CMS
Electromagnetic Calorimeter

US CMS JTERM III

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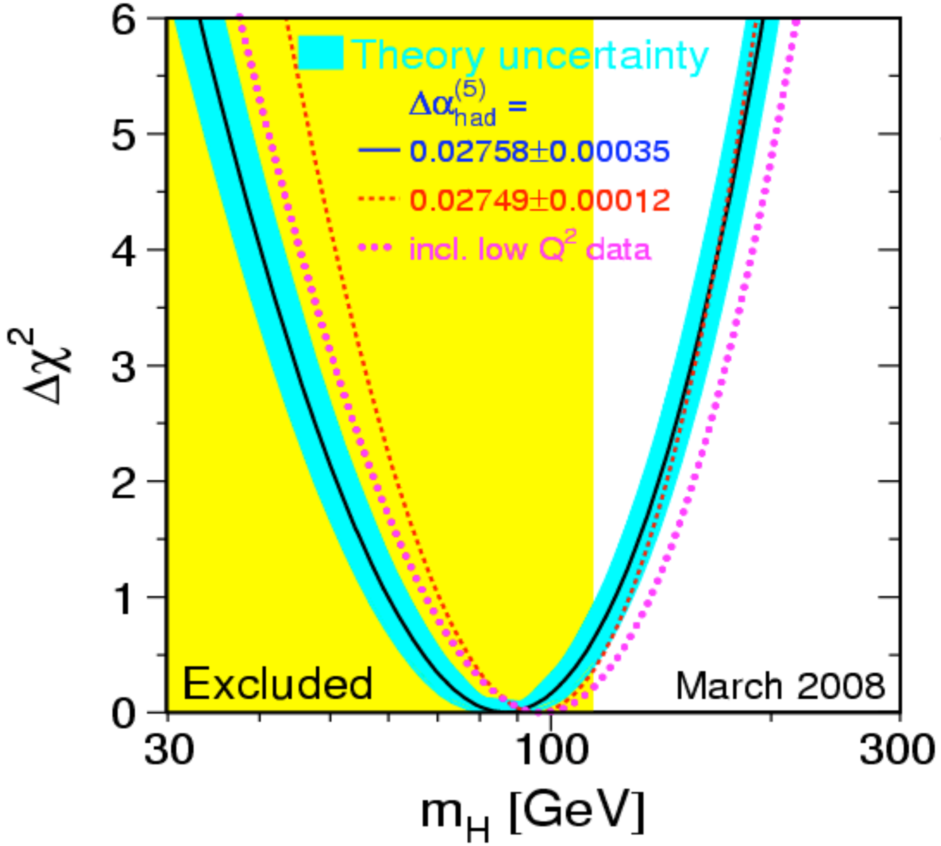
Outline

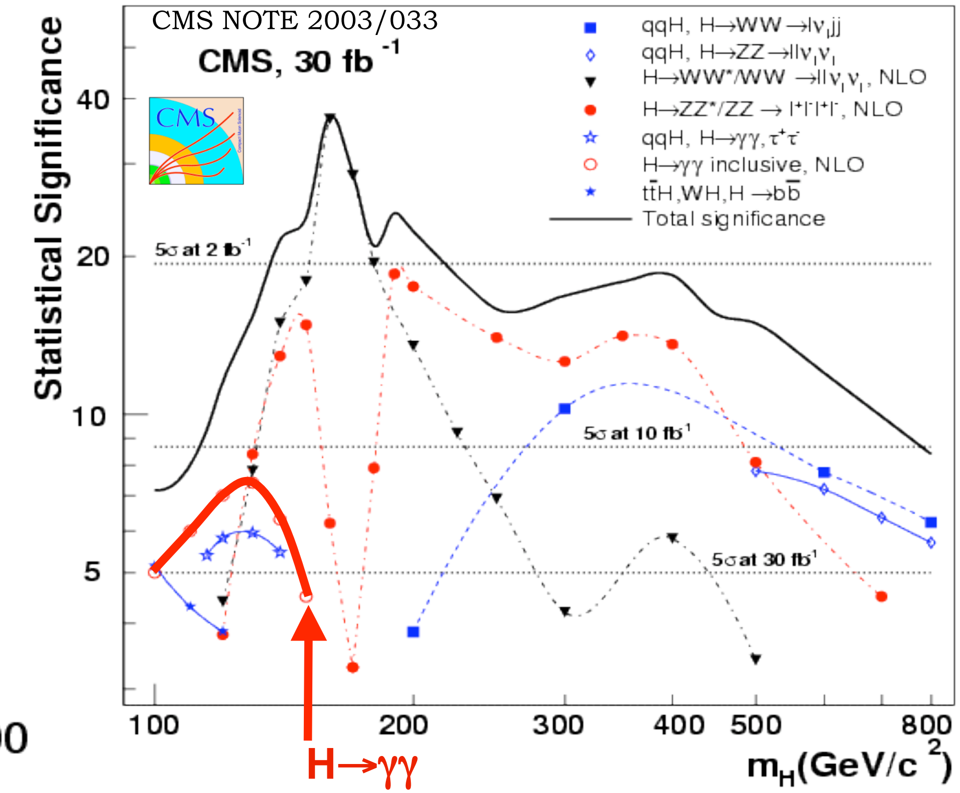
- Physics & Design Requirements
- Technology Choice
- ECAL Design & Readout
- Calibration & Monitoring
- Results with Cosmics Data
- Results with First Beam Data
- Conclusions

Physics Requirements: Discovery Potential

A light Higgs has not yet been excluded by current measurements, and we may be able to measure it at the LHC.



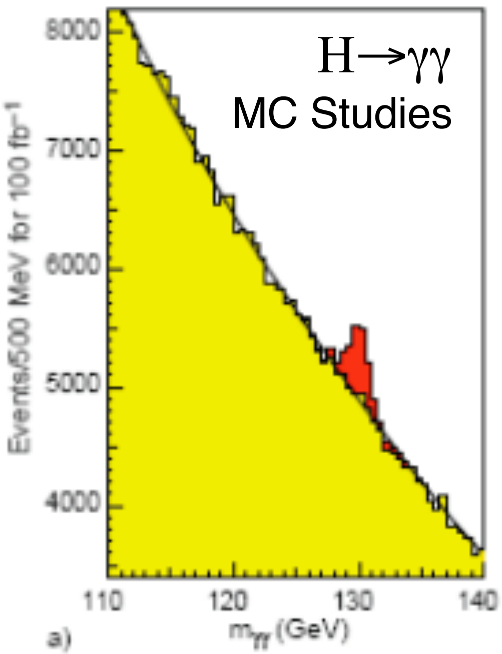
Current limit from electroweak measurements is m_H > 114 GeV.

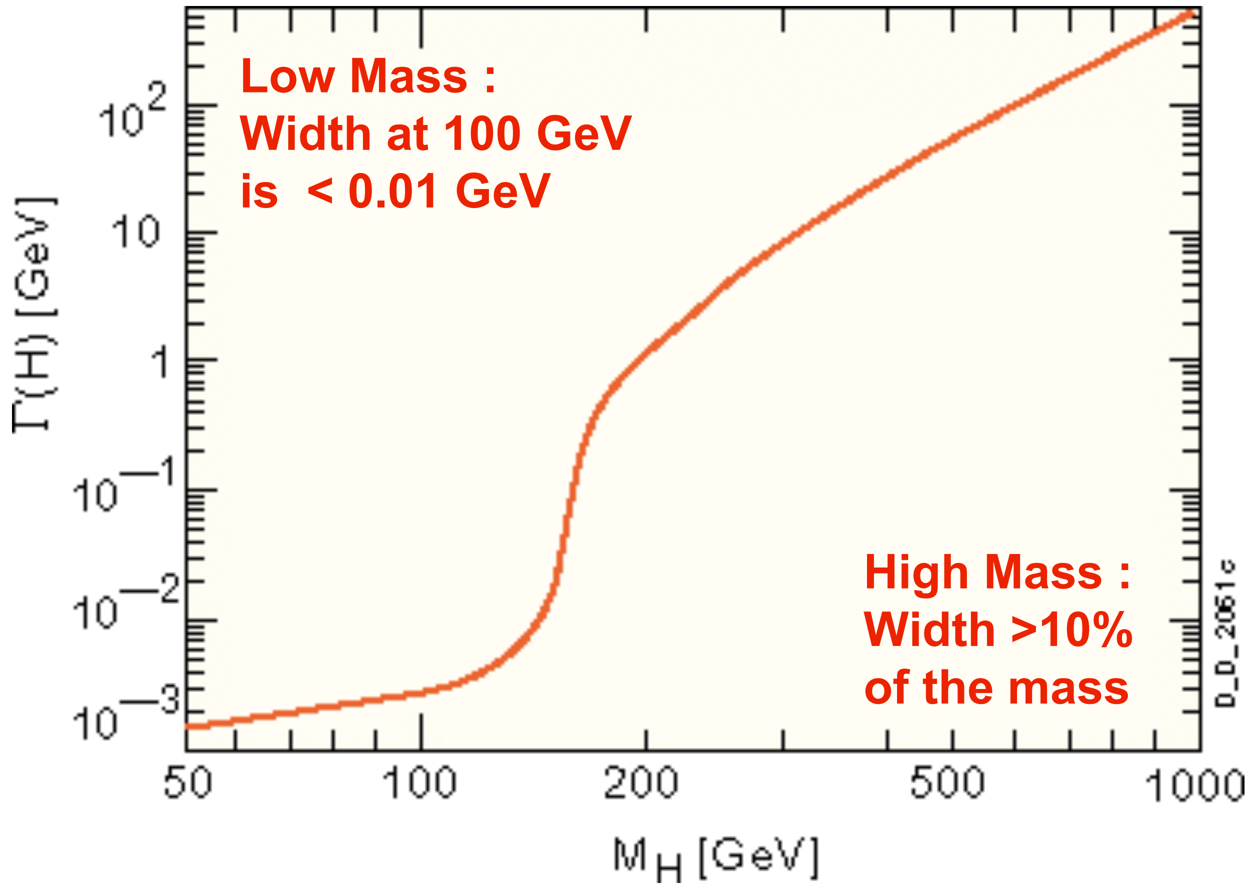


At mass ~120 GeV, the Higgs decay into the diphoton channel presents a very promising yet challenging possibility.

Physics Requirements: Light Higgs

If such a low mass Higgs does exist, its natural width will very narrow.





For narrow resonances, the observed width will be determined by the instrumental mass resolution; that is, we will need the best possible calorimeter resolution to observe the Higgs in the diphoton channel.

Detector Energy Resolution

Energy resolution: corresponds to how well we reconstruct signals as a function of energy. The calorimeter energy resolution is determined by the following components:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + \frac{b}{E} + c$$

Stochastic Term:
- Lateral Containment
- Photostatistics
- Gain

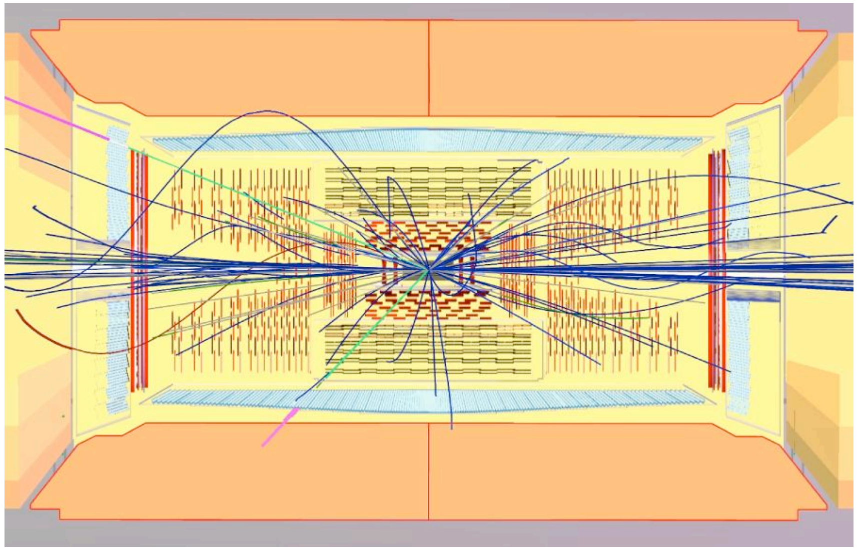
Noise Term:
- Electronics (preamp, APD)
- Pile-up

Constant Term:
- Calibration
- Light Leakage
- Light yield non-uniformity
- Temperature

The LHC Environment

The Large Hadron Collider

- 14 TeV proton proton collider
- Design Luminosity = 10^{34} cm^{-2} s^{-1}
- Bunch crossing (BX) rate 40 MHz (one BX every 25ns)
- Up to 20 p-p interactions and up to 1000 charged particles every BX
- Dose rates of 15 rad/h in Barrel & up to 1500 rad/h in Endcap



Detectors need to be:

- Fast
- High granular
- Radiation resistant

ECAL Design Requirements

Compact:
- To fit inside the magnet

Hermetic:
- To measure missing E_T
- Good resolution up to $|\eta|<2.5$
- Coverage up to $|\eta|<3$

Energy range:
- ~0.1 – 1000 GeV

Fast:
- Pile-up
- Precise timing of signal

Excellent energy, angular resolution:
- As motivated by physics studies

Stable:
- Accurate monitoring system
- Several different calibration procedures

Radiation resistant:
- More than 10 years of operation

Segmented:
- Projective
- Reduce pile-up effects

Triggering ability:
- Appropriate on-off detector electronics

Non magnetic:
- Operable in a 4T field

ECAL Technology Choice

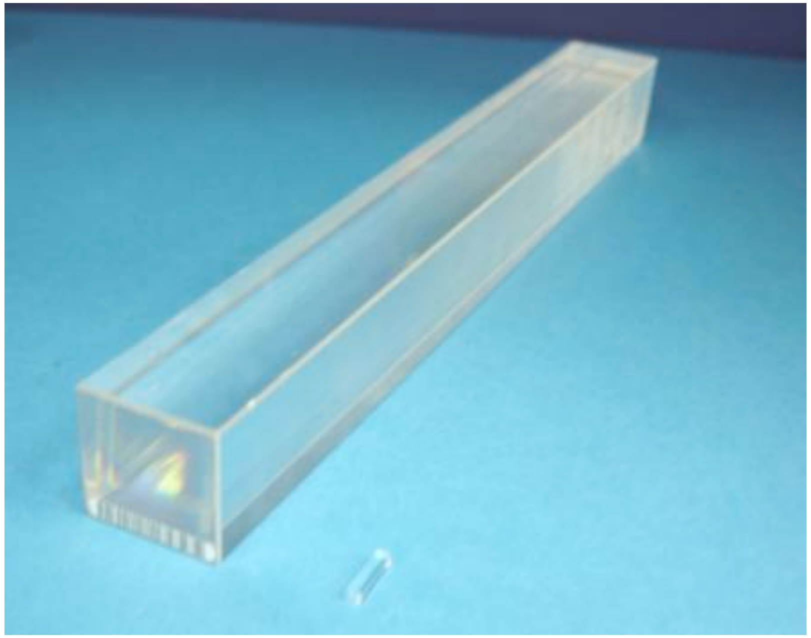
Scintillating Crystal Calorimeter: Lead-Tungstate ($PbWO_4$)

Ideal calorimeter qualities:

- Total absorption calorimeter
- Short radiation length and Moliere radius, X_0=0.89cm and R_M=2.1cm
- Very dense
- Very fast
- Radiation resistant

Non-ideal qualities:

- Expensive
- Small light output
- Temperature dependent (~2.2%/^{o}C)

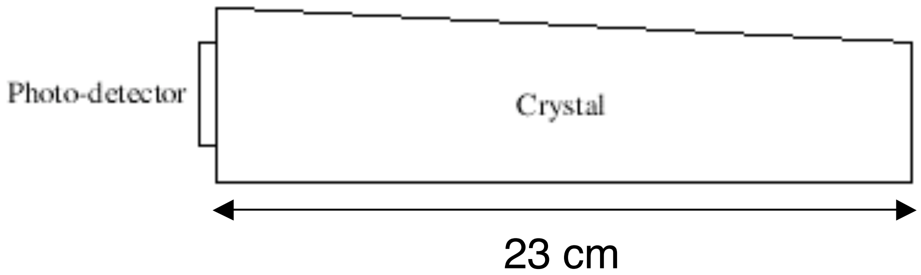


$PbWO_4$ Crystals

- ECAL crystals were produced in Russia and China.
- Strict production control to ensure a uniform, high quality detector.
- All crystals tested for:
  - Light Yield
  - Physical Dimensions
  - Radiation Hardness

- Each crystal is tapered to provide hermeticity and has dimensions:
  - Barrel: ~ 2.5 x 2.5 x 23 cm ($25.8\ X_0$)
  - Endcap: ~ 3.0 x 3.0 x 22 cm ($24.7\ X_0$)

ECAL crystal grown in ingot

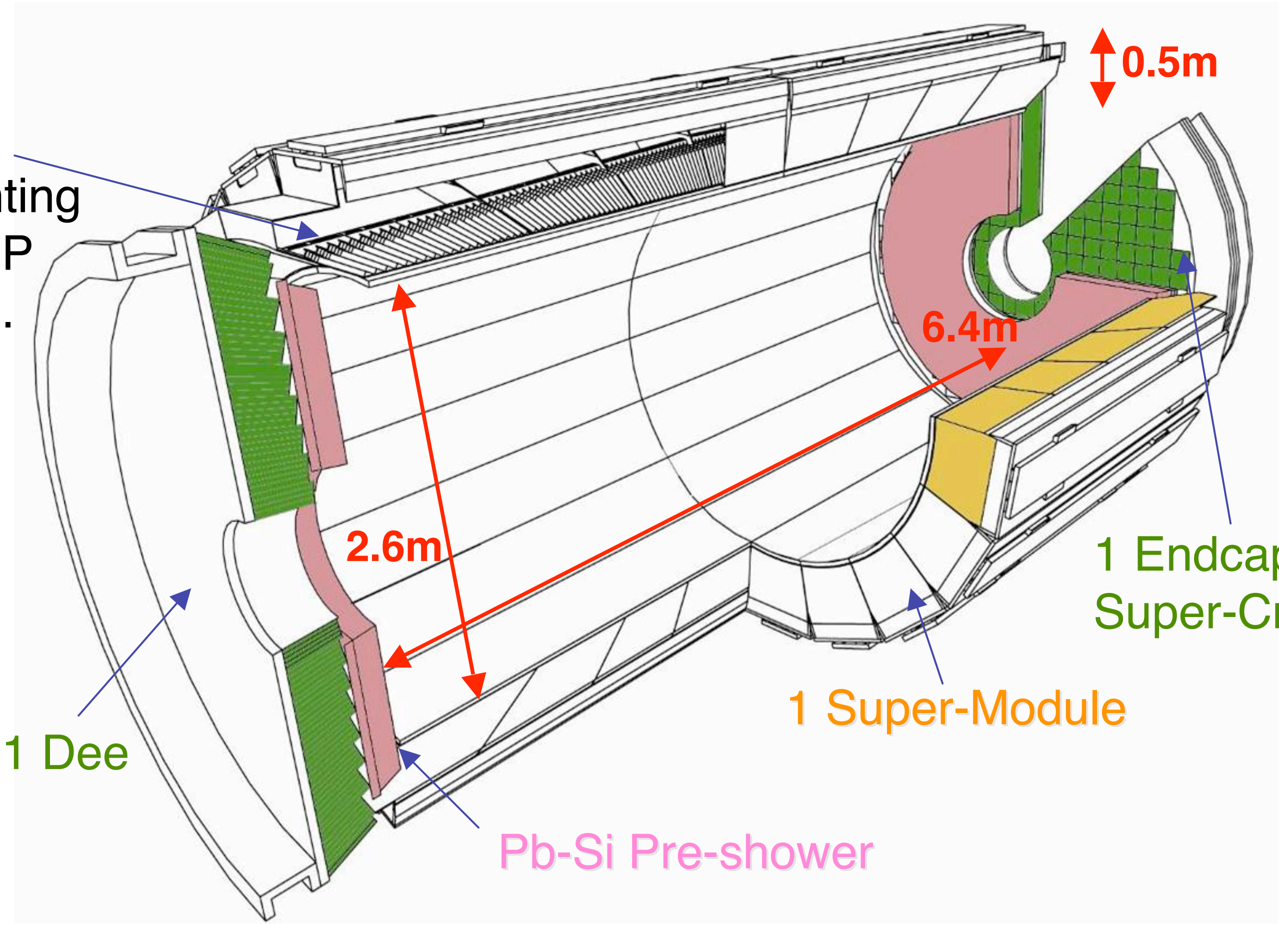


ECAL Detector Design

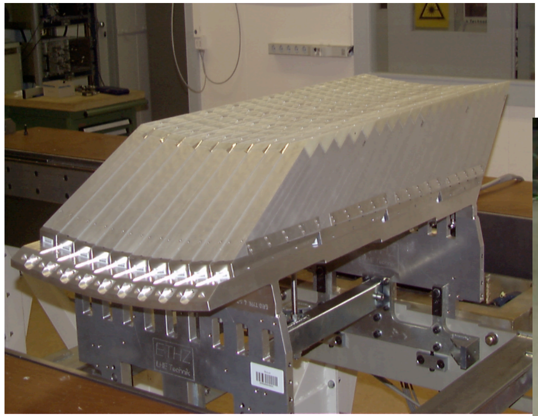
Barrel (EB):
- 61200 crystals total
- 36 Supermodules (SM), each 1.7k crystals

Endcap (EE):
- 14648 crystals total
- 4 Dees, each 3662 crystals
- Crystals combined into SuperCrystals of 5x5 crystals

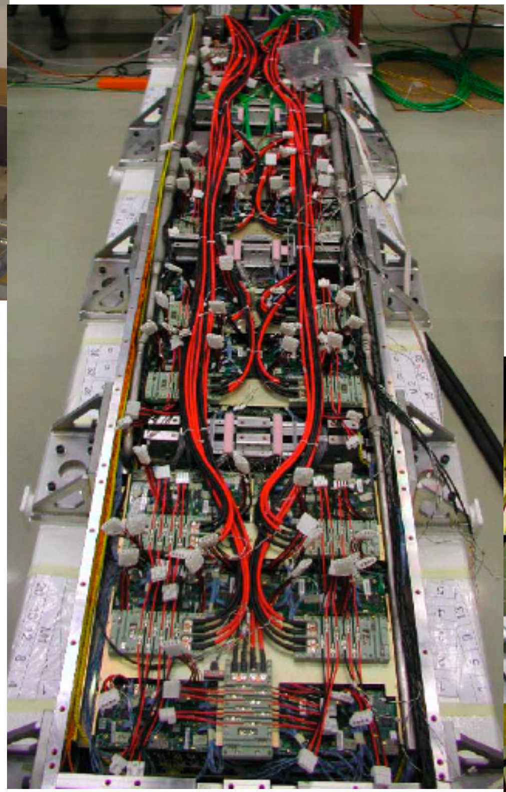
Crystals are projective and positioned pointing slightly off the IP to avoid cracks.



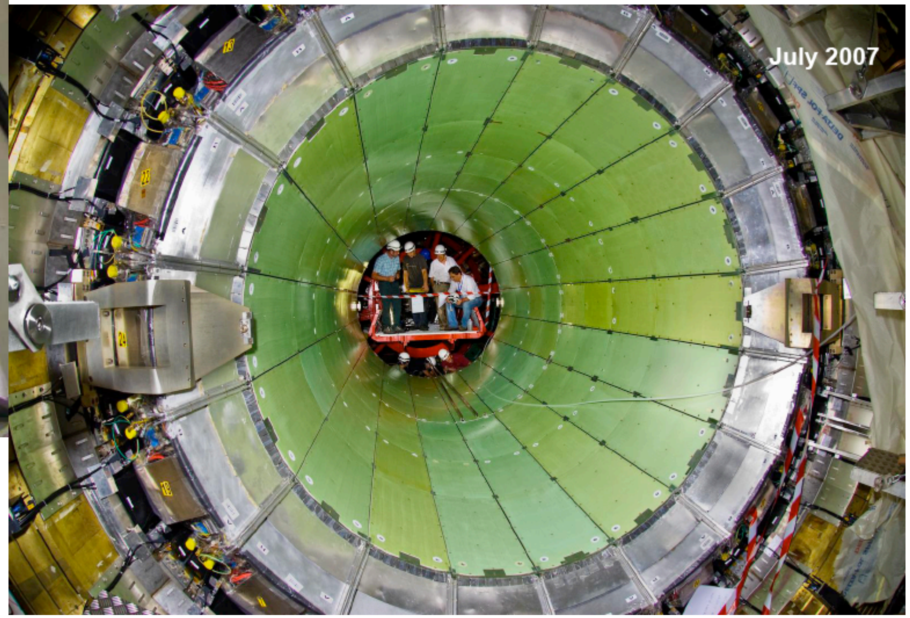
ECAL Barrel (EB) Construction



Module: 400/500 crystals

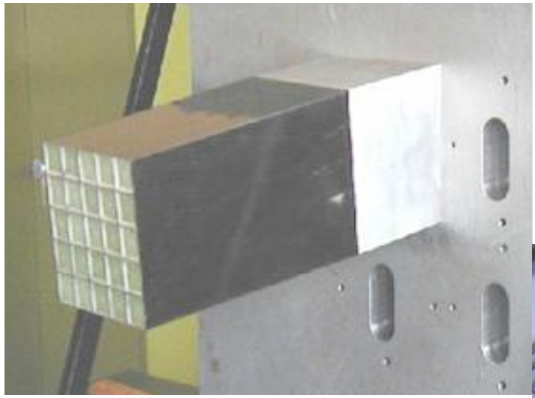


SM with electronics



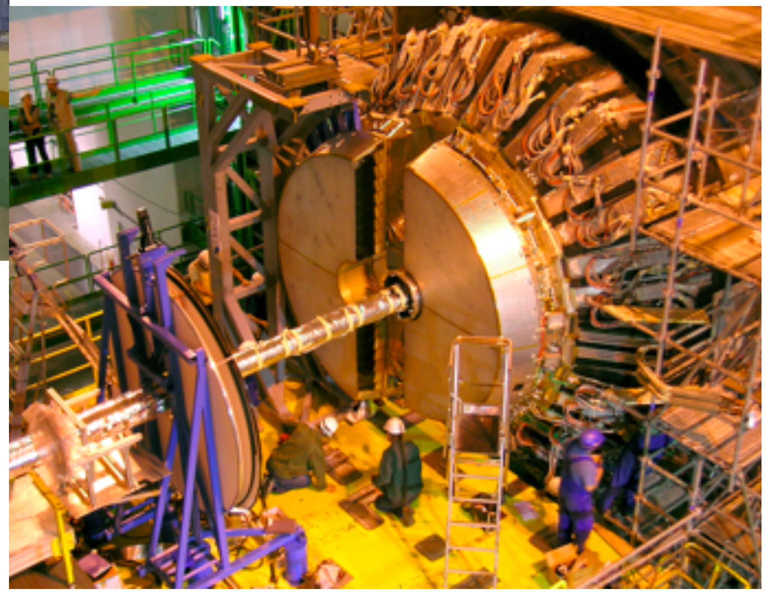
EB @ P5

ECAL End-Cap (EE) Construction



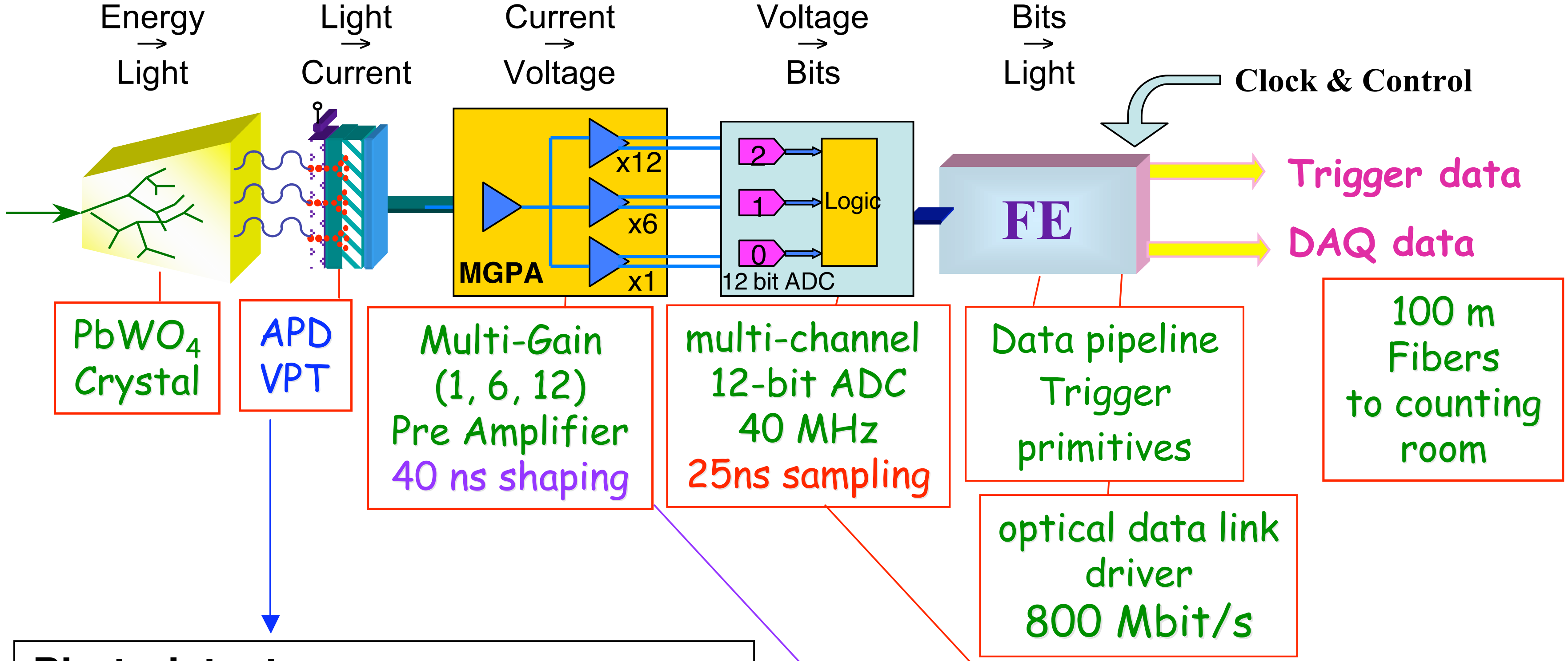
SuperCrystal:
25 crystals

Dee (½ endcap)



EE Dee 1 & 2 @ P5

On-Detector Electronics



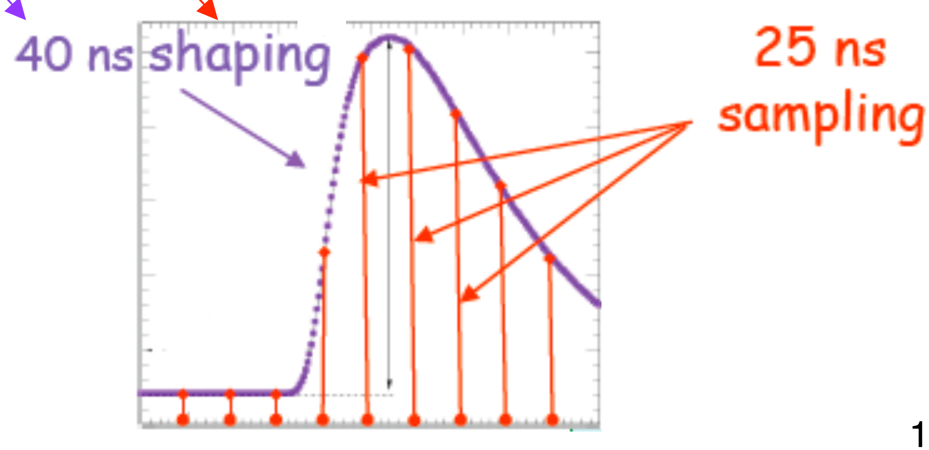
Photodetectors:

EB: Avalanche photodiodes (APD)

- Two 5x5 mm² APDs/crystal
- Gain: 50

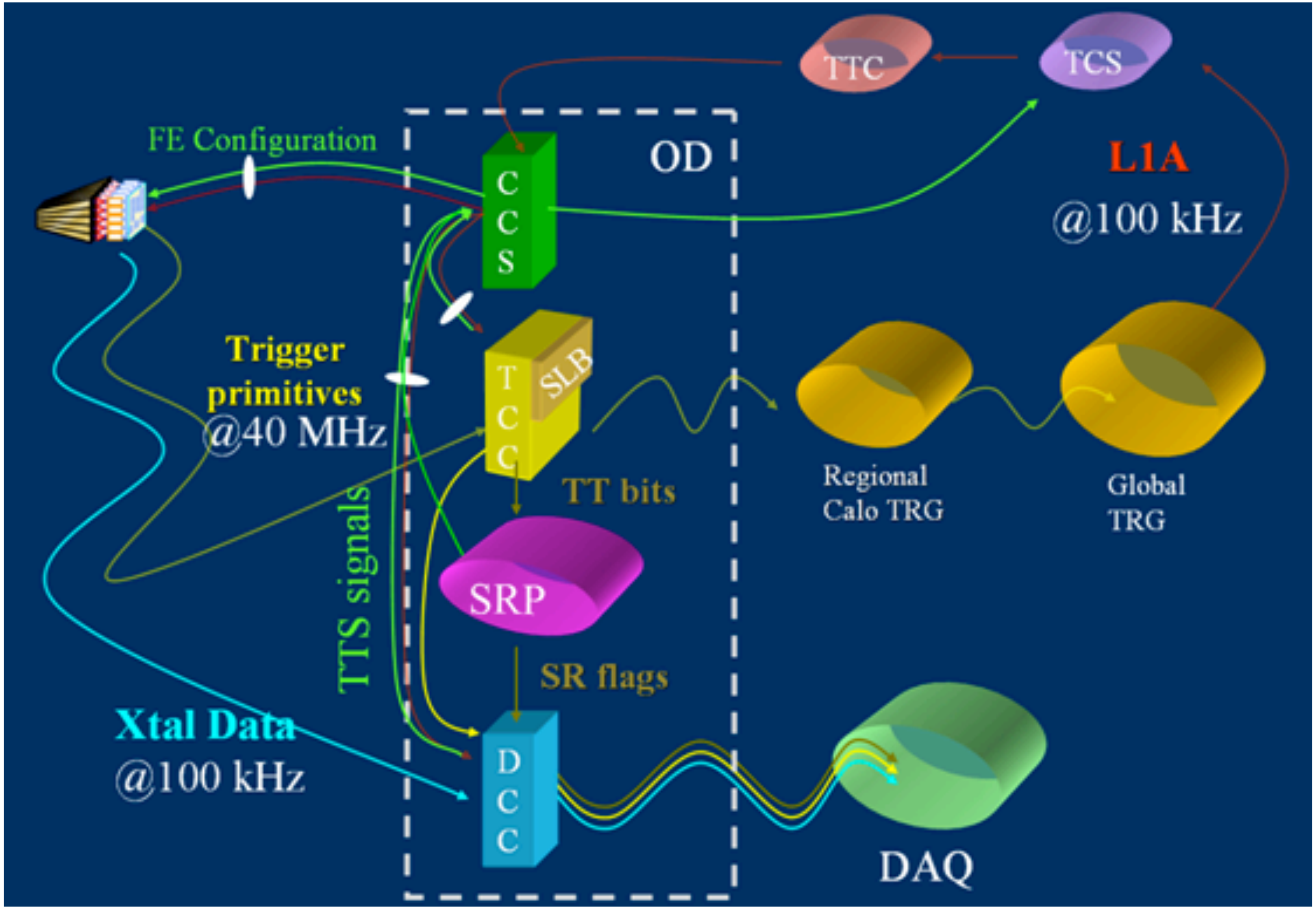
EE: Vacuum phototriodes (VPT)

- Gain 8 - 10 at B = 4 T
- More rad resistant than Si diodes



Off-Detector Electronics

The off-detector electronics is the interface between ECAL and CMS.



Off-Detector Electronics (2)

- CCS: Clock and Control System

  When ECAL is turned on, loads constants into the FE and initializes the electronics; also distributes the clock to be in sync with CMS

- DCC: Data Concentration Card

  When a L1 accept is issued, the DCC merges the data from ECAL with the other sub-detectors.

- TCC: Trigger Concentration Card

  For ECAL trigger, computes the trigger primitive at every BX, and sends the data to the regional calorimeter trigger if energy is above threshold.

- TTS: Trigger Throttling System

  When a subdetector is busy and cannot accept more data, the acquisition has to stop for all sub-detectors. TTS tells each sub-detector when to stop and restart data acquisition.

- SRP: Selective Readout Processor

  When there is energy deposition, we don't read-out the full ECAL, only a selected area around energy deposition.

Calibration & Monitoring

ECAL Calibration: (Maintain Energy Resolution)

Without inter-calibration, the same signal (i.e. 120 GeV electron) would produce different outputs in different crystals.

Raw (uncalibrated) Supermodule:
6%-10% spread in resolution among channels

→

TestBeam Pre-Calibration:
0.3% (9 SM)
Cosmic Pre-Calibration:
1.5-2.5% (36 SM)
Lab Pre-Calibration:
4%

→

In-Situ Physics Calibration:
0.5% resolution

ECAL Monitoring (Monitor Stability and Measure Radiation Effects):

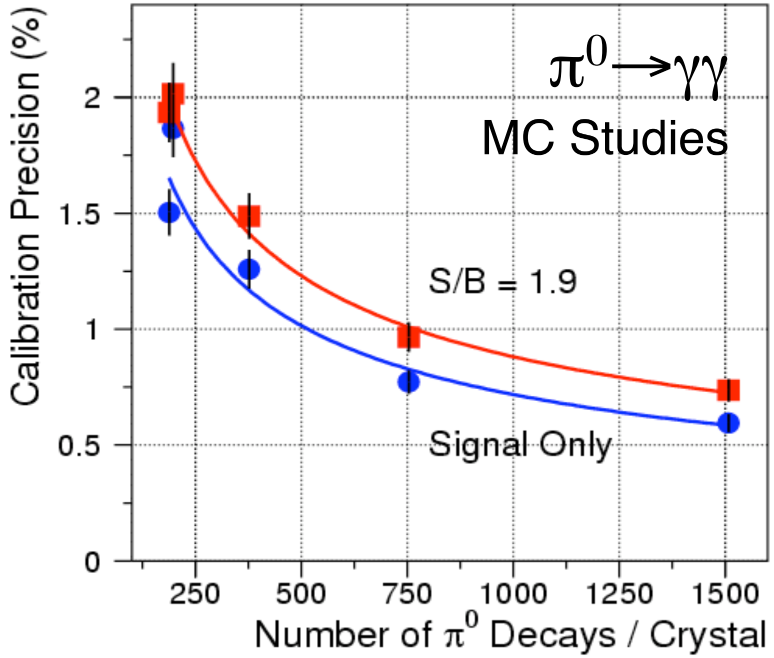
ECAL Stability (<< 0.5%):
Monitored with Laser Monitoring System

→

Transparency Change Correction:
Signal Change under Irradiation, Measured with Laser Monitoring System

Calibration Strategy

- Will start with pre-calibration, but would like to improve calibration quickly in-situ
  - Testbeam calibration only on 9 SM for EB (~500 xtals of EE), others have couple % calibration from cosmics for EB and ~10% lab calibration for EE
- Several paths for in-situ physics calibration



Strategy	Time	Precision
Mean energy deposited by jet triggers independent of ϕ at fixed η (after correction for Tracker material)	few hours	~2-3%
Neutral pion mass peak: @ 2×10^{33} cm^{-2} s^{-1}	few days	≤1%
Z→ ee: absolute calibration	100 pb^{-1}	< 1%
W→ eν: E/p measurement	5-10 fb^{-1}	0.5%

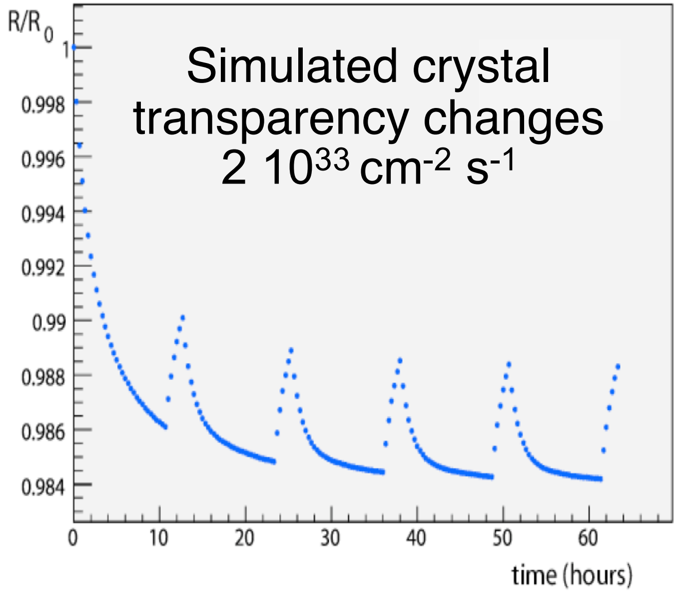
Crystal Transparency Changes & Laser Monitoring System

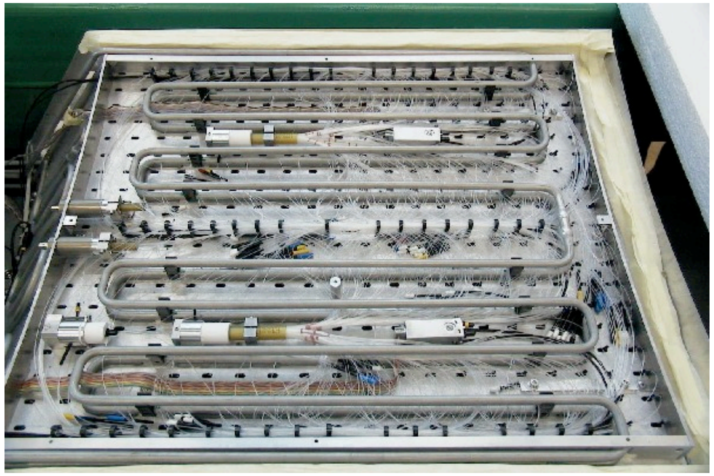
There is a change in ECAL signal during periods of irradiation due to radiation-dependent crystal transparency changes.

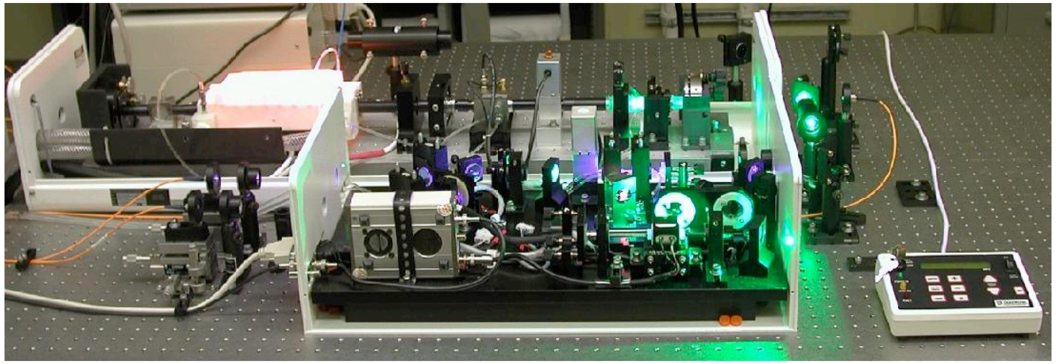
- Dose rate at LHC nominal luminosity is 0.2-0.3 Gy/h in EB and 15 Gy/h in EE
- ~5% changed must be corrected for to maintain energy resolution of detector

Laser Monitoring System to inject light into crystals and monitor output

- Will monitor transparency changes with precision of < 0.1% every 20 minutes during LHC operation



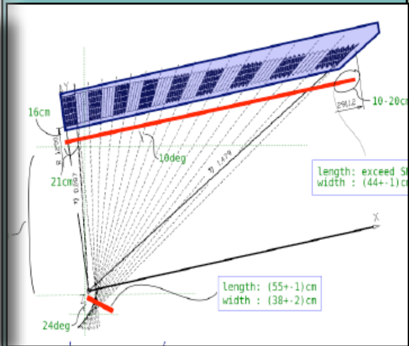




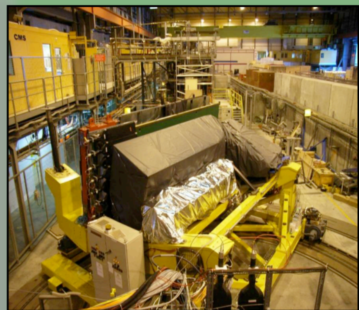
Highlights from Commissioning Timeline

2004:
Test Beam @ H4:
1 EB SM with
final electronics

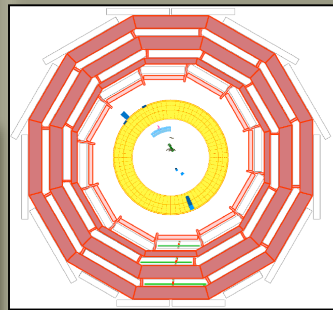
2006-2007:
Commissioning &
calibration of each
SM with cosmics on
surface



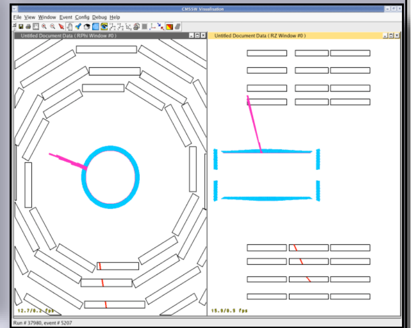
2006:
Test Beam @ H4:
9 SM;
Combined Test
beam @ H2:
ECAL+HCAL



2006:
22 SM tested with
magnetic field in
surface (MTCC)



2008:
Commissioning
with cosmics and
first beam in-situ



2007:
Individual signoff
of each SM
during installation

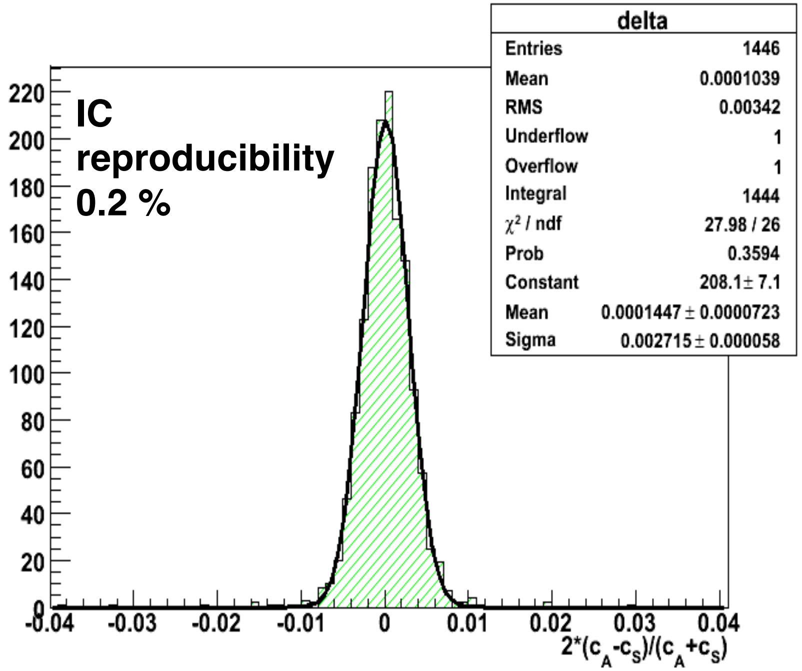
2007:
Test Beam
@ H4: EE

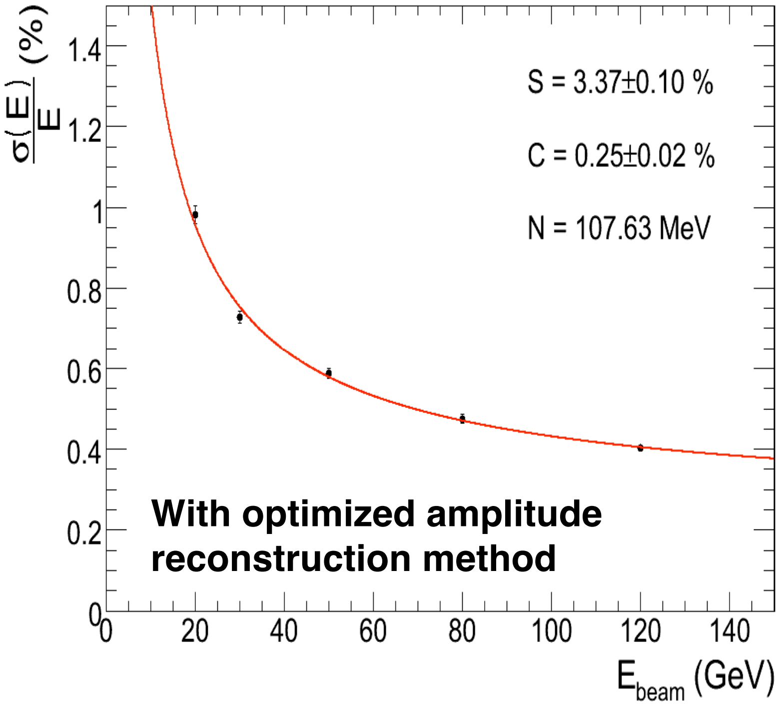
2004 2005 2006 2007 2008

Test Beam Highlights

Inter-calibration (IC) with electron beam

- 9 SMs intercalibrated with electrons @ 120 GeV H4
- 1 SMs partially calibrated with electrons @ 50 GeV H2

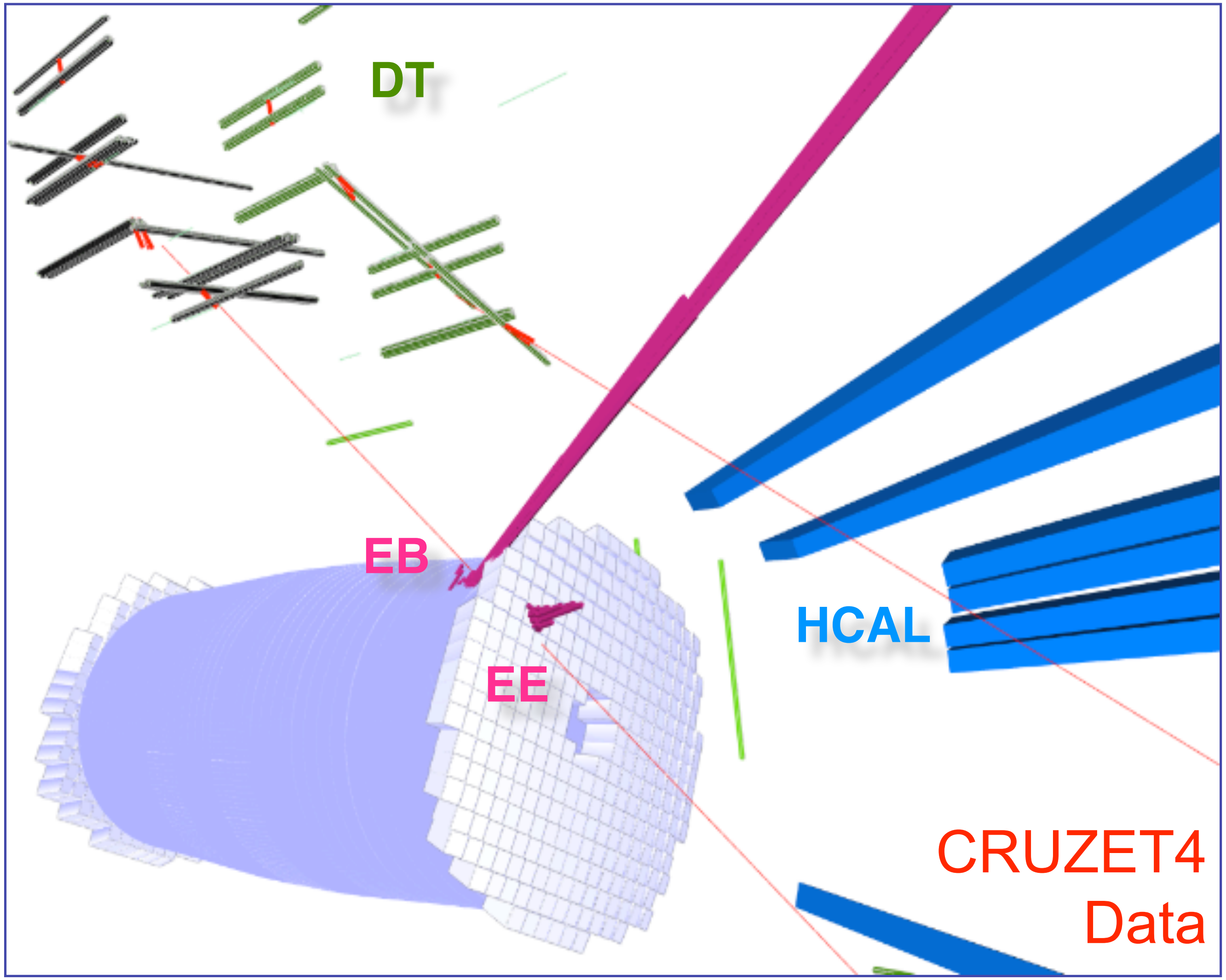




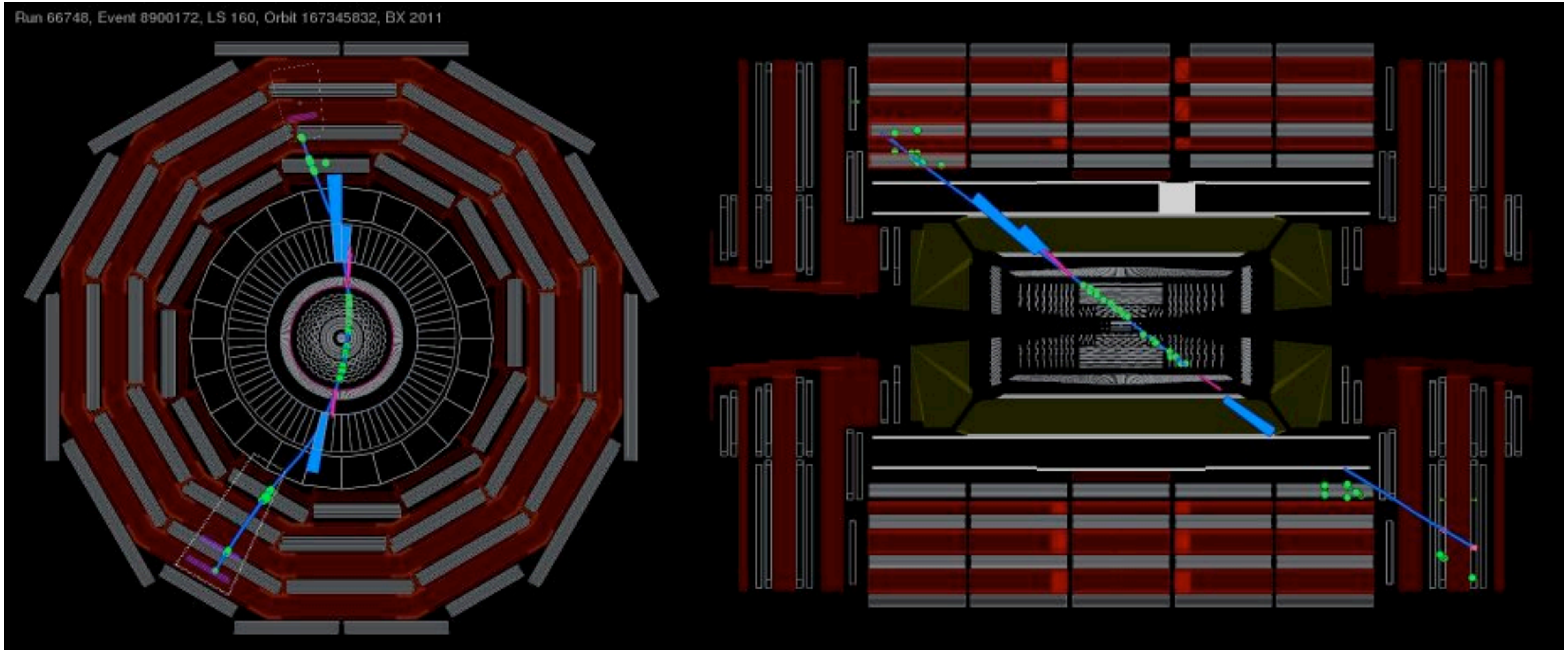
$$\frac{\sigma}{E} = \frac{3.37\%}{\sqrt{E}} \oplus \frac{108}{E} \oplus 0.25\%$$

Cosmic Data Highlights

Muon Showering in EB & EE



Cosmic Signal in B-Field



ECAL in magenta

HCAL in blue

Tracker and Muon hits in green

CRAFT
Data

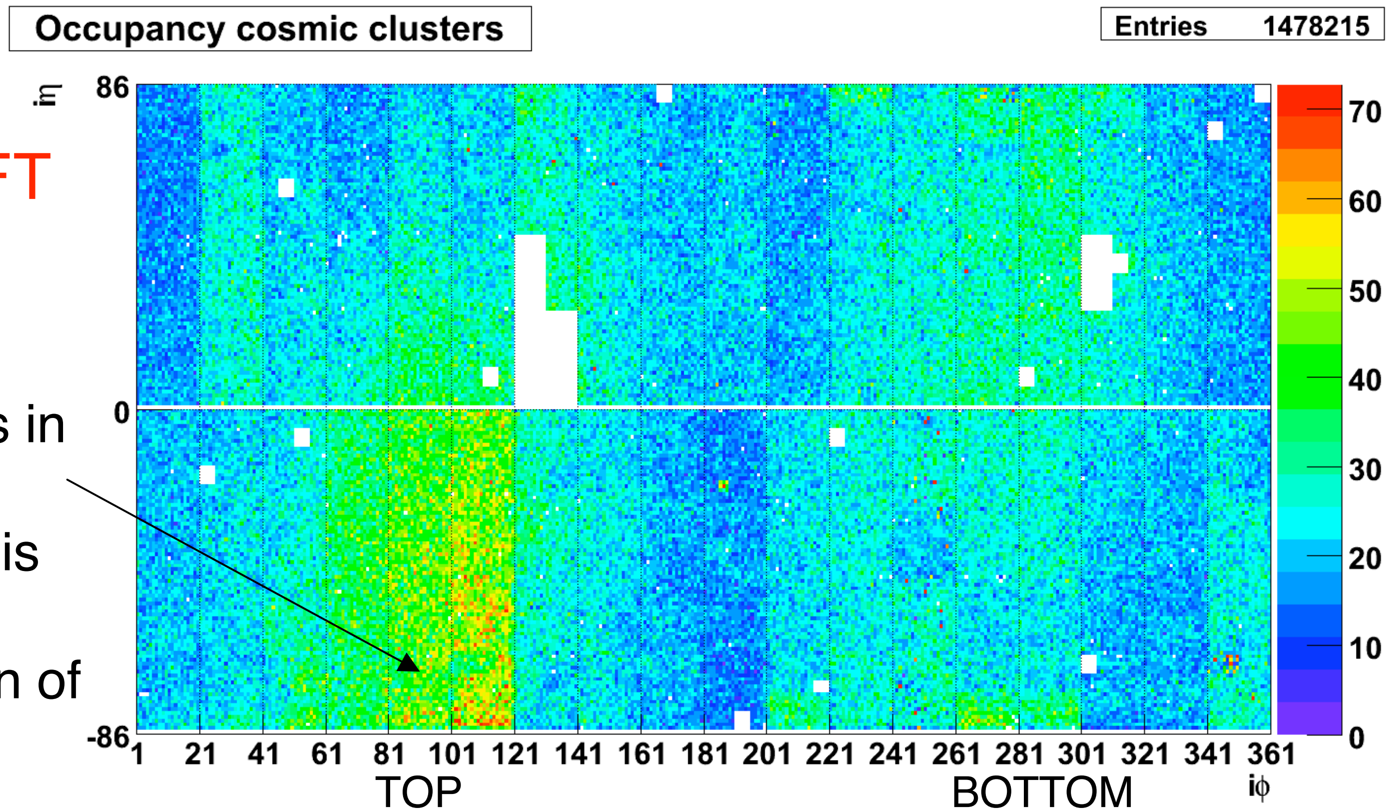
Cosmics Analysis: Occupancy

Occupancy map of clusters in the ECAL barrel in cosmic muon runs

- CRAFT Data: Magnetic field at 3.8T and the APD gain set to 200
- Clusters are seeded from a single crystal above 15 ADC counts (≈ 130 MeV) OR two adjacent crystals above 5 ADC counts (≈ 2x43 MeV).
- Rate of selecting cosmics with gain 200 was ~7% during CRAFT
- Other modulations due to the cluster efficiency varying with light yield.

CRAFT Data

Excess in EB- region is due to position of shaft



Higher occup in Top & Bottom regions due to vertical cosmic ray flux.

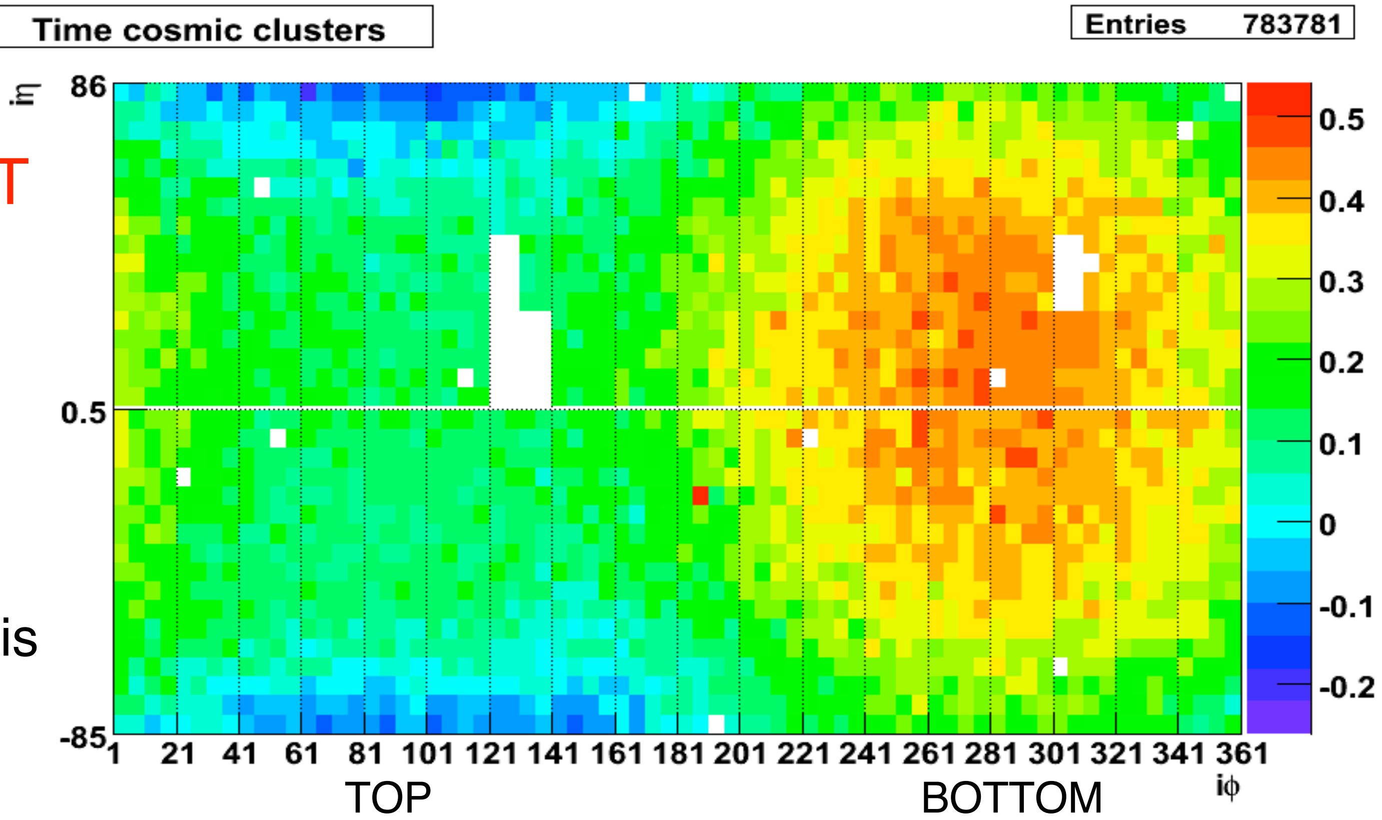
Cosmics Analysis: Timing

Profile map of average time associated with clusters in ECAL barrel

- Time is measured in clock units (25 ns) wrt the settings for collisions.
- Binned in 5x5 TTs; color corresponds to clock units.
- Clusters in the bottom are seen later with respect to the top part as a result of the time of flight of the cosmic rays.

CRAFT Data

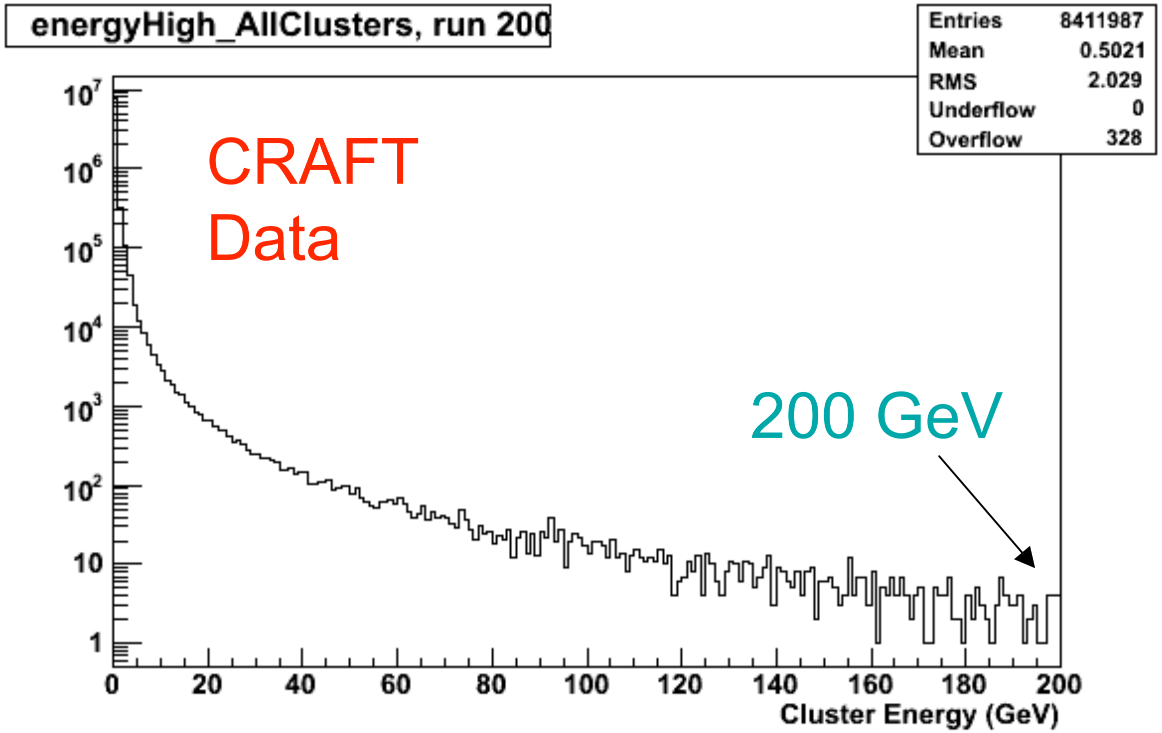
Top is earlier, Bottom is later



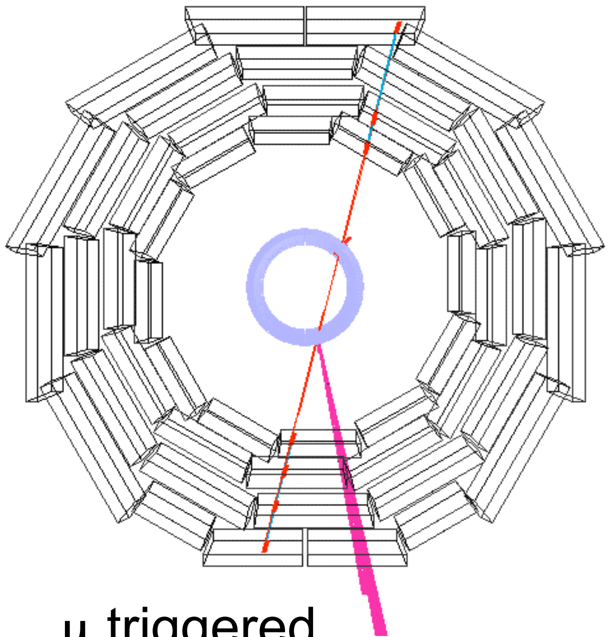
Cosmics Analysis: Energy Spectrum

<u>Energy spectrum in ECAL barrel for CRAFT cosmic muon runs</u>

- Energy is obtained summing the energies of all the crystals belonging to a cluster.
- “High energy” events mostly from muon brem.
- Rate of events with cluster > 2 GeV is ~ 0.3% (~4% of all cosmic clusters)



Toyoko Orimoto, Caltech

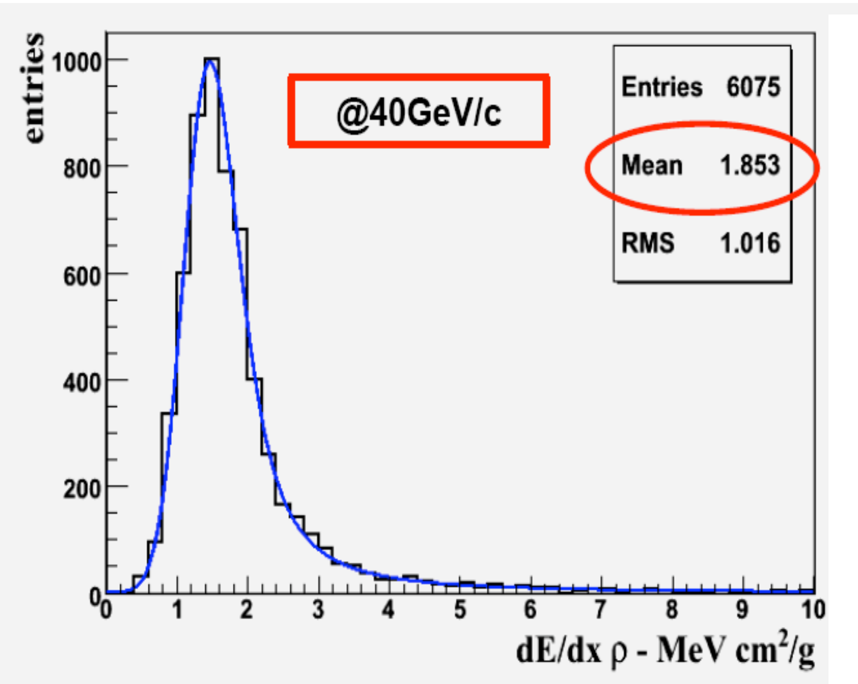


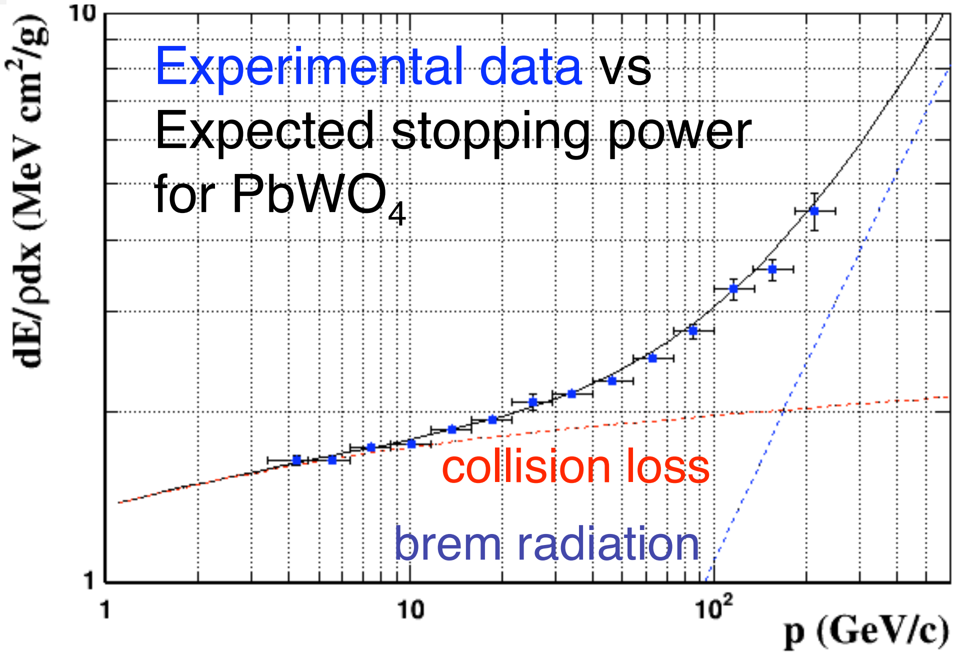
μ triggered CRUZET event 290 GeV cluster!

Cosmics Analysis: dE/ρdX

dE/ρdX with pointing muons

- As function of muon momentum (measured from tracker tracks)
- Results in good agreement with $PbWO_4$ expected stopping power; Demonstrates correctness of the tracker momentum scale and ECAL energy scale from test-beam pre-calibration with electrons.
- More systematic studies needed to understand region below 3 and above 100 GeV/c, comparing also with Cosmics MC

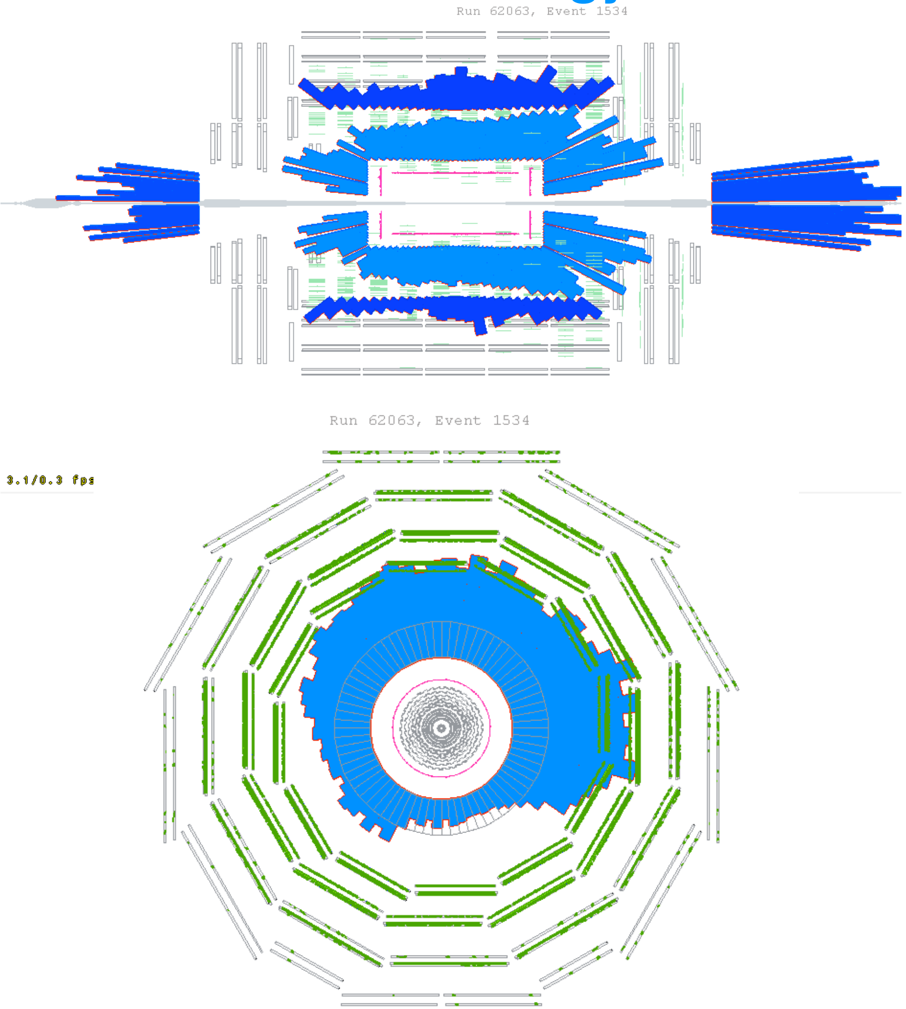




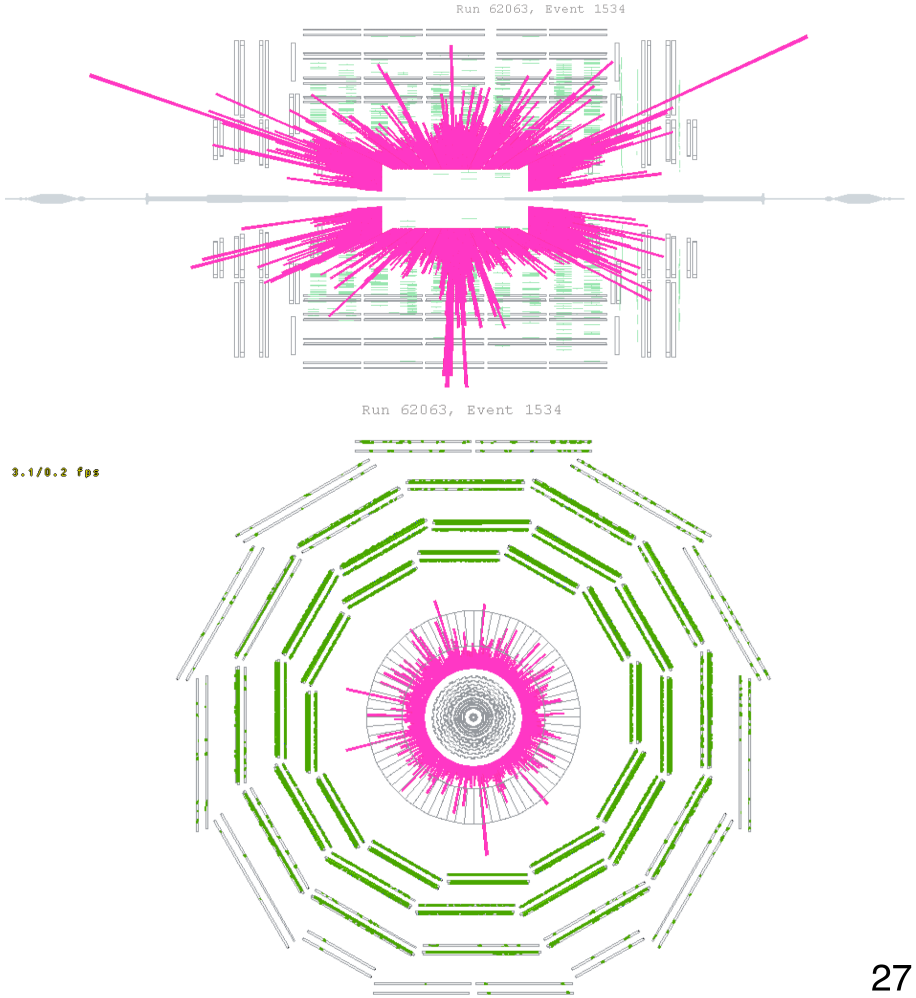
First Beam Data: Splash Events

Beam was sent to collimators ~150m upstream of CMS, creating a fixed target like environment at CMS, ~2x10^9 protons on collimator

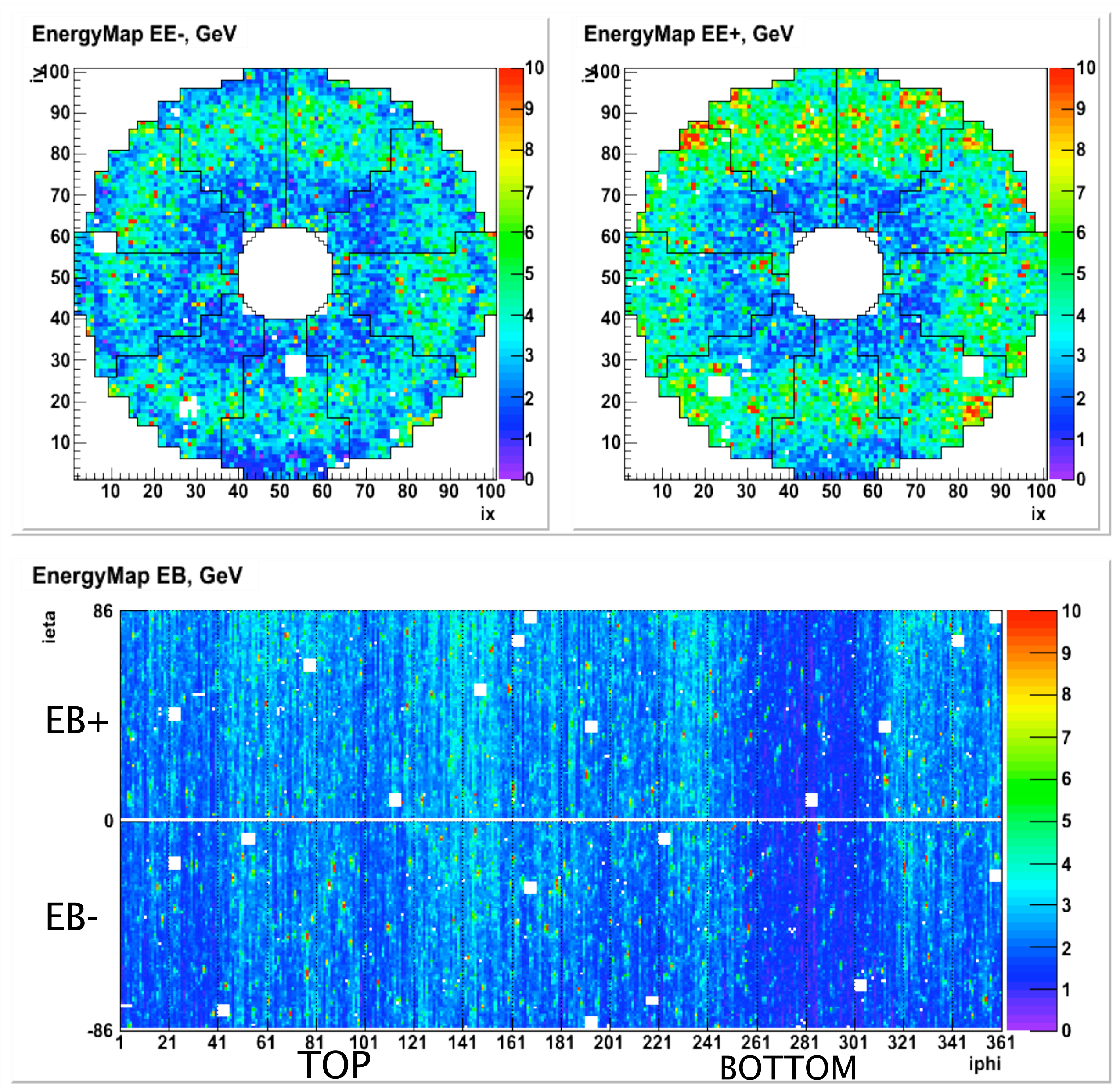
HCAL energy



ECAL energy



Beam Splash: ECAL Energy



> 99% of ECAL channels fired and ~200 TeV energy deposited in EB+EE

Beam (clockwise) came from plus side.

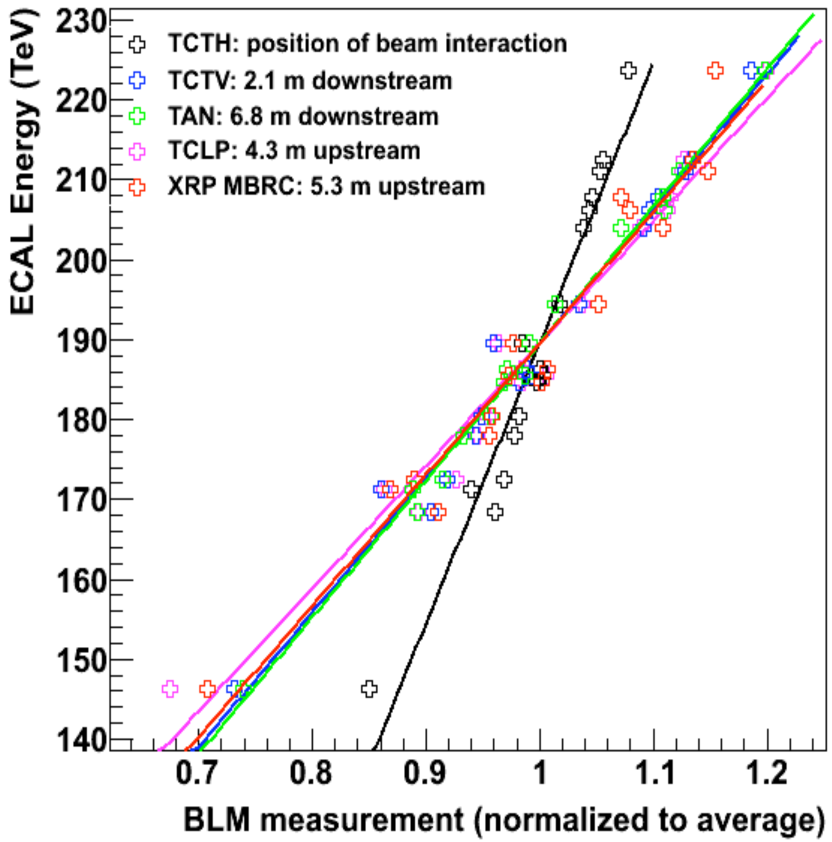
Around 200k muons crossing ECAL per event (~4 muons/cm^2).

EE pre-calibrations were yet applied (lowest gain photodetectors are nearest the beam pipe).

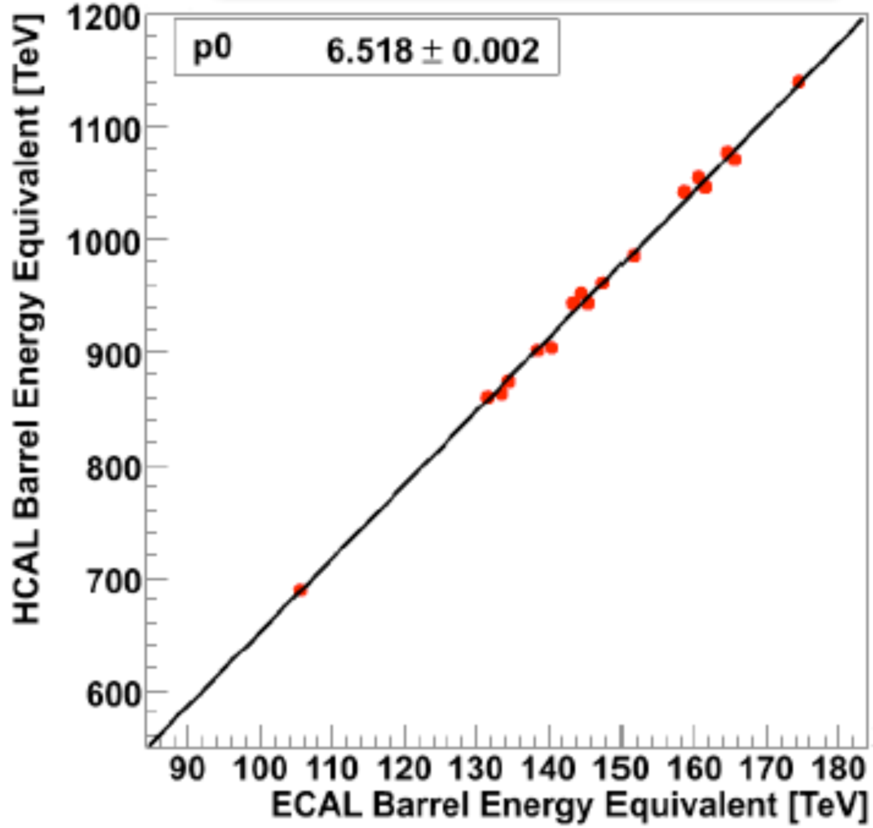
Beam Splash Correlations

Correlation ECAL Energy with Energy Measured by Beam Loss Monitors (BLM) and HCAL

ECAL – BLM correlation



HCAL – ECAL correlation



Conclusions

- **ECAL Barrel & Endcap**
  - Commissioned and have been regularly taking data for many months now; Participated in all global runs (CRUZET-CRAFT)
  - Millions of cosmic data to analyze (on-going)
  - Successful observation of first beam data at LHC; utilizing this data as much as possible

- **Plans for next months**
  - Installation and commissioning of pre-shower
  - EE trigger installation
  - Hardware issues: LV, FE problems, etc need to be resolved
  - Ready analyses for beam: calibration, prompt feedback

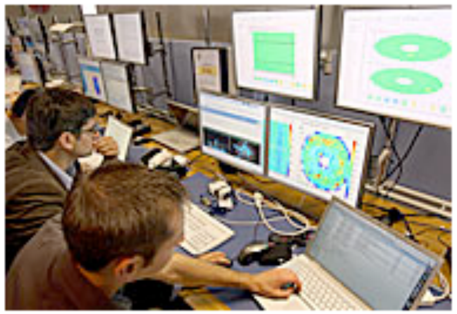
Interested in Joining the ECAL PFG?

ECAL Prompt Feedback Group (PFG)

- Great place for newcomers to start; many young students have started their work on CMS with our group.
- Great way to gain ECAL expertise, but also to learn how to access and analyze data quickly, trouble shoot problems, etc…
- Most of the results shown today have been produced by the PFG
- Prerequisites are a basic knowledge of CMSSW and ECAL, availability to take on-duty shifts and attend PFG meetings; also, your institution should be a part of ECAL Group.

L'ESPERIMENTO DEL CERN

Parte il test del Big Bang a Ginevra, festa e applausi per gli scienziati | Foto



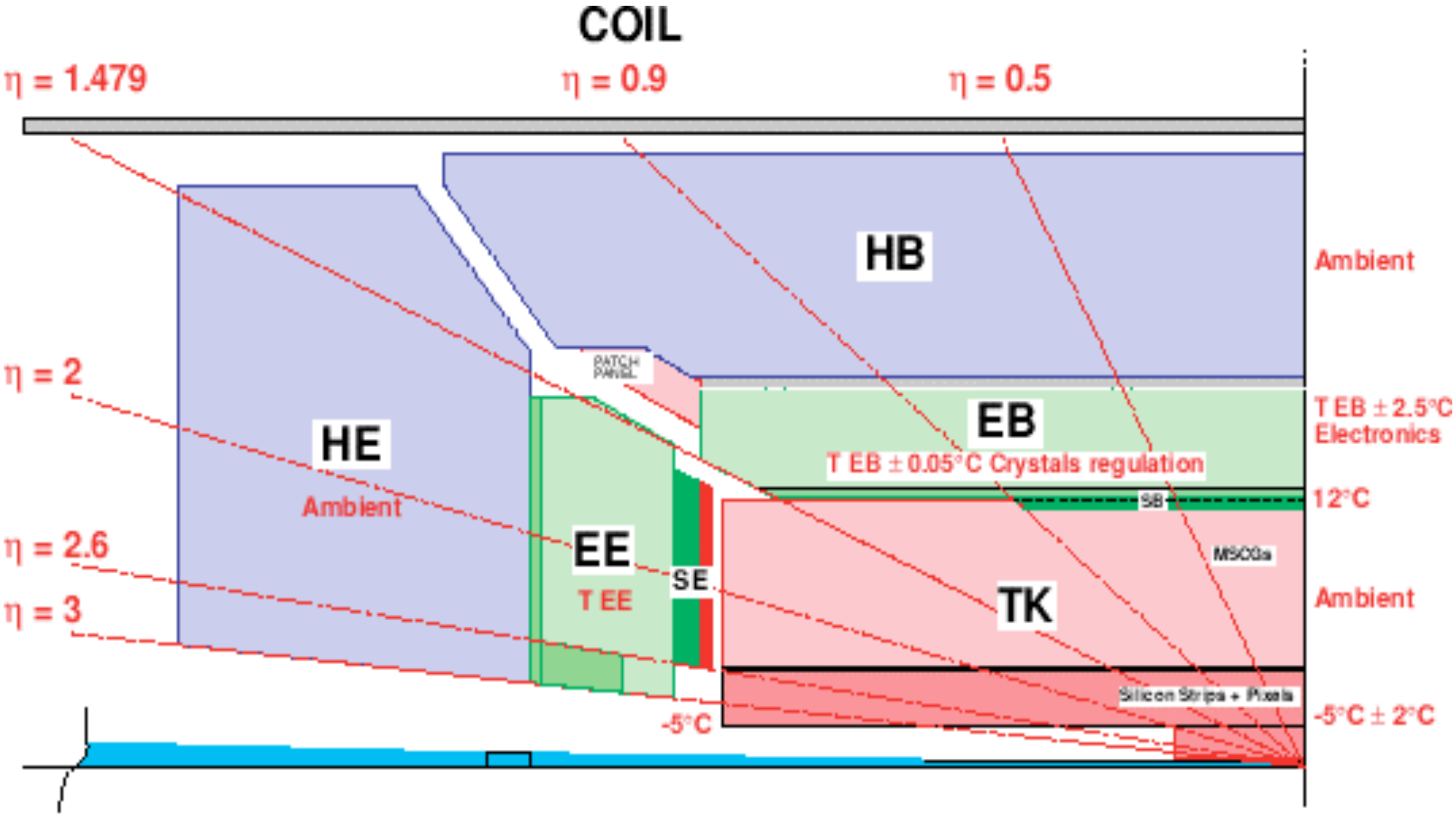
08:44 | SCIENZE | Al via il progetto più ambizioso della fisica moderna, alla ricerca della «particella di Dio». I primi scontri tra nubi di protoni a novembre. Ma Monsignor Sgreccia frena gli entusiasmi sulla particella Higgs: «Dio non si può trovare con gli esperimenti» *Caprara* Video

Reference Links

- CMS 101 Workshop (very nice ECAL intro): http://indico.cern.ch/conferenceDisplay.py?confId=35545
- LPC Run Plan Workshop (ECAL Talk, a bit outdated): http://indico.cern.ch/getFile.py/access?resId=0&materialId=slides&contribId=44&sessionId=7&subContId=2&confId=30825
- ECAL Cosmics Analysis Tutorial (also a bit outdated but still interesting and informative): http://indico.cern.ch/contributionDisplay.py?contribId=4&confId=32360
- ECAL CRAFT Results: http://indico.cern.ch/conferenceDisplay.py?confId=46935
- ECAL TDR: http://cmsdoc.cern.ch/ftp/TDR/ECAL/ecal.html

Extra Slides

CMS Rapidity Coverage



Detector ambient air temperature 18°C
Dew point 9°C ± 1°C
T EB = <12 ; 18°C>
T EE =18°C ± 0.1°C

Lead Tungstate Properties

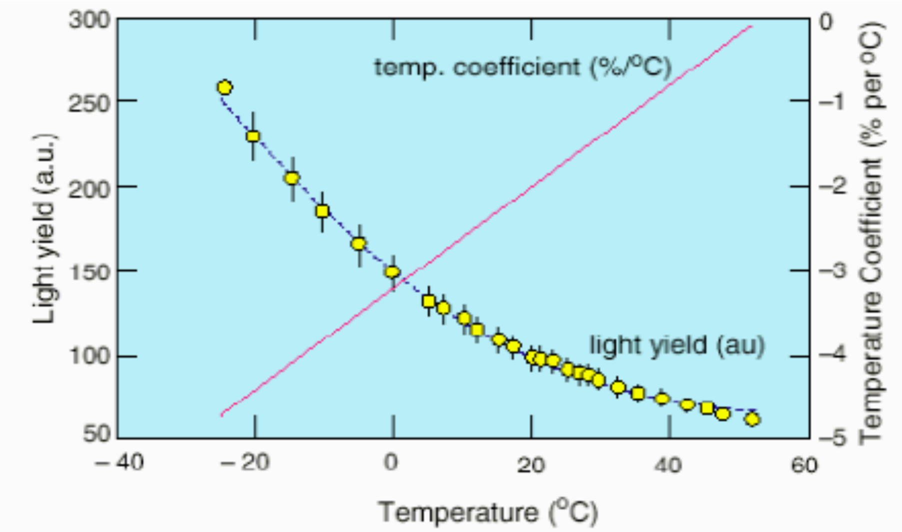
Fast light emission : ~80% in 25 ns

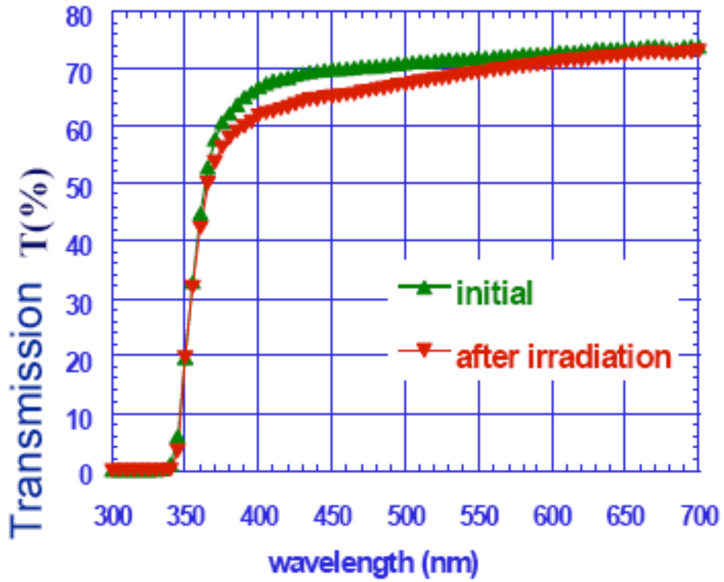
Peak emission : ~425 nm (visible region)

Short radiation length : X_0 = 0.89 cm

Small Molière radius : R_M = 2.10 cm

Radiation resistant to very high doses.





But:

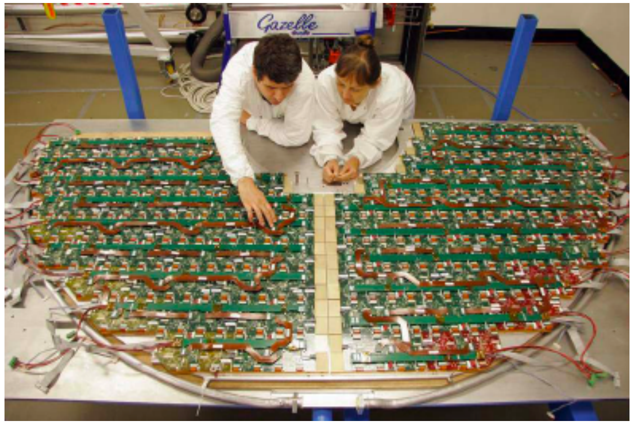
Temperature dependence ~2.2%/°C
→ Stabilise Crystal Temp. to ≤ 0.1°C

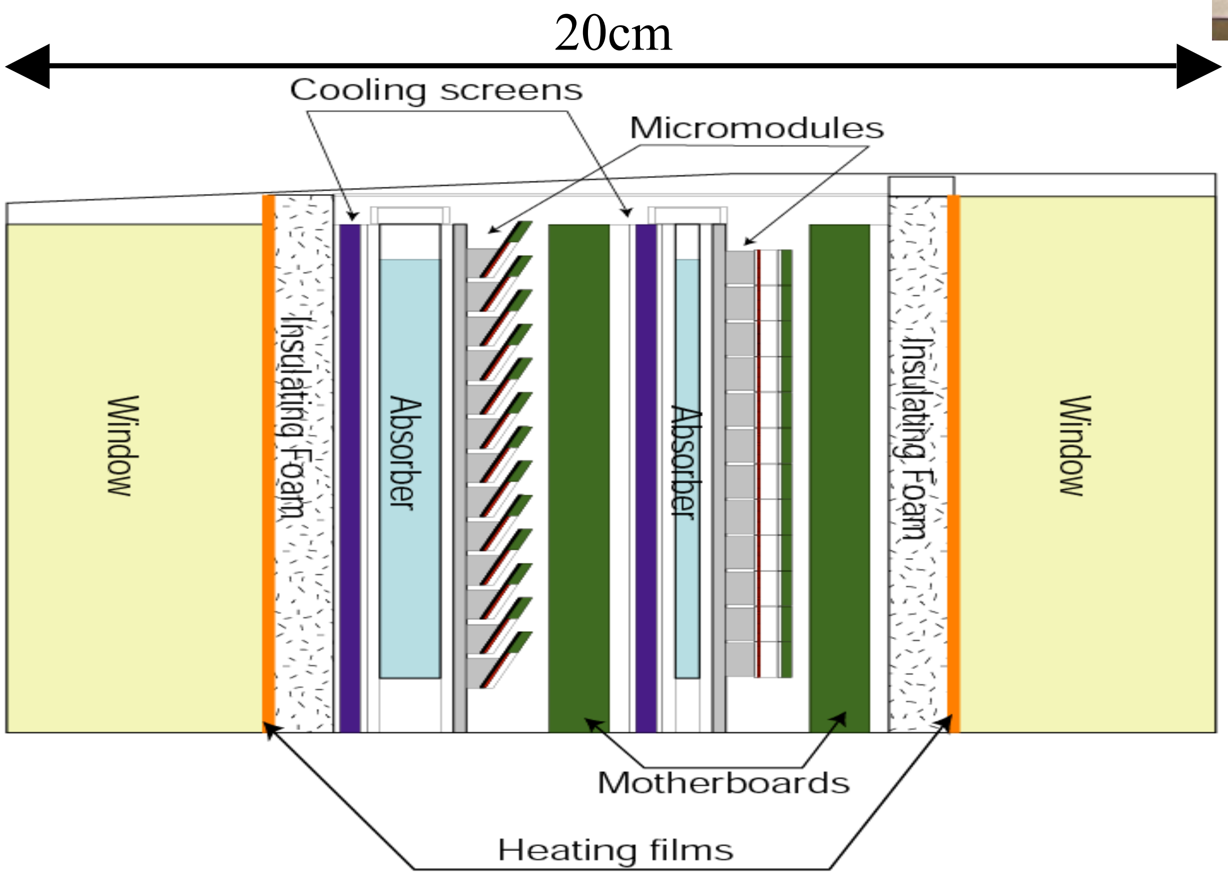
Formation and decay of colour centres in dynamic equilibrium under irradiation
→ Precise light monitoring system

Low light yield (~1% NaI)
→ Photodetectors with gain in mag field

Pre-Shower Detector (ES)

- Two layers of lead followed by silicon sensors placed in front of EE ($1.6<\eta<2.6$)
- 2mm Si strips to distinguish photons from π^0s and for vertex identification
- ES+ installed in Feb, ES- in March





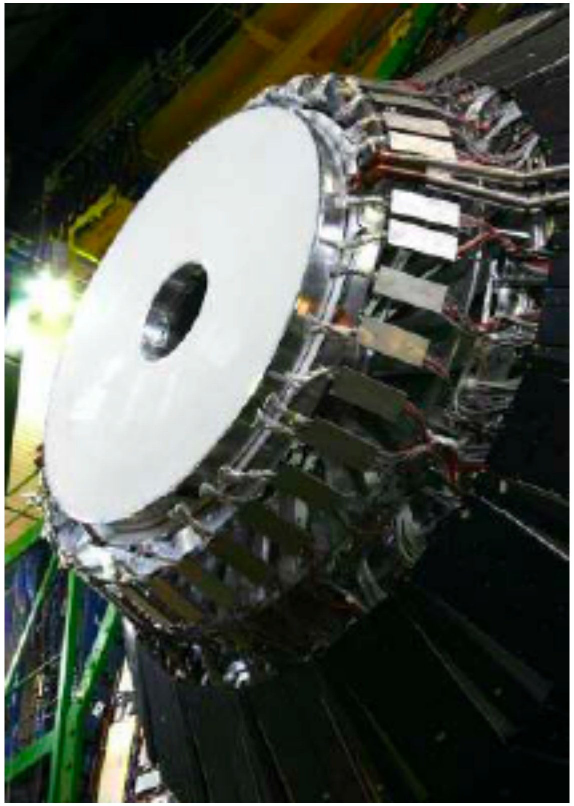


Photo Detectors

PWO4 has a very low light output, need to amplify signal.

Problem: Limited space and 4T field

Solution: A photon-to-current device with built-in gain

Barrel :

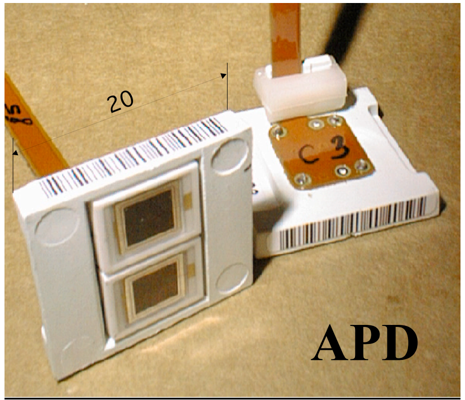
Avalanche photodiodes (APD)

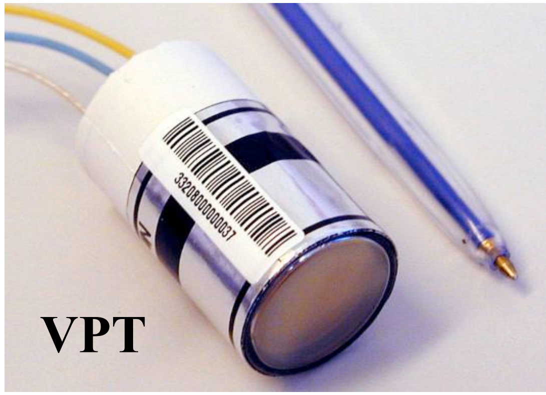
- Two 5x5 mm^2 APDs/crystal
- Gain: 50
- Temperature dependence: -2.4%/^{O}C

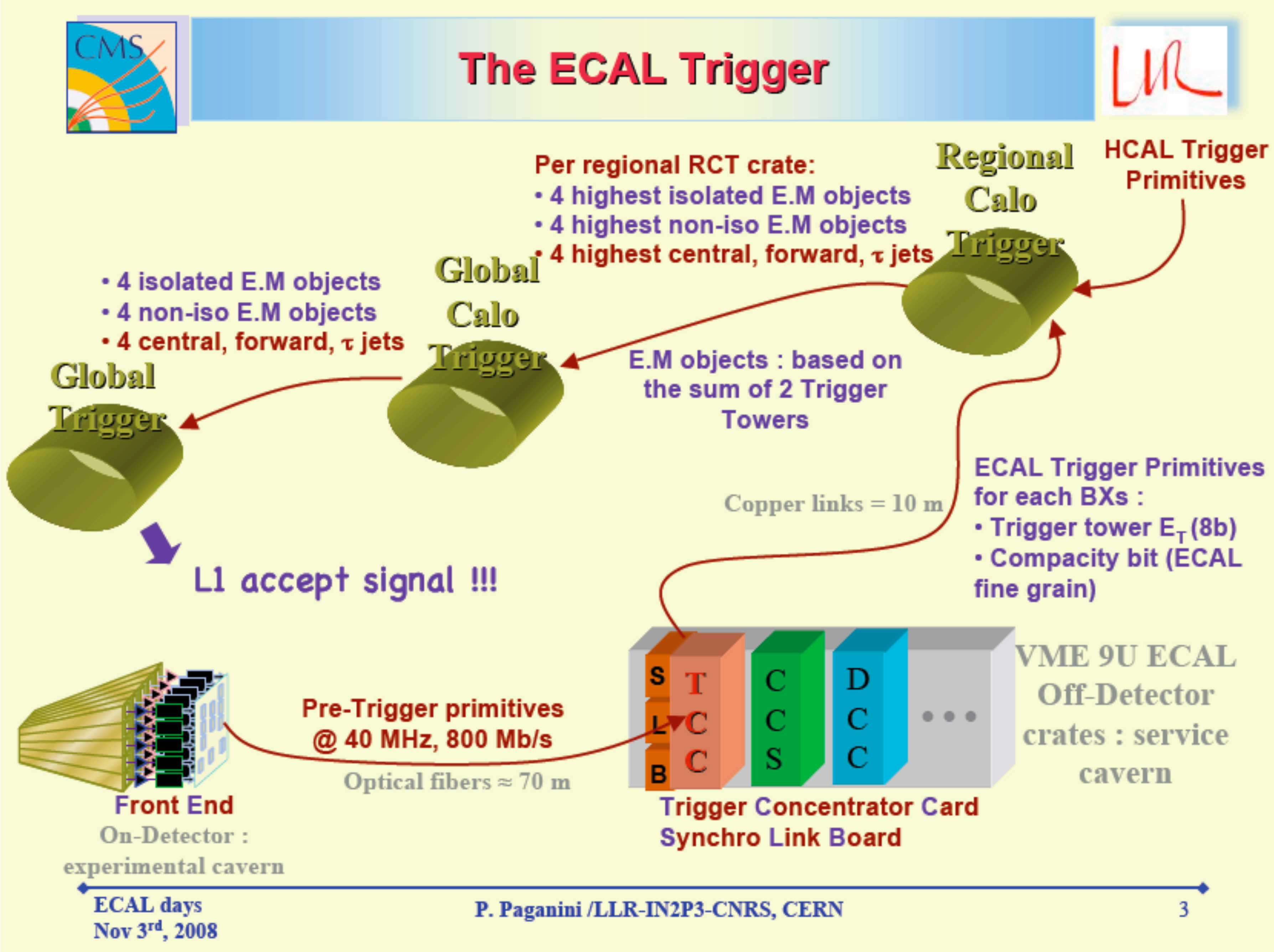
Endcaps:

Vacuum phototriodes (VPT)

- Active area ~ 280 mm^2/crystal
- Gain 8 - 10 at B = 4 T
- More radiation resistant than Si diodes (with UV glass window)

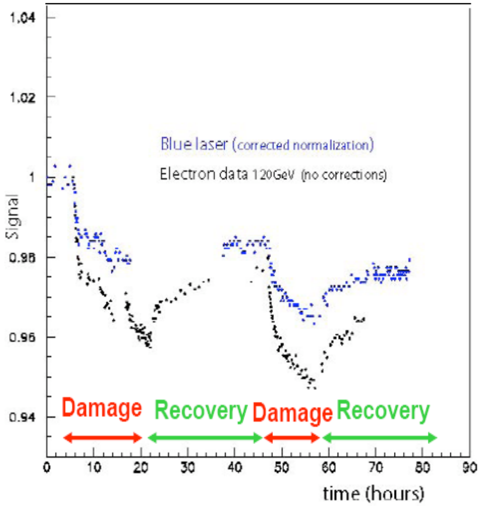






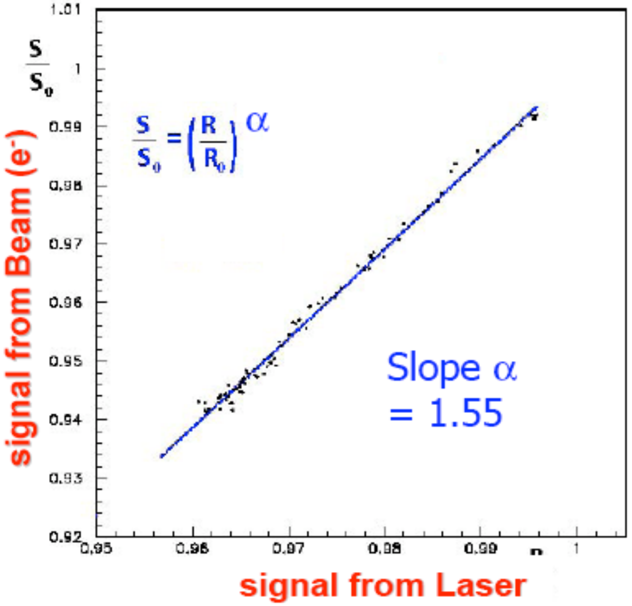
The ECAL Trigger
Per regional RCT crate:
• 4 highest isolated E.M objects
• 4 highest non-iso E.M objects
• 4 highest central, forward, τ jets
Regional Calo Trigger
HCAL Trigger Primitives
• 4 isolated E.M objects
• 4 non-iso E.M objects
• 4 central, forward, τ jets
Global Calo Trigger
Global Trigger
E.M objects : based on the sum of 2 Trigger Towers
ECAL Trigger Primitives for each BXs :
• Trigger tower E_T (8b)
• Compacity bit (ECAL fine grain)
Copper links = 10 m
L1 accept signal !!!
Pre-Trigger primitives @ 40 MHz, 800 Mb/s
Optical fibers ≈ 70 m
S L B
T C C
C C S
D C C
VME 9U ECAL Off-Detector crates : service cavern
Front End
On-Detector : experimental cavern
Trigger Concentrator Card
Synchro Link Board
ECAL days
Nov 3rd, 2008
P. Paganini /LLR-IN2P3-CNRS, CERN
3

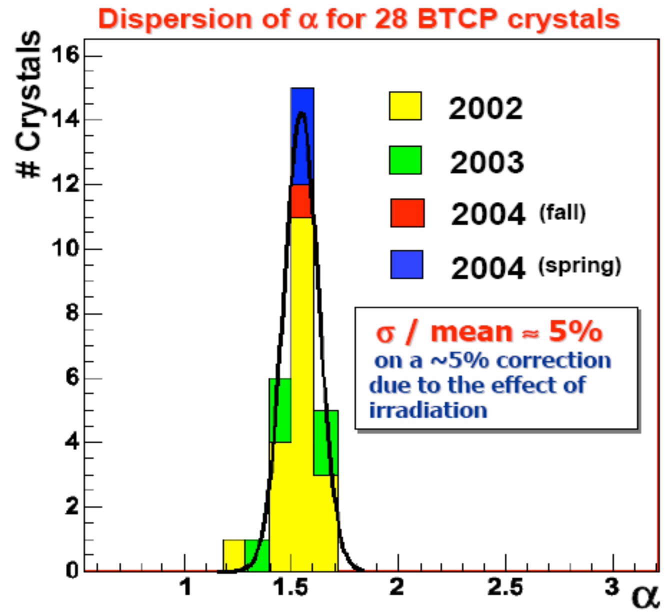
Crystal Transparency Changes



Measured on several irradiation/recovery cycles relation between transparency change and variation of scintillation signal

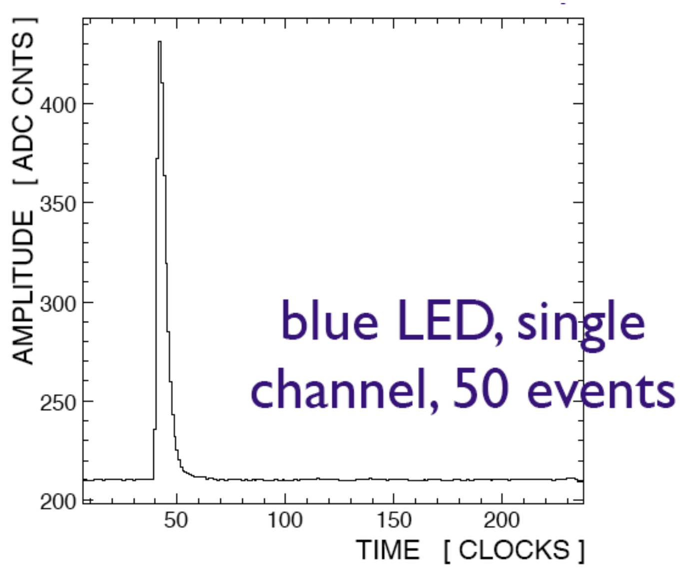
Small dispersion of the α parameter, allow to use a constant for each producer and crystal type (barrel/endcap)





EE VPT Studies & LED Pulser System

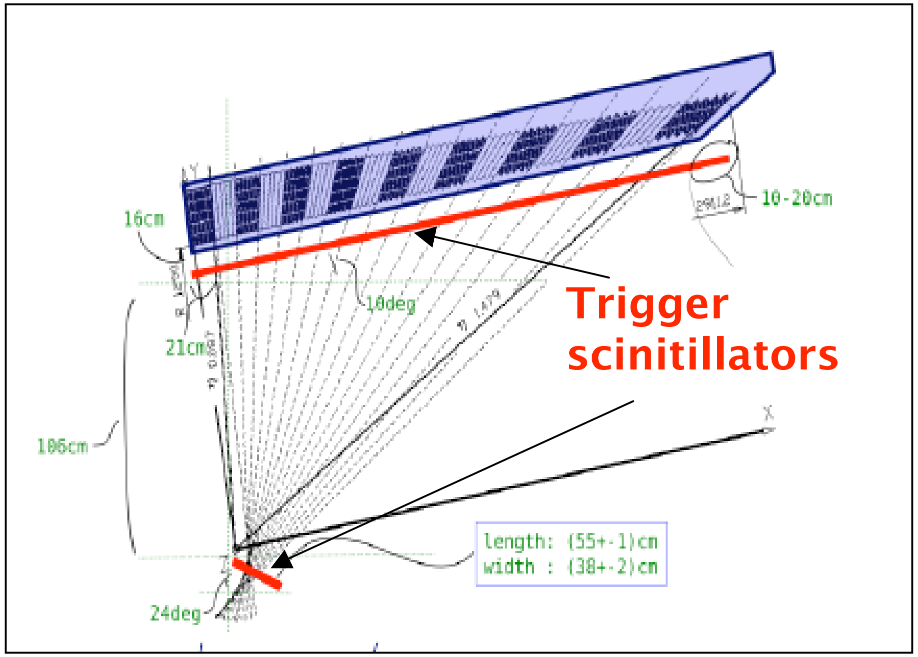
- **EE photodetectors (VPTs) stability:**
  - VPT response is intrinsically rate dependent
    - Need 'stability' system to make their response independent of rate.
    - This effect is much reduced when the B field is ON
- **LED pulser system**
    - Will run constantly, providing 'soak light'
    - Installed and tested at P5
    - VPT response was studied throughout CRAFT to check behavior with field

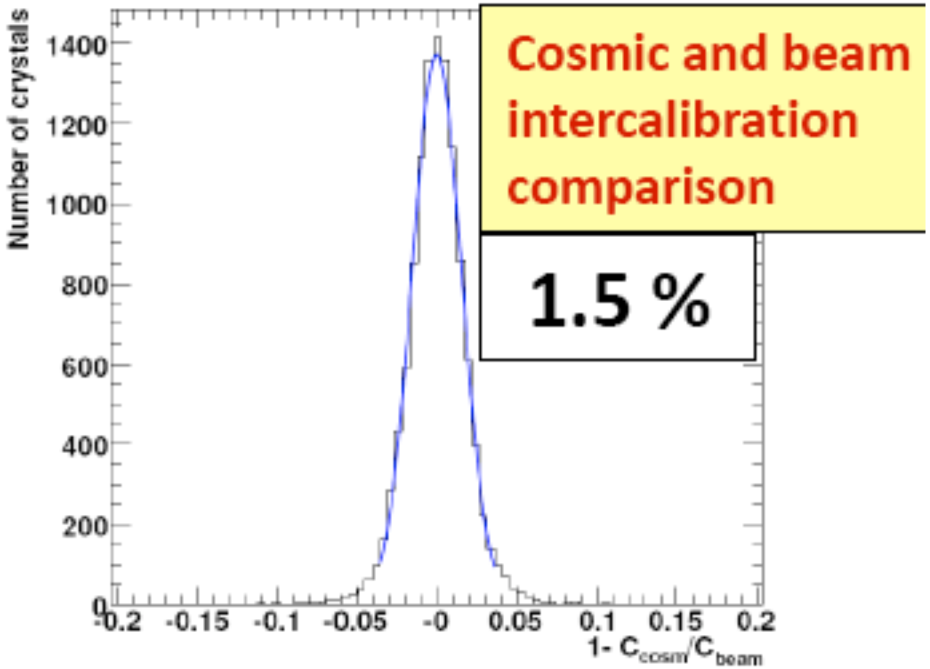


Cosmics Pre-Calibration

Each EB supermodule exposed to cosmics for at least 1 week

- Supermodule inclined 10°
- Increased APD gain (x4)
- ~5 million triggers/SM
- ~500 selected events/crystal



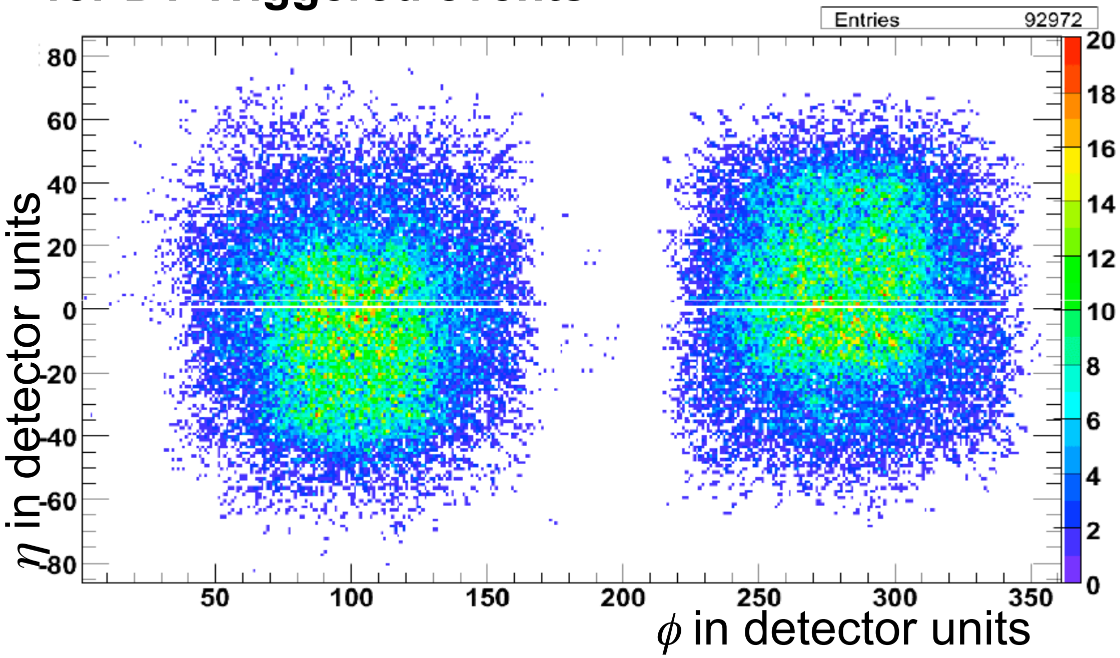


Cosmics Analysis: Muon Track Matching

Cluster matching with muon tracks

- Dominated by multiple scattering in solenoid + HCAL
- η is measured by DT with less points than ϕ

Reconstructed clusters matching muon tracks for DT Triggered events



CRUZET3 Data

Δη & Δϕ btwn extrapolated track match to cluster