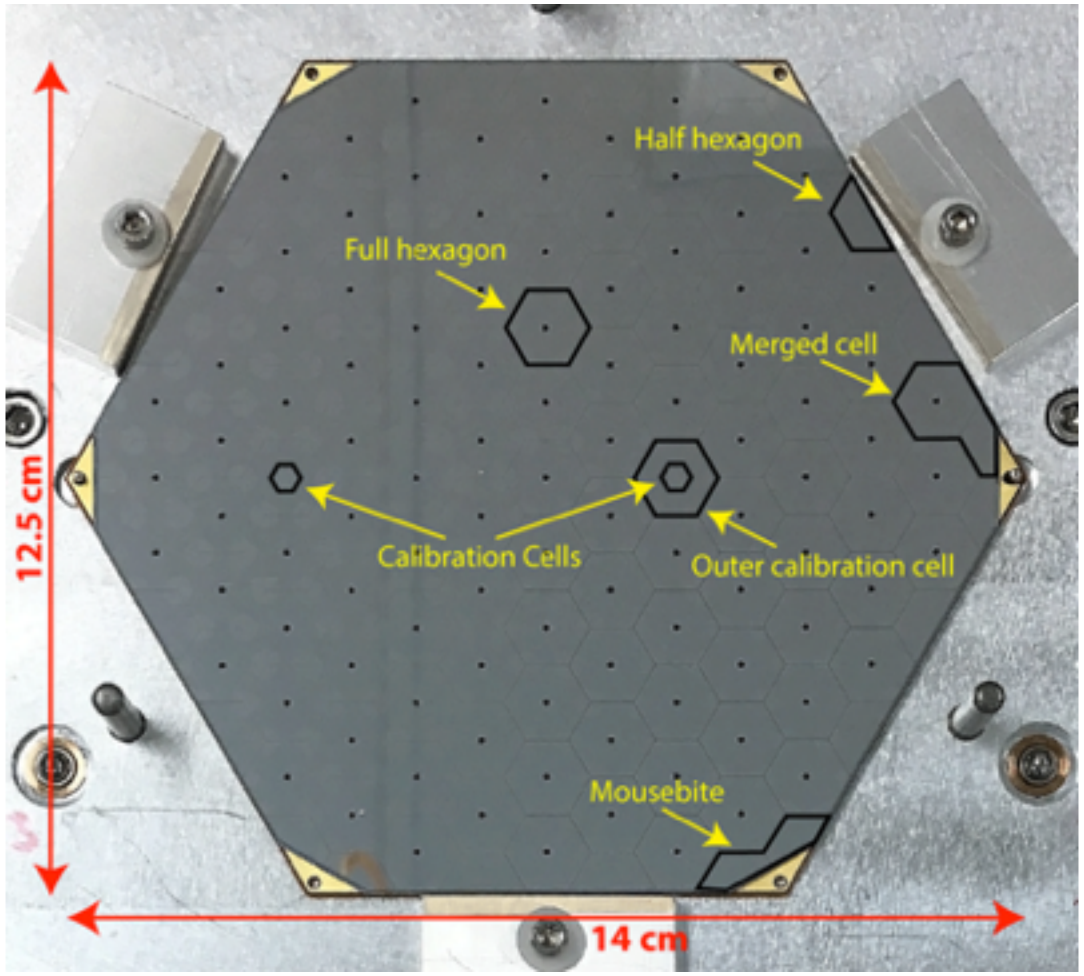
ECAL Barrel to be refurbished

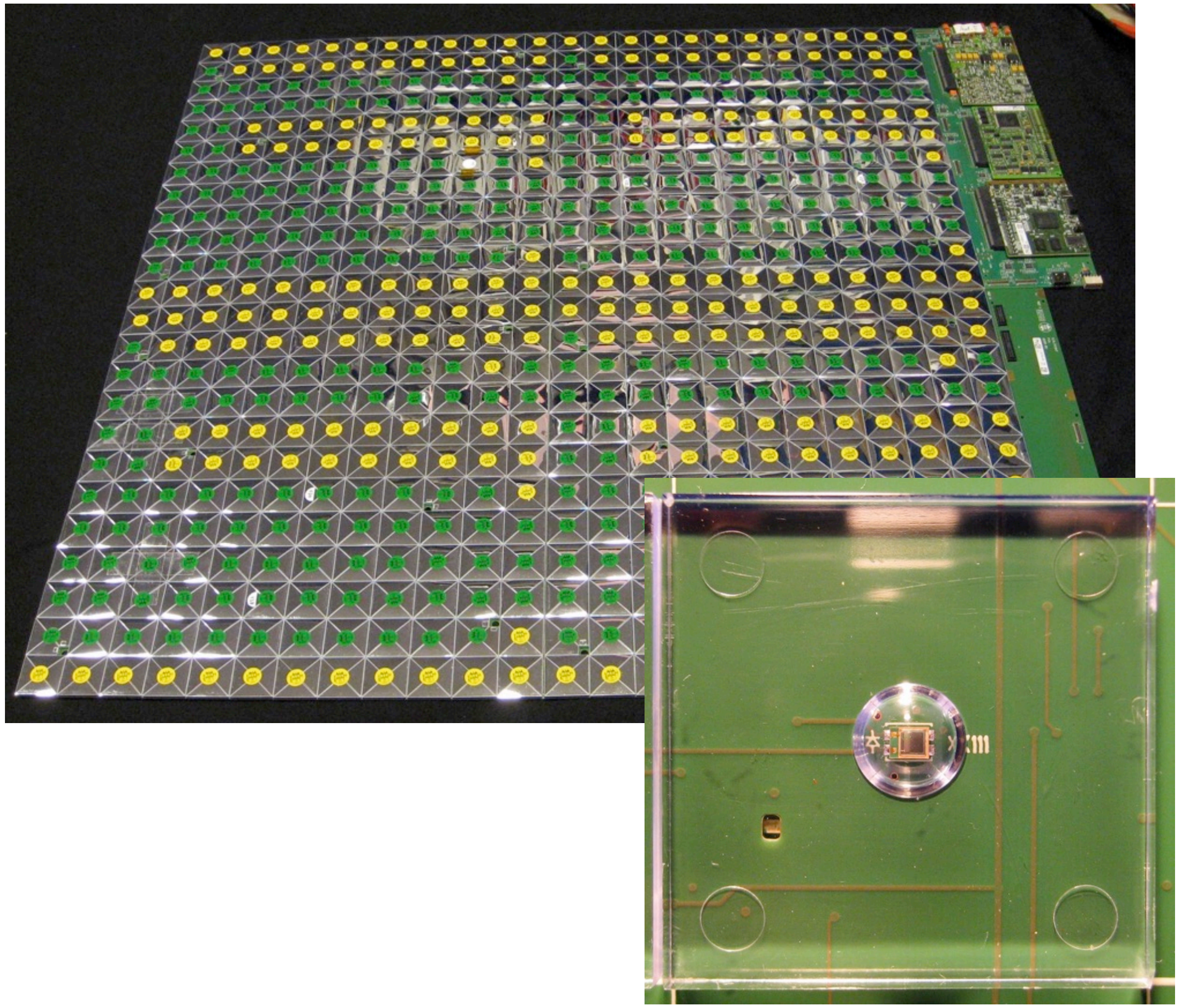
- **Extraction and refurbishment of 36 EB Supermodules during LS3**
  - **Replace Front-End (FE) and Very-Front-End (VFE) readout**
    - **to be compatible with increased HL-LHC trigger requirements**
    - to cope with challenging HL-LHC conditions (noise, PU, anomalous APD signals).
    - Make precise timing measurements for high energy photons.
  - **Run colder** to mitigate increase in radiation induced APD dark current
  - **New off-detector readout** to cope with higher output bandwidth from FE
  - **Crystals + APDs will be retained**



ECAL barrel trigger tower (25 crystals)

Endcap Calorimeter detector elements





Prototype silicon sensor

Hexagonal silicon detector cells

special high gain MIP calibration cells

must operate at -30 degC to limit Si leakage current

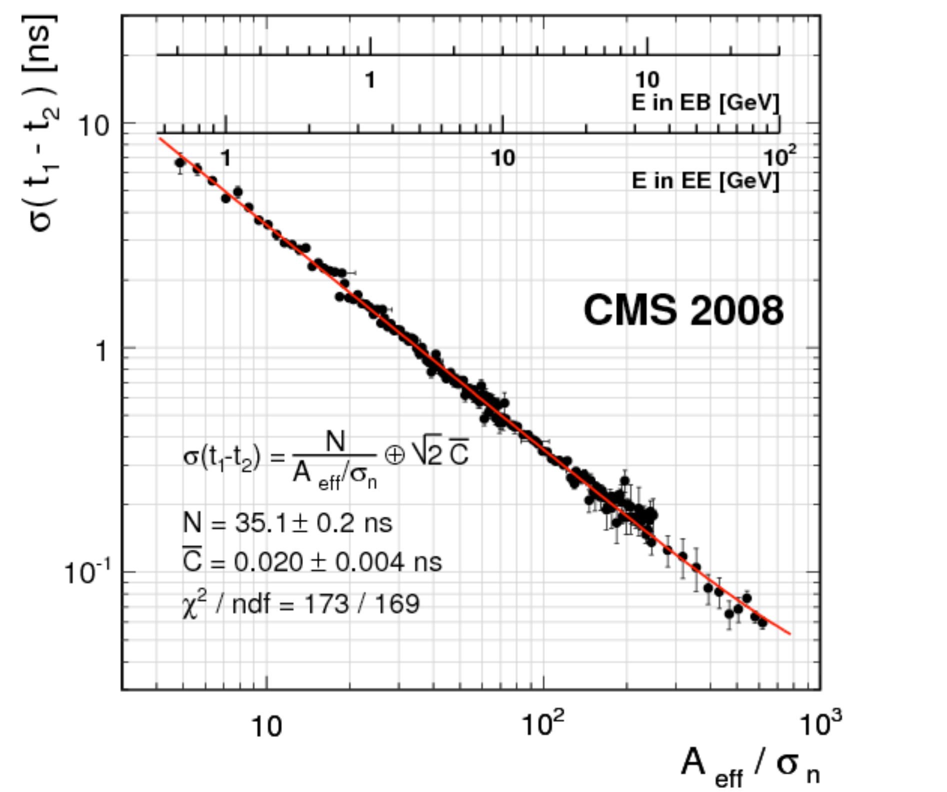
SiPM on tile scintillator cells

$4cm^2$ to $32cm^2$ cells with direct SiPM readout

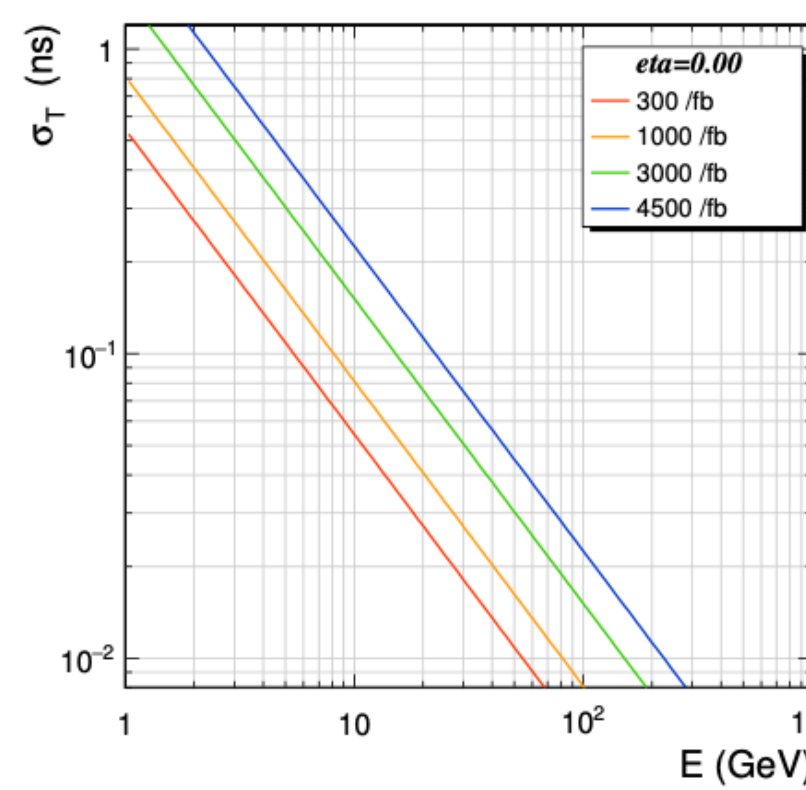
adapted from CALICE HCAL prototype

ECAL crystals are capable of precise timing

- **CMS ECAL crystals and APDs are capable of providing precise timing information**
  - **intrinsic timing resolution: ~20 ps**
- **ECAL timing distribution system was not designed for sub-ns timing measurements**
  - **achieved timing resolution is ~150ps, limited by timing distribution to front-end boards**
- **Phase-2 upgrade prioritises precise timing resolution**
  - **Crystals and APDs will remain in Barrel**
  - **ECAL will use a redesigned front-end preamp and ADC to minimise pulse shaping and over-sample signal pulse**
  - **dedicated timing distribution system to achieve 30ps resolution**
  - **ageing (APD noise increase) gradually degrades performance**

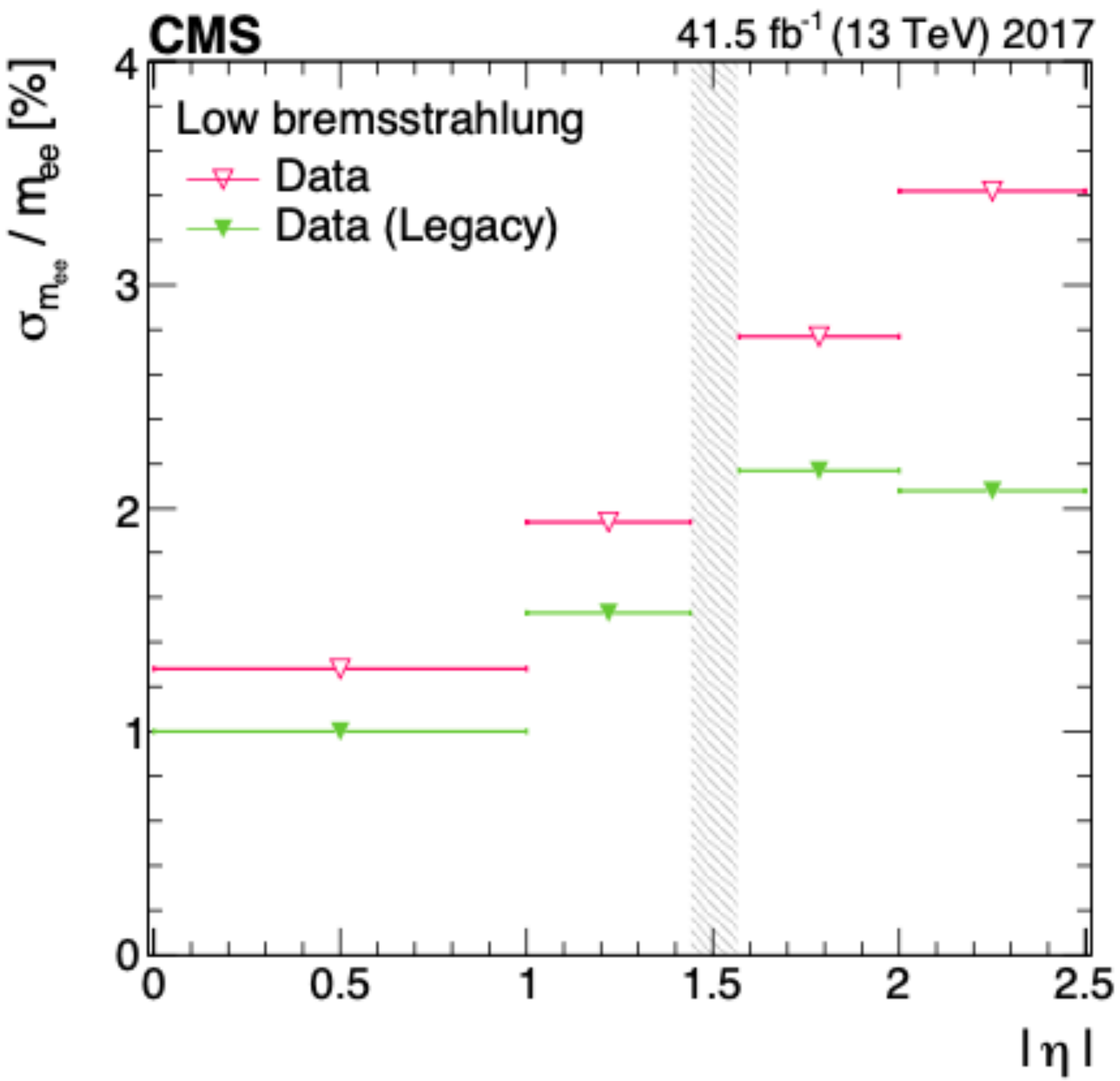


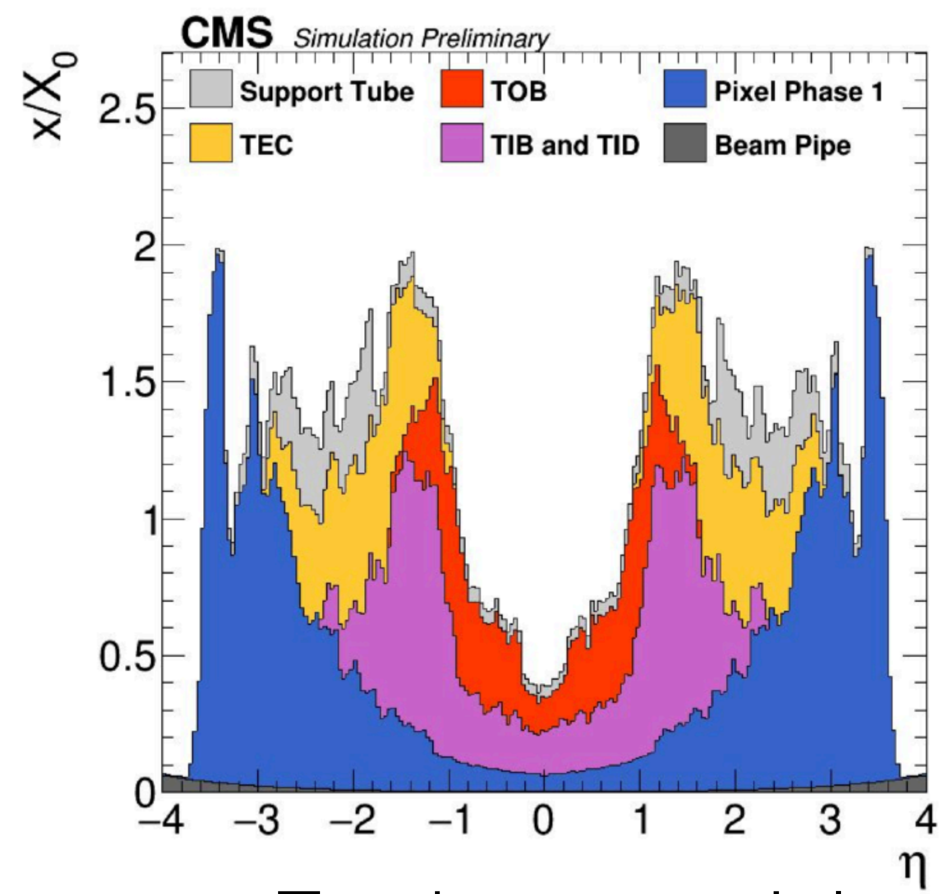
ECAL time resolution measured from test beam



Phase-2 ECAL time resolution vs luminosity

ECAL energy resolution improves with recalibration





Tracker material budget (in X_0)

Z→ee invariant mass resolution vs eta from 2017 CMS data

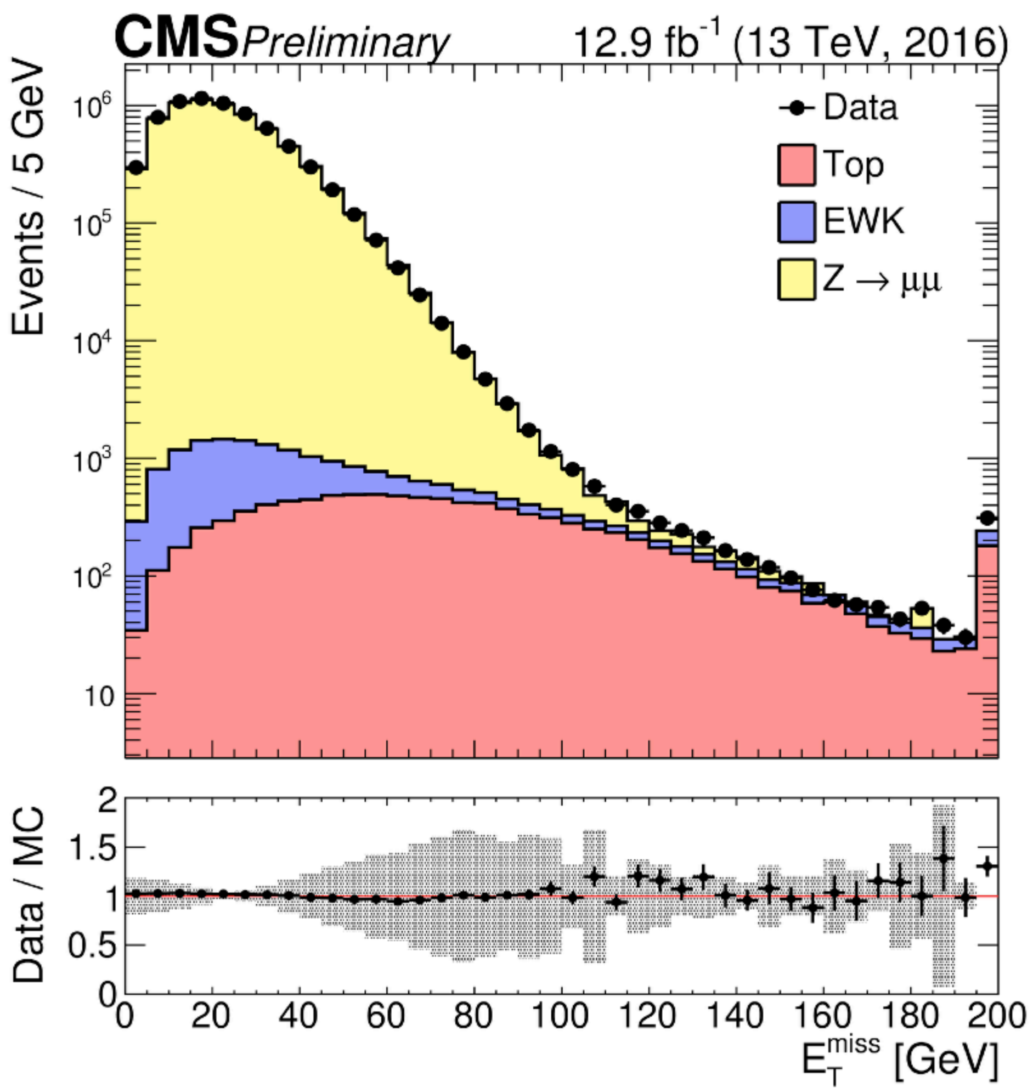
recalibrated data (green) shows significantly better performance, particularly in EE

resolution vs eta trend follows material budget of CMS tracker -> best performance at |eta|=0

MET performance

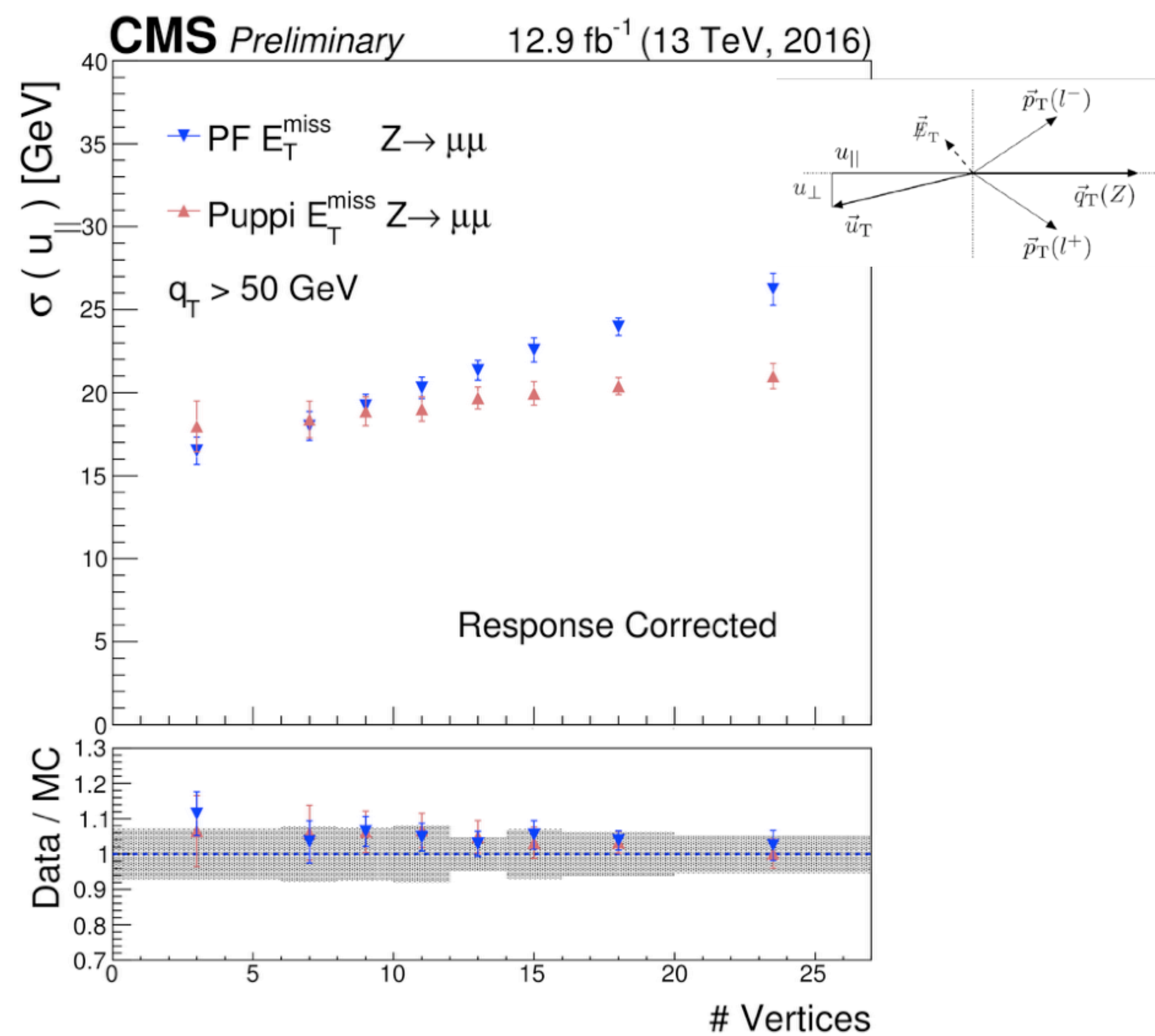
Missing energy distribution is an excellent test of calorimeter understanding

any unexpected noise source or detector miscalibration can generate fake MET



Missing E_T distribution for PF MET

from Z→mumu events



Resolution for PF/PUPPI MET

from Z->mumu events

showing impact of advanced PU mitigation treatment, using calorimeters and tracks

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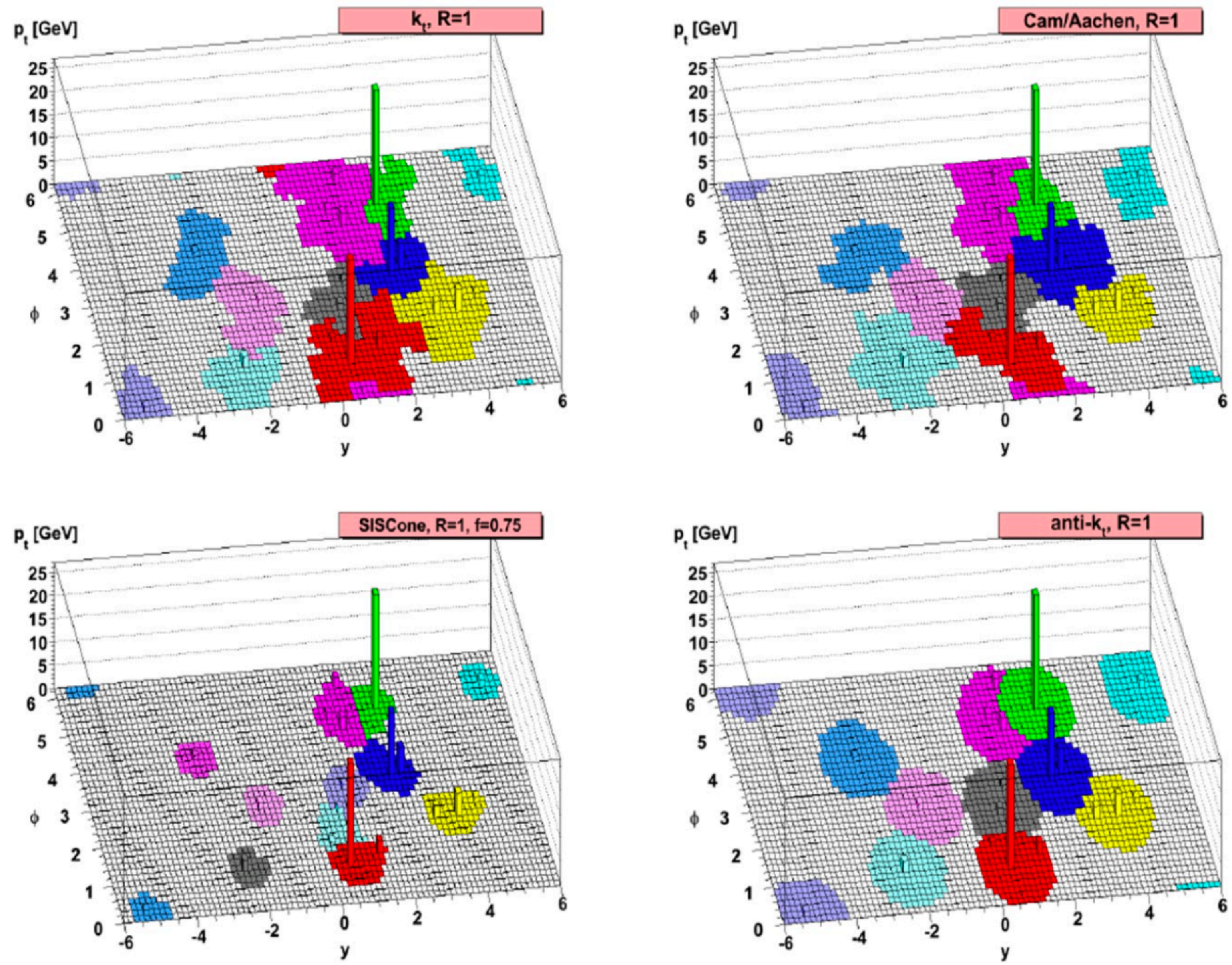
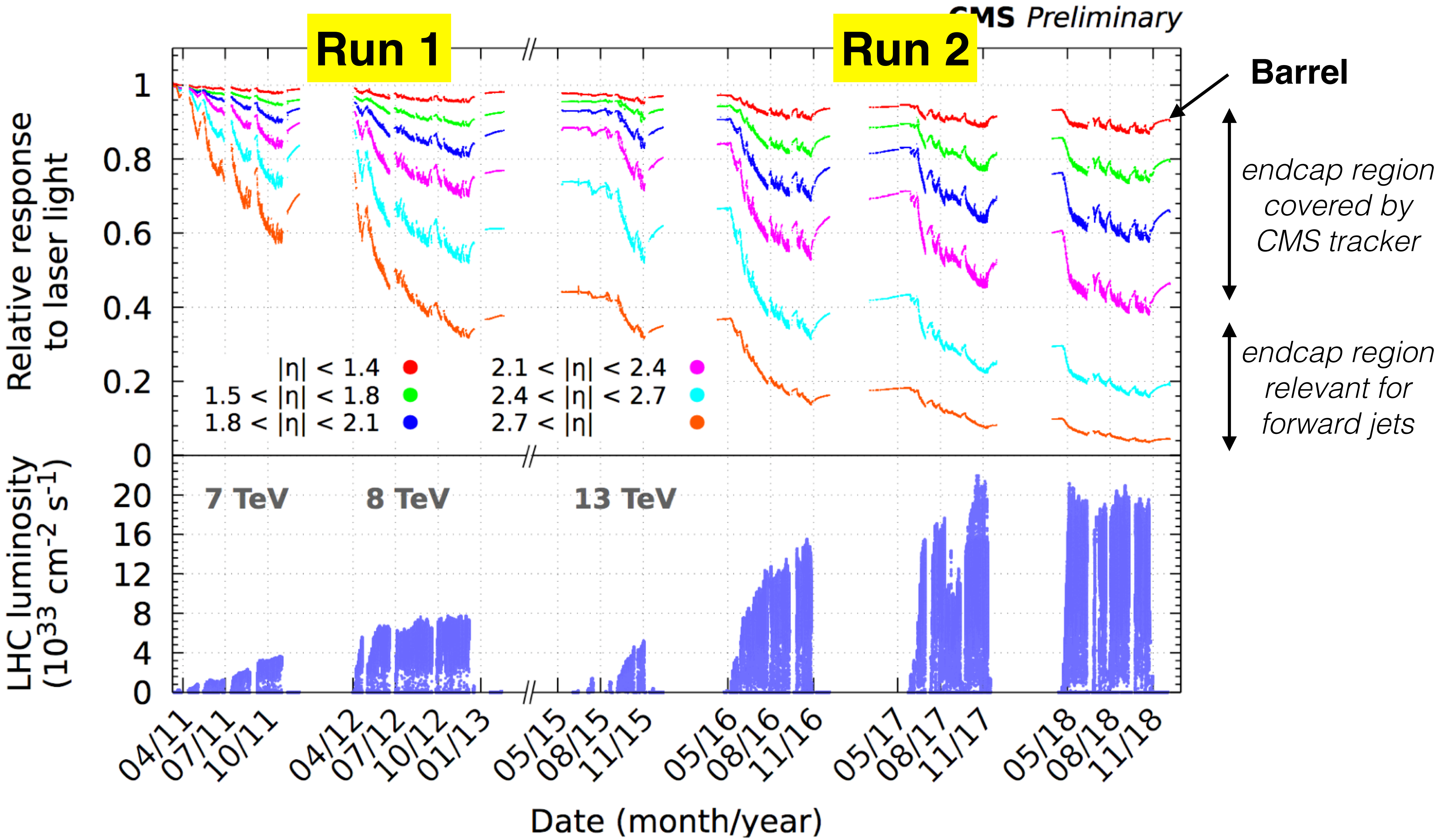
Jet reconstruction

- **Various algorithms used to reconstruct jets**
  - <u>iterative cone algorithms</u>
    - cluster energy deposits based on eta/phi regions
      - not IR or collinear safe
  - <u>sequential clustering algorithms are favoured</u>
    - cluster energy deposits based on particle p_T and eta/phi proximity
- **Preferred approach depends on application**
    - anti-k_T good for resolving jets
    - Cam/Aachen good for studying jet substructure



Comparison of several jet reconstruction algorithms on the same input data

Impact of ageing on ECAL response



Significant response changes (crystal + photodetector) due to LHC irradiation

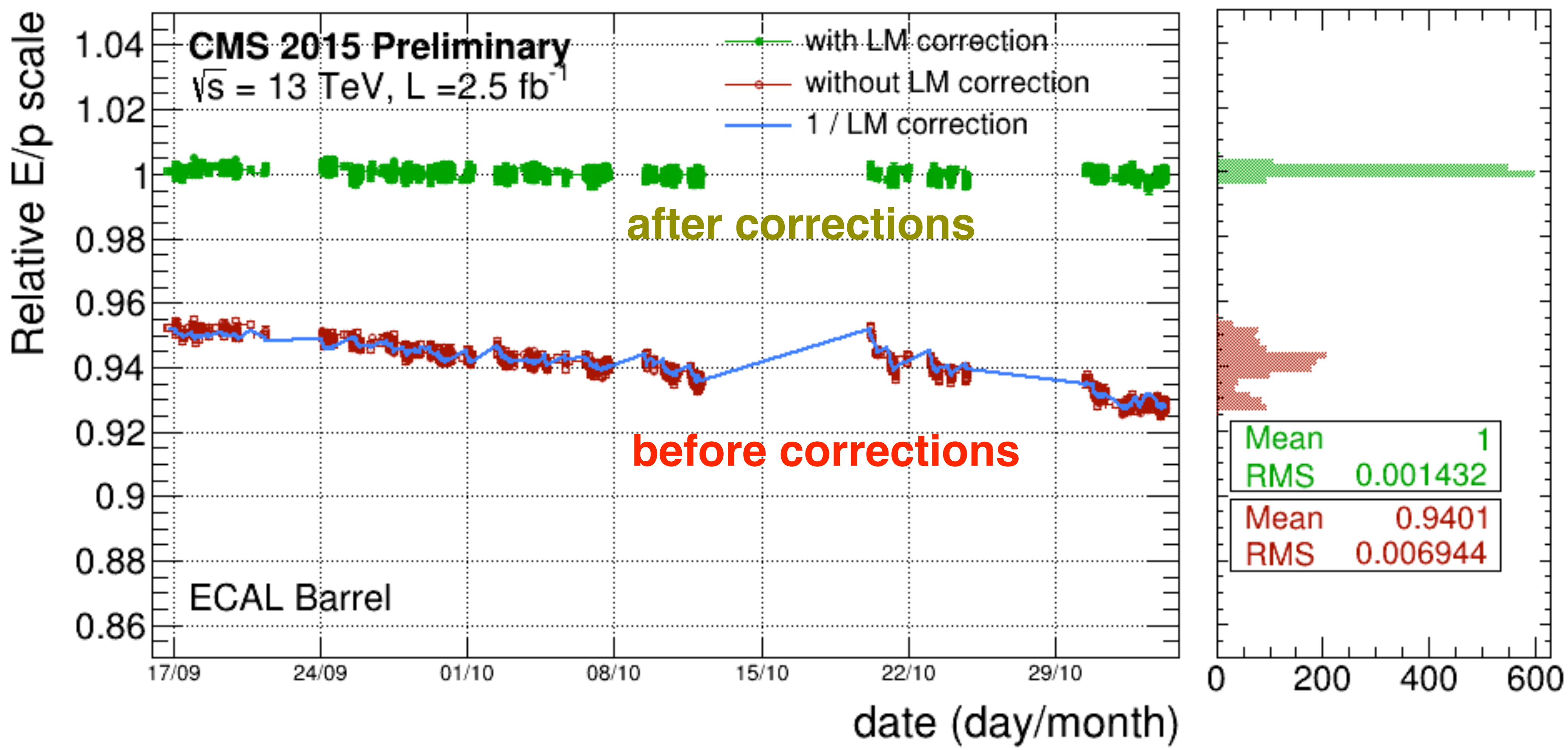
Corrections are provided within 48h via dedicated laser monitoring system

These are crucial to maintain stable ECAL energy scale and resolution over time

Effectiveness of light monitoring corrections

Light monitoring corrections are applied to reconstructed CMS data

validated corrections are needed in <48h



Stability of EB energy scale, from E/p ratio of W->enu decays

(RMS=0.14%)

Homogenous vs sampling calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous

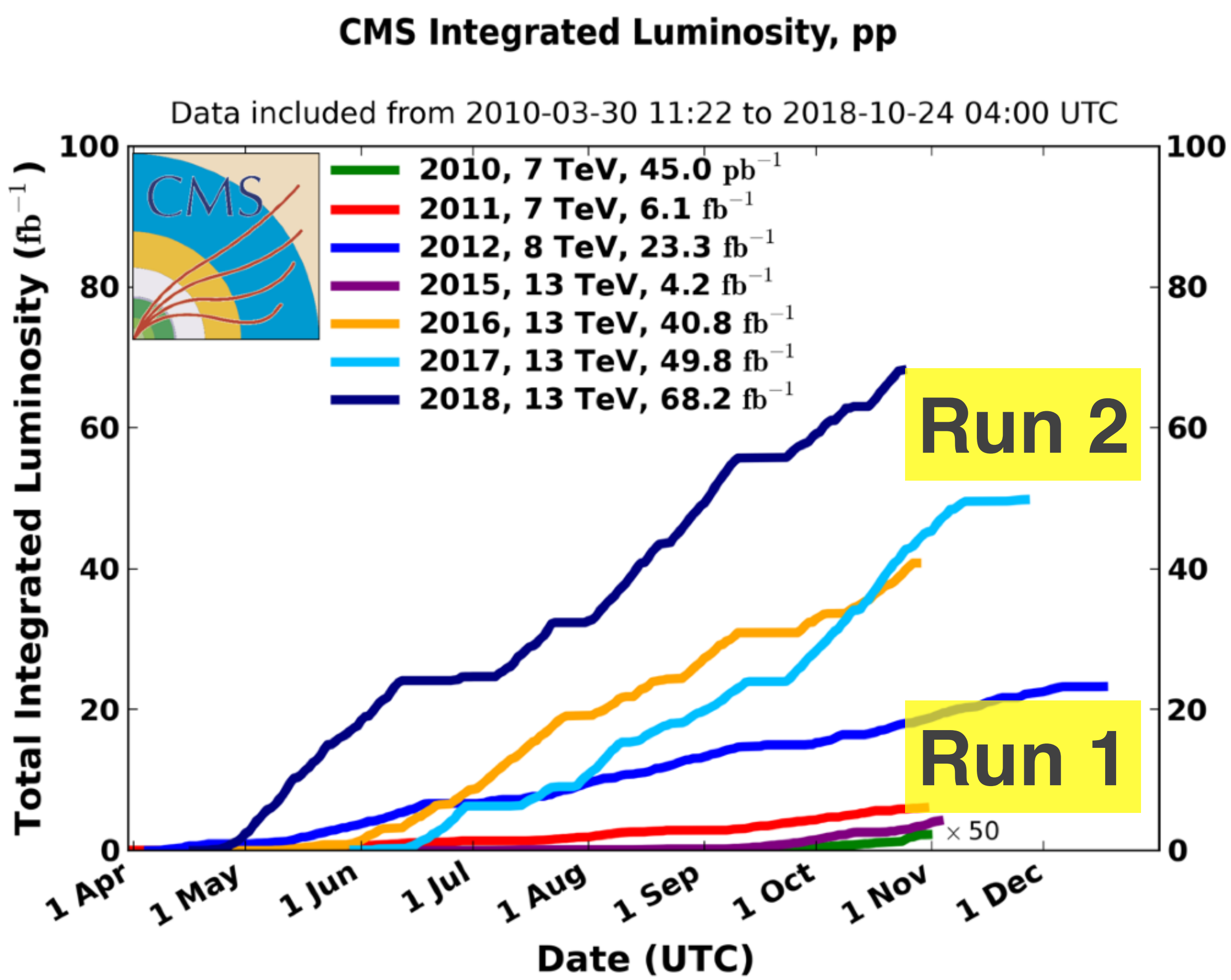
Sampling

Homogenous calorimeters have smaller stochastic term

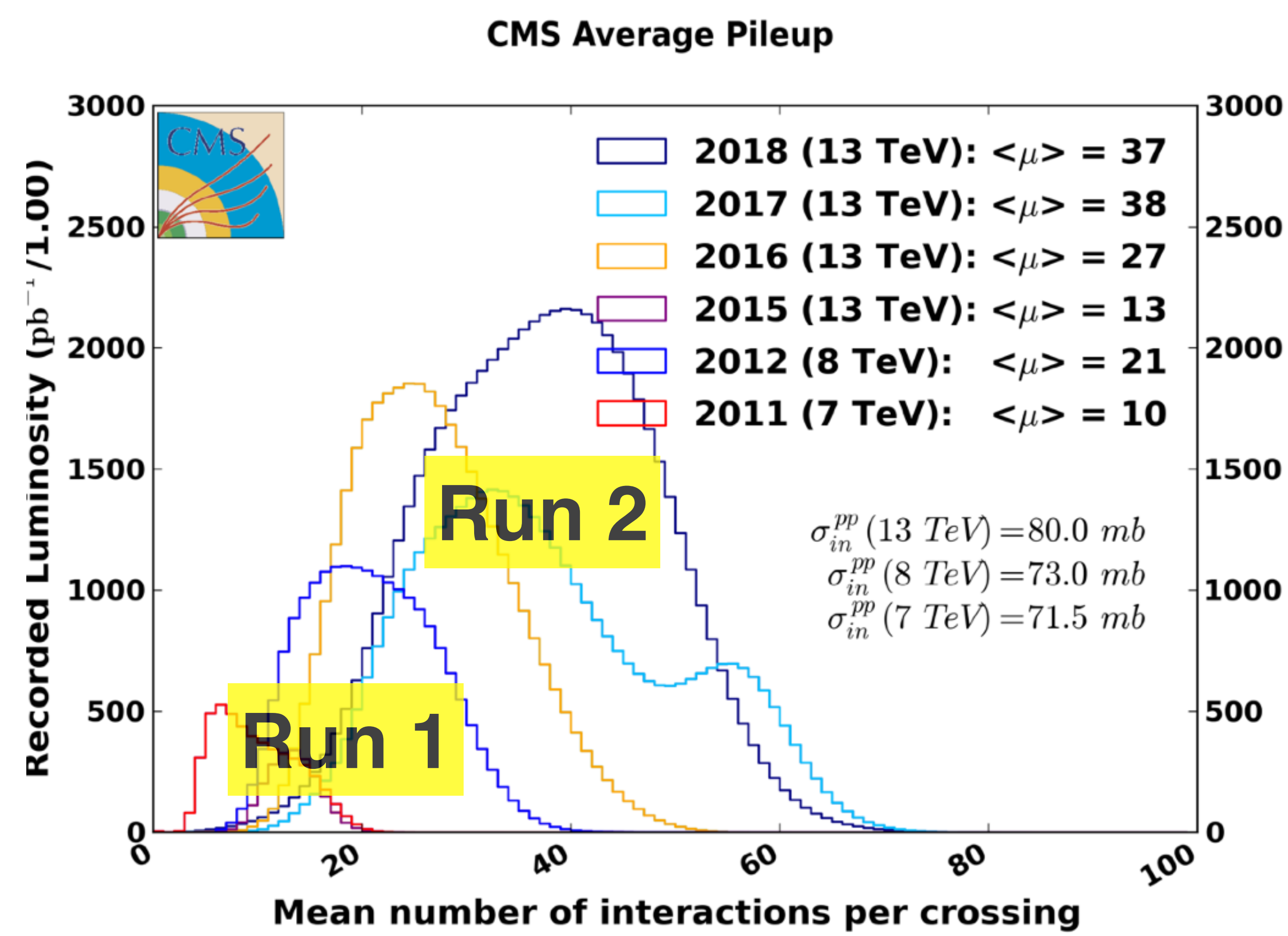
Similar constant terms

ECAL Challenges during Run 2

Higher Integrated luminosity



Larger Average pileup



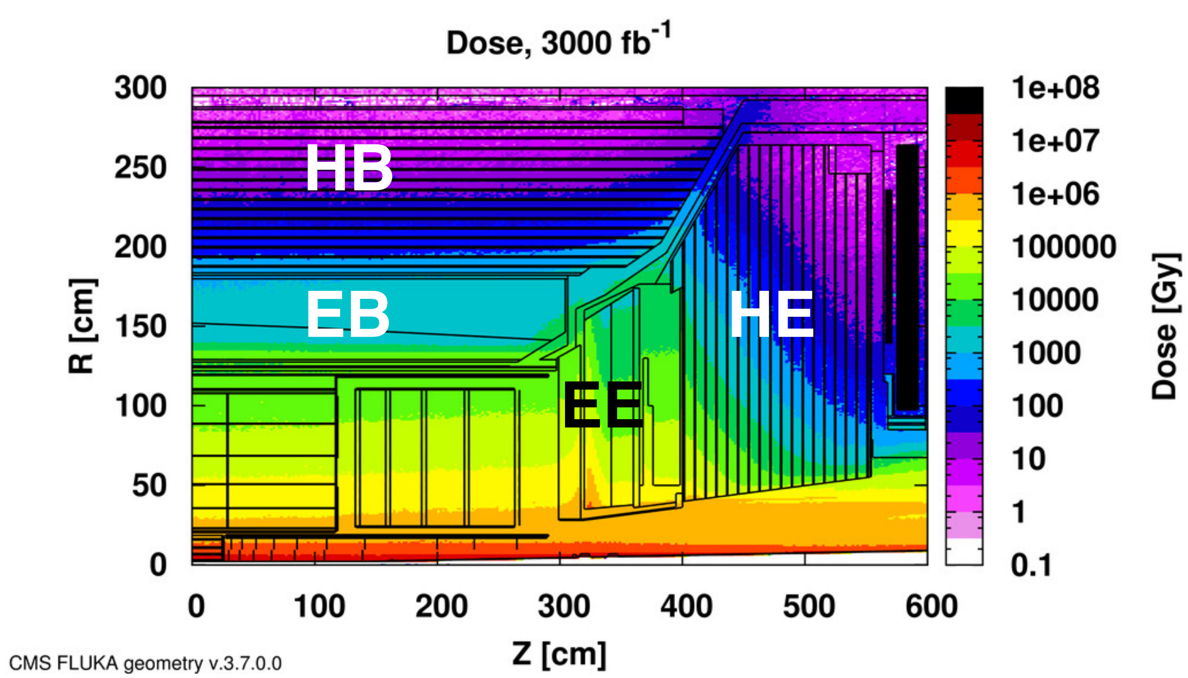
<u>Run 2 challenges:</u>

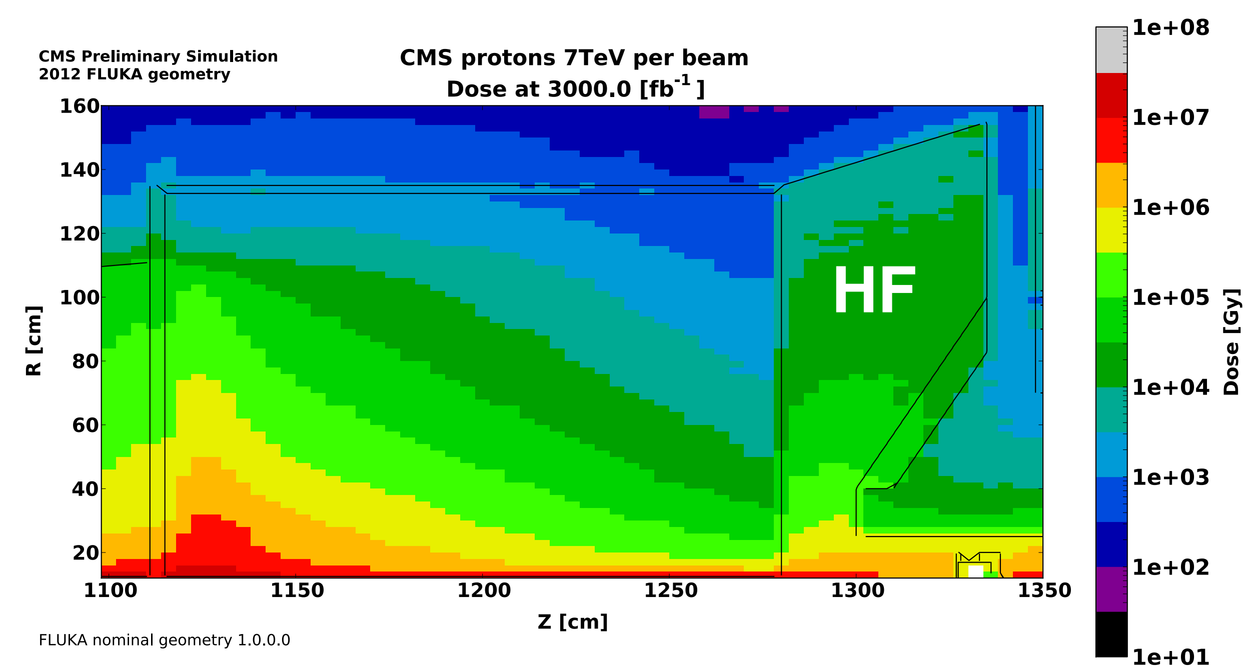
1) Larger radiation dose: increased radiation induced ageing to crystals, photodetectors, on-detector readout

2) Large increases in pileup (PU): from higher bunch intensities, and from 25ns bunch spacing (larger out-of-time PU) → impact on ECAL pulse reconstruction

CMS radiation environment at HL-LHC

- ECAL and HCAL endcaps (|η|>1.48) will experience significant radiation dose after 3000fb^{-1}
  - **ECAL:** up to 50 Mrad (EE, eta=2.6); below 1 Mrad (EB)
  - **HCAL:** up to 10 Mrad (HE); below 0.1 Mrad (HB); up to 500 Mrad (HF)





Why regular recalibration is needed

ECAL response changes significantly over time

light monitoring corrections are used to compensate for this

intercalibration constants are then applied to equalise energy response

This does not fully hold over long periods

imperfections in **light monitoring corrections grow with time**

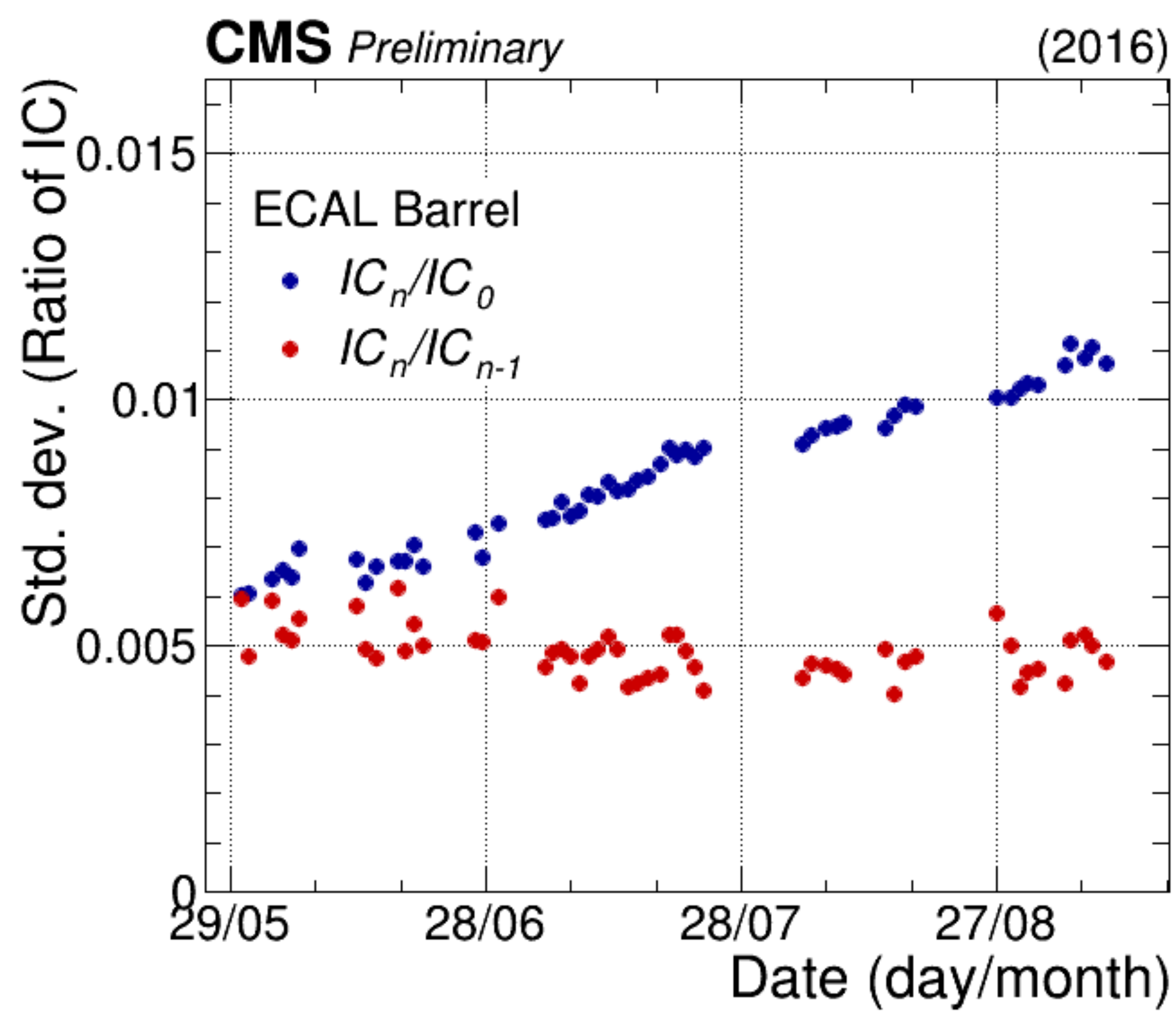
this causes a **spread** in the channel-to-channel response**, degrading resolution**

Regular rederivation of IC needed

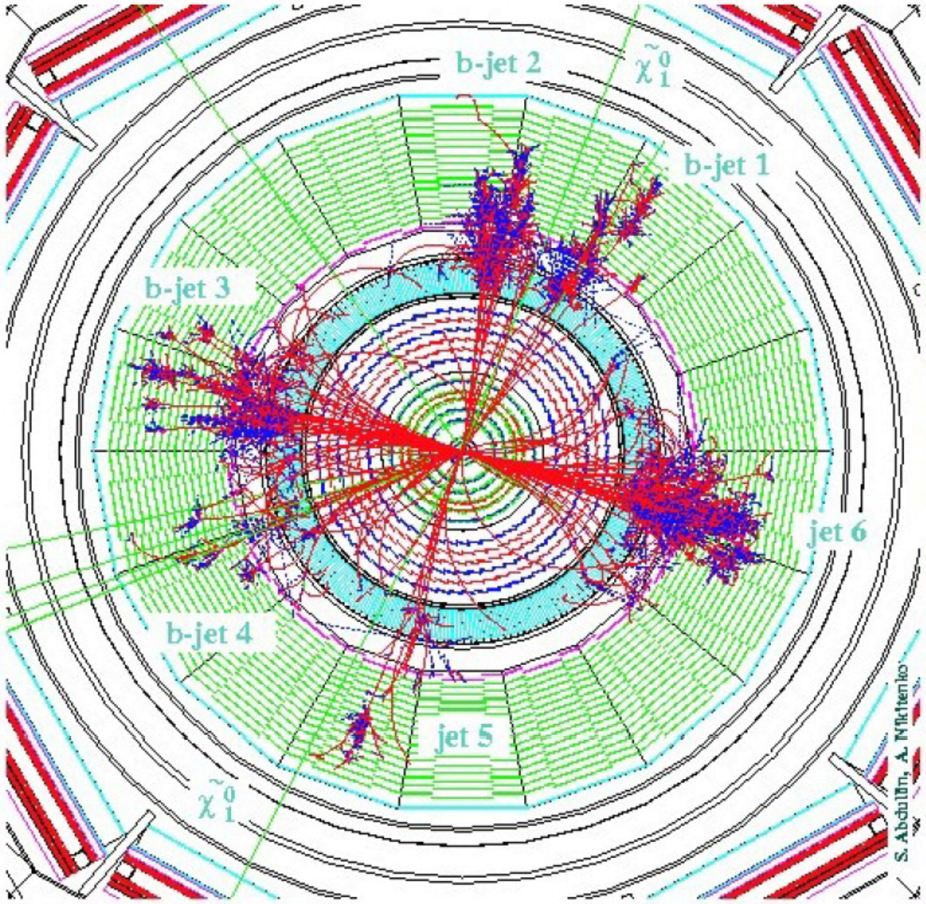
to maintain optimal performance

usually performed at the end of each year of data taking, requiring **full re-reconstruction** of CMS data

Drift in intercalibration constants over time



HCAL performance targets



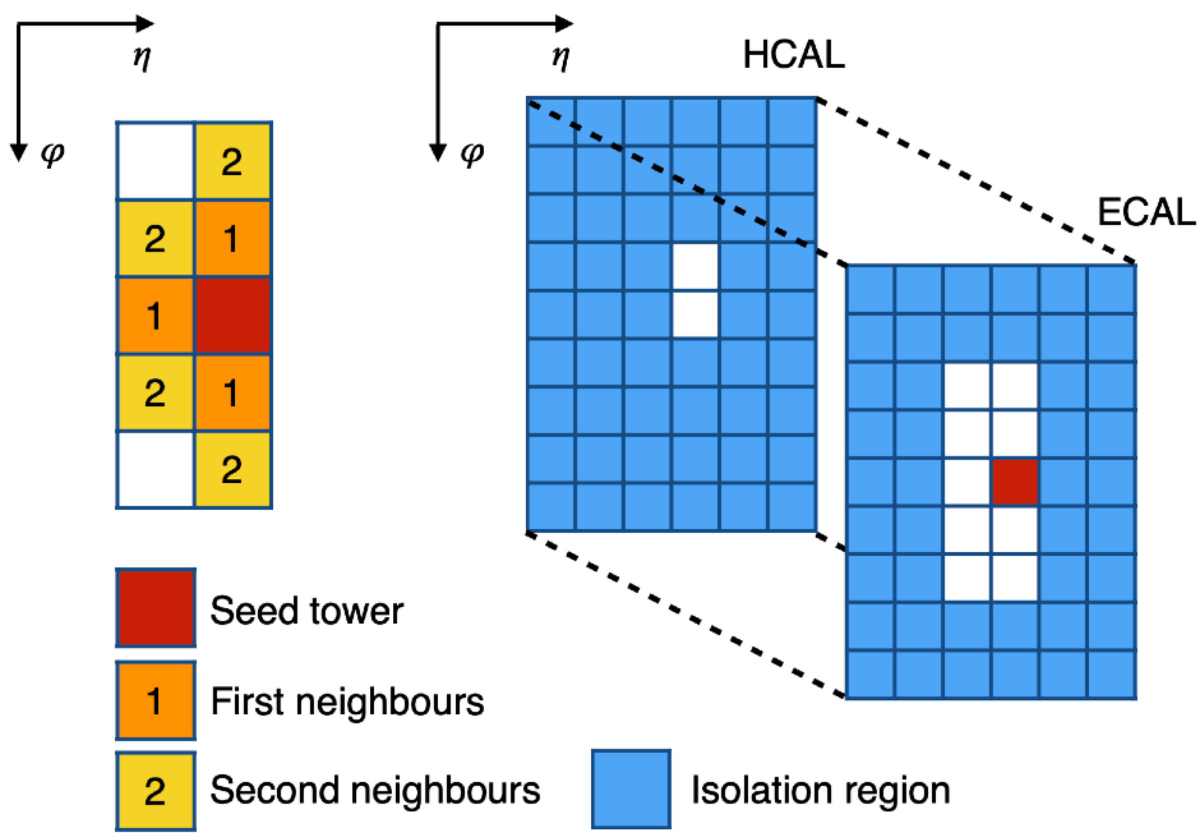
Simulated SUSY multijet event

- Measure jets and missing E_T
- Electron/photon ID via HCAL/ECAL energy ratio (H/E)
- Muon ID via ECAL/HCAL isolation
- Tau ID: narrow jets (for tau->h decays)

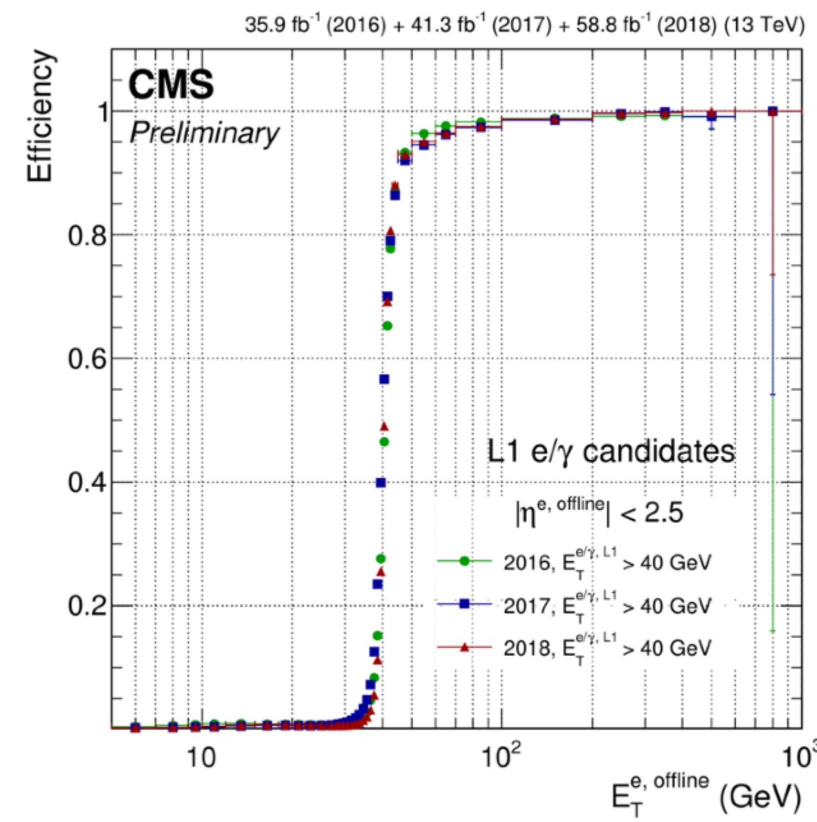
CMS calorimeter trigger algorithms

- **Phase 1 upgrade in 2015-16**
  - more powerful off-detector processing boards
    - allows more complex algorithms to be used, including dynamic clustering of ECAL/HCAL towers and pileup subtraction

Electron/photon dynamic clustering algorithm



Electron/photon trigger efficiency



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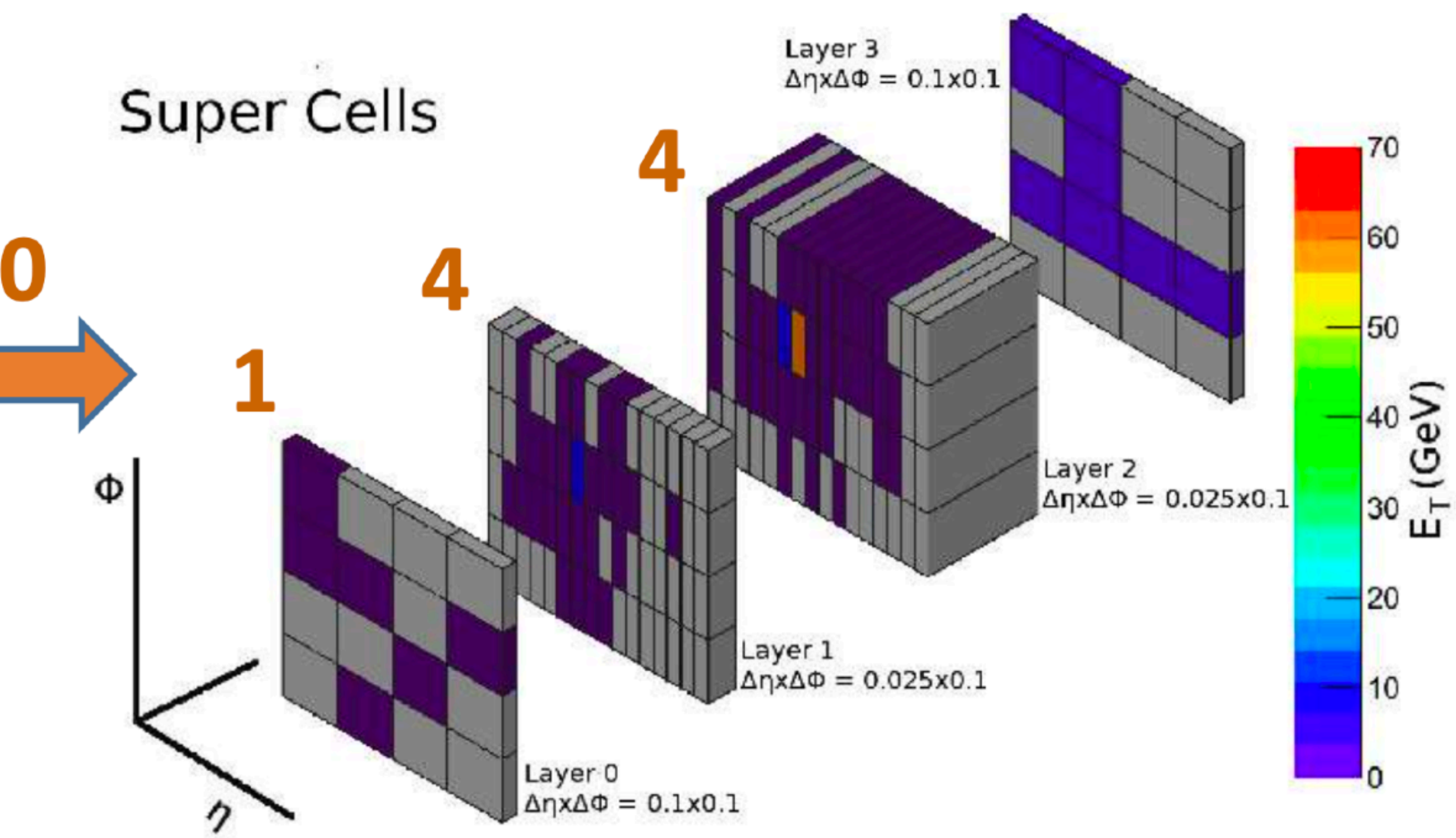
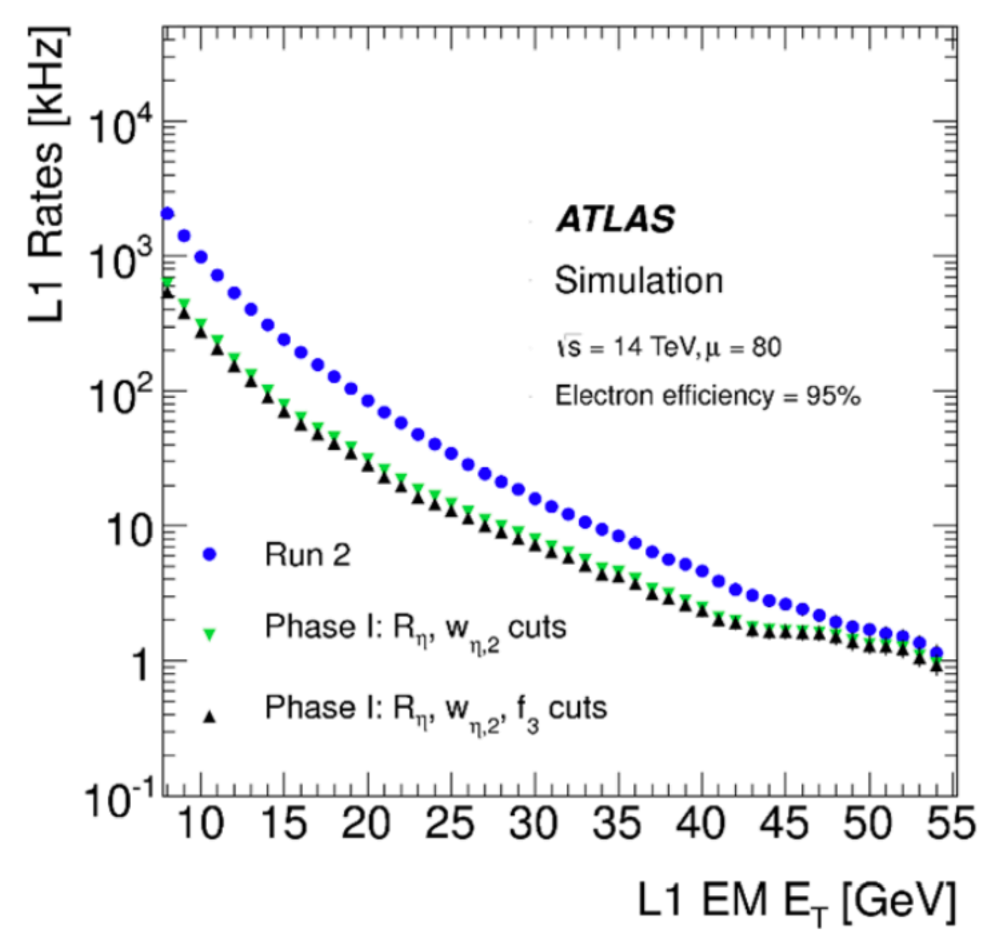
ATLAS calorimeter trigger upgrade

- **Preparation for Run 3 (2021+)**
  - higher granularity trigger data (with depth information
  - more powerful off-detector processing boards
    - allows more complex algorithms to be used, including dynamic clustering of ECAL/HCAL towers and pileup subtraction

Trigger super cells (finer granularity + depth)

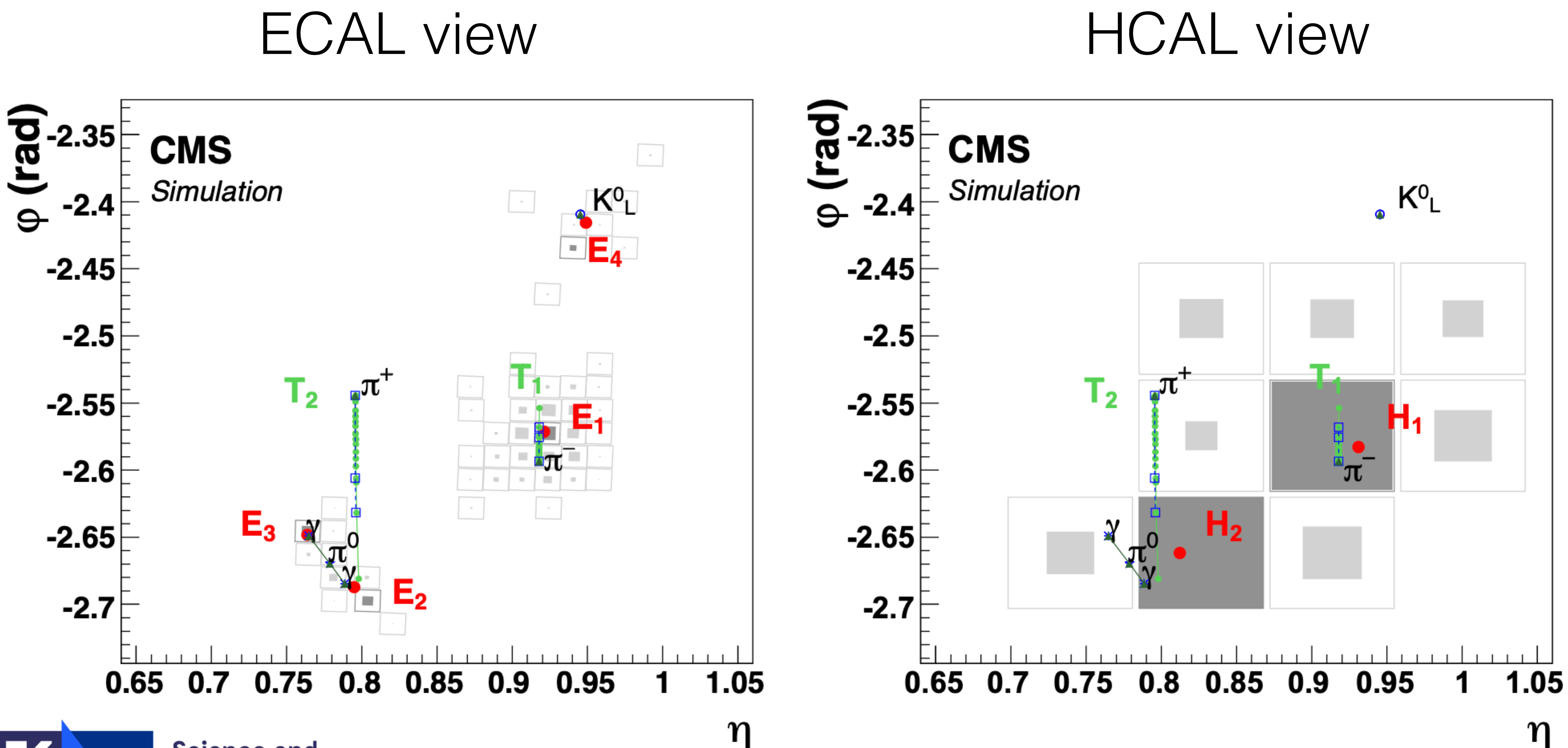


Reduced Electron/photon fake rate



Particle flow reconstruction

- **Particle trajectories mapped on to ECAL and HCAL energy deposits**
  - physics-based particle ID based on combined track/calo information

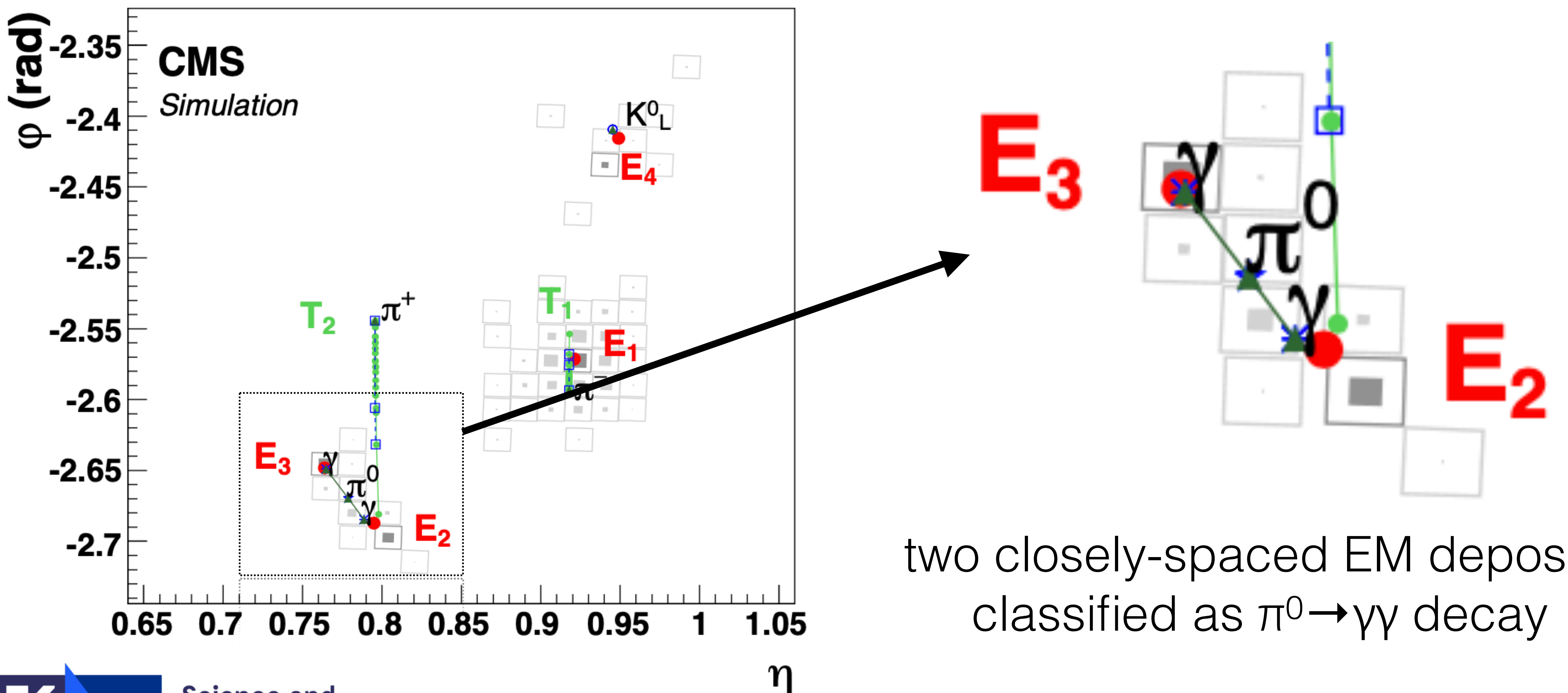


Particle flow reconstruction

- **Particle trajectories mapped on to ECAL and HCAL energy deposits**
  - physics-based particle ID based on combined track/calo information

ECAL view

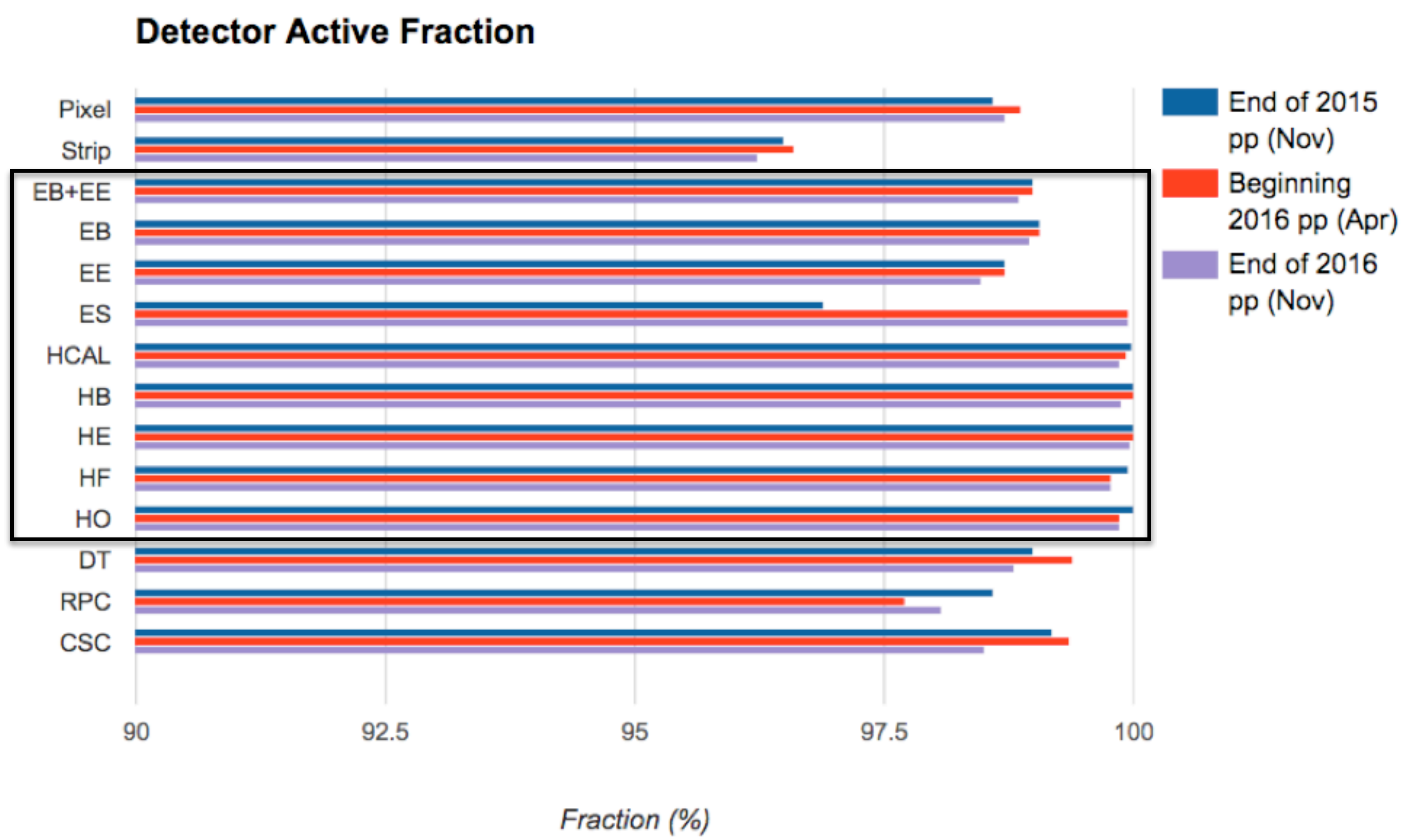
Zoom



two closely-spaced EM deposits classified as $\pi^0 \to \gamma\gamma$ decay

Detector health

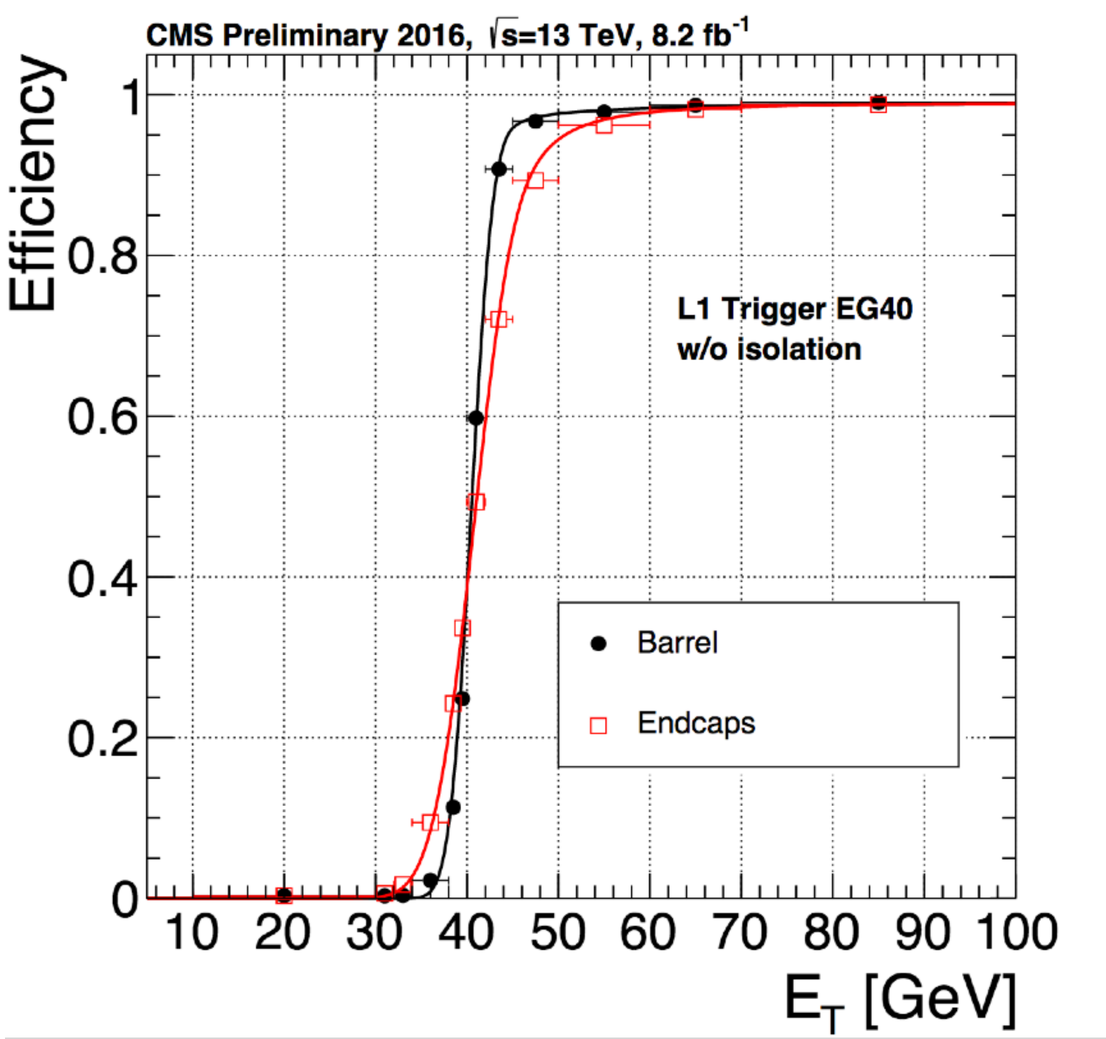
- **ECAL and HCAL detectors performing well, with high active detector fractions**



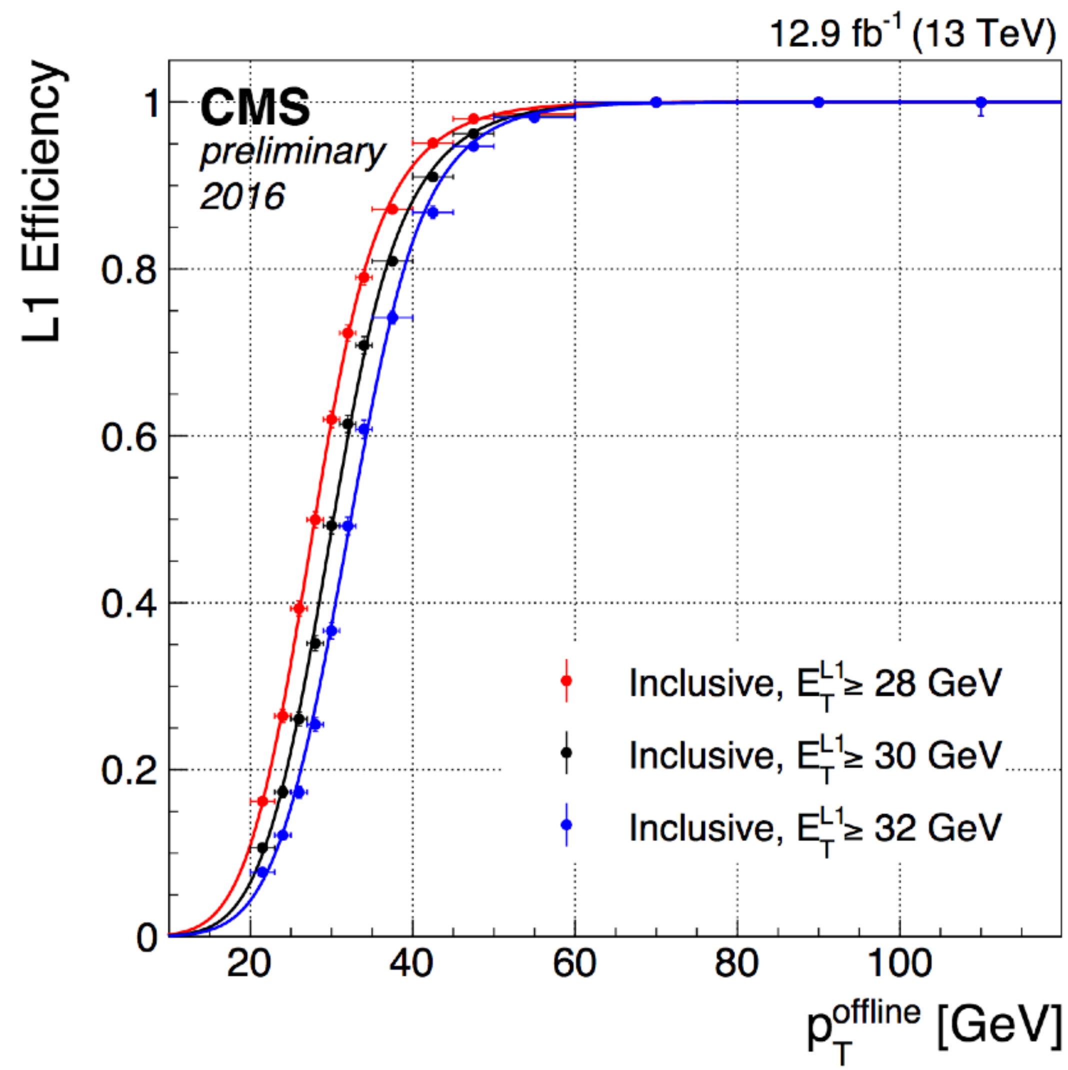
- **Thanks to dedicated efforts of detector experts and operations teams**

Triggering

Single electron



Tau



Improved L1 trigger algorithms in 2016 following Phase I upgrade

full trigger tower granularity available at Level 1

significant improvements in spatial and energy resolution, PU resilience and selection efficiency (especially for tau triggers)

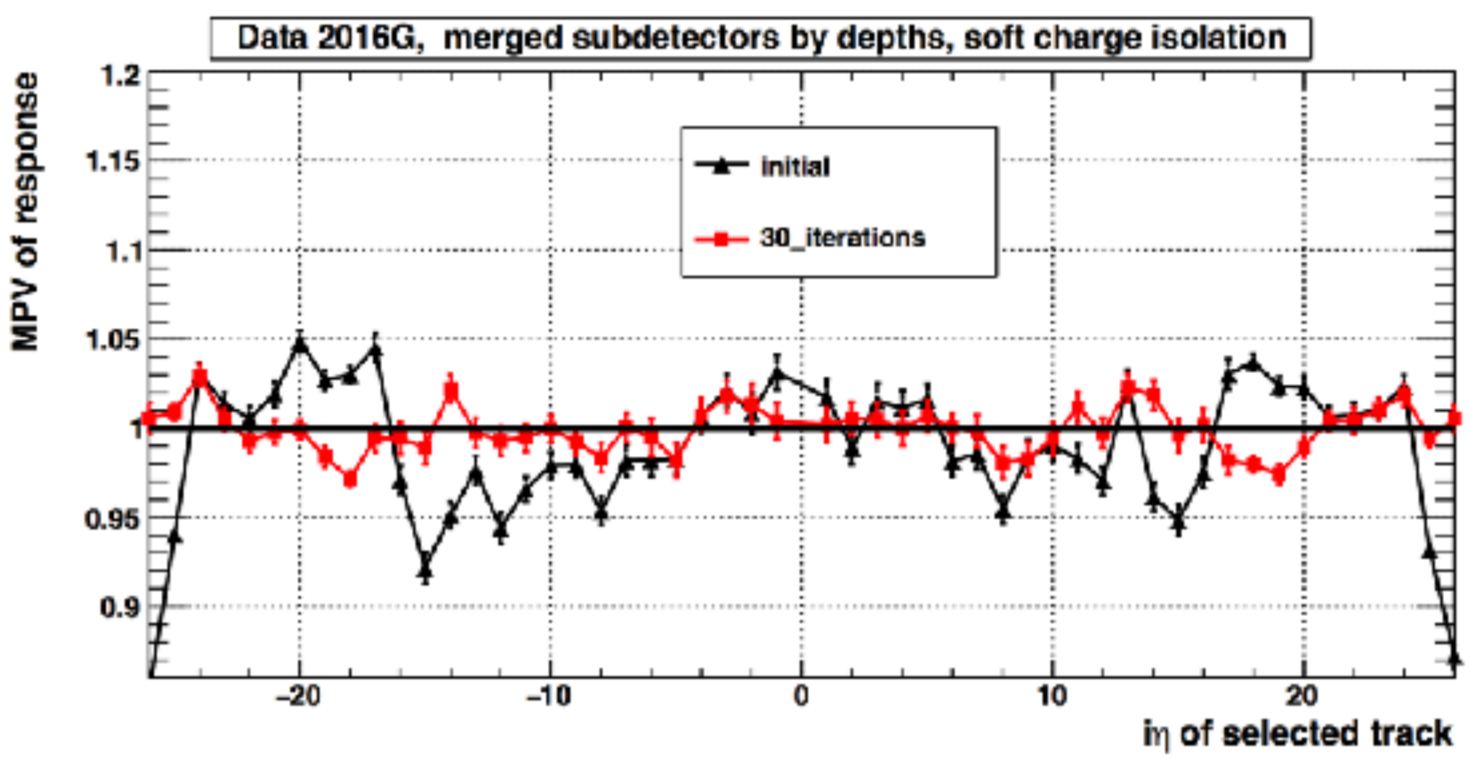
HCAL Calibration methods

- Channels **inter-calibration** at the same eta/depth: **Phi Simmetry**
  - equalizes the channels response wrt each other
  - works for HB, HE, HF

- Absolute scale in HB, HE: **Iso Track method**
  - uses 50 GeV pions momentum as a reference

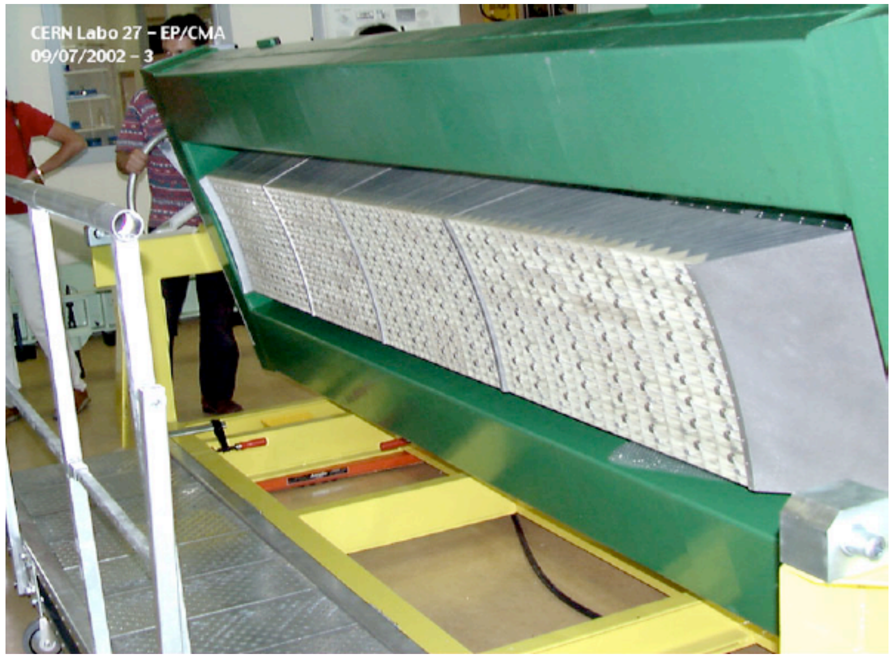
- Absolute scale in HF: **Z—> ee mass**
  - one electron in ECAL, the other in HF
  - check calibration of the response of the deposit in HF

Co60 sourcing (during winter shutdowns) allows absolute normalisation of scintillator + photodetector response



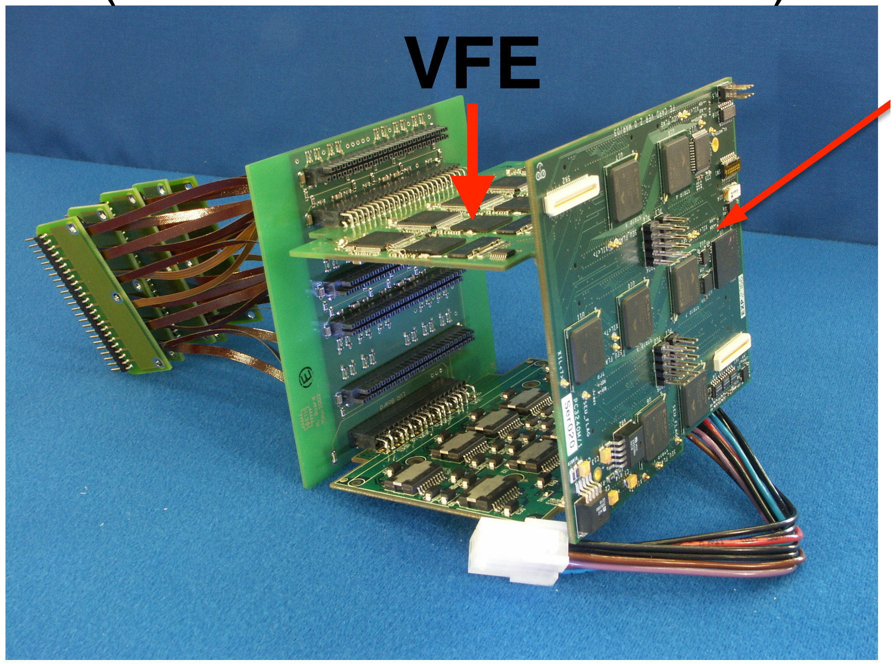
Elements of the ECAL Barrel

36 Supermodules



2448 Trigger towers

(readout of 5x5 channels)



61200 Lead Tungstate crystals

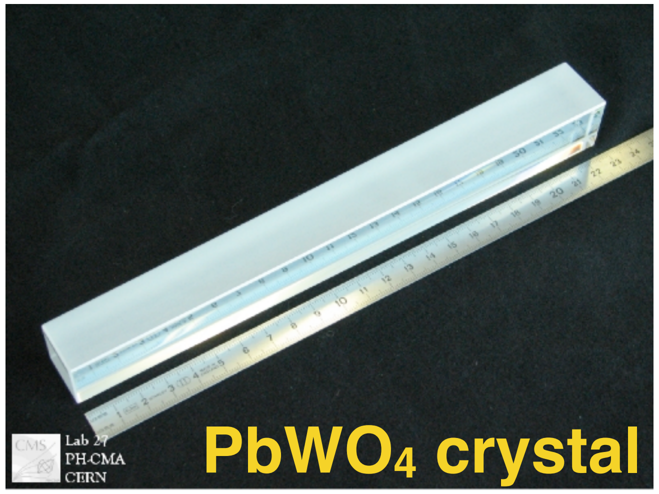
12240 Very Front End cards

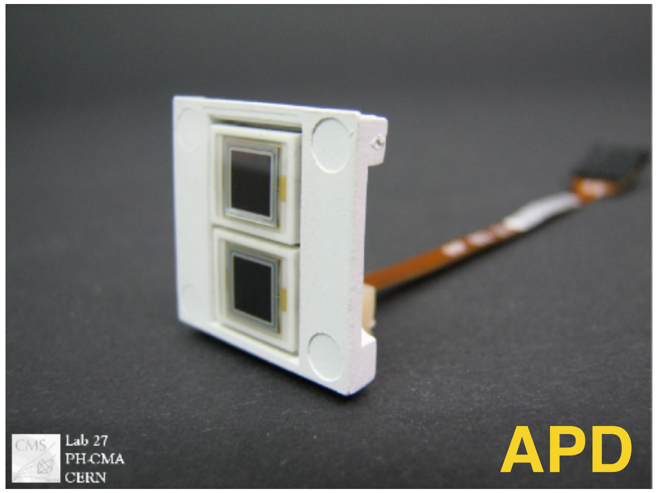
pulse amplification, shaping, digitization

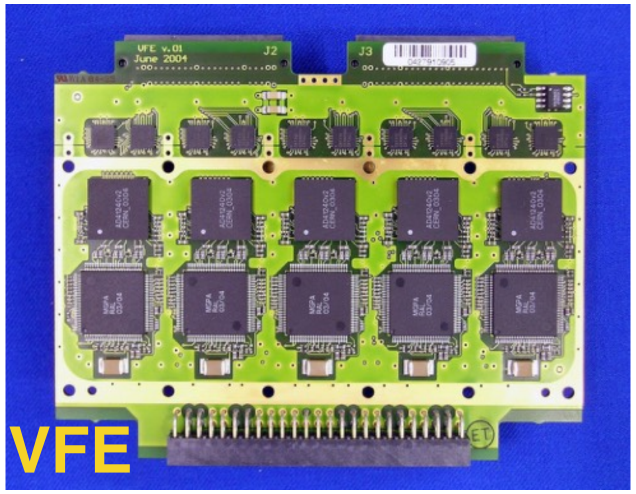
61200 APD pairs

2448 Front End cards

data pipeline and transmission, TP formation, clock/control



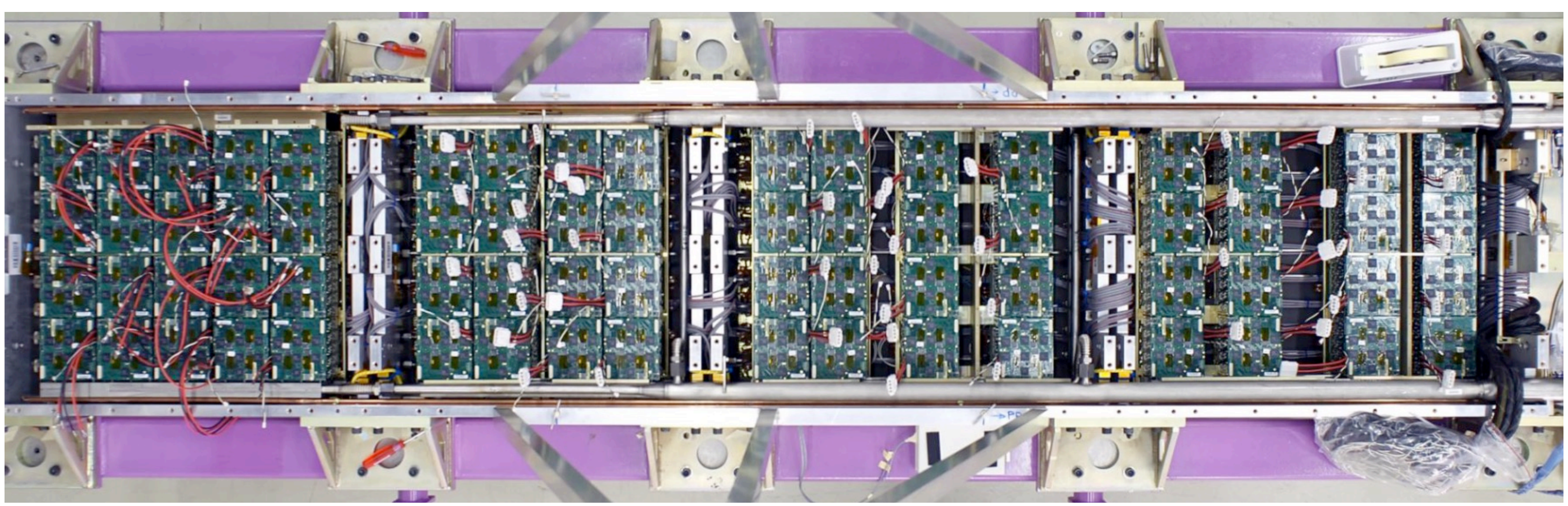




ECAL Barrel construction

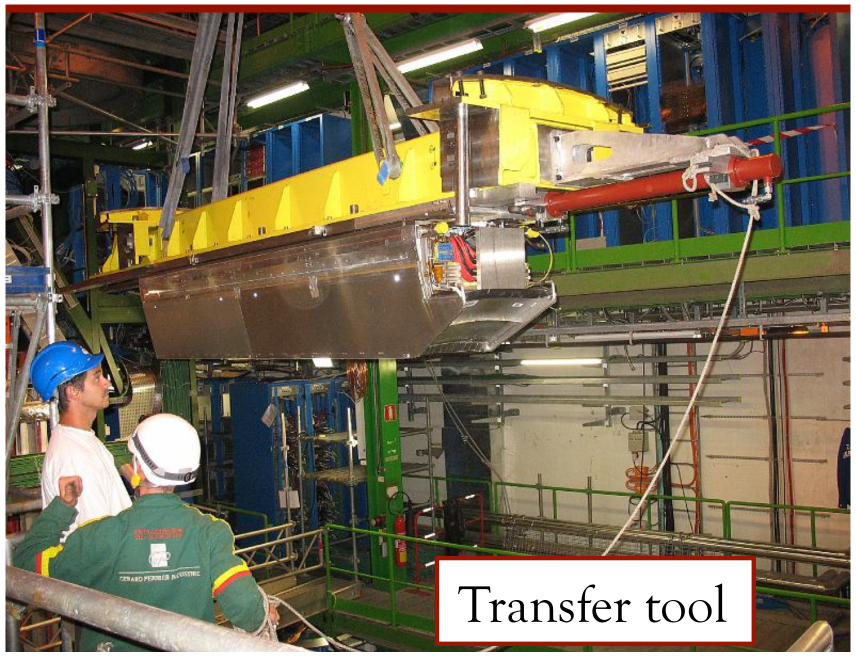
Electronics installation

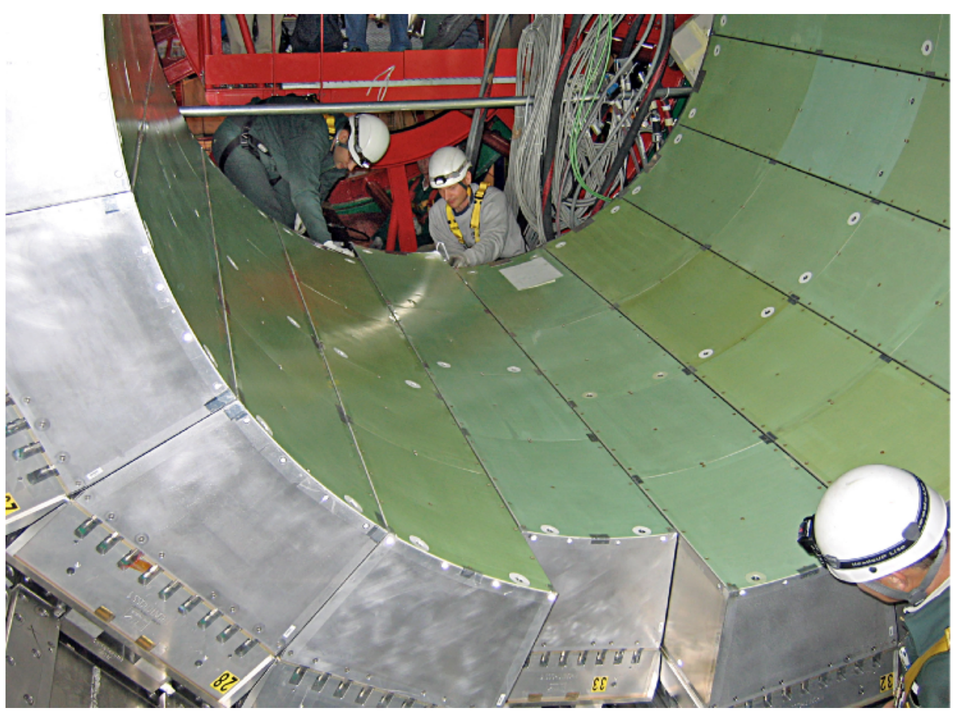
Supermodule integration/test stands @ Prevessin

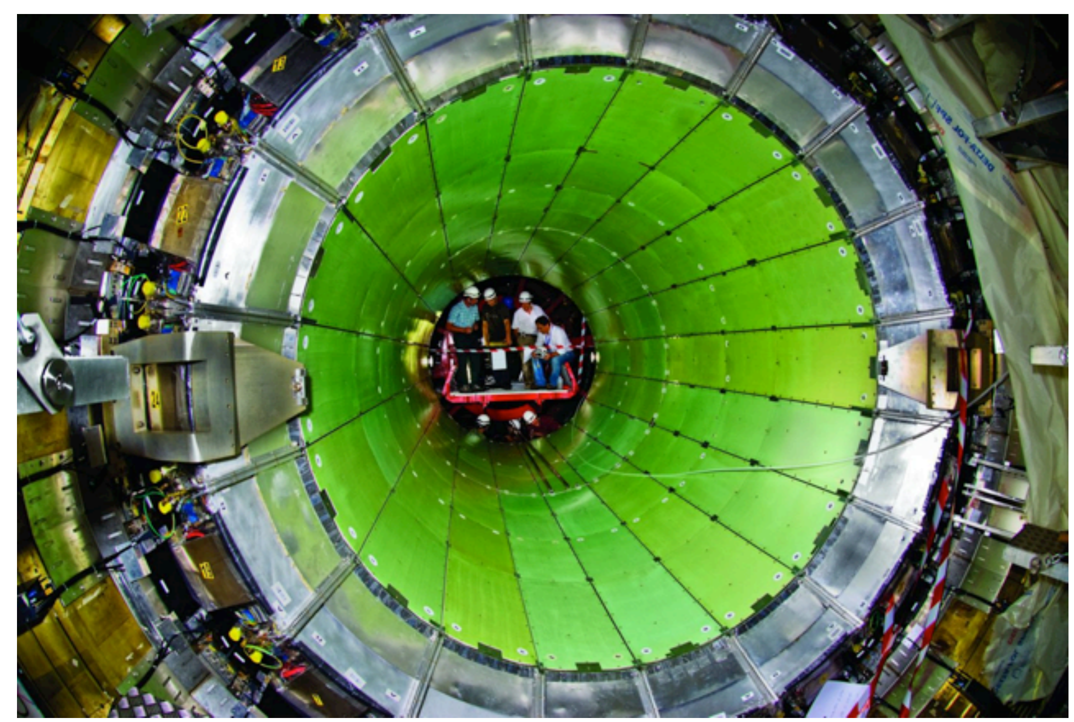


Supermodule in the process of electronics integration

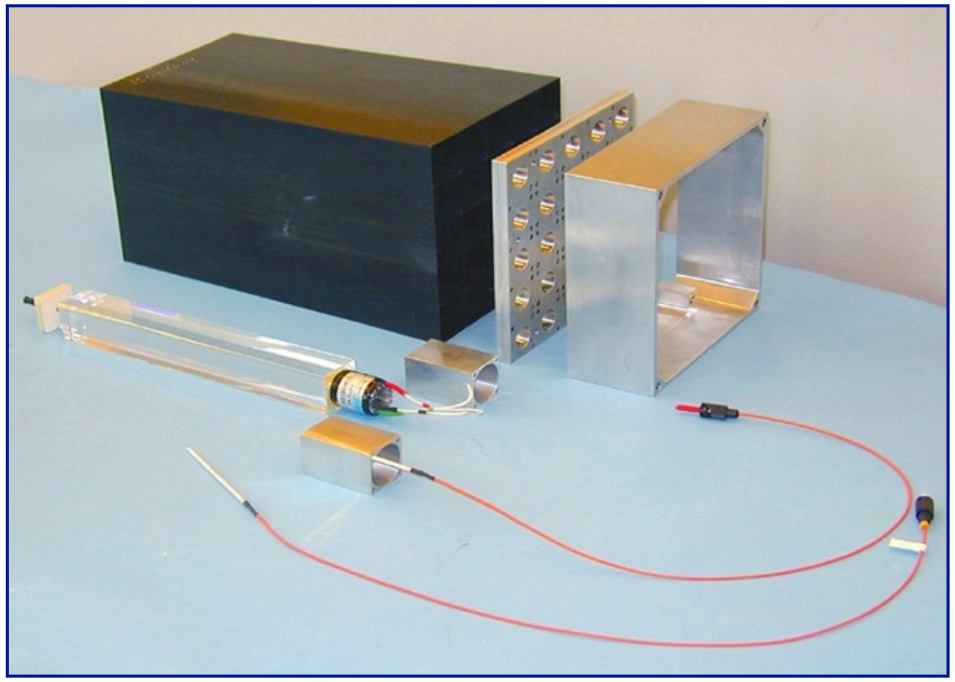
ECAL Barrel installation



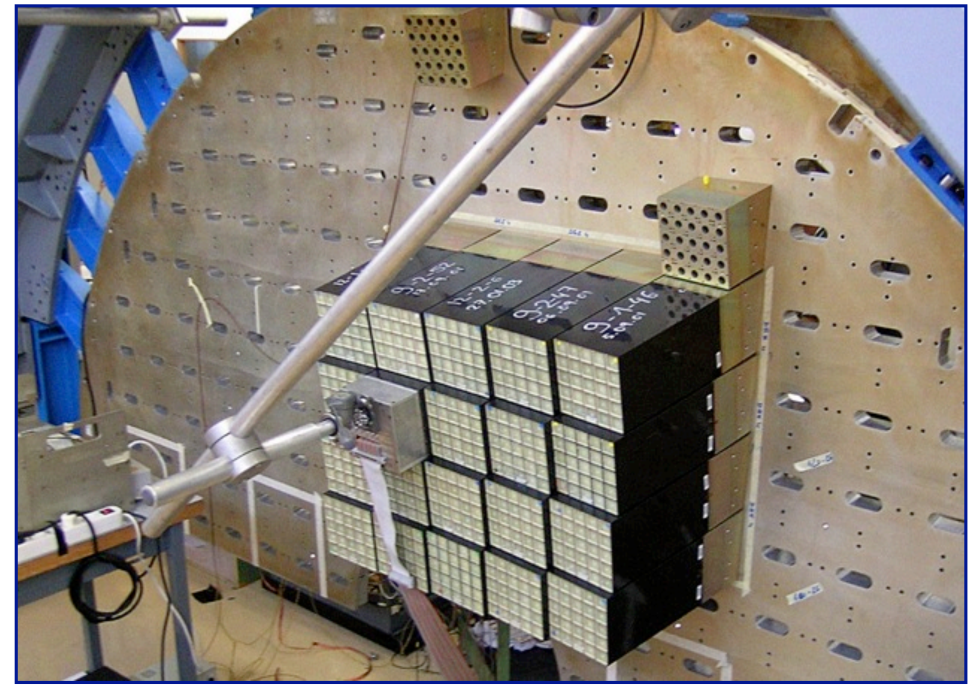




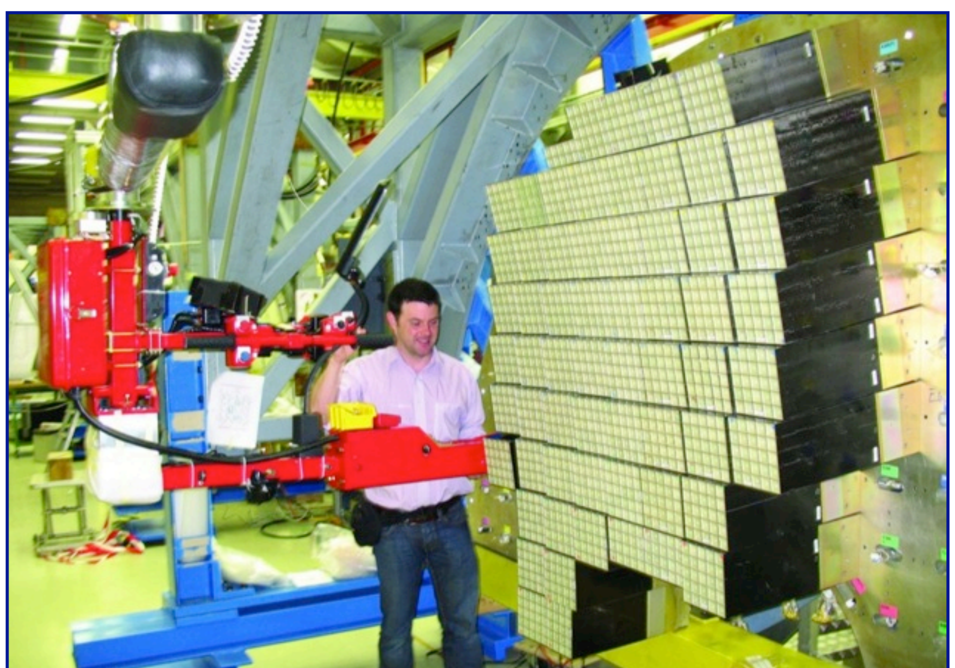
ECAL Endcaps construction



Elements of a EE supercrystal (5x5 channels)



Supercrystals on endcap backplane

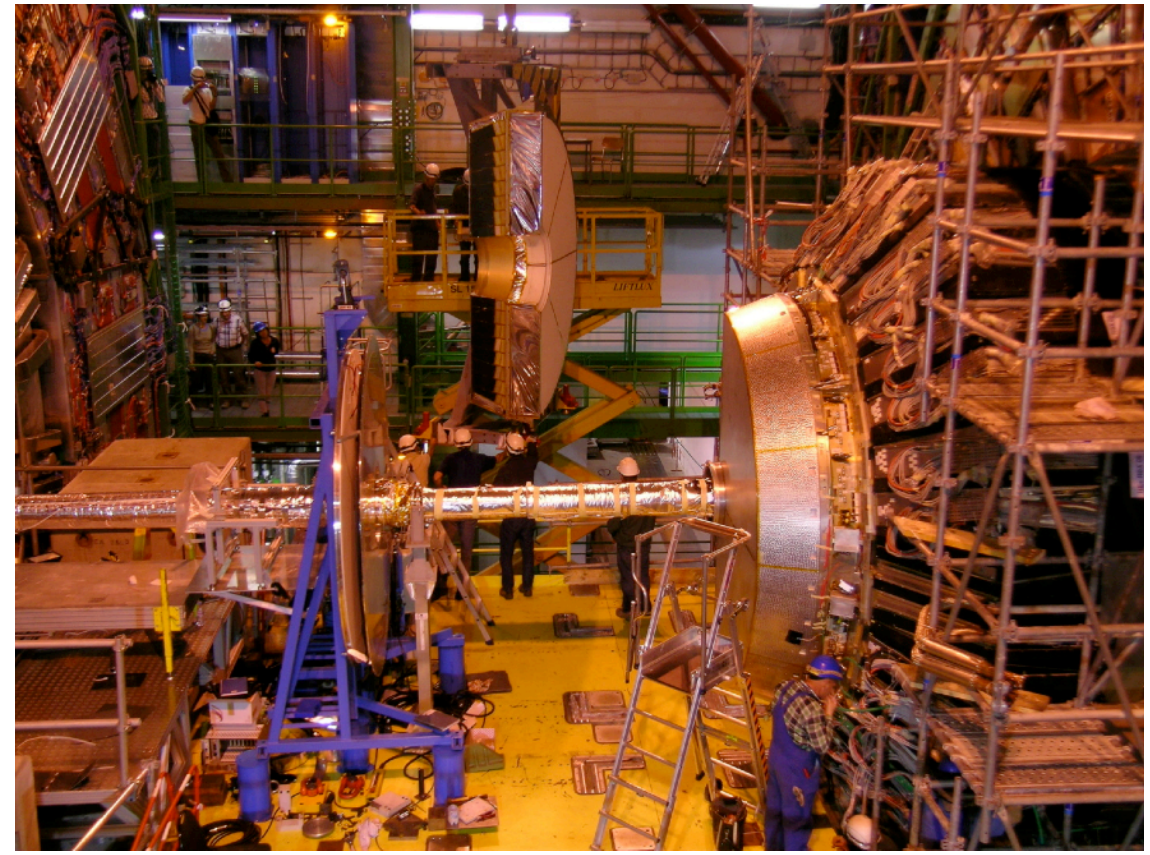


Installing supercrystals

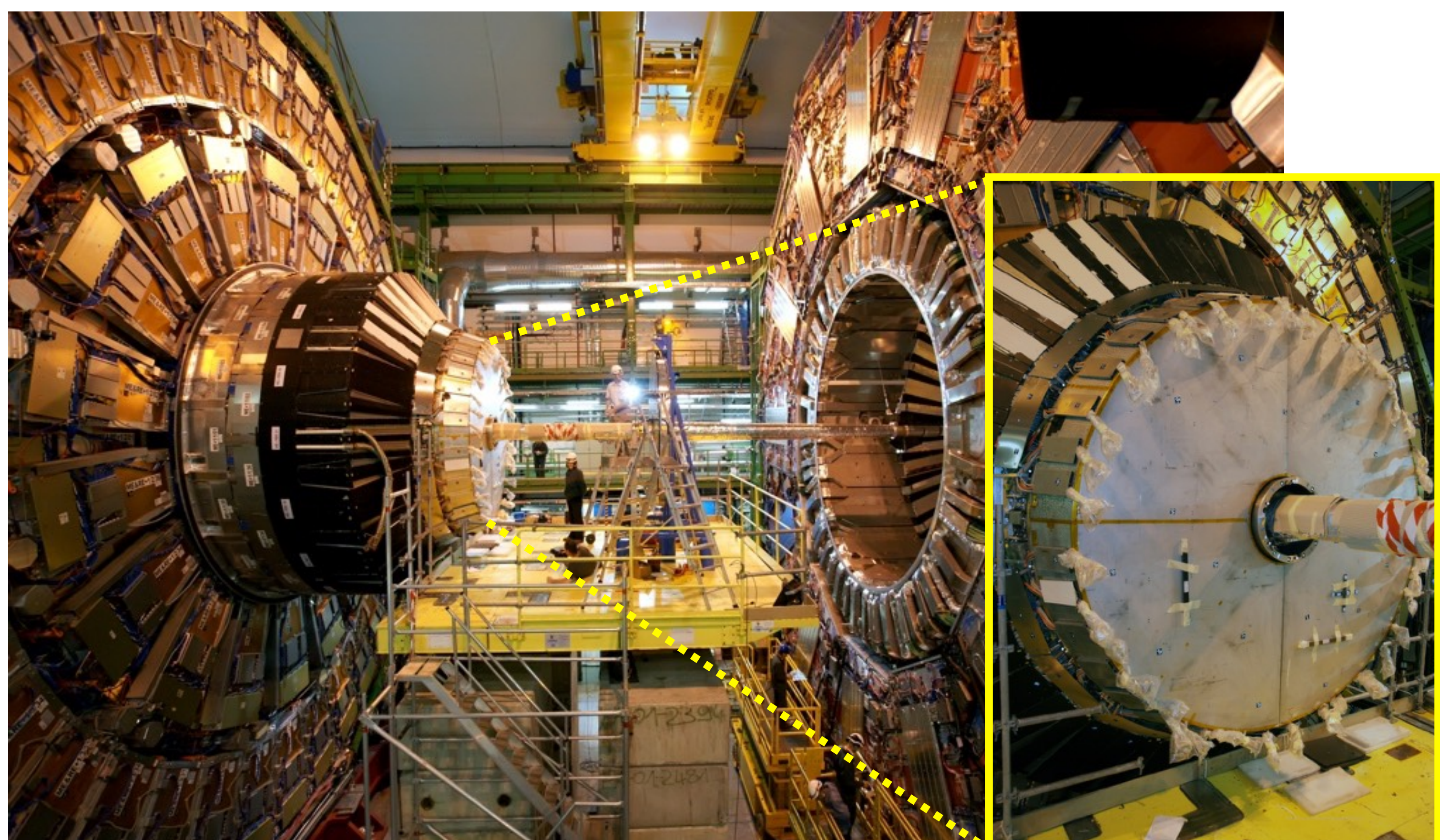
Installation of readout electronics

ECAL Endcaps installation

Endcap half disk (Dee) at Point 5

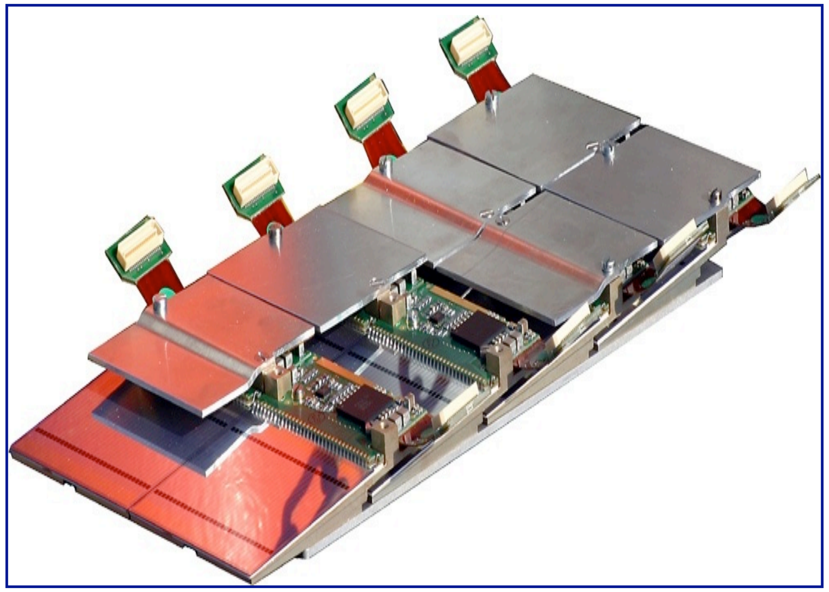


Lowering the second half disk (Dee)

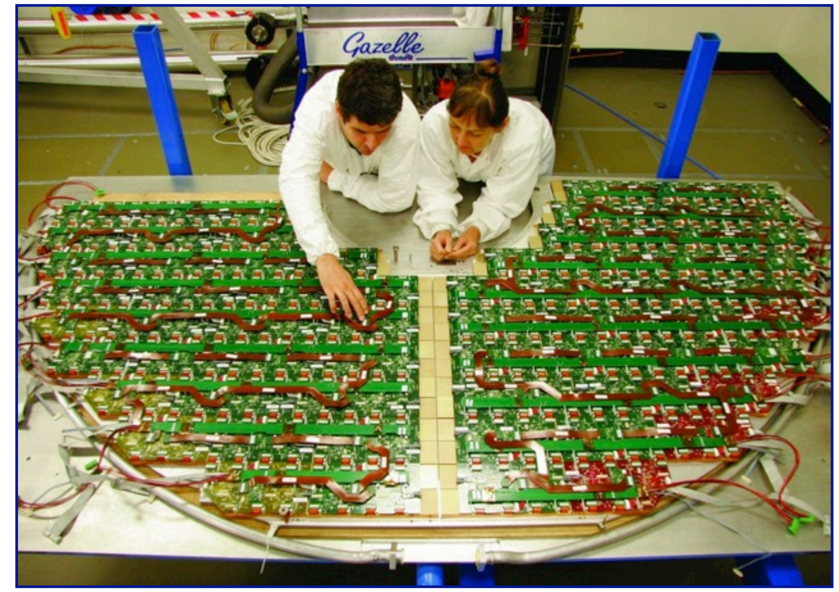


First endcap installed (Aug 2008)

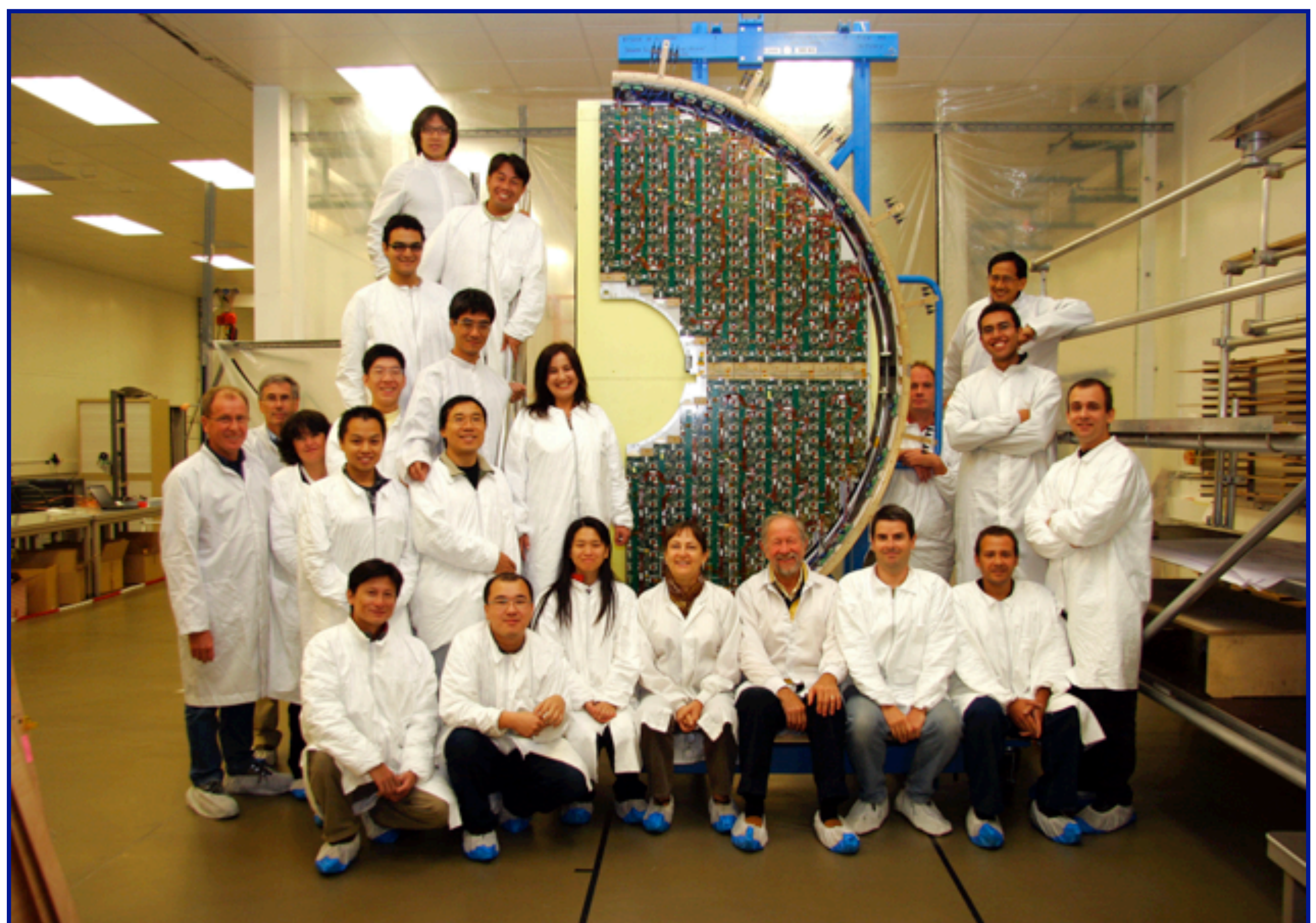
ECAL Preshower construction



Preshower Si hybrids

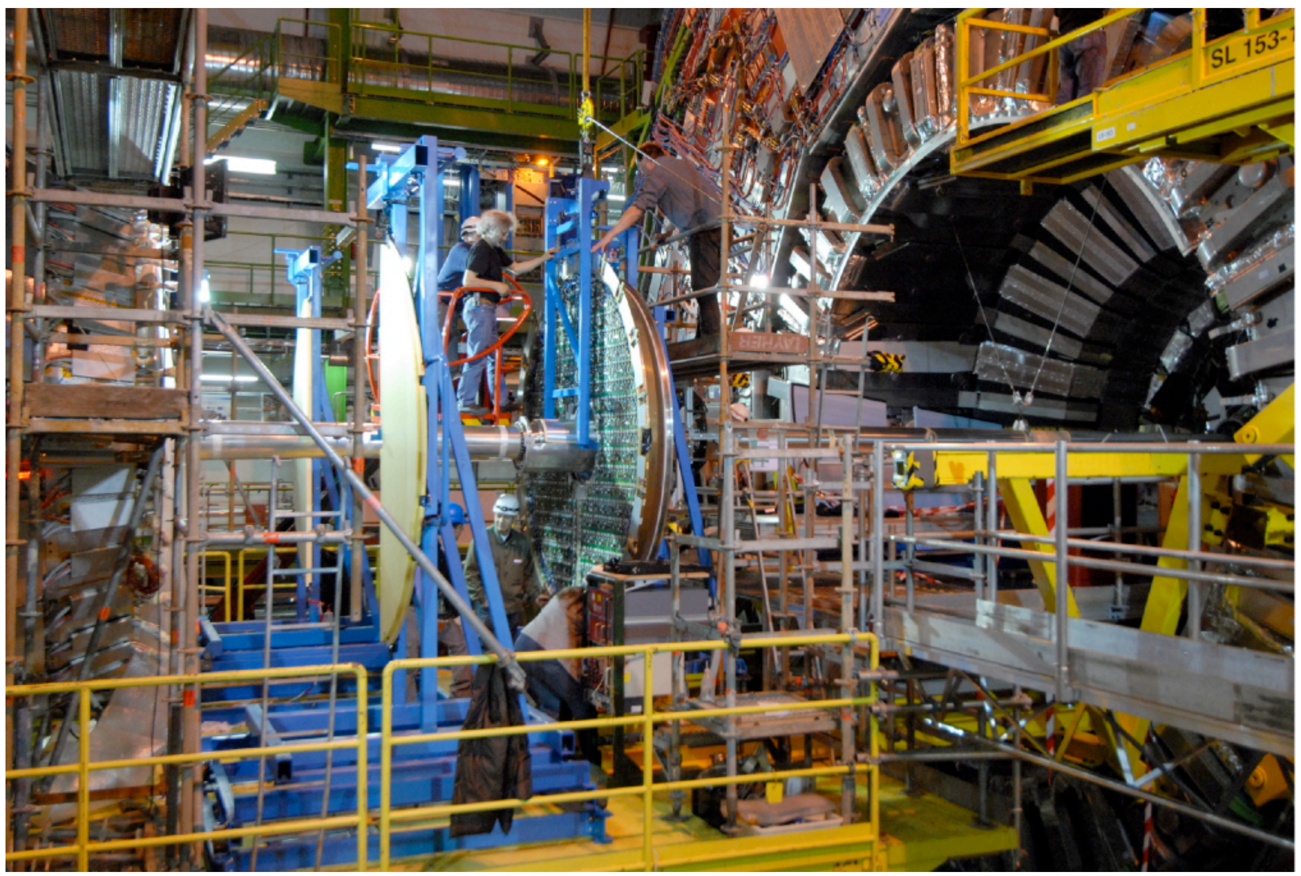


Electronics integration



completed half-disk (Dee)

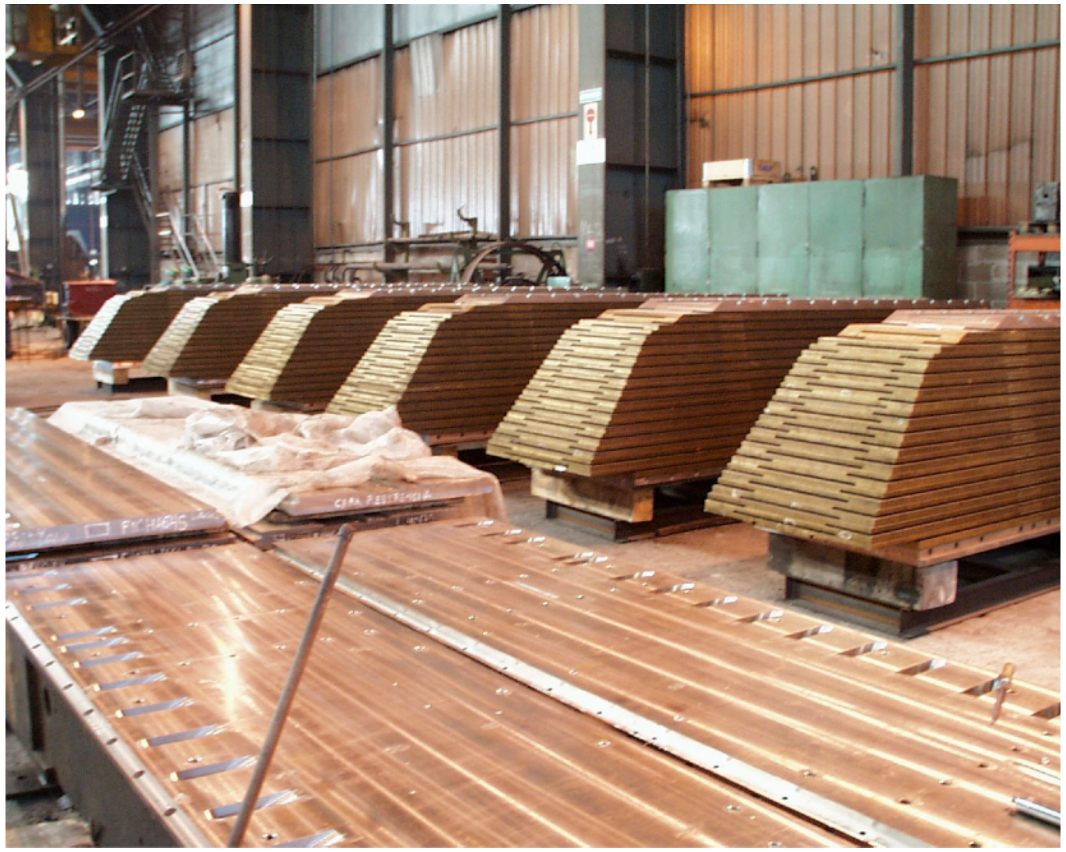
ECAL Preshower installation



Preshower Dees lowered in place

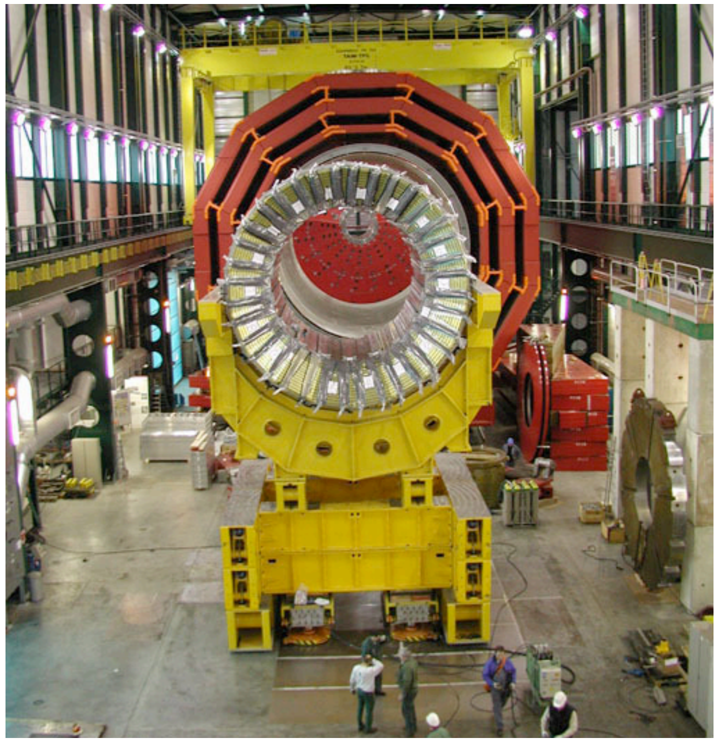
Preshower Dees positioned around beam pipe

HB construction and installation

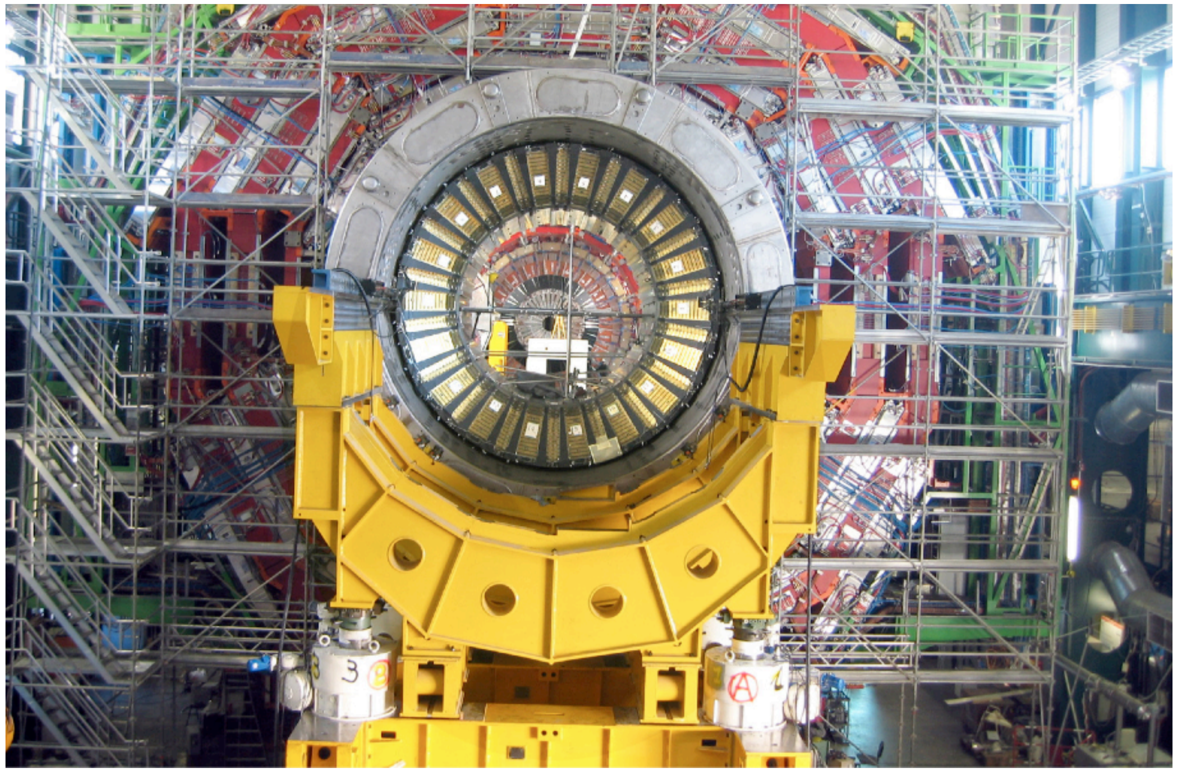


HB brass wedges

HB construction

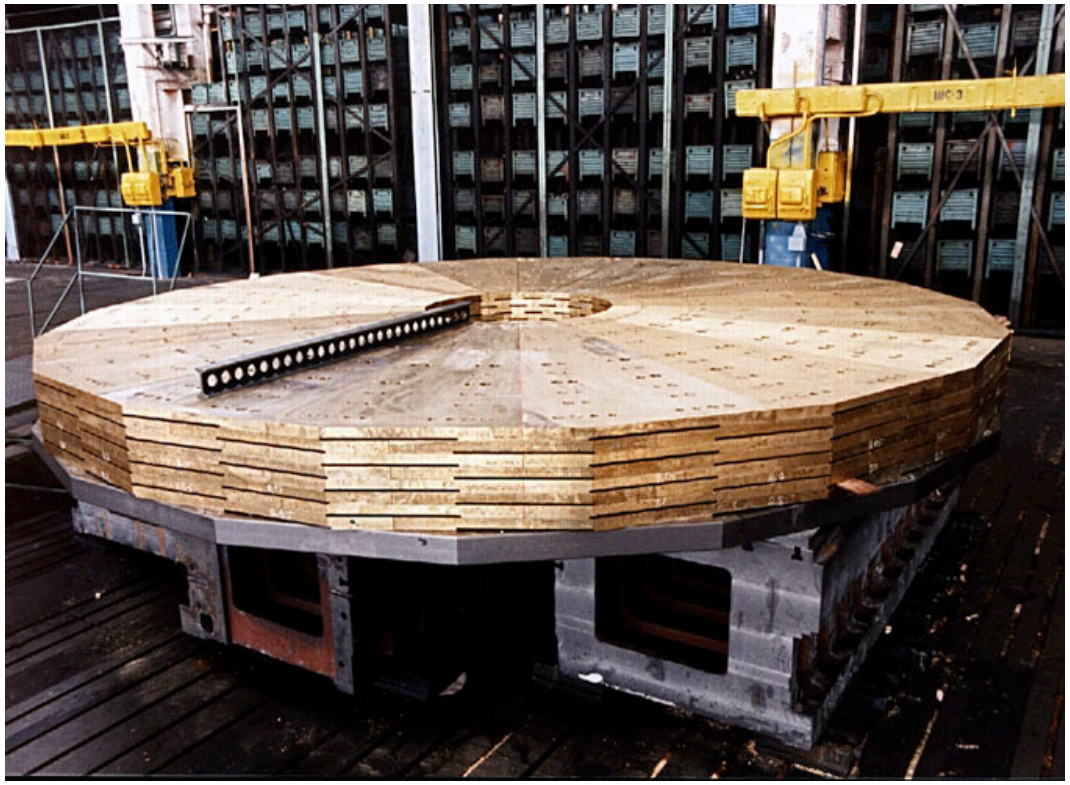


completed HB section ready to enter yoke



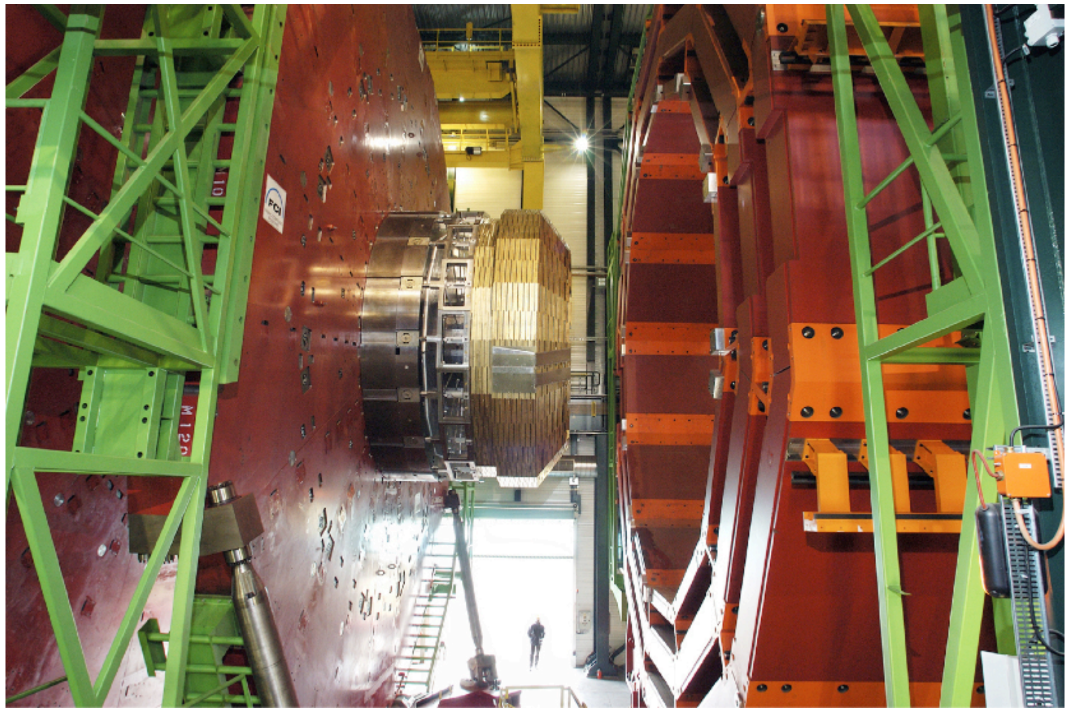
HB section inside yoke

HE construction and installation

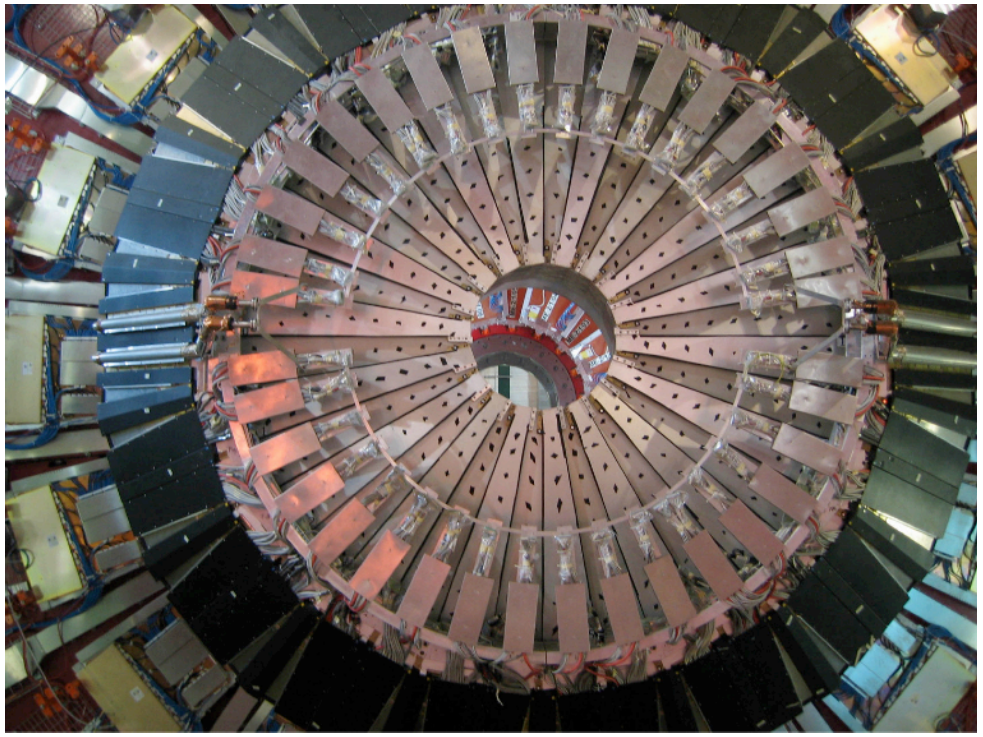


Building up HE brass structure

Completed HE brass structure



Completed HE installed on YE1



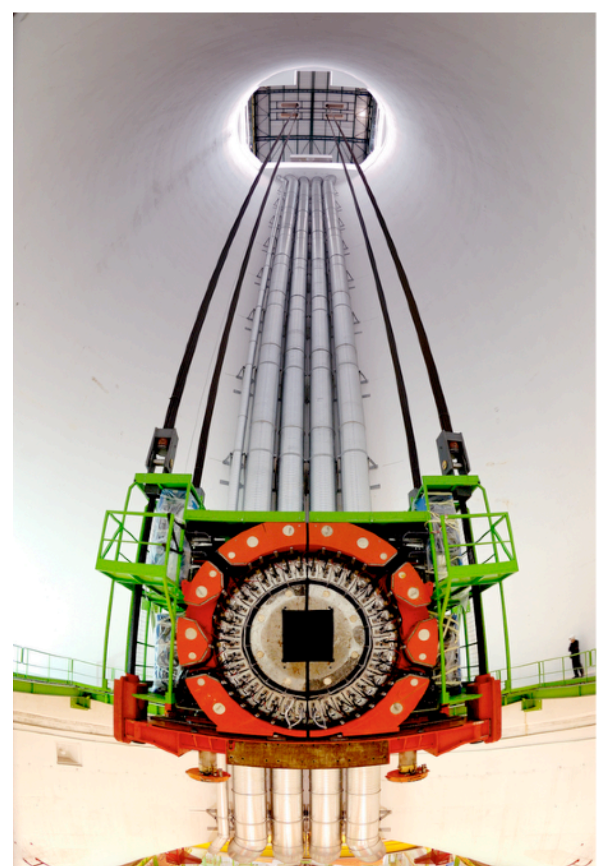
Completed HE with ES services on top

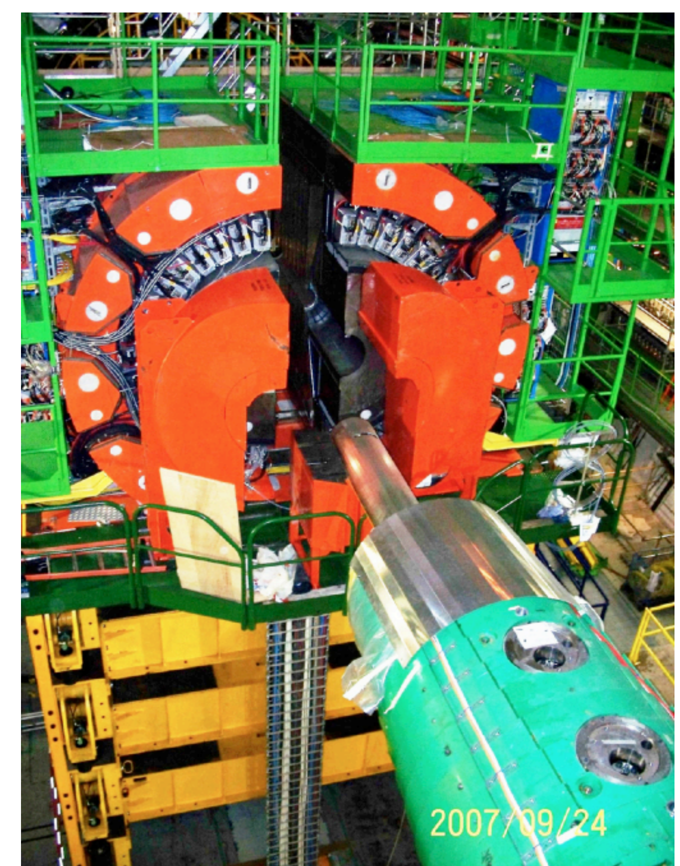
Forward HCAL


Inserting HF quartz fibres


HE wedges + fibre bundles

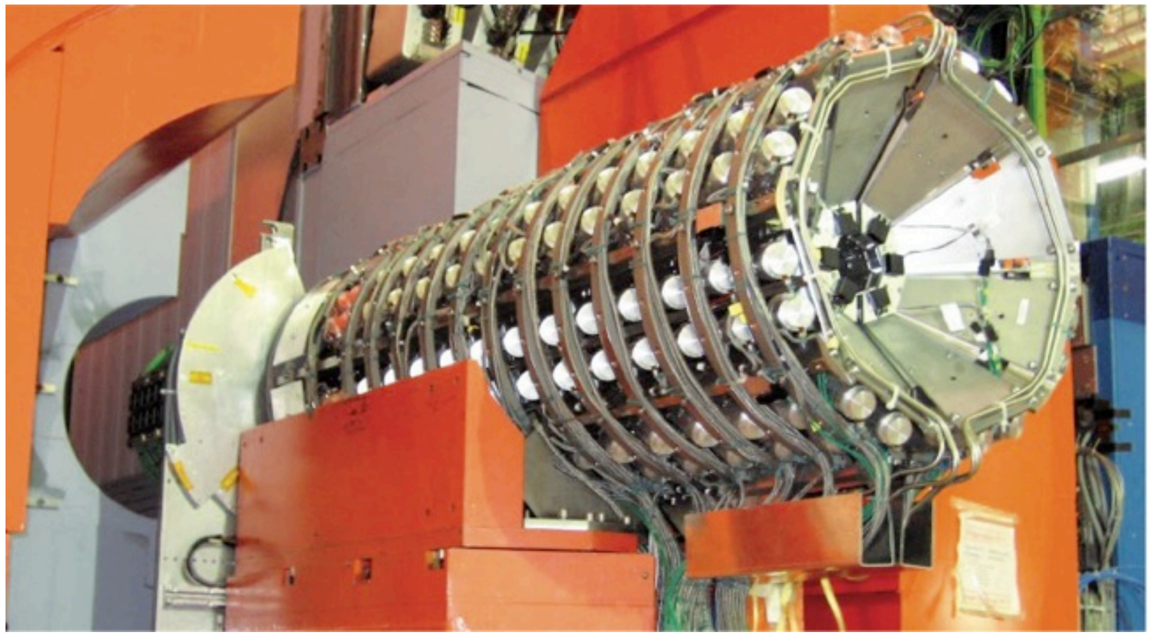

HF transport from Meyrin


Lowering HF



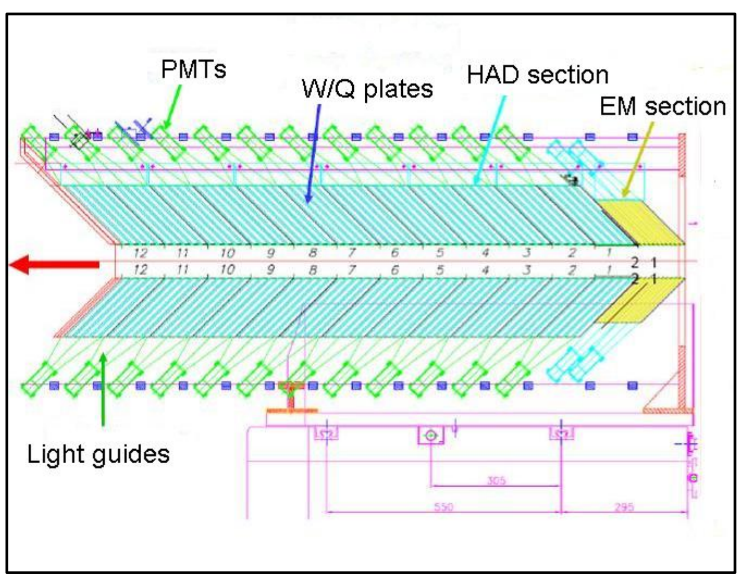
HF installed

Other Forward HCAL detectors



CASTOR

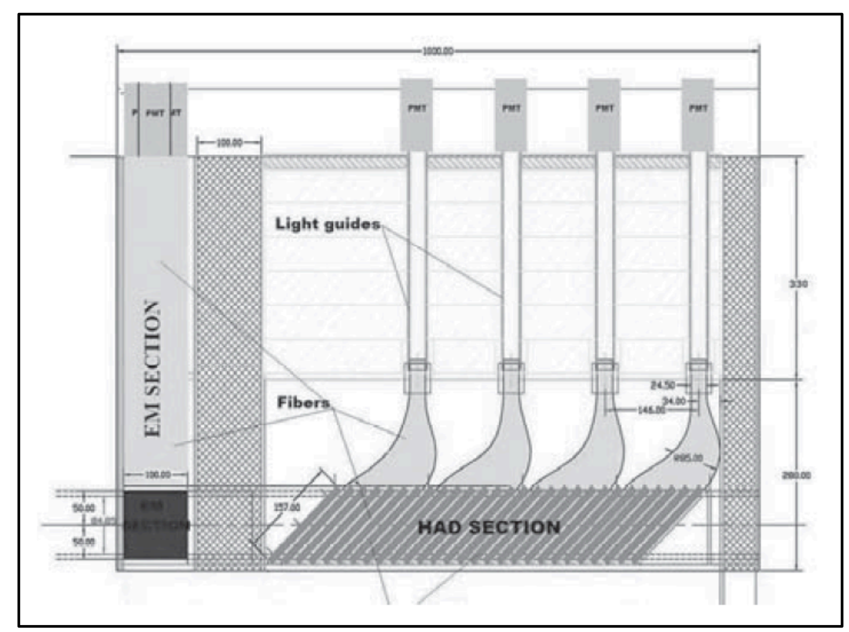
(Centauro and Strange Object Research)



5.2 < |eta| < 6.6
tungsten layers/silica quartz plates
PMT readout

ZDC

(Zero Degree Calorimeter - HI + diffractive physics)



|eta| > 8.3
tungsten plates + quartz fibres
PMT readout

Reasons for the EB upgrade

New L1 requirements

Current FE and OD readout inconsistent with L1 phase II requirements:

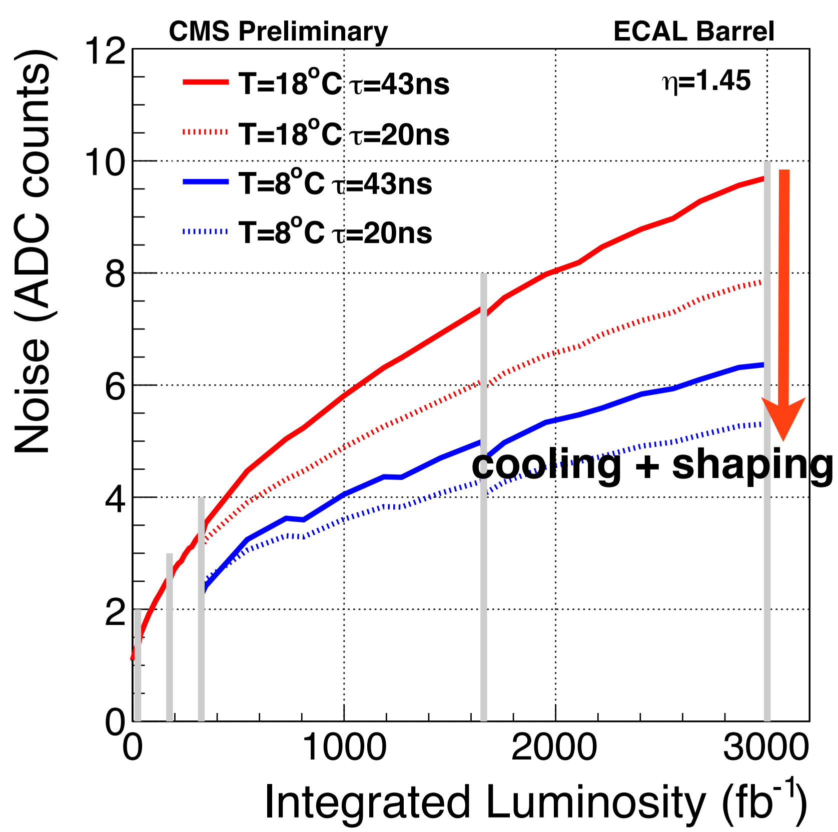
750 kHz L1 accept rate
12.5μs L1 latency

Mandatory to replace:

Front end card
(remove on-detector latency buffer and rate limitation)
OD electronics
(remove rate limitation)

APD noise mitigation

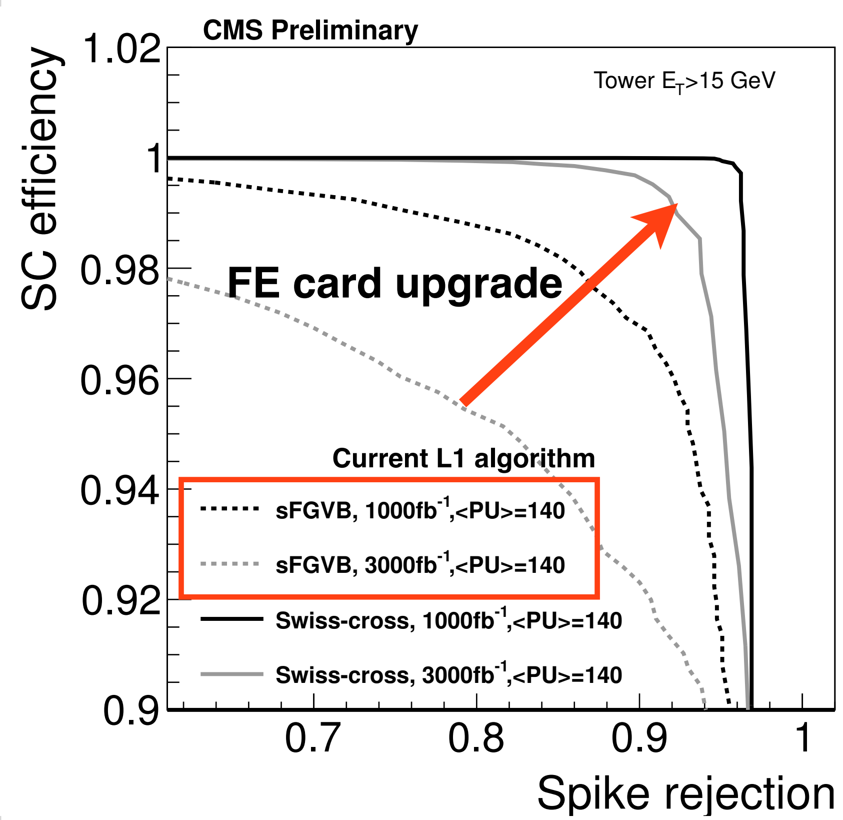
APD noise increase will significantly degrade EM resolution at HL-LHC



Mandatory to mitigate this by cooling the APDs optimising pulse shaping (new VFE)

Spike mitigation

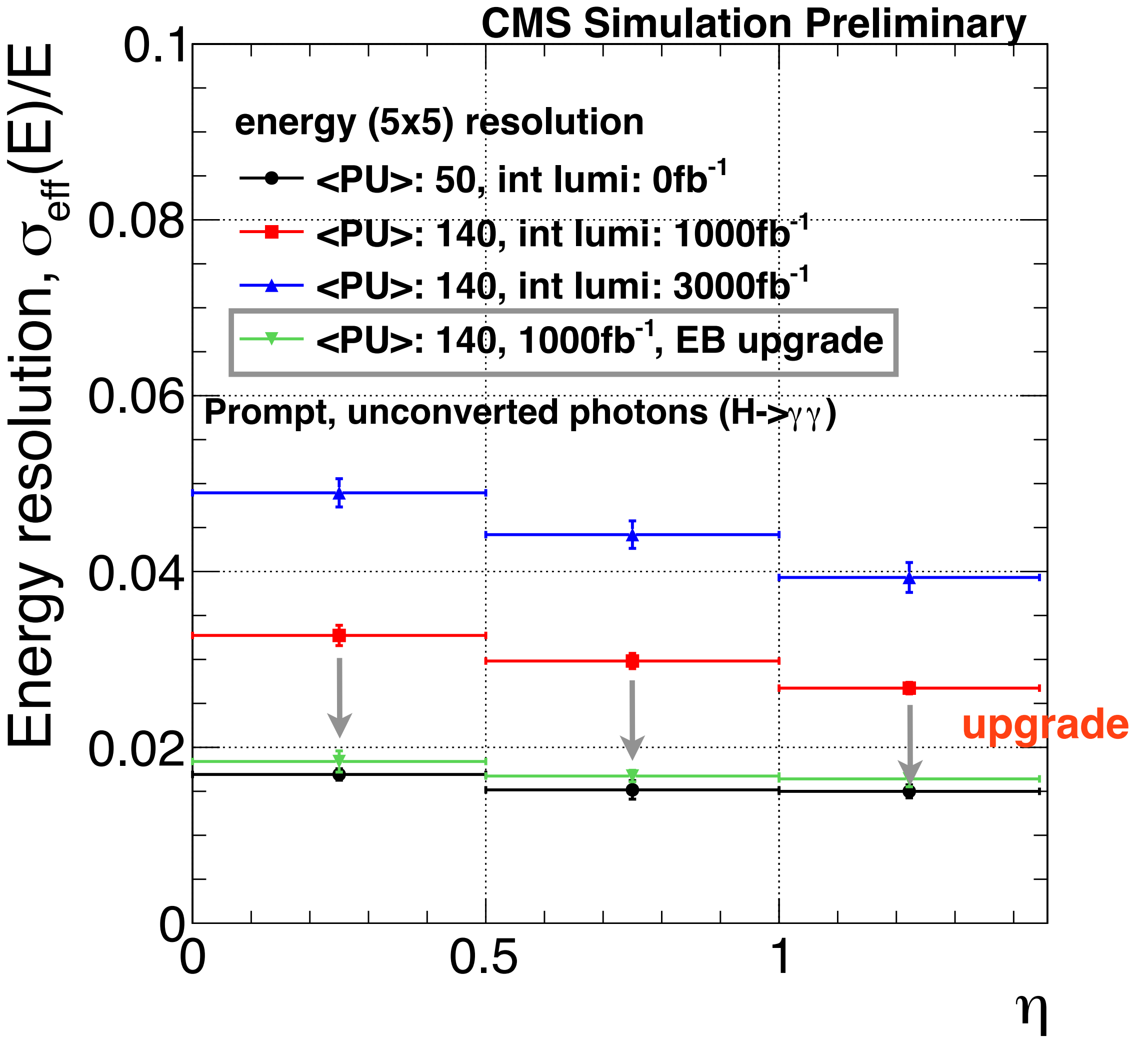
Performance of current L1 spike killer will degrade significantly.



Requires much better spike killing algorithms from new FE and VFE (>>99% efficient)

Physics reasons for the Upgrade

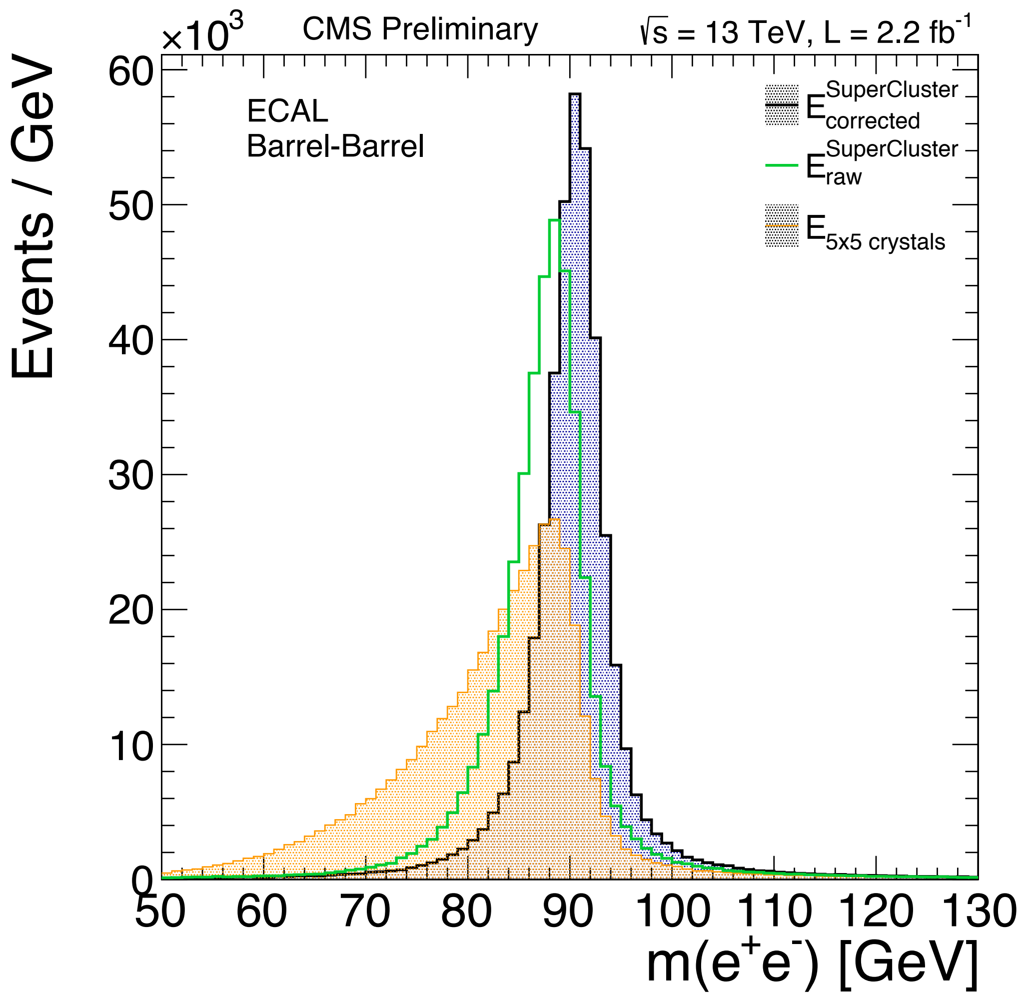
- **Maintain electron/photon resolution for Phase II**
  - **increase in APD leakage current otherwise dominates resolution for HL-LHC luminosities**
  - **<u>Mitigation strategy:</u>**
    - **Cool APDs from 18° to ~8°C**
    - **Implement shorter pulse shaping in a new front-end ASIC**



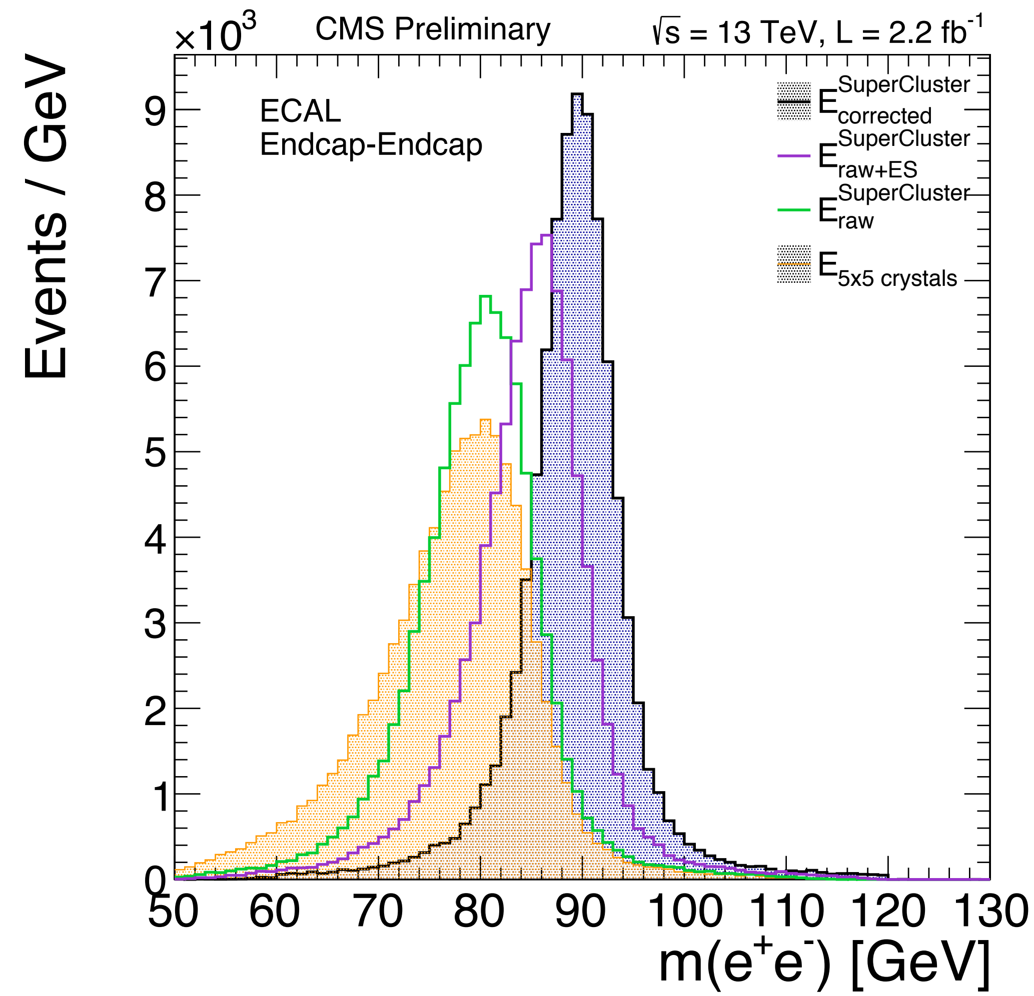
<u>Upgrade is mandatory to maintain good electron/photon resolution in Phase II</u>

ECAL energy reconstruction

barrel



endcap



Z->ee invariant mass distributions for barrel and endcap

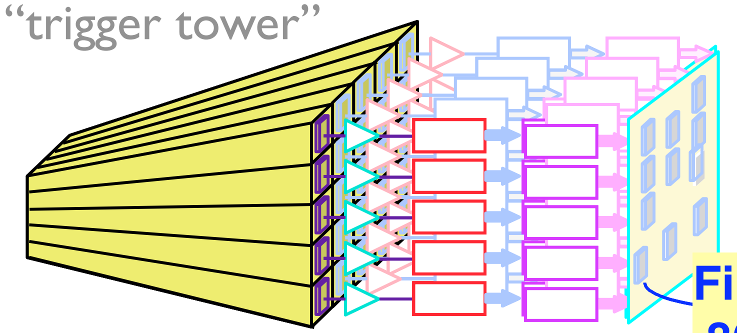
The improvements from advanced clustering and cluster corrections are evident

5. Detector Readout

EB/EE readout

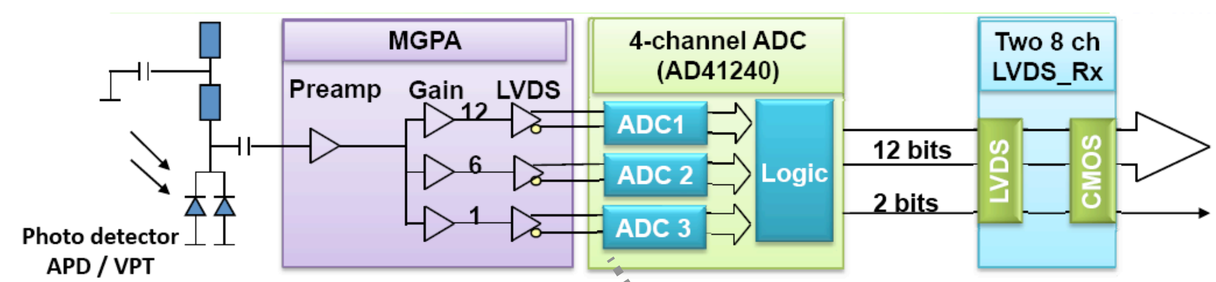
On-detector readout:

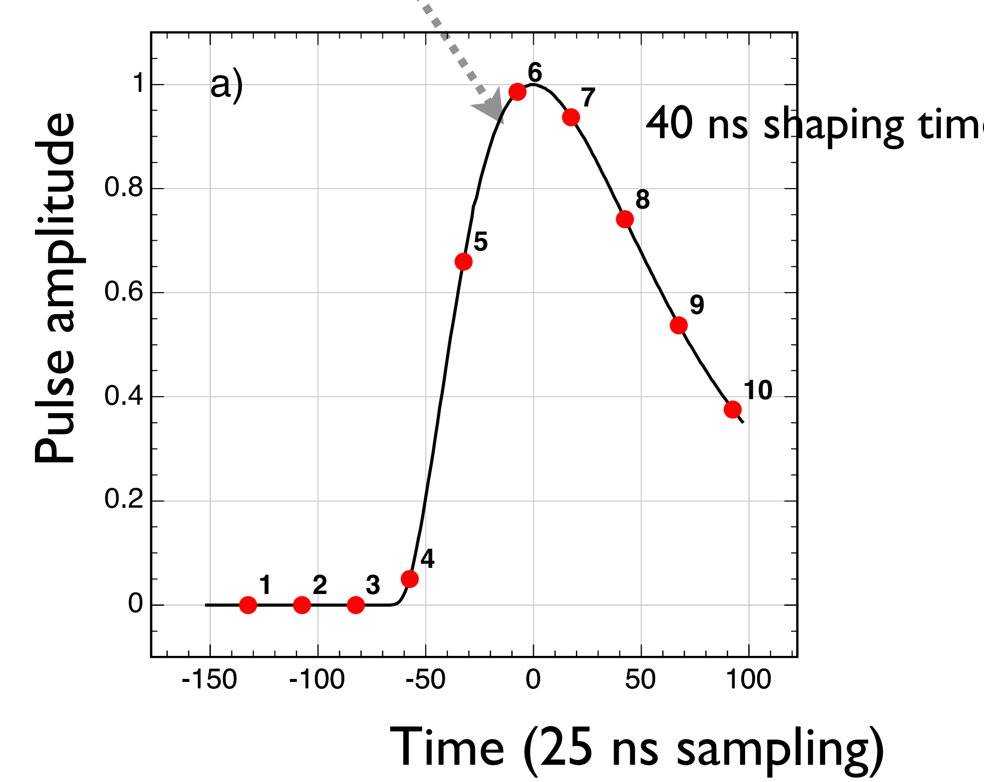
Trigger tower: 25 xtals (5x5):



5 Very Front End cards
Pulse amplification and shaped, 3 parallel gain stages
12 bit ADC records ten 25ns time samples, and selects input with highest non-saturated gain

1 Front End card Performs trigger sums from VFE output. Sends crystal and trigger data on receipt of Level 1 trigger





Off-detector readout:

TCC - Trigger Concentrator card - receives trigger primitive data from FE cards, Sends trigger tower energy sums to Calorimeter Trigger (40MHz)

DCC - Data Concentrator card - receives crystal and trigger data on receipt of a Level 1 trigger. Applies data reduction algorithms and transfers data to DAQ.

+ clock & control board

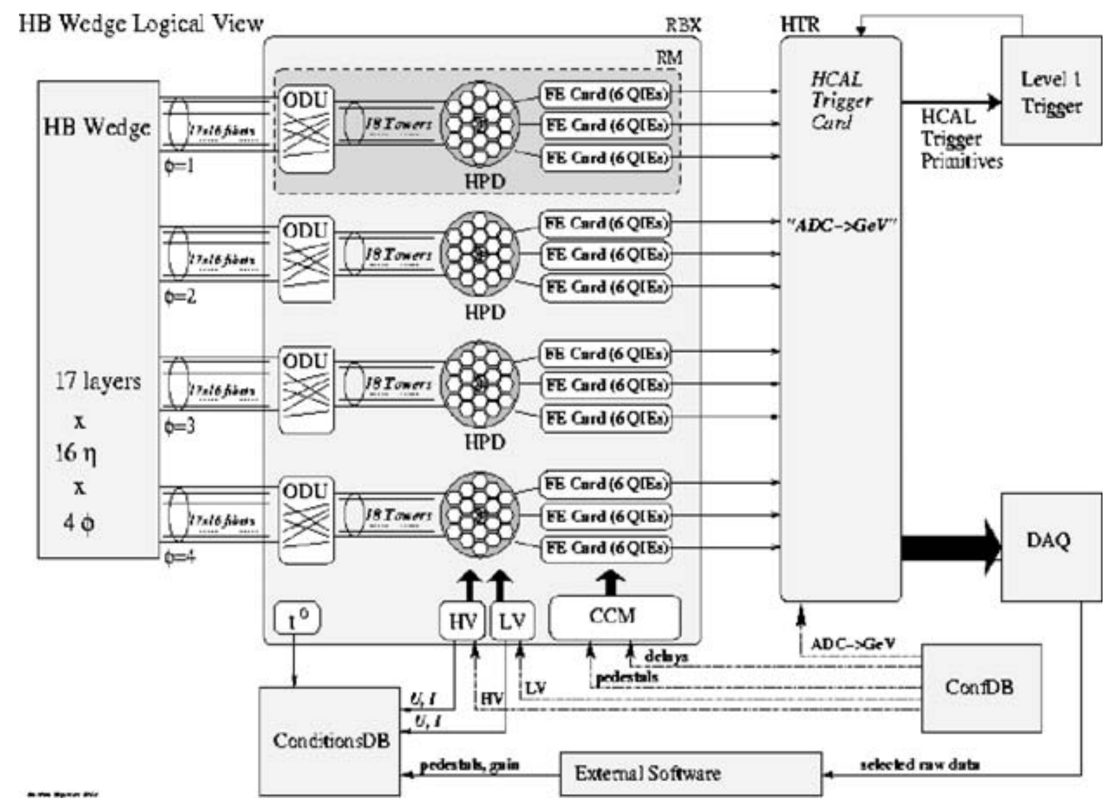
HCAL readout

On-detector readout:

Readout box (RBX): 1 per 20 degree sector, contains 4 readout modules (RM)

Optical decoder unit (ODU): maps fibres from one projective tower to Hybrid PhotoDiode (HPD)

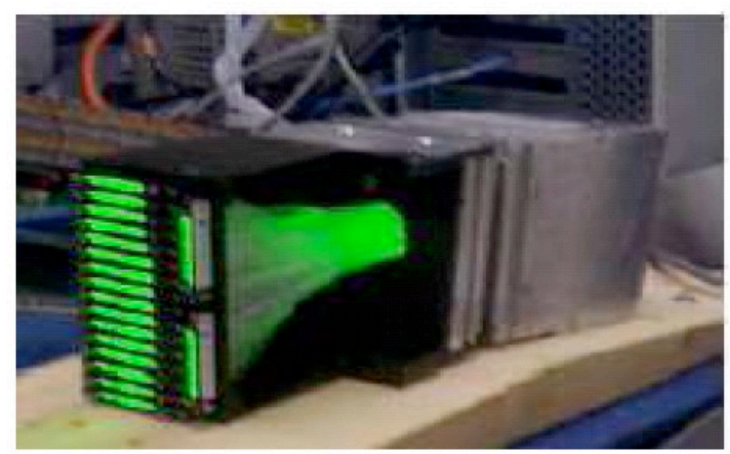
FE card: analogue signal from APDs digitized using charge-integrating preamplifier **(QIE)**



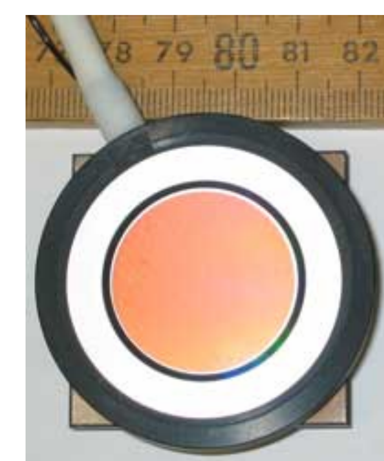
Off-detector readout:

HTR - HCAL Trigger and readout board - trigger primitive formation, data and trigger pipeline
Sends trigger tower energy sums to Calorimeter Trigger (40MHz)

upgraded in 2015/16 to uTCA version - for upgrade Level 1 calorimeter trigger.



RBX
with fibre bundle

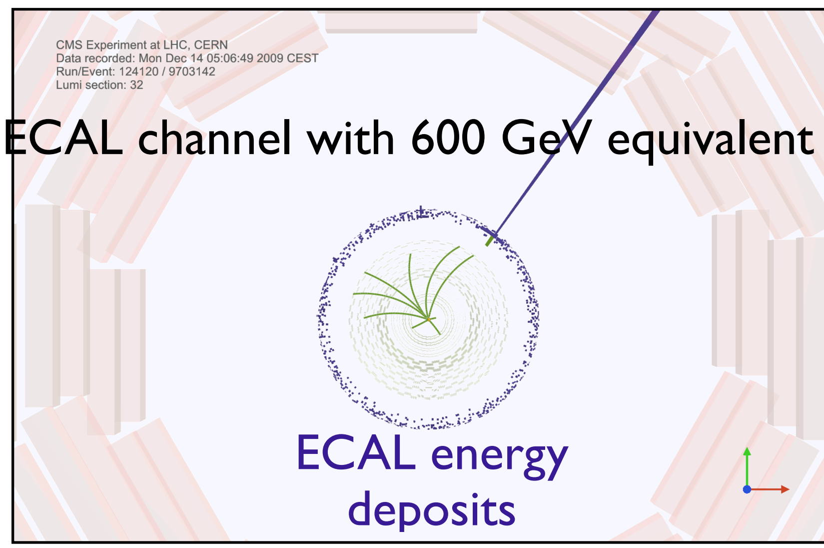


HPD

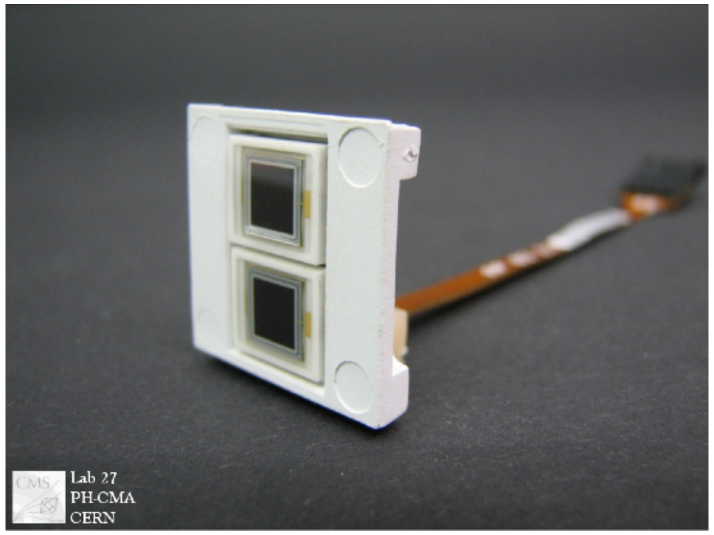
ECAL spikes

- **Anomalous signals ("spikes") unexpectedly observed in ECAL Barrel: large apparent energy deposits with non-physical topological and timing signatures**
- **Caused by direct ionisation of APD active volume by collisions products (chiefly hadrons/pions)**

ECAL APD "spike"



ECAL APD capsule



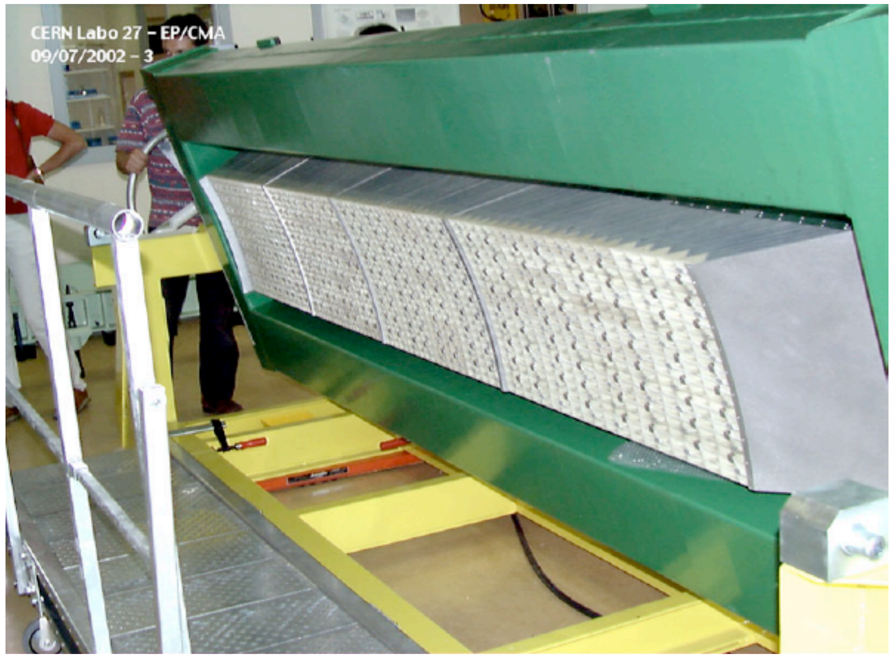
- **Mitigation was challenging, especially for L1 trigger:**
  - no possibility to cure at source - APDs inaccessible
  - spikes will typically hit one of 2 APDs serving one ECAL crystal. However, decision was made to sum these signals rather than read them out individually to reduce cost
  - eventually found a way to remove spikes using **extra unused feature of ECAL front-end ASIC**

Lessons learned: Must rigorously check system in test beam campaigns. Self-triggering would have revealed this problem. Build sufficient flexibility in on-detector and off-detector electronics to deal with unexpected signals. Add redundancy to readout signals?

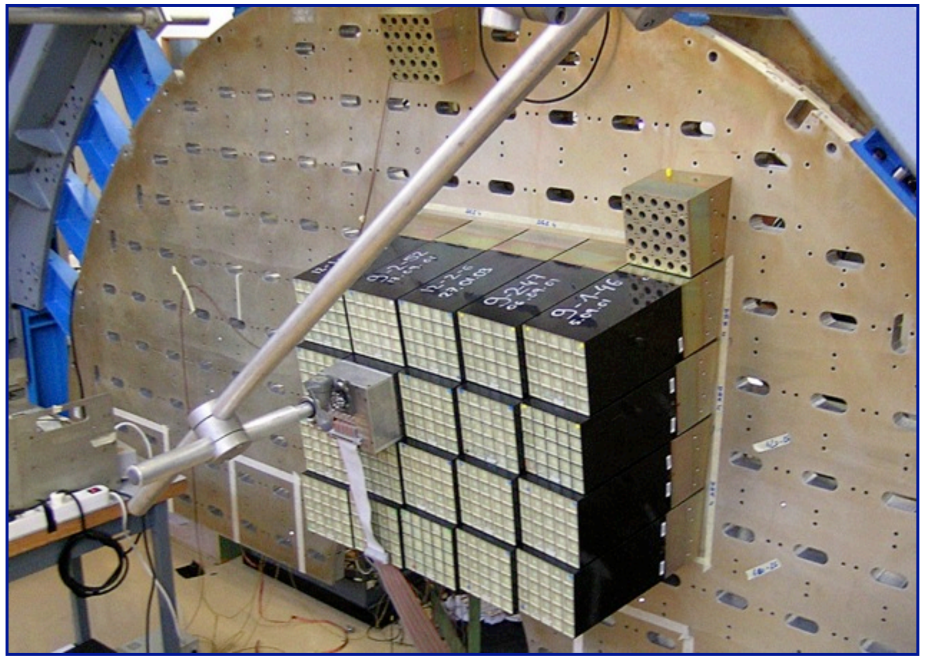
ECAL mechanics

- **Significant differences in mechanical design of ECAL Barrel and Endcaps**
  - barrel design incorporated 17 different module types and 17 different crystal shapes
  - endcap design involves a single module type and one crystal shape

Barrel mechanics: 17 crystal types



Endcap mechanics: 1 crystal type

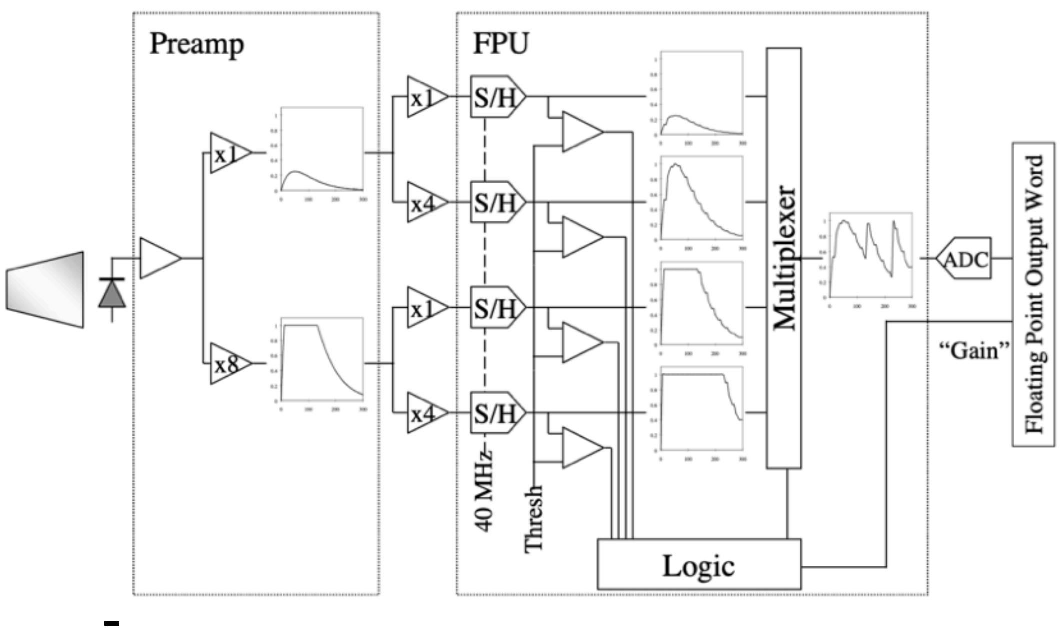


- **This has implications for crystal production and detector construction**
  - much simpler if you only have to deal with a single module/crystal type
- **Should also consider possibility for partial dismounting/replacement of modules**
  - ECAL was not designed with this possibility in mind - partial dismounting difficult/impossible
  - might be a desirable feature for future detectors if certain regions need to be removed/replaced due to large radiation-induced response losses or other performance issues

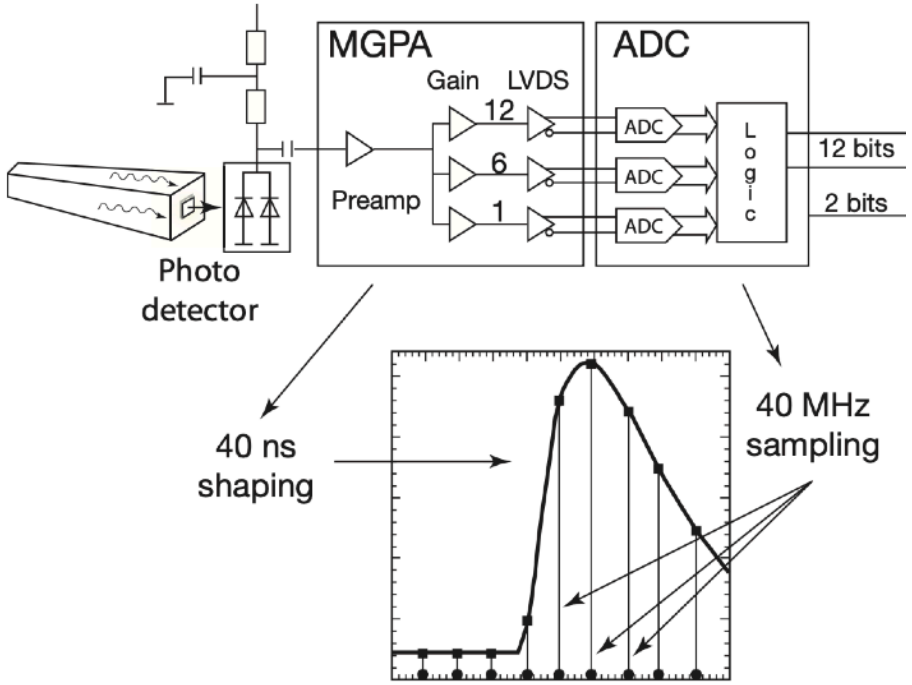
ECAL ASICs

- **UK involvement in ECAL very-front-end ASICs came about due to noise/ performance problems with the original TDR designs**
- **Original preamp and ADC designs had to be dropped and new ASICs developed from scratch**

TDR very-front-end design



Final very-front-end design



Lessons learned:

Issues with ASICs are not uncommon in HEP - but problems can be minimised by careful and conservative design methodologies. Early full-system tests with detector prototypes are a **must** to check system performance and identify any noise issues in a realistic data-taking environment

A1: Energy scale uncertainty

How to convert measurements using electrons from $Z \to ee$ to photons from $H \to \gamma\gamma$?

How different is the energy scale?

- not much:
  - electrons from Z->ee are roughly 45 GeV - but with a spread in energy
  - typical photons from $H \to \gamma\gamma$ are 60 GeV

There are 2 problems to address:

- How do we know that measurements from electrons are valid for photons?
- How do we measure and correct for any discrepancies in energy scale vs E_T?

A1: Energy scale uncertainty

How do we know that measurements from electrons are valid for photons?

Z→ee events can be used to precisely calibrate the electron energy scale
They can also be used to correct for differences in energy scale between data and simulation

Recall that we use simulation to derive “cluster corrections” to account for imperfections in the clustering and loss of energy through gaps/cracks in the calorimeter

For electron/photon object:

Pulse Amplitude — intercalibration — cluster corrections

$$E_{e,\gamma} = \sum_i [A_i \times S_i(t) \times c_i] \times G(\eta) \times F_{e,\gamma}$$

time-dependent response corrections: laser monitoring system — Global scale

for electrons we can use a comparison of the Z→ee in data and simulation to validate these and apply residual corrections to optimise the energy scale

If we want to validate the photon energy scale, we could consider reconstructing electrons as photons and applying the photon cluster corrections to these events

This is only valid if the electrons can be made to “look like” photons.

<u>**How can we do that?**</u>

A1: Energy scale uncertainty

Reconstructing electrons as photons

Photons are either converted or unconverted
- converted: e+e- pair-production in the tracker
- unconverted: no showering prior to the ECAL

Usually $H \rightarrow \gamma\gamma$ mass measurements are done using unconverted photons -> compact showers

Electrons are either showering or non-showering
- showering: bremsstrahlung electrons emitted along the track prior to ECAL -> shower spreads out in B-field direction
- non-showering: no showering prior to the ECAL -> compact showers

Use non-showering electrons
- in CMS ECAL we identify these by requiring that most of the shower energy (typically >94%) is contained within a compact 3x3 crystal matrix

Reconstruct electrons as photons
- just use ECAL information - ignore the tracker
- apply photon cluster corrections
- compare data and MC

A1: Energy scale uncertainty

Measure and correct for energy scale biases vs E_T

Measure corrections to Z->ee energy scale (using electrons reconstructed as photons) as a function of the leading "photon" p_T

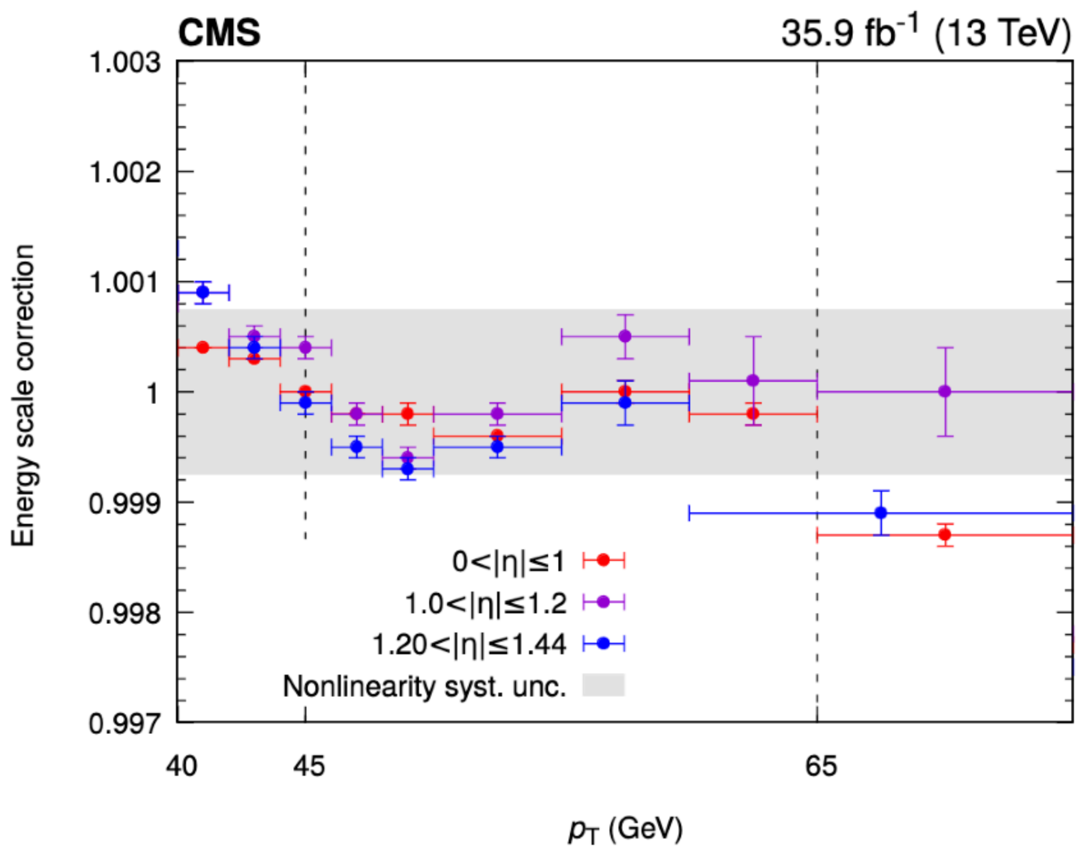


Figure 1: Energy scale corrections as a function of the p_T of the photon. The horizontal bars in the plot represent the variable bin width. The systematic uncertainty associated with this correction is approximately the maximum deviation observed in the p_T range between 45 and 65 GeV for electrons in the EB region.

Use this technique + the fact that the "photons" from Z->ee span a range of p_T to provide the necessary corrections for H->gg photons

electrons from W can also be used, but the invariant mass constraint from Z->ee is more powerful, if you have enough events

A1: Energy scale uncertainty

Estimating energy scale uncertainty at high mass?

How can we obtain event samples that span a large enough range of p_T to extrapolate to the TeV scale?

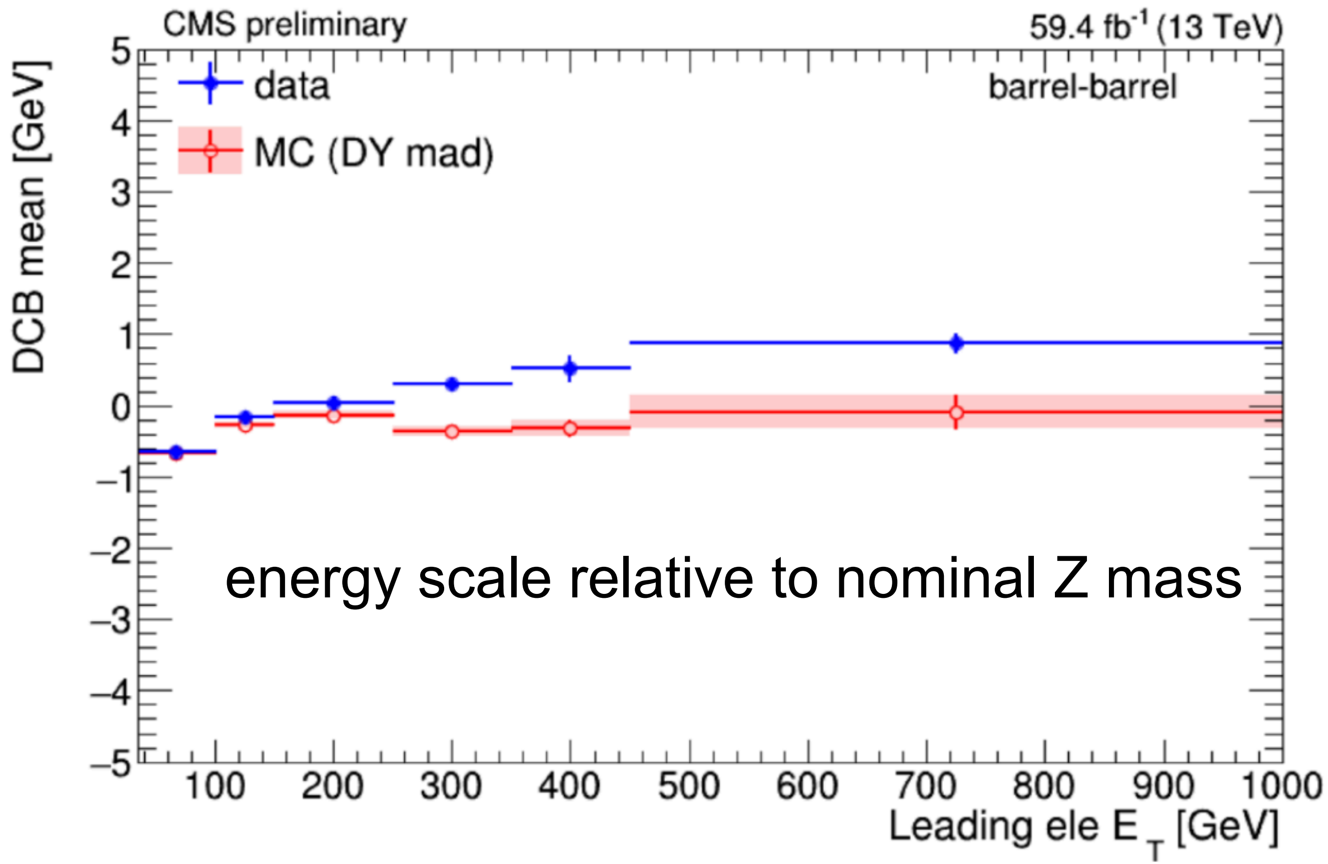
A1: Energy scale uncertainty

Estimating energy scale uncertainty at high mass?

How can we obtain event samples that span a large enough range of p_T to extrapolate to the TeV scale?

We can use Boosted Z boson events - LHC collides at 13.6 TeV - much higher than the c.m. energy needed to produce Z bosons (mass 91.2 GeV)

Small fraction with large Lorentz boost - high p_T electrons with Z invariant mass constraint
Measure energy scale (from Z->ee invariant mass) as a function of electron p_T
run out of events at very large p_T - exponentially falling p_T spectrum - bins become larger.
How would you use this to set an energy scale uncertainty at 1 TeV (2 TeV)?



A2: Detector design

What are the main factors relevant for defining the transverse size of segmented ECAL detectors? Divide this into "physics" and "practical" considerations.

Physics	Practical
How well do you need to point? For electron-track matching and position resolution Use at trigger level to improve electron efficiency and jet background rejection	How well can you point? Tracker resolution/material budget
How granular do you need to be, compared to the X_0 of your detector medium for: single/dual photon separation pattern recognition (including pileup suppression)	How small can you make individual elements: How much will it cost? How will you calibrate it?

A2: Detector design

What are the advantages of longitudinal segmentation for a) electromagnetic and b) hadronic calorimeters? What are the potential negatives?

ECAL detectors:

\+ able to sample the EM shower and detect/compensate for early showering particles

- more gaps and cracks
- bigger calibration challenge
- more readout channels - larger expense

HCAL detectors

\+ able to distinguish the EM and hadronic components and improve the energy response/resolution

- how to calibrate the individual layers?
- needs more complex reconstruction and energy correction scheme

A2: Detector design

If you had the opportunity to design the ultimate particle flow calorimeter (money being no object) what should its main characteristics be?

Could be considered a trick question

for any calorimeter you need to know two things:
what are the physics requirements? Energy resolution and energy range of interest
what environment it is going to operate in?

The optimal design could be quite different based on the answer to these two questions

Some basic thoughts - assuming an e+e- collider scenario with a less stringent radiation tolerance requirement

EM calorimeter: if you want the ultimate stochastic term (for low energies) -> homogenous calorimeter.
if crystal-based, choose a crystal that has less dynamic behaviour than CMS lead tungstate:
LYSO and CeF_3 are possibilities but cost $$$
could choose to read out both ends of crystal to reduce effect of light collection inhomegeneities
If you want high resolution tracking+calorimetry -> very fine granularity sampling silicon detector
Hadron calorimeter: depth segmentation to aid particle flow. Sampling calorimeter - could be scintillator or silicon if money no object