Physics at the ILC

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Introduction

The question:

What could ILC possibly offer to study top couplings beyond LHC capabilities?

This answer is non-trivial because LHC is an excellent top factory.

Introduction

Framework: dimension-six gauge-invariant effective operators

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_6 + \ldots$$

$$\mathcal{L}_4 = \mathcal{L}_{SM} \quad \Rightarrow \quad \text{SM Lagrangian}$$

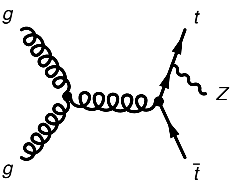
$$\mathcal{L}_6 = \sum \frac{c_x}{\Lambda^2} \mathcal{O}_x \quad \Rightarrow \quad \mathcal{O}_x \text{ gauge-invariant building blocks}$$

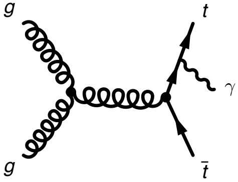
Effects of new physics are parameterized at scale $\Lambda > \nu$.

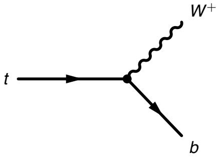
- In general, the effective operator framework allows to reduce the number of independent parameters entering fermion trilinear interactions.
- Allows to set relations between new physics contributions to the top quark interactions. Measurements of different top quark vertices can be compared, such as Wtb and $Zt\bar{t}$.
- Allows to compute radiative corrections and study the effect of anomalous top interactions in loop observables.

Introduction

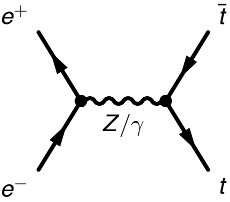
- Large Hadron Collider:







- International Linear Collider:



$$
\begin{aligned}
O_{\phi q}^{(3,3+3)} &= i\left[\phi^\dagger(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\phi\right](\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}) \\
O_{uW}^{33} &= (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi}\, W^I_{\mu\nu} \\
O_{\phi q}^{(1,3+3)} &= i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}_{L3}\gamma^\mu q_{L3}) \\
O_{uB\phi}^{33} &= (\bar{q}_{L3}\sigma^{\mu\nu} t_R)\tilde{\phi}\, B_{\mu\nu} \\
O_{\phi u}^{3+3} &= i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}_R\gamma^\mu t_R)
\end{aligned}
$$

Introduction

Six-dimension operators

	Wtb (LHC)	$Zt\bar{t}$ and $\gamma t\bar{t}$ (ILC)
$O_{\phi q}^{(3,3+3)}$	✔	✔
$O_{\phi\phi}^{33}$	✔	✘
$O_{\phi q}^{(1,3+3)}$	✘	✔
$O_{\phi u}^{3+3}$	✘	✔
O_{uW}^{33}	✔	✔
O_{dW}^{33}	✔	✘
$O_{uB\phi}^{33}$	✘	✔

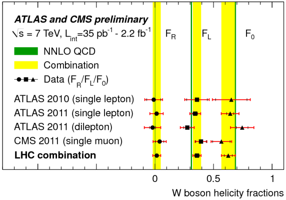
LHC results

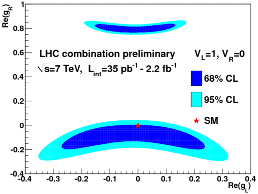
General Wtb vertex

Nucl. Phys. B 812 (2009) 181-204

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-}$$

Vector (V_R) and Tensor like couplings (g_L, g_R) zero @ tree level in SM





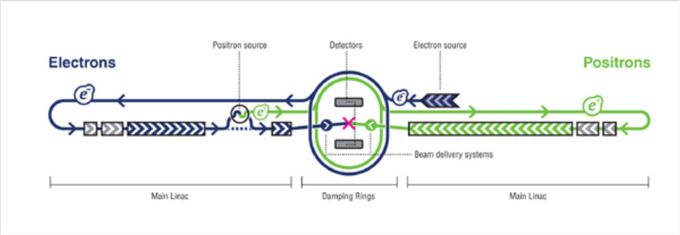
$$\mathrm{Re}(V_R) \in [-0.20, 0.23] \quad \rightarrow \quad \frac{\mathrm{Re}(C^{33}_{\phi\phi})}{\Lambda^2} \in [-6.7, 7.8]\ \mathrm{TeV}^{-2}$$

$$\mathrm{Re}(g_L) \in [-0.14, 0.11] \quad \rightarrow \quad \frac{\mathrm{Re}(C^{33}_{dW})}{\Lambda^2} \in [-1.6, 1.2]\ \mathrm{TeV}^{-2}$$

[JHEP06(2012)088]

$$\mathrm{Re}(g_R) \in [-0.08, 0.04] \quad \rightarrow \quad \frac{\mathrm{Re}(C^{33}_{uW})}{\Lambda^2} \in [-1.0, 0.5]\ \mathrm{TeV}^{-2}$$

International Linear Collider



- The CM energy of $\sqrt{s} = 500$ GeV - possible upgrade to $\sqrt{s} = 1$ TeV.
- Total uncertainties of 5% in the cross-sections, and 2% in the asymmetries, are assumed for 100 fb^{-1} (benchmark numbers).
- Possible use of the electron beam polarization: $P_{e^-} = 0.8$ and $P_{e^-} = -0.8$.

$e^+e^- \to t\bar{t}$ with effective operators

$Zt\bar{t}$ and $\gamma t\bar{t}$ Lagrangians

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\,\gamma^\mu \left(c_L^t P_L + c_R^t P_R\right) t\, Z_\mu - \frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d_V^Z + i d_A^Z \gamma_5\right) t\, Z_\mu$$

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\, A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + i d_A^\gamma \gamma_5\right) t\, A_\mu$$

The effective operators comprise 6 independent parameters. The coefficients c_L^t, c_R^t, d_V^Z, d_A^Z, d_V^γ, d_A^γ, depend on these operators contributions.

$$O_{\phi q}^{(3,3+3)} = i\left[\phi^\dagger(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\phi\right]\,(\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}) \qquad O_{uW}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi}\, W_{\mu\nu}^I$$

$$O_{\phi q}^{(1,3+3)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}_{L3}\gamma^\mu q_{L3}) \qquad O_{uB\phi}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu} t_R)\tilde{\phi}\, B_{\mu\nu}$$

$$O_{\phi u}^{3+3} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}_R\gamma^\mu t_R)$$

[Buchmuller and Wyler NPB 268 (1986) 621, JAAS NPB 812 (2009) 181]

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The effective operators comprise 6 independent parameters. The coefficients c_L^t, c_R^t, d_V^Z, d_A^Z, d_V^γ, d_A^γ, depend on these operators contributions.

$$c_L^t = 1 + \left[C_{\phi q}^{(3,3+3)} - C_{\phi q}^{(1,3+3)}\right]\frac{v^2}{\Lambda^2} - 2s_W^2 Q_t \qquad c_R^t = -C_{\phi u}^{3+3}\frac{v^2}{\Lambda^2} - 2s_W^2 Q_t$$

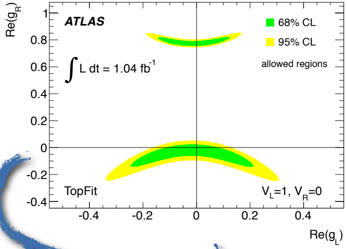
$$d_V^Z = \sqrt{2}\,\mathrm{Re}\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}\right]\frac{v^2}{\Lambda^2} \qquad d_A^Z = \sqrt{2}\,\mathrm{Im}\left[c_W C_{uW}^{33} - s_W C_{uB\phi}^{33}\right]\frac{v^2}{\Lambda^2}$$

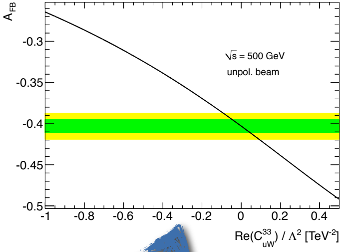
$$d_V^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Re}\left[s_W C_{uW}^{33} + c_W C_{uB\phi}^{33}\right]\frac{v m_t}{\Lambda^2} \qquad d_A^\gamma = \frac{\sqrt{2}}{e}\,\mathrm{Im}\left[s_W C_{uW}^{33} + c_W C_{uB\phi}^{33}\right]\frac{v m_t}{\Lambda^2}$$

[Buchmuller and Wyler NPB 268 (1986) 621, JAAS NPB 812 (2009) 181]

ILC versus LHC sensitivity

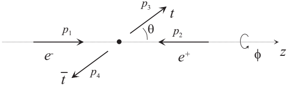
Allowed regions for *Wtb* anomalous couplings extracted from helicity fractions in top decays by ATLAS (left) and dependence of the FB asymmetry on Re C_{uW}^{33} (right):





$$g_R = \sqrt{2} C_{uW}^{33} \nu^2 / \Lambda^2$$

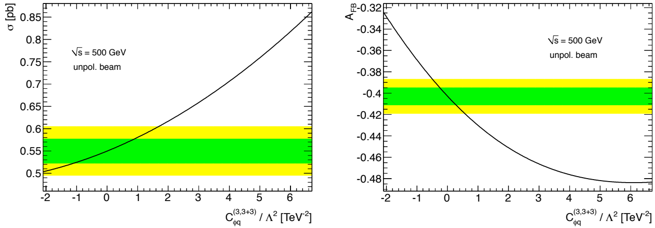
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



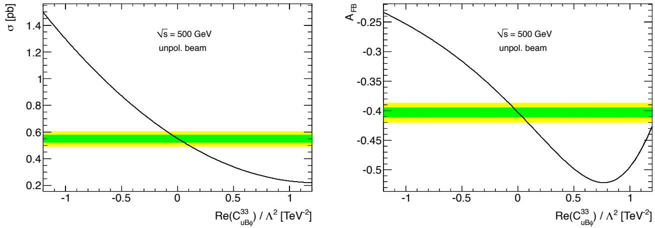
- The CM energy is taken as $\sqrt{s} = 500$ GeV.
- The bands represent a 1σ (green) and 2σ (yellow) variation around the SM value, total uncertainty of 2% in the asymmetry is assumed.

ILC versus LHC sensitivity

Dependence of the unpolarised cross section and FB asymmetry on $C_{\phi q}^{(3,3+3)}$:



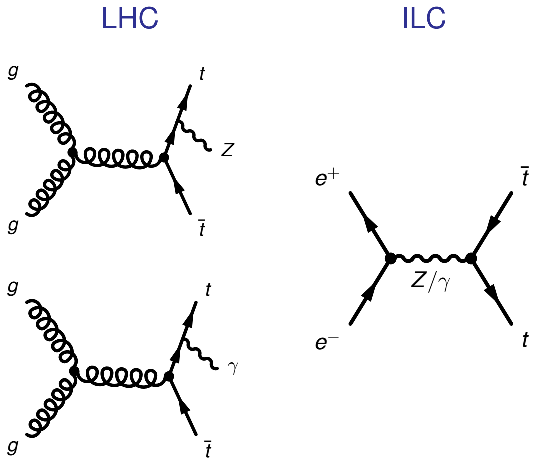
Dependence of the unpolarised cross section and FB asymmetry on Re $C_{uB\phi}^{33}$:



ILC versus LHC sensitivity

- Relations between new physics contributions to different top quark vertices (Wtb, $t\bar{t}Z$ and $t\bar{t}\gamma$), which can be probed in different accelerators (ILC vs LHC).
- Estimates show that the ILC sensitivity may largely surpass the one achievable at the LHC, either in top quark decays (current or envisaged) or in $Zt\bar{t}$ and $\gamma t\bar{t}$ production.
- The different ILC beam polarization options and CM energies allow to disentangle the various effective operator contributions to the $Zt\bar{t}$ and $\gamma t\bar{t}$ vertices.

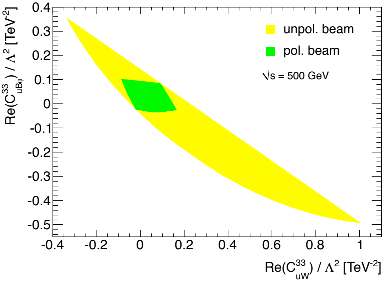
Disentangling operator contributions

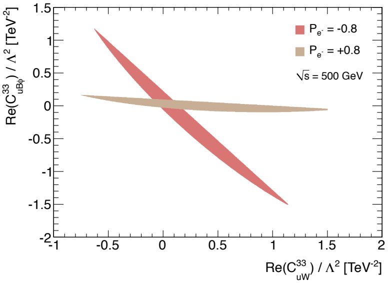


- Beam polarisation distinguishes the Z boson and the photon contributions at the ILC.

Disentangling operator contributions

Combined limits on Re C_{uW}^{33} and Re $C_{uB\phi}^{33}$ without and with beam polarisations (left) and complementarity of the measurements for $P_{e^-} = 0.8$ and $P_{e^-} = -0.8$ (right):

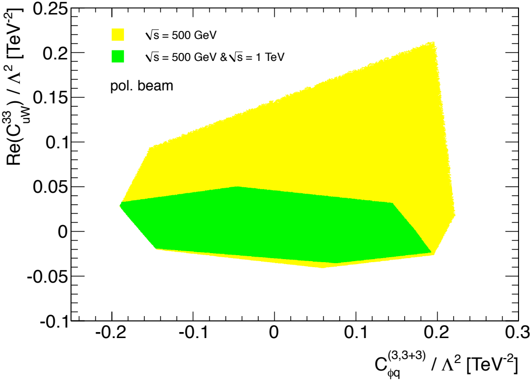




- Beam polarisation allows to separate the Z boson and the photon contributions, because the former is multiplied by a parity-violating coupling and the latter by the electron charge.

Disentangling operator contributions

Combined limits on $C_{\phi q}^{(3,3+3)}$ and C_{uW}^{33} for a CM energy of 500 GeV and also with 1 TeV:



- Observables used: σ^L, σ^R, A_{FB}^L and A_{FB}^R.
- Measurements at different CM energies can help resolve the vector and tensor contributions because the CM energy dependence is different. The tensorial component ($\sigma^{\mu\nu}$) is multiplied by q^ν and the vectorial one (γ^μ) not.

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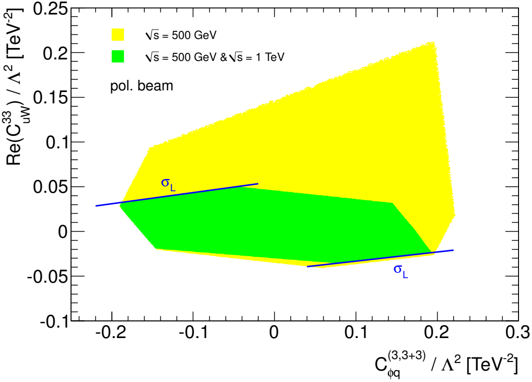

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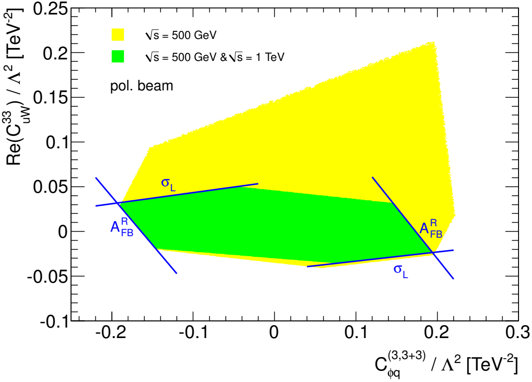

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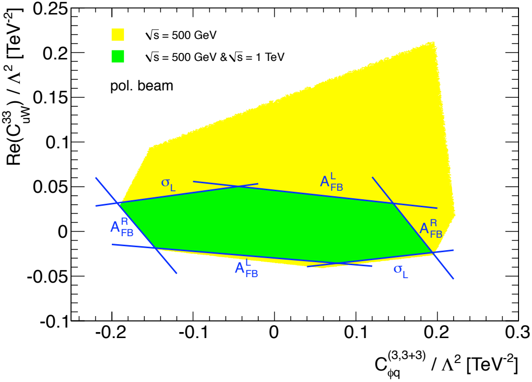
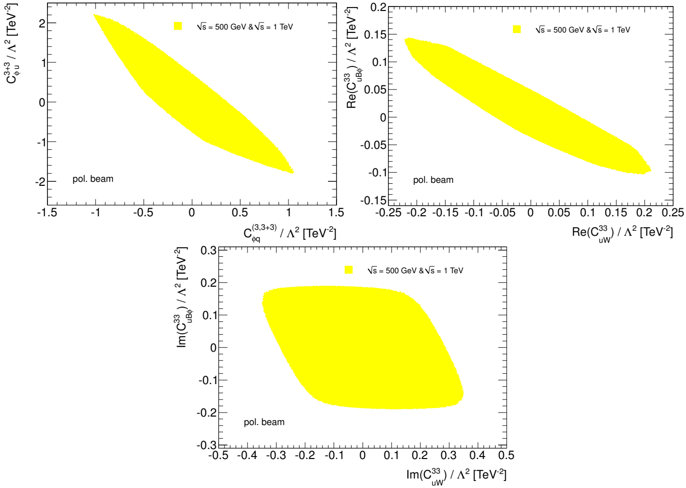


- Observables used: σ^L, σ^R, A_{FB}^L and A_{FB}^R.
- Measurements at different CM energies can help resolve the vector and tensor contributions because the CM energy dependence is different. The tensorial component ($\sigma^{\mu\nu}$) is multiplied by q^ν and the vectorial one (γ^μ) not.

Disentangling operator contributions

General limits for arbitrary $C_{\phi q}^{(3,3+3)}$, $C_{\phi u}^{3+3}$, C_{uW}^{33} and $C_{uB\phi}^{33}$:



Conclusions

- The sensitivity to $Zt\bar{t}$ and $\gamma t\bar{t}$ couplings is better at the ILC, as already known. However, the effective operator framework adopted also allows for a direct comparison with charged current processes at the LHC, like single top production and decays $t \to Wb$.
- Despite the fact that the LHC prospects are already good due to its excellent statistics, the ILC sensitivity is even better for those operators.
- Assuming operator coefficients equal to unity, the new physics scales probed extend up to 4.5 TeV, for a CM energy of 500 GeV.

Conclusions

- We have shown that the use of electron beam polarisation is essential to disentangle contributions, as is the combination of measurements at 500 GeV and 1 TeV.
- The results presented here make manifest that the determination of top interactions constitute a physics case for the use of electron beam polarisation, as well as for a possible CM energy upgrade to 1 TeV.