Update on top CPV couplings and EFT analysis

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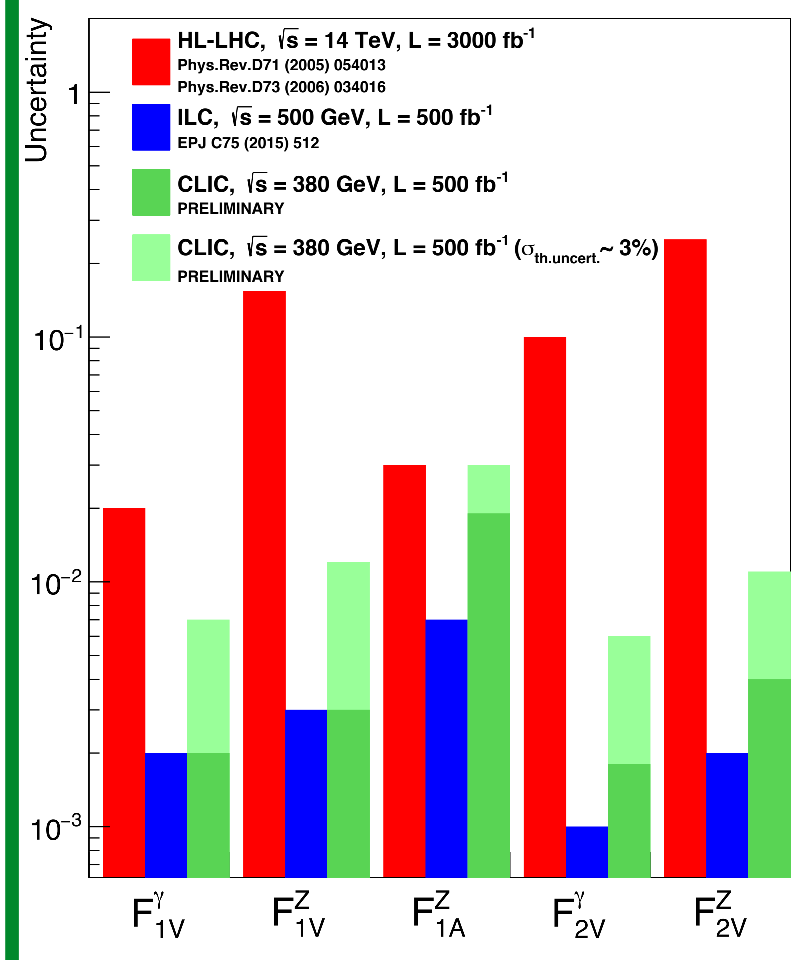
CLICdp WG Analysis Meeting 26/09/17

Top quark electroweak couplings

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

CP-conserving couplings

CP-violating couplings



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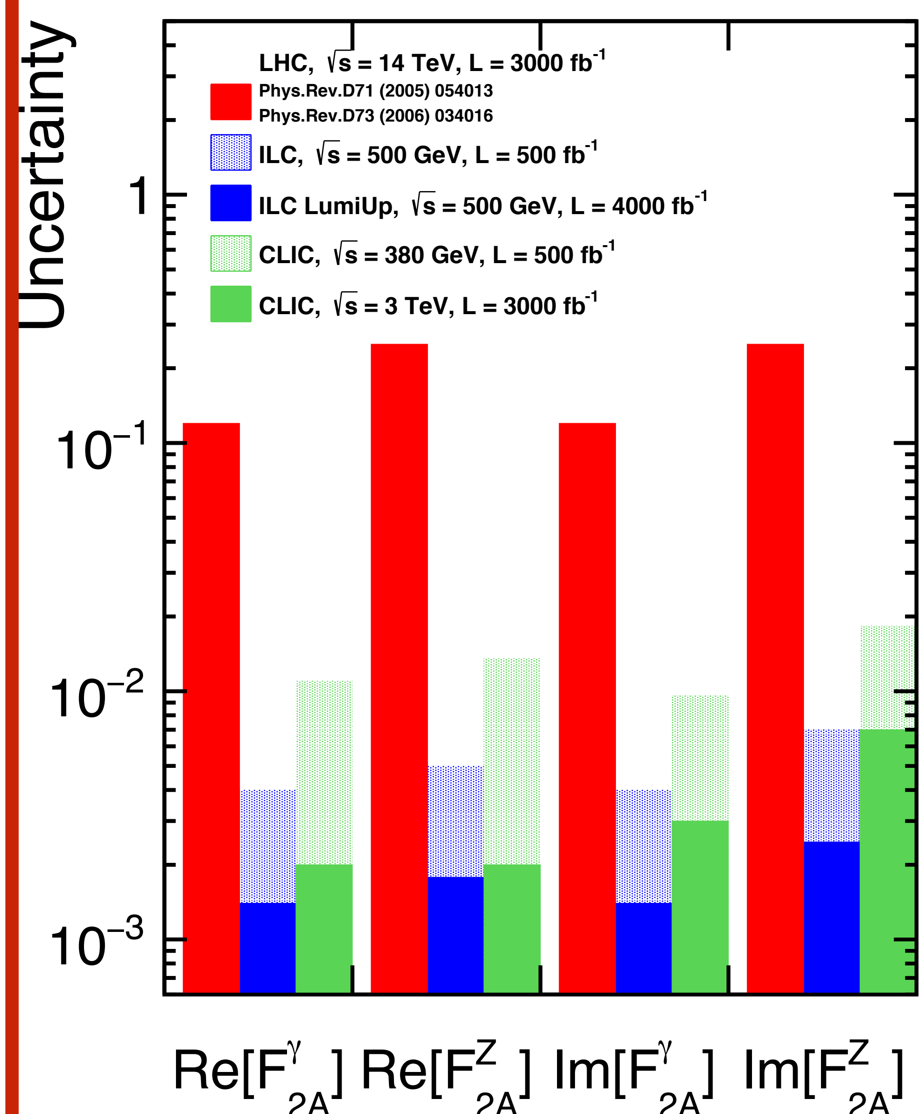

Future e+e- colliders can measure CP-conserving top quark electroweak couplings with a precision that exceeds that of the HL-LHC

CPV paper status

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

CP-violating top quark couplings at future linear e^+e^- colliders

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September 5, 2017

Abstract We study the potential of future lepton colliders to probe violation of the CP symmetry in the top quark sector. In certain extensions of the Standard Model, such as the two-Higgs-doublet model, sizeable anomalous top quark dipole moments can arise, that may be revealed by a precise measurement of top quark pair production. We present results from detailed Monte Carlo studies for the ILC at 500 GeV and CLIC at 380 GeV and explore the potential of high-energy operation. We find that precise measurements in $e^+e^- \to t\bar{t}$ production with subsequent decay to lepton plus jets final states can provide sufficient sensitivity to detect Higgs-boson-induced CP violation in a viable two-Higgs-doublet model. The potential of a linear e^+e^- collider to detect CP-violating electric and weak dipole form factors of the top quark exceeds the prospects of the HL-LHC by over an order of magnitude.

Keywords CP violation · top physics · e^+e^- collider

Useful comments from CLIC people (see all the discussion in CDS):

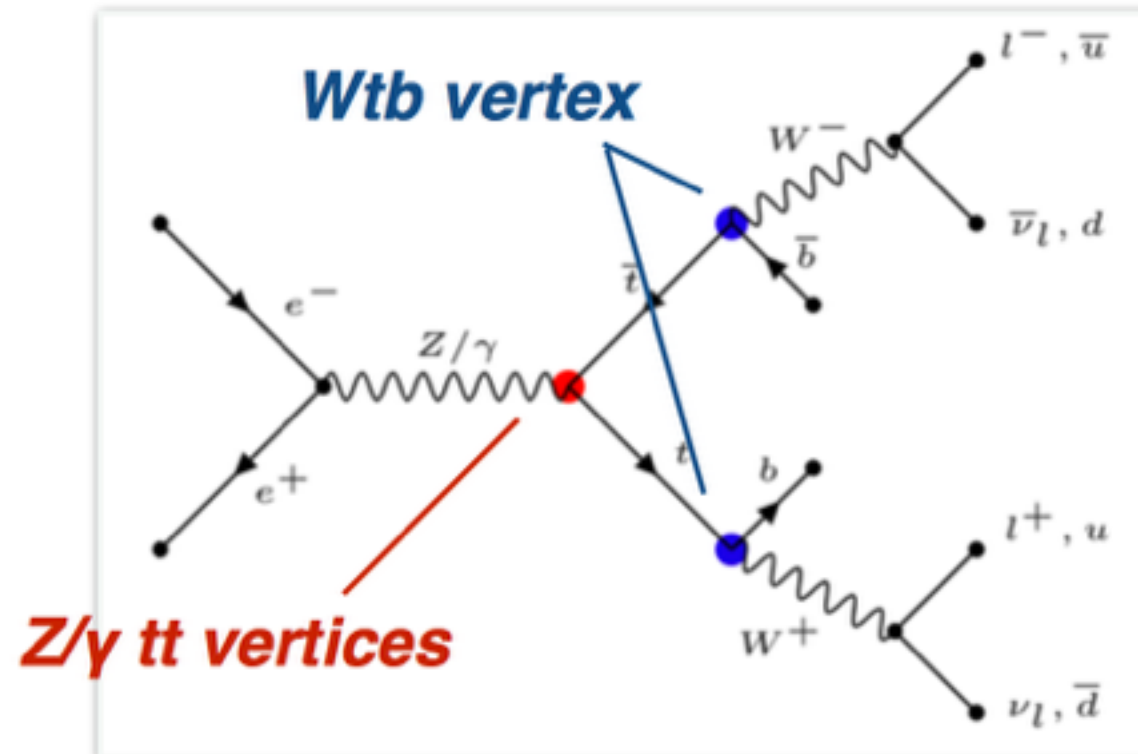
- **Lucie Linssen**
  - low-energy stage -> initial stage when referring to 380GeV
  - changed the phrasing of the positron polarization to a positive variant
  - …
- **Matthias Artur Weber**
  - Introduction of the CP violation as charge conjugation and parity (CP) violation.
  - …
- **Jan Henryk Kalinowski**
  - some redefinitions and writing suggestions
  - …

thanks for all the suggestions!!

Change to an EFT approach

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

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

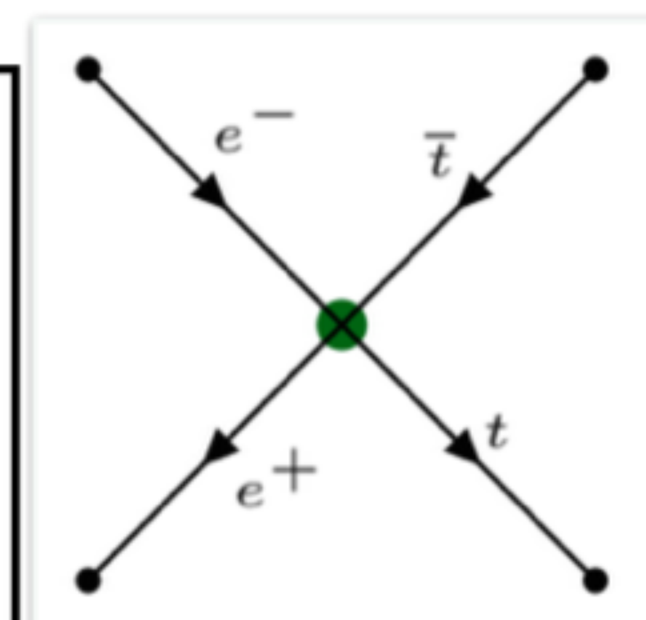


Contact interactions

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

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

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

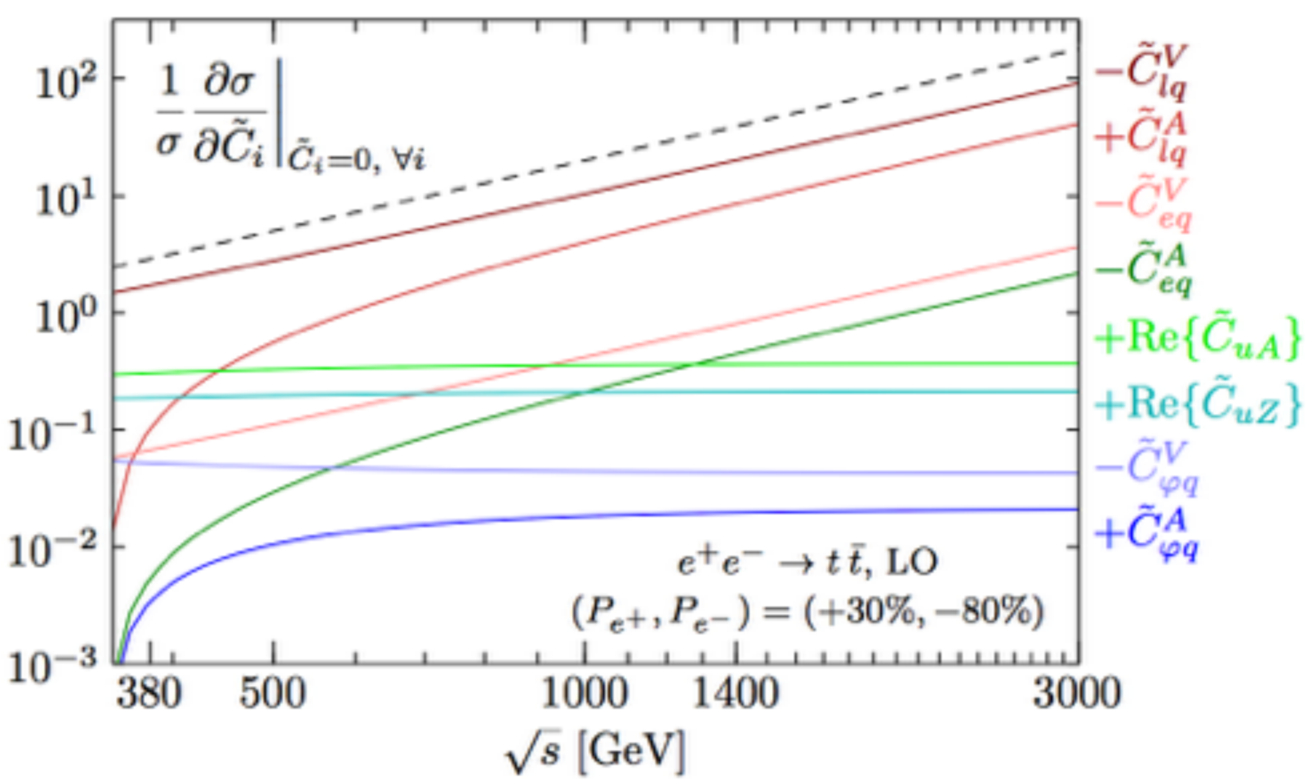


Typical procedure…

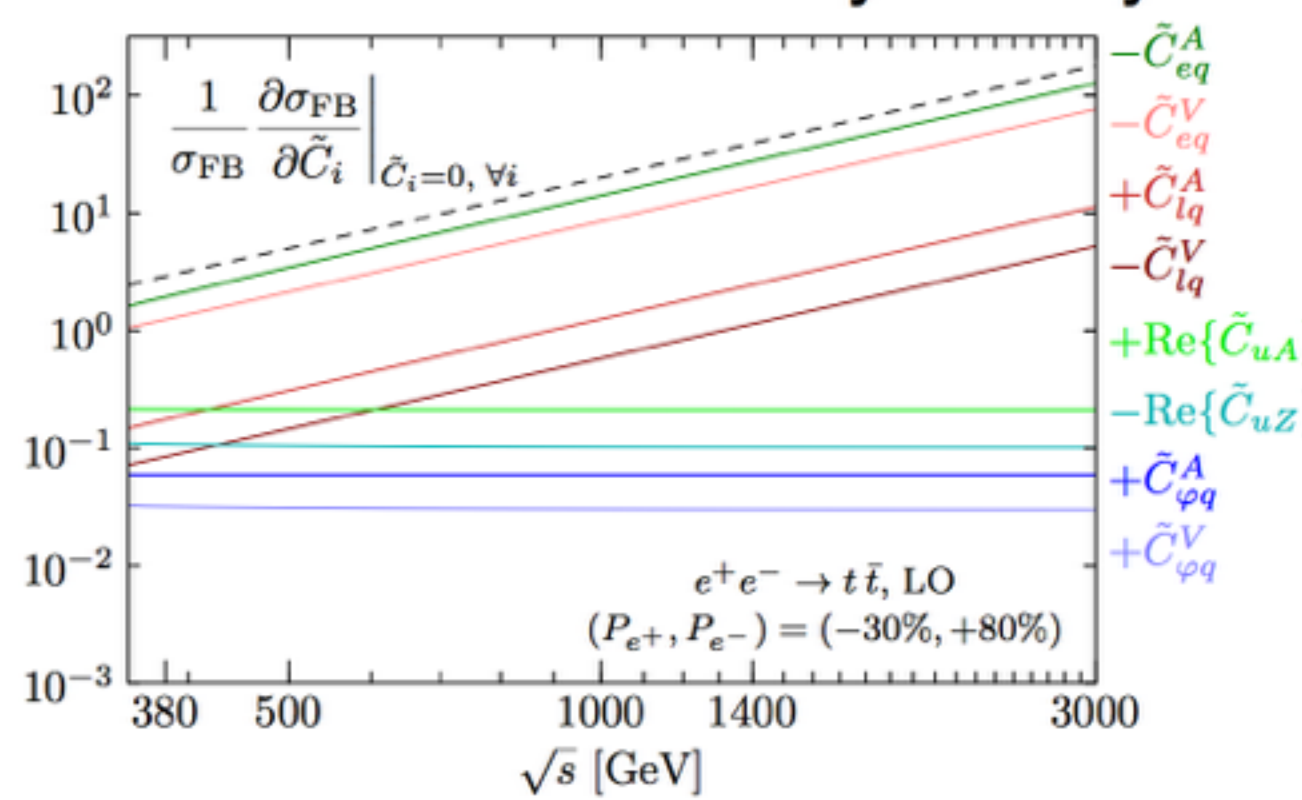
Observables sensitivity

$e^+e^- \rightarrow t\,\bar{t}$, 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
$\Delta\sigma$ (C) / σ / ΔC

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

Full-simulation

Studies included in I. Garcia thesis

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

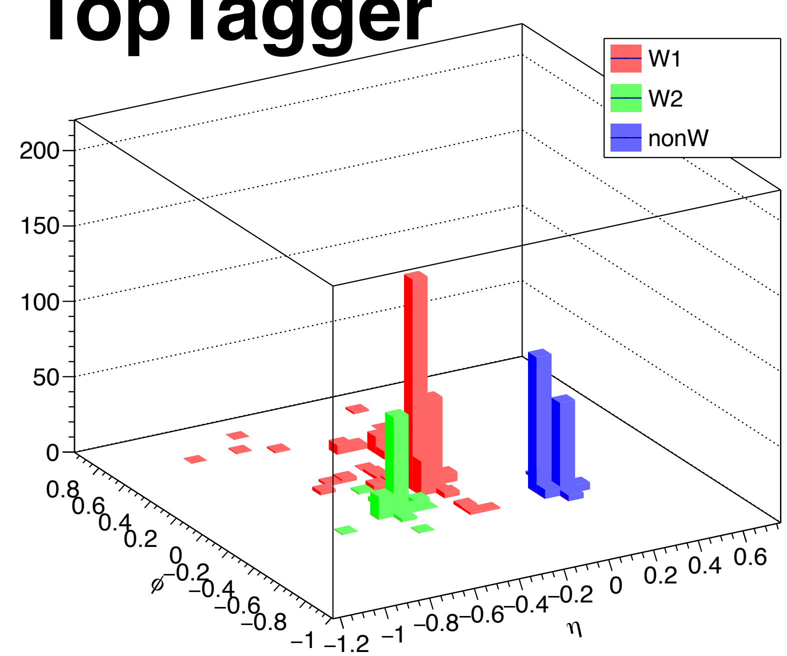
$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{\text{stat.}}$ (%)	$(\delta A^t_{\text{FB}}/A^t_{\text{FB}})_{\text{stat.}}$ (%)
−0.8, +0.3	0.47	1.8
+0.8, −0.3	0.63	1.3

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



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

Numbers not updated!!

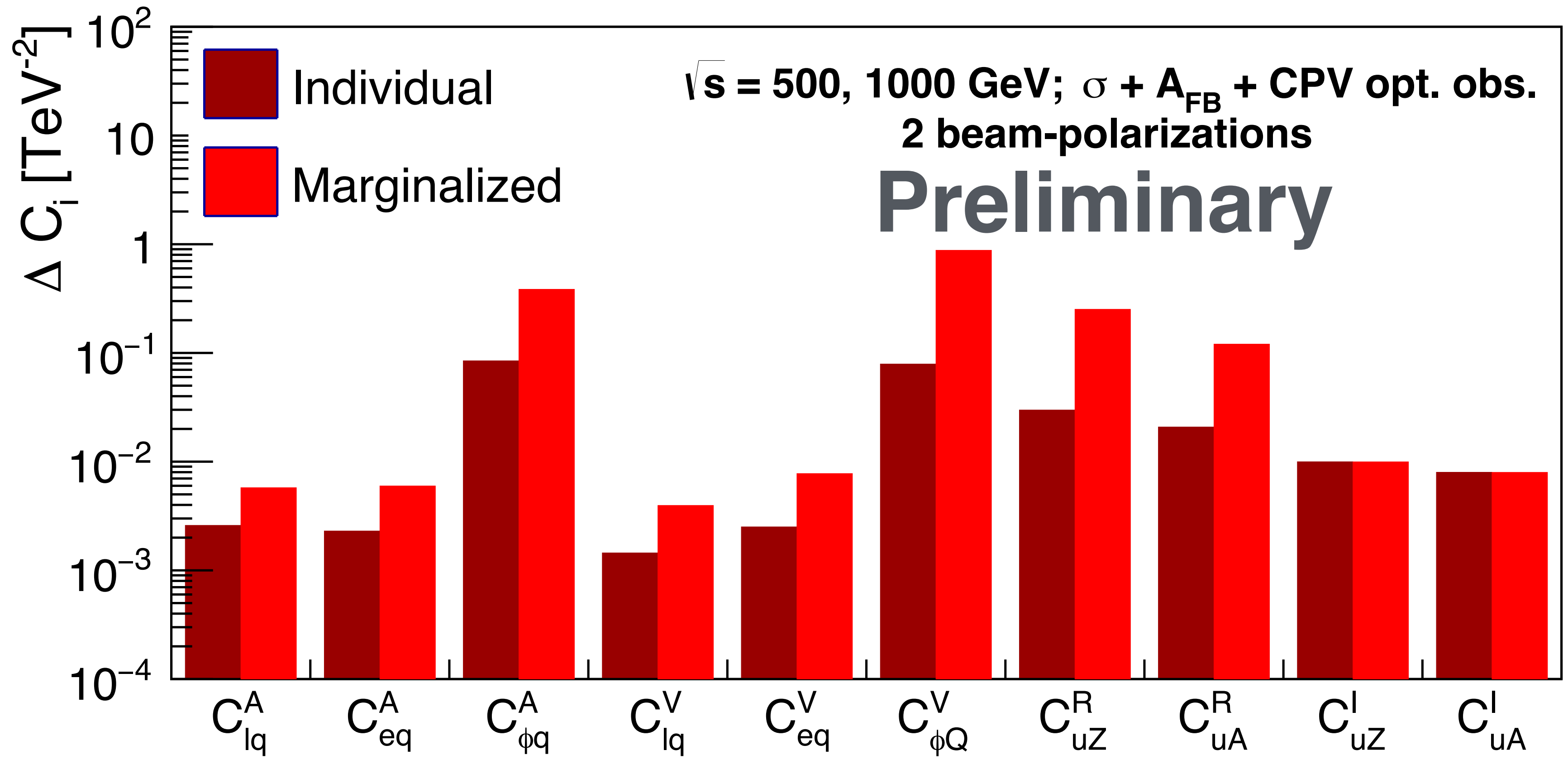
For signal only, w/o scaling or bkg. subtraction

Thanks to Rickard

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

M.P. @TopLC2017

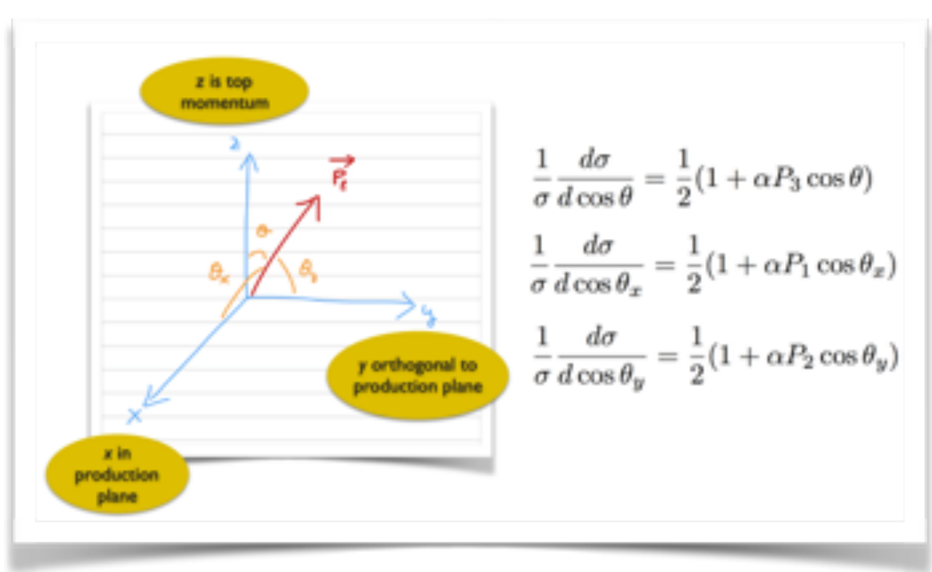
Preliminary status…

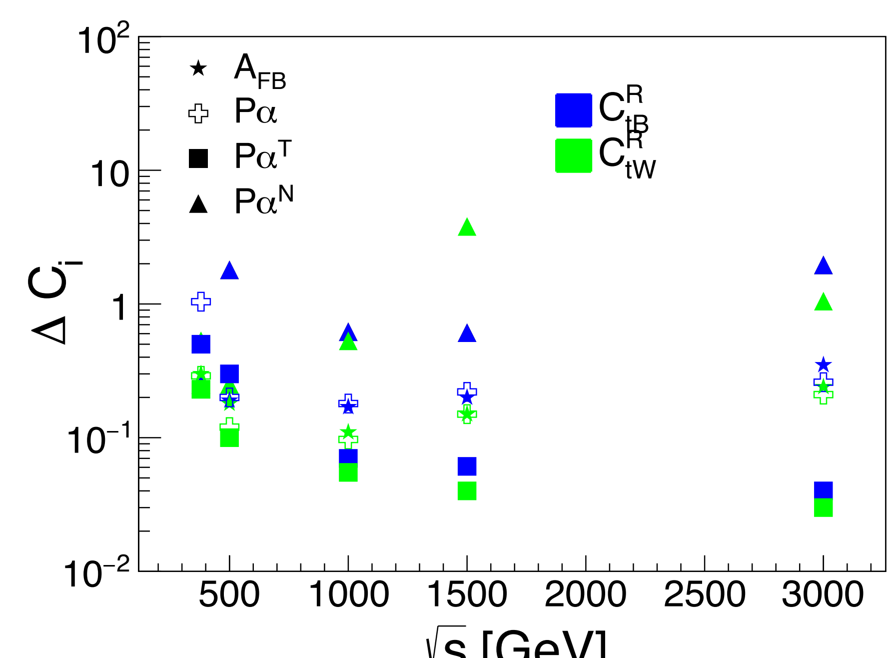


Looking for extra observables to improve the fit

i.e. top polarisation in different axes

motivation from JA Aguilar





G. Durieux @TopLC 2017:

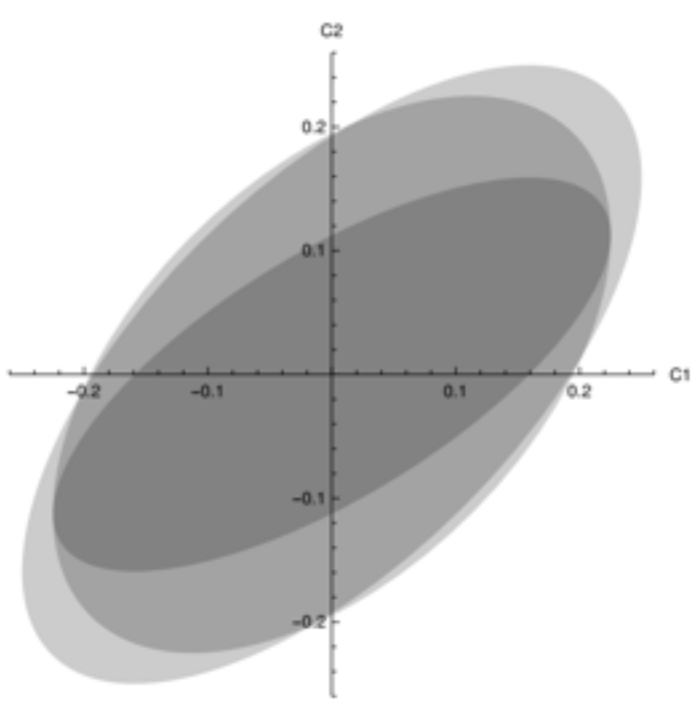
https://indico.cern.ch/event/595651/contributions/2573918/attachments/1473086/2280215/durieux-top-lc-2017.pdf

Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space.
(*joint efficient* set of estimators, saturating the Rao-Cramér-Fréchet bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the statistically optimal set of observables is: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



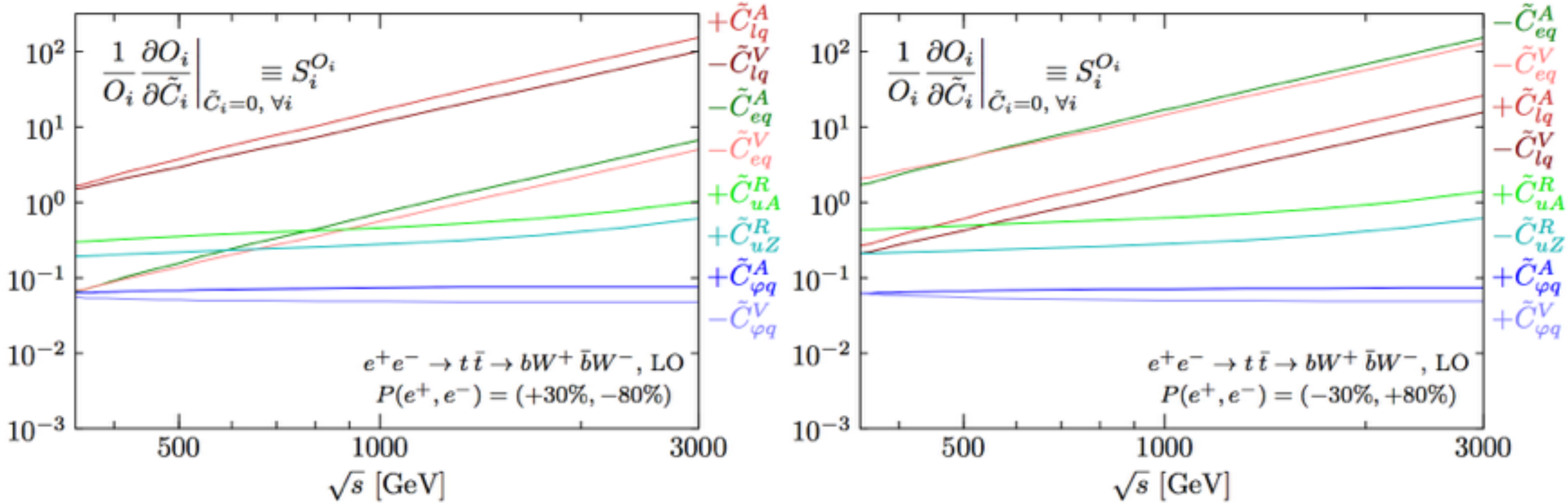
e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1 + \cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

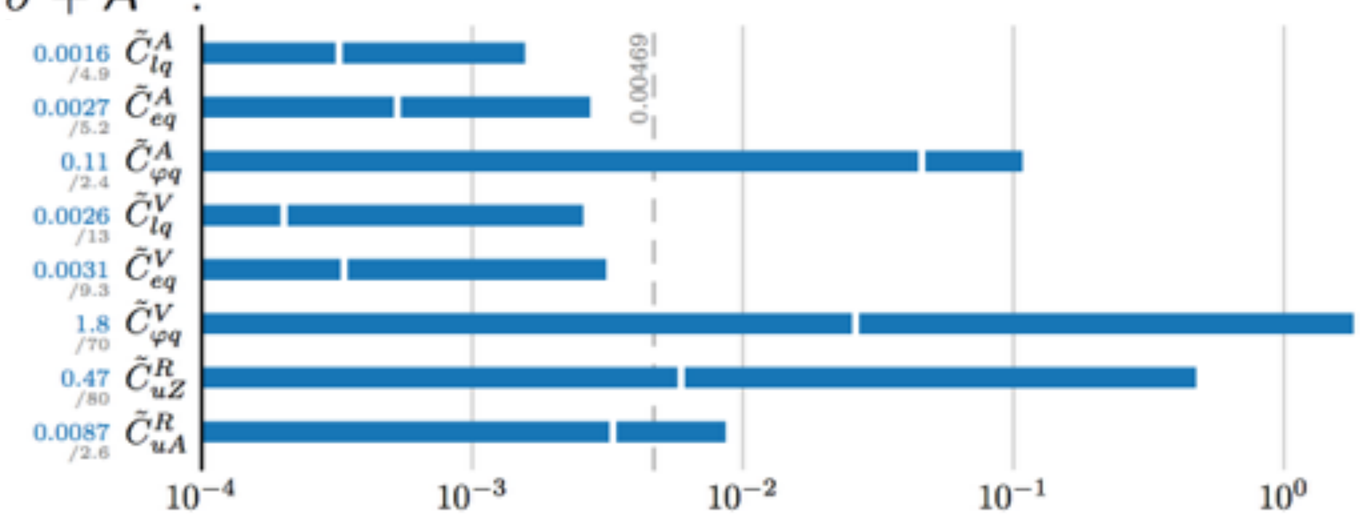
Statistically optimal observable sensitivities



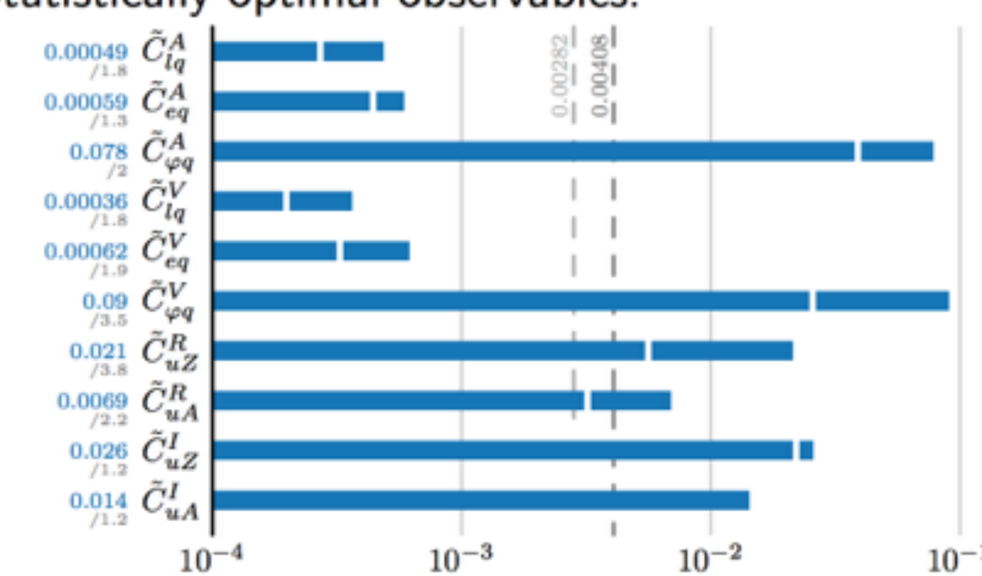
Optimal observables provide much better global limits

Comparison in the global limits (500GeV + 1TeV for 2 pols.):

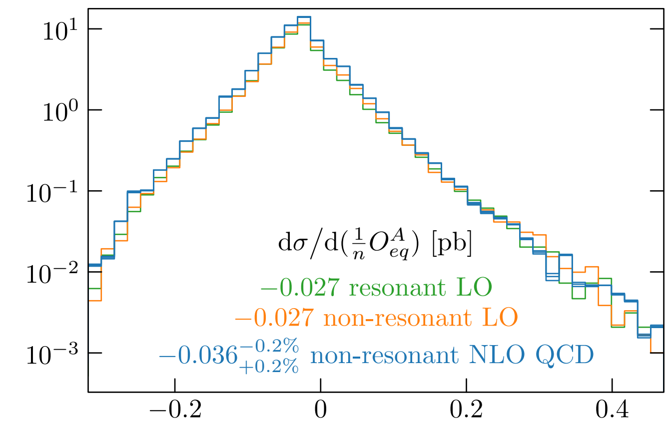
$\sigma + A^{\mathrm{FB}}$:



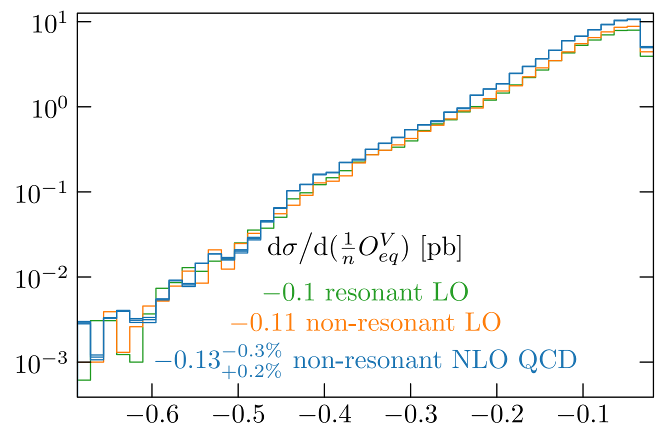
Statistically optimal observables:

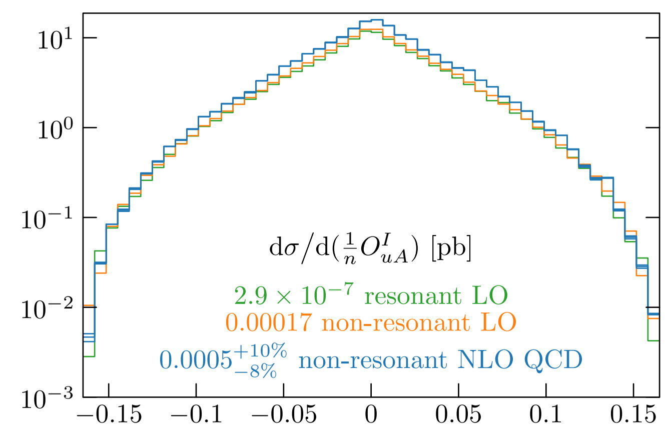


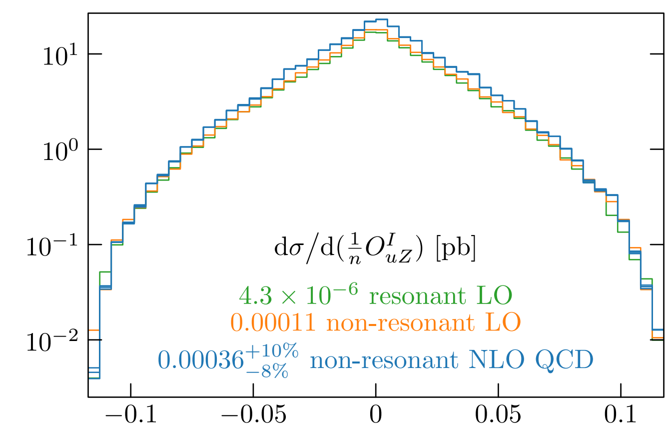
How the optimal observables look like at 500 GeV (e-, e+) = (-0.8, 0.3)

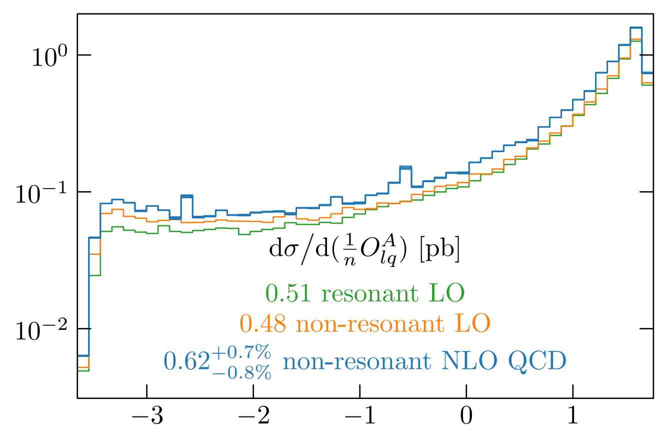


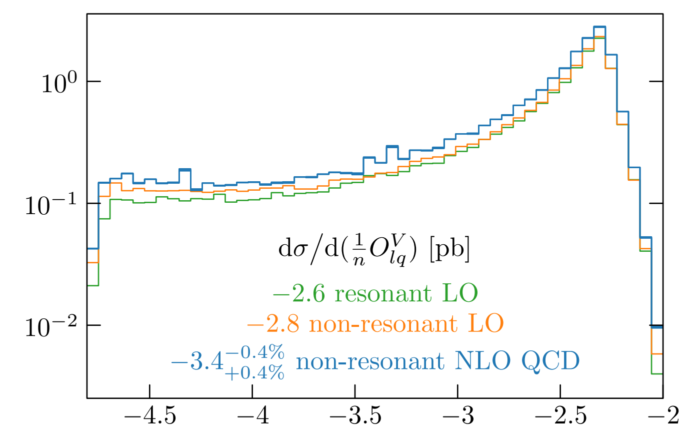
10 observables in total (one per parameter)

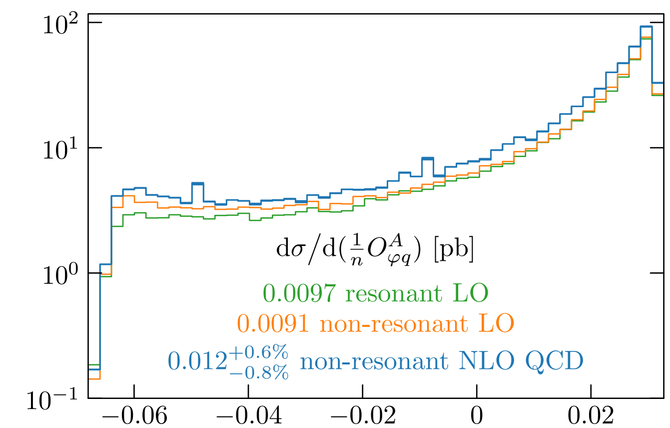


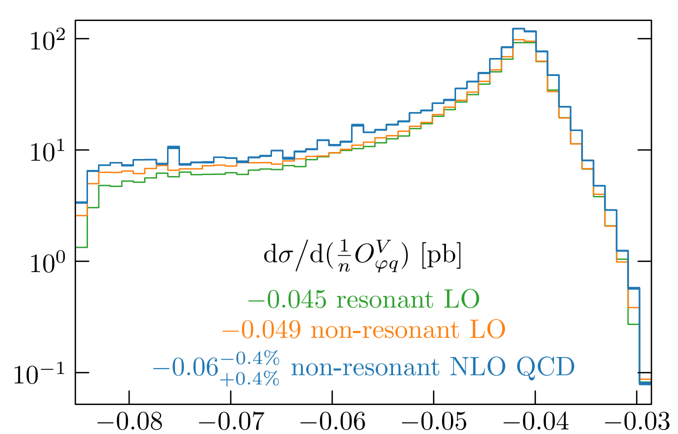


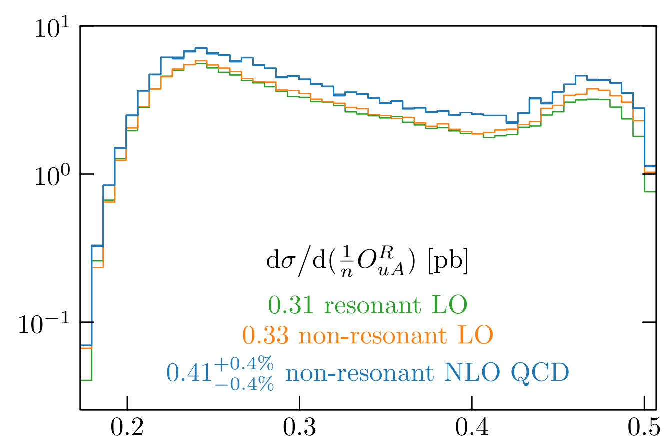


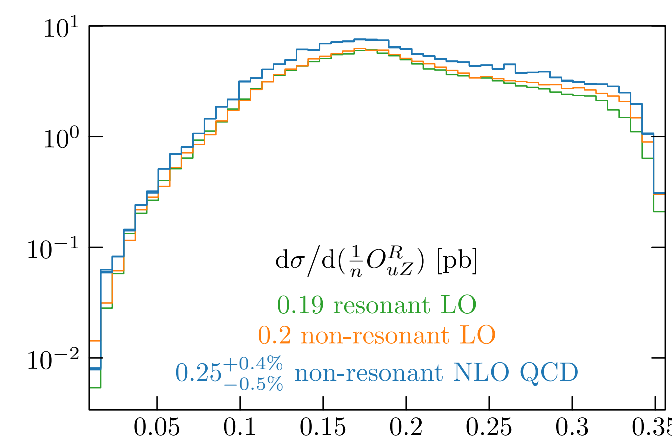












Two approaches for the optimal observables systematic studies

Optimal observables

$$O_i=(\Sigma\ \sigma_i/\sigma_0)$$

- Depends strongly on the cross-section
- Errors on the shape and normalization

Now in progess

Definition based on the mean of normalized distributions

$$O_i=1/n(\Sigma\ \sigma_i/\sigma_0)$$

- Sensitivities are calculated using real definition
- Errors only on the shape

Results in next slides

Starting reconstruction at CLIC@380 and ILC@500

(Same samples that Nacho used in his studies)

Signal selection:

Same cuts used in previous studies which reduce background.

- **Hadronic top in the range: 120 < mt < 230**
- **Hadronic W: 50 < mW < 110**
- **only 1 lepton per event**
- **2 btags (btag1 > 0.8 and btag2 > 0.5)**

Statistical uncertainties:

statistical uncertainty of the distribution mean [%]	lqA	eqA	pqA	lqV	eqV	pqV	ReuZ	ReuA	ImuZ*	ImuA*
380 (e-,e+) = (-0.8, 0)	4	6	4	0,1	0,6	0,1	0,3	0,1	1E-3	2E-3
380 (e-,e+) = (0.8, 0)	6	4	4	0,5	0,2	0,4	0,3	0,2	2E-3	2E-3
500 (e-,e+) = (-0.8, 0.3)	2	10	2	0,2	5	0,3	0,3	0,2	2E-3	4E-3
500 (e-,e+) = (0.8, -0.3)	8	2	2	2	0,5	0,9	0,9	0,3	4E-3	7E-3

*Absolute uncertainty

Starting reconstruction at CLIC@380 and ILC@500

(Same samples that Nacho used in his studies)

Reconstruction effects

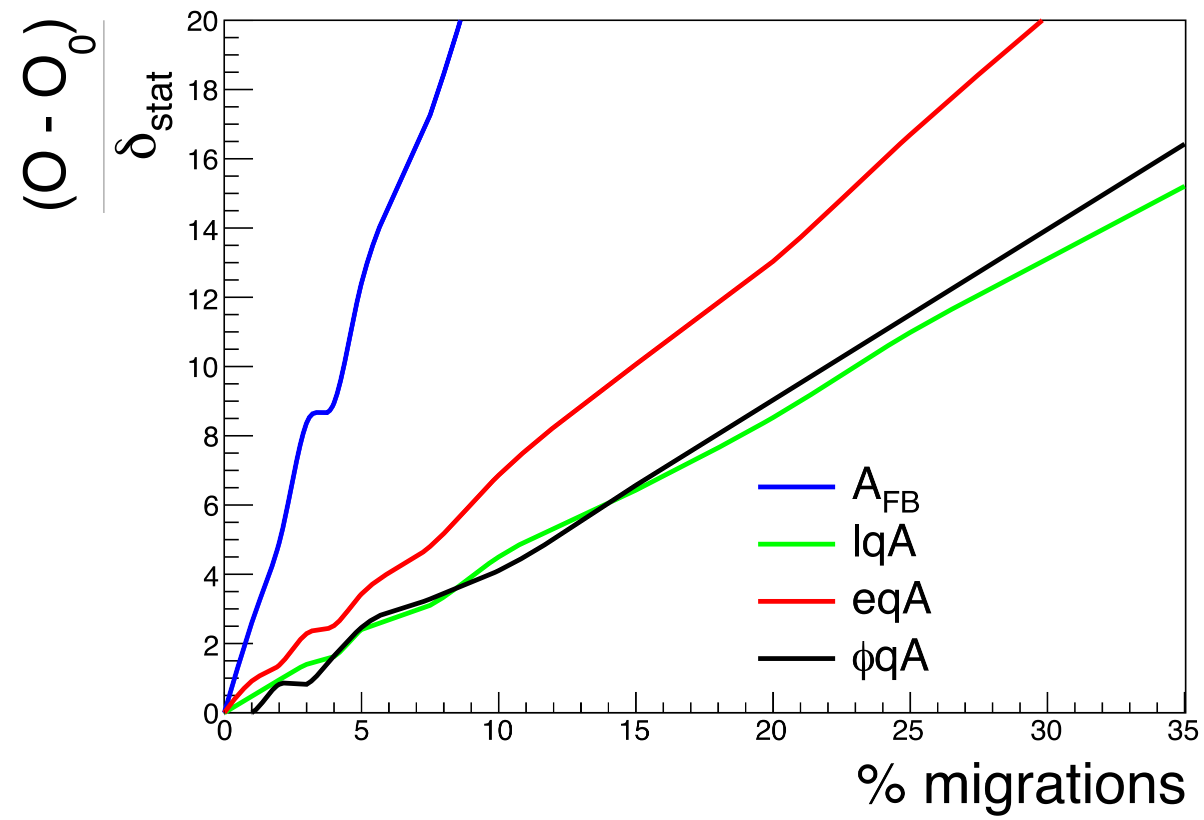
numbers are for CLIC380 (I.Garcia's analysis)

Need of a quality cut (mainly for reducing migrations)

$$\chi^2 = \left(\frac{M_t - 172.5}{\sigma_{M_{top}}}\right)^2 + \left(\frac{E_t - 190}{\sigma_{E_{top}}}\right)^2 + \left(\frac{E_b^* - 68}{\sigma_{E_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} + (-0.6)}{\sigma_{cos\theta_{bW}}}\right)^2$$

	efficiency	quality cut chi2 < X	efficiency after quality cut
380L	37%	5	18%
380R		40	30,4%
500L	34,4%	50	29,4%
500R	35%	50	30,1%

380 GeV (e-,e+) = (-0.8, 0)



Similar behaviour we oberved in the asymmetry.

Systematic uncertainties

(of the distributions means)

selection effect (impact in #σ)	IqA	eqA	pqA	IqV	eqV	pqV	ReuZ	ReuA	ImuZ	ImuA
380 (e-,e+) = (-0.8, 0)	2	3	2	1	3	0	2	1	0,2	0,2
380 (e-,e+) = (0.8, 0)	3	0,5	0,1	0,1	0	0	0,5	0	0,4	0,3
500 (e-,e+) = (-0.8, 0.3)	0,8	0,6	0,6	0,4	0,3	0,1	2	2	0,5	0,5
500 (e-,e+) = (0.8, -0.3)	0,4	2	2	0,7	0,8	0,2	0,2	1	1	1

Selection biases around 1σ in almost all cases

reconstruction effect (impact in #σ)	IqA	eqA	pqA	IqV	eqV	pqV	ReuZ	ReuA	ImuZ	ImuA
380 (e-,e+) = (-0.8, 0)	2	3	1	2	1	2	1	1	0,1	0,1
380 (e-,e+) = (0.8, 0)	2	2	2	1	2	1	1	2	0,2	0,3
500 (e-,e+) = (-0.8, 0.3)	2	0,3	2	1	0,3	1	0,5	2	0,4	0,5
500 (e-,e+) = (0.8, -0.3)	0,5	2	2	0,2	2	1	2	2	0,4	0,5

Reconstruction biases around 1σ in almost all cases

Beam structure effects
(of the distributions means)

Using WHIZARD 2.3.1 for MC generation:

Beamstrahlung switching on/off CIRCE1:

selection effect (impact in #σ)	lqA	eqA	pqA	lqV	eqV	pqV	ReuZ	ReuA	ImuZ	ImuA
380 (e-,e+) = (-0.8, 0)	0,4	0,4	0,3	0,3	0,3	0,2	0	0,3	0	0
380 (e-,e+) = (0.8, 0)	0,5	1	1	0	1	0,8	1	0,9	0	0
500 (e-,e+) = (-0.8, 0.3)	1	2	1	1	0,4	1	0,6	1	0	0
500 (e-,e+) = (0.8, -0.3)	0,4	1	1	0,5	1	0,9	1	1	0	0

Parameterts variaton give rise to much smaller effects

Switching on/off ISR (using parameters by default):

selection effect (impact in #σ)	lqA	eqA	pqA	lqV	eqV	pqV	ReuZ	ReuA	ImuZ	ImuA
380 (e-,e+) = (-0.8, 0)	1	1	1	1	0,1	1	0,7	1	0	0
380 (e-,e+) = (0.8, 0)	1	1	1	0,5	1	0,6	0,7	1	0	0
500 (e-,e+) = (-0.8, 0.3)	2	2	2	3	0,7	3	2	2	0	0
500 (e-,e+) = (0.8, -0.3)	1	2	2	0,7	3	2	3	2	0	0

Low impact of the beam structure

Conclusions

- Optimal observables for global EFT fit are found to be robust

Future work

- EFT paper in preparation
- Complet systematic studies ongoing
- Move to CLIC@1400 (collaboration with Rickard)