Top ElectroWeak Couplings Study at the ILC

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Introduction

Top quark is the heaviest in the Standard Model. Its large mass implies it is strongly coupled to the Electro-Weak Symmetry Breaking (EWSB).

Top EW couplings are good proves to new physics behind EWSB, such as Composite models and Randall–Sundrum model.

The top quark is only created at hadron colliders, where Top EW couplings study, especially $\boldsymbol{ttZ/\gamma}$ **couplings**, is difficult.
The ILC, a future lepton collider, is the best place for the study because top pair is created via the ttZ/γ vertex.

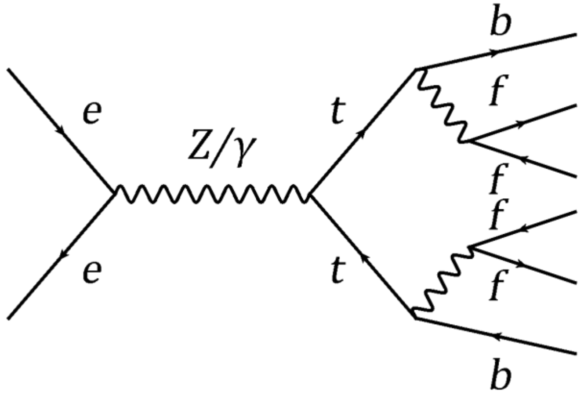
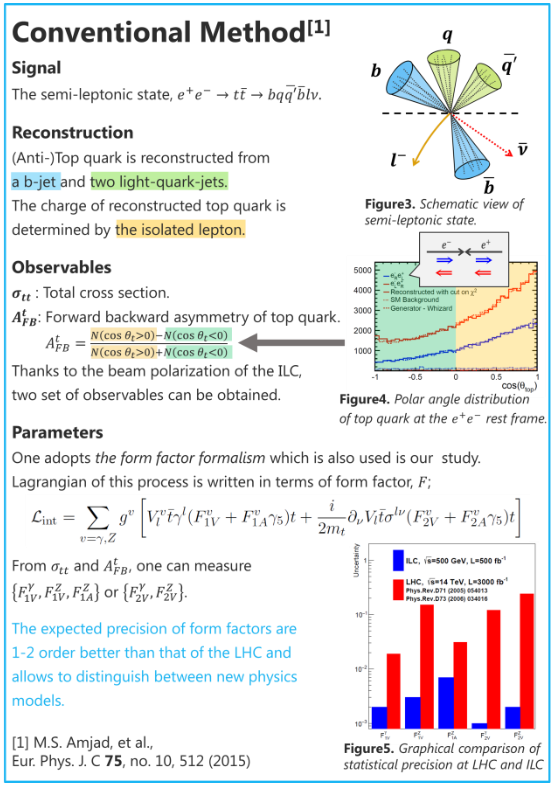


Figure1. *The leading order Feynman diagram of* $e^+e^- \rightarrow t\bar{t} \rightarrow bf\bar{f}\bar{b}f\bar{f}$.

The Conventional Method

The previous study shows that the expected precision at the ILC allows to determine the new physics models.

The bottom left part of the poster. The conventional method in the previous study is explained.



Conventional Method[1]

Signal

The semi-leptonic state, $e^+e^- \to t\bar{t} \to bq\bar{q}'\bar{b}l\nu$.

Reconstruction

(Anti-)Top quark is reconstructed from a b-jet and two light-quark-jets.

The charge of reconstructed top quark is determined by the isolated lepton.

Figure3. *Schematic view of semi-leptonic state.*

Observables

σ_{tt} : Total cross section.

A^t_{FB}: Forward backward asymmetry of top quark.

$$A^t_{FB} = \frac{N(\cos\theta_t>0)-N(\cos\theta_t<0)}{N(\cos\theta_t>0)+N(\cos\theta_t<0)}$$

Thanks to the beam polarization of the ILC, two set of observables can be obtained.

Figure4. *Polar angle distribution of top quark at the e^+e^- rest frame.*

Parameters

One adopts *the form factor formalism* which is also used is our study.

Lagrangian of this process is written in terms of form factor, F;

$$\mathcal{L}_{\rm int} = \sum_{v=\gamma,Z} g^v \left[V^v_l \bar{t}\gamma^l (F^v_{1V} + F^v_{1A}\gamma_5)t + \frac{i}{2m_t}\partial_\nu V_l \bar{t}\sigma^{l\nu}(F^v_{2V} + F^v_{2A}\gamma_5)t\right]$$

From σ_{tt} and A^t_{FB}, one can measure $\{F^\gamma_{1V}, F^Z_{1V}, F^Z_{1A}\}$ or $\{F^\gamma_{2V}, F^Z_{2V}\}$.

The expected precision of form factors are 1-2 order better than that of the LHC and allows to distinguish between new physics models.

Figure5. *Graphical comparison of statistical precision at LHC and ILC*

[1] M.S. Amjad, et al.,
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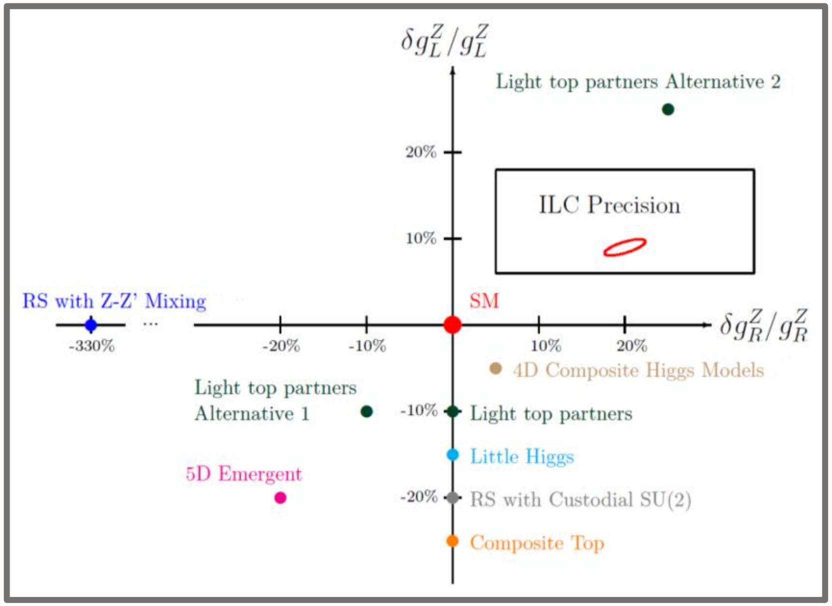


Figure2. *The predicted deviation and expected precision at the ILC of the coupling constant between Z and left-/right-handed top quark.*

Idea of New Method

However the conventional method has still room for improvement.

Top quark decays to bW before the hadronization because of the very short life time. Top quark is the only quark that its spin can be studied from decay products. If one uses the full kinematics not only top quarks, the higher sensitivity for the ttZ/γ couplings can be obtained.

The main goal of the study is to develop a method for ttZ/γ couplings measurements using the full kinematics of the final state.

Reconstruction of the Di-leptonic State

Signal

The di-leptonic state, $e^+e^- \to t\bar{t} \to bl^+\nu\bar{b}l^-\bar{\nu}$

The final state is composed of two b-jets, two isolated leptons and two neutrinos.

Method of reconstruction

Although b-jets and leptons can be reconstructed, neutrinos are not detectable at the ILD detector.

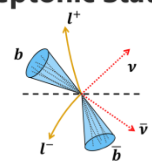


Figure6. *Schematic view of di-leptonic state.*

To recover them one imposes kinematic constraints.

Initial state constraints :

$(E_{total}, \vec{P}_{total}) = (500, \vec{0})$ [GeV]

Mass constraints :

$m_{t,\bar{t}} = 174$ [GeV], $m_{W^\pm} = 80.4$ [GeV]

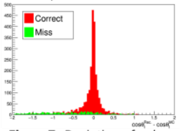


Figure7. *Deviation of polar angle of top quark between reconstructed and MC truth.*

Full kinematics of the di-leptonic state can be reconstructed with good accuracy.

Full Angular Analysis

The Lorentz invariant phase space of this process is 9-dimension.

$$\Omega = (\cos\theta_t, \cos\theta_{W^+}, \phi_{W^+}, \cos\theta_{l^+}, \phi_{l^+}, \cos\theta_{W^-}, \phi_{W^-}, \cos\theta_{l^-}, \phi_{l^-})$$

where the angles are defined in the appropriate rest frames.

One introduce the variables, $\omega_i^{\gamma/Z}$.

$$\omega_i^{\gamma/Z}(\Omega) = \frac{1}{|M(\Omega; F_{SM})|^2} \cdot \frac{\partial |M(\Omega; F)|^2}{\partial F_i^{\gamma/Z}}\Big|_{F=F_{SM}}$$

where $|M(\Omega; F)|^2$ is the full matrix element of this process which is a function of Ω and form factors, F. So the $\omega_i^{\gamma/Z}(\Omega)$ is also a function of Ω and is the optimal variable for measurement of $F_i^{\gamma/Z}$.

Measurement : *Binned Likelihood Method*

One estimates the $F_i^{\gamma/Z}$ dependence of $\omega_i^{\gamma/Z}$ distribution. Then fit the test sample to the simulation samples with following χ^2.

$$\chi^2\left(F_i^{\gamma/Z}\right) = \Sigma_{i=1}^{N_{bin}} \left(\frac{n_i^{\text{Test}} - n_i^{\text{Sim.}}\left(F_i^{\gamma/Z}\right)}{\sqrt{n_i^{\text{Test}}}} \right)^2$$

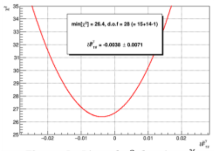


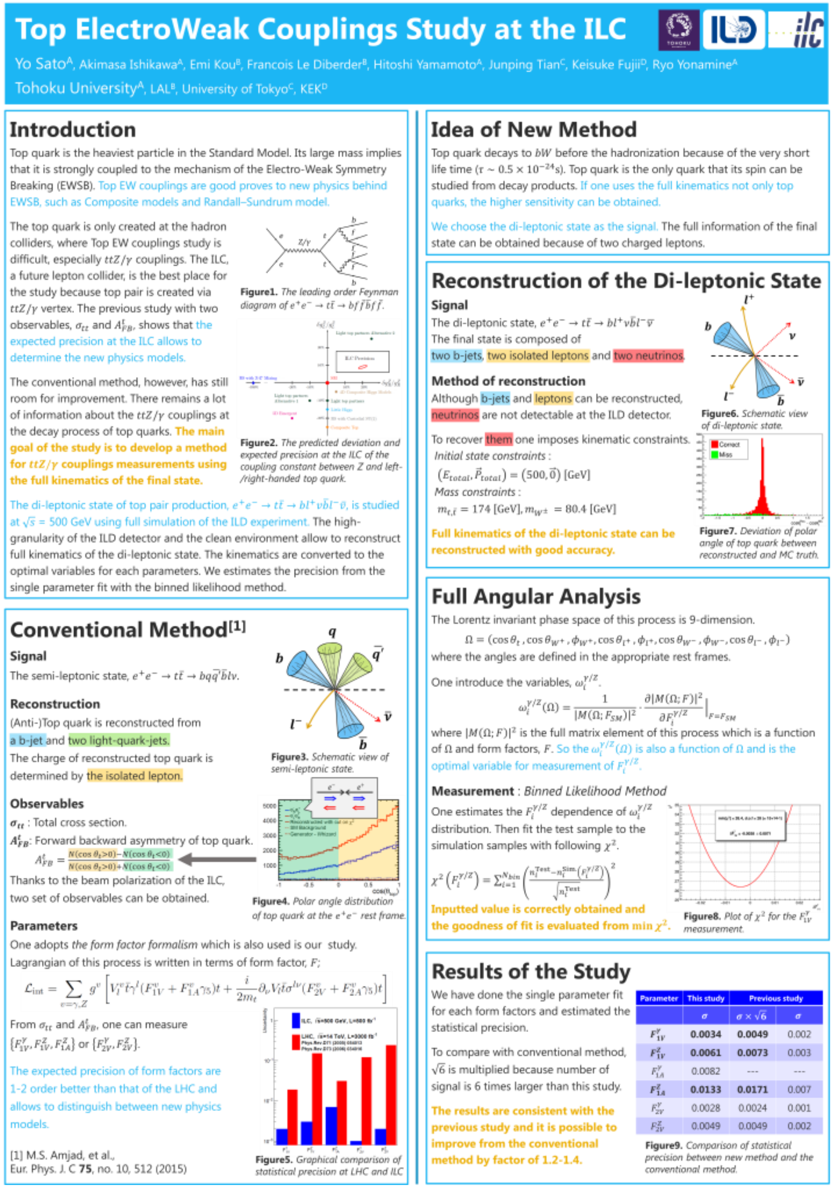
Figure8. *Plot of χ^2 for the F_{1V}^{γ} measurement.*

Inputted value is correctly obtained and the goodness of fit is evaluated from $\min\chi^2$.

The middle right part.
Signal reconstruction and analysis method are explained.

Contents of the poster

Contents



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The top quark is only created at the hadron colliders, where Top EW couplings study is difficult, especially ttZ/γ couplings. The ILC, a future lepton collider, is the best place for the study because top pair is created via ttZ/γ vertex. The previous study with two observables, σ_{tt} and A^t_{FB}, shows that the expected precision at the ILC allows to determine the new physics models.

Figure1. *The leading order Feynman diagram of $e^+e^- \to t\bar{t} \to bf\bar{f}\bar{b}f\bar{f}$.*

The conventional method, however, has still room for improvement. There remains a lot of information about the ttZ/γ couplings at the decay process of top quarks. **The main goal of the study is to develop a method for ttZ/γ couplings measurements using the full kinematics of the final state.**

Figure2. *The predicted deviation and expected precision at the ILC of the coupling constant between Z and left-/right-handed top quark.*

The di-leptonic state of top pair production, $e^+e^- \to t\bar{t} \to bl^+\nu\bar{b}l^-\bar{\nu}$, is studied at $\sqrt{s}$ = 500 GeV using full simulation of the ILD experiment. The high-granularity of the ILD detector and the clean environment allow to reconstruct full kinematics of the di-leptonic state. The kinematics are converted to the optimal variables for each parameters. We estimates the precision from the single parameter fit with the binned likelihood method.

Conventional Method[1]

Signal

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Figure5. *Graphical comparison of statistical precision at LHC and ILC*

Idea of New Method

Top quark decays to bW before the hadronization because of the very short life time ($\tau \sim 0.5 \times 10^{-24}$s). Top quark is the only quark that its spin can be studied from decay products. If one uses the full kinematics not only top quarks, the higher sensitivity can be obtained.

We choose the di-leptonic state as the signal. The full information of the final state can be obtained because of two charged leptons.

Reconstruction of the Di-leptonic State

Signal

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The final state is composed of two b-jets, two isolated leptons and two neutrinos.

Method of reconstruction

Although b-jets and leptons can be reconstructed, neutrinos are not detectable at the ILD detector.

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To recover them one imposes kinematic constraints.
Initial state constraints :
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where the angles are defined in the appropriate rest frames.

One introduce the variables, $\omega^{\gamma/Z}_i$.

$$\omega^{\gamma/Z}_i(\Omega) = \frac{1}{|M(\Omega;F_{SM})|^2} \cdot \frac{\partial |M(\Omega;F)|^2}{\partial F^{\gamma/Z}_i}\Big|_{F=F_{SM}}$$

where $|M(\Omega;F)|^2$ is the full matrix element of this process which is a function of Ω and form factors, F. So the $\omega^{\gamma/Z}_i(\Omega)$ is also a function of Ω and is the optimal variable for measurement of $F^{\gamma/Z}_i$.

Measurement : *Binned Likelihood Method*

One estimates the $F^{\gamma/Z}_i$ dependence of $\omega^{\gamma/Z}_i$ distribution. Then fit the test sample to the simulation samples with following χ^2.

$$\chi^2\left(F^{\gamma/Z}_i\right) = \sum_{i=1}^{N_{bin}} \left(\frac{n^{\rm Test}_i - n^{\rm Sim.}_i\left(F^{\gamma/Z}_i\right)}{\sqrt{n^{\rm Test}_i}} \right)^2$$

Inputted value is correctly obtained and the goodness of fit is evaluated from $\min\chi^2$.

Figure8. *Plot of χ^2 for the F^γ_{1V} measurement.*

Results of the Study

We have done the single parameter fit for each form factors and estimated the statistical precision.

To compare with conventional method, $\sqrt{6}$ is multiplied because number of signal is 6 times larger than this study.

The results are consistent with the previous study and it is possible to improve from the conventional method by factor of 1.2-1.4.

Parameter	This study	Previous study	
	σ	$\sigma \times \sqrt{6}$	σ
F^γ_{1V}	**0.0034**	**0.0049**	0.002
F^Z_{1V}	**0.0061**	**0.0073**	0.003
F^γ_{1A}	0.0082	---	---
F^Z_{1A}	**0.0133**	**0.0171**	0.007
F^γ_{2V}	0.0028	0.0024	0.001
F^Z_{2V}	0.0049	0.0049	0.002

Figure9. *Comparison of statistical precision between new method and the conventional method.*