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

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Kinematical Reconstruction : Strategy

Neutrinos and photon of ISR cannot be reconstructed by detectors.

There are **7 unknowns** in di-muonic state of top pair production.

$$P_{x,\nu}, P_{y,\nu}, P_{z,\nu}, P_{x,\bar{\nu}}, P_{y,\bar{\nu}}, P_{z,\bar{\nu}}, P_{z,\gamma_{\mathrm{ISR}}}$$

To recover them, we impose **8 constraints**,

- Initial state constraints : $E_{total} = 500\ \mathrm{GeV}, \vec{P}_{\mathrm{total}} = \vec{0}$
- Mass constraints : $m_t = m_{\bar{t}} = 174\ \mathrm{GeV}, m_{W^+} = m_{W^-} = 80.4\ \mathrm{GeV}$

There are enough constraints to determine the missing variables.

Kinematical Reconstruction : Algorithm

Introduce ***4 free parameters*** **:** $\boldsymbol{P_{x,\nu}, P_{y,\nu}, P_{z,\nu}, P_{z,\gamma_{ISR}}}$

Other missing variables are defined as follows;

$$P_{x,\bar{\nu}} = -\left(P_{x,\mathrm{Visible}} + P_{x,\nu}\right), P_{y,\bar{\nu}} = -\left(P_{y,\mathrm{Visible}} + P_{y,\nu}\right), P_{z,\bar{\nu}} = -\left(P_{z,\mathrm{Visible}} + P_{z,\nu} + P_{z,\gamma_{\mathrm{ISR}}}\right)$$

(All physics variables also can be computed using these parameters.)

Define the likelihood function;

$$\boldsymbol{L_0 = BW(m_t, 174)BW(m_{\bar{t}}, 174)BW(m_{W^+}, 80.4)BW(m_{W^-}, 80.4)Gaus(E_{total}, 500)}$$

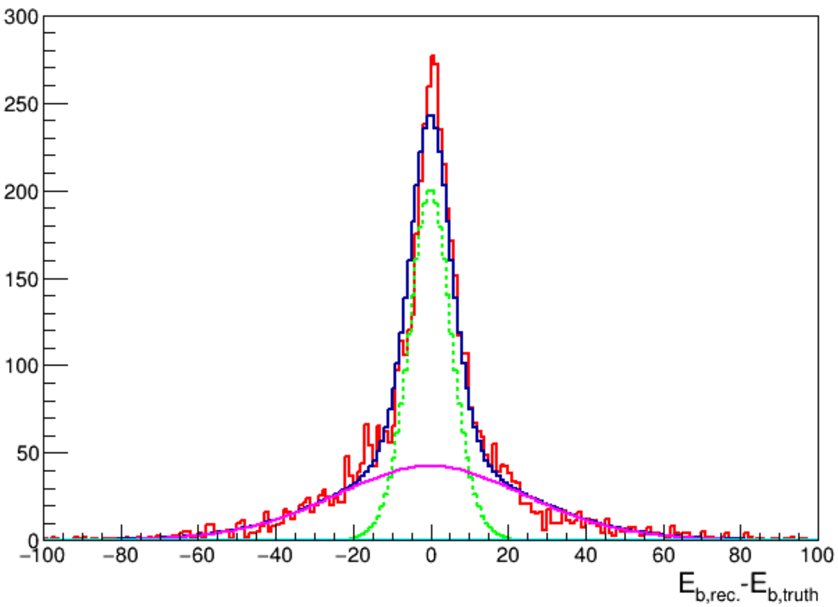
(BW : Breit-Wigner function, $Gaus$: Gaussian function, other parameters are written in backup)

To correct the energy resolution of b-jets reconstruction, we add ***2 parameters,***

$\boldsymbol{E_b, E_{\bar{b}}}$, and resolution functions, R, to the likelihood function.

$$\boldsymbol{L = L_0 * R\left(E_b, E_b^{\mathrm{reconstructed}}\right)R\left(E_{\bar{b}}, E_{\bar{b}}^{reconstructed}\right)}$$

Energy resolution of b-jets



$$G\left(\sigma_j, K; E_b^{\text{Measurement}}\right)$$

$$\propto \exp\left[-\left(\frac{E_b^{\text{Measurement}} - E_b^{\text{MC}}}{\sigma_j * \left(E_b^{\text{Measurement}}\right)^K}\right)^2\right]$$

Define the resolution function R as

$$R = c_1 G_1 + c_2 G_2 + c_3 G_3$$

Results of fit :

$$c_1 = 0.50, \sigma_{j,1} = 0.77, K_1 = 0.45$$

$$c_2 = 0.48, \sigma_{j,2} = \ 6.4, K_2 = 0.31$$

$$c_3 = 0.02, \sigma_{j,3} = \ 4.7, K_3 = 0.69$$

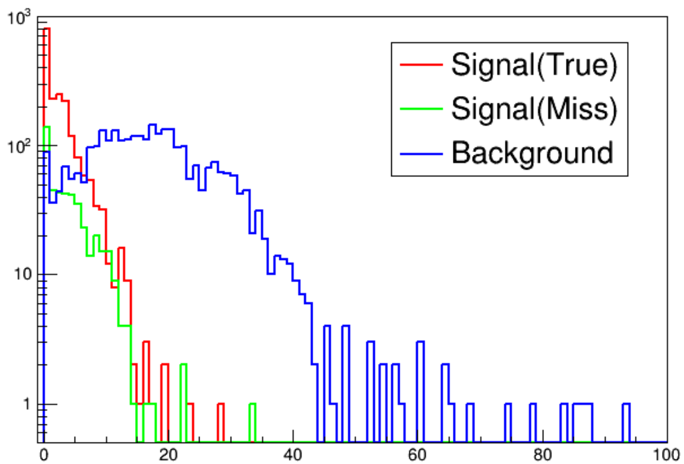
Backup

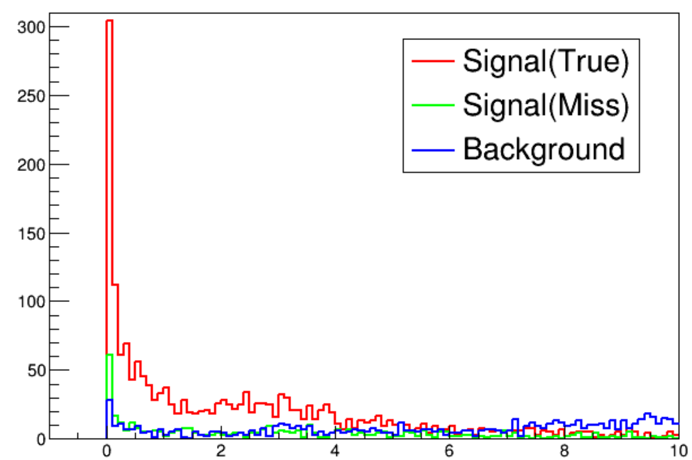
Kinematical Reconstruction

For simplicity, we define $q = -2\log L + C$ (scaled as the minimum value becomes 0)

There are two possibilities for combination of b-jet and muon.

→ Define ***the best candidate*** as a candidate having **smaller** q and $q_{\min}$ as q of the best candidate. One can check that it is true or miss combination by generator information.

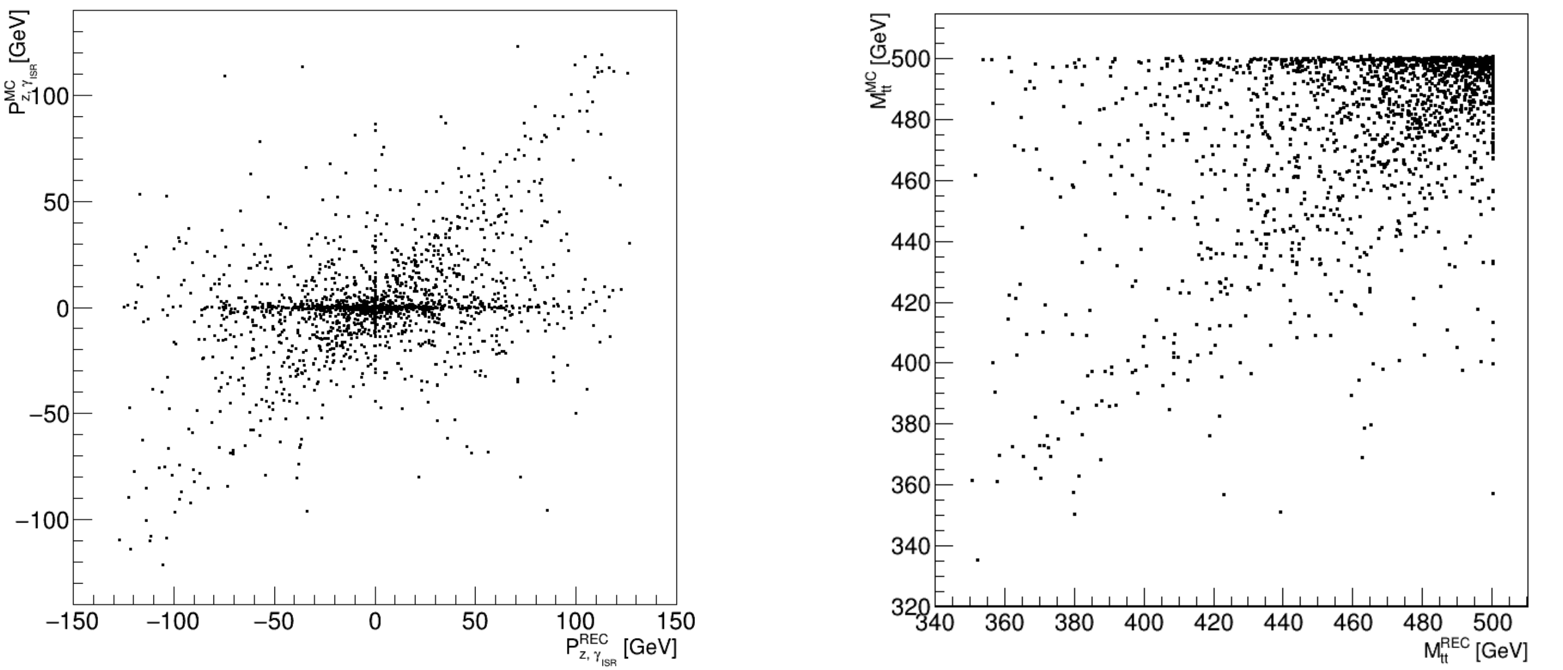




$q_{\min}$ distribution of Left polarization events (left : whole distribution, right : zoomed one)

→ *Cut on $q_{\min}$ is useful to reduce the background and miss combination events.*

ISR photon



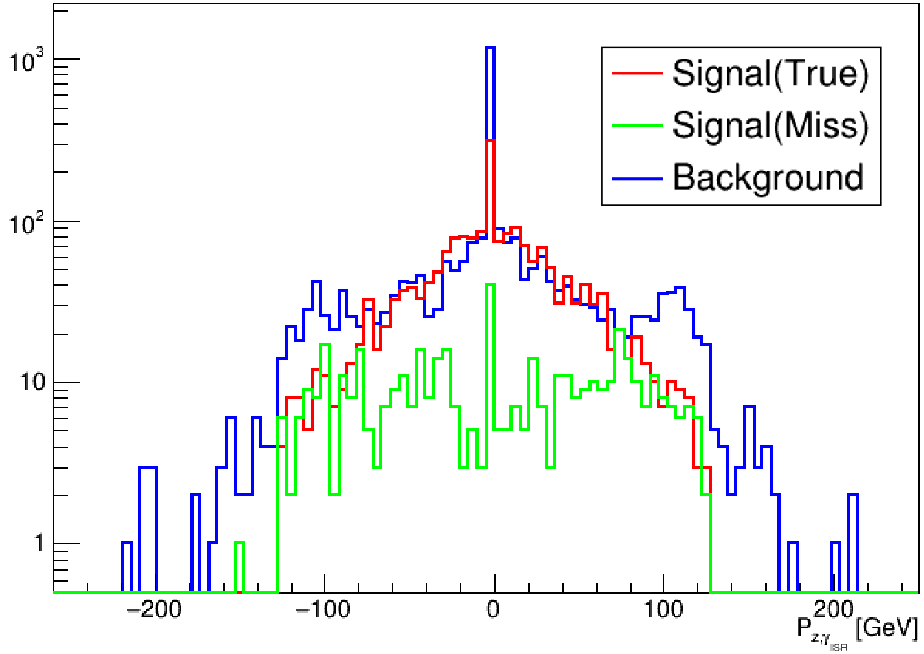
Scatter plots between MC and reconstructed of Left polarization and signal events

(left : $P_{z,\gamma_{\rm ISR}}$, right : mass of top pair)

Small correlations between MC and reconstructed are observed.

→ *Cut on $P_{z,\gamma_{ISR}}$ or M_{tt} is useful to reduce hard ISR events.*

ISR photon



$P_{z,\gamma_{\mathrm{ISR}}}$ distribution of Left polarization events

$P_{z,\gamma_{\mathrm{ISR}}}$ distribution of miss combination events are wider than true combination

→ *Cut on $P_{z,\gamma_{ISR}}$ is also useful to reduce miss combination events*

Cut table

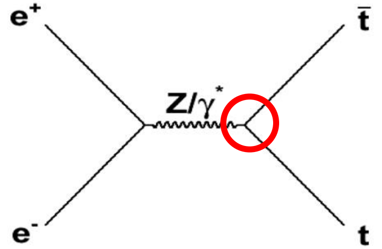
250 fb^{-1} (-0.8,+0.3) Left	initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8	$q_{\min} < 3$ & $\lvert P_{z,\gamma} \rvert < 50$ GeV
Signal $bb\mu\mu\nu\nu$ (True)	**2961**	**2725** (e = 92.0 %)	**1921** (80.9%) (e = 80.2%)	**945** (90.7%) (e = 35.2%)
Signal $bb\mu\mu\nu\nu$ (Miss)			453 (19.1%)	97 (9.3%)
$bbll\nu\nu$ (except $bb\mu\mu\nu\nu$)	23609	387	335	71
$bbl\nu qq$	104114	40	31	3
$qqll$ (ZZ)	91478	13800	2519	21
ll (weight = 4)	212274 (→ 849096)	74961 (→ 299844)	90 (→ 360)	0
$l\nu l\nu$ (WW) (weight = 4)	377058 (→ 1508232)	1884 (→ 7536)	3 (→ 12)	0
$lll\nu l\nu$ $(llWW)$	3021	947	19	0

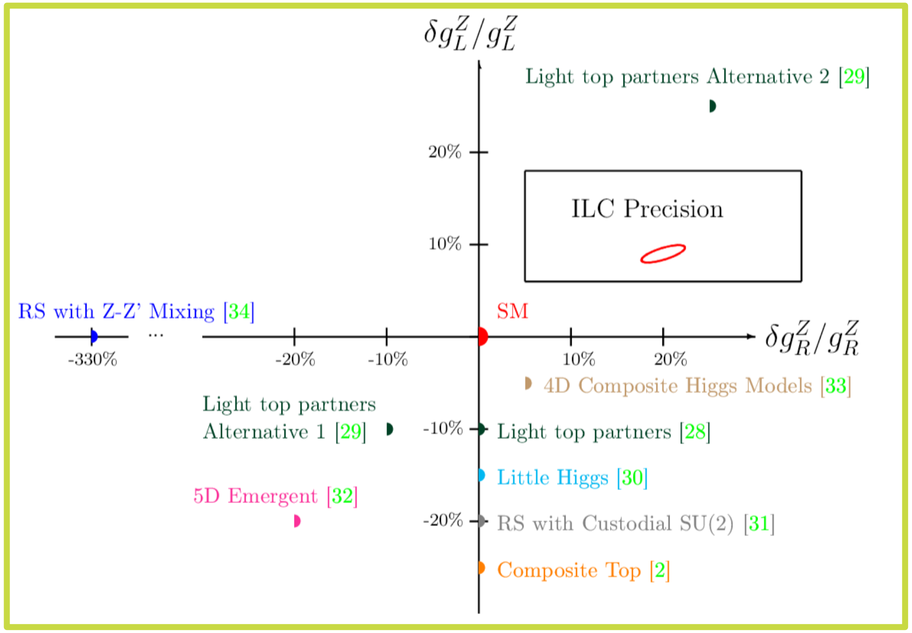
Top EW Couplings Study

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

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

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



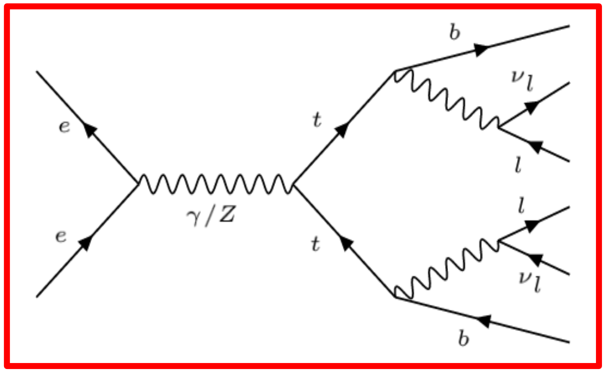


In new physics models, such as composite models, the predicted deviation of coupling constants, $g_L^Z, g_R^Z\ (= F_{1V}^Z \mp F_{1A}^Z)$ from SM is typically 10 %

Di-leptonic State of the top pair production

Top pair production has three different final states:

- Fully-hadronic state $(e^+e^- \to t\bar{t} \to b\bar{b}q\bar{q}q\bar{q})$ 46.2 %
- Semi-leptonic state $(e^+e^- \to t\bar{t} \to b\bar{b}q\bar{q}l\nu)$ 43.5%
- **Di-leptonic state $(e^+e^- \to t\bar{t} \to b\bar{b}l\nu l\nu)$ 10.3%**



Advantage

- More observables be computed

→ Higher intrinsic sensitivity to the form factors, in principle.

Difficulty

- Two missing neutrinos
- Lower statistics : 6 times less events than the semi-leptonic state

((2/3 x 43.5 %) / (4/9 x 10.3 %) = ~ 6.3)

Pre-selection

The quality cut is necessary to reject the b-jet miss-assignment events when we don't use the b-charge reconstruction. The cut might be also effective to reject background events.

We use only two loose constraints, called **Pre-selection**, before the kinematical reconstruction of top quark, which is useful to shorten the CPU time.

- **1 isolated μ^- and 1 isolated μ^+**
- **1 (or 2) jet has high b-tag value obtained by the LCFI Plus (b-tag1 > 0.8 or b-tag2 > 0.8)**

Other constraints that can be considered :

Thrust value, Visible energy, Mass of $\mu^-\mu^+$, ...

Pre-selection : Cut table

250 fb^{-1} (-0.8, +0.3) Left	Initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8
Signal $bb\mu\mu\nu\nu$	2961	2725 (e = 92.0%)	2374 (e = 80.2%)
$bbll\nu\nu$ (except $bb\mu\mu\nu\nu$)	23609	387	335
$bbl\nu qq$	104114	40	31
$qqll$ (ZZ)	91478	13800	2519
ll (weight = 4)	212274 (→849096)	74961 (→ 299844)	90 (→ 360)
$l\nu l\nu$ (WW) (weight = 4)	377058 (→ 1508232)	1884 (→ 7536)	3 (→ 12)
$lll\nu l\nu$ $(llWW)$	3021	947	19

Pre-selection : Cut table

250 fb^{-1} (+0.8, -0.3) Right	initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8
Signal $bb\mu\mu\nu\nu$	1255	1162 (e = 92.6%)	1040 (e = 82.9%)
$bbll\nu\nu$ (except $bb\mu\mu\nu\nu$)	10181	160	138
$bbl\nu qq$	45053	18	12
$qqll$ (ZZ)	46344	6980	1237
ll (weight = 4)	161371 (→64524)	57916 (→ 231664)	61 (→ 244)

Cut table

250 fb^{-1} (-0.8,+0.3) Right	initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8	$q_{\min} < 3$ & $\lvert P_{z,\gamma}\rvert < 50$ GeV
Signal $bb\mu\mu\nu\nu$ (True)	**1255**	**1162** (e = 92.6 %)	**874** (84.0%) (e = 82.9%)	**437** (94.2%) (e = 37.0%)
Signal $bb\mu\mu\nu\nu$ (Miss)			166 (16.0%)	27 (5.8%)
$bbll\nu\nu$ (except $bb\mu\mu\nu\nu$)	10181	160	138	30
$bbl\nu qq$	45053	18	12	0
$qqll$ (ZZ)	46344	6980	1237	6
ll (weight = 4)	161371 (→ 64524)	57916 (→ 231664)	61 (→ 244)	0

Parameters of Likelihood function

Breit-Wigner function of mass of top and W

$$BW(m) \propto \frac{1}{1 + \left(\frac{m - m_0}{m_0 \Gamma_0}\right)^2}$$

$$m_{t,0} = m_{\bar{t},0} = 174, m_{W^+,0} = m_{W^-,0} = 80.4, \Gamma_0 = 5$$

Gaussian function of Beam energy spread

$$Gaus(E_{total}) \propto \exp\left[-\left(\frac{E_{total} - 500}{0.39}\right)^2\right]$$