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RECENT RESULTS OF THE ϕ-MESON STUDY WITH CMD-2 AT VEPP-2M AND RELEVANCE TO FUTURE CP,CPT ϕ FACTORY STUDIES

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НОВОСИБИРСК

Recent results of the ϕ-meson study with CMD-2 at VEPP-2M and relevance to future CP, CPT ϕ factory studies

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Abstract

The general purpose detector CMD-2 is taking data at the e^+e^- collider VEPP-2M at Novosibirsk, with the luminosity $\approx 5.\times10^{30}cm^{-2}s^{-1}$. Data from $\approx 1500nb^{-1}$ of integrated luminosity around 1.02 GeV have been collected (about 1.7×10^6 of ϕ's were produced) and preliminary analyzed. We present progress in the study of the ϕ-meson and K_SK_L system:

a) the measurement of the ϕ-meson parameters;

b) the search for the rare decays of ϕ. The new upper limits $B(\phi\to\eta'\gamma) < 2.4\times10^{-4}$, $B(\phi\to\pi^+\pi^-\pi^+\pi^-) < 1.0\times10^{-4}$ and $B(\phi\to f_0\gamma) < 8\times10^{-4}$ have been obtained;

c) the study of the K_L interactions in the CsI calorimeter;

d) with the help of 32,340 tagged K_S the semi-rare decay of $K_S\to\pi^+\pi^-\gamma$ has been observed with a branching ratio of $(1.82\pm0.49)\times10^{-3}$;

e) the selection of events with K_SK_L coupled decays and interactions. The regeneration cross section of the low momenta K_L was found to be $\sigma^{Be}_{reg} = 63\pm19$mb.

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1 Introduction

As it was realized at the very early steps of the ϕ-meson studies at the colliding beam machines, K_SK_L pairs ($\approx$ 34% of all ϕ decays) may be used as a new source for observing CP and CPT violation. These suggestions, including studies of quantum mechanical correlations, were discussed in papers [1],[2] when an electron-positron collider at Novosibirsk VEPP-2M with luminosity $\approx 5\times10^{30}cm^{-2}s^{-1}$, was under construction. The coupled decays of the K_SK_L mesons will allow demonstration of the quantum mechanical correlations of two particle decays (Einstein-Podolosky-Rosen paradox) [3].

The idea of constructing a more intensive source of ϕ mesons has been discussed by many authors [4],[5]. The flux of events at these so-called "ϕ-factories", now under construction [6],[7], will provide an opportunity to perform new precise measurements of a possible direct component in the decay of the $K_L\to\pi^+\pi^-,\pi^0\pi^0$ (ϵ'/ϵ), as well as the observation of the CP-violating three pion decays of the K_S for the first time. A study of the oscillations in the joint decay distributions could provide an information about real and imaginary parts of any CPT-violating amplitude.

At the VEPP-2M collider at Novosibirsk, which could be considered as a pre ϕ-factory, with the CMD-2 detector we have been proceeding step by step to prepare for work at the ϕ-factory which is under construction here. Studies of upgraded detectors and accelerators are in progress, including an intermediate $\approx 10^{32}$ luminosity collider for investigating the idea of the round beams, an important ingredient in the planned Novosibirsk ϕ-factory project [8],[9].

With the CMD-2 detector, the neutral kaons from ϕ decays are under study and the coupled $K_S K_L$ decays have been observed for the first time. The attempt to select the $K_L \to \pi^+\pi^-$ stressed again problems of the semileptonic decay mode background as well as a high level of neutral kaon nuclear interactions including a regeneration of K_L into K_S. The opening of this kinematic region for a study of the neutral kaon interactions has been an additional argument for the ϕ factory construction, and we anticipate that results obtained from the data now in hand will be important in planning ϕ-factory detectors and physics strategies.

A possible problem with a measurement of ϵ'/ϵ at the level of 10^{-4} - 10^{-5} would be an admixture of C=+1 into the final state, giving a component of $K_S K_S$ instead of the desired $K_S K_L$. Although efficient experimental cuts can reduce the effects of such an admixture [10, 11], a component as large as 5×10^{-5} of a C=+1 state would give a dominant contribution to the uncertainty of ϵ'/ϵ at the level of the planned ϕ-factory experiments [11]. The contamination from such a C-even K-$\overline{K}$ mode has been estimated by several authors giving generally lower values [4, 12, 13, 14], but there are no experiments confirming these results.

The decay of the ϕ to $f_0\ \gamma$ with f_0 decaying to two kaons is too small to be seen at the VEPP-2M collider and we hope to study the decay of ϕ to $f_0\ \gamma$ with a subsequent decay of the f_0 to two charged pions [15]. The two charged pion decay mode can be related to the two kaon decay and a limit on the C-even two kaon final state may be found. Estimates for the branching ratio of $\phi \to f_0\gamma$ range from a very small to as high as 2.5×10^{-4} [12, 13, 14].

The study of the f_0 is interesting by itself. The 20% decay probability into a two kaon final state seems puzzlingly high in case f_0 is a member of the strangeness-0 and isospin-0 meson nonet. Various explanations for this large coupling to kaons have been advanced [12, 13, 14, 16], including the idea that f_0 is made of four quarks, with a "hidden strangeness" component: $(f_0 = s\ \bar{s}(u\ \bar{u}\ +\ d\ \bar{d})/\sqrt{2})$, or that it may be a K-$\overline{K}$ molecule. A limit from VEPP-2M will help to distinguish between these different possibilities.

With expected high luminosity at the ϕ-factories the rare decay modes of ϕ can be measured with high accuracy. For example, a measurement of the B($\phi \to \eta'\gamma$) would give important information about quark structure of light mesons and possible contributions from gluonium states (if any). Our new data obtained with the present statistics already improve the upper limit for this process, as well as for $\phi \to \pi^+\pi^-\pi^+\pi^-$ and $\phi \to f_0\gamma$.

The analysis of the CMD-2 data is in progress and we expect new results in the ϕ-meson study.

2 The CMD-2 Detector And Data Sample

The CMD-2 detector has been described in more detail elsewhere [2, 17]. The CsI barrel calorimeter with $6 \times 6 \times 15$ cm crystal size is placed outside a $0.4X_0$ superconducting solenoid with a 1 Tesla azimuthally symmetric magnetic field. The endcap calorimeter is made of $2.5 \times 2.5 \times 15$ cm^3 BGO crystals and was not installed for the data presented here. The drift chamber inside the solenoid has about 250 μ resolution transverse to the beam and $0.5 - 0.6$ cm longitudinally.

The collected sample of the Bhabha events was used for the calibration and determination of the reconstruction efficiency in the drift chamber and in the calorimeter. A momentum resolution of $6-8\%$ for 500 MeV/c charged particles, and energy resolution of about 10% for gammas in the CsI calorimeter have been obtained.

The luminosity integral collected in $1992 - 1993$ at ϕ was mostly used for the detector study and software development. Not all detector systems were running properly and data presented here are still preliminary – better detector understanding and better reconstruction programs available now will give results with less systematic uncertainties.

About 7.2×10^7 triggers were recorded. The total luminosity integral, determined by selection of Bhabha events, was found to be 1500 nb^{-1}.

The largest part of the integrated luminosity ($\approx$ 1200 nb^{-1} in 14 energy points around the ϕ mass) has been collected during the 1993 summer runs and was used to study rare decay modes of ϕ, coupled decays in the $K_S K_L$ system and nuclear interactions of neutral kaons.

3 ϕ-meson parameters

The main branching ratios of the ϕ have been measured using $\approx$ 300 nb^{-1} of integrated luminosity, collected in 1992. It was the first time, when four major decay modes of ϕ were measured in one experiment. The event selection and other details may be found in paper [18]. The following results were obtained:

$$m_\phi = 1019.380 \pm 0.034 \pm 0.048 \text{ MeV},$$
$$\Gamma_{tot} = 4.409 \pm 0.086 \pm 0.020 \text{ MeV},$$
$$\sigma(\phi \to K^+K^-) = 1993 \pm 65 \pm 82 \text{ nb},$$
$$\sigma(\phi \to K_S K_L) = 1360 \pm 25 \pm 49 \text{ nb},$$
$$\sigma(\phi \to 3\pi) = 656 \pm 24 \pm 30 \text{ nb},$$
$$\sigma(\phi \to \eta\gamma) = 47.9 \pm 3.5 \pm 3.2 \text{ nb},$$
$$\delta_{\omega-\phi} = (147 \pm 16)^o .$$

The first error represents the statistical uncertainty and the second one the systematic uncertainty. The relative phase of $\omega - \phi$ mixing in three pion channel is in good agreement with the most precise measerement presented in [22] $\delta_\phi = (155 \pm 15)^o$. The experimental cross-sections of the ϕ production in the different modes, together with fit functions are shown in Figure 1.

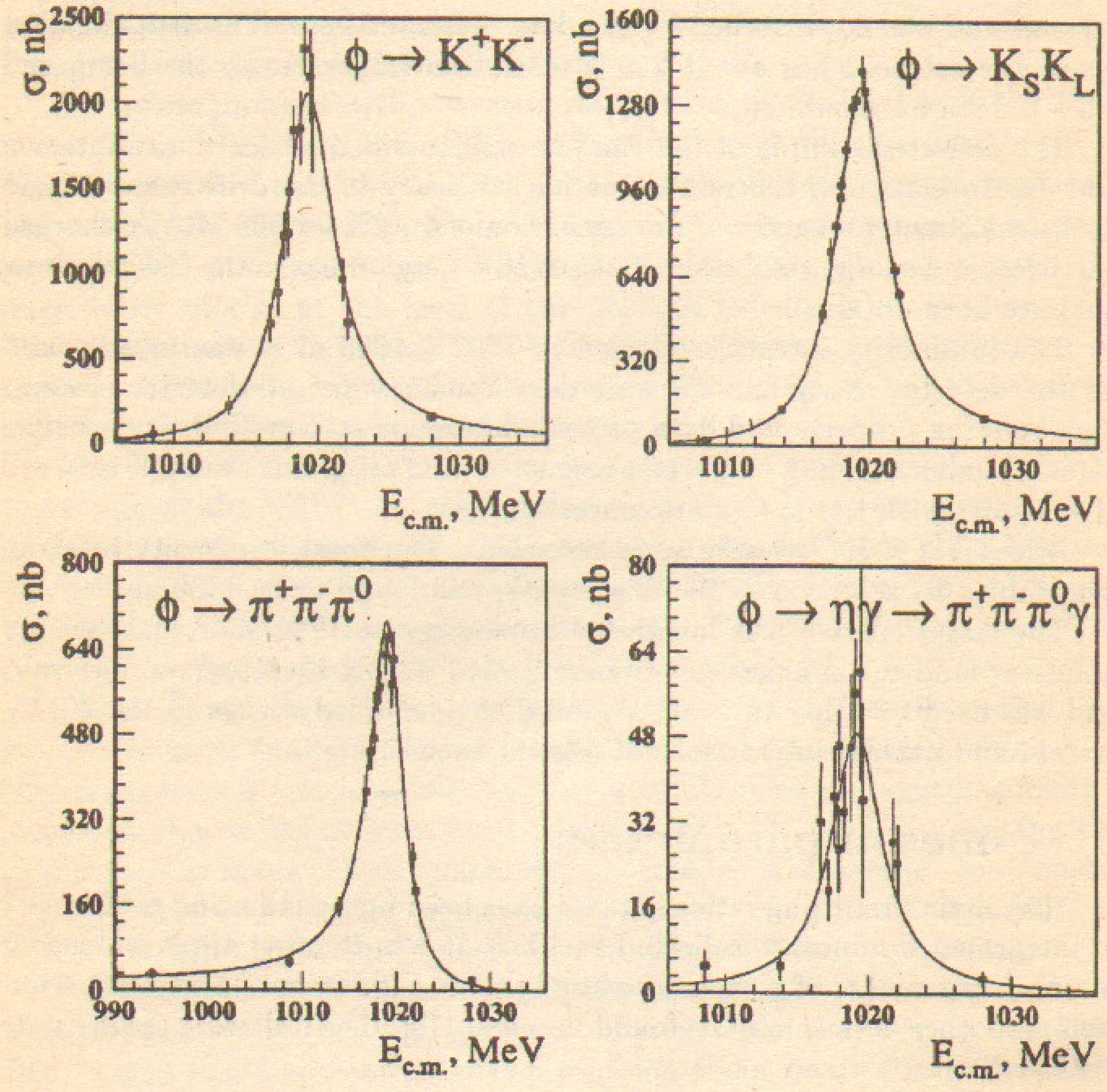

Figure 1: The excitation curves for ϕ-meson in different channels.

All major decay modes were simultaneously measured in one experiment and therefore the branching ratios can be obtained as ratios of integrals over excitation curves independently of the width of the ϕ and the uncertainties

due to the luminosity measurements:

$B(\phi \to K^+K^-) = 49.1 \pm 1.2$ %,
$B(\phi \to K_S K_L) = 33.5 \pm 1.0$ %,
$B(\phi \to 3\pi) = 16.2 \pm 0.8$ %,
$B(\phi \to \eta\gamma) = 1.18 \pm 0.11$ % .

The electron width of the ϕ and its branching ratio to e^+e^- can also be calculated independently and were found to be

$\Gamma_{ee} = 1.27 \pm 0.05$ keV,
$B(\phi \to ee) = (2.87 \pm 0.09) \times 10^{-4}$.

All results are consistent with the Particle Data Group values [23].

Here we note, that in all parameters systematic errors dominate and using all available statistics will improve these results only after systematic errors study and better detector understanding.

4 Study of $\phi \to \eta\gamma$ and Search for $\eta'\gamma$.

The decay of $\phi \to \eta\gamma$ was previously observed in neutral modes ($\eta \to \gamma\gamma$, $\eta \to 3\pi^0$) only. Detector CMD-2 gives the possibility to study $\phi \to \eta\gamma$ decay in the channel with charged particles, when η decays into $\pi^+\pi^-\pi^0$. So, after $\pi^0 \to \gamma\gamma$ decay, the final state consists of two charged pions and three photons. Two photons in the final state are from π^0, the third one has the maximum energy of all three - 362 MeV at the ϕ-meson peak.

We select $\eta\gamma$ events using the information about momenta and angles from the drift chamber for both charged particles and about angles from the CsI calorimeter for a primary photon under suggestion that other photons are from π^0. The reconstructed invariant mass of 3 pions $M_{\pi^+\pi^-\pi^0}$ is the basic parameter we use to study the decay $\phi \to \eta\gamma$ and the distribution over it should have a peak around $M_\eta = 547.45$ MeV.

The distribution over $M_{\pi^+\pi^-\pi^0}$ for all 1993 ϕ-meson data after some simple cuts is presented in Figure 2. These distributions were used to get the numbers of $\eta\gamma$ events for different beam energies.

The calculated cross-section $\sigma_{e^+e^- \to \phi \to \eta\gamma}$ with the fit function is presented in Figure 2. Using the electron width of ϕ from [23] the $Br(\phi \to \eta\gamma)$ was found to be:

$$Br(\phi \to \eta\gamma) = (1.12 \pm 0.06 \pm 0.15)\%$$

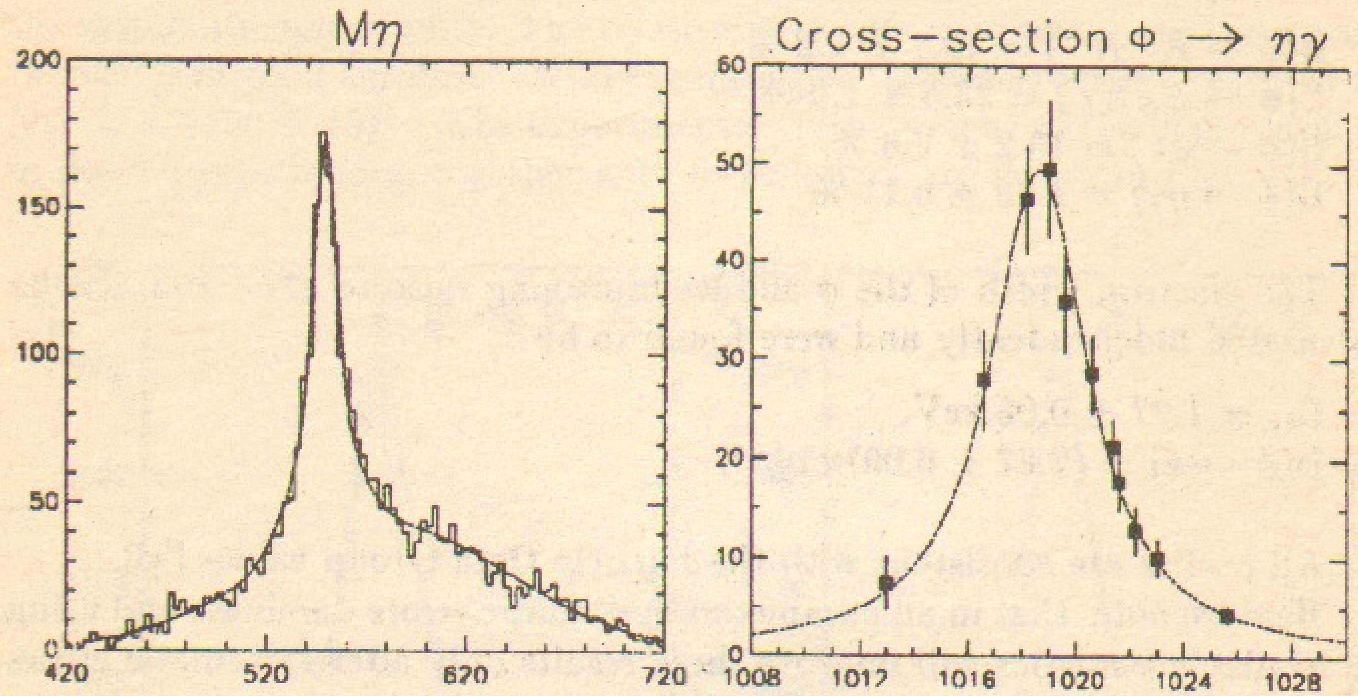

Figure 2: The study of $\phi \to \eta\gamma$: invariant mass $M_{\pi^+\pi^-\pi^0}$; $\phi \to \eta\gamma$ cross-section;

This result is preliminary because the work on efficiency determination is not finished and we hope significantly decrease the systematic error.

The decay $\phi \to \eta'\gamma$ was searched in the mode, when η' decays into $\pi^+\pi^-\eta$ and $\eta \to \gamma\gamma$. So, both in $\eta\gamma$ and in $\eta'\gamma$ the final state there are 2 charged particles and 3 photons. The events with all these particles detected were used for the constrained fit.

The scatter plot of the invariant masses for two soft photons M_{23} versus the hardest photon energy ω_1 for the experimental data is presented in the Figure 3.

The decay into $\eta\gamma$ is the basic background for $\eta'\gamma$. Selecting 481 $\eta\gamma$ events at this plot one can make anti–$\eta\gamma$ cut.

Using this cut the scatter plot of the invariant masses for two hardest photons M_{12} versus the weakest photon energy ω_3 was studied. For $\eta'\gamma$ events M_{12} should be around η mass 547.5 MeV, while ω_3 is a monochromatic 60 MeV photon. The Figure 3 presents the result of 1992–1993 data together with simulation of $\phi \to \eta'\gamma$. We have 1 candidate to $\eta'\gamma$ event with 1 event as estimated background. Using for the 90% C.L. upper limit $N_{\eta'\gamma} < 3$ and the ratio:

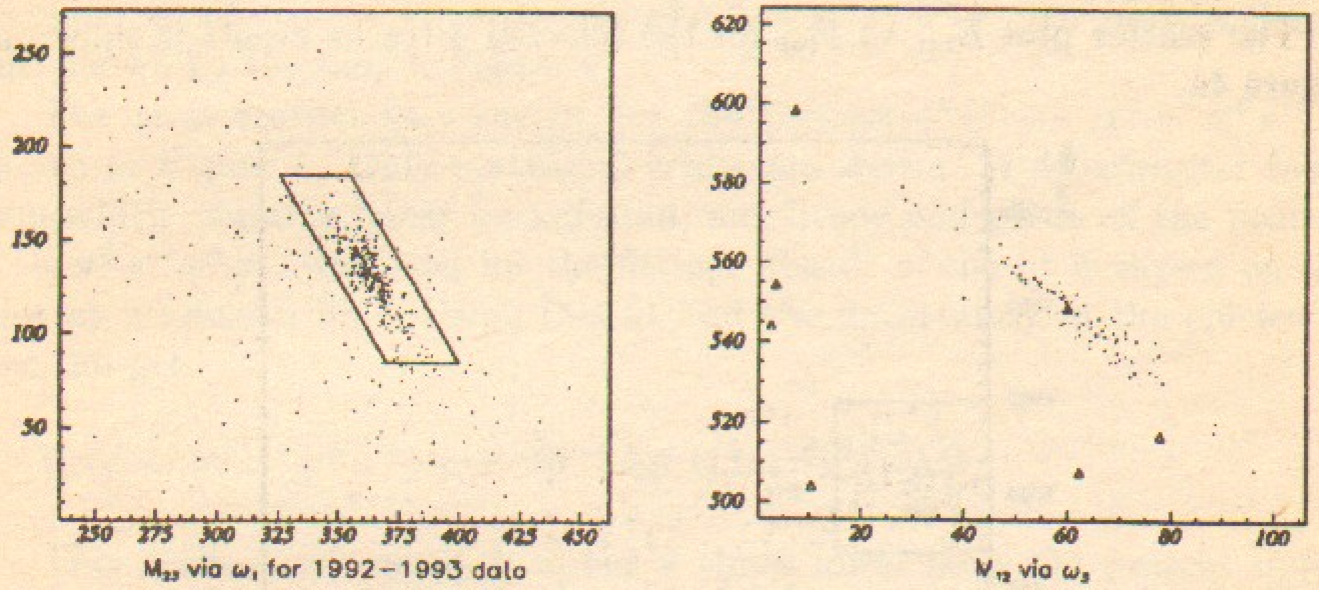

Figure 3: The search for $\phi \to \eta'\gamma$ (1993 data): Invariant mass M_{23} vs. ω_1 after constrained fit. Box shows $\eta\gamma$ cut; Invariant mass M_{12} vs. ω_3 after constrained fit. Dots are simulation, triangles – experiment

$$\frac{Br(\phi \to \eta'\gamma)}{Br(\phi \to \eta\gamma)} = \frac{N_{\eta'\gamma}}{N_{\eta\gamma}} \cdot \frac{Br(\eta \to \pi^+\pi^-\pi^0)}{Br(\eta' \to \pi^+\pi^-\eta)} \cdot \frac{Br(\pi^0 \to \gamma\gamma)}{Br(\eta \to \gamma\gamma)} \cdot \frac{\varepsilon_{\eta\gamma}}{\varepsilon_{\eta'\gamma}} ,$$

with the efficiencies obtained from the simulation, $\varepsilon_{\eta\gamma} = 14.4\%$ and $\varepsilon_{\eta'\gamma} = 6.4\%$, the following result has been obtained:

$$Br(\phi \to \eta'\gamma) < 2.4 \cdot 10^{-4}.$$

5 Search for $\phi \to \pi^+\pi^-\pi^+\pi^-$

A sample of 3- and 4-track events was used to search for the process $\phi \to \pi^+\pi^-\pi^+\pi^-$. In this sample tracks have to originate from the beam-beam interaction point within 0.5 cm in the r-ϕ plane and have at least 9 hits in the drift chamber. The total charge has to be ± 1 for 3-track events and 0 for 4-track events. To suppress background from the two-particle production and cosmic rays with some additional tracks, we reject events with at least two collinear tracks (a mutual angle of any pair should be 0.16 – 3.0 rad in the r-ϕ plane).

Even with these selection criteria we have a high background from the main channels of ϕ decaying into 3-track events. So, in the search for the process $\phi \to \pi^+\pi^-\pi^+\pi^-$ only 4-track events were used. The ratio of 3- and 4-track events at the energy points outside the ϕ-meson region was used (along with simulation) for evaluation of a detection efficiency which was found to be 0.033±0.012.

The scatter plot E_{tot} vs.P_{tot} for the selected 4-tracks events is shown in Figure 4a.

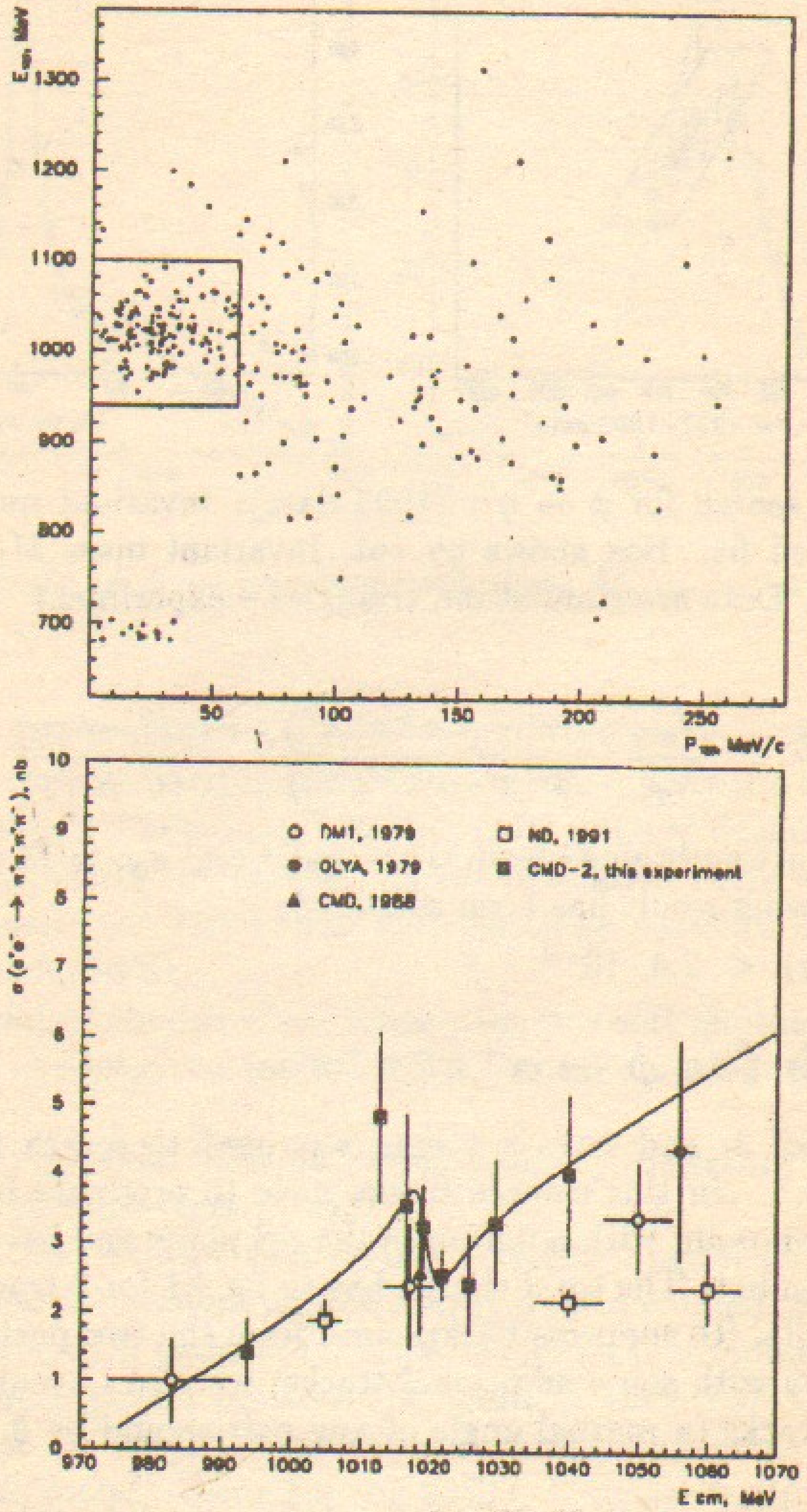

Figure 4: The search for $\phi \to \pi^+\pi^-\pi^+\pi^-$: E_{tot}vs.P_{tot} for 4 – track candidates; cross-section $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$.

Here P_{tot} is the magnitude of the total momentum of 4 charged particles and E_{tot} is their total energy, assuming that all particles are pions. To extract the number of events of the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ we apply a simple cut, shown by the box in Figure 4.

The cross-section vs. energy for the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ is shown in Figure 4. Only statistical errors are shown. A 4-parameter function which contains linear background, amplitude and phase of the process $\phi \to \pi^+\pi^-\pi^+\pi^-$ was used for the fitting. Result of the fit is shown on the plot by a smooth line. Using this fit and the uncertainty in the efficiency, one can get

$$Br(\phi \to \pi^+\pi^-\pi^+\pi^-) < 1 \cdot 10^{-4} \text{ for C.L.}=90\%.$$

This preliminary result is about 9 times lower than the present upper limit for this process [23]. We plan to perform more simulation to improve both efficiency evaluation and data selection. Also we plan to evaluate and apply radiative corrections which are about 5%.

6 Search for $\phi \to f_0\gamma$

In order to extract the resonant contribution associated with the ϕ, two sets of data were used. Energy points at $E_{c.m.}$ from 1016 to 1023.2 MeV with integrated luminosity $660nb^{-1}$ were used for the ϕ region, and points at $E_{c.m.}$ = 996, 1013, 1026, 1030, 1040 MeV with integrated luminosity $440nb^{-1}$ were used for a background estimation (the "non-ϕ" region). The event candidates were selected by a requirement of only two charged tracks and only one photon with energy greater than 20 MeV in the detector. Total energy deposition was required to be less than 600 MeV, average momentum of two charged tracks to be higher than 240 MeV and the radial distance of the found vertex from the interaction region less than 0.15 cm. These cuts removed Bhabha events as well as charged and neutral kaons from ϕ decays. The requirement that the Z-coordinate of the vertex be within 10 cm at the detector center reduces cosmic ray background by a factor of two.

Each charged track was required to have a corresponding cluster in the calorimeter. This requirement reduced the number of pions by about 14%, but avoided nuclear interactions of the pions before the calorimeter with clusters in the wrong place. However split clusters may still be present.

The main visible background for the studied process is $\phi \to \pi^+\pi^-\pi^0$ decay, when one of the photons from π^0 escapes detection. To reduce this background a constrained fit was used. This fit required total energy and momentum conservation within detector resolutions for the three body decay. For χ^2/d.f. less than 3, only events with these requirements survived. But a three pion background was still present, when one of the gammas from the π^0 had a very low energy and the event looked like a three body decay. Figure 5 shows the spectrum of single gammas and the squared missing mass of two charged tracks (taken as pions) vs. detected gamma energy.

In the "ϕ region" data set a broad peak at 200-300 MeV in gamma spectrum, also seen as a broad distribution on the scatter plot at $M^2_{\pi^0}$, represents background from the three pion decays. Points concentrated at zero mass and low energy represent events with one gamma. To reduce the three pion and collinear events background, the cuts $-15000 \leq M^2_{inv} \leq 15000$, $E_\gamma \leq 140$ MeV and $\Delta\phi \geq 0.03$ rad. were applied. The sample of events, selected with above cuts, still contained about 30% of $e^+e^- \to \mu^+\mu^-\gamma$ events.

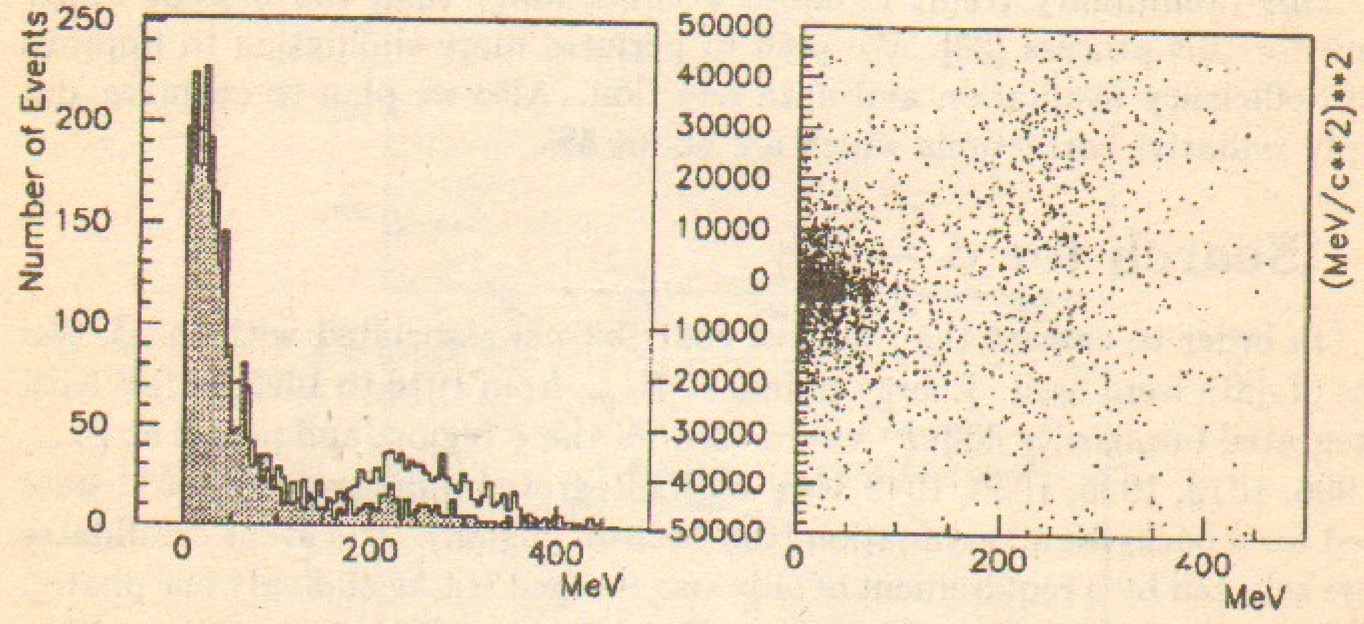

Figure 5: Search for $\phi \to f_0\gamma$: Single gamma spectra. The shaded histogram represents the "not ϕ" region; The squared missing mass vs. photon energy.

The visible cross section of the processes $e^+e^- \to \mu^+\mu^-\gamma + \pi^+\pi^-\gamma$ versus energy is presented in Figure 6a. With the cuts listed above, the detection efficiency of these processes, obtained by simulation, was found to be 0.17, leaving 1.7 nb of the visible cross section. The observed 20% difference from the average experimental cross section is due to the losses of the low energy gammas, not correctly described by a simulation. A line shows a theoretical prediction of the cross section including influence of ϕ on the photon propagator (vacuum polarization) and f_0 production, according to Achasov four quark model. The total branching ratio of $\phi \to \pi^+\pi^-\gamma$ can be extracted from this interference picture.

The signal from the decay of the $\phi \to f_0\gamma$ should be seen as a 30-40 MeV width structure at 45 MeV in the difference of the gamma spectra from the "ϕ" region and "non-ϕ" region shown in Figure 6b together with the theoretical prediction calculated in the Achasov model for the four quark state. With the present statistics only an upper limit can be set.

Taking into account the effective number of ϕ's of 1.1×10^6 and all inefficiencies described above, the upper limit was found to be

$$B(\phi \to f_0\gamma) \leq 8.0 \times 10^{-4} \text{ at C.L.} = 90\%.$$

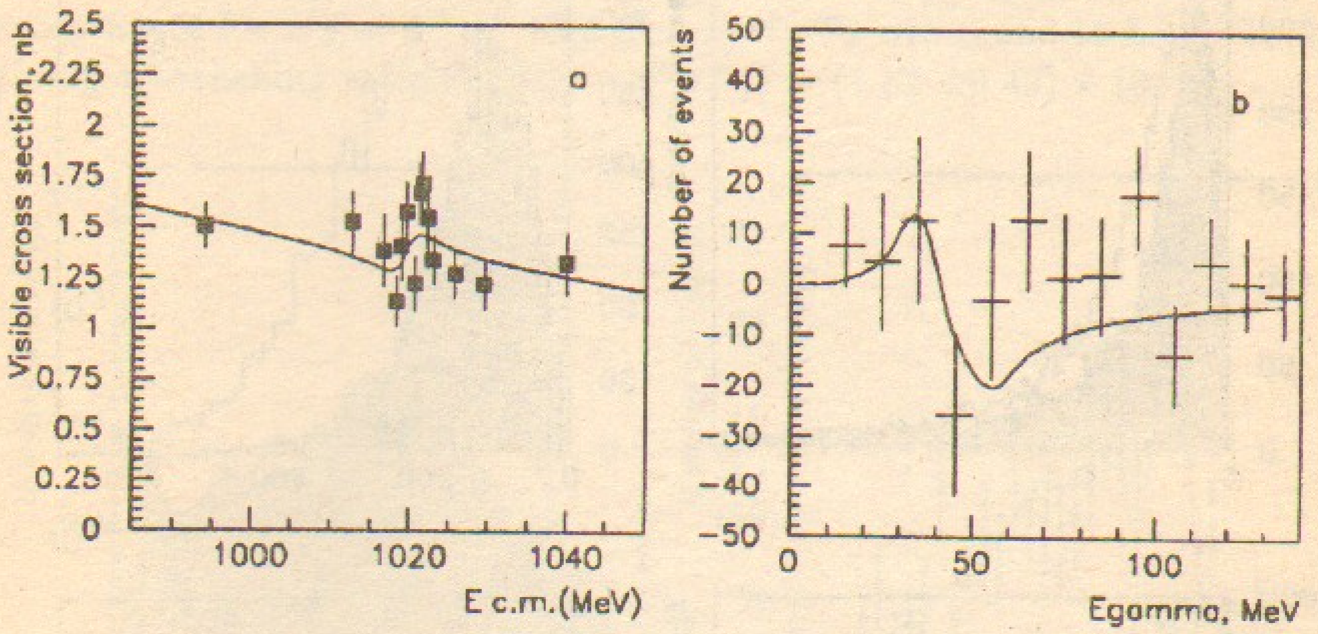

Figure 6: $\phi \to f_0\gamma$ search: a. Visible cross section for $e^+e^- \to \pi^+\pi^-\gamma + \mu^+\mu^-\gamma$ events; b. Normalized difference in photon spectra. A line is a prediction of the four quark model with destructive interference and $B(\phi \to f_0\gamma) = 2.5 \times 10^{-4}$.

7 The K_L nuclear interaction as a tag for K_S rare decay study

K_L candidates are selected by looking at calorimeter clusters opposite a 2-track vertex with an effective mass consistent with that of the kaon. Figure 7a shows the space angle between the predicted missing momentum direction of K_L and the cluster in the calorimeter. Figure 7b shows the energy deposition of the presumed K_L, Figure 7c shows the number of hit crystals, and Figure 7d shows the probability for a K_L to interact, corrected for the interaction in the surrounding materials. The clusters from K_L are very broad and in 25% cases are splitting to 2-4. Simulated distributions are shown shaded. Comparison of the data with the GEANT (with GHEISHA package) simulation shows definite disagreement. The difference is due to completely incorrect cross sections for the low energy kaons, used by GHEISHA package.

Once the properties of the K_L clusters are understood, one can use the K_L cluster as a "tag" for K_S decays. Figures 8a shows the invariant mass distributions for events with two charged tracks opposite to K_L clusters.

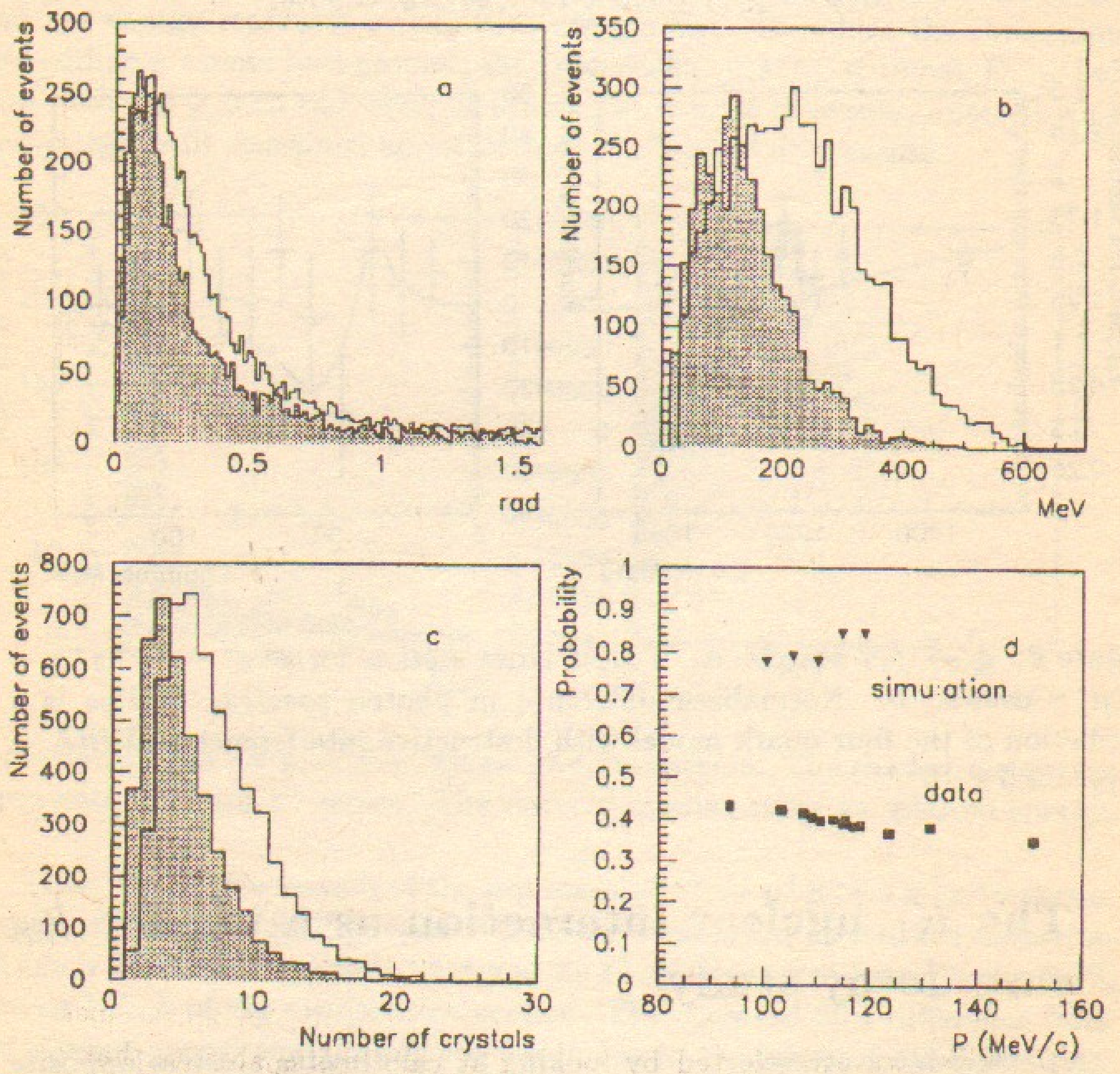

Figure 7: K_L interactions (dashed histograms – simulation): a. Space angle between calorimeter cluster and P_{mis}; b. Energy deposition of K_L clusters; c. Number of hit crystals (dashed histograms – simulation); d. Probability of K_L interactions in CsI.

The constrained fit applied to the decay $K_S \to \pi^+\pi^-$ extracted 32340 events and they were used for a normalization. The rest is shown in Figure 8a by the shaded histogram. In order to search for the $\pi^+\pi^-\gamma$ mode, the sample of events with an acollinearity angle less than 2.4 radians, $M_{inv} \leq 450 MeV/c^2$, and $E_\gamma \geq 50$ MeV has been taken.

Figure 8b shows the missing mass distribution for the two-track vertex, taking the K_S direction from the observed cluster, and the K_S momentum from the known center of mass energy, and assuming $\phi \to K_S K_L$. The 34.5 $\pm$ 8.0 events at zero mass, corresponding to the decay $K_S \to \pi^+\pi^-\gamma$ were found after fitting and background subtraction. The simulated ratio of the acceptances for $K_S \to \pi^+\pi^-$ and $K_S \to \pi^+\pi^-\gamma$ was found to be 2.49±0.30, giving a branching ratio $\text{Br}(K_S \to \pi^+\pi^-\gamma) = (1.82 \pm 0.49) \times 10^{-3}$.

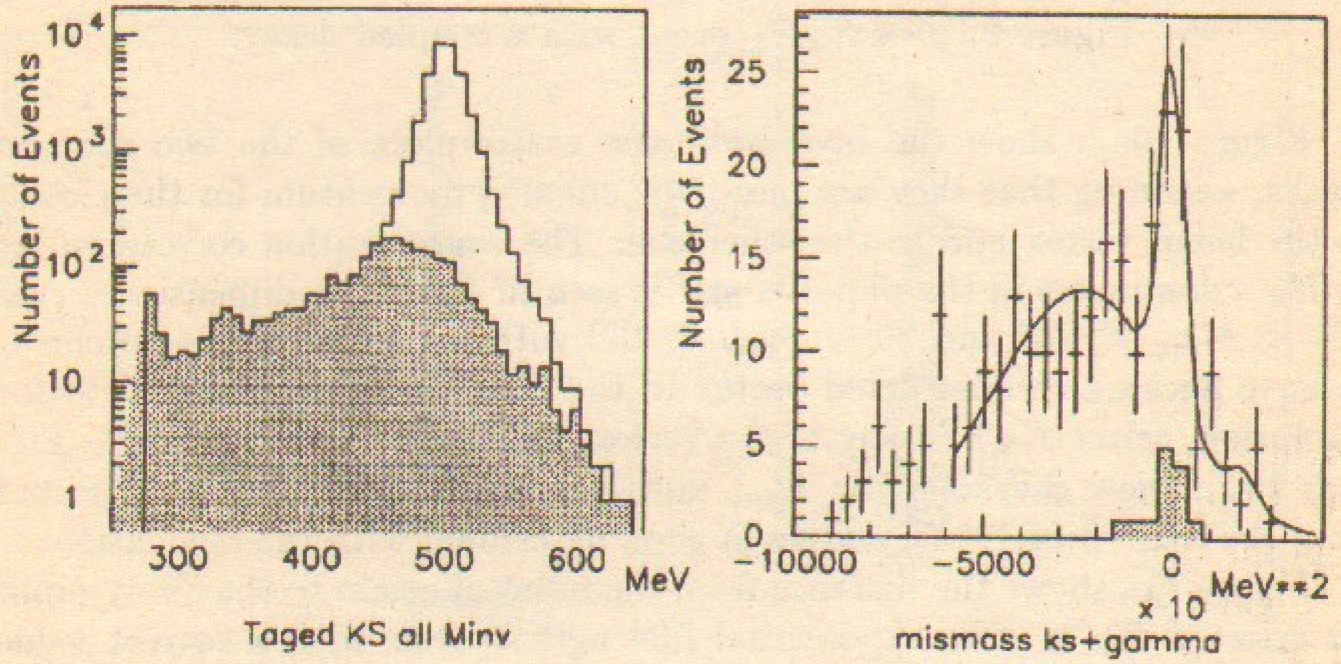

Figure 8: $K_S \to \pi^+\pi^-\gamma$ search: a. Invariant mass for vertices opposite clusters, events without K_S decaying to two pions are shown shaded; b. Missing mass in the frame of K_S, events with a real gamma found are shown shaded.

8 The $K_S K_L$ coupled decays study

The event candidates were selected from a sample in which two vertices, each of two opposite charged tracks, were seen. The example of this kind of events is shown in Figure 9.

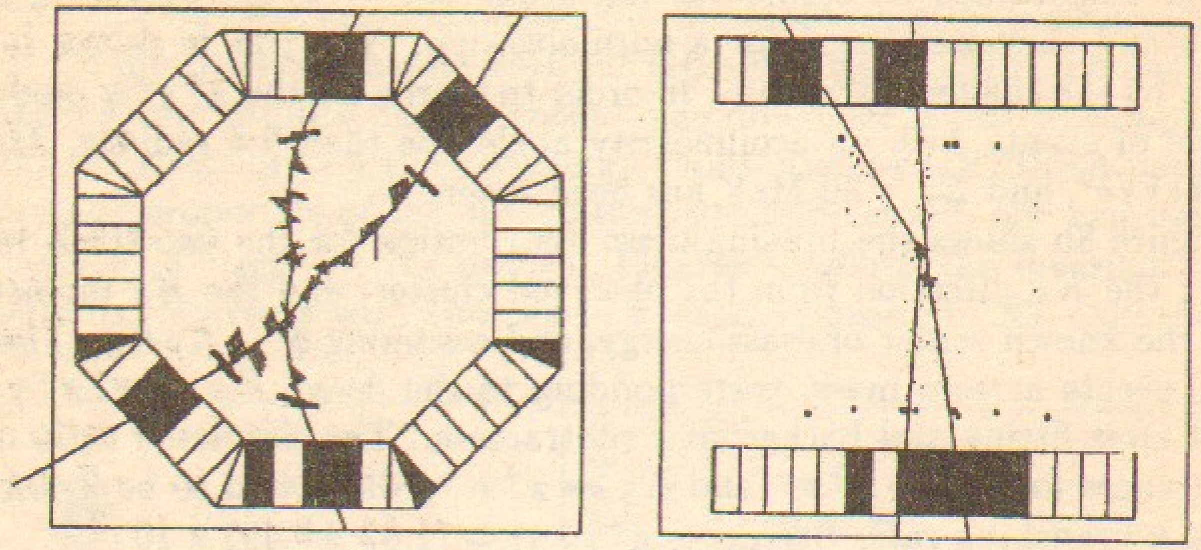

Figure 9: $\phi \to K_S K_L$ event with a coupled decay.

Figure 10a,b show the invariant mass scatterplots of the two charged tracks, assuming that they are pions, vs. missing momentum for the closest to the beam vertex and to the other one. The concentration corresponding to K_S's dominates in the plot 10a and is seen in 10b. Two dimensional cuts $470 < M_{inv} < 525$ and $90 < P_{mis} < 130$ with an additional requirement to have another reconstructed vertex in the P_{mis} direction within detector resolution, select K_S's in any of the vertex, leaving K_L's in the other. Figures 10c,d show characteristic M_{inv} and P_{mis} broad distributions, expected from the main 3-body K_L decays in good agreement with the simulation.

Figure 11a shows the distance from the point of origin to the decay point for selected K_S's. The exponential lifelength is seen with a correct value 0.58±0.03 cm with vertex position resolution 0.23 cm.

Figure 11b shows a vertex radius for K_L decays. A loss of efficiency for these events is seen, since the K_L events should be approximately flat in this spatial region corresponding to the very early part of the K_L lifetime. A significant peak with 59±16 events is also seen and is interpreted as nuclear interactions of K_L at the 0.077 cm Be vacuum beam pipe.

The histogram in Figure 11d shows the events consistent with the two pion decay at the K_L vertex, when the additional cut in M_{inv} was applied. With our resolution the suppression of the semileptonic K_L decays by a factor of 20 was expected, and these events dominated at all radii (only 2 CP violating K_L decays were expected with the present sample), except the beampipe, where 28±6 extra events survived. We interprete these events as regeneration of K_L into K_S.

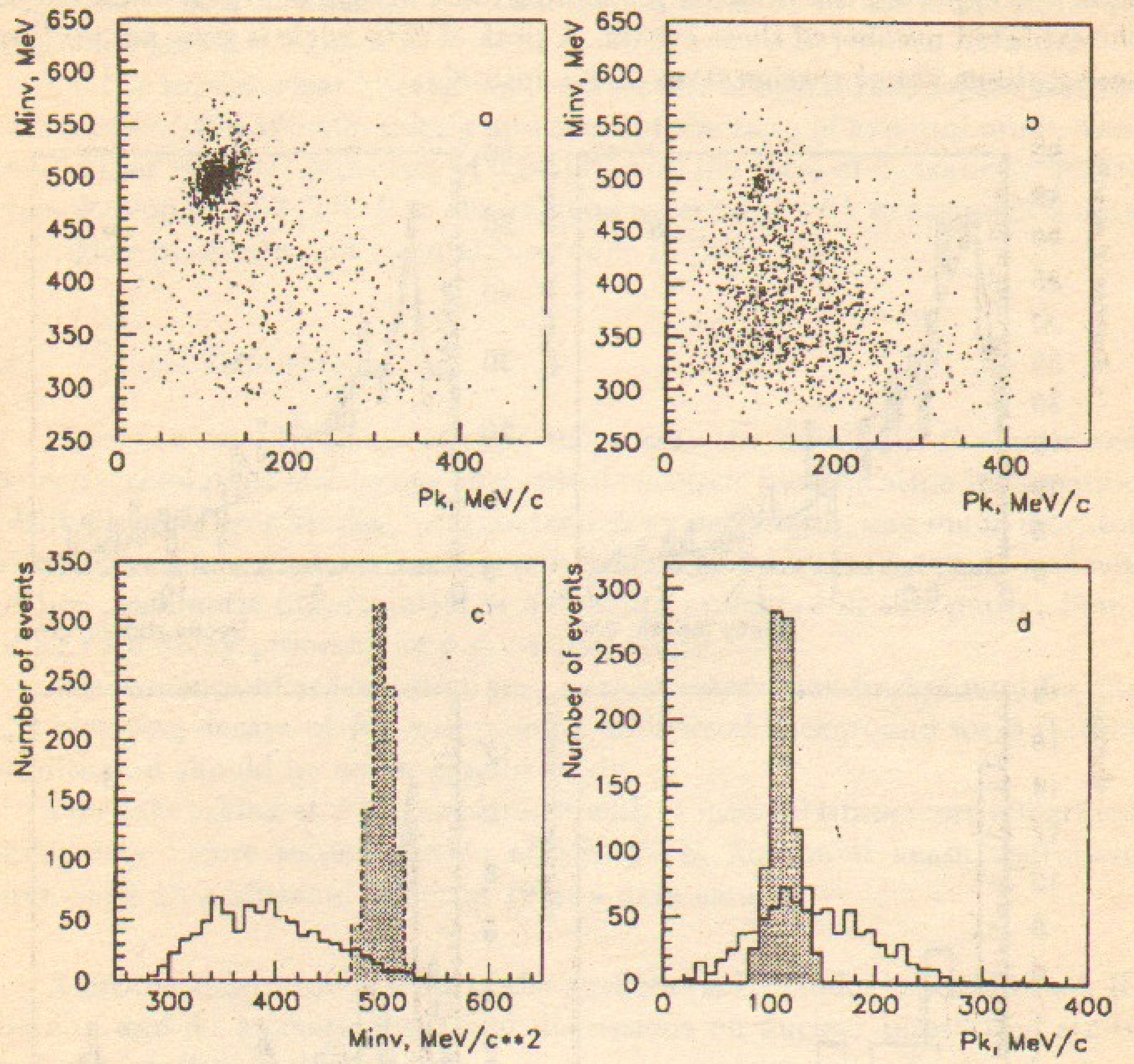

Figure 10: $K_S K_L$ coupled decays study: Invariant mass vs. missing momentum for 1-st (a) and 2-nd (b) vertex; c. Invariant mass for K_L and K_S (shaded) after K_S selection; d. Missing momentum for K_L and K_S (shaded) after K_S selection;

The rest of the peak events may be explained by Σ and Λ production, when two pions are detected and a recoil nucleon is unseen. With the applied M_{inv} cut, about 10% of these events may be interpreted as a pure two pion decay and should be extracted from the candidates for regenerated events.

Figure 11c shows the projected angle difference between the missing momentum direction and a line, connecting the K_L vertex with the beam position, for the events concentrated around the beam pipe. Dots with errors show the expected distribution for semileptonic decays of K_L, normalized to the expected number of these events. A peak at zero angle is seen, supporting expectations about regeneration of K_L into K_S.

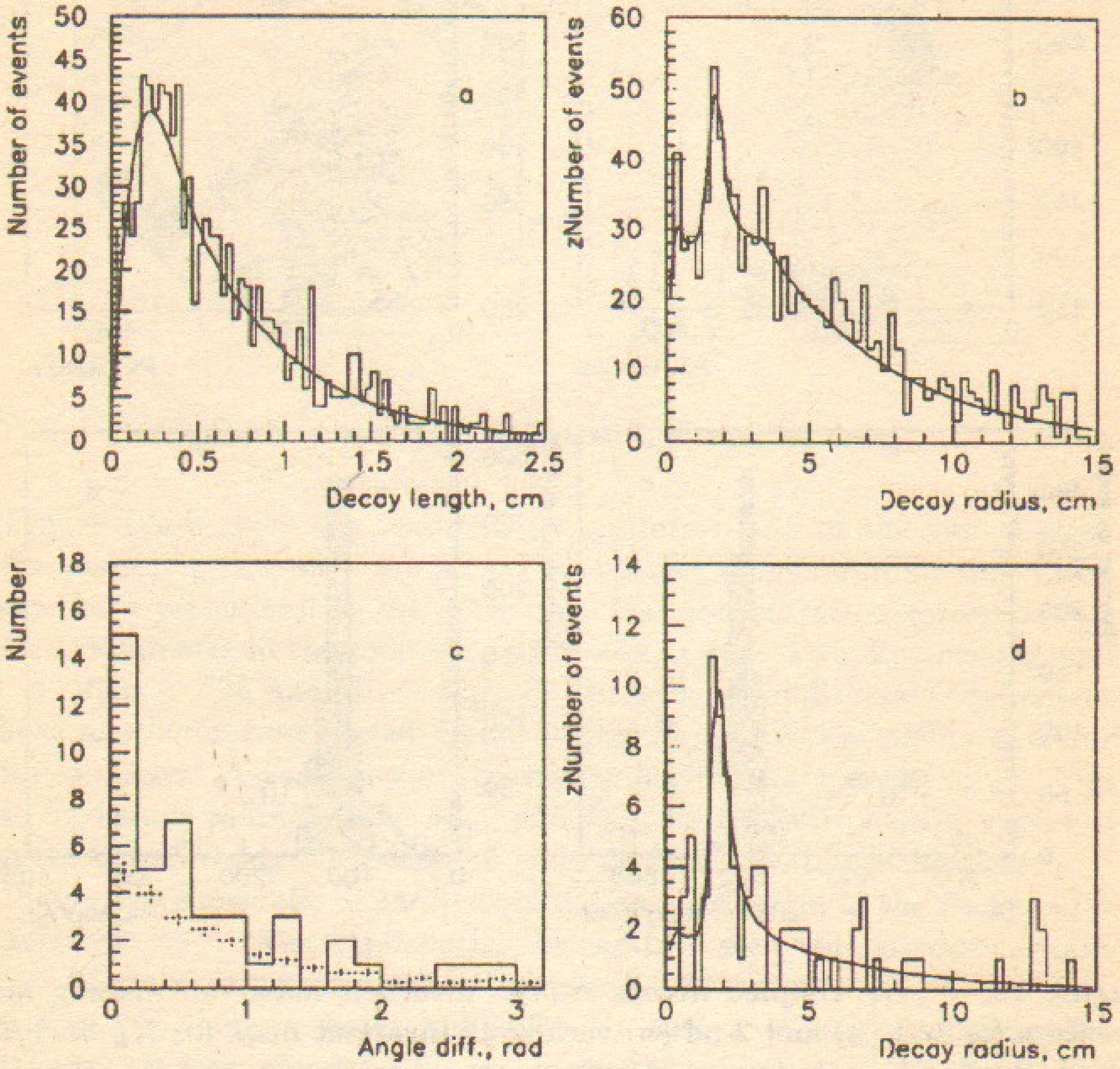

Figure 11: $K_S K_L$ coupled decays study: a. Decay length for K_S's; b. Decay radius for K_L's; c. Difference in angle of P_{mis} and vertex-beam line. d. Decay radius for K_L's after M_{inv} cut; Crosses are from K_L semileptonic decays.

Taking into account 10% corrections for DC mylar window and 10% from nuclear interaction processes background, the regeneration cross section is found to be $\sigma^{Be}_{reg} = 63 \pm 19$ mb. A visible nuclear interaction cross section (excluding regeneration) is found to be $\sigma^{Be}_{nucl} = 60 \pm 18$ mb.

The obtained regeneration cross section is in agreement with the calcula-

tions, performed in Frascati [24] that gave a value of 40 mb for 114 MeV/c long lived kaons.

For the total nuclear interaction cross section of neutral kaons, one can obtain a value 549±165 mb, taking into account the ratio of hyperon production to all other inelastic processes of 0.21 [25] and the ratio of inelastic to elastic cross section of 0.52 [24]. It is also in good agreement with experimental data for higher momenta and calculations, done in [24].

9 Conclusion

The next stage in this work is to process the data with the improved detector resolution and to use all available particle identification information (drift chamber amplitudes, calorimeter energy deposition, and muon detector hits). The detector reconstruction efficiency is under intensive study and will reduce systematic uncertainties in all results presented in this paper. Some other rare decay processes of ϕ are under study.

The presence of regeneration and nuclear interaction background for the CP-violating decays of K_L will pose an additional background for ϕ factory studies and should be under careful study.

The data taking at ϕ is also planned with at least 10 times more integrated luminosity before reconstruction of VEPP-2M for round beam operation, promising an additional factor of 10 in a data sample.

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