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Metrology requirements for the integrated luminosity measurement using small-angle Bhabha scattering at ILC

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Precision measurement of the integrated luminosity $\mathscr{L}$ at future Higgs factories, including ILC, is of crucial importance for the cross-section measurements, and in particular for the line-shape measurements at the Z-pole. Since there is no up-to-date estimate of the integrated luminosity uncertainties arising from metrology effects at ILC, here we review the metrology requirements for the targeted precision of $\mathscr{L}$ at foreseen ILC center-of-mass energies: $91.2\,\mathrm{GeV}$, $250\,\mathrm{GeV}$, $500\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$, using small-angle Bhabha scattering.

This work was carried out in the framework of the ILD Concept Group

1 Introduction

The realistic target for integrated luminosity ($\mathscr{L}$) precision at future high energy e^+e^- colliders is set by the requirements of their physics programs, primarily aiming to study the properties of a Higgs boson in the operation mode at 250 GeV center-of-mass energy. For the most of these measurements, relative systematic uncertainty of the integrated luminosity of $\sim 10^{-3}$ should suffice. The same holds for a TeV scale directly accessible at linear colliders like ILC [1]. At lower center-of-mass energies dedicated for precision EW studies, the targeted luminosity precision is set to $\sim 10^{-4}$, primarily from the line-shape measurements at the Z resonance and the W boson mass measurement from the W-pair production line shape at the threshold [2].

The feasibility of such precision is challenged by numerous effects related to manufacturing, positioning and performance of the luminosity monitor, in addition to the uncertainties of beam properties, collectively referred to as metrology. These effects impact the available phase space for detection of the final state particles, introducing systematic uncertainty in the integrated luminosity measurement.

Since the monitoring systems for the most of these effects are under development, this study aims to provide tolerable margins from the point of view of the integrated luminosity precision goals. Each effect is set to contribute to the relative uncertainty of the integrated luminosity as $1 \cdot 10^{-3}$ $(1 \cdot 10^{-4})$ at the center-of-mass energy of 250 GeV and above (at the Z-pole), limiting the overall contribution from metrology to the relative uncertainty of $\mathscr{L}$ to less than $3.3 \cdot 10^{-3}$ $(3.3 \cdot 10^{-4})$, since many of the precision margins presented here can be easily surpassed with the existing technologies.

The FCAL Collaboration has proposed instrumentation of the very forward region of the ILD detector at ILC [3]. The luminometer design, performance and prototyping are documented in [4], [5] and [6].

At 2500 mm from the IP, the luminometer will be centered around the outgoing beam at 7 mrad polar angle with respect to the z-axis, preserving the symmetry of head-on collisions at ILC with the crossing angle of 14 mrad. Its geometrical aperture is 31-77 mrad, while the sampling term is constant in the range of 41-67 mrad, which defines the fiducial volume (FV) [4]. This study relies only on the size of the fiducial volume and its effective change due to the effects from metrology to be described.

2 Simulation and analysis

We have simulated 10 million small angle Bhabha scattering events using the BHLUMI V4.04 Bhabha event generator [7] for each energy considered. Bhabha events are generated from 20 mrad to 200 mrad, to allow events with non-collinear final state radiation to contribute. Initial state radiation is also considered while beam-beam interactions are neglected. Also, we do not consider electromagnetic deflection of the final state due to interactions with the field of the corresponding outgoing beam. Asymmetrical event selection in polar angles (AS1) is applied, in a way that at one side of the luminometer a full fiducial volume is considered, while at the other side the inner and outer radii of the fiducial volume are narrowed by 1 mm. Modification of the counting volume is applied subsequently on the left and right arm of the luminometer, on event-by-event basis. This approach (with some variations between experiments) has been applied at LEP [8], reducing the net systematic effect arising from left-right asymmetries.

The following systematic effects that will be present due to the uncertainties of the luminometer radial dimensions, positioning with respect to the IP and relative positioning of detector halves, as well as due to luminometer vibrations in the transverse and longitudinal direction are considered:

1. uncertainty of the inner radius of the luminometer's counting volume (Δr_{in}),
2. uncertainty of the outer radius of the luminometer's counting volume (Δr_{out}),
3. RMS of the Gaussian spread of the measured radial shower position with respect to the true hit position[1] (σ_r),
4. uncertainty of the longitudinal distance between left and right halves of the luminometer (Δl) assuming that both halves are moving simultaneously towards the IP or away from it for $\Delta l/2$,

[1] True Bhabha position can be measured by placing a Si tracker plane in front of the luminometer with the precision of several microns. In addition, this would provide electron-photon separation.

5. RMS of the Gaussian distribution of mechanical fluctuations of the luminometer with respect to the IP in the radial direction ($\sigma_{x_{IP}}$),

6. RMS of the Gaussian distribution of mechanical fluctuations of the luminometer with respect to the IP in the axial direction ($\sigma_{z_{IP}}$),

7. tilt of the luminometer (both arms) equivalent to a rotation around y-axis for a certain angle ($\Delta\phi$).

Also, the beam bunches are finite in size and interaction may occur anywhere inside the bunches. In addition, beam synchronization may cause longitudinal (axial) displacements of the IP. Thus we consider:

8. radial (Δx_{IP}) displacements of the interaction point with respect to the luminometer,

9. axial (Δz_{IP}) displacements of the interaction point with respect to the luminometer. From Δz_{IP}, maximal time shift in beam synchronization ($\Delta\tau$) can be determined.

Any asymmetry of the beam energies occurring either on an event-by-event basis as a random variation due to the beam energy spread (BES) or as a permanent bias of one beam energy with respect to the other, will cause a boost (assumed longitudinal[2]) of the initial and consequently of the final electron-positron system. The boost (β_z) of Bhabha particles will lead to an effective change of the luminometer acceptance seen from the final state e^- (e^+) reference frame and to the consequent change of the Bhabha count. We thus consider two additional systematic effects:

10. RMS of the Gaussian distribution of the beam energy spread ($\sigma_{E_{BS}}$) and

11. difference in energy (ΔE) between the colliding beams.

Every effect is individually considered to lead to the overall relative change of count of 10^{-4} (10^{-3}) at the Z-pole (higher center-of-mass energies). In this respect, the maximal tolerance is derived for the parameters under study. The approximate maximal tolerance of the considered metrology parameters is listed in Table 1.

Table 1: Maximal absolute precision of luminometer mechanical parameters and beam parameters, each contributing as $10^{-4}(10^{-3})$ to the relative uncertainty of $\mathscr{L}$ at the Z^0 pole (higher energies).

parameter	**Z-pole**	**250 GeV**	**500 GeV**	**1 TeV**
Δr_{in} (μm)	20	200	200	200
Δr_{out} (μm)	60	600	600	550
σ_r (mm)	0.3	0.5	0.5	0.5
Δl (mm)	0.2	2.5	2.5	2.5
$\sigma_{x_{IP}}$ (mm)	0.3	0.6	0.6	0.6
$\sigma_{z_{IP}}$ (mm)	5	10	10	10
$\Delta\phi$ (mrad)	14	35	35	35
Δx_{IP} (mm)	0.3	0.6	0.6	0.6
Δz_{IP} (mm)	4	8	8	8
$\Delta\tau$ (ps)	13	27	27	30
$\sigma_{E_{BS}}$ (MeV)	110	500	1000	2000
ΔE (MeV)	5	125	250	500

As can be seen in Table 1, at the Z-pole a few challenges are identified, such as the uncertainty of the beam energy and eventual difference in energy between beams present in a form of bias, that should both be known at the level of $\sim 5\,\mathrm{MeV}$. Uncertainty of the luminometer inner aperture is known to be critical due to the $1/\theta^3$ dependence of the Bhabha cross-section on the polar angle. Asymmetric counting with the luminometer positioned at the outgoing beams relaxes to some extent this uncertainty to the level of $\sim 20\,\mu\mathrm{m}$. It is yet to

[2]For the boost to be longitudinal, we assume that the initial state radiation is emitted along the z-axis (in the head-on collisions) and that the final state radiation is emitted in the direction of a final state electron (positron).

be confirmed in a full detector simulation how the uncertainty of the luminometer's inner aperture translates to the definition of the fiducial volume. The beam energy spread smaller than 0.24% at the Z-pole and 0.40% at higher center-of-mass energies should be feasible with the current design of ILC. At studied center-of-mass energies of 250 MeV and above we do not identify critical aspects of metrology from the point of view of existing monitoring technologies.

3 References

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