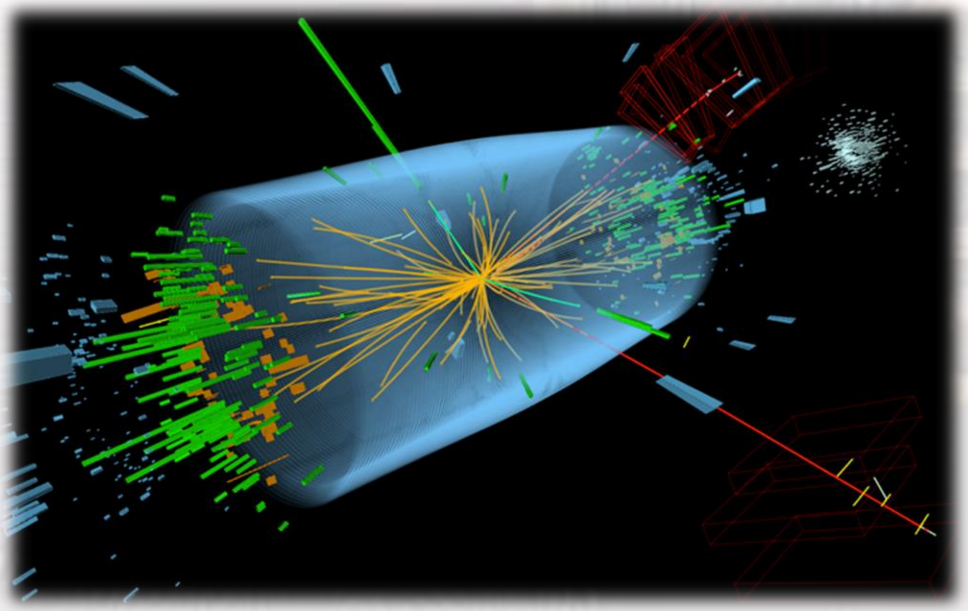
CMS Calorimetry

Introduction for Newcomers

1. Basics, inc. physics drivers
2. Technology choices
3. Data acquisition
4. Construction & Assembly
5. Issues since startup
6. Performance
7. Long-term future (HL-LHC)
8. Organization



David Barney, Subystem Manager, Electromagnetic Calorimeter (ECAL)
Pawel de Barbaro, Subsystem Manager, Hadron Calorimeter (HCAL)

Basics
Technology
Data Acquisition
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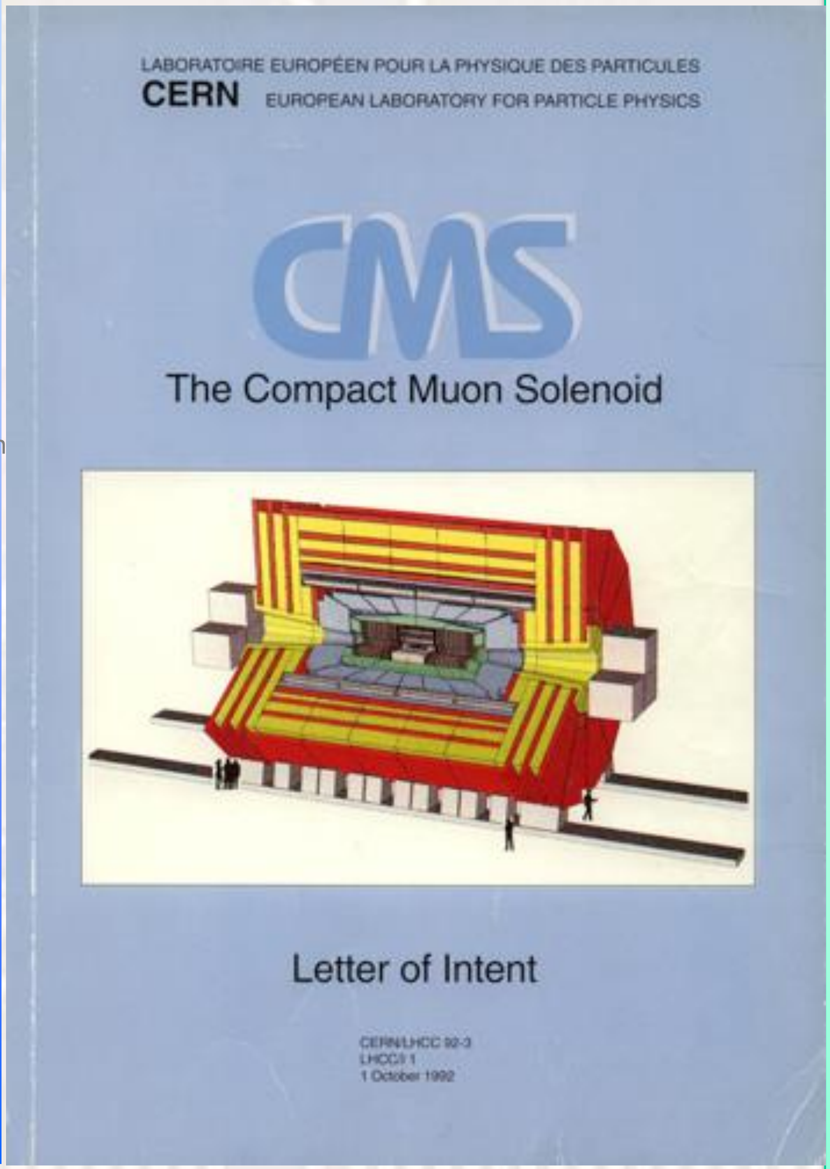
BASICS

Highly performant calorimetry has been mandatory since day 1



From the CMS Letter of Intent (1992): "*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*" …

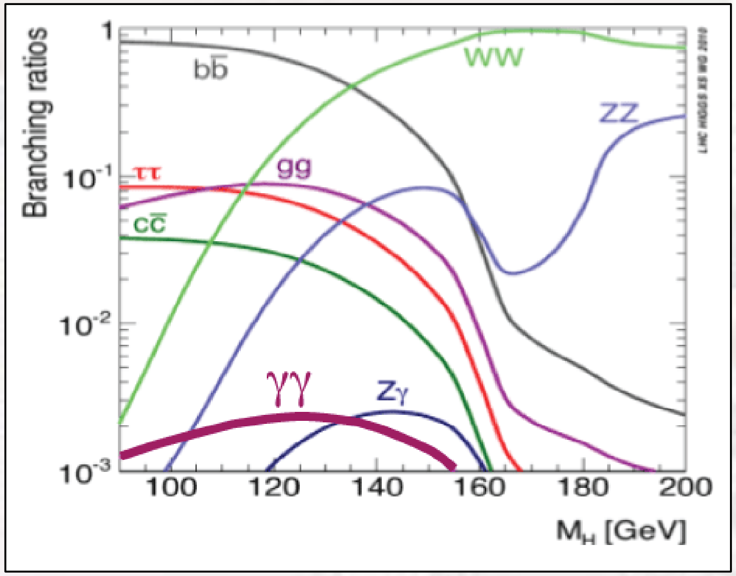
"*A high resolution **crystal electromagnetic calorimeter**, designed to detect the two photon decay of an intermediate mass Higgs, is located inside the coil.*"

"***Hermetic hadronic calorimeters** surround the intersection region up to $|\eta| = 4.7$ allowing tagging of forward jets and measurement of missing transverse energy.* "

CMS Calorimetry: Designed according to the physics of LHC

Benchmark for ECAL: H → γγ

- **Most sensitive channel for $m_H < 130$ GeV**
  - Small branching ratio (~0.3%) but very clean signature:
    - Narrow resonance of **two high E_T photons** over a non-resonant background of genuine or **fake** di-photon events



H → ZZ is the other "golden" channel

- **e/μ final states**

→Need high resolution, high granularity ECAL

HCAL is "*less constrained by the physics processes. Good energy resolution is less important…* ***Emphasis will be laid on hermeticity to ensure a good missing transverse energy (*** **$\not\!E_T$ or MET*****) measurement…***" (CMS Technical Proposal, 1994)

- Coverage up to **|η|~5 is necessary**, e.g. for heavy H → ZZ → $l^+l^-\nu\nu$
- Extending from |η|=3 to |η|=5 **improves resolution of missing E_T by a factor 3**

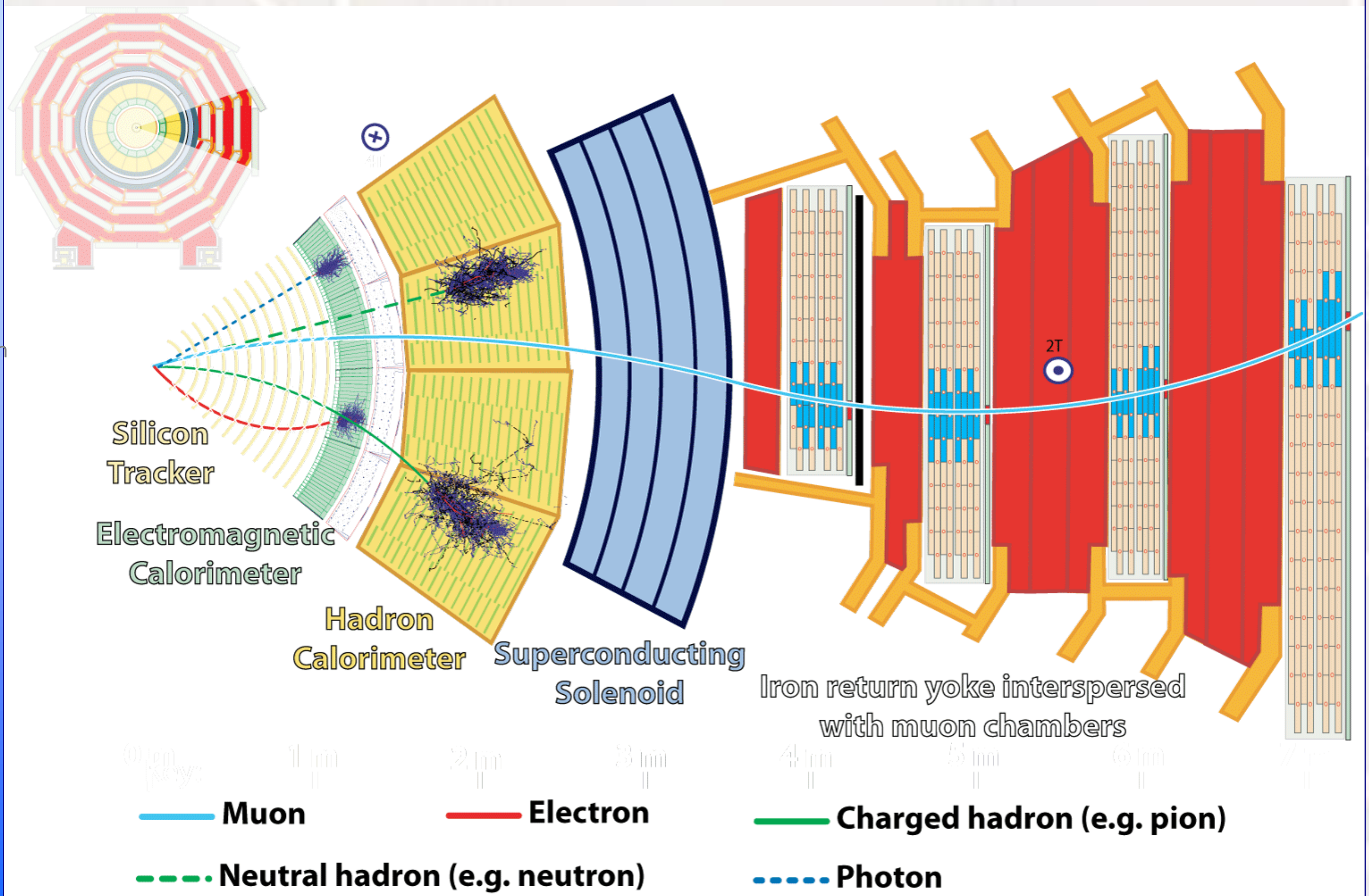
CMS Calorimeter nomenclature

- **Electromagnetic Calorimeters (ECAL)**
  - Measure the energies/positions of electrons/positrons and photons
- **Hadronic Calorimeters (HCAL)**
  - Measure the energies/positions of charged and neutral hadrons

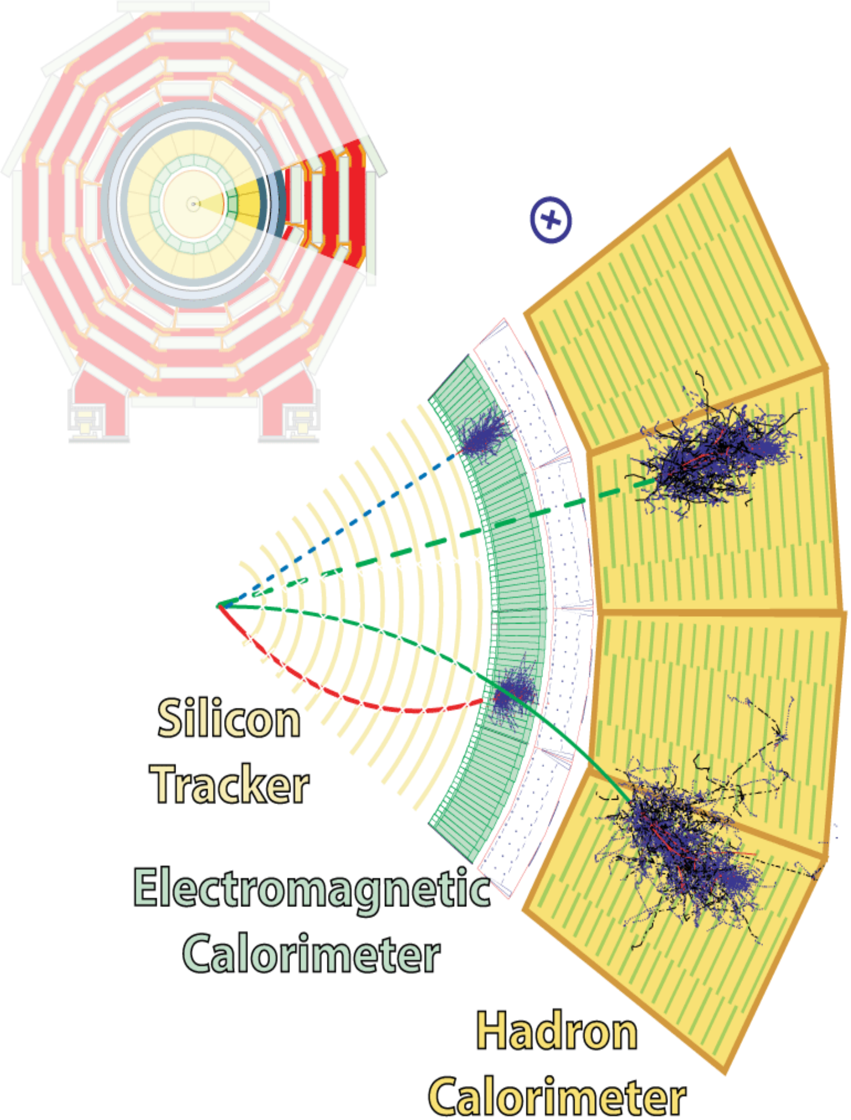
- **ECAL + HCAL divided into "barrel" and "endcap" partitions; HCAL also includes "forward" and "very forward" partitions**
  - ECAL: Barrel (EB), Endcaps (EE), Endcap preShower (ES)
  - HCAL: Barrel (HB), Endcaps (HE), Forward (HF), (CASTOR), ZDC

- **EB, EE, ES, HB, HE: all inside the 3.8T solenoid**

Particle identification in CMS requires all subsystems



Particle identification in CMS requires all subsystems



Electron

Curves in B field: R=P/0.3B
Signals in Tracker
Energy deposit in ECAL
No energy in HCAL

Photon

No curve in B field
No signals in Tracker
Energy deposit in ECAL
No energy in HCAL

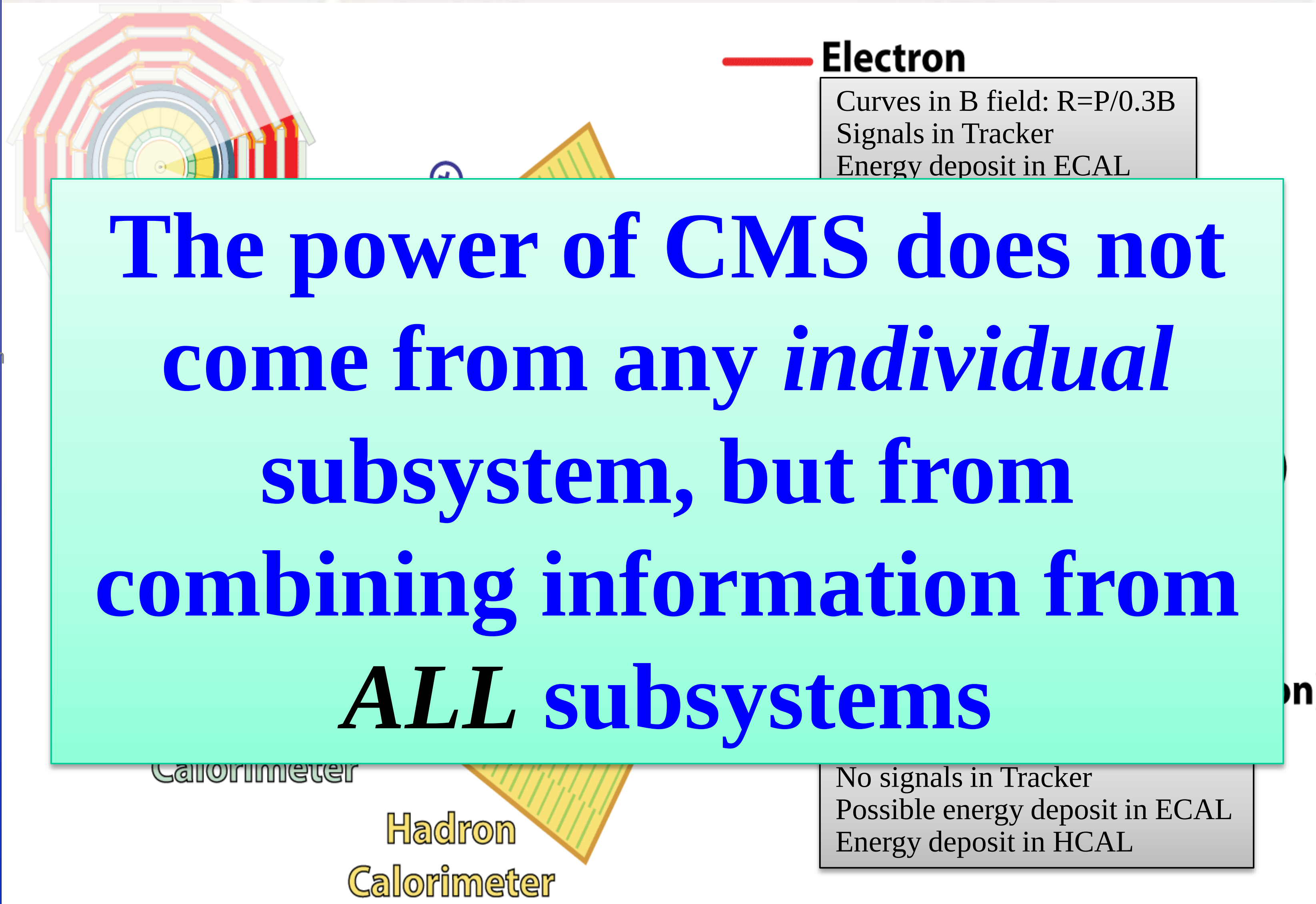
Charged hadron (e.g. pion)

Curves in B field: R=P/0.3B
Signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

Neutral hadron (e.g. neutron)

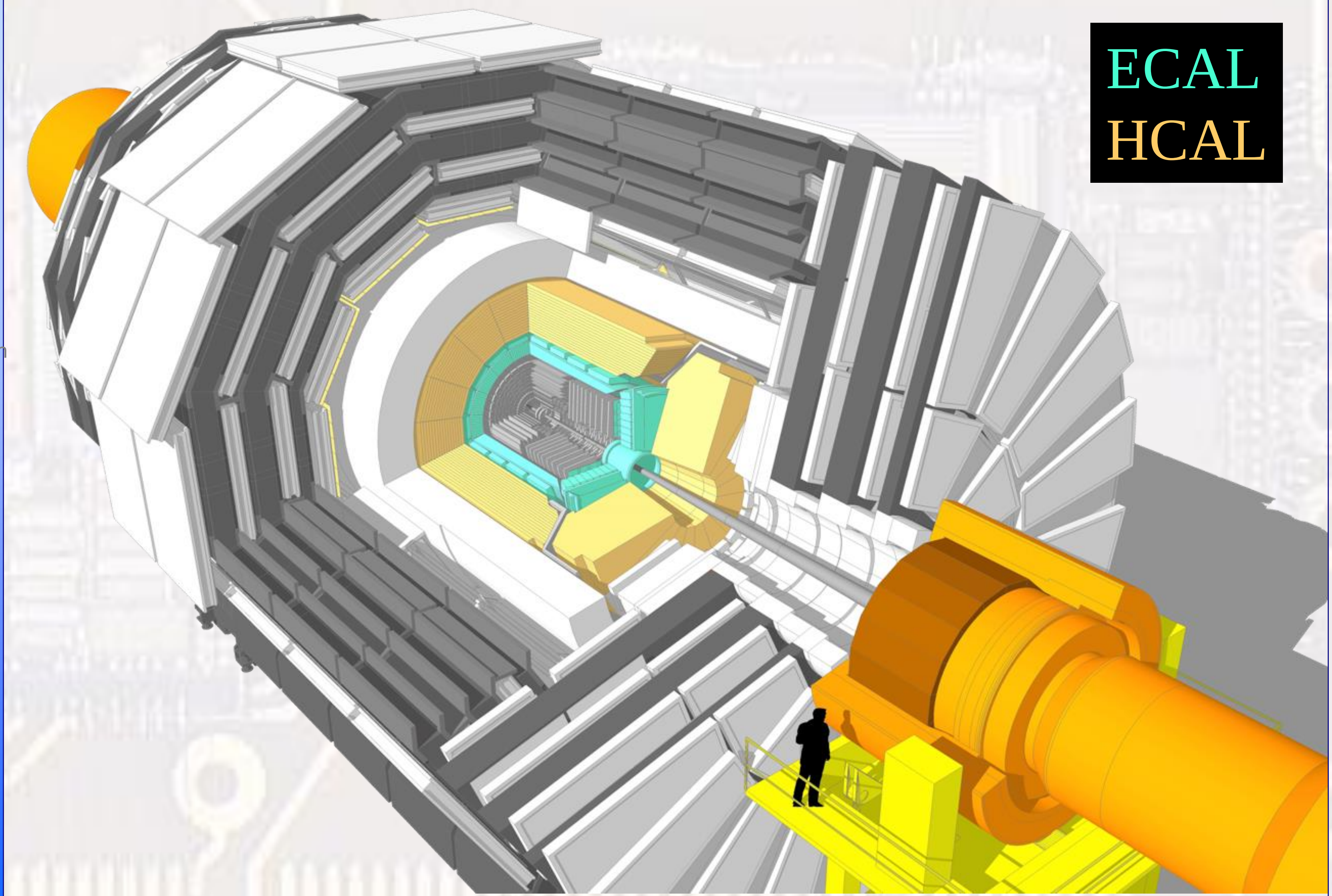
No curve in B field
No signals in Tracker
Possible energy deposit in ECAL
Energy deposit in HCAL

Particle identification in CMS requires all subsystems

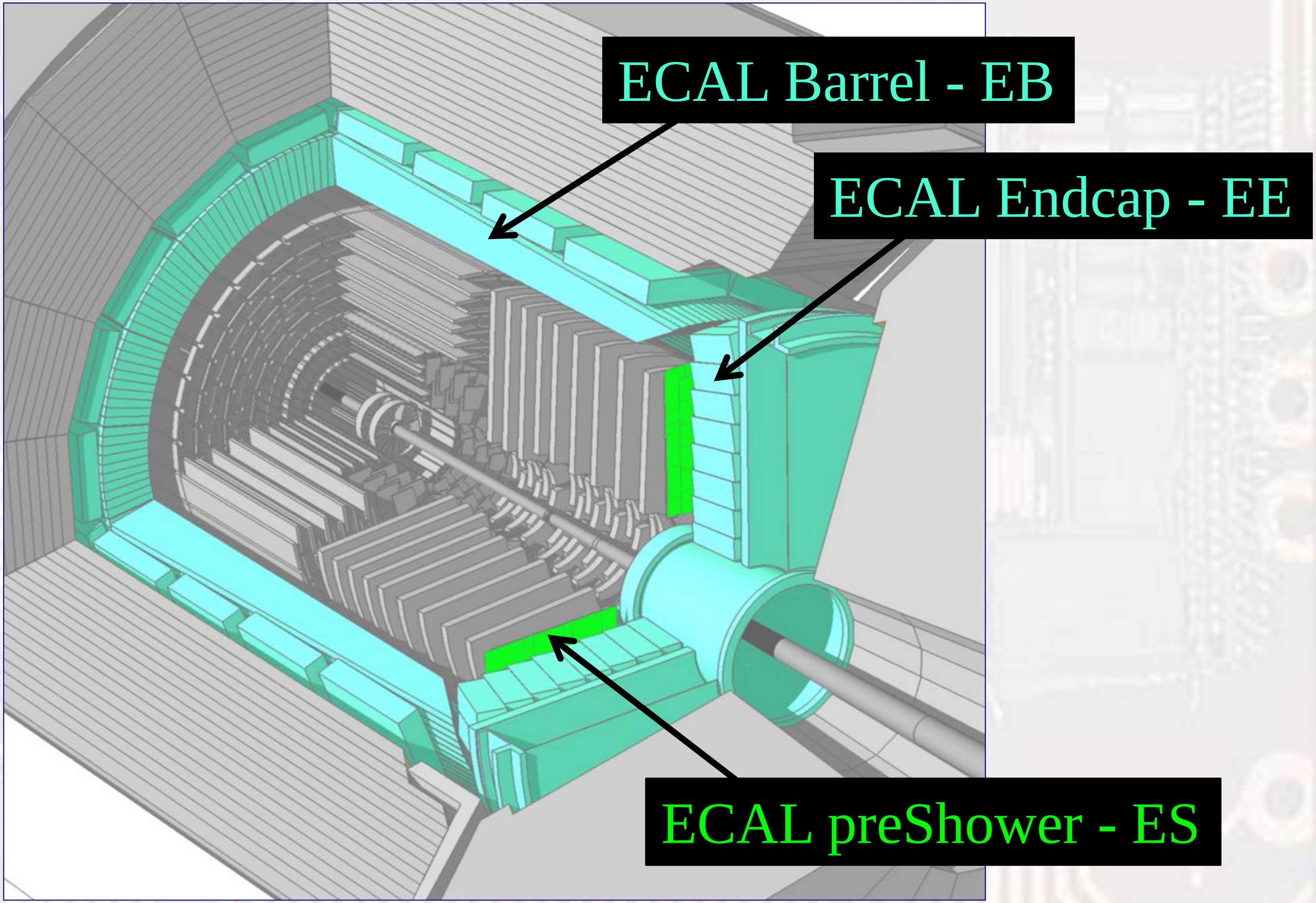


The power of CMS does not come from any *individual* subsystem, but from combining information from *ALL* subsystems

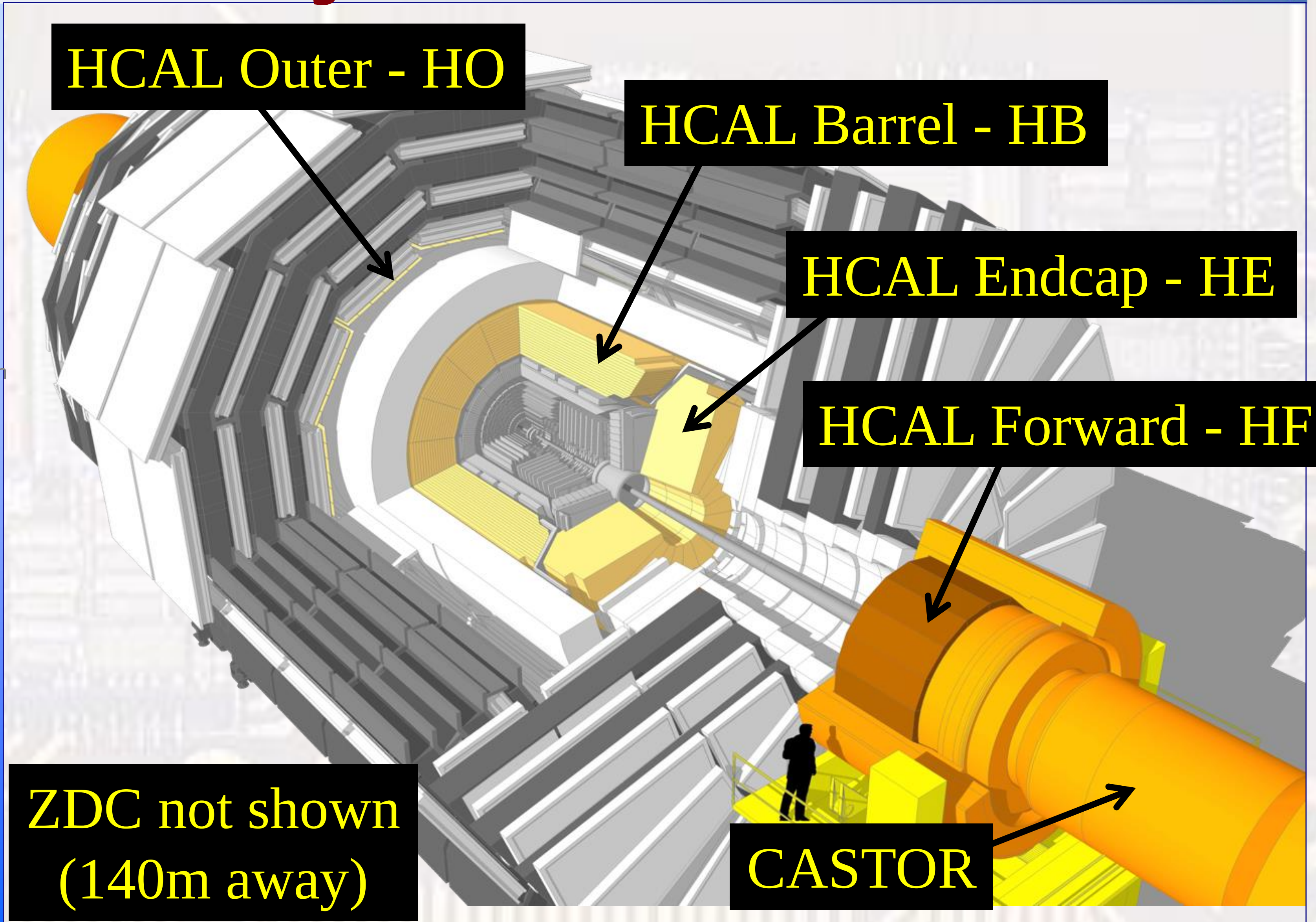
ECAL & HCAL are mostly located within the solenoid



All three parts of ECAL are located within the solenoid



HCAL is divided into 6 parts, mostly within the solenoid



TECHNOLOGY CHOICES

ECAL: based on $PbWO_4$ crystals

- **Criteria for design of ECAL in CMS**
  - Hermetic, compact and granular, with **excellent energy resolution to $|\eta|<2.5$**
    ➔ **homogeneous** calorimeter (minimizes sampling fluctuations)
  - **Large dynamic range**, coupled with excellent linearity, to > 1 TeV
  - Provide **triggering** info. e.g. particle ID, energy, isolation
  - **Radiation tolerant** to expected dose rates and cumulative doses/fluences
  - Endcap Preshower **to aid particle identification**
- **Several options in the early days (early 1990s) of CMS, including:**

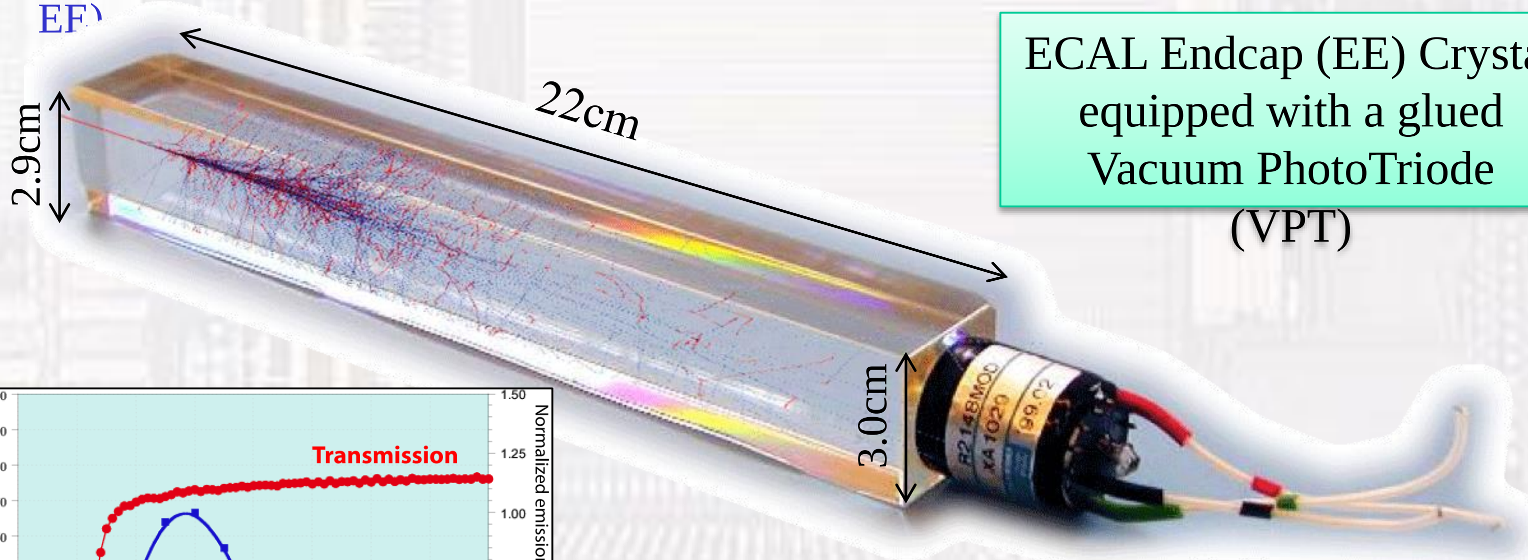
	Sampling	Homogeneous scintillators		
Property	Pb/plastic Shashlik	Liquid Xenon	CeF_3 crystals	**$PbWO_4$ crystals**
Density (g cm^{-3})	4.5	3.06	6.16	**8.28**
Radiation length X_0 (cm)	1.7	2.77	1.68	**0.85**
Molière radius R_M (cm)	3.4	4.1	3.39	**2.19**
Wavelength peak (nm)	500	175	300	**440**
Fast decay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

Selected by CMS in 1994

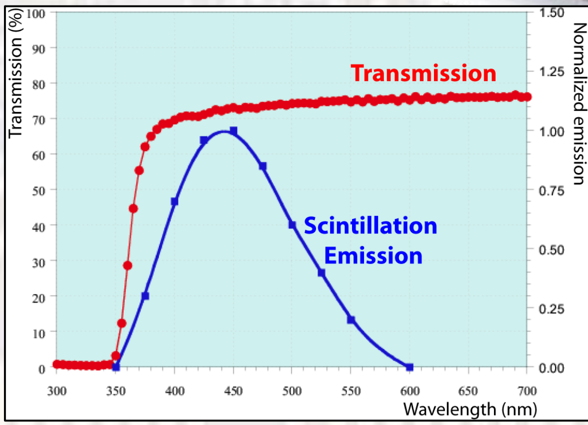
+ Preshower based on Si sensors

Homogeneous $PbWO_4$: generates showers & produces signal

- **Incident electron/photon generates EM shower (spread laterally over several crystals) in the heavy $PbWO_4$ material**
  - Charged particles in the shower produce **scintillation light** isotropically
  - Amount of scintillation light is **proportional to incident particle energy**
  - Scintillation light detected by photodetectors with internal amplification: Silicon **Avalanche PhotoDiodes** - APDs (in EB) or **Vacuum PhotoTriodes** - VPTs (in EE)



ECAL Endcap (EE) Crystal equipped with a glued Vacuum PhotoTriode (VPT)



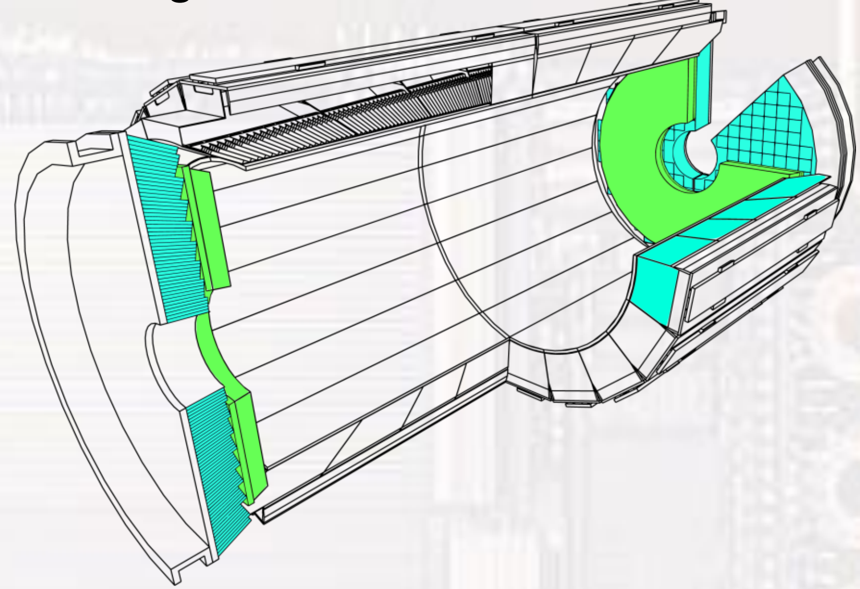
$PbWO_4$ crystals are transparent to the entire scintillation emission spectrum – before irradiation (see later)

The CMS ECAL in Numbers

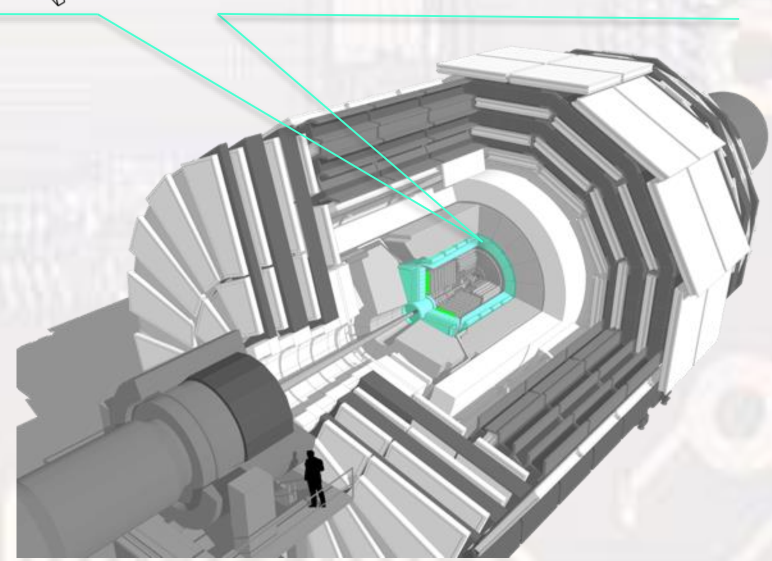
Homogeneous, compact, hermetic, fine grain

$PbWO_4$ crystal calorimeter

- **Emphasis on energy resolution**
- No longitudinal segmentation (except ES)



- **Barrel (EB): $|\eta| < 1.48$**
  - 36 Supermodules: 1700 crystals (1 supermodule = 4 modules): 61200 crystals total, of 17 shapes
  - ($2.2 \times 2.2 \times 23$ cm^3) **~$26X_0$**
- **Endcaps (EE): $1.48 < |\eta| < 3.0$**
  - 4 Dees (2 per endcap): 3662 crystals (mostly in 5x5 supercrystals) 14648 crystals total, of 1 shape
  - ($3.0 \times 3.0 \times 22$ cm^3) **~$25X_0$**
- **Preshower (ES): $1.65 < |\eta| < 2.6$**
  - 4 planes (2 per endcap): 1072 Si sensors 1 sensor = 6.3 x 6.3 x 0.032 cm^3, 32 strips 137216 strips total **$2X_0$** + **$1X_0$** of Pb interspersed with Si strips
  - 1.90×61 mm^2 x-y view

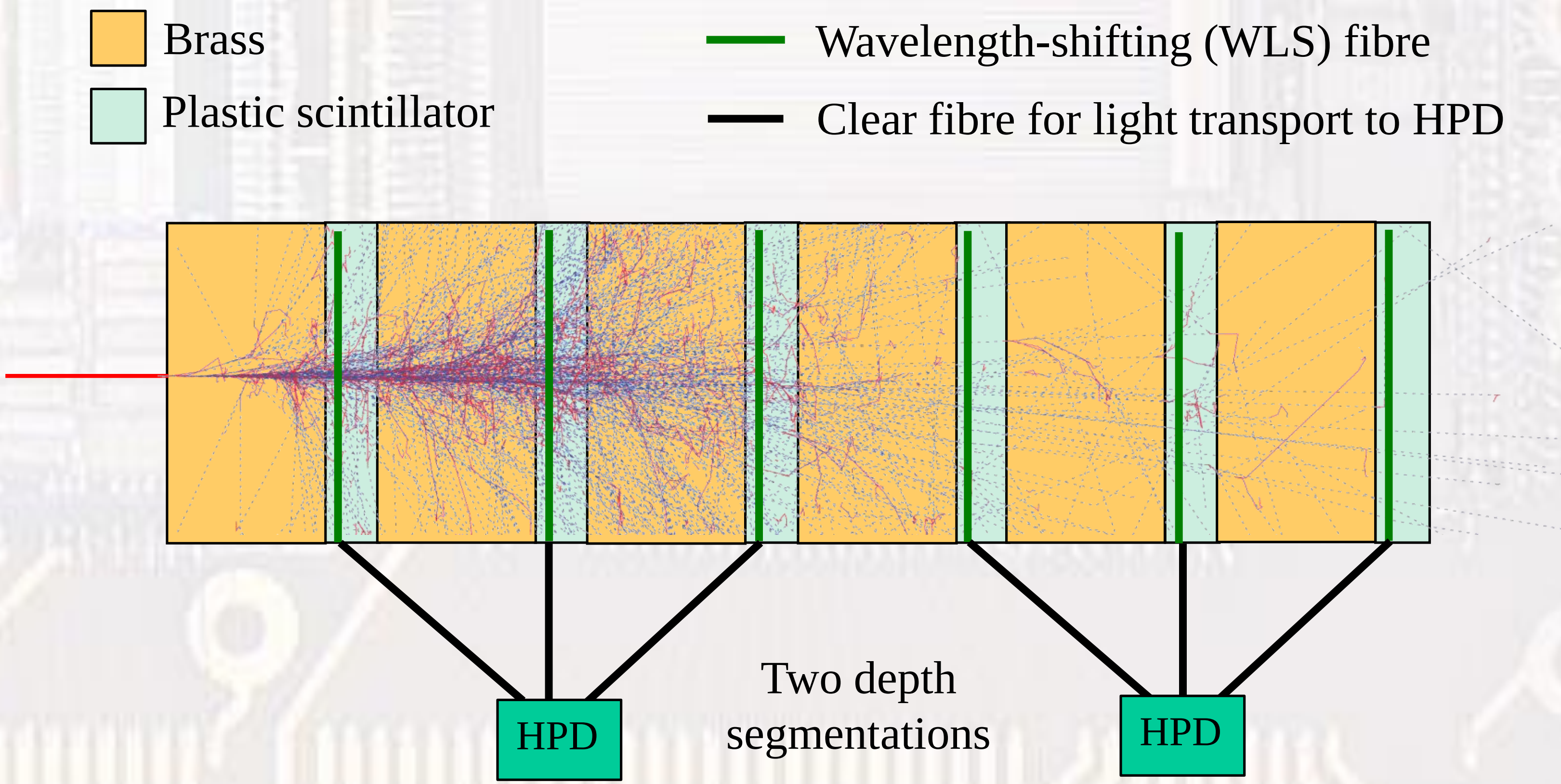


All parts of HCAL are Sampling Calorimeters

- **Criteria for design of HCAL in CMS**
  - **Hermetic and compact** – able to fit within the CMS solenoid up to $|\eta|<3$
  - **Large dynamic range**, coupled with excellent linearity, to > 1 TeV for jets
  - Provide **triggering** info. e.g. particle ID, energy, isolation
  - **Radiation tolerant** to expected dose rates and cumulative doses/fluences
  - **Reasonable energy resolution** with **depth segmentation** → sampling calo.
- **Basic design of HB already fixed at time of LoI**
  - Copper plates interleaved with plastic scintillators with embedded wavelength-shifting (WLS) fibres (**eventually used brass (70% Cu, 30% Zn) absorber**)
  - Light channeled using clear fibres, to photodetectors at the ends of the barrel
- **For HE, initial design was rather ambitious**
  - Cu absorber interleaved with 2 x 2 x 0.04 cm^3 Si sensors → 360m^2 of Si (**eventually used similar structure to HB – brass + scintillator + WLS**)
- **For HF (outside the solenoid), emphasis was on radiation hardness**
  - Steel plates interleaved with parallel-plate chambers (**eventually used steel absorber with Cerenkov-producing quartz fibres**)

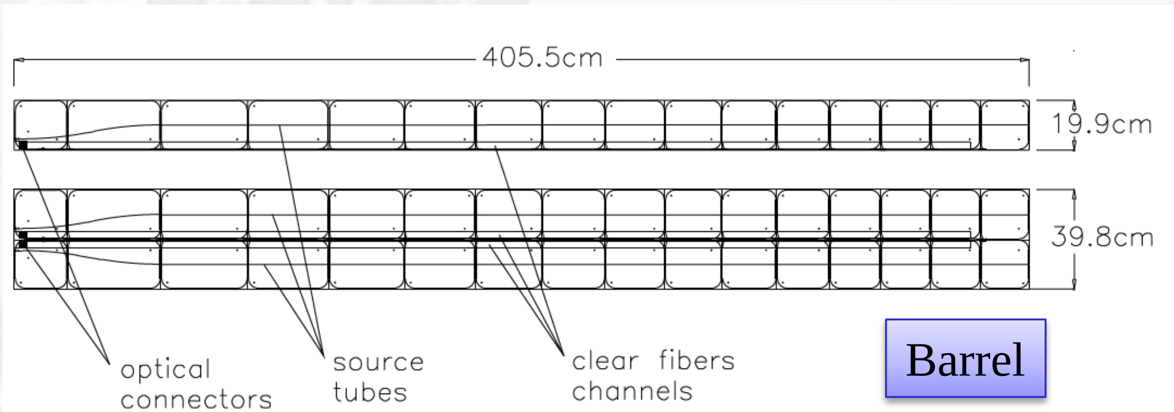
Sampling HB/HE

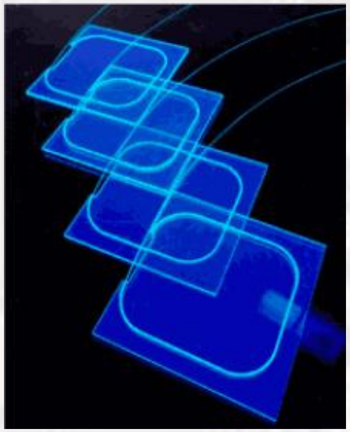
- **Incident charged/neutral hadron generates hadronic shower in the heavy brass absorber**
  - Charged particles in the shower produce **scintillation** light in the plastic
  - Amount of scintillation light is **proportional to incident particle energy**
  - Scintillation light shifted in wavelength & transported to **Hybrid PhotoDiodes**

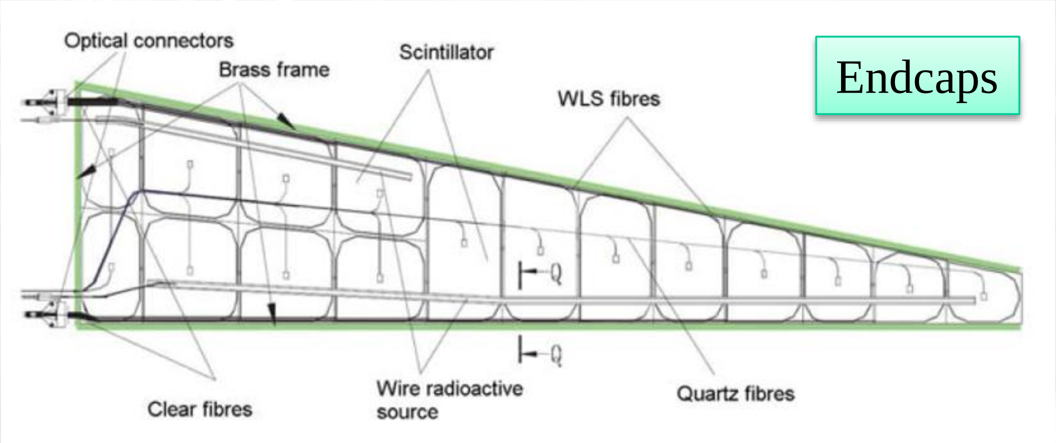


HCAL Megatiles: up to 4m long

- Plastic scintillator + WLS + clear fibres
- Different sizes for the different layers in HB/HE
- Individual tile sizes vary with η/ϕ







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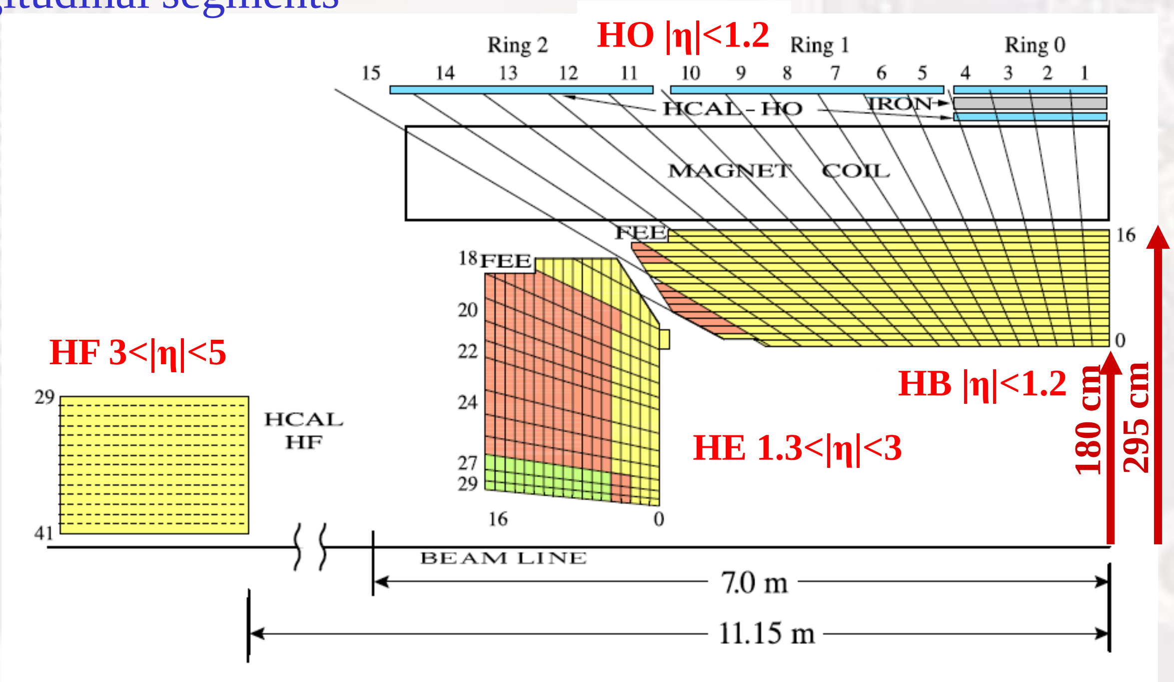
HB and HE: Around 10λ with depth segmentation

- **Barrel (HB): |η|<1.3, 36 wedges (18 HB+, 18 HB-)**
  - 14 layers of brass + steel front/back plates → ~10 λ
  - 16 megatile layers; 16 η and 4 ϕ divisions per wedge
- **Endcaps (HE): 1.3<|η|<3.0, 36 petals per endcap**
  - 17 layers of brass → ~10 λ
  - 17 megatile layers; 12 η and 1 or 2 ϕ divisions per wedge
  - 2 or 3 (high η) longitudinal segments



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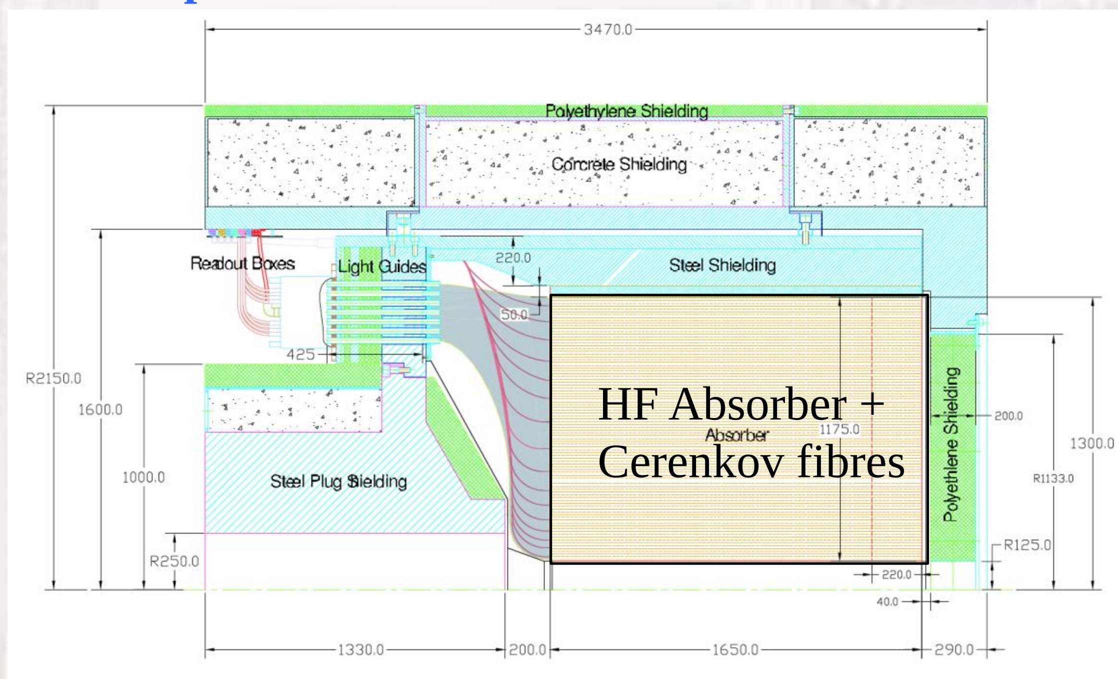
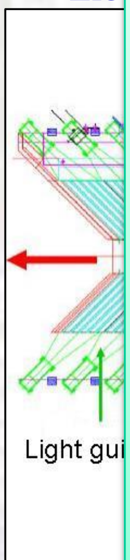
Forward HCAL measures Cerenkov light in quartz fibres

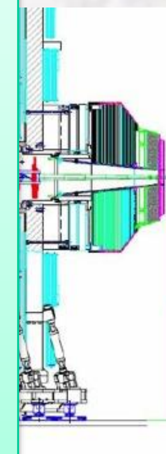
- **Forward (HF): 3.0<|η|<5.0, 18 wedges per end**
  - **Grooved steel plates**, 5mm thick, 165cm long → ~10 λ
  - ~square grid of holes spaced 5mm apart
  - 1mm diameter **fibres** (600μm **quartz core** + cladding + buffer)
  - **2 fibre lengths** (read out separately) to distinguish e/γ from hadron showers:
    - Half are **165cm long**
    - Other half start **after a depth of 22cm**



CASTOR covered very high η region: now removed from CMS

- **CASTOR (Centauro And Strange Object Research), 5.2<|η|<6.6 on "minus" side of CMS only**
  - **Cerenkov-based** calorimeter, similar to HF, 14.38m from the interaction point
  - Lay
  - Lig
  - Ele





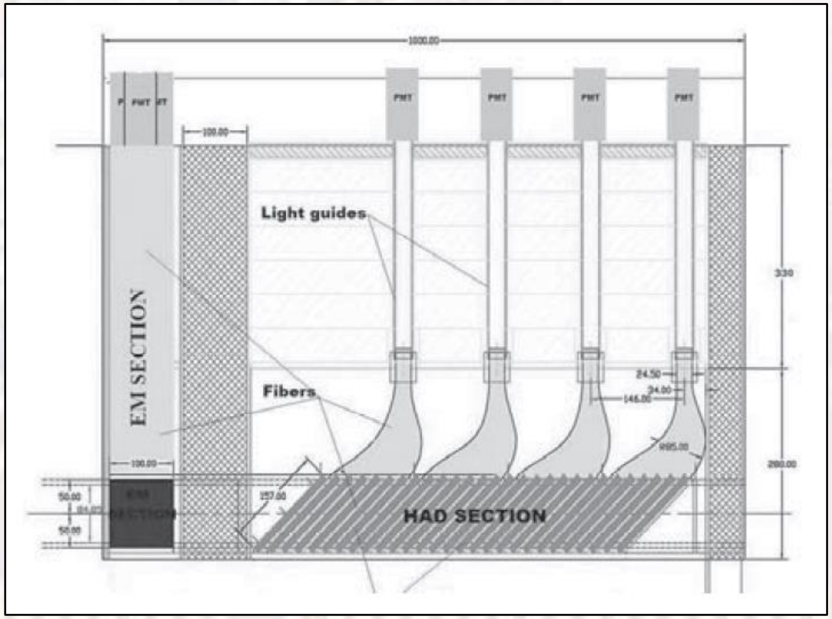
Removed from CMS in June 2015

Desire to go back for other low-lumi pp running with the B-field ON

And should go back into CMS for the heavy-ion run at the end of 2015

Zero Degree Calorimeter - ZDC

- **Especially for heavy-ion and diffractive physics**
  - Located between the two LHC beam pipes inside the LHC neutral particle absorbers (TAN), **~140m from the interaction point** on both sides of CMS, **$|\eta|>8.3$**
  - About 1m of layers of **tungsten plates** interspersed with layers of **quartz fibres** (again similar to HF)



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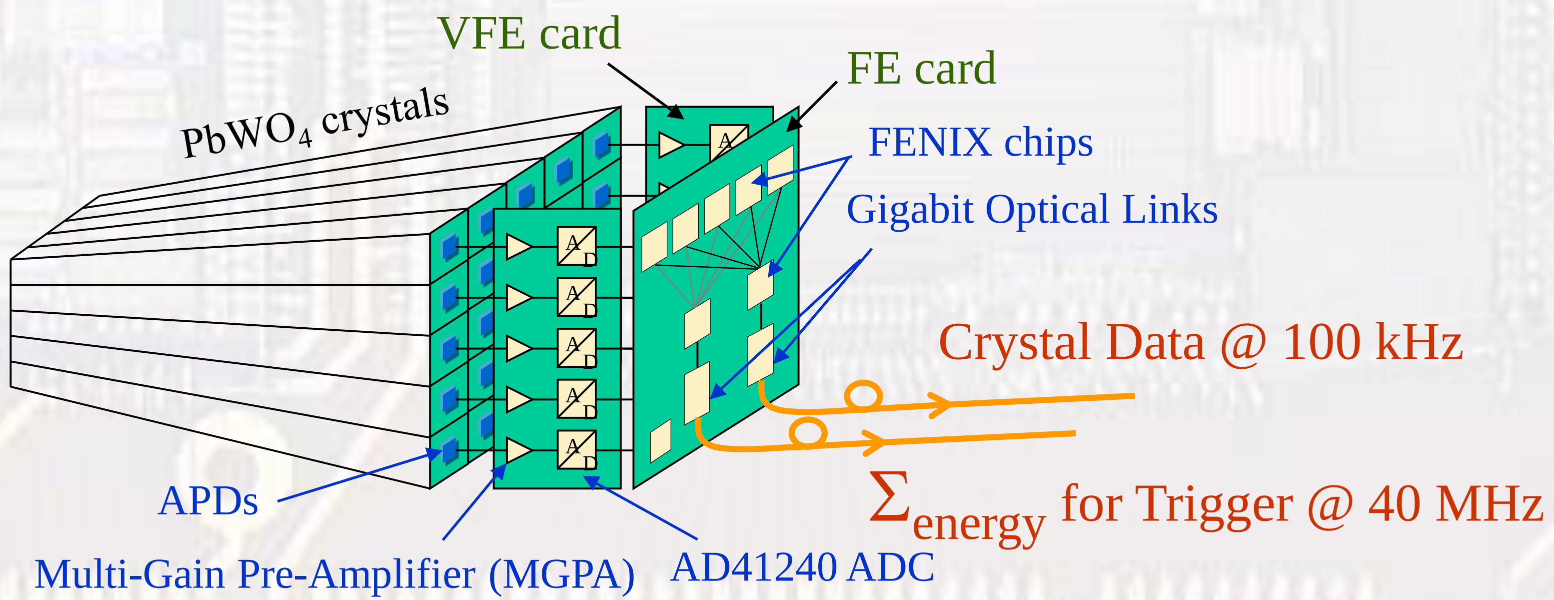
DATA ACQUISITION

ECAL On-detector (Front-end) Electronics

- Current pulses from APDs/VPTs → amplified and shaped by **MGPA** with 3 separate gains → all 3 amplified signals digitized by **ADC** @ 40 MHz
  - **1 MGPA + 1 ADC per crystal**
- **FENIX** chip stores digital signals from multiple crystals until reception of a level-1 trigger signal → data sent via optical link to off-detector data-acquisition electronics
- Another **FENIX** chip sums the energy in a group of crystals (5x5 in EB; 5 in EE) → "trigger primitive" sent to off-detector trigger electronics



ECAL Electronics Chain includes off-detector components

- Basics
- Technology
- Data Acquisition
- Construction
- Issues
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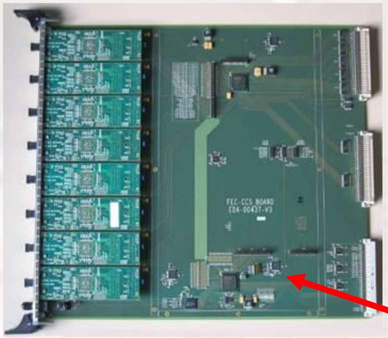
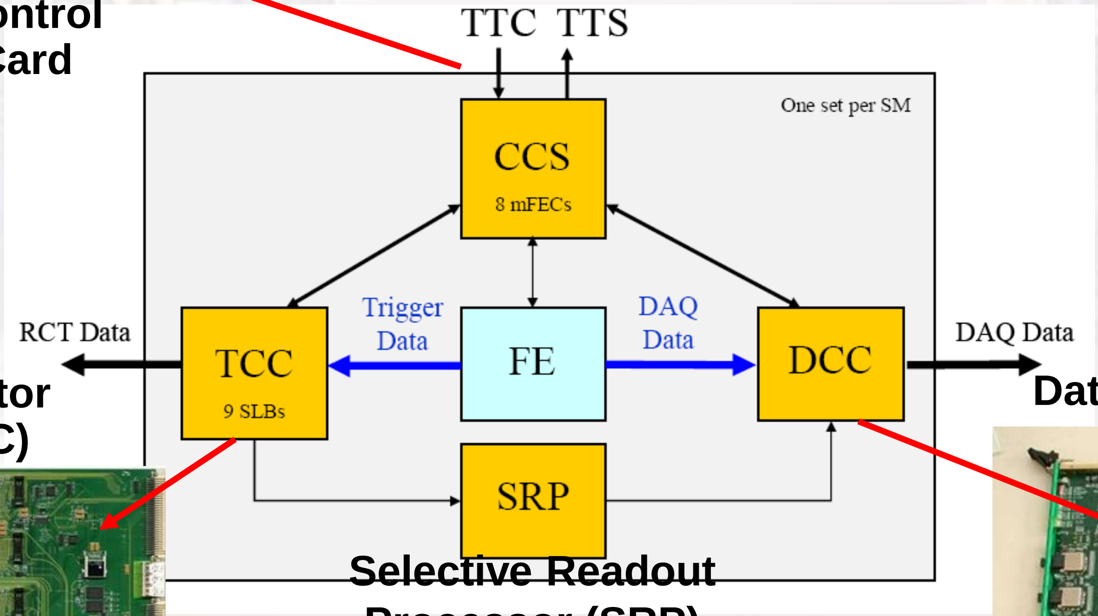


Clock & Control System Card (CCS)

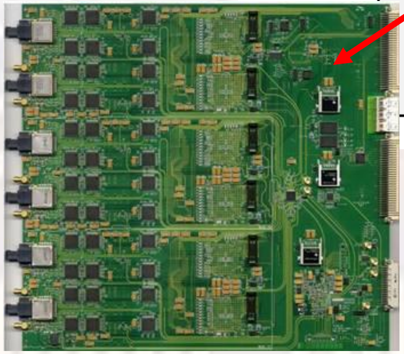
Trigger Concentrator Cards (TCCs) receive FE card trigger primitives

TCCs send trigger tower energy sums to Regional Calorimeter Trigger (RCT) at 40 MHz

Data Concentrator Card (DCC) reads FE data and TCC information upon L1 accept; performs data reduction and transfers to DAQ

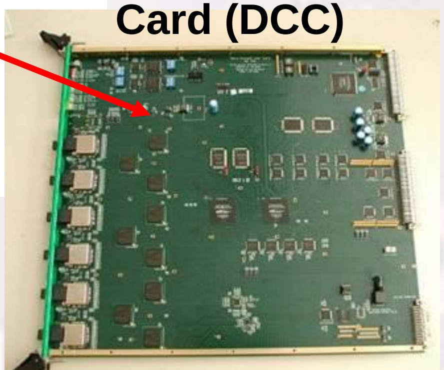


Trigger Concentrator Card (TCC)



Selective Readout Processor (SRP)

Data Concentrator Card (DCC)



(also known as **FED**)

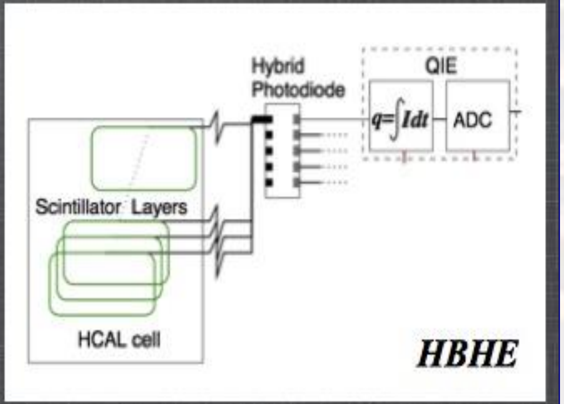
TTC: Trigger, Timing and Control
TTS: Trigger Throttling System
mFEC: mezzanine Front End Controller card (connects to FE card via token ring)
SLB: Synchronization and Link Board mezzanine

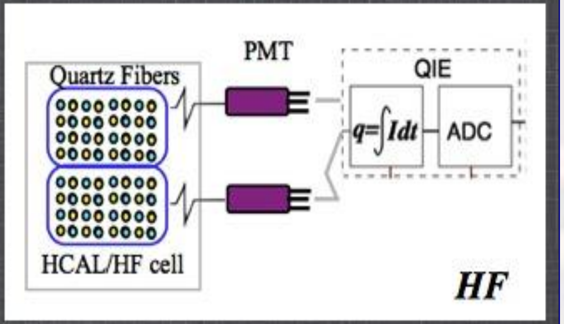
HCAL Readout Chain

- Hybrid Photo-detectors
  - Designed to operate in high magnetic fields, up to 4T.
  - Proximity-focusing with 3.5mm gap, with E field parallel to B field.
  - HV of 8kV with 18 pixels (20mm^2 each).
  - Gain of ~2k, linear response over large dynamic range from min-ionizing particles (muons) up to 3TeV hadron showers.

* 2008 JINST 3 S08004 * P. Cushman et al., NIM A 504 (2003) 502)

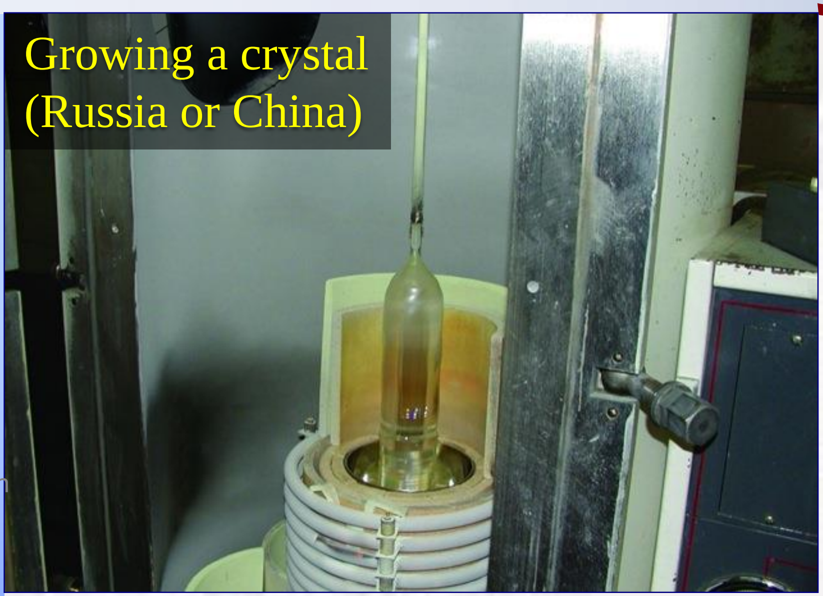
- Charge integrator and encoder (QIE) ADC chips digitize the signals from the HPD / PMT.
- Each QIE has 4 capacitors which are connected to the input by 25ns time intervals.
- Integrated charge from the capacitors is then sent to HCAL trigger boards for further processing.



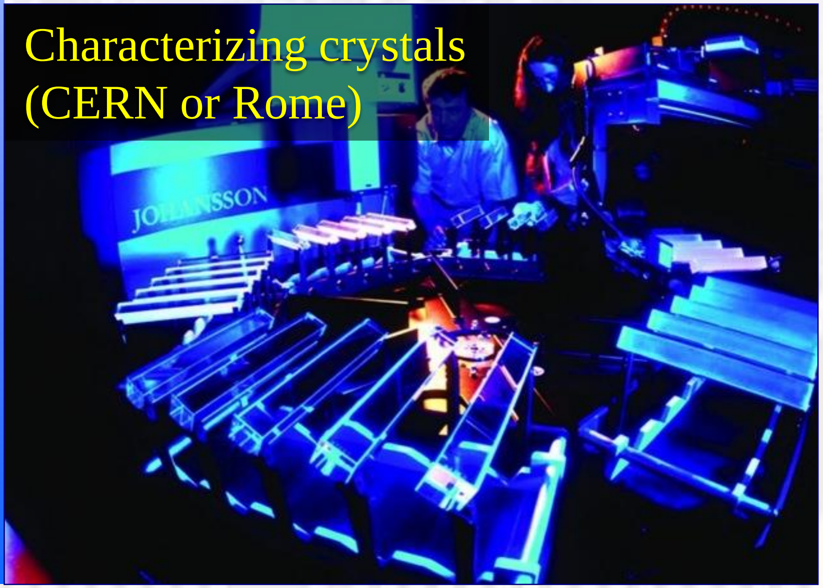


CONSTRUCTION & ASSEMBLY

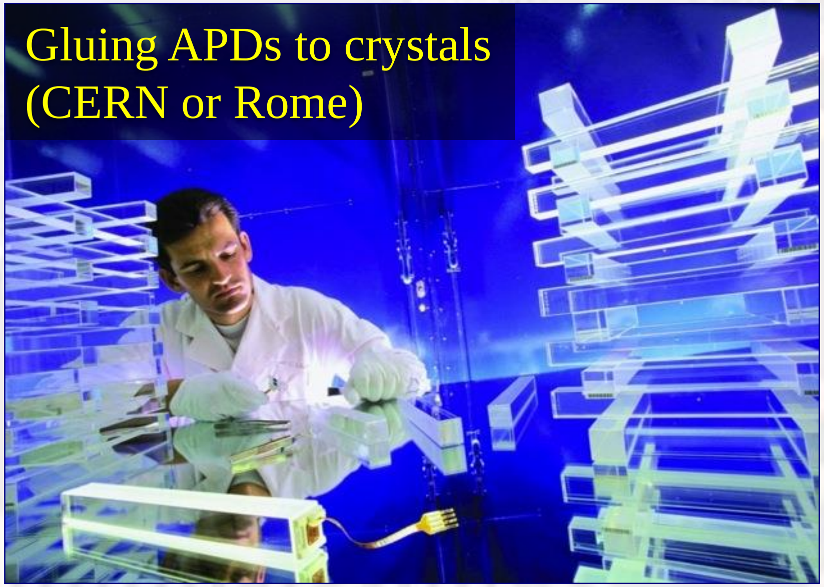
Production of ~80000 EB/EE Crystals


Growing a crystal (Russia or China)

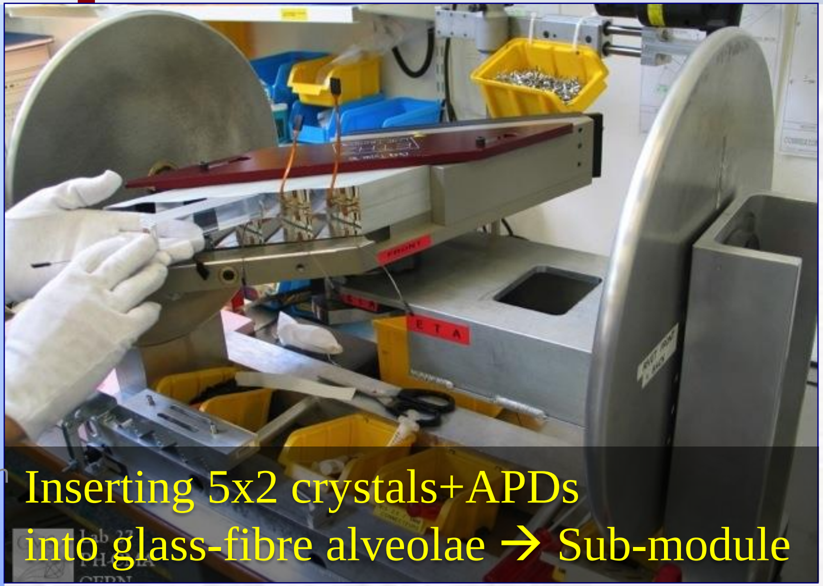

Before and after cutting & polishing



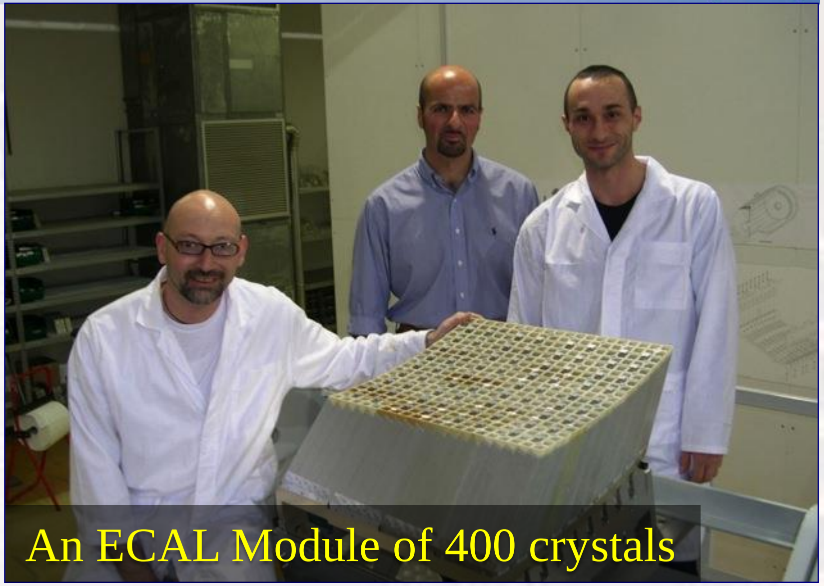
Characterizing crystals (CERN or Rome)


Gluing APDs to crystals (CERN or Rome)

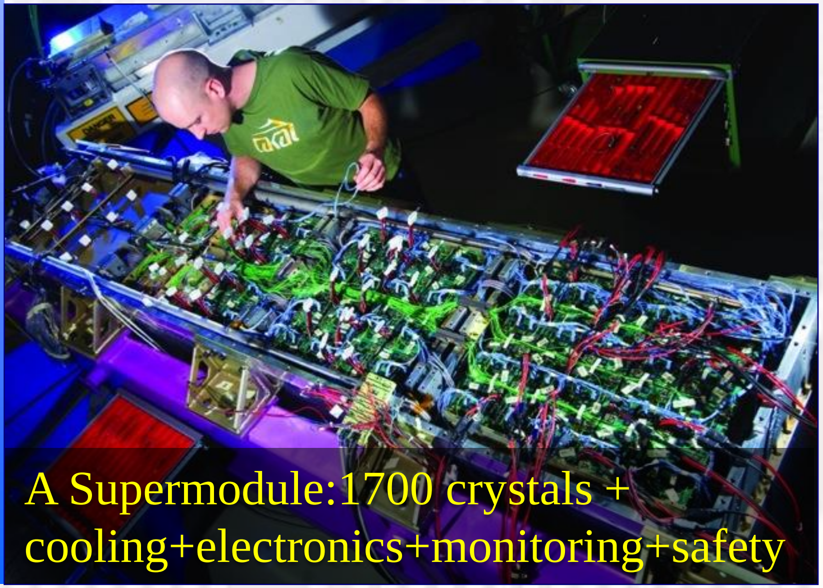
Assembling EB crystals + photodetectors + electronics



Inserting 5x2 crystals+APDs into glass-fibre alveolae → Sub-module



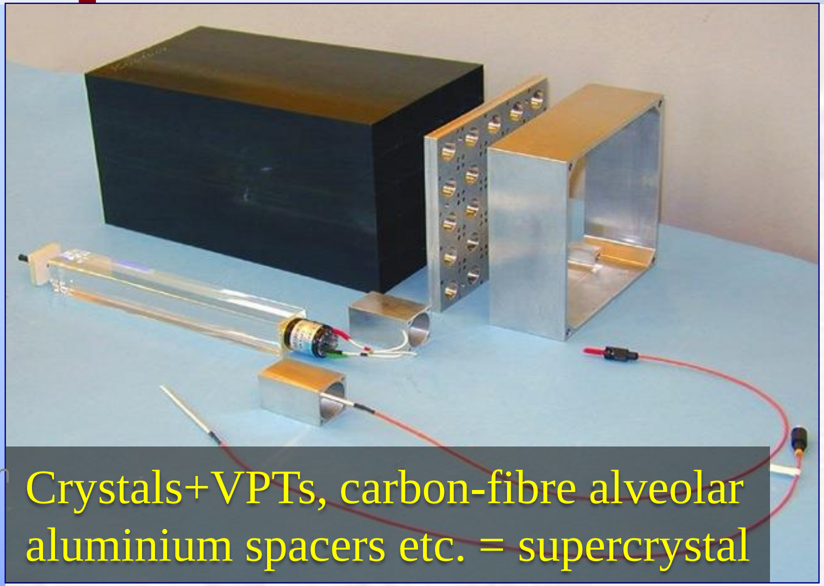
An ECAL Module of 400 crystals



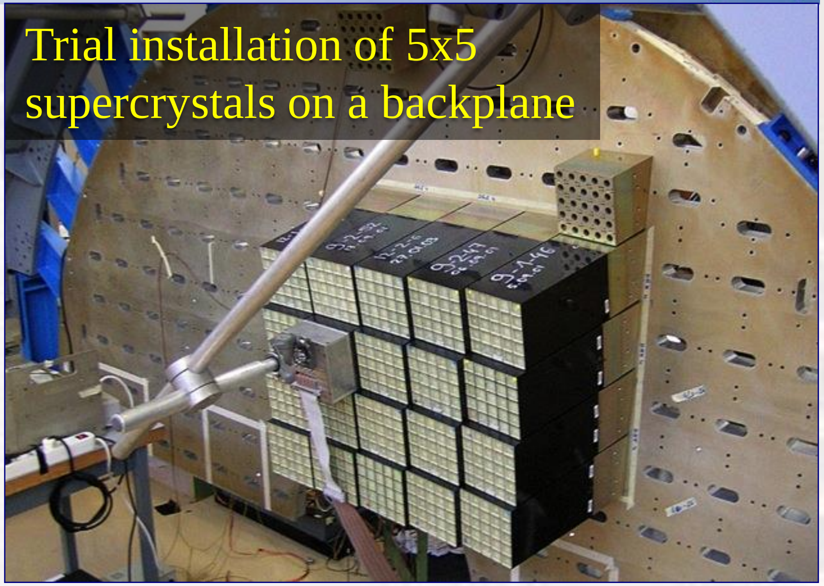
A Supermodule:1700 crystals + cooling+electronics+monitoring+safety

A completed Supermodule ready for tests in a beam

Assembling EB crystals + photodetectors + electronics

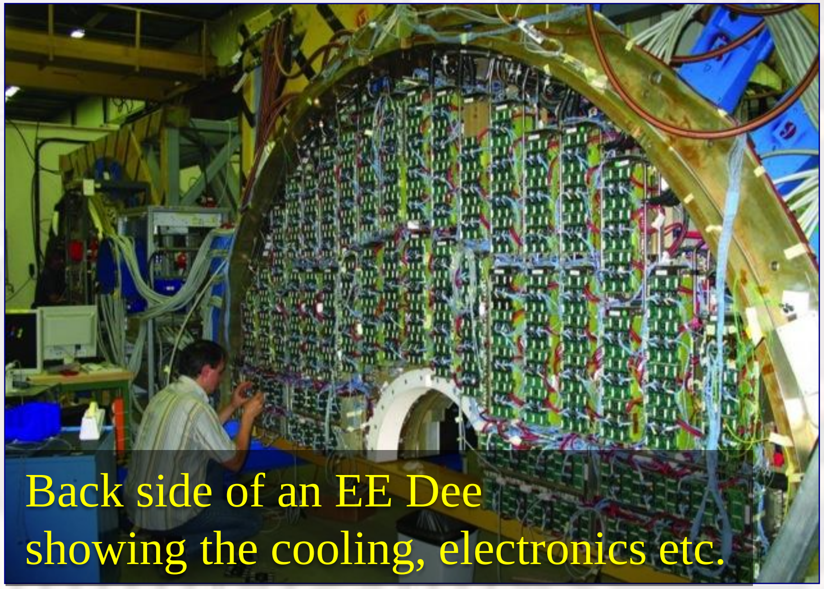


Crystals+VPTs, carbon-fibre alveolar aluminium spacers etc. = supercrystal



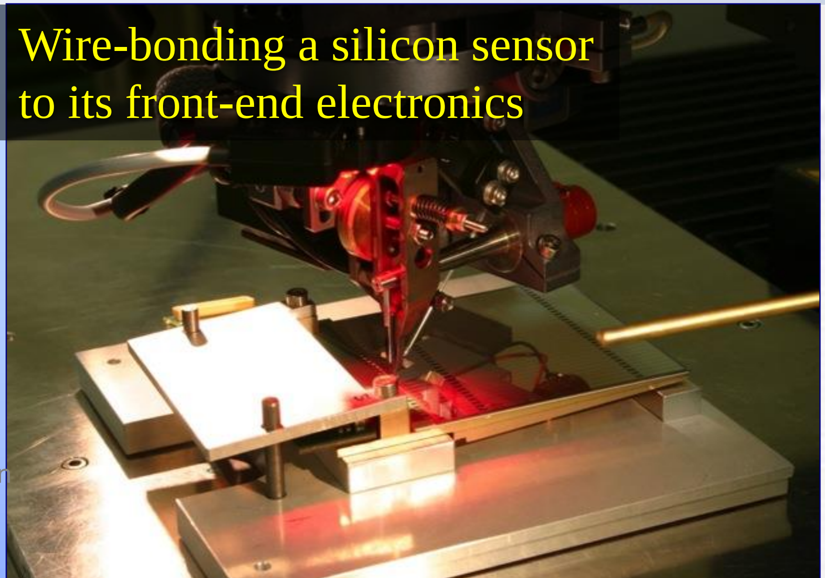
Trial installation of 5x5 supercrystals on a backplane

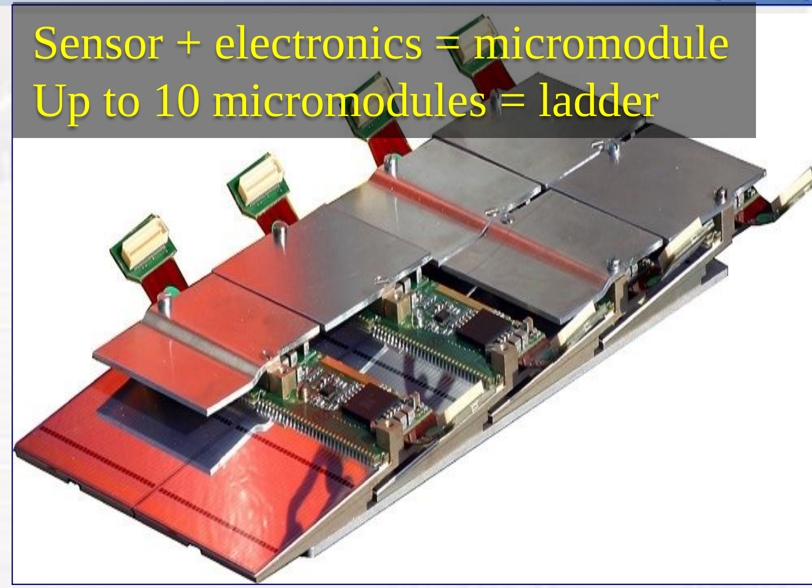
5x5 Supercrystals being mounted to form an EE Dee

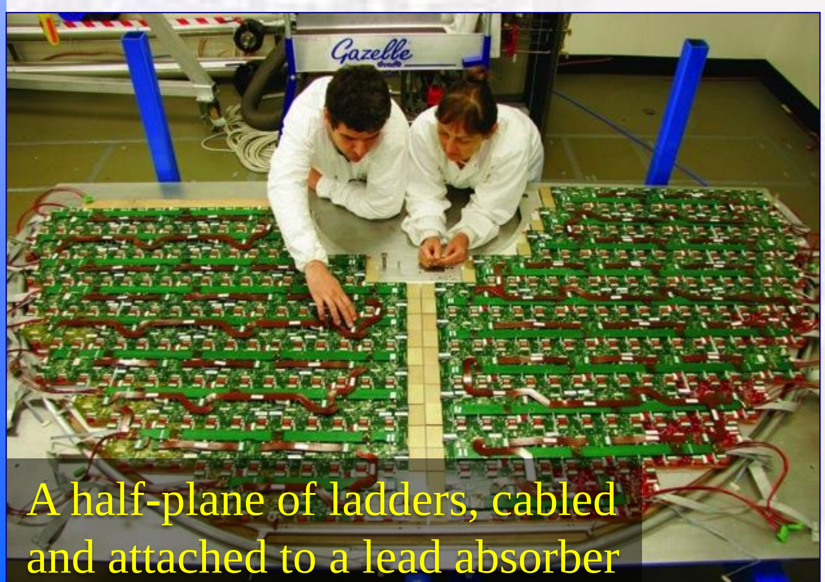


Back side of an EE Dee showing the cooling, electronics etc.

Assembling 4288 silicon sensors for the ES


Wire-bonding a silicon sensor to its front-end electronics

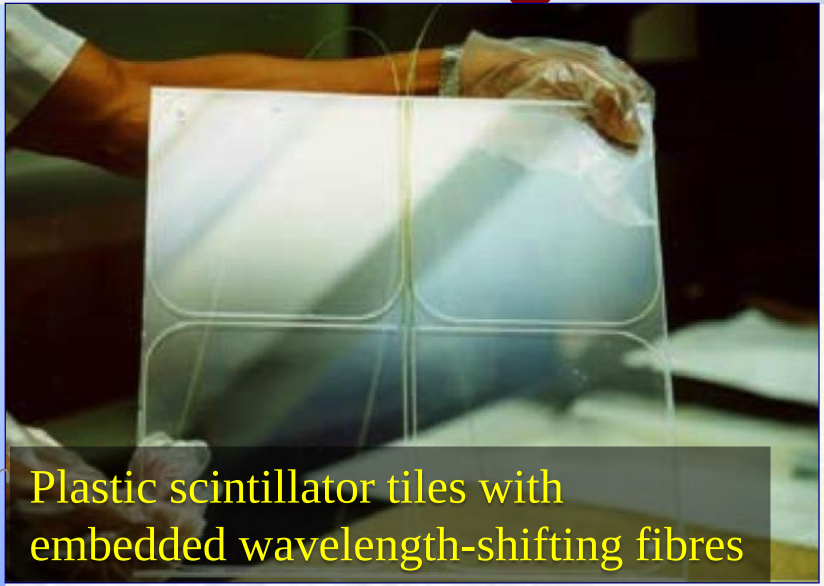

Sensor + electronics = micromodule
Up to 10 micromodules = ladder


A half-plane of ladders, cabled and attached to a lead absorber

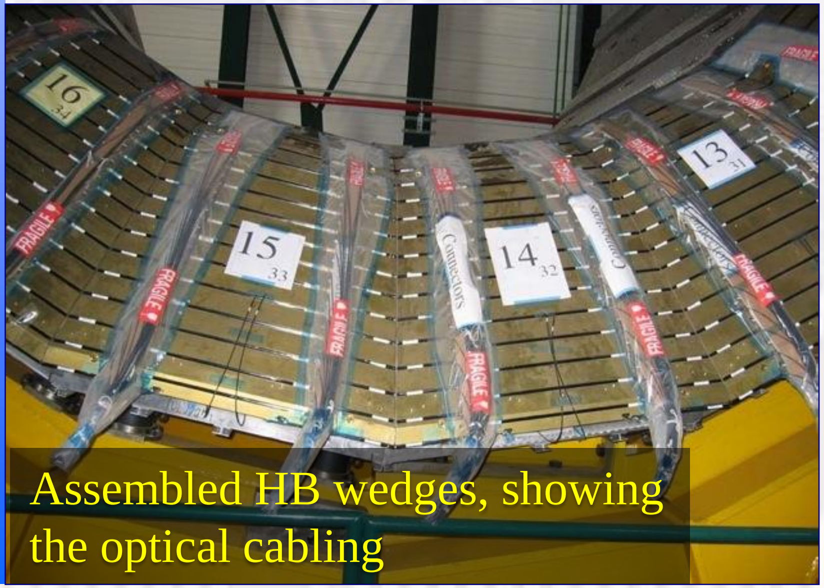

Some of the Preshower team with the first completed Dee

Assembly of brass wedges + megatiles for HB

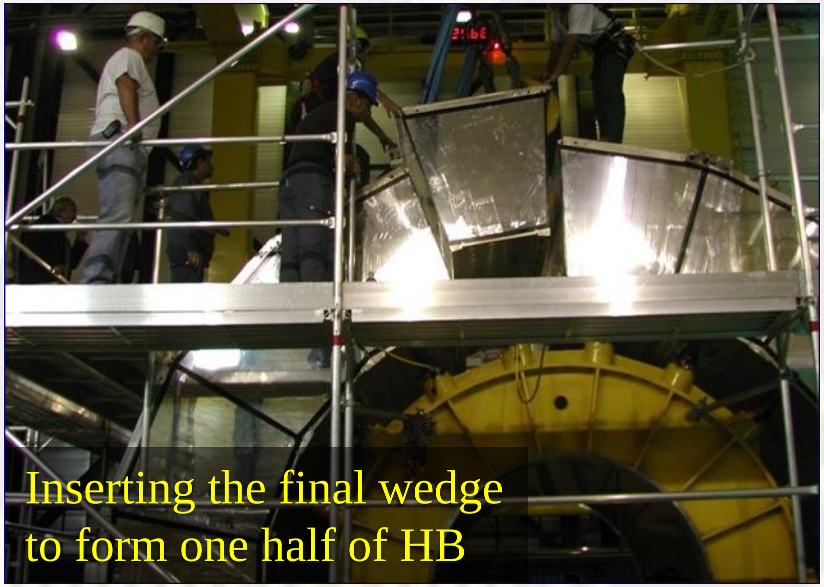
- Basics
- Technology
- Data Acquisition
- **Construction**
- Issues
- Performance
- Long-term
- Organization


Plastic scintillator tiles with embedded wavelength-shifting fibres


One of 36 brass wedges showing gaps for the scintillators



Assembled HB wedges, showing the optical cabling


Inserting the final wedge to form one half of HB

Accidents Happen (rarely!)

HCAL wedge was repaired before being installed in CMS!

From weapons to calorimeter: construction of the HE

Brass for the HE came from Russian artillery shells

Melting the shells

Recycled brass plates

Trial assembly of HE brass “petals”

Assembly of the 350-tonne HFs

- Basics
- Technology
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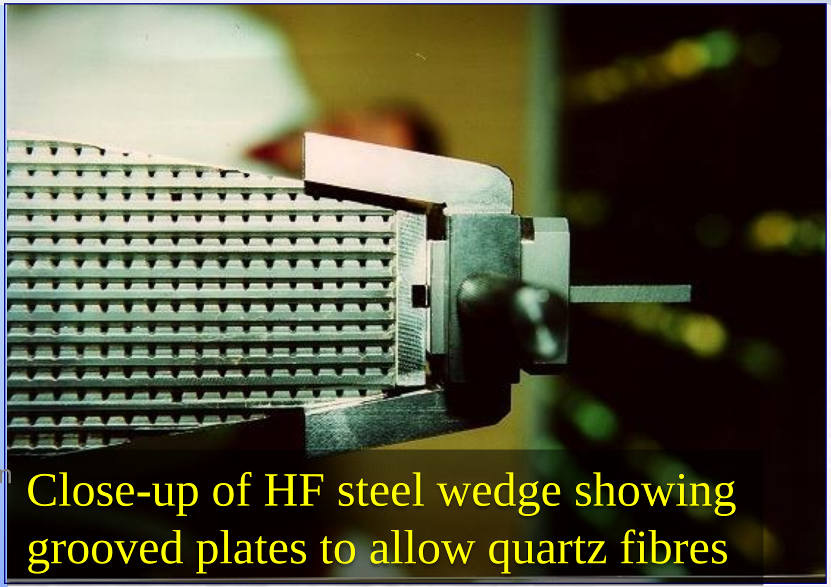


Close-up of HF steel wedge showing grooved plates to allow quartz fibres

Inserting quartz fibres into a steel wedge

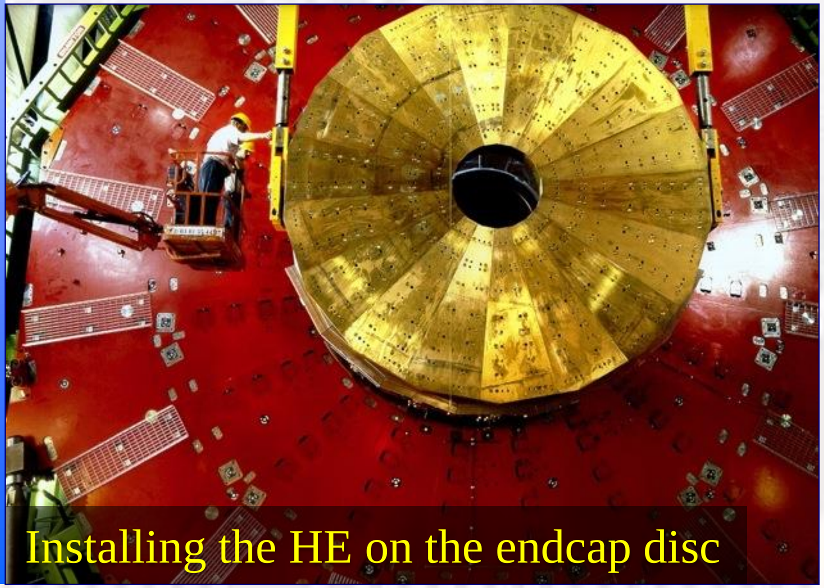
Wedges being assembled into Dees

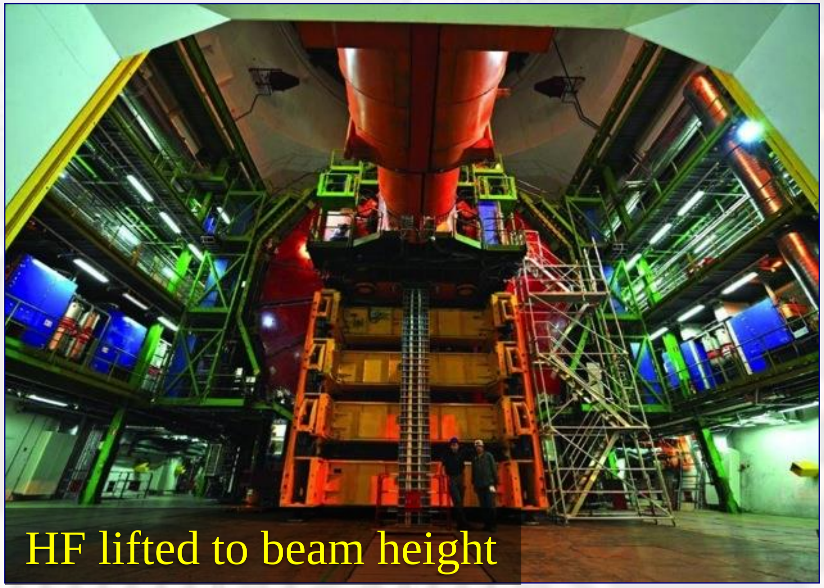
Completed HF ready for installation

HCAL Installation - 2007


Lowering one HB underground


HB+ about to be inserted into YB0


Installing the HE on the endcap disc


HF lifted to beam height

ECAL Installation – 2007-2009

Installing barrel "supermodules" of 1700 crystals each

All 36 barrel supermodules installed - supported by HCAL barrel

Installing the endcap Preshower around the beam pipe

Installing one of four endcap ECAL Dees onto the HCAL Endcap

ISSUES SINCE START OF DATA TAKING IN 2010

Issues since startup: ECAL

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- **Barrel/Endcaps/Preshower**
  - Some non-working single channels and trigger-towers
    - Cannot fix, but number is not (yet) increasing
- **Barrel**
  - Anomalous signals due to direct ionization of the APDs ("spikes")
    - Mitigated with front-end configuration & HLT/offline filtering
- **Endcaps**
  - One non-powered region due to Low Voltage problem
  - On
- **Pres**
  - Tw
    - Fixed in LS1 – but 3 more problems appeared in 2015 ☹
  - Anomalous currents in small fraction (~3%) of sensors after low-level irradiation
    - "cured" after higher levels of radiation

Most problems are due to faulty connectors

Fraction of working channels at the end of Run I and in July 2015

EB: 99.16% → 99.07%
EE: 98.38% → 98.89%
ES: 96.8% → 97.75%

Issues since startup: HCAL

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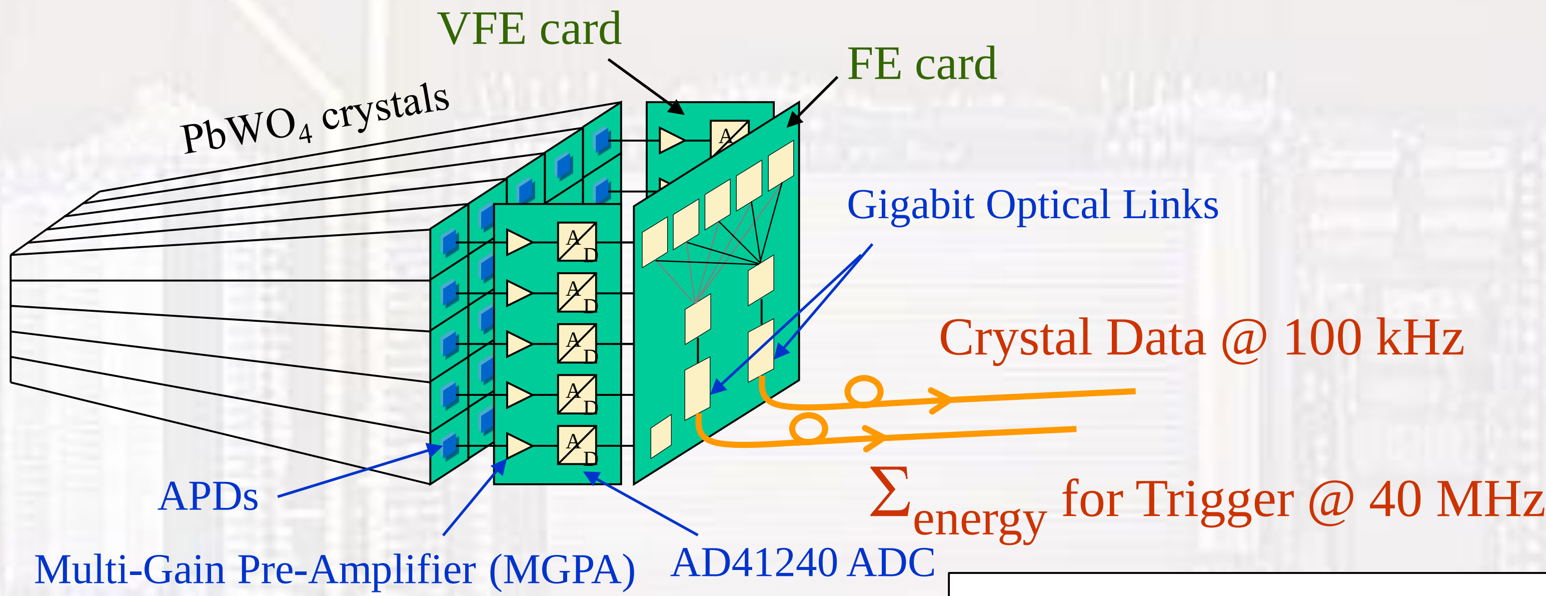
- **Bad channels (out of 9072 total)**
  - 2 malfunctioning HB & 1 malfunctioning HE channel since 2010
  - 3 dead HB channels (front-end chip – QIE – problems) since 2011
    - All but one HE channel fixed during LS1
- **Problematic channels**
  - One HPD (HB, 18 channels) had low bias voltage since 2010 – longer signal
  - Three HB/HE QPLL modules (timing synchronization for 3x36 channels) were not in exact synch with LHC clock
    - All issues fixed during LS1
- **HO (not critical for HCAL operation) had several issues during Run I and was only partly operational**
    - Now the entire HO (with new Silicon Photomultipliers – SiPMs – instead of HPDs) is fully recommissioned and taking data

Fraction of working channels at the end of Run I and in July 2015

HB: 99.81% → 100%
HE: 99.97% → 99.97%
HO: very little → 100%
HF: 100% → 99.9%

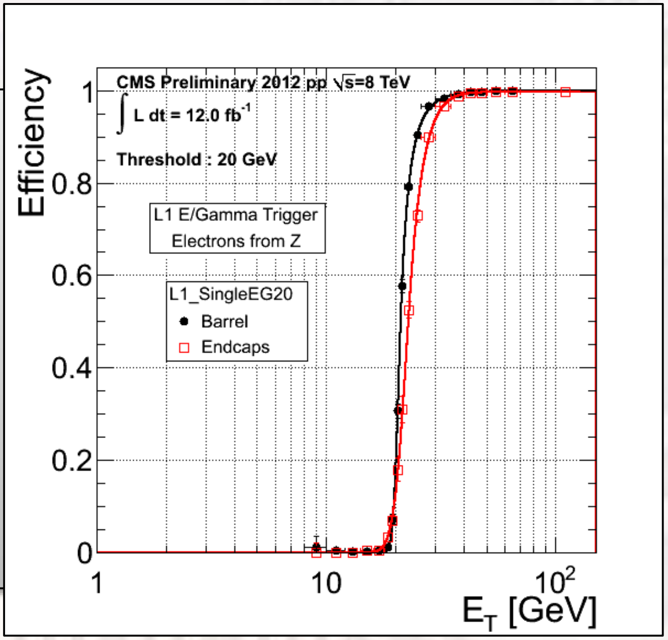
PERFORMANCE: ECAL

Performance: Electronics & Trigger



- Efficient and stable e/γ trigger
  - Level-1: E_T sum of adjacent Trigger Towers (e.g. 5x5 crystals in barrel)
  - EG20 (E_T>20 GeV) un-prescaled

Fully efficient for H→γγ with m_H>100 GeV [leading photon E_T>40 GeV]



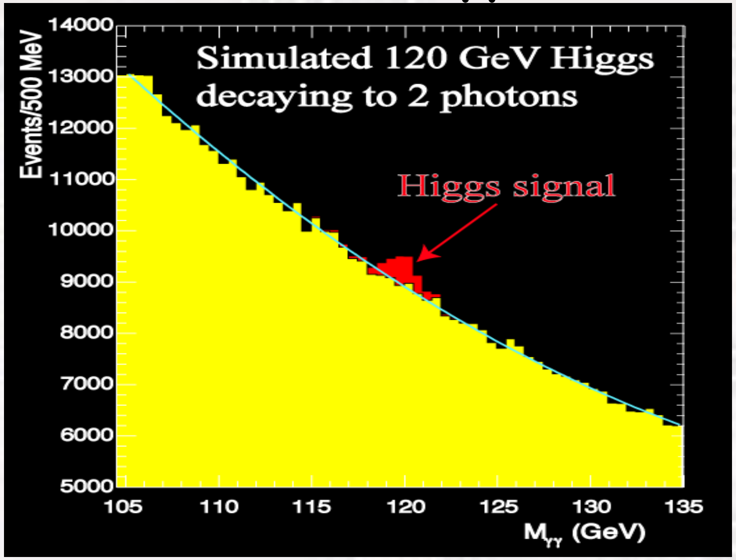
ECAL: H→γγ Resolution

- **SM Higgs boson discovery potential in the H→ γγ channel depends on:**
  - Invariant mass resolution

$$\frac{s_m}{m} = \frac{1}{2}\left(\frac{s_{E_1}}{E_1} \oplus \frac{s_{E_2}}{E_2} \oplus \frac{s_q}{\tan(\frac{q}{2})}\right)$$

$\frac{s_{E_1}}{E_1}, \frac{s_{E_2}}{E_2}$ = energy resolutions of the 2 photons

$\frac{s_q}{\tan(\frac{q}{2})}$ = resolution of angle between 2 photons



  - Background rejection (e.g. prompt γ vs π^0)

- **Energy resolution (σ_E/E) for $e^{\pm}/\gamma$ quantified as:**

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

A = Stochastic term
(quantifies effects of energy fluctuations)

B = Noise term
(quantifies electronics and/or pileup noise)

C = Constant term
(quality of construction, stability, uniformity)

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ECAL Qualification in beam tests

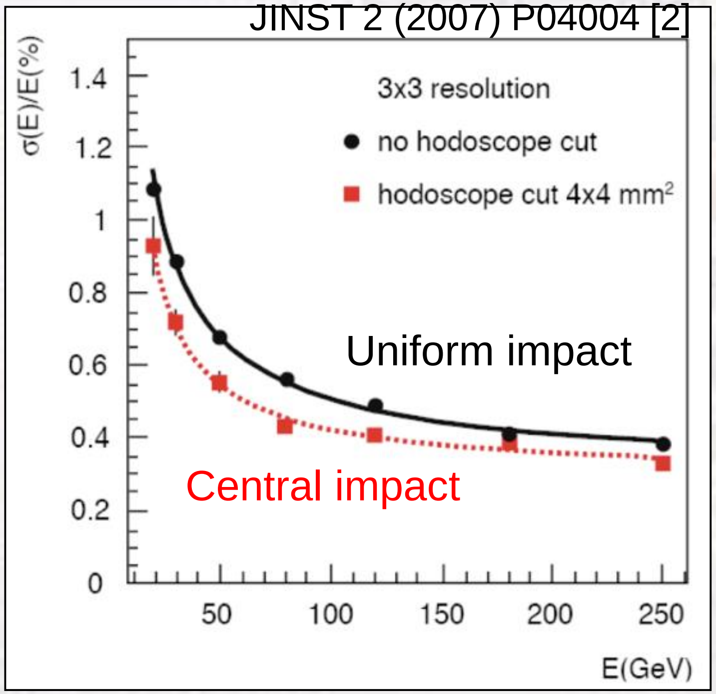
- **ECAL “standalone” performance thoroughly studied at test beams**
  - No magnetic field, no material upstream of ECAL
  - Negligible systematic term from channel response variations

- **Energy resolution for central impact on 3x3 arrays of barrel crystals:**

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus \frac{0.128}{E\,(\mathrm{GeV})} \oplus 0.3\%$$

  - Constant term dominated by longitudinal non-uniformity of light collection
  - Limited to less than 0.3% at construction

- **Results compared to, and used to tune, the Monte-Carlo simulation**



- **Additional contribution to the energy resolution in CMS:**
  - Constant term: environmental stability, calibration and response uniformity to be kept < 1% (assumed 0.4% in CMS Physics TDR)
  - **Electron bremsstrahlung / photon conversion in material upstream of ECAL → affects all terms**

ECAL Clustering & Energy Estimation

- **Goal: obtain the most accurate estimate of e/γ energy**

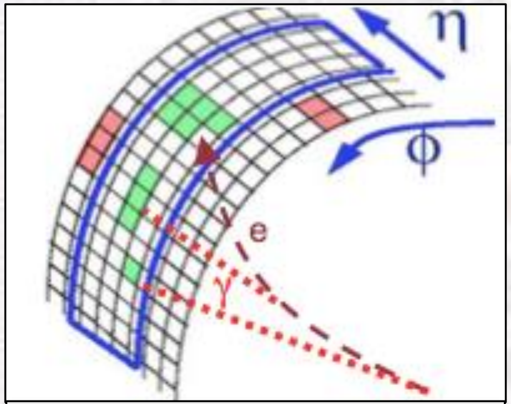
$$E_{e/\gamma} = F_{e/\gamma}\, G \sum_i s_i(t)\, c_i\, A_i$$

Equalization of channel response

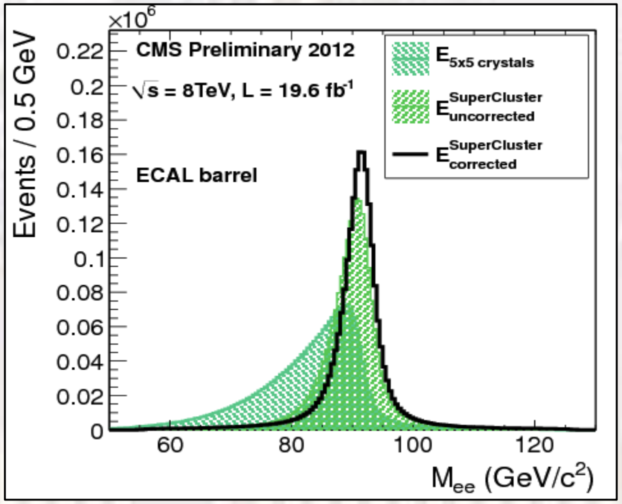
- **A_i:** single channel amplitude (ADC counts)
- **C_i:** inter-crystal calibration coefficient
- **$S_i(t)$:** time-dependent correction for response variations

Absolute energy calibration & corrections

- **G:** global scale calibration (GeV/ADC count)
- **$F_{e/\gamma}$:** energy containment corrections (particle, geometry, clustering, upstream material, …)



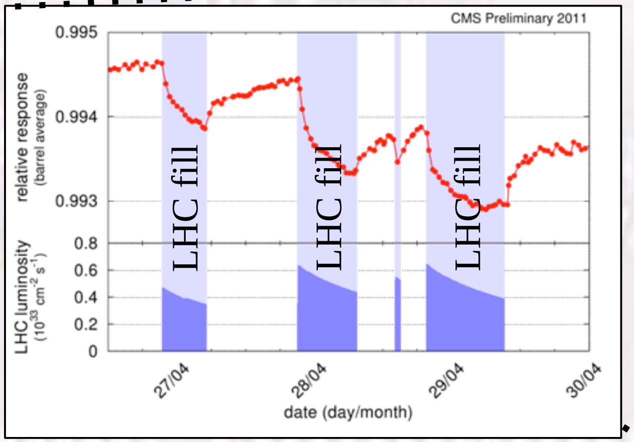
Dynamic "**superclustering**" to recover energy radiated along ϕ due to bremsstrahlung

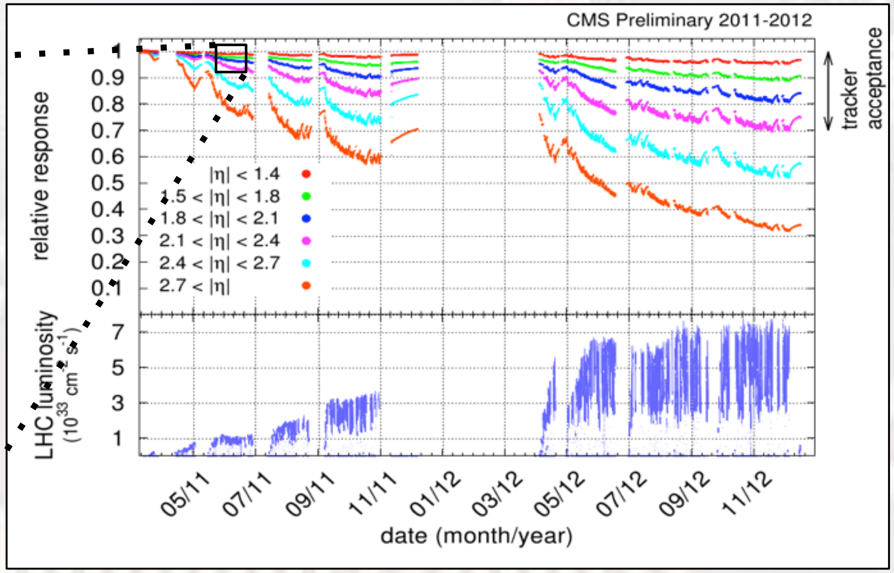


Impact on the $Z \rightarrow e^+e^-$ energy scale and resolution from the incorporation of sophisticated "superclustering" and cluster correction algorithms

ECAL Time-dependent Instabilities

- **Minimize environmental instabilities**
  - Achieved $\Delta T < 0.02^oC$, $\Delta V_{APD} < 20$ mV (well within spec.)
- **Radiation-induced effects – heavily η dependent**
  - Crystal **transparency** changes
    - Colour-centre formation, **but no damage to scintillation mechanism**
    - Electromagnetic damage is **spontaneously recovered** at room temperature
      - Fast damage and recovery on the order of hours
    - Hadronic damage causes **permanent** (at room temp.) and **cumulative** defects
  - VPT photocathode conditioning with accumulated charge*
  - APD leakage current increases

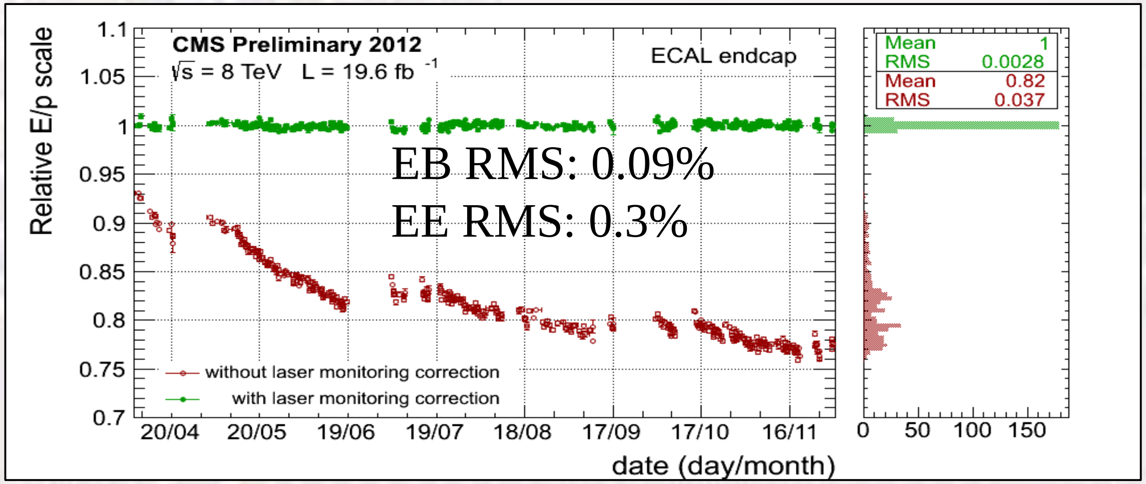


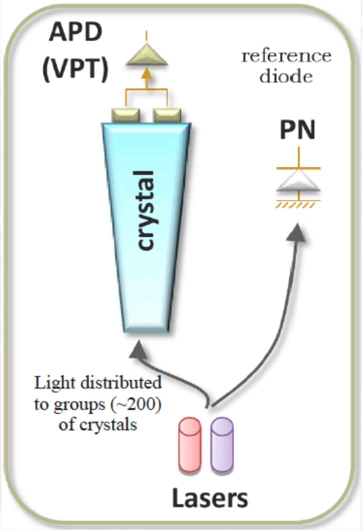


*Not disentangled from transparency changes

ECAL Monitoring the Response Stability

- **Light from laser (447nm, ~peak emission) injected through fibres into each crystal: measure the transparency**
  - One (averaged) measurement per crystal **every 40 minutes**
    - Normalized with reference PN diodes
    - Corrected for differences in light paths for scintillation and laser light
  - Corrections ready for prompt reconstruction in **less than 48 hours**!
    - Validity checked using electrons from W decays





  - Weekly corrections for optimizing the L1 e/γ trigger

(Inter)Calibrating the ECAL

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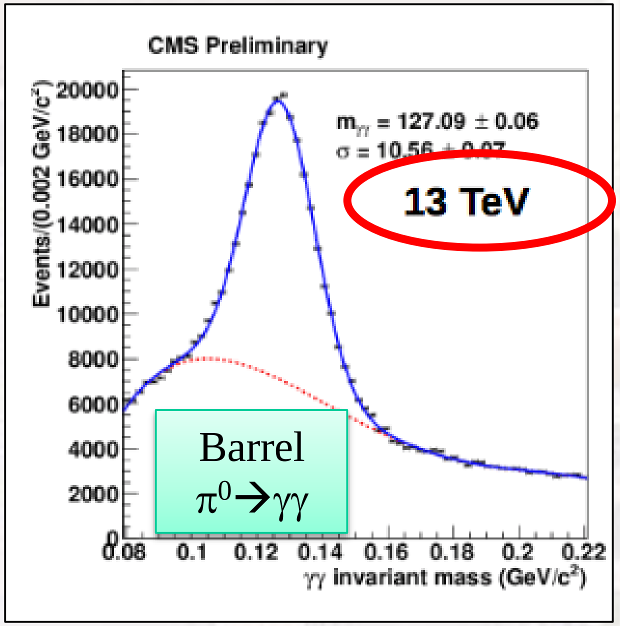
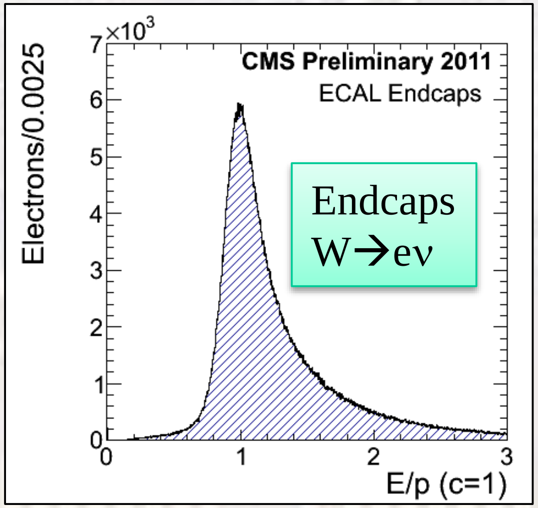
- ϕ- and time-invariance of energy flow in crystals at given η
  - Short calibration periods ~ 2 days
  - Excellent for checking ECAL stability
- $\pi^0/\eta \rightarrow \gamma\gamma$ invariant mass
  - Average calibration periods ~weeks

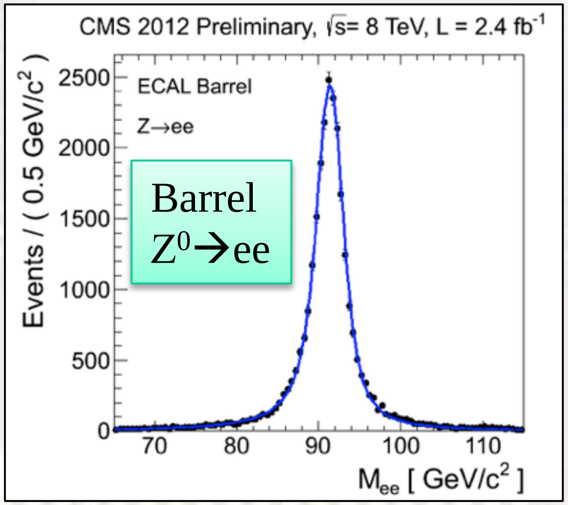
Dedicated high-rate (~10 kHz) trigger streams

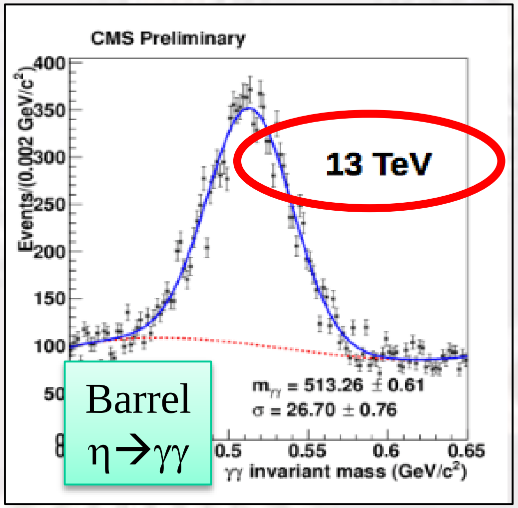
- $Z \rightarrow e^+e^-$ invariant mass and E/p with electrons from $W \rightarrow e\nu$
  - Long calibration periods ~months
  - Z peak also → absolute energy scale

Non pre-scaled analysis triggers



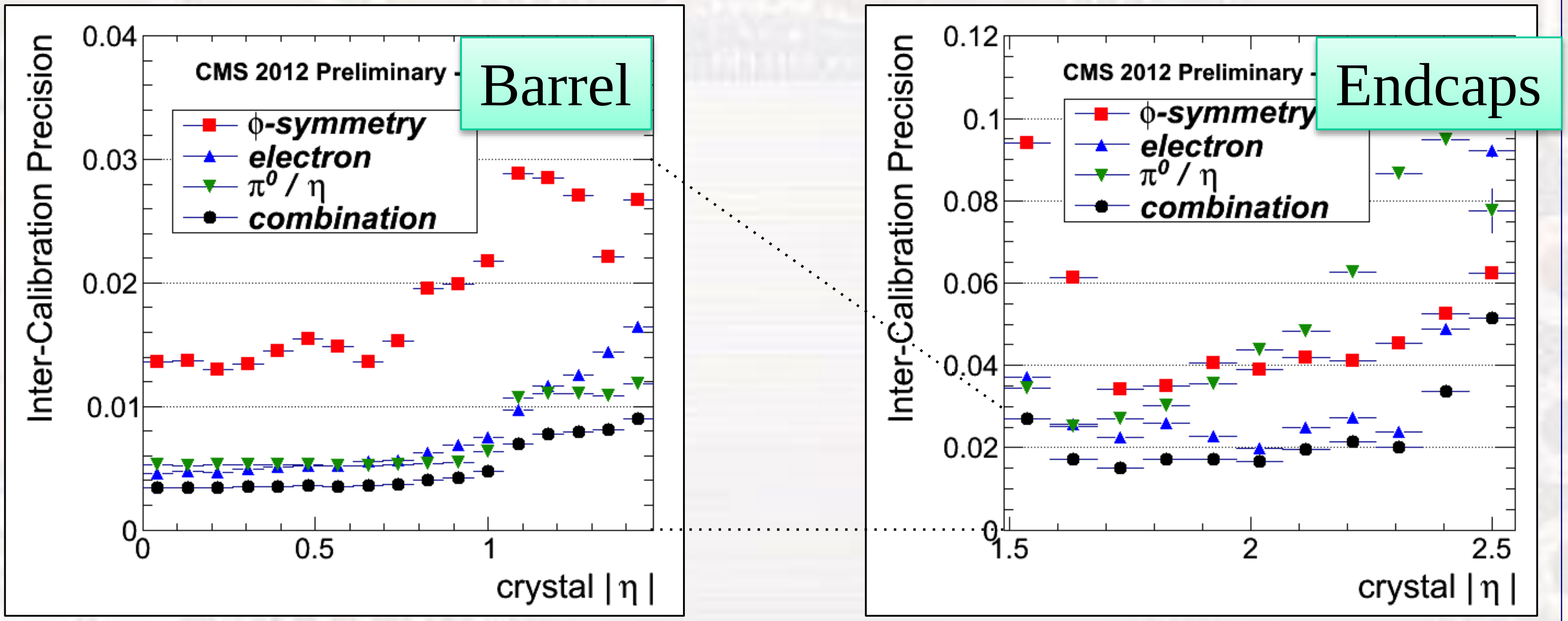






(Inter)Calibrating the ECAL

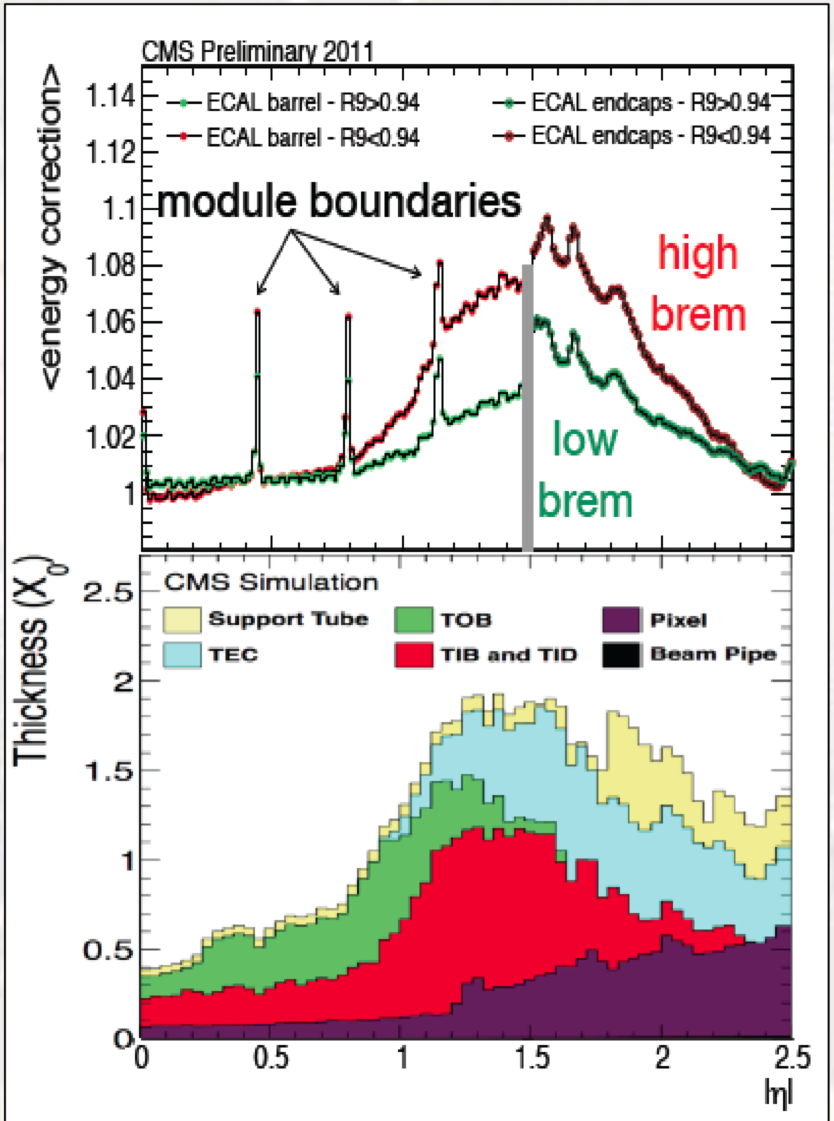
- **Combining all calibration methods**



- ϕ-symmetry limited by systematic uncertainties
  - E/p statistically limited for |η|>1
- π^0/η limited by systematic uncertainties for |η|>2

Combination Precision
Barrel: <1% (~0.4% for |η|<1)
Endcaps: ~2% (almost everywhere)

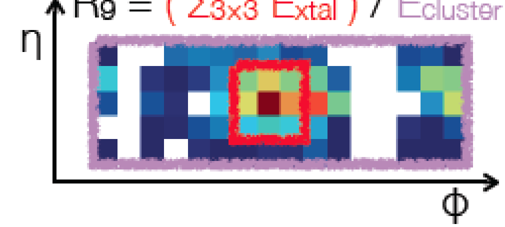
ECAL Energy Corrections



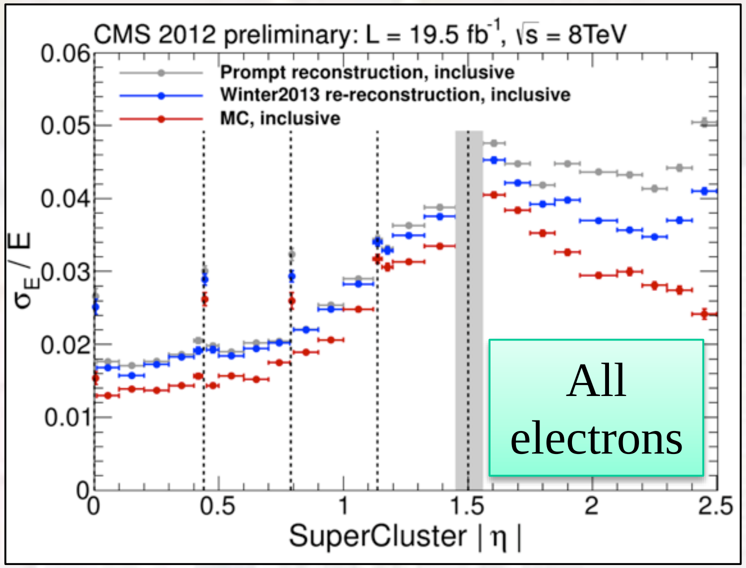
- **Correct energy clusters for:**
  - Energy loss in material upstream of ECAL
    - e^+e^- bremsstrahlung and γ conversions
  - Local shower containment
  - Crystal geometry
- **Corrections currently derived with an MC-driven multivariate (MVA) technique**
  - Using shower location, shape and global event variables

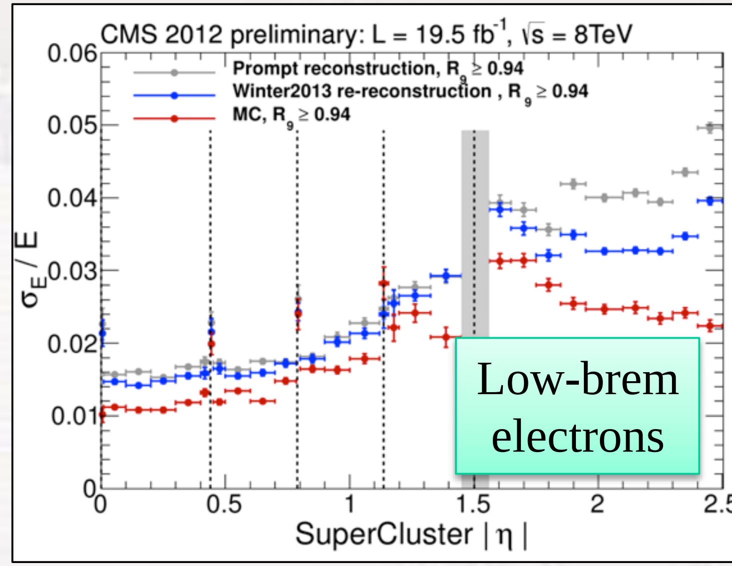
Use R9 shower-shape variable to discriminate:
- low / high bremsstrahlung electrons
- unconverted / converted photons

$R_9 = (\Sigma_{3x3} E_{xtal}) / E_{cluster}$

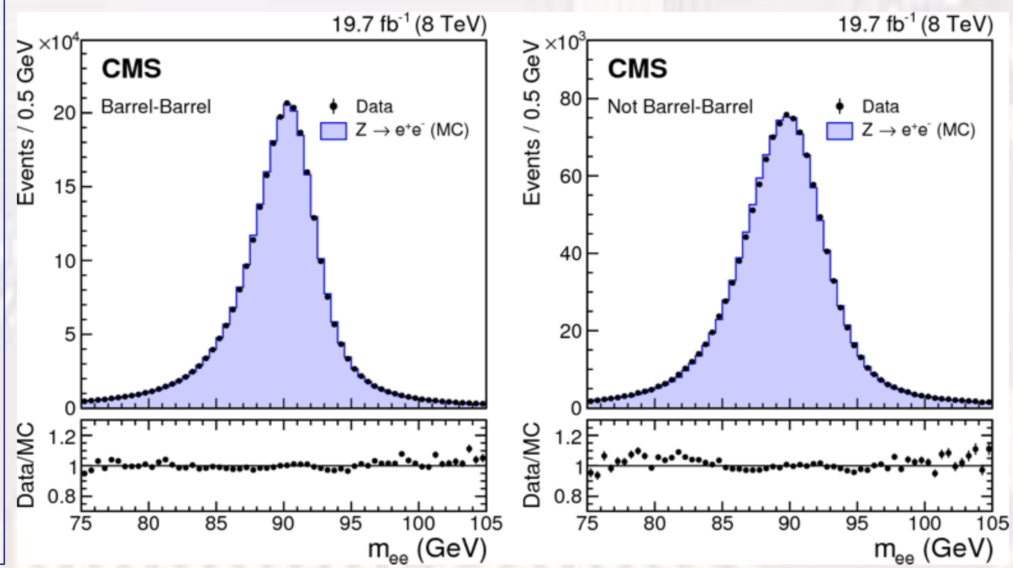


ECAL Energy Resolution

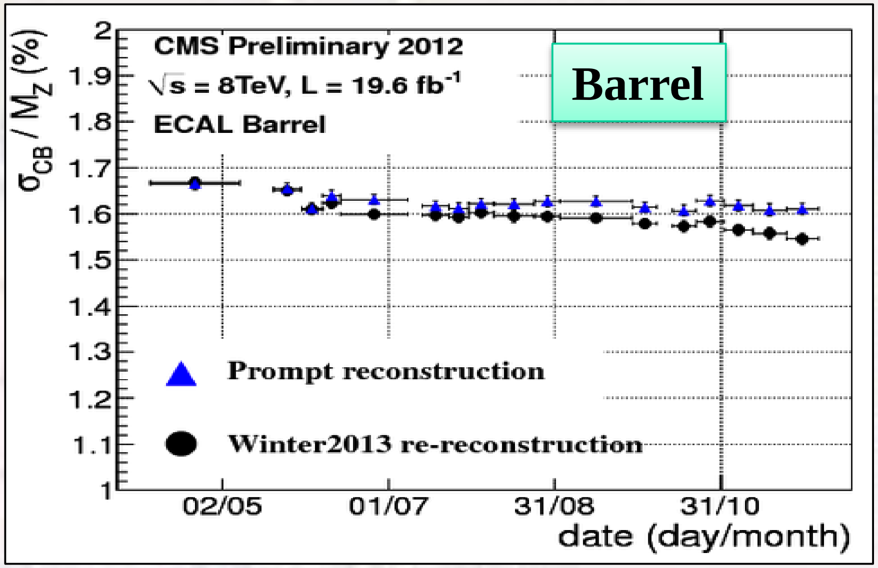


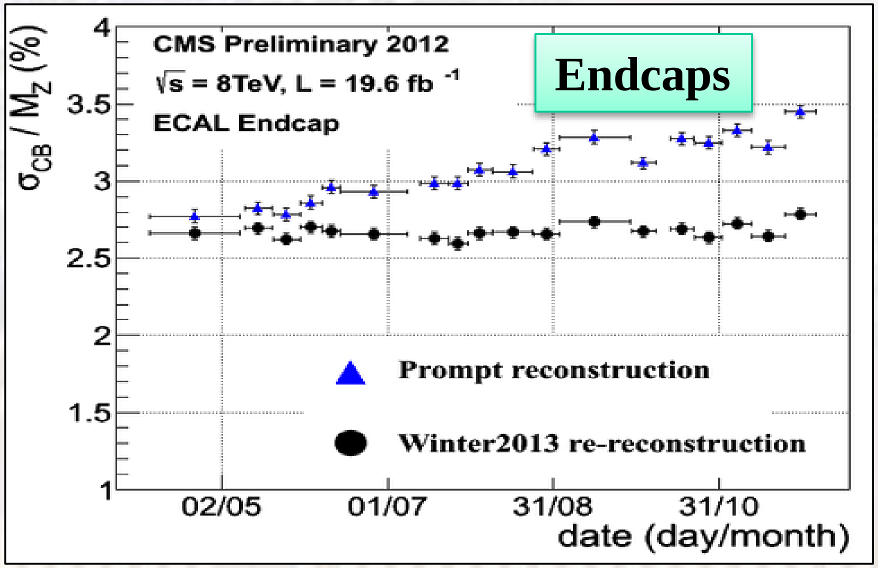


- Derive electron energy resolution from Z→e$^+$e$^-$ width
- ~1.2% for low-brem. electrons in central barrel
- Differences observed between data/MC
  - MC adapted by adding an extra smearing term (conservative at high energies)



ECAL Resolution Stability with Time





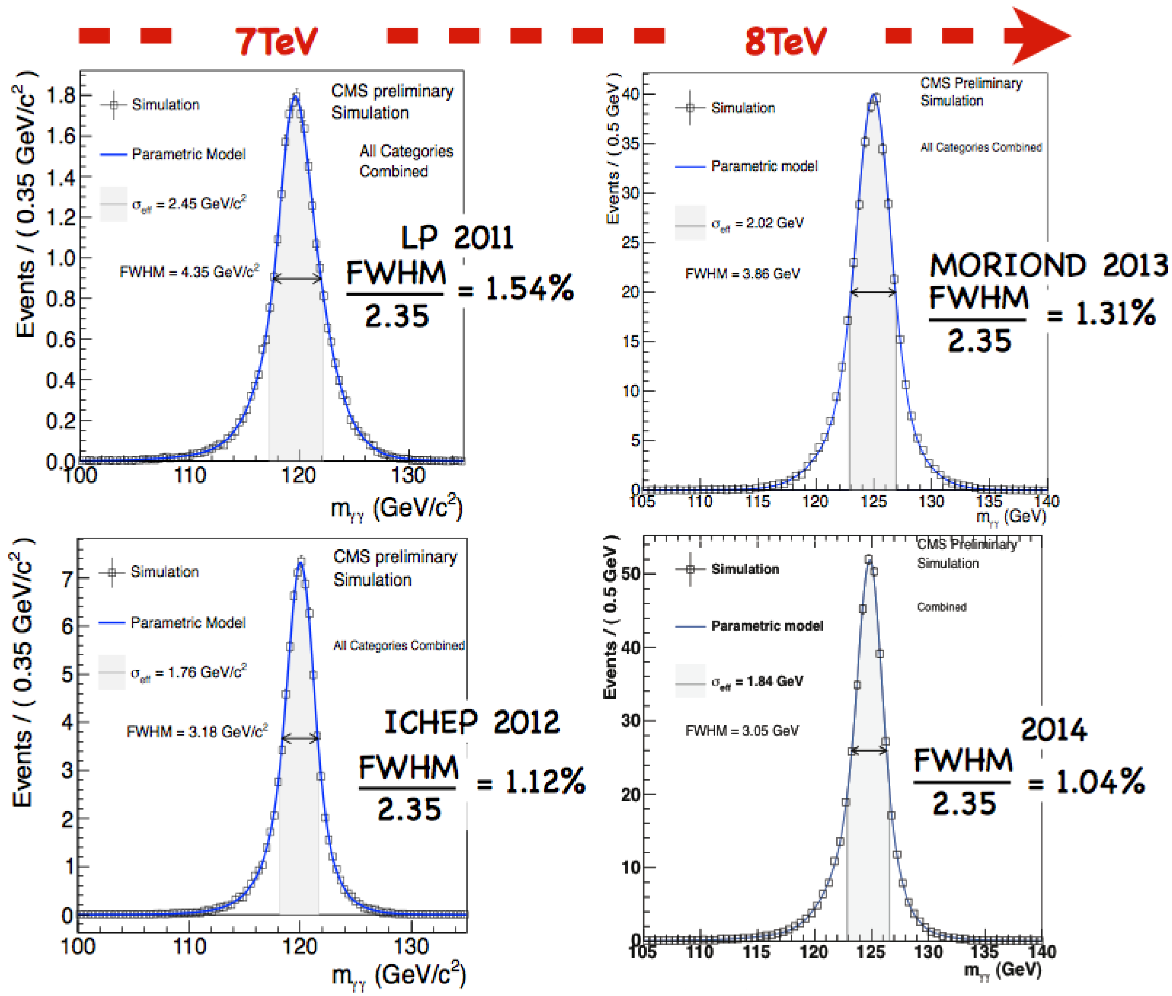
- Width of the Z→e^+e^- peak fitted with a Crystal Ball (CB) function convoluted with a Gaussian
  - Use CB width as a measure of the mass resolution
- "Prompt" reconstruction (<48 hours after data taken) already excellent
- Absolute resolution and stability improved further once final inter-crystal calibration applied for a "re-reconstruction", especially in the endcaps

ECAL Benchmark: $H \to \gamma\gamma$

- The energy resolution measured in data with $Z \to ee$ is used to model the expected $H \to \gamma\gamma$ signal in the simulation
- **Steady progress and excellent results**

PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions



PERFORMANCE: HCAL

HCAL: Pre-Calibration & σ_E/E

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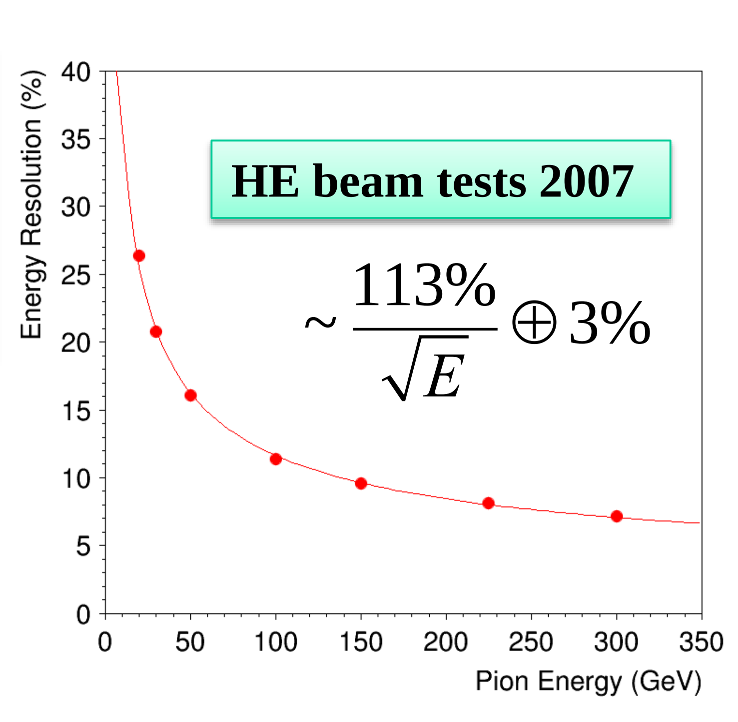
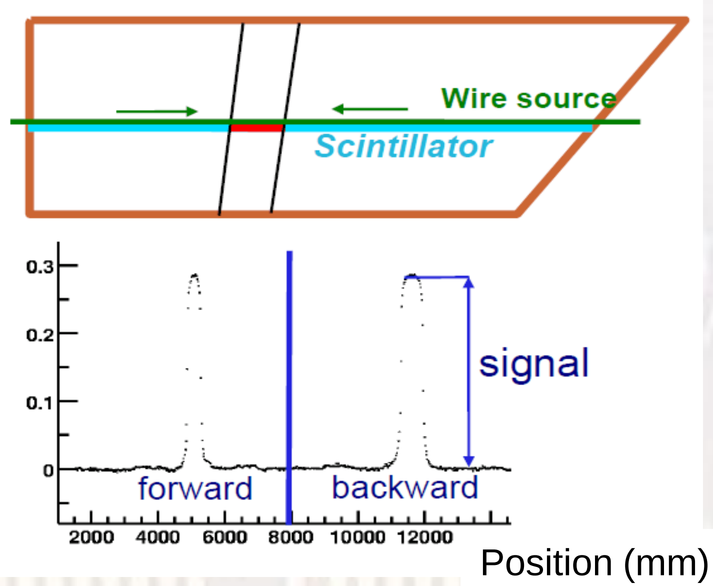
- **LED: illuminate megatiles for checks of FE electronics; monitoring stability of HPD gains**

Beam tests: absolute scale calibration with single hadrons for a few barrel and endcap wedges; study of linearity and energy resolution σ_E/E





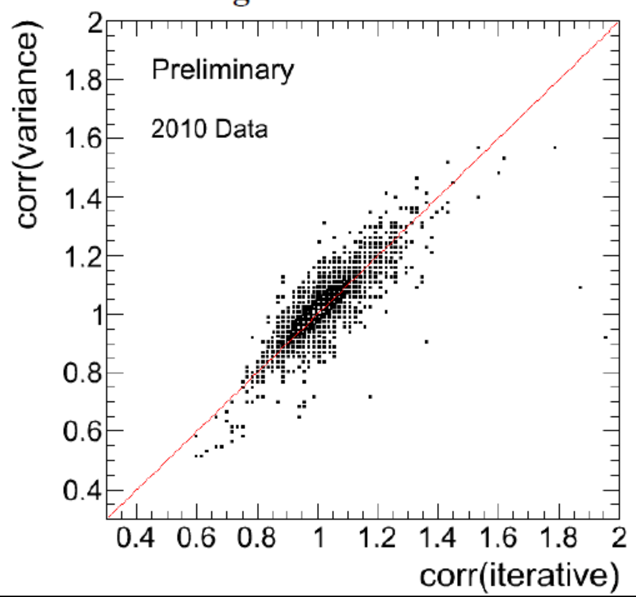
- Wire-sourcing (Co^{60}): relative calibration of all HB/HE towers
- Cosmic muons (in situ) can be used for cross-checks & additional calibration

HCAL: Intercalibration in Run I

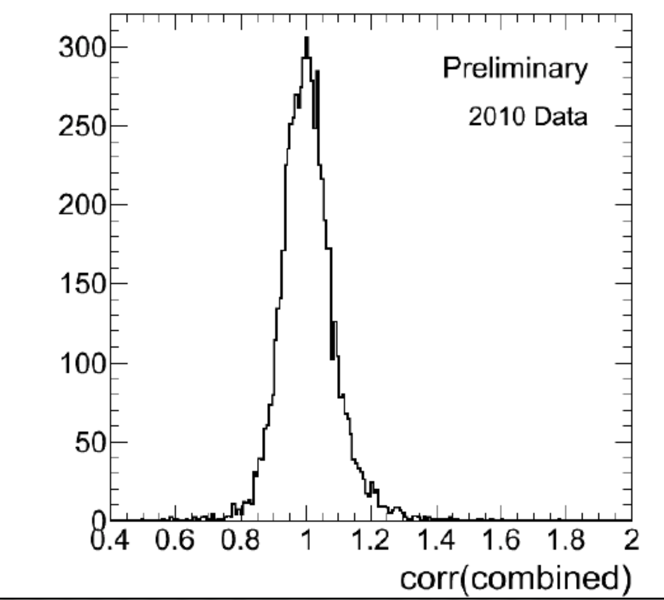
- **Φ-symmetry intercalibration uses two independent methods (giving similar results)**
  - Method of moments (variance) on non-zero-suppressed **minimum-bias data**
  - Iterative method on high-energy **e/γ-triggered** events
    → **weighted sum of both methods used for final intercalibration coefficients**

σ_{stat} :11.2% for HB, and 0.12% for HE
σ_{syst}: ~2% for HB/HE

Comparison of corrections obtained using the 2 methods

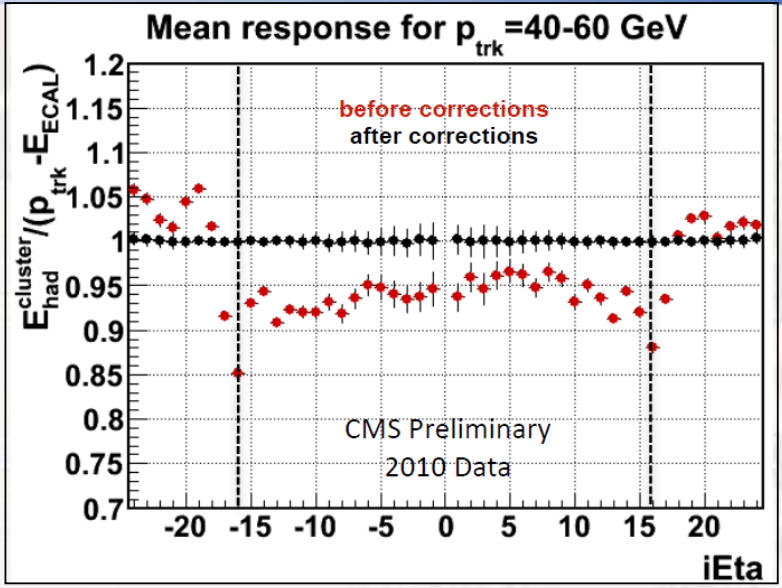


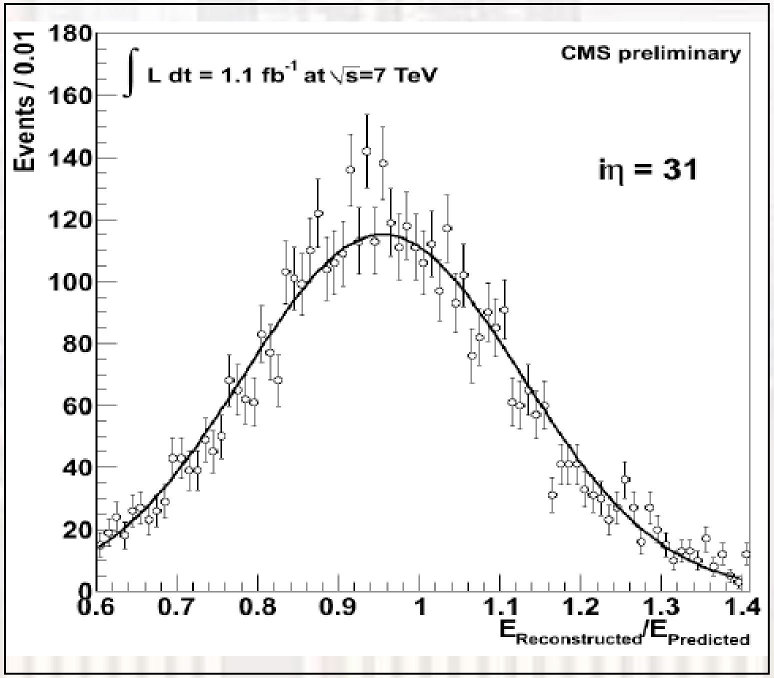
Final corrections determined by an error-weighted average of the 2 methods



HCAL: Absolute Calibration

- **Dedicated triggers for isolated tracks with p_T>40 GeV**
  - Compare HCAL energy with TK p_T and ECAL energy
  - Absolute calibration of all HB and part of HE (to $|\eta|<2$)

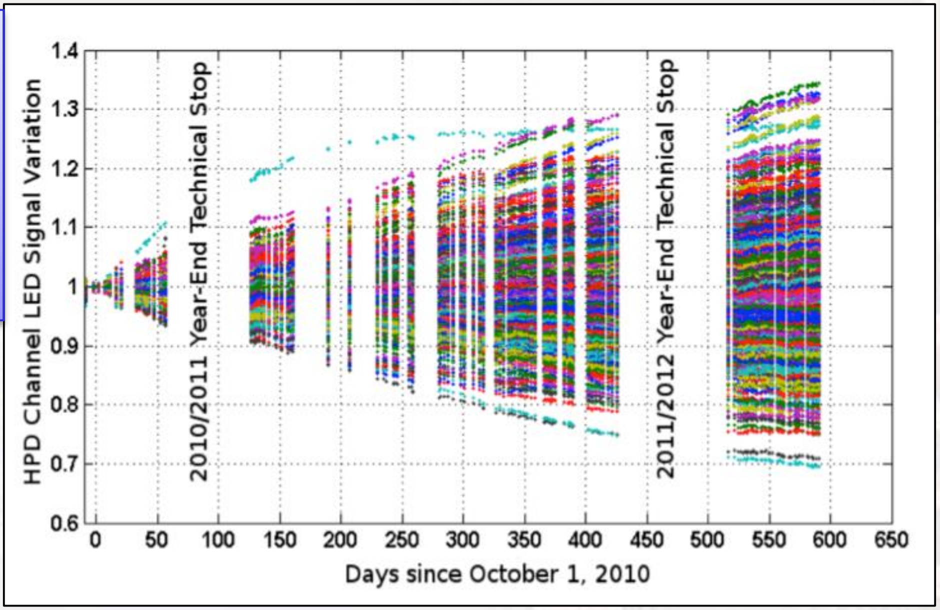




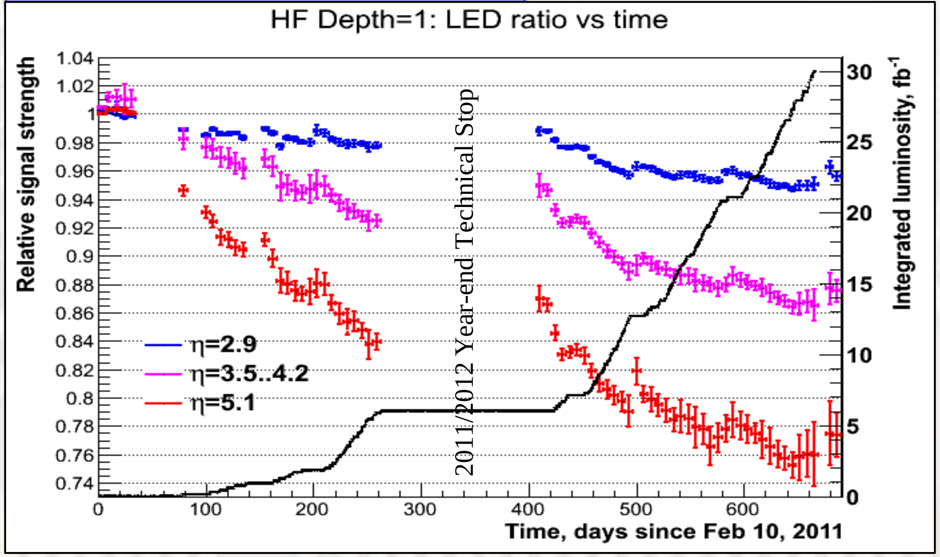
- **Absolute scale for HF from Z→ee**
  - First electron precisely measured in ECAL; second in HF
  - Use constraint on Z mass to derive expected energy in HF
  - Fit $E_{reconstructed}/E_{predicted}$ as a function of η

HCAL: Time-dependent Variations

HPD pixel response drifts (HB, HE, HO)
- Changes are consistent with photocathode migration in HPDs



PMT gain loss (HF)
- Related to luminosity



Both effects addressed during Run I by applying **calibration corrections** at various stages of data-taking and analysis
- Adjustment of energy look-up-tables for L1 trigger
- Adjustment of calibration constants in HLT and offline analysis

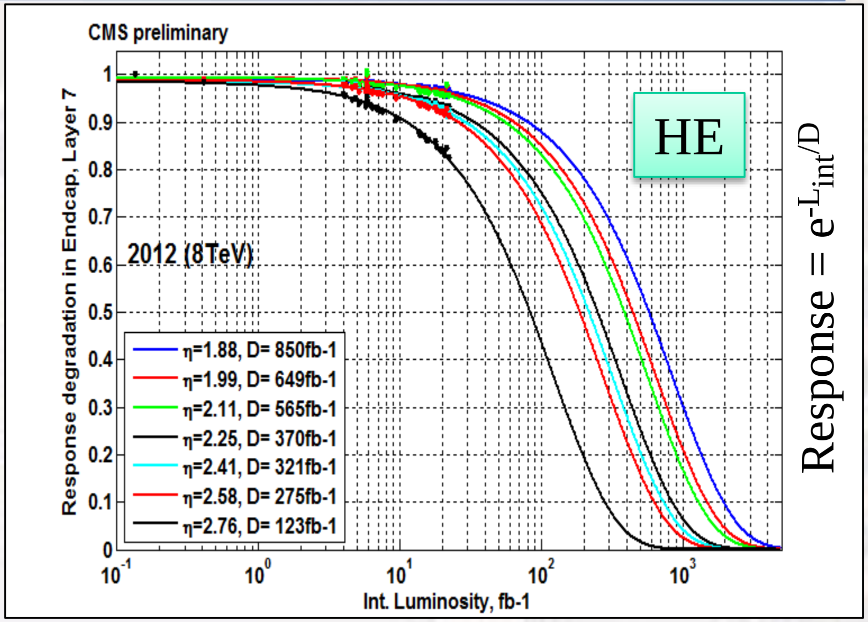
HCAL: Radiation-induced effects

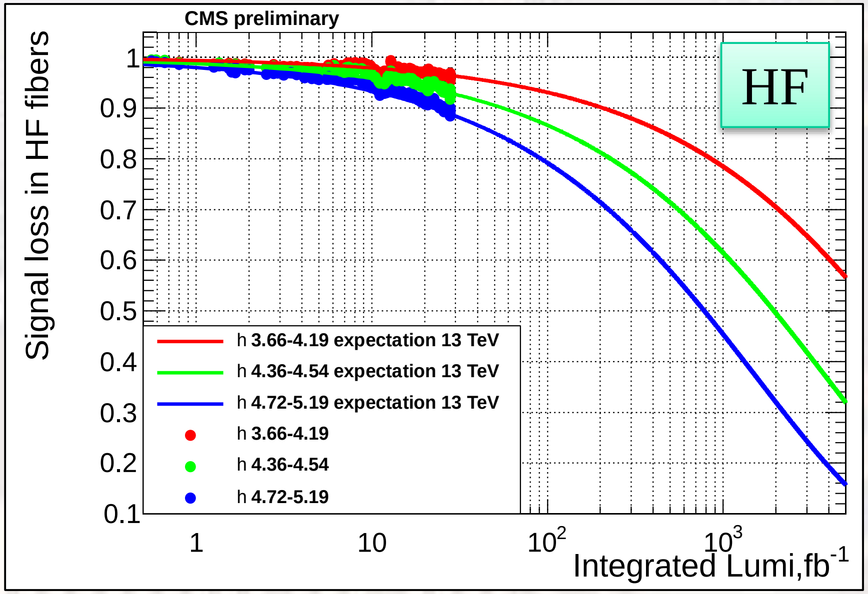
HE:

- Loss of scintillation and reduced transmission of light
- Effect observed in Run1 at the level of 30% in the highest η region of HE (η=3)

HF:

- Reduced light transmission in quartz fibres
- Effect observed during Run1 at the level of 10% in the highest η region of HF (η=5)





HCAL: Energy Response

<response> = <E_{HCAL}/p_{track}>

- $\sqrt{s}$=7 TeV minimum-bias data
- ~no signal in ECAL; Isolated tracks p_T>5 GeV
  - Cone-based isolation at HCAL surface

Corrections necessary to take into account the energy deposited in upstream material, particularly for low E_T particles/jets

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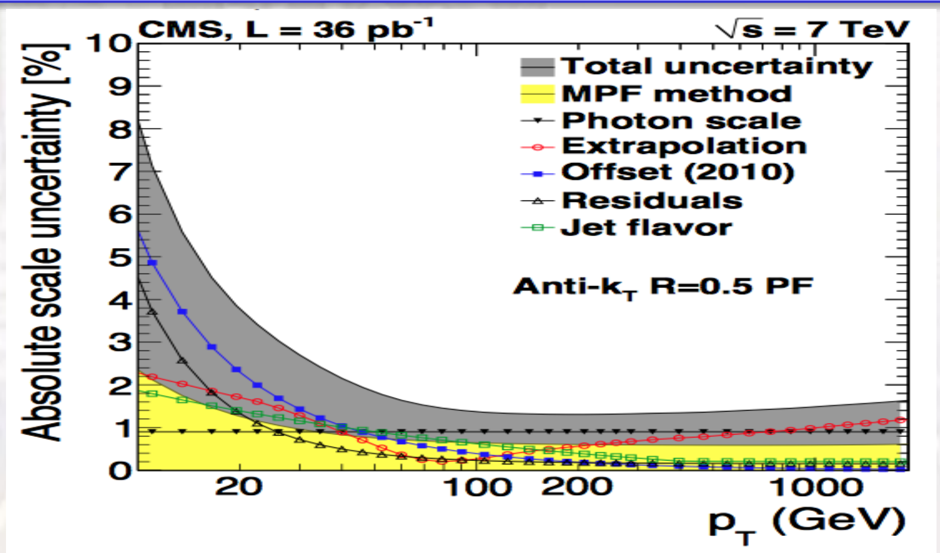
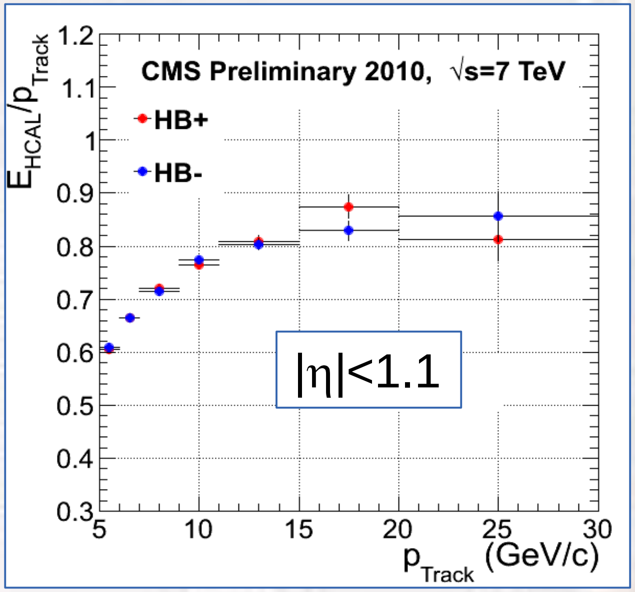
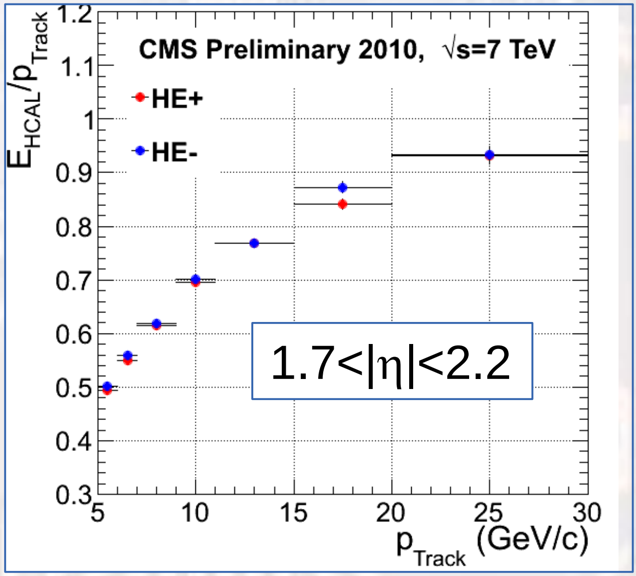


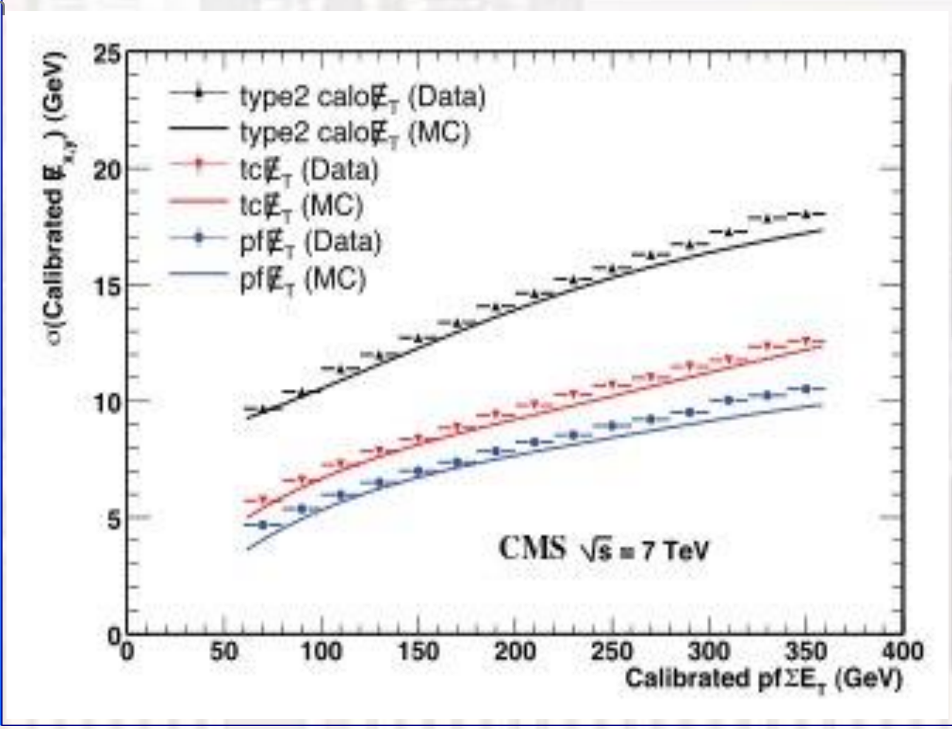




The Particle Flow technique gives a substantial improvement in Jet energy resolution

HCAL: Missing-E_T Resolution

- **Missing E_T (MET) calculated using a combination of measurements in all calorimeters (CaloMET) and also the Tracking detectors (Particle Flow - PF_MET and Tracker-Corrected - TC_MET)**
  - Differences in responses & non-linearities necessitate E_T and η-dependent corrections
  - Special filters developed to eliminate noise, which could otherwise affect MET performance

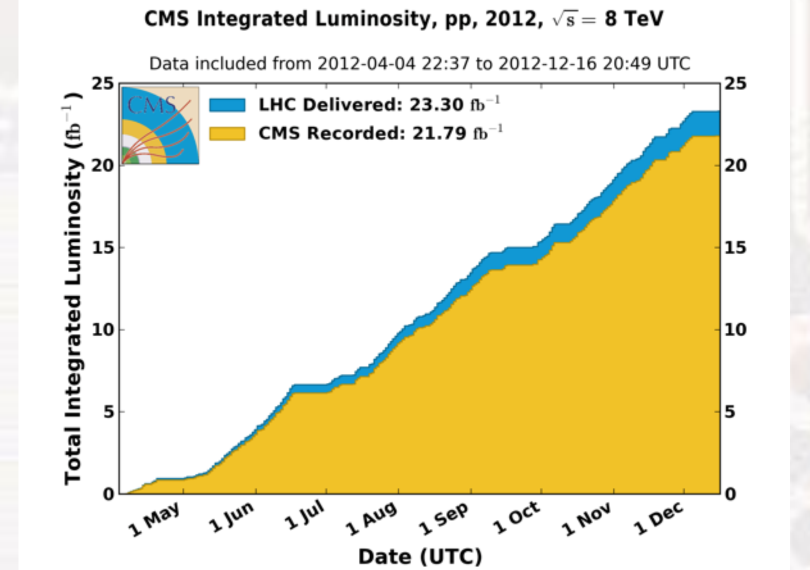


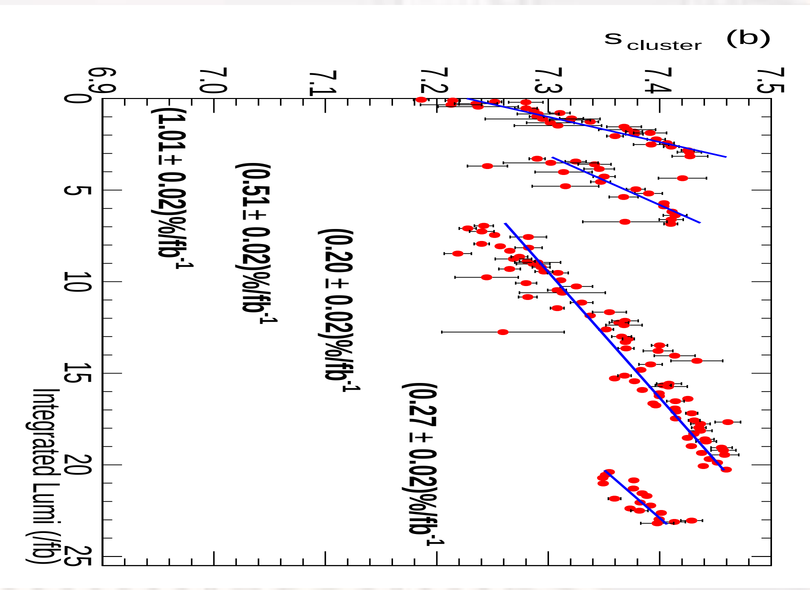
Resolution for the calibrated MET for multijet events with two jets with p_T>25 GeV

The Particle Flow technique gives a substantial improvement in MET resolution

HCAL: Luminosity Measurement

- **CMS provides real-time monitoring of the LHC luminosity to determine an overall normalization for use in physics analyses**
  - **The online luminosity measurement is based on the forward hadronic calorimeter (HF) – "HF lumi"**
- **The HF Lumi is subject to calibration drift as a result of gain changes in the HF PMTs and possible other effects. Such drifts typically occur over a long period of time**
  - **These drifts are calibrated-out**

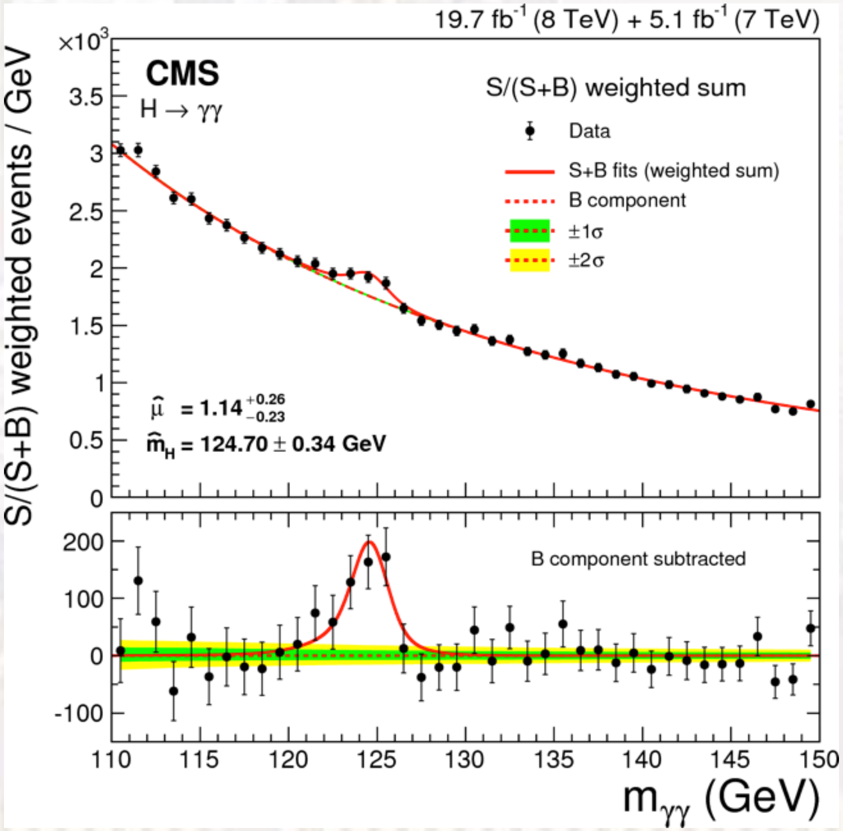




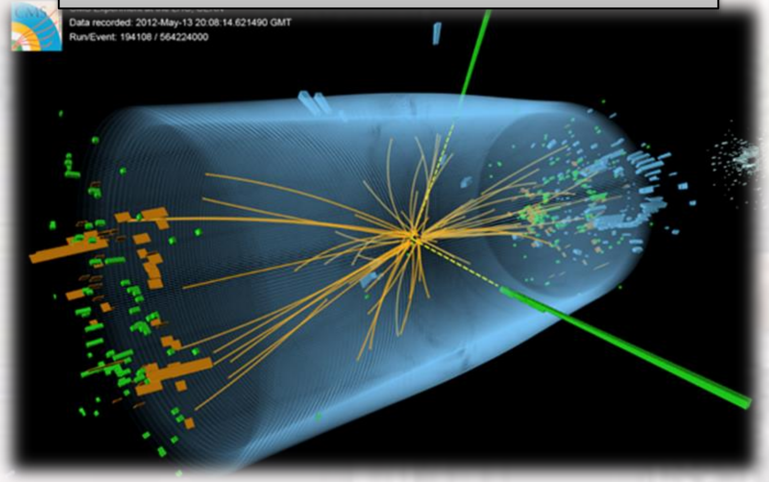
BENCHMARK PHYSICS

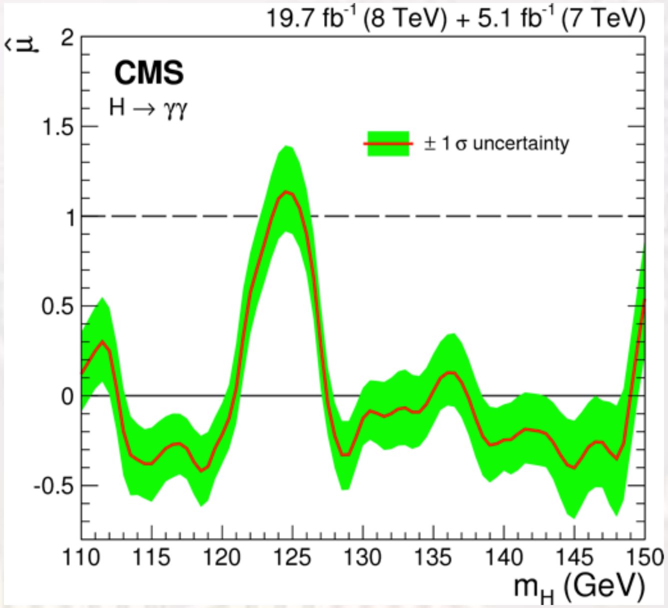
ECAL Benchmark: H→γγ

- **Excess of events seen in H→γγ channel at around 125 GeV/c²**
  - Diphoton final state implies that the new particle is a boson with integer spin different from unity



Candidate H→γγ event in CMS

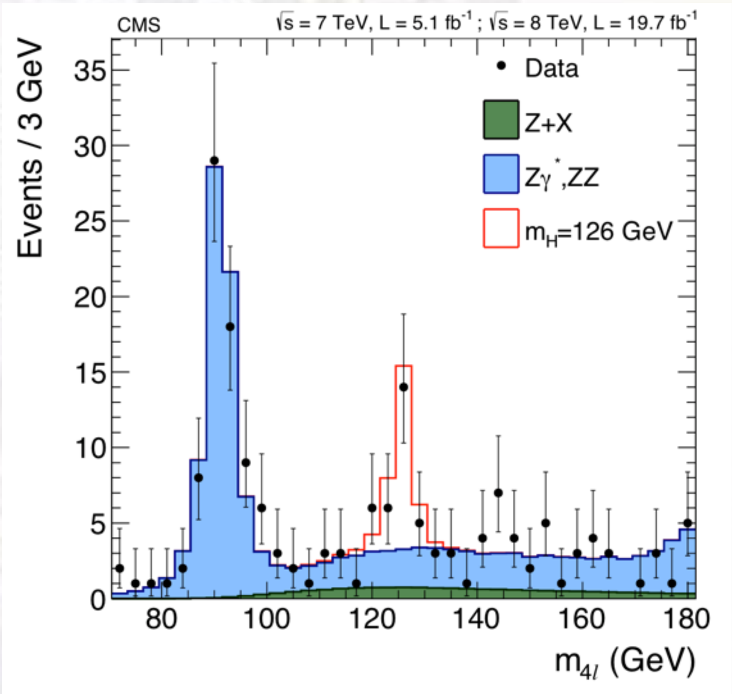




Basics
Technology
Data Acquisition
Construction
Issues
Performance
Long-term
Organization

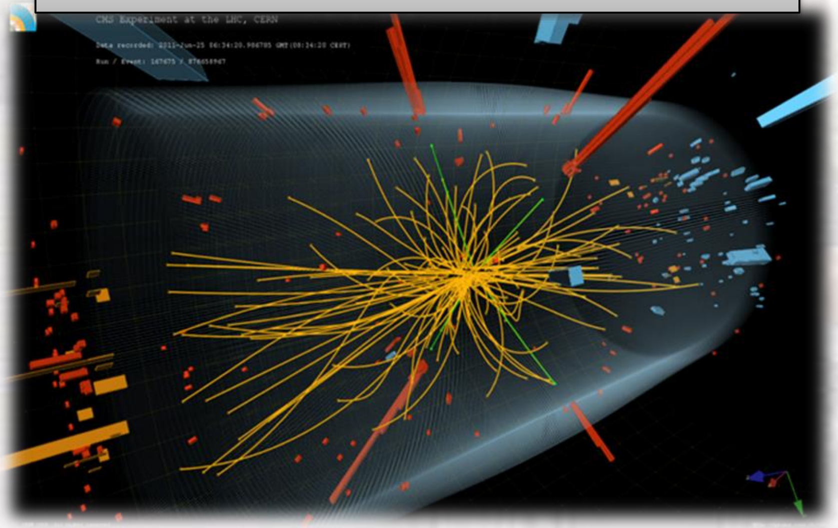
H → ZZ → 4 leptons

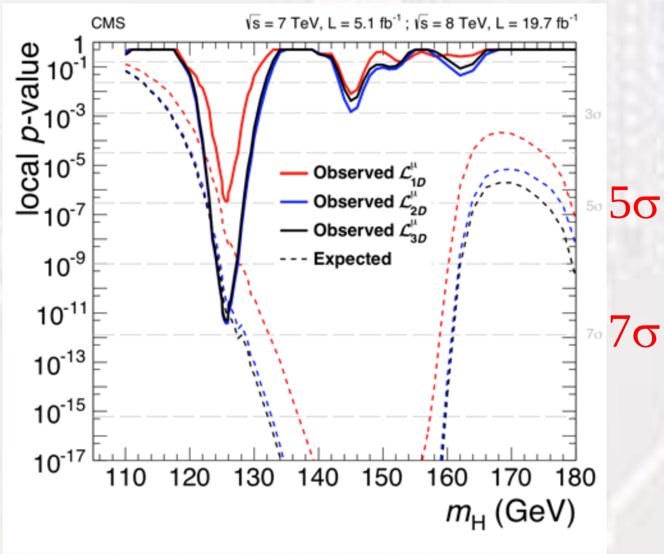
- **Excess of events seen in all 4-lepton channels at an invariant mass ~ 125 GeV/c^2**



Channel	4e	4μ	2e2μ	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

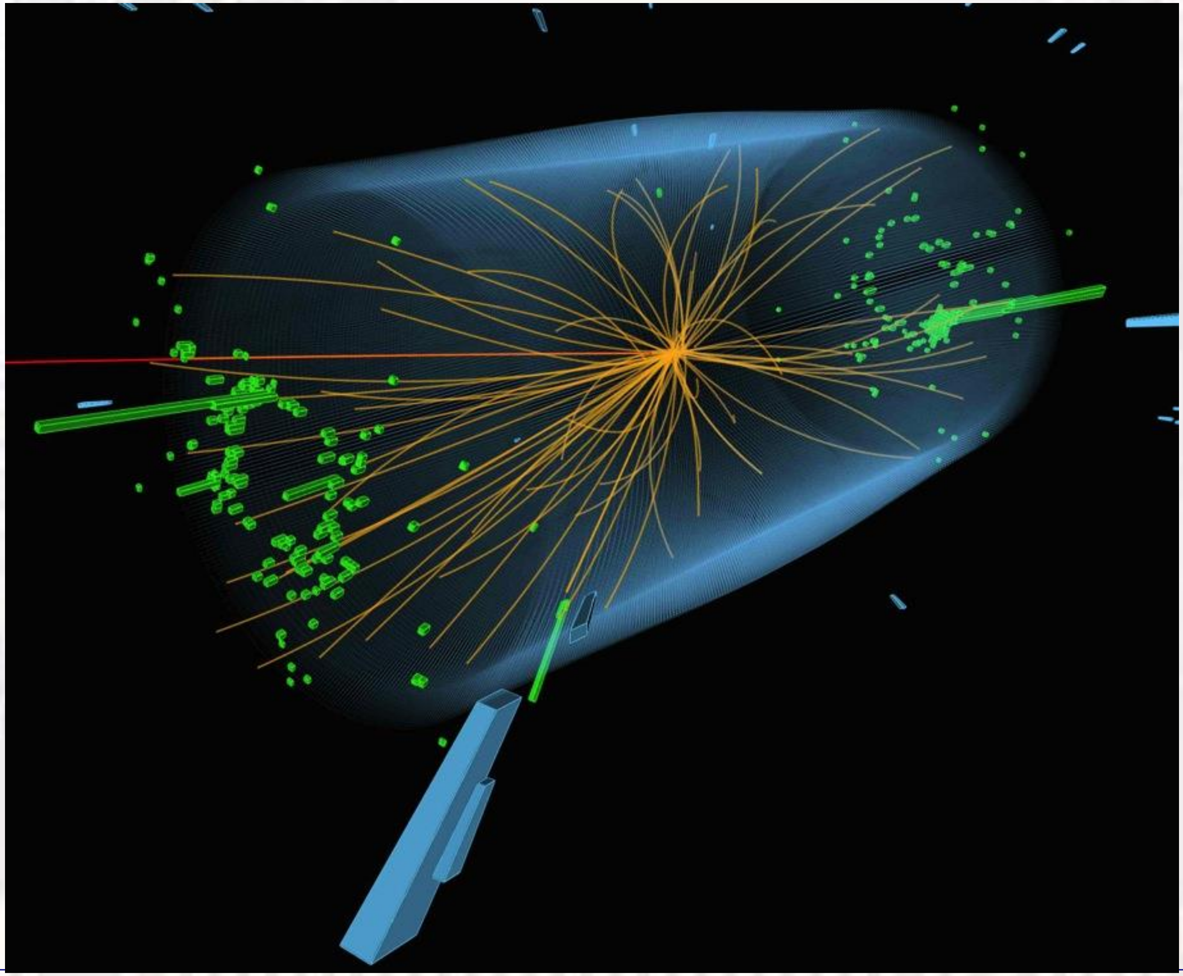
Candidate H→ZZ→4e event in CMS





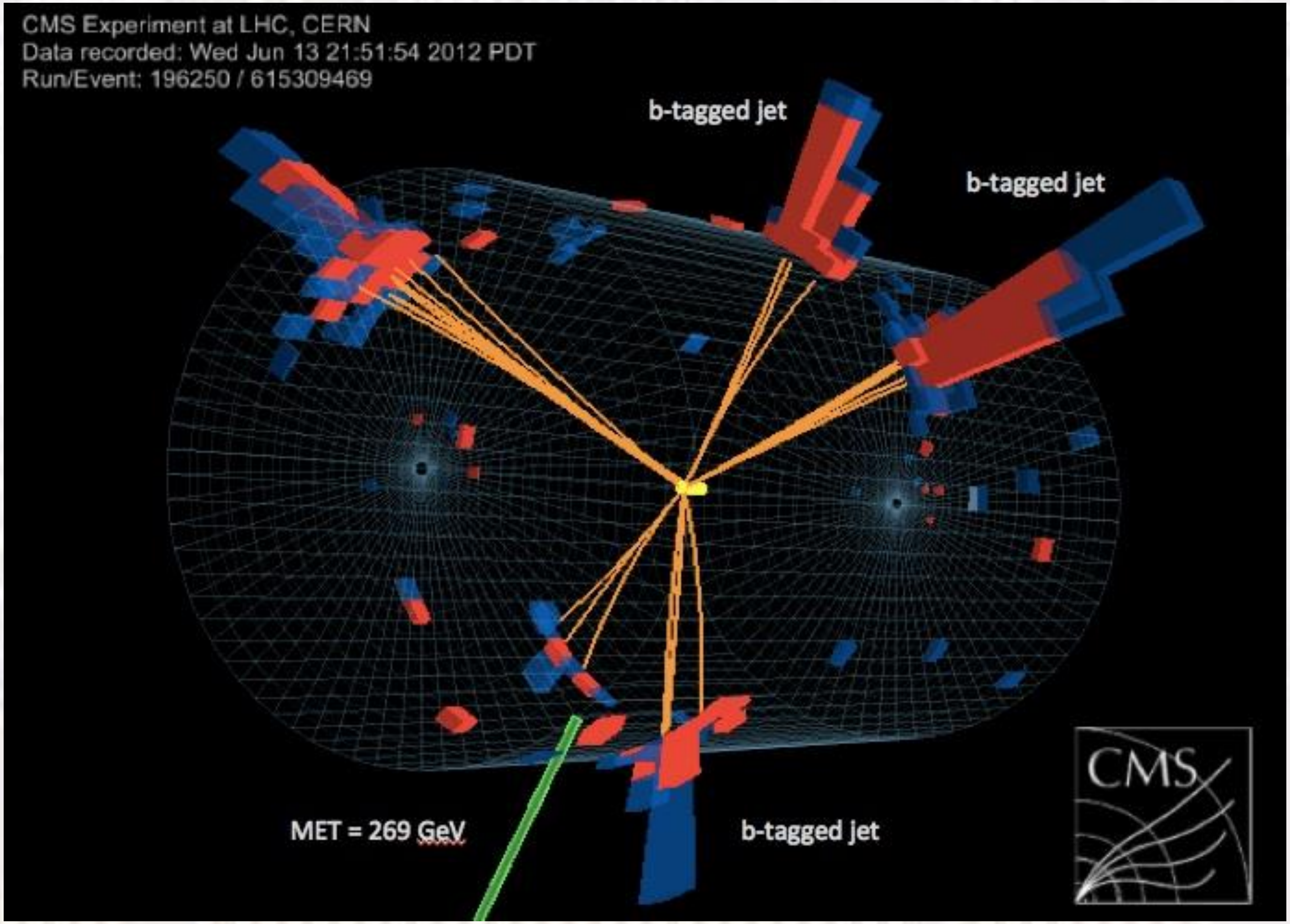
HCAL: Benchmark Physics

- H(ττ) candidate event in the VBF channel, as indicated by the presence of two forward jets (in green) and a central jet (blue) from hadronically decaying tau



HCAL: Benchmark Physics

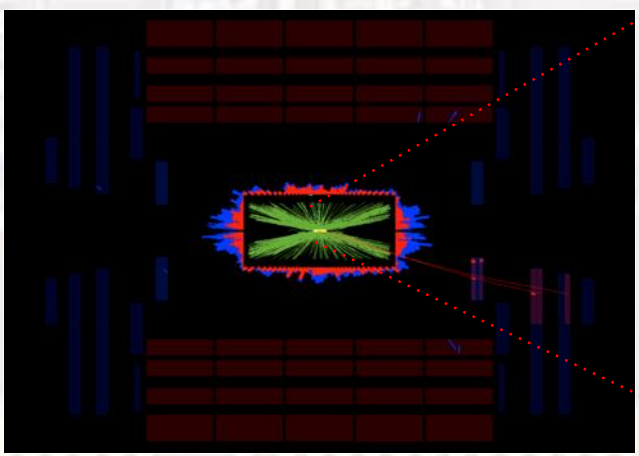
- **Event with several hadronic jets and large MET, as it would be typical of a gluino-mediated bottom or top squark pair production**

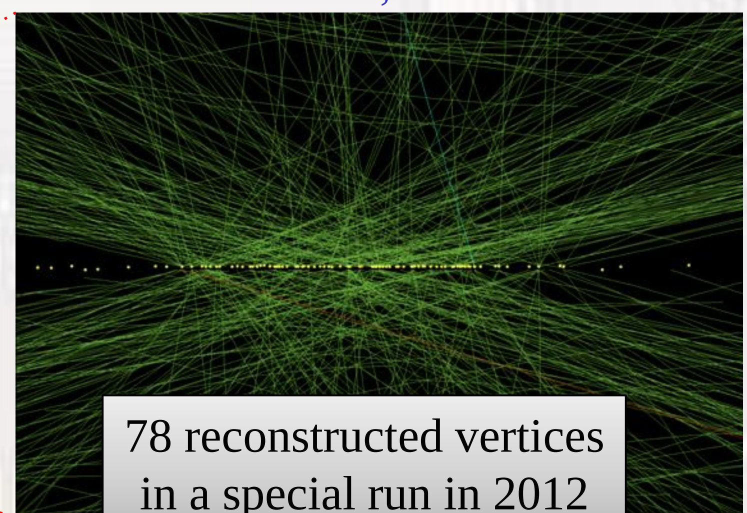


PERSPECTIVES FOR THE LONG-TERM FUTURE: HIGH-LUMINOSITY LHC

Perspectives for the long-term future

- **CMS has collected about 30 fb^{-1} so far**
  - LHC Run II (2015-2018) will be at higher energy (~13 TeV) and at an instantaneous luminosity up to ~$2x10^{34}$ $cm^{-2}s^{-1}$ → 2x higher than CMS was designed for
    - But ECAL and HCAL will still be highly performant!
  - Expect 300-500 fb^{-1} by the end of nominal LHC operation (~2024)
  - High Luminosity LHC (HL-LHC) will take this to ~3000 fb^{-1} by ~2035-2040 → **we have collected ~1% of the total data expected!**
- **HL-LHC conditions will be even more challenging than LHC**
  - Collision pileup ~140-200 (c.f. ~20-40 in LHC)
  - Up to 65 Gy/hour in endcaps (c.f. ~6.5 Gy/h in LHC; barrel is ~20x lower)
  - Up to $2x10^{14}$ hadrons/cm^2 in endcaps (c.f. ~$3x10^{13}$h/cm^2 in LHC; barrel is ~100x lower)



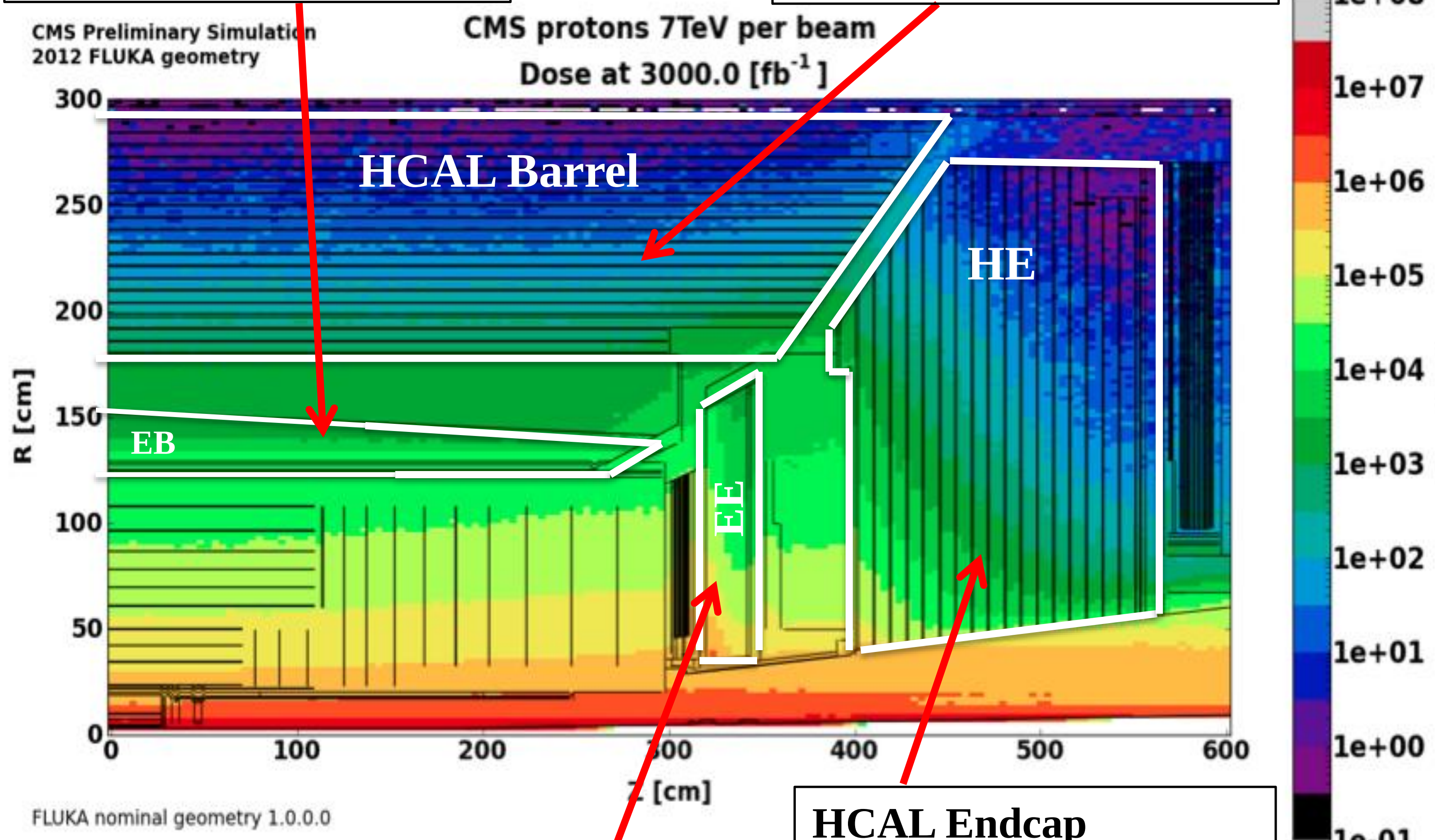


78 reconstructed vertices in a special run in 2012

HL-LHC radiation environment: OK for barrel detectors; bad for endcaps!

ECAL Barrel
below 10^4Gy (1 Mrad)

HCAL Barrel
below 10^3Gy (0.1 Mrad)

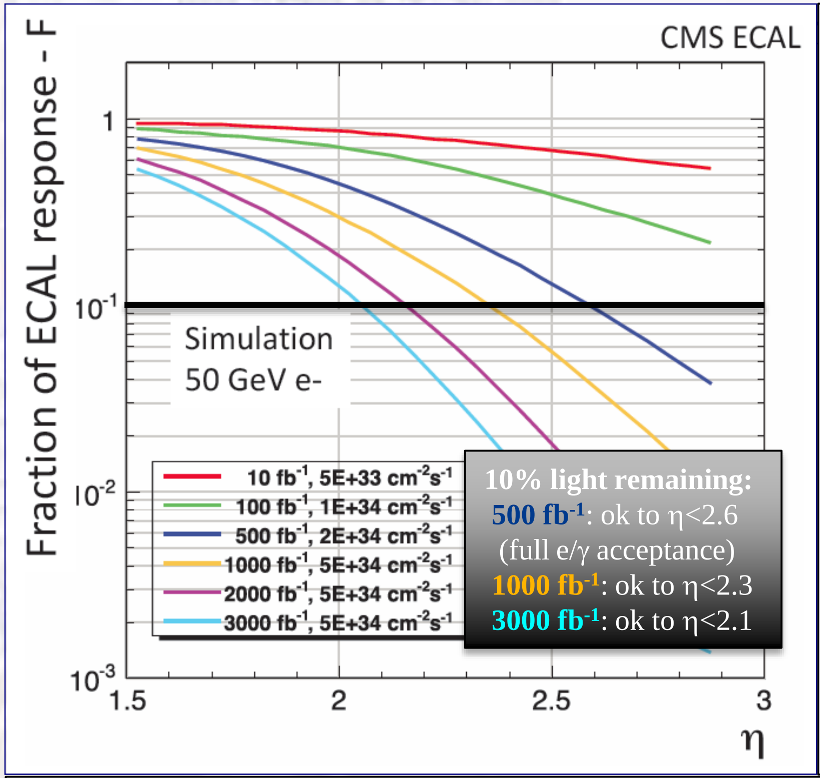


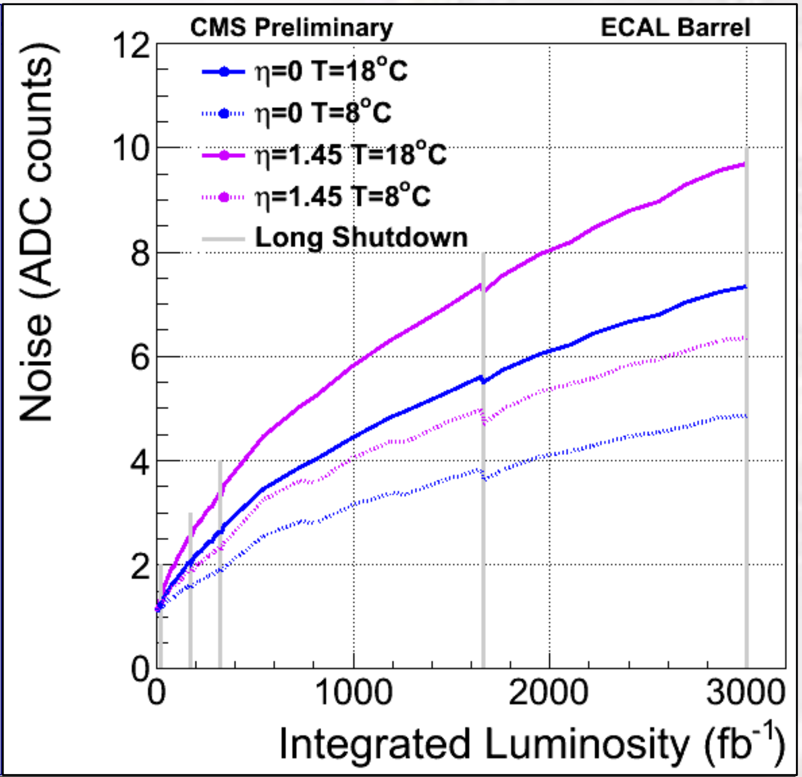
HCAL Endcap
up to 10^5Gy (10 Mrad)

ECAL Endcap
At η=2.6: 3×10^5Gy (30 Mrad), 2×10^{14} h/cm^2

ECAL Perspectives for the Future: EB and EE response degradation

- **Huge amount of work to qualify ECAL long-term performance**
  - Main concern is crystal transparency degradation with integrated hadron fluence
    → affects energy resolution, trigger performance, particle identification

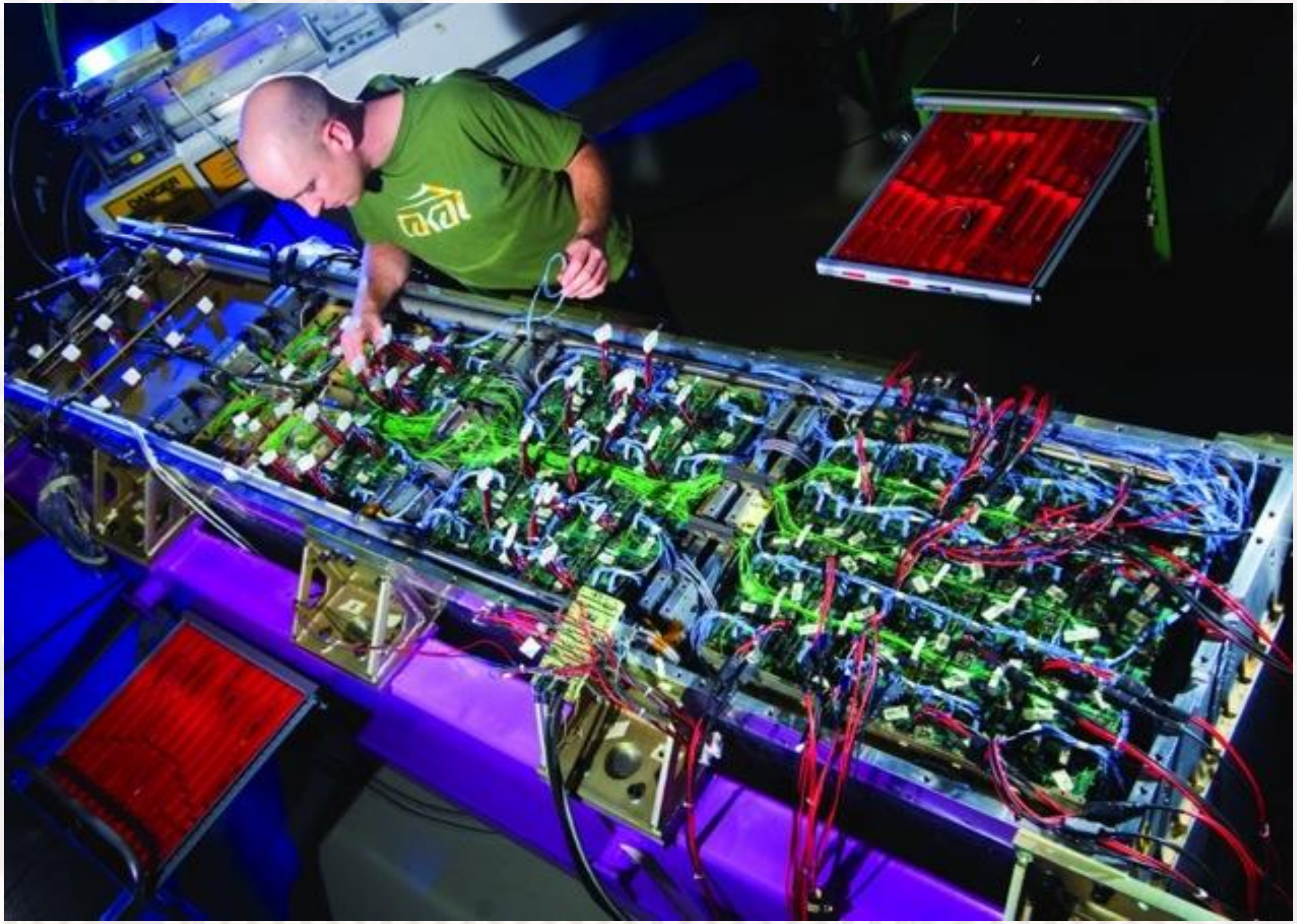




EB crystals: highly performant to 3000 fb^{-1}; *electronics need to be changed*
EE and ES will be ok until 500 fb^{-1}; they need to be replaced for HL-LHC

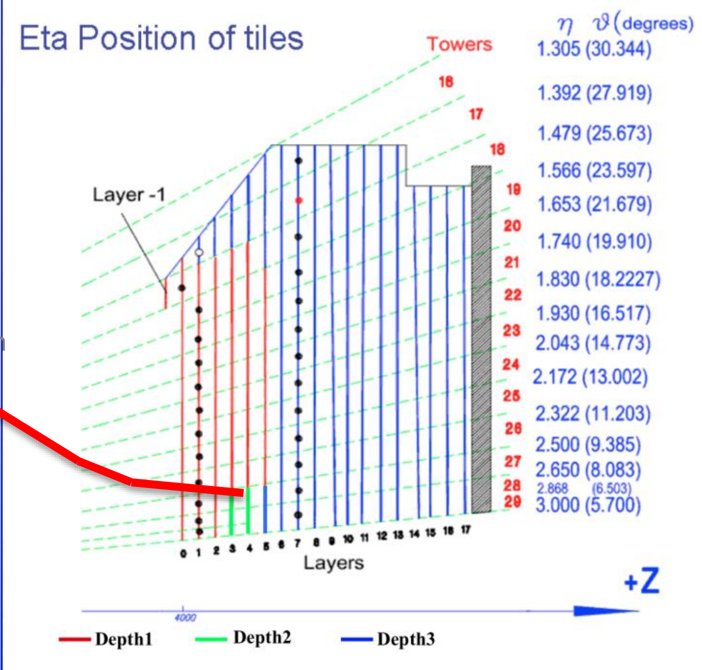
Changing the EB electronics

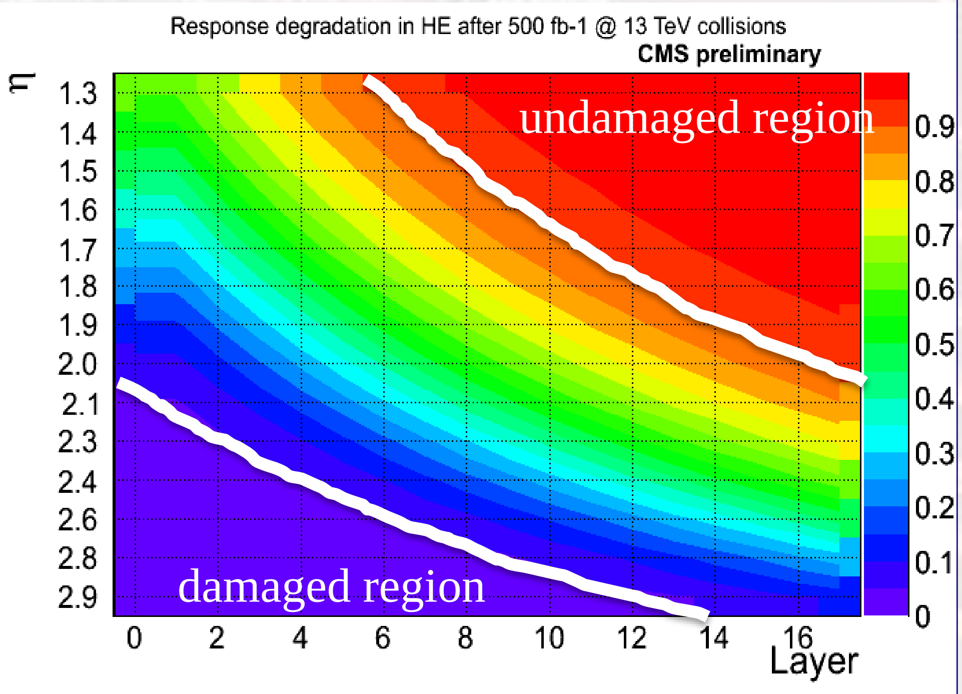
- All on-detector "active" electronics, and all off-detector cards, will be replaced – a major challenge for LS3!



HCAL Perspectives for the Future

- **Expected radiation damage to HE by ~2023**

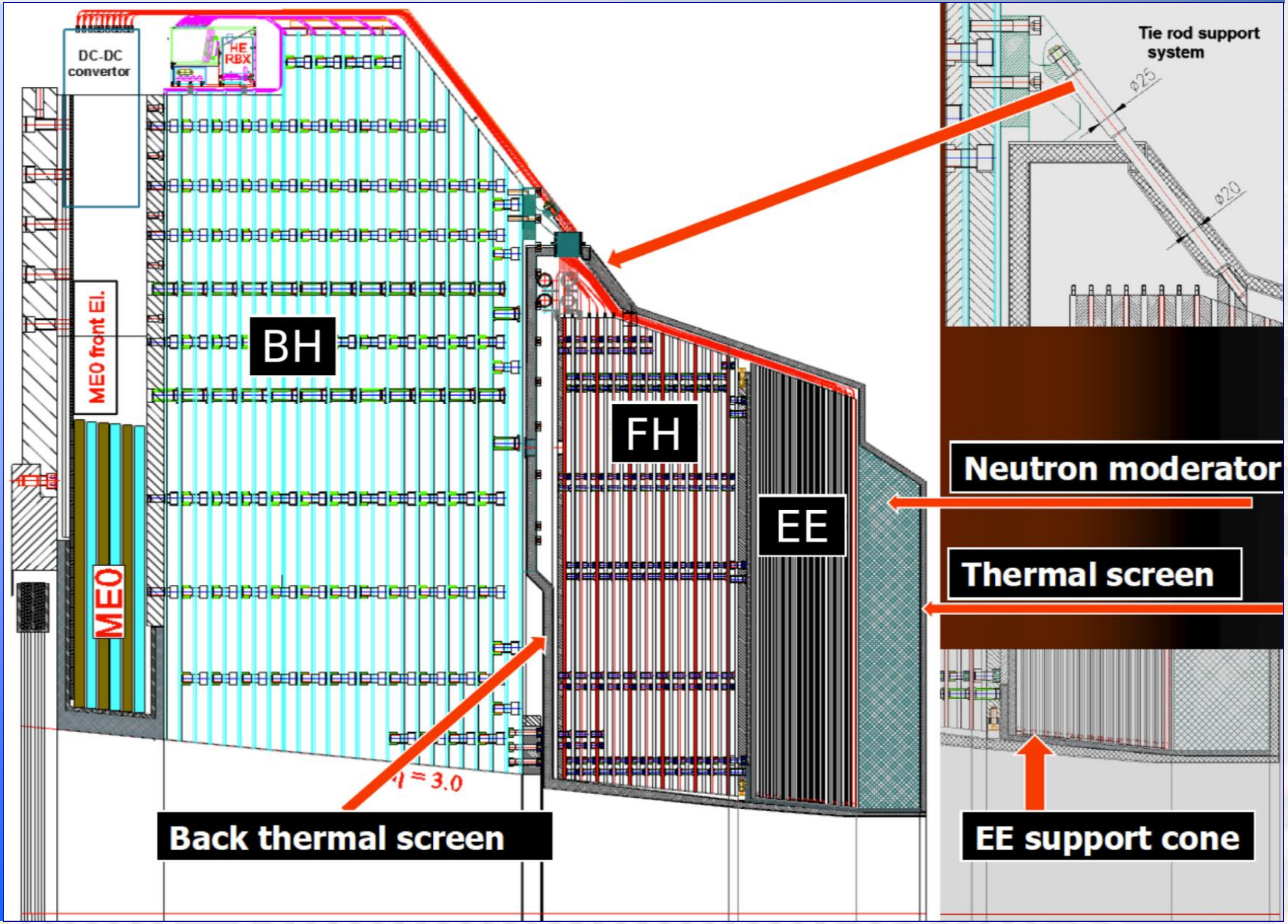




HB and HF will be highly performant to 3000 fb^{-1}
Endcaps will be ok until 500 fb^{-1}; they need to be replaced for HL-LHC

Note: the Phase1 upgrade in LS2 will extend the performance of HE to LS3.
- QE of SiPMs x3 higher wrt HPDS
- finer depth segmentation allowing re-weighting for radiation damage)

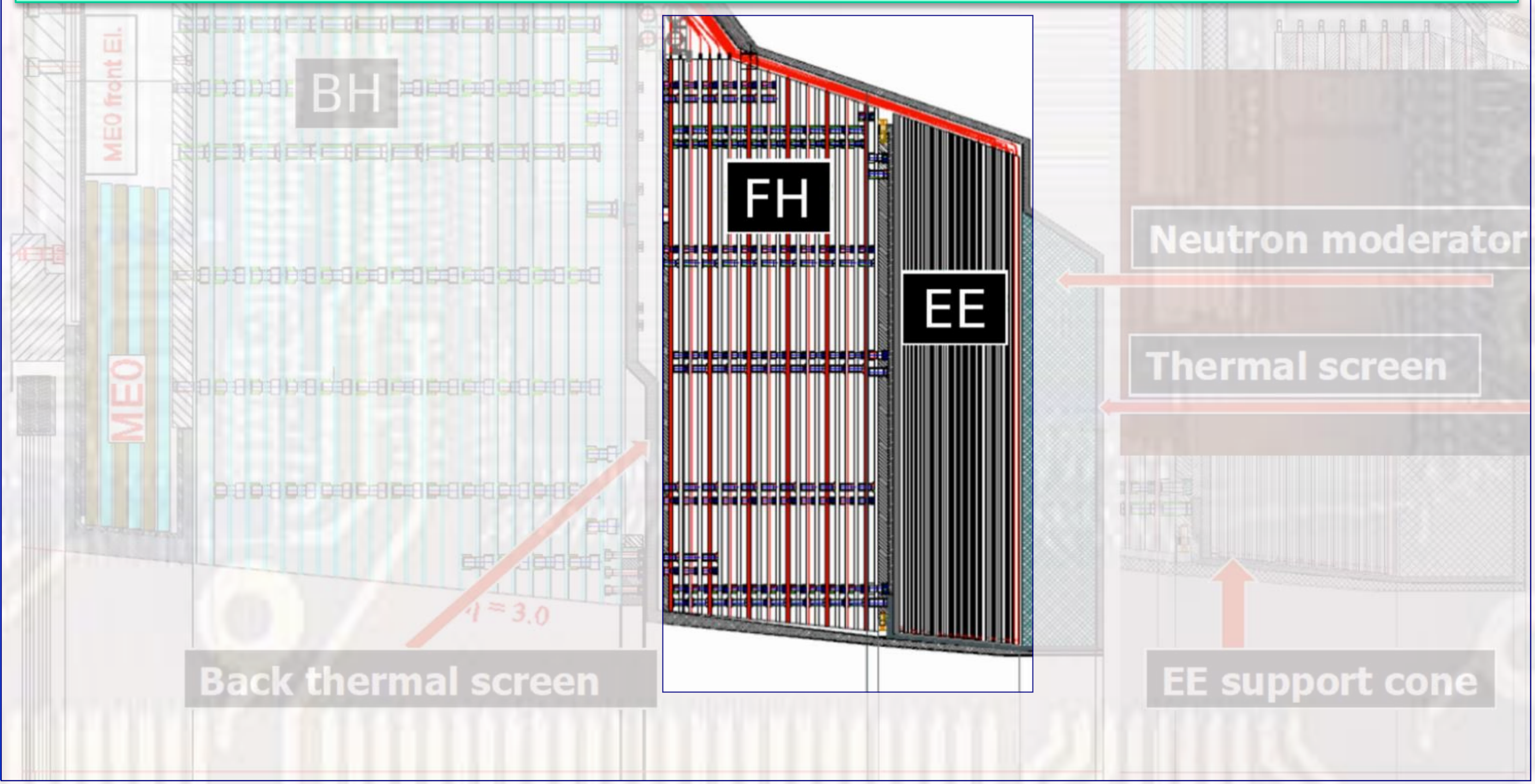
High Granularity Endcap Calorimeter for HL-LHC



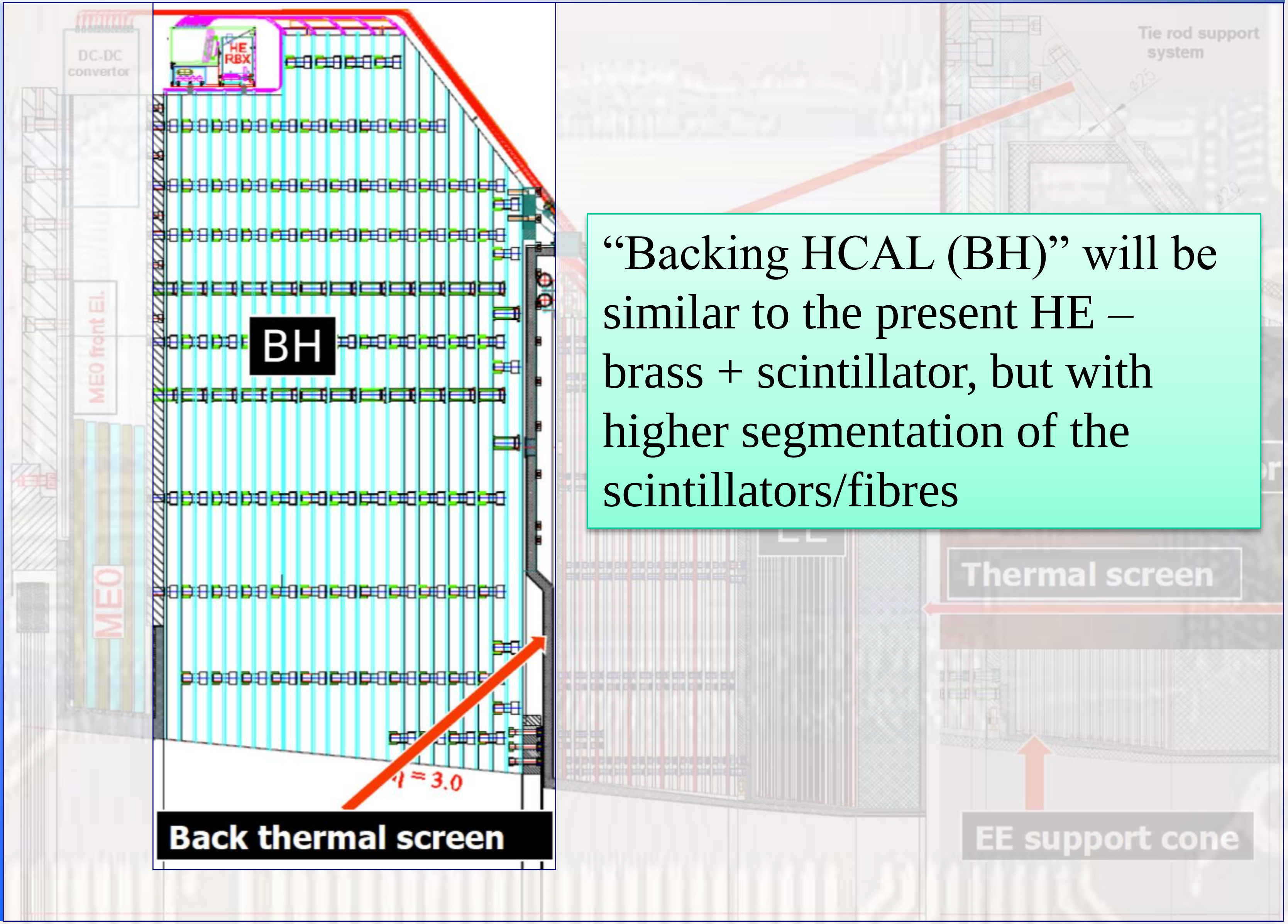
High Granularity Endcap Calorimeter for HL-LHC

New “ECAL Endcap (EE)” and “Front HCAL (FH)” will be based on layers of silicon pad sensors, interleaved by W absorbers (a bit like ES)

Highly segmented both transversally and longitudinally: to facilitate deep understanding of electromagnetic and hadronic showers → particle flow



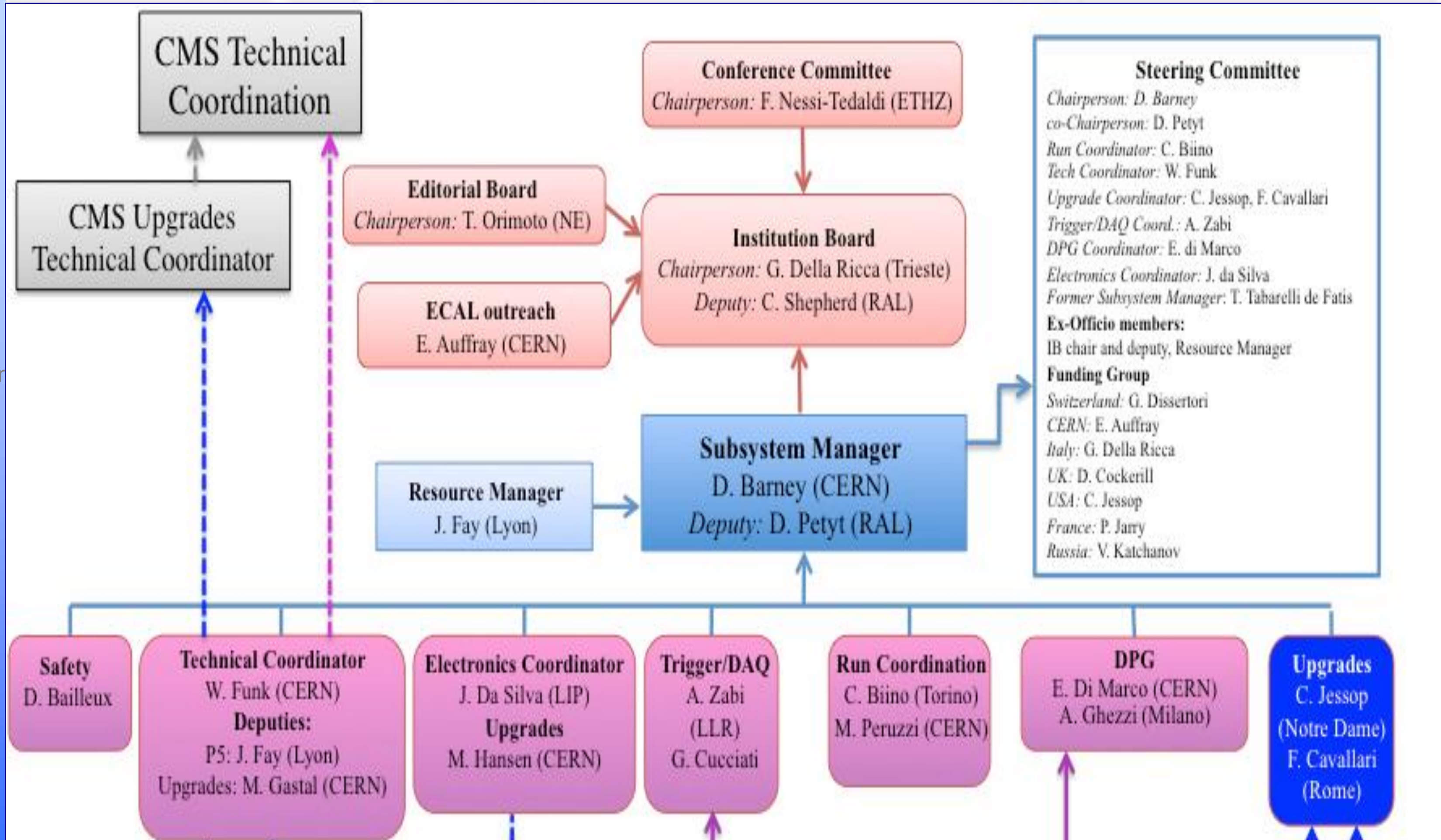
High Granularity Endcap Calorimeter for HL-LHC



"Backing HCAL (BH)" will be similar to the present HE – brass + scintillator, but with higher segmentation of the scintillators/fibres

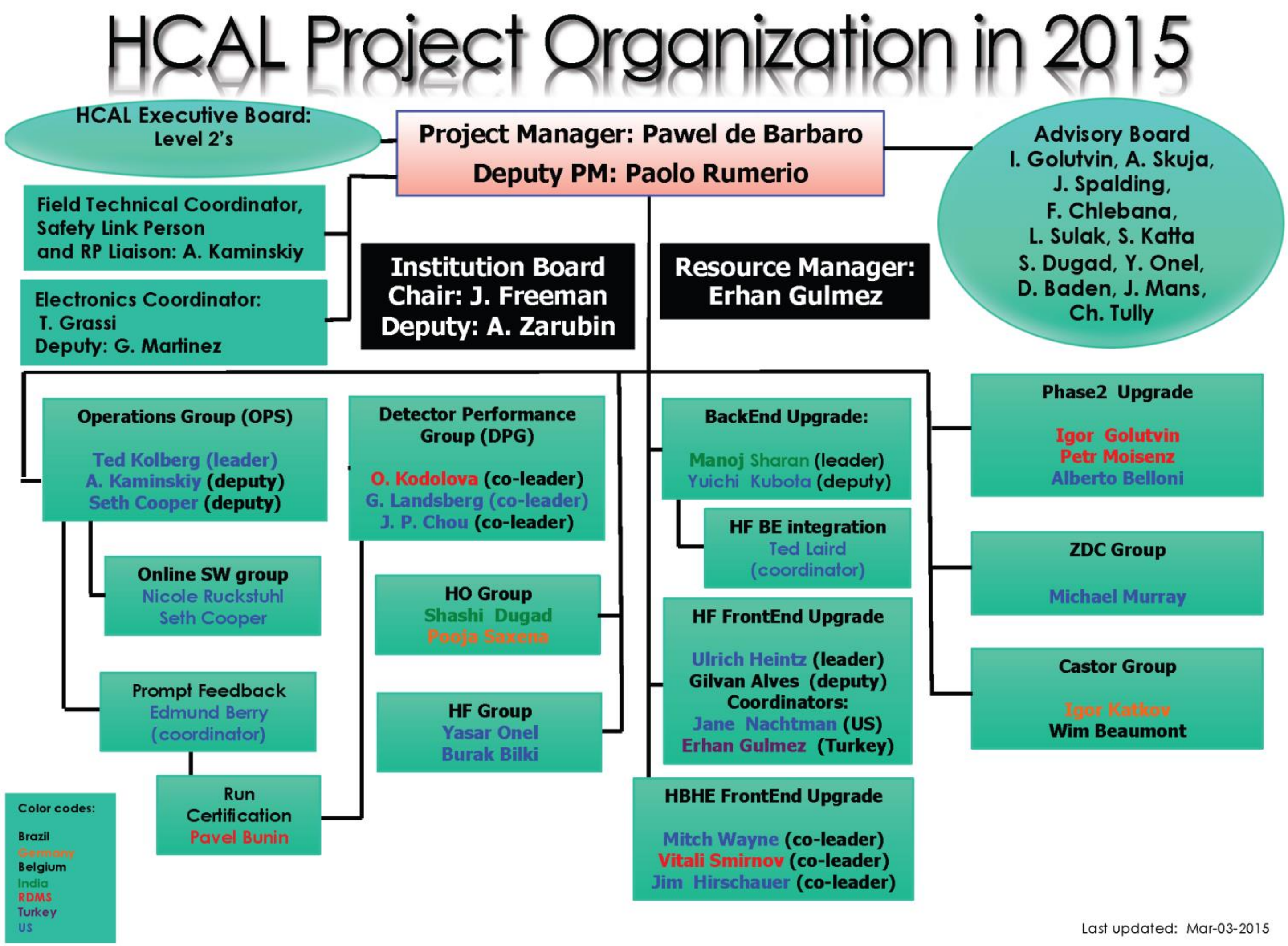
ORGANIZATION

ECAL Organization 2015



David Petyt will take over as ECAL Subsystem Manager in Sept. 2015

HCAL Organization 2015



Plenty of opportunities for YOU to make major contributions!

- **Detector operations at P5**
  - ECAL or HCAL "DoC" – "Detector expert On Call"
  - Other "Experts on Call" for components of ECAL/HCAL
    ➔ these are great for exercising your "problem solving" abilities!

- **Detector performance**
  - Prompt feedback
  - Triggering
  - Monitoring & Calibration
  - Alignment
  - Energy resolution
  - Particle identification

- **Longevity & Upgrades**
  - HCAL Phase 1
  - ECAL & HCAL Barrel detectors for Phase 2
  - Endcap High Granularity Calorimeter

About 50% of activities can be done in your home institute!

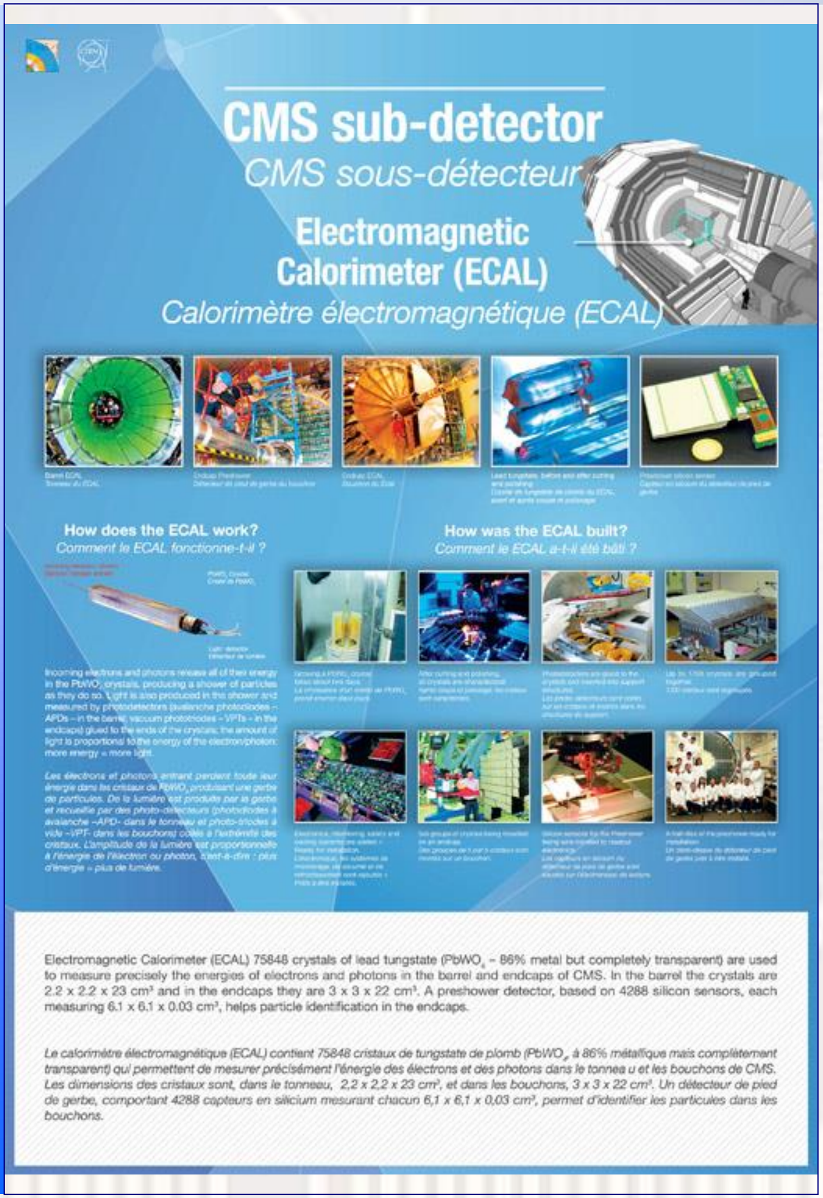
Enjoy your time with CMS!

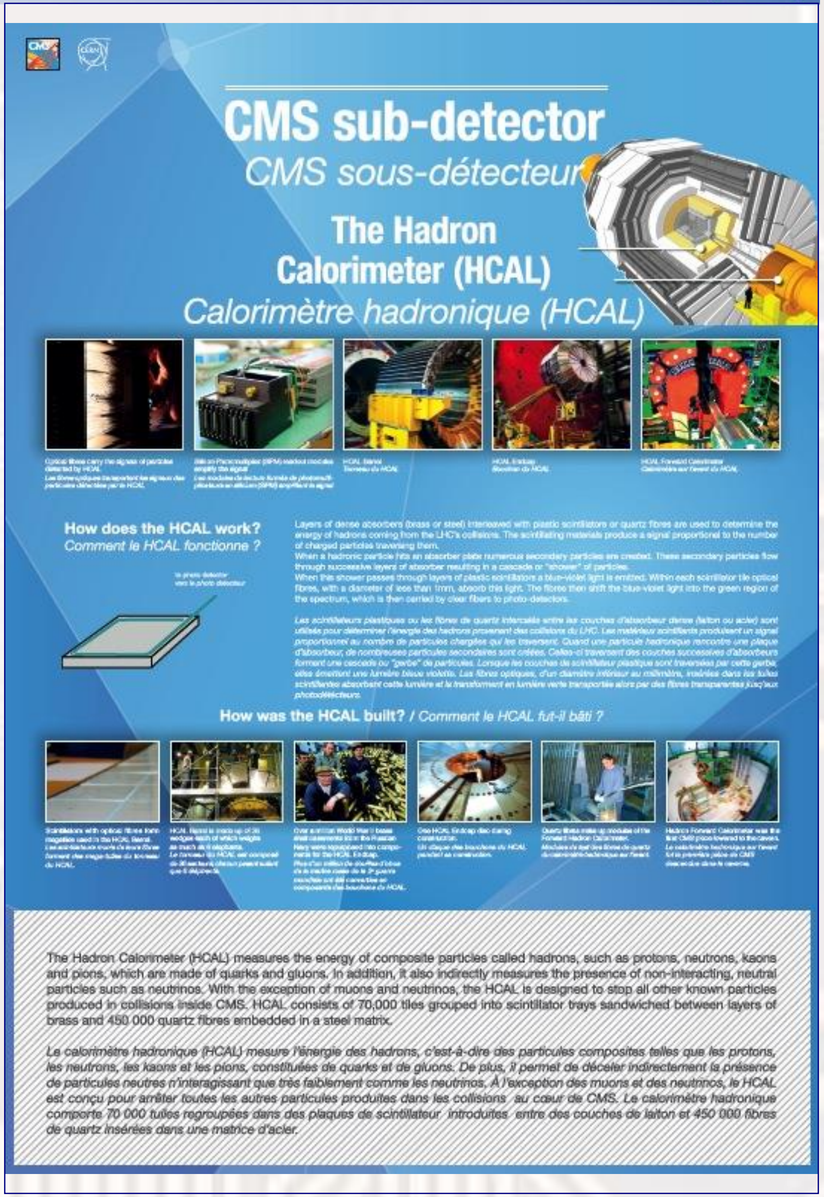
And don't hesitate to come to talk to us about our calorimeters and how you can get involved

Dave & Pawel *et al*

MORE INFORMATION

ECAL & HCAL Posters





Some Useful Links

- **ECAL Web site:** **https://twiki.cern.ch/twiki/bin/viewauth/CMS/DrupalEcal**
- **ECAL DPG Opportunities page:** **https://twiki.cern.ch/twiki/bin/view/CMS/ECALDPGOpportunities**
- **HCAL Web site: http://cmshcal.web.cern.ch/cmshcal/**
- **“The CMS Experiment at the LHC”, 2008 J. INST 3 S08004 http://iopscience.iop.org/1748-0221/3/08/S08004**

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[12] L. Zhang (for CMS Coll.), *A diode-pumped solid state blue laser for monitoring the CMS lead tungstate crystal calorimeter at the LHC*, J. Phys.: Conf. Ser. 404 012042 (2012)

[13] CMS Coll., *Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel*, CMS-PAS-HIG-13-001 (2013)

[14] CMS Coll., *Search for a Higgs boson decaying into two photons in the CMS detector*, CMS-PAS-HIG-11-021 (2011)

[15] CMS Coll., *A search using multivariate techniques for a standard model Higgs boson decaying into two photons*, CMS-PAS-HIG-12-001 (2012)

[16] CMS Coll., *Evidence for a new state decaying into two photons in the search for the standard model Higgs boson in pp collisions*, CMS-PAS-HIG-12-015 (2012)

[17] CMS Coll., *Updated results on the new boson discovered in the search for the standard model Higgs boson in the ZZ to 4 leptons channel at sqrt(s) = 7 and 8 TeV*, CMS-PAS-HIG-12-041 (2012)

[18] CMS Coll., *Properties of the Higgs-like boson in the decay H to ZZ to 4l in pp collisions at sqrt s = 7 and 8 TeV*, CMS-PAS-HIG-13-002 (2013)

[19] CMS Coll., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30

[20] CMS Coll., Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV, CMS-PAS-HIG-13-005 (2013)

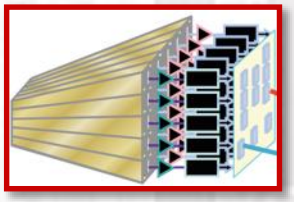
SPARES

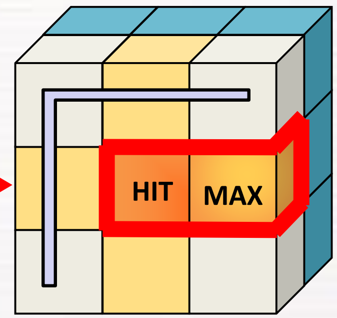
TRIGGERING

Level-1 e/γ Trigger

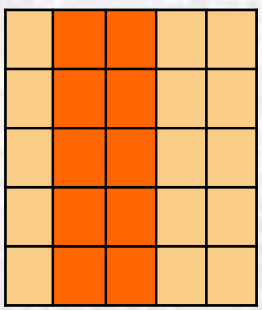
- ✧ Use coarse information (1 tower = 5x5 crystals in barrel, more complex in endcaps)
- ✧ Build 4 L1 EM candidates (most energetic pair of towers) per region (4x4 towers)
- ✧ Keep the 4 candidates with highest E_T in the entire ECAL

1 tower (5x5 crystals)





L1 decision
3.5 μs
100 kHz



EM shower :
- narrow in η
- spread in ϕ

VETOES

• **Fine Grain** (FG): **90%** tower E_T contained within **2 adjacent strips** (tower E_T>6 GeV)

• **H/E** : ratio of E_T in the corresponding **HCAL** and **ECAL** towers **< 5%** (L1 E_T > 2 GeV)

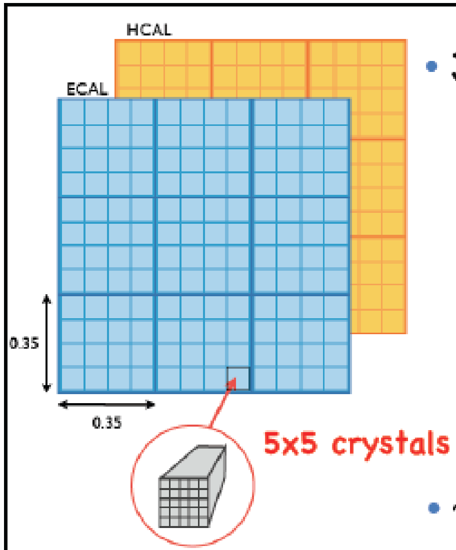
STREAMS

• **Isolated** stream :
  - at least one « **quiet corner** » ⬄ ∑(5 adjacent towers) < 3.5 GeV
  - **8 neighbour** towers must pass **FG** and **H/E** selections

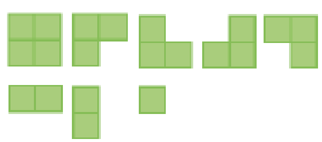
• **Non-Isolated** stream

L1 Jet Trigger

L1 jets



- **Jets $|\eta|<5$**
  - Sliding window 12x12 ECAL+HCAL towers
  - Central 4x4 E_T^{sum} > neighbours
- **τ-jets $|\eta|<3$**
  - same as jets
  - energy must be inside a τ-pattern denoting a narrow jet



HLT jets, E_T^{miss}

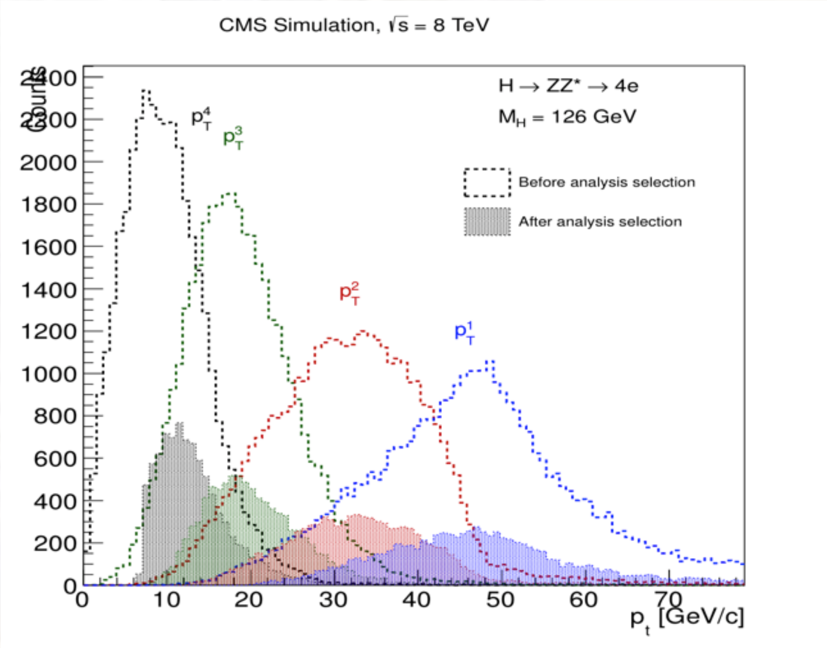
- **Jets :**
  - Use an iterative cone algorithm of amplitude $\Delta R = 0.5$
- **E_T^{miss} :**
  - Algebraic sum of calorimeters objects plus muons

Basic trigger tower size:
$\Delta\eta \times \Delta\phi = 0.087 \times 0.087$

Algorithms (e/γ and jets) being updated for Run II; new trigger hardware also being built, to be installed in CMS in stages from now until 2016

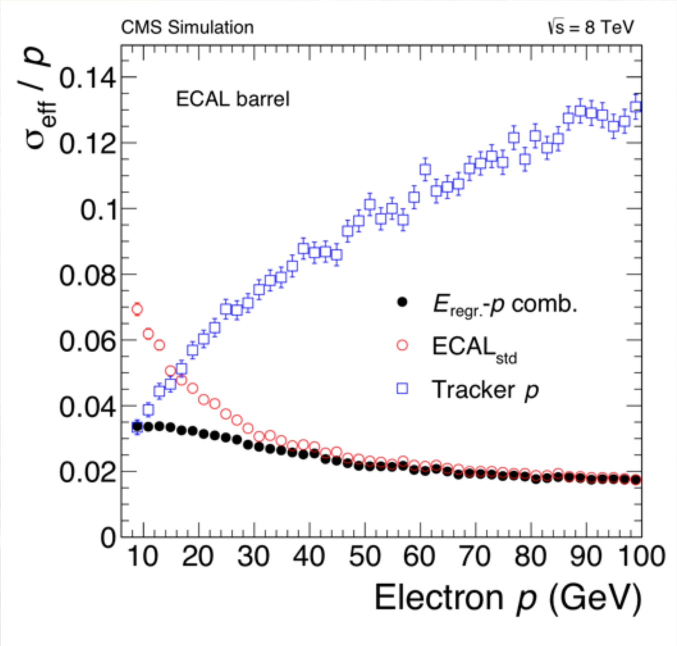
H → ZZ → 4 leptons

- **Final state with 4e particularly challenging**
  - Softest electron often has p_T < 15 GeV
    - Difficult kinematic region due to B-field and bremsstrahlung
    - Crucial to identify and reconstruct electrons down to p_T ~ 7 GeV



electron ID variables include:
- Shower spread vs η
- Isolation (pileup corrected)
- Matching Track with ECAL cluster

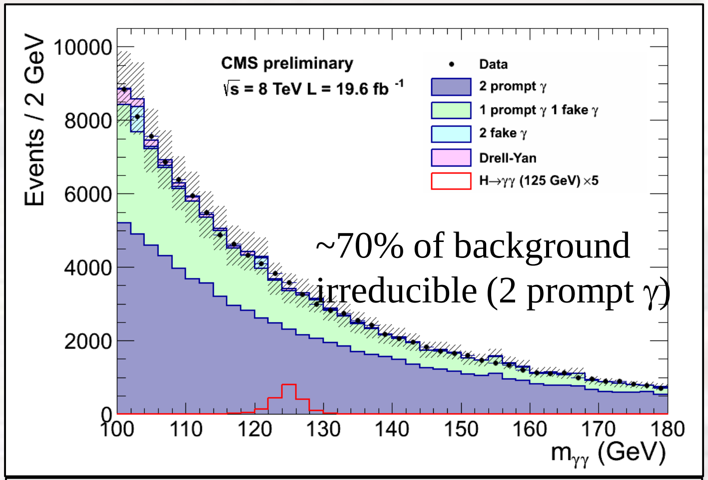
ECAL resolution/granularity at work



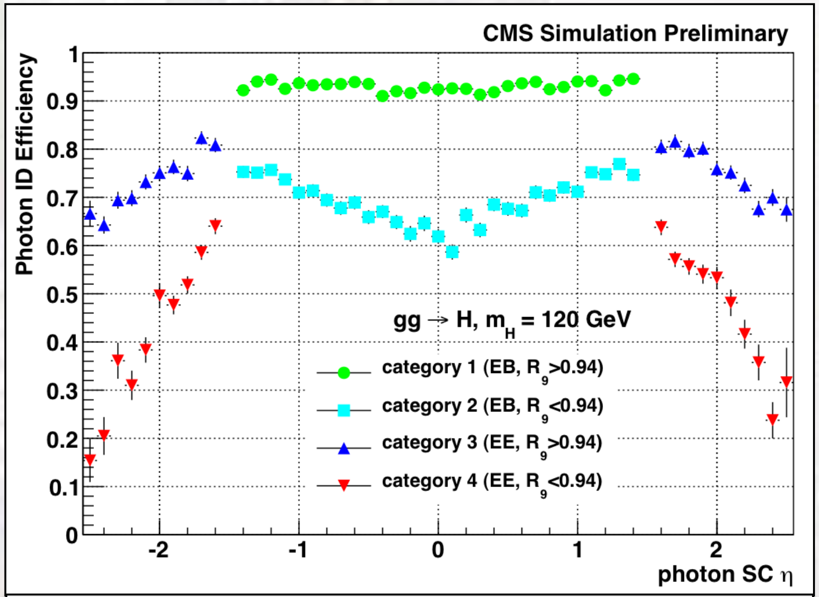
At low p_T the tracker improves the ECAL electron energy measurement

ECAL Benchmark: H→γγ

- **Look for a small narrow excess of γγ events on a falling background**
- **Key analysis requirements:**
  - Excellent γ energy resolution
  - Highly efficient γ ID and γγ vertex-finding



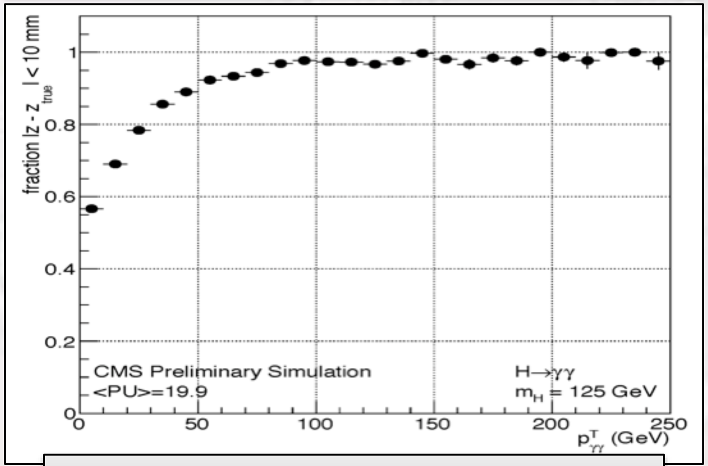
MC bkg used only for analysis optimization
Real background shape derived from data



γ ID variables include:

- Shower spread vs η
- Isolation (pileup corrected)
- Electron track veto
- H/E

ECAL resolution/granularity at work



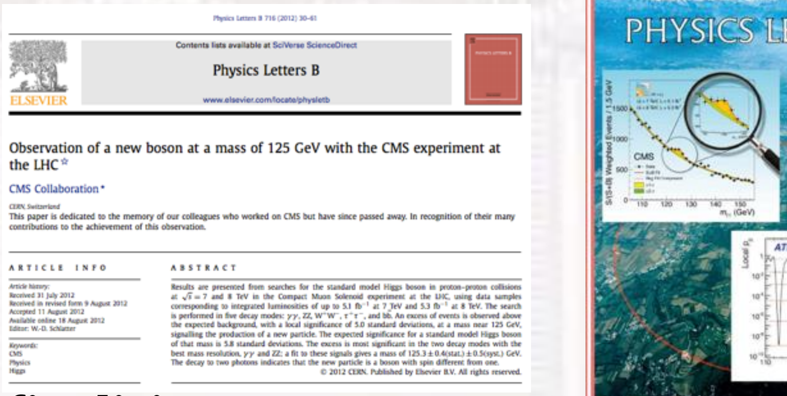
Vertex-finding efficiency close to 100% for high p_T diphoton events

Summary

- **The CMS ECAL meets the high expectations from the design phase**
  - A Higgs boson was discovered with the strongest signals in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels
  - Excellent energy resolution in the ECAL barrel drives the sensitivity for $H \rightarrow \gamma\gamma$
    - ~1% diphoton mass resolution for unconverted photons with $|\eta|<1$
  - Energy resolution is continuously being improved. Working on improving:
    - Calibration and time-dependent response corrections
    - Local containment and upstream-material corrections
- **HL-LHC will require new ECAL endcap, but barrel will remain highly performant until at least 3000fb^{-1}**
- **Looking forward to the next LHC run starting 2015!**

Discovery of a Higgs boson

- **First announced on 4th July 2012**
  - 5 channels examined
    - $H \rightarrow gg$
    - $H \rightarrow ZZ \rightarrow 4l$
    - $H \rightarrow WW$
    - $H \rightarrow bb$
    - $H \rightarrow \tau\tau$
  - ***All critically depend on ECAL***



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Physics Letters B
www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *
CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

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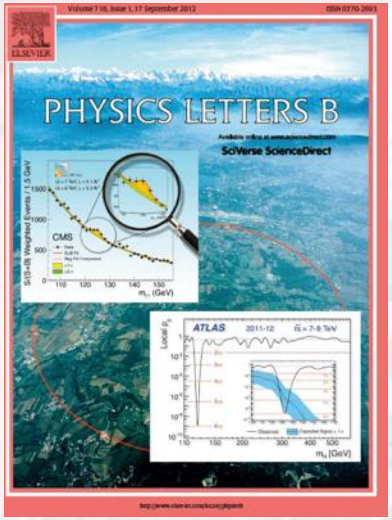
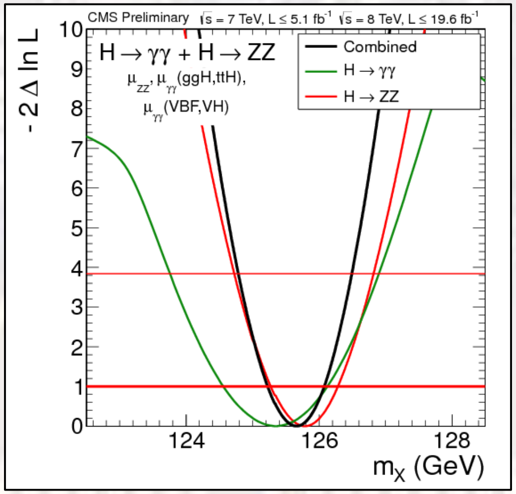
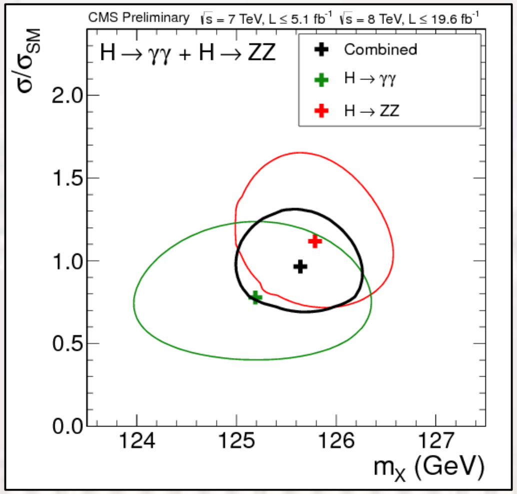
ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(stat.) \pm 0.5(syst.)$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.



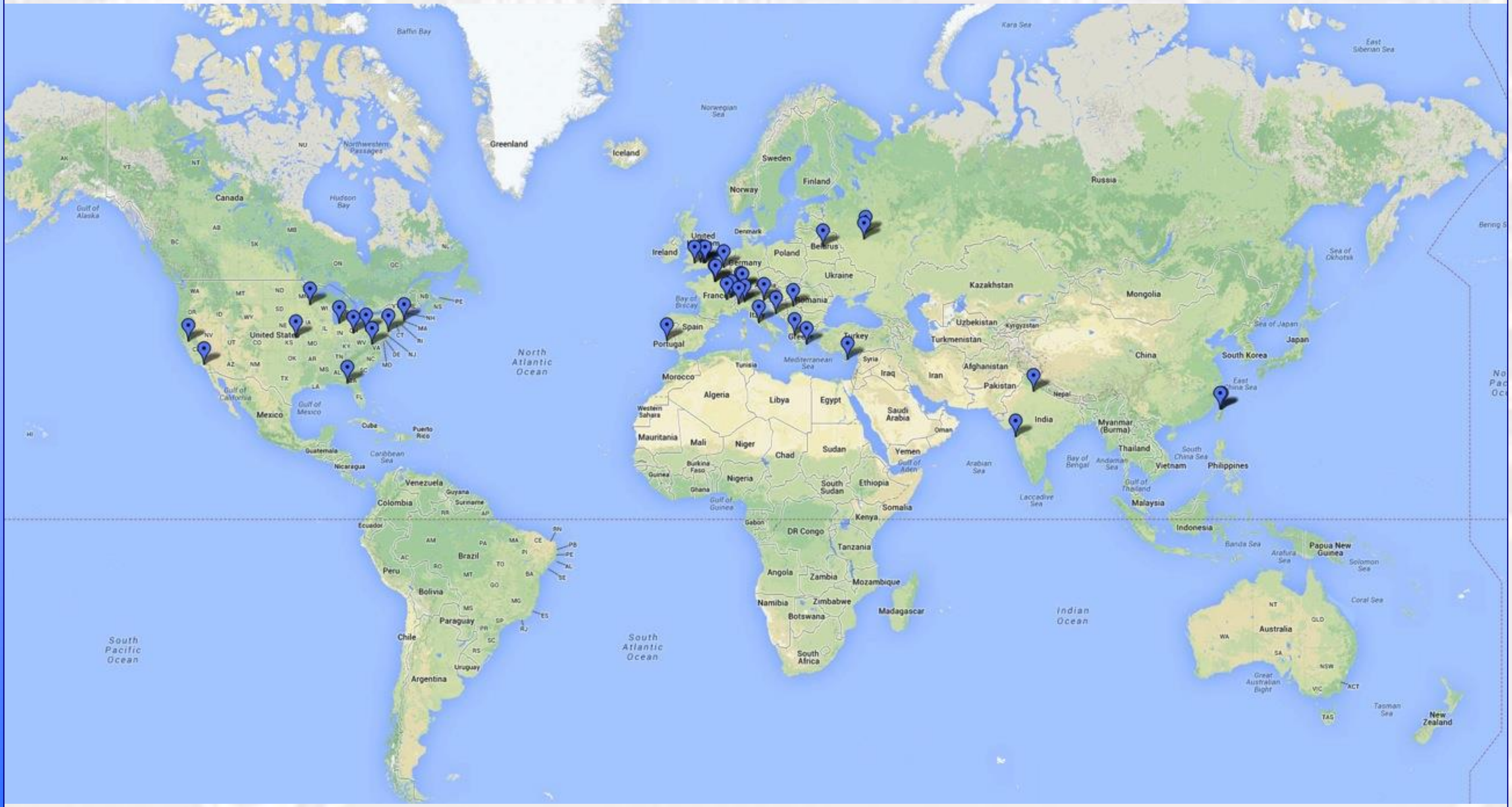
- **Analysis of 2010-2012 data finalizing**
- **Best mass estimate comes from the two "golden" channels**





Higgs boson has a mass of around 125.6 GeV and its decay rates are consistent with the Standard Model predictions…*but what will we find in Run 2 of LHC?*

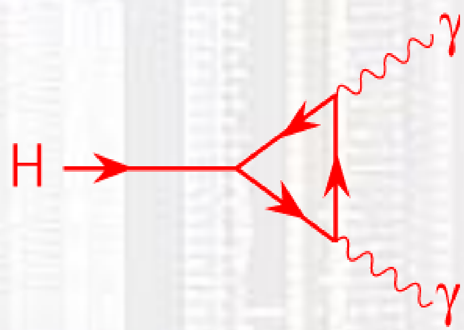
ECAL Groups Worldwide



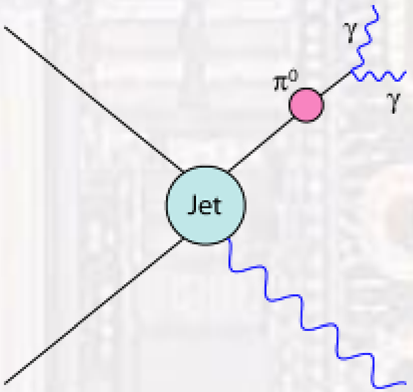
Idea of Endcap Preshower

One of the main physics goals of CMS is search for SM Higgs

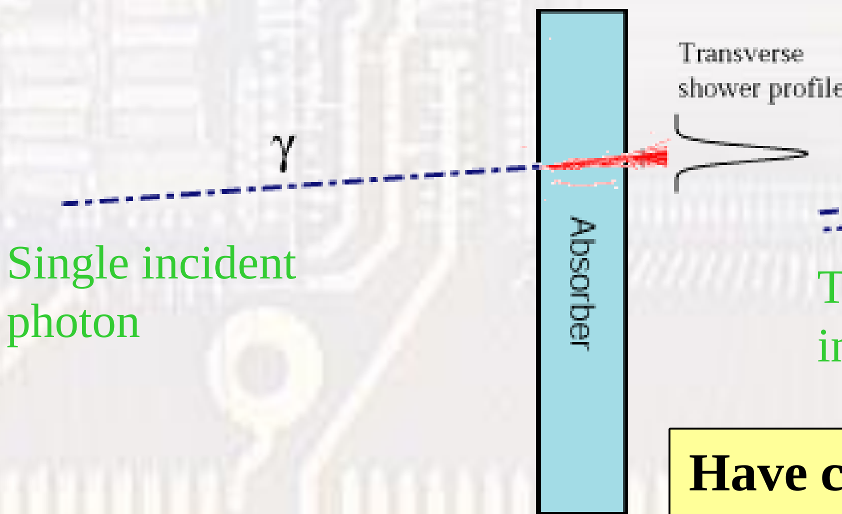
If $m_H < 150$ GeV/c^2 best chance is through 2γ decay

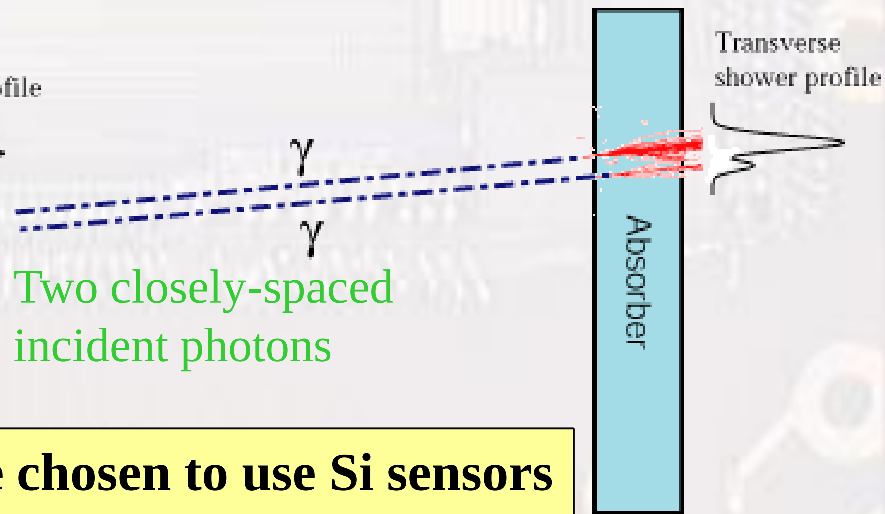


But large reducible background from π^0 faking single photons



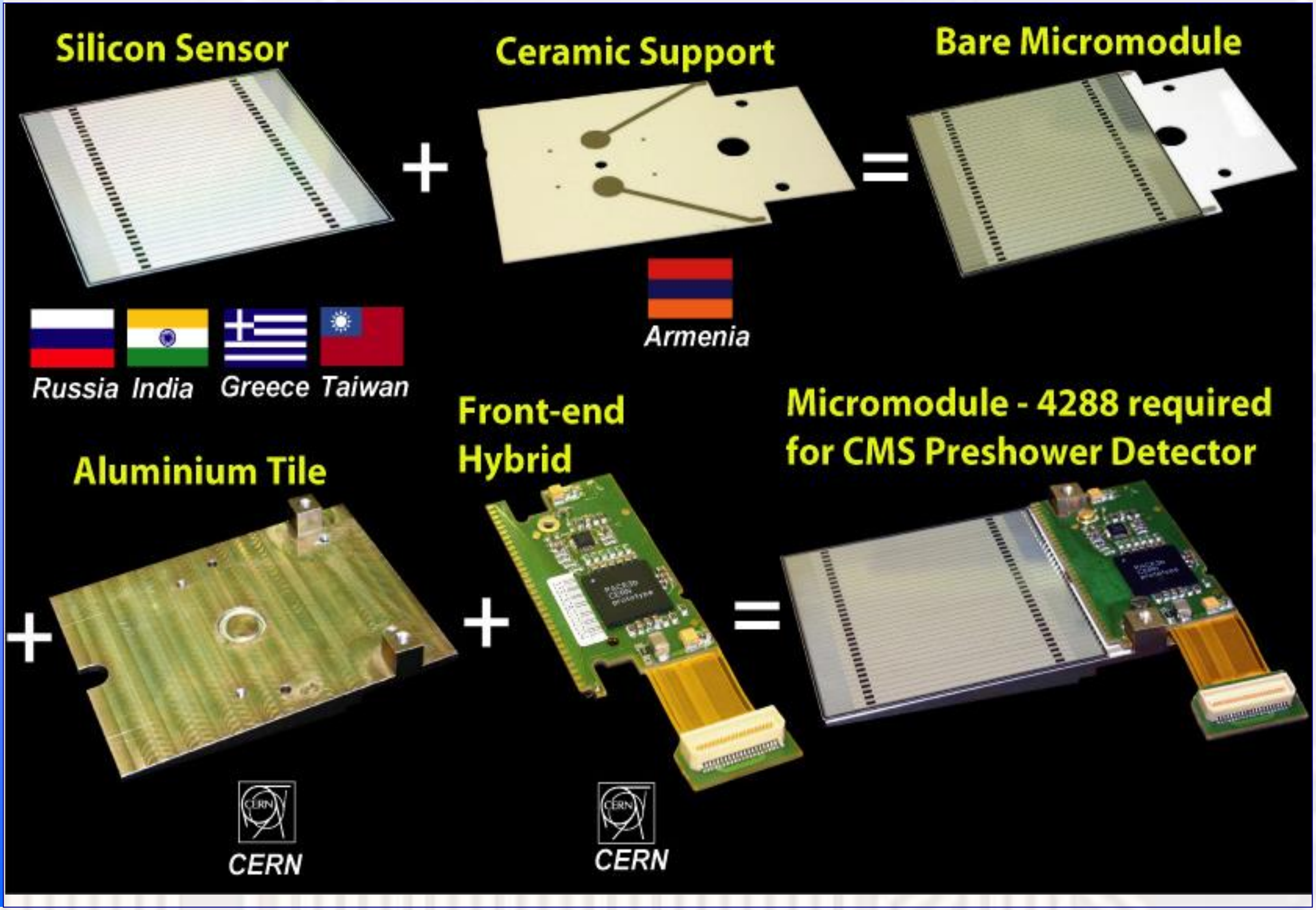
Idea of Preshower:





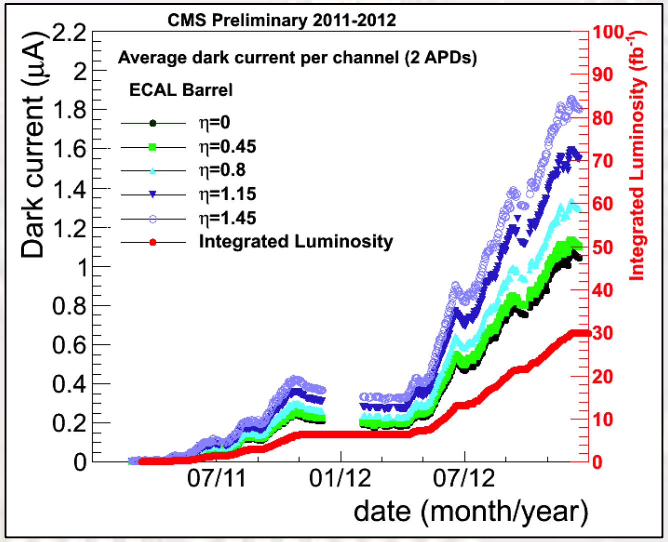
Have chosen to use Si sensors 6.3cm x 6.3cm, 1.9mm strips

The CMS ECAL: Silicon Sensors



Modifications to ECAL Barrel

- **Change front-end (and back-end) electronics**
  - Driven by HL-LHC requirements of trigger system
    - 1 MHz L1 rate (c.f. 100kHz now)
    - ~10-20 μsec latency (c.f. 6.4 μsec now)
  - Move to individual crystal readout at 40 MHz
    - All triggering moved off-detector for ultimate flexibility
    - Improved rejection of APD anomalous signals at L1
  - Requires removal of all ECAL Supermodules, upgrade, then reinstallation
- **APDs also suffer from increasing leakage currents → increased noise**
  - Can mitigate by cooling EB by 8-10°C
  - Currently studying technical feasibility & implications

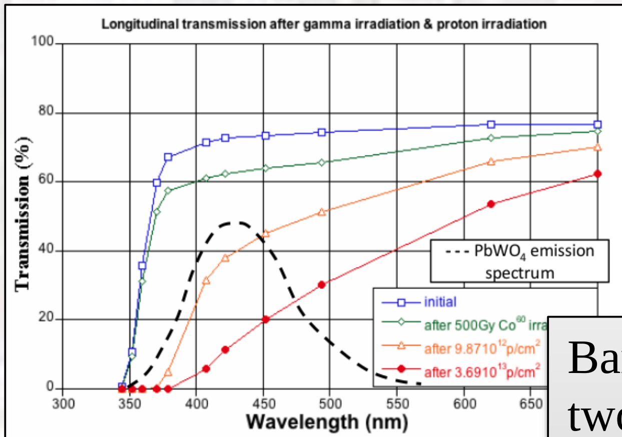


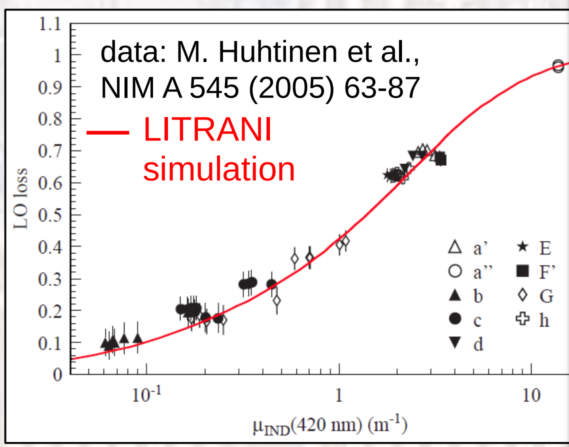
Time-dependent Instabilities

- **Radiation-induced crystal transparency losses (cont.)**
  - Hadronic damage causes deeper defects; permanent (at room temperature) and cumulative

Define "induced absorbtion" μ_{IND} to quantify the damage

$$\frac{T(\lambda)}{T_0(\lambda)} = e^{-\mu_{IND}(\lambda)\,x\,L}$$





Barrel crystals from two producers BTCP (Russia) & SIC (China) irradiated with 20 GeV protons; Endcap crystals irradiated with 24 GeV protons LHC fluences up to ~3×10^{13} p/cm^2