KLOE Note n. 202

The KLOE Luminosity Measurement

Achim Denig[a] and Federico Nguyen[b]

[a] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[b] *Dipartimento di Fisica dell'Università "Roma Tre" e Sezione INFN, Roma, Italy*

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Abstract

The precise knowledge of the luminosity provided by the accelerator DAΦNE is crucial for the precision measurement of the hadronic cross section performed with the KLOE detector and is of importance for many other KLOE analyses. For the luminosity measurement we use the KLOE detector itself using large angle Bhabha events. From the experimental point of view this process shows a very clean signature and is almost background-free. From the theoretical side, the cross section and the kinematical spectra are predicted with high precision. The measurement and the evaluation of the systematic errors are discussed in this document. A total precision of 0.6% has been achieved. This precision is limited by the theory error of 0.5%, while the experimental error contributes 0.3%.

1 Introduction

At DAΦNE no dedicated luminosity monitors at small polar angles are present like they have been used for instance at LEP. The luminosity is measured using the KLOE detector itself by counting the number $N_{\rm obs}$ of large angle Bhabha events in a given phase space region and normalizing this number to the effective Bhabha cross section $\sigma_{\rm eff}$:

$$\int \mathcal{L}\,{\rm d}t = \frac{N_{\rm obs} - N_{\rm bkg}}{\sigma_{\rm eff}} \ , \tag{1.1}$$

This effective cross section is evaluated by inserting in the detector simulation Monte Carlo `GEANFI` [1] an event generator which includes QED radiative corrections at a high level of precision. On the experimenal side background, $N_{\rm bkg}$, has to be subtracted and the validity of the simulated detector response (resolutions, efficiencies) has to be studied.

The main advantages of this method are:

i) the high theoretical accuracy by which the process is known;

ii) the clean event topology of the signal;

iii) the high statistics available for the process; for $\sigma_{Bhabha} \sim 430$ nbarn ($45^\circ < \theta_{e^\pm} < 135^\circ$), even at the lowest luminosities obtained in the 2001 data taking period, *i.e.* $\mathcal{L} \sim 3 \times 10^{31}$ cm^{-2} s^{-1}, the statistical error is $\delta\mathcal{L}/\mathcal{L} \sim 0.3\%$ in about two hours of data taking.

In the Born approximation and in the limit $m_e/\sqrt{s} \to 0$ the differential cross section with respect to the polar angle θ of the scattered electron is given by the following formula:

$$\frac{\mathrm{d}\sigma_{Bhabha}}{\mathrm{d}\cos\theta} = \frac{2\,\pi\alpha_{em}^2}{s}\left[\frac{1+\cos^2\theta}{2} - 2\,\frac{\cos^4\frac{\theta}{2}}{\sin^2\frac{\theta}{2}} + \frac{1+\cos^4\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}\right], \tag{1.2}$$

where the first term is due to the s-channel Feynman diagram, the third term is due to the dominating t-channel diagram and the second term is the s-t interference term. At DAΦNE energies the cross section is huge even at large polar angles as shown before. It is therefore convenient to use large angle Bhabha events, where the polar angle distribution is less steep than at small angles, which helps to minimize systematic effects due to the definition of the borders of the phase space region. Moreover, at large polar angles the machine background contamination from DAΦNE is much reduced. A downscaling of small angle Bhabha events at the trigger level had originally been foreseen as an option in order to minimize the DAQ rate at high luminosity. This option has however never been chosen in the past.

2 The Large Angle Bhabha Events (`LAB`)

In the KLOE online and offline environment several independent luminosity counters exist. In this document we will concentrate on the description of the most refined and precise selection, which is the so called Very Large Angle Bhabha `VLAB` selector. `VLAB` events are selected in two steps. First, Large Angle Bhabha events, `LAB`, are filtered using only calorimeter information [2]. In a second step a cleaner sample, called Very Large Angle Bhabha, `VLAB`, is selected including also tracking information [3] and tightening the angular cuts. It is important to notice that Bhabha events which did not pass the `LAB` selection are lost for the `VLAB` filter.

`LAB` Selection

The `LAB` selection, which serves as a prefilter for the `VLAB` events, is based on the following requirements:

1) At least two calorimeter clusters with an energy 300 MeV $< E_{clu} <$ 800 MeV must be present in the event.

2) For all the pairs of clusters fulfilling the energy requirement above, the polar angle acollinearity $\zeta = |\theta_{clu1} + \theta_{clu2} - 180^\circ|$ is calculated. The pair of clusters minimizing ζ is chosen and $\zeta_{\min} < 10^\circ$ is required.

3) These two clusters must satisfy the time cut $|t_{clu1} - t_{clu2}| < 4$ ns.

4) Both clusters have to be located at large polar angles $45^\circ < \theta_{clu} < 135^\circ$.

5) An additional cut on the three-dimensional angle between the 2 clusters is applied: $\cos\alpha > -0.975$, where $\cos\alpha = \dfrac{\vec{r}_{clu1} \cdot \vec{r}_{clu2}}{|\vec{r}_{clu1}|\,|\vec{r}_{clu2}|}$. This cut has been introduced in order to reject $e^+ e^- \to \gamma\,\gamma$ events, which are completely back-to-back.

6) At least 50 DC-hits have to be present: $N_{hits} \geq 50$.

The precision with which `LAB` events are selected is limited by the energy resolution of the calorimeter ($\sigma_E = 40$ MeV for $E_{clu} = 500$ MeV) . Especially in the case of an EmC response to electrons varying with time with respect to the photon response ($e^+e^- \to \gamma\gamma$ events are used for calibrating the energy) the borders of the energy cut (300 MeV $< E_{clu} <$ 800 MeV) lead to non-negligible systematic uncertainties. By adding information from the high resolution KLOE drift chamber [4] the precision can be considerably improved and the background of $\pi^+\pi^-$ and $\mu^+\mu^-$ events (1.2% contamination) is cut further. The `LAB` precision is of the order of 1%.

3 Selection of Very Large Angle Bhabha events (`VLAB`)

The `VLAB` selection adds information from the high resolution KLOE DC to the events preselected by the `LAB` counter. This tracking information is used to obtain a more precise control over the track momenta, while the information on polar angles is still taken from the EmC clusters. There is no need to use the tracks for the angular information since EmC clusters and tracks show similar angular resolutions (of the order of 1°) and hence no further systematics is introduced. The phase space cuts of `VLAB` events are a little tighter than in the `LAB` selection as can be seen in the following list of `VLAB` requirements:

1) For the two tracks $tr1$, $tr2$ with the largest number of associated hits to the tracks we require the track's point-of-closest-approach to the origin (PCA) to be close to the interaction point: $\sqrt{x^2_{pca} + y^2_{pca}} < 7.5$ cm and $|z_{pca}| < 15$ cm

2) If d is the spatial distance between the first hits of $tr1$ and $tr2$ we require $d > 50$ cm. This cut rejects a contamination from the process $e^+\,e^- \to \gamma\,\gamma \to \gamma\,e^+\,e^-$, where the e^+e^- pair in the final state results from photon conversion (e.g. at the inner wall of the DC). For illustration the signature of such an event is displayed in Fig. 1.

3) The two selected tracks $tr1$ and $tr2$ are required to have opposite signs of curvature.

4) For both tracks the momentum cut $p \equiv |\vec{p}\,| \geq 400$ MeV is applied.

5) For the 2 clusters preselected by the `LAB` filter a tighter cut on the polar angle is applied: $55^\circ < \theta < 125^\circ$ ($\theta \equiv \theta_{clu}$ hereafter).

6) Also the cut on the polar angle acollinearity for the 2 `LAB` clusters is further tightened: $\zeta < 9^\circ$.

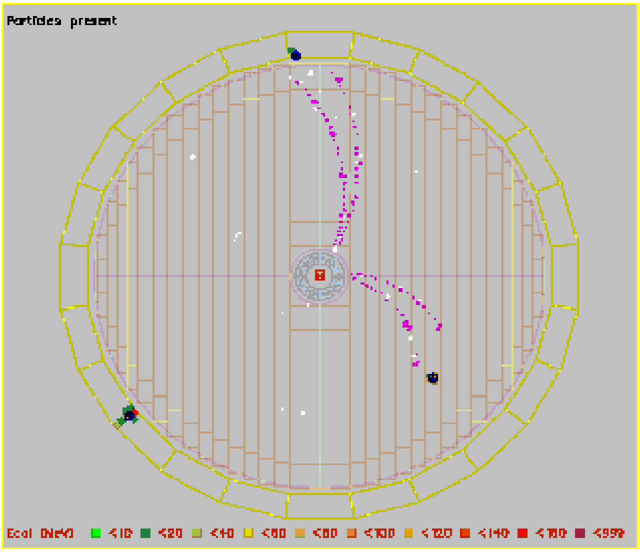


Figure 1: *An event of the type $e^+ e^- \to \gamma\gamma$ with one of the photons converting into an electron-positron pair: $e^+ e^- \to \gamma\gamma \to \gamma\ e^+ e^-$. This background process is removed by requiring the first hits of the 2 tracks to have a minimum distance $d > 50$ cm.*

4 The VLAB cross section

The MC generators Bhagenf [5, 6] and Babayaga [7] have been interfaced with GEANFI and used for evaluating the effective cross section as well as for estimating the systematic uncertainties. After applying the VLAB selection we find an agreement to better than 0.1% between the cross sections evaluated from the two generators, including the reconstruction efficiency:

$$\begin{aligned} \texttt{Babayaga}: \quad \sigma_{\text{eff}} = & \quad (431.0 \pm 0.3) \quad \text{nbarn} \,, \\ \texttt{Bhagenf}: \quad \sigma_{\text{eff}} = & \quad (430.7 \pm 0.3) \quad \text{nbarn} \,. \end{aligned}$$

The cross section from Babayaga before the simulation of the detector response is $\sigma = 472.10 \pm 0.09$ nbarn.

The systematic theoretical uncertainty claimed by the authors is 0.5% in both cases and the error given in the above cross section is due to the limited Monte Carlo statistics. The two event generators Bhagenf and Babayaga have been compared with two further theoretical event generators: the Bhwide code by S. Jadach [8] and the Novosibirsk Bhabha generator Mcgpj [9]. For this comparison we applied the kinematic VLAB requirements on the generated momenta, but no detector smearing effects are simulated. Before coming to the result the main features of the four codes are summarized in the following.

Bhagenf

- complete $\mathcal{O}(\alpha)$ radiative corrections; in particular the process $e^+ e^- \rightarrow e^+ e^- \gamma$ is simulated,
- contains the ϕ exchange Feynman diagram;

`Babayaga 3.5`

- contributions from multiphoton emission are obtained in the Parton Shower approach by a numerical evaluation of the structure functions,
- each initial or final $e^{\pm}$ is allowed to emit up to four photons,
- contains the ϕ exchange Feynman diagram;

`Bhwide 1.04`

- complete $\mathcal{O}(\alpha)$ radiative corrections,
- exact phase space integration,
- collinear and infrared corrections taken into account to all orders
- no limit on the number of soft photons and a maximum of three real photons per event;

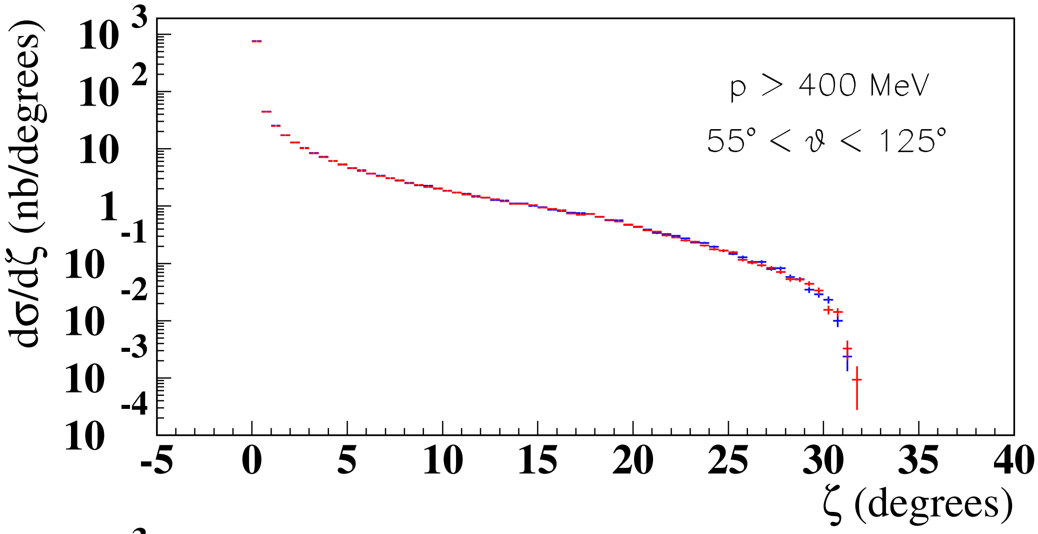
`Mcgpj`

- complete $\mathcal{O}(\alpha)$ radiative corrections,
- higher order corrections taken into account from analytical solutions of the structure functions,
- corrections from $e^+ e^- \rightarrow e^+ e^- \gamma$.

The computed `VLAB` cross sections for the last three generators are shown in the table below. Notice again that these numbers are obtained without considering detector smearing effects and therefore the results are considerably different from the effective `VLAB` cross section presented before, where a full detector simulation has been performed.

MC code	σ (nb)
`Babayaga`	459.4 ± 0.1
`Mcgpj`	457.4 ± 0.1
`Bhwide`	456.2 ± 0.1

Contributions from the ϕ decay and vacuum polarization effects, which are simulated in all codes, have been switched off. In this way only the radiative effects due to pure ISR and FSR are considered, which is actually the aim of this comparison. All three generators are in good agreement on the level below one percent. The maximum difference, 0.7%, between



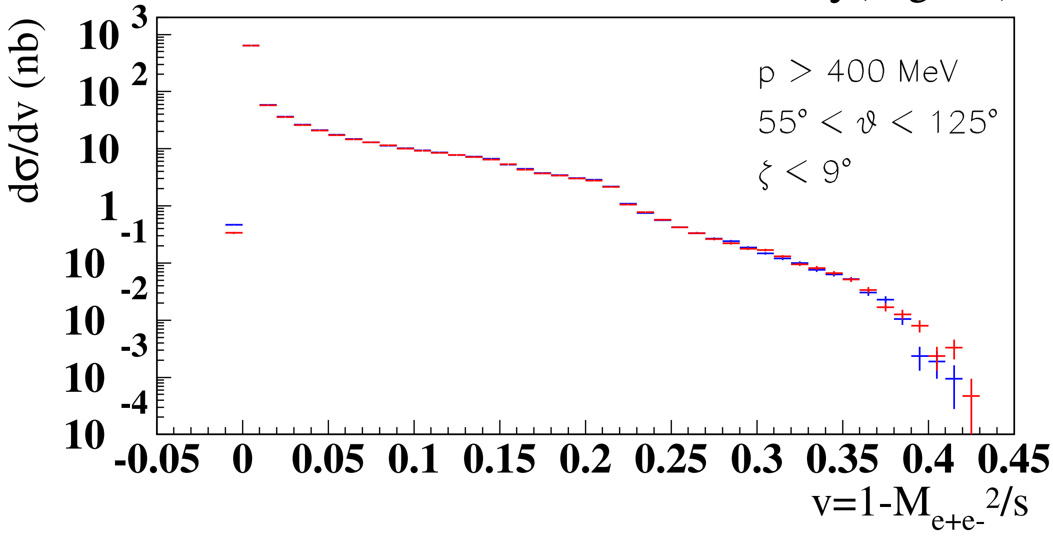


Figure 2: *Above: comparison between* `Babayaga` *(blue points) and* `Bhwide` *(red points) for the differential cross section with respect to the acollinearity (after momentum and polar angle cuts). Below: comparison between* `Babayaga` *and* `Bhwide` *for the differential cross section with respect to the missing energy fraction (after momentum, polar angle and acollinearity cuts).*

`Babayaga` and `Bhwide`, is taken as a confirmation of the systematic uncertainty claimed by the authors of `Babayaga` and `Bhagenf` and we take their error of 0.5% as the theory uncertainty of our luminosity measurement. Moreover, we have compared the differential distributions for the relevant quantities used in the large angle Bhabha measurement. Especially the acollinearity and the missing energy fraction $\mathrm{v} = 1 - \mathrm{M}^2_{e^+e^-}/s$ are very sensitive to the difference in the treatment of radiative effects. Also in this case we find excellent agreement as can be seen in Fig. 2.

5 Evaluation of systematic effects for `VLAB` events

Since the effective `VLAB` cross section is obtained from Monte Carlo, it is important to check that the resolutions and efficiencies of the selection are well reproduced by the detector simulation, and to correct for any mismatch between data and Monte Carlo. In particular a difference in the resolution of the kinematic variables can give rise to systematic effects at the borders of the chosen phase space. The studies presented in this document refer to the data sample collected in 2001 since these data have been used for the measurement of the pion form factor [11].

5.1 Acceptance studies

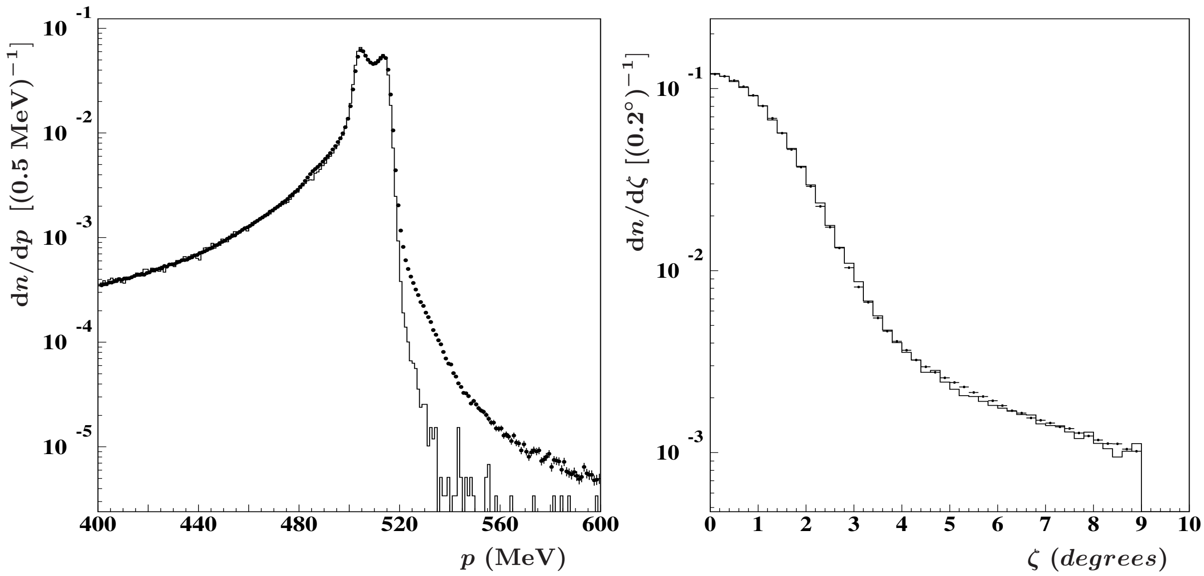


Figure 3: *Left: the comparison between data (• points) and Monte Carlo (solid line) histograms for the momentum of the tracks, normalized to the total number of events. Right: the same comparison for the acollinearity ζ.*

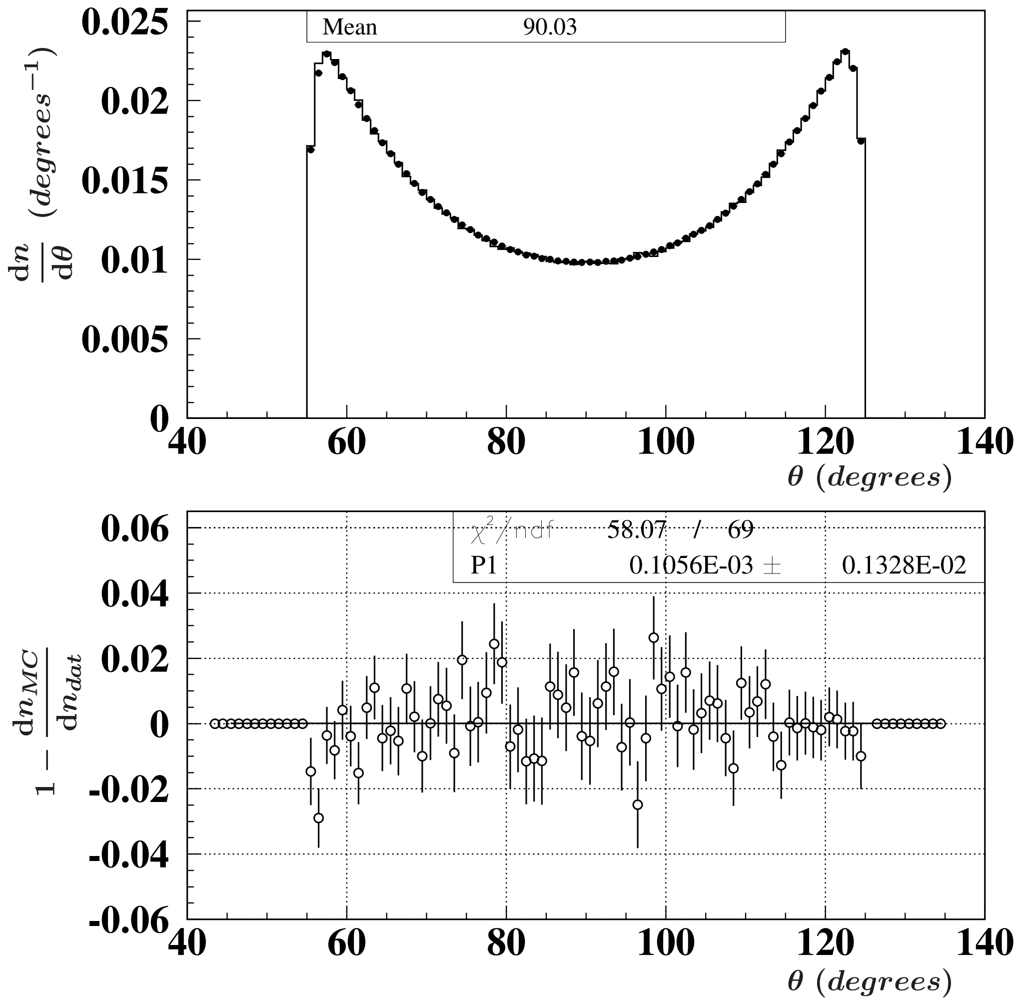


Figure 4: *Above: the comparison between data and Monte Carlo histograms for the polar angles of* $e^{\pm}$*, normalized to the total number of events. Below: the relative difference between the two shapes plotted in the upper figure and the result of fitting this difference by a constant term.*

Fig. 3 shows the comparison data versus Monte Carlo for momentum, p, and acollinearity, ζ, distributions [1].

In both variables the cuts, $p > 400$ MeV and $\zeta < 9°$, occur far from the peak, where the agreement is very good and furthermore in a region where the variable has a smooth behaviour. Thus, any systematic error from the cuts on p and ζ is considered as negligible.

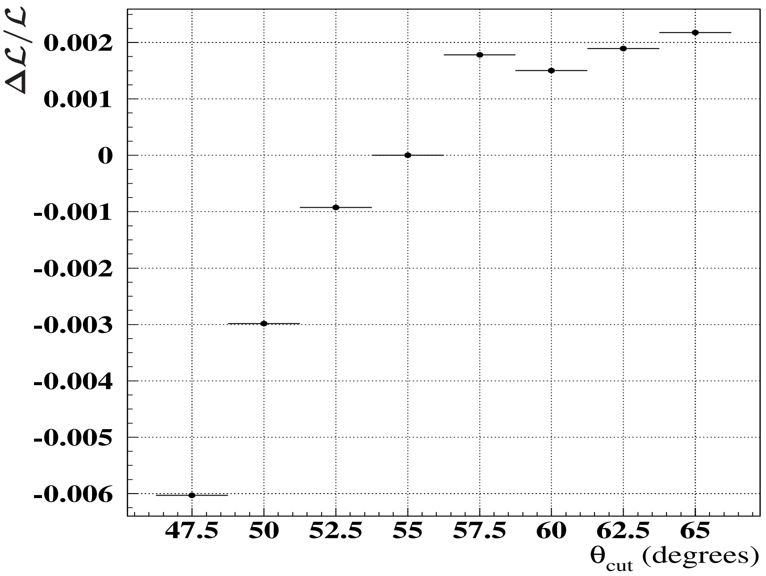


Figure 5: *Relative variarion of the luminosity as a function of the cut value for the polar angle.*

The difference seen at high particle momenta is due to non-Gaussian tails in the DC reconstruction which are not simulated in MC. However, since no high-momentum cut is applied in the selection, no systematic effect arises due to this small effect.

The situation is different for the requirements on the polar angle, θ. In this case the cut, $55° < \theta < 125°$, is applied in a region with a very steep rise of the distribution, with a-priori possible large systematic effects. Fig. 4 shows the comparison of the data histogram with the simulated one, both normalized to the total number of events. The overall agreement is very good. The polar angle resolution from the measurement of the EmC clusters is $\approx 1°$. Therefore a net gain or loss of events due to a systematic difference between the polar angle resolution in data and the one predicted by Monte Carlo, can only occur from the bins very close to the borders. For an estimate of this effect, the MC and data histograms are normalized to coincide in the region $65° < \theta < 115°$, then the relative difference at the borders is computed:

$$\frac{N^{dat}_{[55:65]+[115:125]} - N^{MC}_{[55:65]+[115:125]}}{N^{dat}_{TOT}} = -\frac{42190}{16668072} = -(0.25 \pm 0.03)\% \ , \qquad (5.1)$$

[1]In the following we will implicitly refer to the Monte Carlo generator `Babayaga`.

with $N^{dat}_{[55:65]+[115:125]}$, $N^{MC}_{[55:65]+[115:125]}$ being the number of events with $55° < \theta < 65°$ or $115° < \theta < 125°$, in the data and Monte Carlo histograms respectively, and N^{dat}_{TOT} being the total number of events in the data histogram. The value in eq.(5.1), $\Delta_{accept} = (-0.25 \pm 0.03)\%$, is used both as the systematic uncertainty due to effects at the borders of the phase space region, and as the relative correction to the MC effective cross section.

The estimate in eq.(5.1) is confirmed by looking at the relative change in the luminosity as a function of the cut value for the polar angle. With the following definitions:

$$\begin{aligned}
\frac{\Delta\mathcal{L}}{\mathcal{L}} &= \frac{\Delta N}{N} - \frac{\Delta\sigma}{\sigma} \, , \\
\frac{\Delta N}{N} &= \frac{N_{\mathtt{VLAB}}(\theta_{\rm cut} < \theta < 180° - \theta_{\rm cut})}{N_{\mathtt{VLAB}}(55° < \theta < 125°)} - 1 \, , \\
\frac{\Delta\sigma}{\sigma} &= \frac{\sigma_{\rm eff}(\theta_{\rm cut} < \theta < 180° - \theta_{\rm cut})}{\sigma_{\rm eff}(55° < \theta < 125°)} - 1 \, ,
\end{aligned}$$

the behaviour of $\Delta\mathcal{L}/\mathcal{L}$ as a function of $\theta_{\rm cut}$ is evaluated and shown in Fig. 5. Even for a 5° difference in the angular region selected (compared with an angular resolution of 1°) the luminosity estimate changes by +0.003 or -0.002 relative, which is consistent with the stated error.

Moreover, the border effect is attenuated with increasing $\theta_{\rm cut}$, then working at higher angular cuts, say $\theta_{\rm cut} = 60°$, could be a good idea for a smaller systematic uncertainty.

5.2 Tracking efficiency

To evaluate the tracking efficiency we can use `LAB` events because no tracking information is used in selecting this sample[2]. For the purpose of estimating the tracking efficiency we select a tagging track and look for the presence of the second candidate track. We ask for a subsample of `LAB` events with the following event topology:

- For the three-dimensional acollinearity of the two `LAB` clusters we require: $\cos\alpha > -0.9$. In this way we reject radiative Bhabha events, in which either a FSR or an ISR photon, rather than an electron (positron), is selected as one of the `LAB` clusters. Those radiative events with very high photon radiation could mimic a tracking inefficiency while in reality one of the tracks has very low momentum and therefore cannot be selected.
- One track is required to have $p_{\rm tag} > 400$ MeV and one of the two `LAB` clusters has to be associated to it. This track is called the tagging track.
- The second `LAB` cluster must have an energy $E_2 > 300$ MeV, which implies that the second track (the one we are looking for in the efficiency evaluation) has momentum $p \gtrsim 400$ MeV. Since we want to study the tracking efficiency of `VLAB` events (*i.e.* events with $p > 400$ MeV), we are not interested in low momentum tracks.

In particular this guarantees that the Bhabha tracks lie in a restricted range of polar angles, similar to that used in the selection in the selection of `VLAB` events.

[2] The requirement of at least 50 DC Hits in the `LAB` selection can be neglected for the following since it does not introduce any bias to the efficiency measurement.

Out of this subsample we define as a good tracking Bhabha event one that satisfies the following requirements:

1) At least one second candidate track arising from the interaction point must exist and this track must be one of the two with the largest number of associated hits.

2) This candidate track is required to have a momentum $p_{\rm cand} > 400$ MeV and opposite charge with respect to the tagging track.

3) A further cut on the spatial distance between the first hits of tagging and candidate track $d > 50$ cm is applied.

An event is counted as having been successfully reconstructed if a candidate track according to the above requirements is found. We have systematically varied the values for d, $p_{\rm tag}$, E_2 and $p_{\rm cand}$ and have found the tracking efficiency essentially unaffected by these variations. Comparing the ϵ_{track} values for data and for Monte Carlo we find a good agreement:

$$\epsilon^{dat}_{track} = (99.824 \pm 0.005)\%, \qquad \epsilon^{MC}_{track} = (99.764 \pm 0.011)\% \ ,$$

where the errors are statistical.

The relative difference $\Delta_{track} = (6.0 \pm 1.2) \times 10^{-4}$ is taken as the systematic uncertainty due to the tracking efficiency in the luminosity measurement.

5.3 Clustering efficiency

A dedicated filter using only tracking information has been developed for selecting an unbiased control sample for the clustering efficiency measurement. In order to obtain a background-free Bhabha sample we have developed a selection asking for 2 tagging tracks with the following requirements:

– One and only one vertex located in $|\vec{r}_V| < 5$ cm is required to be present in the event.

– Two and only two tracks are present in the event and both tracks are connected to this vertex.

– We require the two selected tracks to be at large polar angles: $50^\circ < \theta < 130^\circ$, where the polar angle of the track is measured at the vertex position.

– Both tracks have to fulfill the following requirements on the spatial position of the first hit (FH) and last hit (LH) of the track in the DC: $|\vec{\rho}_{FH}| = \sqrt{x^2_{FH} + y^2_{FH}} < 40$ cm and $|\vec{\rho}_{LH}| = \sqrt{x^2_{LH} + y^2_{LH}} > 180$ cm. These requirements exclude splitted tracks.

– The invariant mass M_{ee} (under the hypothesis of a Bhabha event) of the two tracks has to be close to the ϕ mass: 1017.5 MeV $< M_{ee} <$ 1021.5 MeV.

– Finally we add a requirement on the track mass: $m_{trk} < 90$ MeV, where m_{trk} is the reconstructed mass of a charged track under the hypothesis of a final state made up of two charged particles of the same mass and opposite charge plus one photon. The formula from which m_{trk} is extracted reads as:

$$\sqrt{s} = \sqrt{|\vec{p}_1|^2 + m_{trk}^2} + \sqrt{|\vec{p}_2|^2 + m_{trk}^2} + |\vec{p}_1 + \vec{p}_2 - \vec{p}_\phi| \ ,$$

where $\vec{p}_1$, $\vec{p}_2$, $\vec{p}_\phi$ are respectively the the reconstructed momenta of the two tracks and the ϕ momentum, given by a run average measured from `VLAB` events.

The last two cuts in the above list efficiently remove background from $\mu^+\mu^-$ and $\pi^+\pi^-$ events. Among the tracks selected this way, we check if there are two clusters satisfying:

1) $|\vec{\rho}_{LH} - \vec{\rho}_{clu}| < \Delta\rho = 40$ cm, $\vec{\rho}_{clu}$ being the position of the cluster in the x-y plane. With this cut we ask the cluster to be associated to one of the two tracks.

2) $||\vec{p}_{tr}| - E_{clu}| < \Delta E = 210$ MeV, Since the kinematic cut on M_{ee} for the tracks select events with both tracks having ≈ 510 MeV, this cut selects clusters with $E_{clu} \gtrsim 300$ MeV, which is the cut value chosen in the `LAB` filter.

3) $|t_{clu1} - t_{clu2}| < \Delta t = 4$ ns.

The clustering efficiency is defined as the fraction of events in the control sample which fulfills these requirements. Comparing the clustering efficiency, $\epsilon_{cluster}$, between data [3] and Monte Carlo we obtain the following values:

$$\epsilon_{cluster}^{dat} = (99.58 \pm 0.11)\%, \qquad \epsilon_{cluster}^{MC} = (99.65 \pm 0.02)\% \ . \tag{5.2}$$

We have systematically changed the cut values $\Delta\rho$, Δt and ΔE in reasonable ranges. The result for the clustering efficiency has been found stable under these variations and no significant change of the result has been found.

We found that a part of the very small inefficiency in data can be understood as a consequence of cluster splitting, in which a genuine Bhabha cluster of $E \simeq 500$ MeV is actually split into two clusters of $E < 300$ MeV, neither of them surviving the cut on ΔE. We have found out that almost all cluster splitting events arise from the same spatial position, *i.e.* from one malfunctioning channel in the EmC. The size of this unexpected loss has been estimated on a sample of data runs and found to be stable in time. An average correction of $\delta_{split} = (0.135 \pm 0.007)\%$, due to this specific EmC channel, has been applied to $\epsilon_{cluster}^{dat}$, yielding the following difference between data (after the correction) and Monte Carlo:

$$\epsilon_{cluster}^{dat} \rightarrow \tilde{\epsilon}_{cluster}^{dat} = \epsilon_{cluster}^{dat} + \delta_{split} \, , \qquad \Delta_{cluster} = \tilde{\epsilon}_{cluster}^{dat} - \epsilon_{cluster}^{MC} = (0.07 \pm 0.11)\% \ ,$$

Since both data and Monte Carlo agree within the statistical error, we take the value for the error of 0.11% as the systematic uncertainty in the cluster efficiency.

5.4 Background contamination

Given the cut value of the track momentum, $p \geq 400$ MeV, the only relevant background processes are $e^+ e^- \rightarrow \mu^+ \mu^-$ and $e^+ e^- \rightarrow \pi^+ \pi^-$ The estimate of background is based

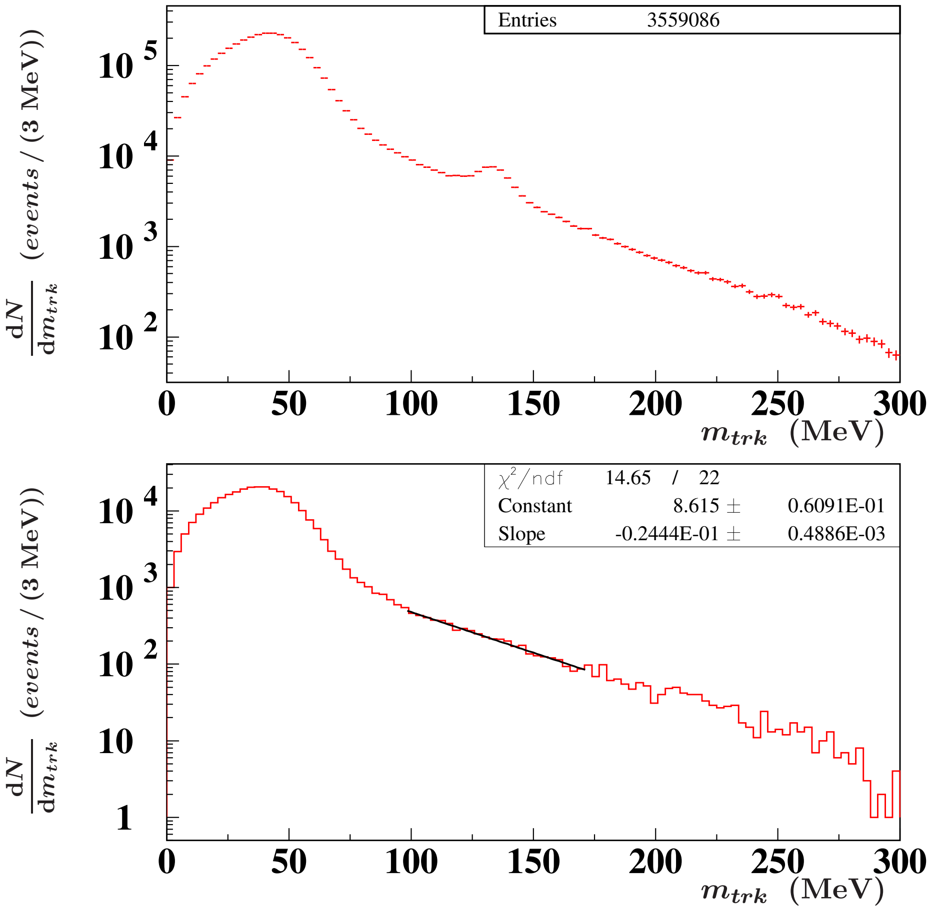


Figure 6: *Above: the m_{trk} distribution for a sample of data selected according to the* `VLAB` *procedure. Below: the same distribution generated by the Monte Carlo code* `Babayaga` *interfaced with* `GEANFI`*.*

on the track mass variable, m_{trk}. The upper plot in Fig. 6 shows the m_{trk} distribution for a data sample selected by the `VLAB` procedure. Besides Bhabha events, clustered at low values of m_{trk}, the only significant structure is the peak associated with $\pi^+\pi^-$ events around $m_{trk} \simeq 135$ MeV. There is no evidence for background from di-muon events because of the veto of cosmic events (see section 5.5 below). We have developed two methods in order to measure the absolute amount of background contamination. Both methods are based on data. The first strategy consists in fitting the track mass distribution both for signal and background, while in the second method we use a particle identification tool based on a likelihood method for discriminating pions (muons) from electrons.

5.4.1 Approach 1: fitting the m_{trk} spectrum

The lower plot in Fig. 6 shows the m_{trk} distribution as simulated by MC (the `Babayaga` event generator interfaced with `GEANFI`). The range $m_{trk} \in [100, 170]$ MeV is well described by an exponential function. Then, we fit the data m_{trk} spectrum in the same range with a function consisting of a Gaussian (background) plus an exponential function (signal), assuming that background gives rise to a Gaussian peak in the track mass distribution at m_π. We obtain a sufficiently good fit of the track mass distribution, as can be seen in Fig. 7 (upper plot). The background yield after having subtracted the exponential function is shown in the lower plot. The relative amount of background is given by dividing the background yield by the total number of `VLAB` events:

$$\frac{N_{bkg}}{N_{tot}} = (0.541 \pm 0.004)\ \% \ . \tag{5.3}$$

5.4.2 Approach 2: pion - electron separation

The `Likelihood` function [12] is a particle identification tool, which allows to discriminate pions from electrons on an event-by-event basis by means of calorimetric information. The function has been developed in connection with the measurement of the pion form factor at KLOE and has an efficiency of 98% in distinguishing pions from electrons. The function exploits the systematic differences in the shape of energy deposit and in the time of flight of clusters associated to tracks. In particular, the energy deposit in the first plane versus the energy in the last plane of the calorimeter shows a significant difference between pions and electrons. The `Likelihood` function gives an estimate of the particle type (pion or electron) for each track. It has been shown that muon tracks are generally identified as pions by the function.

In order to measure the background content in the `VLAB` sample, the likelihood function has been applied to data and we look at the track mass distribution for events for which at least one track has been identified by the `Likelihood` function as a pion. Fig. 8 shows the m_{trk} distribution for these events. The event yield of background events obtained like this looks very similar to the one obtained in the previous approach. The fraction of background events estimated with this method is:

$$\frac{N_{bkg}}{N_{tot}} = (0.623 \pm 0.015)\% \ , \tag{5.4}$$

[3] The runs in 2001 with a low level of machine background have been chosen for this estimate.

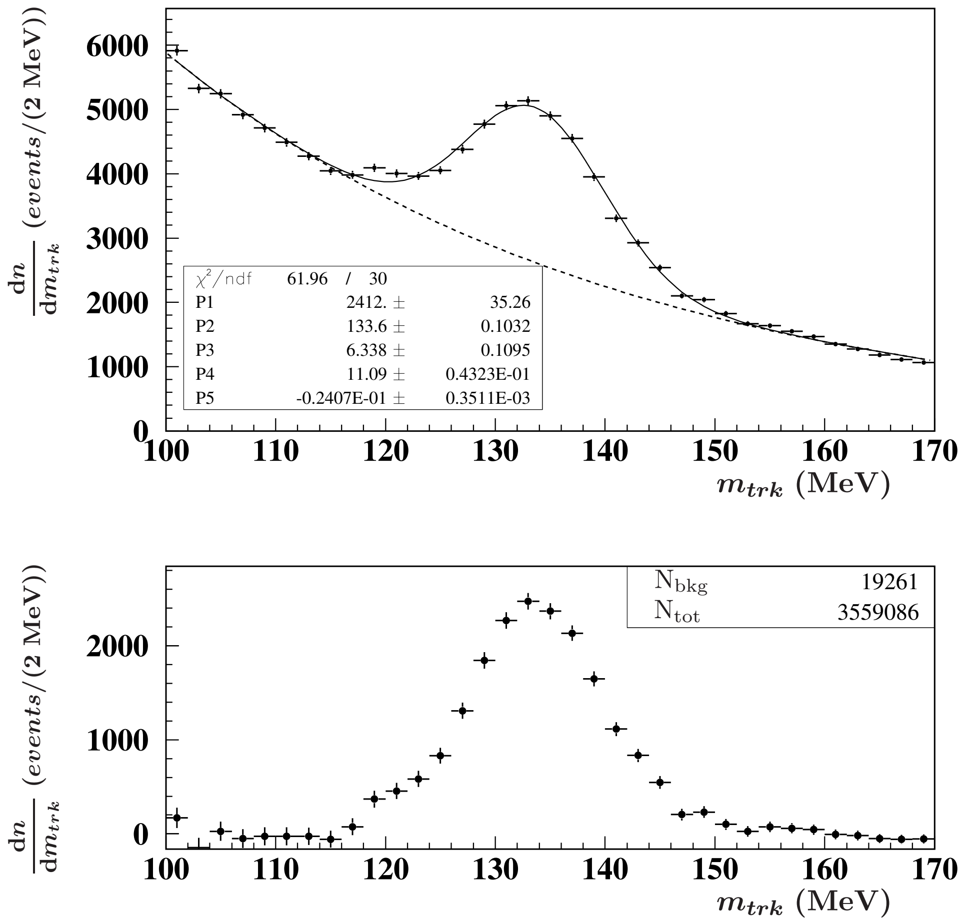


Figure 7: *Above: the m_{trk} spectrum from data (points), the result of the fit with an exponential plus a Gaussian (solid line), and only the exponential (dashed line). Below: the m_{trk} spectrum from data after the subtraction of the exponential.*

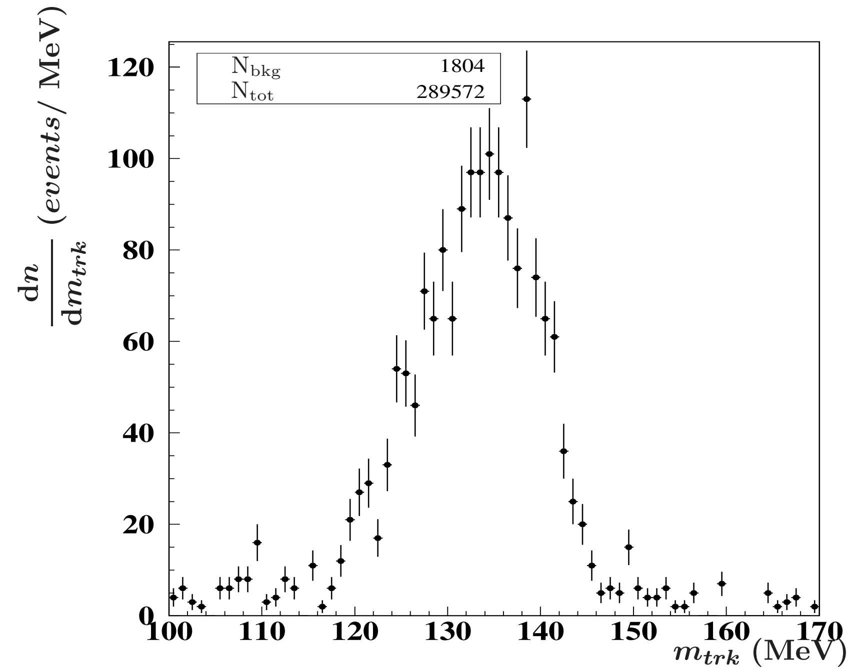


Figure 8: *The m_{trk} distribution for a sample of* `VLAB` *events, for which at least one track has been identified as a pion.*

where the error is of statistical nature.
Comparing these results with the one from the previous approach, eq.(5.3), we find a weighted average of $N_{bkg}/N_{obs} = (0.546 \pm 0.004)\%$, which is taken as the background contamination in the `VLAB` event sample. For the systematic uncertainty of the method we take the difference between the two methods: $\Delta_{bkg} = (0.082 \pm 0.016)\%$.

5.5 Cosmic veto inefficiency

Cosmic ray events are vetoed at KLOE at the trigger level [10], in the Barrel–Barrel or Endcap–Barrel configuration, by means of an algorithm looking for two energy releases larger than 30 MeV in the most external plane of the calorimeter. A fraction of these events is flagged and recorded for calibration purposes with a downscaling factor of 5. Running the `VLAB` selection on these downscaled events, we estimate the total fraction of `VLAB` events lost due the cosmic veto. The inefficiency is stable in time and gives rise to a loss of events in the order of 0.1% for the downscaled events. An averaged total correction of $1 - \epsilon_{cosmic} = 4 \times (0.100 \pm 0.008)\% = (0.40 \pm 0.03)\%$ therefore has to be applied to data[4].

[4]Considering that there is a downscaling factor of 5 and that we do not cut on the cosmic veto flag in the standard `VLAB` selection.

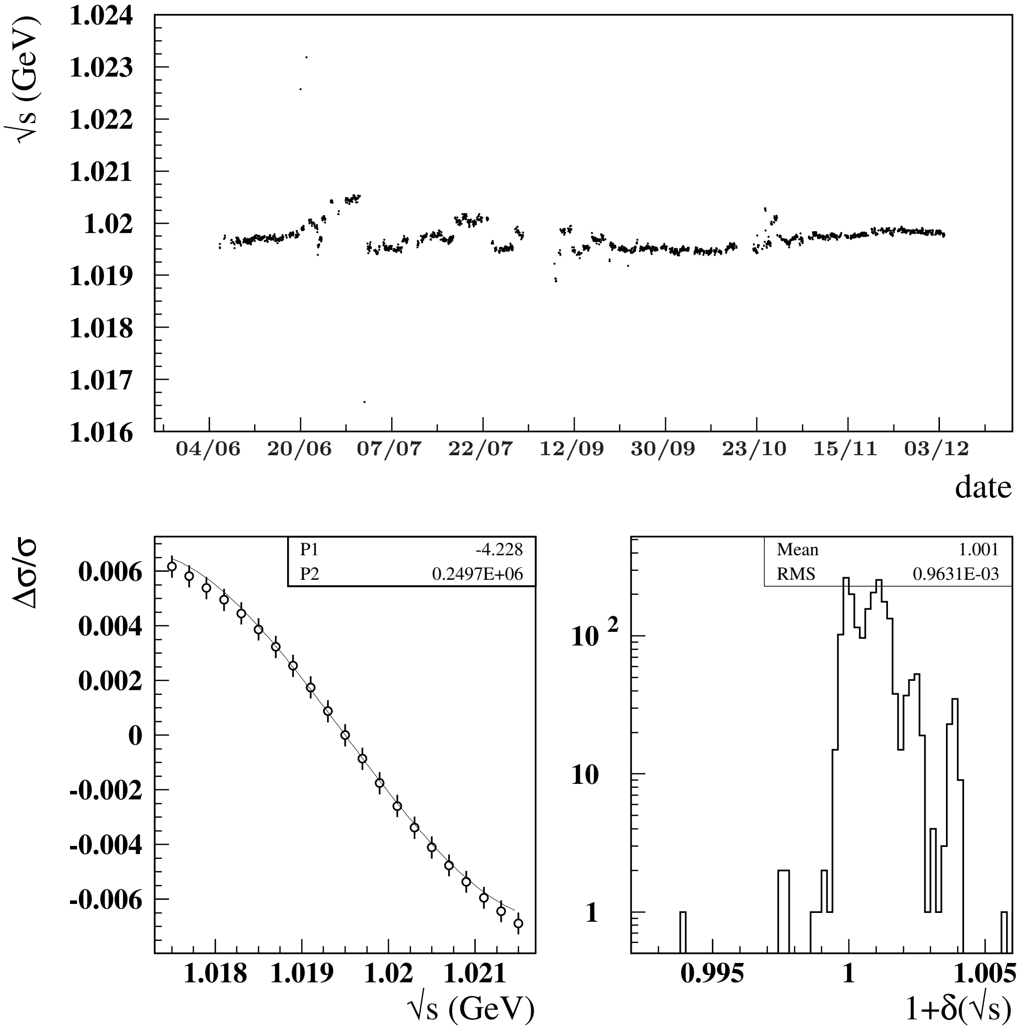


Figure 9: *Above: the distribution of the measured* $\sqrt{s}$ *values as a function of the run of data taken in 2001. Below left: the relative change in the cross section as a function of* $\sqrt{s}$*, as evaluated from the code* **Babayaga** *and parameterized as* $\Delta\sigma/\sigma = \mathrm{P1}\,(x - 1.0195) + \mathrm{P2}\,(x - 1.0195)^3$*. Below right: the distribution of the multiplicative correction applied to the luminosity, for the above data runs.*

The effect of the cosmic veto is not well simulated by the MC (it actually overestimates the inefficiency) and therefore we do not consider the cosmic ray veto flag in the MC when calculating the effective `VLAB` cross section. In this case the correction described above can be applied directly to data and we do not have to correct for the difference between data and MC.

5.6 Run-by-Run corrections

The acceptance and efficiency studies discussed so far did not show any variation in time and therefore they are applied constantly to each run. In the following we are discussing two corrections which require to be studied on a run-by-run basis because they depend on the actual run conditions. As we will see the time dependence for both corrections came out to be very small.

5.6.1 Variations of the center-of-mass energy $\sqrt{s}$

The effective `VLAB` cross section is evaluated by Monte Carlo at the nominal value of $\sqrt{s} = 1.0195$ GeV. To take into account the fluctuations in data around this central value, we correct the luminosity for the relative change in σ_{eff}: $\Delta\mathcal{L}/\mathcal{L}_0 = -\Delta\sigma/\sigma_0$. In this relation $\mathcal{L}_0$ is the luminosity obtained with the nominal cross section σ_0 at $\sqrt{s} = 1.0195$ GeV and $\Delta\mathcal{L} = \mathcal{L} - \mathcal{L}_0$ and $\Delta\sigma = \sigma - \sigma_0$ express the variation of the luminosity and cross section with changing values of $\sqrt{s}$.

The upper plot in Fig. 9 shows the spread in $\sqrt{s}$ for the data runs taken in 2001. The

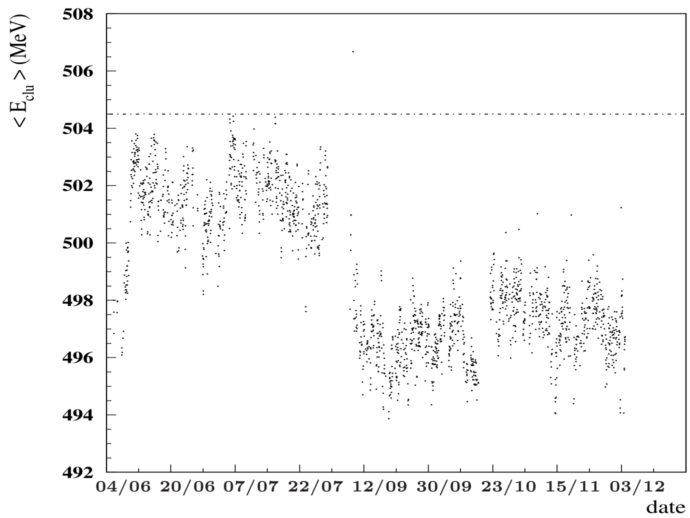


Figure 10: *Average value of the cluster energy in `VLAB` events, as a function of the date. The dashed line is the mean value from Monte Carlo, $\langle E_{clu} \rangle = 504.5$ MeV, and it is adopted as the reference value for estimating miscalibration effects in the cluster energy of `VLAB` events.*

variations never exceed a few hundred keV and therefore the correction to the luminosity due to such changes is expected to be very small. In fact the lower plot (left) shows the relative variation of the Bhabha cross section for different values of $\sqrt{s}$ and the lower plot (right) shows the distribution of corrections $1 + \delta = 1 + \Delta\mathcal{L}/\mathcal{L}$ to be applied to the runs taken in 2001. The corrections for a single run never exceed 0.5% and partly compensate, such that we have to apply a total correction to the integrated luminosity for all 2001 runs of only 0.1%. We take this value also as the uncertainty for the $\sqrt{s}$ correction. For calculating the energy dependence of the Bhabha cross section we have used the `Babayaga` event generator, which includes the resonant contribution $e^+ e^- \to \phi \to e^+ e^-$.

5.6.2 Variations of the energy calibration of the calorimeter

As stressed before, the `VLAB` selection runs on the `LAB` sample and therefore any systematic loss in `LAB` events affects directly the `VLAB` precision. We have therefore studied the effect of a variation of the energy scale on the `LAB` selection, which requires two EmC clusters in the energy interval 300 − 800 MeV and have computed the effect of these variations on the `VLAB` precision. A variation in the energy calibration first of all affects the low energy border at 300 MeV since only very few tracks release a cluster energy of about 800 MeV, while ISR-/FSR-radiation lowers the particle energy and hence populates the low energy range down to 300 MeV and lower. Moreover, we have to consider a possible systematic difference in the energy response between data and MC even at stable running conditions. Fig. 10 shows the average value of the cluster energy in `VLAB` events as a function of the date. Three populations are identified, corresponding to three data taking periods. For each population, the E_{clu} spectrum is evaluated and compared with the one from Monte Carlo. All these spectra are shown both in logarithmic and linear scales in Fig. 11. We draw the following conclusions from these plots:

- the Monte Carlo overestimates the high energy tail with respect to data;
- there is a systematic shift in the mean value, which is smallest for the first running period and larger in the second and third periods.

Concerning the first point we have calculated the systematic effect due to the overestimate of the high energy tail in MC by extrapolating the MC distribution above 800 MeV. Therefore the energy shape has been fitted with a superposition of three Gaussian functions (see Fig. 12 for the result of the fit) and the fraction of events above 800 MeV has been calculated to be $\Delta_{tail} = (6.1 \pm 1.6) \times 10^{-4}$. This effect results in an effective cross section evaluated by Monte Carlo that is lower than it should be. The Δ_{tail} value is taken as a systematic effect in the luminosity measurement and it is considered the same in all three data taking periods mentioned above.

The systematic shift of the energy distribution in data with respect to MC gives rise to an additional systematic effect. It has been estimated by taking the difference between the mean values of the distributions with respect to the mean value from Monte Carlo as a measure of the shift and by adding (subtracting) the events, which are gained (lost) according to this shift. In more detail, the following estimate is used:

$$\frac{\delta\mathcal{L}_{run}(\langle E_{clu}\rangle)}{\mathcal{L}_{run}} = \frac{\langle E_{clu}\rangle_{run} - \langle E_{clu}\rangle_{MC}}{\Delta_{E_{clu}}} \frac{\mathrm{N}_{300}}{\mathrm{N}_{run}} , \tag{5.5}$$

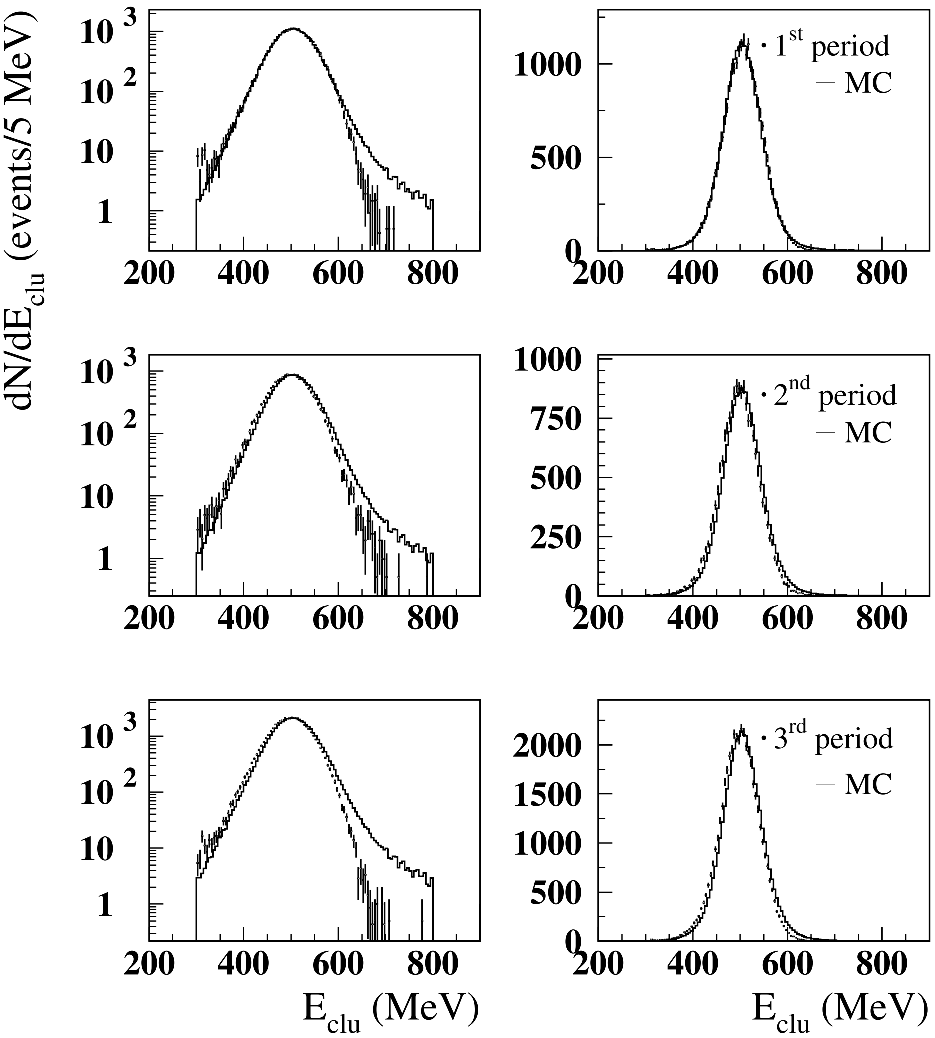


Figure 11: *Data (points with statistical errors) – MC (solid line) comparisons of the cluster energy spectrum in* `VLAB` *events, for three runs, one from each of the periods sketched in Fig. 10. The MC spectrum is always normalized to the number of events in the run and compared with the distribution from data in both logarithmic (left) and linear (right) scale.*

where $\langle E_{clu} \rangle_{run}$ is the mean cluster energy in a single run, $\Delta_{E_{clu}} = 5$ MeV is the bin width in the E_{clu} distribution, and $\mathrm{N}_{300}/\mathrm{N}_{run} \simeq 5 \times 10^{-4}$ is the ratio between the number of events in a bin from 300 MeV to 320 MeV (see Fig. 14) and the total number of `VLAB` events in a single run. Fig. 13 shows the average fractional variation in the luminosity

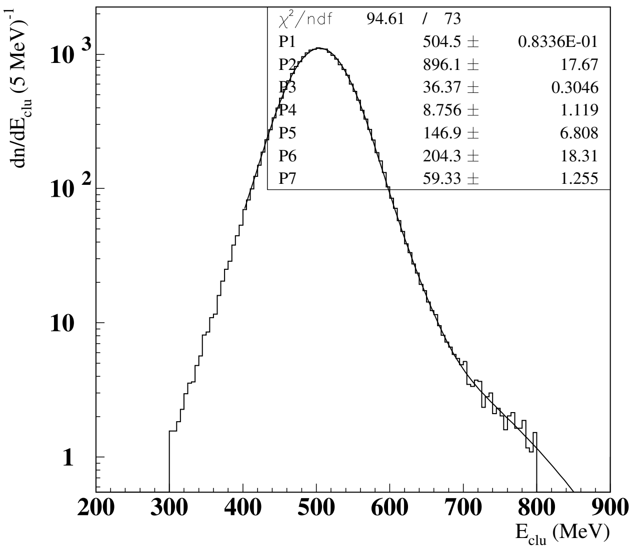


Figure 12: *The Monte Carlo spectrum fitted with the superposition of three Gaussians, each with same mean value,* P1 = 504.5.

measurement due to this estimate. The mean value of this distribution, weighted for the number of `VLAB` events in each run, is $\Delta_{calib} = 6 \times 10^{-4}$, which we take as the relative systematic uncertainty connected to the variations of the EmC scale. This amount is the correction to be added to the observed number of `VLAB` events because of a larger loss of events for the cut $E_{clu} > 300$ MeV in data with respect to Monte Carlo. Furthermore we have checked that, aside from a coherent shift, the shape of the cluster energy in `VLAB` events is stable among the three periods, which is confirmed by the plots in Fig. 14.

In conclusion we introduce a systematic uncertainty connected to energy calibration drifts between data and Monte Carlo, which is given by:

$$\Delta_{E_{clu}} = \Delta_{tail} \oplus \Delta_{calib} = 8.6 \times 10^{-4} \simeq 0.1\%.$$

Since the two effects compensate, a larger loss of events in Monte Carlo for the high energy tail compared to a larger loss in data due to the E_{clu} drifts in the low energy range, no correction is applied to the luminosity evaluation.

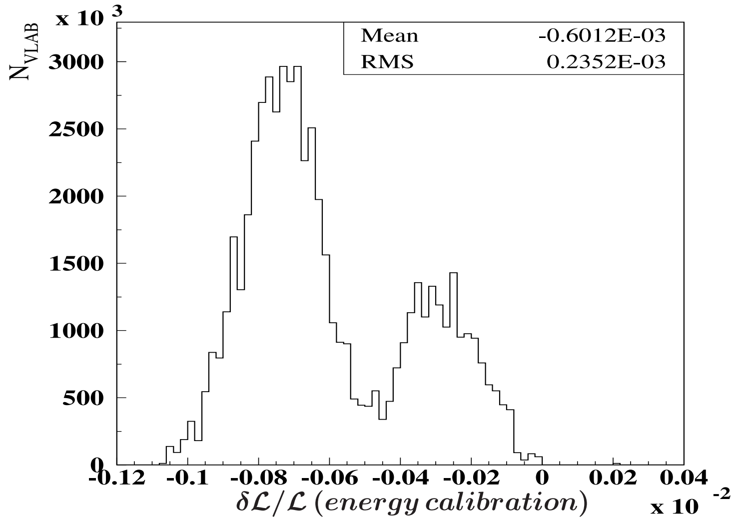


Figure 13: *Distribution of the relative variation of the luminosity for the runs of 2001, due to the shifts in the energy scale of the EmC between data and Monte Carlo.*

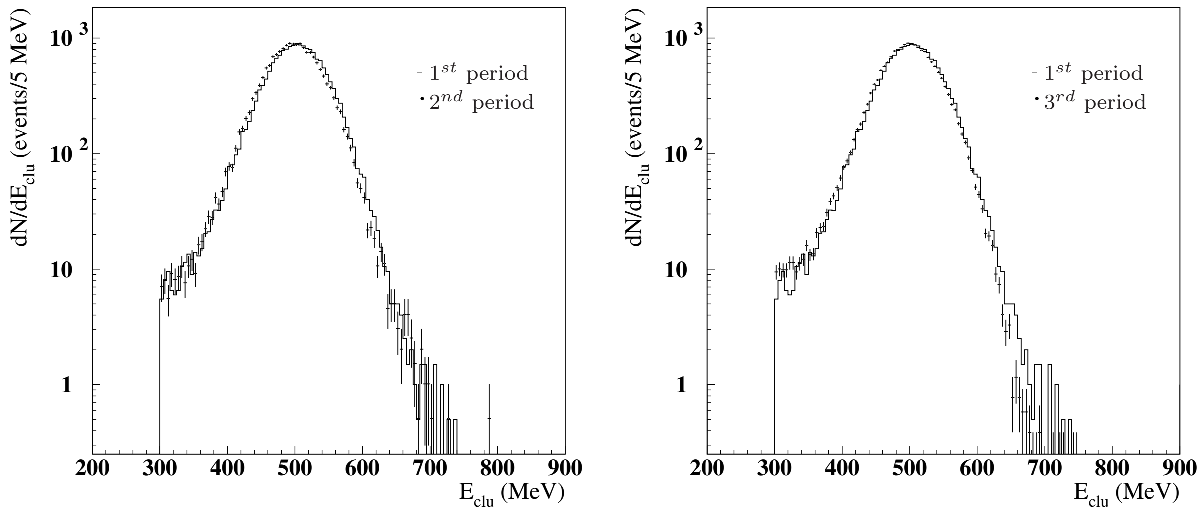


Figure 14: *Cluster energy spectra from data. Left: comparison between the energy spectrum for runs from the second (points with statistical errors) and the first (solid line) periods. Right: comparison between energy spectrum for runs from the third (points with statistical errors) and the first (solid line) periods. All spectra are normalized to the number of events in the run for the first period.*

	correction (%)	systematic error (%)
acceptance	$\delta_{accept} = +0.25$	$\Delta_{accept} = 0.25$
tracking	–	$\Delta_{track} = 0.06$
clustering	$\delta_{split} = +0.14$	$\Delta_{cluster} = 0.11$
background	$\delta_{bkg} = -0.55$	$\Delta_{bkg} = 0.08$
cosmic veto	$\delta_{cosmic} = +0.40$	–
dependence on $\sqrt{s}$	$\delta_{\sqrt{s}} = +0.10$	$\Delta_{\sqrt{s}} = 0.10$
E_{clu} drifts	–	$\Delta_{E_{clu}} = 0.10$
Total experimental	$\boldsymbol{\delta_{tot} = +0.34}$	$\boldsymbol{\Delta_{tot} = 0.32}$

Table 1: *Summary of the different corrections and systematic errors in the measurement of the luminosity by `VLAB` events. In the case of the acceptance correction we decided to quote a systematic error equal to the correction, to be conservative. The correction and the uncertainties related to the dependence on $\sqrt{s}$ and to the drifts in the cluster energy should be regarded as average values.*

5.7 Results and conclusions

All the corrections and sources of systematic errors that have been worked out for the luminosity measurement using `VLAB` events are summarized in Tab. 1. We assume that the sources of these systematic effects are not correlated. Then, summing in quadrature all errors, the relative experimental uncertainty for the luminosity measurement using `VLAB` events is $\delta\mathcal{L}_{\text{exp}}/\mathcal{L}_{\text{exp}} = 0.3\%$. The theoretical uncertainty due to the knowledge of the effective `VLAB` cross section is 0.5% [7] and hence we arrive at the total error of the KLOE luminosity measurement:

$$\frac{\delta\mathcal{L}}{\mathcal{L}} = \frac{\delta\mathcal{L}_{\text{exp}}}{\mathcal{L}_{\text{exp}}} \oplus \frac{\delta\sigma_{\text{eff}}}{\sigma_{\text{eff}}} = 0.6\% \;.$$

We conclude that the major source of uncertainty arises from theory, *i.e.* from the knowledge of the QED radiative corrections.

A comparison between the luminosity measurement using `VLAB` events and using the `GGL` counter, i.e. using the process $e^+ e^- \to \gamma\,\gamma$, shows very good agreement. The average difference in a run-by-run comparison between `VLAB` and `GGL` is 0.3%. However, it should be mentioned that according to the authors of `Babayaga` the knowledge of the effective `GGL` cross section is not better than $\mathcal{O}(1\%)$. We therefore plan to introduce into GEANFI a new event generator for $\gamma\,\gamma$ events by Berends and Kleiss [13].

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