Case study: The Lead Tungstate Calorimeter for CMS

(With acknowledgements to CMS colleagues, particularly R M Brown at RAL but all errors and omissions are the responsibility of Peter Hobson at Brunel!)

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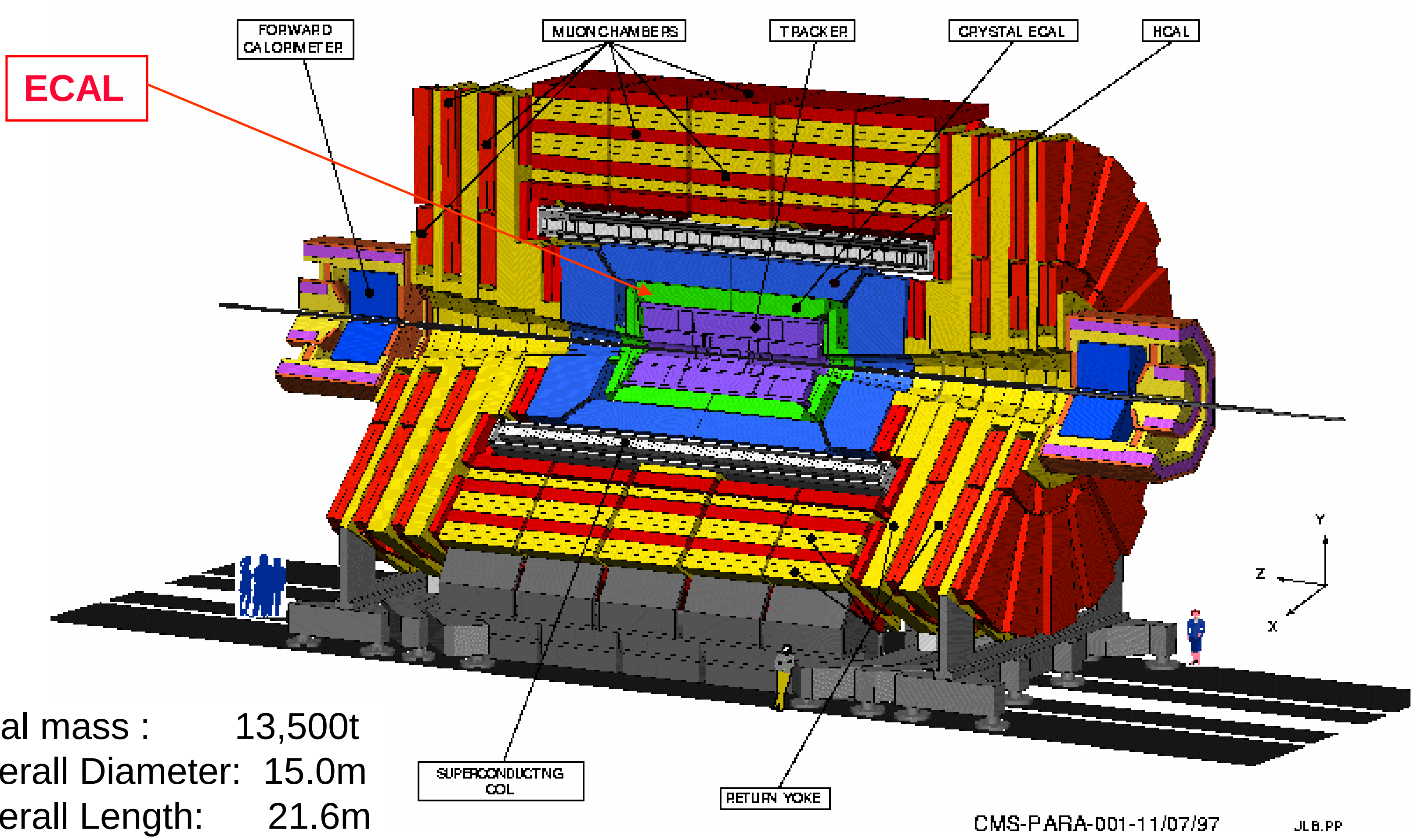
The **C**ompact **M**uon **S**olenoid Detector for LHC

Physics goals: SUSY, Higgs, Heavy flavours, heavy ions



Total mass :	13,500t
Overall Diameter:	15.0m
Overall Length:	21.6m
Magnetic field:	4T

ECAL design objectives

High resolution electromagnetic calorimetry is a basic design objective of CMS

Benchmark physics process:

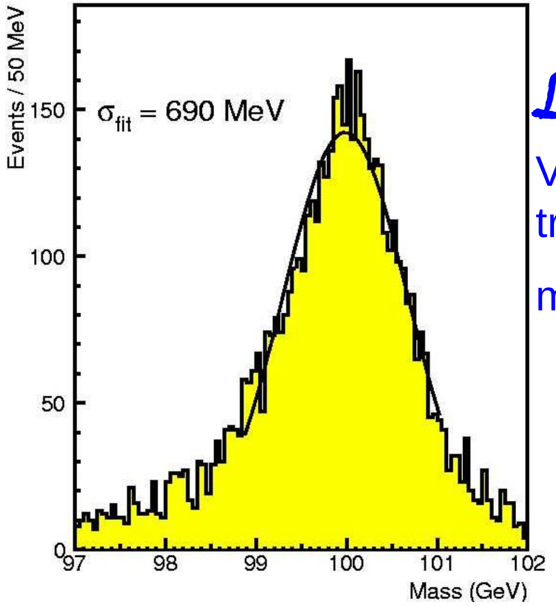
Sensitivity to a low mass Higgs via H → $\gamma\gamma$

$$\sigma_m / m = 0.5 [\sigma_{E_1}/E_1 \oplus \sigma_{E_2}/E_2 \oplus \sigma_\theta / \tan(\theta/2)]$$

Where $\sigma_E / E = a/\sqrt{E} \oplus b \oplus c/E$

Aim:		Barrel	End cap
Stochastic term:	a =	2.7%	5.7%
(photoelectron statistics/shower fluctuations)			
Constant term:	b =	0.55%	0.55%
(non-uniformities, shower leakage)			
Noise term: Low $\mathcal{L}$	c =	155 MeV	205 MeV
High $\mathcal{L}$		210 MeV	245 MeV

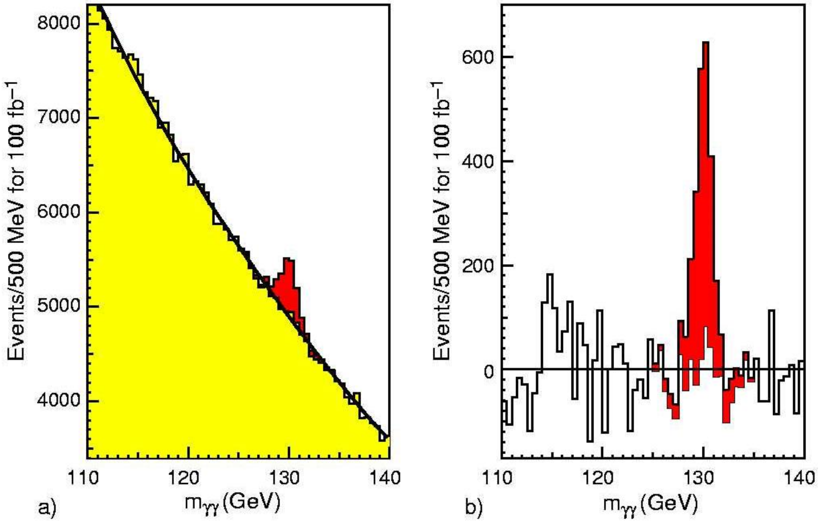
(Angular resolution limited by uncertainty in position of interaction vertex)



$\mathcal{L} = 10^{34}$ cm^2s^{-1}

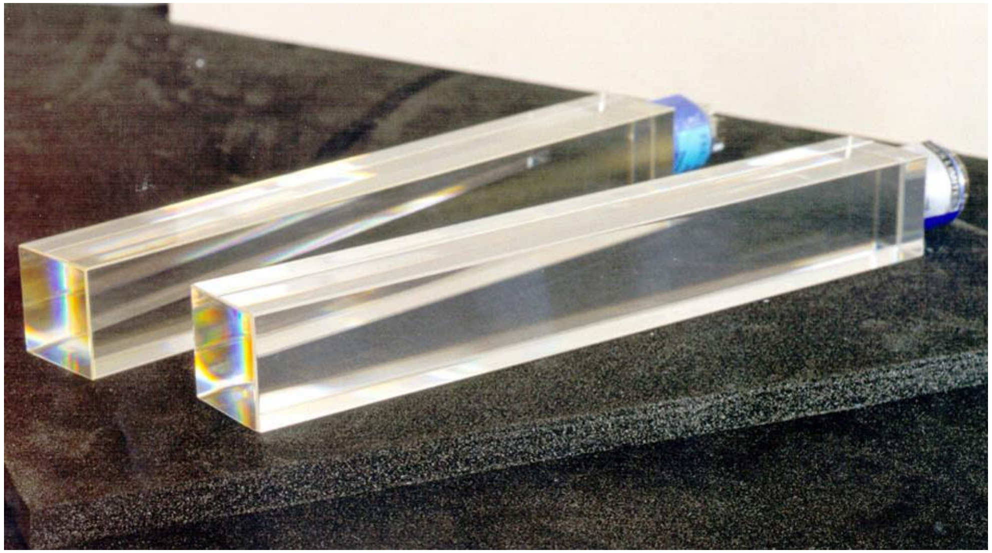
Vertex by track finding

$m_H = 100$ GeV



ECAL design choices

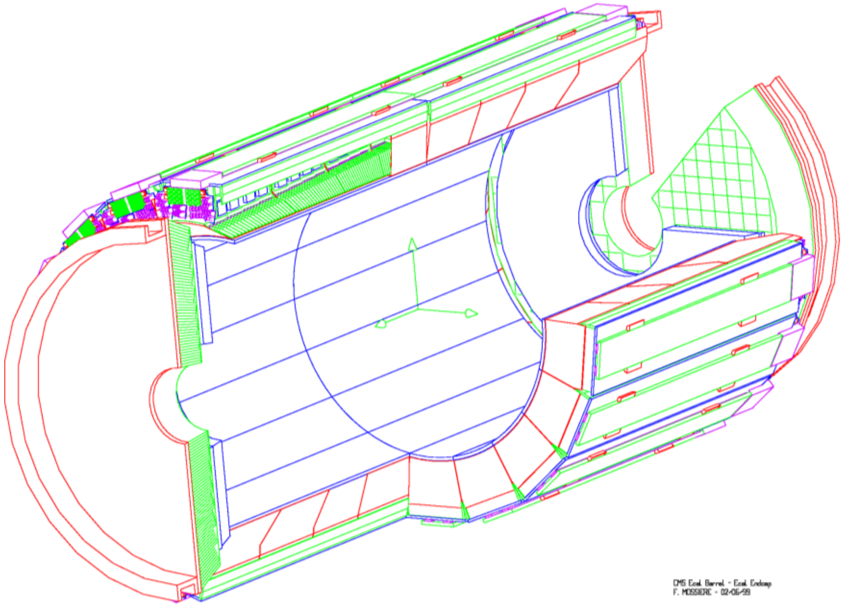
- ECAL (and HCAL) within magnetic vol
- Homogenous active medium ($PbWO_4$)
- Magnetic field-tolerant photodetectors with gain:
  - Avalanche photodiode (APD) for barrel
  - Vacuum phototriode (VPT) for end caps
- Pb/Si Preshower detector in end caps

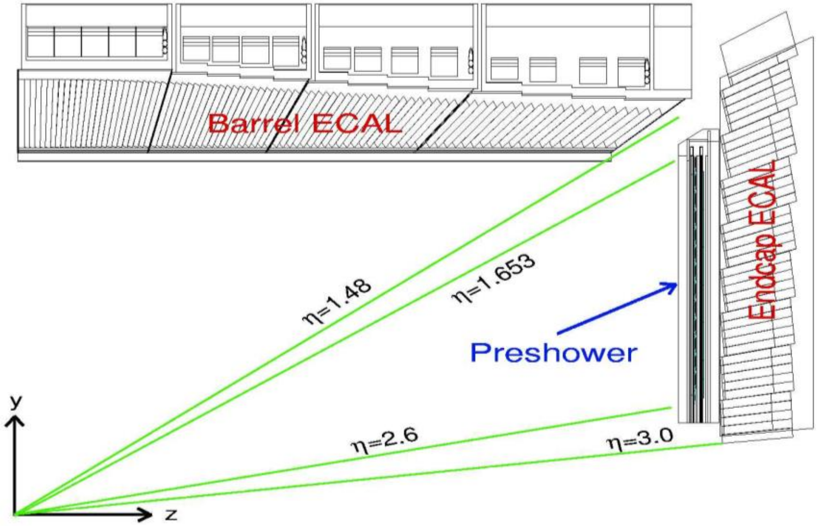


Properties of dense inorganic scintillators

Property	BGO	BaF_2	CeF_3	$PbWO_4$
Density [g/cm^3]	7.13	4.88	6.16	8.28
Rad length [cm]	1.12	2.06	1.68	0.89
Int length [cm]	21.8	29.9	26.2	22.4
Molière rad [cm]	2.33	3.39	2.63	2.19
Decay time [ns]	60 300	0.9 630	8 25	5(39%) 15(60%) 100(1%)
Refractive index	2.15	1.49	1.62	2.30
Max emiss [nm]	480	210 310	300 340	420
Temp coef [%/ºC]	-1.6	0 -2	0.14	-2
Rel light yield	18	4 20	8	1.3

ECAL Parameters

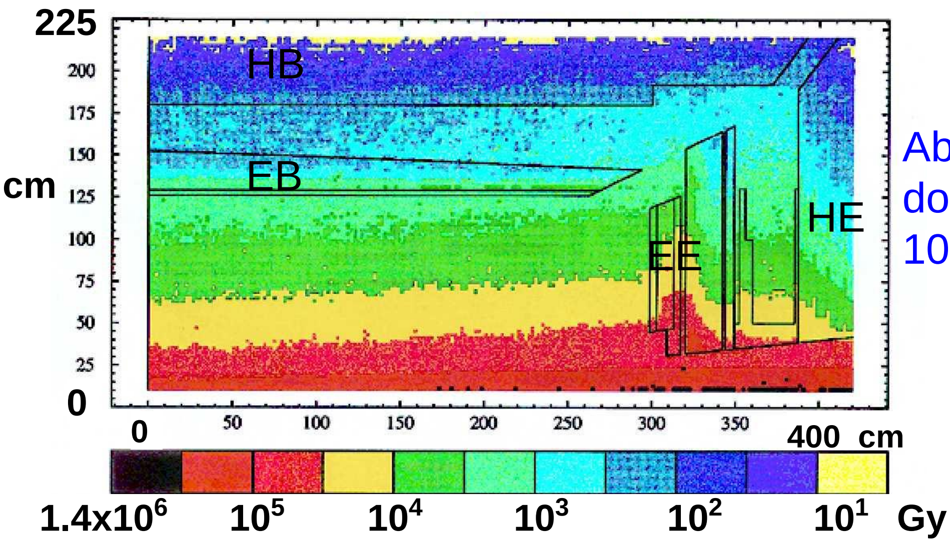




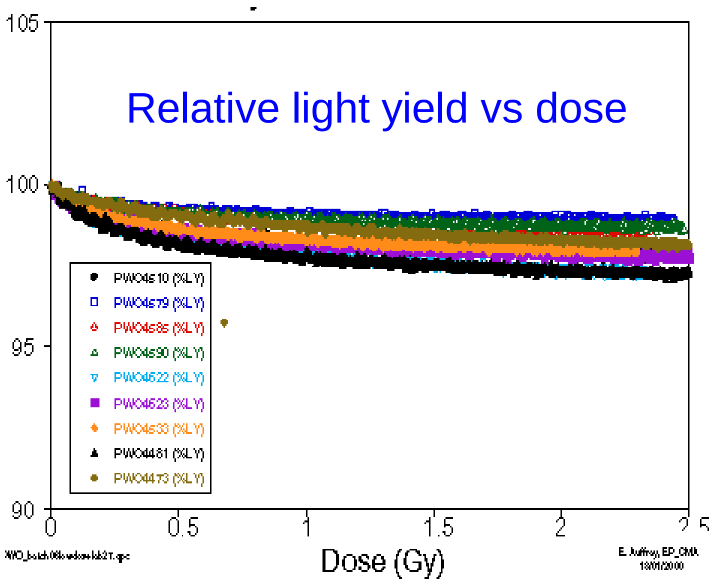
Parameter	Barrel	End caps
Coverage	| η | <1.48	1.48 < | η | < 3.0
$\Delta\varphi$ x Δη	0.0175 × 0.0175	0.0175 × 0.0175 to 0.05 × 0.05
Xtal size (mm^3)	21.8 × 21.8 × 230	30.0 × 30.0 × 220
Depth in X_0	25.8	24.7
# of crystals	61200	14648
Volume (m^3)	8.14	2.7
Xtal mass (t)	67.4	22.0

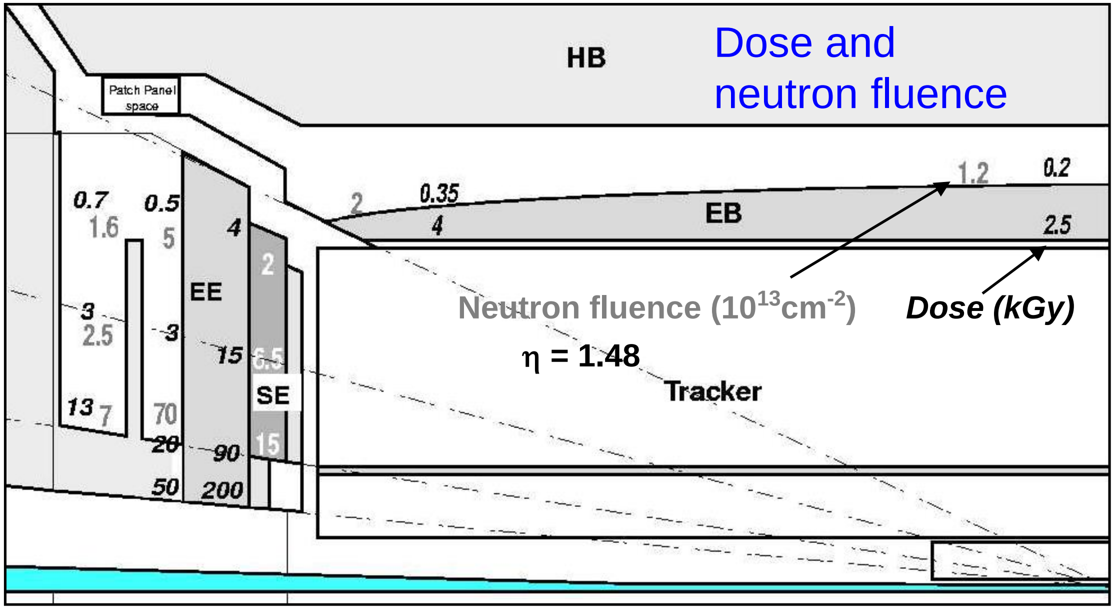
3° off-pointing pseudo-projective geometry

Radiation levels in ECAL



Absorbed dose after 10 years


Relative light yield vs dose


Dose and neutron fluence

Effect of radiation on $PbWO_4$

(after intense R&D)

- No change in scintillation properties
- Small loss in transmission through formation of colour centres
- Damage saturates
- Slow self-annealing occurs
- Loss in light yield of a few percent corrected with monitoring system
- No damage observed with neutrons

BUT see later slides!

Photodetectors –solid state

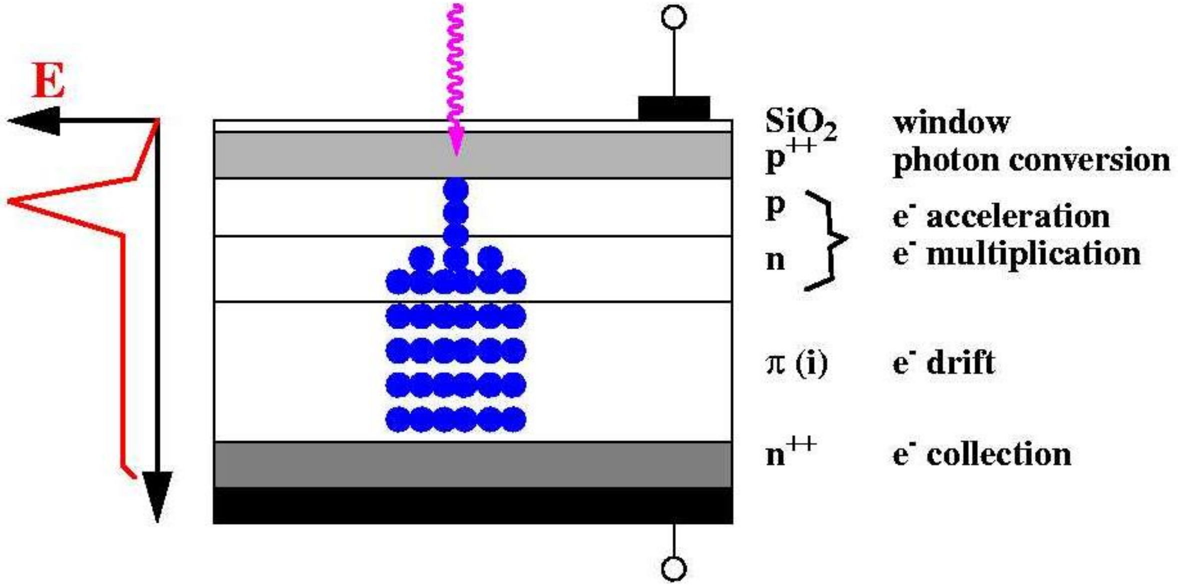
- Silicon is the primary material since in general we are detecting fast scintillation or Cherenkov light (near UV to visible)
- Silicon diode technology is well advanced and the quantum efficiency (QE) is high (around 80% peak)
- Silicon devices are tolerant to quite high radiation levels, although there are problems with hadrons.
- Silicon photodiodes are linear over many orders of magnitude
- The *Avalance Photodiode* has internal gain of about 30 (optimum value).
- See
  - http://www.hamamatsu.com/jp/en/product/category/3100/4003/index.html

Photodetectors: barrel

Avalanche photodiodes (APD)

- Operated at a gain of 50
- Active area of 2 x 25mm^2/crystal
- Q.E. ~ 80% for $PbWO_4$ emission
- Excess noise factor is F = 2.2
- Insensitive to shower leakage particles (d_{eff} ~ 6 μm)
- Irradiation causes bulk leakage current to increase

➔ electronic noise doubles after 10 yrs - **acceptable**

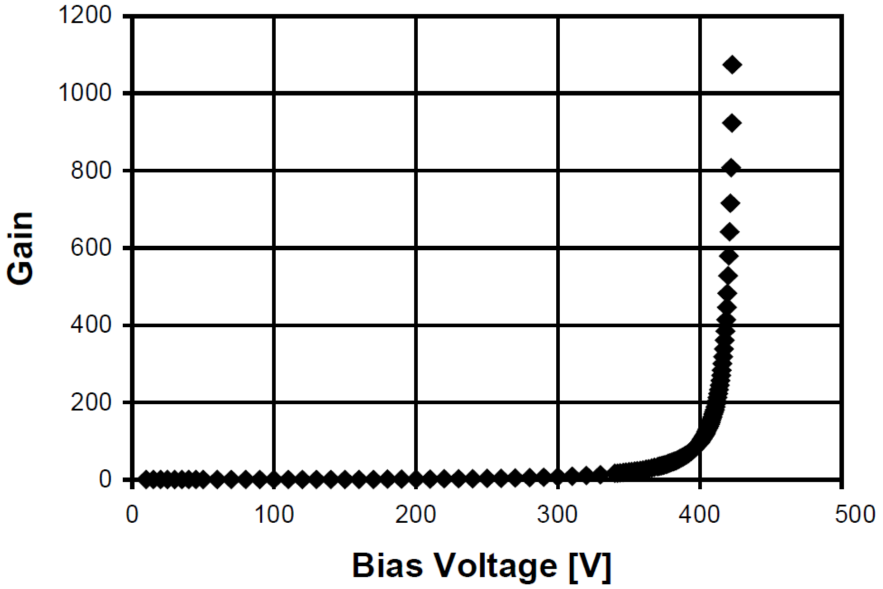


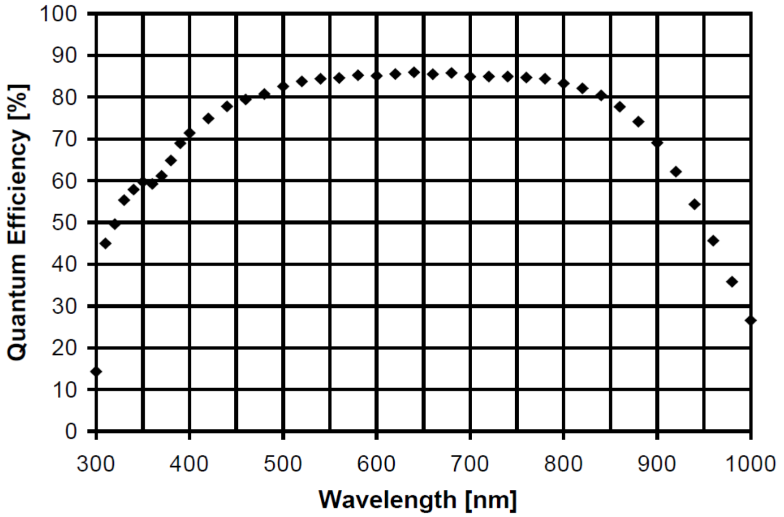
Hamamatsu APD

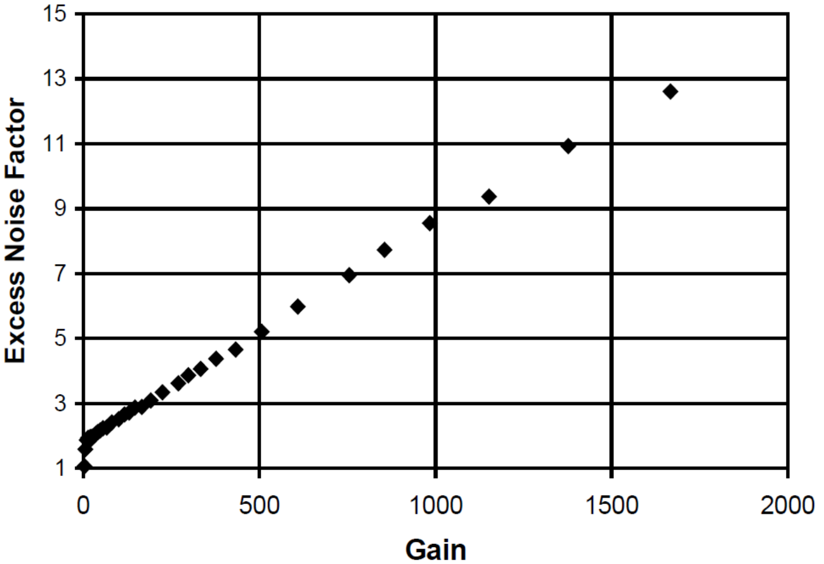
Hamamatsu type S8148

QE, Gain *vs* applied bias voltage,

Excess Noise Factor







See D. Renker, *NIM A* 486 (2002) 164

Photodetectors –solid state

- Silicon is *not* cheaper per unit area than vacuum photodetectors (for areas greater than a few mm$^{2)}$
- Really large devices cannot be made (200 mm^2 is the upper limit)
- Problem of damage from high neutron flux in hadron collider experiments such as those at the LHC.
- Need low noise (= expensive) pre-amplifiers
- Hard to do *photon counting*.

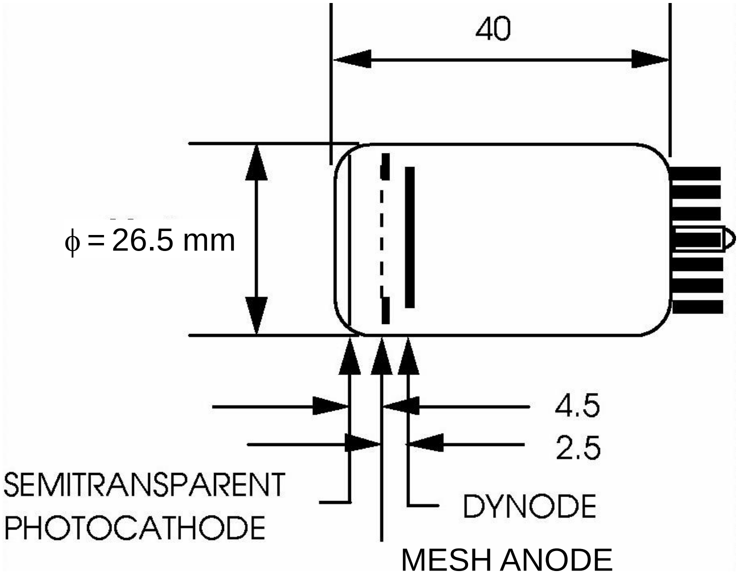
Photodetectors: end caps

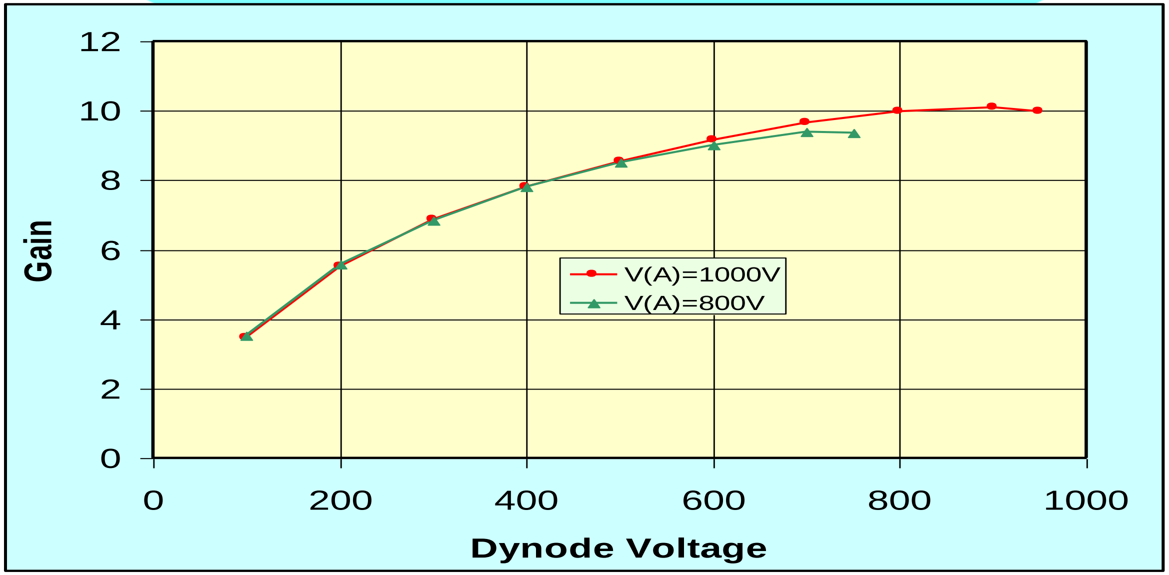
Endcaps: Vacuum phototriodes (VPT)

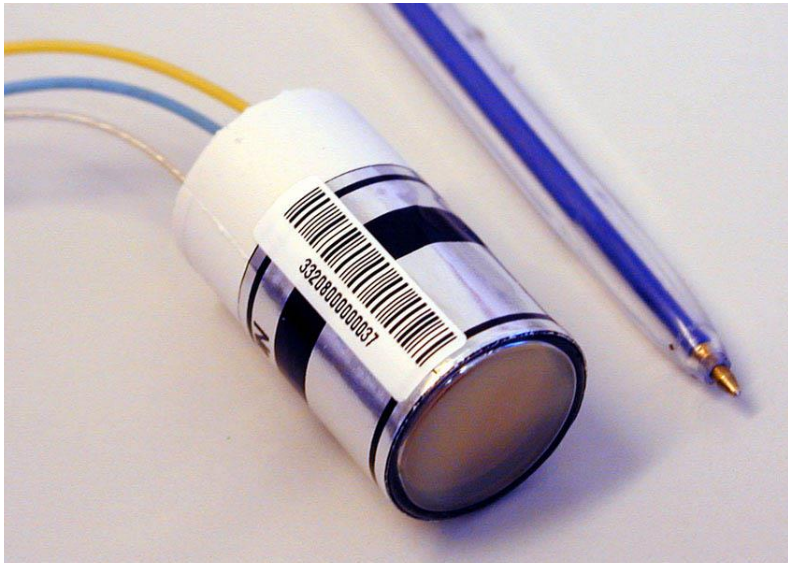
Produced by RIE, St Petersburg, Russia

More radiation resistant than Si diodes (with UV glass window)

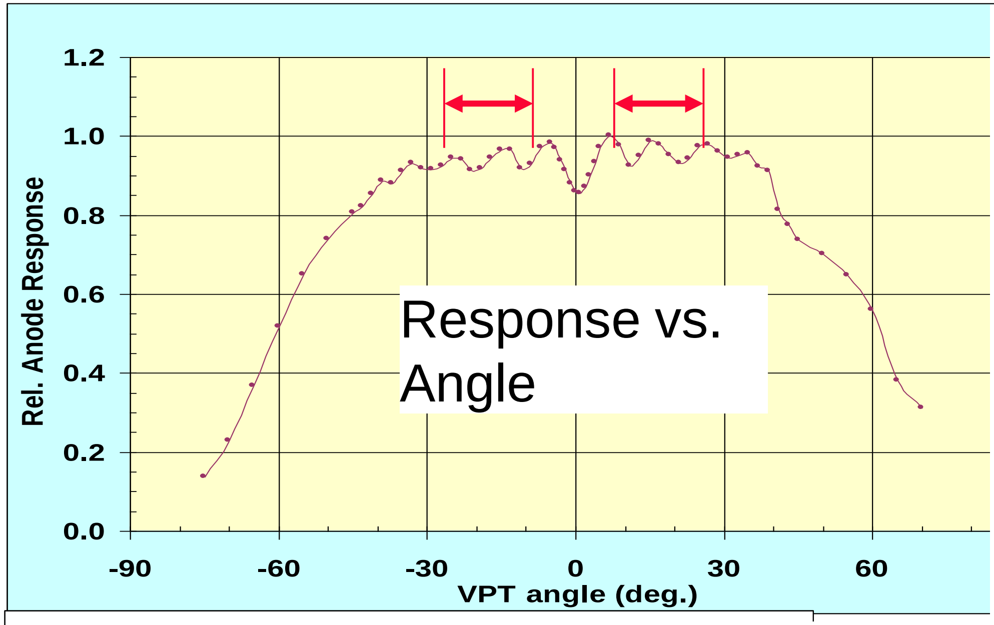
- Active area ~ 280 mm^2
- Gain ~10 (B=4T) Q.E.~ 20% (420 nm)
- Fast devices (simple planar structure)



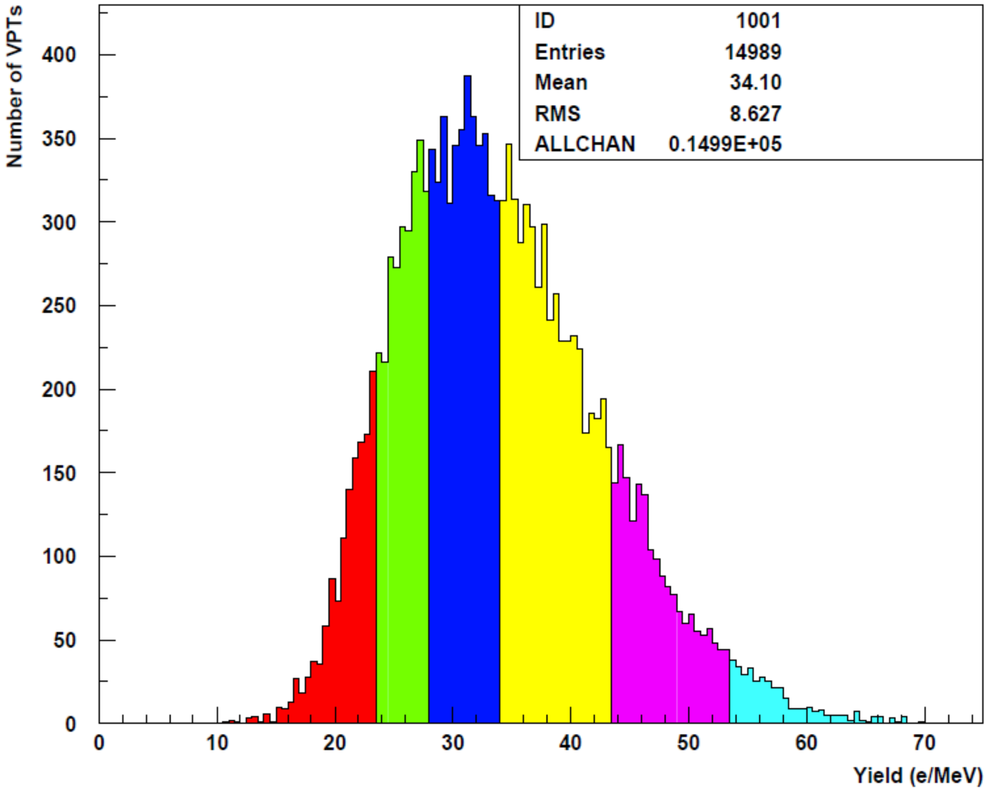


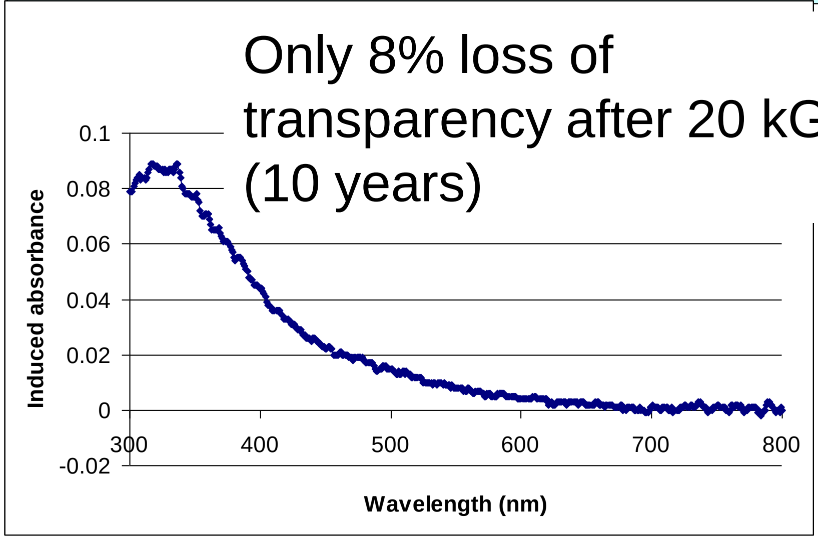


VPT Characteristics



Response vs. Angle





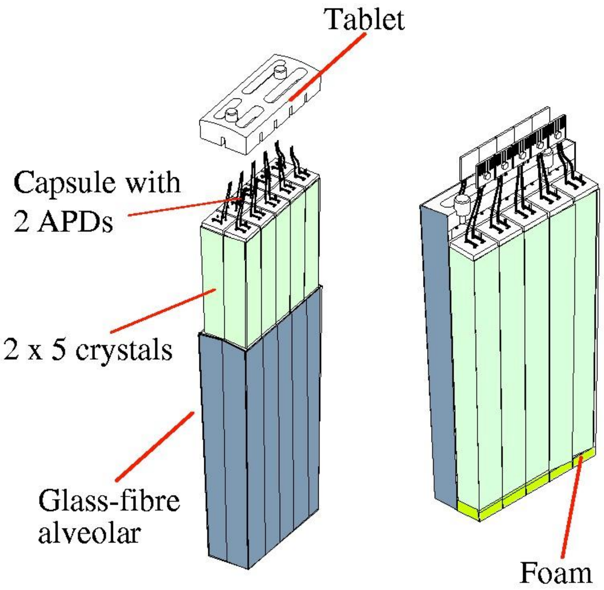
Only 8% loss of transparency after 20 kGy (10 years)

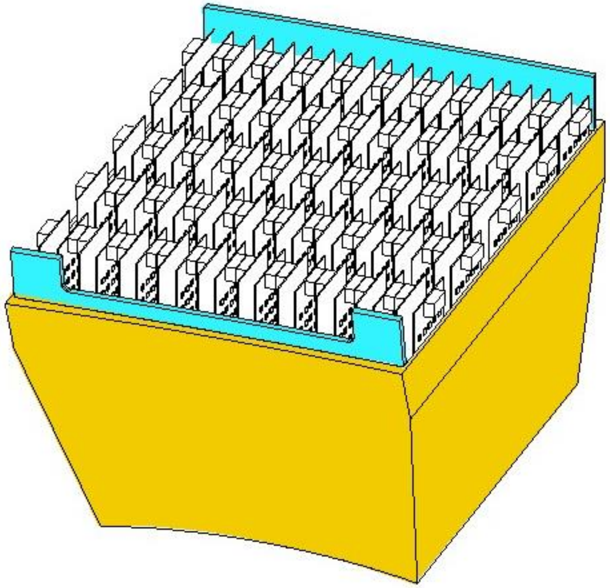
Critical magnetic field and radiation tolerance tests are done in the UK

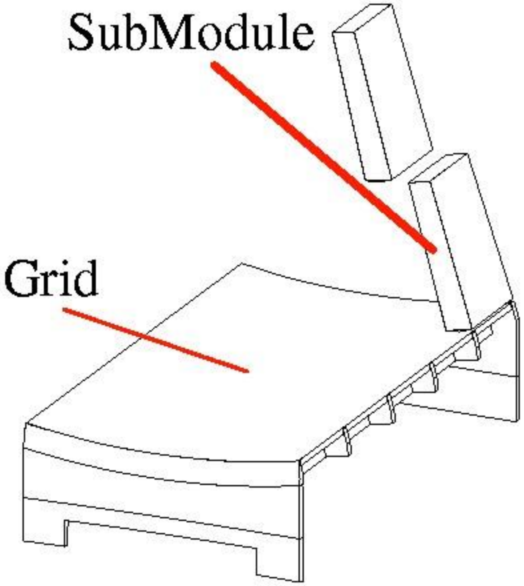
Construction: barrel

Submodule: 2x5 Xtals with APD and FE electronics in 200μm glass fibre alveola

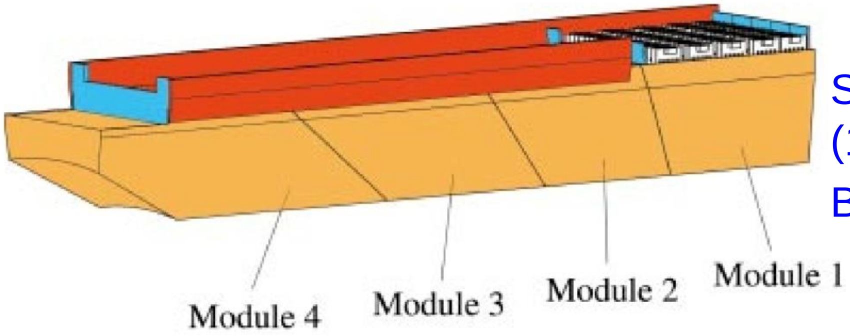
Module: 10x4 or 10x5 submodules mounted on a ‘Grid’, inside a ‘basket’







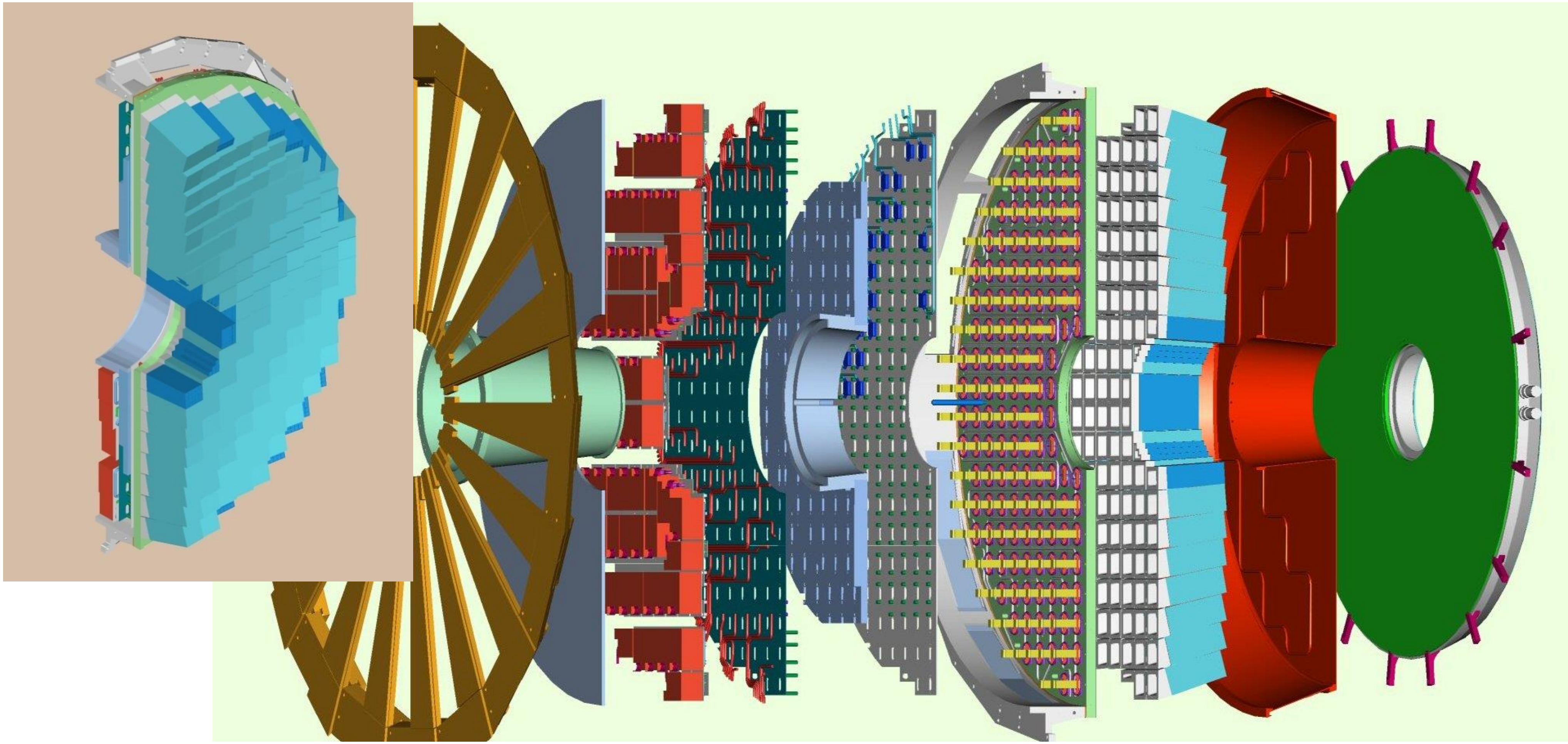
Assembled Submodules



Supermodule: 4 Modules (1700 Xtals)

Barrel = 36 Supermodules

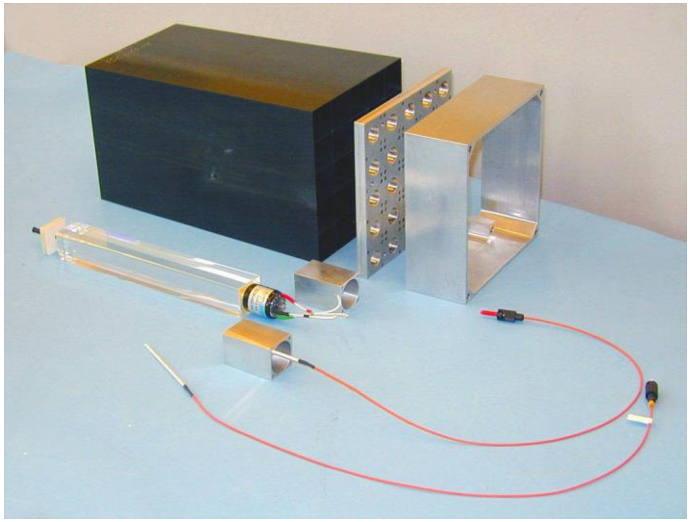
Construction: end caps



The endcap is mechanically complex

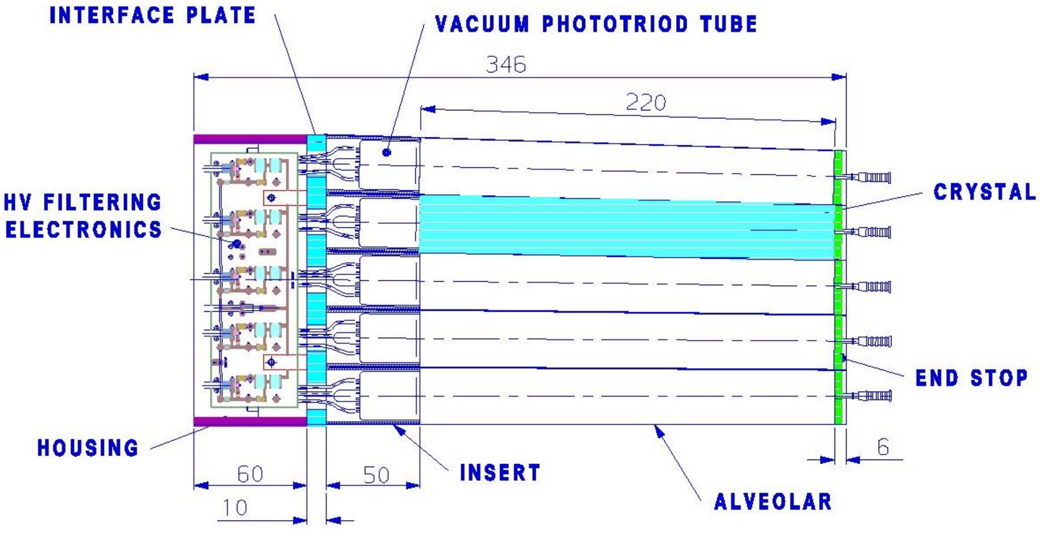
Tight tolerance on dimensions, deflections and thermal management.

Construction: end caps

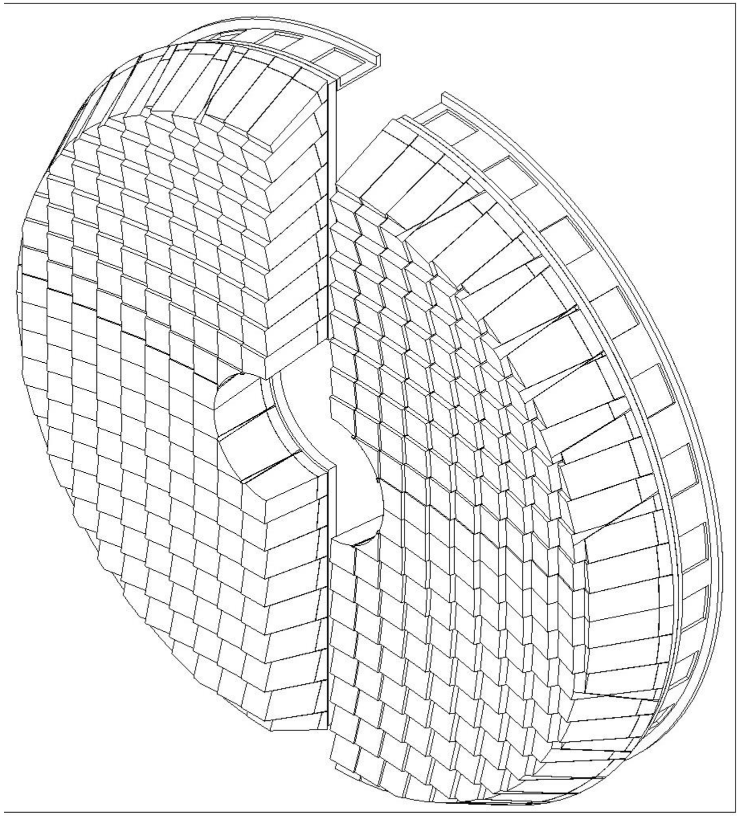


‘**Supercrystal**’: carbon-fibre alveola containing 5x5 tapered crystals + VPTs + HV filter

- 156 Supercrystals per **Dee**
- All crystals have identical dimensions
- All Supercrystals are identical
  (apart from inner and outer circumference)



SUPER CRYSTAL SIDE VIEW



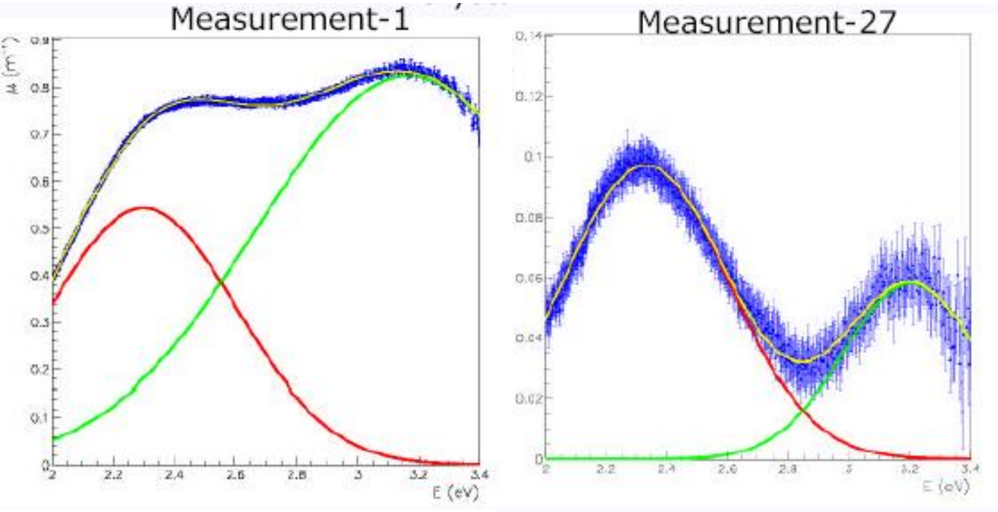
Evaluation of endcap crystals

Ongoing developments have progressively increased the boule diameter:

Two barrel crystals are now cut from a single boule in current production

Even larger boules have been grown which could provide four crystals per boule

Crystal lab at ICSTM has studied in detail the formation and annealing of colour centres



- Transmission loss due to irradiation at 15 Gy/h for 24 hours.
- Induced absorption fitted with Gaussians at 2.3 eV (540nm) and 3.1 eV (400nm).

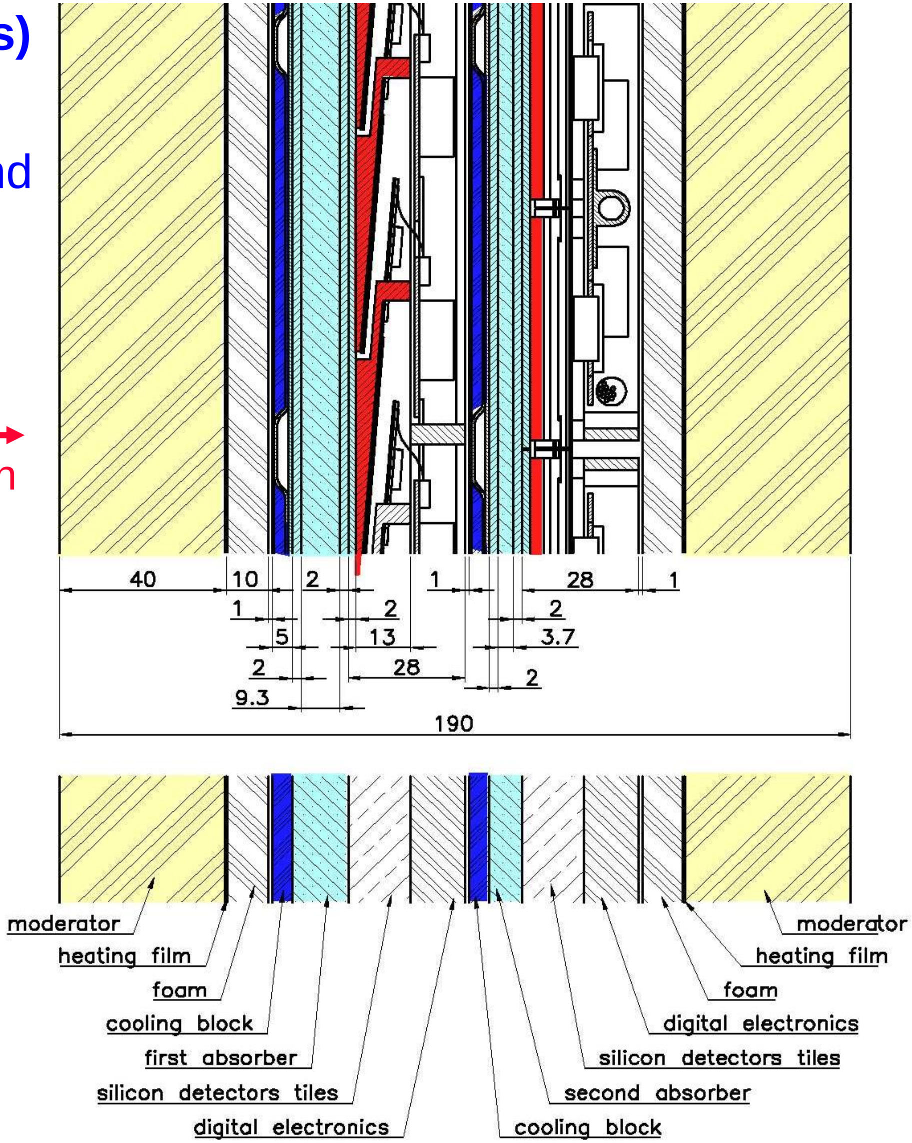
Preshower detector

Rapidity coverage: $1.65 < |\eta| < 2.6$ (End caps)

Motivation: Improved π^0/γ discrimination

- 2 orthogonal planes of Si strip detectors behind $2\,X_0$ and $1\,X_0$ Pb respectively
- Strip pitch: 1.9 mm (60 mm long)
- Area: 16.5 m^2 (4300 detectors, 1.4×10^5 channels)

Incident → Direction



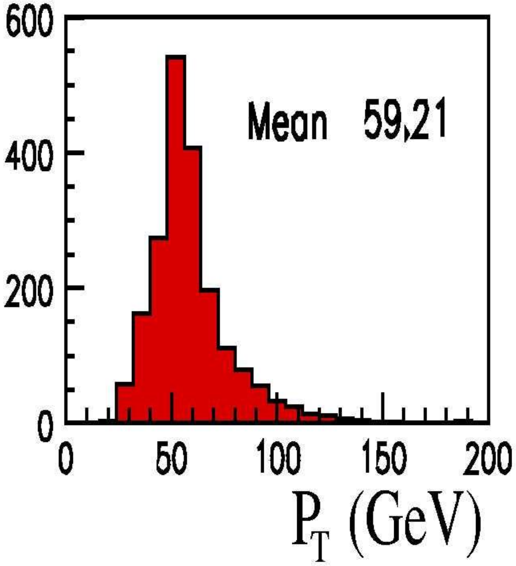
High radiation levels - Dose after 10 years:

- ~ 2×10^{14} n/cm^2
- ~ 60 kGy

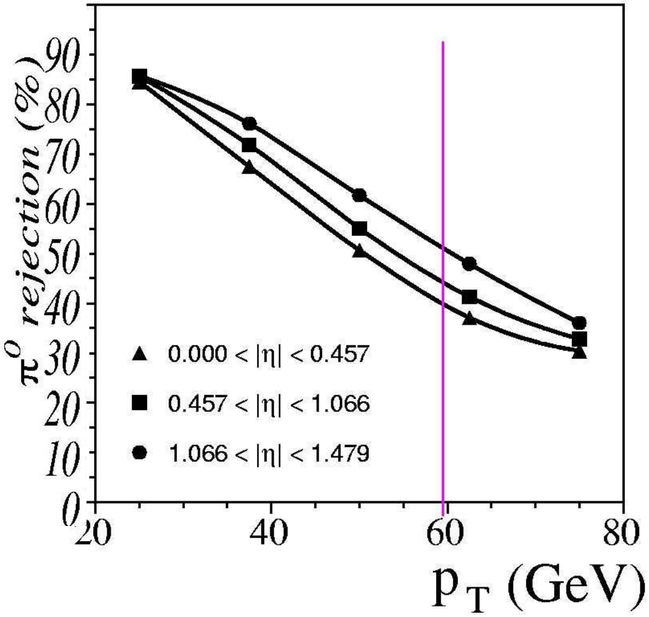
➔ **Operate at -10° C**

π^0/γ Discrimination

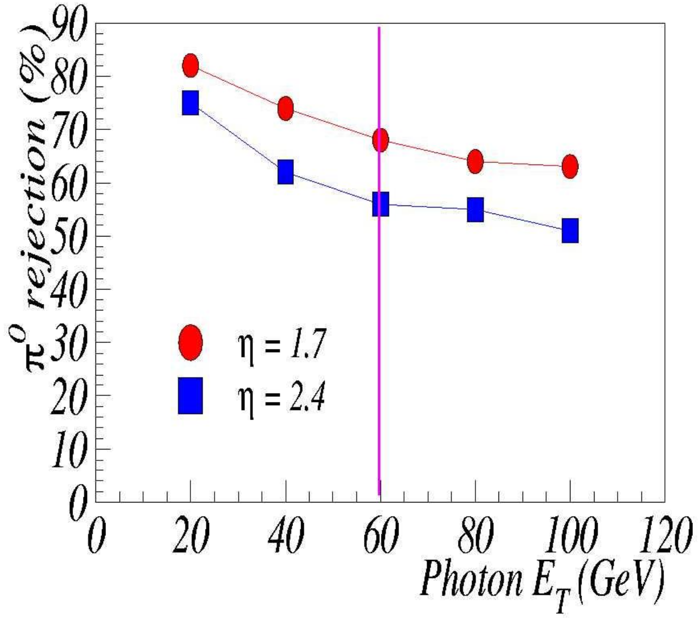
Photon P_T from 110 GeV Higgs



Barrel - use Crystals



Endcaps - use Preshower



(γ-jet) is potentially the most serious background to $H \rightarrow \gamma\gamma$

Track isolation cut reduces (γ-jet) to ≈ 50% of the intrinsic (γ-γ) background (p_T cut = 2GeV/c)

Use π^0/γ discrimination in the ECAL to gain an extra margin of safety

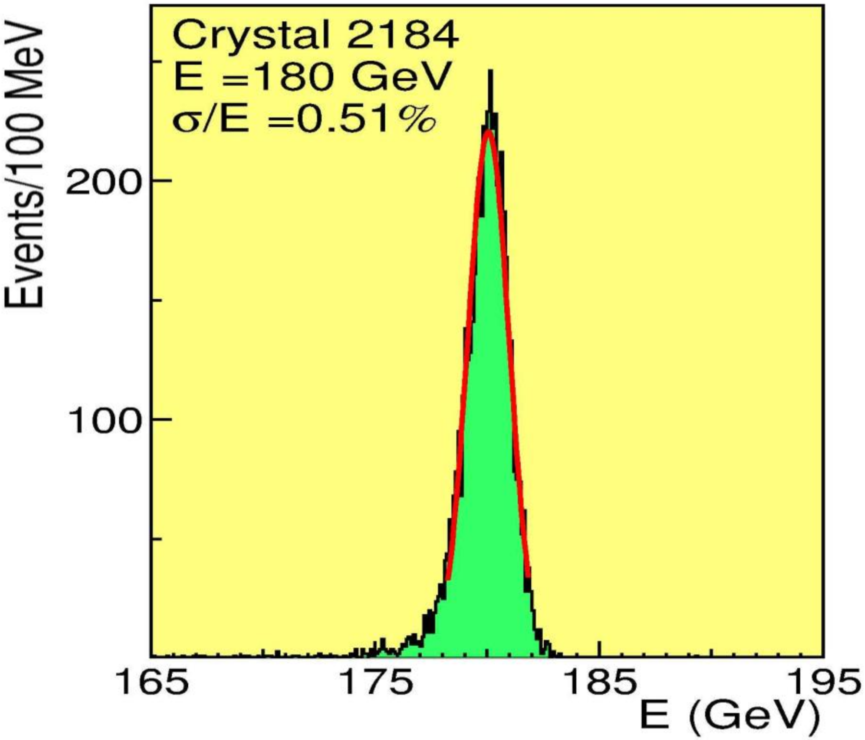
Barrel: Lateral shower shape in crystals (limited by crystal size at high E_{π^0})

End cap: Cluster separation in preshower (limited by shower fluctuations at $3X_0$)

Test beam:Energy Resolution

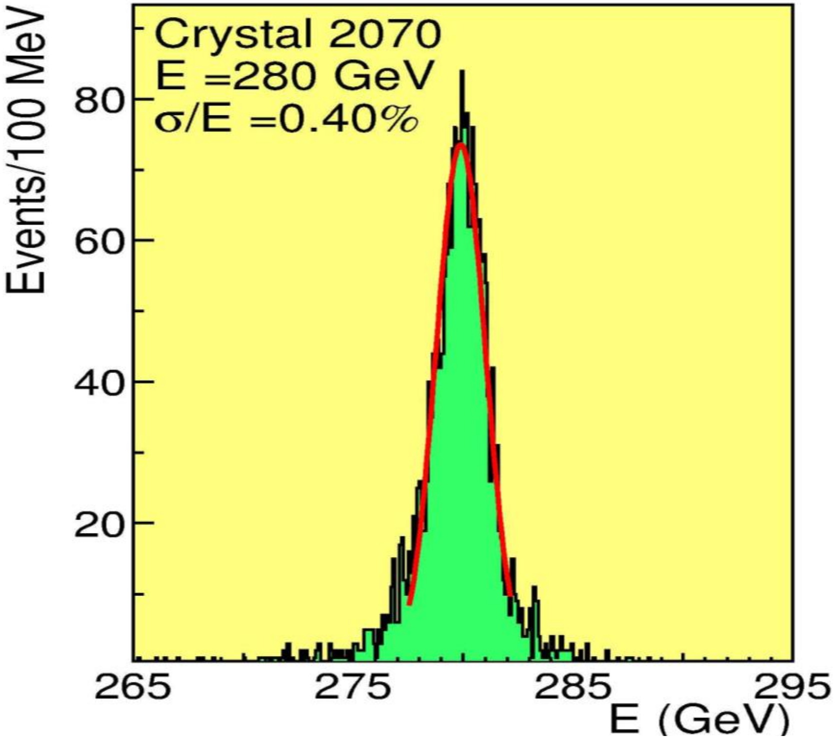
Barrel - 3x3 crystals

$$\frac{\sigma_E}{E} = \frac{2.7\,\%}{\sqrt{E}} \oplus \frac{140\ \mathrm{MeV}}{E} \oplus 0.4\,\%$$



Endcap - 3x3 crystals

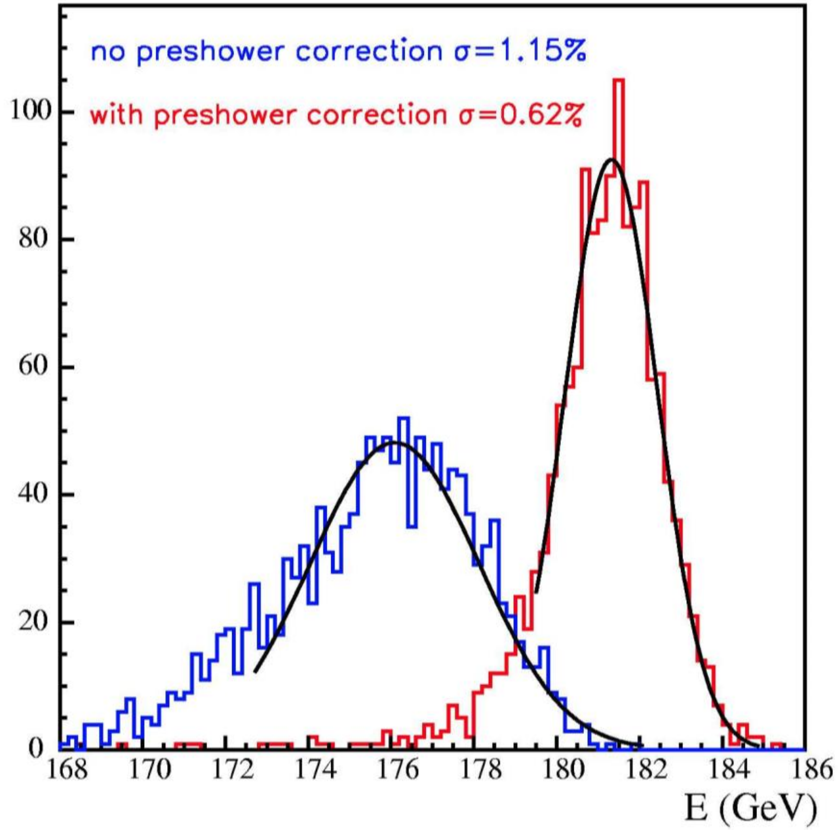
$$\frac{\sigma_E}{E} = \frac{4.1\,\%}{\sqrt{E}} \oplus \frac{140\ \mathrm{MeV}}{E} \oplus 0.25\,\%$$

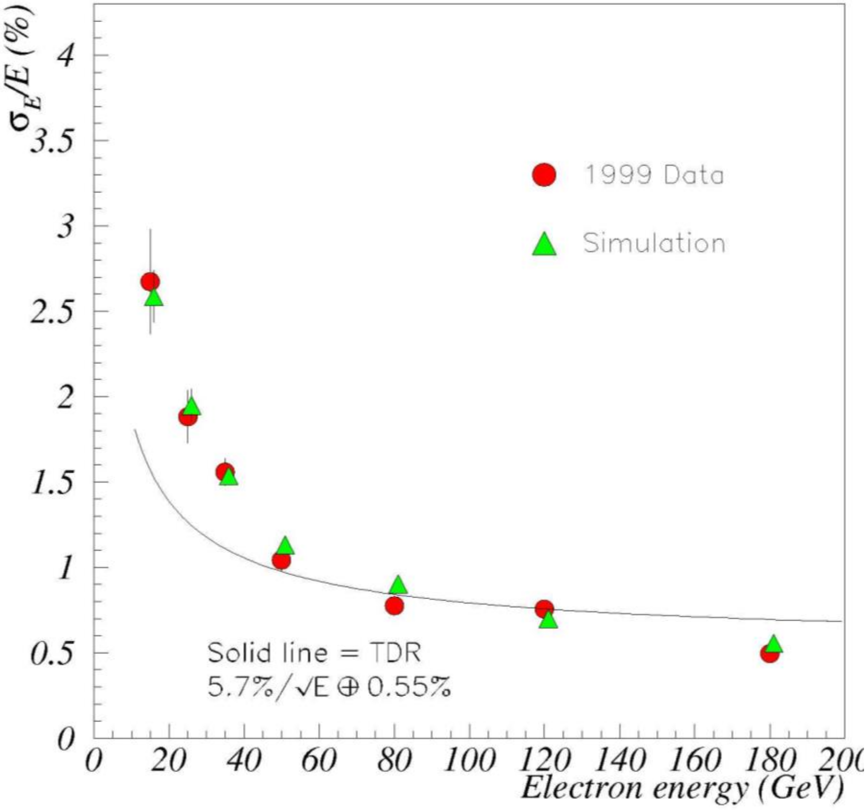


Barrel specifications: $$\frac{\sigma_E}{E} = \frac{2.7\,\%}{\sqrt{E}} \oplus \frac{155\ \mathrm{MeV}}{E} \oplus 0.55\,\%$$

No preshower detector

Energy resolution with preshower





Energy resolution degraded by Pb absorber

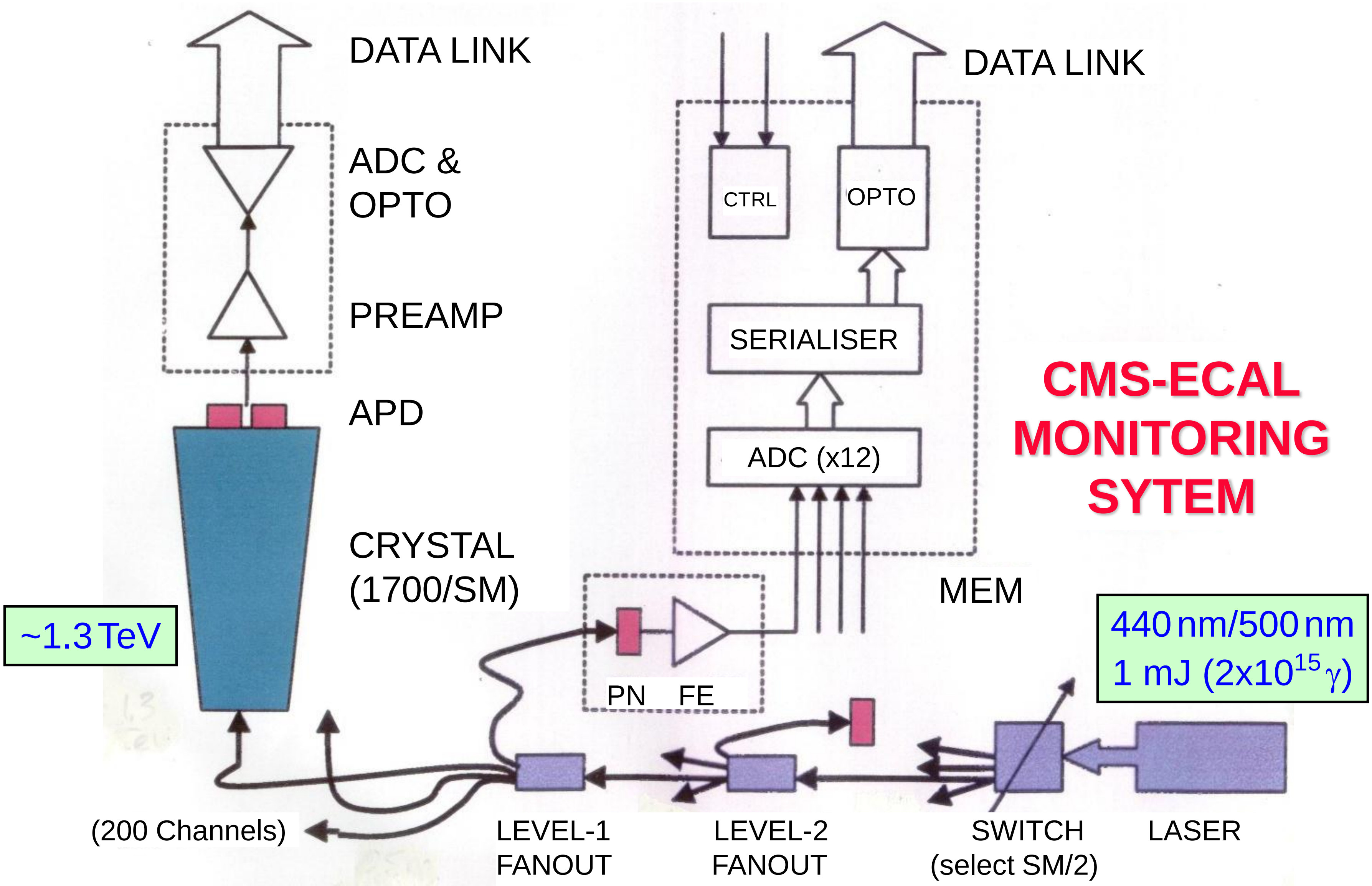
- partially restored using Si p.h. information

Excellent agreement between MC and data

TDR performance achieved for E > 80 GeV
(➔E_T > 30 GeV - OK for H →γγ)

(even though Pb 10% too thick in this test!)

Laser Monitoring System



DATA LINK

ADC &
OPTO

PREAMP

APD

CRYSTAL
(1700/SM)

~1.3 TeV

(200 Channels)

DATA LINK

CTRL

OPTO

SERIALISER

ADC (x12)

MEM

PN FE

LEVEL-1
FANOUT

LEVEL-2
FANOUT

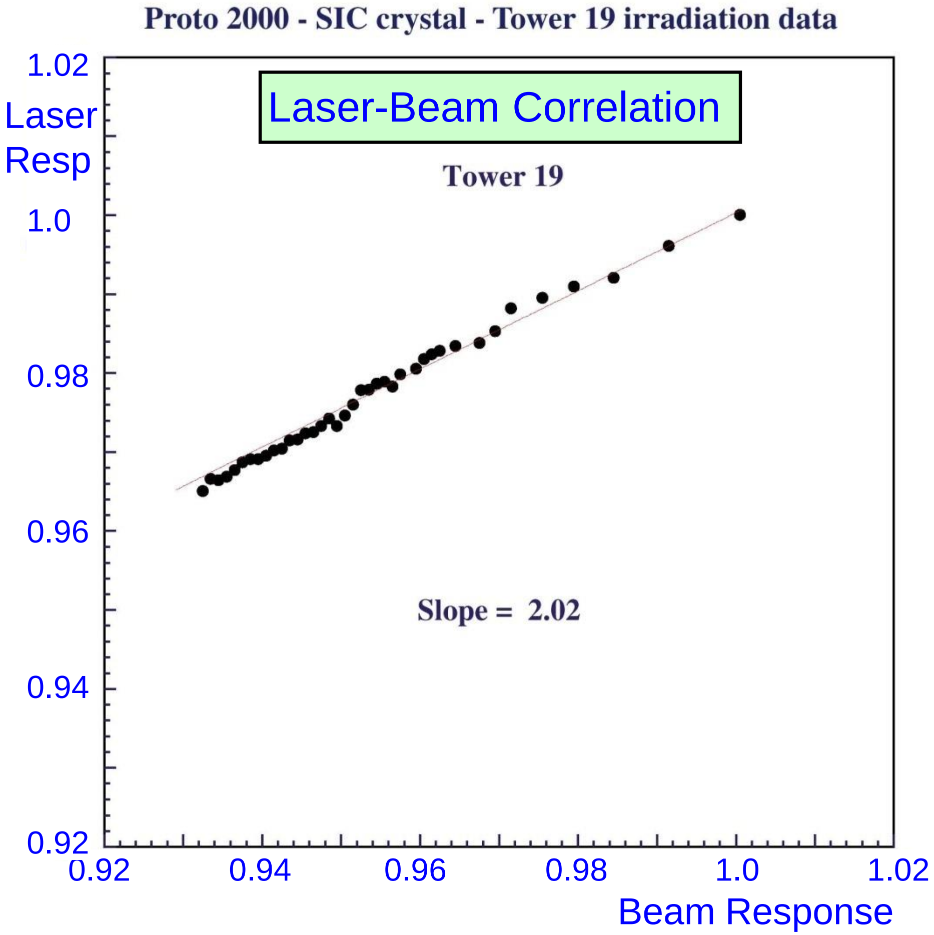
SWITCH
(select SM/2)

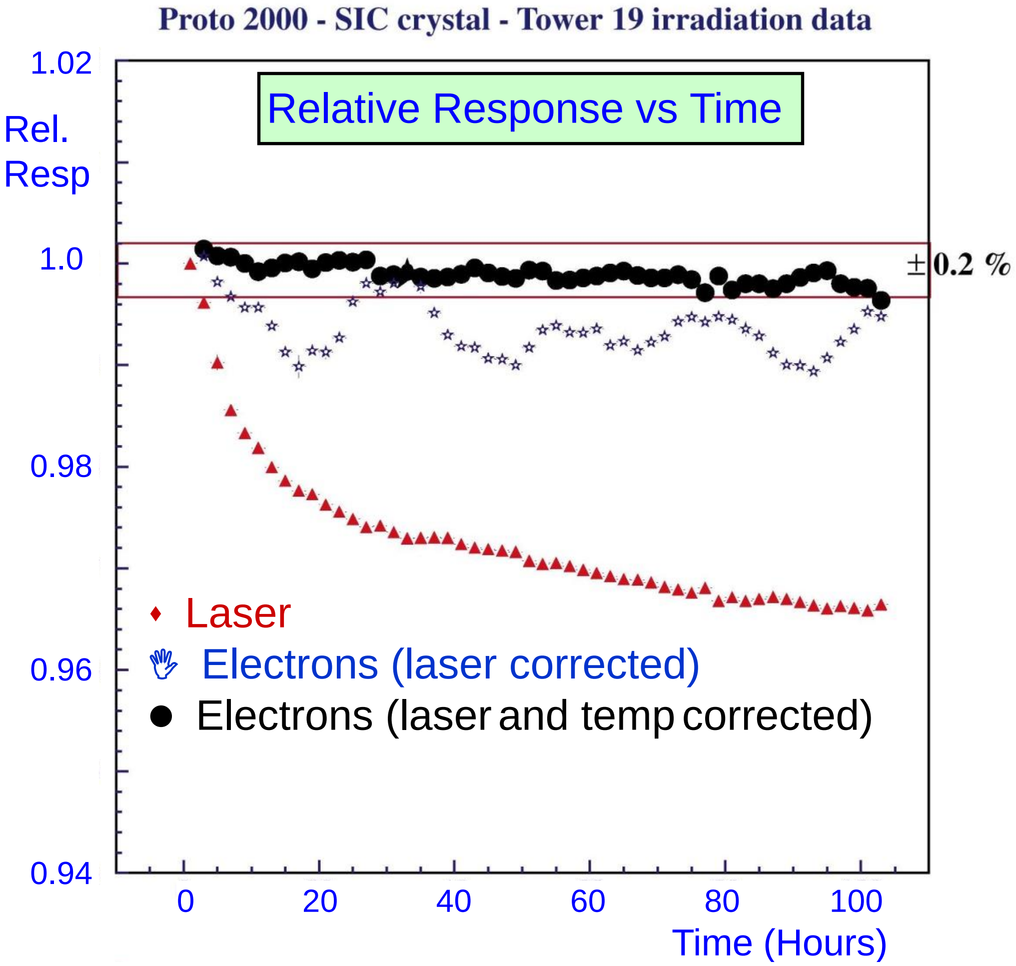
LASER

440 nm/500 nm
1 mJ ($2x10^{15}\gamma$)

**CMS-ECAL
MONITORING
SYTEM**

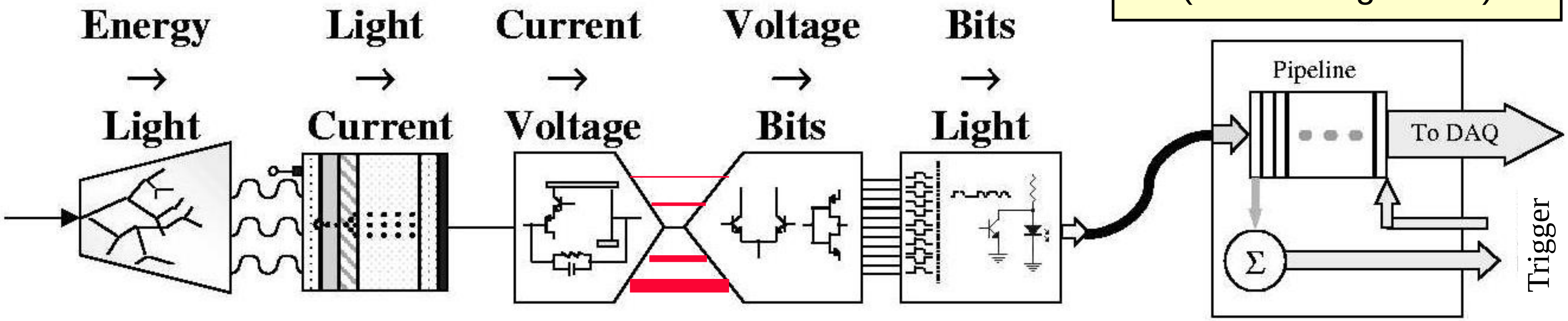
Laser Correction for Effect of Radiation Damage





Readout architecture

Upper-level VME readout
(in Counting Room)



PbWO$_4$ Crystal

APD VPT

Preamp

Gain select

ADC

Serialiser + VCSEL

Optical link

Pipeline control
Interface → DAQ
Interface → Trigger

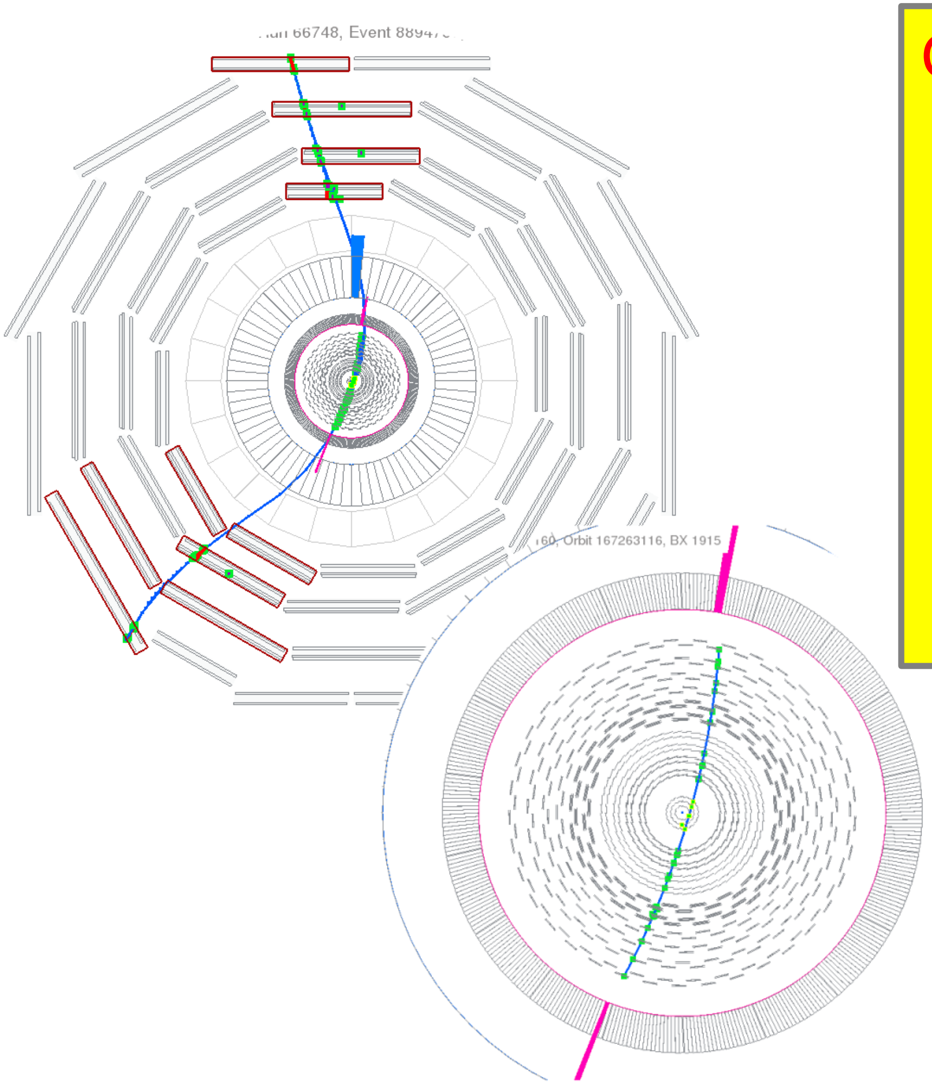
On-detector *light-to-light* readout

- 40 MHz Clock
- 12 bit precision
- 4 different gains ➔ >17 bit dynamic range

Cosmic ray data

CRAFT: Cosmic Run At Four Tesla

- continuous running for several weeks to gain operational experience
- > 300 M cosmic events collected
- magnetic field operated at 3.8T
- most CMS subsystems participating



Minimum ionizing particles deposit 250 MeV in ECAL. Increase efficiency: signal/noise enhanced (x4) in EB to the value of 20, by increasing the gain of the APD.

From Biino at ICATPP11 2009

$PbWO_4$ Stopping Power

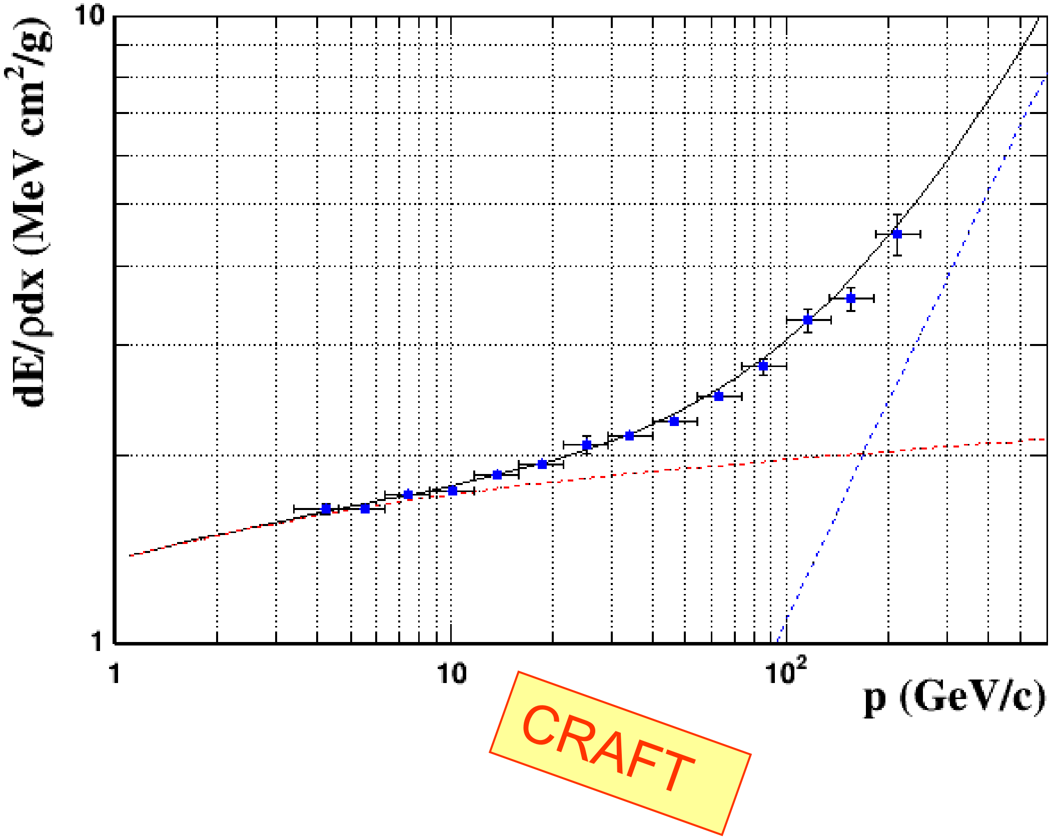
Validate ECAL calibration with muons: measure energy deposition vs muon momentum

momentum p measured in the CMS silicon tracker

dE: energy from ECAL cluster

dx: length traversed in ECAL crystals

dE/ρdx energy deposit matched to the track corrected for muon path length



Tracker momentum matches well with ECAL energy loss, energy scale is correct

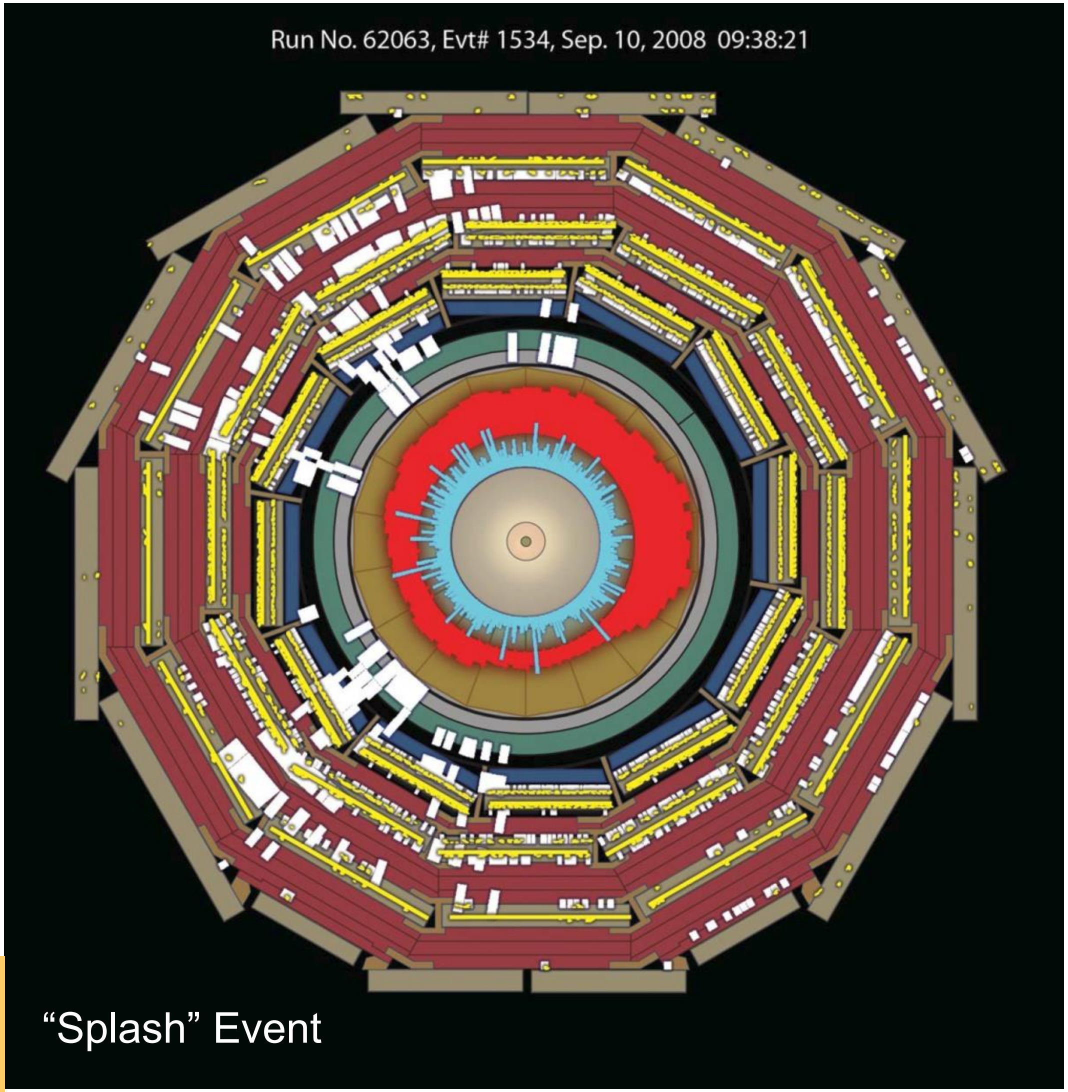
From Biino at ICATPP11 2009

LHC data

Data-taking with LHC beam.

- Wed, 10 Sept. 2008
  - "Splash" events observed when beam (450 GeV, 4.10^9 p) struck closed collimators 150m upstream of CMS
  - Halo muons observed once beam (uncaptured and captured) started passing through CMS

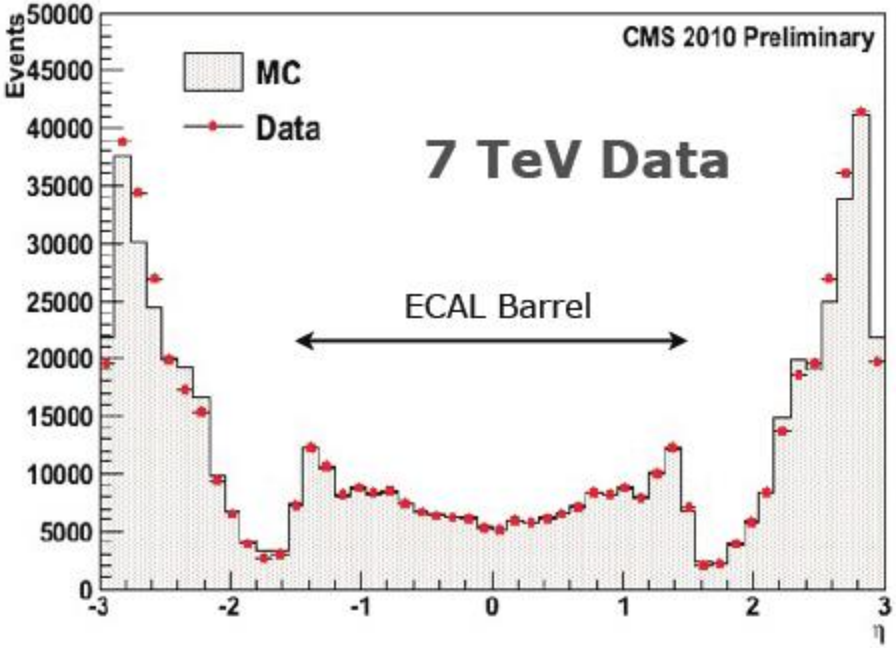
High energy deposit in the calorimeters,
particles travelling horizontally
useful to commission forward detectors

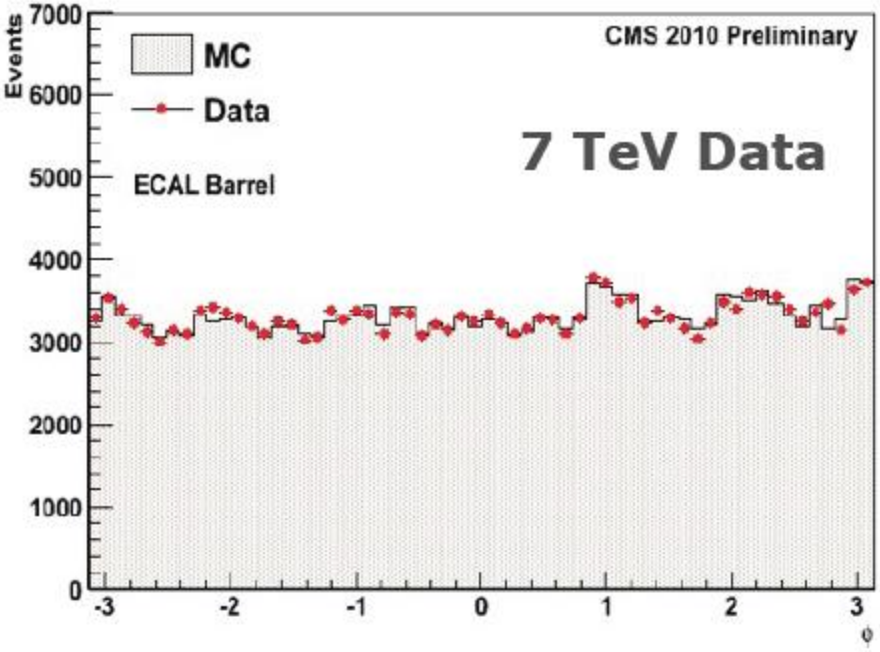


"Splash" Event

From Biino at ICATPP11 2009

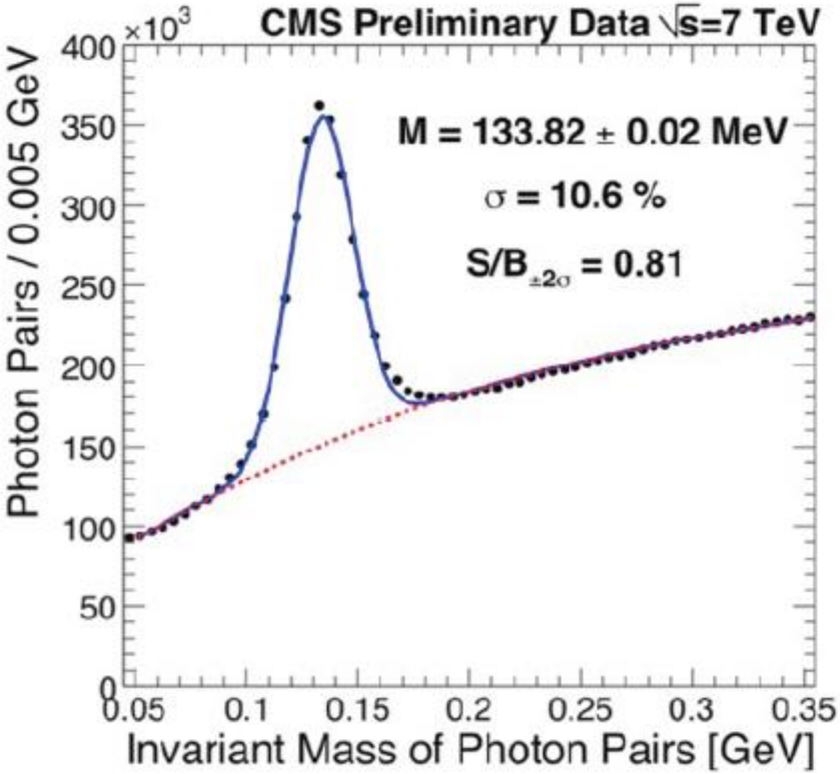
Rapidity and Phi



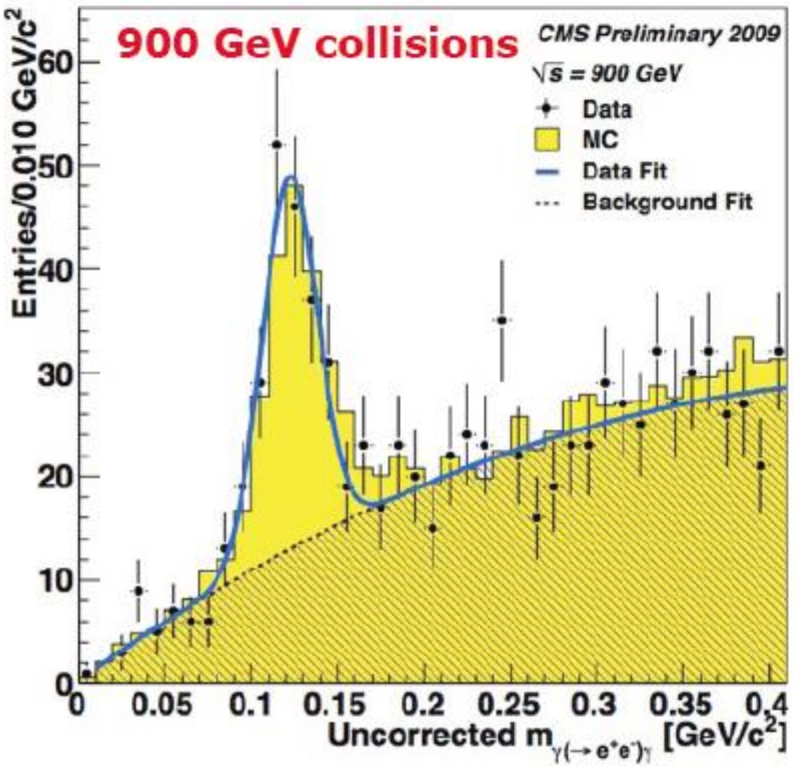


- Rapidity and azimuth distributions of the ECAL channel with the highest ET in minimum bias events at 7 TeV
- Variations as a function of η are due to the detector geometry; ECAL endcap data are prescaled by a factor six for presentation purposes
- Variations as a function of phi, accurately reproduced in MC, reflect modularity and the inhomogeneity of the energy-equivalent noise in ECAL

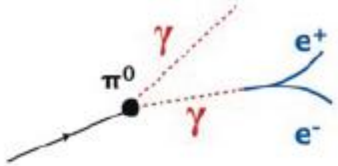
Neutral pions



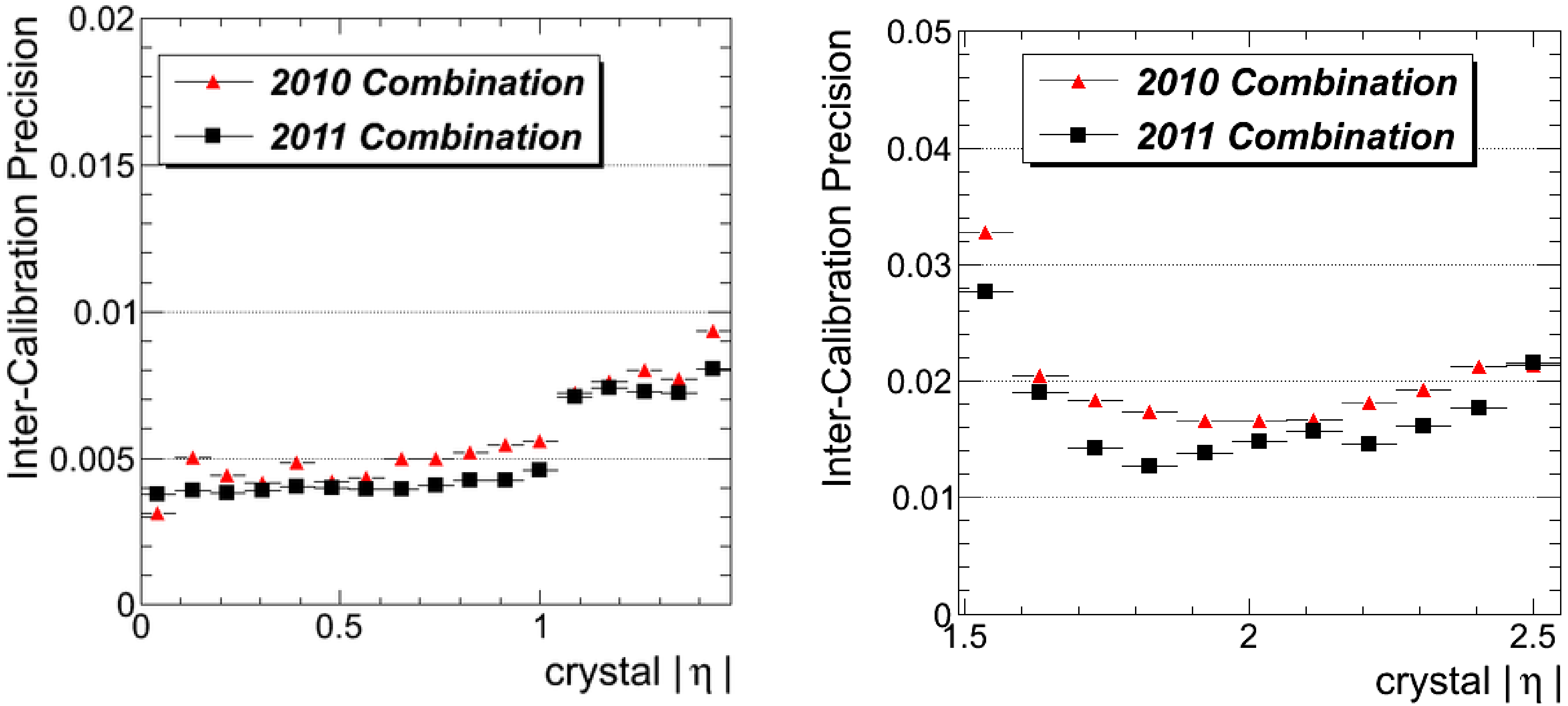
$\pi^0 \to \gamma\gamma$ in **7 TeV** data about 1461 thousands candidates for $\int L = 0.43 \mathrm{nb}^{-1}$



$\pi^0 \to \gamma\gamma$ where one of the two photons is reconstructed as a conversion

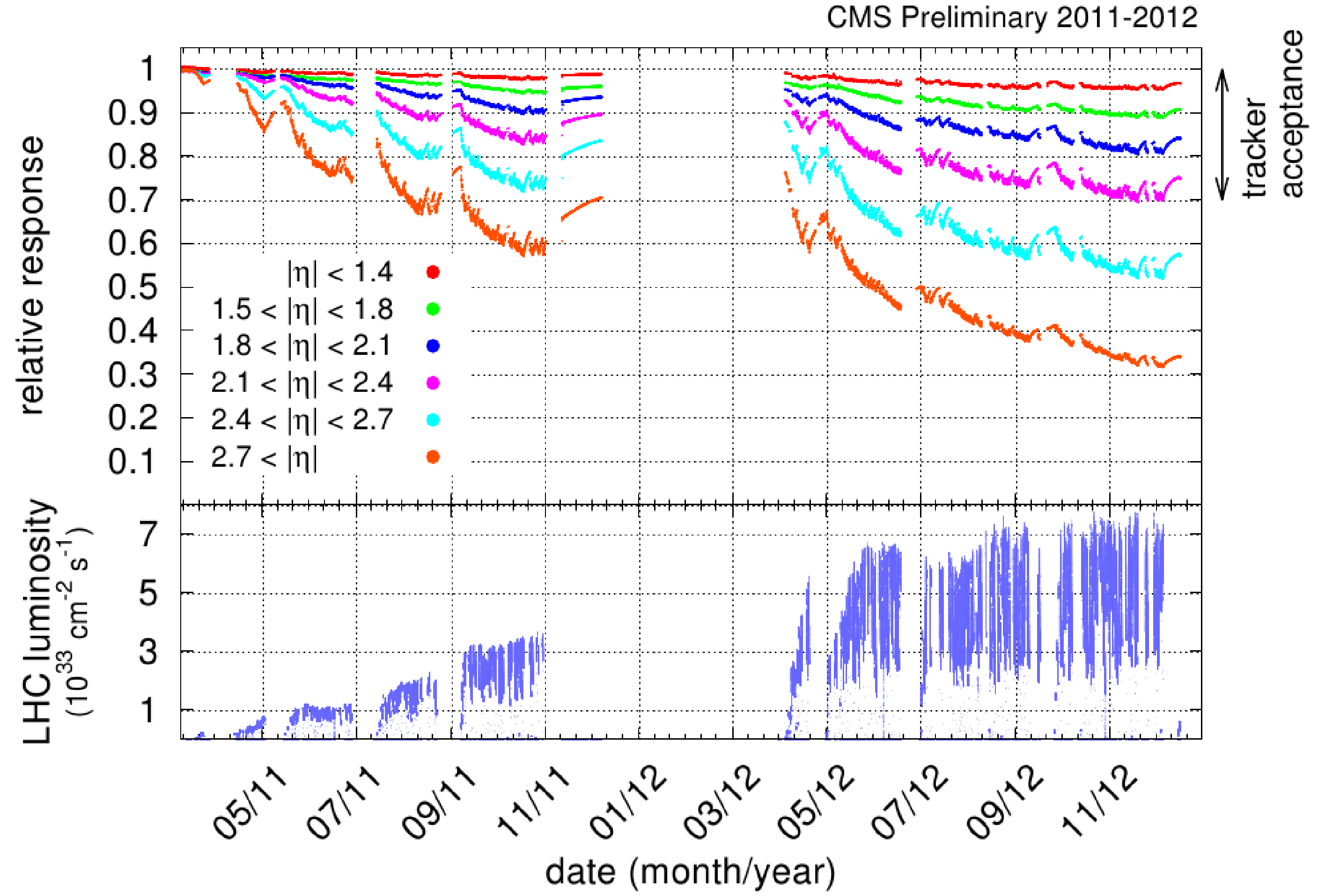


Intercalibration



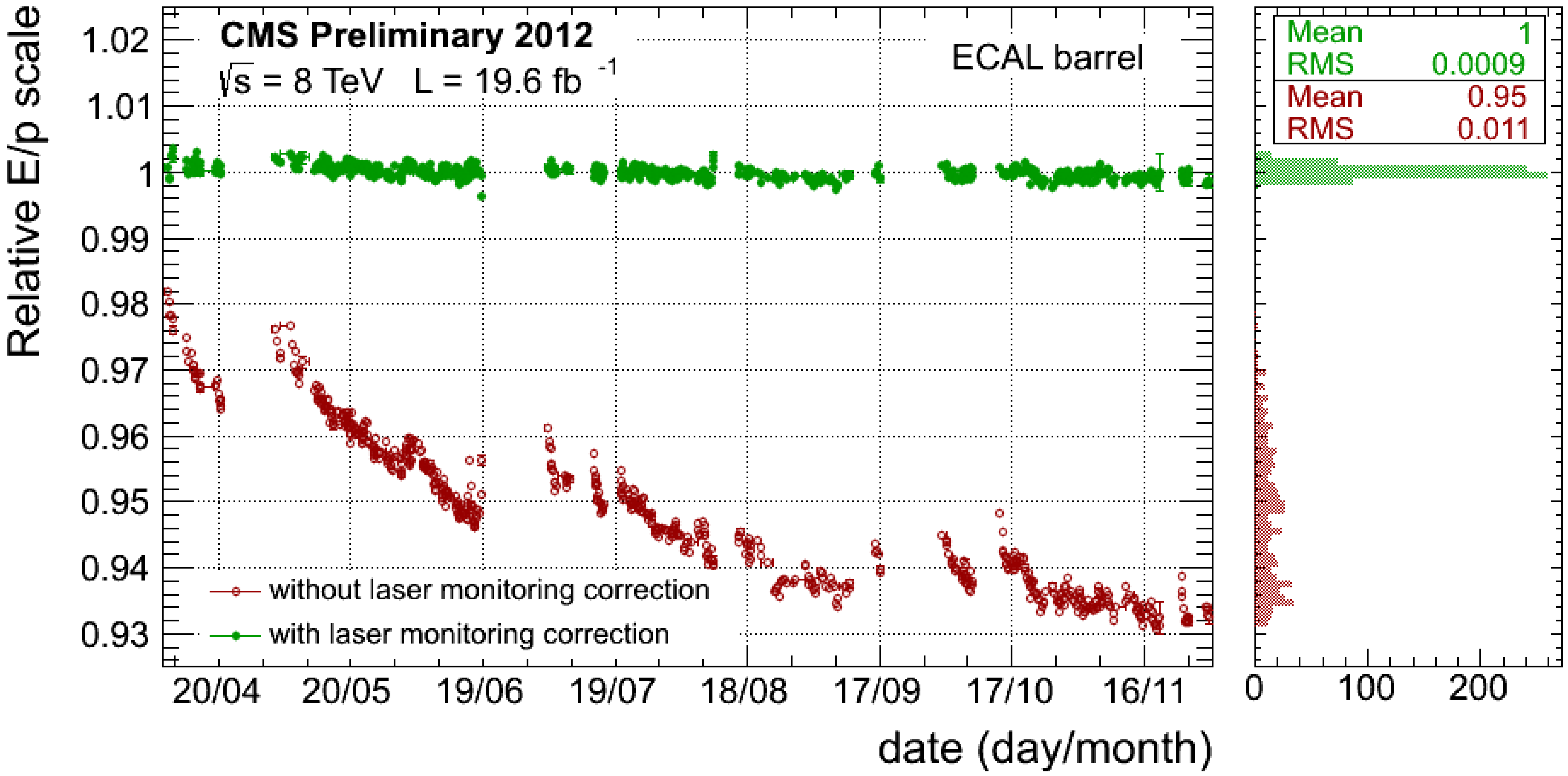
The precision of channel inter-calibration, using energy deposits, as a function of pseudo-rapidity in the ECAL barrel and endcap detectors

LHC radiation damage



Relative response to laser light (440 nm) measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity, for the 2011 and 2012 data taking periods

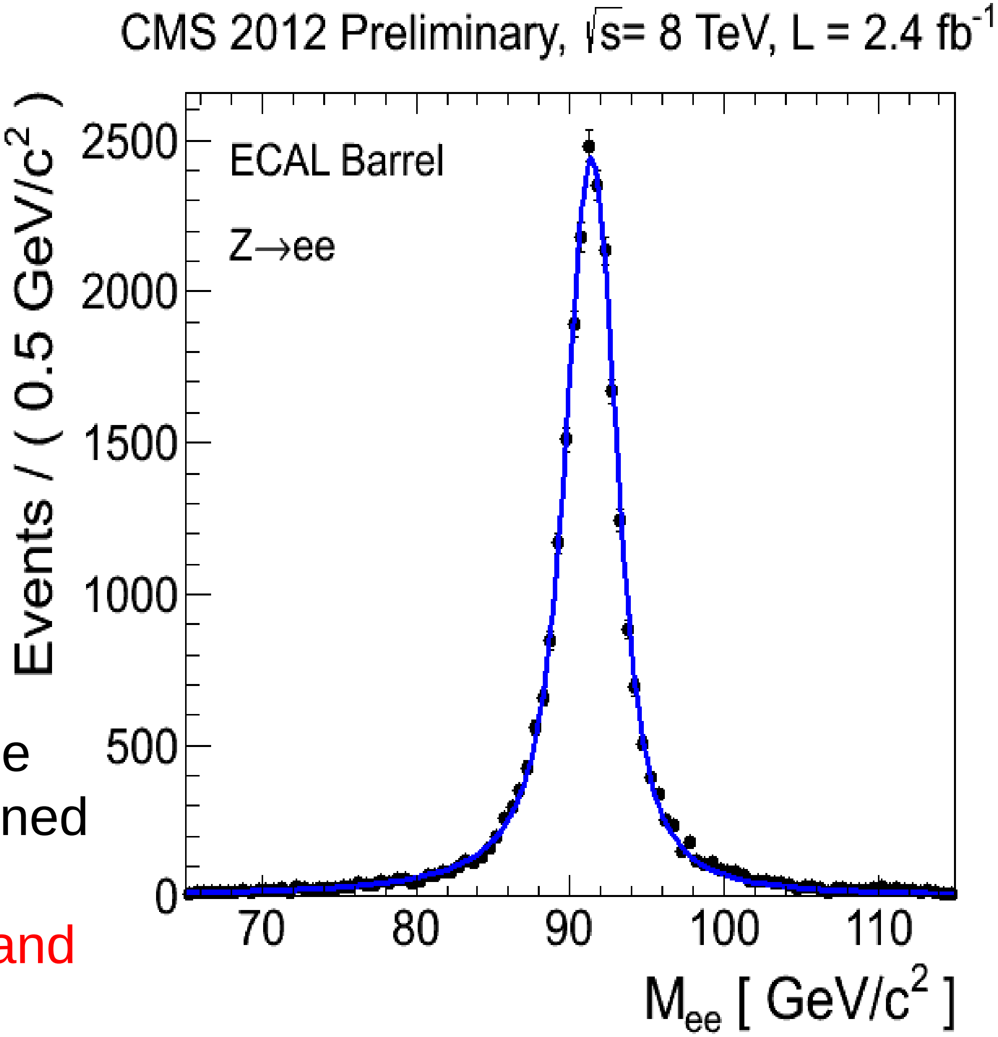
LHC radiation damage



Correcting for the effects of radiation damage using the laser monitoring system. Barrel calorimeter shown here.

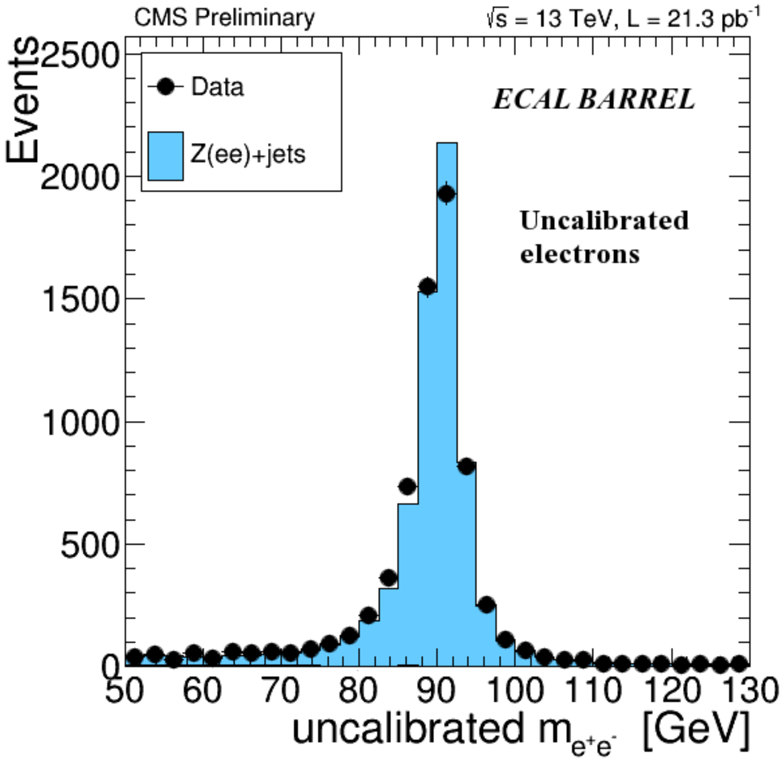
The corrections work

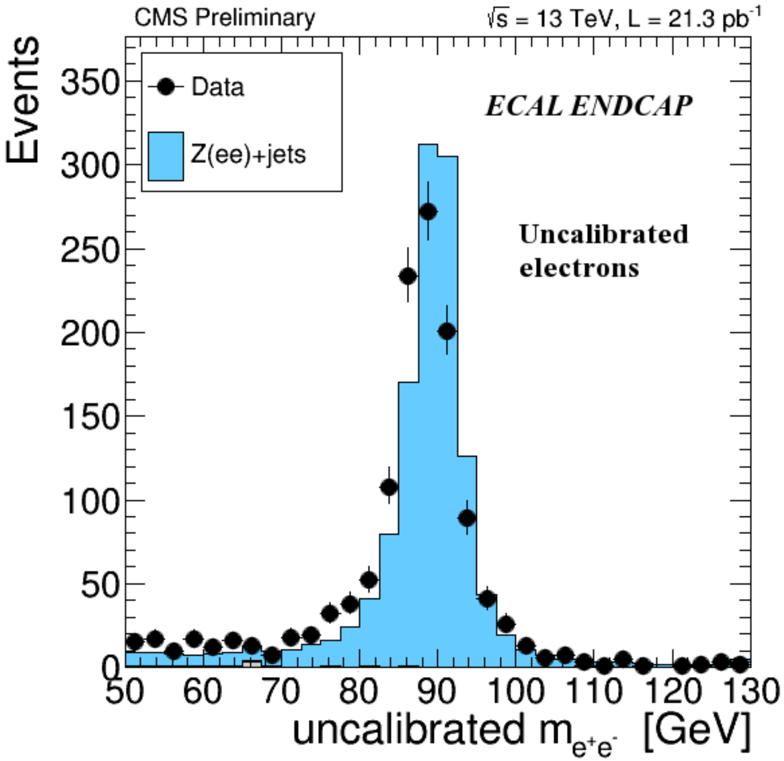
Instrumental resolution in barrel is 1 GeV at the Z peak



The plot shows the improvements in Z->ee energy scale and resolution that are obtained from applying energy scale corrections to account for the intrinsic spread in crystal and photo-detector response, and time-dependent corrections to compensate for crystal transparency loss

What about 13 TeV?





Non-optimised data (shown at EPS conference) from early Run 2 data in 2015.

MC number is normalised to data and calibration is based on an extrapolation from Run 1 constants.