REVIEW OF CRYSTAL CALORIMETERS

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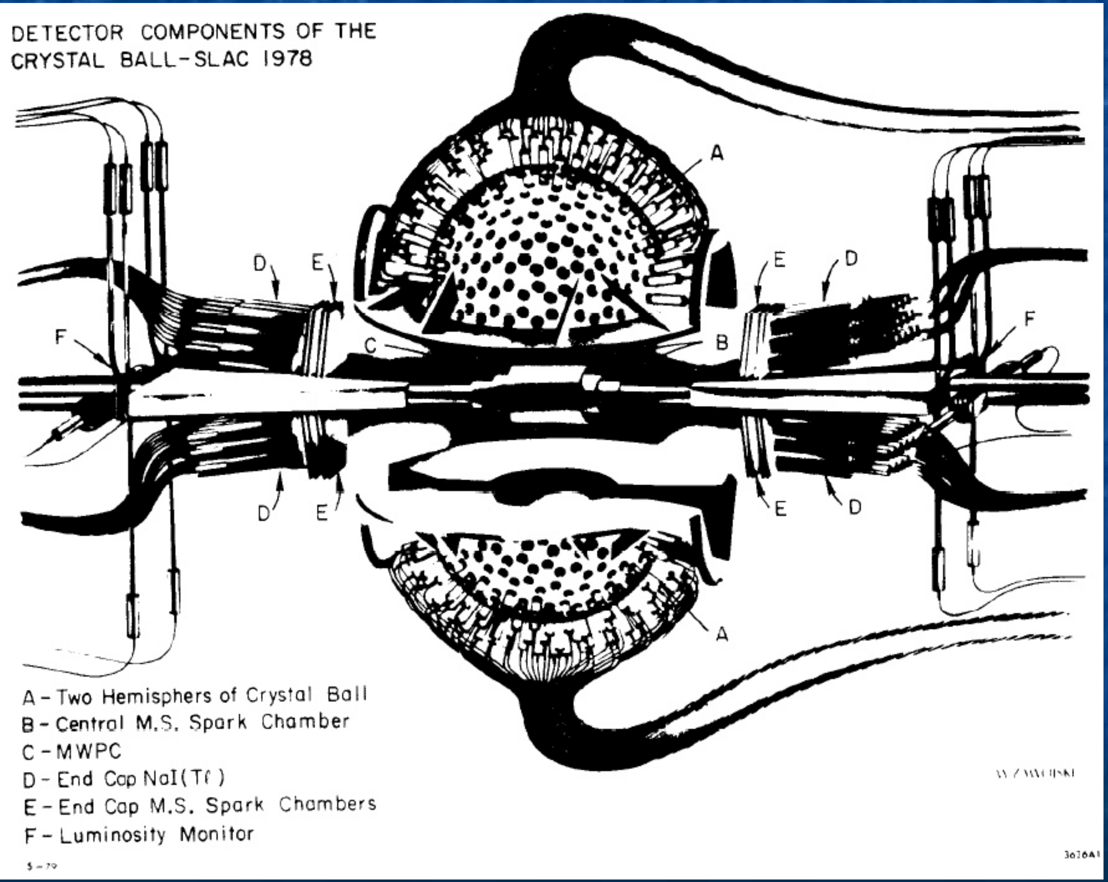
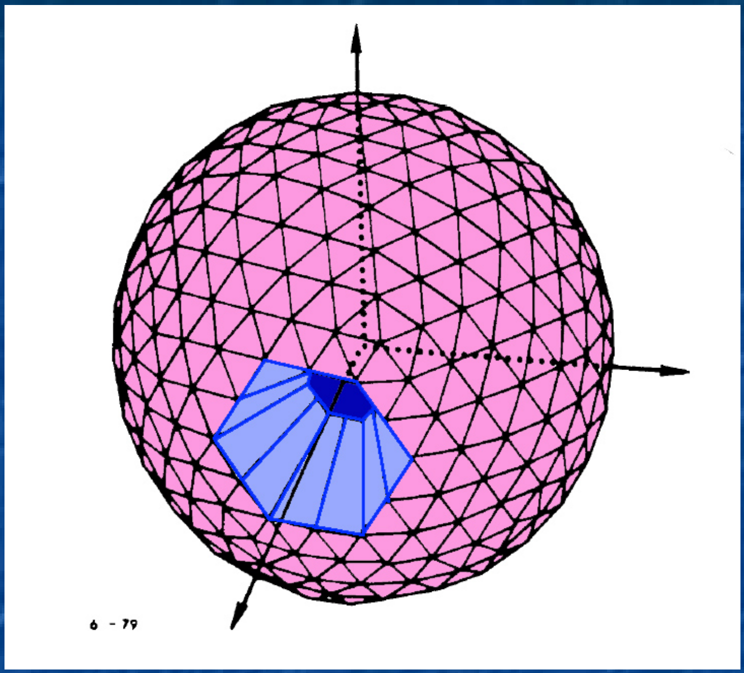
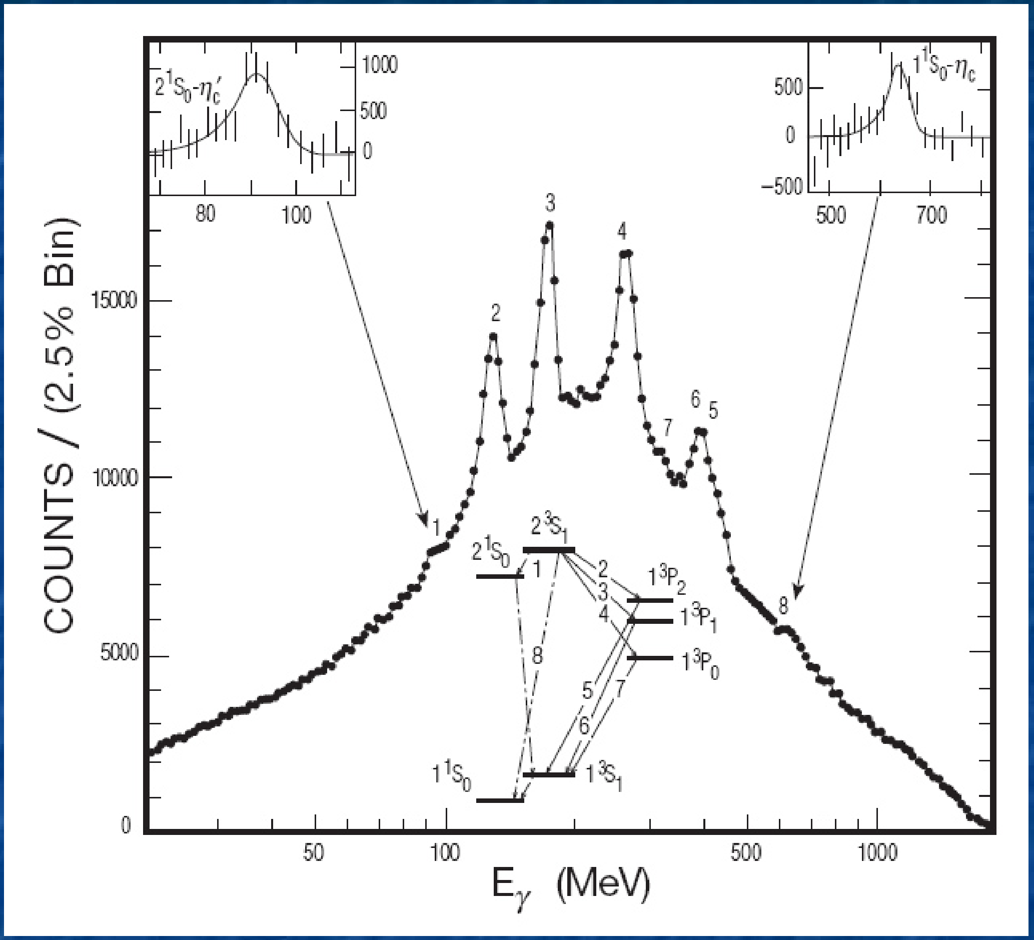
Crystal Ball Detector

The first large-scale crystal calorimeter in high energy physics was the NaI(Tl) calorimeter of the Crystal Ball detector. It showed high discovery potential of the crystal calorimeters.



Crystal Ball NaI(Tl) Calorimeter





Number of crystals 672
Inner radius 25.4 cm
Outer radius 66.0 cm
Thickness 16 X_0
Solid angle coverage 93%
Photodetector PMT
Noise 0.05 MeV
Dynamic range 10^4

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt[4]{E(\mathrm{GeV})}}$$

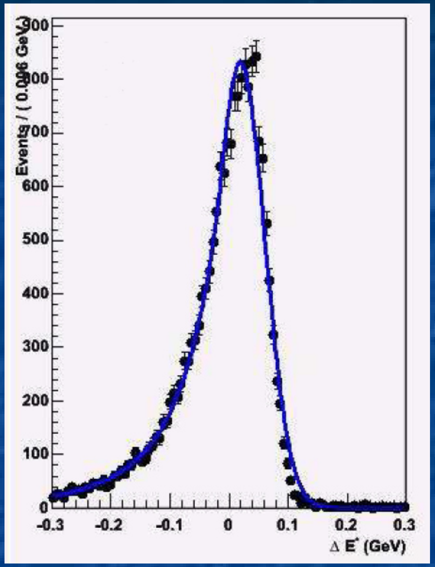
Inclusive photon spectrum at ψ(2S) resonance

Crystal calorimeter benefits

- High efficiencies for electrons and photons
- Best energy resolution and good position and angular resolution for photons and electrons
- High linearity and wide dynamic range
- Radiation hardness
- Reliability and simplicity of maintenance
- Compact size

Energy resolution and line shape

- Light collection and crystal light output nonuniformities
- Fluctuations of the shower energy losses
- Photoelectron statistics
- Inaccuracy of the calibration of individual channels
- Electronics noise and instabilities



BABAR calorimeter line shape.
Fit – Crystal Ball function

Commonly used parameterizations of the calorimeter line shape:

Crystal Ball function

$$C(x) = \begin{cases} N \exp\left[-\dfrac{(x-x_0)^2}{2\sigma^2}\right] & \text{for } x > x_0 - \alpha\sigma \\ N \dfrac{(n/\alpha)^n e^{-\frac{\alpha^2}{2}}}{[(x_0 - x)/\sigma + n/\alpha - \alpha]^n} & \text{for } x \le x_0 - \alpha\sigma \end{cases}$$

N – norm. factor
x_0 – peak position
σ – Gaussian width
α – joint parameter

Logarithmic Gaussian (Novosibirsk function)

$$W(x) = N \exp\left[-\frac{1}{2}\left(\frac{\log[1+\tau(x-x_0)\dfrac{\sinh[\tau\sqrt{\log 4}]}{\sigma\tau\sqrt{\log 4}}]}{\tau}\right)^2 + \tau^2\right]$$

N – norm. factor
x_0 – peak position
σ – FWHM/2.35
τ – peak asymmetry

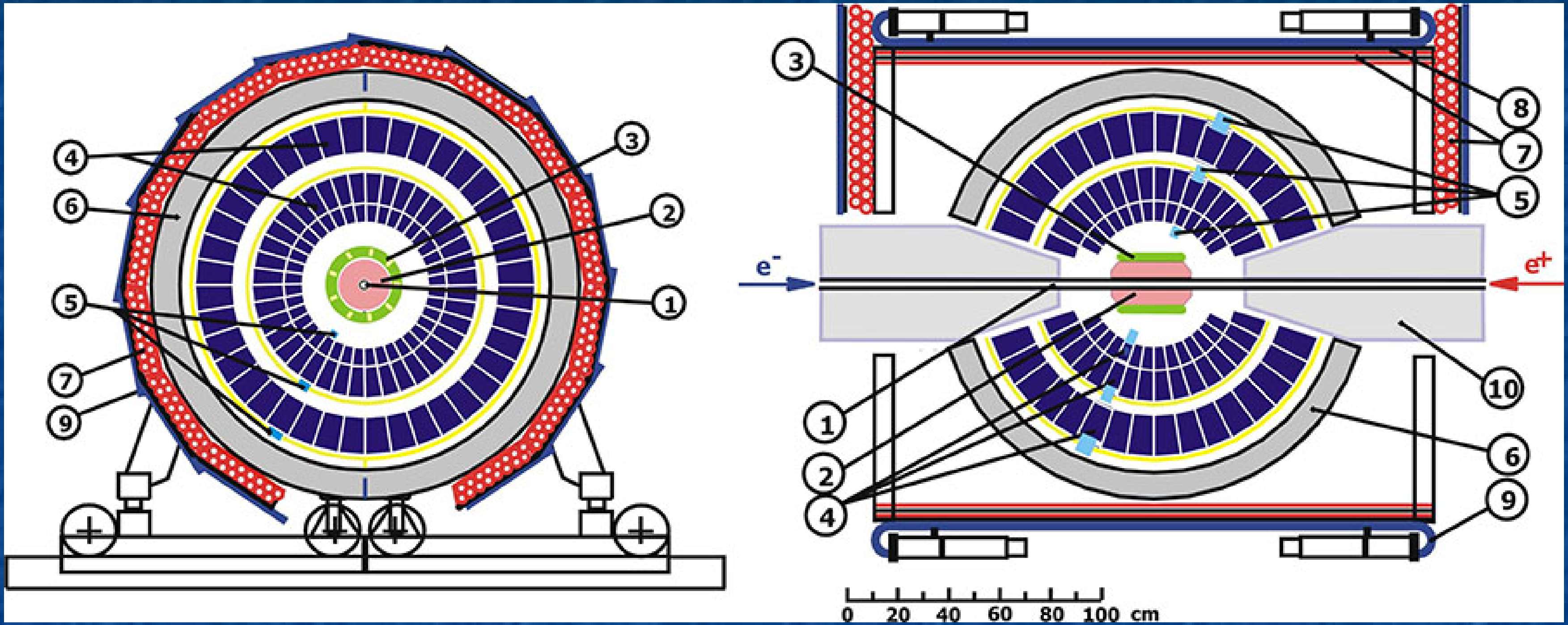
HEP Crystal Calorimeters

Experiment	**Crystal Ball, SPEAR, SLAC**	**SND, VEPP-2M, VEPP-2000 BINP Novosibirsk**	**L3, LEP, CERN**	**KTeV Tevatron Fermilab**	**CLEO c, CESR, Cornell**	**BABAR PEP II SLAC**	**BELLE KEKB KEK**	**CMS, LHC, CERN**
Time	75–85	90–15	80–00	96–00	80–08	94–08	94–	95–20
Crystal	NaI(Tl)	NaI(Tl)	BGO	CsI	CsI(Tl)	CsI(Tl)	CsI(Tl)	$PbWO_4$
N crystals	672	1640	11400	3260	7800	6580	8800	76000
Inner radius (m)	0.254	0.25	0.55	-	1.0	0.9	1.25	1.29
Volume (m^3)	1	1	1.5	2	7	5.9	9.5	11
Thickness (X_0)	16	13.4	22	27	16	16-17.5	16.2	26
Photo sensor	PMT	VPT	Si PD	PMT	Si PD	Si PD	Si PD	APD, VPT
Noise (MeV)	0.05	0.2	0.8	-	0.5	0.15	0.2	30
Dynamic range	10^4	10^3	10^5	10^4	10^4	10^4	10^4	10^5

Scintillation crystals for calorimetry

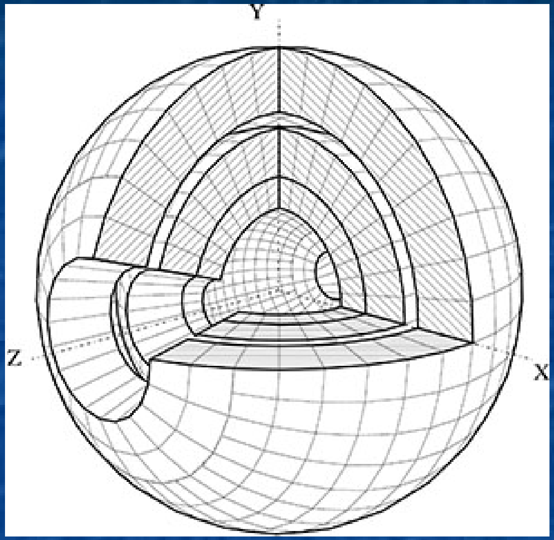
Crystal	Density g/cm^3	Refractive index	Radiation Length cm	Moliere Radius cm	λmax nm	Light yield %NaI(Tl)	Decay time ns	dLY/dT %/°C	Melting point °C
NaI(Tl)	3.67	1.85	2.59	4.13	410	100	230	~0	651
CsI(Tl)	4.51	1.79	1.86	3.57	560	165	1250	0.3	621
CsI	4.51	1.95	1.86	3.57	420 310	3.6 1.1	30 6	-0.6	621
BaF_2	4.89	1.50	2.03	3.10	300 220	36 3.4	630 0.9	–2 ~0	1280
CeF_3	6.26	1.62	1.70	2.41	300	7.3	30	0.14	
BGO ($Bi_3Ge_3O_{12}$)	7.13	2.15	1.12	2.23	480	21	300	-1.6	1050
PWO ($PbWO_4$)	8.3	2.20	0.89	2.00	425 420	0.29 0.083	30 6	-1.9	1123
LSO (Lu_2SiO_5:Ce)	7.40	1.82	1.14	2.07	420	84	42	~0	2050
GSO (Gd_2SiO_5:Ce)	6.71	1.85	1.38	2.23	440	30	60	-0.1	1950

SND detector

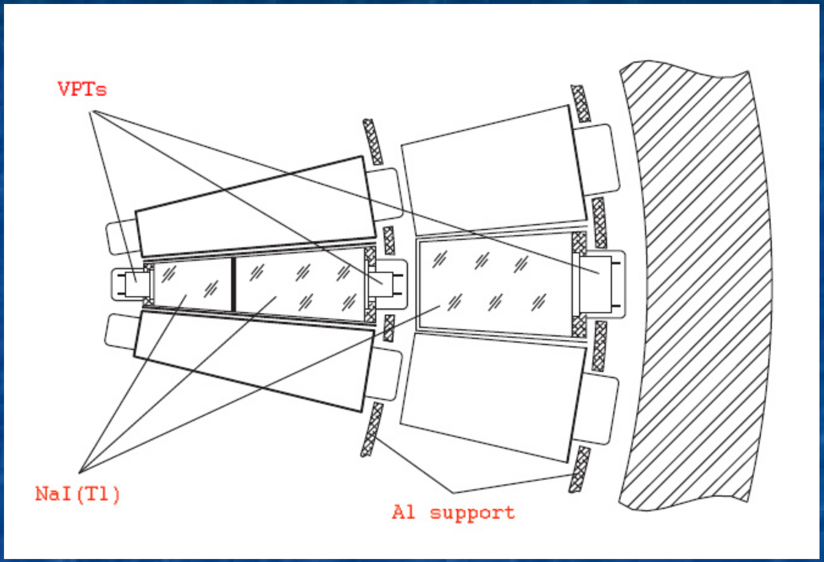


SND detector; 1 – Be vacuum chamber, 2 – tracking system, 3 – aerogel Cherenkov counters, 4 – NaI(Tl) scintillation counters, 5 – vacuum phototriodes, 6 – iron absorber, 7,8 – muon system.

SND NaI(Tl) calorimeter



SND calorimeter geometry

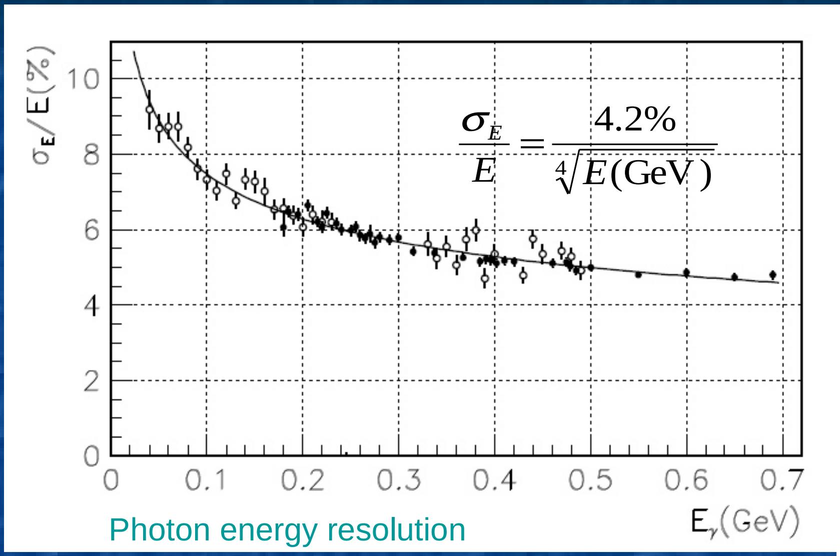


SND calorimeter segment

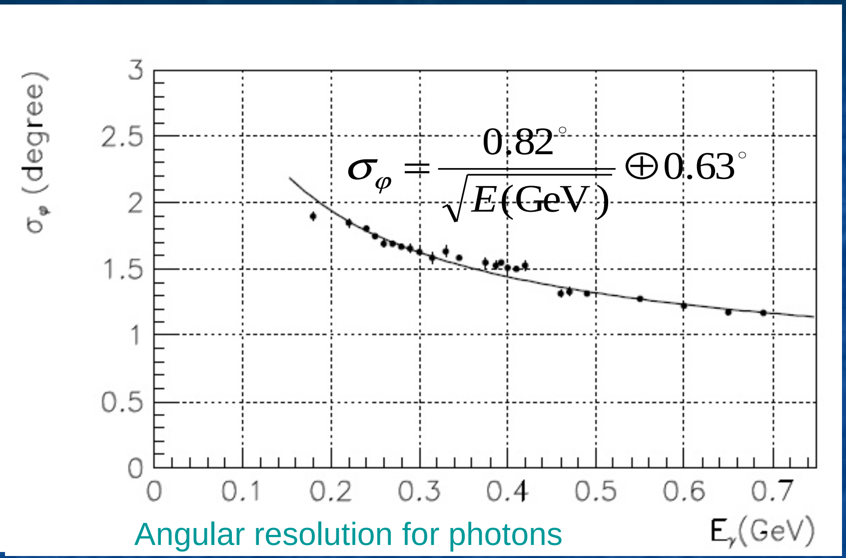
Number of crystals - 1632, thickness – 13.5 X_0, mass – 3.5 tons
Photodetectors – vacuum phototriodes with photocathode quantum efficiency of ~15% and gain ~10.

Three-layer structure allows high quality e/π separation by using measurement of the shower energy deposition longitudinal profile

SND calorimeter resolution



Photon energy resolution

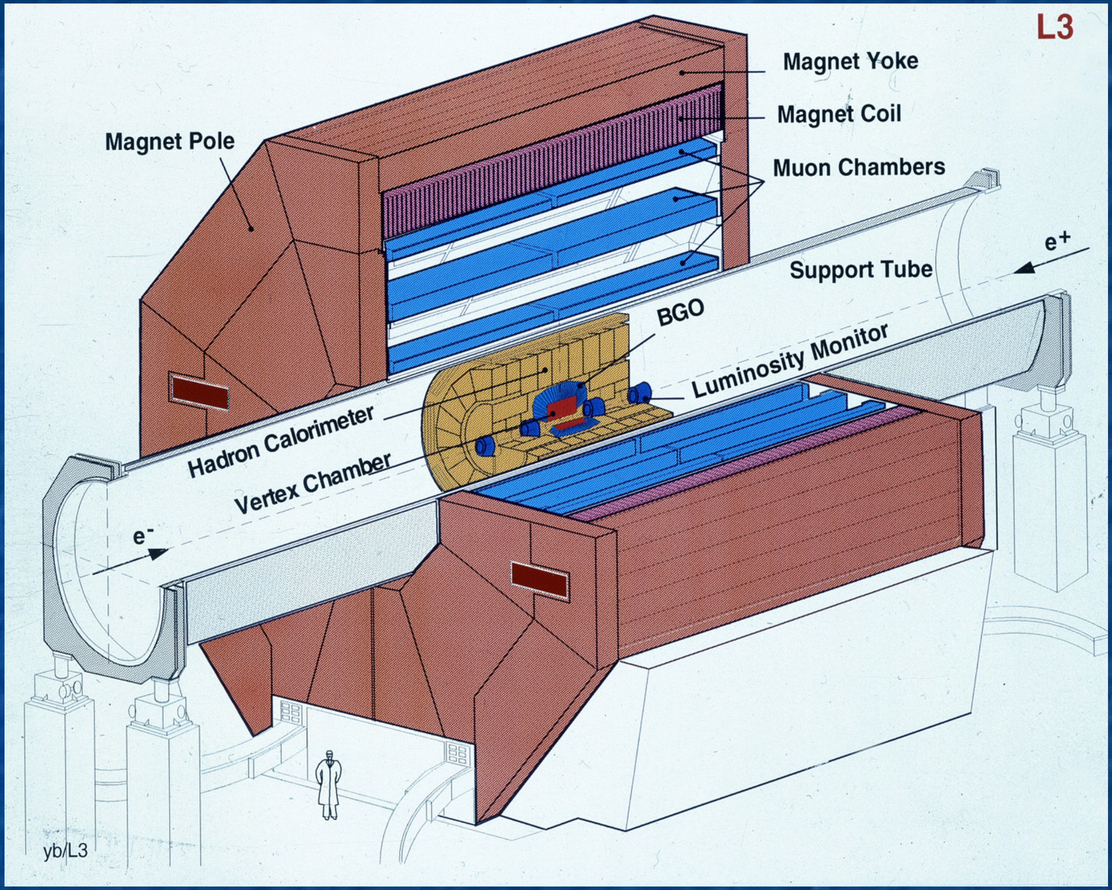


Angular resolution for photons

Crystal calibration – using cosmic muons (precalibration) and Bhabha scattering events (final calibration)

Future plans – the use of the calorimeter for the time of flight measurement for selection of e+e− ->nnbar events. The resolution of 2ns for energy deposition of 70 MeV was achieved in the test with an SND calorimeter crystal (to be presented at INSTR08 poster session)

L3 BGO calorimeter



L3 detector at LEP 1980-2000

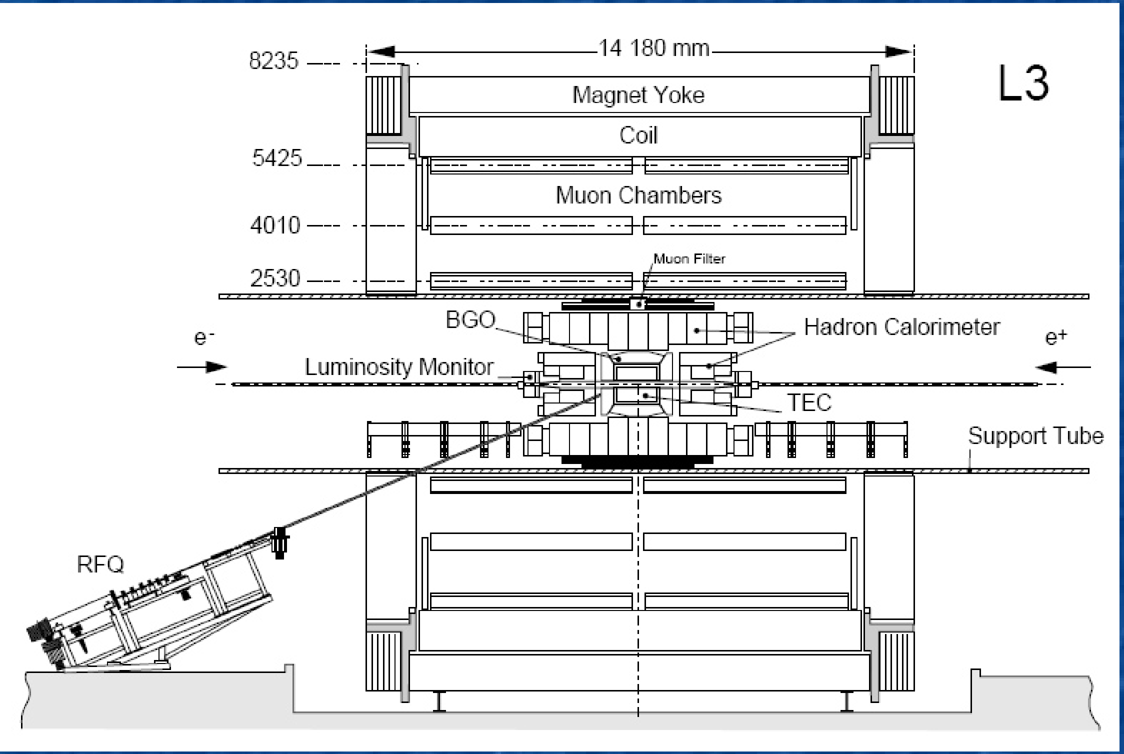
Number of crystals:
- Barrel – 7680
- Endcaps – 2×1527

Thickness – $22X_0$

Photodotector – Si PD

L3 calorimeter calibration

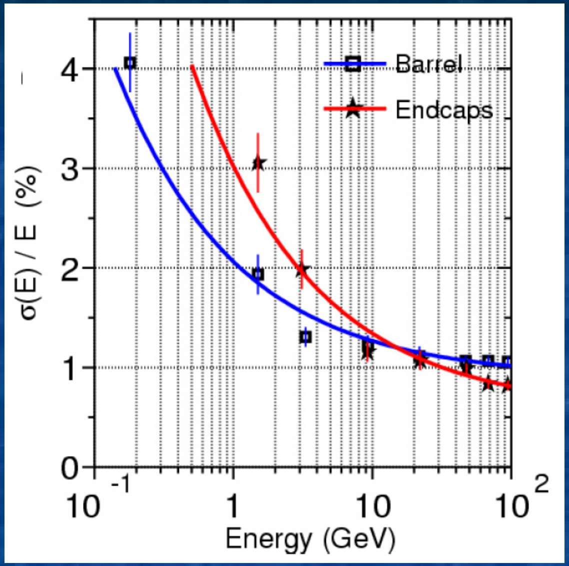
Proton RFQ accelerator-based calibration system

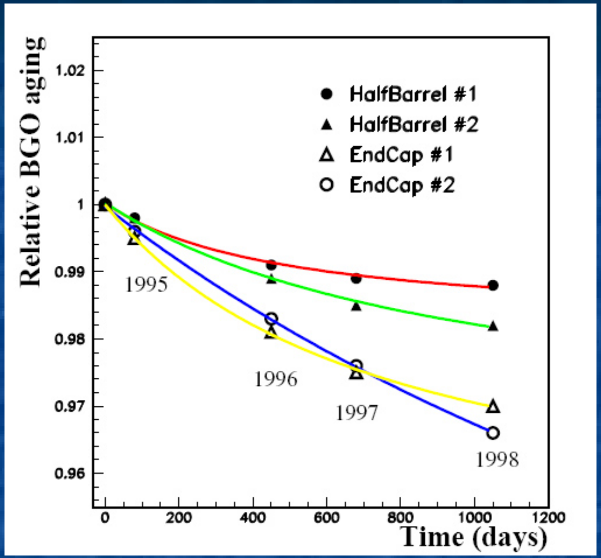


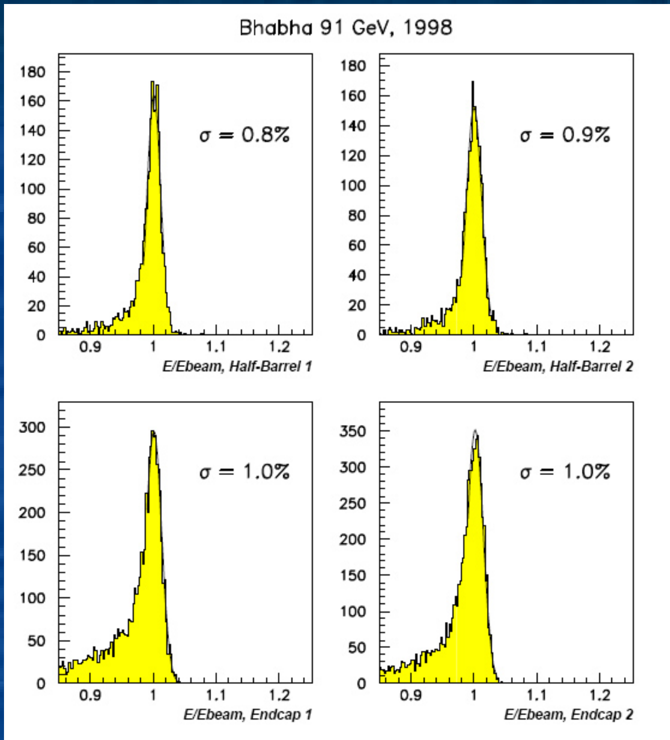
RFQ accelerator produces 1.85 MeV H^- beam. After focusing and steering it is neutralized and directed through the detector magnetic field to Li target inside the detector.
Resonant proton radiative capture reaction (σ=5mb) produces calibration photons:
$p+{}^7Li \rightarrow {}^8Be + \gamma$ (17.6 MeV)

Calibration accuracy – 0.5%

L3 calorimeter energy resolution

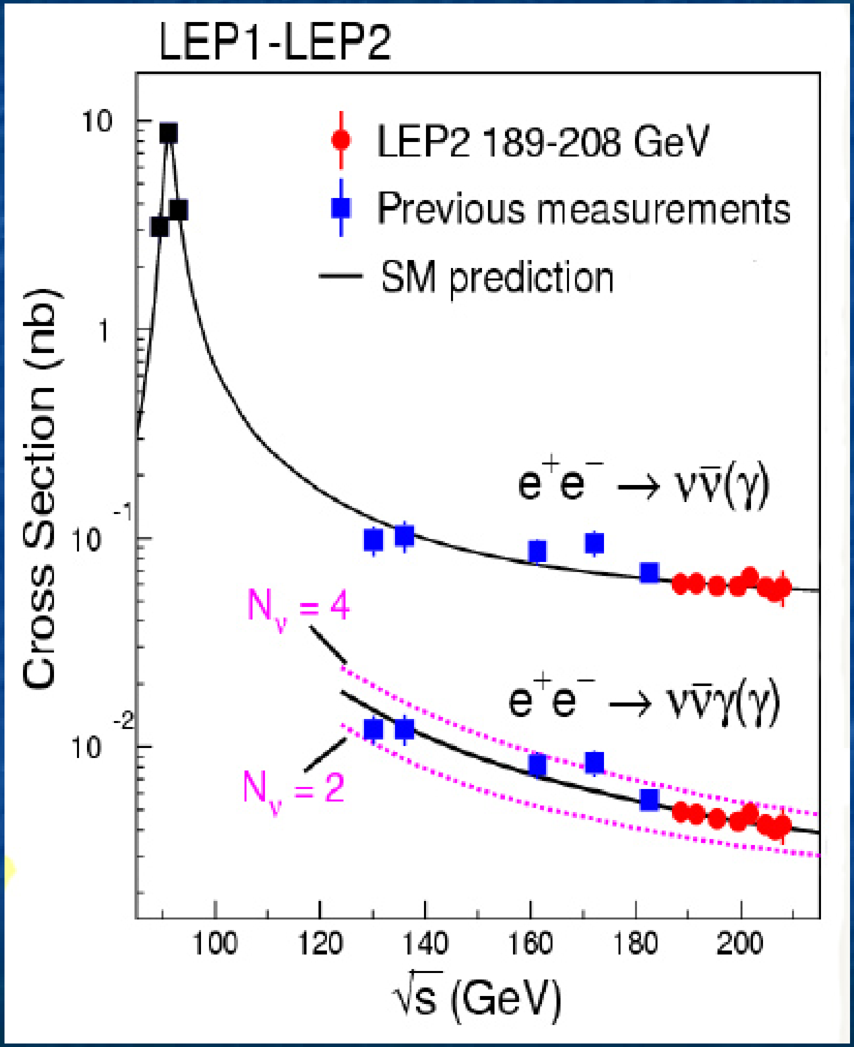






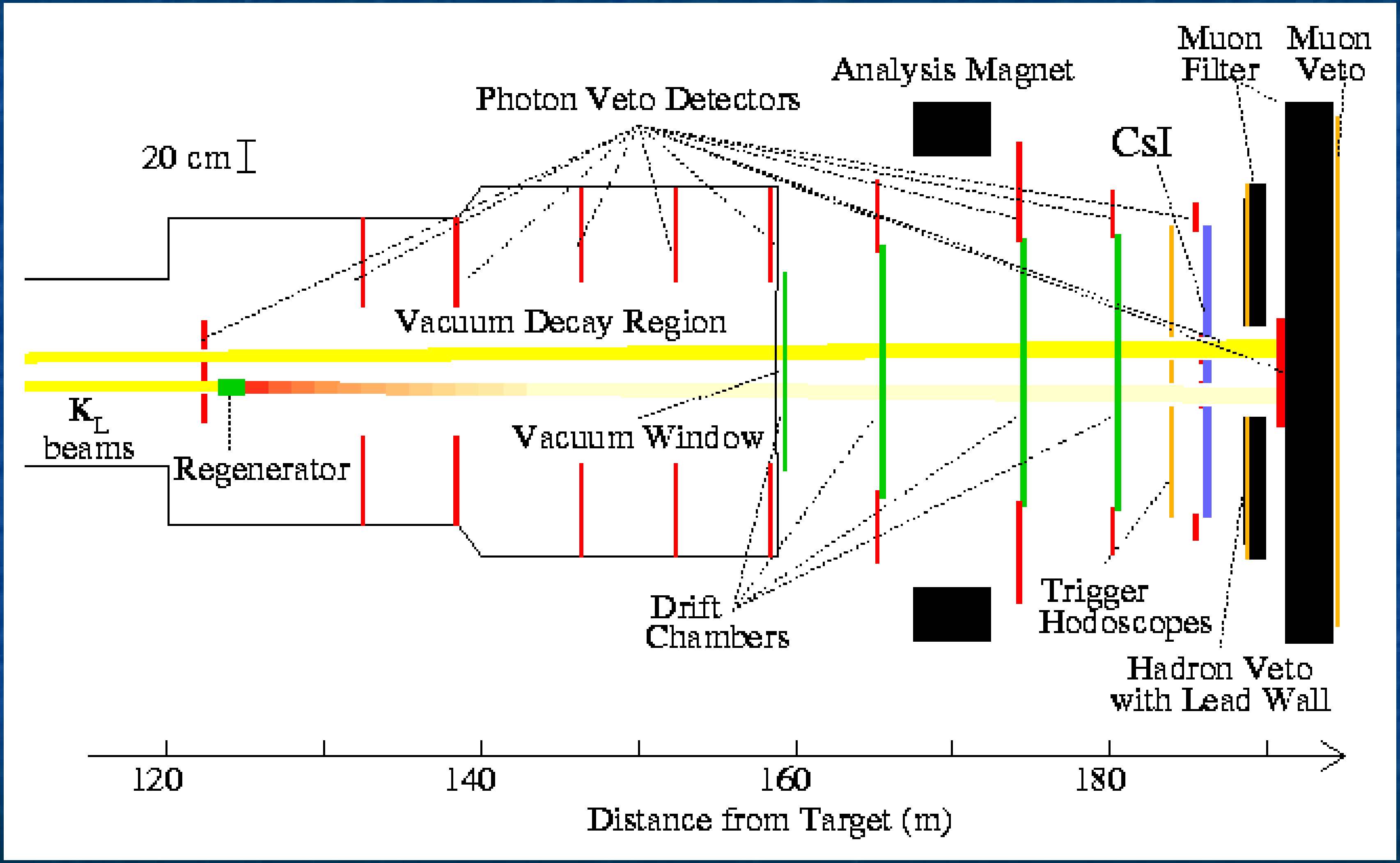
Contribution	Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcap	0.6%	0.5%	0.4%	0.88%

L3 calorimeter discovery potential



Study of the process
$e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$
Determination of the number of light neutrinos

KTeV detector



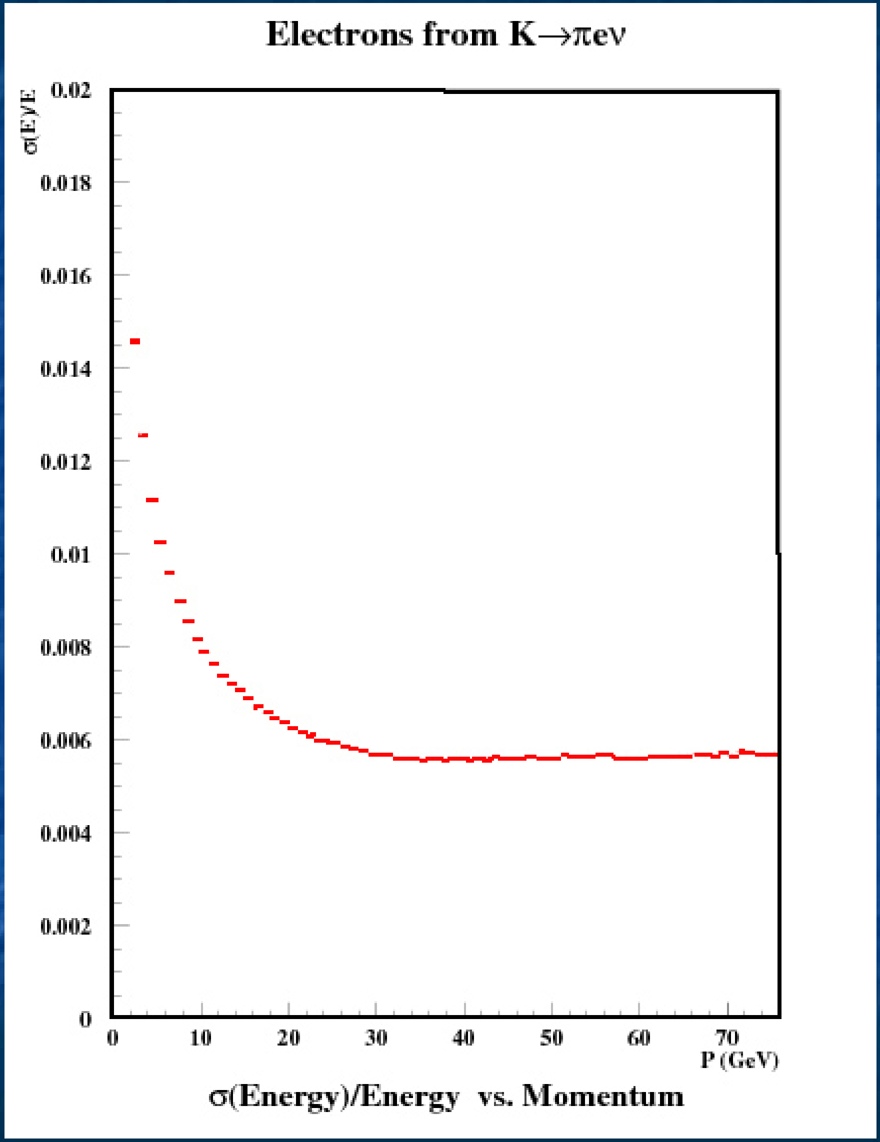
KTeV CsI calorimeter

- Calorimeter size 1.9x1.9 m^2
- Number of crystals 3100
- Thickness 27 X_0
- Crystal size 2.5x2.5x50 cm^3 (central part), 5.0x5.0x50 cm^3 outer part
- Photodetector – PMT
- Calibration – electrons from K_{e3} decays

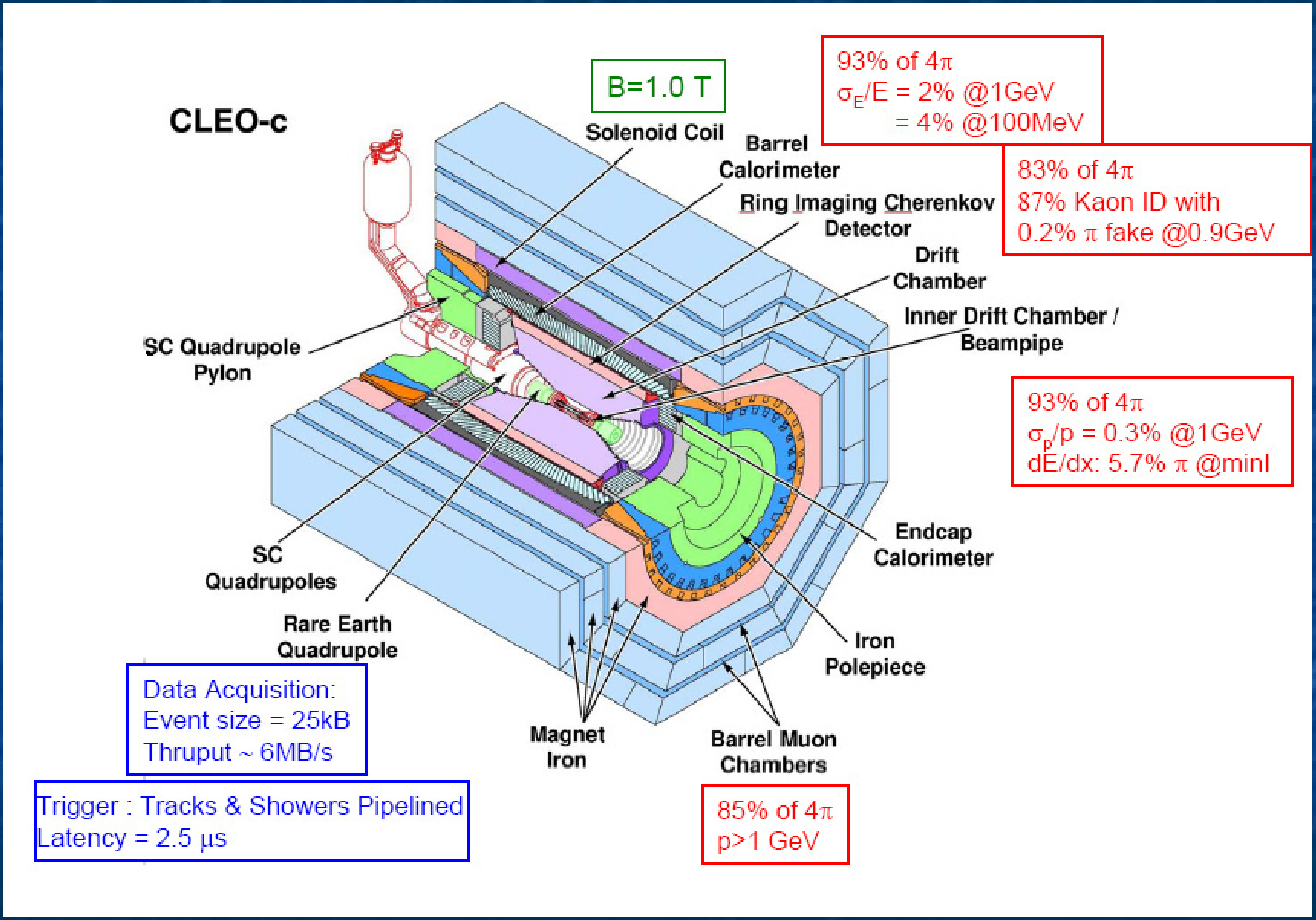
$$\frac{\sigma_E}{E} = \frac{2\%}{\sqrt{E(\mathrm{GeV})}} \oplus 0.45\%$$

Nonlinearity (3 – 75 GeV) 0.4%

Spacial resolution for photons ~1 mm

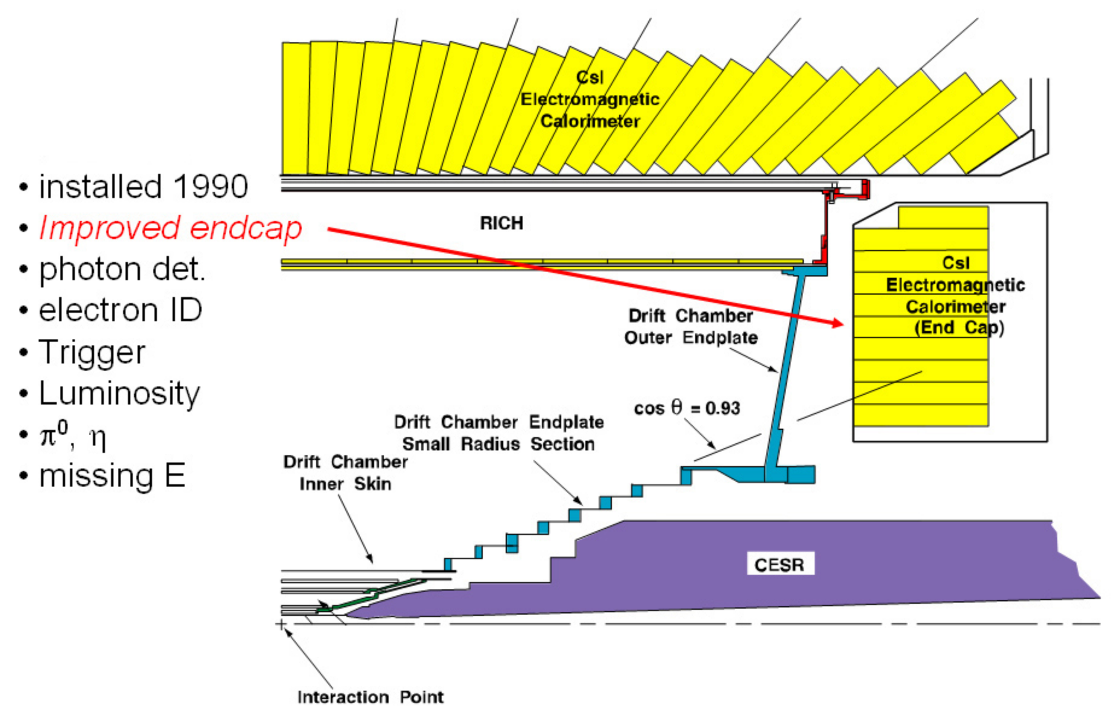


CLEO-c detector

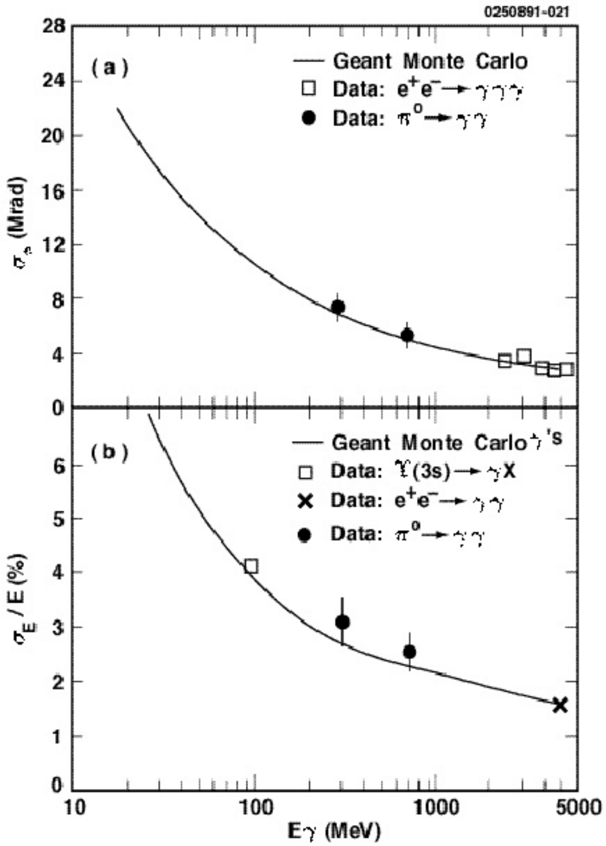


CLEO-c CsI(Tl) calorimeter

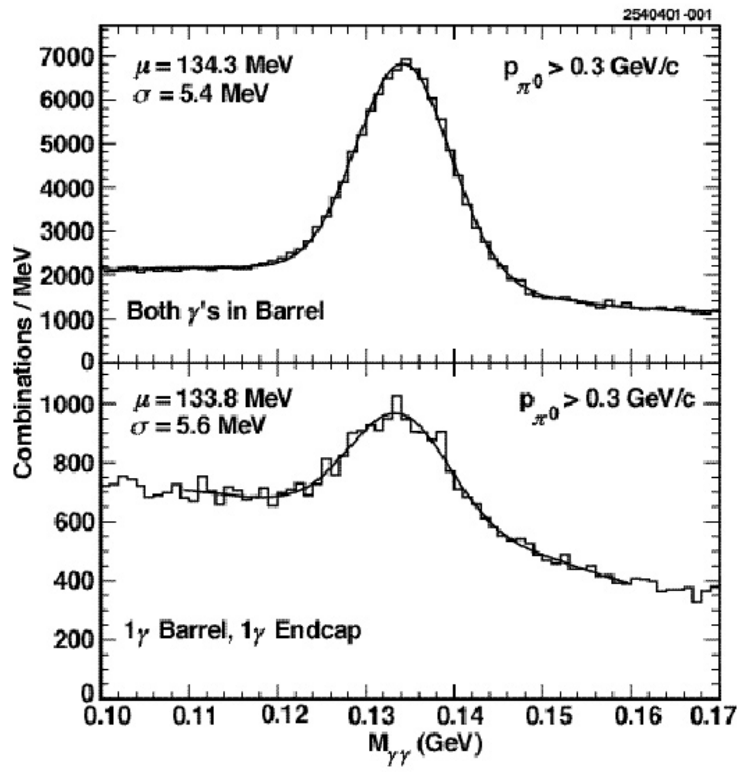
- Number of crystals 7784:
  Barrel – 6144
  Endcaps – 2×820
- Crystal size – 5x5x30 cm3
- Thickness – 16.2 X_0
- Inner radius – 1.02 m
- Barrel length – 3.26 m
- Total CsI(Tl) mass – 27000 kg
- Solid angle coverage – 95%
- Photodetector Si photodiode (4 per crystal)
- Material in front of the barrel part – $0.18X_0$



CLEO calorimeter performance

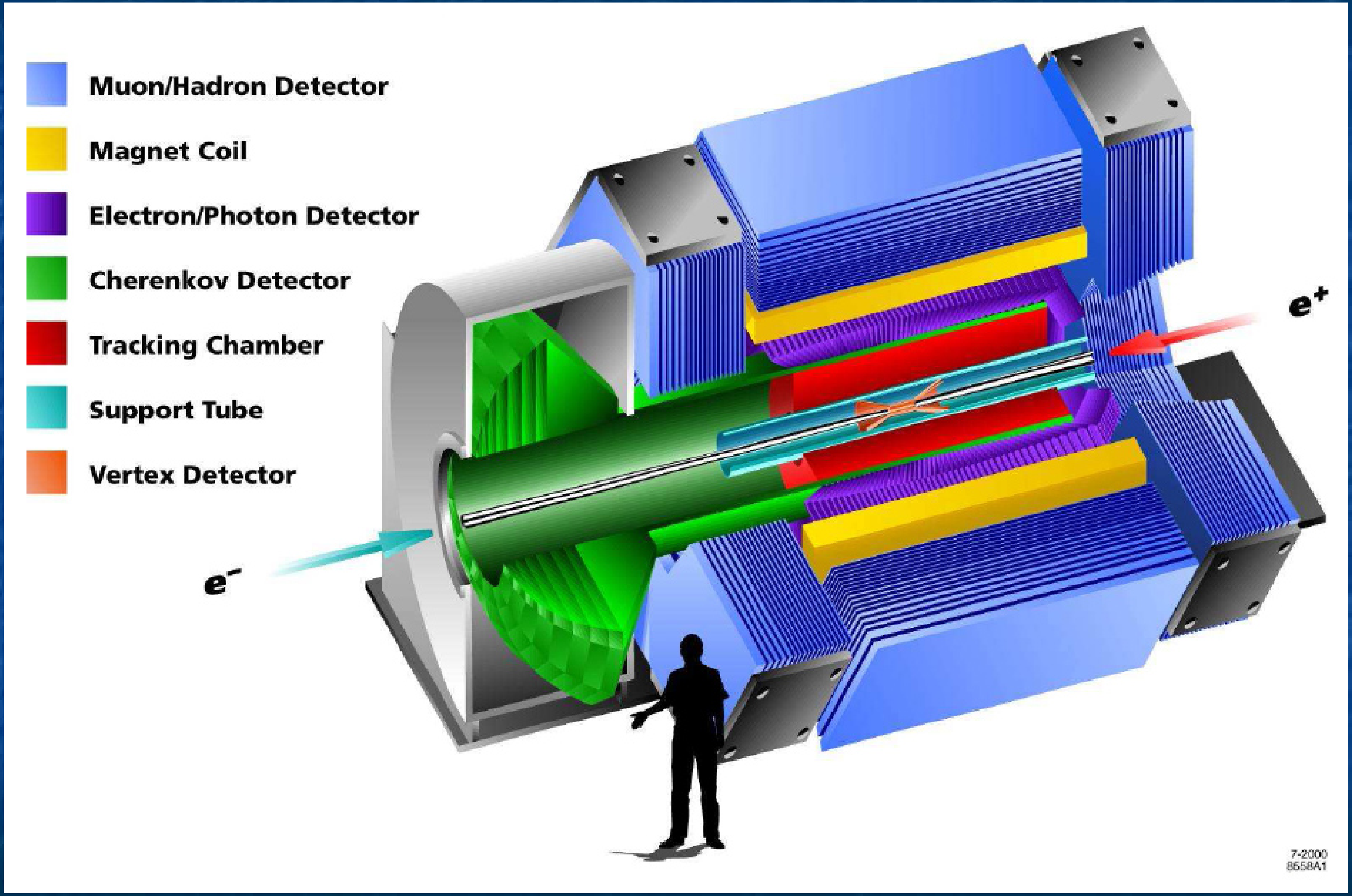


Angular and energy resolution

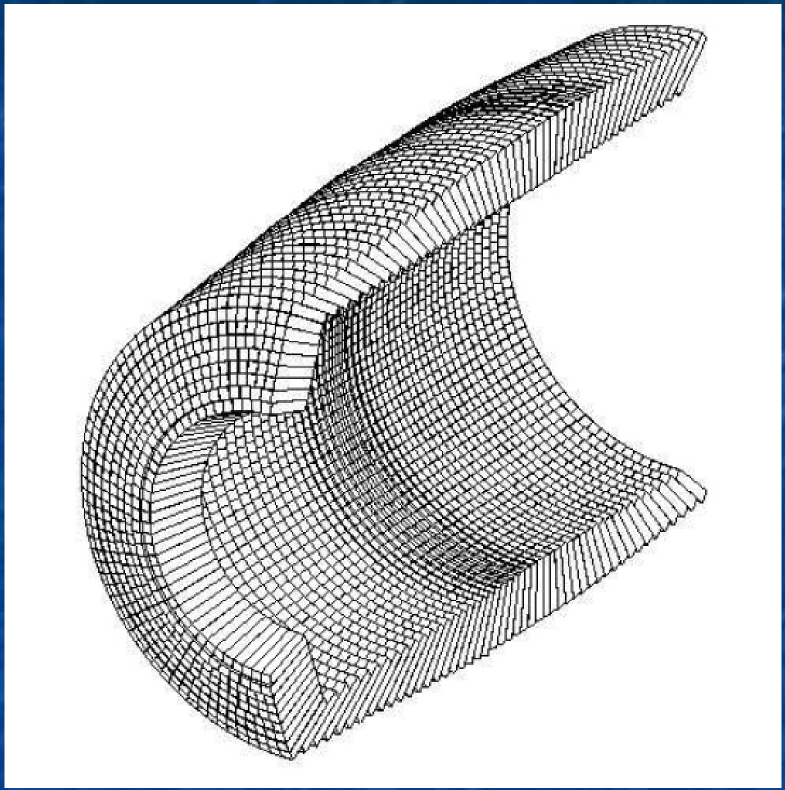


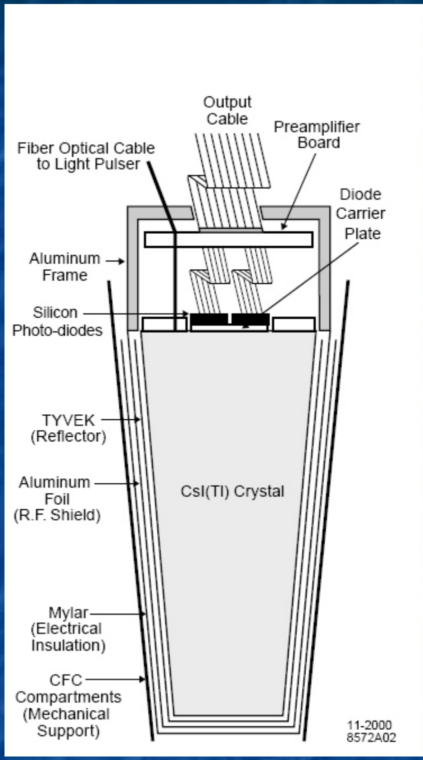
π^0 mass resolution

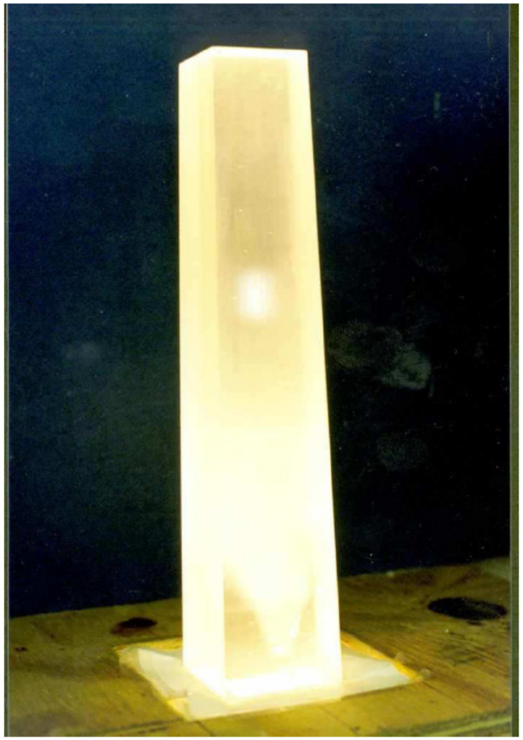
BABAR Detector



BABAR CsI(Tl) Calorimeter







Number of crystals – 6580,
Thickness – 16÷17.5 X_0
Inner radius – 0.92 m
Length – 2.9 m
Solid angle coverage 90% (in cms)

$$\frac{\sigma_E}{E} = \frac{(2.3 \pm 0.03 \pm 0.3)\%}{\sqrt{E(\mathrm{GeV})}} \oplus (1.35 \pm 0.08 \pm 0.2)\%$$

BABAR Calorimeter Calibration

- Liquid radioactive source based on the reaction: $^{19}F(n,\alpha)^{16}N$; ^{16}N (7s) $\rightarrow {}^{16}O^* \rightarrow {}^{16}O+\gamma$(6.13 MeV);
- Bhabha scatterig (2.5 – 8 GeV), 200 direct hits per crystal, 0.35% statistical and 1% systematic error;
- Additional corrections using π^0 decays, $e^+e^- \rightarrow e^+e^-\gamma$ and $\mu^+\mu^-\ \gamma$ reactions

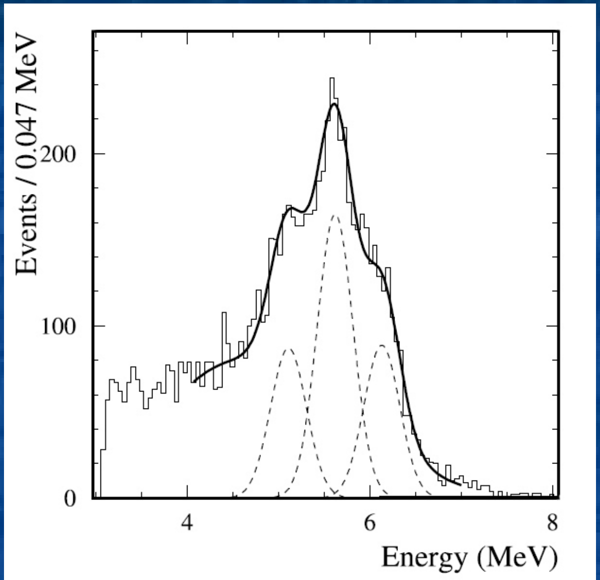
Neutron generator based on deuterium-tritium fusion reaction.

Generates up to 10^9 14 MeV n/s, when high voltage on.

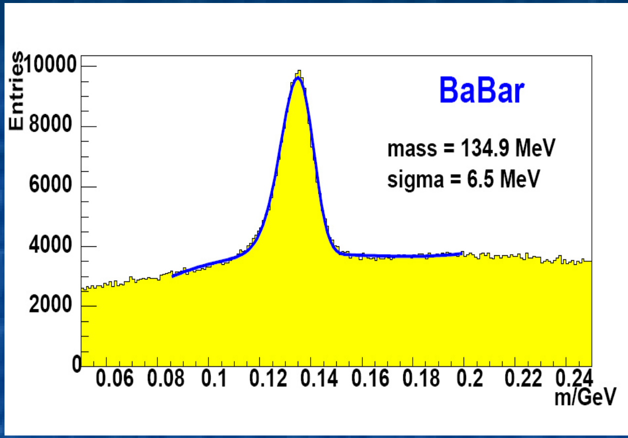
Activates Fluorinert FC77 liquid
Counting rate 40 photons per crystal per second

Calibration accuracy ~0.25% for 15-30 minute run

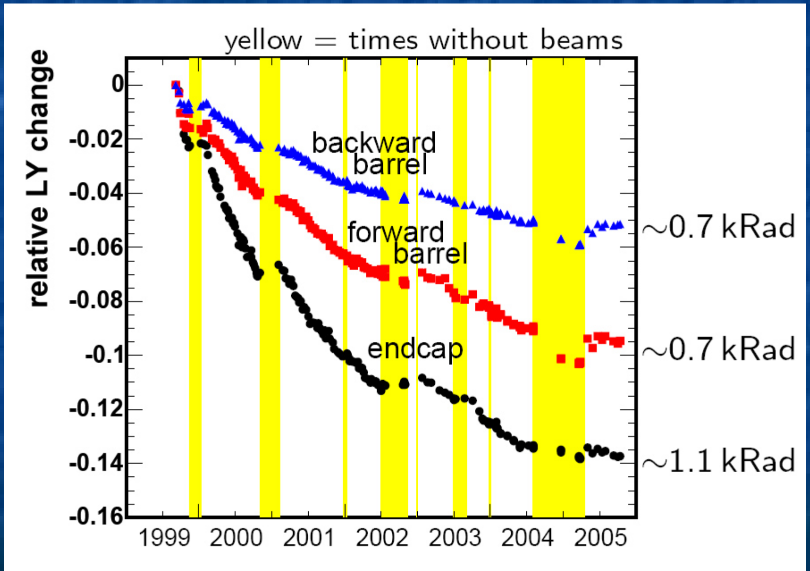
BABAR Calorimeter Performance



Liquid source calibration spectrum in one crystal.
Fit – 3 Gaussians (6.13 MeV peak + 2 escape peaks) and parameterized background.
Resolution – σ=0.3 MeV

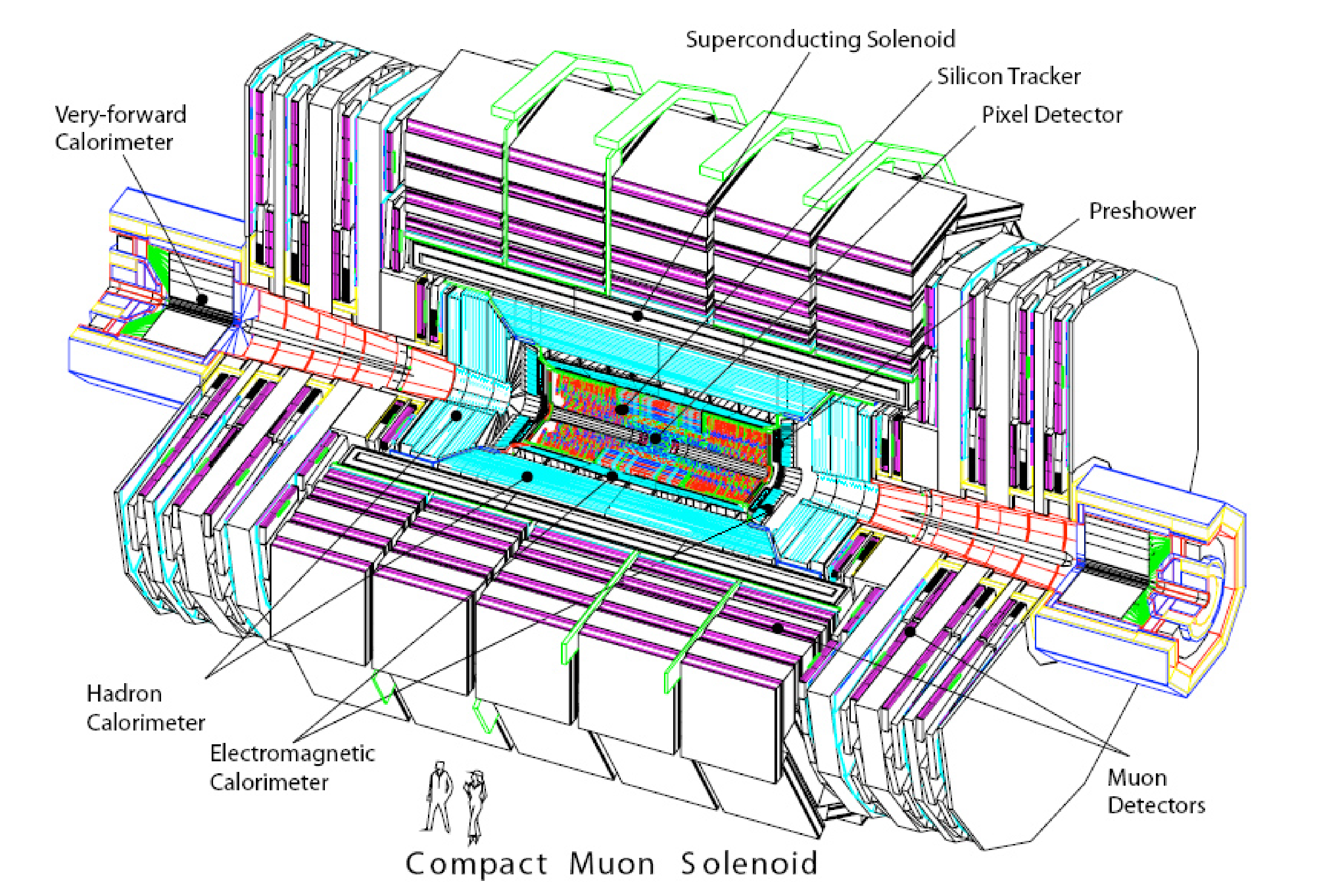


π^0 peak in $\gamma\ \gamma$ invariant mass spectrum for Eπ >300MeV



Relative drop in light yield versus time

CMS Detector



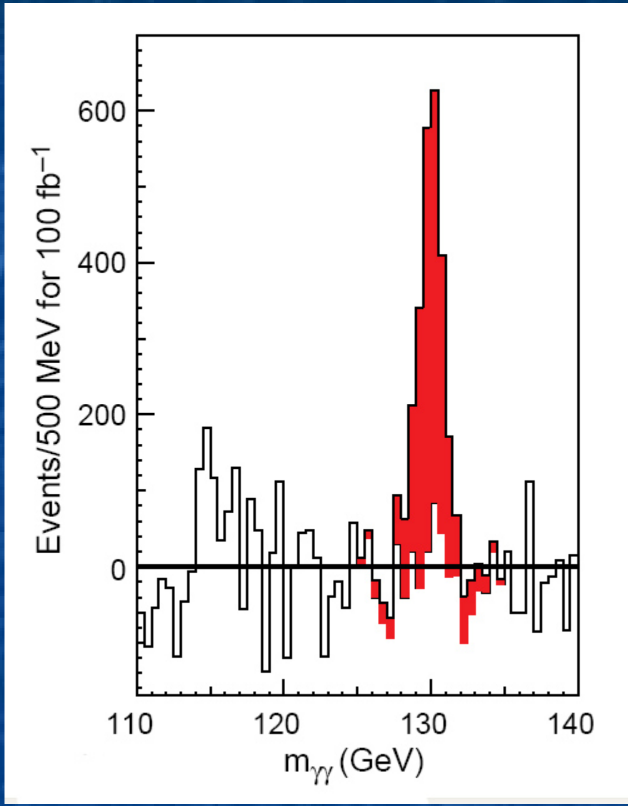
CMS calorimeter requirements

One of the main goals of the CMS detector is a discovery of the Higgs boson. For the M_H= 100÷150GeV the golden decay mode is $H \rightarrow \gamma\gamma$.

The CMS EM calorimeter design resolution:

$$\frac{\sigma_E}{E(\mathrm{GeV})} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c,$$

where $a = 2.7\%, b = 200\ \mathrm{MeV},\ c = 0.5\%$



Radiation doses at high LHC luminosities:
Barrel center – 0.15Gy/h, Endcap – 15Gy/h

Typical loss of transparency in $PbWO_4$ is 3% at 0.15 Gy/s – requires precision real time monitoring of the crystal optical properties.

Expected total γ-radiation doses for 10-year running at highest luminosity are 10^4 Gy in the barrel and ~10^6 Gy in endcaps. Expected neutron fluence is 10^{13} n/cm^2

New crystals for HEP calorimetry and ILC calorimeter proposal

Cube: 1.7 X1.7 x 1.7 cm (1.5 X_0)
Bar: 2.5 x 2.5 x 20 cm (18 X_0)

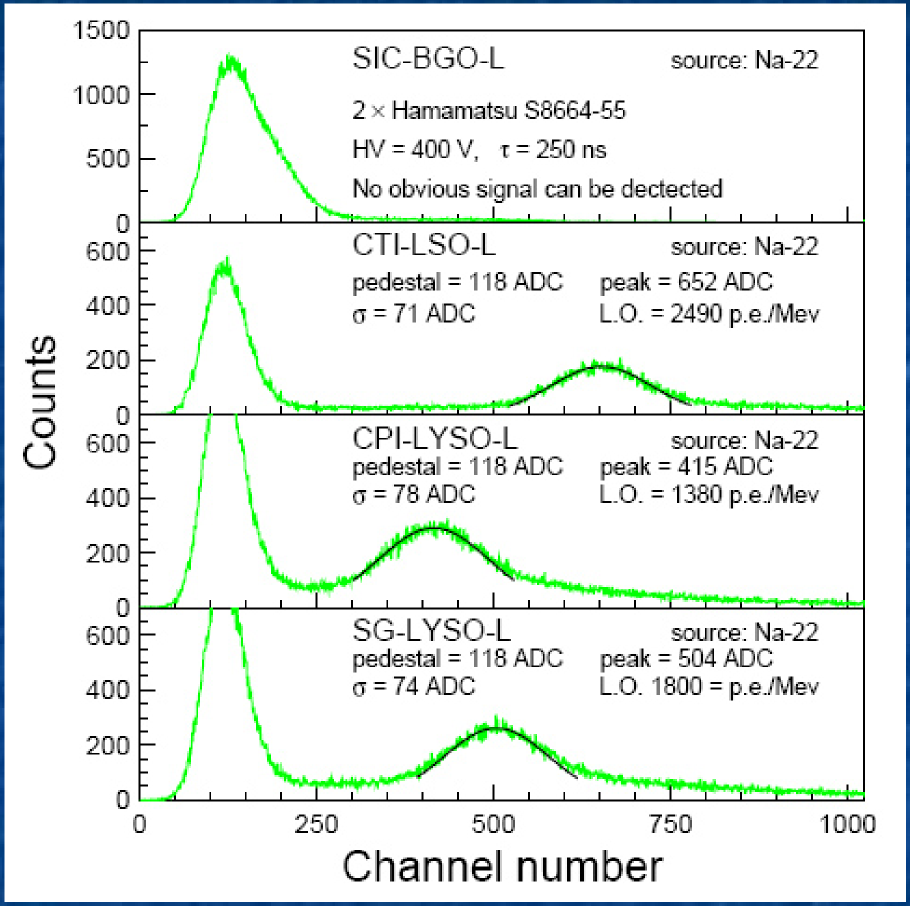
R.Y. Zhu, 2005 ALCPG & ILC Workshops Snowmass, USA[1]

LSO – Lu_2SiO_5 (Ce)

LYSO – $Lu_{2(1-x)}Y_{2x}SiO_5$(Ce)
x=5 – 10%

In a last decade the mass production capabilities for LSO and LYSO crystals were established mostly for the medical industry. Their potential applications in HEP were also explored

LSO properties



- Density – 7.40 g/cm^3
- Radiation length – 1.14 cm
- Moliere radius – 2.07 cm
- Light yield – 84% of NaI(Tl)
- λmax – 420 nm
- Decay time – 42 ns
- Small temperature dependence of the light yield

0.511 MeV ^{22}Na spectra from long crystal samples
Photodetector – 2 Hamamatsu 5x5 mm^2 APDs per crystal.
Light output – 2000 p.e./MeV
Noise – 35 keV

LSO (LYSO) radiation hardness

The tests of radiation hardness of L(Y)SO crystals (J.M.Cheng et al., IEEE Trans Nucl Sci. 52 (2002)[2]; P.Kozma and P.Kosma Jr., NIM A539(2005)132[3]) showed that the radiation hardness of LSO crystals is very high.

Complete recovery after 10^5Gy gamma irradiation takes few days. The radiation hardness of LSO is higher than that of BGO and PWO.

The main problem with the LSO crystal radiation damage could be radiation-induced phosphorescence. The estimated radiation-induced read-out noise is ~1 MeV for 100 ns gate and 500 rad/h dose rate [2].

Thus, the LSO and LYSO crystals are good candidates for ILC detector calorimeter. Another possible applicaion is the SuperB datector calorimeter endcaps.

Summary

- In crystal calorimeters the e/γ showers are totally absorbed in sensitive media. This provides the best energy resolution for electrons and photons and also a good spatial resolution.
- Crystal calorimeters have wide dynamic range of up to 10^5 and low energy threshold of few MeV or less.
- Crystal calorimeters are highly reliable and simple in maintenance.
- New high-density scintillation crystals like LSO and LYSO have high light output and transparency, short scintillation decay time and very high radiation hardness. This makes the crystal calorometers based on these crystals a good choice for future HEP detectors including detector for ILC.