Light on top quark FCNC interactions through single top production at 250 GeV ILC

Updates on our study

by

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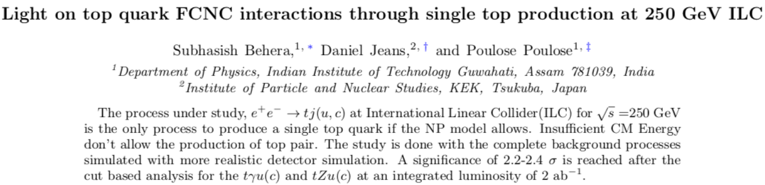

Light on top quark FCNC interactions through single top production at 250 GeV ILC

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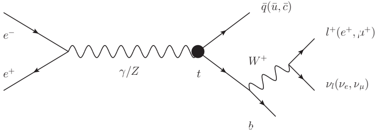
The process under study, $e^+e^- \to tj(u,c)$ at International Linear Collider(ILC) for $\sqrt{s}$ =250 GeV is the only process to produce a single top quark if the NP model allows. Insufficient CM Energy don't allow the production of top pair. The study is done with the complete background processes simulated with more realistic detector simulation. A significance of 2.2-2.4 σ is reached after the cut based analysis for the $t\gamma u(c)$ and $tZu(c)$ at an integrated luminosity of 2 ab^{-1}.

- Process : $e^-e^+ \to t(\bar{t})j, (t(\bar{t}) \to Wb, W \to l\nu_l)$



- Beam Polarization: $e^-_L e^+_R$, $e^-_R e^+_L$, $e^-_L e^+_L$, $e^-_R e^+_R$
- Annihilation: $(e^-_L e^+_R,\ e^-_R e^+_L)$
- Enhanced σ value for s-ch process:

$$\sigma_{P_{e^-}P_{e^+}} = (\frac{1-P_{e^-}}{2})(\frac{1+P_{e^+}}{2})\sigma_{LR} + (\frac{1+P_{e^-}}{2})(\frac{1-P_{e^+}}{2})\sigma_{RL}$$

FCNC in Top quark sector

Limits on the branching ratio for anomalous flavor changing top couplings at LHC for the 95% C.L.

Process	$\sqrt{s}$	BR limits on 95% C.L.	Ref.
$t \to gu(c)$	8 TeV	$4.0(20) \times 10^{-5}$	[Eur.Phys.J. C76 (2016) no.2, 55]
$t \to \gamma u(c)$	8 TeV	$1.6(18.2) \times 10^{-4}$	[JHEP 1604 (2016) 035]
$t \to Zu(c)$	13 TeV	$1.7(2.4) \times 10^{-4}$	[JHEP 1807 (2018) 176]

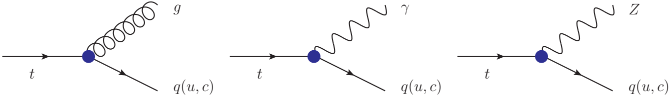
FCNC in Top quark sector

Summary of the projected reach for the 95% C.L. limits on the branching ratio for anomalous flavor changing top couplings at HL-HE LHC

B limits on 95% C.L.	3 ab^{-1}, 14 TeV	15 ab^{-1}, 27 TeV	Ref.
$t \rightarrow gu$	3.8×10^{-6}	5.6×10^{-7}	[CMS-PAS-FTR-18-004]
$t \rightarrow gc$	32.1×10^{-6}	10^{-7}	[CMS-PAS-FTR-18-004]
$t \rightarrow Zq$	$2.4 - 5.8 \times 10^{-5}$		[ATL-PHYS-PUB-2016-019]
$t \rightarrow \gamma u$	8.6×10^{-6}		[Collaboration:2293646]
$t \rightarrow \gamma c$	7.4×10^{-5}		[Collaboration:2293646]
$t \rightarrow Hq$	10^{-4}		[ATL-PHYS-PUB-2016-019]

Introduction : *Top Quark* FCNC Effective Lgrangian

- Non-standard vertices :



- The complete Effective Lagrangian : [AguilarSaavedra:2008zc]

$$
\begin{aligned}
-\mathcal{L}_{\rm fcnc} =& g_s \bar{q} \lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{gqt} P_L + \kappa^R_{gqt} P_R) t G^a_\mu \\
&+ e \bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{\gamma qt} P_L + \kappa^R_{\gamma qt} P_R) t A_\mu \\
&+ \frac{g}{2c_W} \bar{q} \gamma^\mu (X^L_{zqt} P_L + X^R_{zqt} P_R) t Z_\mu \\
&+ \frac{g}{2c_W} \bar{q} \frac{i\sigma^{\mu\nu} q_\nu}{\Lambda} (\kappa^L_{zqt} P_L + \kappa^R_{zqt} P_R) t Z_\mu + \mathrm{H.c},
\end{aligned}
$$

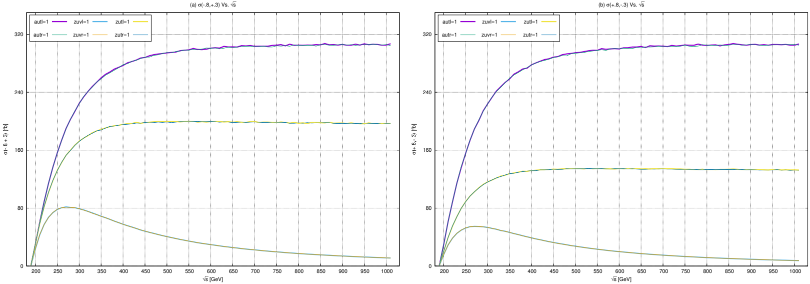
where $q_\nu = p^\nu_t - p^\nu_q$, with $\Lambda = m_t$.

Signal process :

Coouping	$\kappa^L_{\gamma qt}$	$\kappa^R_{\gamma qt}$	X^L_{zqt}	X^R_{zqt}	κ^L_{zqt}	κ^R_{zqt}
σ_{unpol} (fb)	506.64	508.92	215.88	215.52	357.96	357.48
$\sigma(-80\%, +30\%)$ (fb)	626.00	625.20	311.88	312.36	526.8	527.20
$\sigma(+80\%, -30\%)$ (fb)	628.24	631.56	214.52	216.04	358.44	356.72

The New Physics(NP) couplings parameters value set to unity.

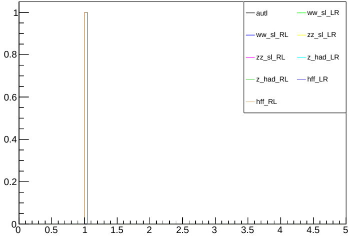
CS Vs. $\sqrt{s}$:



Cross section of signal process : $e^- e^+ \to tj, (t \to W^+ b, W^+ \to \mu^+ \nu_\mu)$ at different $\sqrt{s}$ values. The tensor couplings for γ looks better than that of Z-boson at higher energy scale, whereas the vector couplings of Z-boson peaks at almost 250 GeV.

- Identification of objects :
    - Leptons : IsolatedLeptonTaggingProcessor gives distinguish muon or electron.
    - Jets(includes b-jets) : jet clustering with flavour tagging in LCFIplus

_n_isomuon_autl_maj_bkg



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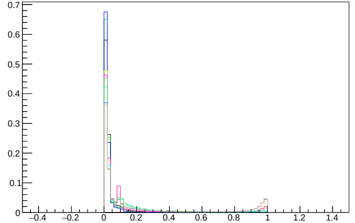

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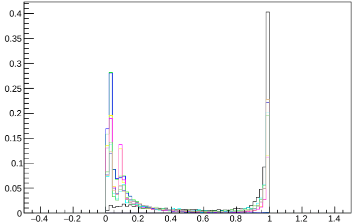

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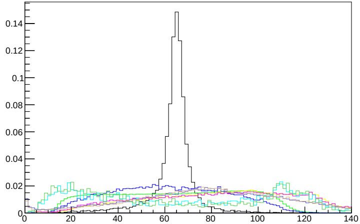

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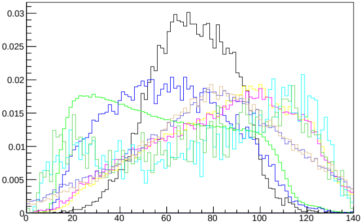

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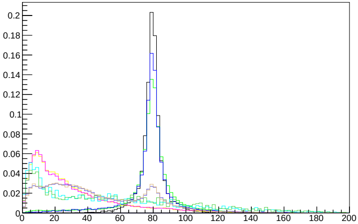

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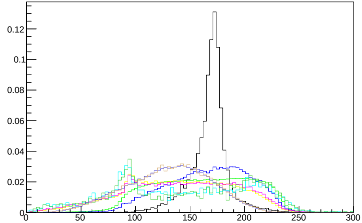

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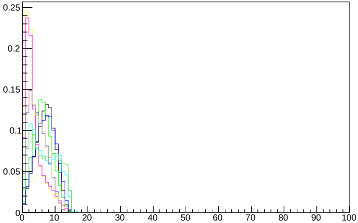
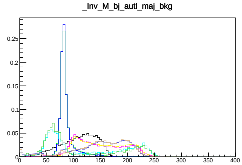
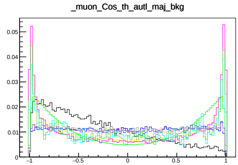
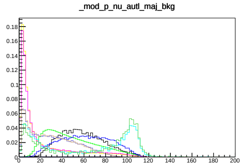








- Kinematic Cuts : $55 < E_j < 75$, $20 < E_b < 120$, $50 < m_W < 110$, $110 < m_t < 240$, $180 < M_{tj} < 270$, $65 > M_{bj} > 95$, $|p_\nu| > 30$, $\cos\theta_\mu < .95$, $|\cos\theta_\nu| > .95$, and $\Delta\theta_{j,\mu} < 1.5$.

Cut flow table for Signal and Background for $\{P_{e^-}, P_{e^+}\} = \{-.8, +.3\}$, $\mathcal{L} = 0.45\times 2/\text{ab}$ for LR and RL and $0.05\times 2/\text{ab}$ for LL and RR :

Process	$\sigma_{-.8,+.3}[fb]$	N_{eve}	$\text{N}_l=\text{N}_j=\text{N}_b=1$	$\text{Btag}_b > 0.8$	Kinematic Cuts
$\kappa^L_{ut}(\gamma)$	625.18	562662	545470	351380	196780
$\kappa^R_{ut}(\gamma)$	625.72	563148	549378	354300	203628
X^L_{ut}	312.32	281088	273370	177886	109034
X^R_{ut}	312.46	281214	273844	176430	90516
κ^L_{ut}	527.26	474534	460222	297856	167008
κ^R_{ut}	526.92	474228	461848	296674	172616
$e^-e^+ \to WW \to l\nu_l 2j$ WW-semileptonic	10992.9	9893624	5150518	30138	597
$e^-e^+ \to ZZ \to 2l2j + 2\nu_l 2j$ ZZ-semileptonic	856.927	771234	194230	18258	110
$e^-e^+ \to ffh$ hff-sample	312.937	281642	24750	3295	114

The major backgrounds which are non zero even after the cuts are listed in the bottom three row of the above table.

Cut flow table for Signal and Background for $\{P_{e^-}, P_{e^+}\} = +.8, -.3$, $\mathcal{L} = 0.45\times 2/\mathrm{ab}$ for LR and RL and $0.05\times 2/\mathrm{ab}$ for LL and RR :

Process	$\sigma_{+.8,-.3}[fb]$	N_{eve}	N_l=N_j=N_b=1	$\mathrm{Btag}_b > 0.8$	Kinematic Cuts
$\kappa^L_{\gamma ut}$	628.24	564246	547686	351924	196384
$\kappa^R_{\gamma ut}$	631.56	565434	551442	350624	199556
X^L_{zut}	214.52	191034	185798	119876	72514
X^R_{zut}	216.04	191826	186466	119636	60402
κ^L_{zut}	358.44	321300	311704	202858	113790
κ^R_{zut}	356.72	320688	312658	201076	114558
$e^-e^+ \to WW \to l\nu_l 2j$ WW-semileptonic	758.383	682544	355641	2105	78
$e^-e^+ \to ZZ \to 2l2j + 2\nu_l 2j$ ZZ-semileptonic	467.188	420469	112252	10658	112
$e^-e^+ \to ffh$ hff-sample	205.277	184748	16525	2243	152

Tensor	Obtainable reach (TeV $^{-1}$) , pol=$+.8, -.3$		
Coupling	at C.L. $= 2\sigma$	3σ	5σ
$\kappa^L_{\gamma qt}/\Lambda$	± 0.009	± 0.012	± 0.016
$\kappa^R_{\gamma qt}/\Lambda$	± 0.009	± 0.012	± 0.016
X^L_{zqt}	± 0.003	± 0.003	± 0.026
X^R_{zqt}	± 0.003	± 0.003	± 0.028
κ^L_{zqt}/Λ	± 0.013	± 0.016	± 0.021
κ^R_{zqt}/Λ	± 0.013	± 0.016	± 0.021

Estimated limits on the couplings :taking value of the CS with one couplings present at a time, at 2-, 3- and 5-σ significance.

BR reach of the study

	$BR(t \to Vq) \times 10^{-5}$		
Couplings	2σ	3σ	5σ
$\frac{\kappa^L_{\gamma ut}}{\Lambda}$	4.44	11.10	6.66
$\frac{\kappa^R_{\gamma ut}}{\Lambda}$	4.37	10.92	6.55
X^L_{zut}	6.40	16.00	9.60
X^R_{zut}	6.36	15.90	9.54
$\frac{\kappa^L_{zut}}{\Lambda}$	0.37	0.92	0.55
$\frac{\kappa^R_{zut}}{\Lambda}$	0.44	1.11	0.67

Conclusion :

- 250GeV ILC has limited options to study top quark physics. We have proposed a clean way to probe the FCNC top couplings through single top production.
- With a detailed study including close-to-realistic ILD detector simulation and all possible backgrounds, we have demonstrated the couplings can be probed to somewhat better levels than that can be achieved by HL-LHC.

Observables at Top quark rest frame :

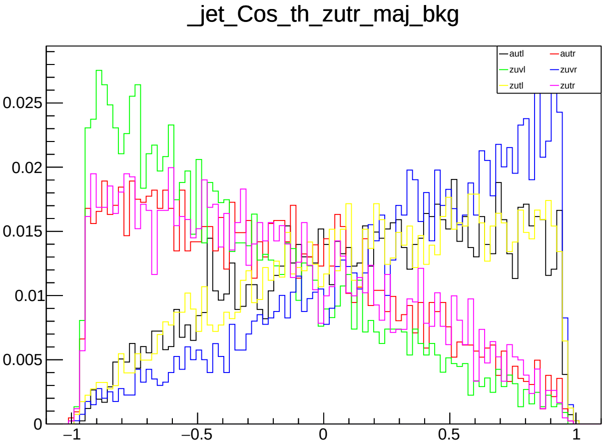
$$\sigma(+,+) = \frac{1}{2}(1+P_z),$$
$$\sigma(-,-) = \frac{1}{2}(1-P_z),$$
$$\sigma(+,-) = \frac{1}{2}(P_x+iP_y)$$
$$\sigma(-,+) = \frac{1}{2}(P_x-iP_y).$$

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma}{d\Omega_\ell} = \frac{1}{4\pi}\Big(1+P_z\cos\theta_\ell + P_x\sin\theta_\ell\cos\phi_\ell + P_y\sin\theta_\ell\sin\phi_\ell\Big),$$

$$A_x \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi_\ell\frac{d\sigma}{d\phi_\ell} - \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} d\phi_\ell\frac{d\sigma}{d\phi_\ell}\right] = \frac{1}{2}P_x,$$
$$A_y \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{0}^{\pi} d\phi_\ell\frac{d\sigma}{d\phi_\ell} - \int_{\pi}^{2\pi} d\phi_\ell\frac{d\sigma}{d\phi_\ell}\right] = \frac{1}{2}P_y,$$
$$A_z \equiv \frac{1}{\sigma_{\rm tot}}\left[\int_{0}^{1} d\mathrm{c}_{\theta_\ell}\frac{d\sigma}{d\mathrm{c}_{\theta_\ell}} - \int_{-1}^{0} d\mathrm{c}_{\theta_\ell}\frac{d\sigma}{d\mathrm{c}_{\theta_\ell}}\right] = \frac{1}{2}P_z.$$

Lab frame observables :

$$A_j^{FB} \equiv \frac{\sigma(\cos\theta_j > 0) - \sigma(\cos\theta_j < 0)}{\sigma(\cos\theta_j > 0) + \sigma(\cos\theta_j < 0)}.$$



$\cos\theta_j$ - distributions in the Lab frame. Show $\kappa^L_{\gamma qt}$, κ^L_{zqt}, X^R_{qt} picks in the forward direction and $\kappa^R_{\gamma qt}$, κ^R_{zqt}, X^L_{qt} on the back direction of the initial e^- beam.

Coupling	A_x	A_y	A_z	A_j^{FB}	A_μ^{FB}
$\kappa^L_{\gamma ut}$	0.37	0.00	-0.15	0.28	-0.44
$\kappa^R_{\gamma ut}$	0.37	-0.01	-0.10	-0.33	-0.35
X^L_{zut}	0.29	0.00	-0.41	-0.53	-0.33
X^R_{zut}	0.35	0.05	0.15	0.52	-0.54
κ^L_{zut}	0.39	-0.03	-0.12	0.29	-0.49
κ^R_{zut}	0.40	-0.01	-0.12	-0.34	-0.38

A_z	A_j^{FB}	Coupling
$-$ve	$-$ve	X^L_{zqt}, $\kappa^R_{\gamma qt}$, κ^R_{zqt}
$+$ve	$+$ve	X^R_{zqt}
$-$ve	$+$ve	$\kappa^L_{\gamma qt}$, κ^L_{zqt}

Observable used for distinguishing different Lorentz Structure.

Work to do :

- Analyse the value of the limits with Asymmetry mentioned above with systematic and other uncertanity.
- We will do a multi parameter analysis, with the simultanious presence of all mentioned couplings.

Thank you...

Backup slides

Introduction : Expression of Decay width

$$\Gamma(t \to bW^+) = \frac{\alpha}{16\, s_W^2} |V_{tb}|^2 \frac{m_t^3}{M_W^2} \left[1 - 3\frac{M_W^4}{m_t^4} + 2\frac{M_W^6}{m_t^6}\right] ,$$

$$\Gamma(t \to qZ)_\gamma = \frac{\alpha}{32\, s_W^2 c_W^2} |X_{qt}|^2 \frac{m_t^3}{M_Z^2} \left[1 - \frac{M_Z^2}{m_t^2}\right]^2 \left[1 + 2\frac{M_Z^2}{m_t^2}\right] ,$$

$$\Gamma(t \to qZ)_\sigma = \frac{\alpha}{16\, s_W^2 c_W^2} |\kappa_{qt}|^2 m_t \left[1 - \frac{M_Z^2}{m_t^2}\right]^2 \left[2 + \frac{M_Z^2}{m_t^2}\right] ,$$

$$\Gamma(t \to q\gamma) = \frac{\alpha}{2} |\kappa_{\gamma qt}|^2 m_t ,$$

$$\Gamma(t \to qg) = \frac{2\alpha_s}{3} |\kappa_{gqt}|^2 m_t ,$$

$$\Gamma(t \to qH) = \frac{\alpha}{32\, s_W^2} |g_{qt}|^2 m_t \left[1 - \frac{M_H^2}{m_t^2}\right]^2 .$$

Value of Decay width

- Consider value of the constants as : $m_t =$, $\alpha(m_t) =$, $s_w^2(m_t) =$, $\alpha_s(m_t) =$, $(m_H) =$, $m_Z =$.
- $\Gamma(t \to W^+ b) \simeq$
- $\Gamma(t \to qZ)_\gamma \simeq$
- $\Gamma(t \to qZ)_\sigma \simeq$
- $\Gamma(t \to q\gamma) \simeq$
- $\Gamma(t \to qg) \simeq$
- $\Gamma(t \to qH) \simeq$