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

ILD Analysis/Software Meeting
19/07/2017

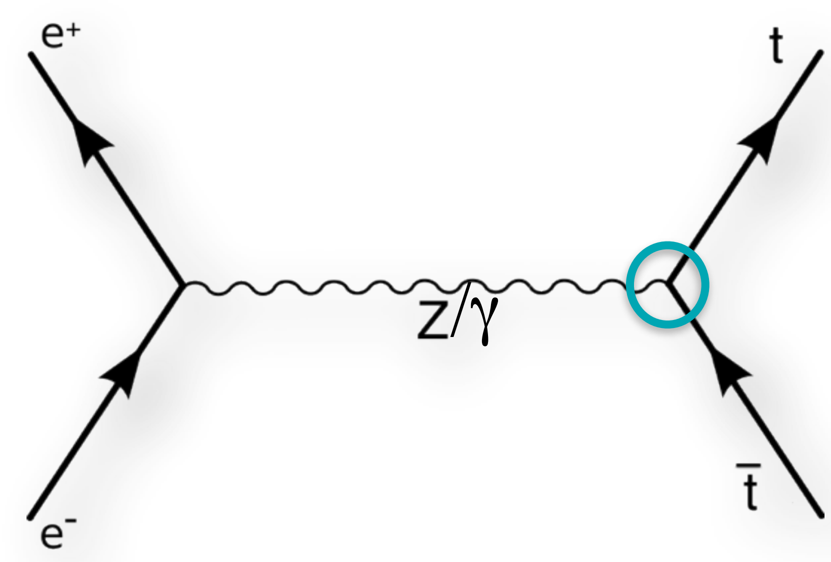
W. Bernreuther, L. Chen, **I.García**, M. Perelló, R. Poeschl, F. Richard, E. Ros, M. Vos

Outline

- CP-violating top quark couplings
- Optimal CP-odd observables
- Full simulation
- Systematic uncertainties
- Prospects for CP-violating form factors
- Conclusions

Top quark electroweak couplings

- **New physics** may **modify the electro-weak $\bar{t}t$X vertex** described in the SM
- **e^+e^- colliders** allow to probe these vertices directly. The **leading-order** process $e^+e^- \rightarrow t\bar{t}$ goes directly through the **$\bar{t}t$Z and $\bar{t}t\gamma$ vertices**



- ➡ *X = Z, γ*
- ➡ *V = Vector coupling*
- ➡ *A = Axial coupling*

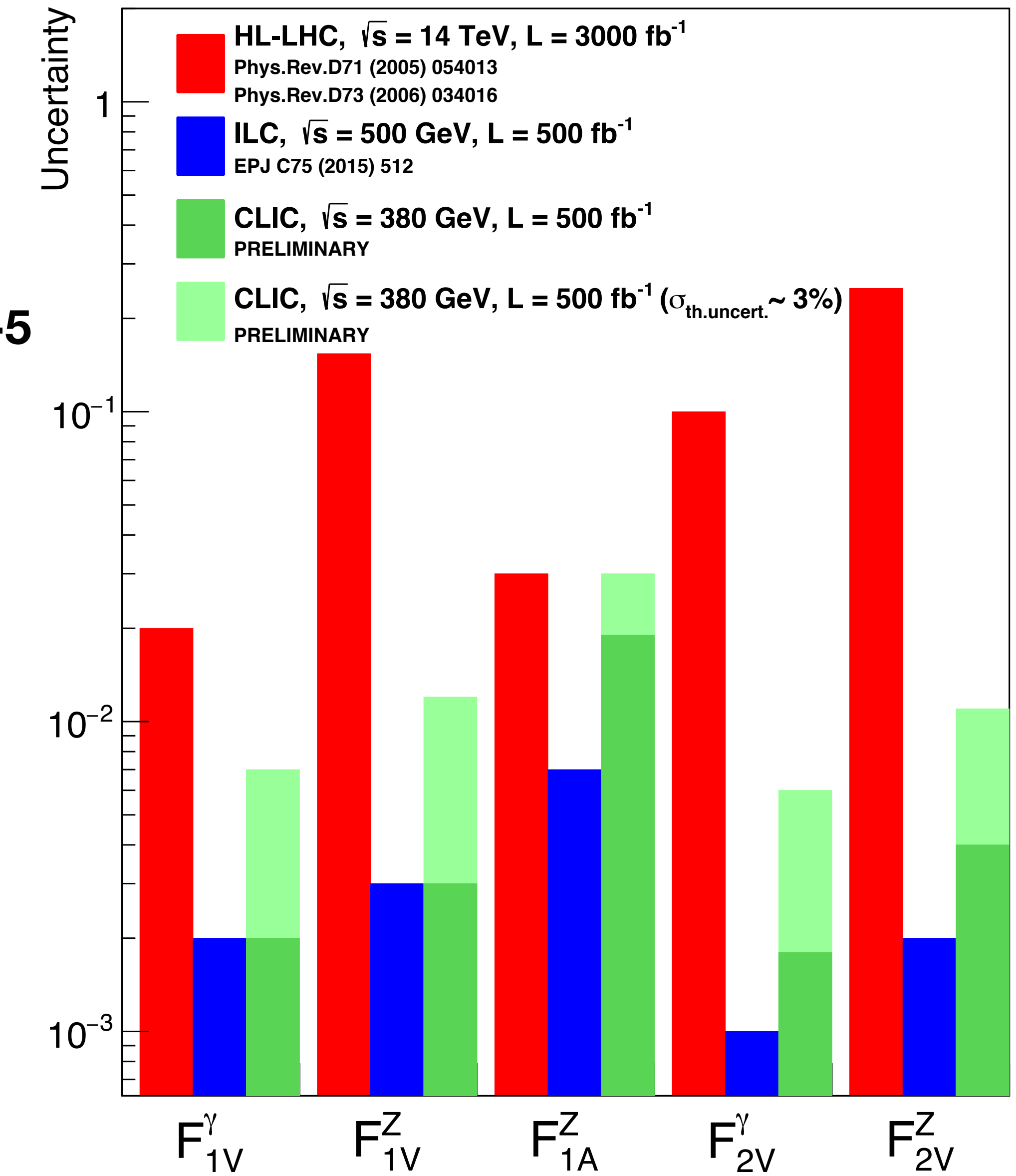
- A **parametrisation of the $t\bar{t}$X vertex** for on-shell t and $\bar{t}$ and off-shell γ, Z is:

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

Top quark electroweak couplings

Eur. Phys. J. C (2015) 75:512
DOI 10.1140/epjc/s10052-015-3746-5

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



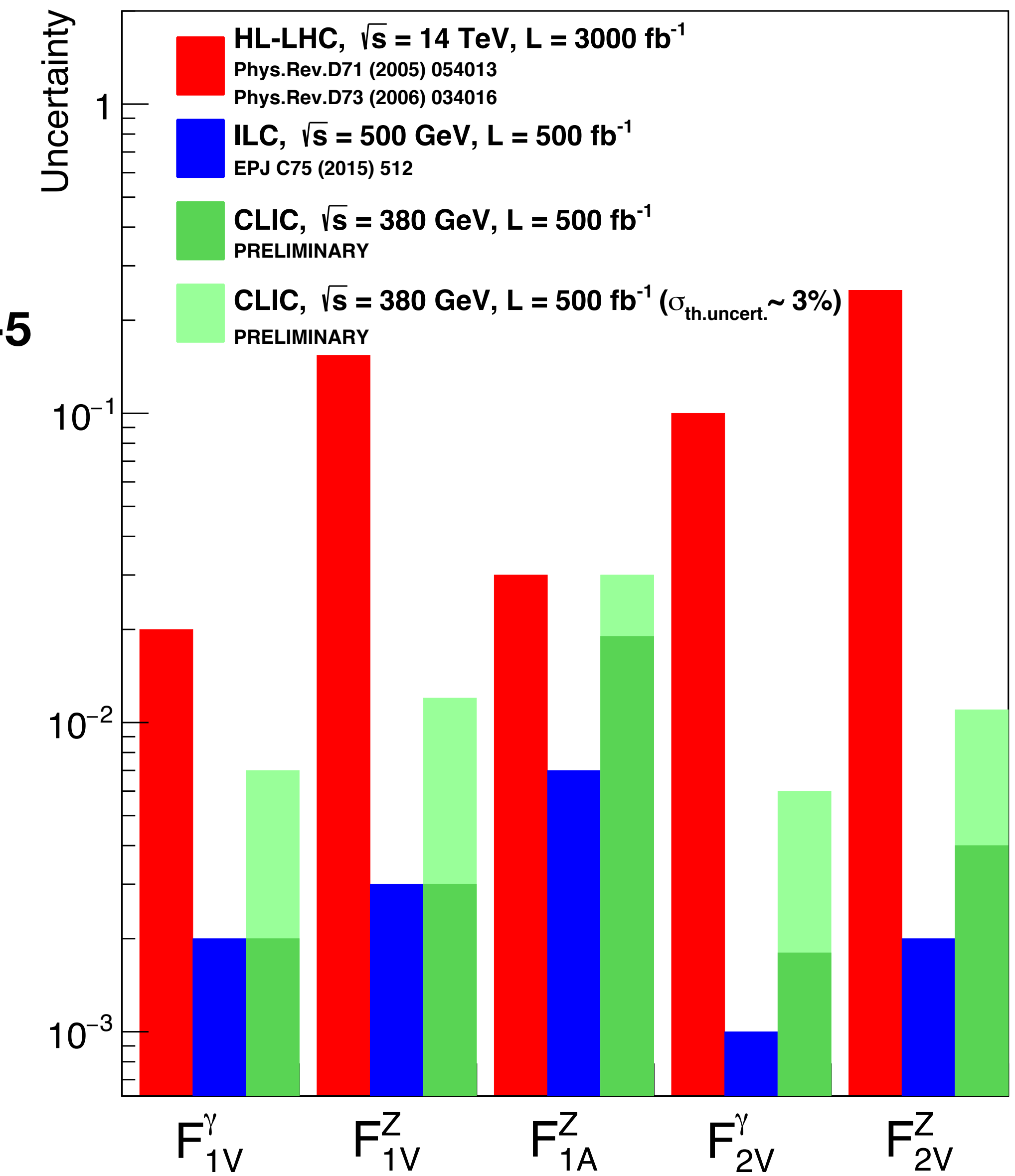
$$\Gamma_{\mu}^{ttX}(k^2) = -ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}k^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

CP-conserving couplings

Top quark electroweak couplings

Eur. Phys. J. C (2015) 75:512
DOI 10.1140/epjc/s10052-015-3746-5

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



CP-violating 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-violation: $e^+e^- \rightarrow tt$

- **CP-violating couplings can have abortive parts, i.e., imaginary parts, then**
- **4 CP-violating form factors can be extracted.**

$$\mathrm{Re} F_{2A}^{\gamma,Z}(s) \qquad \mathrm{Im} F_{2A}^{\gamma,Z}(s)$$

- **Electric dipole form factor (EDF) and a weak dipole form factor (WDF)**

$$d_t^X(s) = -\frac{e}{2m_t} F_{2A}^X(s)\,, \quad X = \gamma, Z$$

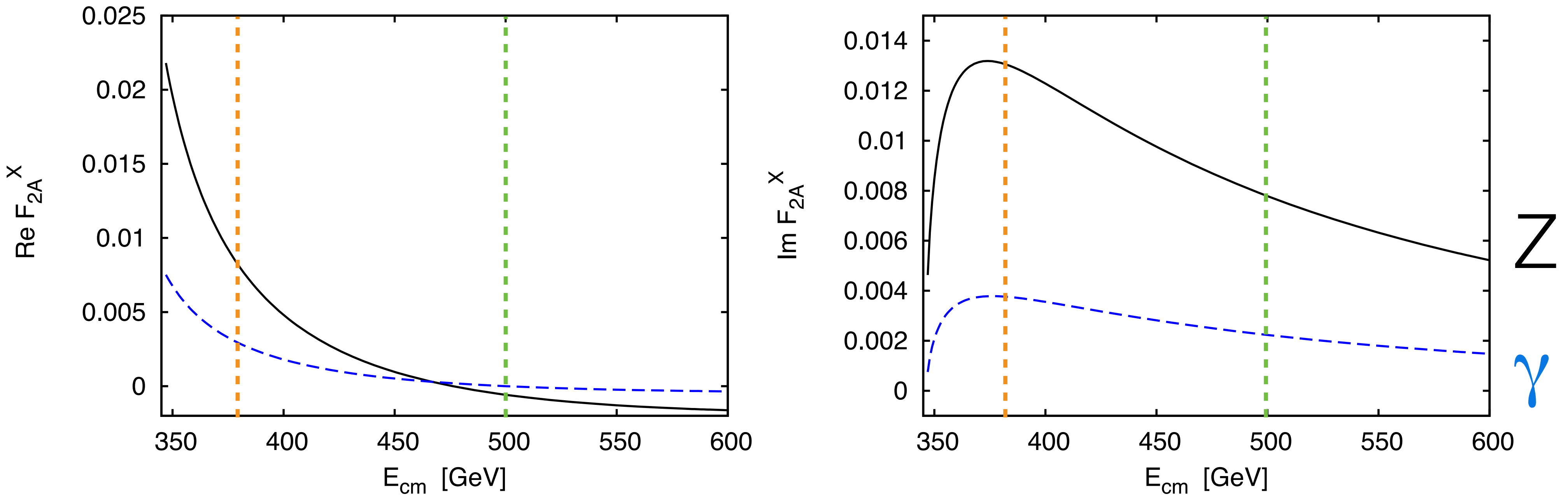
F^X_{2A} are zero at tree level in the SM

- **Sizeable CP-violting effects** involving top quarks may be observed in SM extensions, in particular we consider the **2HDM** and **MSSM**

- The **CP-violating** form factors in the **t → Wb decay** amplitude are **very small** and of no further interest to us here

CP-violation in SM extensions

- Within the **2HDM** the real and imaginary part of the top-quark electric dipole form factor **F_{2A}^{γ} can be as large as ~ 0.01** in magnitude near the tt production threshold, taking into account the present constraints from LHC data



$\sqrt{s}$ [GeV]	Re F_{2A}^{γ}	Re F_{2A}^{Z}	Im F_{2A}^{γ}	Im F_{2A}^{Z}
380	8.1×10^{-3}	2.9×10^{-3}	1.3×10^{-2}	3.8×10^{-3}
500	-0.6×10^{-3}	0.7×10^{-6}	7.8×10^{-3}	2.2×10^{-3}

- Within the **MSSM** the top-quark **EDF and WDF** are smaller, with maximum values compatible with current experimental constraints **below 10^{-3}**

$$|\mathrm{Re}\ F_{2A}^{\gamma}|,\ |\mathrm{Re}\ F_{2A}^{Z}| < 10^{-3}\,, \quad |\mathrm{Im}\ F_{2A}^{\gamma}|,\ |\mathrm{Im}\ F_{2A}^{Z}| < 10^{-4} \quad \text{for } \sqrt{s} \lesssim 500\ \text{GeV}$$

Optimal CP-odd observables

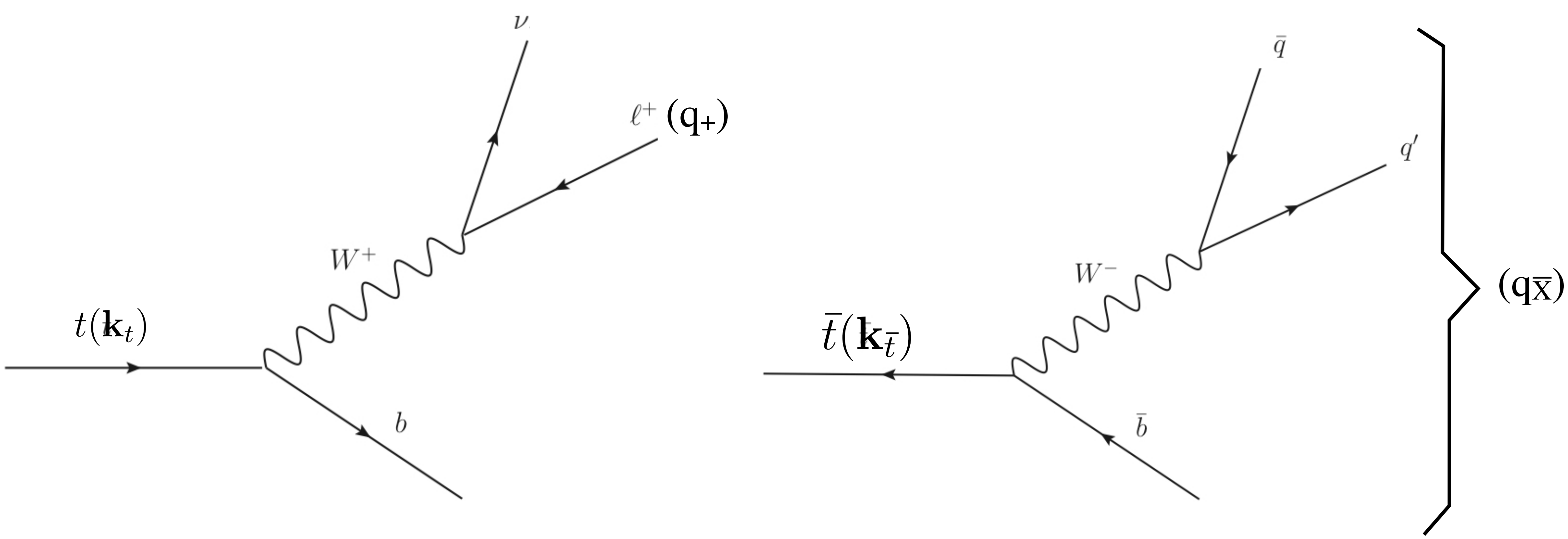
$$e^+(\mathbf{p}_+, P_{e^+}) + e^-(\mathbf{p}_-, P_{e^-}) \quad \rightarrow \quad t(\mathbf{k}_t) + \bar{t}(\mathbf{k}_{\bar{t}})$$

The **CP-violating effects** in e+e− → tt̄ manifest themselves in specific **top-spin effects**, namely **CP-odd top spin-momentum correlations and tt̄ spin correlations**.

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

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

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



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 corresponding observables **O-** are defined to be the **CP image of O+**

- The way to **extract** the **CP-violating form factors** is to construct **asymmetries sensitive to CP-violation effects,** as the difference of the expectation values of O+ and O-

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

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

${\mathcal{A}_{\gamma,Z}^{Re}}^{L}$	${\mathcal{A}_{\gamma,Z}^{Re}}^{L}$
${\mathcal{A}_{\gamma,Z}^{Im}}^{R}$	${\mathcal{A}_{\gamma,Z}^{Im}}^{R}$

Coefficients vs $\sqrt{s}$

Coefficients $c_\gamma(s)$ and $cZ(s)$ depend on the e- and e+ polarizations -> disentangle contributions of the CP-violating photon and Z vertices

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

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

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

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

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

Simulation samples (6f -> lepton+jets)

Full simulation

ILC@500GeV (ILD detector)

500fb^{-1}, P(e-)=∓80%, P(e+)=∓30%

ILC LumiUp 4ab^{-1}

CLIC@380GeV (CLIC_ILD detector)

500fb^{-1}, P(e-)=∓80%

Loose timing cuts

CLIC@1.4TeV (CLIC_ILD detector) -> Still preliminary

1.5ab^{-1}, P(e-)=∓80%

Tight timing cuts,

Efficiency inputs from top tagging studies

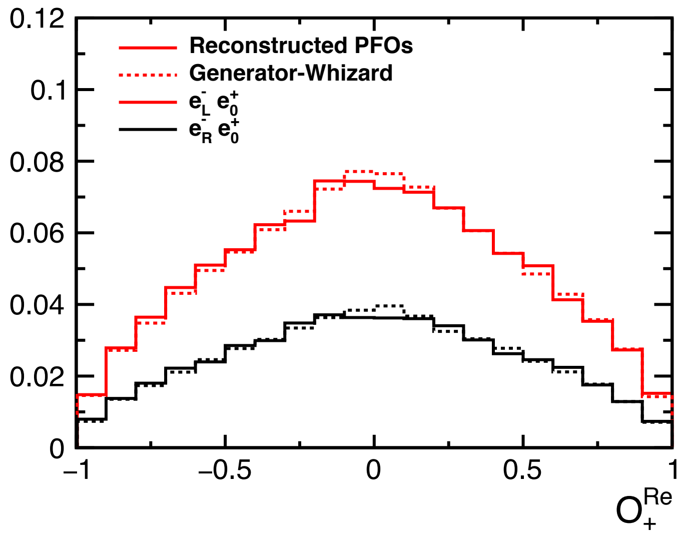
Fast Simulation

CLIC@3TeV

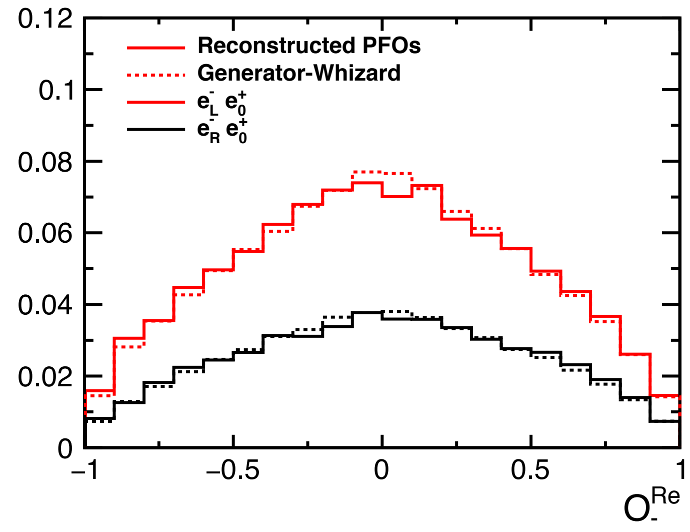
3ab^{-1}, P(e-)=∓80%

Extrapolate numbers from low-energy stages results

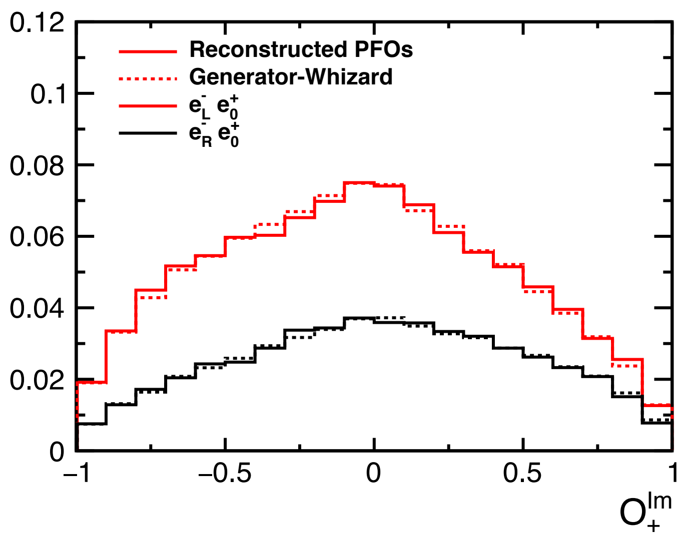
Full simulation: CLIC@380GeV



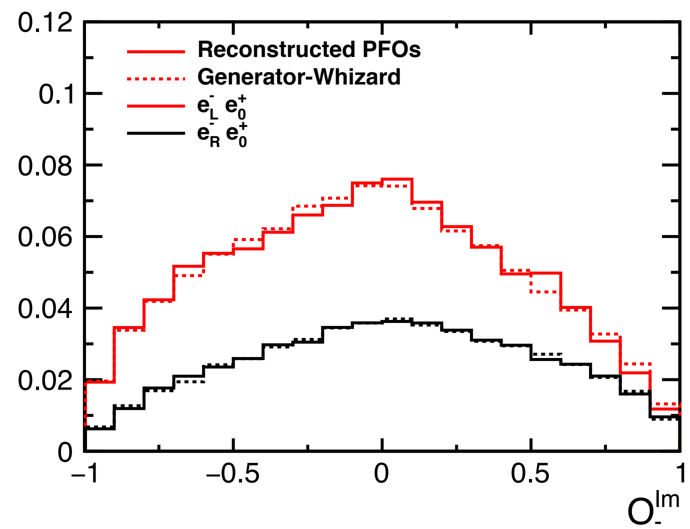
(a) $\mathcal{O}_+^{Re}$



(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 ± 0.003	0.0072 ± 0.003
$\mathcal{A}^{Im}$	0.0004 ± 0.003	-0.0019 ± 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

Systematic uncertainties

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%	-

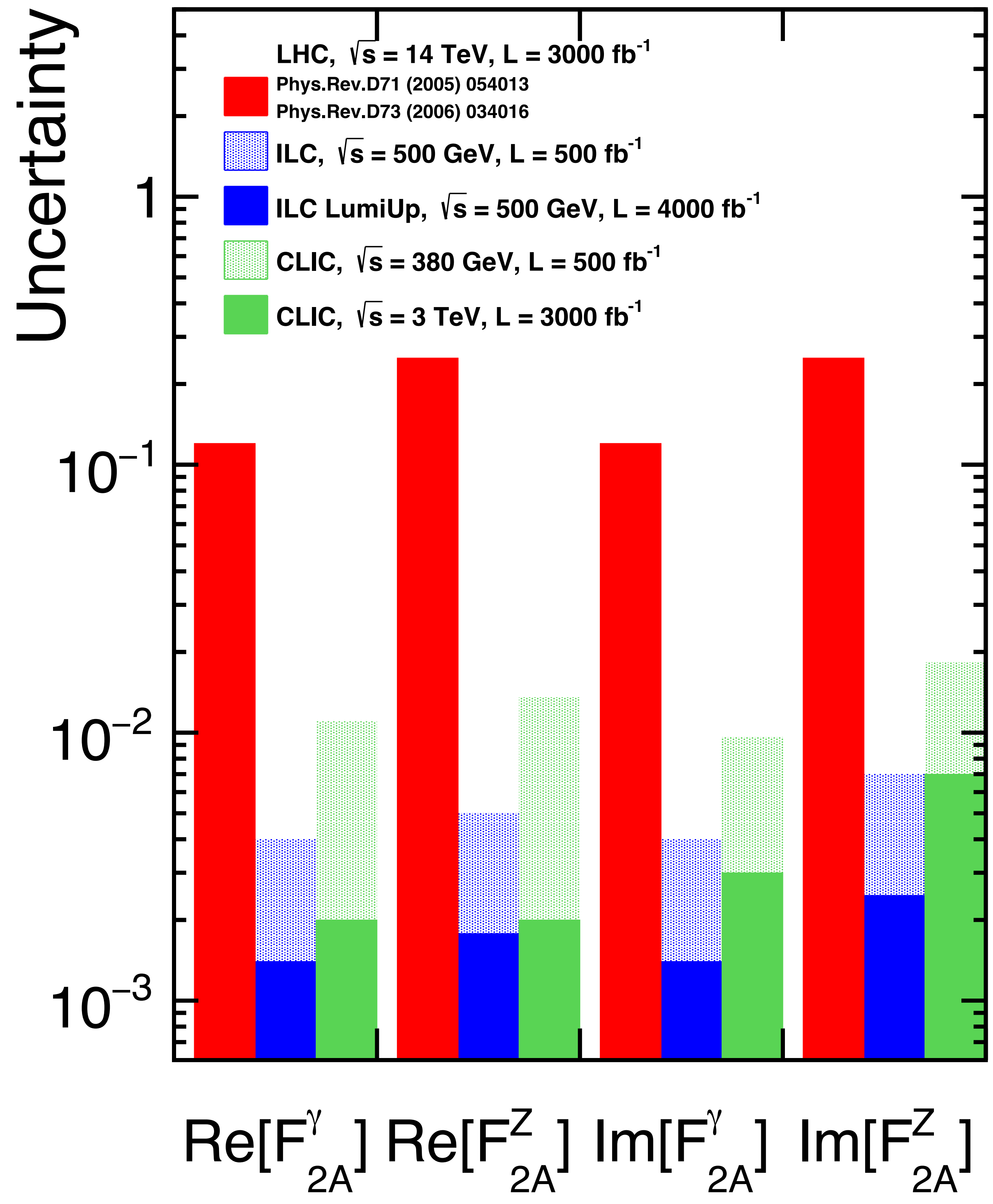
Bias: upper limit

Linearity: expected relative modification

- The **SM values for A_{Re} and A_{Im} are 0** and the **detector response is symmetric** (equal for t and t)
- 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 (as envisaged in the ILC TDR)
- **Distortions** and **migrations** on the distributions **O+ and O- don't generate a non-zero asymmetry** at least not at the level of **0.005**
- Parton-level study: The **selection tends to enhance the reconstructed asymmetry** while the **migration and resolution dilute it**. This effect is particularly pronounced at 3TeV.
- Theory uncertainties are taken as the NLO SM corrections the tt production and decay including EDF and WDF
- **Our study has not found any sources of systematic uncertainty that yield a spurious asymmetry when the true asymmetry is zero**

Prospects for CP-violating form factors

- The measurements at **hadron colliders** are expected to be considerably **less precise** than those that can be made at lepton colliders
- 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**



Conclusions

- Paper draft ready for circulation
- **The CP-violating top-quark form factors $F_{2A}^{\gamma,Z}$**, whose static limits are the electric and weak dipole moment of the top quark can be as large as **0.01 in magnitude in a viable 2HDM**
- **Asymmetries A_{Re} and A_{Im}** expected to be **robust against ambiguities** and **good control** over experimental and theoretical **systematic uncertainties**
- **The sensitivity of a future e+e- collider** to CP-violating dipole form factors of the top quark **exceeds** that of the **complete LHC programme** by an order of magnitude **and** that of the **FCChh** by a factor four

Conclusions

- Paper draft ready for circulation

- **The CP-violating top-quark form factors $F_{2A}^{\gamma,Z}$**, whose static limits are the electric and weak dipole moment of the top quark can be as large as **0.01 in magnitude in a viable 2HDM**

- **Asymmetries A_{Re} and A_{Im}** expected to be **robust against ambiguities** and **good control** over experimental and theoretical **systematic uncertainties**

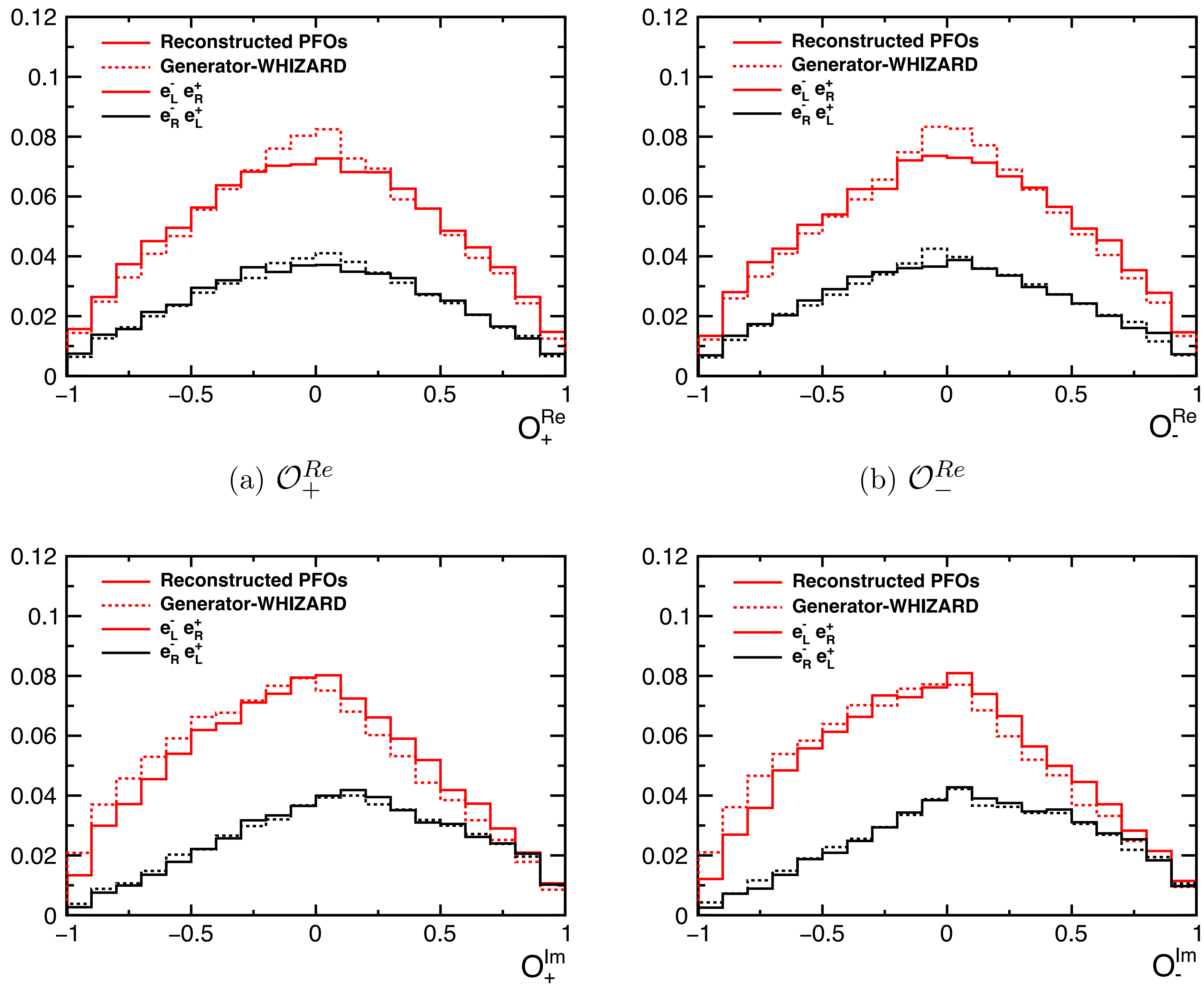
- **The sensitivity of a future e+e- collider** to CP-violating dipole form factors of the top quark **exceeds** that of the **complete LHC programme** by an order of magnitude **and** that of the **FCChh** by a factor four

THANKS FOR YOUR ATTENTION

Prospects for CP-violating form factors

	ReF2Agamma	ReF2AZ	ImF2Agamma	ImF2AZ
CLIC@380 GeV	0,011	0,014	0,010	0,018
CLIC@1.4 teV	0,002	0,002	0,006	0,012
CLIC@3 teV (1/2:1/2)	0,002	0,002	0,003	0,006
CLIC@3 teV (1/3:2/3)	0,002	0,002	0,003	0,007
CLIC@3 teV (2/3:1/3)	0,002	0,003	0,004	0,007
ILC@500 GeV	0,004	0,005	0,004	0,007
ILC-LumiUP@500 GeV	0,0014	0,0017	0,0014	0,002

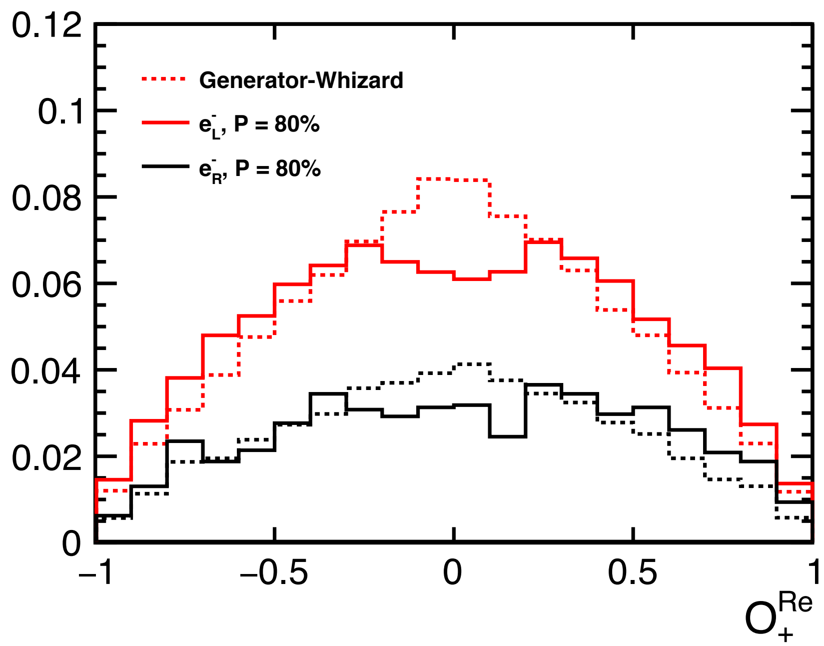
Full simulation: ILC@500GeV



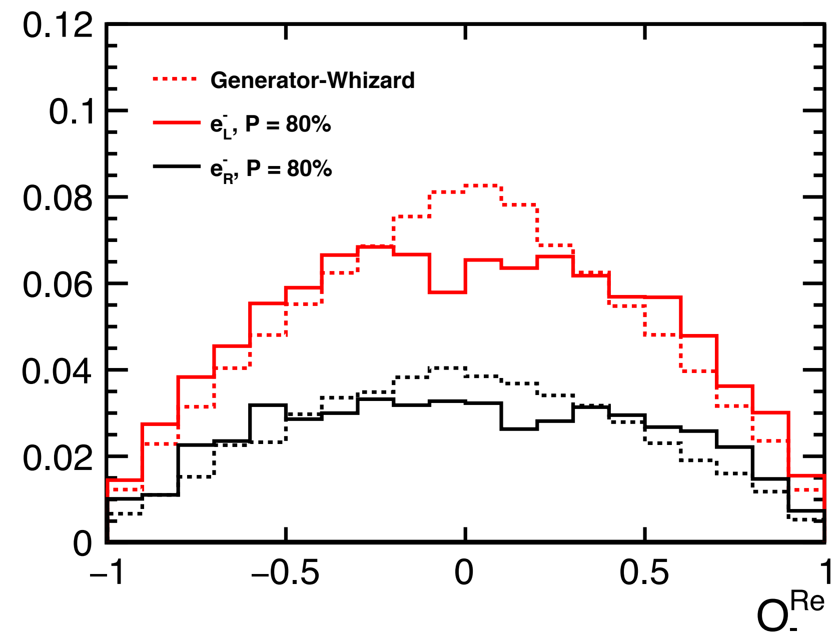
(a) $\mathcal{O}^{Re}_+$ (b) $\mathcal{O}^{Re}_-$

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

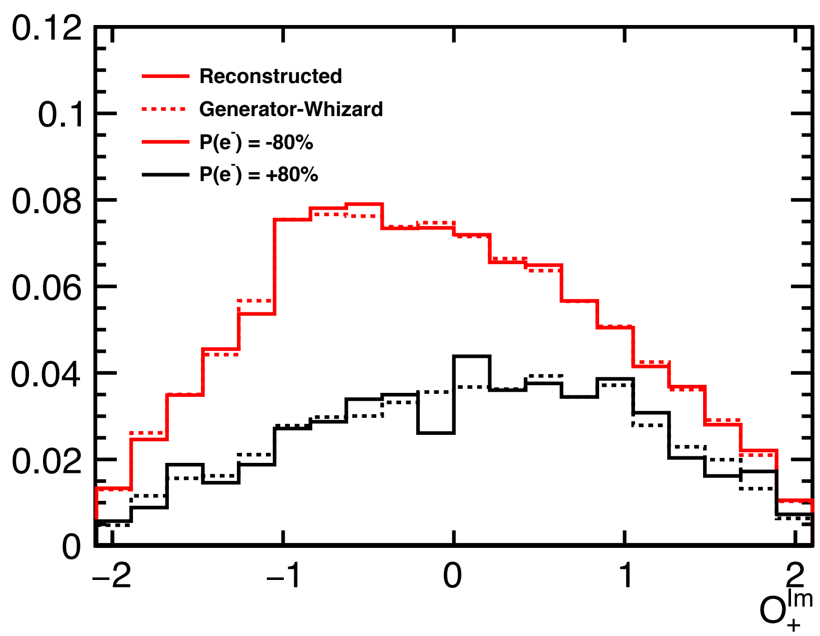
Full simulation: CLIC@1.4TeV



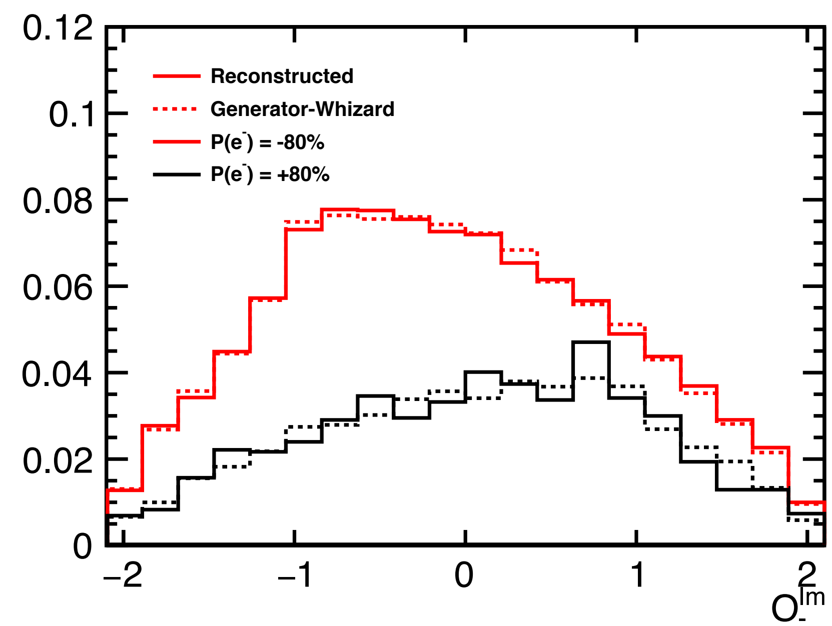
(a) $\mathcal{O}^{Re}_+$



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



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



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

Prospects for CP-violating form factors

Quantity	Re F_{2A}^{γ}	Re F_{2A}^{Z}	Im F_{2A}^{γ}	Im F_{2A}^{Z}
SM value at tree level	0	0	0	0
Prospects derived in this study:				
CLIC low-energy stage ($\sqrt{s} = 380$ GeV, 500 fb^{-1})				
CLIC380	0.011	0.014	0.010	0.018
ILC nominal operation ($\sqrt{s} = 500$ GeV, 500 fb^{-1})				
ILC500	0.004	0.005	0.004	0.007
ILC Luminosity Upgrade ($\sqrt{s} = 500$ GeV, 4 ab^{-1})				
ILC500LumiUp	0.0014	0.0017	0.0014	0.002
CLIC high energy ($\sqrt{s} = 3$ TeV, 3 ab^{-1})				
CLIC3000 (fast simulation)	0.002	0.002	0.003	0.006
Previous studies for lepton colliders:				
Aguilar et al. [81] (e^+e^-, $\sqrt{s} = 500$ GeV, 500 fb^{-1})				
TESLA	0.007	0.008	0.008	0.010
Prospects for hadron colliders:				
Baur et al. [75, 76] (pp, 3 ab^{-1} at 14 TeV)				
HL-LHC	0.12	0.25	0.12	0.25
Röntsch & Schulze [77] (pp, 3 ab^{-1} at 14 TeV)				
HL-LHC	-	0.16	-	-
Mangano et al. [79] (FCChh study, pp, 3 ab^{-1} at 13 TeV)				
HL-LHC	-	0.16	-	-
Mangano et al. [79] (FCChh study, pp, 3 ab^{-1} at 100 TeV)				
FCChh	-	0.04	-	-
Bouzas et al. [80] (LHeC, ep, 100 fb^{-1} with $E_e = 140$ GeV)				
LHeC	0.1	-	-	-

The 68% C.L. limits on F_{2A}^{Z} and F_{2A}^{γ}