Electro-weak couplings of the top quark

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Introduction

- **Top quark precision measurements** have never been done in a **lepton collider.**

- In such colliders **we can distinguish between top/anti-top, top polarisations**, etc. ⟶ **Access to new observables.**

- **Some models BSM have strong couplings to the top quark** which provide a great sensitivity to high energy scales. **Two approaches** for top quark couplings:

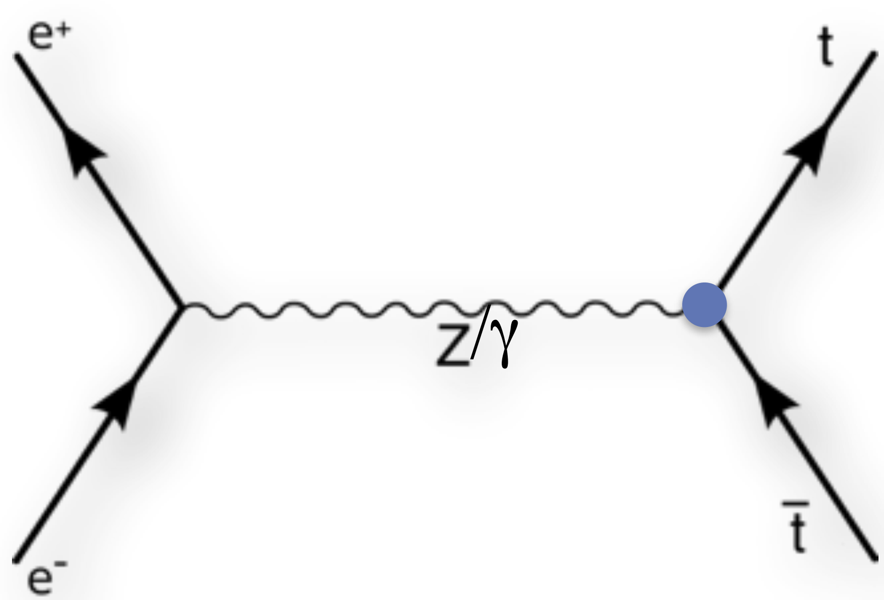
  - ***Form-factors scheme.***
  - ***Effective operators scheme*** *from an EFT.*

- This brings a great opportunity to provide a **bright window to new physics.**

Status of form-factors scheme

Assume production is dominated by SM and NP scale is beyond direct reach.

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2) + \gamma_5 \underline{F_{1A}^X}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2) + \gamma_5 \underline{F_{2A}^X}(k^2)\right)\right\}$$



IFIC - LAL Collaboration

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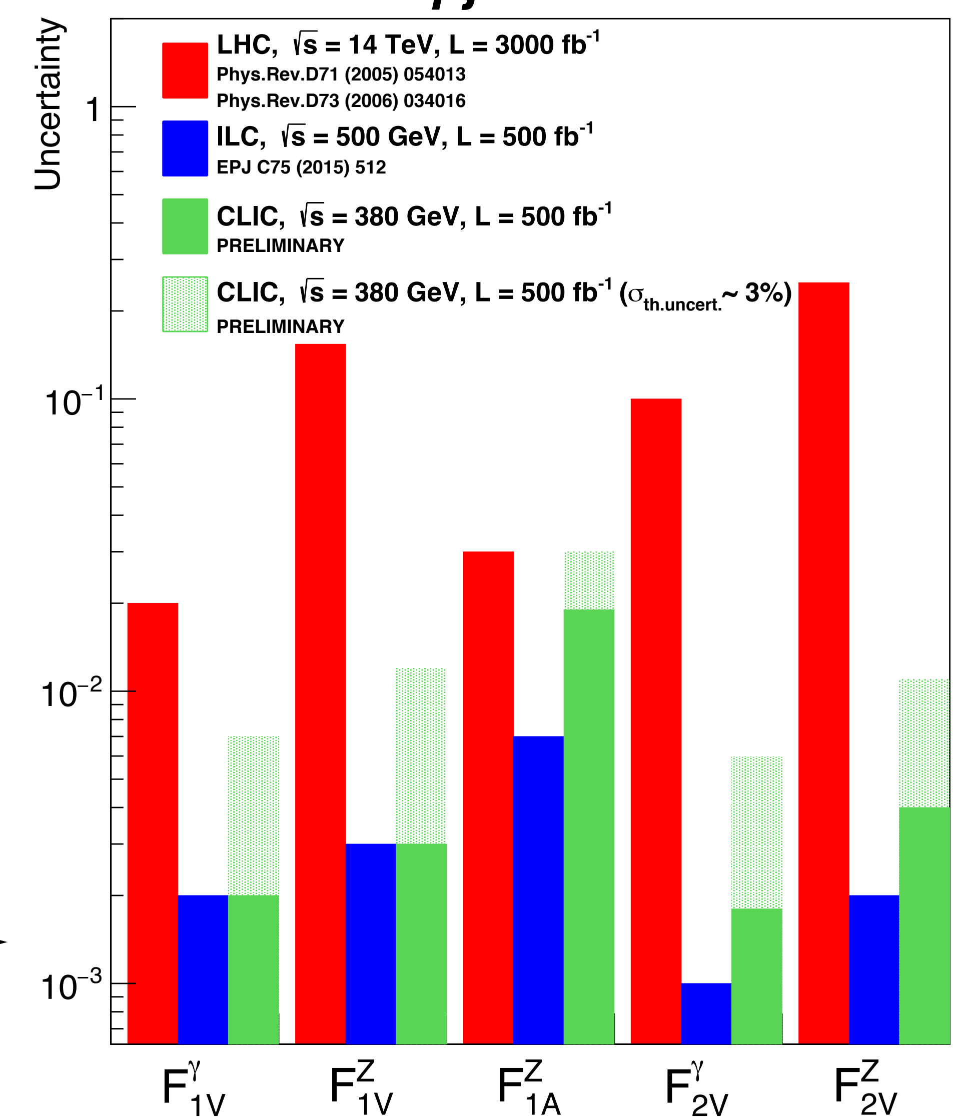


Measure 2 observables for 2 beam polarizations at ILC500 and CLIC380 (full-simulation):

$F_{1A}^{\gamma,SM} = 0$ always because of the gauge invariance

$\sigma(+)$	$A_{FB}(+)$	$(+ = e_R^-)$	$\Rightarrow$	F_{1V}^{γ} * F_{2V}^{γ}
$\sigma(-)$	$A_{FB}(-)$	$(- = e_L^-)$		F_{1V}^{Z} F_{1A}^{Z} F_{2V}^{Z}
Measure				**Extract**

Form-factors: CPV

$$\Gamma_{\mu}^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 \underline{F_{2A}^X}(k^2)\right)\right\}$$

Observables:

$$O_+^{Re} = (\hat{q}_+^* \times \hat{q}_{\bar{X}})\cdot \hat{e}_+$$

$$O_+^{Im} = -[1+(\frac{\sqrt{s}}{2m_t}-1)(\hat{q}_{\bar{X}}\cdot\hat{e}_+)^2]\hat{q}_+^*\cdot\hat{q}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{q}_{\bar{X}}\cdot\hat{e}_+\hat{q}_+^*\cdot\hat{e}_+$$

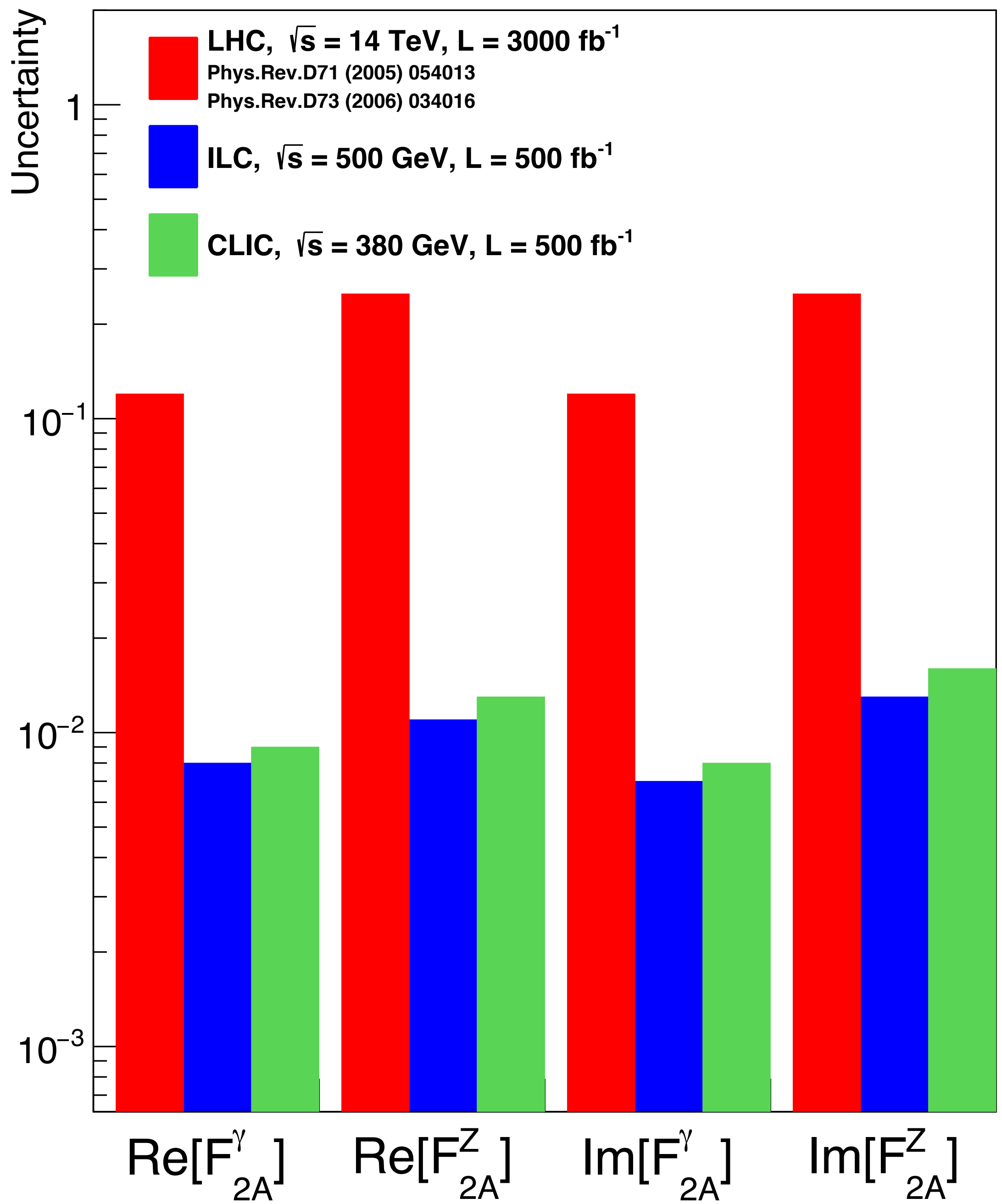
These observables have **simple relations to the four F2A form factors**:

$$A_{\gamma,Z}^{Re} = \langle O_+^{Re}\rangle - \langle O_-^{Re}\rangle = c_\gamma[PRe(F_{2A}^\gamma)+KZRe(F_{2A}^Z)]$$

$$A_{\gamma,Z}^{Im} = \langle O_+^{Im}\rangle - \langle O_-^{Im}\rangle = d_\gamma[Im(F_{2A}^\gamma)+PKZIm(F_{2A}^Z)]$$

Paper of LC potential in the CPV sector in preparation (IFIC-LAL collaboration)

Quantity	$Re[F_{2A}^\gamma]$	$Re[F_{2A}^Z]$	$Im[F_{2A}^\gamma]$	$Im[F_{2A}^Z]$
SM value at tree level	0	0	0	0
LHC	0.12	0.25	0.12	0.25
TESLA TDR	0.007	0.008	0.008	0.010
ILC@500 GeV	0.007	0.011	0.007	0.012
CLIC@380 GeV	0.009	0.013	0.008	0.016



Effective field theory

Alternative to form-factors: **describe BSM effect through effective D6 operators.**

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

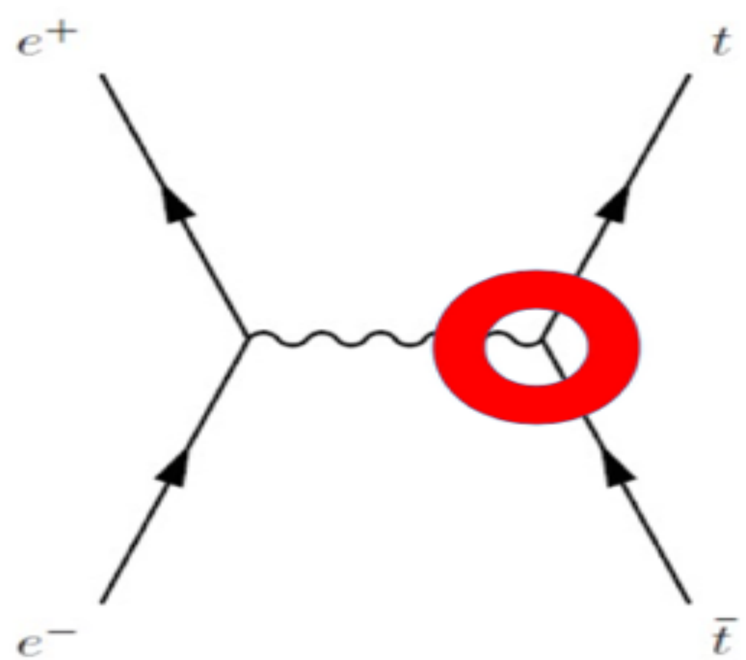
- **More fundamental representation**.
- We can **connect different physics processes with the same operators** (for instance the tt production and the top quark decay share some operators).
- These measurements can be done in the LHC too, so **we can compare LHC and LC measurements easily**.
- An effective theory allows the **study of contact interactions**.

EFT: 2-fermion operators

Alternative to form-factors: Integrate out explicit mediators and **describe BSM effect through effective D6 operators.**

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Operators acting on EW vertices (“2-fermion” operators).



ttZ/ttγ vertices

$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}\gamma^\mu q\right)$$

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{q}\gamma^\mu \tau^I q\right)$$

$$O_{tB} = y_t g_Y \left(\bar{q}\sigma^{\mu\nu} t\right)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tW} = y_t g_w \left(\bar{q}\sigma^{\mu\nu}\tau^I t\right)\tilde{\varphi} W^I_{\mu\nu}$$

tWb vertices

$$O_{bW} = y_b g_w \left(\bar{q}\sigma^{\mu\nu}\tau^I b\right)\varphi W^I_{\mu\nu}$$

$$O_{\varphi\varphi} = i\frac{1}{2}y_t y_b\left(\tilde{\varphi}^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu b\right)$$

$O_{\varphi Q}^{(3)}$ $\quad O_{tW}$

Form-factors vs. effective operators

Operators acting on ttZ, ttγ vertices (**"2-fermion" operators**) can be transformed into the form-factors scheme:

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

Transformation between effective operators and form-factors:

$$F_{1,V}^Z = \frac{1}{2}\left(C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^V\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F_{1,A}^Z = \frac{1}{2}\left(-C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^A\frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$F_{2,V}^Z = \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t^2}{\Lambda^2 s_W c_W} = C_{uZ}\frac{4m_t^2}{\Lambda^2}$$

$$F_{2,V}^\gamma = \left(C_{tW} + C_{tB}\right)\frac{2m_t^2}{\Lambda^2} = C_{uA}\frac{2m_t^2}{\Lambda^2}$$

$$F_{2,A}^Z = F_{2,A}^\gamma = 0$$

#4

We cannot access to CPV sector through effective operators in our setup by the moment.

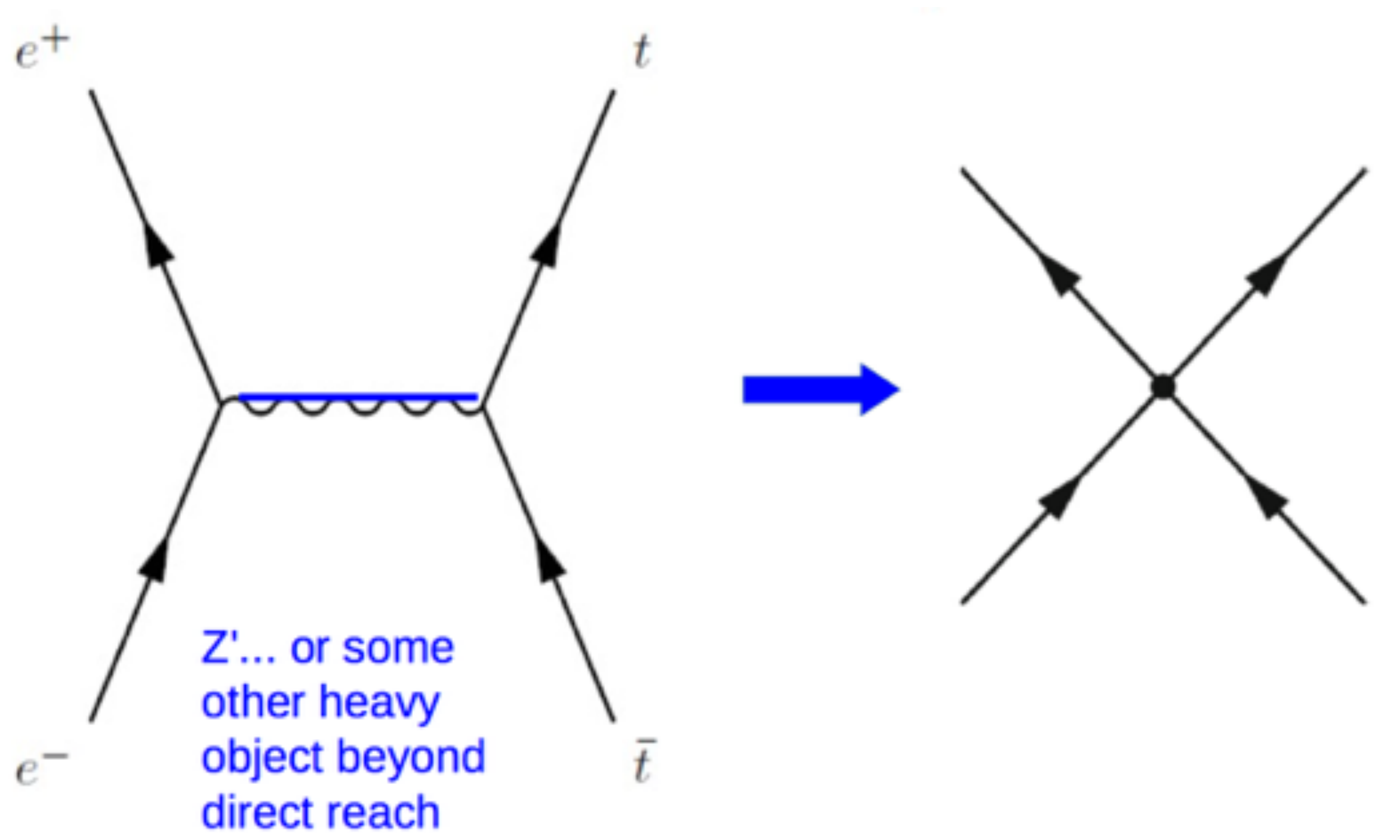
We change to a more appropriate basis (**Vector/Axial - Vector**)

EFT: 4-fermion operators

Alternative to form-factors: Integrate out explicit mediators and **describe BSM effect through effective D6 operators.**

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

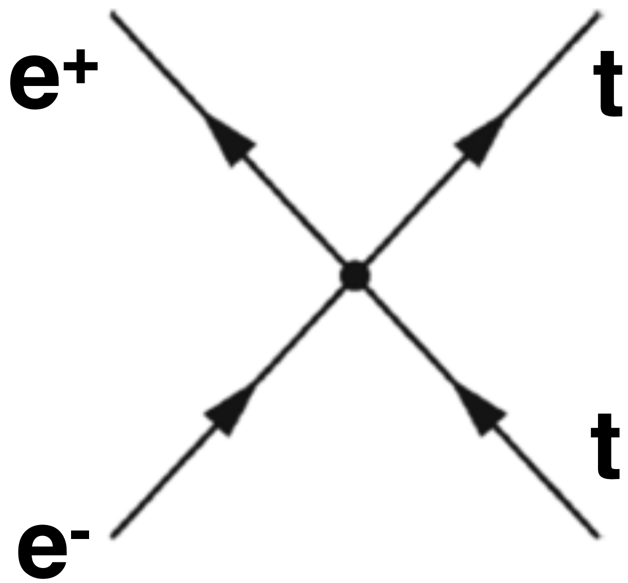
Other group of D6 effective operators collect the $e^- e^+ \to t\bar{t}$ contact interaction (**"4-fermion" operators**) :



We cannot access to the contact interaction setup through form-factors.

Form-factors vs. effective operators

Other group of D6 effective operators collect the e-e+tt contact interaction (**"4-fermion" operators**) :



$(\bar{L}L)(\bar{L}L)$	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)\,(\bar{q}\gamma^\mu q)$
	$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)\,(\bar{q}\gamma^\mu \tau^I q)$
$(\bar{R}R)(\bar{R}R)$	$\mathcal{O}_{eu}$	$(\bar{e}\gamma_\mu e)\,(\bar{u}\gamma^\mu u)$
$(\bar{R}R)(\bar{L}L)$	$\mathcal{O}_{eq}$	$(\bar{e}\gamma_\mu e)\,(\bar{q}\gamma^\mu q)$
$(\bar{L}L)(\bar{R}R)$	$\mathcal{O}_{lu}$	$(\bar{l}\gamma_\mu l)\,(\bar{u}\gamma^\mu u)$
$(\bar{L}R)(\bar{R}L)$ & $(\bar{R}L)(\bar{L}R)$	$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}e)\,\epsilon\,(\bar{q}u)$
	$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}\sigma_{\mu\nu}e)\,\epsilon\,(\bar{q}\sigma^{\mu\nu}u)$

Conversion to V/A - V basis:

$$C_{lq}^{V} \equiv C_{lu} + C_{lq}^{(1)} - C_{lq}^{(3)} \qquad C_{eq}^{V} \equiv C_{eu} + C_{eq} \qquad C_{lequ}^{(1)}$$

$$C_{lq}^{A} \equiv C_{lu} - C_{lq}^{(1)} + C_{lq}^{(3)} \qquad C_{eq}^{A} \equiv C_{eu} - C_{eq} \qquad C_{lequ}^{(3)}$$

#6

multi-TeV operation

MC simulation for effective operators parameterisation: **MG5_aMC@NLO with an EW Effective Theory model** (*courtesy of C. Zhang, G. Durieux, et al.*).

$e^- e^+ \to t\bar{t}$ **production at…**

$\sqrt{s}$ **= {380, 500, 1000, 1400, 3000} GeV**

■ **CLIC**

■ **ILC**

	380 GeV	500 GeV	1 TeV	1.4 TeV	3 TeV
Pol (e-, e+)	(-0.8, 0)	(-0.8, +0.3)	(-0.8, +0.2)	(-0.8, 0)	(-0.8, 0)
	(+0.8, 0)	(+0.8, -0.3)	(+0.8, -0.2)	(+0.8, 0)	(+0.8, 0)
Cross-section (pb)	0,792	0,930	0,256	0,113	0,025
Lumi (fb-1)	500	500	1000	1500	3000

Parameterisation of different observables through effective operators…

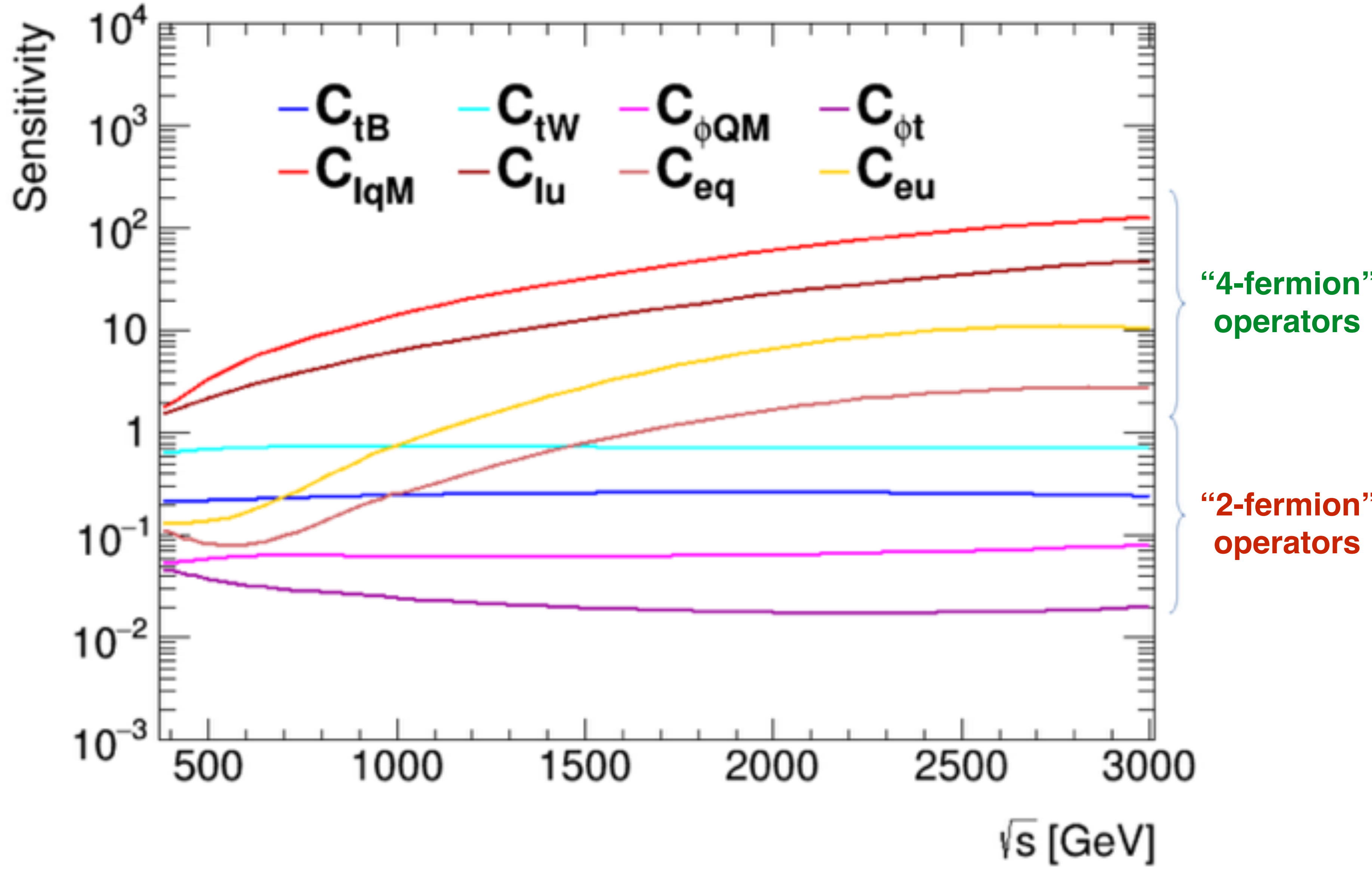
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

Cross-section sensitivity

$O_{lq}M = O_{lq}(1) - O_{lq}(3)$ ***$O_{\phi Q}M = O_{\phi Q}(1) - O_{\phi Q}(3)$***

Sensitivity:
Relative change in cross-section due to non-zero operator coefficient
$\Delta\sigma\,(C)\,/\,\sigma\,/\,\Delta C$

"2-fermion" operators have a better bound by lower energy data (lower statistical uncertainty).

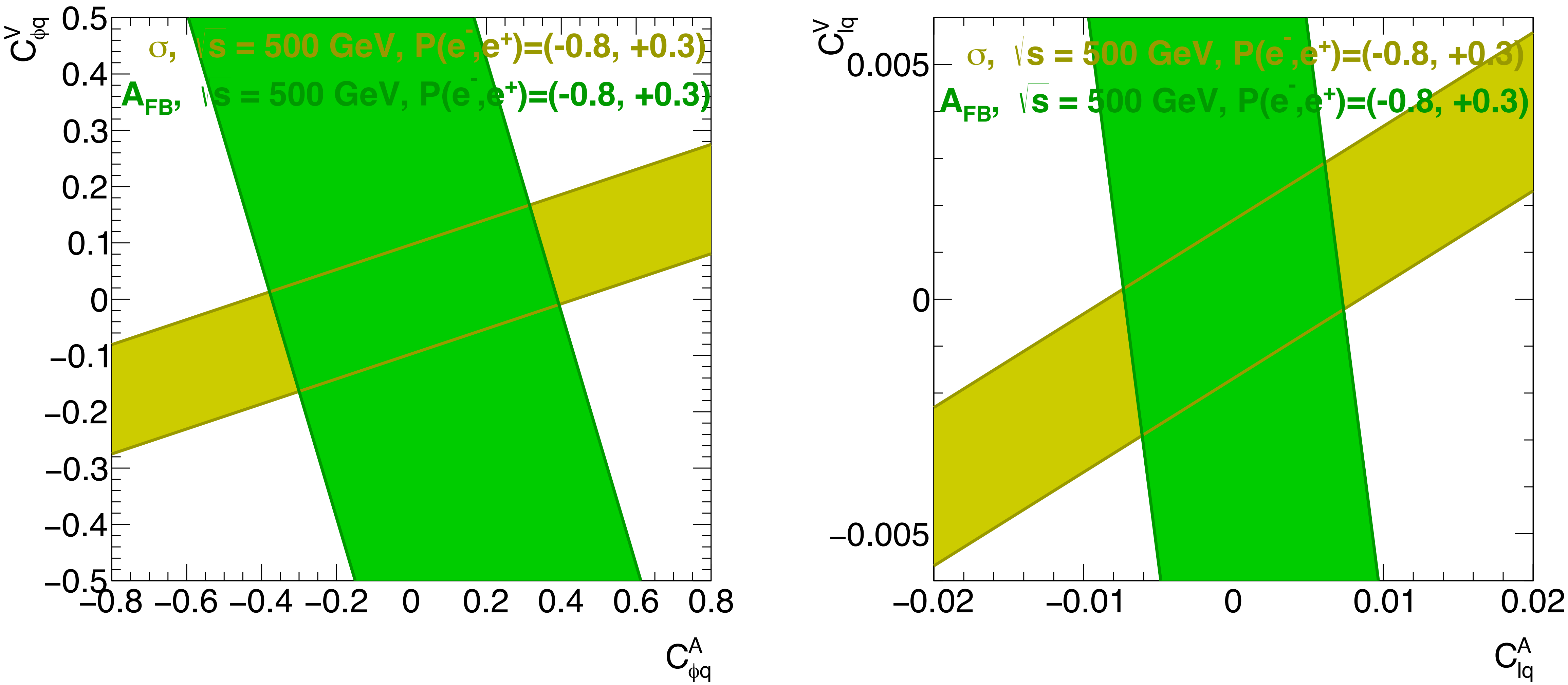


(multi-) TeV operation provides better sensitivity to four-fermion operators

Cross-section vs Asymmetry

Objective: find different observables which provide an ideal complementarity between operators.

Axial and vector operators can be disentangled by using the cross-section and the forward-backward asymmetry in the fit.

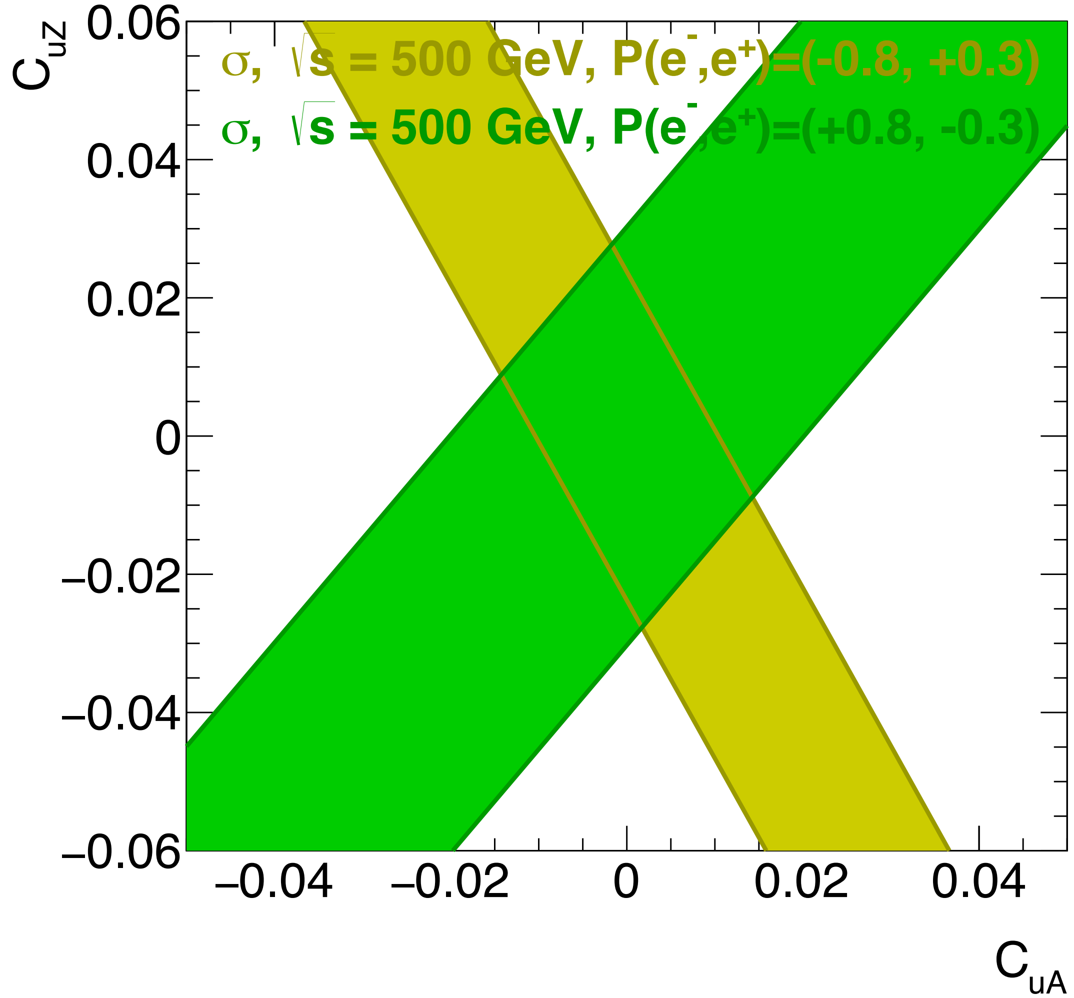


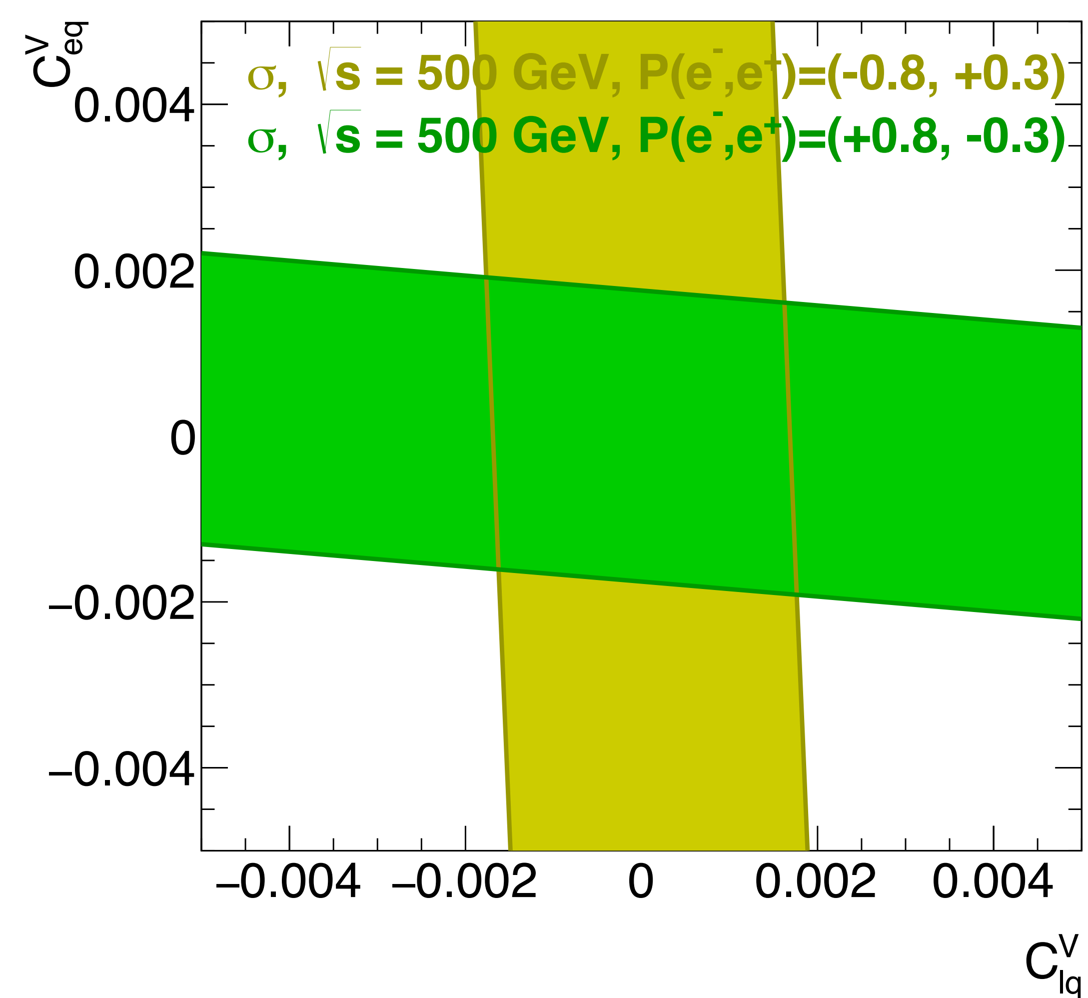
68%CL χ^2 bands: 1 measurement → 1 band in C1-C2 space.

The power of polarisation

Objective: find different observables which provide an ideal complementarity between operators.

Only with one observable, the initial state polarisation provides complementary constraints.





68%CL χ^2 bands: 1 measurement → 1 band in C1-C2 space.

Global Fit

$$\chi^2 = \sum_i \left(\frac{O_i^{meas} - O_i[C]}{\delta O_i^{meas}} \right)^2 \qquad O_i[C] = O_{SM} + \frac{1}{\Lambda^2} \sum_j a_{i,j} C_j + \frac{1}{\Lambda^4} \sum_{k,l} b_{i,k,l} C_k C_l$$

Temporary assumption:

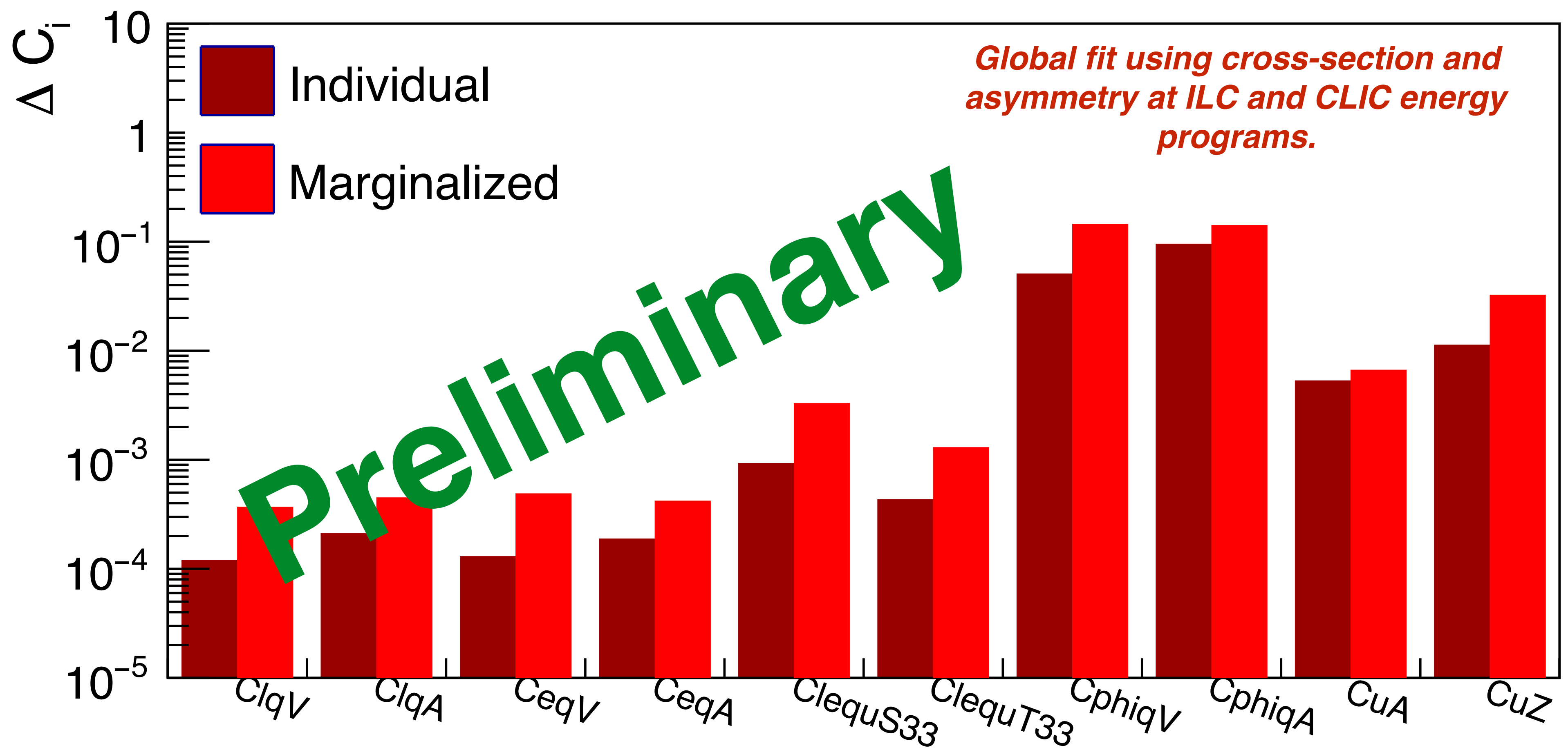
$$O_i^{meas} = O_{SM}$$

$$\chi^2 = \sum_i \left(\frac{\frac{1}{\Lambda^2} \sum_j a_{i,j} C_j + \frac{1}{\Lambda^4} \sum_{k,l} b_{i,k,l} C_k C_l}{\delta O_i^{meas}} \right)^2$$

We find consistency with form-factors results (arXiv:1505.06020)

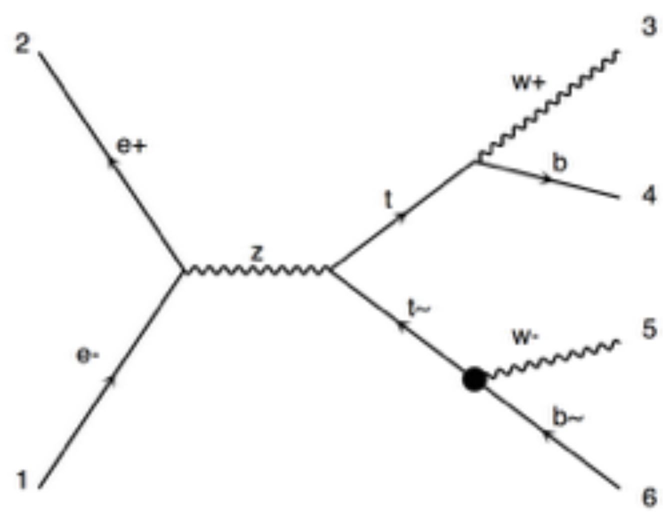
Individual: assuming variation in only 1 parameter each time.

Marginalized: assuming variation in all the parameters at the same time.

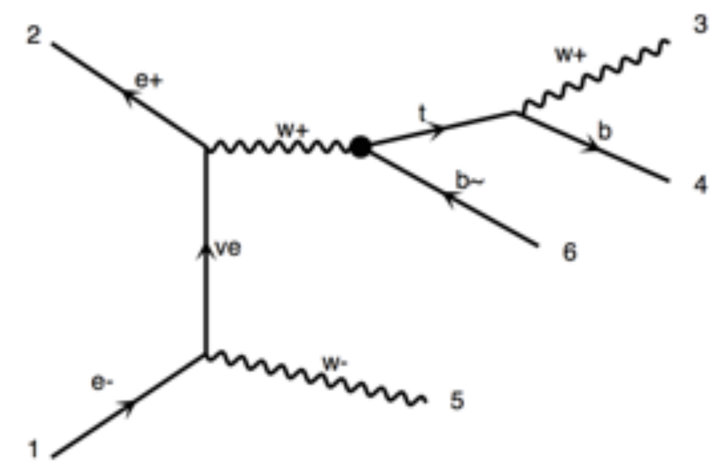


WbWb study at 300 GeV

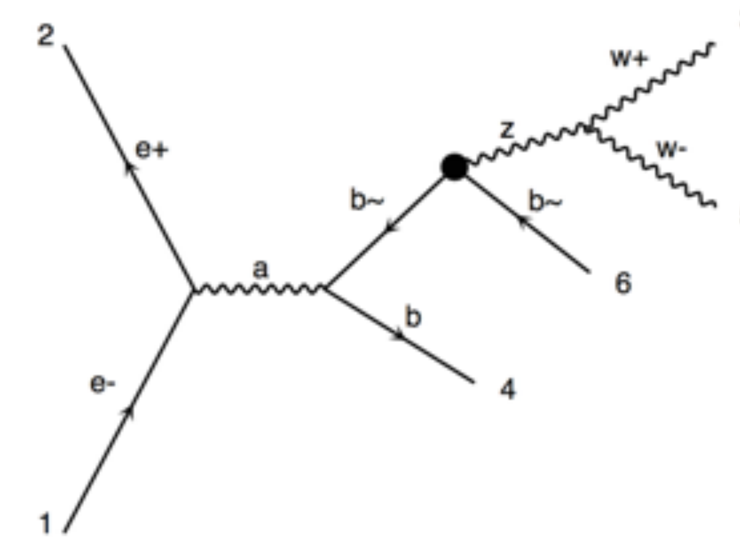
ttbar production



single top production



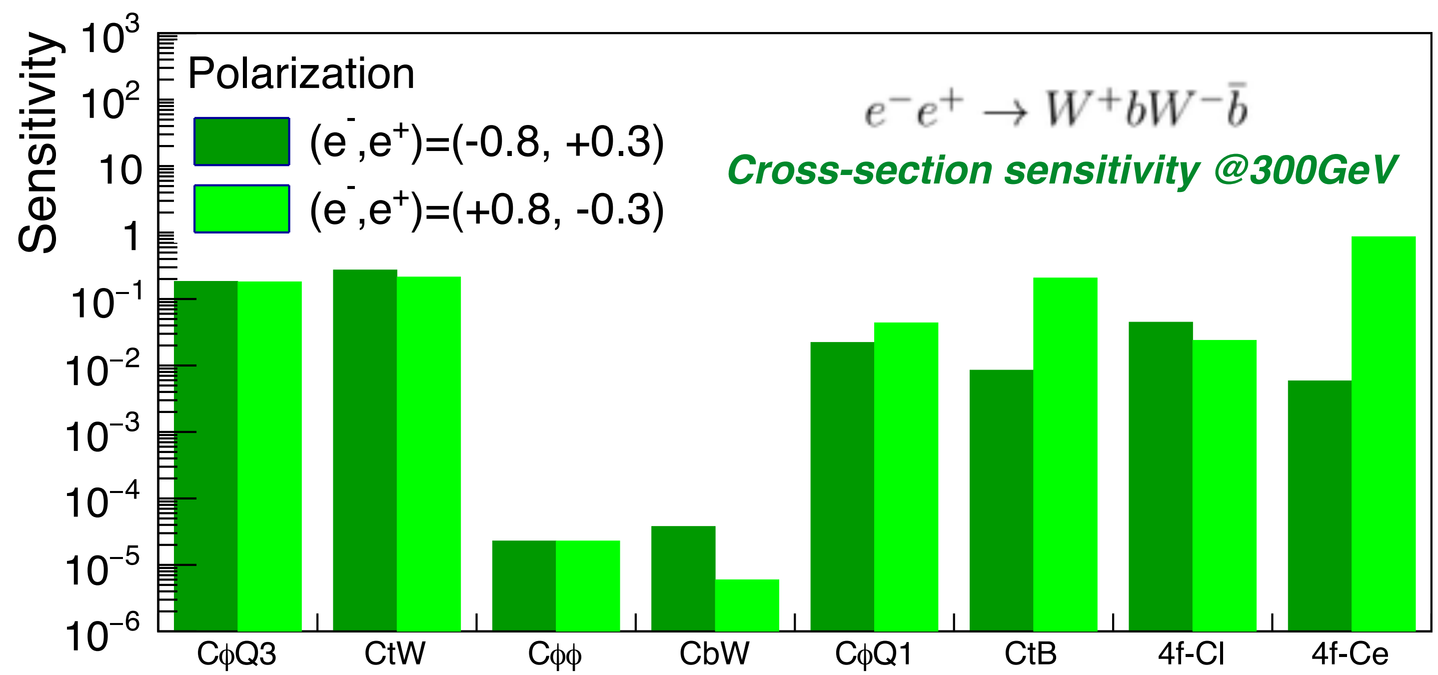
non-top production



WbWb production allows the **study of the Wtb vertex**. This can be **useful for disentangling $C_{\phi Q}(1)$ and $C_{\phi Q}(3)$**.

We choose a point below threshold for trying to avoid tt production.

Cross-section at 250 GeV is to low, and operator sensitivities are not enough higher. **At 300 GeV, sensitivities and cross-section grow.**



Difficulty in isolating Wtb contributions.

Different operators *contribute due to the* ***tt off-shell production.***

Conclusion

- We have two alternatives for the study of top quark couplings: form-factors and effective operators. From the latter we can distinguish between "2-fermion" operators (comparable with form-factors) and "4-fermion" operators (contact interactions).
- Observables parameterisation in terms of the effective operators allow us the extraction of the operators coefficients. Complementarity between different observables at different energies allow us to decrease operators correlations providing a better χ^2 fit.
- First results show low uncertainties in the operators coefficients and a consistency between both schemes.

Status of form-factors scheme

Assume production is dominated by SM and NP scale is beyond direct reach.

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu \left(\underline{F_{1V}^X}(k^2) + \gamma_5 \underline{F_{1A}^X}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(i\underline{F_{2V}^X}(k^2) + \gamma_5 \underline{F_{2A}^X}(k^2)\right)\right\}$$

$F_{1A}^{\gamma,SM} = 0$ always because of the gauge invariance

$$\begin{matrix} \sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-) \end{matrix} \qquad \left.\begin{matrix}(+ = e^-_R) \\ (- = e^-_L)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z \end{matrix}\right\}$$

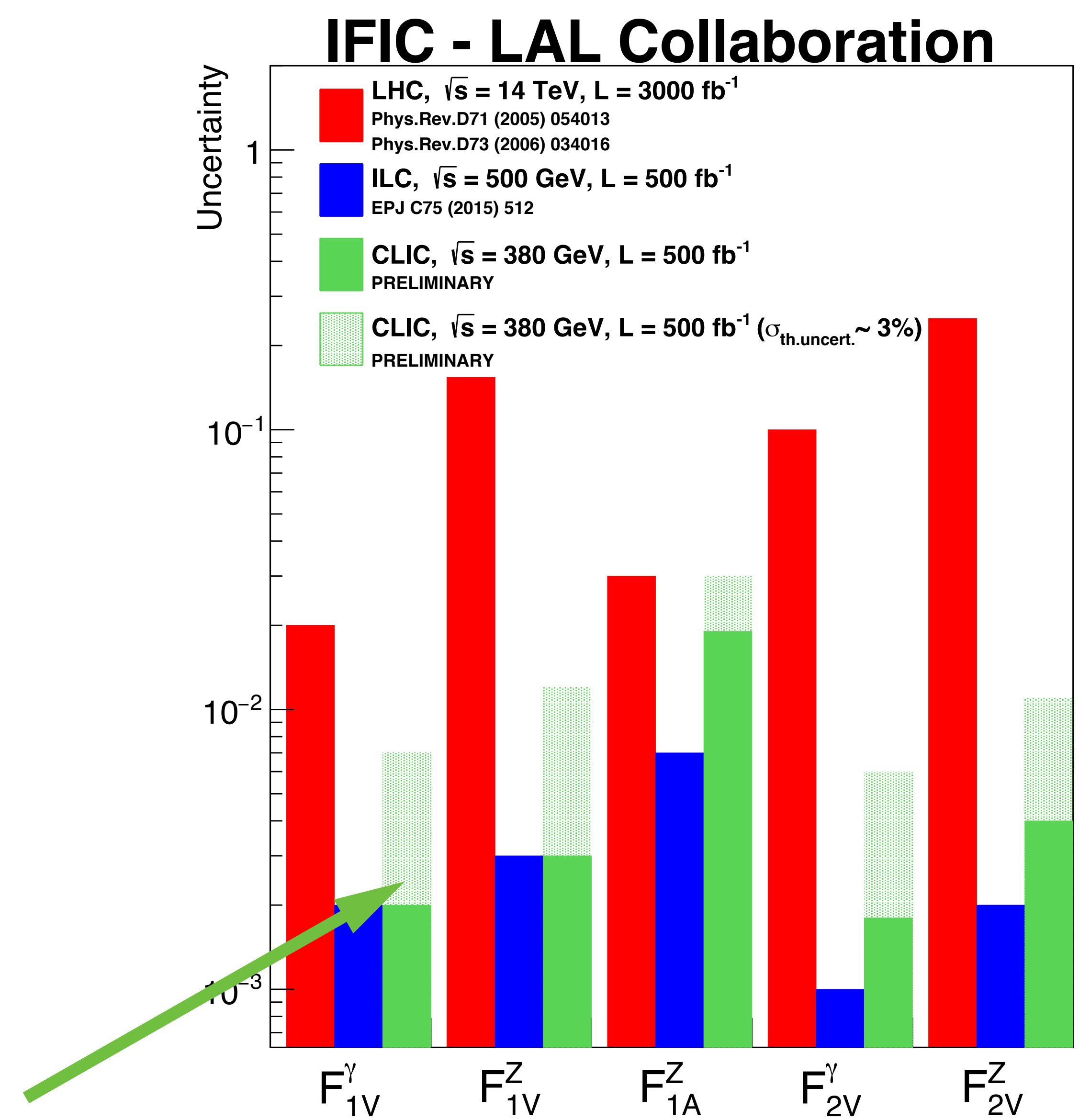
Measure **Extract**

ILC@500GeV L=500fb^{-1}

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A_{FB}^t/A_{FB}^t)_{\text{stat.}}$ (%)
−0.8, +0.3	0.47	1.8
+0.8, −0.3	0.63	1.3

CLIC@380GeV L=500fb^{-1}

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A_{FB}^t/A_{FB}^t)_{\text{stat.}}$ (%)
−0.8, 0	0.47	3.8
+0.8, 0	0.83	4.6



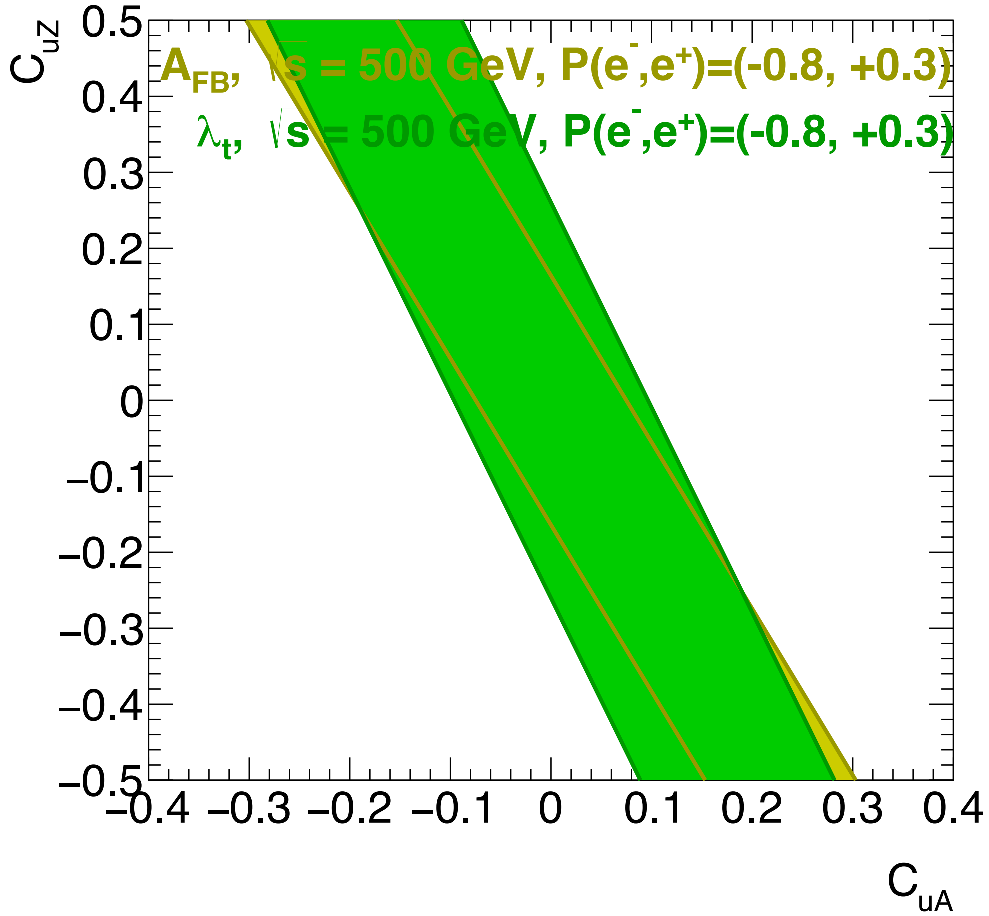
Conservative scenario for CLIC: NNNL calculations
at threshold predict a **3% theory uncertainty**

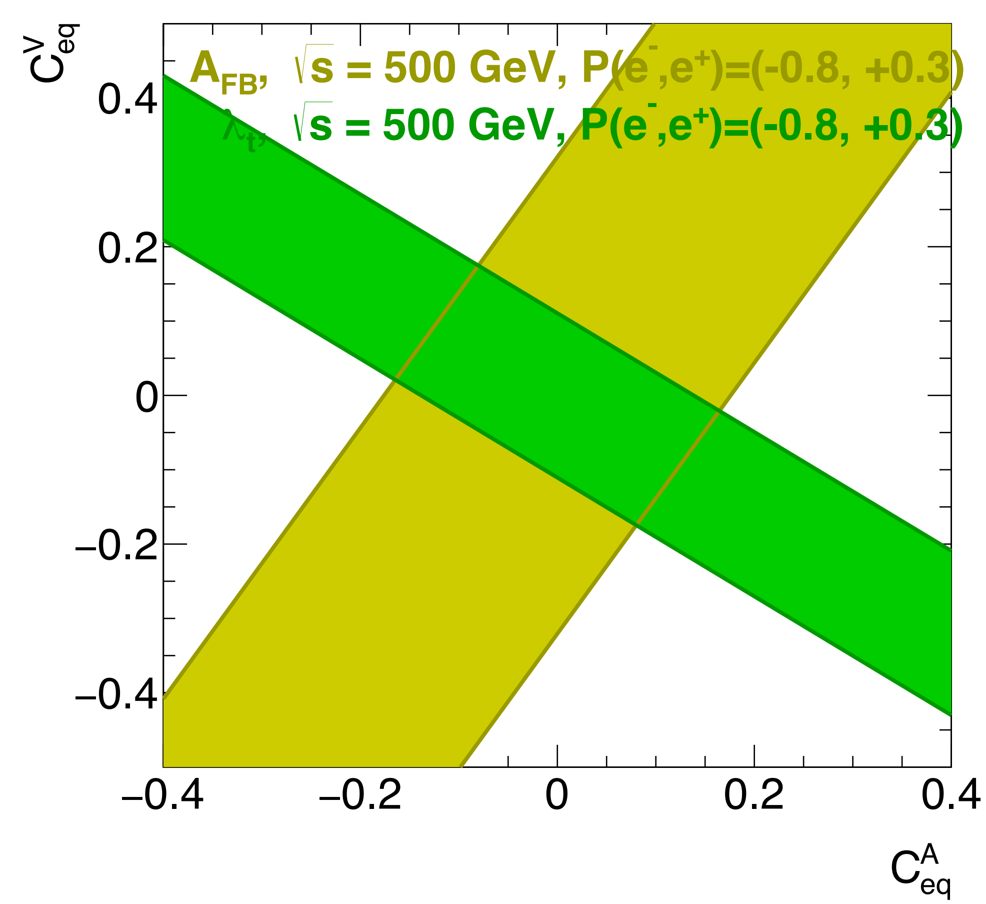
Helicity angle

In the rest system of the t quark, the angle of the lepton from the W boson follows:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1+\lambda_t\cos\theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1)\,\frac{\cos\theta_{hel}}{2}$$

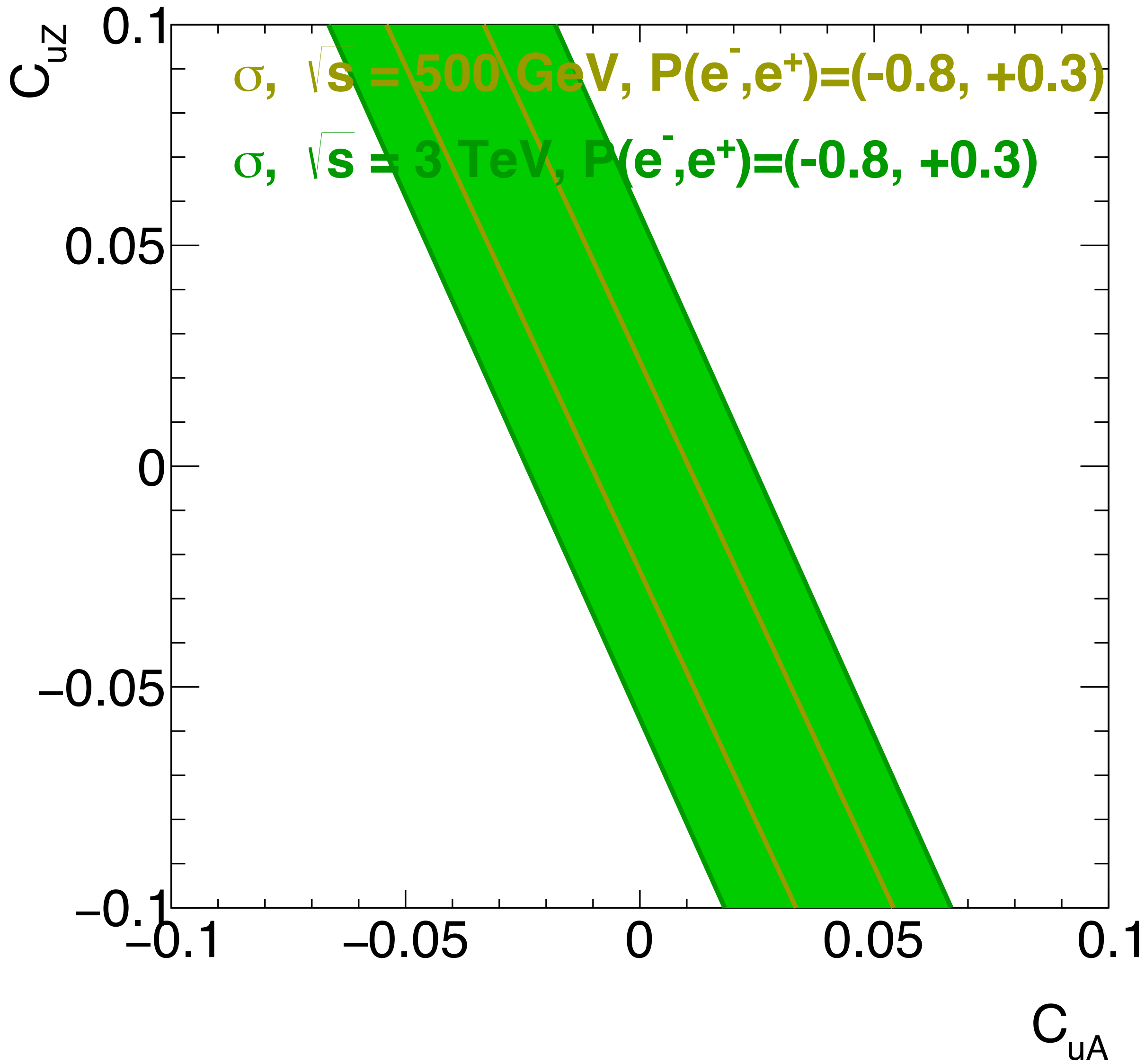
We study the possibility of including the **slope of the distribution of the helicity angle, λt** as a **third observable**.

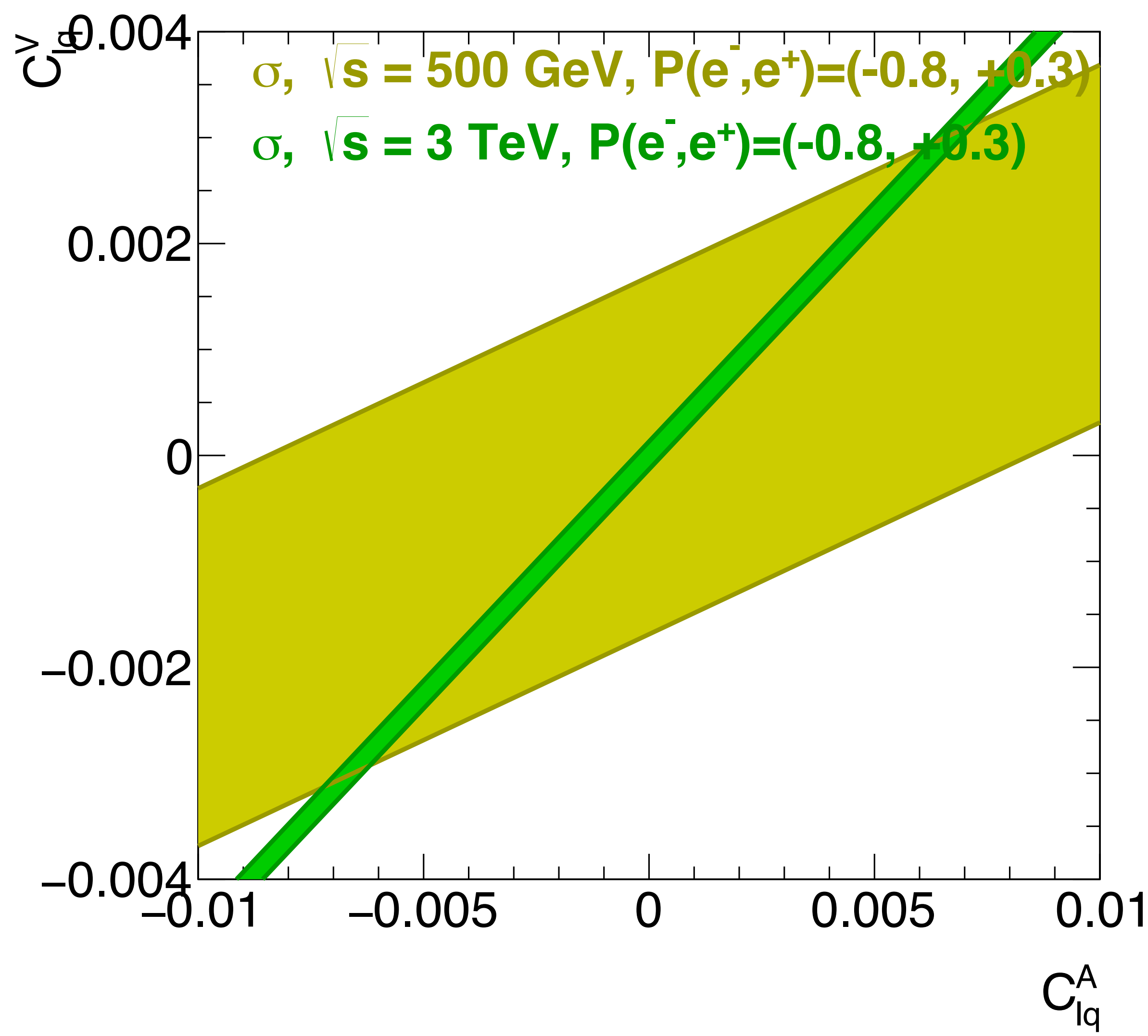




Good complementarity with Afb in the 4-fermion sector.

Energy complementarity





68%CL χ^2 bands: 1 measurement → 1 band in C1-C2 space.

Contribution of $1/\Lambda^4$ terms

$$\mathcal{O}_i \propto |\mathcal{M}|^2 \propto \left[|\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} \left(\mathcal{M}_{SM} \times \mathcal{M}_O^{dim6} \right) + \frac{1}{\Lambda^4} |\mathcal{M}_O^{dim6}|^2 + \mathcal{O}\left(\Lambda^{-4}\right) + \ldots \right]$$

Parameters extraction without Clequs operators using cross-section and forward-backward asymmetry at 5 center-of-mass energy and 2 initial state polarisations.

Preliminary

	Only Λ^2	$\Lambda^2 + \Lambda^4$ (diagonal)	$\Lambda^2 + \Lambda^4$ (diagonal + off-diagonal)
ClqV	0,00068	0,00039	0,00037
ClqA	0,00057	0,00046	0,00045
CeqV	0,00083	0,00051	0,00049
CeqA	0,00062	0,00044	0,00042
CphiqV	0,53	0,14	0,13
CphiqA	0,16	0,15	0,15
CuA	0,0073	0,0069	0,0068
CuZ	0,14	0,04	0,03

WbWb study below threshold

From 250 GeV to 300 GeV there is a difference in cross-section of approximately an order of magnitude.

Assuming an ingrate luminosity of 250fb-1 in both points we find 25 events at 250 against 500 events at 300 GeV.