

# Top effective operators at the ILC

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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

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

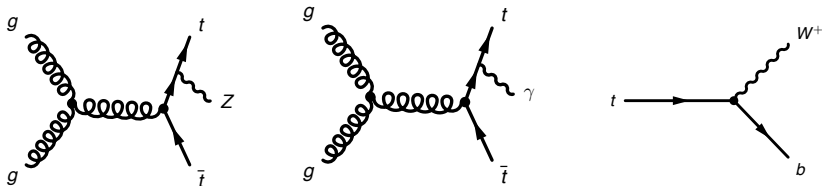
$$\begin{aligned} \mathcal{L}_4 &= \mathcal{L}_{SM} & \Rightarrow & \text{SM Lagrangian} \\ \mathcal{L}_6 &= \sum \frac{c_x}{\Lambda^2} \mathcal{O}_x & \Rightarrow & \mathcal{O}_x \text{ gauge-invariant building blocks} \end{aligned}$$

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

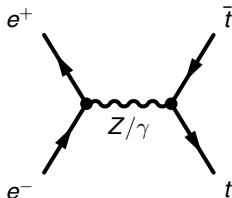
- In general, the effective operator framework allows to reduce the number of independent parameters entering fermion trilinear interactions.
- Allows to set relations between new physics contributions to the top quark interactions. Measurements of different top quark vertices can be compared, such as  $Wtb$  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:



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

# Introduction

## Six-dimension operators

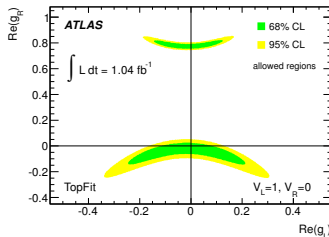
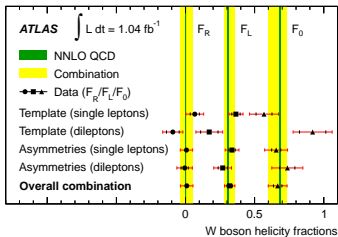
	$Wtb$ (LHC)	$Zt\bar{t}$ and $\gamma t\bar{t}$ (ILC)
$O_{\phi q}^{(3,3+3)}$	✓	✓
$O_{\phi\phi}^{33}$	✓	✗
$O_{\phi q}^{(1,3+3)}$	✗	✓
$O_{\phi u}^{3+3}$	✗	✓
$O_{uW}^{33}$	✓	✓
$O_{dW}^{33}$	✓	✗
$O_{uB\phi}^{33}$	✗	✓

## General Wtb vertex

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

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

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

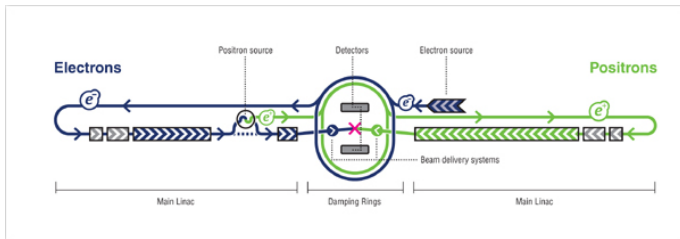


$$\text{Re}(V_R) \in [-0.20, 0.23] \rightarrow \frac{\text{Re}(C_{\phi\phi}^{33})}{\Lambda^2} \in [-6.7, 7.8] \text{ TeV}^{-2}$$

$$\text{Re}(g_L) \in [-0.14, 0.11] \rightarrow \frac{\text{Re}(C_{dW}^{33})}{\Lambda^2} \in [-1.6, 1.2] \text{ TeV}^{-2} \quad [\text{JHEP06(2012)088}]$$

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

# International Linear Collider



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

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

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

$$\begin{aligned}\mathcal{L}_{Zt\bar{t}} &= -\frac{g}{2c_W} \bar{t} \gamma^\mu \left( c_L^t P_L + c_R^t P_R \right) t Z_\mu - \frac{g}{2c_W} \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} \left( d_V^Z + i d_A^Z \gamma_5 \right) t Z_\mu \\ \mathcal{L}_{\gamma t\bar{t}} &= -e Q_t \bar{t} \gamma^\mu t A_\mu - e \bar{t} \frac{i\sigma^{\mu\nu} q_\nu}{m_t} \left( d_V^\gamma + i d_A^\gamma \gamma_5 \right) t A_\mu\end{aligned}$$

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

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

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



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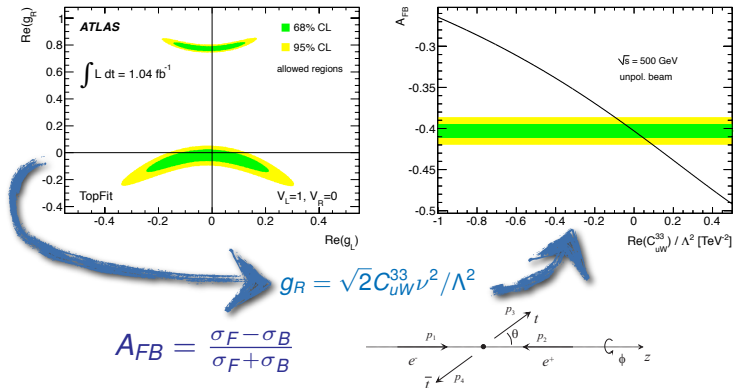
The effective operators comprise 6 independent parameters. The coefficients  $c_L^t$ ,  $c_R^t$ ,  $d_V^Z$ ,  $d_A^Z$ ,  $d_V^\gamma$ ,  $d_A^\gamma$ , depend on these operators contributions.

$$\begin{aligned}c_L^t &= 1 + \left[ C_{\phi q}^{(3,3+3)} - C_{\phi q}^{(1,3+3)} \right] \frac{v^2}{\Lambda^2} - 2s_W^2 Q_t & c_R^t &= -C_{\phi u}^{3+3} \frac{v^2}{\Lambda^2} - 2s_W^2 Q_t \\ d_V^Z &= \sqrt{2} \operatorname{Re} \left[ c_W C_{uW}^{33} - s_W C_{uB\phi}^{33} \right] \frac{v^2}{\Lambda^2} & d_A^Z &= \sqrt{2} \operatorname{Im} \left[ c_W C_{uW}^{33} - s_W C_{uB\phi}^{33} \right] \frac{v^2}{\Lambda^2} \\ d_V^\gamma &= \frac{\sqrt{2}}{e} \operatorname{Re} \left[ s_W C_{uW}^{33} + c_W C_{uB\phi}^{33} \right] \frac{vm_t}{\Lambda^2} & d_A^\gamma &= \frac{\sqrt{2}}{e} \operatorname{Im} \left[ s_W C_{uW}^{33} + c_W C_{uB\phi}^{33} \right] \frac{vm_t}{\Lambda^2}\end{aligned}$$

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

# ILC versus LHC sensitivity

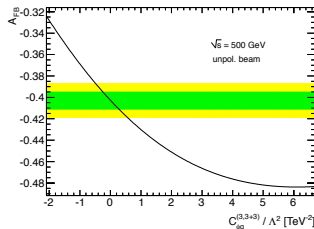
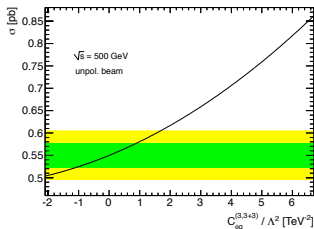
Allowed regions for  $Wtb$  anomalous couplings extracted from helicity fractions in top decays by ATLAS (left) and dependence of the FB asymmetry on  $\text{Re } C_{uW}^{33}$  (right):



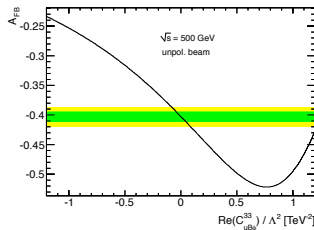
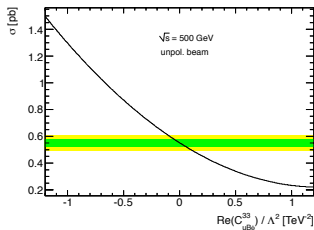
- ATLAS result on  $\text{Re } C_{uW}^{33}$  is currently the most constrained [JHEP06(2012)088].
- The CM energy is taken as  $\sqrt{s} = 500 \text{ GeV}$ .
- The bands represent a  $1\sigma$  (green) and  $2\sigma$  (yellow) variation around the SM value, total uncertainty of 2% in the asymmetry is 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  $\text{Re } C_{uB\phi}^{33}$ :

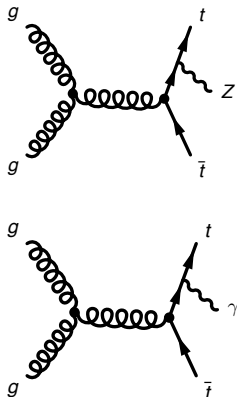


# ILC versus LHC sensitivity

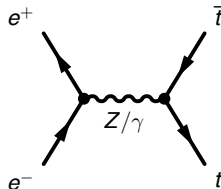
- Relations between new physics contributions to different top quark vertices ( $Wtb$ ,  $t\bar{t}Z$  and  $t\bar{t}\gamma$ ), which can be probed in different accelerators (ILC vs LHC).
- Estimates show that the ILC sensitivity may largely surpass the one achievable at the LHC, either in top quark decays (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

LHC



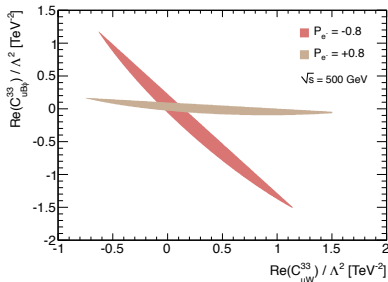
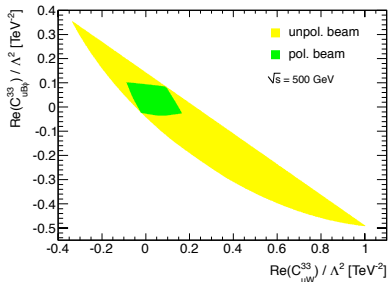
ILC



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

# Disentangling operator contributions

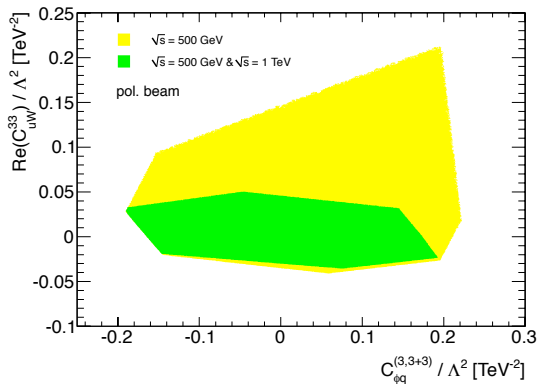
Combined limits on  $\text{Re } C_{uW}^{33}$  and  $\text{Re } C_{uB\phi}^{33}$  without and with beam polarisations (left) and complementarity of the measurements for  $P_{e^-} = 0.8$  and  $P_{e^-} = -0.8$  (right):



- 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

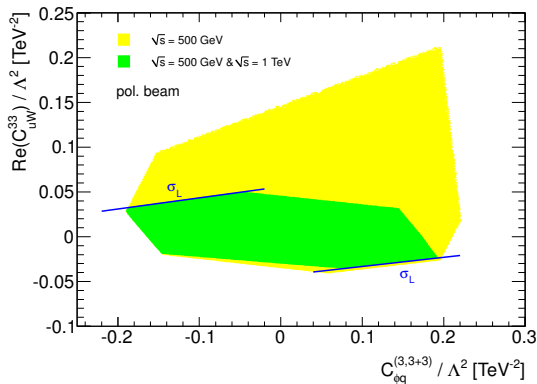
Combined limits on  $C_{\phi q}^{(3,3+3)}$  and  $C_{uW}^{33}$  for a CM energy of 500 GeV and also with 1 TeV:



- Observables used:  $\sigma^L$ ,  $\sigma^R$ ,  $A_{FB}^L$  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  $q^\nu$  and the vectorial one ( $\gamma^\mu$ ) not.

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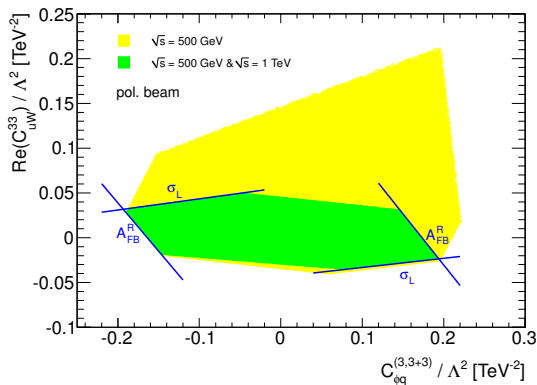


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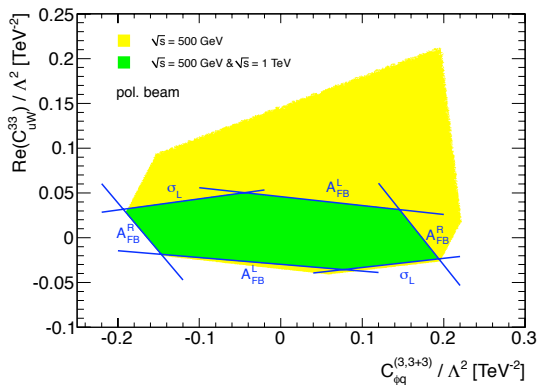
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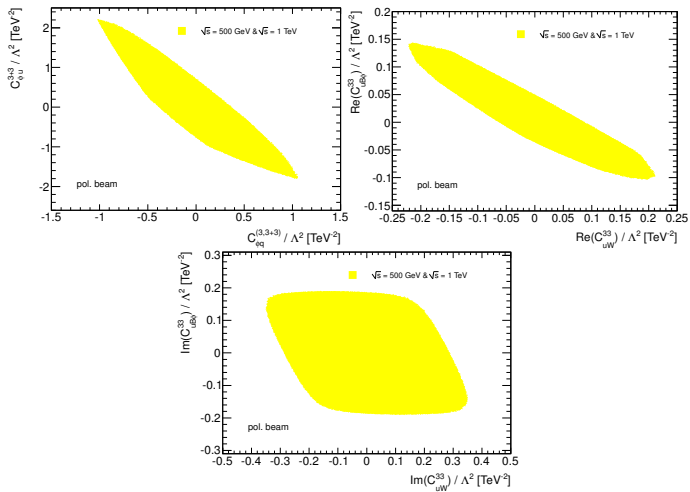
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# Disentangling operator contributions

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  $t \rightarrow Wb$ .
- 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.