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学位論文題目	Full simulation studies of photon and jet energy scale calibration and precise measurement of Left-Right Asymmetry using $e^+e^- \rightarrow \gamma Z$ process at the ILC
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（様式３）

博士論文の要旨

氏　　名　水野　貴裕

論文題目　Full simulation studies of photon and jet energy scale calibration and precise measurement of Left-Right Asymmetry using $e^+e^- \rightarrow \gamma Z$ process at the ILC

The International Linear Collider (ILC) is a proposed energy frontier electron-positron collider to look for new physics. Its initial center of mass energy is 250 GeV, which is extendable to 1 TeV or higher. Both electron and positron beams can be polarized. Thanks to electrons and positrons being elementary particles, the initial state is well defined and there is significantly less QCD background at the ILC than at the LHC. The resultant clean experimental environment makes it possible to perform various precision measurements including those regarding the Higgs boson properties. The ILC will thus be an ideal Higgs factory. The clean environment also allows highly sensitive searches for new particles that are difficult to find in the high QCD background environment at the LHC. To take full advantage of the ILC, a high performance detector system which can reconstruct all final states in terms of fundamental particles, i.e. leptons, quarks, gauge bosons, and the Higgs boson is essential. By measuring each final-state particle energy with the most appropriate sub-detectors (Particle Flow Analysis: PFA), we can achieve sufficient jet energy resolution to distinguish the W, Z, and the Higgs boson decaying into jets by reconstructing their invariant masses. The International Large Detector (ILD) is a proposed detector system at the ILC optimized for PFA. In order to make the PFA method work, not only the precision of the energy measurement but also the reduction of the energy scale uncertainty is essential. Photon and jet energy scale (JES) calibration is a key to achieve high performance PFA.
In this thesis we developed data-driven methods using the $e^+e^- \rightarrow \gamma Z$ process to calibrate the photon and jet energy in order to reduce the systematic error due to photon and jet energy scale uncertainties. These methods make use of kinematical reconstruction based on measured production angles of the final state photon and the Z-decay daughters, and in the case of JES calibration, also measured jet masses, without reference to their measured energies. Comparison of the kinematically reconstructed energies with their corresponding measured values allows a very precise control of the JES. This study demonstrates the effectiveness of these new methods using GEANT4-based full simulation, including expected energy scale accuracies and their dependences on energy, direction, and flavor.
Being a Higgs factory, the primary target of ILC 250 is to precisely measure the coupling constants between the Higgs boson and various other Standard Model (SM)

particles. The coupling constants can deviate from their SM values due to possible Beyond the Standard Model (BSM) effects. The pattern and size of the deviations depend on the BSM models. The precision measurements of the Higgs couplings at the ILC will thus provide a new and powerful tool not only to look for BSM effects but also to identify the type of new physics thereby showing the future direction of particle physics. In order to precisely determine various Higgs couplings as model independently as possible, it has recently been recognized that SM effective field theory (SMEFT) provides an appropriate theoretical analysis framework. In the SMEFT framework, we can express deviations from SM independently of new physics models as long as the new particles are heavy enough and their field degrees of freedom can be integrated out. The deviation from the SM is expressed by a set of higher dimensional operators. It has been shown that there is a finite but complete subset of dimension-6 operators that are related to Higgs physics at electron-positron colliders whose operators can be determined simultaneously by a global SMEFT fit using observables that would be measurable at ILC experiments. In this SMEFT analysis, not only the processes having Higgs bosons in the final state but also other processes with no Higgs boson will play a significant role. The $e^+e^- \rightarrow \gamma Z$ process is one of the most important such processes since this process has the potential to significantly improve the currently available A_{LR} measurement by the SLC experiment which would otherwise limit the Higgs coupling precision.

It turns out that the precision of the A_{LR} measurement done at SLC, being at around 1.5% i.e. $A_{LR} = 0.1514 \pm 0.0019$ (stat) ± 0.0011 (syst), is not good enough for the global fit. It is hence motivated to improve this observable at the ILC. A_{LR} was previously measured at the Z-pole, but at the ILC, we can measure A_{LR} at 250 GeV, the so-called radiative return events with both electron and positron polarization and 150 times larger statistics than at the SLC experiment. We therefore perform a full simulation study to evaluate by how much we can improve the precision on A_{LR}.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏　　名　水野　貴裕

Title
論文題目　Full simulation studies of photon and jet energy scale calibration and precise measurement of Left-Right Asymmetry using $e^+e^- \rightarrow \gamma Z$ process at the ILC

The research subject concerns precision measurements of the electroweak sector at the International Linear Collider (ILC) using the radiative return process $e^+e^- \rightarrow \gamma Z$, and the use of the same events to perform an absolute calibration of the ILC detector' s energy scale, with respect to the very precisely known mass of the Z boson.

The major aim of the ILC is to search for the effects of new physics beyond the Standard Model by means of a high precision exploration of the Higgs mechanism of Electro-Weak symmetry breaking. A complete picture of this mechanism requires measurements of the Higgs boson and its decays and of the Electro-weak bosons Z and W. The ILC will produce large numbers of Higgs, W and Z bosons allowing a complete set of measurements required to probe the symmetry breaking mechanism.
Mizuno's study concentrated on the so-called "radiative-return" sample, in which photon radiation from the initial state brings the effective centre-of-mass energy close to the Z mass, producing a large number of on-shell Z bosons, significantly more than were available at previous experiments at LEP and SLC, with the advantage of polarized electron and positron beams.

Mizuno used full simulation of ILC conditions and a detailed computer model of the ILD detector to study how these events can be used to measure the Left-Right Asymmetry A_LR of the Z boson's couplings. He developed a procedure to select the radiative return events and to reject backgrounds due to other two- and four-fermion processes expected at ILC, and estimated the precision with which A_LR will be measured. He also discussed various sources of systematic uncertainty. Due to the proposed measurement method, a large fraction of systematic effects cancel out in the final A_LR determination, with remaining sources being dominated by precise knowledge of the beam polarization and the portion of uncertainties due to the selection efficiency and luminosity which are uncorrelated between different event samples. With some estimates of the size of these effects, the final precision on A_LR at ILC-250 is expected to be 8.8 times better than the current best measurement.

This same radiative return process can be used to provide an absolute calibration of the detector's energy scale. Mizuno again used full simulation of the ILC and its detector ILD to develop methods to calibrate the energy measurement of photons and hadronic jets. By considering constraints from four-momentum conservation, Mizuno showed that the precisely measured directions in which particles are produced can be used to independently extract the less well measured energy of the same particles. He has demonstrated that considering events in which the Z decays to muons and the photon is within the detector acceptance, the absolute photon energy scale can be calibrated to better than the per-mille level, between 10 and 80 MeV for photons of energy in the range 250 to 140 GeV. Events in which the Z boson decays hadronically can be used to calibrate the absolute Jet Energy Scale of the detector in a similar way, with resulting energy scale uncertainties again significantly better than the per-mille level, between 5 and 23 MeV for jet energies in the range 20 to 120 GeV.

The studies presented in Mizuno's thesis are a world-first exploration of the radiative return process at the ILC based on full detector simulation, and the data-driven calibration methods he has developed represent the first time that such an approach has been proposed at ILC. As such, they are of considerable importance to the ILC experimental program. Mizuno has performed his research to a very high standard, and has documented his results in a very well written thesis. The work meets the requirements for a doctor degree.