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

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Current status

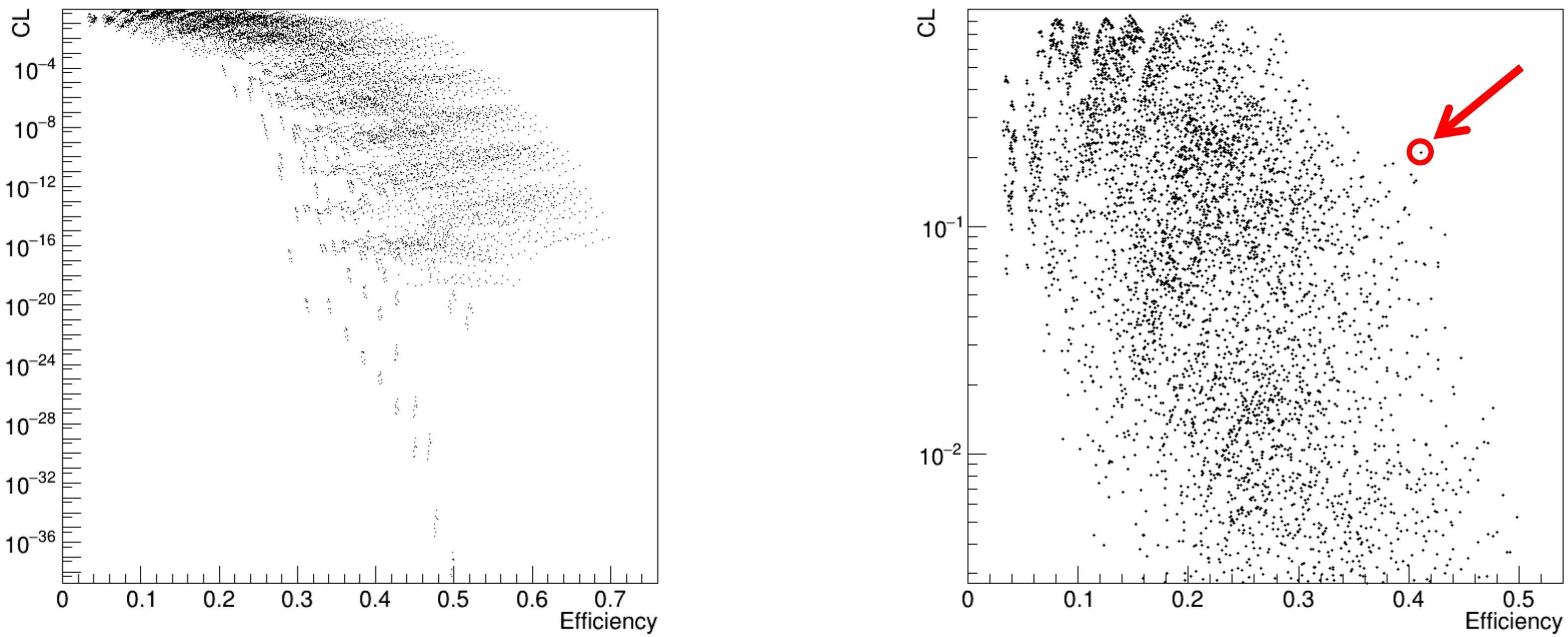
Up to last meeting

- Main background : (other) di-leptonic state of $t\bar{t}$, ZZ
- We obtained good results of form factor's fit after the quality cut.
  - CL is ~21% for CPC form factors fit and efficiency ($N/N_{preselection}$) is ~42%

→ **Verify that results remain good after same cuts on other samples.**

- Brief results using another sample of events
- Optimization and investigation of criteria of the quality cut

Optimization of criteria for the quality cut (Last meeting)



Confidence level of 6 CPC form factors fit vs. Efficiency ($N/N_{\mathrm{pre-selection}}$) (left : **whole**, right : **zoomed**)

Each point has different criteria for $\left(\chi^2_{\mathrm{Left}}, \Delta\chi^2_{\mathrm{Left}}, \chi^2_{\mathrm{Right}}, \Delta\chi^2_{\mathrm{Right}}\right)$.

A point which have relatively large confidence level and efficiency is selected as a trial ; $\left(\chi^2_{\mathrm{Left}} < 5, \Delta\chi^2_{\mathrm{Left}} > 1, \chi^2_{\mathrm{Right}} < 7, \Delta\chi^2_{\mathrm{Right}} > 1\right)$

One should verify on another sample of events that this criteria remains good.

Cut table

250 fb^{-1} (-0.8,+0.3) Left	initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8	$\chi^2 < 5$ & $\Delta\chi^2 > 1$
Signal (True)	2961 (e = 100%)	2725 (e = 92.0%)	1838 (77.4%) (e = 80.2%)	763 (92.4%) (e = 27.9%)
Signal (Miss)	-	-	536 (22.6%)	63 (7.6%)
$t\bar{t}$ di-leptonic	23609	387	335	57
$t\bar{t}$ semi-leptonic	104114	40	31	3
ZZ	100570	17346	2560	20
2 lepton (weight = 4)	212274 (→ 849096)	74961 (→ 299844)	90 (→ 360)	0
WW (weight = 4)	377058 (→ 1508232)	1884 (→ 7536)	3 (→ 12)	0
llWW	3021	947	19	0

Cut table

250 fb^{-1} (-0.8,+0.3) Right	initial		$\mu^+\mu^-$		b-tag1>0.8 or b-tag2>0.8		$\chi^2 < 7$ & $\Delta\chi^2 > 1$	
Signal (True)	1255	(e = 100%)	1162	(e = 92.6%)	811 (88.0%)	(e = 82.9%)	545 (94.3%)	(e = 46.1%)
Signal (Miss)	-		-		229 (22.0%)		33 (5.7%)	
$t\bar{t}$ di-leptonic	10181		160		138		48	
$t\bar{t}$ semi-leptonic	45053		18		12		1	
ZZ	51928		9051		1252		17	
2 lepton (weight = 4)	161371 (→ 64524)		57916 (→ 231664)		61 (→ 244)		0	

Results of fit : aft. the quality cut (Last meeting)

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0068 \pm 0.0128 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & +0.0163 \pm 0.0235 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & +0.0210 \pm 0.0184 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0556 \pm 0.0285 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0579 \pm 0.0386 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & +0.0149 \pm 0.0645 \end{bmatrix}$$

Result of 6 form factor (CPC) fit. CL $= 21.1181$ %

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & +0.0002 \pm 0.0238 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & +0.0195 \pm 0.0422 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & +0.0190 \pm 0.0236 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & -0.0270 \pm 0.0339 \end{bmatrix}$$

Result of 4 form factor (CPV) fit. CL $= 81.4708$ %

Results are consistent with SM.

Results of fit : aft. the quality cut (another sample)

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & -0.0219 \pm 0.0128 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.0001 \pm 0.0226 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & -0.0114 \pm 0.0180 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.1070 \pm 0.0283 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V} & -0.1552 \pm 0.0361 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2V} & +0.0123 \pm 0.0602 \end{bmatrix}$$

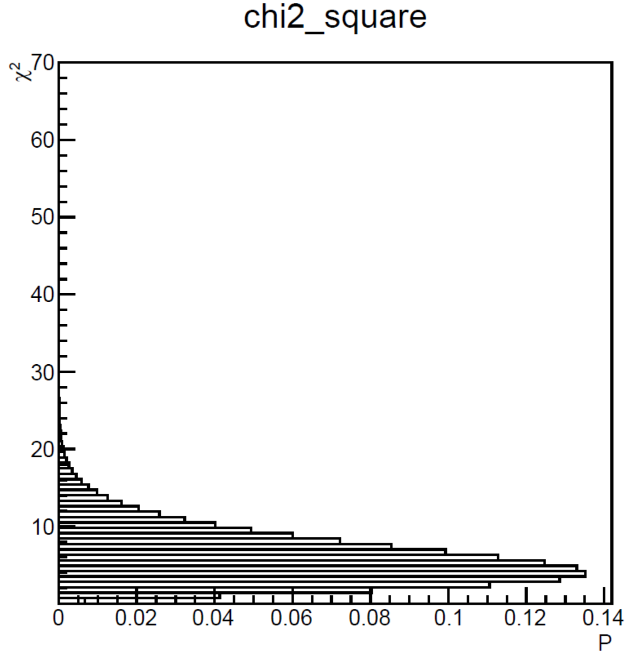
Result of 6 form factor (CPC) fit. CL $= 0.0001$ %

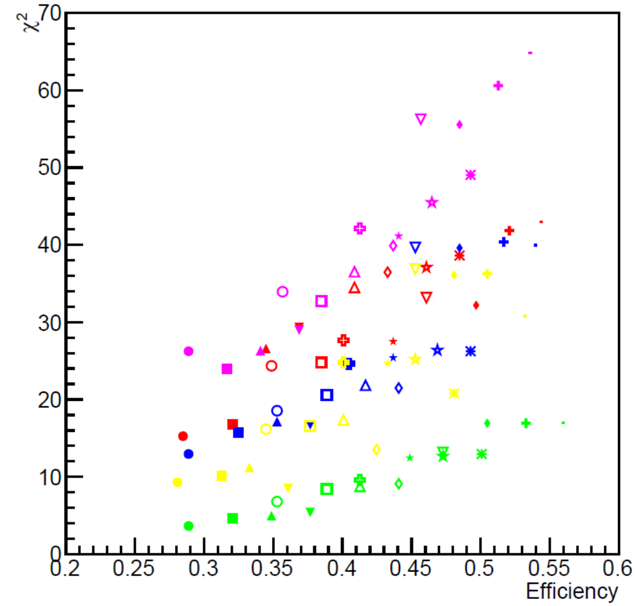
$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A} & -0.0232 \pm 0.0220 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2A} & +0.0089 \pm 0.0391 \\ \mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A} & +0.0039 \pm 0.0233 \\ \mathcal{I}m\ \delta\tilde{F}^{Z}_{2A} & +0.0215 \pm 0.0338 \end{bmatrix}$$

Result of 4 form factor (CPV) fit. CL $= 80.2959$ %

Results are **inconsistent** with SM. → Investigating the cause

Investigation of criteria of the quality cut





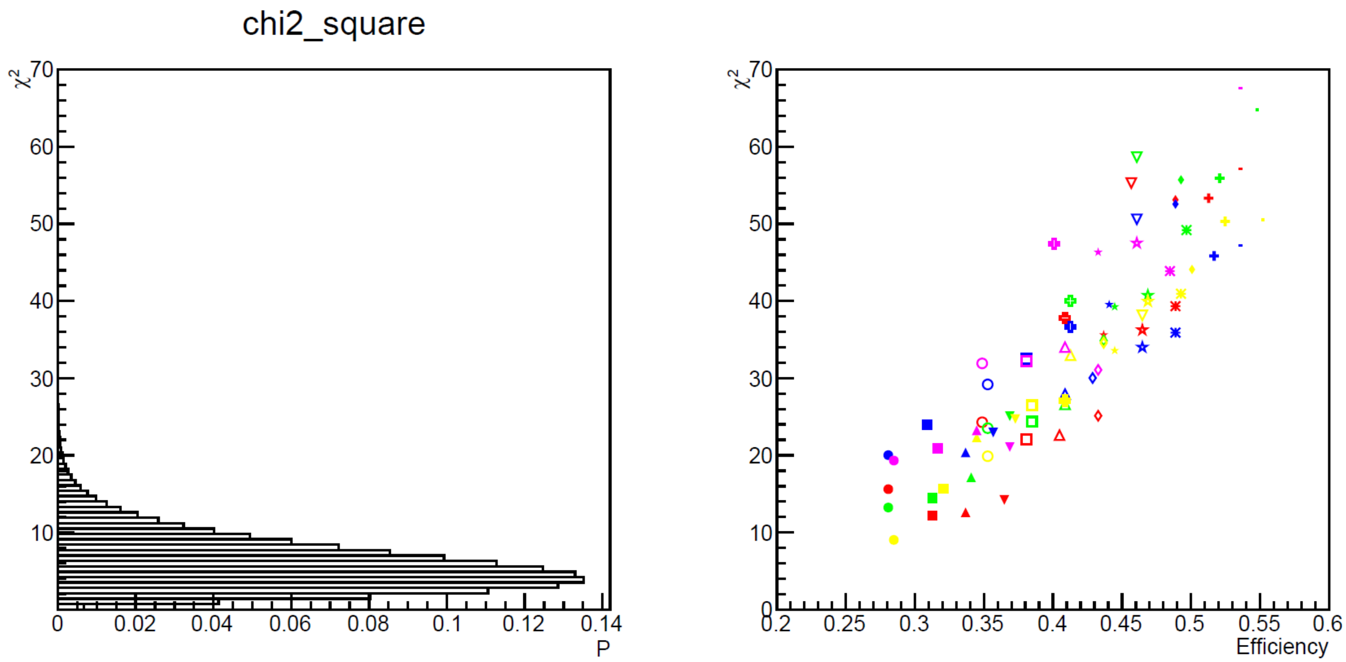
Left : χ^2 of 6 DOF distribution, Right : Scatter plot of efficiency (horizontal) and χ^2 (vertical).

We use 5 samples, each of them corresponds to 500 fb^{-1} which includes other di-leptonic state of $t\bar{t}$ but not ZZ.

- Color : sample, Maker : set of criteria

The fluctuation of χ^2_{test} (⇔ CL) is too large.

Investigation of criteria of the quality cut



Left : χ^2 of 6 DOF distribution, Right : Scatter plot of efficiency (horizontal) and χ^2 (vertical).

We use 5 samples, each of them corresponds to **1 ab^{-1}** which includes other di-leptonic state of $t\bar{t}$ but not ZZ.

- Color : sample, Maker : set of criteria

The fluctuation of χ^2_{test} (⇔ CL) becomes smaller but still not so small.

Summary

- When we use another sample of events, the results are inconsistent with SM even if same criteria of the quality cut are used.
- The fluctuation of χ^2 ($\Leftrightarrow$ CL) is too large and it becomes smaller when we use large statistics.

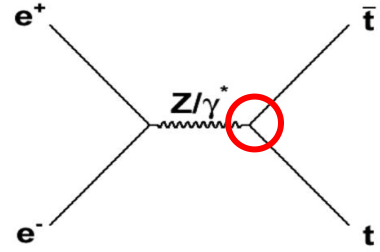
  → It means this is statistical fluctuation?
- The transfer function of detector resolution is not included in the likelihood function of MEM so far. If it is included, maybe the fluctuation becomes smaller and CL becomes better (but precision becomes worse.

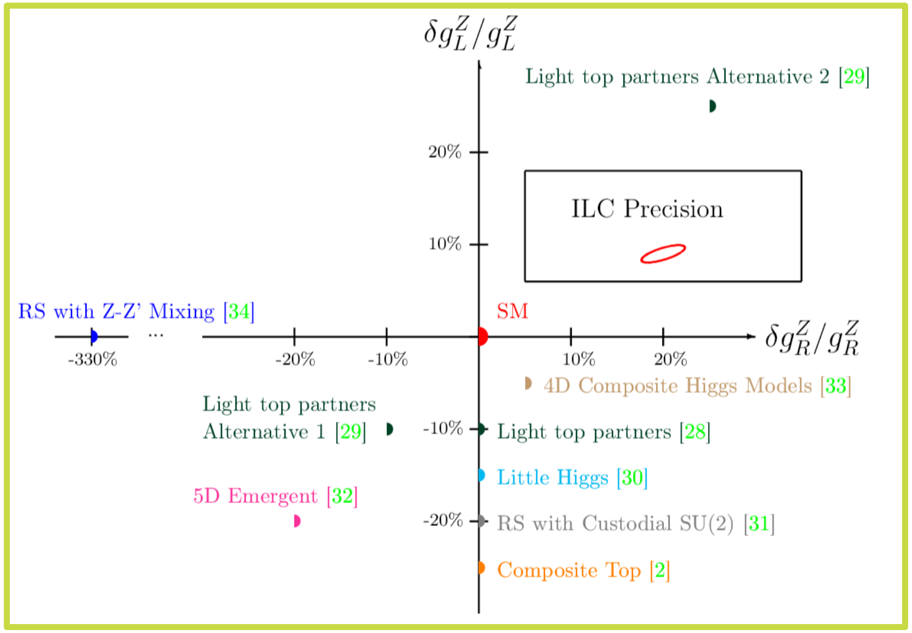
Top EW Couplings Study

- 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**

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



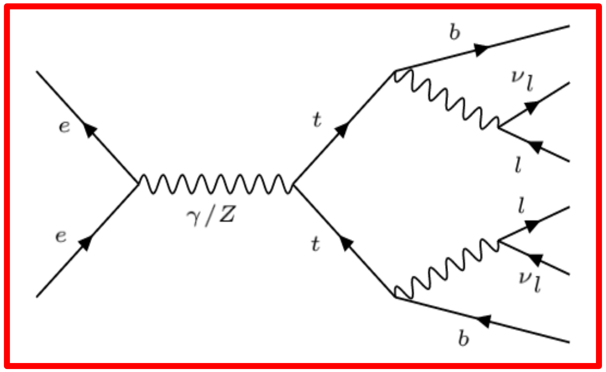


In new physics models, such as composite models, the predicted deviation of coupling constants, g_L^Z, g_R^Z $(= F_{1V}^Z \mp F_{1A}^Z)$ from SM is typically 10 %

Di-leptonic State of the top pair production

Top pair production has three different final states:

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



Advantage

- 9 helicity angles can be computed (details will be described later)

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

Difficulty

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

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

Set Up of Analysis

Situation	On / Off
Full simulation of ILD	On
Hadronization	On
Gluon emission from top	On
ISR/BS	On
γγ→hadrons	On
bkg. events	On

Sample	Consistent with Standard model (SM-LO)
$\sqrt{s}$	500 GeV
Polarization (P_{e^-}, P_{e^+})	(-0.8, +0.3) "Left" / (+0.8, -0.3) "Right"
Integrated luminosity	500 fb^{-1} (50/50 between Left and Right)
Generator	Whizard
Detector	ILD_01_v05 (DBD ver.)

Reconstruction Process

- Isolated leptons tagging
- Suppression of γγ → hadrons
  - k_t algorithm (cf. the Semi-leptonic analysis, R = 1.5)
- b-jet reconstruction
  - LCFI Plus (Durham algorithm)
  - The b-charge measurement is not used
- Kinematical reconstruction of top quark

Pre-selection

Quality cut

Pre-selection

The quality cut (definitions in following slides 9 and 13) 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.

- **One isolated μ^- and one isolated μ^+**
- **One (or two) 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

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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	1255	1162 (e = 92.6%)	1040 (e = 82.9%)
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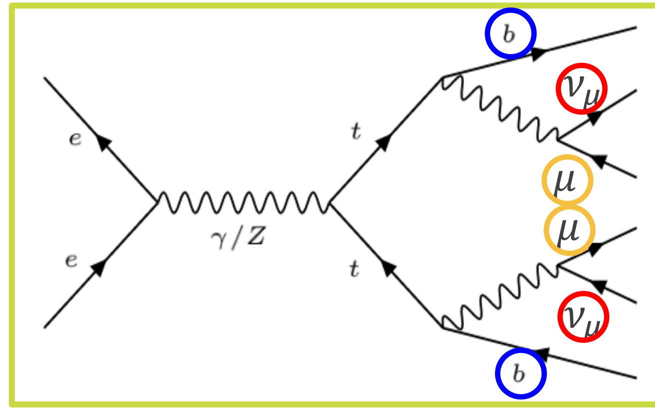
Kinematical Reconstruction of top quark

$\boldsymbol{e^+e^- \to t\bar{t} \to b\bar{b}\mu^+\nu\mu^-\bar{\nu}}$



Measurable
- muon's : $E_{\mu^+}, \theta_{\mu^+}, \phi_{\mu^+}, E_{\mu^-}, \theta_{\mu^-}, \phi_{\mu^-}$
- b-jet's : $E_{b1}, \theta_{b1}, \phi_{b1}, E_{b2}, \theta_{b2}, \phi_{b2}$

Missing
- neutrino's : $E_\nu, \theta_\nu, \phi_\nu, E_{\bar{\nu}}, \theta_{\bar{\nu}}, \phi_{\bar{\nu}}$
- **=> 6 unknowns**

To recover them, impose the kinematical constraints;

- Initial state constraints : $(\sqrt{s}, \vec{P}_{\text{init.}}) = (500, \vec{0})$
- Mass constraints : $m_t, m_{\bar{t}}, m_{W^+}, m_{W^-}$

=> 8 constraints (2 in excess)

We don't need E_{b1} and E_{b2} which are relatively difficult to reconstruct.

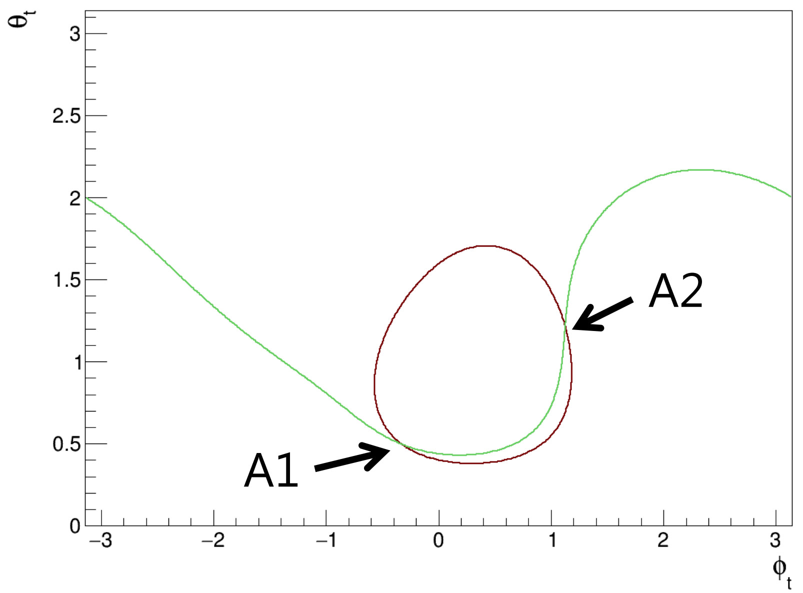
→ Just use to decide the assignment of b-jets

Kinematical Reconstruction of top quark

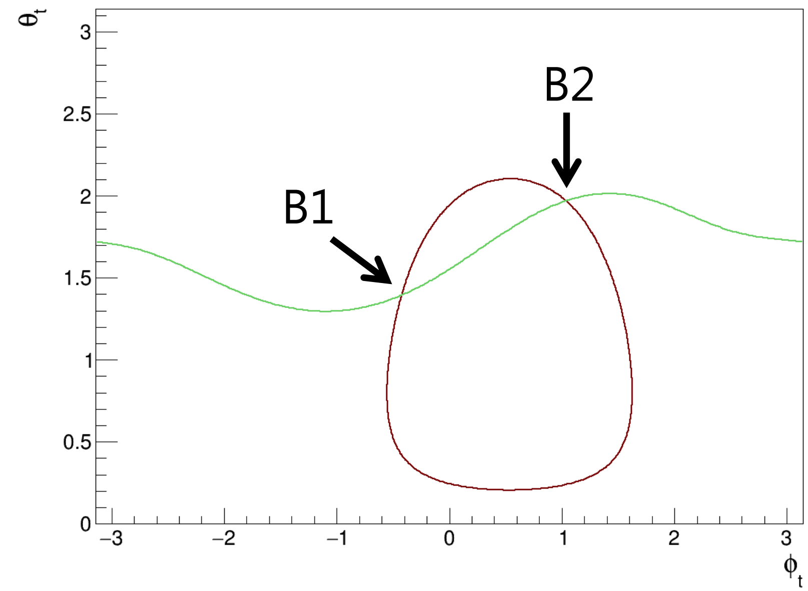
To detect the solution, we solve the following equations.

$$E_{\mu^\pm}^{W^\pm \text{ rest frame}}(\theta_t, \phi_t) = m_{W^\pm}/2 \ (\text{Red} : \mu^+, \ \text{Green} : \mu^-)$$

assignment A (correct), $b1 = b, \ b2 = \bar{b}$



assignment B (wrong), $b1 = \bar{b}, \ b2 = b$



Typically, 4 candidates exist for each event.

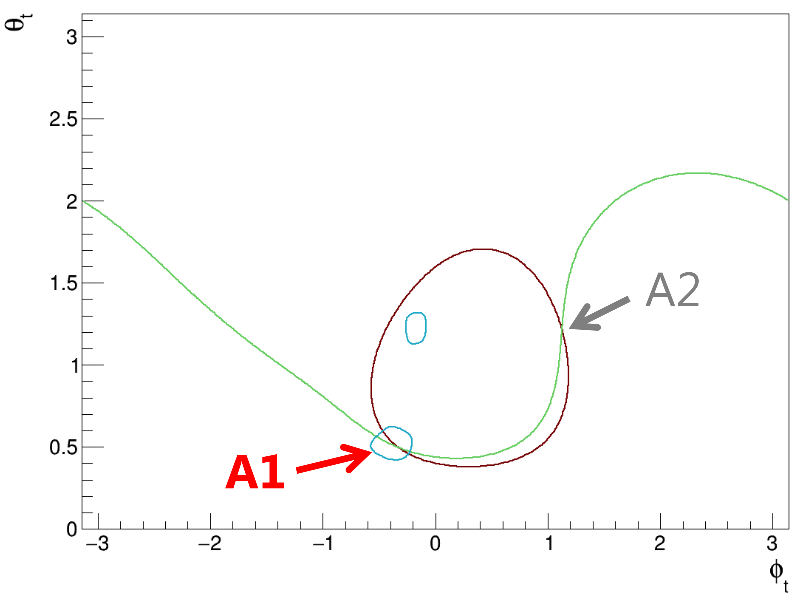
We need to select the optimal solution from these candidates.

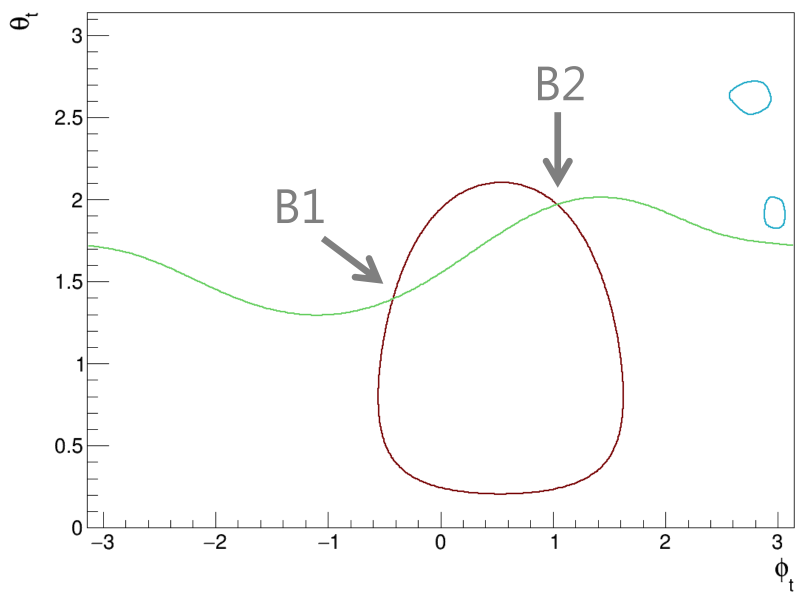
Kinematical Reconstruction of top quark

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

assignment A (correct), $b1 = b,\ b2 = \bar{b}$

assignment B (wrong), $b1 = \bar{b},\ b2 = b$



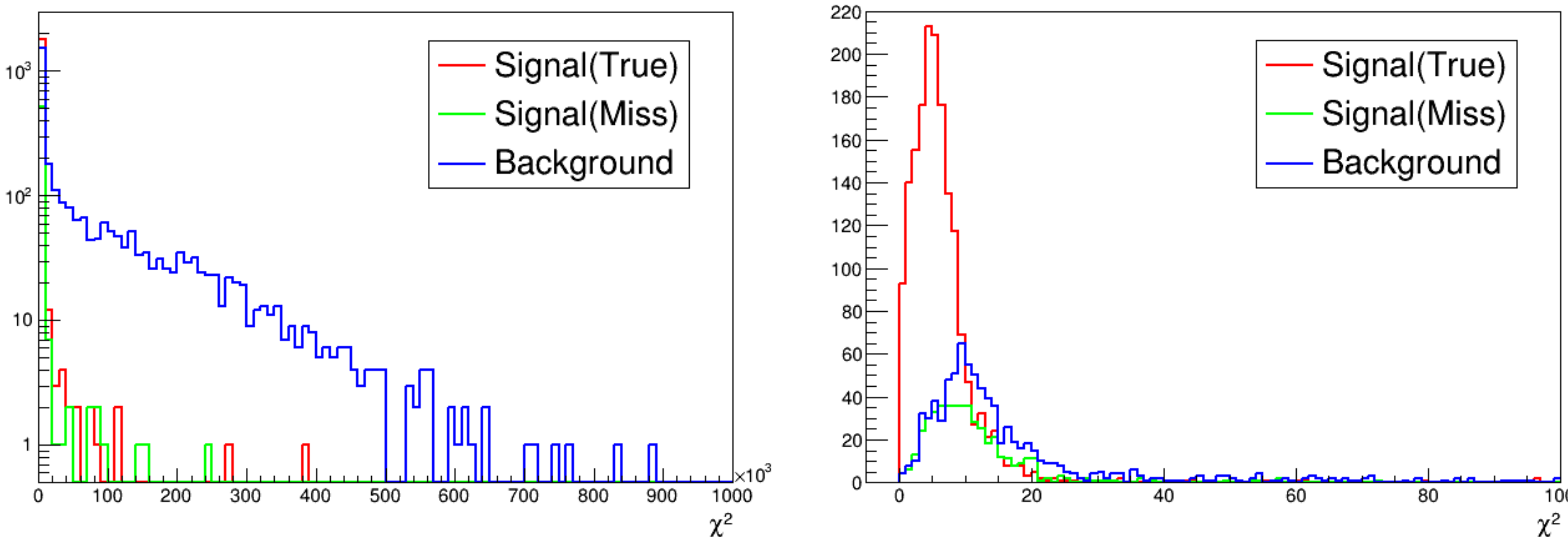


The candidate A1 has the minimum χ_b^2

→ The assignment A is selected and the solution is $(\theta_t,\phi_t) \simeq (0.5,-0.35)$

χ^2 distribution

Left



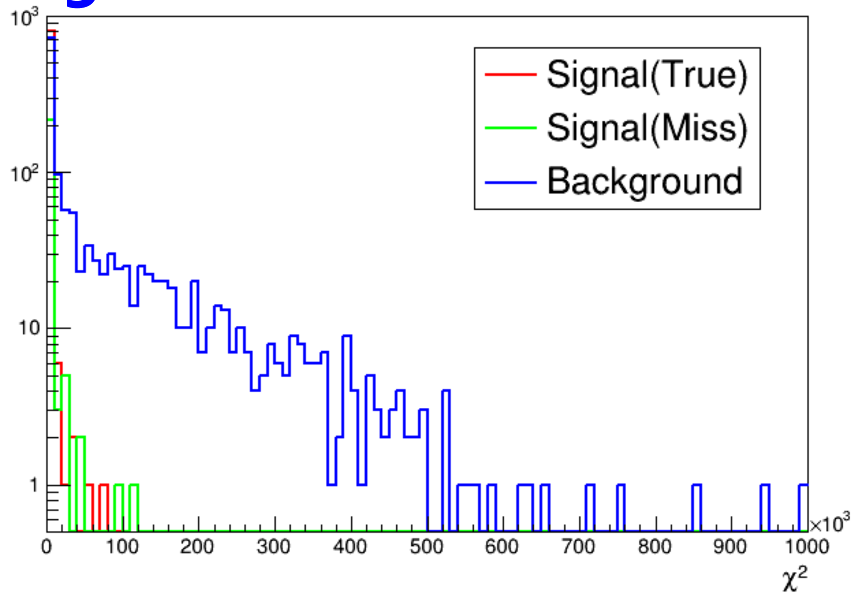
χ^2 distribution (left : whole distribution, right : zoomed one)

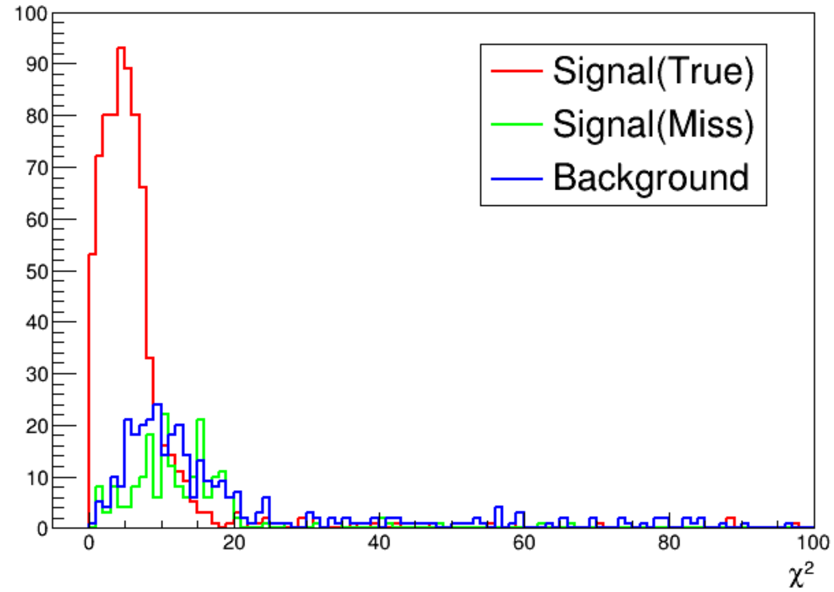
Background events have larger χ^2 and the distribution is broad.

→ Cut of χ^2 is useful to reject background events.

χ^2 distribution

Right





χ^2 distribution (left : whole distribution, right : zoomed one)

Background events have larger χ^2 and the distribution is broad.

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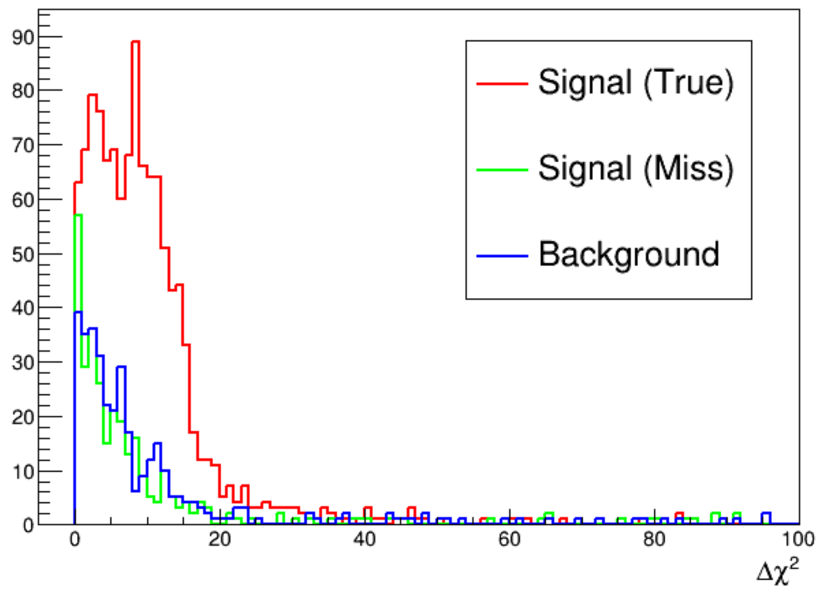
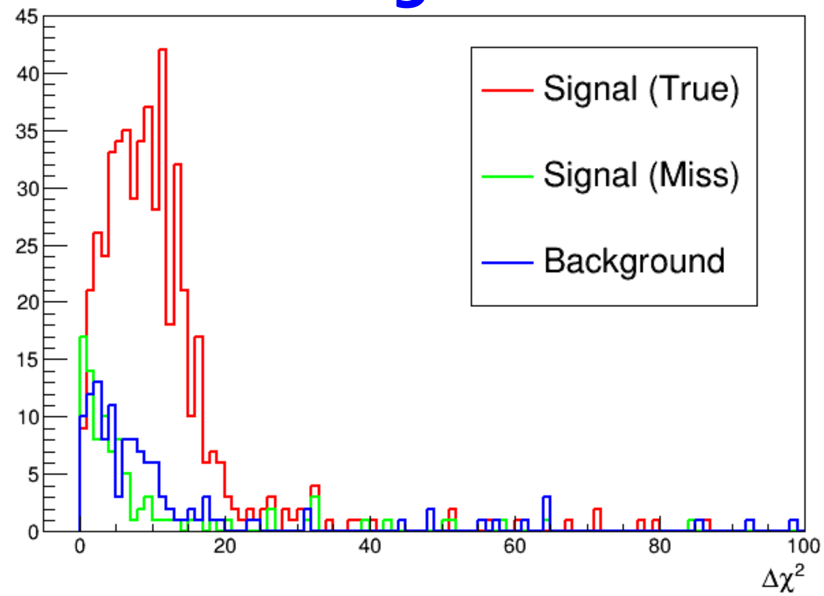
$\Delta\chi^2$ distribution

Left



Right



$\Delta\chi^2$ distribution (left : **Left** polarization, right : **Right** polarization)

$\Delta\chi^2$ is difference of χ^2 between two assignments.

Background events have smaller $\Delta\chi^2$.

→ Cut of $\Delta\chi^2$ is useful to reject background events, too.

Matrix Element Method Analysis

Matrix element method is based on the maximum likelihood method.

$$-2\log L(F)\left(=\chi^2(F)\right) = -2\left(\sum_{e=1}^{N_{\text{event}}} \log|M|^2(\Phi_e, F) - N(F)\right)$$

$|M|^2$: the full matrix element, Φ_e : the 9 helicity angles, F : the form factors, $N(F)$: the expected number of events.

The minimization of $\chi^2(F)$ automatically introduces the derivatives;

$$\omega_i(\Phi_e) = \frac{1}{|M|^2(\Phi_e)} \frac{\partial |M|^2(\Phi_e)}{\partial F_i}\bigg|_{F \text{ at SM}}, \qquad \Omega_i = \frac{1}{N}\frac{\partial N}{\partial F_i}\bigg|_{F \text{ at SM}}$$

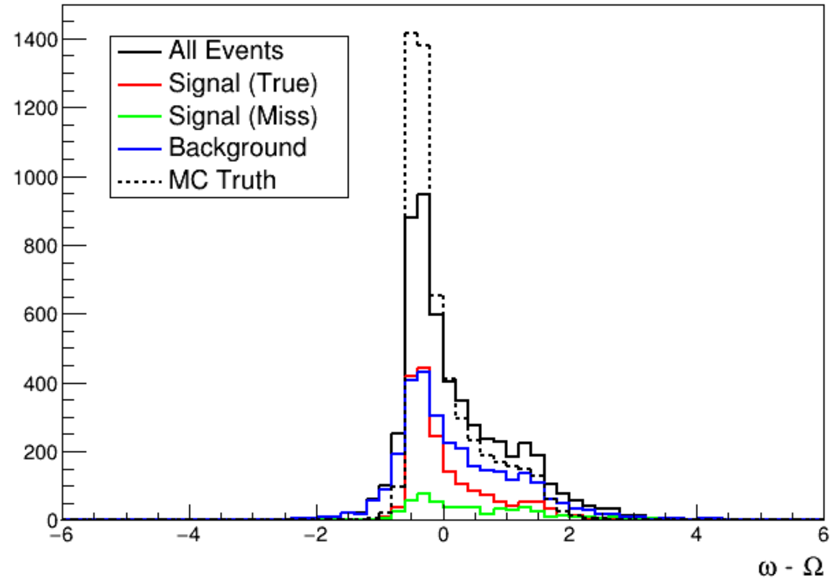
The results of fit are related with $\omega_i(\Phi_e)$ and Ω_i which are called **Optimal variables**;

- $\delta F_i \; (= F_{\text{fit}} - F_{\text{SM}}) \simeq \frac{<\omega_i - \Omega_i>}{<{\omega_i}^2>}$
- covariance matrix, V_{ij} ;

$$V_{ij}^{-1} = N_{\text{event}} < (\omega_i - \Omega_i)(\omega_j - \Omega_j) >$$

The distributions of $\omega - \Omega$ (bef. quality cut)

Left



The distribution of optimal variable ($\omega - \Omega$) of $\delta\tilde{F}_{1V}^{\gamma}$ before the quality cut

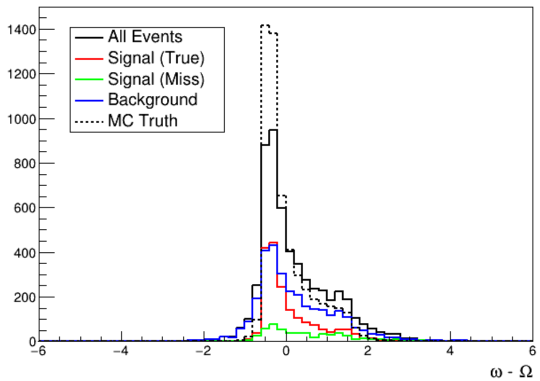
The distribution of background is very different from the signal.

It needs to be reject to fit form factors correctly.

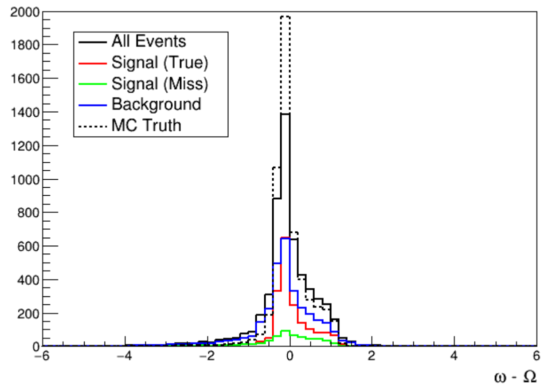
The distributions of $\omega - \Omega$ (bef. quality cut)

Left

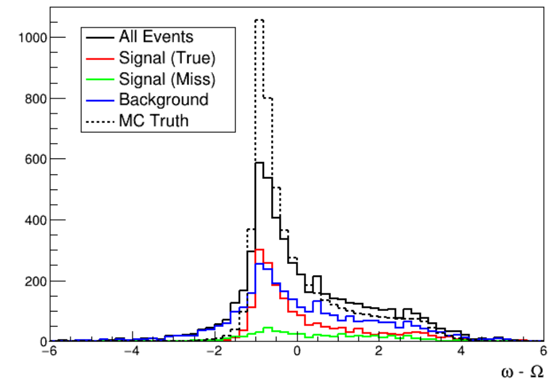
$\left(\delta\tilde{F}_{1V}^{\gamma}\right): \Omega = 2.26$



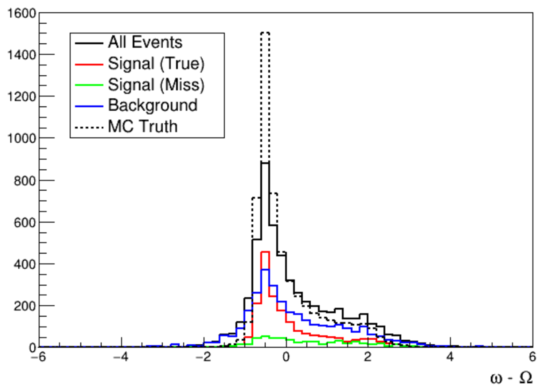
$\left(\delta\tilde{F}_{1V}^{Z}\right): \Omega = 1.39$



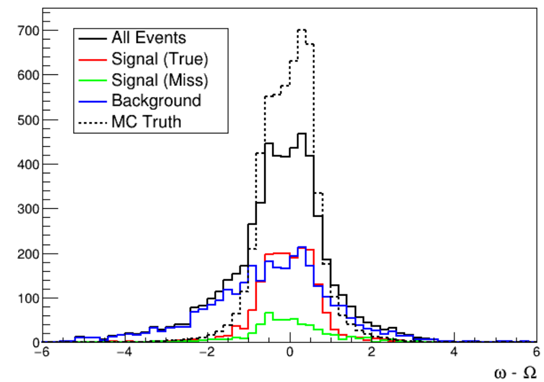
$\left(\delta\tilde{F}_{1A}^{\gamma}\right): \Omega = -0.413$



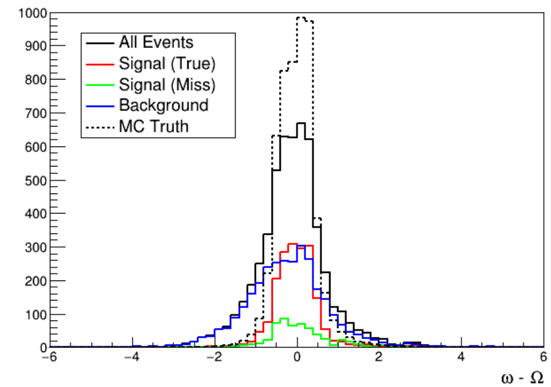
$\left(\delta\tilde{F}_{1A}^{Z}\right): \Omega = -0.300$



$\left(\delta\tilde{F}_{2V}^{\gamma}\right): \Omega = -0.472$



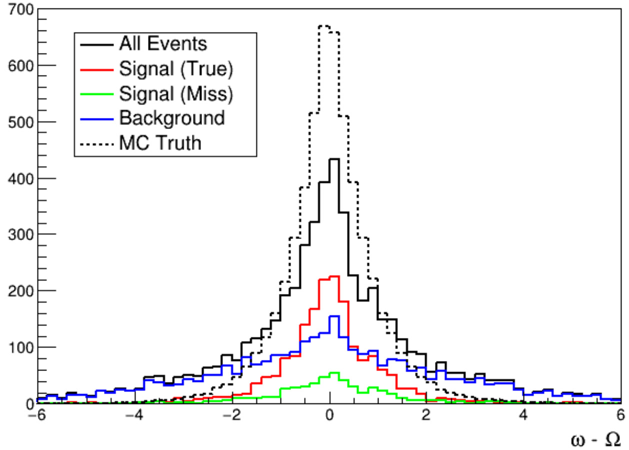
$\left(\delta\tilde{F}_{2V}^{Z}\right): \Omega = -0.290$



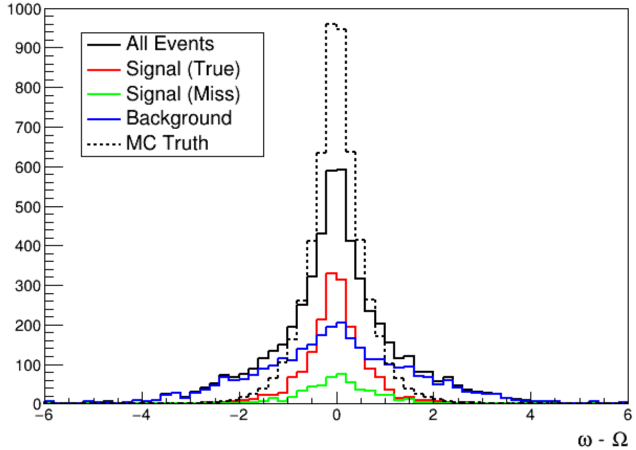
The distributions of $\omega - \Omega$ (bef. quality cut)

Left

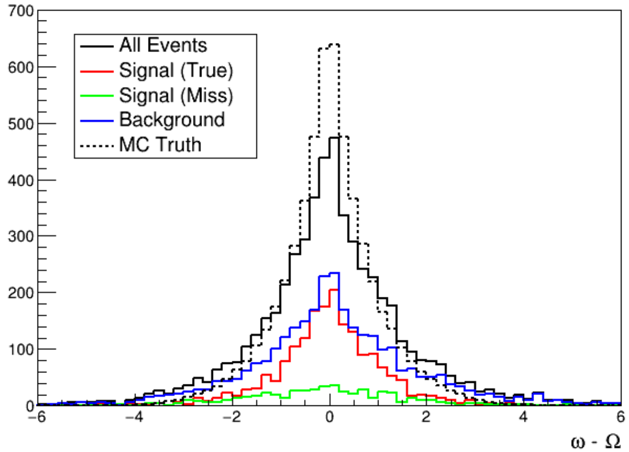
$\left(Re\delta\tilde{F}_{2A}^{\gamma}\right) : \Omega = 0$



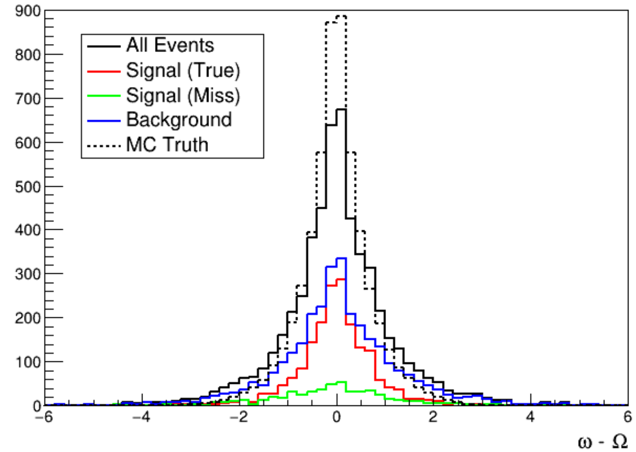
$\left(Re\delta\tilde{F}_{2A}^{Z}\right) : \Omega = 0$



$\left(Im\delta\tilde{F}_{2A}^{\gamma}\right) : \Omega = 0$



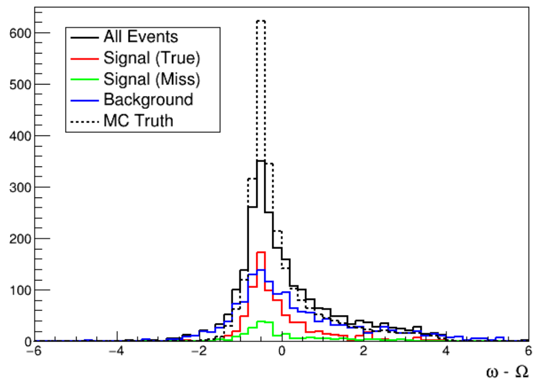
$\left(Im\delta\tilde{F}_{2A}^{Z}\right) : \Omega = 0$



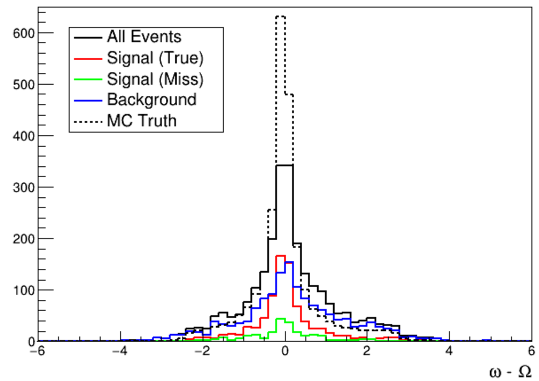
The distributions of $\omega - \Omega$ (bef. quality cut)

Right

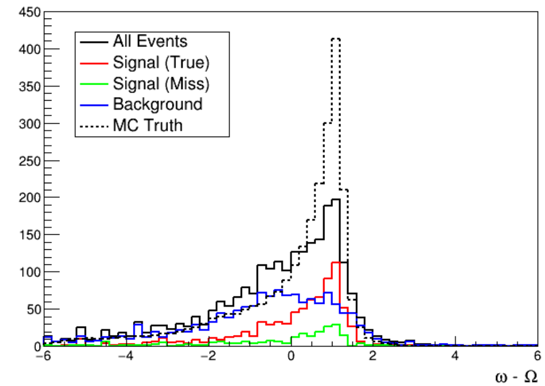
$\left(\delta\tilde{F}_{1V}^{\gamma}\right) : \Omega = 3.09$



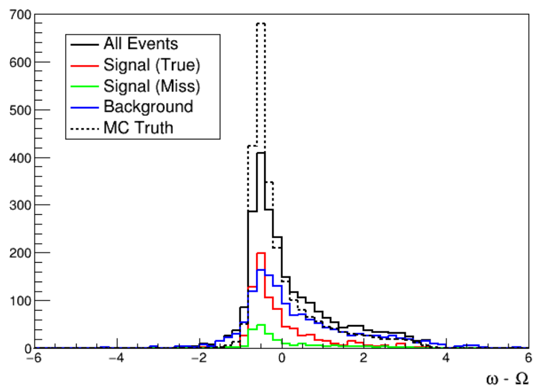
$\left(\delta\tilde{F}_{1V}^{Z}\right) : \Omega = -1.43$



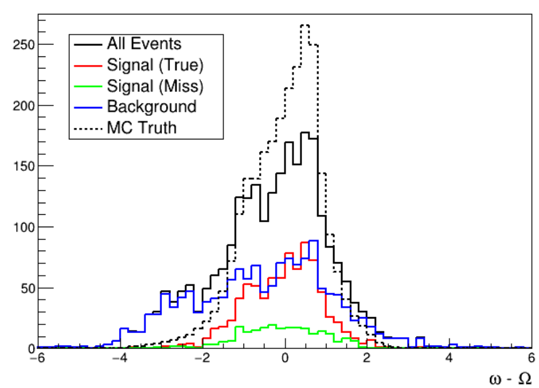
$\left(\delta\tilde{F}_{1A}^{\gamma}\right) : \Omega = 0.688$



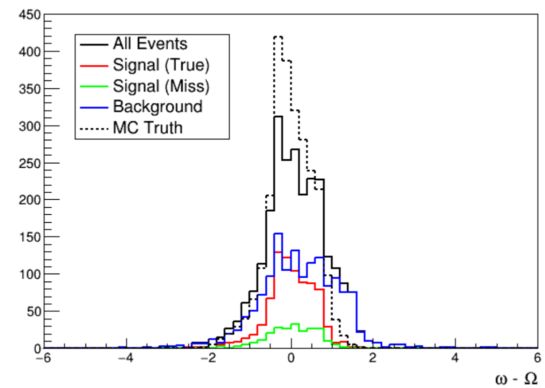
$\left(\delta\tilde{F}_{1A}^{Z}\right) : \Omega = -0.453$



$\left(\delta\tilde{F}_{2V}^{\gamma}\right) : \Omega = -0.645$



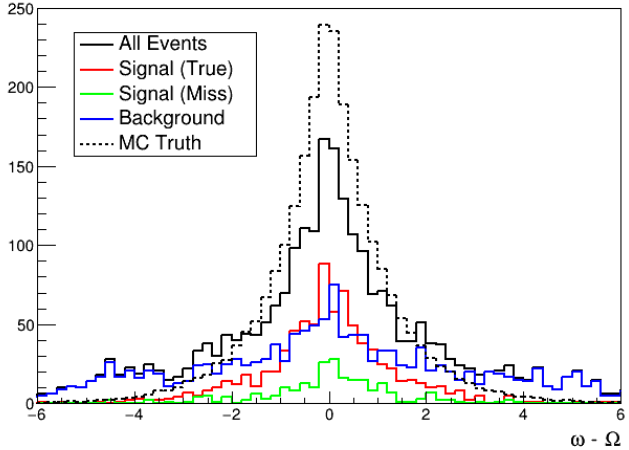
$\left(\delta\tilde{F}_{2V}^{Z}\right) : \Omega = 0.300$



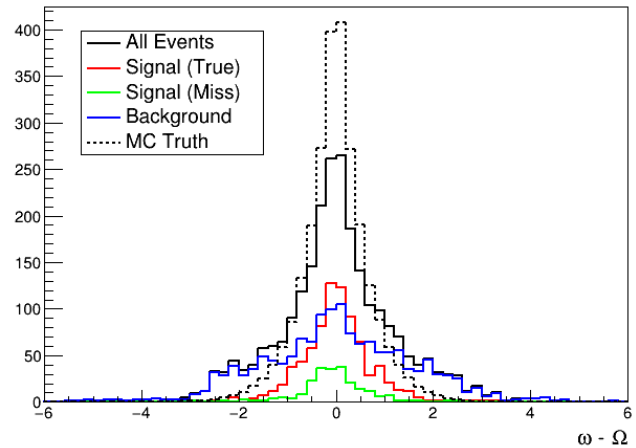
The distributions of $\omega - \Omega$ (bef. quality cut)

Right

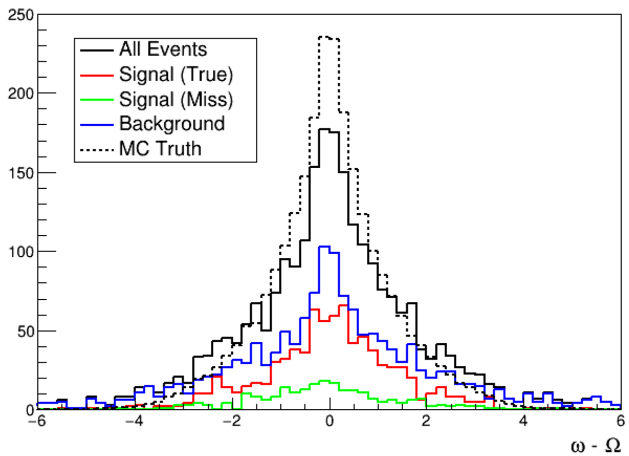
$\left(Re\delta\tilde{F}_{2A}^{\gamma}\right) : \Omega = 0$



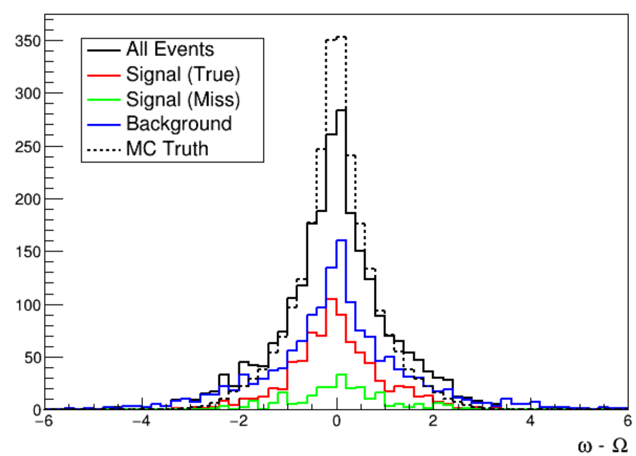
$\left(Re\delta\tilde{F}_{2A}^{Z}\right) : \Omega = 0$



$\left(Im\delta\tilde{F}_{2A}^{\gamma}\right) : \Omega = 0$



$\left(Im\delta\tilde{F}_{2A}^{Z}\right) : \Omega = 0$



0922

Results of fit : bef. quality cut

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.2078 \pm 0.0086 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & -0.1337 \pm 0.0164 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & -0.1325 \pm 0.0114 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.2844 \pm 0.0175 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.7514 \pm 0.0194 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & -0.3024 \pm 0.0387 \end{bmatrix}$$

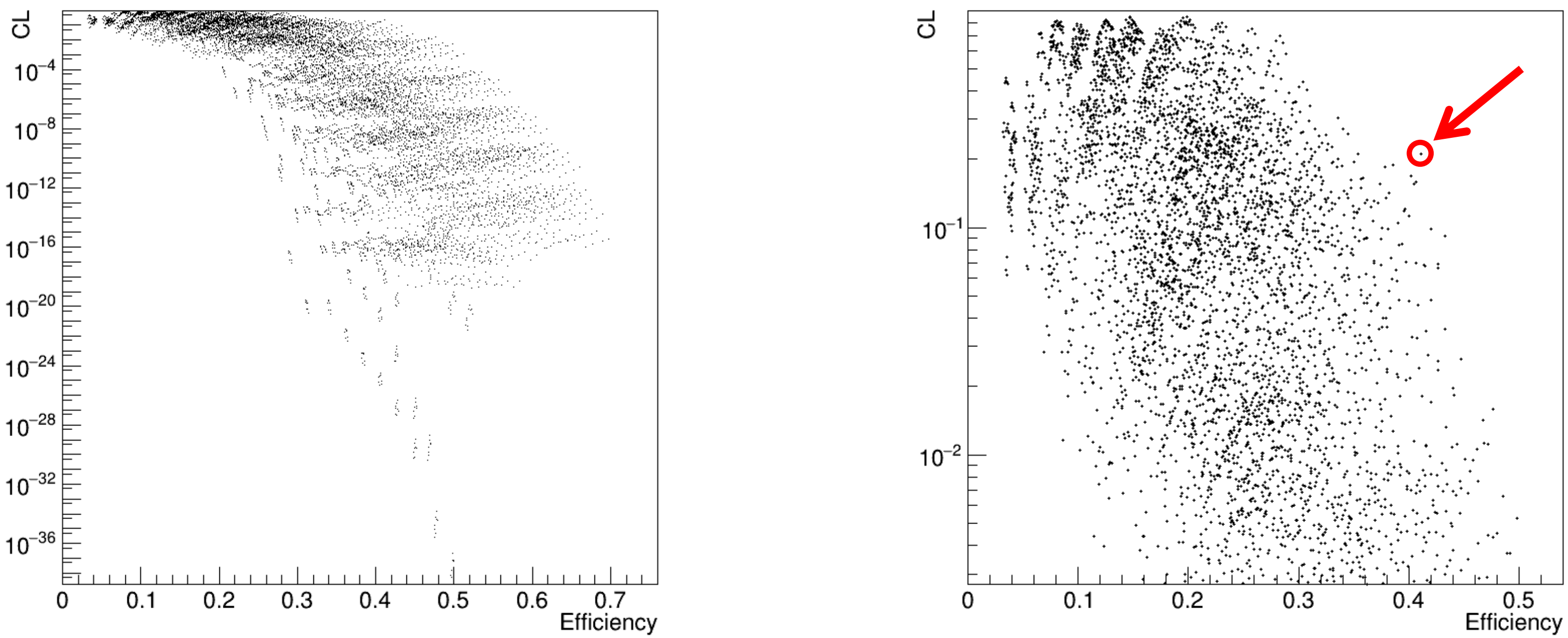
Result of 6 form factor (CPC) fit. CL $= 0.0000$ %

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & -0.0342 \pm 0.0194 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & -0.0742 \pm 0.0386 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & +0.5788 \pm 0.0097 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & +0.0850 \pm 0.0194 \end{bmatrix}$$

Result of 4 form factor (CPV) fit. CL $= 0.0000$ %

Both of them are completely inconsistent with SM.

Optimization of criteria for the quality cut (On-going)



Confidence level of 6 CPC form factors fit vs. Efficiency ($N/N_{\text{pre-selection}}$) (left : **whole**, right : **zoomed**)

Each point has different criteria for $(\chi^2_{\text{Left}}, \Delta\chi^2_{\text{Left}}, \chi^2_{\text{Right}}, \Delta\chi^2_{\text{Right}})$.

A point which have relatively large confidence level and efficiency is selected as a trial ; $(\chi^2_{\text{Left}} < 5, \Delta\chi^2_{\text{Left}} > 1, \chi^2_{\text{Right}} < 7, \Delta\chi^2_{\text{Right}} > 1)$

One should verify on another sample of events that this criteria remains good.

Cut table

250 fb^{-1} (-0.8,+0.3) Left	initial	$\mu^+\mu^-$	b-tag1>0.8 or b-tag2>0.8	$\chi^2 < 5$ & $\Delta\chi^2 > 1$
Signal (True)	2961 (e = 100%)	2725 (e = 92.0%)	1838 (77.4%) (e = 80.2%)	763 (92.4%) (e = 27.9%)
Signal (Miss)	-	-	536 (22.6%)	63 (7.6%)
$t\bar{t}$ di-leptonic	23609	387	335	57
$t\bar{t}$ semi-leptonic	104114	40	31	3
ZZ	100570	17346	2560	20
2 lepton (weight = 4)	212274 (→ 849096)	74961 (→ 299844)	90 (→ 360)	0
WW (weight = 4)	377058 (→ 1508232)	1884 (→ 7536)	3 (→ 12)	0
llWW	3021	947	19	0

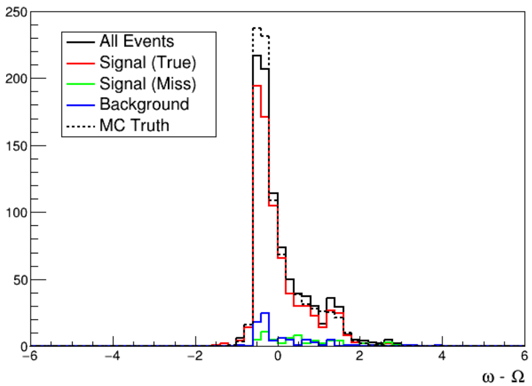
Cut table

250 fb^{-1} (-0.8,+0.3) Right	initial		$\mu^+\mu^-$		b-tag1>0.8 or b-tag2>0.8		$\chi^2 < 7$ & $\Delta\chi^2 > 1$	
Signal (True)	1255	(e = 100%)	1162	(e = 92.6%)	811 (88.0%)	(e = 82.9%)	545 (94.3%)	(e = 46.1%)
Signal (Miss)	-		-		229 (22.0%)		33 (5.7%)	
$t\bar{t}$ di-leptonic	10181		160		138		48	
$t\bar{t}$ semi-leptonic	45053		18		12		1	
ZZ	51928		9051		1252		17	
2 lepton (weight = 4)	161371 (→ 64524)		57916 (→ 231664)		61 (→ 244)		0	

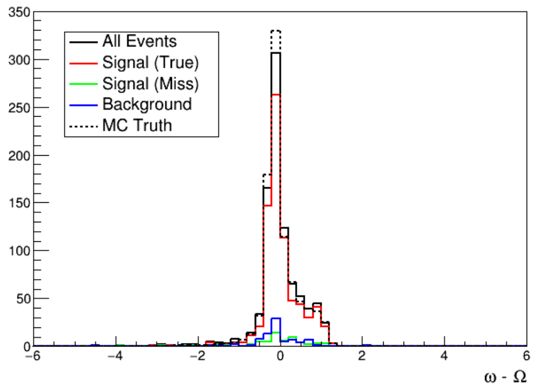
The distributions of $\omega - \Omega$ (aft. quality cut)

Left

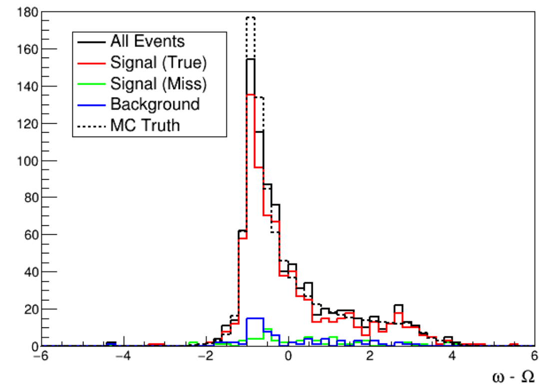
$\left(\delta\tilde{F}_{1V}^{\gamma}\right) : \Omega = 2.26$



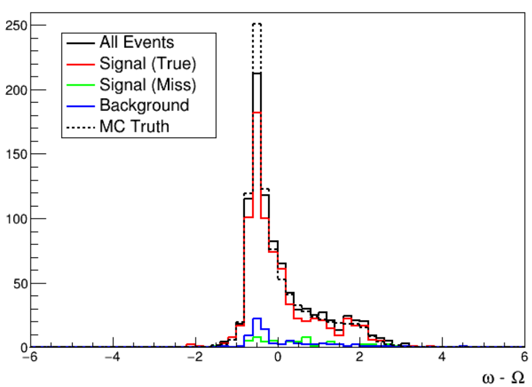
$\left(\delta\tilde{F}_{1V}^{Z}\right) : \Omega = 1.39$



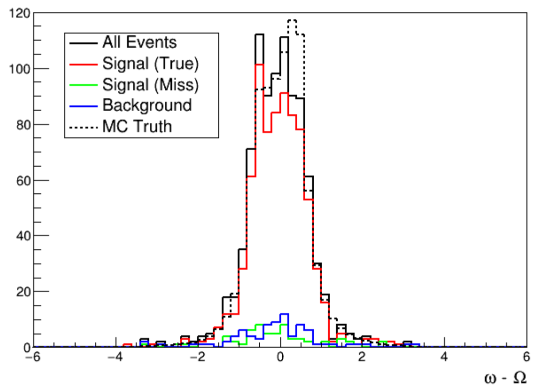
$\left(\delta\tilde{F}_{1A}^{\gamma}\right) : \Omega = -0.413$



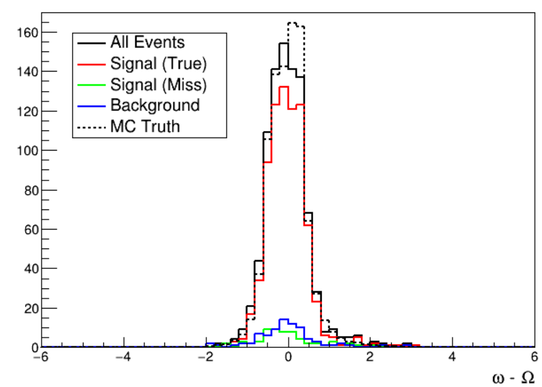
$\left(\delta\tilde{F}_{1A}^{Z}\right) : \Omega = -0.300$



$\left(\delta\tilde{F}_{2V}^{\gamma}\right) : \Omega = -0.472$



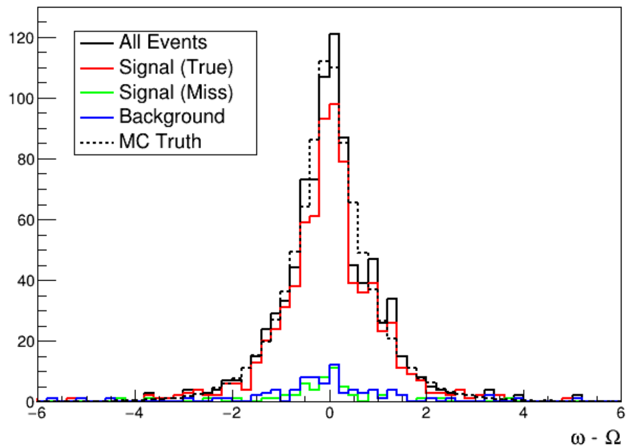
$\left(\delta\tilde{F}_{2V}^{Z}\right) : \Omega = -0.290$



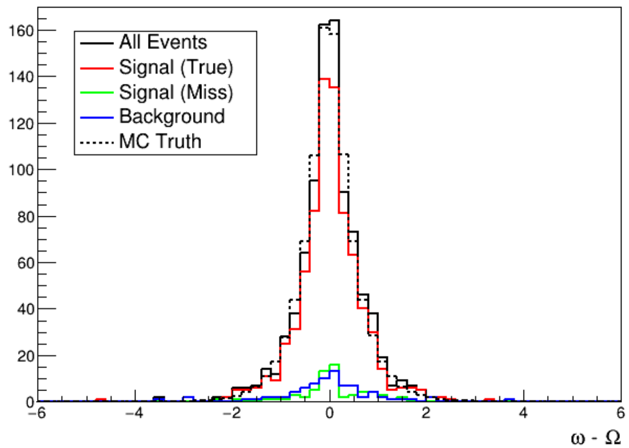
The distributions of $\omega - \Omega$ (aft. quality cut)

Left

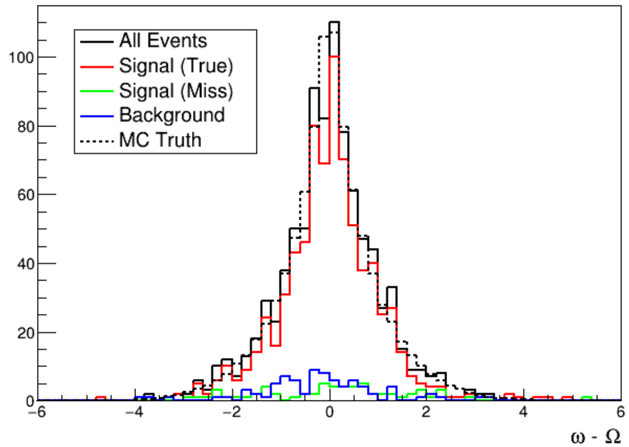
$\left(Re\delta\tilde{F}^{\gamma}_{2A}\right): \Omega = 0$



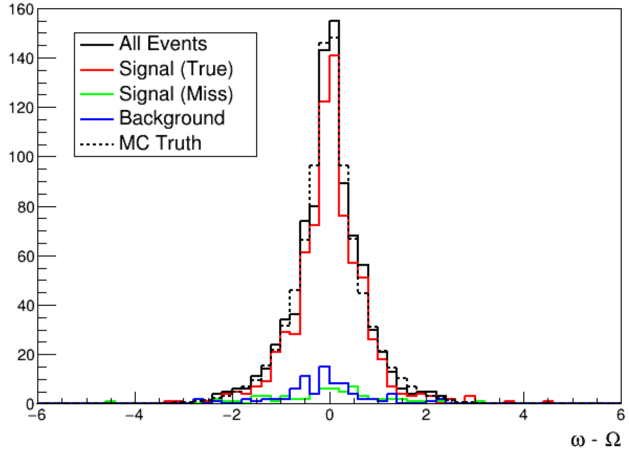
$\left(Re\delta\tilde{F}^{Z}_{2A}\right): \Omega = 0$



$\left(Im\delta\tilde{F}^{\gamma}_{2A}\right): \Omega = 0$



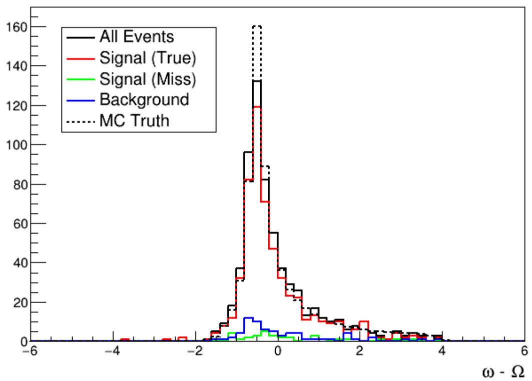
$\left(Im\delta\tilde{F}^{Z}_{2A}\right): \Omega = 0$



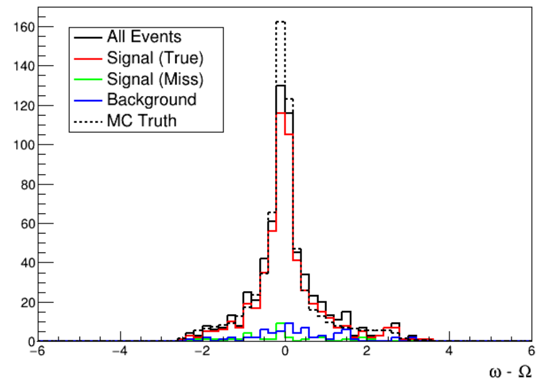
The distributions of $\omega - \Omega$ (aft. quality cut)

Right

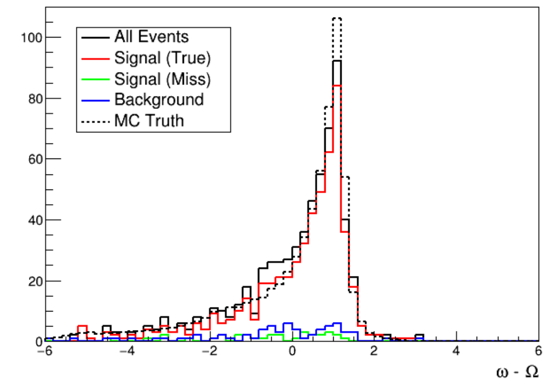
$\left(\delta\tilde{F}_{1V}^{\gamma}\right) : \Omega = 3.09$



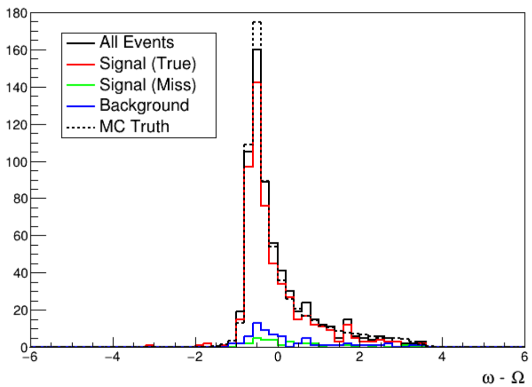
$\left(\delta\tilde{F}_{1V}^{Z}\right) : \Omega = -1.43$



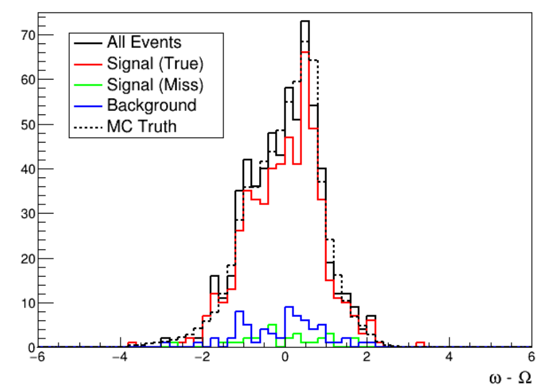
$\left(\delta\tilde{F}_{1A}^{\gamma}\right) : \Omega = 0.688$



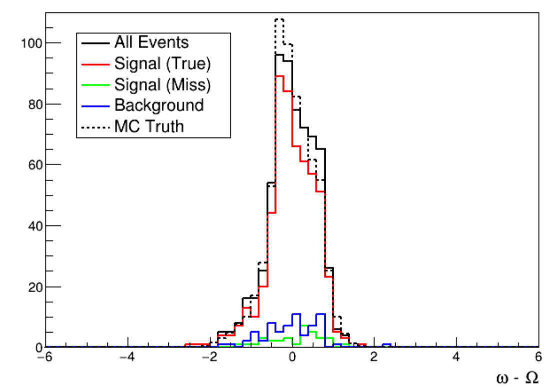
$\left(\delta\tilde{F}_{1A}^{Z}\right) : \Omega = -0.453$



$\left(\delta\tilde{F}_{2V}^{\gamma}\right) : \Omega = -0.645$



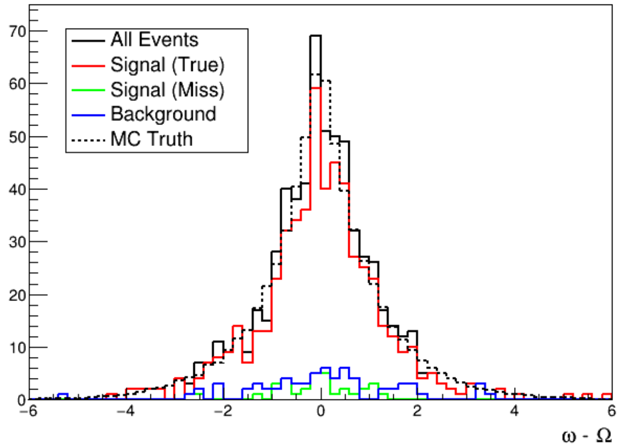
$\left(\delta\tilde{F}_{2V}^{Z}\right) : \Omega = 0.300$



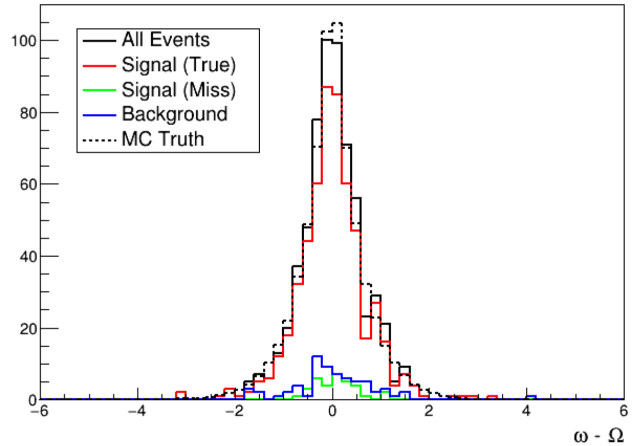
The distributions of $\omega - \Omega$ (aft. quality cut)

Right

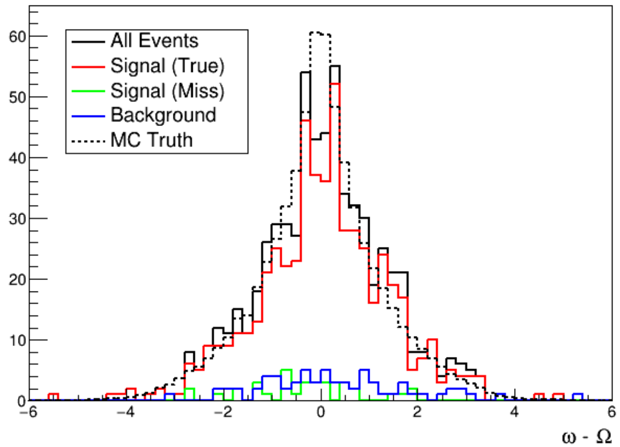
$(Re\delta\tilde{F}_{2A}^{\gamma}) : \Omega = 0$



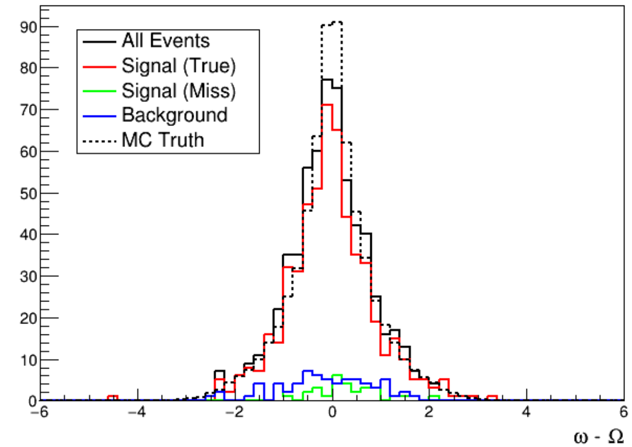
$(Re\delta\tilde{F}_{2A}^{Z}) : \Omega = 0$



$(Im\delta\tilde{F}_{2A}^{\gamma}) : \Omega = 0$



$(Im\delta\tilde{F}_{2A}^{Z}) : \Omega = 0$



Results of fit : aft. the quality cut

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{1V}^{\gamma} & -0.0068 \pm 0.0128 \\ \mathcal{R}e\ \delta\tilde{F}_{1V}^{Z} & +0.0163 \pm 0.0235 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{\gamma} & +0.0210 \pm 0.0184 \\ \mathcal{R}e\ \delta\tilde{F}_{1A}^{Z} & +0.0556 \pm 0.0285 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{\gamma} & -0.0579 \pm 0.0386 \\ \mathcal{R}e\ \delta\tilde{F}_{2V}^{Z} & +0.0149 \pm 0.0645 \end{bmatrix}$$

Result of 6 form factor (CPC) fit. CL $= 21.1181$ %

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}_{2A}^{\gamma} & +0.0002 \pm 0.0238 \\ \mathcal{R}e\ \delta\tilde{F}_{2A}^{Z} & +0.0195 \pm 0.0422 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{\gamma} & +0.0190 \pm 0.0236 \\ \mathcal{I}m\ \delta\tilde{F}_{2A}^{Z} & -0.0270 \pm 0.0339 \end{bmatrix}$$

Result of 4 form factor (CPV) fit. CL $= 81.4708$ %

Results are consistent with SM.

Results of fit : aft. the quality cut (other samples)

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1V} & -0.0219 \pm 0.0128 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1V} & -0.0001 \pm 0.0226 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{1A} & -0.0114 \pm 0.0180 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{1A} & +0.1070 \pm 0.0283 \\ \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2V} & -0.1552 \pm 0.0361 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2V} & +0.0123 \pm 0.0602 \end{bmatrix}$$

Result of 6 form factor (CPC) fit. CL $= 0.0001$ %

$$\begin{bmatrix} \mathcal{R}e\ \delta\tilde{F}^{\gamma}_{2A} & -0.0232 \pm 0.0220 \\ \mathcal{R}e\ \delta\tilde{F}^{Z}_{2A} & +0.0089 \pm 0.0391 \\ \mathcal{I}m\ \delta\tilde{F}^{\gamma}_{2A} & +0.0039 \pm 0.0233 \\ \mathcal{I}m\ \delta\tilde{F}^{Z}_{2A} & +0.0215 \pm 0.0338 \end{bmatrix}$$

Result of 4 form factor (CPV) fit. CL $= 80.2959$ %

Results are **inconsistent** with SM. → Investigating the cause

statistical fluctuation, physical reason, or just bugs?

Backup

Kinematical Reconstruction of top quark

We minimize χ^2 ;

$$\chi^2(\theta_t,\phi_t) = \chi^2_\mu(\theta_t,\phi_t) + \chi^2_b(\theta_t,\phi_t)$$

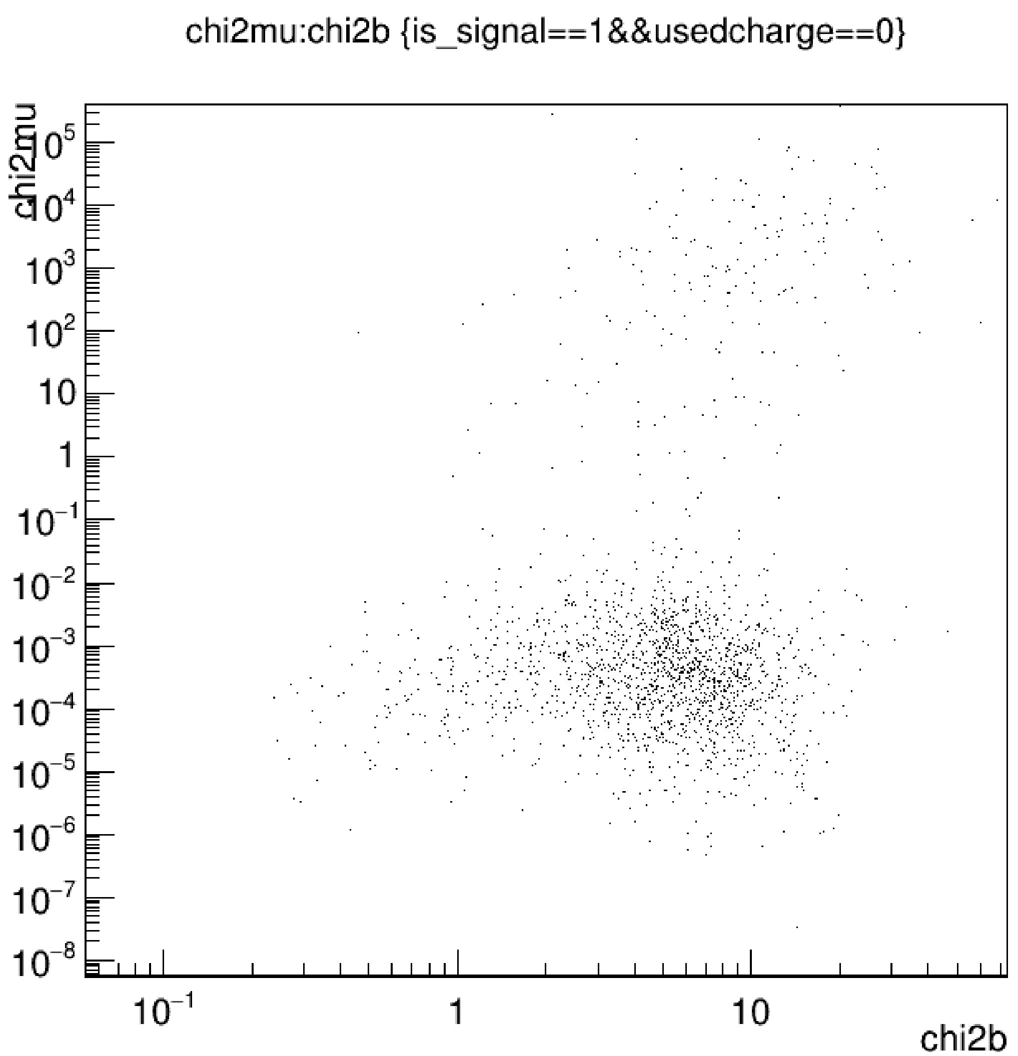
where $\chi^2_\mu(\theta_t,\phi_t) \equiv \left(\frac{E_{\mu^+}^{(W^+\text{ rest frame})}(\theta_t,\phi_t) - m_{W^+}/2}{\sigma\left[E_{\mu^+}^{(W^+\text{ rest frame})}\right]}\right)^2 + \left(\frac{E_{\mu^-}^{(W^-\text{ rest frame})}(\theta_t,\phi_t) - m_{W^-}/2}{\sigma\left[E_{\mu^-}^{(W^-\text{ rest frame})}\right]}\right)^2,$

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

χ^2_μ is dominant to determine (θ_t,ϕ_t) because $\sigma\left[E_\mu^{(W\text{ rest frame})}\right] \ll \sigma[E_b]$.

χ^2_b is used to select the optimal solution and E_b is modified from observed value.

Scatter plot of χ_b^2 and χ_μ^2



Helicity Angles Computation

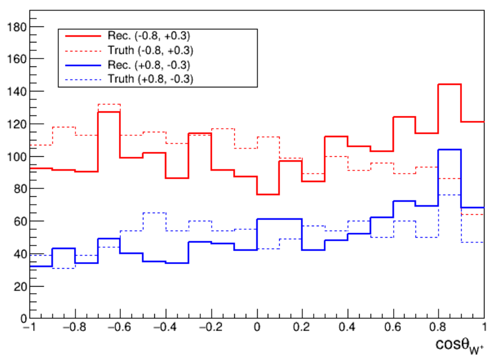
All final state particles including two neutrinos can be calculated. The 9 helicity angles which are related to the ttZ/γ vertex are computed.

$$\theta_t, \theta_{W^+}^{t\ \mathrm{frame}}, \phi_{W^+}^{t\ \mathrm{frame}}, \theta_{\mu^+}^{W^+\ \mathrm{frame}}, \phi_{\mu^+}^{W^+\ frame}, \theta_{W^-}^{\bar{t}\ frame}, \phi_{W^-}^{\bar{t}\ frame}, \theta_{\mu^-}^{W^-frame}, \phi_{\mu^-}^{W^-frame}$$

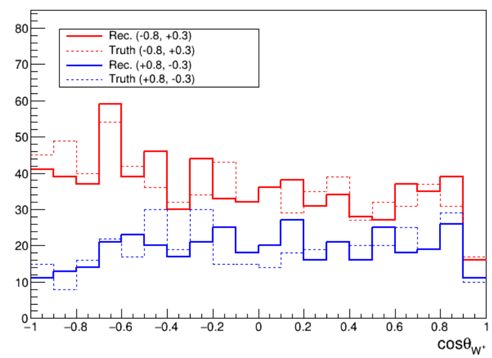
(G. L. Kane, G. A. Ladinsky, C.-P. Yuan, Phys.Rev. D45 (1992) 124-141)

eg)

$\cos\theta_{W^+}^{t\ \mathrm{frame}}$



$\chi^2_{tot}<5,\ \Delta\chi^2_{tot}>6$



$\cos\theta_{\mu^+}^{W^+\ \mathrm{frame}}$