Luminosity Determination at CLIC

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A preliminary study of the accuracy in the determination of the absolute and differential luminosity at CLIC, for e^+e^- collisions at $\sqrt{s} = 3$ TeV, has been performed. The effective collision energy $\sqrt{s'}$ has been reconstructed from the measured acolinearity of large angle Bhabha $e^+e^- \to e^+e^-$ events.

1. Introduction

The CLIC design aims at a linear collider able to deliver e^+e^- collisions at centre-of-mass energies $\sqrt{s}$ in the range 1 - 5 TeV with a luminosity of 10^{35} cm^{-2} s^{-1} [1]. Due to the intense electromagnetic interaction of the colliding beams, part of the beam energy is radiated in beamstrahlung, causing a significant fraction of the collisions to happen at energies $\sqrt{s'}$, below the nominal $\sqrt{s}$ value. This effect will need to be accurately measured and unfolded from the observed data, to relate them to the theoretical predictions. Accurate determinations of both the absolute luminosity and the luminosity spectrum are therefore crucial to preserve the CLIC physics potential. Bhabha scattering $e^+e^- \to e^+e^-$ represents a favourable reaction with a cross section still sizeable beyond 1 TeV (9.4 pb at $\sqrt{s} = 3$ TeV) and simple, accurately measureable final state. This note summarises the preliminary results on the estimation of the theoretical uncertainties on the absolute luminosity determination and the accuracy on the reconstruction of the differential luminosity spectrum using Bhabha events.

2. Luminosity Determination with Bhabha Scattering

At LEP-1 the final luminosity precision of 0.07% was achieved, by using double-tags for the Bhabha process. The theoretical QED prediction for the Bhabha process at LEP was obtained using BHLUMI Monte Carlo program [2]. The theoretical uncertainty σ_{th} of the BHLUMI prediction was estimated originally to be 0.1% [3], and later reduced to the level of 0.07% [4, 5, 6]. The main contributions to the theoretical uncertainties at LEP1 were (a) the photonic second order subleading correction $\mathcal{O}(\alpha^2 L_e)$ where $L_e = \ln \frac{|t|}{m_e^2}$, (b) the hadronic vacuum polarization, and (c) the $\mathcal{O}(\alpha^2)$ light fermion-pair production. The s-channel Z contribution being only $\sim 1\%$, its contribution was well under control. At LEP-1, the measured Bhabha rate had to be substantially larger than that of the s-channel Z at the resonance peek. Hence, the polar angle acceptance was pushed down to 25–50 mrad range, corresponding to $\sqrt{|t|}$ of 1-2 GeV.

At a high energy linear collider, the angular range of Bhabha luminometer will probably need to be shifted to $\sim$ 50–100 mrad due to background conditions. At 3 TeV, the t-channel transfer becomes 75–150 GeV and the t-channel Z_t exchange can in principle be as important as that of the t-channel photon exchange γ_t. The contribution from hadronic vacuum polarization increases at higher transfers too. It is thus important to estimate the magnitude of these theoretical uncertainties in the low angle Bhabha (LABH) process at TeV energies.

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The contributions from photonic corrections will scale linearly with L_e, if some part of $\mathcal{O}(\alpha^2 L_e)$ will still be missing from the Monte Carlo generators (which is however unlikely by a realistic time for CLIC operation). We therefore estimate the photonic uncertainty to increase, at most, by $\simeq 30\%$ w.r.t. its LEP-1 value. The Z_t contribution was estimated by completely removing the Z contribution. This changes the cross section by a few 0.1% at 0.8 TeV and by $2-6\%$ at 3 TeV.

The theoretical uncertainty of the $\mathcal{O}(\alpha)$ electroweak corrections in the LABH process at CLIC have been estimated with the help of the DIZET EW library of ZFITTER [7, 8]. This was obtained by manipulating the nonleading $\mathcal{O}(\alpha^2)$ EW corrections of $\mathcal{O}(G_F^2 M_t^2 M_Z^2)$ of Degrassi et.al., keeping $\mathcal{O}(G_F^2 M_t^4)$ as accounted for. This is shown in Figure 1, where the effect of change of M_H from 120GeV to 500GeV is also given. We estimate them to be 0.025% at 0.8 TeV and 0.10% at 3 TeV. Changing M_t from 165 GeV to 185 GeV has lead to even smaller effect. In summary, $\sigma_{th} \simeq 0.10\%$ of the LABH luminometer at CLIC due to EW corrections emerges as a conservative estimate.

The theoretical uncertainties of LABH due to hadronic vacuum polarization (HVP), taking 1995 estimates of HVP of [9, 10] was estimated as 0.03% at LEP-2. Using the same calculation of HVP we get 0.12% at 3TeV, i.e. larger by a factor of four. This means that HVP would become the dominant component of theory systematics on the absolute luminosity at CLIC, However the recent improvements of HVP [11, 12] improve the situation substantially; according to our preliminary estimates we get factor 2 reduction in the error due to HVP. By the time of CLIC operation we hope for another factor 2 of improvement.

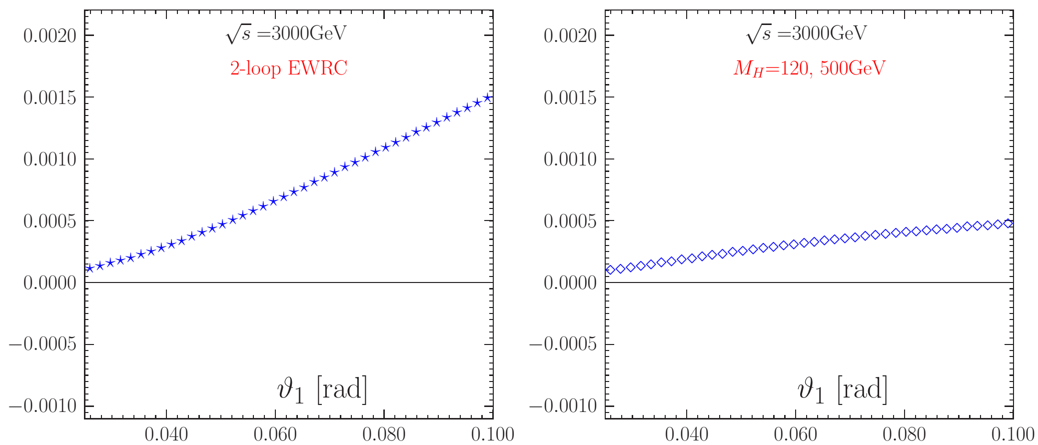

Figure 1: Change of Bhabha differential cross section due to uncontrolled 2-loop corrections and due to Higgs mass error. Results were obtained using DIZET library of ZFITTER [7, 8].

Summarizing we think that a theoretical uncertainty $\sigma_{th} \simeq 0.1\%$ for the low angle Bhabha process at energies up to 3 TeV is realistic.

Since the LABH cross section depends as $1/s$ on the total CMS energy, in order to preserve the 0.1% precision of LABH, a knowledge of the absolute beam energy calibration to $\sim 0.05\%$ accuracy is needed.

The energy spectrum of the luminosity also needs to be determined and this can be obtained accurately using the acolinearity of Bhabha scattering as discussed in the next section.

3. Bhabha Scattering and $\sqrt{s'}$

The reconstruction of the effective e^+e^- energy $\sqrt{s'}$ from the acolinearity in large angle Bhabha events has been proposed for a lower energy linear collider [13], extending the experience with the $\sqrt{s'}$ determination at LEP-2 [14].

In the approximation where the energy lost before the e^+e^- interaction is radiated in a single direction, the effective collison energy $\sqrt{s}$ can be related to the final state e^+e^- acolinearity by

$$\sqrt{s'} = \sqrt{s}\sqrt{1 - 2\frac{\sin(\theta_1 + \theta_2)}{\sin(\theta_1 + \theta_2) - \sin\theta_1 - \sin\theta_2}}$$

where θ_1 and θ_2 are the angles of the final electron and the positron w.r.t. the photon direction. Therefore, with this assumption, the $\sqrt{s'}$ distribution can be measured by a determination of the e^+ and e^- directions. At CLIC, there are two main processes leading to electron and positron energy loss, beamstrahlung (BS) and initial state radiation (ISR). In order to infer the $\sqrt{s'}$ spectrum due to BS it is important that ISR can be reliably computed and unfolded from the measured distribution.

4. Accuracy for $\sqrt{s'}$ Reconstruction

Bhabha events have been generated with the BHLUMI 4.04 generator [2]. The electron and positron energy spectra have been obtained with the GUINEAPIG [15] beam simulation for the CLIC parameters at 1.5 TeV beam energy. The generator has been modified to allow for varying centre-of-mass energy and for the final state particles particles to be boosted from the c.m. to the laboratory system.

The effect of the beam energy spread in the Linac has been included in the form of a Gaussian smearing with r.m.s. of 6 GeV. The determination of $\sqrt{s'}$ has been based only on the electron and positron direction determination, assuming a tracking coverage down to 7^o in polar angle. While the calorimetric information may provide further important constraints, it needs to be validated by a full simulation accounting for the background conditions at small angles. Therefore, no attempt to reconstruct ISR photons has been made in this study. The measurement of the final state particle energy is also important to be able to disentangle the effect of the correlations in the energies of the colliding particles, not taken into account in the approximation introduced. A detailed study of this effect has shown that the effect of these correlations is important for precisely describing the full beamstrahlung spectrum and need to be taken into account in future studies.

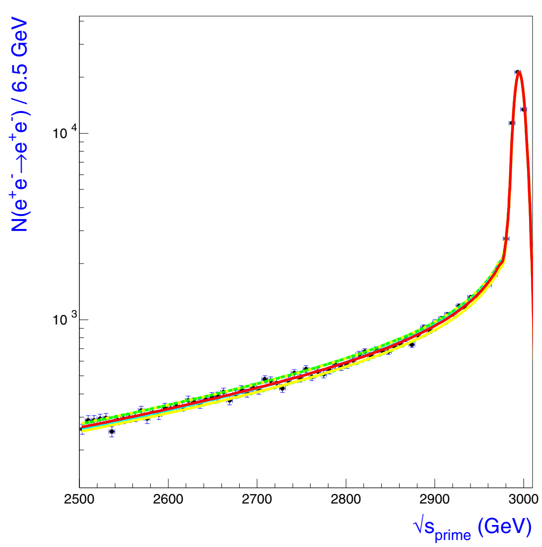

Figure 2: The reconstructed luminosity spectrum for CLIC at 3 TeV (points with error bars). The continuous lines represent the fit obtained using the first of the parametrizations discussed in the text, for the fitted value and by varying the parameters within the $\pm 2\sigma$ range.

The beamstrahlung spectrum has been parametrised using two models: 1) the modified Yokoya-Chen approximation [16]: $e^{-N_\gamma}(\delta(x-1) + \frac{e^{-k(1-x)/x}}{x(1-x)}h(x))$, $h = f(\Upsilon)$ where N_γ and Υ are treated as free parameters and 2) the CIRCE polynomial form: $a_0\delta(1-x) + a_1 x^{a_2}(1-x)^{a_3}$ were the free parameters are a_0, a_2, a_3 are respectively. The fraction F of events outside the 0.5% of the nominal $\sqrt{s}$ energy has also been left free and extracted from the reconstructed data.

A study of the mass and width of a broad resonance, such as a Z' additional gauge boson, by energy scan showed that, for the differential luminosity spectrum shape not to contribute significantly to the overall measurement accuracy δN_γ needs to be measured to $< 5 \times 10^{-2}$ and δF to $< 2 \times 10^{-2}$ [17] .

The accuracy on the parameters has been obtained by peforming a likelihood MINUIT fit to reconstructed $\sqrt{s'}$ spectrum and the uncertainty on the mean $\sqrt{s'}/\sqrt{s}$ has been extracted accounting for correlations. Results are given for an equivalent luminosity $\int \mathcal{L} = 15$ fb^{-1}, corresponding to $\simeq$ 3 days at the nominal luminosity of 10^{35} cm^{-2}s^{-1}. The study has been performed for two different assumptions on the CLIC parameters, denoted here as CLIC01 and CLIC02, corresponding to different beamstrahlung spectra.

Par.	CLIC.01	CLIC.02
$\delta N_\gamma / N_\gamma$	$\pm$ 0.044	$\pm$ 0.084
$\delta \Upsilon / \Upsilon$	$\pm$ 0.019	$\pm$ 0.018
$\delta \sqrt{s'}/\sqrt{s}$	$\pm 7.8 \times 10^{-5}$	$\pm 5.3 \times 10^{-5}$

Par.	CLIC.01	CLIC.02
$\delta a_0 / a_0$	$\pm$ 0.044	$\pm$ 0.049
$\delta a_2 / a_2$	$\pm$ 0.089	$\pm$ 0.058
$\delta a_3 / a_3$	$\pm$ 0.018	$\pm$ 0.021
$\delta \sqrt{s'}/\sqrt{s}$	$\pm 9.8 \times 10^{-5}$	$\pm 7.2 \times 10^{-5}$

The sensitivity to details of the beamstrahlung spectrum obtained in this analysis needs to be further validated once the detector resolution effects have been taken into account. However it has been shown that the detector resolution can be made small compare to the intrinsic beam energy spread.

5. Conclusions

A first investigation of the accuracy in the determination of the absolute and differential luminosity for CLIC at multi-TeV e^+e^- collisions has been performed. The preliminary results show that, despite the significantly different regime compared to LEP and lower energy e^+e^- linear collider projects, the absolute luminosity of CLIC can be determined with a theoretical accuracy of the order of 0.1% using Bhabha scattering. The differential luminosity spectrum can also be extracted from the study of the same process. The analysis of the acolinearity distribution of the scattered e^+ and e^- particles allows to reconstruct the effective centre-of-mass energy $\sqrt{s}$ with a relative accuracy of the order of 10^{-4} or better depending on the assumed beam parameters. A full analysis, taking into account the energy correlations of the colliding beams, but also the possibility of measuring the energy of the final state particles is needed to further improve the description of the differential luminosity spectrum.

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