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Current status of luminosity measurement with the CMD-3 detector at the VEPP-2000 e\textsuperscript{+}e\textsuperscript{−} collider

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ABSTRACT: Since December 2010 the CMD-3 detector has taken data at the electron-positron collider VEPP-2000. The collected data sample corresponds to an integrated luminosity of 60 pb$^{-1}$ in the c.m. energy from 0.32 up to 2 GeV. The preliminary results of the luminosity measurement are presented in various energy ranges. The current accuracy for integrated luminosity is estimated to be 1%.

KEYWORDS: Particle tracking detectors; Particle identification methods; Accelerator Subsystems and Technologies
1 Introduction

The electron-positron collider VEPP-2000 [1] has been operating at Budker Institute of Nuclear Physics since 2010. The collider is designed to provide luminosity up to $10^{32}$ cm$^{-2}$s$^{-1}$ at the maximum center-of-mass energy $\sqrt{s} = 2$ GeV. Two detectors, CMD-3 [2] and SND [3], are installed in the beams interaction regions of the collider. Both of the detectors have high detection efficiency, good energy and angular resolutions for charged particles as well as for photons. The current integrated luminosity collected by each detector is $\sim 60$ pb$^{-1}$.

The luminosity is a key part in many experiments which study the hadronic cross sections at $e^+e^-$ colliders. As a rule, the systematic error of the luminosity determination represents one of the largest sources of uncertainty which can cause significant reduction of the hadronic cross sections accuracy. Therefore it is very important to have several well known QED processes such as $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma$ to determine the luminosity. The combined application of them will help to better understand and estimate a real systematic accuracy of the luminosity. The CLEO collaboration was the first to show in practice how a combined application of the processes $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-$ and $\gamma\gamma$ helped to achieve a 1% accuracy for the luminosity [4].

The process $e^+e^- \rightarrow \gamma\gamma$ has essential advantages for luminosity determination [5] with respect to the first two. It is free of difficulties related to both radiation of the final state particles and Coulomb interaction. It is also of utmost importance that corresponding Feynman graphs do not contain photon propagators affected by the vacuum polarization effects. Events of this process have
two collinear photons with similar energy deposition in calorimeters providing a clean signature for their selection among other events. These reasons are the main motivation to explore these processes as independent tools for luminosity determination. The preliminary results of the luminosity determination are presented in a wide energy range.

2 CMD-3 detector

Cryogenic Magnetic Detector, CMD-3, is a general purpose detector shown in figure 1. Coordinates, angles and momenta of charged particles are measured by the cylindrical drift chamber (DC). The coordinate resolution in r-φ plane is \( \sim 120 \mu m \), resolution along beam axis is \( \sim 2 \) mm and it is measured by charge division techniques. The proportional Z-chamber is mounted directly behind DC and provides more accurate z-coordinate determination of the tracks in DC. The signals coming from anode sectors are used for the first level trigger and have time jitter \( \sim 5 \) ns.

The calorimeter consists of three subsystems. The endcap BGO calorimeter with a thickness 13.4\( X_0 \) is placed on both sides of the DC flanges. The barrel part, which is placed outside of the superconducting solenoid with 1.3 T magnetic field (0.13\( X_0 \)), consists of two systems: inner Liquid Xenon calorimeter (5.4 \( X_0 \)) and calorimeter based on the CsI crystals with the thickness 8.1\( X_0 \) (1152 crystals) which are combined in 8 octants. The LXe calorimeter has a tower structure (264 channels) and seven cylindrical double layers with strips readout (2112 channels). The strip-information allows to measure coordinates of the photon conversion point with precision about 1–2 mm.

The outer muon range system is located outside of yoke and consists of 36 scintillation counters in the barrel part and 8 counters at the endcap. This system is used as cosmic veto and has time resolution \( \sim 1 \) ns.
3 Energy scan and collected luminosity

The energy range from 1 to 2 GeV was scanned up and down with a step of 50 MeV. At each energy
point the integrated luminosity $\sim 500 \text{ nb}^{-1}$ was collected. During the scan down the energy points,
which the data were collected, have been shifted to the previous one by 25 MeV. At each energy
point the integrated luminosity $\sim 4 \cdot 10^{30} \text{s}^{-1} \text{cm}^{-2}$. At the highest energies the peak luminosity
reached the values about $2 \cdot 10^{31} \text{s}^{-1} \text{cm}^{-2}$ and was restricted by the positron storage rate in the
booster. The project luminosity $\sim 10^{32} \text{s}^{-1} \text{cm}^{-2}$ will be provided only with start of operating
of new positron injection facility in 2015. The beam energy has been monitored ($\sim 0.5 \text{MeV}$)
by measuring the current in dipole magnets of the main ring. The time period of this run was
extend from January to June 2011. In 2012 the luminosity was measured at 16 energy points from
1.32 GeV to 1.98 GeV and collected luminosity was about $\sim 14 \text{ pb}^{-1}$.

In 2013 the energy range from 0.32 GeV to 1 GeV was scan with the 10 MeV step. The inte-
grated luminosities about 8.3 and 8.4 $\text{ pb}^{-1}$ were collected around $\omega$ and $\phi$ mesons. Over the 2013
year the integrated luminosity $\sim 25 \text{ pb}^{-1}$ has been collected.

Two type of the first level triggers "CHARGED" and "NEUTRAL" were used while data
taking. A special combination of signals from DC cells and Z-chamber, which roughly reproduce
"track", start a special processor "TRACKFINDER" (TF). "CLUSTERFINDER" (CF) was started
by signals coming from calorimeters. A positive decision of any processor generates a command
for the data acquisition system. The average trigger counting rate was about 200 - 400 Hz and
strongly depends on the fine tune of the beam optics. The signals coming from CF were delayed in
average by 240 ns with respect to TF signals, that corresponds to time of three beams rotation in
the VEPP-2000 ring.

4 Luminosity measurement based on the process $e^+e^- \rightarrow e^+e^-$

At the first step the collinear events were selected according to the next criteria: "CHARGED"
trigger produced positive decision; "NEUTRAL" trigger can produce positive decision too; at least
two tracks were reconstructed in DC; total charge of two particles in every event must be equal to
zero; distance of the both tracks from the beam axis in r-$\phi$ plane is less than 0.5 cm; distance of the
both tracks along beam axis from the interaction point does not exceed 10 cm; acollinearity angle
between two tracks in the scattering plane (contains the beam axis), $|\Delta \Theta| = |\Theta_1 - (\pi - \Theta_2)| \leq 0.25$
rad; acollinearity angle between two tracks in the azimuthal plane (perpendicular to the beam axis),
$|\Delta \Phi| = |\pi - |\Phi_1 - \Phi_2|| \leq 0.15 \text{ rad}$; average polar angle of two tracks $|\Theta_1 + (\pi - \Theta_2)|/2$ should be
between 1 and ($\pi - 1$) rad.

The sample of collinear events $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$ and cosmic background were
selected for luminosity determination. The two-dimensional plot of energy deposition in calorimeters
for these events is presented in figure 2 for the beam energy 950 MeV. It is clearly seen that Bhabha
events are distributed predominantly at the upper right corner whereas other particles are concen-
trated in the bottom left one. Thus, the integrated luminosity can be determined by the well selected
Bhabha events:

$$\int L \cdot dt = \frac{N_{ee}}{\epsilon_{tr} \cdot \epsilon_{rec} \cdot \epsilon_{cal} \cdot \epsilon_{en} \cdot \epsilon_{ee} \cdot \epsilon_{rad}}, \quad (4.1)$$
where $N_{ee}$ is the number of selected Bhabha events, $\epsilon_{tr}$ is an efficiency of the charged trigger, $\epsilon_{rec}$ is a track reconstruction efficiency in DC, $\epsilon_{cal}$ is an efficiency of the calorimeter, $\epsilon_{en}$ - cluster selection efficiency due to energy deposition in calorimeters, $\sigma_{ee}$ is the Bhabha cross section integrated inside detector acceptance, $\epsilon_{rad} \sim 0.947 \pm 0.002$ is a radiative correction calculated according to [6].

4.1 Track reconstruction and trigger efficiencies

To determine the track reconstruction efficiency $\epsilon_{rec}$ the test Bhabha events were selected with two back-to-back clusters in calorimeters without any information from DC with the more hard restrictions for the tracks collinearity for these events, as it is shown in figure 3.

The central peak corresponds to $\gamma\gamma$ events whereas left and right peaks - Bhabha events when their rotation in a magnetic field is taking into account with additional condition, that Z-chamber sectors, associated with two collinear clusters, triggered too. The last condition allows to suppress a small part of $\gamma\gamma$ events which can seep under left or right peaks, and thereby imitate DC inefficiency.

The track reconstruction efficiency was determined with relation: $\epsilon_{DC} = N_{2tr}/N_{total}$, where $N_{2tr}$ - number of test events with two tracks in DC, $N_{total}$ - the whole number of test events. This approach was applied at all energy points and in average the reconstruction efficiency is $\epsilon_{rec} = 0.996 \pm 0.002$.

A similar approach was applied to estimate the trigger efficiency using the same test events. Among selected events there are three sorts: $N_{1}$ - number of events when signal is only from "CHARGED TRIGGER", $N_{2}$ - number of events when signal is only from "NEUTRAL TRIGGER", $N_{3}$ - number of events when signals comes from both triggers. Then "CHARGED" and "NEUTRAL" efficiencies are defined as: $\epsilon_{ch.tr.} = N_{3}/(N_{3} + N_{2})$ and $\epsilon_{n.tr.} = N_{3}/(N_{3} + N_{1})$. So the trigger efficiency can be presented as $\epsilon_{tr} = 1 - (1 - \epsilon_{ch.tr.}) \cdot (1 - \epsilon_{n.tr.})$ and in average was found to be $\epsilon_{tr} = 0.999 \pm 0.001$.

To determine the cluster efficiency $\epsilon_{cal}$ the Bhabha events were selected with two back-to-back tracks in DC and at least one cluster in the calorimeter associated with one of two tracks. As a result, it was found that $\epsilon_{cal} = 0.999 \pm 0.001$. We assumed the energy depositions of each...
particle corrected on their polar angle to be not correlated between themselves. So the calorimeter detection efficiency caused by the Bhabha events is $\epsilon_{cal} = 0.998\pm0.002$.

5 Luminosity measurement based on the process $e^+e^- \rightarrow \gamma\gamma$

Events of the process $e^+e^- \rightarrow \gamma\gamma$ were also used to determine the integrated luminosity but this method has absolutely different systematic errors compared to those based on the Bhabha events. To do that neutral collinear events were selected according to the following criteria: back-to-back clusters in the barrel calorimeters; the energy of each cluster should be inside interval from $0.5E_{beam}$ to $1.5E_{beam}$; no tracks in DC coming from the interaction region of the beams and no hits are in Z-chamber sectors associated with clusters. The last condition helps to eliminate Bhabha events which slightly seep through the previous cuts. The polar angle of the cluster is calculated by the center-of-gravity method using the analog information from strips of LXe calorimeter [7].

To select $\gamma\gamma$ events the information about their energy deposition in calorimeters is used. Two dimensional plot of energy deposition $E_0$ vs $E_1$ is presented in figure 4. It is seen that the signal events are concentrated as a cluster of dots in upper-right corner of this plot. At the same time two train seen - concentration of dots in two mutually perpendicular directions due to ISR. The events of this sample should have energy deposition inside interval: $0.5E_{beam} < E_0, E_1 < 1.5E_{beam}$. Unfortunately as it is seen in figure 3 the small part of the Bhabha events can seep under the central peak and imitate $\gamma\gamma$ events. To exclude such events the additional condition was applied - the Z-chamber sectors associated with clusters must be triggered. Visual scan of the remaining events proofed - there are not Bhabha events under central peak presented in figure 3. Unfortunately this condition delete some $\gamma\gamma$ events due to albedo coming from showers. The fraction of such events amounts to $\sim6\%$ and as a result we should include correction about 0.36% to restore the number of $\gamma\gamma$ events.

The registration efficiency of the $\gamma\gamma$ events is determined as $\epsilon_{reg} = \epsilon_{LXe}^2 \cdot \epsilon_{en}^2 \cdot \epsilon_{nt.tr.}$, where $\epsilon_{LXe}$ - photon detection efficiency in LXe calorimeter, $\epsilon_{en}$ — cluster selection efficiency due to energy deposition in calorimeters, $\epsilon_{nt.tr.}$ — neutral trigger efficiency. The radiation length of LXe
calorimeter for photons is about $4X_0$ only, resulting in $\sim 0.999$ interaction probability of one or two photons with this calorimeter.

To determine the efficiency due to cut applied to the energy deposition of photons, the $\gamma\gamma$ events were selected with more tight restrictions on one variable: $0.8E_{\text{beam}} \leq E_0 \leq 1.2E_{\text{beam}}$. The distribution vs second variable was studied. It was found that efficiency is $\epsilon_en = 99.1 \pm 0.2\%$ for the case when energy deposition is inside interval from $0.5E_{\text{beam}}$ to $1.5E_{\text{beam}}$. It is naturally to assume that detection efficiencies of both photon are not correlated between themselves.

5.1 Interaction with the vacuum pipe

The central part of vacuum chamber with length 20 cm is made of aluminum with thickness 0.5 mm ($5.3 \cdot 10^{-3}X_0$). When electron (positron) passes through the wall of vacuum pipe the hard photon can be emitted and this event can be lost due to considerable acollinearity angle between tracks. For $\gamma\gamma$ events one of the photons can be converted on pipe into $e^+e^-$ pair and will be lost due to cut of the selection filter. These corrections vs energy were studied and simulation results are presented in figure 5, where red points - $e^+e^- \rightarrow \gamma\gamma$ process, blue points - $e^+e^- \rightarrow e^+e^-$ process.

5.2 Correction due to finite angle resolution

Since the Bhabha and $\gamma\gamma$ cross sections are the complicated functions vs polar angular $\theta$ so there are the systematic corrections to them due to finite angular resolution $\sigma_\theta$. For example, if $\sigma_\theta \sim 0.03$ rad and polar angle $\theta = 60^\circ$ the correction is about 0.5% for Bhabha and for the $\gamma\gamma \sim 0.6\%$ if $\sigma_\theta \sim 0.1$ rad. To determine the calorimeter angular resolution the test Bhabha events were used. To do that the track from DC is extended up to intersection with LXe calorimeter. The width of the distribution of the difference between coordinates determined by strips and track serves as angular resolution and is better $\sim 0.05$ rad.

6 Results of luminosity measurement

The luminosities ratio determined with use of two processes vs energy is presented in figure 6 and in figure 7, where only statistical errors are shown. The blue circles correspond to the scan up, whereas red circles - scan down. The horizontal line is a fit for this ratio for scan down. In this case the relative difference between luminosities is in average $0.73 \pm 0.35\%$. However, at the beginning of the run the difference was $\sim 3\%$ and explained by hardware problems and the quality of inter-calibration of the detector subsystems. Collecting all the main sources which contribute to systematic error of the luminosity, we estimate the current accuracy as $\sim 1\%$ while. The first energy scan below 1 GeV was performed at VEPP-2000 during the season of 2013. The preliminary results of the luminosity measurement are shown in figure 8.

The already collected statistics is higher than that in the previous CMD-2 experiment and at the level or better than in BaBar and KLOE experiments. One of the tests in this analysis is to measure the cross section of the process $e^+e^- \rightarrow \mu^+\mu^-$ at low energy, where particles separation is possible using only momentum information from DC. Preliminary results of this test are consistent with the QED prediction as it is seen in figure 9. The radiative corrections (RC) to this cross section with photon jets radiation in collinear regions were taken into account according to [6] and their accuracy is better than 0.2\%.
7 Luminosity systematics

One of the main goals of the CMD-3 experiment is to reduce a systematic uncertainty of the cross section of two pion production to the level 0.3%. The geometry of this process allows to select a clean sample of $e^+e^−,\mu^+\mu^−,\pi^+\pi^−$ collinear events practically without physical background. These final states can be separated using either the information about energy deposition in the calorimeter or that about particle momenta in the DC at energy $E_{\text{beam}} \lesssim 330\text{MeV}$. These two methods overlap in the energy range 250÷330 MeV and crosscheck allows to keep a systematic error of the event separation under control and we hope to reduced it to $\sim 0.2\%$.

The fiducial volume of the CMD-3 detector can be determined independently with the LXe calorimeter and Z-chamber. It allows to monitor the detector operation stability during data taking. The possibility to cross check a z-scale measurement by two subsystems will allow to keep a systematic uncertainty from this source at the level of $\sim 0.1\%$. Measurement of the beam energy by Compton back scattering of the laser light with precision $\sigma_E < 50 \text{keV}$ [8] will keep a systematic uncertainty from this source below 0.1%.
Another important source of systematics is the theoretical precision of radiative corrections [6]. Additional studies are required in this field and the comparison with experimental data are necessary. We expect that this uncertainty can be reduced to 0.1%.

The axis of the CMD-3 detector has a slight slope with respect to the beams axis and this parameter is not stable in time. Due to this factor the integrated luminosity can be changed up to 0.4% and required a careful monitoring. Event selection criteria (filter) for collinear tracks also contributes to systematic error of the integrated luminosity as well as energy and momentum resolutions, angular resolution, stability of z-scale in DC and so on. The first glance consideration of these effects show they all are about 0.1%.

8 Summary and concluding remarks

The VEPP-2000 collider successfully operates with a goal to get ∼ 1 fb⁻¹ in 5-10 years and provide new precise results on the hadron physics. The current integrated luminosity of the collider was measured using two well known QED processes \( e^+e^- \rightarrow e^+e^- \), \( \gamma\gamma \). Two type of the first level triggers "CHARGED" and "NEUTRAL" delivered the independent information that allowed to determine the detection efficiencies and to estimate their uncertainties. The collected integrated luminosity is ∼60 pb⁻¹ with about 34.5 pb⁻¹ above the \( \phi \) energy, 8.3 and 8.4 pb⁻¹ at the \( \omega \) and \( \phi \) resonances respectively, and 9.4 pb⁻¹ from a scan below the \( \phi \). The peak luminosity ∼2 · 10³¹ cm⁻² s⁻¹ was reached and currently is limited by a deficit of positrons and maximum beam energy of the booster (825 MeV now). An upgrade of the injection facility will increase the luminosity at least by a factor of ten. It is worth to note that the systematic uncertainties of luminosity are totally different for these processes and not be compensated in their ratio. Data analysis is in progress, the already collected data sample are delivered the same or better statistical precision for the hadronic cross sections than in previous experiments were achieved. The current luminosity accuracy is estimated to be 1%. The study of the different systematics is in progress now and in forthcoming future we hope to reduce it to the level ∼0.5%.

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