Study of search technique for anomalous couplings between top quark and gauge particles Z/γ using top pair creation at the ILC

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Outline

- Introduction
- Goal of this study
- Setup of simulation
- Signal Reconstruction
- Analysis
- Summary

Introduction

The ttZ/γ couplings

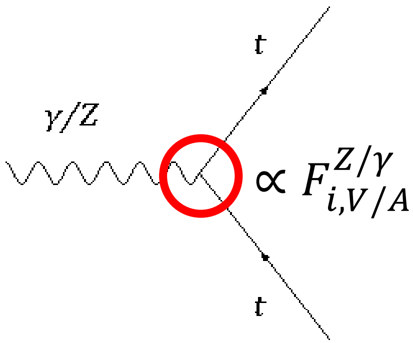
Previous study at the ILC

Full angular analysis

The ttZ/γ couplings

The ttZ/γ couplings are important probes for new physics

(e.g.) Predicted deviation of F or g from SM is ~10 % in composite models.



$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left[\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right] (X = Z, \gamma)$$

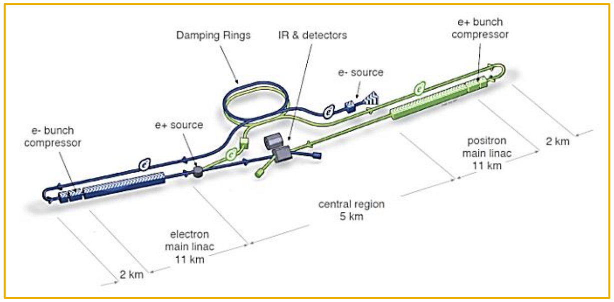
$$g_L = F_{1V} - F_{1A}, g_L = F_{1V} - F_{1A}$$

- The measurement of the ttZ/γ couplings is difficult in hadron colliders.
- Energy of current lepton colliders are not enough for $t\bar{t}$ creation.

→ Study at a future lepton collider is needed !

Previous study at the ILC

ILC (International Linear Collider)



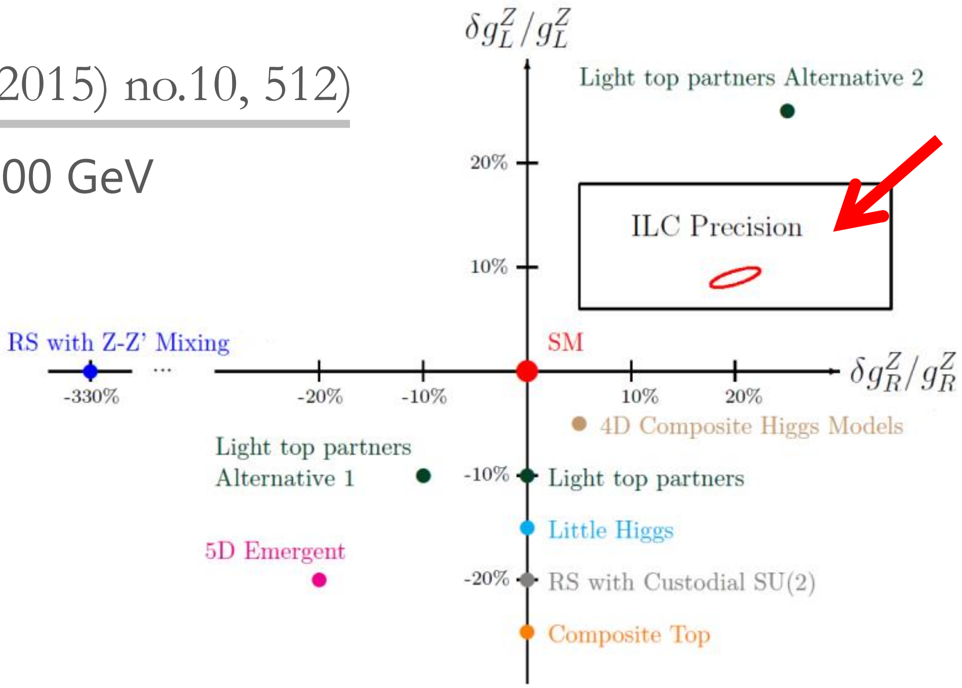
The most mature project of a future $e^- e^+$ collider

Clean data & 250-500 GeV & Polarized beam

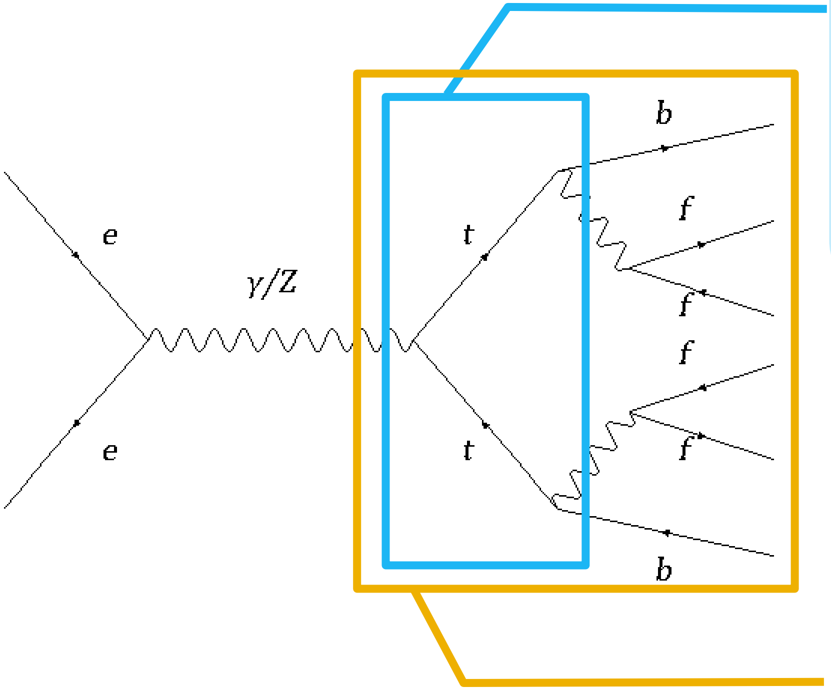
→ Suitable for the ttZ/γ measurement

Previous study (Eur.Phys.J. C75 (2015) no.10, 512)

- Signal : Semi-leptonic process at 500 GeV
  $e^- e^+ \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow bq\bar{q}\bar{b}l\nu$
- Beam polarization :
  $(P_{e^-}, P_{e^+}) = (\mp 0.8, \pm 0.3)$
- Observables : A_{FB}, σ
- Parameters : F (form factor) or
  g (coupling constant)



Full angular analysis



The previous study used A_{FB}, σ

- Robust and countable observables
- Obtained from $e^-e^+ \to t\bar{t}$ process

Decay process has also the information of the ttZ/γ couplings

- Top quark decays before hadronization
- Angular distributions of decay particles depend on the spin of top quark

Full angular analysis gives intrinsic higher sensitivities

Goal of this study

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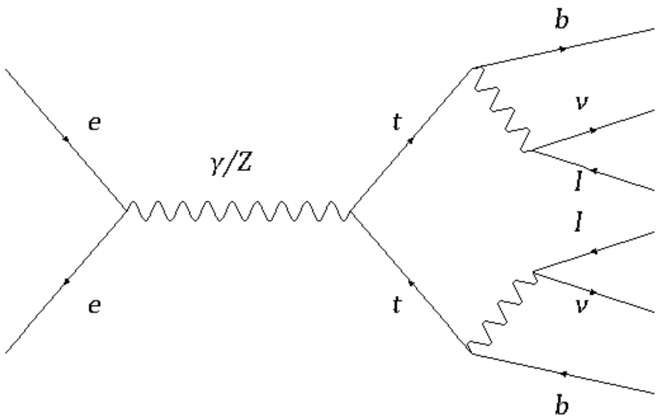
Development of the search technique for the anomalous ttZ/γ couplings with the full angular analysis based on the ILD full simulation.

- Reconstruction of the di-leptonic process;
  $e^-e^+ \to t\bar{t} \to bW^+\bar{b}W^- \to bl^+\nu\bar{b}l^-\bar{\nu}$
  - The most observables can be obtained



- Analysis with the matrix element method
- Analysis with the binned likelihood method

Setup of simulation

Parameter setup

Signal and major backgrounds

Parameter setup

Event generator : WHIZARD, Pythia

Detector simulation : Mokka, Marlin

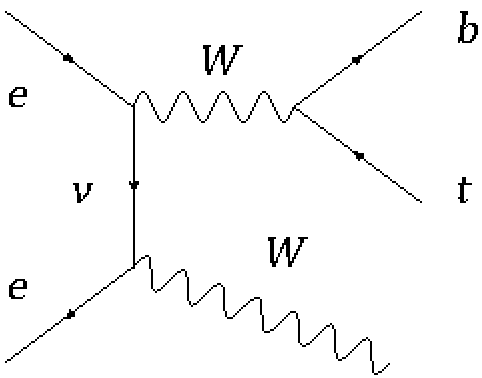
Parameter setup is based on the TDR and DBD.

Center-of-mass energy	$\sqrt{s}$	500 GeV
Beam polarization	(P_{e^-}, P_{e^+})	(-0.8, +0.3) / (+0.8, -0.3) Left / Right
Integrated luminosity	L	250 fb^{-1} / 250 fb^{-1}
Top quark mass	m_t	174 GeV
Other physics parameters		Consistent with SM-LO

Signal and major backgrounds

Signal : $e^-e^+ \to b\bar{b}\mu^-\mu^+\nu\bar{\nu}$

- We focus on the process of ***W's* decay to $\boldsymbol{\mu\nu_\mu}$**
  The most accurate to be reconstructed
  in the di-leptonic decay process
- Includes the single top production, ZWW etc.
  These are the irreducible background

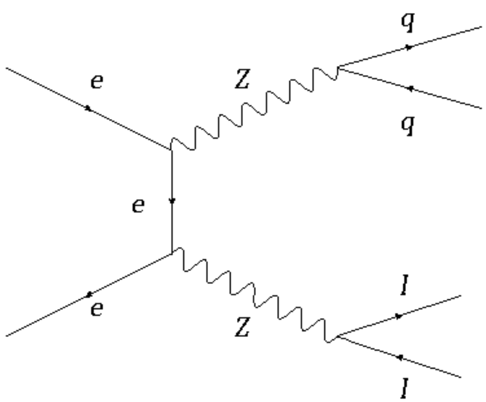


Single top production

Major backgrounds

- $e^-e^+ \to q\bar{q}l^-l^+$ (mainly $e^-e^+ \to ZZ \to q\bar{q}l^-l^+$)
- $e^-e^+ \to b\bar{b}l^-l^+\nu\bar{\nu}$ (except for $b\bar{b}\mu^-\mu^+\nu\bar{\nu}$)

They can have 2 b-jets and 2 isolated muons



$e^-e^+ \to ZZ \to q\bar{q}l^-l^+$

Signal Reconstruction

Reconstruction process

Algorithm of the kinematical reconstruction

Combination of mu and b-jet

Event selection

Reconstruction Process

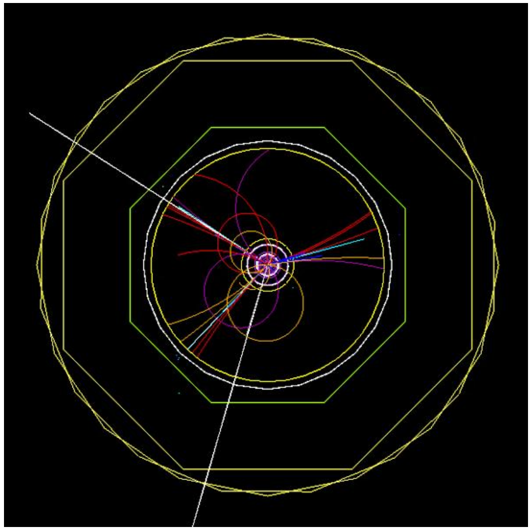
1. Selection of μ^+ and μ^-

   μ from W decay are isolated from jets

2. Jet clustering and b-tagging

   Cluster jet particles corresponding $b, \bar{b}$

   Assess the "b-likeness" from the vertex information (such as # of vtx. and distance between IP and vtx.)



Pre-selection

Events not having μ^+, μ^- and b-jets are rejected.

Left Polarization **Cut Criteria**	**Signal** $bb\mu\mu\nu\nu$	**All bkg.**	$qqll$	$bbll\nu\nu$
No cut	2837	8410633	91478	8491
$N_{\mu^-} = 1$ & $N_{\mu^+} = 1$	2618	327488	13827	381
b-tag$_{max}$ >0.5 or b-tag$_{2nd}$ >0.3	2489	4143	2943	358

Reconstruction Process

3. Kinematical Reconstruction

- $\nu, \bar{\nu}$ are not detectable at the ILD detector.
- To recover them, impose the following constraints
  - Initial state constraints : $E_{\mathrm{total}} = 500\ \mathrm{GeV}, \vec{P}_{\mathrm{total}} = \vec{0}\ \mathrm{GeV}$
  - Mass constraints : $m_{t,\bar{t}} = 174\ \mathrm{GeV}, m_{W^{\pm}} = 80.4\ \mathrm{GeV}$
- γ of the ISR/Beamstrahlung deteriorates the initial state condition. Assume the photon is along the beam direction (z-axis).

Unknowns

$\vec{P}_{\nu}, \vec{P}_{\bar{\nu}}, P_{\gamma,z}$ => 7

Constraints

$E_{\mathrm{total}}, \vec{P}_{\mathrm{total}},$

$m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}$ => 8

Algorithm of the Kinematical Reconstruction

- Introduce 4 free parameters : $\vec{P}_{\nu}, P_{\gamma,z}$

  $\vec{P}_{\bar{\nu}}$ can be computed using the initial momentum constraints

$$\vec{P}_{\bar{\nu}} = -\vec{P}_{\text{vis.}} - \vec{P}_{\nu} - \vec{P}_{\gamma}, \qquad (\vec{P}_{\text{vis.}} = \vec{P}_{b} + \vec{P}_{\bar{b}} + \vec{P}_{\mu^+} + \vec{P}_{\mu^-})$$

- Define the likelihood function :

$$L_0\left(\vec{P}_{\nu}, P_{\gamma,z}\right) = BW(m_t)BW(m_{\bar{t}})BW(m_{W^+})BW(m_{W^-})Gaus(E_{\text{total}})$$

- To correct the energy resolution of b-jets, add 2 parameters, $E_b, E_{\bar{b}}$, with the resolution functions to L_0 :

$$L\left(\vec{P}_{\nu}, P_{\gamma,z}, E_b, E_{\bar{b}}\right) = L_0 \times Res(E_b, E_b^{\text{meas.}})Res\left(E_{\bar{b}}, E_{\bar{b}}^{\text{meas.}}\right)$$

  Define $q\left(\vec{P}_{\nu}, P_{\gamma,z}, E_b, E_{\bar{b}}\right) = -2\log L + \text{Const.}$

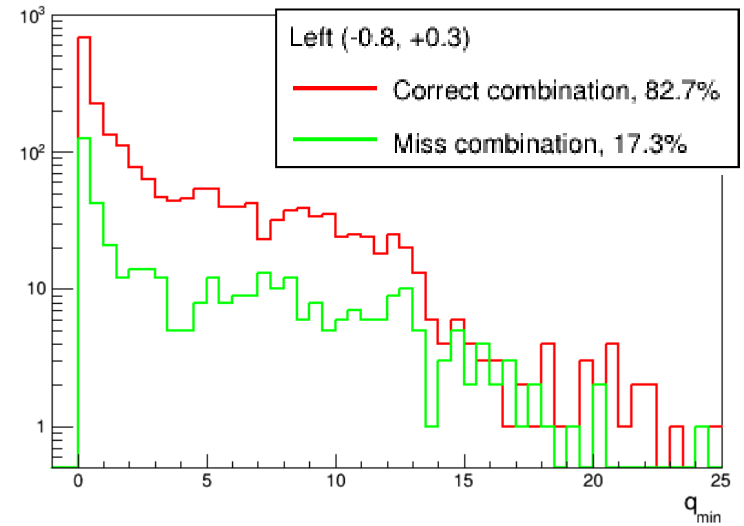
  (scaled as the minimum of each component is equal to 0)

Combination of μ and b-jet

Choice of a combination of μ and b-jet

There are two candidates for the combination

- Select one having smaller q, defined as $\boldsymbol{q}_{\mathbf{min}}$
- Ratio of the correct combination is ~83%

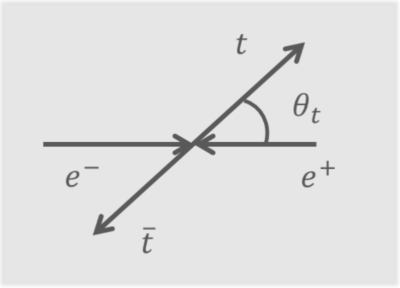


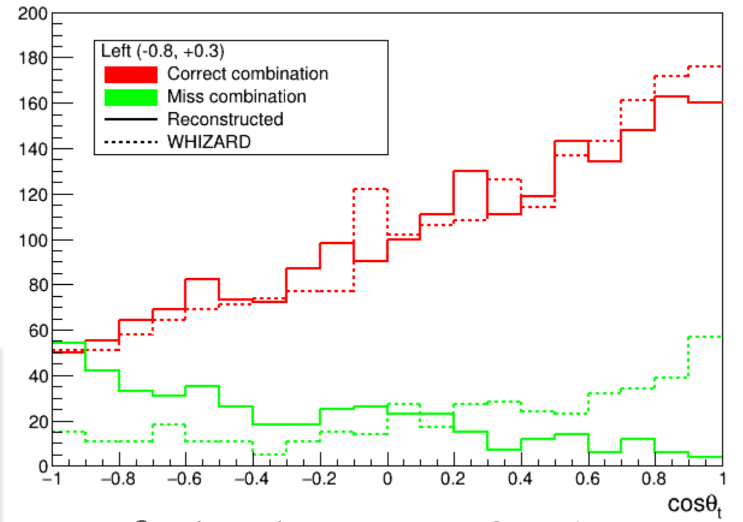
q_{min} distribution (Left polarization)

Difference in the $\cos\theta_t$ distribution

- Correct : OK !
- Miss : Disagree with the MC truth.

Need to estimate the effects of the miss combination for the analysis.





$\cos\theta_t$ distribution (Left polarization)

Event Selection

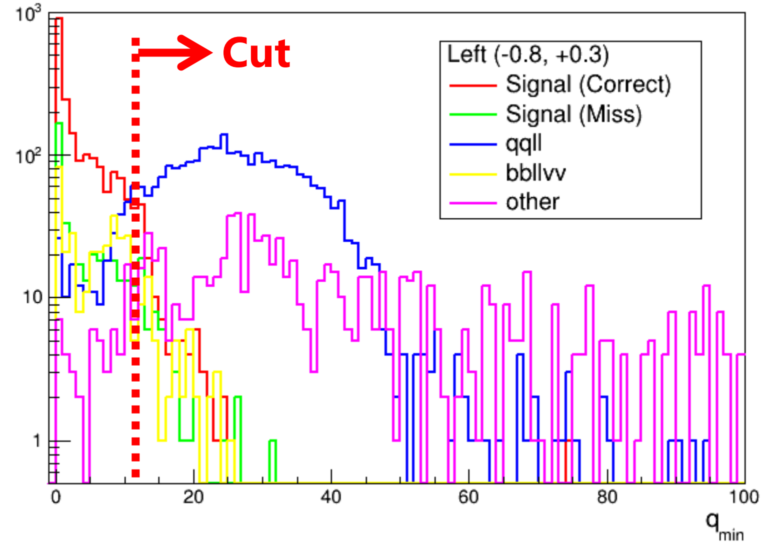
- Pre-selection has already been applied
- Quality cut :

  $q_{\min}$ means the quality of reconstruction.
  Useful to suppress the backgrounds.

Criteria is optimized for the significance,

$$S = \frac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{background}}}}$$

$q_{\min}$ distribution (Left polarization)



Left Polarization **Cut Criteria**	**Signal** $b b \mu \mu \nu \nu$	tt	**except for** tt	**All bkg.**	$qqll$	$bbll\nu\nu$
No cut	2837			8410633	91478	8491
Pre-selection	2489	2215	273	4143	2943	358
Quality cut ($q_{\min} < 11.5$)	2396	2103	195	624	258	312

(*) Separate signals into $t\bar{t}$ and the other process from WHIZARD information

Analysis

The amplitude of the di-leptonic process

Expansion of the amplitude at SM values

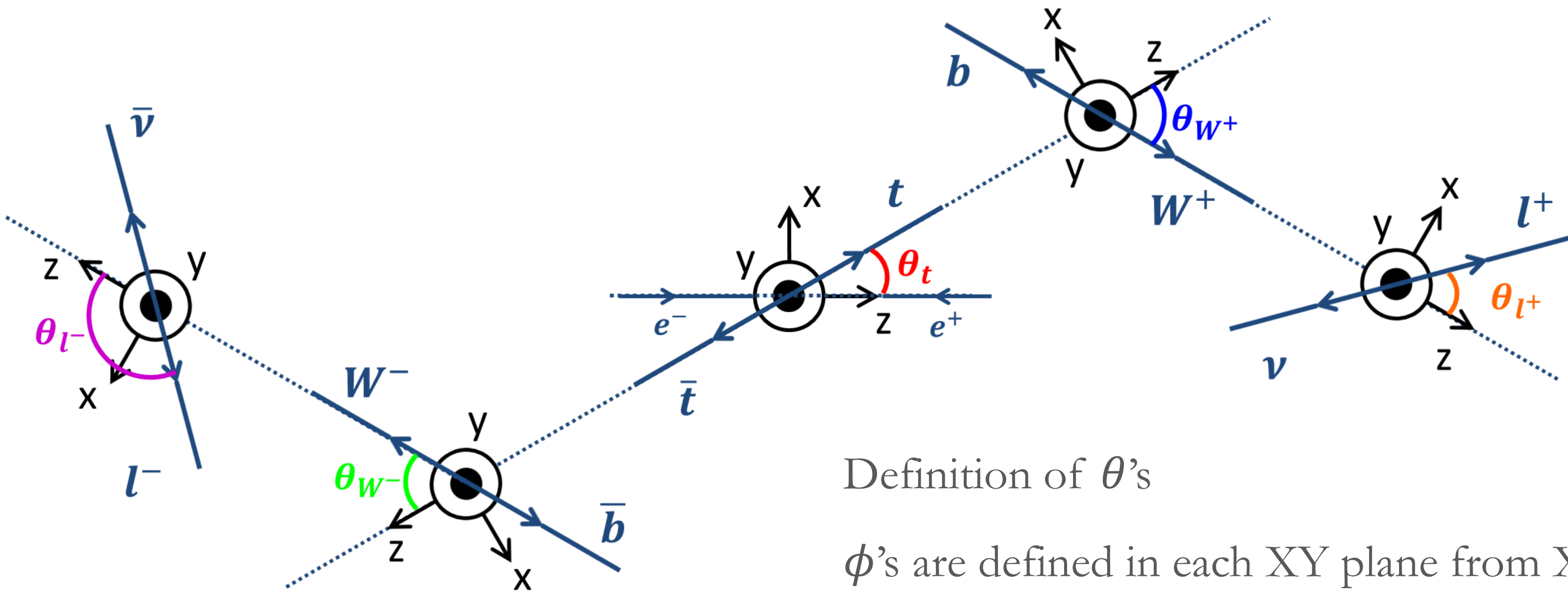
Binned likelihood method

Comparison with Previous study

The amplitude of the di-leptonic process

The amplitude of the di-leptonic process is a function of 9 angles.

$$|M|^2(\cos\theta_t\,, \cos\theta_{W^+}\,, \phi_{W^+}, \cos\theta_{W^-}\,, \phi_{W^-}, \cos\theta_{l^+}\,, \phi_{l^+}, \cos\theta_{l^-}\,, \phi_{l^-}; F)$$



Definition of θ's

ϕ's are defined in each XY plane from X-axis

- Rich observables can be computed
- It is difficult to handle the 9-dimention phase space

Expansion of the amplitude at SM value

Expand the amplitude in the form factors, F, at SM value :

$$|M|^2(\Phi;F) = \left(1 + \sum_i \omega_i(\Phi)\delta F_i + \sum_{ij} \widetilde{\omega}_{ij}(\Phi)\delta F_i \delta F_j\right)|M^{SM}|^2(\Phi;F^{SM})$$

$$\omega_i = \frac{1}{|M|^2(\Phi)} \frac{\partial |M|^2(\Phi)}{\partial F_i}\bigg|_{\delta F=0}, \widetilde{\omega}_{ij} = \frac{1}{|M|^2(\Phi)} \frac{\partial^2 |M|^2(\Phi)}{\partial F_i \partial F_j}\bigg|_{\delta F=0}, \delta F_i = F_i - F_i^{\mathrm{SM}}$$

$\omega, \widetilde{\omega}$ are the optimal variables for the form factors

(*) Matrix element method

Use all ω and $\widetilde{\omega}$ with the unbinned likelihood method.

It is difficult to involve the experimental effects to the likelihood function

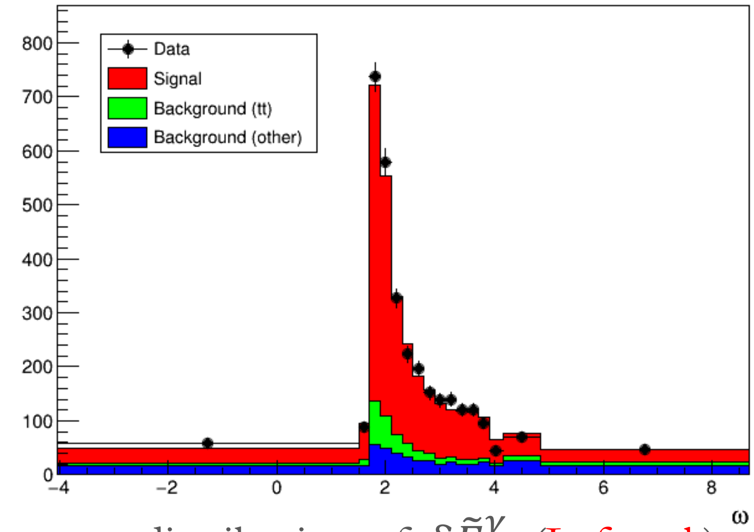
Binned likelihood method

Use only ω ignoring the second order of δF

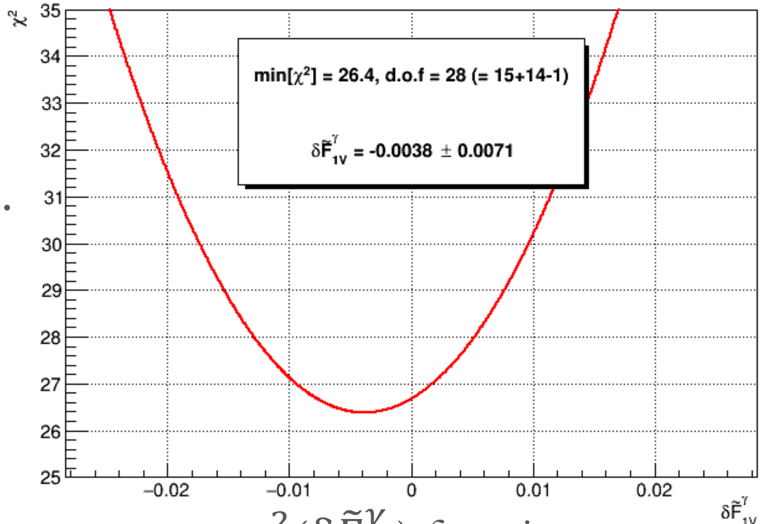
- Prepare ω distribution with large full simulation
- Fit the simulation distribution to a binned "data"(*) using the following χ^2

$$\chi^2(\delta F) = \sum_{i=1}^{N_{bin}} \left(\frac{n_i^{\mathrm{Data}} - n_i^{\mathrm{Sim.}}(\delta F)}{\sqrt{n_i^{\mathrm{Data}}}} \right)^2$$

(*) The "data" is also obtained from the full simulation. It will be replaced for real data.



ω distribution of $\delta\tilde{F}_{1V}^{\gamma}$ (Left pol.)



$\chi^2(\delta\tilde{F}_{1V}^{\gamma})$ function

We have done single parameter fit for each F.

(e.g.) $\delta\tilde{F}_{1V}^{\gamma} = -0.0038 \pm 0.0071$

C.L. = 55.2 %

Consistent with SM (input) value

Comparison with previous study

Form factor	Previous (1) semi-lep	This study $bb\mu\mu\nu\nu$
F_{1V}^{γ}	± 0.002	± 0.0071
F_{1V}^{Z}	± 0.003	± 0.0128
F_{1A}^{γ}	---	± 0.0162
F_{1A}^{Z}	± 0.007	± 0.0262
F_{2V}^{γ}	± 0.001	± 0.0058
F_{2V}^{Z}	± 0.002	± 0.0102

Form factor	Previous (2) semi-lep	This study $bb\mu\mu\nu\nu$
ReF_{2A}^{γ}	± 0.005	± 0.0238
ReF_{2A}^{Z}	± 0.007	± 0.0351
ImF_{2A}^{γ}	± 0.006	± 0.0223
ImF_{2A}^{Z}	± 0.010	± 0.0394

Difference of N_{signal} is

$$\frac{N_{\text{semi-lep}}}{N_{bb\mu\mu\nu\nu}} \simeq \frac{\frac{6}{9} \times \frac{2}{9} \times 2}{\frac{1}{9} \times \frac{1}{9}} = 24$$

→ A factor of 5 can be expected

- Consistent with the previous study
- If this method is applied for the semi-leptonic process, it’s possible that the precision will be improved

(*) Although some results of previous study are from multi-fit, the correlation is small.

(1) Eur.Phys.J. C75 (2015) no.10, 512

(2) arXiv:1710.06737 [hep-ex].

Summary

Summary

Summary

- Development of the search technique for the anomalous ttZ/γ couplings with full angular analysis based on the ILD full simulation.
- Reconstruct full kinematics of the di-leptonic process (especially $\mu\mu$) from the kinematical reconstruction.
- Estimate the statistical errors from the binned likelihood fit for the ω distribution and confirm the validity of this method.
- The precision is consistent with the previous study and there's a possibility of improvement if this method is applied for the semi-leptonic state.