Top electroweak couplings

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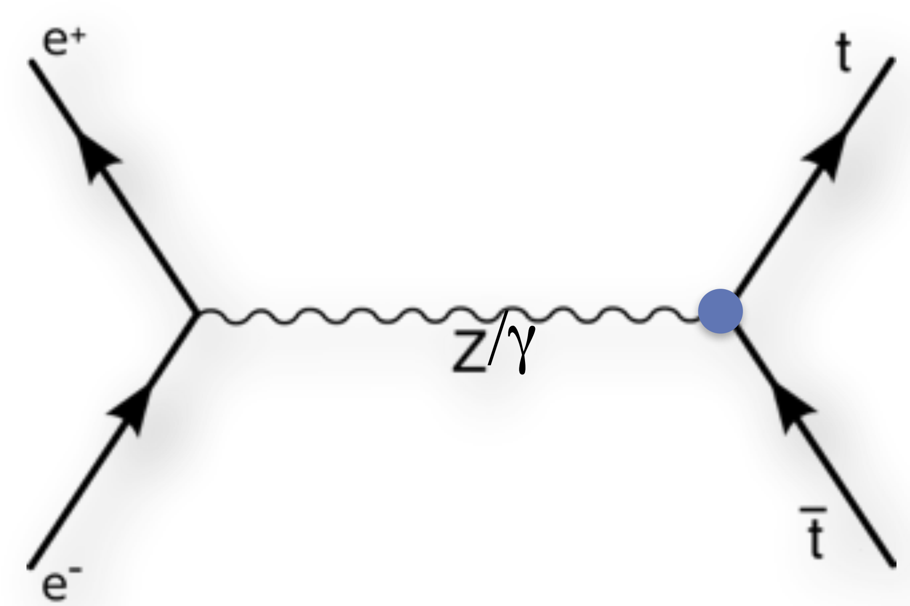
Introduction

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

- **ttZ** and **ttGamma vertices** directly accessible in an electron-positron collider. **Two approaches** for top quark **couplings study**:

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



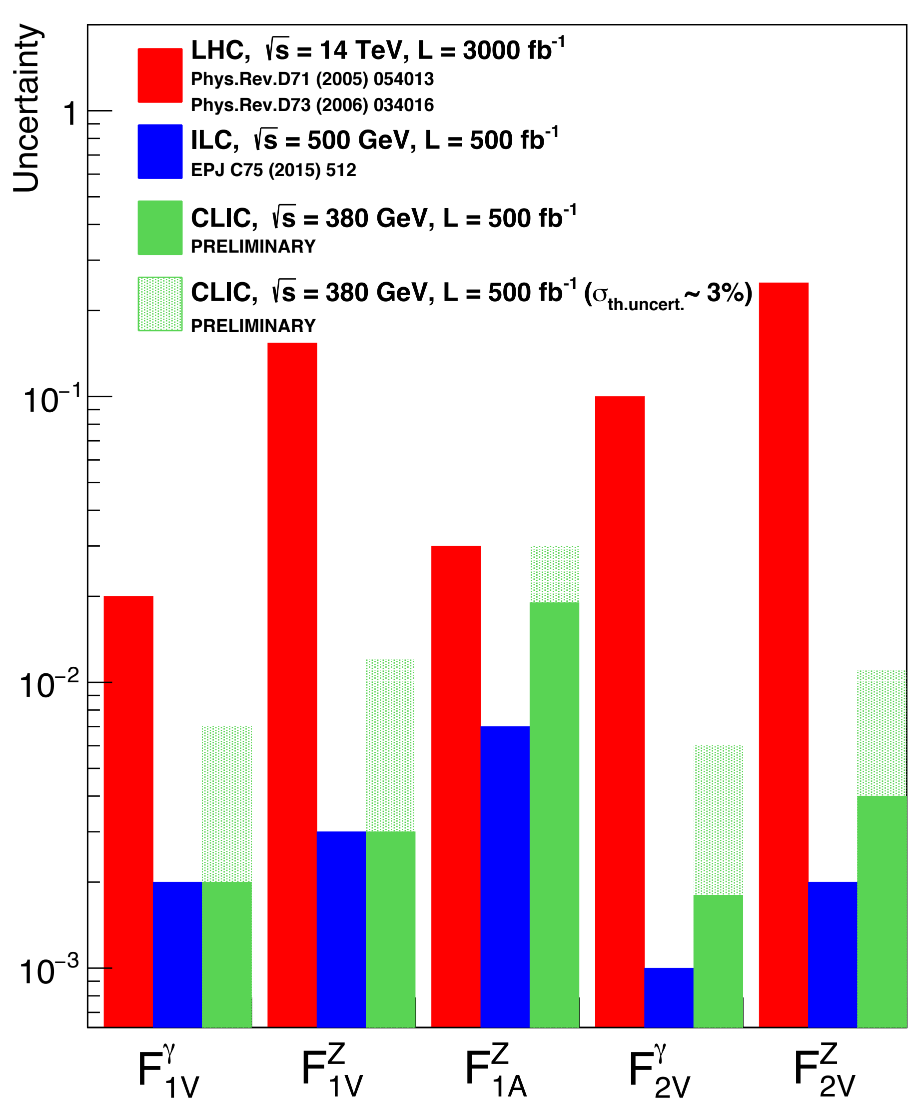
Form-factors status

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

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

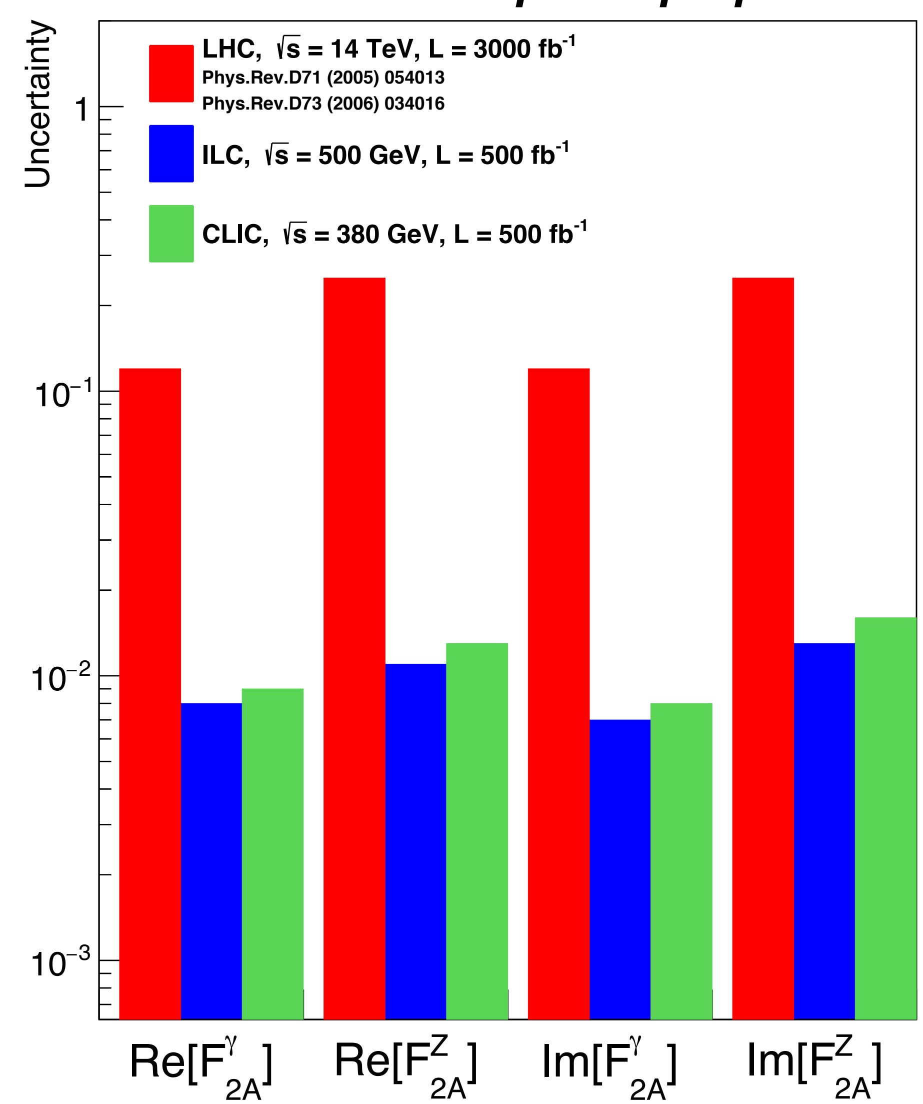
CP conservation

IFIC - LAL: arXiv:1505.06020



CP violation

IFIC - LAL: Paper in preparation



Effective field theory (EFT)

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

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

- 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: dimension-6 operators

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

Gauthier Durieux in TopLC 2016 (KEK):

Use: – SM fields (fermion gauge eigenstates: q, u, d, l, e)
– SM symmetries (gauge and Lorentz)

dim-3 · no allowed fermion mass term: —

dim-4 · gauge: $\bar{\psi} \not{D} \psi$ and Yukawa: $\bar{\psi}\varphi\psi'$ operators

dim-5 · left-handed neutrino masses ($\Delta L = \pm 2$): $\overline{l^c}\varphi \; l\varphi$

dim-6 · four-fermion ($\Delta L = \Delta B = \pm 1$, or 0) [Grzadkowski et al 10']

basis reduction with Fierz and Schouten identities

· two-fermion:

D	φ			
3	0	—		
2	1	$\bar{\psi}\sigma^{\mu\nu}\psi'\varphi$	$X_{\mu\nu}$	Tensor
1	2	$\bar{\psi}\gamma^{\mu}\psi$	$\varphi^{\dagger}D_{\mu}\varphi$	Vector
0	3	$\bar{\psi}\psi'\varphi$	$\varphi^{\dagger}\varphi$	Scalar

basis reduction with EOMs

dim-7 · $\Delta L \neq 0$: ... [Lehman 14']

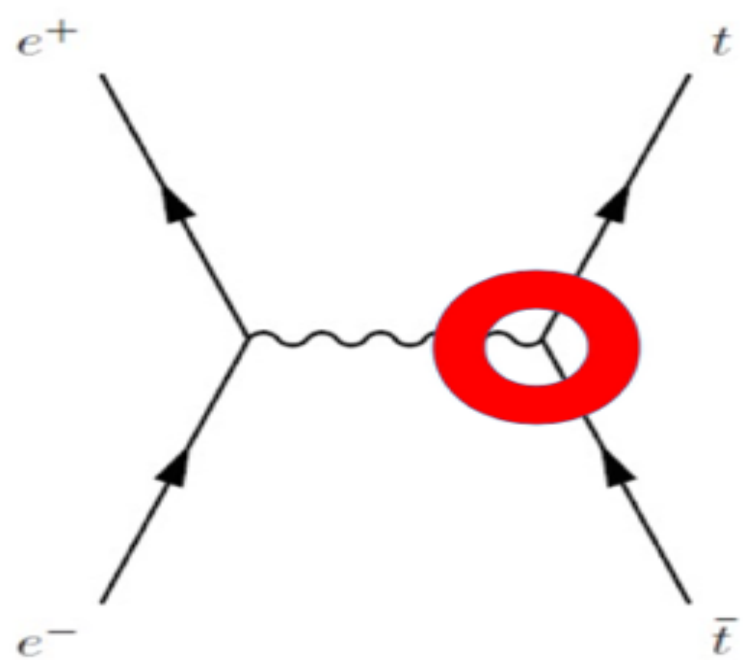
...

EFT: 2-fermion (vertex) 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

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

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

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

Form-factors vs. effective operators

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

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

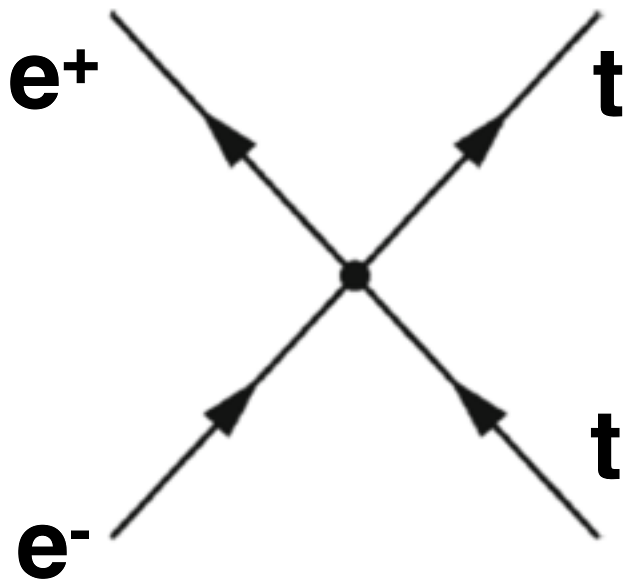
Transformation between effective operators and form-factors:

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

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

EFT: 4-fermion (contact interaction) 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:

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

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

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.*).

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

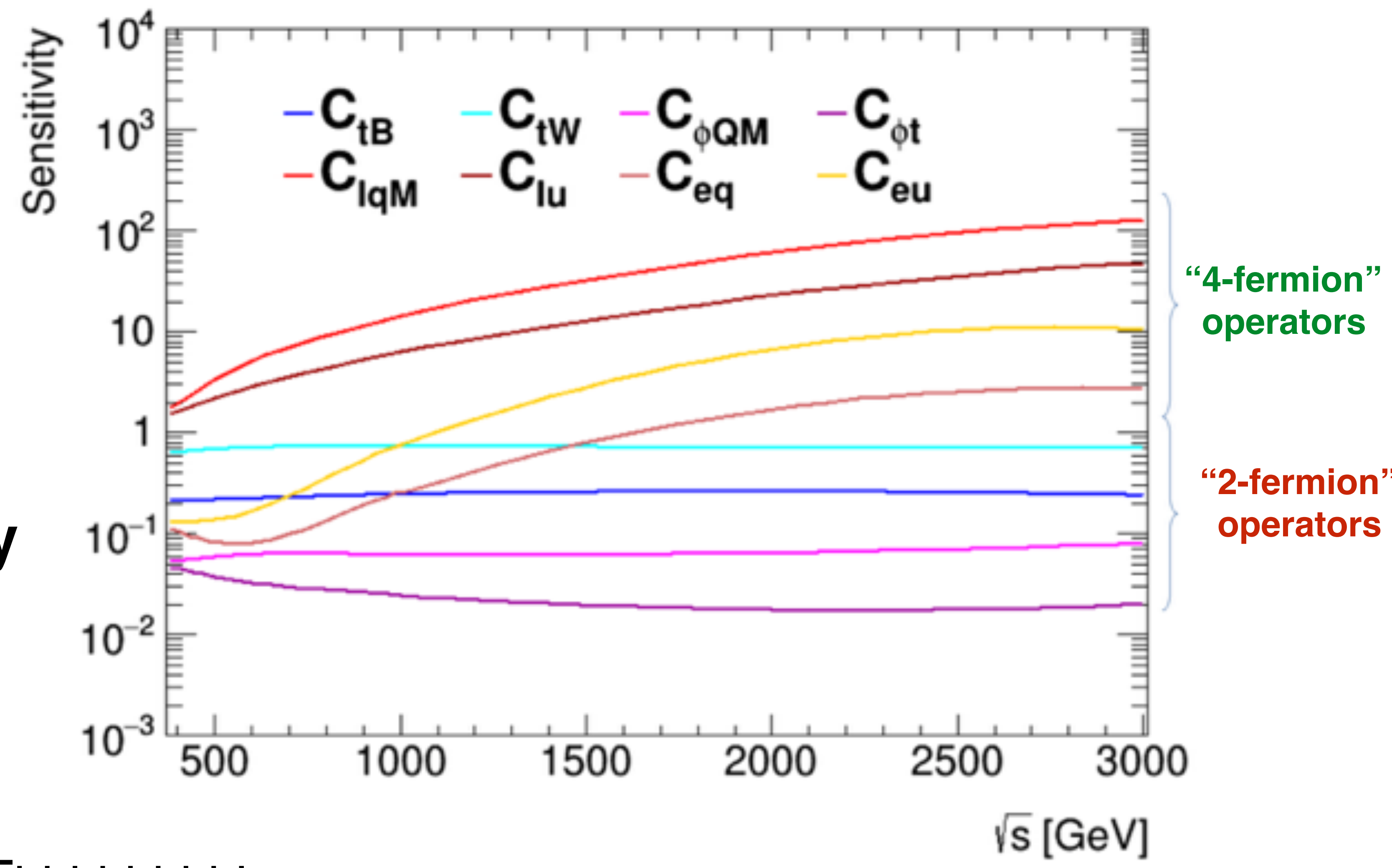
	Full - Simulation		Temporary scaling		
	380 GeV	**500 GeV**	**1 TeV**	**1.4 TeV**	**3 TeV**
Pol (e-, e+)	(-0.8, 0)	(-0.8, +0.3)	(-0.8, +0.2)	(-0.8, 0)	(-0.8, 0)
	(+0.8, 0)	(+0.8, -0.3)	(+0.8, -0.2)	(+0.8, 0)	(+0.8, 0)
Cross-section (pb)	0,792	0,930	0,256	0,113	0,025
Lumi (fb-1)	500	500	1000	1500	3000

Parameterisation of different observables through effective operators…

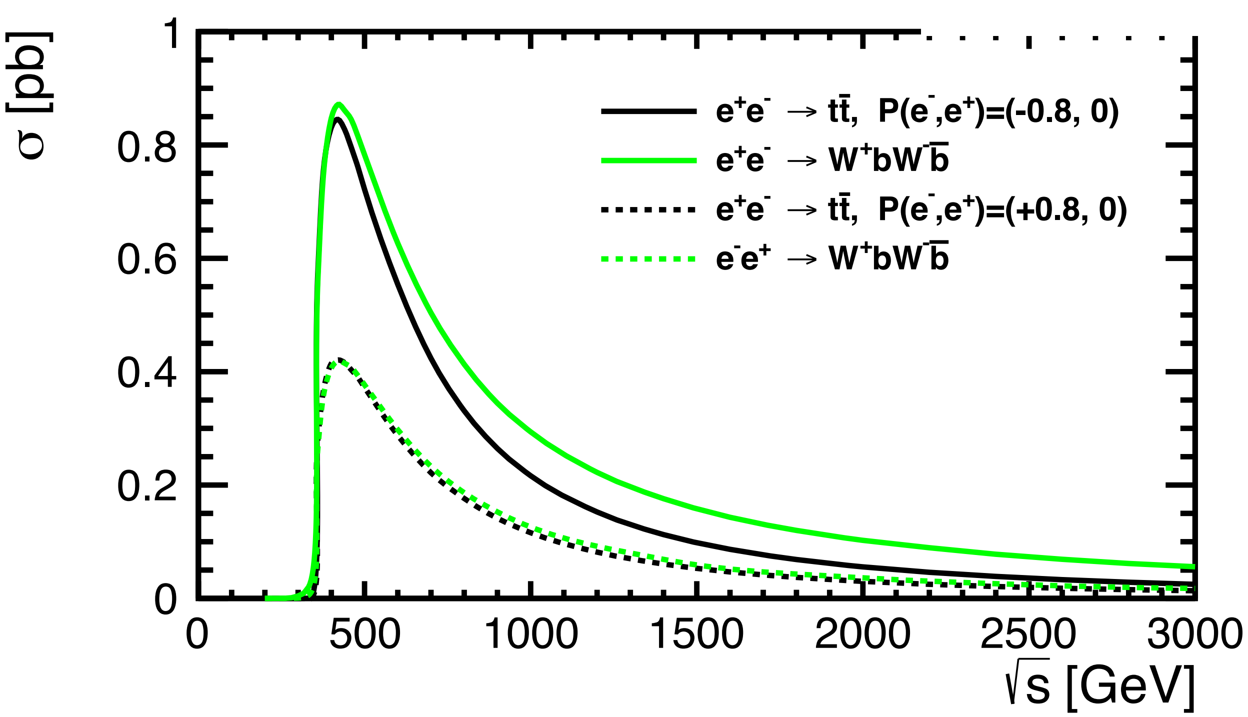
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

Cross-section sensitivity

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



(multi-) TeV operation provides better sensitivity to "4-fermion" operators.



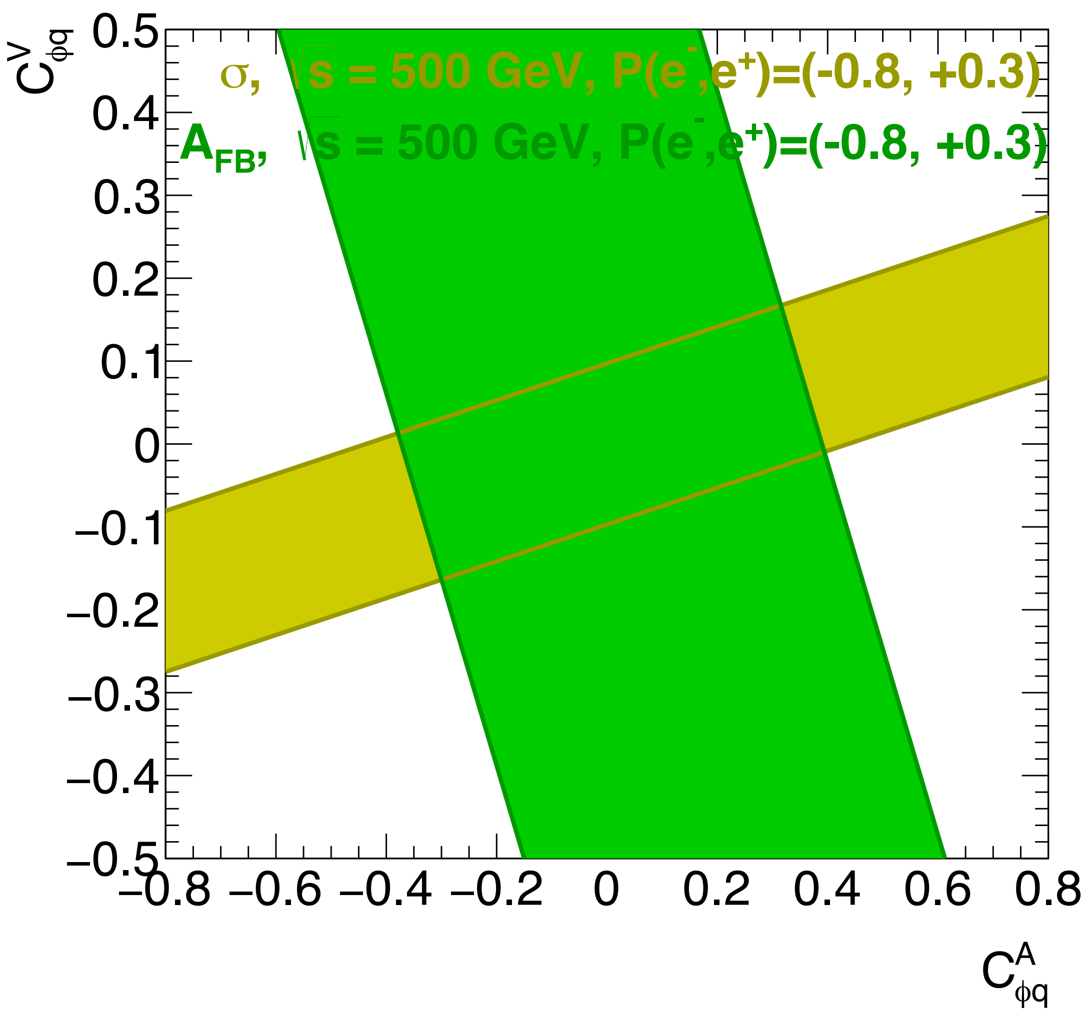
"vertex" operators have a better bound by lower energy data (lower statistical uncertainty).

Complementarity

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

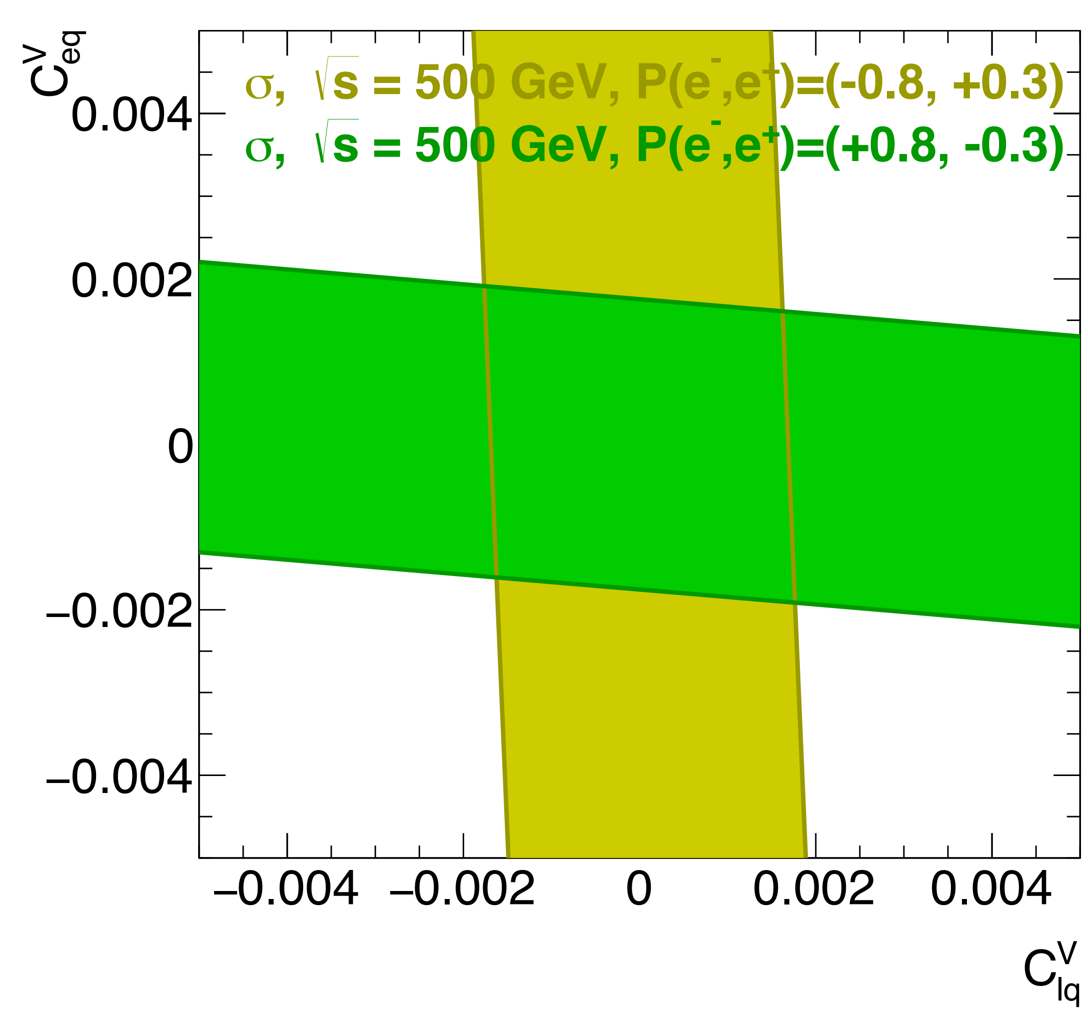
Cross-section vs asymmetry

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



The power of polarisation

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



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

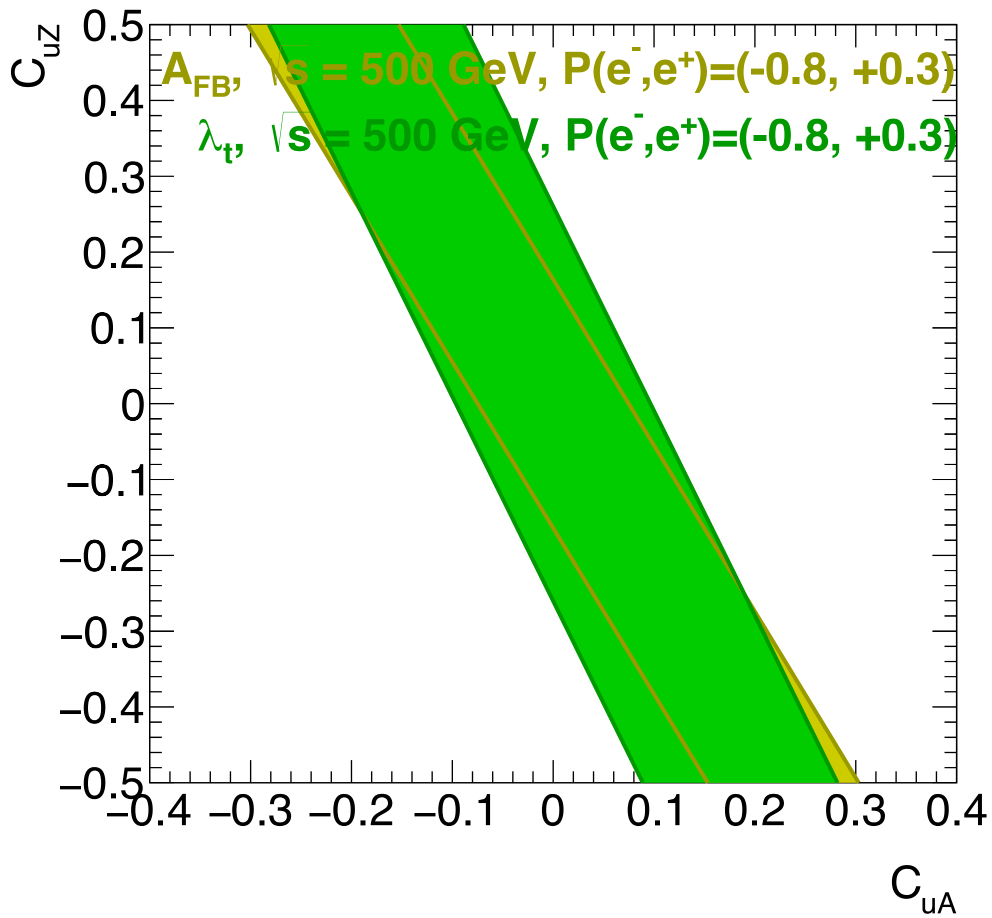
Fraction of right-handed tops

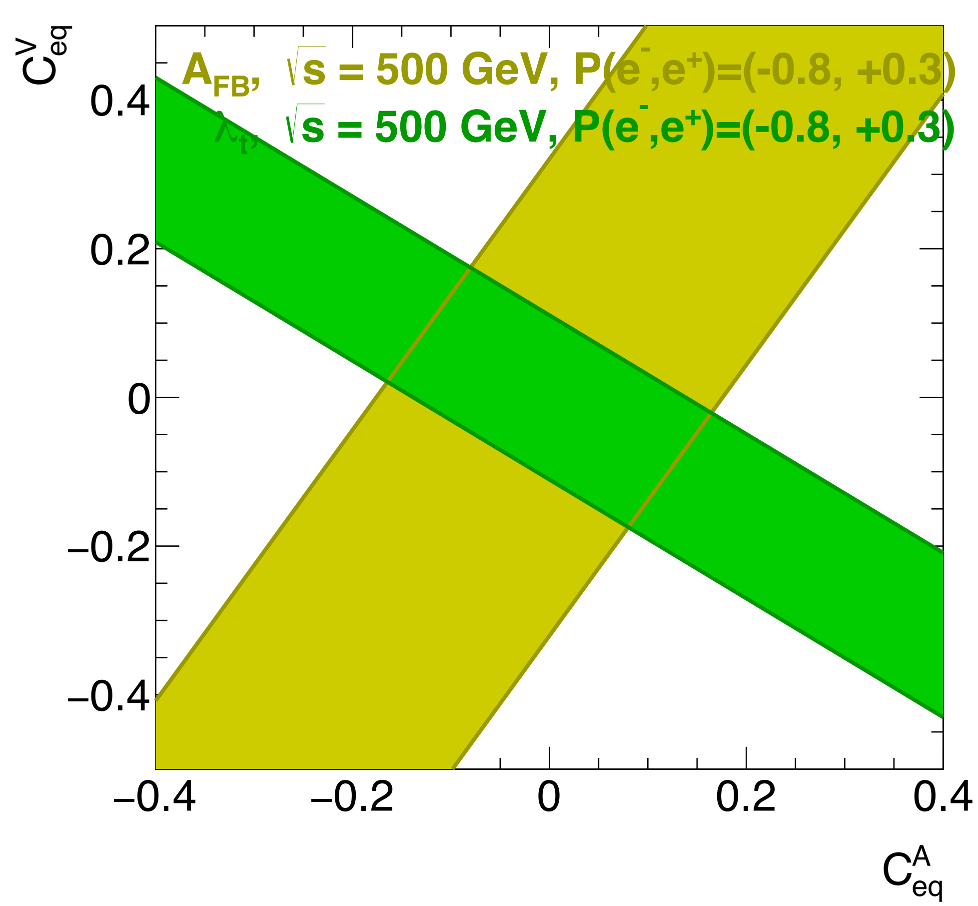
In the rest system of the t quark, the angle of the lepton from the W boson is distributed like *(motivation from 1307.8102v1)*:

The angle θhel is measured in the rest frame of the t quark with the z-axis defined by the direction of motion of the t quark in the laboratory.

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

Fraction of right-handed tops.





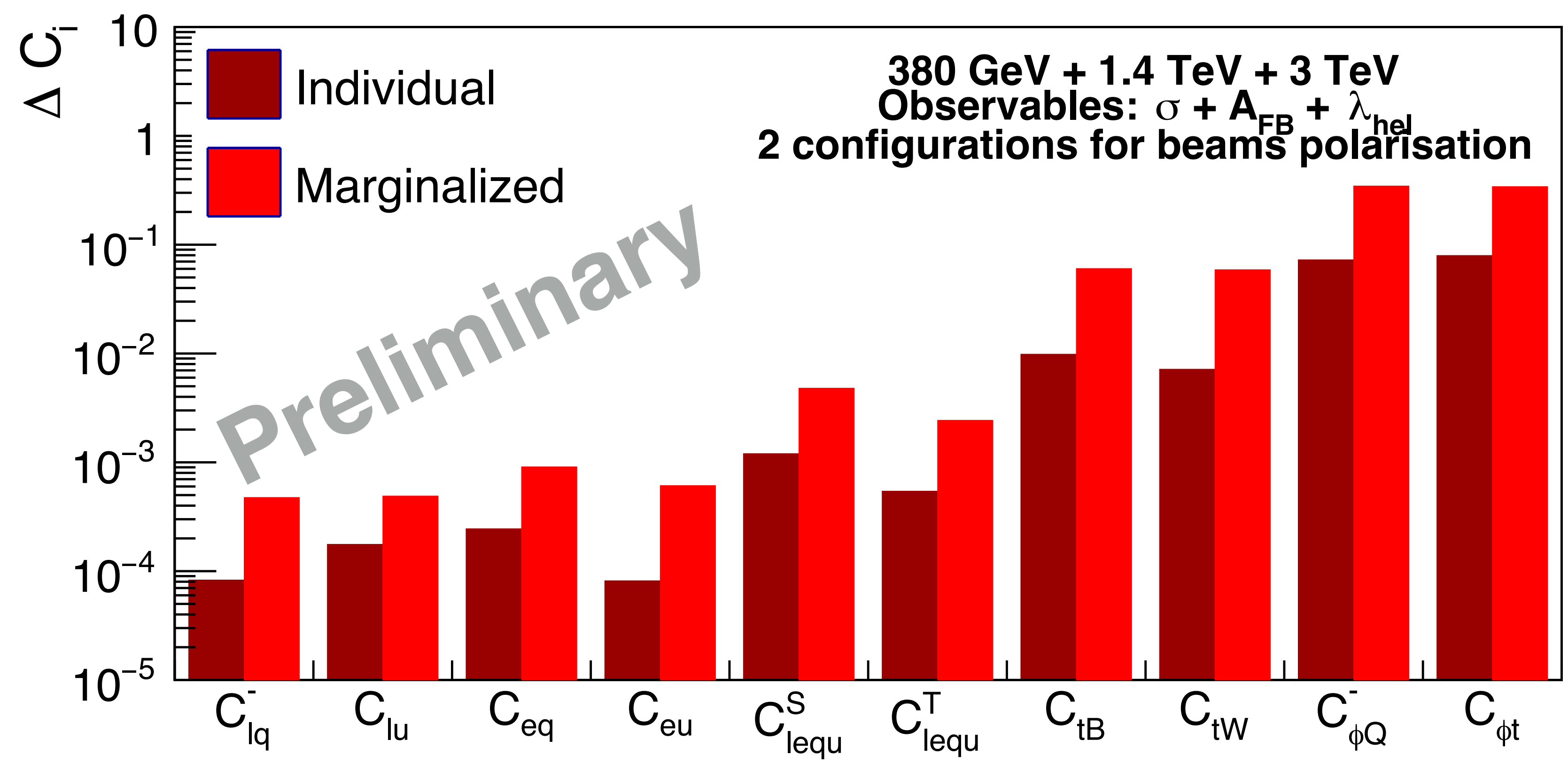
Good complementarity with Afb in the 4-fermion sector.

Global Fit: CLIC program

Globat fit in the CLIC energy program: **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.



- **We find consistency between the EFT scheme and the form-factor scheme** *(fit described in arXiv:1505.06020v2)*.
- We are **looking for a perfect agreement between the individual fit** (*best case*) **and the marginalized fit** (*more realistic case*).

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 [**hep-ph/0007316**]:

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

R-S models with the SM fermion and gauge fields propagating in the extra dimension **- KK modes [0709.0007]**:

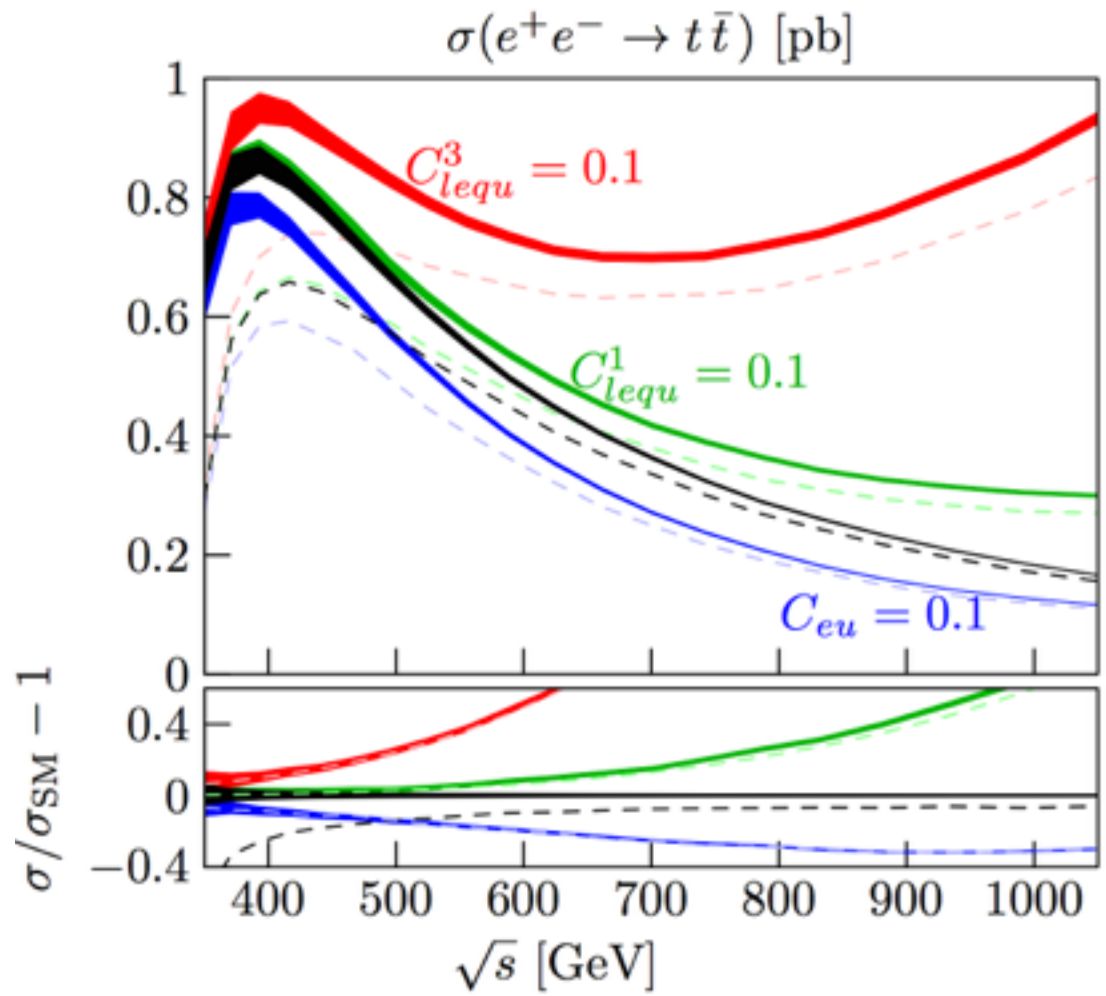
Mkk > 13 TeV *(indv fit)*
Mkk > 8 TeV *(marg. fit)*

Work in progress…

- ***(NOW in progress)*** Impact at NLO:
  - **First results show the same sensitivity at LO and NLO in almost all the operators**.
  - **New operators appear** (those concerning gluons). In principle they can be constraine better at the LHC.

Gauthier Durieux in TopLC 2016 (KEK):

MadGraph for NLO QCD in the effective field theory



$\Lambda = 1$ TeV, $\Lambda^{-2,-4}$ terms, $m_t = 172.5$ GeV, unpolarised beams, α_s scale

- Study of the process $e^-e^+ \to W^+bW^-\bar{b}$.
  - **New operators appear** (those concerning the Wtb vertex).
  - First results **below ttbar threshold show low sensitivity to new Wtb operators**.

Top reconstruction at high energies

Collaboration with I.Garcia, P. Roloff, R. Ström and M.Vos.

Reconstruction Strategy

Trimming technique: remove background. *Consists in the inclusive reconstruction of subjets inside the big boosted top jet.*

+

Top tagging: distinguish tops from QCD background (see R. Ström talk later in this session).

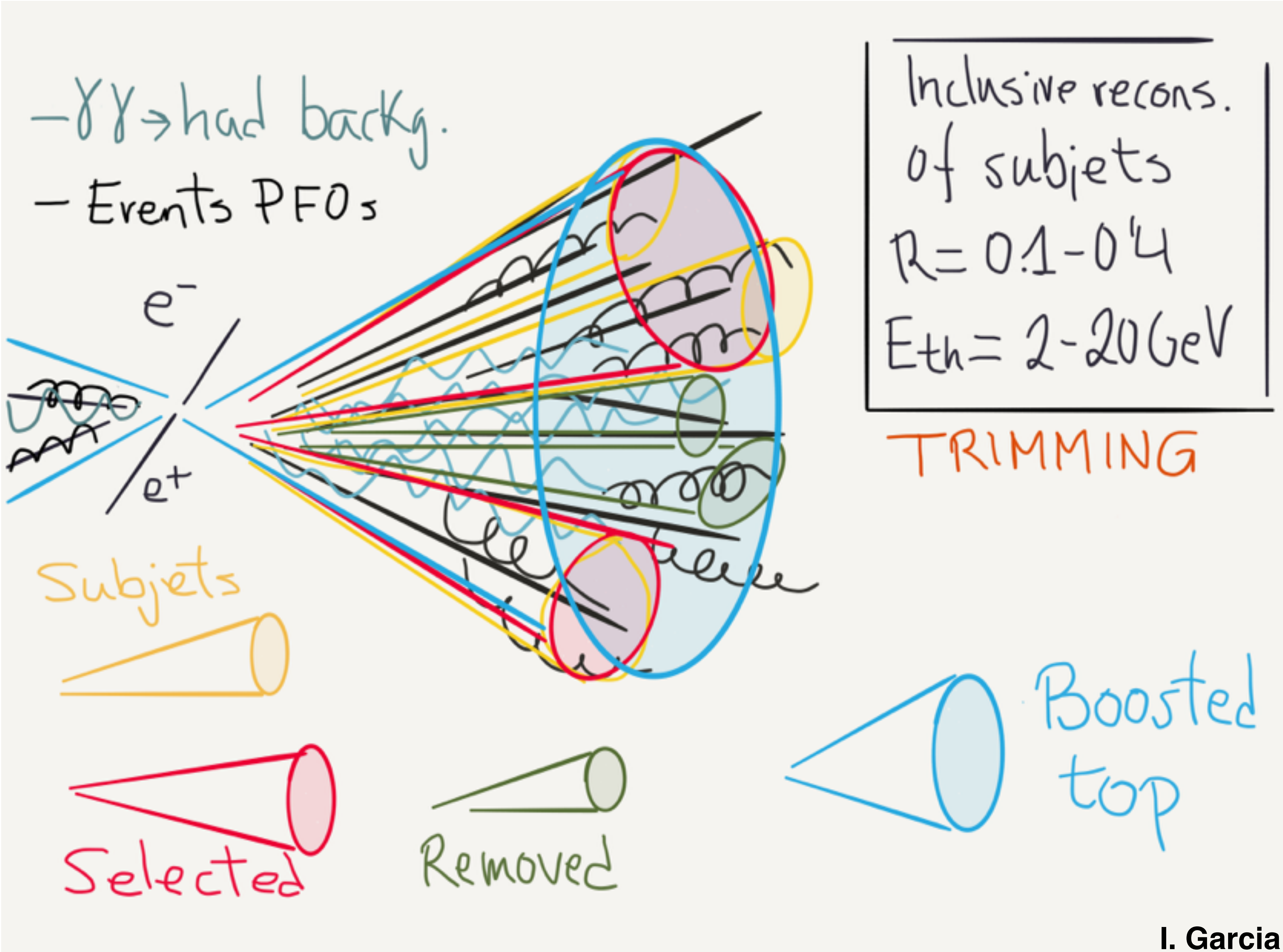
Studied Samples

6 fermion final-state samples CLIC@1.4TeV

P(e-) = -80%

Marlin processors under development

Trimming technique



Summary

- We have two alternatives for the study of top quark couplings: form-factors and effective operators.
- 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.
- We can put limits on different BSM models through the EFT operators.
- We need new top reconstruction techniques at high energies (under development).

An EFT analysis

Gauthier Durieux in TopLC 2016 (KEK):

- Go global!
  - NP can generate several operators at a high scale
  - RG running down to low scales can mix them with others (Renormalisation Group)
  - Operators are re-express as combinations of others to form a basis

- Face interferences!

$$\sigma_{e^+e^-\to t\bar{t}}^{\sqrt{s}=500\text{ GeV}}\,[\text{fb}] = +568 + \left(\frac{1\text{ TeV}}{\Lambda}\right)^2 \begin{pmatrix} C^A_{lq} \\ C^A_{eq} \\ C^A_{\phi q} \\ C^V_{lq} \\ C^V_{eq} \\ C^V_{\phi q} \\ C^R_{uZ} \\ C^R_{uA} \\ C^I_{uZ} \\ C^I_{uA} \end{pmatrix}^T \begin{pmatrix} +221 \\ -194 \\ +7.01 \\ -1110 \\ -737 \\ -8.24 \\ +33.8 \\ +209 \\ \cdot \\ \cdot \end{pmatrix} + \left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \begin{pmatrix} C^A_{lq} \\ C^A_{eq} \\ C^A_{\phi q} \\ C^V_{lq} \\ C^V_{eq} \\ C^V_{\phi q} \\ C^R_{uZ} \\ C^R_{uA} \\ C^I_{uZ} \\ C^I_{uA} \end{pmatrix}^T \begin{pmatrix} +367 & \cdot & +13.2 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & +367 & -11.5 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & +0.209 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & +868 & \cdot & +31.1 & -128 & -197 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & +868 & -27.3 & +112 & -197 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & +0.493 & -4.05 & -0.432 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +9.36 & +2 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +25.2 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +2.51 & +0.536 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & +6.75 \end{pmatrix} \begin{pmatrix} C^A_{lq} \\ C^A_{eq} \\ C^A_{\phi q} \\ C^V_{lq} \\ C^V_{eq} \\ C^V_{\phi q} \\ C^R_{uZ} \\ C^R_{uA} \\ C^I_{uZ} \\ C^I_{uA} \end{pmatrix}$$

$$+ \left(\frac{1\text{ TeV}}{\Lambda}\right)^4 \left\{ + 1600 \left|C^S_{lequ}\right|^2 + 13900 \left|C^T_{lequ}\right|^2 \right\}$$

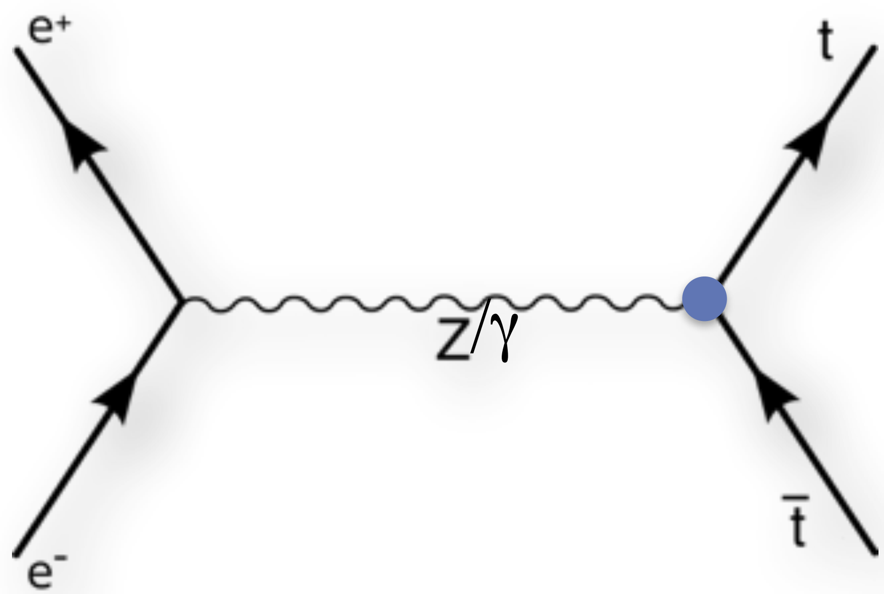
- Combine observables!

- Offer yourself N^nLO!

Form-factors status

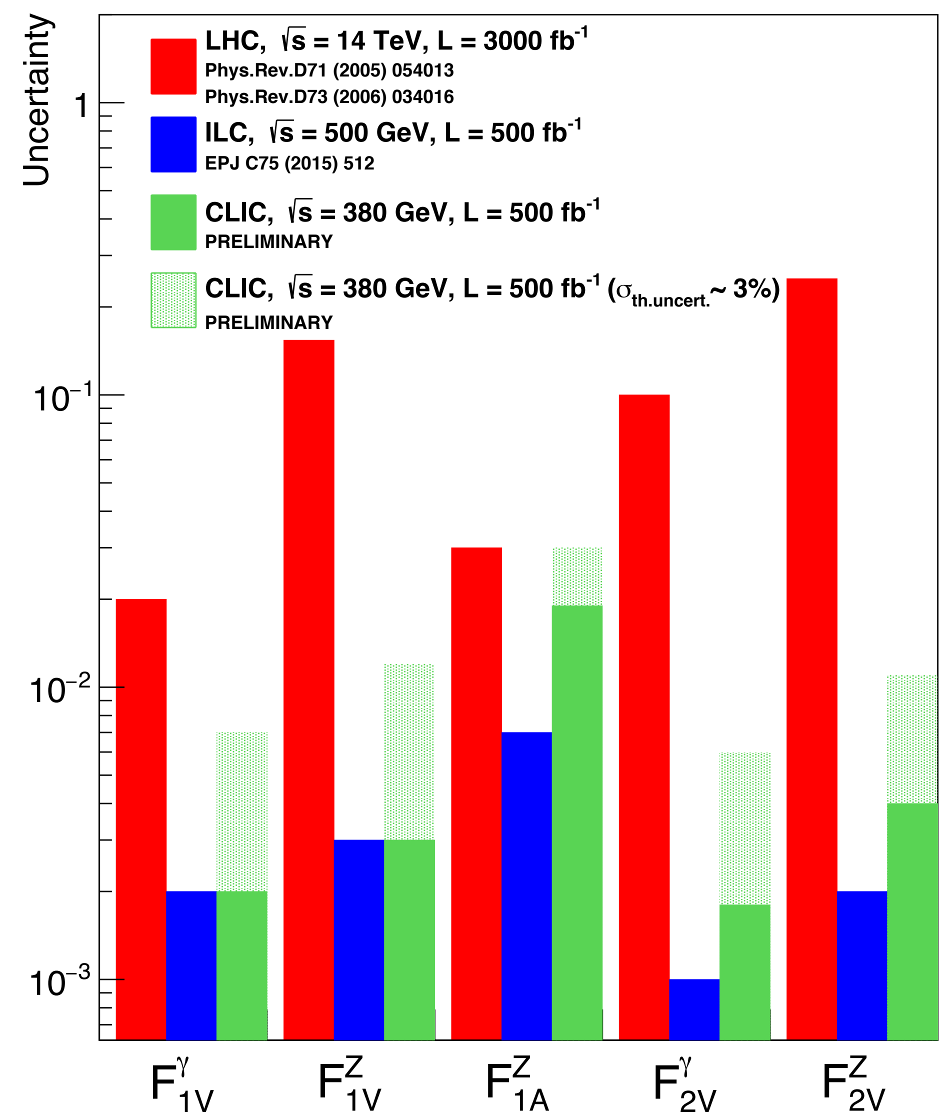
Assume production is dominated by SM and NP scale is beyond direct reach.

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2)+\gamma_5\underline{F_{1A}^X}(k^2)\right)-\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2)+\gamma_5F_{2A}^X(k^2)\right)\right\}$$



IFIC - LAL Collaboration

arXiv:1505.06020



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

$F_{1A}^{\gamma,SM}=0$ 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**

Form-factors status: CPV

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

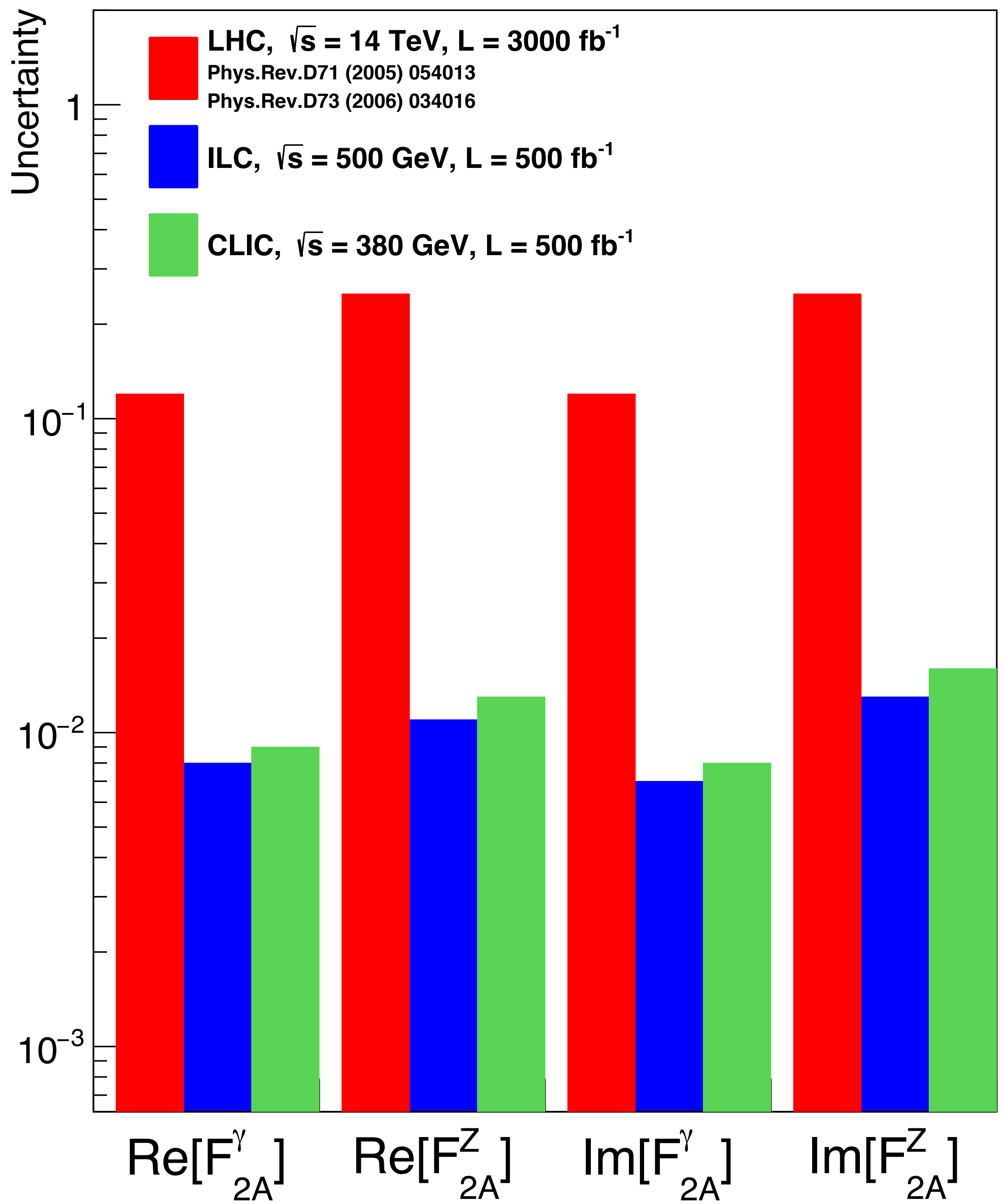
Observables:

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

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

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

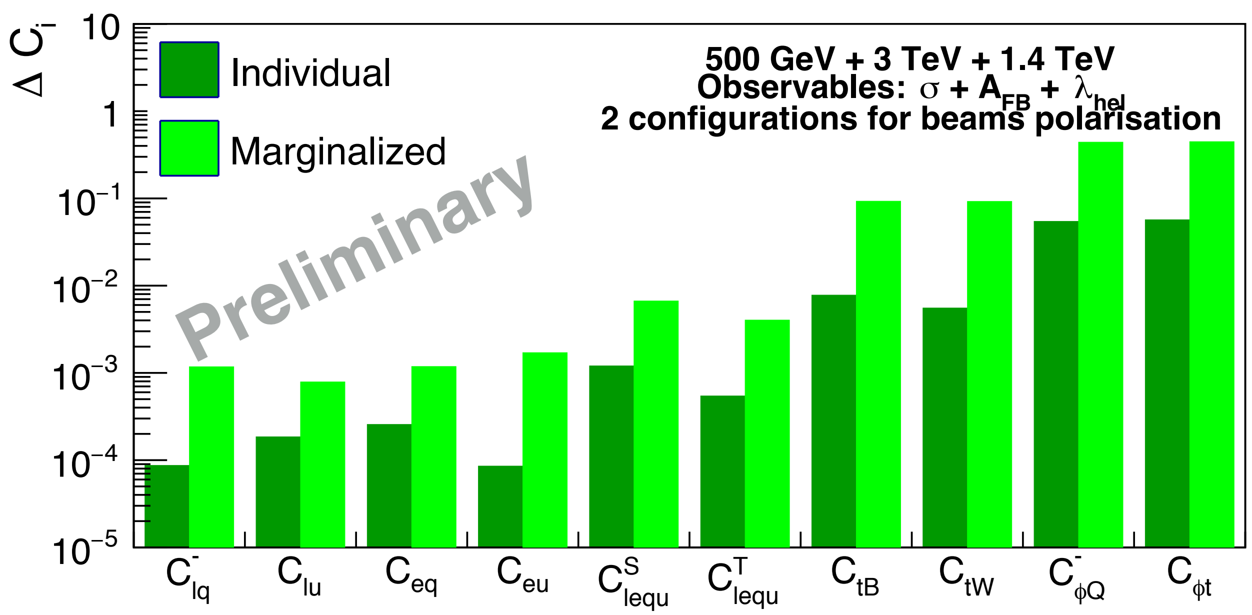
Quantity	$Re[F_{2A}^\gamma]$	$Re[F_{2A}^Z]$	$Im[F_{2A}^\gamma]$	$Im[F_{2A}^Z]$
SM value at tree level	0	0	0	0
LHC	0.12	0.25	0.12	0.25
TESLA TDR	0.007	0.008	0.008	0.010
ILC@500 GeV	0.007	0.011	0.007	0.012
CLIC@380 GeV	0.009	0.013	0.008	0.016



Global Fit

Globat fit in the energy program: **500 GeV + 3 TeV + …**

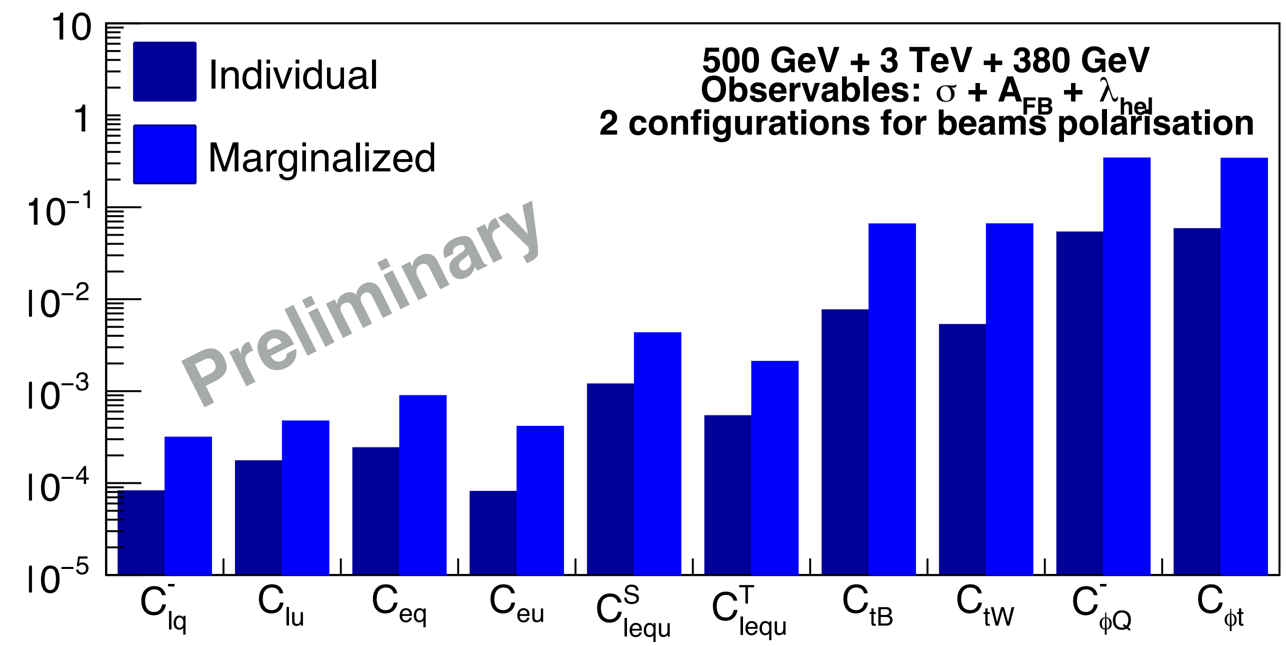
+ 1.4 TeV?



4-fermion:
Improvement of 5%

Vertices:
Improvement of 10 - 14%

+ 380 GeV?



4-fermion:
Improvement of 0.05 - 0.15%

Vertices:
Improvement of 10 - 13%

Better to add high energy points

Trimming technique: energy threshold selection

Trimming threshold impact

- Durham algorithm on smaller jets.
- R for subjets = 0.2