Single Top Quark and Higgs-Boson Production in ep collisions

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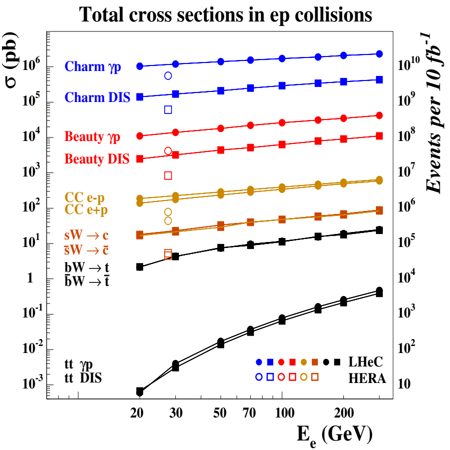
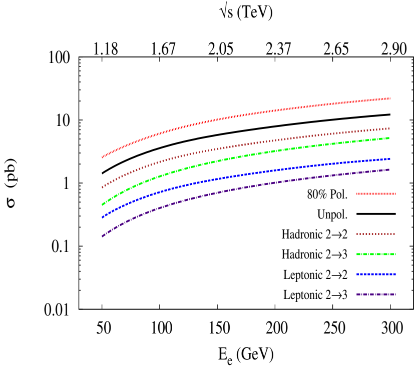
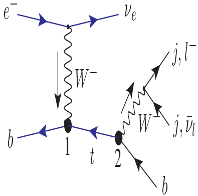
arXiv: 1307.1688, 1203.6285, 1502.xxxxx

Single Top at LHeC: *Wtb* vertex







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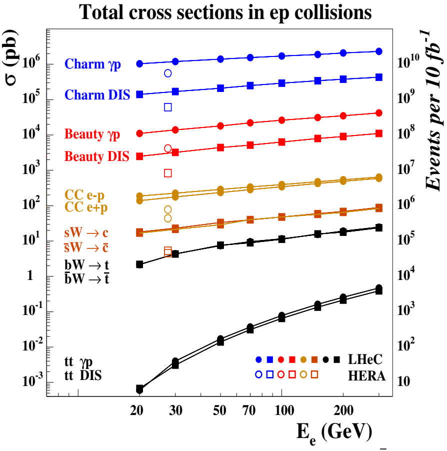

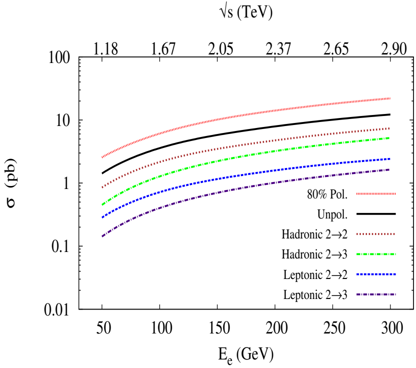

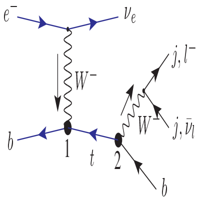

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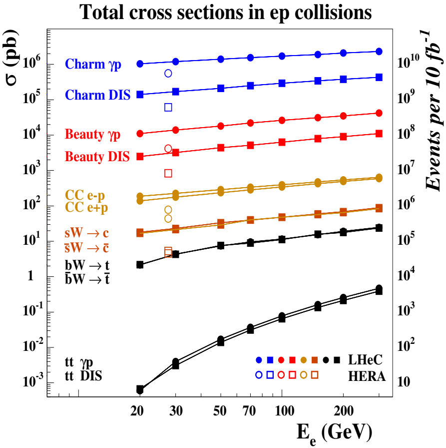
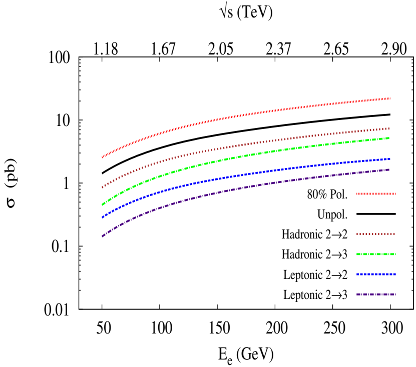
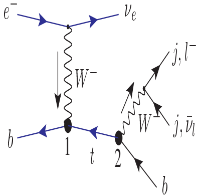
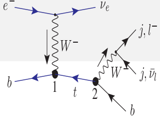




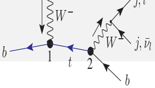


Lagrangian & Processes:



- $\mathscr{L}_{Wtb} = \frac{g}{\sqrt{2}}\left[W_\mu \bar{t}\gamma^\mu(V_{tb}f_1^L P_L + f_1^R P_R)b - \frac{1}{2\,m_W}W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_2^L P_L + f_2^R P_R)b\right] + \text{h.c.}$;
  where $f_1^L \equiv 1 + \Delta f_1^L$, $W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu$, $D_\mu = \partial_\mu - ieA_\mu$,
  $\sigma^{\mu\nu} = i/2\,(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.
- In SM $|V_{tb}|f_1^L \approx 1$ and at tree level $\Delta f_1^L, f_1^R, f_2^L$ & f_2^R vanishes.
- CP-conseving $\rightarrow$ (can take) real couplings
- CP-violation $\rightarrow$ complex couplings [arXiv:06050190]
  - $f_1^R = 0.1e^{i\phi_{f_1^R}}, f_2^L = 0.1e^{i\phi_{f_2^L}}, f_2^R = 0.1e^{i\phi_{f_2^R}}$
  - f_1^R, f_2^L not affected but in case of f_2^R phase is dominant $\rightarrow$ Angular asymmetries are not sufficient
  - Other observable: Spin Asymmetry, triple product asymmetries in dileptonic channel in $t\bar{t}$ production
- Processes: $e^- p \rightarrow \bar{t}\nu_e, \bar{t} \rightarrow W^-\bar{b}$
  - Helicity fractions: $\mathcal{F}_0 = N_0/N, \mathcal{F}_+ = N_+/N, \mathcal{F}_- = N_-/N, N = N_0 + N_+ + N_-$
  - Hadronic decay: $W^- \rightarrow jj$
  - Leptonic decay: $W^- \rightarrow l\nu_l, l = e, \mu$

Constrain on f_i's

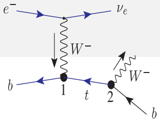


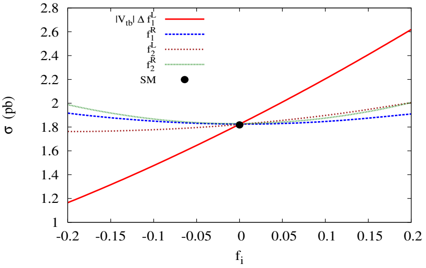
- Assuming only one anomalous coupling to be non-zero at a time $-0.13 \leq |V_{tb}|f_1^L \leq 0.03$, $-0.0007 \leq f_1^R \leq 0.0025$, $-0.0015 \leq f_2^L \leq 0.0004$, $-0.15 \leq f_2^R \leq 0.57$ from B decays [Phys. Rev. D **78**, 077501 (2008)]
- Single top production at DØ assuming $|V_{tb}|f_1^L = 1$, $|f_1^R| \leq 0.548$, $|f_2^L| \leq 0.224$, $|f_2^R| \leq 0.347$ [Phys. Lett. B **713**, 165 (2012)]
- Associated tW production at LHC through γp collision $|f_1^R| \leq 0.55$, $|f_2^L| \leq 0.22$, $|f_2^R| \leq 0.35$ [Phys. Rev. D **86**, 074026 (2012)]
- ATLAS: asymmetries associated through angular distribution $\mathrm{Re}\left(f_1^R\right) \in$ [-0.44,0.48], $\mathrm{Re}\left(f_2^L\right) \in$ [-0.24,0.21], $\mathrm{Re}\left(f_2^R\right) \in$ [-0.49,0.15]. [ATLAS-CONF-2011-037]

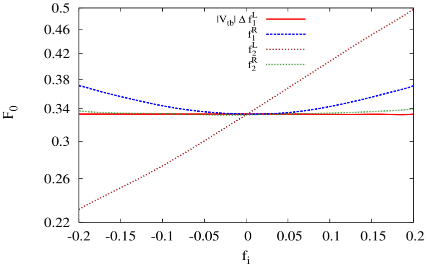
Loop Corrections:[arXiv:1308.3652]

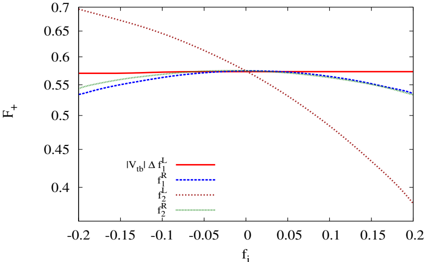
- QCD: $f_2^R = -6.61 \times 10^{-3}, f_2^L = -1.118 \times 10^{-3}$ ($m_t = 171$ GeV)
- EW: $f_2^R = -(1.24 \pm 1.23i) \times 10^{-3}, f_2^L = -(0.102 \pm 0.014i) \times 10^{-3}$ ($m_H = 126$ GeV)
- SM: $f_2^R = -(7.85 \pm 1.23i) \times 10^{-3}, f_2^L = -(1.220 \pm 0.014i) \times 10^{-3}$

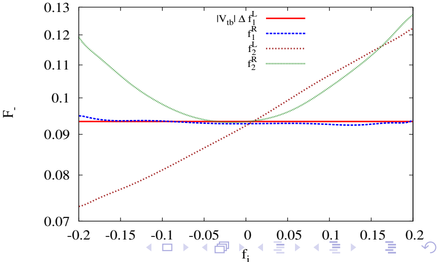
$e^- p \to \bar{t}\nu_e \to \bar{b}W^-\nu_e$ & W^- helicity fractions:











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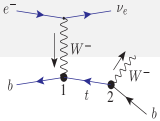

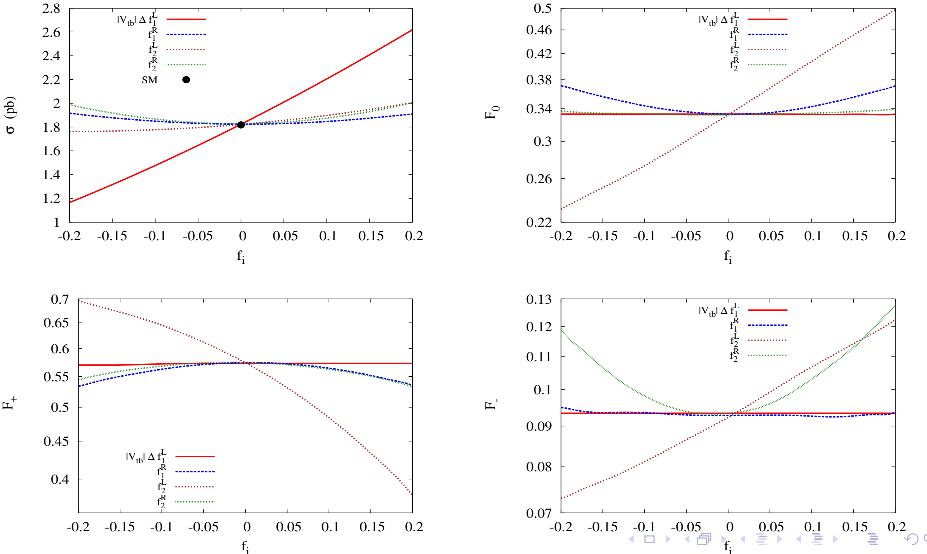

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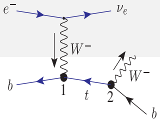
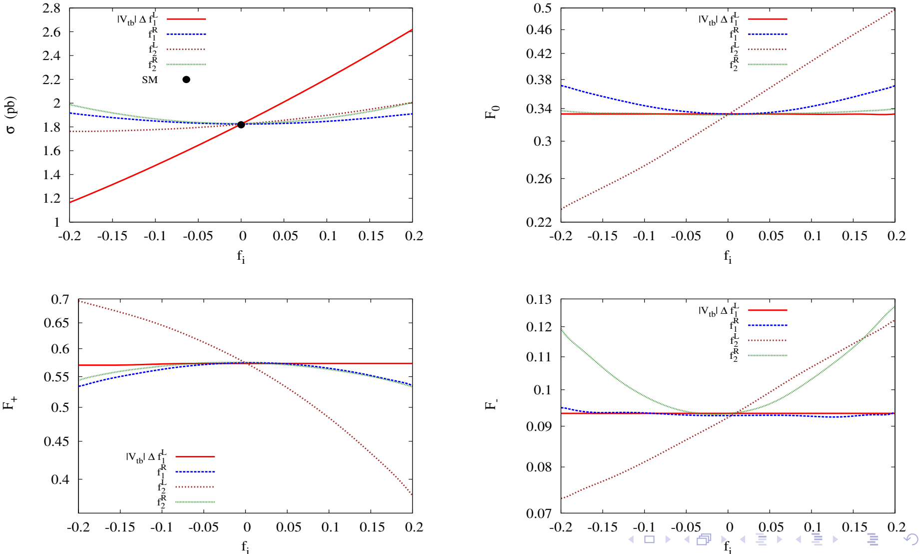




Hadronic: $E_e = 60$ GeV, $E_p = 7$ TeV, $L = 100\,\text{fb}^{-1}$

No.	Background Process	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	$\sigma_{\text{eff.}}$
1	$e^- p \to \nu_e W^- \bar{b}$ without anti-top line	7.5×10^{-3}	6.8×10^{-3}	4.5×10^{-3}	2.7×10^{-3}
2	$e^- p \to \nu_e jjj$	4.2×10^{0}	3.6×10^{0}	2.4×10^{0}	7.2×10^{-2}
3	$e^- p \to \nu_e cjj$ & $e^- p \to \nu_e \bar{c}jj$	1.5×10^{0}	1.2×10^{0}	8.6×10^{-1}	8.6×10^{-2}
4	$e^- p \to \nu_e c\bar{c}j$	5.8×10^{-2}	5.0×10^{-2}	3.2×10^{-2}	6.7×10^{-3}
5	$e^- p \to \nu_e b\bar{b}j$	2.5×10^{-2}	2.2×10^{-2}	5.6×10^{-3}	1.3×10^{-3}
6	$e^- p \to \bar{c}\nu_e$ $(\bar{c} \to W^- \bar{s})$	2.5×10^{-2}	2.2×10^{-2}	1.5×10^{-2}	1.5×10^{-4}

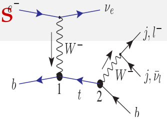
Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5, \lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$	$\lvert m_{j_1 j_2} - m_W\rvert \leq 22$ GeV	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	3.2×10^4	2.3×10^4	2.2×10^4	66.7 %	–
SM+$\sum_i$ Bkg$_i$	6.5×10^4	5.0×10^4	4.0×10^4	61.5 %	
$\lvert V_{tb}\rvert\,\Delta f_1^L = .5$	7.3×10^4	5.0×10^4	5.0×10^4	68.0 %	1.92
$f_1^R = .5$	4.6×10^4	3.2×10^4	3.2×10^4	69.7 %	1.43
$f_2^L = .5$	4.9×10^4	3.6×10^4	3.6×10^4	73.2 %	1.55
$f_2^L = -.5$	3.4×10^4	2.3×10^4	2.3×10^4	69.6 %	1.40
$f_2^R = .5$	5.7×10^4	4.1×10^4	4.1×10^4	72.3 %	1.69

Leptonic: $E_e = 60$ GeV, $E_p = 7$ TeV, $L = 100\,\text{fb}^{-1}$

No.	Background Process	$p_{T\,j,b,l} \geq 20$ GeV, $\Delta R_{j,b/j} \geq 0.4$, $\not{E}_T \geq 25$ $\lvert\eta_j\rvert \geq 5$, $\lvert\eta_{b,l}\rvert \geq 2.5$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	$\sigma_{\text{eff.}}$
1	$e^- p \to l^- \bar{\nu}_l \nu_e j$	1.5×10^{-1}	1.4×10^{-1}	1.4×10^{-3}
2	$e^- p \to l^- \bar{\nu}_l \nu_e c$ & $e^- p \to l^- \bar{\nu}_l \nu_e \bar{c}$	6.6×10^{-3}	6.1×10^{-3}	6.1×10^{-4}
3	$e^- p \to l^- \bar{\nu}_l \nu_e b$ & $e^- p \to l^- \bar{\nu}_l \nu_e \bar{b}$ Without top line	3.6×10^{-3}	3.2×10^{-3}	1.9×10^{-3}
4	$e^- p \to e^- l^- \bar{\nu}_l c$	1.5×10^{-2}	6.9×10^{-3}	6.9×10^{-4}
5	$e^- p \to e^- l^- \bar{\nu}_l j$	1.2×10^{-1}	5.5×10^{-2}	5.5×10^{-4}

Event Selection	$p_{T\,j,b} \geq 20$ GeV $\lvert\eta_j\rvert \leq 5$, $\lvert\eta_b\rvert \leq 2.5$ $\Delta R_{j,b/j} \geq 0.4$ $\not{E}_T \geq 25$	$\Delta\Phi_{\not{E},j} \geq 0.4$ $\Delta\Phi_{\not{E},b} \geq 0.4$ $\Delta\Phi_{\not{E},l} \geq 0.4$	Fiducial Efficiency	$S/\sqrt{S+B}$
SM	1.2×10^4	1.1×10^4	92.0 %	–
SM+$\sum_i$ Bkg$_i$	1.3×10^4	1.2×10^4	92.0 %	–
$\lvert V_{tb}\rvert\, \Delta f_1^L = .5$	4.5×10^4	2.5×10^4	92.6 %	1.55
$f_1^R = .5$	2.8×10^4	1.6×10^4	94.1 %	1.23
$f_2^L = .5$	3.1×10^4	1.7×10^4	89.5 %	1.27
$f_2^L = -.5$	1.8×10^4	1.0×10^4	90.9 %	0.95
$f_2^R = .5$	3.6×10^4	2.0×10^4	90.9 %	1.38

Estimators and χ^2 Analysis: Angular Asymmetries



- Angular Asymmetries from Histogram:
  - $A_{\theta_{ij}} = \frac{N_+^A(\cos\theta_{ij}>0) - N_-^A(\cos\theta_{ij}<0)}{N_+^A(\cos\theta_{ij}>0) + N_-^A(\cos\theta_{ij}<0)}$,
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  where i, j may be any partons (including b), charged lepton or missing energy.
- Statistical error in Asymmetry: $\sigma_a = \sqrt{\frac{1-a^2}{L\cdot\sigma}}$, where $a = \frac{N_+^A - N_-^A}{N_+^A + N_-^A}$ and $N = \left(N_+^A + N_-^A\right) = L\cdot\sigma$,
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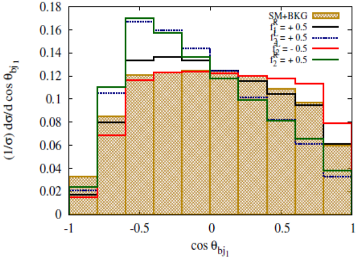
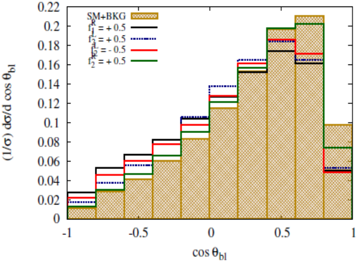
  $\times BR\left(W^- \to jj/l^-\nu_l\right)$





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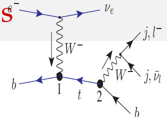

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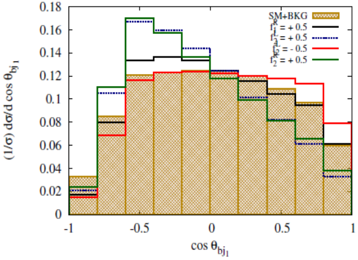

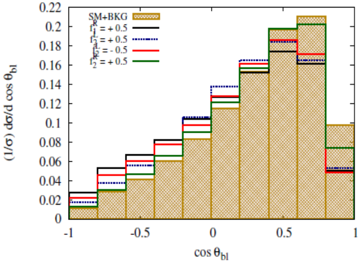

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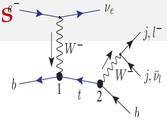

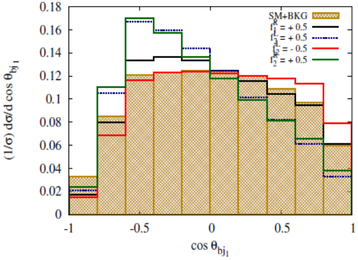

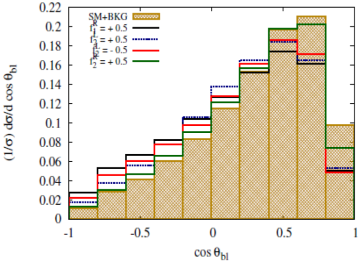

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  - $A_{\Delta\Phi_{ij}} = \frac{N_+^A\left(\Delta\phi_{ij}>\frac{\pi}{2}\right) - N_-^A\left(\Delta\phi_{ij}<\frac{\pi}{2}\right)}{N_+^A\left(\Delta\phi_{ij}>\frac{\pi}{2}\right) + N_-^A\left(\Delta\phi_{ij}<\frac{\pi}{2}\right)}, 0 \le \Delta\phi_{ij} \le \pi$.

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  $$\sigma \equiv \sigma\left(e^-p \to \bar{t}\nu_e, \bar{t} \to W^-\bar{b}\right) \times BR\left(W^- \to jj/l^-\nu_l\right)$$

Estimators and χ^2 Analysis: Angular Asymmetries

Hadronic:

	$A_{\Delta\Phi_{\not{E}_T j_1}}$	$A_{\Delta\Phi_{\not{E}_T \bar{b}}}$	$A_{\Delta\Phi_{\not{E}_T W^-}}$	$A_{\Delta\Phi_{W^- \bar{b}}}$	$A_{\theta_{\bar{b} j_1}}$	$A_{\Delta\eta_{\bar{b} j_1}}$
$\mathrm{SM}+\sum_i \mathrm{Bkg}_i$	$.532 \pm .003$	$.282 \pm .005$	$.503 \pm .004$	$.799 \pm .003$	$.023 \pm .001$	$-.712 \pm .003$
$f_1^R = +.5$	$.327 \pm .004$	$.231 \pm .004$	$.564 \pm .004$	$.778 \pm .003$	$.0005 \pm .004$	$-.806 \pm .003$
$f_2^L = -.5$	$.528 \pm .004$	$.082 \pm .004$	$.716 \pm .003$	$.748 \pm .003$	$-.196 \pm .004$	$-.868 \pm .002$
$f_2^L = +.5$	$.390 \pm .005$	$.269 \pm .004$	$.585 \pm .004$	$.683 \pm .004$	$.106 \pm .005$	$-.795 \pm .003$
$f_2^R = +.5$	$.330 \pm .004$	$.363 \pm .004$	$.566 \pm .003$	$.656 \pm .003$	$-.197 \pm .004$	$-.823 \pm .002$

Leptonic:

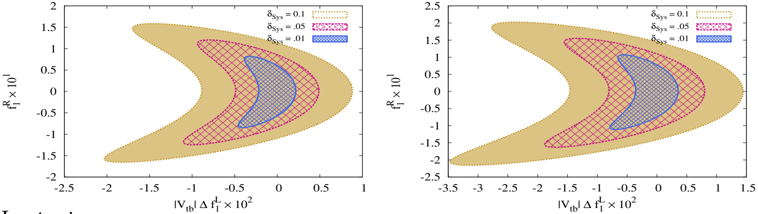
	$A_{\Delta\Phi_{\not{E}_T l_1}}$	$A_{\Delta\Phi_{\not{E}_T \bar{b}}}$	$A_{\theta_{\bar{b} l_1}}$	$A_{\Delta\eta_{\bar{b} l_1}}$
$\mathrm{SM}+\sum_i \mathrm{Bkg}_i$	$.384 \pm .004$	$.710 \pm .003$	$.551 \pm .006$	$-.765 \pm .007$
$f_1^R = +.5$	$.484 \pm .004$	$.702 \pm .003$	$.332 \pm .006$	$-.821 \pm .003$
$f_2^L = -.5$	$.526 \pm .004$	$.620 \pm .003$	$.410 \pm .006$	$-.831 \pm .002$
$f_2^L = +.5$	$.353 \pm .005$	$.812 \pm .003$	$.392 \pm .007$	$-.850 \pm .003$
$f_2^R = +.5$	$.424 \pm .004$	$.684 \pm .003$	$.507 \pm .005$	$-.809 \pm .003$

Estimators and χ^2 Analysis: Bin Analysis

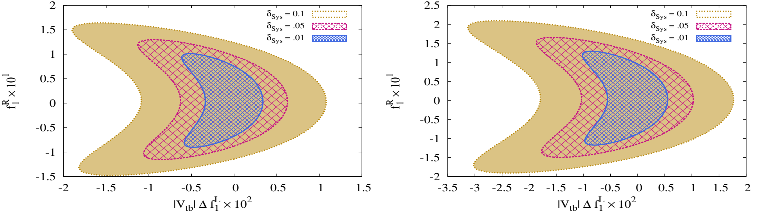
$$\chi^2(f_i,f_j) = \sum_{k=1}^{N} \left(\frac{\mathcal{N}_k^{\mathrm{SM}+\sum_i \mathrm{Bkg_i}} - \mathcal{N}_k^{\mathrm{th}}(f_i,f_j)}{\delta\mathcal{N}_k^{\mathrm{SM}+\sum_i \mathrm{Bkg_i}}} \right)^2,$$

where $\delta\mathcal{N}_k^{\mathrm{SM}+\sum_i \mathrm{Bkg_i}} = \sqrt{\mathcal{N}_k^{\mathrm{SM}+\sum_i \mathrm{Bkg_i}} \left(1 + \delta_{sys}^2 \mathcal{N}_k^{\mathrm{SM}+\sum_i \mathrm{Bkg_i}}\right)}.$

Hadronic



Leptonic



Estimators and χ^2 Analysis: Error & Correlation

Errors and Correlation matrix:

- $\chi^2(f_i, f_j) = \chi^2_{\text{min}} + \sum_{i,j}(f_i - \bar{f}_i)\left[V^{-1}\right]_{ij}(f_j - \bar{f}_j)$, where
  $f_i - \bar{f}_i = \pm\Delta f_i = \pm\sqrt{V_{ii}}$, $\rho_{ij} = V_{ij}/\sqrt{V_{ii}V_{jj}}$.
- $\chi^2_{\text{comb.}}(f_i, f_j) = \sum_{k=1}^{n} \chi^2_{\text{mink}} + \sum_{k=1}^{n} \sum_{i,j}(f_i - \bar{f}_i)\left[V^{-1}\right]_{ij}(f_j - \bar{f}_j)$

$$\begin{aligned} |V_{tb}|\,\Delta f_1^L &= \pm\, 3.2\times 10^{-4} \\ f_1^R &= \pm\, 4.6\times 10^{-4} \\ f_2^L &= \pm\, 4.2\times 10^{-4} \\ f_2^R &= \pm\, 2.6\times 10^{-4} \end{aligned} \quad \begin{pmatrix} 1 & & & \\ -.05 & 1 & & \\ -.04 & -.06 & 1 & \\ -.02 & .03 & -.04 & 1 \end{pmatrix}$$

Luminosity Error: $L \equiv \beta\bar{L},\ \beta = 1 \pm \Delta\beta$; $\chi^2_{\text{comb.}}(f_i, f_j) \to \chi^2_{\text{comb.}}(f_i, f_j, \beta)$

- $\chi^2_{\text{comb.}}(f_i, f_j, \beta) = \sum_{k=1}^{n} \chi^2_{\text{mink}} + \sum_{k=1}^{n} \sum_{i,j}(f_i - \bar{f}_i)\left[V^{-1}\right]_{ij}(f_j - \bar{f}_j) + \left(\frac{\beta_k - 1}{\Delta\beta_k}\right)^2$

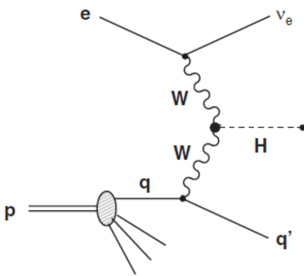
$$\begin{aligned} |V_{tb}|\,\Delta f_1^L &= \pm\, 5.0\times 10^{-2} \\ f_1^R &= \pm\, 4.6\times 10^{-4} \\ f_2^L &= \pm\, 4.2\times 10^{-4} \\ f_2^R &= \pm\, 2.6\times 10^{-4} \end{aligned} \quad \begin{pmatrix} 1 & & & \\ 0 & 1 & & \\ 0 & -.068 & 1 & \\ 0 & .032 & -.041 & 1 \end{pmatrix} \text{ with } \Delta\beta = 10\%.$$

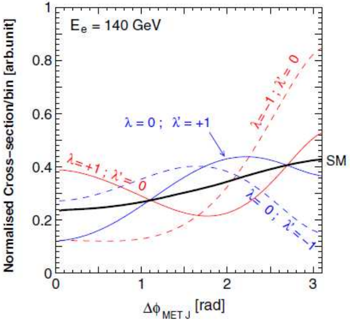
Conclusion

- We observe high yields of single anti-top quark production with fiducial effeciency of $\sim 70\%$ and $\sim 90\%$ in the hadronic and leptonic decay of W^-, respectively after imposing selection cuts.
- Sensitivity of polarization of W^- helicities are studied with respect to variation of anomalous couplings.
- Asymmetries of different kinematic variable provide the sensitivity of anomalous couplings of the order of 10^{-1}.
- Exclusion contours through bin analysis further improves the sensitivity of anomalous couplings to the order of 10^{-3} - 10^{-2} for $|V_{tb}|\ \Delta f_1^L$ with the variation of 1%-10% systematic error and others are of order 10^{-2}-10^{-1} at 95%.
- Combined analysis through error and correlation matrix improves the sensitivity of the left-handed vector and tensor couplings to the order of 10^{-4}, while right-handed anomalous couplings remain same as in bin analysis.
- Luminosity error affect $|V_{tb}|\ \Delta f_1^L$.
- Overall comparison with different data shows that Wtb anomalous couplings can be probed at LHeC with very high accuracy.

Higgs at LHeC

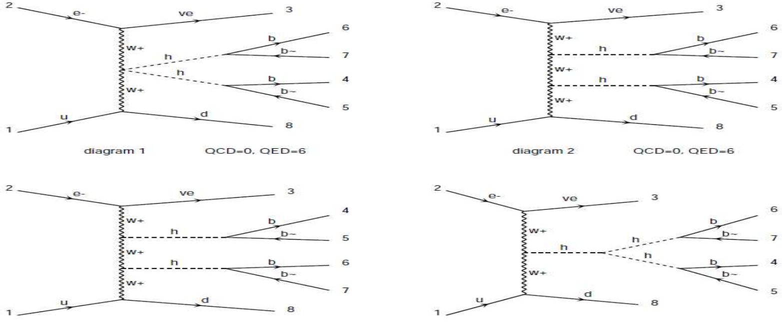
- "Higgs boson searches and the $Hb\bar{b}$ coupling at the LHeC", B. Mellado, Tao Han, PRD **82** 016009 (2010)
  - use of forward jet tagging as a means to secure the observation and to significantly improve the purity of the Higgs boson signal in $H \to b\bar{b}$
- "Azimuthal angle probe of Anomalous HWW couplings at a High energy e p Collider" , B. Mellado et al, PRL 109, 261801 (2012)
  - $\Gamma^{SM}_{\mu\nu} = -gM_V g_{\mu\nu}$
  - $\Gamma^{BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma$

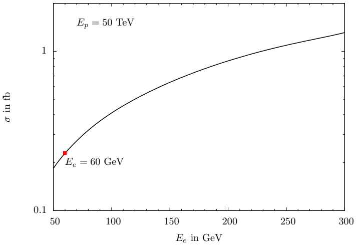




Di-higgs production at e^- p Collider

CC production channel: $e^- p \to \nu_e hhj, h \to b\bar{b}$





Lagrangian and Effective vertices

- $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(3)}_{hhh} + \mathcal{L}^{(3)}_{hWW} + \mathcal{L}^{(4)}_{hhWW}$, where

$$\mathcal{L}^{(3)}_{hhh} = \frac{m_h^2}{2v}(1 - g^{(1)}_{hhh})h^3 + \frac{1}{2} g^{(2)}_{hhh} h\partial_\mu h \partial^\mu h,$$

$$\mathcal{L}^{(3)}_{hWW} = -\frac{g}{2m_W} g^{(1)}_{hWW} W^{\mu\nu} W^\dagger_{\mu\nu} h - \frac{g}{m_W}\left[g^{(2)}_{hWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.}\right] - \frac{g}{2m_W}\tilde{g}_{hWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu} h,$$

$$\mathcal{L}^{(4)}_{hhWW} = -\frac{g^2}{4m_W^2} g^{(1)}_{hhWW} W^{\mu\nu} W^\dagger_{\mu\nu} h^2 - \frac{g^2}{2m_W^2}\left[g^{(2)}_{hhWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h^2 + \text{h.c.}\right] - \frac{g^2}{4m_W^2}\tilde{g}_{hhWW} W^{\mu\nu}\tilde{W}^\dagger_{\mu\nu} h^2$$

- Effective Vertices:

$$\mathrm{i}\Gamma_{hhh} = -6\mathrm{i}v\lambda_{SM} g^{(1)}_{hhh} - \mathrm{i}g^{(2)}_{hhh}(p_1\cdot p_2 + p_2\cdot p_3 + p_3\cdot p_1)$$

$$\mathrm{i}\Gamma_{hW-W+} = \mathrm{i}\Bigg[\left\{\frac{g^2}{2}v + \frac{g}{m_W} g^{(1)}_{hWW} p_2\cdot p_3 + \frac{g}{m_W} g^{(2)}_{hWW}(p_2^2 + p_3^2)\right\}\eta^{\mu_2\mu_3}$$

$$- \frac{g}{m_W} g^{(1)}_{hWW} p_2^{\mu_3} p_3^{\mu_2} - \frac{g}{m_W} g^{(2)}_{hWW}(p_2^{\mu_2} p_2^{\mu_3} + p_3^{\mu_2} p_3^{\mu_3}) - \mathrm{i}\frac{g}{m_W}\tilde{g}_{hWW}\epsilon_{\mu_2\mu_3\mu\nu} p_2^\mu p_3^\nu\Bigg]$$

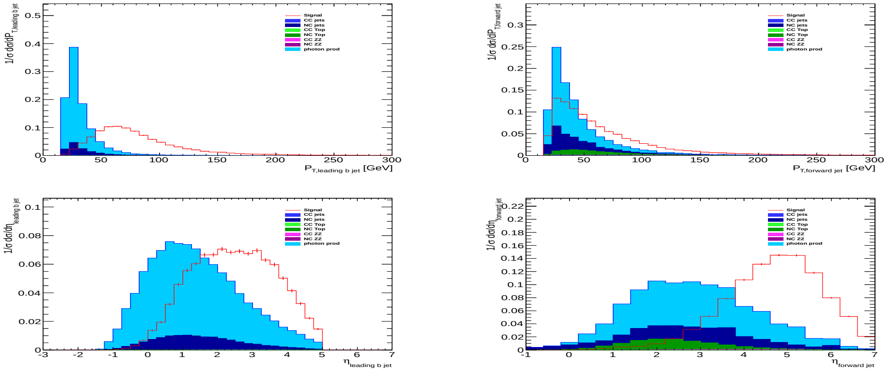
$$\mathrm{i}\Gamma_{hhW-W+} = \mathrm{i}\Bigg[\left\{\frac{g^2}{2} + \frac{g^2}{m_W^2} g^{(1)}_{hhWW} p_3\cdot p_4 + \frac{g^2}{m_W^2} g^{(2)}_{hhWW}(p_3^2 + p_4^2)\right\}\eta^{\mu_3\mu_4}$$

$$- \frac{g^2}{m_W^2} g^{(1)}_{hhWW} p_3^{\mu_4} p_4^{\mu_3} - \frac{g^2}{m_W^2} g^{(2)}_{hhWW}(p_3^{\mu_3} p_3^{\mu_4} + p_4^{\mu_3} p_4^{\mu_4}) - \mathrm{i}\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu} p_3^\mu p_4^\nu\Bigg]$$

Cross section and Distributions

Process	CC (fb)	NC (fb)	PHOTO (fb)
Signal:	2.40e-01		
$b\bar{b}b\bar{b}j$:	8.20e-01	3.60e+03	2.85e+03
$b\bar{b}jjj$:	6.50e+03	2.50e+04	1.94e+06
$zzj(z \to b\bar{b})$:	7.40e-01	1.65e-02	1.73e-02
$t\bar{t}j$(hadronic):	3.30e-01	1.40e+02	3.27e+02
$t\bar{t}j$(semi-leptonic):	1.22e-01	4.90e+01	1.05e+02

Table : *Cross sections (in fb): $E_e = 60$ GeV, $E_p = 50$ TeV, $j = gu\bar{u}d\bar{d}s\bar{s}c\bar{c}$. Initial cuts: $|\eta| \leq 10$ for jets, leptons and b, $P_T \geq 10$ GeV, $\Delta R_{\min} = 0.4$ for all particles.*



Cross section and Distributions

Process	CC (fb)	NC (fb)	PHOTO (fb)
Signal:	2.40e-01		
$bb\bar{b}bj$:	8.20e-01	3.60e+03	2.85e+03
$b\bar{b}jjj$:	6.50e+03	2.50e+04	1.94e+06
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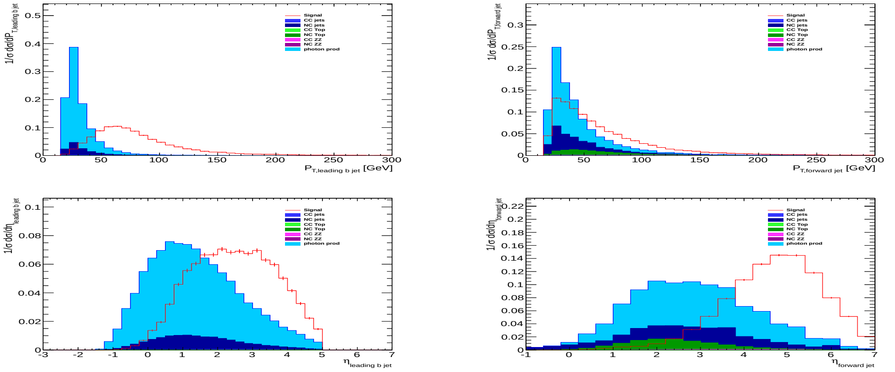

Cross section and Distributions

Process	CC (fb)	NC (fb)	PHOTO (fb)
Signal:	2.40e-01		
$bb\bar{b}bj$:	8.20e-01	3.60e+03	2.85e+03
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$t\bar{t}j$(hadronic):	3.30e-01	1.40e+02	3.27e+02
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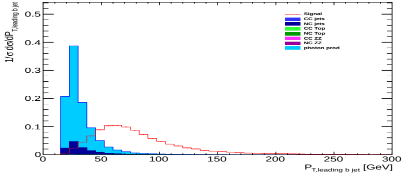
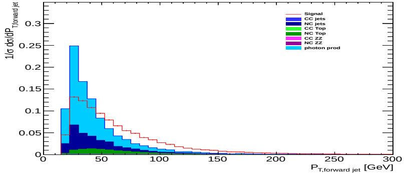
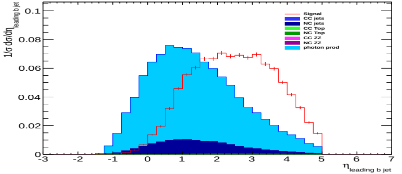
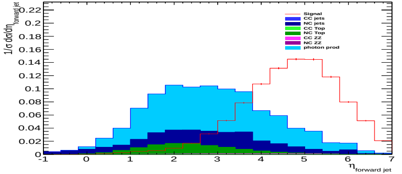








Cut-based Analysis

- Select 4 b + 1-jet: $p_T^{jet} > 20$ GeV, $|\eta| < 7$ for *non-b*-jets, $|\eta| < 5$ for b-jets. The four b jets must be well separated within $\Delta R > 0.7$ in case of the overlapped truth matching in the b-tagging.
- Rejecting leptons with $p_T^{e^-} > 10$ GeV (suppress the NC process)
- $\eta_{forward-jet} > 4.0$, the forward jet as defined as the *non-b*-jet which has the largest p_T after selecting at least 4 b-jets.
- $E_T^{miss} > 40$ GeV and $\Delta\Phi_{E_T^{miss},leadingjet} > 0.4$, $\Delta\Phi_{E_T^{miss},subleadingjet} > 0.4$.
- Pair the four b-jets into two pairs and calculate the invariant masses of each pair. The composition of the pairs which has the smallest variance of mass to $(m_H - 40)$ GeV is chosen. The first pair is defined as $90 < M_1 < 125$, which must have the leading b-jet. The other pair is defined as $75 < M_2 < 125$.
- Choosing the invariant mass of all four b-jets > 280 GeV.

Significance: $s = \sqrt{2\left((S+B)\,log\,(1+S/B) - S\right)}$

Expected relative error: $\frac{\Delta S}{S} = \frac{\sqrt{2\times S + 2\times B + (0.05\times S)^2 + (0.05\times B)^2}}{S}$, where S and B are expected signal and background yields in $\mathcal{L} = 10\,ab^{-1}$ with 5% systematic error.

Cut-based Analysis

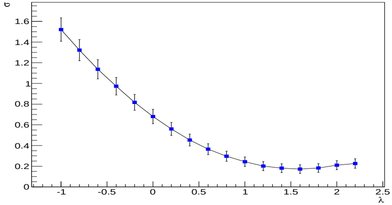
Samples	Signal	CCJet	NCJet	CCTop	NCTop
Initial	2.36e+03 ± 4.82	6.45e+06 ± 9.3e+03	2.5e+08 ± 4.26e+05	4.49e+03 ± 5.03	7.4e+06 ± 6.86e+03
4 b and 1 light jets	299 ± 1.16	293 ± 7.56	2.23e+04 ± 678	5.72 ± 0.023	9.87e+03 ± 31.1
Electron rejection	299 ± 1.16	293 ± 7.56	6.84e+03 ± 385	5.66 ± 0.0229	6.43e+03 ± 28
Forward jet	224 ± 1.01	22.9 ± 1.39	864 ± 65.1	0.399 ± 0.00537	307 ± 5.8
E_T^{miss}	149 ± 0.823	18.7 ± 0.981	93.9 ± 26.7	0.372 ± 0.00524	85.4 ± 2.86
$E_T^{miss} - \phi$ rejection	128 ± 0.76	16.8 ± 0.957	45.3 ± 14	0.326 ± 0.00493	63.6 ± 2.48
$M_1 M_2$	71 ± 0.568	1.49 ± 0.216	0.151 ± 0.0866	0.06 ± 0.00212	11.1 ± 1.08
M_{4b}	63.4 ± 0.536	0.849 ± 0.191	0.151 ± 0.0866	0.0346 ± 0.00141	5.4 ± 0.776

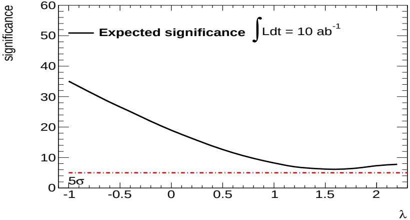
Samples	CCZZj	NCZZj	NCPhotoProd	Total background	Significance
Initial	7.36e+03 ± 10.6	338 ± 0.426	2.1e+09 ± 3.43e+06	2.36e+09 ± 3.5e+06	0.049
4 b and 1 light jets	678 ± 2.19	21.7 ± 0.0707	7.36e+04 ± 4.21e+03	1.07e+05 ± 4.3e+03	0.92
Electron rejection	678 ± 2.19	14 ± 0.0614	6.23e+04 ± 1.29e+03	7.65e+04 ± 1.4e+03	1.1
Forward jet	380 ± 1.64	1.04 ± 0.014	1.43e+04 ± 297	1.59e+04 ± 3e+02	1.8
E_T^{miss}	342 ± 1.55	0.18 ± 0.00575	980 ± 21.9	1.52e+03 ± 35	3.8
$E_T^{miss} - \phi$ rejection	287 ± 1.42	0.1 ± 0.00427	440 ± 10.4	853 ± 18	4.3
$M_1 M_2$	16.8 ± 0.344	0.00613 ± 0.00117	54.4 ± 1.21	84.00 ± 1.68	6.9
M_{4b}	7.43 ± 0.229	0.00239 ± 0.000661	21.9 ± 0.63	35.78 ± 1.05	8.7

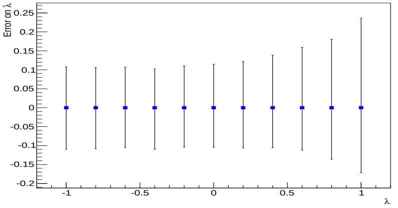
Table : *Number of events after optimization and weighted with luminosity $\mathcal{L} = 10\,\text{ab}^{-1}$. The abbreviations CC(NC)Jet and CC(NC)Top accounts for the weighted sum of CC(NC) backgrounds 1, 2 and 4, 5 as given in Table 1. NCPhotoProd refer to weighted sum of all* PHOTO*-production.*

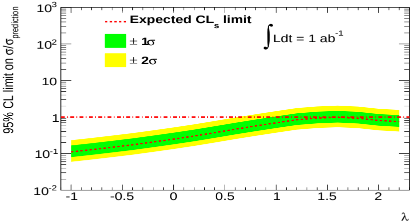
Statistical Analysis

- $g_{hhh}^{(1)} \to \lambda, g_{hhh}^{(2)} \sim 10^{-4} - 10^{-3}$,
- $g_{hWW}^{(1)} \sim 10^{-1}, g_{hWW}^{(2)} \sim 10^{-3} - 10^{-2}$,
- $g_{hhWW}^{(1)} \sim 10^{-2}, g_{hhh}^{(2)} \sim 10^{-3} - 10^{-2}$,
- $\tilde{g}_{hWW} \sim 10^{-1}, \tilde{g}_{hhWW} \sim 10^{-2}$.



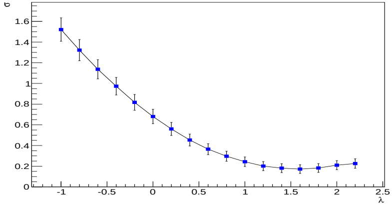


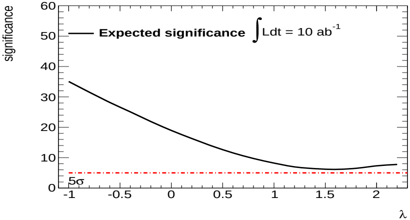


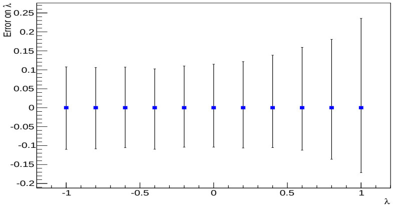


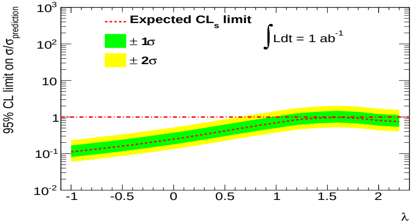
Statistical Analysis

- $g^{(1)}_{hhh} \to \lambda, g^{(2)}_{hhh} \sim 10^{-4} - 10^{-3}$,
- $g^{(1)}_{hWW} \sim 10^{-1}, g^{(2)}_{hWW} \sim 10^{-3} - 10^{-2}$,
- $g^{(1)}_{hhWW} \sim 10^{-2}, g^{(2)}_{hhh} \sim 10^{-3} - 10^{-2}$,
- $\tilde{g}_{hWW} \sim 10^{-1}, \tilde{g}_{hhWW} \sim 10^{-2}$.









Statistical Analysis

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- $g_{hhWW}^{(1)} \sim 10^{-2}, g_{hhh}^{(2)} \sim 10^{-3} - 10^{-2}$,
- $\tilde{g}_{hWW} \sim 10^{-1}, \tilde{g}_{hhWW} \sim 10^{-2}$.