



Potential and challenges of the physics measurements with very forward detectors at linear colliders

Ivanka Božović Jelisavčić^{a,*}, G. Kačarević^a, S. Lukić^a, S. Poss^b, A. Sailer^b, I. Smiljanić^a
on behalf of the FCAL collaboration

^a Vinča Institute of Nuclear Sciences, M. Petrovica Alasa 12-14, 11000 Belgrade, Serbia

^b CERN, 1211 Geneva 23, Switzerland

Abstract

The instrumentation of the very forward region of a detector at a future linear collider (ILC, CLIC) is briefly reviewed. The status of the FCAL R&D activity is given with emphasis on physics and technological challenges. The current status of studies on absolute luminosity measurement, luminosity spectrum reconstruction and high-energy electron identification with the forward calorimeters is given. The impact of FCAL measurements on physics studies is illustrated with an example of the $\sigma_{\text{HWW}} \cdot \text{BR}(H \rightarrow \mu^+ \mu^-)$ measurement at 1.4 TeV CLIC.

Keywords: forward region, calorimeters, luminosity, particle identification, linear collider

1. Introduction

The instrumentation of the very forward region at a future linear collider is facing numerous challenges: the angular coverage down to the smallest polar angles requires good radiation hardness of the sensors for the calorimeters, while reconstruction of the EM shower to be associated with a high-energy electron is performed in presence of intense background. Finally, beam-beam effects present challenges for the luminosity measurement.

2. Instrumentation of the very forward region

Two dedicated calorimeters of high energy and polar angle resolution are foreseen to instrument the very forward region of the future linear collider

detectors – Luminosity Calorimeter (LumiCal) and Beam Calorimeter (BeamCal) (Fig. 1). The position and size of the apertures of the calorimeters are dictated by beam-induced backgrounds at low angles (see Table 1). The same background drives radiation-hardness requirements, as well as the trade-off between granularity and occupancies.

Both forward calorimeters are twin Si-W compact sampling calorimeters that consist of 30/40 layers at ILC/CLIC. The Molière radius is of the order of 1 cm [1, 2]. LumiCal is required to measure the luminosity with a precision of $\sim 10^{-3}/10^{-2}$ at ILC/CLIC [1], and BeamCal will perform a bunch-by-bunch estimate of the luminosity and, accompanied by a pair monitor [4], assist the beam tuning when included in a fast feedback system [5].

* Corresponding author. Tel./fax. +381-116-455-041; e-mail: ibozovic@vinca.rs

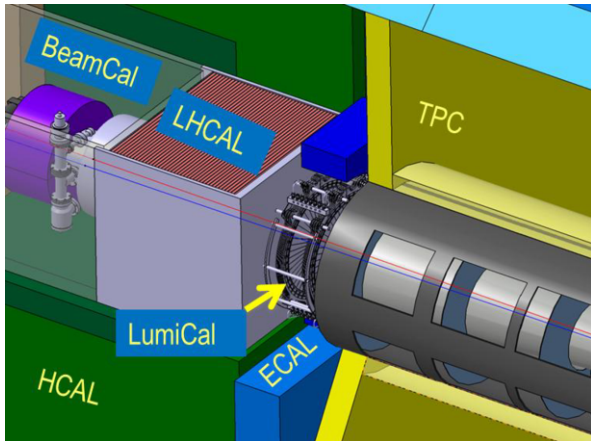


Fig. 1. The very forward region of the ILC detector. TPC denotes the central track chamber, ECAL the electromagnetic and HCAL the hadron calorimeter [1].

Table 1. Angular acceptance of BeamCal and LumiCal for ILC and CLIC [1, 2]

Angular acceptance [mrad]	ILC	CLIC
BeamCal	5-40	15-38
LumiCal	31-77	38-110

3. Status of the FCAL R&D

In order to examine forward detectors under realistic conditions, several tests of LumiCal and BeamCal sensor plane prototypes are performed in 2010 and 2011, using an electron beam (2 GeV, 4 GeV and 4.5 GeV) at DESY Hamburg.

Prototypes of LumiCal silicon sensors have been designed at the Institute of Nuclear Physics PAN in Cracow [6] and manufactured by Hamamatsu Photonic (Fig. 2 left). The BeamCal prototype GaAs sensors (Fig. 2 right) have been produced by Tomsk State University [7]. The front-end and readout electronics is developed and fabricated at AGH-UST Cracow [8, 9]

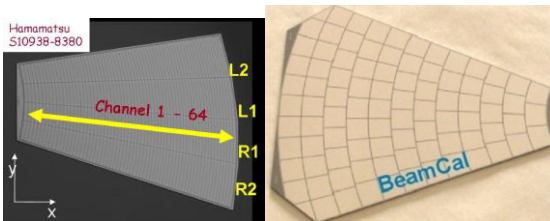


Fig. 2. Left: A prototype silicon sensor for LumiCal [7]. Right: Prototype of a GaAs sensor for BeamCal. The numbers on the pads are later used to assign results to certain pads [10].

Prototypes of sensor planes assembled with FE and ADC ASICs, were built using LumiCal and BeamCal sensors and installed in an electron beam. The trajectories of beam particles were measured by four planes of a silicon strip telescope [11]. The front-end electronics outputs were sampled synchronously with the beam clock, a mode to be used at the ILC [1]. Data were taken for different pads and also for regions covering pad boundaries. Signal-to-noise ratios better than 20 were measured for beam particles both for LumiCal and BeamCal sensors, as illustrated in Figure 3 left. The impact point on the sensor is reconstructed from the telescope information. Using a colour code for the signals on the pads the structure of the sensor becomes nicely visible, as also seen in Fig. 3. The sensor response was found to meet all the requirements.

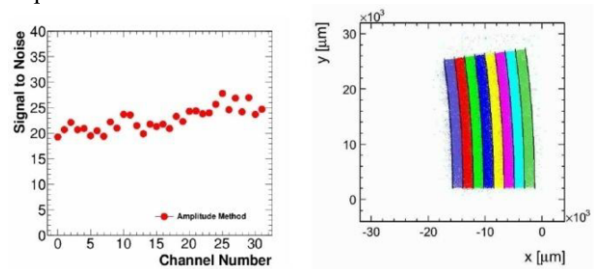


Fig. 3. Left: The signal-to noise ratio of all readout channels before calibration. Right: Distribution of the predicted impact points on pads with a colour coded signal [1].

4. FCAL measurements

4.1. Integral luminosity measurement

The absolute value of the luminosity L and the luminosity spectrum $L(E_{CM})$ are key figures in most physics analyses at collider experiments. The basic expression,

$$L\sigma_a = N_a \quad (1)$$

relates the luminosity, the cross section σ_a of an elementary process a in a given part of the phase space defined by experimental selection cuts, and the number of detected events N_a of the process a in the same part of the phase space.

Presently the most precise way to measure luminosity at a linear collider is to use Bhabha-scattering as the gauge process a . The cross section scales approximately with θ^{-3} meaning that final state particles are emitted at very low angles below 5 deg. The energies of the final-state particles are close to the beam energy. The cross section is relatively high, ensuring good statistical accuracy. A precision of

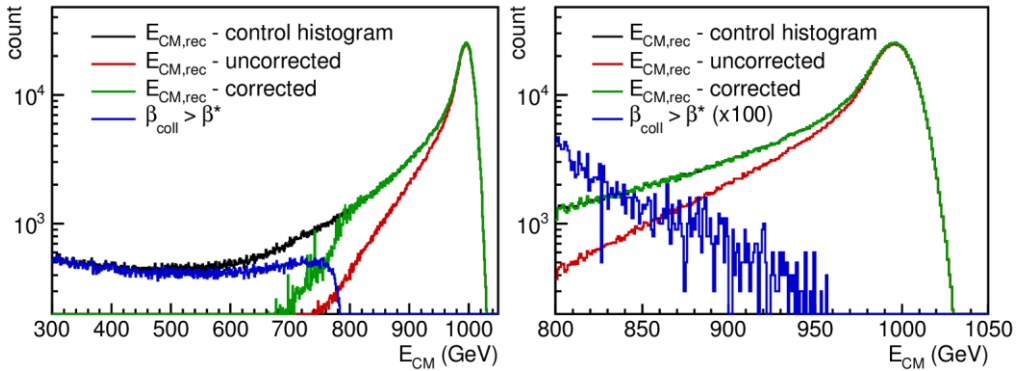


Figure 4: Correction of the counting loss due to Beamstrahlung and ISR at 1 TeV. Left: whole spectrum; Right: zoom on energies above 800 GeV. (Black: Simulated control spectrum without counting loss due to Beamstrahlung and ISR; red: Reconstructed ECM spectrum affected by the counting loss; Green: Reconstructed spectrum with correction for the counting loss due to Beamstrahlung and ISR; Blue: events inaccessible to the correction).

better than 10^{-3} was reached at LEP, thanks to a careful experimental setup, and precise QED calculations [12–15]. At future linear colliders, the CM energy will be 3 to 30 times higher, and the luminosity up to thousand times higher. In such conditions, intense beam-beam effects induce severe counting biases of Bhabha-events, which requires dedicated correction procedures, as pointed out in Ref. [16].

The beam-beam EM interaction results in a very strong focusing effect of the bunches, which enhances the luminosity, but induces emission of intense and energetic EM radiation, *Beamstrahlung*, from the electrons in the bunch. The angular distribution of Beamstrahlung is contained in several hundred milliradians around the beam axis. The distribution of energy loss of individual electrons is very wide, and depending on the conditions, may reach the beam energy. This leads to the creation of the low-energy tail of the luminosity spectrum. At the level of individual collision events, Beamstrahlung energy loss prior to the collision is asymmetric between the two colliding particles, resulting in non-zero velocity of the CM frame of the collision β_{coll} with respect to the lab frame.

As the final Bhabha angles are collinear in the collision frame, and β_{coll} is to a good approximation collinear with the beam axis, β_{coll} can be determined from the final angles using the Lorentz equations for both final Bhabha particles. This allows event-by-event correction of the angular counting loss with permille precision as described in Refs. [17,18]. Figure 4 shows the result of this correction in the case of a 1 TeV ILC. The control spectrum (black) contains all events that would hit the fiducial volume of the LumiCal if the velocity of the collision frame was

always zero. The detected spectrum is shown in red, and the corrected spectrum in green. The blue line represents the events for which β_{coll} is higher than the limiting value β^* , at which the effective acceptance of LumiCal is reduced to zero. Due to kinematic constraints, high values of β_{coll} are possible only with high energy loss, which explains the sudden drop of such events at 80% of the nominal CM energy. However, a small number of events with apparent $\beta_{coll} > \beta^*$ is present also at energies above 80% of the nominal CM energy, because occasionally the assumption that β_{coll} is collinear with the beam axis is broken due to off-axis ISR. This is visible in the zoomed figure 1 right, where these events are scaled by a factor 100. ISR and FSR are QED phenomena, and their energy- and angular distributions can be precisely calculated [19], which allows for a reliable correction of the fraction of events with $\beta_{coll} > \beta^*$ in the upper part of the spectrum.

After scattering, the final electrons may emit FSR. Beside that, their trajectories are deflected inwards by a fraction of mrad under the influence of the EM field of the opposing bunch, thus inducing a small additional angular counting loss termed Electromagnetic Deflection (EMD) effect. Beamstrahlung may be emitted at this stage as well, but since it is emitted under very small angles with respect to the final electrons, it is summed with the electrons in the calorimeters. The effect of EMD is of the order of one permille. It can be corrected by simulation to good precision.

Precise reconstruction of the shape of the luminosity spectrum in the peak, as well as down to at least 50% of the nominal CM energy is possible by fitting a 2D model of the luminosity spectrum,

describing both the distribution of the CM energy and the asymmetry between the energies of the initial-state particles, to the 3D measured data that include the measured energies of both final Bhabha particles, as well as the acollinearity of their momenta [20].

4.2. High-energy electron identification

In the region below 8 degrees, the tracking information, as well as hadronic calorimetry, are not available. Background processes involving spectator electrons escaping near the beam tube mimic the missing energy signature of the signal. Electron detection in the very forward region involves the reconstruction of EM showers in the presence of intense beam-induced background consisting of a large number of low-energy particles, mostly incoherent pairs and hadrons [21]. This requires clustering algorithms adapted for intense background, as well as basic particle distinction based on shower profile shapes.

At very low angles, electron tagging is affected by a relatively high probability of detection of individual final-state particles from Bhabha events in random coincidence with the analysed processes. This causes a loss of statistics because of indiscriminate rejection of a fraction of interesting physics events. In the example of a 1.4 TeV CLIC, taking into account the boost of the Bhabha event CM frame due to beam-beam effects, as well as the 0.5 ns bunch spacing, and assuming a digitizer timing step of 10 ns, more than 30% of all events can be expected to be falsely tagged because of coincident detection of at least one final particle from a Bhabha event [23]. In order to reduce the rate of coincident tagging of Bhabha particles, energy and angular cuts must be imposed on electron tagging. For example, if only showers with energy higher than 200 GeV and polar angle above 1.7 degrees are tagged, the Bhabha coincidence probability drops to 7%.

The tagging probability can be simulated by parameterisation of the distribution of the reconstructed energy fluctuations due to the presence of the background and to the intrinsic energy resolution of the calorimeters. Figure 5 shows the longitudinal profiles of energy deposition by EM showers and by the beam-induced background in the LumiCal at CLIC. One can readily see that the background profile is fairly flat in the region of the maximum of the signal profile. This implies that in the limiting case of low energy events, the signal will be

distinguishable from background in certain cells near the maximum of the signal profile.

A rough estimate of the tagging probability can be obtained in a simulation by adding random Gaussian fluctuations, corresponding to the estimated background fluctuations, to the energy of the MC particles entering the angular range of the calorimeters. An ad hoc requirement is then imposed that the signal is above the background by at least 2σ background fluctuations in at least 10 aligned pads in consecutive layers of the detector. Considering that the width at half maximum of the signal profile is about ten layers, this translates to a requirement that the signal is above the mean background level by at least 4σ background fluctuations in the pad with the maximum signal deposition. The dependence of the tagging probability on the electron energy obtained in this way is shown in Figure 6 for the case of BeamCal at a 3 TeV CLIC.

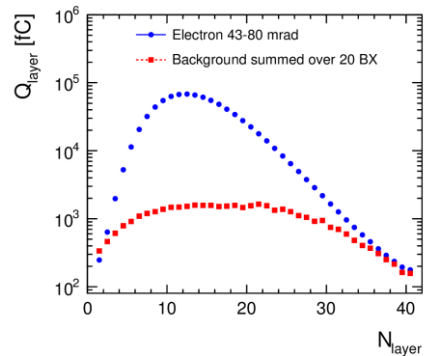


Figure 5: Longitudinal profiles of energy deposition by EM showers and by the beam-induced background in the LumiCal at CLIC. Taken from Ref. [21].

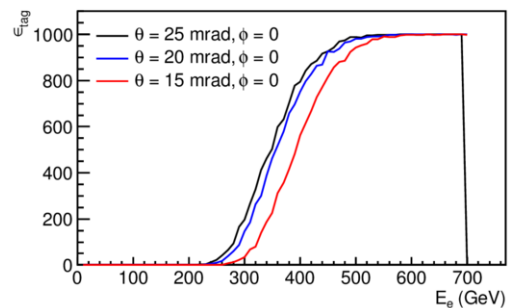


Figure 6: Tagging probability as a function of electron energy and angle in BeamCal. Estimated using the assumption of a 4σ requirement for the layer with maximum energy.

5. Impact on other physics measurements

The uncertainty of the measured absolute luminosity enters the systematic uncertainty figure of all cross-section measurements. Moreover, at colliders for which the luminosity spectrum reaches to the lowest energies, the luminosity is folded with the differential cross section starting from the threshold of the analyzed process. This requires precise knowledge of the luminosity spectrum, as well. In threshold scans, the luminosity spectrum, in particular the luminosity peak shape affects the results of the scan in a considerable way [22]. It is thus indispensable to know the luminosity spectrum to sufficient precision in order to be able to fit the theoretical distributions of the kinematic parameters to the measurement. In Ref. [20] it was shown that the impact of the luminosity-spectrum on the final uncertainty in the measurement of the smuon mass and neutralino mass from smuon pair production in the SUSY search at a 3 TeV CLIC is smaller than the statistical uncertainty.

The electron tagging in the very forward region improves the sensitivity of measurements with the missing energy signature. In the measurement of the $H \rightarrow \mu\mu$ decay, it allows vetoing over 40% of the events in background processes with spectator electrons [23].

6. Conclusion

The main deliverables from the very forward calorimetry at both ILC and CLIC are: fast luminosity and beam-parameter estimate using beamstrahlung, precision integrated luminosity measurement at the permille level at the top 30% of the spectrum, luminosity spectrum reconstruction within less than 5% and the low-angle electron tagging. The latest three have been discussed in this paper illustrating the mature stage of design, performance in the test-beam and simulation studies of the very forward detectors.

In addition, instrumentation of the very forward region is relevant for physics analyses beyond the scope of the FCAL, whenever processes of interest have missing energy signatures or are peaked very forward.

Acknowledgments

We acknowledge the support from the MPNTR of the Republic of Serbia for supporting the FCAL related studies within the national project OI171012.

References

- [1] T. Behke et al. (Editors), The International Linear Collider – Technical Design Report, Vol. 4: Detectors, 2013.
- [2] M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte and N. Toge (Editors), A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report, CERN-2012-007
- [3] P. Bambade, V. Drugakov, and W. Lohmann, “The Impact of BeamCal performance at different ILC beam parameters and crossing angles on stau searches” *Pramana* 69, 1123–1128, arXiv:physics/0610145 [physics]. LAL-06-145, 2007.
- [4] Y. Sato, Study of Pair-monitor for ILD, Proceedings of the Workshop of the Collaboration on Forward Calorimetry at ILC, Vinca Inst. of Nucl. Sciences, 22-23 September 2008, 2008.
- [5] C. Grah and A. Saponov, “Beam parameter determination using beamstrahlung photons and incoherent pairs” *JINST* 3 (2008) P10004.
- [6] J. Blocki et al., Silicon Sensors Prototype for LumiCal Calorimeter, Eudet-Memo-2009-07, <http://www.eudet.org/e26/e28/e42441>, 2009.
- [7] H. Abramowitz et al. [FCAL Collaboration], Performance of a fully instrumented sensor plane of the forward calorimeter of a LC detector, draft, 2014.
- [8] M. Idzik, Sz. Kulis, D. Przyborowski, Development of front-end electronics for the luminosity detector at ILC, *Nucl. Inst. And Meth. A*, vol. 608, pp.169-174, 2009.
- [9] M. Idzik, K. Swientek, T. Fiutowski, Sz. Kulis, P. Ambalathankandy, A power scalable 10-bit pipeline ADC for Luminosity Detector at ILC, *JINST* 6 P01004, 2011.
- [10] J. A. Aguilar et al., Luminometer for the future International Linear Collider - simulation and beam test results, *Physics Procedia* 00, 2013.
- [11] I. Gregor, http://www.desy.de/~gregor/MVD_Telescope, 2010
- [12] OPAL Collaboration, *Precision luminosity for Z0 line shape measurements with a silicon tungsten calorimeter*, *Eur.Phys.J. C* 14 (2000) 373–425, [hep-ex/9910066].
- [13] **ALEPH Collaboration**, *Measurement of the Z resonance parameters at LEP*, *Eur.Phys.J. C* 14 (2000) 1–50.
- [14] **L3 Collaboration**, *Measurements of cross-sections and forward backward asymmetries at the Z resonance and determination of electroweak parameters*, *Eur.Phys.J. C* 16 (2000) 1–40, [hep-ex/0002046].
- [15] A. Arbuzov et al., *The present theoretical error on the Bhabha scattering cross section in the luminometry region at LEP*, *Physics Letters B* 383 (1996) 238.
- [16] C. Rimbault, P. Bambade, K. Mönig, and D. Schulte, *Impact of beam-beam effects on precision luminosity measurements at the ILC*, *Journal of Instrumentation* 2 (2007) P09001.
- [17] S. Lukić, I. Božović-Jelisavčić, M. Pandurović, and I. Smiljanić, *Correction of beam-beam effects in luminosity measurement in the forward region at CLIC*, *Journal of Instrumentation* 8 (2013) P05008, [arXiv:1301.1449]. LCD-Note-2012-008.
- [18] I. Božović-Jelisavčić, S. Lukić, G. Milutinović-Dumbelović, M. Pandurović, and I. Smiljanić, *Luminosity measurement at ILC*, *Journal of Instrumentation* 8 (2013) P08012, [arXiv:1304.4082].

- [19] S. Jadach, W. Placzek, E. Richter-Was, B. Ward, and Z. Was, *Upgrade of the Monte Carlo program BHLUMI for Bhabha scattering at low angles to version 4.04*, Computer Physics Communications **102** (1997) 229.
- [20] S. Poss and A. Sailer, *Luminosity spectrum reconstruction at linear colliders*, Eur. Phys. J **C74**, 2833 (2014), ISSN : 1434-6044.
- [21] R. Schwartz, *Luminosity measurement at the Compact Linear Collider*, CERN-THESIS-2012-345, MSc thesis, Tel Aviv University, Tel Aviv, Israel, 2012.
- [22] F. Simon, *Optimum lumi spectrum and required accuracy for a tt scan near threshold*, in FCAL workshop, DESY Zeuthen, Germany, 7-9 May, 2012.
<https://indico.desy.de/conferenceDisplay.py?confId=5333>.
- [23] G. Milutinović-Dumbelović et al., *Physics potential for the measurement of $\sigma(H\nu) \times BR(H \rightarrow \mu\mu)$ at a 1.4 TeV CLIC collider*, CLICdp-Note-2014-012, CERN 2014.