E1-2001-77

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APPLICATION OF A KINEMATIC FITTING PROCEDURE IN AN ANALYSIS OF $K_L \to 3\pi^0$ DECAYS AT THE **NA48** EXPERIMENT AT THE **CERN SPS**

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1 Introduction

The method of kinematic fitting is used widely in the high energy physics experiments. Basically kinematic fitting is a mathematical procedure in which one uses physical and geometrical constraints to improve the estimations of the measured variables. Usually the procedure is based on the least squares technique and in the most cases is applied to reconstructed tracks of charged particles in tracking chambers [1].

The presented in this paper kinematic fitting procedure was applied in an analysis of $K_L \to 3\pi^0 \to 6\gamma$ decays and was based only on the information coming from the NA48 Liquid Krypton Electromagnetic Calorimeter (LKr).

2 Experimental setup and data taking

The NA48 experiment is dedicated to the measurement of direct CP violation in $K^0_{L,S} \to 2\pi$ decays. The K_L beam is produced by 450 GeV/c protons from the CERN SPS hitting a 2 mm diameter and 400 mm long beryllium target at a production angle of 2.4 mrad. Passing through a set of collimators, a ± 0.15 mrad divergent K_L beam enters the decay volume 126 m downstream of the target. The evacuated 89 m long decay volume is followed by a helium tank which contains four drift chambers of the charged particle spectrometer. After the tank a scintillator hodoscope, a liquid krypton electromagnetic calorimeter, a hadron calorimeter and muon veto counters are placed.

The liquid krypton calorimeter is designed to measure the energy, position and time of electromagnetic showers [2]. The 127 cm long detector consists of 13212 readout cells and has projective tower geometry which points to the middle of the decay volume. Each cell of 2×2 cm^2 cross section is made of copper-beryllium ribbons which are extended longitudinally in a ± 48 mrad accordion structure. The readout cells are contained in a cryostat filled with about 20 t liquid krypton at 121 K. The initial current induced on the copper-beryllium electrodes is measured by 80 ns FWHM and digitized by 40 MHz FADCs. The energy and position resolutions of the calorimeter were estimated to be:

$$\frac{\sigma(E)}{E} \simeq \frac{3.5\%}{\sqrt{E}} \oplus \frac{11\%}{E} \oplus 0.5\% \tag{1}$$

$$\sigma(x) \simeq \sigma(y) \simeq \frac{0.4cm}{\sqrt{E}} \oplus 0.05cm \tag{2}$$

with E measured in GeV.

The time resolution was better than 300 ps for photons with energies above 20 GeV.

The energy nonlinearity in the calorimeter response was found to be less than 1×10^{-3} for photons with an energy between 6 GeV and 100 GeV [3].

A detailed description of the whole experimental setup can be found elsewhere [4].

3 Event selection and reconstruction

The selection criteria for $K_L \to 3\pi^0 \to 6\gamma$ events required 6 or more LKr clusters satisfying the following conditions:

- The energy of the cluster had to be between 3 GeV and 100 GeV;
- To avoid energy losses in the LKr, the distance from the cluster to the closest dead calorimeter cell was required to be greater than 2 cm and the cluster had to be more than 5 cm from the beam pipe and the outer edge of the calorimeter.

All possible combinations of 6 clusters which passed these requirements were considered. In addition, the following selection criteria were applied on each combination:

- The distance between clusters in each pair had to be greater than 10 cm in order to avoid the overlapping of the clusters;
- All 6 clusters had to lie within 5 ns from the average cluster time;
- The sum of the cluster energies had to exceed 60 GeV;

- The radial position of the so-called "center of gravity"

$$\overrightarrow{C.O.G.} = \frac{\sum_{i=1}^{6} E_i \overrightarrow{(x_i, y_i)}}{\sum_{i=1}^{6} E_i} \tag{3}$$

where E_i and x_i, y_i are the energies and positions of the six selected clusters, had to be less than 10 cm to ensure the decaying kaon emerged from the K_L target;

- No additional clusters with an energy > 1.5 GeV were allowed within $\pm 3ns$ from the event time to minimize possible accidental effects.

The longitudinal position of vertex candidate was reconstructed as follows:

$$z_{vertex} = z_{LKr} - \frac{\sqrt{\sum_{i=1}^{6} \sum_{j>i}^{6} E_i E_j \left[(x_i - x_j)^2 + (y_i - y_j)^2 \right]}}{m_K} \tag{4}$$

where E_i and x_i, y_i are the energies and positions of the six selected clusters and z_{LKr} is the longitudinal position of the calorimeter. As far as the trajectory of the decaying kaon is lying on the line which connects the COG and the production target, x and y positions of the vertex candidate are calculated as:

$$\overrightarrow{(x,y)}_{vertex} = \left[\frac{z_{vertex} - z_{target}}{z_{LKr} - z_{target}} \right] \overrightarrow{C.O.G.} \tag{5}$$

where z_{target} is the longitudinal position of the target. Then the momenta and the directions of the six photons are calculated using the estimated vertex position and the measured cluster energies and coordinates.

For each combination the invariant masses m_1, m_2 and m_3 of all 15 possible photon pairings were computed. Among all the combinations and pairings, the one with m_1, m_2 and m_3 masses closest to the nominal π^0 mass were picked.

A total of about 12×10^6 $K_L \to 3\pi^0 \to 6\gamma$ events met all the described criteria were fully reconstructed and selected for further analysis.

4 Kinematic fitting procedure

Assuming the neutral kaon coming from the K_L target and a $K \to 3\pi^0 \to 6\gamma$ decay, each event could be parametrized with 15 independent parameters p_k:

- the kaon energy E_{kaon} (which is simply the sum of the energies of the six selected clusters);
- the decay vertex position $(x, y, z)_{decay}$;
- the Dalitz plot variables[1] R^2 and θ;
- 3 angles which describe the orientation of the plane formed by three pions in c.m.frame;
- 2 angles for each of the decaying π^0s which define the flight direction of the photons.

The initial values p_k^{init} of all these 15 decay parameters are calculated using the reconstructed four-momenta of the photons. After that χ^2 are constructed as:

$$\chi^2_{fit} = \sum_{i=1}^{6} \frac{(E_i - E_i^{fit})^2}{\sigma(E_i)^2} + \sum_{i=1}^{6} \frac{(x_i - x_i^{fit})^2}{\sigma(x_i)^2} + \sum_{i=1}^{6} \frac{(y_i - y_i^{fit})^2}{\sigma(y_i)^2}, \qquad (6)$$

[1] the $K_L \to 3\pi^0$ decay Dalitz plot can be expressed in terms of two Dalitz variables - the squared radius R^2 and the angle θ:

$$\left|M_{000}(R^2, \theta)\right|^2 \propto 1 + hR^2 ,$$

where h is the Dalitz plot slope parameter and

$$R^2 = \left(u^2 + v^2/3\right) \ , \ \theta = \arctan\left(v/\sqrt{3}u\right)$$

$$u = \frac{(s_3 - s_0)}{m^2_{\pi+}} \ , \ v = \frac{(s_1 - s_2)}{m^2_{\pi+}}$$

$$s_0 = \frac{(s_1 + s_2 + s_3)}{3} \ , \ s_i = (P_K - P_i)^2 \ , \ i = 1, 2, 3$$

where P_K and P_i are the four-momenta of the decaying kaon and i-th pion, respectively. For detailed description of the Dalitz plot definition see for example [5].

where E_i^{fit}, x_i^{fit}, y_i^{fit} are functions of the decay parameters p_k and $\sigma(E_i)$, $\sigma(x_i)$, $\sigma(y_i)$ are the energy and the position resolutions from (1) and (2), respectively.

For each event the χ^2_{fit} has been minimized varying the parameters p_k. The minimization was based on the MINUIT package [6]. The obtained χ^2_{fit} distribution is shown in Fig.1. Taking into account that each event is described by 15 independent out of 18 measured parameters, this distribution is represented by χ^2 function with 3 degrees of freedom. Nevertheless, the tail in the real χ^2_{fit} distribution from Fig.1 differs from one in the pure χ^2 function which indicates the presence of non-gaussian tails in the calorimeter response.

Due to the applied physical and geometrical constraints, the fitted cluster energies and coordinates E_i^{fit}, x_i^{fit}, y_i^{fit} are expected to be closer to the true cluster energies and coordinates than the measured ones and in principle are nontrivial functions of the calorimeter resolution and the kinematics of the considered decays. In order to establish the effect of the kinematic fitting procedure on the energy resolution and nonlinearity it was also applied to a set of Monte Carlo simulated events. The obtained energy and the position resolutions of the fitted cluster energies and coordinates E_i^{fit}, x_i^{fit}, y_i^{fit} are significantly better compared to the resolutions of the measured cluster energies and coordinates (Fig.2(a)). Moreover, the kinematic fitting procedure takes into account considerable part of the energy nonlinearity in the calorimeter response (Fig.2(b)). As a consequence, one of the main advantages of the application of kinematic fitting procedure is the achieved significant improvement of the resolutions of the Dalitz variables R^2 and θ (Fig.3). Thus the RMS widths of $(R^2 - R^2_{true})$ and $(\theta - \theta_{true})$ from 8.8×10^{-2} and 48 $mrad$ become 3.0×10^{-2} and 31 $mrad$, respectively.

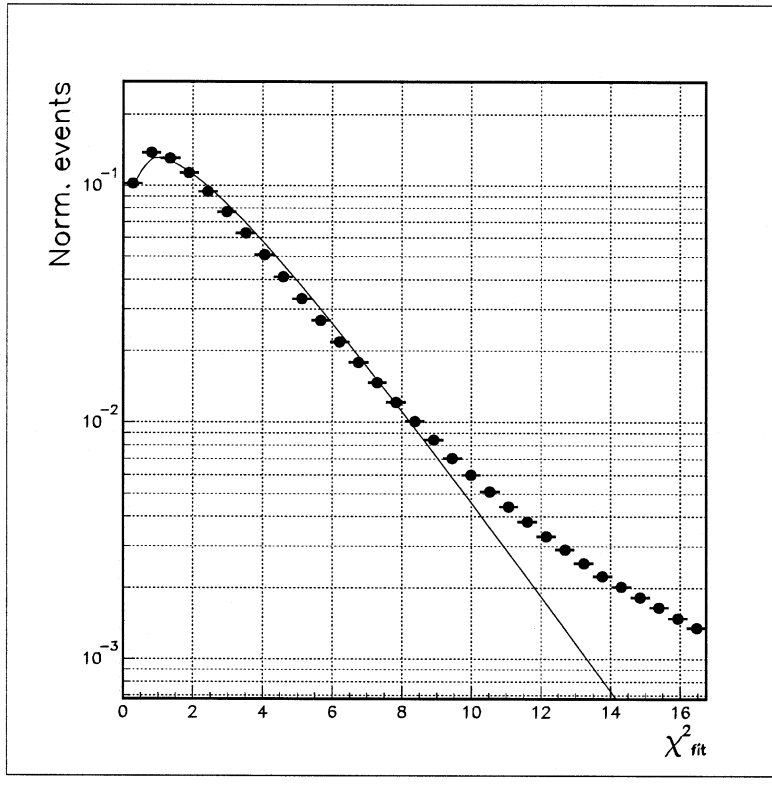

Figure 1: The normalized χ^2_{fit} distribution. The curve represents χ^2 function with 3 degrees of freedom.

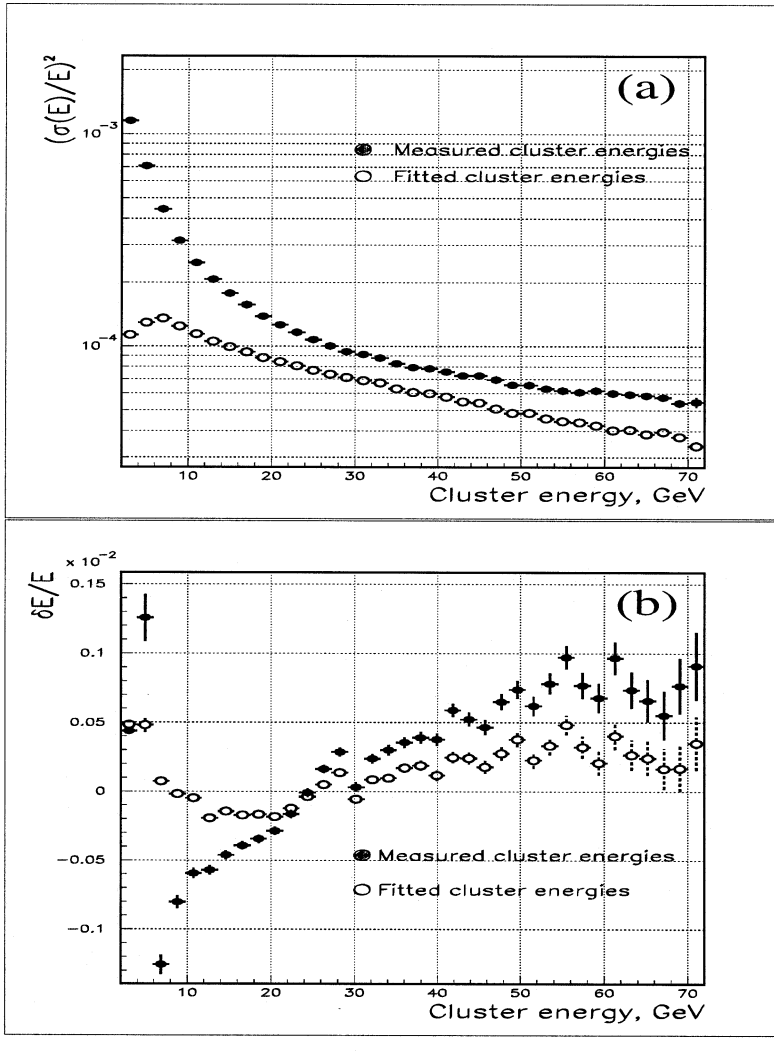

Figure 2: The squared relative resolution $(\sigma(E)/E)^2$ (a) and the relative nonlinearity $(E - E^{true})/E^{true}$ (b) of the measured and fitted cluster energies as functions of the cluster energies.

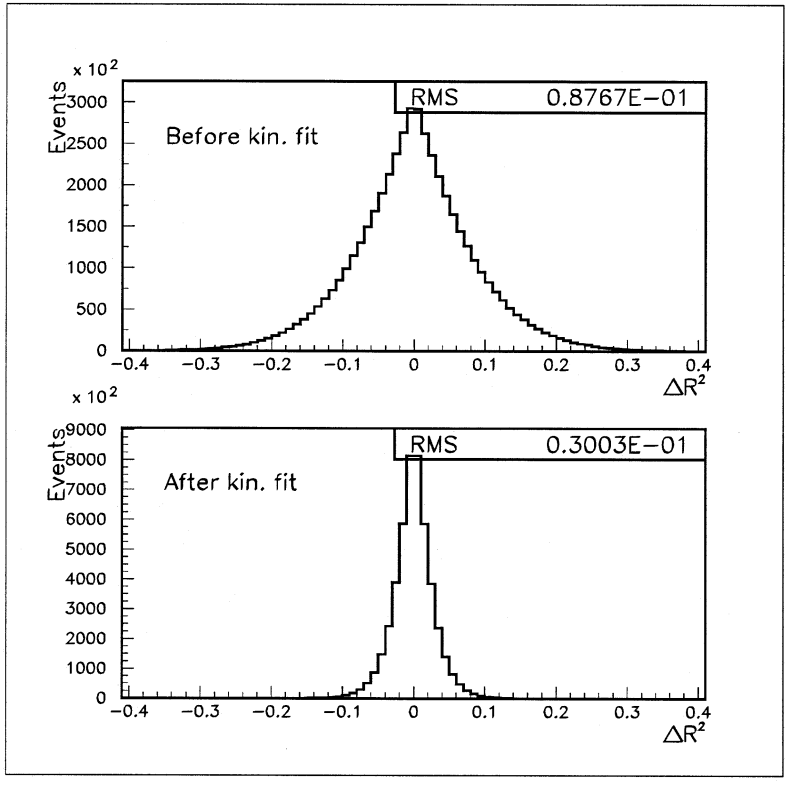

Figure 3: The resolution of the Dalitz plot variable R^2 before and after applying the kinematic fitting procedure.

5 Estimation of the energy nonlinearity in the calorimeter response

In principle during the data analysis the cluster energies and coordinates are corrected in order to account for various physical processes which take place in the calorimeter [3]. However, the accuracy in the estimation of these corrections is limited by the amount of data statistics or/and the inaccurate knowledge of the characteristics of the corresponding processes. One of the main systematic effects which partly survives after the applied corrections is the energy nonlinearity[2] in the calorimeter response.

Taking into account all the systematic effects and the applied corrections, the expected residual energy nonlinearity can be parametrized in the following way [3]:

$$\delta E_{cl} = \begin{cases} E_{cl}(a + c/E_{cl} + dE_{cl} + er_{cl}) , & E_{cl} \geq 7GeV \\ E_{cl}(b + f(E_{cl} - 7\,GeV)^2) , & E_{cl} < 7GeV \end{cases} \tag{7}$$

where E_{cl} and r_{cl} are the energy and the coordinates of a given cluster, a, b, c, d, e and f are unknown parameters.

In the present section we describe a method for a precise estimation of the residual energy nonlinearity based on the selected and kinematically fitted $K_L \to 3\pi^0 \to 6\gamma$ decays. The basic idea is to perform a global fitting procedure over the whole data sample. This means that each event is kinematically fitted in terms of the 15 local parameters p_k and a set of global parameters[3] q_l, $l = (1 \div s)$, which correspond to the residual systematic effects. The aim is to minimize the sum over all the individual kinematic fitting χ^2_{fit}:

$$\chi^2_{sum} = \sum_j \chi^2_{fit\,j}(p_k, q_l) \to min , \tag{8}$$

where $\chi^2_{fit\,j}$ is the result from the kinematic fitting of the j-th event. Although the numerical minimization of (8) for millions of events requires very huge

[2] the energy nonlinearity is defined as nonlinear systematic deviations of the measured cluster energies from the true ones

[3] in the considered case the parameters a, b, c, d, e and f from (7)

computing resources, straightforward algebra gives a simple solution for the parameters q_l.

Lets consider the individual $\chi^2_{fit\,j}$ defined in (6) using matrix notation:

$$\chi^2_{fit\,j} = (\mathbf{y} - \mathbf{f}(\mathbf{p}) - \delta\mathbf{y})^T \mathbf{V}_\mathbf{y}^{-1} (\mathbf{y} - \mathbf{f}(\mathbf{p}) - \delta\mathbf{y}) \ , \tag{9}$$

where

$$\mathbf{y} = \begin{pmatrix} E_1 \\ \vdots \\ x_1 \\ \vdots \\ y_1 \\ \vdots \\ y_6 \end{pmatrix} , \ \mathbf{p} = \begin{pmatrix} p_1 \\ \vdots \\ p_{15} \end{pmatrix} , \ \mathbf{q} = \begin{pmatrix} q_1 \\ \vdots \\ q_s \end{pmatrix} , \ \mathbf{f}(\mathbf{p}) = \begin{pmatrix} E_1^{fit}(\mathbf{p}) \\ \vdots \\ x_1^{fit}(\mathbf{p}) \\ \vdots \\ y_1^{fit}(\mathbf{p}) \\ \vdots \\ y_6^{fit}(\mathbf{p}) \end{pmatrix} ,$$

$\mathbf{V}_\mathbf{y}^{-1}$ is a diagonal matrix inverse of the covariant matrix of the measured cluster energies and coordinates in LKr:

$$\mathbf{V}_\mathbf{y}^{-1} = \begin{pmatrix} 1/\sigma(E_1)^2 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 1/\sigma(x_1)^2 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 1/\sigma(y_1)^2 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 1/\sigma(y_6)^2 \end{pmatrix} ,$$

and $\delta\mathbf{y} = \mathbf{B}\mathbf{q}$ are the systematic effects parametrized as linear functions of the parameters q_l and $\mathbf{B}$ is a $18 \times s$ dimensional matrix which is represented by (7). Since the fitted cluster energies and coordinates are closer to the true energies and coordinates than the measures ones, the elements of the matrix $\mathbf{B}$ are calculated using E_i^{fit}, x_i^{fit}, y_i^{fit}.

Assuming that the functions $\mathbf{f}(\mathbf{p})$ vary slowly enough they can be expanded to first order about the defined in section 4 initial decay parameters $\mathbf{p}^{init}$:

$$\mathbf{f}(\mathbf{p}) \approx \mathbf{f}(\mathbf{p}^{init}) + \left.\frac{\partial \mathbf{f}(\mathbf{p})}{\partial \mathbf{p}}\right|_{\mathbf{p}^{init}} (\mathbf{p} - \mathbf{p}^{init}) = \mathbf{f}(\mathbf{p}^{init}) + \mathbf{A}\mathbf{u}\,, \qquad (10)$$

where $\mathbf{u} = \mathbf{p} - \mathbf{p}^{init}$ and $\mathbf{A}$ is a 18×15 dimensional matrix of partial derivates of the functions $\mathbf{f}$ upon the parameters $\mathbf{p}$.

Obviously, the minimization of the (8) can be expressed in terms of a set of equations $\partial\chi^2_{fit\,j}/\partial\mathbf{p} = 0$[4] and $\partial\chi^2_{sum}/\partial\mathbf{q} = 0$. Therefore the linear approximation of the functions $\mathbf{f}(\mathbf{p})$ (10) reduces the relation (8) to the following set of linear equations:

$$\begin{aligned} \mathbf{A}_j^T \mathbf{V}_{\mathbf{y}\,j}^{-1} (\Delta\mathbf{y}_j - \mathbf{A}_j\mathbf{u}_j - \mathbf{B}_j\mathbf{q}) &= 0 \\ \sum_j \mathbf{B}_j^T \mathbf{V}_{\mathbf{y}\,j}^{-1} (\Delta\mathbf{y}_j - \mathbf{A}_j\mathbf{u}_j - \mathbf{B}_j\mathbf{q}) &= 0 \end{aligned}$$

where j is the event index and $\Delta\mathbf{y} = \mathbf{y} - \mathbf{f}(\mathbf{p}^{init})$. Then the straightforward algebra gives very simple solution for the parameters q_l and their covariant matrix $\mathbf{V_q}$:

$$\begin{aligned} \mathbf{q} &= \mathbf{S}^{-1}\mathbf{s} \\ \mathbf{V_q} &= \mathbf{S}^{-1} \end{aligned}$$

where $\mathbf{s}$ and $\mathbf{S}$ are defined as follows:

$$\begin{aligned} \mathbf{s} &= \sum_j \mathbf{B}_j^T \mathbf{V}_{\mathbf{y}\,j}^{-1} \mathbf{r}_j \\ \mathbf{S} &= \sum_j (\mathbf{B}_j^T \mathbf{V}_{\mathbf{y}\,j}^{-1} \mathbf{B}_j - \mathbf{U}_j^T \mathbf{V}_{\mathbf{A}\,j} \mathbf{U}_j) \end{aligned}$$

[4] 15 equations for each event

Table 1: The obtained values of the parameters q_l.

a	b, MeV	c, GeV^{-1}	d, cm^{-1}	e	f, GeV^{-2}
-2.4×10^{-4}	7.6	2.3×10^{-6}	-2.0×10^{-6}	8.5×10^{-4}	-7.0×10^{-4}

The auxulary matrixes $\mathbf{V_{A}}_j$ and $\mathbf{U}_j$ are calculated as $\mathbf{V_{A}}_j = (\mathbf{A}_j^T \mathbf{V}_{\mathbf{y}j}^{-1} \mathbf{A}_j)^{-1}$ and $\mathbf{U}_j = \mathbf{A}_j^T \mathbf{V}_{\mathbf{y}j}^{-1} \mathbf{B}_j$, respectively.

It has to be stressed that $\mathbf{r} = \Delta\mathbf{y} - \mathbf{A}\mathbf{u}$ is essentially the vector of so-called "residuals" of the kinematically fitted cluster energies and positions without taking into account any systematic effects. Following their definition the "residuals" are simply the deviations of the measured cluster energies and coordinates from the fitted ones and therefore are reasonable estimates[5] of the residual systematic effects in the calorimeter response.

Using the described procedure, the parameters $\mathbf{q}_l$ can be obtained by performing individual kinematic fits over all the events[6] and accumulating the results of each fit in $\mathbf{s}$ and $\mathbf{S}$. Obviously, the corrected for nonlinearity energies and coordinates of the clusters can not be computed during the accumulation because they depends on the parameters $\mathbf{q}_l$. Nevertheless, this can be done by repeating the kinematic fitting procedure after the correction of cluster energies based on the now known values of the parameters $\mathbf{q}_l$.

The described method was successfully applied in the estimation of the energy nonlinearity giving the precise values of the parameters a, b, c, d, e and f (Table 1)[7]. The relative "residuals" of the fitted cluster energies as functions of the energies and the radii of the clusters in LKr are presented in Fig.4. As it can be seen from the figure, the corrections based on the six defined above parameters q_l do not entirely solve the problem with the energy nonlinearity in the calorimeter response. Moreover, at small cluster energies ($< 7\ GeV$) these corrections are significantly larger then needed. In order to find the reason for this, one can plot a two-dimensional distribution of the energies "residuals" as a function of the cluster radii versus the cluster energies (Fig.5). Obviously, the parameters a, b, c, d, e and f are

[5] since the fitted cluster energies and positions are close to the true ones

[6] ignoring the systematic effects

[7] the obtained parameters errors are $< 0.1\%$ and therefore are omitted in the table

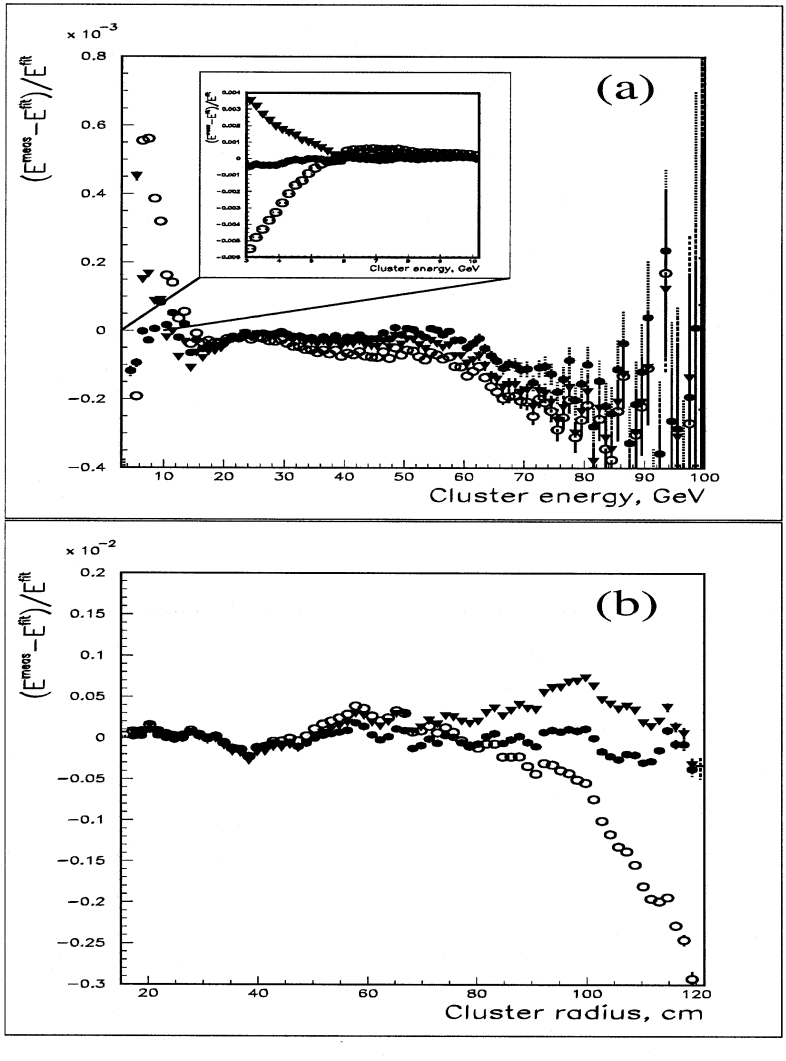

Figure 4: The obtained relative "residuals" of the fitted cluster energies $\left(E^{meas} - E^{fit}\right)/E^{fit}$ as functions of the energies (a) and radii (b) of the clusters. ○ - uncorrected cluster energies; ▼ - after a correction based on constant parameters a, b, c, d, e and f; ● - after a correction based on variable parameters $a(r_{cl})$, $b(r_{cl})$, $c(r_{cl})$, $d(r_{cl})$, $e(r_{cl})$ and $f(r_{cl})$.

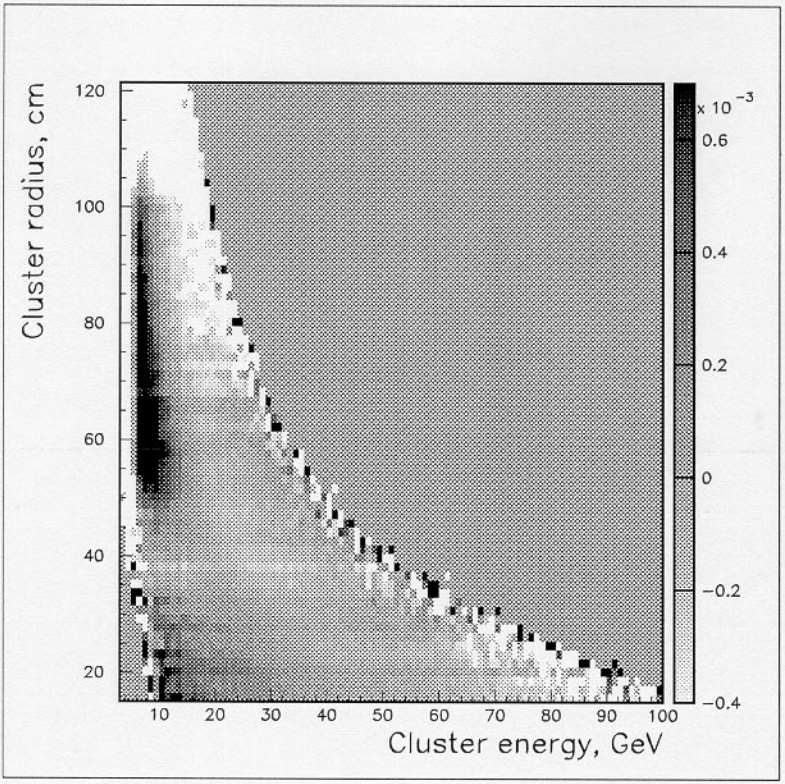

Figure 5: A two-dimensional distribution of the relative "residuals" of the fitted cluster energies $\left(E^{meas} - E^{fit}\right)/E^{fit}$ before the corrections as a function of the cluster radii versus the cluster energies.

strongly correlated and therefore the energy nonlinearity has more sophisticated structure compared to one used in parameterization (7). In order to take into account the correlation, the constant parameters a, b, c, d, e and f were substituted by power functions of the cluster radii r_{cl}:

$$a(r_{cl}) = a_1 + a_2 r_{cl}^2 + a_3 r_{cl}^3 + a_4 r_{cl}^4 + a_5 r_{cl}^5 \quad (11)$$

$$c(r_{cl}) = c_1 + c_2 r_{cl} + c_3 r_{cl}^2 + c_4 r_{cl}^3 + c_5 r_{cl}^4 + c_6 r_{cl}^5 + c_7 r_{cl}^6 \quad (12)$$

$$d(r_{cl}) = d_1 + d_2 r_{cl} + d_3 r_{cl}^2 + d_4 r_{cl}^3 + d_5 r_{cl}^4 + d_6 r_{cl}^5 \quad (13)$$

$$e(r_{cl}) = e_1 \quad (14)$$

$$b(r_{cl}) = b_1 + b_2 r_{cl} + b_3 r_{cl}^2 + b_4 r_{cl}^3 + b_5 r_{cl}^4 + b_6 r_{cl}^5 \quad (15)$$

$$f(r_{cl}) = f_1 + f_2 r_{cl} + f_3 r_{cl}^2 + f_4 r_{cl}^3 + f_5 r_{cl}^4 + f_6 r_{cl}^5 \quad (16)$$

After that the whole procedure was repeated over the new set of 31 parameters q_l defined in (11)-(16). Now the energy nonlinearity is corrected much more reasonably and becomes less than $\pm 10^{-4}$ (for $E_{cl} < 7\ GeV$ - $\pm 5 \times 10^{-4}$) over the almost entire cluster energy spectrum (Fig.4).

Finally the corrections to the cluster energies based on the constant and the variable parameters a, b, c, d, e and f have been used in the analysis of $K_{L,S} \to 2\pi^0$ decays in order to estimate the correction and the corresponding uncertainty of direct CP-violation parameter ϵ'/ϵ, due to the residual energy nonlinearity in the calorimeter response.

6 Conclusions

The applied kinematic fitting procedure has considerably decreased the resolution and the nonlinearity in the electromagnetic calorimeter response. This fact has allowed to study the $K_L \to 3\pi^0$ decay Dalitz plot in a almost systematic-free manner.

Despite of the fact that the presented method based on $K_L \to 3\pi^0 \to 6\gamma$ decays is a powerful tool for a determination of the energy nonlinearity, it has several limitations:

- The phase space allocated by the decays does not cover the whole range of the possible cluster energies and coordinates in the calorimeter;
- The non-gaussian tails seen in the energies measured by the calorimeter could hinder the correct estimation of the energy nonlinearity since they are not taken into account in the kinematic fitting procedure;
- Additional bias might arise because the event selection is done using the measured cluster energies and coordinates while the analysis of the energy nonlinearity is based on the fitted ones. This could introduce systematic shifts near the edges of the phase space.

We would like to thank the colleagues from the NA48 collaboration for their support and co-operation.

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Received by Publishing Department
on April 19, 2001.

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E1-2001-77

Применение процедуры кинематического фитирования в анализе распадов $K_L \to 3\pi^0$ в эксперименте NA48 на ускорителе ЦЕРН

Описано применение процедуры кинематического фитирования при исследовании диаграмм Далитца в распадах $K_L \to 3\pi^0$. Процедура позволила улучшить разрешение экспериментальной установки по переменным диаграмм Далитца, определить энергетическую нелинейность в отклике электромагнитного калориметра и минимизировать связанные с ними систематические эффекты.

Работа выполнена в Лаборатории физики частиц ОИЯИ и в ЦЕРН, Швейцария.

Сообщение Объединенного института ядерных исследований. Дубна, 2001

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E1-2001-77

Application of a Kinematic Fitting Procedure in an Analysis of $K_L \to 3\pi^0$ Decays at the NA48 Experiment at the CERN SPS

An application of a kinematic fitting procedure in the $K_L \to 3\pi^0$ decay Dalitz plot study is described. It allows one to improve the resolution on the Dalitz plot variables, to estimate the energy nonlinearity in the calorimeter response, and to minimize the systematic effects related to them.

The investigation has been performed at the Laboratory of Particle Physics, JINR and at the CERN, Switzerland.

Communication of the Joint Institute for Nuclear Research. Dubna, 2001

Макет Т.Е.Попеко

Подписано в печать 05.07.2001
Формат 60 × 90/16. Офсетная печать. Уч.-изд. л. 1,28
Тираж 375. Заказ 52758. Цена 1 р. 75 к.

Издательский отдел Объединенного института ядерных исследований
Дубна Московской области