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

ILD Analysis/Software Meeting
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W. Bernreuther, L. Chen, **I.García**, M. Perelló, R. Poeschl, F. Richard, E. Ros, M. Vos

Outline

Overview

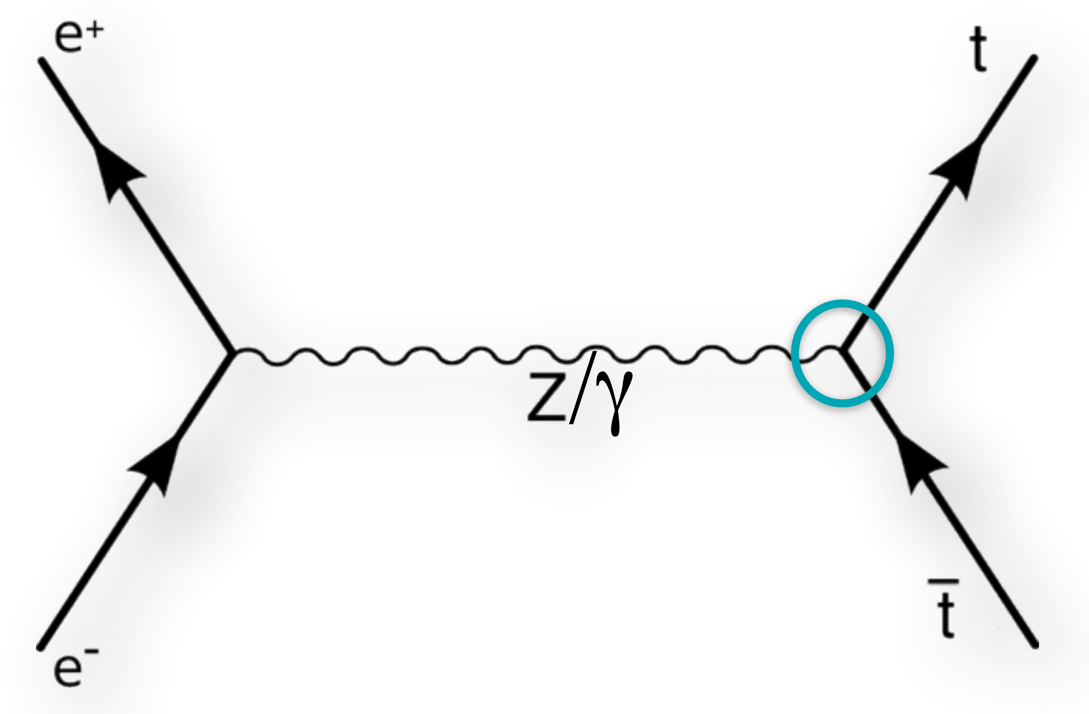
- CP-violating top quark couplings
- Optimal CP-odd observables
- Full simulation
- Systematic uncertainties
- Prospects for CP-violating form factors

Paper Report

- Most relevant modifications
- Acknowledgements

Top quark electroweak couplings

- **New physics** may **modify the electro-weak $t\bar{t}X$ 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 **$t\bar{t}Z$ and $t\bar{t}\gamma$ vertices**



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

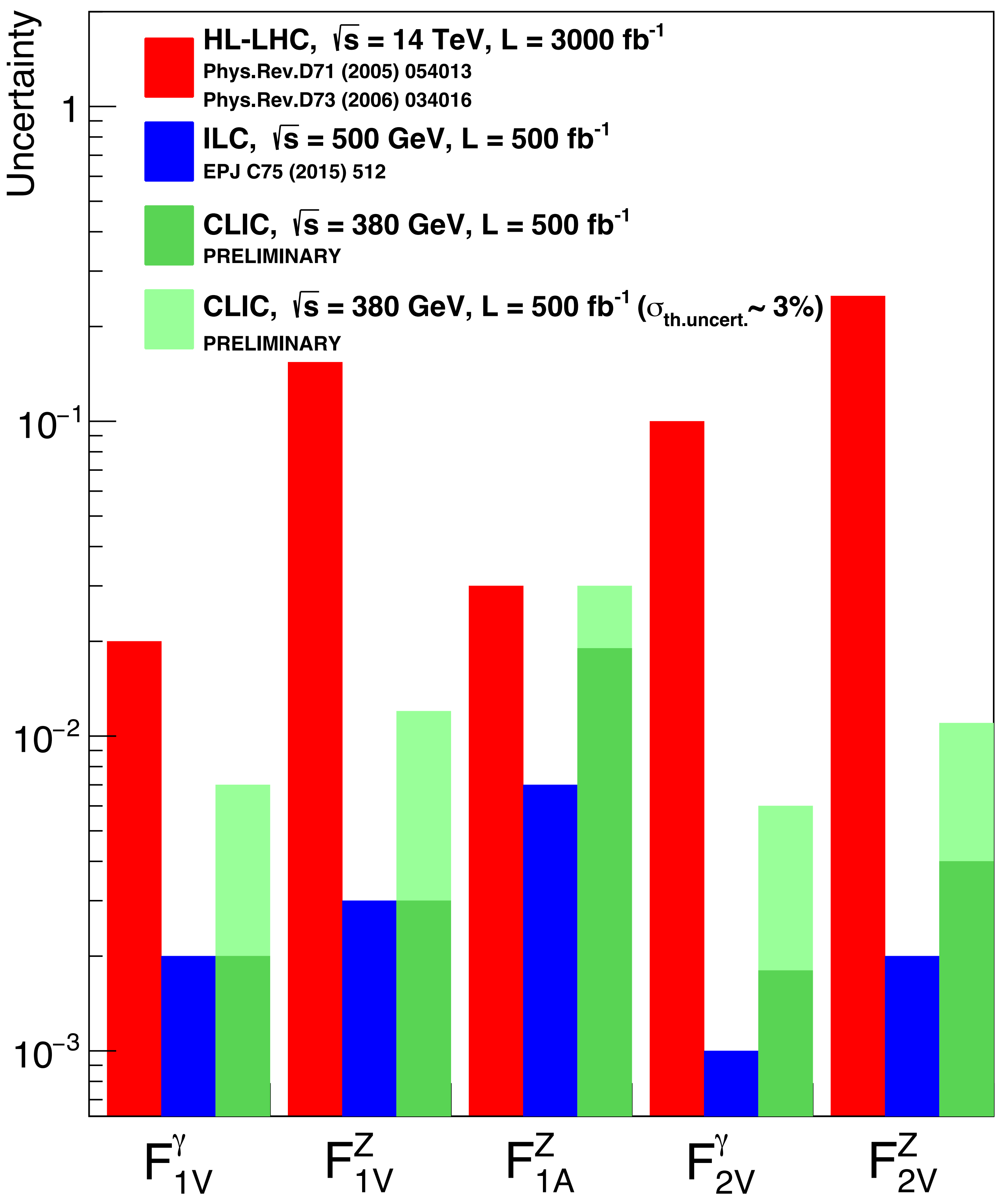
- The structure **of the ttX vertex** for on-shell t and $\bar{t}$ and off-shell γ, Z is:

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

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



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CP-conserving couplings

Top quark electroweak couplings

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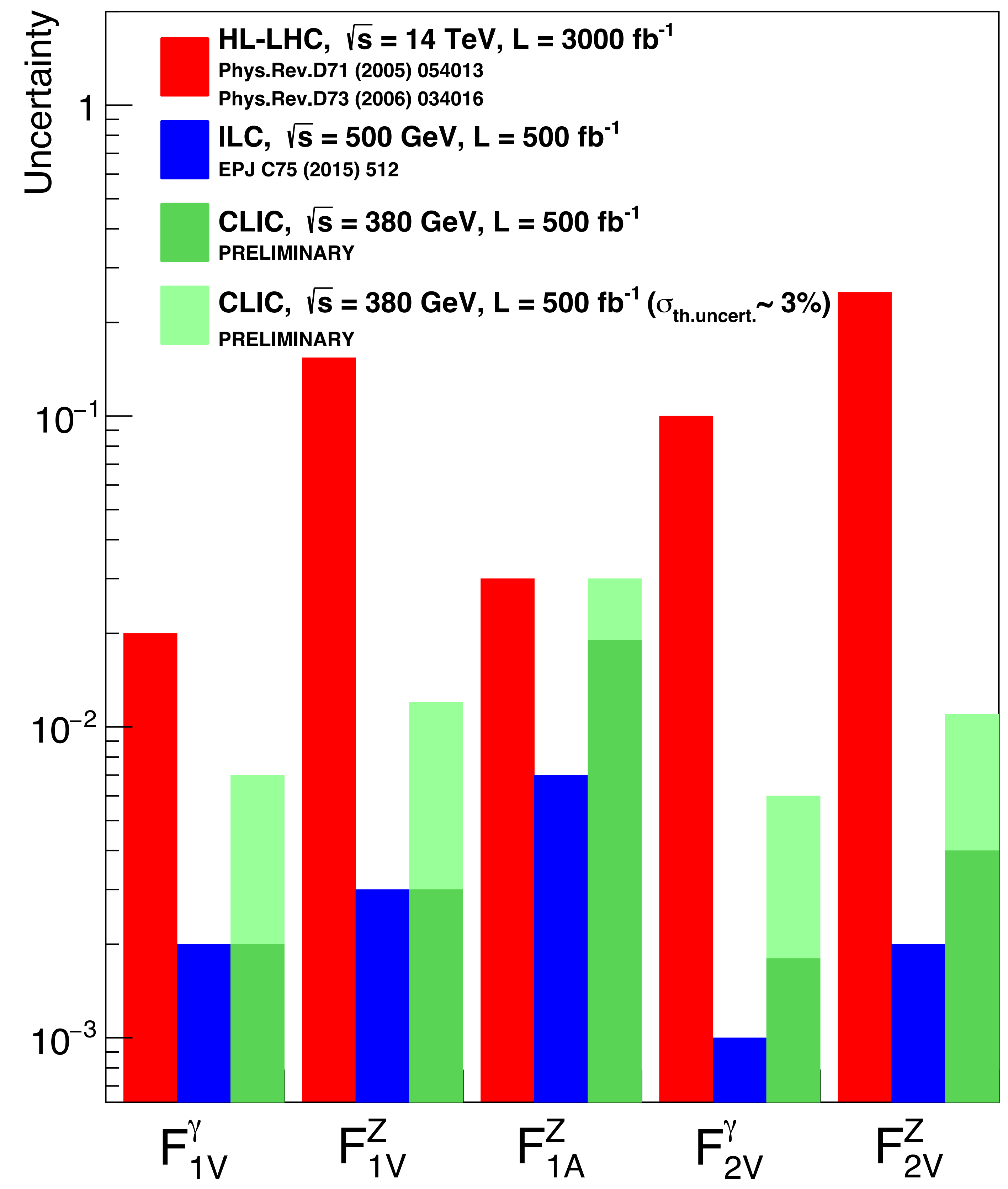


CP-violating couplings

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

CP-conserving couplings

CP-violation: $e^+e^- \to t\bar{t}$

- **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)**

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

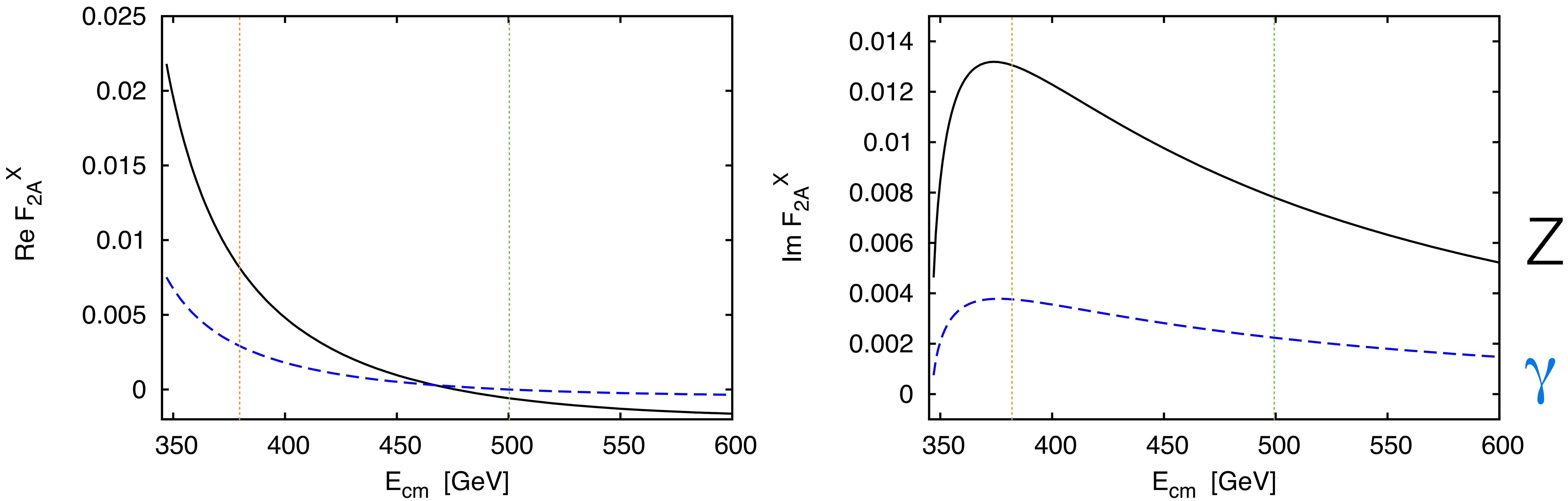
F^X_{2A} are zero at tree level in the SM

- **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

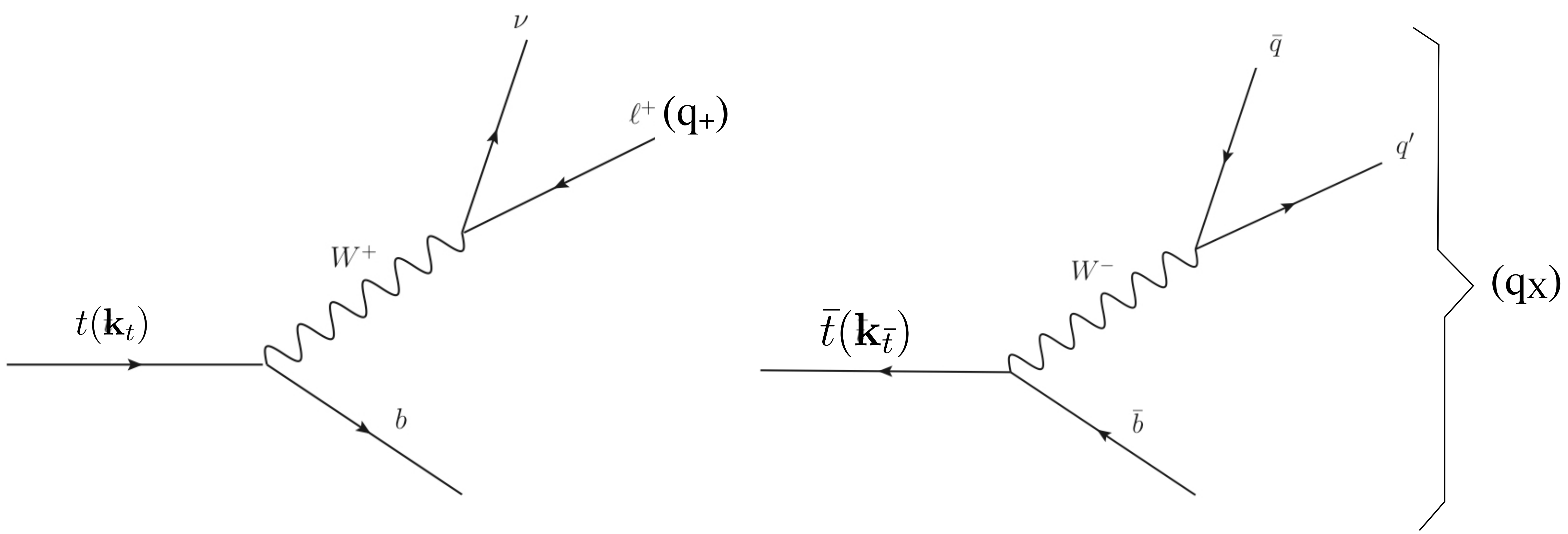
$$e^{+}(\mathbf{p}_{+}, P_{e^{+}}) + e^{-}(\mathbf{p}_{-}, P_{e^{-}}) \quad \rightarrow \quad t(\mathbf{k}_t) + \bar{t}(\mathbf{k}_{\bar{t}})$$

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

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

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

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



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

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

Coefficients vs √s

Coefficients $c_\gamma(s)$ and $c_Z(s)$ 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

Simulation samples (6f -> lepton+jets)

Full simulation

- WHIZARD: event generation
- GEANT4: detector simulation
- Pandora PFOs
- LCFIPlus: Heavy-flavour jets

ILC@500GeV initial (ILD detector)

$500fb^{-1}$, P(e-)=∓80%, P(e+)=∓30%

ILC@500GeV nominal (ILD detector)

$4ab^{-1}$, P(e-)=∓80%, P(e+)=∓30%

CLIC@380GeV (CLIC_ILD detector)

$500fb^{-1}$, P(e-)=∓80%

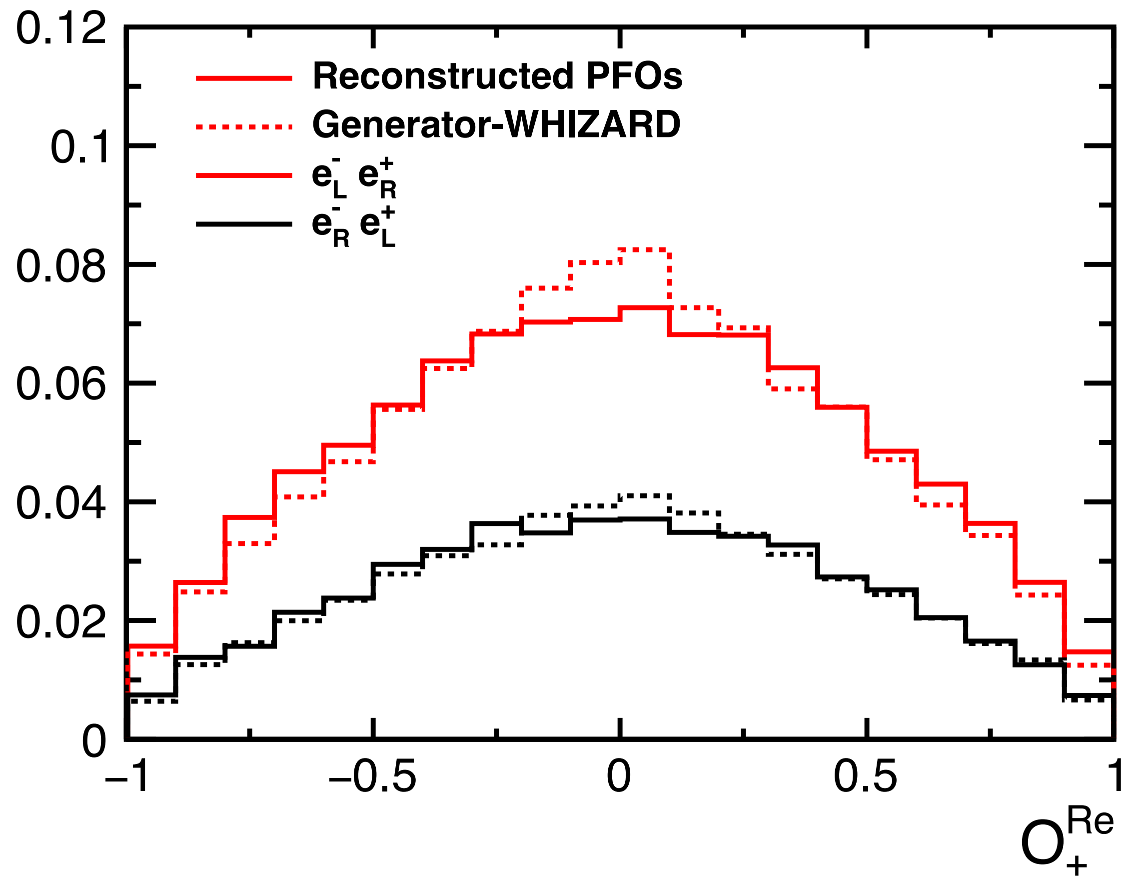
Parton level study for high-energy operation

- MG5 aMC@NLO
- Boosted top quarks
- Detector resolution: smearing of the parton 4-vectors

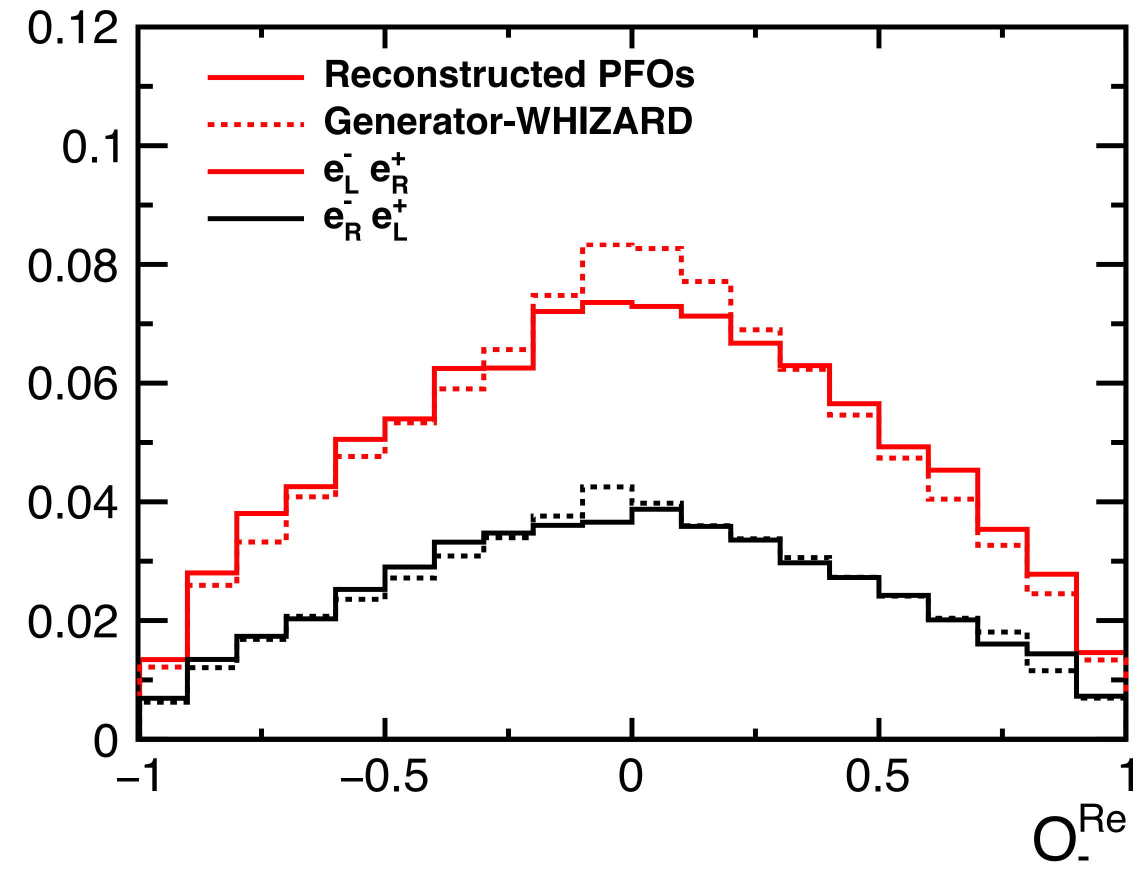
CLIC@3TeV

$3ab^{-1}$, P(e-)=∓80%

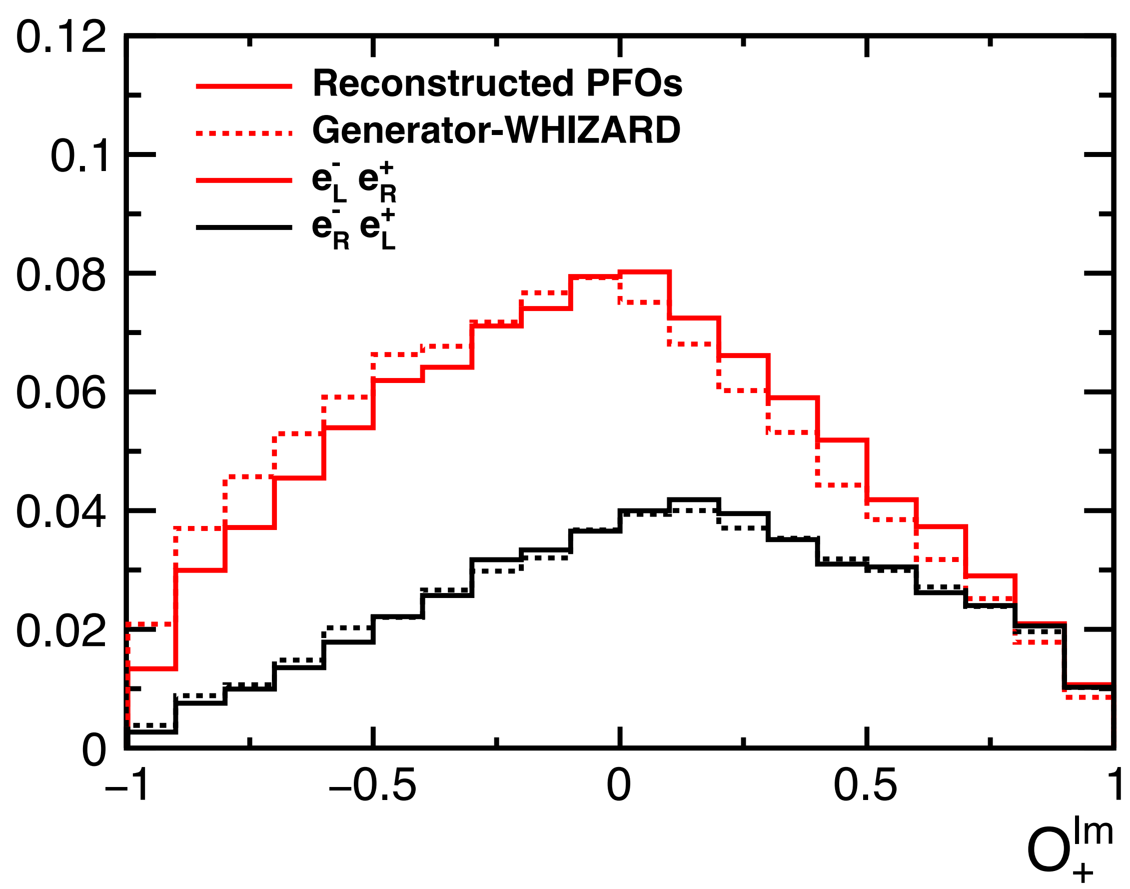
Full simulation: ILC@500GeV



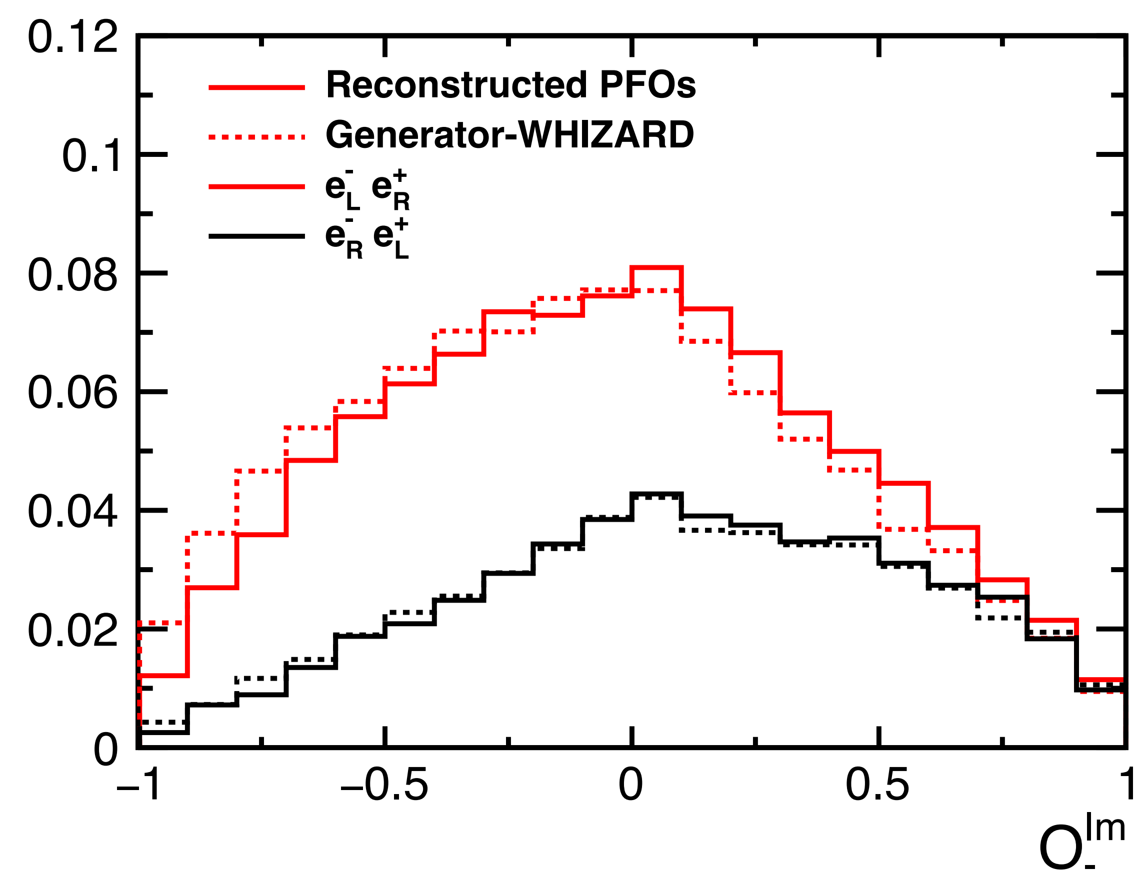
(a) $\mathcal{O}^{Re}_+$



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



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



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

- 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}

ILC $\sqrt{s}$ = 500 GeV, 500fb^{-1} [%]		
$P(e^-), P(e^+)$	$\mathcal{A}^{Re}_{\gamma,Z}$	$\mathcal{A}^{Im}_{\gamma,Z}$
-0.8, +0.3	0.0053 ± 0.003	-0.0022 ± 0.003
+0.8, -0.3	0.0025 ± 0.004	-0.007 ± 0.004

- **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 (non-linearity)	+3%	+5%	+10%
exp. reconstruction (non-linearity)	-5%	-5%	-15%
theory (bias)	$<< 0.001$	$<< 0.001$	$<< 0.001$
theory (non-linearity)	$\pm$ 2%	$\pm$ 0.9%	$\pm$ 0.5%

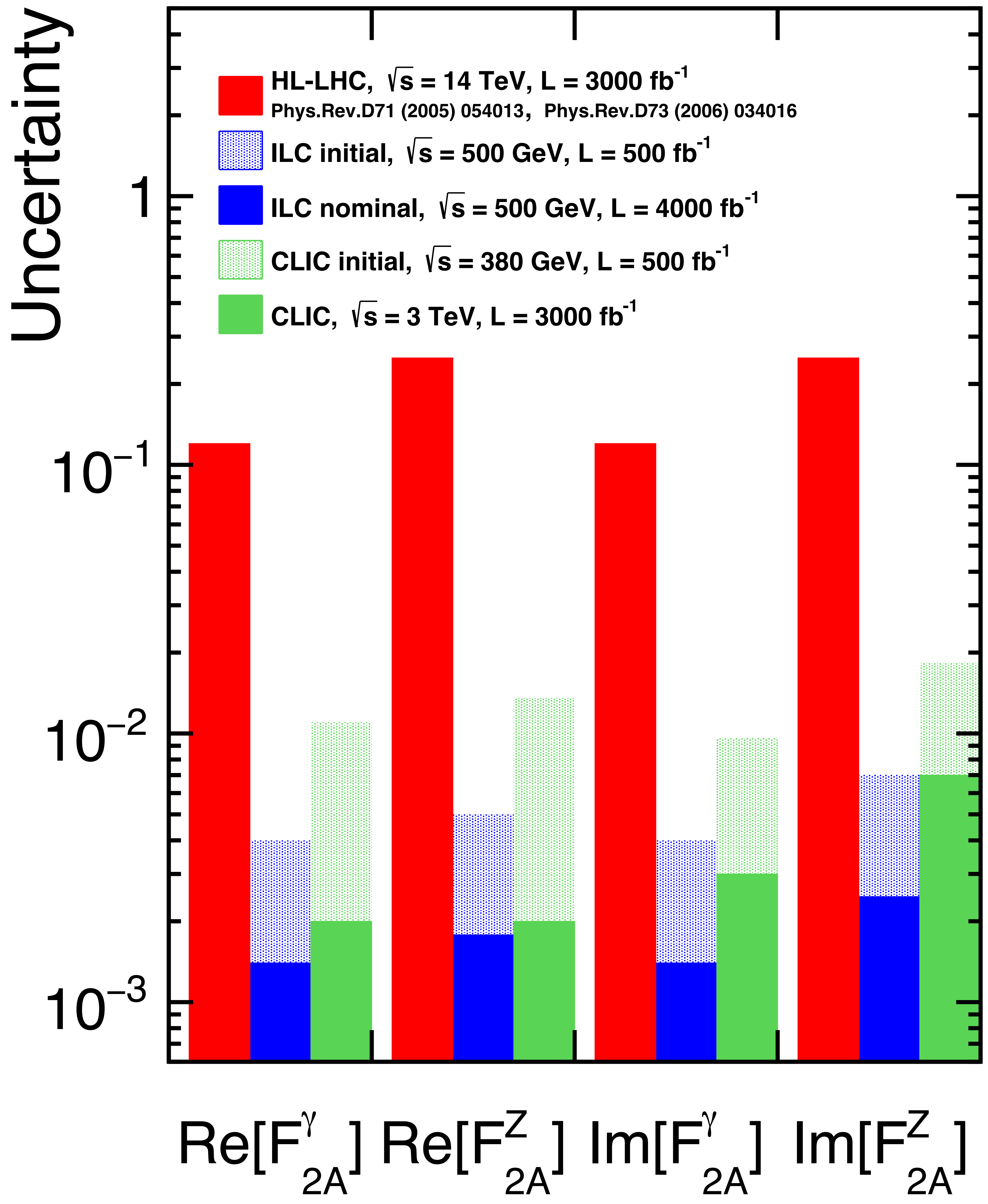
Bias: upper limit

Non-linearity: expected relative modification

- The determination of P(e-) and P(e+) at the $\mathbf{10^{-3}}$ level (as envisaged in the ILC TDR) does not lead to significant uncertainties in the form factor extraction
- The **uncertainties of other machine parameters** (luminosity or √s) have a **negligible effect** on the results
- **Distortions** and **migrations** on the distributions **O+ and O- vanish in the asymmetry. Systematics effects** 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
- **Initial ILC** and **CLIC 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**



Most relevant modifications

1. Addition of a **new paragraph with detector details** -> Balance theoretical and experimental content of the paper

2. Modified the **TESLA TDR luminosity to 300fb-1** instead of 500fb-1

3. **Table of systematic uncertainties** and the table of the **colliders prospects** on the top quark form factors extraction have been **properly modified**

4. **Legend of the Manhattan plot** (and in the overall text)
    - ILC (500fb-1) -> ILC initial
    - ILC (4ab-1) -> ILC nominal

5. Other suggestions implemented from the feedback of the CLICdp reviewers

Acknowledgements

Very appreciated comments and suggestions from ILD reviewers

- **Daniel Jeans**: done (draft paper v9)
- **Junping Tian**: done (draft paper v9)
- **Jenny List**: the implementation of her comments is ongoing and a v10 of the paper will be available on the following days

Many thanks!!

Review report by Daniel in the next talk

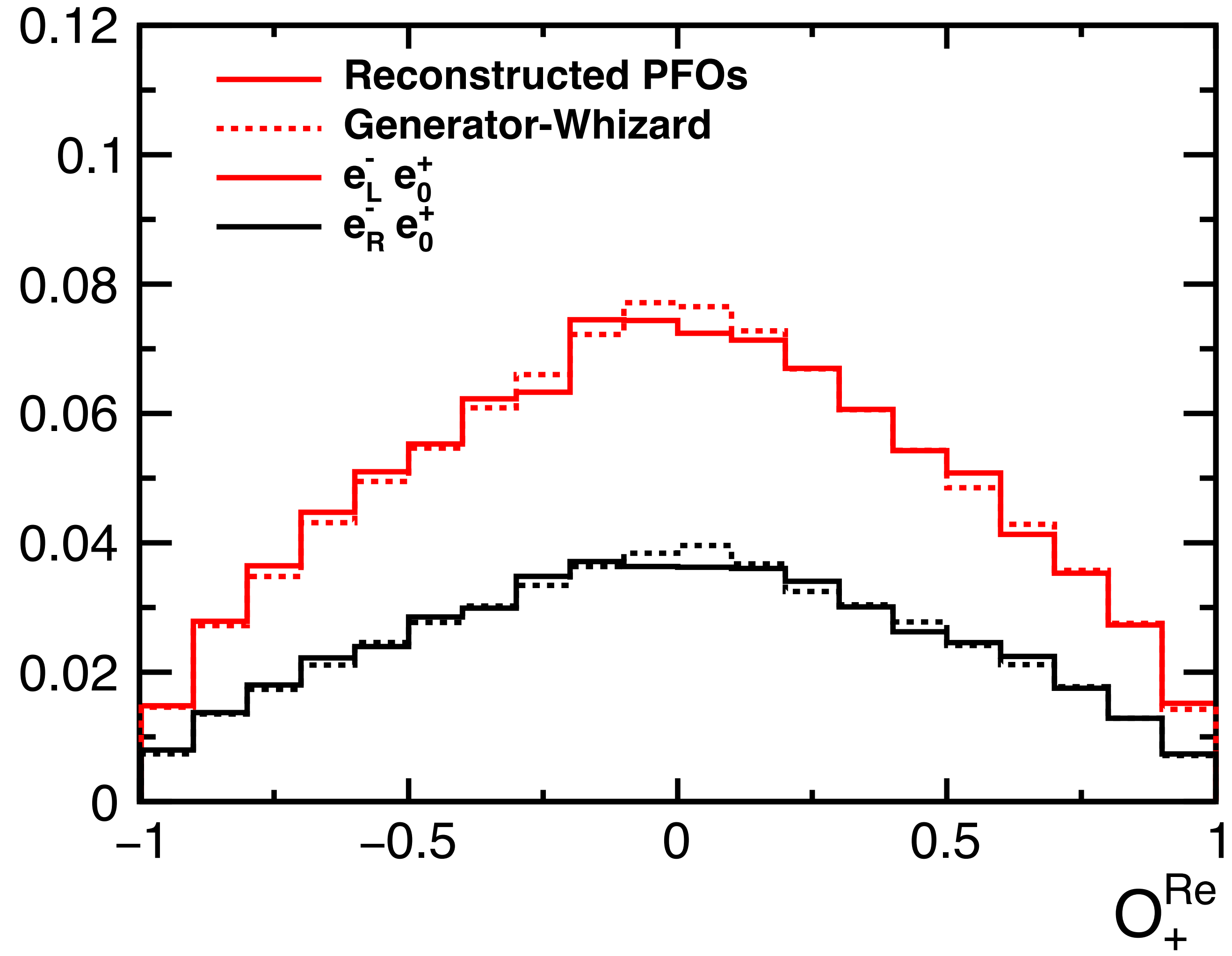
Recent acknowledgements:

- **CLICdp and ILD**: The authors acknowledge the use of the ILC and CLIC simulation infrastructure. The study in Section 6 has been carried out in the framework of the ILD detector concept, that of Section 7 in the CLICdp collaboration.
- **LCG Resources**: This work benefits from services provided by the ILC Virtual Organisation, supported by the national resource providers of the EGI Federation (ILCDIRAC v26r0p13 documentation)

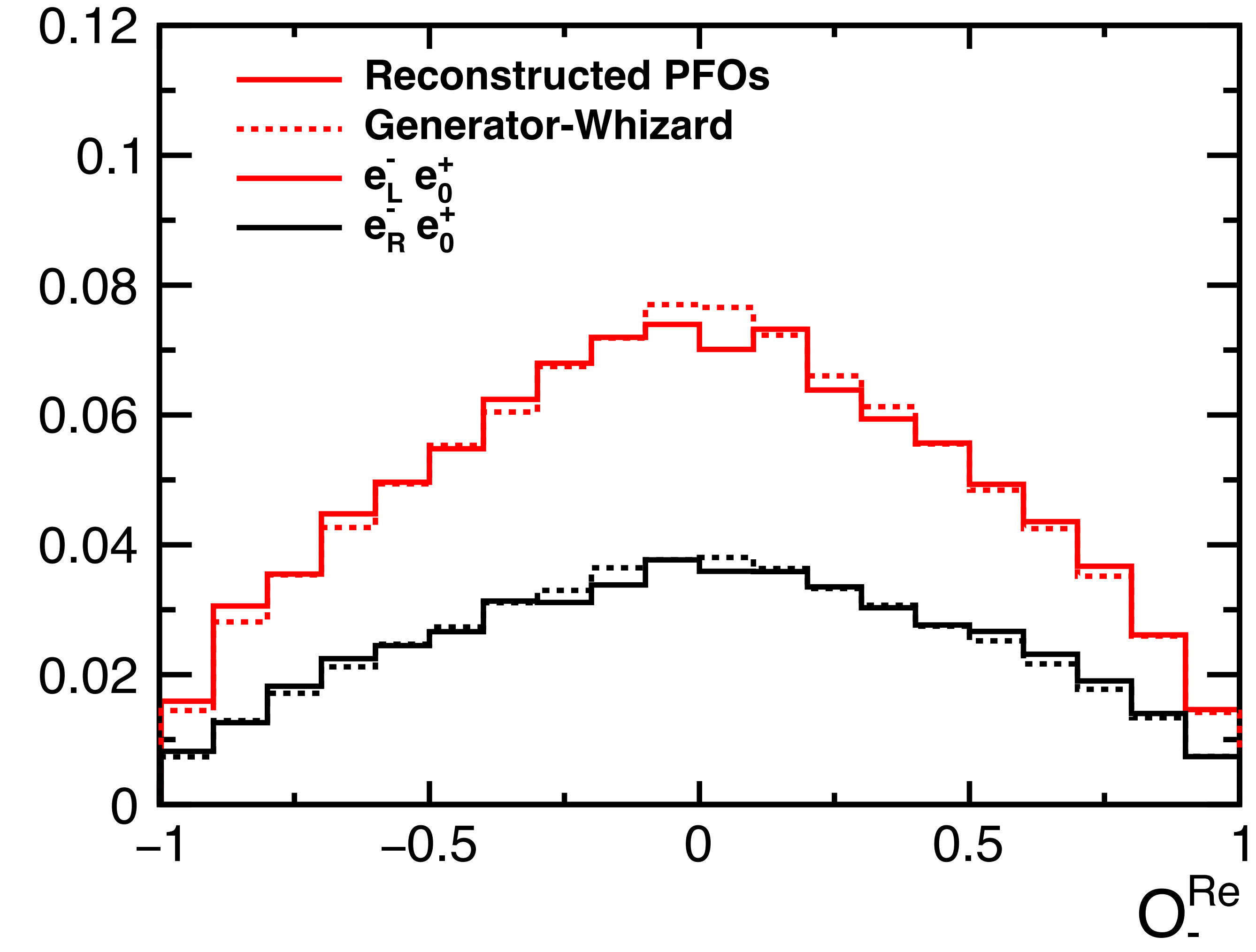
New

- **OSG Resources:** This research was done using resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science (ILCDIRAC v26r0p13 documentation)
- Any proposal for a default **acknowledgement sentence for the ILD** MC production team? Jenny suggested being more cordial

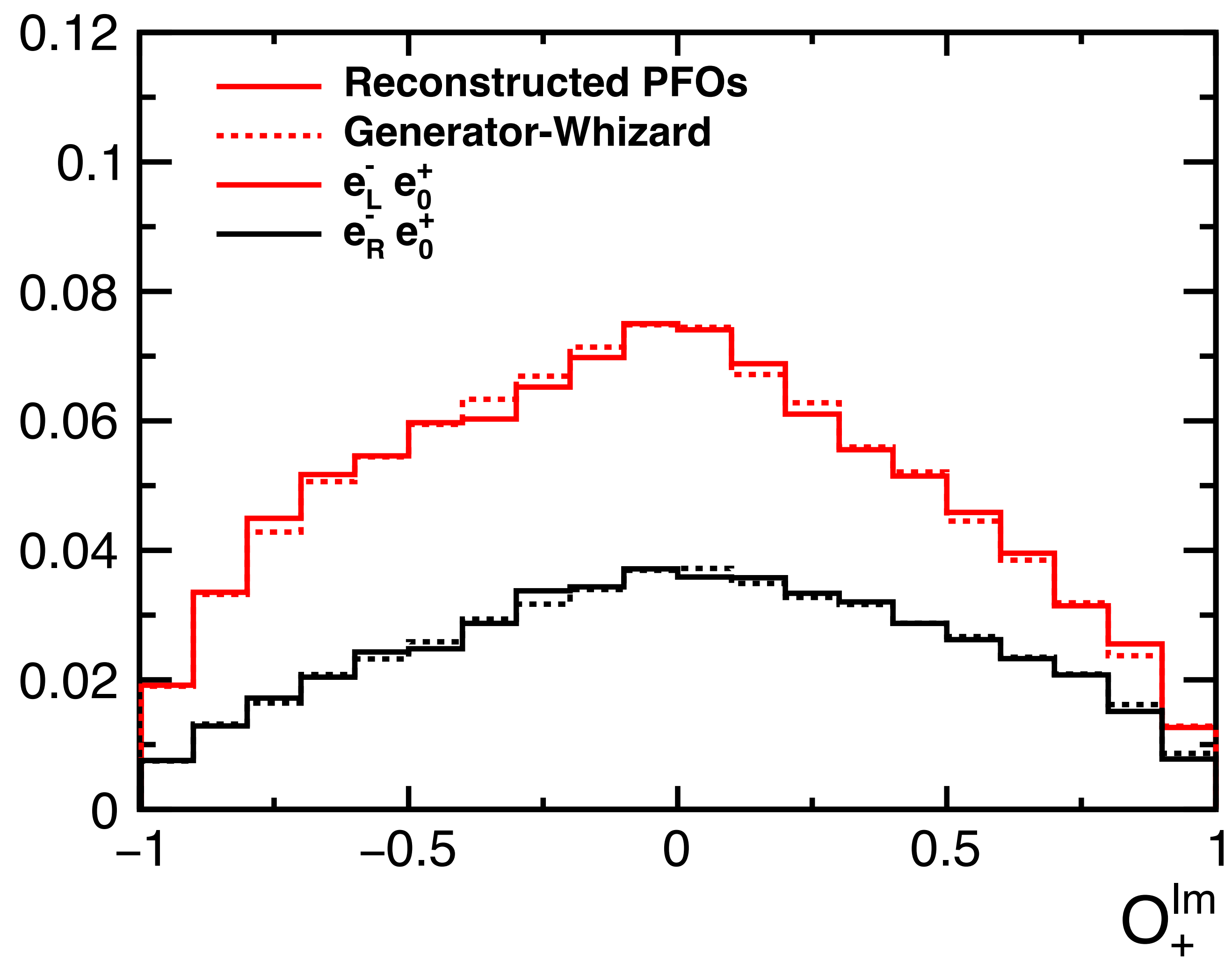
Full simulation: CLIC@380GeV



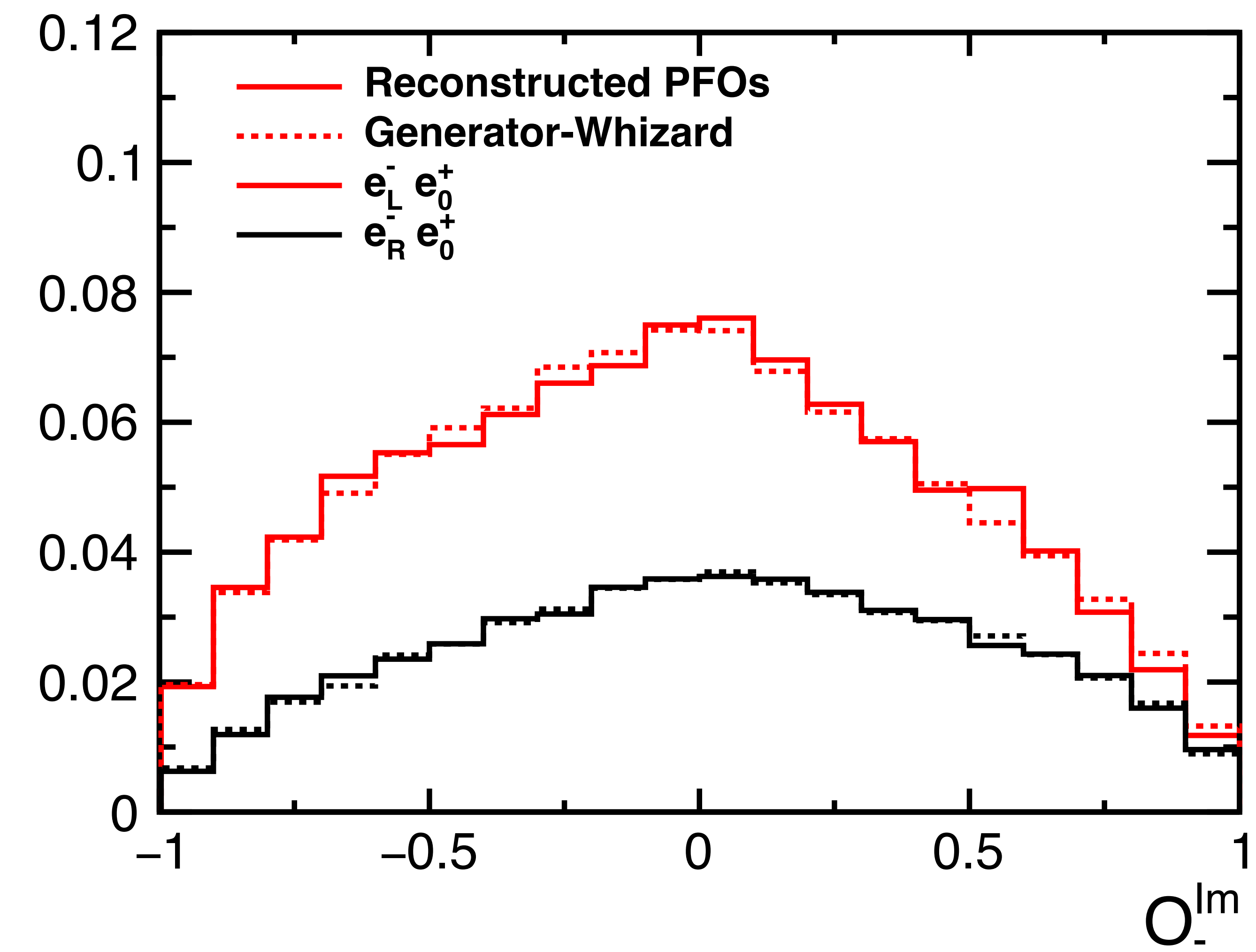
(a) $\mathcal{O}_+^{Re}$



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

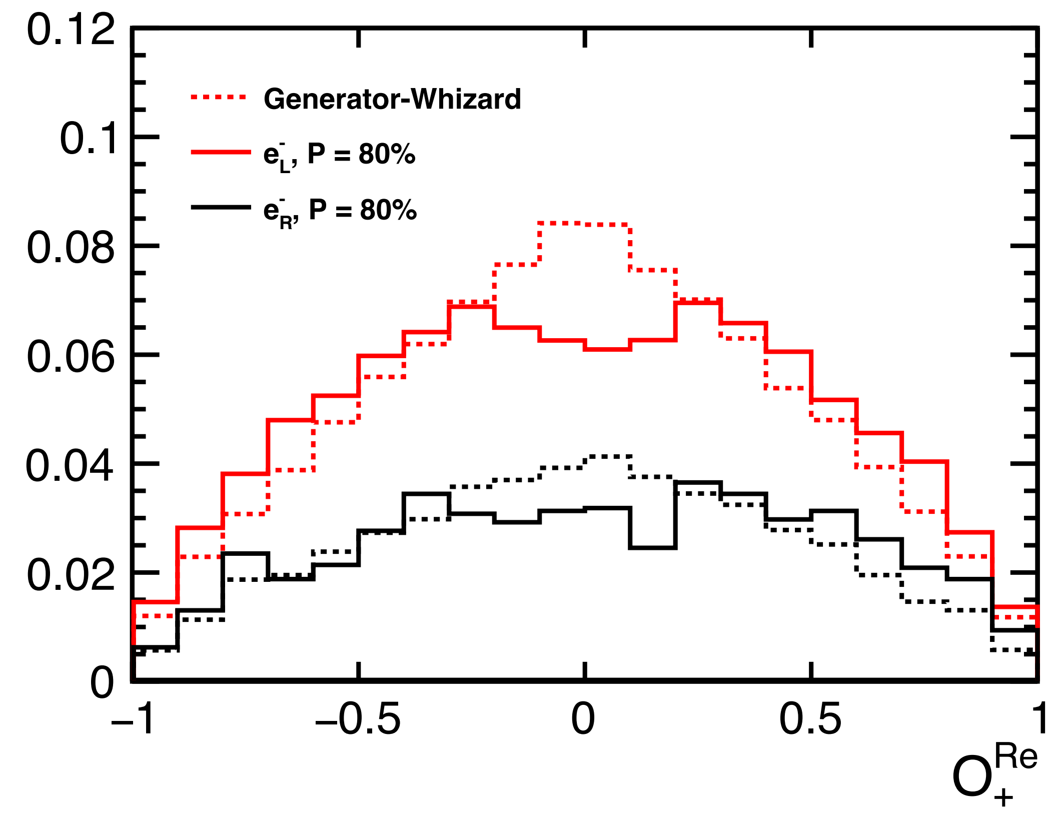


(c) $\mathcal{O}_+^{Im}$



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

Full simulation: CLIC@1.4TeV



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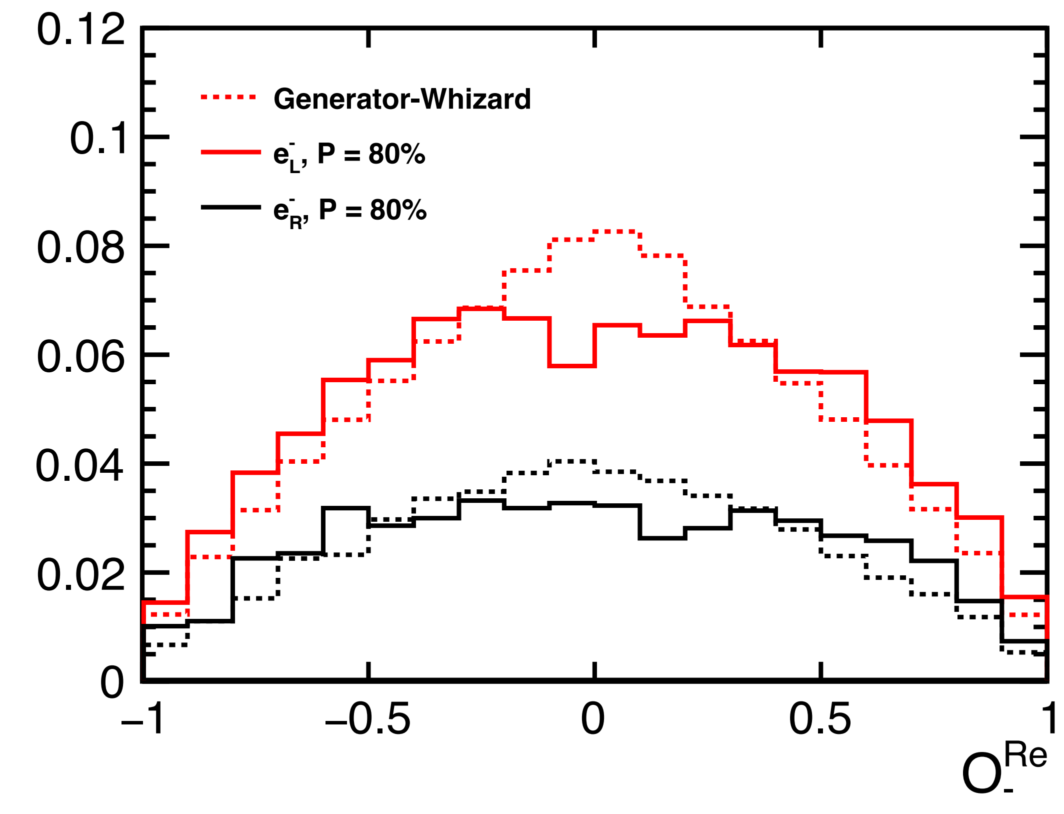
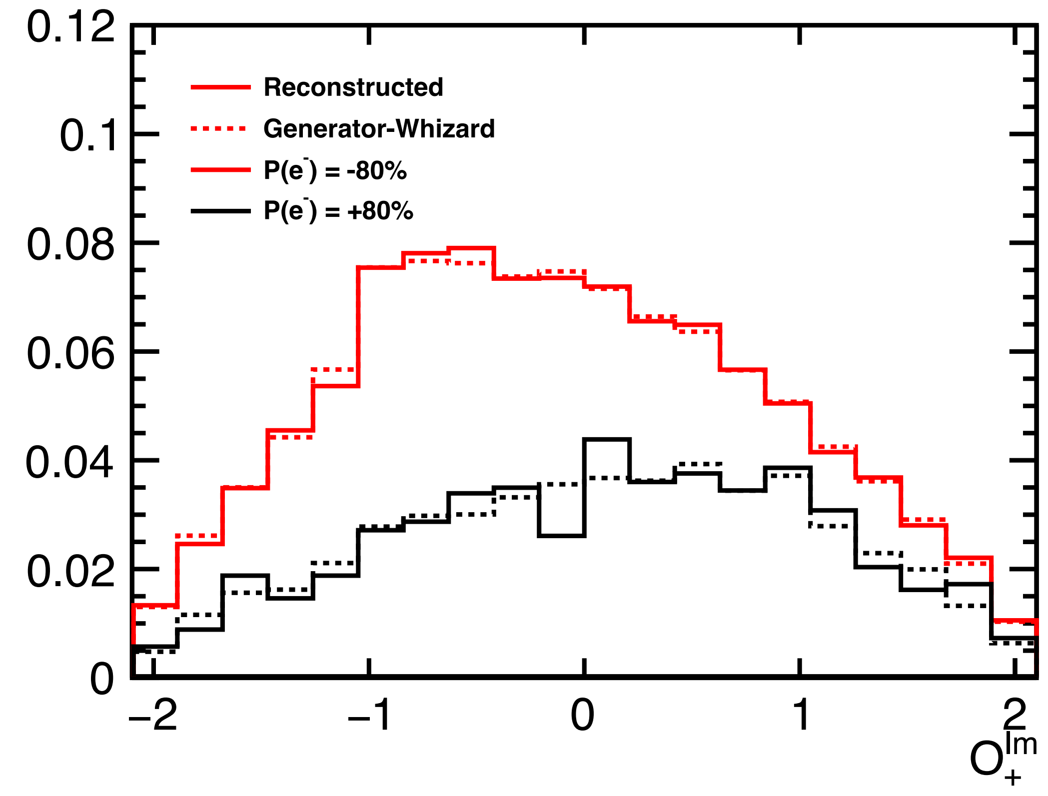


(b) $\mathcal{O}_-^{Re}$



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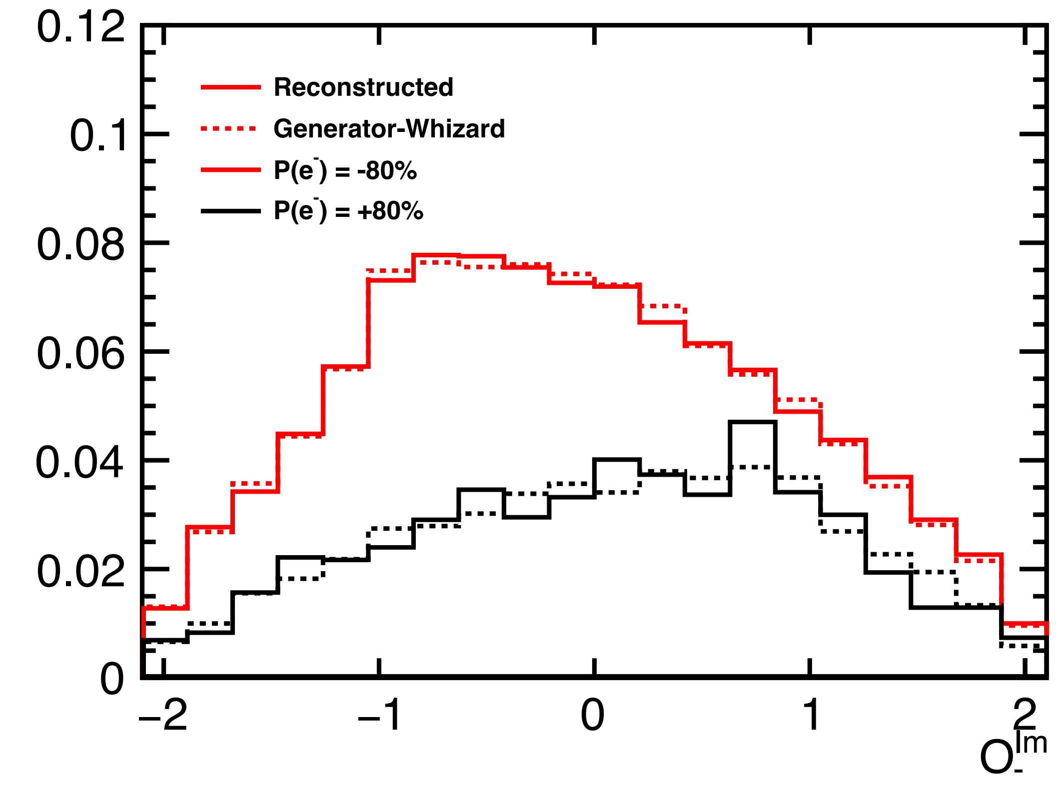
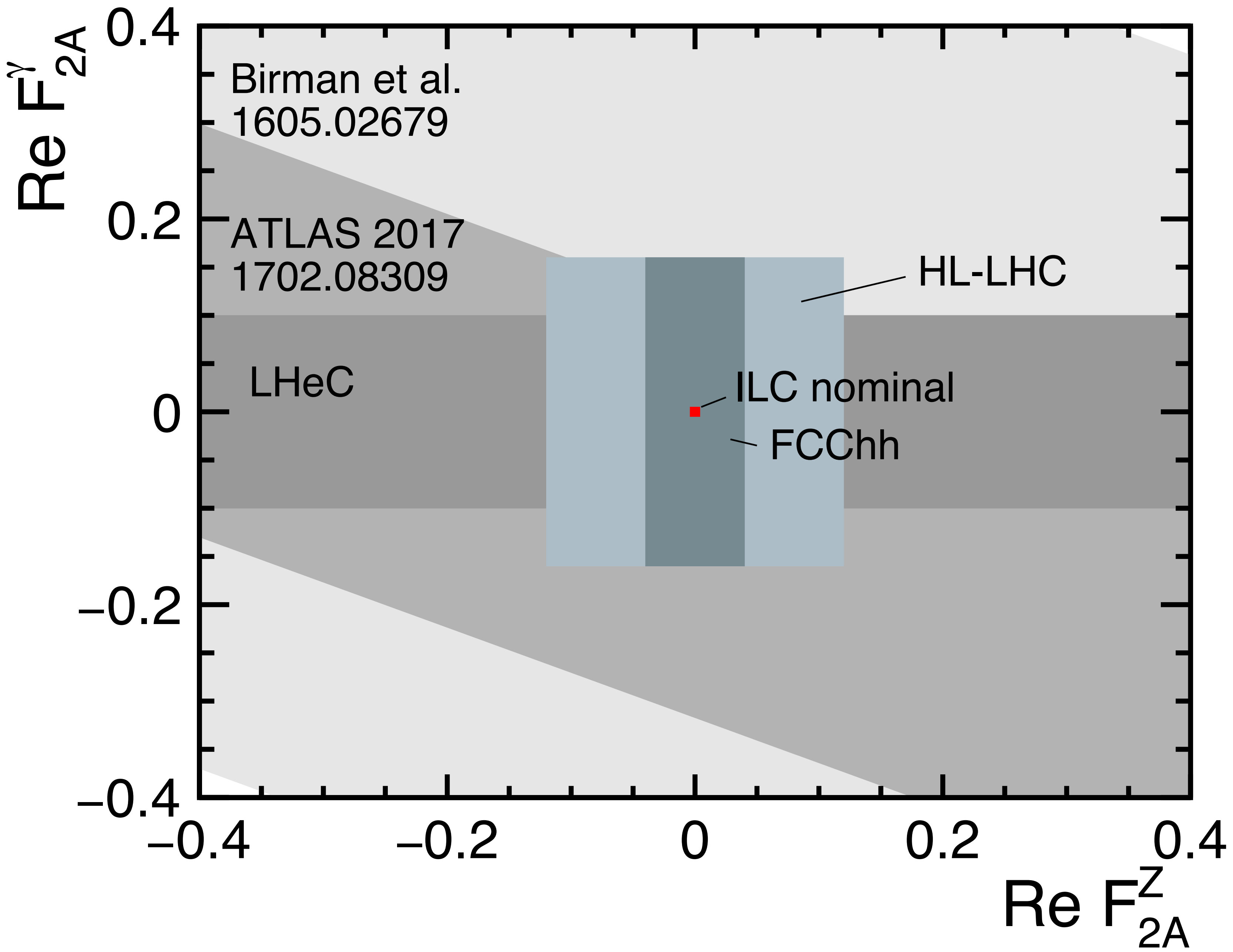


(d) $\mathcal{O}_-^{Im}$

Prospects for CP-violating form factors

machine	collision	$\sqrt{s}$ [TeV]	L_{int} [ab^{-1}]	Re F_{2A}^{γ}	Re F_{2A}^{Z}	Im F_{2A}^{γ}	Im F_{2A}^{Z}
Prospects derived in this study:							
CLIC initial	e^+e^-	0.38	0.5	0.011	0.014	0.010	0.018
ILC nominal	e^+e^-	0.5	0.5	0.004	0.005	0.004	0.007
ILC LumiUp	e^+e^-	0.5	4	0.0014	0.0017	0.0014	0.002
CLIC (fast simulation)	e^+e^-	3	3	0.002	0.002	0.003	0.006
Previous studies for lepton colliders:							
TESLA (Aguilar et al. [75])	e^+e^-	0.5	0.3	0.007	0.008	0.008	0.010
Prospects for hadron colliders:							
HL-LHC (Baur et al. [76,77])	pp	14	3	0.12	0.25	0.12	0.25
HL-LHC (Röntsch & Schulze [5])	pp	14	3	-	0.16	-	-
FCChh (Mangano et al. [79])	pp	100	3	-	0.04	-	-
LHeC (Bouzas et al. [80])	ep	-	0.1	0.1	-	-	-



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

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