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Optimization of detectors for the ILC

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Abstract

International Linear Collider (ILC) is a next-generation e^+e^- linear collider to explore Higgs, Beyond-Standard-Models, top and electroweak particles with great precision. We are optimizing our two detectors, International Large Detector (ILD) and Silicon Detector (SiD) to maximize the physics reach expected in ILC with reasonable detector cost and good reliability. The optimization study on vertex detectors, main trackers and calorimeters is underway. We aim to conclude the optimization to establish final designs in a few years, to finish detector TDR and proposal in reply to expected "green sign" of the ILC project.

Keywords: International Linear Collider, detector optimization

1. Introduction

International Linear Collider (ILC) is a next-generation e^+e^- linear collider project. The center-of-mass energy is designed to be from 250 to 500 GeV, with possible upgrade to 1 TeV. Tunnel length is 31 (up to 500 GeV) to 50 (1 TeV upgrade) kilometers. The luminosity in the current plan is 250, 500 and 1000 fb^{-1} with high-luminosity option of 1150, 1600, 2500 fb^{-1} in 250, 500 and 1000 GeV center-of-mass energy, respectively. The luminosity is now being reconsidered to maximize the capability of ILC to explore Higgs and other physics.

ILC project has a long history back to 1980's. At first we had independent e^+e^- linear collider projects in America, Europe and Japan, called NLC, TESLA and JLC. The efforts of individual projects have been unified to one ILC project in 2005, after International Technology Recommendation Panel (ITRP) endorsed the cold technology. In 2007, we published the Reference Design Report (RDR)[1] to show the physics program, accelerator technology and detector design of ILC. In 2009, Letter-of-Intents (LoIs) of ILC detectors were called and submitted. We have three LoIs from International Large Detector (ILD)[2], Silicon Detector (SiD)[3] and Fourth concept. Those detectors were preliminary optimized to specify the reference design of each detector for the LoIs. The LoIs were reviewed by International Detector Advisory Group (IDAG) and LoIs from ILD and SiD were validated. The physics, accelerator and detector studies had been proceeded with increasing interest, and they resulted in Technical Design Report (TDR) in 2012. The detector part was called Detailed Baseline Design (DBD)[4] since the detector designs were not final at that stage and further improvements towards detector TDRs were expected. First cost estimation of each detector was presented at DBD. Concurrently we had a big news from Large Hadron Collider (LHC) experiments about the Higgs discovery[5][6]. These two events strongly pushed the realization of ILC, especially raised an interest from Japan. Japanese candidate site of ILC was selected as Kitakami Mountains in 2013. At the same time, Science Council of Japan (SCJ) recommended to start investigation to host ILC in Japan officially. Now ILC has clearer physics target, timeline and specific sites than ever. We are re-optimizing our detectors towards detector TDRs

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to prepare for a "green-sign" of ILC expected in a few years.

Higgs boson is one of the main targets of ILC. After the discovery of a Higgs boson in LHC, precise measurements of the Higgs boson, especially its couplings to other particles are the next step. Many new physics models predict deviations to Higgs couplings, and the deviations have information of structure of new physics (see Fig. 1 for an example). Usually the deviation of TeV-scale new physics to the couplings is a few-percent level, so we should have percent to sub-percent coupling measurements over various Higgs couplings to fully investigate the TeV physics. The direct searches of Beyond-Standard-Model (BSM)s are also important targets in ILC. Especially ILC has a good capability for degenerated lightest new particles, which are expected in Higgsino or Wino Lightest Supersymmetric Particle (LSP) cases in Minimal Supersymmetric Standard Model (MSSM). ILC has plenty of other physics channels sensitive to new physics, for example, direct dark matter search with initial-state radiation photons, top and electroweak precise measurements and direct searches of exotic particles.

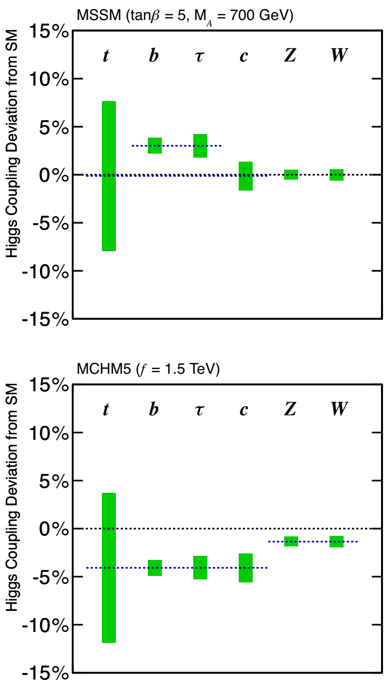

Figure 1: Typical deviations of Higgs couplings to various SM particles by MSSM (upper) and a composite Higgs model (MCHM5) (lower).

Environment of ILC for detectors is different from that of LHC in many aspects. The biggest impact is caused by the difference of QCD background. LHC has numerous QCD qq production while in ILC qq production is electroweak, so cross section of the qq production is similar to that of final states of interest. This enables ILC to analyze "jet-only" final states, for example, $ZH \rightarrow qqbb$, while the jet analysis is only possible with very distinctive features such as leptons, large missing energy or very high energy jets in LHC. Four-momentum conservation is another ILC feature to have better signal-to-noise ratio by using additional kinematic constraints to separate signal and background. Number of pileup events is also different as well. LHC expects more than 100 pileup events in every bunch in its high-luminosity run, but ILC has only 1.2 low-energy pile-up events of $\gamma\gamma \rightarrow$ hadrons in 500 GeV center-of-mass energy run. Required radiation tolerance to the vertex detector is only about $10^{11} n_{eq}$/year, compared to $3.3\times10^{15} n_{eq}$ at ATLAS IBL in 550 fb^{-1} accumulation[7] (the distance to the interaction point is about half in the ILC vertex detector). In results of those difference, ILC enables triggerless operation, and construct detectors which have more emphasis on resolution rather than rate and radiation tolerance.

Our two detectors, ILD and SiD (shown in Fig. 2), are based on similar concept of particle-flow detectors. Particle Flow Algorithm (PFA)[8] is a method to obtain high-precision jet energy measurements. Without particle flow, jet energy is usually measured only by calorimeter without separation of each particle inside the jet. In such a case, about 70% of the jet energy is measured by hadron calorimeter (HCAL), which has much worse energy resolution than electromagnetic calorimeter (ECAL) or trackers. In contrast, particle flow algorithm separates each particle in jets to separate charged particles from neutrals. With particle flow, energy of charged hadrons, which carry about 60% of jets, can be calculated from momentum measured by trackers with much better resolution to any calorimeters. Most of remained neutral particles are photons (because of decay of neutral pions to two photons) with only around 10% of energy contribution of neutral hadrons. This improves the jet energy measurement by almost factor two, with latest particle flow software and DBD detectors. Requirements to the particle flow detector are very high, especially on granularity of calorimeters. Both ILD and SiD adopt highly granular calorimeter with spatial separation of around 5 mm in ECAL and 1-3 cm in HCAL. While ILD and SiD are based on the same particle flow concept, two have several differences. The most prominent difference is their size, where SiD is more compact with higher magnetic field.

Main tracker is another point, where ILD employs Time Projection Chamber (TPC) with additional silicon tracking layers, while SiD uses silicon-only tracking.

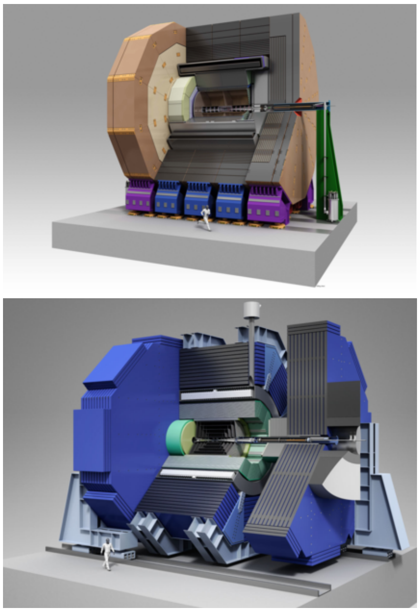

Figure 2: Drawings of ILD (upper) and SiD (lower) detectors.

For the total construction cost, sum of ILD and SiD costs roughly correspond to 10% of the accelerator cost. Between the two detectors SiD gives around 20% less total price estimation than ILD, mainly thanks to the smaller configuration. The main cost driver is electromagnetic calorimeter (ECAL) and the magnets (coil and return yoke) in both detectors. We should optimize the detectors not only by performance but also with cost and reliability.

For the detector optimization, we have three key components: vertex detectors mainly for precise origin of tracks, main trackers mainly for better momentum resolution of tracks, and calorimeters for better jet energy resolution. Physics requirements are the most essential aspects for optimizing every component. Three key components are reviewed one by one in the following sections.

2. Vertex Detector

Track pointing capability is one of the most important performance in ILC detector, especially to achieve excellent quark flavor tagging performance. The performance of b- and c- tagging are strongly depending on the point resolution of vertex detectors. Measurement of $H \to bb$ coupling with < 1% accuracy and $H \to cc$ coupling are unique functions of ILC, which is essentially important to explore TeV-scale BSM.

b-tagging also involves another critical target of Higgs measurement, Higgs self-coupling. Measuring Higgs self-coupling is extremely hard even in ILC since the signal cross section is only few tens of attobarns and numerous background of top-pairs overlaps the signal region especially in 500 GeV analysis where $ZHH \to qqbbbb$ is the main decay mode. The b-tagging performance at high purity is especially important to separate the $t\bar{t}$ background.

Point resolution of tracks is also important in other physics channels, such as tau tagging and metastable beyond-SM searches. Both ILD and SiD vertex detectors consist of 5 or 6 layers at distance of 15 to 60 mm, which are less than half of LHC vertex detectors. They are designed to have very small pixels (less than 25×25 μm^2) and low material budget (< 0.3% X_0). The important background is low-energy e^+e^- pairs from beam-beam interaction, which causes many hits especially at the innermost layer of the detectors. The ILC has 1312 bunches in a train in baseline, with bunch spacing of 337 nanoseconds. Accumulating all bunches in one readout results in too high occupancy to separate hits in the innermost layer.

Many sensor and readout technologies are proposed for both ILD and SiD to solve this issue. One strategy is the fast readout to acquire multiple dataset in a bunch. This is proposed by many sensor technologies, such as CMOS, DEPFET and 3D. Another is a novel chronopix sensor proposed in SiD. This sensor can hold multiple hits in each pixel before readout one time at a train, with bunch-tagging capability. We also have alternate direction to get smaller pixels to reduce the occupancy, proposed at FPCCD sensor in ILD. The FPCCD with 5×5 μm^2 pixels are being developed.

Performance of those can be compared using simulations, shown in Fig. 3. For the point resolution, it is trivial that smaller pixels give better resolution. For flavour tagging without pair background, especially in c-tagging we have some gain with smaller pixels, while in b-tagging difference is much smaller. However, rejection of pair background is not well implemented in the current software with smaller pixels, so more study is necessary to confirm the rejection especially in the granular technology.

3. Main Tracker

Main tracker is important not only in measuring momentum of tracks with good resolution but also as a component of PFA to measure charged particles in jets.

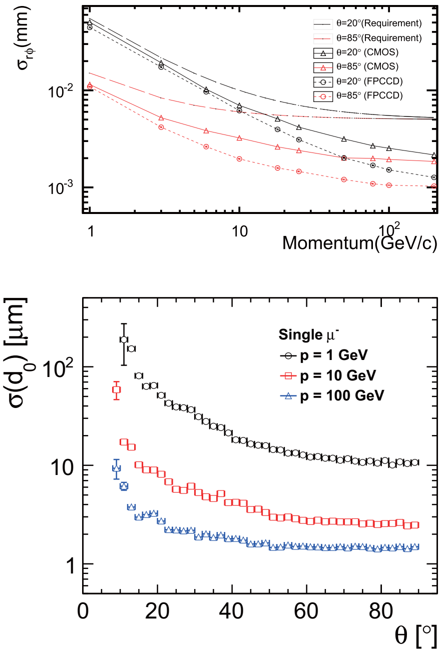

Figure 3: Impact parameter resolution in $r - \phi$ direction. (Upper) Dependence on energy in ILD options. FPCCD with smaller pixel size gives better resolution. (Lower) Dependence on angle in SiD.

One important measurement which critically depends on the momentum resolution is the Higgs recoil mass measurement with $Z \to \ell\ell$. With $ZH \to \ell\ell H$ process, only two leptons from Z and four momentum conservation are required to reconstruct the four momentum of Higgs. In this case Higgs mass can be measured with resolution much better than 100 MeV, thanks to the accurate momentum measurements at trackers. This also gives a completely model-independent ZH coupling measurement, which can calibrate all other measurements of Higgs couplings to absolute value. However, in 250 GeV CM energy the resolution of mass mainly depends rather on energy spread of the initial beam than on the tracker resolution. In 350 GeV tracker resolution still has significant effects especially for Higgs mass measurement, so the importance of momentum resolution depends on our running scenario which is still under discussion.

Another important measurement is SUSY detection with degenerated mass of chargino and neutralino, which is usually expected in the Wino or Higgsino LSP (lightest supersymmetric particle) scenario. The detection of those scenario is difficult in LHC if there are no other SUSY particles in accessible mass range. This requires efficient low-momentum tracking, which should be covered also in the main trackers.

ILD employs Time Projection Chamber (TPC) for the main tracking device, operating with inner and outer silicon strip layers. SiD, in constrast, has only five silicon strip layers in addition to the vertex layers. ILD has a larger tracking system of about 1800 mm radius with 3.5 Tesla of magnetic field in the current design, while SiD has smaller one of 1200 mm with 5.0 Tesla of magnetic field.

For the performance, ILD gives better momentum resolution in low pT tracks, with SiD better in high pT tracks, as shown in Fig. 4. For the material budget, ILD and SiD have similar material at barrel region, but in endcap region ILD has more material because of electronics of TPC at endplates. As a unique capability of ILD, dE/dx can be obtained at the energy deposit from TPC. The effect of dE/dx to physics is now being investigated. On the other hand, SiD tracking is more robust on dense track environment.

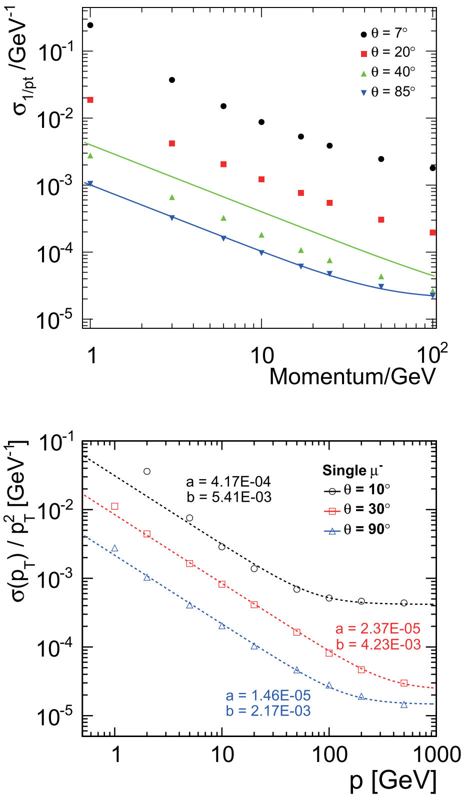

Figure 4: Momentum resolution of tracks in ILD (upper) and SiD (lower).

4. Calorimeters

Improving jet energy resolution is one of the main focus of detector development for ILC. ILC is capable of doing many important physics analyses with jets. However, most of those are with many jets in final states, where effect of jet clustering is rather dominant than the particle flow for jet energy resolution. Jet clustering does not heavily depend on detectors, but rather on software algorithm. The final state of fewer jets, eg. 2-jets, has more direct dependence on jet energy resolution by PFA. One important example is $H \to$ invisible with $Z \to qq$. Since the visible final state has only 2-jets, jet energy resolution directly corresponds to the performance in this analysis. Other important physics for PFA include ZH total cross section measurement with $Z \to qq$ and precise electroweak coupling measurements with single W and Z. We also have non-jet physics with calorimeter such as Higgs CP measurements with $H \to \tau\tau$ decay, $H \to \gamma\gamma$, and BSM models with off-axis photons provided.

Since ECAL is especially expensive in both ILD and SiD, we are now reconsidering configuration of cost reduction on ECAL. We already have some studies on jet energy resolution with reducing inner radius and number of layers, shown in Fig. 5. In ILD case, it has been shown that the jet energy resolution is controlled at reasonable level (~10% degradation) with ~20% reduction of total size or number of layers, which reduces the cost significantly, but we should investigate the effects on physics results caused by the degradation. There is possibility to use alternate technology of scintillator strips with lower cost, but some discussions exist on the reliability and feasibility of the technology. Hybrid of those two are also being investigated.

Readout technique is also important in optimization. The options for readout are analog (such as 8 bit per pixel), digital (1 bit per pixel), or semi-digital with three thresholds (2 bits). This is mainly discussed for HCAL with 3×3 cm tiles for analog and 1×1 cm for digital or semi-digital readout. Detailed comparison of those needs to be done with more optimization of PFA software.

We also have muon detectors sandwiched at the return yoke, but the optimization is still in early stage. For the forward detectors, we plan to cover $\cos\theta < 0.990$ in SiD and < 0.996 in ILD with tracking device, and 31-77 mrad (ILD) and 40-90 mrad (SiD) with LumiCal silicon-tungsten calorimeter, and 7-40 mrad (ILD) with BeamCal. The forward detectors are important to reduce beam-induced background especially for low energy particles coming from BSM models. Detailed optimization has not done also for forward detectors yet.

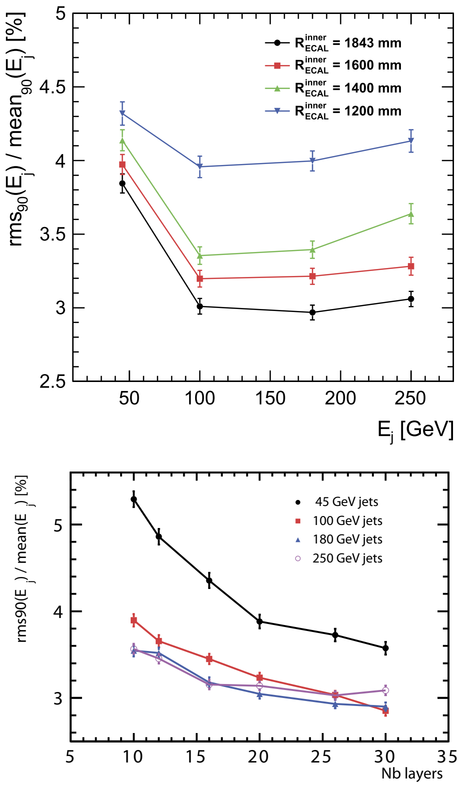

Figure 5: Dependence of jet energy resolution on different inner radius of ECAL [9] (upper) and different number of layers in ECAL (lower).

5. Summary

ILC detectors should be highly optimized for various physics analyses to maximize physics reach with reasonable cost. For the vertex detectors, flavor tagging capability of ILC is important for Higgs analysis, $H \to bb, cc, gg, ttH$ and self-coupling analysis so should maximize the performance. Rejection of pair background should be carefully investigated. For main trackers, requirements from the physics point of view is not strong for the momentum resolution, but we should keep efficiency of low momentum tracks to maximize BSM search capability. Calorimeters, especially ECAL is the cost driver, so we are considering ECAL at lower cost, either in size or in alternative options to the silicon sensor. Effects to the performance on physics analysis should be studied.

Intensive studies of reconstruction algorithms and analysis details are important to assure the reliability of optimization using them. We aim to conclude the optimization to establish final designs in a few years, to finish detector TDR and proposal in reply to expected ”green sign” of the ILC project.

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