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THE ELECTROMAGNETIC CALORIMETER IN THE HYPERON BEAM EXPERIMENT AT CERN[#]

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Abstract

An electromagnetic calorimeter has been built for the hyperon beam experiment WA89 at CERN. It is composed of 642 lead glass Cerenkov counters. The detector was calibrated with an electron test beam and with an extensive π^0 sample produced in hyperon beam runs. The set-up, the performance, and results from operation in WA89 are presented.

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1 Introduction

Experiment WA89 is performed at the charged hyperon-beam of the CERN-SPS and can be regarded as a continuation of other hyperon-beam experiments carried out at CERN [1]. It is intended to study the production of charmed-baryon states like the Ξ_c^+ already observed in WA62 [2] and its isospin-partner Ξ_c^0 which was first observed only recently [3],[4],[5]. Another field of interest is the search for the exotic states such as the U(3100), for which evidence was found in WA62[6] as well as in the neutron beam experiment BIS-2 at Serpukhov [7].

In November 1989 a new beamline [8] has been brought into operation producing about $2 \cdot 10^5$ Σ^- per average SPS-spill of $4 \cdot 10^{10}$ protons hitting a beryllium-oxide target at 450 GeV. Negatively charged particles with a mean momentum of 350 ± 35 GeV are brought to the experimental target after 15 m. There the ratio of hyperons to the background of π^- is about 1:3.

A sketch of the experimental set-up is shown in Fig. 1. The main detector is the Omega spectrometer, a superconducting magnet with an integrated field of 7.5 Tm used for the momentum analysis of charged particles. Downstream of the target, silicon-microstrip planes and a total of 67 drift chambers are used for track and vertex reconstruction. A big ring-imaging Cherenkov counter placed behind the magnet is used for particle identification.

The last detector down-stream from the target is the lead glass calorimeter for photon detection that is described here. One aim of the calorimeter is to search for a possible radiative transition between the symmetric and antisymmetric state of the charmed strange baryon Ξ_c^0 similar to the well known decay $\Sigma^0 \rightarrow \Lambda \gamma$. Another aim is to search for decay channels of charmed and exotic states containing Σ^0 or π^0 such as $\Xi_c^0 \rightarrow \Lambda K^- \pi^+ \pi^0$, $\Xi_c^0 \rightarrow \Sigma^0 K^- \pi^+$ etc.

We will describe here the set-up of the detector, its calibration, the flash lamp based monitor system and first results from two runs performed at the hyperon beamline.

2 Design considerations

The detector design was optimized to suit WA89 requirements. Computer simulations were performed to calculate the range of photon energies and the acceptance of the calorimeter for the decays mentioned above.

A diameter of the lead glass detector array of about 2 m was chosen. This choice ensures a high acceptance for photons from radiative decays of forwardly produced charmed strange baryons: 70 % at $x_F=0.3$, 95 % at $x_F=0.8$. The photon energies range up to 30 GeV at the highest x_F . For photons stemming from π^0 -decays the probability to observe both photons in the calorimeter is about 60 % at $x_F=0.3$ rising to 85 % at $x_F=0.8$. The energies of these photons are as high as 80 GeV at $x_F=0.8$. Fig. 2 shows the acceptance of the lead glass calorimeter for photons from some decays of charmed strange Ξ s at 200 GeV: $\Xi_c^+(S)(2560) \rightarrow \Xi_c^+(A)(2460)\gamma$, $\Xi_c^+(S)(2660) \rightarrow \Xi_c^+(A)(2460)\pi^0$ and $\Xi_c^0(A)(2460) \rightarrow \Lambda K^- \pi^+ \pi^0$.

Since the calorimeter is located far from the target (about 30 m), the invariant mass resolution of secondary states containing photons or π^0 s is more sensitive to the energy resolution than to the position resolution. An energy resolution of $\sigma(E)/E = 6\%/\sqrt{E}$ for instance contributes 3 % to the error of the mass difference measurement $m_S - m_A$ for a radiative decay. An accuracy of $\sigma(x)=10$ mm for the impact coordinate of the photon results in an error of 2.5 % in this mass difference. For the measurement of the mass of a secondary

state containing a π^0 such as $\Lambda K^- \pi^+ \pi^0$ the mentioned energy and spatial resolutions would contribute an error of 4 and 7 MeV/c² respectively to the $\Xi_c^0(A)$ mass.

To obtain the required spatial resolution over a wide energy range we chose a face size of a single detector module of 7.5×7.5 cm² corresponding to $(1.44 \cdot R_M)^2$, R_M being the Molière radius. For the length of the block we chose 36 cm corresponding to about 23 radiation lengths. Simulations have shown that this is a good compromise between the needs to contain as much as possible of the shower in the detector and to keep light absorption in the lead glass itself low. More than 97 % of an electromagnetic shower of energy up to 100 GeV are released in a layer of lead glass of this thickness.

3 Detector set-up

3.1 Description of the calorimeter

The electromagnetic calorimeter consists of 642 counters arranged in a circular array of 1 m radius. At its center two module slots have been left empty to provide a beam hole. A single counter is shown in (Fig. 3).

The lead glass is of type SF57¹ whose properties are listed in table 1. Due to its high lead content it has a very short radiation length compared to other glasses. The blocks are cut with a precision of few tenths of a mm and the surfaces are highly polished. Each block is wrapped in 25 μ m thick aluminized mylar foil and covered with black 0.1 mm thick polyethylene foil. To improve the shielding of the photomultiplier by the mu-metal a cylindrical light guide of 6 cm diameter and 2.7 cm thickness made from the same lead glass is glued with an epoxy glue² to the back of the modules.

The photomultiplier³ has been designed by Thorn EMI to our special needs of a high linearity over a wide range (table 2). It has 10 dynode stages and is supplied with high voltage by a voltage divider of type EMI C625A (Fig.4). The cathode window (cathode diameter 54 mm) is glued to the lead glass with a silicon rubber⁴ covering about 41 % of the surface of the lead glass block.

A surrounding plastic tube that is housing the mu-metal and providing light-tightness is fixed to a flange which is glued⁵ to the surface of the lead glass. This flange is made of titanium matching exactly the thermal expansion-coefficient of SF57.

The whole array is mounted on a frame which can be moved vertically by 2 m using a hydraulic system and horizontally with an electric motor on rails (Fig.5). The precision of this movement is better than 1 mm. Control and position read out is performed by a processor allowing to use a automatized calibration procedure at the electron testbeam.

In the WA89-experiment the detector is installed at a distance of 28.4 m downstream of the experimental target.

3.2 Electronics

The anode signals of all photomultipliers are passed to the ADC modules by 120 m long coaxial cables providing the delay necessary for triggering. Eight FASTBUS ADC modules

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(LeCroy 1885) are used to digitize the signals of all 642 lead glass modules and of the two alpha sources used for gain monitoring (see 3.3). The ADCs have a resolution of 12 bits, plus an additional capability of automatic switching between low and high range differing by a factor of eight. A calibration and trigger module (LeCroy 1810 CAT) is used to test all ADC channels.

The ADCs are read out via FASTBUS by a Segment Manager/Interface module (LeCroy 1821 SM/I) which is able to do hardware pedestal subtraction and threshold comparison. By this suppression of empty ADC channels the amount of data of a typical event is reduced by a factor of 10. The compressed data are stored in the data memory of the 1821 module and then read out by an Aleph Event Builder (STR501)⁶ using an interface which connects the front panel bus of the 1821 to the AEB memory bus. The AEB collects all data of one accelerator spill (2.4 s) in a 1 Mbyte memory, which is read out during spill pause (12.0 s) by the central event builder via a FASTBUS cable segment. Fig.6 shows the electronics set-up.

The conversion time of the ADC modules is 275 μ s. Data transfer rates of 40 MB/s on the FASTBUS and 3.8 MB/s between SM/I and AEB have been achieved. Since the ADCs can accept a new event once they have been read out by the 1821 module, the total dead time for an event is less than 400 μ s (ADC conversion + FASTBUS readout time). In the case of an event not being accepted by a later trigger stage, the ADC can be reset by a fast clear signal.

3.3 Monitoring

For monitoring purposes light pulses produced by a highly stable xenon flash lamp (Hamamatsu L2360)⁷ are delivered by a flexible 4 m long optical plastic fibre⁸ to the backplane of each module (Fig. 3). The spectral distribution of the lamp ranges from about 280 to 600 nm covering the Cherenkov light spectrum in the lead glass blocks. The duration of light pulses from the lamp is about 1 μ s, and the timing of the 140 ns wide ADC gate was positioned in the middle of the photomultiplier pulse to minimize a possible timing dependence of the measured values. This gate was triggered by the signal from a separate photomultiplier that was directly connected to one of the optical fibres.

The flash intensity was adjusted by means of light absorbers in a way that it corresponds to signals produced by 10-15 GeV electrons. The resolution of the flash amplitudes of an average module is of about $\sigma \approx 1.3\%$. The long-term flash lamp stability was monitored using two separate photomultipliers additionally detecting the light produced by two ²⁴¹Am α -sources in a plastic scintillator. The widths of the α signals are $\sigma \approx 7\%$. The lamp intensity depends on the temperature of the lamp and its power supply and it was measured to be about 0.2 %/°C. This dependence leads to signal day-night variations of no more than 0.5 % . A small effect of aging of the lamp has been detected after 2 months of detector operation, causing about 0.8 % of intensity decrease.

The flash lamp data are taken continuously with an average rate of 10 Hz. The α -signal data are taken between accelerator cycles with a rate of about 10 kHz. The high stability of the lamp allows to monitor every burst using on-burst flash data. The off-burst measurements have shown that the typical value of the drift of the photomultiplier gain is about 3 % per month, though for a few channels the drifts are as high as 15 %. The gain

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stability during beam bursts depends on the beam intensity and positions of the modules in the detector array. An additional current in the PM bases causes a certain gain rise. For a typical WA89 beam flux of about $3 \cdot 10^5$ charged particles per second the gains of several modules, positioned close to the beam hole, rise for 2 to 10 %, compared to the off-burst gains. This change of the gain occurs within the first 100 ms of the burst and then no other time dependence inside the burst has been noticed.

For the off-line analysis the calibration factors of all modules were corrected according to the monitor measurements.

4 Electron beam tests

4.1 The test beam

The CERN X3 electron beam is produced by the CERN-SPS as a tertiary particle beam [9]. The energy of the electrons can be varied between 2 and 50 GeV. The last stage of the beam line consists of two dipole bending magnets and two focussing quadrupole magnets. The beam energy was tuned with the bending magnets and a collimator placed between them. Two Cherenkov threshold counters were used for electron identification. For setting the different energies we used values obtained by the L3 collaboration for the BGO-calorimeter calibration [10]. The beam momentum resolution (from 0.88 % at 2 GeV to 0.19 % at 50 GeV) was smaller than the lead glass detector's energy resolution.

Downstream of the last magnet we used 4 wire chamber planes to measure the beam position. Signals of two scintillating plastic counters were used as a trigger in combination with the Cherenkov threshold counters.

The size of the beam spot on the calorimeter was about 1 cm, and the beam flux was up to several thousand electrons per second. We used a set of energies (2, 10 and 20 GeV) for the calibration of the detector in the low ADC range and 35 and 50 GeV for the calibration of the high ADC range. At each energy the whole detector was moved to expose the centers of all modules to the beam, and about $(2-10) \cdot 10^3$ showers for every module were measured. Some parts of the calorimeter were scanned through the beam in smaller steps to study the spatial dependence of the energy measurement and to check methods of determining shower centers.

4.2 Energy calibration

As a first step the high voltage values for all PMs were tuned to adjust the signals from 20 GeV electrons to about channel 2800 in the low ADC range. This allows to measure photons up to about 25 GeV in this ADC range.

Test measurements and simulations had shown that more than 98 % of an electromagnetic shower of energies up to 100 GeV are contained in an array of 3×3 detector modules. Thus we only summed up the deposits in the 9 mainly hit modules for the measurement of shower energies, neglecting the energy deposits in the surrounding modules. This practically does not deteriorate the energy resolution but has the advantage to reduce the background in high multiplicity events at the hyperon beam.

Two methods to calculate the calibration factors for each module have been used. In the first method the calibration factors were calculated iteratively, at every iteration equalizing the beam energy to the deposits in the 9 mainly hit modules. We started with some approximative calibration constant for every module. Then the value for the module exposed

to the beam was changed during every iteration cycle. As far as this module contains about 92% of the shower the method converges relatively fast; about 15 iterations are sufficient.

The second method minimizes a χ^2 , constructed by the differences of all energy deposits per event and the beam energy. This method leads to the problem of the solution of a system of linear equations in which the signal amplitudes and the beam energy are the known values and the calibration factors have to be found.

The differences between the final calibration factors obtained using these two methods were less than 0.1%.

4.3 Energy resolution and linearity

To study the linearity from 2 to 50 GeV we had to match the calibration factors in both ranges. For that purpose a sample of modules was additionally exposed to the beam at 20 GeV in the high ADC range. No nonlinearity was noticed within 1% accuracy from 2 up to 50 GeV.

We determined the energy resolution of the detector for all 642 modules and separately for 4 modules that had been calibrated in a short period of time. The latter should allow us to obtain a resolution less affected by time-dependent smearing of values and compare it to the overall detector performance. Fig. 7 shows the energy resolution at various energies for both cases. The energy dependence of the resolution in the low range of the ADC for 4 modules can be expressed by the formula:

$$\sigma(E)/E = 0.061/\sqrt{E} + 0.004 \quad (1)$$

where E is the energy in GeV. In the high range of the ADC the constant term is close to 0.01. Taking into account all modules of the calorimeter the constant term is about 0.006.

4.4 Position calibration and resolution

As the electromagnetic shower spreads through several modules, the energy deposit in different counters can be used to reconstruct the impact position of the incoming particle.

Various methods have been used elsewhere [11],[12],[13]. They are based on the idea to use the knowledge about the lateral shower profile to deduce the impact point from the detector amplitudes. They differ strongly in practicability, accuracy and complexity of the calculation. The most obvious approach is to use the two dimensional parameterization of the lateral shower profile, that has been obtained in calibration measurements to fit the obtained cluster. A χ^2 method is used to determine the impact point. Although this algorithm is the most accurate one, it has the disadvantage of consuming a large amount of computation time.

Simpler methods assume that there is an exponential relation between energy deposits in neighbouring detector modules due to the fact that the shower itself can be fit to a certain extent by an exponential function. Knowing the parameters of this exponential the position can be determined directly from the ratio of amplitudes in adjacent modules of the shower cluster. This method is very fast, but not very precise mainly because the assumption of the shower to have an exponential profile is not very good close to the impact point.

We have chosen an algorithm that is starting from a simple calculation of the center-of-gravity of the shower cluster. Using calibration data where the position of the beam electron was measured with proportional chambers, the impact point obtained with this method can be compared with the "true" coordinate from the wire chambers. Fig. 8 shows

the relation between the real beam position and the position of the shower center-of-gravity. This graph can now be fit by a high order polynomial to obtain the position calibration. We used a 9th-order polynomial to fit the data.

Applying this correction to the center-of-gravity-method one gets a good agreement of the directly measured electron position and the coordinates calculated from the cluster. The position resolutions obtained using this method at different energies are summarized in table 3. The results are described by the following formula:

$$\sigma(x) = \frac{1.82 \text{ cm} - |0.31 \cdot x|}{\sqrt{E}} \quad (2)$$

where x is the distance from the module center in cm and E is the beam energy in GeV.

5 Performance in the hyperon beam experiment

The hyperon beam data were taken with a trigger requirement for at least 4 charged particles passing downstream the Ω -magnet, 2 of which should have momenta higher than 40 GeV. Requiring a minimum energy of a cluster of 0.5 GeV, the mean number of clusters in the calorimeter per event was about 8 out of which 2 were caused by charged particles.

5.1 Separation of close clusters

When photons hit the calorimeter close to each other the problem of impact point reconstruction becomes more complicated than in the case of a single photon. The reason is that several clusters may overlap. The best method to separate different clusters and to calculate their impact points is to fit two dimensional functions to the set of detected amplitudes, varying the impact coordinates and the gamma energies [14]. Unfortunately the computing time needed for this method is high and rapidly increasing with the number of overlapping clusters. We used a simpler algorithm that also gave satisfying results, described here for the case of two hits.

Starting from the impact points of the photons calculated with the corrected center-of-gravity-method the hypothetical energy deposit in the overlapping modules is calculated. A pure exponential approximation of the lateral shower profile was used to compute the integral over the surface of a module for a given impact point and photon energy. These calculated energy deposits are subsequently used to determine new impact positions of the two photons with the usual method. This process is repeated until convergence is reached, usually after few iterations.

Fig. 9 shows the effect of taking into account cluster overlap by the algorithm described above. The width of the π^0 peak reconstructed from high-energy pairs of photons is decreased from $\sigma = 10.4$ MeV to $\sigma = 6.9$ MeV. Clusters could be separated down to distances corresponding to one module diameter.

5.2 Energy recalibration in the hyperon beam

The hyperon beam line of WA89 does not provide an electron beam for periodical recalibration of the detector during beam time, like some other fixed target experiments could take advantage of (see for example [16] [15] or [17]). Our original strategy was to calibrate the detector with an electron beam, then move it to the hyperon beam line for the duration of the experiment and to use the flash lamp to monitor drifts in calibration factors. It turned

out however that we were able to recalibrate the detector and perform a fine tuning of all calibration factors on the basis of the hyperon beam data using the π^0 's produced and the strong computing power of the experiment.

About 10^7 events were used for fine tuning of the calibration factors, out of $16 \cdot 10^7$ events recorded in the spring run of 1990. Only the electromagnetic calorimeter data were taken into account. For every event all clusters in the calorimeter were located and assuming them to be caused by photons emitted from the center of the target, we reconstructed the $\gamma\gamma$ invariant mass of all combinations. The parameters of pairs of clusters reproducing the mass of a π^0 within $\pm 50 \text{ MeV}/c^2$ were recorded on a special file. There were two separate streams of such data: one for the low ADC range clusters, the other for pairs with at least one amplitude in the high ADC range. About $3 \cdot 10^7$ pairs were recorded, containing about $3 \cdot 10^6$ π^0 -s. For the iterative tuning of the calibration factors in a certain ADC range the π^0 data were read at each iteration, and a $\gamma\gamma$ invariant mass histogram was filled for every module, whenever one of the clusters had its center in this module. The histograms were then fit and corresponding calibration factors were tuned. The convergence of this method had been tested before in a simulation. In the low ADC range the statistics of π^0 's in the peaks varied from about 10^3 at the edges of the calorimeter to about 10^4 for modules close to the beam hole. Resulting deviations of $\gamma\gamma$ invariant mass peaks from the π^0 mass became lower than $0.1 \text{ MeV}/c^2$ for all modules. Measured π^0 invariant mass resolutions (r.m.s.) for all modules are shown in Fig. 10. The tail from 5 to 7 MeV/c^2 is caused by the modules at the edges of the calorimeter where some part of the shower is lost.

5.3 Illustration of the calorimeter performance

The performance of the calorimeter in the WA89 environment was checked by reconstruction of $\gamma\gamma$ pairs to obtain π^0 and η , by comparison of spectrometer momenta for e^+ and e^- to the energy release in the calorimeter and by the reconstruction of $\Lambda\gamma$ events to obtain Σ^0 . All this analysis was done after having applied the above explained recalibration method for the whole calorimeter.

The π^0 peak for all detector modules is shown in Fig. 11. The mean mass resolution is $\sigma = 4.2 \text{ MeV}/c^2$ and is slightly dependent on the π^0 energy. From the π^0 mass resolutions at various energies the energy and position resolution in the environment of the hyperon beam was determined. The so derived energy resolution is:

$$\sigma(E)/E = 0.070/\sqrt{E} + 0.02 \quad (3)$$

and the average spatial resolution is about $\sigma(x) = 0.6 \text{ cm}$ which is in reasonable agreement with the measurements at the electron test beam (see 4.4).

However the constant term in the energy resolution formula is higher than the value obtained in the electron beam (4.3). This deterioration of the resolution can be explained by the generally worse measurement conditions at the hyperon beam line. Material of other detectors and air adds up to about $10 \text{ g}/\text{cm}^2$ of matter between the target and the calorimeter surface. Tests at the electron beam showed that this can cause an increase of the resolution of this order of magnitude. Other reasons can be the high multiplicity of clusters on the detector surface at the hyperon beam and some deterioration of the effectiveness of the monitor corrections with time.

The information of the magnetic Ω -spectrometer can be used to predict impact points of charged particles on the calorimeter surface. One purpose of this procedure is to reduce the background caused by these particles by subtracting their clusters from the data. Another

reason is to use the e^+ and e^- among those particles and the associated momenta measured in the magnetic field to check the energy resolution of the calorimeter. The ratio of the calorimeter energy to the spectrometer momentum for such a track should be close to unit. The peak in the histogram of ratios that corresponds to e^+ or e^- has in our case a mean value of 1.002 ± 0.001 and a r.m.s. of 2.4 % (Fig. 12). Due to the sweeping power of the magnet the mean energy of these particles is of about 50 GeV. The Ω -spectrometer momentum resolution is of about $\sigma(P)/P = 10^{-4} \cdot P$, where P is in GeV/c, and is in the observed momentum range better than the calorimeter resolution.

Fig. 13 presents the invariant mass spectrum for $\gamma\gamma$ combinations in the region of the η meson. The η signal is weak over a big background. This can be explained by the low acceptance of the electromagnetic calorimeter for η decays. They are not produced forwardly in a baryon beam. The measured mass of the η is $550.5 \pm 0.4 \text{ MeV}/c^2$ being by $1 \text{ MeV}/c^2$ off the particle data book mass [18]. The mass resolution is $\sigma(M) = 13 \text{ MeV}/c^2$ - in good agreement with the resolution achieved with π^0 s.

To illustrate that the detector matches its main goal, detecting radiative decays, a radiative decay of Σ^0 to $\Lambda\gamma$ was searched for. Σ^0 are produced abundantly in the Σ^- beam. About $6 \cdot 10^4$ events with Λ candidates were analysed. The invariant mass spectrum of $\Lambda\gamma$ is shown on Fig. 14. The peak has a mean value of $M(\Lambda\gamma) - M(\Sigma^0) = 0.1 \text{ MeV}/c^0$ and $\sigma(M) = 4.1 \text{ MeV}/c^2$.

6 Conclusion

The WA89 lead glass calorimeter has been designed and built according to the requirements of the hyperon beam experiment. The expected values for the energy and mean position resolution of $6\%/\sqrt{E}$ and $\sigma(x) = 10 \text{ mm}$ respectively have been attained.

The good performance of the calorimeter at the hyperon beam line has been demonstrated by identifying π^0 , η and Σ^0 decays.

A calibration of the detector using π^0 data from the experiment proved to be very useful in addition to the flash lamp based monitor system.

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Figure captions

Figure 1: Set up of the experiment WA89

Figure 2: Simulation of the radial distribution dN/dr of photon impacts on the lead glass calorimeter as a function of the distance r to the beam axis for decays of 200 GeV ($x_F=0.6$) $\Xi_c^+(S)$ and $\Xi_c^0(A)$. The straight vertical dashed lines indicate the limits of the detector acceptance.

Figure 3: A single block of the lead glass detector array

Figure 4: Lay-out of the high voltage divider circuit of type EMI C625A

Figure 5: Front view of the electromagnetic calorimeter

Figure 6: Schematic of the readout electronics. The symbols denote: AEB: aleph event builder front-end processor, SI-F900: fastbus segment interconnect, STR330: fastbus-SCSI-bus interface, DS3100: DEC risc workstation, MEM: fastbus memory module, SM/I: LeCroy fastbus segment manager/interface, CAT: LeCroy calibration and trigger module

Figure 7: Energy resolution for the various electron beam energies. Rectangles denote four selected modules, triangles the mean value of all lead glass detector modules.

Figure 8: Two dimensional histogram of reconstructed impact (center of gravity of surrounding modules) versus impact position (measured with wire chambers) for 20 GeV electrons

Figure 9: Mass peaks of $\gamma\gamma$ -combinations using a) a method neglecting the cluster overlap, b) a method correcting for overlapping clusters

Figure 10: π^0 -mass resolutions for all lead glass detector modules. We define the mass resolution of a single module as the resolution obtained by taking all $\gamma\gamma$ combinations for which one of the two shower centers is laying in this specific module.

Figure 11: Invariant mass spectrum of $\gamma\gamma$ -pairs in the π^0 -mass region for all detector modules after application of the recalibration

Figure 12: Ratio of energies of clusters measured in the calorimeter to momenta of associated tracks measured with the Ω -spectrometer. The peak corresponds to electrons and positrons among secondary particles.

Figure 13: Invariant mass spectrum of $\gamma\gamma$ -pairs in the η -mass region

Figure 14: Invariant mass spectrum of $\Lambda\gamma$ combinations. The peak corresponds to Σ^0 -decays

Table 1
Properties of lead glass block

Type:	SF57
Composition (by weight %)	23.90 SiO ₂ 74.80 PbO
Refractive index	1.89 at 435.8 nm
Density	5.51 g/cm ³
Radiation length	1.546 cm
Critical energy	12.44 MeV
Molière Radius	2.61 cm

Table 2
The photomultiplier EMI 9236KB

diameter	60 mm
length	140 mm
cathode diameter	2.5 inch = 54 mm
dynodes	10
amplification	10^5 to $5 \cdot 10^6$
nonlinearity	< 1 % for $I < 100$ mA
rise time	$\simeq 2$ ns
dark current	2 nA
high voltage	1000 V to 2200 V
quantum efficiency max.	22 % at 430 nm
spectral sensitivity	300 nm to 600 nm

Table 3
Position resolution for different energies

	block edge	block center
2 GeV	5 mm	13 mm
10 GeV	2.0 mm	5 mm
20 GeV	1.5 mm	4 mm
50 GeV	1.5 mm	3 mm

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14