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# CMS Conference Report

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## Recent Developments in Crystal Calorimeters (featuring the CMS PbWO<sub>4</sub> Electromagnetic Calorimeter)

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### Abstract

In the mass range of 110-150 GeV the favored process for Higgs boson detection via p-p collisions is via its decay into two photons, which demands a very high-resolution electromagnetic calorimeter. This physics goal plus the Large Hadron Calorimeter (LHC)-imposed design constraints of 25ns bunch spacing and a hostile radiation environment have led the Compact Muon Solenoid (CMS) collaboration to the choice of lead tungstate (PbWO<sub>4</sub>) crystals. These factors plus the presence of a 4T magnetic field and the relatively low room-temperature scintillation photon yield of PbWO<sub>4</sub> make photodetection a real challenge, which CMS has met via the choice of devices providing gain amplification: Avalanche photodiodes (APD) in the central barrel region and vacuum phototriodes (VPT) in the forward and backward endcap regions.

In the past year the CMS electromagnetic calorimeter has entered the construction phase. We review progress in the areas of crystals, barrel and endcap photodetection devices, plans for detector calibration as well as the status of assembly and quality control. We also invoke relevant developments in other crystal calorimeters currently in operation or under development. Crystal calorimeters remain the medium of choice for precision energy and position measurements in high energy physics.

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# 1 INTRODUCTION

Crystal calorimeters have historically been used in high energy physics for precision energy measurements of electromagnetically-interacting particles such as  $e$ ,  $\gamma$  and  $\pi^0$ , and to help in precision position measurements. Since Crystal Ball[1], the first large-scale apparatus (672 NaI crystals, 15.7 radiation lengths ( $X_0$ )) in 1977, whose goal was the study of the charmonium spectrum, crystal calorimeters have evolved significantly. Calorimeter size in number of crystals has increased by more than two orders of magnitude (e.g. the 12000-crystal L3 BGO calorimeter[2] at LEP (1989)), innovations in crystal composition (e.g. doping) and machining techniques have made possible increased crystal length such that nearly-perfect longitudinal shower containment ( $>25 X_0$ ) has become possible, and the range of applications has become very wide, from physics of b-quark-containing hadrons and CP violation (CLEOIII[3], with 7800 CsI(Tl) crystals; KTEV[4], with 3256 pure CsI crystals, the currently-running BaBar[5] and BELLE[6] experiments, with 6580 and 8636 CsI(Tl) crystals, respectively, and the future BTeV[7], with 23000 PbWO<sub>4</sub> crystals) to searches for new phenomena (L3 and the future CMS[8], described in this presentation) to physics of heavy ions (the future ALICE[9] at the LHC, with 18000 PbWO<sub>4</sub> crystals), all with accelerators, to astrophysics experiments such as the future gamma-ray telescope GLAST[10], which will use 1536 CsI(Tl) crystals.

The electromagnetic calorimeter[11](ECAL) currently under construction for the general-purpose CMS experiment at the LHC at CERN, scheduled to begin data collection in 2007, will consist of  $\sim 77,000$  lead tungstate (PbWO<sub>4</sub>) crystals, and thus will become by more than a factor of 5 the largest crystal calorimeter ever built. The PbWO<sub>4</sub> crystals have been chosen in order to optimize the probability of observing the Higgs boson in the mass range of 110-150 GeV via its decay into 2 photons, which demands a very high-resolution ECAL and in particular maximal longitudinal containment of electromagnetic showers. To achieve a targeted mass resolution of  $\sigma(M)/M < 1\%$  given the LHC-imposed constraints of a 25ns bunch spacing and a hostile radiation environment (0.15-0.3 Gy/hour in the barrel and 0.3-15 Gy/hour in the endcap region), some light yield (that of PbWO<sub>4</sub> at room temperature is three orders of magnitude less than that of NaI) has been sacrificed in favor of a very short light decay time ( $\sim 10$ ns) and radiation length (0.9cm).

The CMS ECAL barrel, which will be off-pointing by  $3^\circ$  in each of  $\eta$  and  $\phi$ , will consist of 61,200 crystals of  $\sim 26 X_0$  in 17 truncated pyramidal shapes of slightly different dimensions, with an extent of  $\eta < 1.48$ . The two endcaps, each consisting of 2 “dees”, will consist of a total of 16,000 identical crystals of  $\sim 25 X_0$ , having a slightly larger cross-section than the barrel crystals, and extending from  $1.48 < \eta < 3.0$ . In addition, a sampling preshower detector located in front of each endcap, comprising 3  $X_0$  of layers of lead and silicon ladders, will increase granularity in the forward/backward zones and thus aid in rejection of  $\pi^0$ s faking Higgs photons. The target parametrized calorimeter energy resolutions are

$$\sigma/E = \frac{2.7\%}{\sqrt{E(\text{GeV})}} \oplus 0.55\% \oplus \frac{0.155(0.210)}{E(\text{GeV})} \quad (1)$$

and

$$\sigma/E = \frac{5.7\%}{\sqrt{E(\text{GeV})}} \oplus 0.55\% \oplus \frac{0.770(0.915)}{E(\text{GeV})} \quad (2)$$

for barrel and endcap regions, respectively<sup>1)</sup>. The targeted contributions to each term in the above resolution expression are detailed in[11].

## 2 CRYSTALS

The Bogoroditsk Techno-Chemical Plant (BCTP)<sup>2)</sup> will furnish all of the CMS PbWO<sub>4</sub> crystals, although R&D (which began in 1994) was also undertaken and continues with the Shanghai Institute of Ceramics (SIC). To date 8700 production-ready barrel crystals have been received and 6000 characterized. Figure 1 shows longitudinal scintillation light transmission (in %) vs. wavelength for a typical production crystal, superimposed upon which is the distribution of longitudinal transmission at 420 nm (the scintillation emission peak value) for the 6000 measured crystals. Virtually all meet the CMS minimum specified value of 55%.

Light yield non-uniformity, defined as the percentage change in scintillation light yield per radiation length as a function of the distance from the photodetector, will contribute significantly to the calorimeter resolution via the

<sup>1)</sup> The first (second) numbers in the numerators of the third terms of the above expressions refer to the expected “low-” (“high-”) luminosity conditions at the LHC; where low (high) luminosity  $\sim 10^{33(34)} \text{cm}^{-2}\text{s}^{-1}$ .

<sup>2)</sup> Tula, Russia

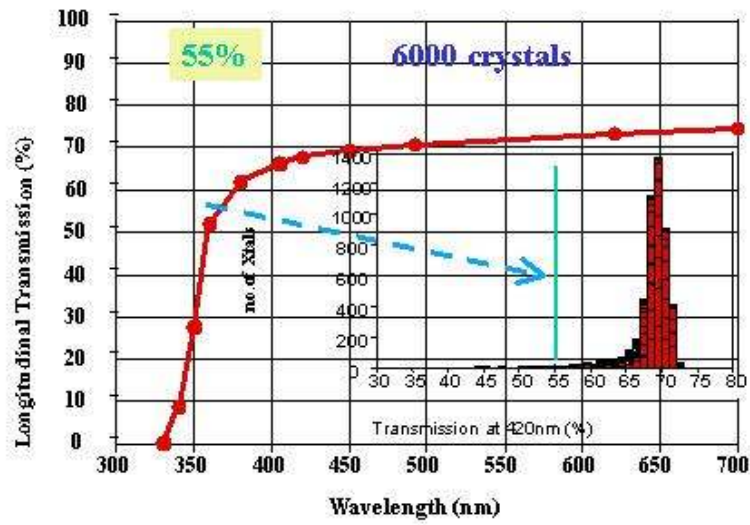


Figure 1: CMS experiment: Longitudinal scintillation light transmission in % vs. wavelength in nm for a typical production  $\text{PbWO}_4$  crystal. Inset: Distribution of longitudinal transmission at 420 nm (minimum acceptable is 55%) for the 6000 measured production-quality crystals[12].

constant term[11]. The targeted contribution of 0.3% corresponds to a maximal absolute value of frontal non-uniformity (FNUF) in the region of shower maximum of  $3.5\%/X_0$ . To achieve this goal one face of each barrel crystal is depolished to a roughness of  $0.34\mu$ . The 6000 crystals measured to-date overwhelmingly satisfy the FNUF requirement as well as the minimal light yield specification of 8 photoelectrons/MeV[12]<sup>3)</sup>.

Crystal radiation hardness will be crucial at the LHC. In  $\text{PbWO}_4$  radiation does not affect the scintillation mechanism directly, but affects light yield through decreased transmission. The CMS crystals are sample-tested with a longitudinal irradiation of 10 hours at a typical LHC dose rate (0.15Gy/hour). Of 368 production-ready crystals thus tested so far, only 1% have suffered losses in transmission in excess of the permitted 6% (the average loss being  $2.45 \pm 1.06\%$ ), and almost all of these have in addition been rejected by other selection criteria[12]. Improvements in radiation hardness since the beginning of the R&D period have been due to stoichiometric fine-tuning, optimization of crystal growth conditions and doping with yttrium and niobium. These last two factors have also contributed to improvements in scintillation light transmission.

The BTEV experiment, which will also use  $\text{PbWO}_4$  crystals of a size comparable to the CMS endcap crystals, recently presented first testbeam results on radiation hardness[13]. Figure 2 shows signal loss in one crystal furnished by BCTP vs. dose rate and integrated dose from an 85-hour irradiation in a 27GeV electron beam at Protvino in April 2002. Also reported were the results of a cross-check performed on two CMS endcap crystals: After a low-dose rate (50 rad/hour at Protvino) irradiation, BTEV obtained comparable signal loss rates to those obtained by CMS on the same crystals after a high-dose-rate (20 krad/hour at the Hôpital Cantonal de Genève) irradiation.

Since the end of 2000, BCTP has been able to produce ingots large enough (65mm wide vs. 32mm) to allow the obtention of two barrel crystals per ingot instead of one. The “pair-produced” crystals seem optically indistinguishable from the singly-produced ones[12]. In the future, the fabrication of even larger ingots (75, 85mm wide) may be possible, thus allowing the obtention of two endcap crystals or 4 barrel crystals per ingot.

<sup>3)</sup> as measured with a photomultiplier

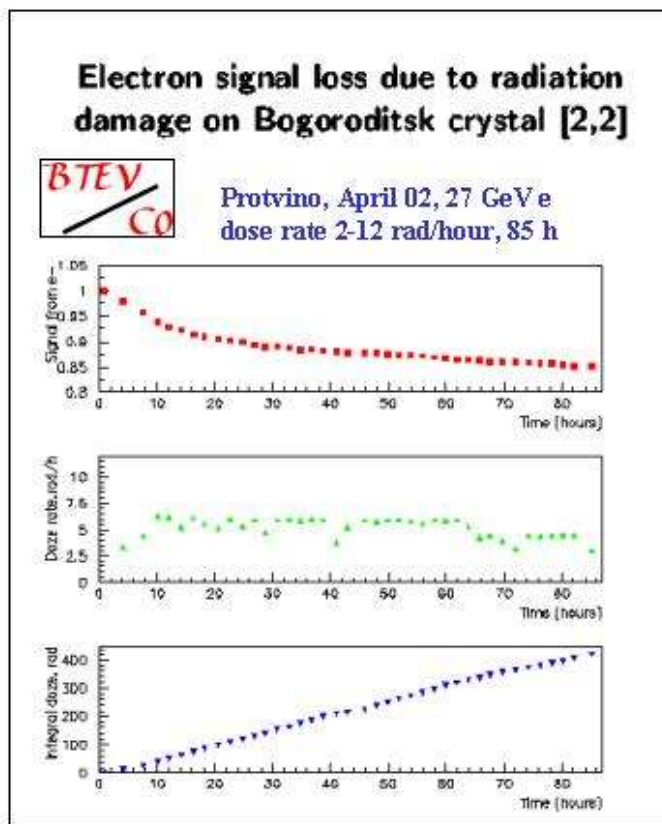


Figure 2: BTEV collaboration: Relative signal loss in one BCTP PbWO<sub>4</sub> crystal vs. dose rate and integrated dose from an 85-hour irradiation during test beam, April 2002.[13].

### 3 PHOTODETECTORS

#### 3.1 Avalanche photodiodes (APDs)

The CMS barrel avalanche photodiode (APD) is a gain-amplification-providing, magnetic-field-insensitive, fast, radiation-hard device and is the fruit of a 10-year R&D effort between the collaboration and Hamamatsu Photonics<sup>4)</sup>. The principle of operation is shown in Figure 3: Scintillation photons enter the device and convert in a p<sup>++</sup>-layer; these conversion electrons are then accelerated by a strong-gradient electric field in a p-layer. This field peaks at a p-n junction so as to induce avalanche multiplication of the electrons, which then drift under constant electric field in an n-region and are collected in an n<sup>++</sup>-region as the photoelectric current. Figure 3 also shows a schematic of the APD[14], a key feature of which is the groove added to minimize surface leakage current.

Two APDs connected in parallel constitute the fundamental barrel photodetection device, known as a 'capsule', providing an active area per crystal of  $2 \times 25 \text{ mm}^2 = 50 \text{ mm}^2$ . The capsules influence the calorimeter energy resolution through all three terms in the parametrization: The active area and APD quantum efficiency ( $\sim 75\%$ ) contribute to the stochastic term, the operating gain (M) of 50 (gains in excess of 1000 are possible) contributes to the constant term through intercalibration effects, and the APD capacitance ( $\sim 80 \text{ pF}$ ) and excess noise factor F ( $F=2$  at  $M=50$ ) contribute to the noise term (F also contributes to the part of the stochastic term represented by statistical fluctuations introduced by the gain amplification process.). The APDs are relatively charged-particle-insensitive, with an effective thickness  $d_{eff} \sim 6 \mu\text{m}$ .

Once glued to the crystal and mounted inside the calorimeter, the capsules become essentially inaccessible during the 10-year life of the experiment, giving rise to a maximum allowed APD failure rate of 1/1000. To fulfil this criterion all APDs are subjected to a predictive screening program involving a 500-krad pre-irradiation with a Co<sup>60</sup> gamma source followed by combined annealing and accelerated ageing under bias. A selection is then made based on the following quantities: Difference between breakdown and operating voltages, difference in breakdown

<sup>4)</sup> Hamamatsu City, Japan. An R&D program was also undertaken with EG&G Corporation (Canada)

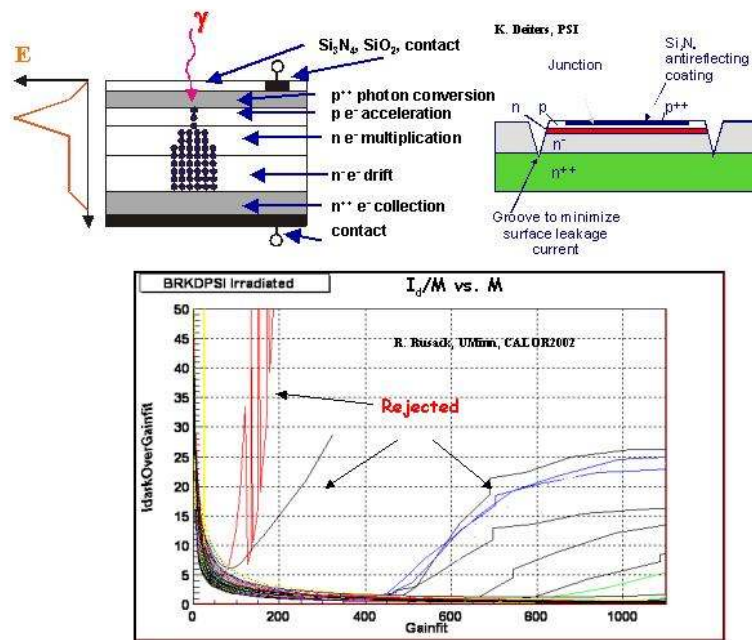


Figure 3: CMS experiment: Upper left: Principle of operation of a silicon avalanche photodiode (APD). Upper right: Schematic of the CMS barrel APD furnished by Hamamatsu Photonics[14]. Below: Dark current ( $I_{dark}$ ) normalized to gain ( $M$ ) vs. gain for a group of CMS APDs[15]

voltage before and after the pre-irradiation, dark current ( $I_{dark}$ ),  $I_{dark}/M$  vs.  $M$  and noise. Figure 3 shows  $I_{dark}/M$  vs.  $M$  curves for a group of APDs; those having a portion of the curve with positive slope are rejected[15]. The APDs are also sample-irradiated with a neutron source having a flux of  $2 \times 10^{13}$  neutrons/cm.

Each capsule is fully characterized[16] as to its gain, dark current, breakdown voltage, noise and pulse shape; the first three measurements are repeated after the capsule is glued to a crystal. Good correlations have been found between capsule measurements and Hamamatsu test results on the constituent APDs as well as with the post-gluing test results. Barrel photodetection performance continues to be checked in photovoltaic mode at each subsequent stage of calorimeter assembly.

The electromagnetic calorimeter of the ALICE experiment, which will study interactions from colliding heavy-ion beams at the LHC, will also be made of  $PbWO_4$  crystals and will use the same APDs as the CMS ECAL. Figure 4 shows the parametrized energy resolution parameters obtained from measurements during the August-September 2001 test beam run, using 3X3 matrices of crystals furnished by BCTP and Apatity<sup>5)</sup>, with one APD per crystal; the values are close to those targeted[17]. The plot shows the distribution of the 3X3 energy sum from a 30-GeV electron beam; the lack of a high-energy tail attests to the insensitivity of the APD to the direct passage of charged particles.

### 3.2 Vacuum Phototriodes (VPTs)

Silicon photodetectors are not suitable for use in the CMS ECAL endcaps, where the radiation rates can be orders of magnitude higher than in the barrel. The CMS collaboration has instead chosen vacuum phototriodes (VPTs), single-stage photomultiplier tubes with fine metal grid anodes and UV windows (see Figure 5), which will be furnished by the RIE corporation<sup>6)</sup>. With an active area of  $280\text{mm}^2/\text{crystal}$ , they will provide gains of between 8 and 10 in the CMS magnetic field of 4T. In particular, the VPT response is uniform for the range of angles their axes make with the magnetic field direction. They have a quantum efficiency of  $\sim 20\%$  at 420nm and an excess noise factor of 3. The decrease in VPT response due to irradiation over the 10-year life of the experiment is anticipated to be less than 10%, which is deemed acceptable.

<sup>5)</sup> Murmansk, Russia

<sup>6)</sup> St. Petersburg, Russia

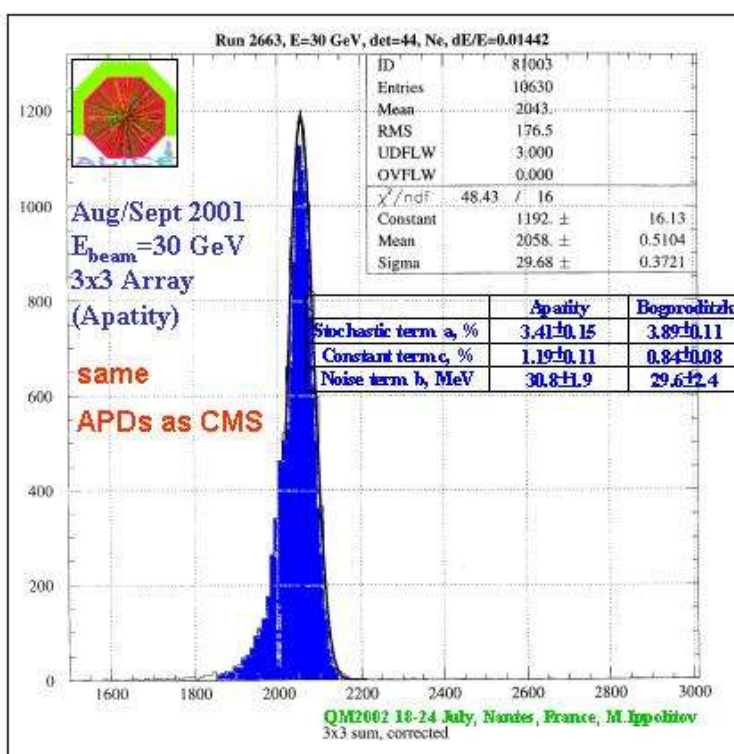


Figure 4: ALICE experiment: Distribution of the 3 X 3 Apatity  $PbWO_4$  crystal energy sum from a 30-GeV electron beam, and parametrized energy resolution parameters (Apatity and BCTP crystals) from test beam, August-September 2001[17].

Figure 5 also shows the distribution of the anode response of production VPTs (expressed as a light yield) measured in a magnetic field of 1.8T under pulsed light versus the VPT net gain in zero magnetic field measured by the producer under continuous light (result preliminary). The correlation attests to a good understanding of the measurement schematics.

The photoelectric currents from the APDs/VPTs will be processed by a 'light-to-light' on-detector readout chain consisting of only radiation-hard components[11, 18, 19].

## 4 CALORIMETER CALIBRATION

The dominant contribution to the energy resolution constant term for the CMS ECAL will be that from crystal intercalibration[11]. It is planned to perform the calibration of the CMS ECAL in four steps: First, by using the correlations between direct laboratory measurements performed during the detector construction and the same quantities calculated indirectly from test beam measurements[20], it is estimated that the final calibration constants can be predicted to within 6%. Second, a 'pre-calibration' of a significant fraction of the detector prior to installation will be performed in test beam with 50 and 120 GeV electrons, which should produce calibration constants with an estimated accuracy of within 2%[21]. Third, once data-taking starts, the crystals in a given ring in  $\phi$  could be intercalibrated with minimum bias or jet trigger events in less than two hours, with a precision of 1-2%[22]. The process  $Z \rightarrow e^+e^-$  would then be used to set the absolute energy scale for the  $\phi$ -rings and to intracalibrate them in less than one day, to 1%. Finally, electrons from  $W \rightarrow e\nu$  events will be used for definitive periodic calibrations which will take 2 months to perform, with a final precision of within 0.5%[11].

The KTeV experiment, which collected data during 1996-1997 and 1999, has used a total of 600 million decays from the interaction  $K_L \rightarrow \pi^\pm e^\pm \nu$  to establish the energy scale for each of the 3256 channels every 1-2 days with a precision of 0.03%[23]. Figure 6 (a) shows the ratio E/p for electrons/positrons from these decays, where E is measured with the calorimeter and p from tracks in a spectrometer. The crystal calorimeter resolution is obtained by subtracting the momentum resolution from the E/p resolution (calorimeter and momentum resolutions shown in Figure 6 (b)). The dependence of the mean E/p value on momentum, shown in Figure 6 (c), indicates an average

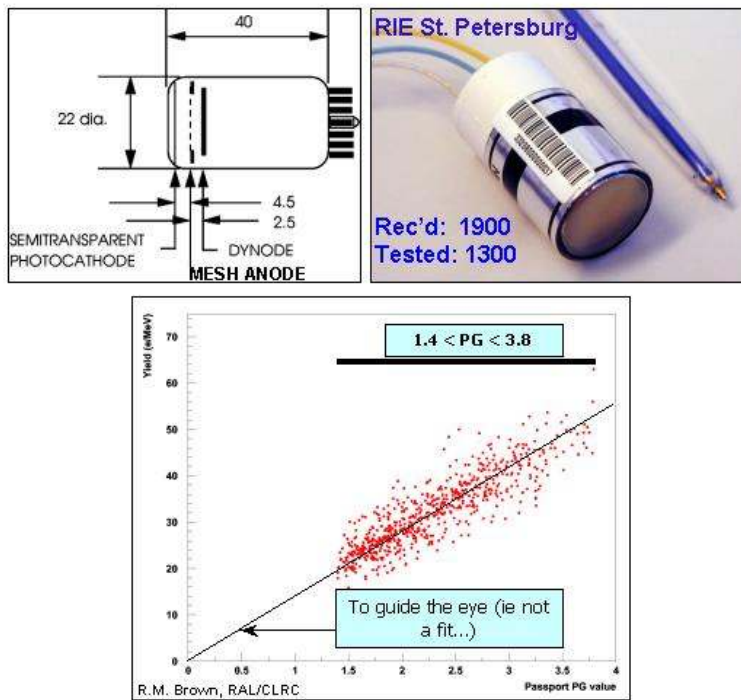


Figure 5: CMS experiment: Top: Schematic of the CMS endcap vacuum phototriode (VPT) furnished by RIE corporation. Bottom: Anode response at 1.8T under pulsed light vs. VPT net gain at 0T under continuous light for production VPTs (preliminary result)

energy nonlinearity of 0.5% in the energy range of  $3 \text{ GeV} < E < 75 \text{ GeV}$ . This nonlinearity, measured separately for each CsI crystal is used as a correction.

The BaBar experiment, running since 1999, uses three different processes to calibrate the 6580 CsI(Tl) crystals in three different energy regimes[24]: A neutron-activated fluid circulating through tubes in front of the crystals provides 6.13 MeV photons with which relative and absolute calibrations can be performed in a half-hour. Relative and absolute calibrations can be performed in 12 hours using Bhabha scattering events for the energy range 3-9 GeV. Finally, an absolute energy calibration in the energy range of 0.03-3 GeV is provided in 4 hours by pi-zero decays into two photons. Figure 7 shows the resolution  $\Delta E/E$  vs. photon energy for the three calibration processes and in addition for two physics processes:  $\eta \rightarrow \gamma\gamma$  and  $\chi_c \rightarrow J/\Psi\gamma$ , from which the two-term energy resolution parametrization and precisions shown are then extracted.

## 5 SCINTILLATION LIGHT LOSS MONITORING

Between calibrations with physics events, CMS will dynamically correct the calibration constant of each crystal for temporary losses in scintillation light transmission due to radiation[25]. Laser light of three frequencies will be distributed through a 2-level fanout system with cross-verification by precision radiation-hard PN diodes at each level, and eventually to each crystal via a radiation-hard optical fiber. Under radiation, the loss of the scintillation signal from the laser light follows that from particles according to a ratio  $R \equiv \Delta_{particle}/\Delta_{laser}$ , considered to be sufficiently linear and uniform between crystals.

Figure 8 shows a demonstration of the laser monitoring system performed in test beam in 2000. The intercalibration constants for three neighboring crystals in a 30-crystal matrix after the monitoring corrections are shown as a function of time. Only the middle crystal has been irradiated and has undergone three successive exposures (0.57, 2.05 and 1.47 Gy, respectively) and recoveries. Within errors, the stability of the calibration constants is the same as for the two non-irradiated crystals.

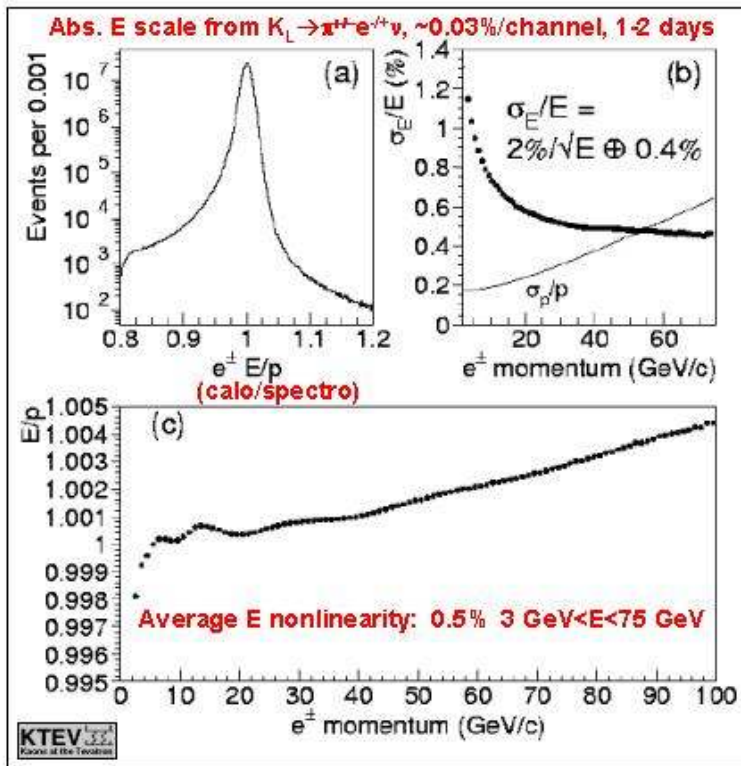


Figure 6: KTeV experiment: a) Ratio of energy  $E$  (from CSI crystal calorimeter) to track momentum  $p$  (from spectrometer) for electrons from the decay  $K_L \rightarrow \pi^+ e^- \nu$  b) Crystal calorimeter energy resolution vs. electron momentum and spectrometer momentum resolution c)  $E/p$  vs. electron momentum[23].

## 6 THE CMS ECAL: ASSEMBLY STATUS AND QUALITY CONTROL

Each of the CMS ECAL barrel crystals undergoes fully automated testing of geometrical dimensions, scintillation light transmission, light yield and uniformity on a multipurpose system called ACCOS (Automatic Crystal CONTROL System) [26]. CMS has received  $\sim 35,000$  production Hamamatsu APDs and fabricated and characterized  $\sim 6500$  barrel photodetection capsules. Of these, 4300 have been glued to crystals. Up to the module (400 or 500 crystals each) level, production and quality control activity proceeds in parallel at two distinct assembly centers, one at CERN and one at INFN ENEA/Casaccia (Rome); supermodule (1700 crystals) assembly, including FE electronics mounting, is performed at CERN.

The construction of the barrel began in September 2001 and is now well underway. In June 2002, the mechanical assembly of the first supermodule was completed. All construction and test activities are managed by and data input to the CRISTAL (Concurrent Repository & Information System for Tracking Assembly and production Lifecycles)[27] production management/quality control system, built on an object-oriented database.

For the endcaps, 1900 production VPTs have been received and 1300 tested.

## 7 CONCLUSION

Crystals remain the medium of choice for precision energy measurements in medium- and high-energy physics and astroparticle physics experiments. Construction of the CMS ECAL, the largest (in number of crystals) crystal calorimeter ever built, is now well under way, with as much as  $\sim 10\%$  of some components already delivered and validated. A complete module with 100 channels equipped with near-final very-front-end electronics is currently in beam at CERN, representing the first large-scale system test. In summer 2003 the first supermodule (1/36th of the calorimeter) will be beam-tested with final front-end electronics.



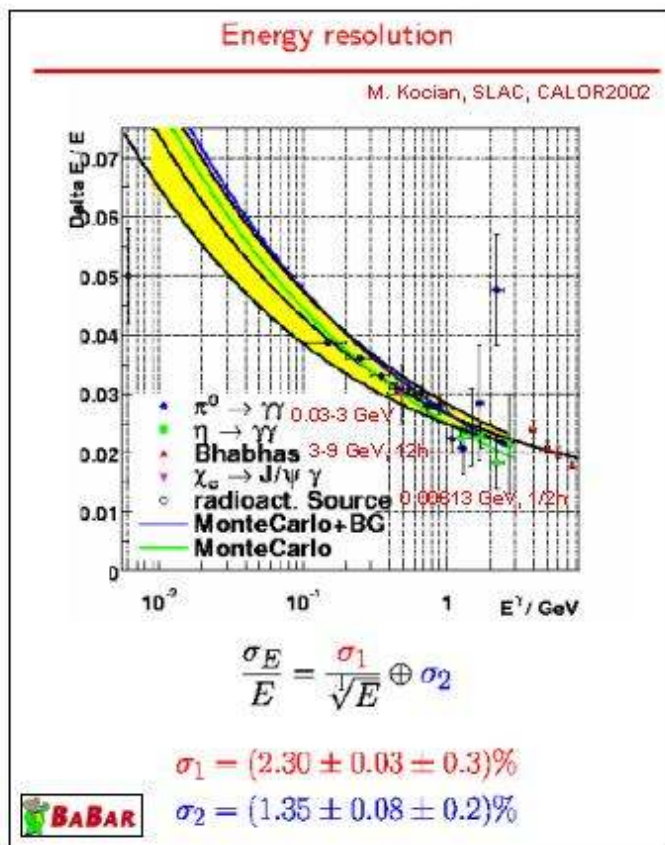


Figure 7: BaBar experiment: CSI(TI) calorimeter energy resolution vs. photon energy for three calibration processes and two physics processes[24].

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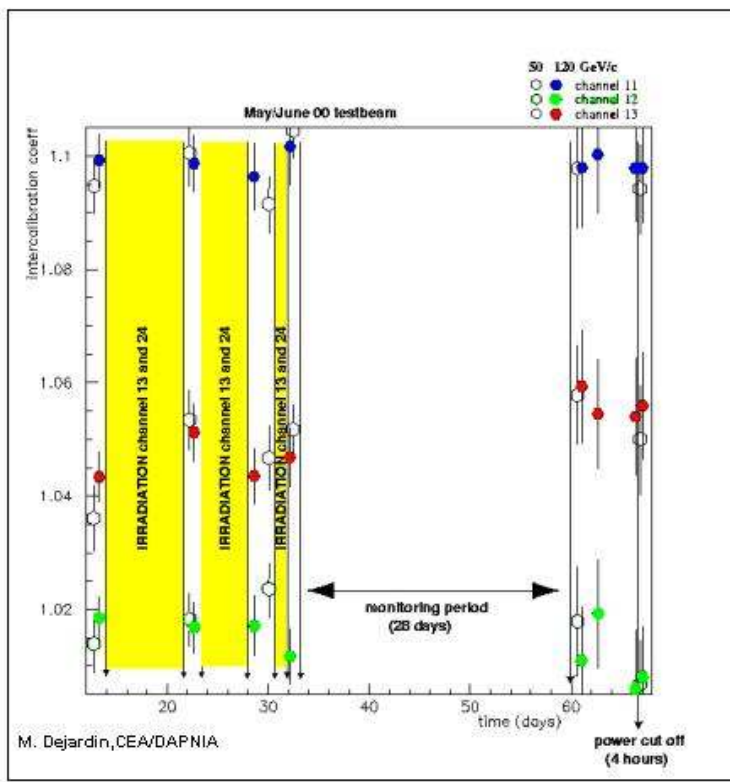


Figure 8: CMS experiment: Normalized intercalibration constants vs. time for three neighboring  $\text{PbWO}_4$  crystals in a 30-crystal matrix, of which one (middle) has been irradiated, after laser monitoring corrections, during test beam May-June 2000.

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