Top electroweak couplings study with the Matrix Element Method using di-muonic state at $\sqrt{s} = 500$ GeV, ILC

51th General Meeting

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Outline

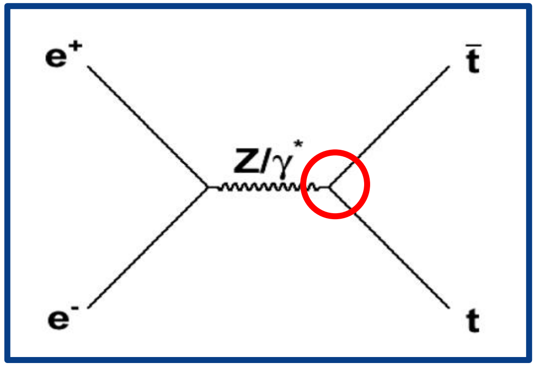
- Introduction
- Status
  - Seed issues
  - Analysis with Matrix element method
- Summery and Plan

Top EW couplings at the ILC

- Top quark is the heaviest particle in the SM. Its large mass implies that this is strongly coupled to the mechanism of electroweak symmetry breaking (EWSB)

  → **Top EW couplings are good proves for New physics behind EWSB**

- **The ILC is advanced in the $t\bar{t}Z^0$ and $t\bar{t}\gamma$ couplings study**
  - Top pair production process, $e^+e^- \rightarrow t\bar{t}$, goes directly through the $t\bar{t}Z^0$ and $t\bar{t}\gamma$



The general Lagrangian

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

F_{2A}^v can be a complex number → **10 real form factors**

eg)

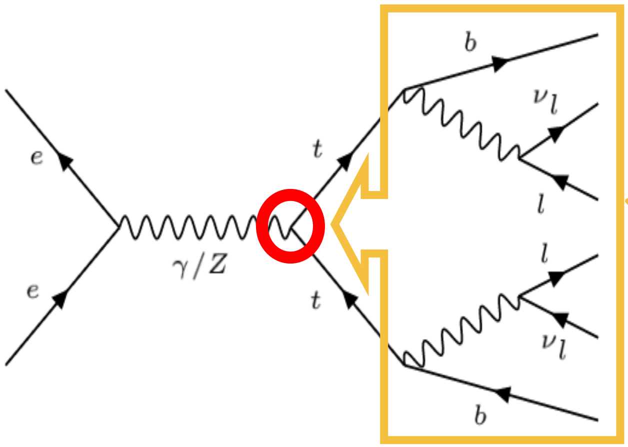
- Composite models yields typically 10% deviation of ${g_{L,R}}^Z (= F_{1V}^Z \pm F_{1A}^Z)$
- In the 2HDM, F_{2A}^γ which is a CP-violating parameter can be non-zero

Alternative : Di-leptonic state

Idea : Top quark decays before hadronization because of its large width

→ **Angles of the final state have the information of $t\bar{t}Z^0/\gamma$ vertex**

→ Use the di-leptonic state to obtain more angles



At most, there are 9 angles related to ttZ/γ vertex
$(\cos\theta_t, \cos\theta_{W^+}, \phi_{W^+}, \cos\theta_{l^+}, \phi_{l^+}, \cos\theta_{W^-}, \phi_{W^-}, \cos\theta_{l^-}, \phi_{l^-})$

Situation

- ☑ The hadronization of b, $\bar{b}$
- ☑ ISR, beamsstrahlung, beam energy spread
- ☑ γγ → hadrons
- ☑ The detector effects } **case A.**
- ☑ Gluon emission from $t, \bar{t}$
- ☐ Background events

(detector effects and gluon emission from $t, \bar{t}$: **case B.**)

Kinematical reconstruction

1. Define the χ_μ^2 ;

$$\chi_\mu^2 = \chi_{\mu^+}^2 + \chi_{\mu^-}^2, \quad \chi_{\mu^\pm}^2 = \left(\frac{E_{\mu^\pm}^{**}(\theta_t,\phi_t) - m_{W^\pm}/2}{\sigma\left[E_{\mu^\pm}^{**}\right]}\right)^2$$

The energy of $\mu^\pm$ in the $W^\pm$ rest frame, $E_{\mu^\pm}^{**}$, must be equal to $m_{W^\pm}/2$ and it can be written by two parameters (θ_t, ϕ_t).

2. Define the χ_b^2 ;

$$\chi_b^2 = \left(\frac{E_b^{meas.} - E_b^{rec.}(\theta_t,\phi_t,)}{\sigma\left[E_b^{meas.}\right]}\right)^2 + \left(\frac{E_{\bar{b}}^{meas.} - E_{\bar{b}}^{rec.}(\theta_t,\phi_t)}{\sigma\left[E_{\bar{b}}^{meas.}\right]}\right)^2$$

Although the energy of b quarks can be only poorly measured, we can eliminate b-charge ambiguity by comparing the measured energy to the reconstructed energy.

3. Compound χ_{tot}^2 ; $\chi_{tot}^2 = \chi_\mu^2 + \chi_b^2$

One minimizes the χ_{tot}^2 to obtain optimal solution of (θ_t, ϕ_t).

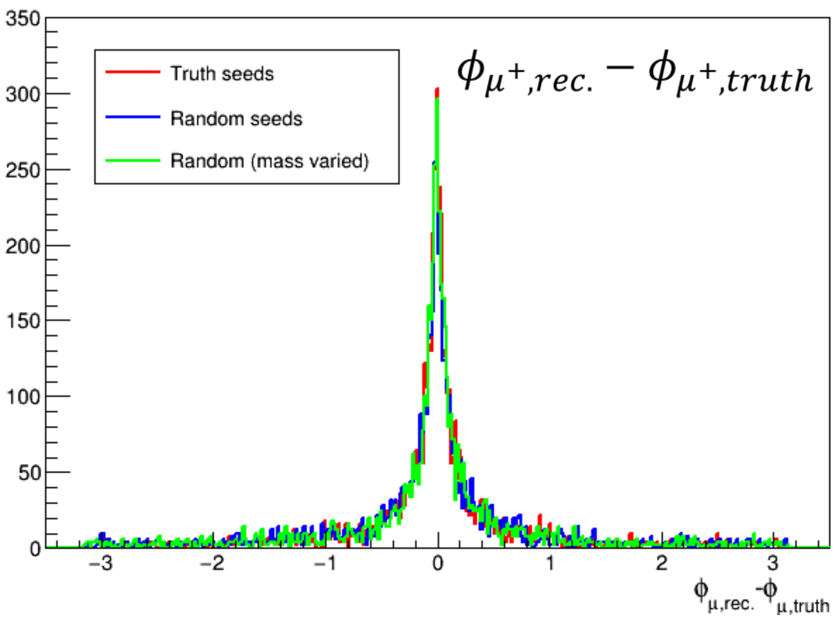
Seed issues

Until last GM : Truth values were used for initial seeds of the parameters.

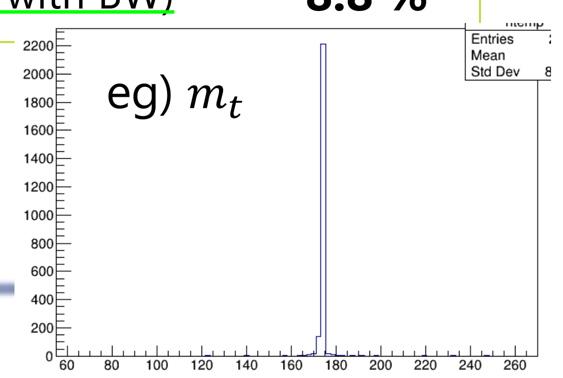
→ Repeat to put complete random values on seeds ~20 times.

Sample A.

- Distributions can be reconstructed but miss pairing of bW slightly increase.
- When masses are varied with BW constraints, results are almost same



Ratio of the miss pairing of bW	
Truth seeds	**8.8 %**
Random seeds	**9.6 %**
Random (mass varied with BW)	**8.8 %**



Seed issues

Sample B.

It doesn't work for now ...

We have used k_{e^-}, k_{e^+} to reconstruct the ISR/BS effects. (as next slide)

- ◆ Unknown parameters : $\vec{P}_{\nu}, \vec{P}_{\bar{\nu}}, (E_b, E_{\bar{b}}), k_{e^-}, k_{e^+}$ => 8 (10)
- ◆ Constraints : $E_{CM}, \vec{P}_{\text{init.}}, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}, (E_b, E_{\bar{b}})$ => 8 (10)

→ Although solutions are obtained, the optimal one cannot be selected.

→ Have not well discussed about this problem yet.

(It seems that an Ukrainian student is working on it with Francois.)

Considering ISR/BS effects

Collinear approximation:
Photons are emitted on the beam directions by ISR/BS

$$\vec{e}^{\,-} = \hat{\eta}_{e^-} E_{e^-} \quad (1)$$
$$\vec{e}^{\,+} = \hat{\eta}_{e^+} E_{e^+} \quad (2)$$

with,

$$\hat{\eta}_{e^-} = (\sin\theta_c, 0, \cos\theta_c) \quad (3)$$
$$\hat{\eta}_{e^+} = (\sin\theta_c, 0, -\cos\theta_c) \quad (4)$$
$$E_{e^\pm} = E = 250 \text{ GeV} \quad (5)$$

where θ_c is the beam crossing angle, $\theta_c = 7$ mrad.

In this approximation, the directions are not changed but only the energies are changed. Then the electron and positron thre-momenta become:

$$(\vec{e}^{\,-})^* = \hat{\eta}_{e^-} E^*_{e^-} = \hat{\eta}_{e^-} E(1 - k_{e^-}) \quad \text{with} \quad k_{e^-} = \frac{E - E^*_{e^-}}{E} \quad (6)$$
$$(\vec{e}^{\,+})^* = \hat{\eta}_{e^+} E^*_{e^+} = \hat{\eta}_{e^+} E(1 - k_{e^+}) \quad \text{with} \quad k_{e^+} = \frac{E - E^*_{e^+}}{E} \quad (7)$$

where $E^*_{e^\pm}$ is the energy of electron or positron just before collision.

Investigate the effects of reducing angles

At most we can reconstruct 9 angles with di-leptonic channel;

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

We investigate the effects of reducing number of angles

(1) 9 (full)

(2) 7 $(\cos\theta_t, \cos\theta_{W^+}, \phi_{W^+}, \cos\theta_{l^+}, \phi_{l^+}, \cos\theta_{W^-}, \phi_{W^-})$ or $(\cos\theta_t, \cos\theta_{W^+}, \phi_{W^+}, \cos\theta_{W^-}, \phi_{W^-}, \cos\theta_{l^-}, \phi_{l^-})$

(3) 5 $(\cos\theta_t, \cos\theta_{W^+}, \phi_{W^+}, \cos\theta_{W^-}, \phi_{W^-})$

(4) 1 $(\cos\theta_t)$

→ (2)~(4) can be reconstructed with the semi-leptonic state in principle.

Status

Estimate the precision at Truth level for each case.

→ At first, we fit 4 form factors simultaneously. $(\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V}, \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V}, \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A}, \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A})$

Sample (made by my brief generator)

Di-muonic state of top pair production

500 GeV, 500 fb^{-1}, (P_{e^-}, P_{e^+}) = $(\pm 0.8, \mp 0.3)$

$(\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V}, \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V}, \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A}, \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A}) = (0, -0.1, 0, +0.1)$

- (1) provides the best precision.
- (4) cannot reconstruct precisely

  → Need to check if there are bugs

→ **Investigate sensitivity for other parameters**

$$(1)\quad \begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & -0.0025 \pm 0.0059 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.0984 \pm 0.0103 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & -0.0064 \pm 0.0108 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.0805 \pm 0.0170 \end{bmatrix}$$

(2) Ongoing

$$(3)\quad \begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & -0.0011 \pm 0.0060 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.0985 \pm 0.0110 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & +0.0077 \pm 0.0134 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.0905 \pm 0.0196 \end{bmatrix}$$

$$(4)\quad \begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & +0.0026 \pm 0.0060 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.2143 \pm 0.0157 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & -0.1120 \pm 0.0113 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.0842 \pm 0.0198 \end{bmatrix}$$

$$\text{or}\quad \begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & +0.0047 \pm 0.0061 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.1845 \pm 0.0152 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & 0 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.0717 \pm 0.0196 \end{bmatrix}$$

Summery

Seed issues

- Random values are used for seeds instead of MC truth values.
  - Sample A.

    Similar distribution can be reconstructed.
  - Sample B.

    When k_{e^-}, k_{e^+} are included, reconstruction doesn't work well

Analysis

- Investigate the effects of reducing number of angles.
  - More angles are used, higher precision can be obtained.
  - Sensitivity for other parameters should be checked.

Back up

Investigate the effects of reducing angles

Modify the $|M|^2$ for each cases as following

$$(1)\ \left|M_{\lambda_{e^-},\lambda_{e^+}}\right|^2 = \sum_{\lambda_b,\lambda_{\bar{b}}}\left|\sum_{\lambda_t,\lambda_{\bar{t}}}\left[M^{\lambda_t\lambda_{\bar{t}}}_{e^-e^+\to t\bar{t}}\left(\sum_{\lambda_{W^+}} M^{\lambda_t\lambda_b\lambda_{W^+}}_{t\to bW^+} M^{\lambda_{W^+}}_{W^+\to l^+\nu}\right)\left(\sum_{\lambda_{W^-}} M^{\lambda_{\bar{t}}\lambda_{\bar{b}}\lambda_{W^-}}_{\bar{t}\to\bar{b}W^-} M^{\lambda_{W^-}}_{W^-\to l^-\bar{\nu}}\right)\right]\right|^2$$

$$(2)\ \left|M_{\lambda_{e^-},\lambda_{e^+}}\right|^2 = \sum_{\lambda_b,\lambda_{\bar{b}},\lambda_{W^-}}\left|\sum_{\lambda_t,\lambda_{\bar{t}}}\left[M^{\lambda_t\lambda_{\bar{t}}}_{e^-e^+\to t\bar{t}}\left(\sum_{\lambda_{W^+}} M^{\lambda_t\lambda_b\lambda_{W^+}}_{t\to bW^+} M^{\lambda_{W^+}}_{W^+\to l^+\nu}\right) M^{\lambda_{\bar{t}}\lambda_{\bar{b}}\lambda_{W^-}}_{\bar{t}\to\bar{b}W^-}\right]\right|^2 \text{(vise versa)}$$

$$(3)\ \left|M_{\lambda_{e^-},\lambda_{e^+}}\right|^2 = \sum_{\lambda_b,\lambda_{\bar{b}},\lambda_{W^+},\lambda_{W^-}}\left|\sum_{\lambda_t,\lambda_{\bar{t}}}\left[M^{\lambda_t\lambda_{\bar{t}}}_{e^-e^+\to t\bar{t}} M^{\lambda_t\lambda_b\lambda_{W^+}}_{t\to bW^+} M^{\lambda_{\bar{t}}\lambda_{\bar{b}}\lambda_{W^-}}_{\bar{t}\to\bar{b}W^-}\right]\right|^2$$

$$(4)\ \left|M_{\lambda_{e^-},\lambda_{e^+}}\right|^2 = \sum_{\lambda_t,\lambda_{\bar{t}}}\left|M^{\lambda_t\lambda_{\bar{t}}}_{e^-e^+\to t\bar{t}}\right|^2$$

Alternative : The Matrix Element Method

The Matrix Element Method (MEM)

The most efficient method when all the kinematics can be reconstructed

MEM with the 9 angles and the cross-section

- **All 10 form factors can be fitted simultaneously**

→ ~0.01 precision is obtained at parton level study with di-leptonic state

Statistical uncertainties and correlation with the SM LO as normalization

Kheim, E.K. Kurihara, Le Diberder: arXiv:1503:04247

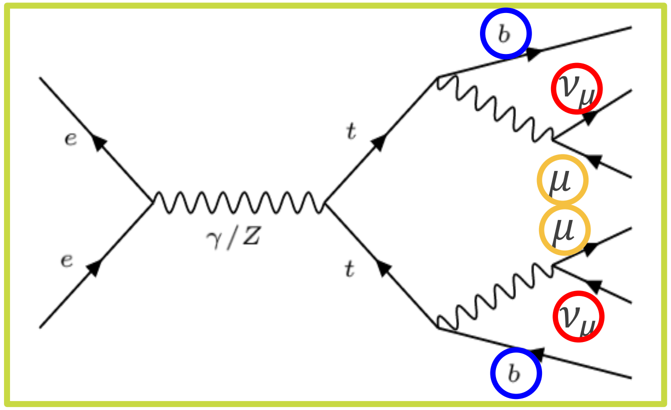
$\mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{1V}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{1A}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{2V}^{Z}$	$\mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma}$	$\mathcal{R}e\ \delta\tilde{F}_{2A}^{Z}$	$\mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma}$	$\mathcal{I}m\ \delta\tilde{F}_{2A}^{Z}$
0.0037	−0.18	−0.09	+0.14	+0.62	−0.15	0	0	0	0
	0.0063	+.14	−0.06	−0.13	+0.61	0	0	0	0
		0.0053	−0.15	−0.05	+0.09	0	0	0	0
			0.0083	+0.06	−0.04	0	0	0	0
				0.0105	−0.19	0	0	0	0
					0.0169	0	0	0	0
						0.0068	−0.15	0	0
							0.0118	0	0
								0.0069	−0.17
									0.0100

500 GeV&500 fb^{-1} Polarization 50/50 between ±80% and ±30%

→ Estimate the ultimate precision considering all effects

Kinematical Reconstruction : Strategy

Di-muonic state : $e^+e^- \rightarrow t\bar{t} \rightarrow b\bar{b}\mu^+\nu\mu^-\bar{\nu}$



Measurable
- muon's : $E_{\mu^+}, \theta_{\mu^+}, \phi_{\mu^+}, E_{\mu^-}, \theta_{\mu^-}, \phi_{\mu^-}$
- b-jet's : $(E_b), \theta_b, \phi_b, (E_{\bar{b}}), \theta_{\bar{b}}, \phi_{\bar{b}}$

Missing
- b-jet's : $(E_b), (E_{\bar{b}})$
- neutrino's : $E_\nu, \theta_\nu, \phi_\nu, E_{\bar{\nu}}, \theta_{\bar{\nu}}, \phi_{\bar{\nu}}$

=> 6 (8) unknowns

Strategy

① **Recover them from 8 kinematical constraints**
- initial state : $(\sqrt{s}, \vec{P}_{\text{init.}}) = (500, \vec{0})$
- mass : $m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}$

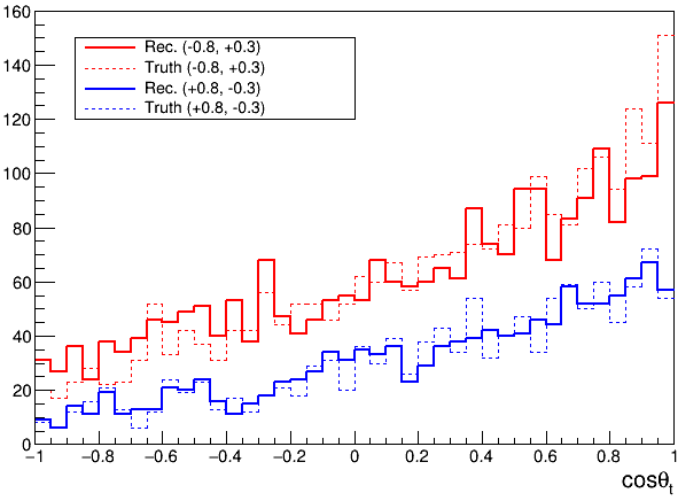
→ But the equation is non-linear and the b-charge ambiguity remains.

→ Typically 4 solutions per an event

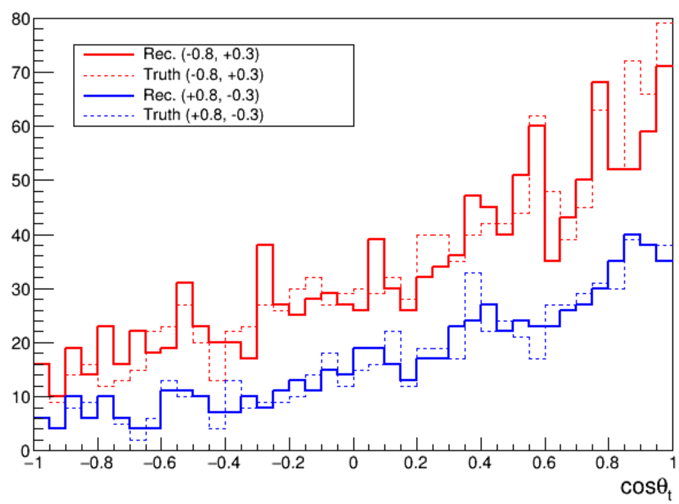
② **Select the optimal one by comparing $E_b, E_{\bar{b}}$ between recovered and measured**

Results : Polar angle distribution of top, $\cos\theta_t$

(Before cut)



(After cut)



- In the case of **Left,** migrations of events passing from forward to backward are observed.

  ← The miss pairing of W and b

- After selection of reliable events by the quality of the kinematical reconstruction, migrations become smaller.

Ratio of the miss pairing	Left	Right
Before cut (efficiency = ~92 %)	**8.9 %**	**6.0 %**
After cut (efficiency = ~50 %)	**5.5 %**	**3.0 %**

Results : All 10 form factors fit with MEM

Fit of all 10 form factors at same time

- Precision is typically ~0.03

eg) $\tilde{F}^{\gamma}_{1V}$

	Precision of $\tilde{F}^{\gamma}_{1V}$	$N/N_{\text{di-muonic}}$
This result	**0.011**	**1**
Parton level	**0.004**	**~4**
Semi-leptonic study	**0.002**	**~25**

→ Comparable with the previous study

- Biases are thought to results from the detector effects and the miss pairing of Wb

→ One can reduce them by convoluting $|M|^2$ with the detector effects and applying relevant cuts.

Preliminary

(efficiency = ~50 %)

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & -0.0015 \pm 0.0108 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.0271 \pm 0.0187 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & -0.0314 \pm 0.0156 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.0277 \pm 0.0246 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V} & -0.0266 \pm 0.0317 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2V} & -0.0702 \pm 0.0504 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A} & -0.0082 \pm 0.0211 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2A} & -0.0164 \pm 0.0360 \\ \mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A} & -0.0427 \pm 0.0206 \\ \mathcal{I}m\ \delta\tilde{F}^{Z}_{2A} & +0.0220 \pm 0.0297 \end{bmatrix}$$

$$F^{\tilde{v}}_{1V} = -(F^{v}_{1V} + F^{v}_{2V}), \quad F^{\tilde{v}}_{2V} = F^{v}_{2V}$$

$$F^{\tilde{v}}_{1A} = -F^{v}_{1A}, \quad F^{\tilde{v}}_{2A} = -iF^{v}_{2A}$$

Thrust axis method

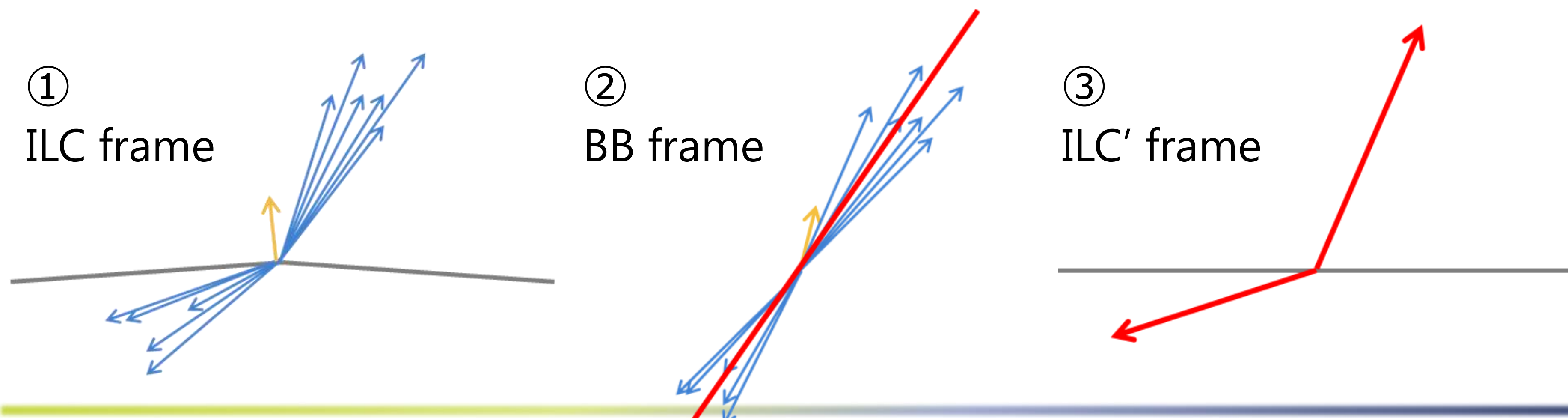
We use the thrust axis method for the measurement of 2 b-jets.

① Collect all hadronized particles and photons from isolated leptons in the ILC frame

② Boost them to their rest frame and calculate thrust axis in this frame (defined as the BB frame in this slide)

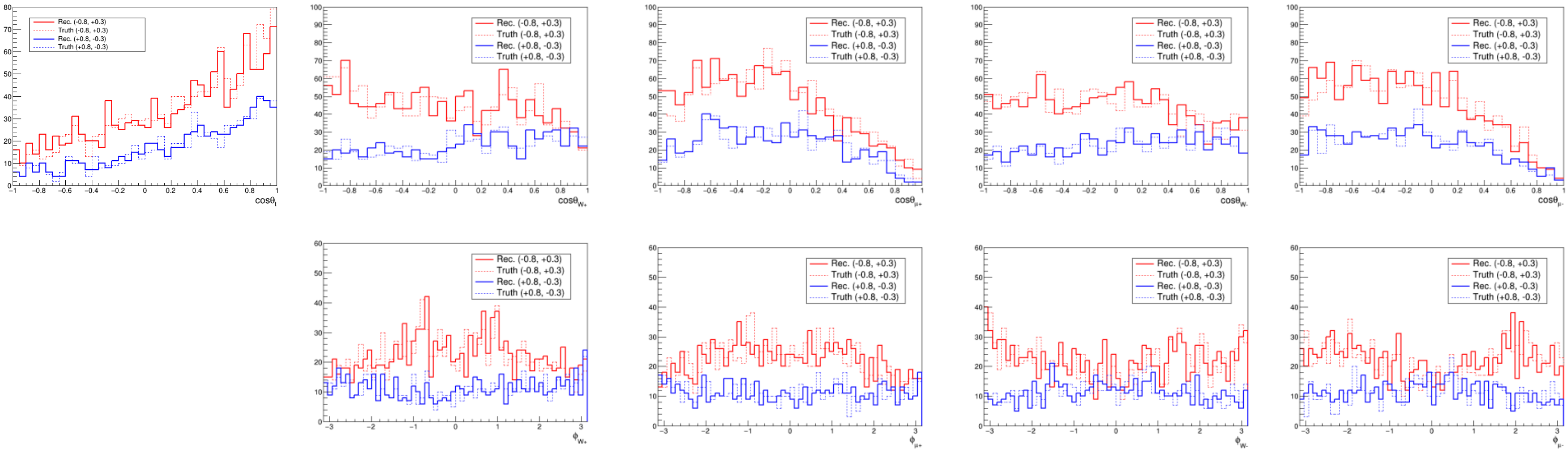
③ Boost the vectors along thrust axis to the ILC′ frame

(ILC′ frame : the frame in which head-on-collision occurs)



Results : Distributions of the 9-angles

$$\cos\theta_t\,,\cos\theta_{W^+}\,,\phi_{W^+},\cos\theta_{\mu^+}\,,\phi_{\mu^+},\cos\theta_{W^-}\,,\phi_{W^-},\cos\theta_{\mu^-}\,,\phi_{\mu^-}$$



- Different between Left and Right polarization

→ These have the information of the polarization of top

Results : Variance matrix of 10 form factors fit

Preliminary (efficiency = ~50 %)

$$
\begin{bmatrix}
\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V} & \mathcal{R}e\ \delta\tilde{F}^{Z}_{2V} & \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A} & \mathcal{R}e\ \delta\tilde{F}^{Z}_{2A} & \mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A} & \mathcal{I}m\ \delta\tilde{F}^{Z}_{2A} \\
0.0108 & -0.14 & -0.03 & +0.09 & +0.62 & -0.10 & +0.02 & -0.06 & +0.04 & -0.02 \\
 & 0.0187 & +0.09 & -0.02 & -0.10 & +0.61 & -0.06 & +0.02 & -0.01 & +0.03 \\
 & & 0.0156 & -0.11 & -0.01 & +0.03 & +0.02 & 0 & +0.05 & +0.01 \\
 & & & 0.0246 & -0.01 & 0 & +0.01 & +0.03 & +0.01 & +0.05 \\
 & & & & 0.0317 & -0.17 & +0.03 & -0.12 & 0 & -0.03 \\
 & & & & & 0.0504 & -0.11 & -0.06 & -0.02 & 0 \\
 & & & & & & 0.0211 & -0.17 & -0.04 & +0.01 \\
 & & & & & & & 0.0360 & -0.01 & -0.45 \\
 & & & & & & & & 0.0206 & -0.13 \\
 & & & & & & & & & 0.0297
\end{bmatrix}
$$

Results : No cut & Loose cut & Tight cut

No cut (efficiency = ~92 %)

Left 8.9% Right 6.0%

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0054 \pm 0.0081 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & -0.0228 \pm 0.0142 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & -0.0421 \pm 0.0117 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0587 \pm 0.0185 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0681 \pm 0.0233 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & -0.0129 \pm 0.0387 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & +0.0179 \pm 0.0153 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & -0.0207 \pm 0.0274 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & -0.0287 \pm 0.0150 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & -0.0011 \pm 0.0218 \end{bmatrix}$$

Loose cut (efficiency = ~80 %)

Left 8.1% Right 5.5%

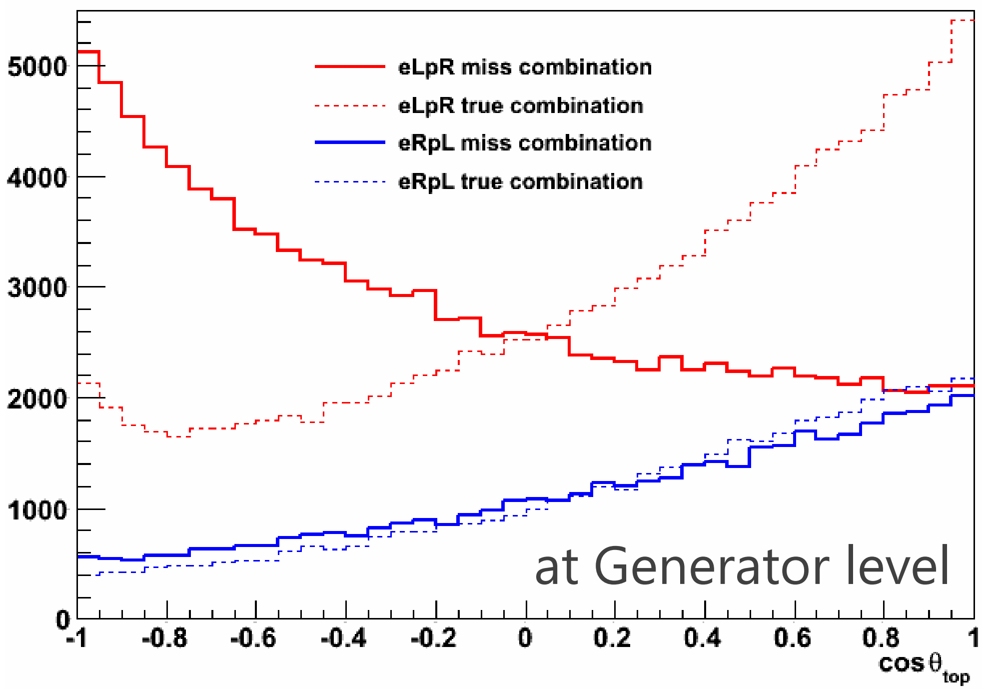
$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0047 \pm 0.0088 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & -0.0236 \pm 0.0154 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & -0.0460 \pm 0.0126 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0631 \pm 0.0198 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0669 \pm 0.0253 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & -0.0206 \pm 0.0417 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & +0.0011 \pm 0.0160 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & -0.0370 \pm 0.0283 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & -0.0143 \pm 0.0163 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & -0.0110 \pm 0.0237 \end{bmatrix}$$

Tight cut (efficiency = ~50 %)

Left 5.5% Right 3.0%

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0015 \pm 0.0108 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & -0.0271 \pm 0.0187 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & -0.0314 \pm 0.0156 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0277 \pm 0.0246 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0266 \pm 0.0317 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & -0.0702 \pm 0.0504 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & -0.0082 \pm 0.0211 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & -0.0164 \pm 0.0360 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & -0.0427 \pm 0.0206 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & +0.0220 \pm 0.0297 \end{bmatrix}$$

True and Miss pairing of Wb



Right-handed electron case (eRpL), Blue line

Little difference between true and miss associated distributions

Left-handed electron case (eLpR), Red line

Miss association changes angular distribution significantly

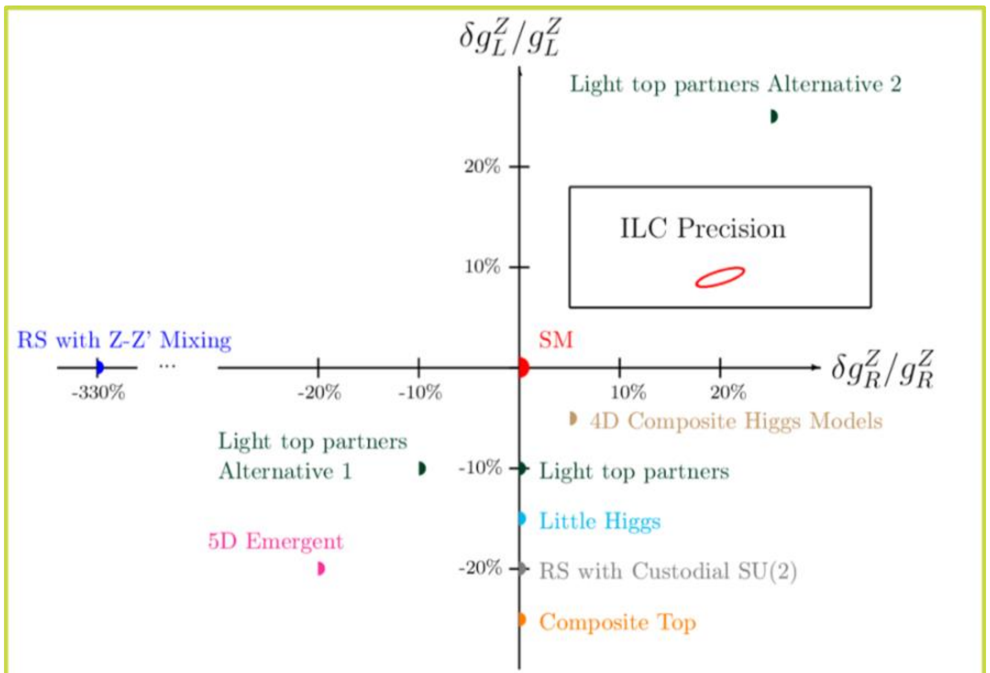
→The migration effect happens in only the case of eLpR

The $t\bar{t}Z^0/\gamma$ couplings : CP-conserving

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

$$g_L^Z = F_{1V}^Z - F_{1A}^Z, \qquad g_R^Z = F_{1V}^Z + F_{1A}^Z$$

- Deviation from the SM of g_L^Z, g_R^Z will be typically 10% in composite models



arXiv:1505.06020 [hep-ph]

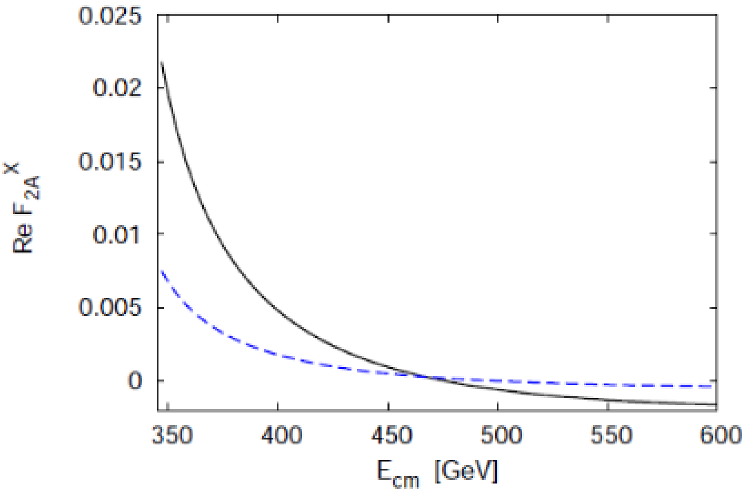
The $t\bar{t}Z^0/\gamma$ couplings : CP-violating

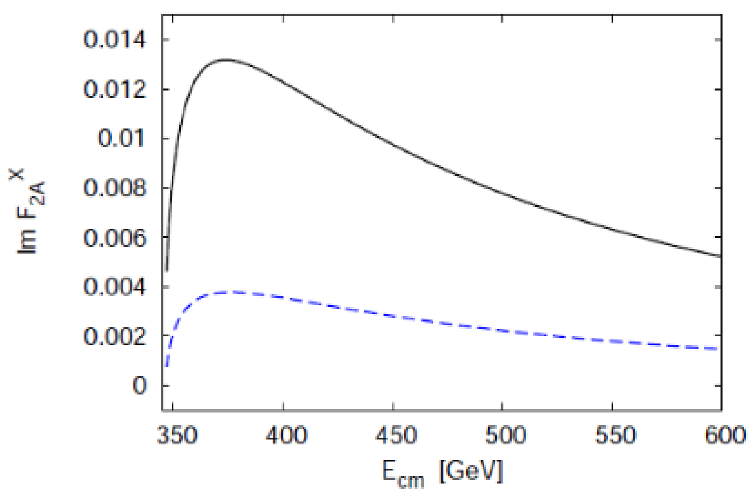
$$\mathcal{L}_{\rm int} = \sum_{v=\gamma,Z} g^v \left[V_l^v \bar{t}\gamma^l (F_{1V}^v + F_{1A}^v \gamma_5) t + \frac{i}{2m_t} \partial_\nu V_l \bar{t} \sigma^{l\nu} (F_{2V}^v + F_{2A}^v \gamma_5) t \right]$$

- F_{2A}^{γ} is the electric dipole moment which is forbidden in the SM

→ Probes for CP-violating beyond the Kobayashi-Maskawa mechanism

eg) 2HDM can yield ~0.01





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Kinematical Reconstruction : True pairing

- Intersections of green and red lines are solutions in terms of (θ_t, ϕ_t)
- Blue line shows the comparison of the $E_b, E_{\bar{b}}$ between rec. and meas.

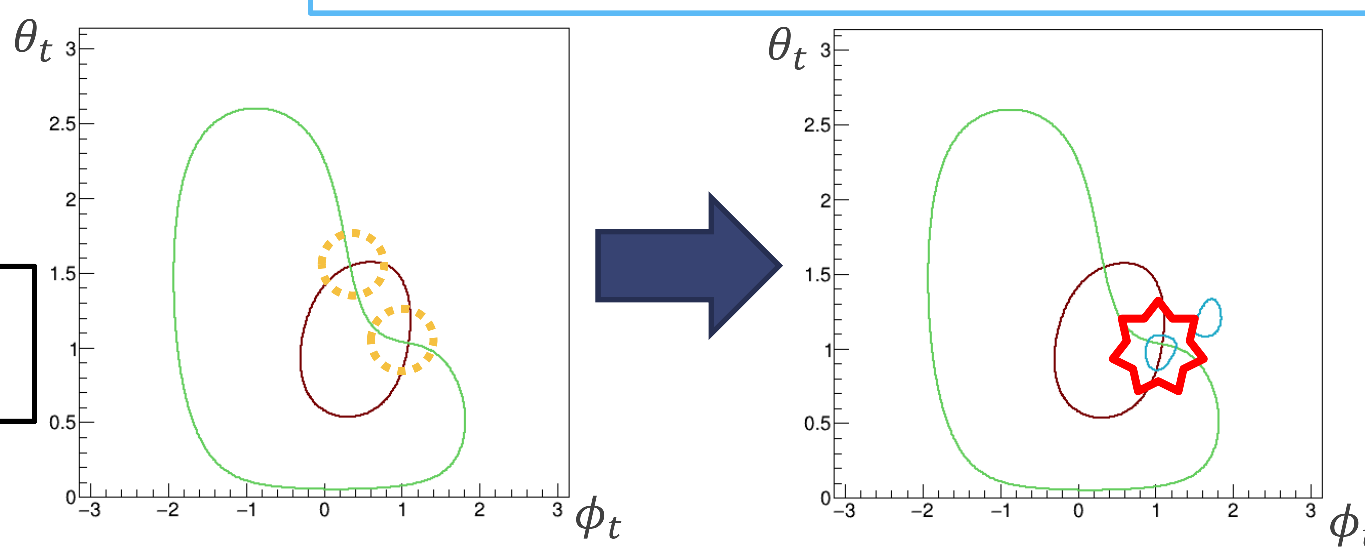
→ The optimal solution is selected obtained

$$E^{**}_{\mu^+}(\theta_t, \phi_t) = \frac{m_{W^+}}{2}$$

$$E^{**}_{\mu^-}(\theta_t, \phi_t) = \frac{m_{W^-}}{2}$$

The energy of $\mu^\pm$ in $W^\pm$ frame is equal to $m_{W^\pm}/2$

$$\chi^2_b = \left(\frac{E_b^{meas.} - E_b^{rec.}(\theta_t, \phi_t)}{\sigma[E_b^{meas.}]}\right)^2 + \left(\frac{E_{\bar{b}}^{meas.} - E_{\bar{b}}^{rec.}(\theta_t, \phi_t)}{\sigma[E_{\bar{b}}^{meas.}]}\right)^2 = 20$$



Kinematical Reconstruction : Miss pairing

- Blue line is far from intersections of green and red line

→Miss pairing is excluded by the $E_b, E_{\bar{b}}$ comparision.

$$E^{**}_{\mu^+}(\theta_t, \phi_t) = \frac{m_{W^+}}{2}$$

$$E^{**}_{\mu^-}(\theta_t, \phi_t) = \frac{m_{W^-}}{2}$$

The energy of $\mu^{\pm}$ in $W^{\pm}$ frame is equal to $m_{W^{\pm}}/2$

$$\chi^2_b = \left(\frac{E_b^{meas.} - E_b^{rec.}(\theta_t, \phi_t)}{\sigma[E_b^{meas.}]}\right)^2 + \left(\frac{E_{\bar{b}}^{meas.} - E_{\bar{b}}^{rec.}(\theta_t, \phi_t)}{\sigma[E_{\bar{b}}^{meas.}]}\right)^2 = 20$$