The crystals are back!

THE CMS CRYSTAL ECAL

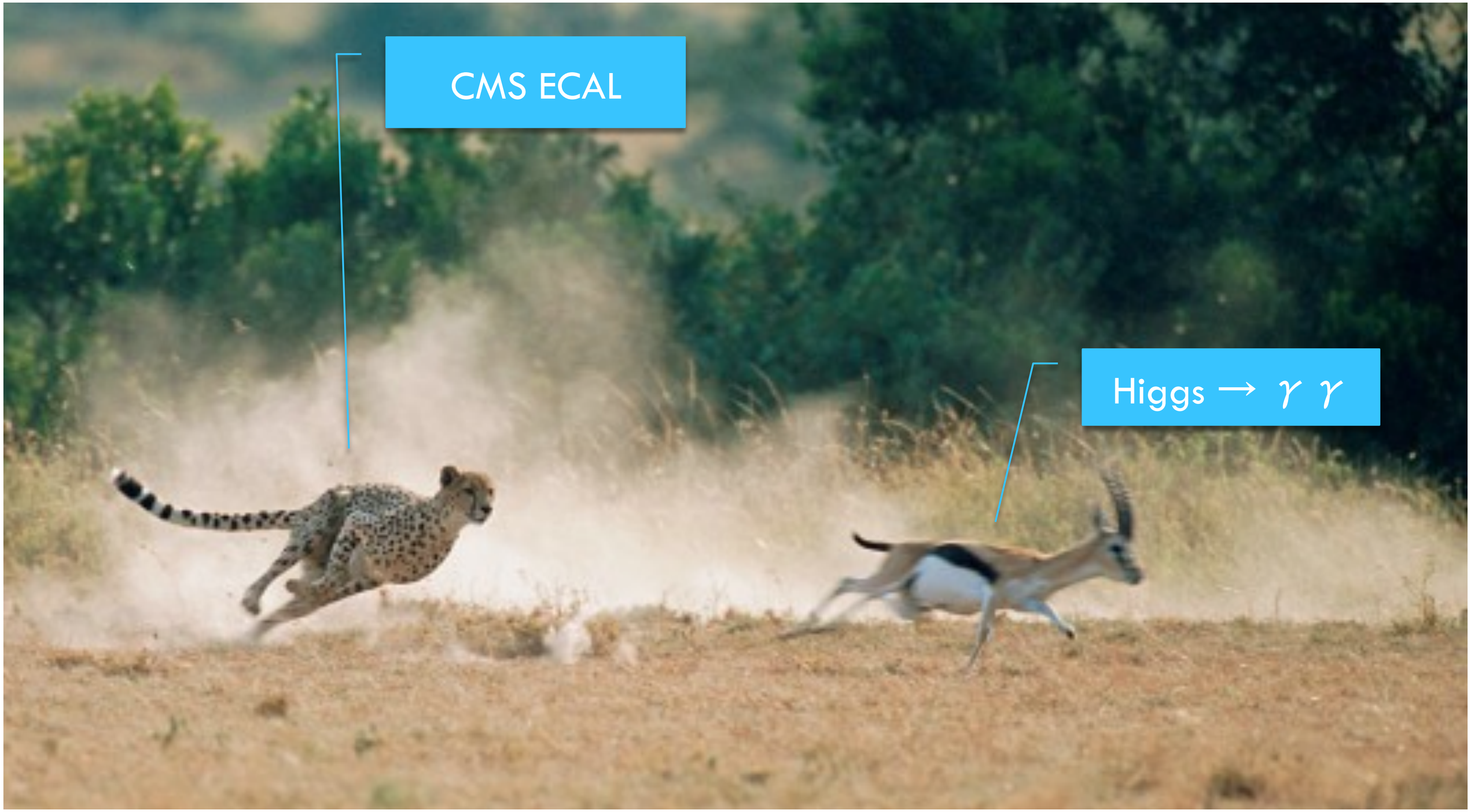
November 26, 2010

from the end of the cold war to the LHC first physics

Outline

- The hunt
- Crystal R&D
- Construction & commissioning
- Running and first physics results

The hunt

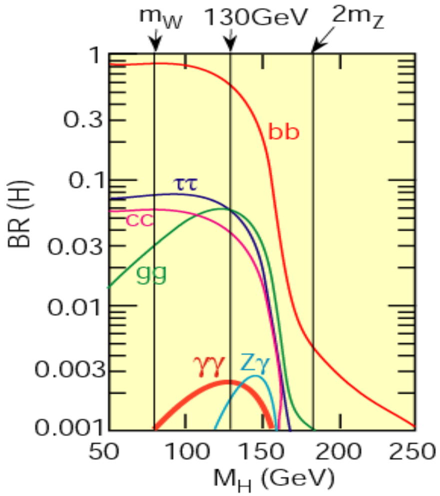


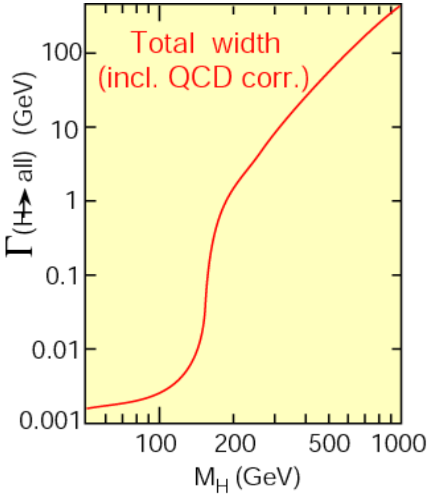
CMS ECAL

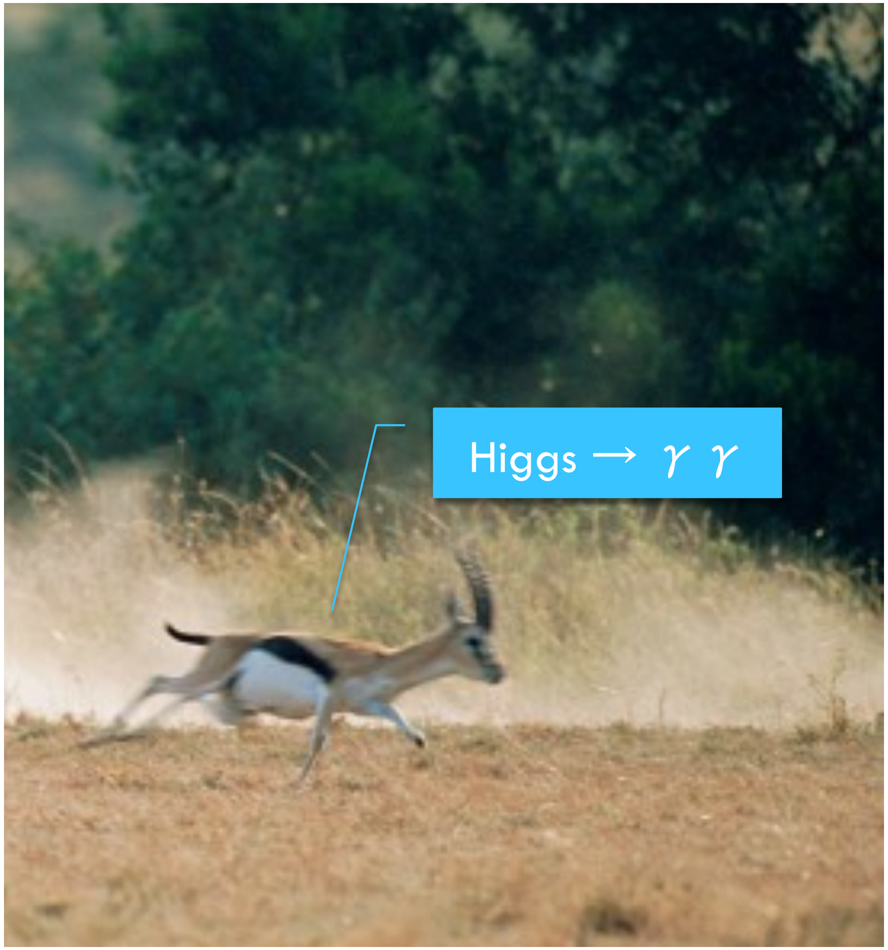
Higgs → $\gamma\ \gamma$

The (elusive) prey

- Di-photon channel
- For $m_H < 130$ GeV
  - Clean signature
  - Higgs width O(MeV)
  - Smooth background
- But
  - 10^{-3} branching fraction
  - Irreducible background as large as signal



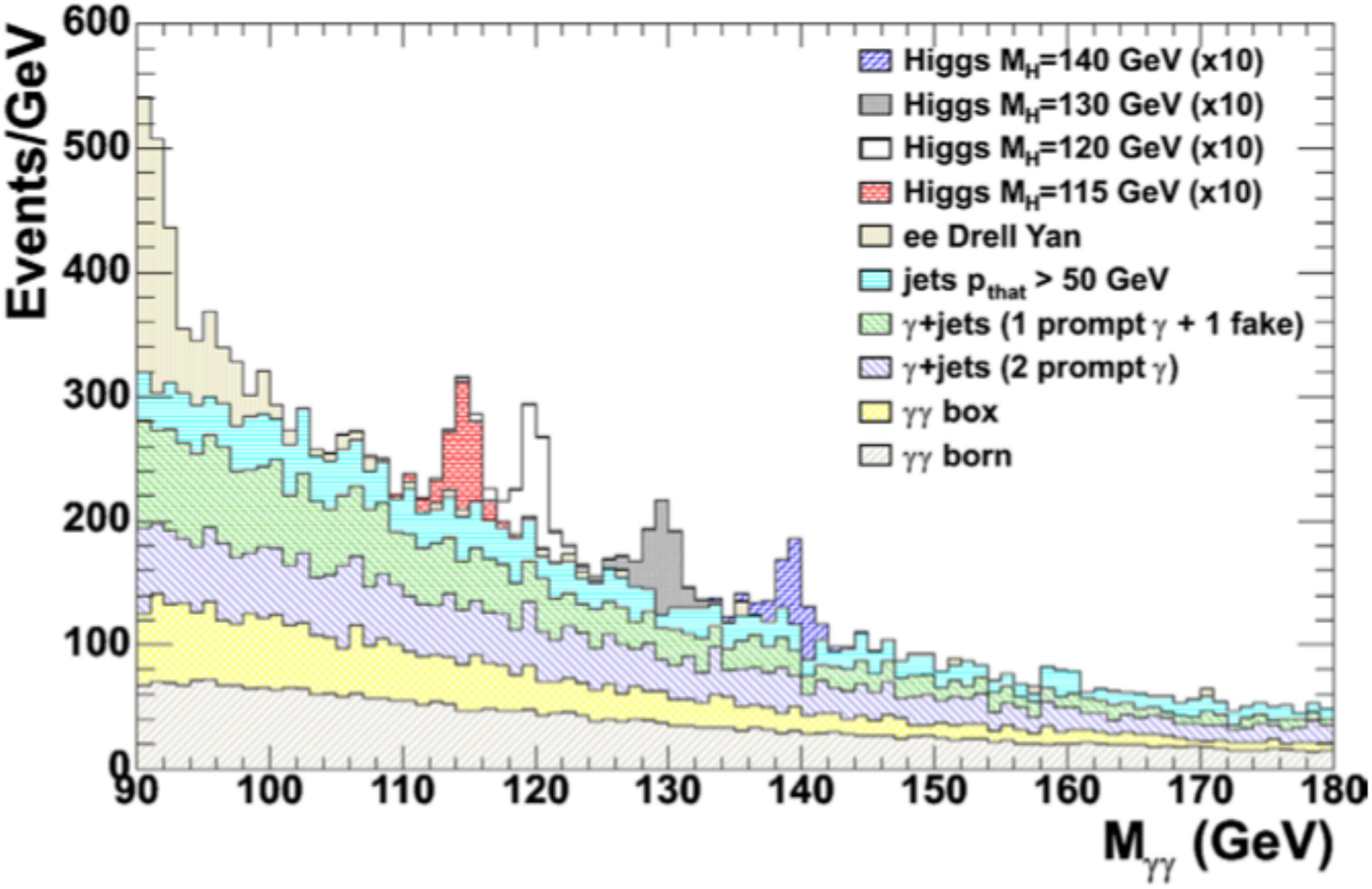




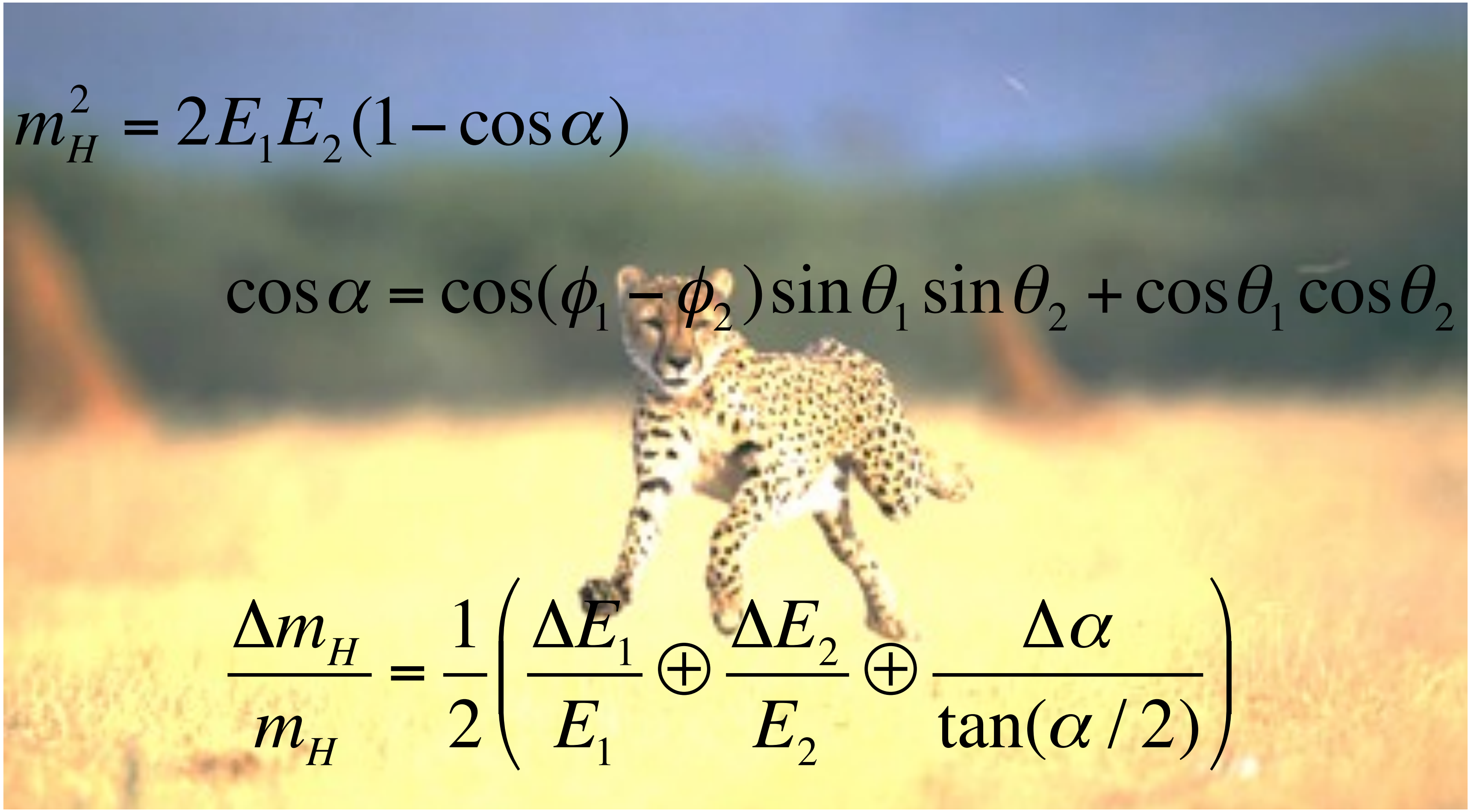
Higgs → γ γ

It’s all about mass resolution

2007 J. Phys. G: Nucl. Part. Phys. 34 995



Anatomy of di-photon mass resolution



$$m_H^2 = 2E_1E_2(1-\cos\alpha)$$

$$\cos\alpha = \cos(\phi_1-\phi_2)\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2$$

$$\frac{\Delta m_H}{m_H} = \frac{1}{2}\left(\frac{\Delta E_1}{E_1} \oplus \frac{\Delta E_2}{E_2} \oplus \frac{\Delta\alpha}{\tan(\alpha/2)}\right)$$

Energy and angular resolution

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

a, **stochastic term** – photoemission/sampling fluctuations
b, "**noise term**" – electronics and pileup energy
c, "**constant term**" – non-uniformities, shower containment etc.

Energy resolution

- Each term should be ~the same at relevant energies ($E=m_H/2$ ~ 60 GeV)
- An homogeneous ECAL has the potential to achieve a stochastic term of ~2%/√E – but quite difficult to control the systematics that build-up the constant term

Angular resolution

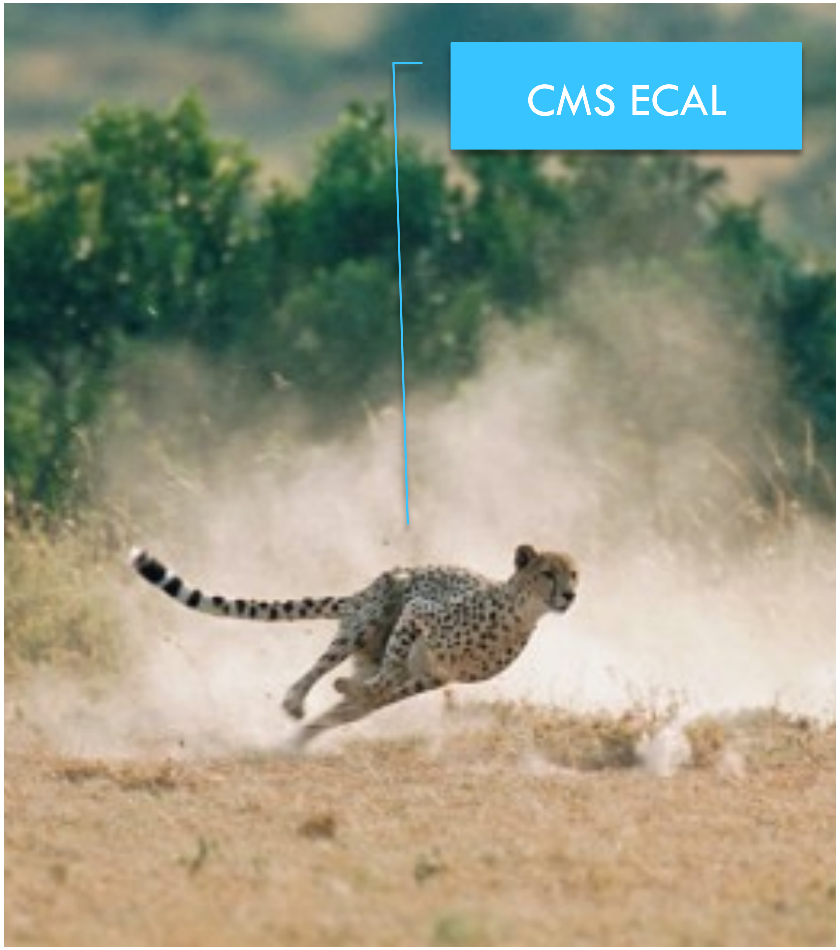
- Primary vertex position along beam axis + photon incidence positions on ECAL → θ
- At high $\mathcal{L}$ need to use hard tracks associated to Higgs production to define the correct vertex (there may be ~20 vertices spread over ~20 cm along the beam axis)

goal → *a* ~ 2.5%
b < 200 MeV
c ~ 0.5%

and an angular resolution

σ_θ ~ 50 mrad/√E

The making of the hunter



CMS ECAL

Early chronology

- 1990: HEP meeting in Aix-la-Chapelle
  - LHC and possible future experiments presented
- 1990: Creation of a CERN R&D programme (DRDC)
- 1991: Creation of the Crystal Clear collaboration (RD18)
  - R&D on scintillating inorganic crystals for the LHC
- 1992: 1st conference on inorganic scintillators organized by Crystal Clear
  - Chamonix Crystal 2000

HEP crystal favorites

	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$
Xo [cm]	2.59 ☹	2.03 ☹	1.86 😐	1.66 😐	1.12 🙂	0.92 🙂
ρ [g/cm^3]	3.67 ☹	4.89 ☹	4.53 ☹	6.16 🙂	7.13 🙂	8.2 🙂
τ [ns]	230 ☹	0.6 🙂 620 ☹	1050 ☹	30 🙂	340 😐	15 🙂
λ [nm]	415 🙂	230 🙂 310 😐	550 🙂	310 😐 340 😐	480 🙂	420 😐
$n@\lambda_{max}$	1.85 😐	1.56 🙂	1.80 😐	1.68 🙂	2.15 ☹	2.3 ☹
LY [%NaI]	100 🙂	5 ☹ 16 ☹	85 🙂	5 😐	10 🙂	0.5 ☹

PbWO$_4$

- CMS chose to construct an homogeneous ECAL based on lead-tungstate (PbWO$_4$) crystals

Reason for PbWO$_4$ crystals

- potential to achieve 2% stochastic term
- very compact - 26X$_0$ in <25cm (X$_0$ = 0.89cm) – able to place entire calorimeter inside 4T solenoid of CMS
- small Molière radius (~2.2cm) – excellent granularity possible – for isolation efficiency, pileup rejection and spatial precision
- fast light emission (average ~25ns)
- radiation hard

Difficulties

- relatively low light yield – need photodetectors with gain
- uniformity of light production and collection important
- light yield is temperature dependant – need to stabilize xtal temperature to 0.1°C (see later)
- some low-level radiation damage – need to monitor the xtal transparency using lasers (see later)
- test and assembly of ~80000 crystals

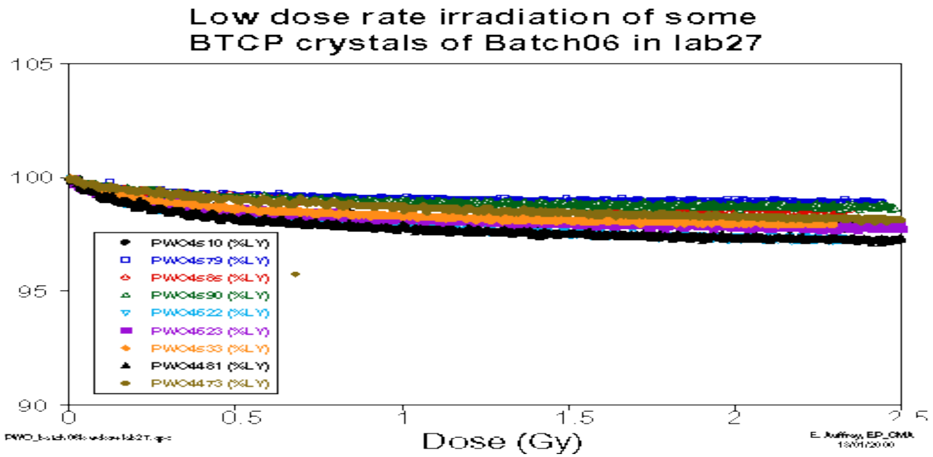
15+ years of work with crystals

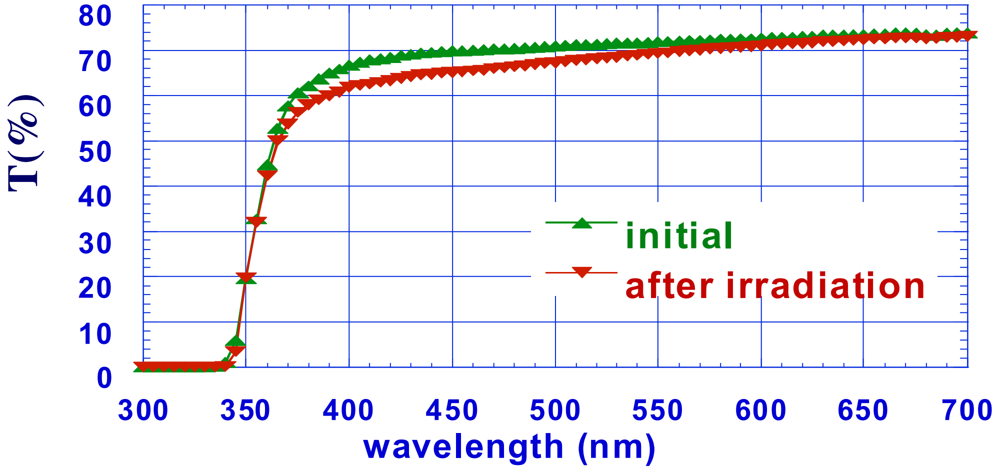
- 1990-1993: Several candidate technologies on the table
  - Liquid Xe, CeF, Shashlik
- 1993/4: PWO chosen for CMS ECAL
- 1994-1998: intense R&D on PWO
- 1998-2000: pre-production of 6000 crystals in Russia
  - Increase production rate
  - Improve homogeneity of production quality
- 2001: start of production in Russia
- 2005: start of production in China
- 2007: last barrel crystal produced
- 2008: last endcap crystal produced

Crystal Performance

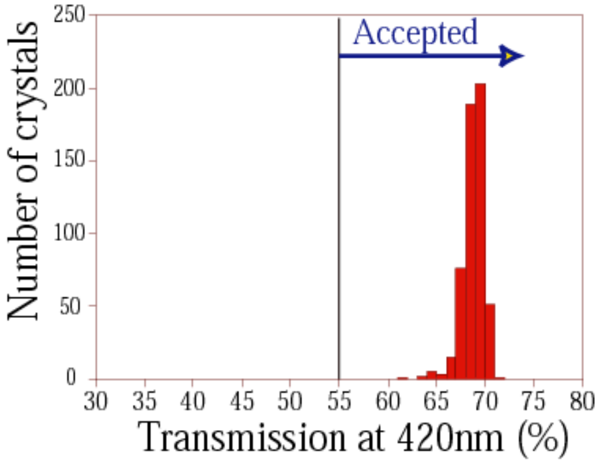
Radiation Hardness

After an initial small drop in light yield the crystals are very stable

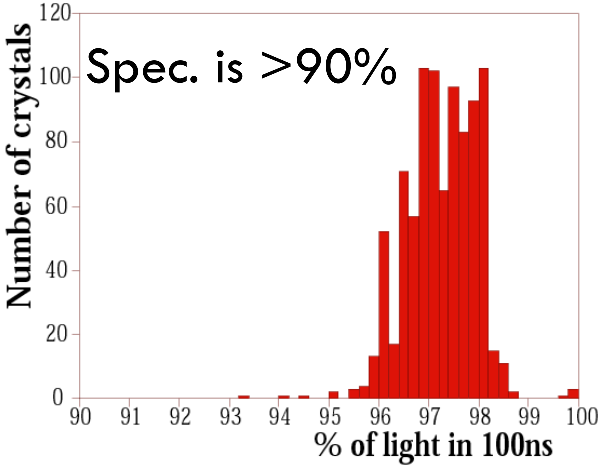




Optical Transparency



Light emission time



Spec. is >90%

The end of the cold war

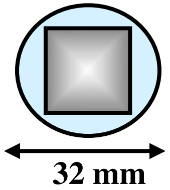
- The G8 founded the ISTC to retrofit/adapt the USSR military industry to peaceful results.
- In the mid-90s a study was commissioned to evaluate the ability of the USSR to produce:
  - Crystals, extensively used in sighting lasers.
  - Photodetectors, extensively used in night vision equipment.

- Funding to convert crystal factory secured
  - Factory in Bogoroditsk, close to Kalachnikov factory.

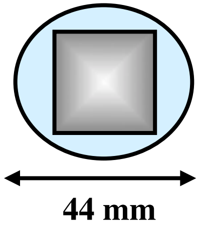
Crystal Production – 1996 to 2008

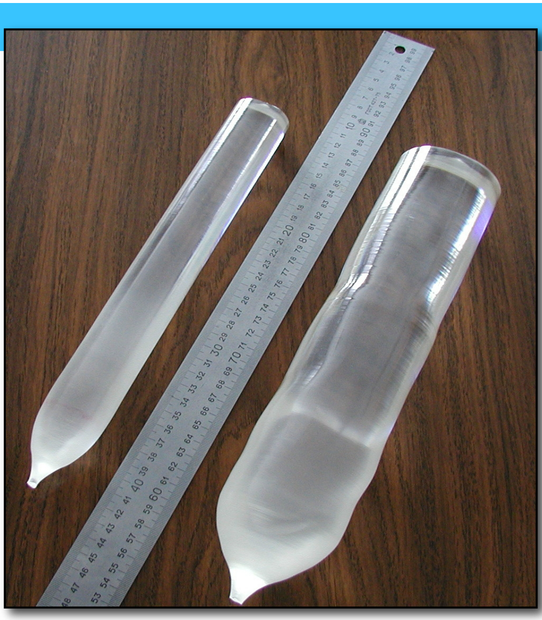
in Bogoroditsk (Russia)

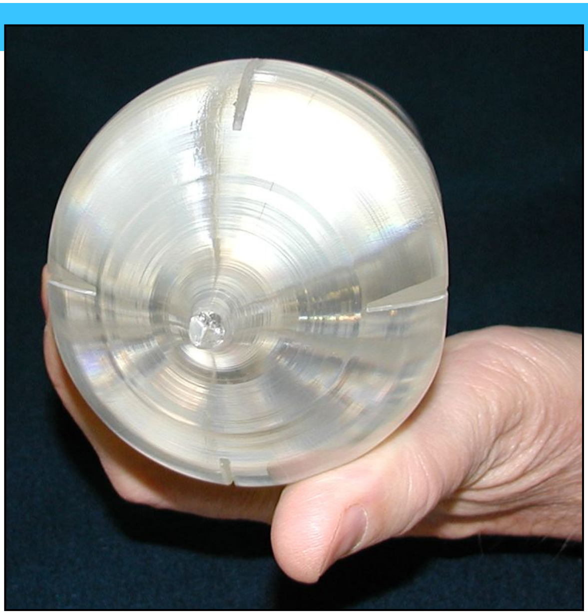
Barrel
1996



Endcap
1999

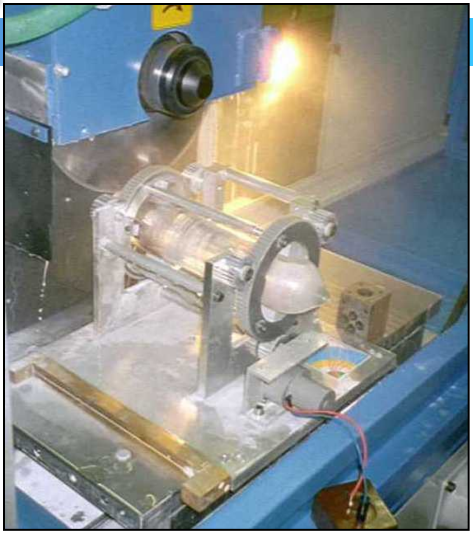


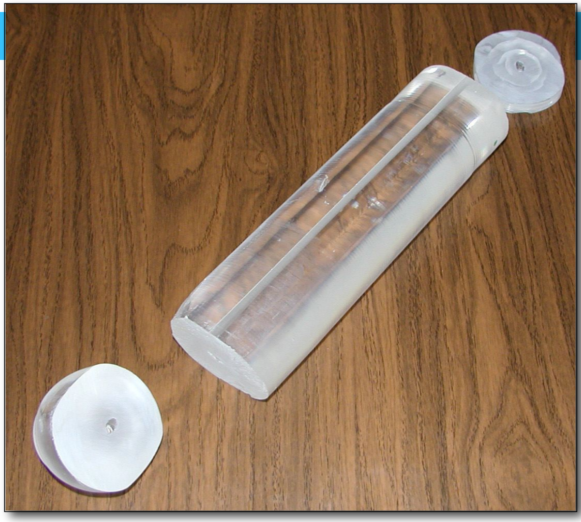


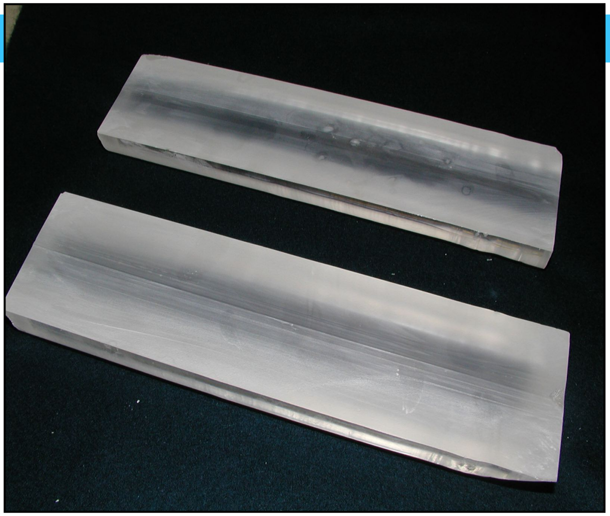


Eventually, increased production rate to

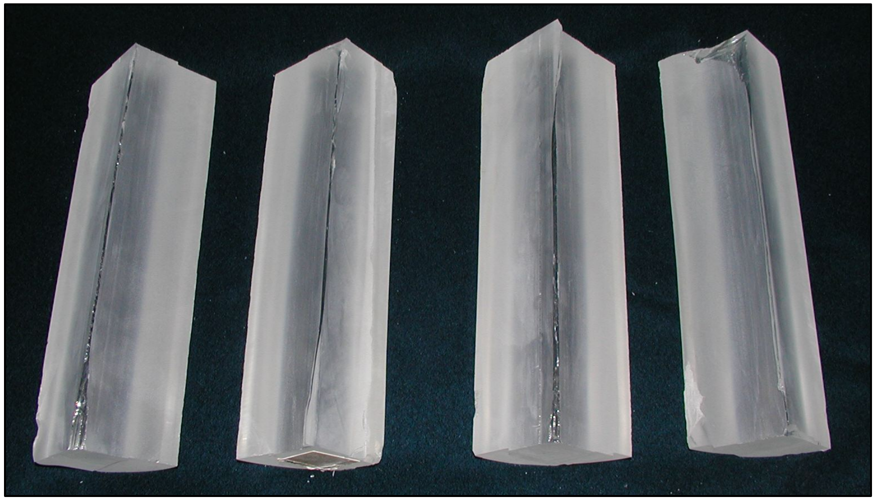
Crystal Cutting

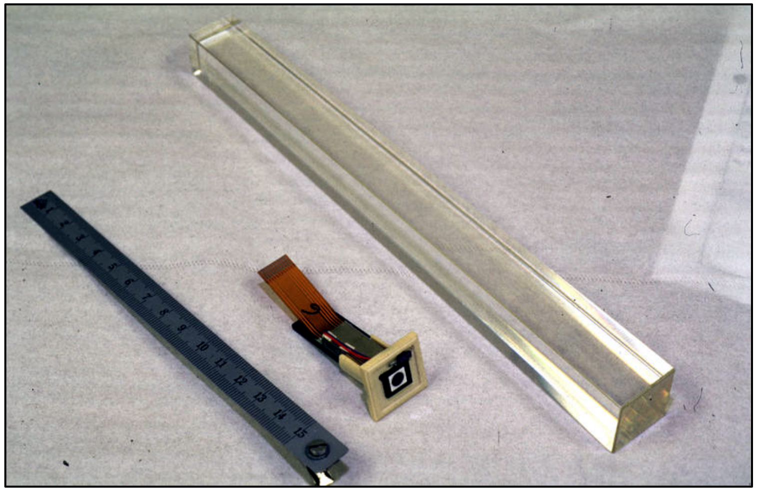




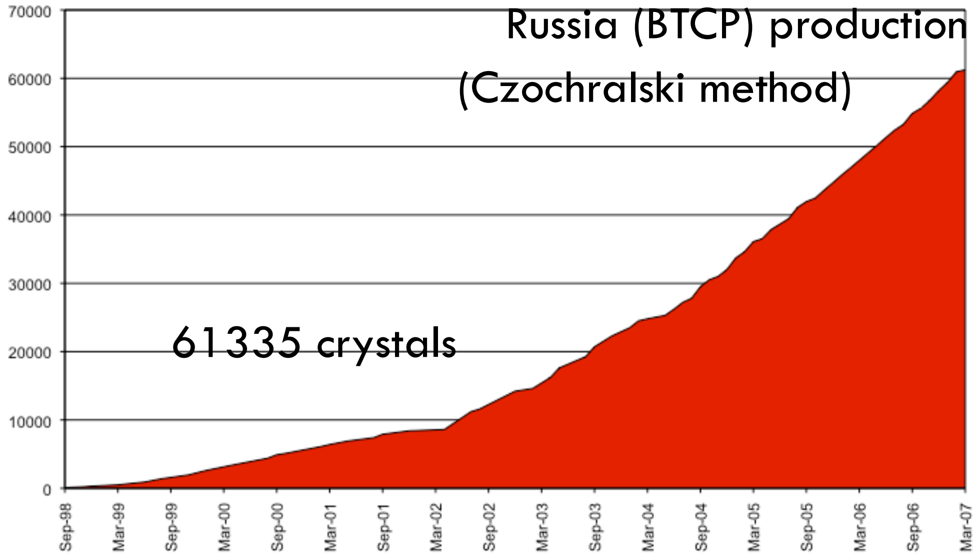


Not a trivial procedure – crystals are not simply cut along their axes as they have to be tapered

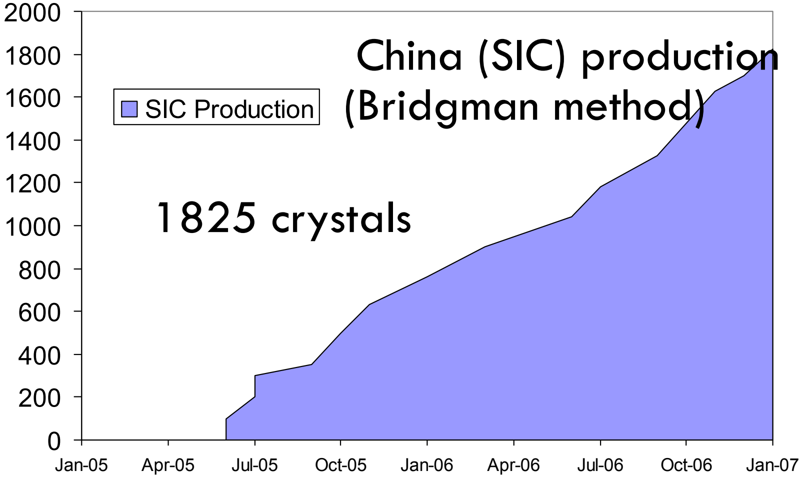




Barrel crystal production

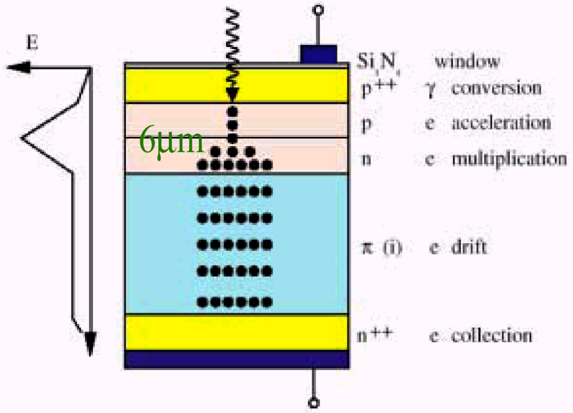

Russia (BTCP) production
(Czochralski method)

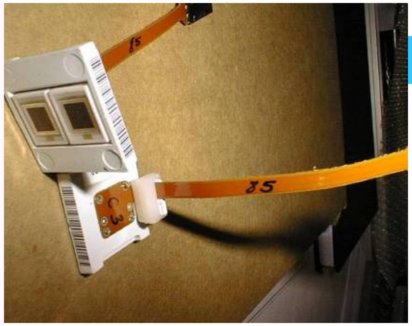
61335 crystals


China (SIC) production
(Bridgman method)

1825 crystals

CMS ECAL photodetectors





Barrel: Avalanche Photodiodes (APD, Hamamatsu)

- Characteristics optimized with an extensive R&D Program
- insensitive to B-field as PIN diodes
- Internal gain (M=50 used, M=200 for cosmics calibration)
- good match to Lead Tungstate scintillation spectrum (Q.E. ~ 70%)
- dM/dV = 3%/V and dM/dT = -2.3%/°C :

→ T and V stabilization needed

Endcaps: Vacuum phototriodes (VPT by Research Institute Electron in St. Petersburg)

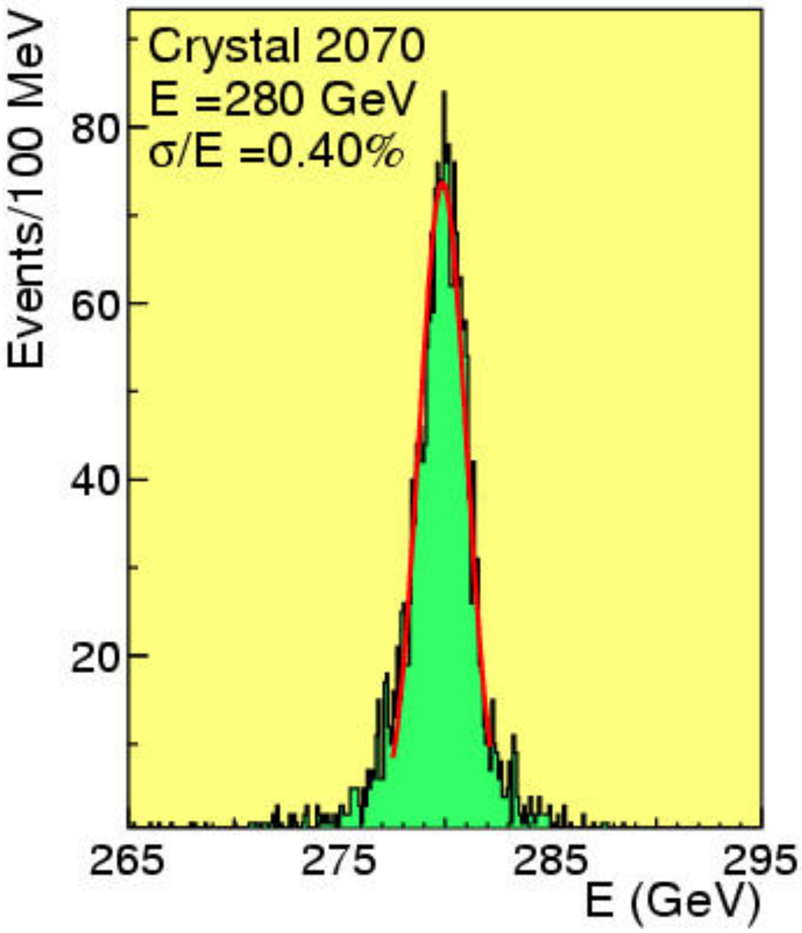
- A VPT is a single-gain-stage photomultiplier tube
- Diameter 25.4 mm
- Quantum eff. ~22 % at 420nm
- Gain at 0 magnetic field ~10
- Rad. tolerance <10% loss after 20 kGy
- Magn. field resp. loss at 4T < 15% w.r.t. 0T

1999: prototype energy resolution

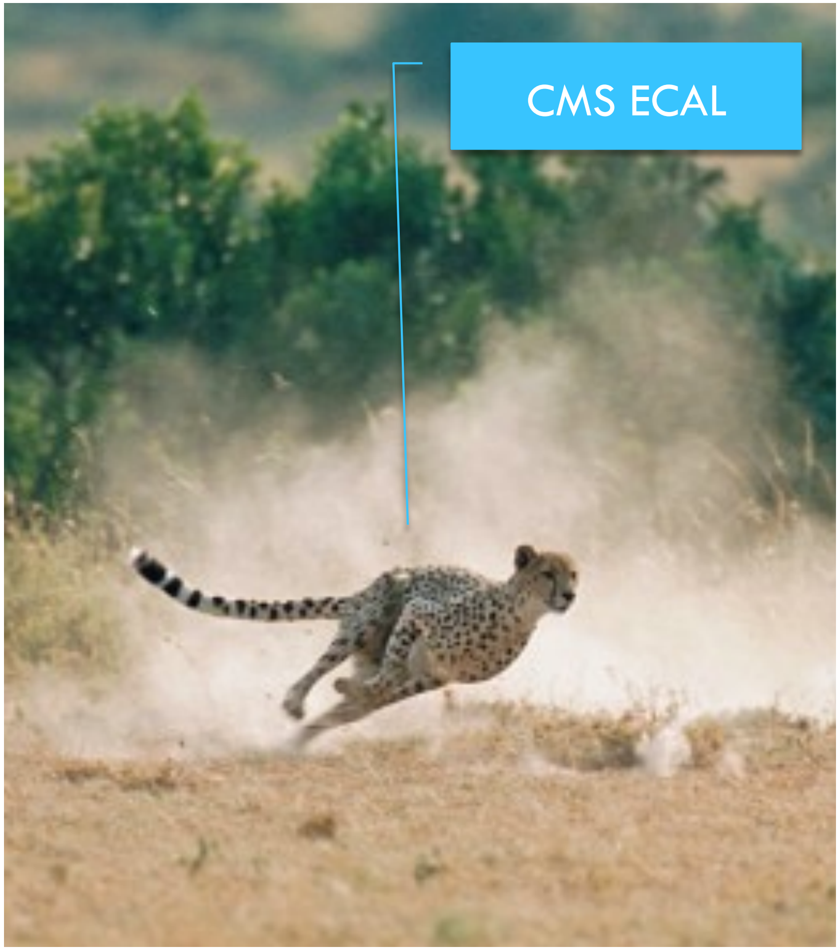
1999 prototype:
30 preproduction
crystals and APDs

fit as a function of E:

$$\frac{\sigma}{\mathrm{E}} = \frac{2.74\%}{\sqrt{E}} \oplus 0.40\% \oplus \frac{142MeV}{E}$$

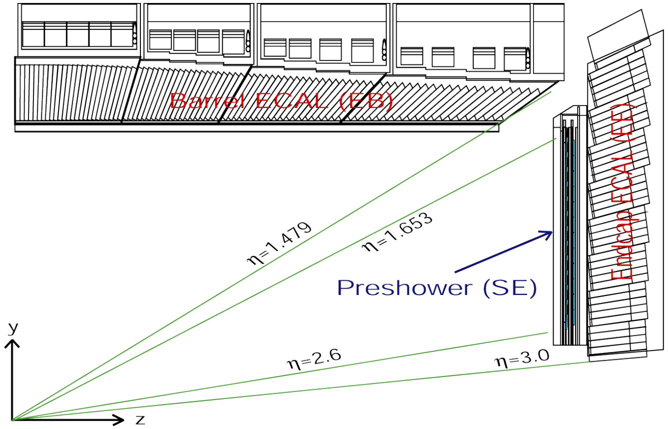


The making of the hunter



CMS ECAL

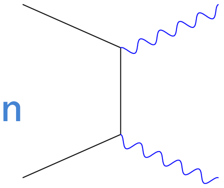
- 70000 $PbWO_4$ crystals
- Si-preshower in the endcaps



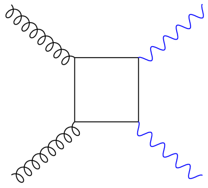
The endcap reducible difficulty

Irreducible

Quark annihilation



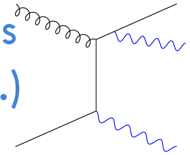
Gluon fusion



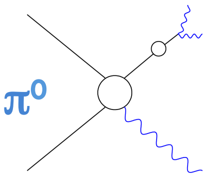
Isolation

Reducible

Higher orders (mainly brem.)



Jets – γ faked by π^0



Isolation

π^0 rejection

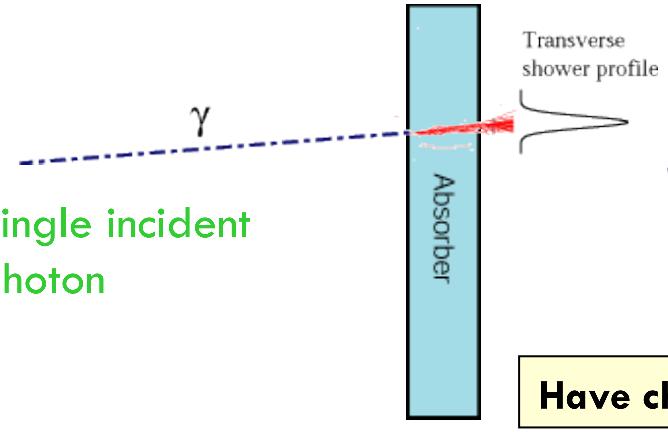
Both isolation and π^0 rejection require high granularity detectors

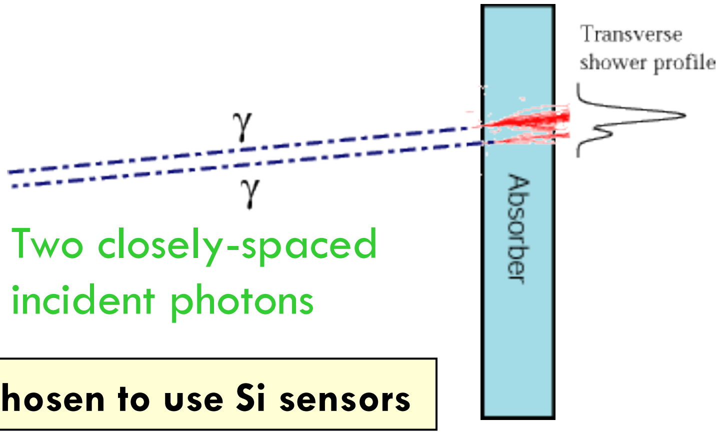
A π^0 with p_T~60 GeV will produce 2 photons separated by a small distance in CMS

~ 1cm in the barrel after travelling ~1-3m

~ few mm in the endcaps after travelling > 3m

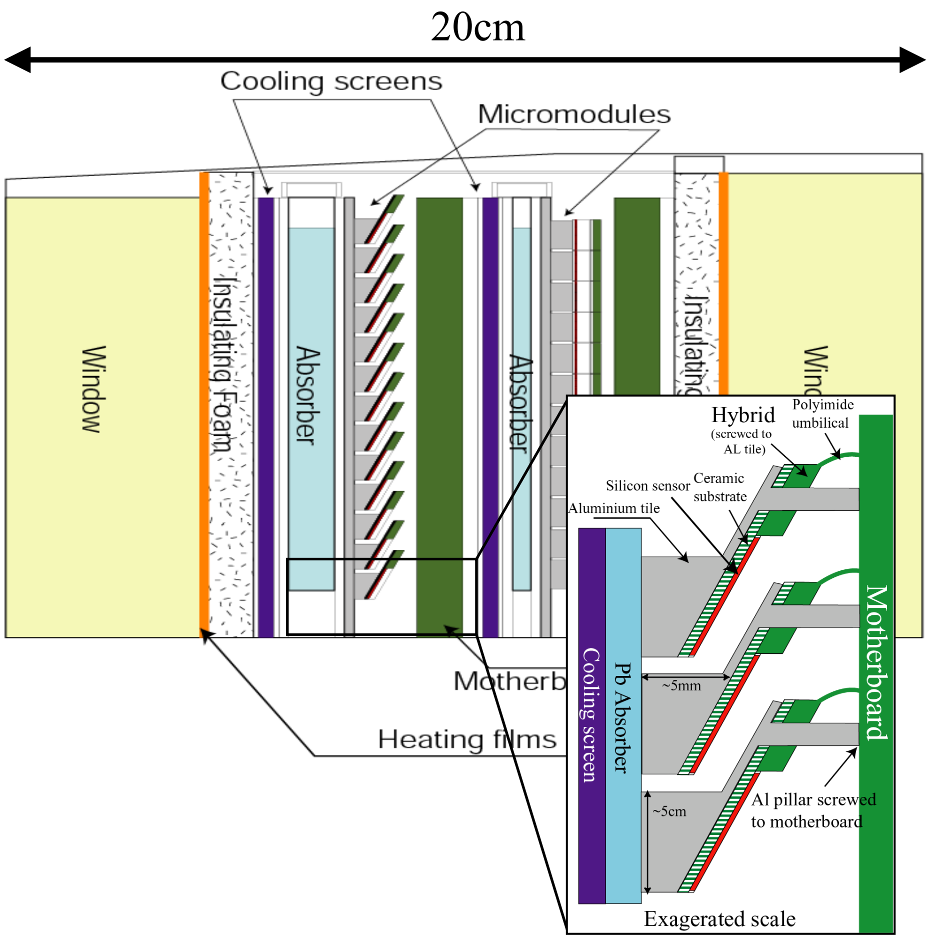
Idea of Preshower:

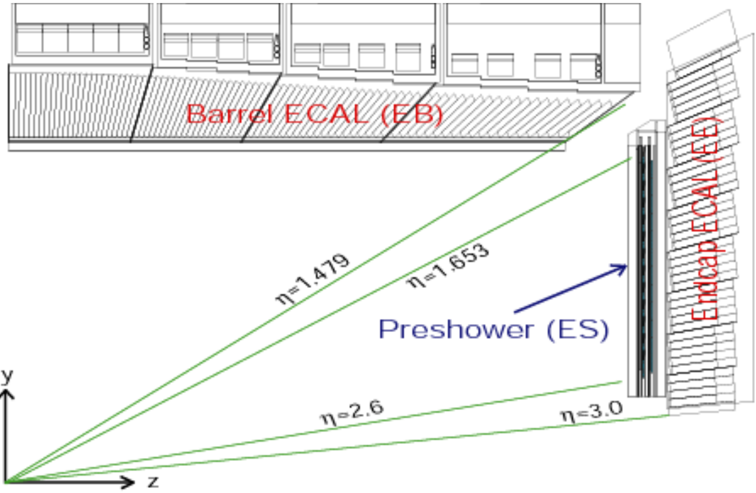


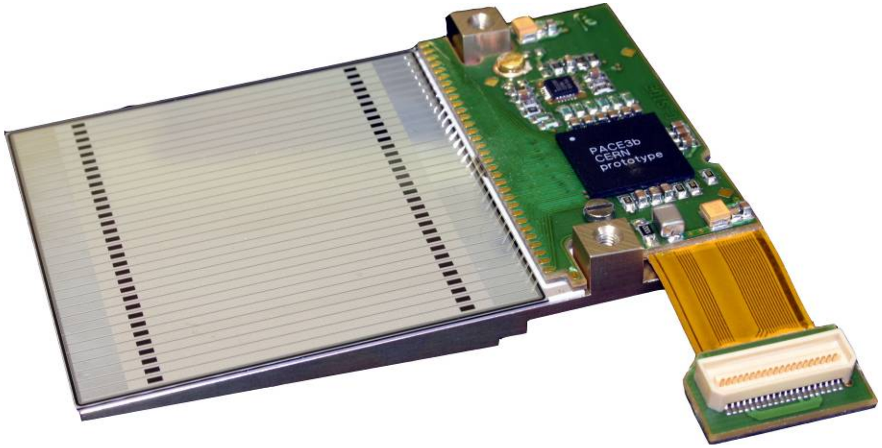


Have chosen to use Si sensors

CMS ECAL Preshower



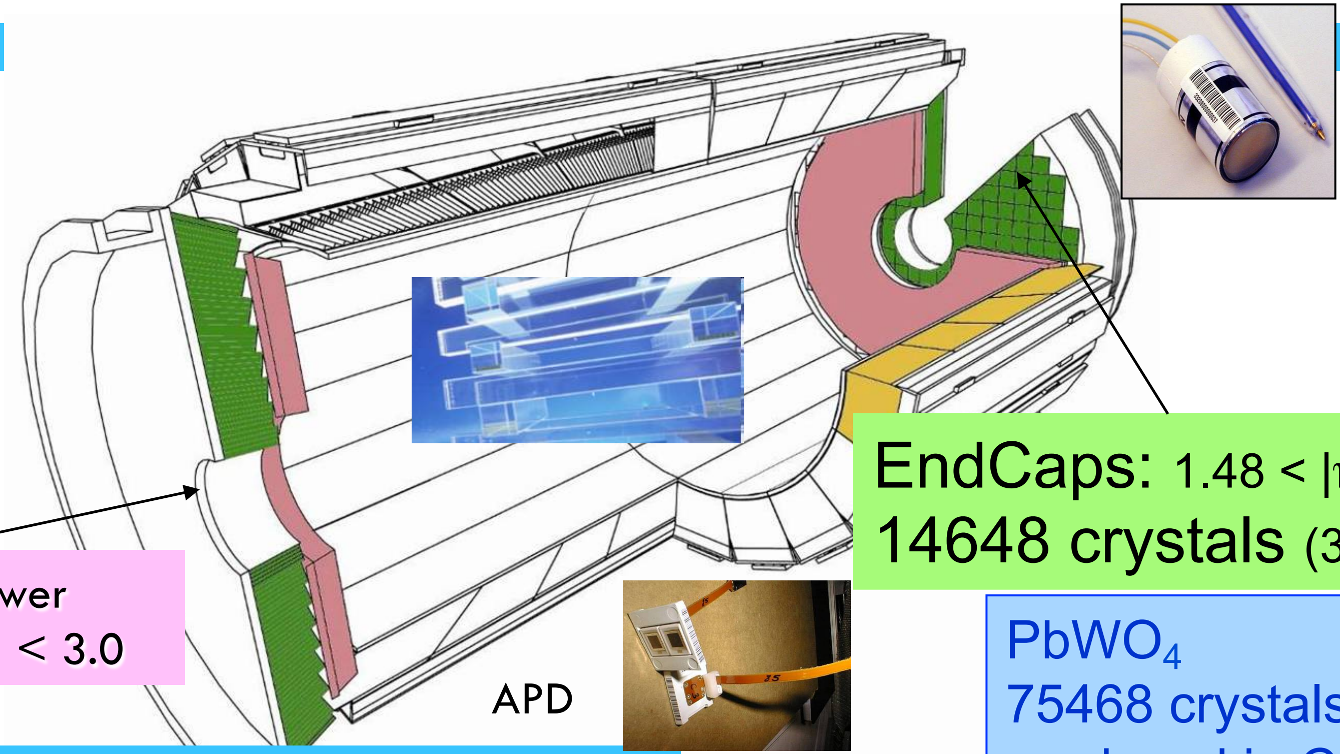




~4300 micromodules

- 2mm-pitch Si sensors

CMS electromagnetic calorimeter



EndCaps: $1.48 < |\eta| < 3.0$
14648 crystals ($3 \times 3 \times 22\,\text{cm}^3$)

Pb/Si preshower
$1.65 < |\eta| < 3.0$

Barrel: $|\eta| < 1.48$
61200 crystals ($2 \times 2 \times 23\,\text{cm}^3$)

$PbWO_4$
75468 crystals
produced in China (SIC) and Russia
X_0 0.89 cm
LY~100 pe/MeV (PMT)

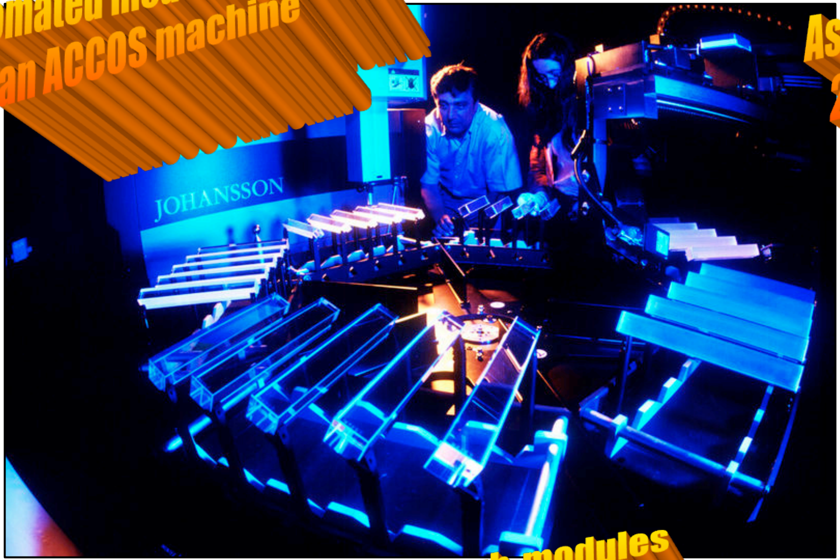
DESIGN ENERGY RESOLUTION (BARREL)

$$\frac{\sigma(E)}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{155 MeV}{E}$$

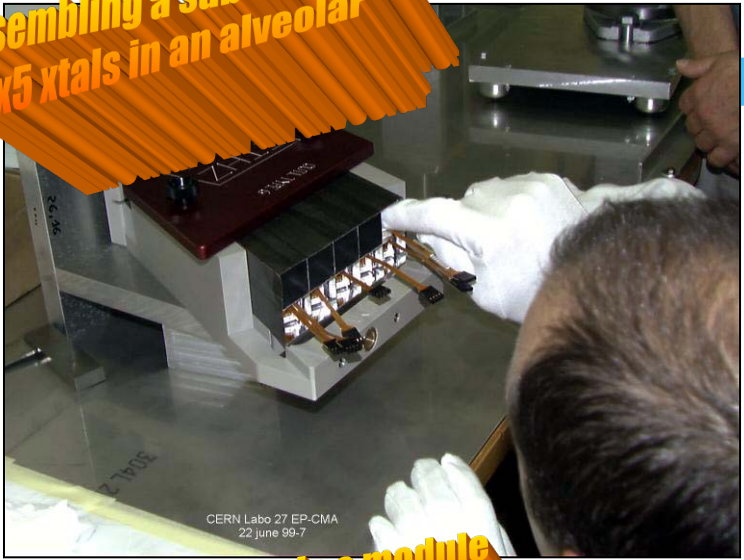
Granularity Barrel
$\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$

Barrel Assembly (1) at CERN and ROME

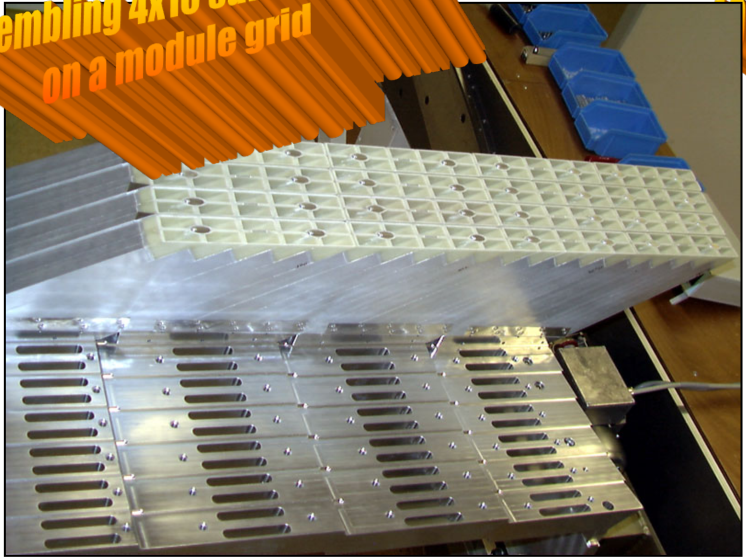
Automated measurements:
an ACCOS machine



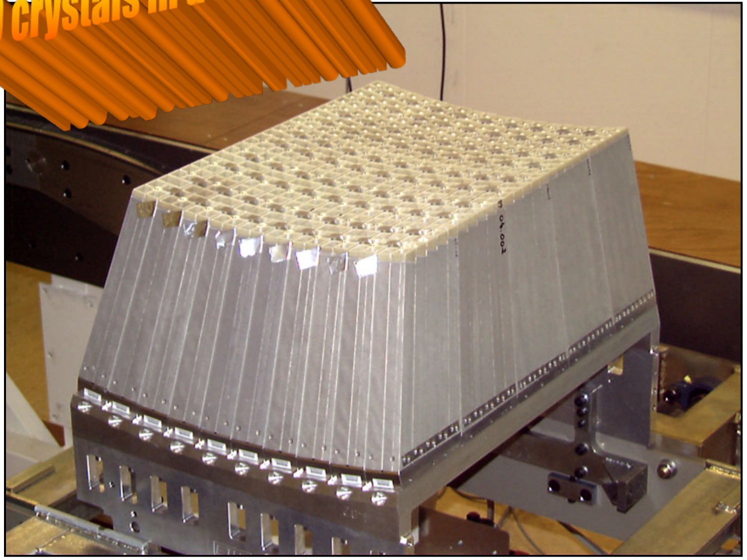
Assembling a sub-module:
2x5 xtals in an alveolar



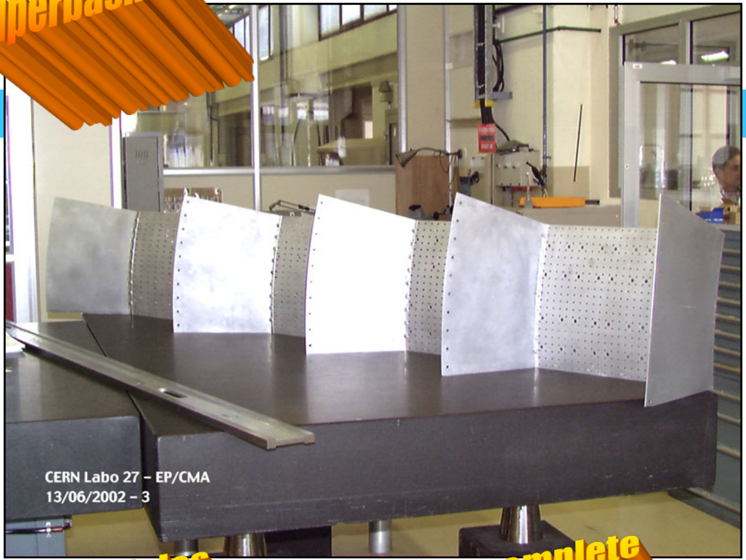
Assembling 4x10 sub-modules
on a module grid



0 crystals in a module

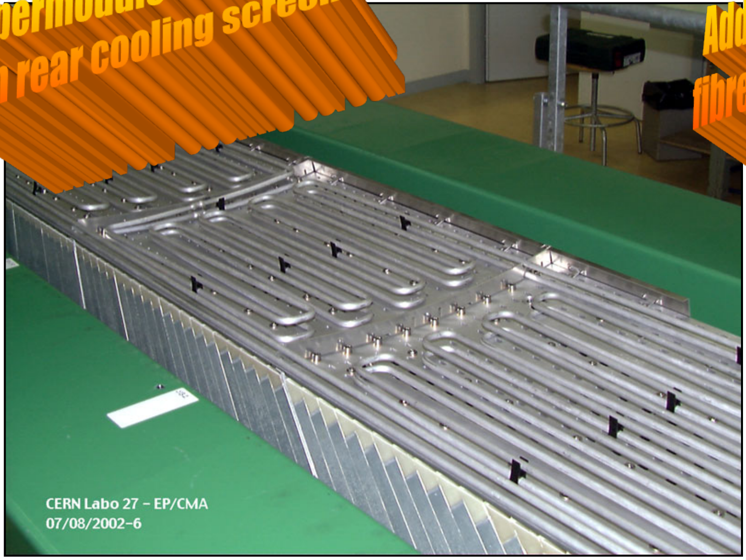


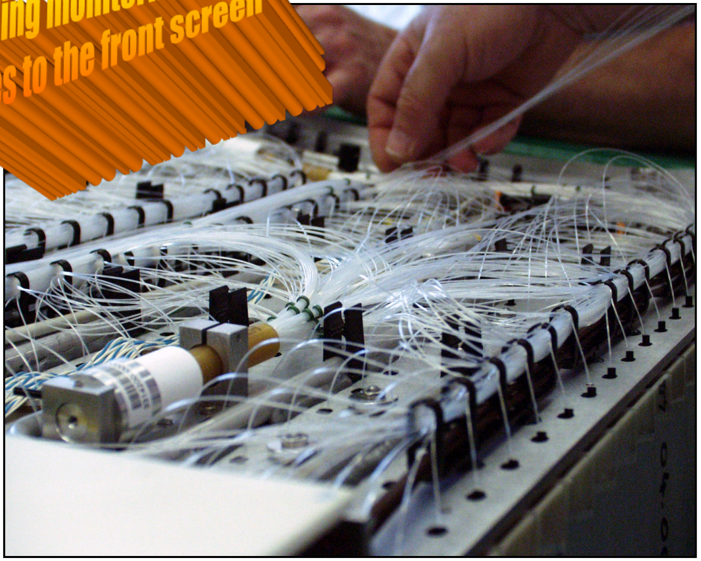
Supermodule Assembly (1) at CERN


Superbasket


Front cooling screen

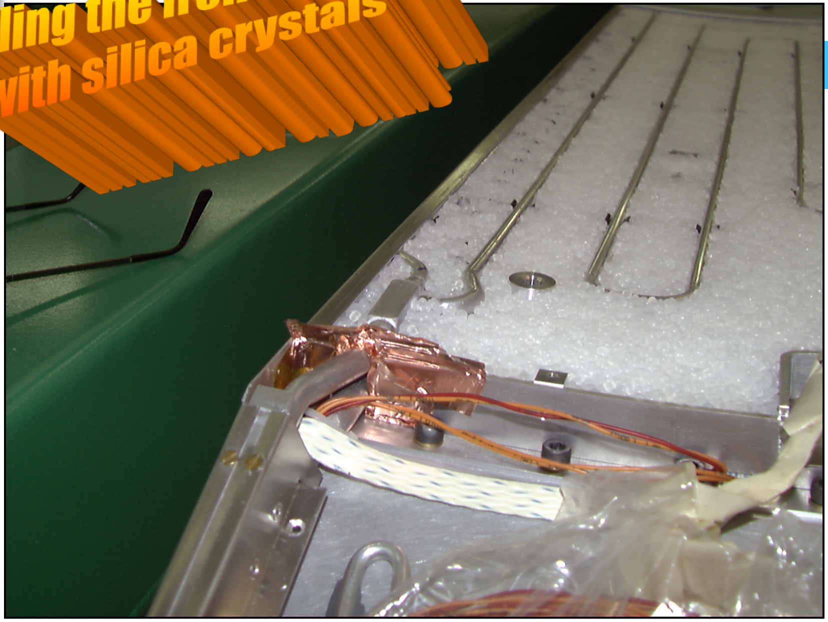

ssembling 4 modules into a supermodule


Supermodule complete with rear cooling screen


Adding monitoring/DCS fibres to the front screen

Supermodule Assembly (2) at CERN

Filling the front screen with silica crystals



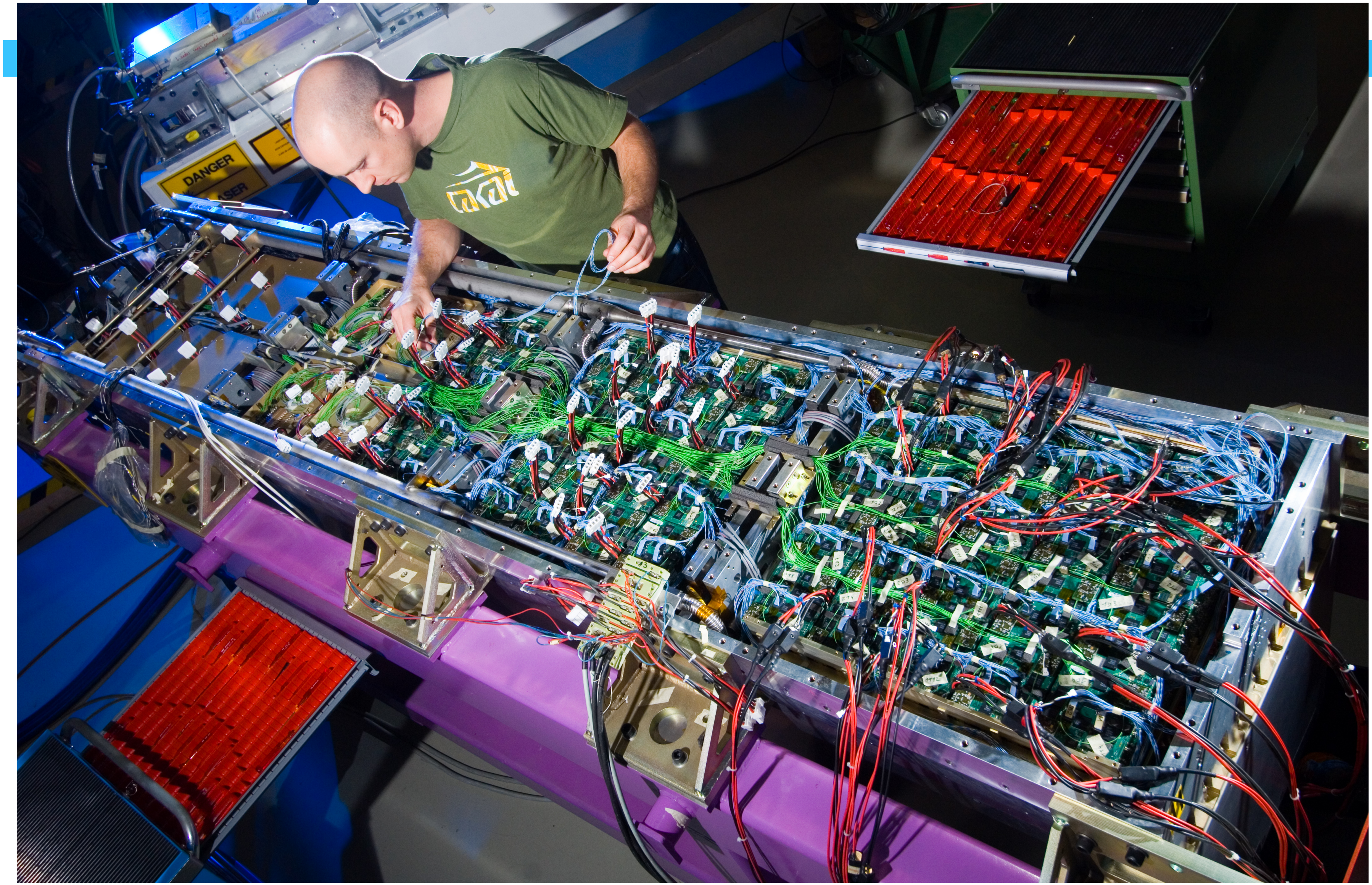
Adding the backplate

A finished supermodule being moved to storage

Then the electronics need to be added!

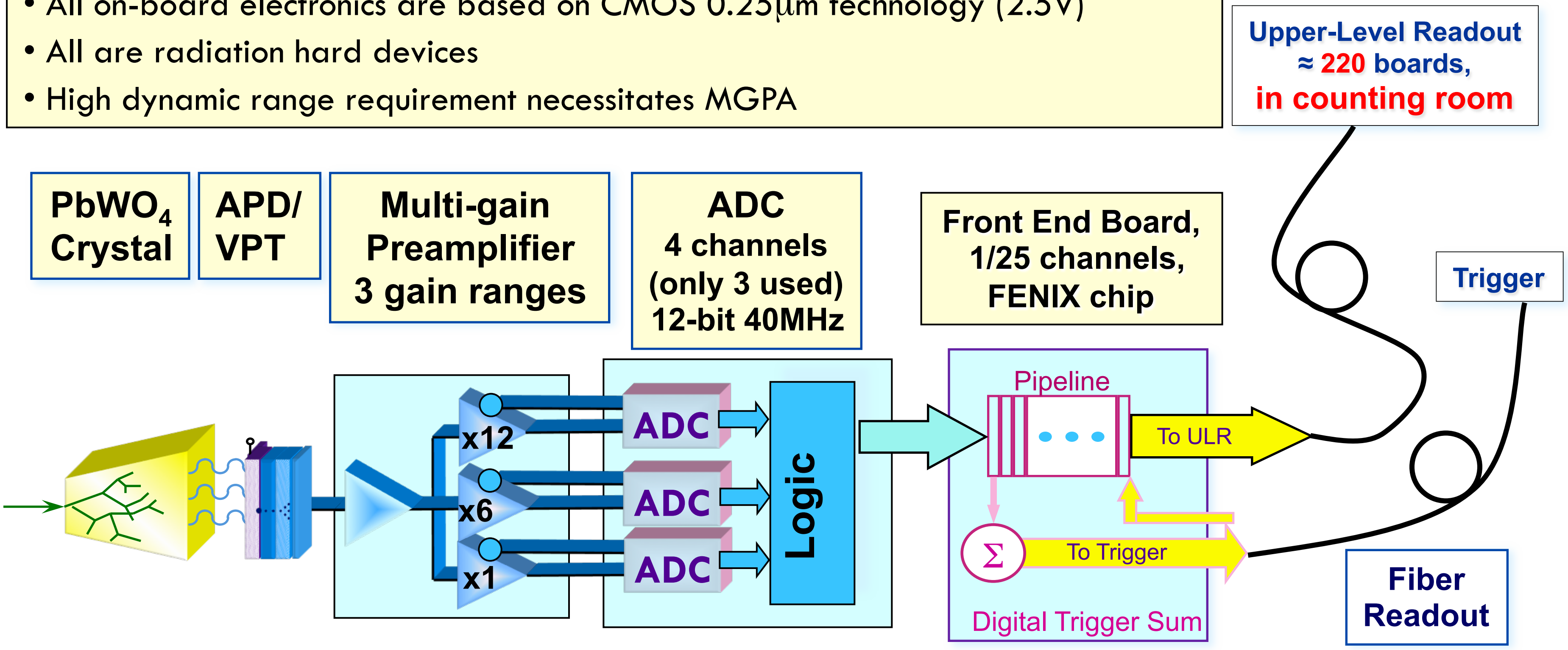
36+1 supermodules assembled at CERN between 2003 and 2007

Assembly of front-end electronics



ECAL front-end electronics

- All on-board electronics are based on CMOS 0.25μm technology (2.5V)
- All are radiation hard devices
- High dynamic range requirement necessitates MGPA



three optical links per Trigger Tower

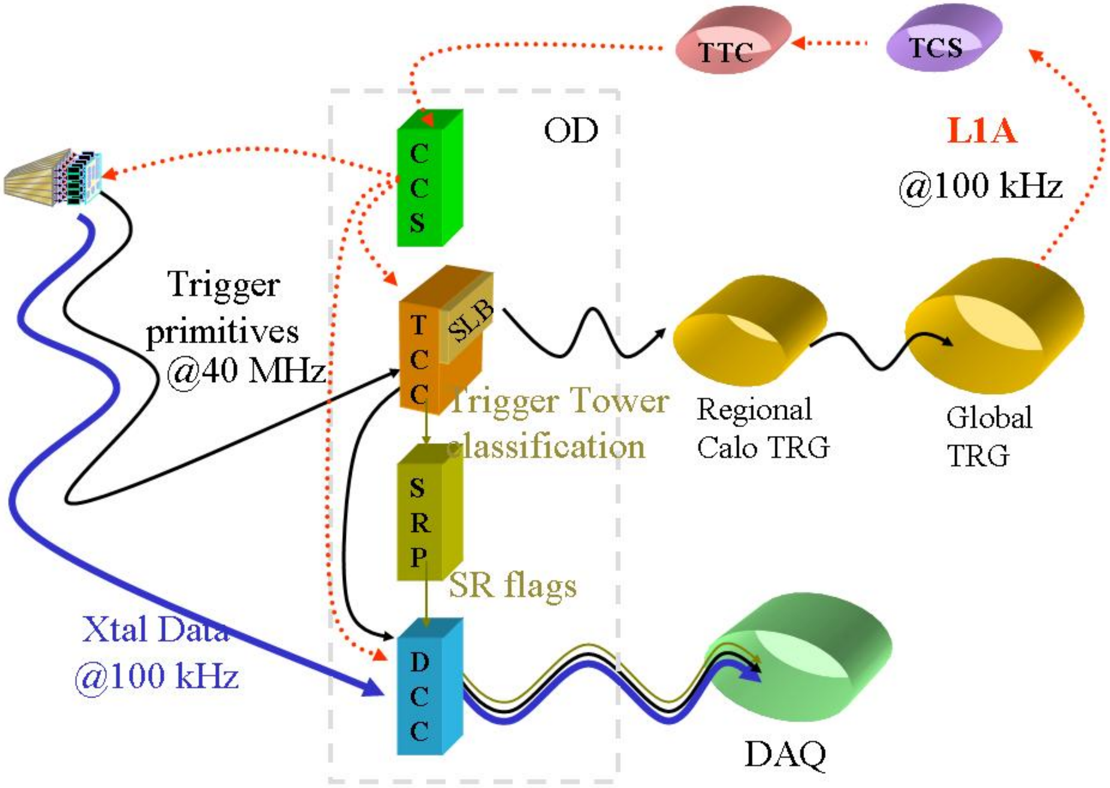
25 xtals

800 Mbit/s

Light-to-light readout system

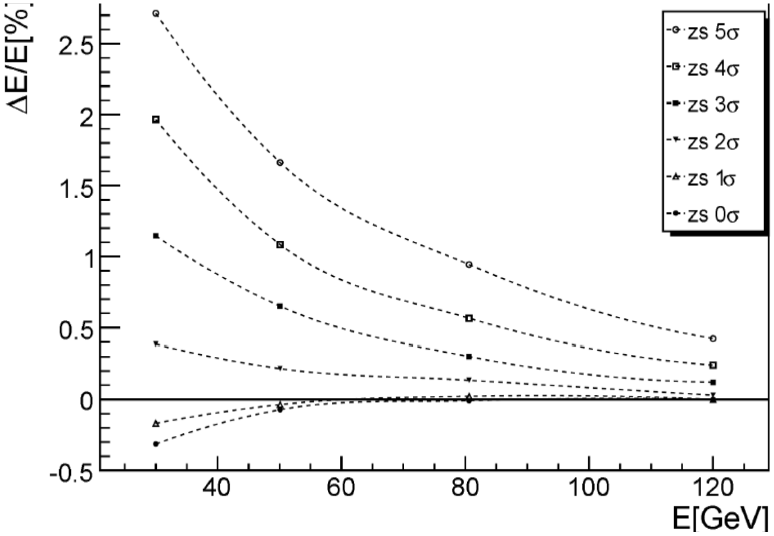
ECAL off-detector electronics

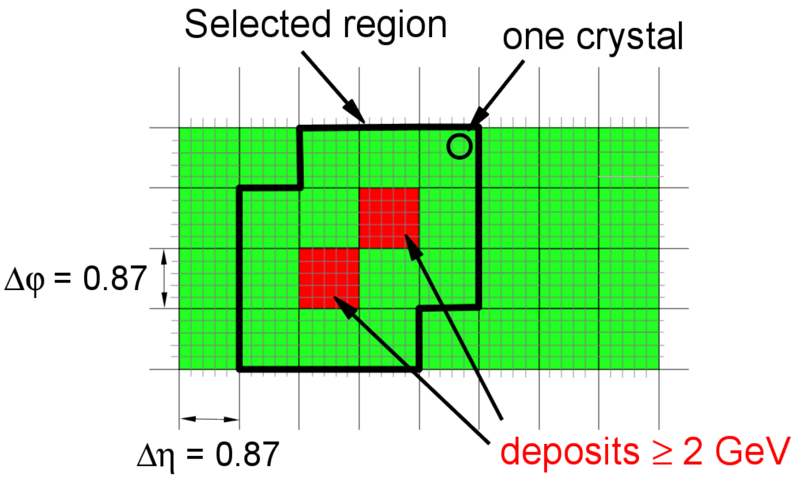
- Part of the CMS Level 1 trigger
- Readout of 10 time samples at 100 kHz
- Data reduction of factor 20 needed
  - Internal Selective Readout Processor to preserve energy resolution



Selective readout

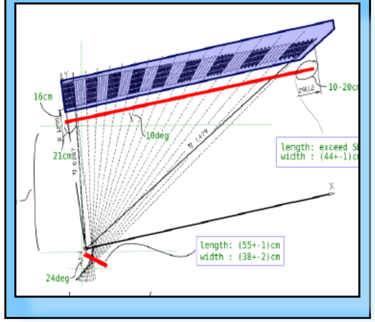
- Factor 20 reduction in data size needed to fit within CMS event budget
- Simple zero suppression would spoil energy resolution
- Perform selective readout of zones neighboring large deposits
  - Selective = ignore, 2 ZS thresholds or full readout



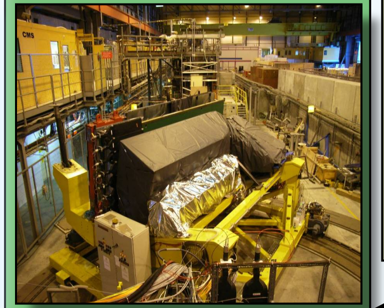


Highlights from the CMS ECAL Timeline

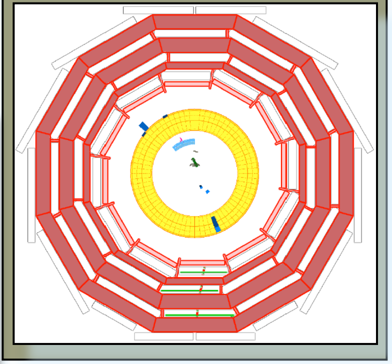
2006-2007
Commissioning & calibration of each SM with cosmics on surface



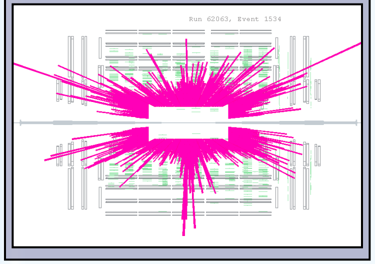
2006
H4 Test Beam: 9 SM calibrated; H2 Combined Test Beam: ECAL+HCAL



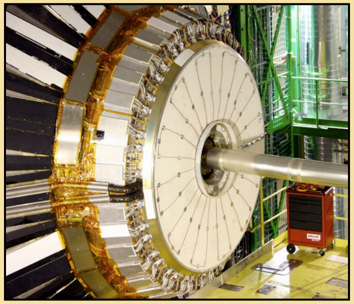
2006
2 SM tested with B-field on surface (MTCC)



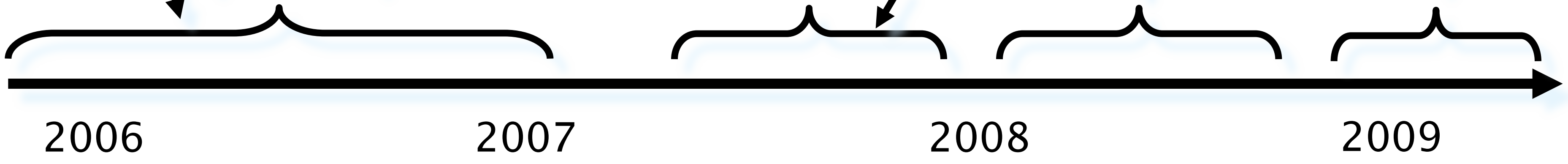
2008
Endcap Installation. Commissioning with cosmics and first beam in-situ



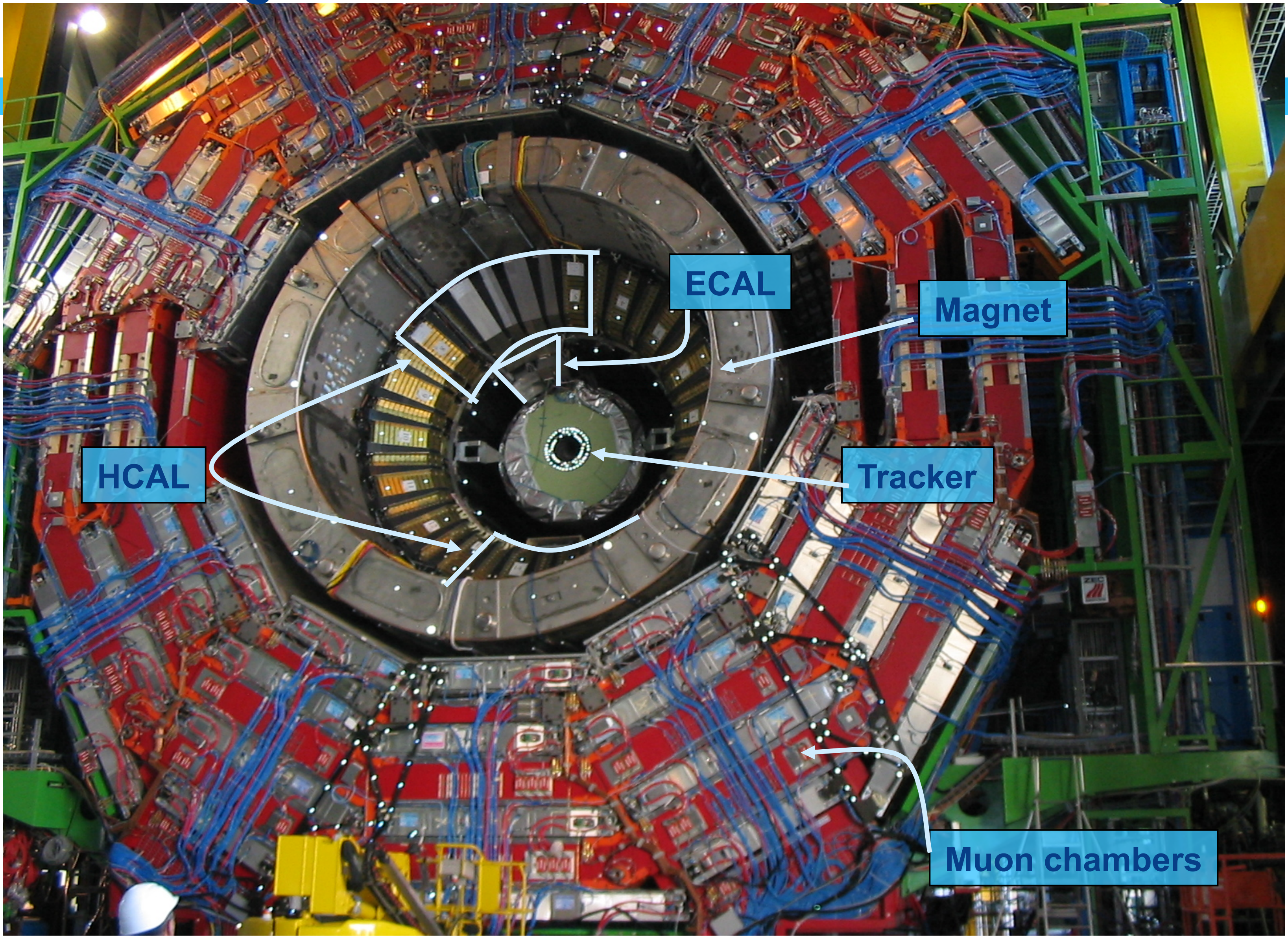
2009
Installation of preshower and commissioning of Endcap trigger



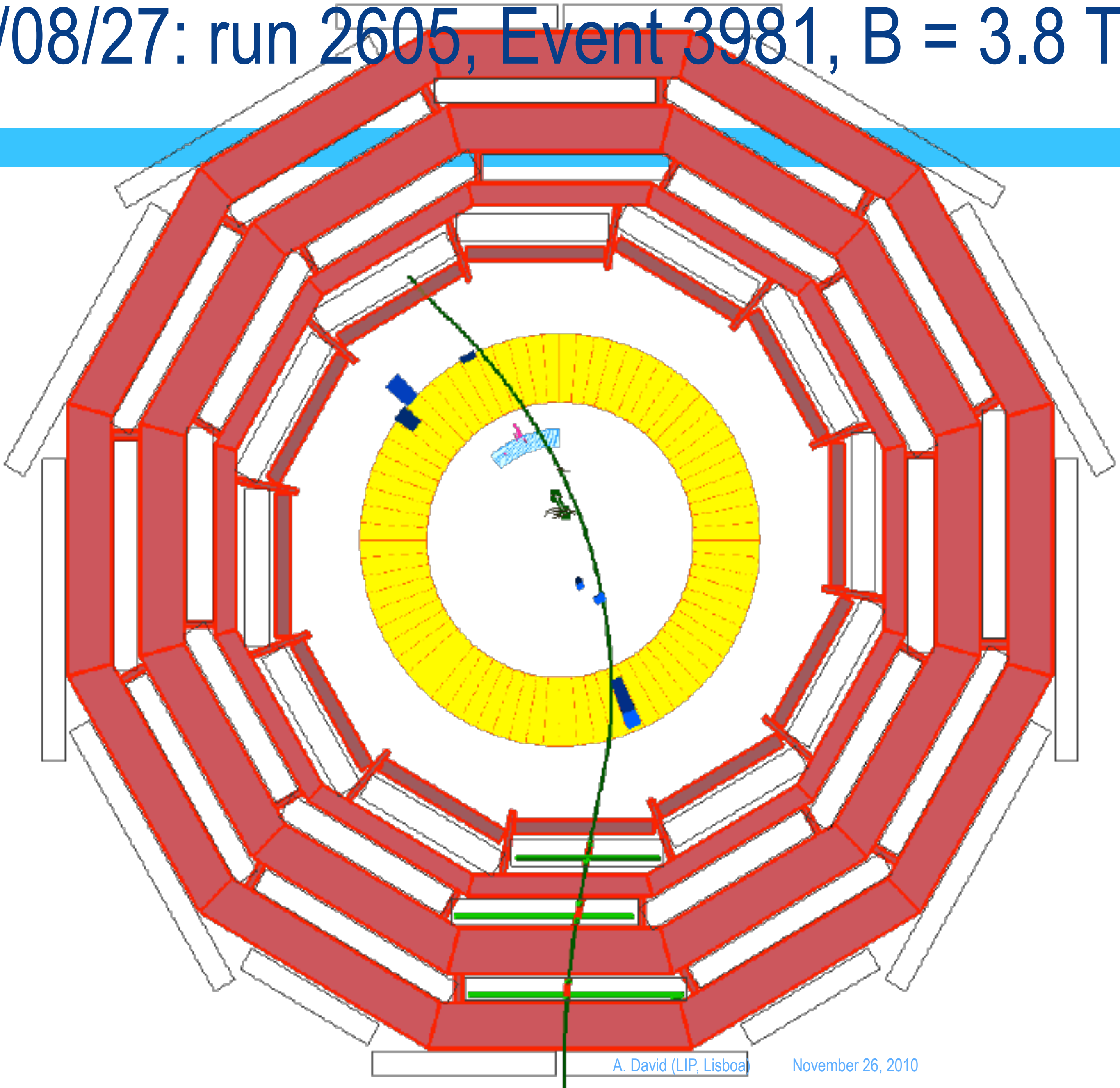
2007
H4 EE Test Beam; Individual signoff of each SM during installation



2006: Magnet Test and Cosmic Challenge



2006/08/27: run 2605, Event 3981, B = 3.8 T

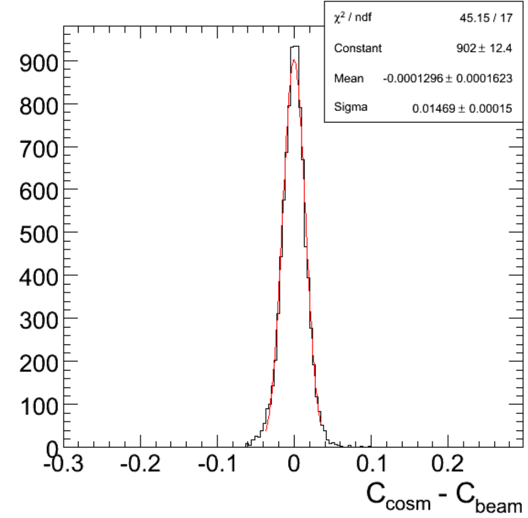


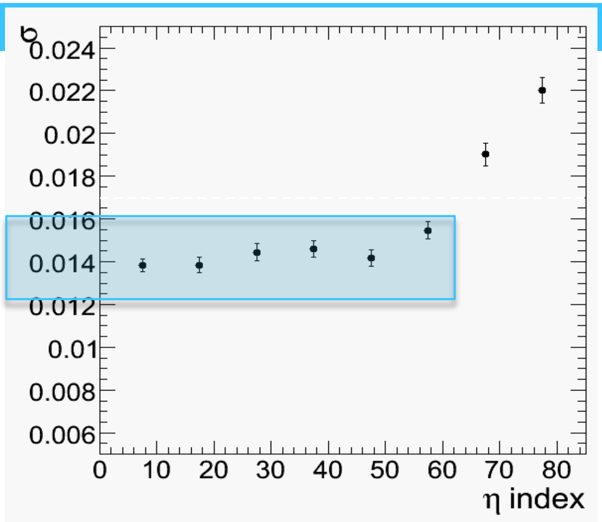
Summer 2006/7: ECAL barrel calibration

- First operation of the trigger electronics of the ECAL
- Large fraction of ECAL barrel intercalibrated with **electron beam**
- All ECAL barrel collected **cosmic muon data**
- **{E,H}CAL combined performance** test beams

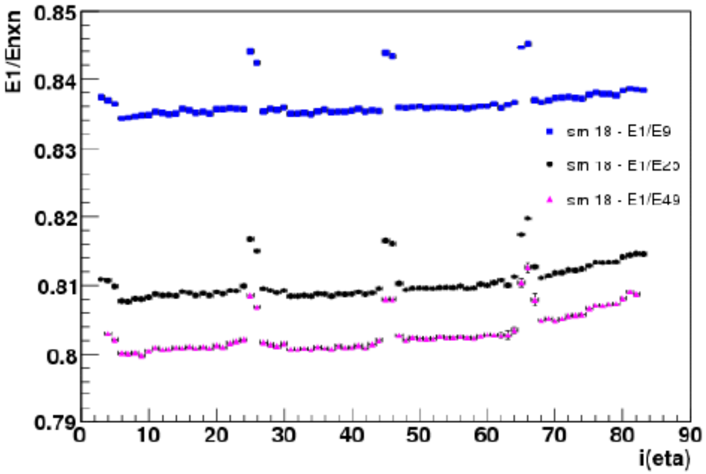
Barrel ECAL: Calibration & Test Beam

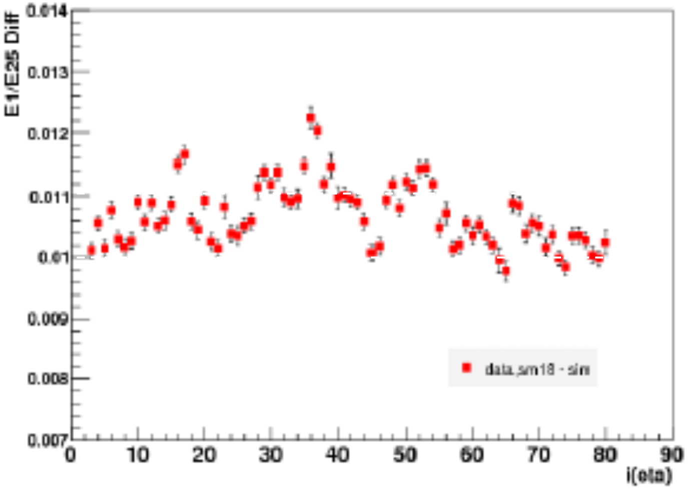
All SMs recorded cosmics for 1 week: crystal inter-calibration of ~ 1.5 %.



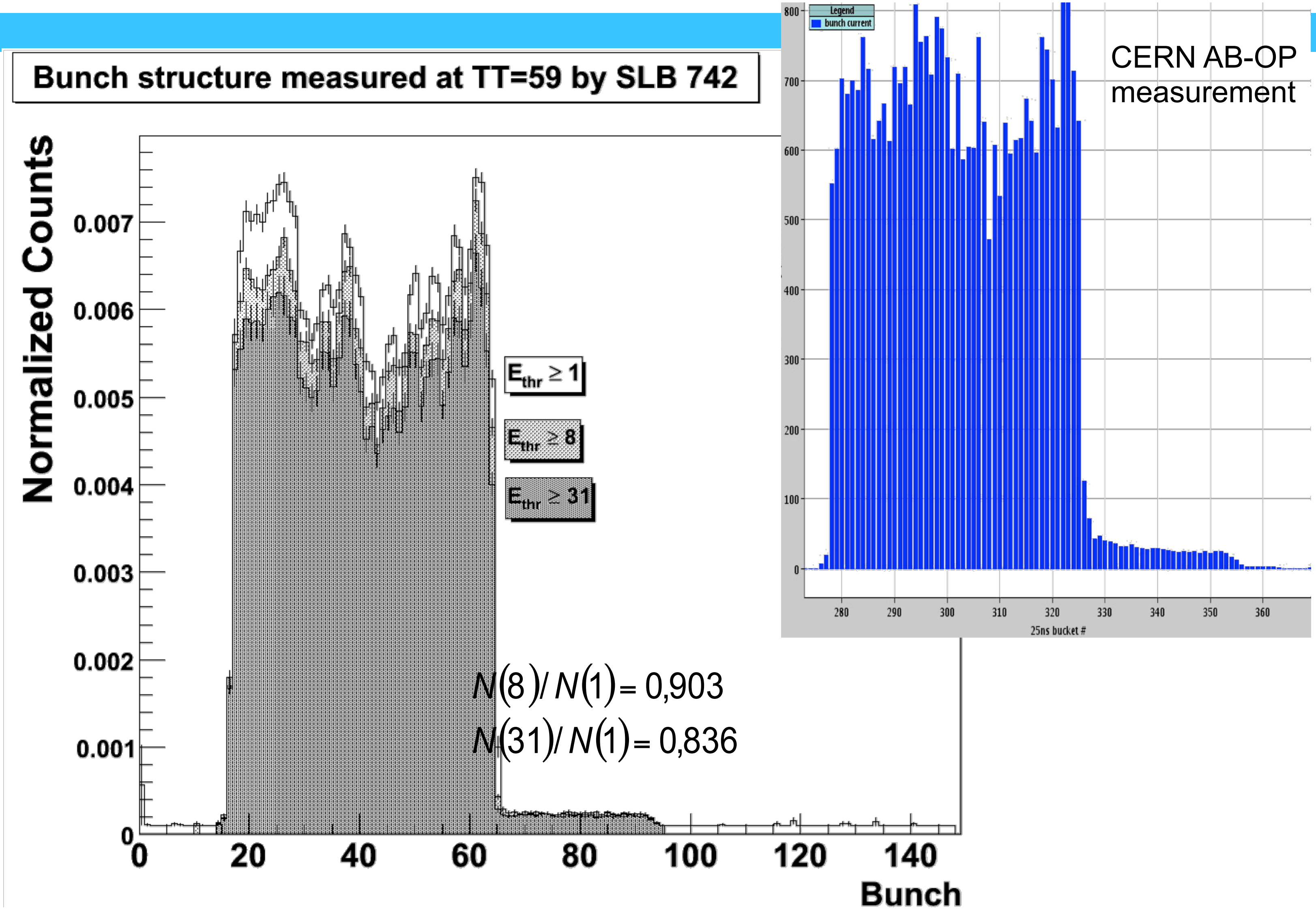


Test Beam: Containment ratios E1/E9, E1/E25 and E1/E49 versus rapidity.





Beam structure using the trigger electronics



$$N(8)/N(1) = 0{,}903$$

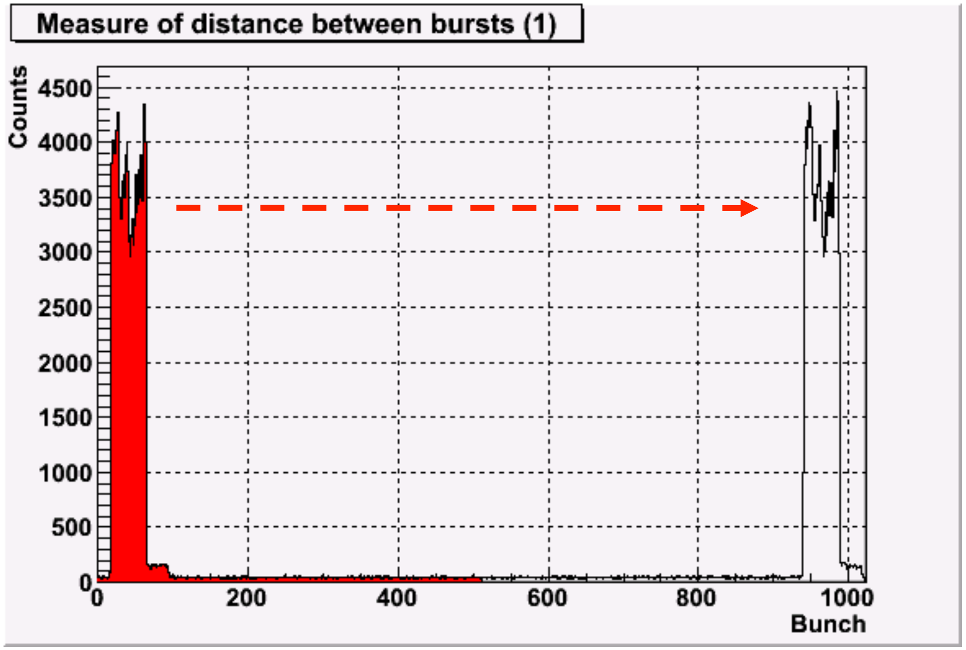
$$N(31)/N(1) = 0{,}836$$

CERN AB-OP measurement

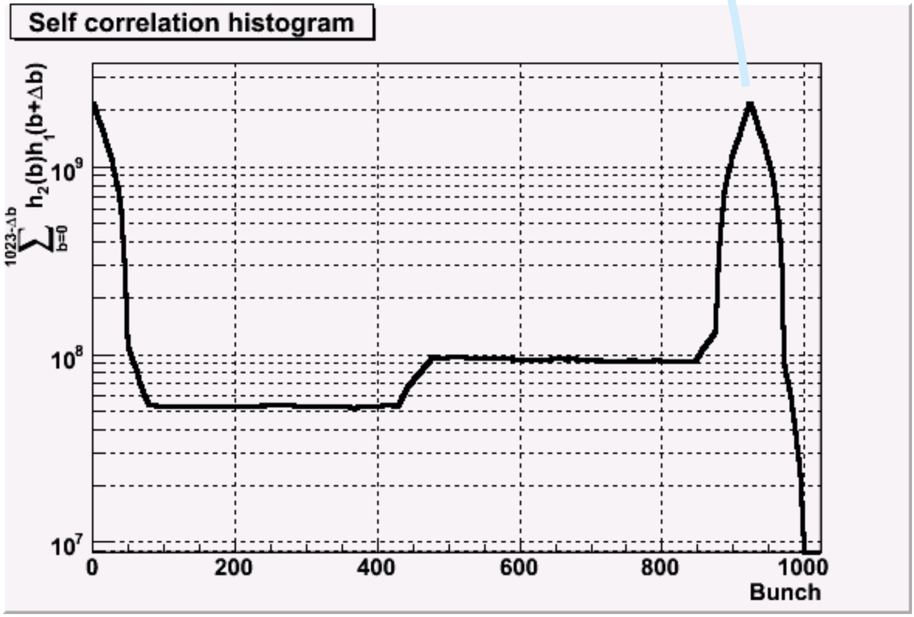
Beam timing analysis using trigger electronics

Time structure of the trigger primitive distribution: **T = 23.1 μs** (SPS revolution)

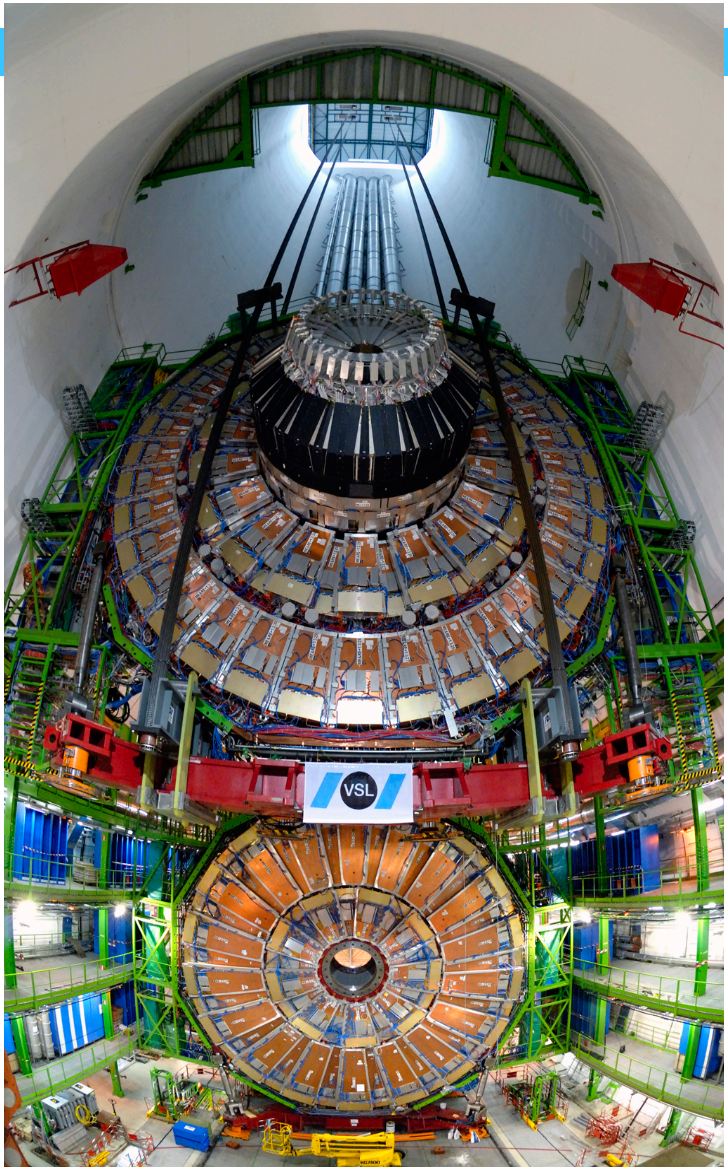
Contents of the accumulator for the Trigger Tower under the beam

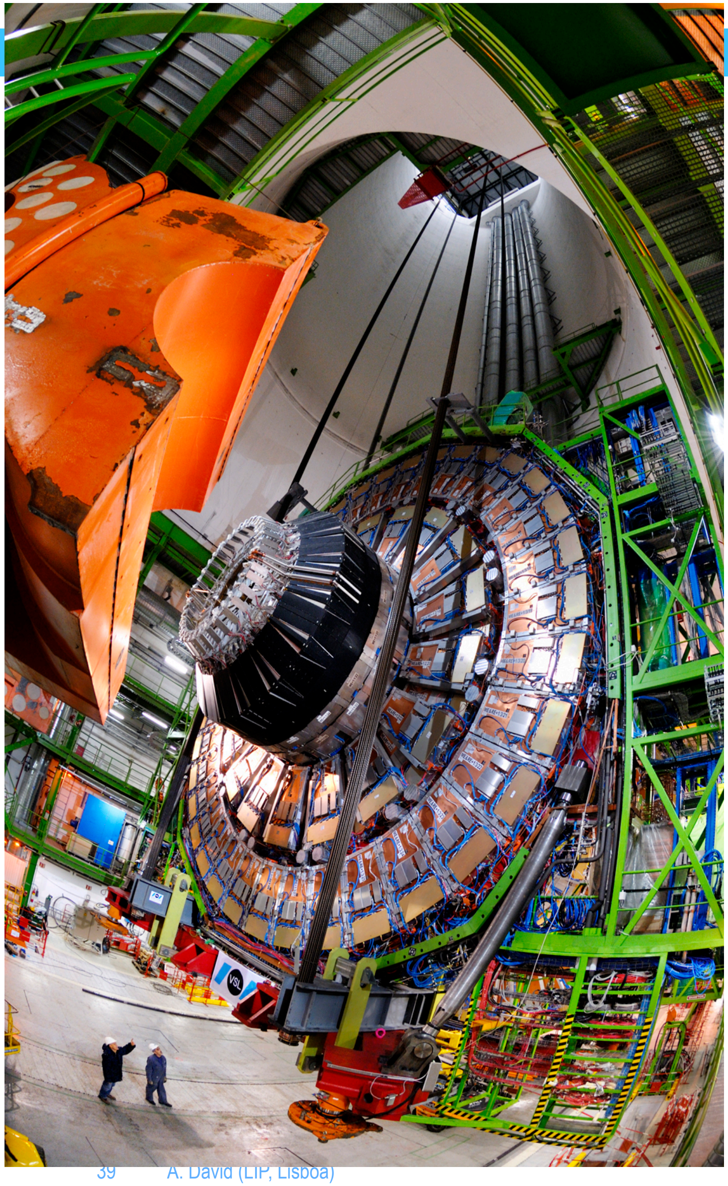


$$Corr(\Delta b) = \sum_{b=0}^{1023-\Delta b} h_2(b)\, h_1(b+\Delta b)$$

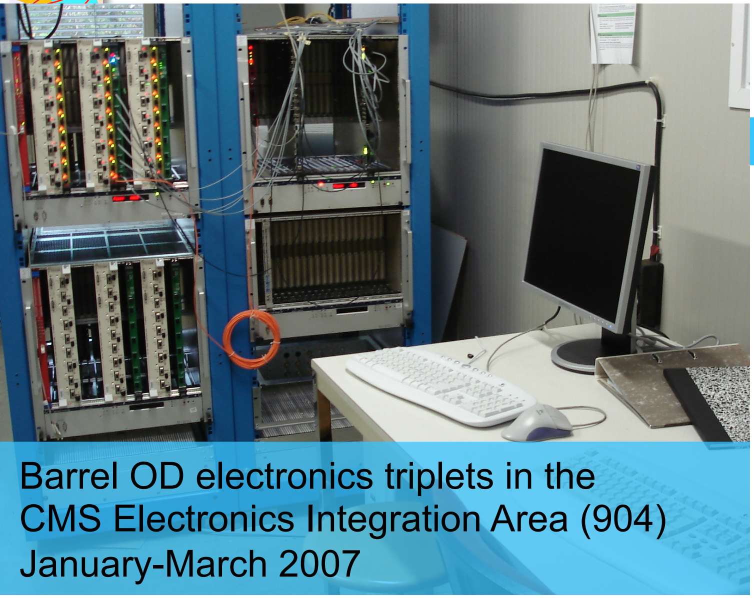


Jan 2007: lowering the first endcap wheel



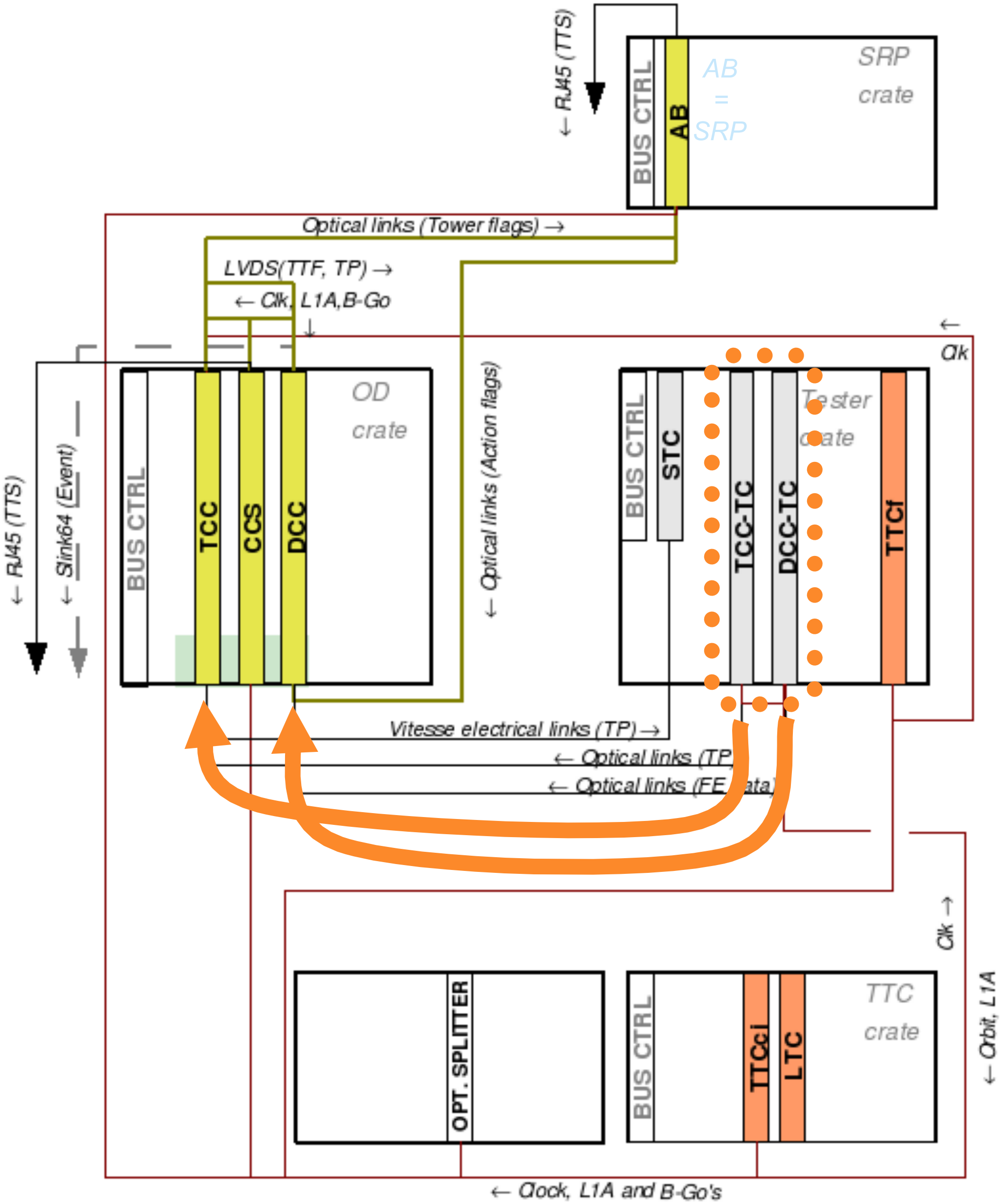


Electronics to test the electronics

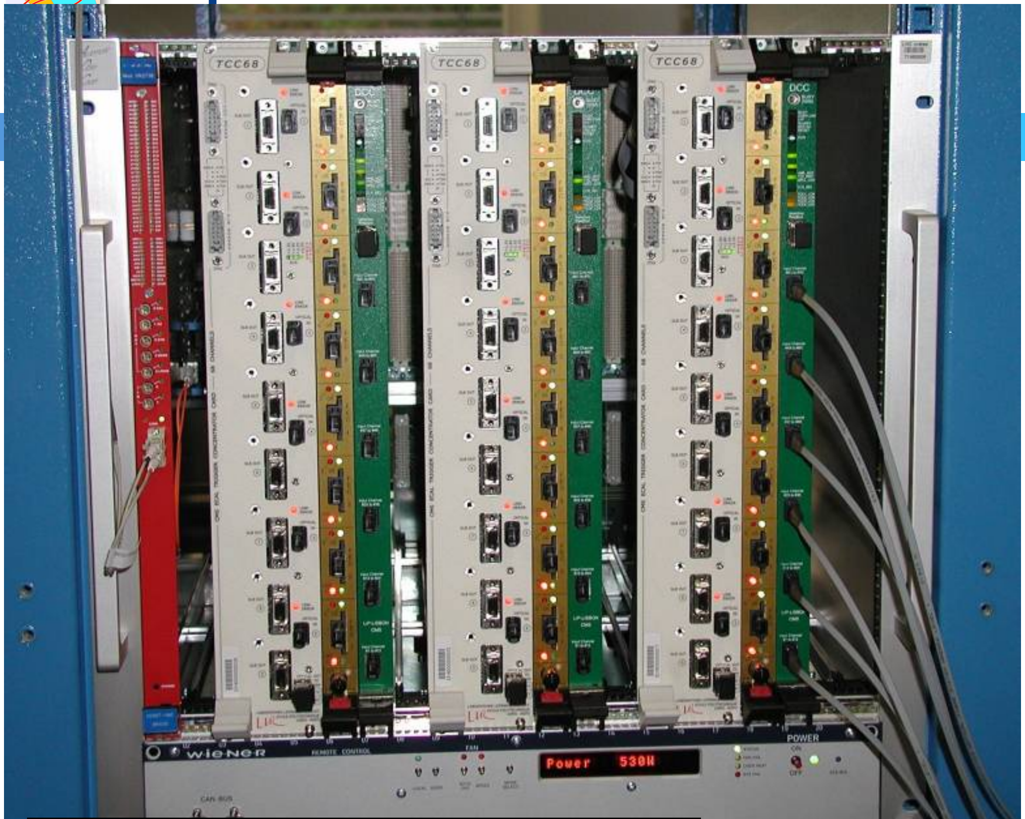


Barrel OD electronics triplets in the CMS Electronics Integration Area (904) January-March 2007

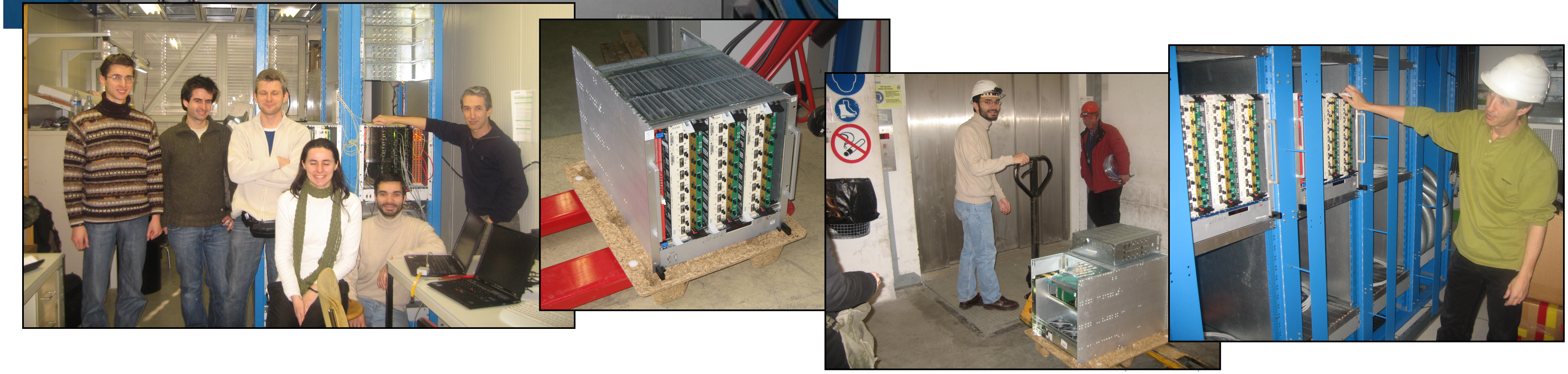
Selective Readout Processor installed in CMS October 2007



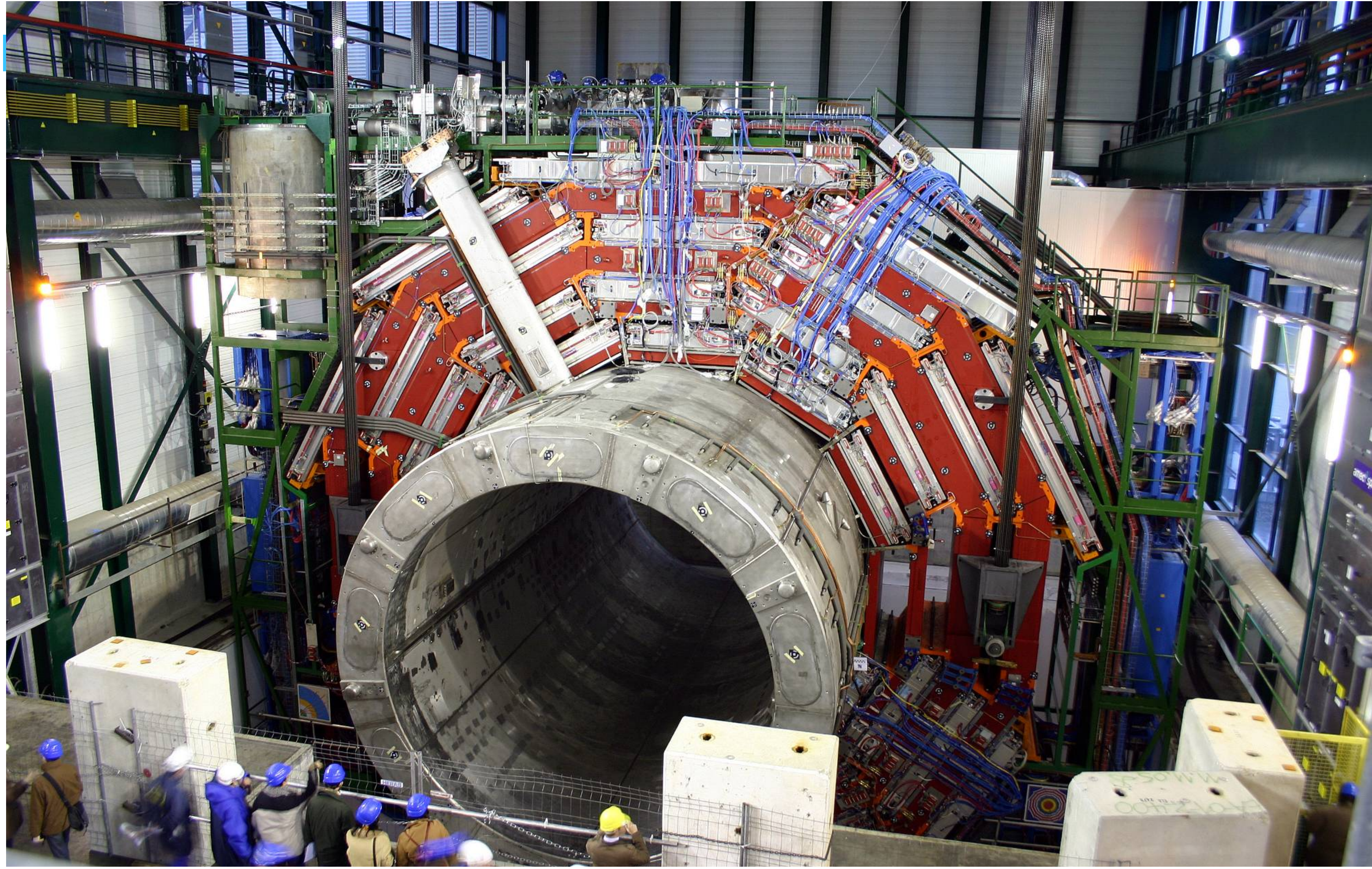
April 2007: ECAL electronics integration



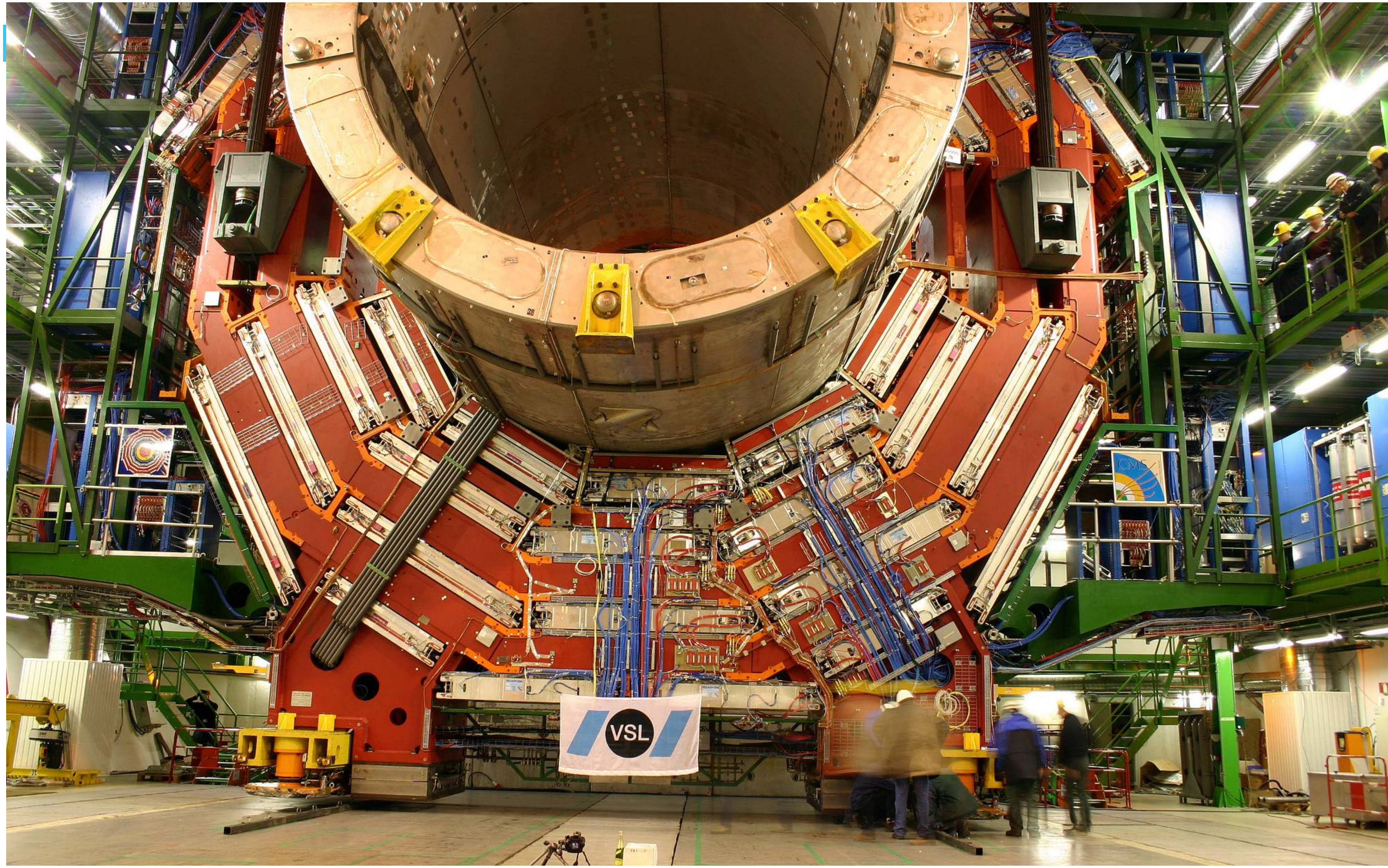
- ☐ **Integrated tests** of Data, Trigger and Control cards prior to installation
- ☐ 12 crates with **110 cards** intensively tested
- ☐ **>10 hours of continuous testing** per crate



2007: lowering of the central barrel



Touch down !



May 2007: ECAL barrel installation

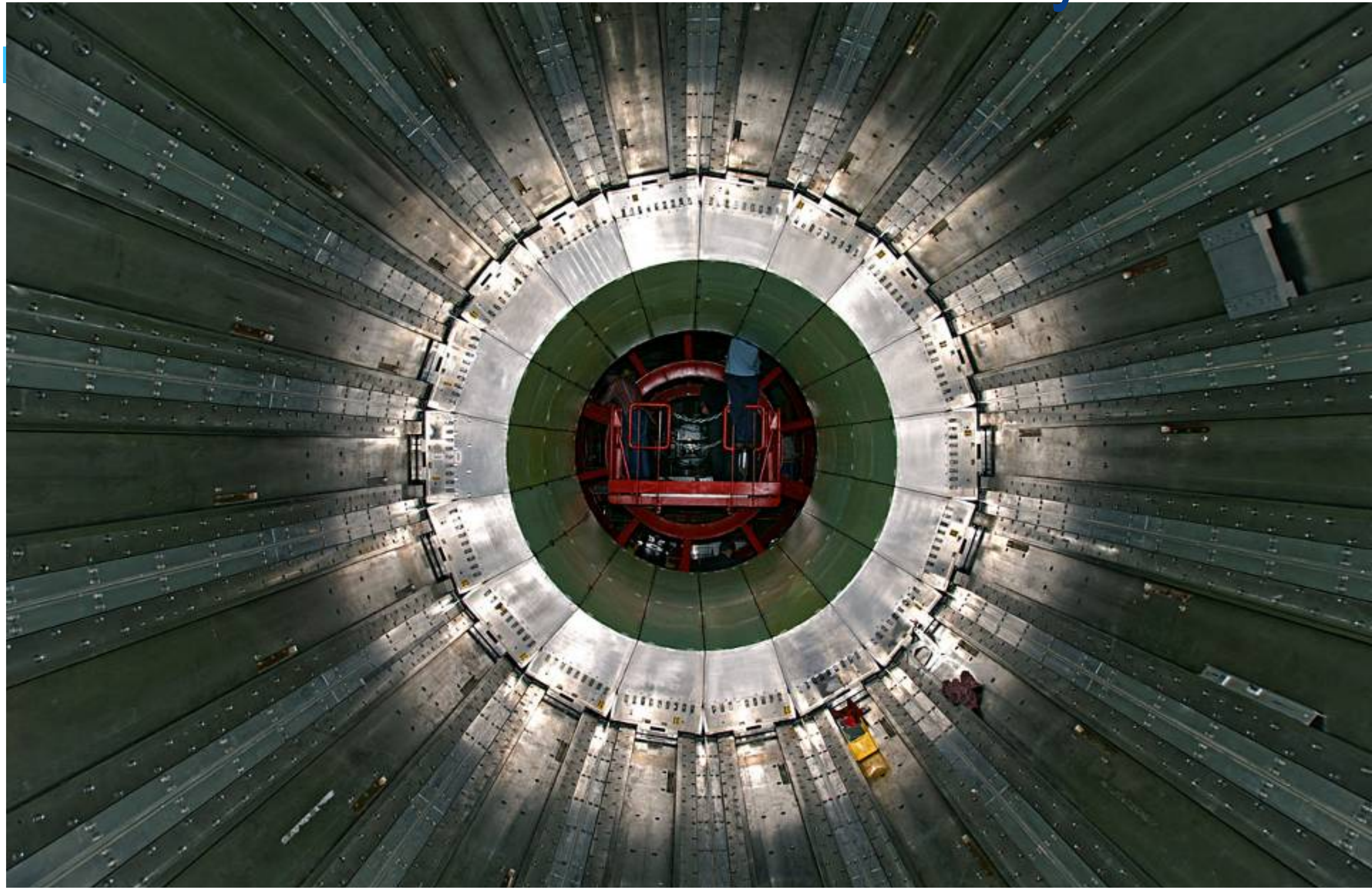
Start ECAL Barrel installation

- **36 Supermodules** tested before and after insertion in the central barrel:
  - Front-end functionality
  - Data acquisition functionality
  - Trigger primitive generation functionality

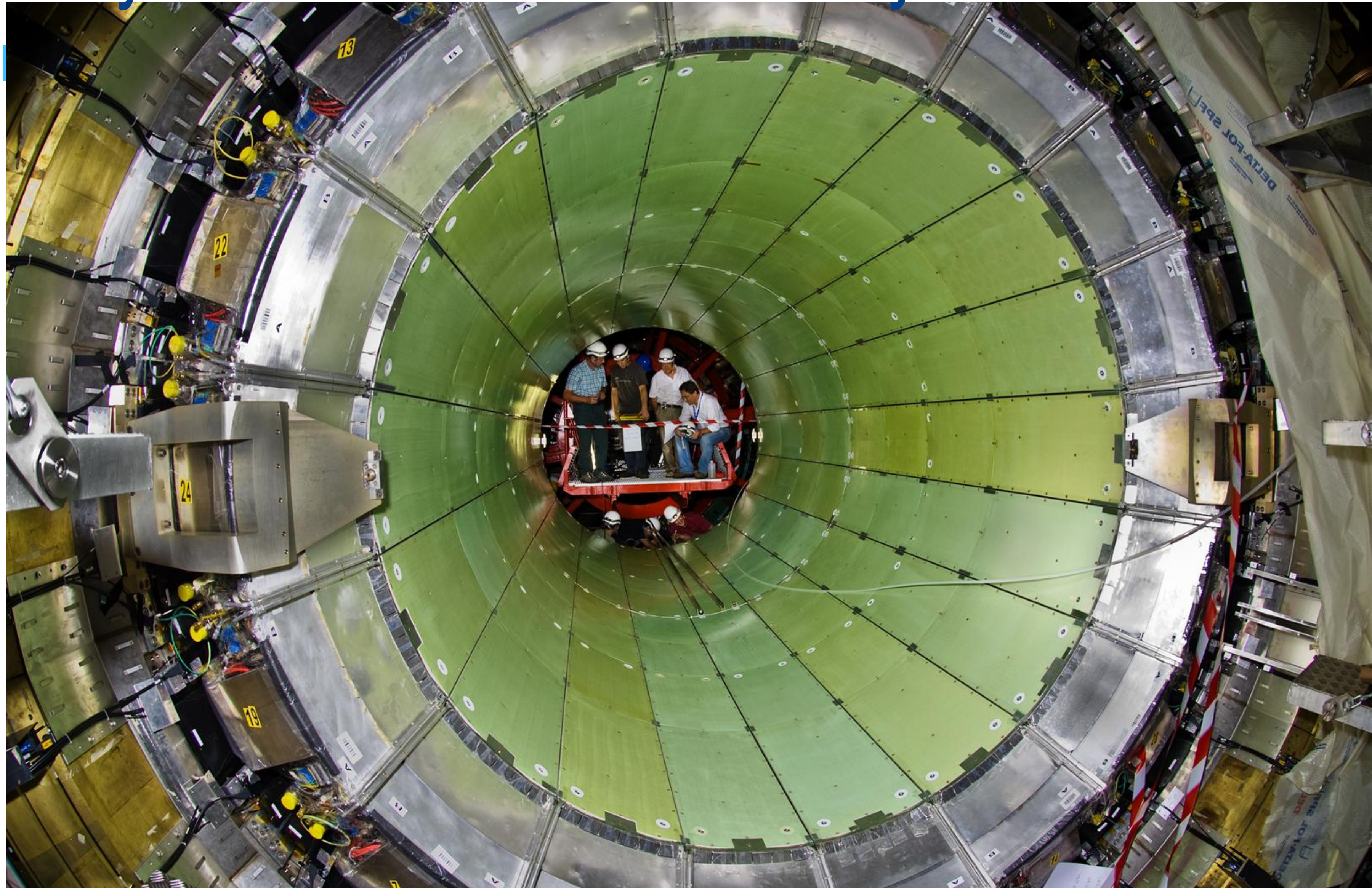
- Sample logbook entry

```
1) Token rings - OK
2) I2c devices access - OK
3) HV - TT57 and TT58 draw high current (~200uA),
   this problem has appeared on the floor, current was 50uA.
4) DCU - OK, except channel 1427 (TT58) has high APD current (~200uA)
          except APD temperature TT9, cry245 bad DCU measurement (known from floor)
          except APD temperature TT57, cry1441 bad DCU measurement (~15 C, known from floor)
6) Pedestal run 1591 - OK, except
           ch 1427 (TT58) is noisy (RMS12=41.2),
           ch 115 has rms6=1.8 rms12=4.2 (new problem)
           all MEM box channels are noisy in gain 16, as before
7) Test pulse run 1592 - OK, except channel 331 (TT15);
    it had big HV current and has been disconnected from the HV in 867
8) Pedestal HV off run 1593 - OK, except channel 331 (TT15) as explained above
9) Trigger links - OK
```

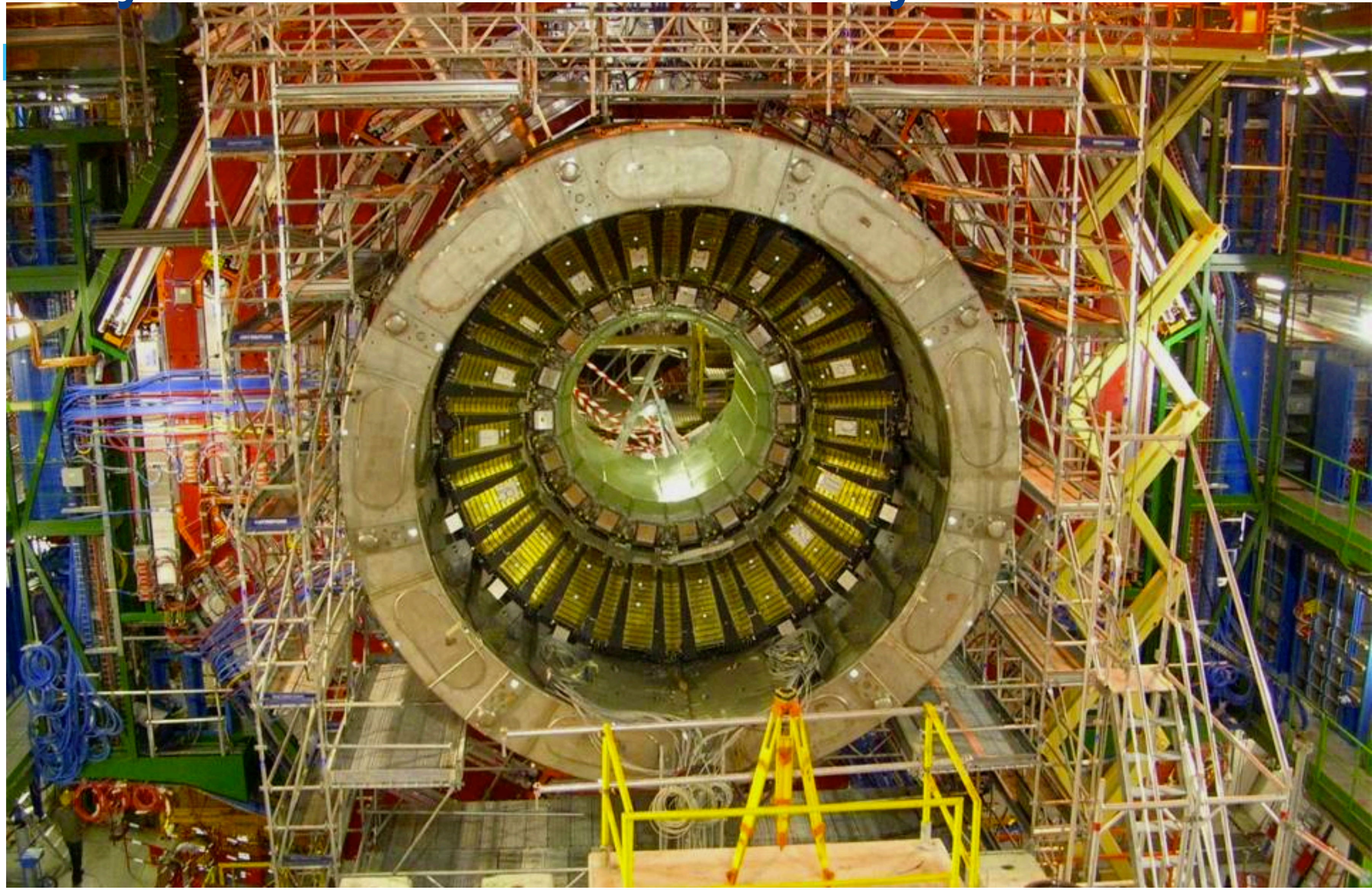
ECAL Barrel installation half-way



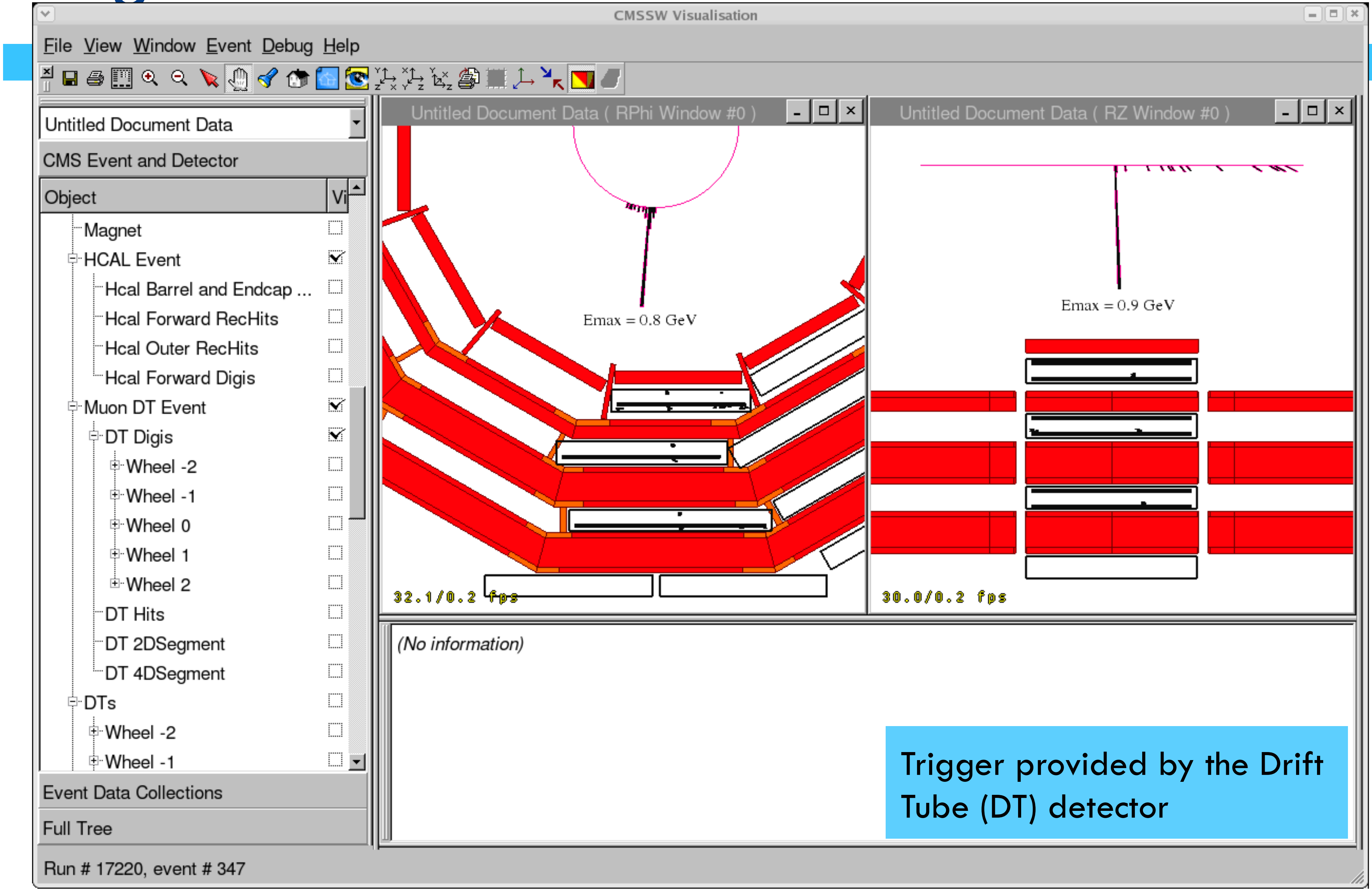
July 2007: ECAL barrel fully installed



July 2007: ECAL barrel fully installed



August 2007: muons seen in the ECAL



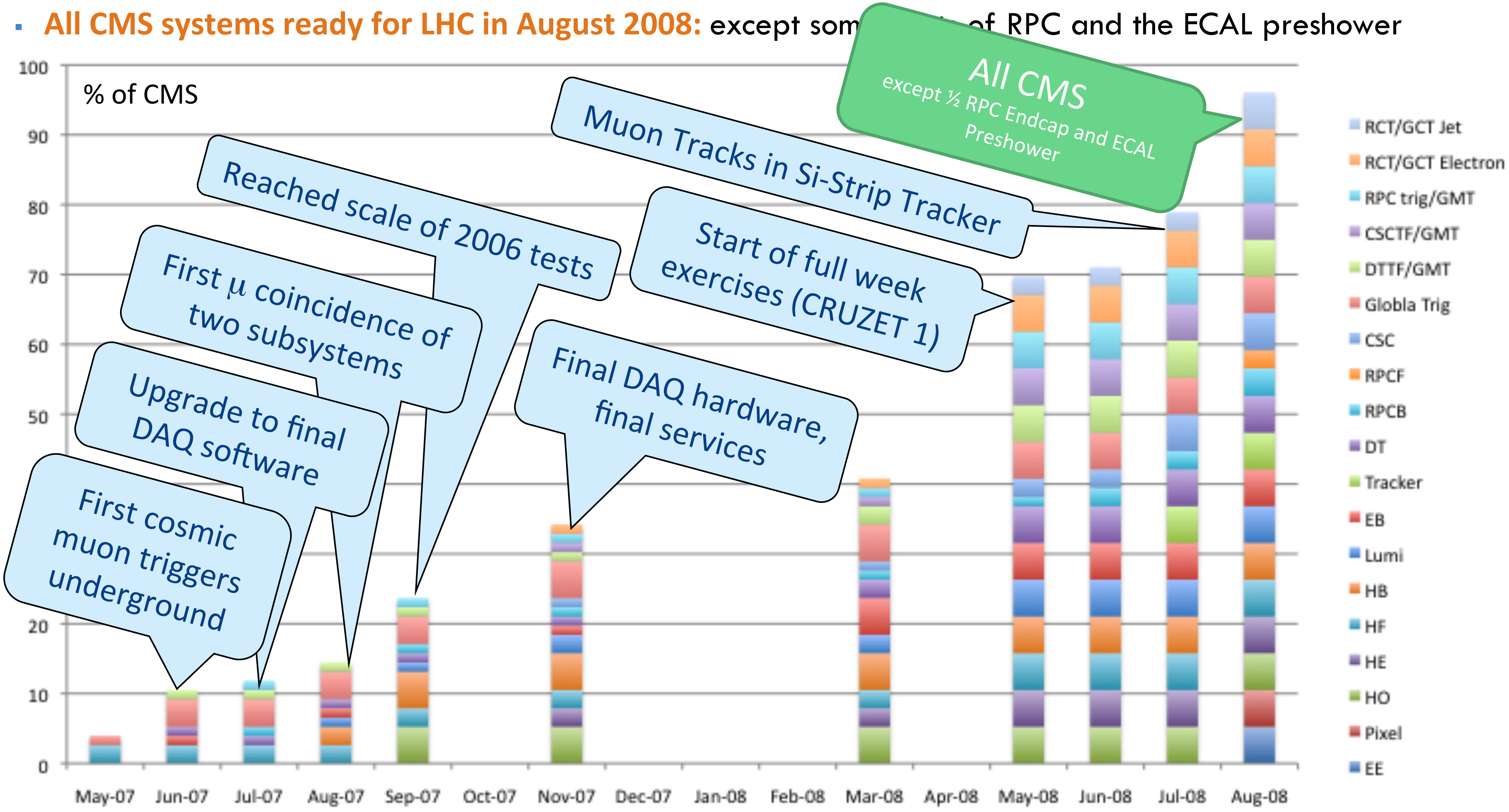
(No information)

Run # 17220, event # 347

Trigger provided by the Drift Tube (DT) detector

2007/8 – Putting the pieces together

- Integration of **subdetectors** and **trigger:** considered separately: 19 items, each equally weighted
- **All CMS systems ready for LHC in August 2008:** except som of RPC and the ECAL preshower



First cosmic muon triggers underground

Upgrade to final DAQ software

First μ coincidence of two subsystems

Reached scale of 2006 tests

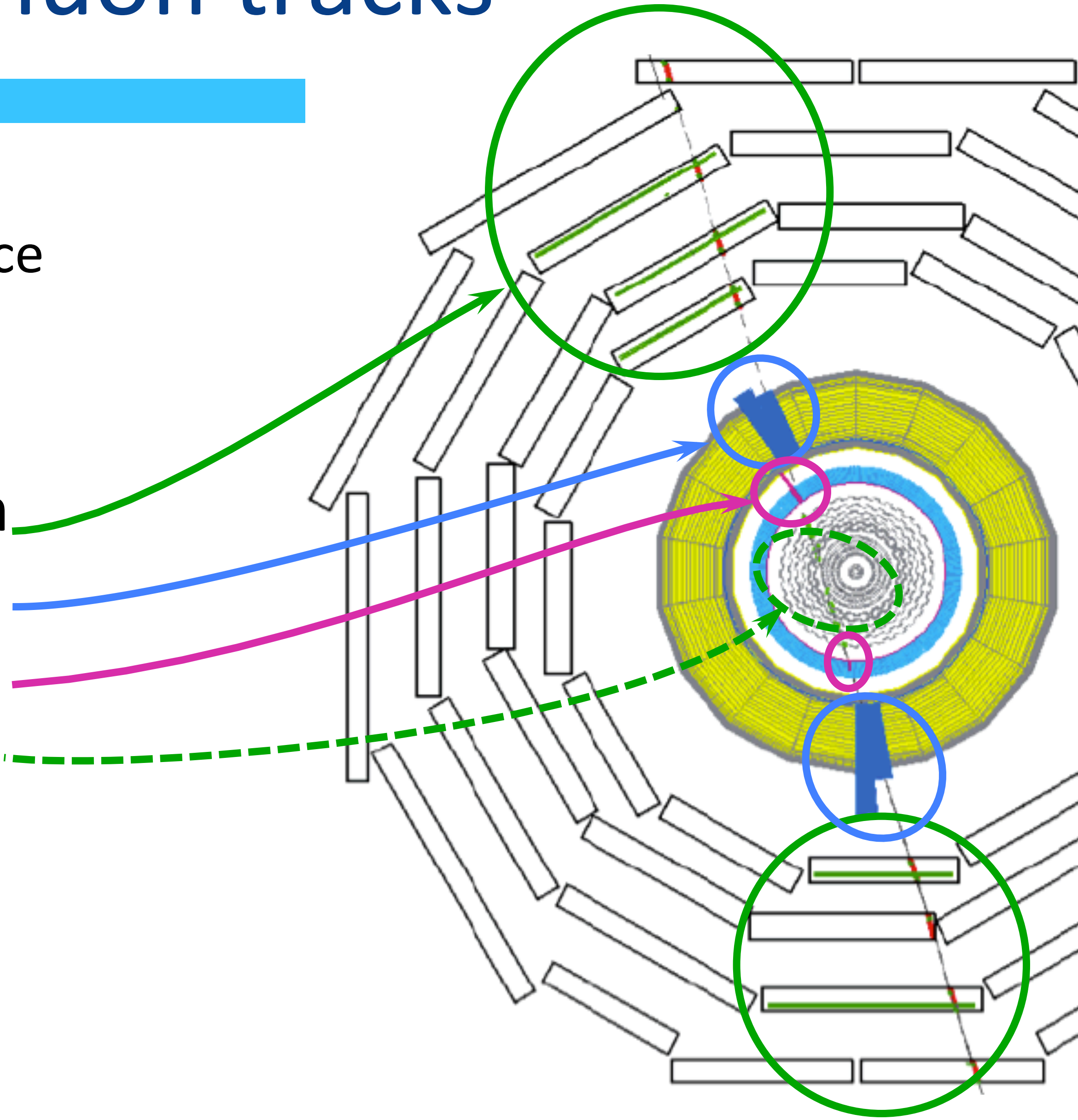
Final DAQ hardware, final services

Start of full week exercises (CRUZET 1)

Muon Tracks in Si-Strip Tracker

All CMS except ½ RPC Endcap and ECAL Preshower

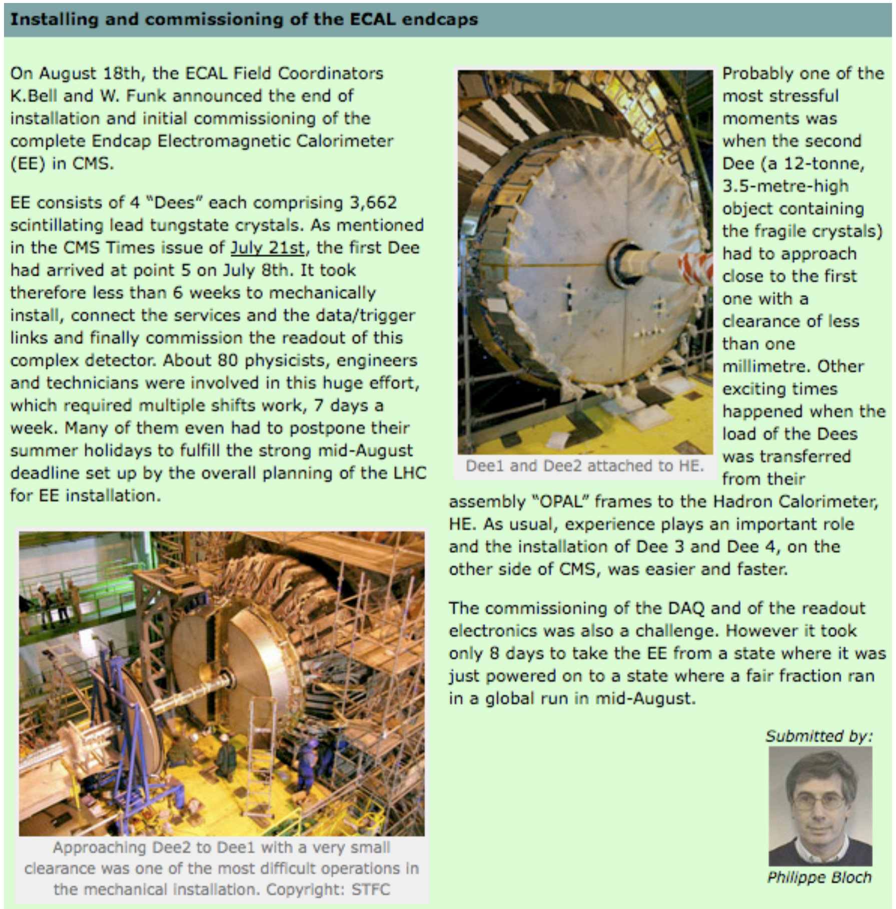
First global muon tracks



- Dimuon trigger
  - Top-bottom coincidence
  - ≥ 2 station segments
- Muon signals found in
  - **Muon chambers**
  - **HCAL**
  - **ECAL**
  - **Tracker TOB + TIB**
- **Global track fits**
  - First alignment data

ECAL Endcap – a flash commissioning

- First piece of the detector in P5 on July 8, 2008
- Hand over to commissioning team on **August 6**
- All done by **August 16**
- Issues
  - Fibres broken inside EE
    - 1 / 550 data
    - 1 / 3000 trigger



Installing and commissioning of the ECAL endcaps

On August 18th, the ECAL Field Coordinators K.Bell and W. Funk announced the end of installation and initial commissioning of the complete Endcap Electromagnetic Calorimeter (EE) in CMS.

EE consists of 4 "Dees" each comprising 3,662 scintillating lead tungstate crystals. As mentioned in the CMS Times issue of July 21st, the first Dee had arrived at point 5 on July 8th. It took therefore less than 6 weeks to mechanically install, connect the services and the data/trigger links and finally commission the readout of this complex detector. About 80 physicists, engineers and technicians were involved in this huge effort, which required multiple shifts work, 7 days a week. Many of them even had to postpone their summer holidays to fulfill the strong mid-August deadline set up by the overall planning of the LHC for EE installation.

Dee1 and Dee2 attached to HE.

Probably one of the most stressful moments was when the second Dee (a 12-tonne, 3.5-metre-high object containing the fragile crystals) had to approach close to the first one with a clearance of less than one millimetre. Other exciting times happened when the load of the Dees was transferred from their assembly "OPAL" frames to the Hadron Calorimeter, HE. As usual, experience plays an important role and the installation of Dee 3 and Dee 4, on the other side of CMS, was easier and faster.

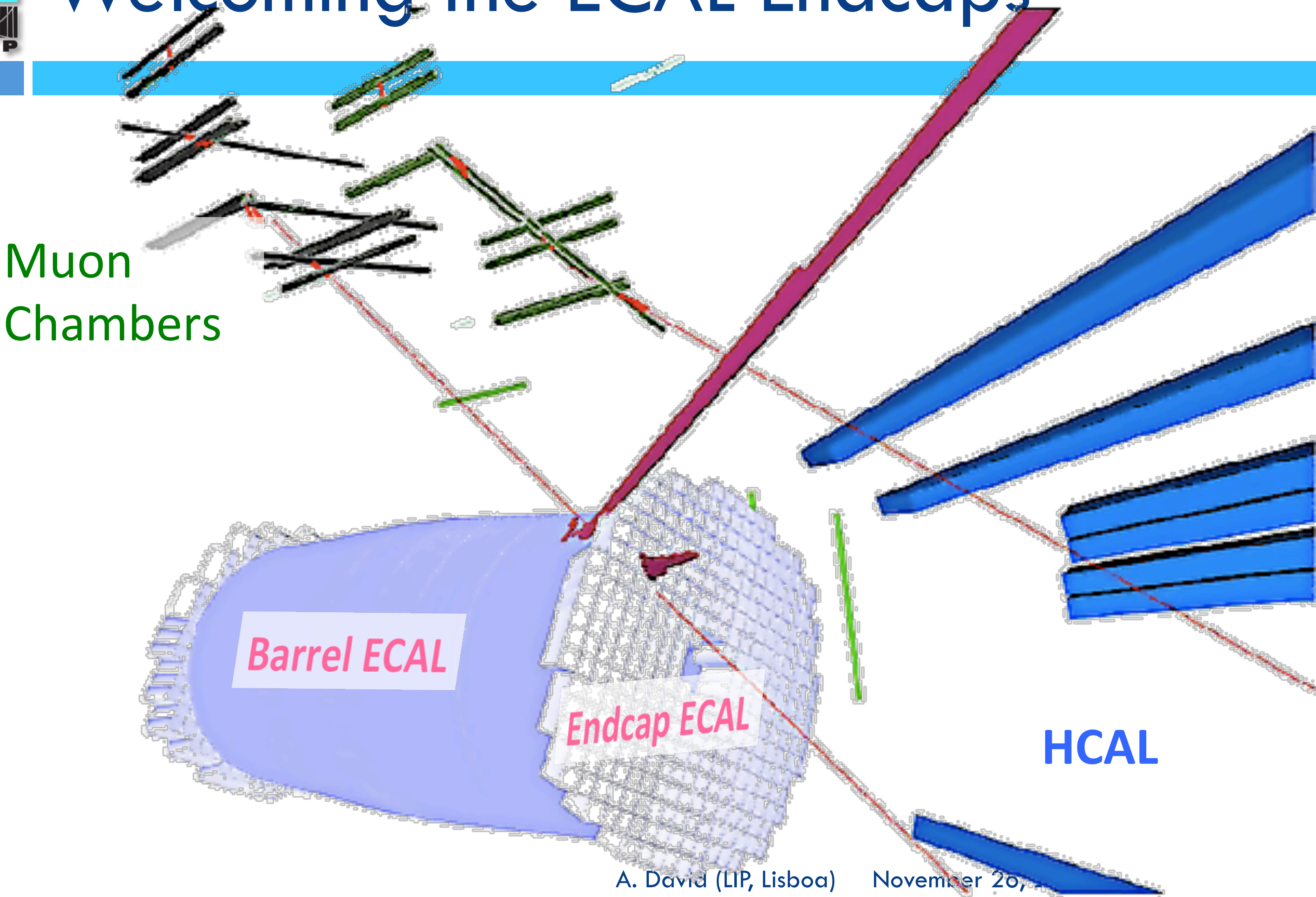
The commissioning of the DAQ and of the readout electronics was also a challenge. However it took only 8 days to take the EE from a state where it was just powered on to a state where a fair fraction ran in a global run in mid-August.

Approaching Dee2 to Dee1 with a very small clearance was one of the most difficult operations in the mechanical installation. Copyright: STFC

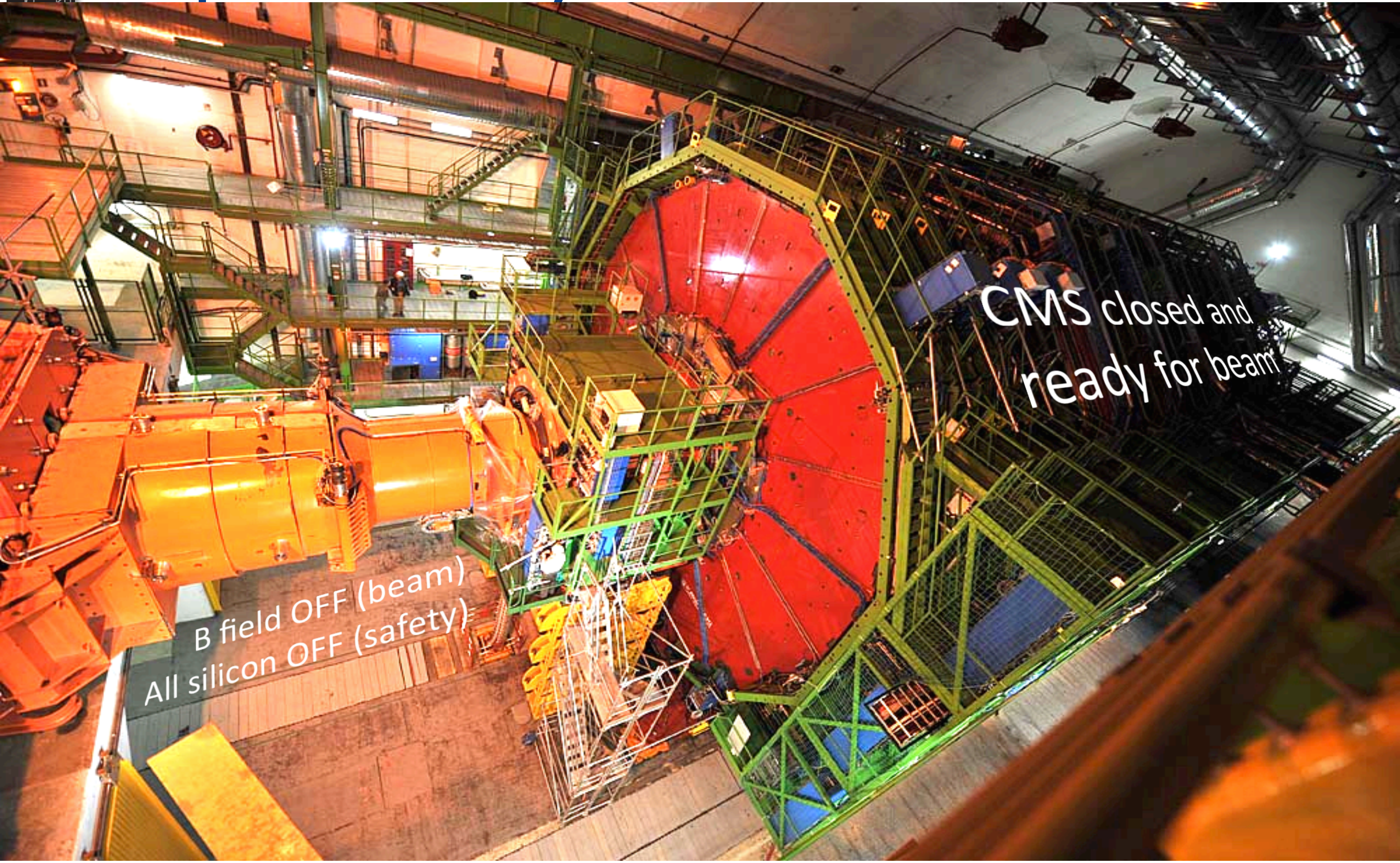
Submitted by:

Philippe Bloch

Welcoming the ECAL Endcaps



September 3, 2008 at 20:30

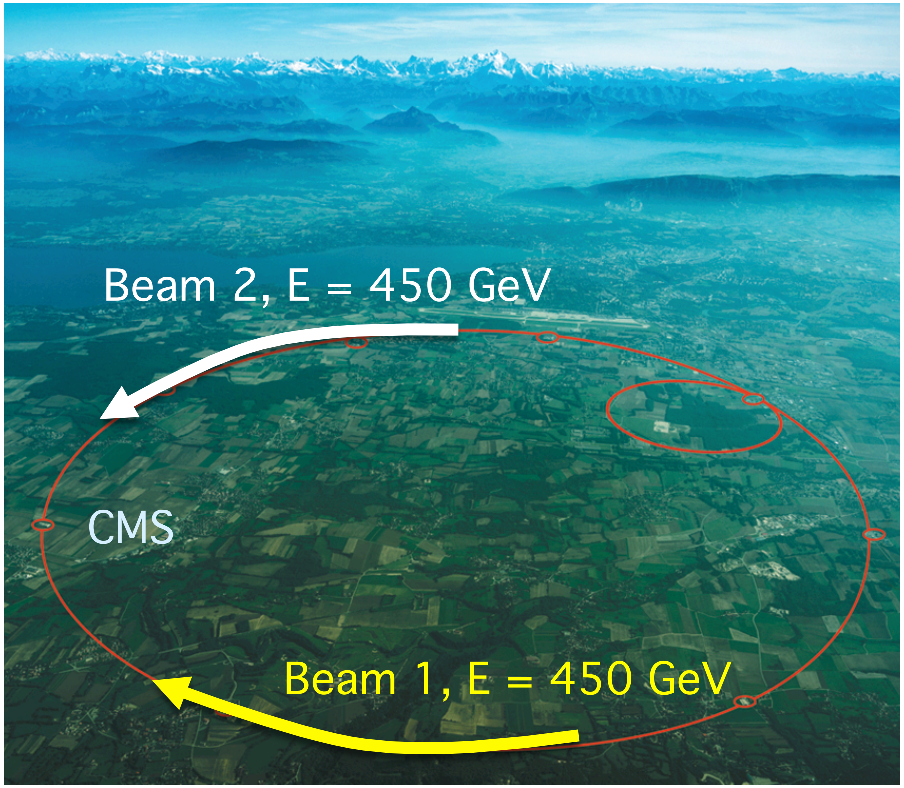


CMS closed and ready for beam

B field OFF (beam)
All silicon OFF (safety)

2008 beams in the LHC

- September 7
  - Beam 1 on collimators (upstream of CMS)
- September 10 (D-day)
  - Beam 1, then Beam 2 circulating (hundreds of turns)
- September 11
  - RF capture (millions of orbits)
  - Beam halo through CMS
  - Beam-gas events
- About 40 hours of beam at or through CMS
  - All systems ON except Tracker and Solenoid



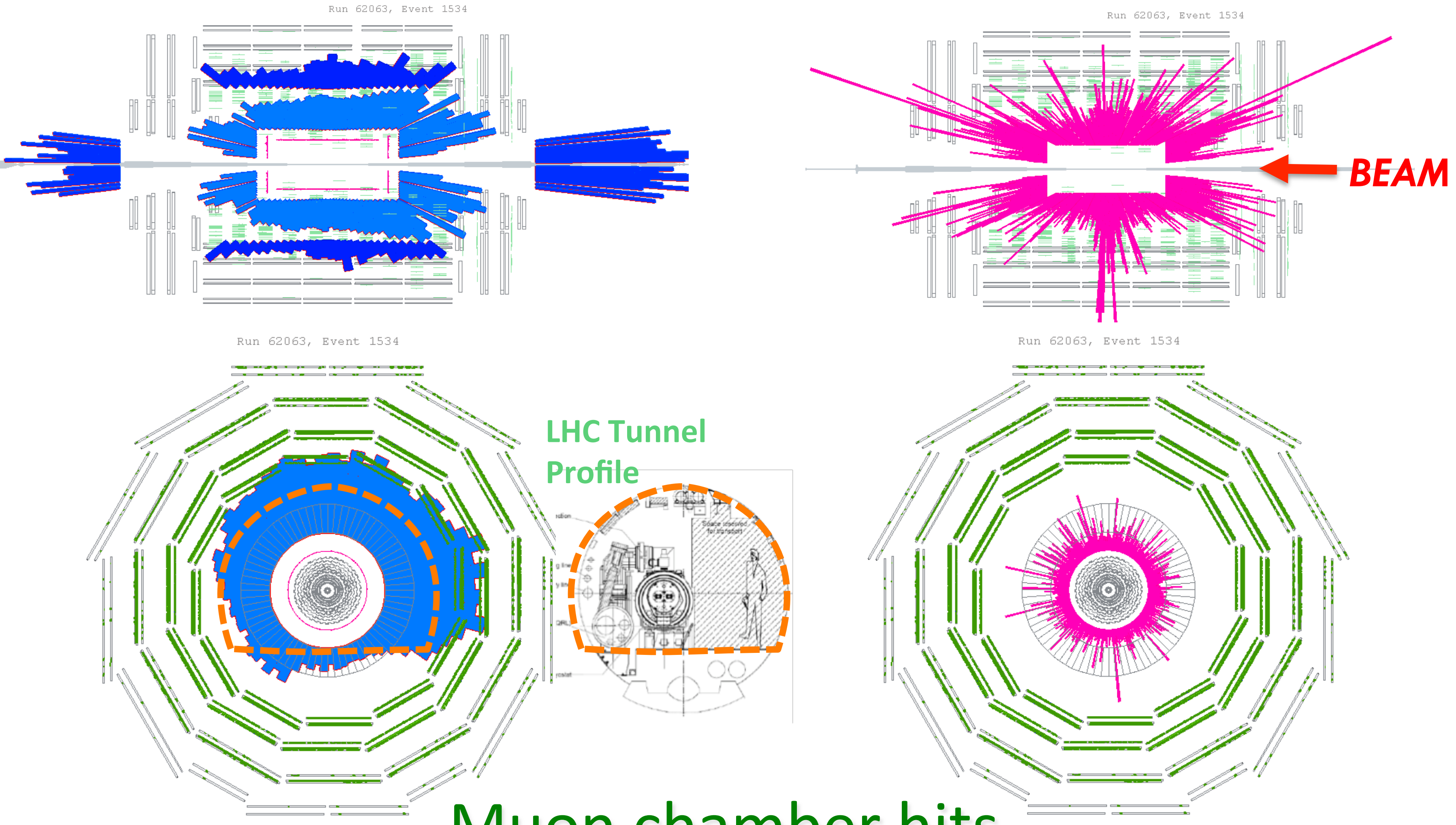
Beam Splash Event Display

HCAL energy

ECAL energy

Longitudinal

Transverse

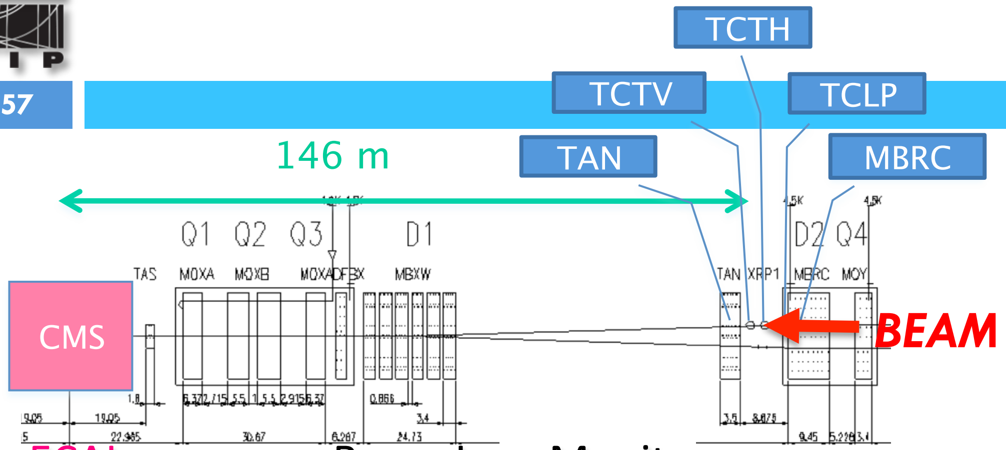


BEAM

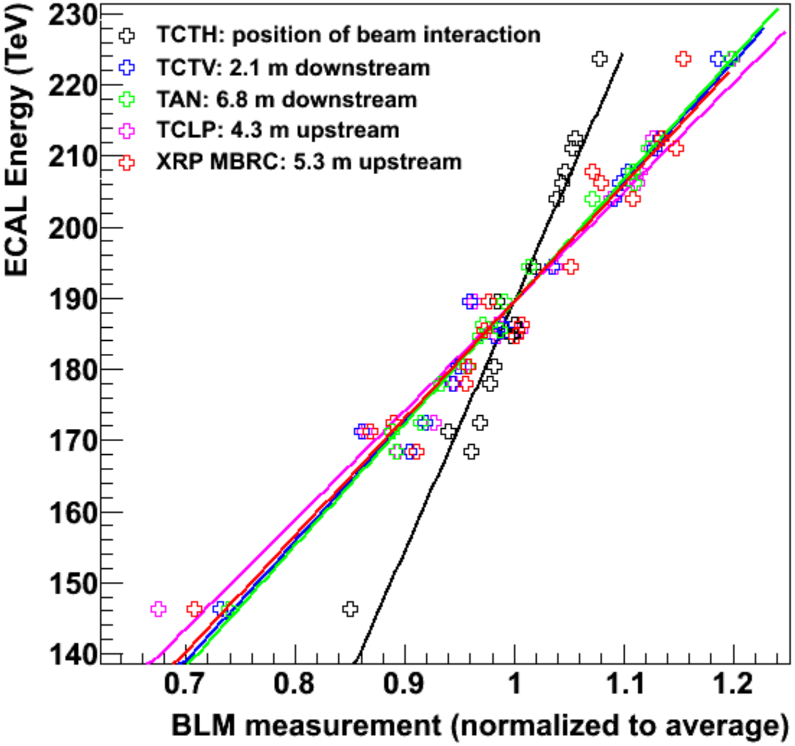
LHC Tunnel Profile

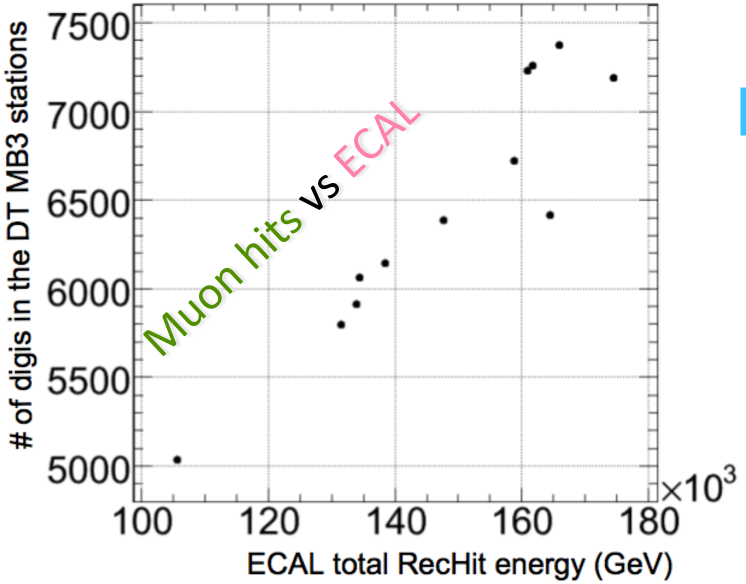
Muon chamber hits

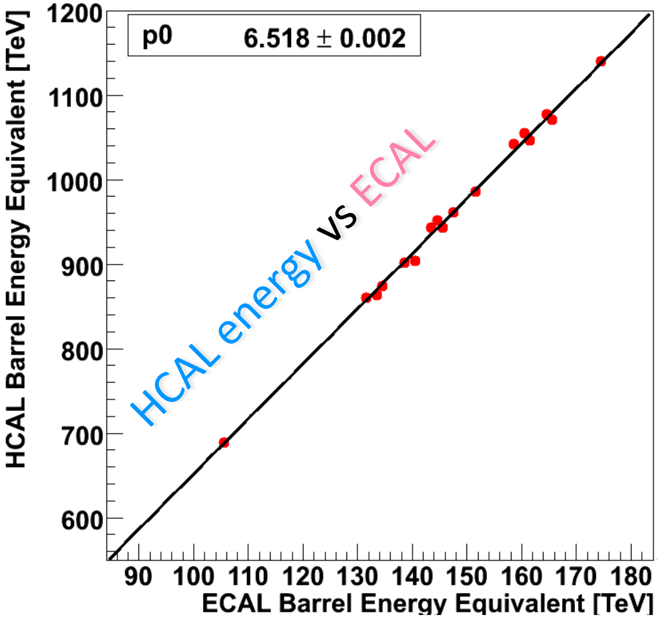
Beam Splashes – energy in CMS



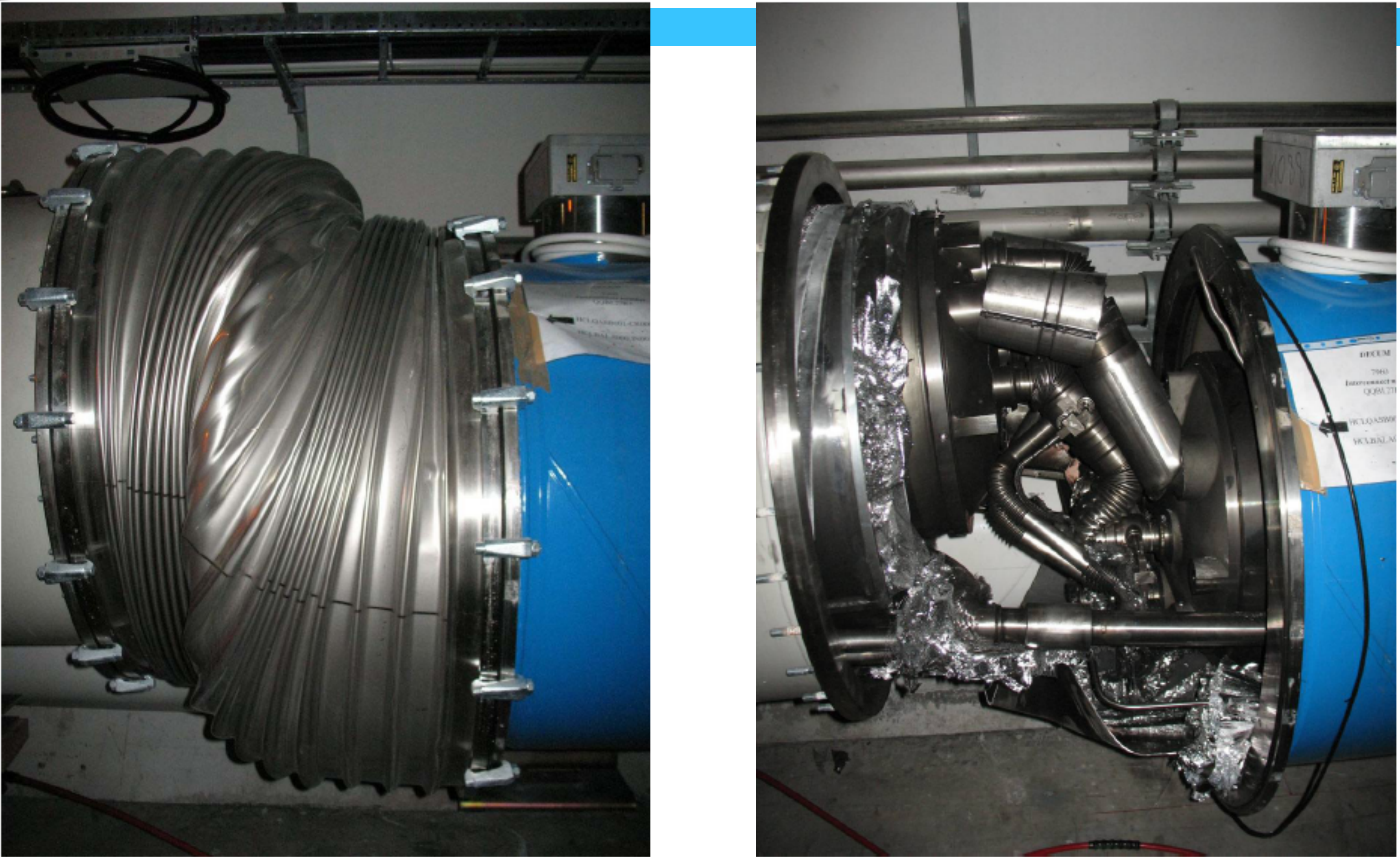
ECAL energy vs Beam Loss Monitors



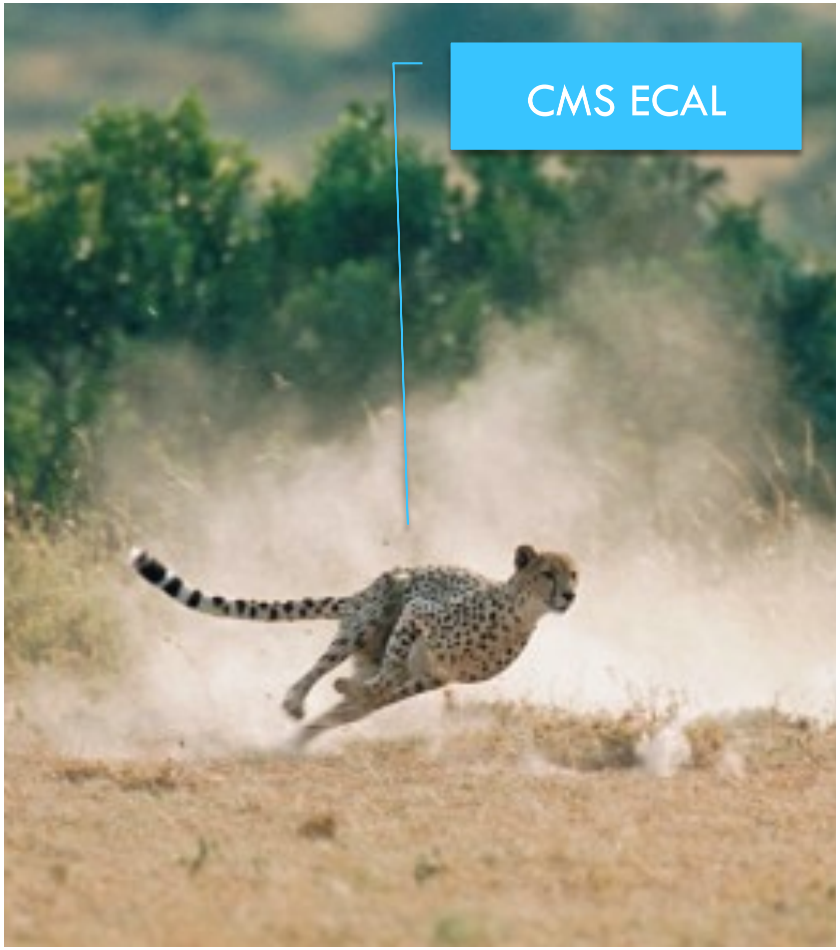




And then, Sep 19…



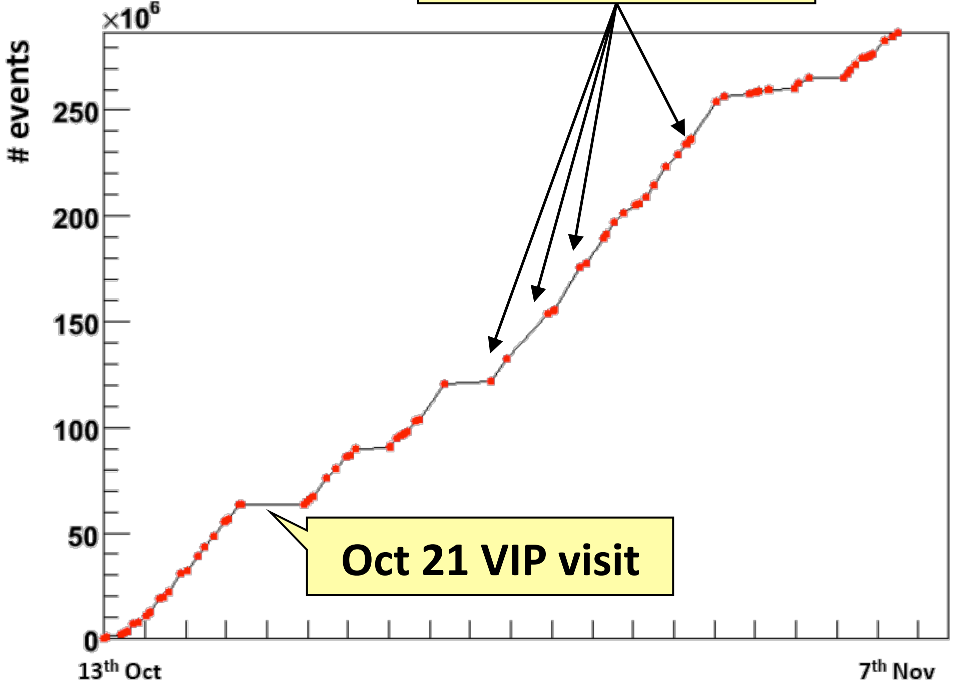
The coming of age of the hunter



CMS ECAL

Cosmics Run at 4 Tesla – CRAFT

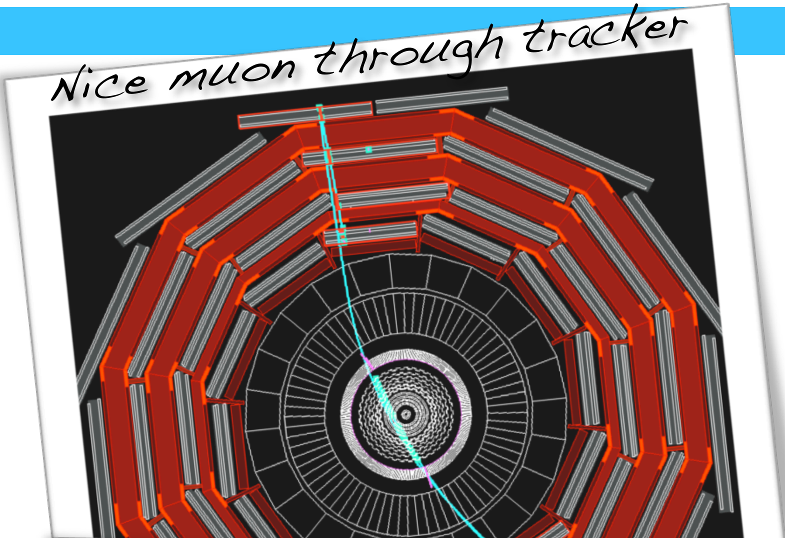
- Four weeks of continuous running
  - **19 days with B = 3.8 T**
  - gain operational experience in 24/7 operation
- 370 M cosmic events
  - **290 M events at B = 3.8 T**
  - 87 % events with muons
  - 3 % also have Si strip hits
  - 0.03 % have Si pixel hits
- Data Operations
  - 600 TB transferred
  - Prompt reconstruction within hours
  - Reconstructed 10+ times
    - Increasing understanding

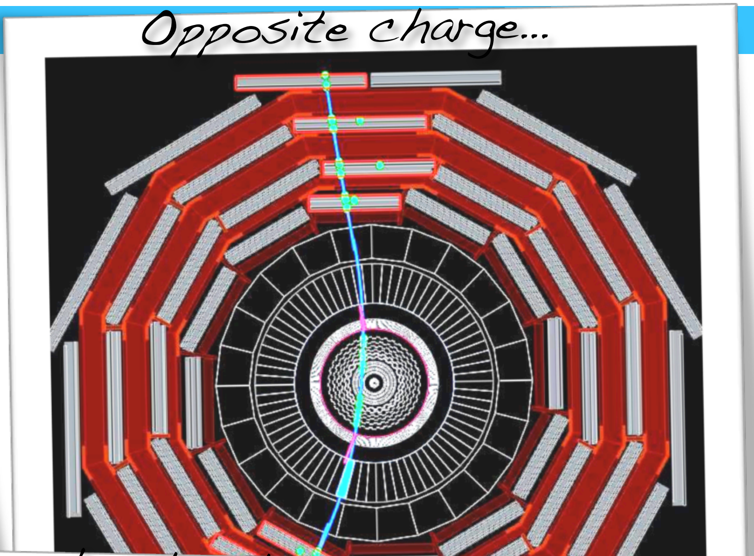


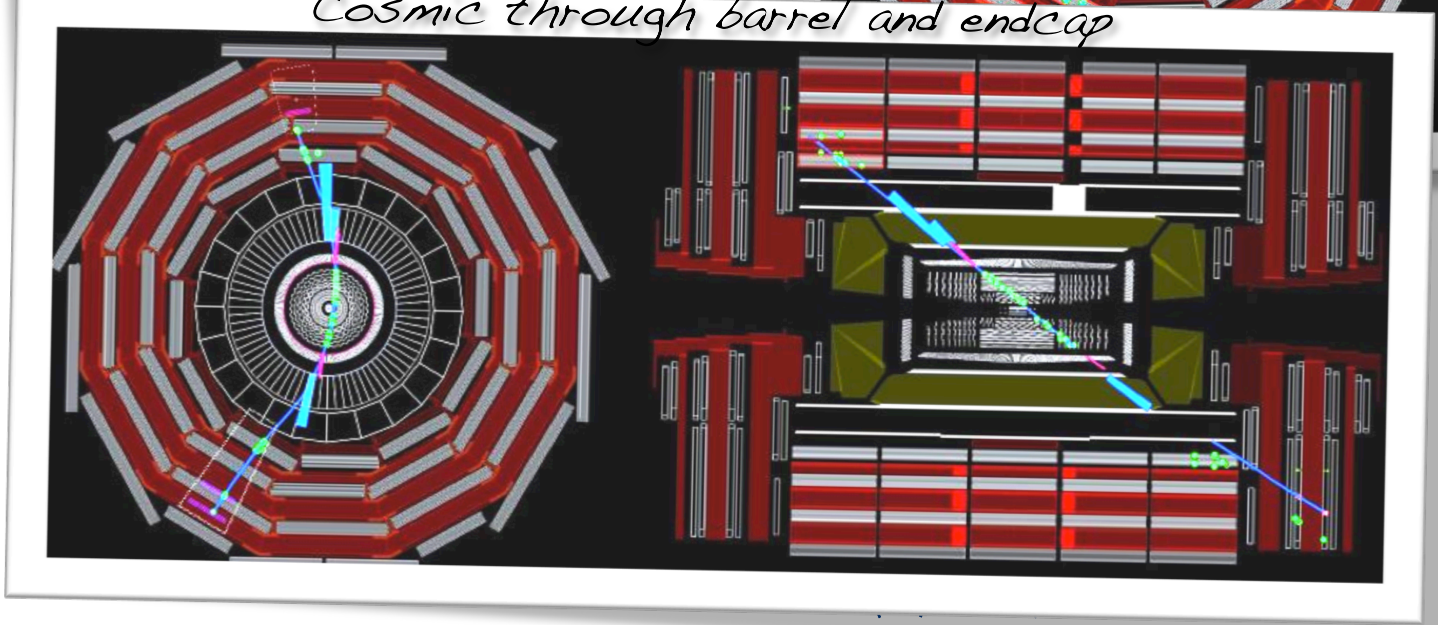
4 runs exceed 15h

Oct 21 VIP visit

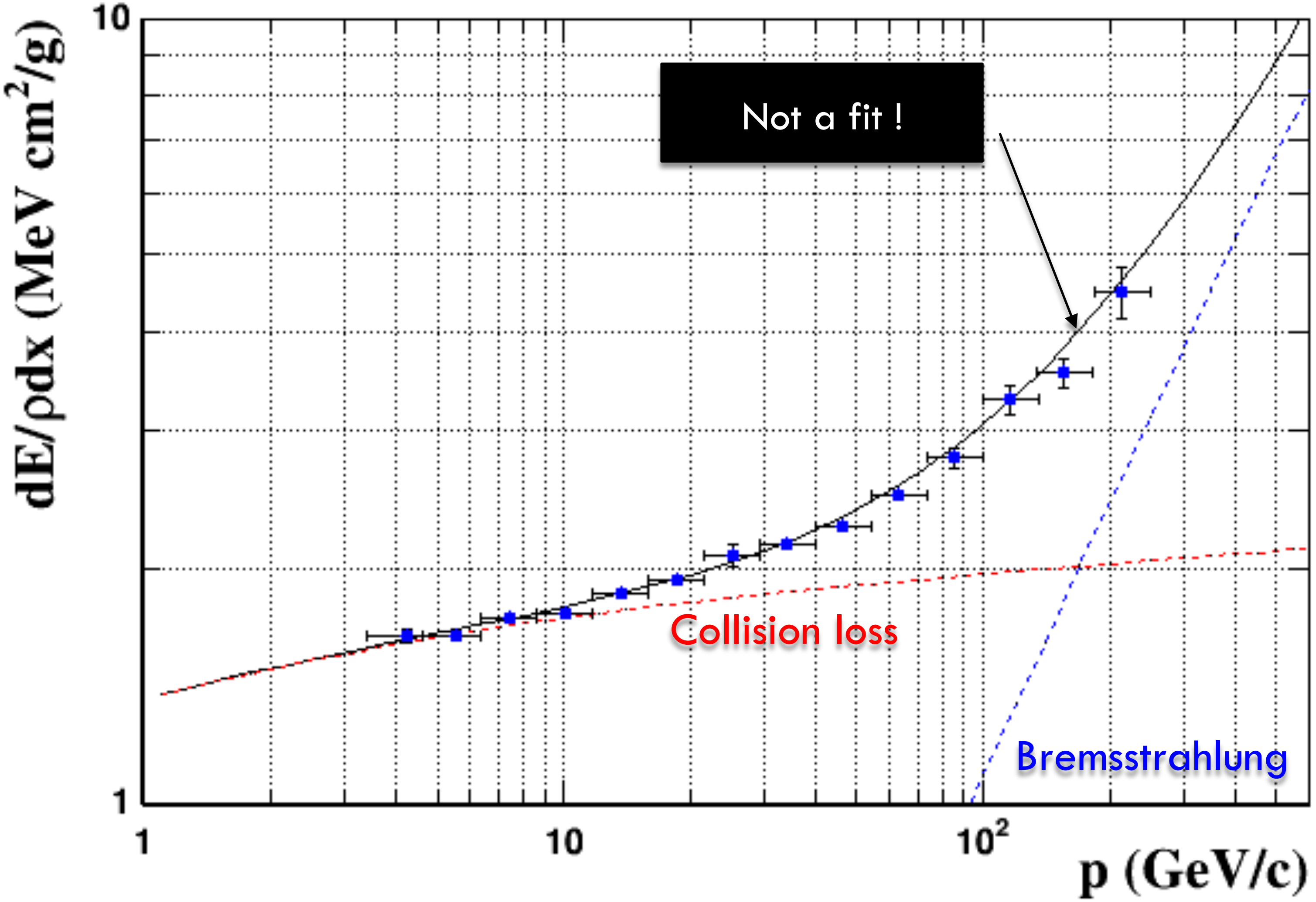
From the CMS Album


Nice muon through tracker


Opposite charge...


Cosmic through barrel and endcap

Muon stopping power in PbWO4

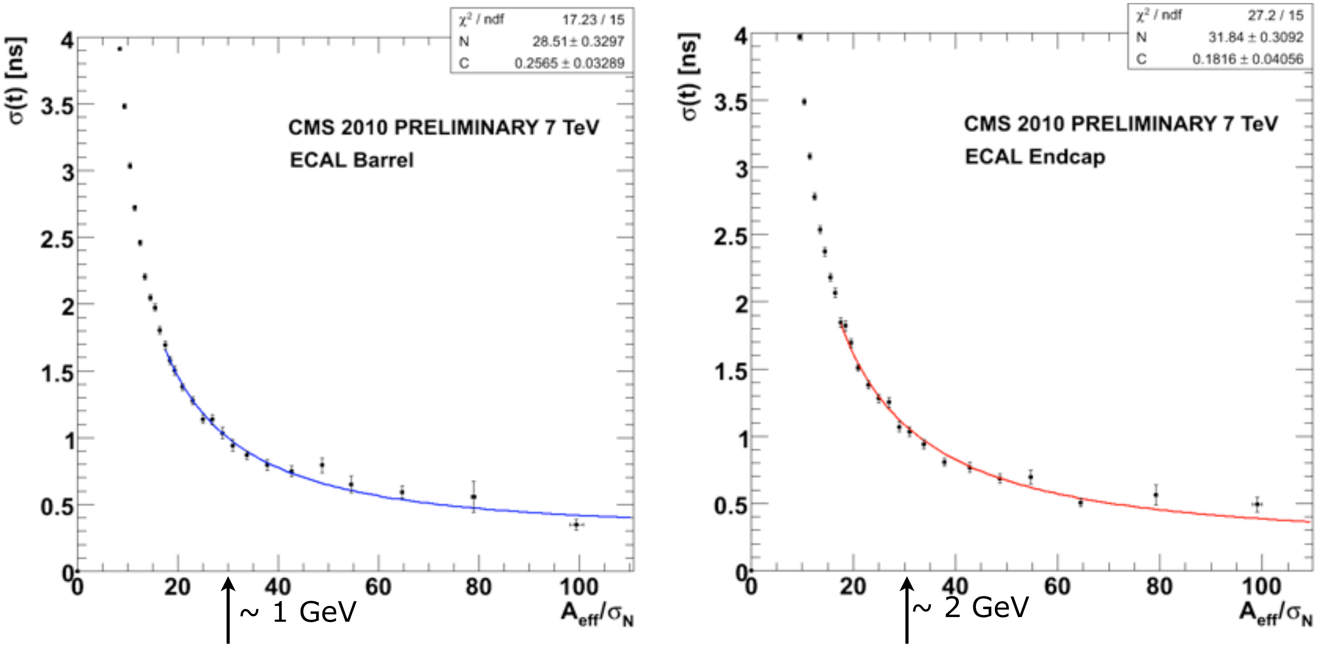


Not a fit !

from ECAL

from Tracker

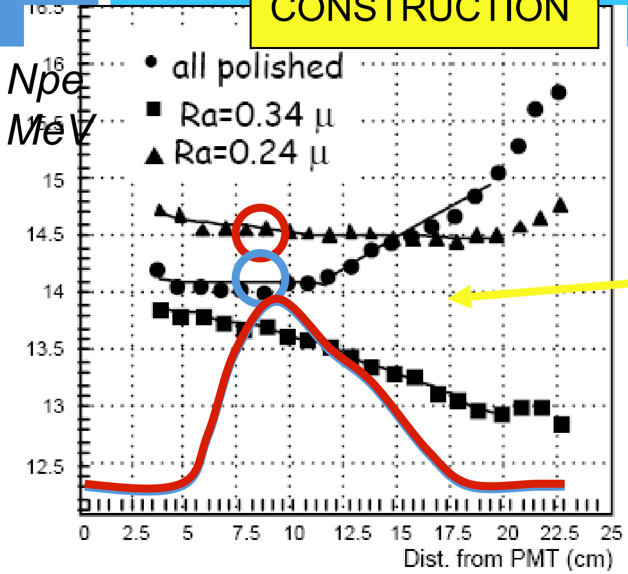
Time resolution



- **The plot shows the time resolution as a function of the effective amplitude, derived by comparing the time in nearby crystals, in the same cluster**
  - The noise and the systematic term in the time resolution are extracted from a parametric fit to data (see CFT-09-006 for a discussion of the analysis procedure)
  - The observed noise term is consistent with expectations from test beam data and measurements during Cosmic Run at 4 Tesla (2008)
  - The constant term in the time resolution due to local systematic effects is of about 200 ps

Fighting for the constant term

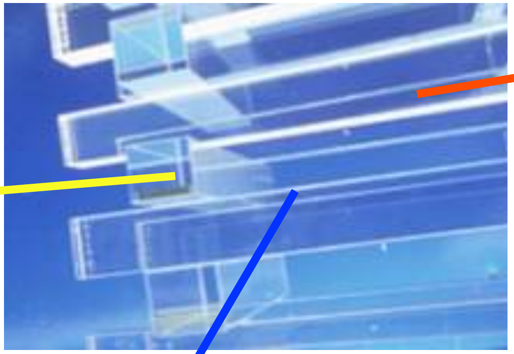
CONSTRUCTION



Crystal uniformity ~0.3%

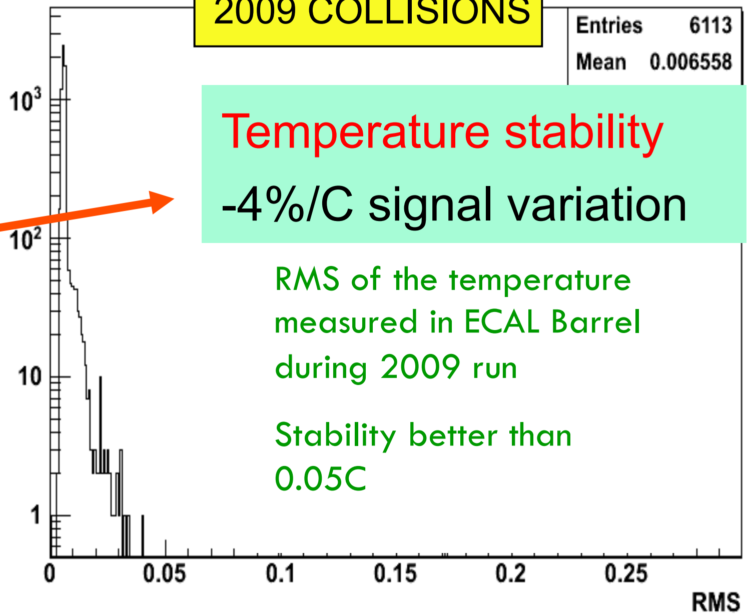
|dLY/X0 | < 0.35%/X0

between 3 and 13 X0



Radiation damage followed by monitoring ~0.2%

2009 COLLISIONS



Temperature stability

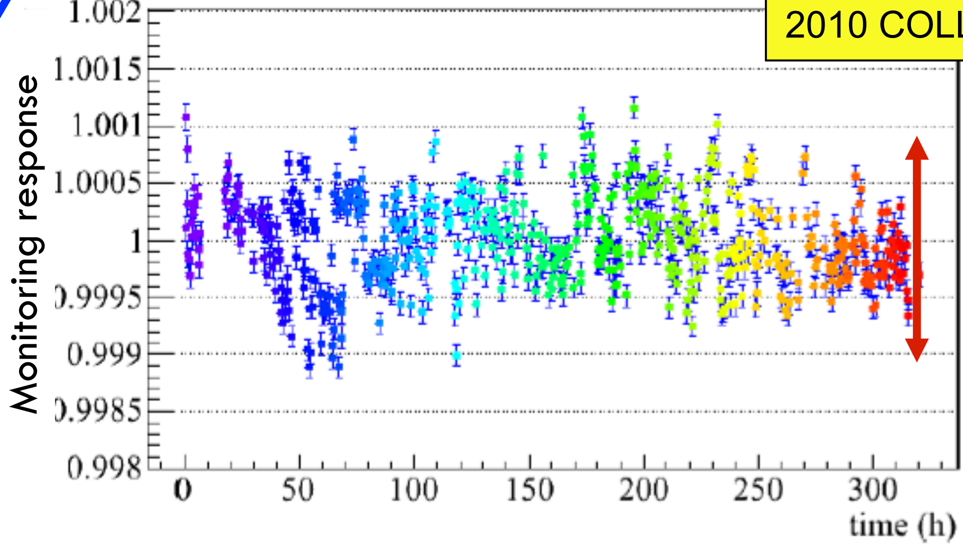
-4%/C signal variation

RMS of the temperature measured in ECAL Barrel during 2009 run

Stability better than 0.05C

Stability for a typical channel over about 350 h

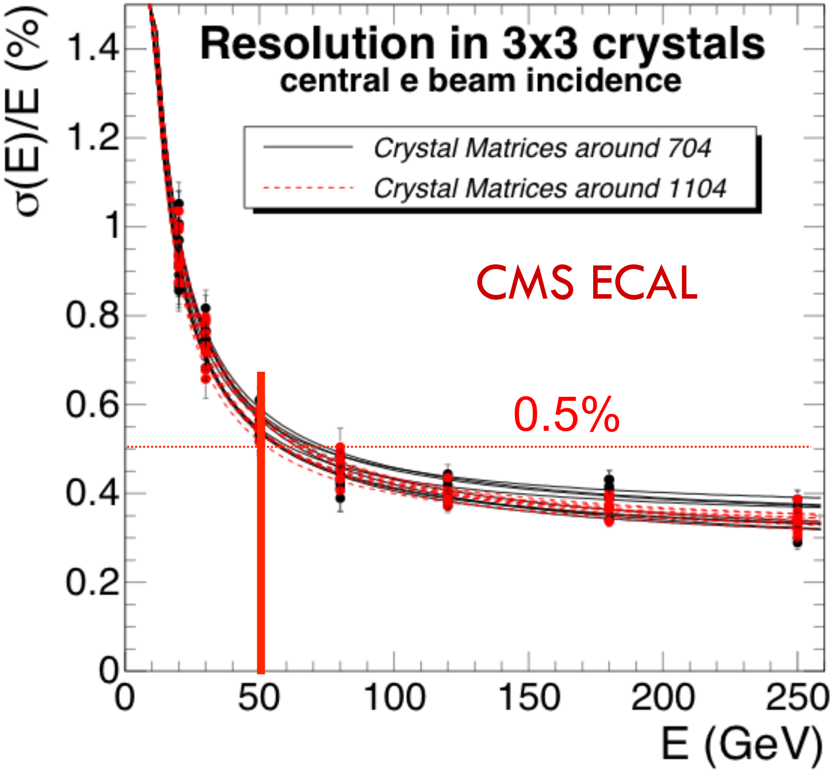
2010 COLLISIONS



+/- 0.1%

Test-beam performance

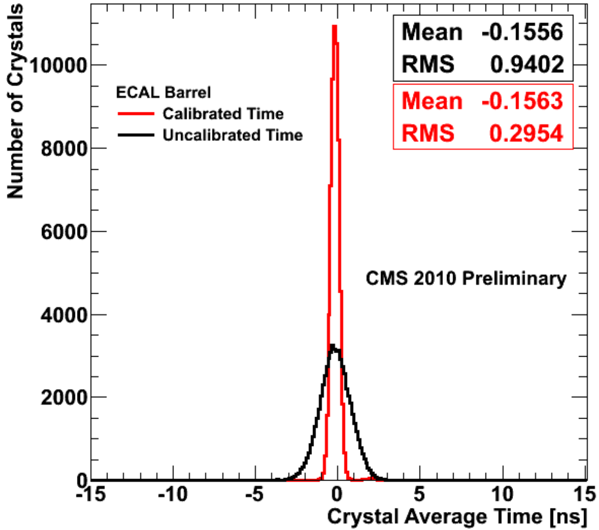
TEST-BEAM



50 GeV -> 0.5-0.6%

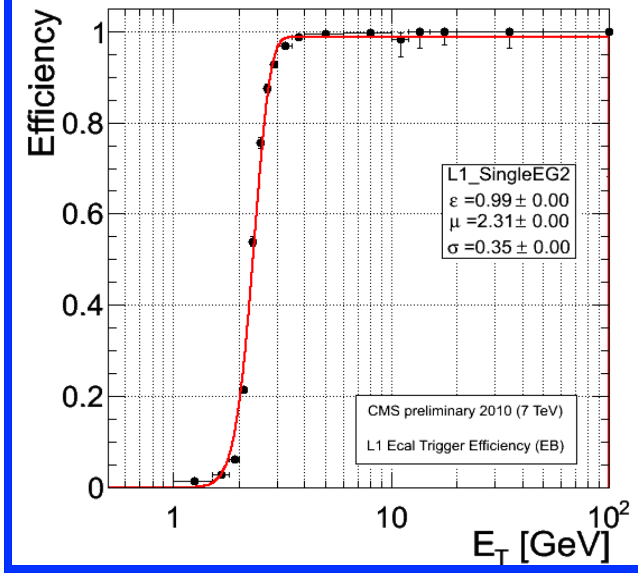
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Performance with collisions



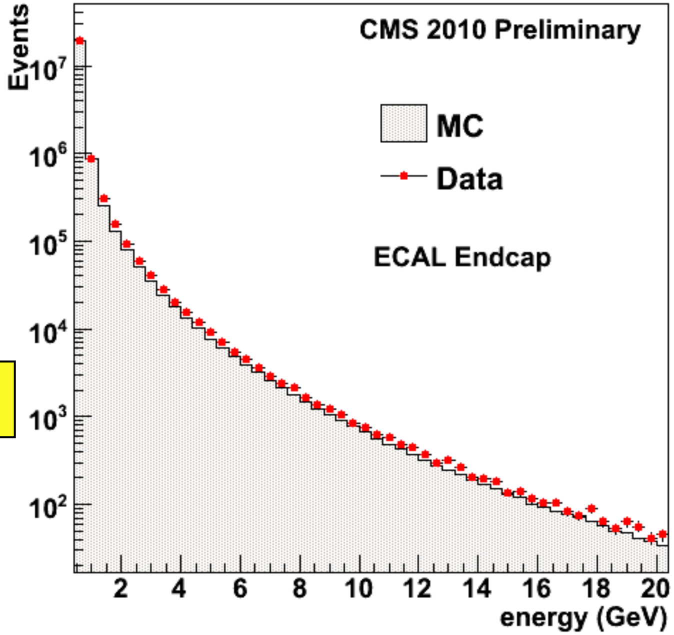
Mean crystal timing before and after calibration RMS= 0.3 ns

2010 COLLISIONS



L1 trigger detection efficiency of e/ γ -like patterns in ECAL Barrel for the trigger requiring ET>2 GeV

Energy spectra in the individual channels.

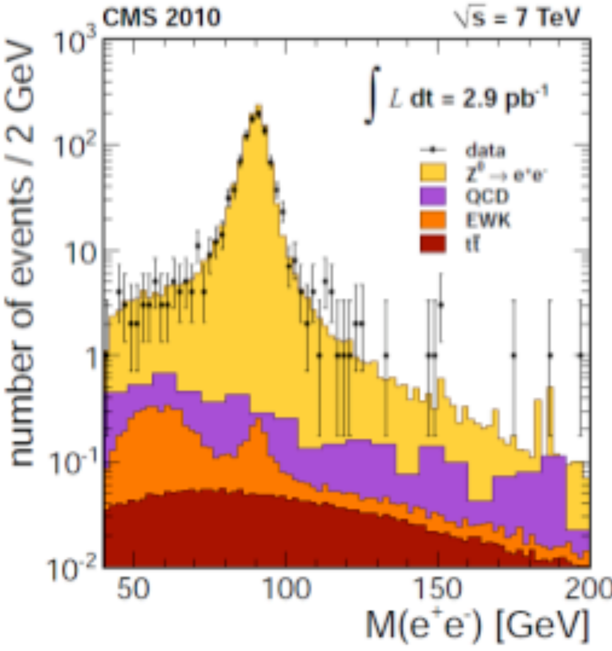


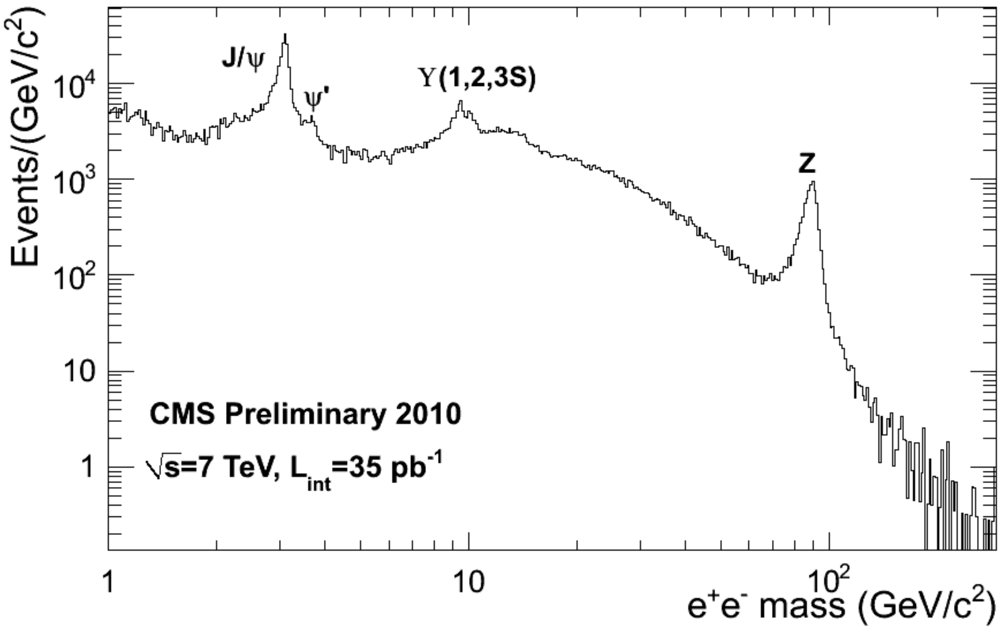
EB 61200 channels
99% operational

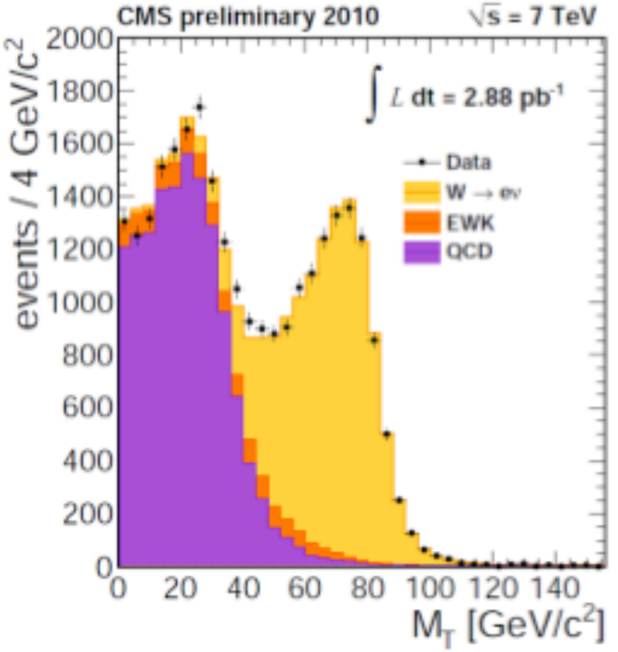
EE 14648 channels
99.3% operational

Single- and di-electrons

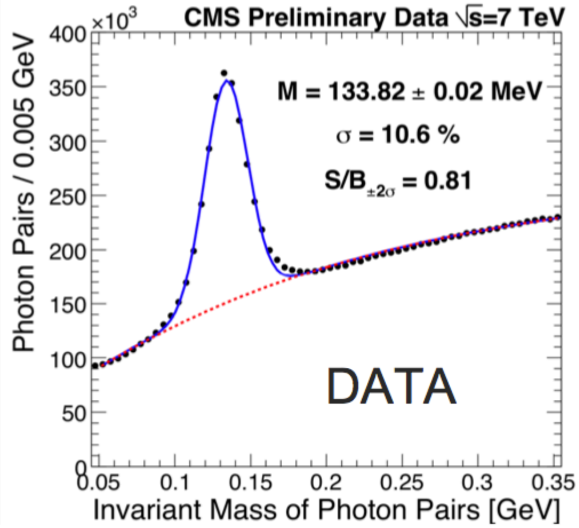
- ☐ Important source of calibration
- ☐ Important customer of calibration

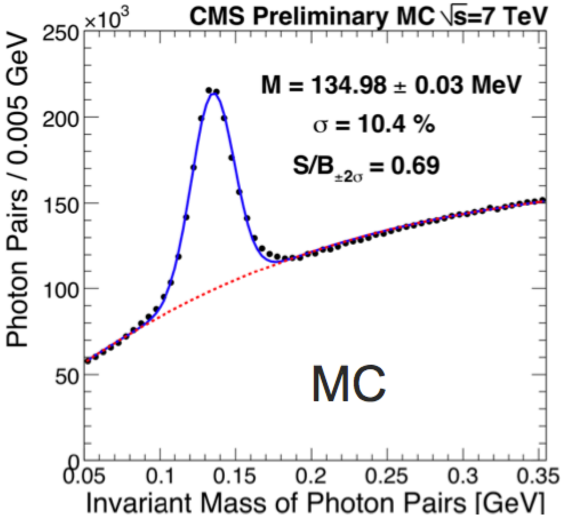


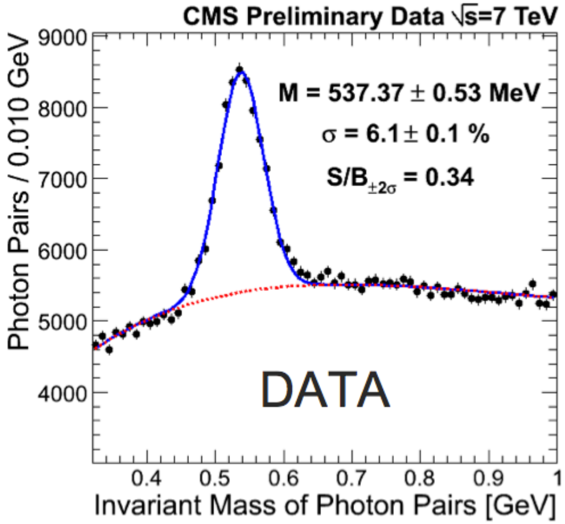


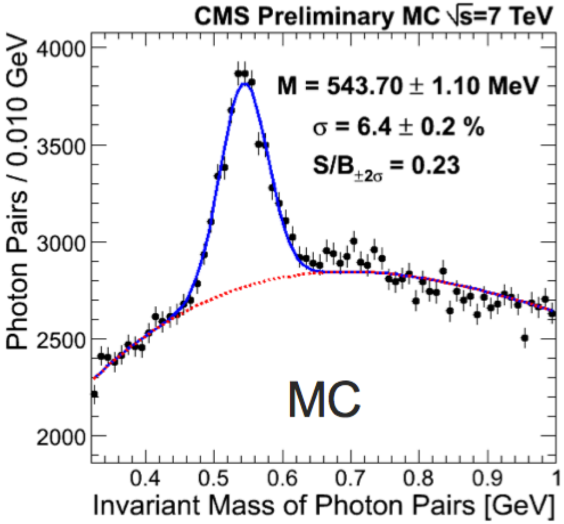


η and π^0 reconstruction/calibration







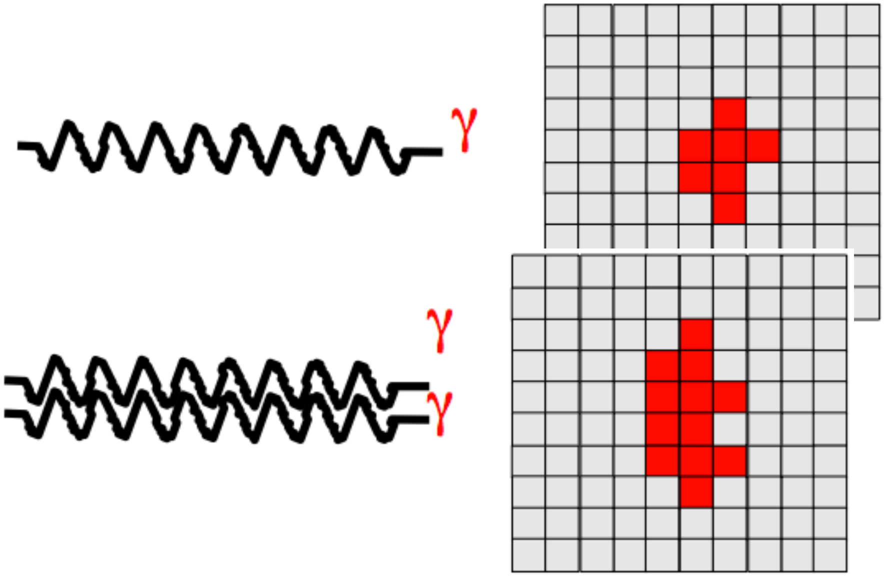


Isolated photons

- Studied experimentally since 30 years
  - Large contamination from the decay of energetic neutral mesons.
  - Experimentally accessible objects: **isolated photons.**
  - Main handles:
    - track and calorimeter sums,
    - shower shapes.

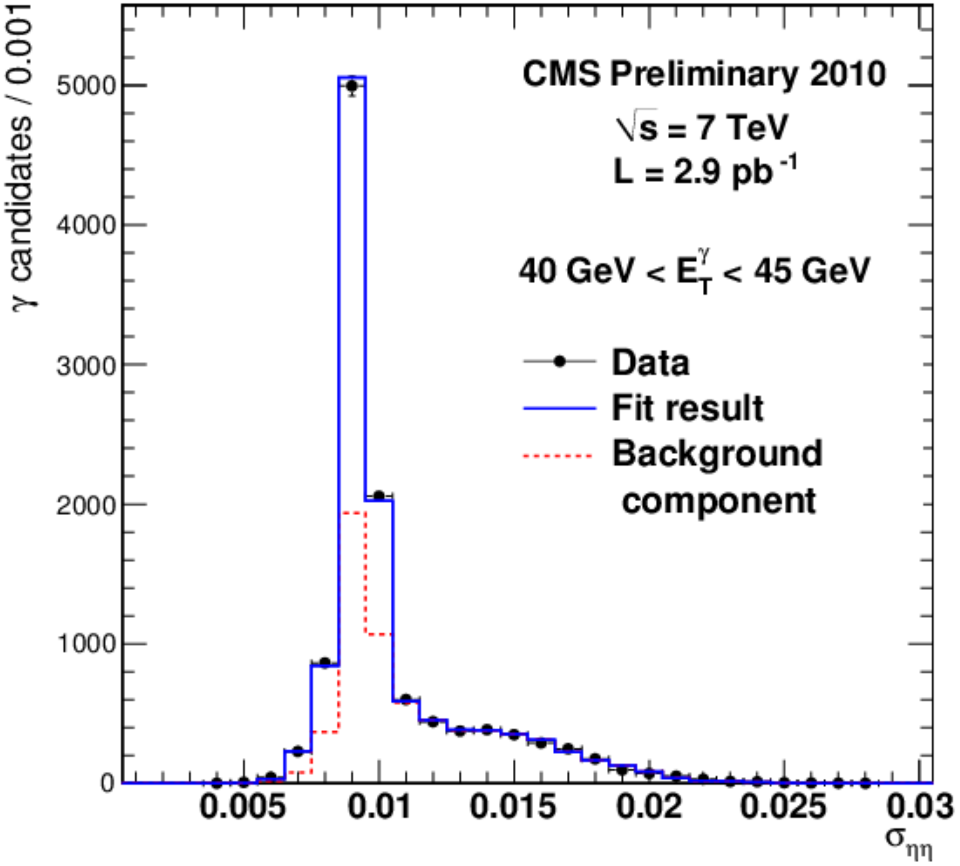
Handles for photon signal yield extraction

- Main background for isolated photons are neutral mesons decaying into 2γ.
- Two main tools to disentangle
  - Candidate isolation in Tracker, ECAL, HCAL.
  - Shower shape in ECAL. ➘



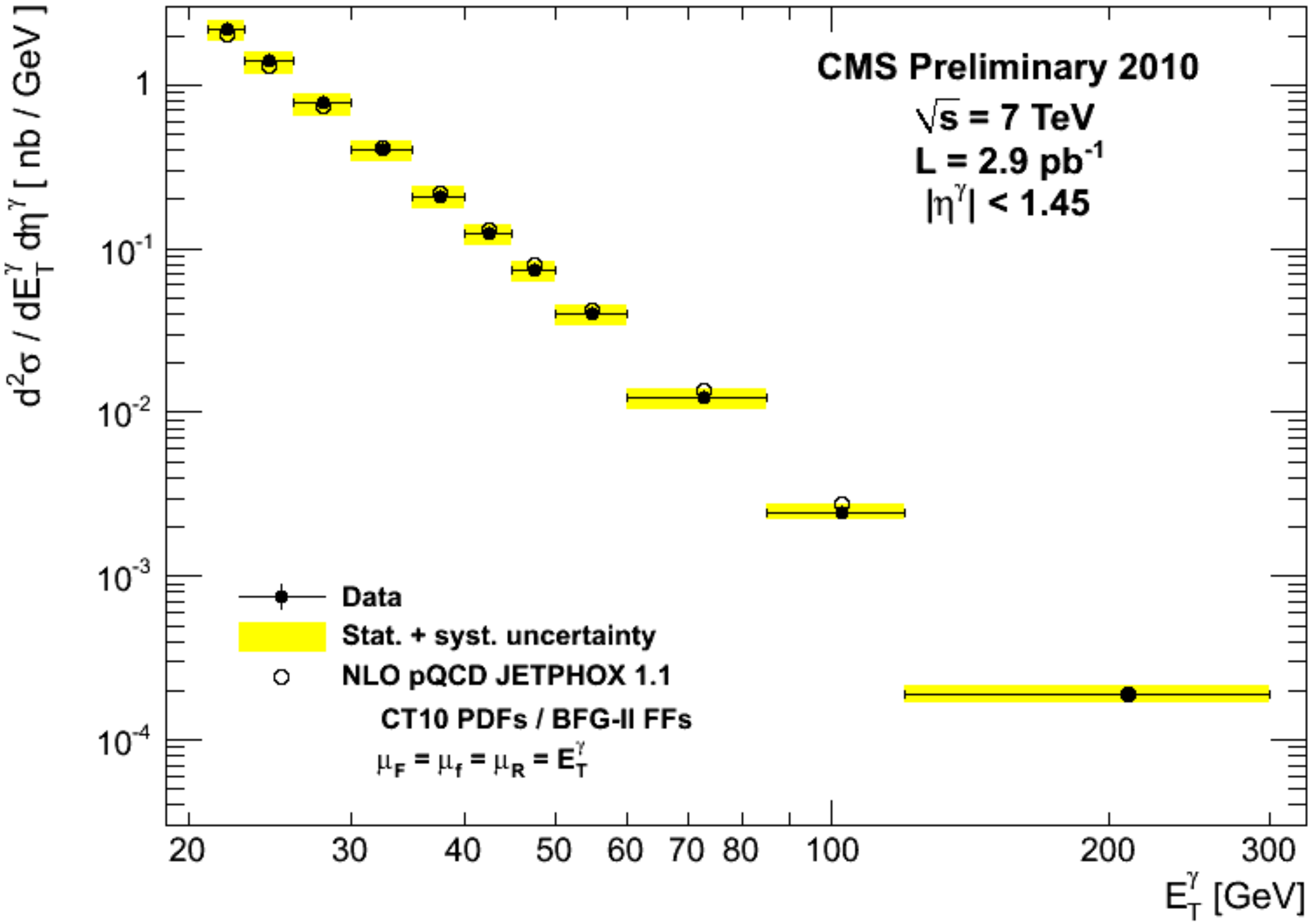
Two-component fit to the data

- Good **fit** to the **data**
  - Signal shape from MC
    - Corrected by Z-electron data.
    - Not yet enough Z γ events
  - Background from data in isolation sideband.



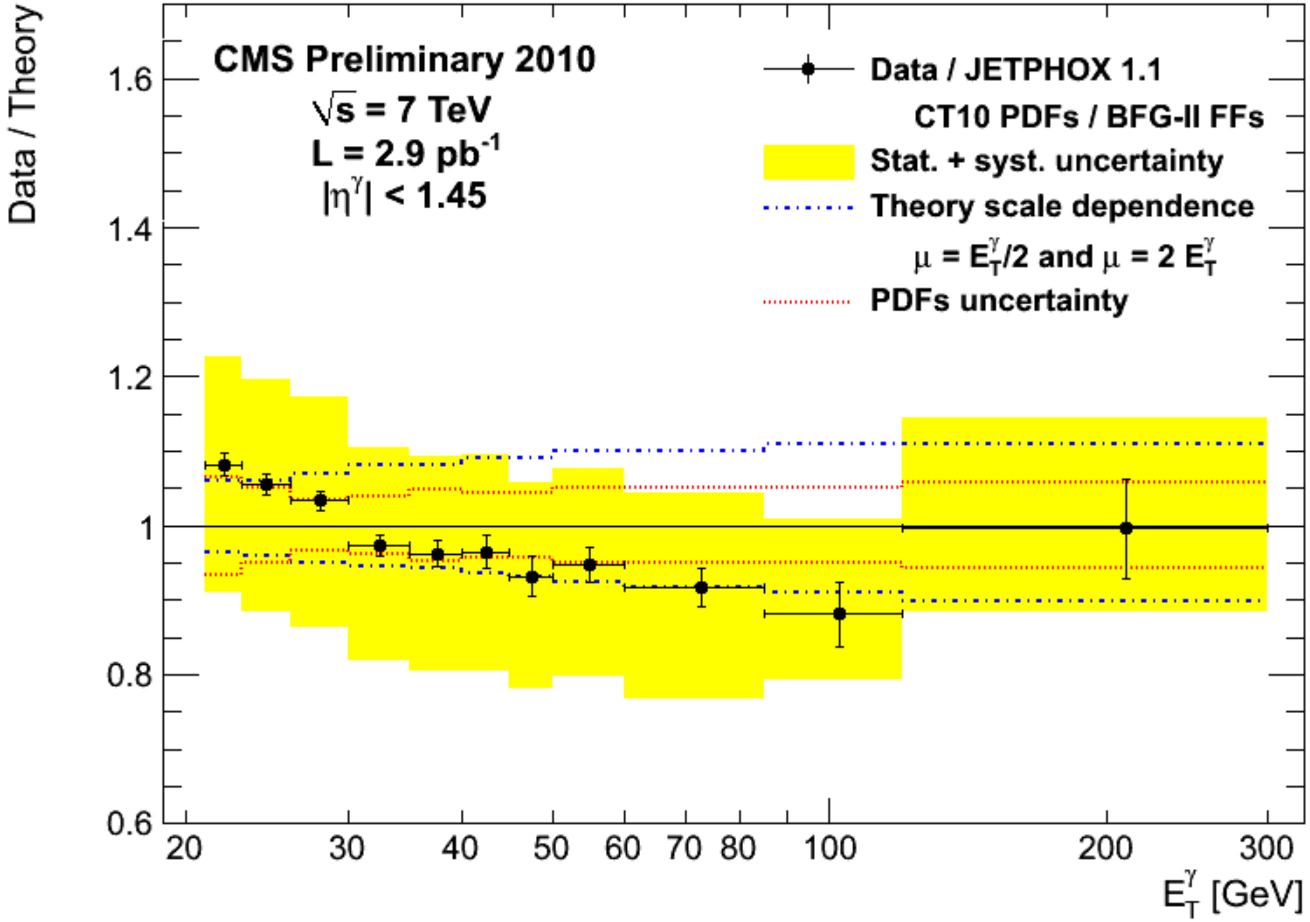
Differential cross section

- 11% lumi uncertainty not included
- Isolation efficiency from Z-electron data

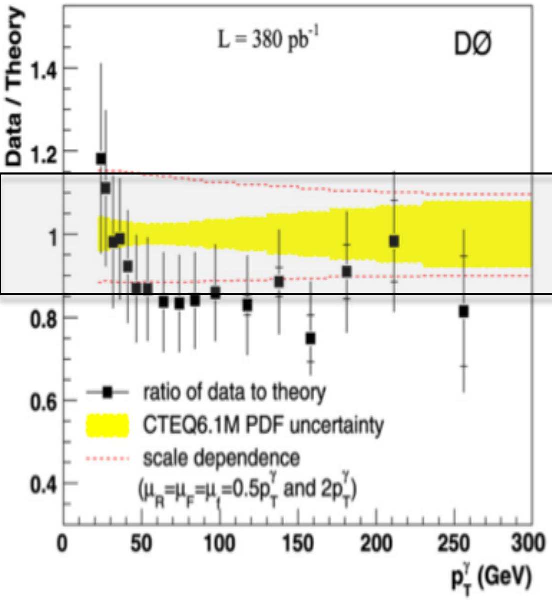


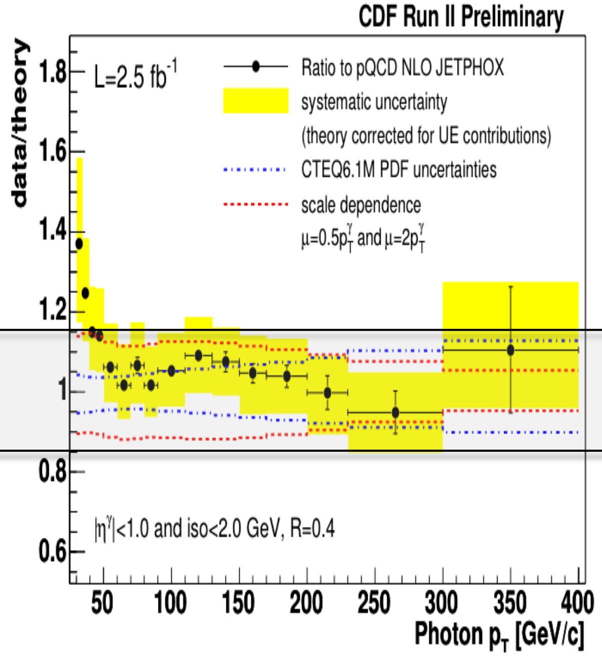
Comparison between theory and data

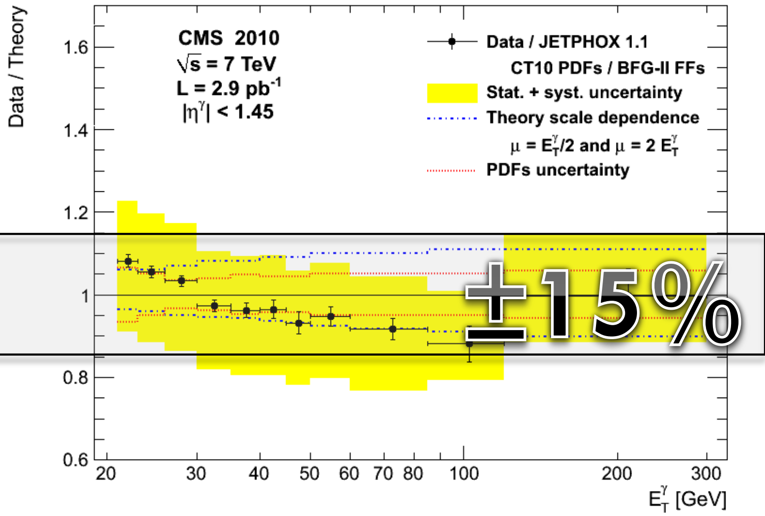
- 11% lumi uncertainty not included



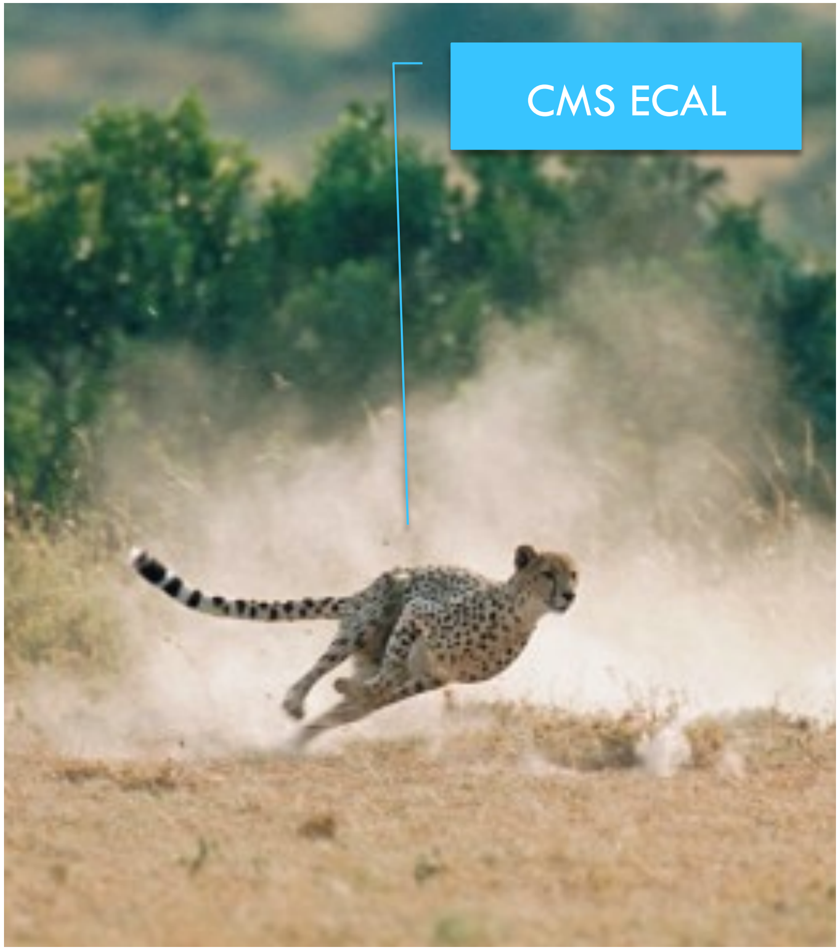
The data and the theory





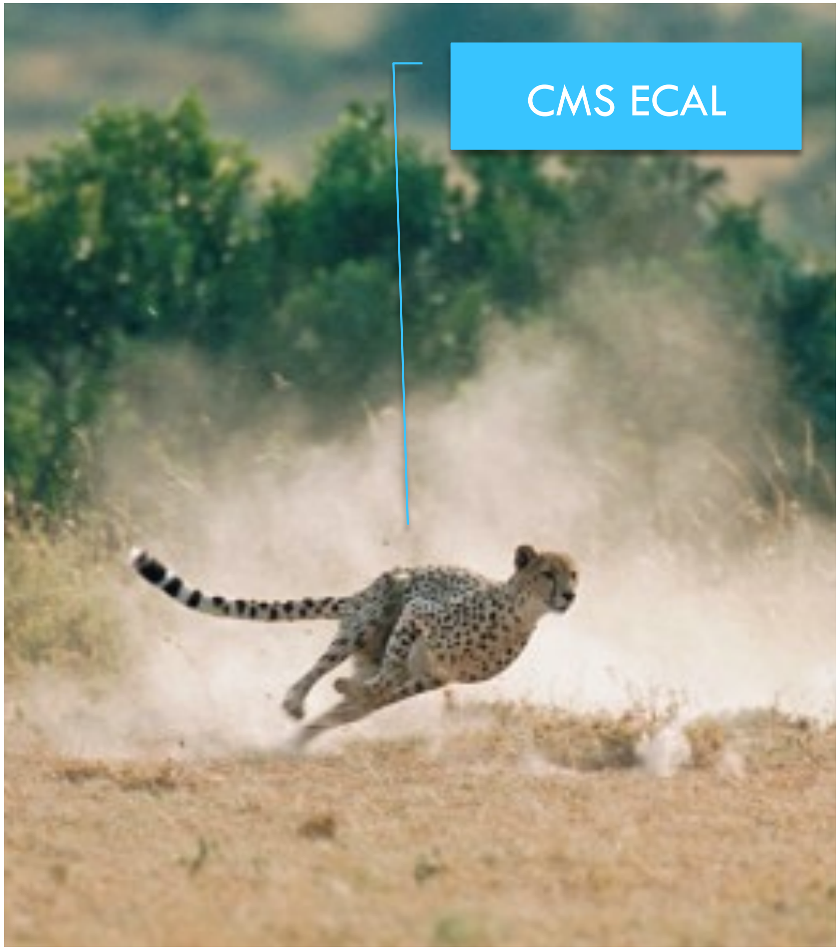


The hunter


CMS ECAL

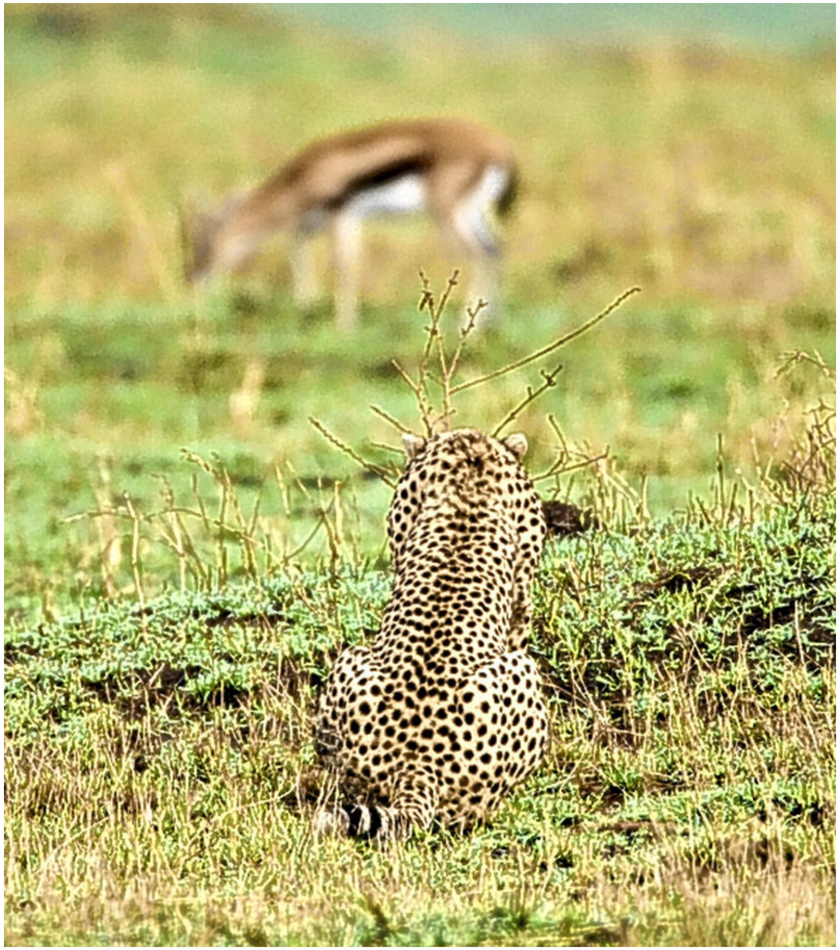
- High-granularity in >70000 crystals
- Light yield monitoring to better than 0.2%
- APD HV stability better than 10 mV
- Temperature stability better than 0.05 C
- Selective full readout

Conclusions



- A long way since the 90s
- **Excellent performance in first measurements**
  - Single photons, Z and W bosons, etc
- **Careful follow-up of the detector**
  - Monitoring, stability, calibration
- First life of the calorimeter
  - **Not yet probing the constant term**
- Looking out for **the** (elusive) prey !

Acknowledgement



Higgs, we're watching you.

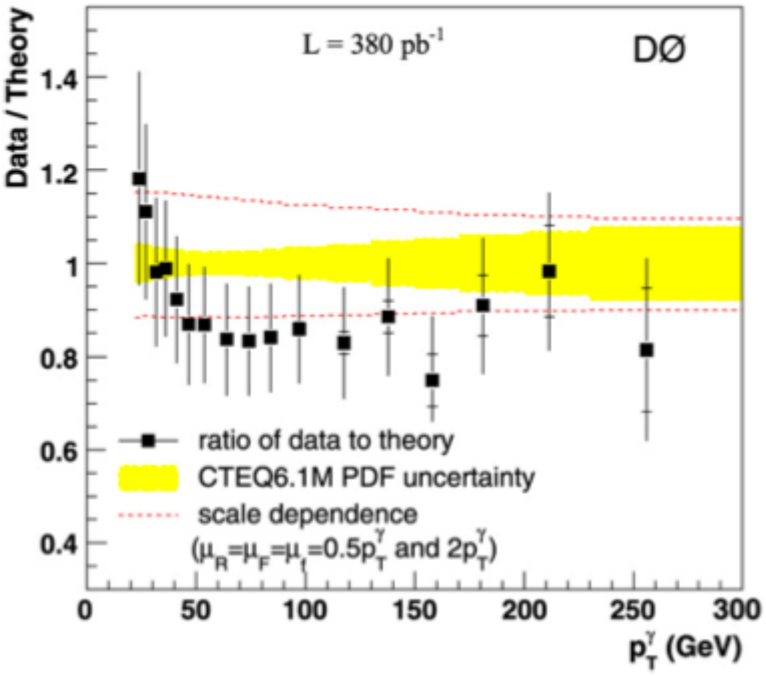
- The CMS ECAL collaboration
  - All who were involved in making this detector an extraordinary reality.
  - In particular J.-L. Faure, E. Auffray, D. Barney, E. Longo and P. Lecoq for sharing material and history.

More than you want to know

Recent results on isolated photons

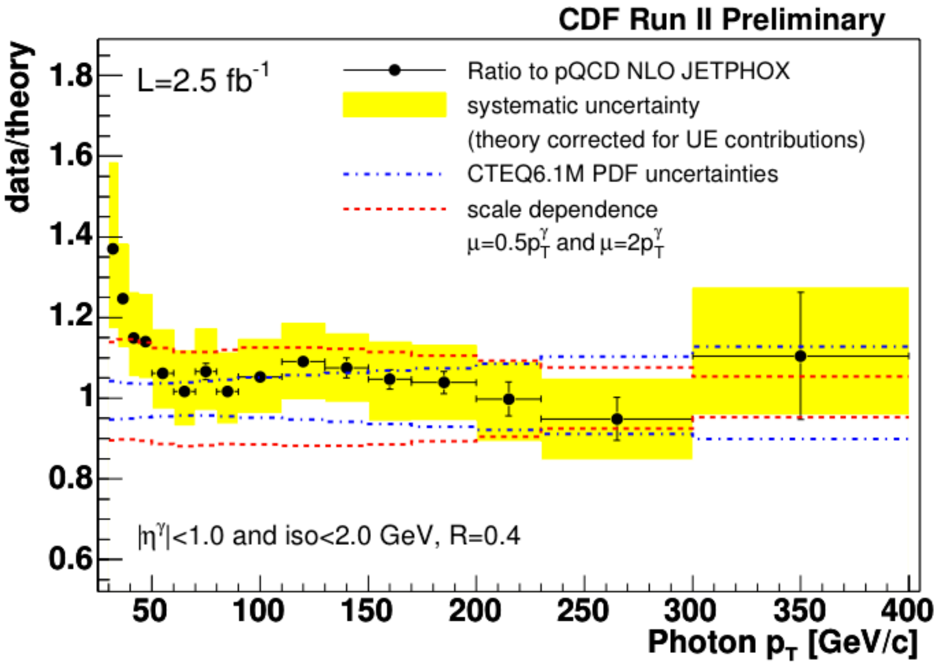
PLB 639, 151 (2006) + 658, 285(E) (2008)

- DØ 2006/2008
  - ppbar at 1.96 TeV
  - **Syst. Uncertainty 10 – 20%**



PRD 80, 111106 (2009)

- CDF 2009
  - ppbar at 1.96 TeV
  - **Syst. Uncertainty 10 – 15%**

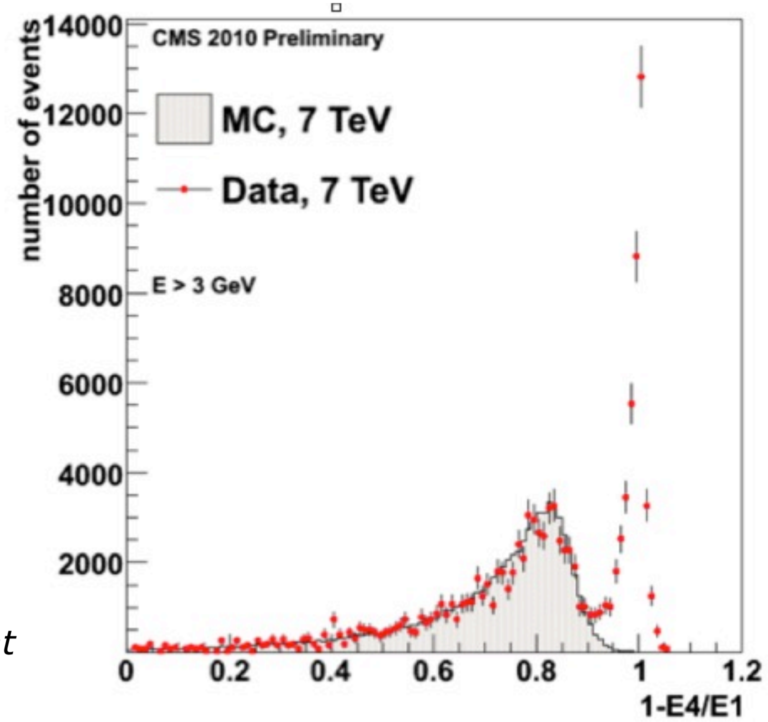


Anomalous signals

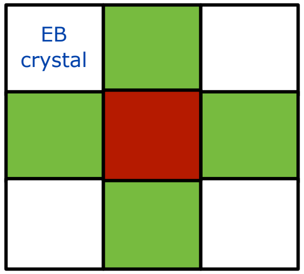
In a small fraction of collision data we observe anomalous signals in ECAL:

- distinct pulse shape
- different timing
- single crystal energy deposit
- uniformly distributed in EB
- not seen in EE (VPTs readout)

Origin: highly ionizing particles in the APDs



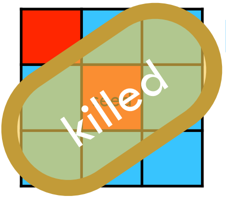
pulse shape exhibits faster rising time and is *inconsistent* with the signal shape from scintillation



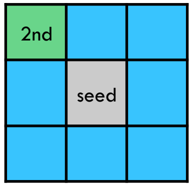
Easily identified and removed by a quality selection (e.g. an energy ratio **E4**/**E1**). Timing and pulse shape discriminants could also be deployed to tag these signals.

Double spikes after swiss-cross cleaning

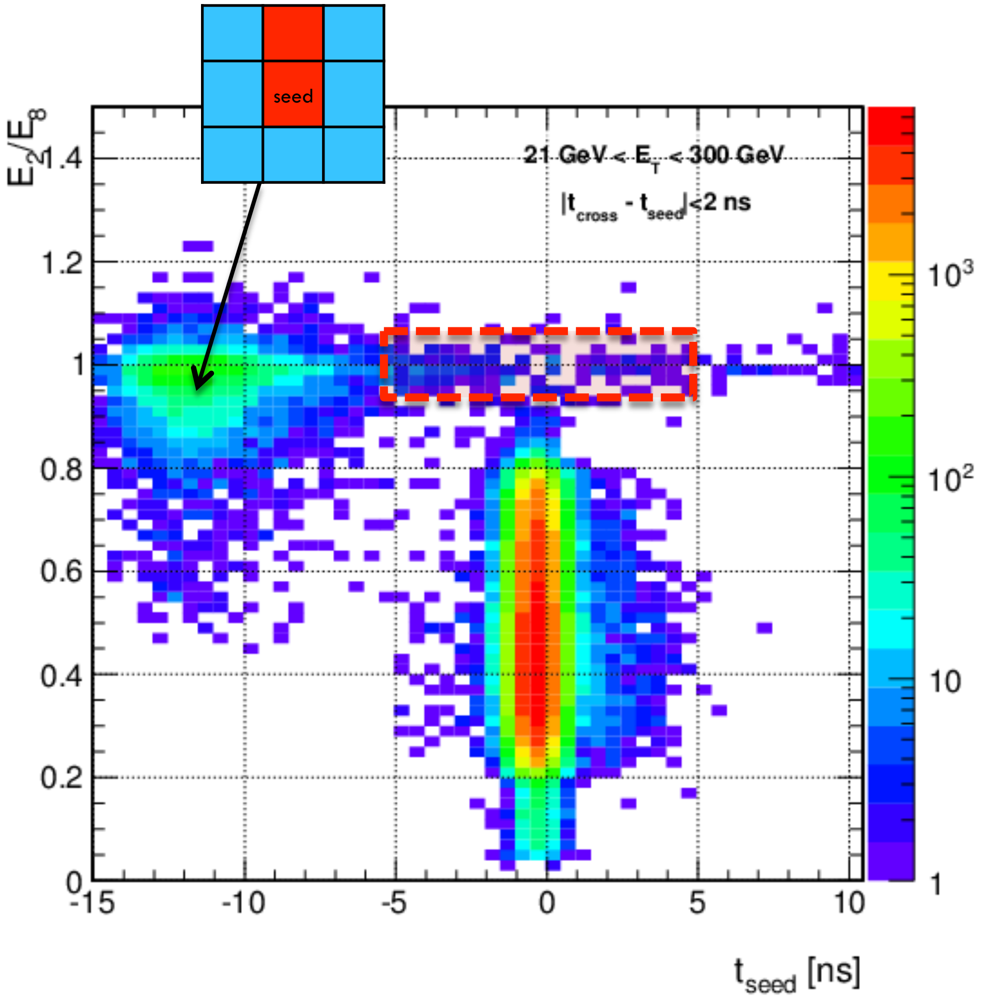
- Require
  - Photon ID
  - $\sigma_{\eta\eta} < 0.01$
  - Swiss-cross cleaning: $1 - S_4/S_1 < 0.95$



- Remaining double spikes clearly visible at $E_{2nd}/E_{3\times3\ \mathrm{rim}} \sim 1$ ➚

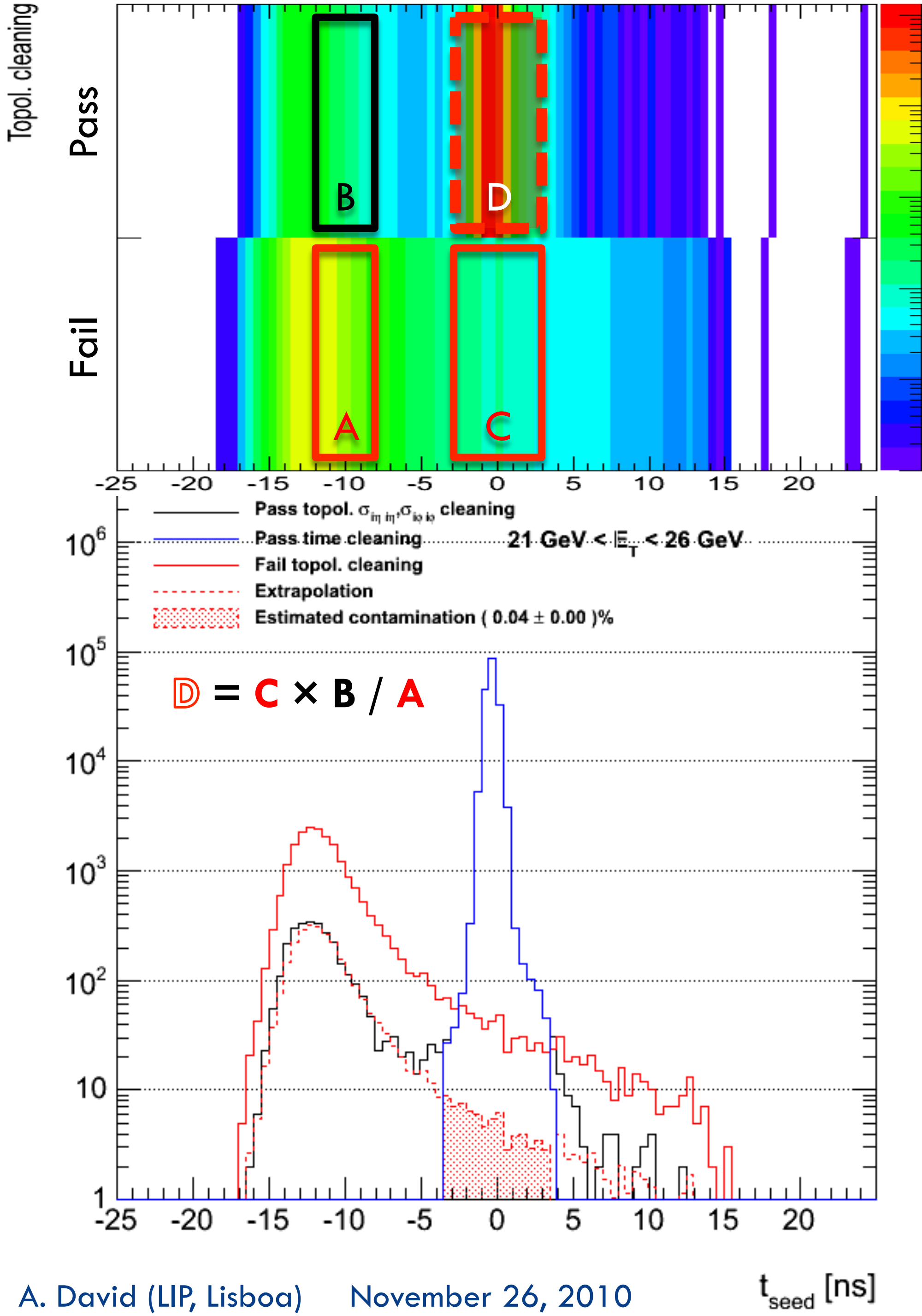


- Removed using $\sigma_{\eta\eta} > 0.001$ or $\sigma_{\varphi\varphi} > 0.001$



Spike contamination

- Estimate remaining spikes in data
  - Crucial for ECAL-driven analysis
- Pre-select events with
  - $\sigma_{\eta\eta}<0.01$
  - $(1-S_4/S_1)<0.95$ (Swiss-cross)
- Perform ABCD on ➔
  - Seed time vs pass/fail topological cleaning
    - $\sigma_{\eta\eta}>0.001$ or $\sigma_{\varphi\varphi}>0.001$
- **Effect on the signal <0.2%**

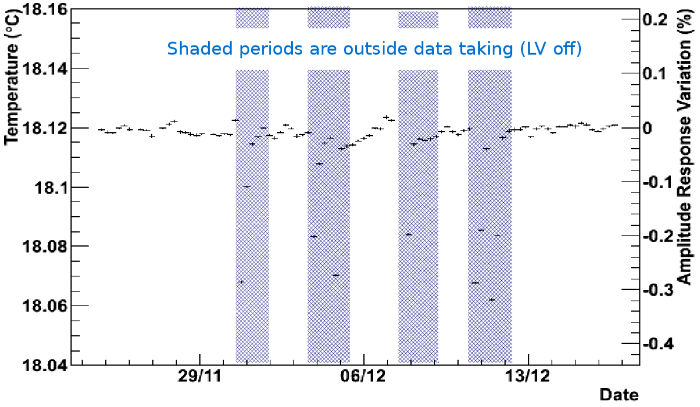


Temperature stability

- nominal temperature of 18 °C
- water flow to stabilize the detector temperature
- thermistors with nominal sensitivity of 0.012 °C: on the back of each 5×2 (5×5) matrix of crystals in the barrel (endcap)

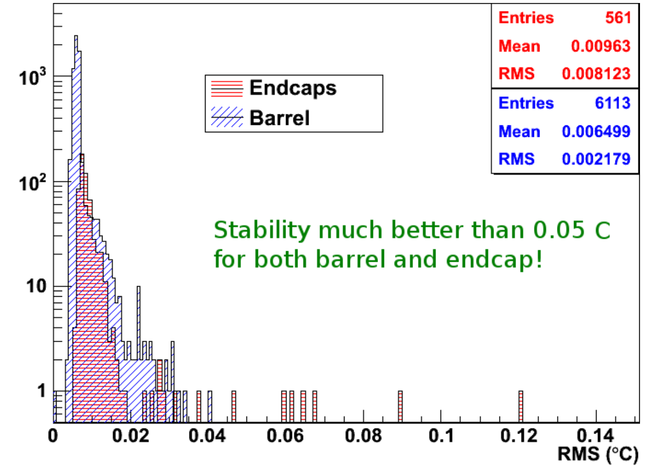
- the APD temperature dependence is absorbed into the transparency corrections
- local in-homogeneities are absorbed into the definition of the inter-calibration constants; only the time stability is relevant for the energy resolution.

average temperature of the ECAL barrel over one month of data taking



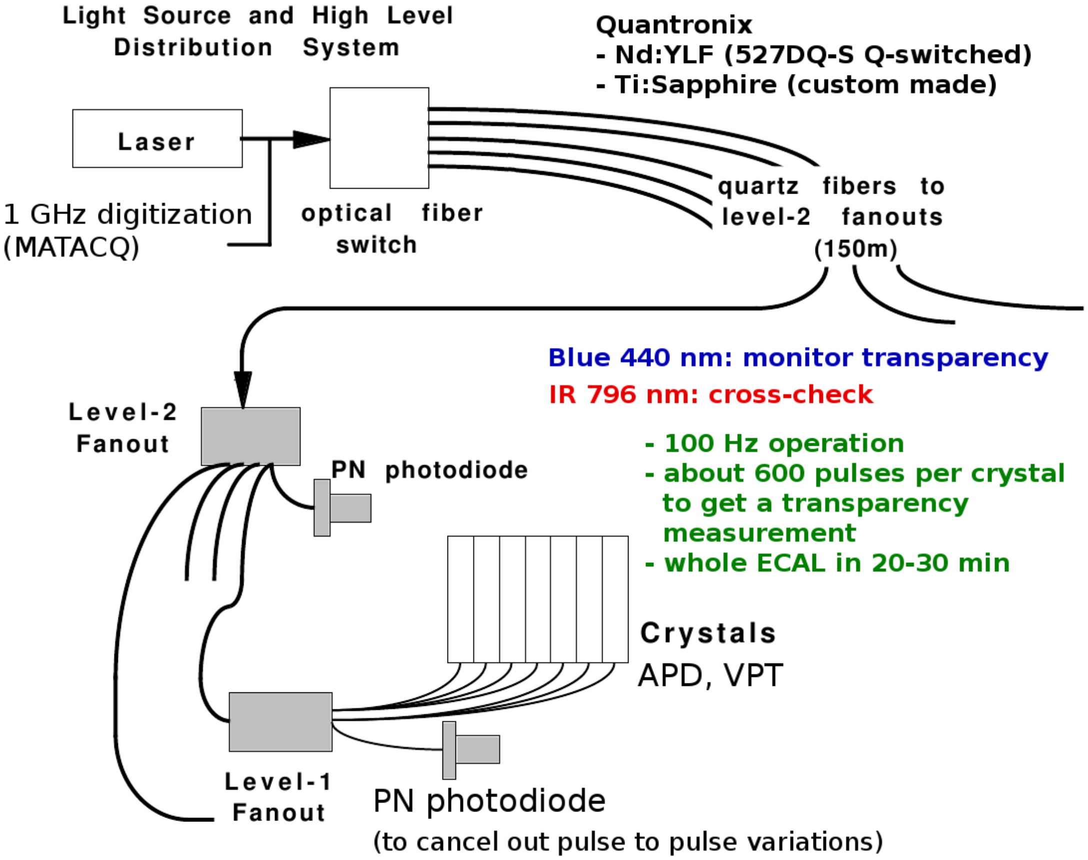
Shaded periods are outside data taking (LV off)

Corresponding tempeature stability measured by each single thermistor for barrel and endcap



Stability much better than 0.05 C for both barrel and endcap!

Laser monitoring system



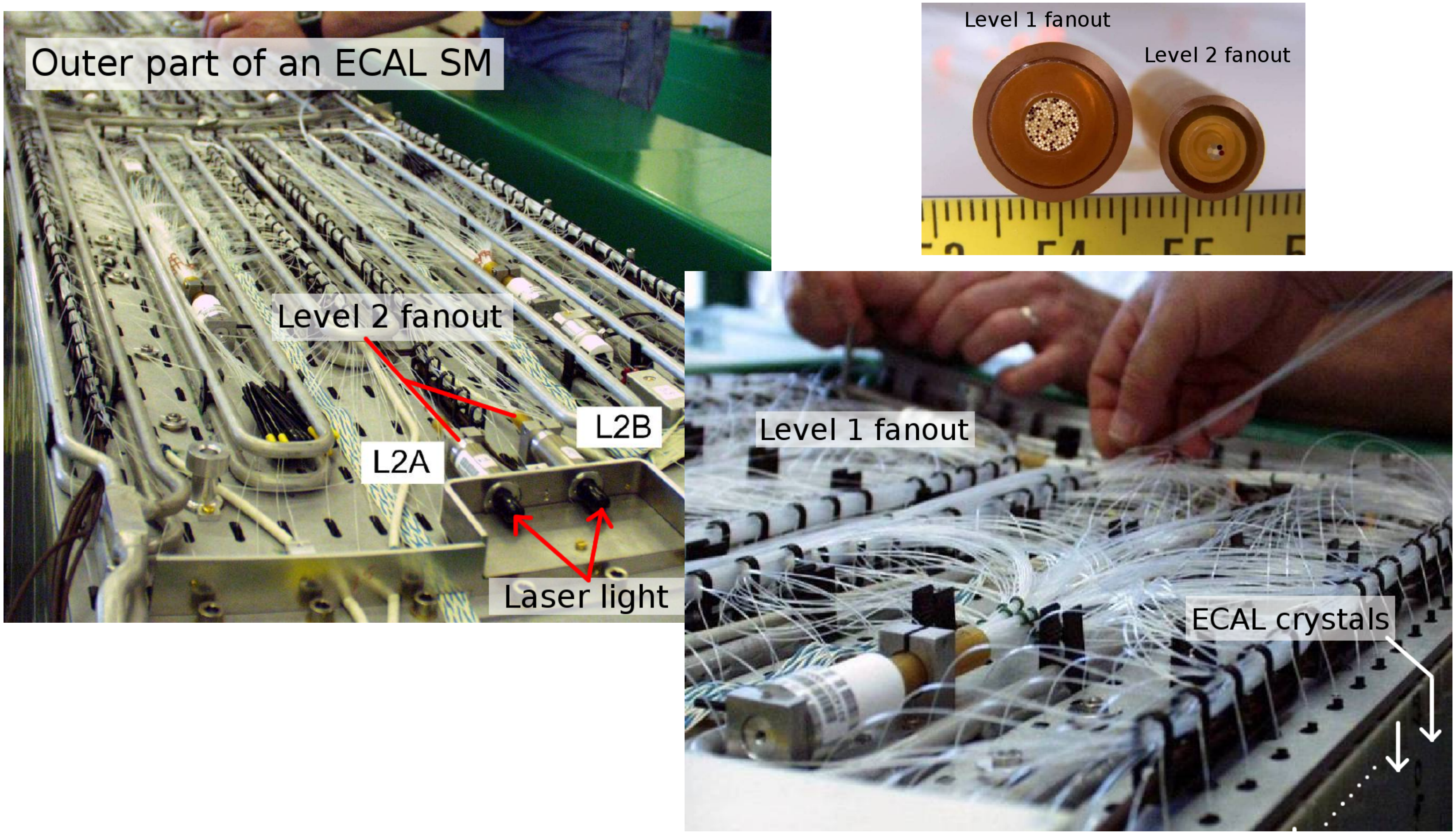
Blue 440 nm: monitor transparency

IR 796 nm: cross-check

- **100 Hz operation**
- **about 600 pulses per crystal to get a transparency measurement**
- **whole ECAL in 20-30 min**

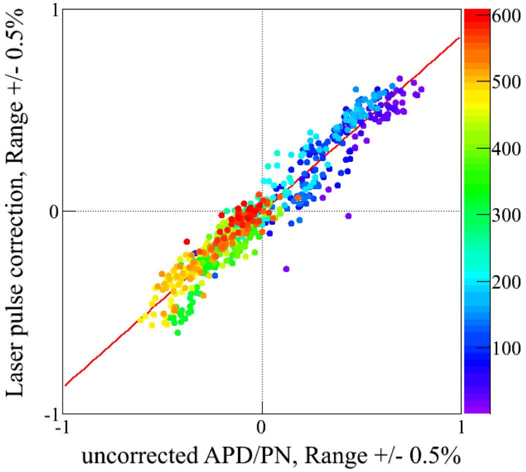
- Spectral contamination: $< 10^{-3}$
- Pulse energy: 1 mJ at the source, dynamic range up to 1.3 TeV equivalent
- Pulse width: < 40 ns FWHM to match the ECAL readout
- Pulse jitter: < 4 ns (24 hours), < 2 ns (30 min).
- Pulse to pulse instability: < 10%

Laser monitoring system

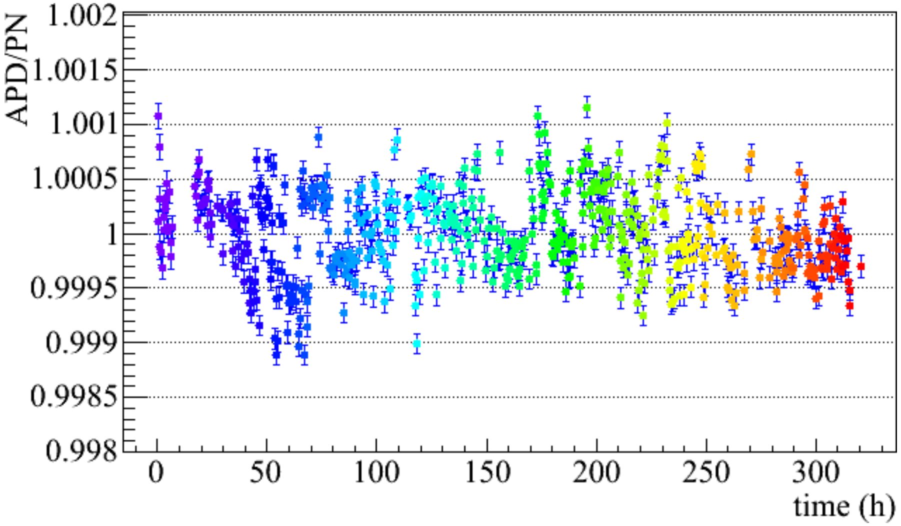


Crystal transparency measurement

- PN linearity correction
- correction for the different shaping time of APD (VPT) and PN using the Single Pulse Response of each individual channel of APD (VPT) and PN convoluted with the laser shape from the 1 GHz digitization



Stability for a typical channel over about 350 h

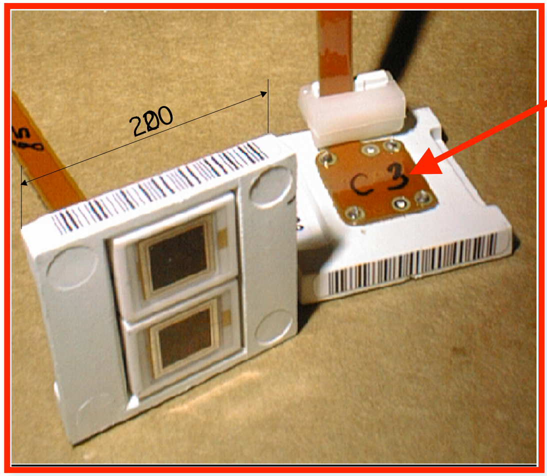


- stability defined as the r.m.s. of the considered quantity

- standard loose quality selections applied
- excellent stability: $< 4 \cdot 10^{-4}$

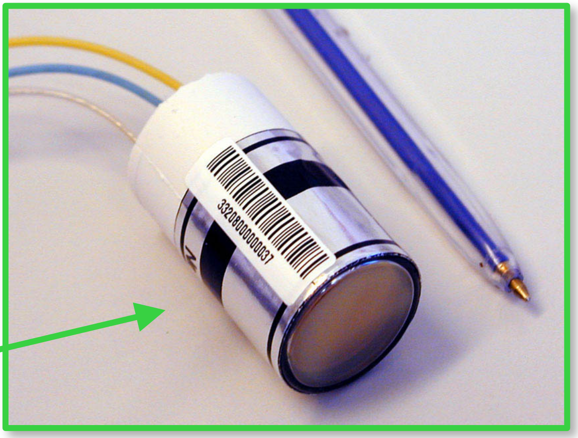
Photodetectors

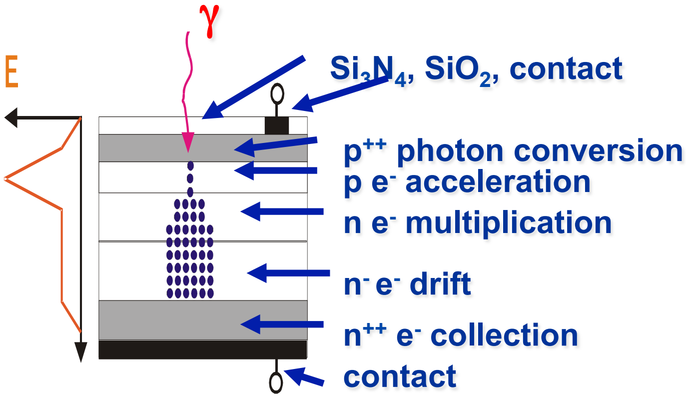
- $PbWO_4$ crystals have fairly low light yield – need photodetectors with gain
- Need to work in a 4T field and an intense radiation environment



Barrel: Avalanche PhotoDiodes (APDs)

Endcaps: Vacuum PhotoTriodes (VPTs)





Si_3N_4, SiO_2, contact

p^{++} photon conversion

p e^- acceleration

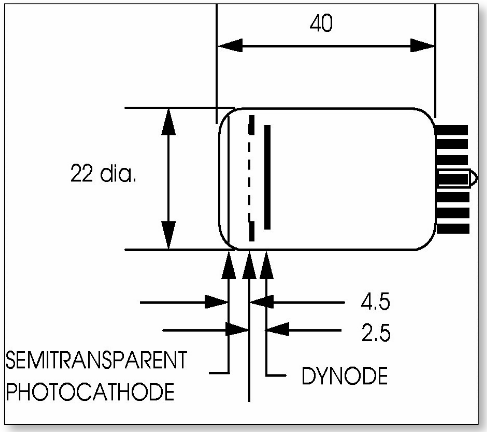
n e^- multiplication

n^- e^- drift

n^{++} e^- collection

contact

APDs (Hamamatsu), VPTs (RIE, Russia)



Energy resolution: stocastic term *a*

- photostatistics contribution, including
  - Light Yield
  - light collection efficiency
  - geometrical efficiency of the photodetector
  - photocatode quantum efficiency

N_{pe}/GeV = 4000 for 0.5 cm^2 APD → 1.6%

- electron current multiplication in APD, contributing a square root of excess noise factor, F = 2

1.6×1.4 = 2.25%

- Lateral containment (5×5 matrix) → 1.5%

Total stochastic term a = 2.7 %

Energy resolution: noise term *b*

40 ns shaping time, summed over 5x5 channels

- Serial noise (p.d. capacitance) $\propto 1/\sqrt{t}$
  - 150 MeV
- Parallel noise (dark current) $\propto \sqrt{t}$, mostly radiation induced
  - 100 MeV after one year at high luminosity
- Physics pile-up (simulated, with big uncertainties)
  - high luminosity 100 MeV

Total contribution

- **high luminosity 210 MeV**

Energy resolution: constant term c

- leakage (front, rear, blind material)

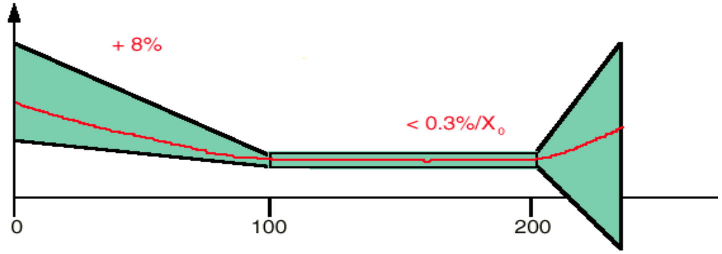
  CMS full shower simulation < 0.2 %

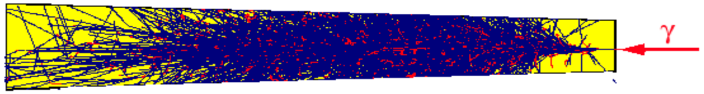
- system instabilities designed to be at the permill level
  - temperature stabilization < 0.1 °C (ΔLY = -1.9 % per °C)
  - APD bias stable at 20 mV (dM/dV = 3%/V)

- light collection uniformity,

  Specifications to stay < 0.3% ⇒

  reached by
  single face depolishing





- **Key issue to have c ~ 0.5 %**

  ⇒ intercalibration by monitoring and physics signals at 0.5 %

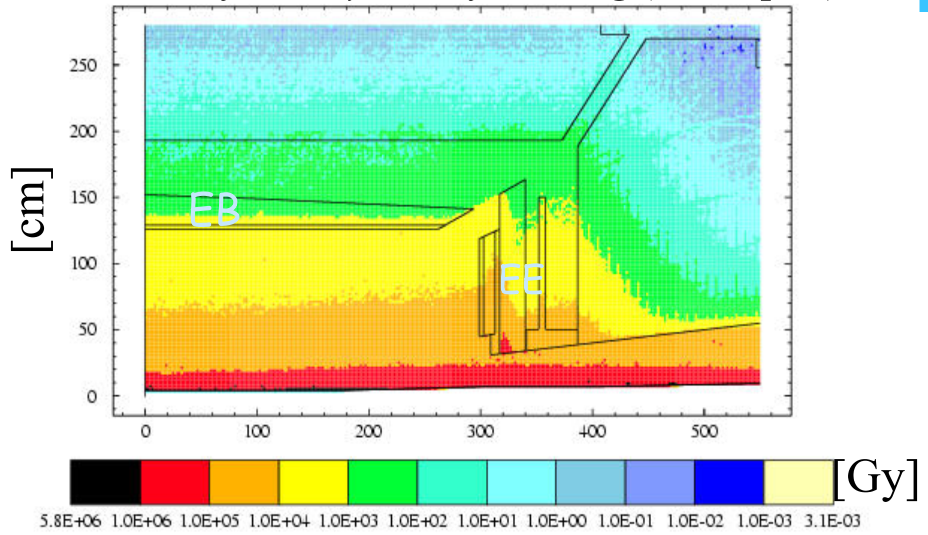
  including the radiation damage effect

Requirements for the EM calorimeters

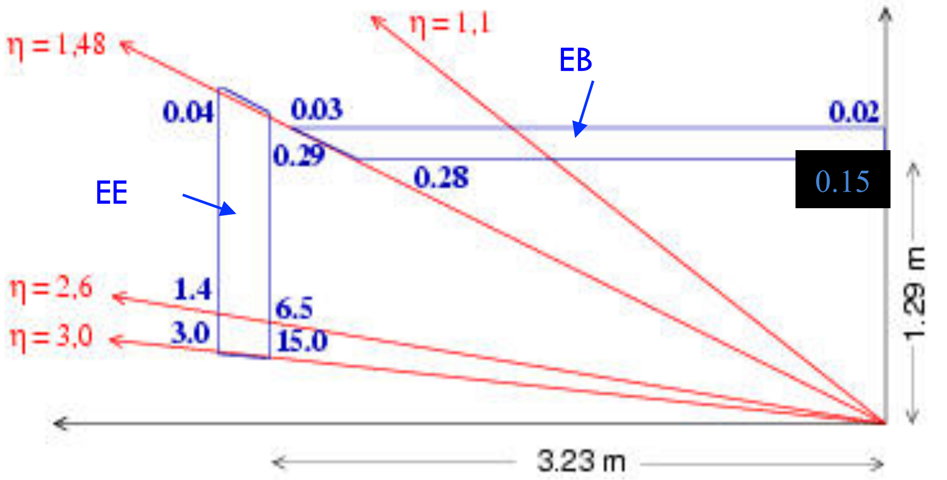
	CMS	Atlas
•Large acceptance		
•Extremely good energy and position resolution for high energy em showers up to $|\eta| <2.5$	• Excellent energy resolution	•Good energy resolution
•Fast	•Fast	•Fast
•compact	•compact	
•granular	• High granularity	• High granularity
		• Longitudinally segmented
•radiation tolerant	• Radiation resistance	• Radiation resistance
•Large dynamic range (from 200 MeV to ~2 TeV)	•E range MIP → TeV	• E range MIP → TeV
•linear		
•Particle identification (e/jet and γ/π^0 separation)	•Homogeneous calorimeter made of 75000 $PbW0_4$ scintillating crystals + PS FW	•Sampling LAr-Pb, 3 Longitudinal layers + PS

Radiation environment in CMS

Total dose after 10 years of running ($5x10^5$ pb^{-1})



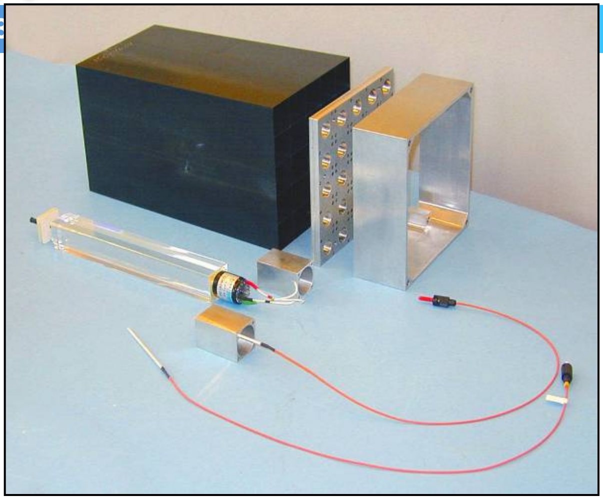
Total dose in the barrel after 10 years at the LHC is ~$2\text{-}4{\cdot}10^3$Gy and neutron fluence $2{\cdot}10^{13}$ n/cm^2



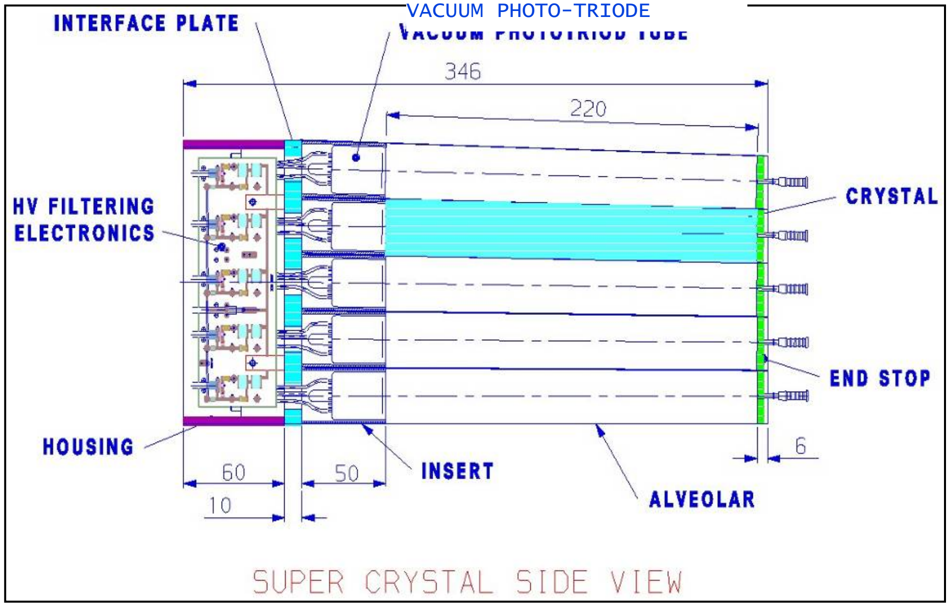
Dose rates [Gy/h] in ECAL at luminosity $L=10^{34}cm^{-2}s^{-1}$

Dose rate at high L in the Barrel is 0.15 – 0.3 Gy/h in the Endcaps 0.3-15 Gy/h

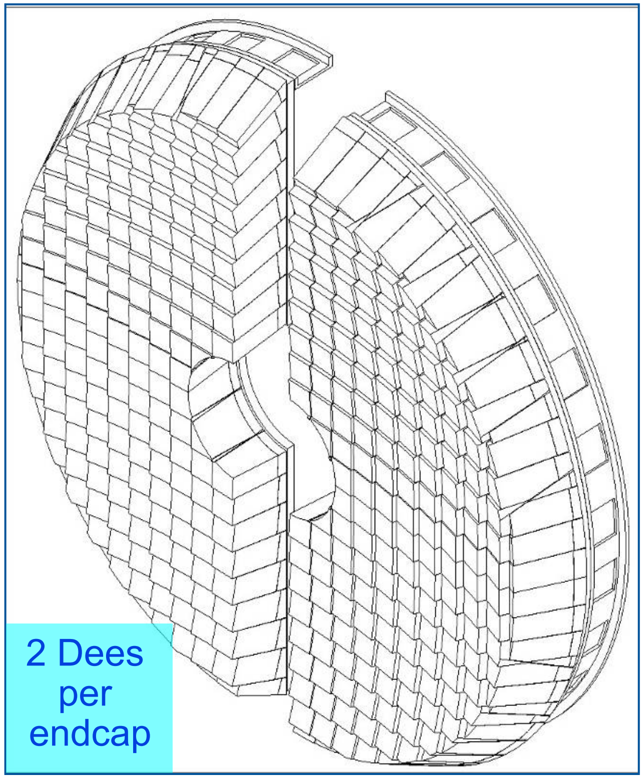
CMS ECAL Endcaps



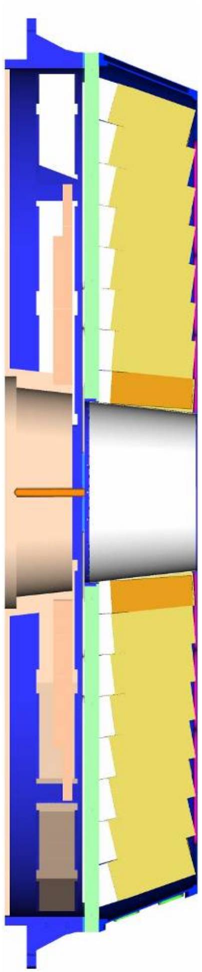
- 'SuperCrystal': carbon-fibre alveola containing
  5x5 tapered crystals + VPTs + HV filter cards
- 156 Supercrystals per Dee
- All crystals have identical dimensions
- All Supercrystals are identical
  (apart from 'partials' at inner/outer perimeter)



SUPER CRYSTAL SIDE VIEW



2 Dees per endcap

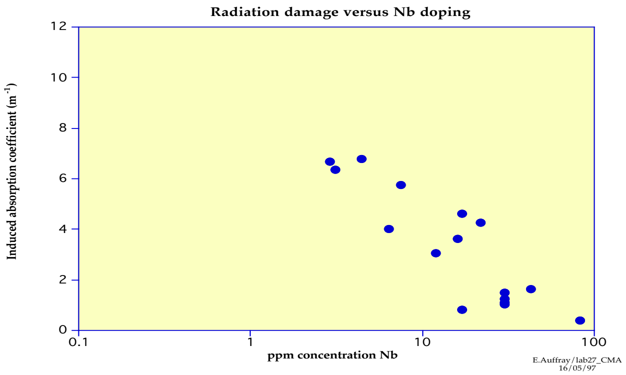


ATLAS and CMS ECALs

	Atlas		**CMS**	
Technology	Lead/Lar accordion		PbWO4 scintillating crystals	
	Barrel	**Endcaps**	**Barrel**	**Endcaps**
η coverage	0-1.475	1.4-3.2	0-1.48	1.48-3
channels	110208	63744	61200	14648
Granularity	ΔηxΔΦ		ΔηxΔΦ	
pre-sampler	0.025x0.1	0.025x0.1	-	-
Strips/Si-preshower	0.003x0.1	0.003-0.006x0.1	-	32x32 Si-Strips per 4 crystals
Main sampling	0.025x0.025	0.025x0.025	0.017x0.017	0.018x0.003 to 0.088x0.015
Back	0.05x0.025	0.05x0.025	-	-
Depth				
pre-sampler	10 mm	2x2mm	-	-
Strips/Si-preshower	~4.3 Xo	~4.0 Xo	-	~3 Xo
Main sampling	~16 Xo	~20 Xo	26 Xo	25 Xo
Back	~2 Xo	~2 Xo	-	-
Energy Resolution				
Stochastic Term	10%	10-12%	3%	5.50%
Local constant term	0.20%	0.35%	0.50%	0.50%
Noise per cluster(MeV)	250	250	200	550

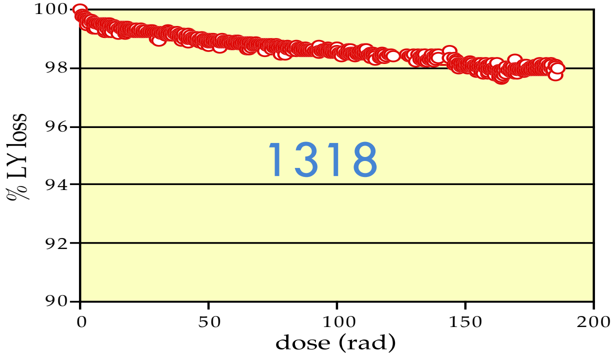
Radiation hardness progress highlights

- 1994: Nb doping
  - Suppress stable di-hole centres
  - Suppress induced 620nm band
    - Lecoq et al., MRS Proceedings Vol348 p99
    - Annenkov et al. et al., NIM A 365(1995) p291



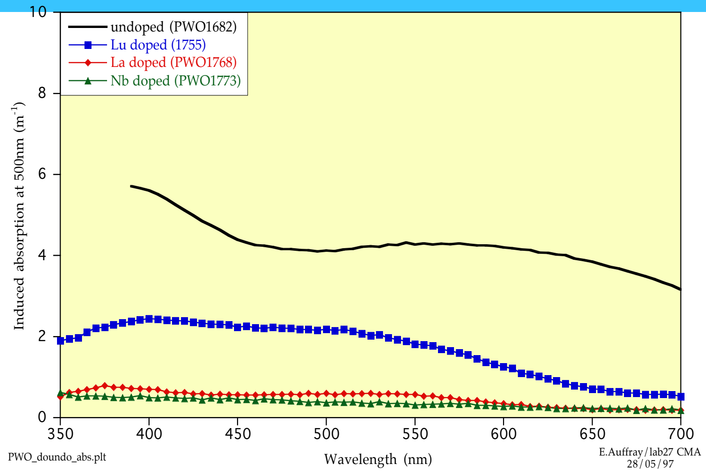
E.Auffray/lab27_CMA
16/05/97

- 1996: Y doping
  - Suppress stable e- centre on Vo
  - Suppress induced bands in visible
  - 1318: best crystal in test beam
    - Lecoq, CMS LHCC 1996-146

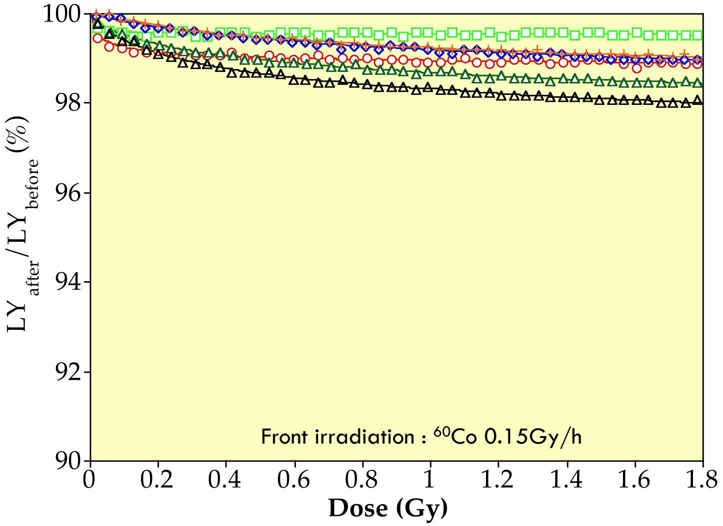


Radiation hardness progress highlights

- 1997: More trivalent doping
  - La, Lu, Y, Al
  - Improves transmission and decay
  - Improves Rad. hardness (see Y)
    - Kobayashi for La: KEK 1997-12
    - Lecoq et al., NIM A 402(1998) p75



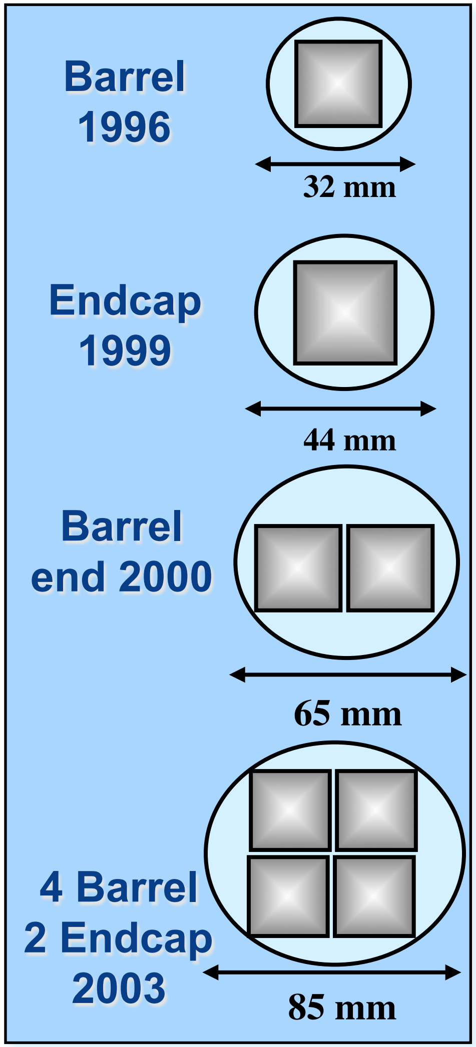
- 1998: New optimization
  - Factor 2 better than Nb or La
  - No sign of the drawback seen with La
    - Annenkov et al., NIM A426 (1999) p486-490



Front irradiation : ^{60}Co 0.15Gy/h

Crystal Production – 1996 to 2008

Technological steps in Bogoroditsk (Russia)

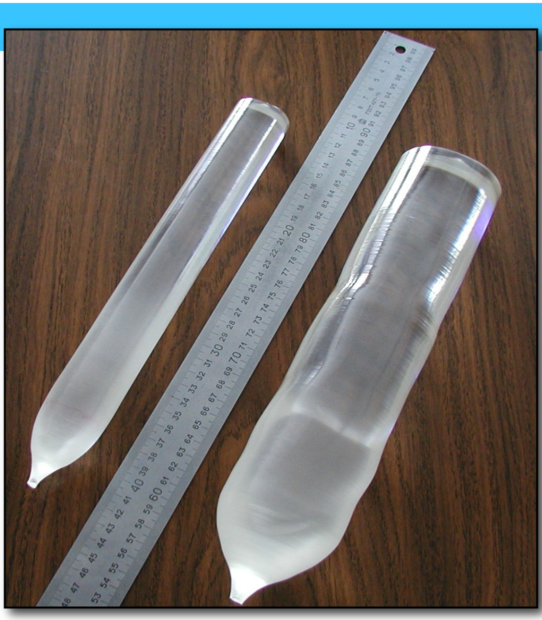


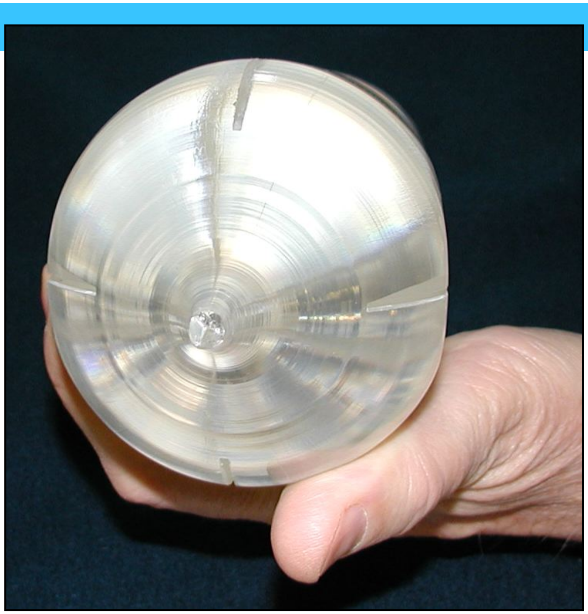
Barrel 1996
32 mm

Endcap 1999
44 mm

Barrel end 2000
65 mm

4 Barrel 2 Endcap 2003
85 mm





Attempted to grow 85mm diameter boules