Top electroweak couplings using an EFT

M. Perelló Roselló

Acknowledging input/contributions from:

M. Boronat, E. Fullana, J. Fuster, I. Garcia, P. Gomis, V. Miralles, E. Ros, M. Vos (IFIC - U. Valencia/CSIC)

G. Durieux (DESY), C. Zhang (BNL), R. Pöschl, F. Richard (LAL, Orsay)

R. Ström, P. Roloff (CERN), W. Bernreuther, L. Chen (TTK, Aachen)

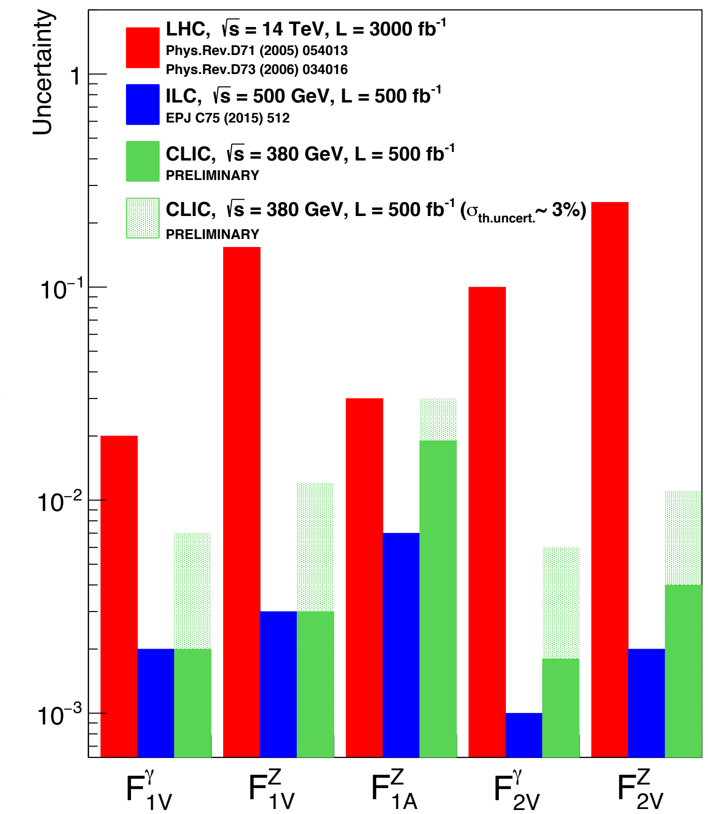
J. A. Aguilar (University of Granada)

Outline

- Introduction: top quark couplings
- Multi-TeV operation, full-simulation
- Global fit
- CPV observables
- Further observables

Top quark couplings

Objective: to study the potential of a global fit in the top EW sector.



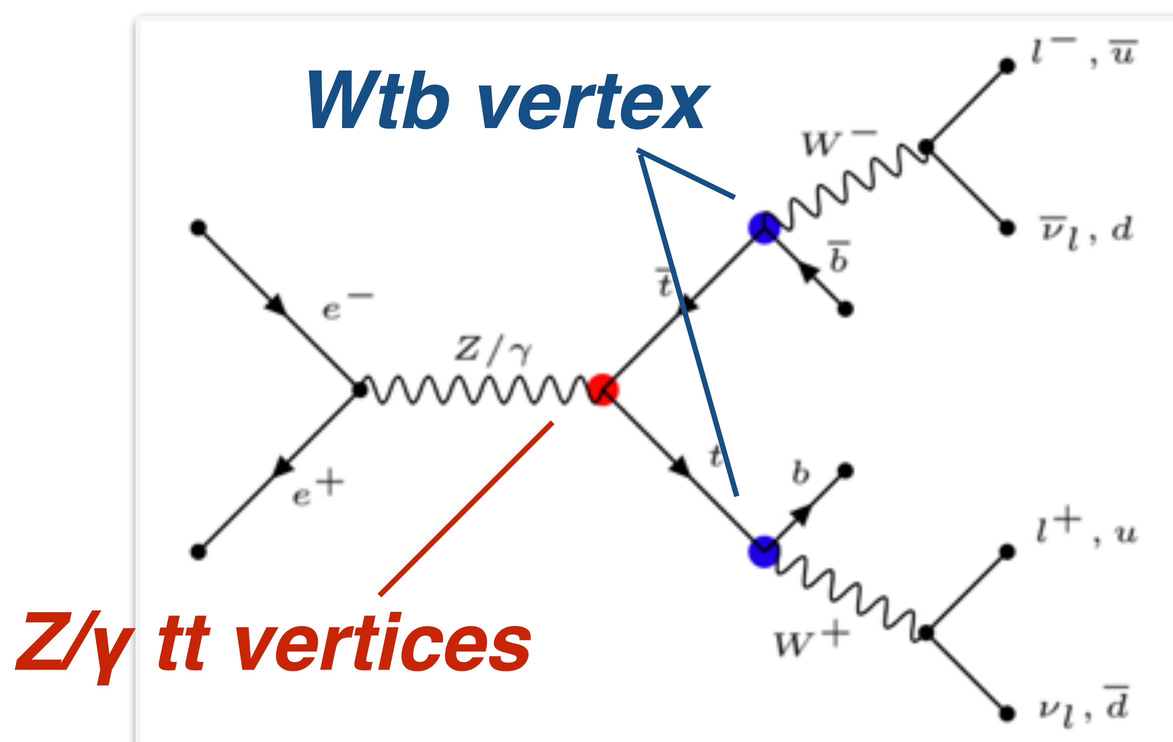
Form-factors

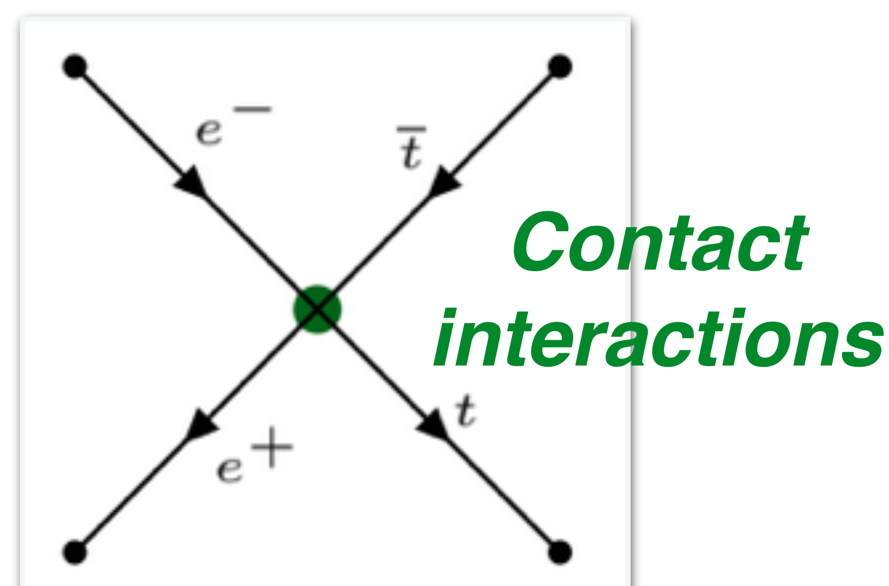
$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X(k^2)}+\gamma_5\underline{F_{1A}^X(k^2)}\right)-\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X(k^2)}+\gamma_5\underline{F_{2A}^X(k^2)}\right)\right\}$$

CP Conserving **CPV**

Effective Field Theory

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

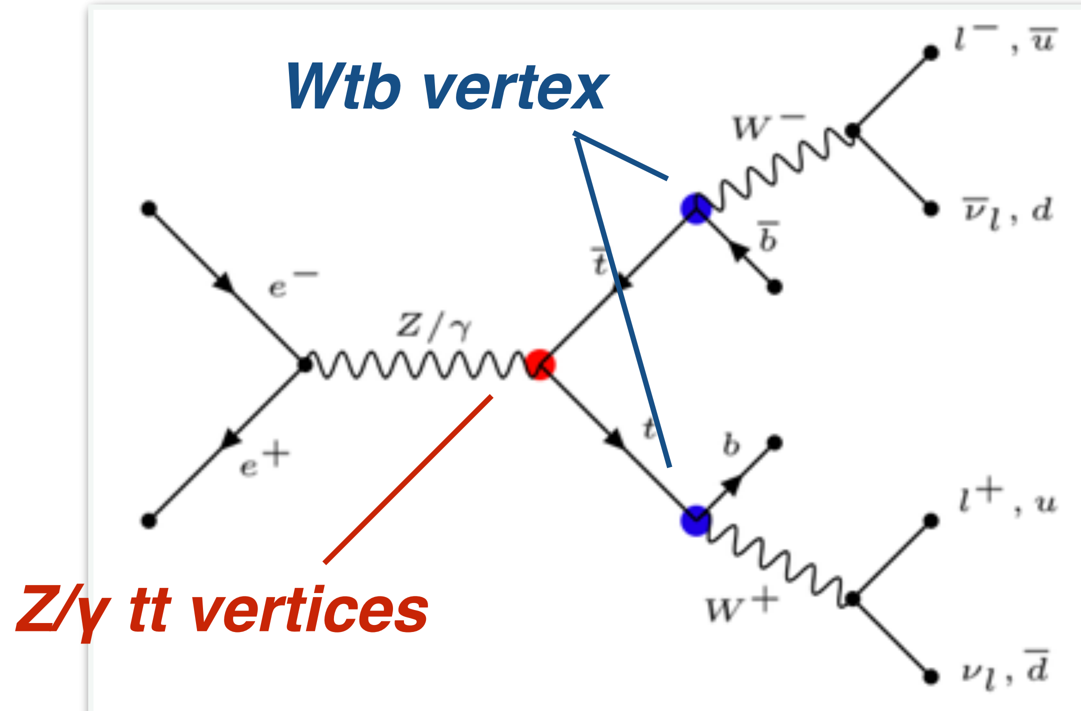




Dim-6 operators

$$
\begin{aligned}
O^1_{\varphi q} &\equiv \frac{y_t^2}{2} \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \\
O^3_{\varphi q} &\equiv \frac{y_t^2}{2} \quad \bar{q}\tau^I\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \\
O_{\varphi u} &\equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \\
O_{\varphi ud} &\equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T \epsilon\, iD_\mu \varphi
\end{aligned}
$$

$$
\begin{aligned}
O_{uG} &\equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu} u \quad \epsilon\varphi^* G^A_{\mu\nu} \\
O_{uW} &\equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu} u \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{dW} &\equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu} d \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{uB} &\equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu} u \quad \epsilon\varphi^* B_{\mu\nu}
\end{aligned}
$$

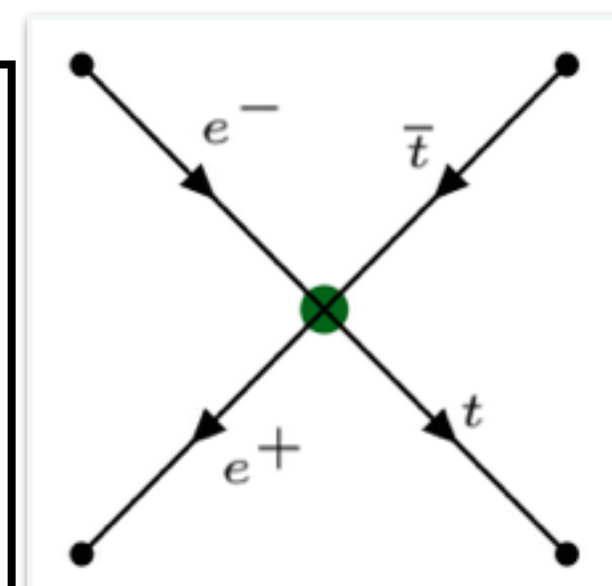


Contact interactions

$$
\begin{aligned}
O^1_{lq} &\equiv \bar{q}\gamma_\mu q \quad \bar{l}\gamma^\mu l \\
O^3_{lq} &\equiv \bar{q}\tau^I\gamma_\mu q \quad \bar{l}\tau^I\gamma^\mu l \\
O_{lu} &\equiv \bar{u}\gamma_\mu u \quad \bar{l}\gamma^\mu l \\
O_{eq} &\equiv \bar{q}\gamma_\mu q \quad \bar{e}\gamma^\mu e \\
O_{eu} &\equiv \bar{u}\gamma_\mu u \quad \bar{e}\gamma^\mu e
\end{aligned}
$$

$$O^T_{lequ} \equiv \bar{q}\sigma^{\mu\nu} u \;\epsilon\; \bar{l}\sigma_{\mu\nu} e$$

$$
\begin{aligned}
O^S_{lequ} &\equiv \bar{q}u \;\epsilon\; \bar{l}e \\
O_{ledq} &\equiv \bar{d}q \quad \bar{l}e
\end{aligned}
$$



Change of basis

Transformation between effective operators and form-factors:

$$
\begin{aligned}
F_{1,V}^{Z} - F_{1,V}^{Z,SM} &= \frac{1}{2}\left(\underline{C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C_{\varphi q}^{V}}\frac{m_t^2}{\Lambda^2 s_W c_W}\\
F_{1,A}^{Z} - F_{1,A}^{Z,SM} &= \frac{1}{2}\left(\underline{-C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t}}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}\underline{C_{\varphi q}^{A}}\frac{m_t^2}{\Lambda^2 s_W c_W}\\
F_{2,V}^{Z} &= \left(\underline{\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2}\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{\underline{C_{uZ}}\}\frac{4m_t^2}{\Lambda^2}\\
F_{2,V}^{\gamma} &= \left(\underline{\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{\underline{C_{uA}}\}\frac{4m_t^2}{\Lambda^2}\\
[F_{2,A}^{Z}, F_{2,A}^{\gamma}] &\propto [\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}]
\end{aligned}
$$

We can change to an alternative basis (**Vector/Axial - Vector**)

Conversion to V/A - V basis in contact interactions:

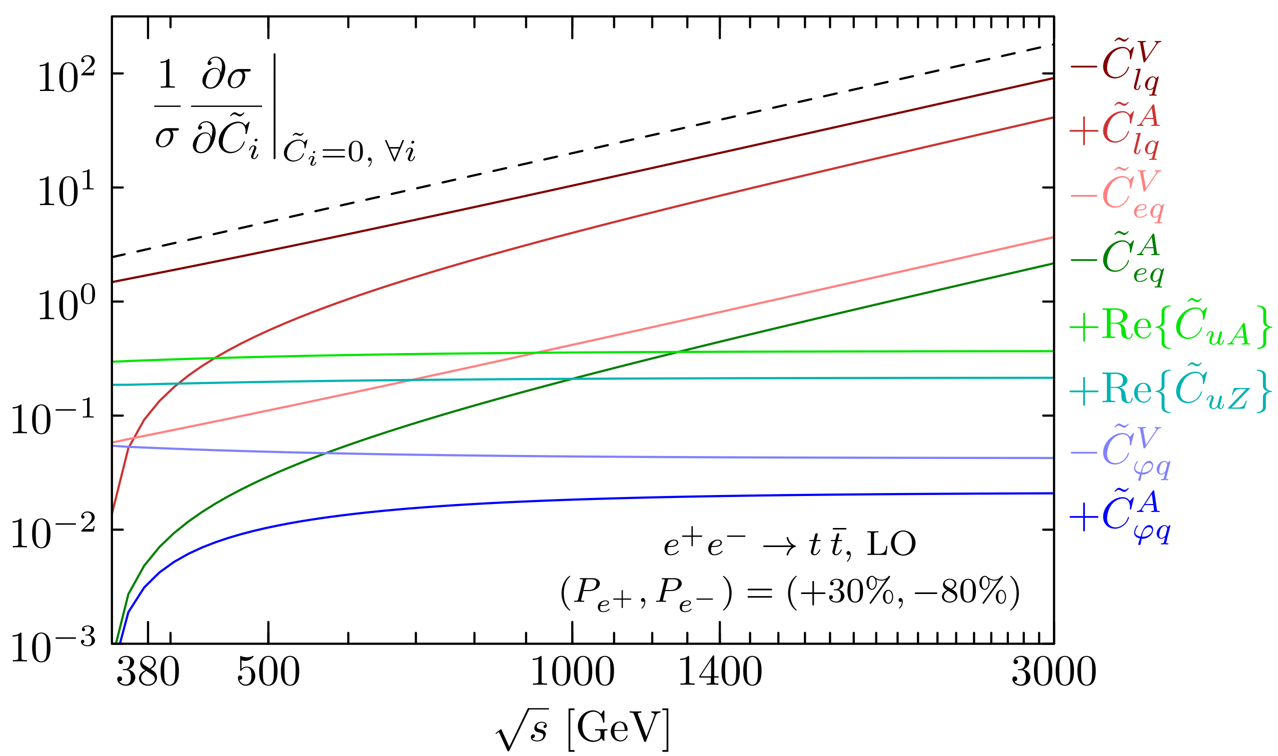
$$
\begin{aligned}
C_{lq}^{V} &\equiv C_{lu} + C_{lq}^{(1)} - C_{lq}^{(3)} & \qquad C_{eq}^{V} &\equiv C_{eu} + C_{eq}\\
C_{lq}^{A} &\equiv C_{lu} - C_{lq}^{(1)} + C_{lq}^{(3)} & \qquad C_{eq}^{A} &\equiv C_{eu} - C_{eq}
\end{aligned}
$$

Observables sensitivity

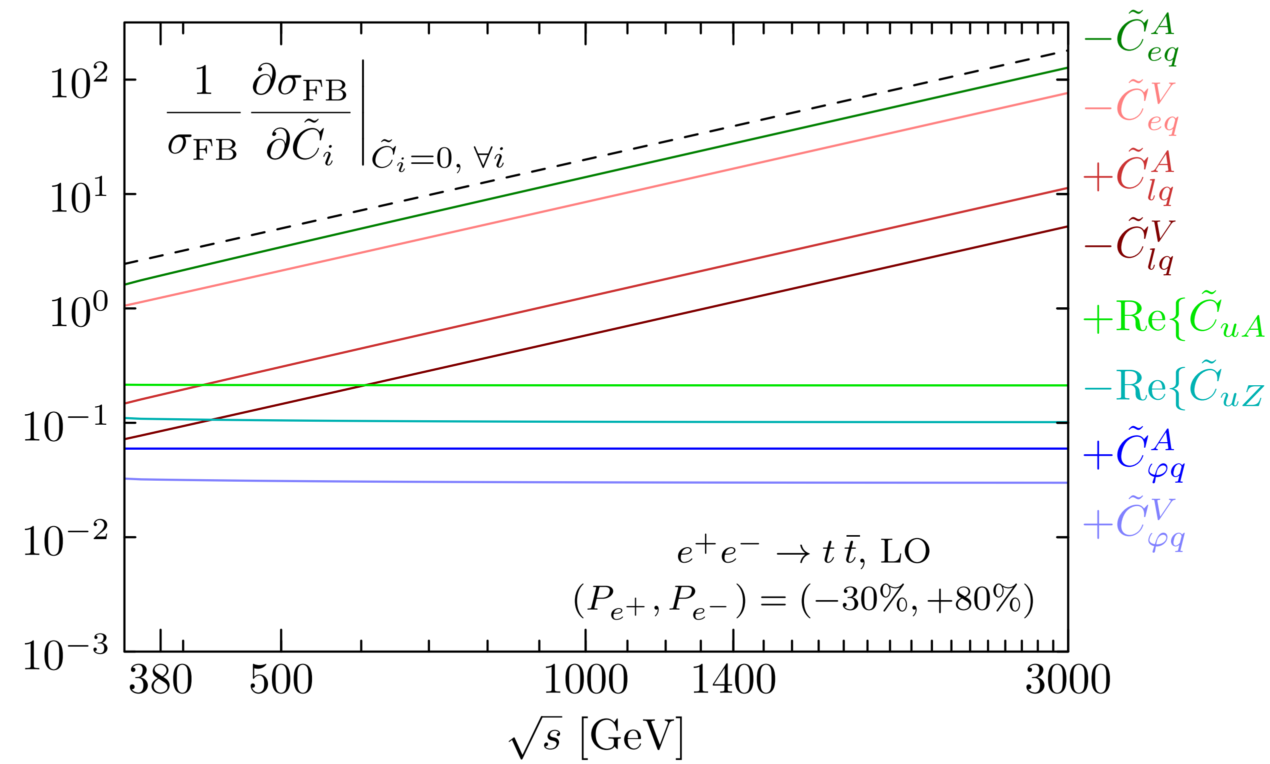
$e^+e^- \to t\,\bar{t}$, LO

Durieux, Perelló, Vos, Zhang, to be published

Cross-section



Forward-backward asymmetry



Sensitivity:
Relative change in cross-section due to non-zero operator coefficient
Δσ (C) / σ / ΔC

(multi-) TeV operation provides better sensitivity to contact-interaction operators.

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…**

■ **CLIC**

■ **ILC**

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

	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)
σ[L,R] (fb)	792	930	256	113	25
σ[R,L] (fb)	418	480	142	66	15
Lumi (fb-1)	500	500	1000	1500	3000

Parameterisation of different observables through effective operators…

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

Full-simulation

Studies included in I. Garcia thesis

ILC@500GeV L=500fb^{-1} **[arXiv:1505.06020]**

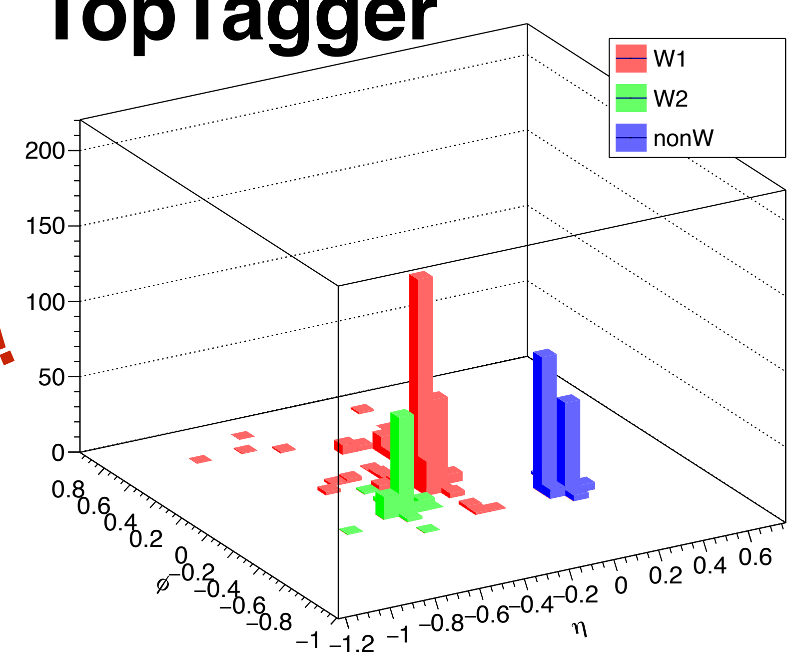
$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

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

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

At higher energies…

TopTagger



See R. Ström's yesterday talk!!

CLIC@1.4TeV L=1500fb-1

Results	P(e-) = -80%	P(e-) = +80%
ΔA^t_{FB}	0.011	0.015
$\frac{\Delta A^t_{FB}}{A^t_{FB}}$	0.025	0.028

For signal only, w/o scaling or bkg. subtraction

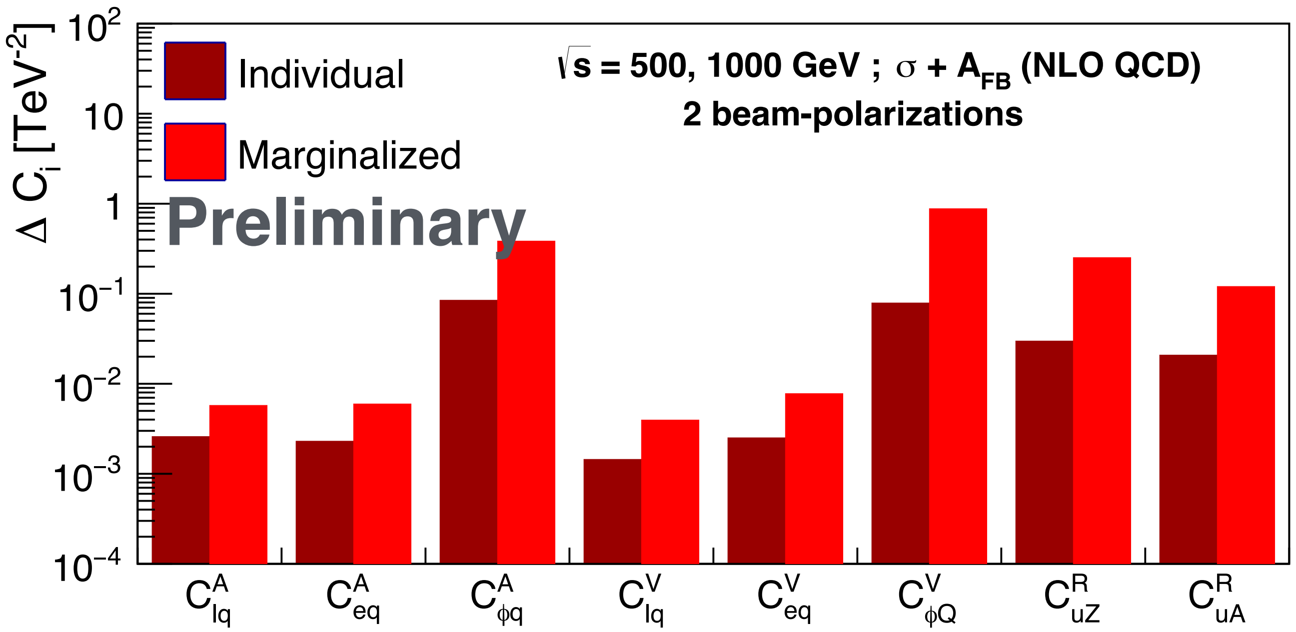
Thanks to Rickard

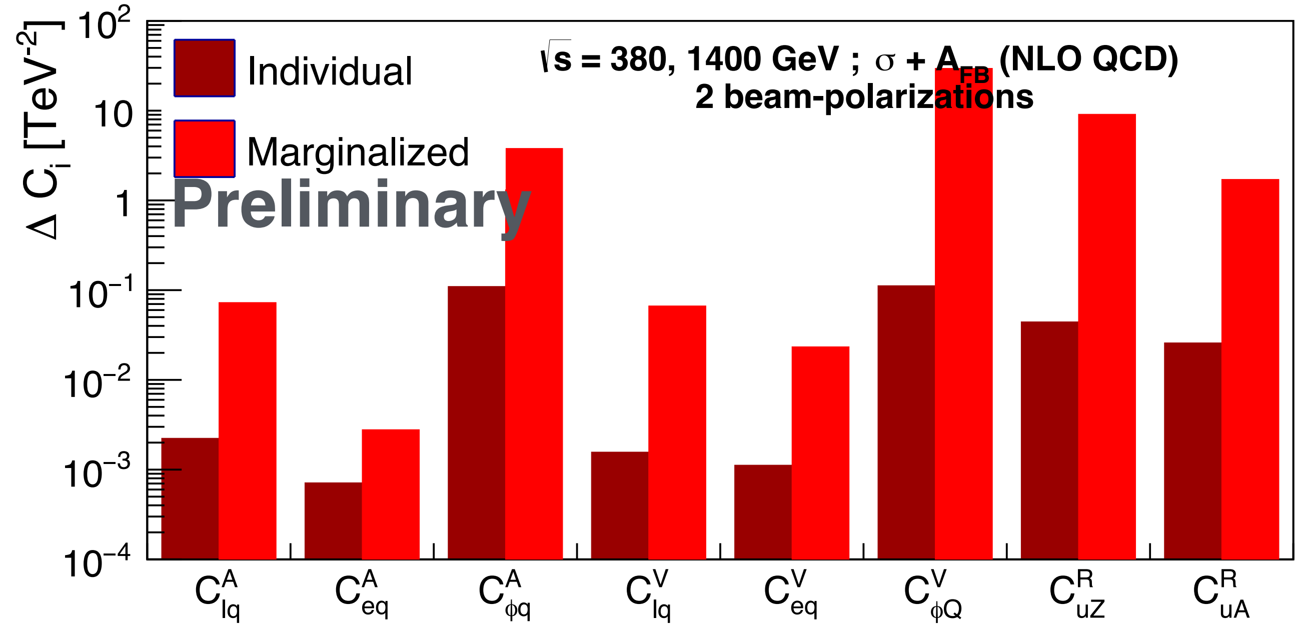
Fast-simulation (luminosity scaling) for **ILC@1TeV** and **CLIC@3TeV**

Global Fit: Afb + σ

Studied process $e^-e^+ \to W^+bW^-\bar{b}$ @NLO **[Motivation from arXiv:1411.2355]**

ILC: **500 GeV + 1 TeV** CLIC: **380 GeV + 1.4 TeV + (3) TeV**





Individual: assuming variation in only 1 parameter each time.
Marginalized: assuming variation in all the parameters at the same time.

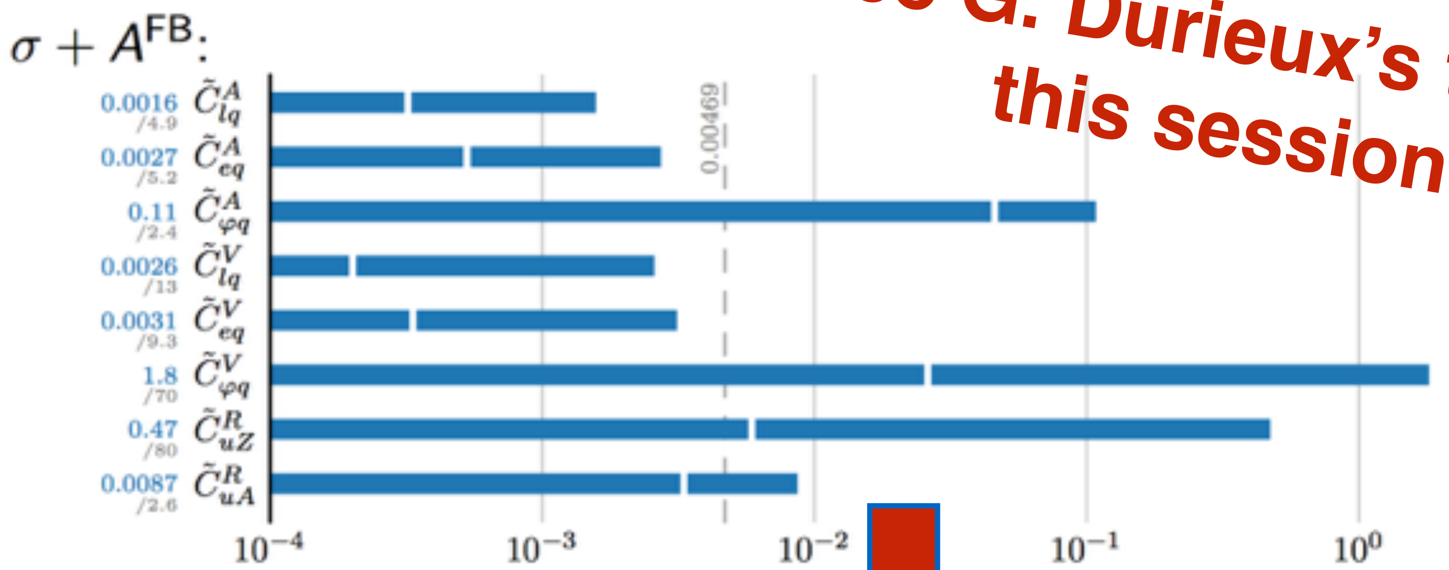
Similar behaviour at $e^-e^+ \to t\bar{t}$ @LO and $e^-e^+ \to W^+bW^-\bar{b}$ @NLO (QCD)

Low uncertainties are achieved, but we can do it better

We should improve the marginalized fit

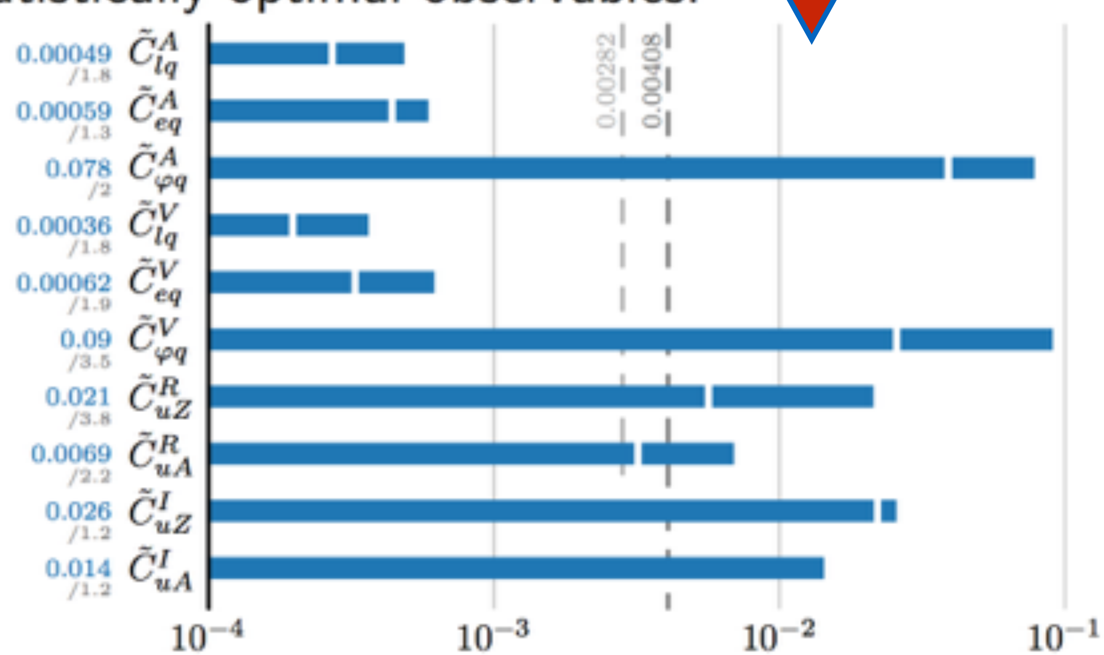
Optimal observables

See G. Durieux's talk in this session



How can we proceed?

Statistically optimal observables:



1) **Find extra observables** with a friendly reconstruction and try to meet in a middle point (and with a competitive fit).

2) **Try to reconstruct that optimal observables** (could be very challenging, maybe doable)

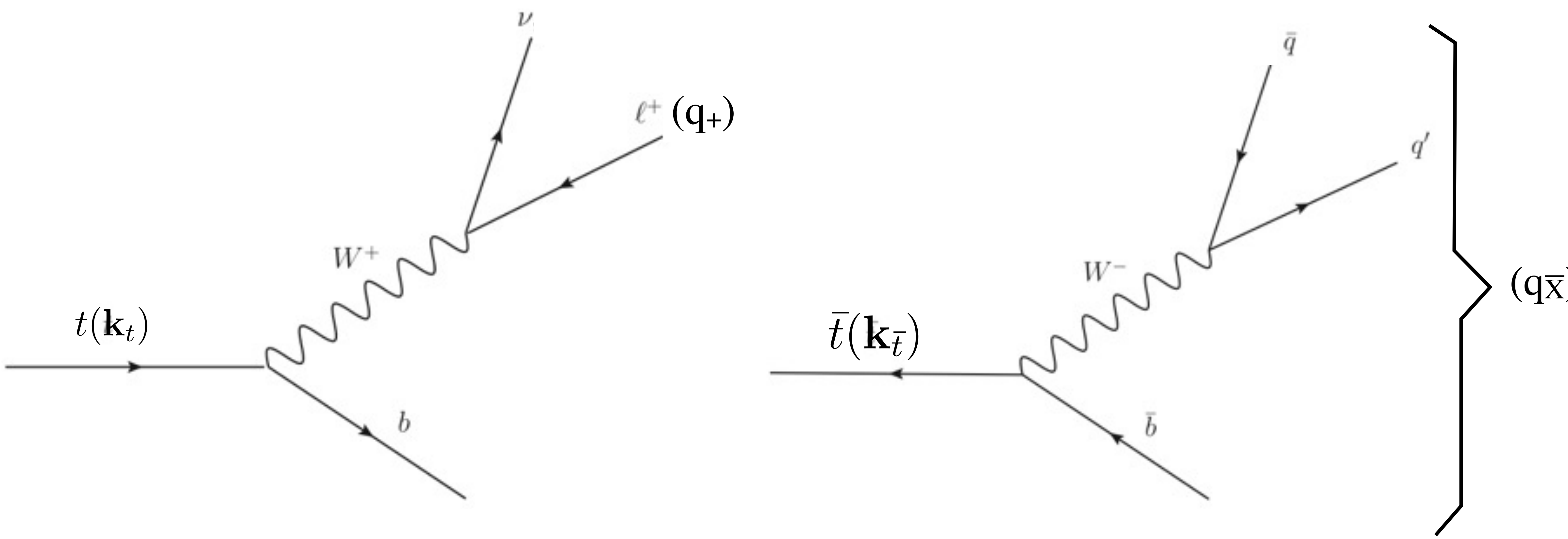
Optimal CP-odd observables

$$e^+(\mathbf{p}_+, P_{e^+}) + e^-(\mathbf{p}_-, P_{e^-}) \quad \to \quad t(\mathbf{k}_t) + \bar{t}(\mathbf{k}_{\bar{t}})$$

The **CP-violating effects** in $e^+e^- \to t\bar{t}$ manifest themselves in specific **top-spin effects**, namely **CP-odd top spin-momentum correlations and $t\bar{t}$ spin correlations**.

$$t\ \bar{t} \quad \to \quad \ell^+(\mathbf{q}_+) + \nu_\ell + b + \overline{X}_{\text{had}}(\mathbf{q}_{\bar{X}})$$

$$t\ \bar{t} \quad \to \quad X_{\text{had}}(\mathbf{q}_X) + \ell^-(\mathbf{q}_-) + \bar{\nu}_\ell + \bar{b}$$



Lepton+jets final state
The **charged lepton** is the **best analyzer** of the **top spin**

Optimal CP-odd observables

- **CP-odd observables** are defined with the **four momenta available in tt semi-leptonic decay channel**

$$\mathcal{O}_{+}^{Re} = (\hat{\mathbf{q}}_{\bar{X}} \times \hat{\mathbf{q}}_{+}^{*}) \cdot \hat{\mathbf{p}}_{+} ,$$
$$\mathcal{O}_{+}^{Im} = -[1 + (\frac{\sqrt{s}}{2m_t} - 1)(\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_{+})^2]\hat{\mathbf{q}}_{+}^{*} \cdot \hat{\mathbf{q}}_{\bar{X}} + \frac{\sqrt{s}}{2m_t}\hat{\mathbf{q}}_{\bar{X}} \cdot \hat{\mathbf{p}}_{+}\hat{\mathbf{q}}_{+}^{*} \cdot \hat{\mathbf{p}}_{+}$$

- The way to **extract** the **CP-violating form factor** is to construct **asymmetries sensitive to CP-violation effects**

$$\mathcal{A}^{Re} = \langle \mathcal{O}_{+}^{Re} \rangle - \langle \mathcal{O}_{-}^{Re} \rangle = \boxed{c_\gamma(s)}\mathrm{Re}F_{2A}^{\gamma} + \boxed{c_Z(s)}\mathrm{Re}F_{2A}^{Z}$$

$$\mathcal{A}^{Im} = \langle \mathcal{O}_{+}^{Im} \rangle - \langle \mathcal{O}_{-}^{Im} \rangle = \boxed{\tilde{c}_\gamma(s)}\mathrm{Im}F_{2A}^{\gamma} + \boxed{\tilde{c}_Z(s)}\mathrm{Im}F_{2A}^{Z}$$

$$\boxed{\begin{array}{cc} {\mathcal{A}_{\gamma,Z}^{Re}}^{\mathrm{L}} & {\mathcal{A}_{\gamma,Z}^{Re}}^{\mathrm{L}} \\ {\mathcal{A}_{\gamma,Z}^{Im}}^{\mathrm{R}} & {\mathcal{A}_{\gamma,Z}^{Im}}^{\mathrm{R}} \end{array}}$$

Coefficients vs sqrt(s)

The sensitivity of A_{Re}/A_{Im} to F_{2A} increases strongly with the c.o.m. energy

$$P_{e^-} = -1 \ , \ P_{e^+} = +1$$

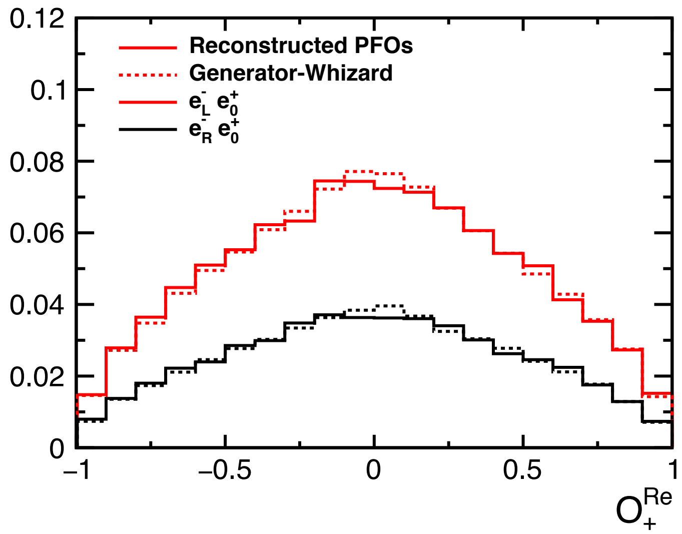
c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	0.245	0.173	0.232	0.164
500	0.607	0.418	0.512	0.352
1000	1.714	1.151	1.464	0.983
1400	2.514	1.681	2.528	1.691
3000	5.589	3.725	10.190	6.791

$$P_{e^-} = +1, \ P_{e^+} = -1$$

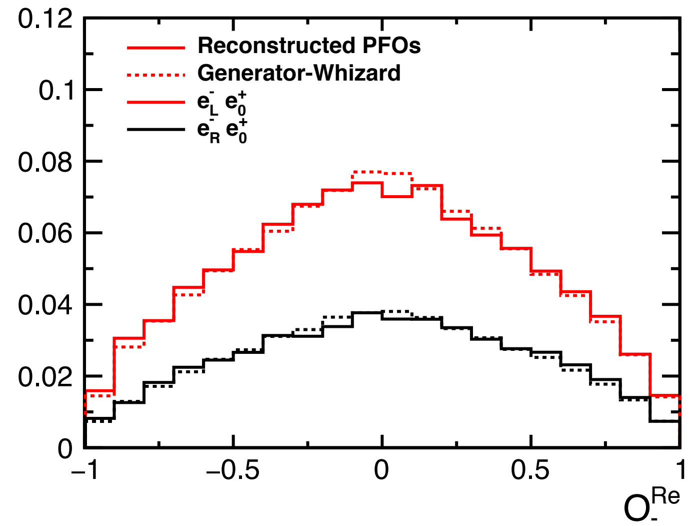
c.m. energy $\sqrt{s}$ [GeV]	$c_\gamma(s)$	$c_Z(s)$	$\tilde{c}_\gamma(s)$	$\tilde{c}_Z(s)$
380	-0.381	0.217	0.362	-0.206
500	-0.903	0.500	0.761	-0.422
1000	-2.437	1.316	2.081	-1.124
1400	-3.549	1.909	3.569	-1.920
3000	-7.845	4.205	14.302	-7.667

Thanks to Bernreuther

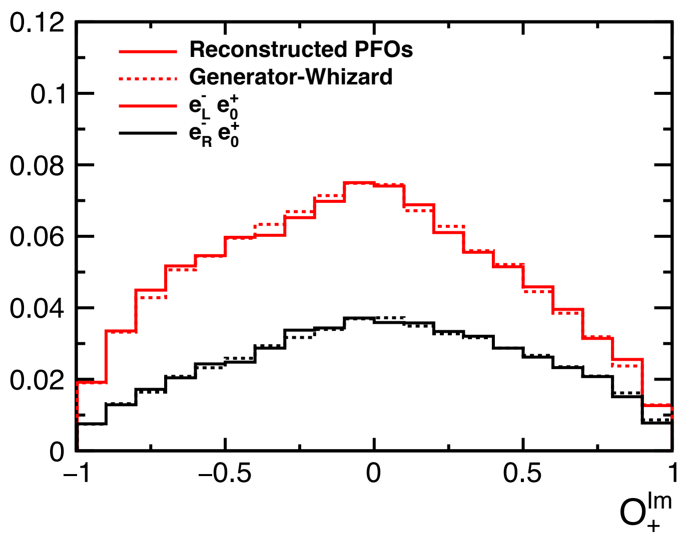
Full-simulation: CLIC@380GeV



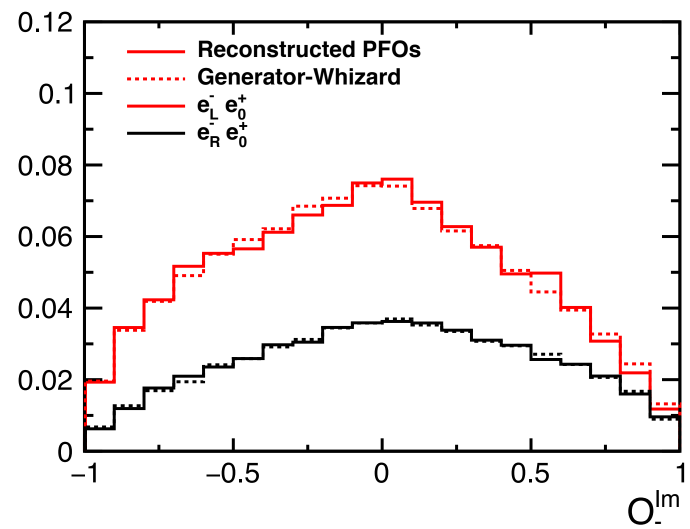
(a) $\mathcal{O}^{Re}_+$



(b) $\mathcal{O}^{Re}_-$



(c) $\mathcal{O}^{Im}_+$



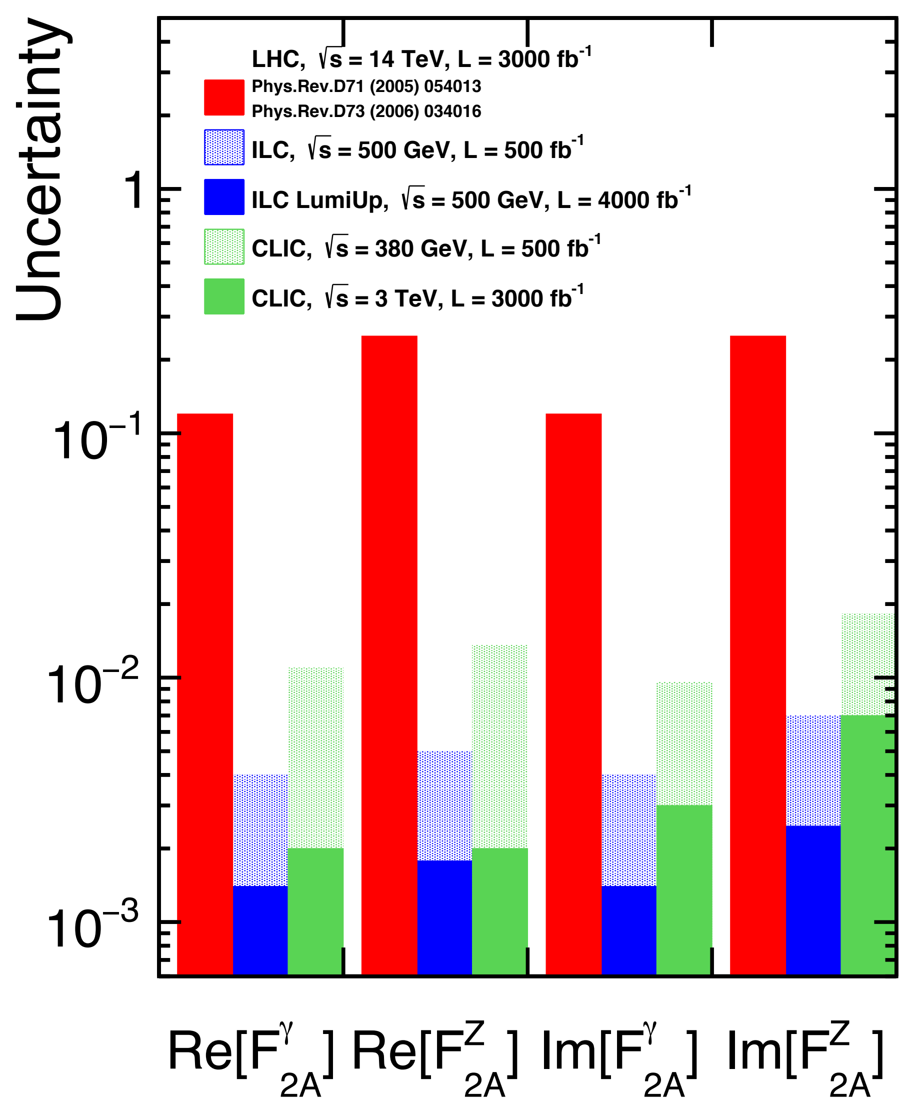
(d) $\mathcal{O}^{Im}_-$

polarization	e^-_L $(P_{e^-} = -0.8)$	e^-_R $(P_{e^-} = +0.8)$
$\mathcal{A}^{Re}$	-0.00006 $\pm$ 0.003	0.0072 $\pm$ 0.003
$\mathcal{A}^{Im}$	0.0004 $\pm$ 0.003	-0.0019 $\pm$ 0.003

- Distributions are **centered at zero**
- **Differences** between reconstructed and generated events are **very small**.
- Any **distortions** in the reconstructed distributions are **expected to cancel in the asymmetries** A_{Re} and A_{Im}
- **Asymmetries** are **compatible with zero** within the statistical error

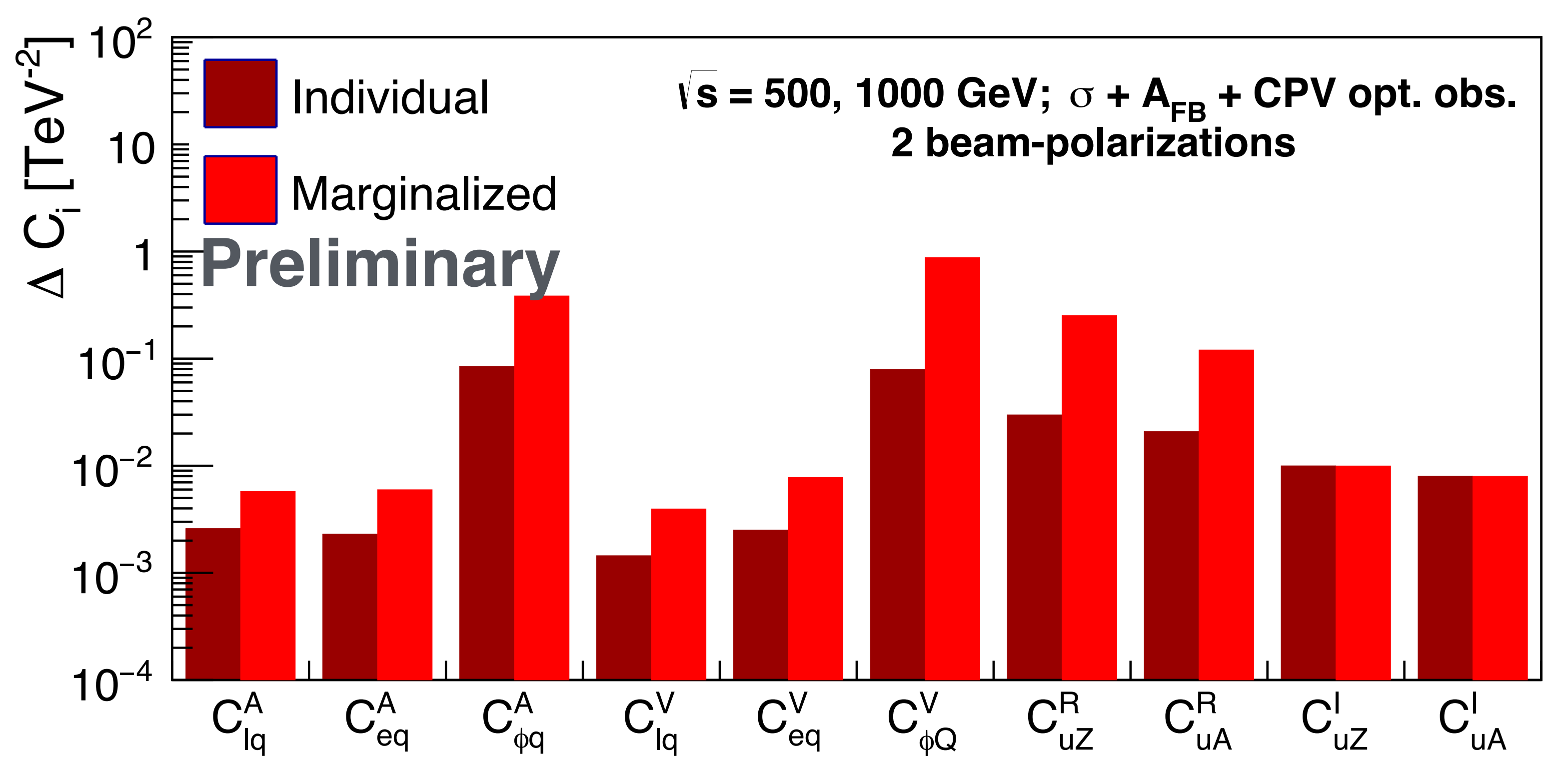
Prospects of CPV opt. obs.

- Nominal **ILC** and the **CLIC low-energy stages** have a very similar sensitivity to these form factors, reaching **limits of $|F_{2A}^{\gamma}|$<0.01** for the EDF
- Assuming that systematic uncertainties can be controlled to the required level, a luminosity upgrade of both machines **may bring a further improvement**



Including CPV observables in the EFT global fit…

$$[F_{2,A}^{Z}, F_{2,A}^{\gamma}] \;\propto\; [\mathrm{Im}\{C_{uA}\}, \mathrm{Im}\{C_{uZ}\}]$$

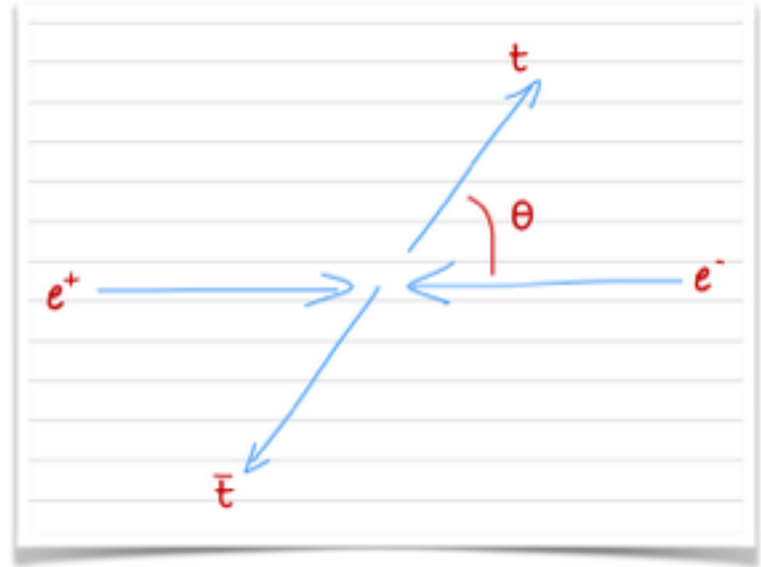


Top quark polarization at different axes

J. A. Aguilar-Saavedra and J. Bernabeu. [arXiv:1005.5382].

See J. A. Aguilar's yesterday talk!!

Unified approach to polarisation measurements

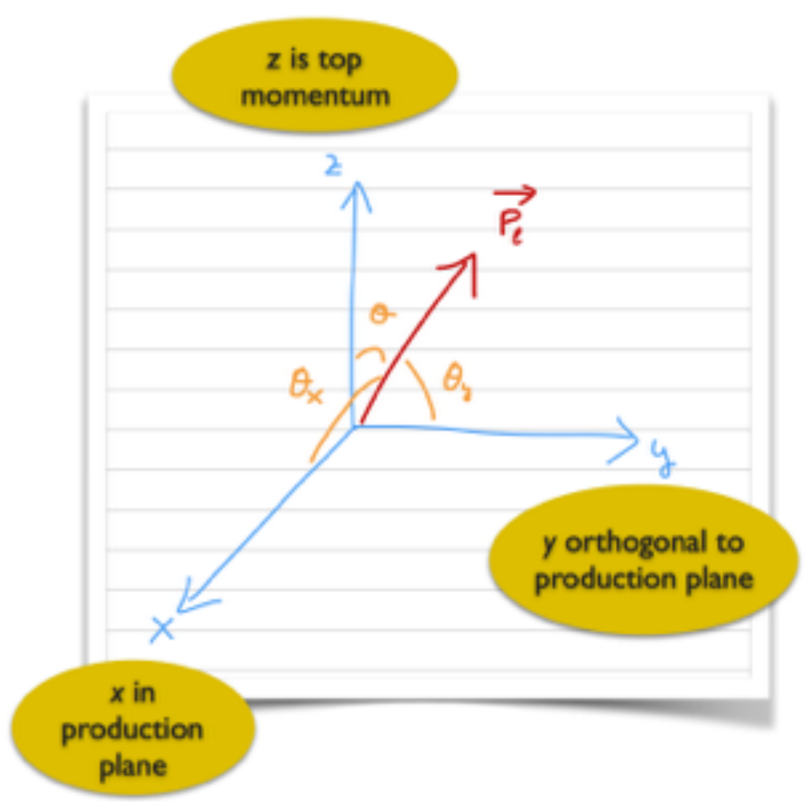


initial state well defined: $e^+ \neq e^-$

$$\hat{z} = \frac{\vec{p}_t}{|\vec{p}_t|}$$

$$\hat{y} = \frac{\vec{p}_t \times \vec{p}_{e^+}}{|\vec{p}_t \times \vec{p}_{e^+}|}$$

$$\hat{x} = \hat{y} \times \hat{z}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1 + \alpha P_3 \cos\theta)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_x} = \frac{1}{2}(1 + \alpha P_1 \cos\theta_x)$$

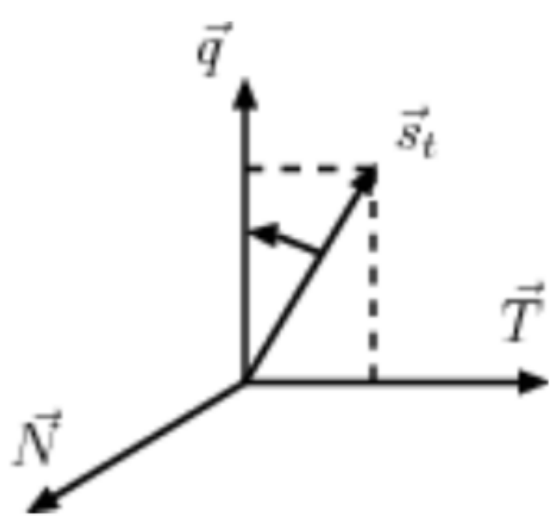
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_y} = \frac{1}{2}(1 + \alpha P_2 \cos\theta_y)$$

Top quark polarizations at different axes

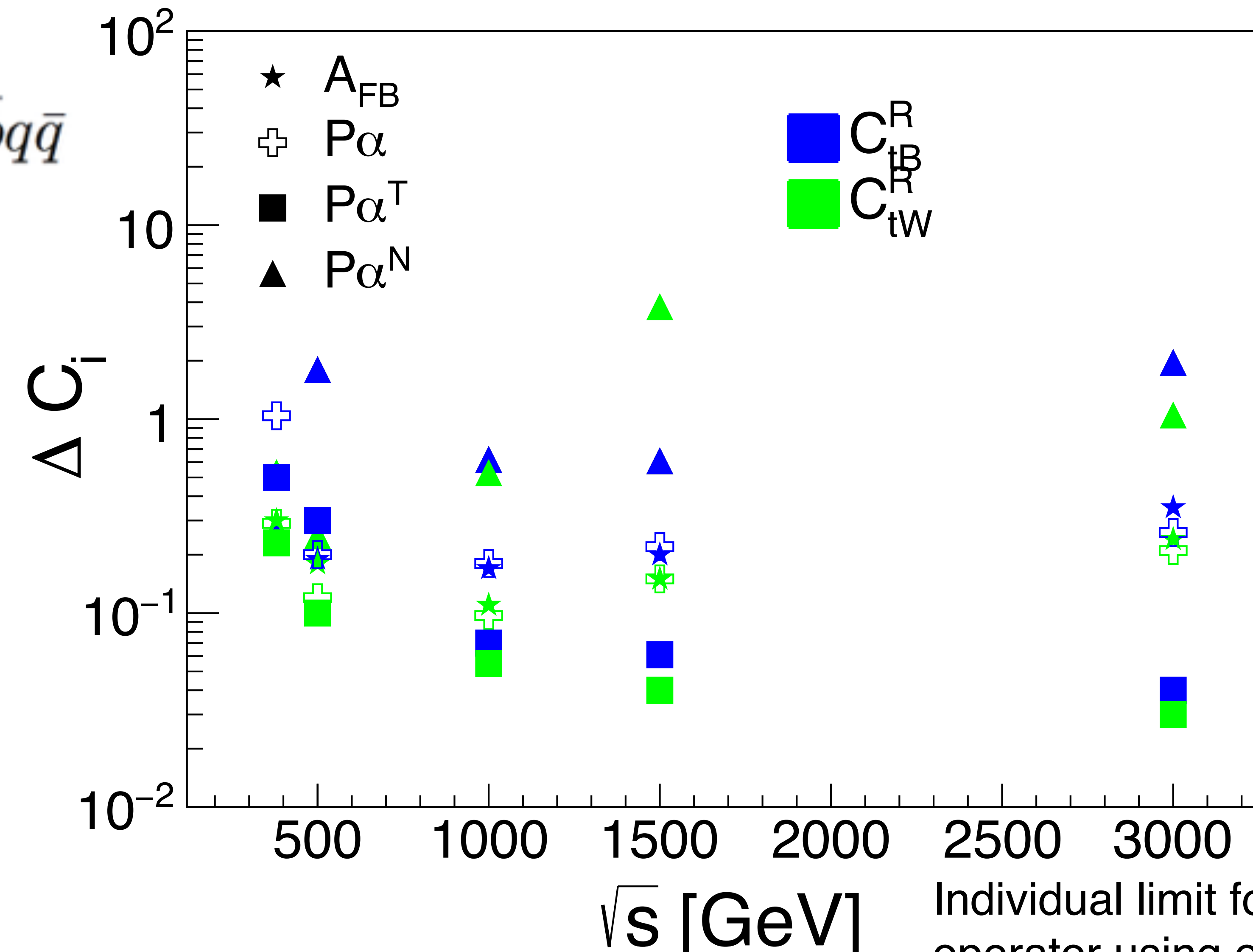
Studied process

$$e^-e^+ \to t\bar{t} \to W^+bW^-\bar{b} \to l\nu b\bar{b}q\bar{q}$$

Defining…



$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}.$$



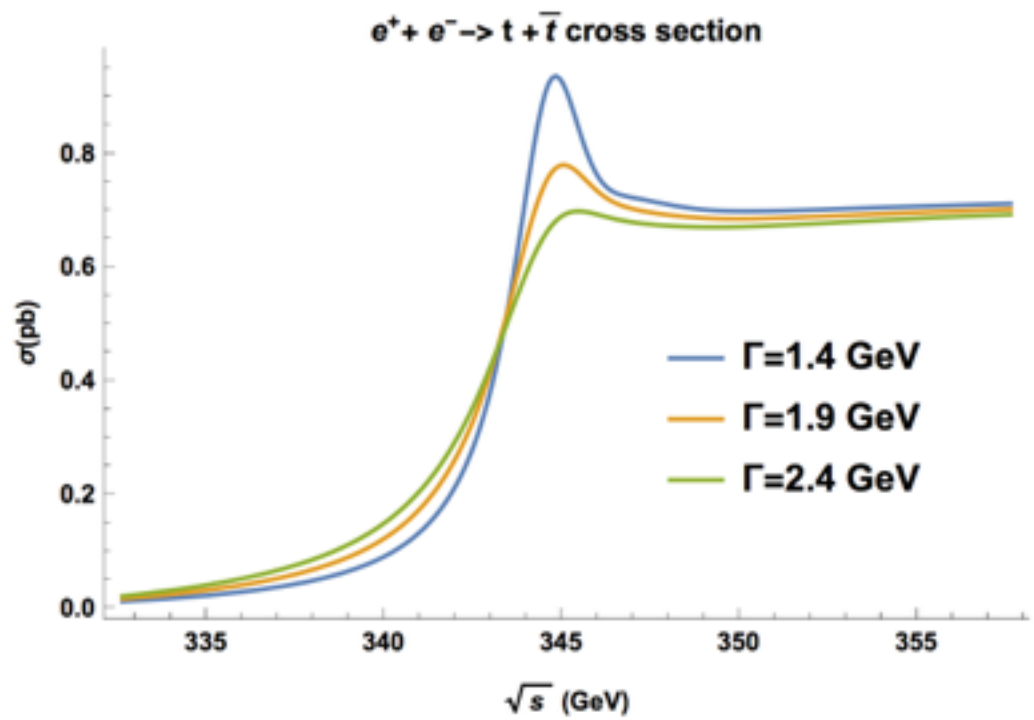
Individual limit for each operator using one observable and energy each time

Transverse axis provide good sensitivity for the **real parts of CtB and CtW** operators at **high energies**.

Next step: include this observable in the global fit.

Top decay width

Good measurement at tt~ production threshold



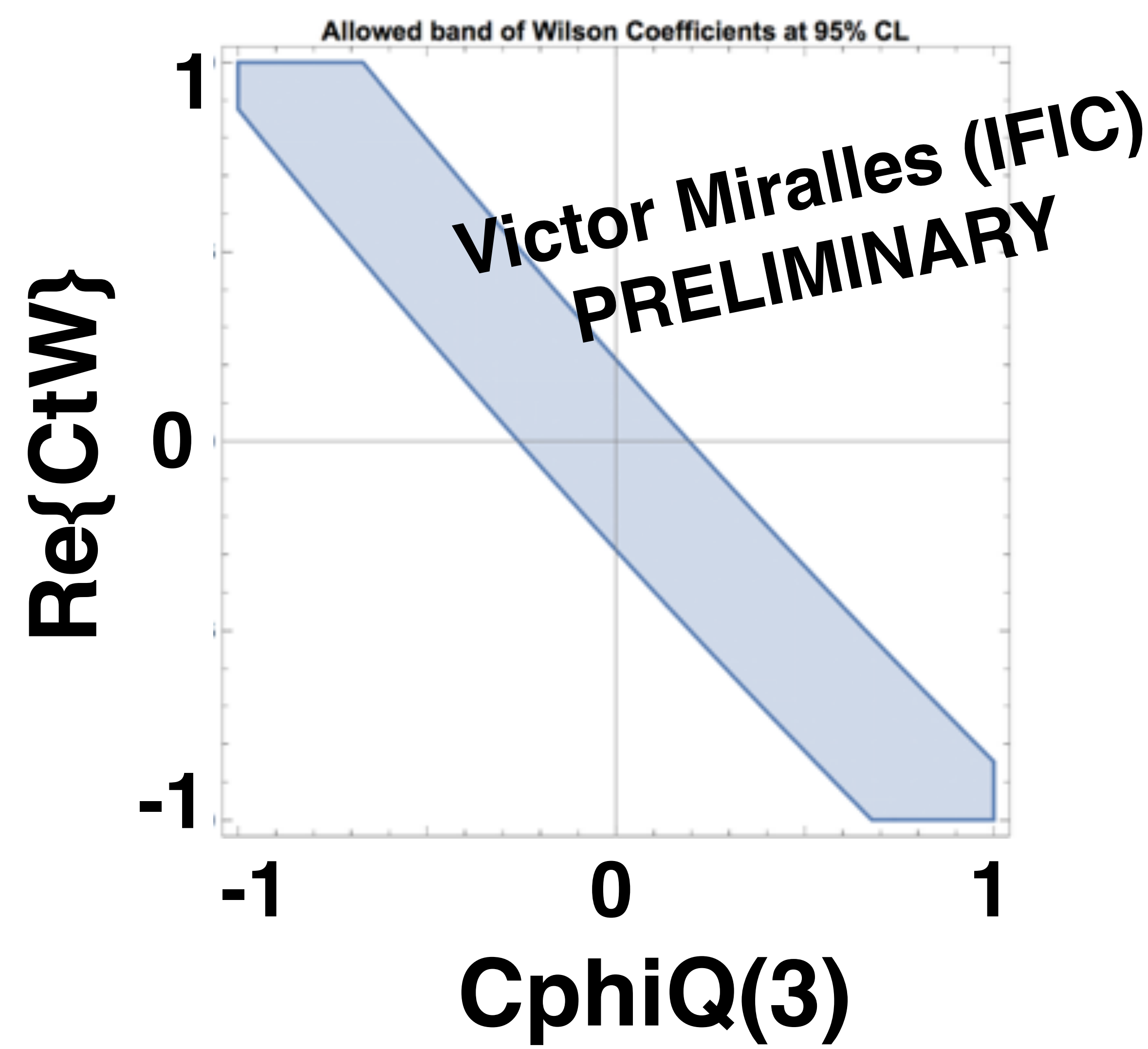
Update of the threshold scan measurements in F. Simon's talk

T. Horiguchi, et al. "Study of top quark pair production near threshold at the ILC". arXiv:1310.0563 [hep-ex]. ⇨ **21 MeV stat. uncert.**

V. Miralles at his Master. QQbar threshold library @NNNLO ⇨ **30 MeV theo. uncert.**

Dependence in **Re{CtW}** and **CphiQ(3)**. Individual limits:

| Re{CtW} | < 0.23 TeV-2
| CphiQ(3) | < 0.21 TeV-2



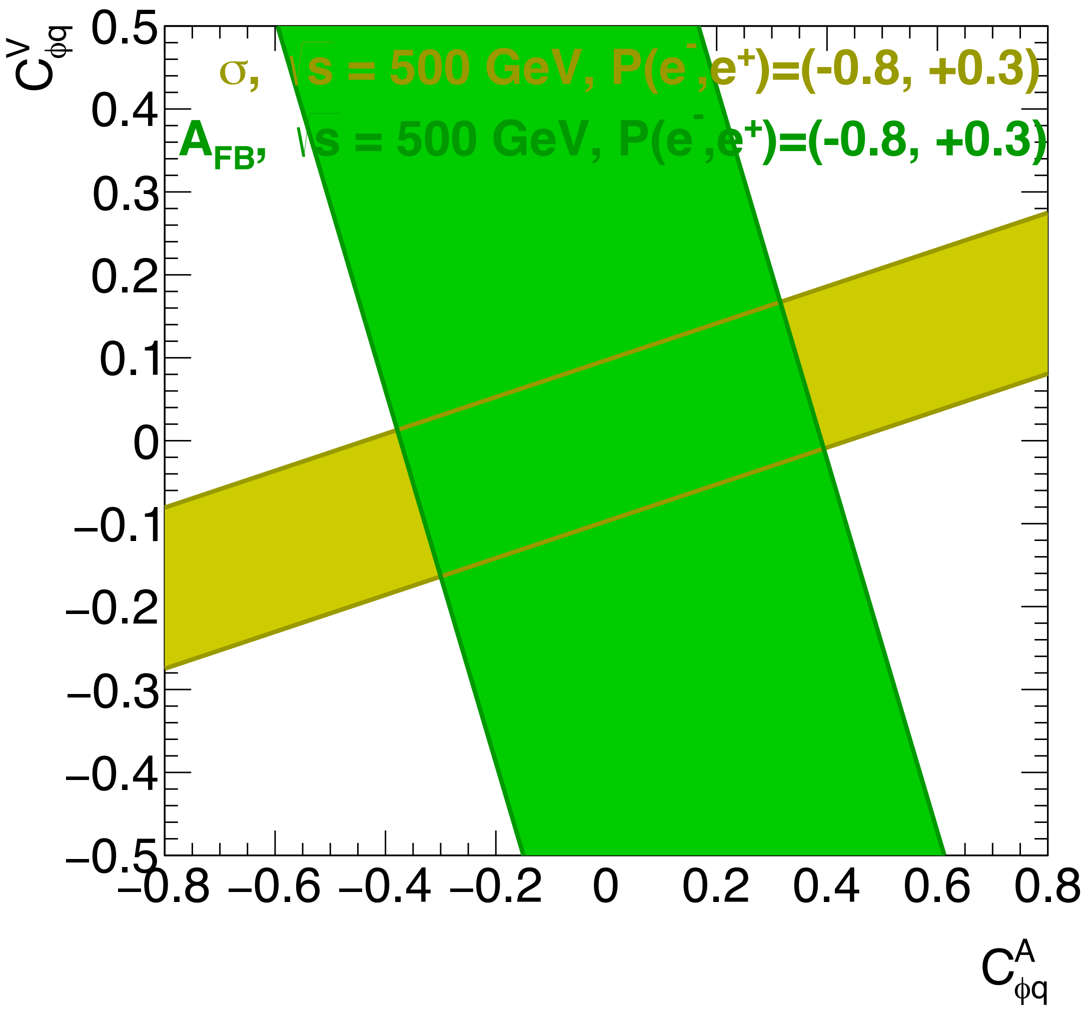
Conclusions

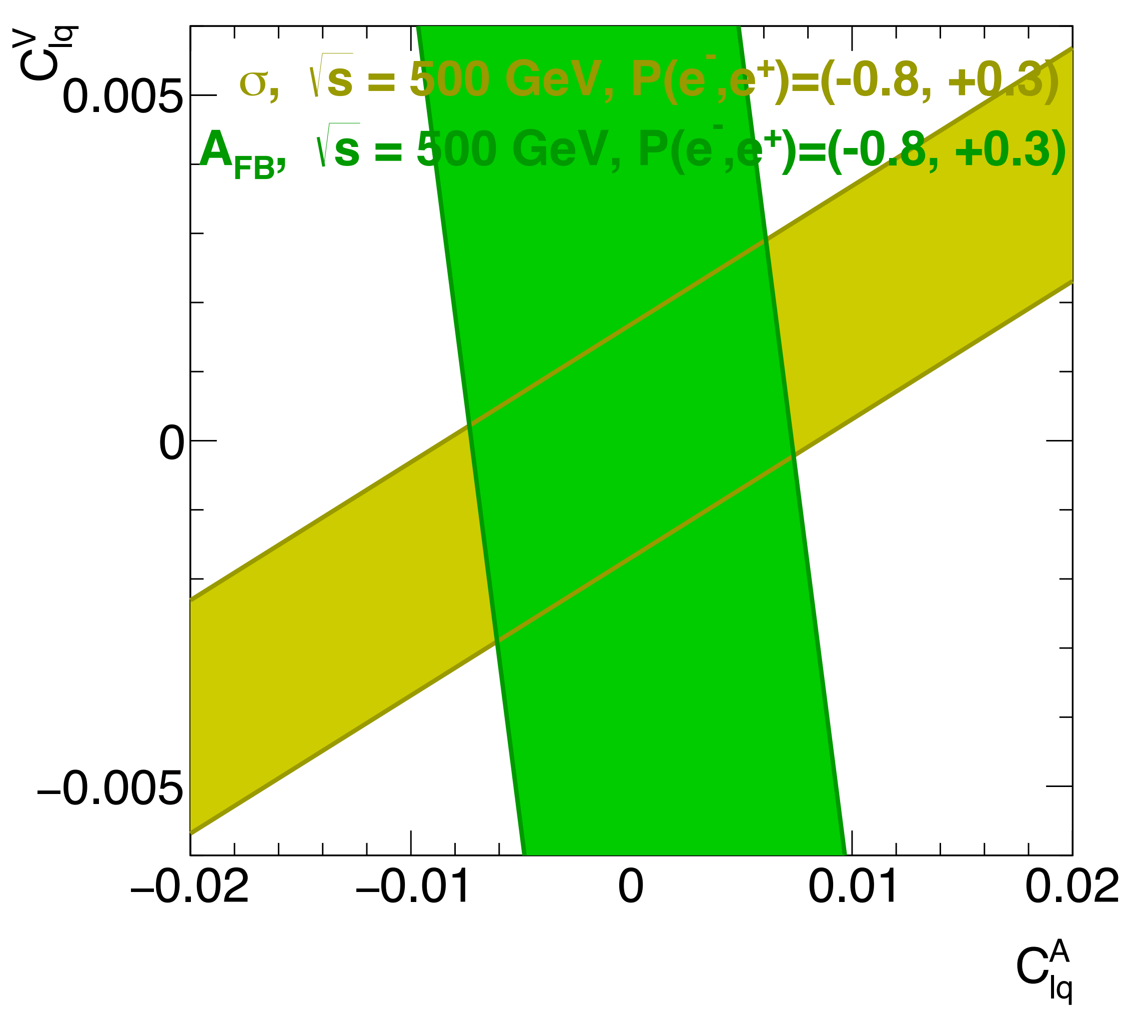
- Global fit in the top EW sector at different energy programs provide low uncertainties for top quark couplings.
- The global fit can be improved: looking for further observables or going to the optimal ones.
- The CPV sector is well constrained through specific observables (**to be published soon**).
- Top quark polarization at different axes provides new sensitivities to the couplings (**to be studied further**).

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.



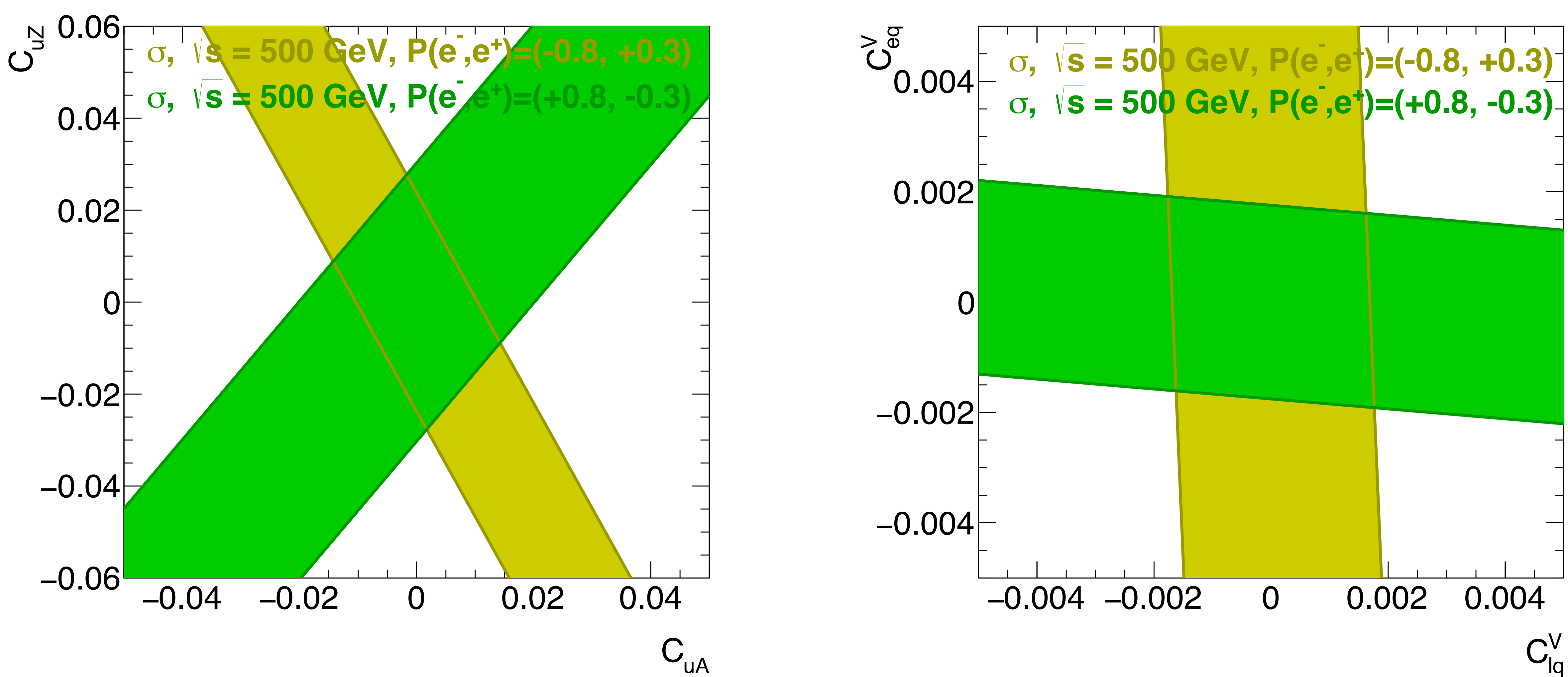


68%CL χ^2 bands: 1 measurement → 1 band in C1-C2 space.

The power of polarisation

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

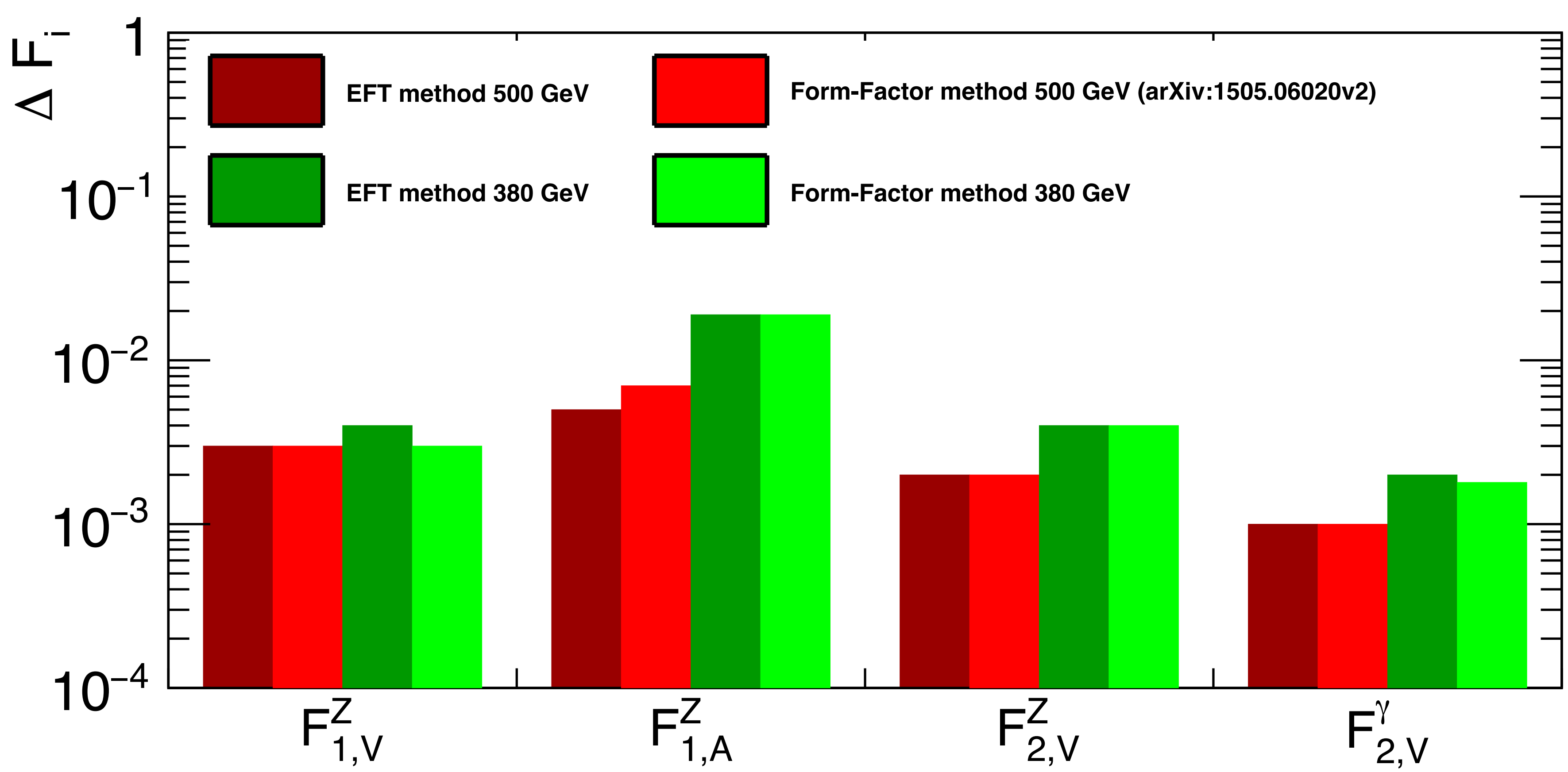
Only with one observable, the initial state polarisation provides complementary constraints.



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

Comparison with form-factors

- Cross-check between EFT and form-factors techniques in the couplings study.
- We find an almost **perfect consistency**. We assume that little discrepancies are due to fit fluctuations.



Fit described in **arXiv:1505.06020v2**

Limits on BSM models

- The effective field theory can be matched to specific BSM models. **Different models will lead to different combination of operator coefficients**.
- If evidence of any nonzero coefficient is observed, **studying the pattern of the deviation will give us hints on high scale physics**.

Vector-like quarks mixed with the third generation quarks (only involves vertex operators) [**hep-ph/0007316**]:

Isospin singlet U: $\lambda \bar{U}_R \tilde{\phi}^\dagger Q_L$ $$\frac{C_{\phi Q}^{(-)}}{\Lambda^2} = \frac{\lambda^2 y_t^{-2}}{2M_U^2}$$

Isospin doublet T=(X,U): $\lambda \bar{T} \phi t$ $$\frac{C_{\phi t}}{\Lambda^2} = \frac{\lambda^2 y_t^{-2}}{2M_U^2}$$

Current LHC bound: MU > 700 - 800 GeV (regardless of λ)
MU / λ > 3 TeV *(indv fit)*
MU / λ > 1.4 TeV *(marg. fit)*

Limits on BSM models

- The effective field theory can be matched to specific BSM models. **Different models will lead to different combination of operator coefficients**.
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R-S models with the SM fermion and gauge fields propagating in the extra dimension **- KK modes** (involving both vertex and 4-fermion operators) **[0709.0007]**:

$$\frac{C_{lq}^{(-)}}{\Lambda^2} = \frac{-0.022}{m_{KK}^2}$$
$$\frac{C_{lu}}{\Lambda^2} = \frac{-0.032}{m_{KK}^2}$$
$$\frac{C_{eq}}{\Lambda^2} = \frac{-0.004}{m_{KK}^2}$$
$$\frac{C_{eu}}{\Lambda^2} = \frac{-0.064}{m_{KK}^2}$$

$$\frac{C_{\phi Q}^{(-)}}{\Lambda^2} = \frac{1.2}{m_{KK}^2}$$
$$\frac{C_{\phi t}}{\Lambda^2} = \frac{-5.1}{m_{KK}^2}$$

$\Rightarrow$ Combining two kind of operators:
Mkk > 13 TeV *(indv fit)*
Mkk > 8 TeV *(marg. fit)*

Simulation samples for CPV obs.

Full simulation

ILC@500GeV

$500fb^{-1}$, P(e-)=∓80%, P(e+)=∓30% (ILC LumiUp $4ab^{-1}$)

CLIC@380GeV

$500fb^{-1}$, P(e-)=∓80%

Loose timing cuts

CLIC@1.4TeV

$1.5ab^{-1}$, P(e-)=∓80%

Tight timing cuts,

Efficiency inputs from Rickard and Martin top tagging studies

Fast Simulation

CLIC@3TeV

$3ab^{-1}$, P(e-)=∓80%

Extrapolate numbers from low-energy stages results

Systematic uncertainties in CPV obs.

source	380 GeV	500 GeV	3 TeV
machine parameters (bias)	-	-	-
machine parameters (non-linearity)	$<< 1\%$	$<< 1\%$	$<< 1\%$
experimental (bias)	< 0.005	< 0.005	< 0.005
exp. acceptance (linearity)	+3%	+5%	+10%
exp. reconstruction (linearity)	-5%	-5%	-15%
theory (bias)	$<< 0.001$	$<< 0.001$	$<< 0.001$
theory (linearity)	$\pm$ 2%	$\pm$ 0.9%	-

- The **SM values for A_{Re} and A_{Im} are 0** and the **detector response is symmetric** (equal for top and anti-top)
- The **uncertainties of machine parameters** have a **negligible effect** on the results. Only the determination of P(e-) and P(e+) at the 10^{-3} level
- **Distorsions** of the distributions **O+ and O- generate a non-zero asymmetry** at the level of **0.005** (upper limit due to the MC statistics)
- The **selection tends to enhance the reconstructed asymmetry** while the **migration and resolution dilute it**. This effect is particularly pronounced at 3TeV.
- NLO Electroweak and QCD corrections to coefficients