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PHYSICS BACKGROUND AS A SYSTEMATIC EFFECT IN LUMINOSITY MEASUREMENT AT INTERNATIONAL LINEAR COLLIDER

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Abstract. *In order to achieve required precision of luminosity measurement at the International Linear Collider (ILC), that is, of order of 10^{-4}, systematic effects have to be understood at the level of this precision. Apart from machine background originating from pairs converted from beamstrahlung, physics background from 2-photon processes is one of the main systematic effects. Properties of these processes, as well as their separation from the Bhabha signal have been studied.*

Keywords: *International Linear Collider, luminosity, precision measurements*

INTRODUCTION

International Linear Collider is a proposed future international particle accelerator. It would create high-energy particle collisions between electrons and positrons, and provide a tool for scientists to address many of the most compelling questions about the fundamental nature of matter, energy, space and time. It is designed [1] to achieve an initial centre-of-mass (cms) energy up to 500 GeV with the ability to upgrade to 1 TeV, and the nominal luminosity of $2\cdot10^{34}\ cm^{-2}s^{-1}$. ILC will work in complement with the LHC (Large Hadron Collider) at CERN dedicated primarily to discover Higgs bosons and SUSY particles, while ILC will provide precise measurements of the characteristics of these particles since a collision between an electron and a positron is much simpler than a collision between many quarks, antiquarks and gluons. Thus not the full centre-of-mass energy of 14 TeV will be available at LHC, due to parton distributions inside the proton ($\sqrt{s_{eff}} \approx 3$ TeV). The initial state is unknown, the proton remnants disappear in the beam pipe and the energy-momentum conservation can not be used in event reconstruction. Also, there is huge QCD background to be dealt with. At the other hand, the full $\sqrt{s}$ is

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available at ILC, with defined initial state, including helicity. The full final state can be reconstructed employing energy-momentum conservation. Due to the small background, practically all process of interest will be visible at the ILC. Hence it is anticipated that ILC will be used to make precision measurements of the properties of particles discovered at LHC. In addition, it will complement the answers to the following questions [2]:

– How is the electroweak symmetry broken (EWSB)? ILC will provide either precision study of the Higgs system or evidence for the strong EWSB.

– What is the dark matter? ILC is supposed to see either supersymmetric or Kaluza-Klein dark matter candidates.

– Is there a common origin of forces? Unification of couplings as well as SUSY breaking parameters can be checked with enlarged precision with respect to the LHC.

– Is space-time more then four-dimensional? ILC is sensitive to extra dimensions up scales of a few TeV and may give a hint towards quantum gravity at the GUT scale.

Error on luminosity affects many precision measurements, and limits some of them, as the additional component of a systematic error. Precision of luminosity measurement is driven by physics requirements for the cross-section measurements (i.e. the total hadronic cross-section at Z^0 resonance, 2-fermion production at high energy) and precision EW measurements (EWSB - anomalous gauge boson couplings).

METHOD

Integrated luminosity at ILC will be determined from the total number of Bhabha events N_{th} produced in the acceptance region of the luminosity calorimeter and the corresponding theoretical cross-section σ_B .

$$L_{\text{int}} = \frac{N_{th}}{\sigma_B} \tag{1}$$

In a real experiment, the number of counted Bhabha events N_{exp} has to be corrected for the number of background events misidentified as Bhabhas N_{bck}, and for the selection efficiency ε.

$$L_{\text{int}} = \frac{N_{\text{exp}} - N_{bck}}{\varepsilon \cdot \sigma_B} \tag{2}$$

A cylindrical calorimeter has been designed for measurement of the total luminosity. It is a compact electromagnetic sandwich calorimeter consisting of 30 longitudinal layers of silicon sensor followed by tungsten absorber and the interconnection structure. It is located at z = 2270 mm from the IP, covering the polar angle range between 44 and 155 mrad, for the 14 mrad crossing-angle between the beams. Layout of the forward region in the 'Large Detector Concept' (LDC) is shown in Figure 1 [3]. As illustrated, calorimeters in the very forward region, are shielding the central detectors from the back-scattered particles, providing, at the same time, hermeticity of the LDC detector. In case of the large crossing angle α of 14 mrad, luminosity calorimeter is centred along the outgoing beam causing a tilt of 7 mrad with respect to the LDC detector axis. This is to avoid φ dependent systematic shift of $\Delta L / L$, as illustrated in Figure 2 [4].

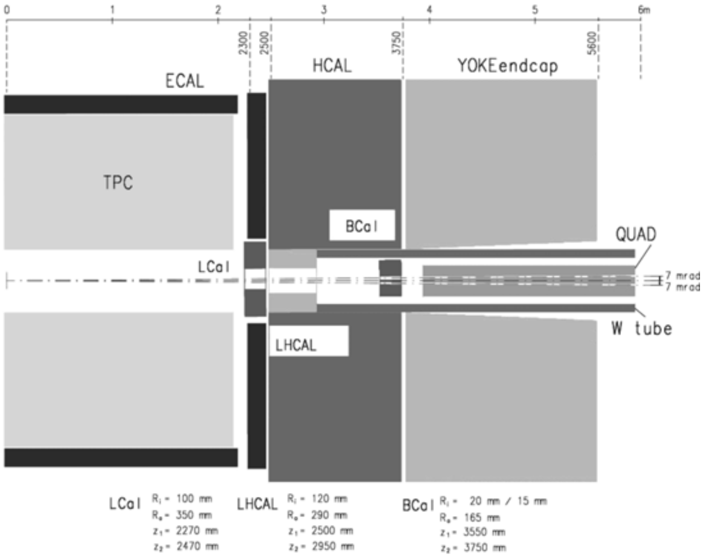

Fig. 1. Layout of the forward region in the LDC concept for the 14 mrad crossing-angle between the beams. Abbreviations stands for: Time Projection Chamber (TPC), Electromagnetic Calorimeter (ECAL), Hadron Calorimeter (HCAL), Luminosity Calorimeter (LCAL), Beam Calorimeter (BCal).

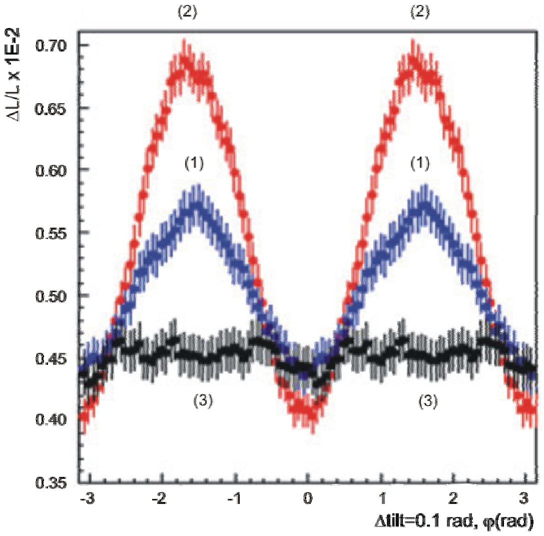

Fig. 2. Relative shift of the measured luminosity as a function of the azimuthal angle, for luminosity calorimeter centred on the LDC detector axis for 14 and 20 mrad crossing angle (1)/(2) and for luminosity calorimeter centred along the outgoing beam (3).

The top view of the suggested beam line orientation, with the Detector Integrated Dipole (DID) field indicated, is given in Figure 3 [5]. The angle between incoming beam and the z axis is α/2.

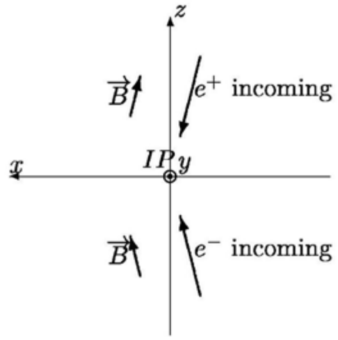

Fig. 3. Definition of the right-handed coordinate system for ILC studies. Incoming particles will approach IP from the negative side of the x axis.

RESULTS

Signal for luminosity measurement

Bhabha scattering at small angle is precisely calculable in QED ($\Delta\sigma_{th} \approx 10^{-4}$) and has a sufficiently large cross-section to deliver high statistics for luminosity measurement of the required precision. With the cross-section of approximately 4 nb in the luminosity calorimeter angular range, at 500 GeV centre-of-mass energy and the nominal luminosity of ILC of $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$, about 10^9 events will be collected per year, corresponding to the statistical error of order of 10^{-5}. In Figure 4, dependence of the visible cross-section for Bhabha scattering with the centre-of-mass energy is given [6].

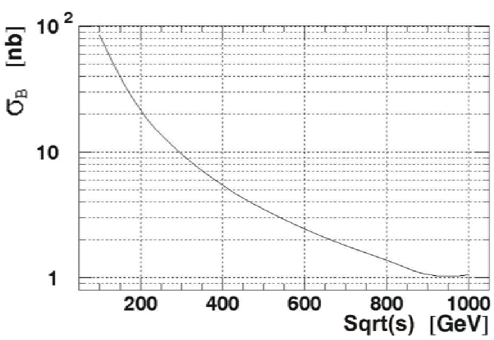

Fig. 4. Bhabha cross-section as a function of the centre-of-mass energy.

Bhabha cross-section at small scattering angles is given to the lowest order by:

$$\frac{d\sigma_B}{d\theta} = \frac{32\pi\alpha^2}{s} \cdot \frac{1}{\theta^3} \tag{3}$$

where α is the fine structure constant, θ is the scattering angle and $\sqrt{s}$ is the centre-of-mass energy. The cross-section is falling steeply with increasing polar angle, causing luminosity measurement to be sensitive to the reconstruction of the polar angle, as well as to the lower edge of polar angle range $\theta_{\min}$ (or corresponding inner radius of the luminosity calorimeter) (4).

$$\frac{\Delta L}{L} \approx 2 \cdot \frac{\Delta\theta}{\theta_{\min}} \tag{4}$$

The resolution of the polar angle measurement is given in Figure 5 [7].

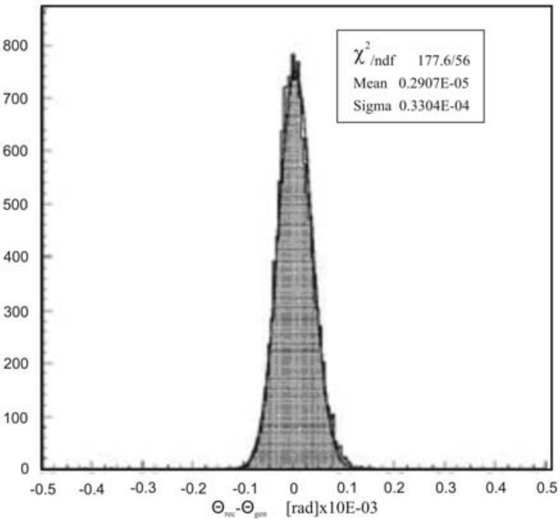

Fig. 5. Resolution plot for the Bhabha polar angle reconstruction in the luminosity calorimeter.

Polar angle of the scattered Bhabha particle can be reconstructed in the luminosity calorimeter with $\sigma(\theta) = 3.3 \cdot 10^{-5}$ *rad* and $\Delta\theta = 2.9 \cdot 10^{-6}$ *rad*. The signal corresponds to the rate of $8 \cdot 10^{-3}$ particles per bunch crossing in the detector acceptance region. Bhabha events are characterized by the two electromagnetic clusters, with the full beam energy, that are back-to-back in azimuthal and polar angle. Based on this topology, separation criteria for signal from background will be derived. Figure 6 illustrates Bhabha energy and polar angle distributions.

A sample of 10^5 Bhabha events has been generated with BHLUMI [8] small angle Bhabha generator, integrated into BARBIE V4.1 [9] detector simulation package. Both s and t channels have been included, vacuum polarization, as well as the initial state radiation. For the purpose of this study we assumed head-on collisions of the beams and the corresponding detector acceptance between 26 and 82 mrad. For head-on collisions we assumed luminosity detector that is axially symmetric around beam axis. Sensor planes of the luminosity calorimeter are segmented into 120 azimuthal sectors and 64 radial strips, alternately.

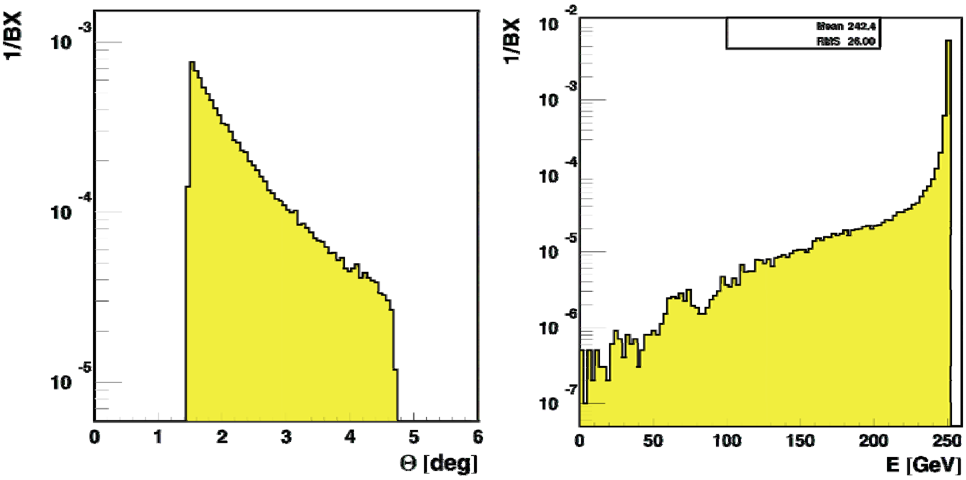

Fig. 6. Polar angle and energy distributions of Bhabha events in the luminosity calorimeter.

Physics background

Four-fermion NC processes $e^-e^+ \to e^-e^+ f^- f^+$ ($f = l,q$) are considered to be the main source of physics background for luminosity measurement. They are dominated by the multiperipheral processes (2-photon exchange). The corresponding Feynman diagrams are given in Figure 8. Outgoing e^+e^- pairs are emitted along the beam pipe carrying the most of energy, while low-energetic l^+l^- pairs are distributed over a wider polar angle range (Figure 7). Due to the steep polar angle distribution of the produced particles, the most of energy is to be deposited in the beam calorimeter while low-energetic particles are mainly deposited in the luminosity calorimeter.

Both this study and an independent study [10] of two-photon processes ($2\gamma \to e^-e^+$), using Vermasseren generator [11], found occupancy in the luminosity calorimeter acceptance region of 10^{-3} particles/BX.

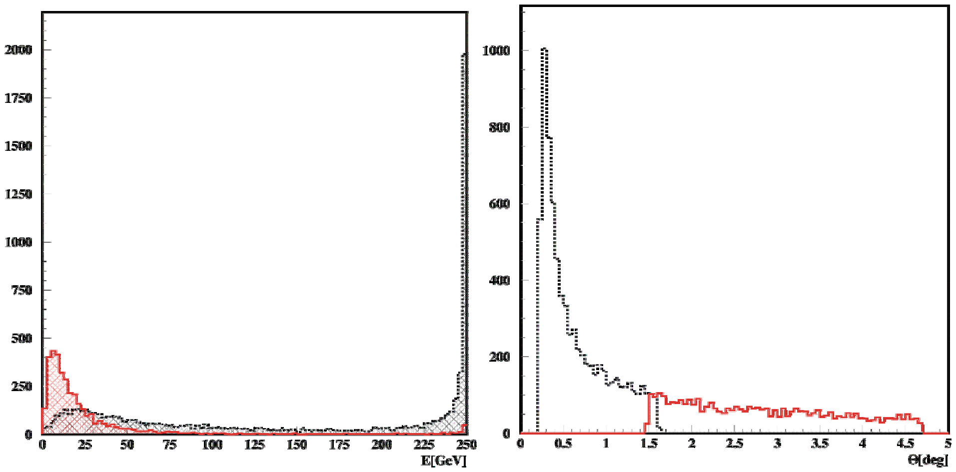

Fig. 7. Energy and polar angle distributions of generated particles in the beam calorimeter (dashed-line) and luminosity calorimeter (solid-line) acceptance regions.

To simulate physics background, a sample of 10^6 four-lepton events $e^- e^+ \rightarrow e^- e^+ l^- l^+$ ($l = e,\mu$) and a sample of 10^5 hadronic events $e^- e^+ \rightarrow e^- e^+ q\bar{q}$ ($q = u,d,c,s,b$) have been generated with WHIZARD [12], with the total cross section of (1.68±0.03) nb. For the event generation, contributions of all neutral current tree-level processes are considered. The simulation is performed in the full polar angle range, assuming that the invariant mass of outgoing lepton pair is greater than 1 GeV/c^2 and momentum transferred in photon exchange is also greater then 1 GeV/c. No assumptions have been made on beam structure or polarization.

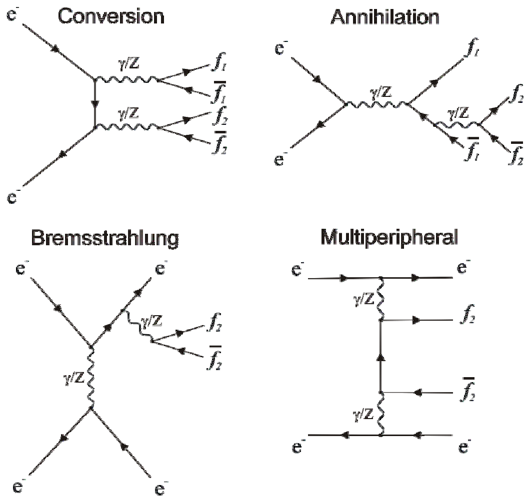

Fig. 8. Feynman diagrams contributing to NC four-fermion production.

Energy distributions of hadronic and leptonic background in the luminosity calorimeter are given in Figure 9.

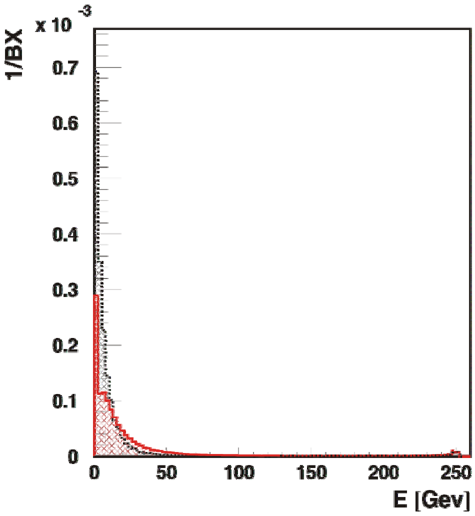

Fig. 9. Energy distributions for leptonic (solid line) and hadronic (dashed line) background in the luminosity calorimeter

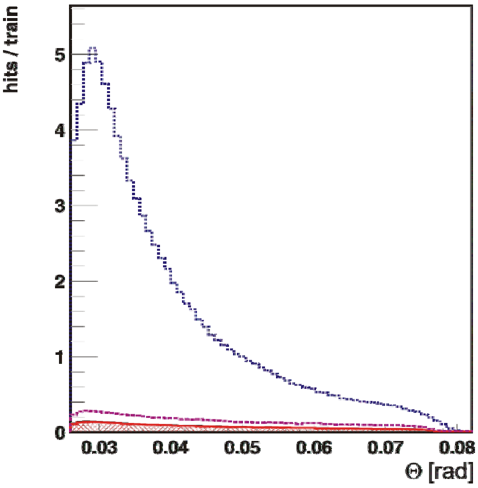

Fig. 10. Occupancy in the sensors of the luminosity calorimeter for signal (dotted line), hadronic background (solid line) and the total background (dashed line)

Occupancy of the sensors of the luminosity calorimeter is dominated by the machine background. In terms of the detector occupancy, physics background contributes approximately 10 times less then the signal. The maximal occupancy of a sensor plane is given per train, for signal and background, in Figure 10.

Though rates of signal and background are comparable in the luminosity calorimeter, well known characteristics of Bhabha events (colinearity, complanarity, energy distribution) allow isolation cuts to be applied. Discrimination of the signal from physics background is based on the set of cuts established to optimize detector performance [13]:

- Acolinearity cut $|\Delta\theta| < 0.06$ deg;
- Acomplanarity cut $|\Delta\varphi| < 5$ deg;
- Energy balance cut $| E_R - E_L | < 0.1 \cdot E_{\min}$;
- Relative energy cut $(E_R+E_L)/2 > 0.75 \cdot E_{\text{beam}}$,

$E_{\min} = \min(E_R, E_L)$ and E_R , E_L being the total energy deposited on the right (front) and left side (back) of the luminosity calorimeter, respectively, and E_{beam} is the energy of the beam. All isolation cuts are applied assuming ideal reconstruction, since later will be shown that detector resolution does not affect the suppression of background, and assuming 100% reconstruction efficiency. It has been shown that Bhabha electrons can be detected very efficiently even in the regions with high beamstrahlung background [15].

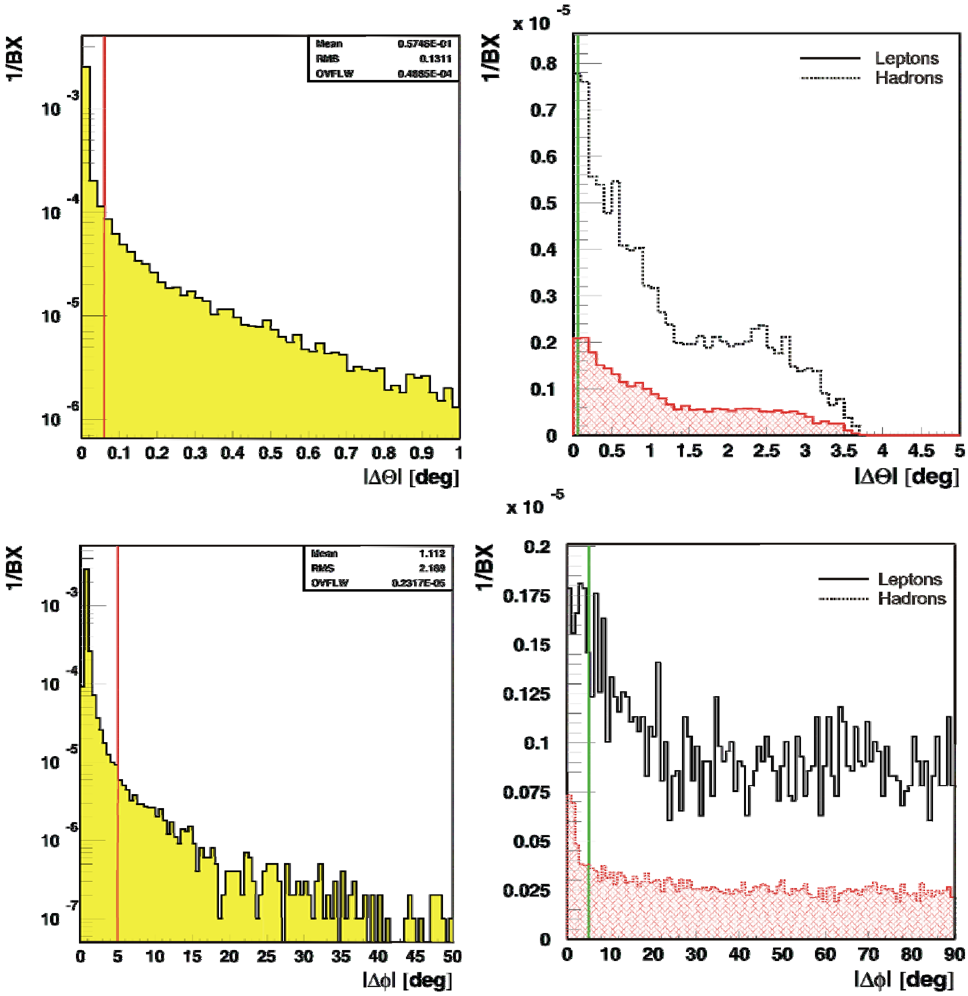

Fig. 11. |Δθ| and |Δφ| distributions for signal (left) and background (right). Vertical lines indicate cut-off values.

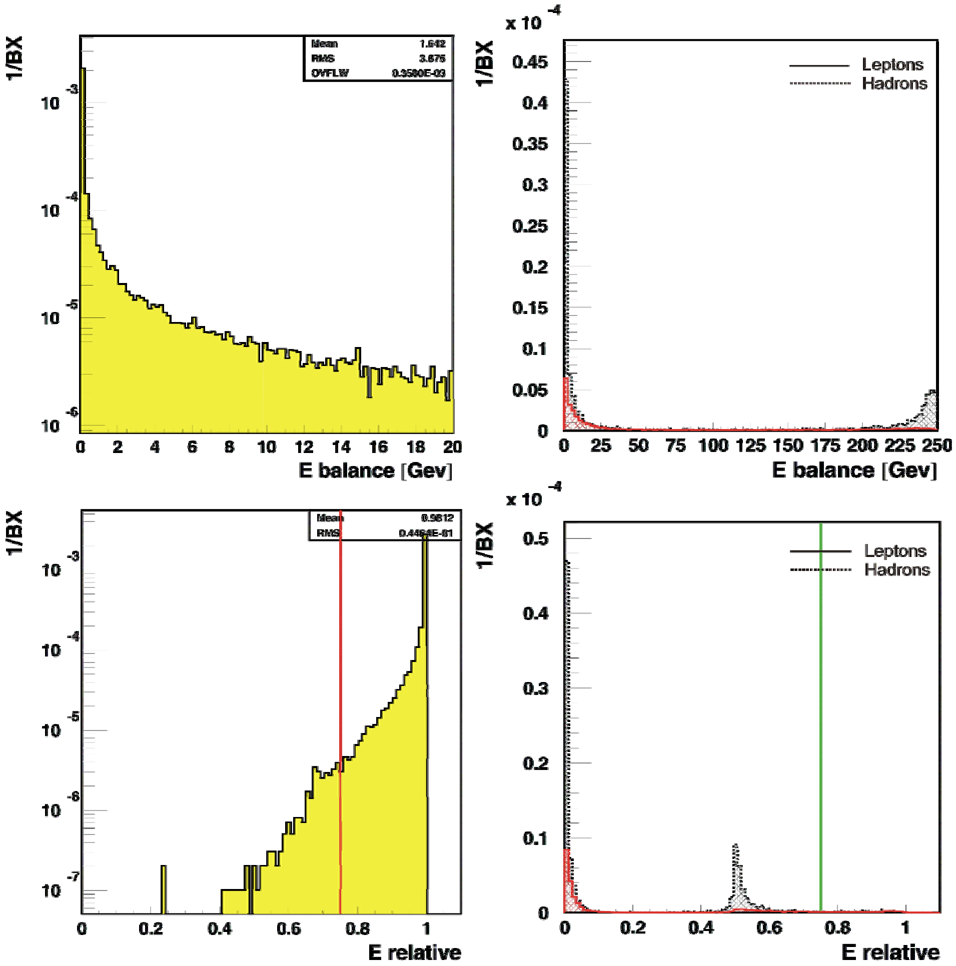

Fig. 12. Energy balance and relative energy distributions for signal (left) and background (right). Vertical lines indicate cut-off values.

Background rejection efficiency and signal efficiency are given in the Table 1, for the proposed set of cuts. As illustrated in Table 1, physics background is reduced to the level of 10^{-4}, with the loss of signal efficiency of ~20 %. Background to signal ratio is the bias to correct the measured total luminosity, as can be derived from (2).

Table 1. Selection and rejection efficiency for signal and background.

	Bhabha selection efficiency		Leptonic background rejection efficiency	Hadronic background rejection efficiency
1. $\|\theta\|<0.06$ deg	81.87%		95.20%	95.27%
2. $\|\Delta\varphi\|<5$ deg	97.96%		89.53%	90.42%
3. $E_{bal}<0.1.E_{min}$	90.61%		94.58%	95.45%
4. $E_{rel}>0.75$	99.08%		88.73%	95.96%
B/S(1,2,3)	$1.3\cdot10^{-4}$	80.60%	99.38%	99.78%
B/S(1,2,4)	$2.6\cdot10^{-4}$	80.80%	99.26%	99.47%

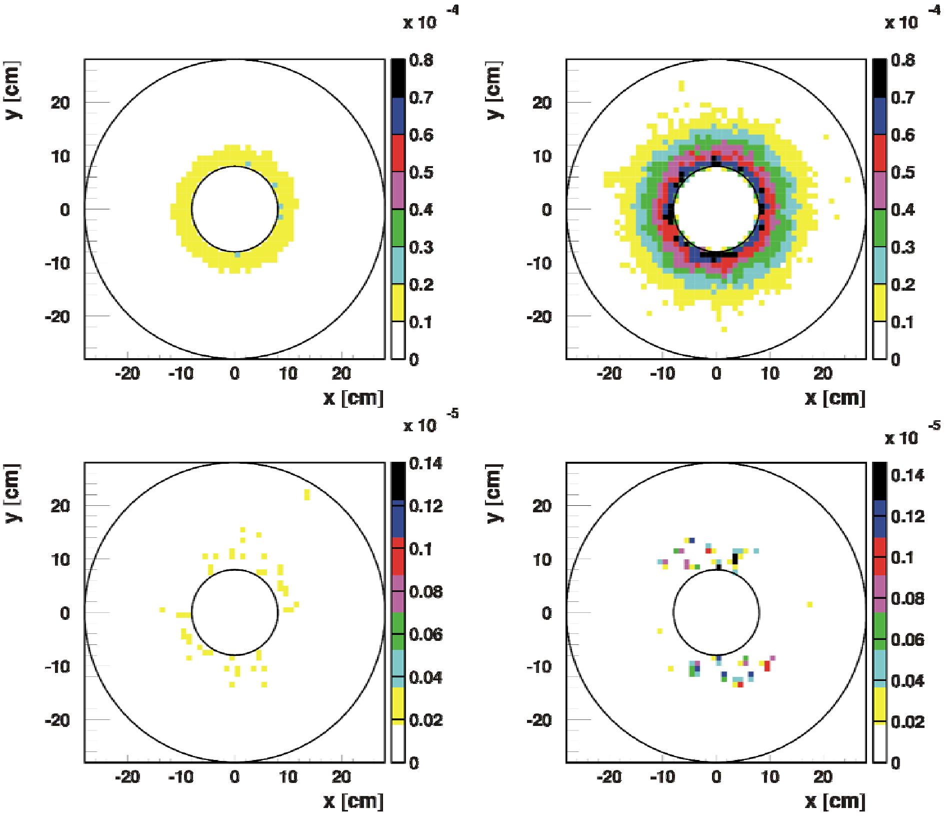

Fig. 13. Distribution of hits projected at the front plate of the luminosity calorimeter for leptonic (left) and hadronic (right) background, before (up) and after (down) applying the set of isolation cuts (1, 2, 3).

Distribution of hits projected at the front plate of the luminosity calorimeter is given in Figure 13, before and after cuts (1, 2, 3), for events that have at least a pair of showers at opposite sides of the luminosity calorimeter.

Background to signal ratio can be maintained at the level of 10^{-4}, with detector resolution in θ of order of mrad, as illustrated in Figure 14. This is far below the detector resolution of order of 10^{-2} mrad estimated from the detector performance study [7], [13]. We can conclude that, with the set of isolation cuts applied, signal to background ratio is practically insensitive to detector resolution effects.

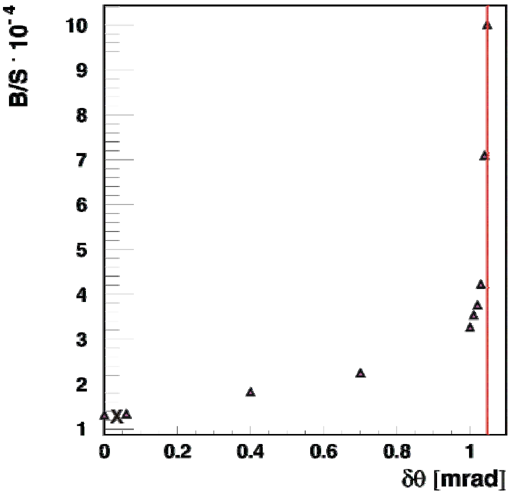

Fig. 14. Background to signal ratio versus absolute error in reconstruction of the polar angle. Vertical line represents acolinearity cut-off value. Detector resolution is indicated with cross.

Signal and background will be additionally affected by the beam-beam interaction effects. They will modify both initial and the final state through electromagnetic deflection and beamstrahlung, resulting in the total suppression of the Bhabha cross-section (BHSE) of order of 4.4% [16]. In order to minimize the effect of beam-beam interaction, the following set of cuts can be applied [16]:

- $E_{rel} > 0.8$
- $30\,mrad < |\theta| < 75\,mrad$

where the second cut has been subsequently applied to the forward and backward side of the detector, to accommodate enhanced acolinearity of Bhabha events.

Table 2. Selection and rejection efficiency for signal and background for cuts optimized to beam-beam interaction.

	Bhabha selection efficiency	Leptonic background rejection efficiency	Hadronic background rejection efficiency
1. 30 mrad<|θ|<75 mrad	64.99%	42.11%	41.95%
2. $E_{rel} > 0.8$	98.5%	90.74%	96.57%
All cuts	64.33%	93.69%	97.48%
B/S	$1.87 \cdot 10^{-3}$		

As shown in Table 2, these asymmetric cuts are cutting-off more than one third of the signal, with the presence of background ten times larger then with symmetric cuts. In principal, an annual Bhabha statistics of 10^9 events should allow a tolerance for 30% loss of the signal to still keep the statistical error of order of 10^{-4}. Uncertainty of background to signal ratio will influence the luminosity measurement as a component of the total systematic error. If the only uncertainty of this ratio comes from the (generated) cross-section, the corresponding systematic error is of order of 10^{-5}.

SUMMARY

The background to Bhabha events from the four-fermion NC processes has been studied for the luminosity calorimeter designed for ILC. It is shown that, due to the characteristic topology, Bhabha processes can be separated from physics background at the level of 10^{-4}. In order to reach this separation of signal from the physics background, there are no particular requirements on luminosity calorimeter performances. Physics background would occupy the read-out system approximately ten times less than the signal.

In the luminosity measurement, background to signal ratio will introduce a bias to be corrected for. Contribution to the systematic error of luminosity comes from the uncertainty of that bias. Under the assumptions used in this study, the uncertainty of background to signal comes from the error of the generated background cross-section, leading to the uncertainty of the bias of 10^{-6} for symmetric and 10^{-5} for asymmetric cuts. Considering that beam-beam effects in the luminosity measurement are of order of 10^{-2} (BHSE) and that, in addition, uncertainty of the bias from beam-beam deflection is not known, a holistic study of systematic effects in luminosity measurement is needed in order to optimize selection of the signal in the presence of various sources of systematic error.

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FIZIČKI FON U MERENJU LUMINOZNOSTI NA MEDJUNARODNOM LINEARNOM KOLAJDERU (ILC)

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Precizno merenje luminoznosti na Medjunarodnom linearnom kolajderu (ILC), sa relativnom greškom ne većom od 10^{-4}*, zahteva poznavanje i kontrolu brojnih sistematskih efekata, i to interakcije izmedju snopova koja modifikuje topologiju Bhabha procesa, mašinskog fona koji potiče od konverzije fotona izračenih u interakciji snopova, kao i fizičkog fona kojim dominira produkcija četvoro-fermiona mehanizmom neutralnih struja. U ovom radu su diskutovana svojstva fizičkog fona i njegova separacija od Bhabha procesa kao signala u merenju luminoznosti.*