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# An inference method of the luminosity spectrum in a future $e^+e^-$ linear collider

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**Abstract**

The high-luminosity $e^+e^-$ linear collider has been studied as an energy frontier future project in high energy physics, and is expected to be a good place for the precision experiments. The high-luminosity $e^+e^-$ linear collider no longer produces a monochromatic energy spectrum in the center of mass system, but a continuous and rather broad energy spectrum due to beamstrahlung of colliding $e^+$ and $e^-$ beams. Without precise knowledge of this energy spectrum alias the luminosity spectrum, the precision experiment in the linear collider should be confronted with a crucial problem. A statistical method based on new developments in information technology is examined with a view of determining the luminosity spectrum. A statistical model is formulated and a likelihood fitting is carried out to determine the luminosity spectrum by using Bhabha events. The $e^+$ and $e^-$ beam parameters, describing the luminosity spectrum, can be determined with an uncertainty of several percent by using 10 k Bhabha events under an ideal detector condition.
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*Keywords:* Luminosity spectrum; Linear collider; EM algorithm

## 1. Introduction

The high-luminosity $e^+e^-$ linear collider has been studied as an energy-frontier future project in high energy physics, and is expected to be a good place for precision experiments. It is well known, however, that the colliding $e^+$ and $e^-$ beams no longer have a monochromatic energy spectrum, but have a broad spectrum at the interaction, even if each original beam is tuned to have a monochromatic energy spectrum. This is due to beamstrahlung, where electrons and positrons feel the field produced by an opposite beam with a large density, and lose energy by radiating photons. The collision of $e^+$ and $e^-$ beams with such a broad energy spectrum also produces a broad energy spectrum in the center of mass system, which is called the luminosity spectrum. This broad luminosity spectrum causes a large defect to precision experiments [1]. A precise determination of the luminosity spectrum is indispensable for experimental studies, especially at the particle threshold, such as in $t$-quark physics [2].

In previous $e^+e^-$ collider experiments, the luminosity could be measured [18] just by counting Bhabha events, since the effect of beamstrahlung was negligible, and it was reasonable to assume that the event topology of Bhabha process is back-to-back. In the high-luminosity linear collider, however, Bhabha events are not always in the back-to-back topology, and must be identified by measuring the final $e^+$ and $e^-$ 4-momenta measured CM energy $\sqrt{s}$ of the event is calculated.

Several pioneer studies have been reported on luminosity spectrum measurements using Bhabha events. Most of them have proposed to use the accolinearity angle between the fi-

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nal $e^+$ and $e^-$ momenta for calculating the CM energy $\sqrt{s}$ of an event using the assumption that the nominal beam energy is known from the beam parameter of the collider or from an independent beam energy measurement [3–5,15]. This is the reason why the accolinearity angle is used instead of their 4-momenta, since the energy measurement of a high-energy electron or positron could suffer from low precision, while the accolinearity angle could be measured much more precisely than the 4-momenta. In the work of Ref. [4], determination of the luminosity spectrum by measuring the accolinearity angle of Bhabha events was studied. In a special case, where the $e^+$ and $e^-$ beam parameters are identical, they could extract the beam parameters, namely, the beam-energy spread, the topological beam size and the number of particles in a bunch, from the measured CM energy spectrum by a likelihood fitting. They calculate the CM energy, $\sqrt{s}$, approximately by $\sqrt{s} = \sqrt{s_0} - |\Delta p|$, where $\sqrt{s_0}$ is the nominal CM energy obtained from an independent energy measurement and $\Delta p$ is the momentum difference between the initial electron and positron, which is calculated using the accolinearity angle.

However, there are several limitations in this method. Since, for example, $|\Delta p|$ is positive definite, $\sqrt{s}$ is always less than or equal to the nominal CM energy. Because of the beam-energy spread, those events with a higher CM energy than the nominal value are produced, while their calculated $\sqrt{s}$ values are always less than the nominal value. Moreover, when the initial electron and positron have lost nearly identical amounts of energy, $\Delta p$ becomes almost zero and the $\sqrt{s}$ value is nearly equal to $\sqrt{s_0}$, regardless of the lost energy. The cause of these problems is the use of only the accolinearity angle for calculating the CM energy. The most crucial problem in this method is that when the $e^+$ and $e^-$ beam parameters are different, though this is the usual case, the beam parameters cannot be estimated just from the measured CM energy spectrum because of a lack of information.

To solve the problems experienced in previous work, a statistical method, developed based on recent advance in information technology, such as data mining and learning algorithms in neural computing, is introduced in Section 2. An exact Bhabha-event density function is formulated, using the differential cross section of the Bhabha process, the error distribution function of the 4-momentum measurement, and the luminosity functions represented by the Yokoya–Chen function. Then, the maximum-likelihood method is applied to the Bhabha-event density function as model distribution, and the luminosity function is estimated by taking the $e^+$ and $e^-$ beam parameters as the fitting parameters. Since the Bhabha-event distribution function is described as the marginal distribution function in terms of the $e^+$ and $e^-$ 4-momenta, the expectation-maximization (EM) algorithm is introduced. In Section 3, the Bhabha events at the ILC linear collider parameters are generated by using numerical simulations, and the method is applied to the data. In order to see just the potential of this method for the luminosity spectrum measurement, only the case of experiments with an “ideal detector condition” is considered for simplicity, that is, all measurements by detectors are assumed to be completely accurate.

## 2. Determination of luminosity spectrum by Bhabha event

### 2.1. The formalism

The Bhabha process has been used to determine the luminosity in the usual $e^+e^-$ collider, since it is a well-known elementary process whose cross section can be precisely calculated by perturbation theory of the electro-weak sector. In the ordinary $e^+e^-$ collider experiments, the luminosity can be given by (No. of Bhabha events)/(cross section) because of its monochromatic colliding beam energy, while in a high-luminosity linear collider the luminosity must be determined as the luminosity spectrum by measuring the scattered 4-momenta of electrons and positions as well as the number of events. Bhabha events in our method are parametrized by three kinds of 4-momenta: those of the colliding beams, $p_{e^\pm}$, those of scattered $e^+e^-$ from the Bhabha process (theoretical and not observable), $q'_{e^\pm}$, and those of the detected Bhabha event, $q_{e^\pm}$, respectively. The Bhabha event density function (the model distribution function), $N(q_{e^+}, q_{e^-})\, d^4q_{e^+}\, d^4q_{e^-}$, can be decomposed into the following three parts of the distribution functions:

$$
\begin{aligned}
&N(q_{e^+}, q_{e^-})\, d^4q_{e^+}\, d^4q_{e^-} \\
&\quad = C^{-1}\, d^4q_{e^+}\, d^4q_{e^-} \\
&\qquad \times \int d^4p_{e^+}\, d^4p_{e^-}\, G(q_{e^+}, q_{e^-}; \omega_{q'}, q'_{e^+}, q'_{e^-}) \\
&\qquad \times d\sigma(q'_{e^+}, q'_{e^-}; p_{e^+}, p_{e^-})\, L(p_{e^+}, p_{e^-}; \alpha_{e^+}, \alpha_{e^-}), \qquad (1)
\end{aligned}
$$

where $L(p_{e^+}, p_{e^-}; \alpha_{e^+}, \alpha_{e^-})$ represents a differential luminosity, $d\sigma(q'_{e^+}, q'_{e^-}; p_{e^+}, p_{e^-})$ the differential cross section of Bhabha events, and $G(q_{e^+}, q_{e^-}; \omega_{q'}, q'_{e^+}, q'_{e^-})$ a detection error distribution function, respectively. $C$ denotes the normalization factor used to satisfy $\int N(q_{e^+}, q_{e^-})\, d^4q_{e^+}\, d^4q_{e^-} = 1$. The parameter, $\alpha$, in the differential luminosity function parametrizes the luminosity spectrum, and $\omega_{q'}$ in the error distribution function parametrizes the detection error of the final $e^+$ or $e^-$ 4-momenta, respectively. The differential luminosity is approximately obtained by the beam distribution, $B_e(p; \alpha)$:

$$
L(p_{e^+}, p_{e^-}; \alpha_{e^+}, \alpha_{e^-}) = B(p_{e^+}; \alpha_{e^+}) B(p_{e^-}; \alpha_{e^-}). \qquad (2)
$$

$B(p_{e^\pm}; \alpha_{\mathbf{e}^\pm})$ can be an arbitrary distribution function that parametrizes the beam spectrum.

In this Letter we chose the Yokoya–Chen function as the beam-distribution function, which gives an empirical formula of the beam energy spectrum after beamstrahlung at the interaction point. The beam spectrum is parametrized by the beam parameters, such as the beam size and the density of electrons and positrons. The luminosity spectrum represented by the beam parameters, should be so useful that it gives feedback to parameter adjusting of the accelerator.

The Yokoya–Chen function is given by

$$
B(p; \alpha_{\mathbf{e}^\pm}) = \delta\big(p^{(x)}_{e^\pm}\big)\delta\big(p^{(y)}_{e^\pm}\big)\delta\big(P^{(E)}_{e^\pm} - \big|p^{(z)}_{e^\pm}\big|\big) Y\big(p^{(z)}_{e^\pm}; \alpha_{\mathbf{e}^\pm}\big),
$$

where colliding beams travel along $z$-axis with 4-momentum, $p = (E, 0, 0, \pm E)$, for $E \gg m_e$. The function, $Y(E; \alpha)$, is de-

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