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

Full ILD detector simulation

LCWS2016

Yo Sato[A]

Emi Kou[B], Francois Le Diberder[B], Hitoshi Yamamoto[A]

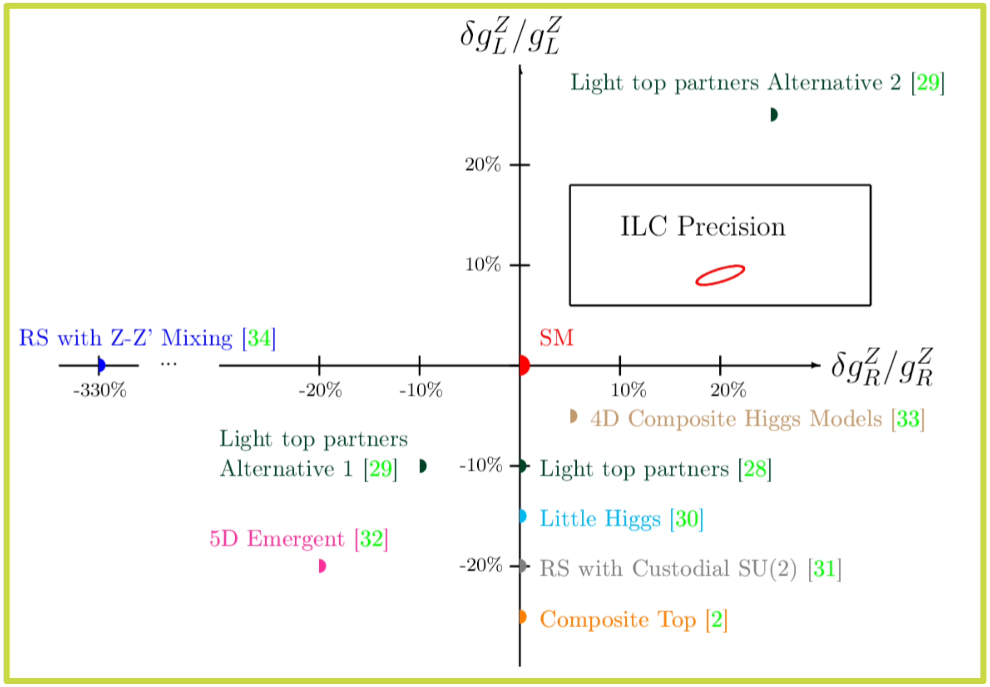
Tohoku University[A], LAL[B]

Outline

- Introduction
  - Top electroweak couplings
  - Matrix element method
- Setting of this study
- Development of reconstruction
  - b-jets reconstruction
  - Kinematical reconstruction
- Analysis with the matrix element method
- Summary

Top electroweak couplings

The top quark mass is comparable with the electroweak symmetry breaking scale. One can speculate that top quark plays a special role for the EWSB, for example such composite models. Therefore top quark electroweak couplings are good probes for New Physics.



Plot shows the predicted deviations from the Standard model of Z^0 couplings to t_L and t_R in composite models

Precision expected at the ILC will allow to distinguish between models.

arXiv:1505.06020 [hep-ph]

Matrix element method

The most efficient method when all the kinematics can be reconstructed.

- Results of previous study show that 10 form factors can be fitted simultaneously at less than a percent precision.

Statistical uncertainties and correlation with the SM LO as normalization

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

$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{1V}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{1A}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{2V}$	$\mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{R}e\ \delta\tilde{F}^{Z}_{2A}$	$\mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A}$	$\mathcal{I}m\ \delta\tilde{F}^{Z}_{2A}$
0.0037	−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

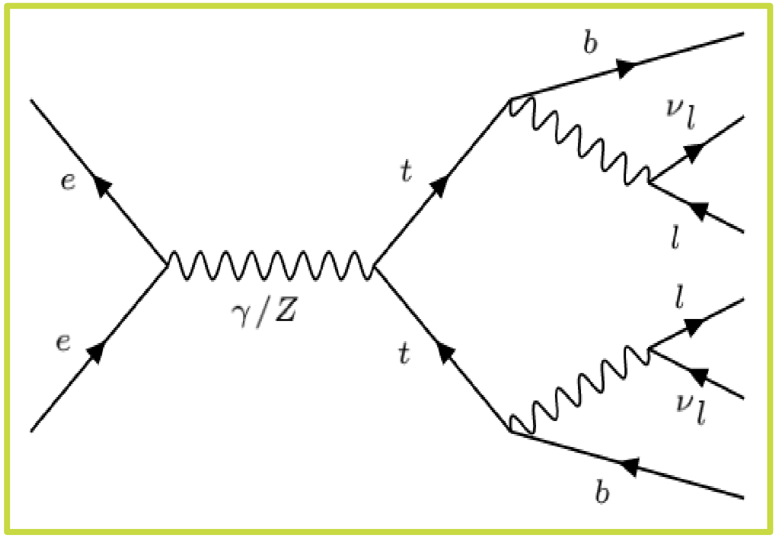
500 GeV&500 fb^{-1} Polarization 50/50 between ±80% and ±30%

Emi Kou (LAL-Orsay)
LFC 15, Trento,
7-11 Sep. 2015

This result is at parton level ignoring the detector effect, ISR and so on.

→More realistic study is required !

Setting of this study



Sample

The top pair production di-muonic state;

$t\bar{t} \rightarrow b\bar{b}\mu^{+}\mu^{-}\nu\bar{\nu}$ at $\sqrt{s}$ = 500 GeV

Situation

✓ The hadronization of b and $\bar{b}$ quark

✓ The detector effects (= Full ILD detector simulation)

× ISR and beamsstrahlung

× Gluon emission from top quark

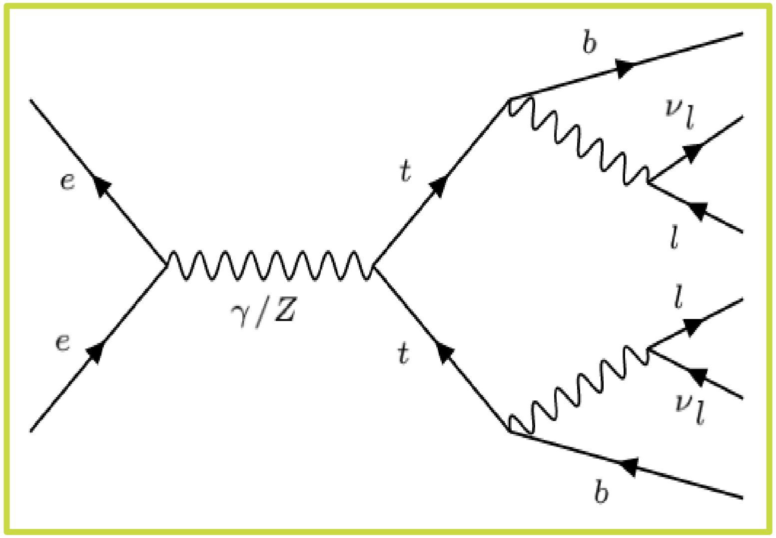
× γγ → hadrons background

× Background events

Development of reconstruction

This state is composed of

- 2 isolated leptons, μ^+, μ^-
- 2 b-jets
- 2 missing neutrinos



We develop

The b-jets reconstruction and **The kinematical reconstruction**

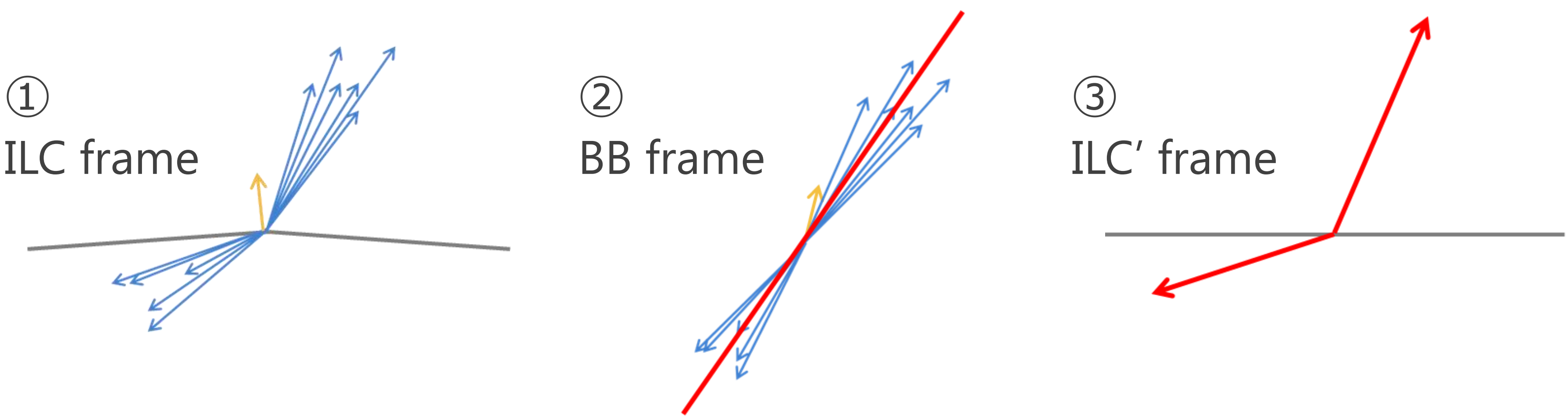
Thrust axis method

① Collect all hadronized particles from b and $\bar{b}$ quark and photons from isolated leptons in the ILC frame

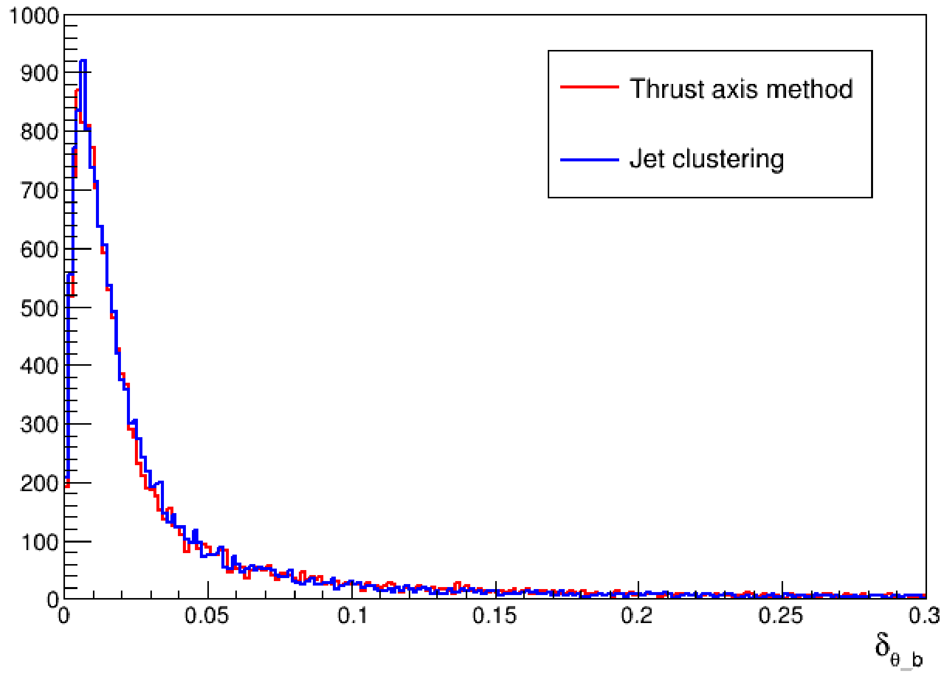
② Boost them to their rest frame and calculate thrust axis in this frame (defined as the BB frame in this slide)

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

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



Comparison Thrust axis method and Jet clustering



The angle between truth direction and reconstructed direction of b quark

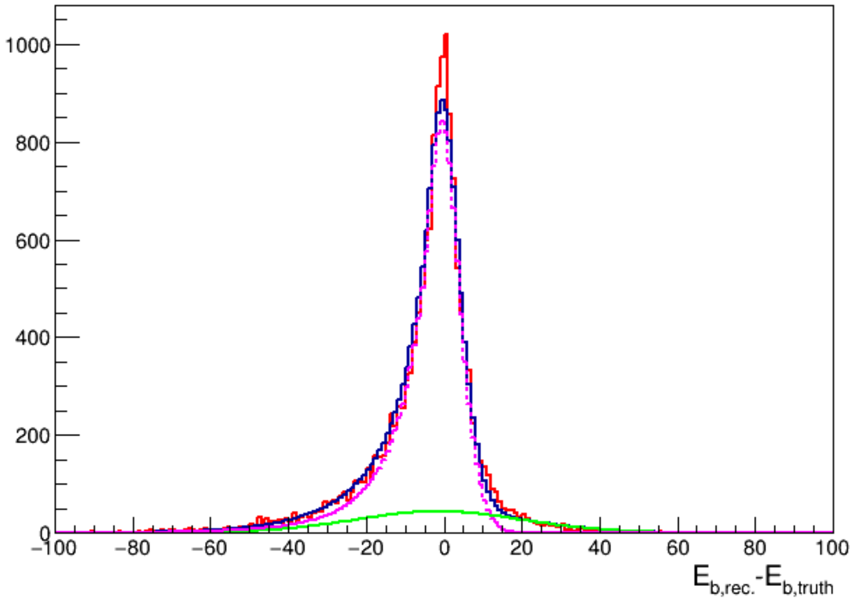
Red : Thrust axis method

Blue : Jet clustering (LCFIPlus)

Two methods produce almost same precision for direction of b-quark.

→We select the thrust axis method for this study so far.

Assessment of energy of b-jet



Deviation of energy of b-jet

(using thrust axis method)

Red : Original

Blue : Fitted

(Blue is a sum of Pink and Green)

To estimate the b-jet energy resolution we use multiple Crystal Ball functions for fitting.

$$CB(x|\alpha, n, \mu, \sigma) = \begin{cases} N \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), & \frac{x-\mu}{\sigma} > -\alpha \\ N \cdot A \cdot \left(B - \frac{x-\mu}{\sigma}\right)^{-n}, & \frac{x-\mu}{\sigma} < -\alpha \end{cases}$$

So far we use $\sigma_{jet} E_b^K$ with two parameters σ_{jet} and K for σ.

Kinematical reconstruction

Strategy of the kinematical reconstruction

- **There are 8 unknown kinematics in this state**

  (= the momenta of two neutrinos and energy of two b-jets)

- **Impose 8 constraints** (= initial state constraints and $m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}$)

  → Solutions are obtained in terms of (θ_t, ϕ_t) → $(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-})$

  But the equation is nonlinear. Furthermore an ambiguity of b-charge remains.

  → **Typically 4 solutions per event.**

- **Select the optimal solution**

  Compare $E_b^{\mathrm{meas.}}$ (by thrust axis method) and $E_b^{\mathrm{rec.}}(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-})$.

χ^2 algorithm : General

1. Define the χ^2_μ ;

$$\chi^2_\mu = \chi^2_{\mu^+} + \chi^2_{\mu^-}, \quad \chi^2_{\mu^\pm} = \left(\frac{E^{**}_{\mu^\pm}(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}) - m_{W^\pm}/2}{\sigma\left[E^{**}_{\mu^\pm}\right]} \right)^2$$

The energy of $\mu^\pm$ in the $W^\pm$ rest frame, $E^{**}_{\mu^\pm}$, must be equal to $m_{W^\pm}/2$.

2. Define the δ^2_b ;

$$\delta^2_b = -2 \log L_b - 2 \log L_{\bar{b}}, \quad L_b = \mathrm{CB}\left(E^{\mathrm{meas.}}_b - E^{\mathrm{rec.}}_b(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-})\right)$$

The likelihood function is obtained from the assessment of b-jets energy.

3. Compound $\chi^2_{\mathrm{tot.}}$; $\chi^2_{\mathrm{tot.}} = \chi^2_\mu + \delta^2_b$

One minimizes the $\chi^2_{\mathrm{tot.}}$ to obtain the optimal solution; $(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-})$.

χ^2 algorithm : Optional

The direction of b-jets is obtained by thrust axis method.

→ Add 4 angles $(\theta_b, \phi_b, \theta_{\bar{b}}, \phi_{\bar{b}})$ to the minimization parameters

→ Add constraints of 4 angles $(\theta_b, \phi_b, \theta_{\bar{b}}, \phi_{\bar{b}})$ to $\chi^2_{\mathrm{tot.}}$ as follows;

$$\chi^2_{\mathrm{direction}} = \chi^2_{\theta_b} + \chi^2_{\phi_b} + \chi^2_{\theta_{\bar{b}}} + \chi^2_{\phi_{\bar{b}}}, \qquad \chi^2_{\theta_b} = \left(\frac{\theta_b^{\mathrm{meas.}} - \theta_b}{\sigma[\theta_b^{\mathrm{meas.}}]}\right)^2$$

$(\chi^2_{\phi_b}, \chi^2_{\theta_{\bar{b}}}, \chi^2_{\phi_{\bar{b}}}$ are same as $\chi^2_{\theta_b})$

$$(\chi^2_{\mathrm{tot.}})' = \chi^2_{\mathrm{tot.}} + \chi^2_{\mathrm{direction}}$$

We can use $(\chi^2_{\mathrm{tot.}})'$ instead of $\chi^2_{\mathrm{tot.}}$ to get the optimal solution,

which is written in $(\theta_t, \phi_t, m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}, \theta_b, \phi_b, \theta_{\bar{b}}, \phi_{\bar{b}})$

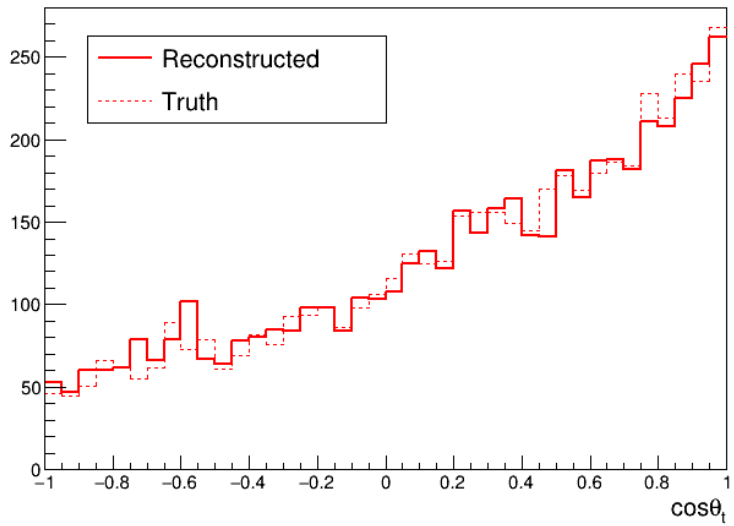
Kinematical reconstruction : Results

Reconstructed particles → 9 helicity angles :

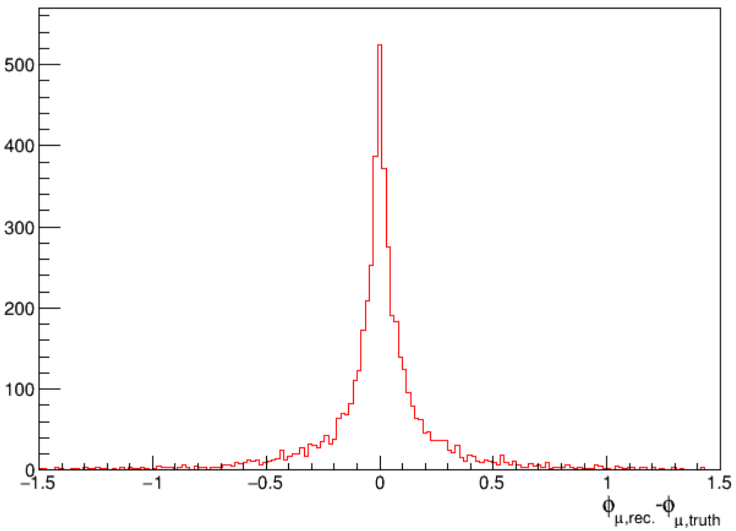
$$\cos\theta_t\,,\cos\theta_{W^+}\,,\phi_{W^+},\cos\theta_{\mu^+}\,,\phi_{\mu^+},\cos\theta_{W^-}\,,\phi_{W^-},\cos\theta_{\mu^-}\,,\phi_{\mu^-}$$

(→ Matrix element squared → Fit Form Factors)

eg.) $\cos\theta_t$



eg.) $\phi_{\mu^+,rec.} - \phi_{\mu^+,truth}$



The ratio of wrong assignment of b-quark is only 2.1 % !

(cf. ~16 % for the semi-leptonic analysis, Yo Sato Top@LC 2016)

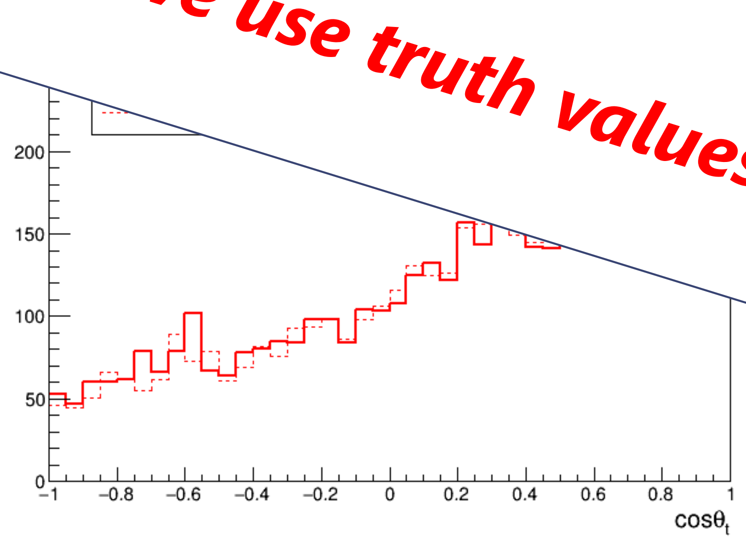
Kinematical reconstruction : Results

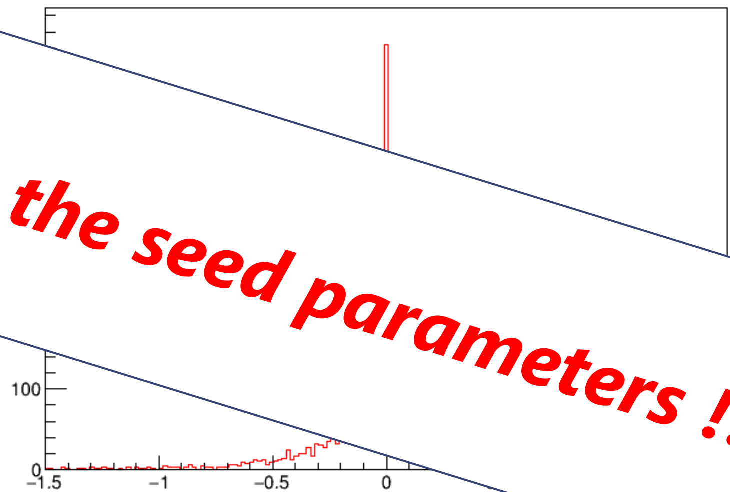
Reconstructed particles → 9 helicity angles :

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

(→ ... ent squared → Fit Form Factors)

eg.) $\phi_{\mu^+,rec.} - \phi_{\mu^+,truth}$





BUT we use truth values for the seed parameters !!!

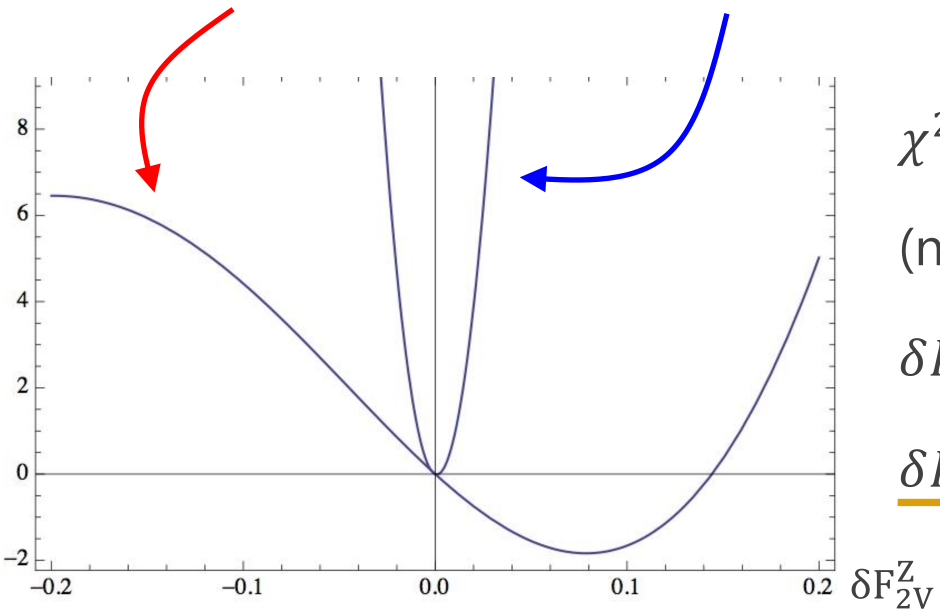
The ratio of wrong assignment of b-quark is only 2.1 % !

(cf. ~16 % for the semi-leptonic analysis, Yo Sato Top@LC 2016)

Analysis with Matrix element method

Illustration of analysis : 5000 unpolarized events

- using only $\cos\theta_t$
- using the complete set of 9 helicity angles



$\chi^2(\delta F^{Z}_{2V})$ function

(normalized such that $\chi^2(0) = 0$)

$\delta F^{Z}_{2V} = 0.080 \pm 0.05$ by $\cos\theta_t$

$\delta F^{Z}_{2V} = 0.001 \pm 0.01$ by the complete set

Number of events not used on purpose to compare the intrinsic power of these two to determine a single form factor, F^{Z}_{2V}.

Status of the 10 form factors fit

Δ_{F1}	-0.0067 $\pm$ 0.0082
Δ_{F2}	0.035 $\pm$ 0.017
Δ_{F3}	-0.056 $\pm$ 0.012
Δ_{F4}	0.035 $\pm$ 0.018
Δ_{F5}	-0.022 $\pm$ 0.026
Δ_{F6}	0.042 $\pm$ 0.045
Δ_{F7}	-0.0081 $\pm$ 0.015
Δ_{F8}	0.010 $\pm$ 0.032
Δ_{F9}	0.013 $\pm$ 0.024
Δ_{F10}	-0.010 $\pm$ 0.022

(Preliminary)

5000 events, after cut on the $\chi^2_{\text{tot.}}$ to keep ~83% of the events.

Some small biases are observed (eg. Δ_{F3}) at few percent level

→ **No show stopper yet !!!**

→ Should be corrected by accounting for detector effects in $|M|^2$

Summary

- **Started realistic study with the matrix element method**

  → Our first targets were the hadronization and the detector effects

- **Development of reconstruction**
  - The thrust axis method produced same accuracy as jet clustering
  - All kinematics can be reconstructed with good accuracy by the kinematical reconstruction

- **Analysis with Matrix element method**
  - Much more powerful than the analysis using only $\cos\theta_t$
  - 10 form factors can be fitted at percent precision

  → Move on to include other effects neglected so far (ISR…)

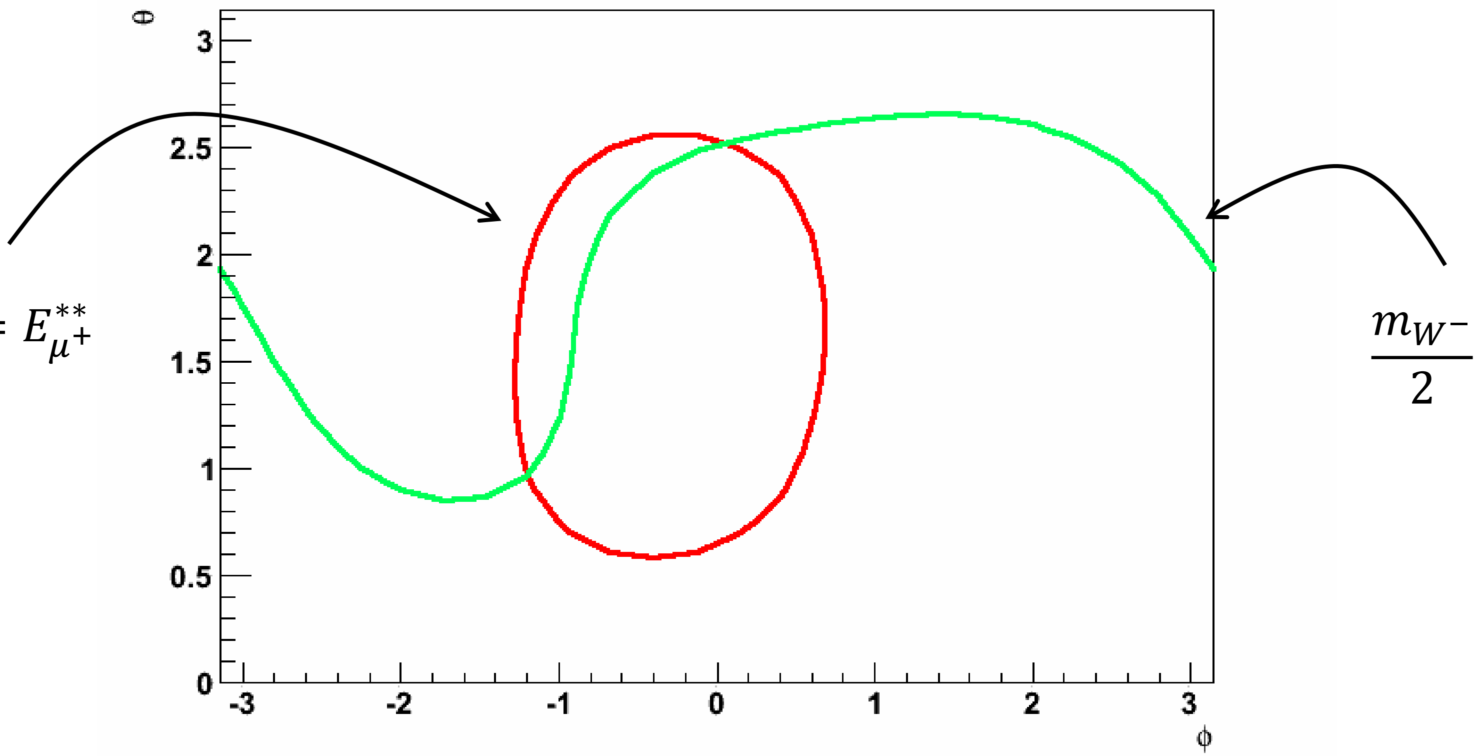
Back up

Kinematical constraints

In the W rest frame, the energy of isolated lepton is equal to $m_W/2$

(with ignoring ISR and bremsstrahlung)

$$\frac{m_{W^+}}{2} = E^{**}_{\mu^+}$$

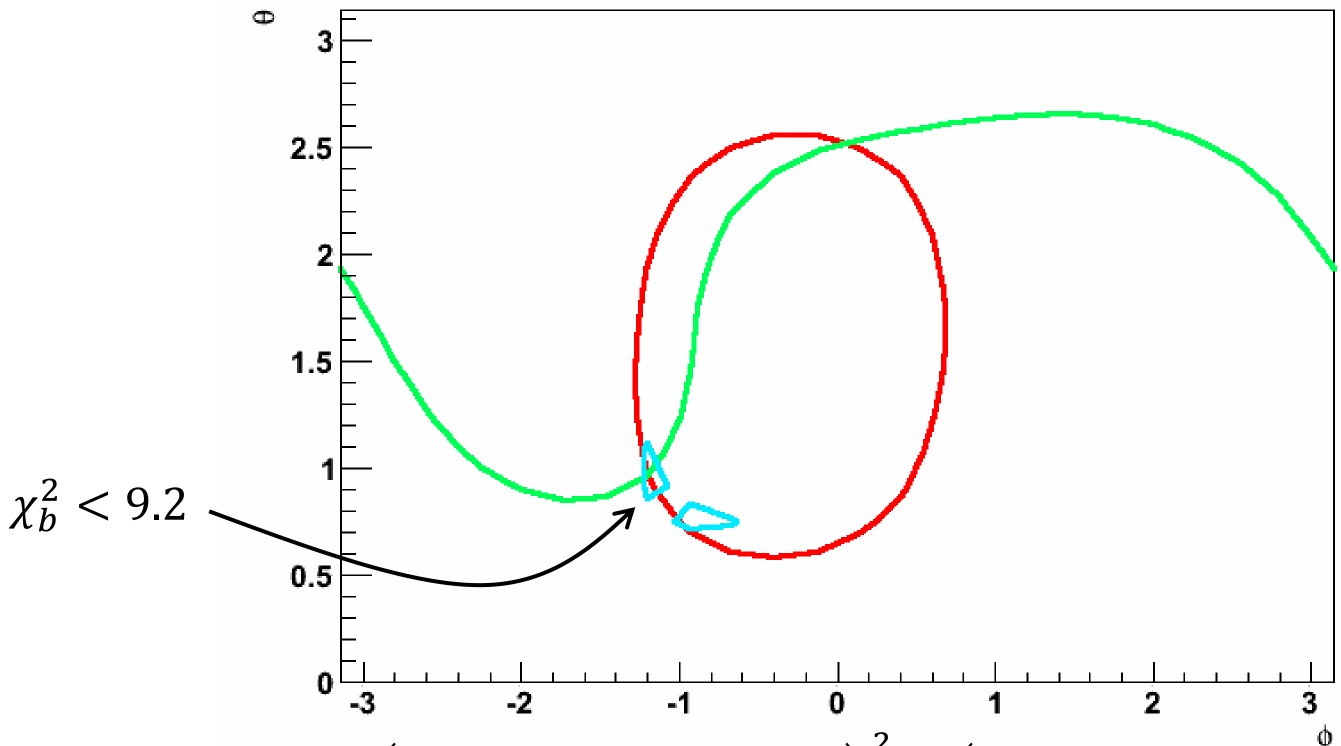


$$\frac{m_{W^-}}{2} = E^{**}_{\mu^-}$$

Measurements of b-quark energies

To select a right solution, we can use the measurement of b-jets energy.

(Because this figure is at parton level, the χ_b^2 doesn't make sense.)



$$\chi_b^2(\phi_t, \theta_t) = \left(\frac{E_{b,mes} - E_{b,reco}(\phi_t, \theta_t)}{\sigma_j \sqrt{E_{b,mes}}}\right)^2 + \left(\frac{E_{\bar{b},mes} - E_{\bar{b},reco}(\phi_t, \theta_t)}{\sigma_j \sqrt{E_{\bar{b},mes}}}\right)^2$$

Miss combination of b-quarks

When we use the anti-b direction for the top reconstruction, the measurements of energy of b-jets excludes this combination.