



Science and
Technology
Facilities Council

Designing and operating calorimeters

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Graduate lecture series
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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)

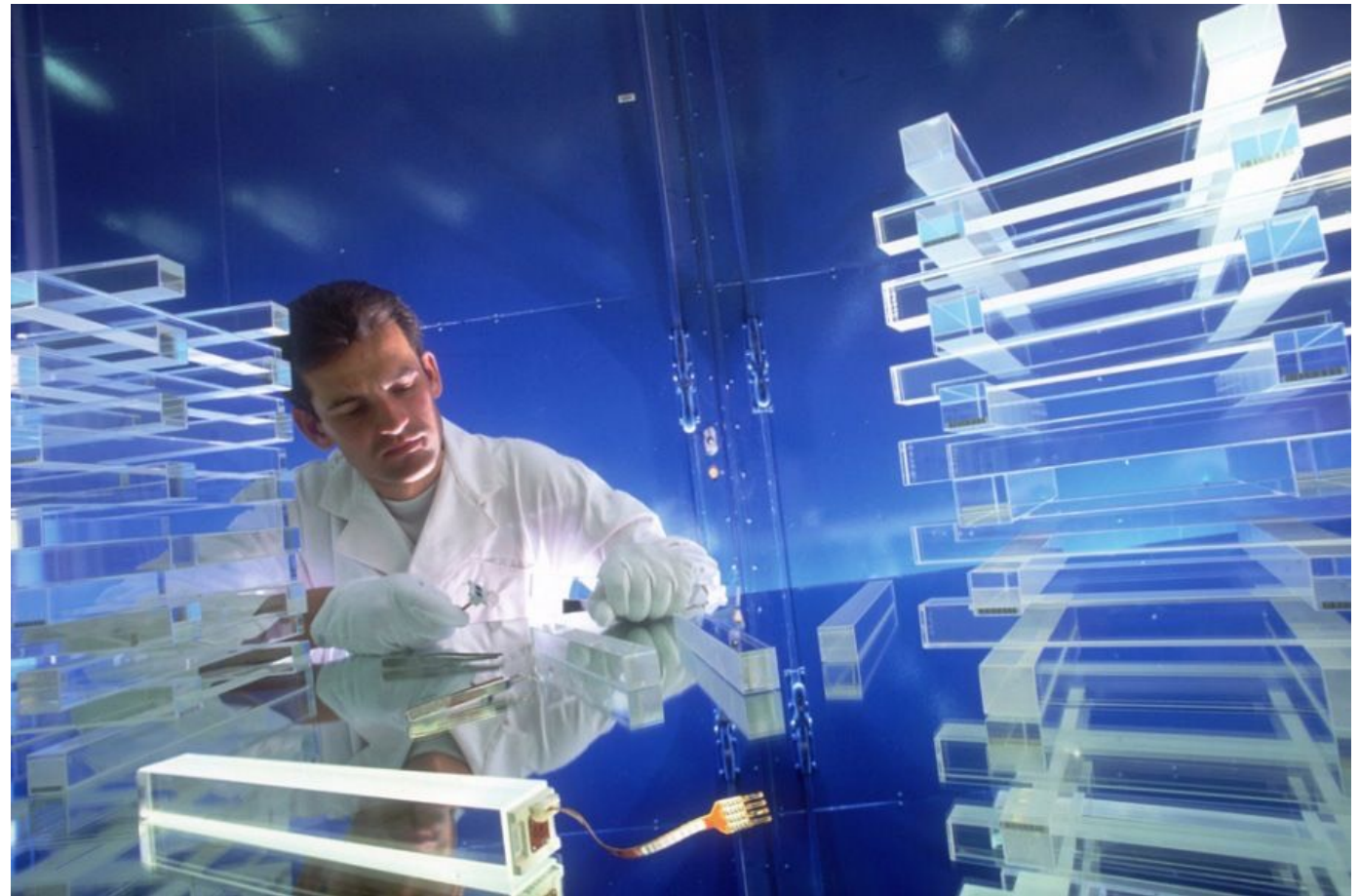
An experimental apparatus for measuring the **total amount of heat** involved in a chemical reaction or other process



What is a particle physics calorimeter?

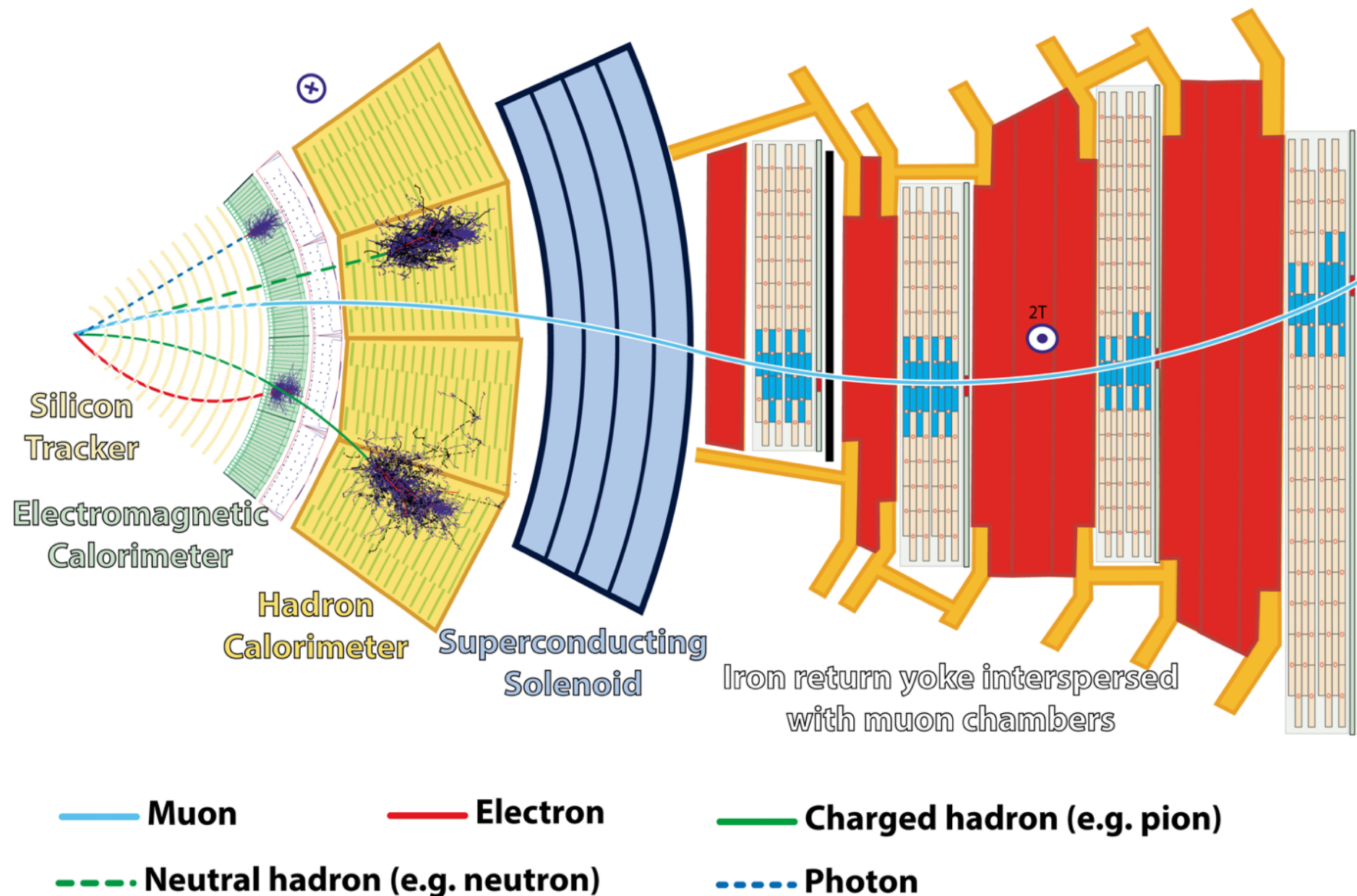
calorimeter noun
,kælə'ɹɪmɪtə(r)

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



What is a particle physics calorimeter?

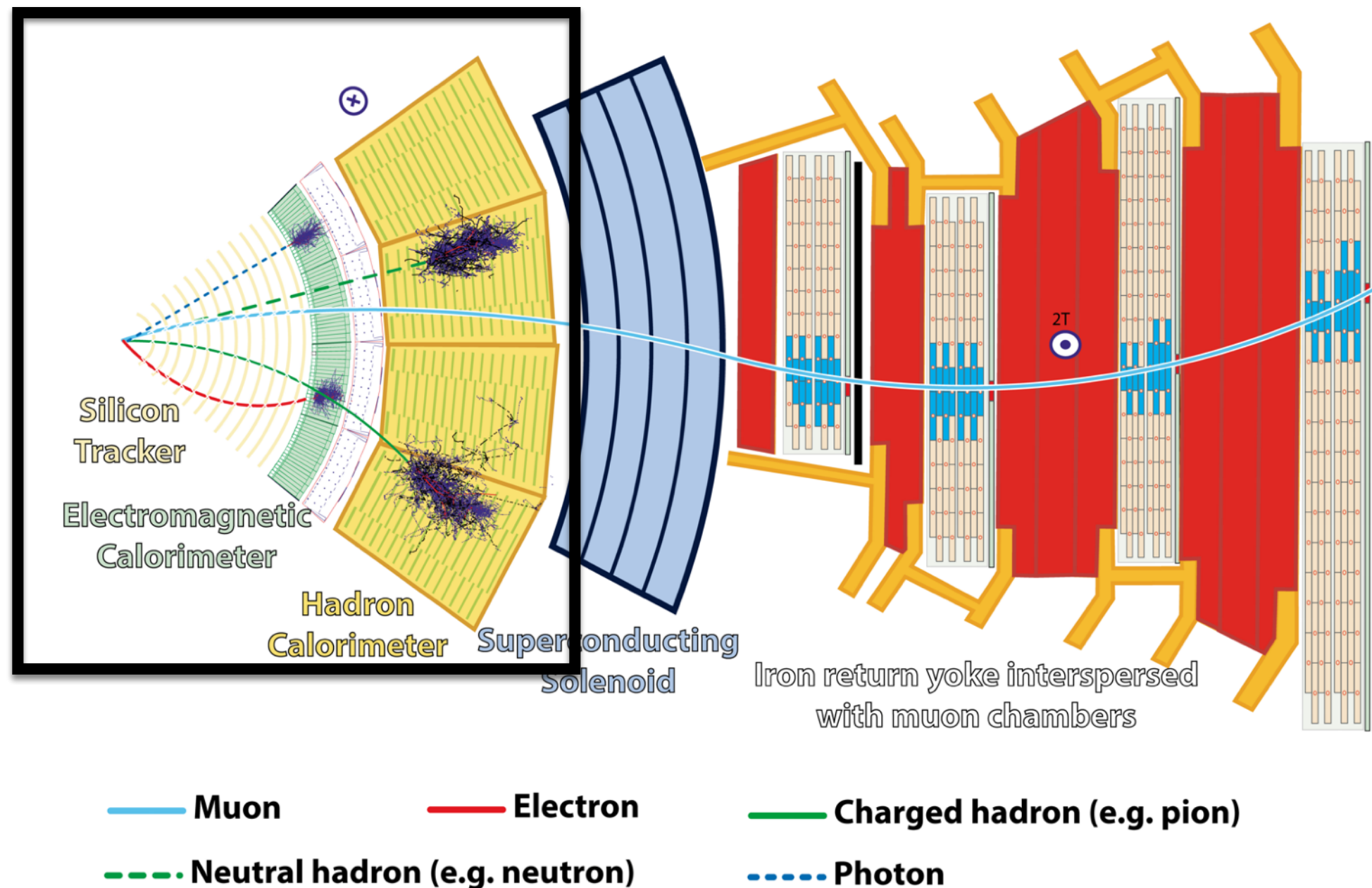
CMS example



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

What is a particle physics calorimeter?

CMS example



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

What is a particle physics calorimeter?

Typically divided into dedicated electromagnetic and hadronic calorimeters

Electromagnetic calorimeter

electrons/positrons and **photons**

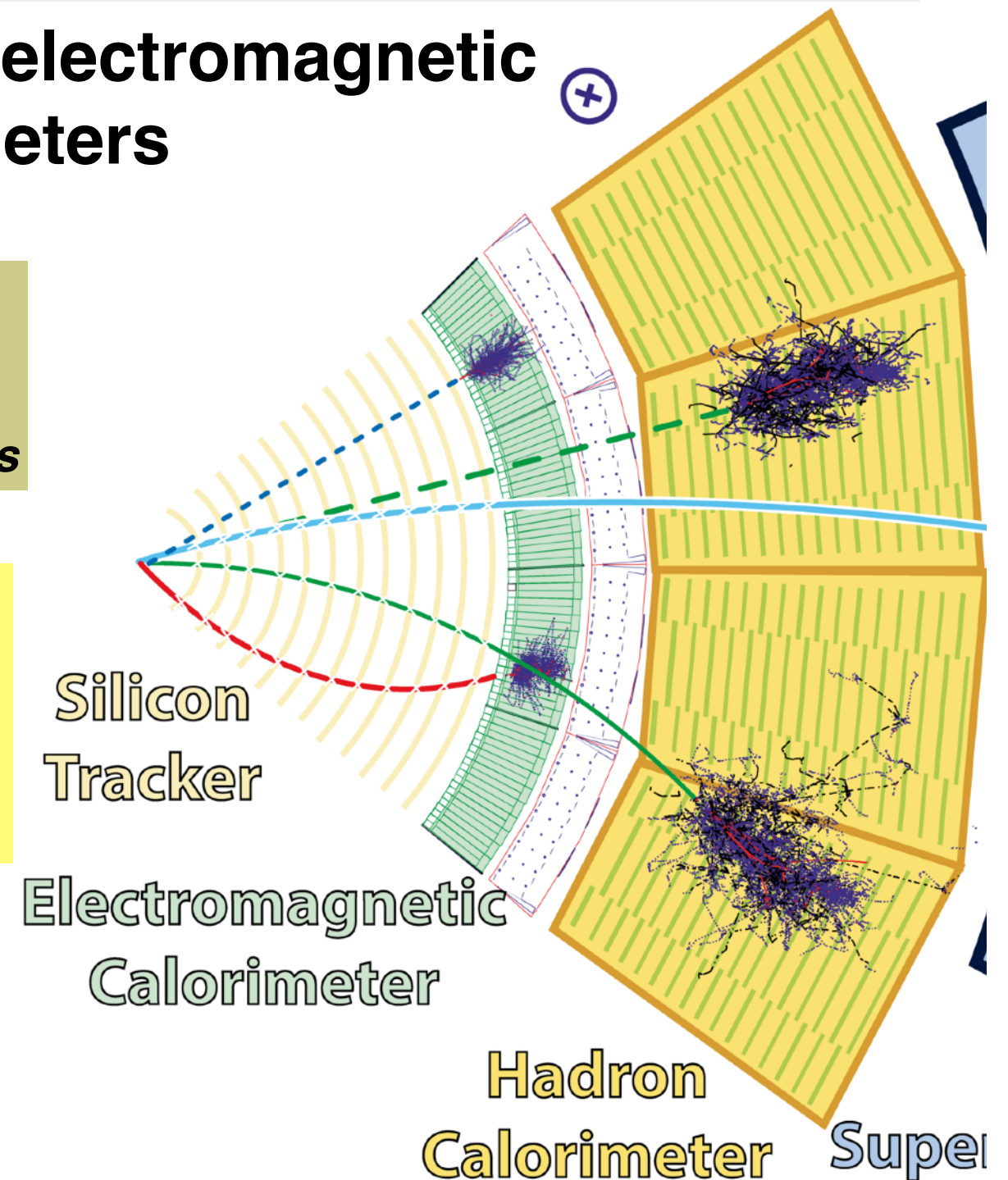
electrons and positrons can be matched to tracks

Hadron calorimeter

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

neutral hadrons: neutron, K^0_L

charged hadrons can also be matched to tracks



— Muon — Electron — Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron) - - - Photon

What is a particle physics calorimeter?

Typically divided into dedicated electromagnetic and hadronic calorimeters

Particle energy

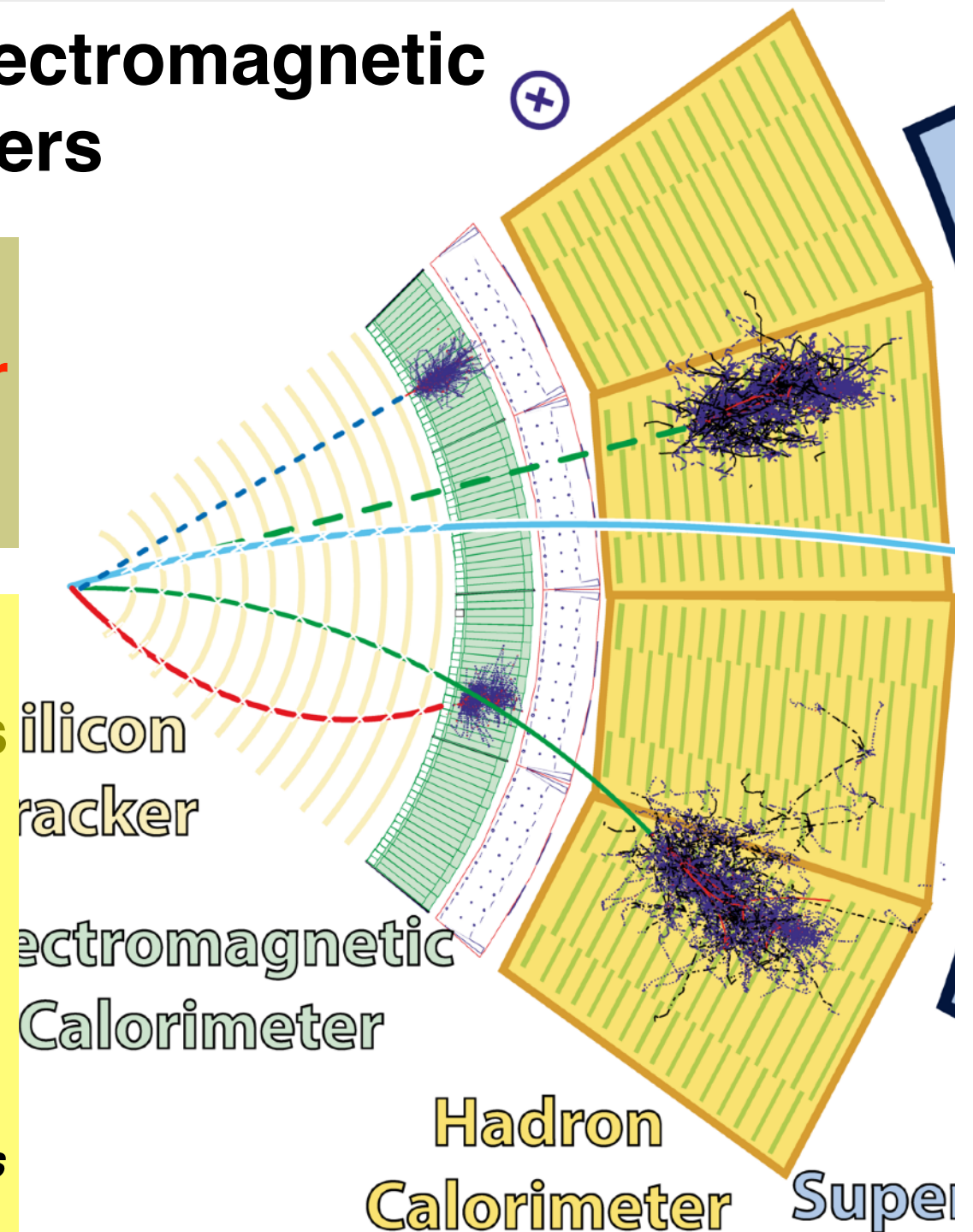
particle energy E absorbed in calorimeter
is converted to electrical signal S
 E is proportional to S

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

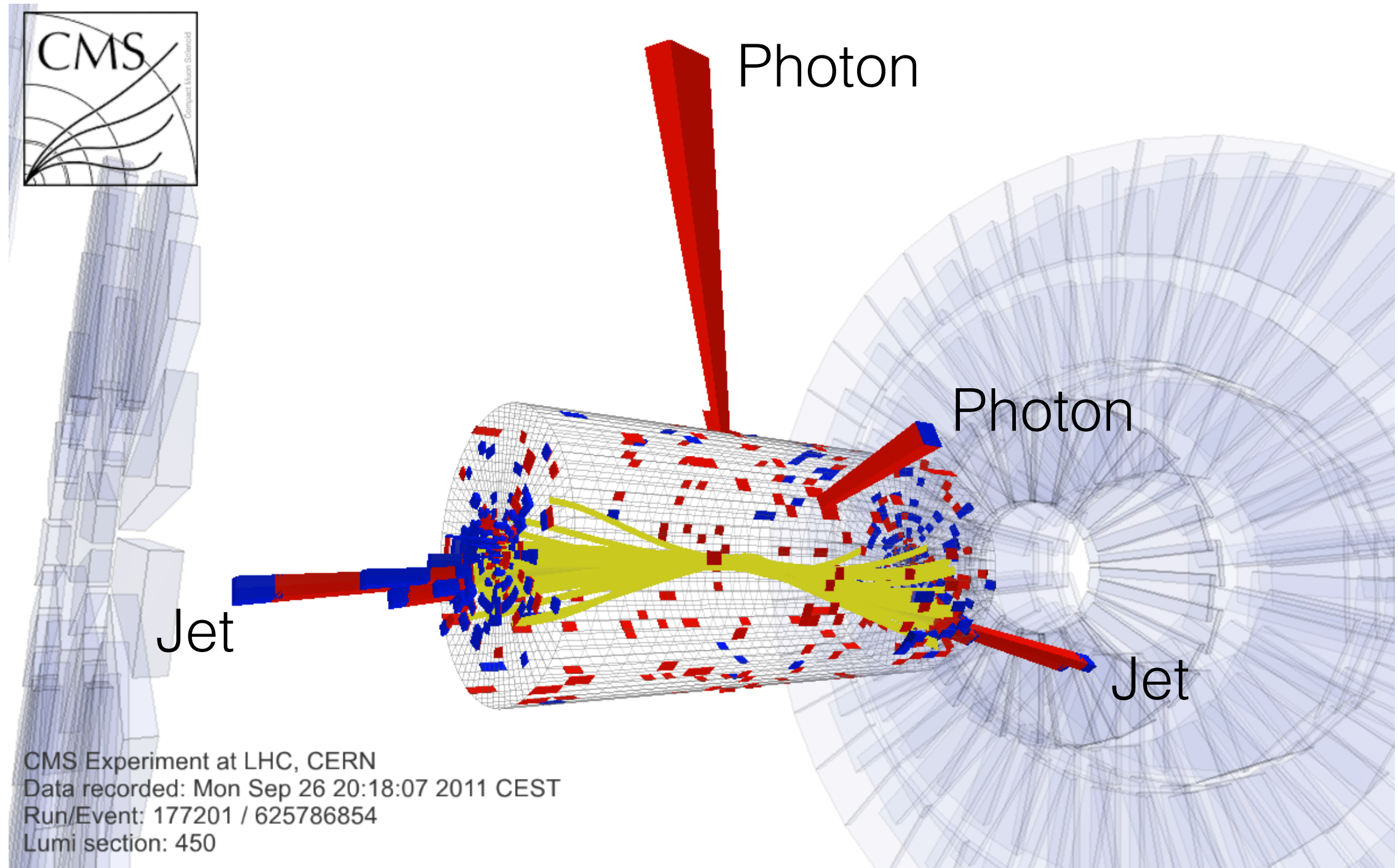
including reconstruction of compound objects, such as jets, which contain both EM and hadronic components



— Muon — Electron — Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron) . . . Photon

Calorimeter event displays

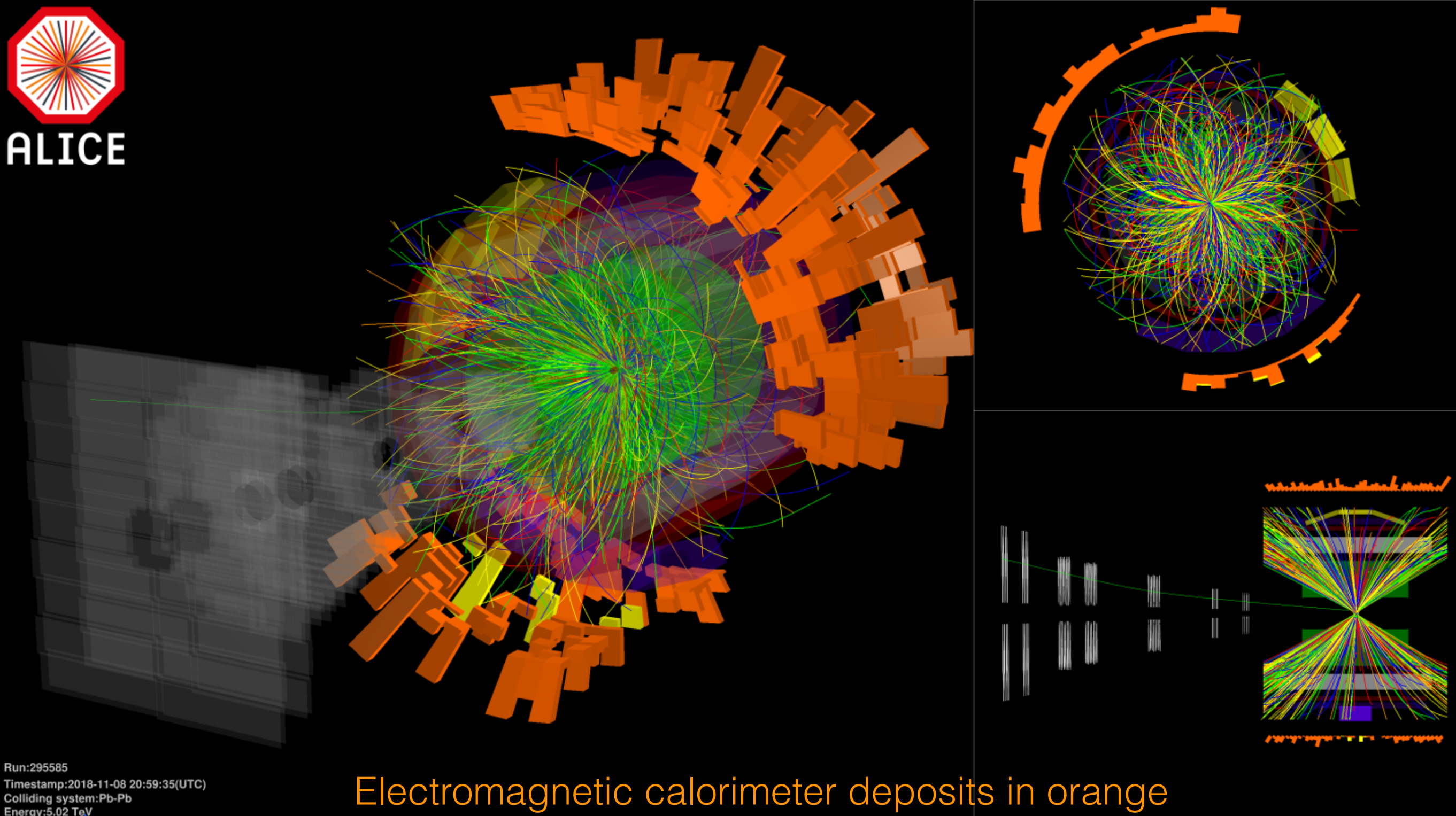
Candidate Higgs particle decaying to two photons, with two forward jets in CMS



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

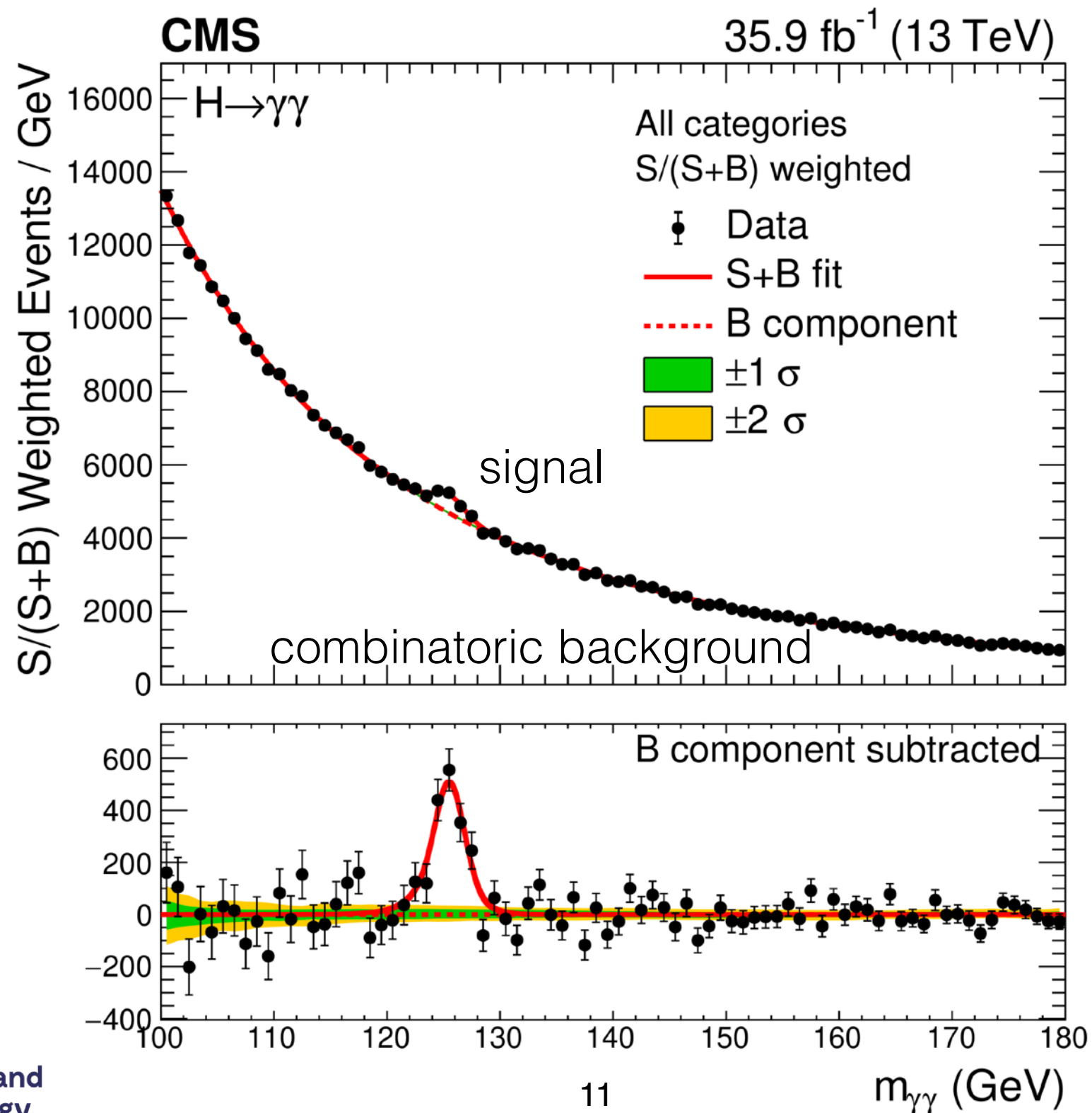
Calorimeter event displays

Pb on Pb particle collision in ALICE



Physics with calorimeters

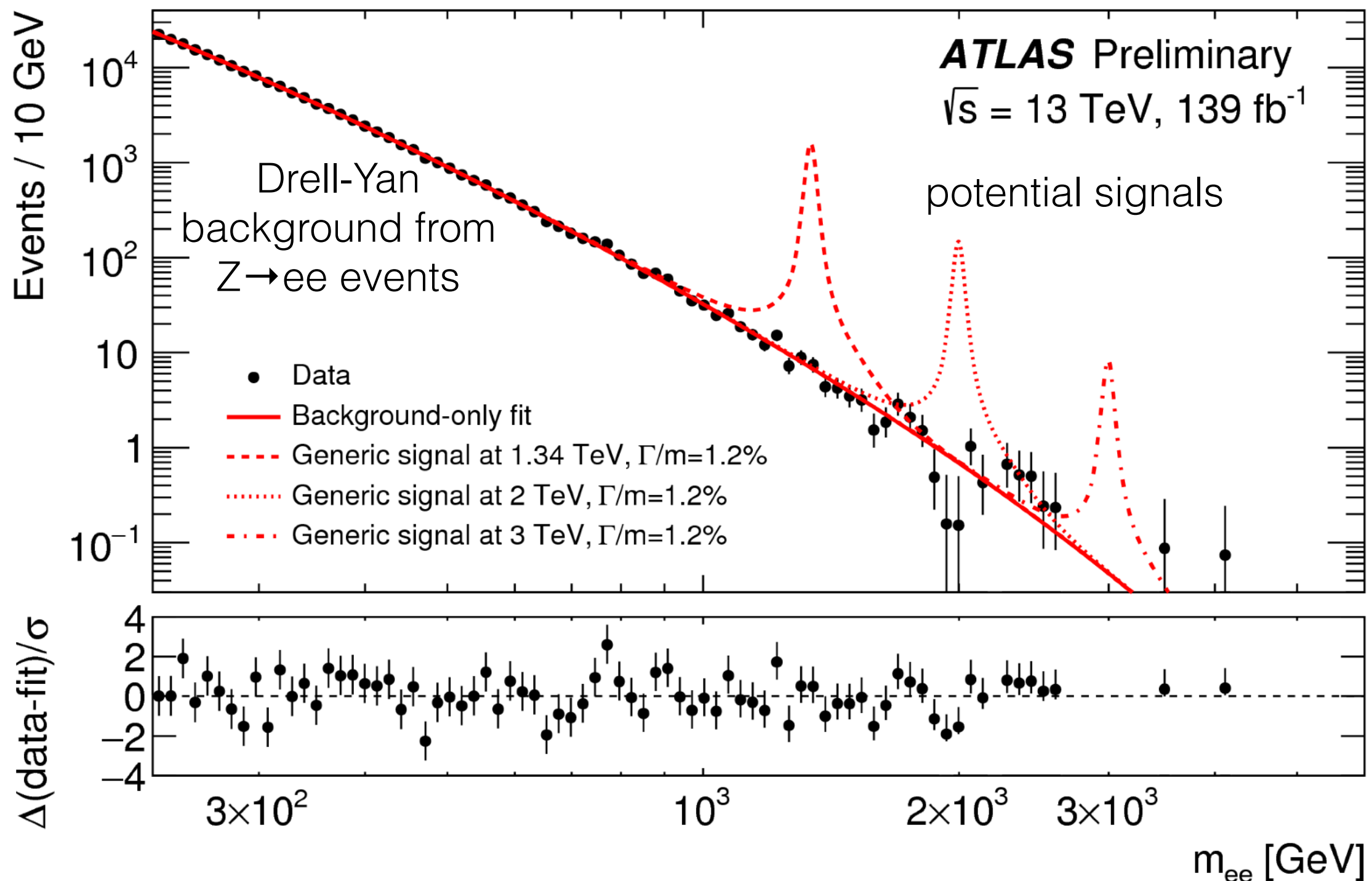
Observation of Higgs decaying to two photons in CMS



Excellent
energy
resolution
required

Physics with calorimeters

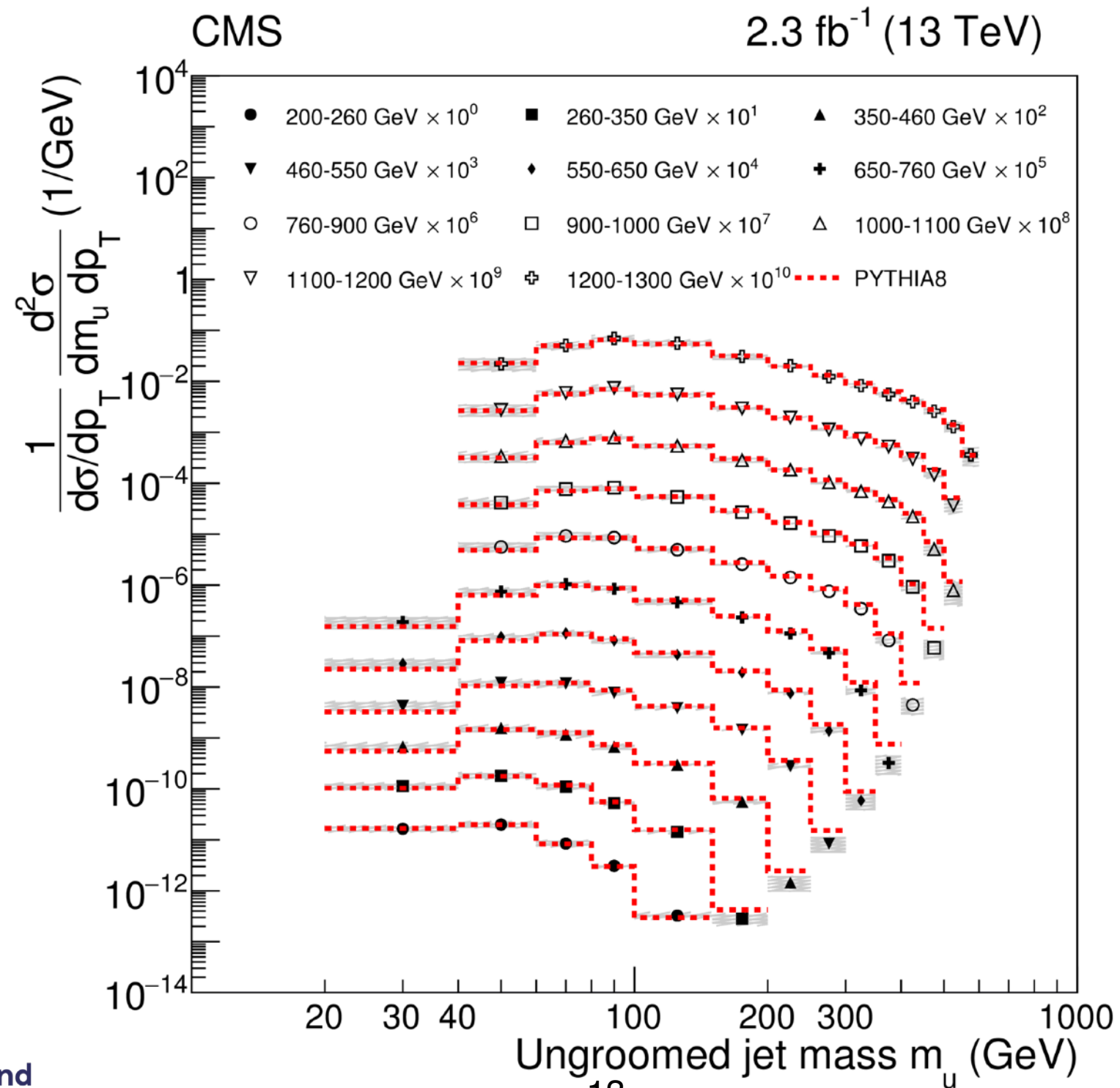
Search for beyond the standard model Z' decaying to 2 electrons in ATLAS



Excellent energy response/
linearity up to several TeV required

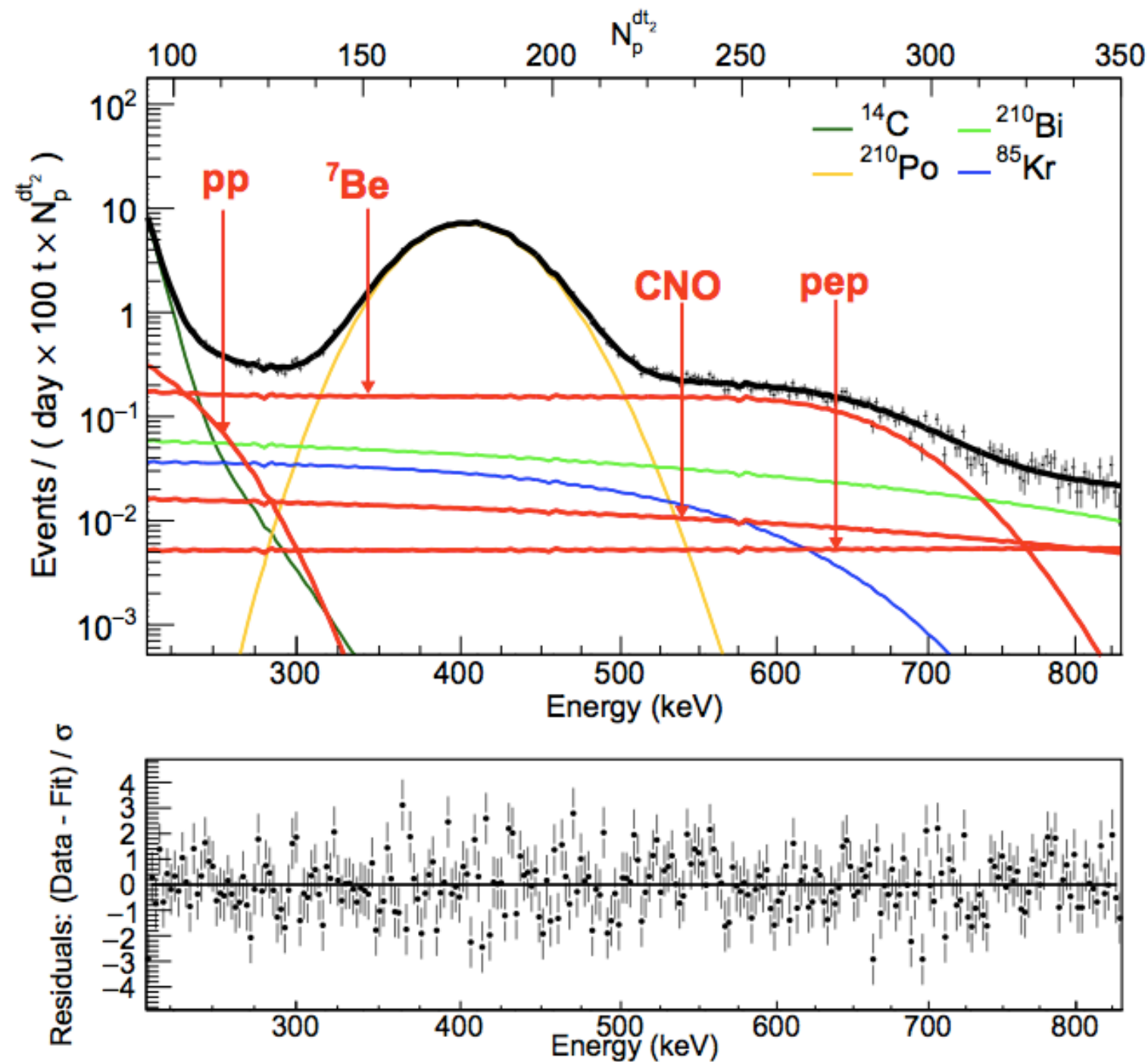
Physics with calorimeters

Jet cross section measurements in CMS and comparison with theory



Physics with calorimeters

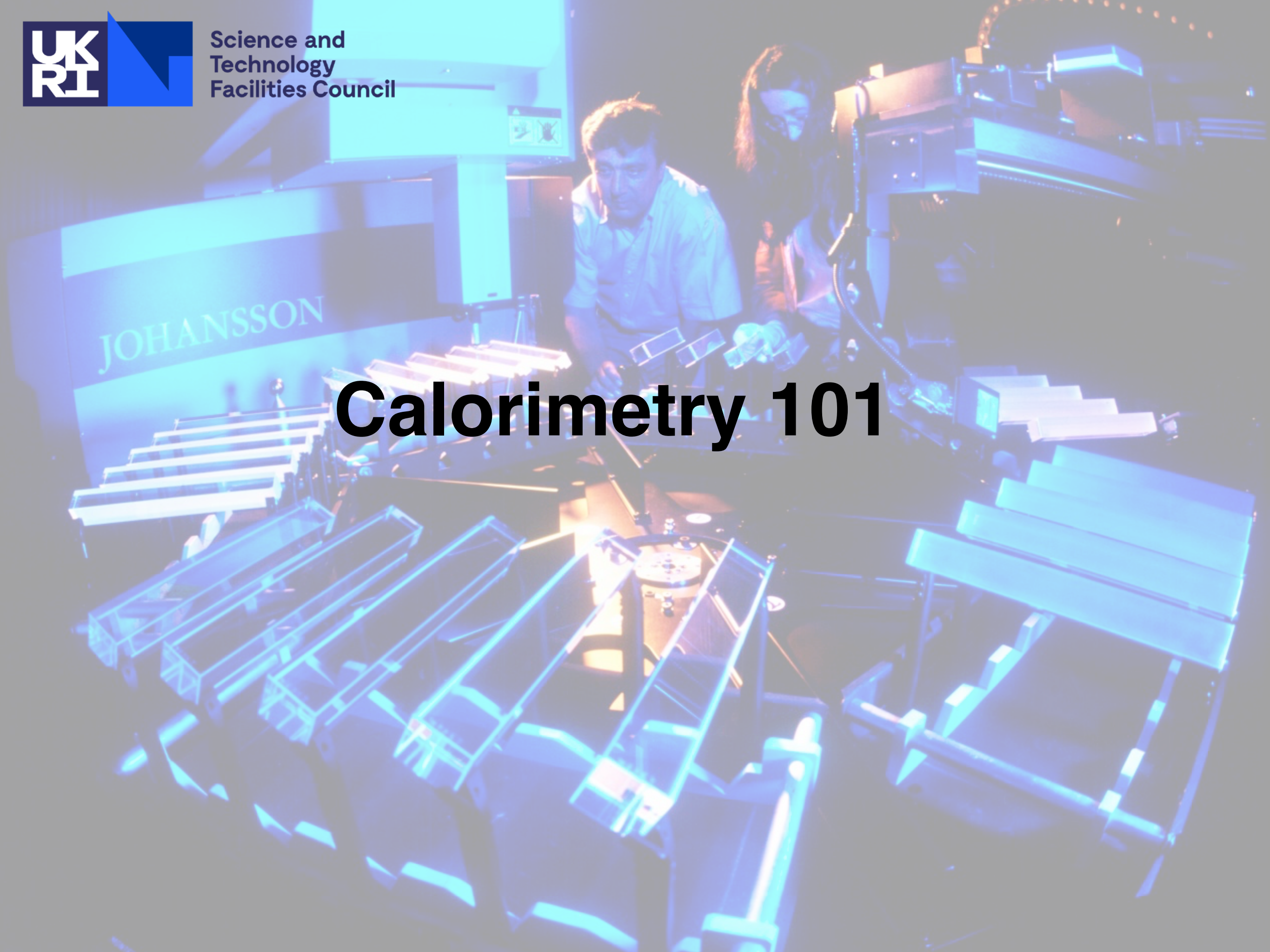
Measurement of components of solar neutrino flux in Borexino





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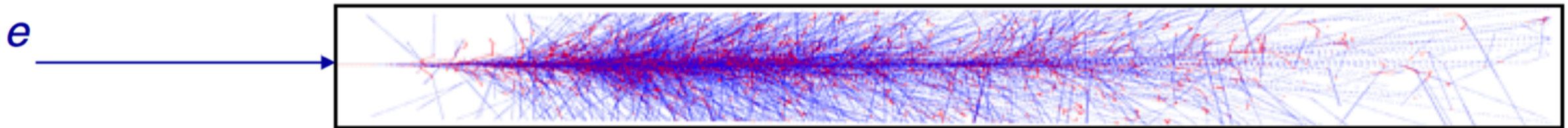
Calorimetry 101



Passage of particles through matter

Electromagnetic shower

PbWO₄ 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

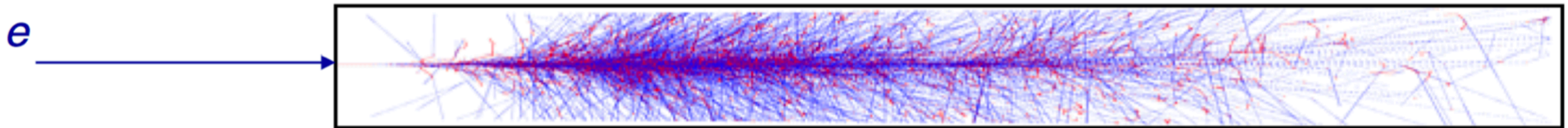
Compton scattering

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

Passage of particles through matter

Electromagnetic shower

PbWO₄ CMS, $X_0=0.89$ cm



Energy loss mechanisms:

Above critical energy E_c

electron bremsstrahlung

$$e^\pm \rightarrow \gamma$$

photon pair production

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

Both processes controlled by radiation length X_0 of the detector medium

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

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

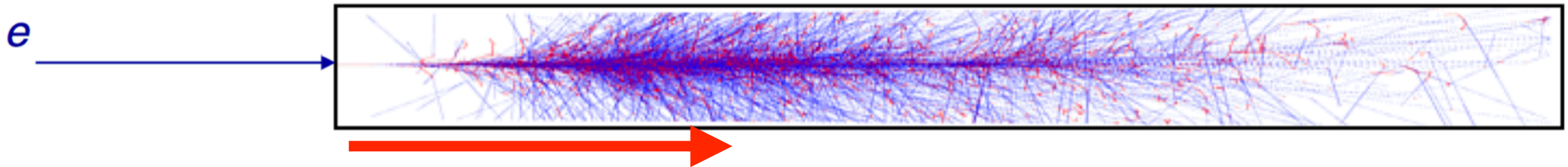
$$X_0 \propto \frac{1}{Z^2}$$

→ compact calorimeters require dense detector media

Passage of particles through matter

Electromagnetic shower

PbWO₄ CMS, $X_0=0.89$ cm



Above critical energy E_c

**electrons lose energy via bremsstrahlung
with characteristic path length X_0**

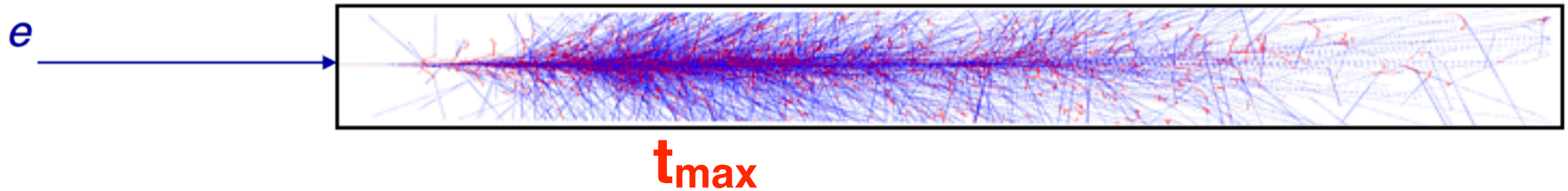
**photons convert to lower energy electrons via pair production
with characteristic path length $9/7 \cdot X_0$**

shower multiplication and development

Passage of particles through matter

Electromagnetic shower

PbWO₄ CMS, $X_0=0.89$ cm



At critical energy E_c

average particle energy $\sim E_c$

ionisation losses are equal to bremsstrahlung and pair production

peak particle multiplicity reached

position of shower maximum: $t_{\max}$

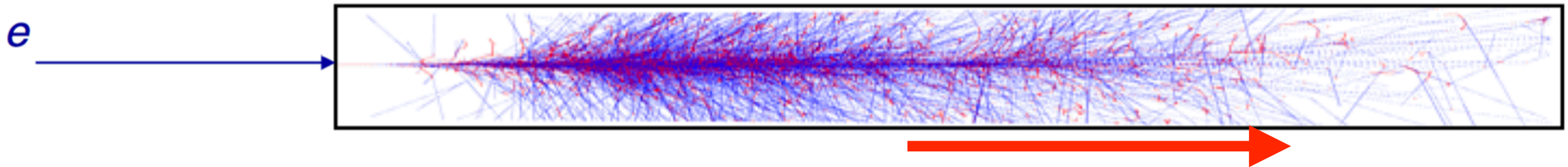
$t_{\max}$ depends logarithmically on incident particle energy

approximately $5 X_0$ for a 10 GeV electron in PbWO₄ crystal

Passage of particles through matter

Electromagnetic shower

PbWO₄ CMS, $X_0=0.89$ cm



Below critical energy E_c

ionisation losses are larger than bremsstrahlung and pair production

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

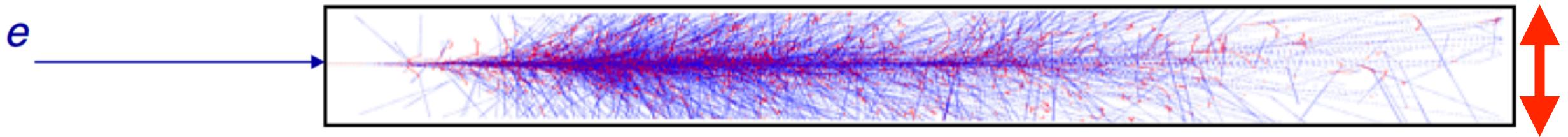
Shower containment depends on energy

100 GeV electron in PbWO₄ crystal contained within around $20 \cdot X_0$

Passage of particles through matter

Electromagnetic shower

PbWO₄ 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 $2 \cdot R_M$
mainly caused by electron multiple coulomb scattering within detector medium

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

CMS example (PbWO₄ crystals)

longitudinal dimensions of 23cm ($25 \cdot X_0$)

lateral dimensions of 2.2cm ($1 \cdot R_M$)

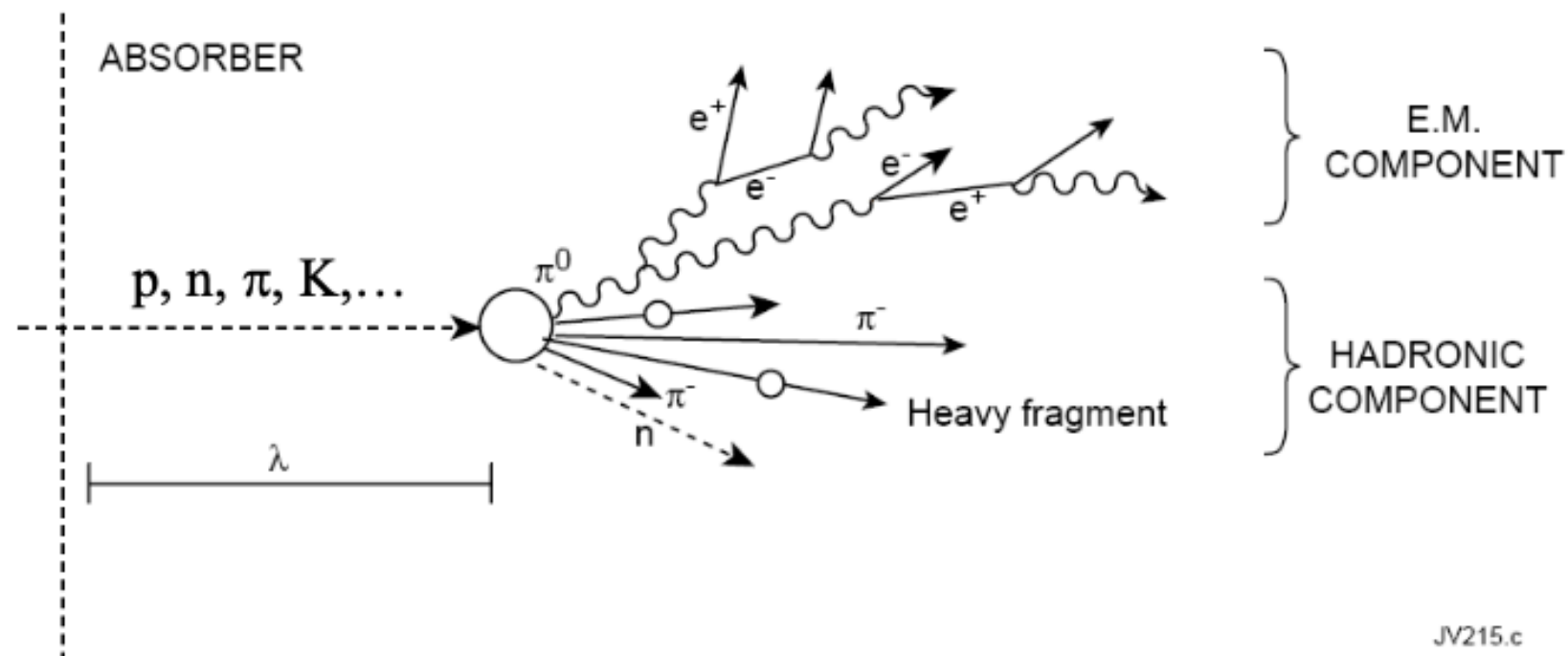
minimises leakage from back of crystal

maximises transverse granularity

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

Passage of particles through matter

Hadron shower



Shower development determined by interaction length λ_I of the detector medium

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

multiparticle production

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

nuclear breakup

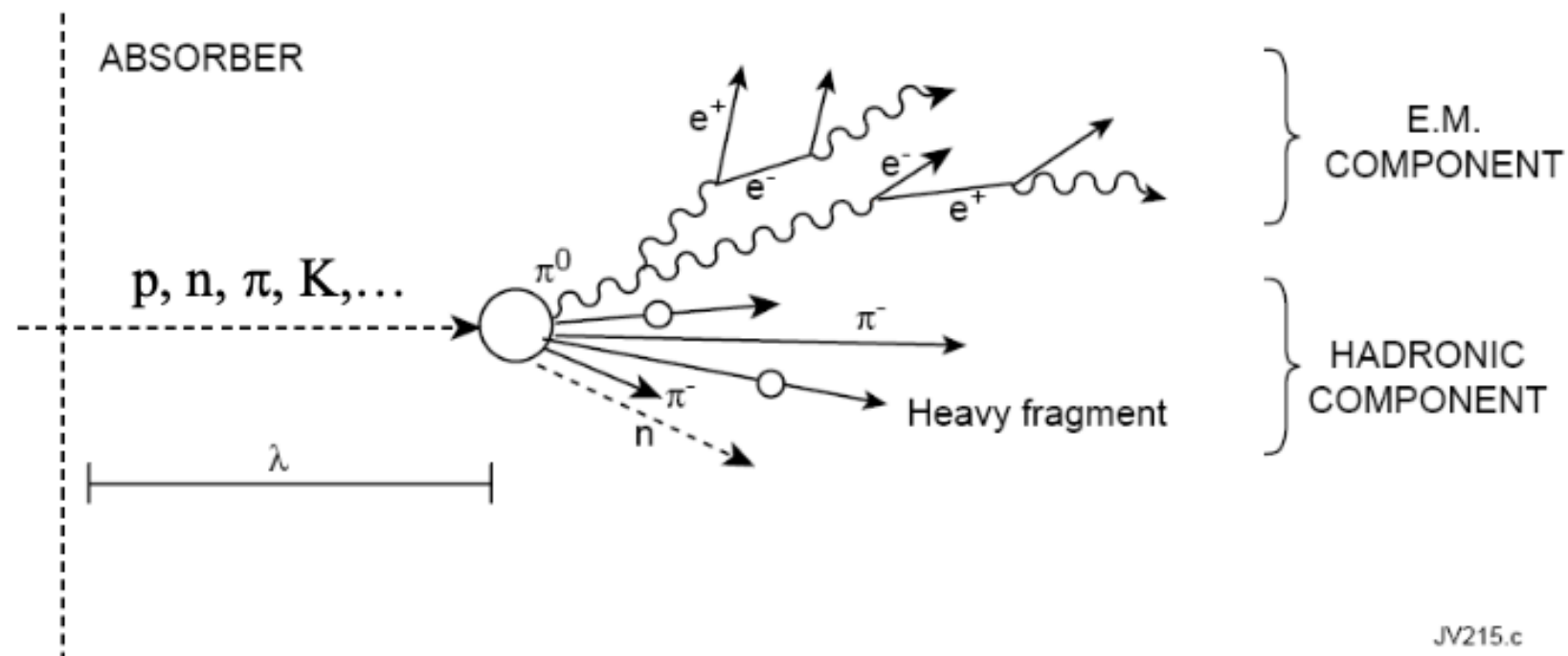
spallation neutrons, protons

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 $\sim 10\lambda_I$ (1.7m of lead)

peak in shower profile at $\sim 1 \lambda_I$ with exponential fall-off

EM component more pronounced at start of shower

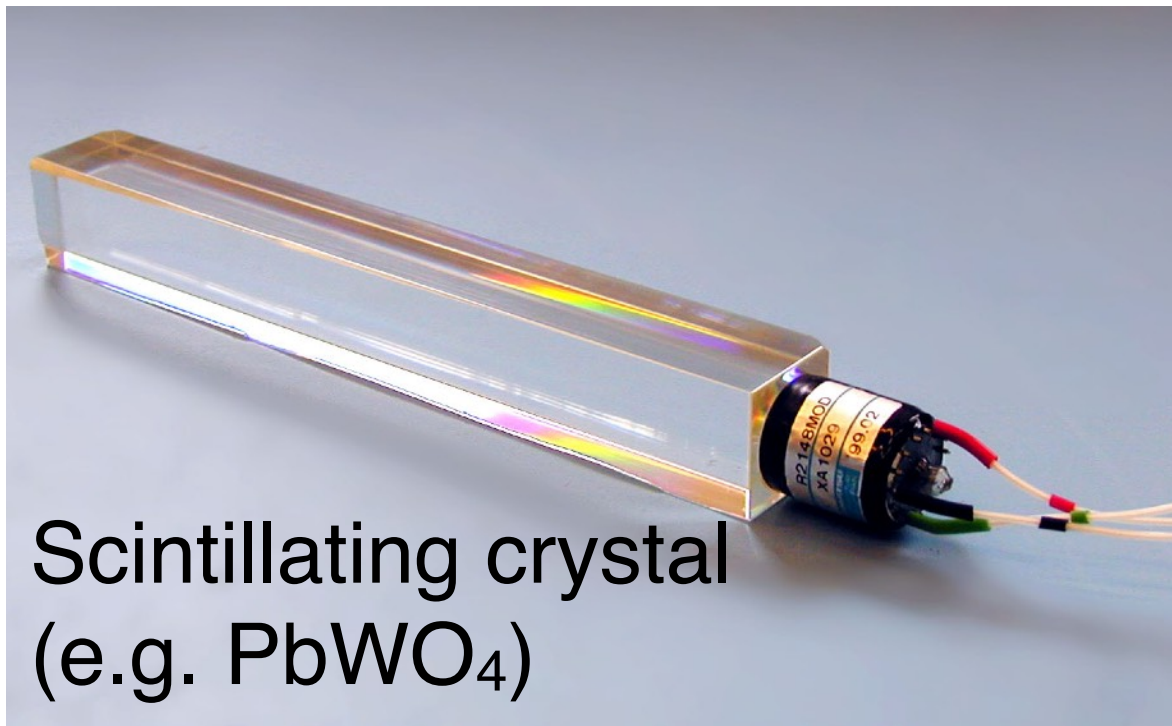
Lateral containment: 95% containment of hadronic shower from 100 GeV pion contained in $\sim 1\lambda_I$ (17cm of lead)

Hadron showers are larger and broader than EM showers

→ reflected in larger dimensions of hadron calorimeters

Homogenous vs sampling calorimeters

Homogenous



Scintillating crystal
(e.g. PbWO₄)

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



Shashlik type
(e.g. W/LYSO)

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

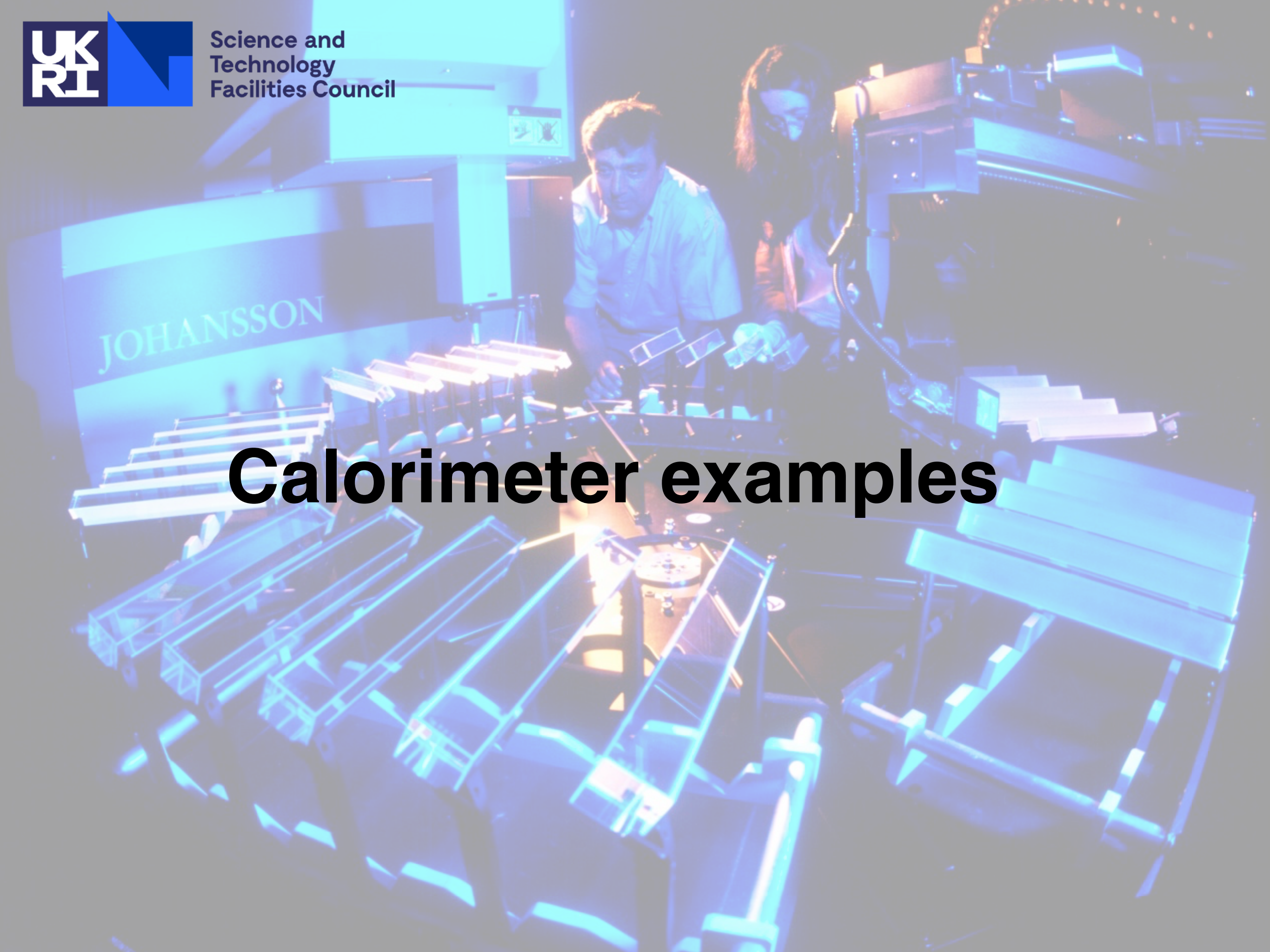
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
Bi ₄ Ge ₃ O ₁₂ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	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

Homogenous calorimeters have smaller stochastic term

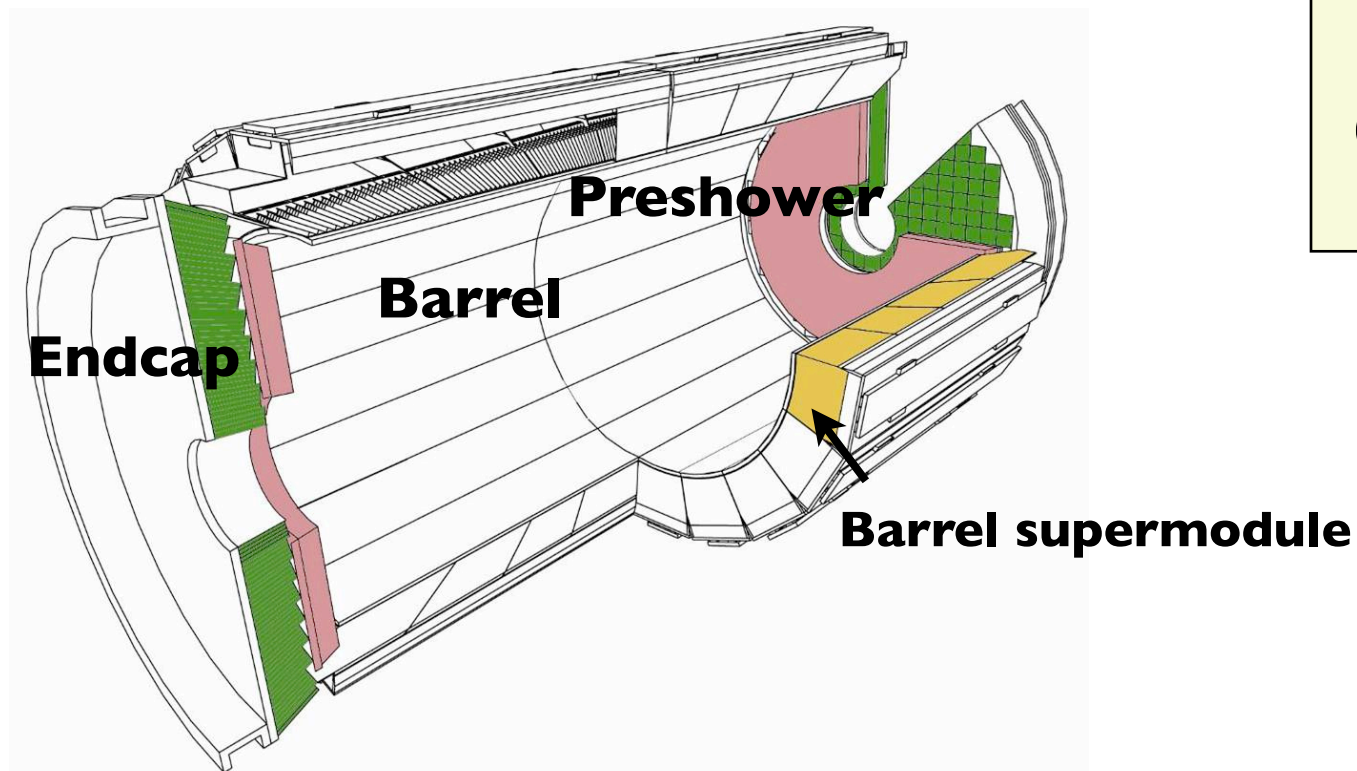
Sampling

Similar constant terms

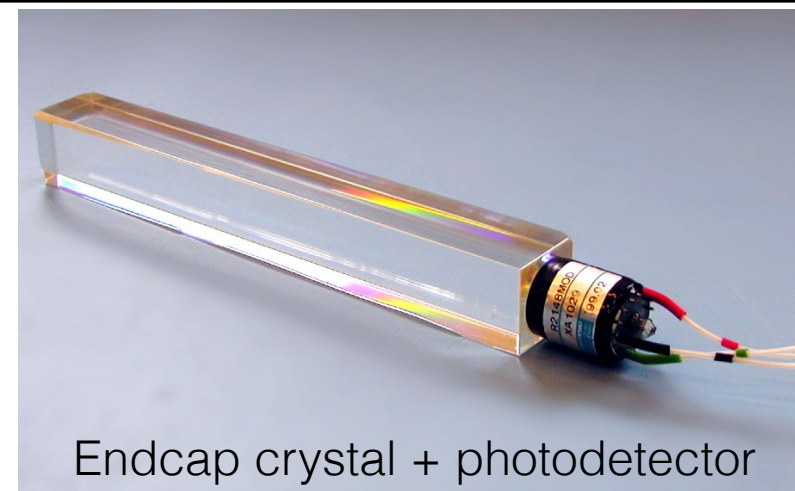
The background image shows a large, complex scientific instrument, a Johansson calorimeter, in a laboratory setting. Two researchers, a man and a woman, are working on the machine. The machine has a large blue panel with the name 'JOHANSSON' in white capital letters. It features several horizontal metal plates and a central circular component. The text 'Calorimeter examples' is overlaid in the center of the image.

Calorimeter examples

The CMS Electromagnetic calorimeter

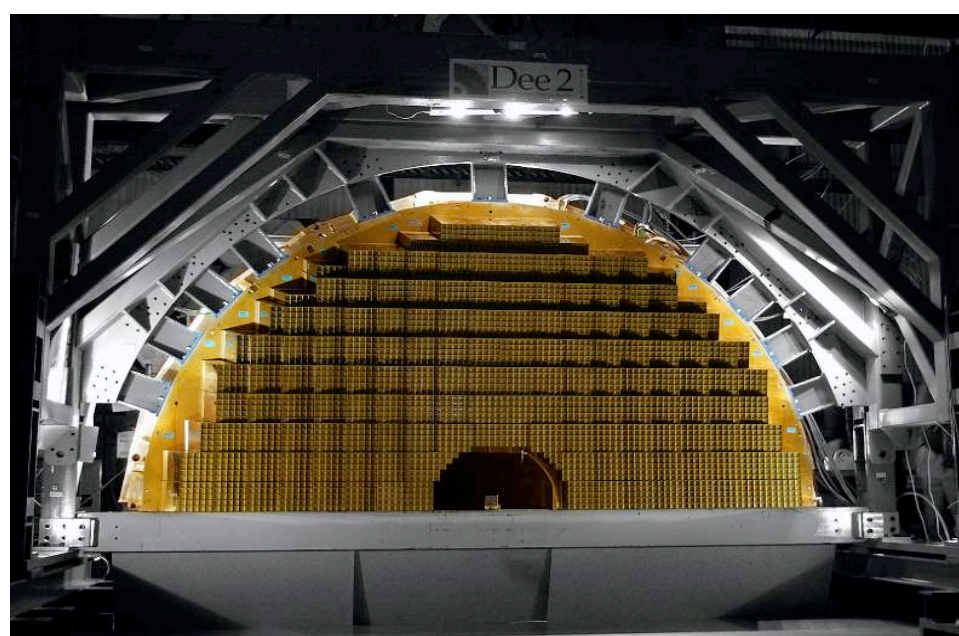


Crystal Barrel & Endcaps
(Lead tungstate PbWO_4 crystals) + Pb/Si
Preshower



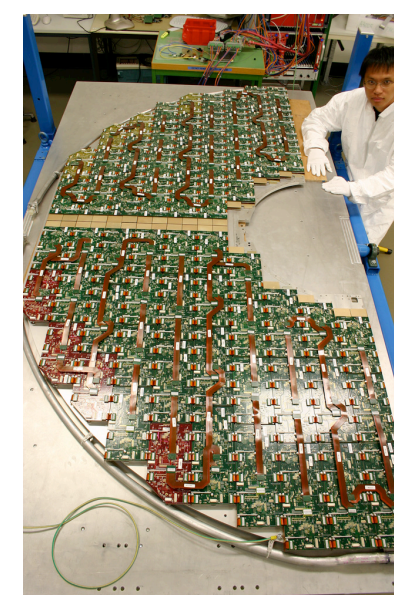
Barrel (EB)

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



Endcap (EE)

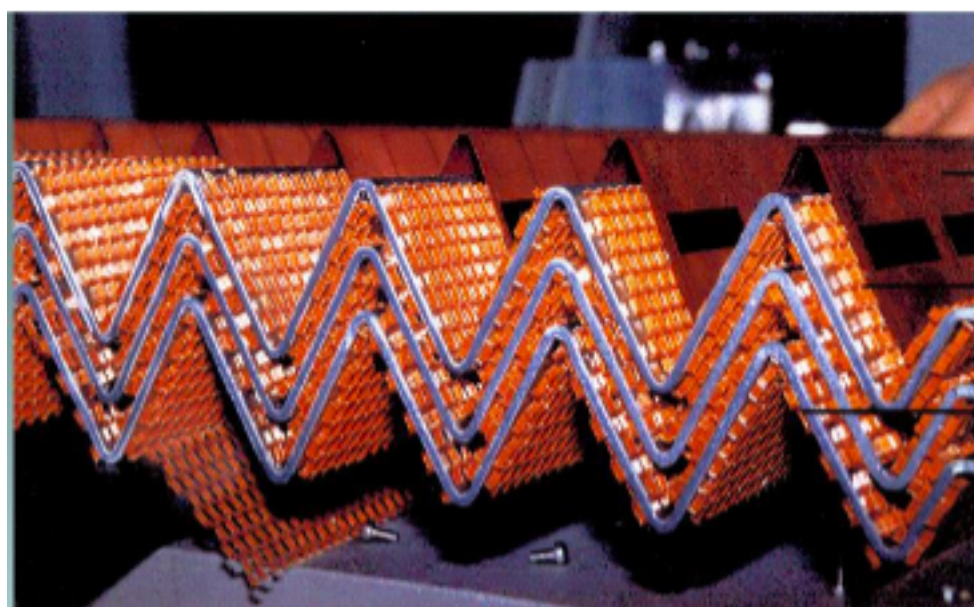
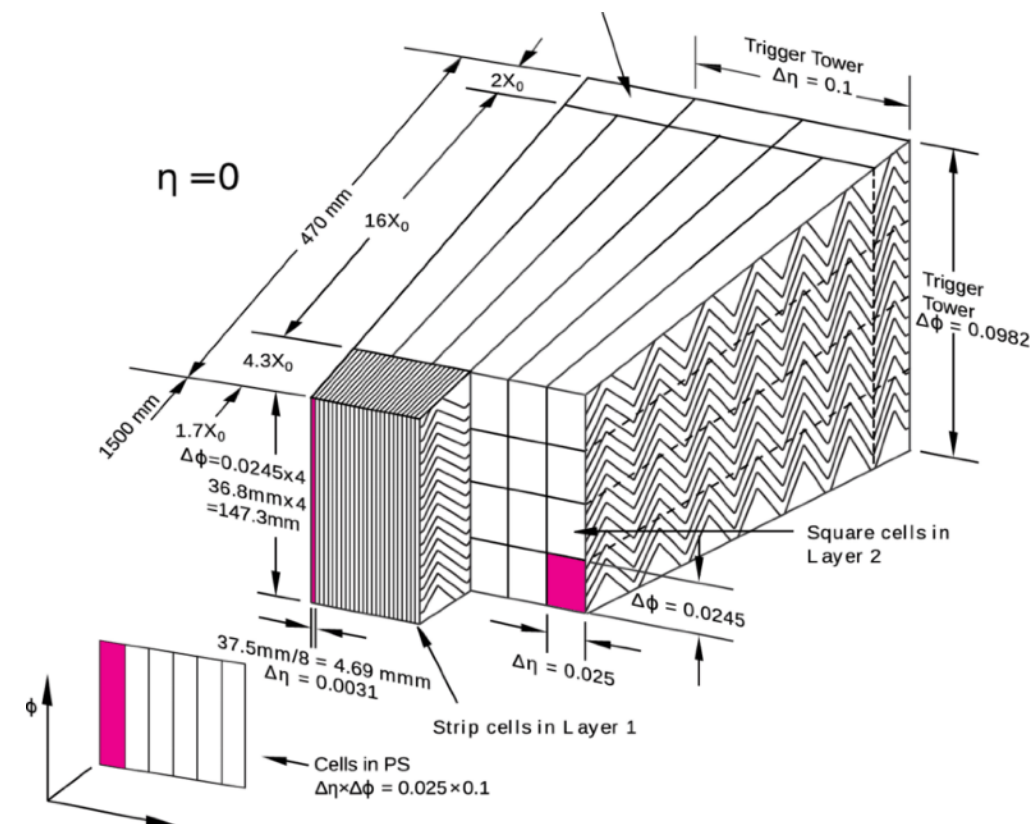
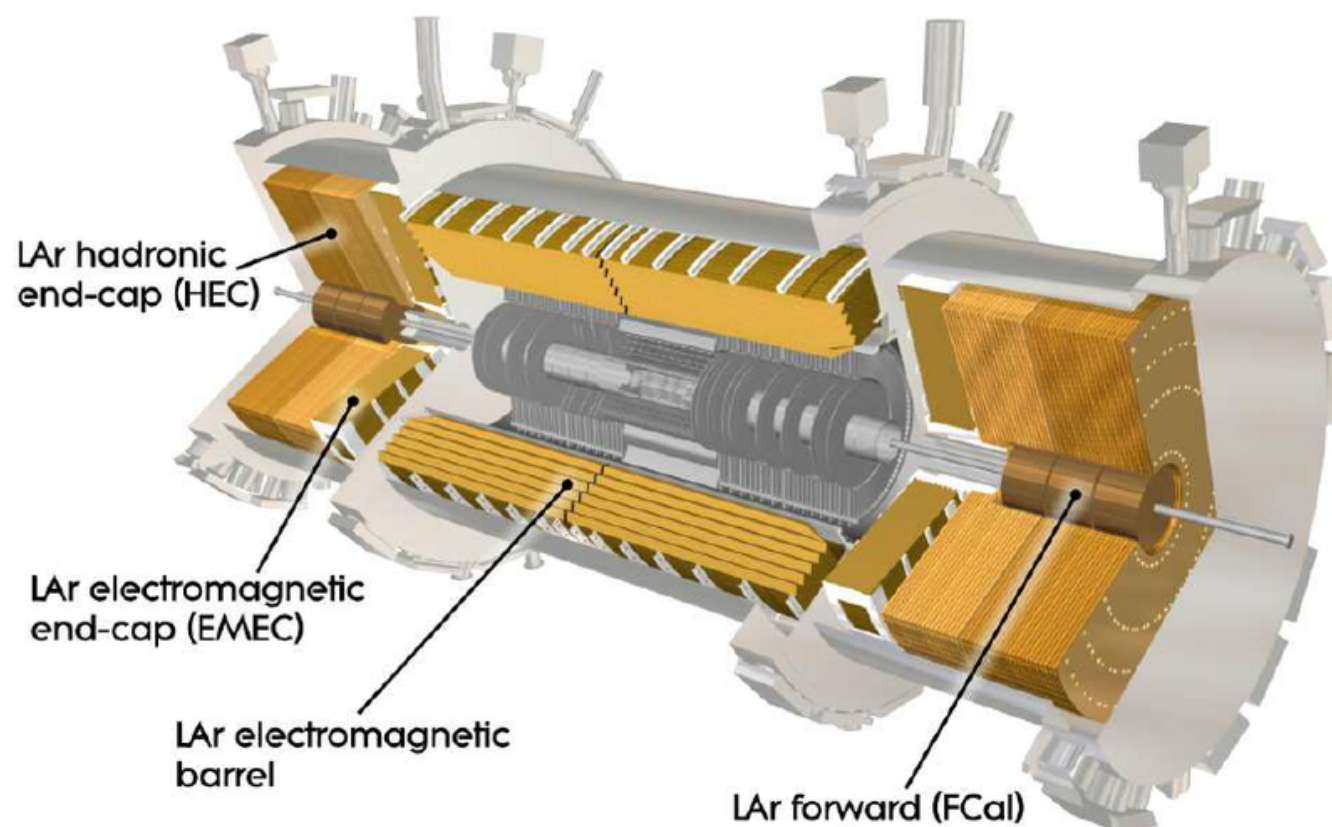
4 half-disk Dees (3662 xtals)
Total of 14648 PbWO_4 crystals
coverage: $1.48 < |\eta| < 3.0$



Preshower (ES)

4 half-disk Dees
Two Lead/Si planes
Total of 137216 Si strips ($1.8 \times 61 \text{ mm}^2$)

The ATLAS Electromagnetic calorimeter



$|\eta| < 1.475$

Cu/kapton electrode

Honeycomb spacer

Stainless-steel-clad Pb absorber plates

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

Barrel

101760 readout channels
3 longitudinal depths

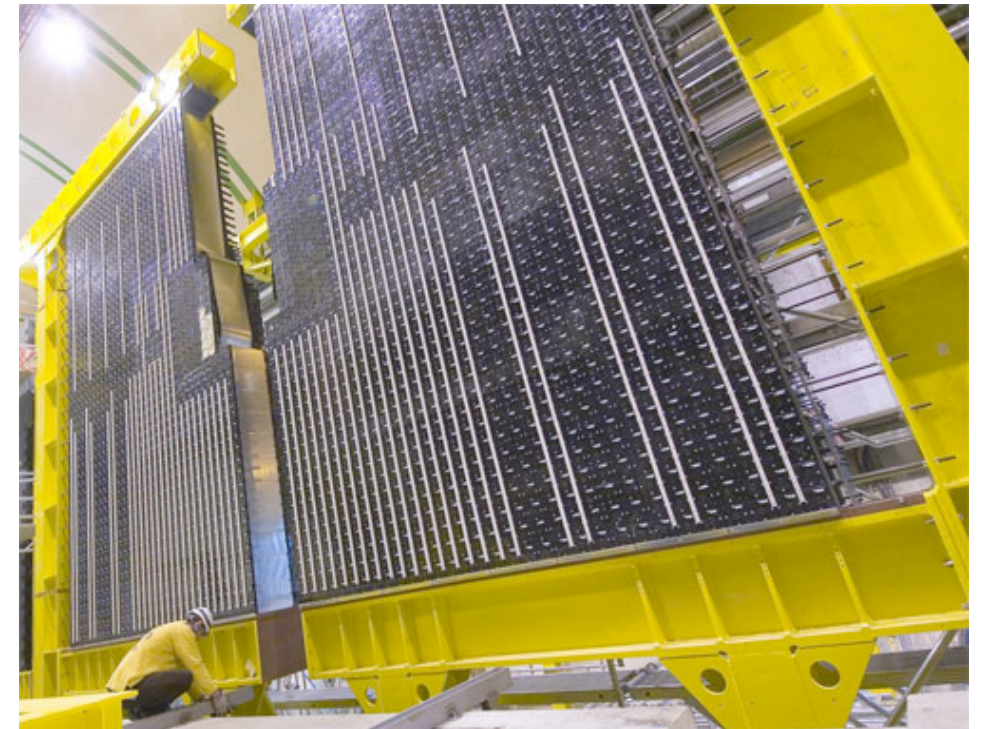
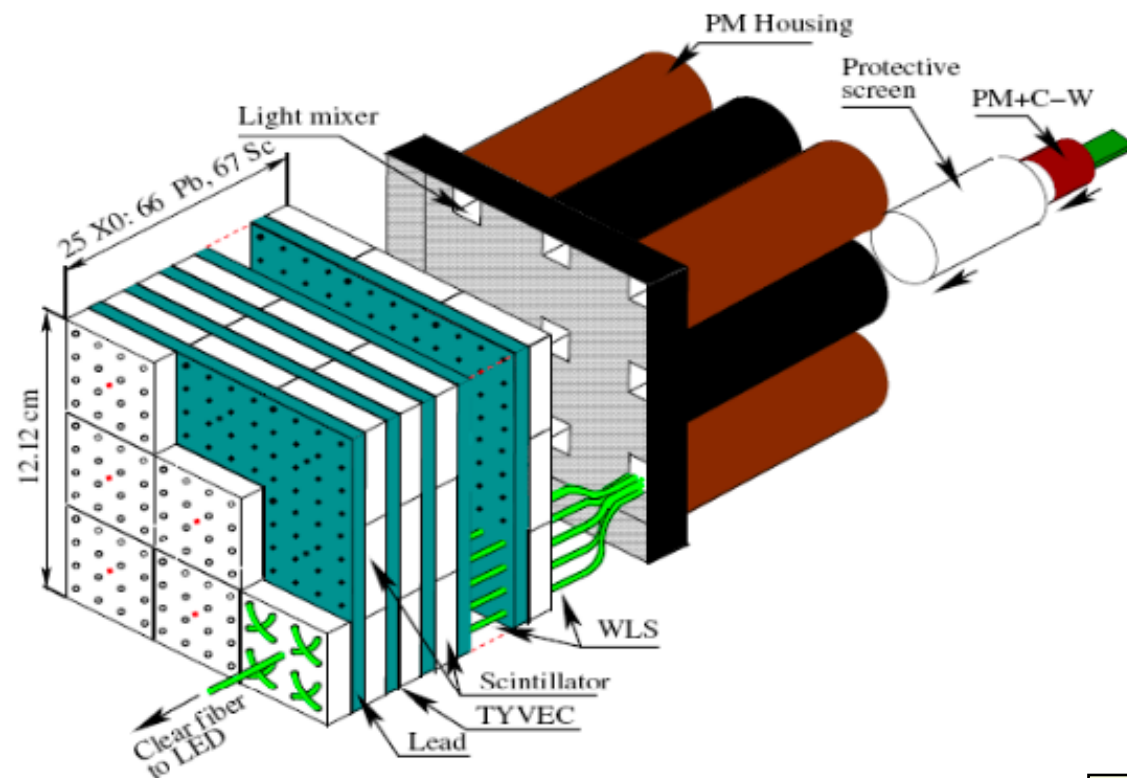
Endcap

62208 readout channels
2 or 3 longitudinal depths

Presampler

9344 readout channels
one longitudinal depth

The LHCb Electromagnetic calorimeter

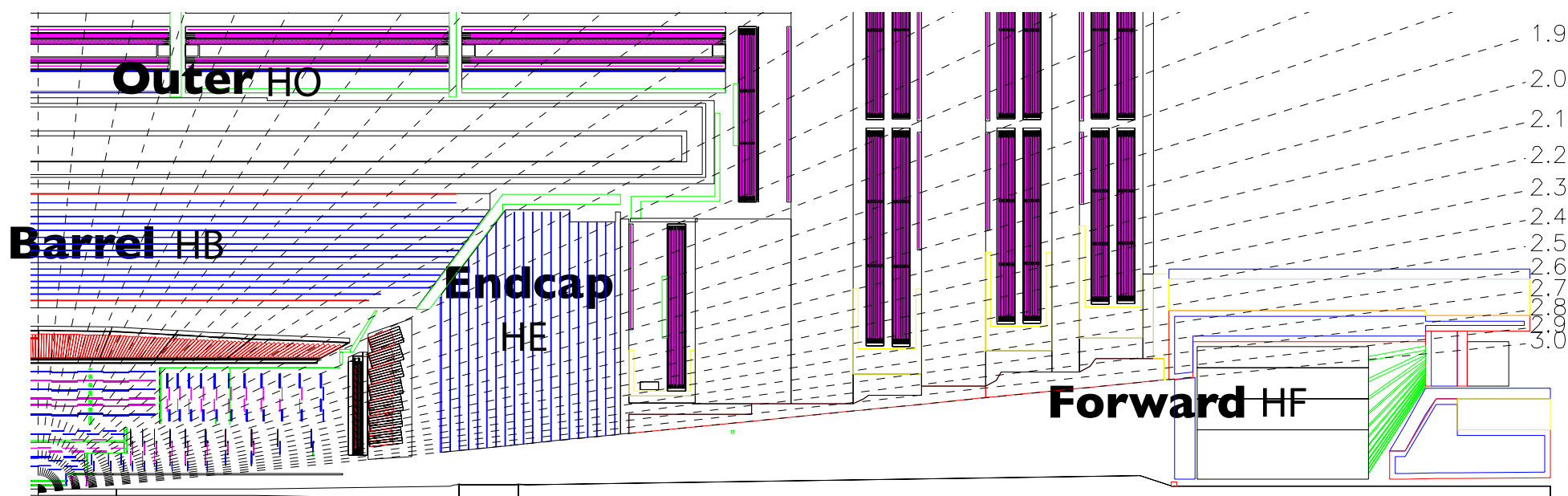


Sampling geometry with 3312 detector modules consist of lead absorbers and plastic scintillator active media
read out by PMTs via wavelength shifting fibres

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 via wavelength
shifting fibres



Barrel (HB)

**36 brass/scintillator
wedges**

17 longitudinal layers

5cm brass + 3.7mm scint

coverage: $|\eta| < 1.3$



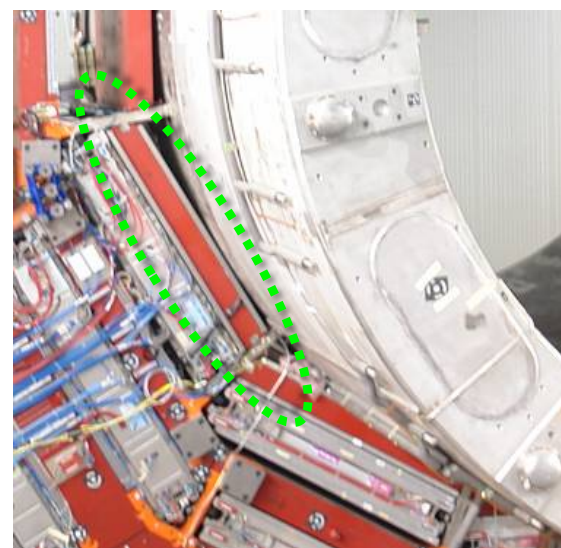
Endcap (HE)

Two brass endcap discs

19 longitudinal layers

8cm brass + 3.7mm scint

coverage: $1.3 < |\eta| < 3.0$



Outer (HO)

scintillator tiles outside yoke

1 or 2 longitudinal layers

10mm scint

coverage: $|\eta| < 1.3$



Forward (HF)

Steel absorber, in 20 deg wedges

Quartz fibre active element ($\sim 1000\text{km}$)

coverage: $3 < |\eta| < 5.0$

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

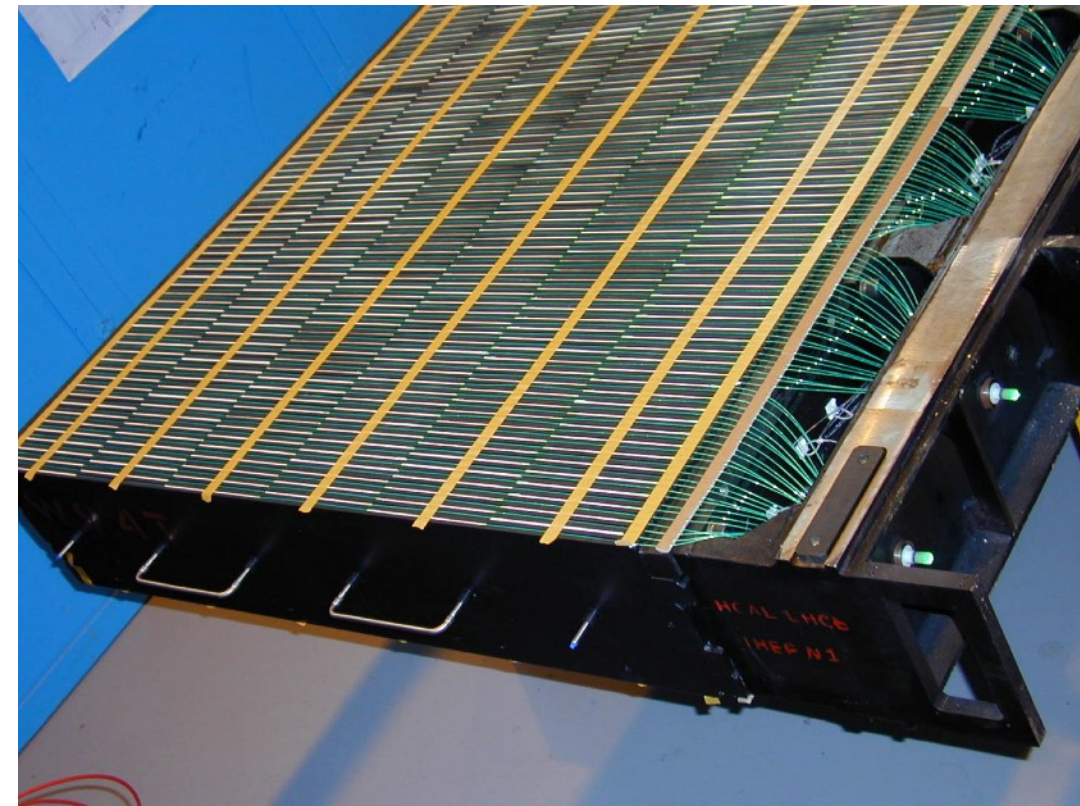
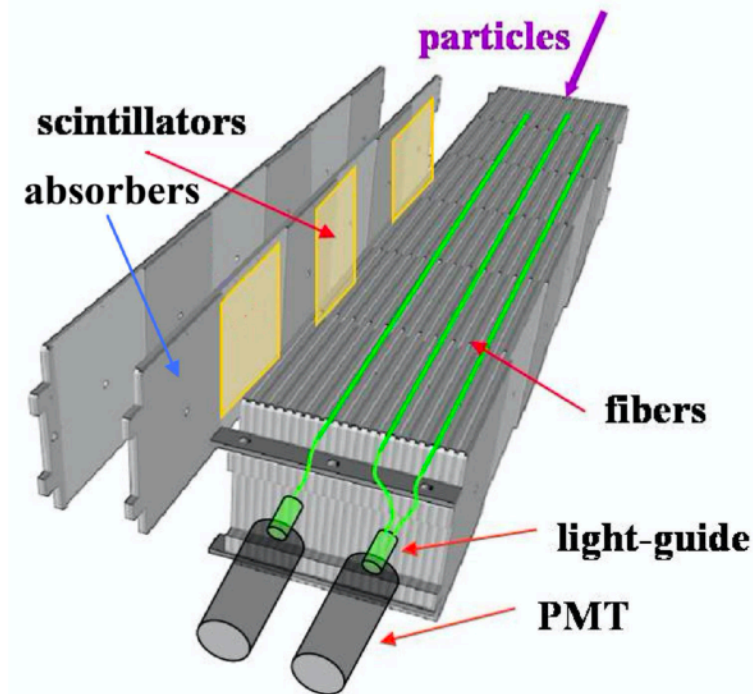
Cu and W absorbers/LAr active media

3 depth segments

3524 readout channels

coverage: $3.1 < |\eta| < 4.9$

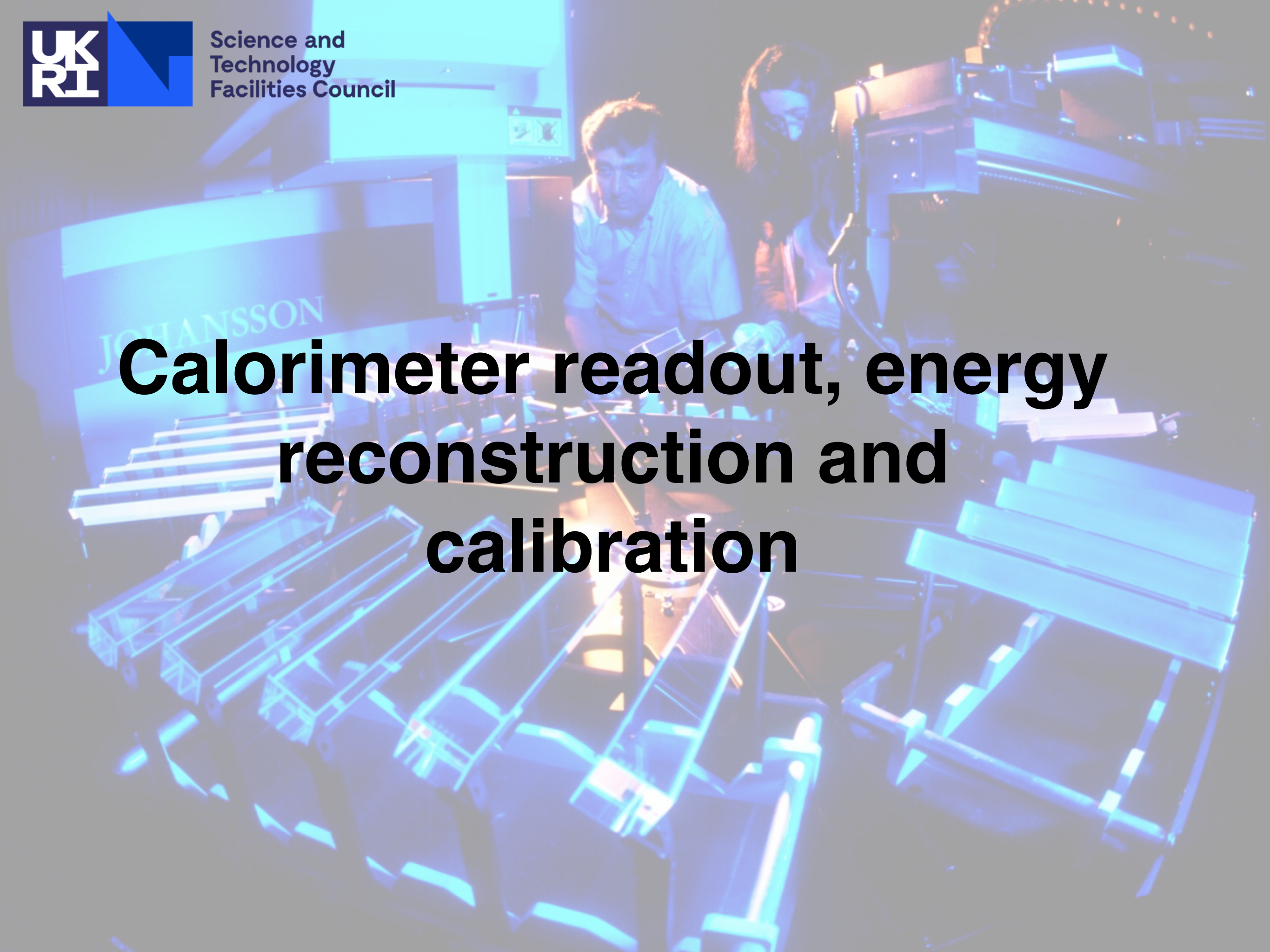
The LHCb Hadron Calorimeter



Sampling geometry with iron absorber and scintillator tile active media oriented parallel to beam
Read out by PMTs via 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

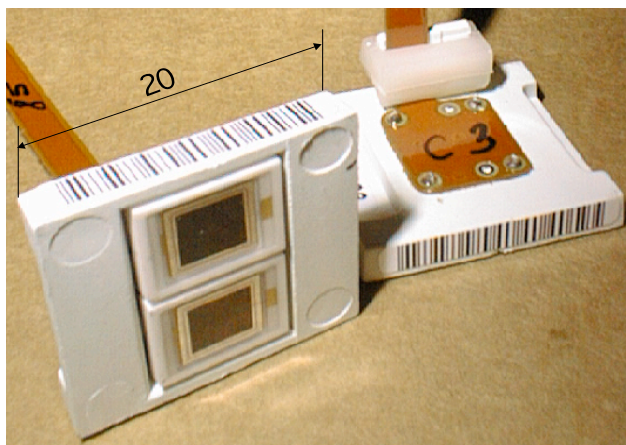
The background image shows a large, complex particle detector, likely a calorimeter, with a grid of rectangular modules. Two people, a man and a woman, are standing in front of the detector, looking at it. The name 'JOHANSSON' is visible on a panel of the detector. The entire image has a blue color overlay.

Calorimeter readout, energy reconstruction and calibration

Calorimeter readout

- **Custom** 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)

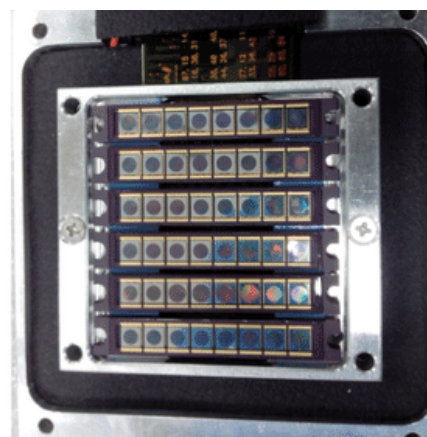
CMS ECAL
Barrel



CMS ECAL
Endcaps



CMS HCAL



LHCb ECAL



APD: Avalanche
PhotoDiodes

VPT: Vacuum
PhotoTriodes

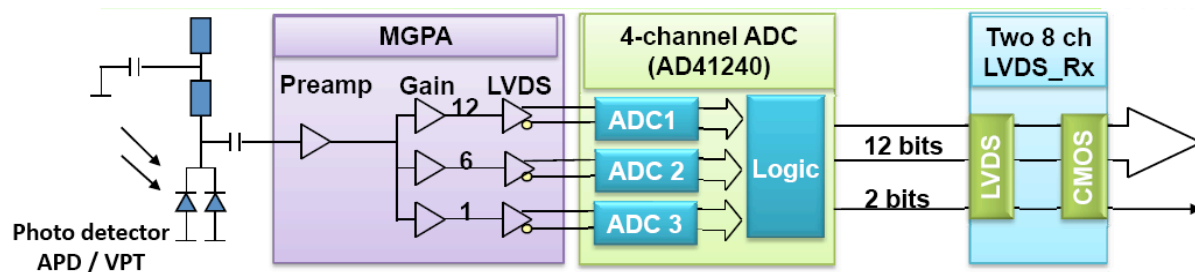
SiPM: Silicon
PhotoMultipliers

PMT: Photo
Multiplier Tubes

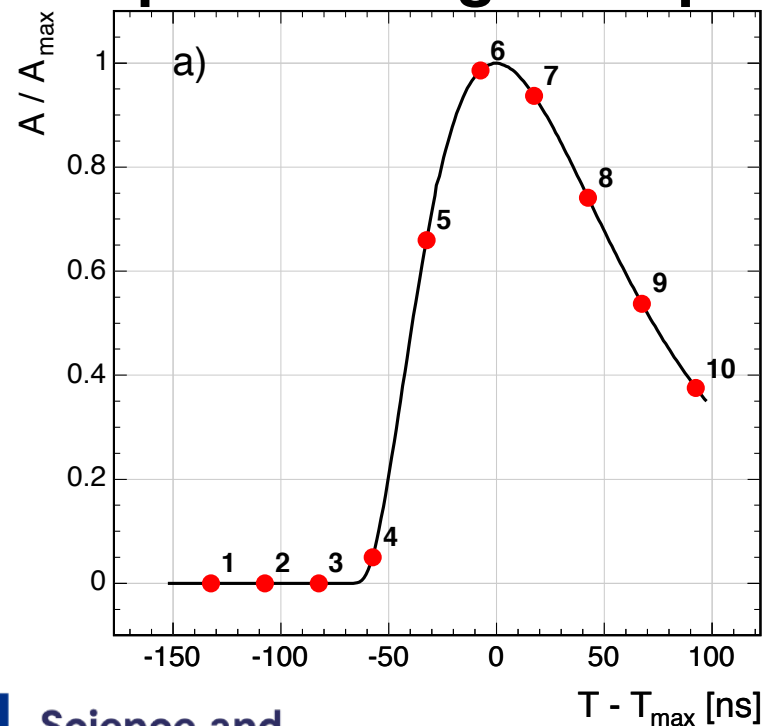
Calorimeter front-end electronics

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

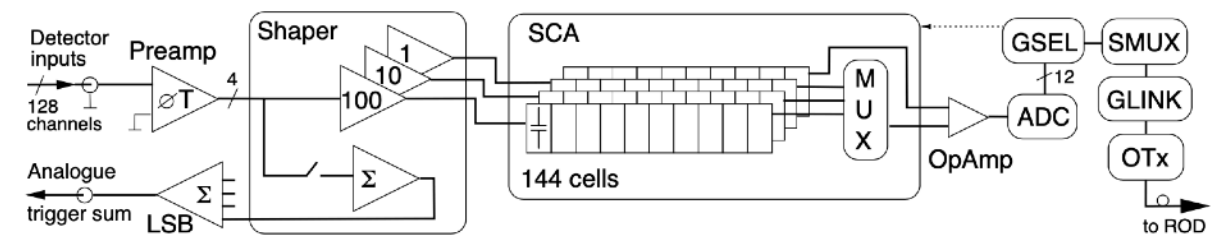
CMS ECAL



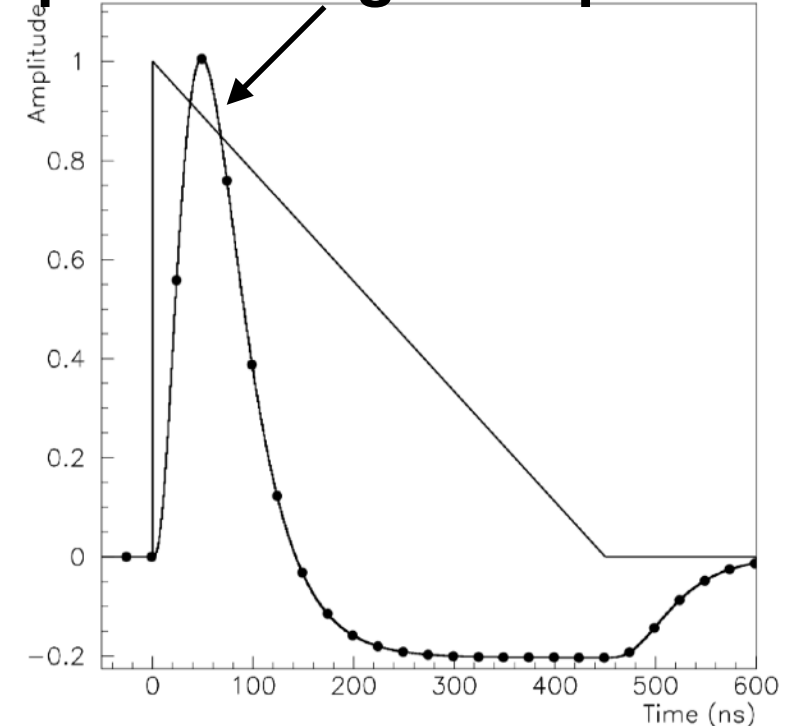
shaped and digitized pulse



ATLAS ECAL

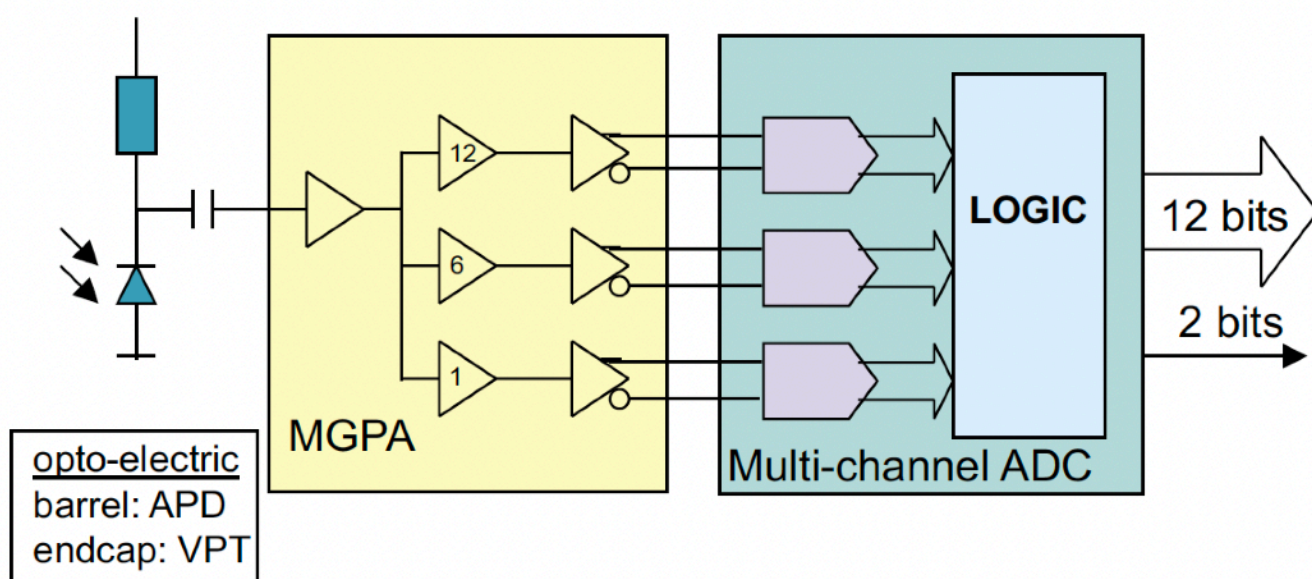


shaped and digitized pulse

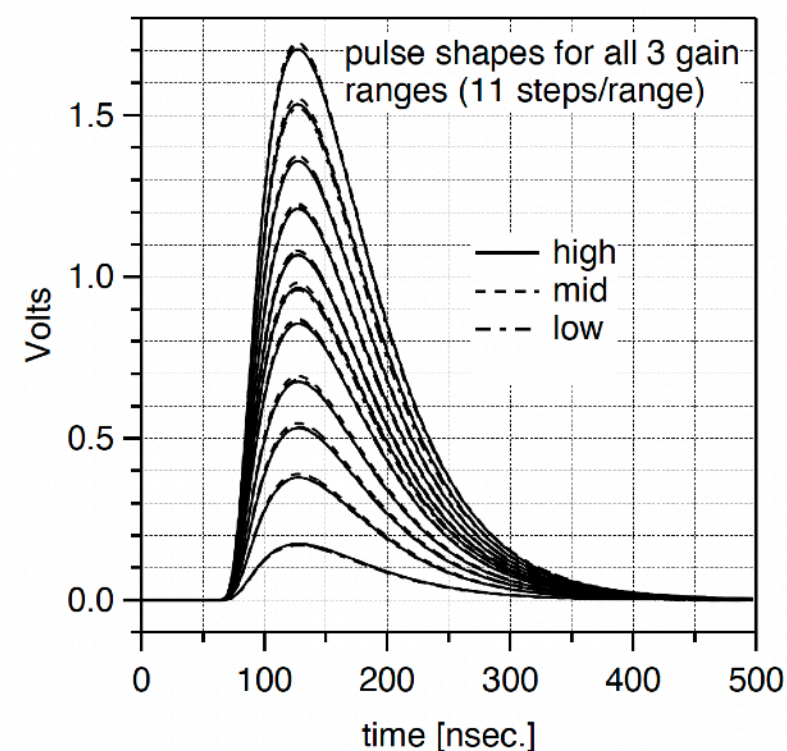


Digitization details

- **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

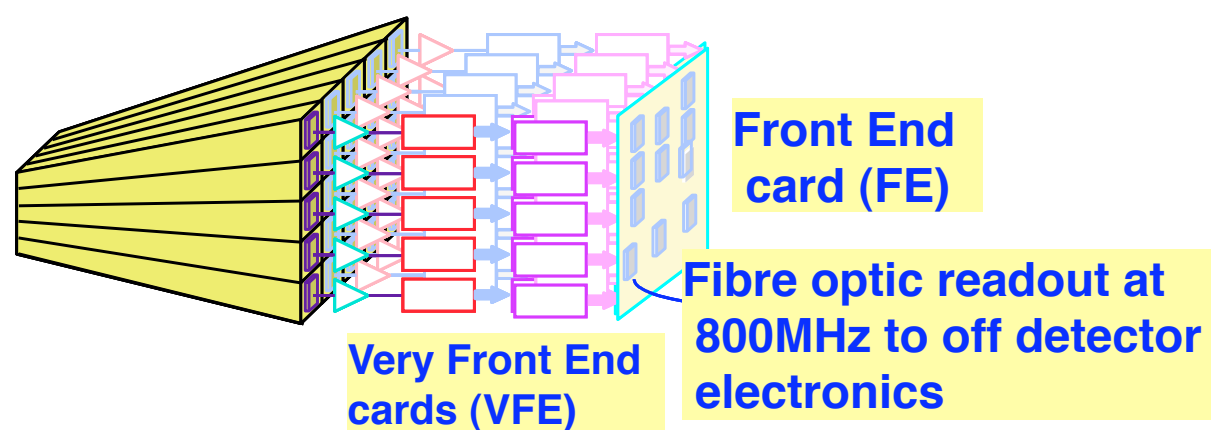


Pulse shape stability vs signal size

Calorimeter trigger sums

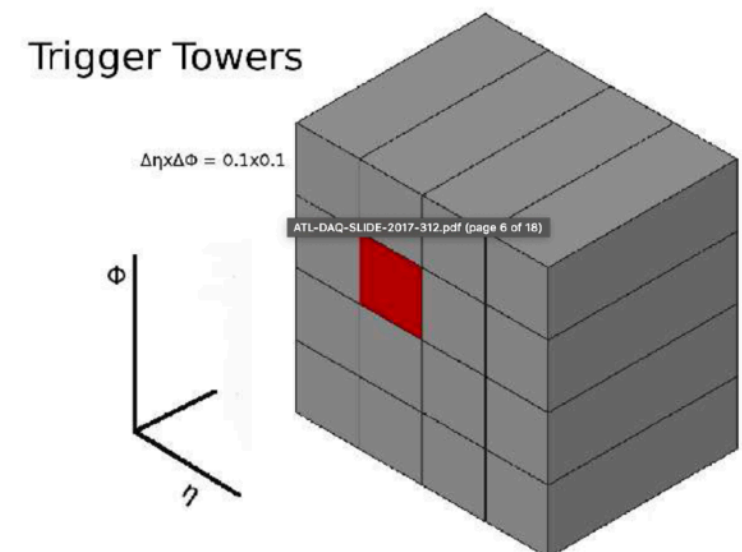
- **Fast energy sums sent every 25ns to first level trigger**
 - identify interesting events from calorimeter energy deposits
- **Computed from sums of calorimeter cells in ECAL and HCAL**
 - termed Trigger Towers
 - combined to form electron/photon, tau, jet candidates

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:

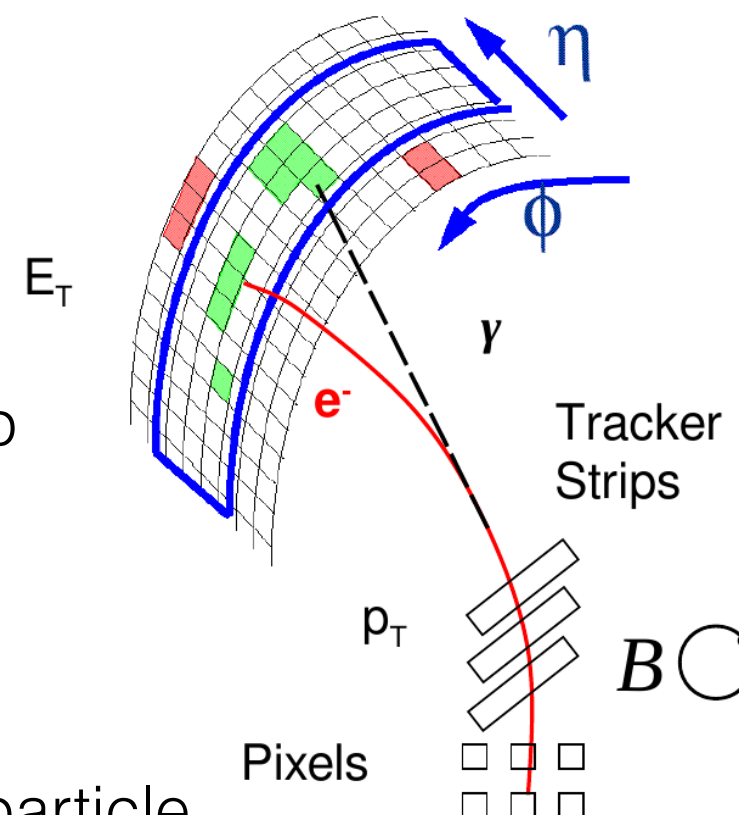
$$E_{e,\gamma} = \sum_i \left[\overset{\text{Pulse Amplitude}}{A_i} \times \underset{\substack{\text{time-dependent response corrections:} \\ \text{laser monitoring system}}}{S_i(t)} \times \overset{\text{intercalibration}}{c_i} \right] \times \underset{\text{Global scale}}{G(\eta)} \times \overset{\text{cluster corrections}}{F_{e,\gamma}}$$

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 minimise 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

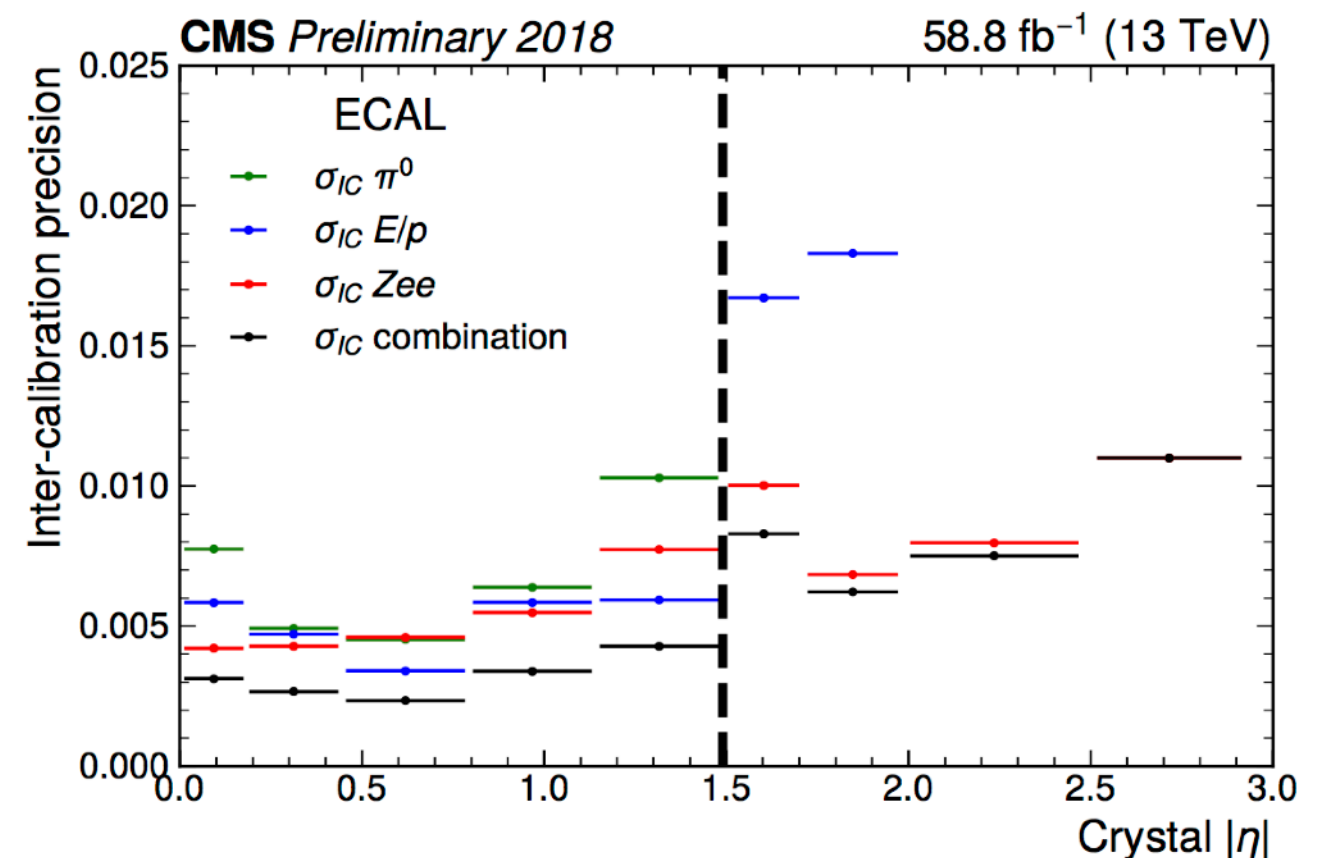
intercalibration sources

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
$Z \rightarrow ee$ 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

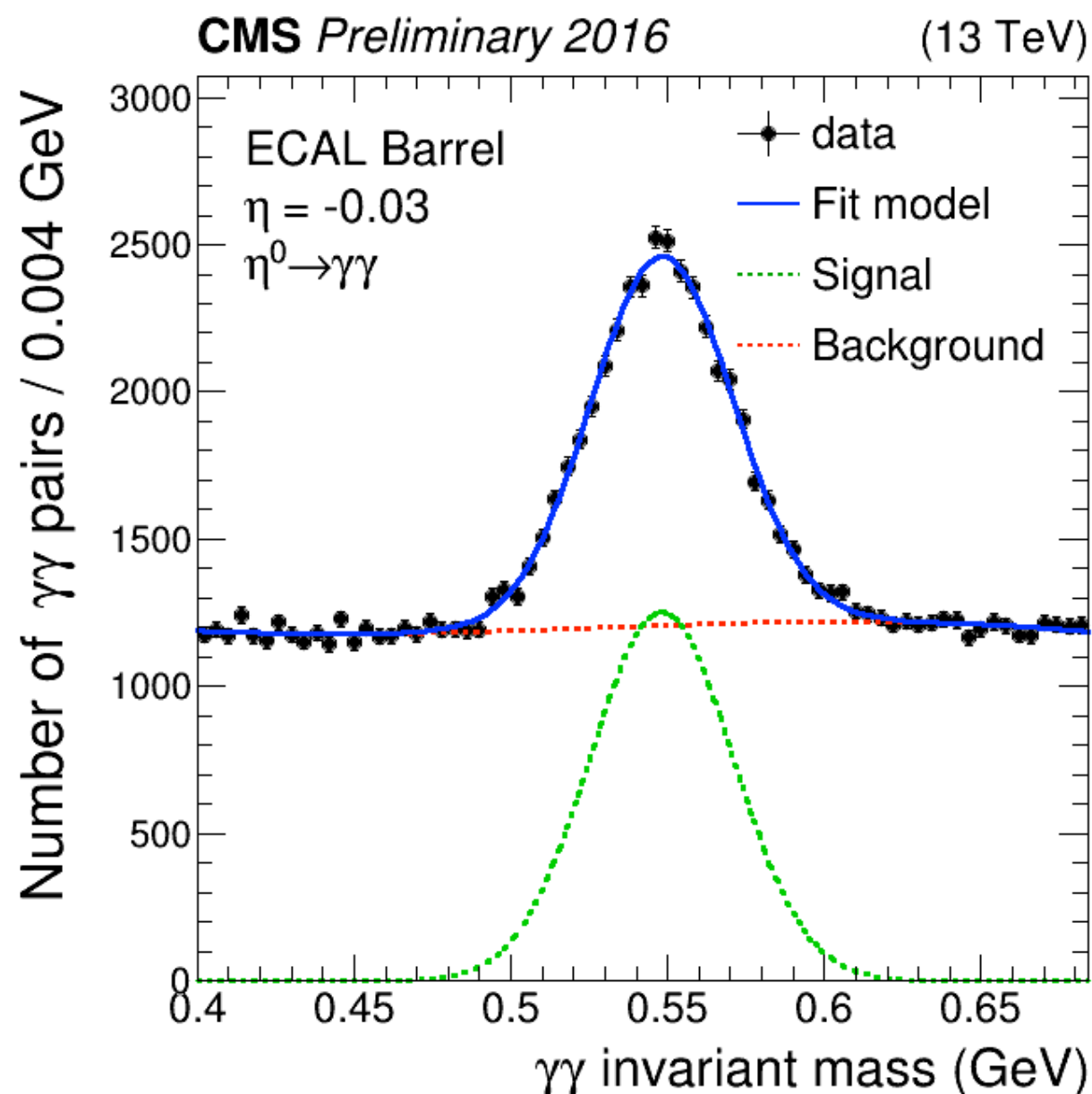
$\pi^0/\eta \rightarrow \gamma\gamma$ and $Z \rightarrow ee$ - use invariant mass constraint to equalise response per channel

ϕ -symmetry (minimum bias events) and E/p ratio from $W \rightarrow ev$ can provide relative calibrations

$Z \rightarrow ee$ fixes absolute energy scale

Energy calibration methods

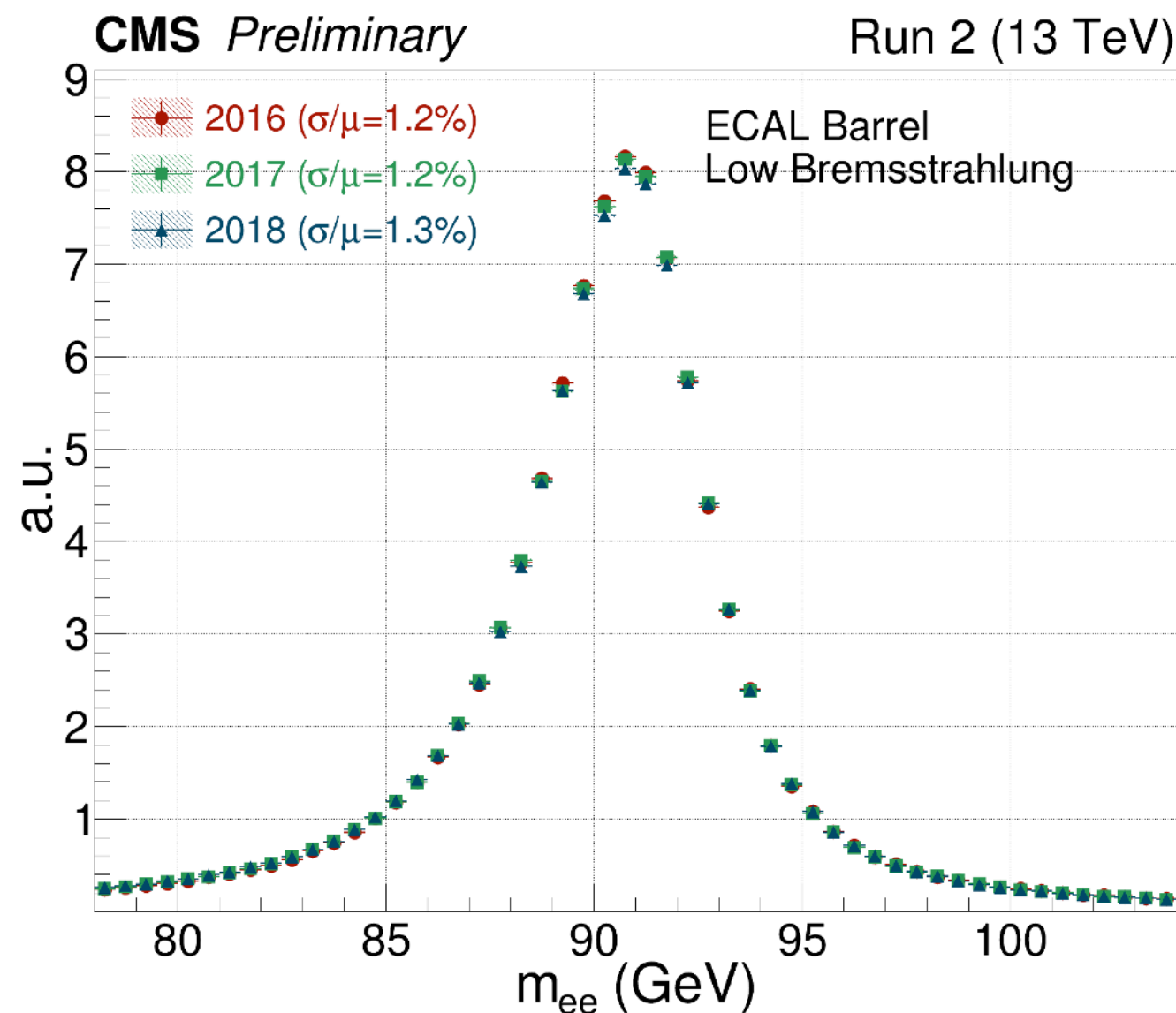
Example of a $\eta^0 \rightarrow \gamma\gamma$ invariant mass fit in CMS



advantages: high statistics, can provide calibrations with high time and spatial granularity

disadvantages: large backgrounds, more sensitive pileup and noise

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



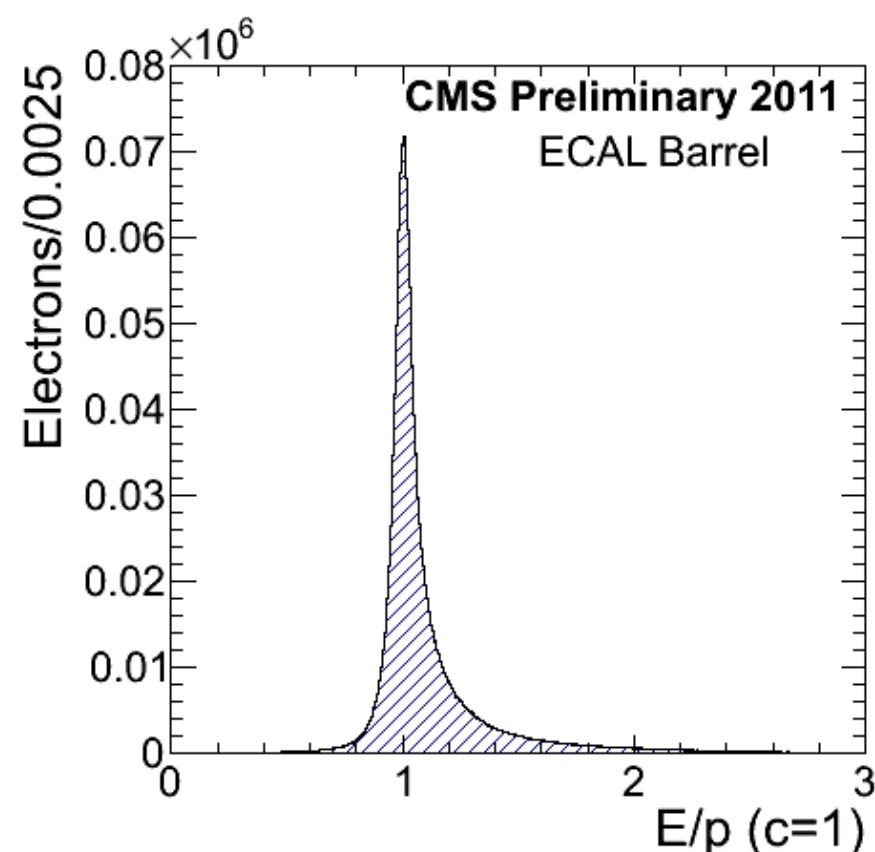
advantages: low background and small systematic errors, provides calibrations at relevant energies for $H \rightarrow \gamma\gamma$ decays

disadvantages: relatively low stats

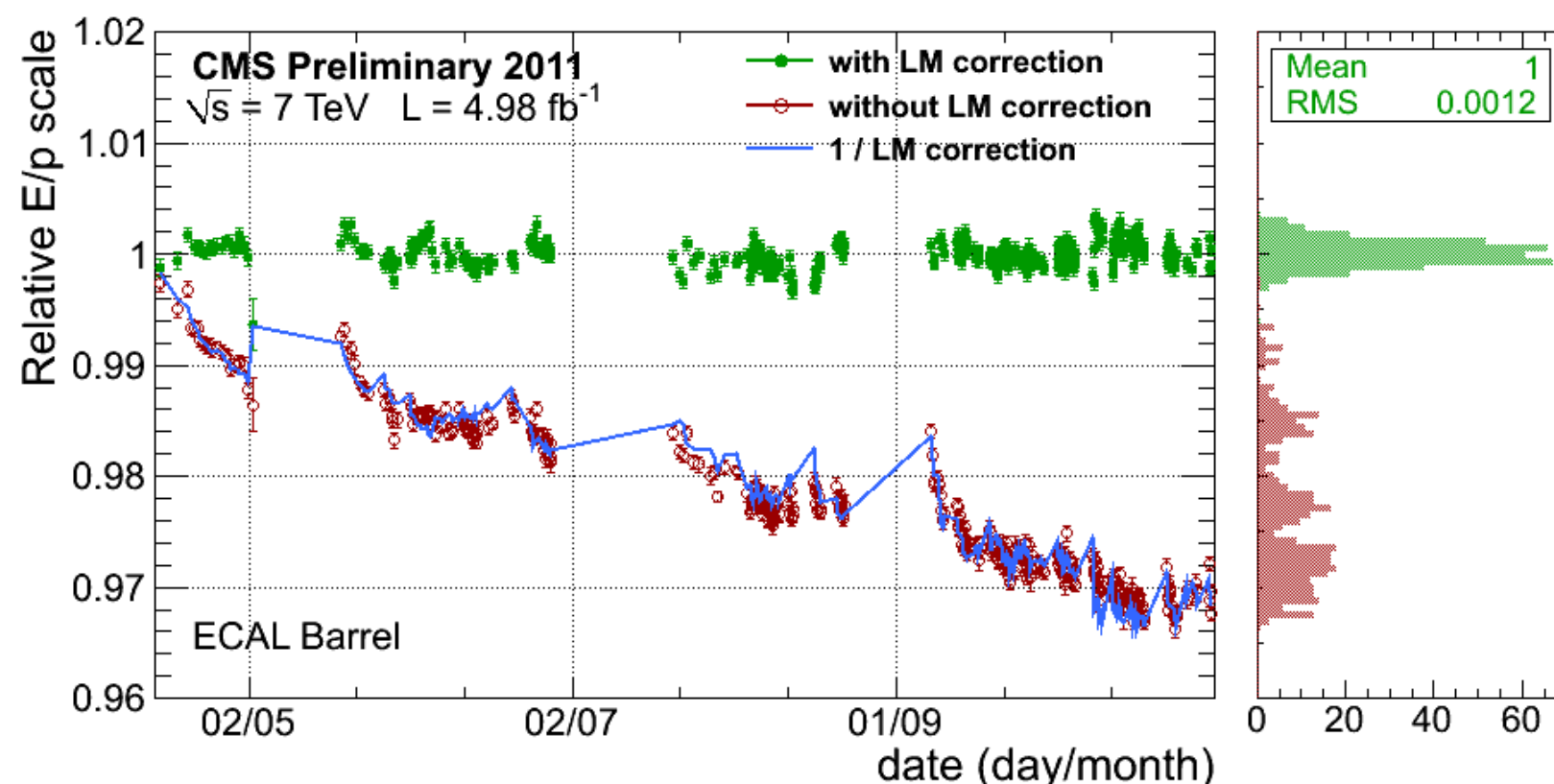
Energy calibration methods

E/p ratio of electrons from $W \rightarrow e\nu$ is a powerful calibration source

Energy scale
(relative to tracker)



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

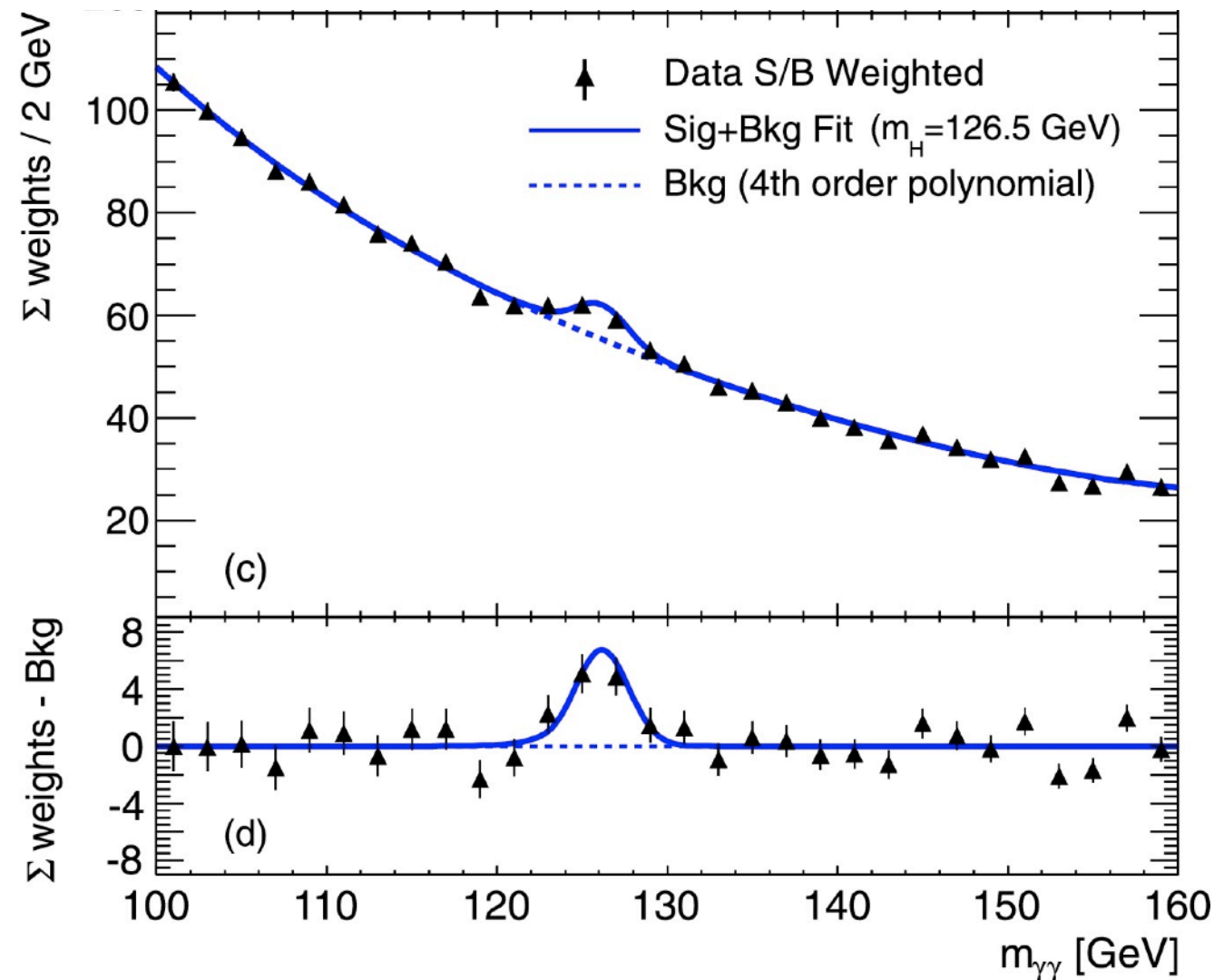


advantages: high statistics (5-6x more events than $Z \rightarrow ee$): can provide energy scale measurements and calibrations with higher time and spatial granularity. Use of independent tracker momentum provides a normalising factor - can probe a large range of electron p_T

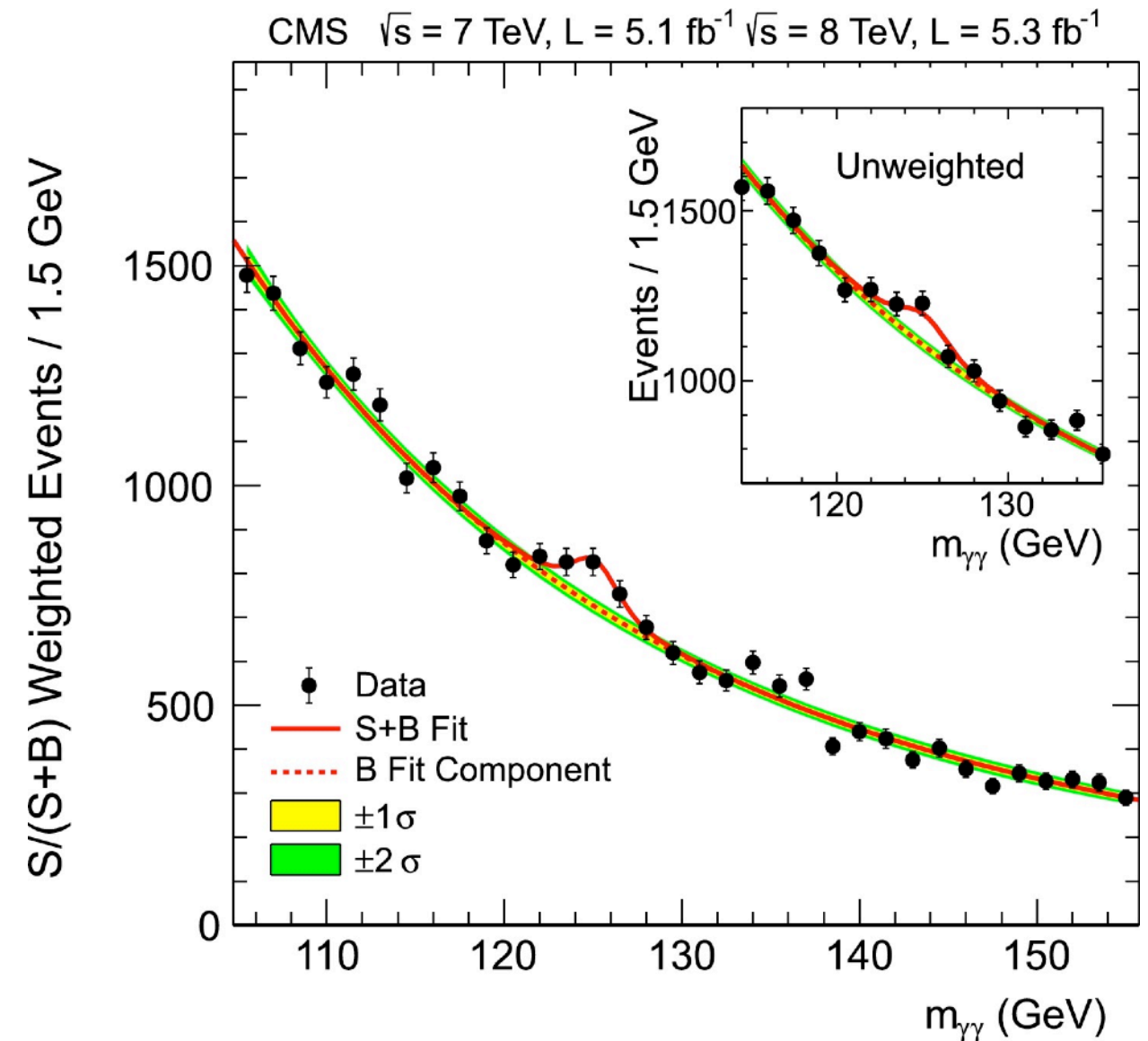
disadvantages: relies on the assumption that track p_T is well-calibrated - sensitive to issues and biases in track momentum measurement

$H \rightarrow \gamma\gamma$ 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

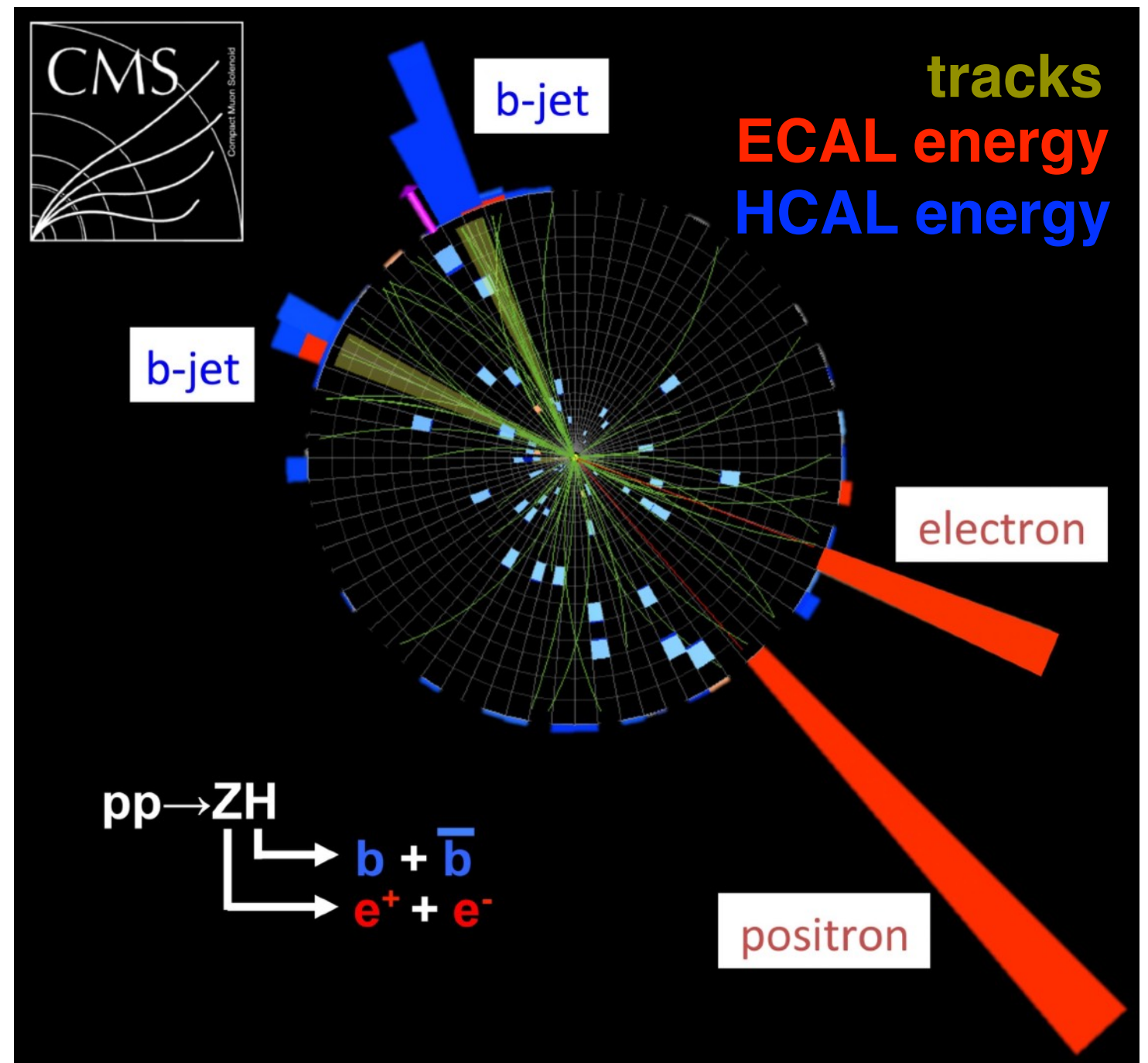
- pattern of deposits in tracker, ECAL, HCAL determines particle type
- **electrons:** ECAL energy matched to tracks, no HCAL energy
- **jets:** multiple tracks associated with ECAL+HCAL deposits

Charge and momentum measurement

- from bending of tracks in magnetic field

Energy measurement

- from clustered deposits in ECAL and HCAL



Electron track matching and E-p combination

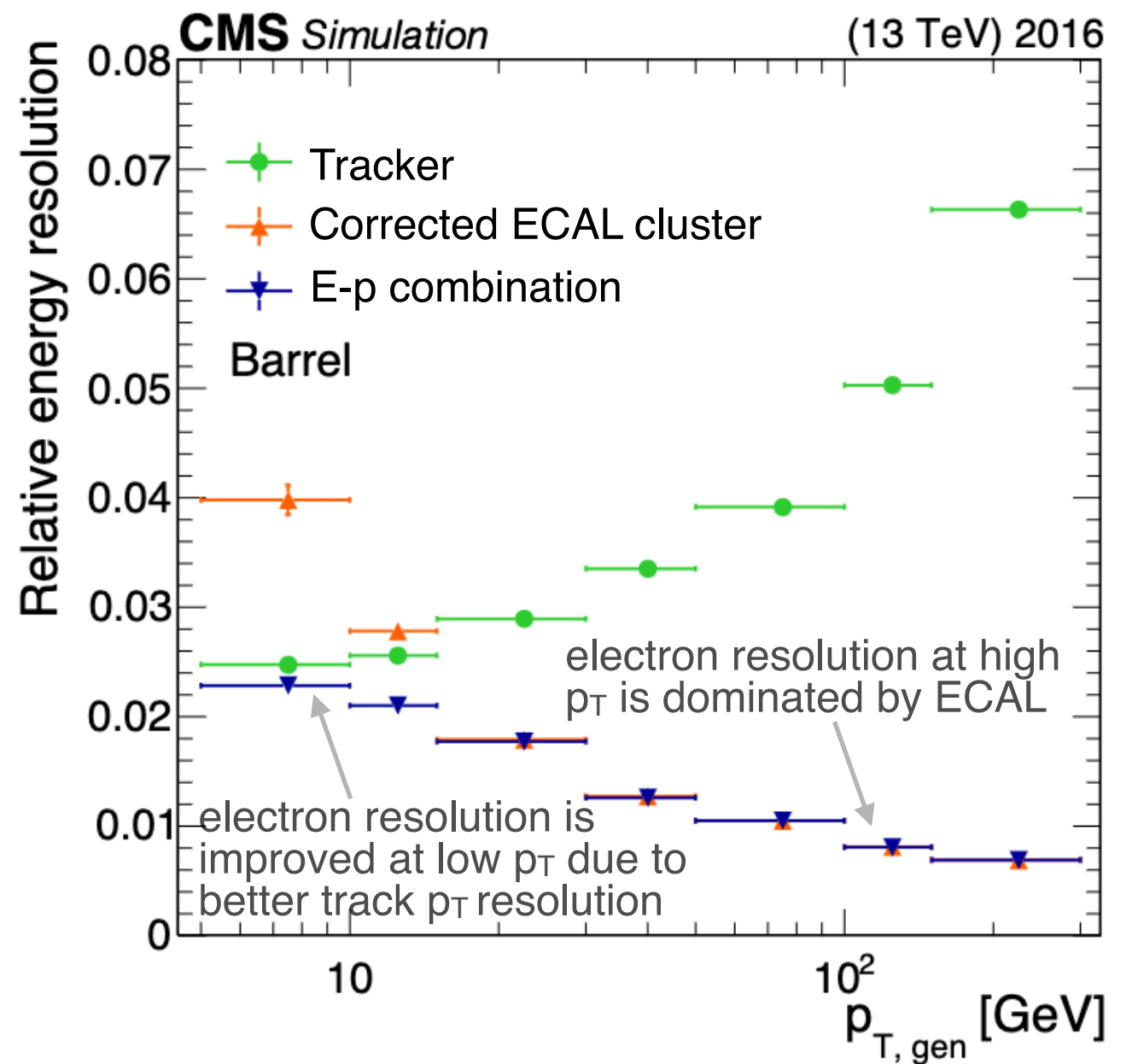
Electron-track matching

- 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

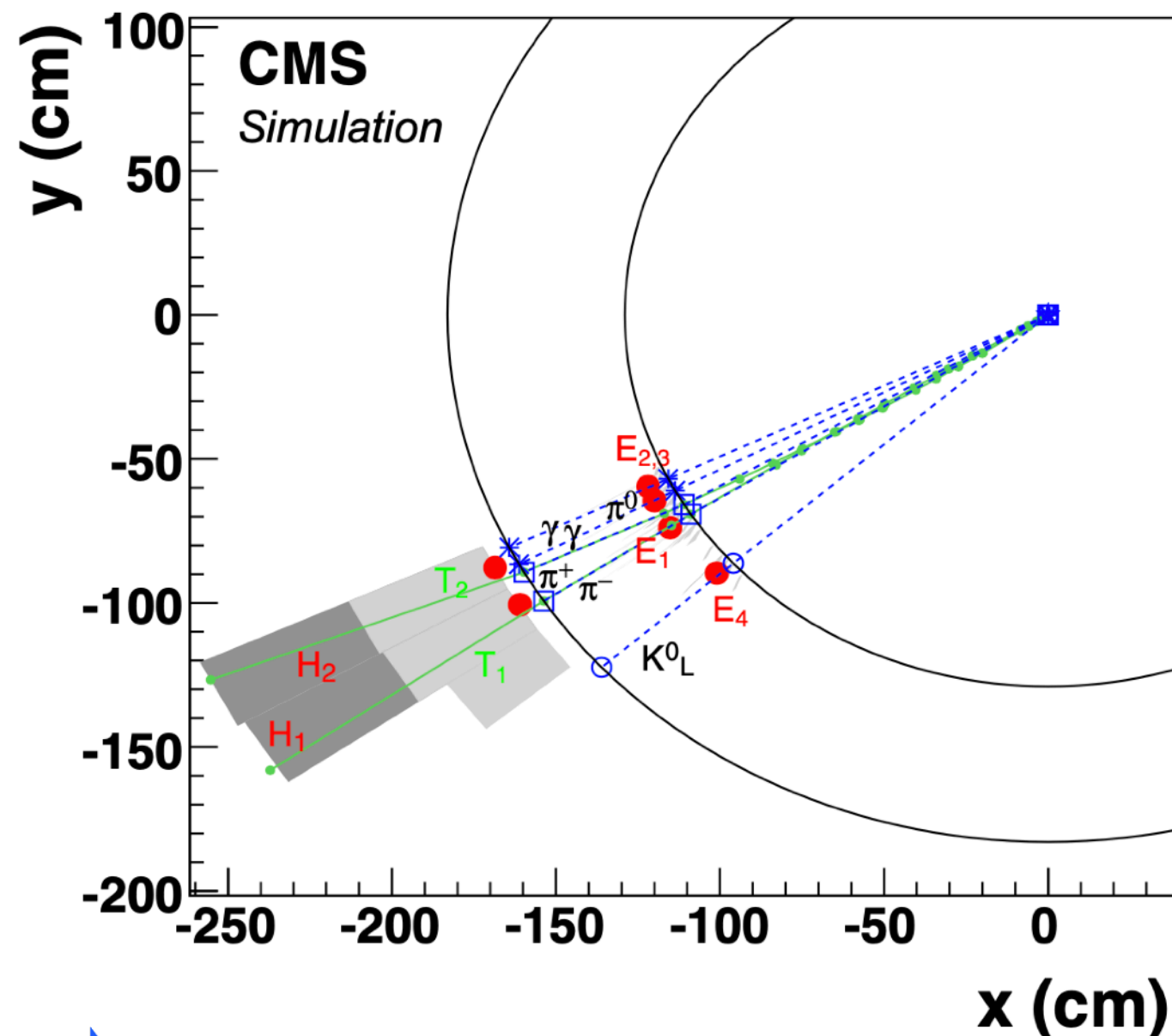
- the ECAL cluster energy and tracker momentum can be combined
- providing the two measurements are consistent (E/p matching)

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



Particle flow reconstruction

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



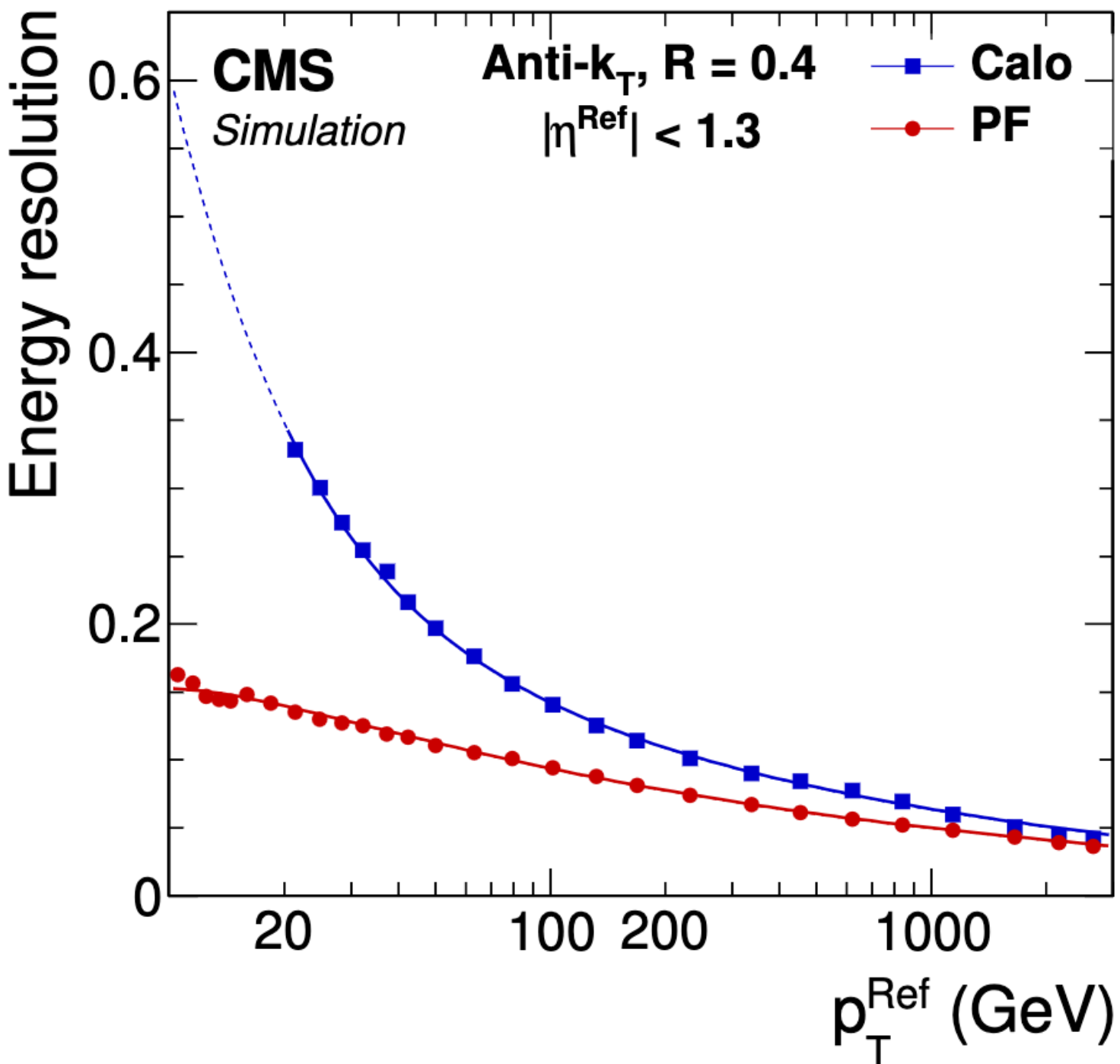
x,y view of particle jet

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)

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)

not enough just to design a good ECAL or HCAL

Need to consider both tracking and calorimetry together

calorimetric approach

Calorimeter design checklist

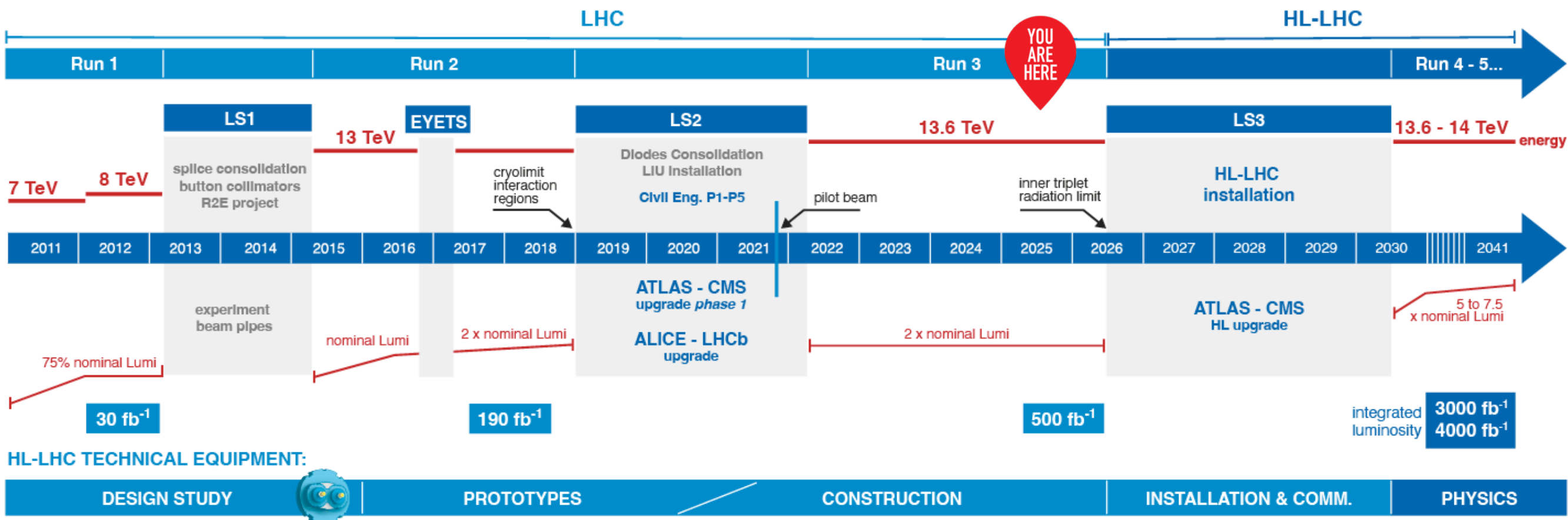
- **High resolution**
 - especially for ECAL - Higgs and rare decay measurements
- **High granularity**
 - for particle ID and position measurement, and particle flow reconstruction
- **Compact and hermetic**
 - with dimensions informed by R_M , X_0 , λ_I
 - relative dimensions of ECAL/HCAL key to aid 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

The background image shows a large, complex particle detector assembly, likely for the CMS experiment. It features a large, curved structure with the name 'JOHANSSON' visible on its side. Two people, a man and a woman, are standing in front of the detector, looking at it. The detector is composed of many layers of material, with some parts illuminated by blue light. The overall scene is dimly lit, with the detector's components providing the main light source.

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: $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ already exceeded by a factor of 2 in 2017, 2018

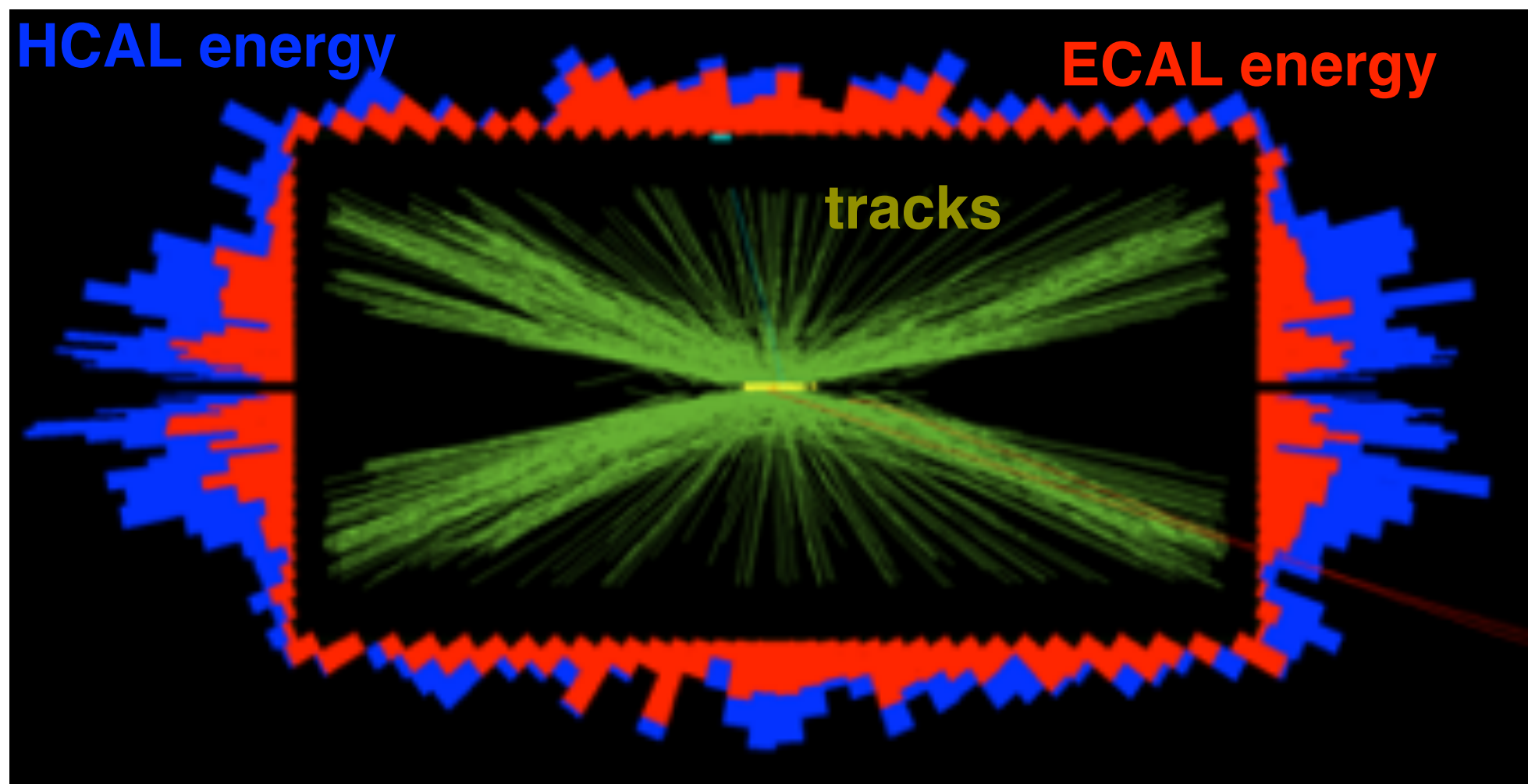
integrated luminosity (size of physics dataset) increased by a factor of 6 in Run 2 (2015+)

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



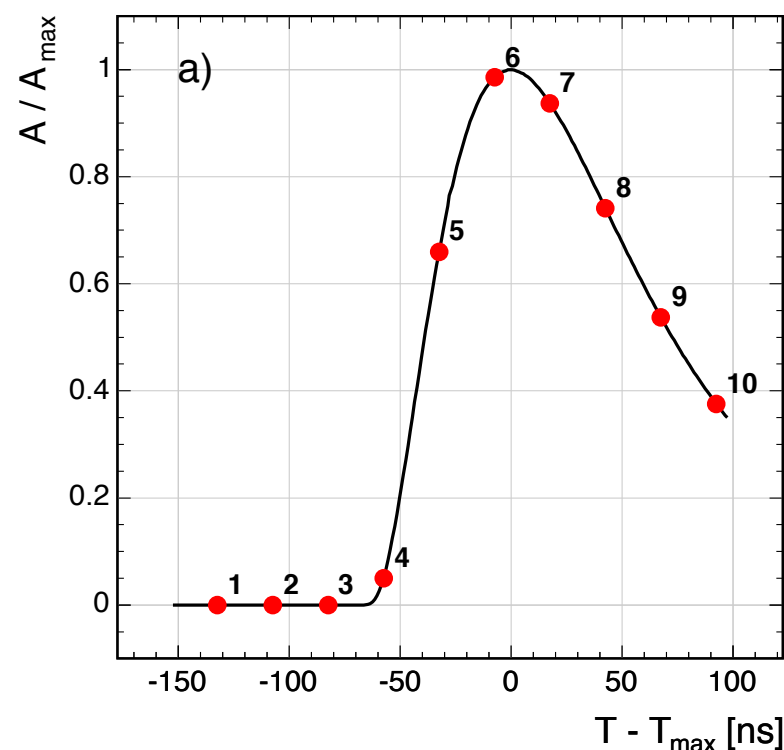
78 simultaneous interactions from one LHC collisions event
a significant challenge to pattern recognition and event reconstruction algorithms
Run 1 average: 10-20, Run 2 average: 40, Run 3 average: 60

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

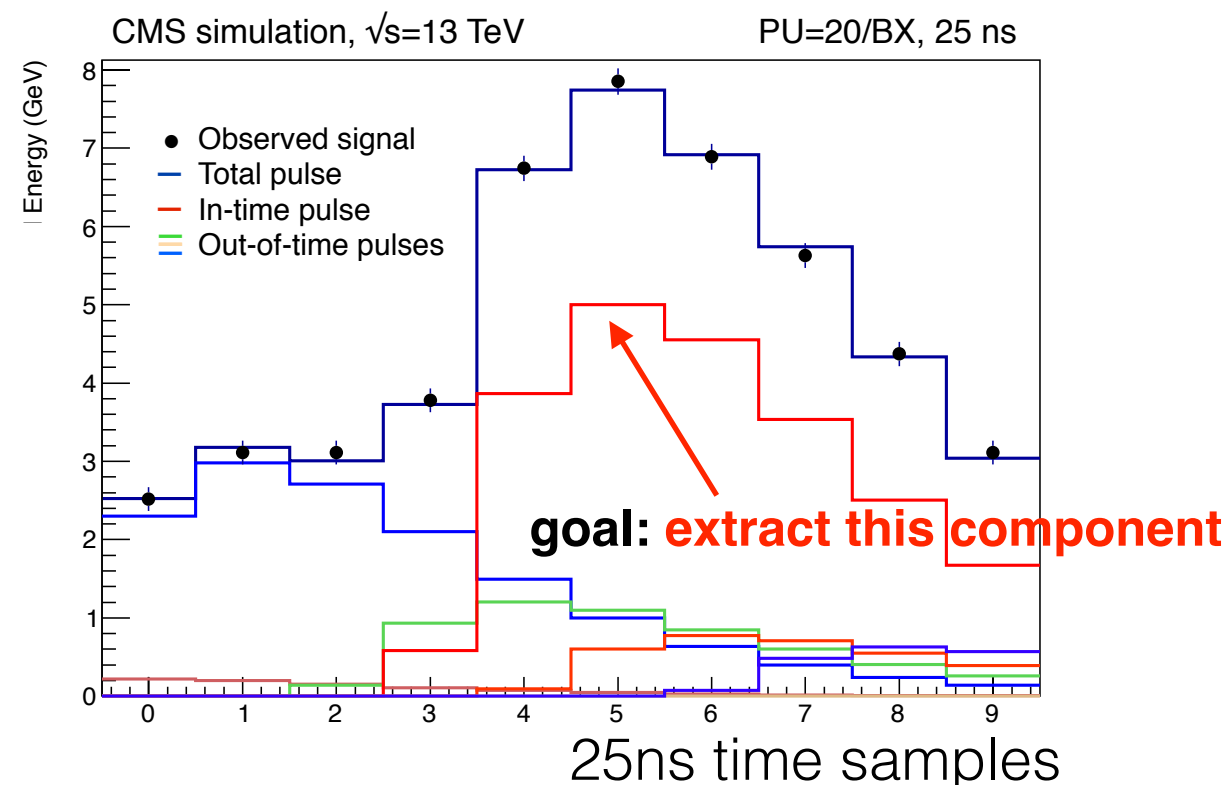
Pulse reconstruction methods

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

ECAL digitized pulse no pileup



ECAL digitized pulse with pileup



Advanced pulse reconstruction algorithms developed to mitigate OOT PU

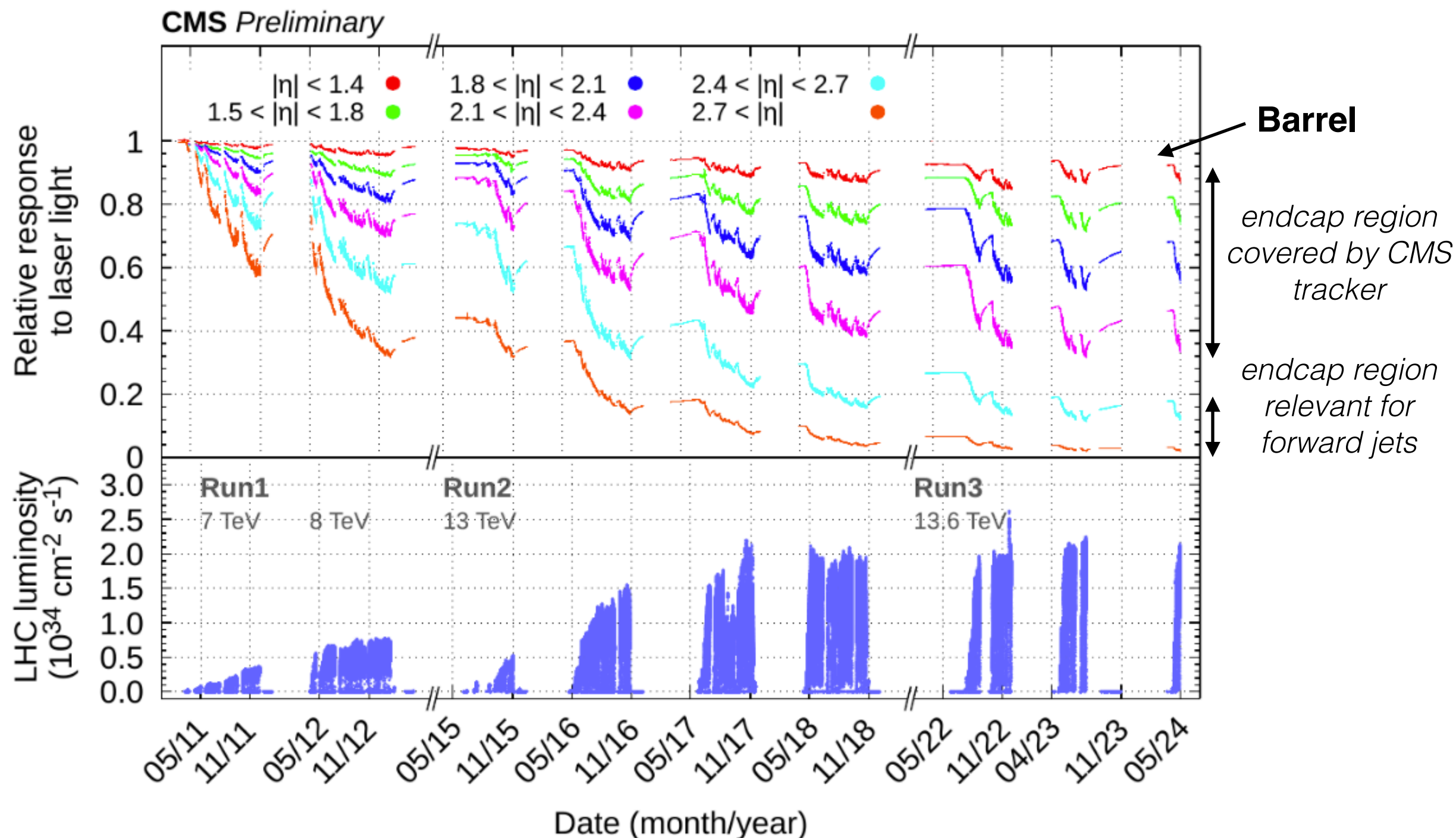
template fit() -> subtracts out-of-time pulses that overlap with in-time signal*
Large improvements in low energy e/ γ and jet response are obtained

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

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

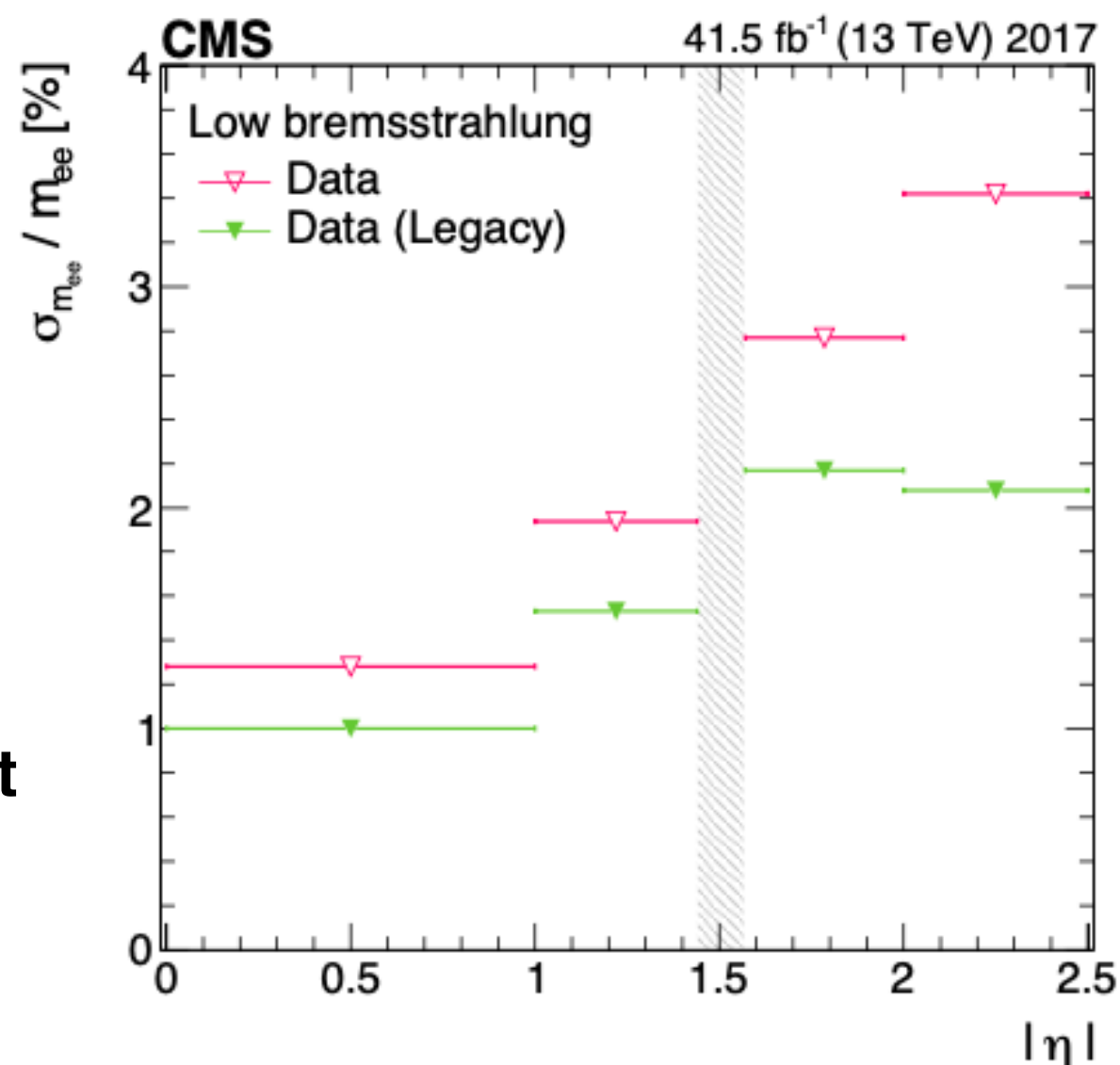
Calibration challenges - CMS ECAL

- 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**



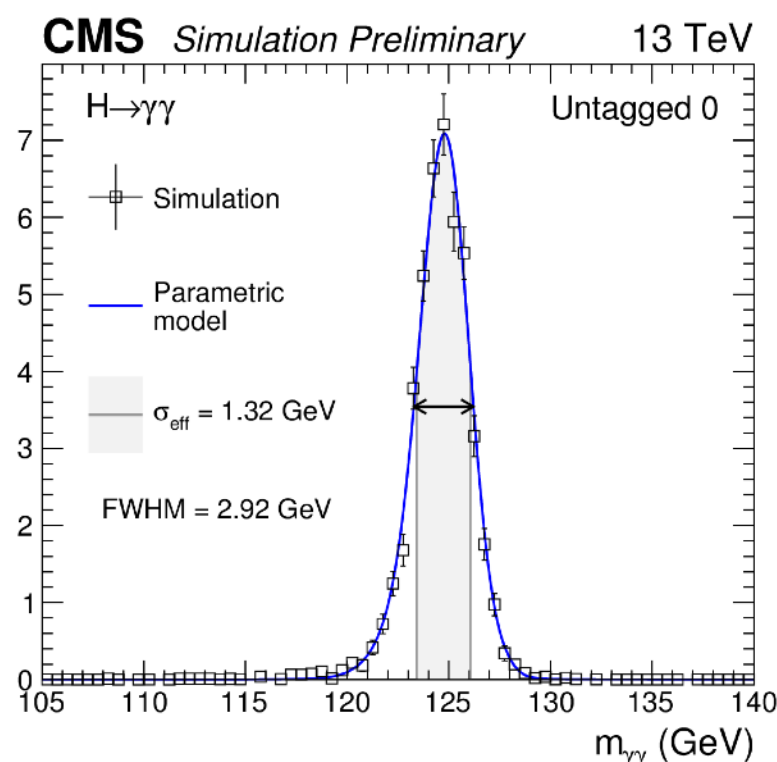
Di-electron Z mass resolution before and after end-year recalibration

Resolution vs eta follows distribution of upstream tracker material: need to minimise this in future detector designs to preserve intrinsic ECAL resolution

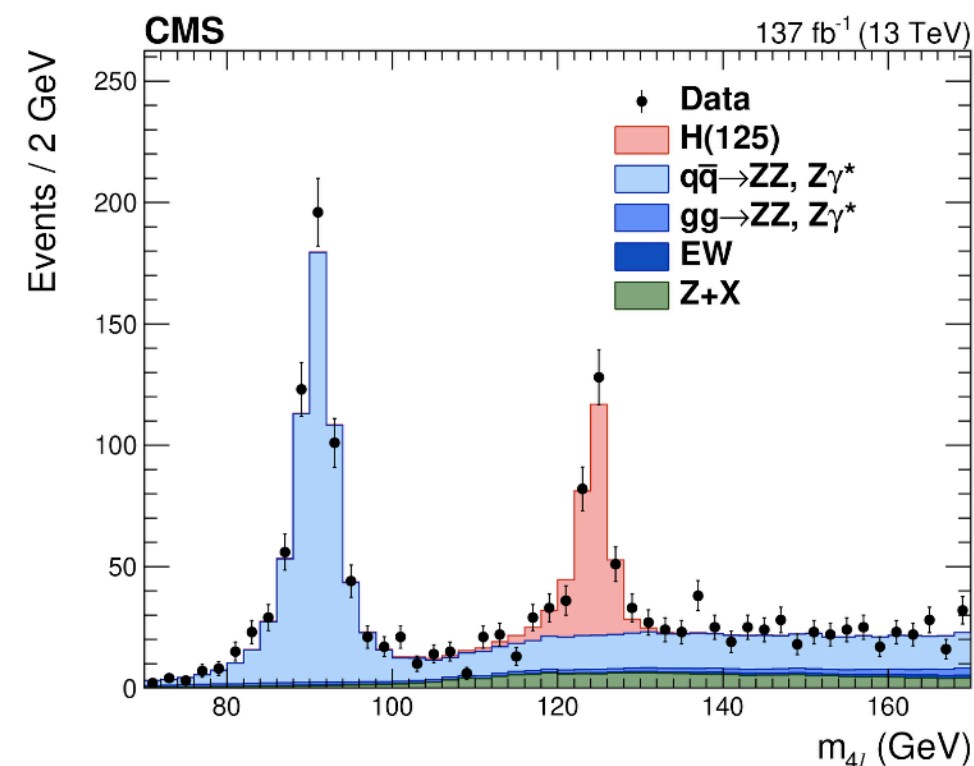
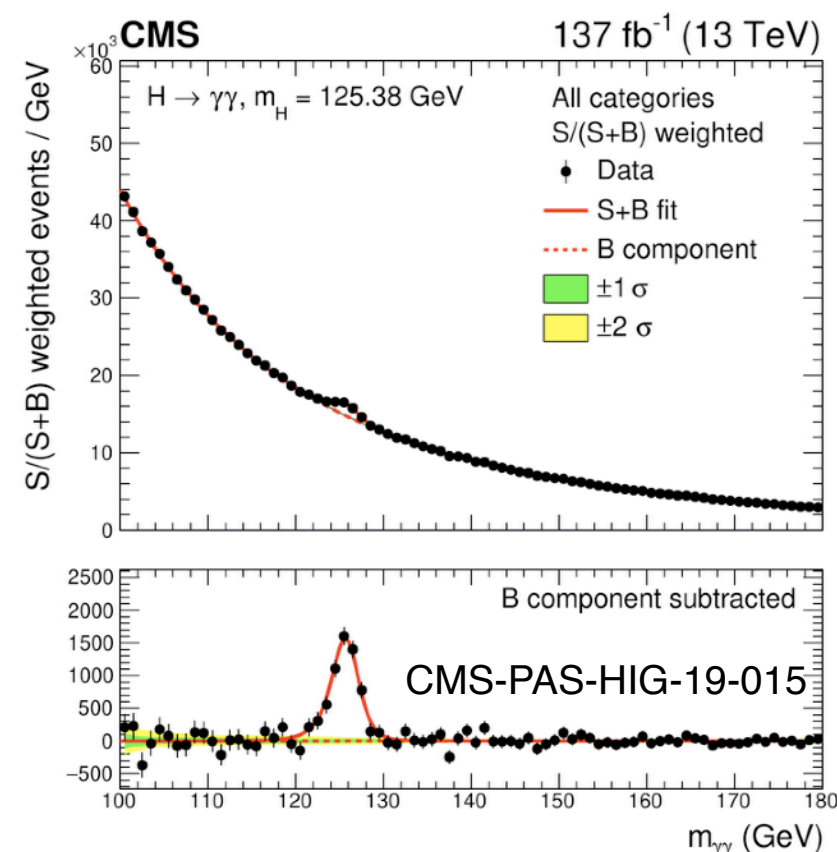
Despite the challenges:

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ \rightarrow 4l$



Mass resolution in best category $\sim 1\%$



... 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



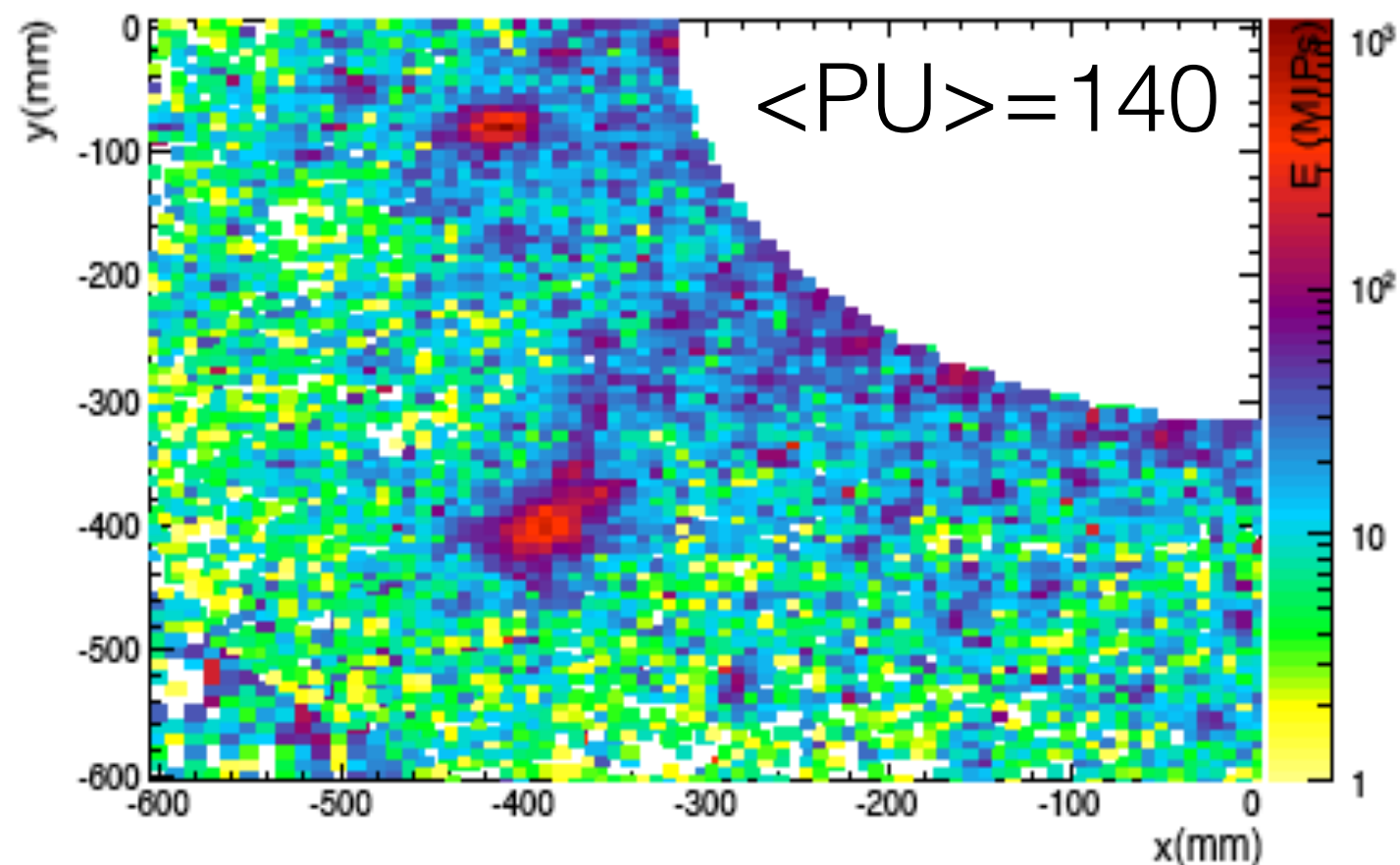
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Upgrades



Challenges for forward calorimetry at HL-LHC

- **Expect LHC to deliver very high luminosity beams:**
 $\langle \text{pileup} \rangle \sim 140\text{-}200$ 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**

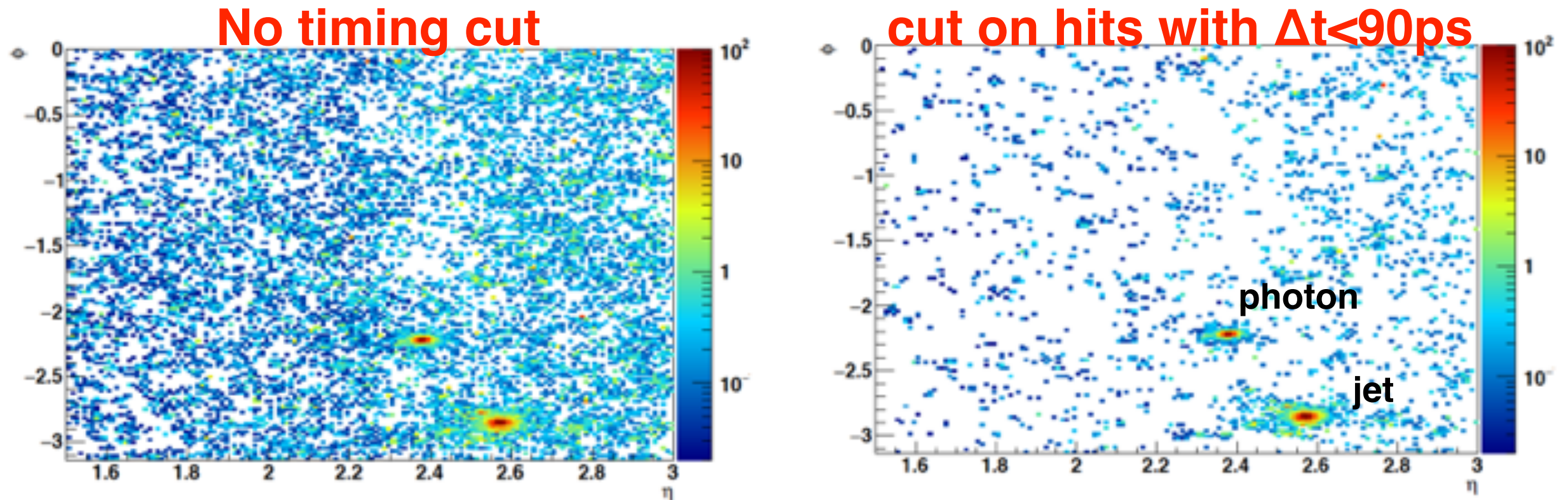


Event display of VBF jets (H->gg)

Impact of precise timing

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

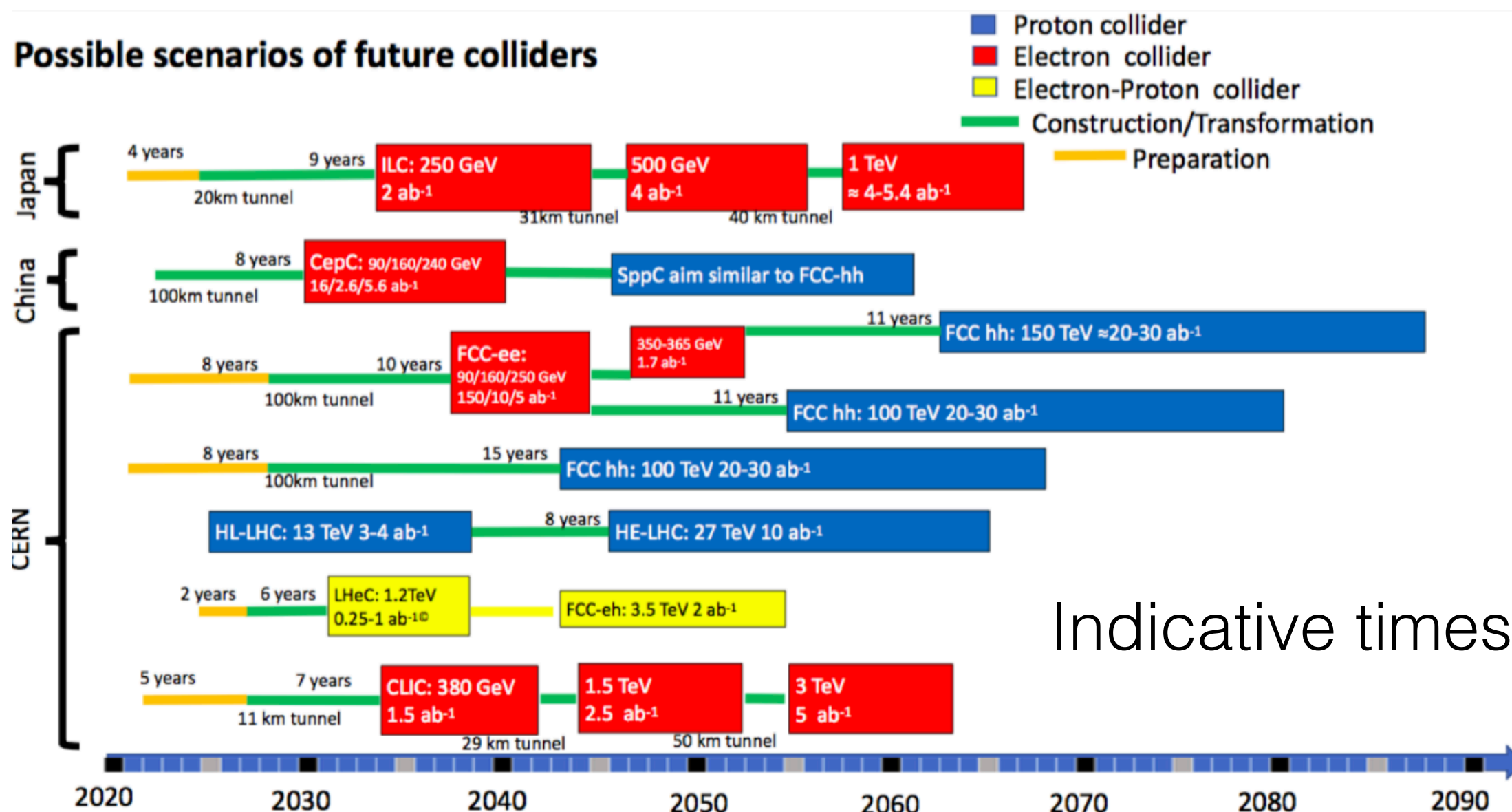
VBF $H \rightarrow \gamma\gamma$ with forward jet



- **Improved vertex localisation and pileup suppression possible with precise timing capability ($\sigma_t \sim 30\text{ps}$)**
 - 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



Calorimeters will be a key element of future collider experiments

Detector requirements from future experiments

From the Detector R&D requirements [ECFA February session](#)

'No-collider' experiments

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

Strong interaction experiments

- Measure low energy photons (down to 10 MeV)
- Photon pointing resolution
- Target energy resolution $\sim 2\% \sqrt{E}$

Hadron colliders

- Pileup mitigation through precision timing and granularity
- Radiation tolerance (up 30 MGy for FCC-hh $\rightarrow \sim 30\times$ HL-LHC)
- Target energy resolution $\sim 10\% \sqrt{E}$

$\mu^+\mu^-$ colliders

- Mitigation of beam induced background (BIB) through precision timing and granularity
- Target energy resolution $\sim 10\% \sqrt{E}$

e^+e^- colliders

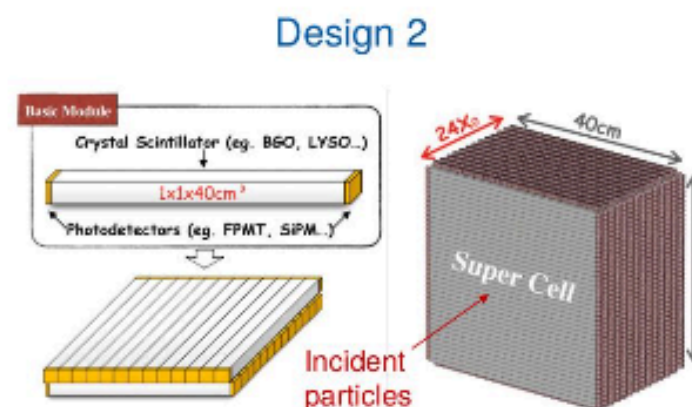
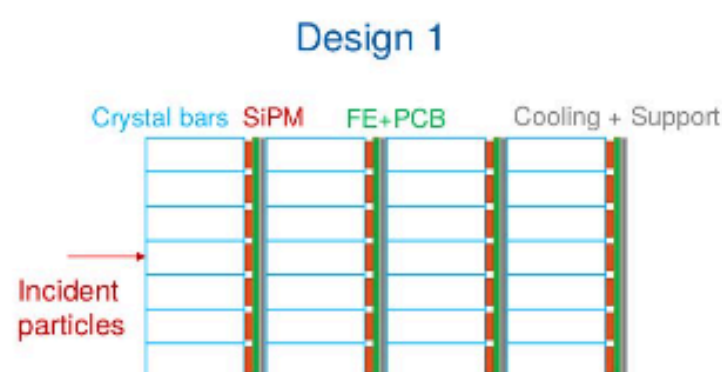
- Improve $Z \rightarrow ee$ recoil mass resolution
- Clustering of π^0 photons
- Heavy flavor program (low energy photons)
- Target energy resolution $\sim 3\% \sqrt{E}$

high granularity, excellent energy resolution, precise timing in focus

Example designs - electron colliders

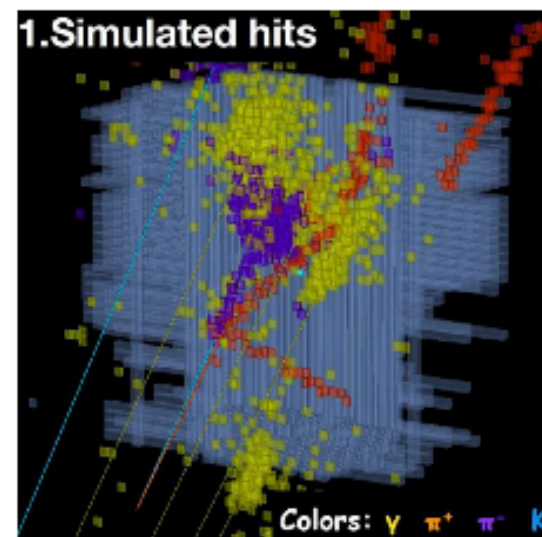
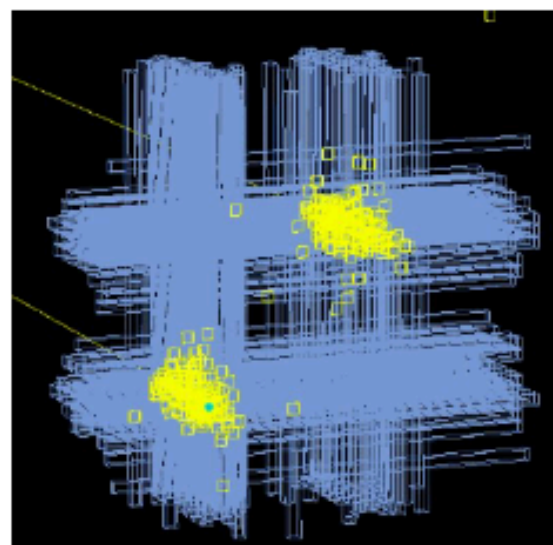
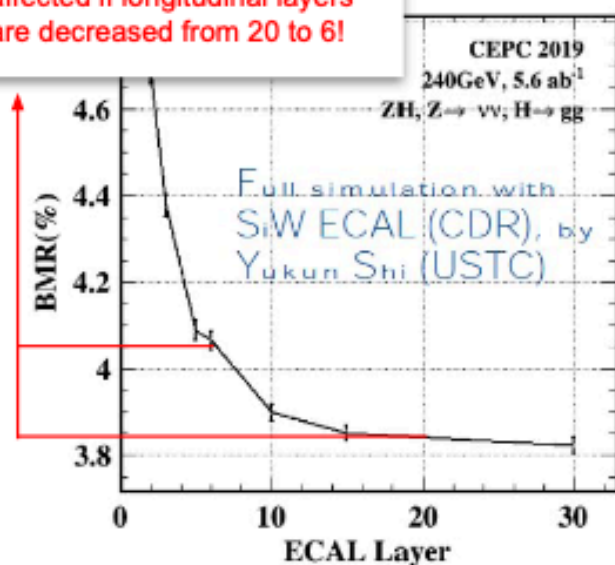
High granularity crystal calorimeter for CEPC

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



Evaluating optimal crystal
configuration for granular
3D imaging

PFA performance not too
affected if longitudinal layers
are decreased from 20 to 6!



Developing precision
particle flow optimized
for crystal calorimetry

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

23

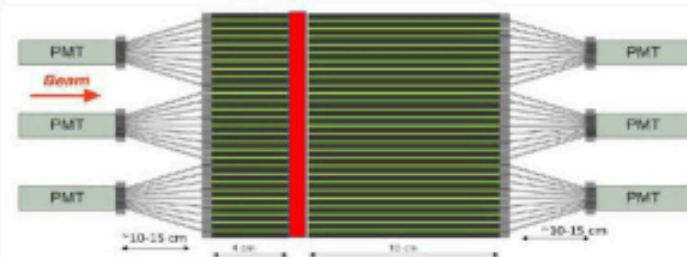
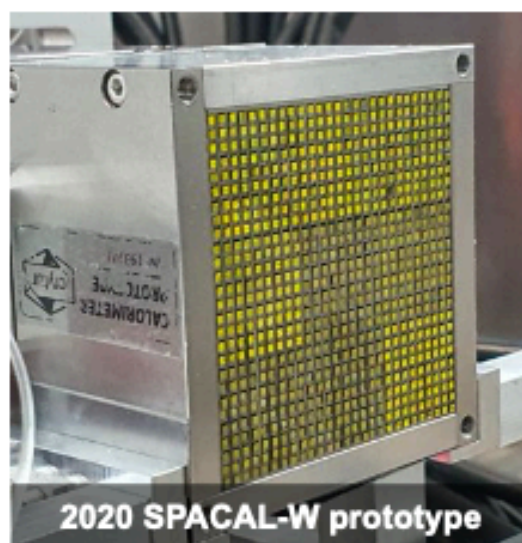
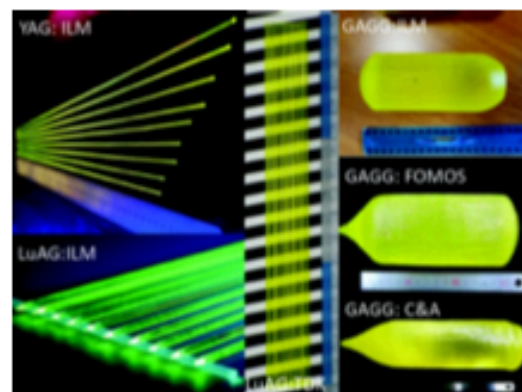
Focus on energy resolution and segmentation for
Particle Flow Reconstruction

Example designs - hadron colliders

Radiation tolerant sampling crystal calorimeters

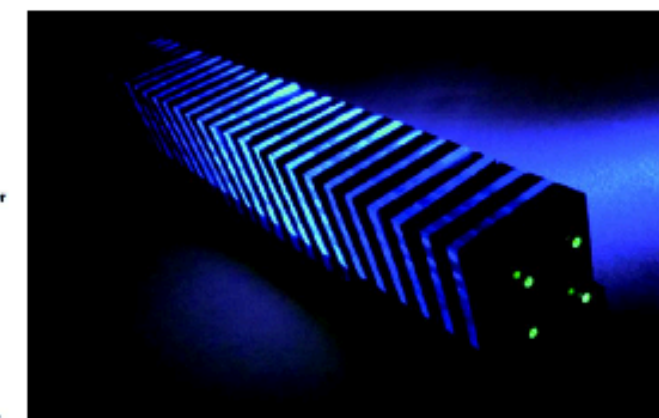
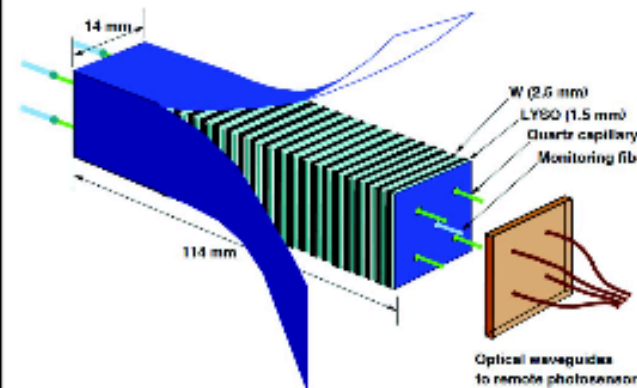
Spaghetti calorimeter (candidate for the LHCb phase II upgrade)

- 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: $\sigma_E/E \sim 10\%/\sqrt{E}$, $\sigma_t \sim O(10)\text{ps}$



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, CeF₃)
- SiO₂:Ce or LuAG:Ce fibers as WLS
- Targets: $10\%/\sqrt{E}$, $\sigma_t \sim O(10)\text{ps}$
- 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 kickoff Calorimeter Detector R&D (DRD6) workshop at CERN in 2023 for an overview:

<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 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ decays.

Assume that we calibrate their respective ECAL detectors using electrons from $Z \rightarrow ee$ (invariant mass) and $W \rightarrow ev$ (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 $H \rightarrow \gamma\gamma$ 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 $Z' \rightarrow ee$ 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?

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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Spares



The background image shows a large, complex particle detector assembly, likely the CMS detector, with various components and structures. Two people are visible in the background, working on the assembly. The name 'JOHANSSON' is visible on a large panel on the left. The text 'Designing and Operating calorimeters' is overlaid in a large, bold, black font.

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

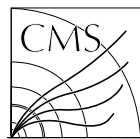
We propose to build a general purpose detector designed to run at the highest luminosity at the LHC. The CMS (Compact Muon Solenoid) detector has been optimized for the search of the SM Higgs boson over a mass range from 90 GeV to 1 TeV, but it also allows detection of a wide range of possible signatures 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

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

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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Project Manager	Deputy Project Manager	Technical Coordinator	Resource Manager
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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://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=2713)

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

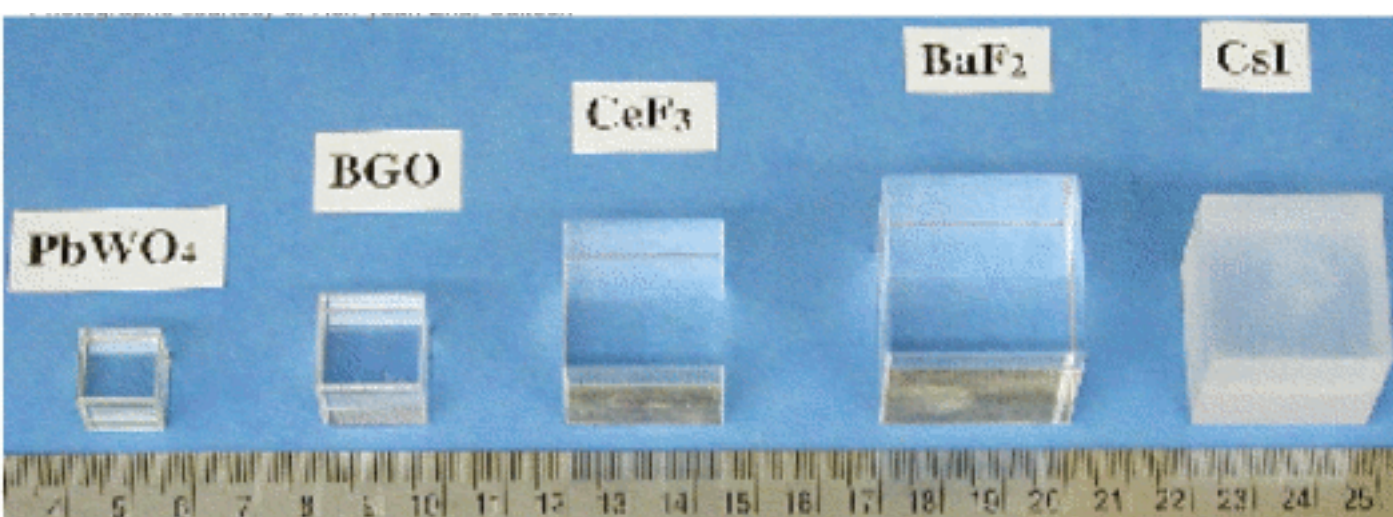
Lead tungstate crystals

Property	Sampling	Homogeneous scintillators		
	Pb/plastic Shashlik	Liquid Xenon	CeF ₃ crystals	PbWO₄ 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

PbWO₄ is used for CMS:
fast, dense and radiation-hard

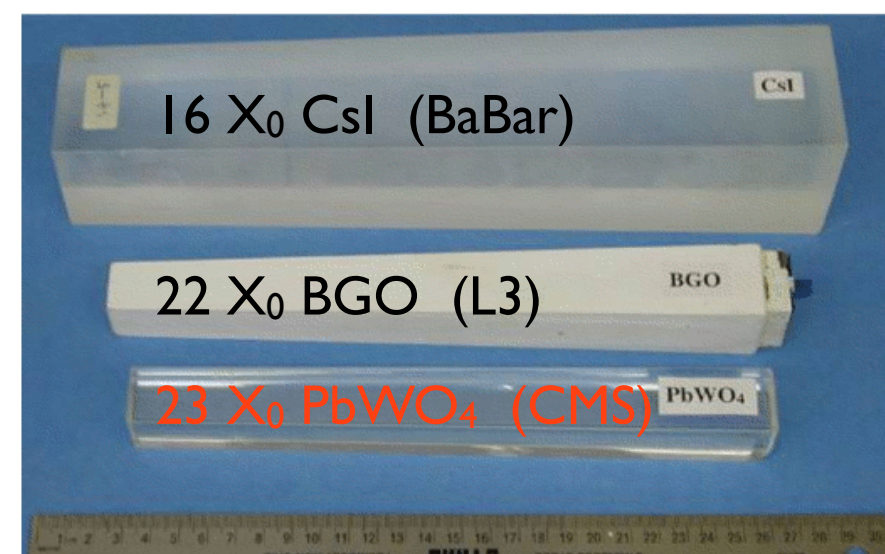
Low relative light-yield mitigated by use of
high-QE/large area photodetectors with
internal gain

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



1.5 X₀ cubes of different xtal materials

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



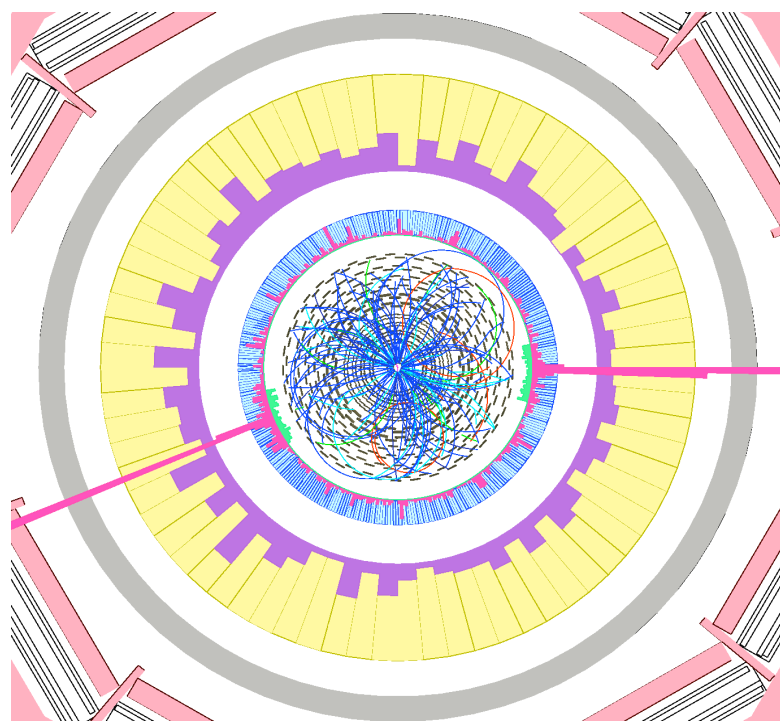
ECAL performance targets

- The CMS ECAL must be **fast** and **radiation tolerant** to survive in the LHC environment, and must possess **excellent energy resolution**

- Benchmark physics process: **$H \rightarrow \gamma\gamma$**

- Energy resolution target:

- **0.5% for unconverted photons**



A $H \rightarrow \gamma\gamma$ event in CMS with $M_H=120\text{GeV}$

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

EM energy resolution

a: Stochastic term: **b: Noise term:** **c: Constant term:**

lateral shower containment
photostatistics, photo-
detector gain

electronic noise
event pile-up

temperature/HV stability
accuracy of inter-
calibration constants
non-uniformity of
longitudinal light
collection

dominates at high energy

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

a=2.8%
stochastic term

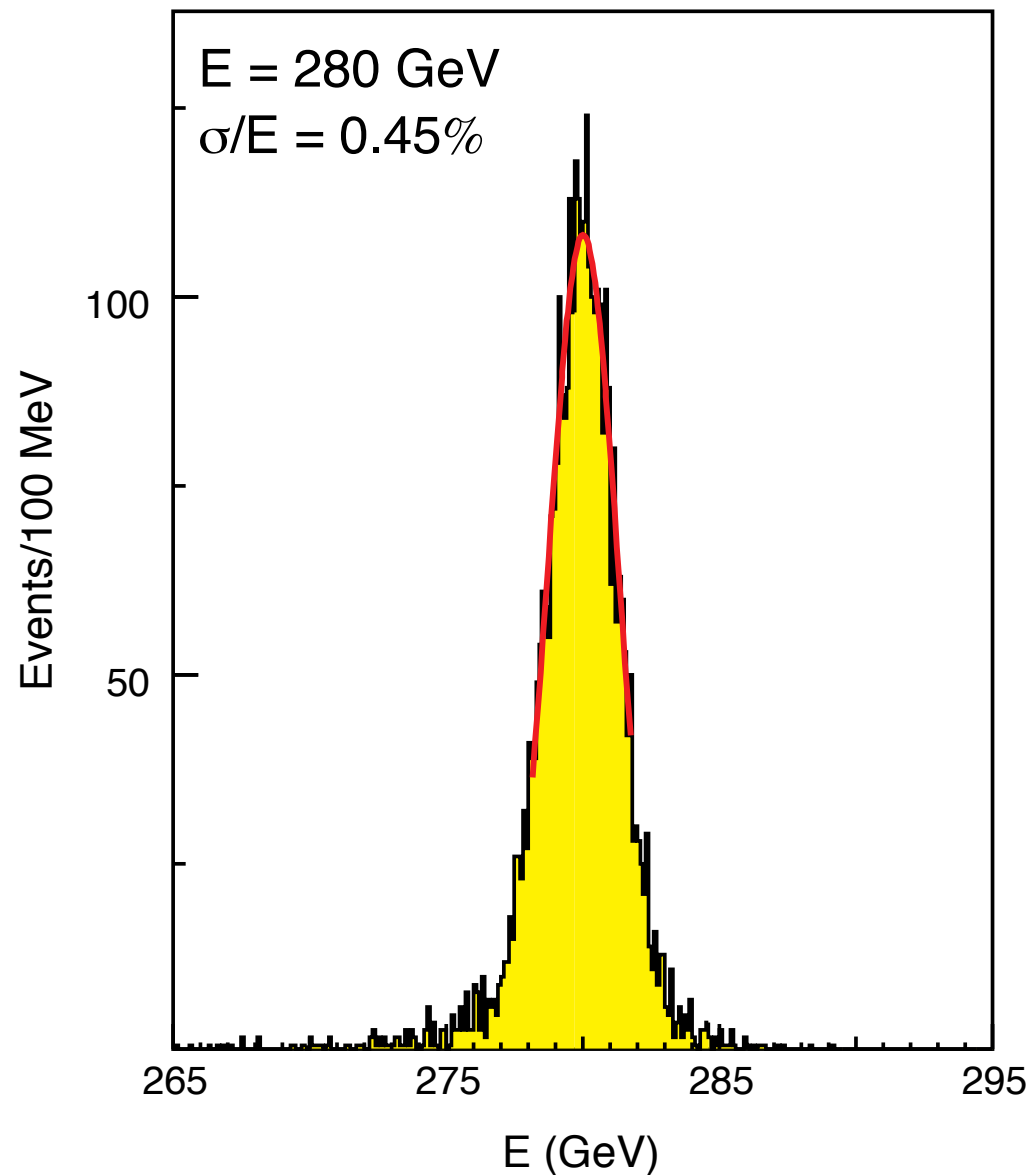
b=41.5 MeV
noise term

c=0.3%
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



ECAL+HCAL

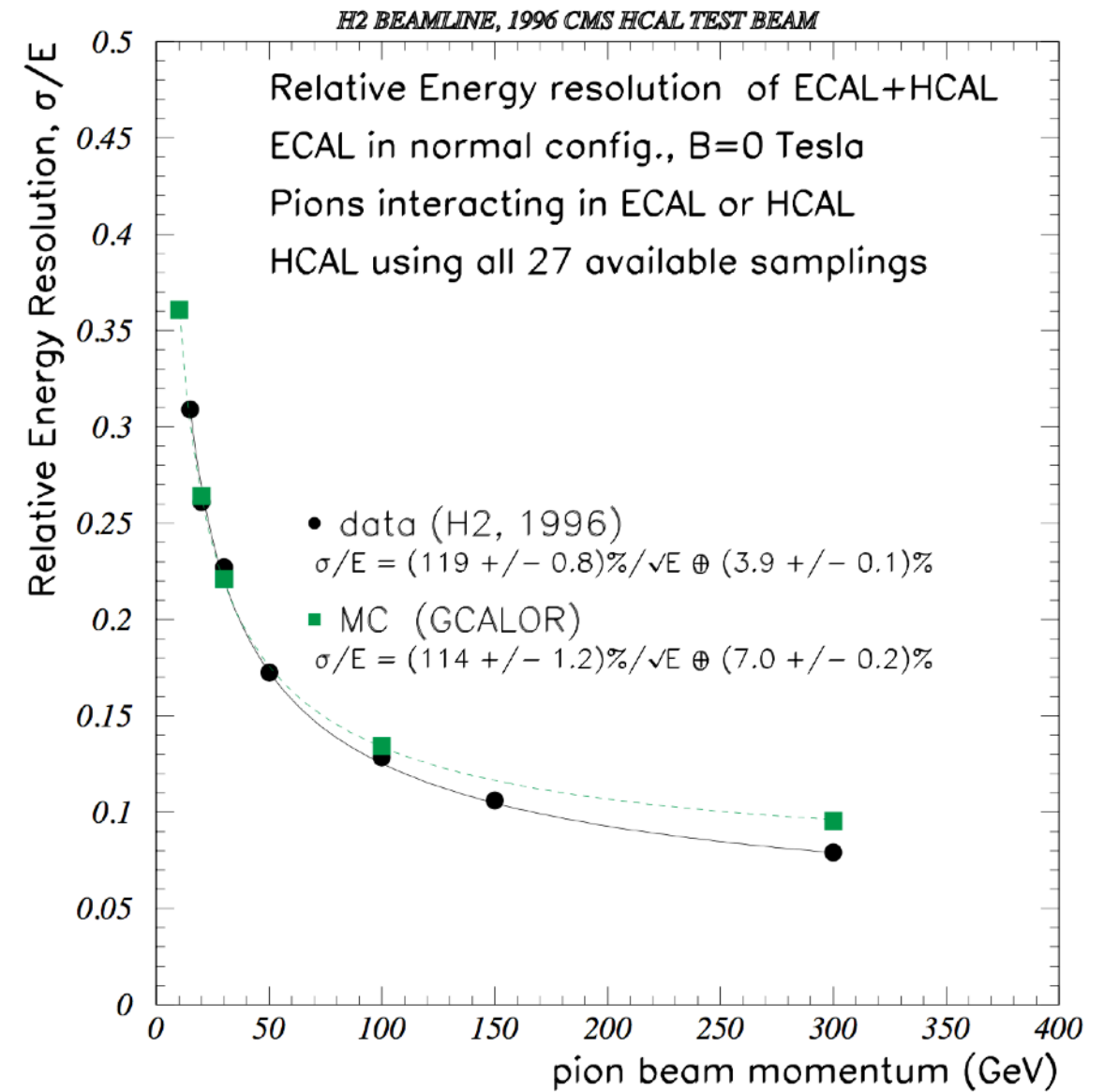
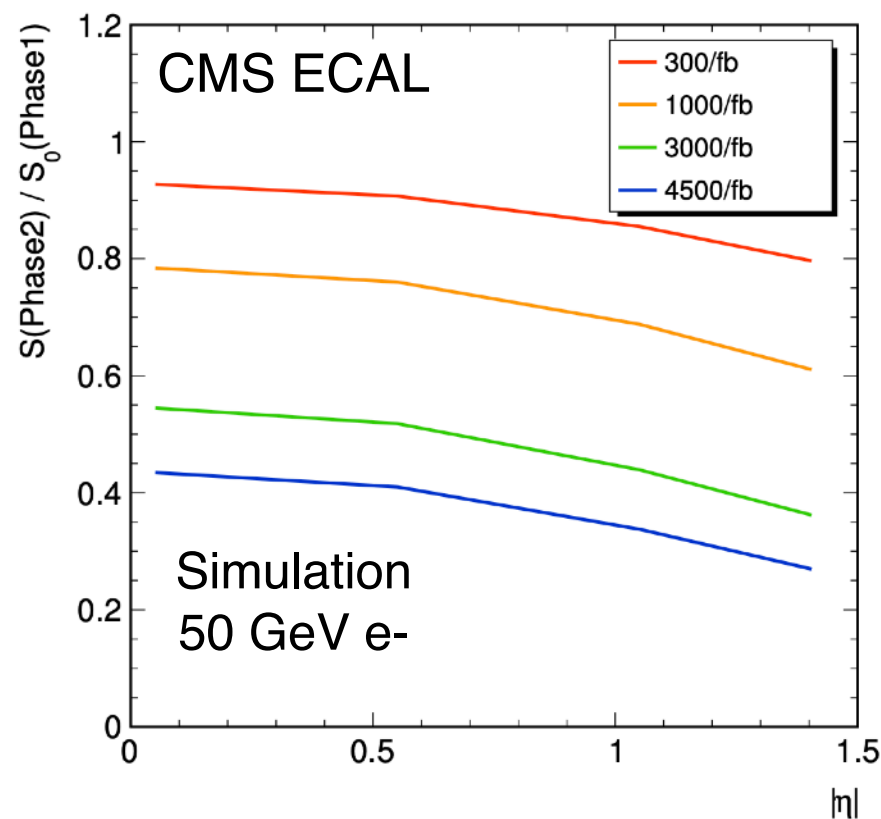


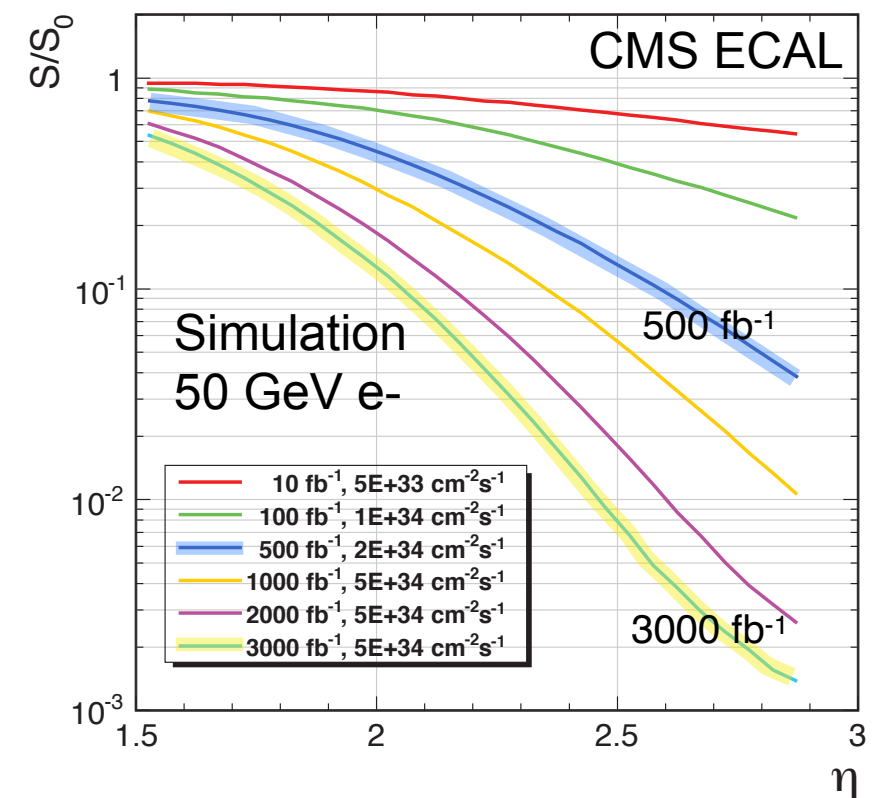
Fig. 1.15: Energy reconstructed in 3×3 crystals with 280 GeV electrons.

Detector longevity

- ECAL and HCAL barrel ($|\eta| < 1.48$) will retain significant light output and will be **retained for HL-LHC operation**
- ECAL and HCAL endcaps ($|\eta| > 1.48$) 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

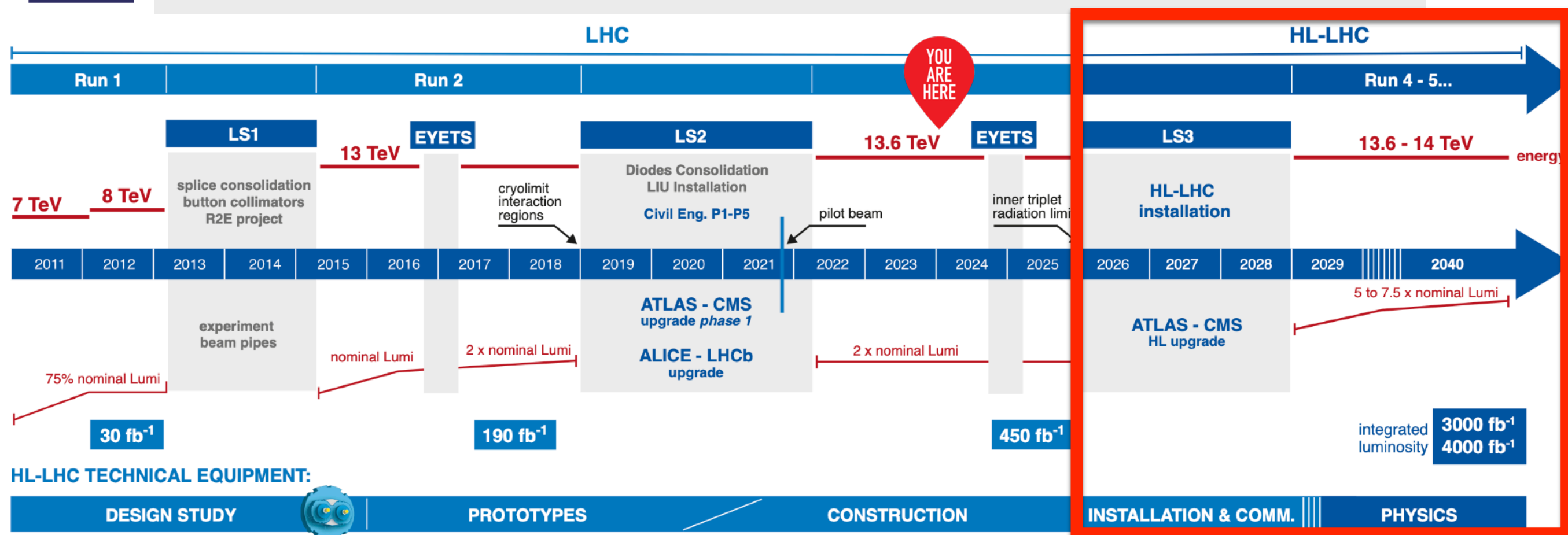


Predicted ECAL Barrel signal response versus integrated luminosity and η



Predicted ECAL Endcap signal response versus integrated luminosity and η

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

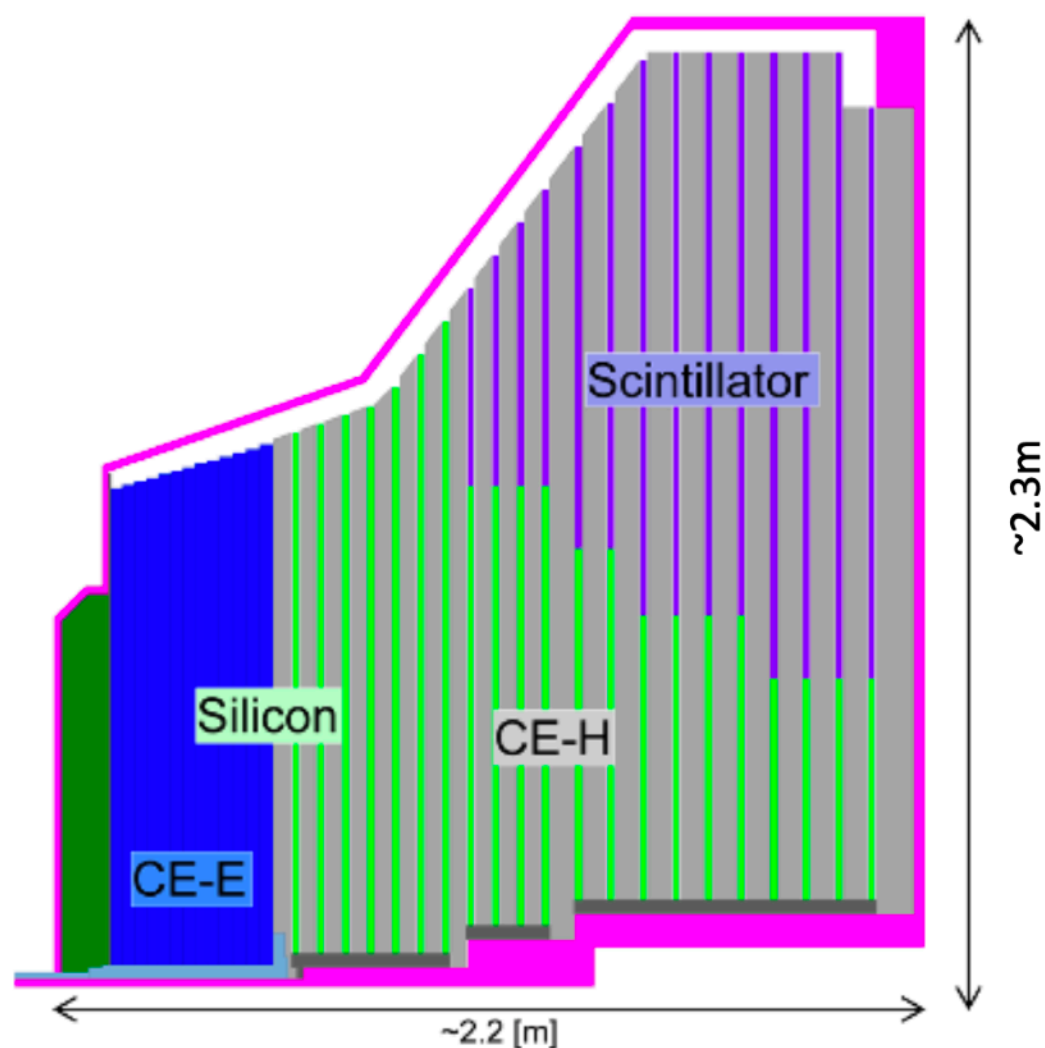
Consequences:

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

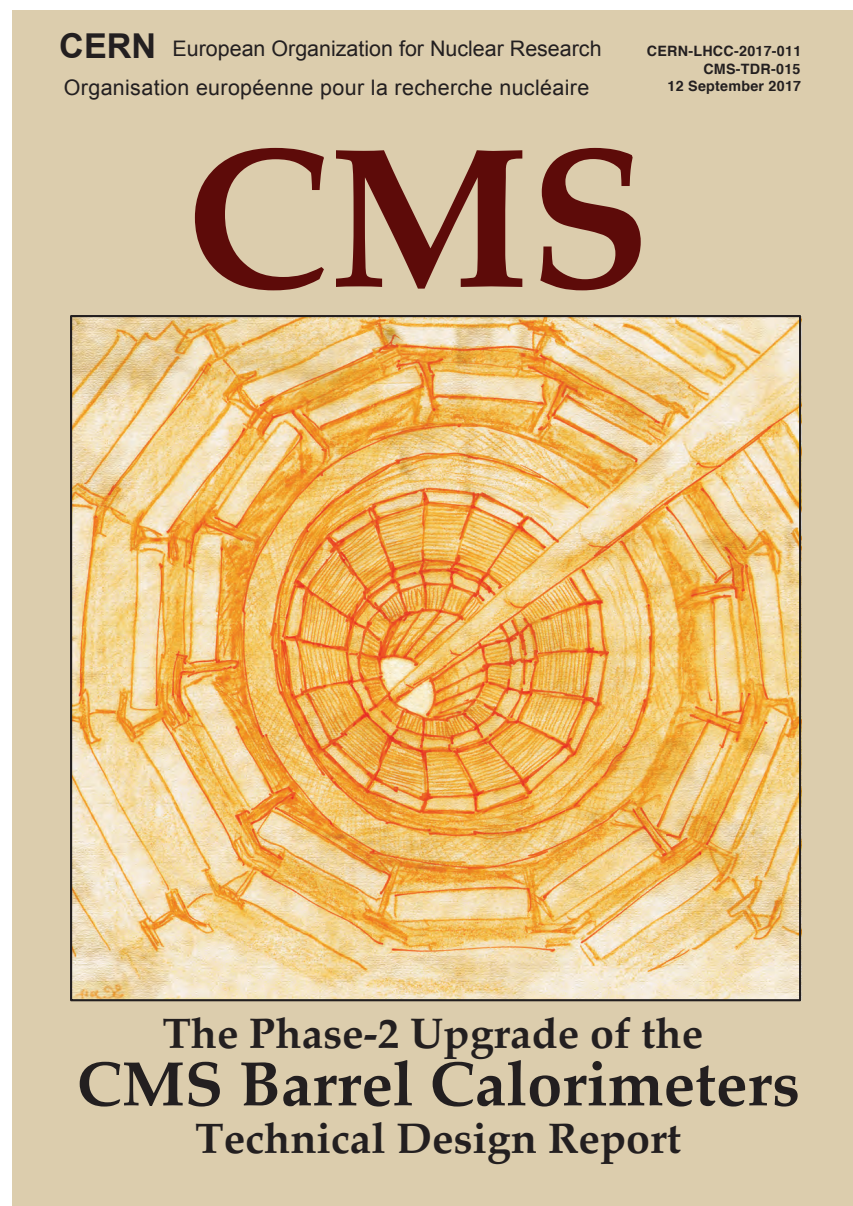
Sampling calorimeter with fine transverse granularity

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

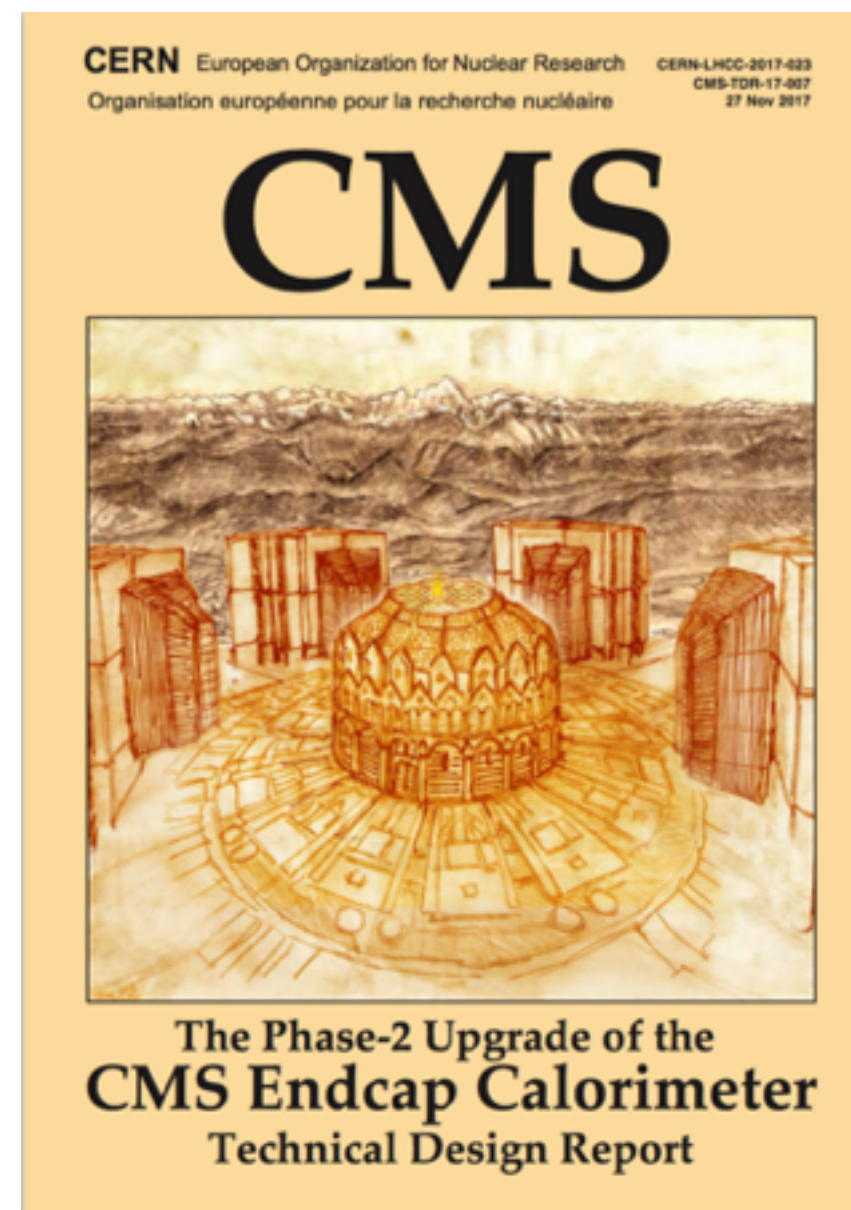
must operate at -30 degC to limit Si leakage current

Coming full circle

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



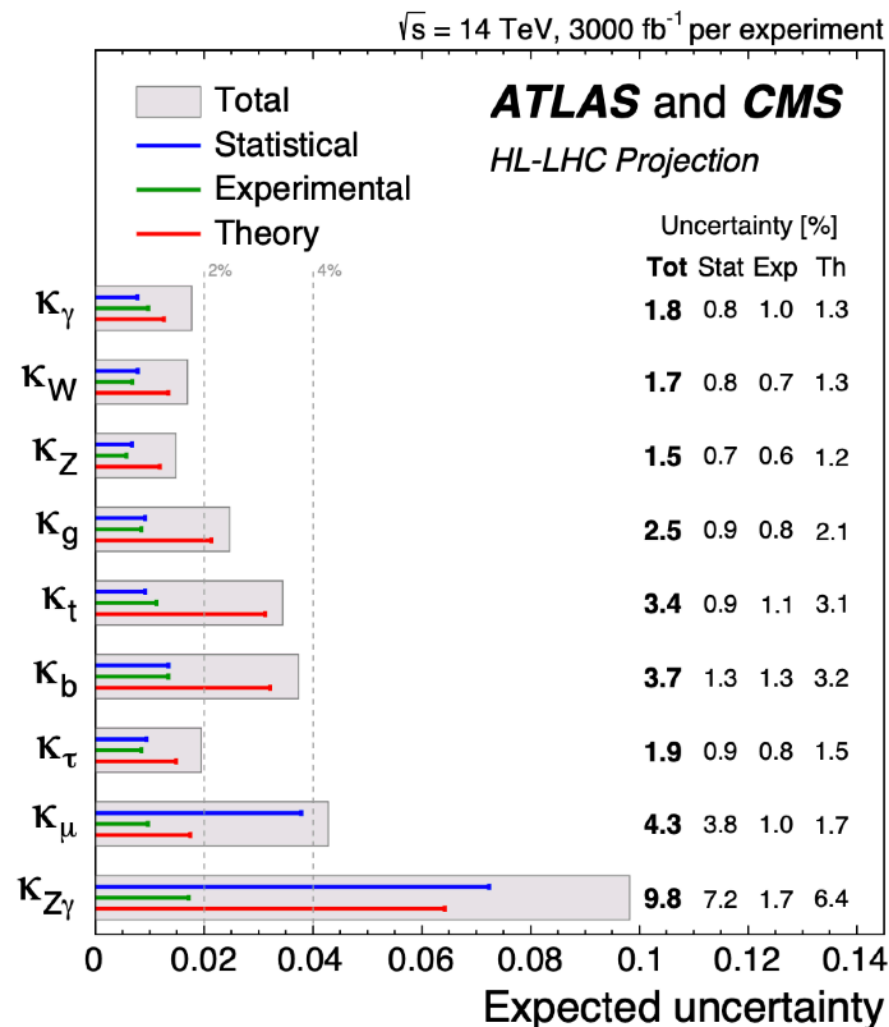
<https://cds.cern.ch/record/2283187/>



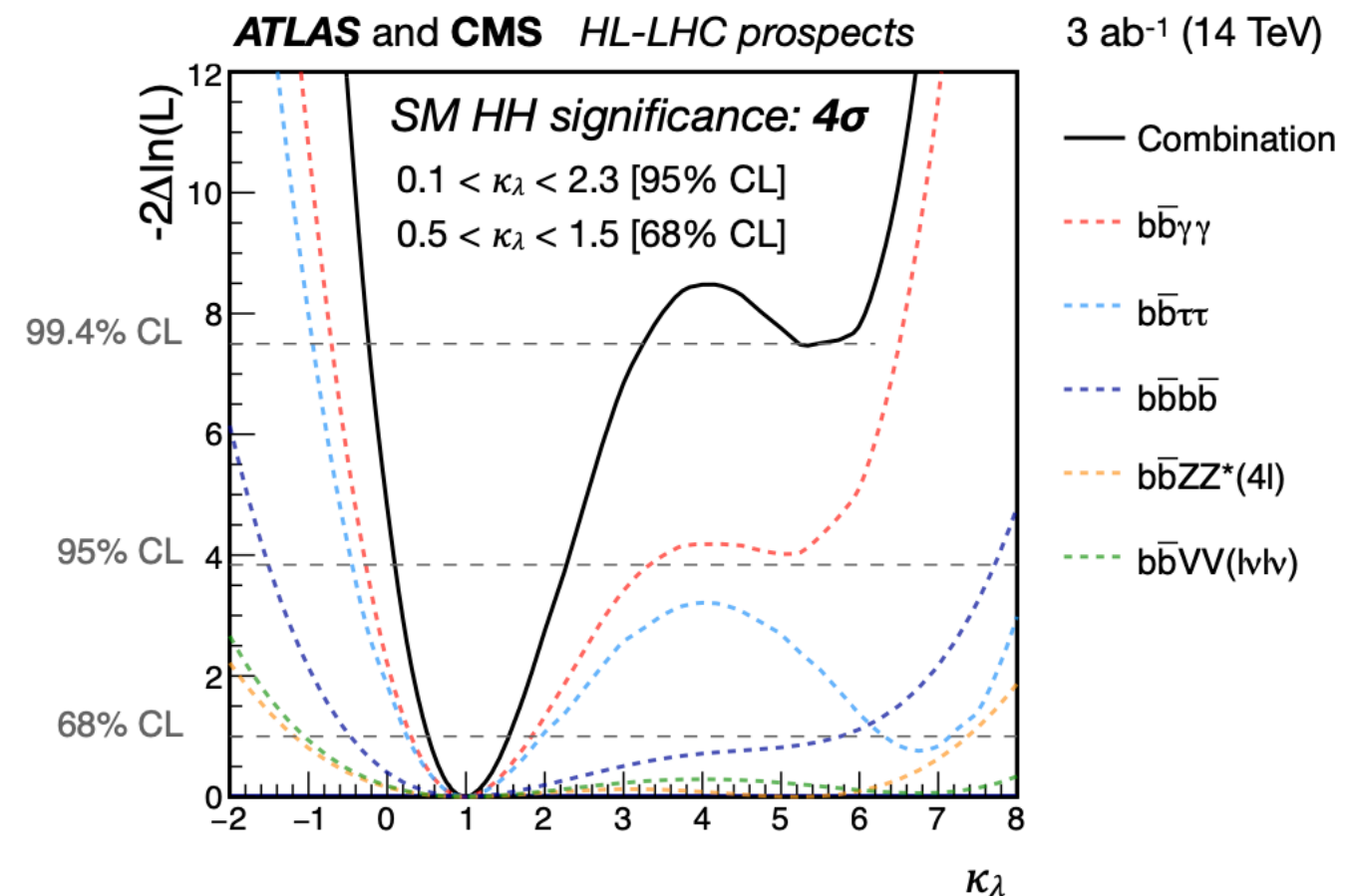
<https://cds.cern.ch/record/2293646/>

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

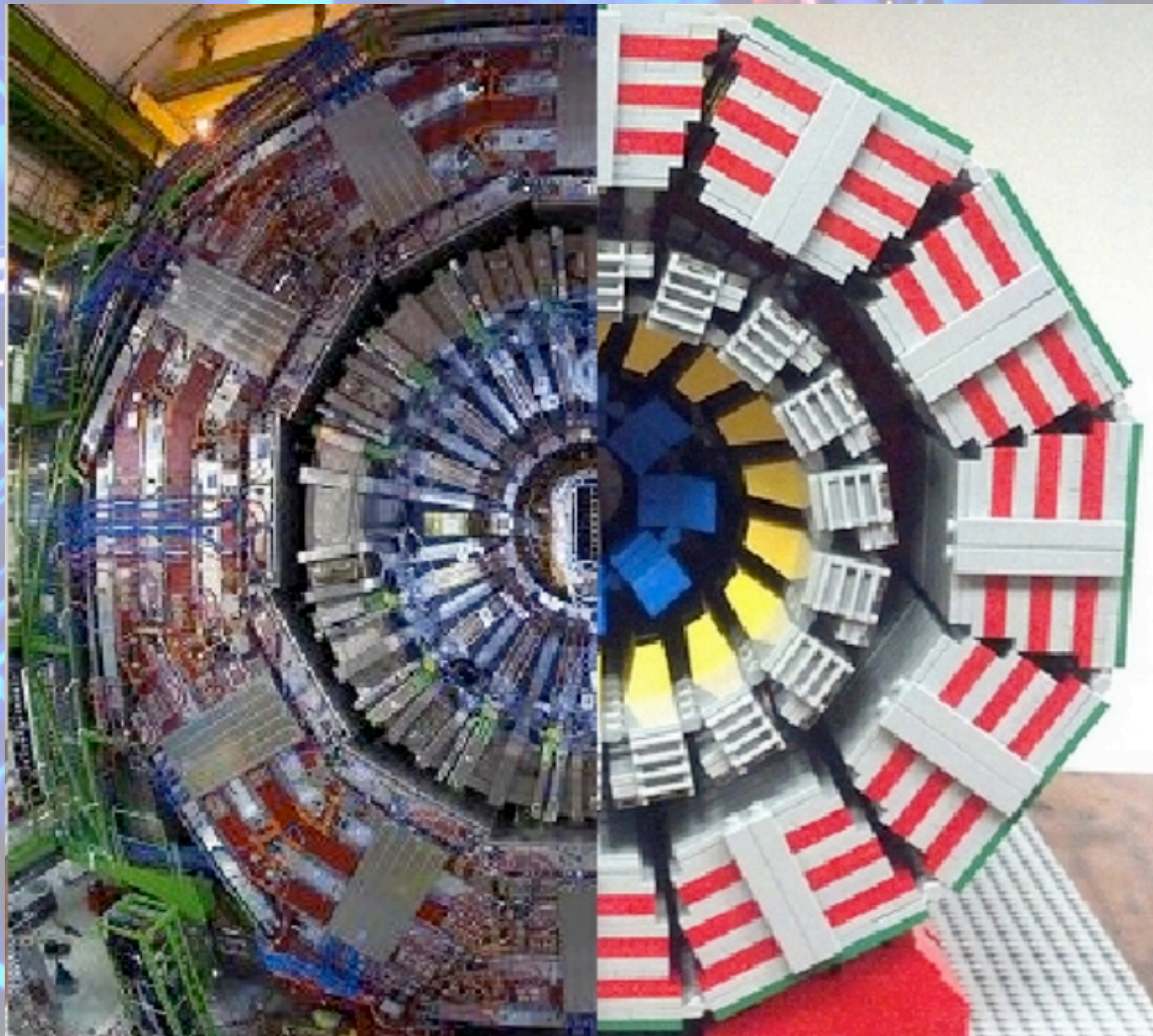


4 σ measurement of Higgs self-coupling

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

$HH \rightarrow b\bar{b}\gamma\gamma$ most sensitive channel

CMS Calorimeters as built



model credit: University of Maryland HEP group

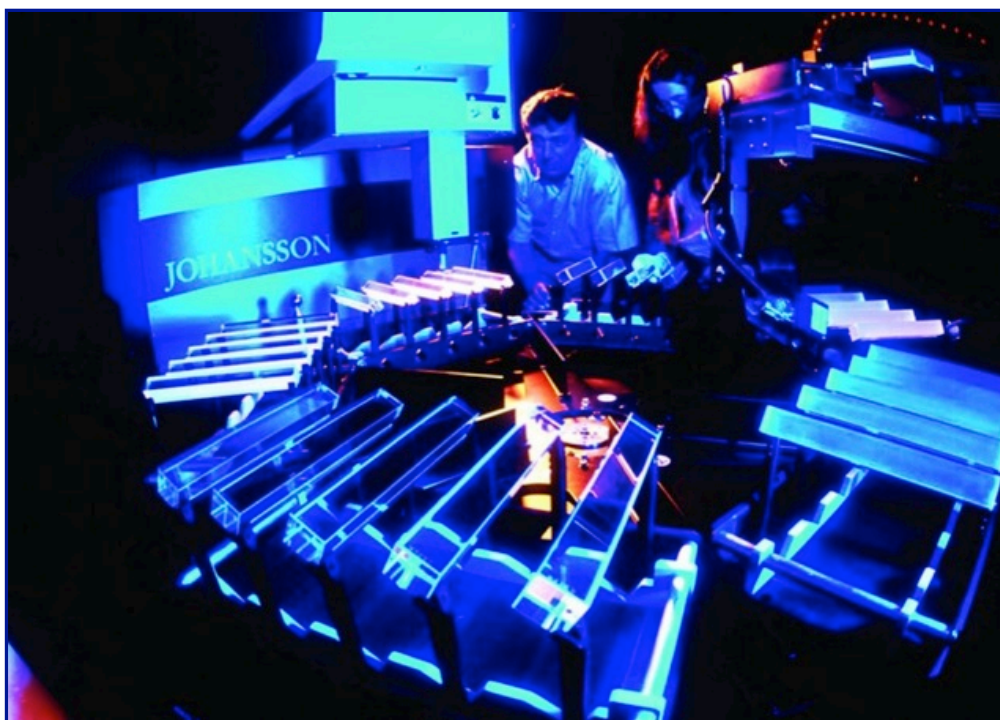
ECAL PbWO_4 crystals

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

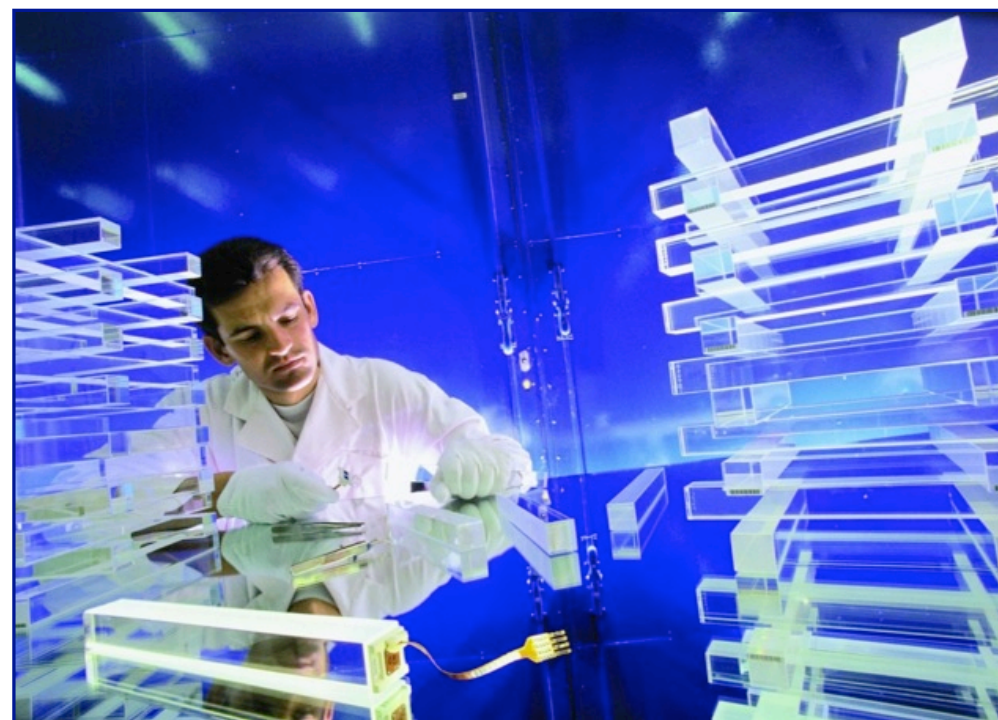
Crystal “growing”



Raw crystal “boule” and cut crystals

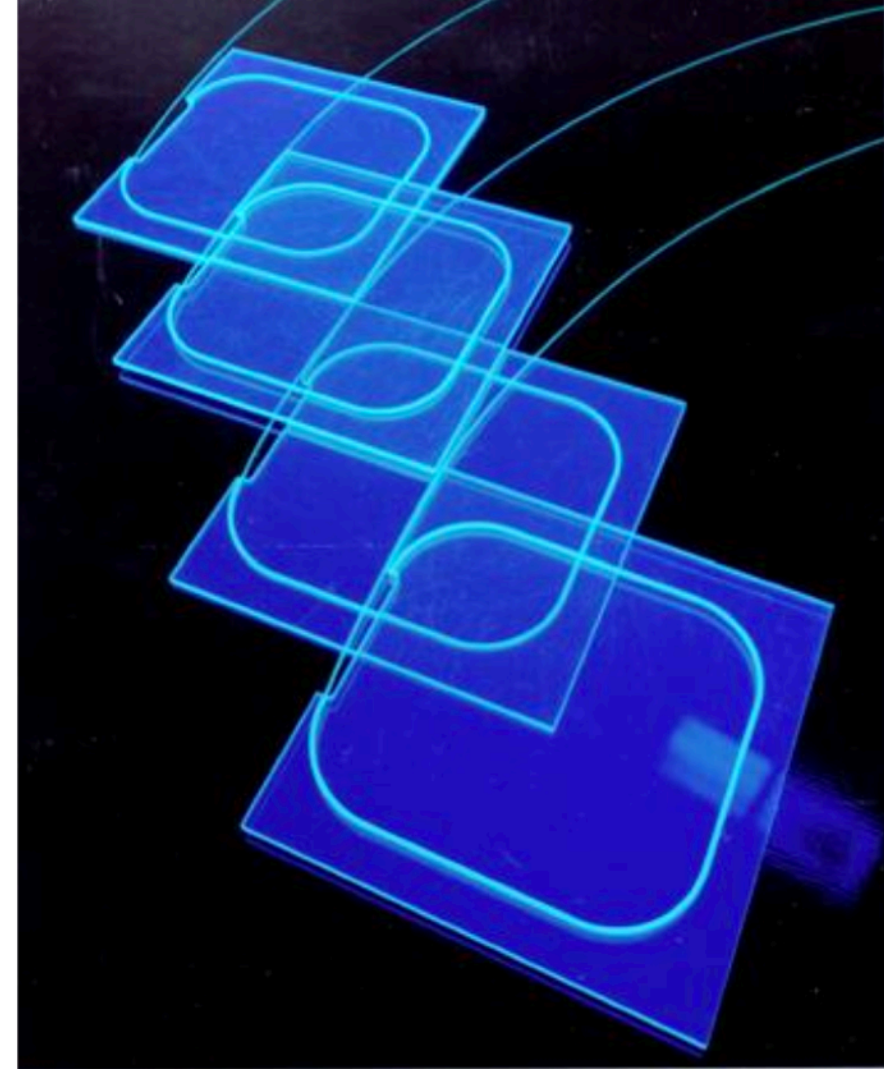
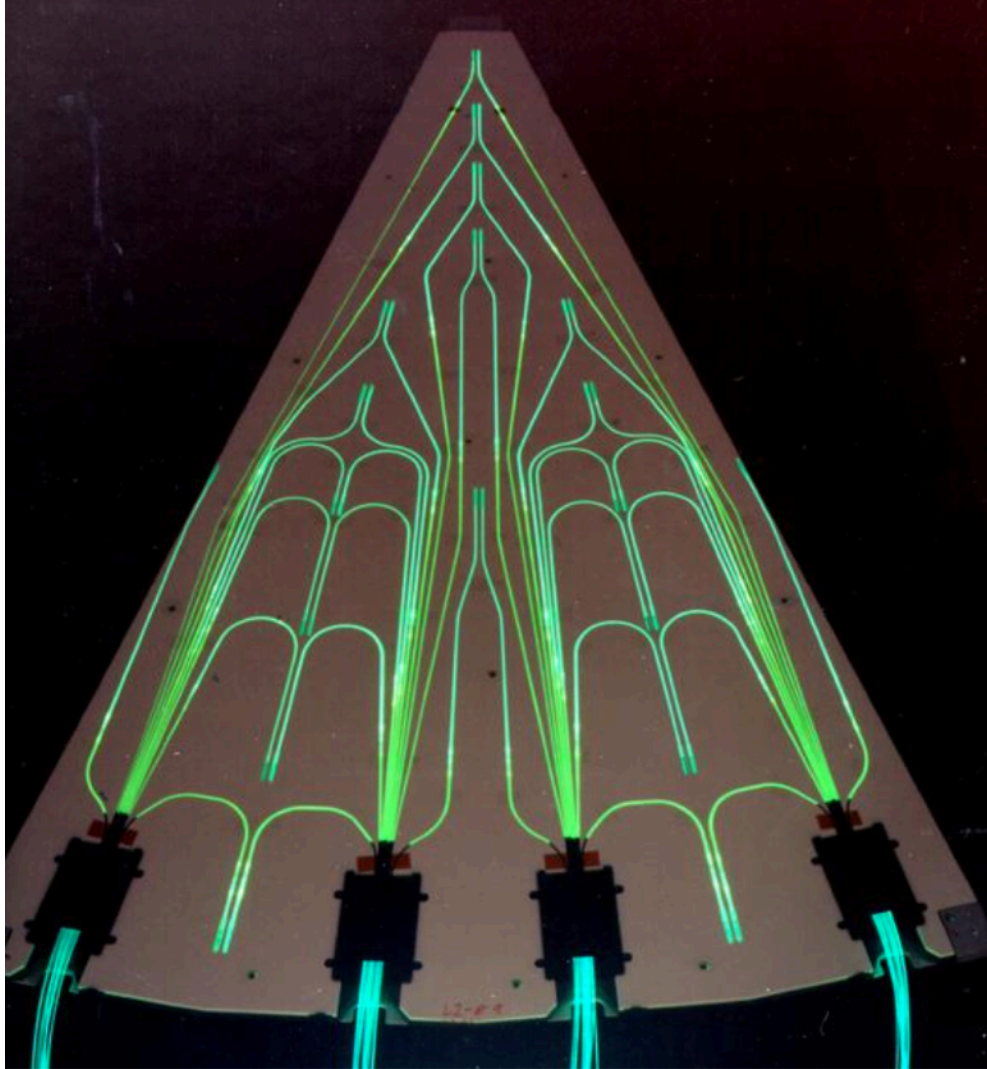


Crystal characterisation



APD gluing

HB/HE active elements



Scintillator tile, wavelength shifter and fibre-optic readout

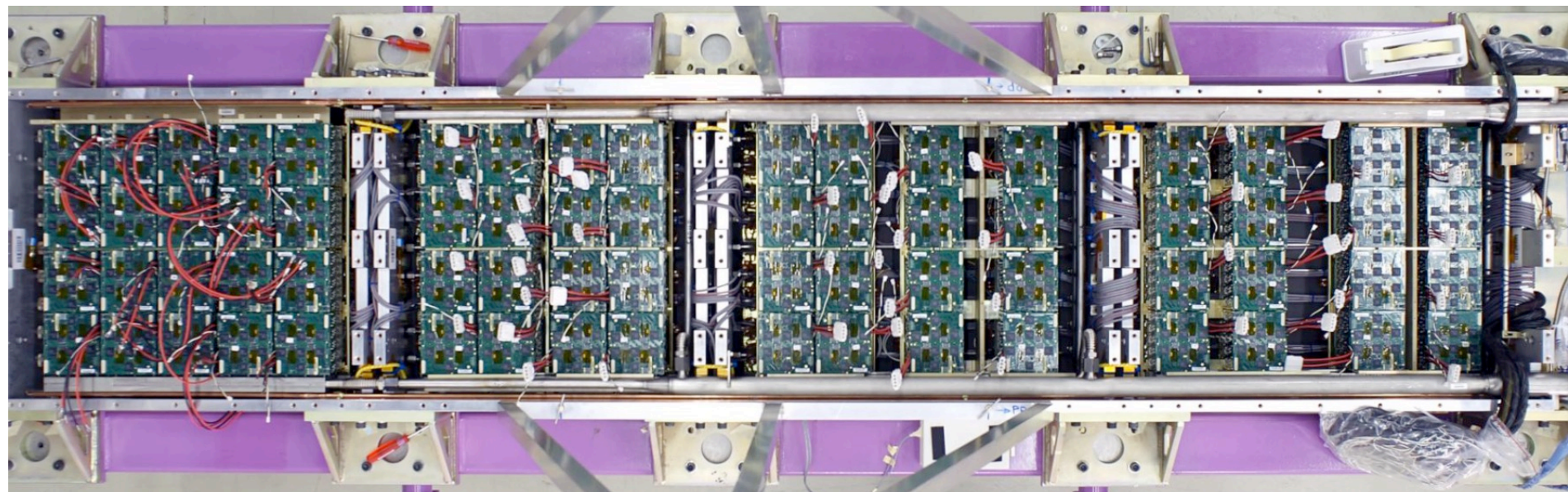
ECAL Barrel construction



Electronics installation

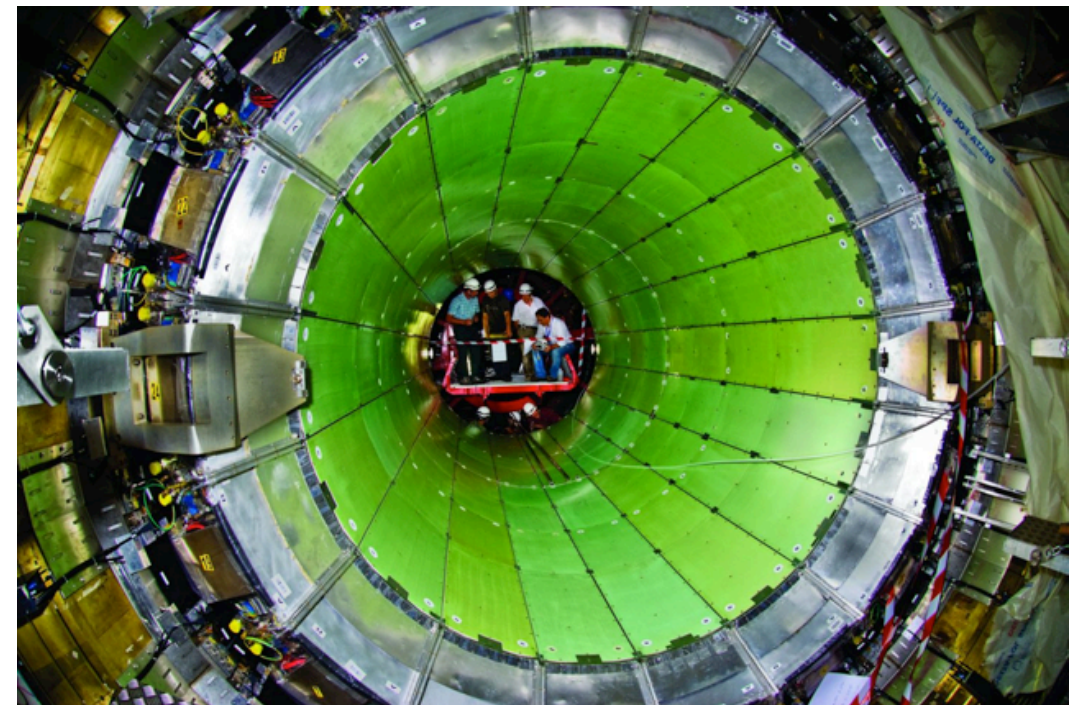
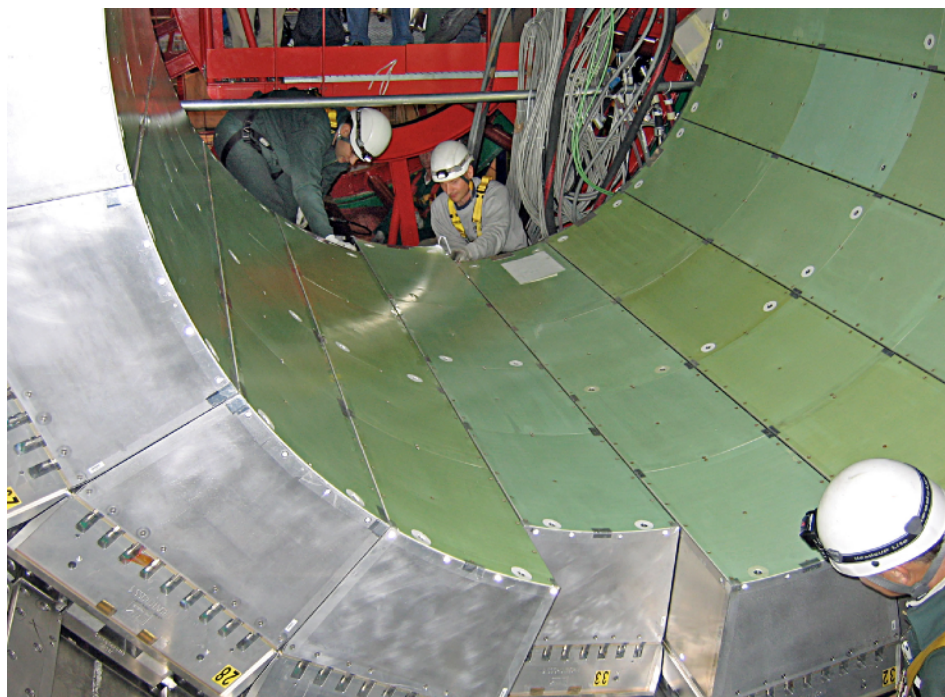
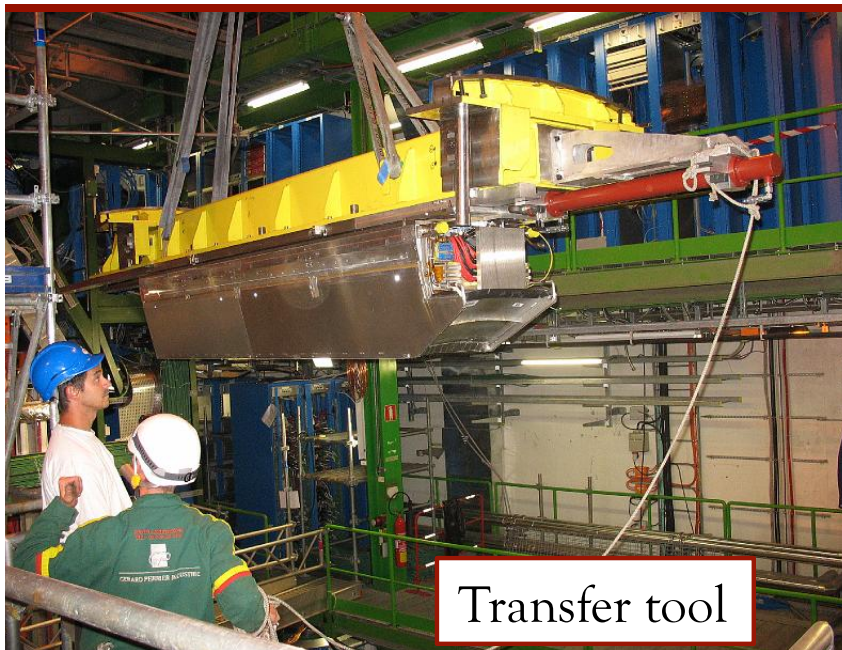


Supermodule integration/test stands @ Preveessin



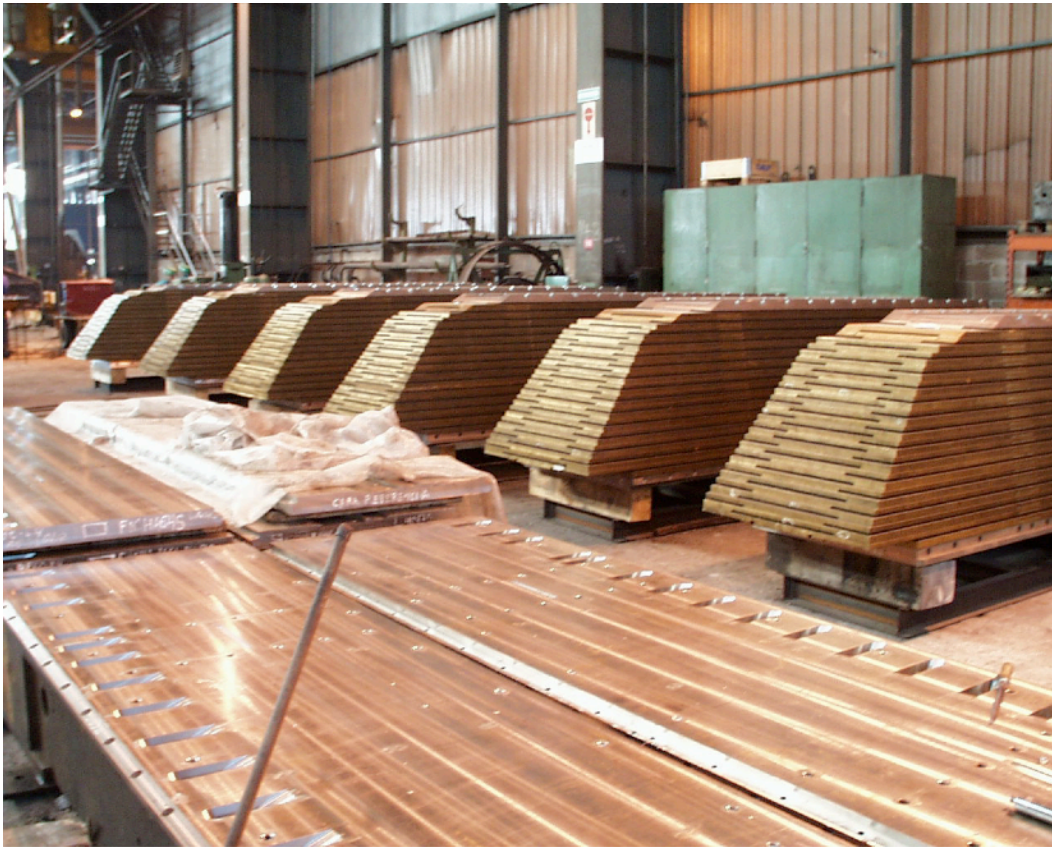
Supermodule in the process of electronics integration

ECAL Barrel installation





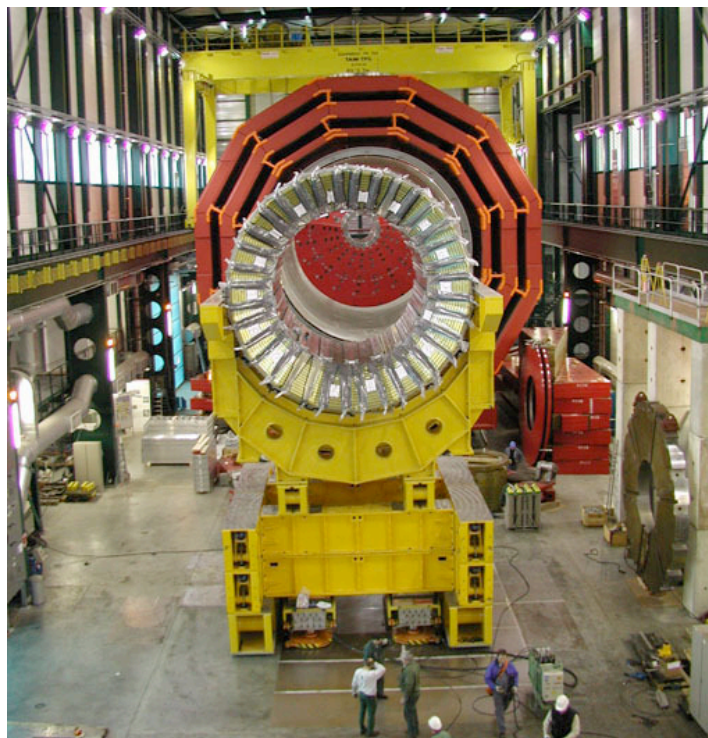
HB construction and installation



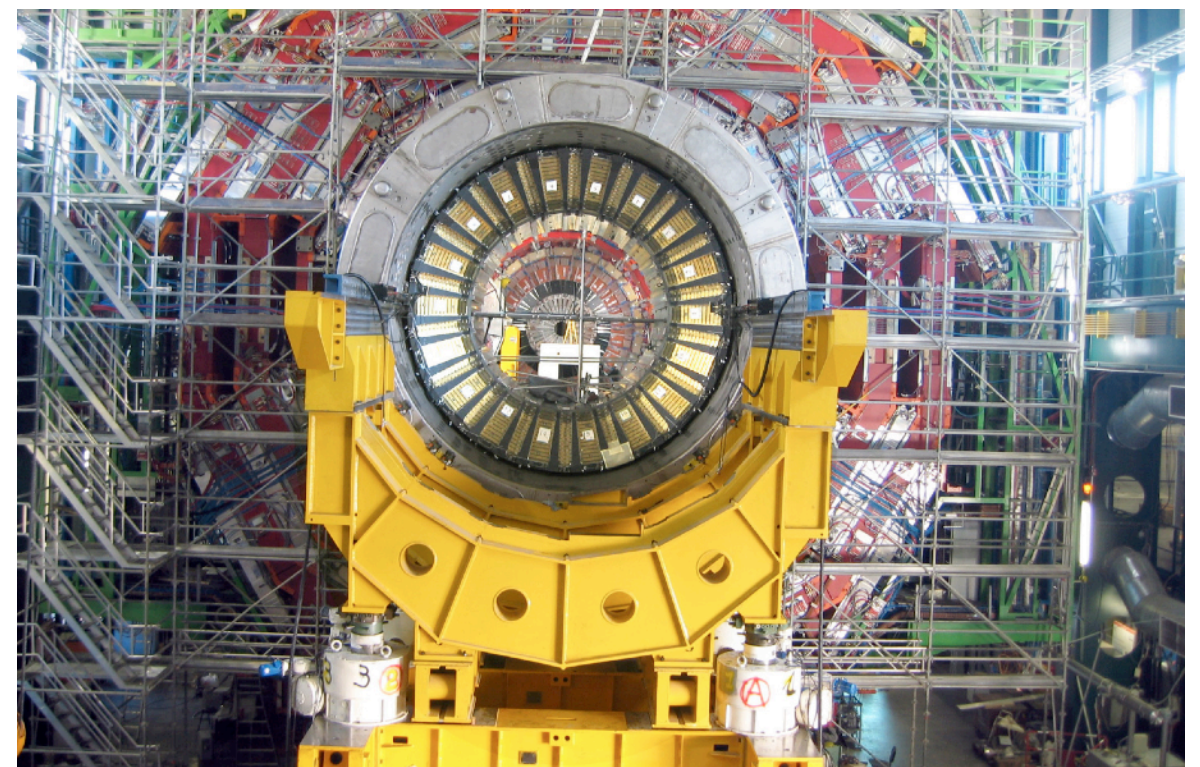
HB brass wedges



HB construction



completed HB section ready to enter yoke



HB section inside yoke

ECFA DRD6 Calorimetry

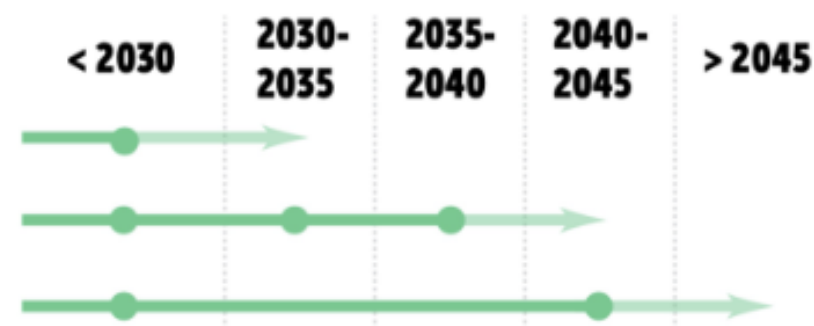
ECFA

Future Facilities and DRDT for Calorimetry



Calorimetry

- DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
- DRDT 6.2** Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
- DRDT 6.3** Develop calorimeters for extreme radiation, rate and pile-up environments



- Calorimeters are 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 Identified Key Technologies and R&D Tasks

Key technologies and requirements are identified in Roadmap

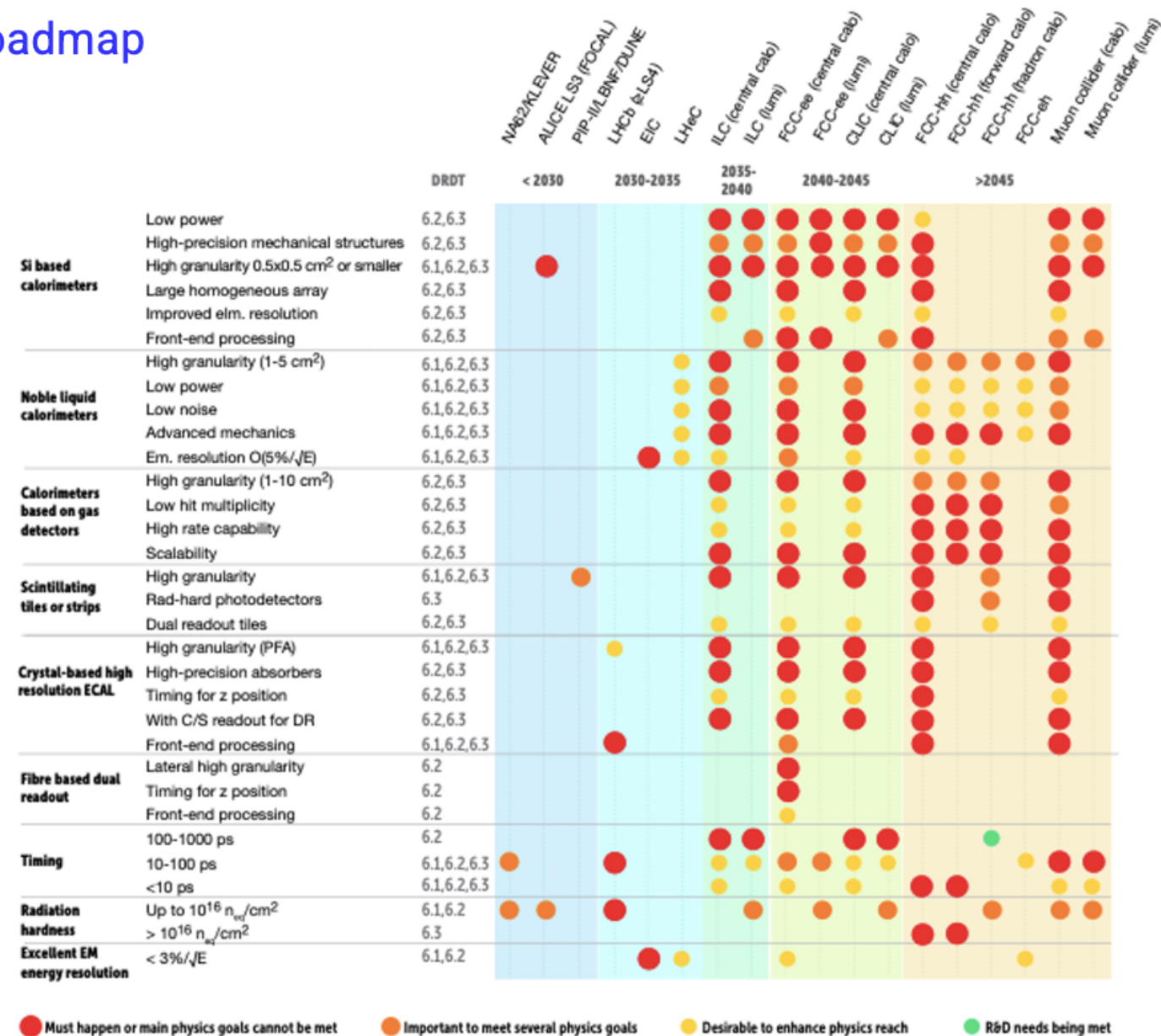
- Si based Calorimeters
- Noble Liquid Calorimeters
- Calorimeters based on gas detectors
- Scintillating tiles and strips
- Crystal based high-resolution ECALs
- Fibre based dual readout

R&D should in particular enable

- Precision timing
- Radiation hardness

R&D Tasks are grouped into

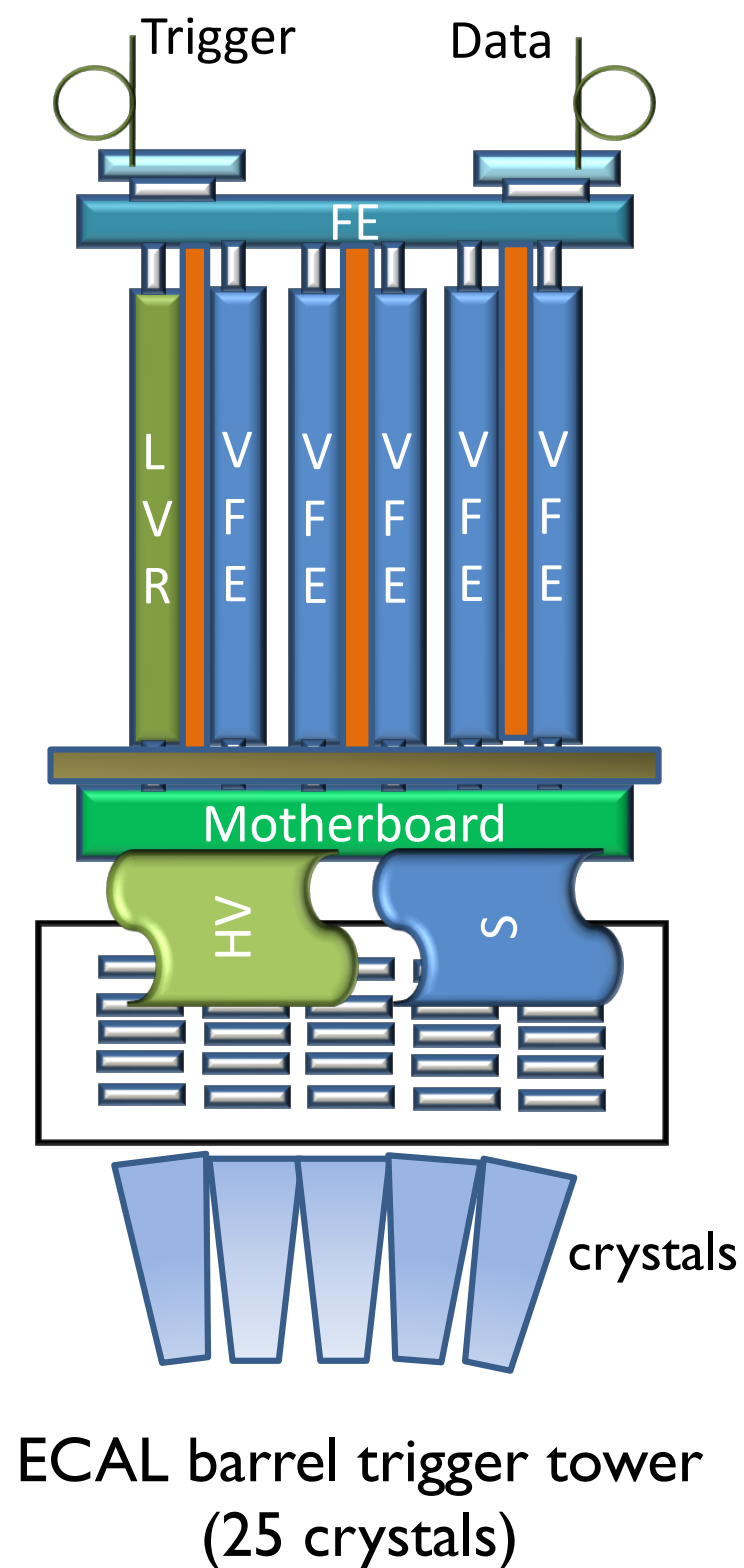
- **Must happen**
- **Important**
- **Desirable**
- **Already met**



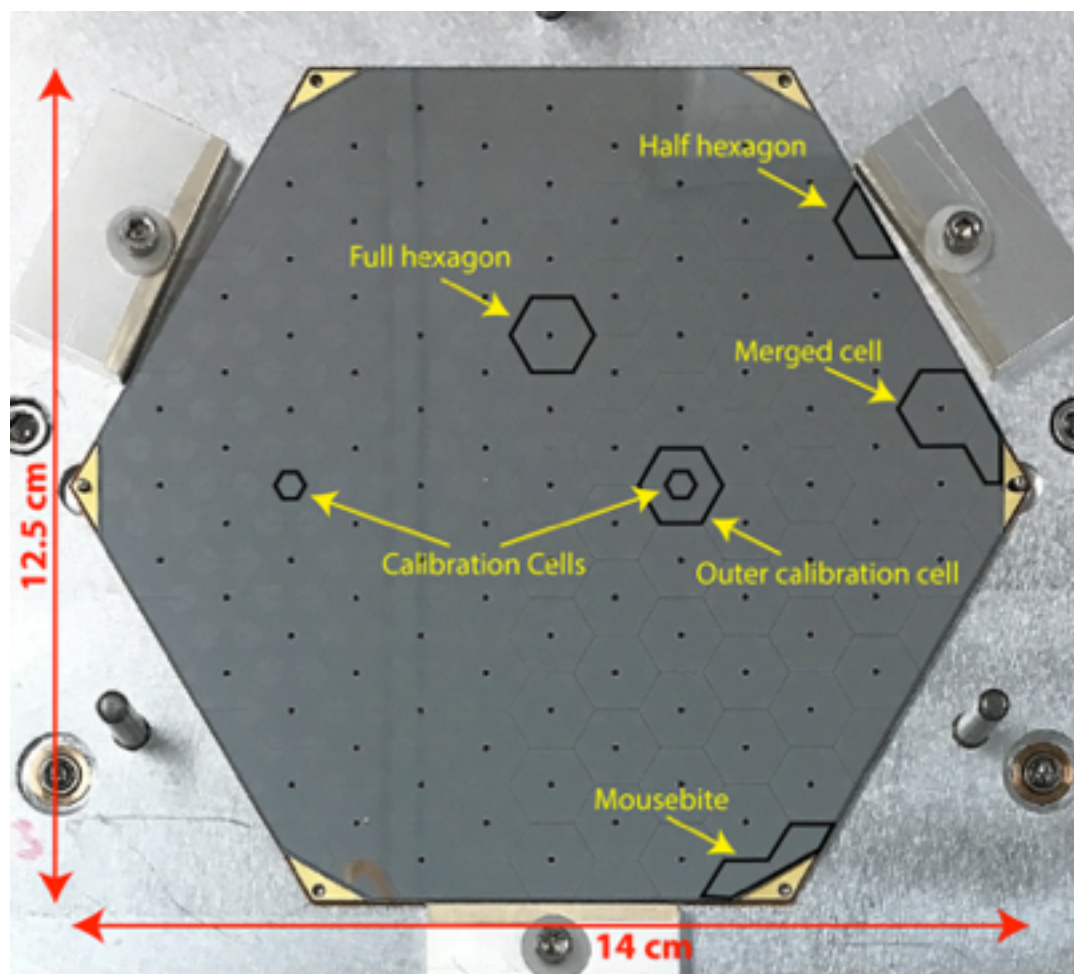
ECAL Barrel to be refurbished

- **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**

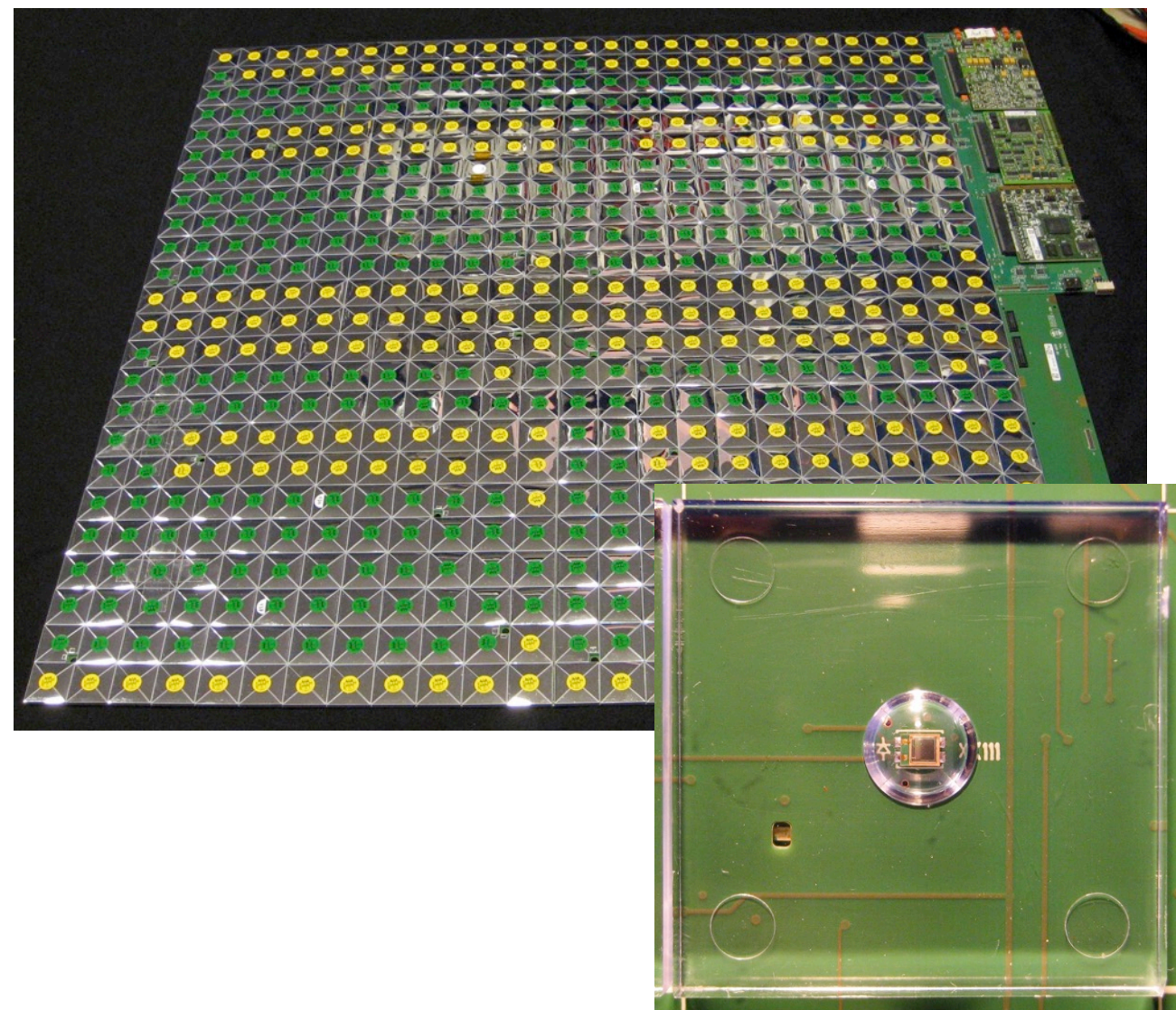


Endcap Calorimeter detector elements



Prototype silicon sensor

Hexagonal silicon detector cells
special high gain MIP calibration cells
must operate at -30 degC to limit Si
leakage current

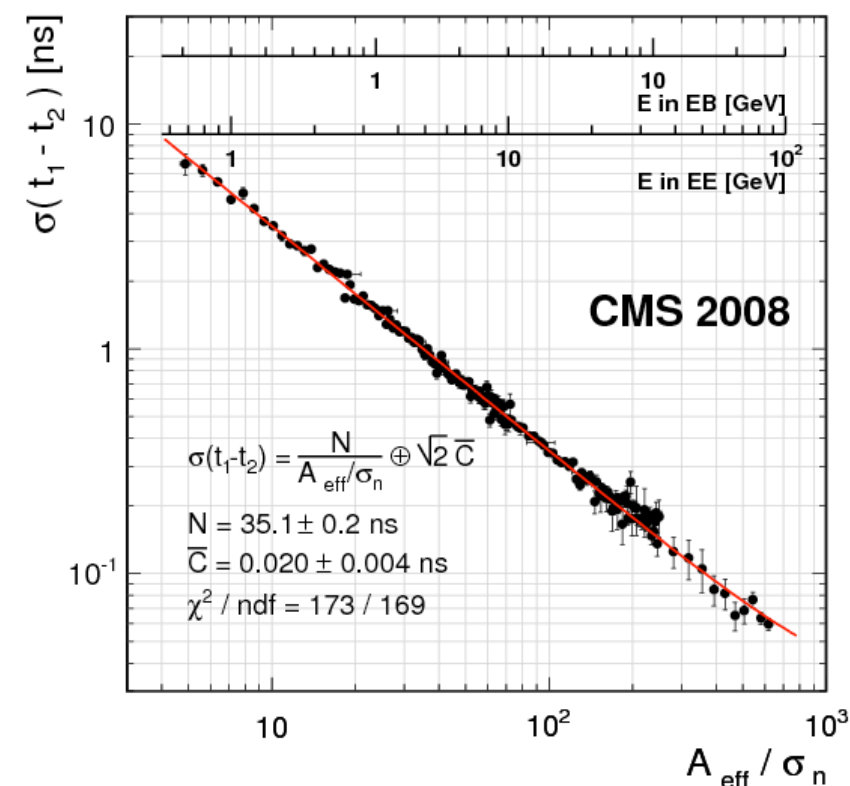


SiPM on tile scintillator cells

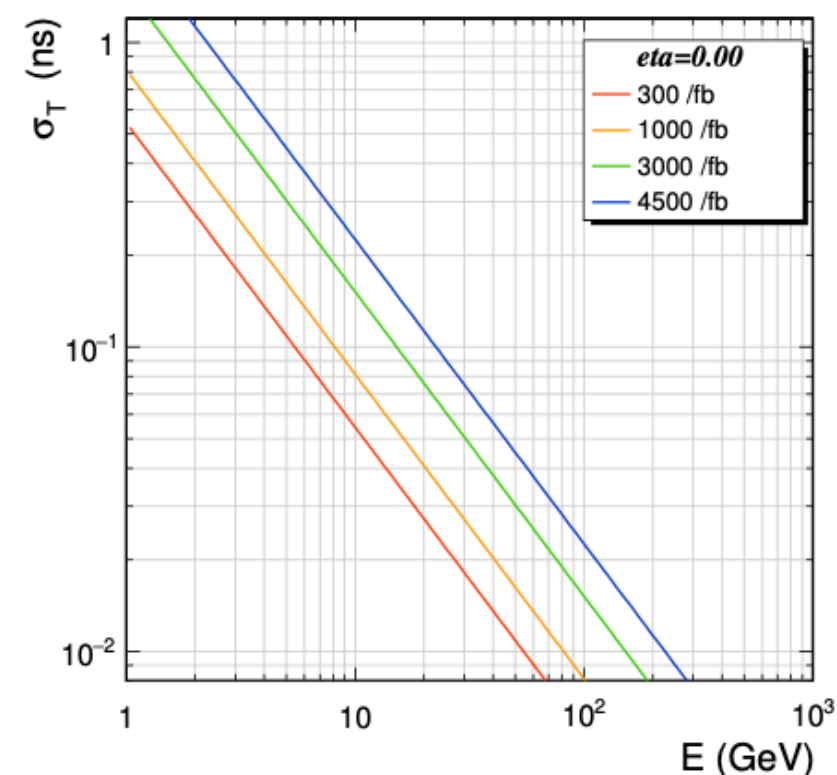
4cm² to 32cm² cells with direct SiPM
readout
adapted from CALICE HCAL prototype

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**

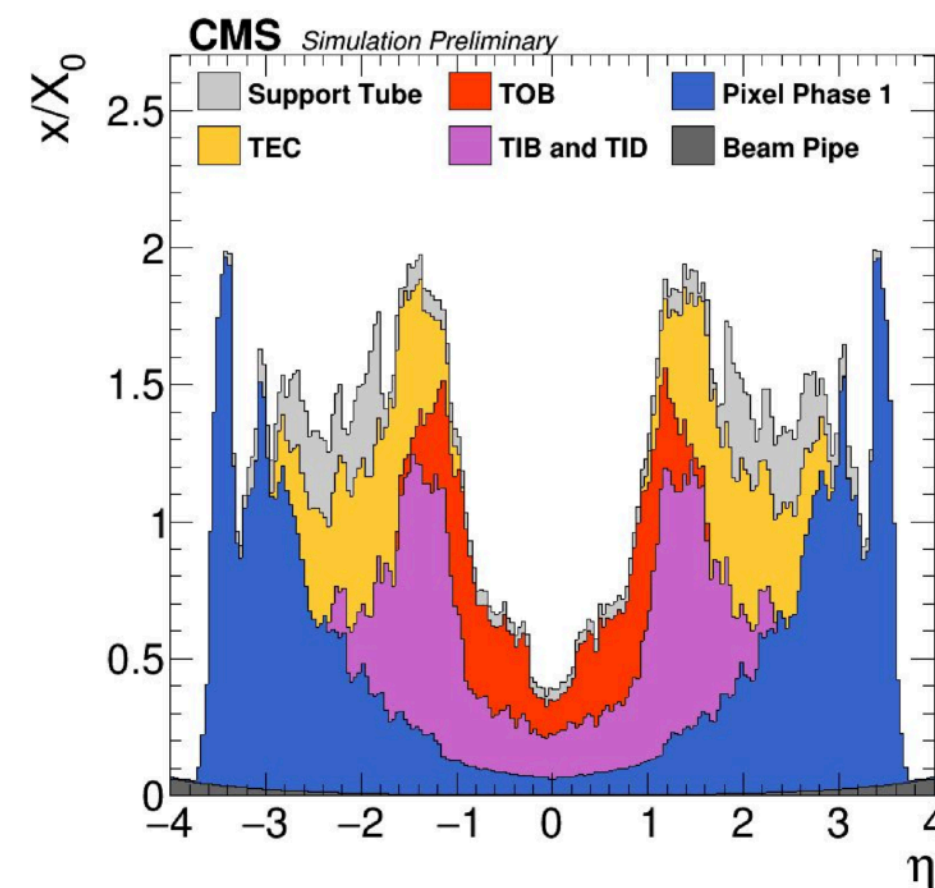
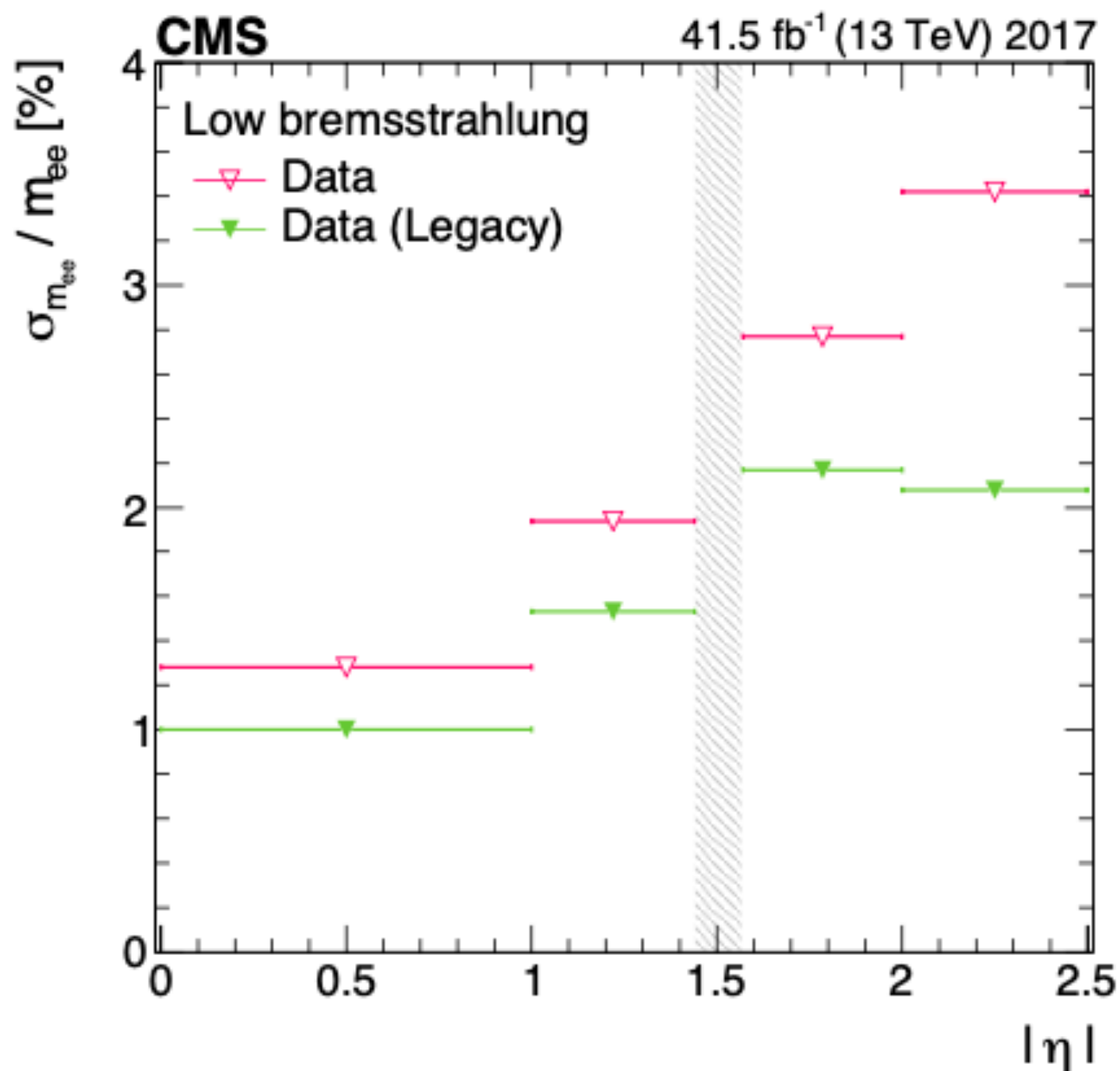


ECAL time resolution measured from test beam



Phase-2 ECAL time resolution vs luminosity

ECAL energy resolution improves with recalibration

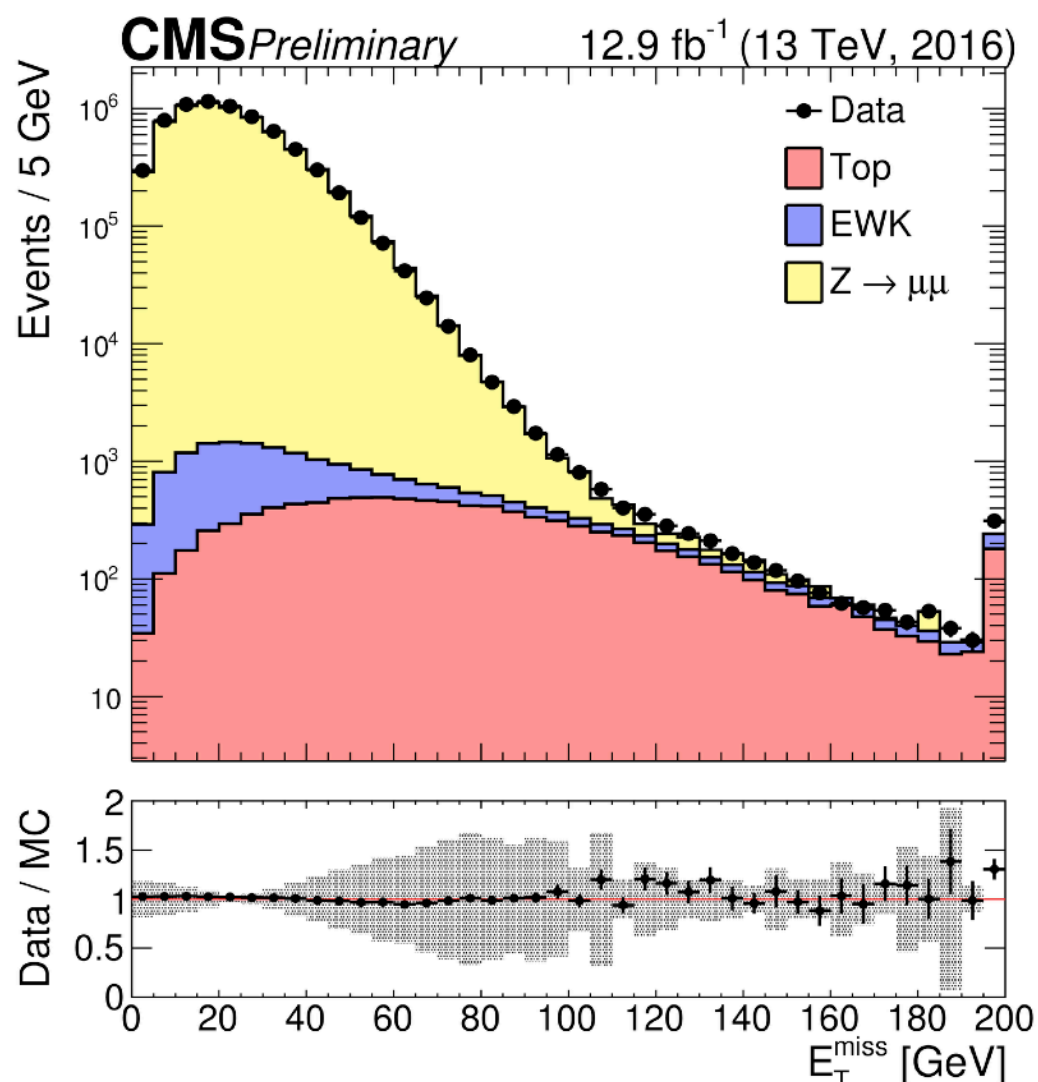


Tracker material
budget (in X_0)

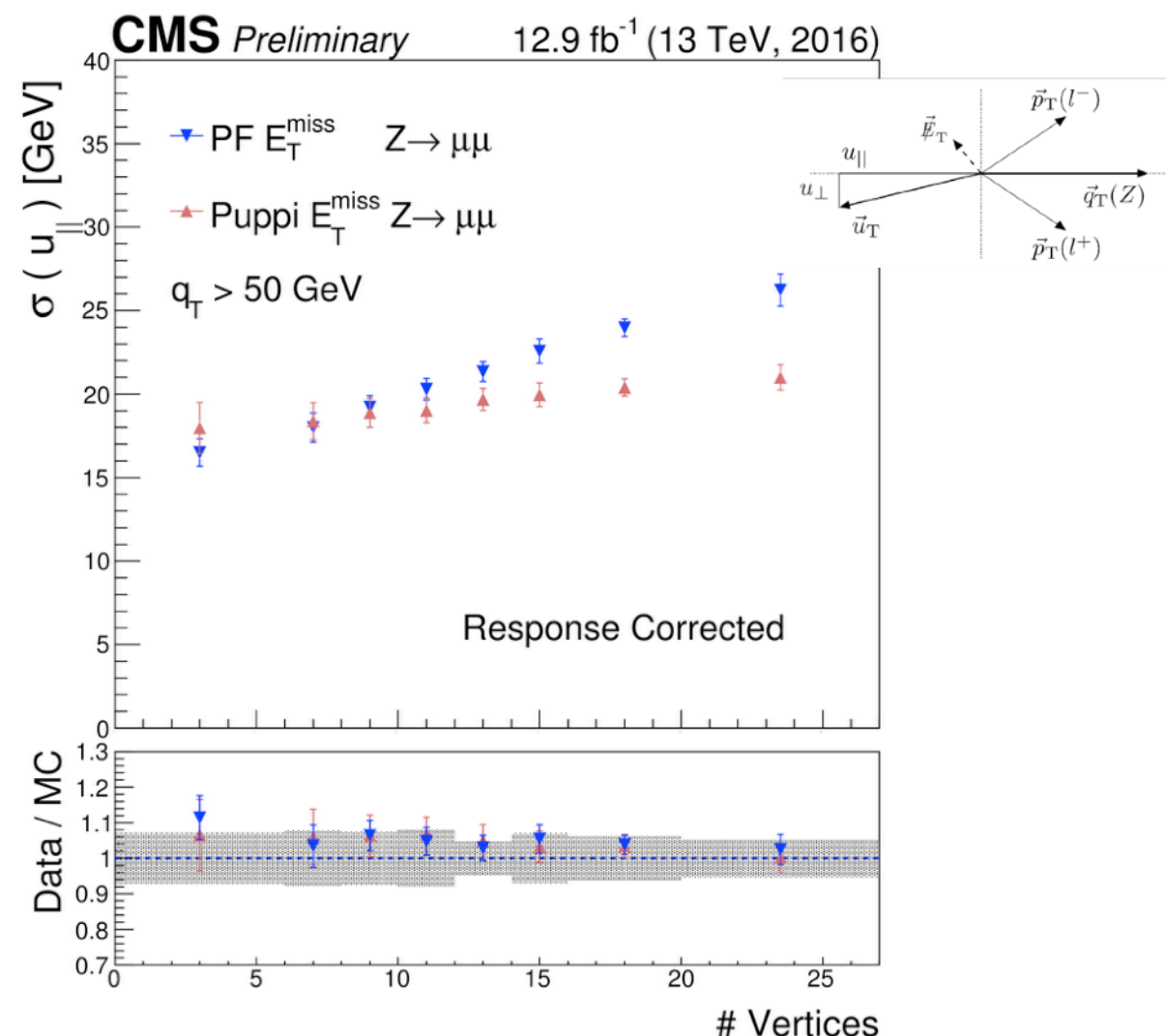
$Z \rightarrow ee$ invariant mass resolution vs eta from 2017 CMS data
 recalibrated data (**green**) shows significantly better performance, particularly in EE
[resolution vs eta trend follows material budget of CMS tracker -> best performance at \$|\eta| = 0\$](#)

MET performance

Missing energy distribution is an excellent test of calorimeter understanding
any unexpected noise source or detector miscalibration can generate fake MET



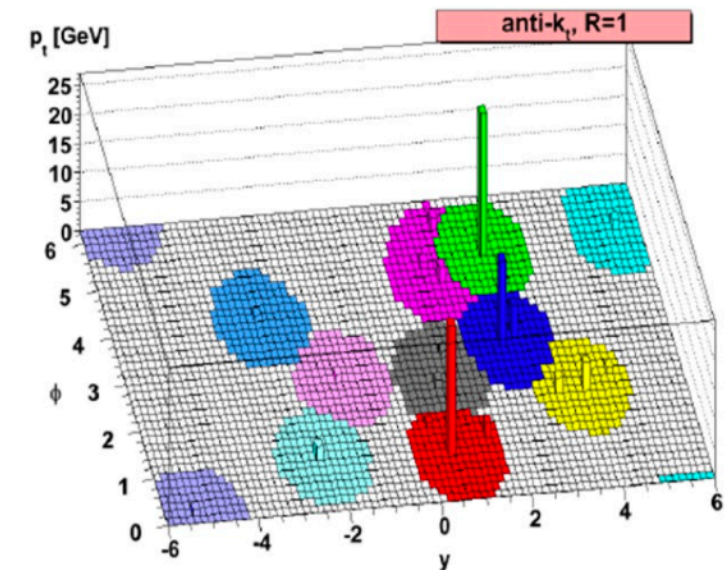
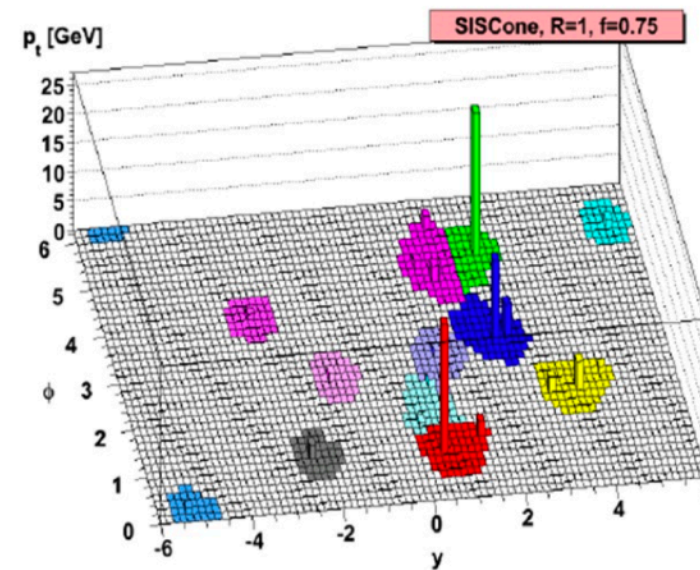
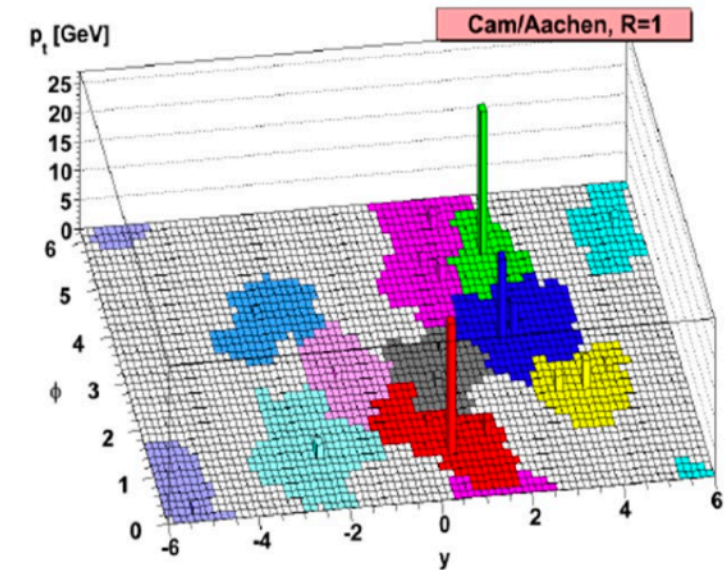
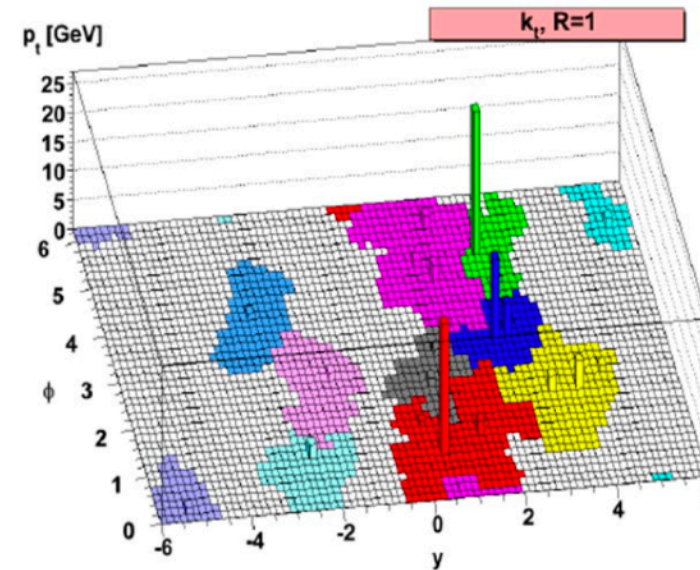
Missing E_T distribution for PF MET
from Z→mumu events



Resolution for PF/PUPPI MET
from Z→mumu events
showing impact of advanced PU mitigation
treatment, using calorimeters and tracks

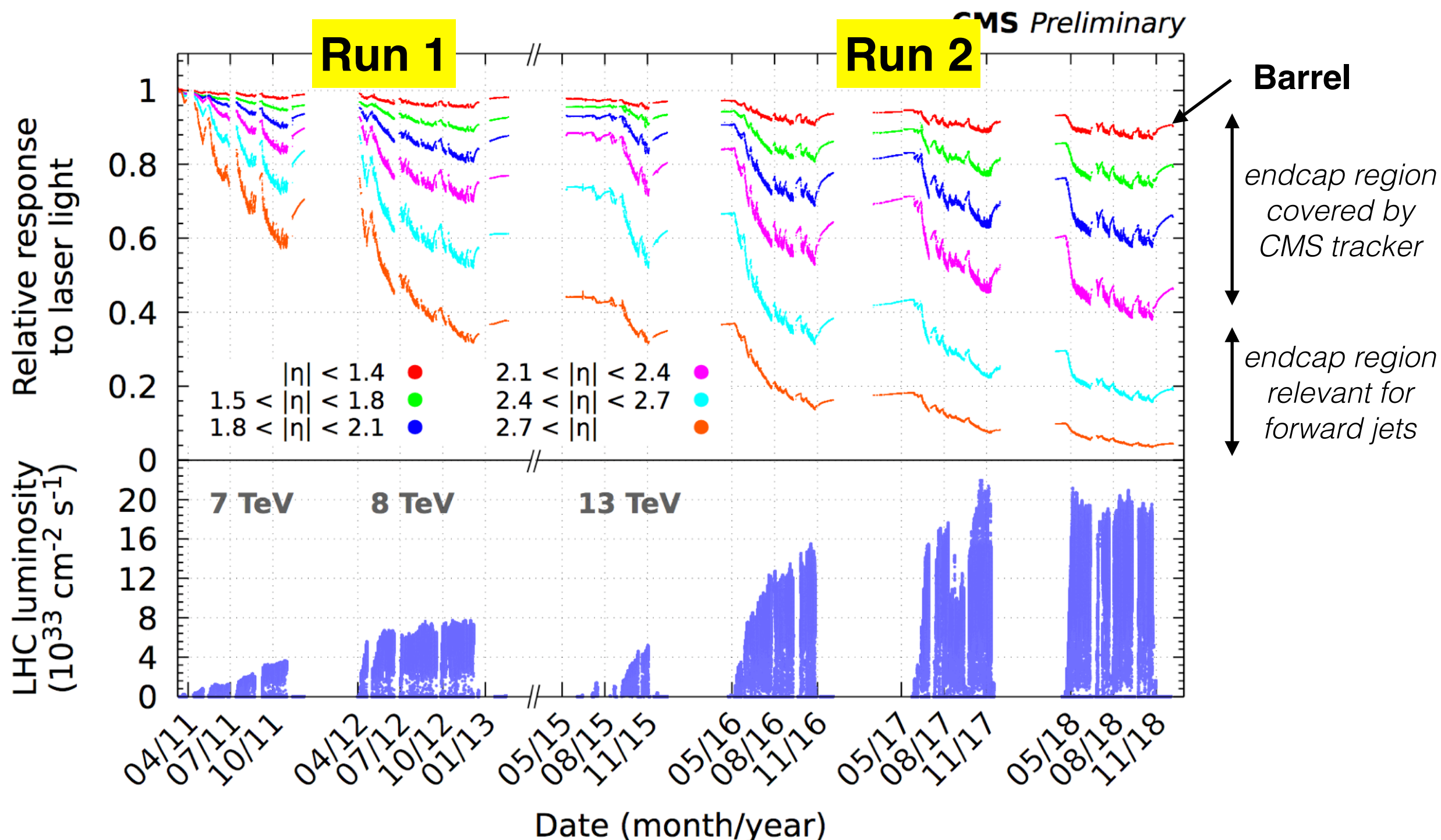
Jet reconstruction

- **Various algorithms used to reconstruct jets**
 - iterative cone algorithms
 - cluster energy deposits based on eta/phi regions
 - not IR or collinear safe
 - sequential clustering algorithms are favoured
 - 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



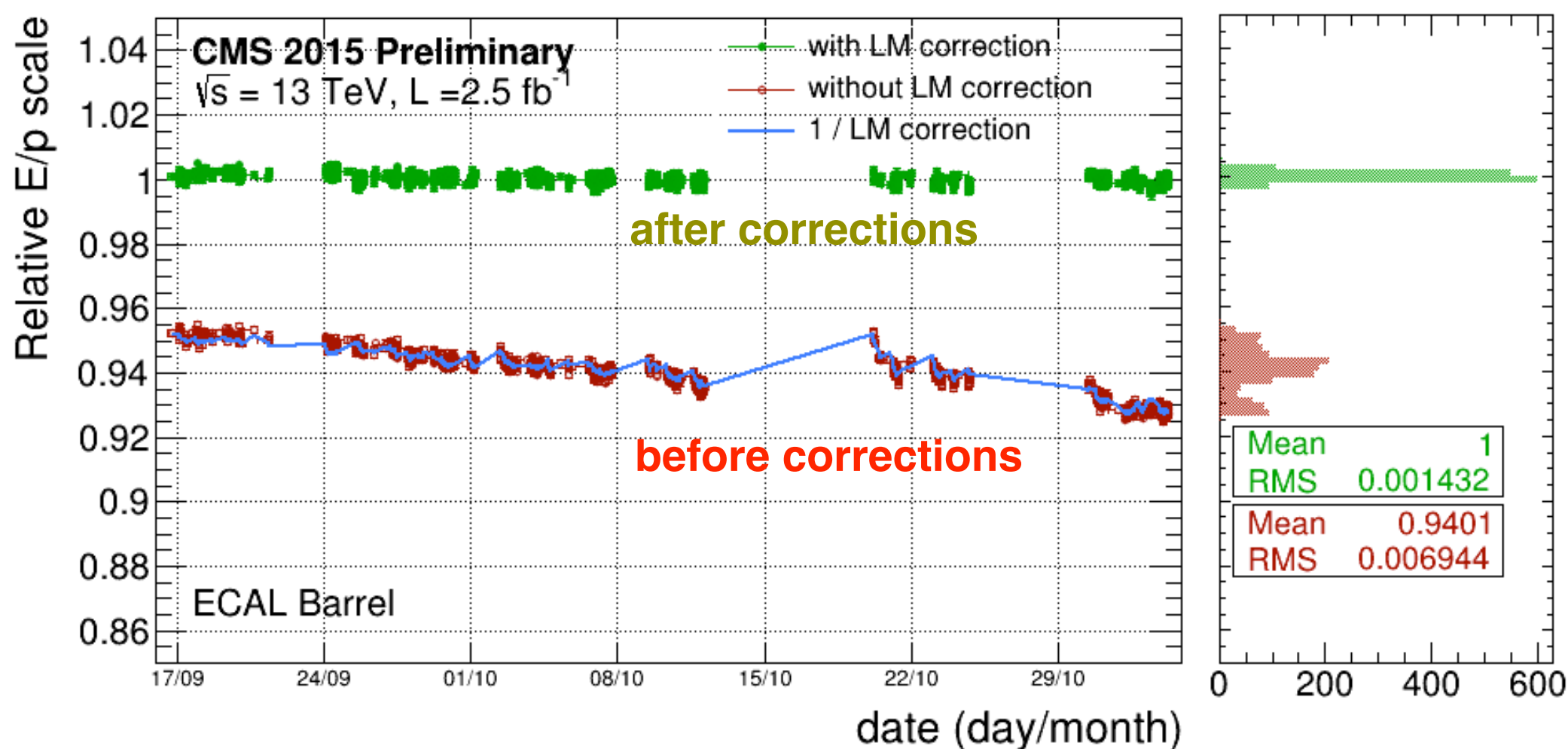
Significant response changes (crystal + photodetector) due to LHC irradiation

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 ₄ Ge ₃ O 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

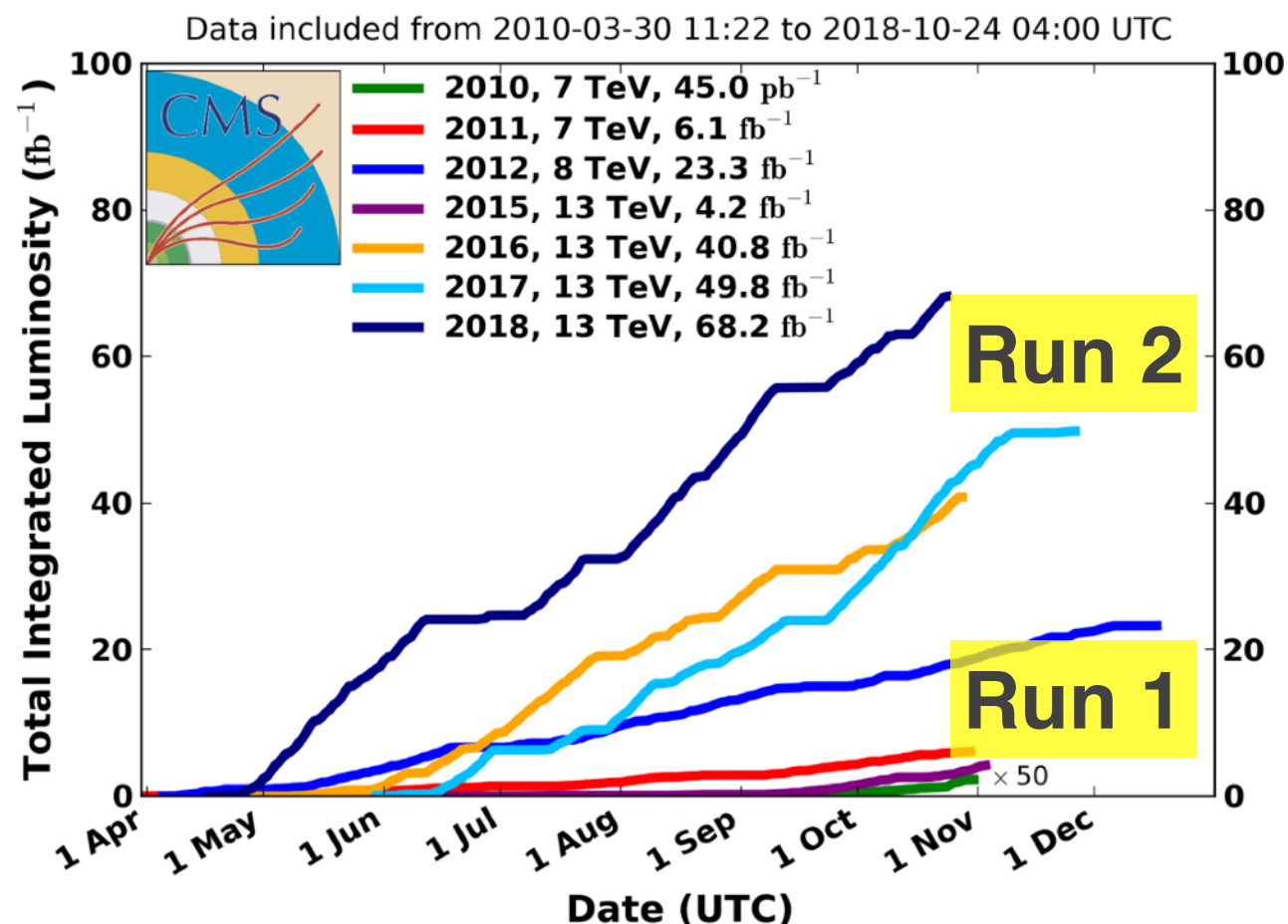
Homogenous
calorimeters
have smaller
stochastic term

Similar constant
terms

ECAL Challenges during Run 2

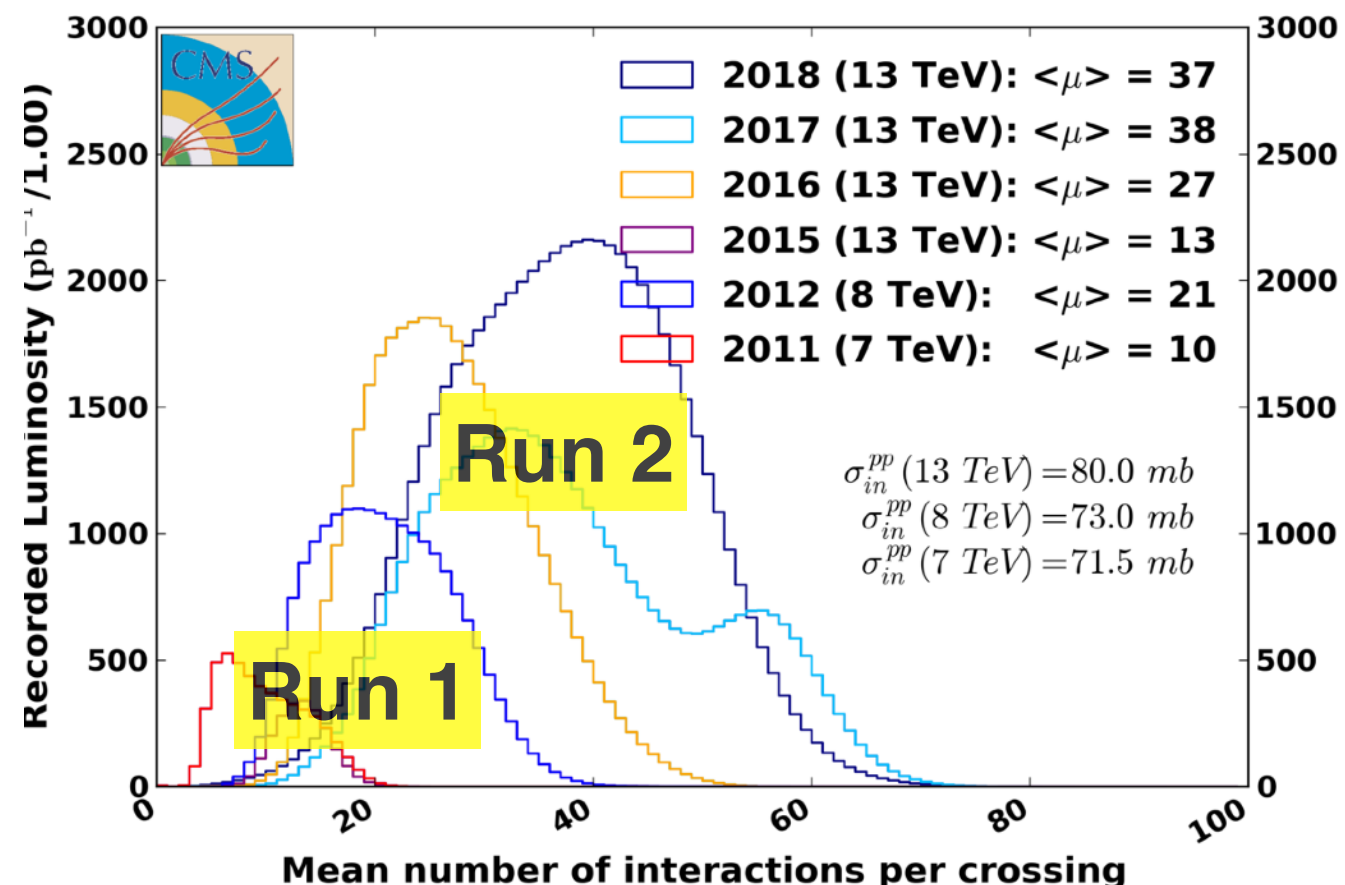
Higher Integrated luminosity

CMS Integrated Luminosity, pp



Larger Average pileup

CMS Average Pileup



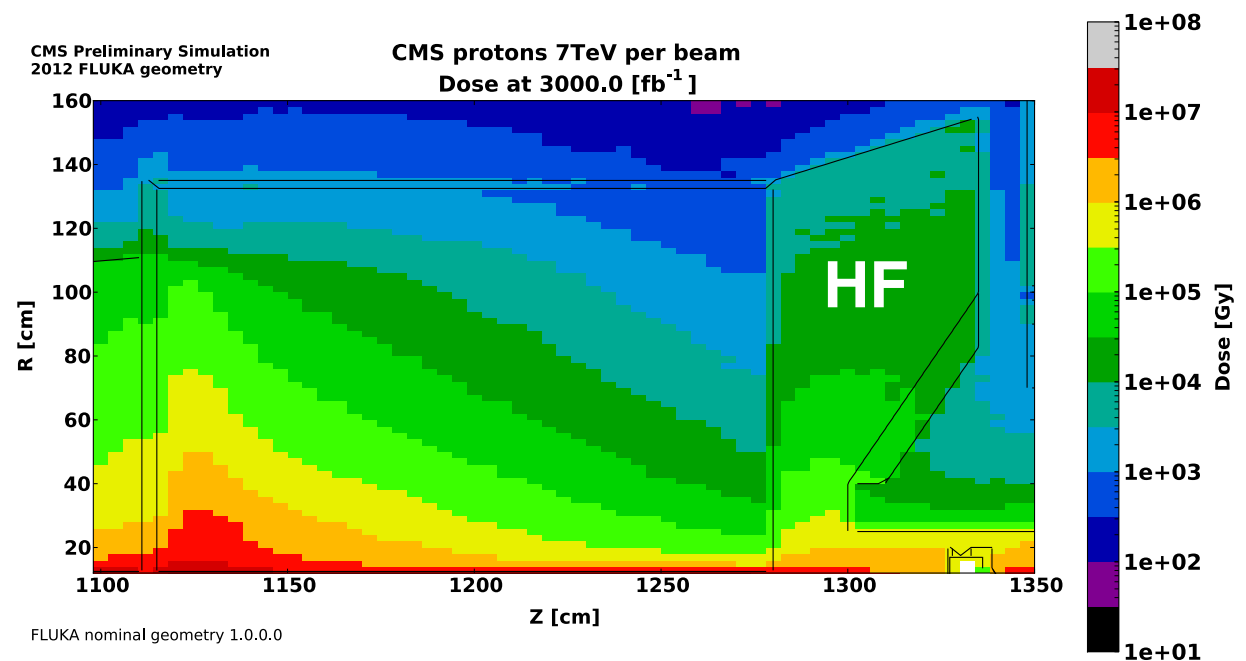
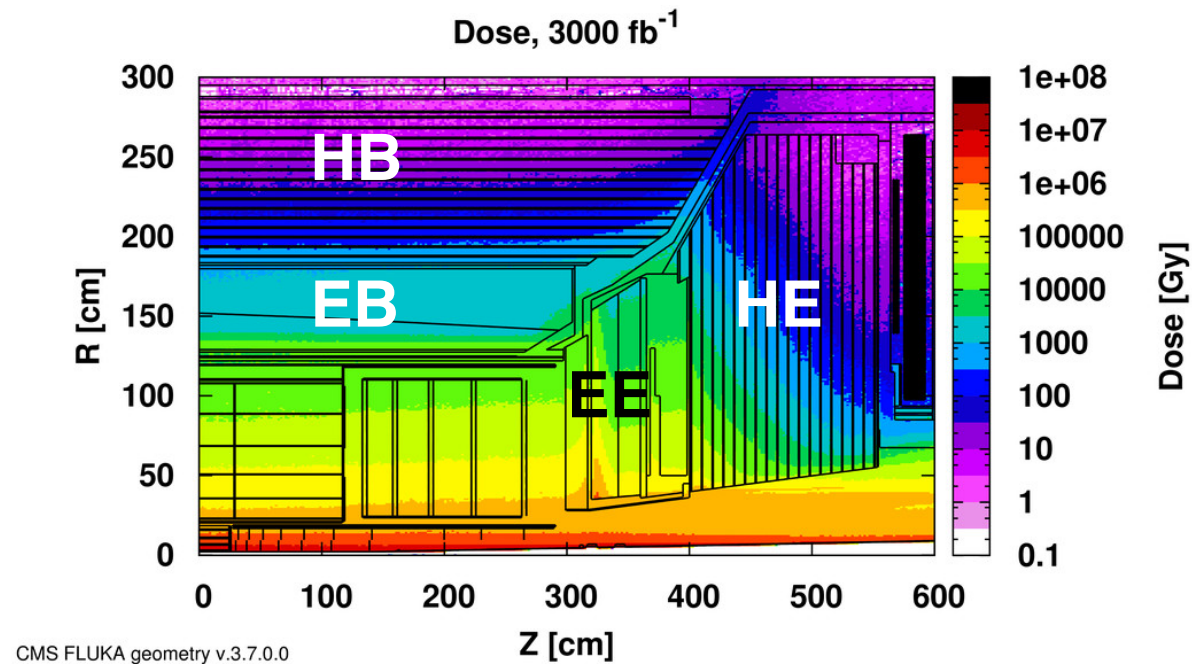
Run 2 challenges:

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 ($|\eta| > 1.48$) 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

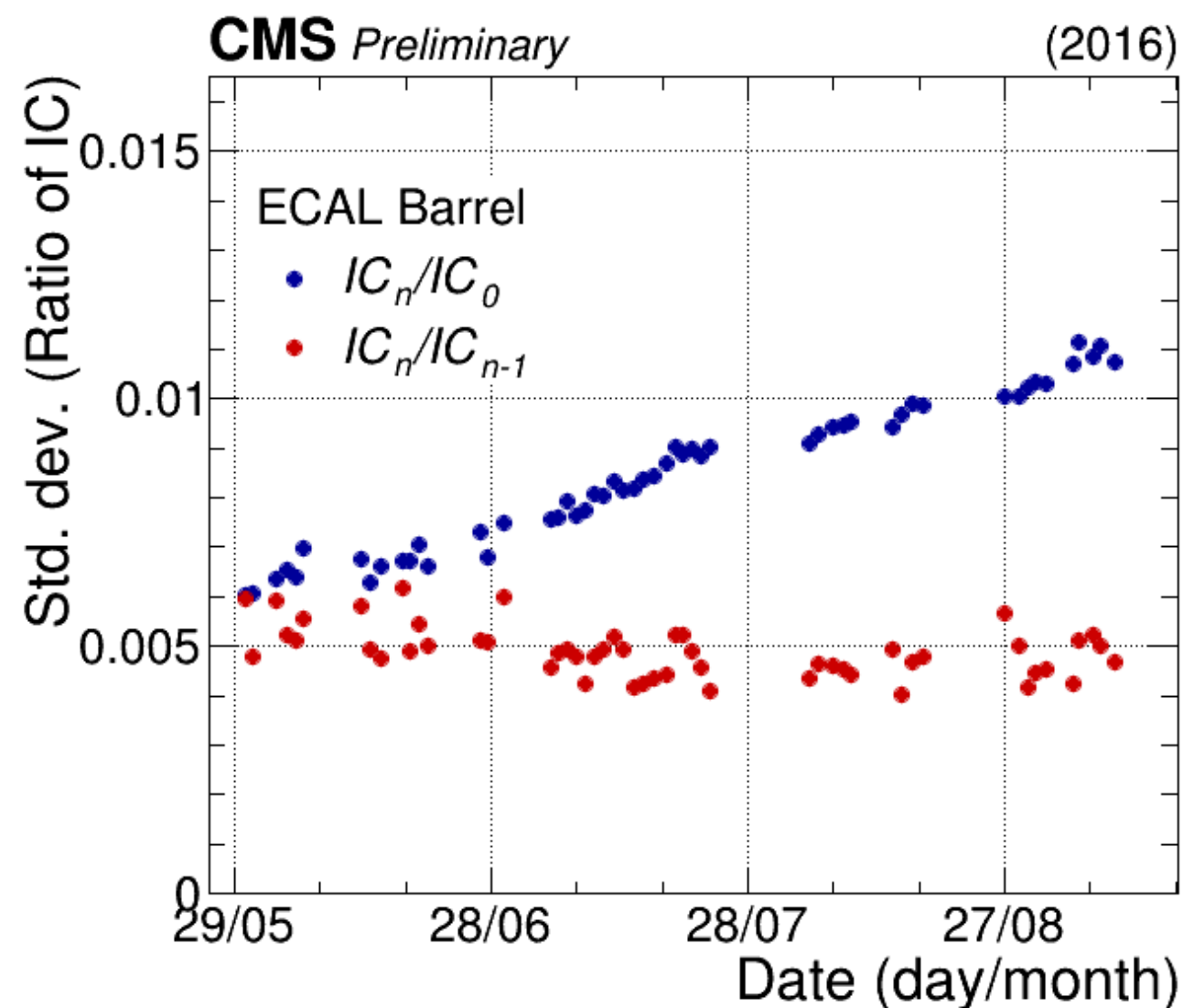
This does not fully hold over long periods

imperfections in **light monitoring corrections** grow with time
this causes a **spread** in the channel-to-channel response, **degrading resolution**

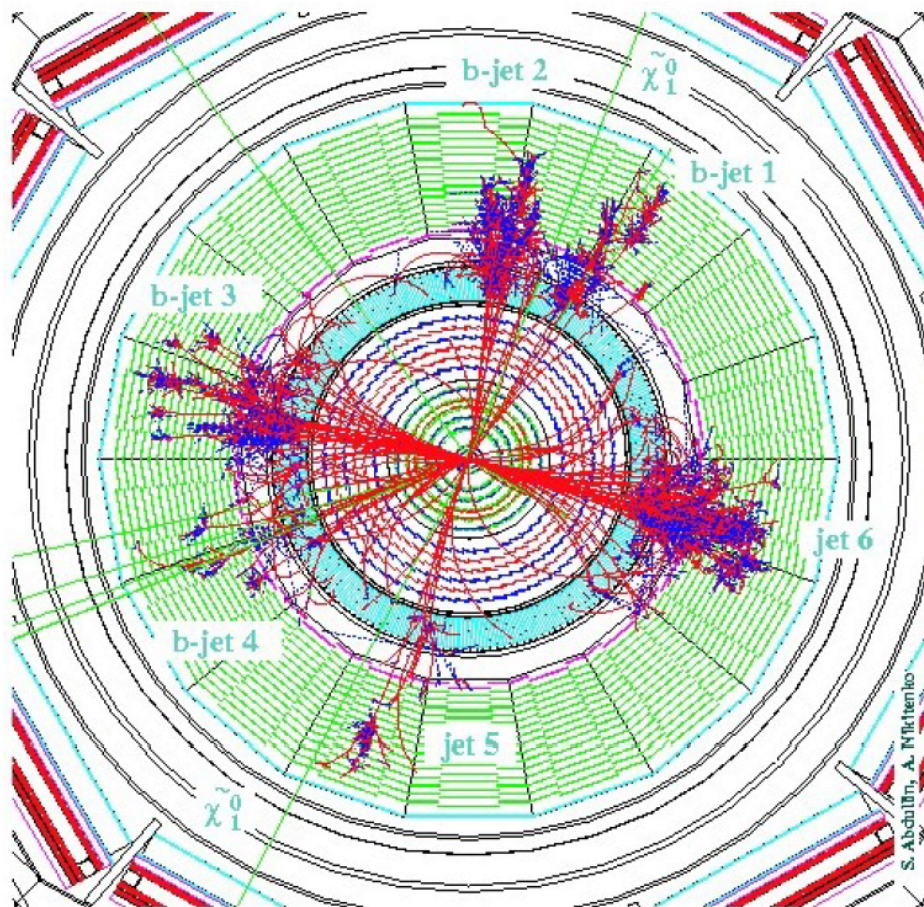
Regular rederivation of IC needed

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



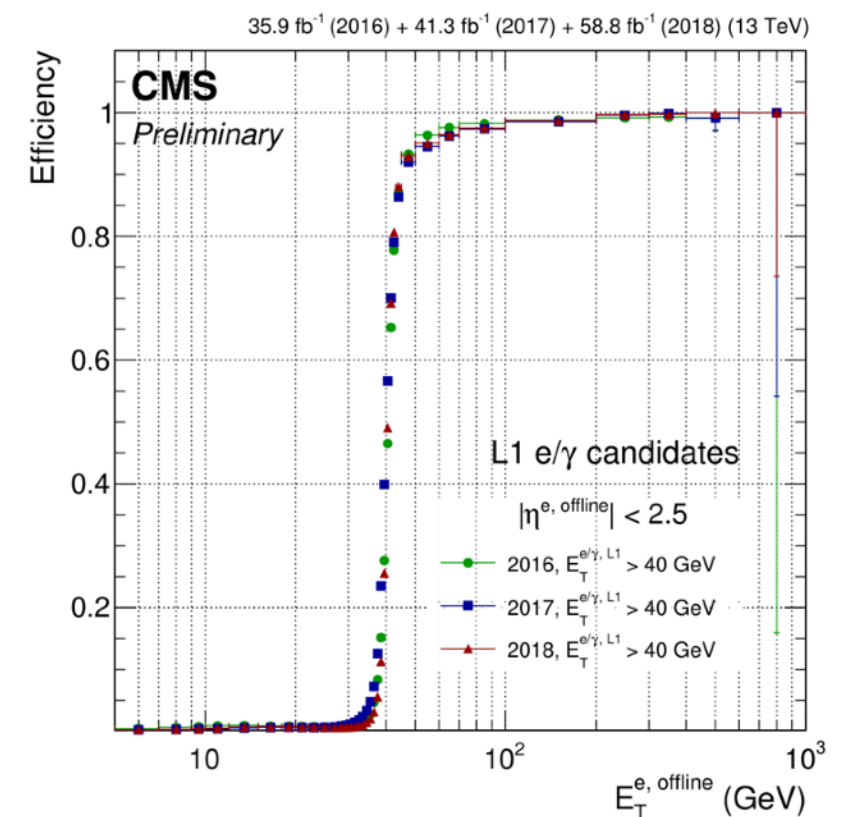
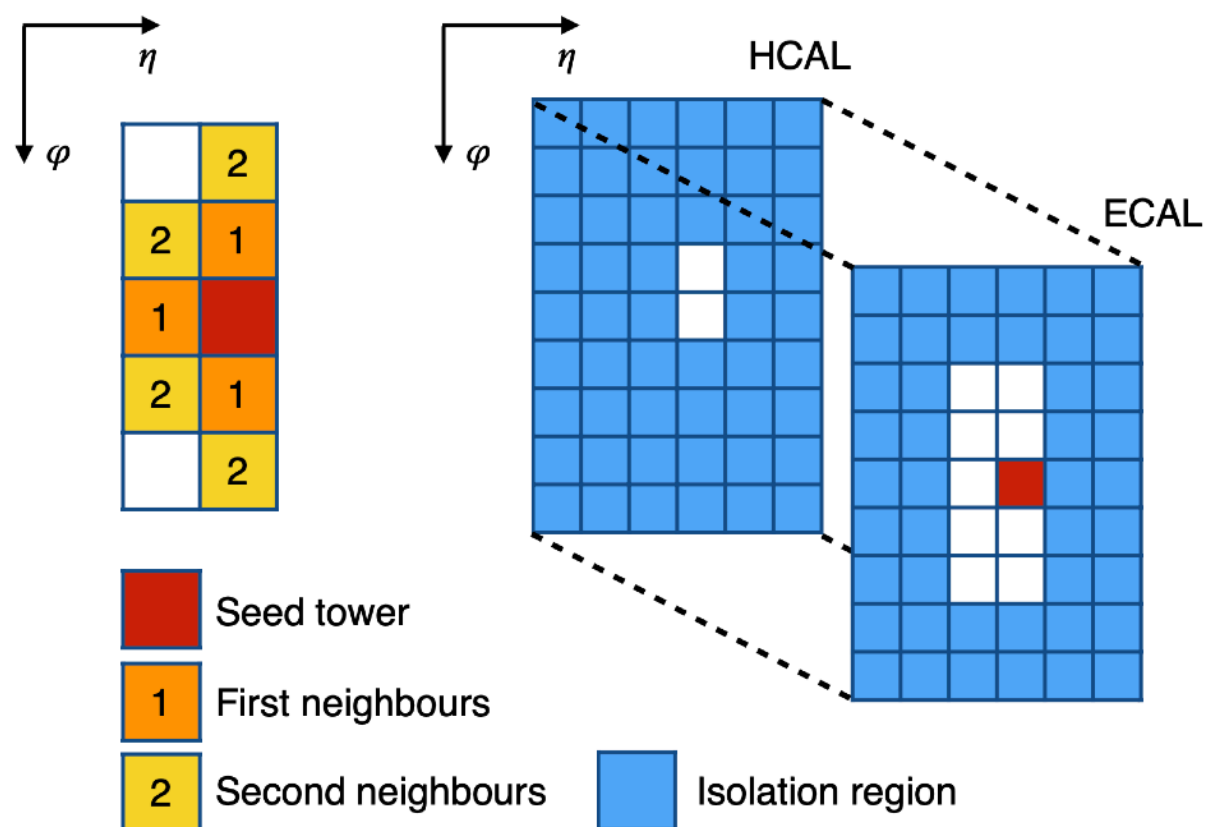
- Measure jets and missing E_T
- Electron/photon ID via HCAL/ECAL energy ratio (H/E)
- Muon ID via ECAL/HCAL isolation
- Tau ID: narrow jets (for $\tau \rightarrow h$ decays)

Simulated SUSY multijet event

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

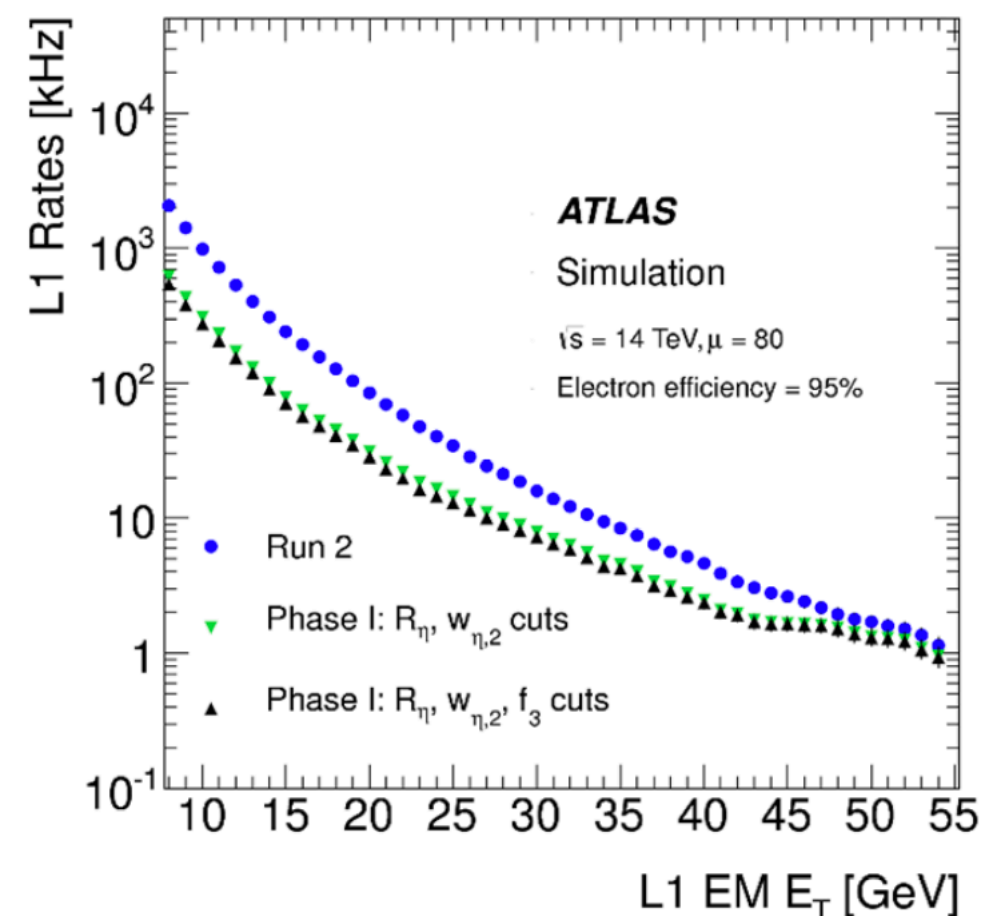
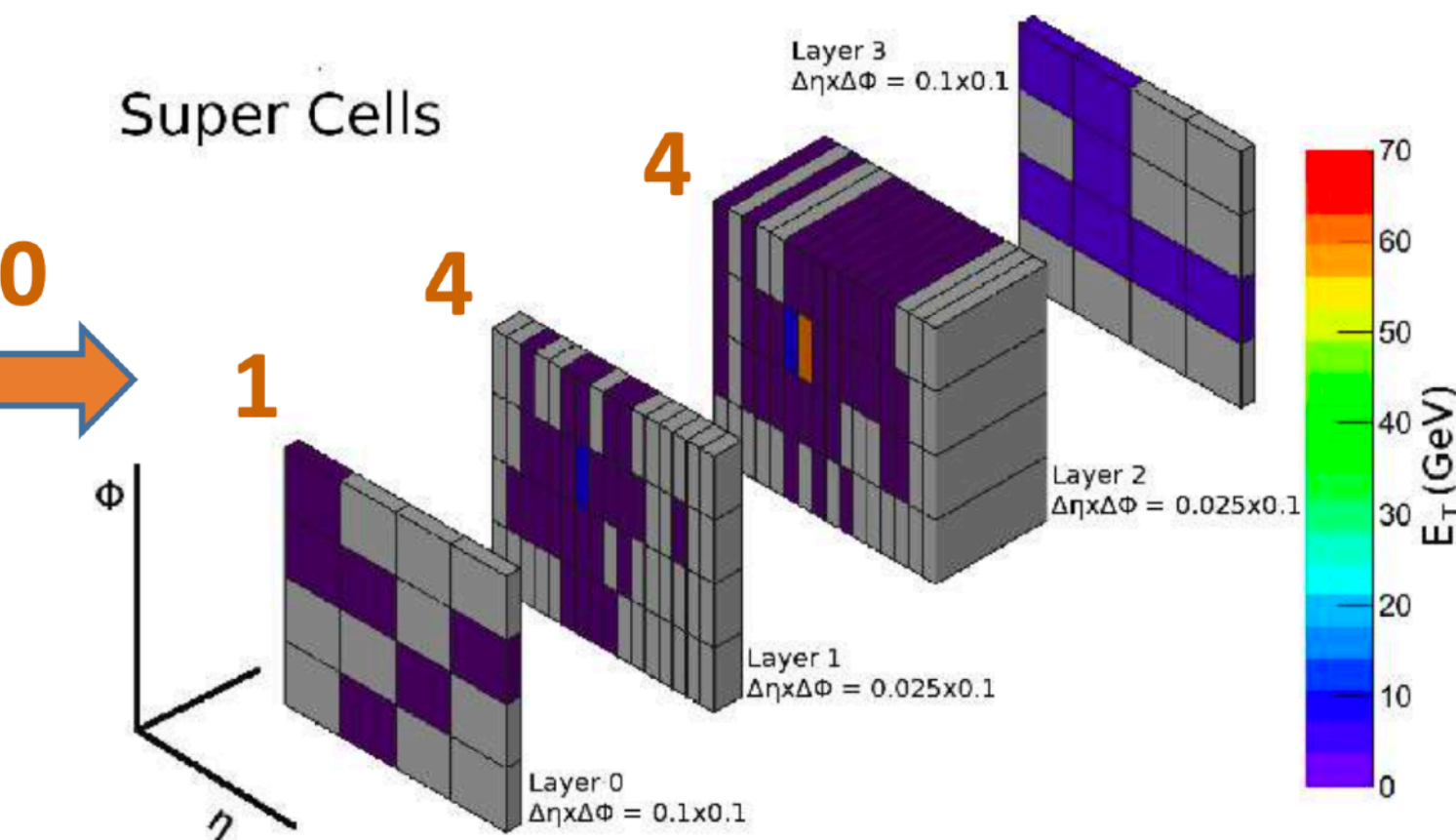
Electron/photon dynamic clustering algorithm Electron/photon trigger efficiency



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

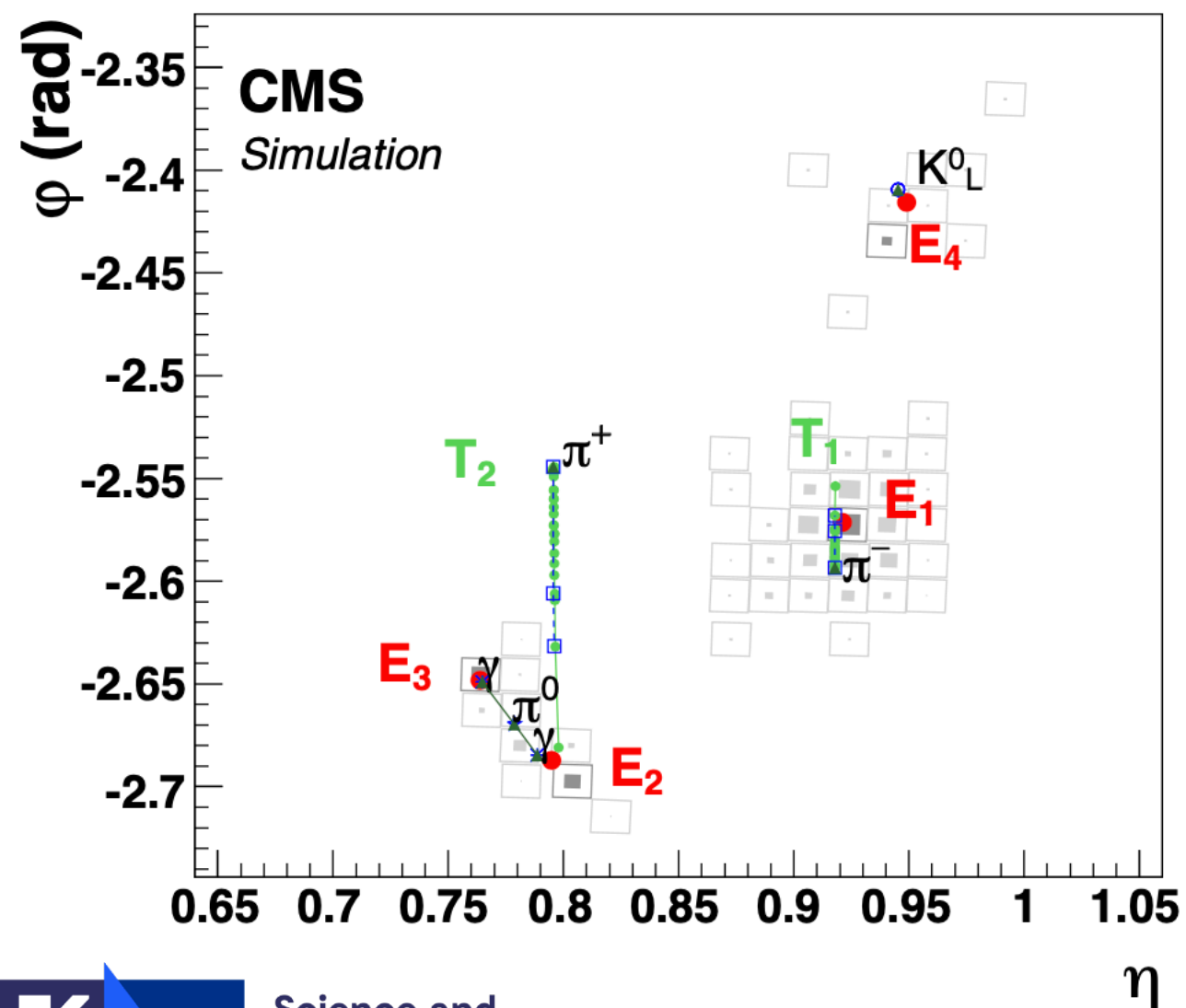
Trigger super cells (finer granularity + depth) Reduced Electron/photon fake rate



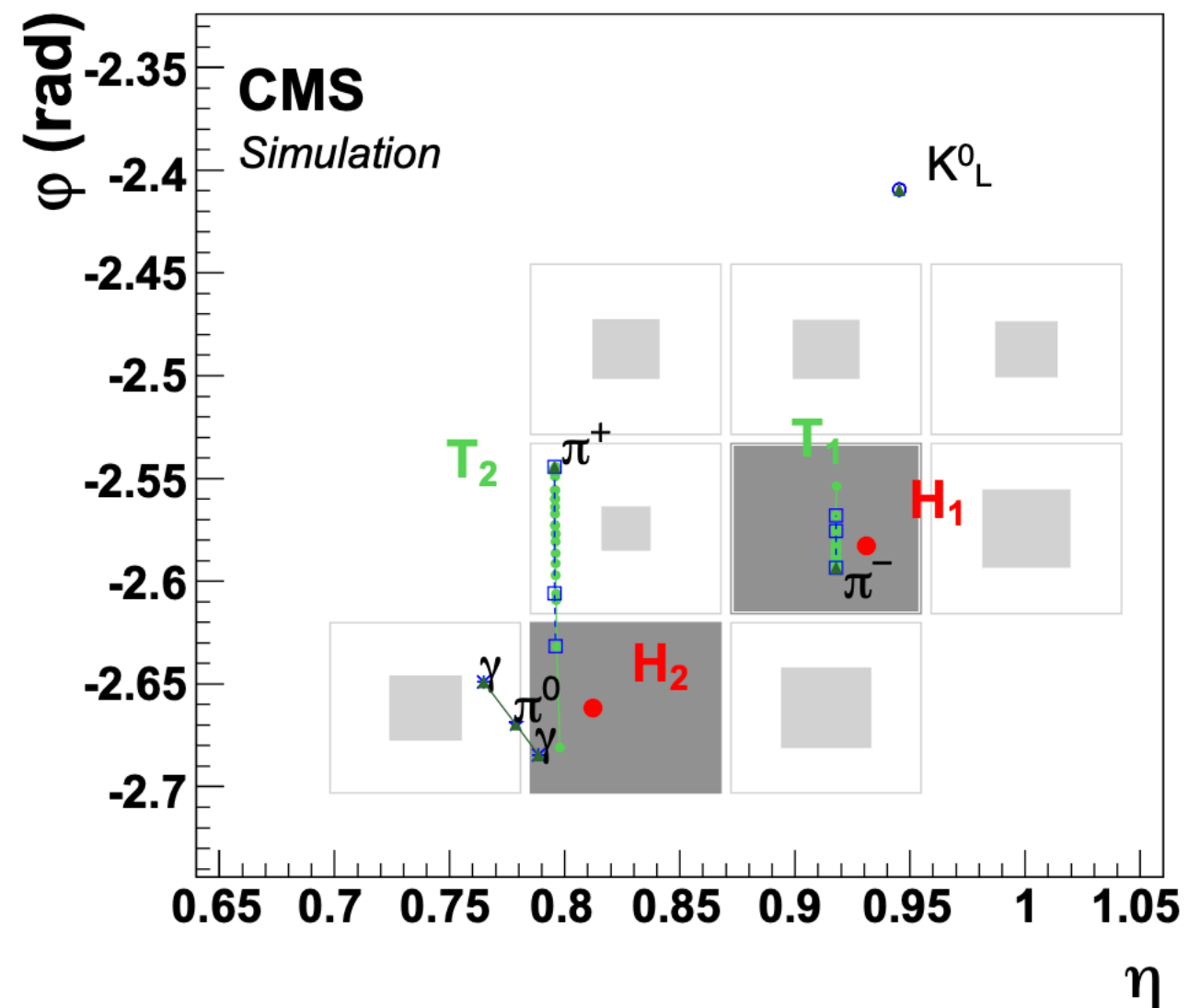
Particle flow reconstruction

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

ECAL view



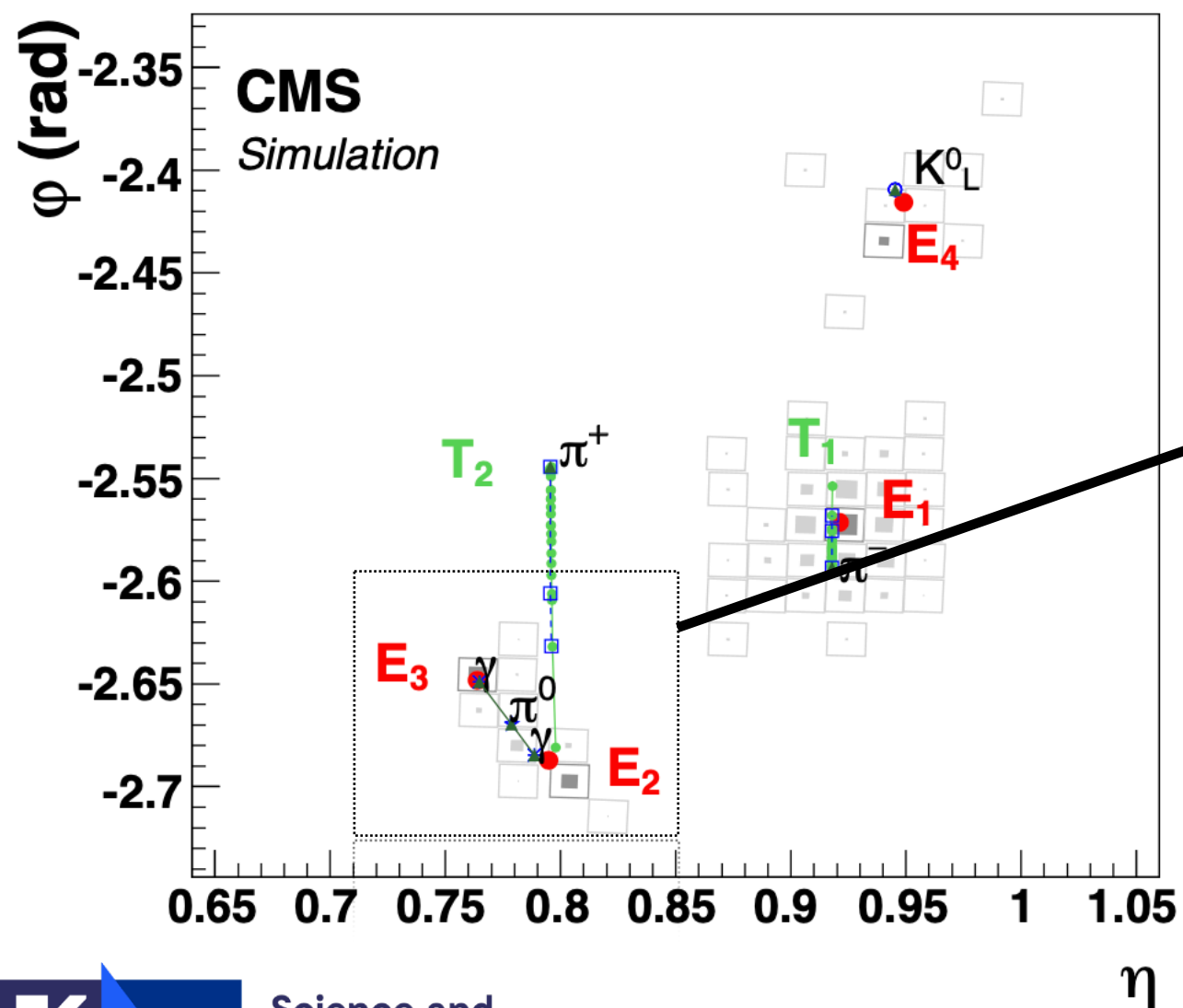
HCAL view



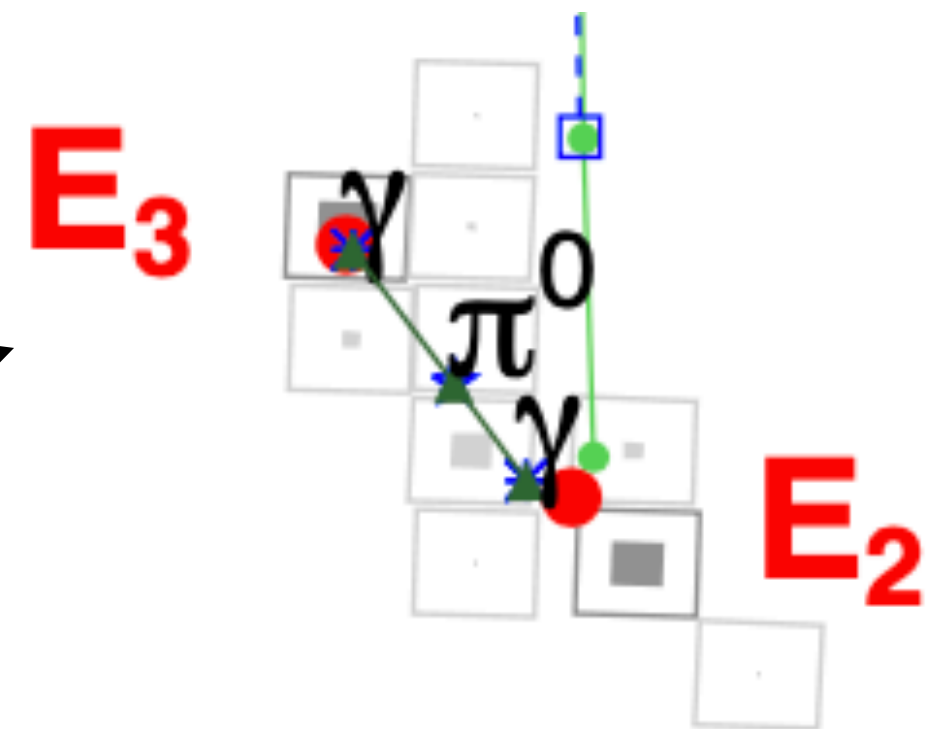
Particle flow reconstruction

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

ECAL view



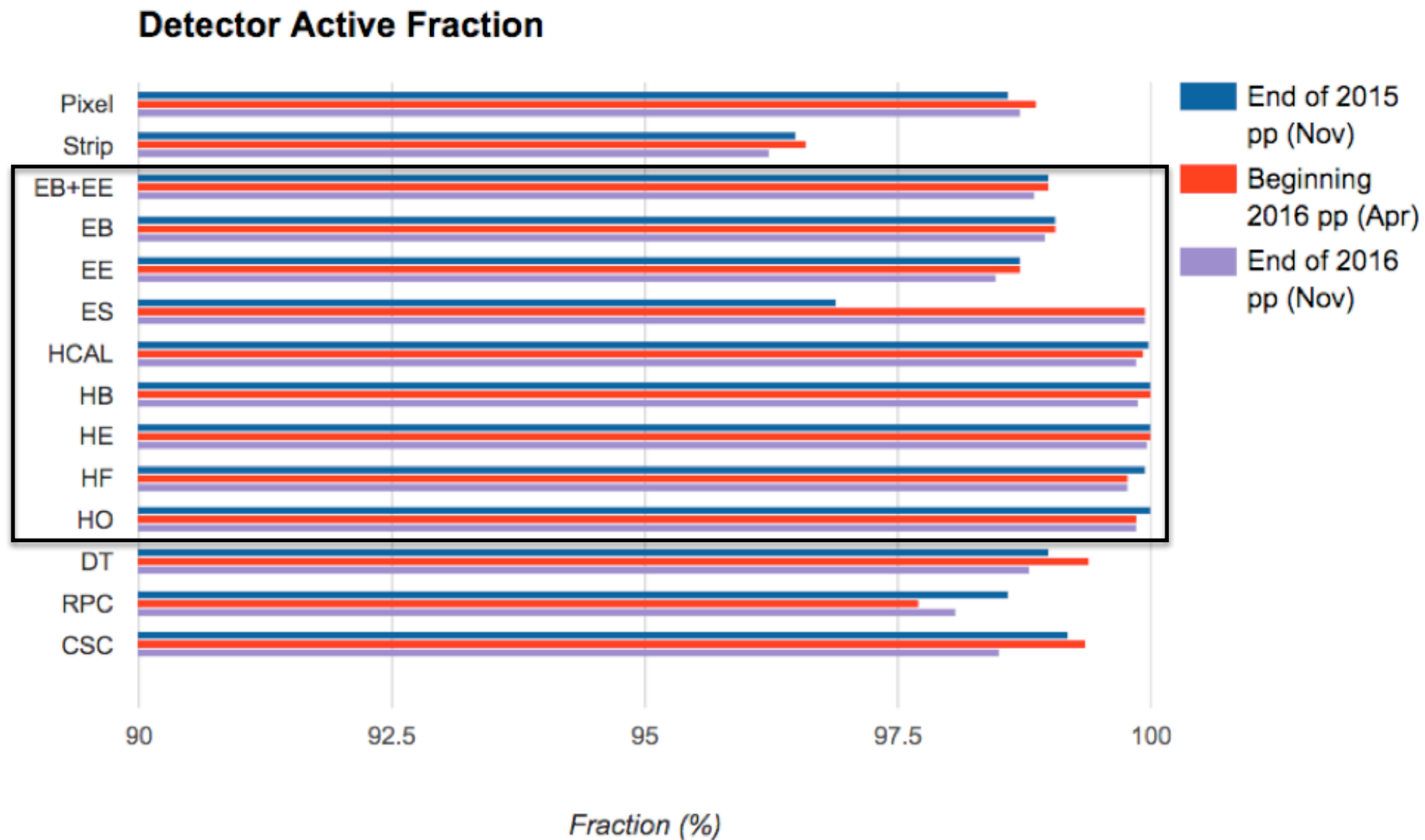
Zoom



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

Detector health

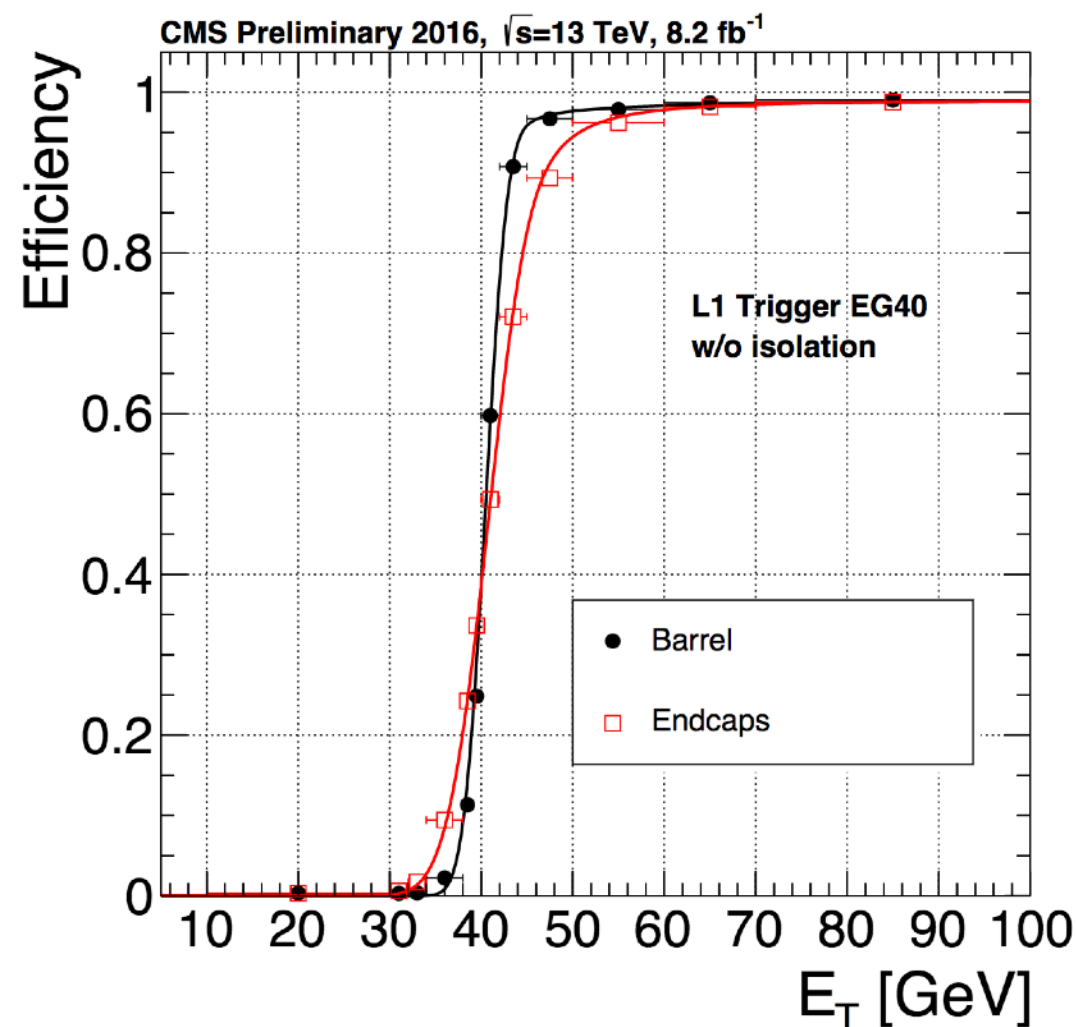
- **ECAL and HCAL detectors performing well, with high active detector fractions**



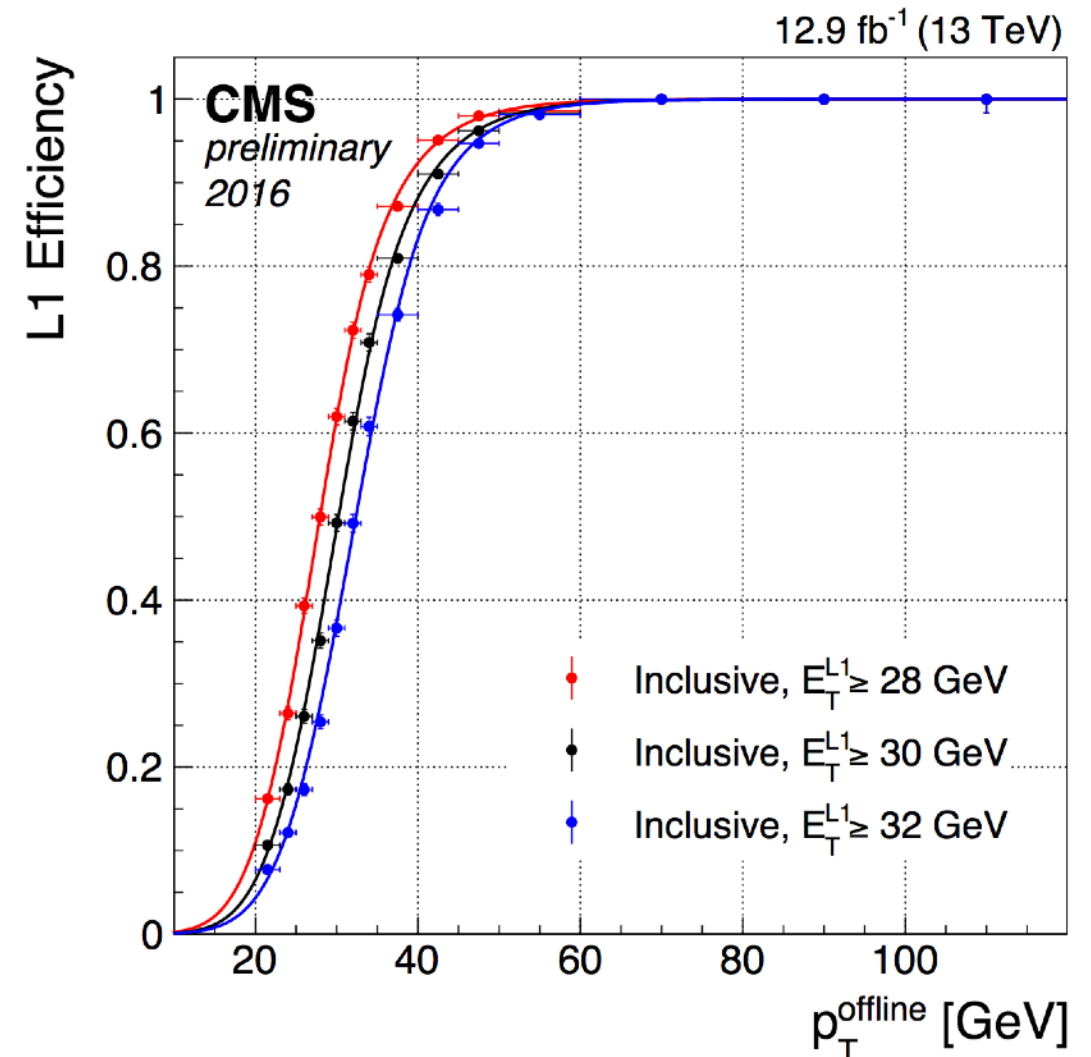
- **Thanks to dedicated efforts of detector experts and operations teams**

Triggering

Single electron



Tau



Improved L1 trigger algorithms in 2016 following Phase I upgrade

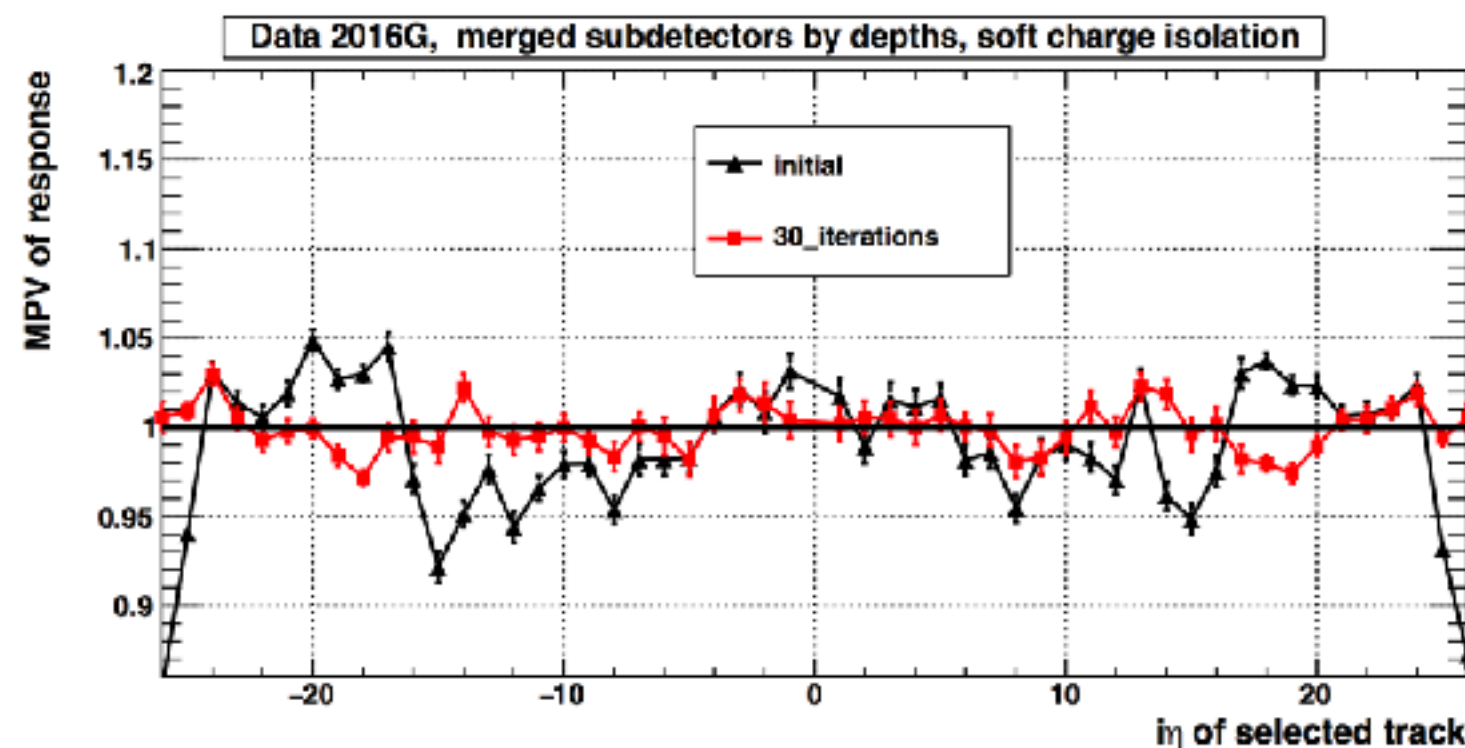
full trigger tower granularity available at Level 1

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 Symmetry**
 - 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

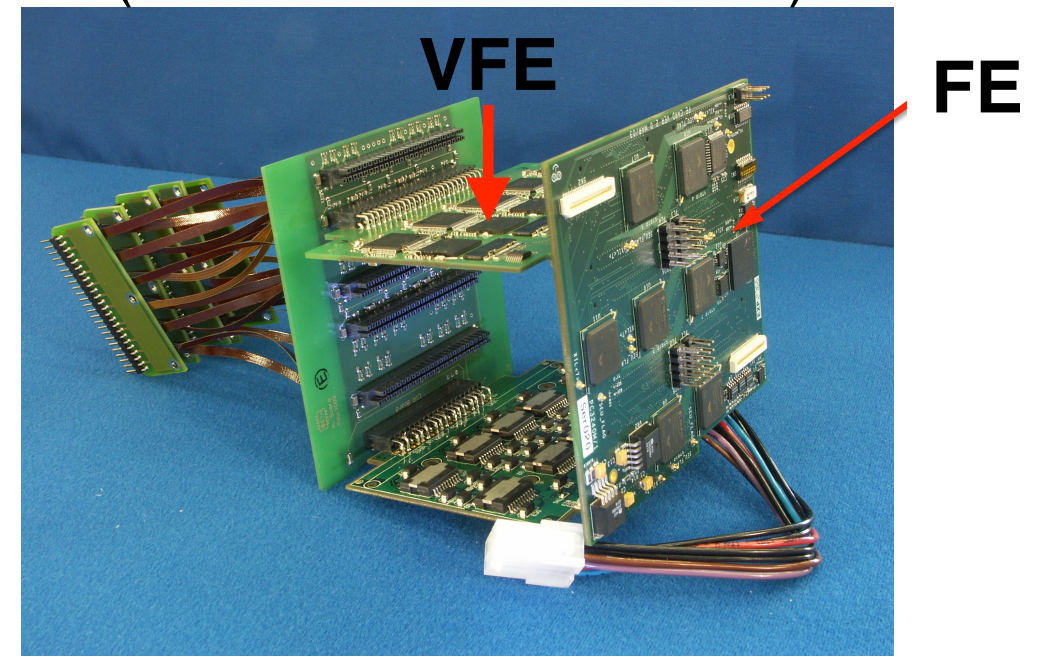


Elements of the ECAL Barrel

36 Supermodules



2448 Trigger towers
(readout of 5x5 channels)



61200 Lead Tungstate crystals

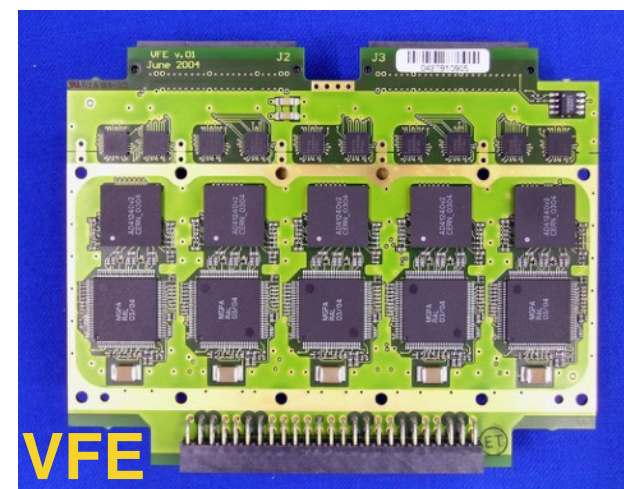
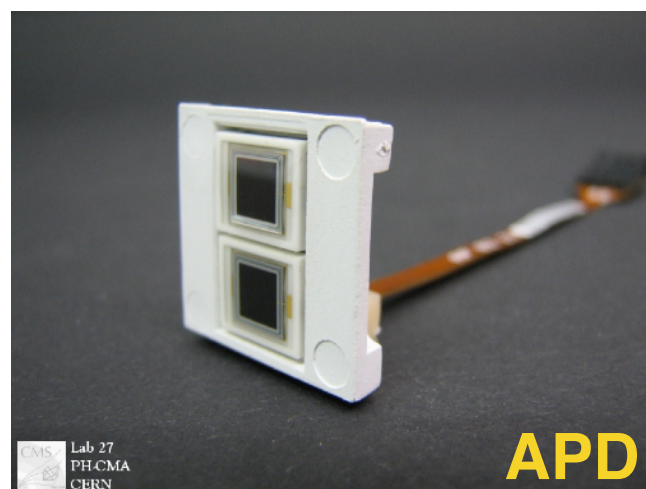
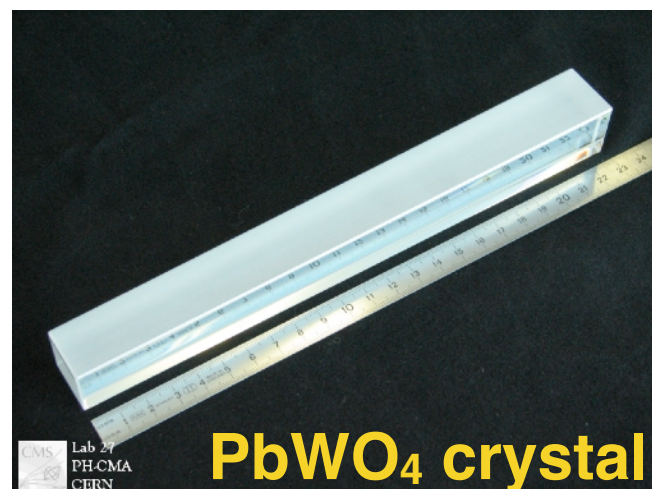
61200 APD pairs

12240 Very Front End cards

pulse amplification, shaping, digitization

2448 Front End cards

data pipeline and transmission, TP formation, clock/control



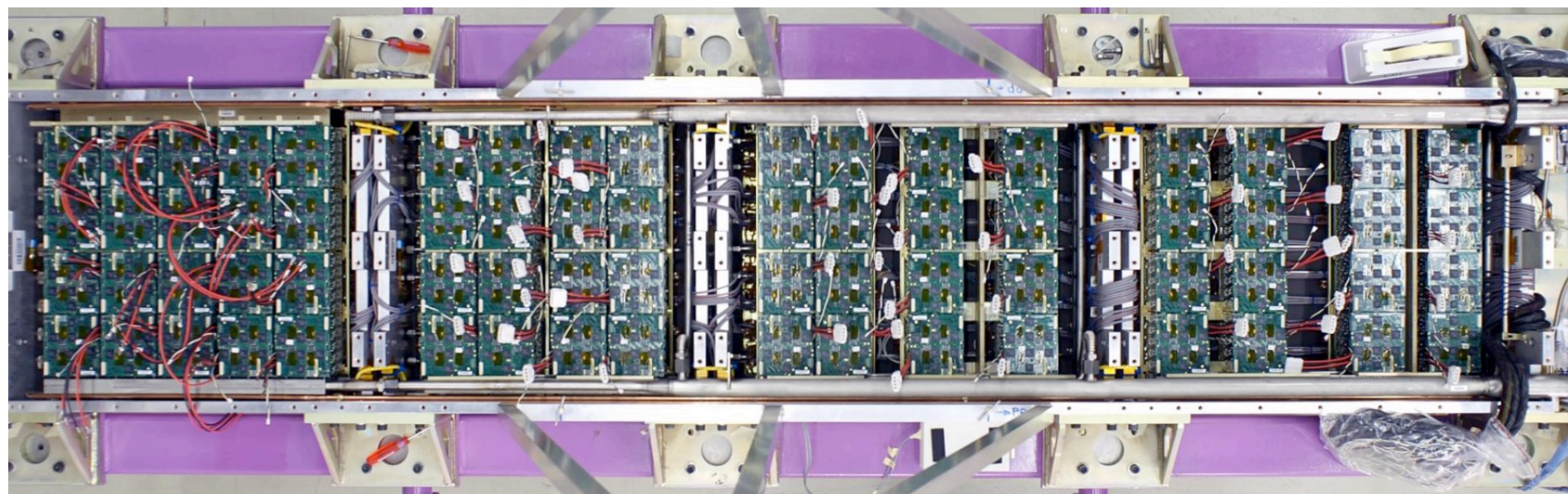
ECAL Barrel construction



Electronics installation

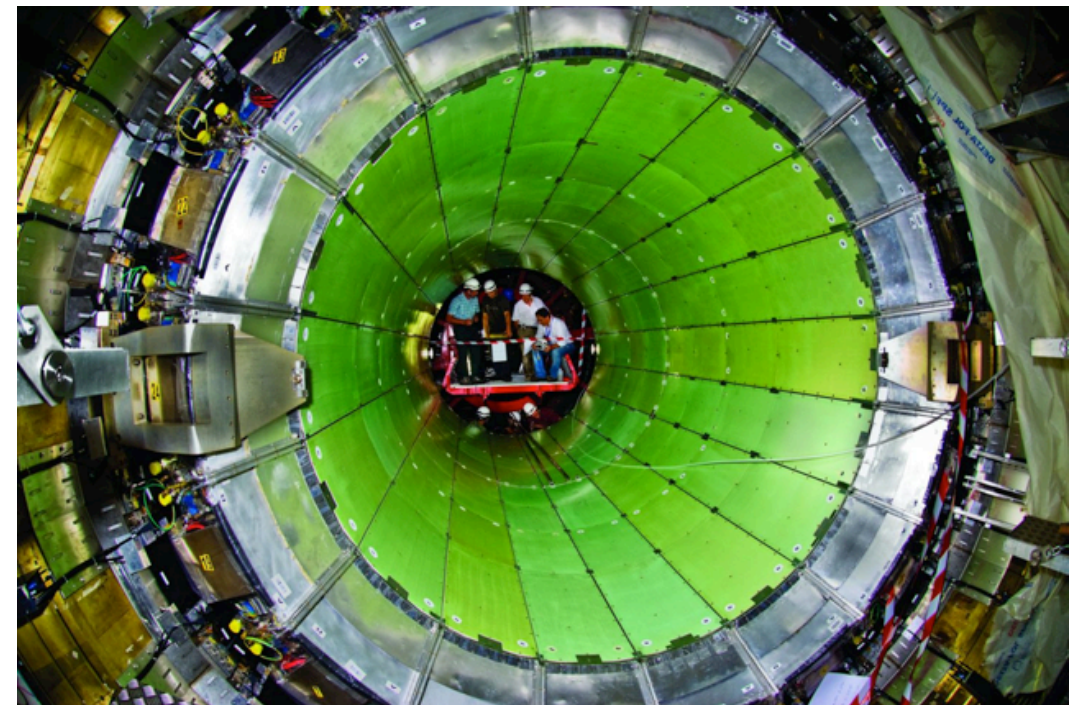
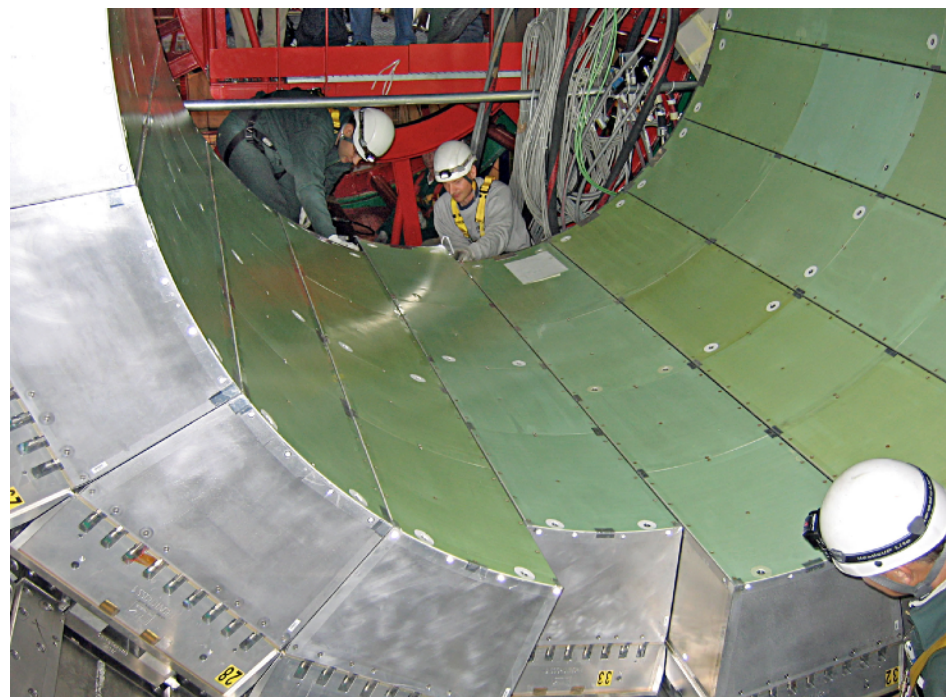
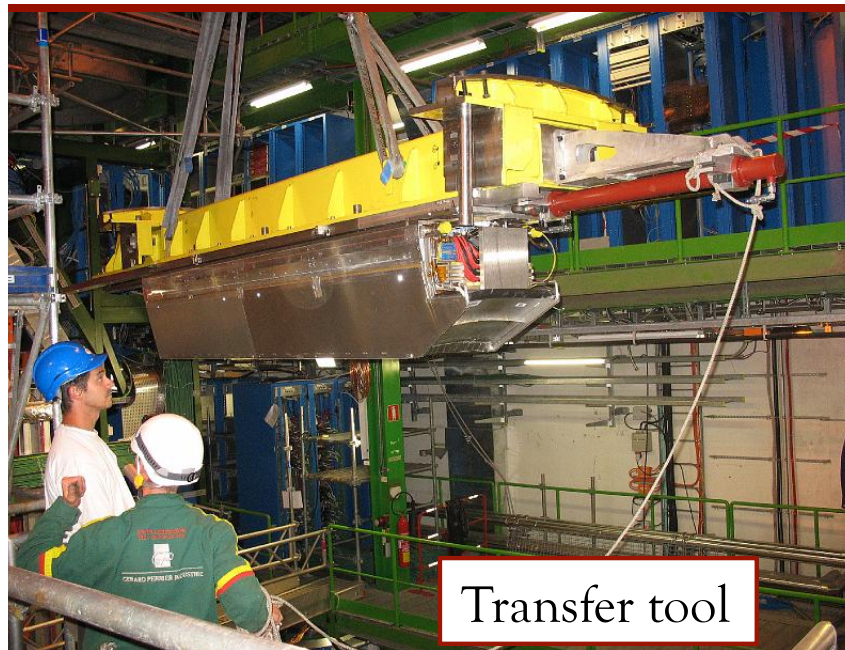


Supermodule integration/test stands @ Preveessin

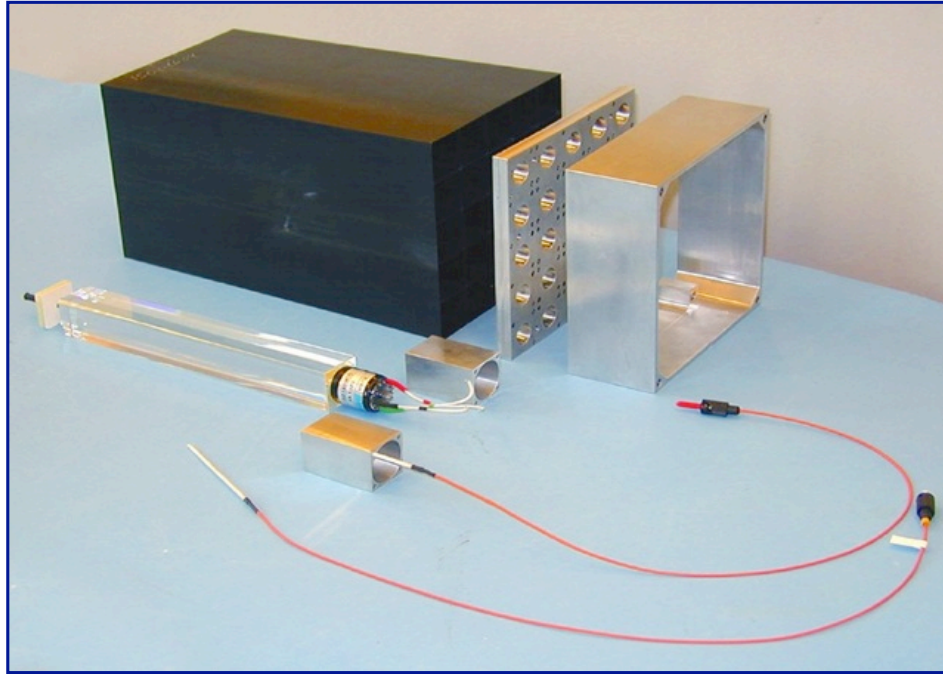


Supermodule in the process of electronics integration

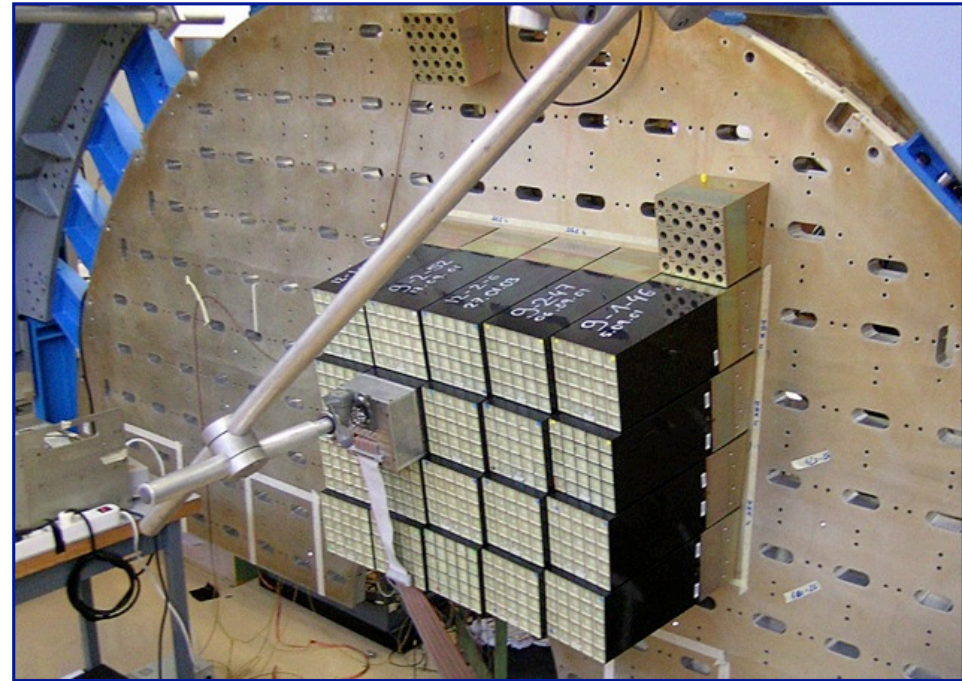
ECAL Barrel installation



ECAL Endcaps construction



**Elements of a EE supercrystal
(5x5 channels)**



Supercrystals on endcap backplane



Installing supercrystals

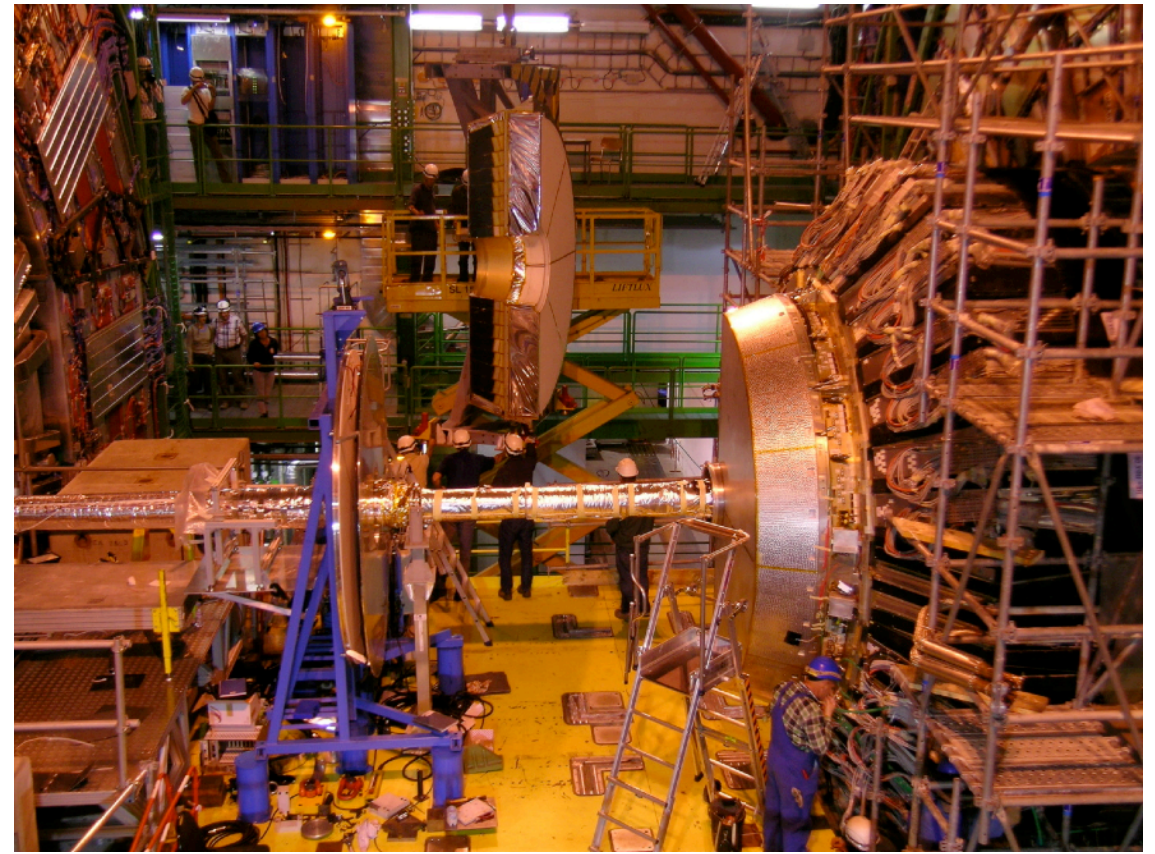


Installation of readout electronics

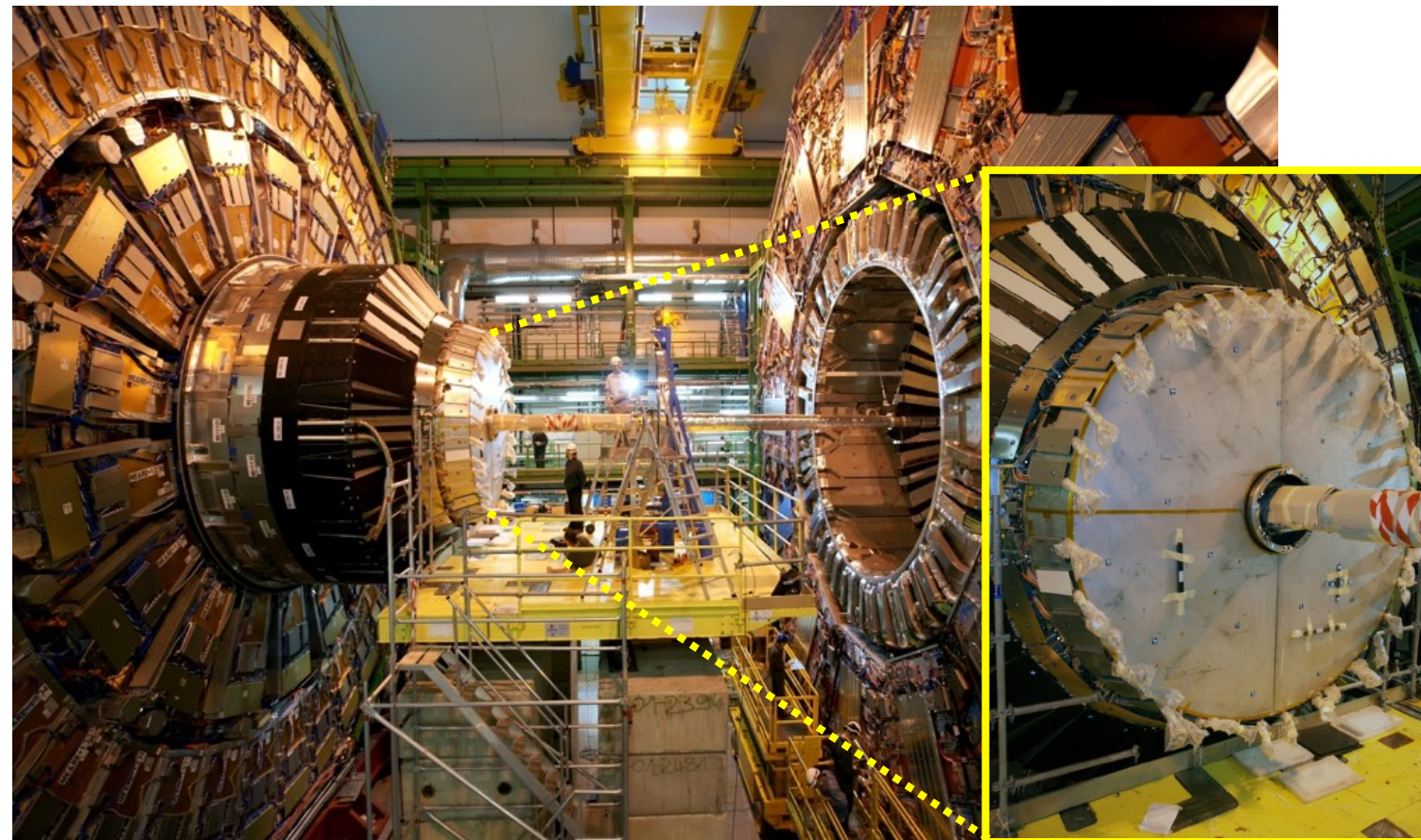
ECAL Endcaps installation



Endcap half disk (Dee) at Point 5

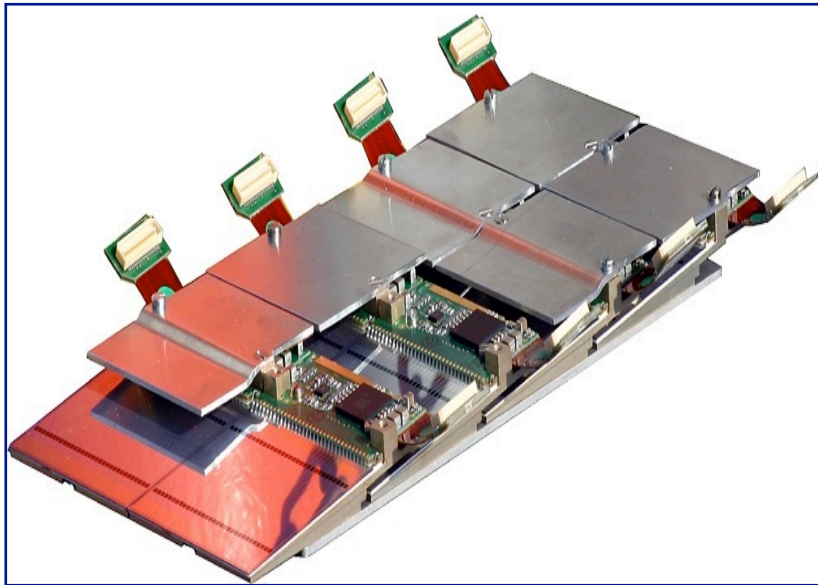


Lowering the second half disk (Dee)

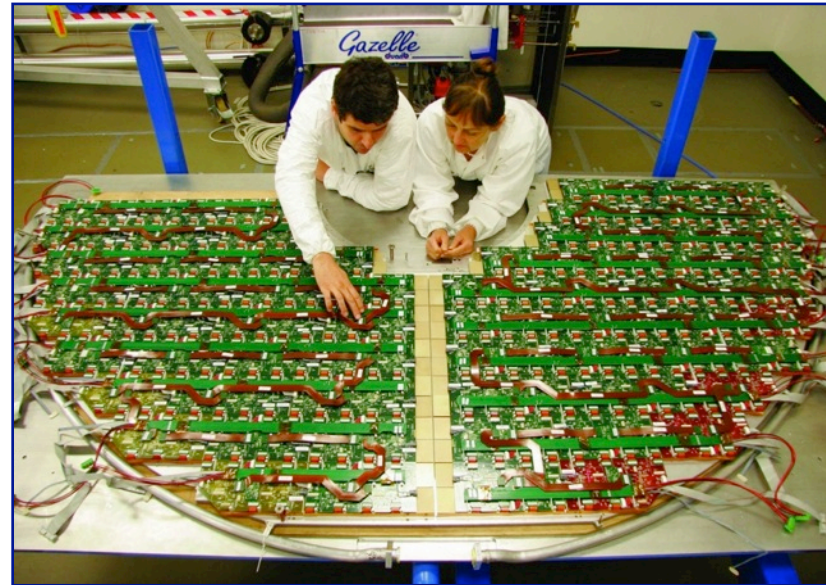


First endcap installed (Aug 2008)

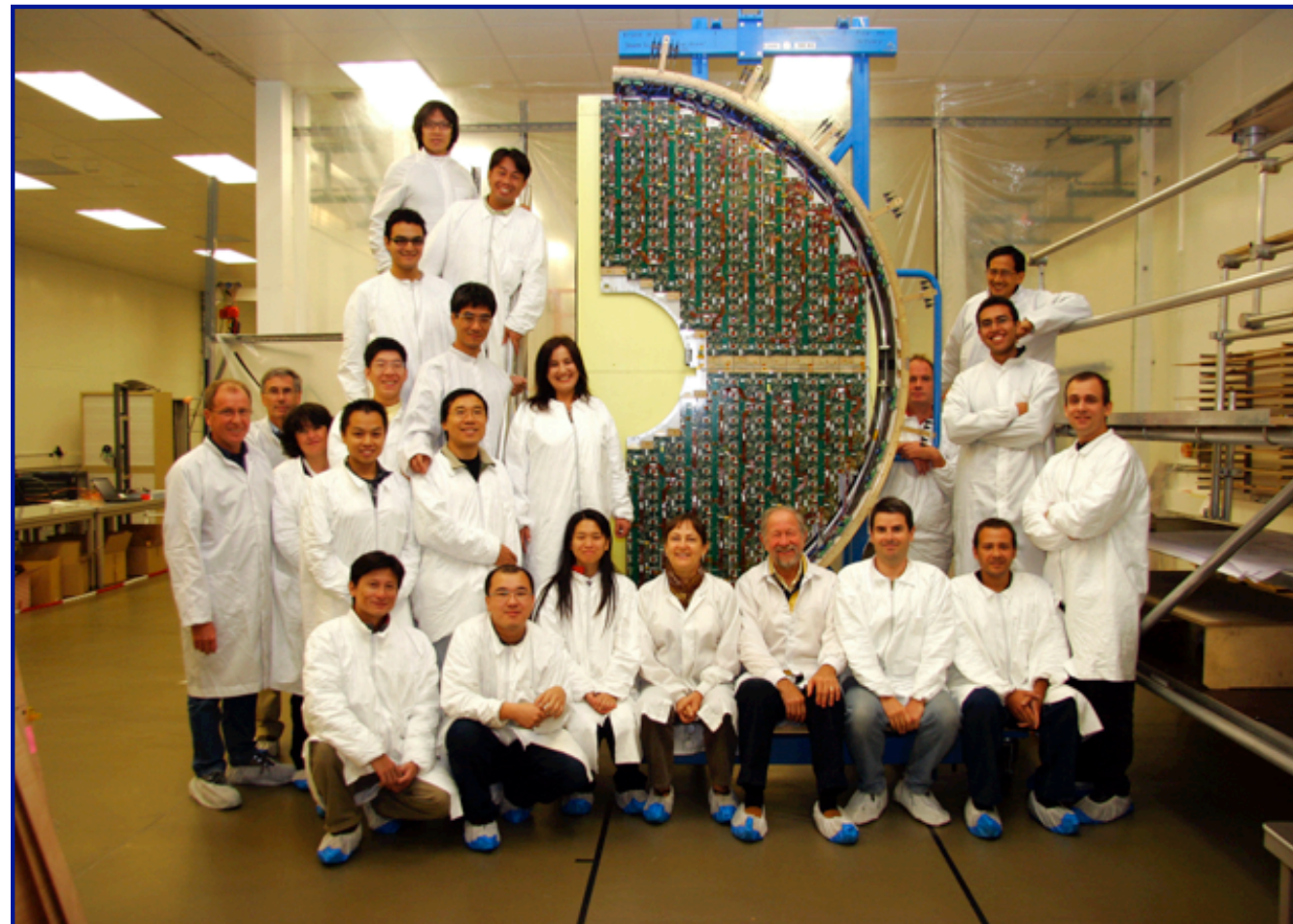
ECAL Preshower construction



Preshower Si hybrids

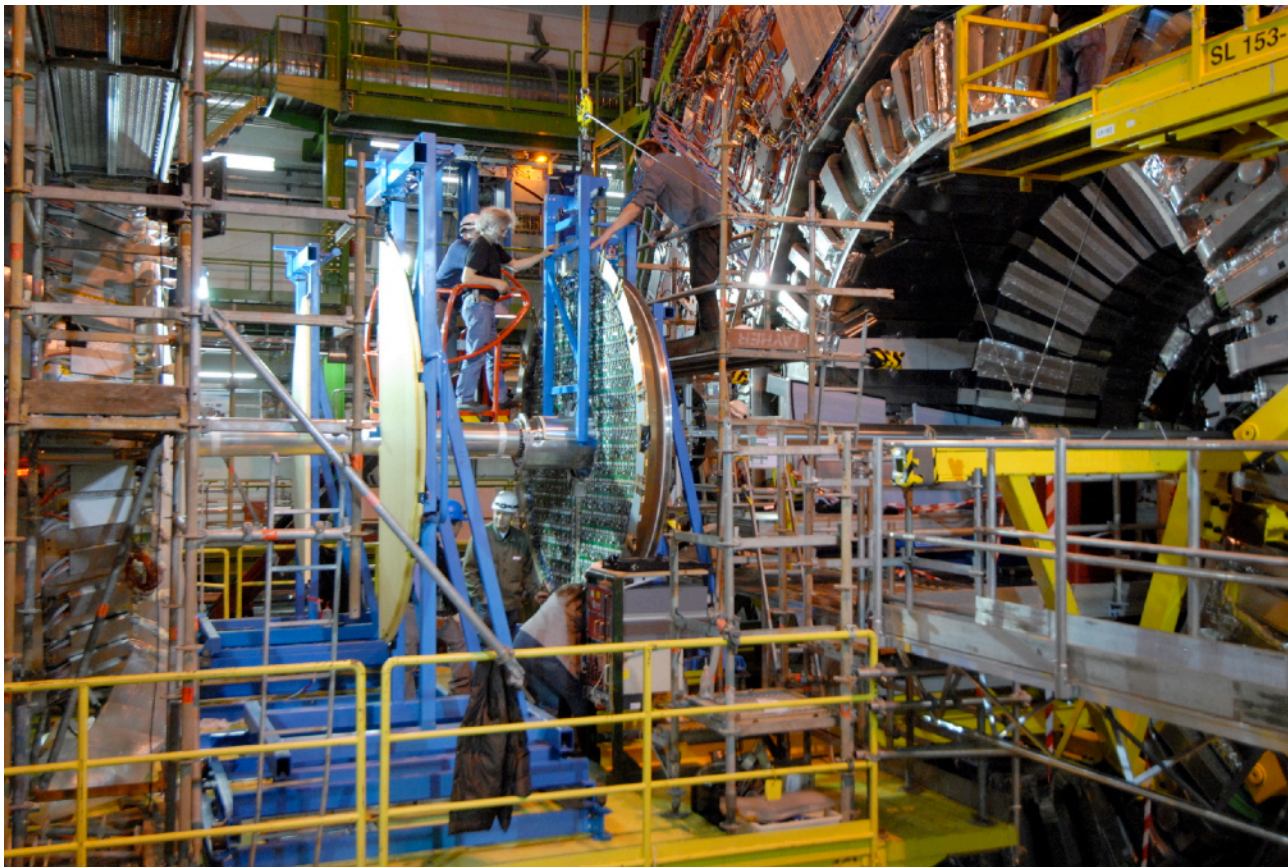


Electronics integration



completed half-disk (Dee)

ECAL Preshower installation

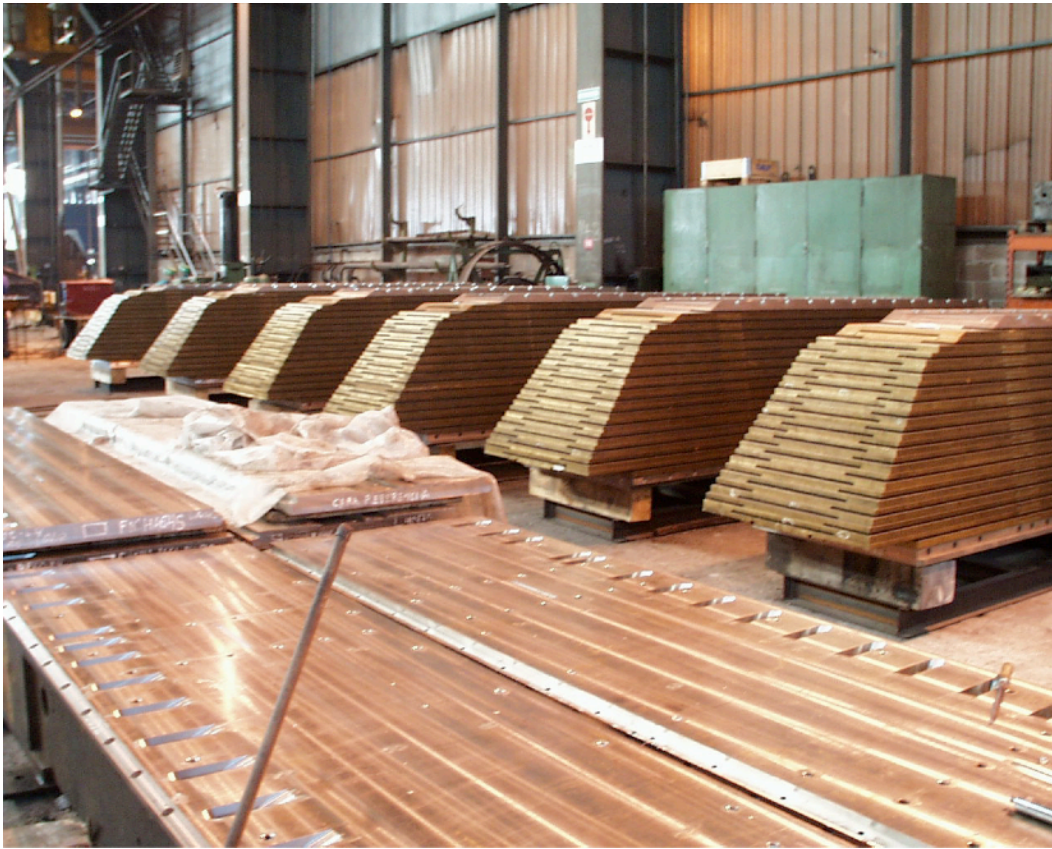


Preshower Dees lowered in place



Preshower Dees positioned around beam pipe

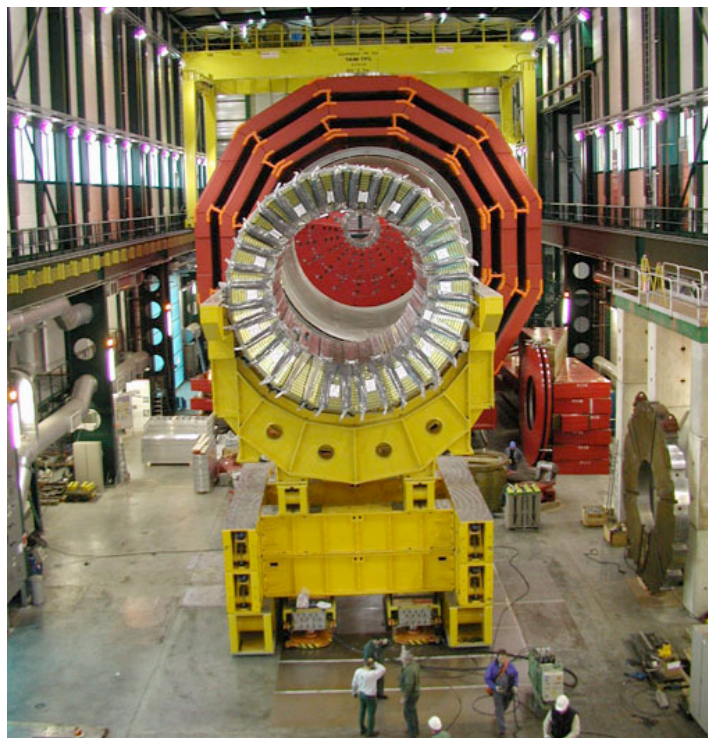
HB construction and installation



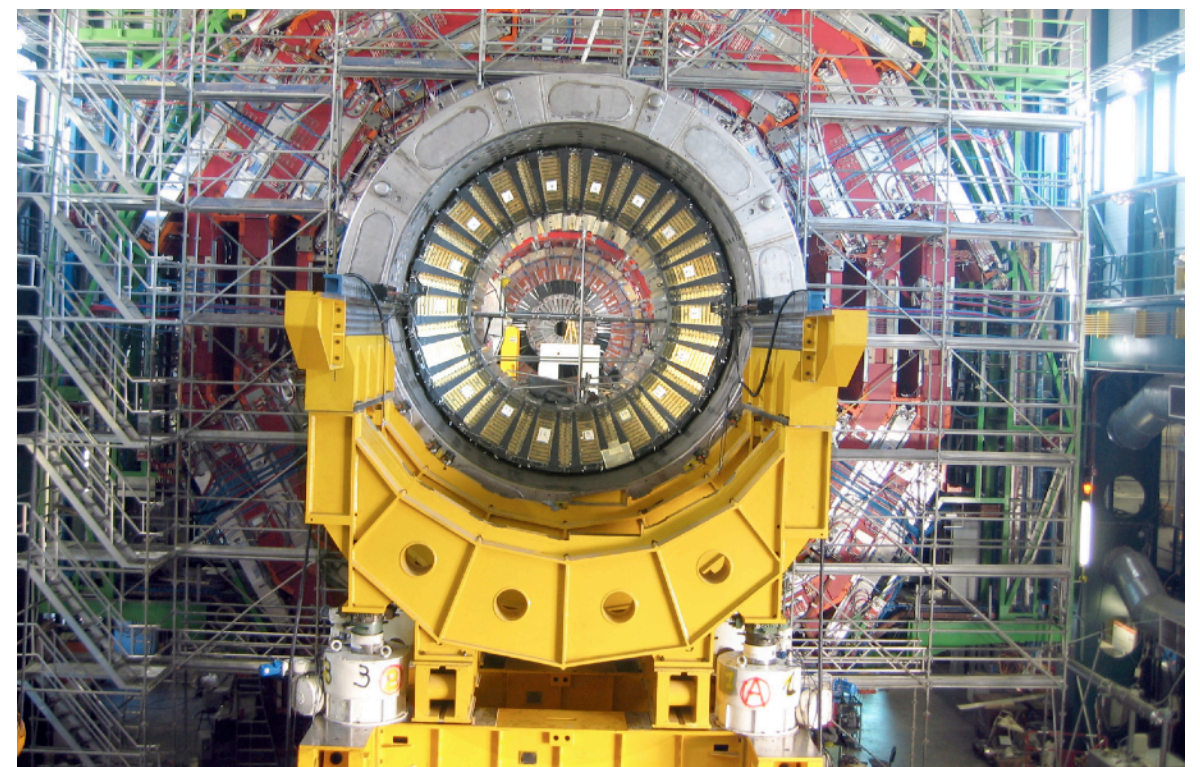
HB brass wedges



HB construction

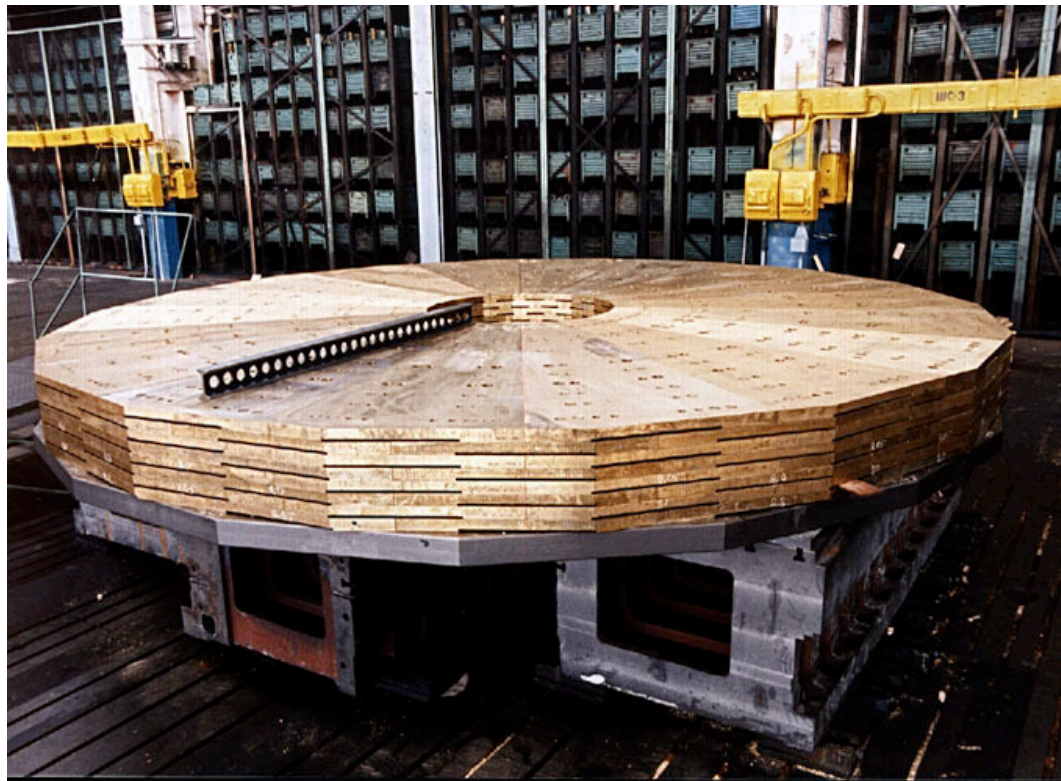


completed HB section ready to enter yoke



HB section inside yoke

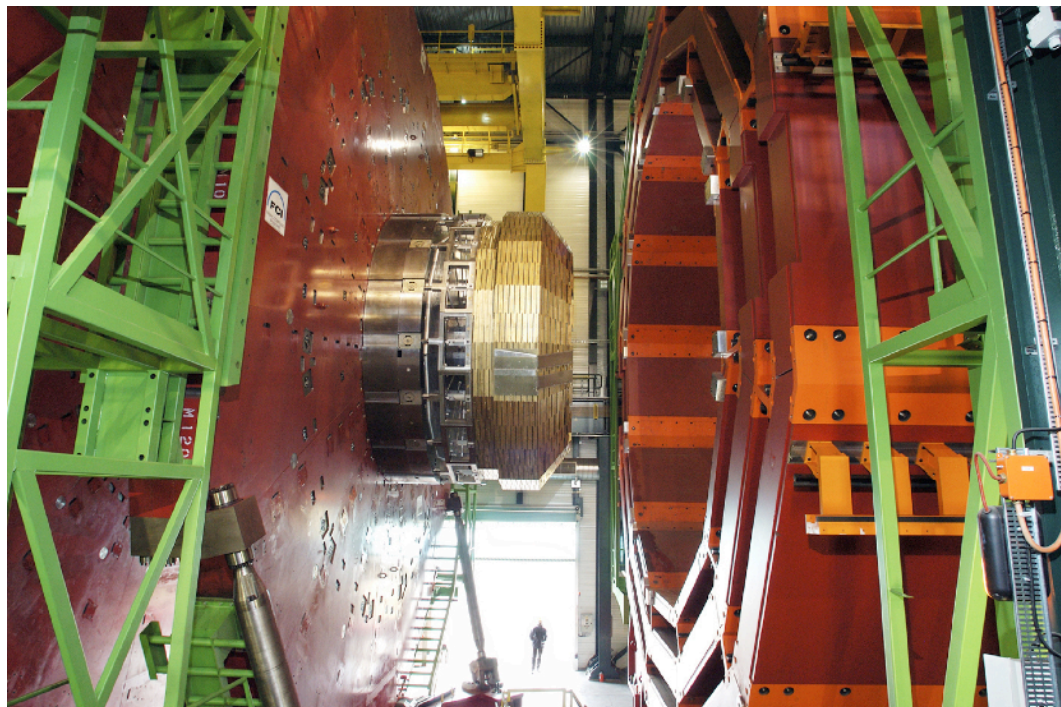
HE construction and installation



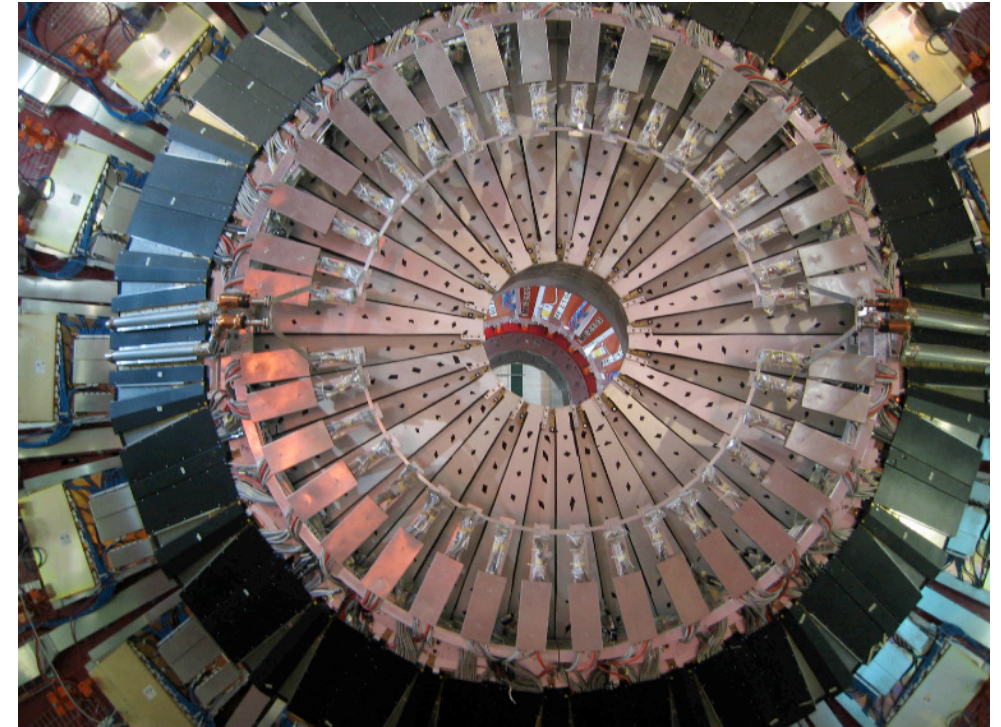
Building up HE brass structure



Completed HE brass structure



Completed HE installed on YEI



Completed HE with ES services on top

Forward HCAL



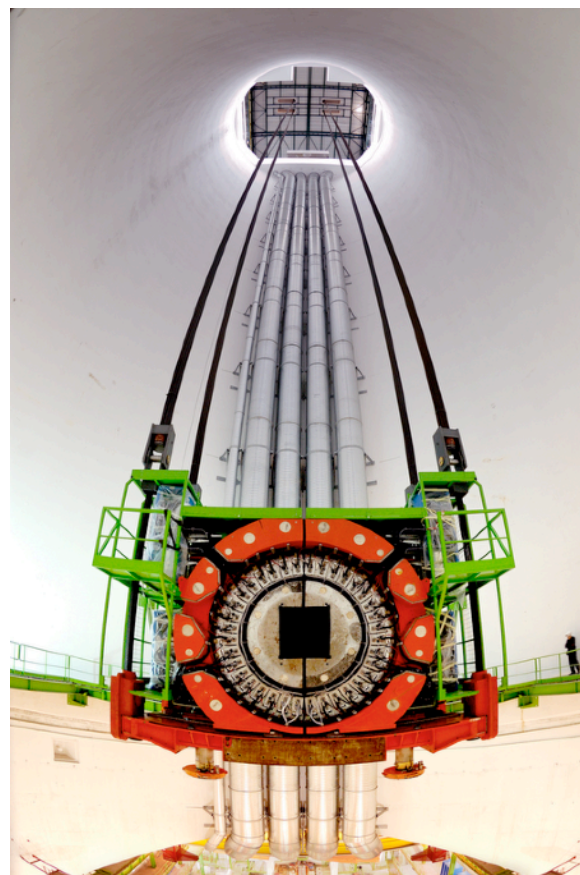
Inserting HF quartz fibres



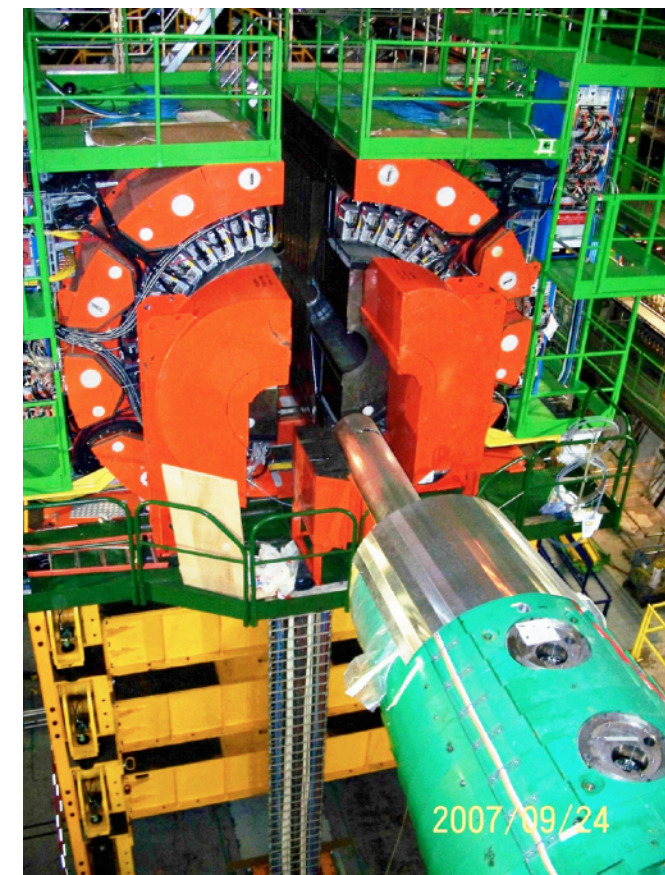
HE wedges + fibre bundles



HF transport from Meyrin

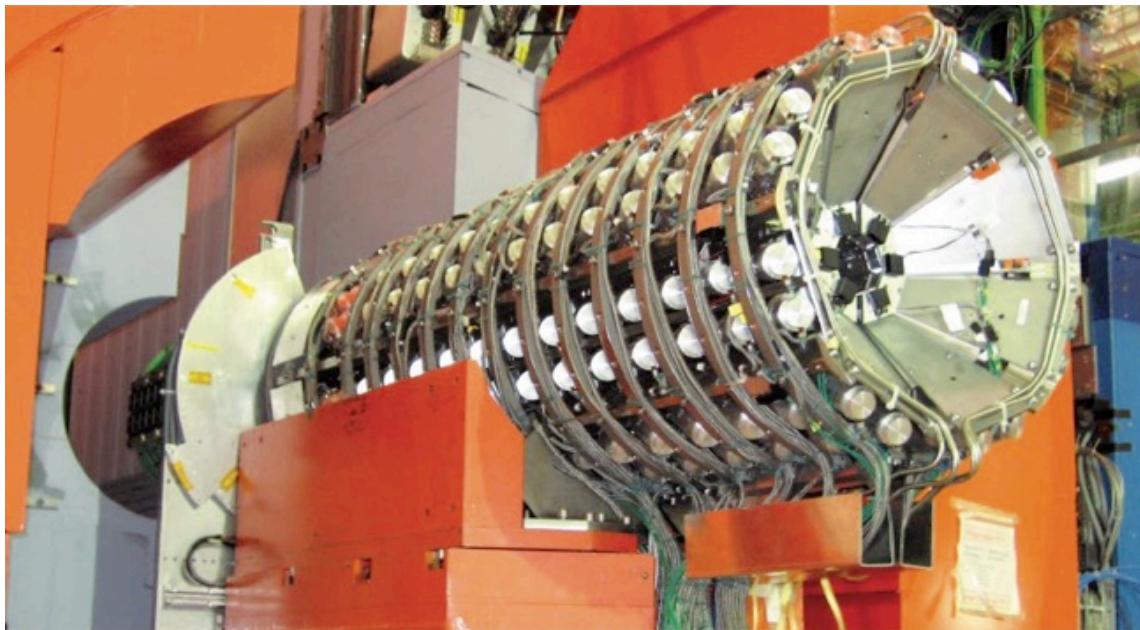


Lowering HF



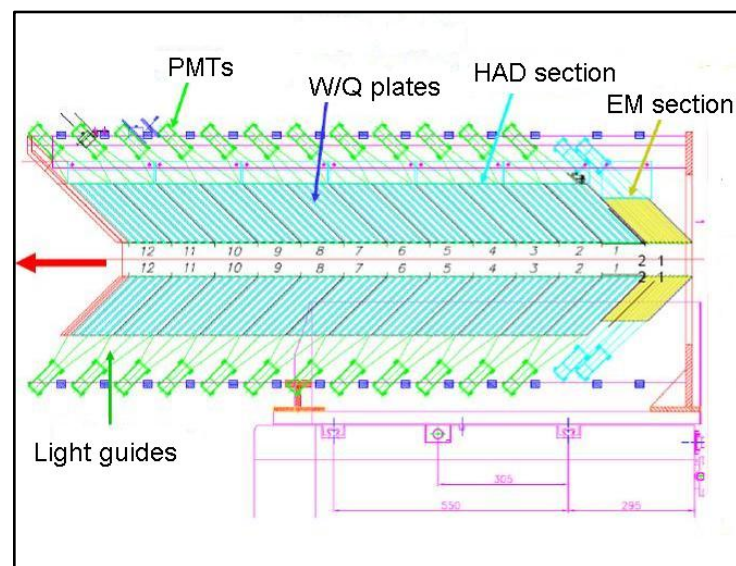
HF installed

Other Forward HCAL detectors



CASTOR

(Centauro and Strange Object Research)



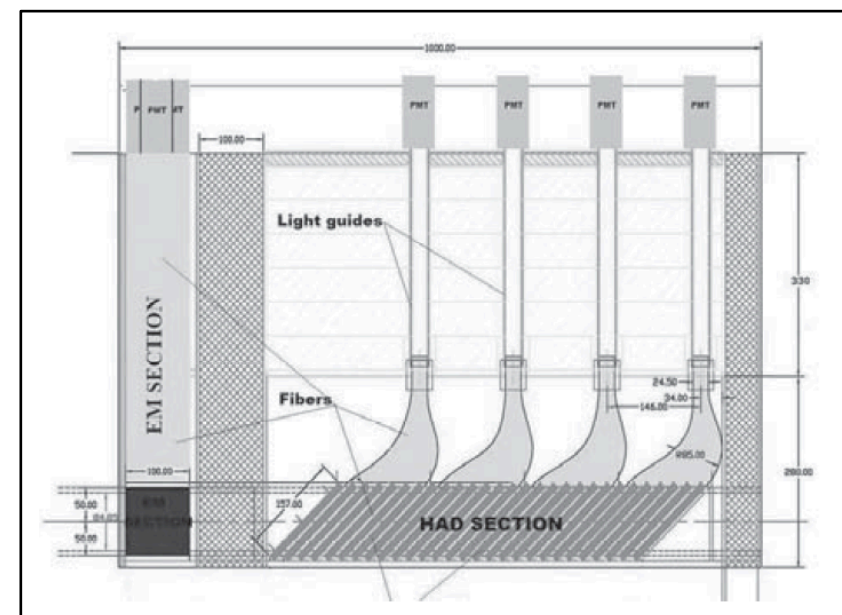
5.2 < |eta| < 6.6

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
12.5 μ s L1 latency

Mandatory to replace:

Front end card

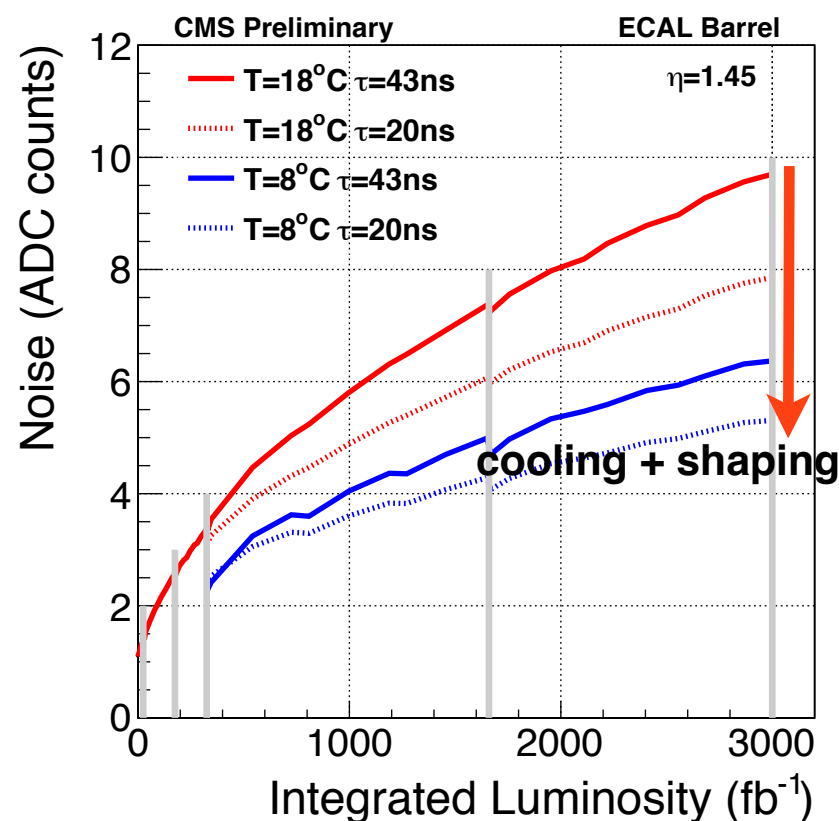
(remove on-detector latency buffer and rate limitation)

OD electronics

(remove rate limitation)

APD noise mitigation

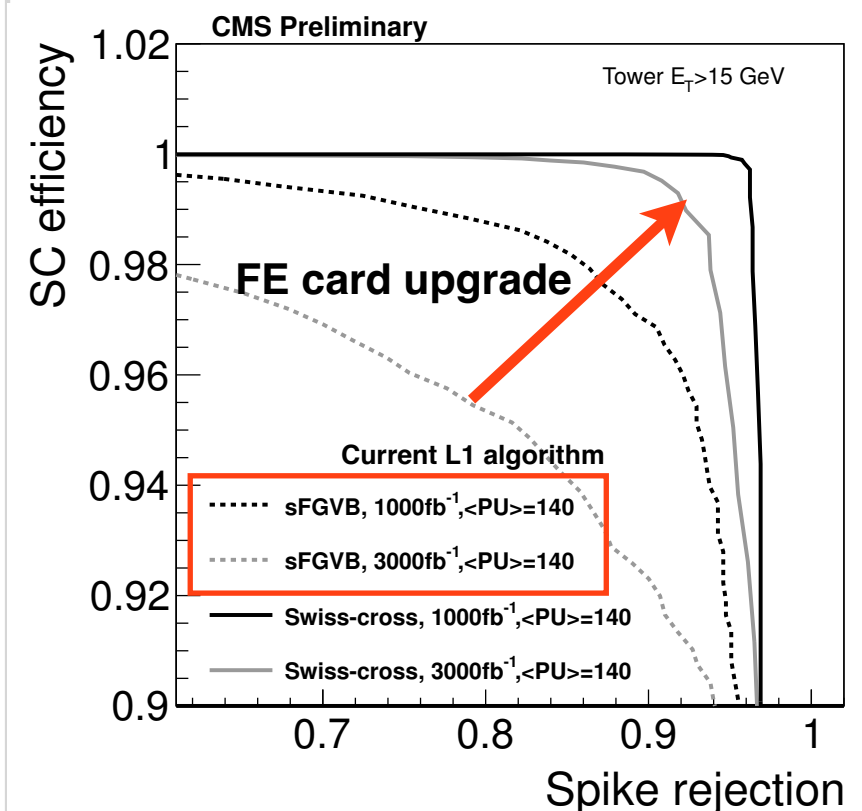
APD noise increase will significantly degrade EM resolution at HL-LHC



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

Spike mitigation

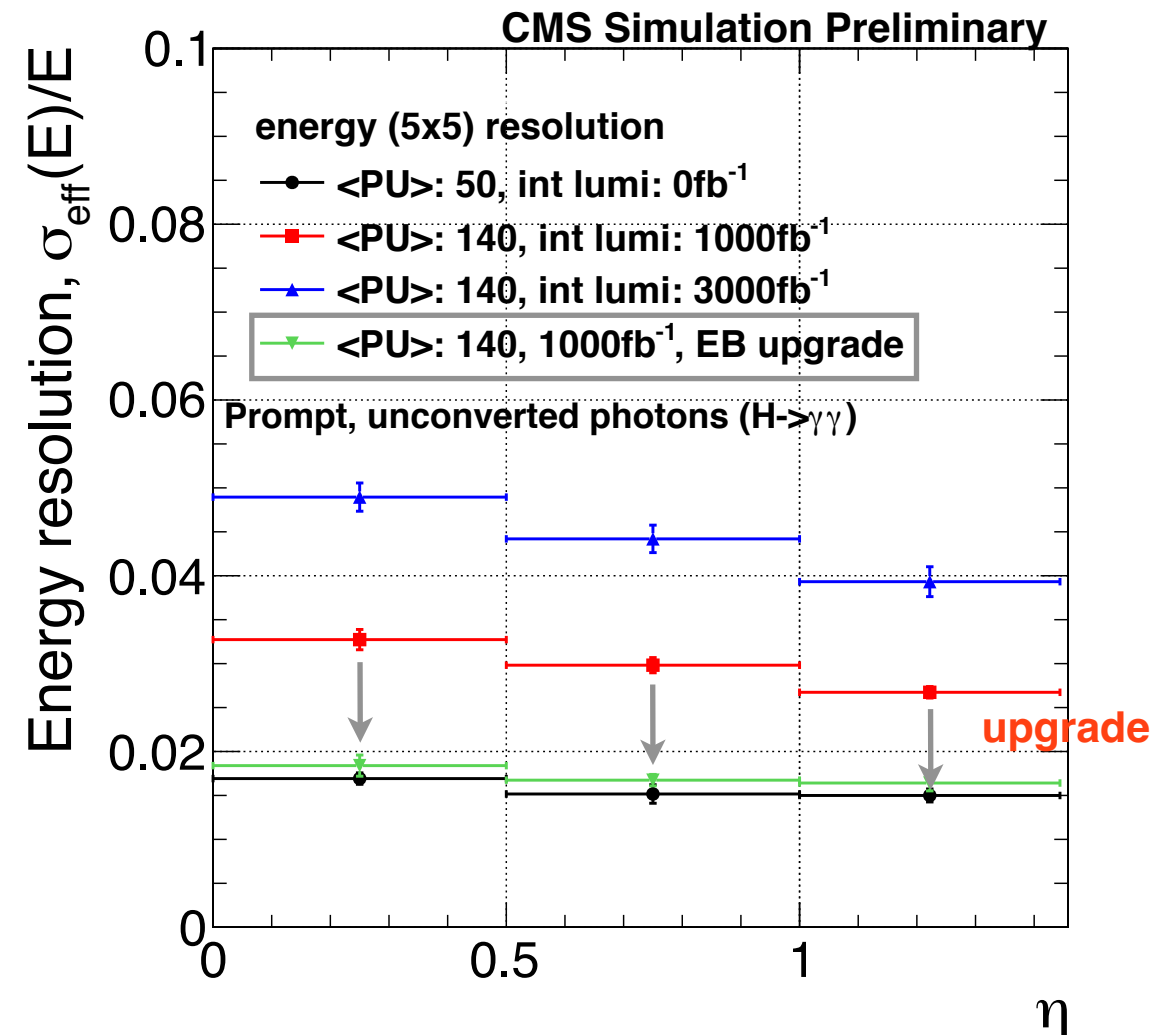
Performance of current L1 spike killer will degrade significantly.



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

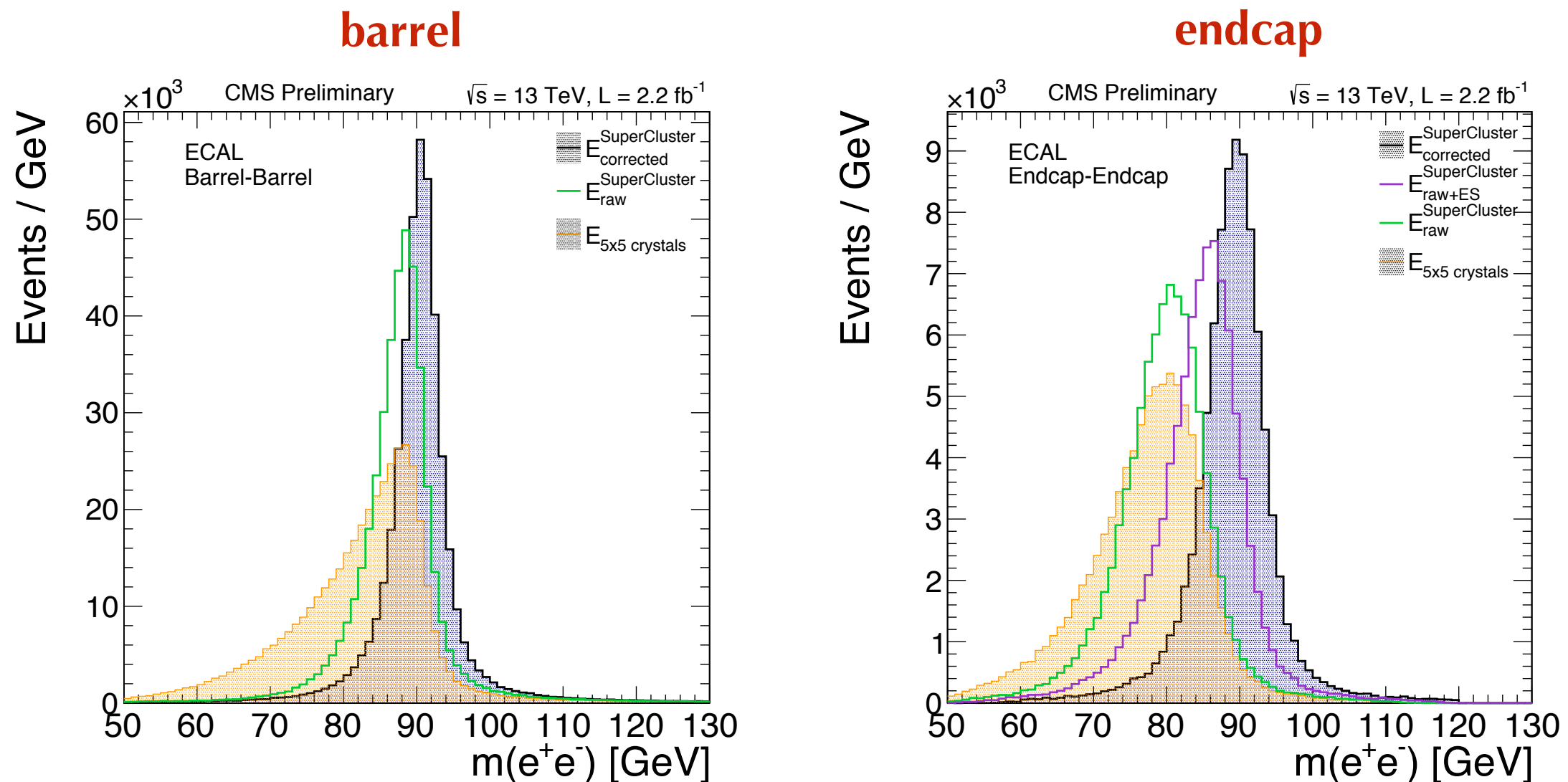
Physics reasons for the Upgrade

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



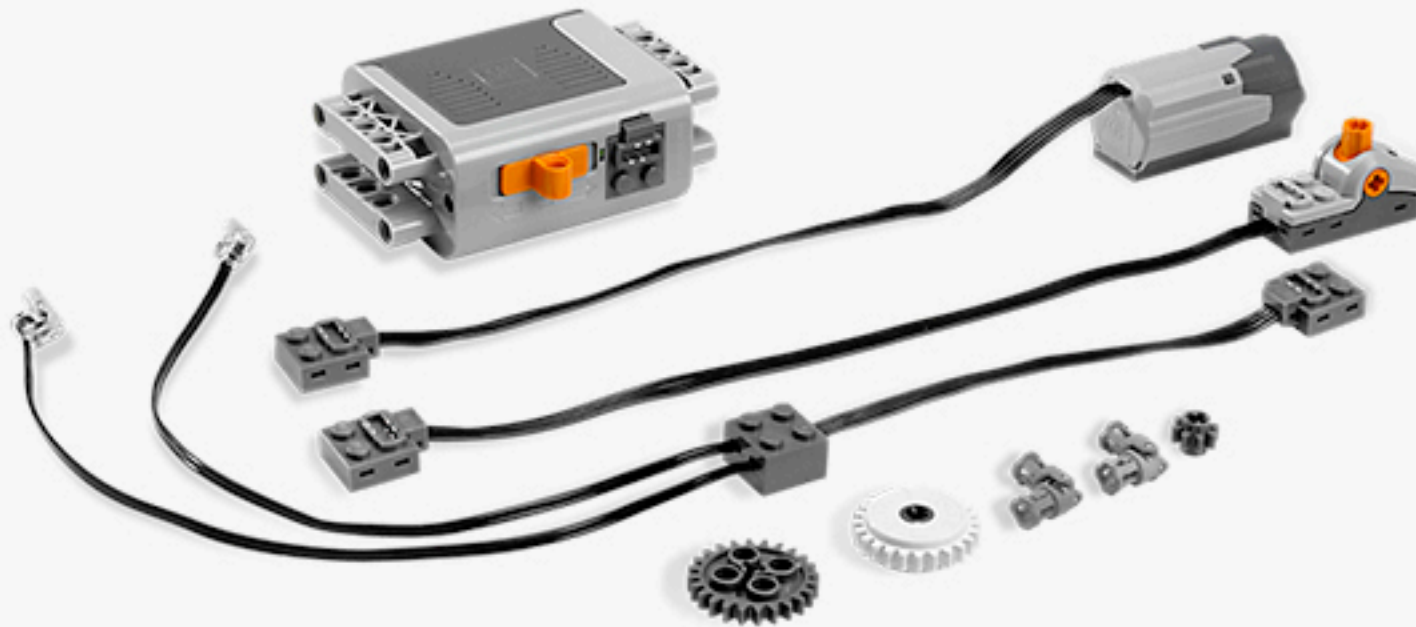
Upgrade is mandatory to maintain good electron/photon resolution in Phase II

ECAL energy reconstruction



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

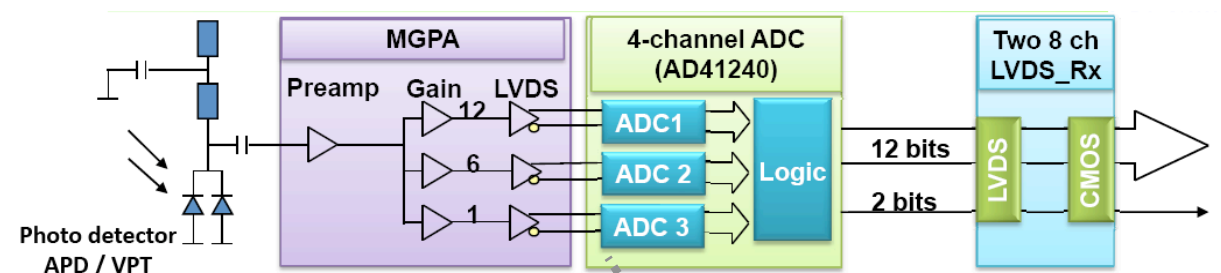
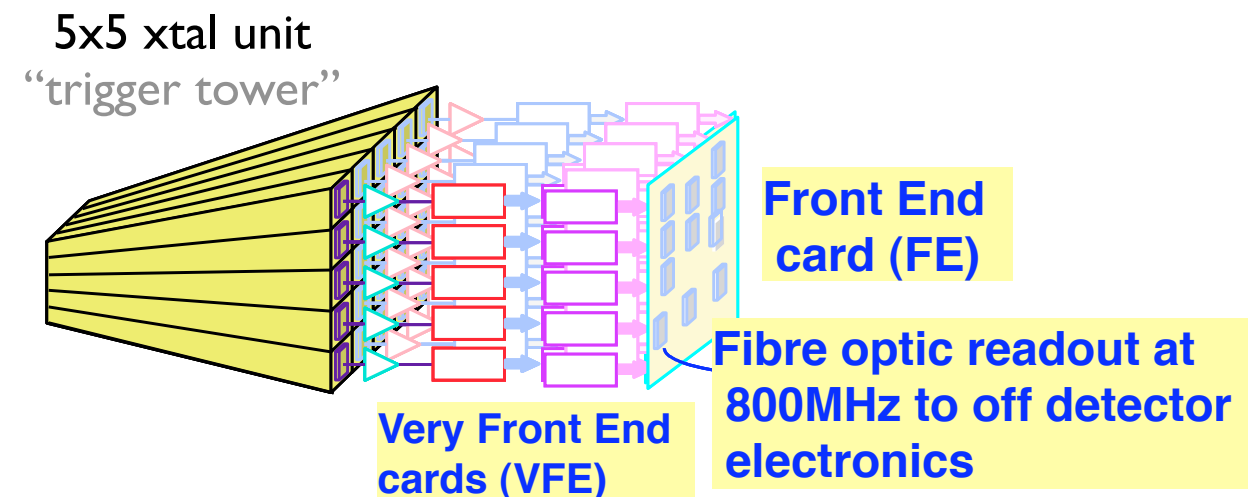
On-detector readout:

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

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

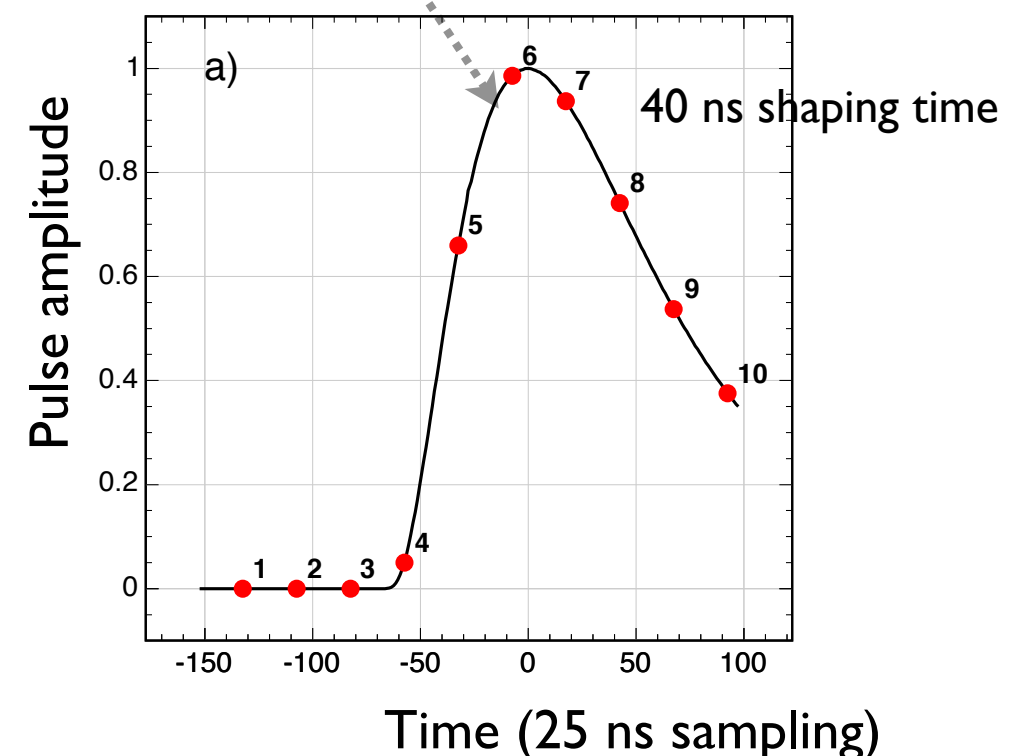


Off-detector readout:

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



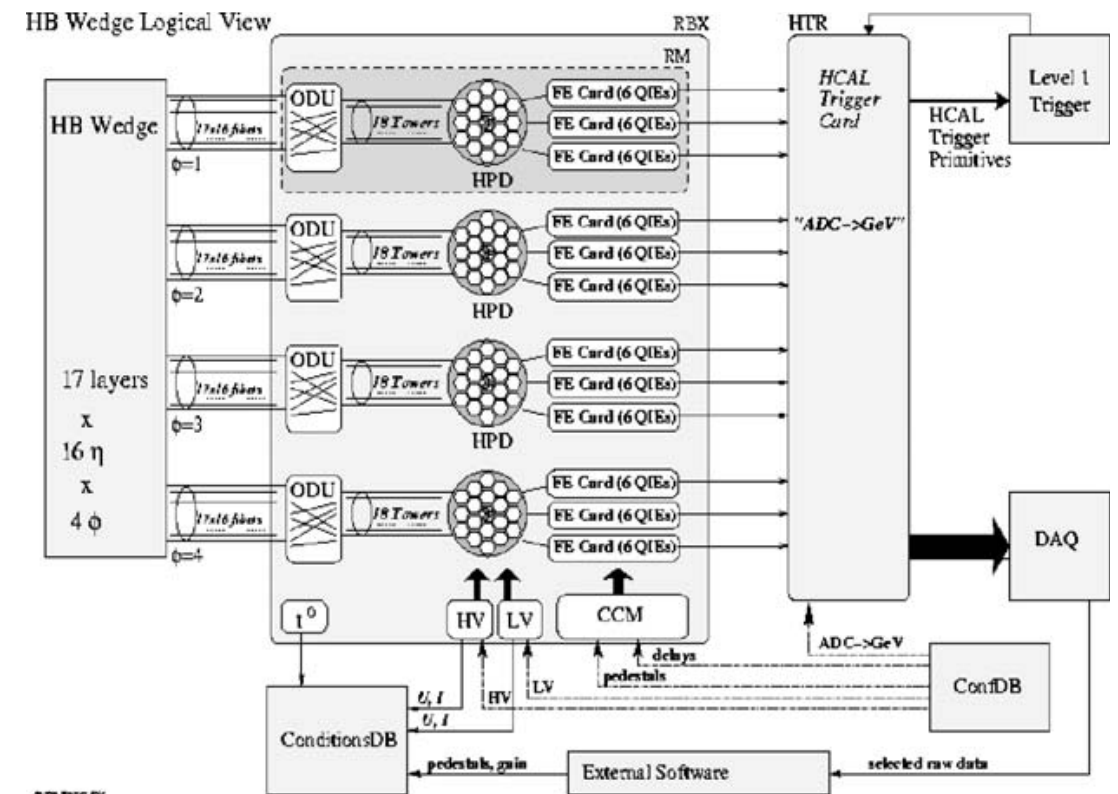
HCAL readout

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)

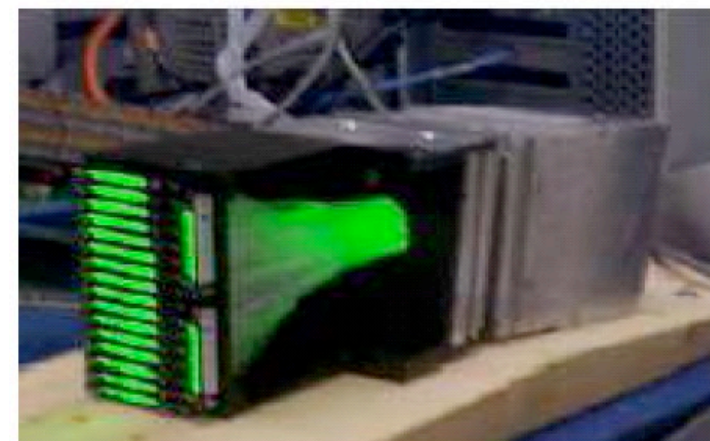
FE card: analogue signal from APDs digitized using charge-integrating preamplifier (**QIE**)



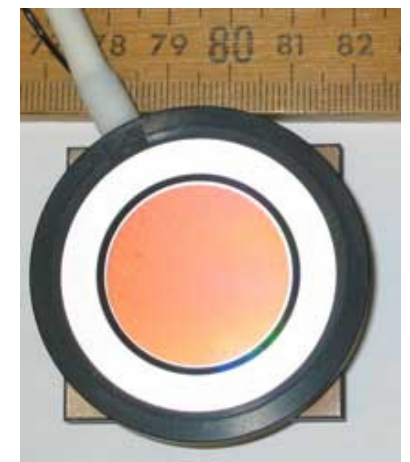
Off-detector readout:

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

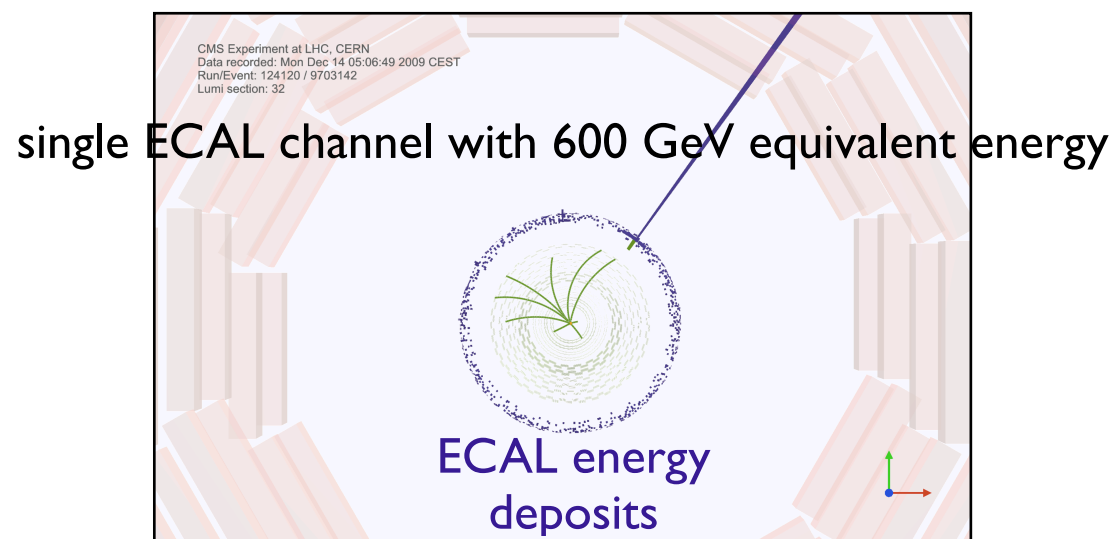


HPD

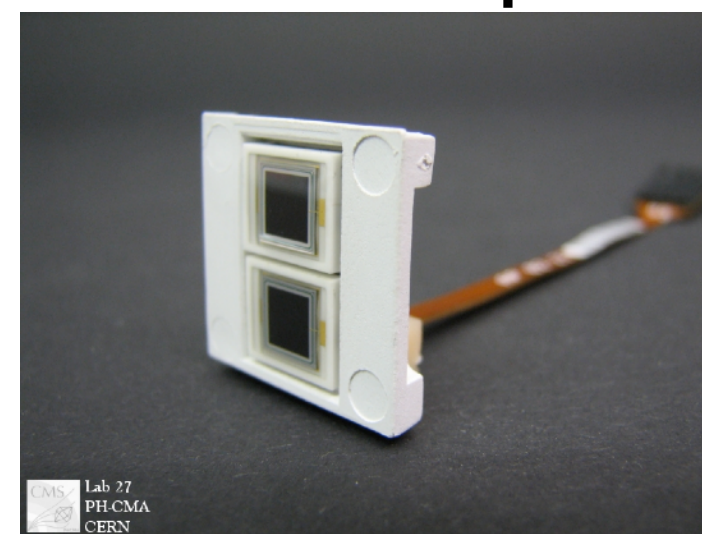
ECAL spikes

- **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

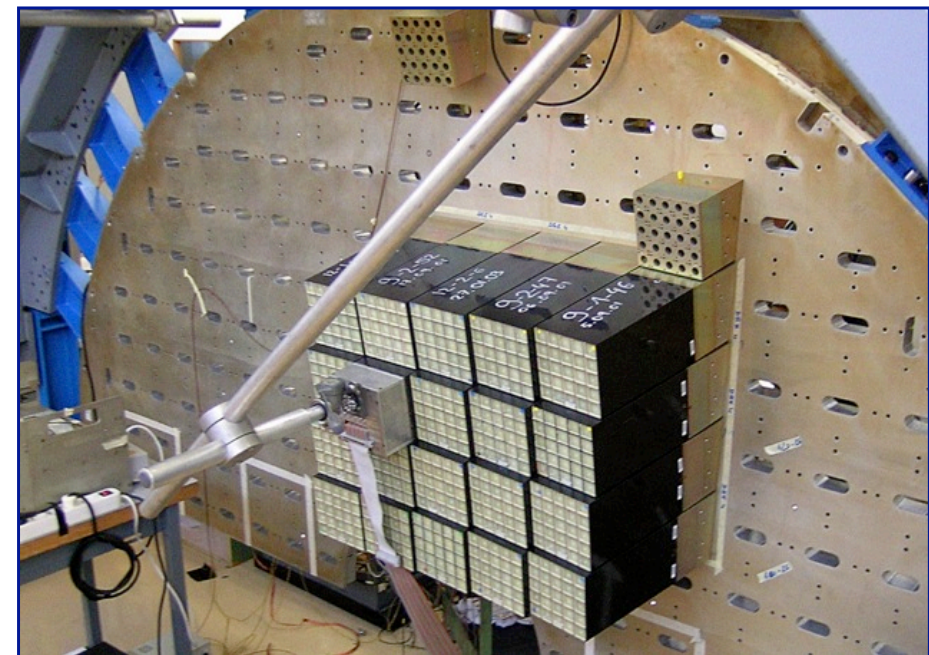
- Significant differences in mechanical design of ECAL Barrel and Endcaps**

- 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

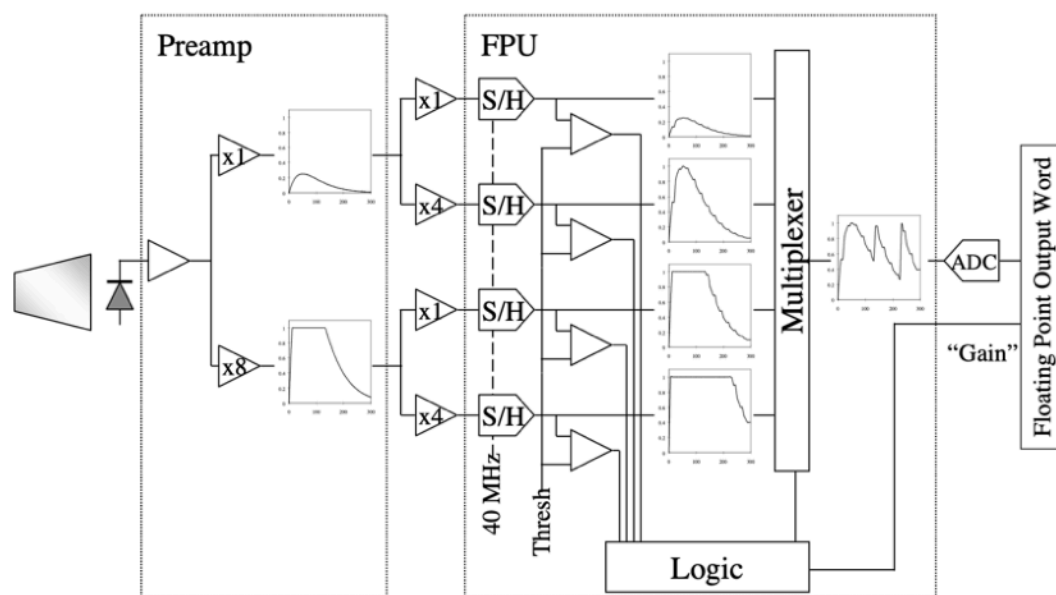
- Should also consider possibility for partial dismounting/replacement of modules**

- 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

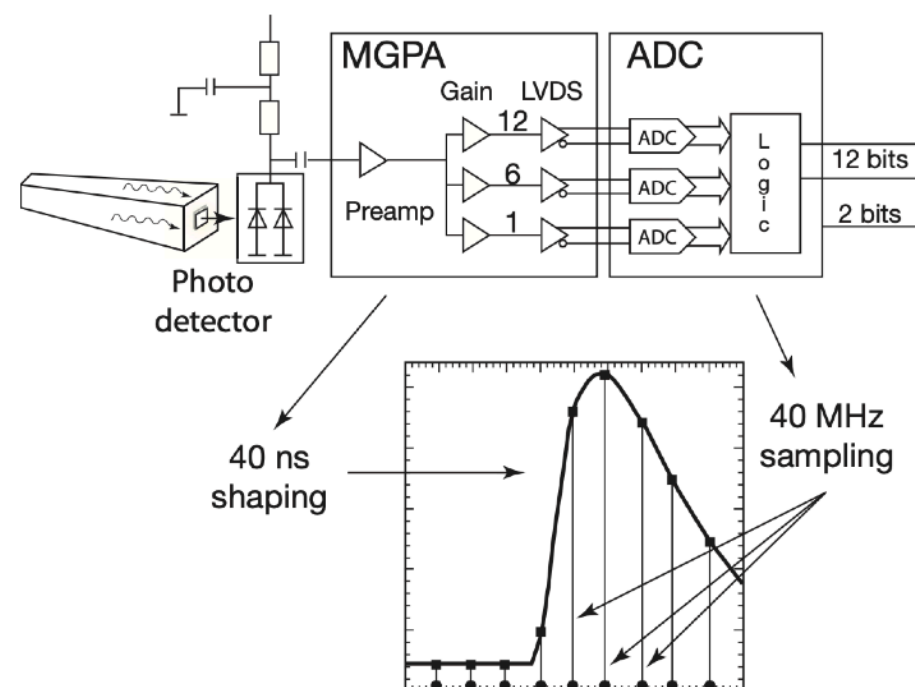
ECAL ASICs

- 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 $Z \rightarrow ee$ to photons from $H \rightarrow \gamma\gamma$?

How different is the energy scale?

not much:

electrons from $Z \rightarrow ee$ are roughly 45 GeV - but with a spread in energy

typical photons from $H \rightarrow \gamma\gamma$ 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:

$$E_{e,\gamma} = \sum_i \left[\overset{\text{Pulse Amplitude}}{A_i} \times \underset{\substack{\text{time-dependent response corrections:} \\ \text{laser monitoring system}}}{S_i(t)} \times \overset{\text{intercalibration}}{c_i} \right] \times \underset{\text{Global scale}}{G(\eta)} \times \overset{\text{cluster corrections}}{F_{e,\gamma}}$$

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.

How can we do that?

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 $\rightarrow$ compact showers

Electrons are either showering or non-showering

showering: bremsstrahlung electrons emitted along the track prior to ECAL $\rightarrow$ shower spreads out in B-field direction

non-showering: no showering prior to the ECAL $\rightarrow$ 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 3×3 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 $Z \rightarrow ee$ energy scale (using electrons reconstructed as photons) as a function of the leading “photon” p_T

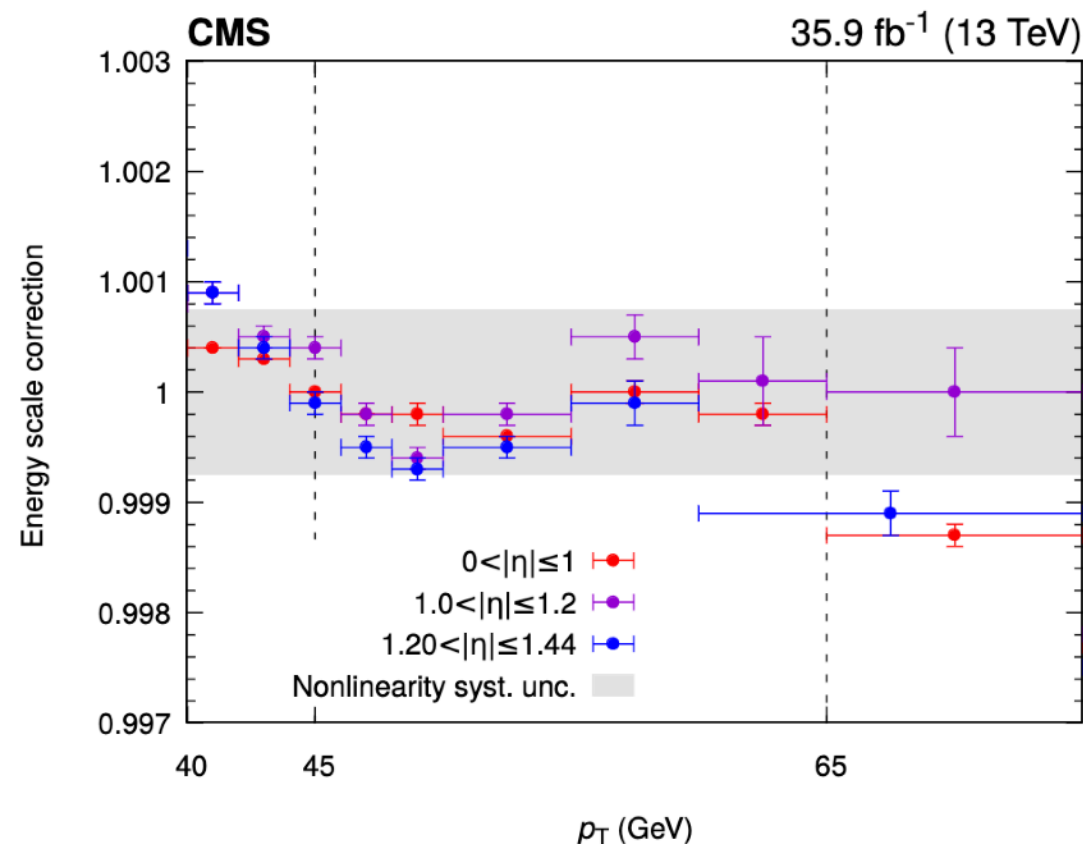


Figure 1: Energy scale corrections as a function of the p_T of the photon. The horizontal bars in the plot represent the variable bin width. The systematic uncertainty associated with this correction is approximately the maximum deviation observed in the p_T range between 45 and 65 GeV for electrons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

Use this technique + the fact that the “photons” from $Z \rightarrow ee$ span a range of p_T to provide the necessary corrections for $H \rightarrow gg$ photons

electrons from W can also be used, but the invariant mass constraint from $Z \rightarrow ee$ 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?



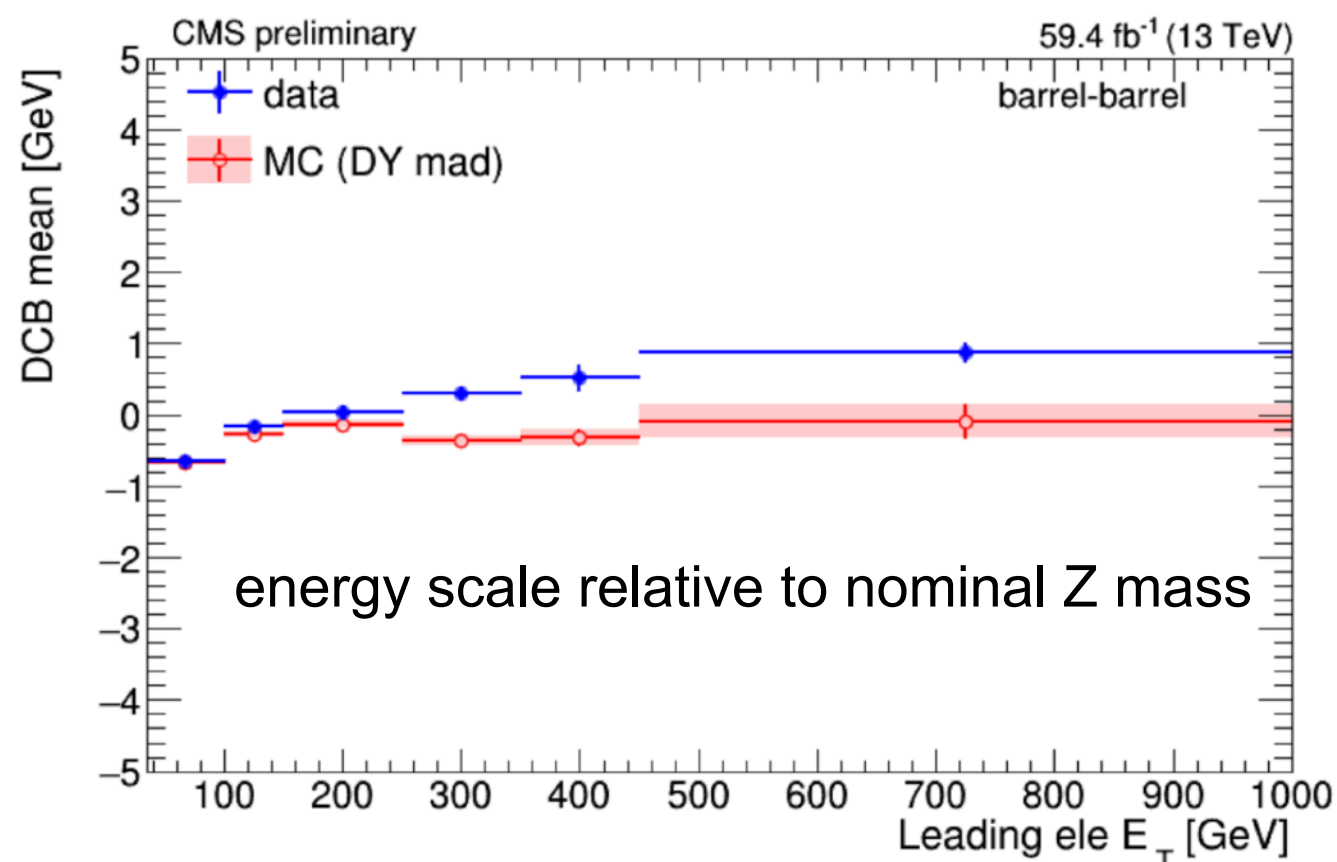
A1: Energy scale uncertainty

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 $\rightarrow$ 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) $\rightarrow$ 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 inhomogeneities

If you want high resolution tracking+calorimetry $\rightarrow$ 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