ILCにおけるe^+e^- → γZ反応を用いた測定器較正シミュレーション

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**Bird’s Eye View of the ILC Accelerator**

**International Linear Collider**

Search new physics directly and indirectly in the unexplored high energy region

Complementary to the Large Hadron Collider (LHC)

The only LC project with TDR

The key technologies mature and in hand

Being seriously considered by the Japanese government

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**e+, e- Main Linac**

Energy: 125GeV + 125GeV

Length: 5.5km + 5.5km

e-: 80%  e+: 30% polarization

# of DRFS Klystron: ~220 total

# of Cryomodules : ~900 total

# of Cavities : ~8000 total

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**Ultra-low emittance**

normalized emittance = 37nm

**Nano-beam collisions**

**High gradient**

world highest gradient as with superconducting cavities = 31.5 MV/m

beam current = 5.8 mA

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**Exacting the Japanese government to express its official view on the ILC project in February 2020**

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**Tunnel Layout Plan for a Japanese Mountain Site**

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**High resolution high granularity detector**
International Large Detector (ILD)

A detector concept for the ILC designed for Particle Flow Analysis (PFA)

- Vertex Detector (VTX) -> Heavy Flavor ID
- Time Projection Chamber (TPC) -> Charged Particles
- Electromagnetic Calorimeter (ECAL) -> Photons
- Hadron Calorimeter (HCAL) -> Neutral Hadrons
- Muon Detector -> Muons

Reconstruct final states in terms of fundamental particles

**Large ILD model (IDR-L)**
- TPC outer radius: 180 cm
- B Field ~3.5 T

**Small ILD model (IDR-S)**
- TPC outer radius: 146 cm
- B Field ~4 T
Introduction
Detector Benchmark Motivation

Primary Target of ILC 250: to precisely measure the coupling constants between Higgs boson and various other particles

-> For this, we need to precisely calibrate energy scales for various particles.

- In this talk, we focus on photon energy calibration and jet energy calibration (additionally), using the $e^+e^- \rightarrow \gamma Z$ process.
Primary Target of ILC 250: to precisely measure the coupling constants between Higgs boson and various particles.

- For this, we need to precisely calibrate energy scales for various particles.

In this talk, we focus on photon energy calibration and jet energy calibration (additionally), using the $e^+e^- \rightarrow \gamma Z$ process.

Energy can be reconstructed using measured direction of $\gamma$ and $\mu^-$, $\mu^+$ or ($\gamma$ and 2 jets) information.
Photon Energy Reconstruction Method

- 4-momentum conservation is considered.
- The mass of muon is neglected.
- Several reconstruction methods (Method A, B, C) are considered.
- Consider Beamstrahlung and Crossing Angle

**Direction Angle**
- $\theta$: polar angle
- $\phi$: azimuthal angle

**Method A: Using Only Angles**

Using ($\theta_{\mu-}, \theta_{\mu+}, \theta_{\gamma}, \varphi_{\mu-}, \varphi_{\mu+}, \varphi_{\gamma}$) -> Determine ($E_{\mu-}, E_{\mu+}, E_{\gamma}, E_{ISR}$)

\[
\begin{align*}
E_{\mu} + E_{\mu+} + E_{\gamma} + |P_{ISR}| &= 500 \\
E_{\mu} \sin \theta_{\mu} \cos \phi_{\mu} + E_{\mu+} \sin \theta_{\mu+} \cos \phi_{\mu+} + E_{\gamma} \sin \theta_{\gamma} \cos \phi_{\gamma} + |P_{ISR}| \sin \alpha &= 500 \sin \alpha \\
E_{\mu} \sin \theta_{\mu} \sin \phi_{\mu} + E_{\mu+} \sin \theta_{\mu+} \sin \phi_{\mu+} + E_{\gamma} \sin \theta_{\gamma} \sin \phi_{\gamma} &= 0 \\
E_{\mu} \cos \theta_{\mu} + E_{\mu+} \cos \theta_{\mu+} + E_{\gamma} \cos \theta_{\gamma} &\pm |P_{ISR}| \cos \alpha = 0
\end{align*}
\]

ISR photon = **additional** unseen photon

Beam Crossing Angle ($\equiv 2\alpha$)

$\alpha = 7.0$ mrad
Reconstruction Method

Method B, C: Also using **Muons’ Energies**
Using \((\theta_\mu-,\theta_\mu+,\theta_\gamma,\phi_\mu-,\phi_\mu+,\phi_\gamma,E_\mu-,E_\mu+)\) -> Determine \((E_\gamma,E_{ISR})\)

- **Method B: Energy and \(P_z\) Conservation**

\[
E_\mu + E_{\mu^+} + E_\gamma + |P_{ISR}| = 500 \\
E_\mu \sin \theta_\mu \cos \phi_\mu + E_{\mu^+} \sin \theta_\mu \cos \phi_{\mu^+} + E_\gamma \sin \theta_\gamma \cos \phi_\gamma + |P_{ISR}| \sin \alpha = 500 \sin \alpha \\
E_\mu \sin \theta_\mu \sin \phi_\mu + E_{\mu^+} \sin \theta_\mu \sin \phi_{\mu^+} + E_\gamma \sin \theta_\gamma \sin \phi_\gamma = 0 \\
E_\mu \cos \theta_\mu + E_{\mu^+} \cos \theta_{\mu^+} + E_\gamma \cos \theta_\gamma \pm |P_{ISR}| \cos \alpha = 0
\]

Need to decide \(P_{ISR}\).

- **Method C: Energy and \(P_y\) Conservation**

\[
E_\mu + E_{\mu^+} + E_\gamma + |P_{ISR}| = 500 \\
E_\mu \sin \theta_\mu \cos \phi_\mu + E_{\mu^+} \sin \theta_\mu \cos \phi_{\mu^+} + E_\gamma \sin \theta_\gamma \cos \phi_\gamma + |P_{ISR}| \sin \alpha = 500 \sin \alpha \\
E_\mu \sin \theta_\mu \sin \phi_\mu + E_{\mu^+} \sin \theta_\mu \sin \phi_{\mu^+} + E_\gamma \sin \theta_\gamma \sin \phi_\gamma = 0 \\
E_\mu \cos \theta_\mu + E_{\mu^+} \cos \theta_{\mu^+} + E_\gamma \cos \theta_\gamma \pm |P_{ISR}| \cos \alpha = 0
\]

This is of no use when \(\sin \theta_\gamma \) or \(\sin \phi_\gamma = 0\) ??

However, photon energy can be determined without calculating \(P_{ISR}\).
Simulation Setup

**Full simulation** (ILCSoft version v02-00-02)

- Event generation by Whizard 1.95 with beamstrahlung and additional ISR photon effects
- Geant4 based full simulation of 2 realistic detector models IDR-L and IDR-S
- Realistic event reconstruction from detector signals

Signal sample: $e^+e^- \rightarrow \gamma Z, Z \rightarrow l^+l^-$

$E_{CM}$ of $e^+e^-$ is 500 GeV.

Two detector models IDR-L and IDR-S are compared.
Signatures of the signal events:
\(\mu^+\mu^-\) pair (inv. mass \(\sim\) Z boson) + one energetic isolated photon

In order to pick up our required process, following cuts are applied.

**Step 1:** Select events with two isolated muons.

\(\Rightarrow\) 3 types of events remain:

\[
\begin{align*}
M(\mu^+\mu^-) &\sim 500 \text{ GeV} \\
M(\mu^+\mu^-) &\sim 91.2 \text{ GeV} \\
M(\mu^+\mu^-) &\sim 0 \text{ GeV}
\end{align*}
\]
Event Selection

Step2:
- Require invariant mass of two muons \( M(\mu^+\mu^-) \) to satisfy
  \[ |M(\mu^+\mu^-) - 91.2| < 10 \text{ GeV} \]

Step3:
- Demand events to have one isolated photon with more than 50 GeV
Method Comparison of Photon

\[
\frac{E - E_{\text{MC\text{truth}}}}{E_{\text{MC\text{truth}}}}
\]

Samples:
\[|M(\mu^+\mu^-) - 91.2| < 10 \text{ GeV}\]
Large ILD model

Method A
Method B
Method C
Method Comparison of Photon

\[ \frac{E - E_{(MC\text{truth})}}{E_{(MC\text{truth})}} \]

Method A
Method B
Method C

Method C is the best for now due to its peak height and shape (symmetry).

Samples: |M(\mu^+\mu^-)-91.2| < 10 GeV
Large ILD model

Energy Resolution of Photon
-0.2
-0.1
0
0.1
0.2

0
500
1000
1500
Entries 13758
Method Comparison of Photon

\[
\frac{E - E_{(MC\text{truth})}}{E_{(MC\text{truth})}}
\]

Method Comparison of Photon

Entries

13758

Mean

0.02208

Std Dev

0.05327

Entries

13758

Mean

0.001983

Std Dev

0.04121

Entries

13758

Mean

0.003378

Std Dev

0.05451

Method Comparison of Photon

Method A

Method B

Method C

Method C is the best for now due to it’s peak height and shape (symmetry).

Rename Method C to “Ang. Method” and use this below.

Samples:

|\(|M(\mu^+\mu^-)-91.2| < 10 \text{ GeV}

Large ILD model
Demonstration of the Validity of Ang. Method

Sigma of \( \frac{(E-E_{MC})/E_{MC}}{\Sigma} \)

dependence on \(|\cos \theta_\gamma|\)

\( |\cos \theta_\gamma| < 0.95 \)

\( \pi/40 < |\phi_\gamma| < 39\pi/40 \)
Calibration of the Measured Energy

- It is shown that the PFO has large dependence on $|\cos\theta_{\gamma}|$.

$\rightarrow$ PFO energy data is divided into 20 groups by the value of $|\cos\theta_{\gamma}|$.

Calibration is performed by each value range of $|\cos\theta_{\gamma}|$.

**Calibration Factor** $(\theta_{\gamma}) = \frac{\text{Mean } E_{\text{Ang.Method}}(\theta_{\gamma})}{\text{Mean } E_{\text{PFO}}(\theta_{\gamma})}$

**Calibrated PFO Energy** = PFO Energy $\times$ Calibration Factor $(\theta_{\gamma})$
Calibration Result

Comparison of \((E - E_{\text{MC}})/E_{\text{MC}}\) among PFO, calibrated PFO, and Ang. Method

Mean of \((E - E_{\text{MC}})/E_{\text{MC}}\) dependence on \(E_{\gamma}\)
Calibration Result

- The calibration procedure removes the overall bias in the raw PFO photon energy.

Comparison of \(\frac{(E_{\gamma} - E_{\gamma}^{MC})}{E_{\gamma}^{MC}}\) among PFO, calibrated PFO, and Ang. Method Mean of \(\frac{(E_{\gamma} - E_{\gamma}^{MC})}{E_{\gamma}^{MC}}\) dependence on \(E_{\gamma}\).
**E_γ Scale Uncertainty**

- \( E_\gamma \) Scale Uncertainty = \( \sqrt{(PFO\text{ Uncertainty})^2 + (\text{Ang. Method Uncertainty})^2} \)

Sigma of \( (E - E_{MC})/E_{MC} \) dependence on \( E_\gamma \)

![Graph showing the dependence of scale uncertainty on \( E_\gamma \)]

E_\gamma Scale Uncertainty
E_γ Scale Uncertainty

- E_γ

It is concluded that the photon energy scale uncertainty is less than 100 MeV when the energy of photon is > 120 GeV.
Jet Energy Reconstruction

Based on 4-momentum conservation

\[
\begin{align*}
\sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| &= 500 \\
P_{J1}\sin\theta_{J1}\cos\phi_{J1} + P_{J2}\sin\theta_{J2}\cos\phi_{J2} + P_\gamma\sin\theta_\gamma\cos\phi_\gamma + |P_{ISR}|\sin\alpha &= 500\sin\alpha \\
P_{J1}\sin\theta_{J1}\sin\phi_{J1} + P_{J2}\sin\theta_{J2}\sin\phi_{J2} + P_\gamma\sin\theta_\gamma\sin\phi_\gamma &= 0 \\
P_{J1}\cos\theta_{J1} + P_{J2}\cos\theta_{J2} + P_\gamma\cos\theta_\gamma \pm |P_{ISR}|\cos\alpha &= 0
\end{align*}
\]

Beam Crossing Angle $\equiv 2\alpha : \alpha = 7.0$ mrad
ISR photon = additional unseen photon
Signal sample: $e^+e^- \rightarrow \gamma + 2\text{Jets}$
On-shell $Z$ is not required.

Jet Mass Distribution

Not necessarily on-shell

Direction Angle
$\theta$ : polar angle
$\phi$ : azimuthal angle

GeV
Reconstruction Method

Method: Consider ISR and solve the full equation
Using \((\theta_{J1}, \theta_{J2}, \theta_\gamma, \varphi_{J1}, \varphi_{J2}, \varphi_\gamma, m_{J1}, m_{J2})\) -> Determine \((P_{J1}, P_{J2}, P_\gamma, P_{ISR})\)

\[
\sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| = 500
\]

\[
\begin{pmatrix}
\sin\theta_{J1}\cos\phi_{J1} & \sin\theta_{J2}\cos\phi_{J2} & \sin\theta_\gamma\cos\phi_\gamma \\
\sin\theta_{J1}\sin\phi_{J1} & \sin\theta_{J2}\sin\phi_{J2} & \sin\theta_\gamma\sin\phi_\gamma \\
\cos\theta_{J1} & \cos\theta_{J2} & \cos\theta_\gamma
\end{pmatrix}
\]

\[
\begin{pmatrix}
P_{J1} \\
P_{J2} \\
P_\gamma
\end{pmatrix}
= \begin{pmatrix}
(500 - |P_{ISR}|)\sin\alpha \\
0 \\
\pm|P_{ISR}|\cos\alpha
\end{pmatrix}
\]

Matrix A

Inserting \(P_{J1}, P_{J2}, P_\gamma\) into the first equation
-> 8 Possible Solutions!
4: Quartic Equation of \(|P_{ISR}| \times 2\): sign of ISR

- Choose real and positive solutions
- Solved \(P_\gamma\) close to the measured \(P_\gamma\)
Result

Relative Error of Jet Energy

- Relative Error
- PFO
- Reconstructed
Reconstructed has less relative error than PFO.
Conclusion

- The methods to calibrate photon energy using $e^+e^- \rightarrow \gamma Z$ process are studied.

- Among the kinematical reconstruction methods studied, the Ang. Method is found to be the best due to its good resolution and its symmetric response.

- The resolution of the photon energy kinematically reconstructed by the Ang. Method is better than that of the PFO photon energy for $|\cos \theta_\gamma| < 0.95$ and $\pi/40 < |\phi_\gamma| < 39\pi/40$. We have hence shown that in this region, PFO photon energy can be calibrated using Ang. Method.

- It is concluded that the photon energy scale uncertainty is less than 100 MeV for photon energy $> 120$ GeV.

- The methods to calibrate jet energy using $e^+e^- \rightarrow \gamma Z$ process are being studied. Kinematical reconstruction methods studied has better resolution than the measured.
Backup
Invariant mass distribution of the $\mu^-\mu^+$ of Large ILD model samples (e$^-$Le$^+$R polarization)

$M(\mu^+\mu^-)$ distribution

After the Step1 Event Selection
Jet Energy Reconstruction

Based on 4-momentum conservation

\[
\begin{align*}
\sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| &= 500 \\
P_{J1} \sin \theta_{J1} \cos \phi_{J1} + P_{J2} \sin \theta_{J2} \cos \phi_{J2} + P_\gamma \sin \theta_\gamma \cos \phi_\gamma + |P_{ISR}| \sin \alpha &= 500 \sin \alpha \\
P_{J1} \sin \theta_{J1} \sin \phi_{J1} + P_{J2} \sin \theta_{J2} \sin \phi_{J2} + P_\gamma \sin \theta_\gamma \sin \phi_\gamma &= 0 \\
P_{J1} \cos \theta_{J1} + P_{J2} \cos \theta_{J2} + P_\gamma \cos \theta_\gamma + |P_{ISR}| \cos \alpha &= 0
\end{align*}
\]

Beam Crossing Angle \( \equiv 2\alpha : \alpha = 7.0 \text{ mrad} \)

- ISR photon = additional unseen photon
- Several reconstruction methods (Method 1, 2', 2, and 3) are considered.

**Method 1: Ignore ISR**

Using \((\theta_{J1}, \theta_{J2}, \theta_\gamma, \phi_{J1}, \phi_{J2}, \phi_\gamma, m_{J1}, m_{J2})\) -> Determine \((P_{J1}, P_{J2}, P_\gamma)\)

\[
\begin{bmatrix}
\sqrt{P_{J1}^2 + m_{J1}^2} & \sqrt{P_{J2}^2 + m_{J2}^2} & |P_\gamma| \\
\sin \theta_{J1} \cos \phi_{J1} & \sin \theta_{J2} \cos \phi_{J2} & \sin \theta_\gamma \cos \phi_\gamma \\
\sin \theta_{J1} \sin \phi_{J1} & \sin \theta_{J2} \sin \phi_{J2} & \sin \theta_\gamma \sin \phi_\gamma \\
\cos \theta_{J1} & \cos \theta_{J2} & \cos \theta_\gamma
\end{bmatrix}
\begin{bmatrix}
P_{J1} \\
P_{J2} \\
P_\gamma
\end{bmatrix}
= \begin{bmatrix}
500 \sin \alpha \\
0 \\
0
\end{bmatrix}
\]

Matrix A

Inverse
Jet Energy Reconstruction

**Method 2′:** Ignore ISR and use smeared $P_\gamma$
Using $(\theta_{J1}, \theta_{J2}, \theta_\gamma, \phi_{J1}, \phi_{J2}, \phi_\gamma, m_{J1}, m_{J2}, P_\gamma)$ -> Determine $(P_{J1}, P_{J2})$

$$\begin{pmatrix}
\sin \theta_{J1} \cos \phi_{J1} & \sin \theta_{J2} \cos \phi_{J2} \\
\sin \theta_{J1} \sin \phi_{J1} & \sin \theta_{J2} \sin \phi_{J2}
\end{pmatrix}
\begin{pmatrix}
P_{J1} \\
P_{J2}
\end{pmatrix}
= 
\begin{pmatrix}
500 \sin \alpha - \sin \theta_\gamma \cos \phi_\gamma P_\gamma \\
- \sin \theta_\gamma \sin \phi_\gamma P_\gamma
\end{pmatrix}$$

**Method 2:** Consider ISR and use smeared $P_\gamma$
Using $(\theta_{J1}, \theta_{J2}, \theta_\gamma, \phi_{J1}, \phi_{J2}, \phi_\gamma, m_{J1}, m_{J2}, P_\gamma)$ -> Determine $(P_{J1}, P_{J2}, P_{ISR})$

$$\begin{pmatrix}
\sin \theta_{J1} \cos \phi_{J1} & \sin \theta_{J2} \cos \phi_{J2} & \sin \alpha \\
\sin \theta_{J1} \sin \phi_{J1} & \sin \theta_{J2} \sin \phi_{J2} & 0 \\
\cos \theta_{J1} & \cos \theta_{J2} & \pm \cos \alpha
\end{pmatrix}
\begin{pmatrix}
P_{J1} \\
P_{J2} \\
P_{ISR}
\end{pmatrix}
= 
\begin{pmatrix}
500 \sin \alpha - \sin \theta_\gamma \cos \phi_\gamma P_\gamma \\
- \sin \theta_\gamma \sin \phi_\gamma P_\gamma \\
- \cos \phi_\gamma P_\gamma
\end{pmatrix}$$

2 solutions for each sign of $P_{ISR}$
-> choose the best answer which satisfies ① better
Jet Energy Reconstruction

Method 3: Consider ISR and solve the full equation
Using \((\theta_{J1}, \theta_{J2}, \theta_\gamma, \phi_{J1}, \phi_{J2}, \phi_\gamma, m_{J1}, m_{J2})\) -> Determine \((P_{J1}, P_{J2}, P_\gamma, P_{ISR})\)

\[
\begin{align*}
\sqrt{P_{J1}^2 + m_{J1}^2} + \sqrt{P_{J2}^2 + m_{J2}^2} + |P_\gamma| + |P_{ISR}| &= 500 \\
\begin{bmatrix}
sin\theta_{J1}\cos\phi_{J1} & \sin\theta_{J2}\cos\phi_{J2} & \sin\theta_\gamma\cos\phi_\gamma \\
\sin\theta_{J1}\sin\phi_{J1} & \sin\theta_{J2}\sin\phi_{J2} & \sin\theta_\gamma\sin\phi_\gamma \\
\cos\theta_{J1} & \cos\theta_{J2} & \cos\theta_\gamma 
\end{bmatrix}
\begin{bmatrix}
P_{J1} \\
P_{J2} \\
P_\gamma 
\end{bmatrix}
&=
\begin{bmatrix}
(500 - |P_{ISR}|)\sin\alpha \\
0 \\
\pm|P_{ISR}|\cos\alpha 
\end{bmatrix}
\end{align*}
\]

Matrix A

Inserting \(P_{J1}, P_{J2}, P_\gamma\) into the first equation
-> 8 Possible Solutions!

4: Quartic Equation of \(|P_{ISR}| \times 2\): sign of ISR

• Choose real and positive solutions
• Solved \(P_\gamma\) close to the measured (smeared) \(P_\gamma\)
Method Comparison Result

Relative Error of Jet Energy

- PFO
- Method 1
- Method 2
- Method 22
- Method 3

Relative Error
Method Comparison Result

Method 3 has less relative error than PFO.

Method 2 and Method 22 have some bias.
Method Comparison Result

If using MCtrue photon energy as input,

PFO photon E as input

MC photon E as input

Biases in Method 2 and 22 disappeared.
Method Comparison Result

If using MCtrue photon energy as input,

- **PFO photon E as input**
  - Biases in Method 2 and 22 disappeared.
- **MC photon E as input**

Biases are due to bias on PFO photon energy.