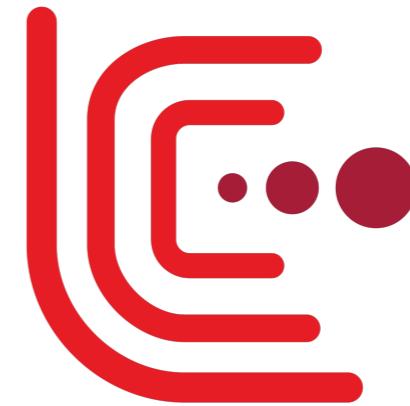


# **Studies of bottom and top quark couplings at 250 GeV and above**

**Martín Perelló Roselló (IFIC - U. Valencia/CSIC)**



## **Acknowledging input/contributions from:**

Junping Tian (U. Tokyo), Sungsoon Jun, Junghwan Lee (SNU - Korea)

I. García, V. Miralles, A. Peñuelas, M. Vos (IFIC - U. Valencia/CSIC)

A. Irles, R. Pöschl (Orsay, LAL), G. Durieux (Technion - IIT), R. Ström (CERN)

CLICdp and ILD Working Groups

# Introduction

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- Some models BSM predict deviations directly related with top quark couplings.
- Top quark EW sector is poorly constrained. Future electron-positron colliders give a big opportunity to access directly to  $t\bar{t}Z/\gamma$ .
- Many studies have put constraints using LHC data and prospects in future colliders.
- In this talk a combined study between top and bottom quarks is presented using an EFT approach.

# Top-bottom quark EFT basis

Durieux, Irles, Miralles, Peñuelas, Perelló, Pöschl, Vos - The electro-weak couplings of the top and bottom quarks - global fit and future prospects- [arXiv:1907.10619](https://arxiv.org/abs/1907.10619)

## dim-6 EW 2-fermion operators

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

$O_{\varphi Q}^1 \equiv \frac{y_t^2}{2}$	$\bar{q}\gamma^\mu q$	$\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi,$
$O_{\varphi Q}^3 \equiv \frac{y_t^2}{2}$	$\bar{q}\tau^I \gamma^\mu q$	$\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi,$
$O_{\varphi u} \equiv \frac{y_t^2}{2}$	$\bar{u}\gamma^\mu u$	$\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi,$
$O_{\varphi d} \equiv \frac{y_t^2}{2}$	$\bar{d}\gamma^\mu d$	$\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi,$
$O_{\varphi ud} \equiv \frac{y_t^2}{2}$	$\bar{u}\gamma^\mu d$	$\varphi^T \epsilon i D_\mu \varphi,$
$O_{uW} \equiv y_t g_W$	$\bar{q}\tau^I \sigma^{\mu\nu} u$	$\epsilon \varphi^* W_{\mu\nu}^I,$
$O_{dW} \equiv y_t g_W$	$\bar{q}\tau^I \sigma^{\mu\nu} d$	$\epsilon \varphi^* W_{\mu\nu}^I,$
$O_{uB} \equiv y_t g_Y$	$\bar{q}\sigma^{\mu\nu} u$	$\epsilon \varphi^* B_{\mu\nu},$
$O_{dB} \equiv y_t g_Y$	$\bar{q}\sigma^{\mu\nu} d$	$\epsilon \varphi^* B_{\mu\nu},$
$O_{u\varphi} \equiv$	$\bar{q}u$	$\epsilon \varphi^* \varphi^\dagger \varphi,$

Left- and right-handed  
couplings of the t- and  
b-quarks to the Z-boson

Charged current interaction.

EW dipole operators.

**Top Yukawa.** In this study we consider  $m_b = 0$ , so bottom Yukawa is not included in the fit.

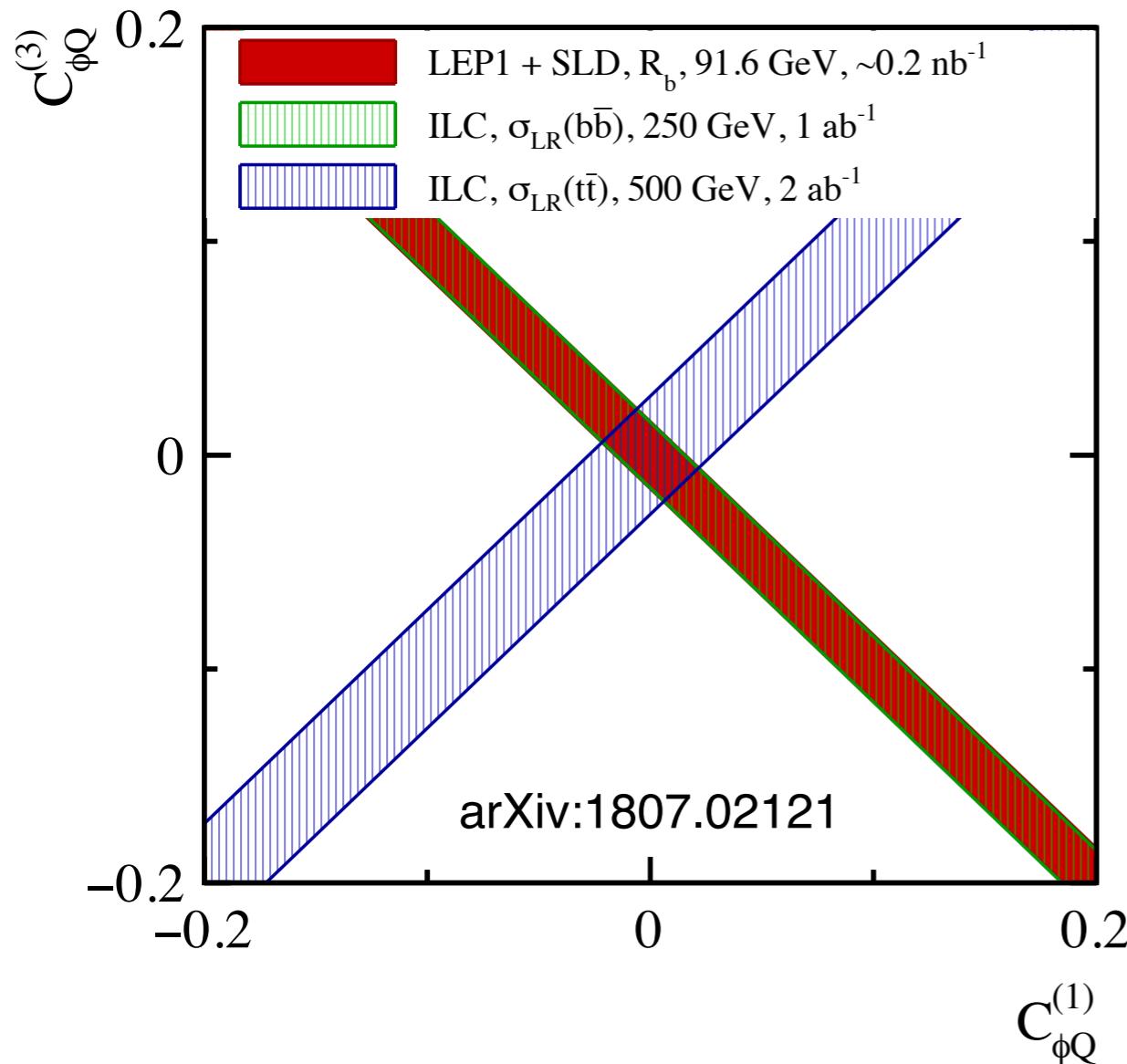
Chromo-magnetic dipole operators and four-quark operators not included in the fit

Two-lepton-two-quark operators discussed later

# Motivation for a combined t- and b-quark fit

Complementarity between bb (LEP) and tt (Future electron-positron collider) production

Excellent precision measurements on the Z resonance - [arXiv:hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008)



the top and bottom left coupling to the Z-boson share the same operators

$$\delta g_L^t = -(C_{\varphi Q}^1 - C_{\varphi Q}^3)m_t^2/\Lambda^2$$

$$\delta g_L^b = -(C_{\varphi Q}^1 + C_{\varphi Q}^3)m_t^2/\Lambda^2$$

$$\delta g_R^t = -C_{\varphi u} m_t^2/\Lambda^2$$

$$\delta g_R^b = -C_{\varphi d} m_t^2/\Lambda^2$$

ILC250 does not help for left-handed couplings compared to LEP

# LHC and LEP data

Durieux, Irles, Miralles, Peñuelas, Perelló, Pöschl, Vos - [arXiv:1907.10619](https://arxiv.org/abs/1907.10619)

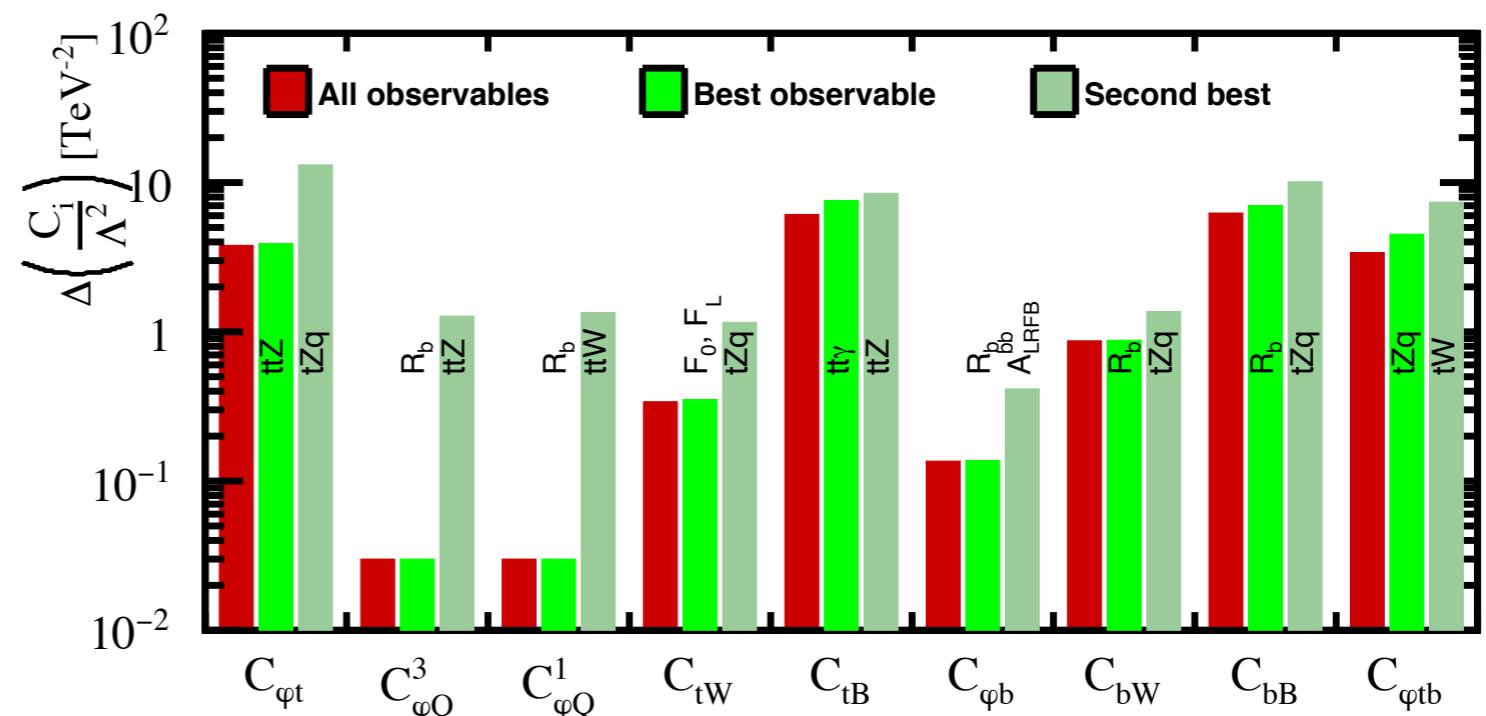
Process	observable	$\sqrt{s}$
$pp \rightarrow t\bar{t}H$	cross section	13 TeV
$pp \rightarrow t\bar{t}Z/W$	cross section	13 TeV
$pp \rightarrow t\bar{t}\gamma$	fid. x-sec.	13 TeV
single-top (t-ch)	cross section	13 TeV
single-top (Wt)	cross section	13 TeV
single-top (tZq)	cross section	13 TeV
$t \rightarrow W^+b$	$F_0, F_L$	8 TeV
$e^-e^+ \rightarrow b\bar{b}$	$R_b, A_{FBLR}^{bb}$	$\sim 91$ GeV

- Observables with tree-level dependence to the dim-6 operators
- We do not include other observables like EWPO or flavour processes

68% probability for each Wilson coefficient. In **red** when all measurements are considered. In **light green** the best limit from a single observable. In **dark green** the second best.

We observe a good interplay between the parameters and the chosen observables.

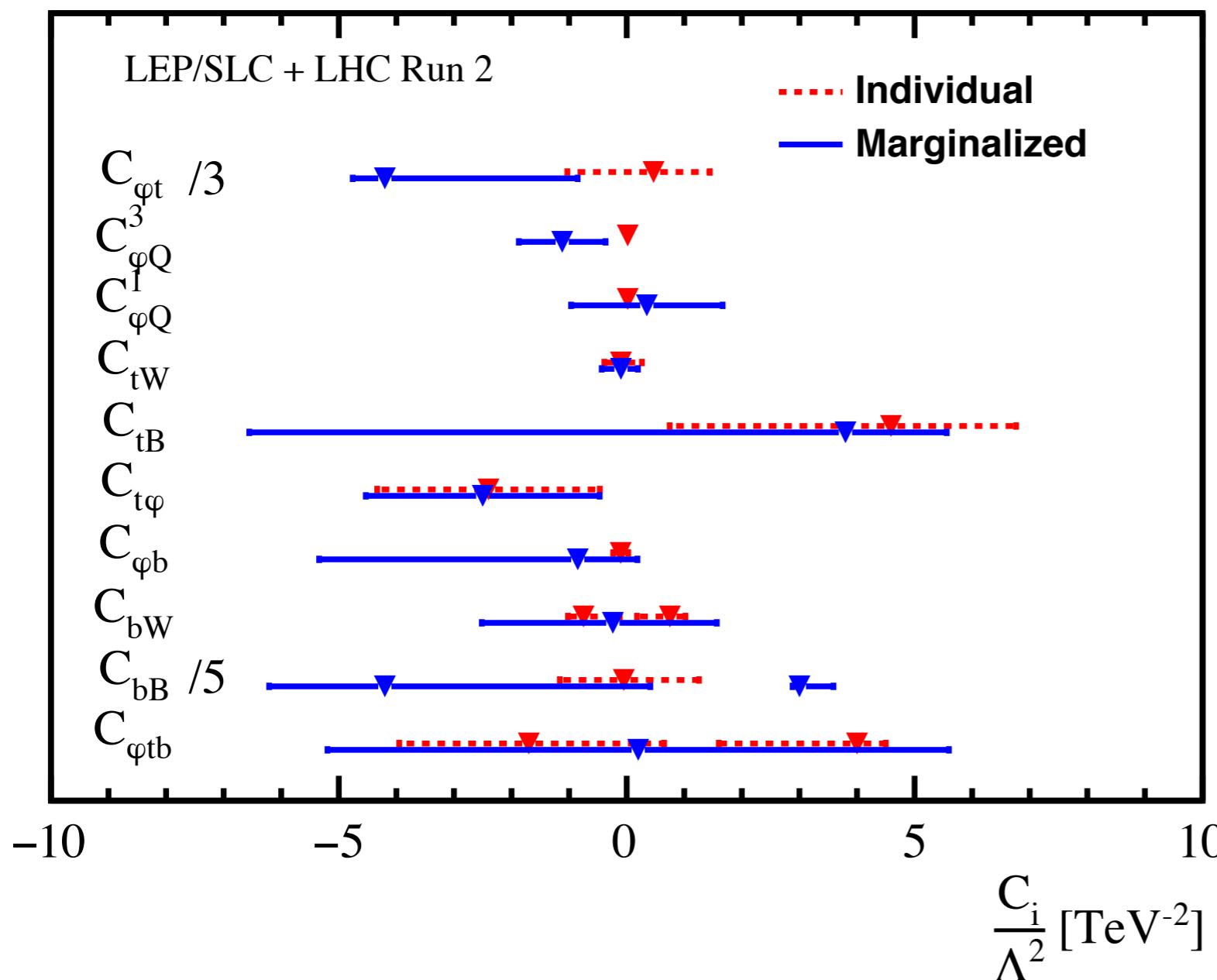
LHC provides good observables for an EW top fit



# Current bounds: 10-parameter fit

Durieux, Irles, Miralles, Peñuelas, Perelló, Pöschl, Vos - [arXiv:1907.10619](https://arxiv.org/abs/1907.10619)

Bayesian fit (HEPfit open source): 68% probability.



The fit yields robust results even when all operator coefficients are varied simultaneously.

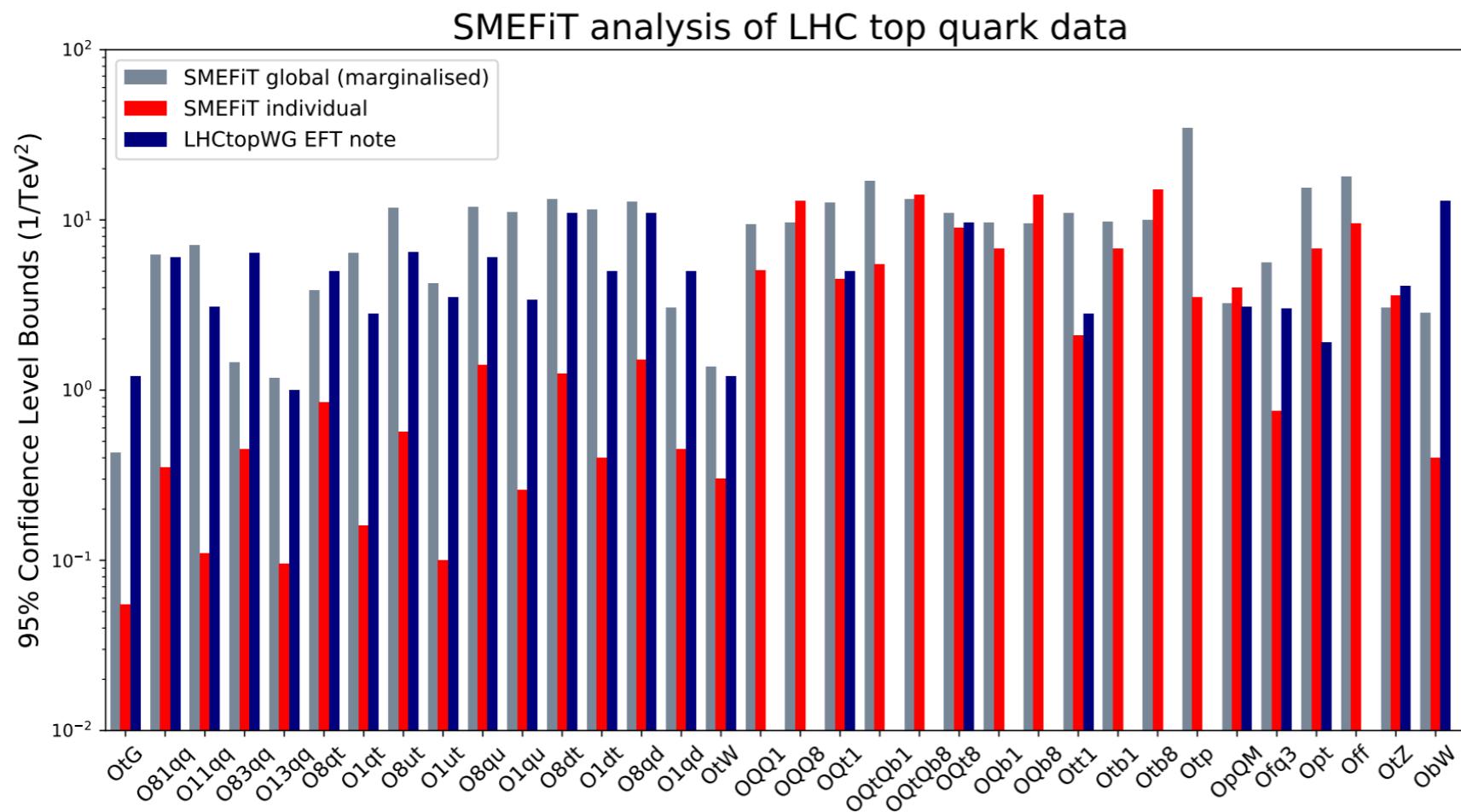
We have to reduce between individual and global limits.

# Going more global

A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector - *Hartland, Maltoni, et al.* - [1901.05965](#)

34-parameter fit including also 4-quark operators using LHC data at 8 and 13 TeV

more than 30 independent measurements from 10 different processes



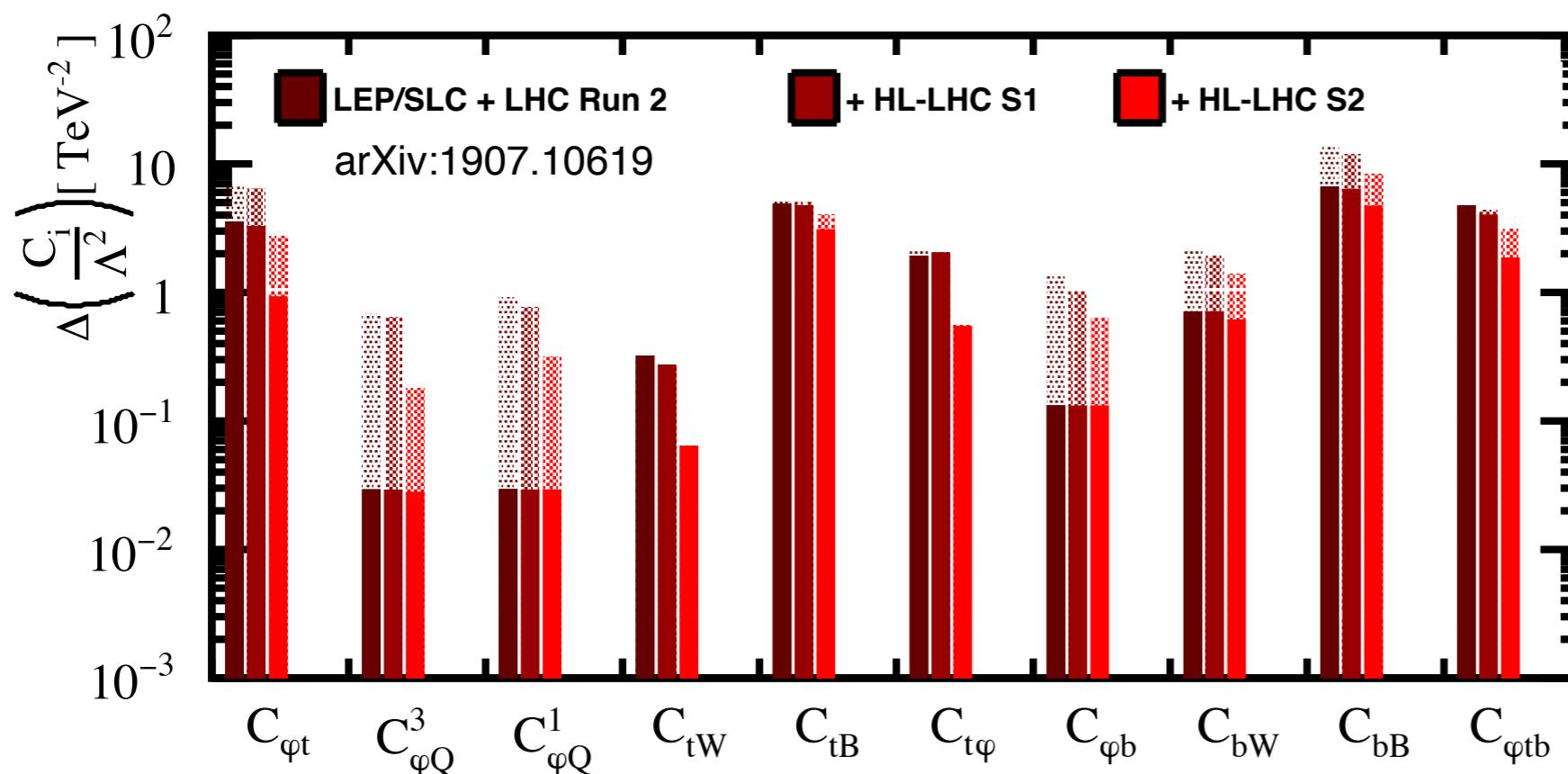
Wider bounds due to a higher number of parameters in the fit.

# Prospects LHC

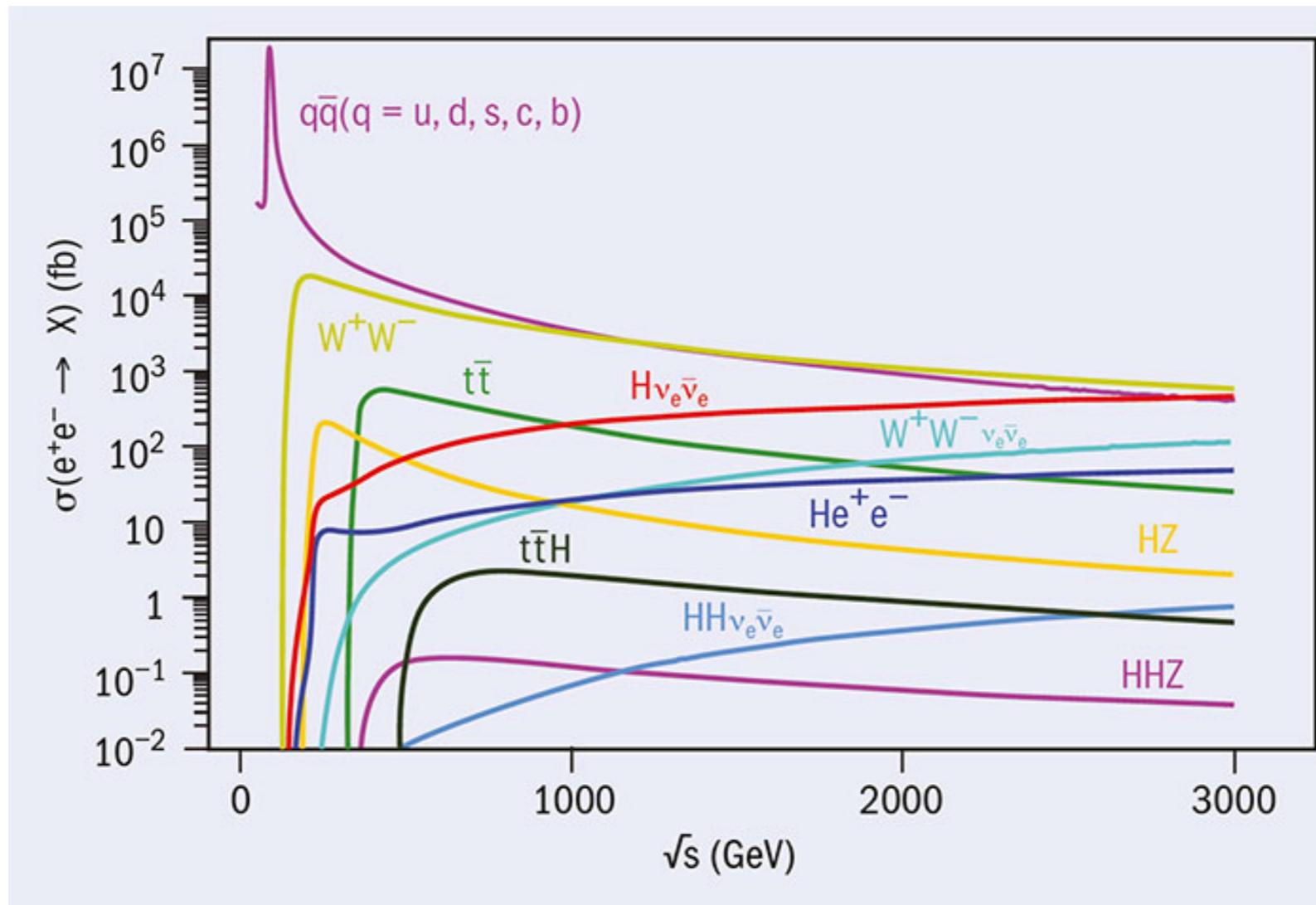
2 scenarios for HL-LHC:

- S1: statistical uncertainty scaled with luminosity.
- S2: stat. and syst. scaled with  $N^{-1/2}$ , theory reduce by a factor 2.

*Inspired by Higgs chapter in  
the HL-LHC Yellow Report*



# Future electron-positron colliders



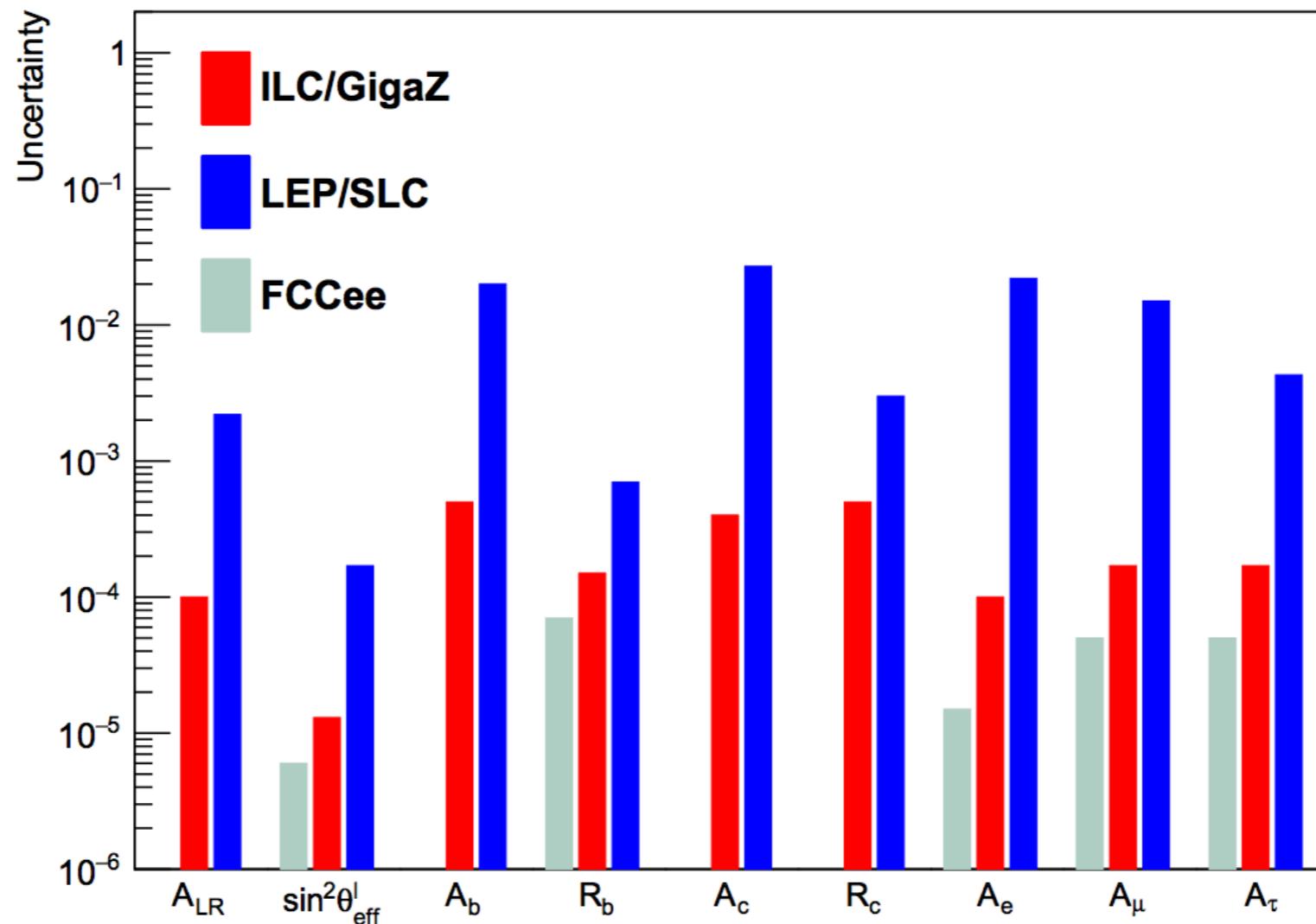
- Special attention to  $bb$ ,  $tt$  and  $ttH$  production
- We start to produce top pairs at  $\sim 350$  GeV

# Giga-Z

Better precision in electroweak observables if we run **Giga-Z** at the ILC

- LCC Physics WG **1908.11299**
- Irles, et al **1905.00220**

*See R. Pöschl talk on Thursday morning about Giga-Z*



# ILC250: bb production

**A. Irles, R. Poeschl, F. Richard in preparation**

**Jet charge identification** originated by a b-quark

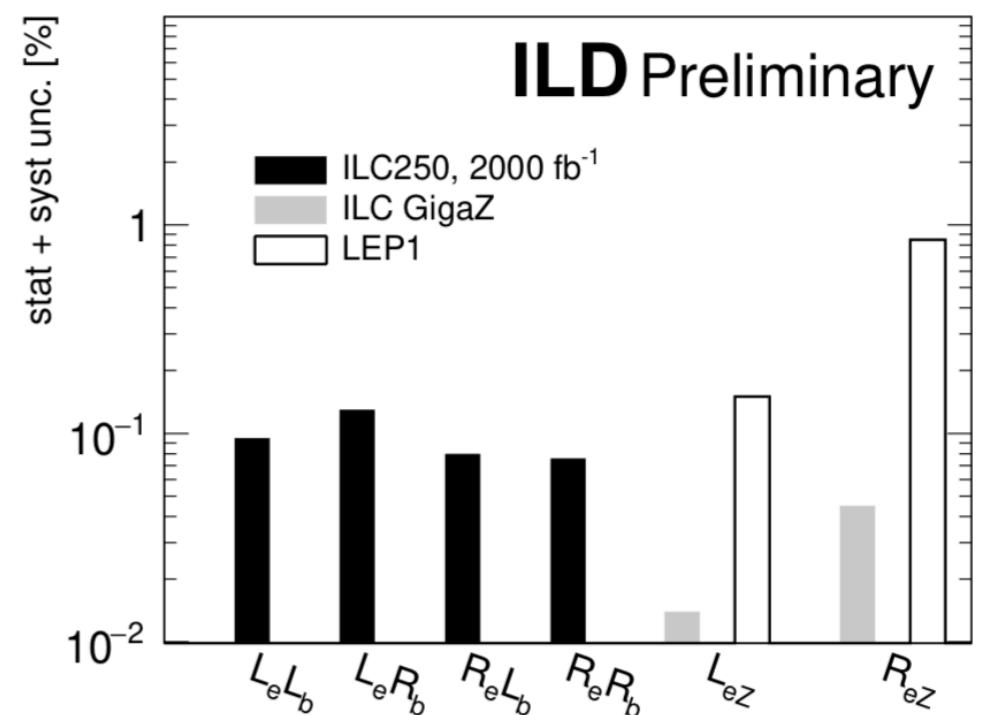
The charge measurement is optimally performed using the precise micro-vertex detector of the detector ILD and the charged kaon identification provided by the  $dE/dx$  information of its TPC.

Main systematic uncertainties: the background subtraction, the errors due to beam polarisation estimation and the b-tagging efficiency.

*See A. Irles on Tuesday afternoon for application of this technique in cc production and R. Pöschl talk on Wednesday morning for a deeper discussion on systematics*

*Statistical and systematic  
uncertainties below 1%*

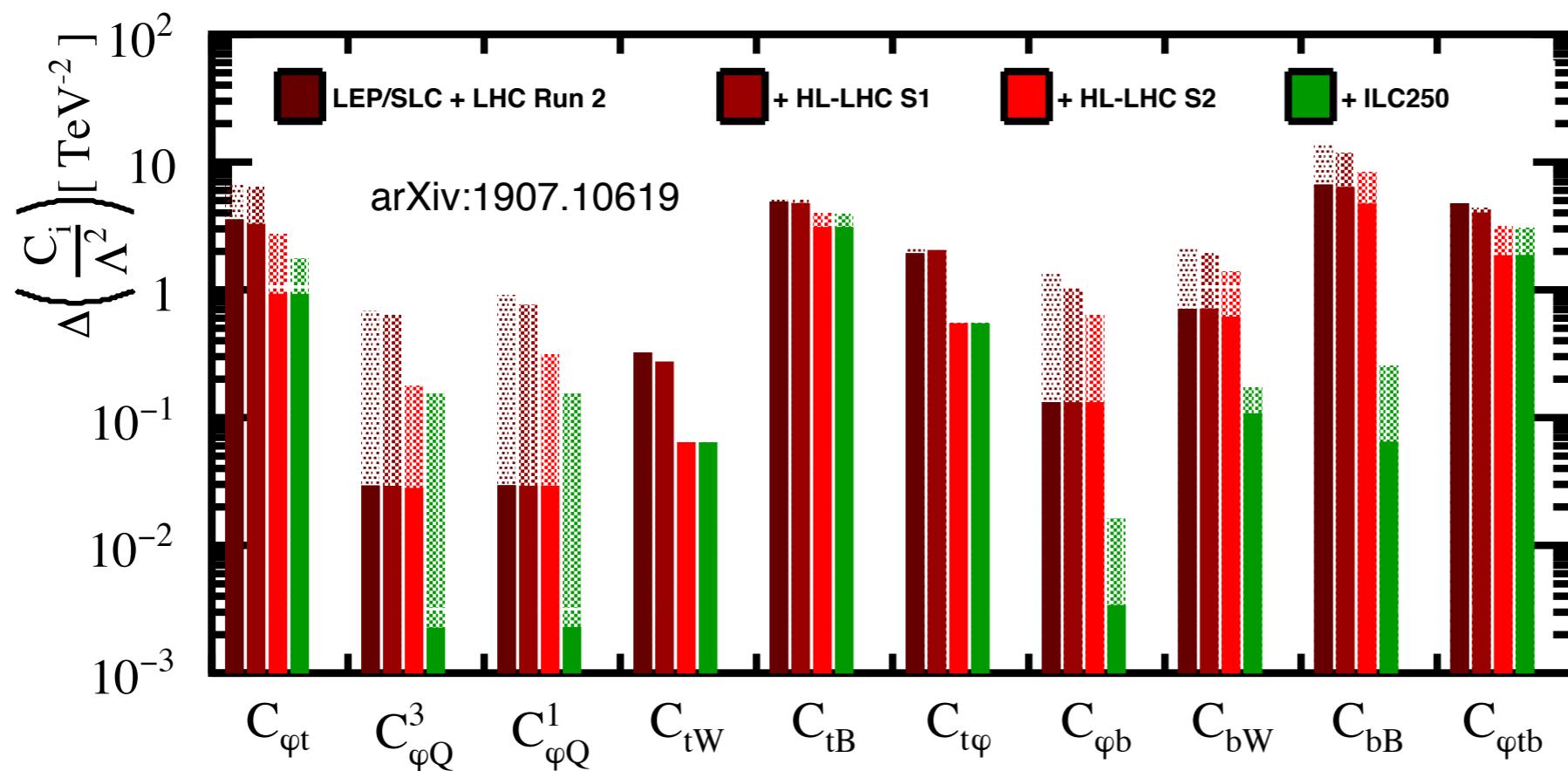
	Beam Polarisations ( $e^-, e^+$ )	
	(-80,30)	(80,-30)
Selection Eff. [%]	29	29
Luminosity [ $fb^{-1}$ ]	900	900
$\Delta S$ (syst.+stat.) [%]	$0.095 + 0.15$	$0.20+0.17$
$\Delta A$ (syst.+stat.) [%]	$0.13 + 0.15$	$0.77+0.26$



# ILC250: bb production

Including **cross-section** and **A<sub>fb</sub>** from bb production with 2 pols...

- reduce substantially the individual limits in all b-quark operators
- in the global fit, left-handed coupling barely improves compared with LEP
- right-couplings and dipole operators improve significantly their bounds.



The top-quark operators improve somewhat as well, due to a reduction of the correlation with the bottom-quark operators.

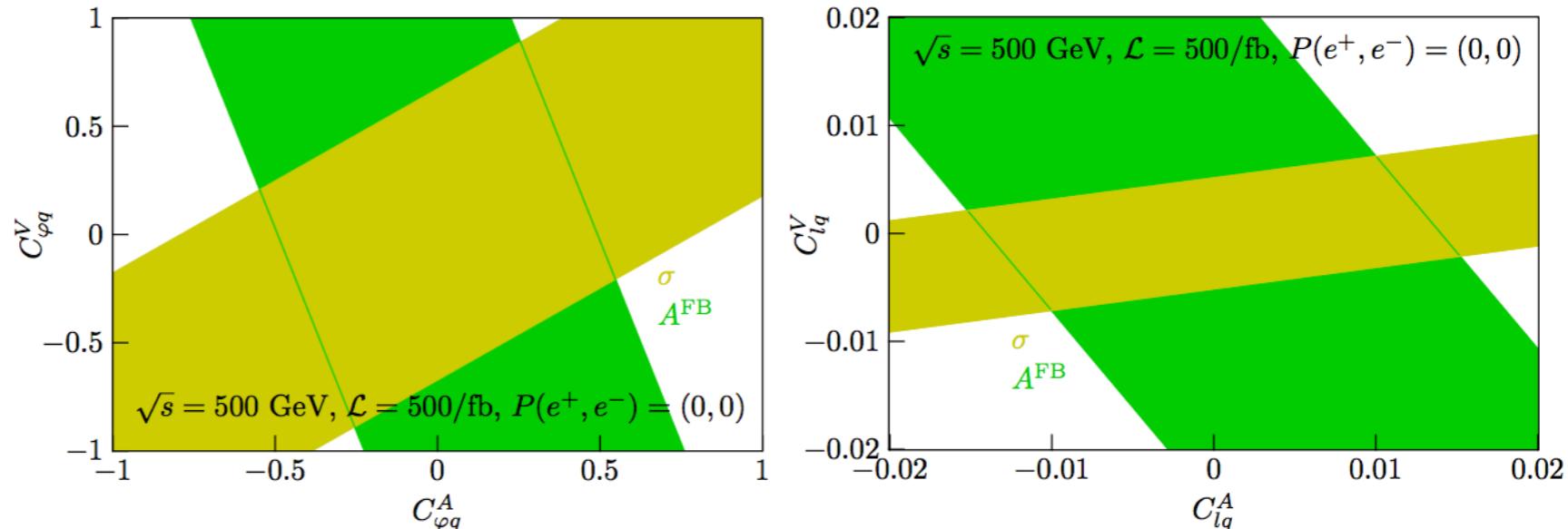
# tt production at electron-positron colliders

Moving to higher energies where tt is activated

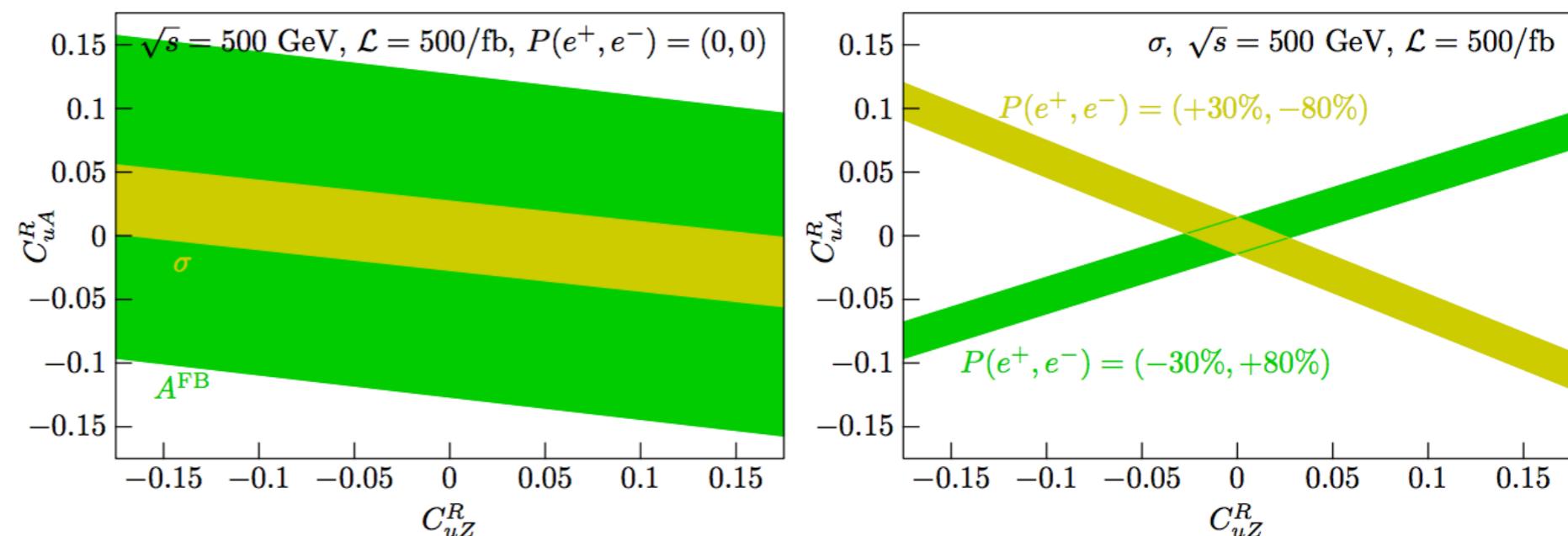
arXiv:1807.02121

Nice **complementarity** between  $A_{fb}$  and cross-section to **disentangle vector and axial operators.**

See talk by **Yuichi Okugawa** about **newest results on the tt cross section measurement** at the LC this afternoon



Role of beams polarization:



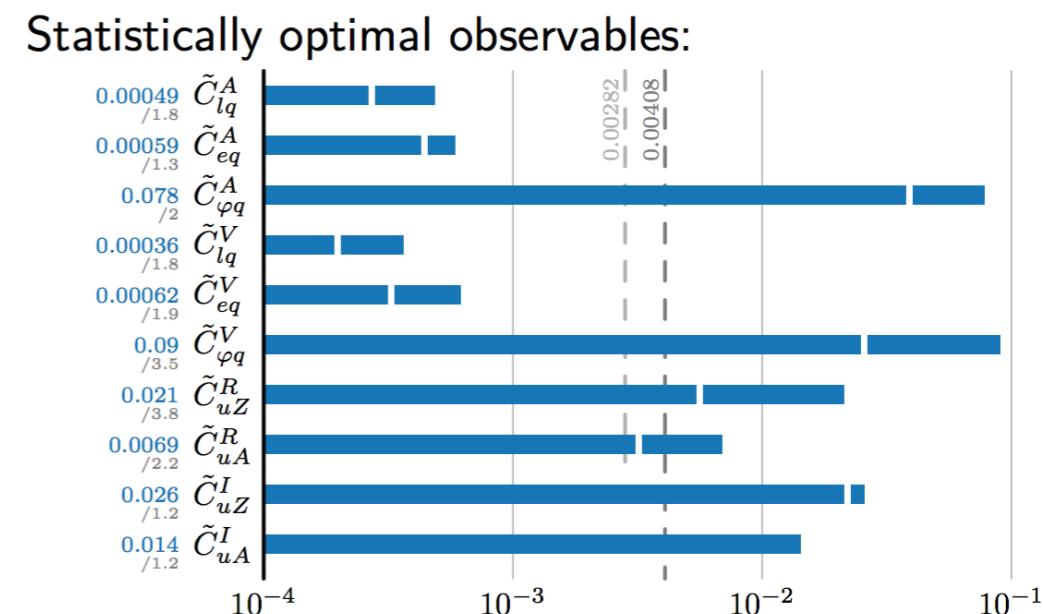
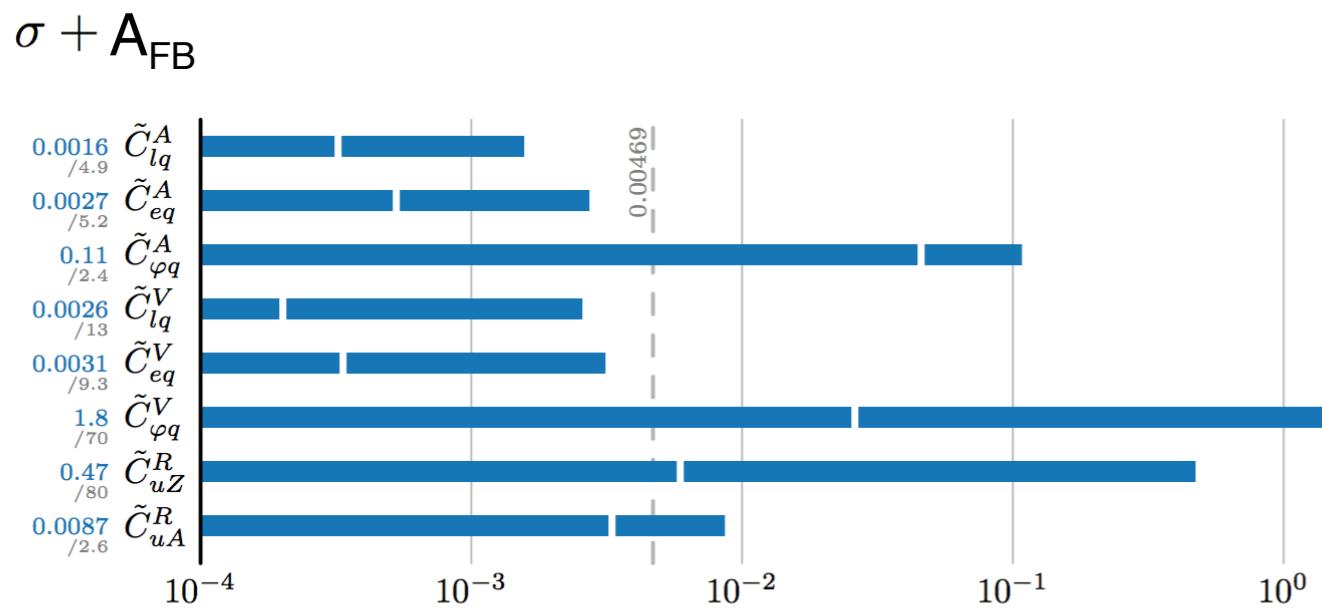
# tt production at electron-positron colliders

## Statistically optimal observables

arXiv:1807.02121

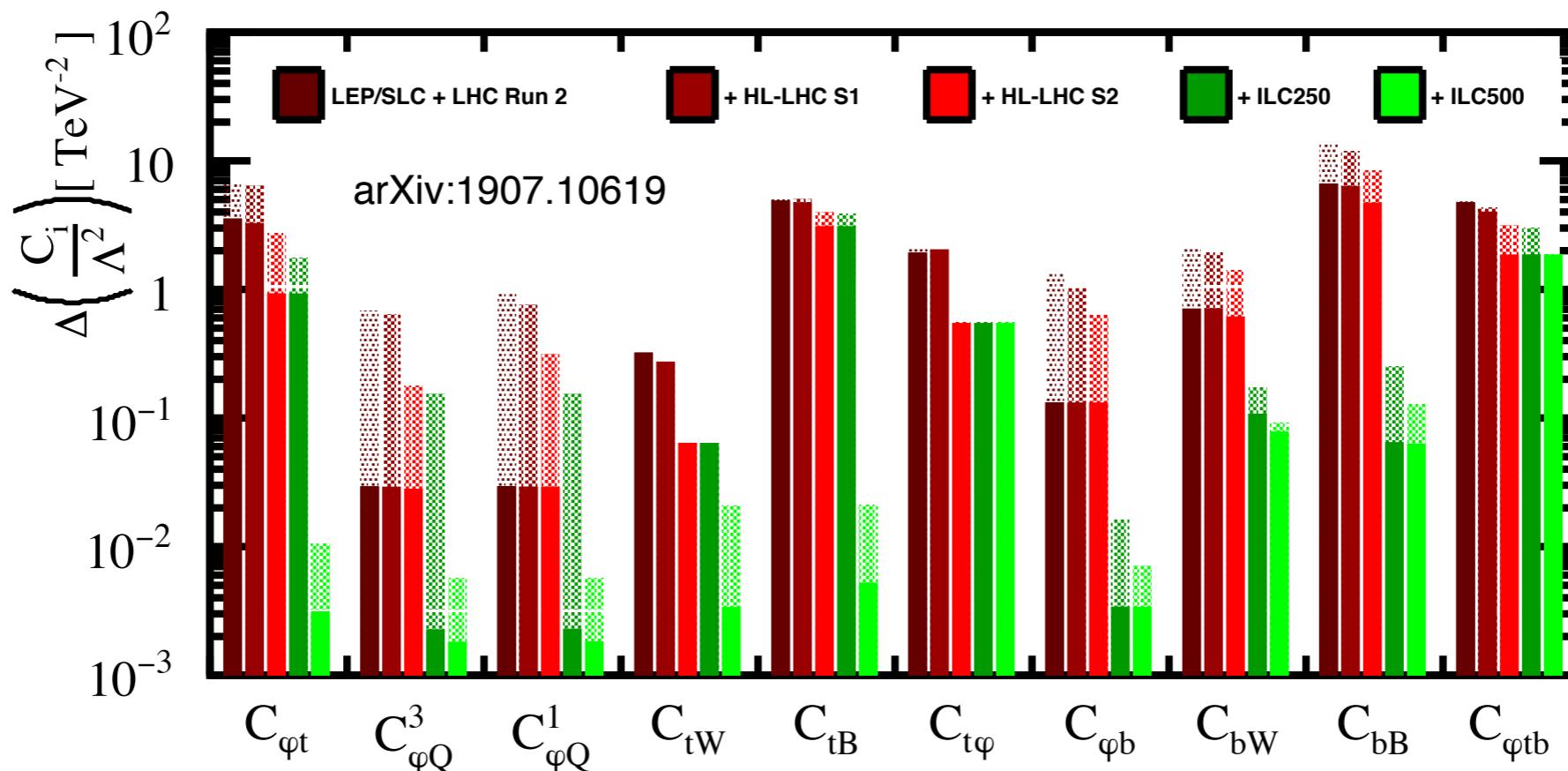
- Construction based on the decomposition of the differential  $ee \rightarrow tt \rightarrow bWbW$  cross section in terms of EFT helicity amplitudes.
- They are constructed to maximally exploit the available differential information and extract the tightest constraints on parameters whose dependence is expanded to linear order only.
- Optimal observables are found to be more robust than forward-backward asymmetry in reconstruction.

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



# ILC500: bb and tt production

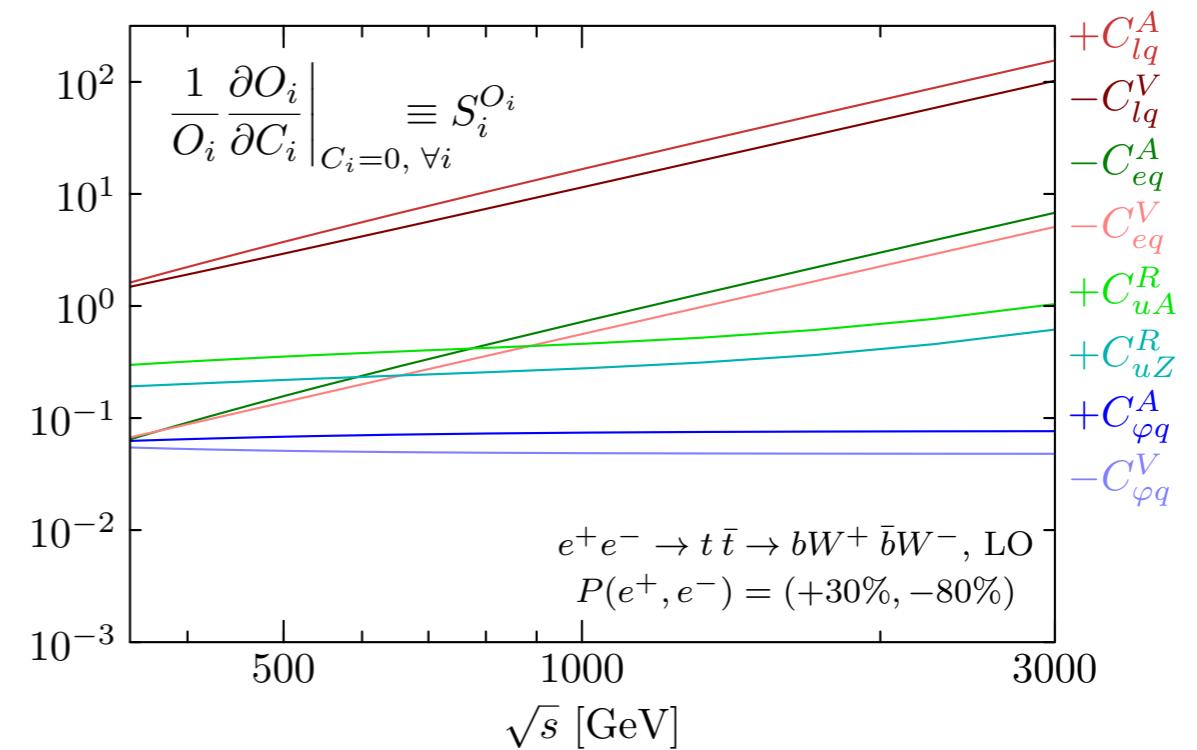
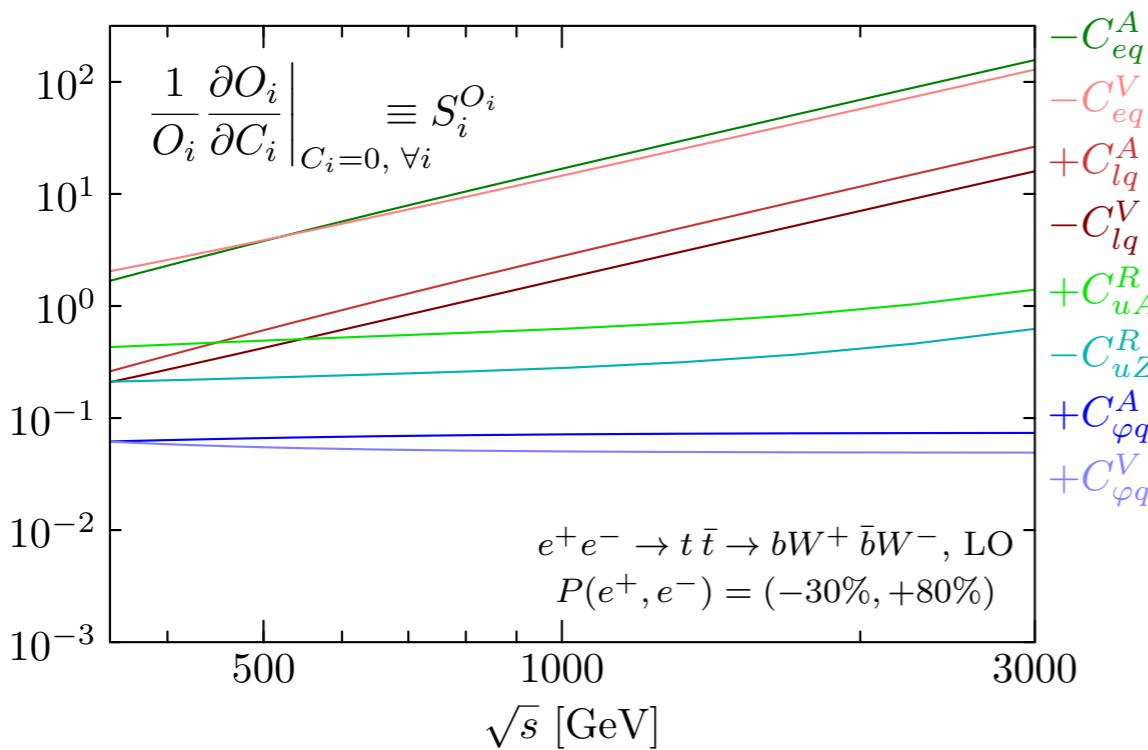
- We include cross-section and  $A_{fb}$  for bb and optimal observables for tt production for 2 different beam polarizations.
- Bounds for top-quark operators are reduced 1-2 order of magnitude. We reduce finally the bounds for the left couplings in the global fit.
- bb production sensitivity at 500 GeV is very similar to 250 GeV. As the bb production cross section decreases with the center-of-mass energy, the addition of the 500 GeV data does not provide an important improvement on the bottom-quark coefficients limits.



# Including 2-lepton-2-quark operators

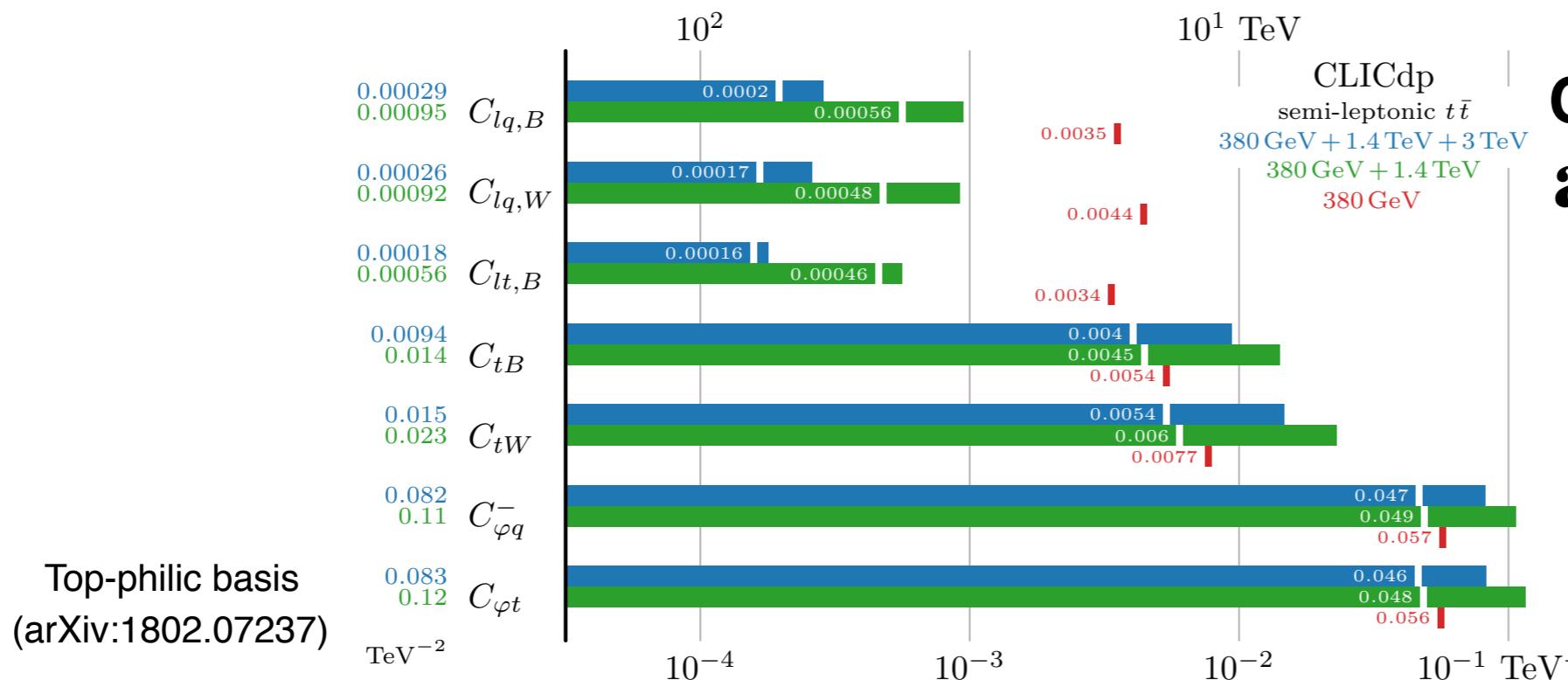
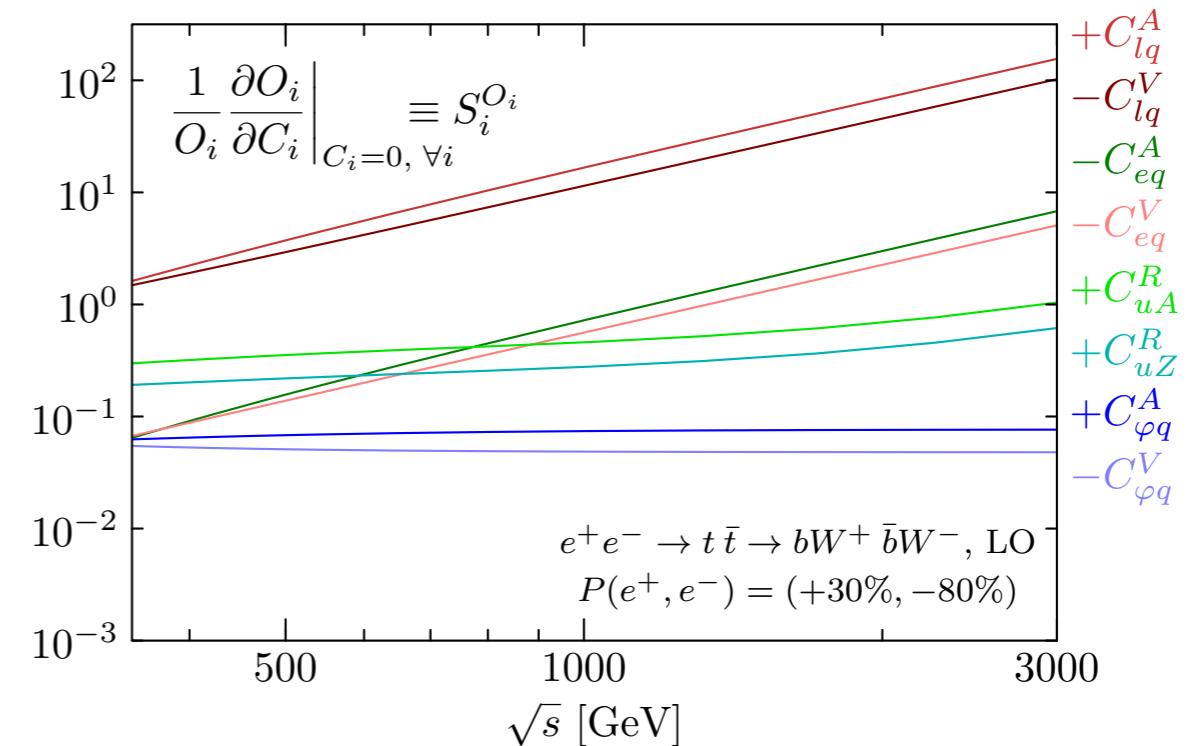
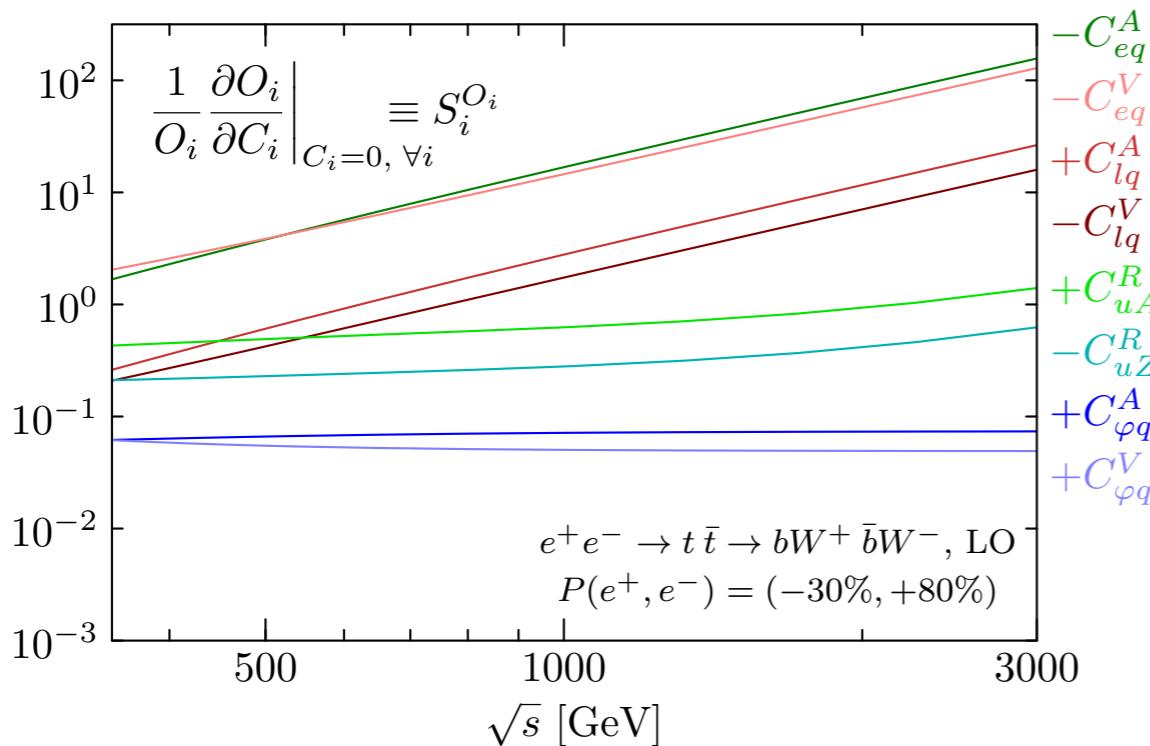
A complete top-bottom fit requires the inclusion of 2-lepton-2-quark operators.  
 A total of 7 new operators should be added.

$$\begin{aligned}
 O_{lq}^1 &\equiv \frac{1}{2} \bar{q} \gamma_\mu q & \bar{l} \gamma^\mu l, \\
 O_{lq}^3 &\equiv \frac{1}{2} \bar{q} \tau^I \gamma_\mu q & \bar{l} \tau^I \gamma^\mu l, \\
 O_{lu} &\equiv \frac{1}{2} \bar{u} \gamma_\mu u & \bar{l} \gamma^\mu l, \\
 O_{ld} &\equiv \frac{1}{2} \bar{d} \gamma_\mu d & \bar{l} \gamma^\mu l, \\
 O_{eq} &\equiv \frac{1}{2} \bar{q} \gamma_\mu q & \bar{e} \gamma^\mu e, \\
 O_{eu} &\equiv \frac{1}{2} \bar{u} \gamma_\mu u & \bar{e} \gamma^\mu e, \\
 O_{ed} &\equiv \frac{1}{2} \bar{d} \gamma_\mu d & \bar{e} \gamma^\mu e,
 \end{aligned}$$



arXiv:1807.02121

# Results based on CLIC



**CLICdp Collaboration**  
arXiv:1807.02441

We can fit with 2 energies

# Constraining 4f with ILC1000

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- **ILC1000** added to the fit. **10% reconstruction efficiency is considered.**
- **$C_{\Phi t}$ ,  $C^1_{\Phi Q}$ ,  $C^3_{\Phi Q}$  and  $C_{bW}$**  a factor  $\sim 10$  worse.
- **Dipole top quark operators** improve thanks to the higher sensitivity at ILC1000 of the optimal observables.
- **$C_{\Phi b}$  and  $C_{bB}$**  slightly worse.
- **$C_{\Phi tb}$  and  $C_{tb\Phi}$**  remain equal.

**For 2-lepton-2-quark operators inclusion we need at least one more energy point with tt production.**

	10-parameter fit ILC250 + ILC500	17-parameter fit + ILC1000
$C_{\varphi t}/\Lambda^2$	0.01	0.09
$C_{\varphi Q}^3/\Lambda^2$	0.005	0.04
$C_{\varphi Q}^1/\Lambda^2$	0.005	0.04
$C_{tW}/\Lambda^2$	0.02	0.014
$C_{tB}/\Lambda^2$	0.02	0.015
$C_{t\varphi}/\Lambda^2$	0.54	0.54
$C_{\varphi b}/\Lambda^2$	0.007	0.008
$C_{bW}/\Lambda^2$	0.09	0.17
$C_{bB}/\Lambda^2$	0.13	0.17
$C_{\varphi tb}/\Lambda^2$	1.9	1.9
$C_{eu}/\Lambda^2$	—	0.0006
$C_{ed}/\Lambda^2$	—	0.0005
$C_{eq}/\Lambda^2$	—	0.0004
$C_{lu}/\Lambda^2$	—	0.0006
$C_{ld}/\Lambda^2$	—	0.0009
$C_{lq}^-/\Lambda^2$	—	0.0006
$C_{lq}^+/\Lambda^2$	—	0.0005

arXiv:1907.10619

# Top quark Yukawa coupling

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We can study the top quark Yukawa coupling through ttH production at LHC and future electron-positron colliders

Assumed 13% uncertainty, limited by statistics

scenario	LHC Run 2 +LEP/SLC	HL-LHC S2 +LEP/SLC	ILC500	ILC550	ILC500 +ILC1000	CLIC1400
$\sqrt{s}, \int \mathcal{L}$	13 TeV, $36 \text{ fb}^{-1}$	14 TeV, $3 \text{ ab}^{-1}$	500 GeV, $4 \text{ ab}^{-1}$	550 GeV, $4 \text{ ab}^{-1}$	+1 TeV, $+8 \text{ ab}^{-1}$	$+2 \text{ ab}^{-1}$
<i>68% probability interval for effective operator coefficient <math>C_{t\varphi}/\Lambda^2 [\text{TeV}^{-2}]</math></i>						
individual	[-4.4, +0.0]	[-0.55, +0.55]	[-1.06, +1.06]	[-0.50, 0.50]	[-0.27, +0.27]	<b>1807.02441</b>
marginalized	[-4.6, -0.2]	[-0.55, +0.55]	[-1.07, +1.07]	[-0.52, +0.52]	[-0.32, +0.32]	<b>CLICdp Collaboration</b>
<i>corresponding relative uncertainty on top-quark Yukawa coupling <math>\Delta y_t/y_t [\%]</math></i>						
individual	13.2	3.3	6.4	3.0	1.62	2.7
marginalized	13.2	3.3	6.4	3.1	1.96	

**arXiv:1907.10619**

- ttH production provides a direct constraint for the top Yukawa coupling.
- The top Yukawa in the global fit is robust but improvable
- The other operators that affect to ttH has to be controlled with other observables

# Top quark Yukawa coupling

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Boselli, Hunter, Mitov [1805.12027]:

“Prospects for determining the top quark Yukawa coupling at future electron-positron colliders”

Collider	$\sqrt{s}$ (GeV)	$\mathcal{L}$ ( $\text{fb}^{-1}$ )	$h \rightarrow gg$	$h \rightarrow \gamma\gamma$	$h\gamma$	$t\bar{t}h$	total
FCC- <i>ee</i>	240	$1.0 \cdot 10^4$	0.7%	5.3%	10%	-	0.7%
	350	$2.6 \cdot 10^3$	1.3%	21%	19%	-	1.3%
CEPC	240	$5.0 \cdot 10^3$	0.6%	16%	14%	-	0.6%
CLIC	350	$5.0 \cdot 10^2$	2.6%	-	-	-	2.6%
	1400	$1.5 \cdot 10^3$	2.5%	27%	-	4.4%	2.2%
	3000	$2.0 \cdot 10^3$	2.2%	18%	-	7.3%	2.1%
ILC	250	$2.0 \cdot 10^3$	1.2%	21%	23%	-	1.2%
	500	$4.0 \cdot 10^3$	0.7%	10%	75%	5.0%	0.7%

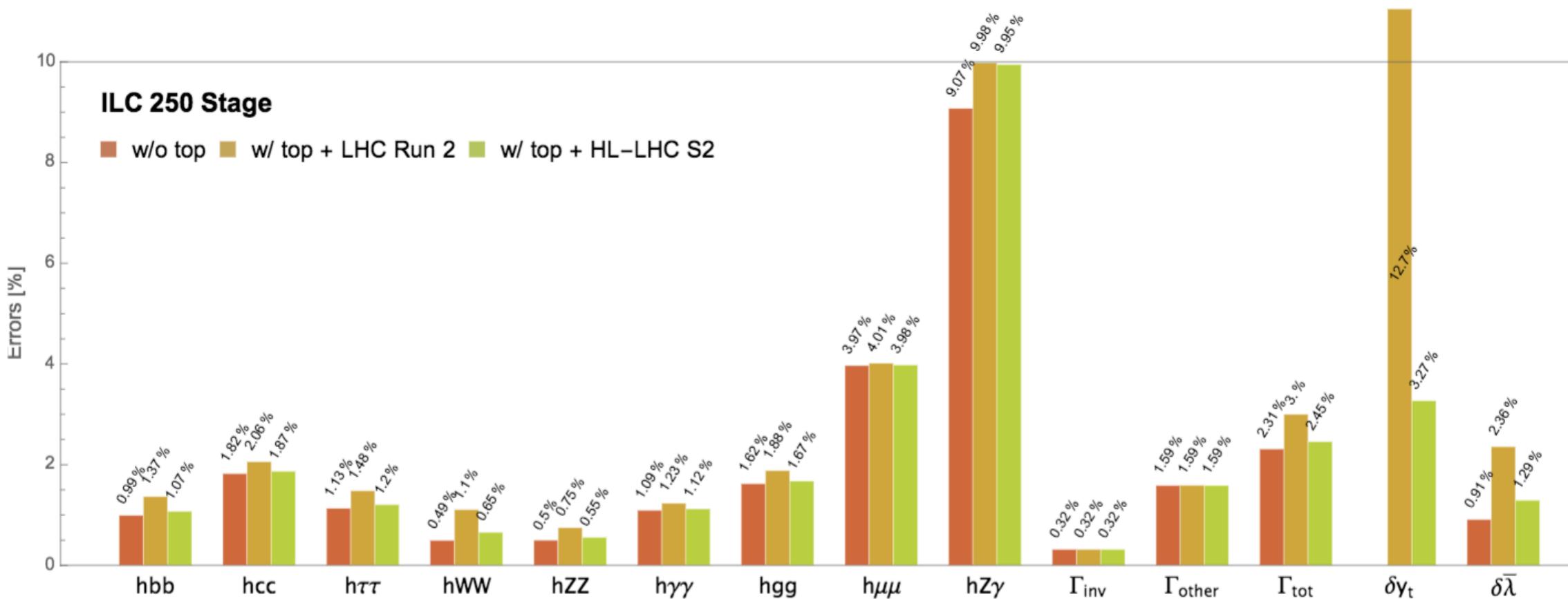
These are individual constraints for top-Yukawa from indirect constraints in Higgs decays

ILC250 would be enough to put an excellent constraint in the top-Yukawa from  $h \rightarrow gg$ . We should study this in a global fit.

# Top-Higgs fit

- A study for a combined fit for Higgs and top couplings including Higgs observables is ongoing ([see talk by Sunghoon Jung this afternoon](#))
- First results show that the global limit one obtains for the top-Yukawa is dominated by ttH

**Sunghoon Jung, Junghwan Lee, MP, Juping Tian, Marcel Vos in preparation**



# Summary

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- A combined top-bottom fit demonstrated to be robust
- Bounds from electron-positron colliders are 1-2 order of magnitude better than data from LHC and LEP
- We need at least two energy points with  $t\bar{t}$  production for constraining 4-fermion operators
- A combined top-bottom-Higgs in preparation

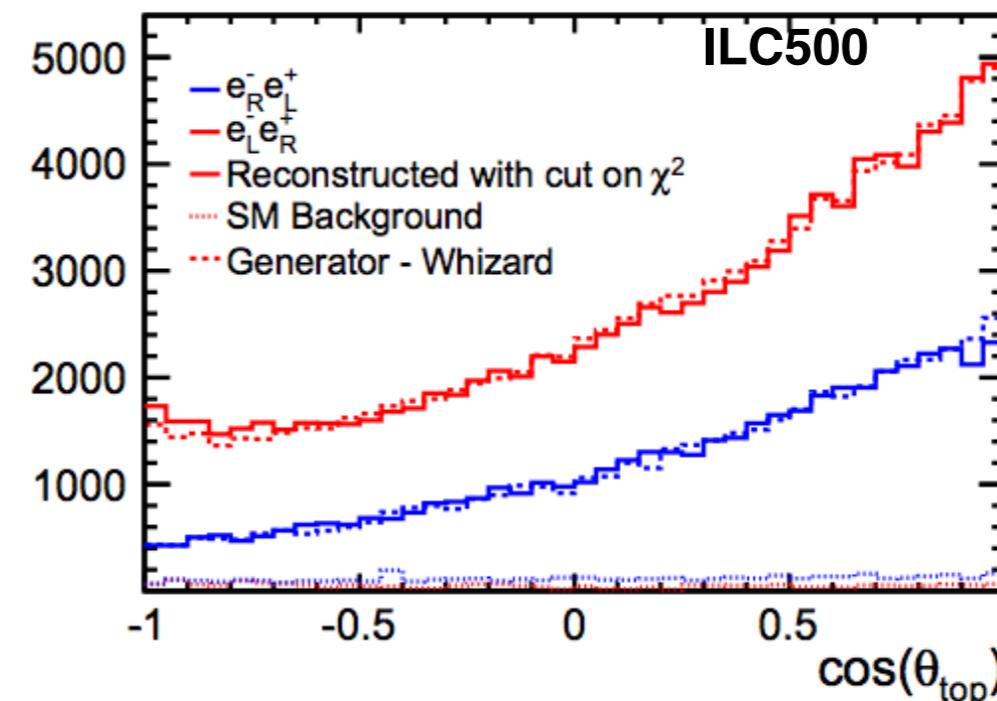
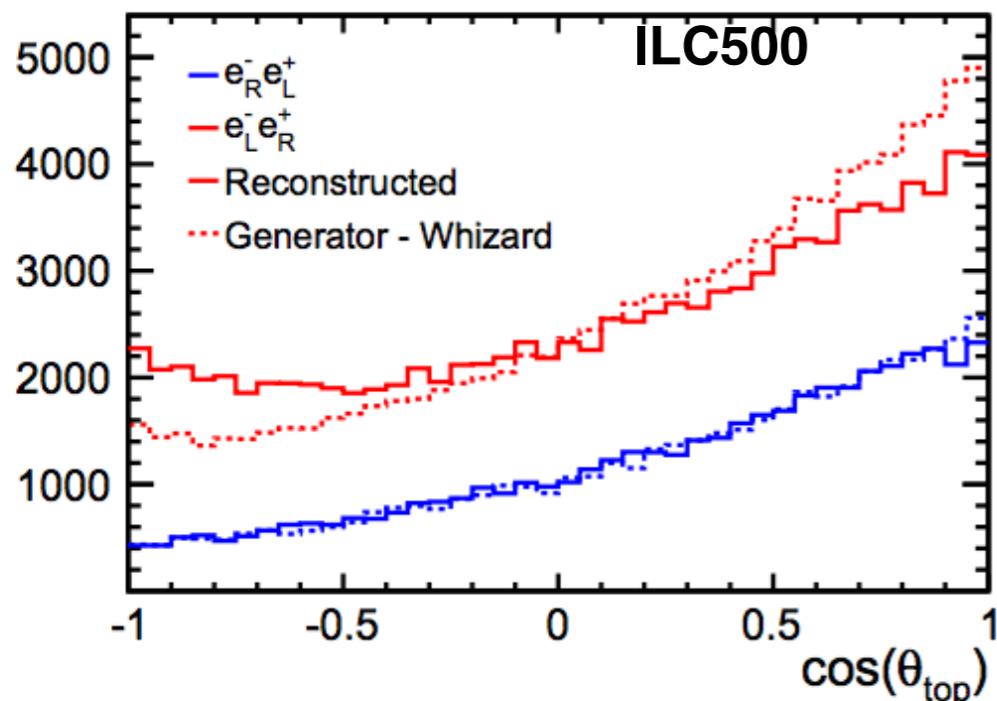
# Full-simulation for tt production

Reconstructed process: ee  $\rightarrow$  tt  $\rightarrow$  4j + l + v<sub>l</sub>

## CLIC380 and ILC500

- **Resolved analysis** - reconstruction of 3 separated jets for the hadronic top, and 1 for the leptonic top.

**Problem on migrations (bad W-b pairing) in some angular distributions, solved using a quality cut with the consequent penalty in efficiency.**



Pure statistical uncertainties at the moment

We expect systematics to be controlled at the same level than statistics

**Alternative:** reconstruction using b quark charge as in bb reconstruction

# High energies above 1TeV

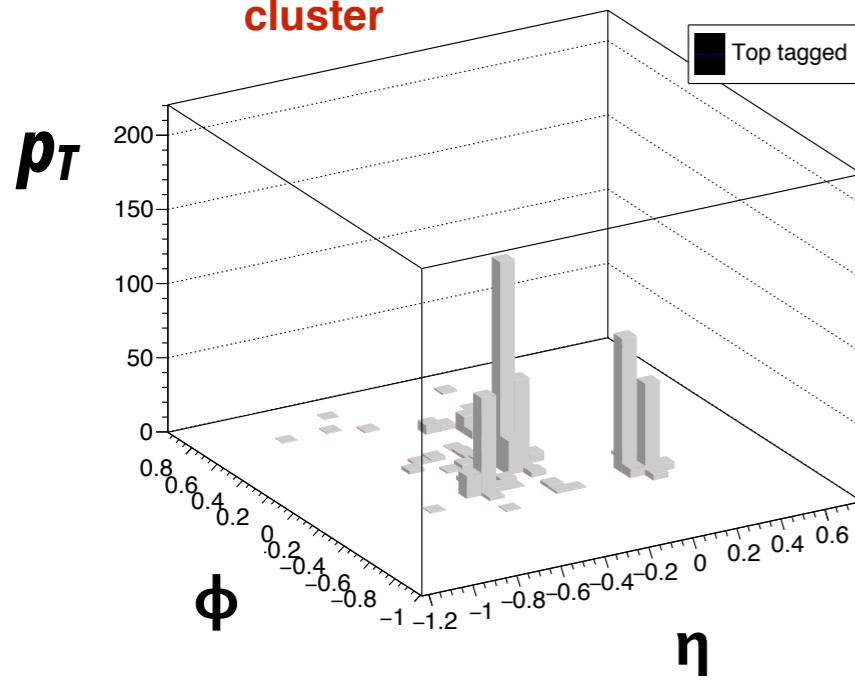
Reconstructed process:  $ee \rightarrow tt \rightarrow 4j + l + \nu_l$

**CLIC1400 and CLIC3000**

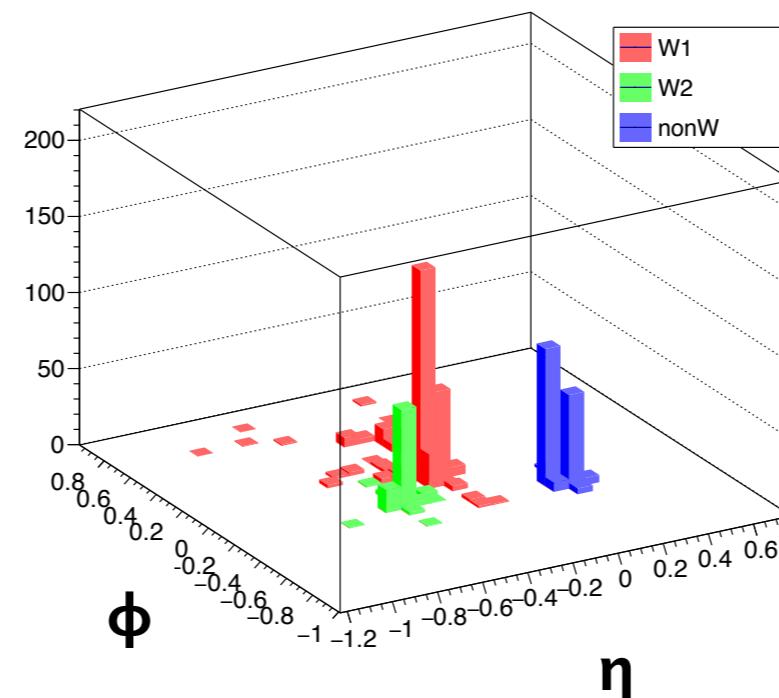
**CLICdp: 1807.02441**

- **Boosted analysis** - reconstruction of 2 big jets, and then look inside them to substructure identification - *Top Tagging*.

Parsing through jet cluster



Three subjects identified



Background rejection has been studied

We extrapolate CLIC results to ILC1000